EXCOSM Summer School

Day 4 Cosmic web and galaxies

Peeter Tenjes, Tartu Observatory

1. Formation of first stars and galaxies
2. Star formation
3. Gas infalls and outflows in galaxies
4. Chemical evolution of galaxies
5. Observing the galaxy evolution with redshift

1.1 Physical conditions before and after the recombination

Before rec radiation and matter are tied together and sound speed is

$$c_S^2 = \frac{\partial p}{\partial \rho} = \frac{\partial(p_r + p_b)}{\partial(\rho_r + \rho_b)} \simeq \frac{c^2}{3}\frac{\partial \rho_r}{\partial \rho_r + \partial \rho_b} = \frac{c^2}{3}\frac{1}{\frac{\partial \rho_r}{\partial \rho_r} + \frac{\partial \rho_b}{\partial \rho_r}} =$$

$$p_b = \frac{\rho_b k_B T}{\mu m_H}, \qquad p_r = \frac{\rho_r c^2}{3}$$

$$\frac{d\rho_b}{d\rho_r} = \frac{3}{4}\frac{\rho_b}{\rho_r}$$

$$= \frac{c^2}{3} 1 + \frac{3}{4}\frac{\rho_b}{\rho_r}^{-1} = \frac{c^2}{3} 1 + \frac{3}{4}\frac{(1+z_{eq})}{(1+z)}^{-1}.$$

$$\frac{\rho_b}{\rho_r} = \frac{1 + z_{eq}}{1 + z}$$

Example: sound speed and Jeans mass at $z = 1500$.

$$c_s = 1.04 \times 10^8\,\mathrm{m/s} \qquad \text{(using } z_{eq} \simeq 3600\text{)}$$

$$M_J = \frac{\pi^{5/2}}{6}\frac{c_s^3}{\rho\ G^{3/2}} = 2.57 \times 10^{48}\,\mathrm{kg} \simeq 10^{18}\,\mathrm{M}_\odot$$

After the recombination, e.g. at $z = 500$:

$$T = 2.73\,(1+z) = 1370\,\mathrm{K}, \qquad c_s = \frac{5k_BT}{3m_H} = 4350\,\mathrm{m/s}$$

$$M_J = \frac{\pi^{5/2}}{6}\frac{c_s^3}{\rho\ G^{3/2}} = 1.9 \times 10^{36}\,\mathrm{kg} \simeq 10^6\,\mathrm{M}_\odot$$

(After that

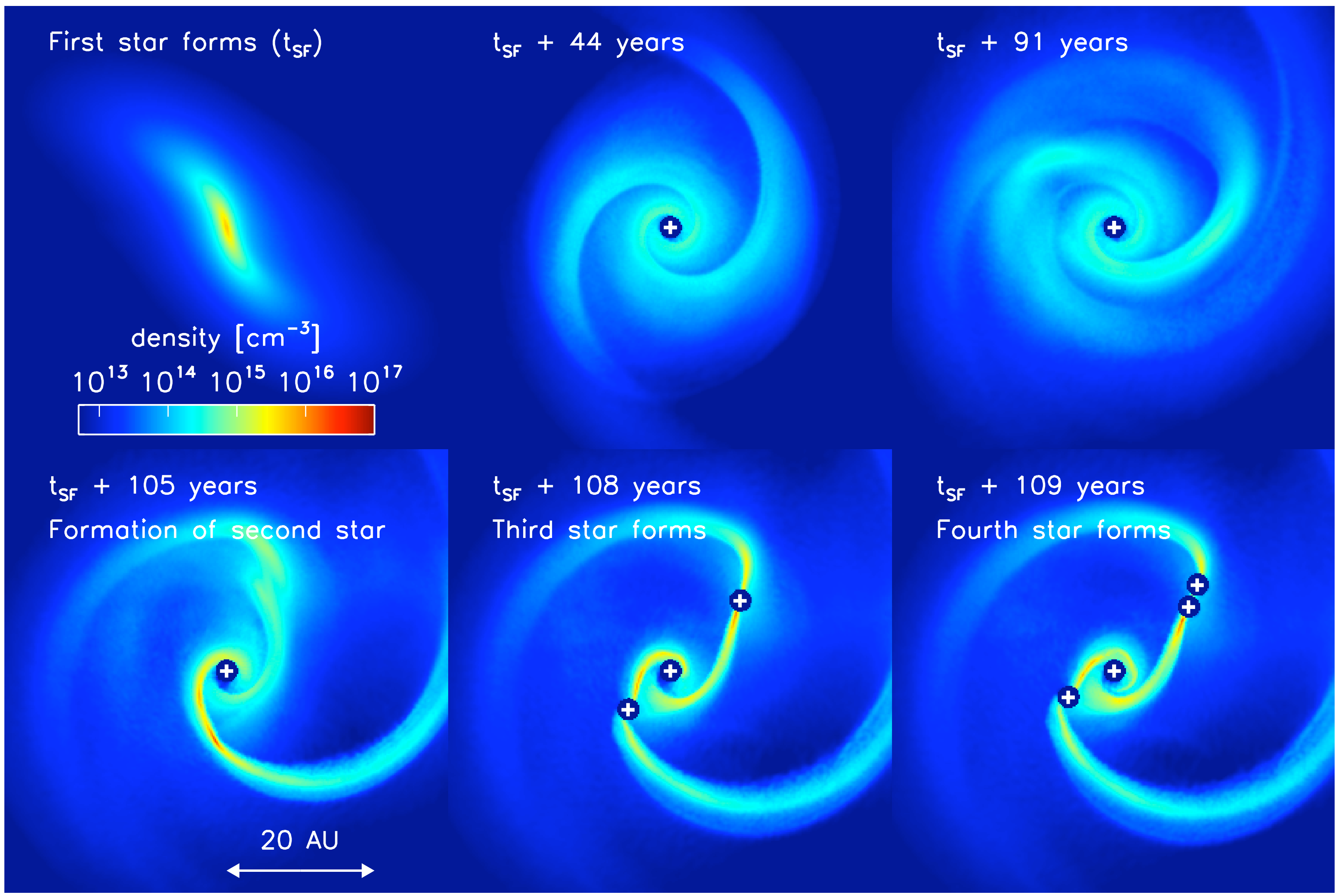
$$T_b \sim (1+z)^2, \quad c_s \sim (1+z), \quad M_J \sim \frac{(1+z)^3}{(1+z)^{3/2}} = (1+z)^{3/2}\,.$$

$z = 20$, $M_J \sim 8000$.)

1.2 First stars

$M_{DM} \simeq 10^7\,\mathrm{M}_\odot, \quad M_b \simeq 10^4\mathrm{M}_\odot$

(Millenium TNG z ~ 10, Kannan et al. 2023). Gas content is primordial. Neutral gas cools due to H_2 until about 400 K (M_J ~ 1500). Then HD until 100 K.



Pop III.1 stars

$z \sim 20 - 30$,

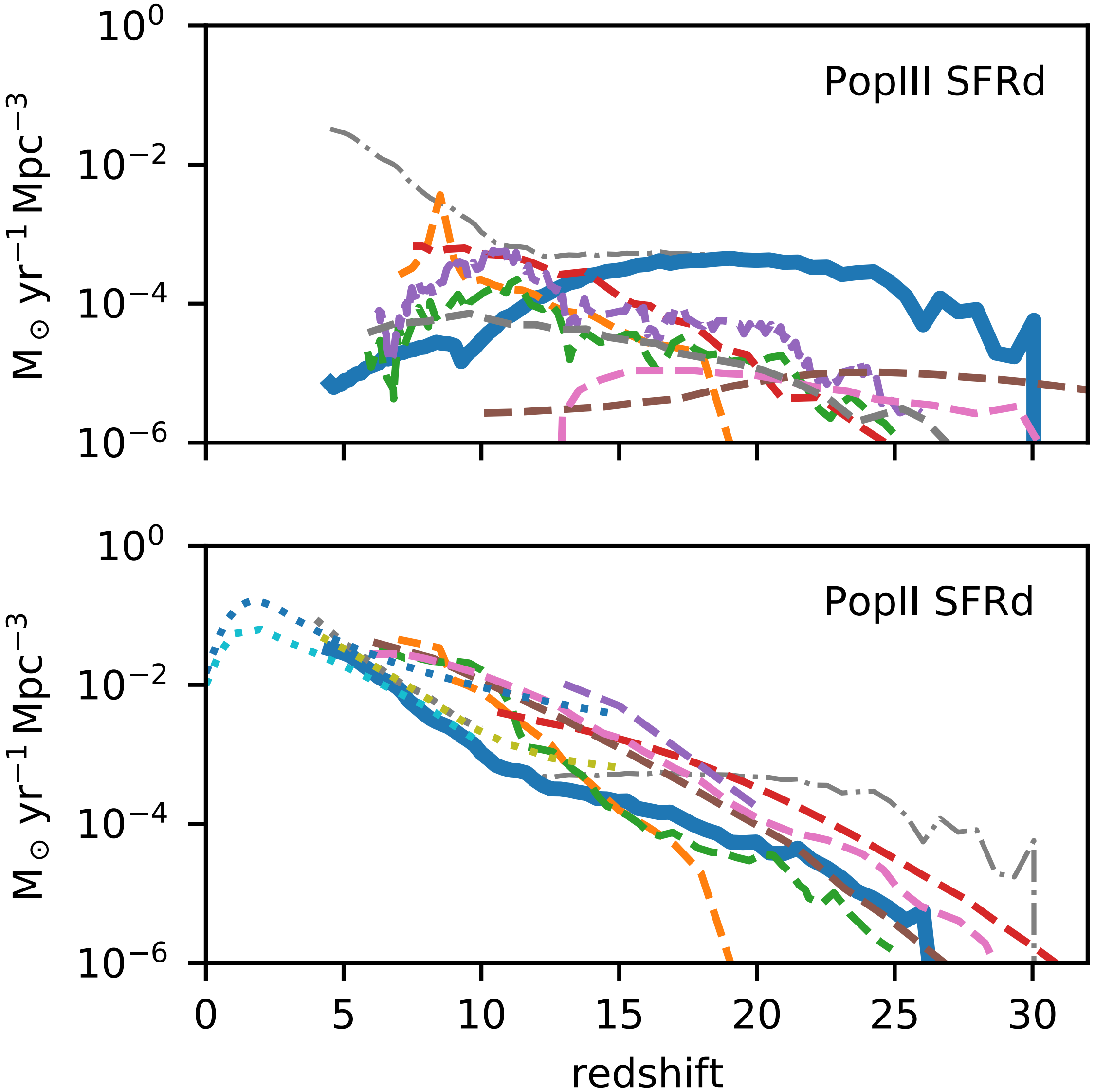
masses from

$30 - 10^3\,\mathrm{M}_\odot$

Pop III.2 stars

$\sim 10 - 30\,\mathrm{M}_\odot$

Clark et al. 2011



Hartwig et al. (2022) - look at thick blue lines to compare formation of Pop III and Pop II stars.

1.3 First galaxies

$E_{bind} \sim GM_{vir}^2/r_{vir} > E_{SN}$ $\qquad$ $M_{vir} \sim 10^9\,\mathrm{M}_\odot$

1.3.1 Dark matter haloes

CDM subhaloes mergers:

violent relaxation (Lynden-Bell): $d\epsilon/dt = \partial\psi/\partial t$ (ϵ is particle energy per unit mass, ψ is grav pot.) and phase mixing give NFW/Einasto profile and DM particle background.

ΛCDM Millennium-II: earler results were ~confirmed. By $z \sim 12 - 15$ masses $\sim 10^9 - 10^{10}\,\mathrm{M}_\odot$ were reached.

1.3.2 Gas within the dark haloes

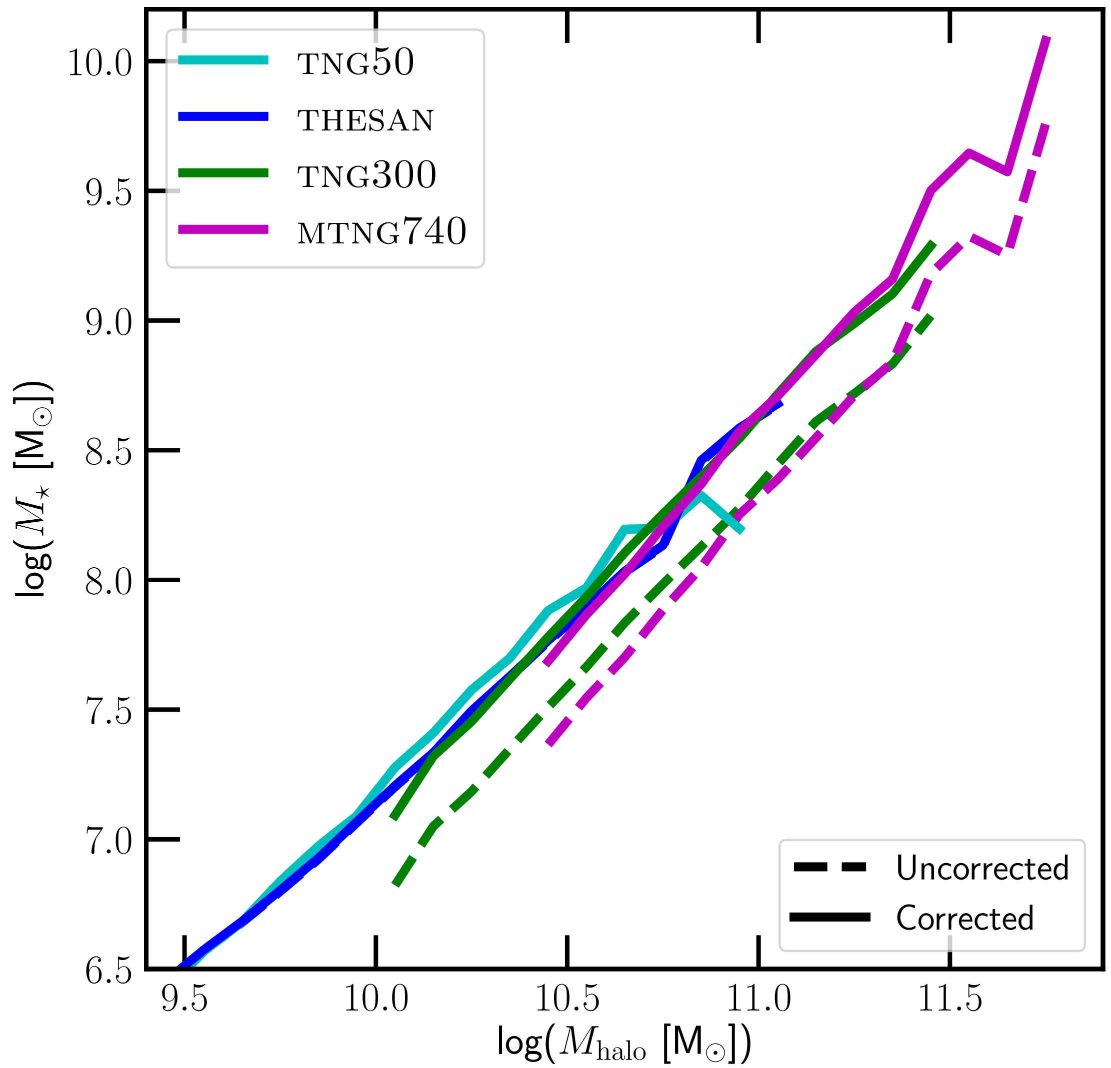
Together with DM subhaloes mergers also gas components merge.

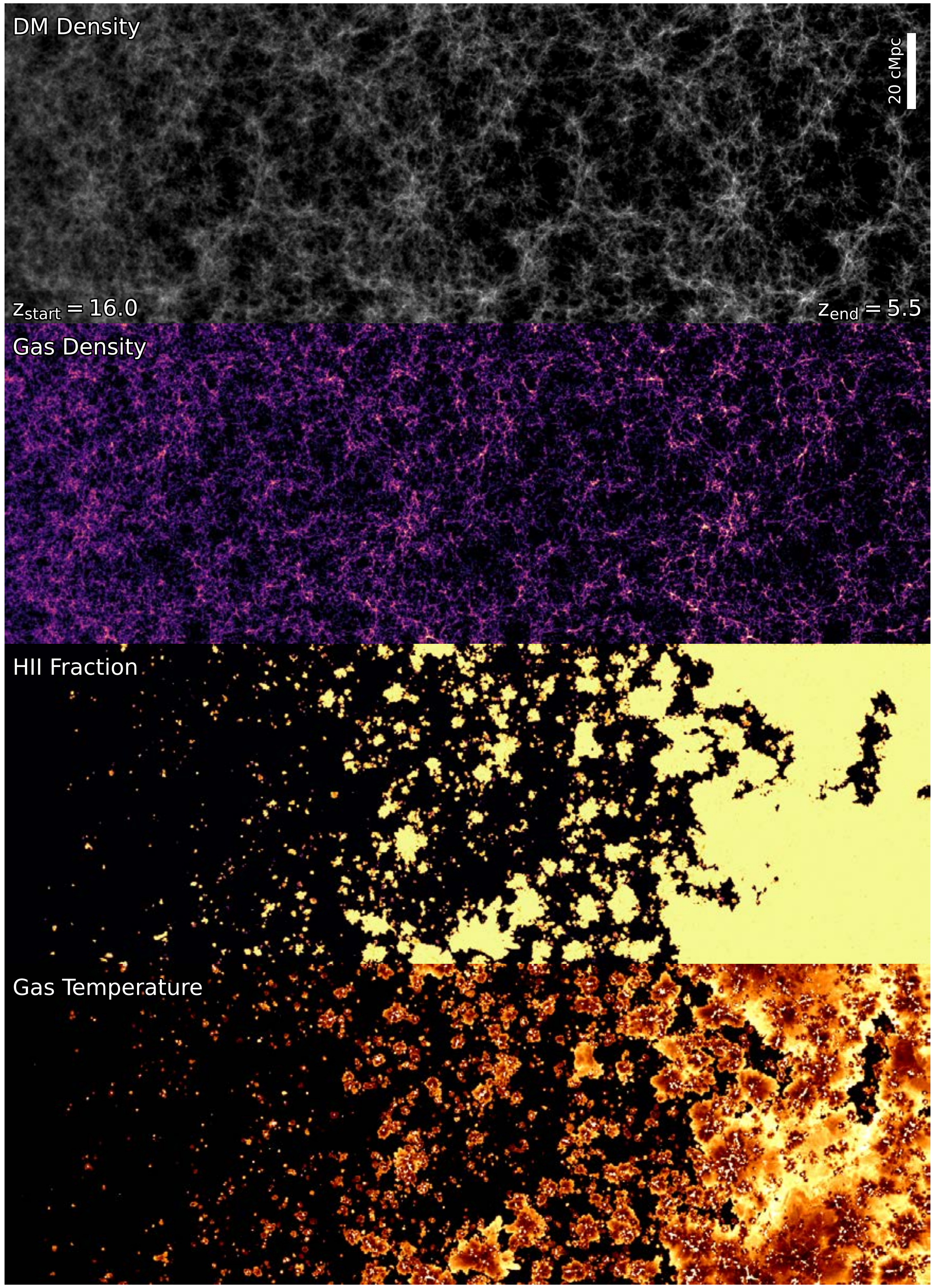
MillenniumTNG + Illustris TNG50 (etc):

740 Mpc, $m_b = 3 \times 10^7 \mathrm{M}_\odot$ + 50 Mpc, $m_b = 8 \times 10^4 \mathrm{M}_\odot$.

Kannan et al. 2023 for $z = 10$ we see a linear relation between

$\log M_{DM} - \log M_*$





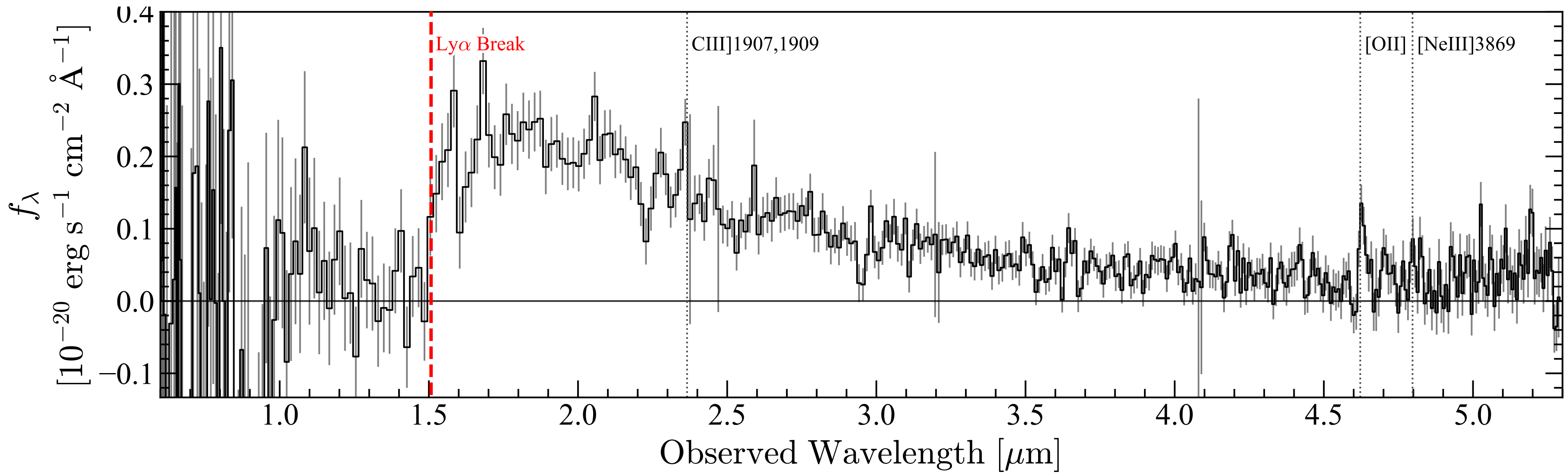
Kannan et al. (2023): evolution from z = 16 (left) to z = 5.5 (right).

DM and gas clustering quite similar but gas has more small structures (due to dissipation).

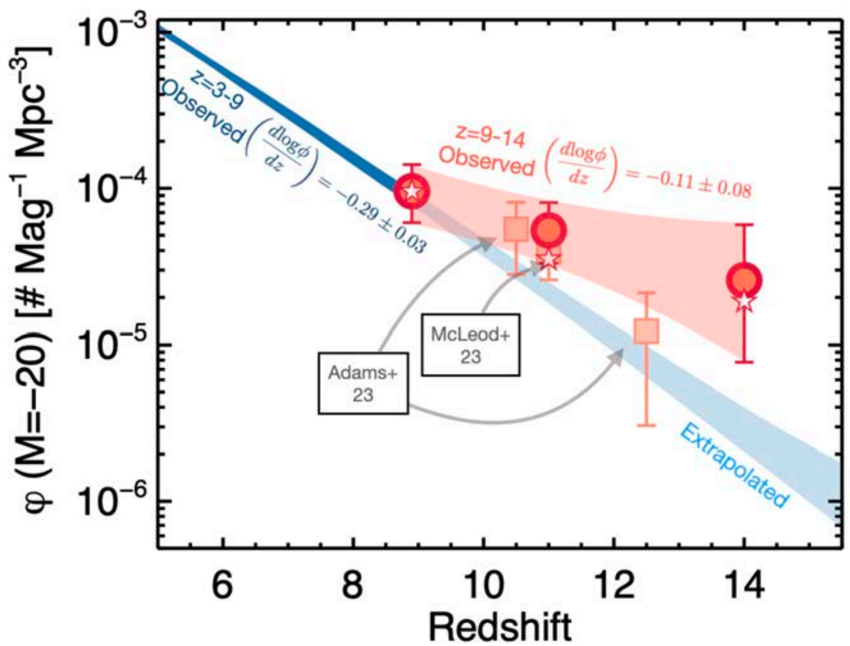
In HII panel reionization is seen to be finished by z = 5.5.

1.4 Observations (JWST)

First stars. Indirect confirmation byHarikane et al. 2024: C, O, Ne lines at z = 11.4



First galaxies. UV lumin funct by Finkelstein et al. 2024: too much luminous galaxies?



Why?

Observations are biased, particular Pop III burst, currections due to dust are wrong, something unknown.

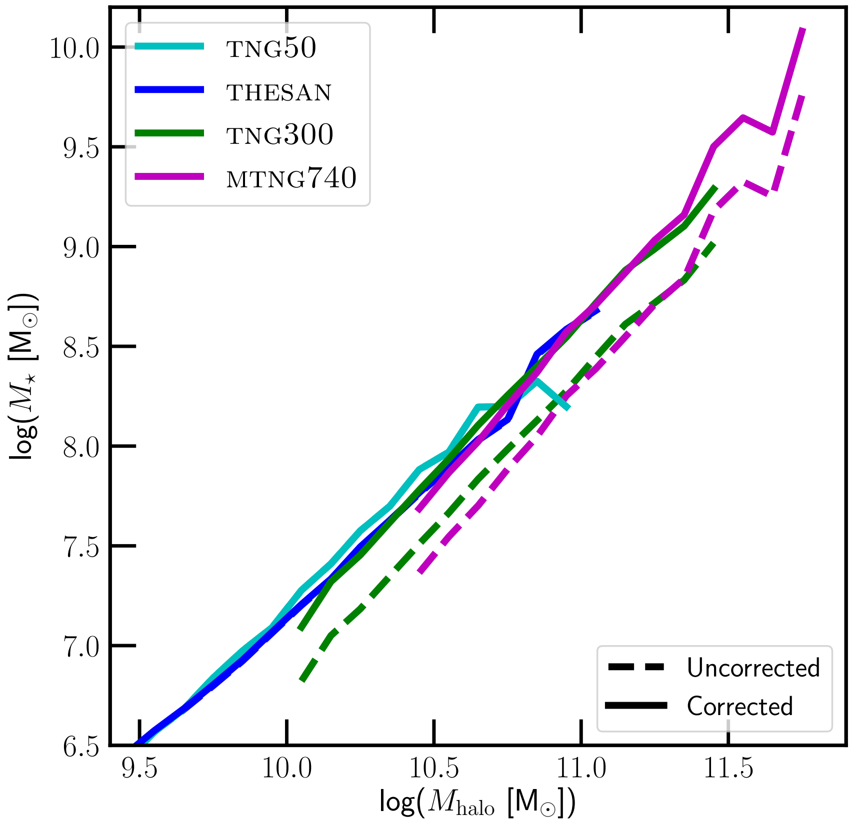
$M_{\rm DM}$ vs M_*

Robertson 2023, 2024: 8 galaxies with $M_* = 10^7 - 10^9 \mathrm{M}_\odot$ (uncertain!),

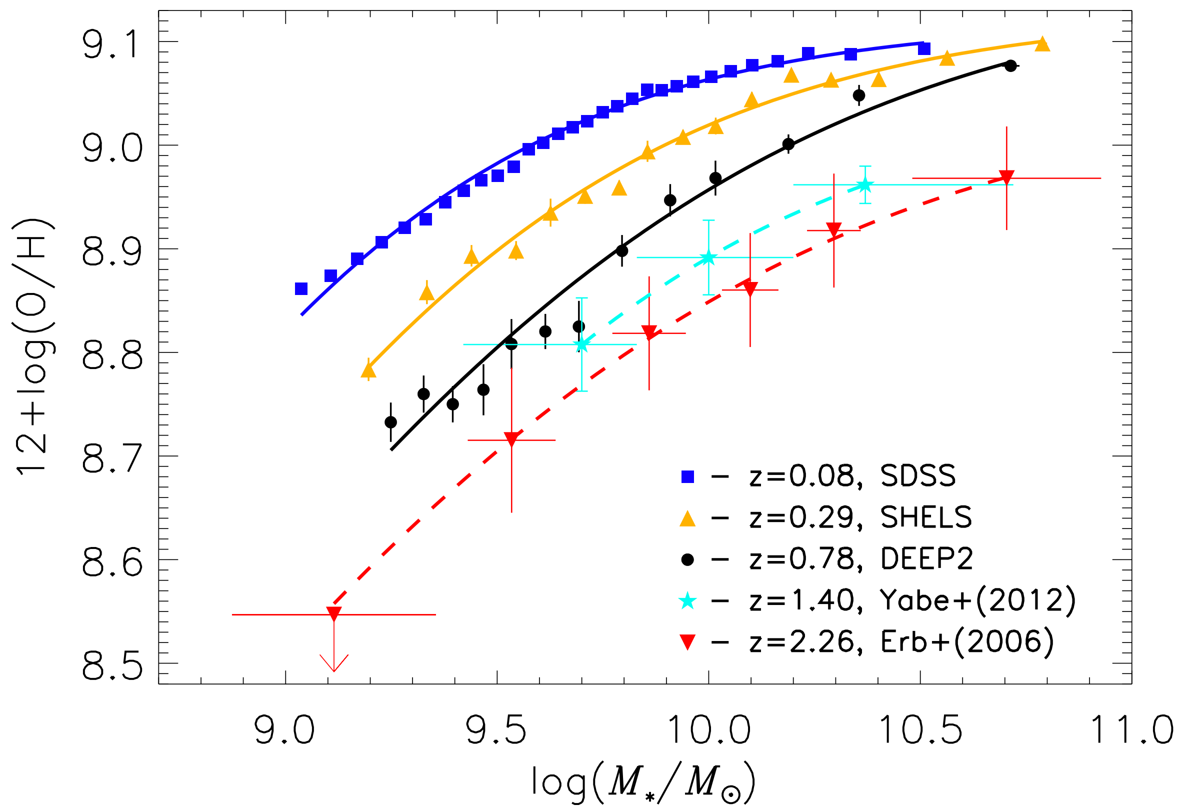
$M_{DM} = (0.4 - 1.6)\ 10^{10} \mathrm{M}_\odot$.

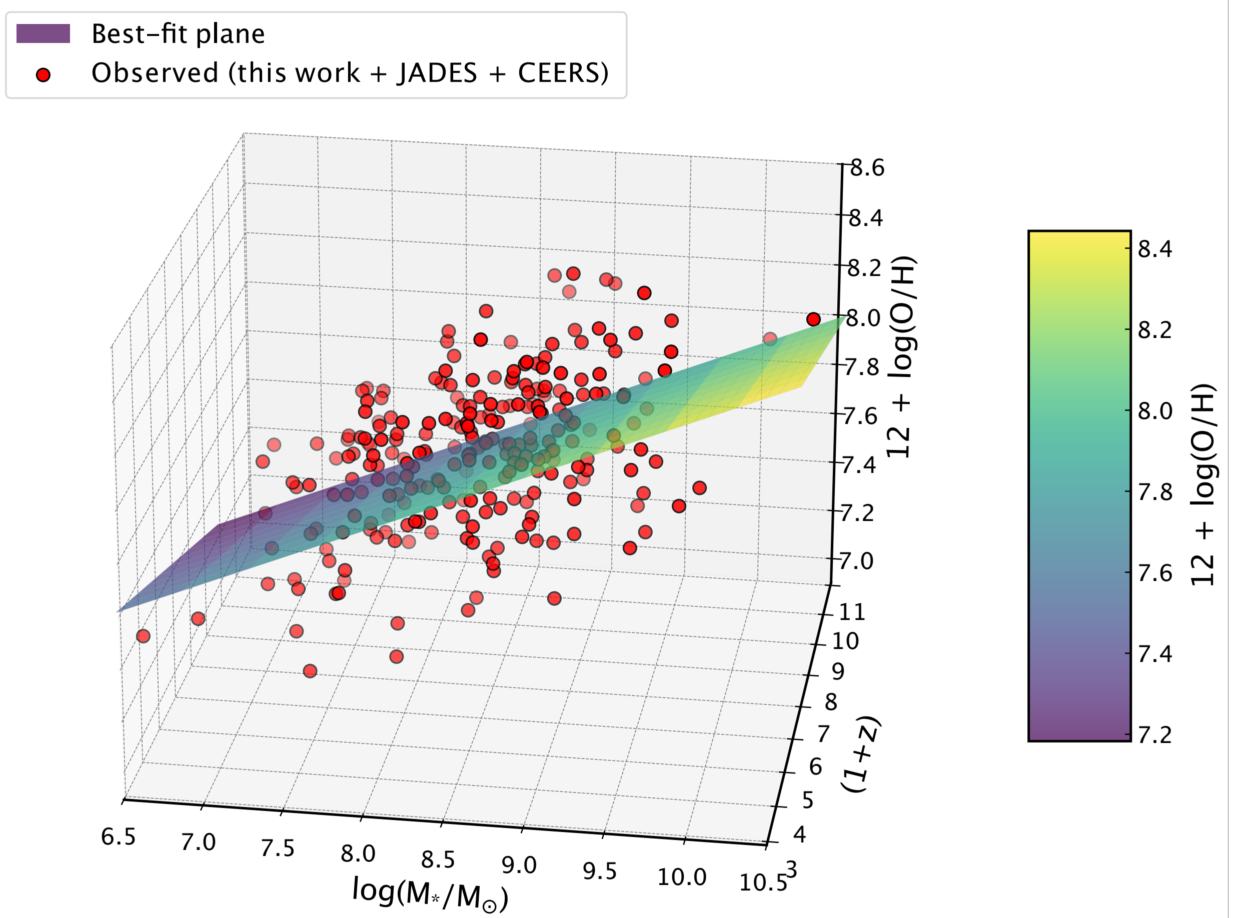
Is it similar ?

No galaxies at z = 15 - 20 .



2. Star formation





Metallicity increases in time: Zahid et al. 2013 (left) and Sarkar et al 2025 (right)

2.1 Thermal instability

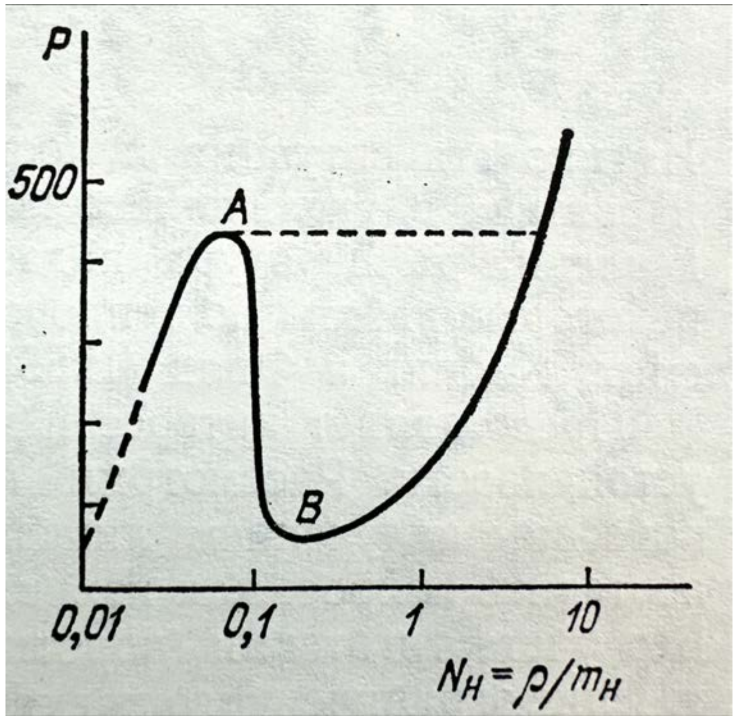
Cooling function (energy change per unit gas mass) $\dot{Q}$.

Example: $\dot{Q} = A\,\rho\,T^{\alpha} - H$ (cooling - heating).

Thermal conductivity, convection, radiation, cosmic rays etc. Both parts are, as a rule, complicated functions). Most important is radiative cooling.

Stationarity condition: $\rho f(T) - H = 0.$

Solution gives $T_{\text{stats}} = F(\rho)$, $\quad p_{\text{stats}} \sim \rho T_{\text{stats}} = \rho F(\rho)$.



Zeldovich, Novikov (1975)

AB is unstable: $\dfrac{dp}{d\rho} < 0$

Example. in the Milky Way three components exist side by side: cold gas (200 K), warm gas (10^4 K), even warmer gas ($> 10^5$ K).

Existence of dense and colder gas clouds is the natural state of interstellar gas in galaxies.

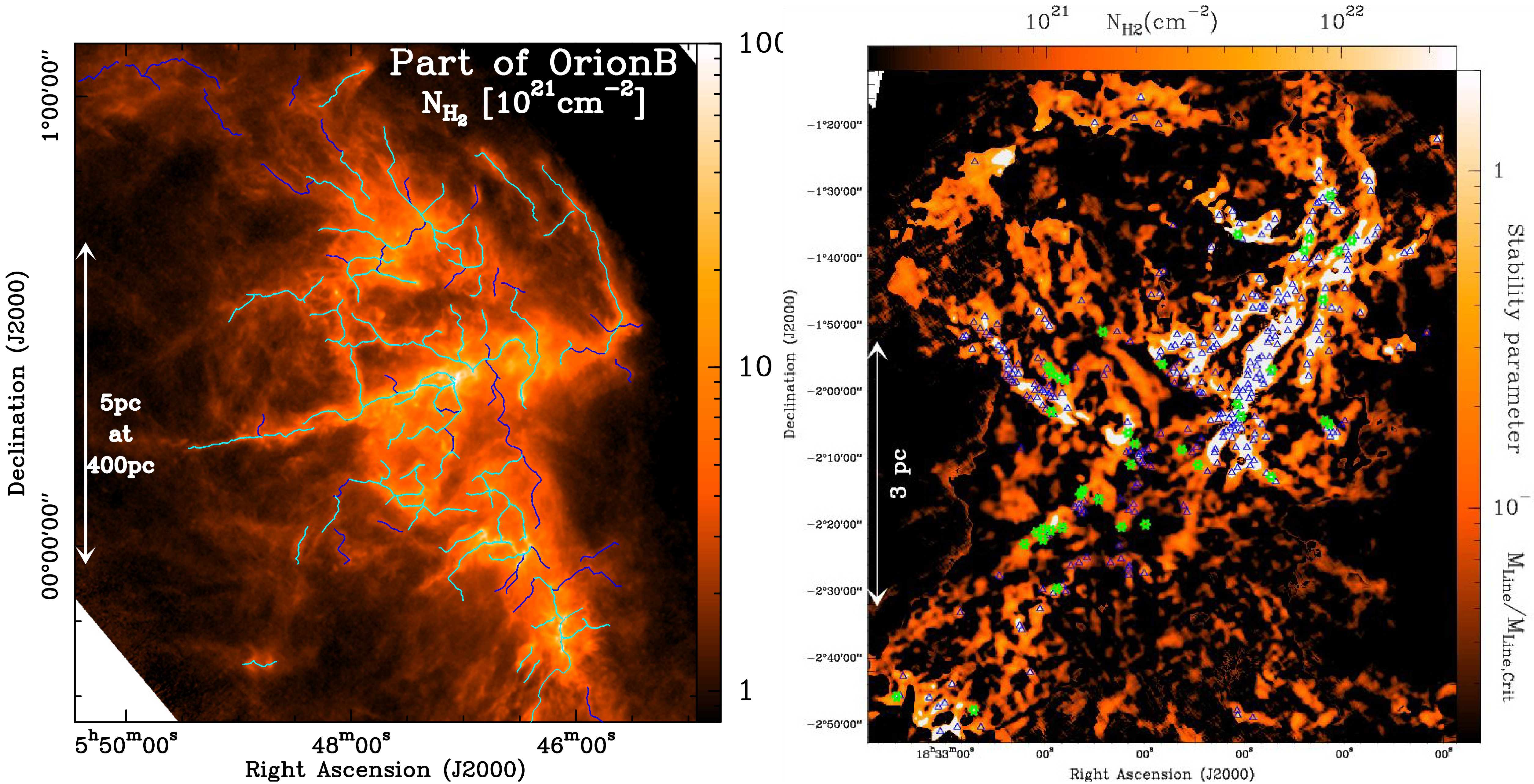
2.2 Molecular clouds - gravitational instability enters the stage

Gas contains now heavier elements, molecules, dust. They are efficient coolers: fine structure, hyperfine structure, vibrational transitions, rotational transitions ...

Gas clouds cool (up to 10-20 K) and become denser. They also accrete matter.

Giant molecular clouds: $10^5 - 10^7\,M_\odot$, 30 - 200 pc,
ordinary molecular clouds: $10^2 - 10^4\,M_\odot$, 10-20 pc.

They contain many substructures: walls, filaments, clumps. Clumps (1 pc) contain cores (0.1 pc).



Herchel Space Telescope: filamentary structure of molecular clouds according to Arzoumanian et al (2019) and Andrè et al. (2010). Length 0.5 - 100 pc, width 0.1-0.4 pc. Filaments are not stationary, they accrete gas and fragment into protostars (right). Their surface fluctuates due to Kelvin-Helmholtz instability and in this way turbulent velocities are maintained.

$$M_J = \frac{\pi^{5/2}}{6}\frac{1}{\rho}{\frac{7k_BT}{3\mu m_p G}}^{3/2}$$

In an average GMC

$T = 15\ \text{K},\ \ \mu = 2.3,\ \ n = 10^9\,\text{m}^{-3}: \quad M_J \sim 30\,\text{M}_\odot$

In a dense clump/core within the GMC

$T = 10\ \text{K},\ \ n = 10^{11}\,\text{m}^{-3}: \quad M_J \sim 1\,\text{M}_\odot$

In general, $c_{eff,s}^2 = c_s^2 + v_A^2 + v_{turb}^2$ (in MW: 0.35 km/s, 1.5 km/s, <u>6 km/s</u>).

Mass distribution function of GMCs

$$\frac{dN}{d\log M} \sim M^{-\gamma}$$

2.3 Initial mass function

The number of stars in unit volume, *dN*, with masses between *m* and *m*+*dm* is

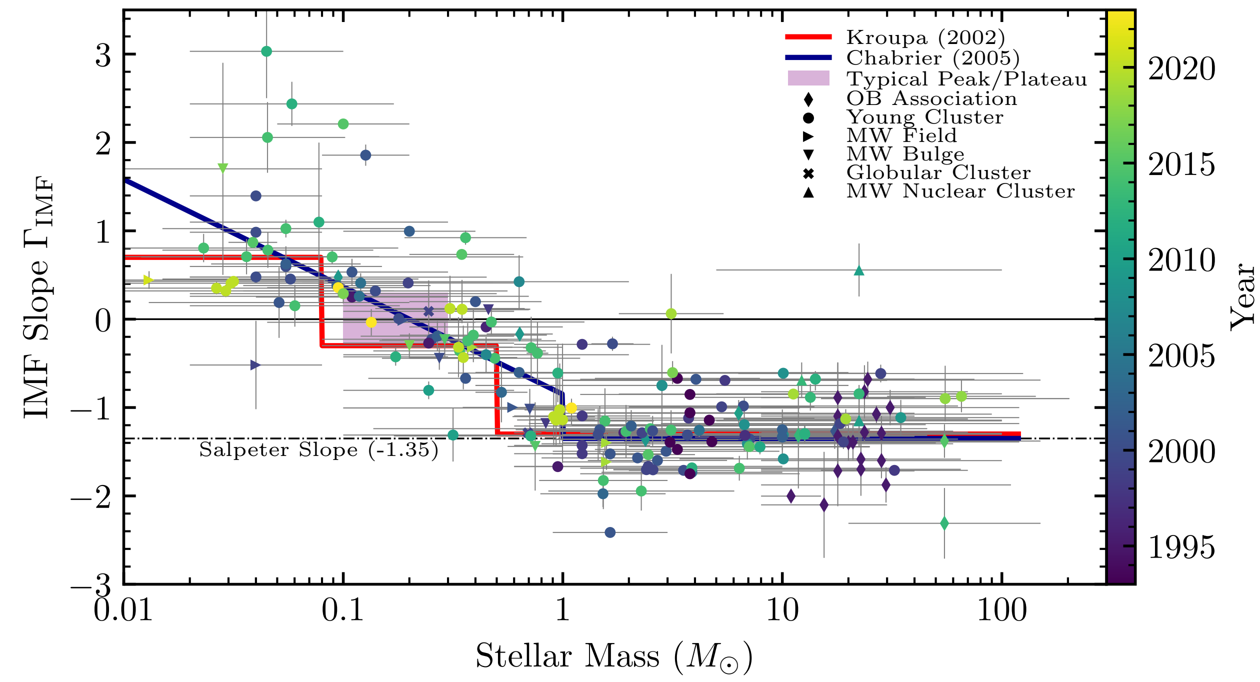
$$\frac{dN}{dm} = A\,\xi(m).$$

$\xi(m)$ in the inital mass function (IMF).

Salpeter (1955) $\xi(m) = m^{-2.35}$ for masses $0.4 - 10\,\mathrm{M}_\odot$.

Scalo (1986), Kroupa (2002) , Chabrier (2005)

2. Star formation



Scalo

$m^{-1.8}$ for $0.2 \le m < 1,$

$m^{-3.25}$ for $1 \le m < 10,$

$0.16\, m^{-2.45}$ for $m \ge 10$

Kroupa

$0.0375\, m^{-1.3}$ for $0.08 \le m < 0.5,$ but also for 0.01 - 0.08

$0.0187\, m^{-2.3}$ for $0.5 \le m < 1,$

$0.0187\, m^{-2.3}$ or $m^{-2.7}$ for $m \ge 1$

Chabrier

$$0.093\, \frac{1}{m} \exp - 1.653 \log \frac{m}{0.2}^{2} \quad \text{for } m < 1,$$

$$0.041\, m^{-2.35} \quad \text{for } m \ge 1$$

Normalizing:

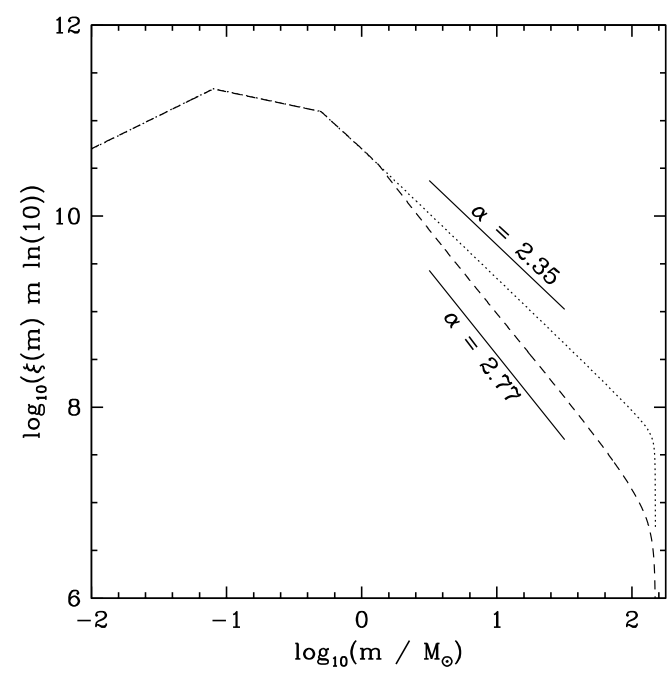
$$A \int_{m_{\rm low}}^{m_{\rm high}} m\,\xi(m)\,dm = \rho_{\rm loc}$$

or

$$A \int_{m_{\rm low}}^{m_{\rm high}} m\,\xi(m)\,dm = 1$$

$$(m_{low} = 0.08\ \mathrm{M}_\odot, \qquad m_{high} = 120\ \mathrm{M}_\odot \text{ or } 150\ \mathrm{M}_\odot)$$

In addition, a galaxy-wide IMF (Kroupa & Weidner 2003):

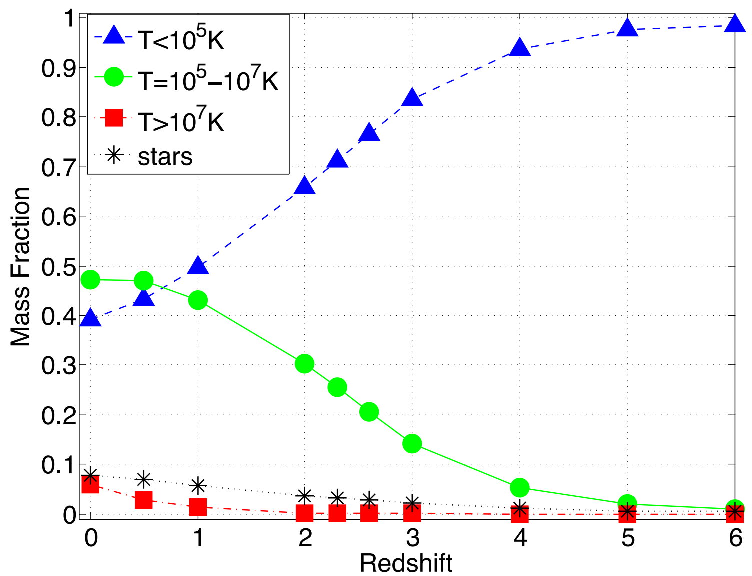


3. Gas infalls and outflows in galaxies

3.1 Gas in and around galaxies - current situation

One possibility to distinguish:

- Cold neutral gas, $T < 10^4$ K, within optical dimensions. Several subcomponents.
- Lukewarm gas $T \sim 10^4 - 10^5$ K.
- Warm gas $T \sim 10^5 - 10^6$ K.
- Hot gas, $T > 10^6$ K, in distant non-virialized regions, soft X-rays.



Cen 2011

We know it by comparing e.g. O II, O V, O VII lines.

- Interstellar, ISM (within opt dimensions)
- Circumgalactic, CGM (within DM halo)
- Intergalactic, IGM (outside galaxies)

3.2 Basic physical characteristics of the gas

3.2.1 Virial temperature of the gas

Virial equilibrium condition is $2K = -U$.

$$K = \frac{3}{2} k_B T N = \frac{3}{2} \frac{k_B T M_{\rm gas}}{\mu m_p} \quad U = -\frac{3 G M_{\rm gas} M}{5 R_g}$$

$$T_{\rm vir} = \frac{\mu m_p G M}{5 k_B R_g} = \frac{\mu m_p}{5 k_B} v_c^2 .$$

If $v = 160$ km/s, then $T_{\rm vir} = 10^6$ K.

3.2.2 Cooling and dynamical timescales

Internal energy per unit volume is

$$\mathscr{E}_{\rm int} = \frac{E_{\rm int}}{V} = \frac{3}{2}\frac{Nk_BT}{V} = \frac{3}{2}nk_BT\,.$$

Cooling time is $t_{\rm cool} \equiv \dfrac{\mathscr{E}}{|d\mathscr{E}/dt|}\,.$

$$\frac{d\mathscr{E}}{dt} = \frac{dE}{V\,dt} = \rho\frac{dE}{M\,dt} = \rho\dot{Q} =_{\text{without heating}} = -n^2\Lambda(T)$$

Thus,

$$t_{\rm cool} = \frac{3k_BT}{2n\Lambda(T)}\,.$$

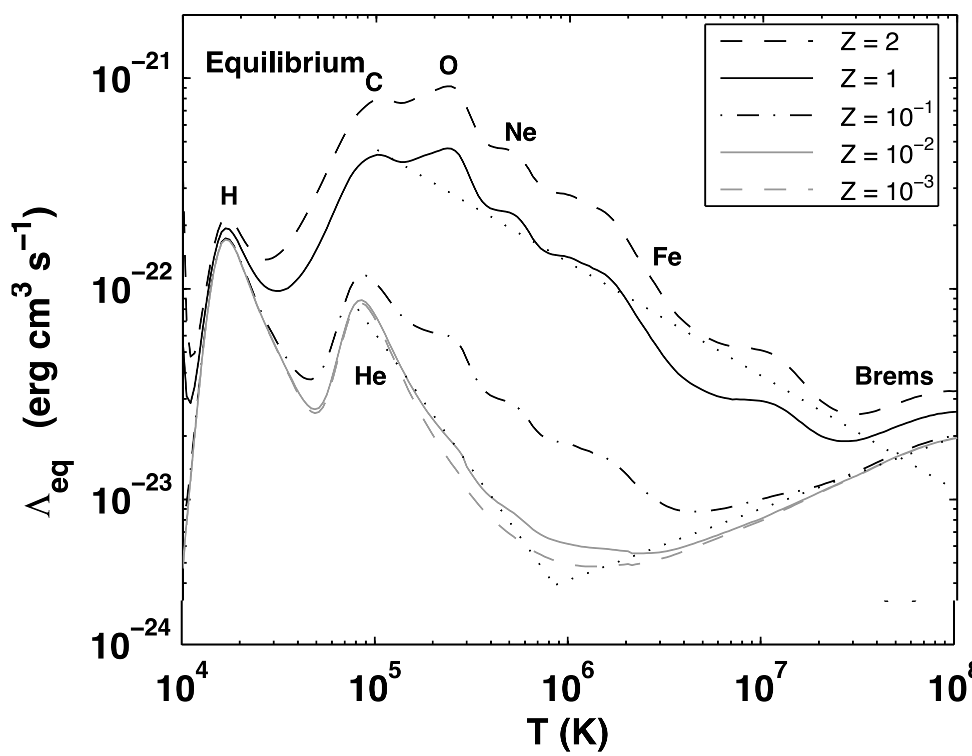
Dynamical time (see Binney, & Tremaine, Sect 2.2)

$$t_{\rm dyn} = \frac{3\pi}{16G\rho}\,.$$

3.2.3 Radiative cooling (most important)

- $\geq 10^7$ K, electrons radiate and loose energy: free-free transitions
- at lower T, free electron recombines with some ion: free-bound transitions
- at lower T, atom is excited and electron in atom/ion returns to the lower state: bound-bound transitions

Radiative cooling strongly depend on the chemical composition of the gas.



Gnat, Sternberg 2007

3.2.4 Basic heating processes

- photoheating: UV photons ionize atoms/ions and e^- acquires kinetic energy and thereafter collides with other particle. For H this is effective for temperatures < 10^5 K. Photons can free electrons also from small dust grains. It may be quite important.
- heating by (cosmic ray) particles. A single CR particle can ionize several atoms - important in dense molecular clouds.
- heating by shock waves (next subsection).

3.2.5 Shock waves

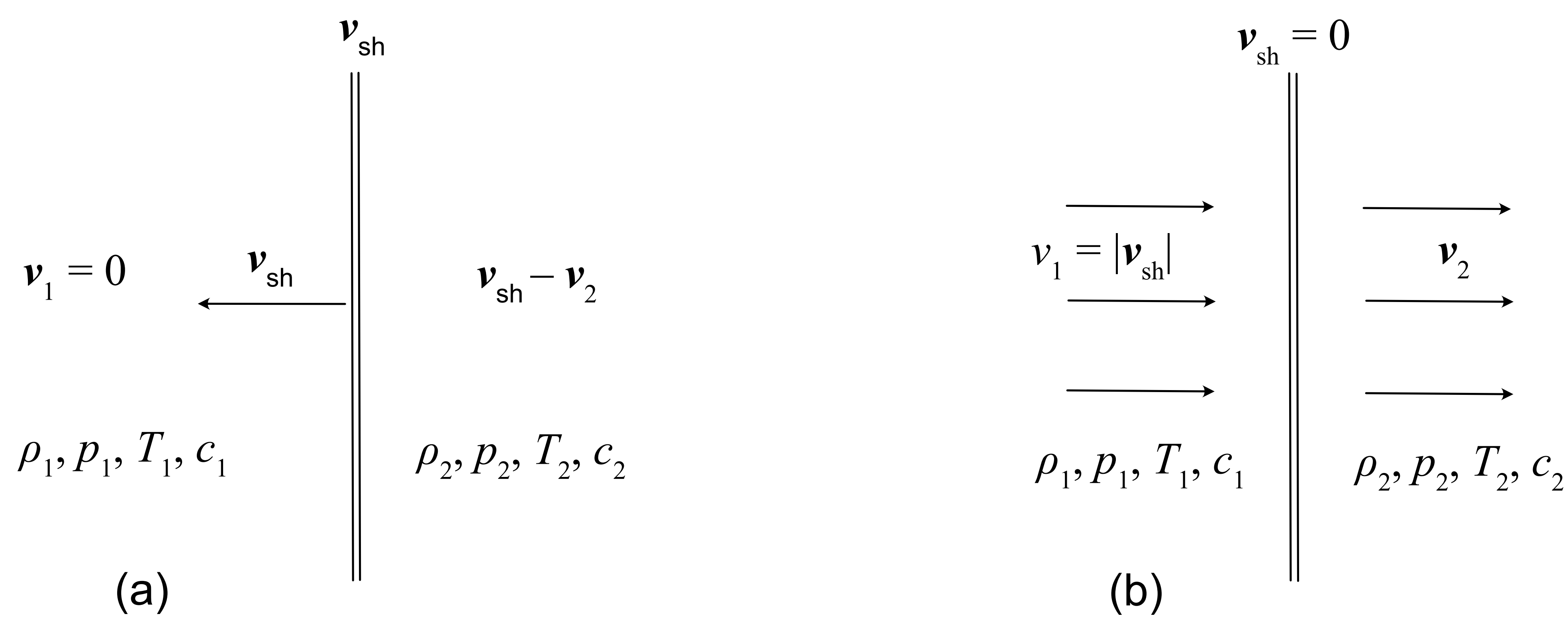
Shock waves form when “something” moves faster than sound speed.

Example: air/water flow and there is something in the air/water. Flow behaviour depends on the flow speed and sound speed.

Mach number $\mathscr{M} \equiv v/c_S$.

$c_s \simeq 0.152T$, thus if $T = 10^6$ K, $c_s = 150$ km/s.

Shock front is very thin, few free path lengths (in average MW gas ~100 au).



Rankine-Huginot conditions

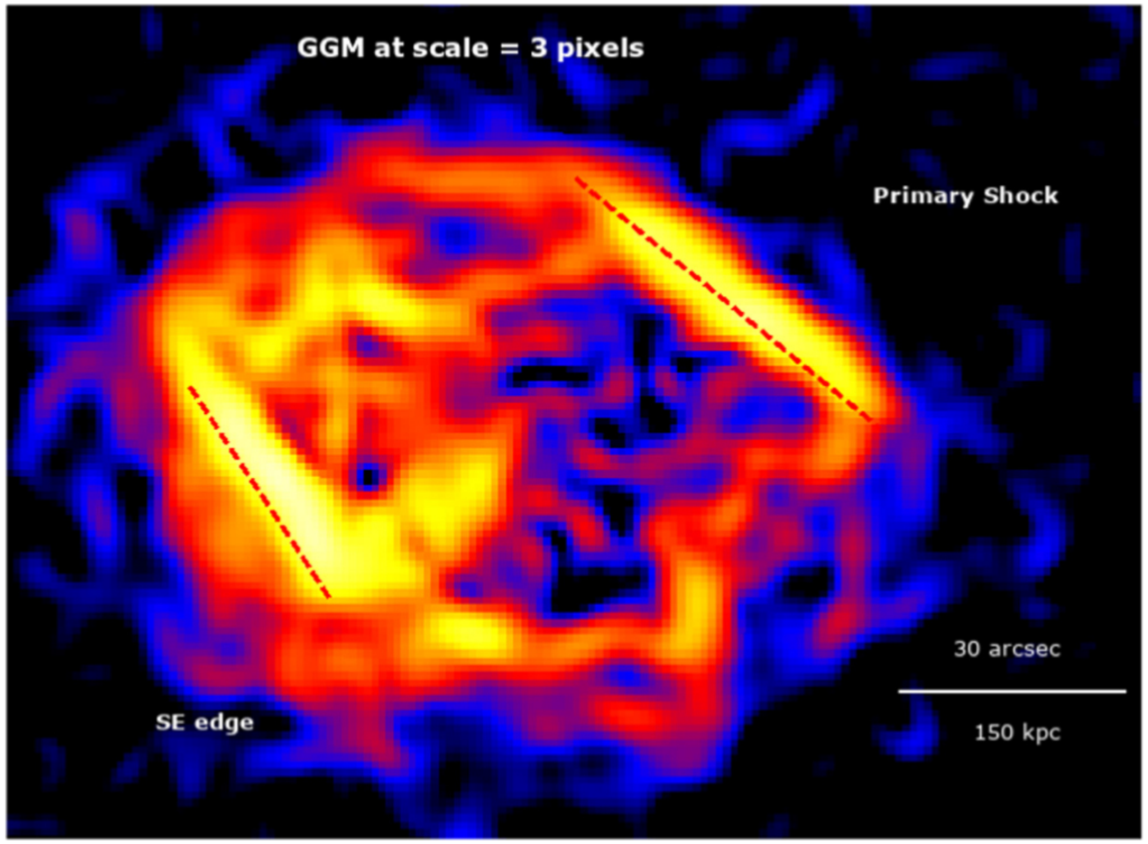
$$\frac{\rho_2}{\rho_1} = \left[\frac{1}{\mathscr{M}_1^2} + \frac{\gamma-1}{\gamma+1}\left(1 - \frac{1}{\mathscr{M}_1^2}\right)\right]^{-1},$$

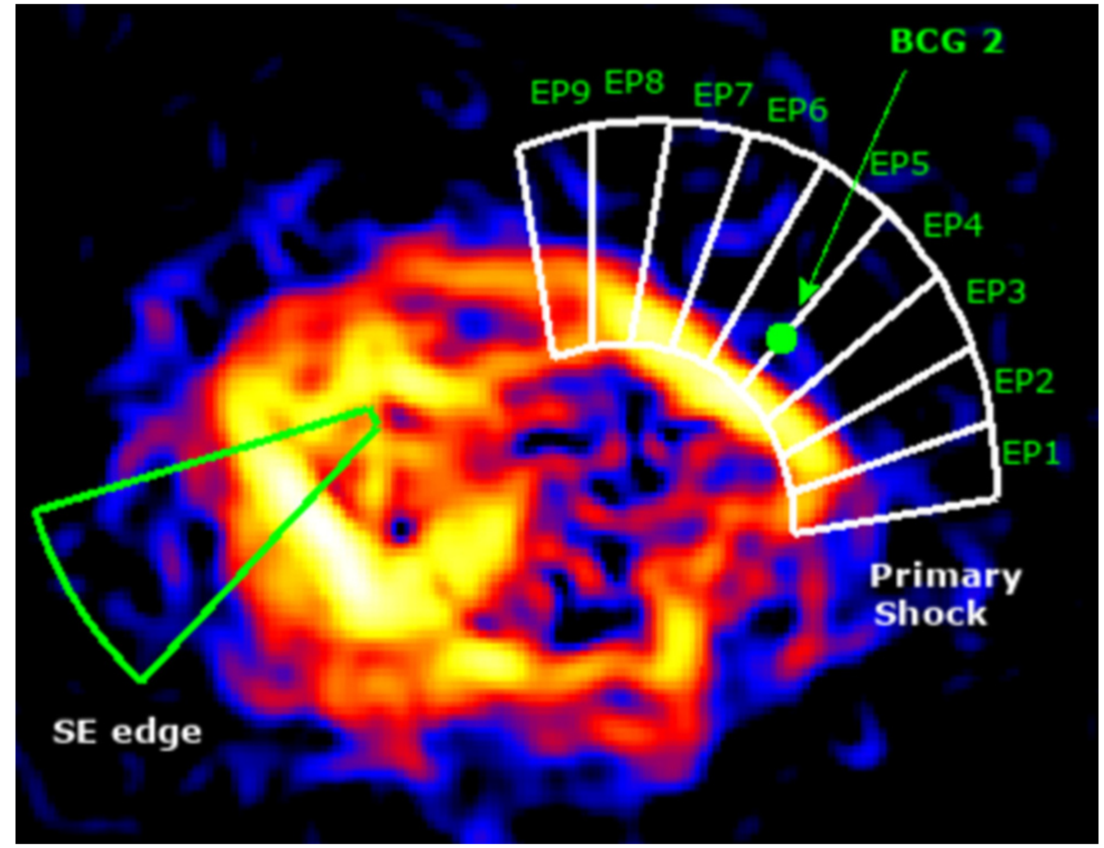
$$\frac{p_2}{p_1} = \frac{2\gamma}{\gamma+1}\mathscr{M}_1^2 - \frac{\gamma-1}{\gamma+1},$$

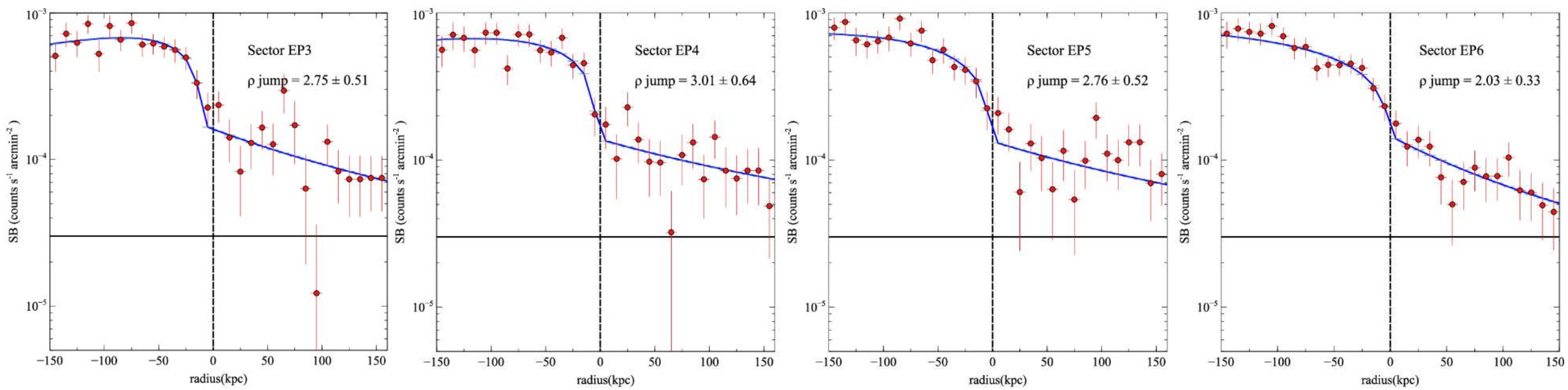
$$\frac{T_2}{T_1} = \frac{\gamma-1}{\gamma+1}\frac{2}{\gamma+1}\left(\gamma\mathscr{M}_1^2 - \frac{1}{\mathscr{M}_1^2} + \frac{4\gamma}{\gamma-1} - \frac{\gamma-1}{\gamma+1}\right).$$

In case of adibatic strong shocks ($\gamma = 5/3, \quad \mathscr{M}_1 >> 1$)

$$\frac{\rho_2}{\rho_1} = 4, \quad \frac{p_2}{p_1} = \frac{5}{4}\mathscr{M}_1^2, \quad \frac{T_2}{T_1} = \frac{5}{16}\mathscr{M}_1^2.$$







A merging cluster, Chandra data, Diwanji et al 2024,

$\mathscr{M} = 3.09^{+0.75}_{-0.43}$

3.3 Gas accretion

Accreting gas falls to the galaxy DM halo. Infalling gas is colder and shock front forms. Shock heats infalling gas, but heated gas cools.

If $t_{\mathrm{cool}} << t_{\mathrm{dyn}}$, cool gas falls to the centre;

if $t_{\mathrm{cool}} >> t_{\mathrm{dyn}}$, gas remains ~equilibrium to the DM halo and may fall slowly later (if $t_{\mathrm{cool}} < t_{\mathrm{Hubble}}$).

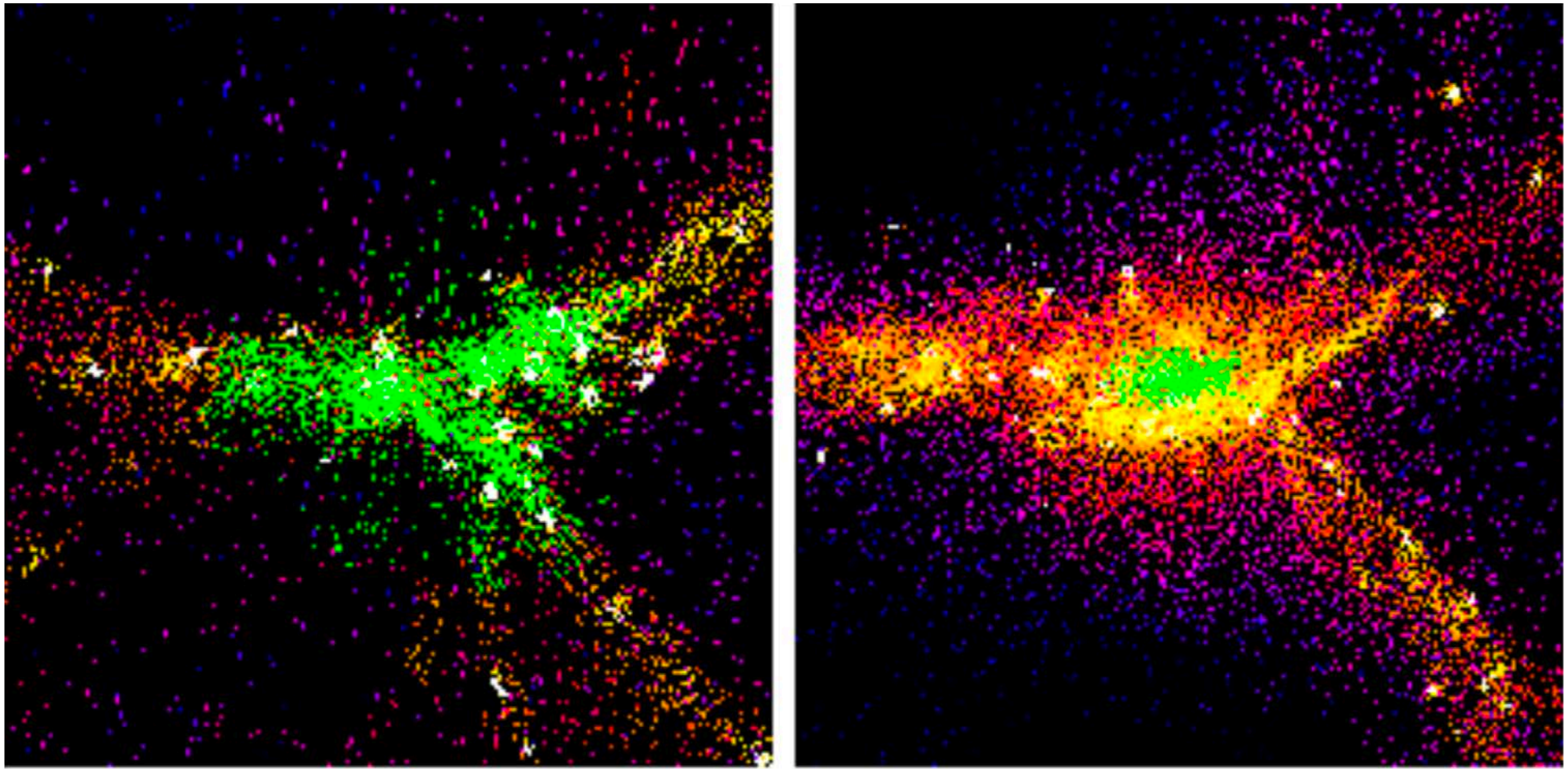
We know already, that $t_{\mathrm{dyn}} \sim 1/\rho \sim 1/n$, $t_{\mathrm{cool}} \sim 1/n$, thus, cooling dominates in denser systems or in denser parts.

Simulations: two forms of accretion: the cold and the hot mode of accretion. Distinction is at about $M \sim (3-5) \times 10^{11}\, \mathrm{M}_\odot$

Cold mode is in smaller systems. Gas cools and falls to the central regions, is stopped by disc. A shock propagates outwards but not to virial radius, then falls again. $T \sim 10^4 - 10^5$ K, this gas is a resource for star formation.

Hot mode is in massive systems. Gas cools too slowly and a moderate shock forms at virial radius. Gas do not fall to the centre, remains at virial radius. (Virial radius slowly moves outwards.)

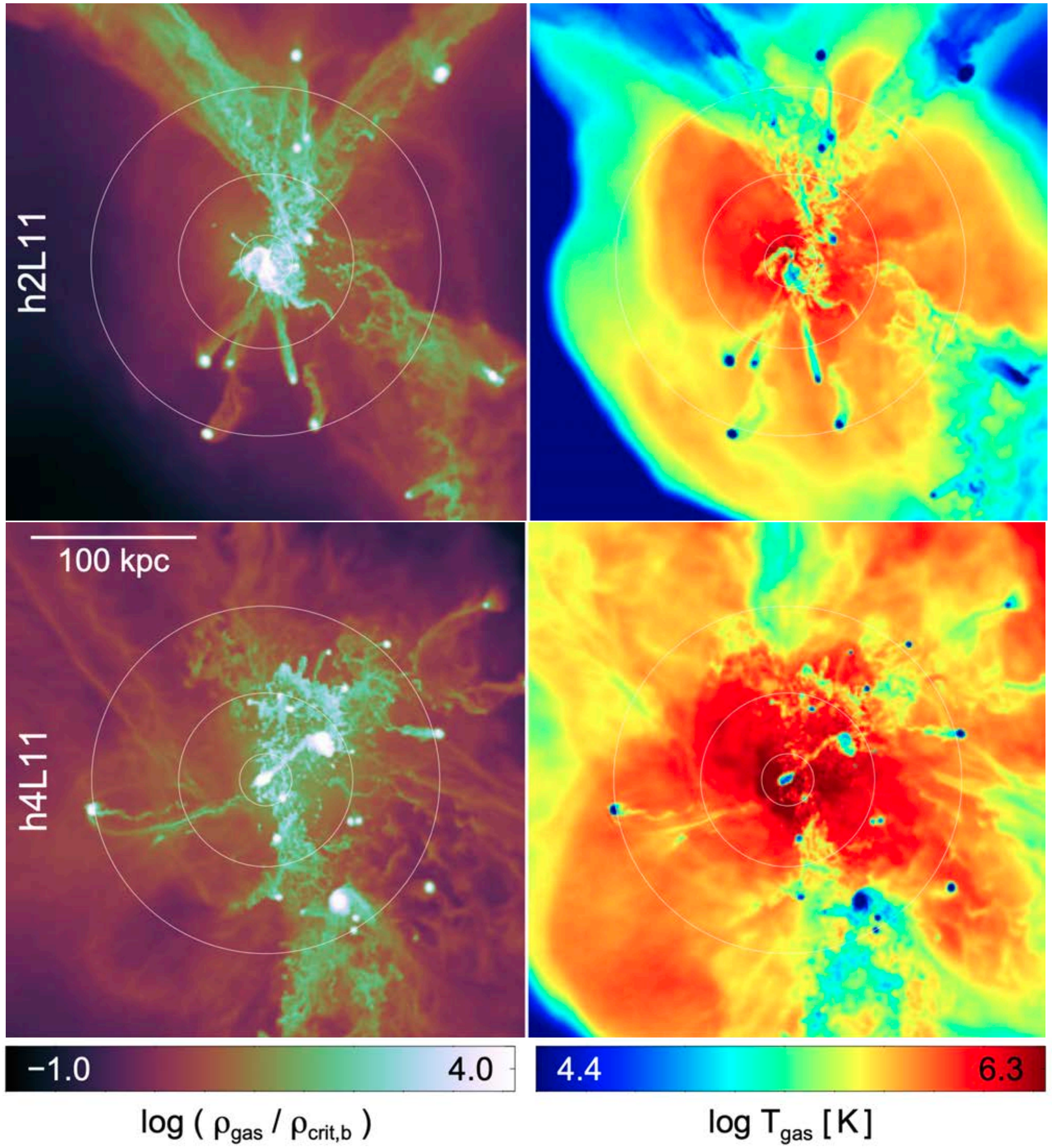
Cold mode is filamentary, hot mode more spherical (see next slides).



Kereš et al 2005,
green - gas,
particles - from
yellow (densest)
to blue.
Box size 4 R_{vir}.

The same galaxy at different redshift

Cold mode	Hot mode
$z = 5.52,\ M = 2.6 \times 10^{11}\,\mathrm{M}_\odot$	$z = 3.24,\ M = 1.3 \times 10^{12}\,\mathrm{M}_\odot$

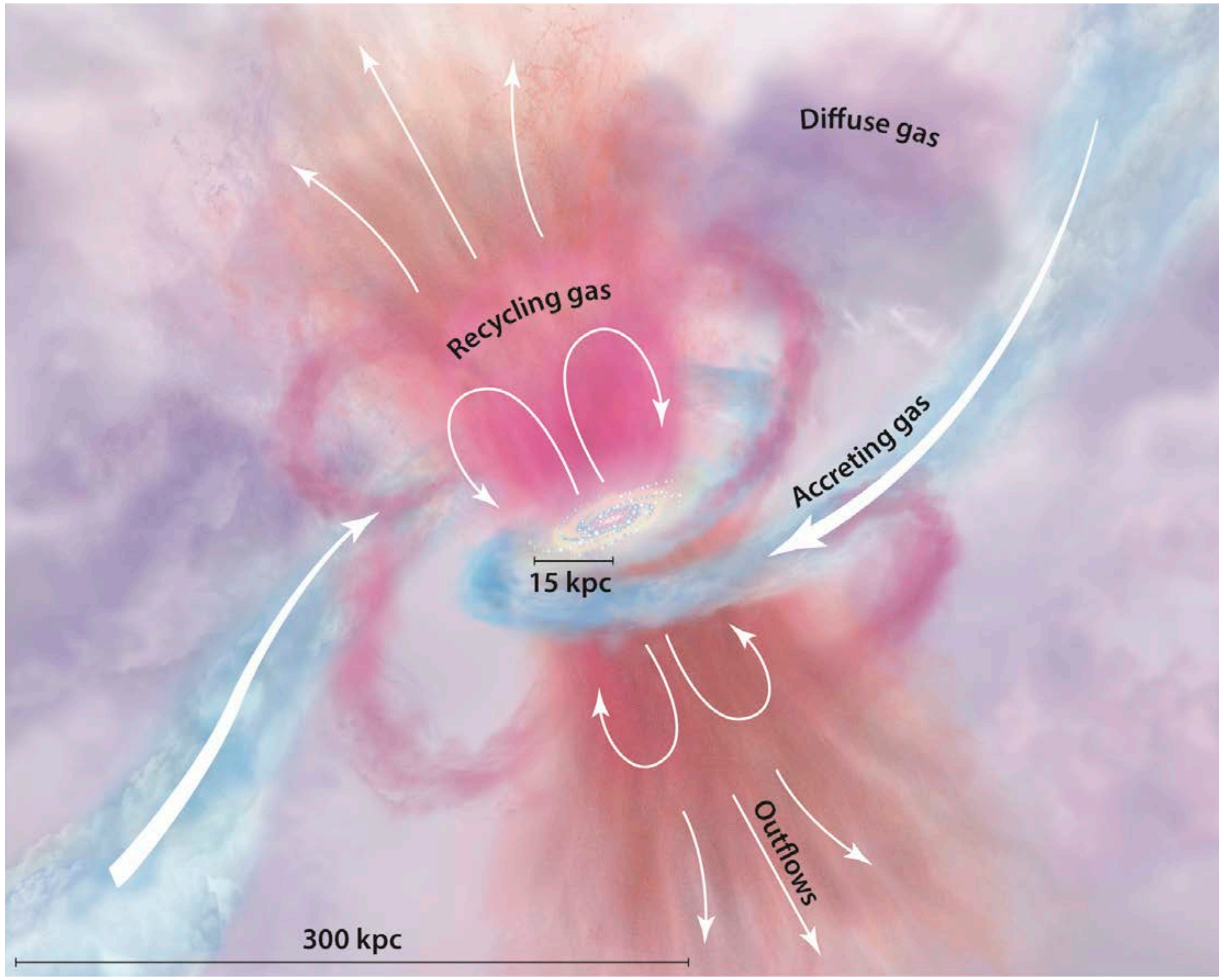


Another example of cold mode. A massive galaxy but here we see simultaneously cold and hot mode.

B.t.w., balance between the $t_{\rm cool}$, $t_{\rm dyn}$ can be different in different parts of the same system.

Nelson et al. 2016

3.4 Gas inflows and outflows

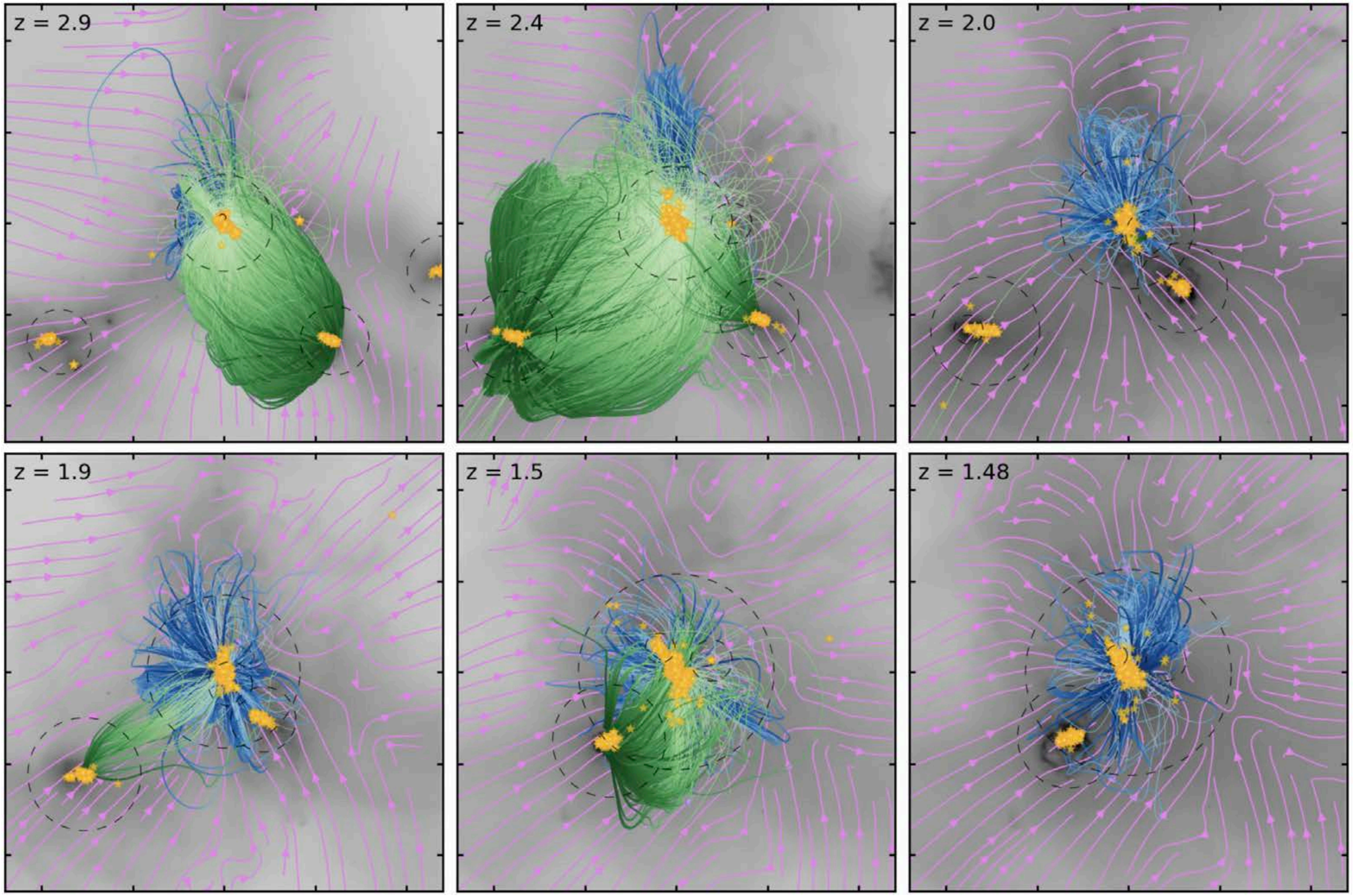


Tumlinson et al. 2017.

SFR exhaust cold gas in discs within 2 - 6 Gyrs. Thus, accretion is needed.

Cold and lukewarm circumgalactic gas reservoirs are seen in Ly limit systems. In several cases the gas is enriched.

Ourflows are often biconical, extending up to 60-100 kpc..



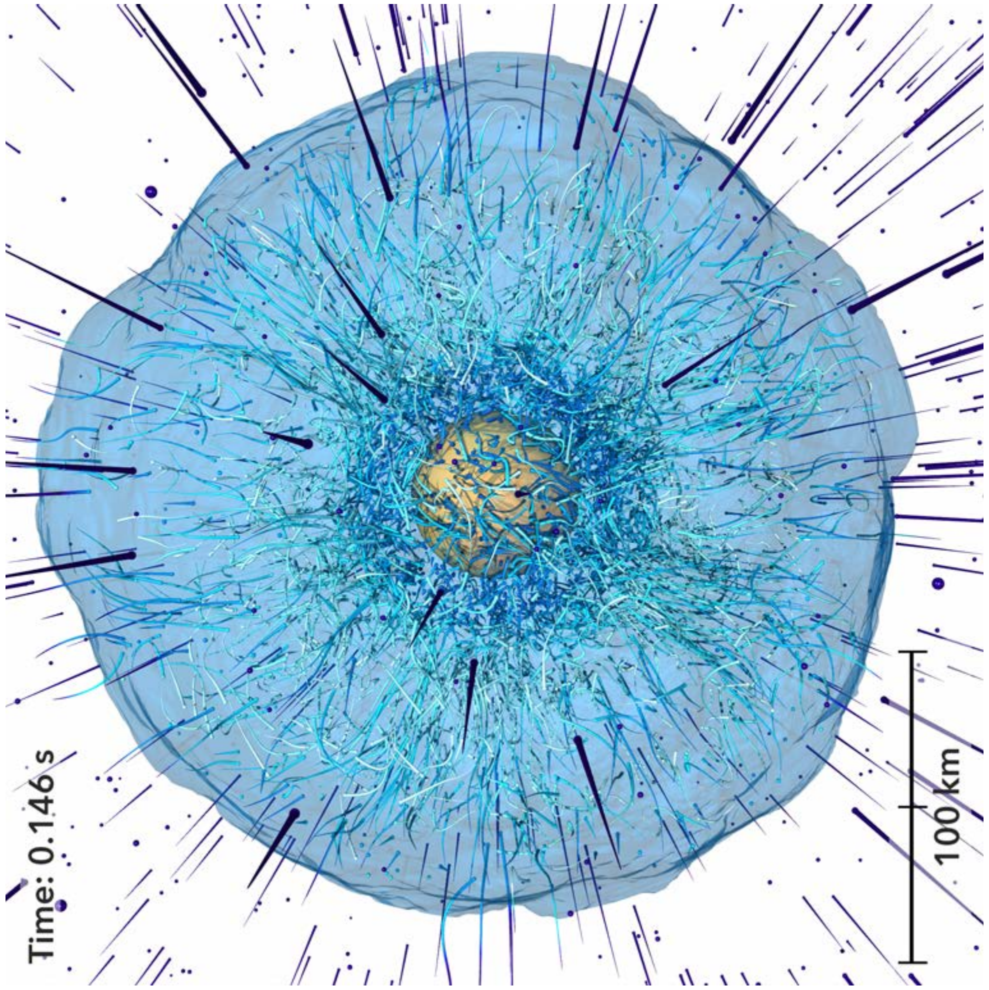
Angles-Alkazar et al 2017, box 240 kpc

yellow - stars, purple - fresh gas, blue - future outflows and falls back, green - accretion from other galaxies

4. Chemical evolution of galaxies

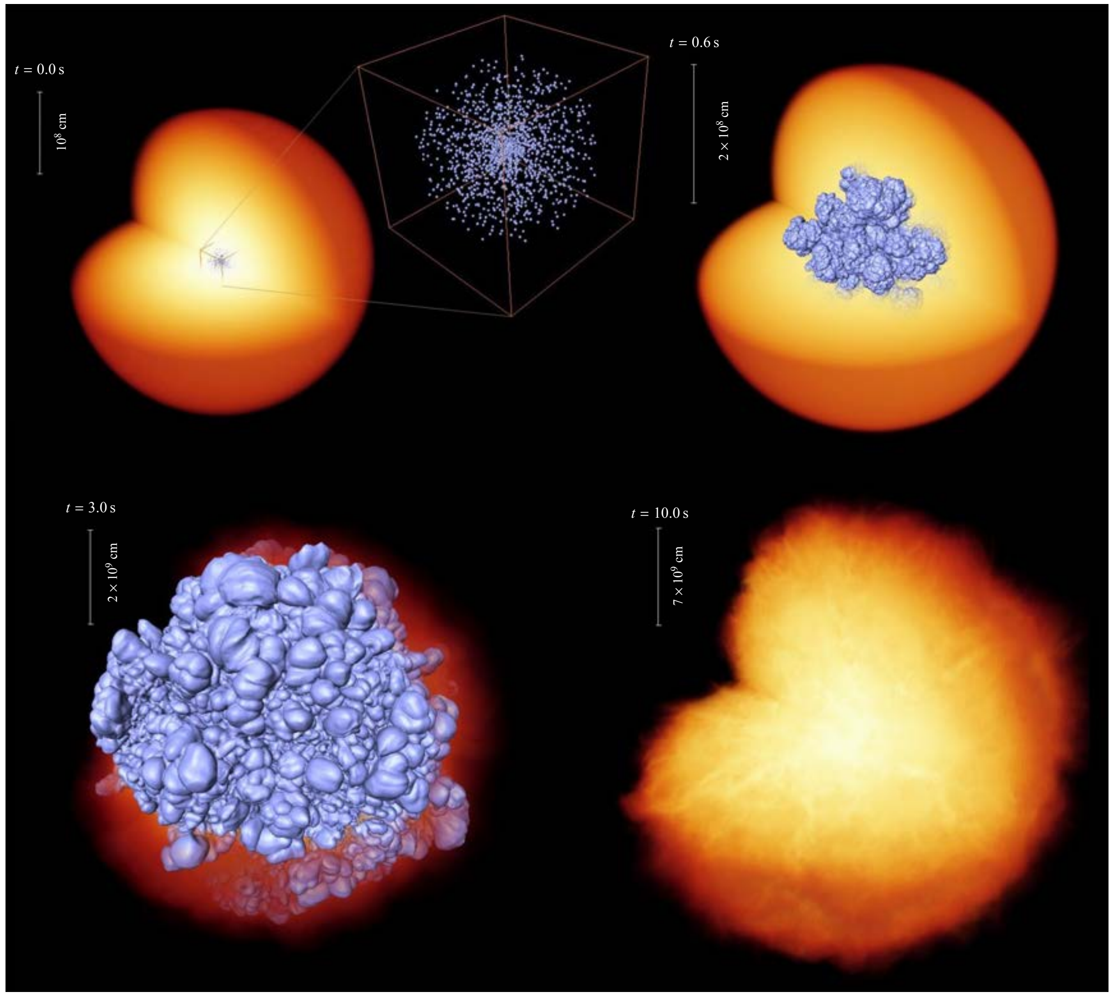
4.1 Supernovae explosions

core-collapse supernovae
($_{8}$O,..., $_{13}$Al,..., $_{31}$Ga,..., $_{37}$Rb,+Fe)



Burrows, Vartanyan 2021

thermonuclear supernovae
($_{14}$Si, ... , $_{30}$Zn, +Fe)



Röpke et al. 2007

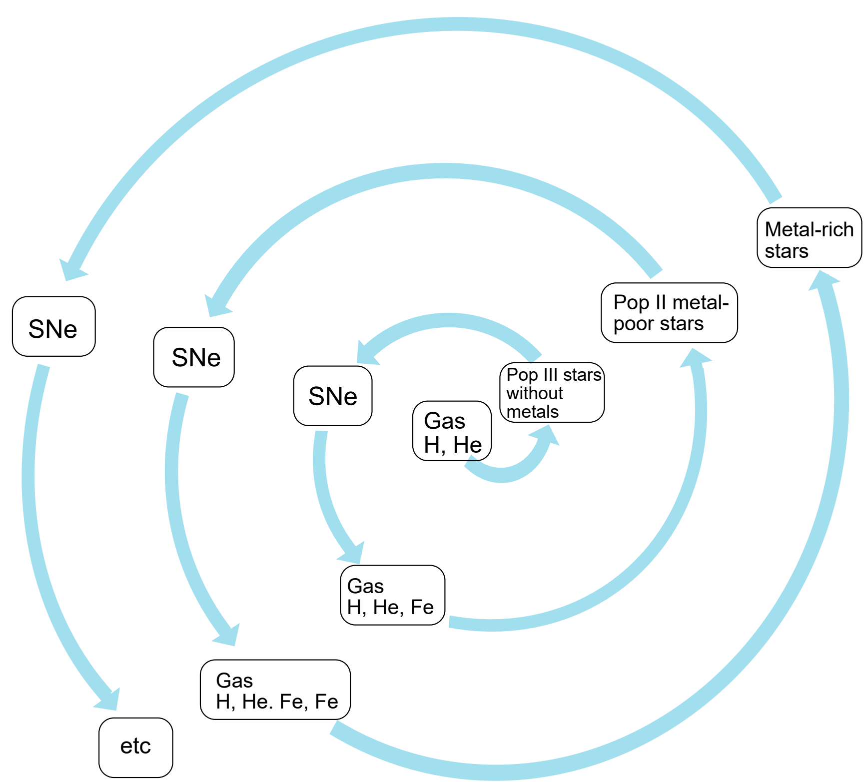
Example: [Mg/Fe] is produced only in core-collapse SNe ($_{12}$Mg),
Fe in both.
If [Mg/Fe] is higher in a galaxy, then contribution of c-c SNe there is larger. Contribution of higher-mass stars is larger, star formation is more recent.

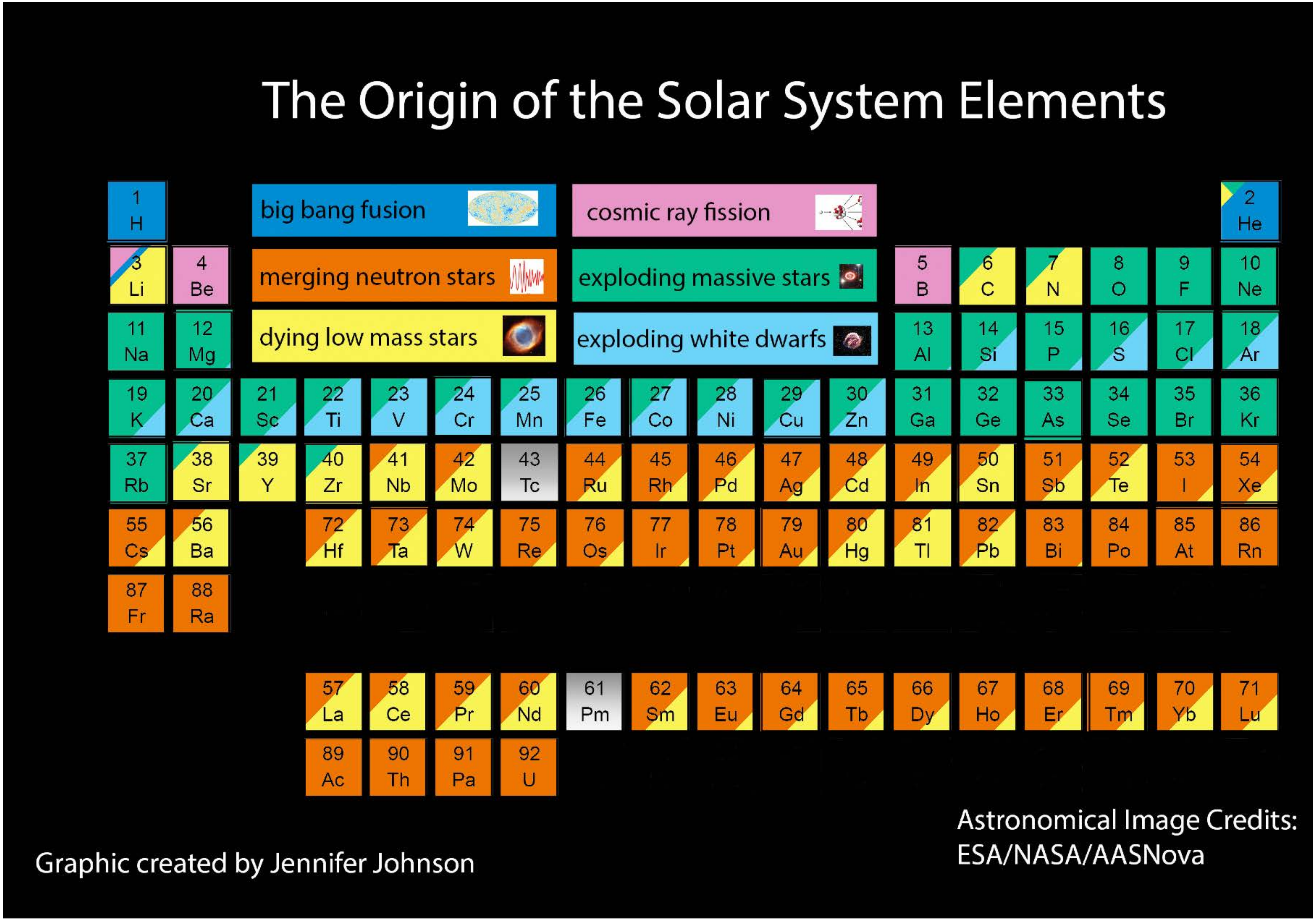
4.2 Mergers of neutron stars

GW170817 event: GWs, 1.7 s later gamma-rays, 11 h later optical (from UV to near IR, spectra), 9 d later X-rays, 16 d later radio.

Understanding of the contribution of r-processes changed.

4.3 Production of chemical elements




The Origin of the Solar System Elements
big bang fusion
cosmic ray fission
merging neutron stars
exploding massive stars
dying low mass stars
exploding white dwarfs
1 H
2 He
3 Li
4 Be
5 B
6 C
7 N
8 O
9 F
10 Ne
11 Na
12 Mg
13 Al
14 Si
15 P
16 S
17 Cl
18 Ar
19 K
20 Ca
21 Sc
22 Ti
23 V
24 Cr
25 Mn
26 Fe
27 Co
28 Ni
29 Cu
30 Zn
31 Ga
32 Ge
33 As
34 Se
35 Br
36 Kr
37 Rb
38 Sr
39 Y
40 Zr
41 Nb
42 Mo
43 Tc
44 Ru
45 Rh
46 Pd
47 Ag
48 Cd
49 In
50 Sn
51 Sb
52 Te
53 I
54 Xe
55 Cs
56 Ba
72 Hf
73 Ta
74 W
75 Re
76 Os
77 Ir
78 Pt
79 Au
80 Hg
81 Tl
82 Pb
83 Bi
84 Po
85 At
86 Rn
87 Fr
88 Ra
57 La
58 Ce
59 Pr
60 Nd
61 Pm
62 Sm
63 Eu
64 Gd
65 Tb
66 Dy
67 Ho
68 Er
69 Tm
70 Yb
71 Lu
89 Ac
90 Th
91 Pa
92 U
Graphic created by Jennifer Johnson
Astronomical Image Credits:
ESA/NASA/AASNova

4.4 Chemical evolution of galaxies

Initial mass function $\xi(m)$ was the number of stars dN in unit volume with masses between m and $m+dm$:

$$\frac{dN}{dm} \sim \xi(m)$$

with m_l and m_h as the lowest and highest masses.

m has its evolutionary end time τ_m, after that: m_r is remnant and $(m-m_r)$ rejected away.

Fraction of mass returned to ISM by the time t is

$$\int_{m_t}^{m_h} \xi(m)(m - m_r)dm \, .$$

(m_t is the lowest mass ended)

Star formation rate (SFR)

$$\psi(t) \equiv \frac{d\rho_s}{dt} = k\rho_g^{\alpha}(t) \qquad \alpha = 1.3 - 1.9$$

ρ_s should be splitted into individual masses according to IMF, gas density should be considered in more detail.

Stellar yield Y_i is mass fraction ejected to ISM in the form of the chemical element i. It is a function of m.

System of equations:

$$\frac{d(M_S + M_g)}{dt} = f(t) - o(t),$$

$$\frac{dM_s}{dt} = \psi(t) - E(t),$$

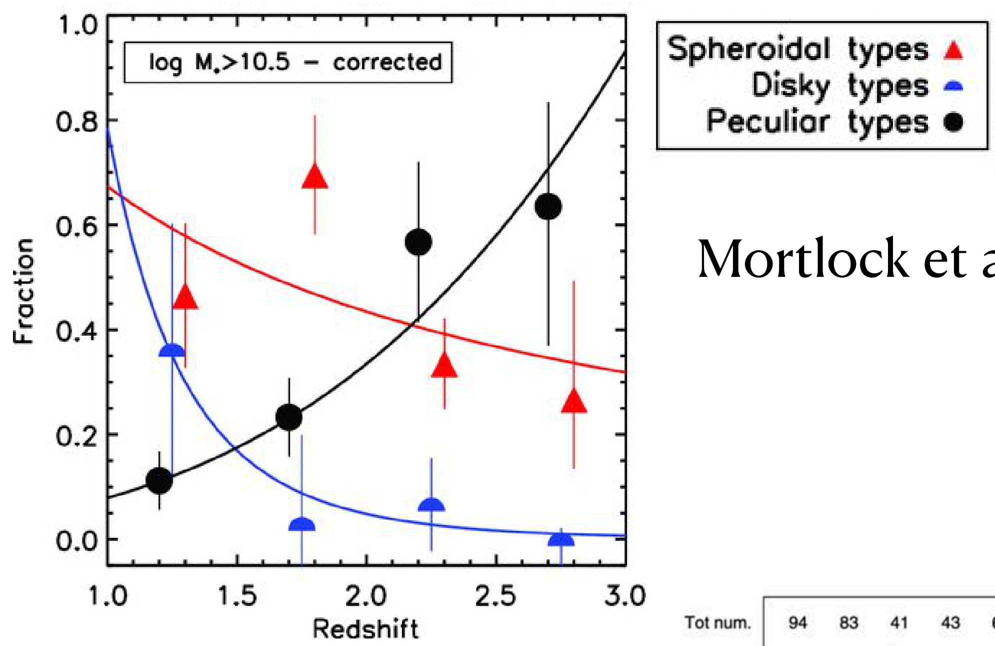
$$\frac{dM_g}{dt} = -\psi(t) + E(t) + f(t) - o(t)\,.$$

Simplifications:

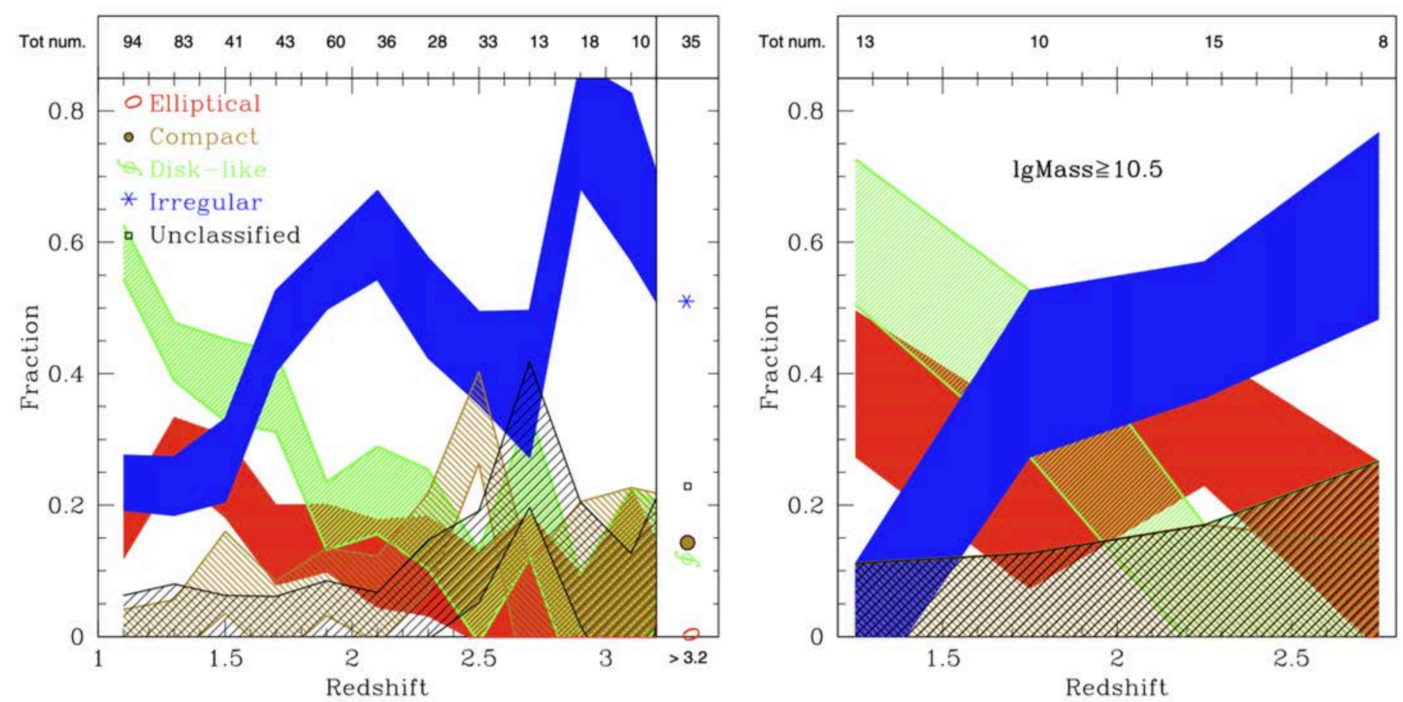
- instantaneous recycling
- closed box, at $t = 0$ $M_s = Z_i = 0$ + instantaneous recycling

5. Observing the galaxy evolution with redshift

5.1 Morphological types

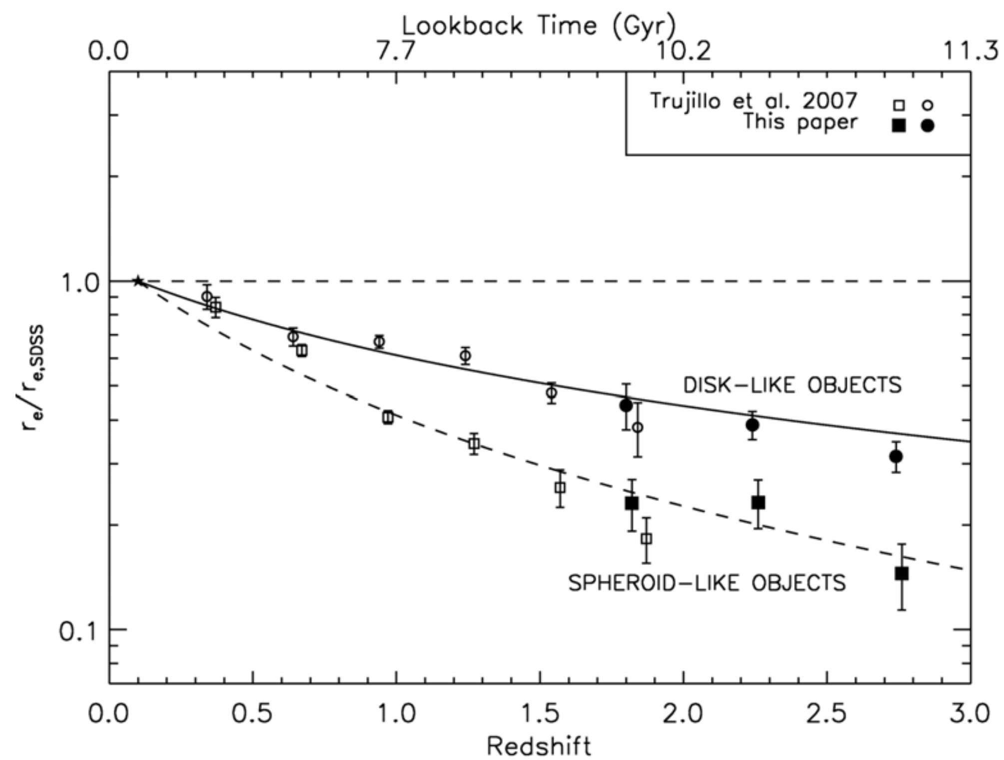


Mortlock et al. 2013

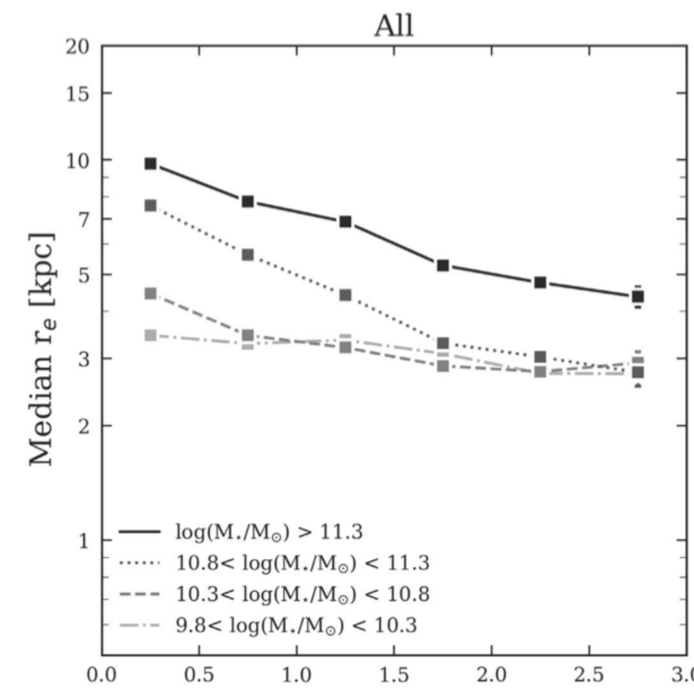


Talia et al. 2014

5.2 Dimensions



Buitrago et al. 2008

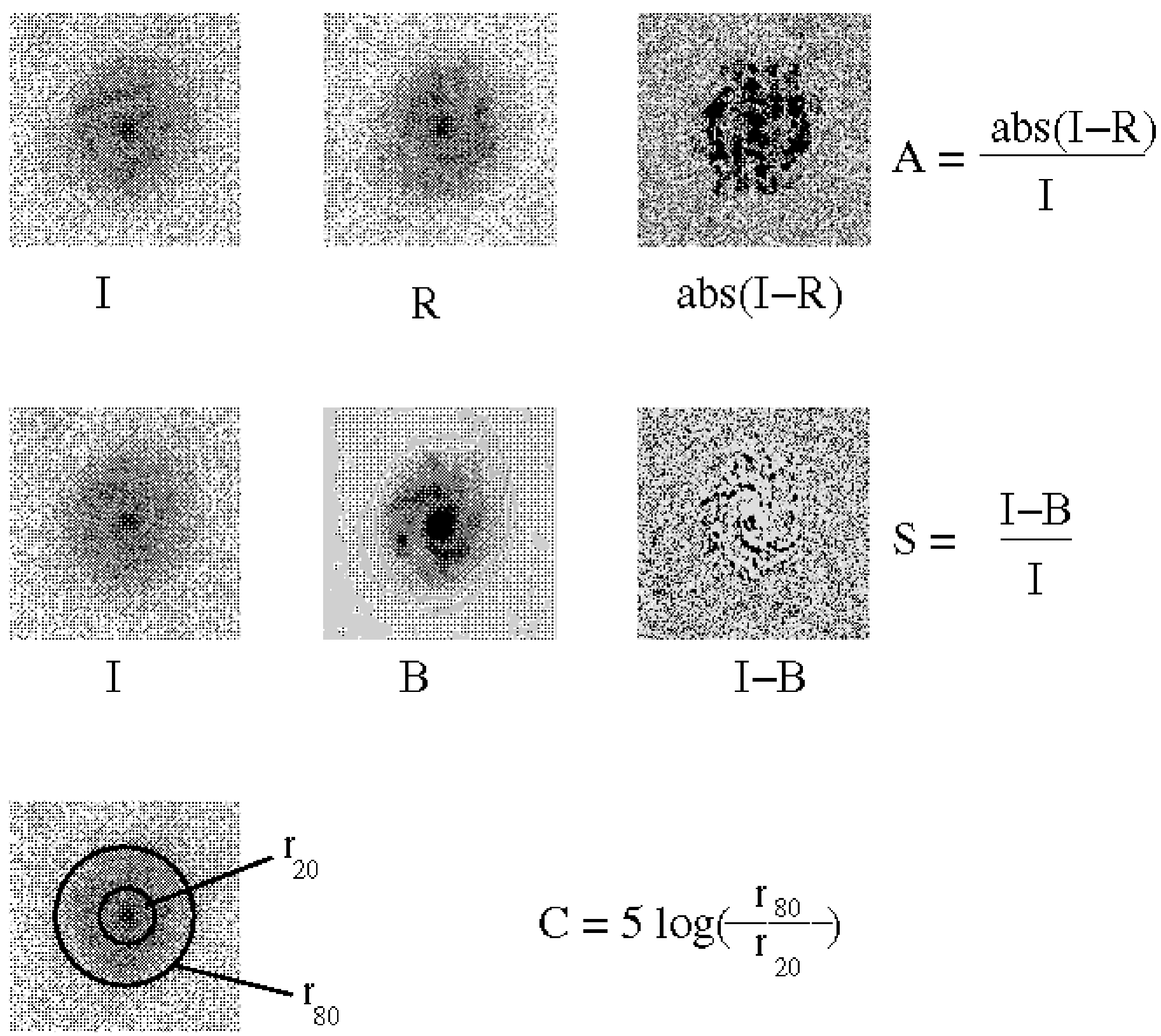


Mowla et al. 2019

$$r_{\rm eff} \sim (1+z)^{\alpha} \qquad \alpha = -1.48, \; -0.82$$

5.3 Mergers

Conselice (2014) CAS parameters:
concentration C, asymmetry A, clumpiness S



The merger fraction

$$f_{\rm m} \equiv \frac{N_m}{N_T}, \qquad f_{\rm m} = f(M_*, z)$$

and merger rate Γ (average time between mergers).

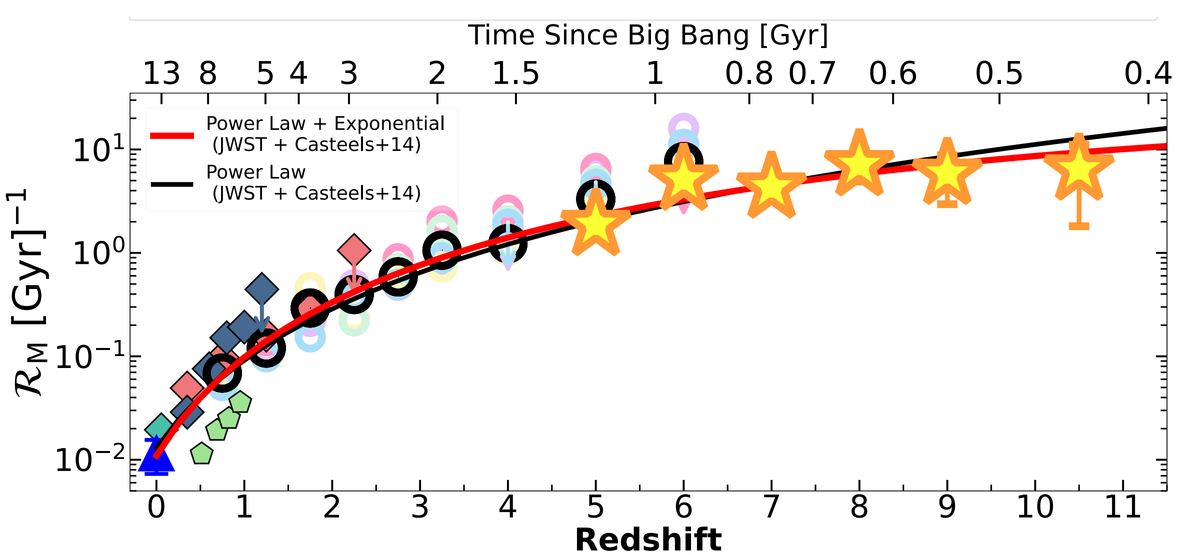
Concelice (2014):

monotonic $f_{\rm m}(z) = f_0(1+z)^m$ or

with a peak $f_{\rm m}(z) = \alpha(1+z)^m \exp[\beta(1+z)]$.

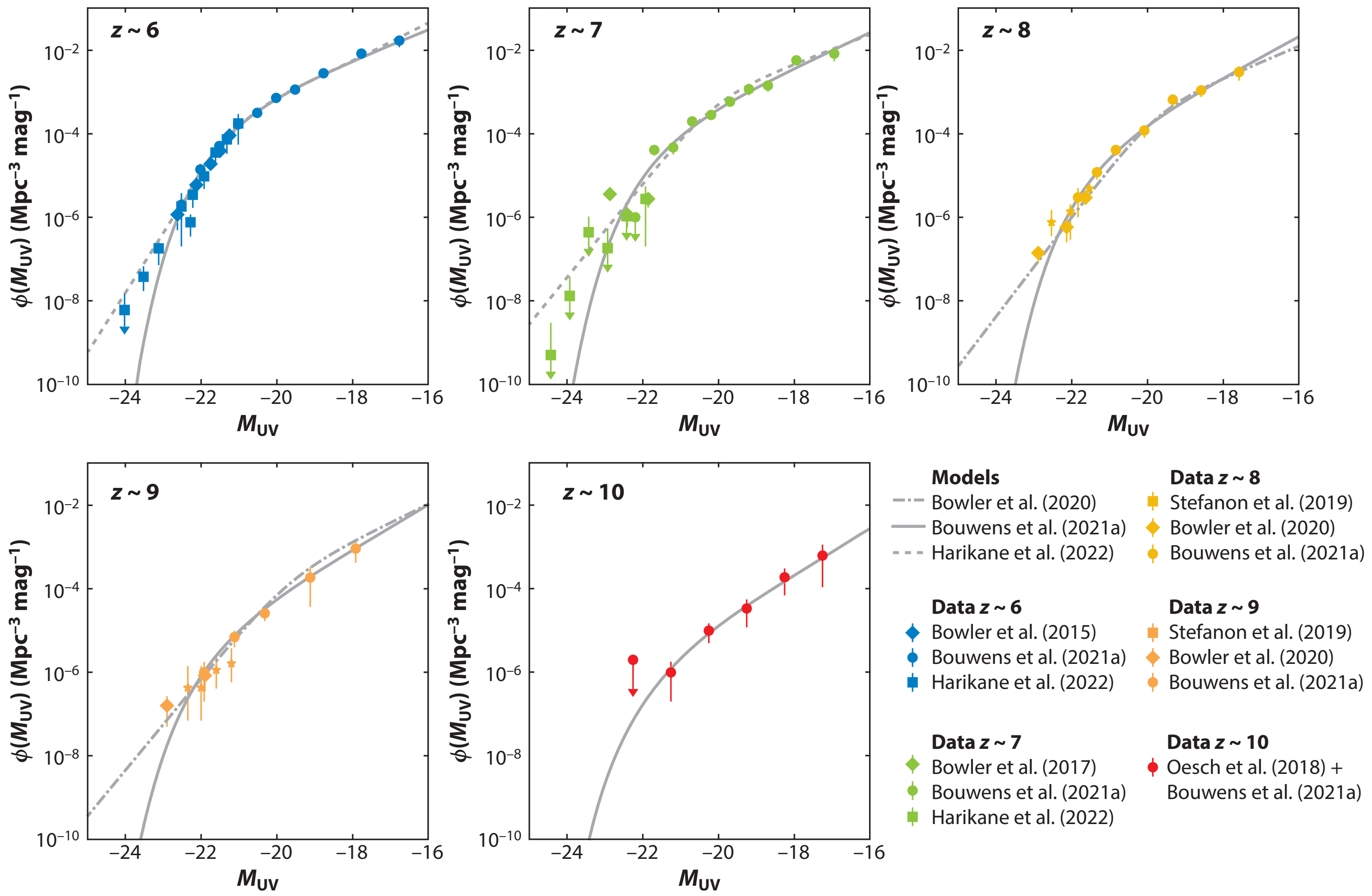
For larger galaxies a peak at z ~ 2.5 was found.

Γ increased 10 times from z ~ 2.8 to 0.5 .



JWST, Duan et al 2024.

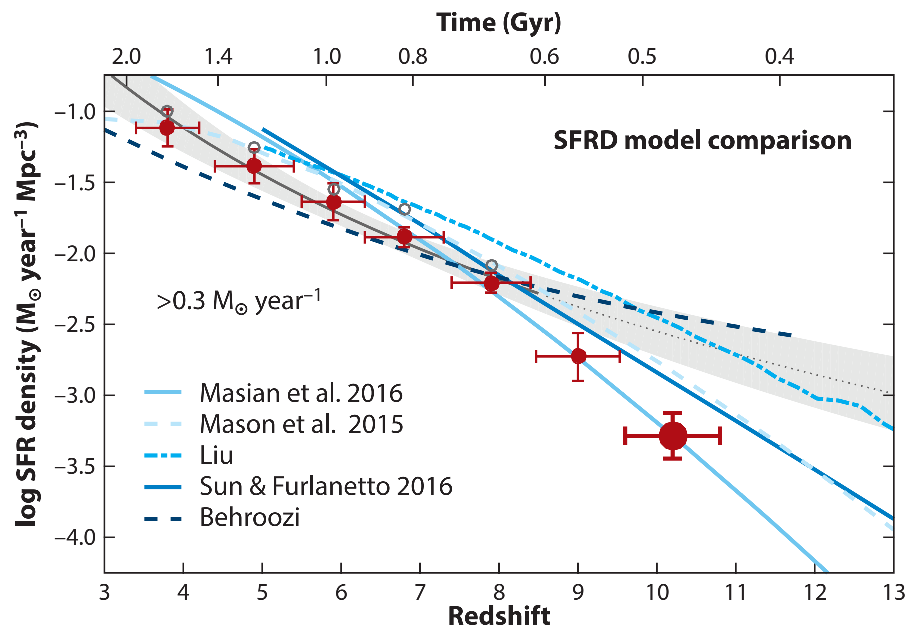
5.4 Luminosity function and star formation rate



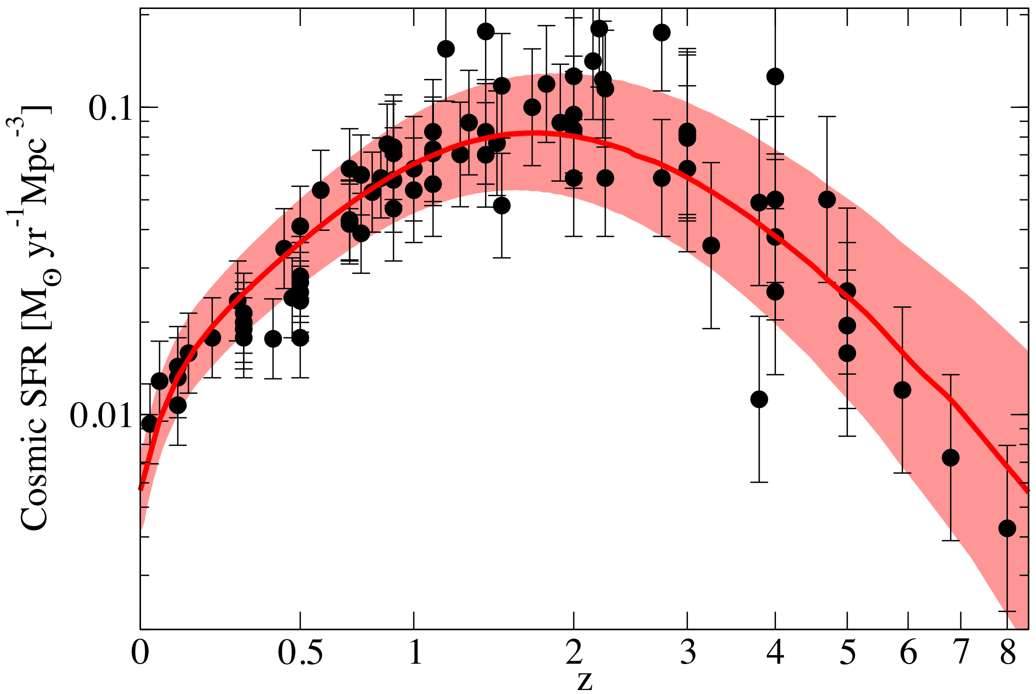
Schechter - solid line

Double power - dashed

Robertson et al 2022



Robertson et al. 2022



Berhoozi et al. 2013