The Simulated Cosmic Web

I: Simulating the Universe

Dr Noam I Libeskind

Cosmography and Large-scale structure

AIP
Leibniz-Institut für
Astrophysik Potsdam

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I: Simulating the Universe
II: Simulating the Local Universe

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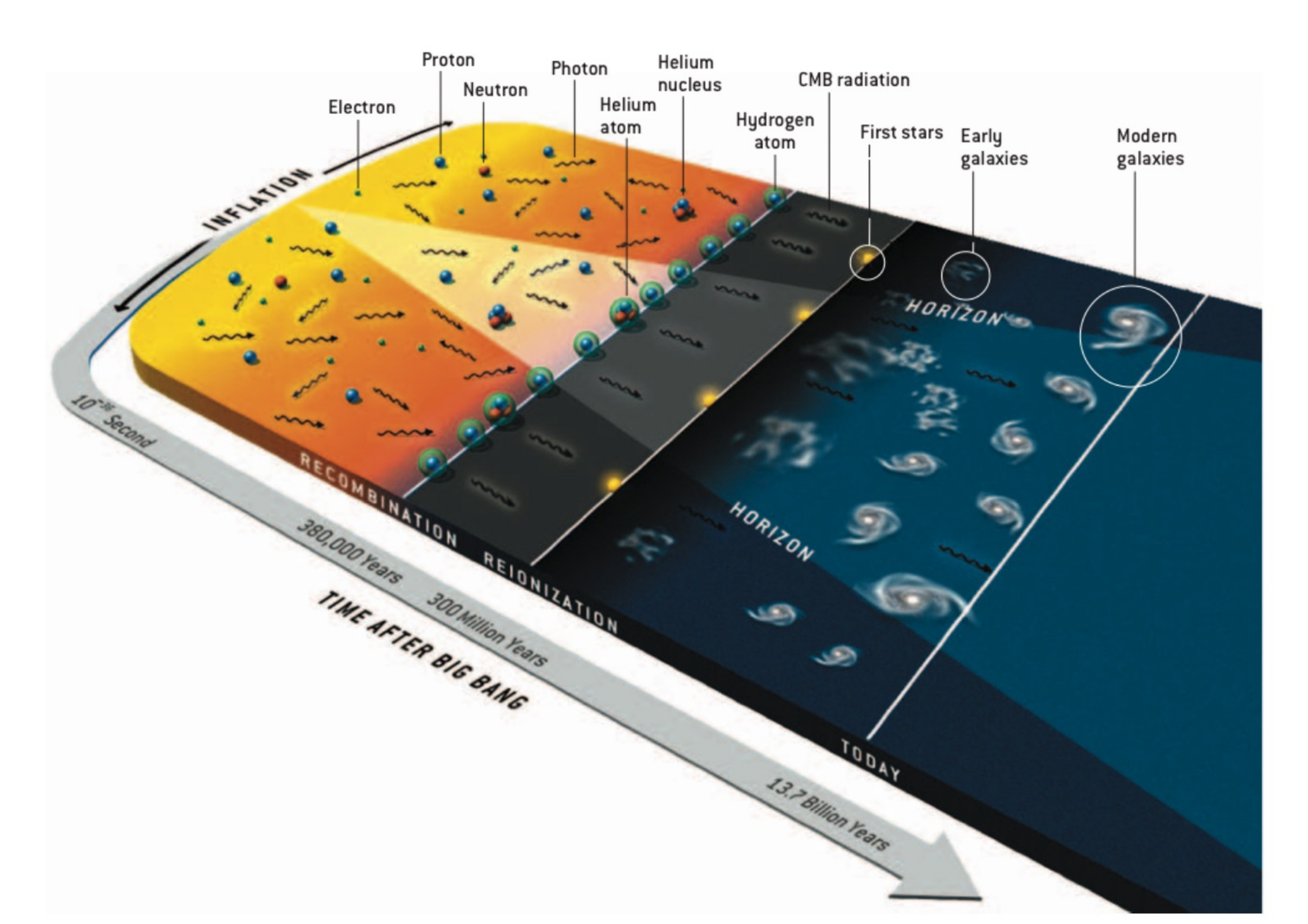
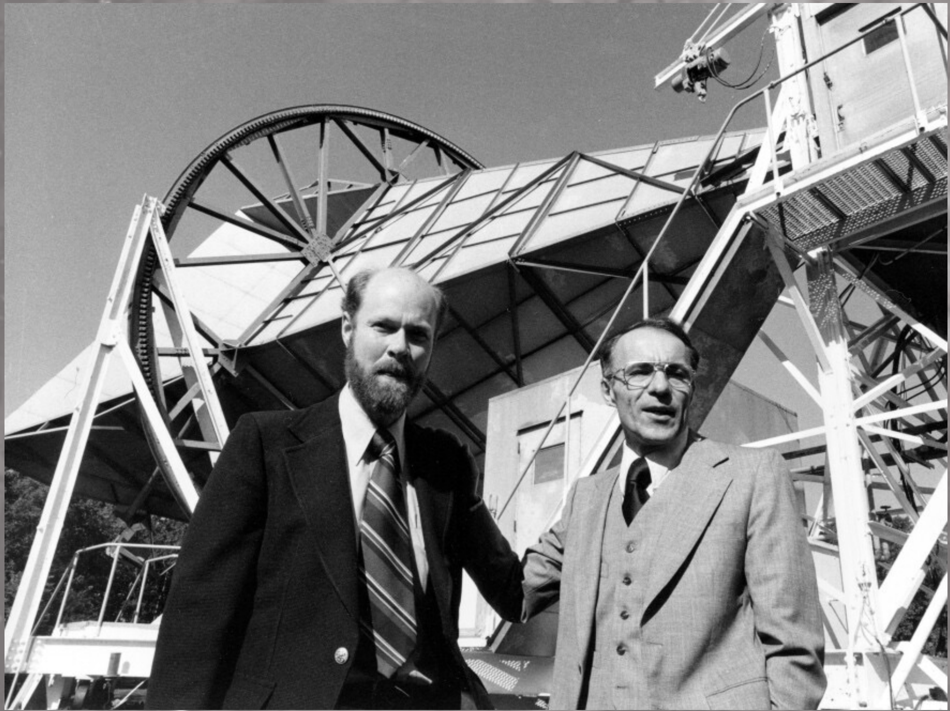
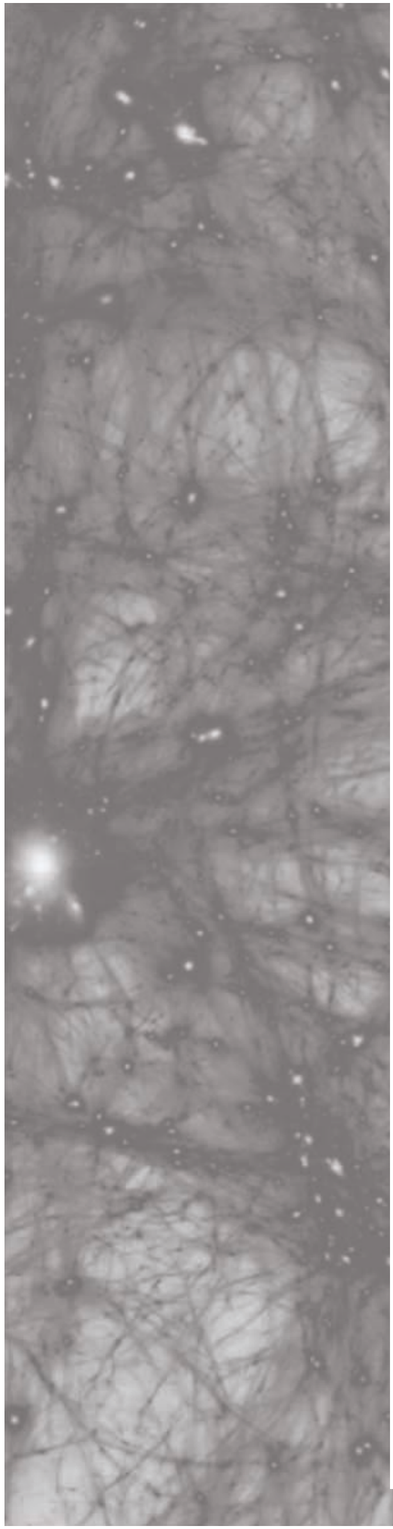
The (hot) big bang model





Penzias & Wilson’s Horn Antenna



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R. H. Dicke
P. J. E. Peebles
P. G. Roll
D. T. Wilkinson

May 7, 1965
Palmer Physical Laboratory
Princeton, New Jersey

REFERENCES

Alpher, R. A , Bethe, H. A , and Gamow, G 1948, *Phys. Rev.*, **73,** 803
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A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE AT 4080 Mc/s

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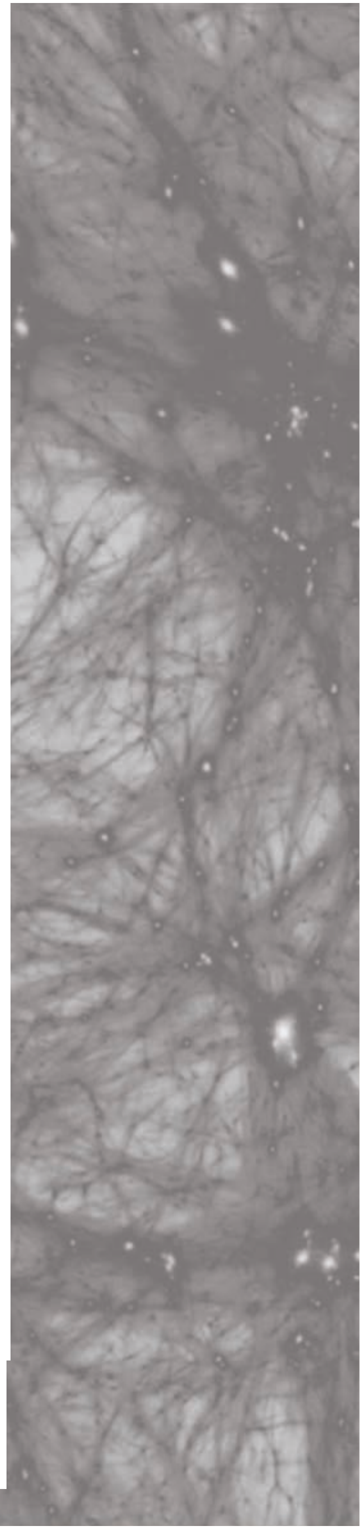

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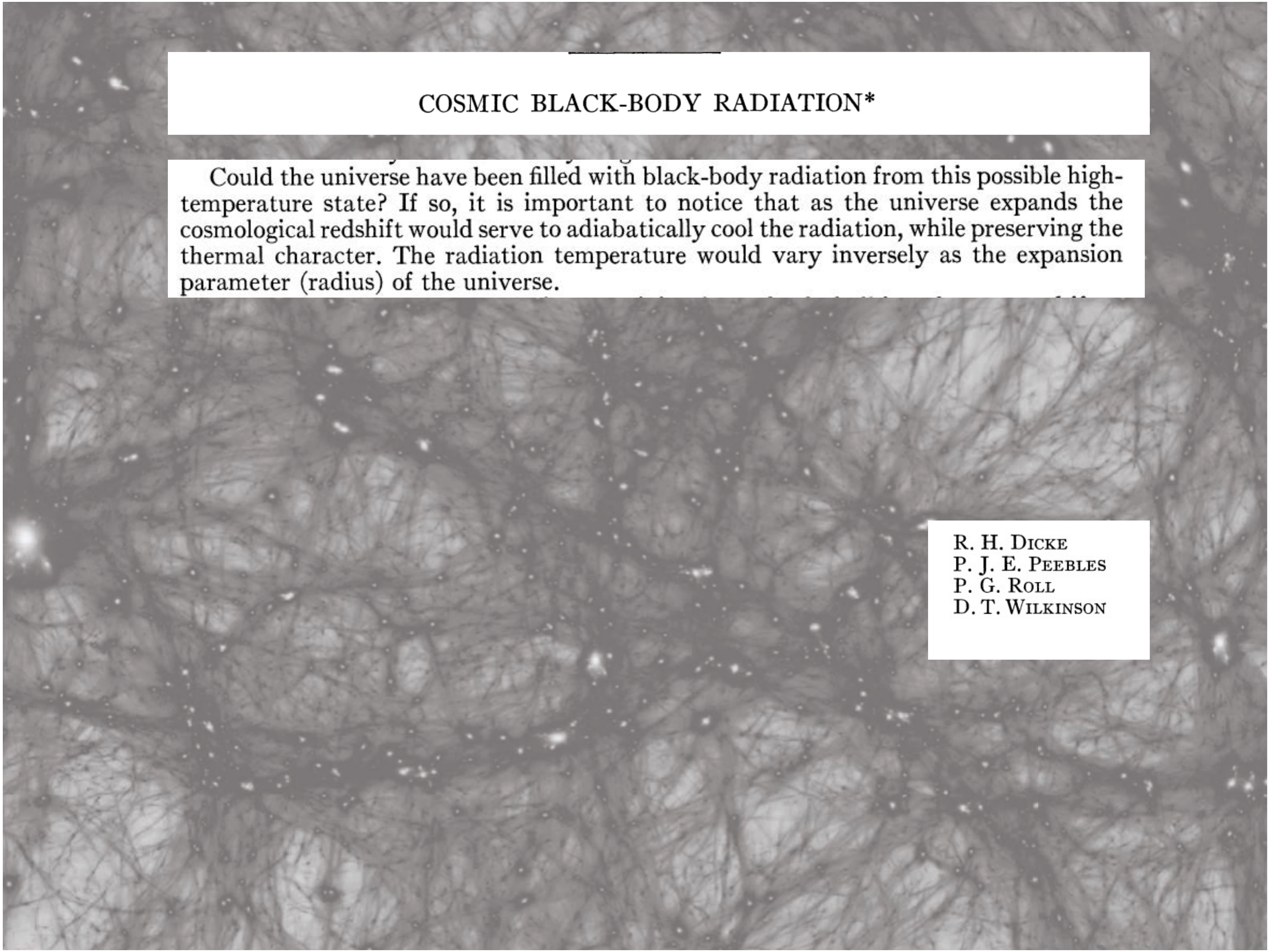

COSMIC BLACK-BODY RADIATION*

Could the universe have been filled with black-body radiation from this possible high-temperature state? If so, it is important to notice that as the universe expands the cosmological redshift would serve to adiabatically cool the radiation, while preserving the thermal character. The radiation temperature would vary inversely as the expansion parameter (radius) of the universe.

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While all the data are not yet in hand we propose to present here the possible conclusions to be drawn if we tentatively assume that the measurements of Penzias and Wilson (1965) do indicate black-body radiation at 3.5° K. We also assume that the universe can be considered to be isotropic and uniform,

R. H. Dicke
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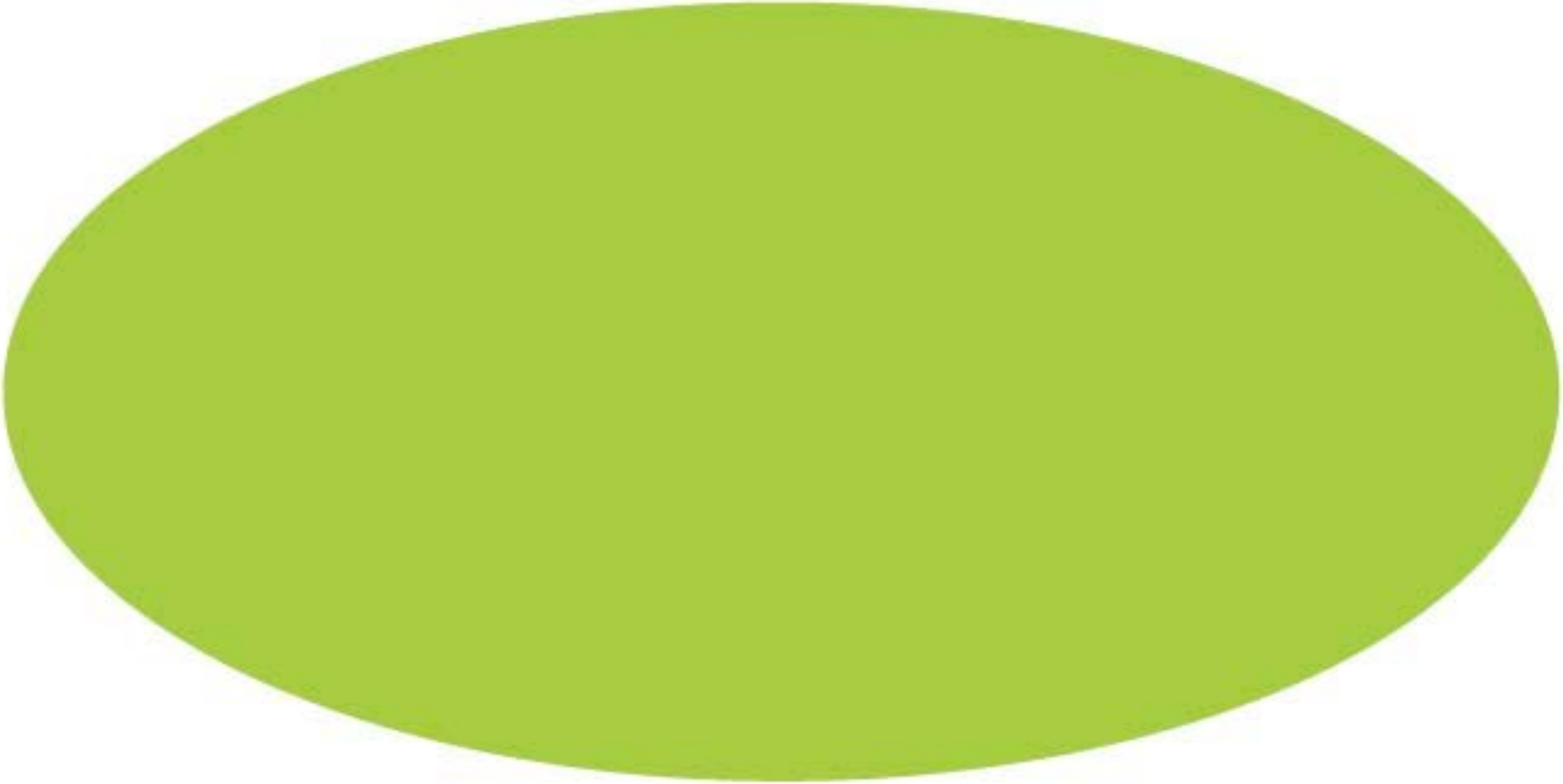
Isotropy of the Cosmic Microwave Background



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THE ASTROPHYSICAL JOURNAL

VOLUME 142 NOVEMBER 15, 1965 NUMBER 4

THE BLACK-BODY RADIATION CONTENT OF THE UNIVERSE AND THE FORMATION OF GALAXIES*

P. J. E. PEEBLES

Palmer Physical Laboratory, Princeton University, Princeton, N J.

Received March 8, 1965; revised June 1, 1965

ABSTRACT

A critical factor in the formation of galaxies may be the presence of a black-body radiation content of the Universe. An important property of this radiation is that it would serve to prevent the formation of gravitationally bound systems, whether galaxies or stars, until the Universe has expanded to a critical epoch. There is good reason to expect the presence of black-body radiation in an evolutionary cosmology, and it may be possible to observe such radiation directly.

Assuming that the Universe is expanding and evolving, very likely most scientists would agree on the over-all picture for the evolution of the Universe. At a remote time in the past the Universe contained only dense gaseous material, with neither stars nor galaxies. As the Universe expanded from this state the material became organized into galaxies and clusters of galaxies, and the material within galaxies passed through the generations of stars. Now a central question is what were the physical processes, and what were the physical parameters and conditions that determined how galaxies formed, with the observed distributions of mass and size, and the observed tendency for galaxies to be distributed in clusters.

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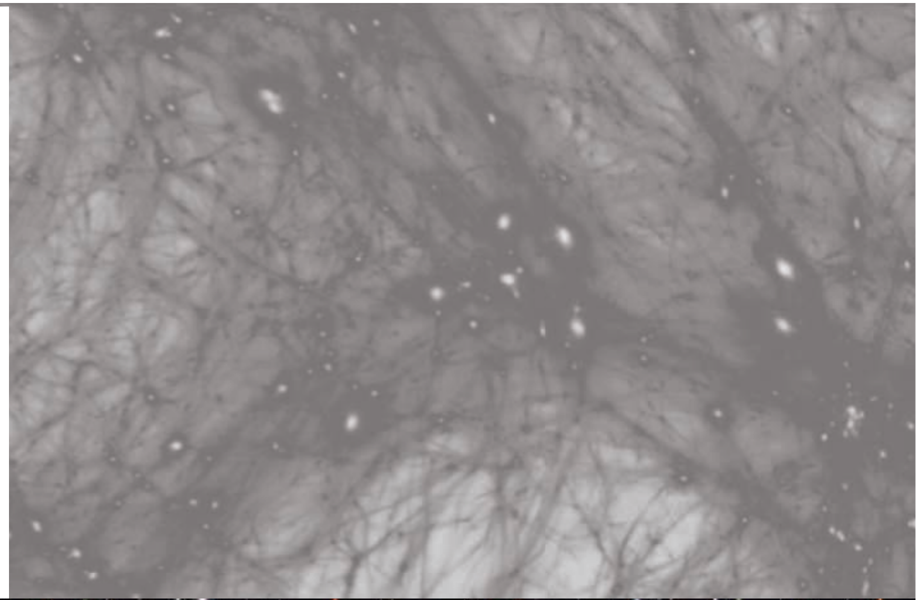

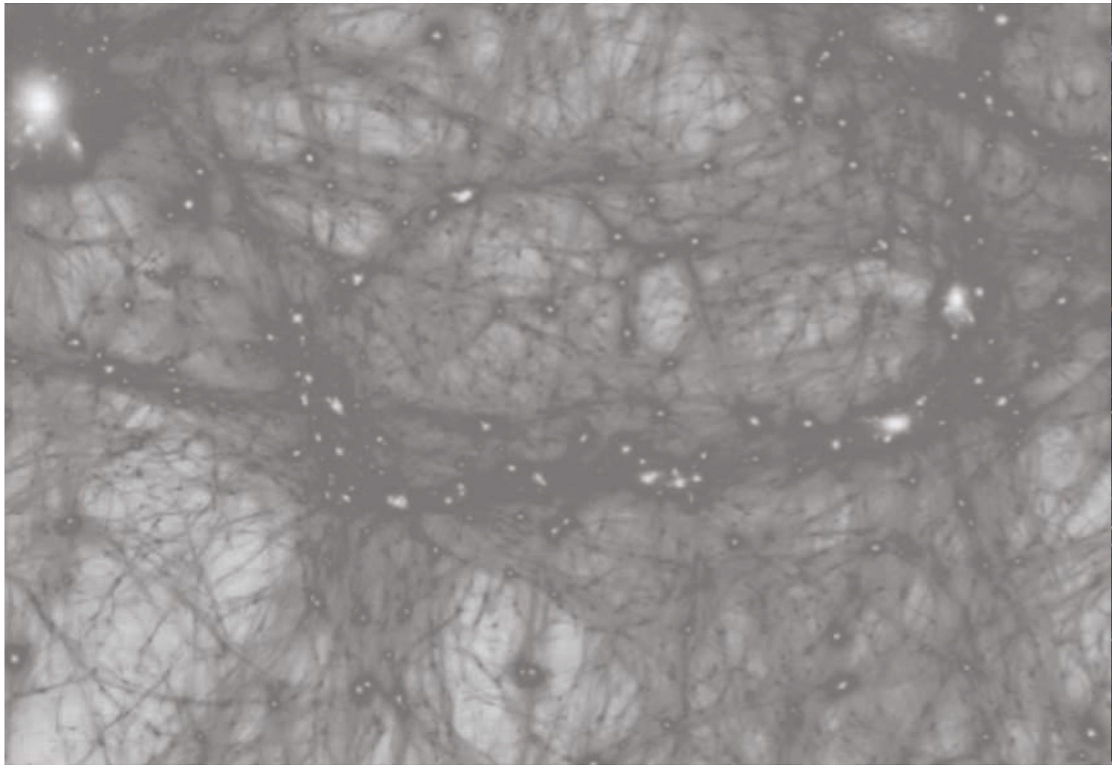

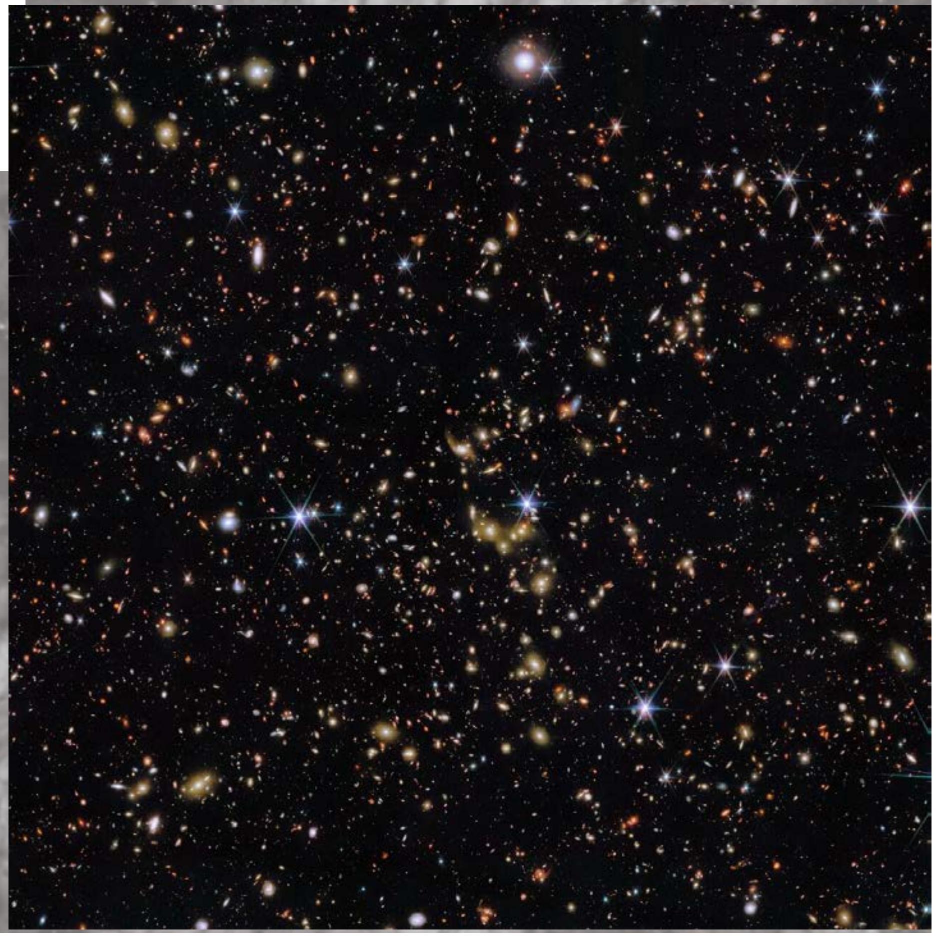

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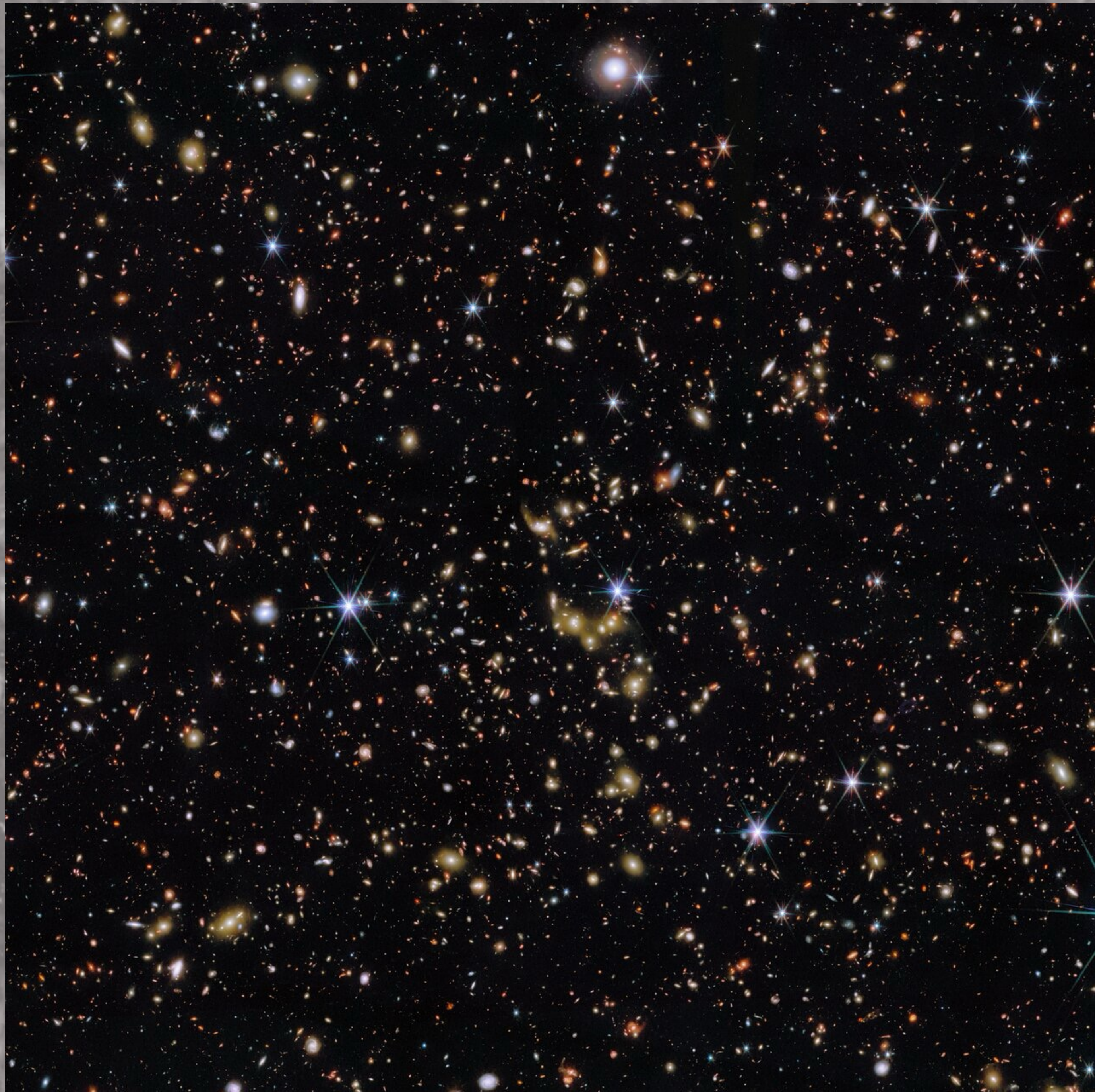

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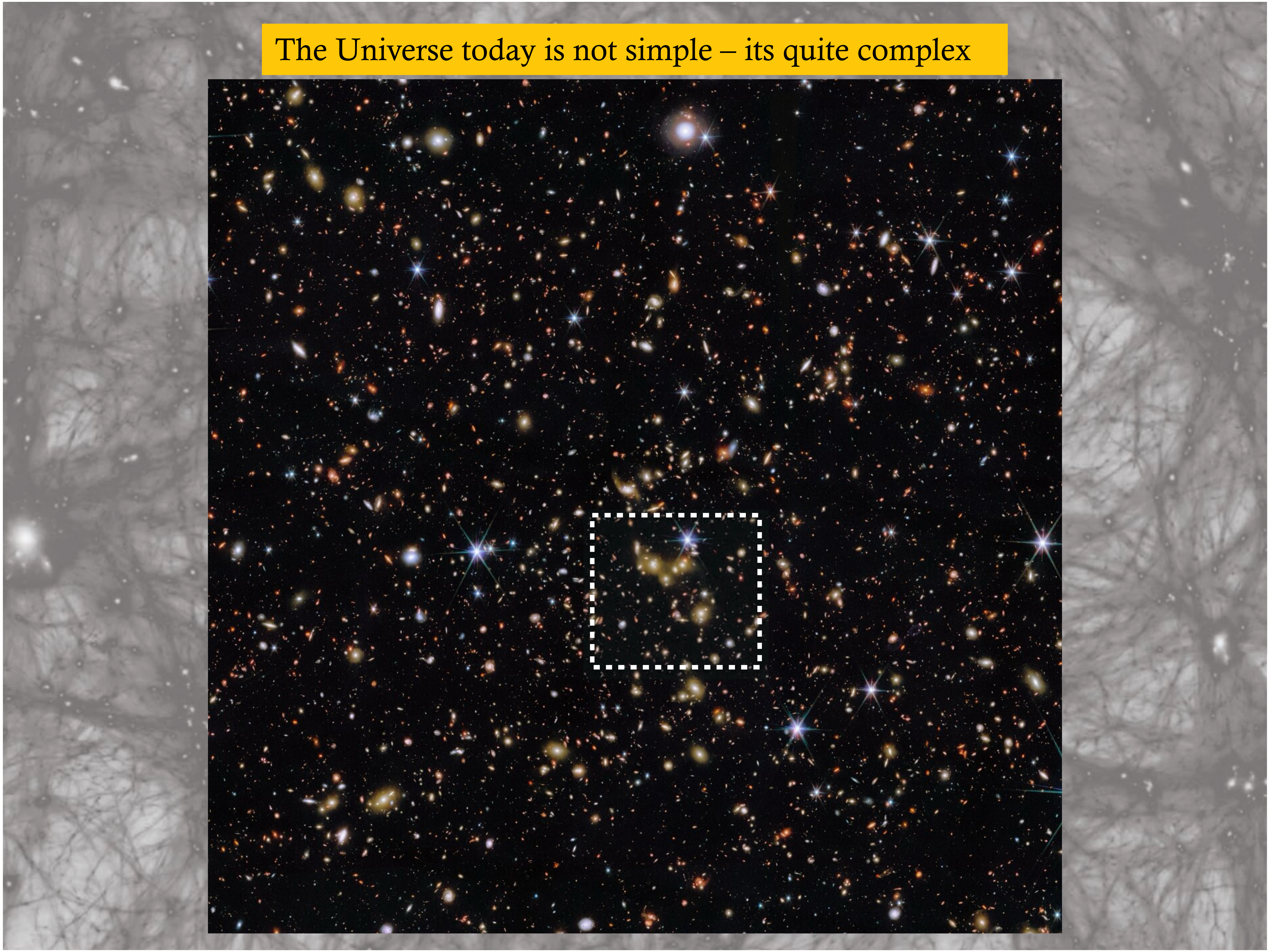

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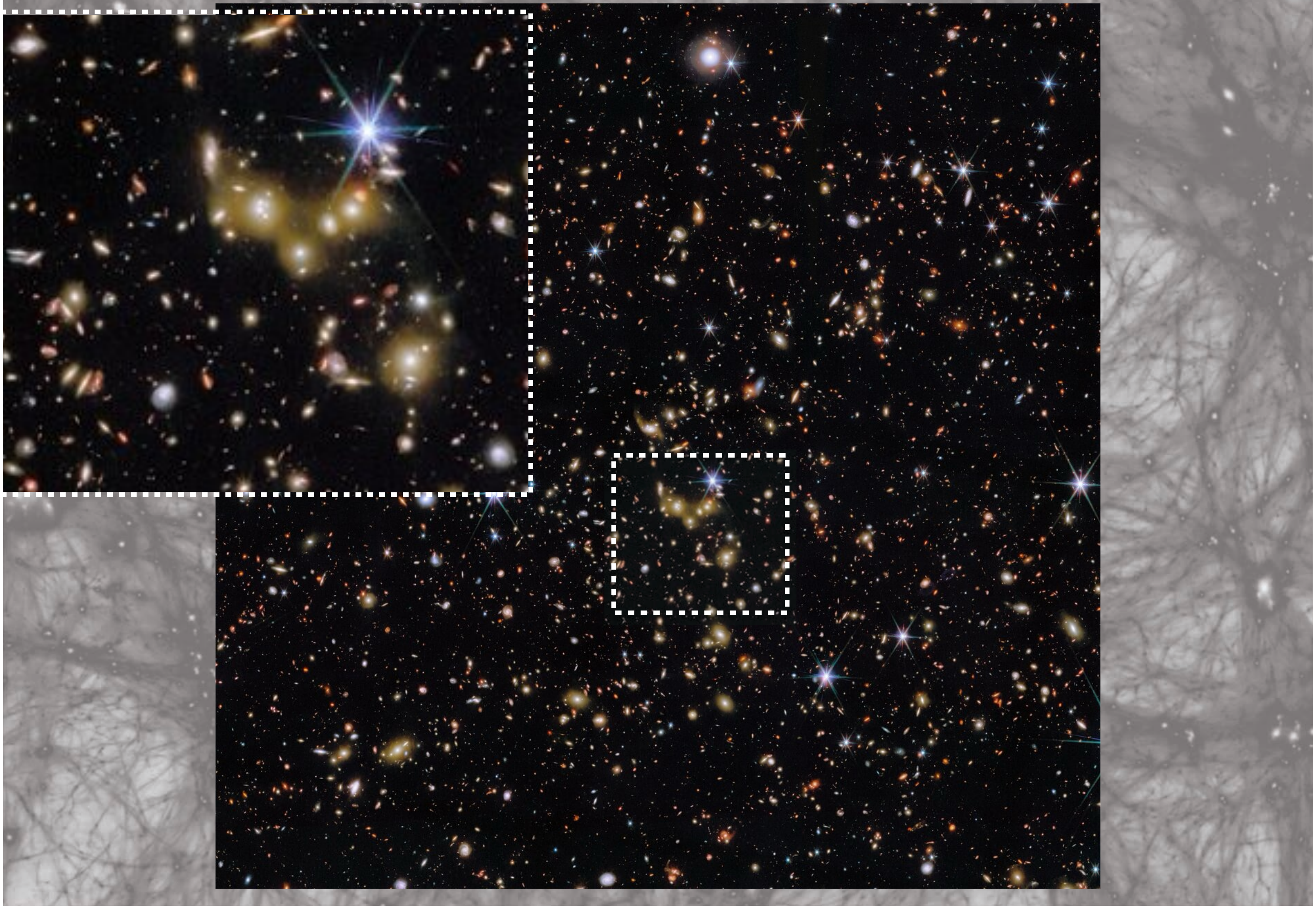

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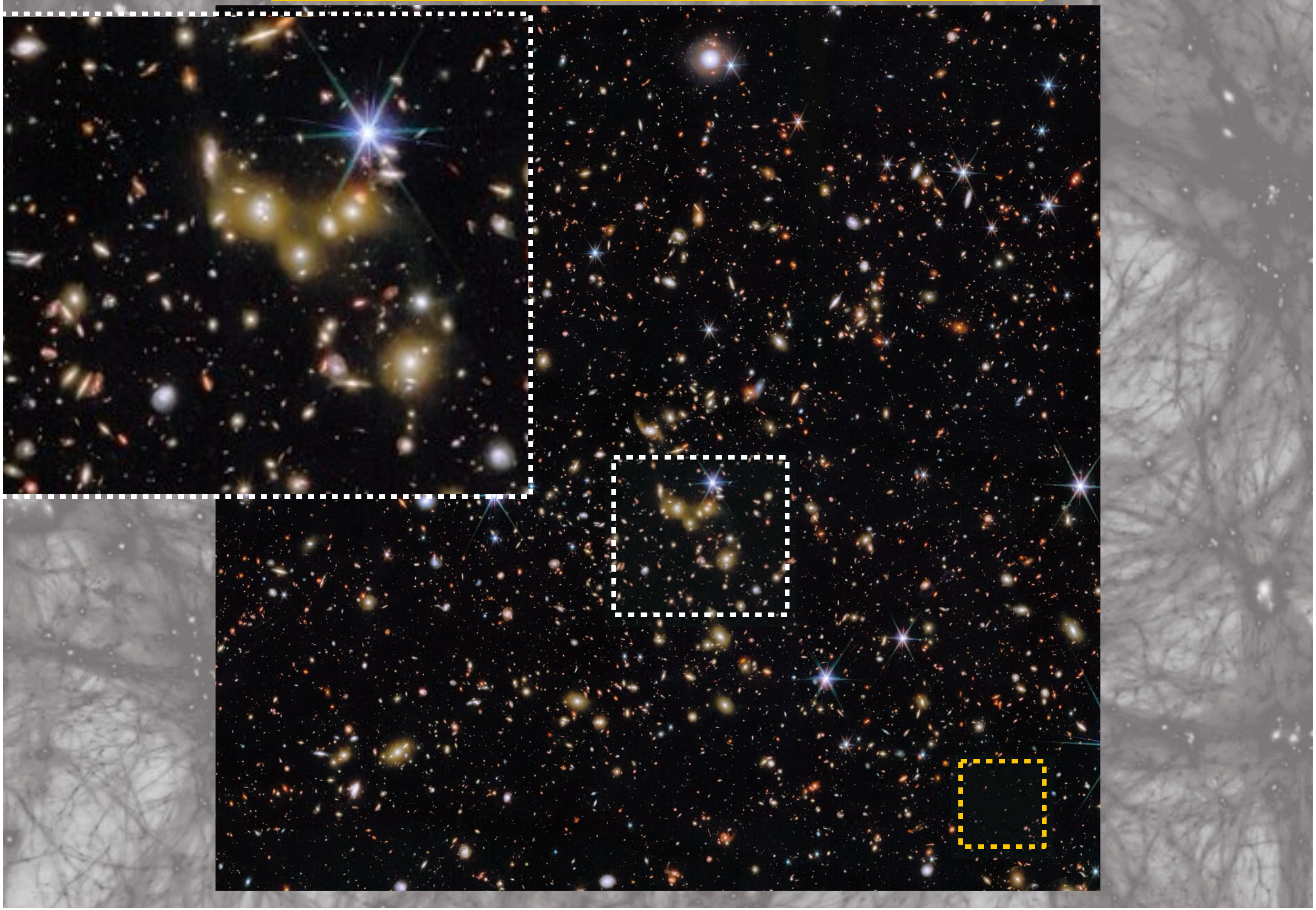

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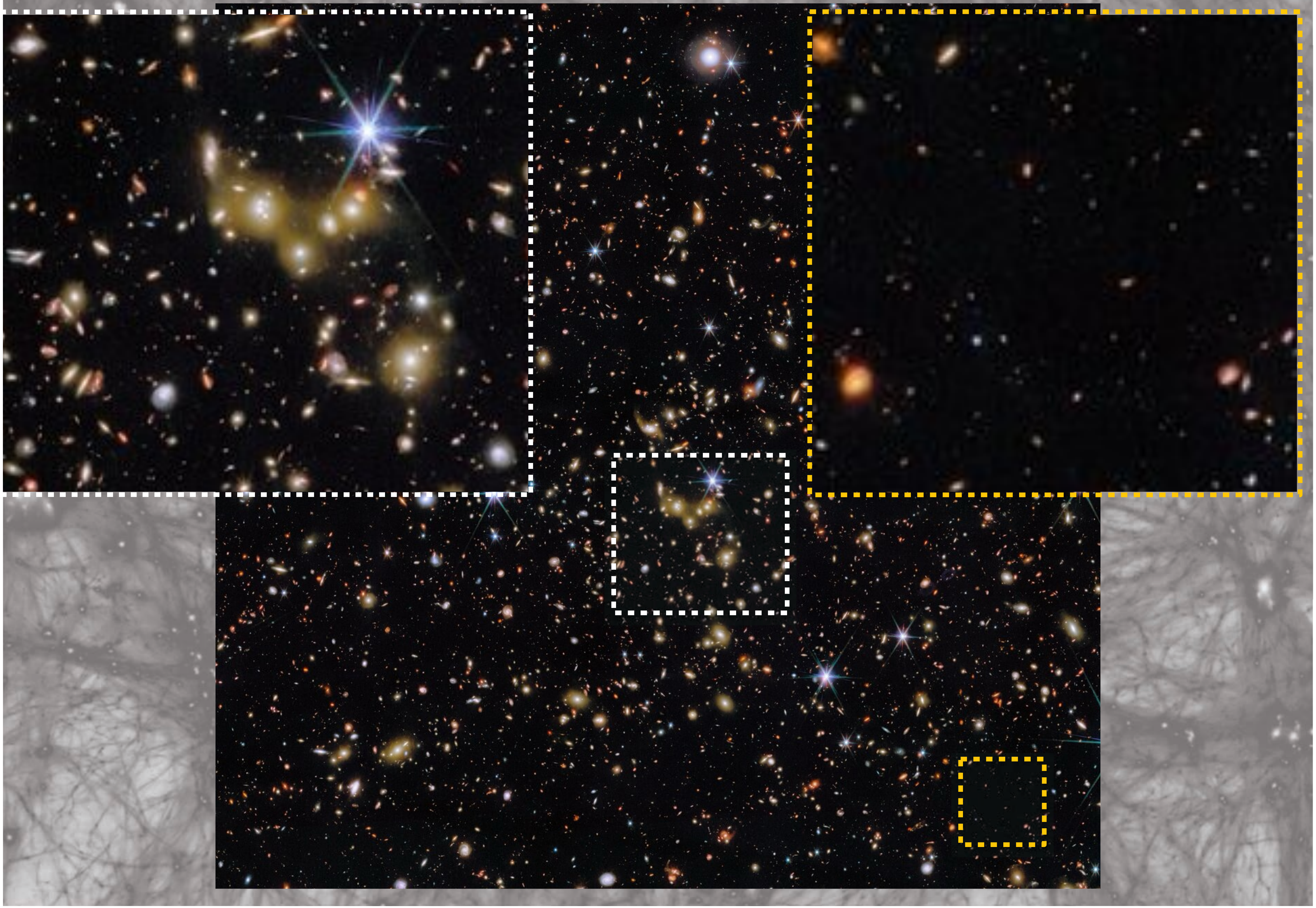
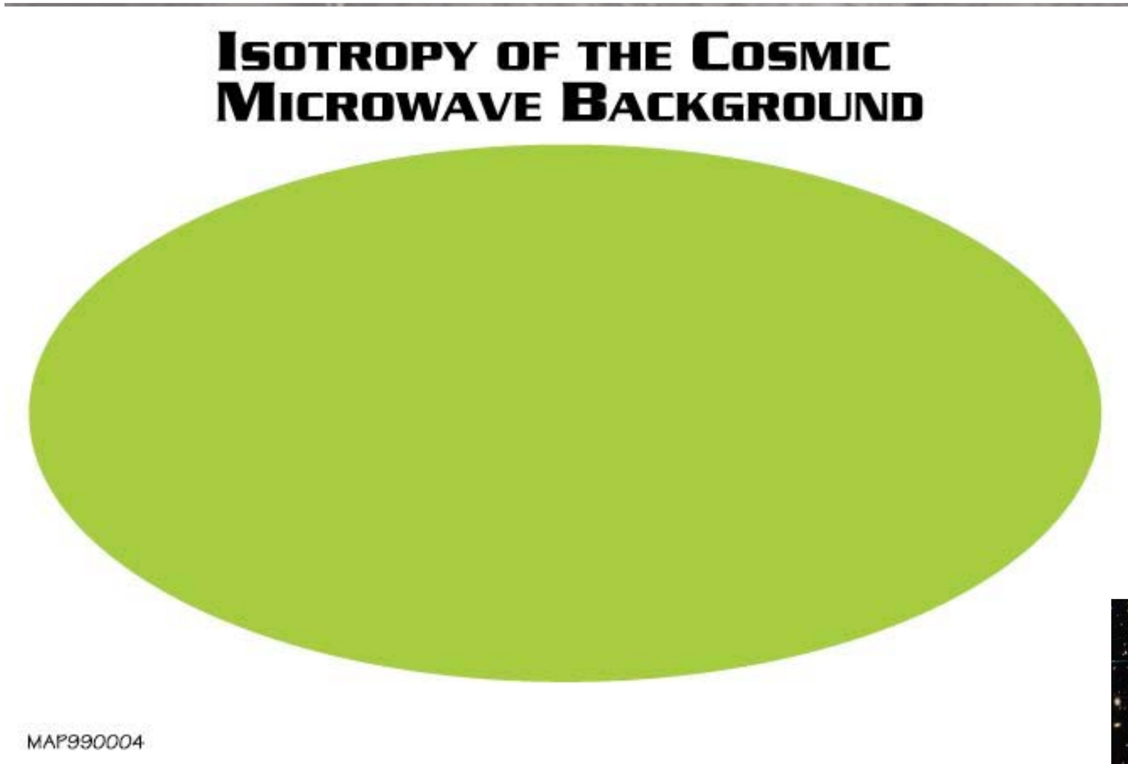
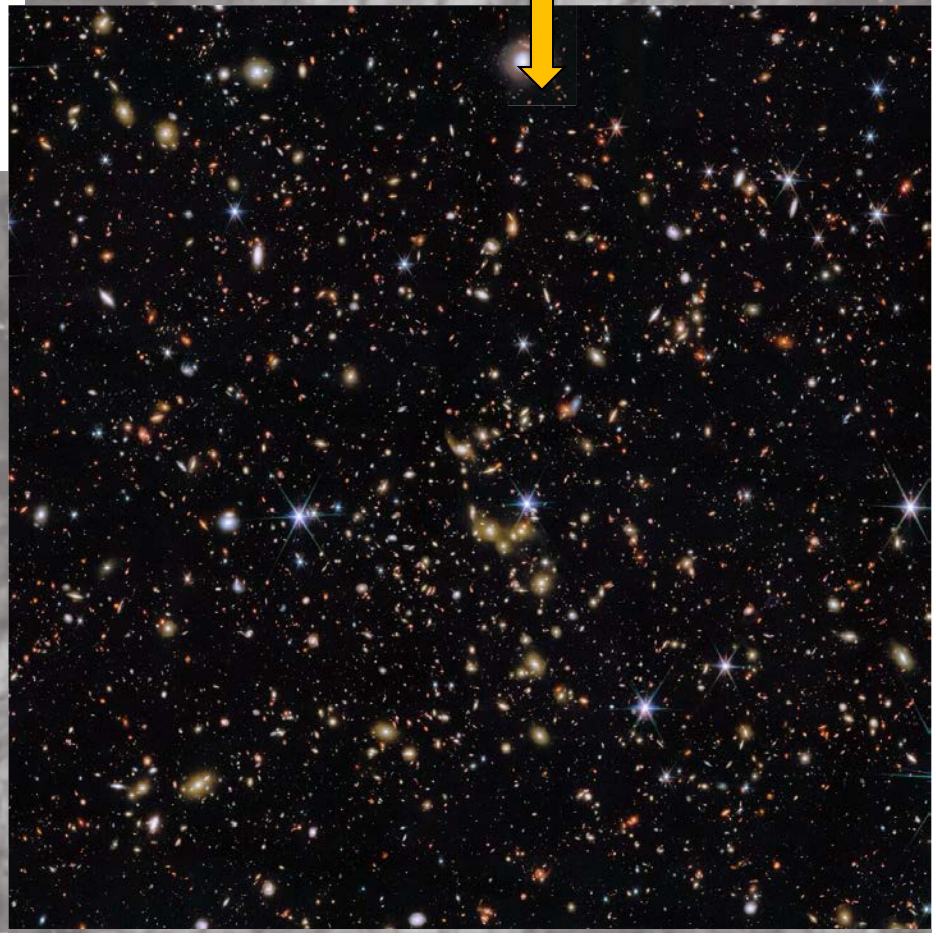




How did small scale inhomogeneities arise from a homogenous start



Where did the richness structure of the cosmic web come from?

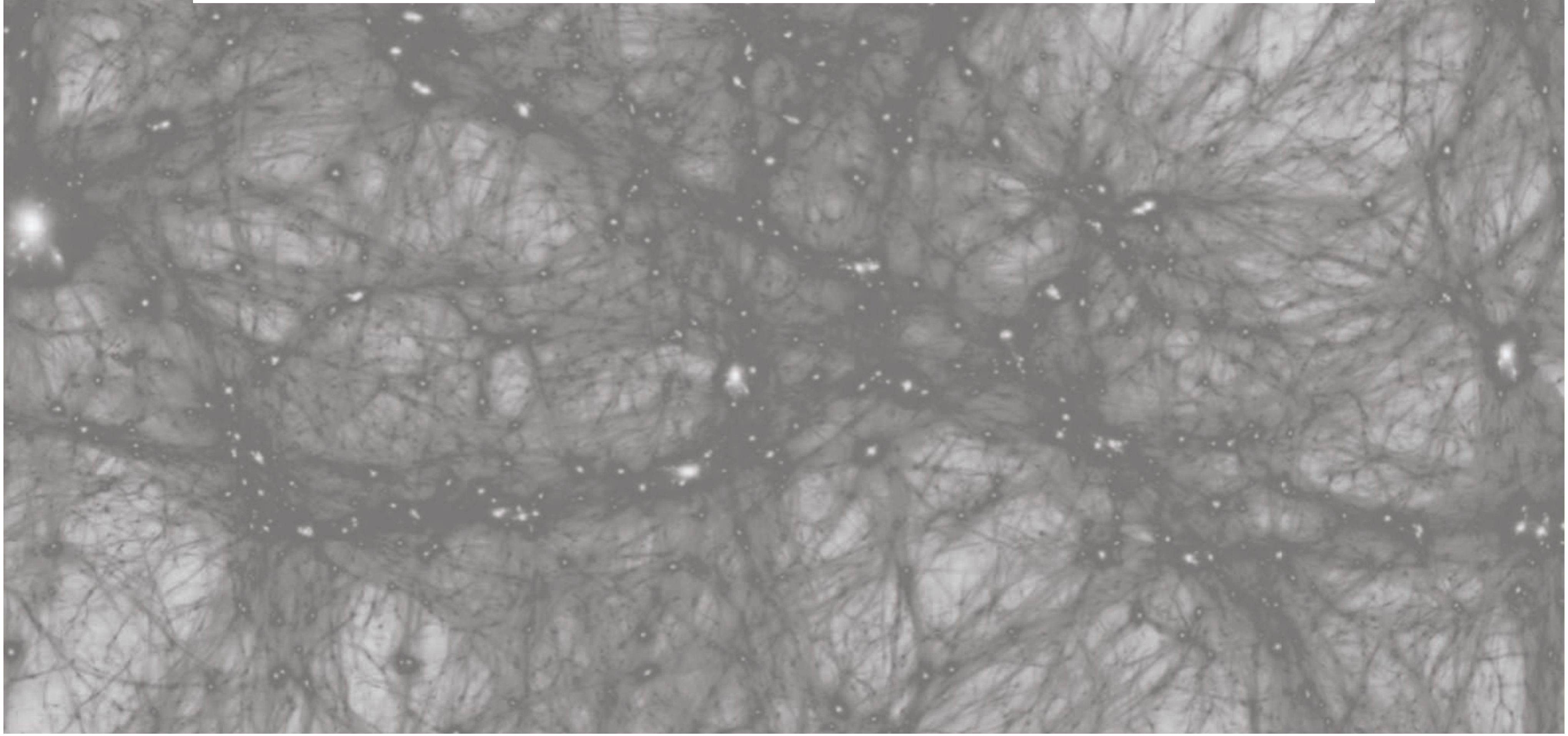
Q. Jl R. astr. Soc. (1970) **11**, 214–217.

The Grin Cosmologies*

E.R.Harrison

'Well! I've often seen a cat without a grin,' thought Alice; 'but a grin without a cat! It's the most curious thing I ever saw in all my life!'

Lewis Carroll, *Alice in Wonderland*



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Everything in the Universe is smeared out into a rudimentary continuous fluid. It is like the grin on the face of the Cheshire Cat. The grin gets larger as we progressively discard the detail and structure of the Universe—and eventually the grin engulfs the whole cat. All that remains is a featureless Universe whose study is the concern of what may be called the 'grin cosmologies'.

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The discovery of the 3 °K background radiation has made the early Universe into an inferno. And consequently the problem of putting structure back into cosmology has become an even more difficult enterprise.

It is too soon to say whether the new ideas will succeed and thus make more realistic our models of the Universe. If they fail, then I am afraid our cosmologies will begin to have an ironical grin.

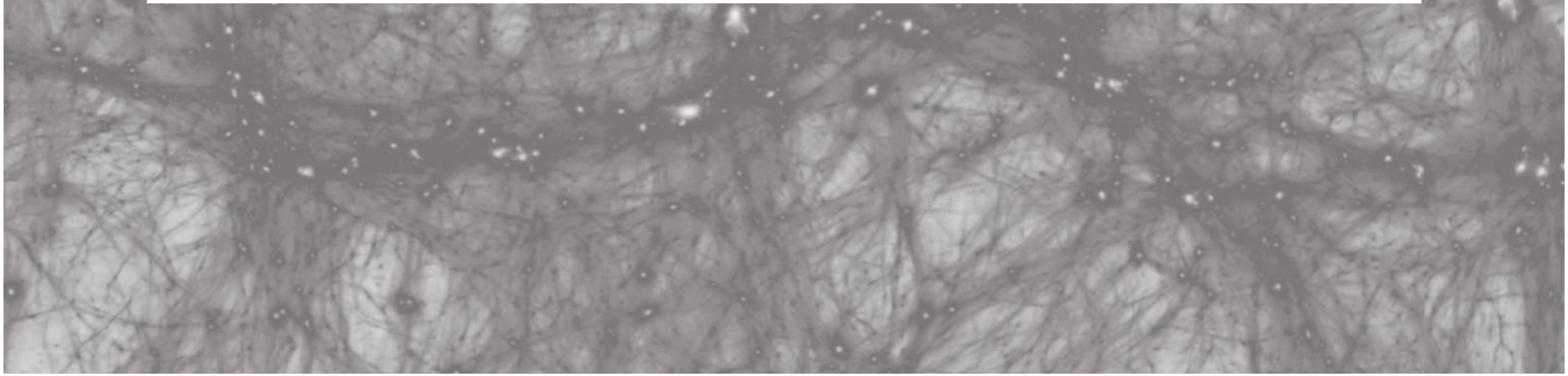
SOVIET ASTRONOMY—AJ VOL. 8, NO. 6 MAY-JUNE, 1965

DELAYED EXPLOSION OF A PART OF THE FRIDMAN UNIVERSE, AND QUASARS

I. D. Novikov

Translated from Astronomicheskii Zhurnal, Vol. 41, No. 6
pp. 1075-1083, November-December, 1964
Original article submitted May 4, 1964

A hypothesis interpreting quasistellar radio sources as parts of the Fridman universe delayed in expansion is considered. The matter comprising these delay cores expands beyond its Schwarzschild sphere at different times for different cores. Collision with matter falling in from outside is held responsible for the quasar phenomenon. The exact solution of the grativational equations describing a cosmological model with delayed cores is derived. The expansion of each core prior to its interaction with the external matter repeats the expansion of the entire Fridman model. The possibility of a situation in which the epoch of expansion of the universe and of the delayed cores is preceded by the epoch of their contraction is also considered.



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paper. We consider here a homogeneous isotropic Fridman cosmological model. We assume that at the initial time (the instant of infinite density), not all the matter included in the model began to undergo explosion. Certain regions, which will be assumed spherically summetrical for simplicity in our treatment, were delayed and failed to expand for some period with respect to the time in the co-moving system (for this possibility and the underlying reasons, see below).

Fridman universe
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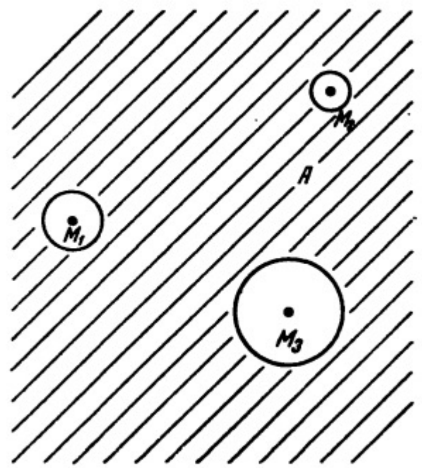

Fig. 1. Vacuole model with delayed cores M_1, M_2, M_3. A) expanding matter of metagalaxy.

Mon. Not. R. astr. Soc. (1972) **160,** *Short Communication.*

A HYPOTHESIS, UNIFYING THE STRUCTURE AND THE ENTROPY OF THE UNIVERSE

Ya. B. Zeldovich

(Received 1972 September 4)

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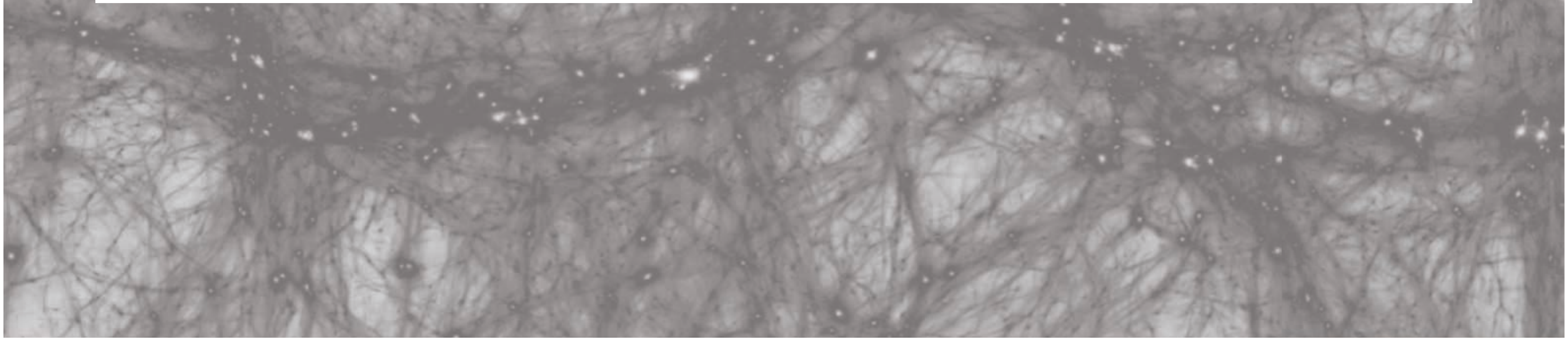

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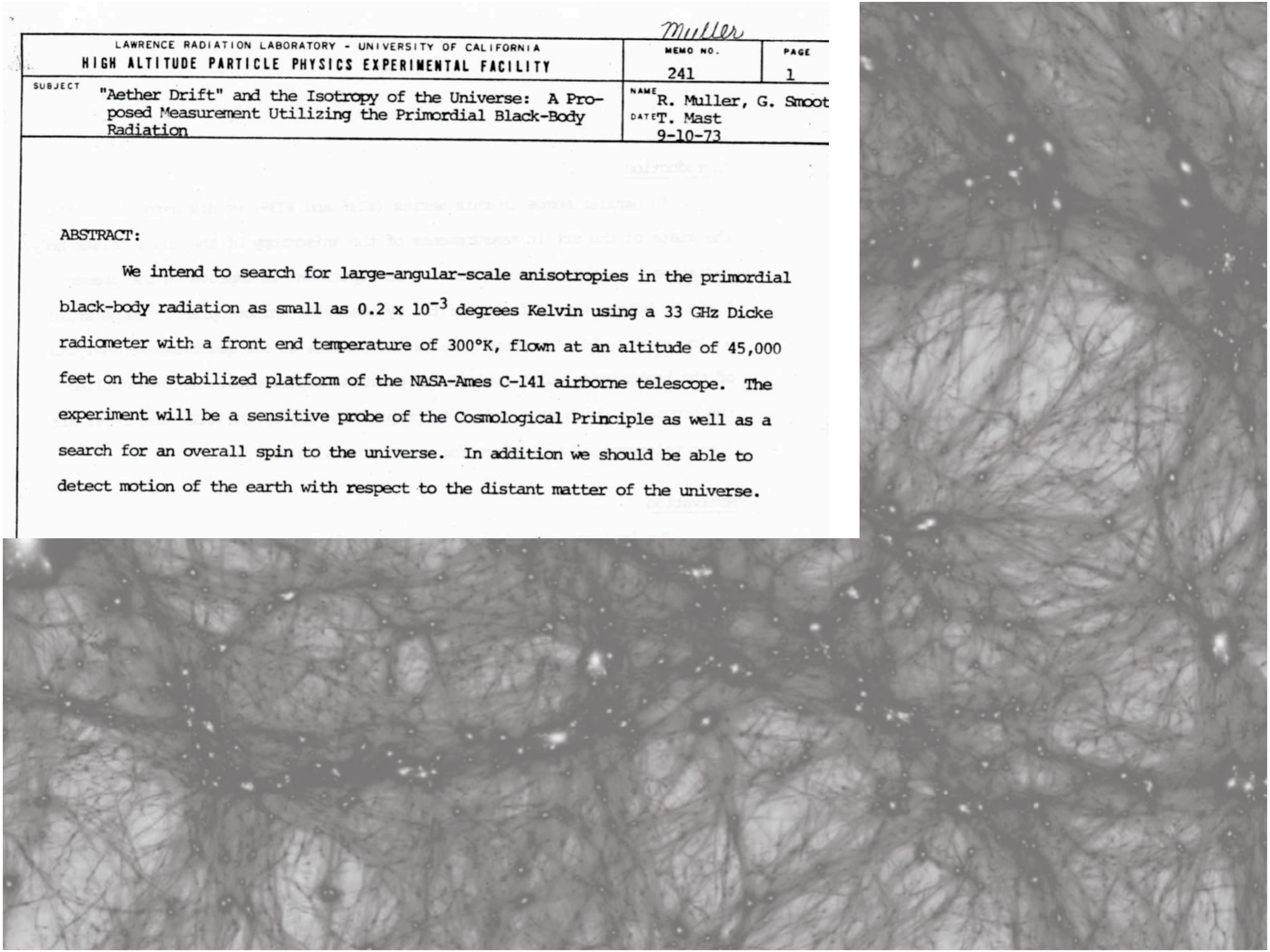
A hypothesis is put forward, assuming that initially, near the cosmological singularity, the Universe was filled with cold baryons. The averaged evolution was described by the uniform isotropic expansion, according to Friedmann solution and the equation of state of cold baryons.

Superimposed on this averaged picture are initial fluctuations of baryon density and corresponding fluctuations of the metric.



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LAWRENCE RADIATION LABORATORY - UNIVERSITY OF CALIFORNIA HIGH ALTITUDE PARTICLE PHYSICS EXPERIMENTAL FACILITY	MEMO NO. 241	PAGE 1
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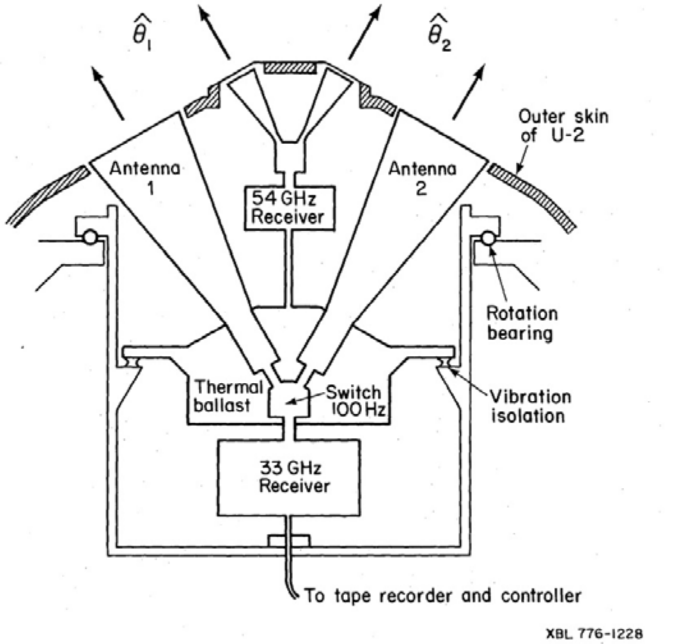

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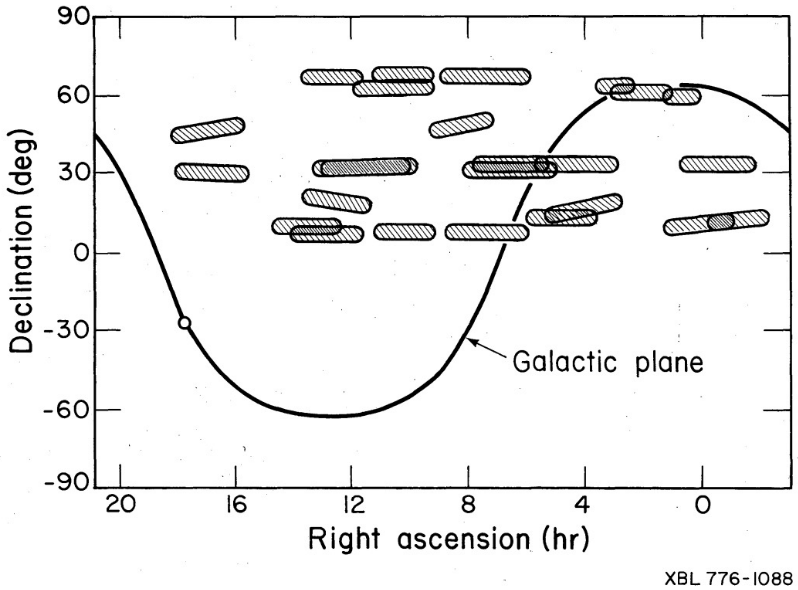
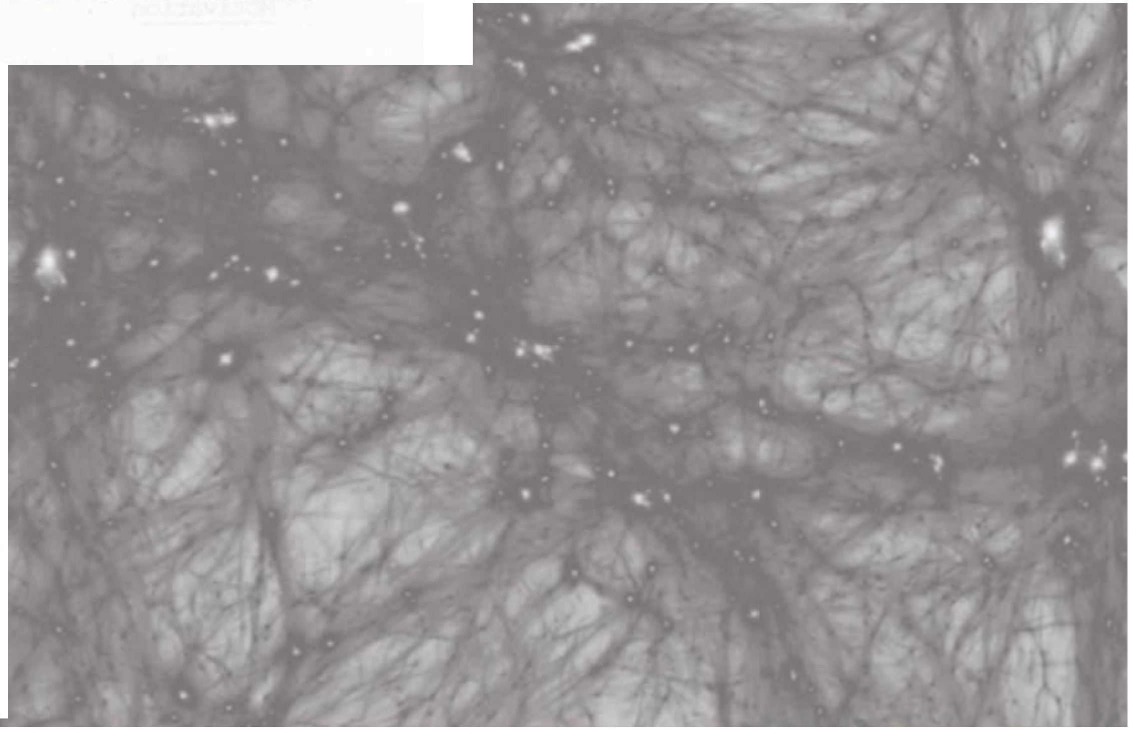


Fig. 2



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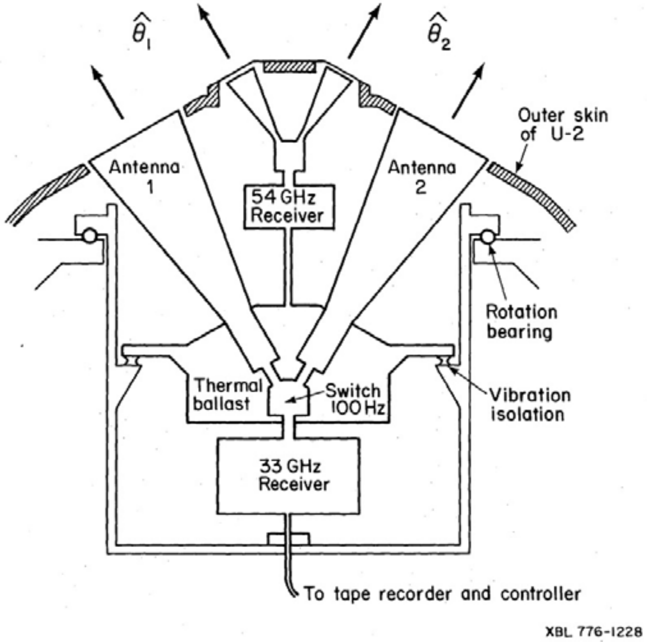


Fig. 1

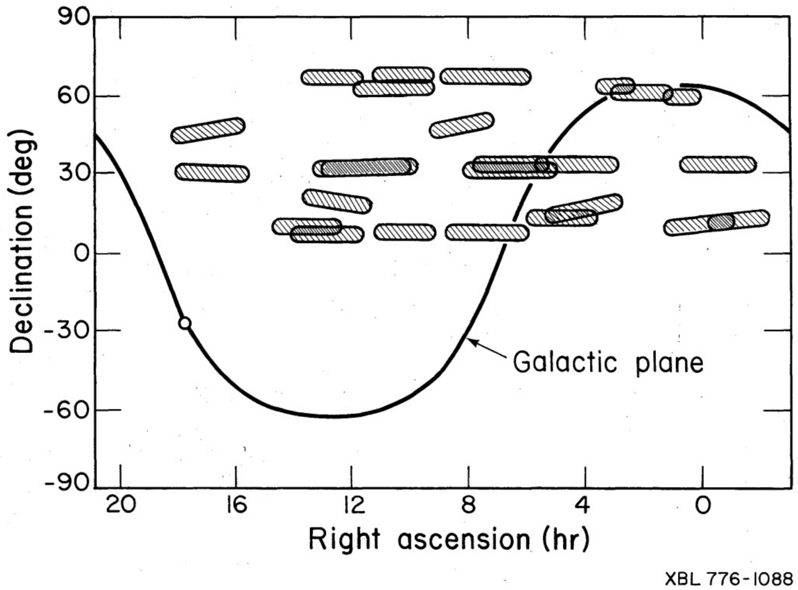
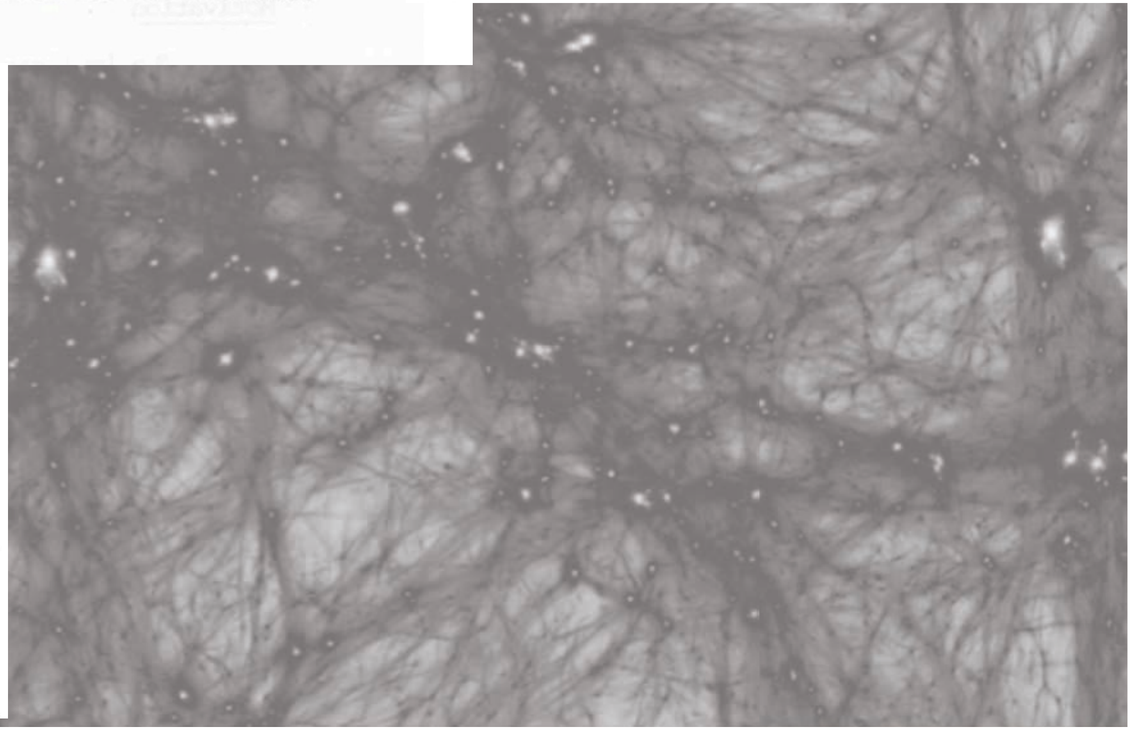
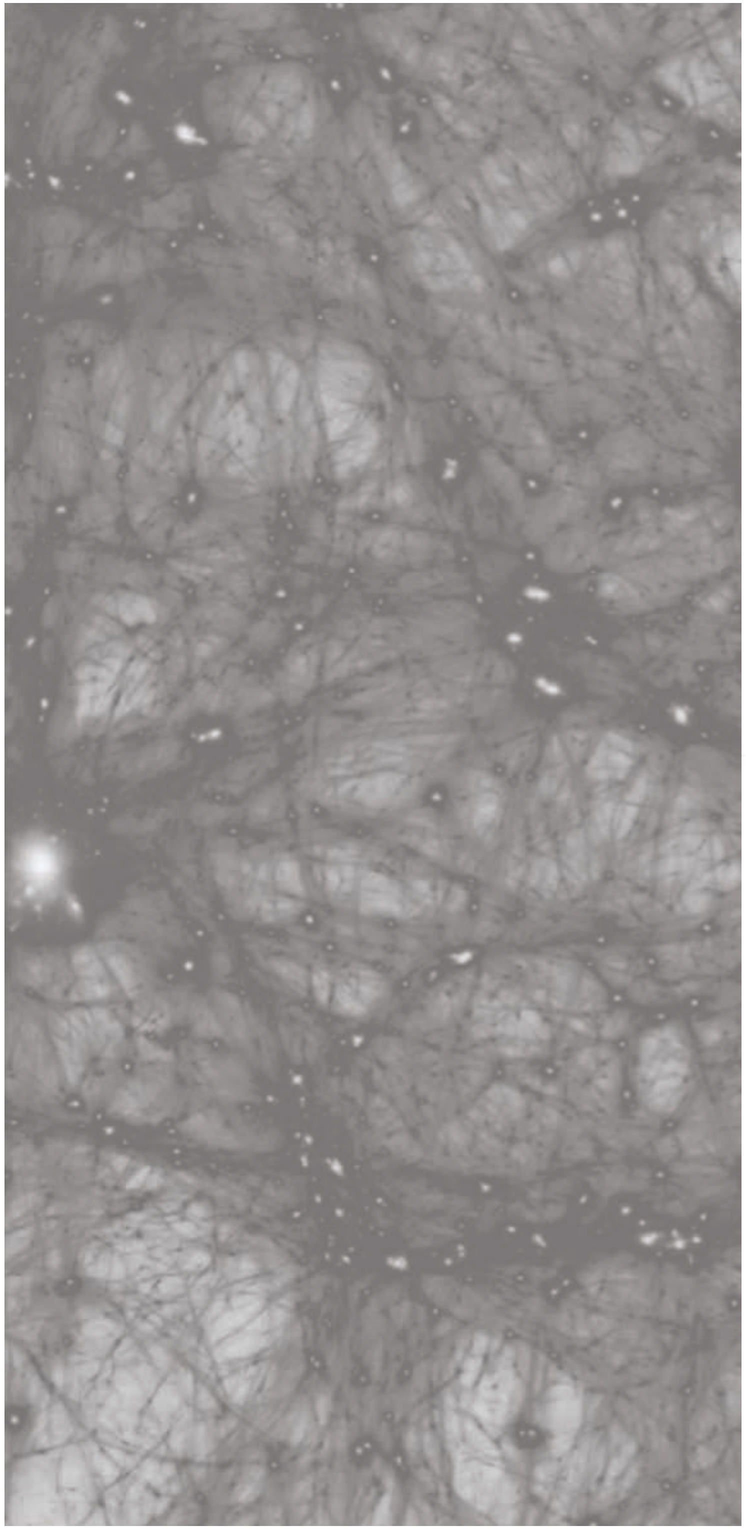


Fig. 2





DETECTION OF ANISOTROPY IN THE COSMIC BLACKBODY RADIATION

G. F. Smoot, M. V. Gorenstein, and R. A. Muller

July 6, 1977

Prepared for the U. S. Energy Research and Development Administration under Contract W-7405-ENG-48

For Reference

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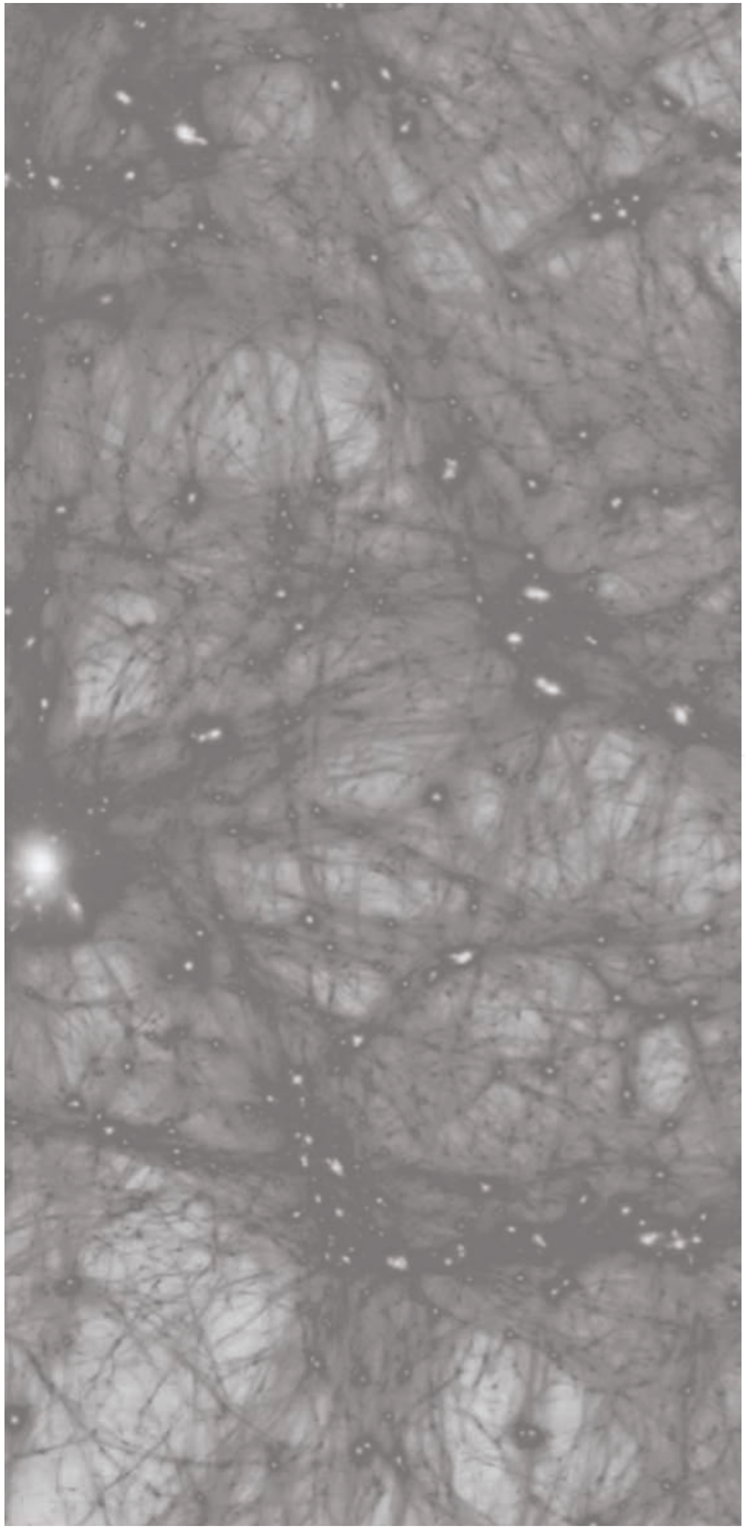

~~Check figure for systematic derivation~~

Draft of 6/13/77

MASTER

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DETECTION OF ANISOTROPY IN THE COSMIC BLACKBODY RADIATION*

G.F. Smoot, M.V. Gorenstein and R.A. Muller

University of California
Lawrence Berkeley Laboratory and Space Sciences Laboratory
Berkeley, California 94720

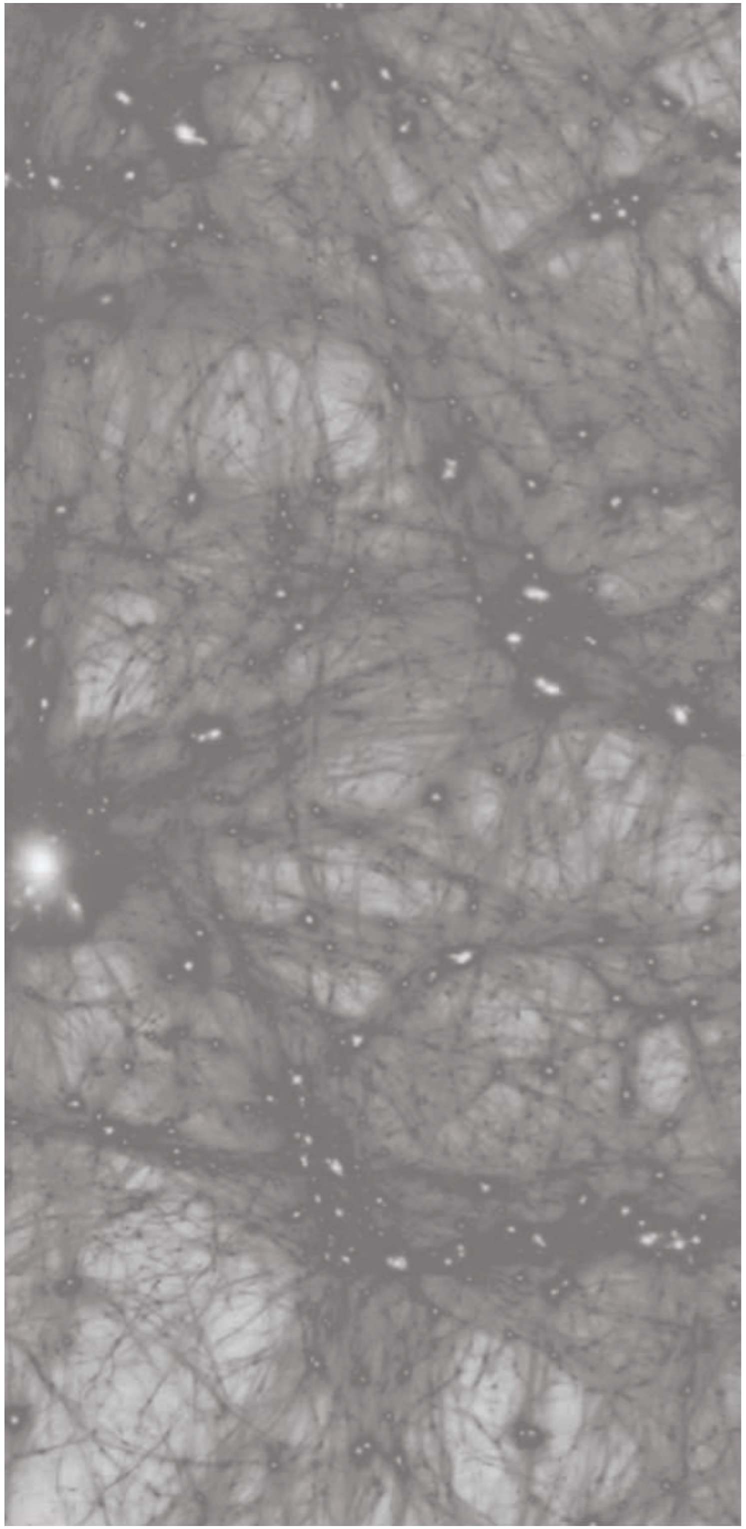
$$T(\hat{r}) = T_0 + T_1 \cos(\hat{r}, \hat{r}_{MAX})$$

ABSTRACT

We have detected anisotropy in the cosmic blackbody radiation with a 33 GHz (0.9 cm) twin-antenna Dicke radiometer flown aboard a U-2 aircraft to an altitude of 20 km. In data spanning approximately two-thirds of the northern hemisphere, we observe an anisotropy which is well-fit by a first-order spherical harmonic with an amplitude of $(3.2 \pm 0.6) \times 10^{-3}$°K, and an axis of symmetry in the direction (10.8 ± 0.5 hr R.A., 5° ± 10° dec). When expected backgrounds are subtracted, the amplitude is $(3.5 \pm 0.6) \times 10^{-3}$°K. This observation is readily interpreted as due to motion of the earth relative to the radiation with a velocity of 390 ± 60 km/sec.

direction of maximum temp

[redacted]



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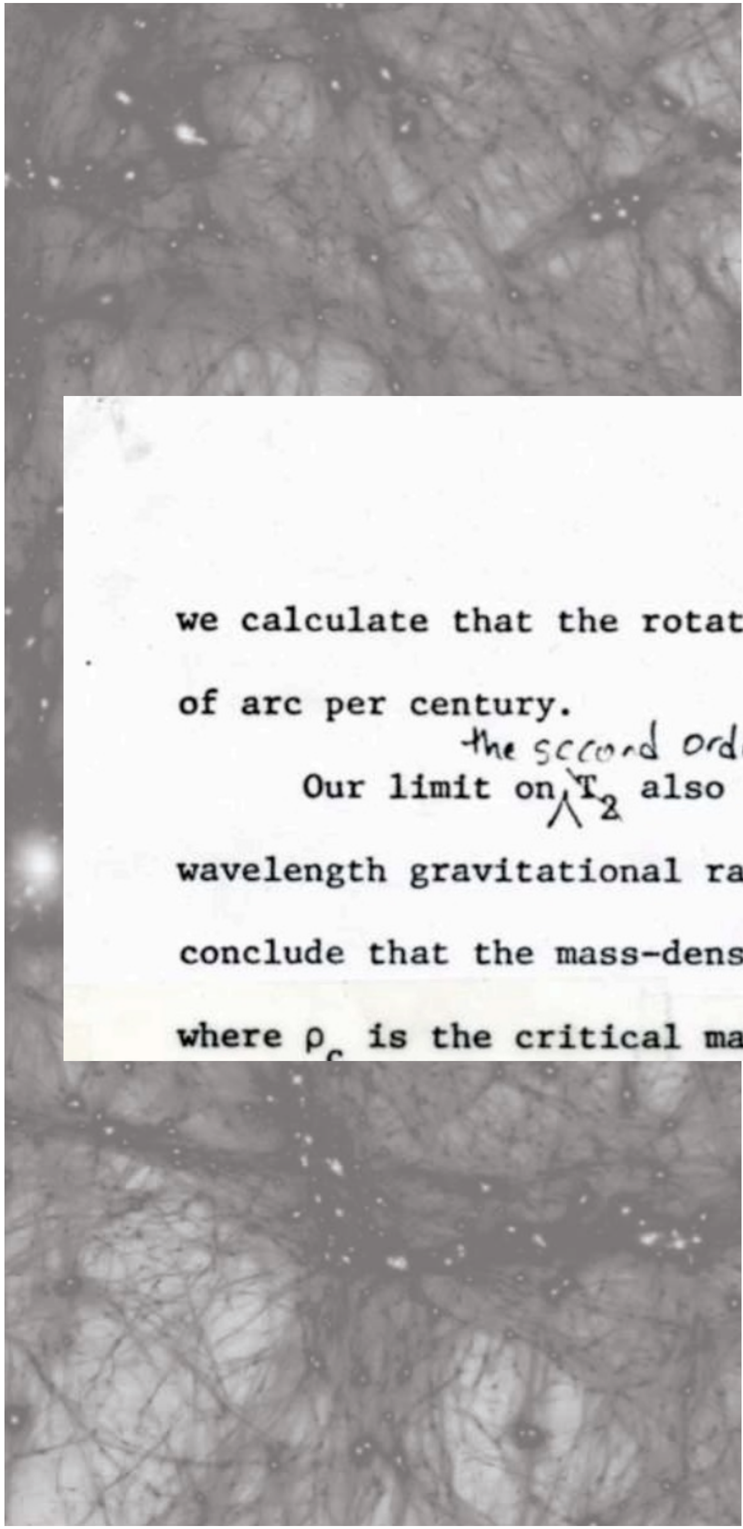

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DETECTION OF ANISOTROPY IN THE COSMIC BLACKBODY RADIATION*

-10-

New ending.

we calculate that the rotation of the Universe is less than [redacted] 10^{-9} seconds of arc per century. (ν_{MAY})

Our limit on the second order spherical harmonic T_2 also puts a constraint on the existence of large wavelength gravitational radiation. Using the calculation of Burke[13], we conclude that the mass-density of such radiation in the Universe is $\lesssim \rho_c$, where ρ_c is the critical mass density necessary to close the universe.

the radiation with a velocity of 390 ± 60 km/sec.

direction of maximum temp

[redacted]

References and Footnotes

1. Peebles, P.J.E., 1971, "Physical Cosmology" (Princeton: Princeton University Press; Weinberg, S., 1972, "Gravitation and Cosmology: Principles and Application of the General Theory of Relativity (John Wiley and Son Inc., N.Y.

2 Both Conklin (ref) and Henry (ref) claimed to observe a first-order harmonic. However in both experiments backgrounds were much larger than the observed effect, and the resulting fits were very poor. In both experiments the one-standard-deviation errors in the direction of the earth's velocity cover a large part of the sky. (Conklin quotes probable errors, not standard-deviations.)

3 Corey, B.E and Wilkinson, D.T. 1976, Bulletin of the AAS 8, 351
~~Cory and Wilkinson, Bulletin of the AAS.~~

4 G. Smoot, invited talk, APS Conference, 28 April 1977., Washington, DC

5 C.F. Smoot, M.V. Gorenstein, R.A. Muller, J.A. Tyson, submitted to the Reviews of Scientific ~~Modern~~ Instruments.

6 The reported errors in the preliminary results of Corey and Wilkinson (ref 3) were statistical only. Newer results from their group (D. Wilkinson, private communication) are in closer agreement with our results.

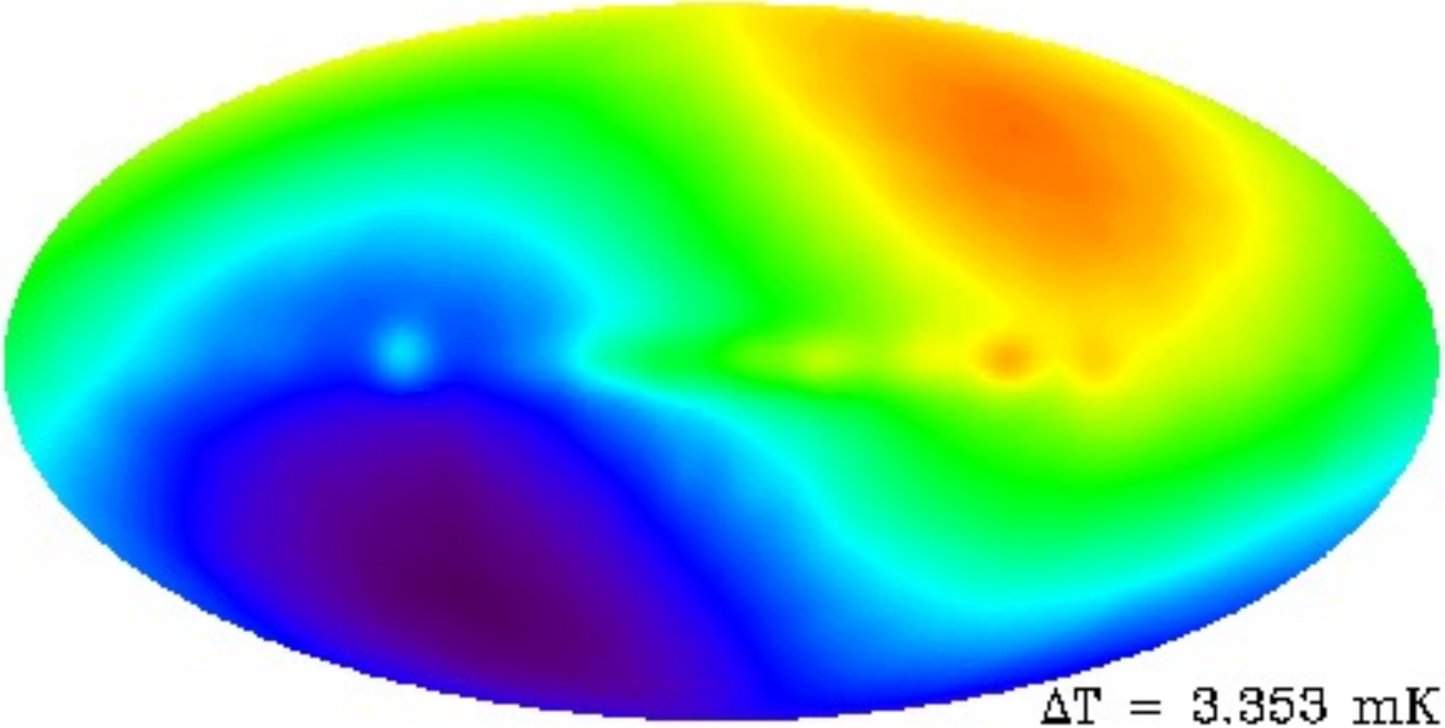
7. Rubin, V.C., Ford, W.K., Thonnard, N., Roberts, M.S. and Graham, J.A. 1976, A.J. 81, 687

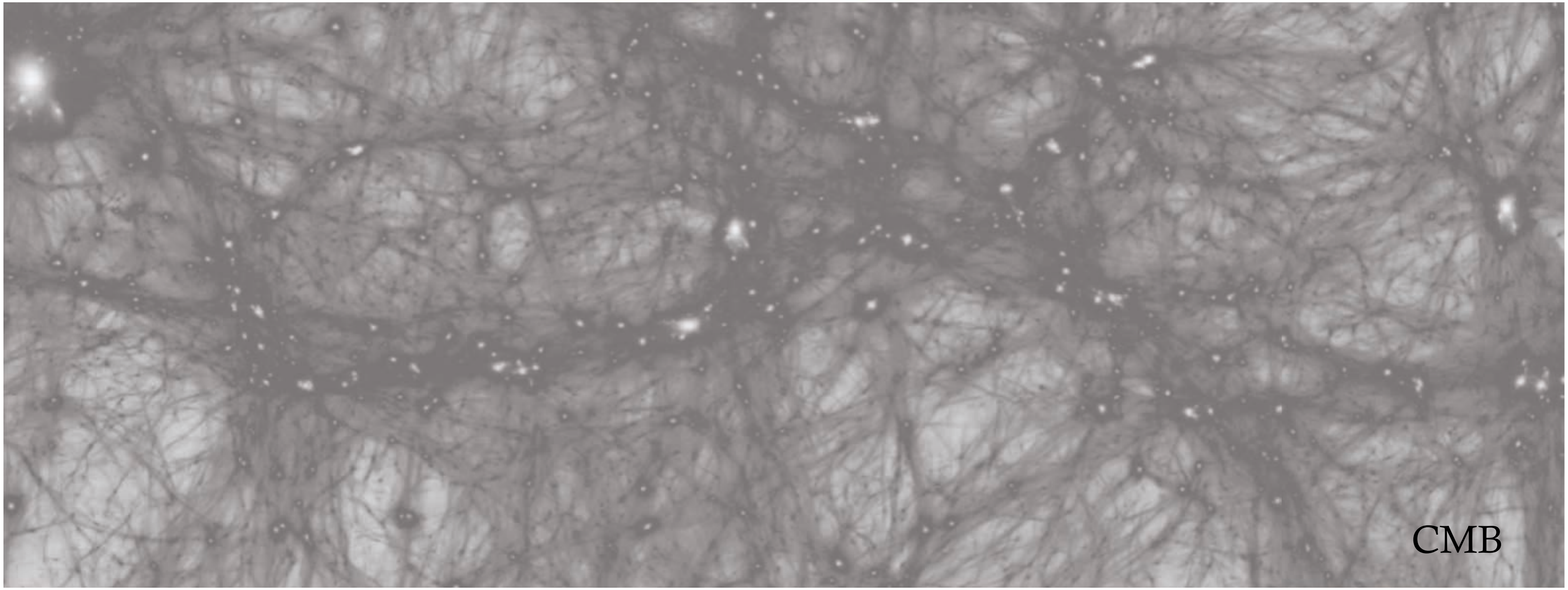
8. Visvanathan, N. and Sandage, A., 1977, ApJ, Aug 15. No 37

9. Yahil, A., Tammann, G.A., and Sandage 1977 ApJ, Nov 15

10. Schecter, P. ho. Steward Observatory, University of Arizona in press

11. Collins, C.B. and Hawking, S.W., 1973, Monthly Not R Astr Soc


ΔT = 3.353 mK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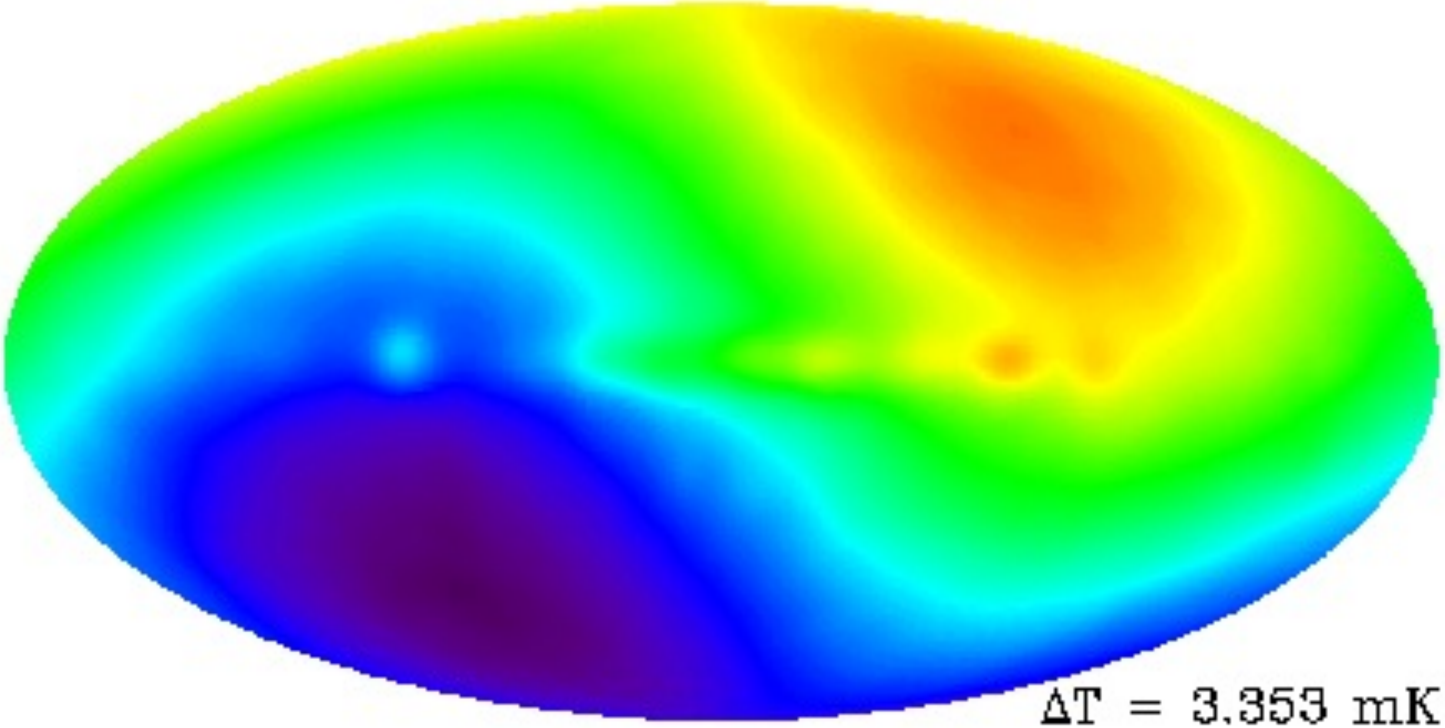
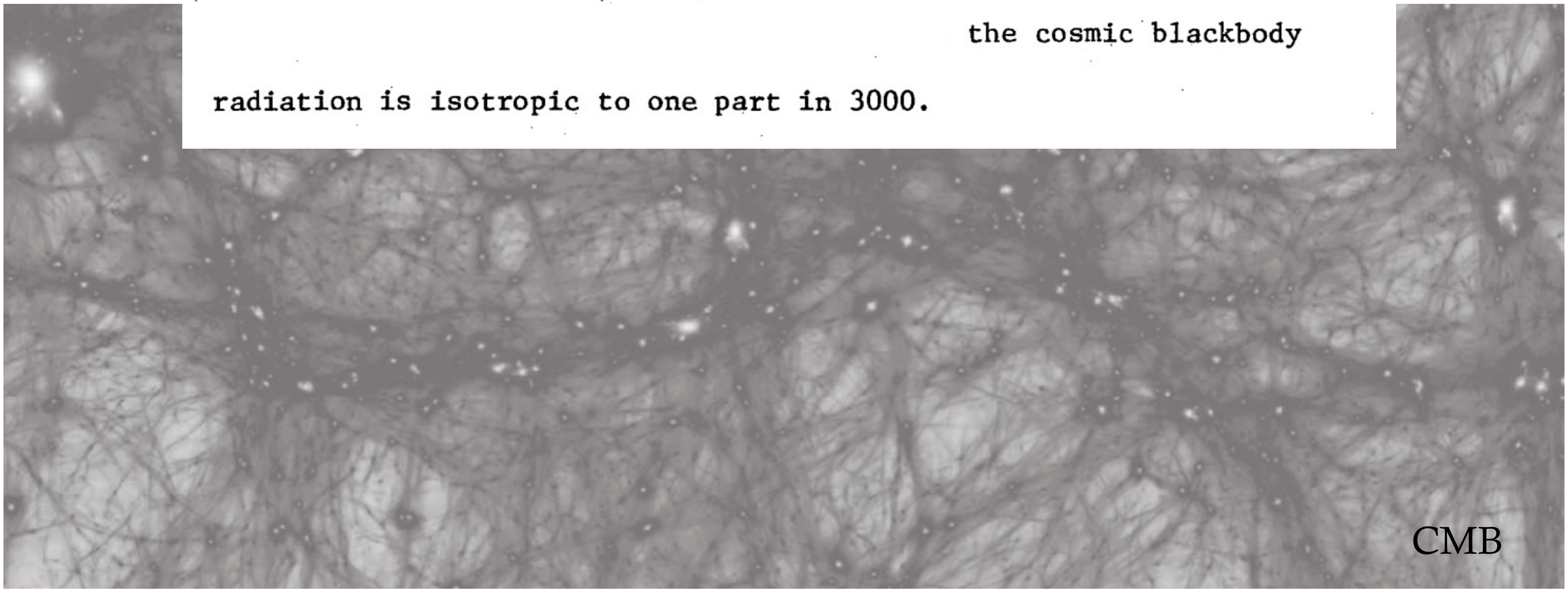
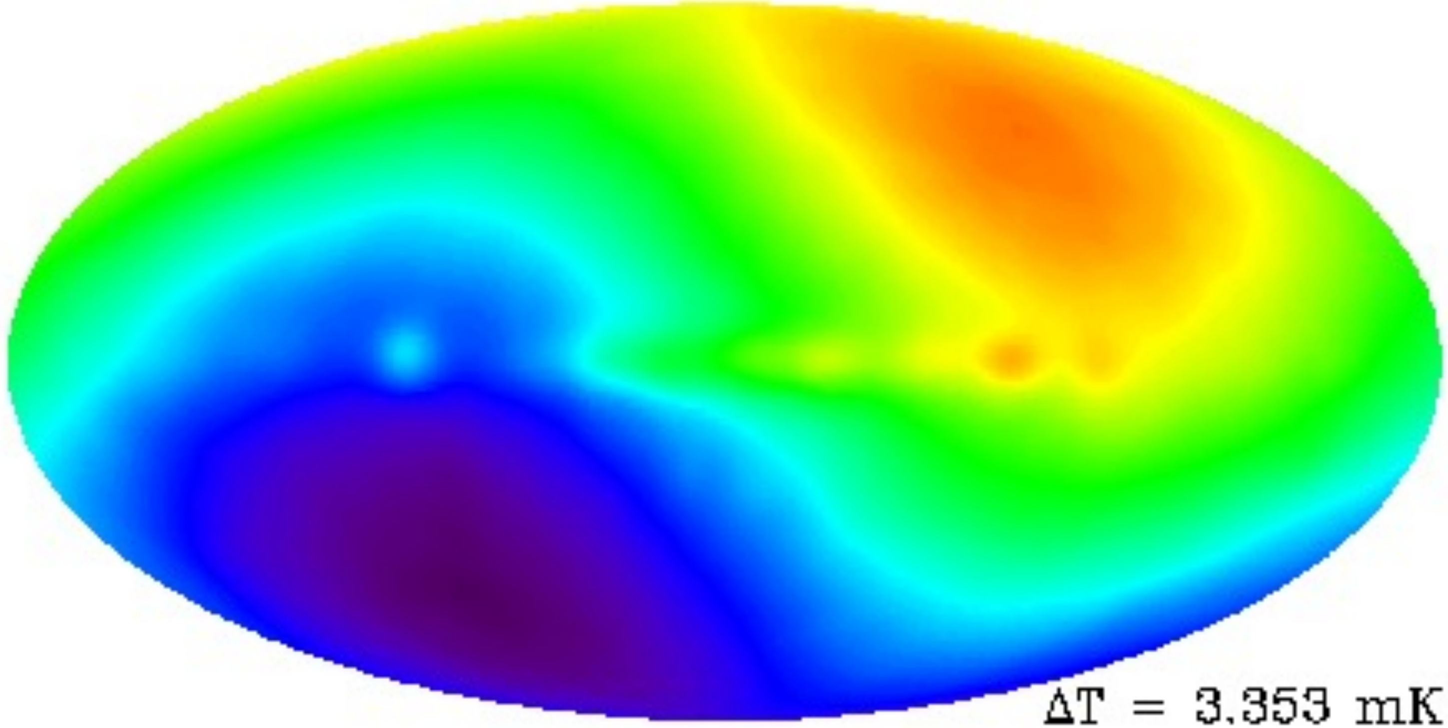
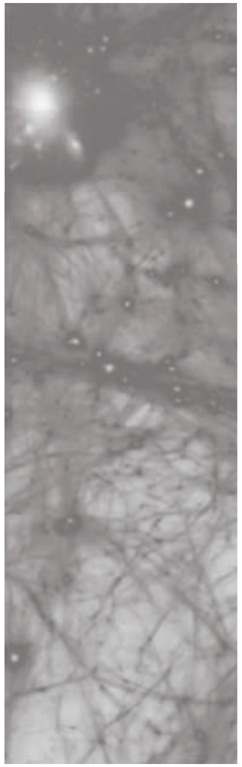


the cosmic blackbody radiation is isotropic to one part in 3000.

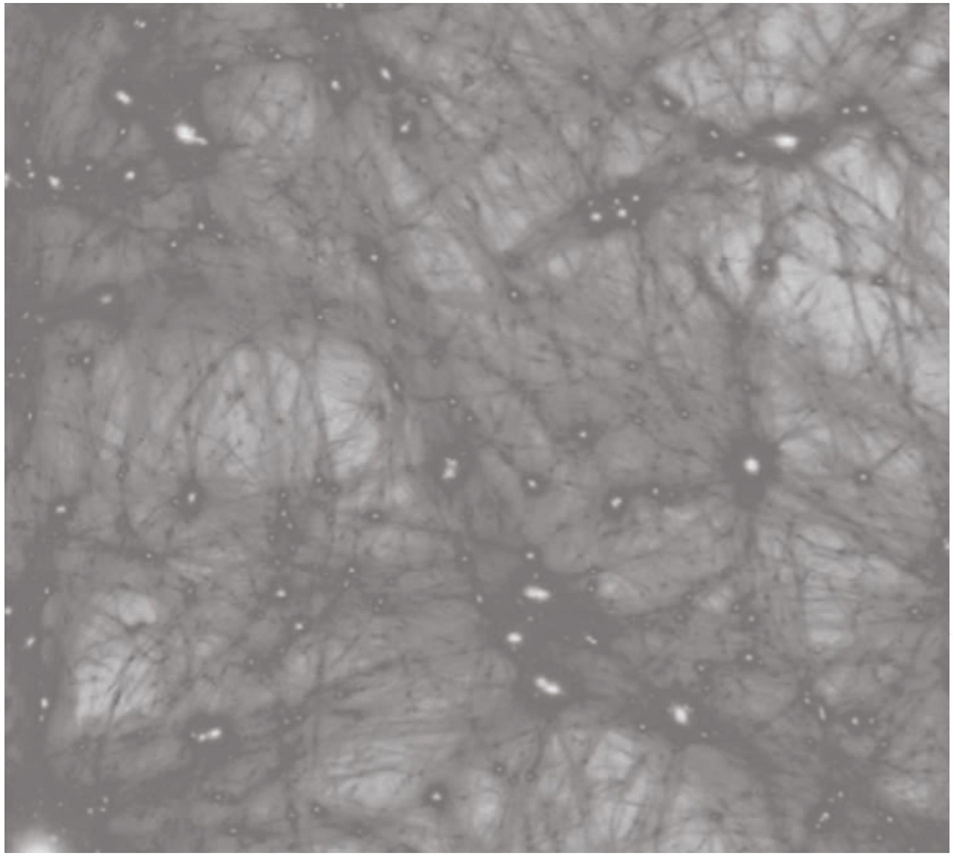






the cosmic blackbody radiation is isotropic to one part in 3000.

If we subtract from our measured velocity the component due to the rotation of the Milky-Way galaxy[9] ≈300 km/sec, we calculate the net motion of the Milky-Way with respect to the canonical reference frame of cosmology to be ∿600 km/sec in the direction (R.A. = 10.4 hr, dec. = -18°). These various velocities are summarized in Table I. The large peculiar velocity of the Milky Way galaxy is unexpected, and presents a challenge to cosmological theory.



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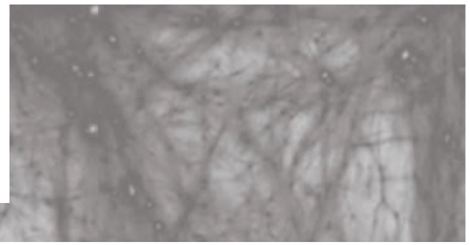
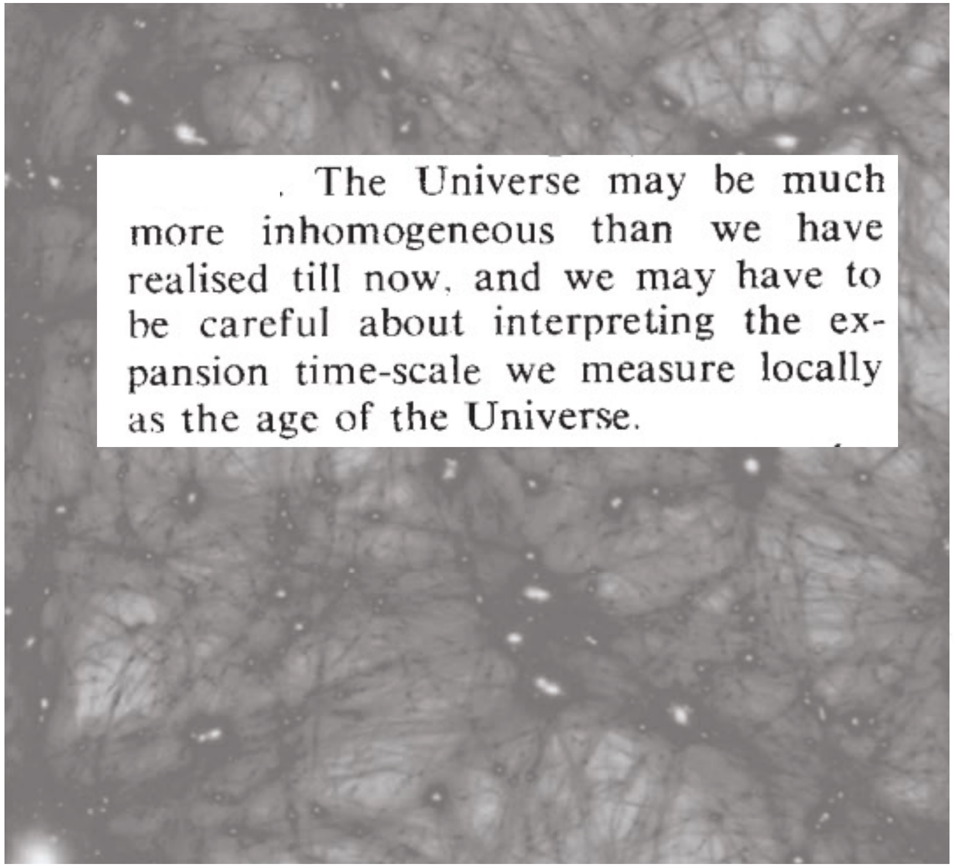
Nature Vol. 270 3 November 1977 9

news and views

Aether drift detected at last

from Michael Rowan-Robinson





The Universe may be much more inhomogeneous than we have realised till now, and we may have to be careful about interpreting the expansion time-scale we measure locally as the age of the Universe.

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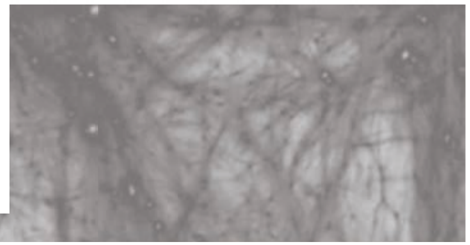


SPECTROSCOPY AND PHOTOMETRY OF ELLIPTICAL GALAXIES. V. GALAXY STREAMING TOWARD THE NEW SUPERGALACTIC CENTER[1]

D. LYNDEN-BELL
Institute of Astronomy, The Observatories, Cambridge

S. M. FABER
Lick Observatory, University of California at Santa Cruz

DAVID BURSTEIN
Department of Physics, Arizona State University

ROGER L. DAVIES
Kitt Peak National Observatory, National Optical Astronomy Observatories

ALAN DRESSLER
Mount Wilson and Las Campanas Observatories of the Carnegie Institution of Washington

R. J. TERLEVICH
Royal Greenwich Observatory

AND

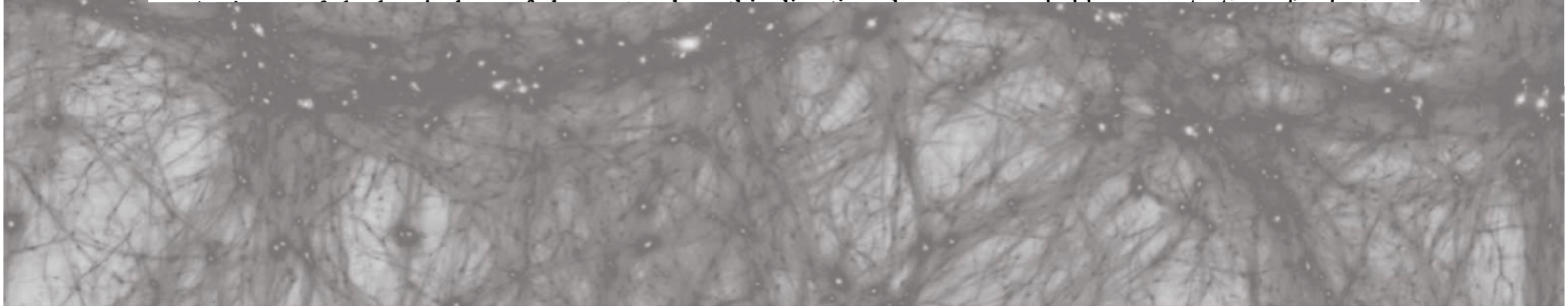
GARY WEGNER
Department of Physics and Astronomy, Dartmouth College

Received 1987 April 14; accepted 1987 August 19

ABSTRACT

We analyze here the dynamics of 400 elliptical galaxies of our all-sky survey.

The motions of the elliptical galaxies, over and above Hubble expansion in the Cosmic Microwave Background (CMB) frame, are best fitted by a flow toward a great attractor centered on $l = 307$, $b = 9$ at a distance of $R_m = 4350 \pm 350$ km s^{-1} in the Hubble flow. The excess mass must be $\sim 5.4 \times 10^{16}$ $M_\odot$, comparable to the largest superclusters in order to generate the streaming motion at the Sun of 570 ± 60 km s^{-1}. This model, which is an enlarged version of that considered earlier by Shaya, Tammann, and Sandage, and Lilje, Yahil, and Jones, gives a much better fit to the motions of the ellipticals than the bulk motion considered earlier. The latter was itself a much better fit than pure Hubble flow in the CMB frame.



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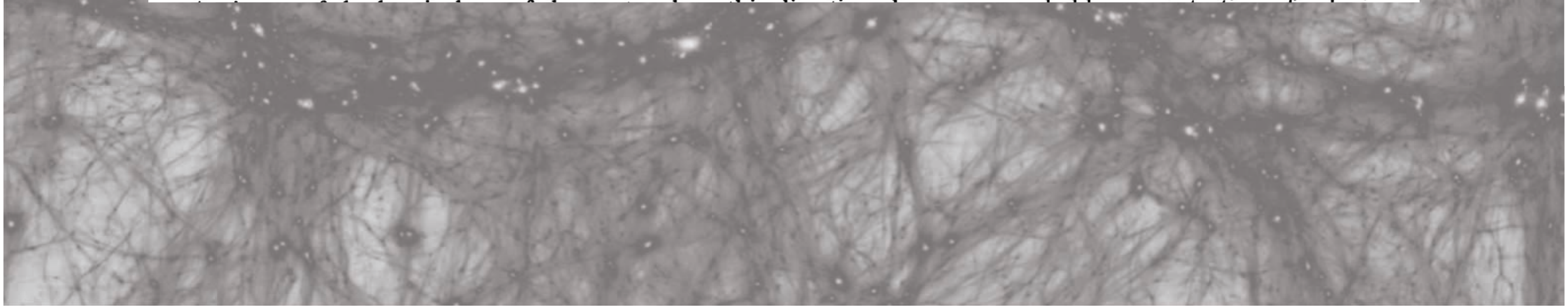

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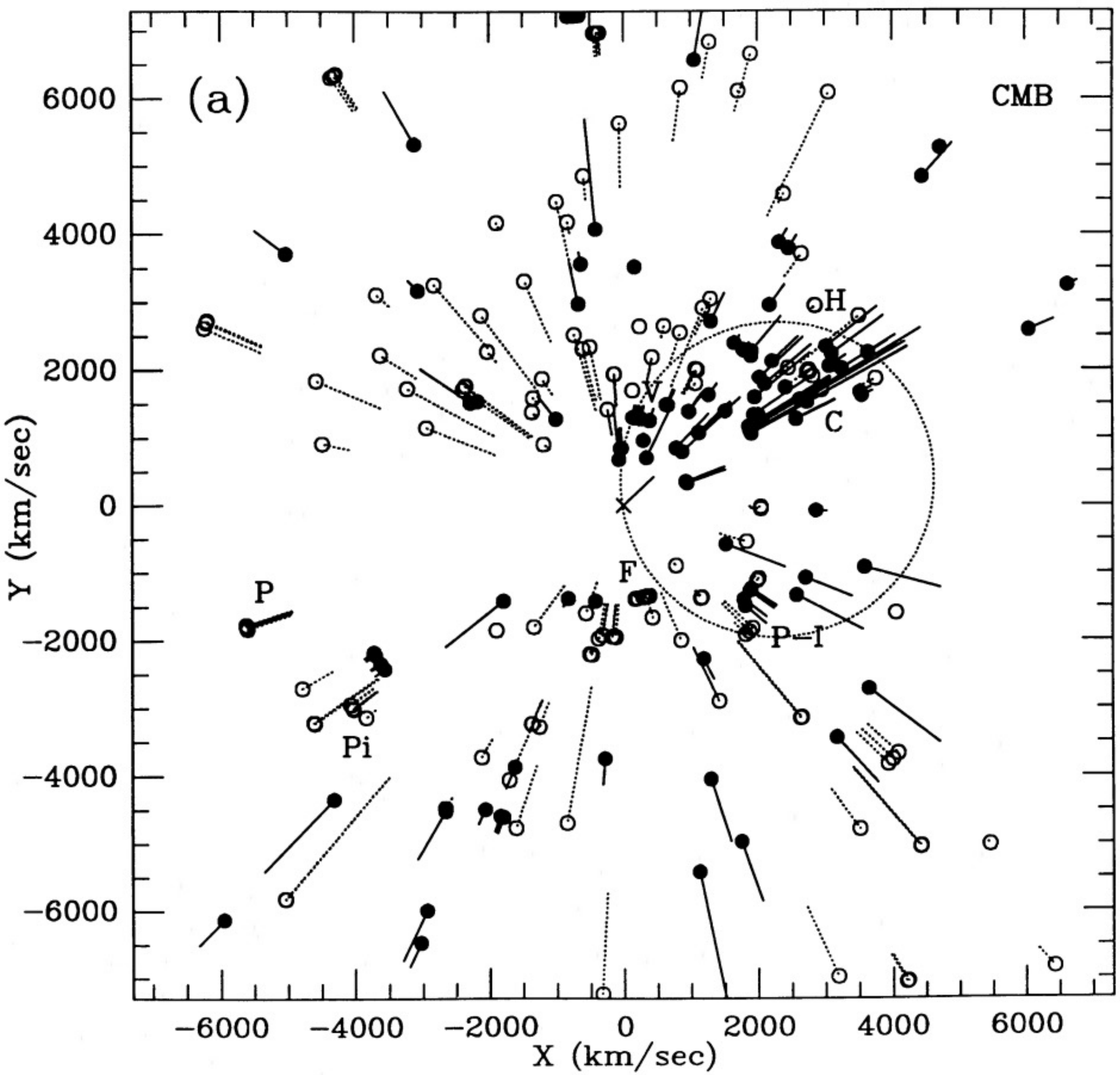

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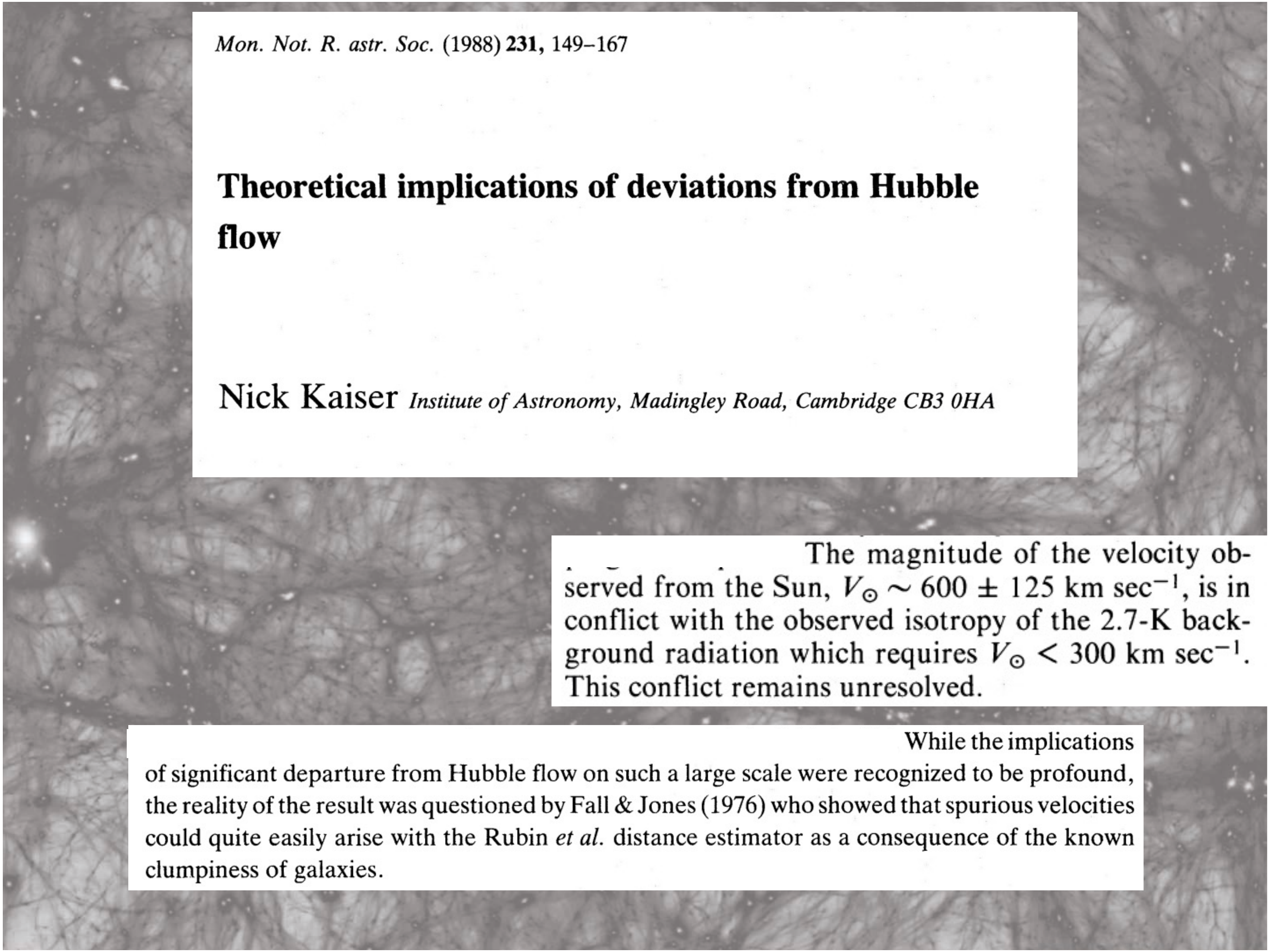


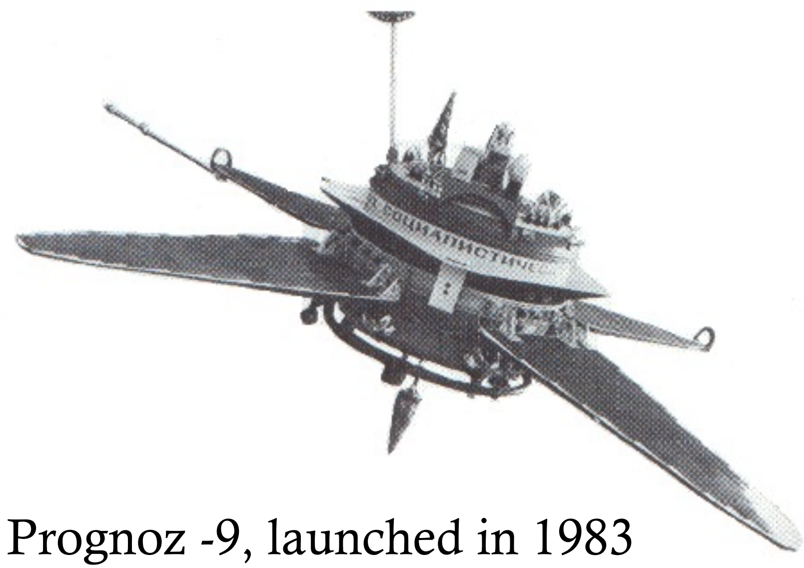
Mon. Not. R. astr. Soc. (1988) **231,** 149–167

Theoretical implications of deviations from Hubble flow

Nick Kaiser *Institute of Astronomy, Madingley Road, Cambridge CB3 0HA*

The magnitude of the velocity observed from the Sun, $V_{\odot} \sim 600 \pm 125$ km sec^{-1}, is in conflict with the observed isotropy of the 2.7-K background radiation which requires $V_{\odot} < 300$ km sec^{-1}. This conflict remains unresolved.

While the implications of significant departure from Hubble flow on such a large scale were recognized to be profound, the reality of the result was questioned by Fall & Jones (1976) who showed that spurious velocities could quite easily arise with the Rubin *et al.* distance estimator as a consequence of the known clumpiness of galaxies.



Prognoz -9, launched in 1983

Deep-space measurements of the microwave background anisotropy: first results of the *Relikt* experiment

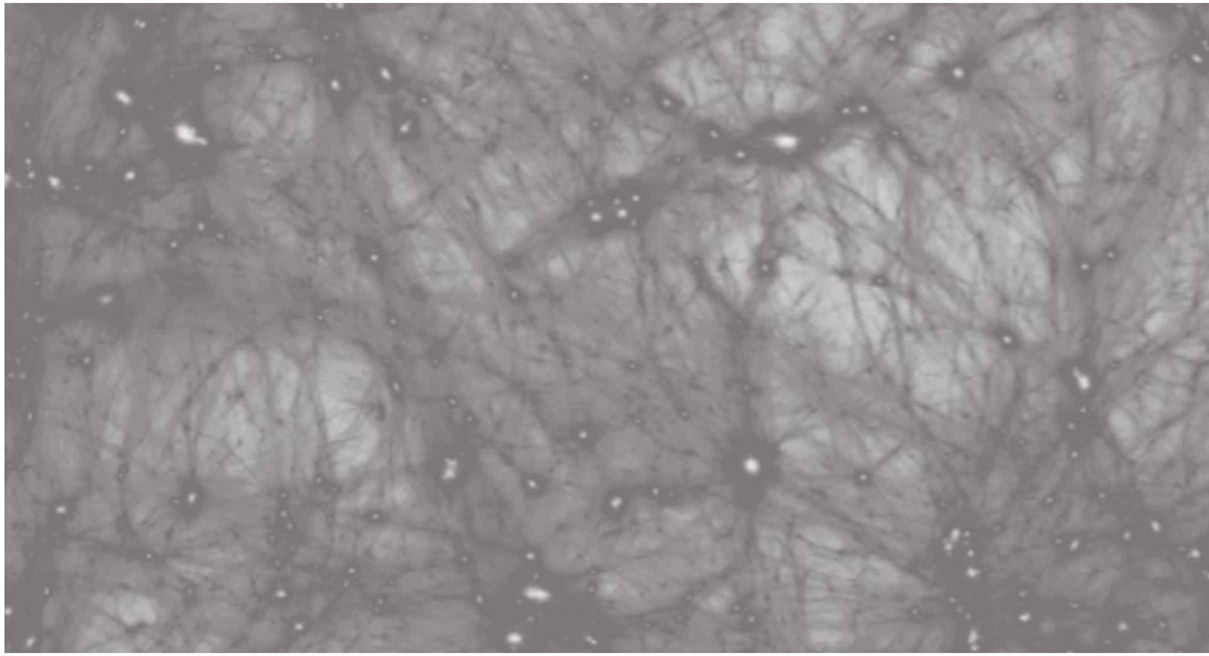
I. A. Strukov and D. P. Skulachev

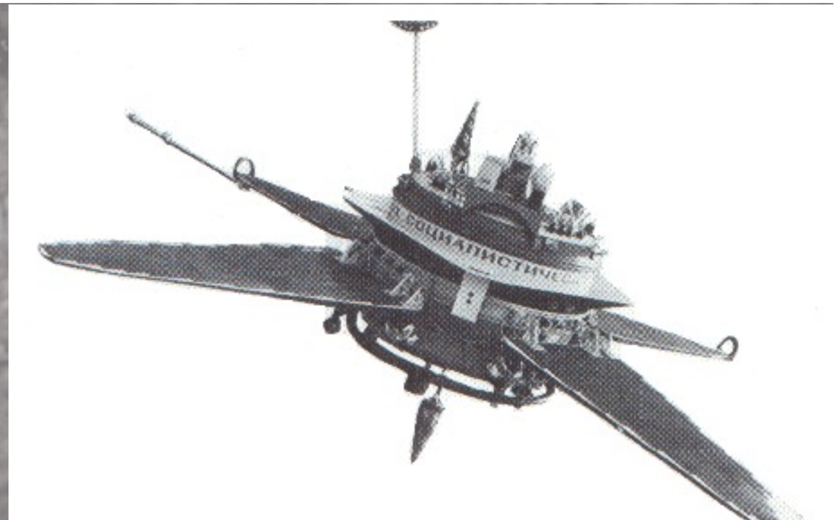
Institute for Space Research, USSR Academy of Sciences, Moscow

(Submitted September 16, 1983)

Pis'ma Astron. Zh. **10**, 3–13 (January 1984)

An 8-mm radiometer system with a degenerate parametric amplifier was launched on the high-apogee (7×10^5 km) *Prognoz 9* satellite in July 1983 to map the large-scale anisotropy of the cosmic background radiation. Early results indicate that the amplitude of the dipole and any quadrupole component is measurable to 0.1-mK rms accuracy, and by the end of the experiment the error should be lower. With 95% confidence the strip of sky investigated thus far exhibits no quadrupole component above the 0.2-mK level.





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Accordingly, at a 95% confidence level the portion of the sky investigated thus far shows no quadrupole component of amplitude above 0.2 mK.

Angular resolution: 6 deg
Temperature resolution: 0.6mK
Frequency: 37GHz

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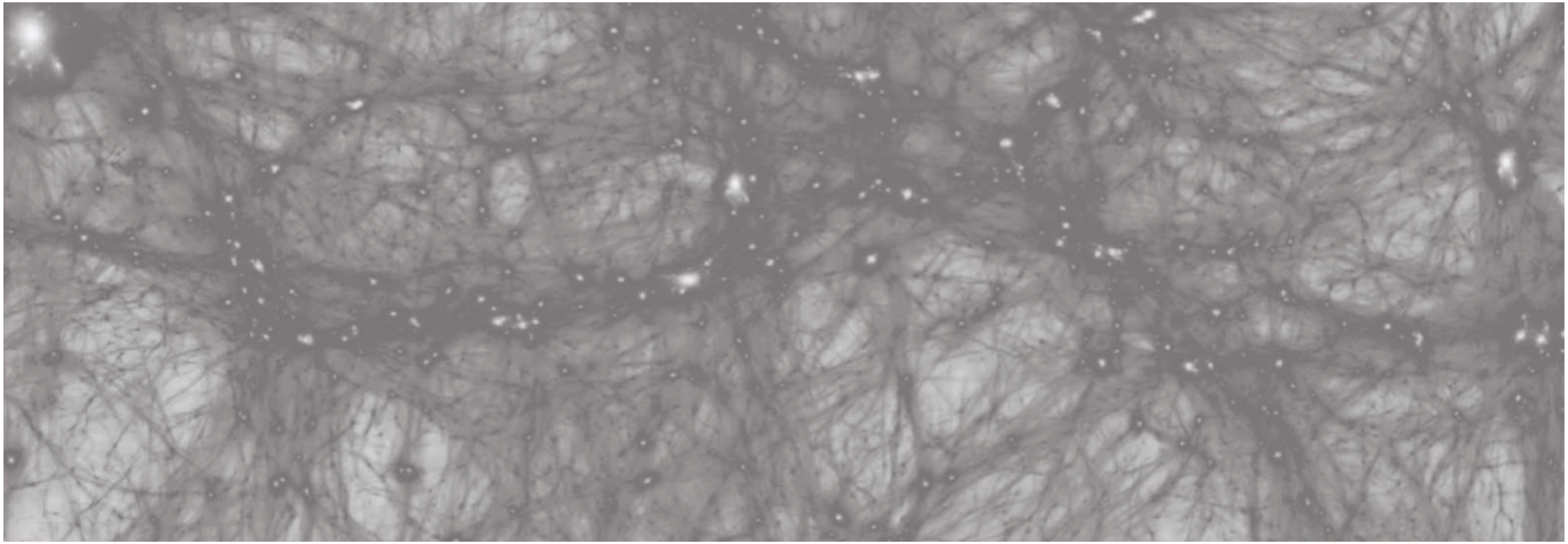
REVIEW ARTICLE

Cosmic microwave background anisotropy

Nick Kaiser* & Joseph Silk†

* Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, UK
† Astronomy Department, University of California, Berkeley, California 94720, USA

Current hypotheses for the origin of structure in the Universe lead to predictions of the amplitudes of anisotropies in the cosmic microwave background radiation. The dipole anisotropy is related to density fluctuations on large scales and to other determinations of our motion relative to distant galaxies. Observation and theory are coming tantalizingly close to measuring the elusive anisotropy, or to revealing that our ideas about the origin of galaxies and large-scale structures are in need of substantial revision.



Cosmic microwave background anisotropy

Nick Kaiser* & Joseph Silk†

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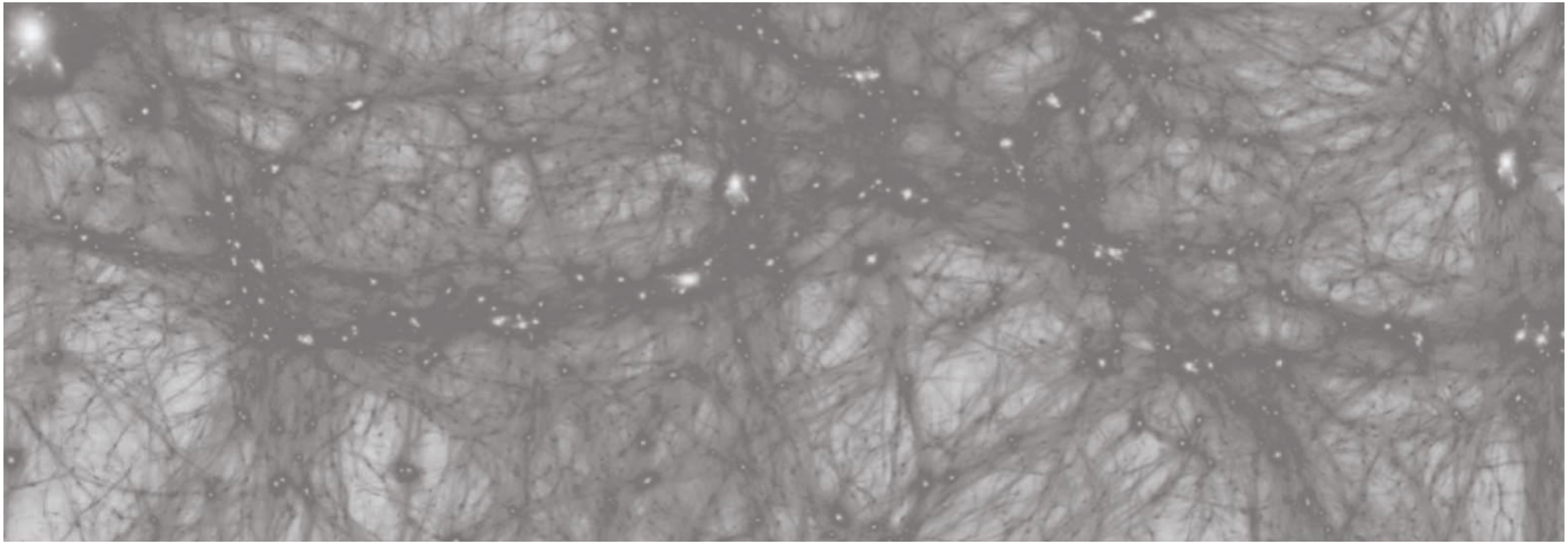
It is of course conceivable that we are completely on the wrong track. Perhaps the primordial fluctuation spectrum was not described by a scale-invariant power law, nor was it gaussian, nor even adiabatic.



Cosmic microwave background anisotropy

Nick Kaiser[*] & Joseph Silk[†]

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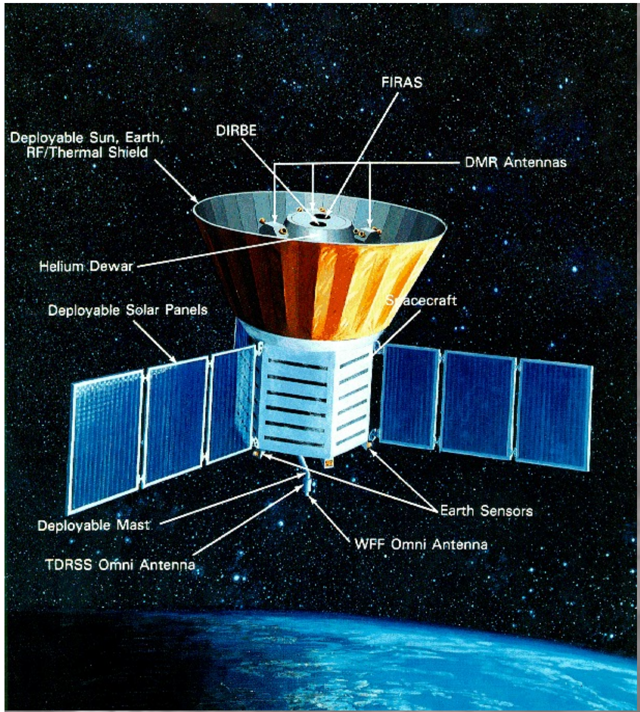
If our interpretation of the CBR in the standard Big Bang model is correct, and there is no real alternative, then we inevitably expect to see some residue of these initial conditions in the background radiation anisotropy. It would be too perverse of Nature to have thrown down an impenetrable screen which renders such fluctuations invisible. Eventual detection of $\delta T/T$ on some angular scale is inevitable, and it will surely elucidate one of the most challenging mysteries of the Big Bang theory, namely the origin and the formation of large-scale structure.



The New York Times

SUNDAY, NOVEMBER 19, 1989

Supersensitive Satellite Starts Search for Echoes of the Universe's Birth

By WARREN E. LEARY

Special to The New York Times

WASHINGTON, Nov. 18 — A robot spacecraft swinging high over the earth's poles today began a search for the beginning of time.

Pushed into space by the thrust of a Delta rocket launched flawlessly today from Vandenberg Air Force Base in California, the craft moved into a circular 559-mile-high orbit that swings top-to-bottom around the earth 14 times a day.

From that height, the Cosmic Background Explorer is to use its cold eyes to take sweeping looks at the black sky, seeking faint, warm traces of the first light.

Over the next year, the 4,850-pound craft is to map the entire sky twice in search of remnants of the Big Bang, the theoretical birth of existence that sprang from the explosion of unknown, primordial material about 15 billion years ago.

The COBE satellite, which contains the most sensitive detectors ever flown on a space mission, is to sweep the sky for "fossil" radiation generated in the period between the first minutes of creation and the time the first stars and galaxies formed. Its polar orbit will keep the reflections from the Sun and Earth from affecting instruments.

The project is one of the most important to date for the science of cosmology, the study of the earliest beginnings of the universe.

'Before the Lights Came On'

"With COBE, we can see things before the lights came on," said Dr. John C. Mather, chief project scientist. "While we probably will not rewrite the book of cosmology with this mission, we will write another chapter."

The solar-powered spacecraft was designed and built at the National Aeronautics and Space Administration's Goddard Space Flight Center in Greenbelt, Md., which will control and monitor the $400 million mission. While the space agency plans to operate the 16-by-28-foot craft for two years, the satellite is designed to complete its mission within a year.

At the start, a month's shakedown is scheduled for checking the spacecraft's condition and position and calibrating its three supersensitive main instruments.

These surveying instruments include a differential microwave radiometer that will distinguish faint microwave radiation from the early universe from that produced within the Milky Way galaxy. The other instruments, the far infrared absolute spectrophotometer and the diffuse infrared background experiment, will examine different wavelenghts of infrared light. To enhance their sensitivity, the infrared instruments are cooled with liquid helium to within 2 degrees Celsius of absolute zero.

Radiation From Everywhere

"The predominant theory of the origin of the universe is the Big Bang," said Dr. Mather in a telephone interview, "and we expect to get details about it, to refine it."

The theory has been evolving since the beginning of this century. First astronomers discovered huge, distant collections of galaxies full of stars that were receding from the Earth's location. Later, they detected large amounts of background radiation in the universe, coming from every direction.

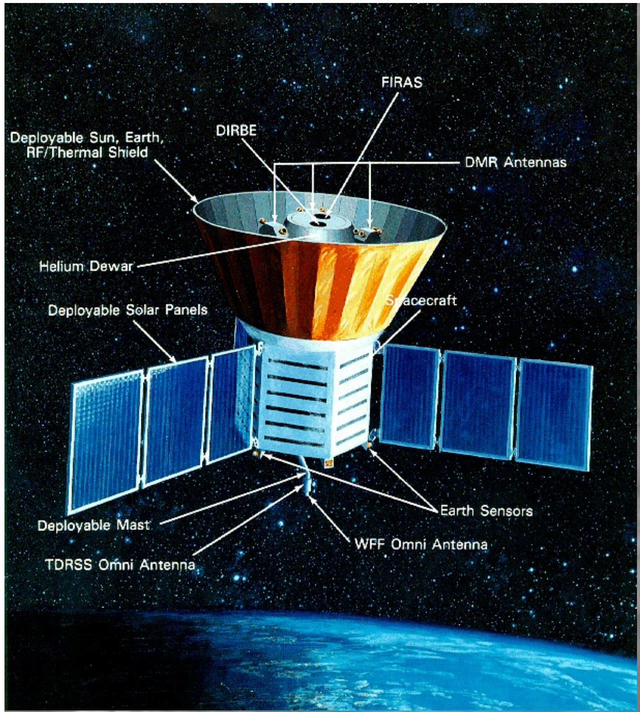
"This radiation, the remains of a huge explosion, amounts to 100 times the energy generated by all the stars, galaxies, gas clouds and other things we know exist in the universe," Dr. Mather said.

The theory holds that at some point before the beginning of time, all the universe's matter and energy existed in a superhot ball of unknown nature that was perhaps no bigger than a baseball. This ball exploded, beginning a process that led, after 500,000 years, to the creation of atoms and in 200 million years to the early formation of stars and galaxies.

At about 300,000 years into the process, the opaque plasma from the primary explosion turned into more transparent gas, a process that released the microwave radiation scientists hope to detect with the Cosmic Background Explorer. Finding bright spots and dark spots in this radiation could be evidence of disturbances in the smooth gas, and such disturbances could be important in explaining the diversity of the universe, Dr. Mather said.

An explosion like the Big Bang should have produced a smooth, uniform sphere of material that spread evenly from the center. But the universe is complex and bumpy, with billions and billions of stars arranged in huge clumps or long strings, and enormous areas of utter void.

The spacecraft's infrared sensors, which measure heat, may help scientists learn if black holes and other exotic phenomena helped create lumps in the universe between three minutes after the Big Bang and the time the first atoms formed.



The New York Times

SUNDAY, NOVEMBER 19, 1989

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Supersensitive Satellite Starts … verse's Birth

By WARREN E. LEARY

Special to The New York Times

WASHINGTON, Nov. 18 — A robot spacecraft swinging high over the earth's poles today began a search for the beginning of time.

Pushed into space by the thrust of a Delta rocket launched flawlessly today from Vandenberg Air Force Base in California, the craft moved into a circular 559-mile-high orbit that swings top-to-bottom around the earth 14 times a day.

From that height, the Cosmic Background Explorer is to use its cold eyes to take sweeping looks at the black sky, seeking faint, warm traces of the first light.

Over the next year, the 4,850-pound craft is to map the entire sky twice in search of remnants of the Big Bang, the theoretical birth of existence that sprang from the explosion of unknown, primordial material about 15 billion years ago.

The COBE satellite, which contains the most sensitive detectors ever flown on a space mission, is to sweep the sky for "fossil" radiation generated in the period between the first minutes of creation and the time the first stars and galaxies formed. Its polar orbit will keep the reflections from the Sun and Earth from affecting instruments.

The project is one of the most important to date for the science of cosmology, the study of the earliest beginnings of the universe.

'Before the Lights Came On'

"With COBE, we can see things before the lights came on," said Dr. John C. Mather, chief project scientist. "While we probably will not rewrite the book of cosmology with this mission, we will write another chapter."

The solar-powered spacecraft was designed and built at the National Aeronautics and Space Administration's Goddard Space Flight Center in Greenbelt, Md., which will control and monitor the $400 million mission. While the space agency plans to operate the 16-by-28-foot craft for two years, the …

… that produced within the Milky Way galaxy. The other instruments, the far infrared absolute spectrophotometer and the diffuse infrared background experiment, will examine different wavelenghts of infrared light. To enhance their sensitivity, the infrared instruments are cooled with liquid helium to within 2 degrees Celsius of absolute zero.

Radiation From Everywhere

"The predominant theory of the origin of the universe is the Big Bang," said Dr. Mather in a telephone inter-…

This radiation, the remains of a huge explosion, amounts to 100 times the energy generated by all the stars, galaxies, gas clouds and other things we know exist in the universe," Dr. Mather said.

The theory holds that at some point before the beginning of time, all the universe's matter and energy existed in a superhot ball of unknown nature that was perhaps no bigger than a baseball. This ball exploded, beginning a process that led, after 500,000 years, to the creation of atoms and in 200 million years to the early formation of stars and galaxies.

… about 300,000 years into the pro- … the opaque plasma from the pri- … explosion turned into more trans- … it gas, a process that released the … wave radiation scientists hope to … with the Cosmic Background … rer. Finding bright spots and … spots in this radiation could be … nce of disturbances in the smooth … and such disturbances could be … rtant in explaining the diversity of the universe, Dr. Mather said.

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Adv. Space Res. Vol. 11, No. 2, pp. (2)193 –(2)205, 1991
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0273–1177/91 $0.00 + .50
1991 COSPAR

FIRST RESULTS OF THE COBE SATELLITE MEASUREMENT OF THE ANISOTROPY OF THE COSMIC MICROWAVE BACKGROUND RADIATION

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[1]Lawrence Berkeley Laboratory and Space Sciences Laboratory, University of California, Berkeley; [2]Laboratory for Astronomy and Solar Physics, NASA, Goddard Space Flight Center;
[3]National Research Council, NASA/GSFC; [4]ST Systems Inc.;
[5]NASA Jet Propulsion Laboratory, Pasadena;
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ABSTRACT

We review the concept and operation of the Differential Microwave Radiometers (DMR) instrument aboard NASA's Cosmic Background Explorer (COBE) satellite, with emphasis on the software identification and subtraction of potential systematic effects. We present preliminary results obtained from the first six months of DMR data and discuss implications for cosmology.

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The results are consistent with a universe described by a Robertson-Walker metric and show no evidence of anisotropic expansion, rotation, or localized defects (strings).

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Political Memo

Why Perot Could Pose a Threat With $100 Million: It's His Own

By R. W. APPLE Jr.
Special to The New York Times

WASHINGTON, April 23 — If he runs for President this fall, which seems more likely with each passing day, Ross Perot says he would be willing to spend up to $100 million of his own money on the effort — much more than the major-party nominees could spend on their own account.

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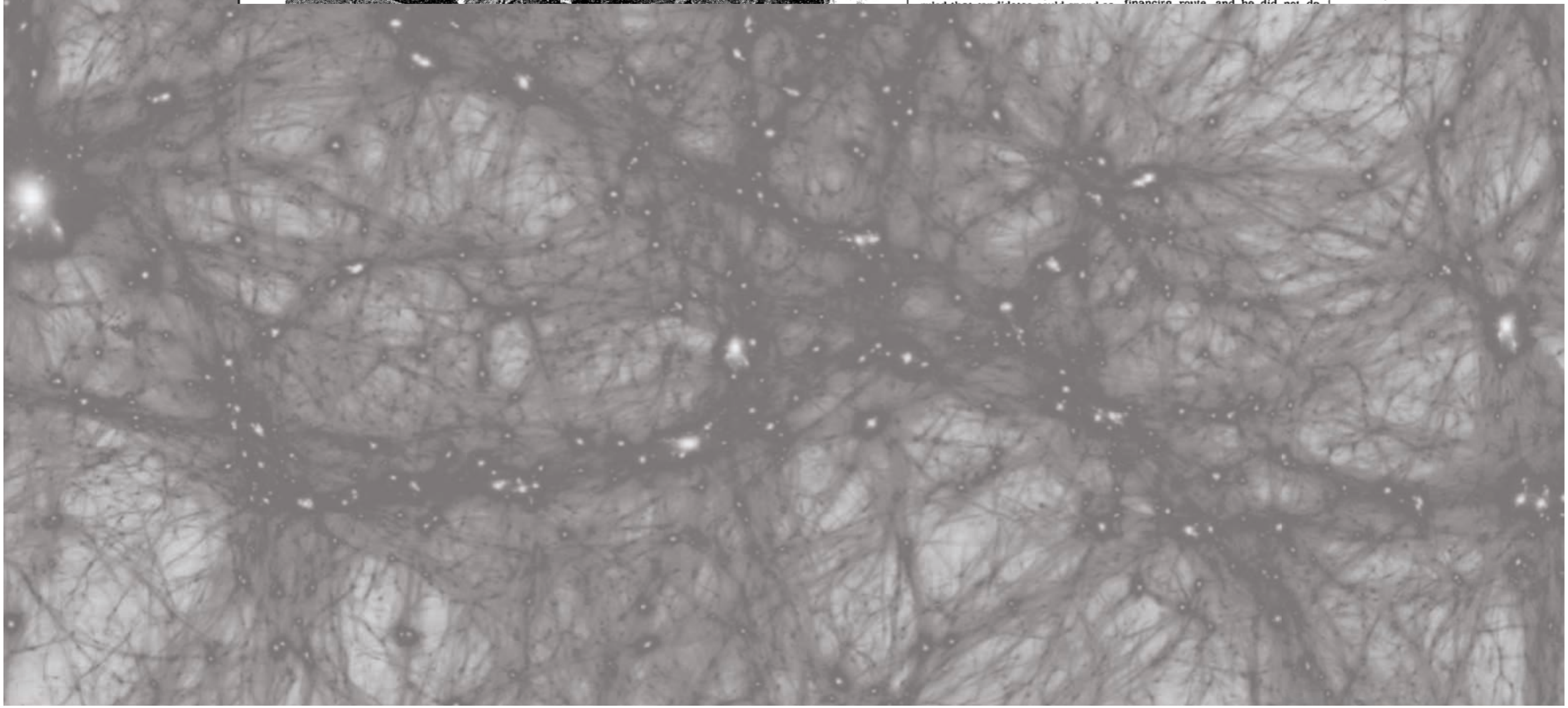

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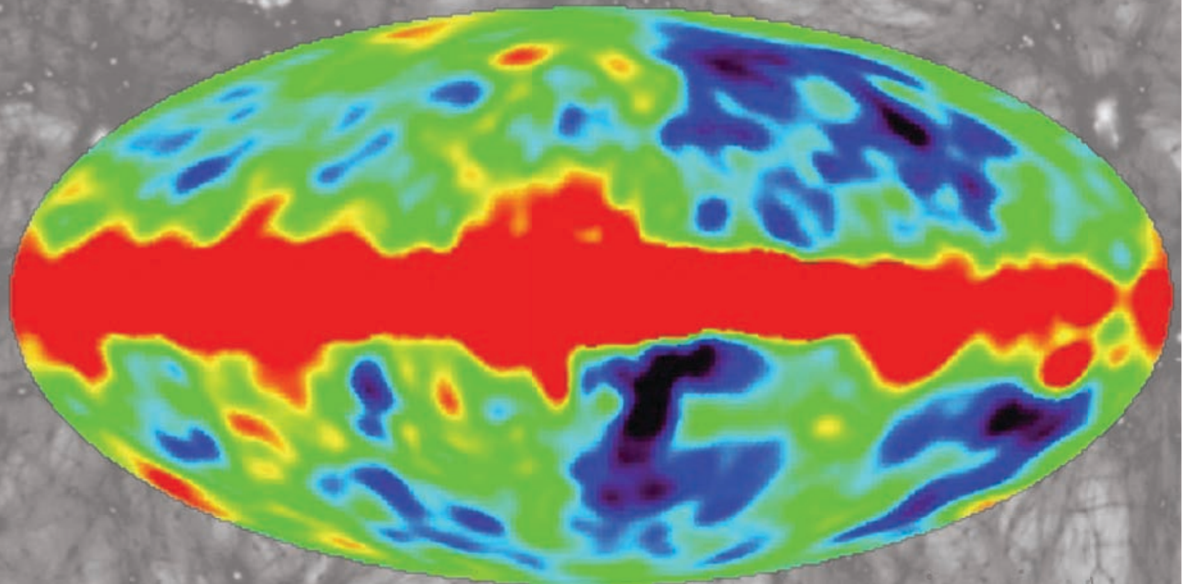

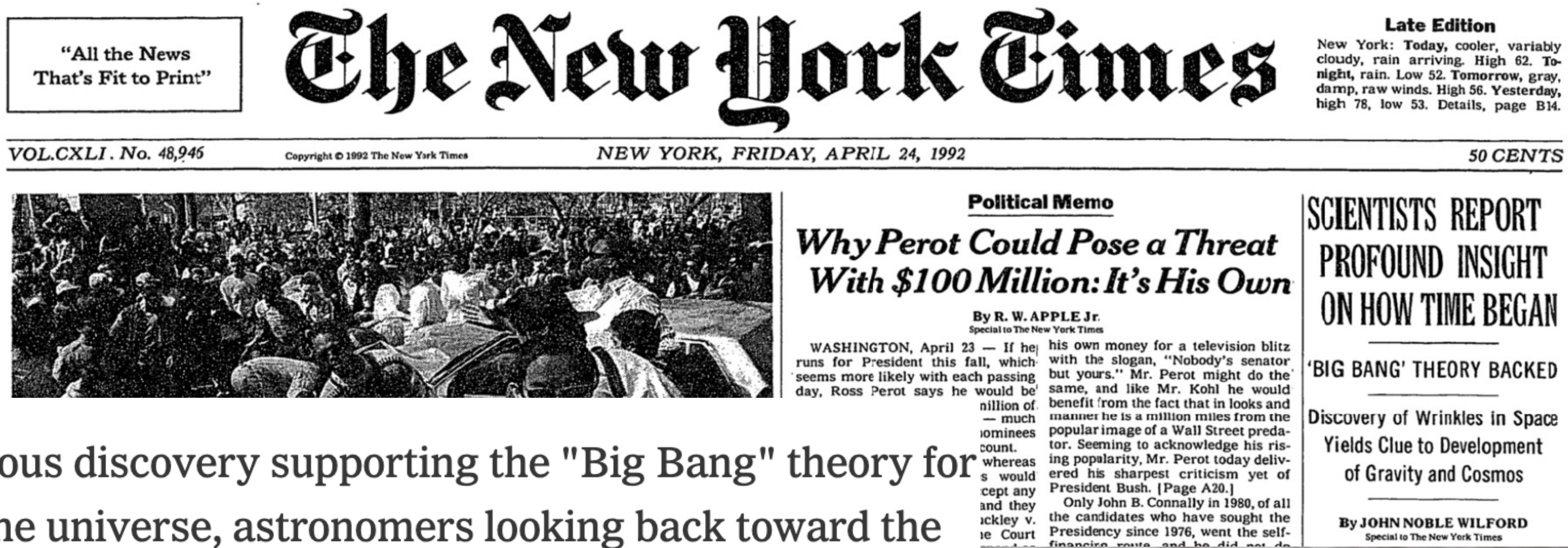

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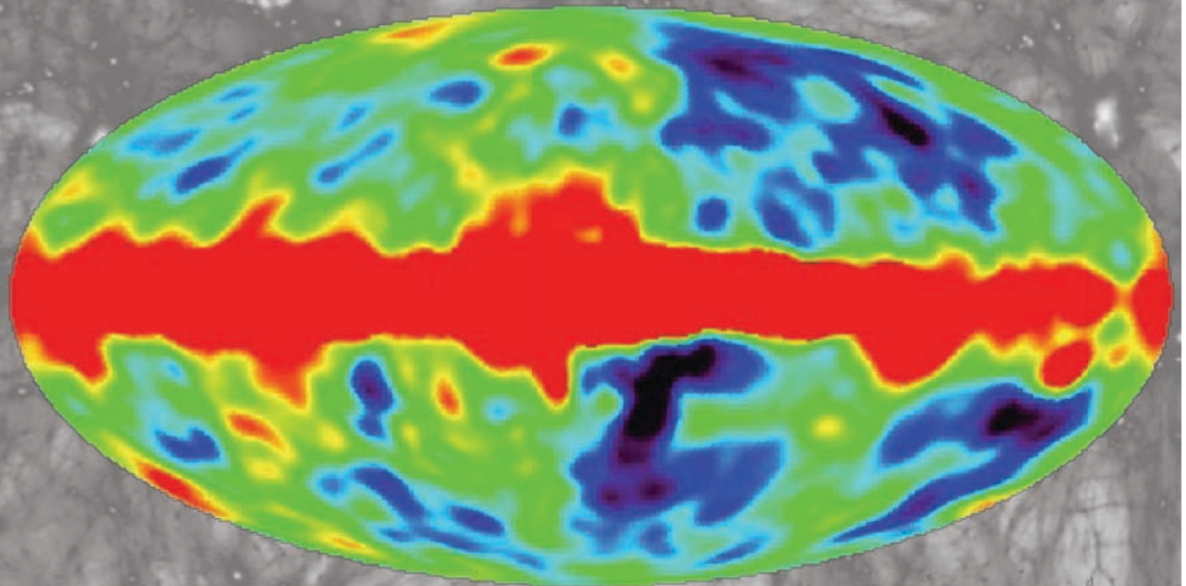

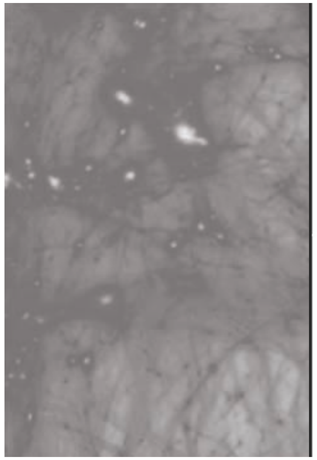

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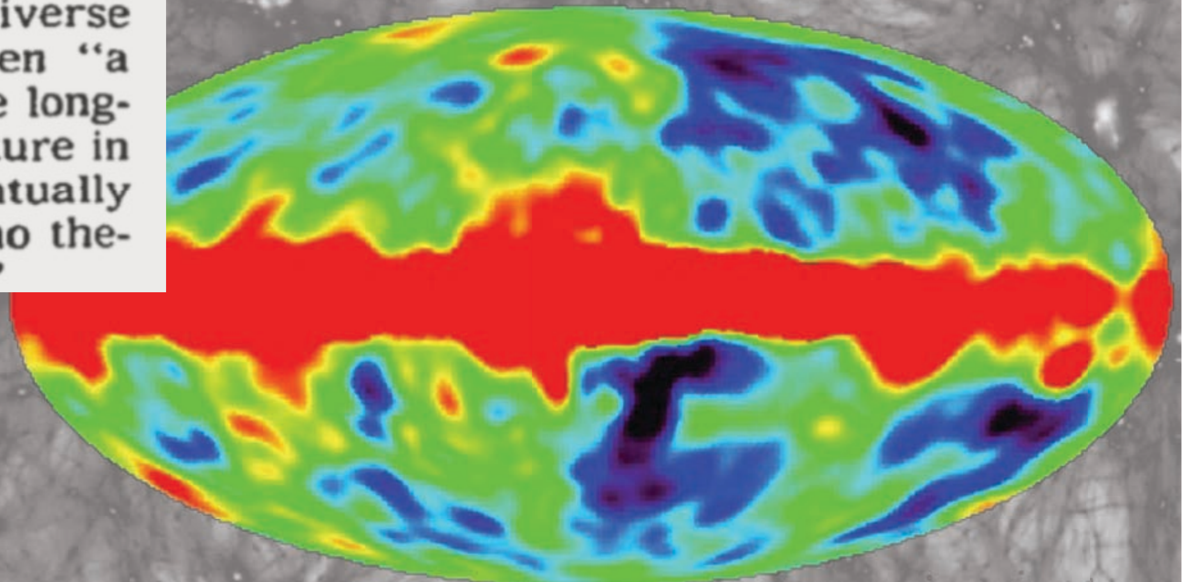
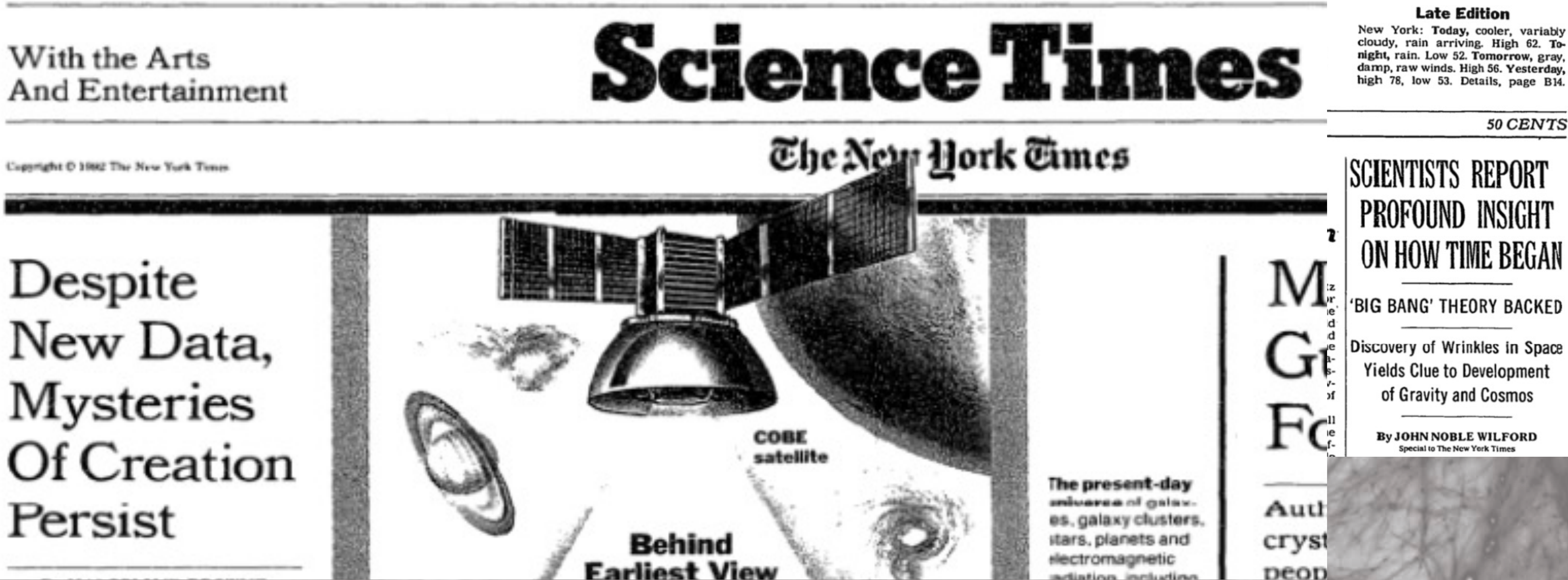
Dr. Steven Weinberg of the University of Texas at Austin, winner of a Nobel Prize in Physics and a leading cosmological theorist, said in an interview that the satellite's detection of unevennesses in radiation dating from the infancy of the universe averted what might have been "a theoretical catastrophe." If the long-sought evidence of early structure in the universe had not been eventually discovered, he said, "there's no theory that would have survived."





With the Arts
And Entertainment

Science Times

The New York Times

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Despite New Data, Mysteries Of Creation Persist

COBE satellite

Behind
Earliest View

The present-day universe of galaxies, galaxy clusters, stars, planets and electromagnetic radiation, including

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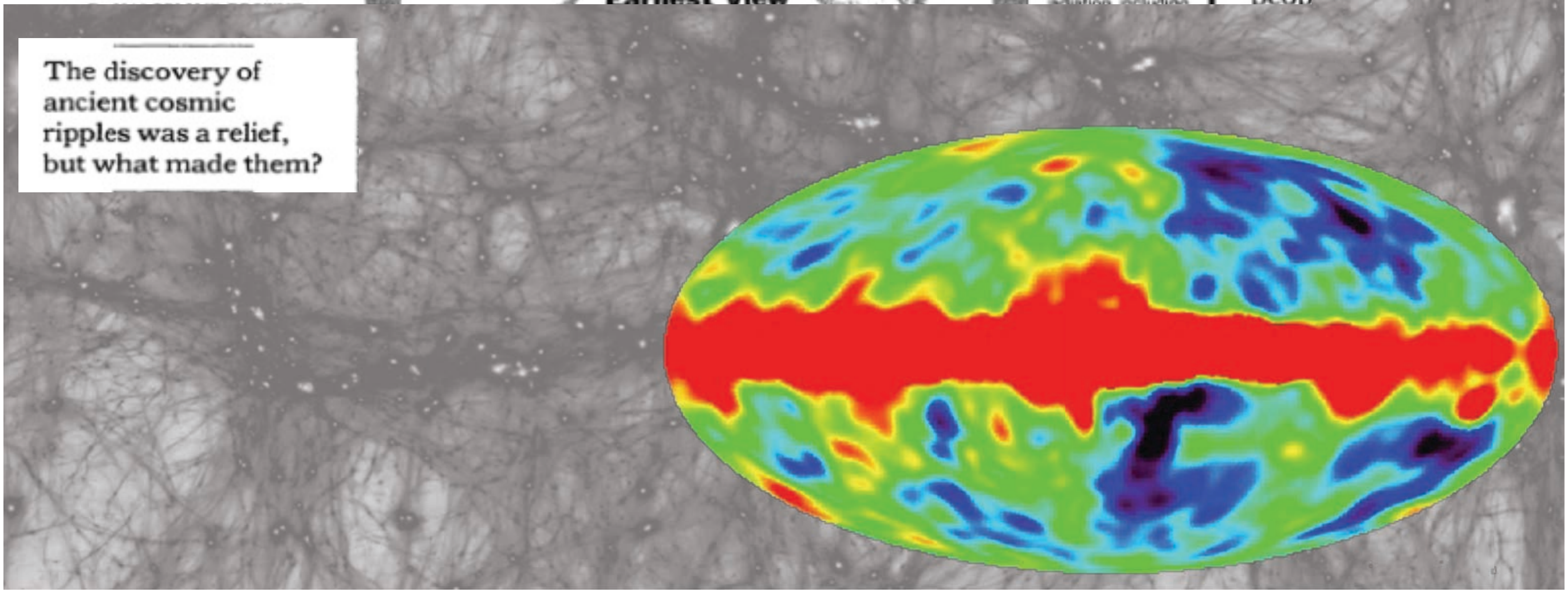
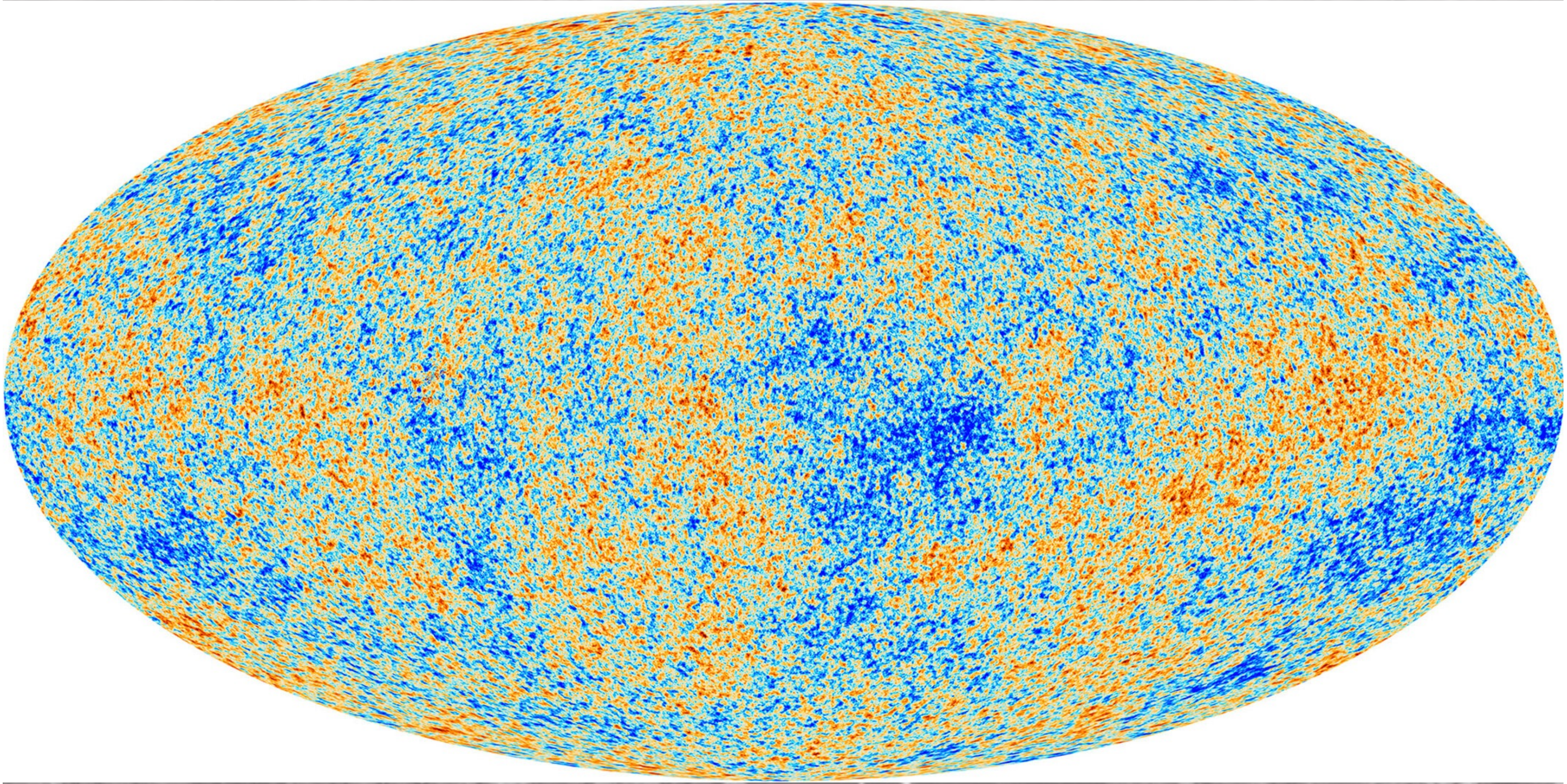
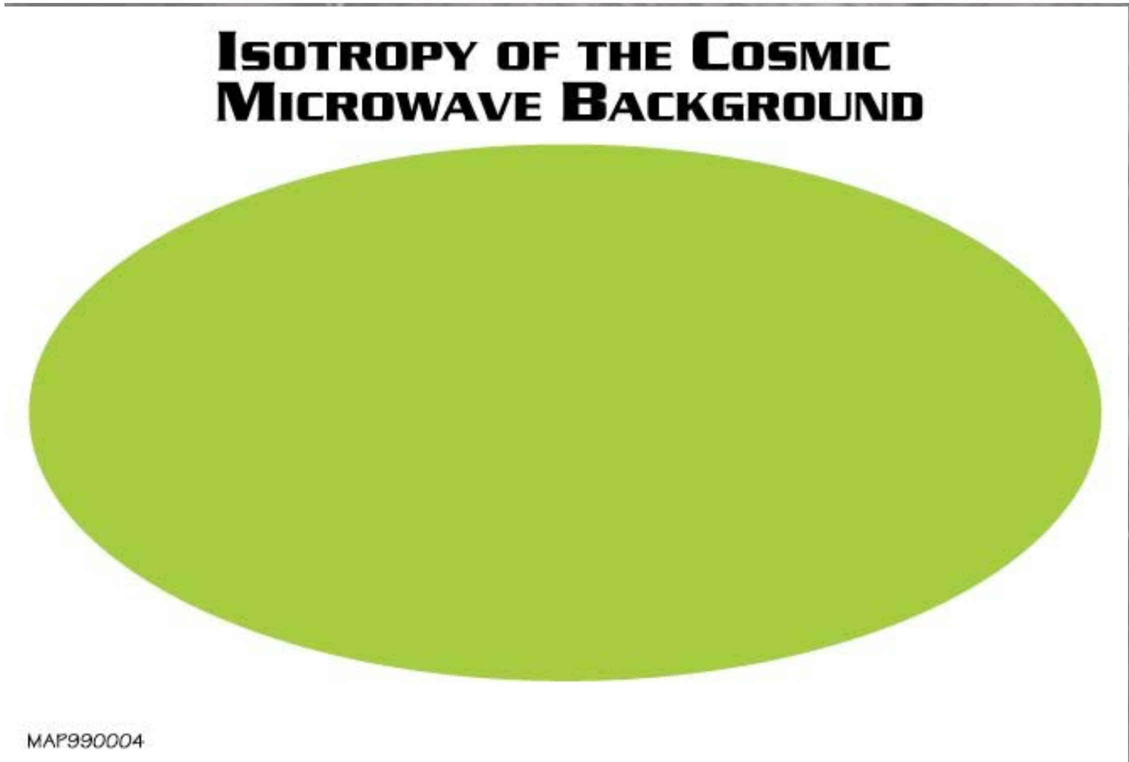


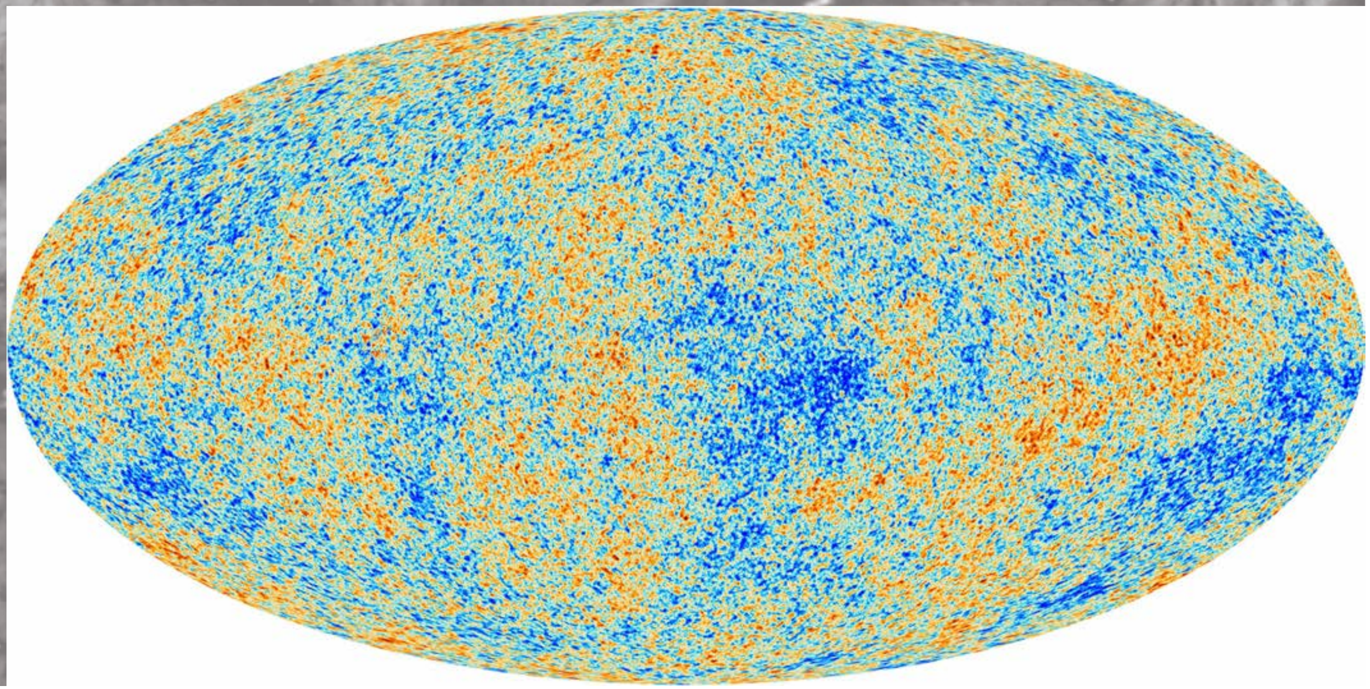
The discovery of ancient cosmic ripples was a relief, but what made them?



Plank 2019



30-50 years



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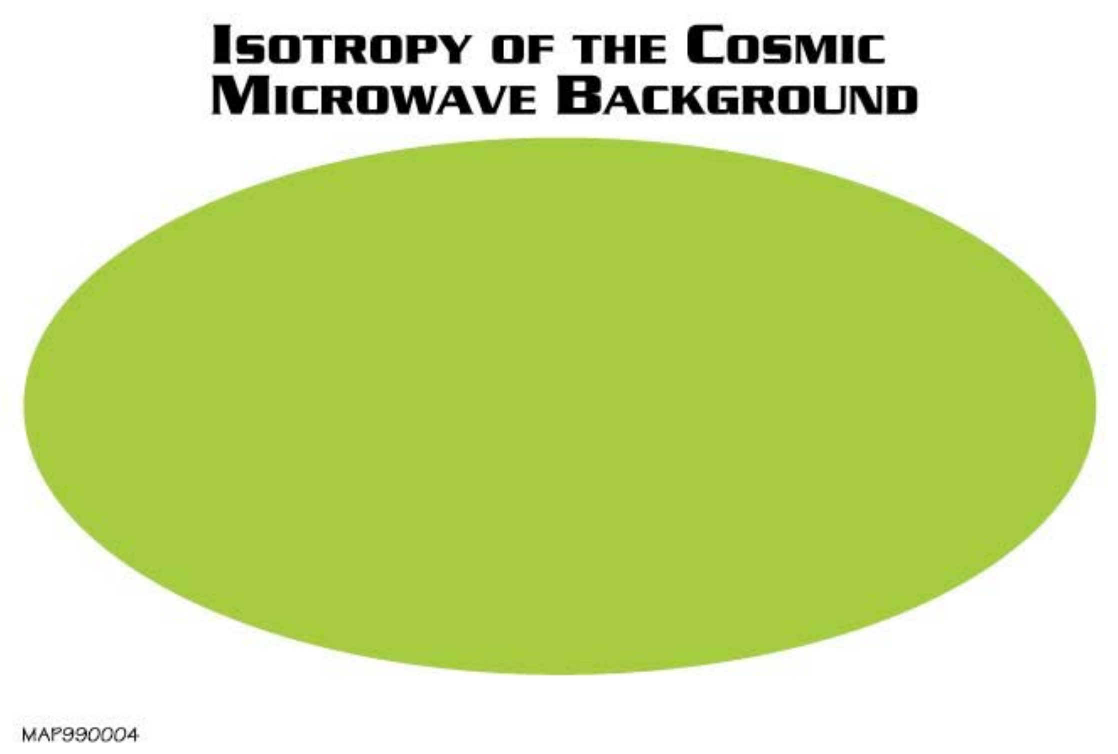

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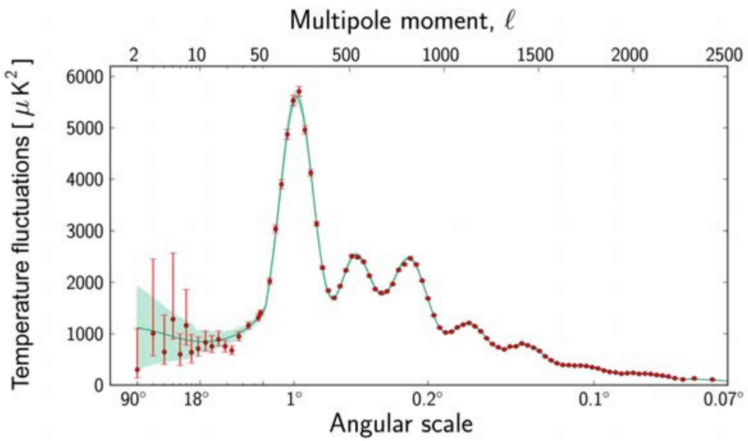
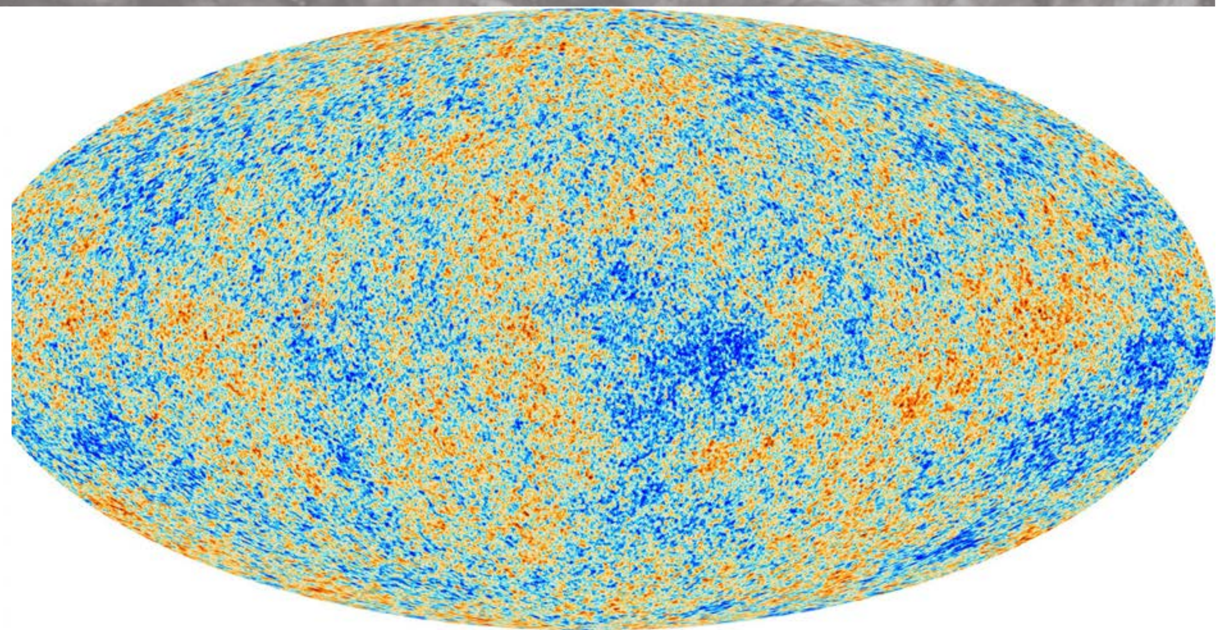
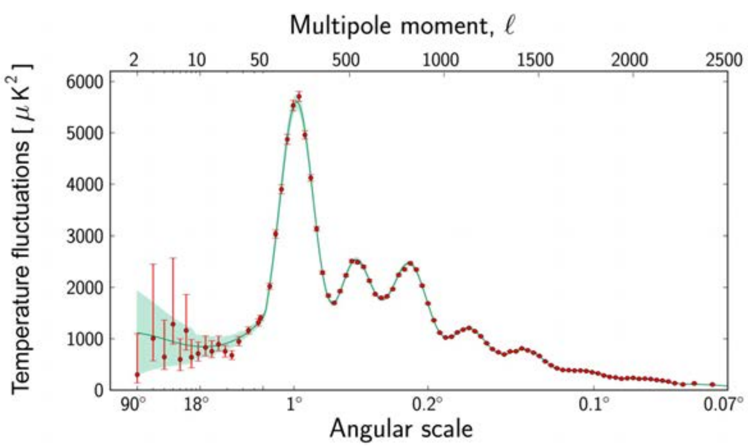


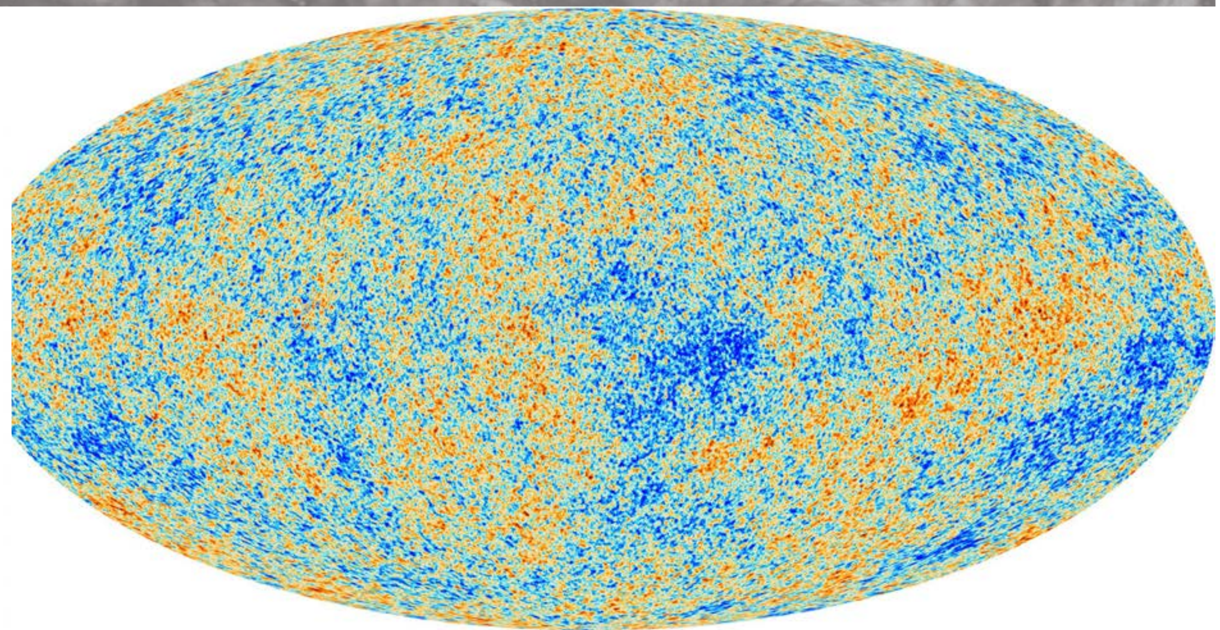


Plank 2019

The Cosmic Microwave Background

- Very simple: Universe was born 13.7 bn years ago, possibly in a singularity





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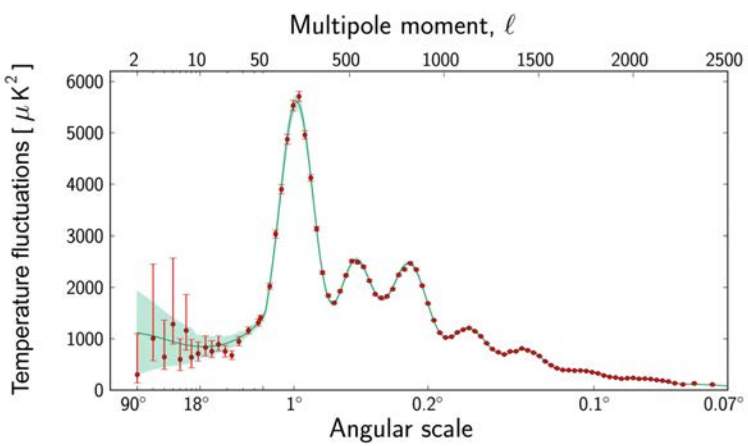

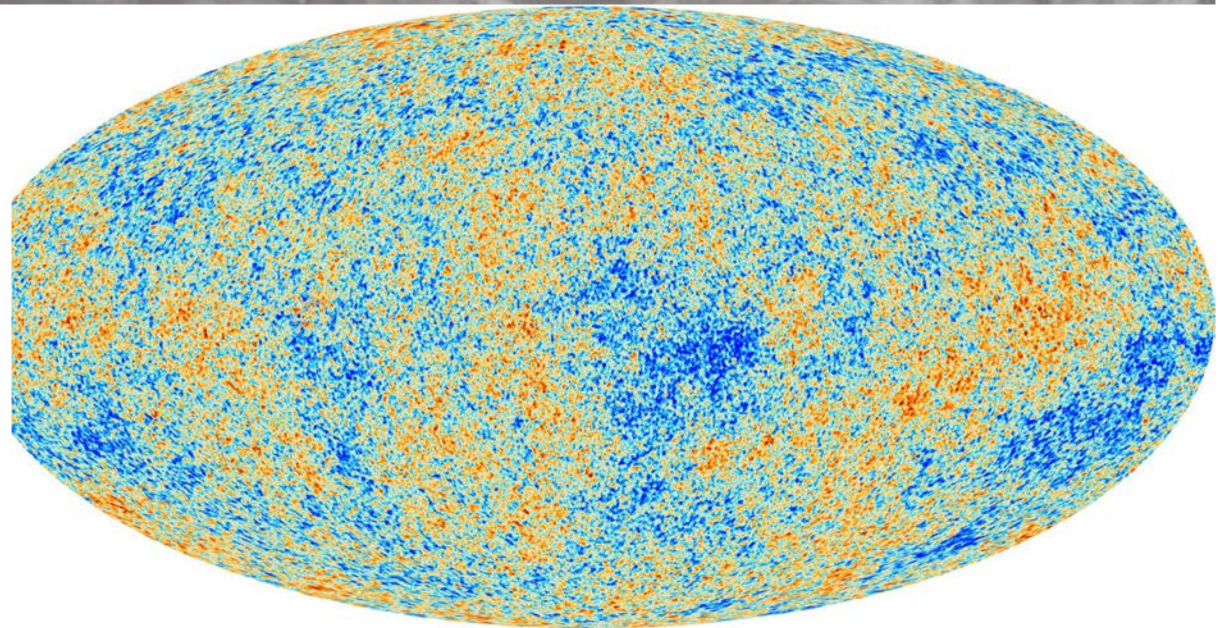

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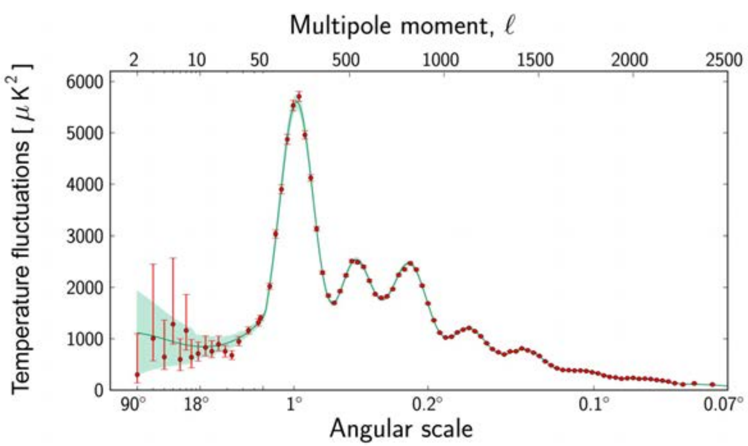

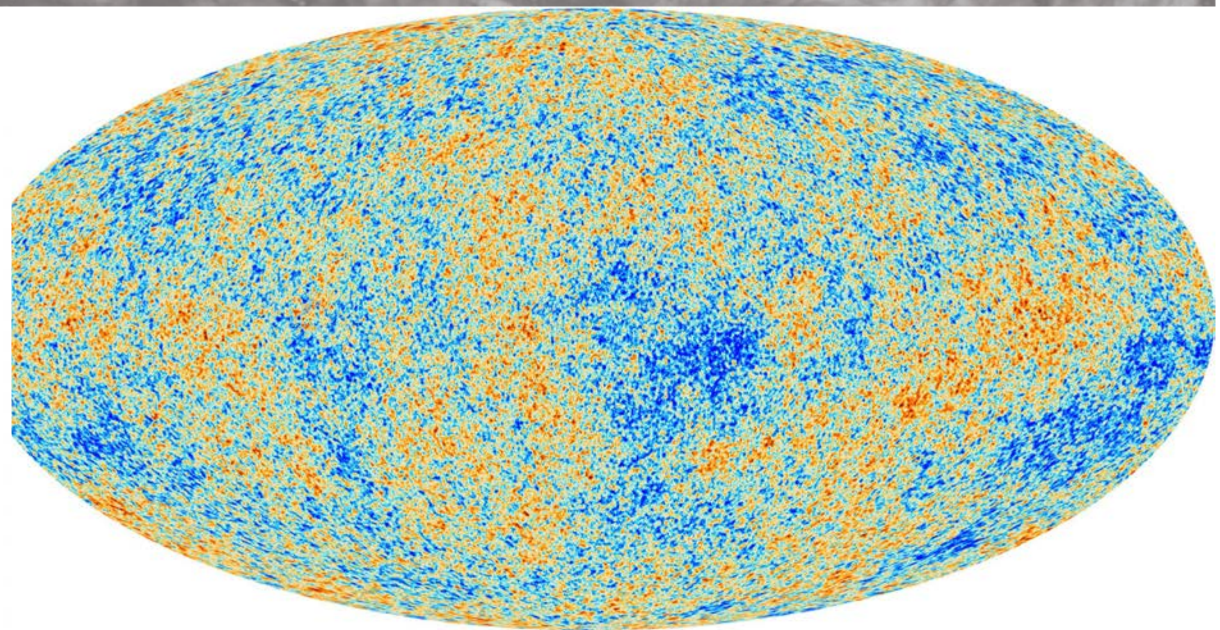

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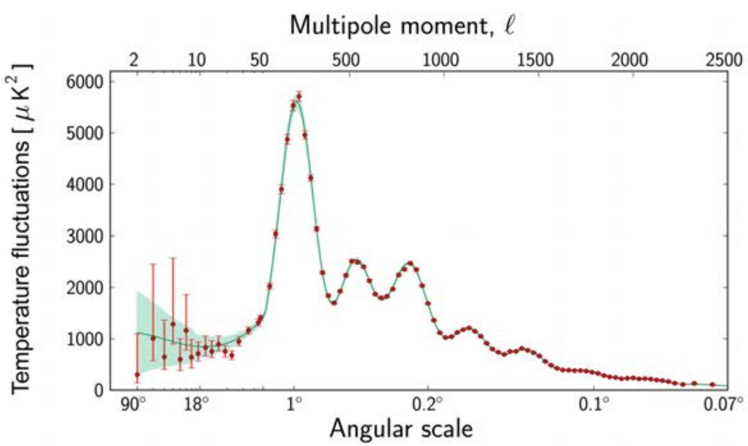

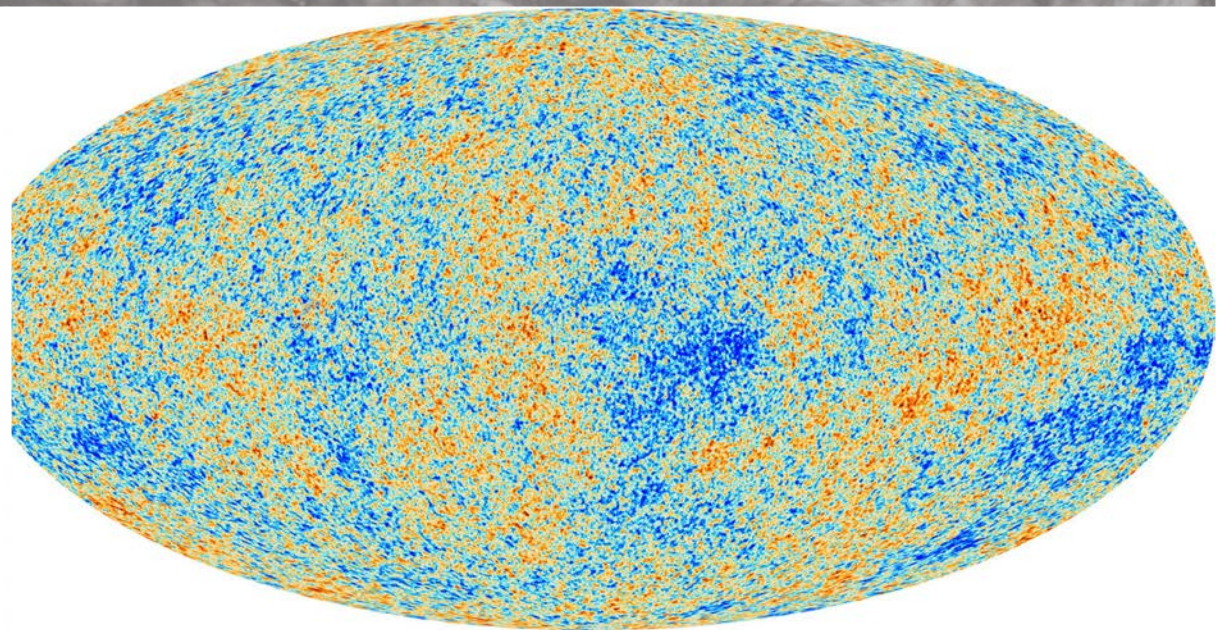

Plank 2019

How did a simple initial state evolve into something so complicated

A problem of classical physics

- governing equations (non-relativistic fluid with pressure)

  - Poisson's equation

$$\Delta\Psi = 4\pi G\rho$$

  - continuity equation

$$\frac{\partial\rho}{\partial t} + \nabla\cdot(\rho\vec{v}) = 0$$

  - conservation of momentum

$$\frac{\partial\vec{v}}{\partial t} + (\vec{v}\cdot\nabla)\vec{v} = -\nabla\Psi - \frac{\nabla p}{\rho}$$

  - equation of state

$$p = c_s^2\rho$$

(c_s: sound speed)

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$$\frac{\mathrm{d}f}{\mathrm{d}t} = \frac{\partial f}{\partial t} + \frac{\partial f}{\partial \mathbf{x}}\cdot\mathbf{v} + \frac{\partial f}{\partial \mathbf{v}}\cdot\left(-\frac{\partial\Phi}{\partial\mathbf{x}}\right) = 0$$

$$\nabla^2\Phi(\mathbf{x},t) = 4\pi G\int f(\mathbf{x},\mathbf{v},t)\,\mathrm{d}\mathbf{v}$$

Vlassov poisson eq

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Complex partial differential equations that requires a numerical solution

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Vlassov poisson eq

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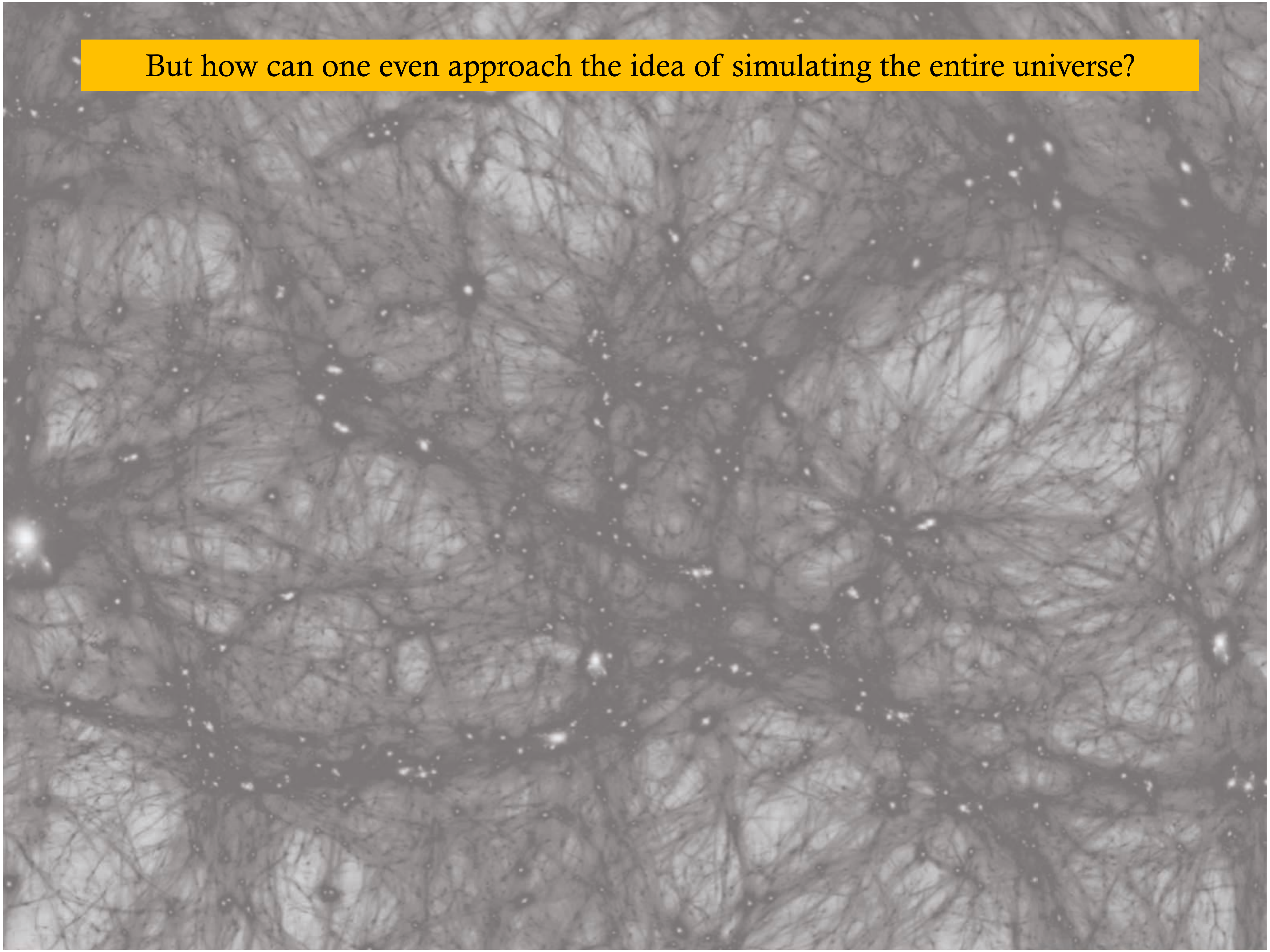

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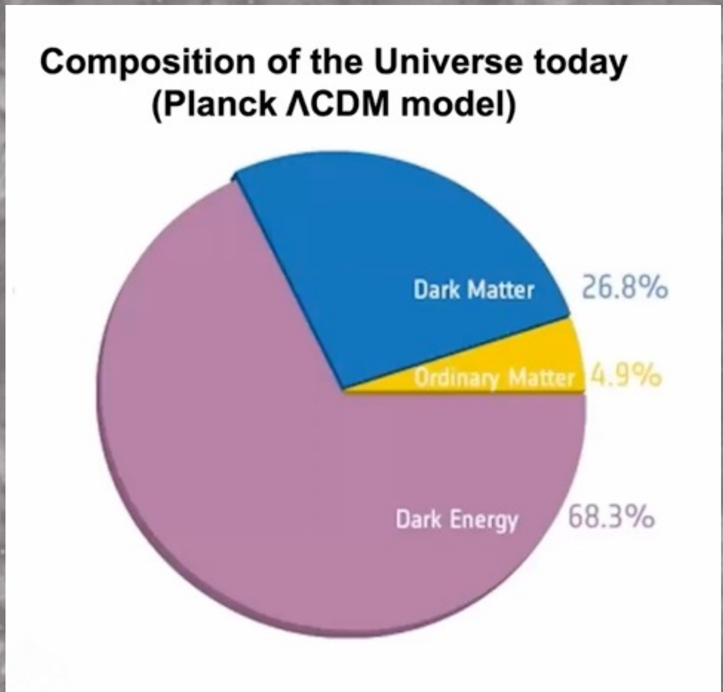
First: make some simplifying assumptions



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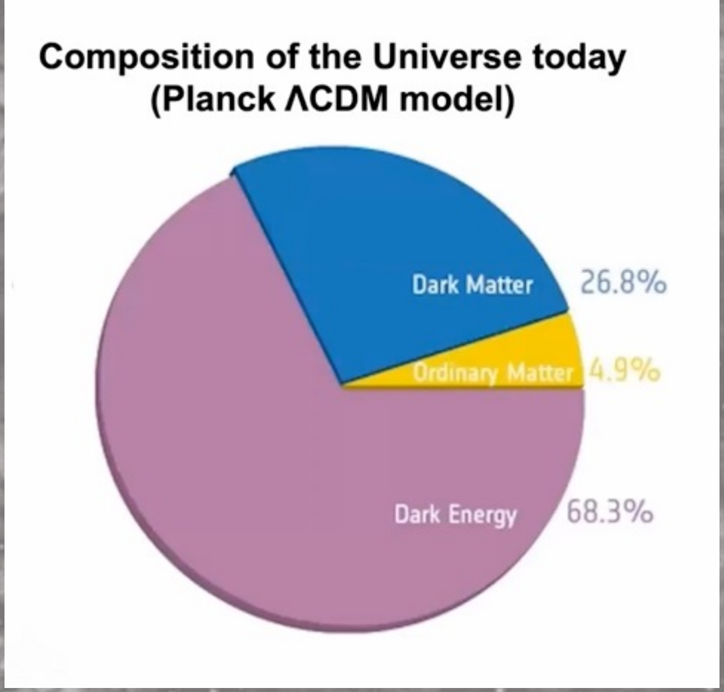
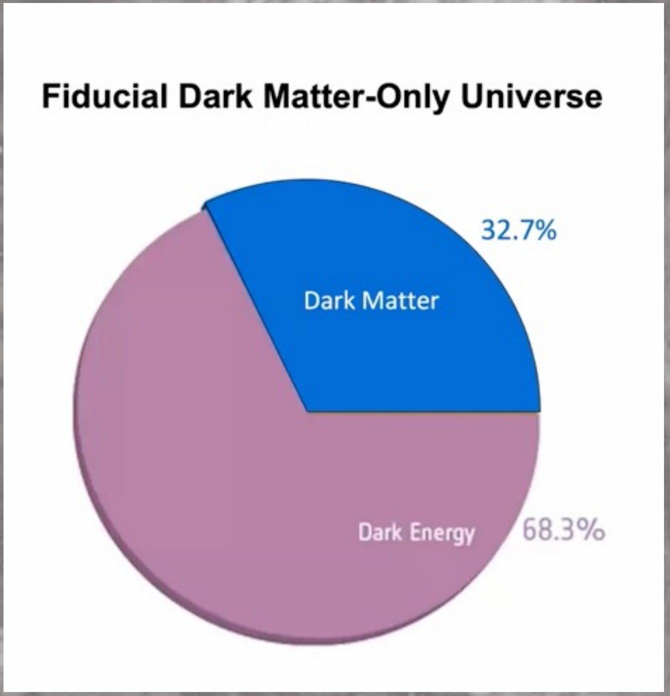
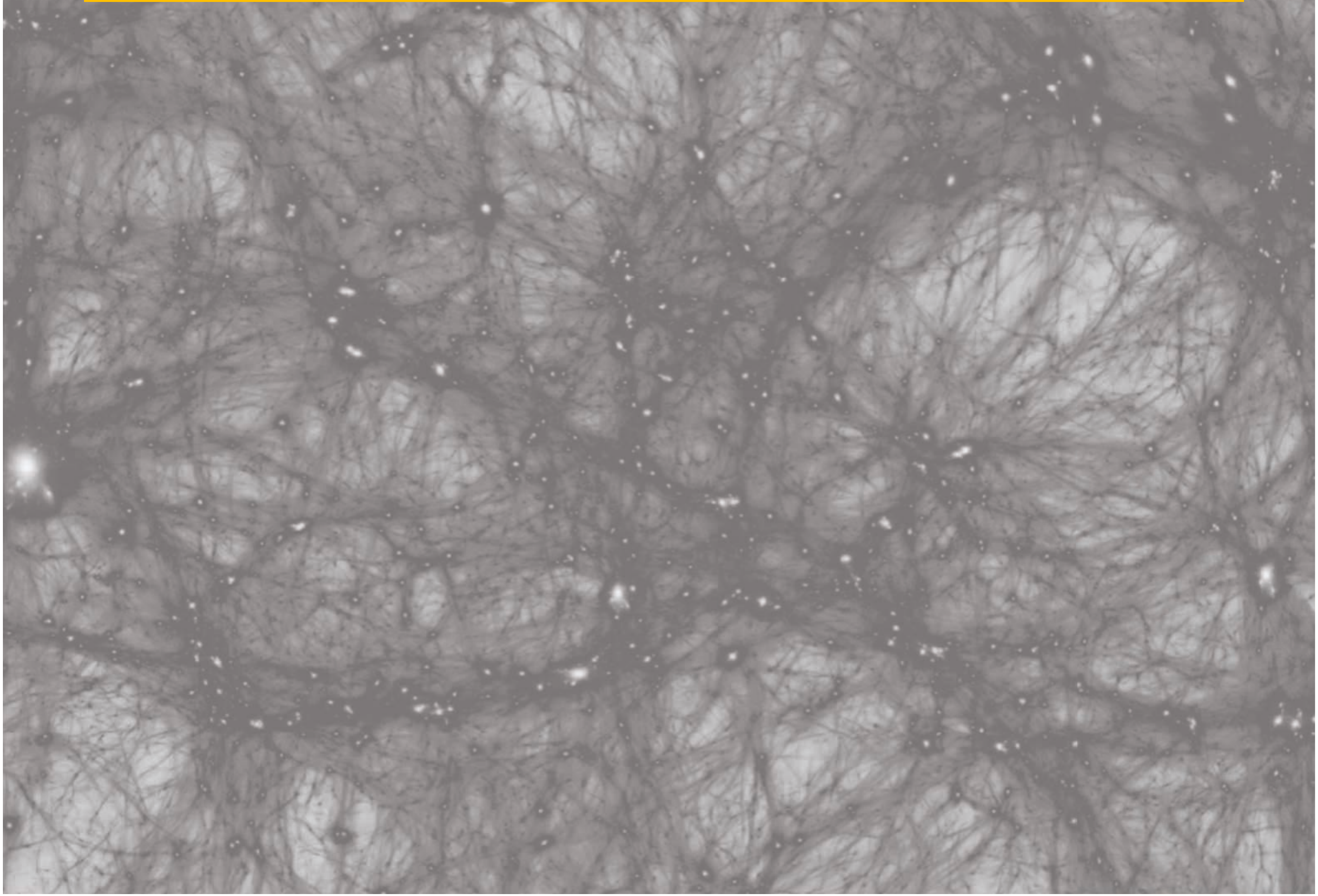




Isn't dark matter complicated?
No its just gravitating !

But how can one simulate gravity??



The first paper suggesting simulations of gravity

Erik Holmberg

THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

VOLUME 94 NOVEMBER 1941 NUMBER 3

ON THE CLUSTERING TENDENCIES AMONG THE NEBULAE

II. A STUDY OF ENCOUNTERS BETWEEN LABORATORY MODELS OF STELLAR SYSTEMS BY A NEW INTEGRATION PROCEDURE

ERIK HOLMBERG

ABSTRACT

In a previous paper[1] the writer discussed the possibility of explaining the observed clustering effects among extragalactic nebulae as a result of captures. The present investigation deals with the important problem of whether the loss of energy resulting from the tidal disturbances at a close encounter between two nebulae is large enough to effect a capture. The tidal deformations of two models of stellar systems, passing each other at a small distance, are studied by reconstructing, piece by piece, the orbits described by the individual mass elements. The difficulty of integrating the total gravitational force acting upon a certain element at a certain point of time is solved by replacing gravitation by light. The mass elements are represented by light-bulbs, the candle power being proportional to mass, and the total light is measured by a photocell (Fig. 1). The nebulae are assumed to have a flattened shape, and each is represented by 37 light-bulbs. It is found that the tidal deformations cause an increase in the attraction between the two objects, the increase reaching its maximum value when the nebulae are separating, i.e., after the passage. The resulting loss of energy (Fig. 6) is comparatively large and may, in favorable cases, effect a capture. The spiral arms developing during the encounter (Figs. 4) represent an interesting by-product of the investigation. The direction of the arms depends on the direction of rotation of the nebulae with respect to the direction of their space motions.

I. THE EXPERIMENTAL ARRANGEMENTS

The present paper is a study of the tidal disturbances appearing in stellar systems which pass one another at small distances. These tidal disturbances are of some importance since they are accompanied by a loss of energy which may result in a capture between the two objects. In a previous paper[1] the writer discussed the clustering tendencies among extragalactic nebulae. A theory was put forth that the observed clustering effects are the result of captures between individual nebulae. The capture theory seems to be able to account not only for double and multiple nebulae but also for the large extragalactic clusters. The present investigation tries to give an answer to the important question of whether the loss of energy accompanying a close encounter between two nebulae is large enough to effect a capture.

A study of tidal disturbances is greatly facilitated if it can be restricted to only two dimensions, i.e., to nebulae of a flattened shape, the principal planes of which coincide with the plane of their hyperbolic orbits. In order to reconstruct the orbit described by

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The first paper suggesting simulations of gravity

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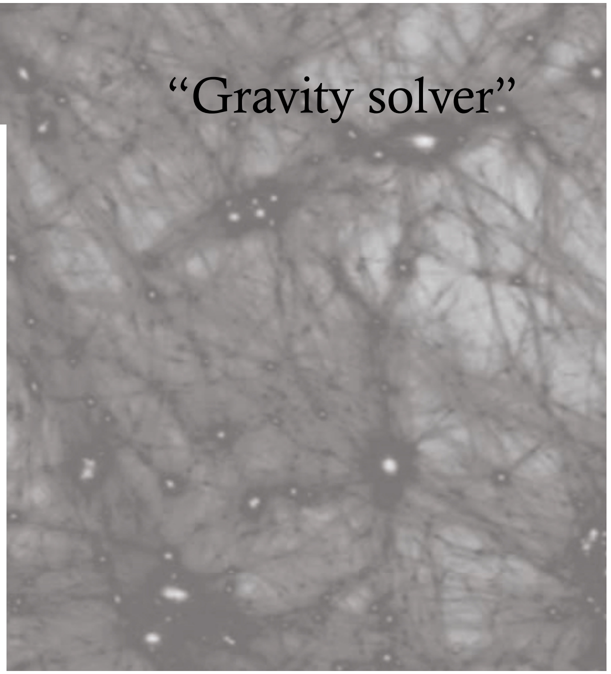

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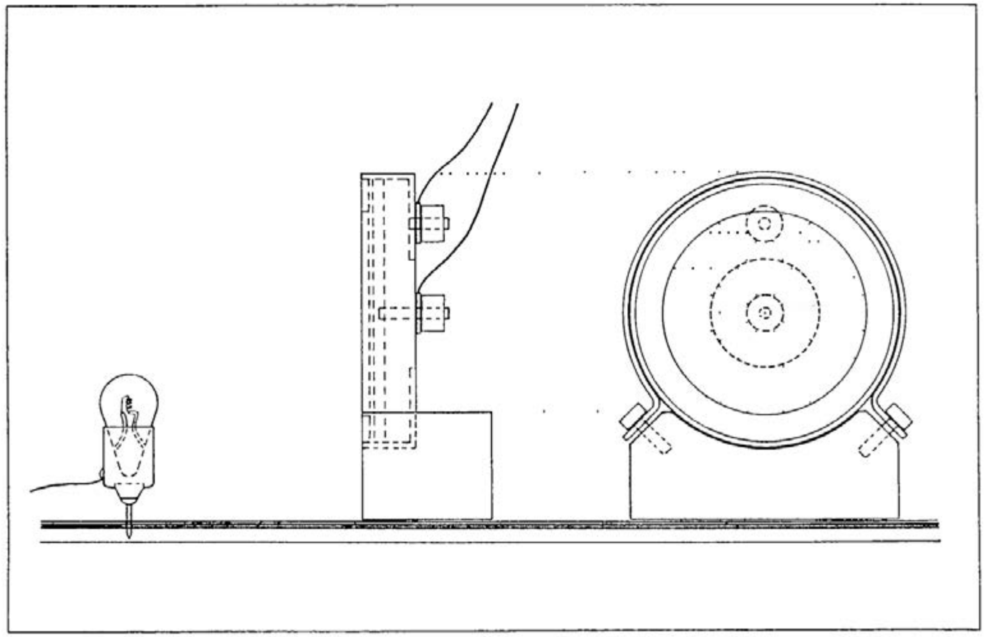


:G. I.—Cross-section of light-bulb and photocell (half-size)

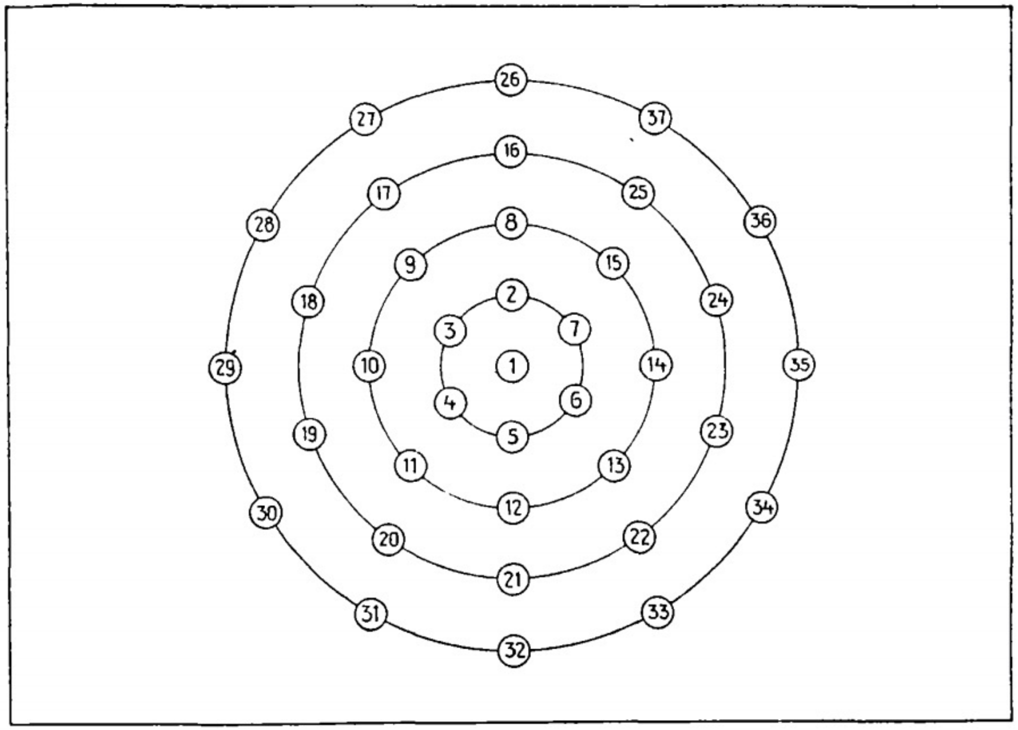
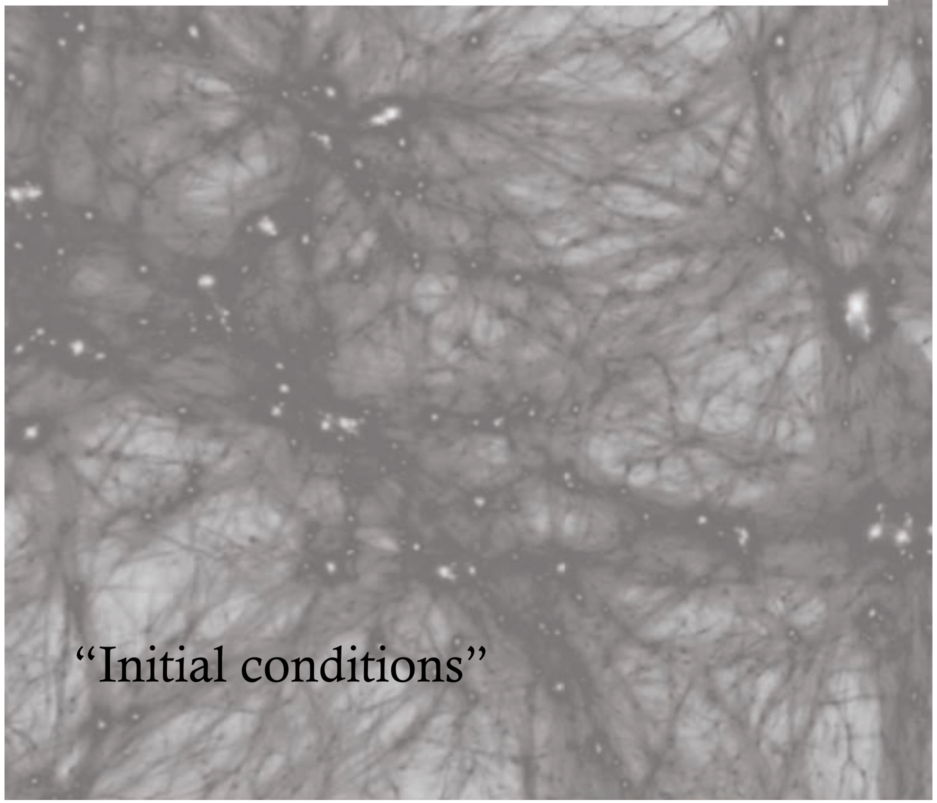


FIG. 3



Light “dilution” is the same as gravity ie ~ r^-2

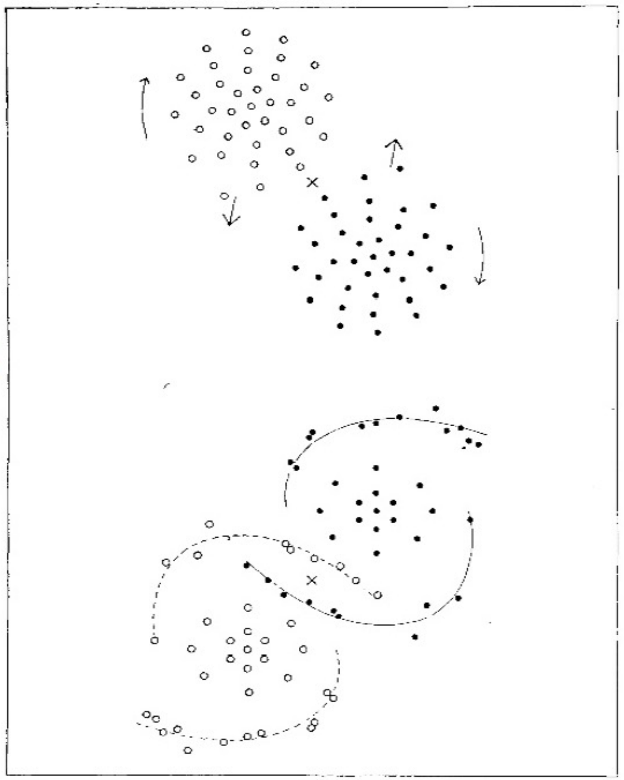
N = 2x 37

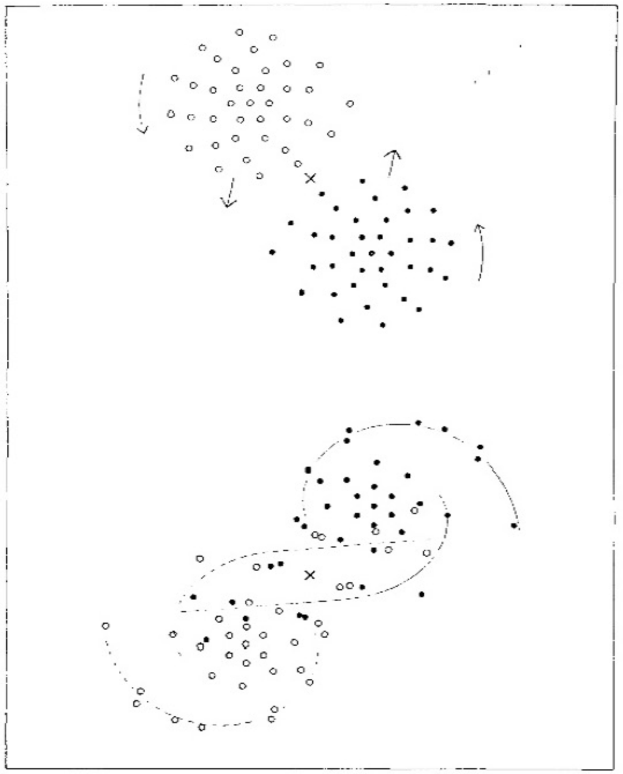
Erik Holmberg

- replacing gravity by light (same $1/r^2$ law)

- formation of tidal features

4m





3m

• gravity of N bodies

$$\boxed{m_i \ddot{\vec{r}}_i = \vec{F}(\vec{r}_i) \quad \forall i \in N}$$

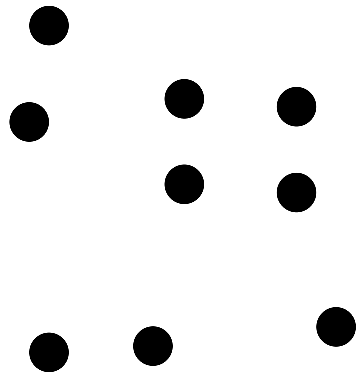
• the "brute force approach" scales like N^2:

$$\vec{F}(\vec{r}_i) = -\sum_{i \neq j} \frac{G m_i m_j}{(r_i - r_j)^3} (\vec{r}_i - \vec{r}_j)$$

the summation over (N-1) particles has to be done for all N particles:

$\Rightarrow$ number of floating point operations $\propto N(N-1) \propto N^2$

- gravity of N bodies



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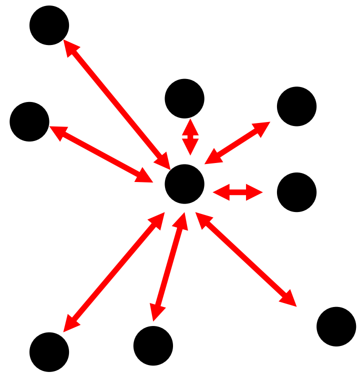

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N-1

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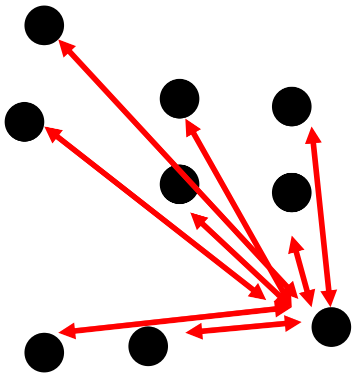

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(N-1)+(N-1) + ….

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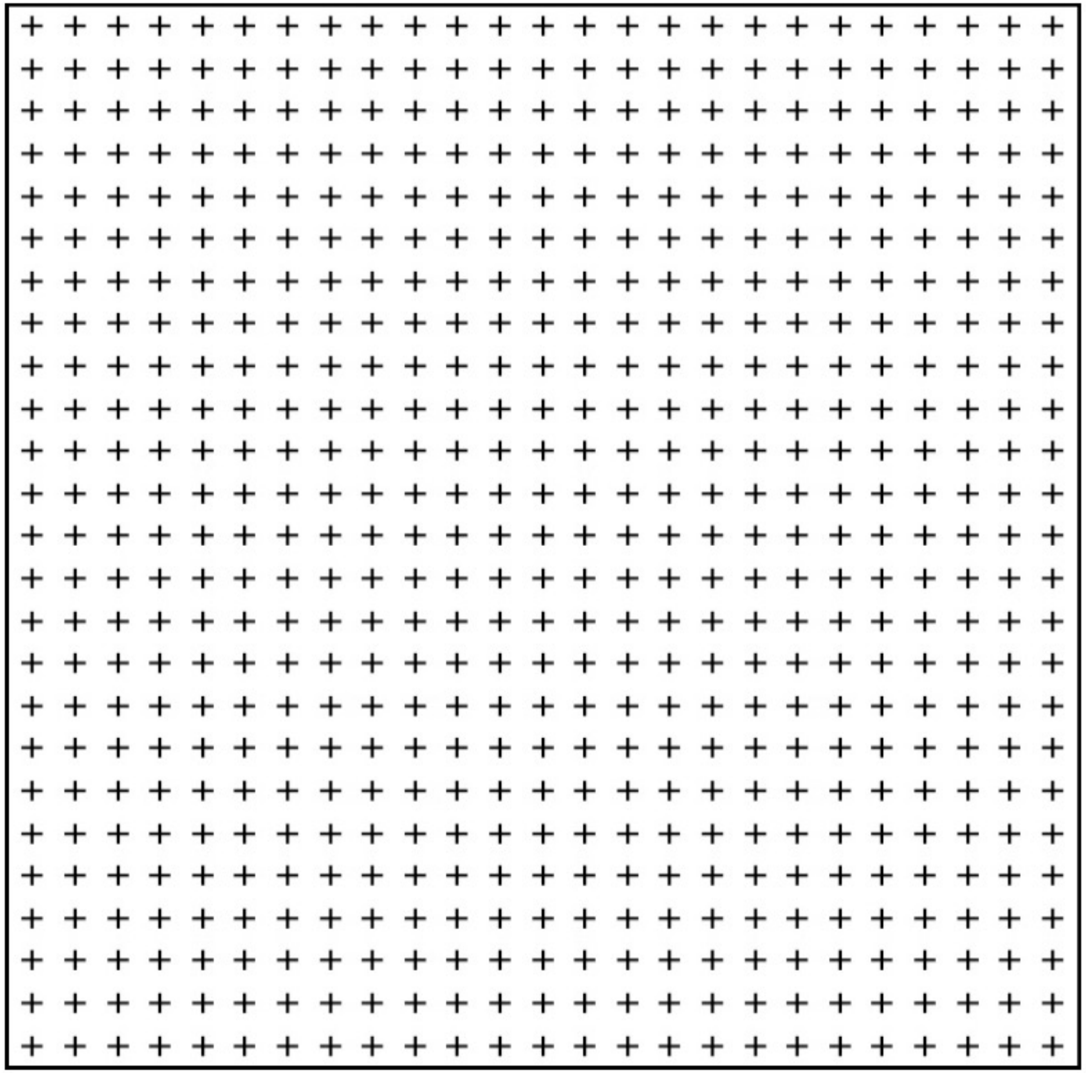
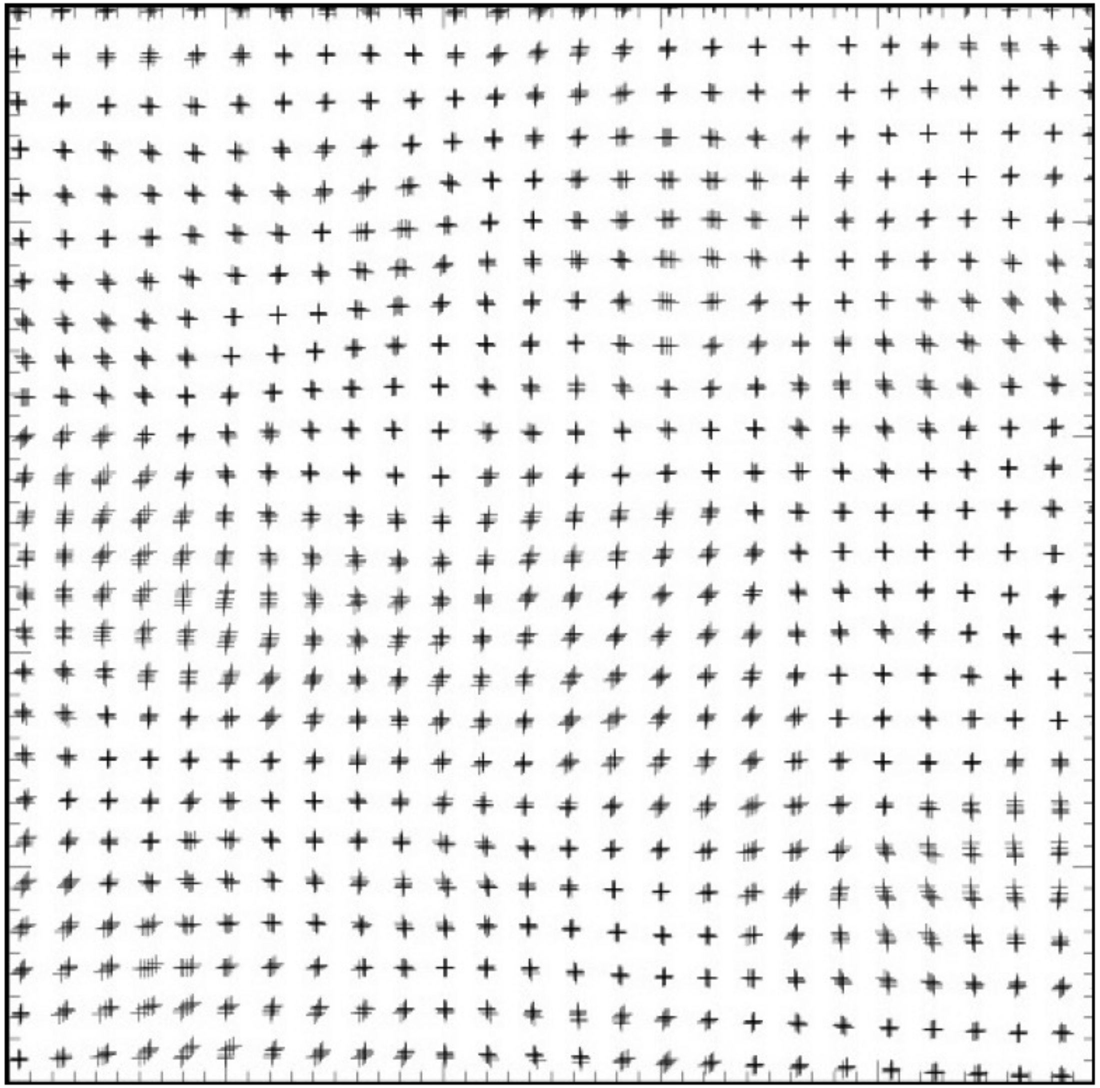
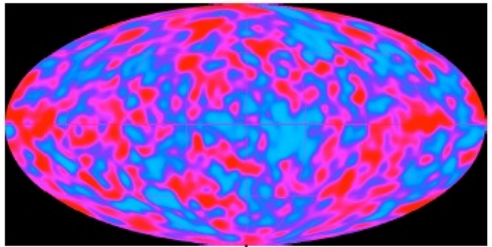
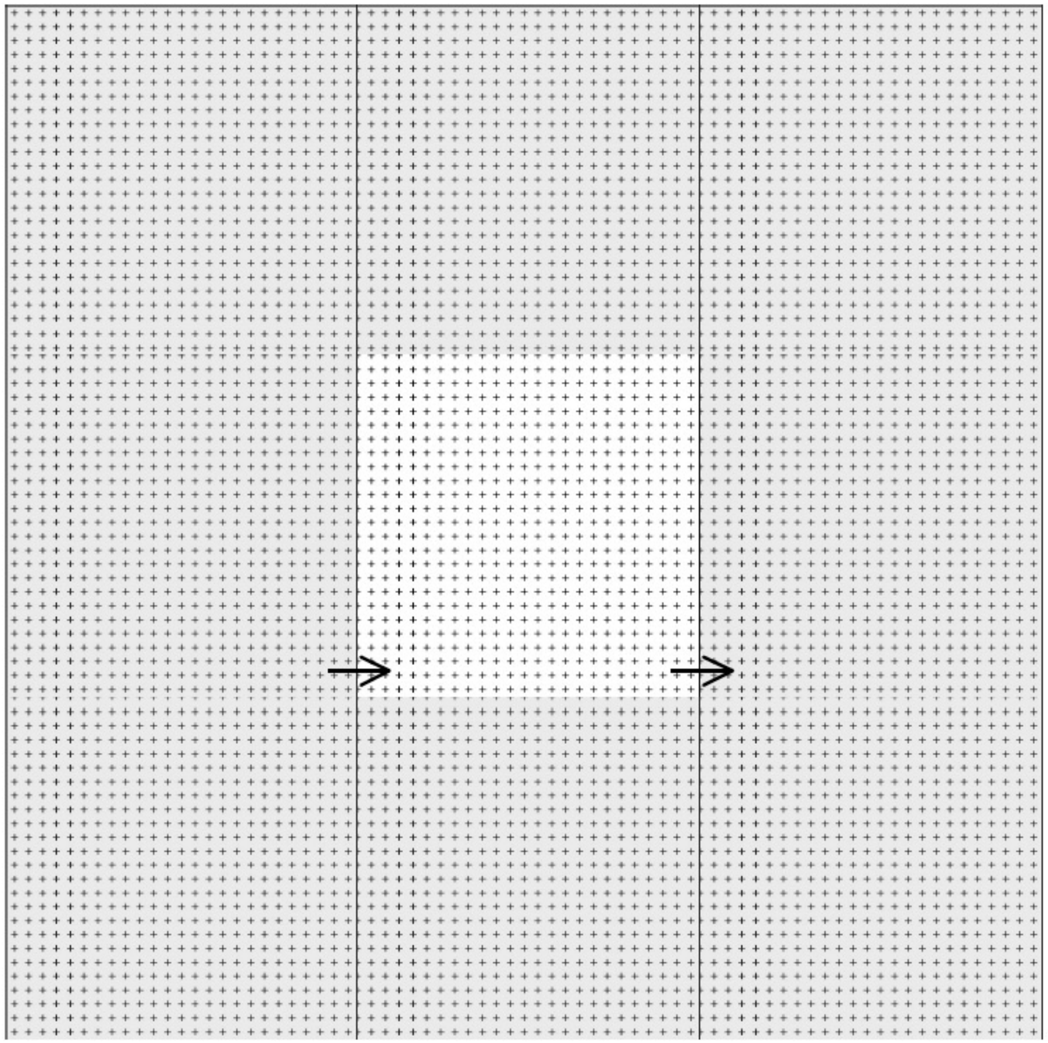


homogeneous
&
isotropic



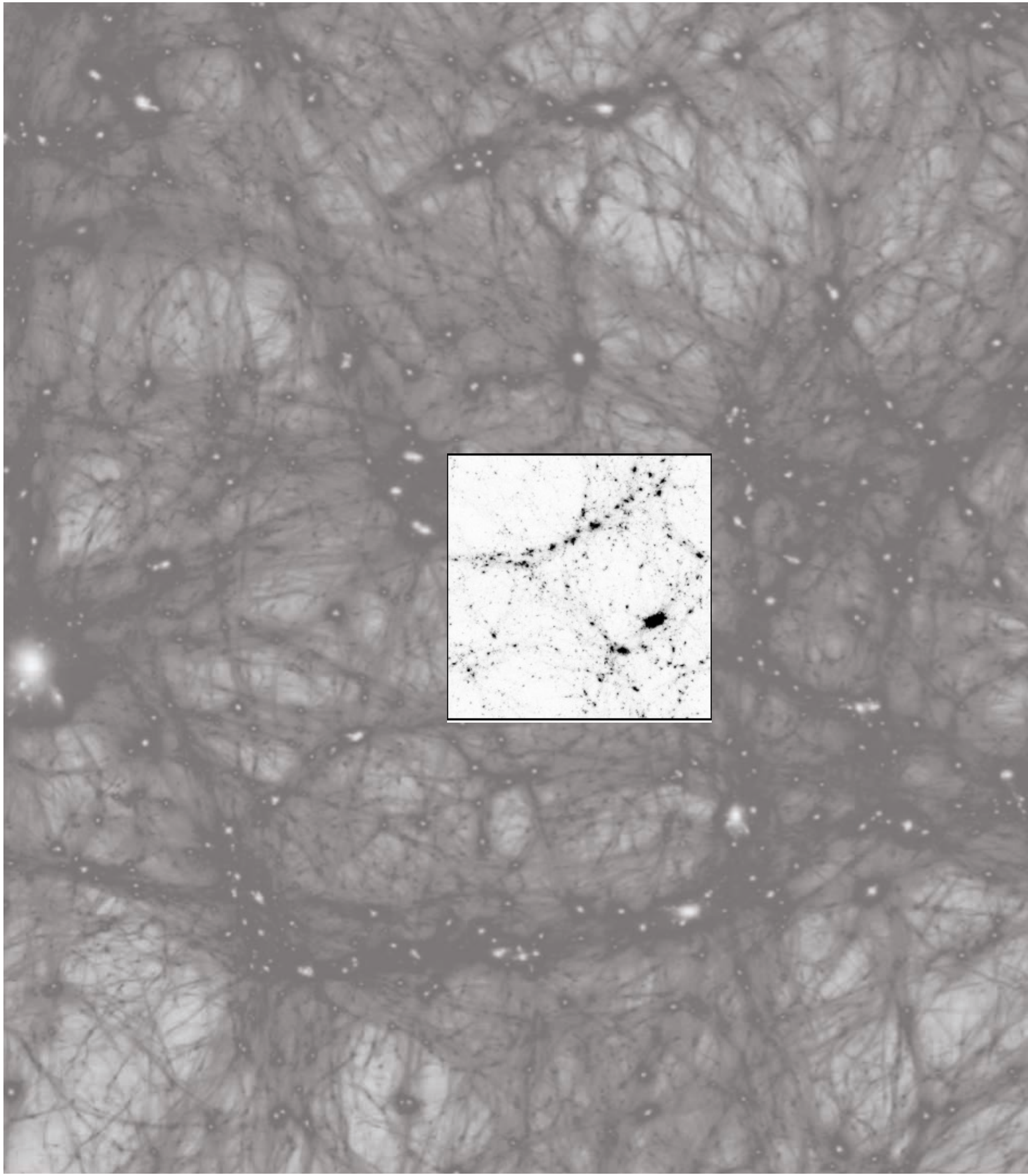


temperature fluctuations
converted into density perturbations



infinite

(periodic boundary conditions)



infinite

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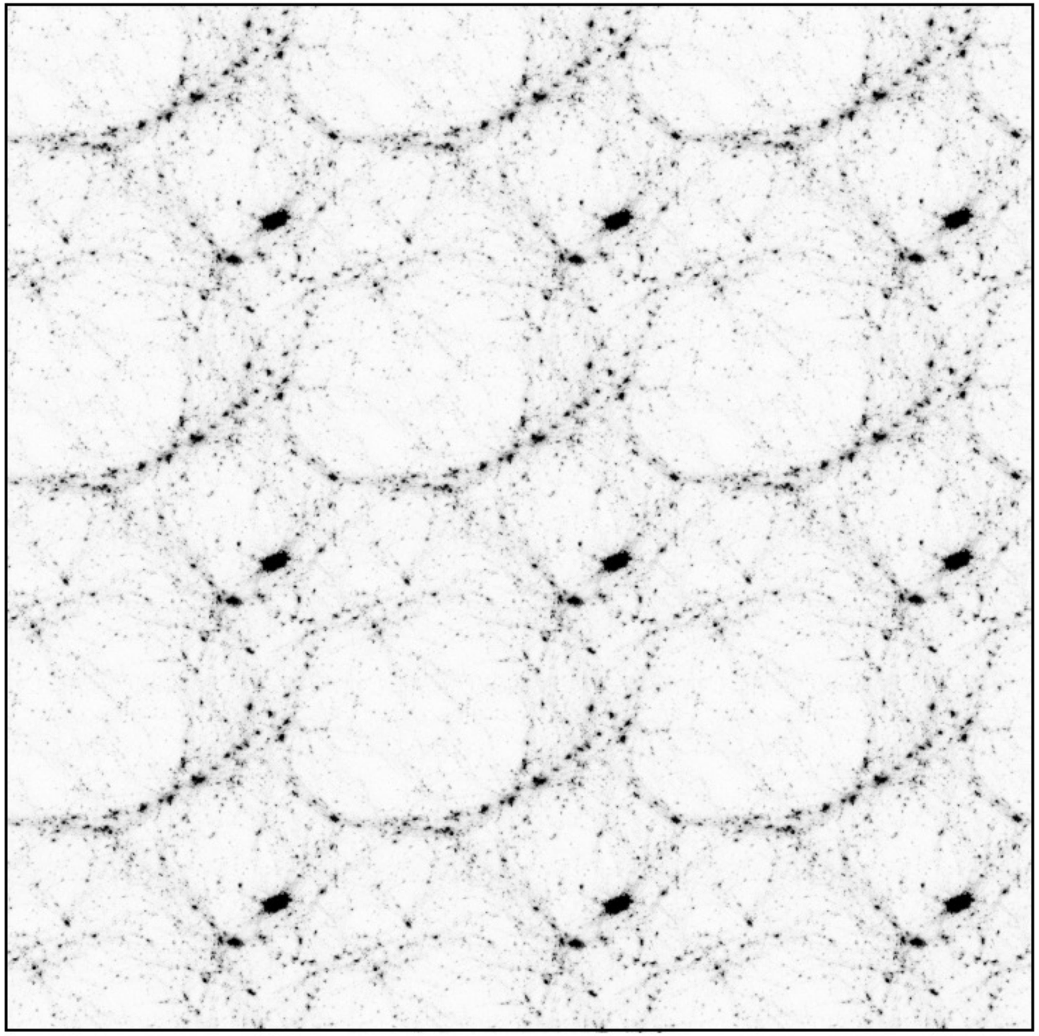


infinite

(periodic boundary conditions)

Mon. Not. R. astr. Soc. (1983) **204,** 891–907

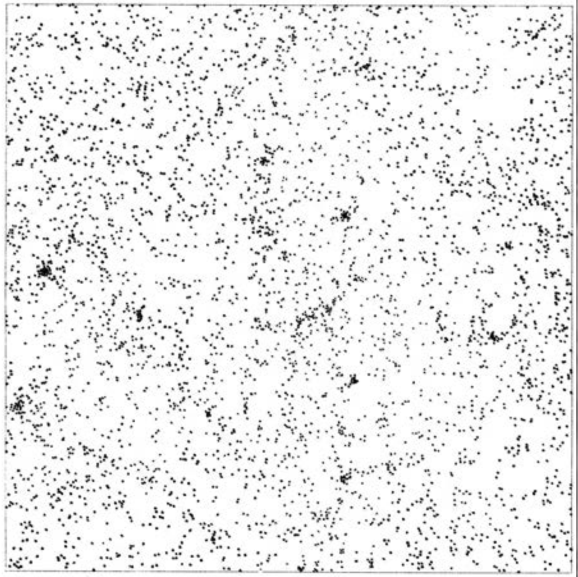
Three-dimensional numerical model of the formation of large-scale structure in the Universe

A. A. Klypin and S. F. Shandarin *The Keldysh Institute of Applied Mathematics, Academy of Sciences of USSR, Miusskaja Sq. 4, Moscow 125047, USSR*

Received 1982 November 15; in original form 1982 April 28

Summary. The first results of numerical fully three-dimensional simulations of formation and evolution of the large-scale structure of the Universe are presented. The simulations were carried out in the framework of the adiabatic scenario of galaxy formation.

The model contains $32^3 = 32\,768$ collisionless particles interacting only gravitationally. Equal mass particles are moving in a collective gravitational field which is smoothed at small scales. Evolution of perturbations is followed in an expanding cosmological model.



(a)

Figure 2. Three snapshots of the system. (a) Scale factor $a = 6.2 a_{\mathrm{start}}$ and $(\delta\rho/\rho)_{r_0} = 1.6$; (b) $a = 13.6 a_{\mathrm{start}}$; $(\delta\rho/\rho)_{r_0} \simeq 3.3$; (c) $a = 18 a_{\mathrm{start}}$; $(\delta\rho/\rho)_{r_0} \simeq 4.8$. Only each eighth particle is plotted in the figures.

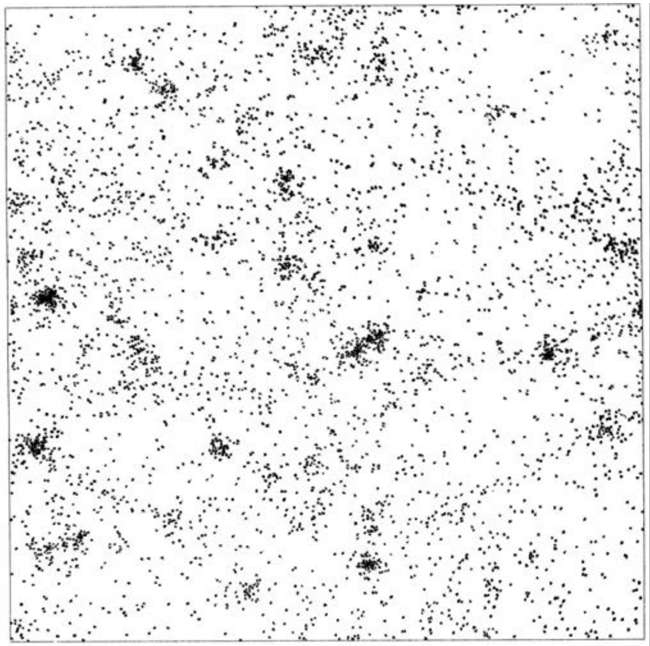


Figure 2 (b)

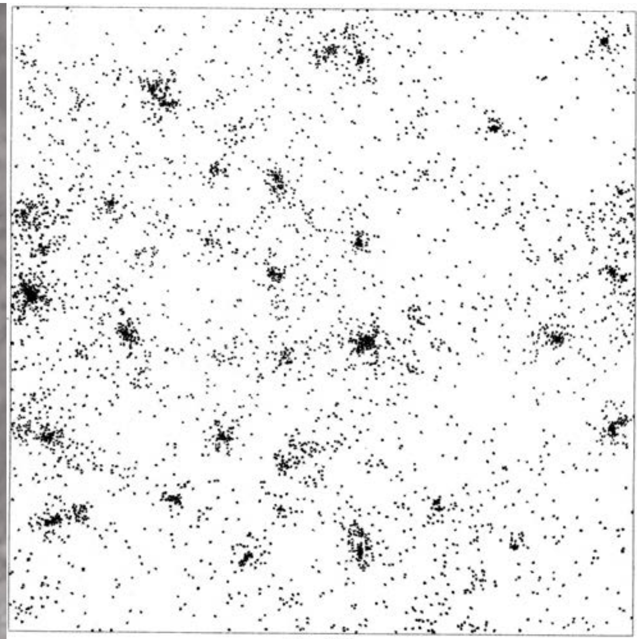
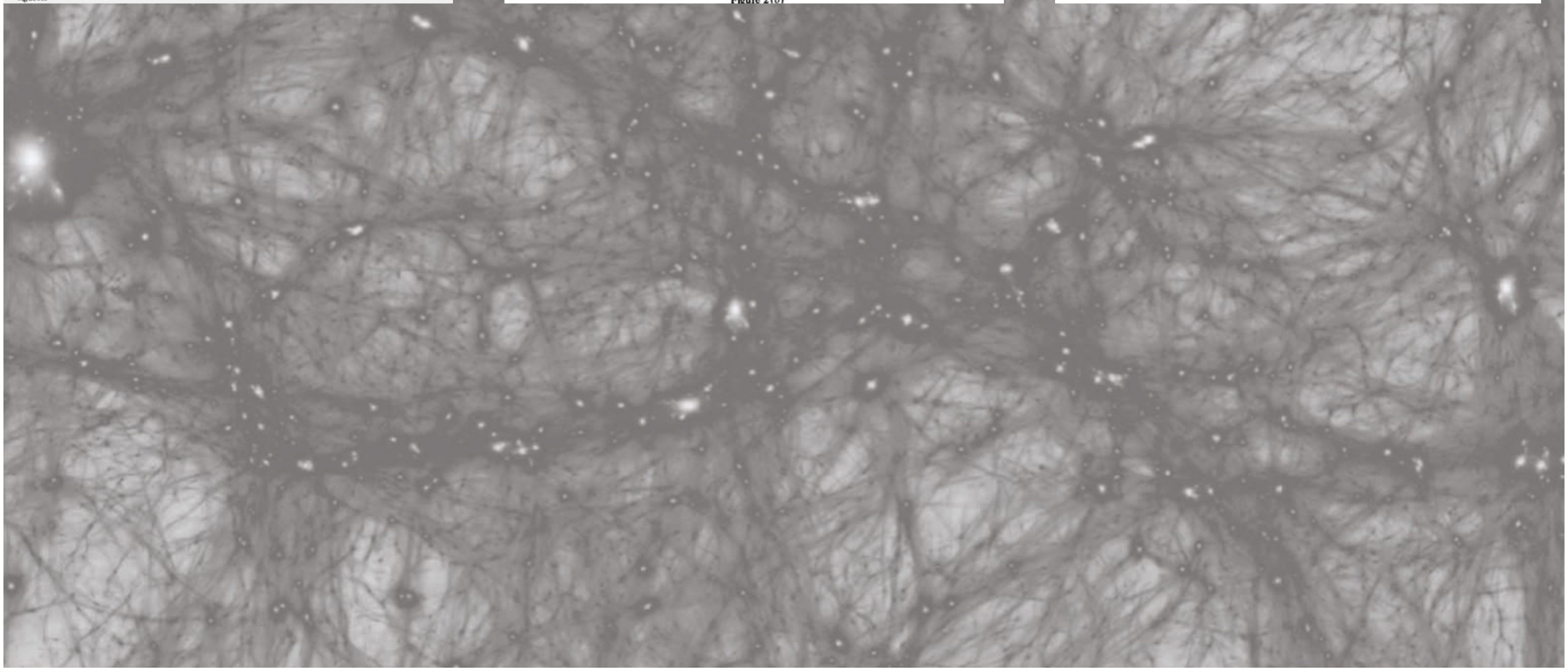


Figure 2 (c)



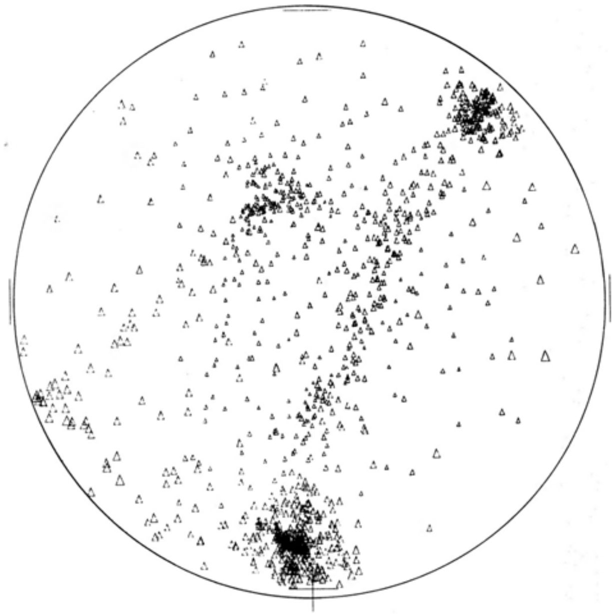
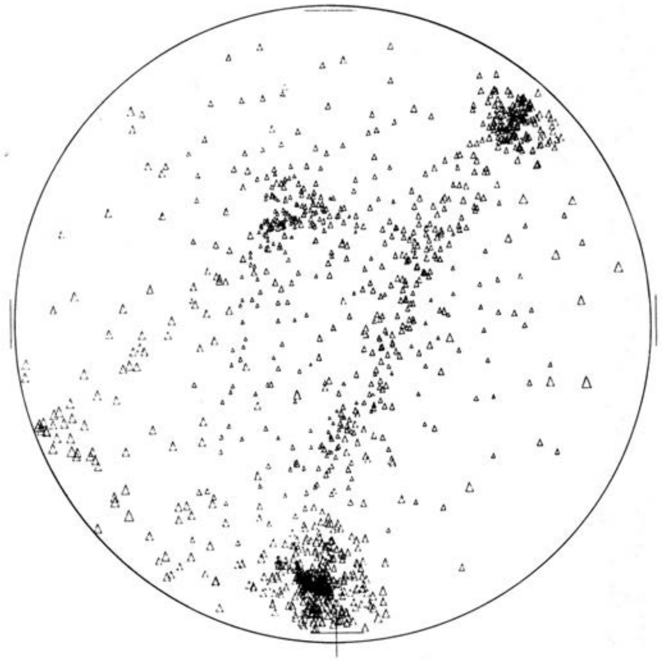


Figure 3 (c)



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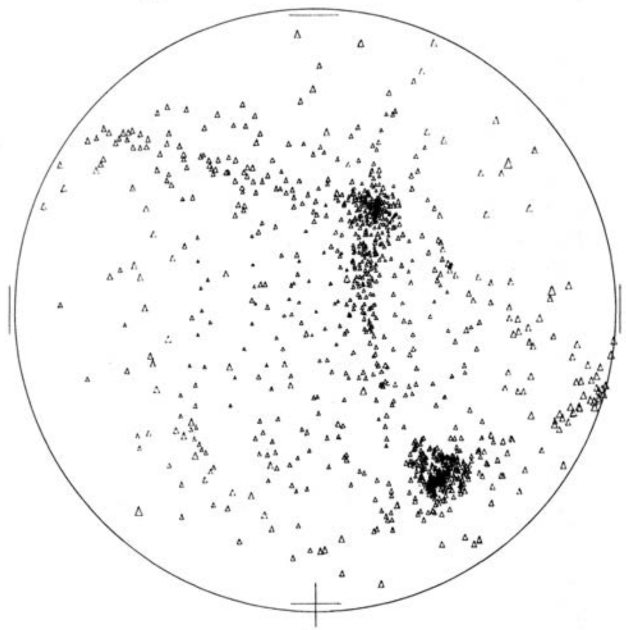


(a)

igure 3. A small fragment of the particle distribution plotted in Fig. 2(b), when $a = 13.6 a_{start}$. As pposed to Fig. 2 here all particles in the sphere with radius $R = 6r_0 = 30h^{-1}$ Mpc are plotted. Every particle is depicted as a triangle whose size is inversely proportional to distance from an observer. The observer is situated at a distance 1.5 R from the centre of the sphere.

In Fig. 3 three different projections of the particle inside the sphere are shown. They were obtained with two successive rotations by 45° around an axis designated by +. One sees that within the sphere there are two rich clusters and two chains. A chain of particles connects the clusters, while another one begins in the bottom cluster, then goes up and left in Fig. 3(c) and leaves the sphere (at the upper left of Fig. 3a) without touching the upper cluster. A very complicated spatial distribution of the particles makes it too difficult to realize the relative location of the chains.

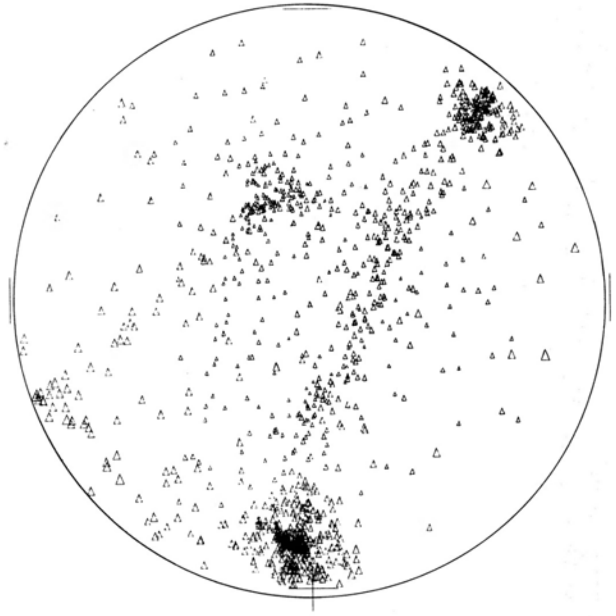
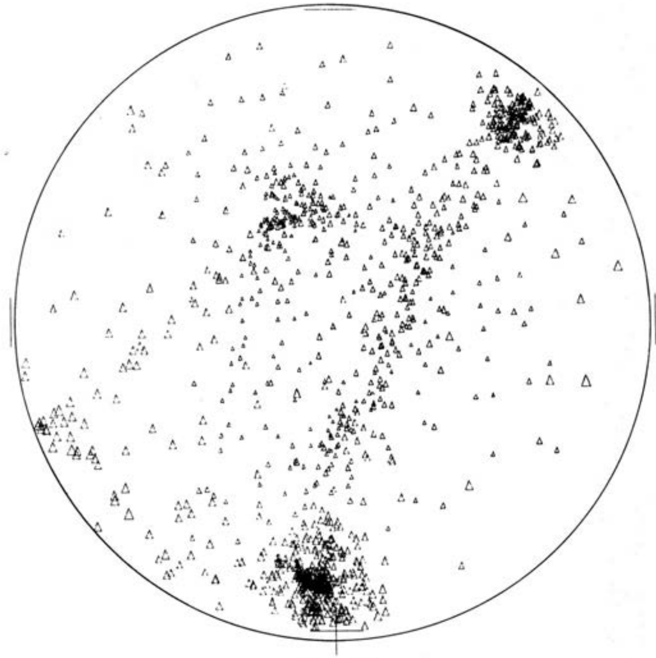


Figure 3 (c)



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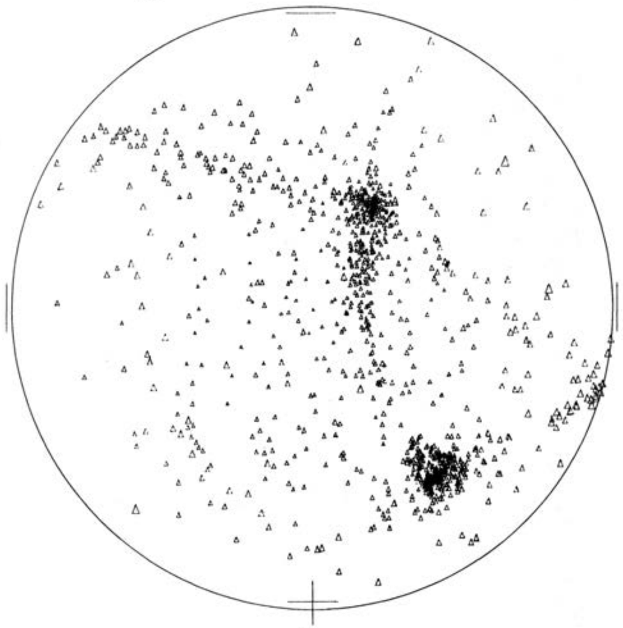

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A more effective but much more complicated way is to draw a surface of a constant density level. In Fig. 4 a part of a surface defined as $\tilde{\rho} = 2.5\tilde{\tilde{\rho}}$ ($\tilde{\tilde{\rho}}$ is the mean density, $\tilde{\tilde{\rho}} = 1$) is shown. It is depicted inside the same sphere. Two dots show the cluster centres. The chains in the figure touch each other near the upper cluster. This is the result of a coarse-grained grid, which was used to define the surface.

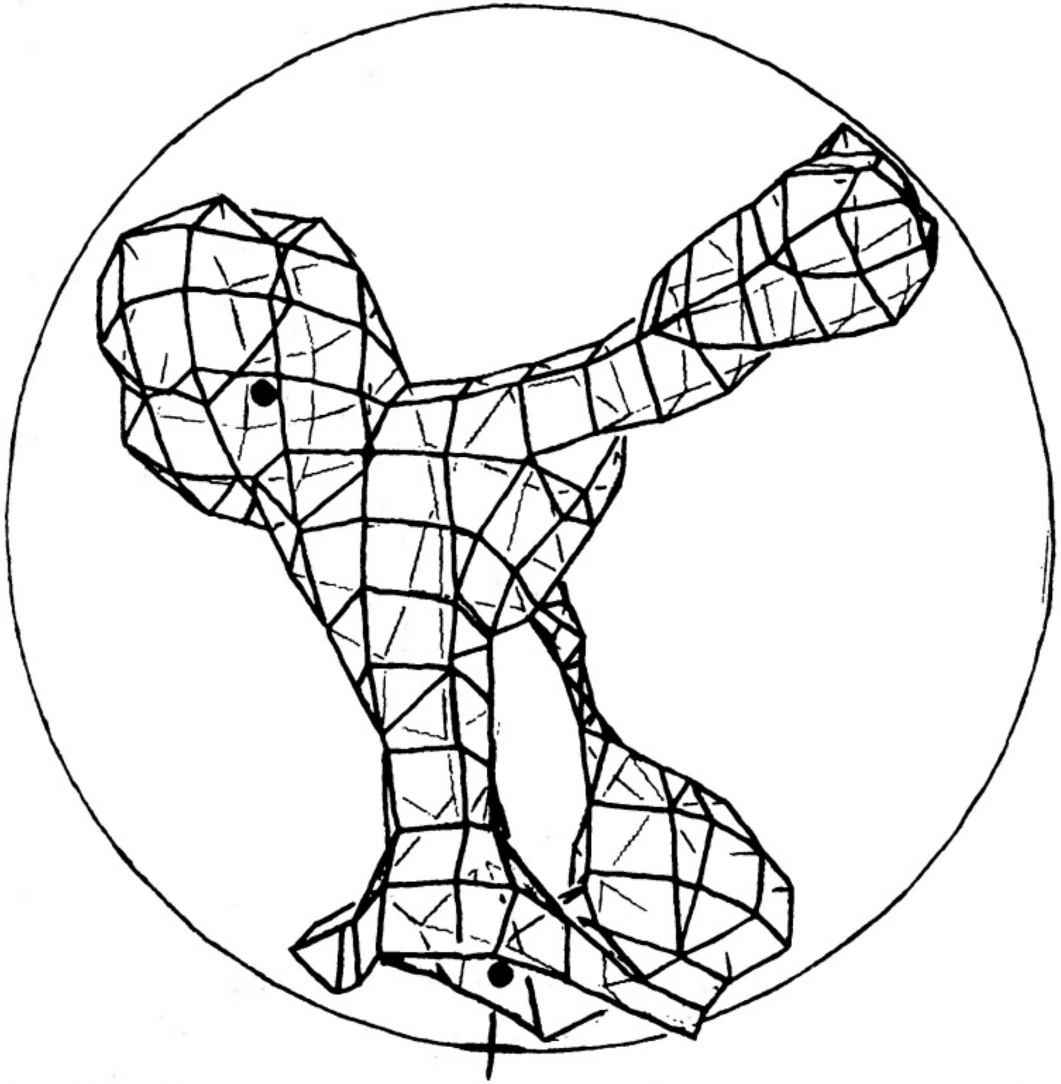

Figure 4. A surface of constant density level is plotted for the same region as that in Fig. 3.

The cosmic Chicken

The computation of the spatial two-point correlation function was based on the standard definition:

$$\xi(r) = \frac{N_{\rm p}}{\bar{r} N_{\rm c} \Delta V} - 1, \qquad N_{\rm c} \ll \bar{n} V = N_{\rm tot} \tag{20}$$

where $N_{\rm p}$ is a number of pairs within the distance interval r, $r + dr$. $N_{\rm c}$ is a number of randomly chosen centres (in our case $N_{\rm c} = 450$); $\bar{n}$ is the mean particle density ($\bar{n} = 1$), and $\Delta V = 4\pi/3\,[(r + dr)^3 - r^3]$ is the volume between successive spheres. The usual difficulty arising from sample boundaries is avoided owing to periodicity. At $z = 0$ (which corresponds

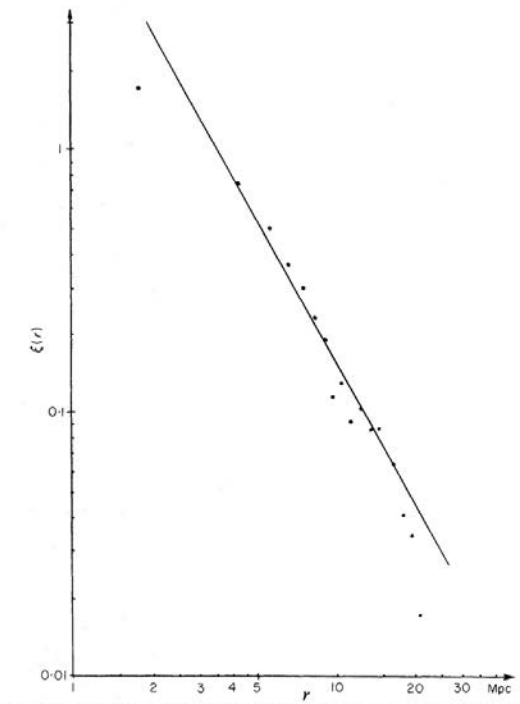

Figure 5. Spatial two-point correlation function computed at the time corresponding to Fig. 2(a). The straight line is a function $\xi = (3.5\,h^{-1}\ {\rm Mpc}/r)^{1.8}$.

George Efstathiou

On the clustering of particles in an expanding Universe

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Received 1980 June 23; in original form 1980 February 20

Summary. We investigate the clustering of particles in Friedmann models of the Universe using 1000- and 20 000-body numerical simulations. The results of these computations are analysed in terms of the two- and three-point correlation functions, the mean relative peculiar velocity between particle pairs $\langle v_{21} \rangle$, and the mean square peculiar velocity dispersion between pairs $\langle v_{21}^2 \rangle$. In the case of Einstein–de Sitter models we find that on scales corresponding to the transition region $\xi \sim 1$, $|\langle v_{21} \rangle| > Hr_{21}$ and this results in a non-power law form for $\xi(r)$, in rough agreement with simple analytic treatments based on the homogeneous spherical cluster models for the collapse of protoclusters. Our results are in conflict with the kinetic theory calculations of Davis & Peebles who studied the problem in the case of an Einstein–de Sitter Universe and found good agreement with observational data. These authors suggest that clusters develop substantial non-radial motions whilst they are still small density fluctuations, so that when a cluster fragments out of the general Hubble expansion, it is already virialized. This 'previrialization' effect does not appear to occur in the numerical models described here. We also examine the effects of particle discreteness and two-body relaxation, which are particularly important in the N-body models but neglected in the approach of Davis & Peebles. Because it is unclear as to whether these effects are important for galaxy clustering in the real Universe, it is difficult to assess the significance of our results. More observational and theoretical work is necessary in order to decide whether our approach is reasonable.

1 Introduction

The aim of this paper is to investigate whether gravitational instability can explain the observed forms of the low-order galaxy correlation functions (Peebles 1974a; Groth & Peebles 1977) under the assumption of some simple initial conditions.

George Efstathi

On the clustering of particles in an expanding Universe

George Efstathiou* *Department of Physics, South Road, Durham DH1 3LE*
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Peebles 1977) under the assumption of some simple initial conditions.

George Efstathiou

Table 2. Number of particles in each of 32×32 X, Y cells for model 4 after expansion by a factor $a = 9.9$ (compare with Fig. 1).

Y/X	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
1	5	12	36	18	48	40	17	83	22	97	11	4	25	102	22	9	26	22	17	24	29	15	18	10	24	31	27	11	22	15	54	6
2	4	27	24	11	24	19	8	53	31	8	27	18	22	11	9	32	18	48	10	23	15	11	8	55	14	10	28	16	1	15	28	20
3	16	20	27	27	12	20	10	31	24	38	23	8	13	7	21	25	22	10	4	33	14	8	11	49	9	1	11	16	34	14	4	7
4	26	37	31	20	16	41	26	19	11	4	10	28	17	22	20	37	8	22	23	33	23	36	21	13	16	26	19	5	4	11	4	22
5	2	6	85	35	16	9	8	17	24	4	13	4	14	8	0	6	21	5	10	30	17	2	11	12	7	2	8	9	4	7	15	6
6	40	38	17	7	6	9	5	56	19	7	14	8	12	9	7	3	3	42	3	6	3	5	54	78	29	24	14	9	8	15	17	33
7	16	26	10	24	12	34	16	26	25	4	13	4	10	3	9	5	14	7	22	19	7	13	31	73	37	22	48	17	20	13	33	9
8	8	11	45	27	8	58	13	67	35	6	18	18	25	1	1	15	23	20	25	26	21	25	27	55	30	68	64	50	3	23	77	12
9	25	22	31	14	19	14	7	17	24	12	17	26	14	5	8	7	5	16	7	16	7	13	18	31	5	46	40	13	1	12	11	19
10	43	58	11	10	48	8	8	21	21	4	15	32	25	22	7	17	27	25	5	42	8	13	4	3	14	57	11	22	10	10	6	16
11	9	9	6	8	9	5	9	3	12	0	12	7	3	8	21	4	5	11	12	11	27	3	6	0	4	14	41	64	18	13	12	67
12	1	38	9	6	6	8	5	2	20	11	4	16	14	41	5	15	6	3	15	7	7	10	7	6	11	21	49	38	52	2	32	44
13	12	7	9	44	8	0	6	15	13	29	24	4	23	26	17	14	7	12	5	4	16	31	15	4	34	1	9	12	36	48	8	10
14	8	25	20	55	7	9	20	12	24	33	42	4	14	6	19	50	0	5	5	11	26	26	10	2	12	3	3	27	27	65	64	29
15	26	42	17	34	31	10	7	13	25	16	26	18	14	9	22	33	4	7	6	2	3	14	5	2	3	12	8	5	19	10	25	3
16	15	9	11	17	28	17	11	20	5	26	6	6	10	17	68	38	40	16	35	6	15	12	31	12	5	2	24	39	29	16	40	14
17	32	15	28	4	19	9	37	12	51	18	19	14	33	13	16	9	7	11	26	23	26	30	43	41	2	5	6	16	17	22	63	43
18	35	23	28	32	8	20	28	53	24	9	25	25	20	8	21	7	1	6	11	18	28	17	40	18	7	12	11	36	12	58	20	23
19	24	16	17	21	28	9	14	46	23	17	24	0	12	24	8	3	1	38	22	21	10	41	8	32	3	37	30	69	25	23	36	18
20	34	15	31	16	20	7	6	8	9	40	39	38	33	22	7	24	5	4	15	37	19	4	17	7	15	28	31	10	23	24	15	1
21	12	11	52	47	5	5	22	11	6	15	20	71	54	64	7	46	4	1	33	19	12	41	23	22	10	11	22	6	28	44	22	1
22	55	17	29	21	41	11	10	17	5	23	12	9	30	36	10	24	7	14	13	15	3	16	6	25	2	1	38	19	7	49	15	28
23	37	24	16	9	7	8	4	54	12	21	21	1	14	28	29	19	15	22	55	4	18	15	15	26	2	1	3	19	6	14	11	22
24	27	12	6	3	6	16	9	20	32	19	13	12	8	5	26	23	11	8	14	5	26	15	2	2	23	1	21	14	4	6	18	21
25	39	33	12	8	8	7	23	15	13	17	50	11	40	8	46	54	36	4	2	7	1	9	12	16	19	18	14	7	32	9	23	19
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27	31	29	13	9	28	12	25	22	18	4	5	5	10	11	14	7	47	24	58	40	20	7	6	32	23	77	18	5	4	21	16	52
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29	16	62	7	11	43	6	22	22	18	8	14	52	0	6	25	8	5	3	31	16	23	5	8	11	12	18	26	8	11	23	8	3
30	17	27	13	2	44	79	14	33	50	21	28	24	10	42	12	11	28	6	22	25	58	29	21	29	4	65	23	34	23	22	9	14
31	24	9	3	5	44	27	9	40	27	19	18	16	22	31	17	16	10	26	25	1	9	45	15	8	35	23	44	11	17	7	45	43
32	36	62	22	0	13	25	7	43	54	7	7	25	38	95	15	17	12	21	22	3	14	34	9	44	45	8	12	9	37	35	18	12

George Efstathiou

Table 2. Number of particles in each of 32 × 32 X, Y cells for model 4 after expansion by a factor a = 9.9 (compare with Fig. 1).

Y/X	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
1	5	12	36	18	48	40	17	83	22	97	11	4	25	102	22	9	26	22	17	24	29	15	18	10	24	31	27	11	22	15	54	6
2	4	27	24	11	24	19	8	53	31	8	27	18	22	11	9	32	18	48	10	23	15	11	8	55	14	10	28	16	1	15	28	20
3	16	20	27	27	12	20	10	31	24	38	23	8	13	7	21	25	22	10	4	33	14	8	11	49	9	1	11	16	34	14	4	7
4	26	37	31	20	16	41	26	19	11	4	10	28	17	22	20	37	8	22	23	33	23	36	21	13	16	26	19	5	4	11	4	22
5	2	6	85	35	16	9	8	17	24	4	13	4	14	8	0	6	21	5	10	30	17	2	11	12	7	2	8	9	4	7	15	6
6	40	38	17	7	6	9	5	56	19	7	14	8	12	9	7	3	3	42	3	6	3	5	54	78	29	24	14	9	8	15	17	33
7	16	26	10	24	12	34	16	26	25	4	13	4	10	3	9	5	14	7	22	19	7	13	31	73	37	22	48	17	20	13	33	9
8	8	11	45	27	8	58	13	67	35	6	18	18	25	1	1	15	23	20	25	26	21	25	27	55	30	68	64	50	3	23	77	12
9	25	22	31	14	19	14	7	17	24	12	17	26	14	5	8	7	5	16	7	16	7	13	18	31	5	46	40	13	1	12	11	19
10	43	58	11	10	48	8	8	21	21	4	15	32	25	22	7	17	27	25	5	42	8	13	4	3	14	57	11	22	10	10	6	16
11	9	9	6	8	9	5	9	3	12	0	12	7	3	8	21	4	5	11	12	11	27	3	6	0	4	14	41	64	18	13	12	67
12	1	38	9	6	6	8	5	2	20	11	4	16	14	41	5	15	6	3	15	7	7	10	7	6	11	21	49	38	52	2	32	44
13	12	7	9	44	8	0	6	15	13	29	24	4	23	26	17	14	7	12	5	4	16	31	15	4	34	1	9	12	36	48	8	10
14	8	25	20	55	7	9	20	12	24	33	42	4	14	6	19	50	0	5	5	11	26	26	10	2	12	3	3	27	27	65	64	29
15	26	42	17	34	31	10	7	13	25	16	26	18	14	9	22	33	4	7	6	2	3	14	5	2	3	12	8	5	19	10	25	3
16	15	9	11	17	28	17	11	20	5	26	6	6	10	17	68	38	40	16	35	6	15	12	31	12	5	2	24	39	29	16	40	14
17	32	15	28	4	19	9	37	12	51	18	19	14	33	13	16	9	7	11	26	23	26	30	43	41	2	5	6	16	17	22	63	43
18	35	23	28	32	8	20	28	53	24	9	25	25	20	8	21	7	1	6	11	18	28	17	40	18	7	12	11	36	12	58	20	23
19	24	16	17	21	28	9	14	46	23	17	24	0	12	24	8	3	1	38	22	21	10	41	8	32	3	37	30	69	25	23	36	18
20	34	15	31	16	20	7	6	8	9	40	39	38	33	22	7	24	5	4	15	37	19	4	17	7	15	28	31	10	23	24	15	1
21	12	11	52	47	5	5	22	11	6	15	20	71	54	64	7	46	4	1	33	19	12	41	23	22	10	11	22	6	28	44	22	1
22	55	17	29	21	41	11	10	17	5	23	12	9	30	36	10	24	7	14	13	15	3	16	6	25	2	1	38	19	7	49	15	28
23	37	24	16	9	7	8	4	54	12	21	21	1	14	28	29	19	15	22	55	4	18	15	15	26	2	1	3	19	6	14	11	22
24	27	12	6	3	6	16	9	20	32	19	13	12	8	5	26	23	11	8	14	5	26	15	2	2	23	1	21	14	4	6	18	21
25	39	33	12	8	8	7	23	15	13	17	50	11	40	8	46	54	36	4	2	7	1	9	12	16	19	18	14	7	32	9	23	19
26	47	46	25	12	22	22	7	31	17	25	16	5	19	2	25	44	13	27	2	20	1	9	17	20	30	21	21	13	0	6	16	18
27	31	29	13	9	28	12	25	22	18	4	5	5	10	11	14	7	47	24	58	40	20	7	6	32	23	77	18	5	4	21	16	52
28	2	9	20	7	4	16	4	19	6	16	29	18	10	13	17	16	72	19	39	29	25	7	5	22	20	17	14	5	31	3	13	20
29	16	62	7	11	43	6	22	22	18	8	14	52	0	6	25	8	5	3	31	16	23	5	8	11	12	18	26	8	11	23	8	3
30	17	27	13	2	44	79	14	33	50	21	28	24	10	42	12	11	28	6	22	25	58	29	21	29	4	65	23	34	23	22	9	14
31	24	9	3	5	44	27	9	40	27	19	18	16	22	31	17	16	10	26	25	1	9	45	15	8	35	23	44	11	17	7	45	43
32	36	62	22	0	13	25	7	43	54	7	7	25	38	95	15	17	12	21	22	3	14	34	9	44	45	8	12	9	37	35	18	12

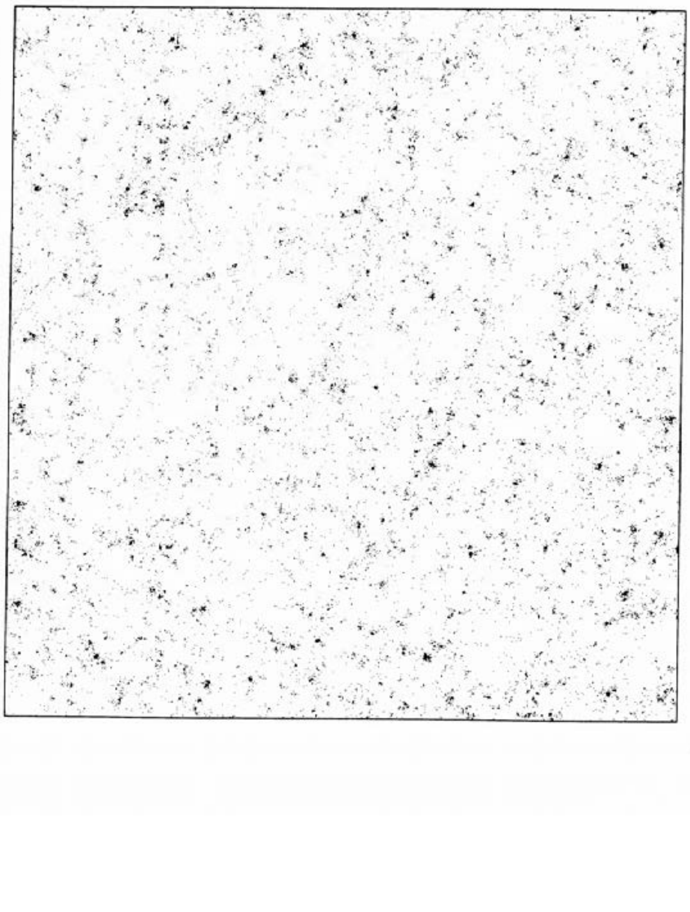

Figure 1. $X-Y$ projection of the particle positions for a 20000-body numerical experiment after the system has expanded by a factor of 9.9. In this case the expansion follows that of an Einstein–de Sitter model, $\Omega_0 = 1.0$.

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× 32 *X*, *Y* cells for model 4 after expansion by a factor $a = 9.9$ (compare with Fig. 1).

9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
22	97	11	4	25	102	22	9	26	22	17	24	29	15	18	10	24	31	27	11	22	15	54	6
31	8	27	18	22	11	9	32	18	48	10	23	15	11	8	55	14	10	28	16	1	15	28	20
24	38	23	8	13	7	21	25	22	10	4	33	14	8	11	49	9	1	11	16	34	14	4	7
11	4	10	28	17	22	20	37	8	22	23	33	23	36	21	13	16	26	19	5	4	11	4	22
24	4	13	4	14	8	0	6	21	5	10	30	17	2	11	12	7	2	8	9	4	7	15	6
19	7	14	8	12	9	7	3	3	42	3	6	3	5	54	78	29	24	14	9	8	15	17	33
25	4	13	4	10	3	9	5	14	7	22	19	7	13	31	73	37	22	48	17	20	13	33	9
35	6	18	18	25	1	1	15	23	20	25	26	21	25	27	55	30	68	64	50	3	23	77	12
24	12	17	26	14	5	8	7	5	16	7	16	7	13	18	31	5	46	40	13	1	12	11	19
21	4	15	32	25	22	7	17	27	25	5	42	8	13	4	3	14	57	11	22	10	10	6	16
12	0	12	7	3	8	21	4	5	11	12	11	27	3	6	0	4	14	41	64	18	13	12	67
20	11	4	16	14	41	5	15	6	3	15	7	7	10	7	6	11	21	49	38	52	2	32	44
13	29	24	4	23	26	17	14	7	12	5	4	16	31	15	4	34	1	9	12	36	48	8	10
24	33	42	4	14	6	19	50	0	5	5	11	26	26	10	2	12	3	3	27	27	65	64	29
25	16	26	18	14	9	22	33	4	7	6	2	3	14	5	2	3	12	8	5	19	10	25	3
5	26	6	6	10	17	68	38	40	16	35	6	15	12	31	12	5	2	24	39	29	16	40	14
51	18	19	14	33	13	16	9	7	11	26	23	26	30	43	41	2	5	6	16	17	22	63	43
24	9	25	25	20	8	21	7	1	6	11	18	28	17	40	18	7	12	11	36	12	58	20	23
23	17	24	0	12	24	8	3	1	38	22	21	10	41	8	32	3	37	30	69	25	23	36	18
9	40	39	38	33	22	7	24	5	4	15	37	19	4	17	7	15	28	31	10	23	24	15	1
6	15	20	71	54	64	7	46	4	1	33	19	12	41	23	22	10	11	22	6	28	44	22	1
5	23	12	9	30	36	10	24	7	14	13	15	3	16	6	25	2	1	38	19	7	49	15	28
12	21	21	1	14	28	29	19	15	22	55	4	18	15	15	26	2	1	3	19	6	14	11	22
32	19	13	12	8	5	26	23	11	8	14	5	26	15	2	2	23	1	21	14	4	6	18	21
13	17	50	11	40	8	46	54	36	4	2	7	1	9	12	16	19	18	14	7	32	9	23	19
17	25	16	5	19	2	25	44	13	27	2	20	1	9	17	20	30	21	21	13	0	6	16	18
18	4	5	5	10	11	14	7	47	24	58	40	20	7	6	32	23	77	18	5	4	21	16	52
6	16	29	18	10	13	17	16	72	19	39	29	25	7	5	22	20	17	14	5	31	3	13	20
18	8	14	52	0	6	25	8	5	3	31	16	23	5	8	11	12	18	26	8	11	23	8	3
50	21	28	24	10	42	12	11	28	6	22	25	58	29	21	29	4	65	23	34	23	22	9	14
27	19	18	16	22	31	17	16	10	26	25	1	9	45	15	8	35	23	44	11	17	7	45	43
54	7	7	25	38	95	15	17	12	21	22	3	14	34	9	44	45	8	12	9	37	35	18	12

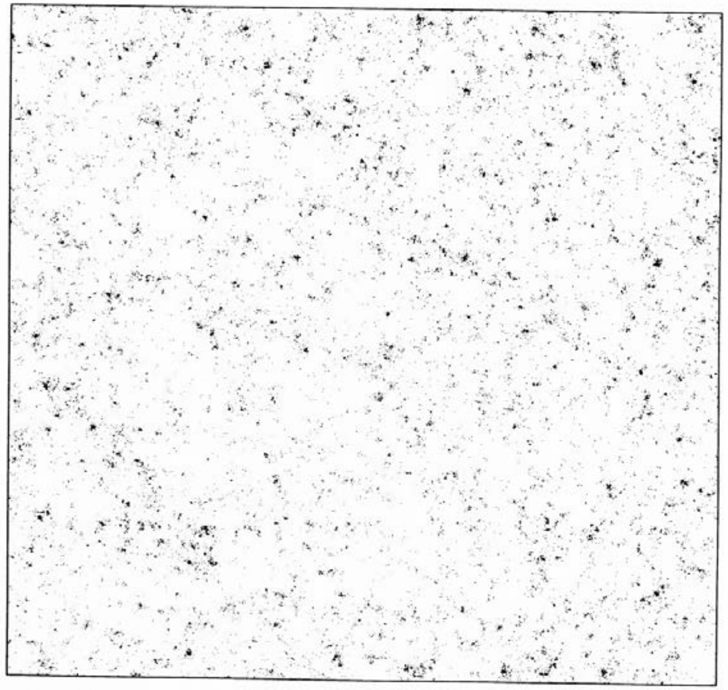

Figure 1. *X–Y* projection of the particle positions for a 20 000-body numerical experiment after the system has expanded by a factor of 9.9. In this case the expansion follows that of an Einstein–de Sitter model, $\Omega_0 = 1.0$.

The number of clustered galaxies within a radius $r_0 = 5h^{-1}$ Mpc (corresponding to $\xi(r_0) = 1$) is $\langle N \rangle \approx 30$ (taking the mean space density of bright galaxies as $0.02\,h^{-3}$ Mpc). This number is comparable to the mean number of clustered particles within radius x_0 $[\xi(x_0) = 1]$ of the particle distributions analysed in Section 4. Hence if we are justified in assuming the existence of some epoch z_* when galaxies were weakly clustered and act thereafter as the fundamental point particles, our approach may be applicable. We now explore the consequences of this hypothesis.

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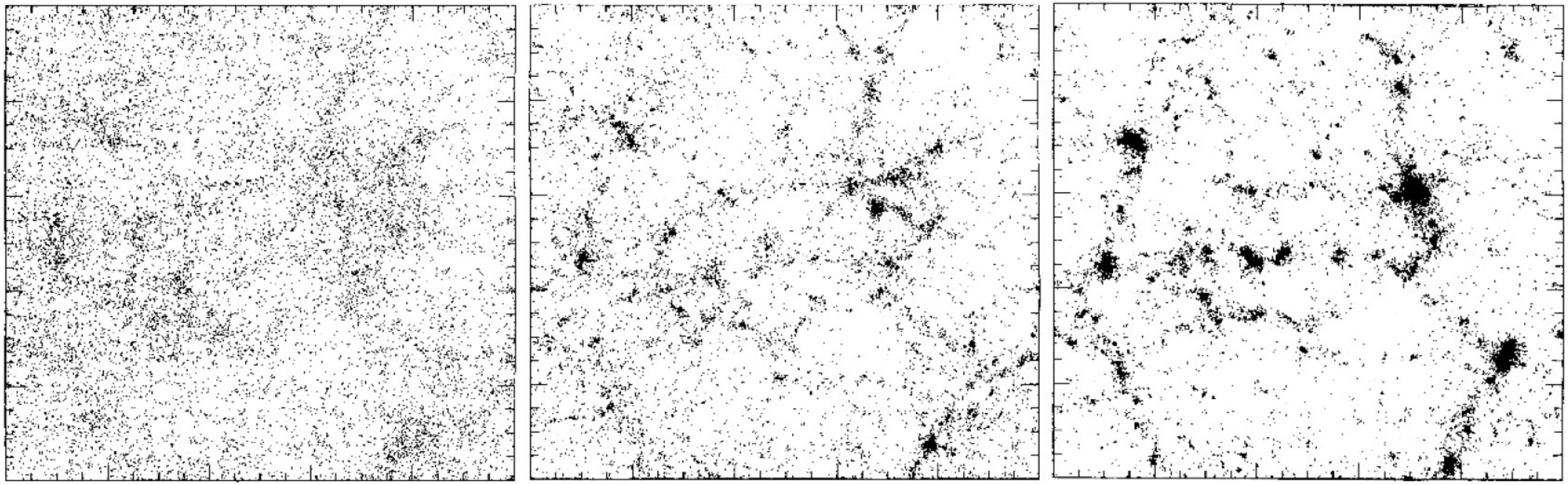
N = 32768

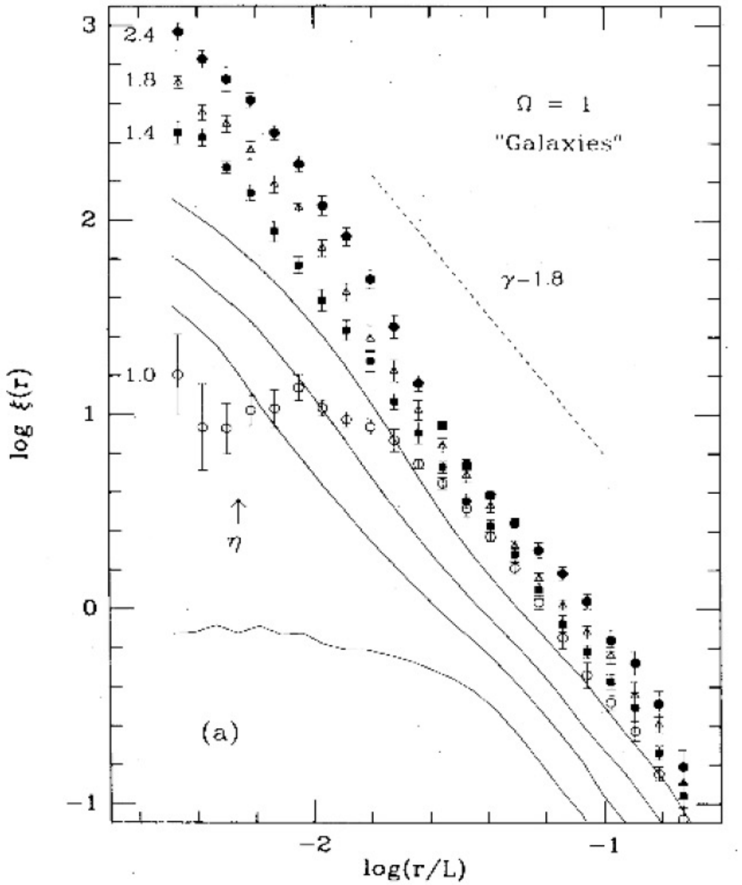
- Zel'dovich approximation for generating realistic initial conditions
- in-depth study of numerical effects

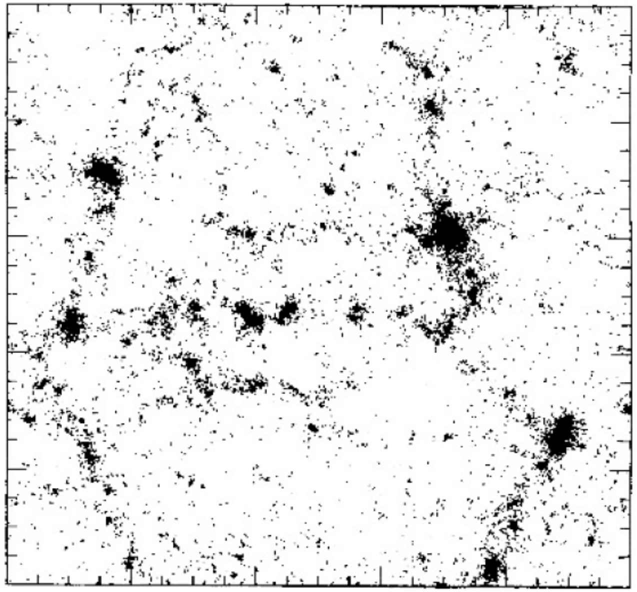


N = 32768

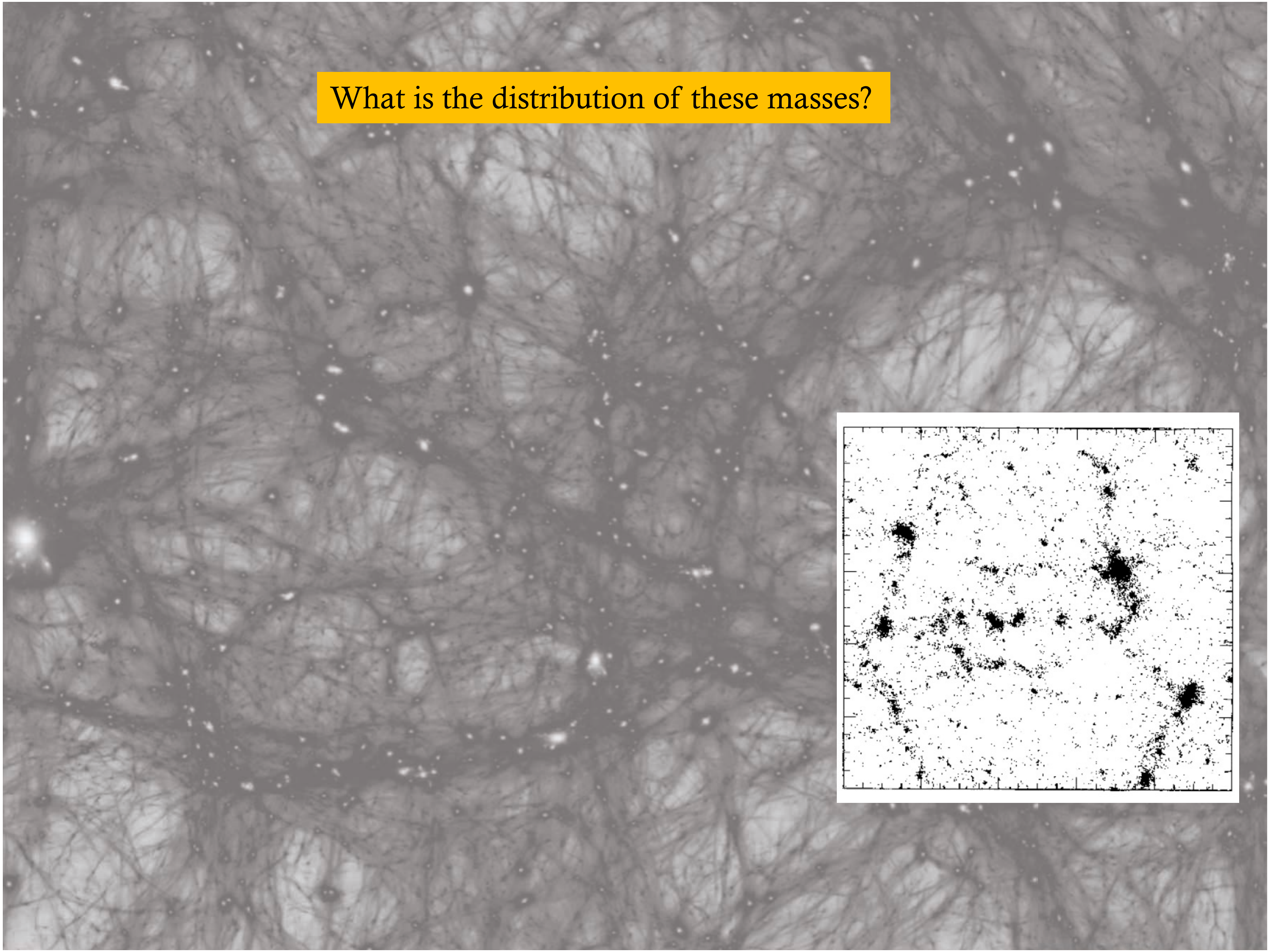
George Efstathiou

- Zel'dovich approximation for generating realistic initial conditions
- in-depth study of numerical effects





What is the distribution of these masses?

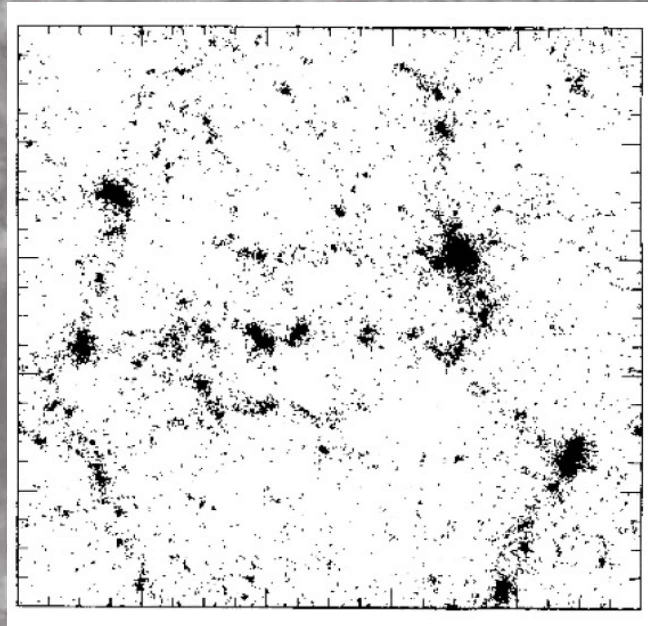


What is the distribution of these masses?

”Friends-of-friends” grouping:
Group together all particles that obey

$$\left|\vec{r}_i - \vec{r}_j\right| \le b\bar{d}$$

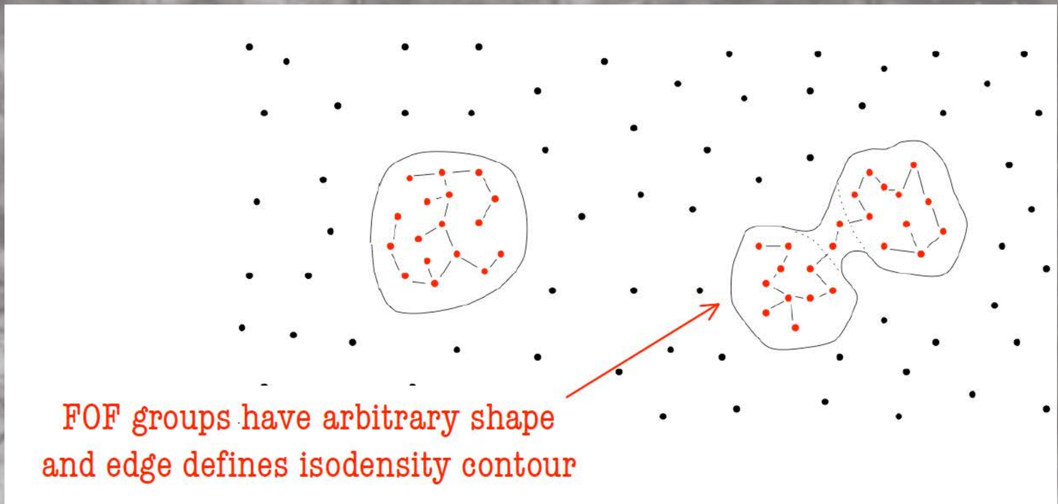
$$\bar{d} = \frac{B}{\sqrt[3]{N}}$$

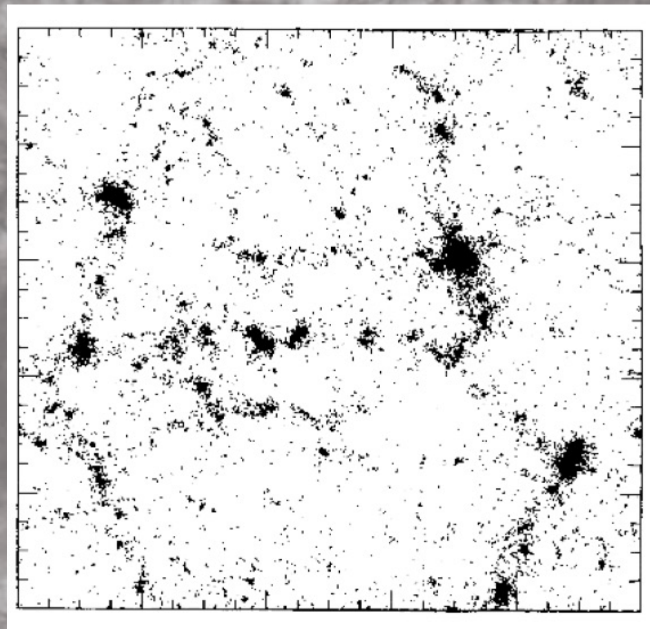


What is the distribution of these masses?

”Friends-of-friends” grouping:
Group together all particles that obey

$$\left|\vec{r}_i - \vec{r}_j\right| \le b\bar{d} \qquad \bar{d} = \frac{B}{\sqrt[3]{N}}$$

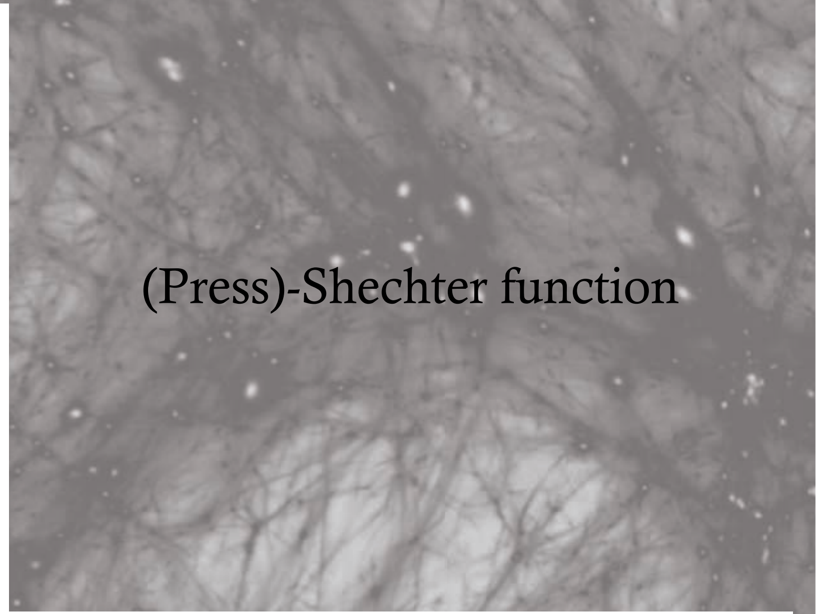




b=0.2 → isodensities~200 mean

$$\frac{dn}{dM}dM = \sqrt{\frac{2}{\pi}}\frac{\langle\rho\rangle}{M}\frac{\delta_c}{\sigma_M}\left|\frac{d\ln\sigma_M}{d\ln M}\right|\exp\left(-\frac{\delta_c^2}{2\sigma_M^2}\right)\frac{dM}{M}$$

(Press)-Shechter function



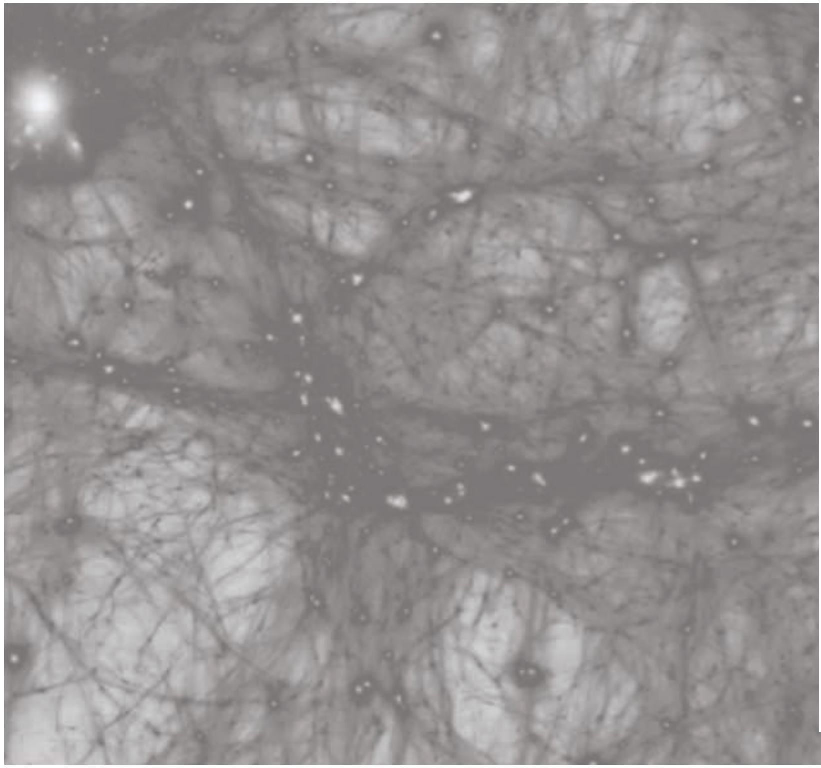
$\langle\rho\rangle$: mean density of Universe

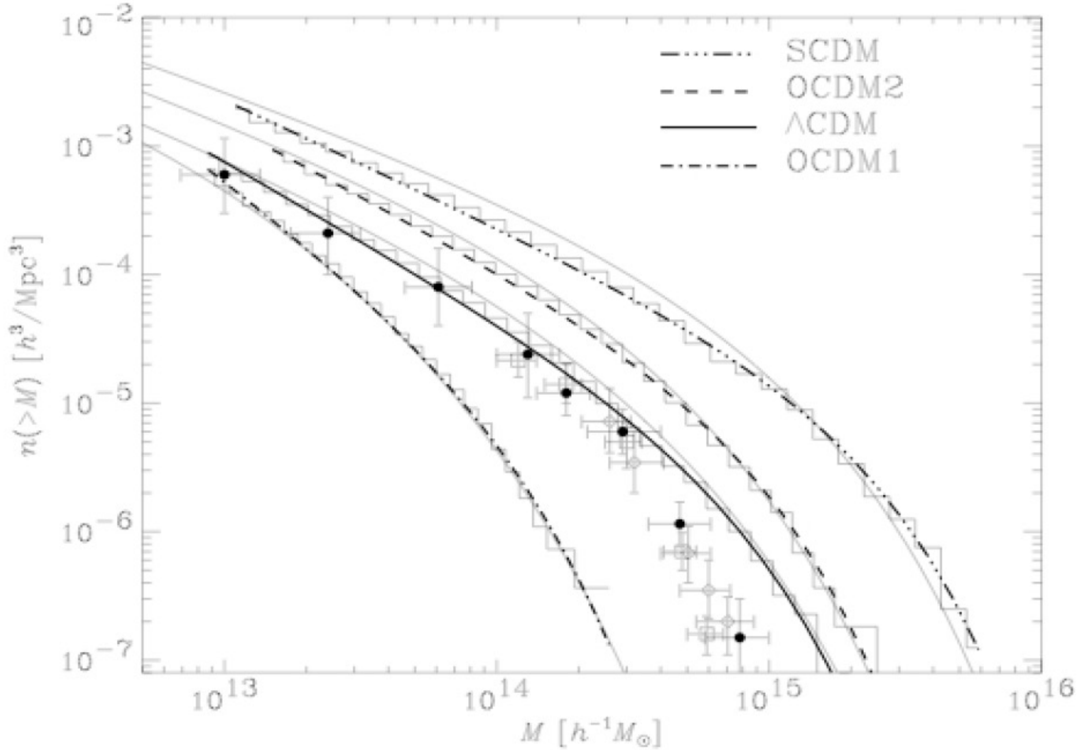
δ_c : density contrast of collapsed structure according to linear perturbation theory

$$\sigma_M^2(r) = \frac{1}{2\pi^2}\int_0^{+\infty} P(k)\hat{W}^2(kr)k^2\,dk,$$

$$\hat{W}(x) = \frac{3}{x^3}(\sin x - x\cos x).$$

power spectrum of density fluctuations (more later...)





(Press)-Shechter function

$$\frac{dn}{dM}dM = \sqrt{\frac{2}{\pi}}\,\frac{\langle\rho\rangle}{M}\,\frac{\delta_c}{\sigma_M}\left|\frac{d\ln\sigma_M}{d\ln M}\right|\exp\left(-\frac{\delta_c^2}{2\sigma_M^2}\right)\frac{dM}{M}$$

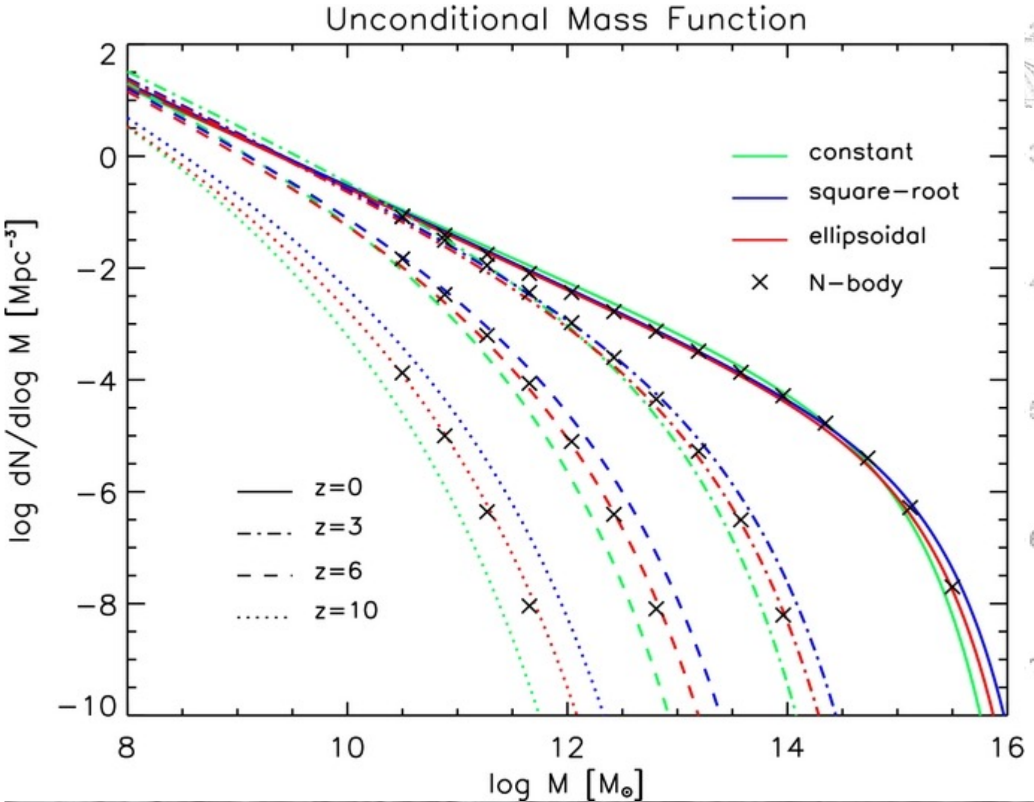
$\langle\rho\rangle$: mean density of Universe

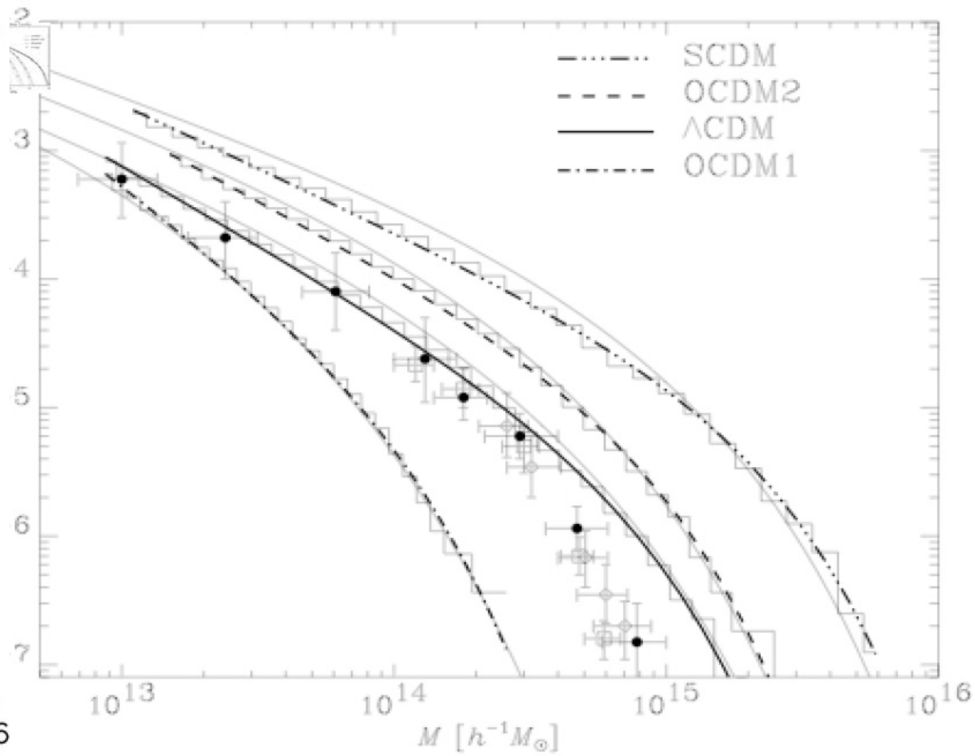
δ_c : density contrast of collapsed structure according to linear perturbation theory

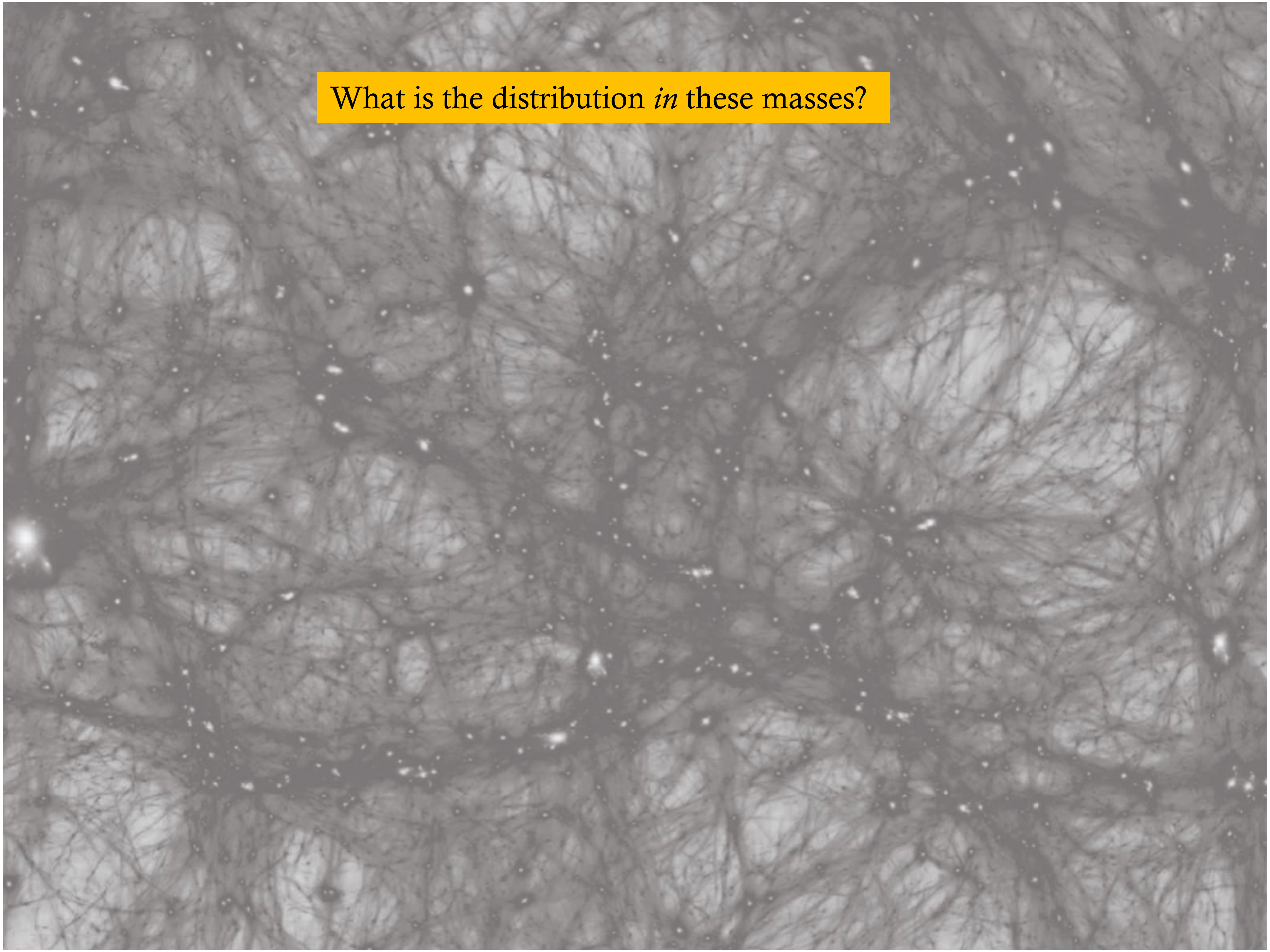
$$\sigma_M^2(r) = \frac{1}{2\pi^2}\int_0^{+\infty} P(k)\hat{W}^2(kr)k^2\,dk,$$

$$\hat{W}(x) = \frac{3}{x^3}(\sin x - x\cos x).$$

power spectrum of density fluctuations (more later...)






What is the distribution *in* these masses?

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The Astrophysical Journal, 490:493–508, 1997 December 1
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A UNIVERSAL DENSITY PROFILE FROM HIERARCHICAL CLUSTERING

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Received 1996 November 13; accepted 1997 July 15

ABSTRACT

We use high-resolution N-body simulations to study the equilibrium density profiles of dark matter halos in hierarchically clustering universes. We find that all such profiles have the same shape, independent of the halo mass, the initial density fluctuation spectrum, and the values of the cosmological parameters. Spherically averaged equilibrium profiles are well fitted over two decades in radius by a simple formula originally proposed to describe the structure of galaxy clusters in a cold dark matter universe. In any particular cosmology, the two scale parameters of the fit, the halo mass and its characteristic density, are strongly correlated. Low-mass halos are significantly denser than more massive systems, a correlation that reflects the higher collapse redshift of small halos. The characteristic density of an equilibrium halo is proportional to the density of the universe at the time it was assembled. A suitable definition of this assembly time allows the same proportionality constant to be used for all the cosmologies that we have tested. We compare our results with previous work on halo density profiles and show that there is good agreement. We also provide a step-by-step analytic procedure, based on the Press-Schechter formalism, that allows accurate equilibrium profiles to be calculated as a function of mass in any hierarchical model.
Subject headings: cosmology: theory — dark matter — galaxies: halos — methods: numerical

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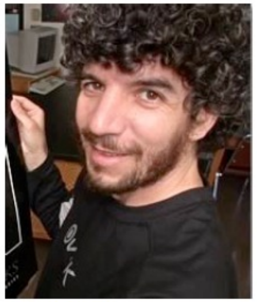
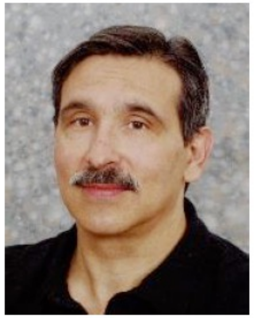

Julio Navarro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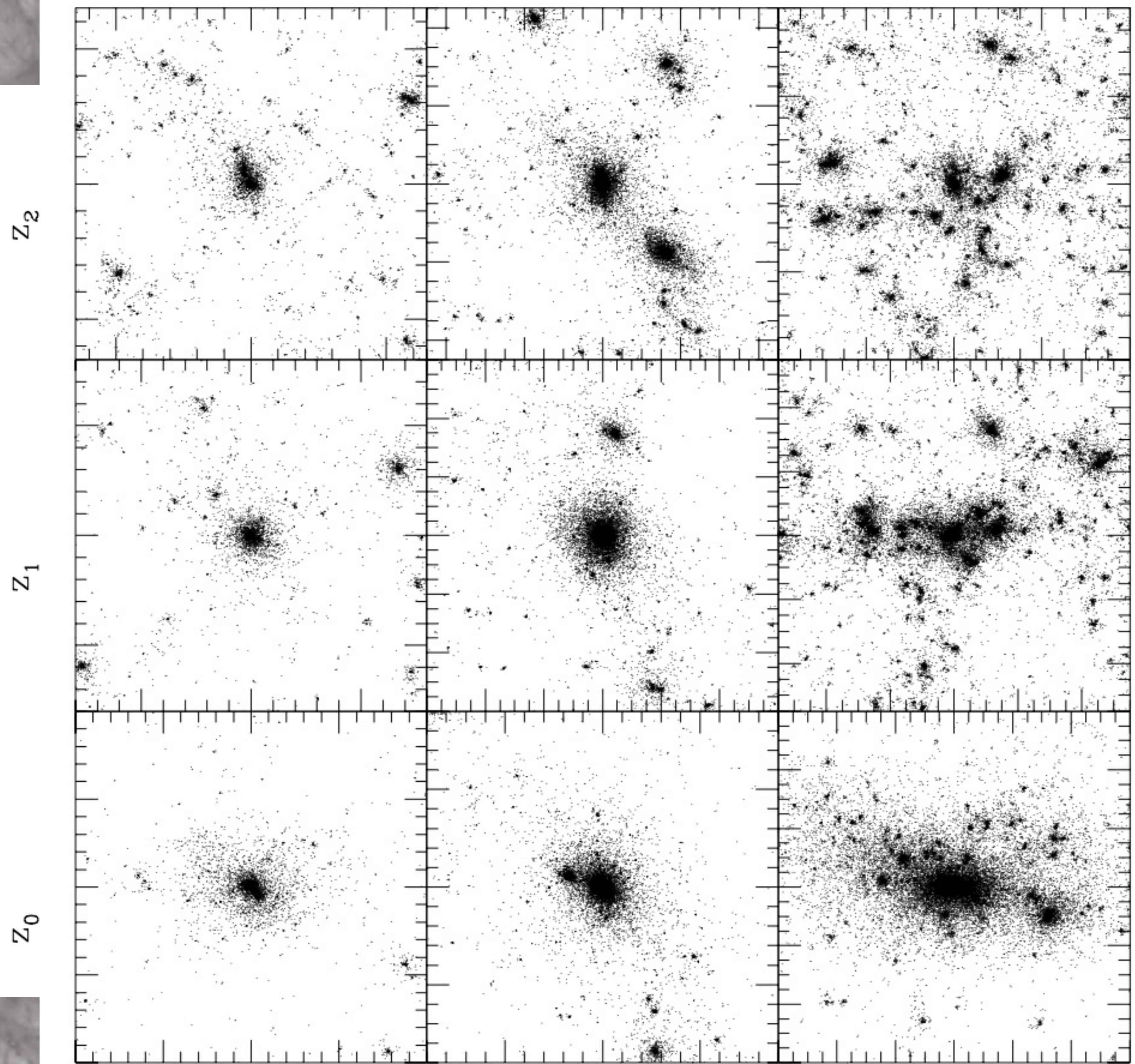
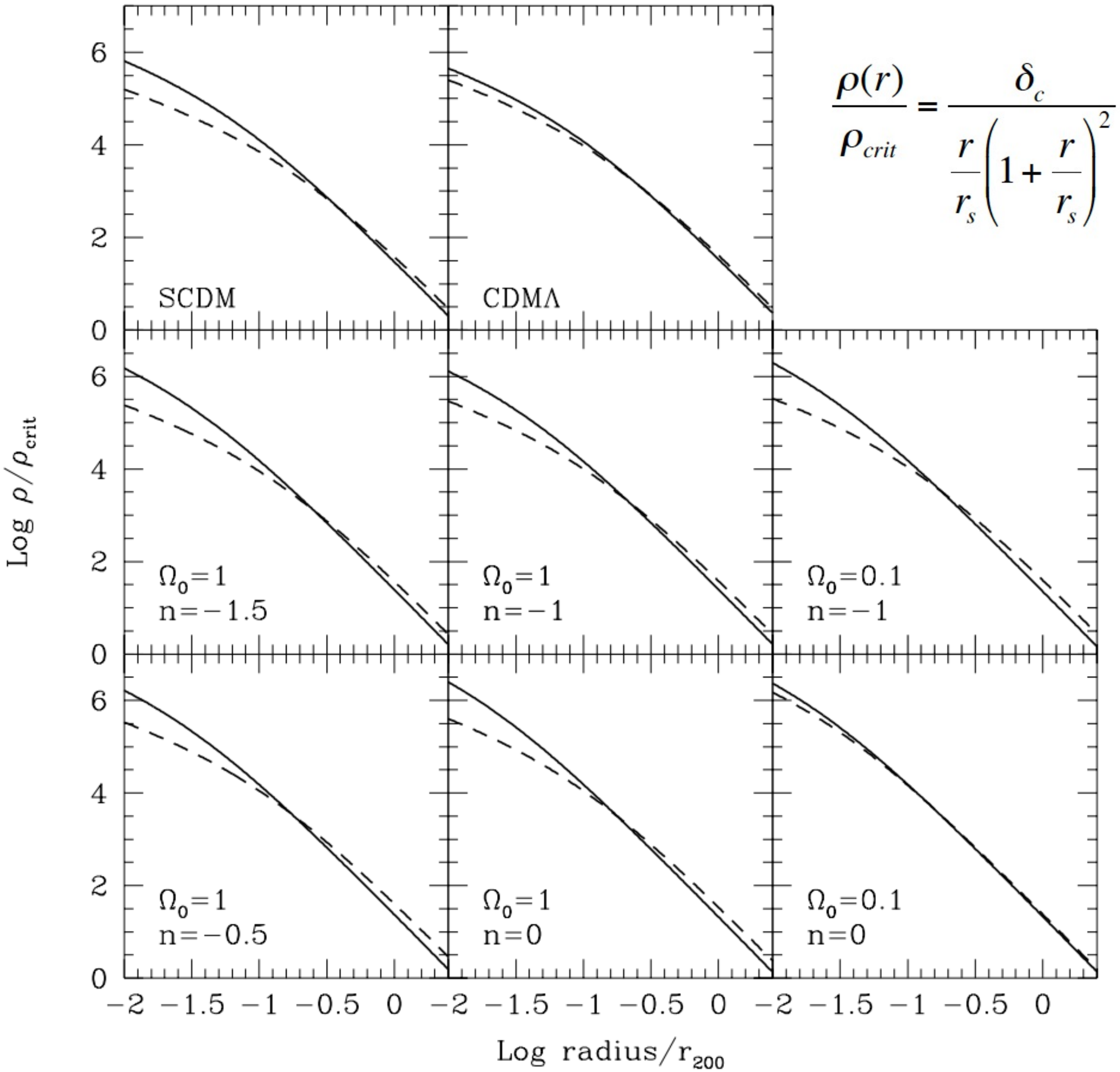
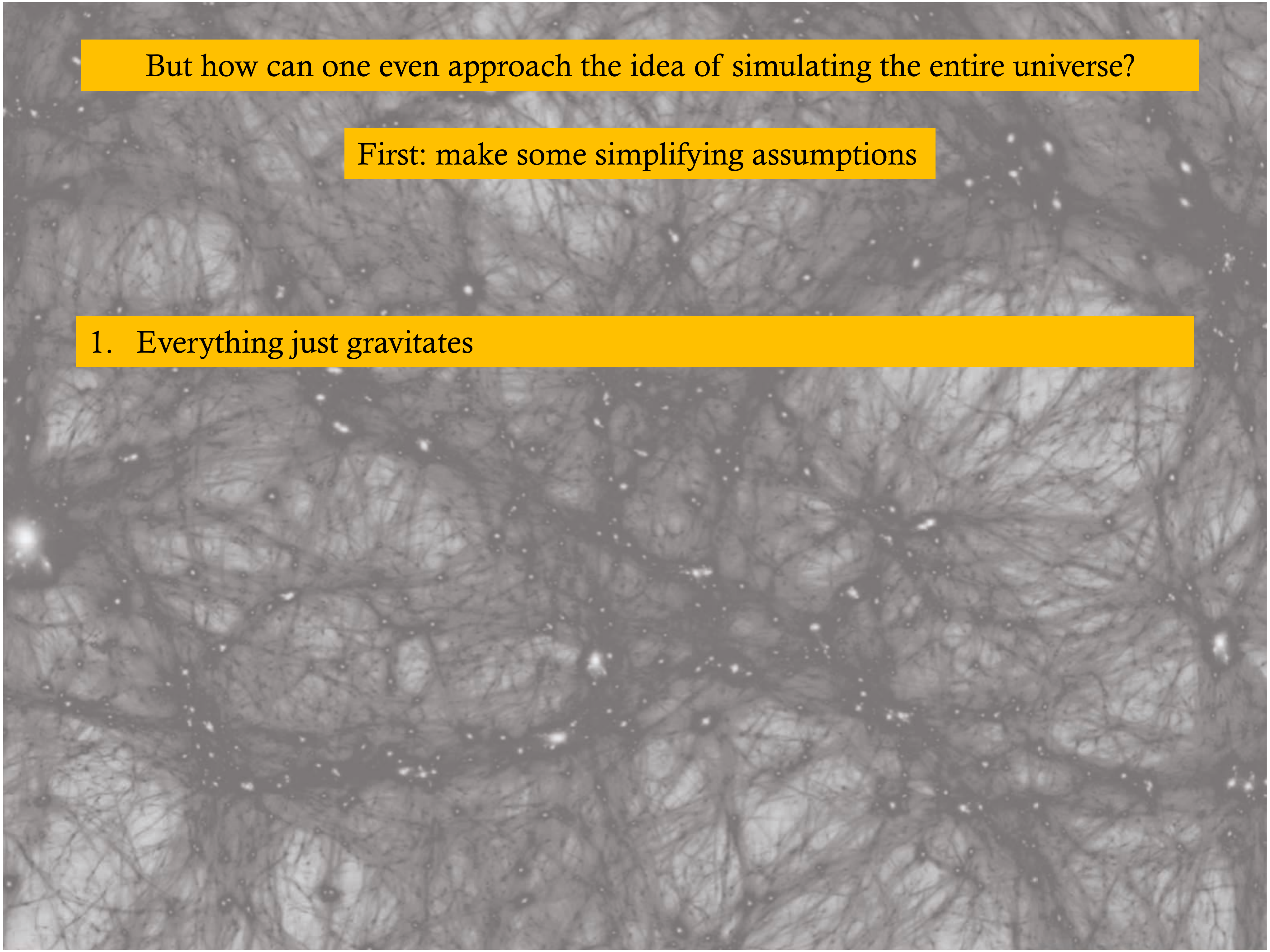




$$\frac{\rho(r)}{\rho_{crit}} = \frac{\delta_c}{\frac{r}{r_s}\left(1+\frac{r}{r_s}\right)^2}$$



But how can one even approach the idea of simulating the entire universe?

First: make some simplifying assumptions

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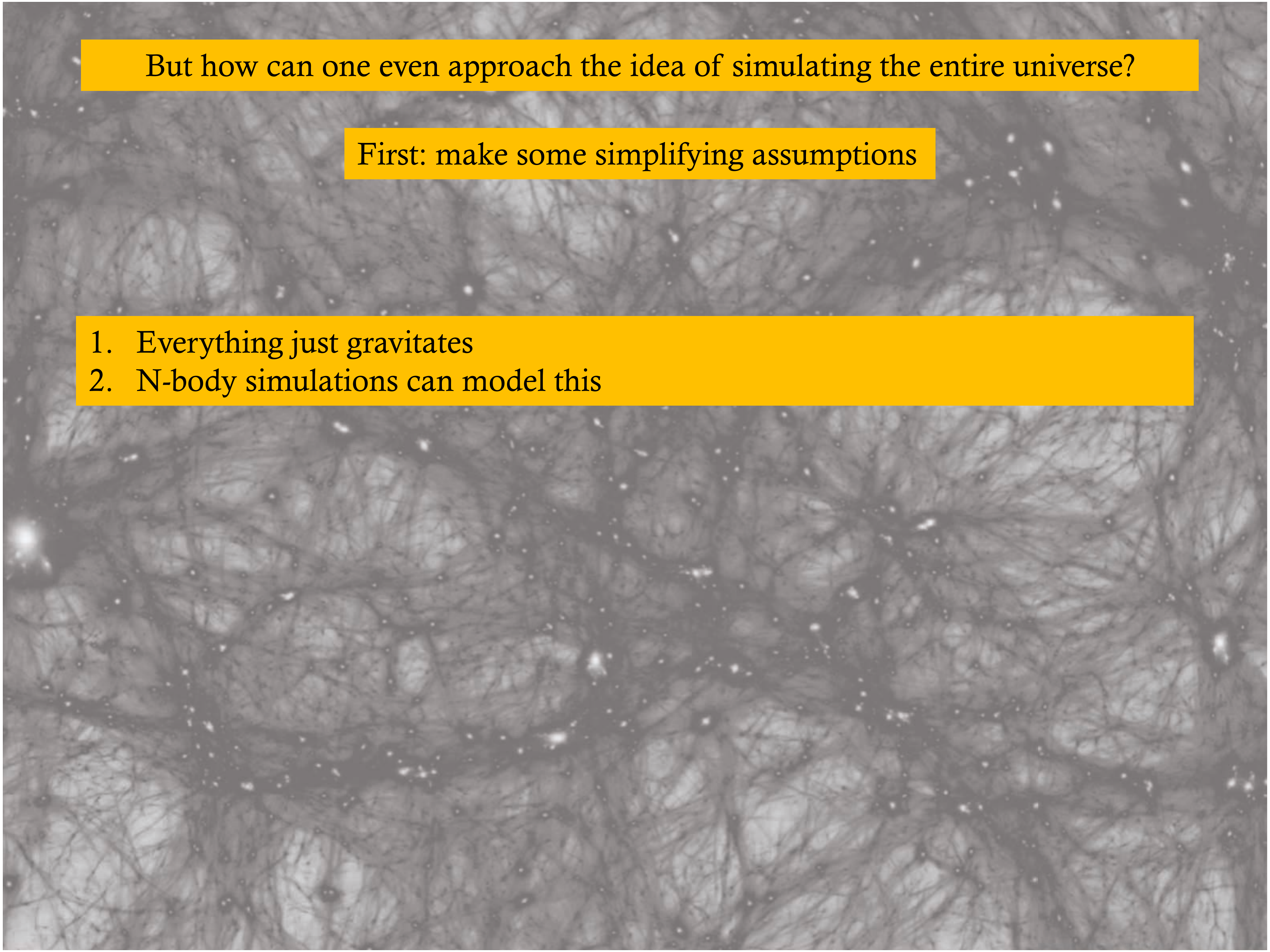

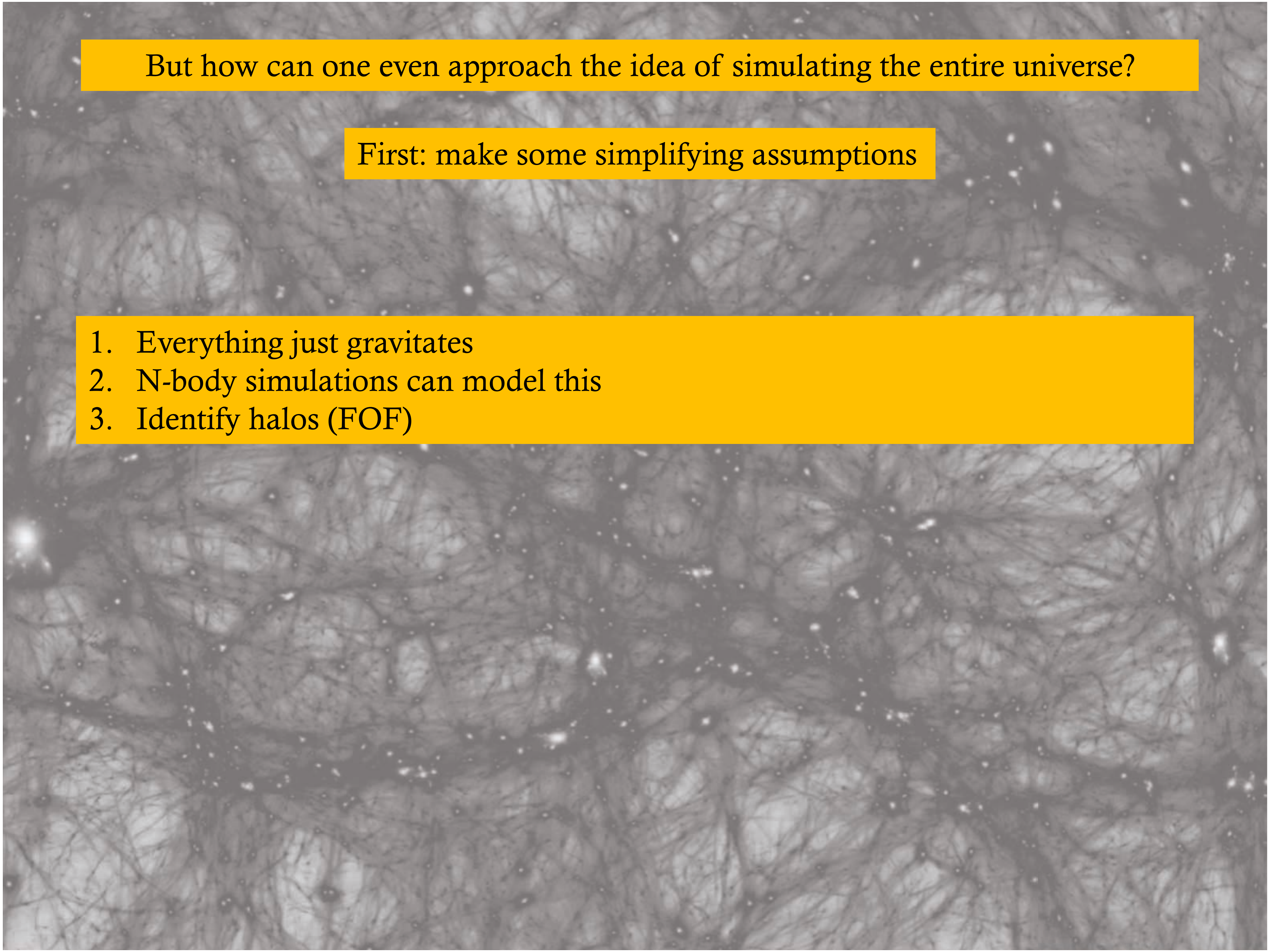

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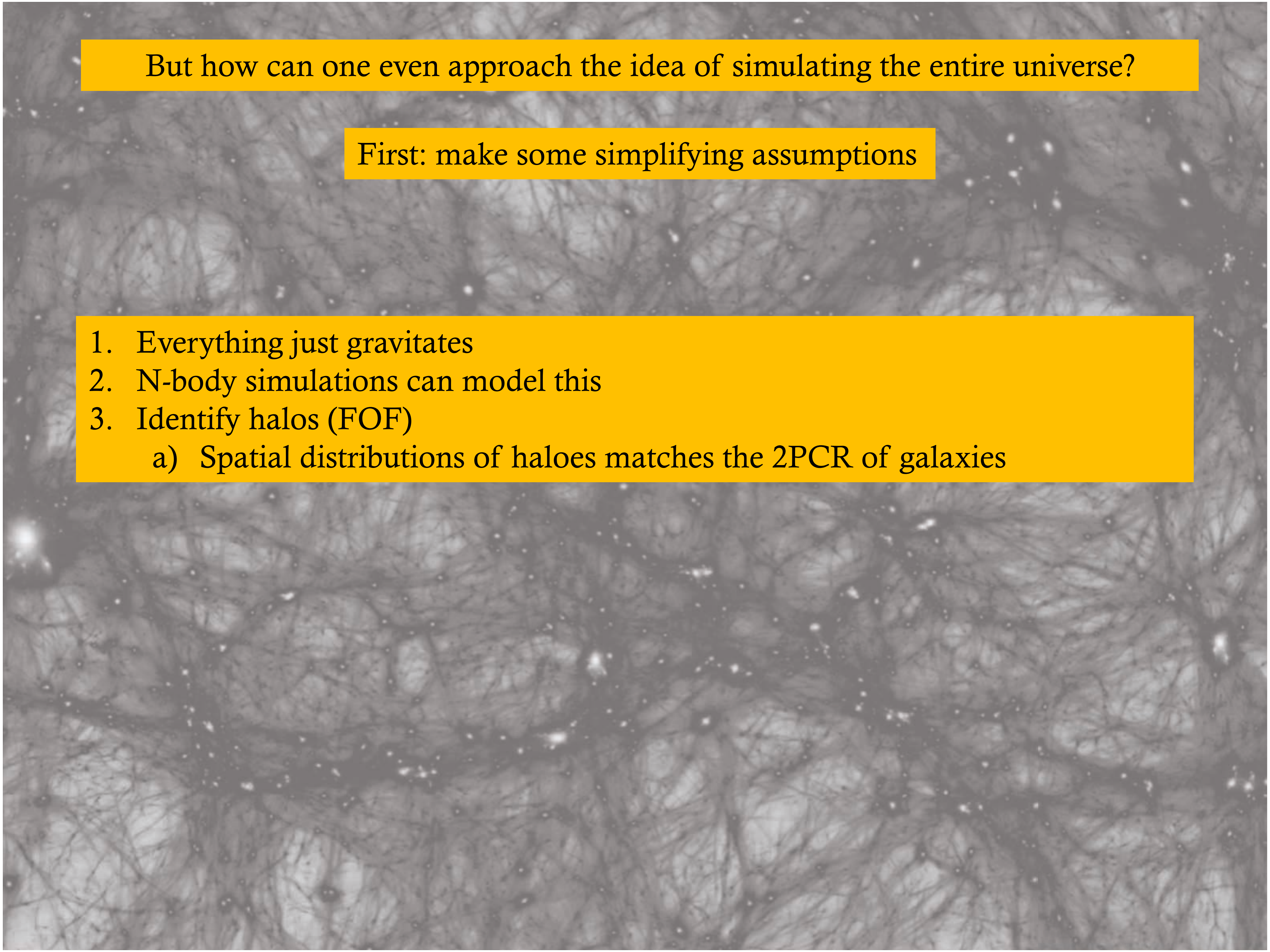

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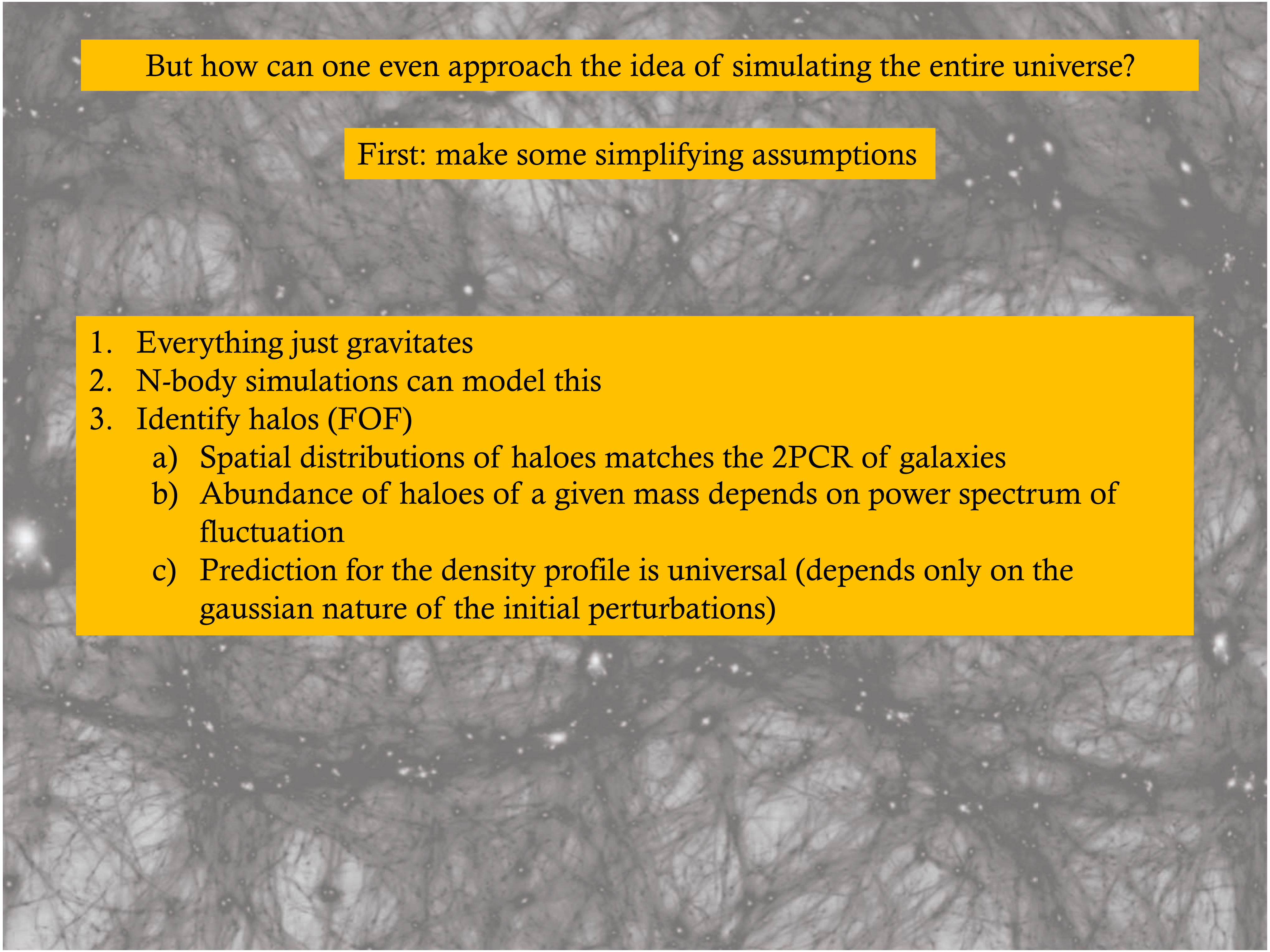

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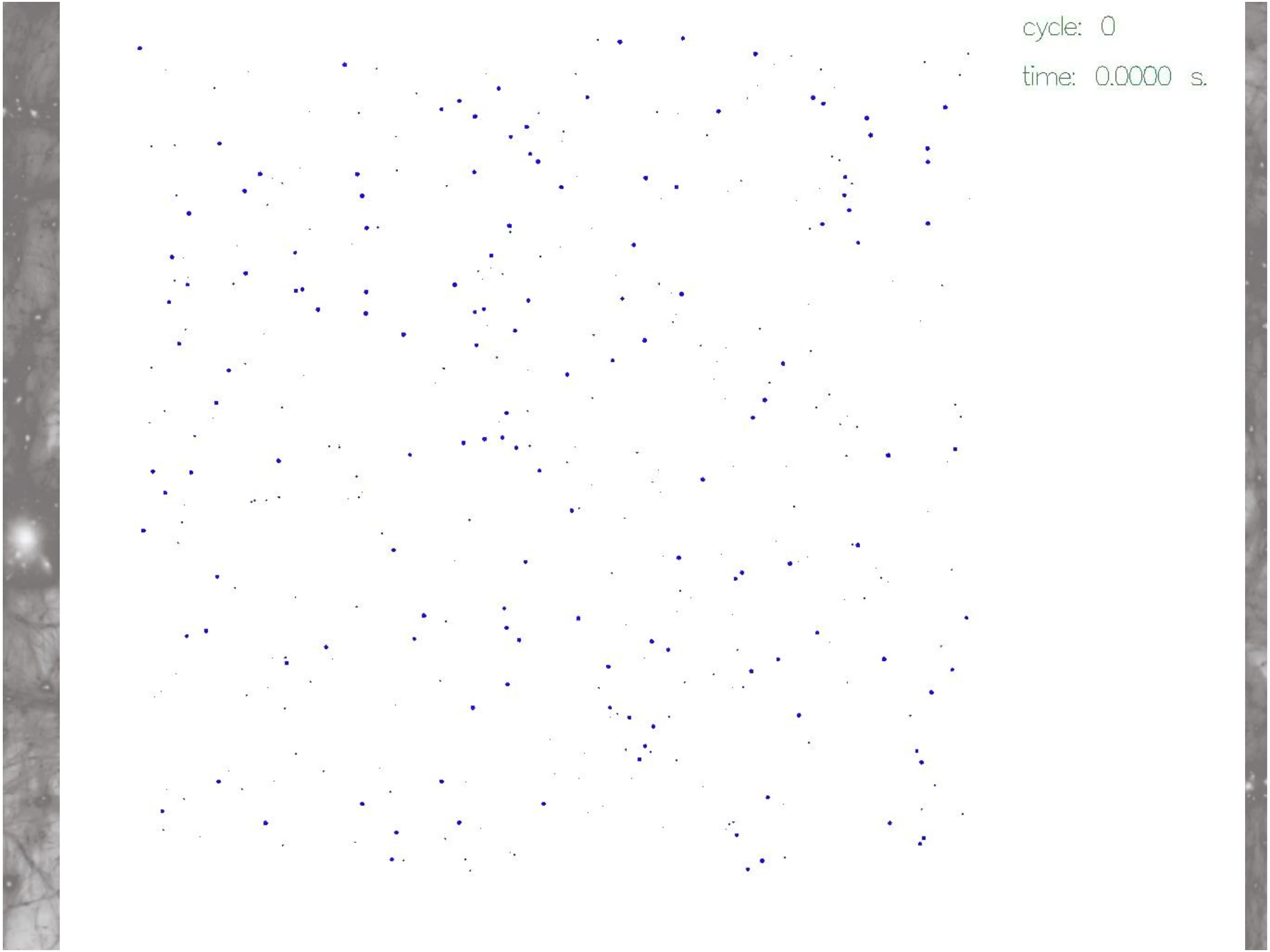
    a) Spatial distributions of haloes matches the 2PCR of galaxies
    b) Abundance of haloes of a given mass depends on power spectrum of fluctuation
    c) Prediction for the density profile is universal (depends only on the gaussian nature of the initial perturbations)

But how can one even approach the idea of simulating the entire universe?

First: make some simplifying assumptions

Second: use a huge computer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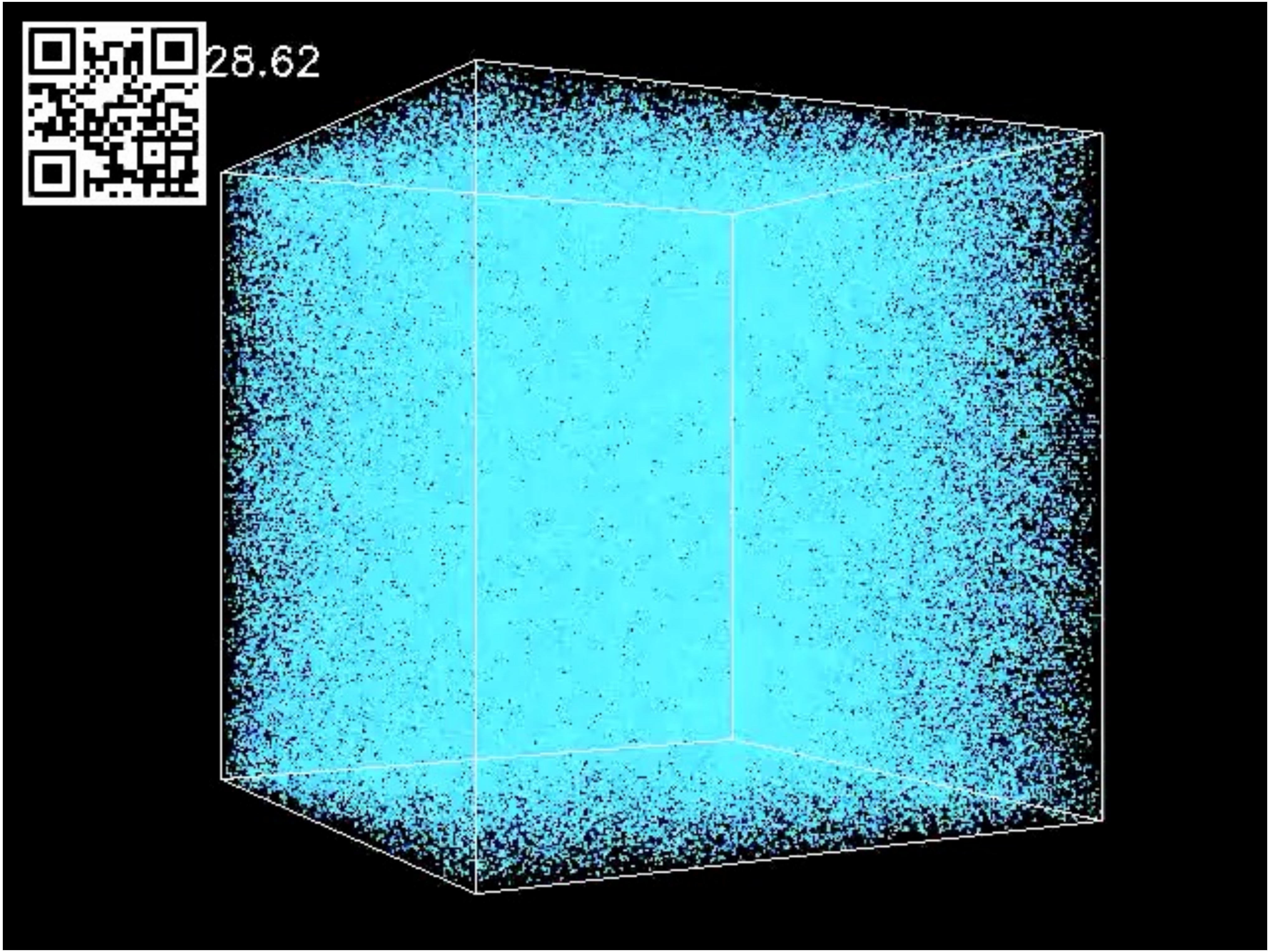
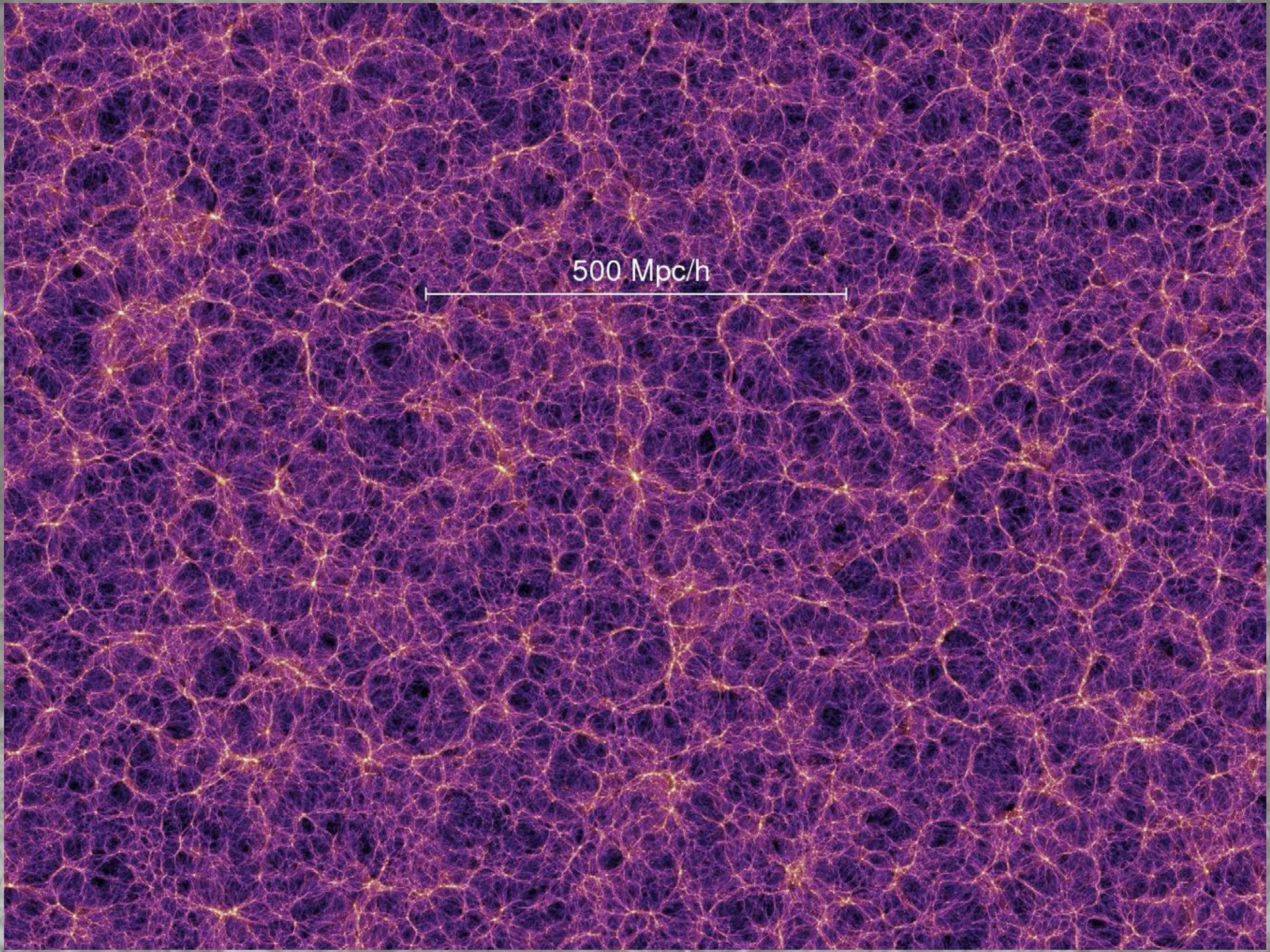
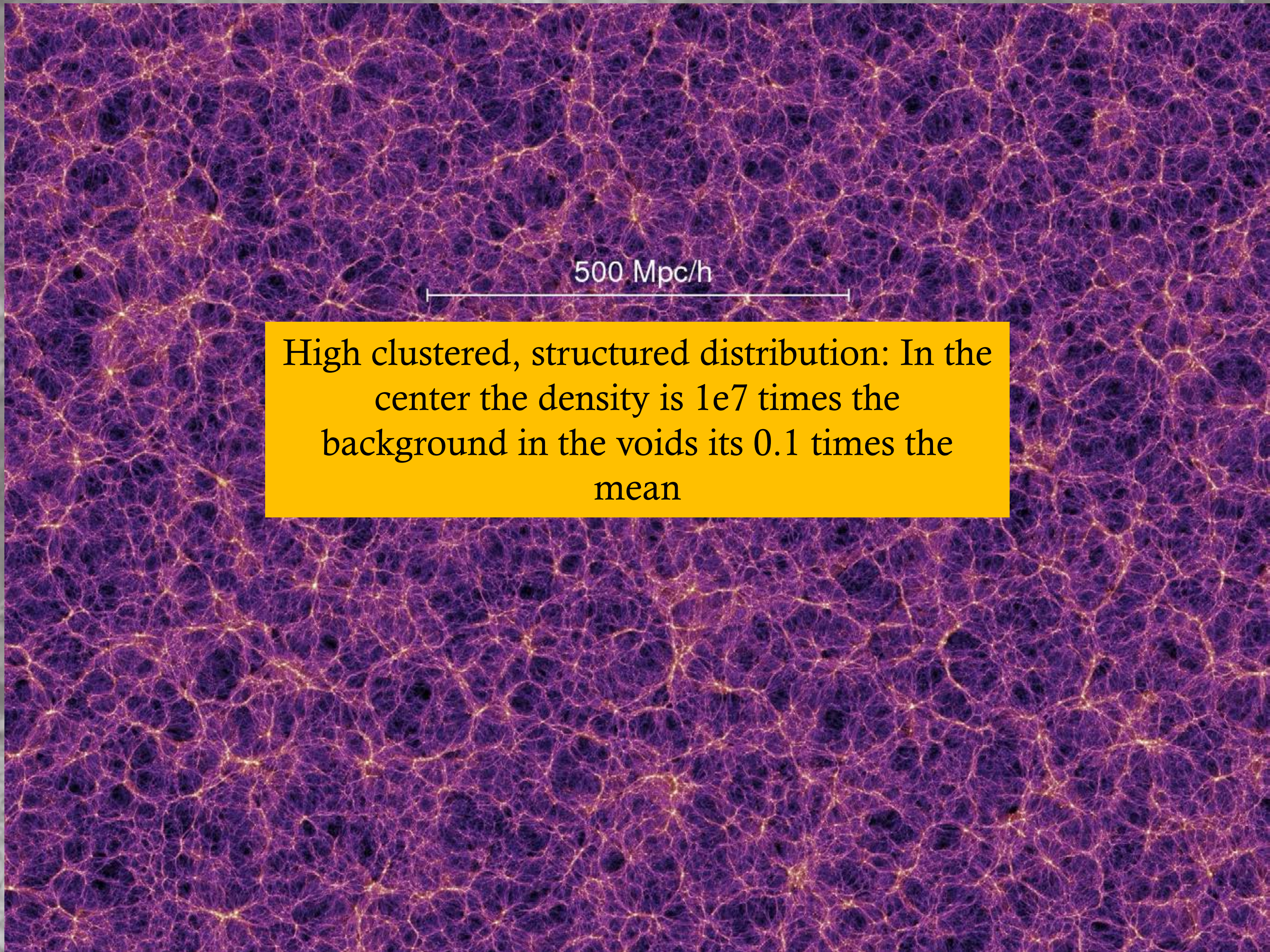

28.62

Large *N*-body cosmological simulations

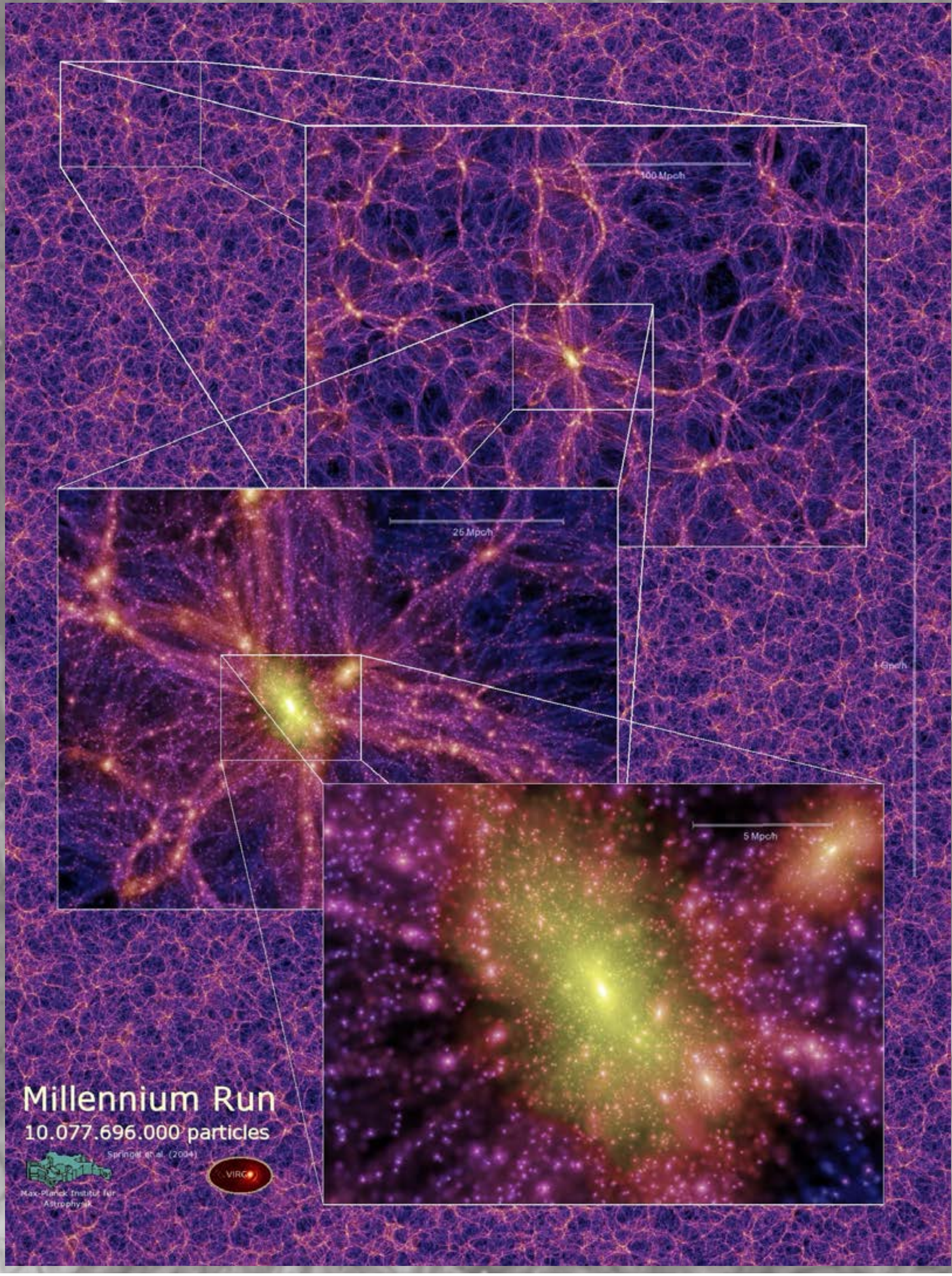


Large *N*-body cosmological simulations



High clustered, structured distribution: In the center the density is 1e7 times the background in the voids its 0.1 times the mean

Large *N*-body cosmological simulations



We can use these simulations to examine basic aspects of the "collapsed" objects

Abundance of haloes as a function of mass and time

Spatial distribution

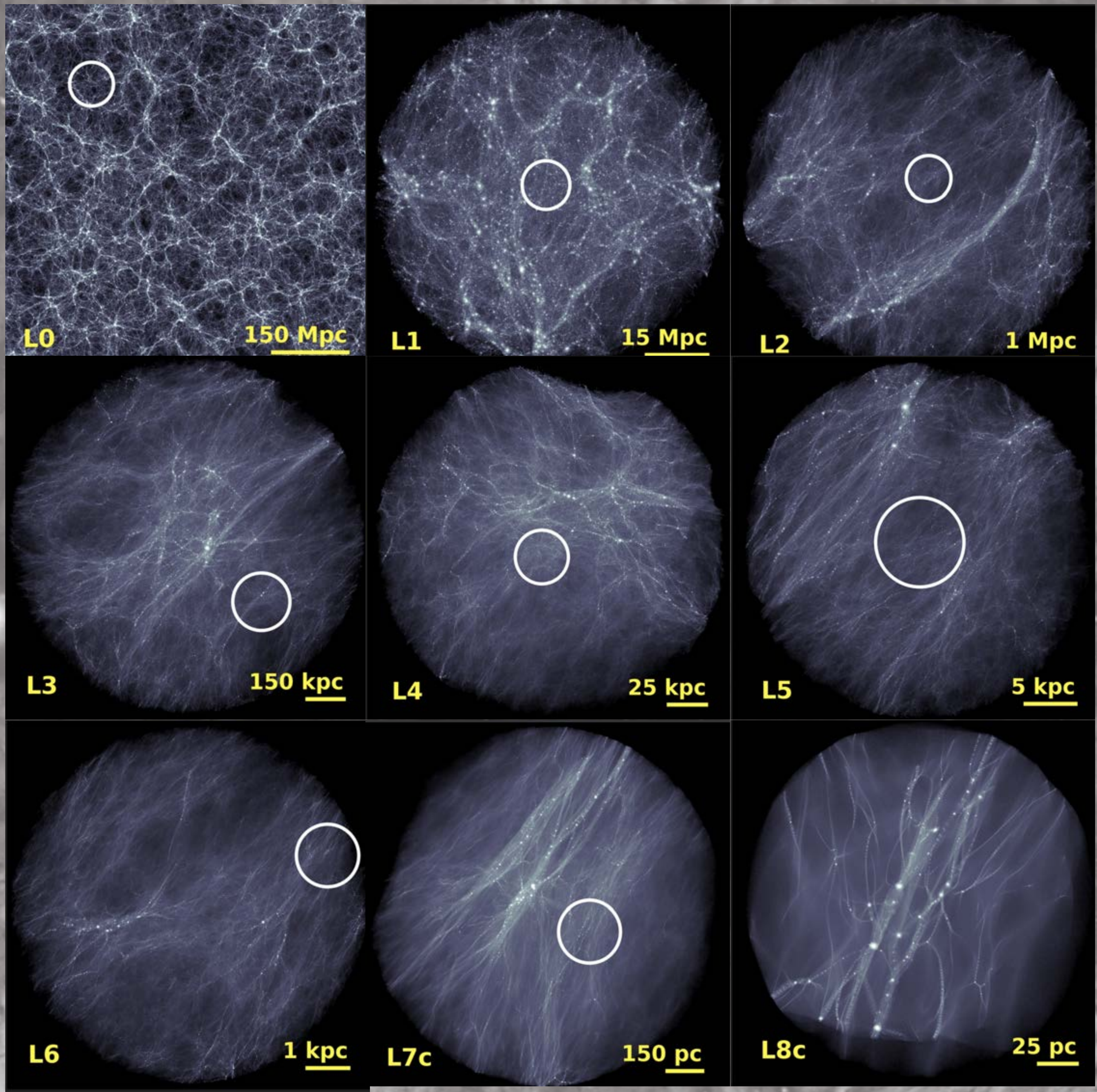
Internal structure (density prof)

Sub structure

Merger rates as function of mass and time

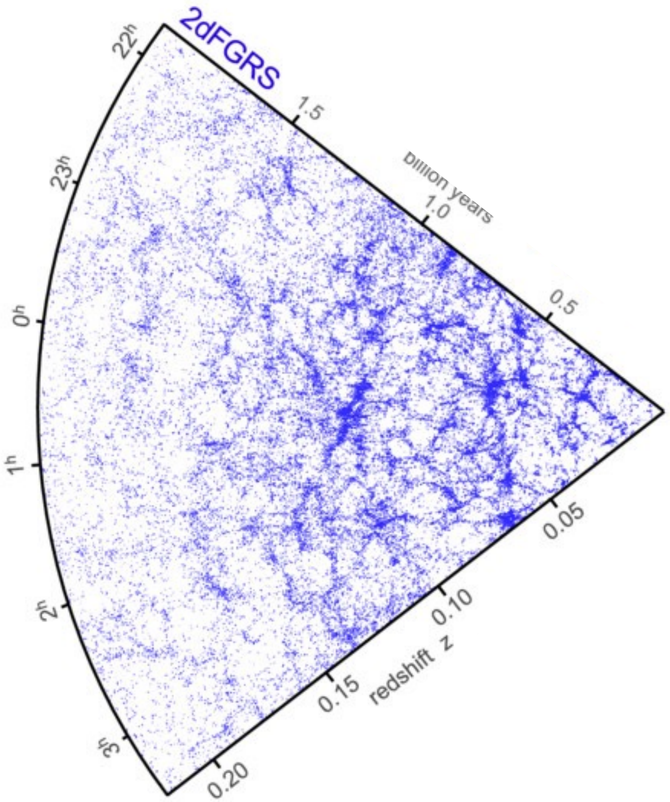
Formation epochs

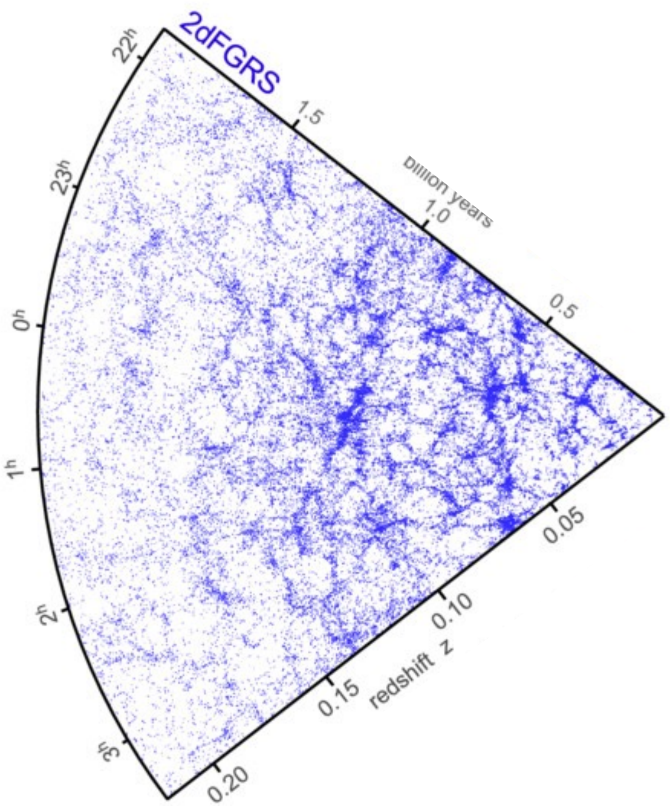
Formation histories



Voids in voids in voids

Wang et al


2dFGRS
22h
23h
0h
1h
2h
3h
billion years
1.5
1.0
0.5
redshift z
0.05
0.10
0.15
0.20


2dFGRS
billion years
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22h
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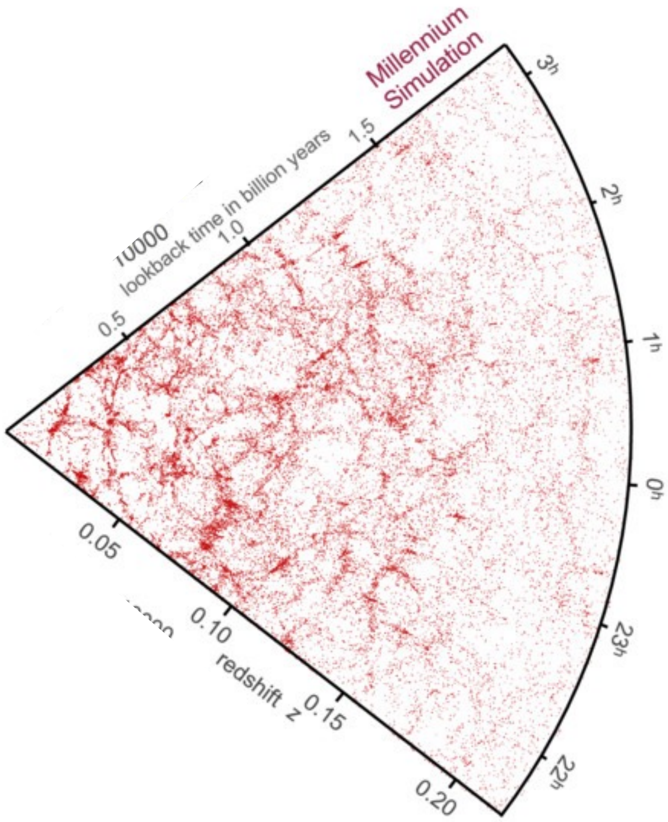
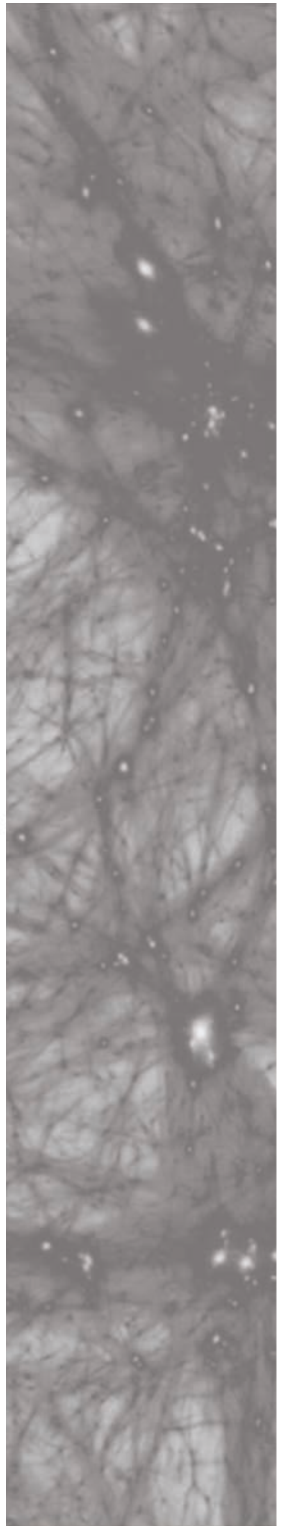
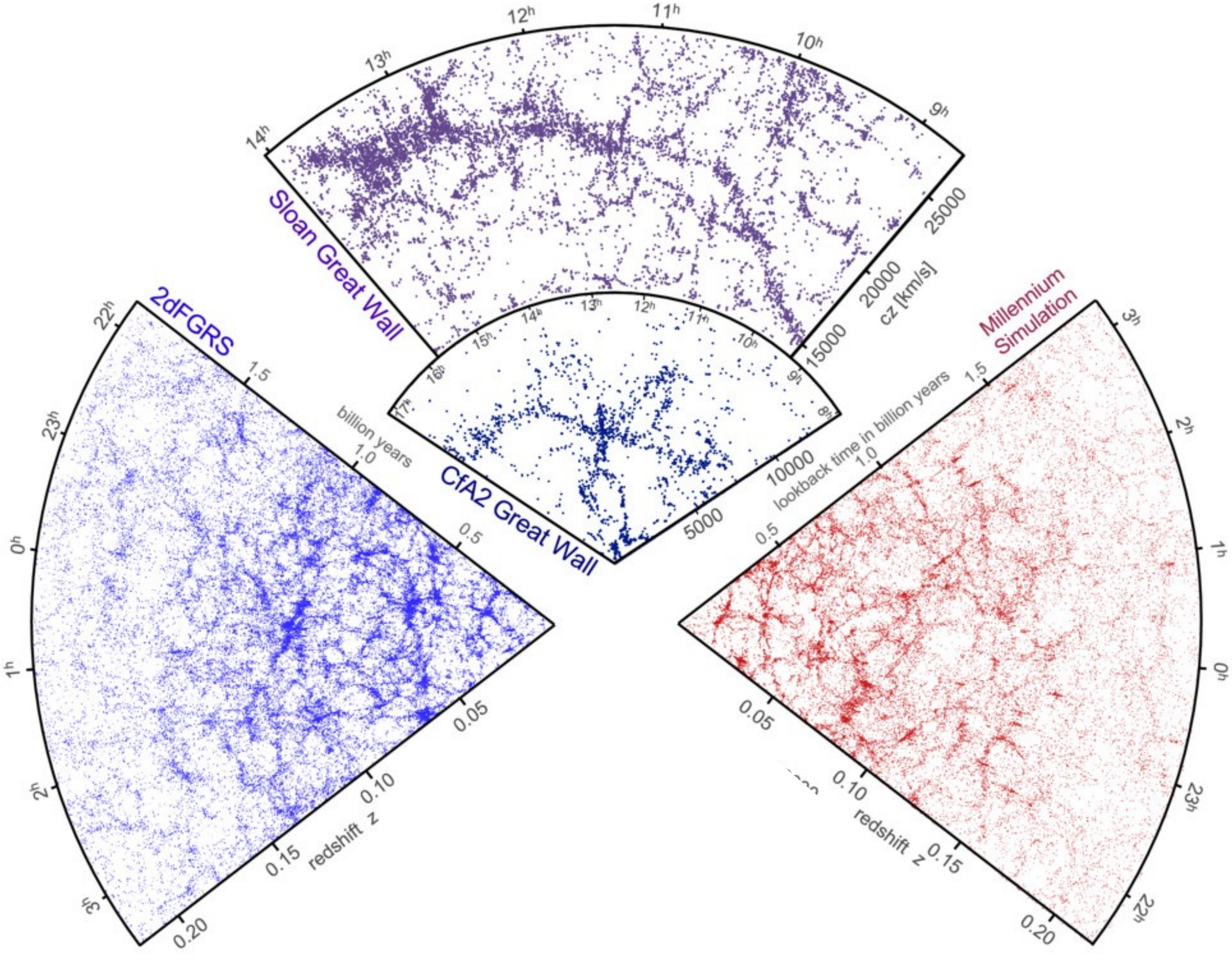
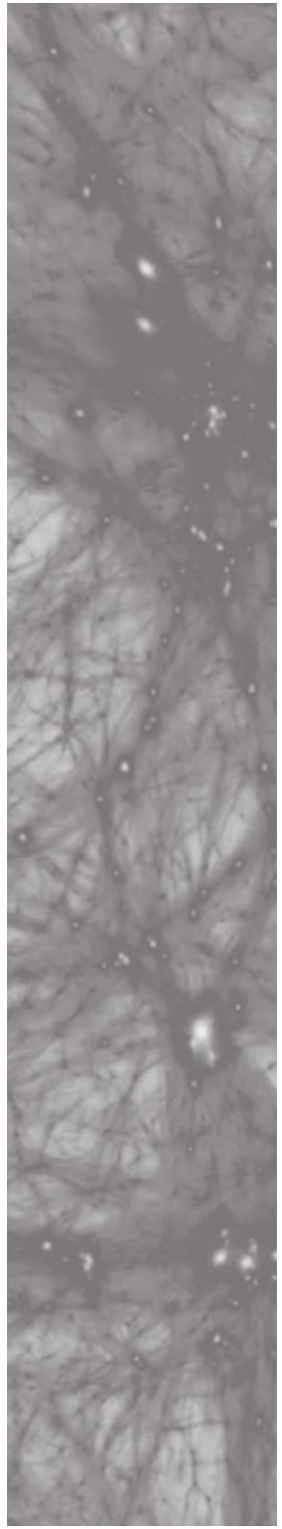
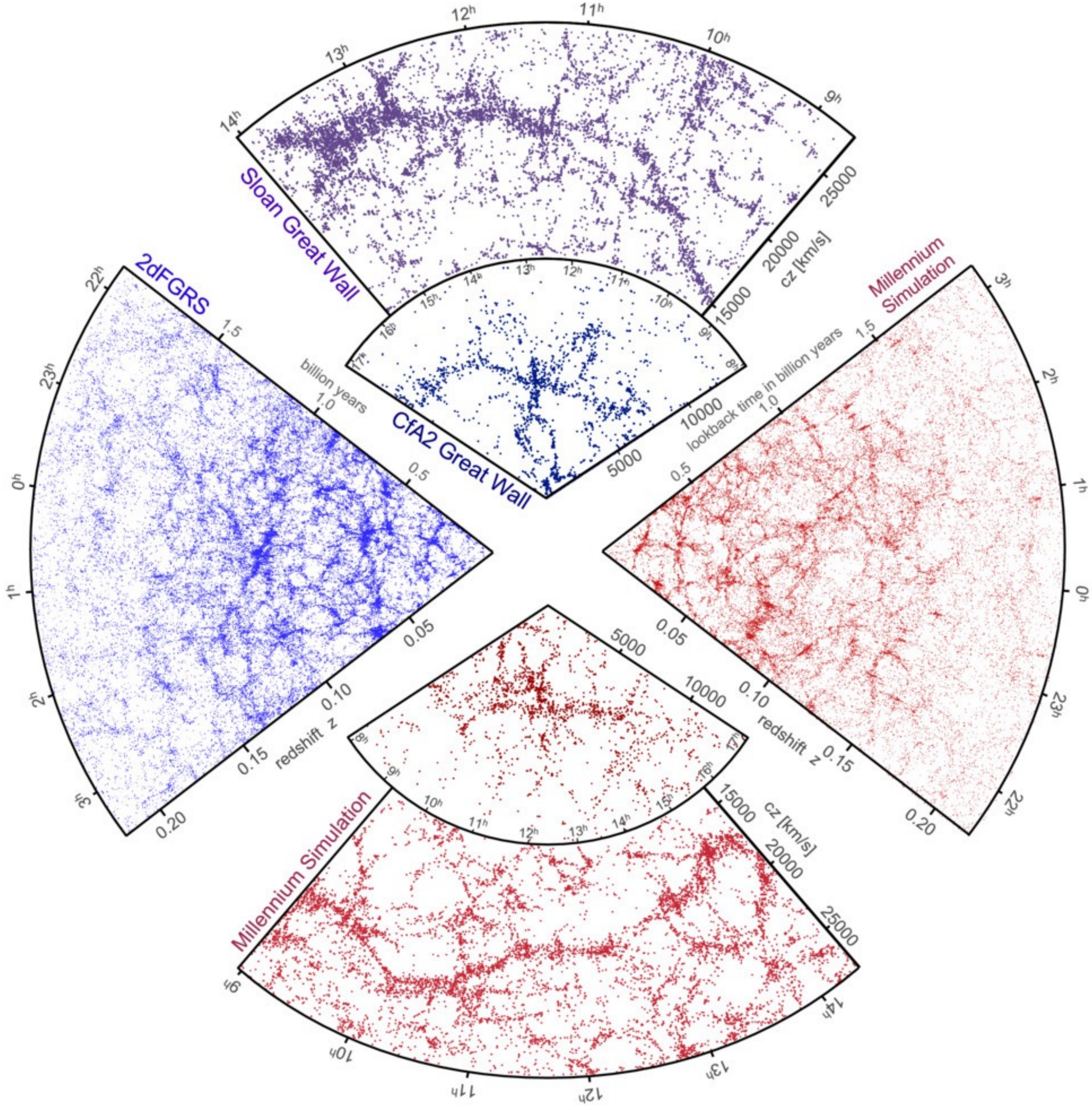

Millennium
Simulation
lookback time in billion years
redshift z
3h
2h
1h
0h
23h
22h
0.5
1.0
1.5
0.05
0.10
0.15
0.20




Sloan Great Wall
2dFGRS
CfA2 Great Wall
Millennium
Simulation
cz [km/s]
billion years
lookback time in billion years
redshift z
15000
20000
25000
10000
5000
0.5
1.0
1.5
0.05
0.10
0.15
0.20




Sloan Great Wall
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cz [km/s]
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redshift z
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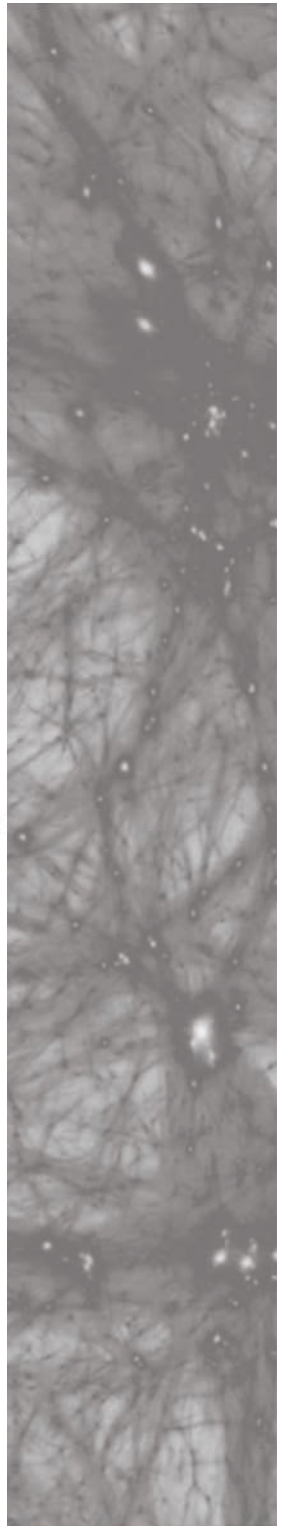
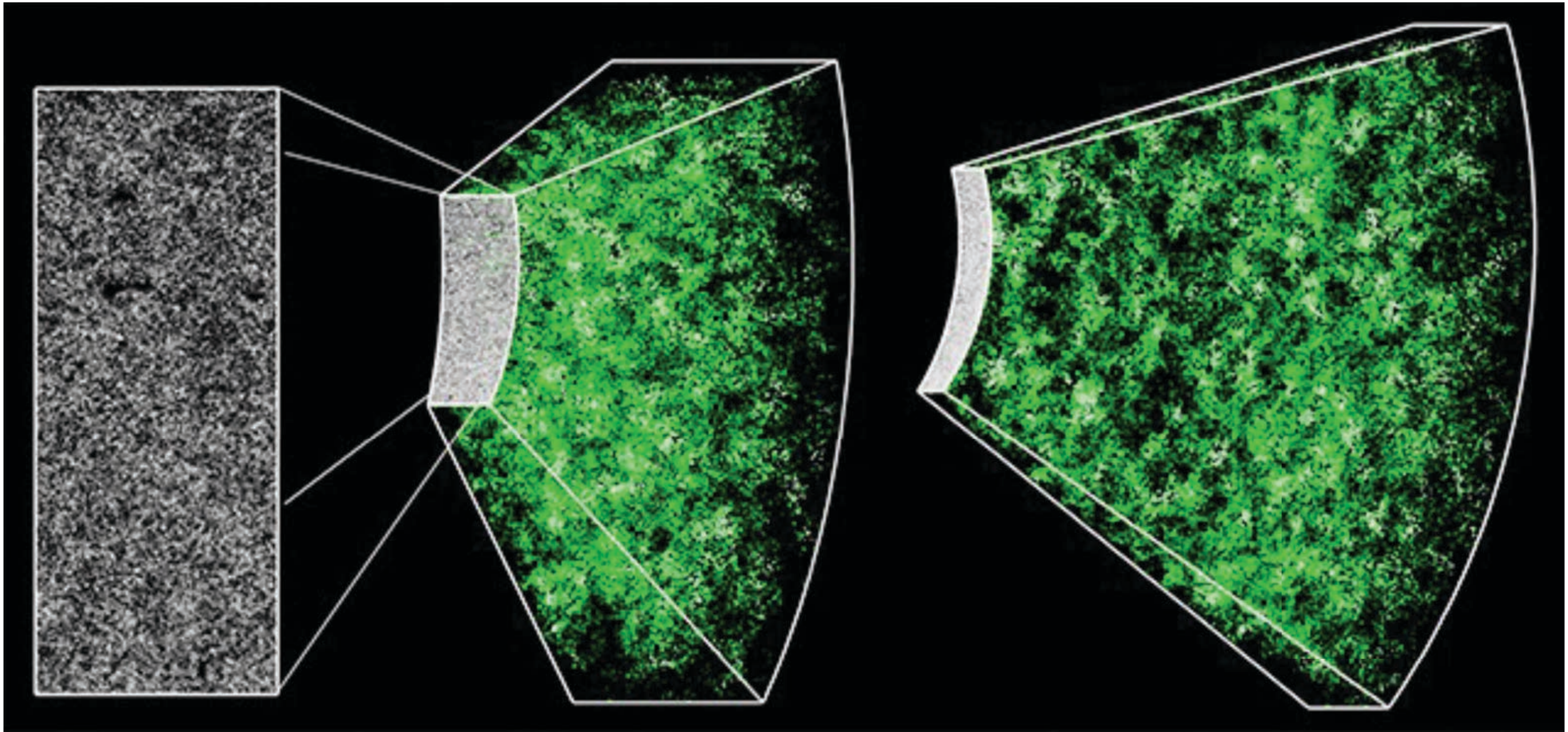
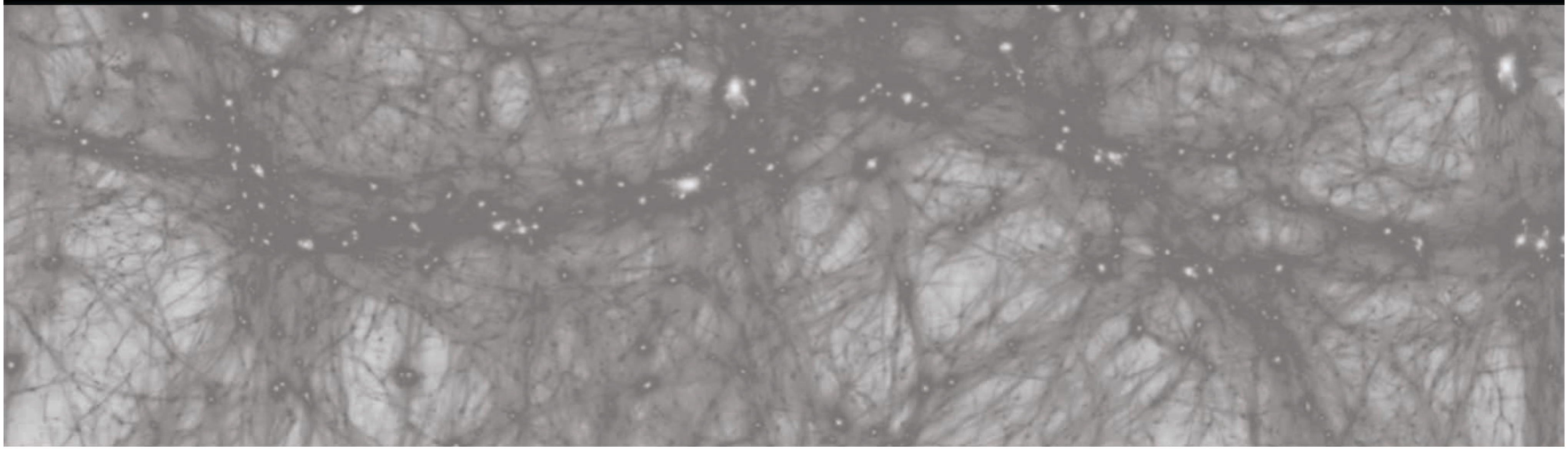
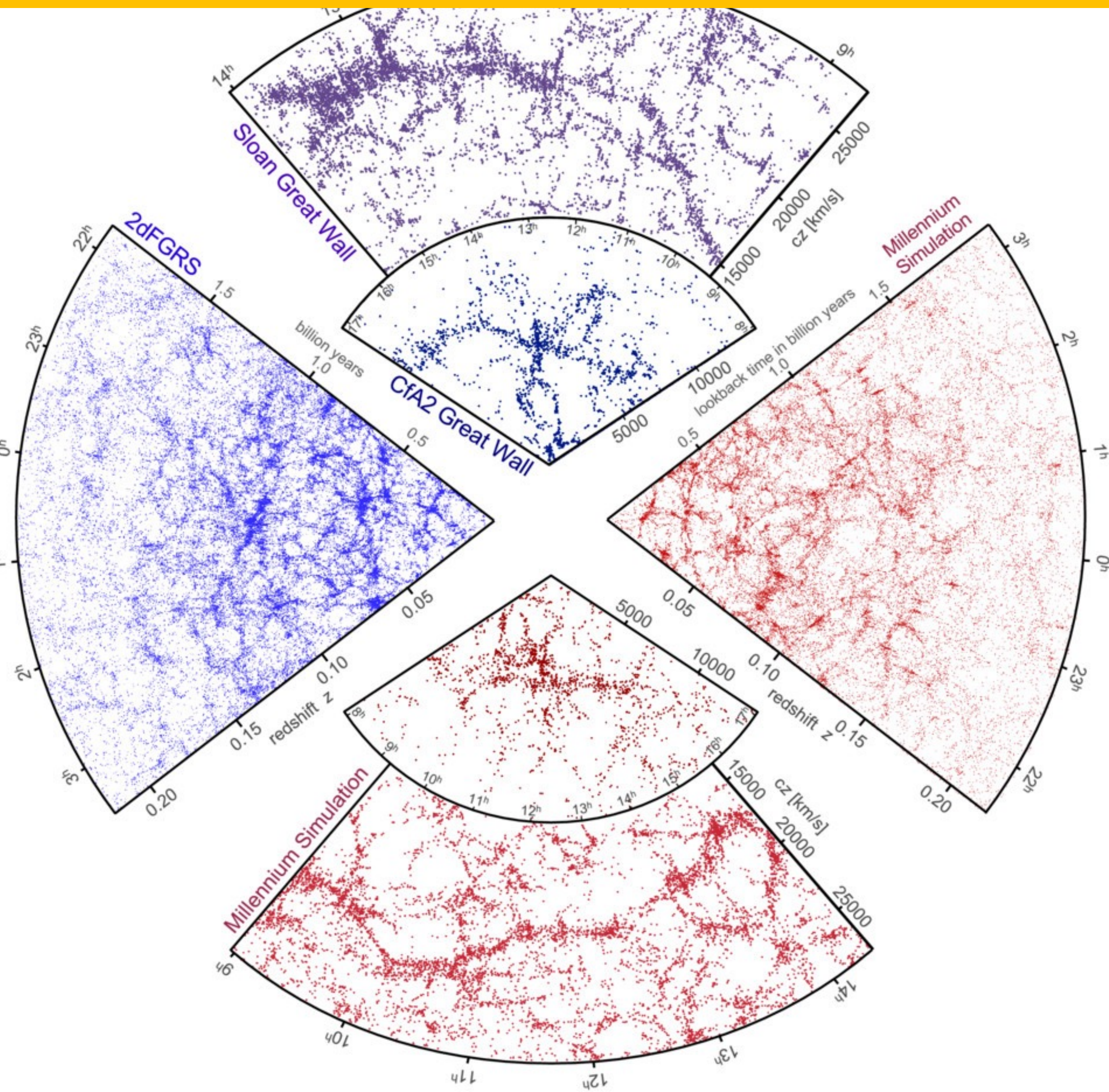
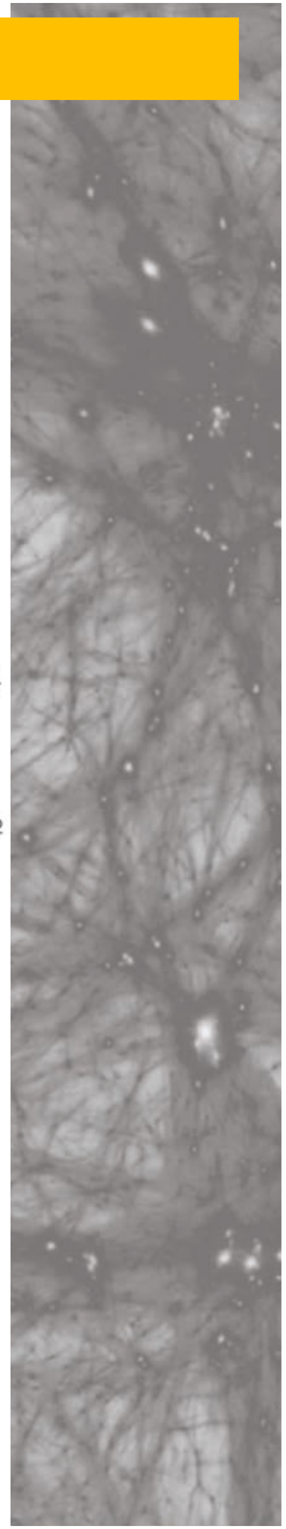






But where are the galaxies?





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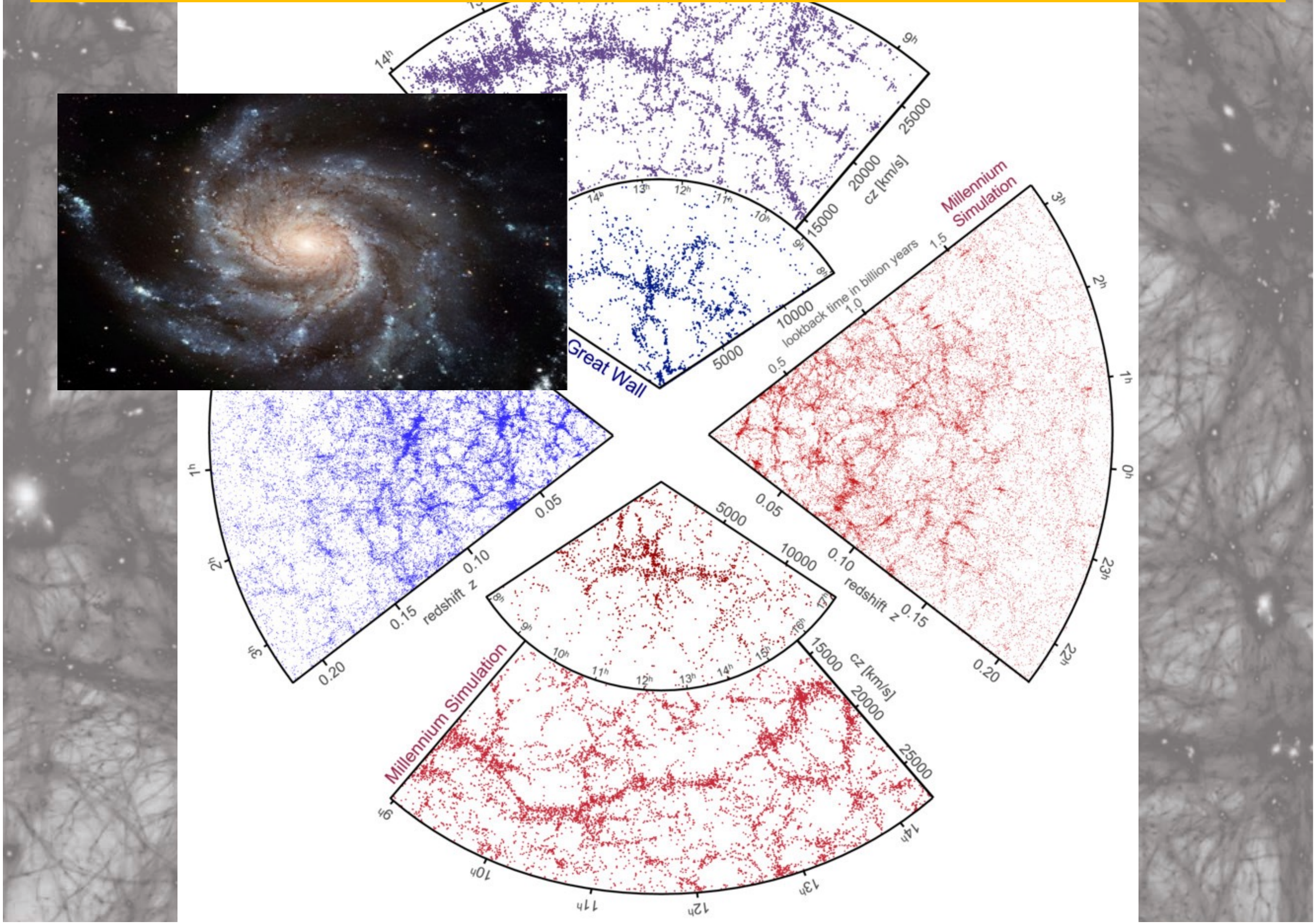

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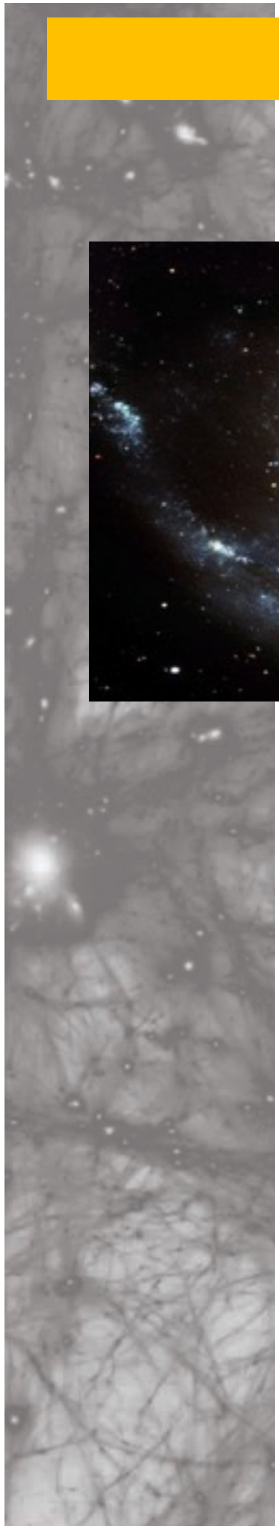
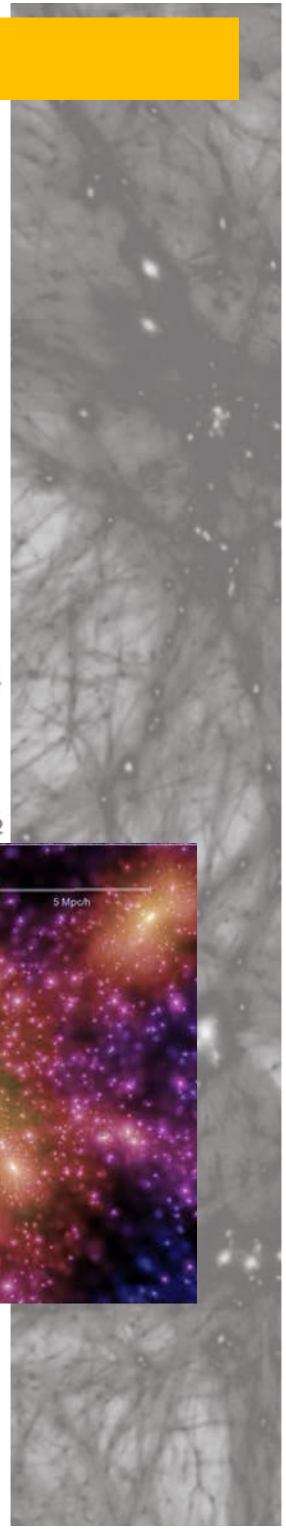
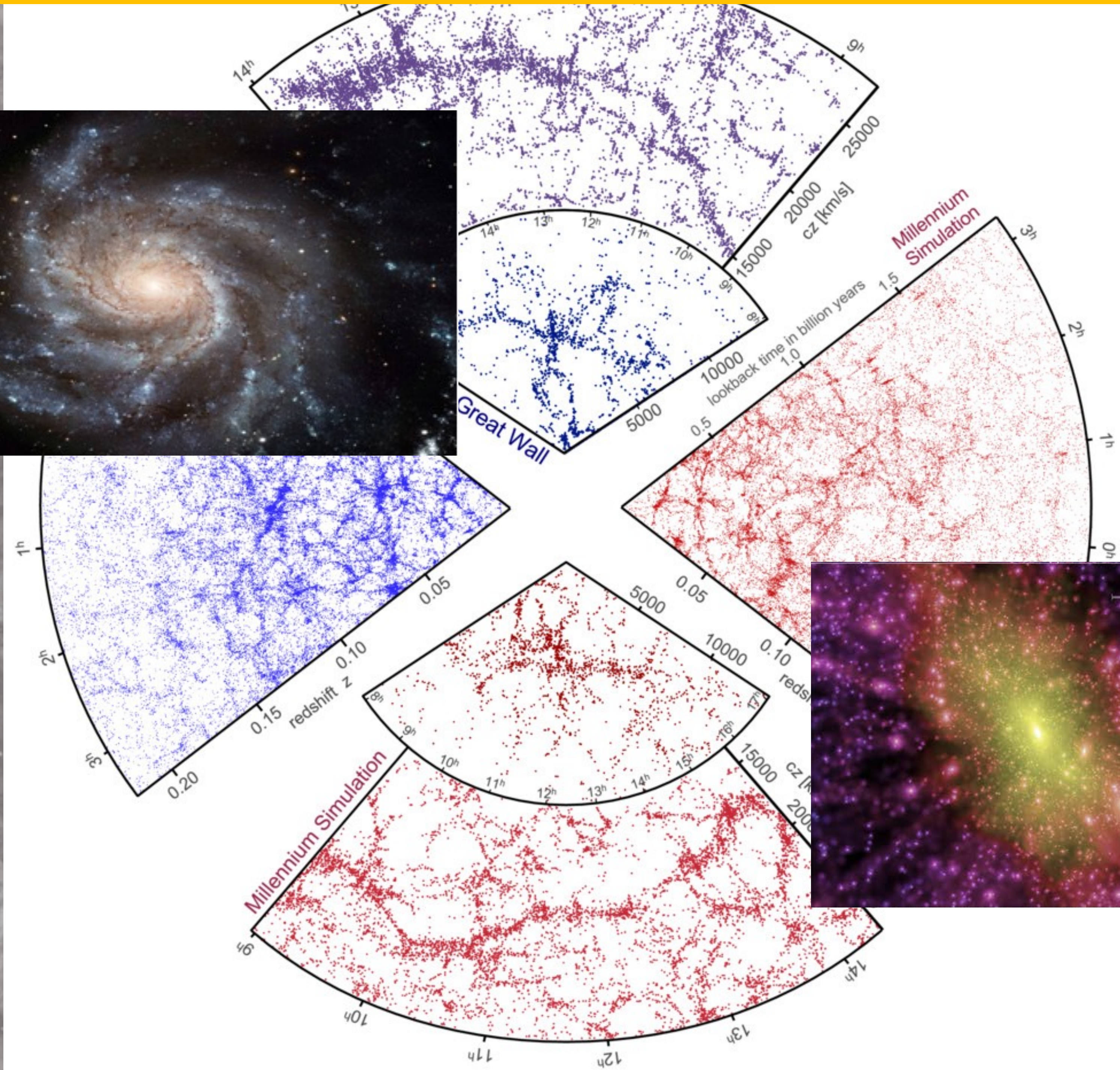
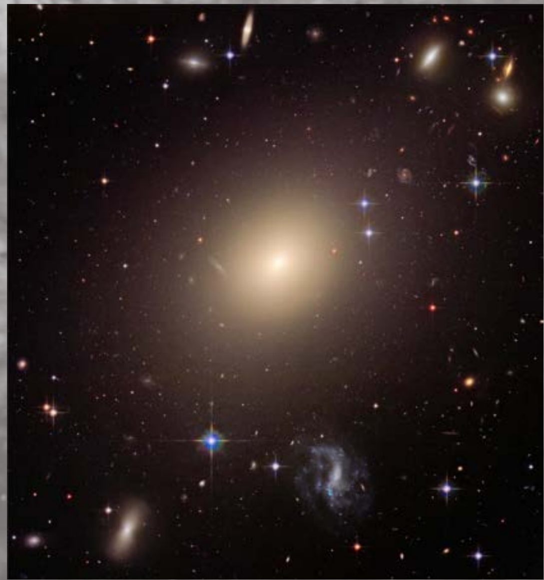


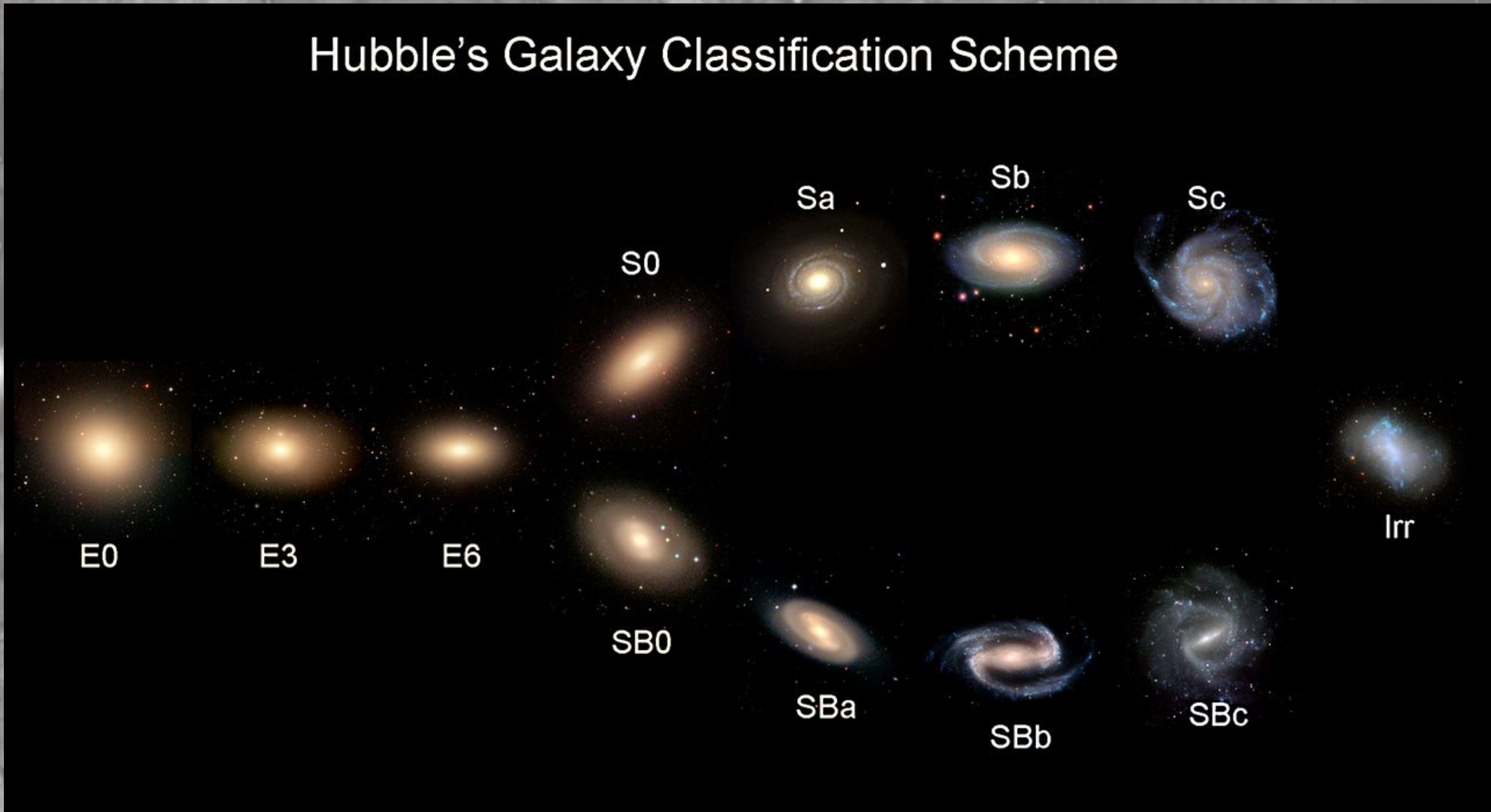




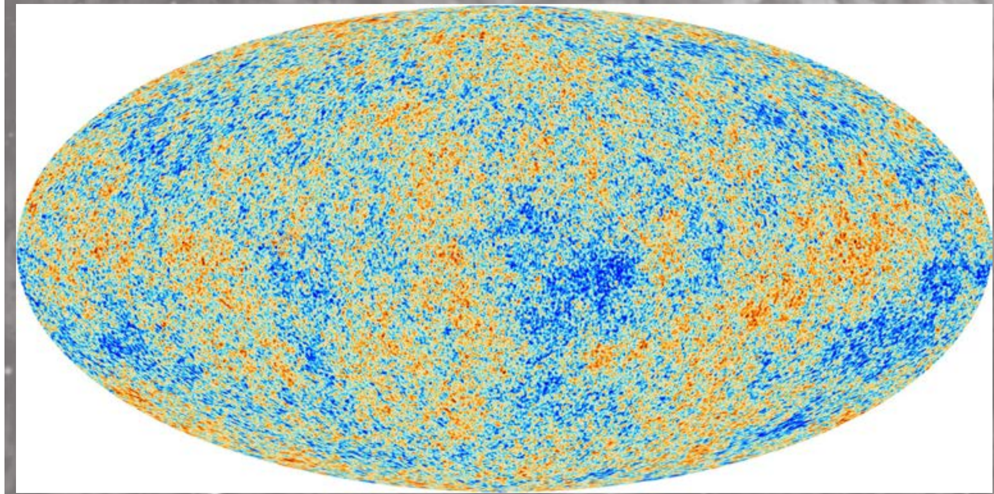
Enormous diversity in the galaxy population



Well known to astronomers for at least a century

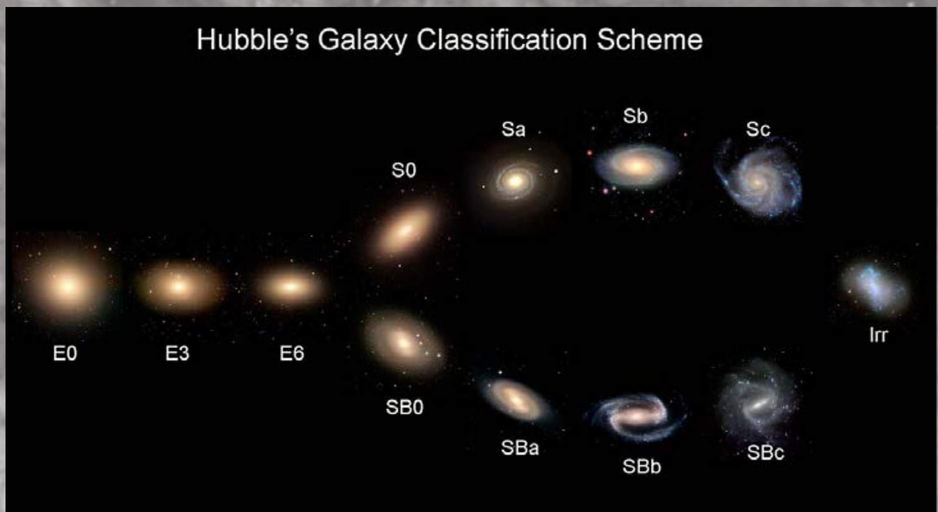


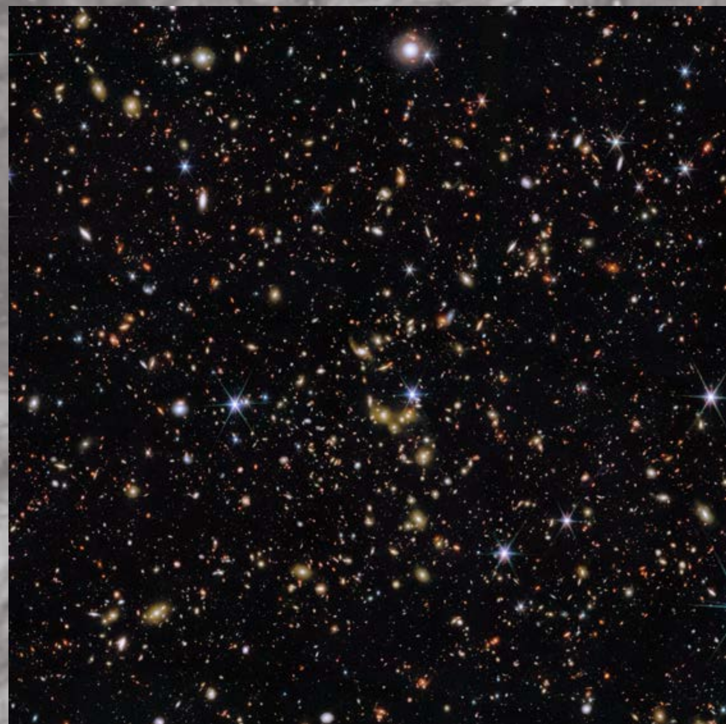
The central questions:



The central questions of cosmology:

Given the initial conditions from the CMB, how did structure in the universe form?





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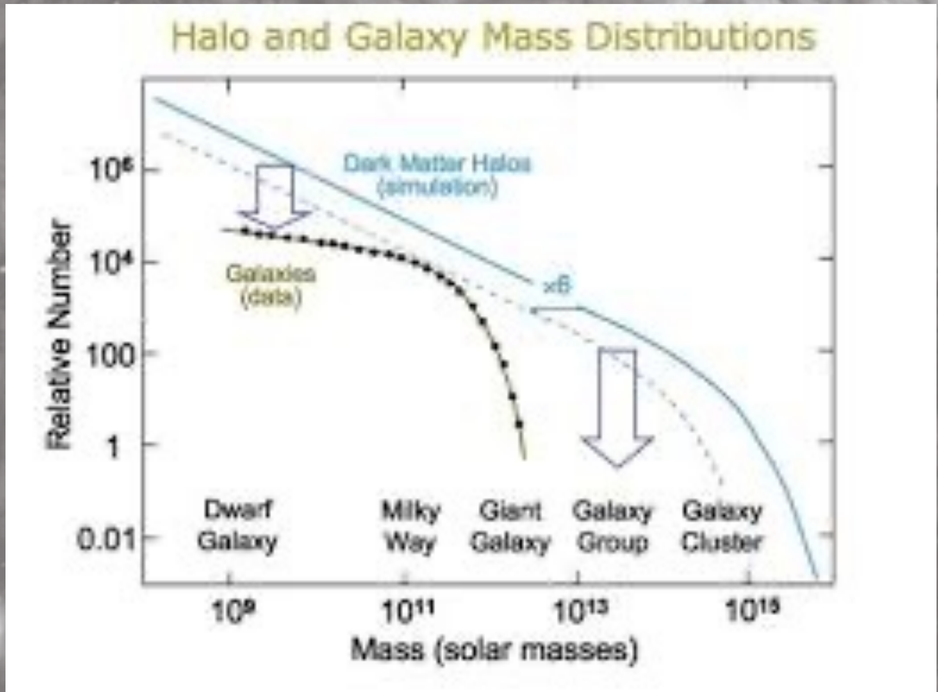

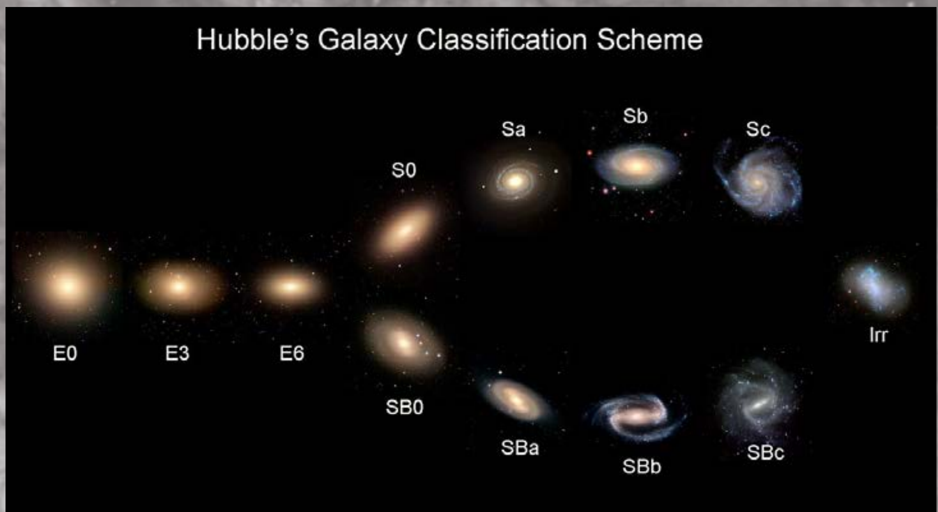

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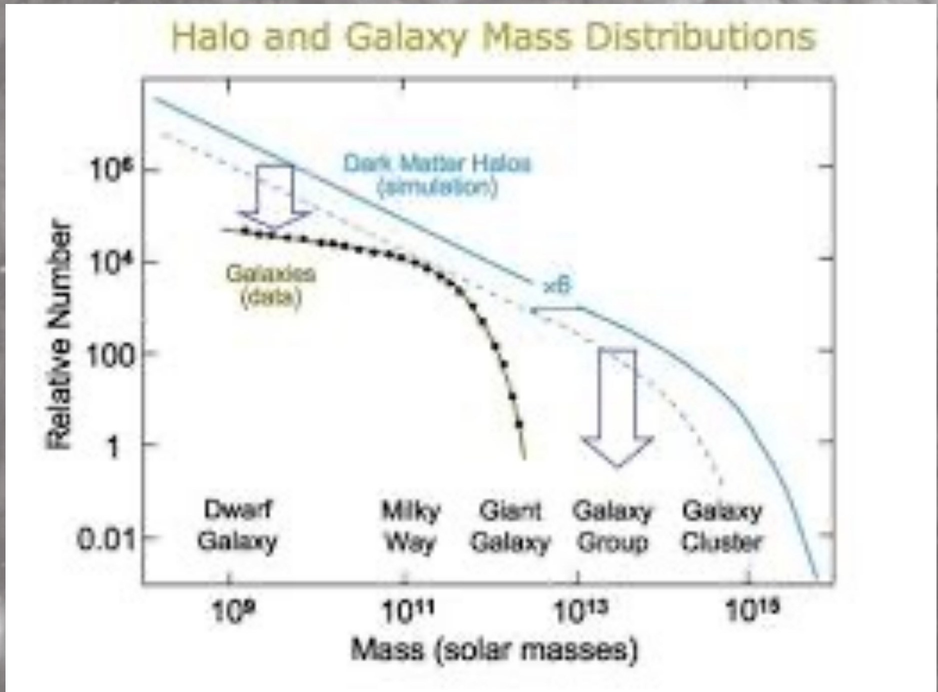
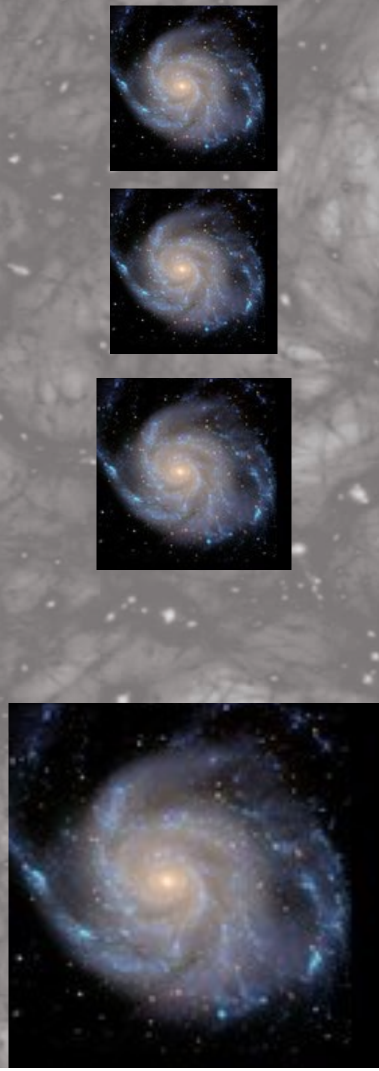
The Central question of galaxy formation

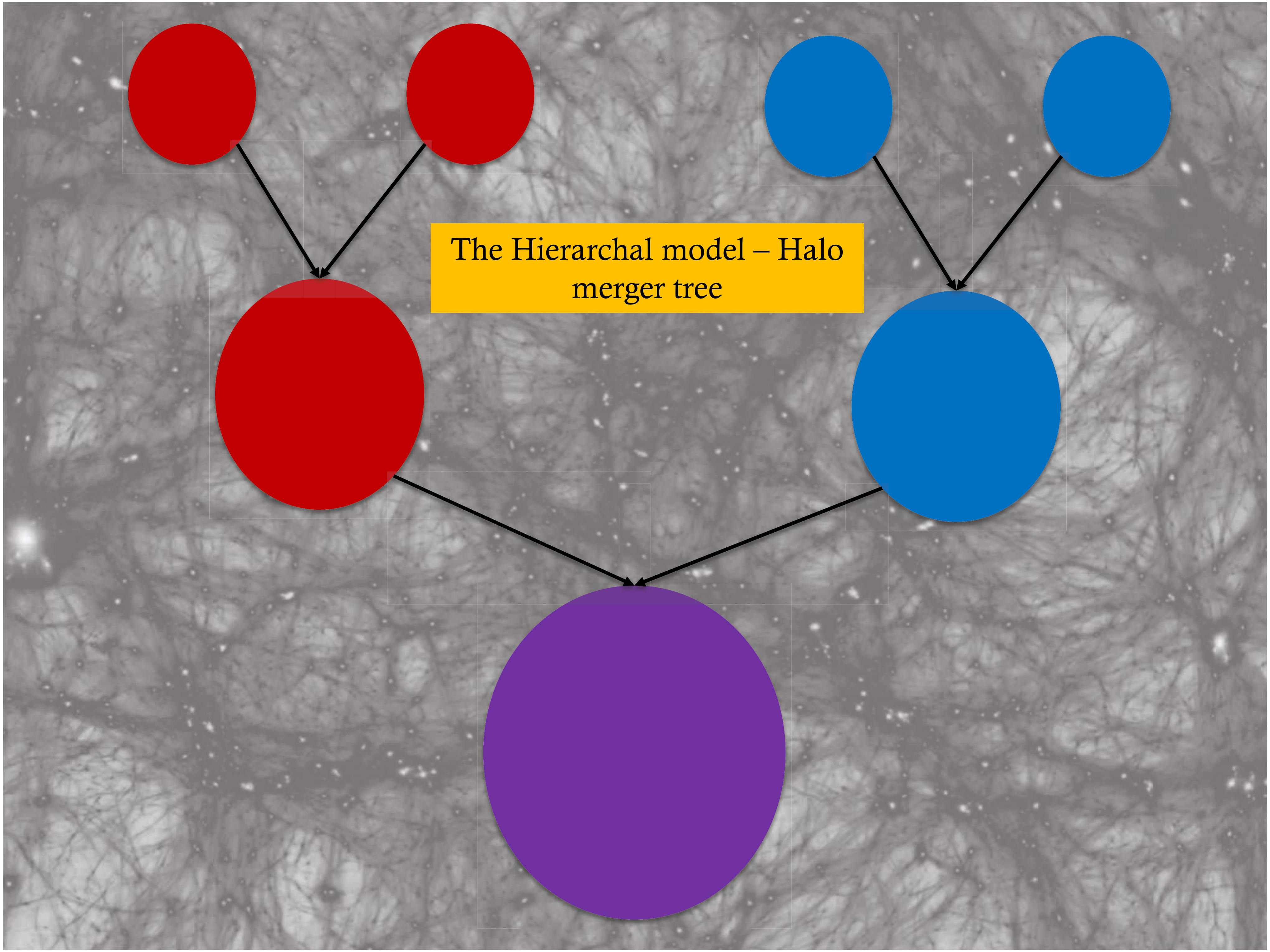
How do you turn the halo mass function into the galaxy luminosity function?

The central questions of cosmology:



N- body simulations allow us to trace the mass accretion history for each object.




The Hierarchal model – Halo merger tree

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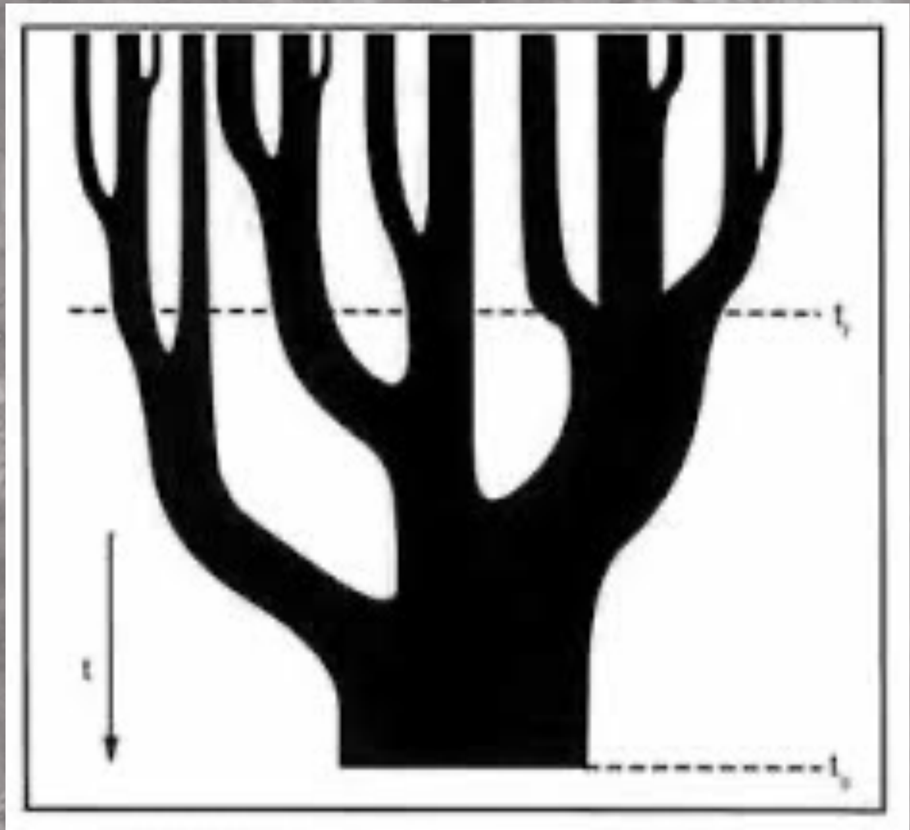
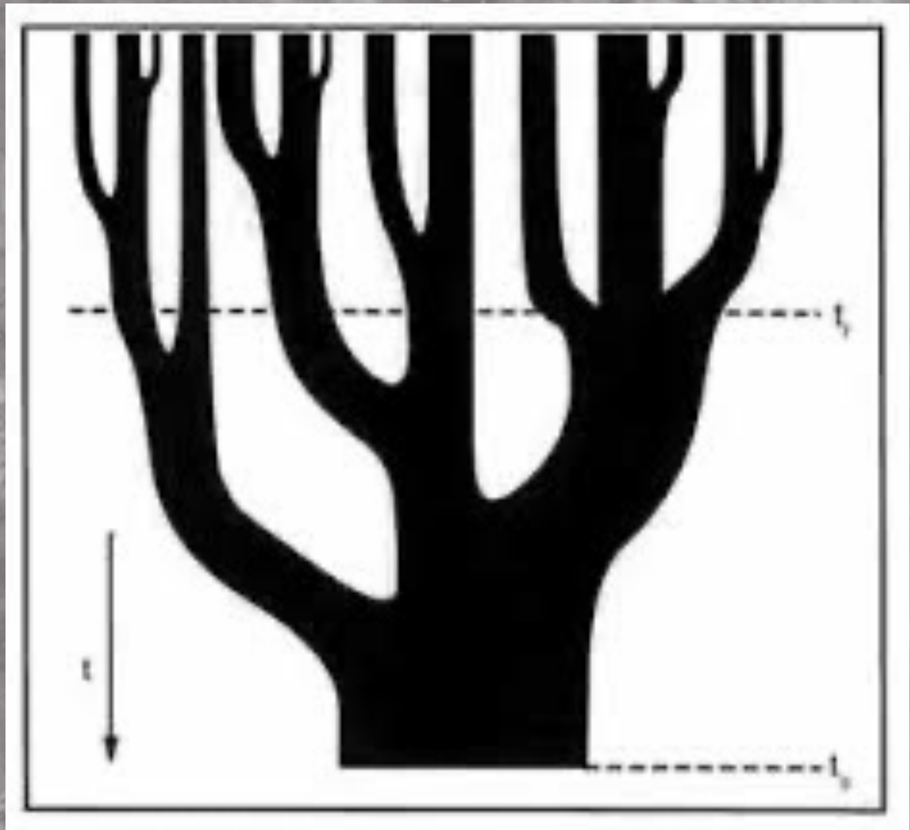


Cole et al 200

LCDM is a model of mergers

The Hierarchal model – Halo merger tree



LCDM is a model of mergers

First small things form ("dwarfs") which then merge to create larger and larger objects ("clusters")

Cole et al 200

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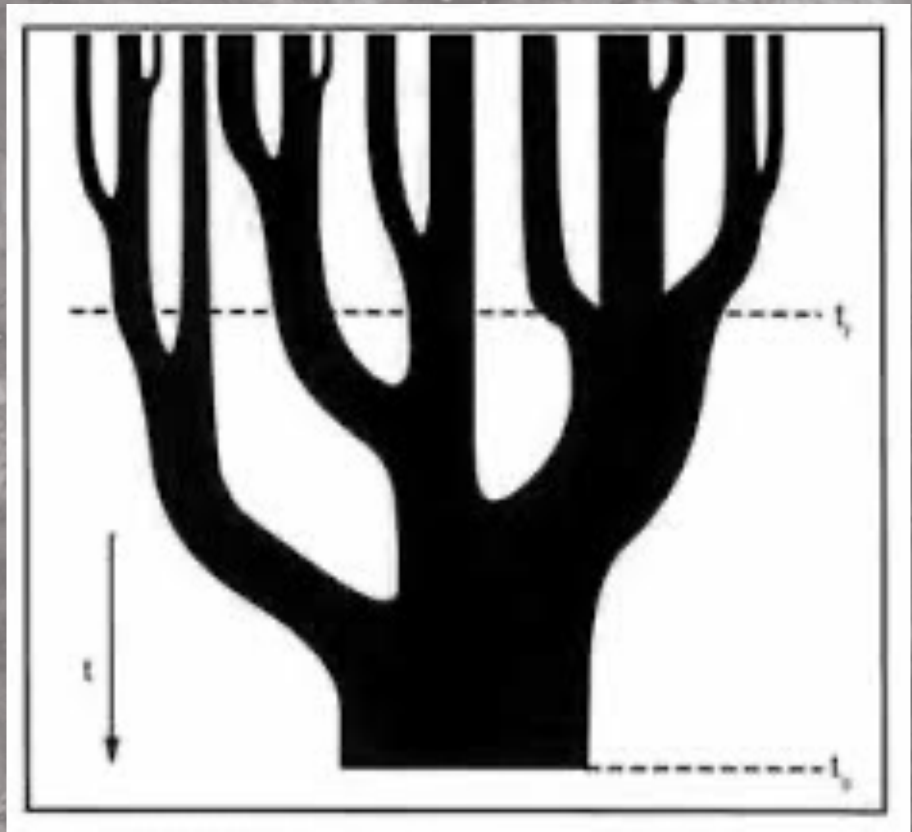


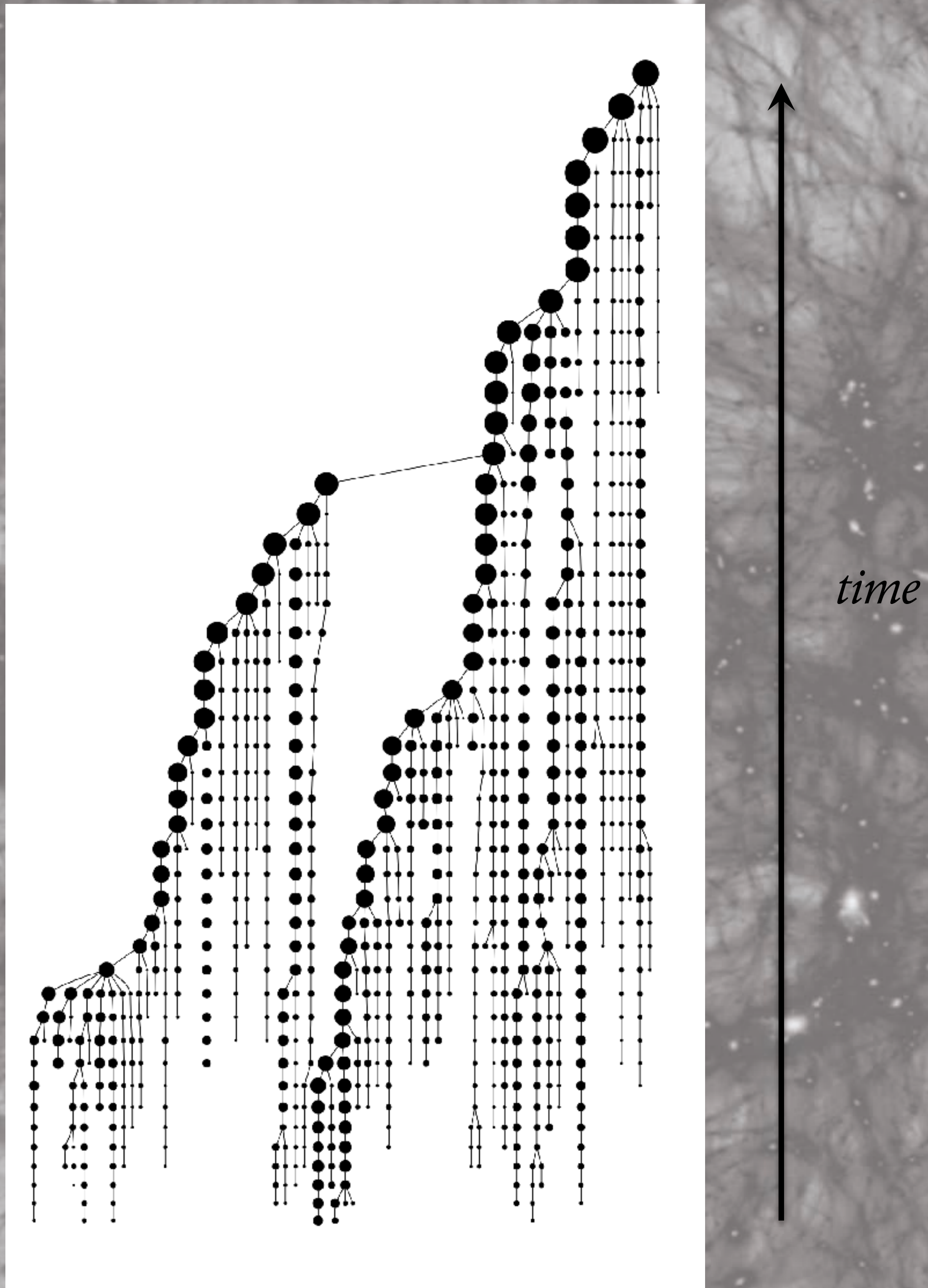
Cole et al 200

LCDM is a model of mergers

First small things form ("dwarfs") which then merge to create larger and larger objects ("clusters")

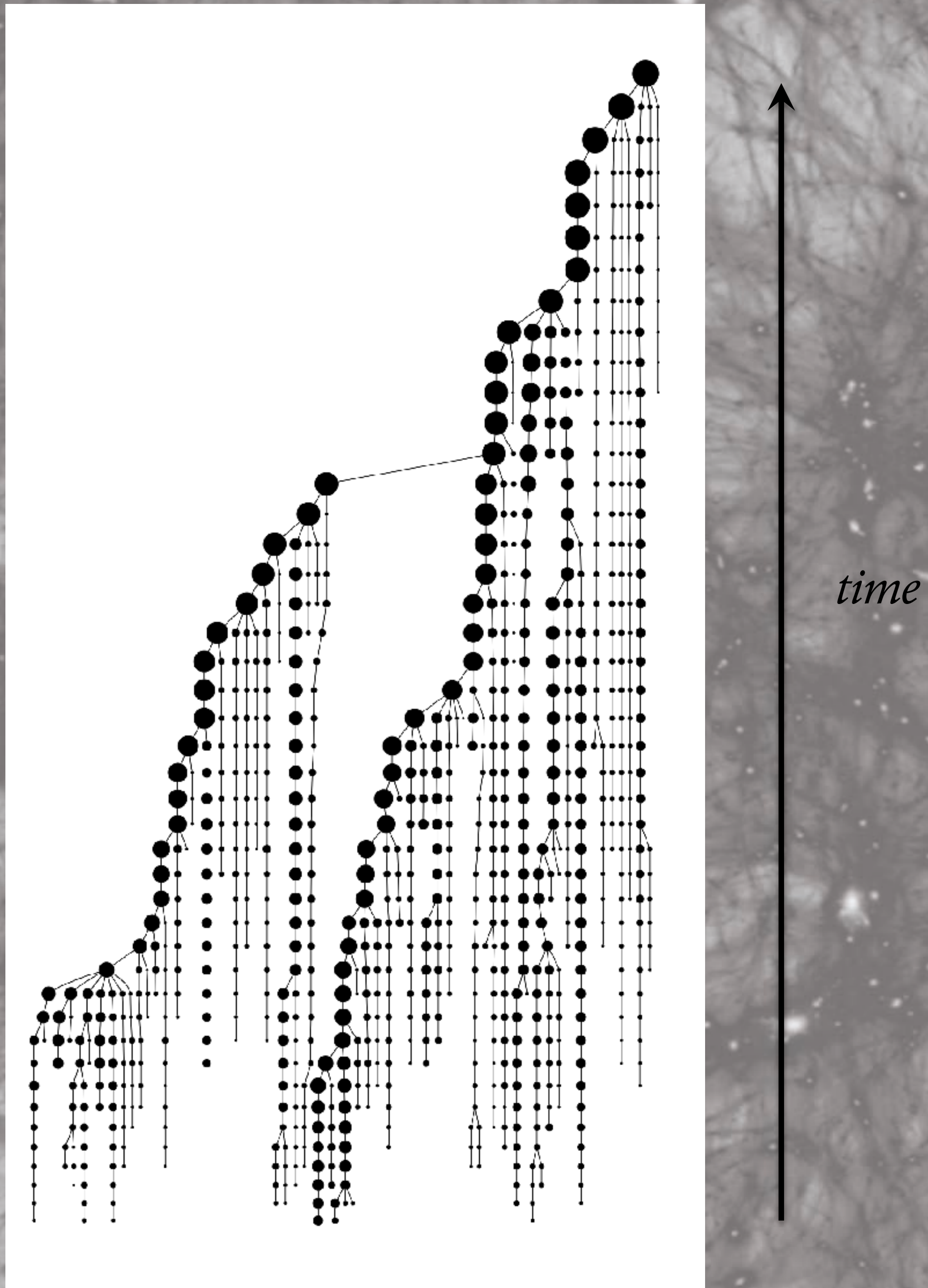
Clusters are dynamically "young". (Yet they typically have the reddest deadest galaxies – cosmic downsizing)

The Hierarchal model – Halo merger tree



Lacey & Cole 1993 described this analytically

The Hierarchal model – Halo merger tree

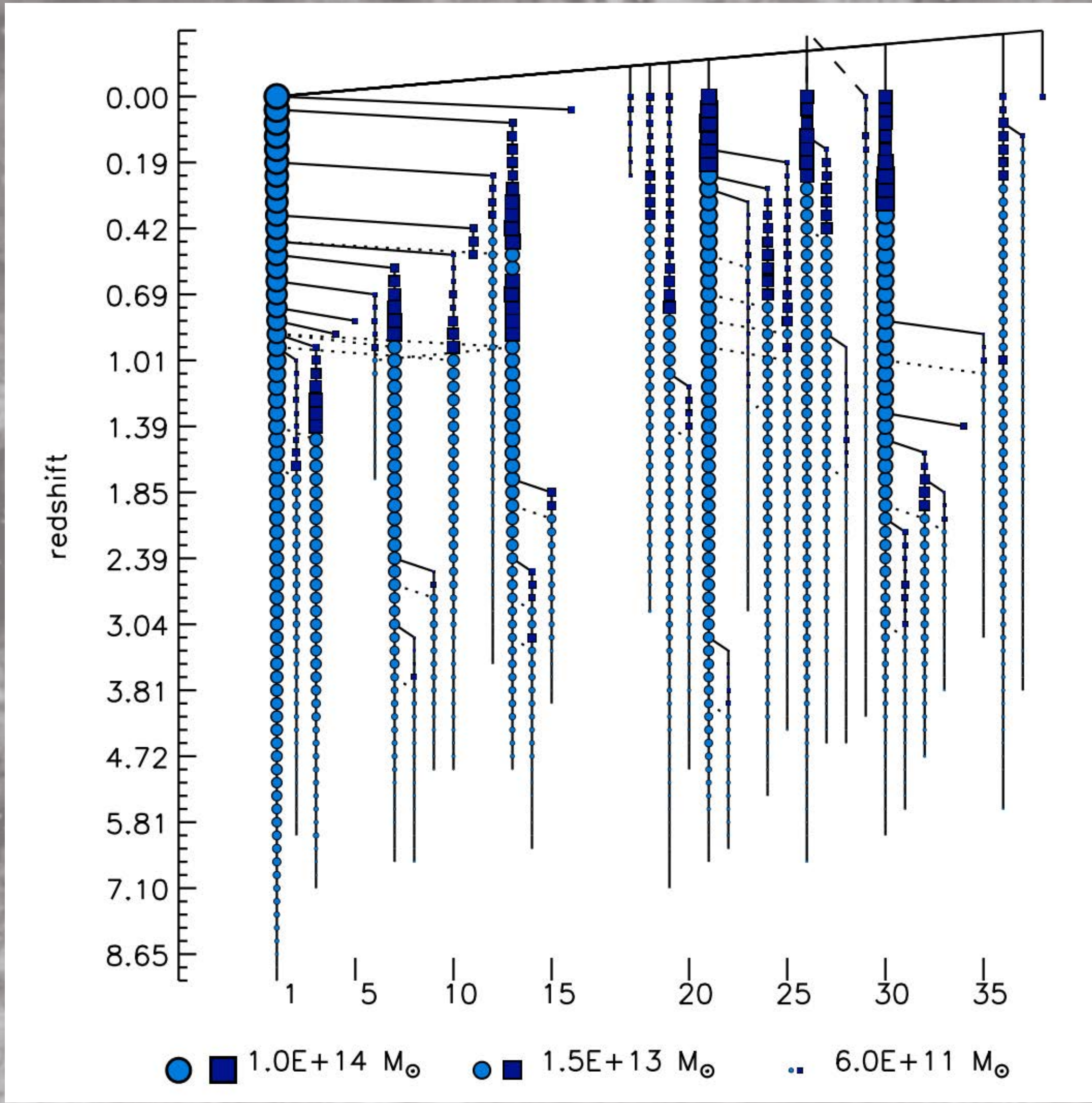


Lacey & Cole 1993 described this analytically

$$
\begin{aligned}
\frac{\mathrm{d}^2 p}{\mathrm{d}\ln \Delta M\,\mathrm{d}t}(M_1 \to M_2|t)
&= 2\sigma(M_2)\left|\frac{\mathrm{d}\sigma_2}{\mathrm{d}M_2}\right| \Delta M \left|\frac{\mathrm{d}\omega}{\mathrm{d}t}\right| \frac{\mathrm{d}^2 p}{\mathrm{d}S_2\,\mathrm{d}\omega}(S_1 \to S_2|\omega) \qquad (2.18)\\
&= \left(\frac{2}{\pi}\right)^{1/2} \frac{1}{t}\left|\frac{\mathrm{d}\ln\delta_c}{\mathrm{d}\ln t}\right| \left(\frac{\Delta M}{M_2}\right) \times \left|\frac{\mathrm{d}\ln\sigma_2}{\mathrm{d}\ln M_2}\right| \frac{\delta_c(t)}{\sigma_2}\,\frac{1}{(1-\sigma_2^2/\sigma_1^2)^{3/2}}\\
&\quad \times \exp\left[-\frac{\delta_c(t)^2}{2}\left(\frac{1}{\sigma_2^2}-\frac{1}{\sigma_1^2}\right)\right],
\end{aligned}
$$

Depends on the power spectrum of perturbations (of course!) the matter content (Omega), the scale …

The Hierarchal model – Halo merger tree



We can extract the halo merger trees from the simulations by linking haloes at one snap shot (via the identity of the particles in it) to its "progenitor" at earlier times

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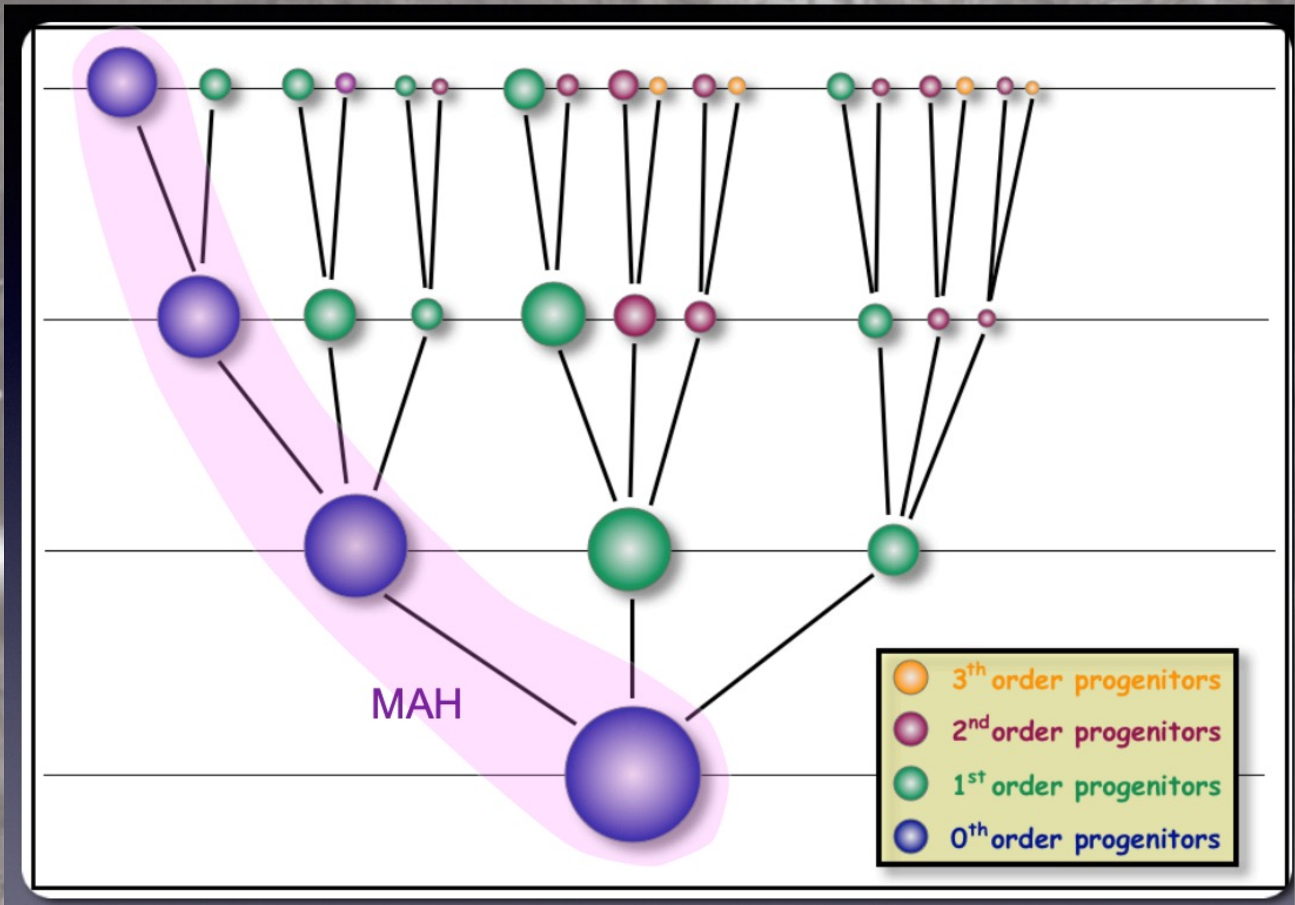

We can extract the halo merger trees from the simulations by linking haloes at one snap shot (via the identity of the particles in it) to its "progenitor" at earlier times

The mass accretion history of a halo is the 0th order progenitor

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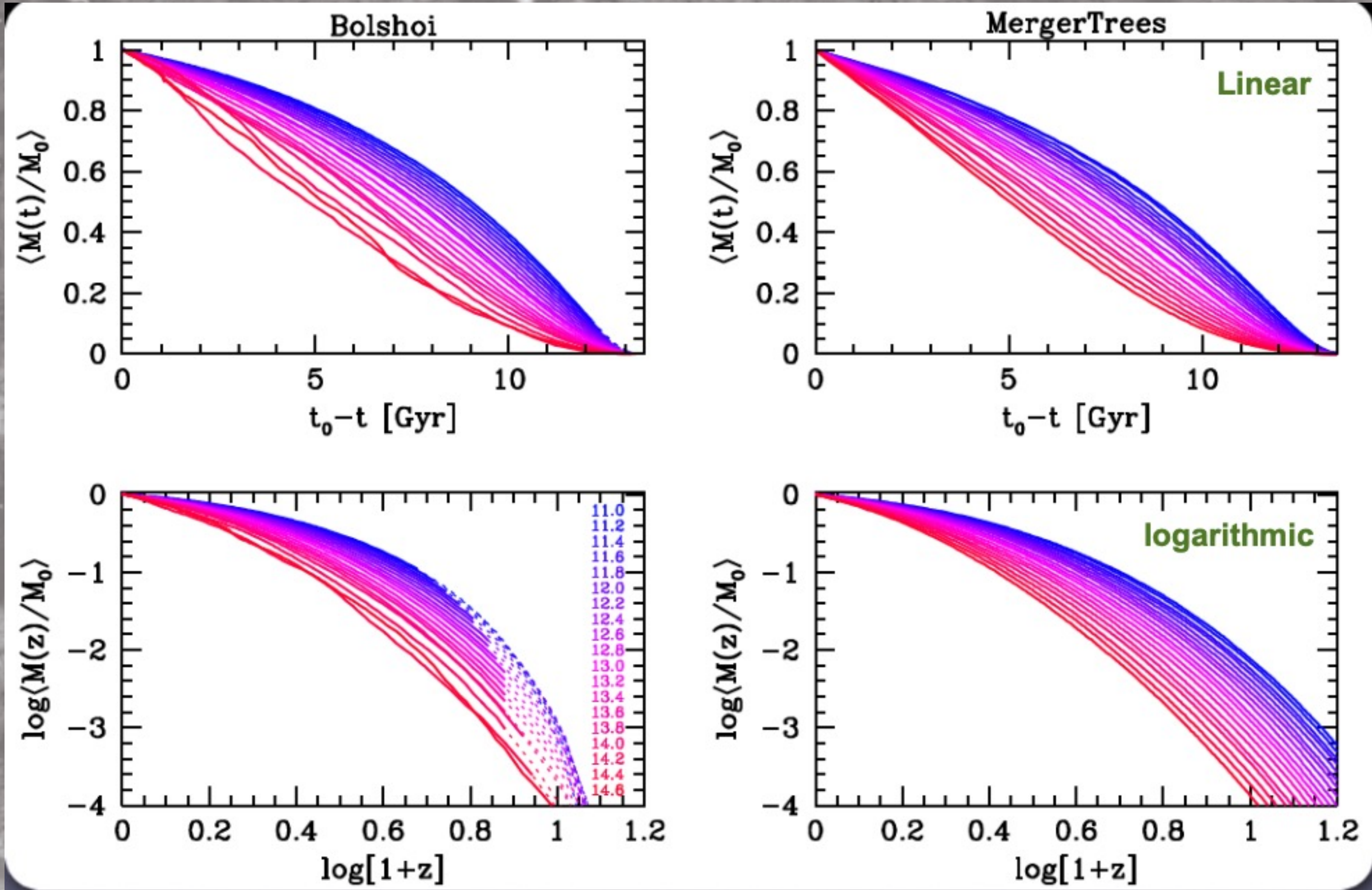
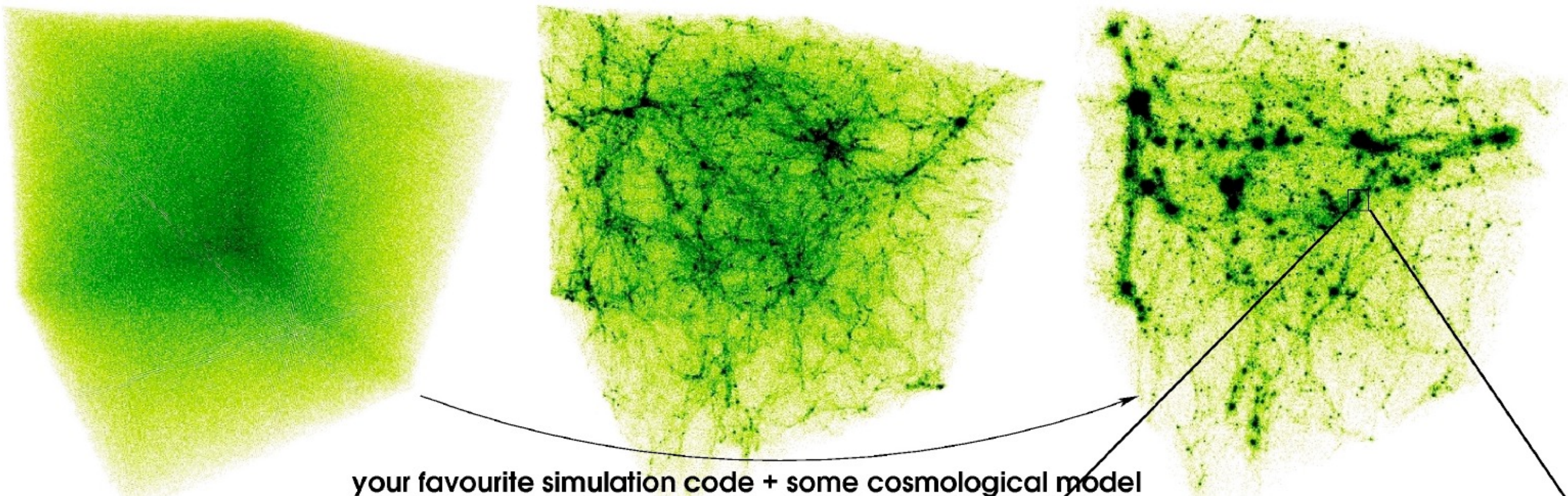


Hierarchical growth – big things form later

Semi-analytical modelling

Assuming a cosmology (power spectrum + parameters), we know “everything” namely the halo mass function (at any z) and the merger history.

We can “paint” the galaxies into the haloes by making physically motivated assumptions about how gas behaves



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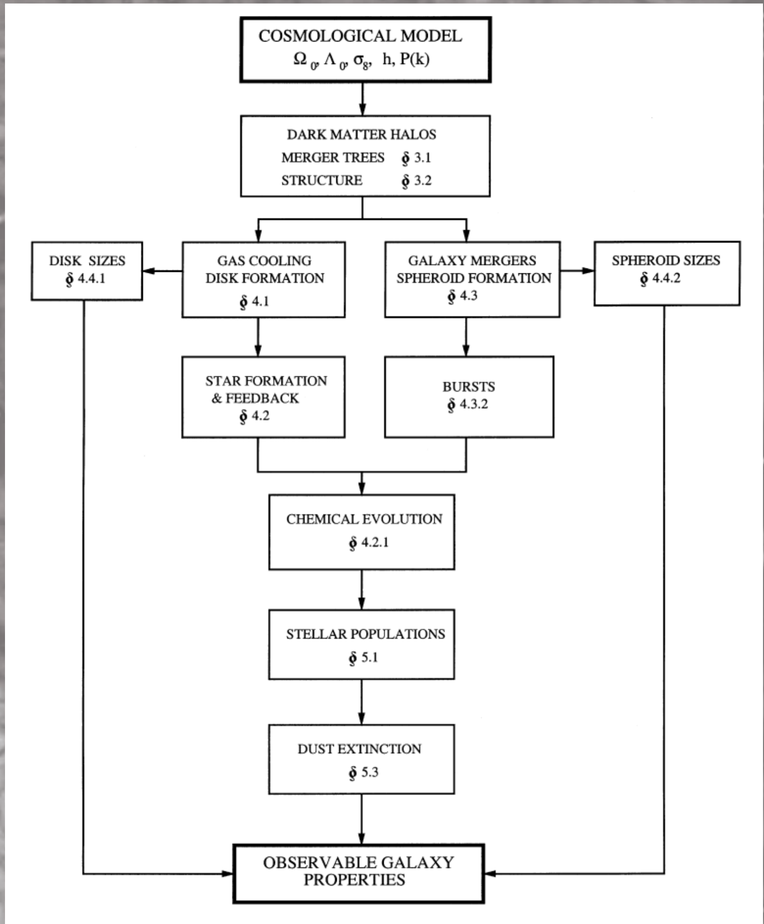

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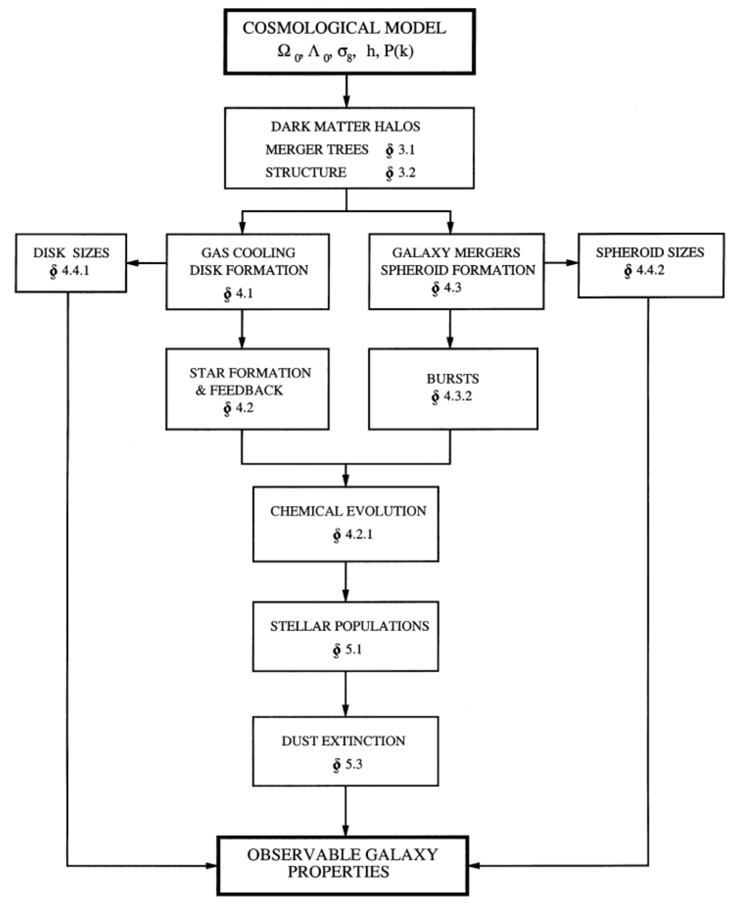

Fill your DM haloes with gas

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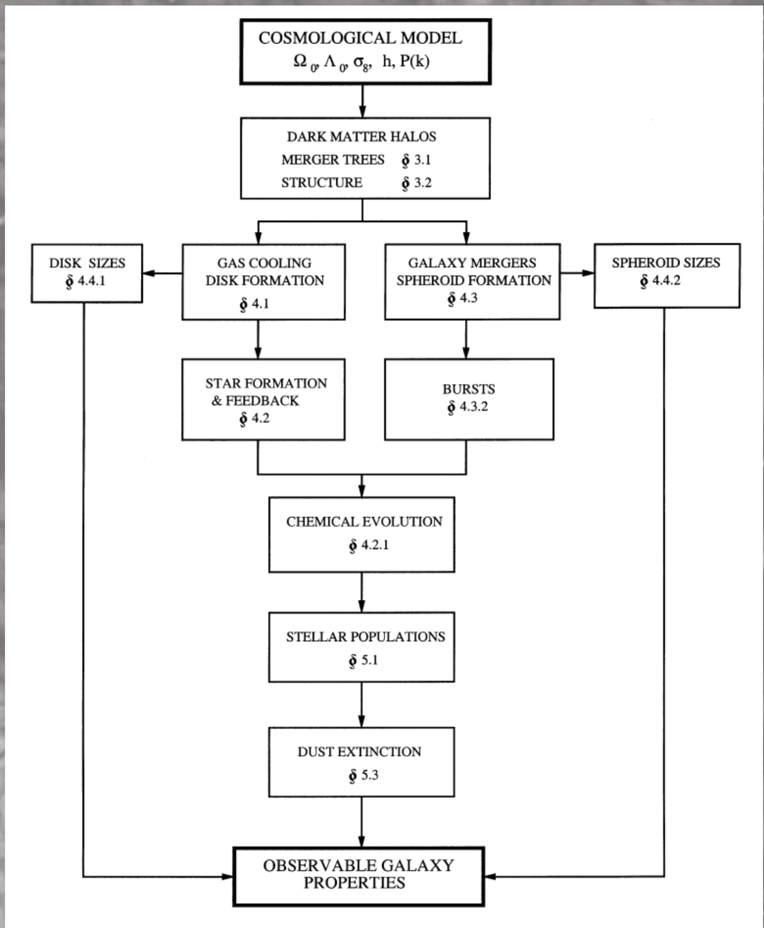

Fill your DM haloes with gas

Compute expected cooling and star formation rates

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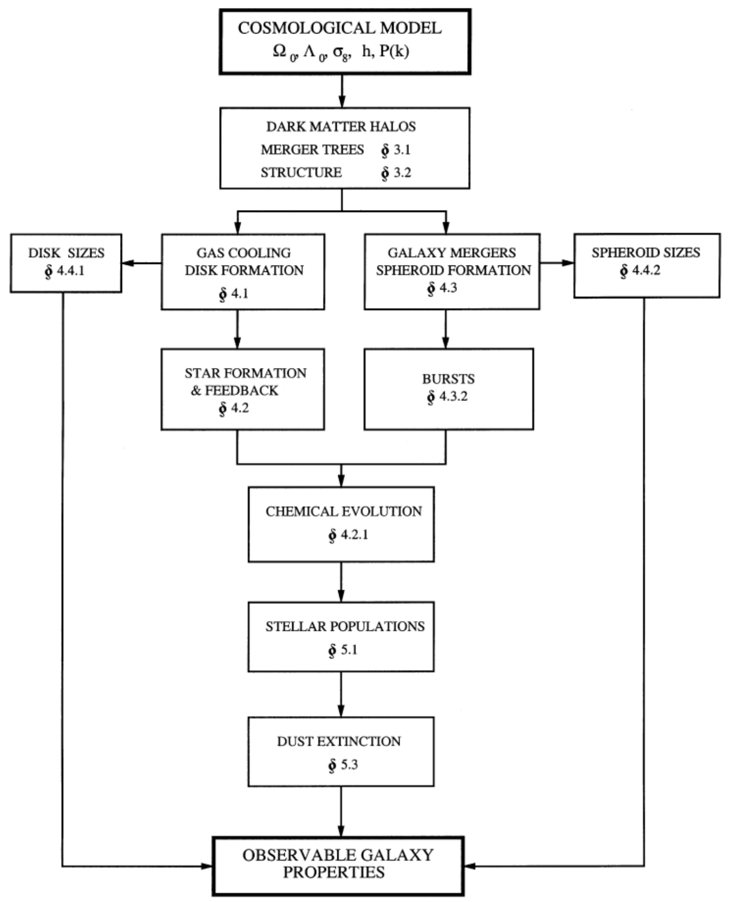

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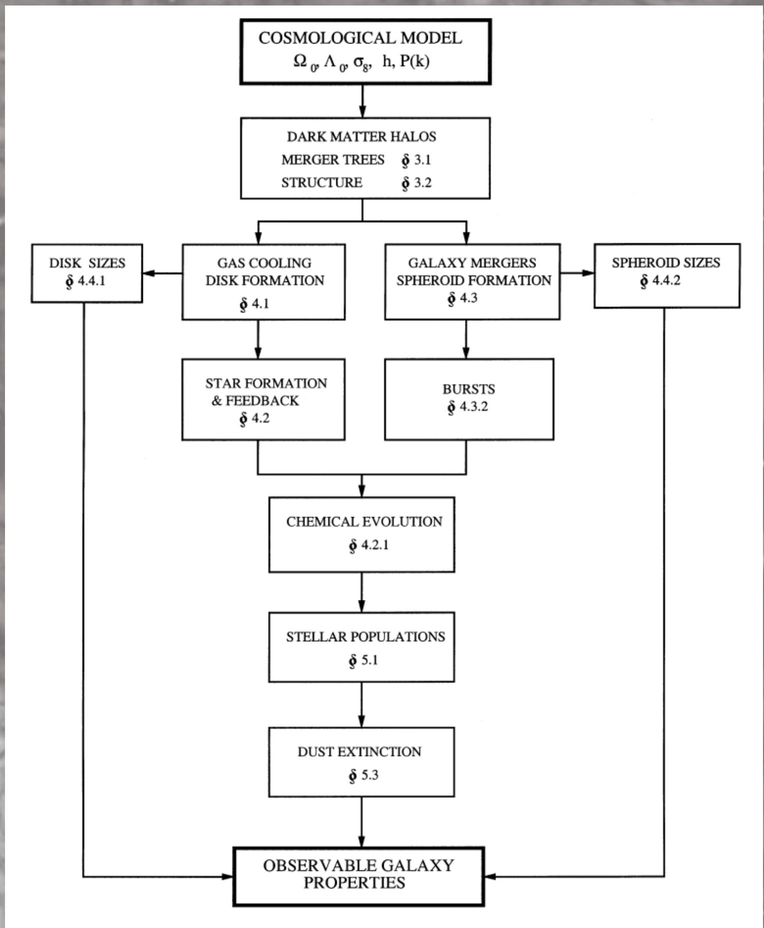

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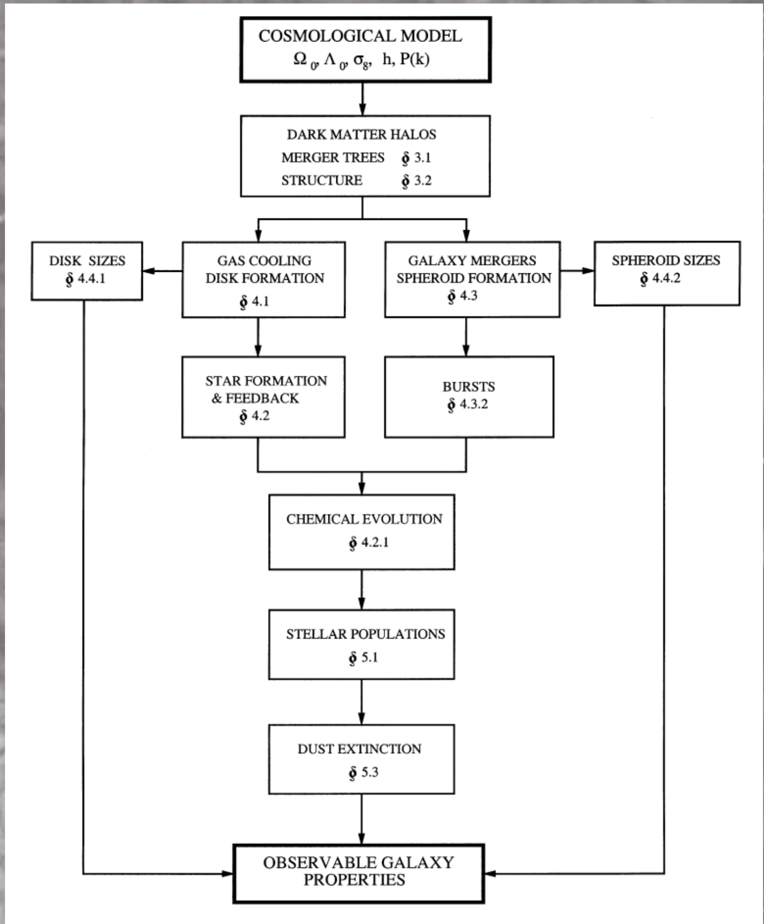

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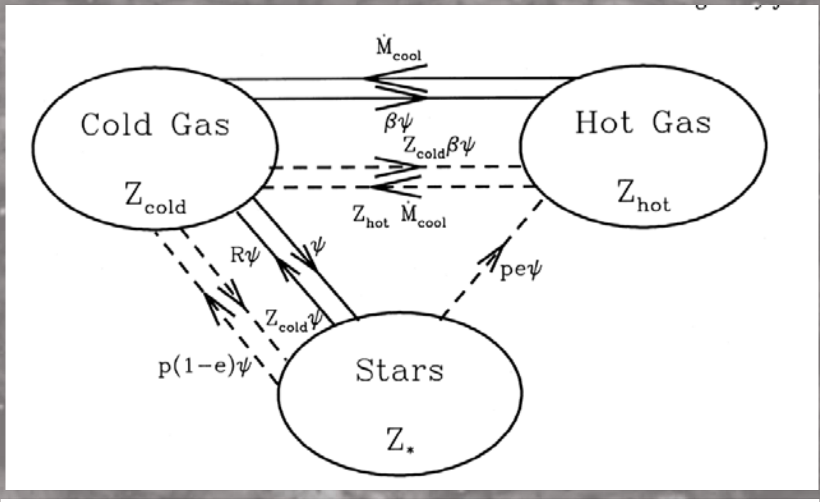

$$\dot{M}_* = (1 - R)\psi \quad (4.6)$$

$$\dot{M}_{hot} = -\dot{M}_{cool} + \beta\psi \quad (4.7)$$

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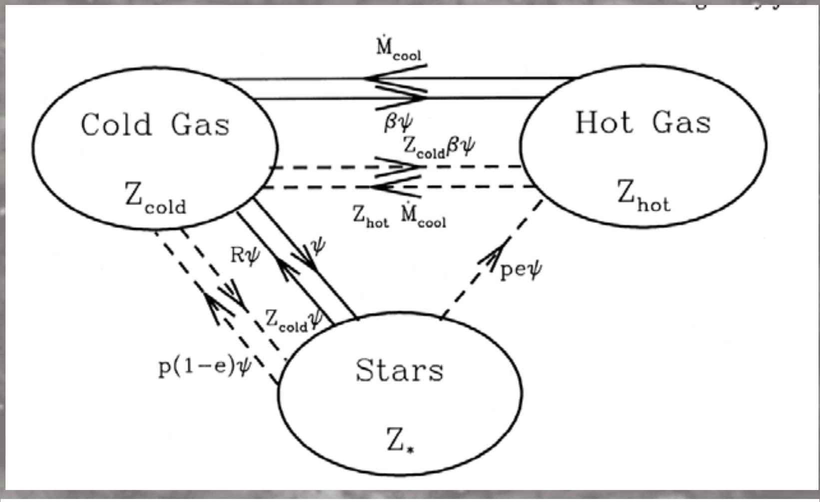

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R- recycled fraction
ψ – instantaneous SFR
M' – cooling rate
Z – metallicity
β, e – Feedback efficiency
p – yield

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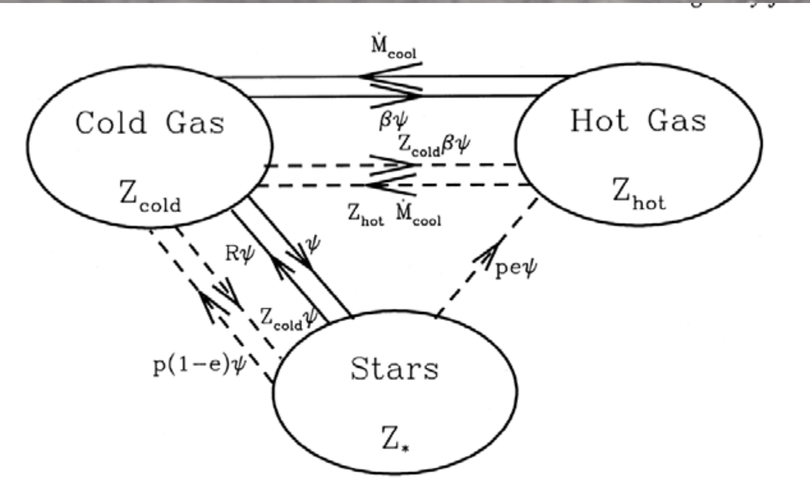

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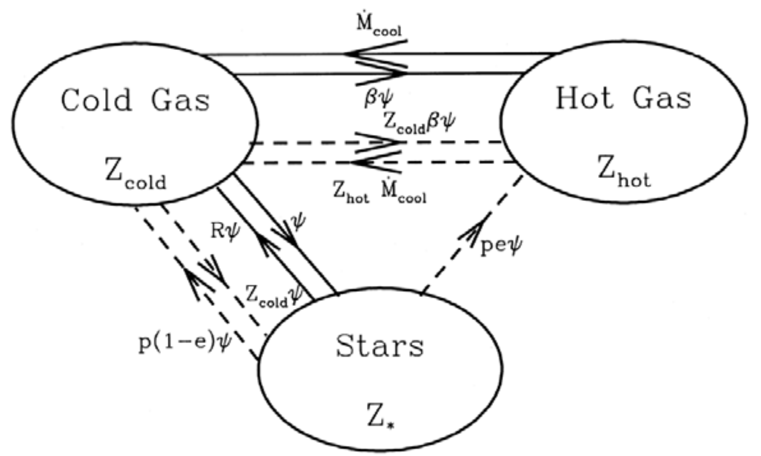

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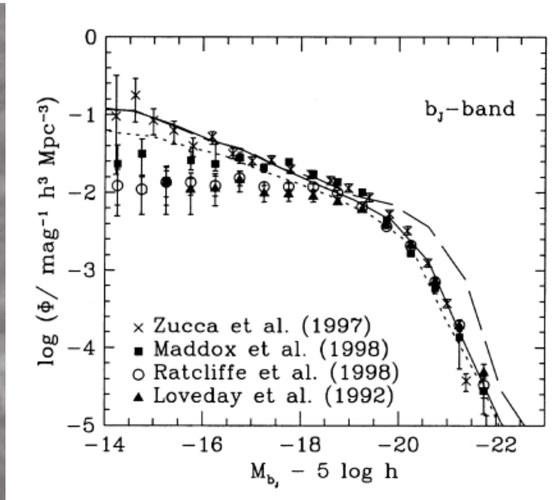

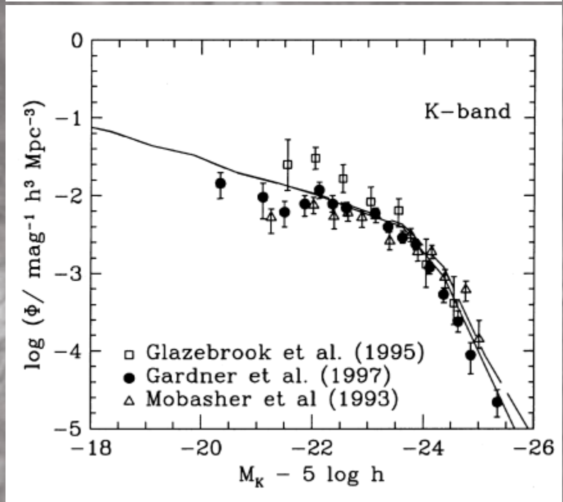

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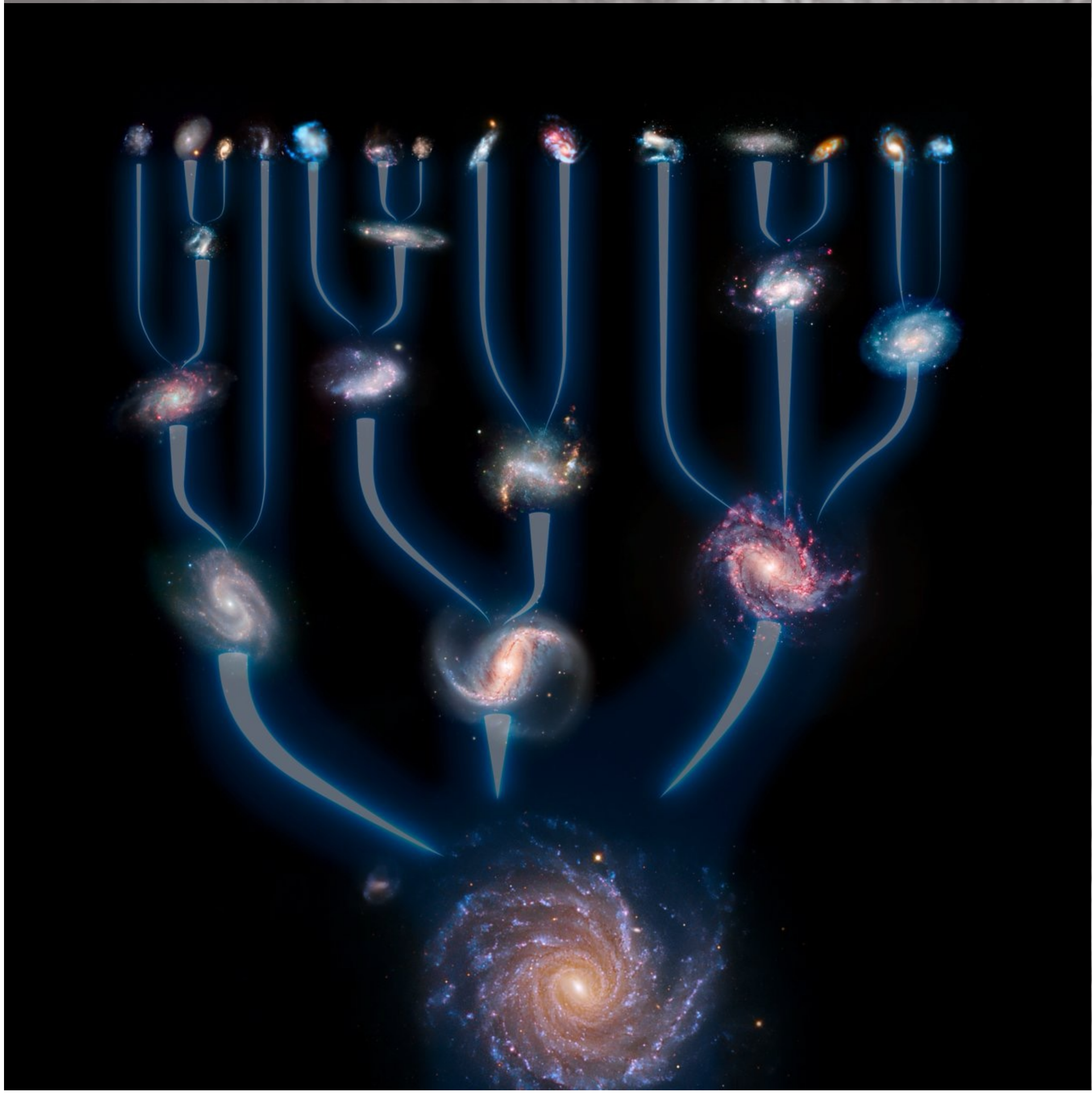
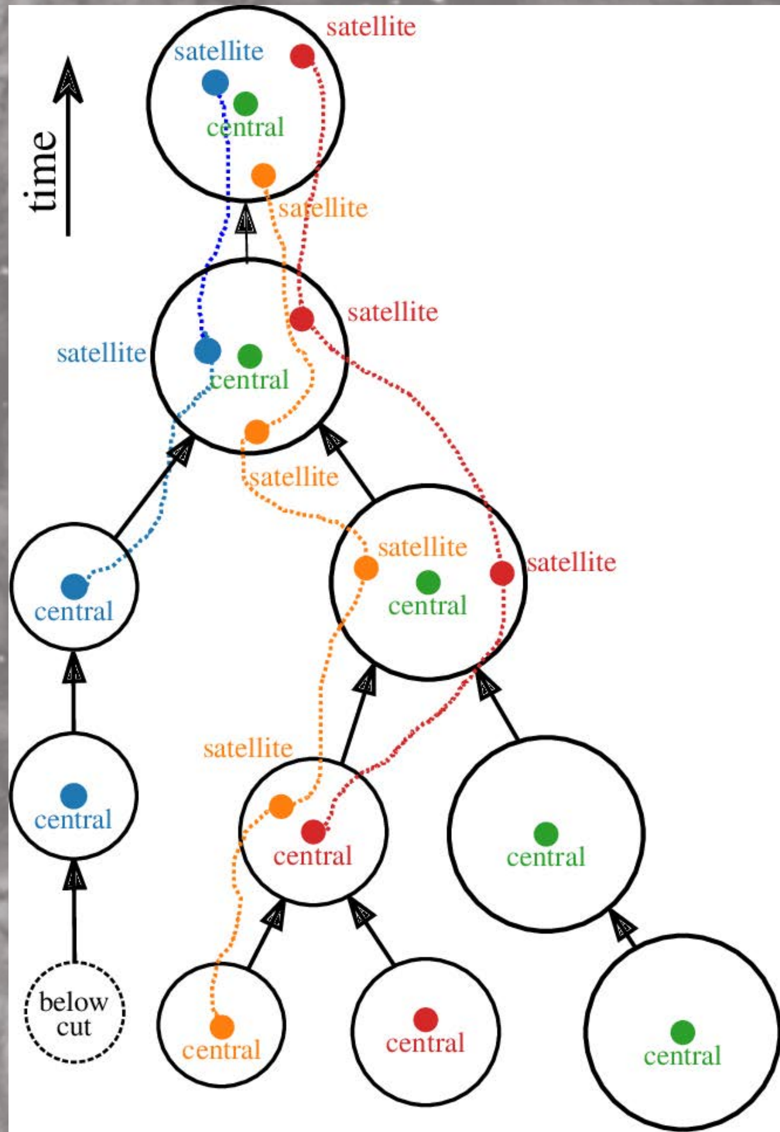
Semi-analytical modelling versus hydro



Allows all properties of the galaxy population at any given time to be computed

Semi-analytical modelling versus hydro

SAMs are powerful ways to test out ideas of galaxy formation – the IMF, cooling etc.



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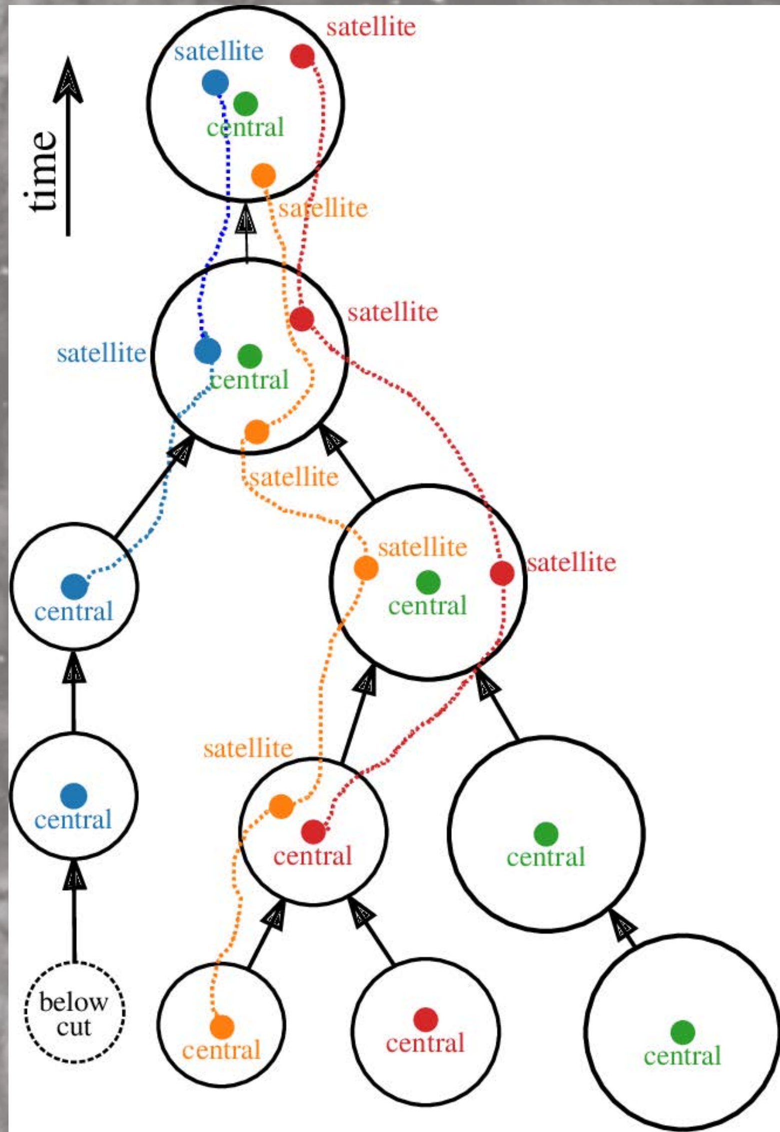
Yet they have huge numbers of parameter that need to be "fine tuned" and which are not necessarily physical

+ resolution

+ time steps



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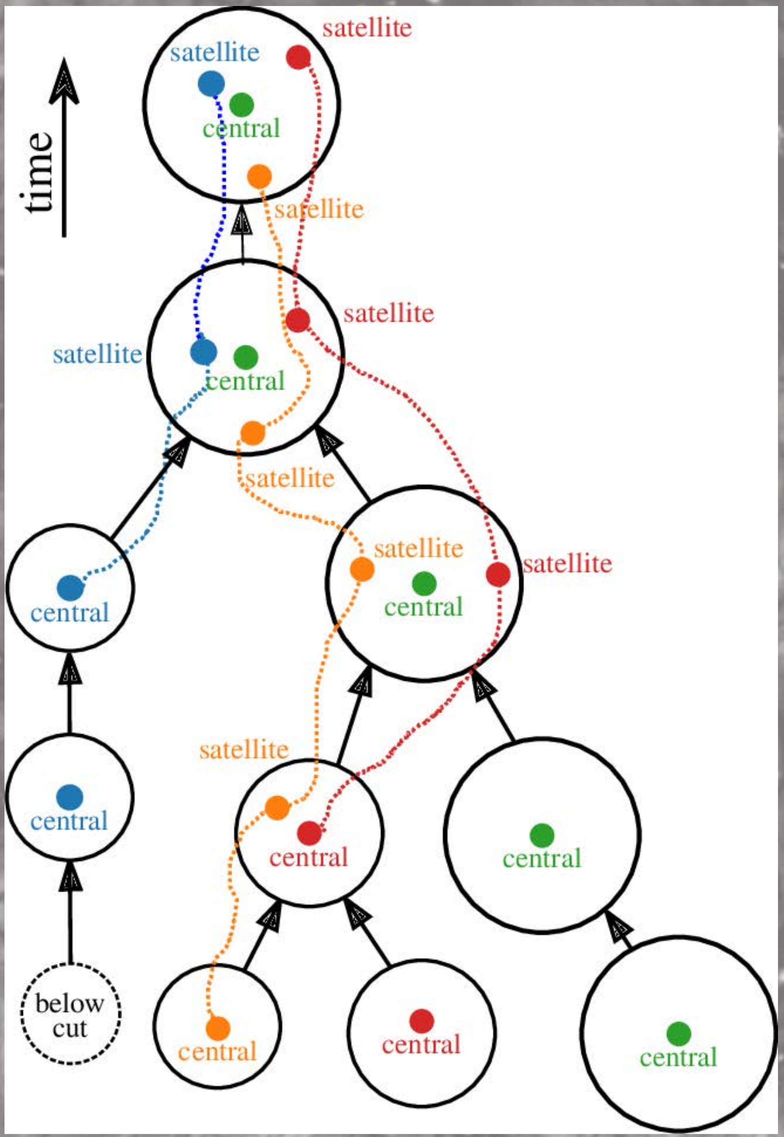

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+ time steps

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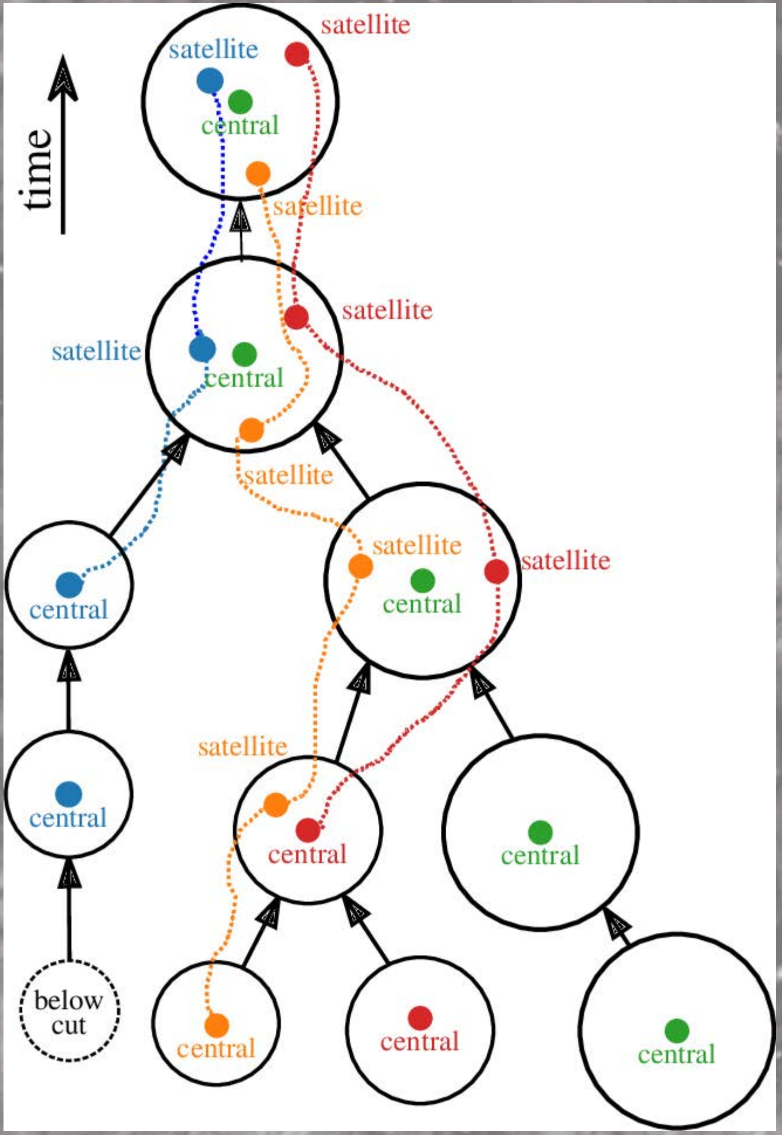
Cant say much of the IGM, or stripped material, or indeed anything outside of the halo



Hydrodynamical simulations

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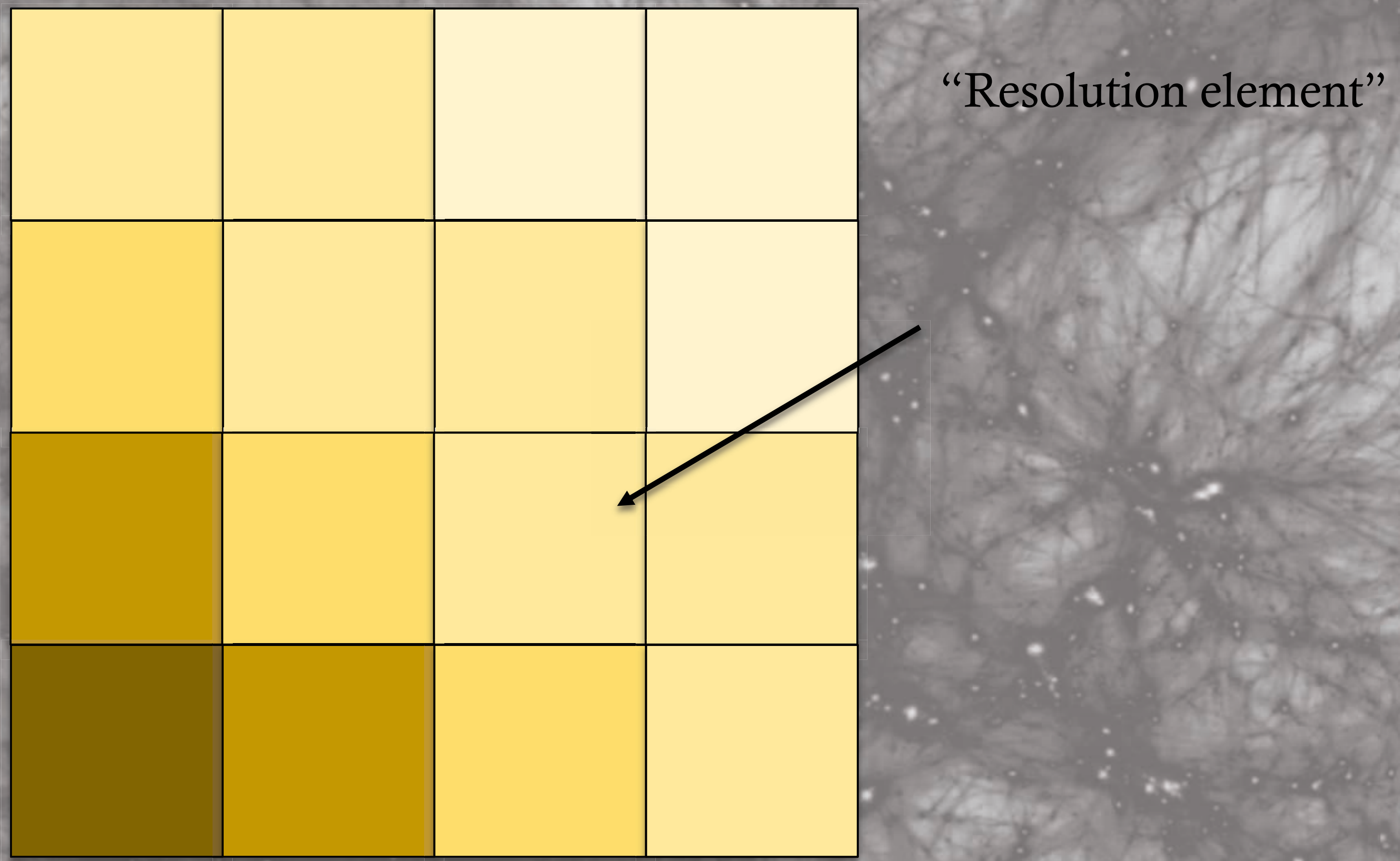

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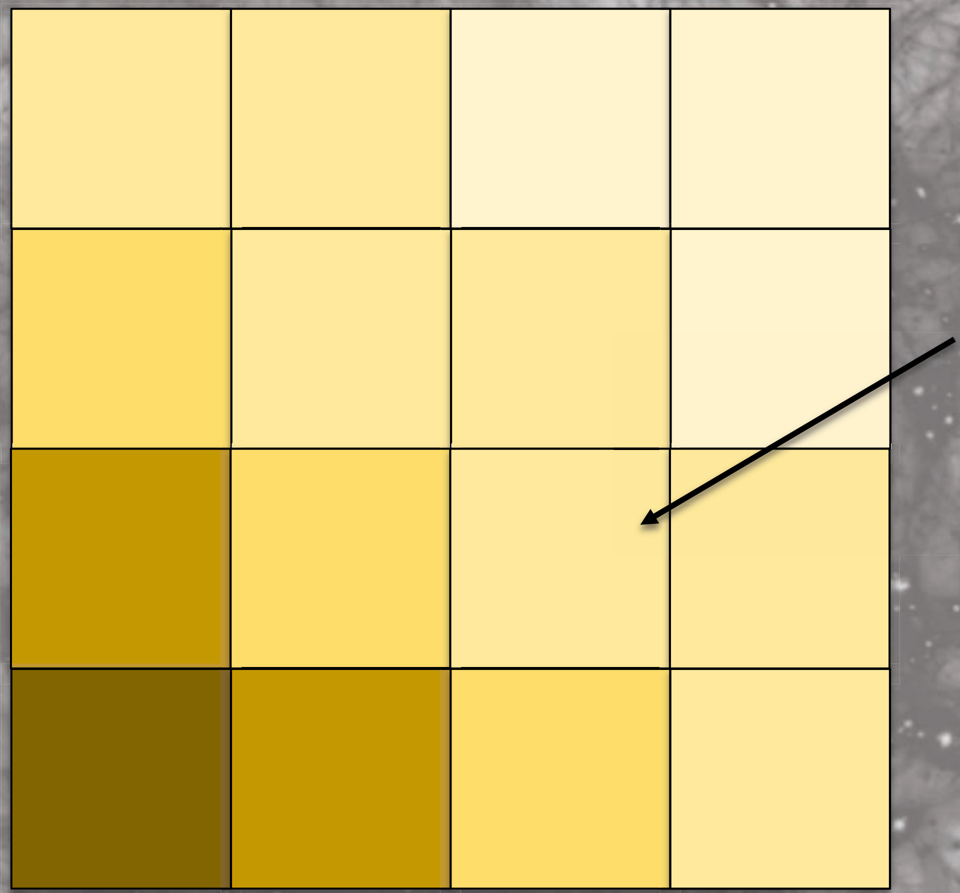

"Resolution element"

- Mass, density (dM/dt, dρ/dt)
- Temperature (heating/cooling)
- Pressure (dP/dt)
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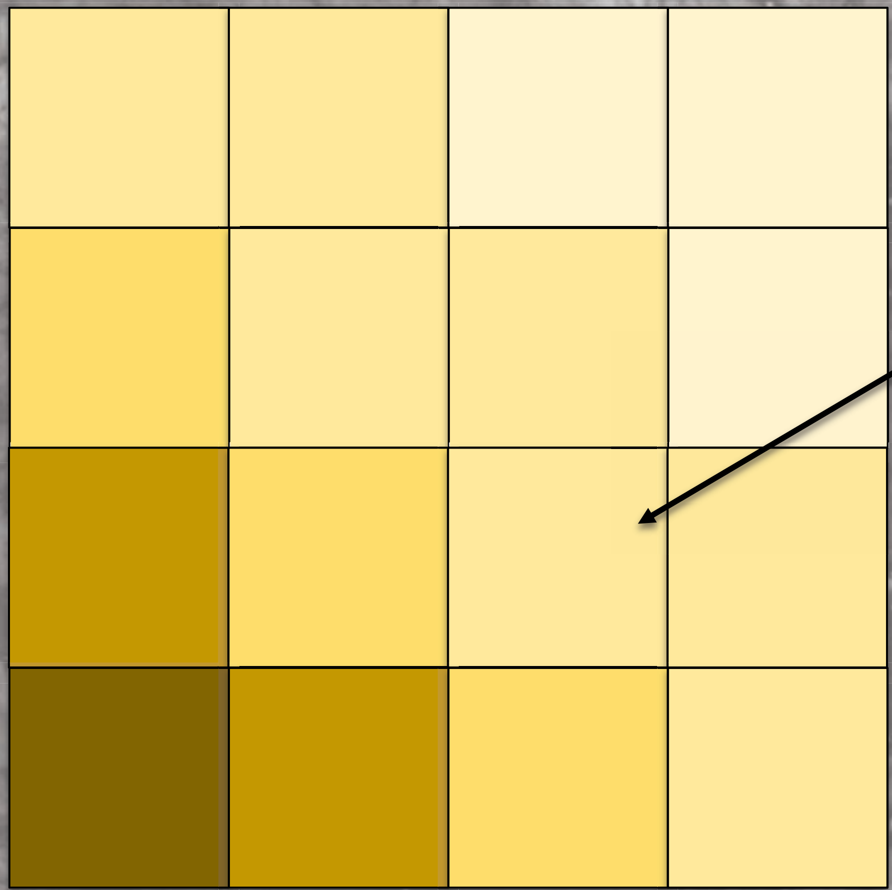

"Resolution element"

- Mass, density (dM/dt, dρ/dt)
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- governing equations (non-relativistic fluid with pressure)
  - Poisson's equation

$$\Delta\Psi = 4\pi G\rho$$

  - continuity equation

$$\frac{\partial\rho}{\partial t} + \nabla\cdot(\rho\vec{v}) = 0$$

  - conservation of momentum

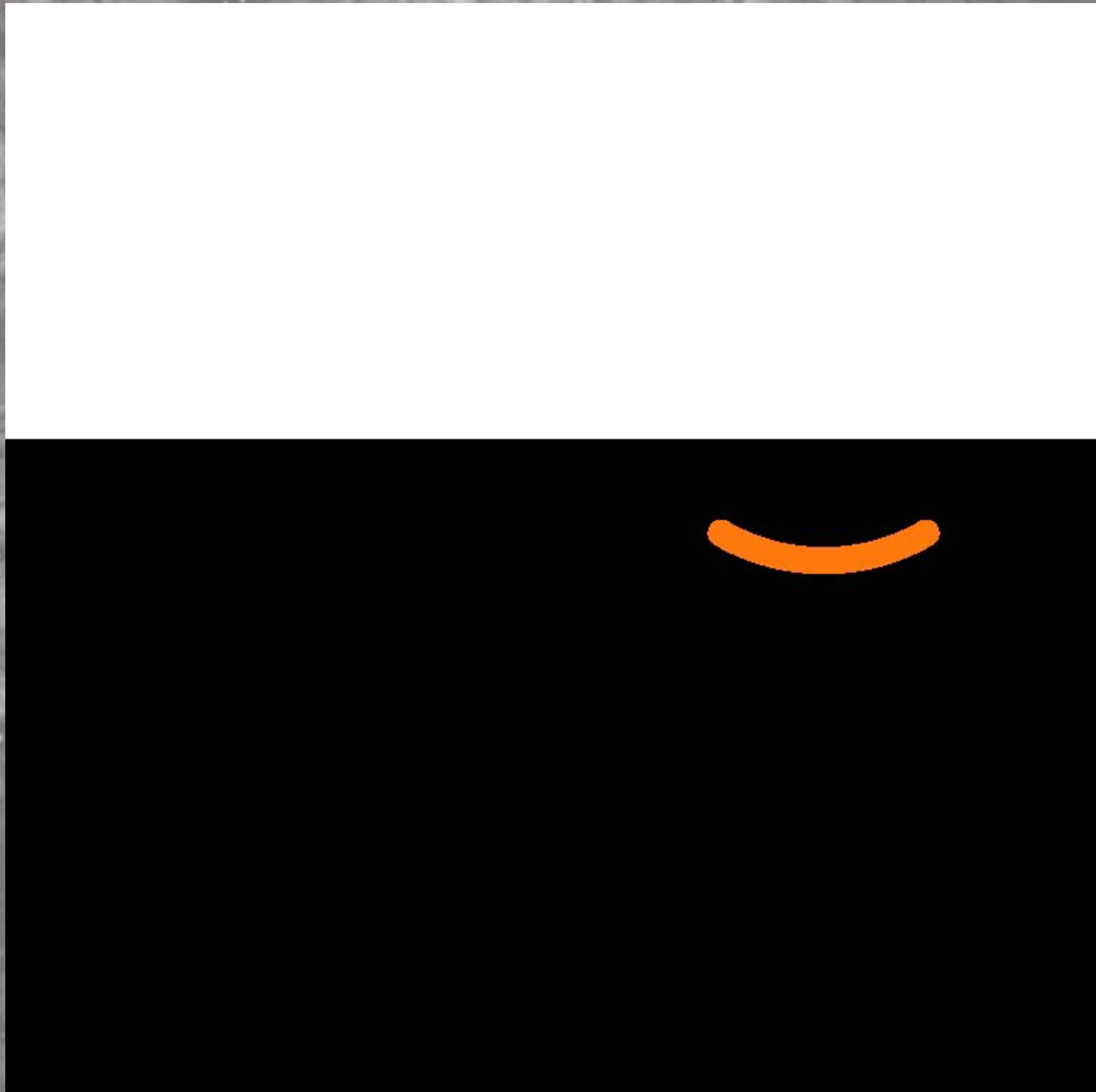
$$\frac{\partial\vec{v}}{\partial t} + (\vec{v}\cdot\nabla)\vec{v} = -\nabla\Psi - \frac{\nabla p}{\rho}$$

  - equation of state

$$p = c_s^2\rho$$

(c_s: sound speed)

Hydrodynamical simulations



The Kevin-Helmholtz instability

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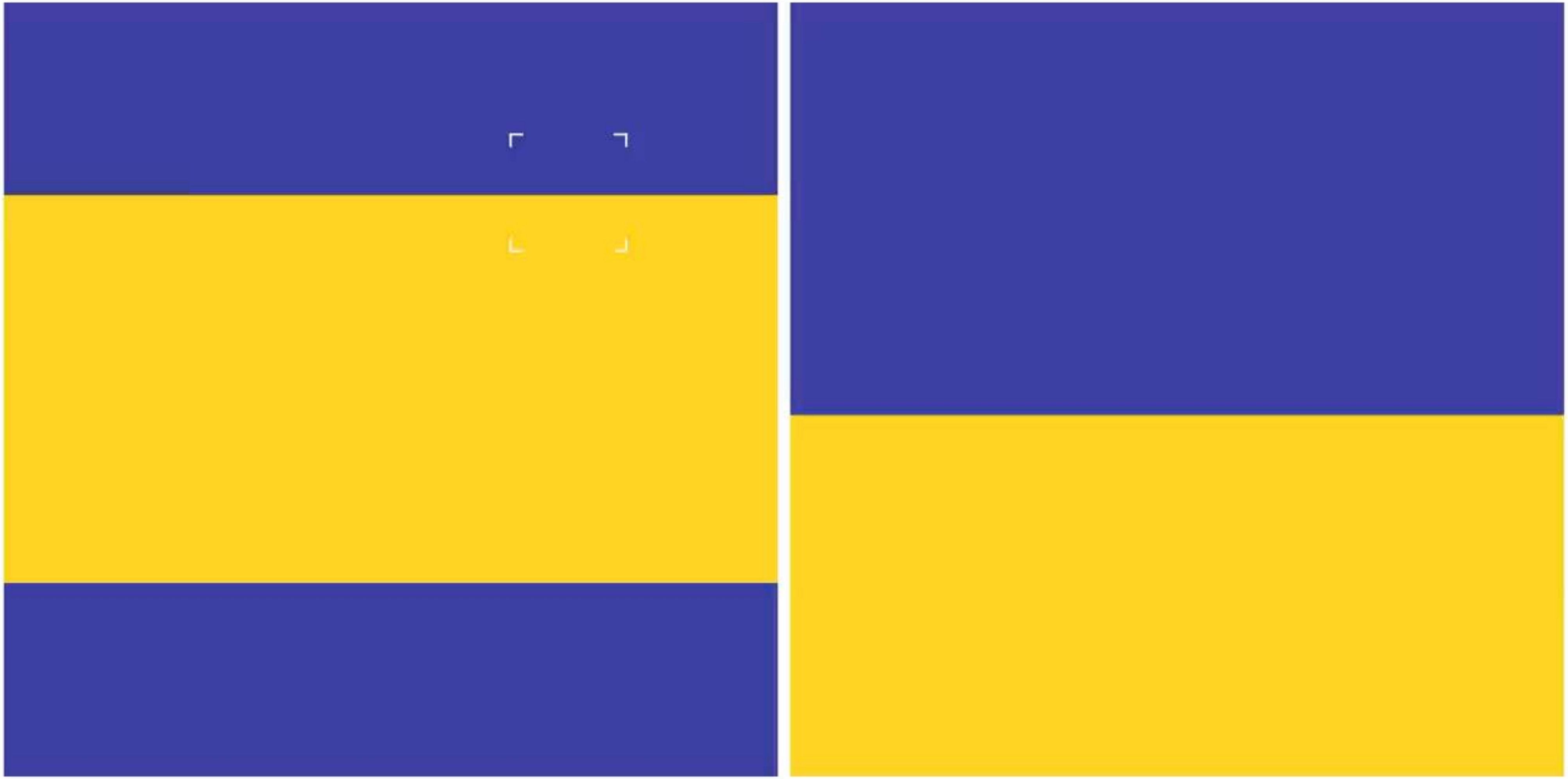

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Object	Scale (m)	Scale (Mpc)
Stars	10^{8}	10^{-14}
Black hole	10^{10}	10^{-12}
Solar system	10^{13}	10^{-9}
Interstellar distances	10^{16}	10^{-6}
Small galaxies	10^{20}	0.01
Milky Way halo	10^{21}	0.1
Local Group distances	10^{22}	1
Cluster	10^{23}	10
Large-scale structures	10^{24}	100

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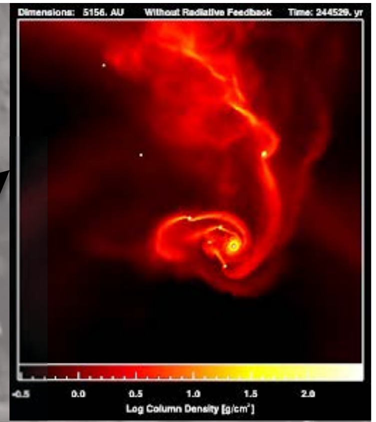
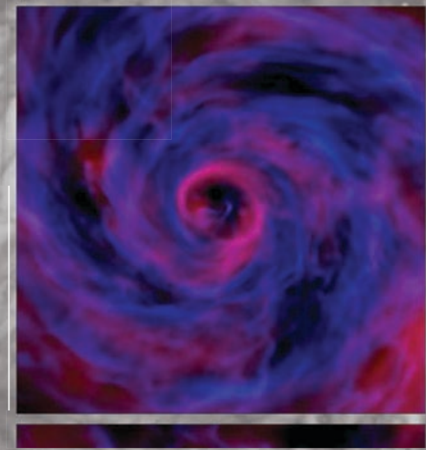
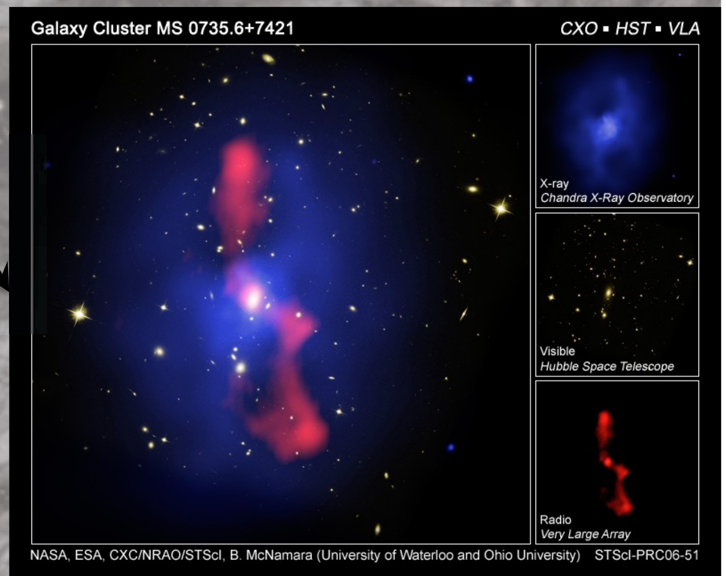


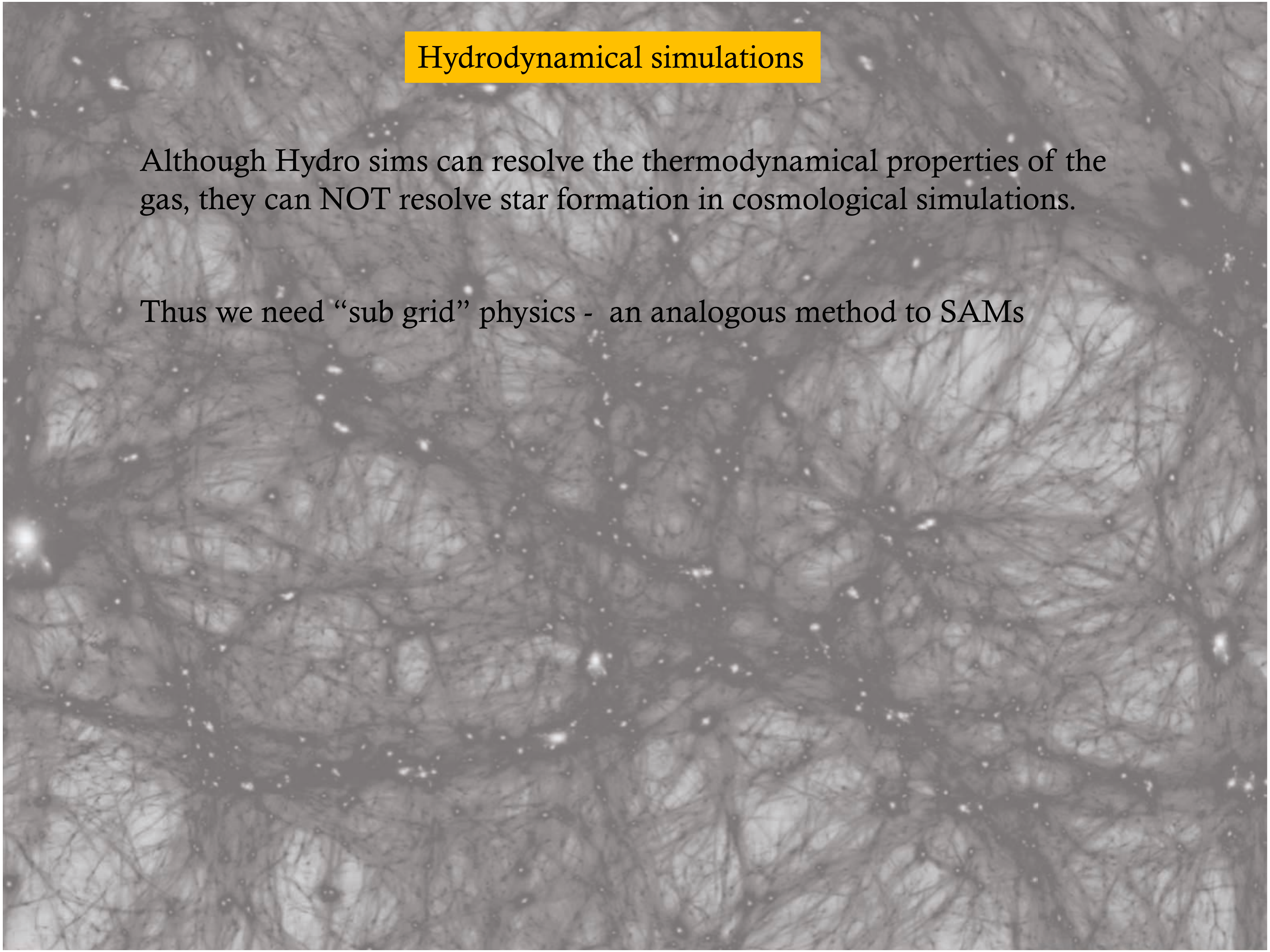




Hydrodynamical simulations

Although Hydro sims can resolve the thermodynamical properties of the gas, they can NOT resolve star formation in cosmological simulations.

Thus we need "sub grid" physics - an analogous method to SAMs



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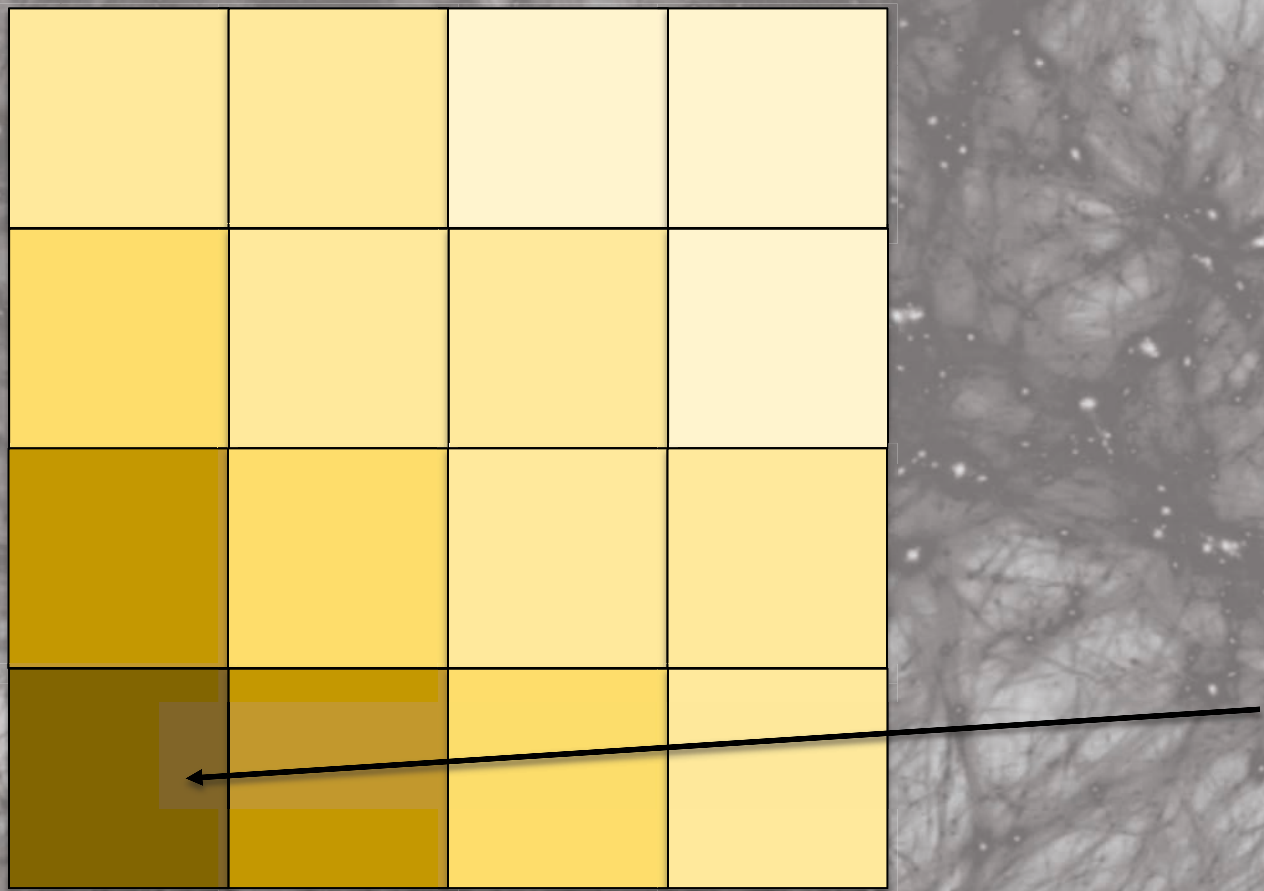

If certain thermodynamic conditions are met: form a star "by hand"

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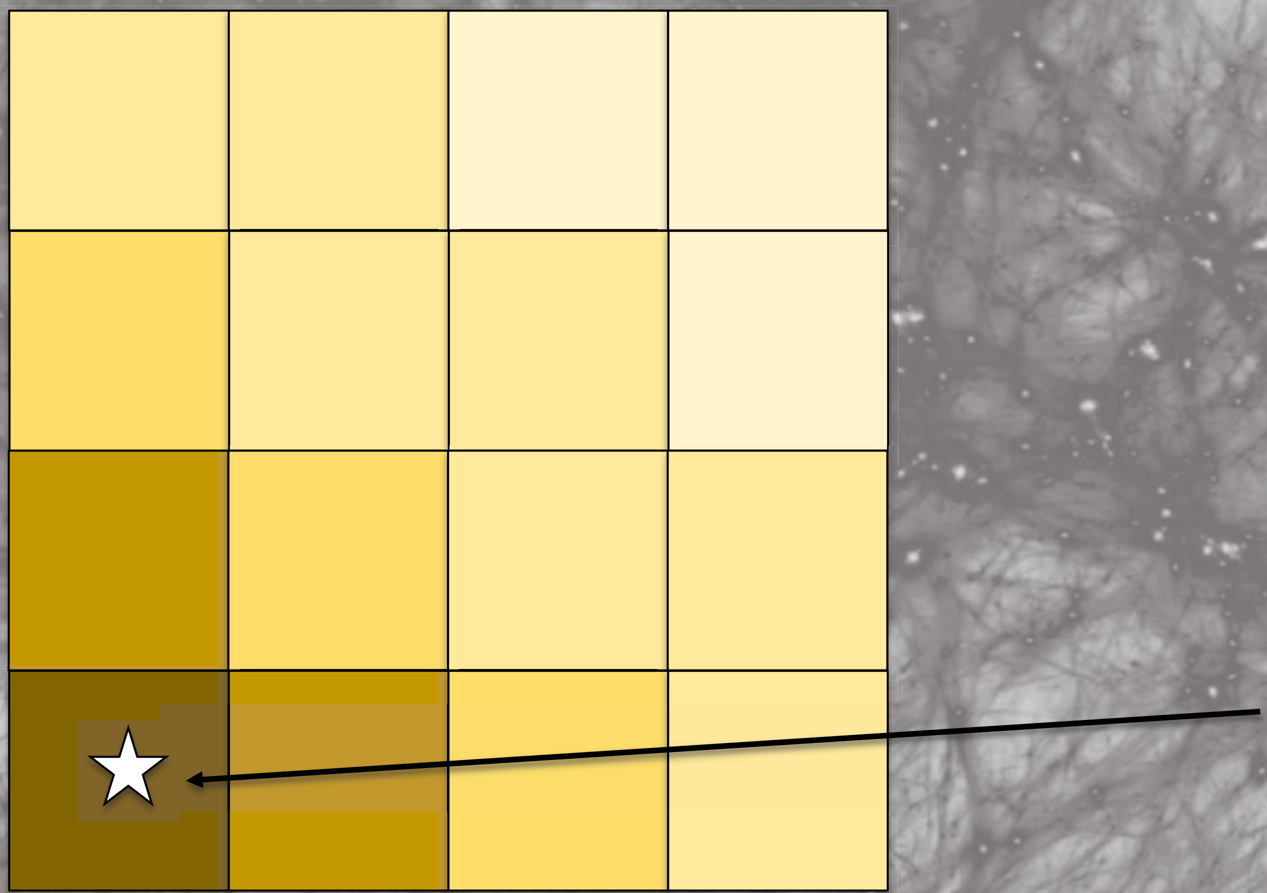

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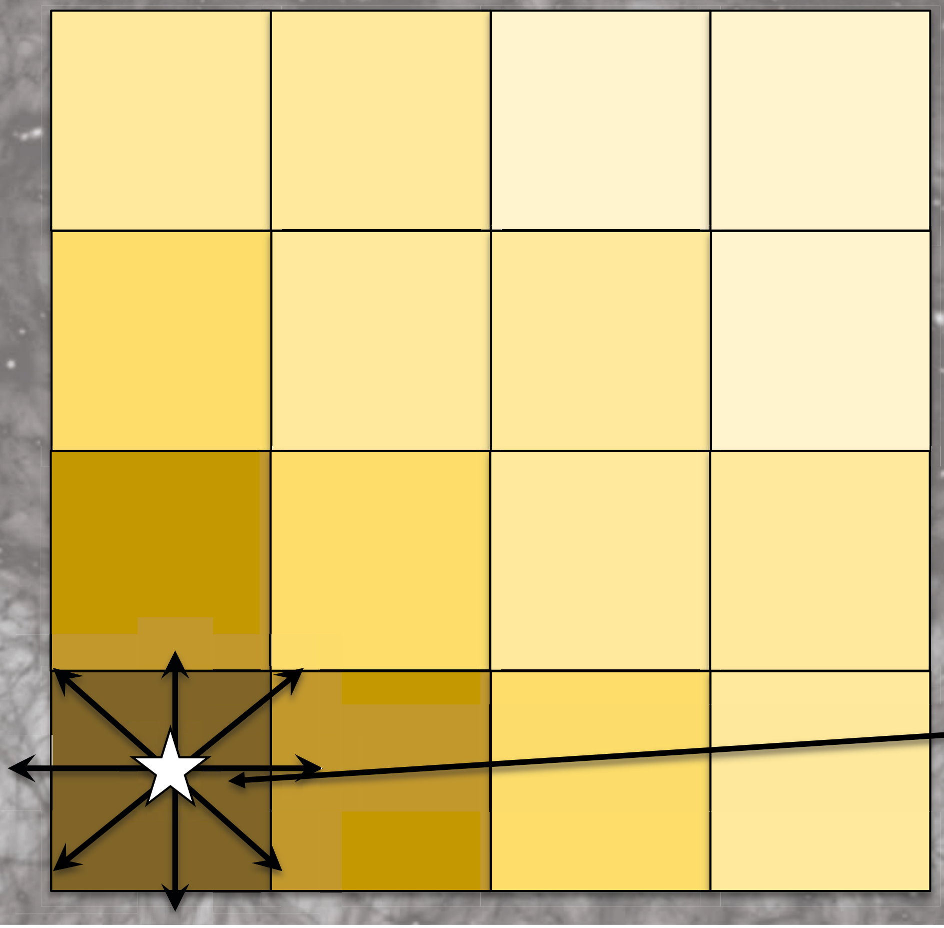

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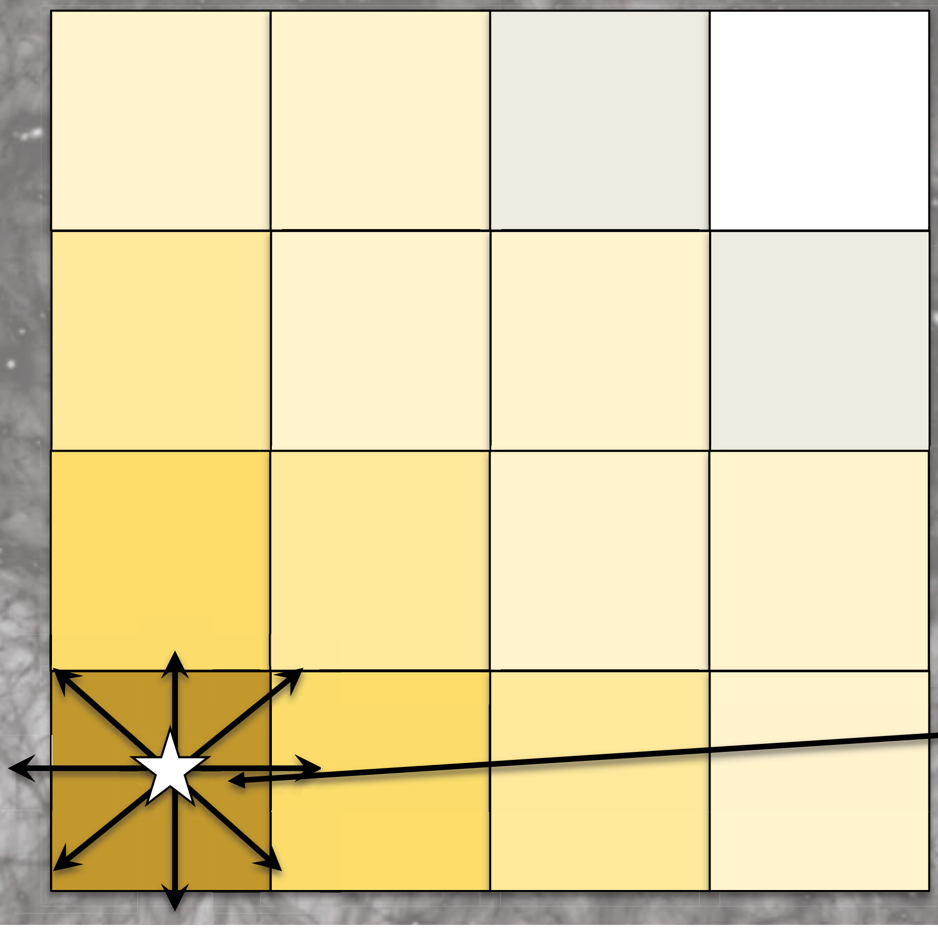

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This star "particle" represents a stellar population usually of 10^4-10^6 Solar masses

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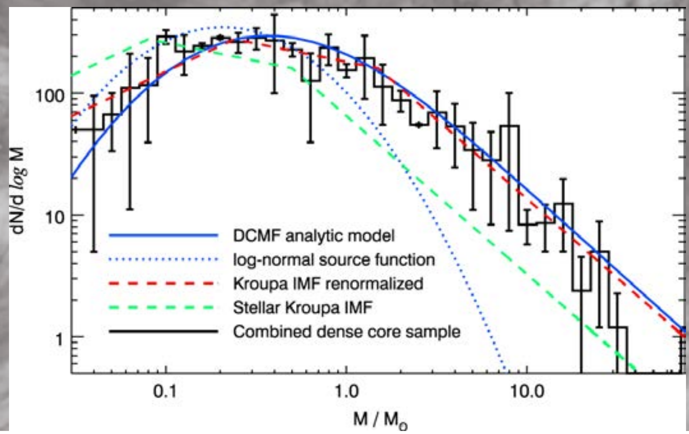
Just like in SAMs – assume an IMF



Hydrodynamical simulations

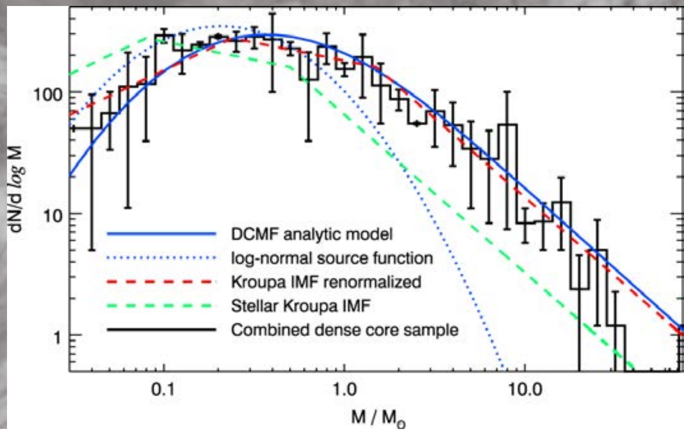
Although Hydro sims can resolve the thermodynamical properties of the gas, they can NOT resolve star formation in cosmological simulations.

Thus we need "sub grid" physics - an analogous method to SAMs

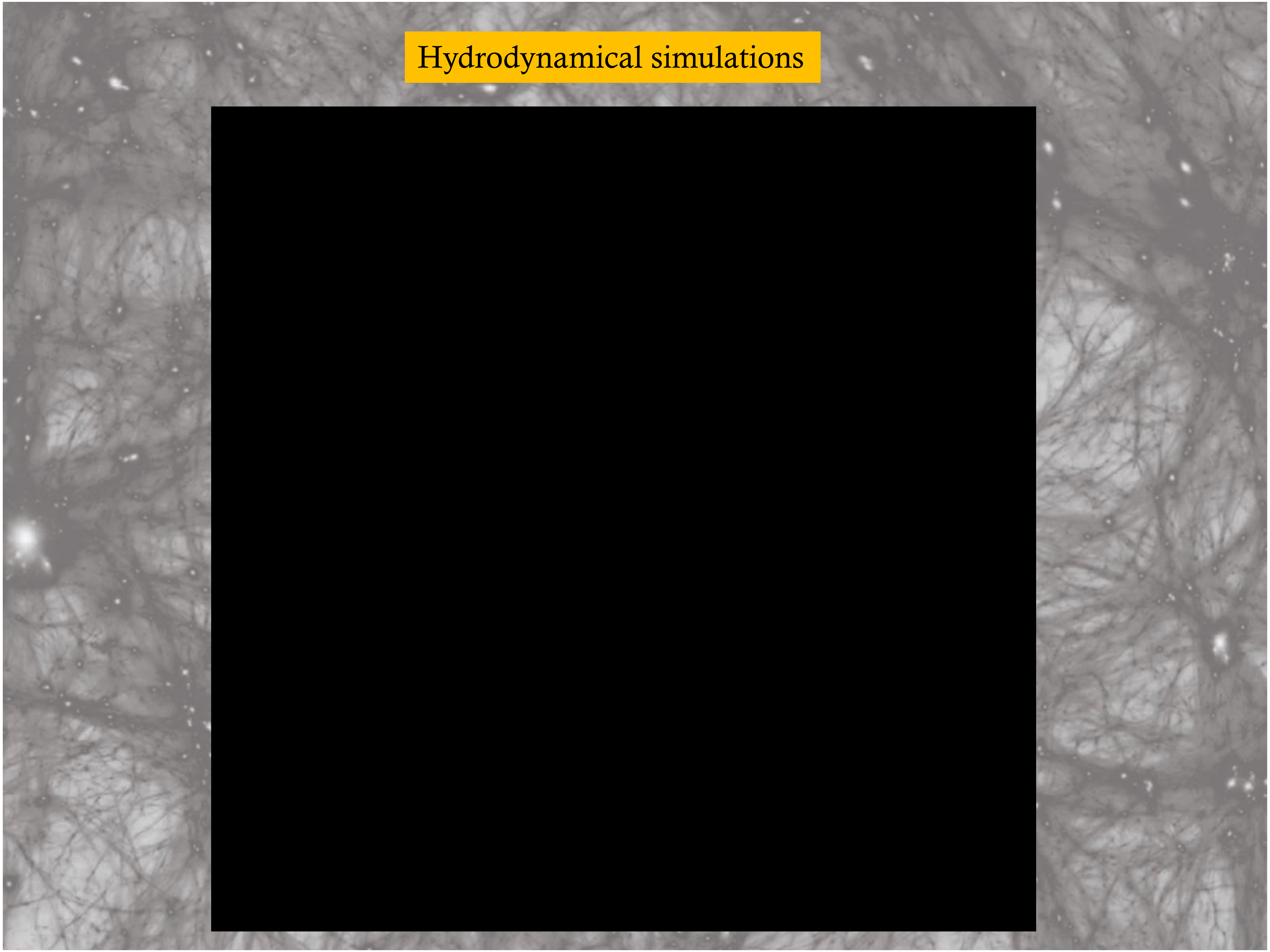
- Colors
- Which stars explode (age)
- Metallicity recycled
- Energy injected

This star "particle" represents a stellar population usually fo 10^4-10^6 Solar masses

Just like in SAMs – assume an IMF



Hydrodynamical simulations



How did a simple initial state evolve into something so complicated

Modelling dark matter

- collisionless Boltzmann equation

$$\frac{df}{dt} = \frac{\partial f}{\partial t} + \mathbf{v}\frac{\partial f}{\partial \mathbf{r}} - \frac{\partial \Phi}{\partial \mathbf{r}}\frac{\partial f}{\partial \mathbf{v}} = 0$$

- Poisson's equation

$$\nabla^2 \Phi = 4\pi G \int f d\mathbf{v}$$

The collisionless Boltzmann equation describes the evolution of the phase-space density or distribution function of dark matter, $f = f(\mathbf{r}, \mathbf{v}, t)$, with $\mathbf{r}$, the positions and $\mathbf{v}$, the velocities, under the influence of the collective gravitational potential, Φ, with G the gravitational constant, given by Poisson's equation. The collisionless Boltzmann equation states the conservation of the local phase-space density; that is Liouville's theorem.

How did a simple initial state evolve into something so complicated

Modelling cosmic gas

- Eulerian formulation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

$$\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot \left(\rho \mathbf{v} \otimes \mathbf{v} + P\mathbb{1}\right) = 0$$

$$\frac{\partial \rho e}{\partial t} + \nabla \cdot \left(\rho e + P\right)\mathbf{v} = 0$$

- Lagrangian formulation

$$\frac{D\rho}{Dt} = -\rho \nabla \cdot \mathbf{v}$$

$$\frac{D\mathbf{v}}{Dt} = -\frac{1}{\rho}\nabla P$$

$$\frac{De}{Dt} = -\frac{1}{\rho}\nabla \cdot P\mathbf{v}$$

- Arbitrary Lagrangian–Eulerian formulation

$$\frac{d}{dt}\int_V \rho dV = -\int_S \rho(\mathbf{v}-\mathbf{w}) \cdot \mathbf{n} dS$$

$$\frac{d}{dt}\int_V \rho \mathbf{v} dV = -\int_S \rho \mathbf{v}(\mathbf{v}-\mathbf{w}) \cdot \mathbf{n} dS - \int_S P\mathbf{n} dS$$

$$\frac{d}{dt}\int_V \rho e dV = -\int_S \rho e(\mathbf{v}-\mathbf{w}) \cdot \mathbf{n} dS - \int_S P\mathbf{v} \cdot \mathbf{n} dS$$

Here, S is the surface (area integrals) and $\mathbf{n}$ is the normal vector on the surface. ρ is th
density, and u is the internal energy. Different forms of the hydrodynamical equation
$D/dt \equiv \partial/\partial t + \mathbf{v} \cdot \nabla$ denotes the Lagrangian derivative and $e = u + \mathbf{v}^2/2$ the total energy pe
unit mass. The equations are closed through $P = (\gamma - 1)\rho u$ with $\gamma = 5/3$. For the arbitrar
Lagrangian–Eulerian formulation, the grid moves with velocity $\mathbf{w}$ and cell volumes evolv
as $dV/dt = \int_V (\nabla \cdot \mathbf{w})dV$.

How did a simple initial state evolve into something so complicated

Box 2 | **Modelling**

Modelling cosmic magnetic fields

- Ideal magnetohydrodynamics (MHD) equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

$$\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot (\rho \mathbf{v} \otimes \mathbf{v} + P\mathbb{1}) = \frac{\mathbf{J} \times \mathbf{B}}{c}$$

$$\frac{\partial (\rho e + e_B)}{\partial t} + \nabla \cdot \left[(\rho e + P)\mathbf{v} + c\frac{\mathbf{E} \times \mathbf{B}}{4\pi}\right] = 0$$

- MHD Maxwell equations

$$\nabla \times \mathbf{B} = \frac{4\pi}{c}\mathbf{J}$$

$$\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t} + \nabla \times \mathbf{E} = 0$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\mathbf{E} = -\frac{\mathbf{v} \times \mathbf{B}}{c}$$

The evolution of the magnetic field, **B**, is given by the induction equation, $\partial \mathbf{B}/\partial t = \nabla \times (\mathbf{v} \times \mathbf{B})$. Magnetic fields act on gas through the Lorentz force, $\mathbf{J} \times \mathbf{B}/c$ with the current density, $\mathbf{J} = c\nabla \times \mathbf{B}/(4\pi)$. The energy equation contains the magnetic energy density, $e_B = ||\mathbf{B}||^2/8\pi$, and the Poynting vector, $c(\mathbf{E} \times \mathbf{B}/4\pi)$, in the flux part.

Modelling cosmic rays

- Ideal magnetohydrodynamics equations with cosmic rays

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

$$\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot (\rho \mathbf{v} \otimes \mathbf{v} + P\mathbb{1}) = \frac{\mathbf{J} \times \mathbf{B}}{c} - \nabla P_{cr}$$

$$\frac{\partial (\rho e + e_B)}{\partial t} + \nabla \cdot \left[(\rho e + P)\mathbf{v} + c\frac{\mathbf{E} \times \mathbf{B}}{4\pi}\right]$$
$$= -(\mathbf{v} + \mathbf{v}_{st}) \cdot \nabla P_{cr} + \Lambda_{th} + \Gamma_{th}$$

- MHD Maxwell equations

$$\nabla \times \mathbf{B} = \frac{4\pi}{c}\mathbf{J}$$

$$\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t} + \nabla \times \mathbf{E} = 0$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\mathbf{E} = -\frac{\mathbf{v} \times \mathbf{B}}{c}$$

- Cosmic rays energy density evolution

$$\frac{\partial \varepsilon_{cr}}{\partial t} + \nabla \cdot \left[\varepsilon_{cr}(\mathbf{v} + \mathbf{v}_{st}) - \kappa_\varepsilon \mathbf{b}(\mathbf{b} \cdot \nabla \varepsilon_{cr})\right]$$
$$= -P_{cr}\nabla \cdot (\mathbf{v} + \mathbf{v}_{st}) + \Lambda_{cr} + \Gamma_{cr}$$

Cosmic rays exhibit a force on the gas through ∇P_{cr}. Their energy density is influenced by streaming with velocity $\mathbf{v}_{st}(\varepsilon_{cr}[\mathbf{v} + \mathbf{v}_{st}])$, anisotropic diffusion with coefficient $\kappa_\varepsilon(\kappa_\varepsilon \mathbf{b}[\mathbf{b} \cdot \nabla \varepsilon_{cr}])$, and adiabatic processes due to the compression of the Alfvèn frame $(P_{cr}\nabla \cdot [\mathbf{v} + \mathbf{v}_{st}])$. cr stands for cosmic ray and th for thermal. Source terms are identified with Γ and the sink terms with Λ.

Modelling cosmic radiation fields

- Radiation hydrodynamics equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

$$\frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{v} \otimes \mathbf{v} + P\mathbb{1}) = \Gamma_p$$

$$\frac{\partial (\rho e)}{\partial t} + \nabla \cdot (\rho e + P)\mathbf{v} = -\Lambda + \Gamma_E$$

- Radiative transfer equation

$$\frac{1}{c}\frac{\partial I_\nu}{\partial t} + \mathbf{n} \cdot \frac{\partial I_\nu}{\partial \mathbf{r}} = -\kappa_\nu I_\nu + j_\nu$$

The radiative transfer equation relates the specific radiation intensity, I_ν, with the absorption coefficient, κ_ν, and the specific emissivity, j_ν. The radiation direction of propagation is represented by the unit vector **n**. Λ is the cooling function, and Γ_p and Γ_E are source terms that describe the transfer of momentum and energy from the radiation to the gas. ρ is the density, c is the speed of light, ν is the frequency, ε_{cr} is the cosmic ray energy density, v is the velocity, P is the pressure, $\mathbf{b} = \mathbf{B}/||\mathbf{B}||$ is the B field direction and e is the specific (per unit mass) gas total energy.

How did a simple initial state evolve into something so complicated

Most important astrophysical processes

Gas cooling	Interstellar medium	Star formation	Stellar feedback	Supermassive black holes	Active galactic nuclei	Magnetic fields	Radiation fields	Cosmic rays
Atomic/ molecular/ metals/ tabulated network	Effective equation of state/ multiphase	Initial stellar mass function/ probabilistic sampling/ enrichment	Kinetic/ thermal/ variety of sources from stars, supernovae	Numerical seeding/ growth by accretion prescription/ merging	Kinetic/ thermal/ radiative/ quasar model radio mode	Ideal MHD/ cleaning schemes/ constrained transport	Ray tracing/ Monte Carlo/ moment based	Production/ heating/ anisotropic diffusion/ streaming

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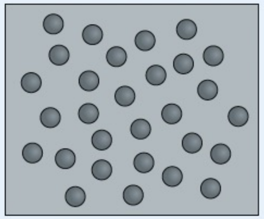
Numerical discretization of matter components

Collisionless gravitational dynamics

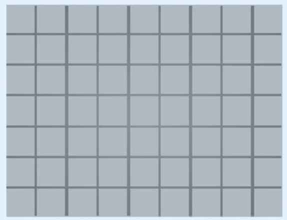
- *N*-body methods based on integral Poisson's equation (such as tree, fast multipole)
- *N*-body methods based on differential Poisson's equation (such as particle-mesh, multigrid)
- *N*-body hybrid methods (TreePM)
- Beyond *N*-body methods (such as Lagrangian tessellation)



Dark matter

Hydrodynamics

- Lagrangian methods (such as smoothed particle hydrodynamics)
- Eulerian methods (such as adaptive mesh refinement)
- Arbitrary Lagrangian–Eulerian methods (such as moving mesh)
- Mesh free/mesh based



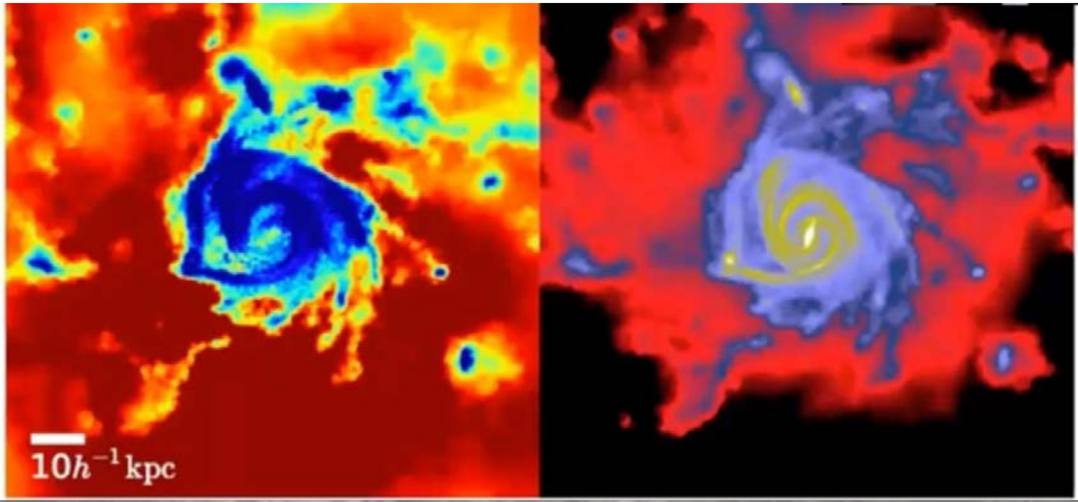
Gas

How did a simple initial state evolve into something so complicated

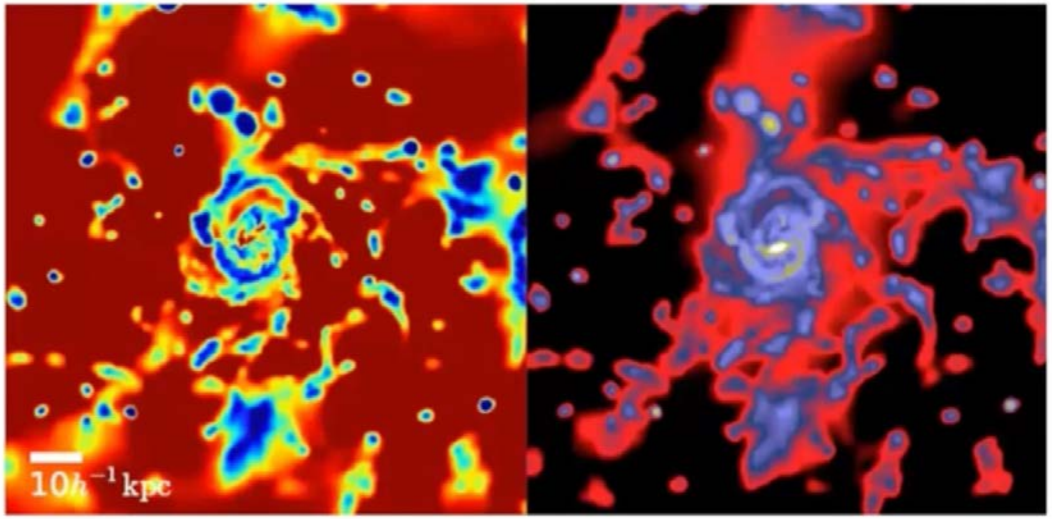
Code name	Gravity treatment	Hydrodynamics treatment	Parallelization technique	Code availability
ART	PM/ML	AMR	Data based	Public
RAMSES	PM/ML	AMR	Data based	Public
GADGET-2/3	TreePM	SPH	Data based	Public
Arepo	TreePM	MMFV	Data based	Public
Enzo	PM/MG	AMR	Data based	Public
ChaNGa[a]	Tree/FM	SPH	Task based	Public
GIZMO[b]	TreePM	MLFM/MLFV	Data based	Public
HACC	TreePM/P^3M	CRK-SPH	Data based	Private
PKDGRAV3	Tree/FM	–	Data based	Public
Gasoline2	Tree	SPH	Task based	Public
SWIFT	TreePM/FM	SPH	Task based	Public

How did a simple initial state evolve into something so complicated

moving-mesh with AREPO



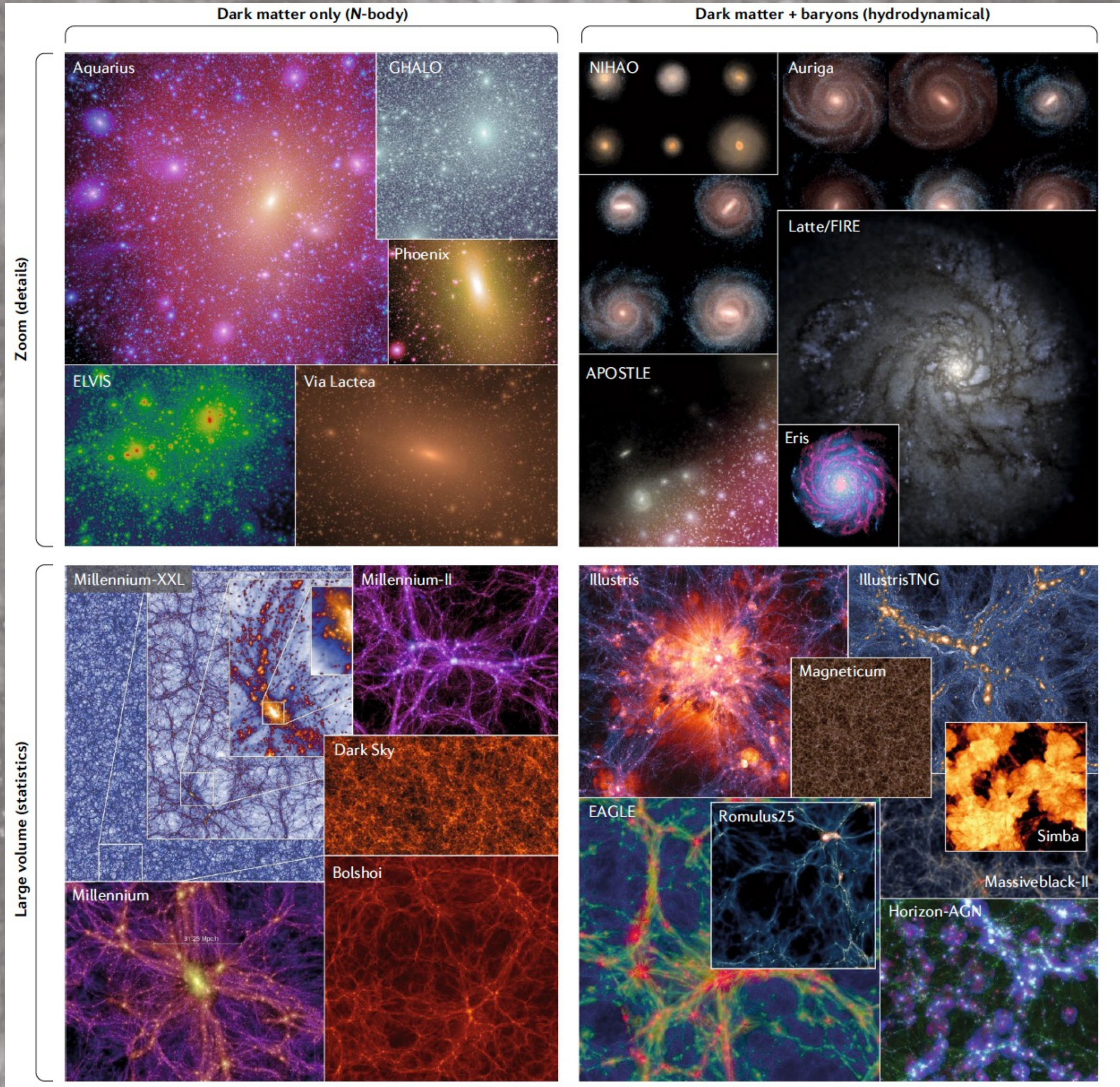
smoothed particle hydrodymamics with GADGET



Effects due to feedback are typically stronger than code differences.

It is often argued that one can hence ignore hydrodynamical code inaccuracies in galaxy formation...

State of the art in numerical simulations



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Simulation	Volume (Mpc^3)	Method	Mass resolution ($M_\odot$)	Spatial resolution (kpc)	Ref.
Dark matter-only					
Millennium	685^3	TreePM	1.2×10^9/–	6.85/–	422
Millennium-2	137^3	TreePM	9.4×10^6/–	1.37/–	423
Horizon 4π	$2{,}740^3$	PM/ML	7.7×10^9/–	10.41/–	424
Bolshoi	357^3	PM/ML	1.9×10^8/–	1.43/–	425
Full Universe Run	$29{,}167^3$	PM/ML	1.4×10^{12}/–	55.6/–	426
Millennium-XXL	$4{,}110^3$	TreePM	8.5×10^9/–	13.7/–	68
MultiDark	$1{,}429^3$	PM/ML	1.2×10^{10}/–	10.00/–	427
Dark Sky	$11{,}628^3$	Tree/FM	5.7×10^{10}/–	53.49/–	42
ν^2 GC	$1{,}647^3$	TreePM	3.2×10^8/–	6.28/–	428
Q Continuum	$1{,}300^3$	TreePM/P^3M	1.5×10^8/–	2.82/–	70
OuterRim	$4{,}225^3$	TreePM/P^3M	2.6×10^9/–	6.00/–	418
EuclidFlagship	$20{,}000^3$	Tree/FM	10^9/–	5.00/–	419
Aquarius	Zoom	TreePM	1.7×10^3/–	0.02/–	91
Via Lactea II	Zoom	Tree	4.1×10^3/–	0.04/–	429
GHALO	Zoom	Tree	1.0×10^3/–	0.06/–	408
CLUES	Zoom	TreePM	3.4×10^5/–	0.21/–	430
Phoenix	Zoom	TreePM	8.7×10^5/–	0.21/–	92
ELVIS	Zoom	TreePM	1.9×10^5/–	0.14/–	409
COCO	Zoom	TreePM	1.6×10^5/–	0.33/–	431
Including baryons					
Illustris	107^3	TreePM+MMFV	$6.7\times10^6/1.3\times10^6$	1.42/0.71	138
Horizon-AGN	142^3	PM/ML+AMR	$8.0\times10^7/1.0\times10^7$	1.0/1.0	432
EAGLE	100^3	TreePM+SPH	$9.7\times10^6/1.8\times10^6$	0.7/0.7	111
MassiveBlack-II	143^3	TreePM+SPH	$1.6\times10^7/3.2\times10^6$	2.64/2.64	411
Bluetides[a]	574^3	TreePM+SPH	$1.7\times10^7/3.4\times10^6$	0.24/0.24	433
Magneticum	68^3	TreePM+SPH	$5.3\times10^7/1.1\times10^7$	1.4/0.7–1.4	71
MUFASA	74^3	TreePM+MLFM	$9.6\times10^7/1.8\times10^7$	0.74/0.74	434
BAHAMAS	571^3	TreePM+SPH	$5.5\times10^9/1.1\times10^9$	0.25/0.25	435
Romulus25	25^3	Tree/FM+SPH	$3.4\times10^5/2.1\times10^5$	0.25/0.25	436
IllustrisTNG[b]	111^3	TreePM+MMFV	$7.5\times10^6/1.4\times10^6$	0.74/0.19	73
Simba[c]	147^3	TreePM+MLFM	$1.4\times10^8/2.7\times10^7$	0.74/0.74	171
Eris	Zoom	Tree+SPH	$9.8\times10^4/2\times10^4$	0.12/0.12	332
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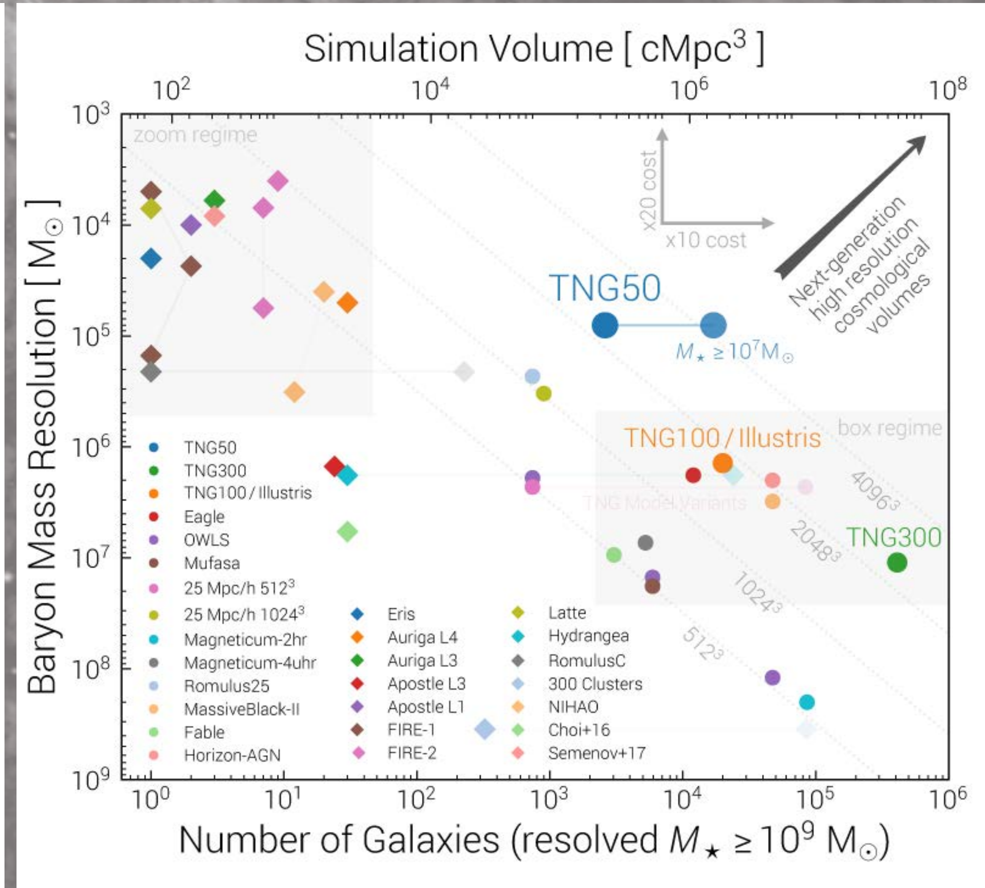
Auriga	Zoom	TreePM+MMFV	$4.0\times10^4/6.0\times10^3$	0.18/0.18[d]	286
MACSIS	Zoom	TreePM+SPH	$6.4\times10^9/1.2\times10^9$	5.77/5.77	438
Cluster-EAGLE	Zoom	TreePM+SPH	$9.7\times10^6/1.8\times10^6$	0.7/0.7	113
Three Hundred	Zoom	TreePM+SPH	$1.9\times10^9/3.5\times10^8$	9.59/9.59	439
FABLE	Zoom	TreePM+MMFV	$8.1\times10^7/1.5\times10^7$	4.15/4.15	440
RomulusC	Zoom	Tree/FM+SPH	$3.4\times10^5/2.1\times10^5$	0.25/0.25	441



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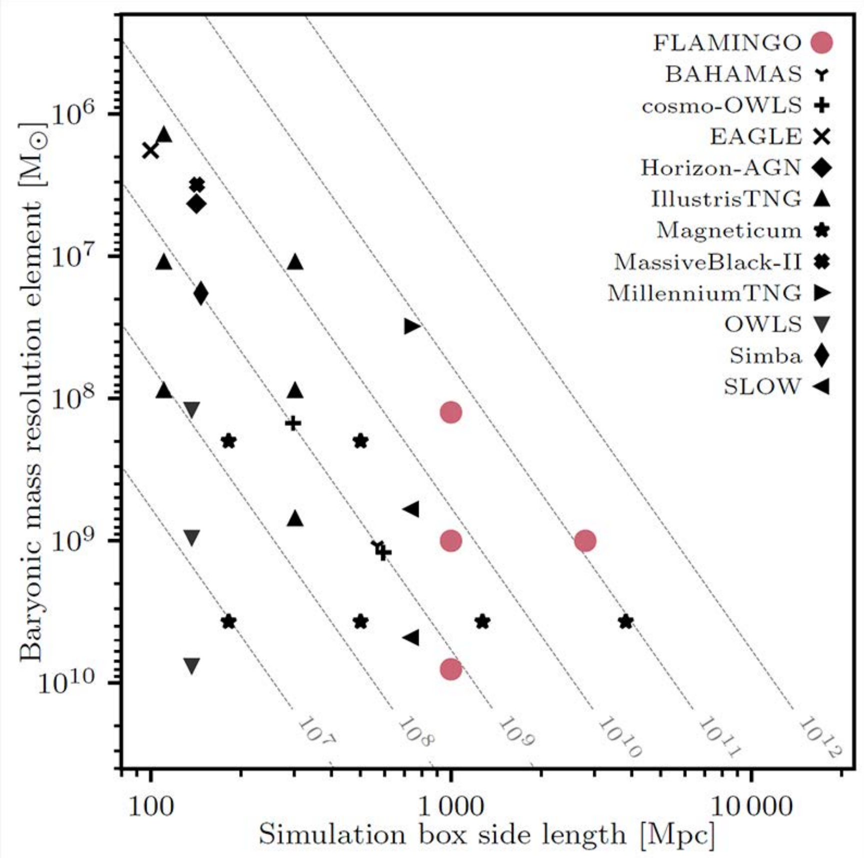

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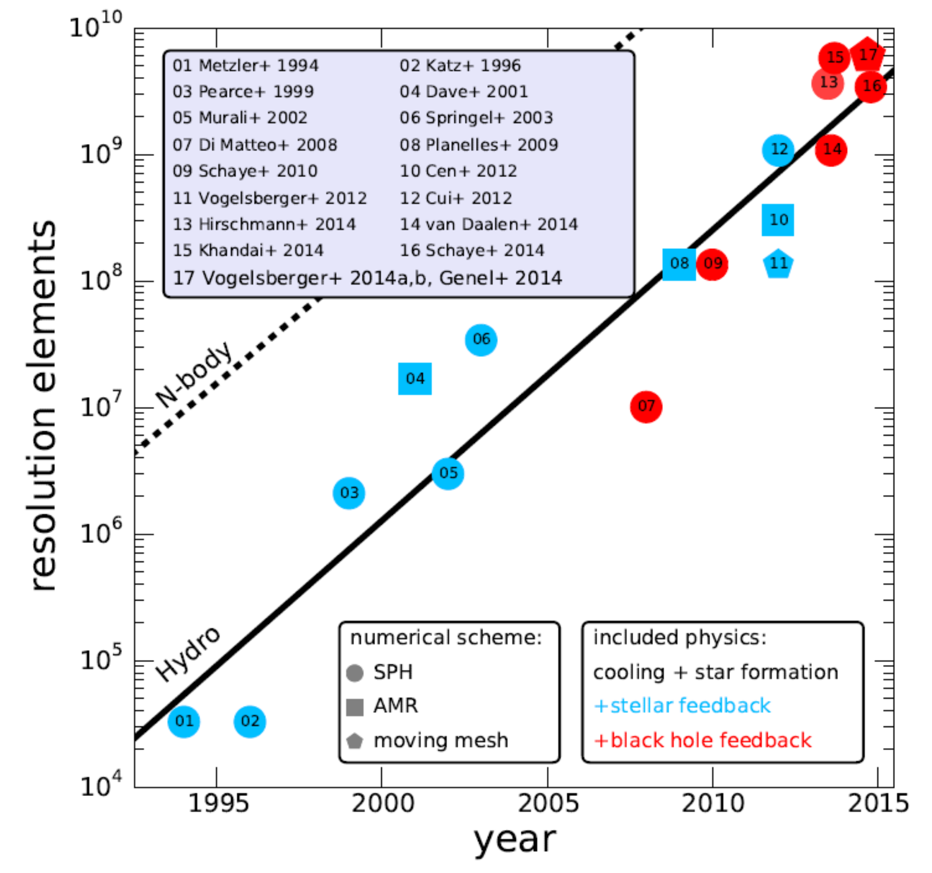
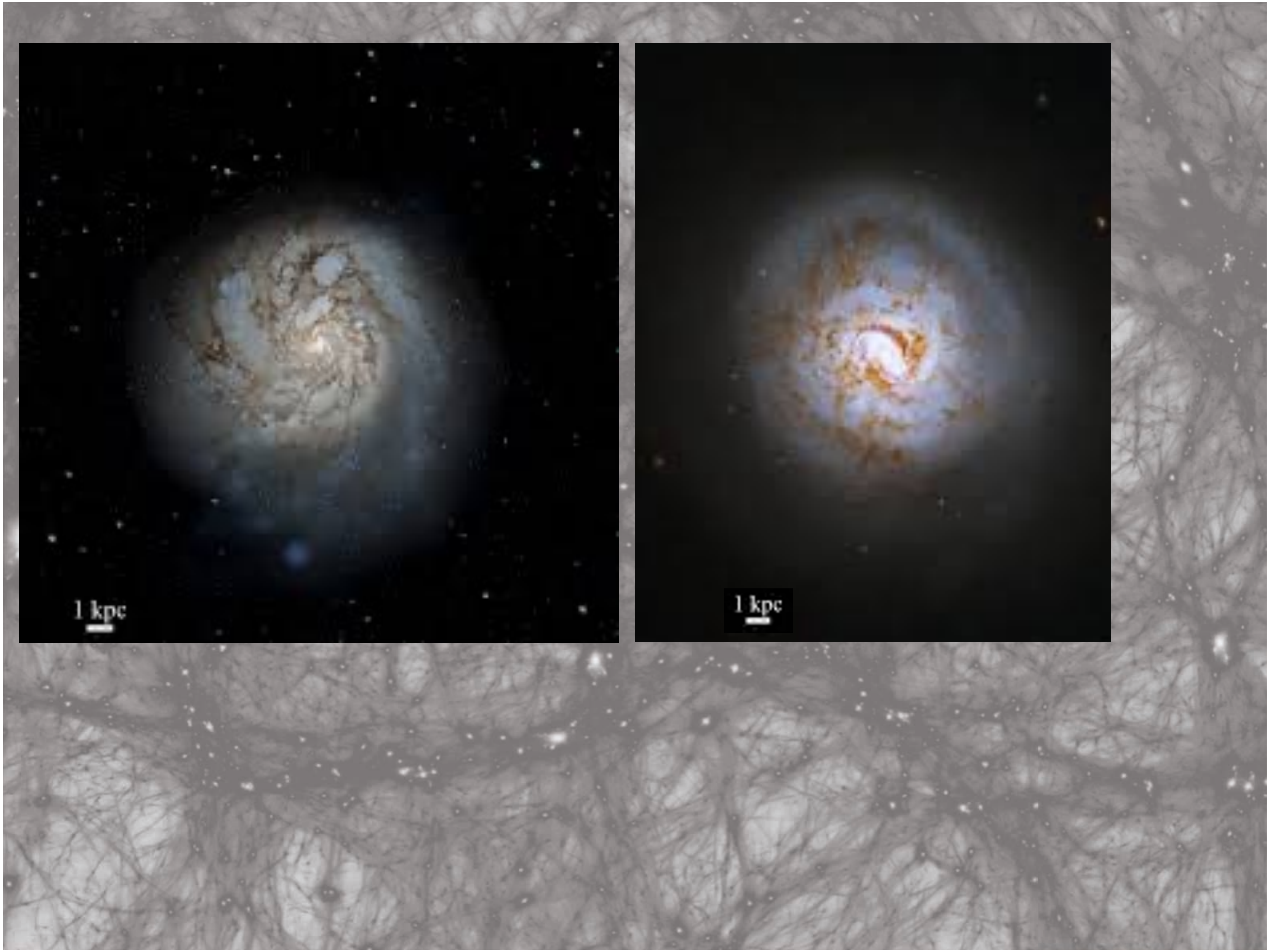
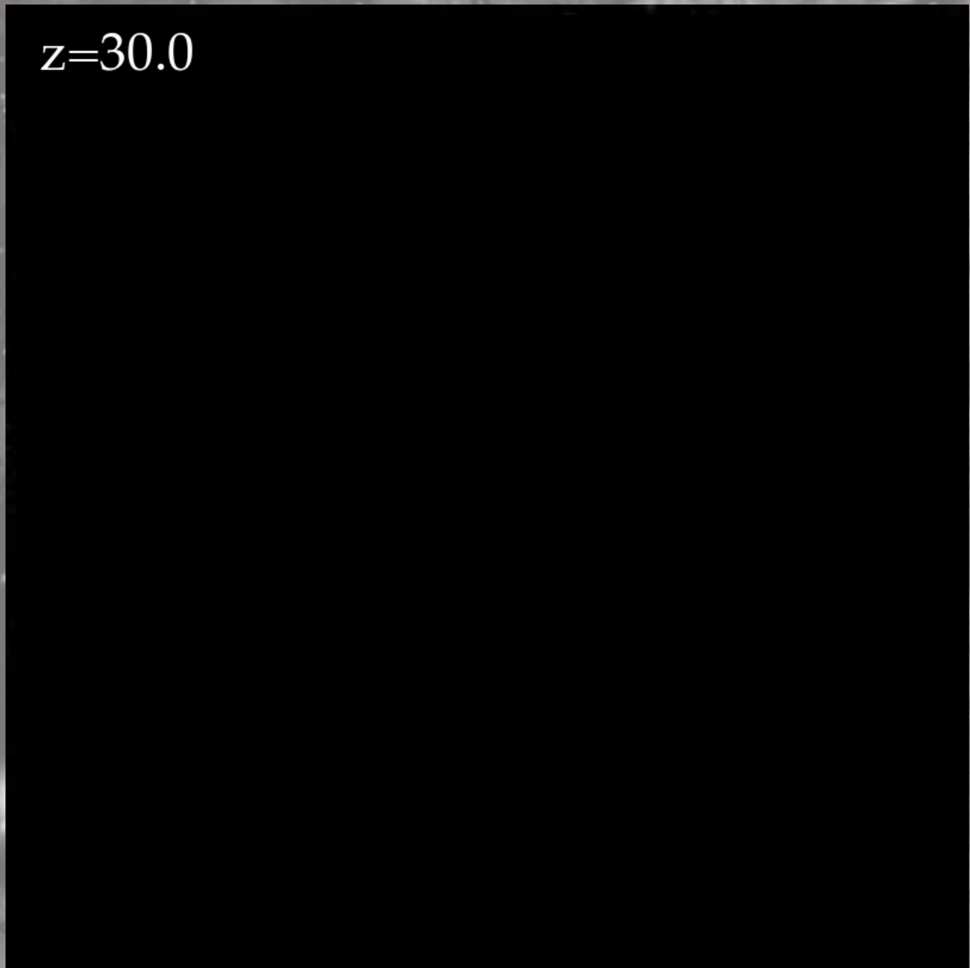
Aquarius	Zoom	TreePM	1.7×10^3/–	0.02/–	91
Via Lactea II	Zoom	Tree	4.1×10^3/–	0.04/–	429
GHALO	Zoom	Tree	1.0×10^3/–	0.06/–	408
CLUES	Zoom	TreePM	3.4×10^5/–	0.21/–	430
Phoenix	Zoom	TreePM	8.7×10^5/–	0.21/–	92
ELVIS	Zoom	TreePM	1.9×10^5/–	0.14/–	409
COCO	Zoom	TreePM	1.6×10^5/–	0.33/–	431
Including baryons					
Illustris	107^3	TreePM+MMFV	$6.7\times10^6/1.3\times10^6$	1.42/0.71	138
Horizon-AGN	142^3	PM/ML+AMR	$8.0\times10^7/1.0\times10^7$	1.0/1.0	432
EAGLE	100^3	TreePM+SPH	$9.7\times10^6/1.8\times10^6$	0.7/0.7	111
MassiveBlack-II	143^3	TreePM+SPH	$1.6\times10^7/3.2\times10^6$	2.64/2.64	411
Bluetides[a]	574^3	TreePM+SPH	$1.7\times10^7/3.4\times10^6$	0.24/0.24	433
Magneticum	68^3	TreePM+SPH	$5.3\times10^7/1.1\times10^7$	1.4/0.7–1.4	71
MUFASA	74^3	TreePM+MLFM	$9.6\times10^7/1.8\times10^7$	0.74/0.74	434
BAHAMAS	571^3	TreePM+SPH	$5.5\times10^9/1.1\times10^9$	0.25/0.25	435
Romulus25	25^3	Tree/FM+SPH	$3.4\times10^5/2.1\times10^5$	0.25/0.25	436
IllustrisTNG[b]	111^3	TreePM+MMFV	$7.5\times10^6/1.4\times10^6$	0.74/0.19	73
Simba[c]	147^3	TreePM+MLFM	$1.4\times10^8/2.7\times10^7$	0.74/0.74	171
Eris	Zoom	Tree+SPH	$9.8\times10^4/2\times10^4$	0.12/0.12	332
NIHAO	Zoom	Tree+SPH	$3.4\times10^3/6.2\times10^2$	0.12/0.05	112
APOSTLE	Zoom	TreePM+SPH	$5.0\times10^4/1.0\times10^4$	0.13/0.13	437
Latte/FIRE	Zoom	TreePM+MLFM	$3.5\times10^4/7.1\times10^3$	0.02/0.001	335
Auriga	Zoom	TreePM+MMFV	$4.0\times10^4/6.0\times10^3$	0.18/0.18[d]	286
MACSIS	Zoom	TreePM+SPH	$6.4\times10^9/1.2\times10^9$	5.77/5.77	438
Cluster-EAGLE	Zoom	TreePM+SPH	$9.7\times10^6/1.8\times10^6$	0.7/0.7	113
Three Hundred	Zoom	TreePM+SPH	$1.9\times10^9/3.5\times10^8$	9.59/9.59	439
FABLE	Zoom	TreePM+MMFV	$8.1\times10^7/1.5\times10^7$	4.15/4.15	440
RomulusC	Zoom	Tree/FM+SPH	$3.4\times10^5/2.1\times10^5$	0.25/0.25	441




1 kpc
1 kpc

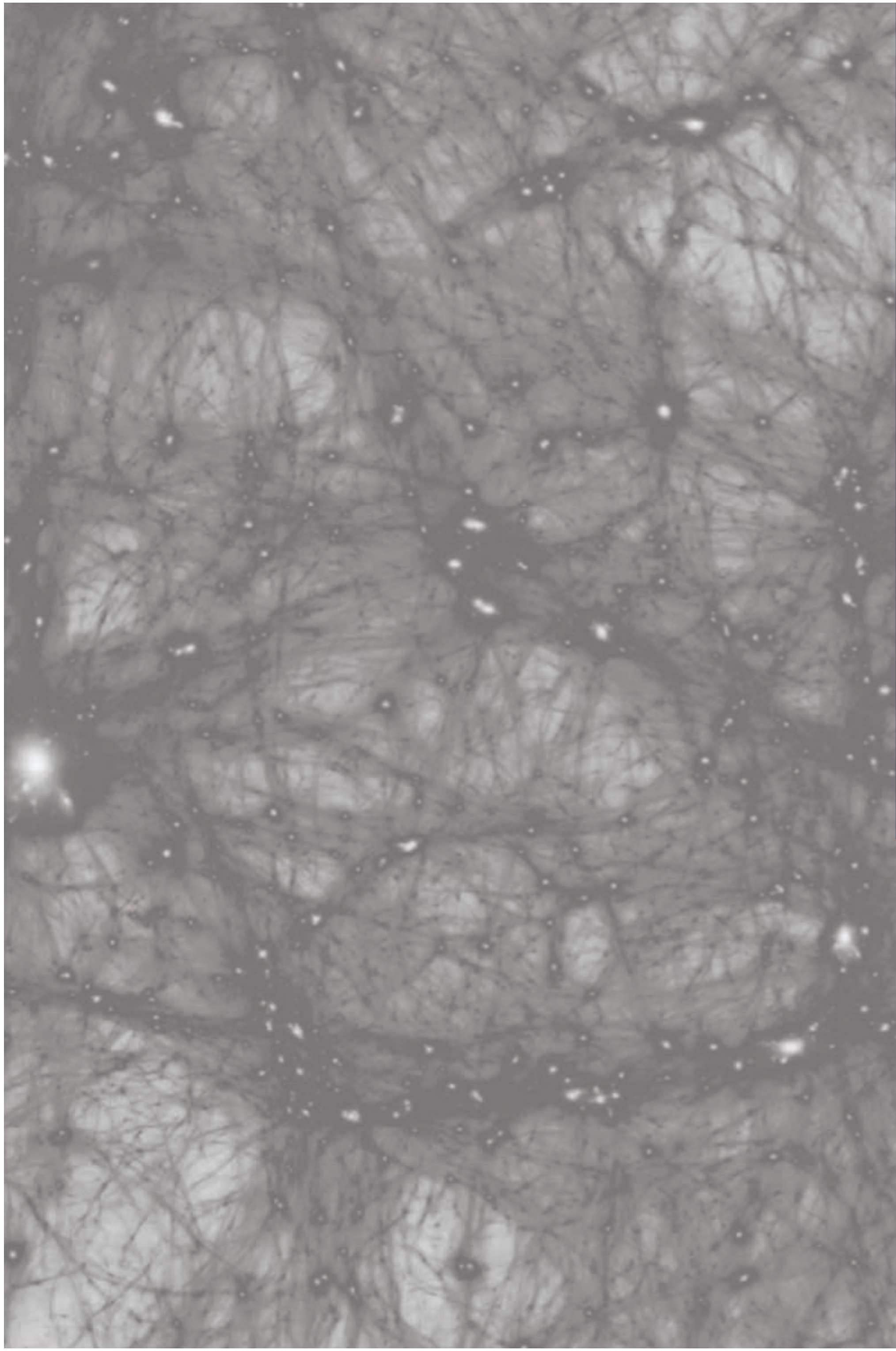
Latte simulation

ESO-420-G013 (HST)



Latte simulation

ESO-420-G013 (HST)



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Vol. XXVII. *May* 10, 1867. No. 7.

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John Joynson, Esq., Waterloo, Liverpool,

were balloted for and duly elected Fellows of the Society.

On the Distribution of the Nebulæ in Space.
By Cleveland Abbe, Esq.

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Hope." If the present Note be found to present nothing new to the generality of those conversant with this field of research, its results may still be worthy of notice as being drawn from the study of a larger number of objects and a more systematic classification of them than seems to have been made the basis of previous opinions.

May your codes be bug free!

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