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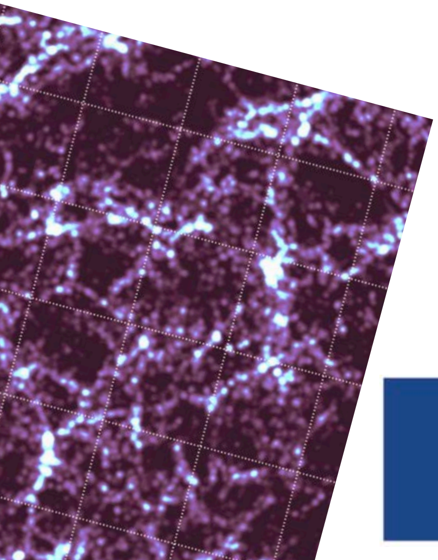
Investing in your future

Observed Cosmic Web

Elmo Tempel

2025



Funded by the European Union

Observed Cosmic Web (Tempel lectures)

- Cosmic Web as revealed in observations
- Galaxy redshift surveys - biased overview
- 4MOST WAVES and 4HS surveys - mapping the Universe
- Preparind a redshift survey - 4MOST example

- Understand your data: observational selection effects
- Galaxy Groups in redshift surveys
- Filaments in the Cosmic Web
- Selected science in Tartu Observatory

Motivation: connecting cosmic web and galaxies

- Understanding the formation and evolution of galaxies is one of the biggest challenges of observational cosmology.

  How galaxies evolve?

- Today's picture of galaxy formation relies largely on numerical and semi-analytical models. To compare these models with the real Universe, we need to know the observed properties of galaxies in detail.

  The observational study of galaxies.

- The large-scale environment can provide a new viewing angle to understand better the evolution of galaxies. Environmental dependency can constrain current theories of galaxy formation.

  What is the role of surrounding environment?

- Better galaxy statistics with respect to various parameters (morphology, colour, group content, etc) could make a strong impact on our understanding of the physical processes that drive the birth and life of galaxies in the Universe.

  Environmental dependency for various subsamples of galaxies.

Discworld Cosmology

Enn Saar

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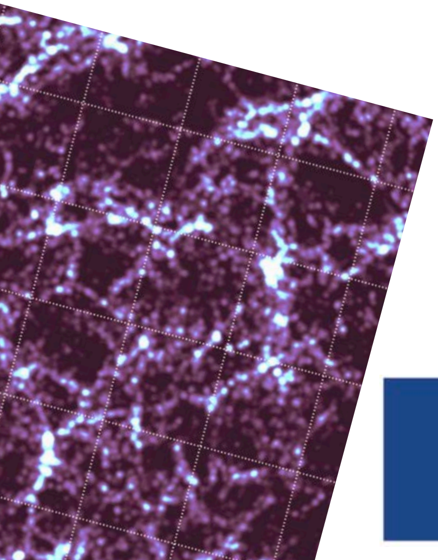
Cosmic Web as revealed in observations



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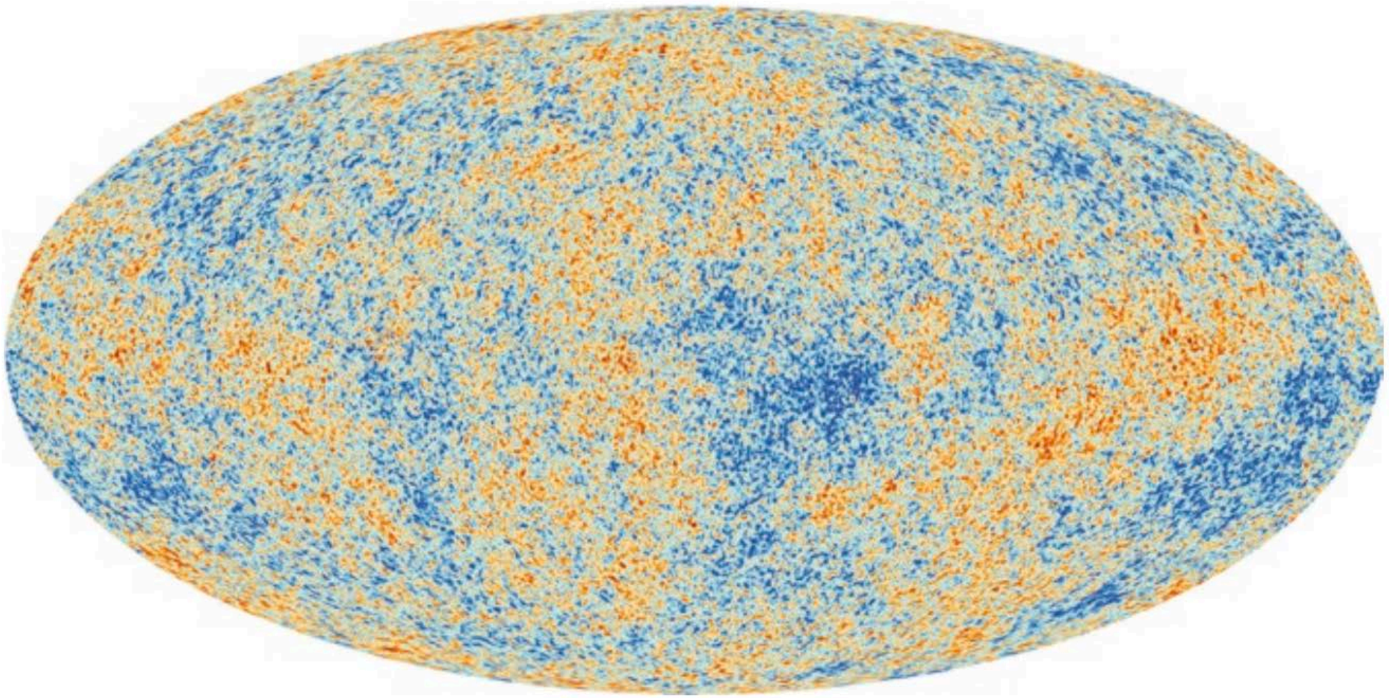
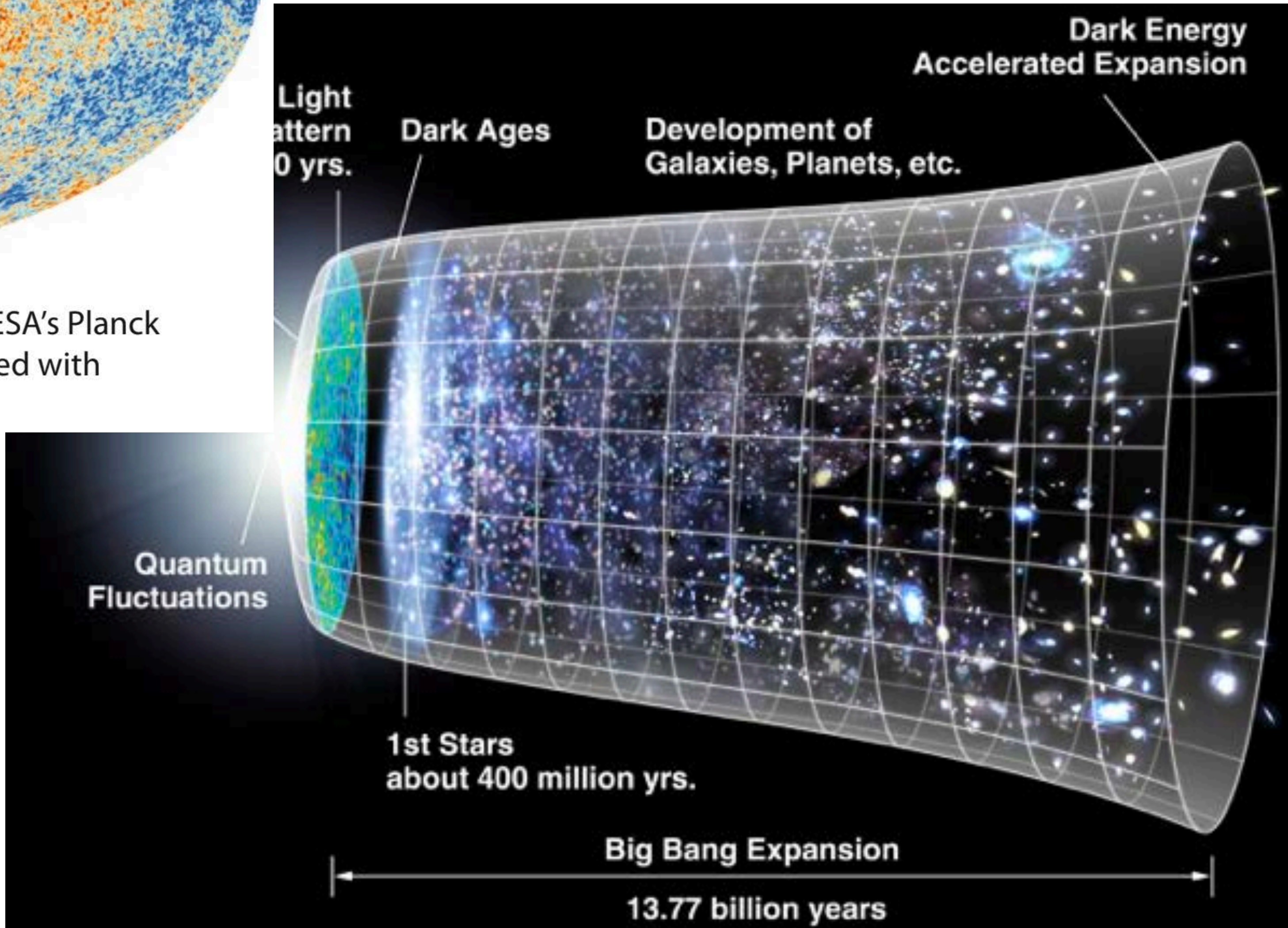
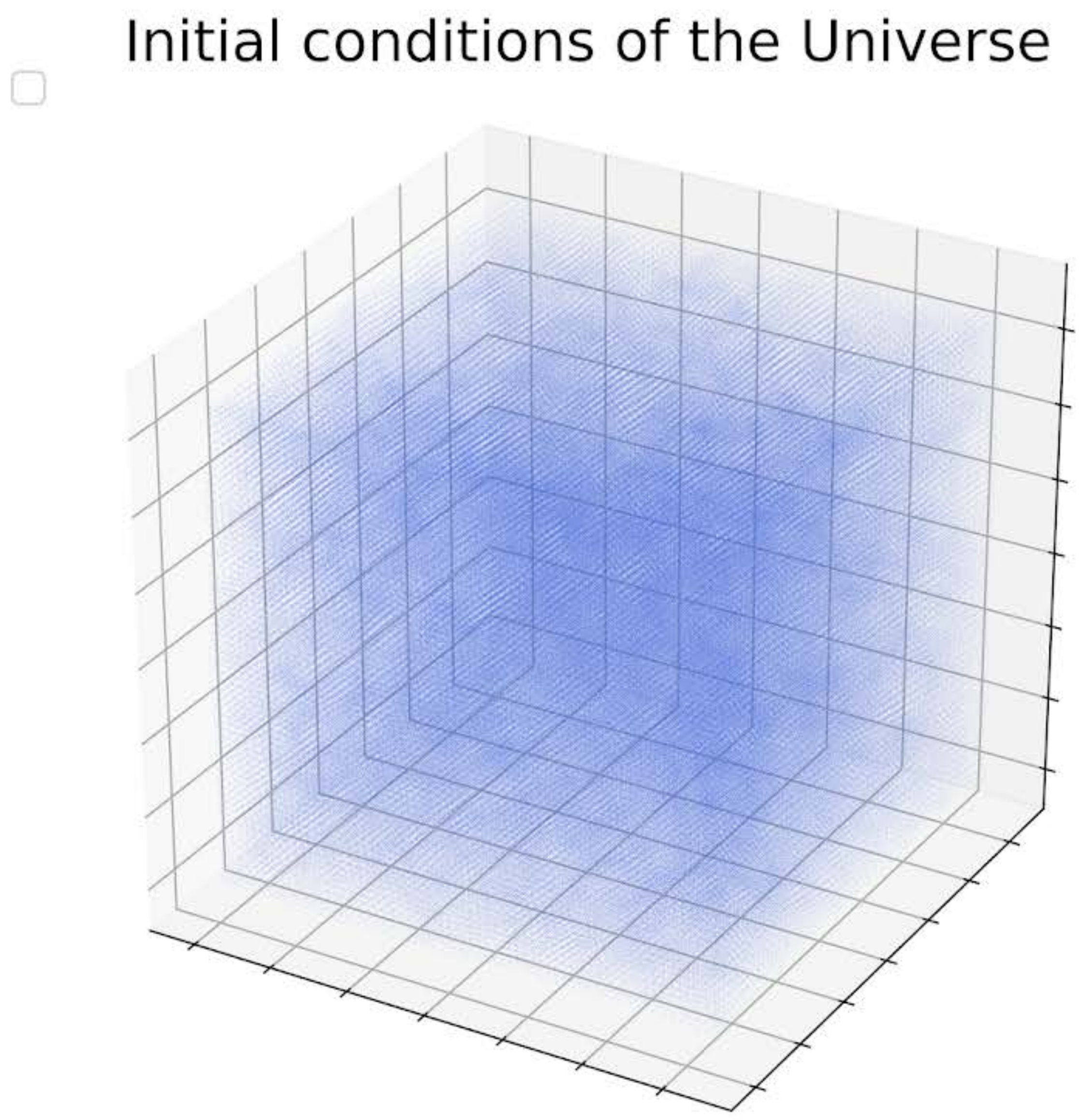


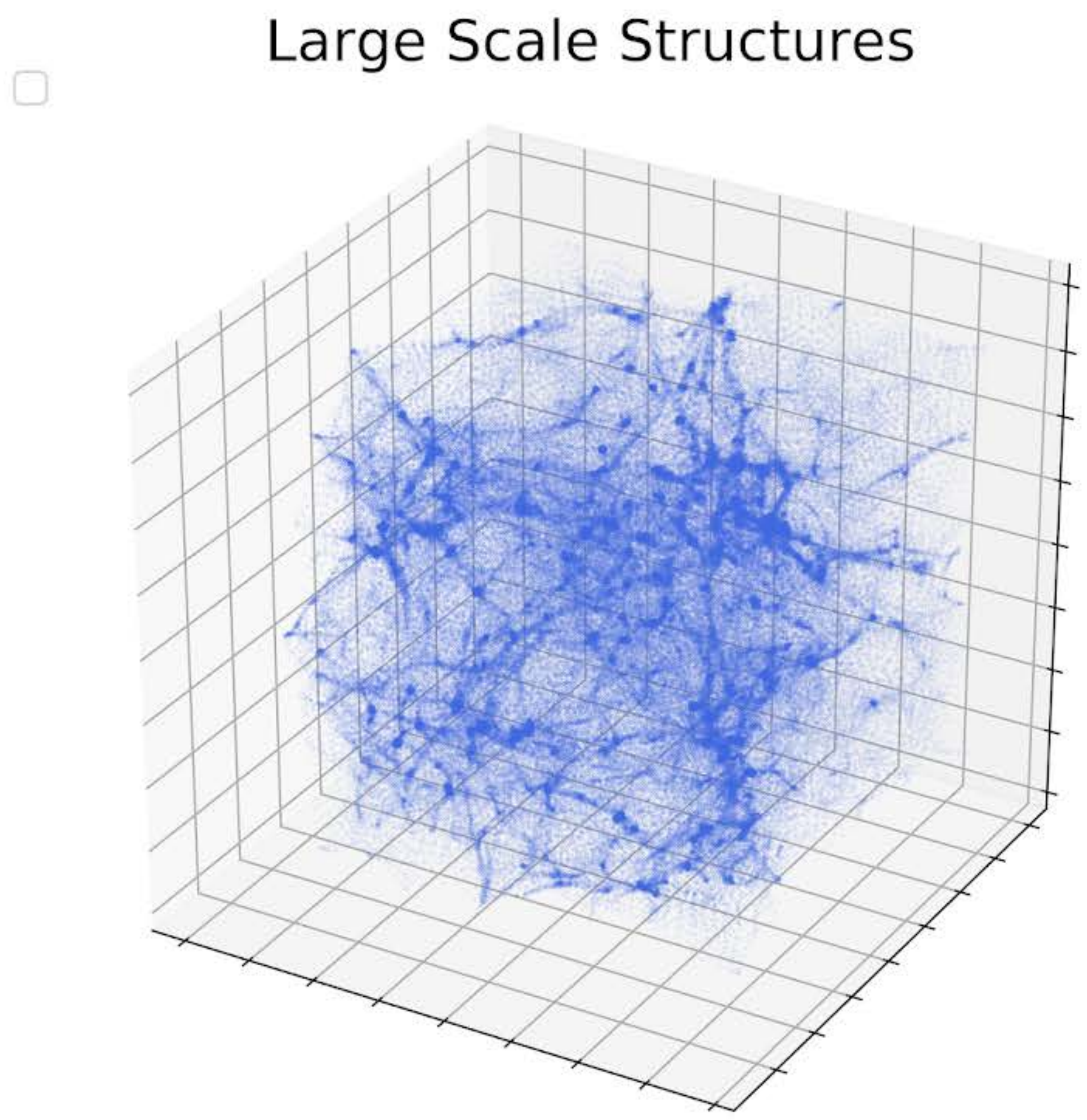
Figure D.34 Fluctuations in temperature of the CMB according to ESA's Planck satellite observatory. (©ESA and the Planck Collaboration, reproduced with permission)



Source: NASA/WMAP Science Team



Early universe



Present-time universe

Cosmic neighbourhood

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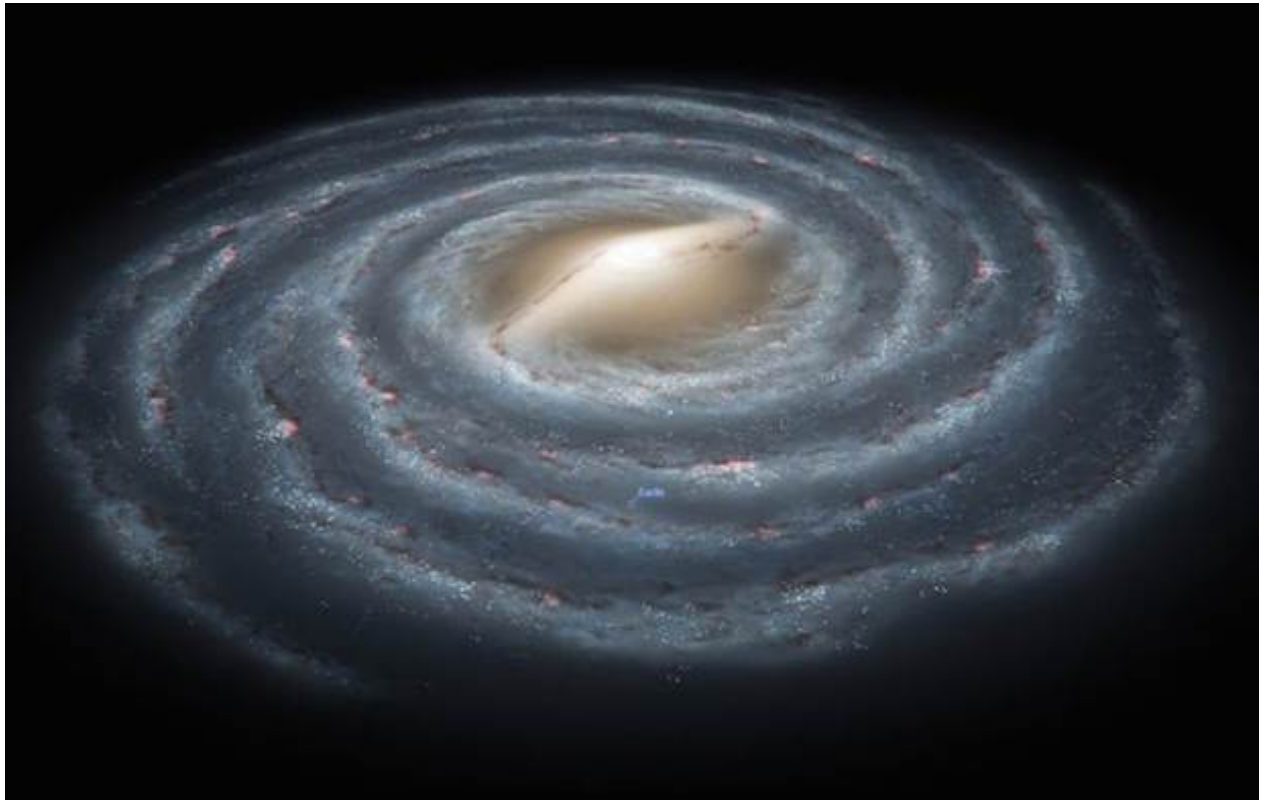
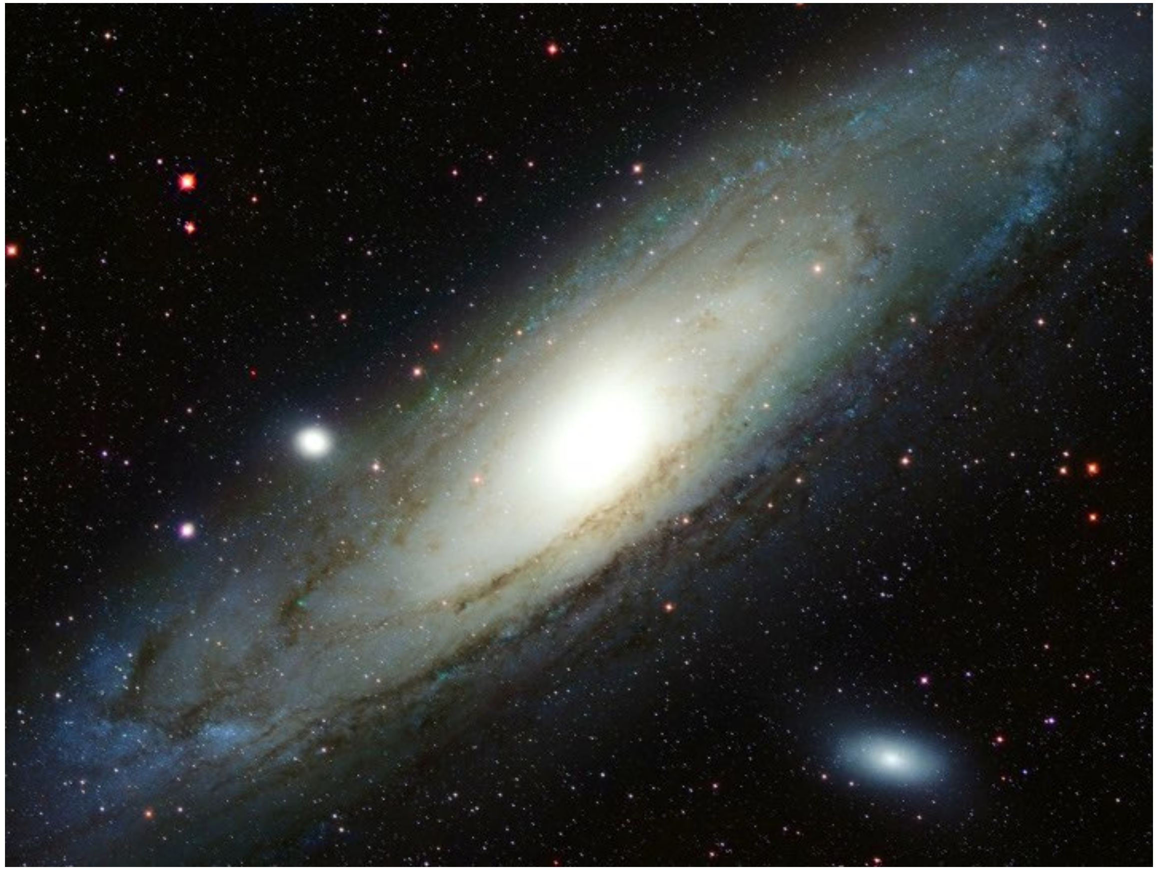
Milky Way galaxy



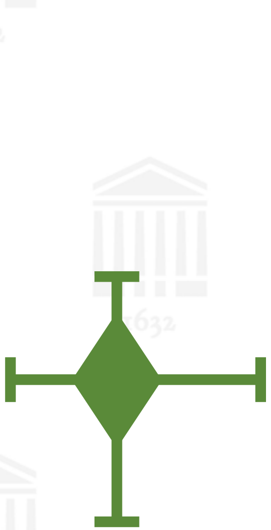
Source: NASA



Andromeda galaxy

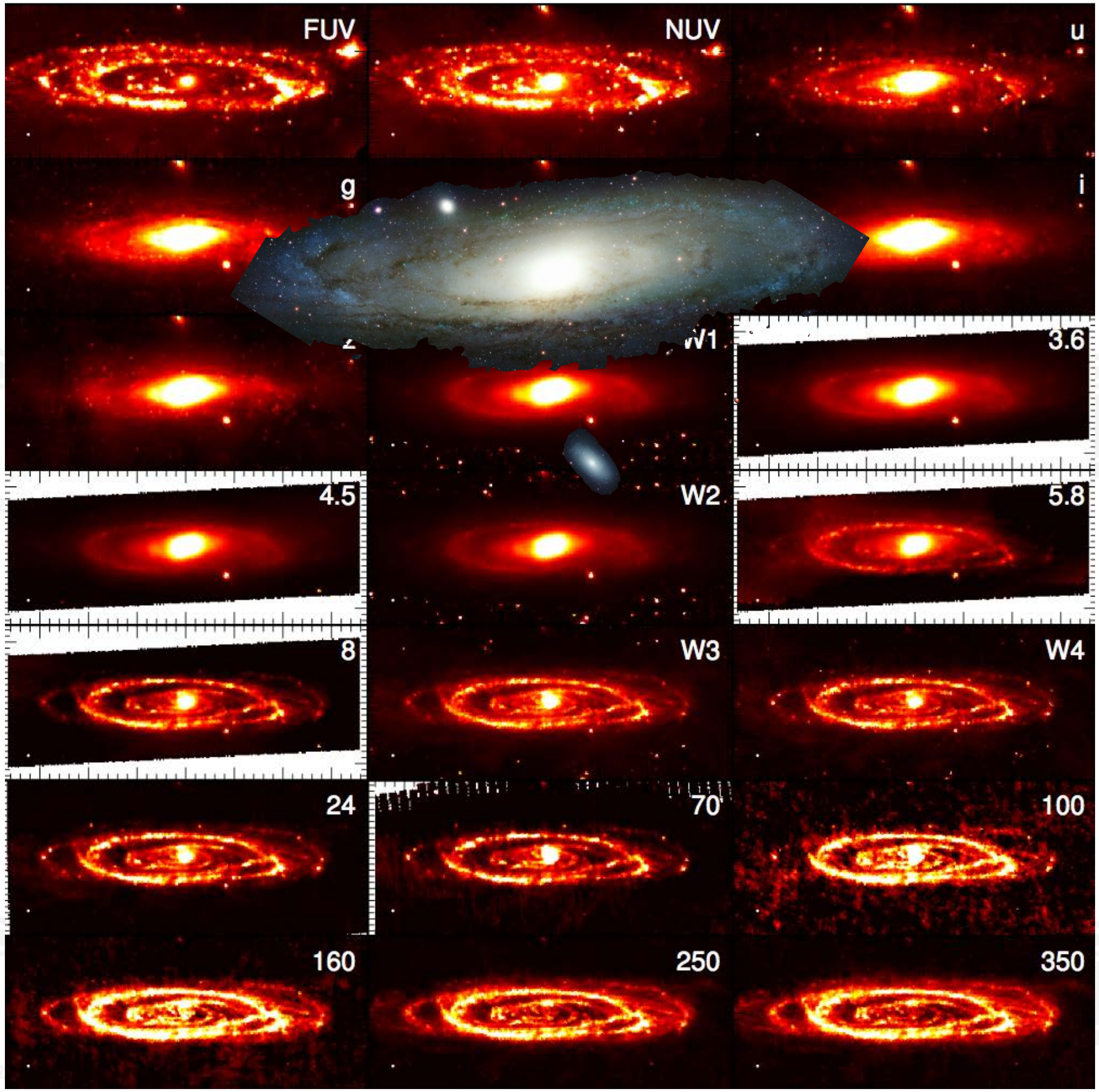
Tempel et al. (2011)

Cosmology vs galaxy physics



vs

ET et al. 2011
Viaene, …, ET, et al. 2014



Cosmologists view

Universe is far more complicated

Local group of galaxies

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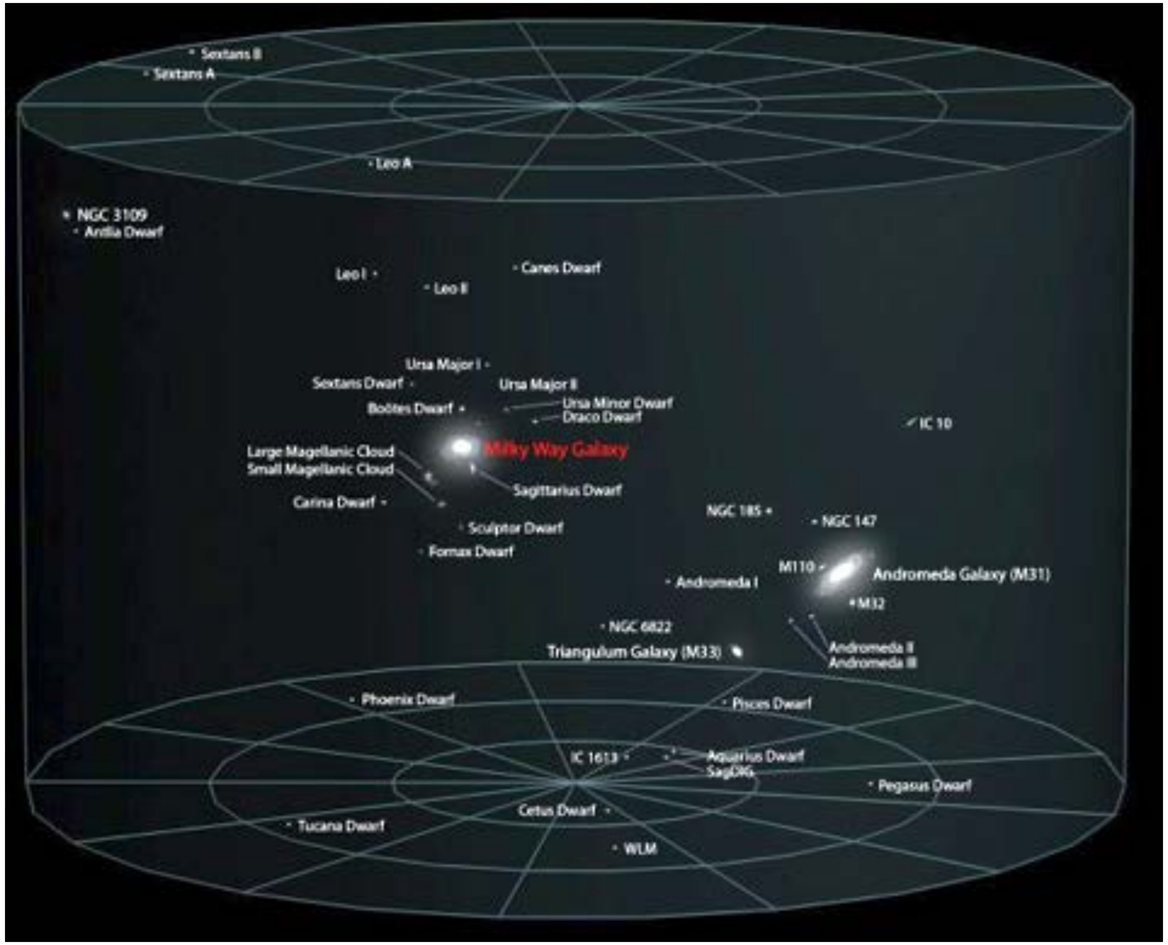
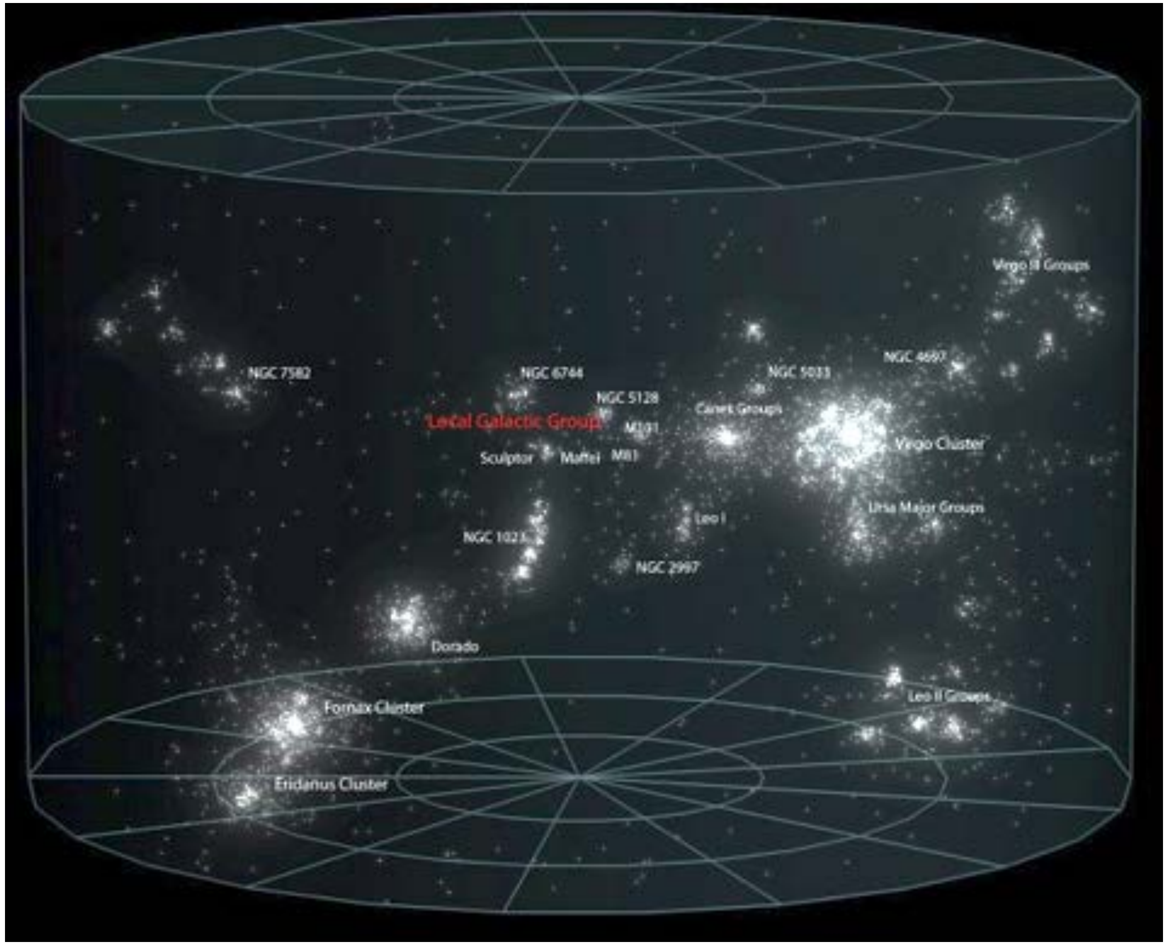




Illustratsioon: Andrew Z. Colvin

(Rien) We have moved about 1pc

How accurately we can measure the location of galaxies?

Local Universe

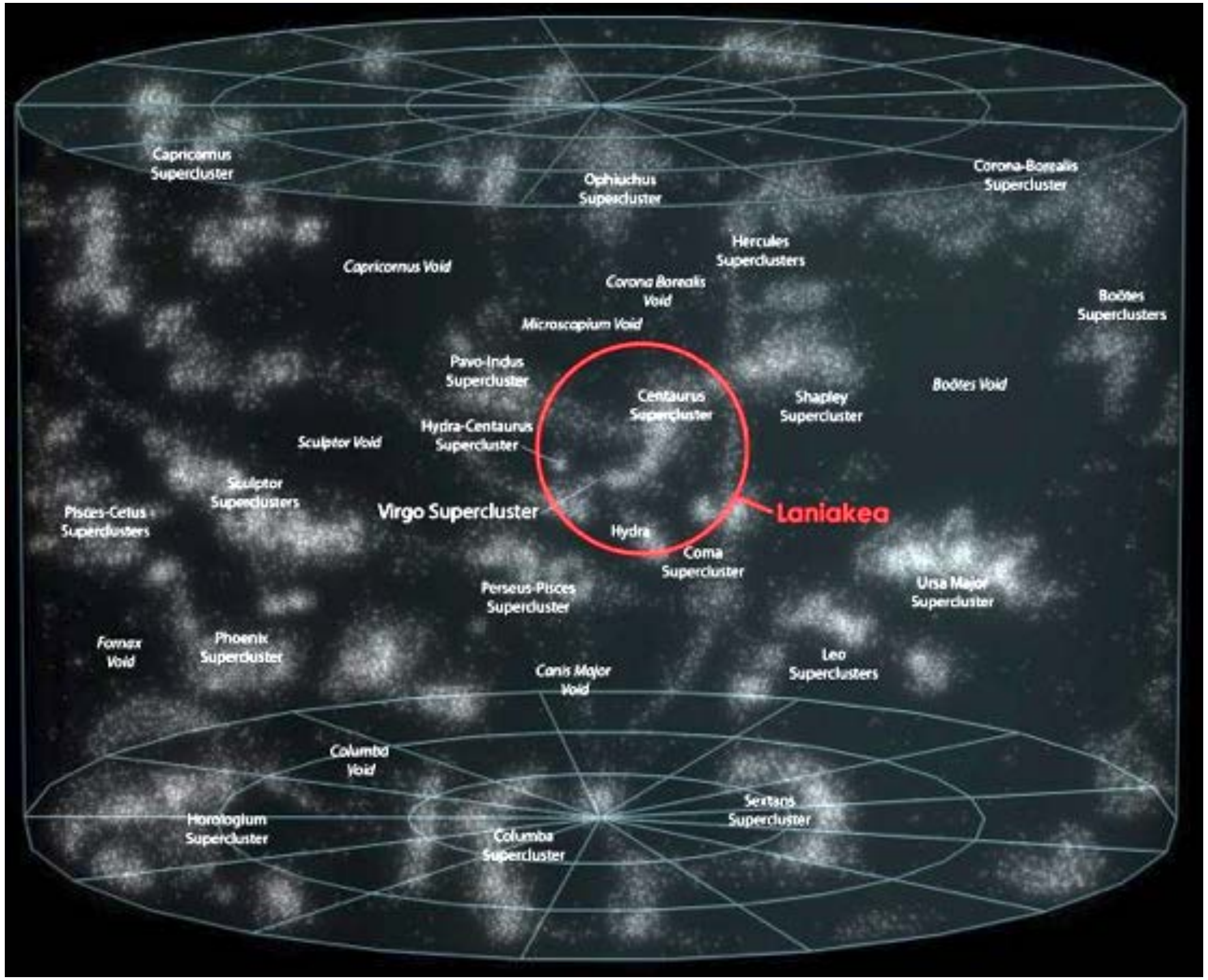
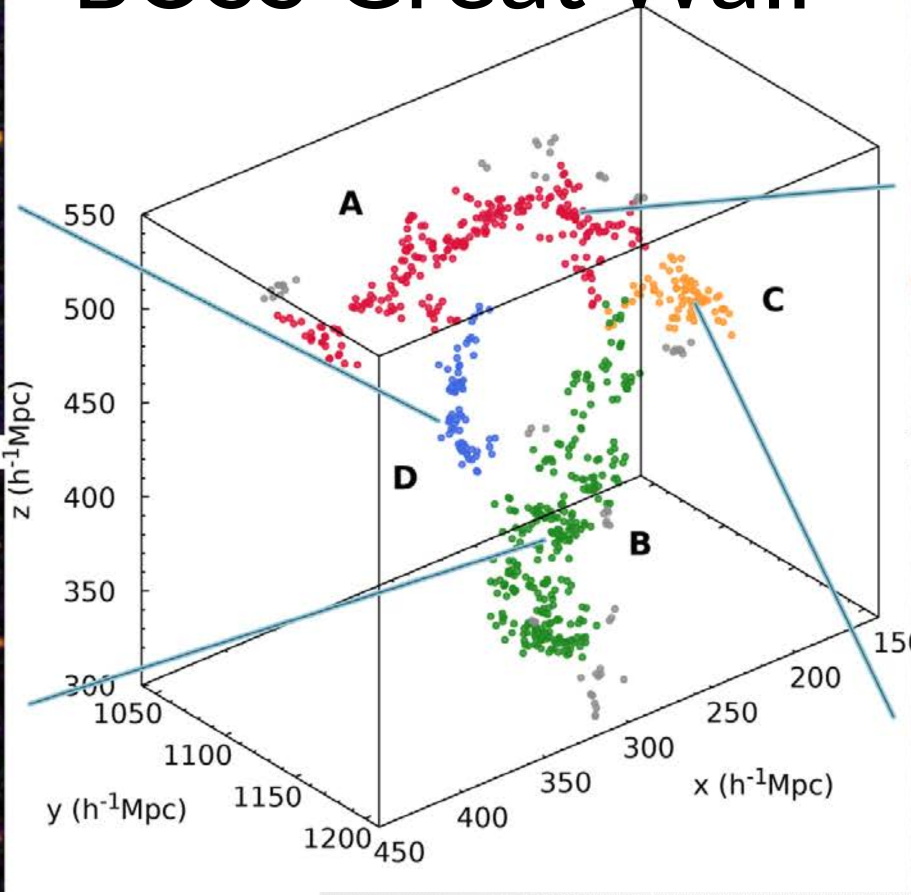
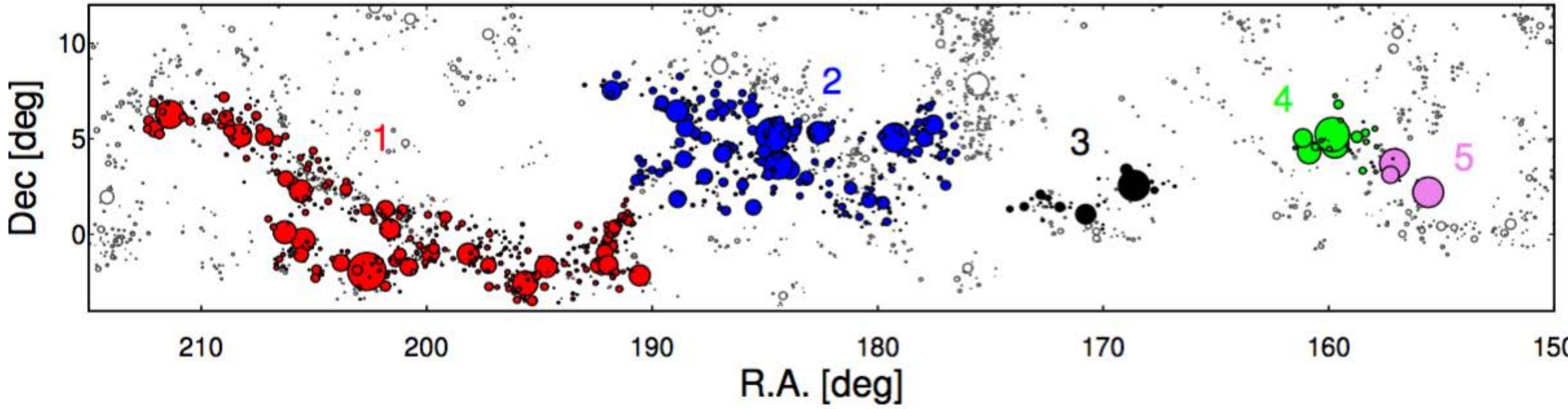


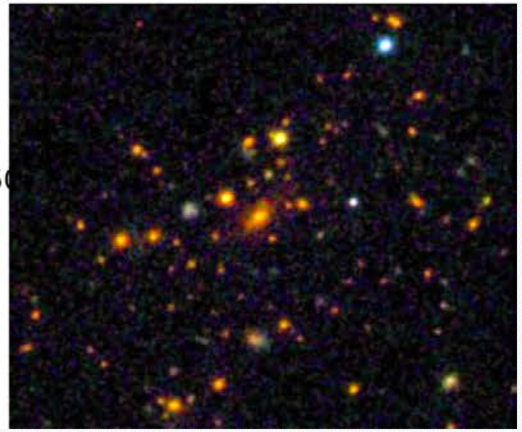
Illustration: Andrew Z. Colvin

BOSS Great Wall

Sloan Great Wall





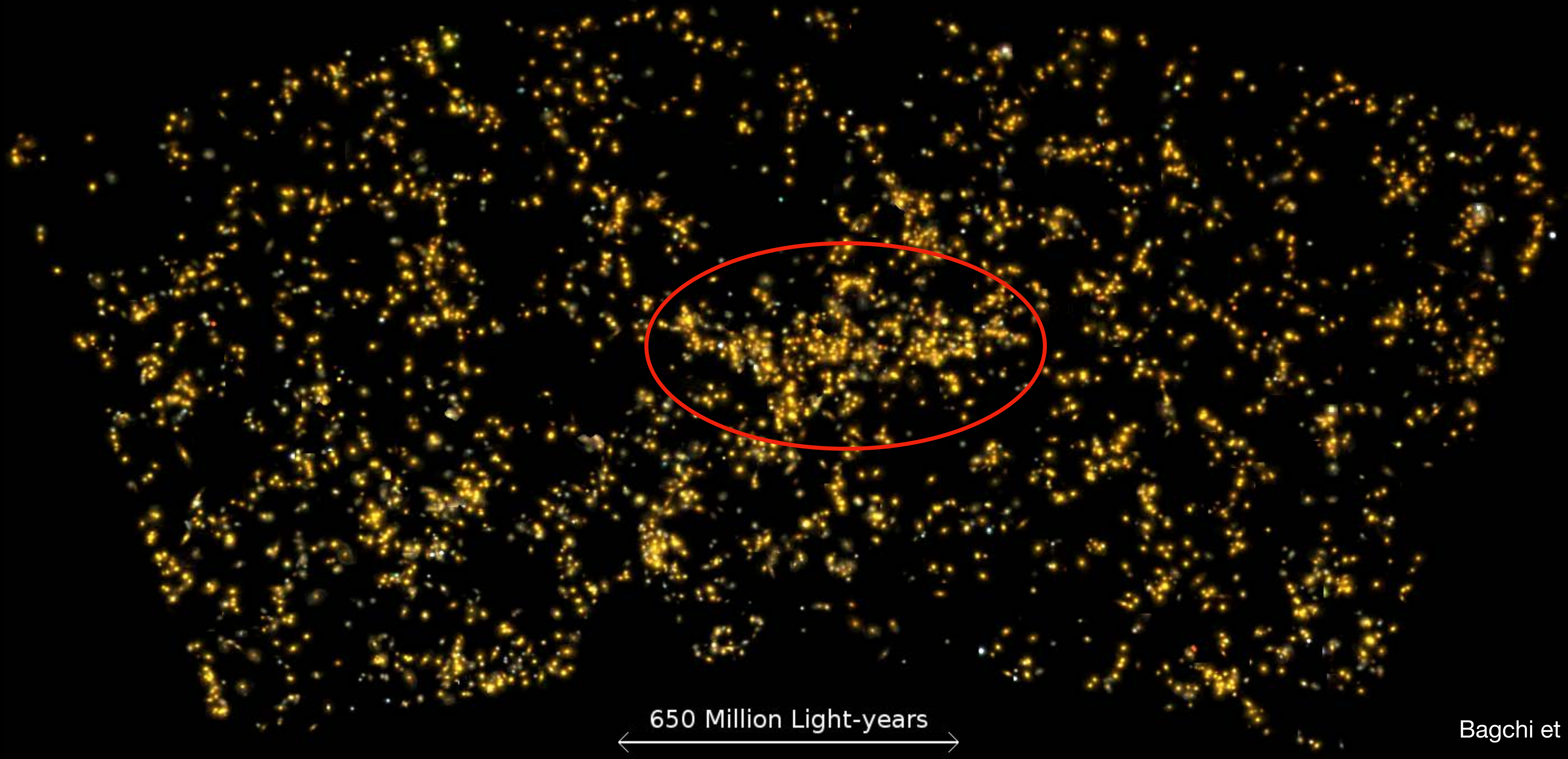


Discovery of a massive supercluster system at $z \sim 0.47$

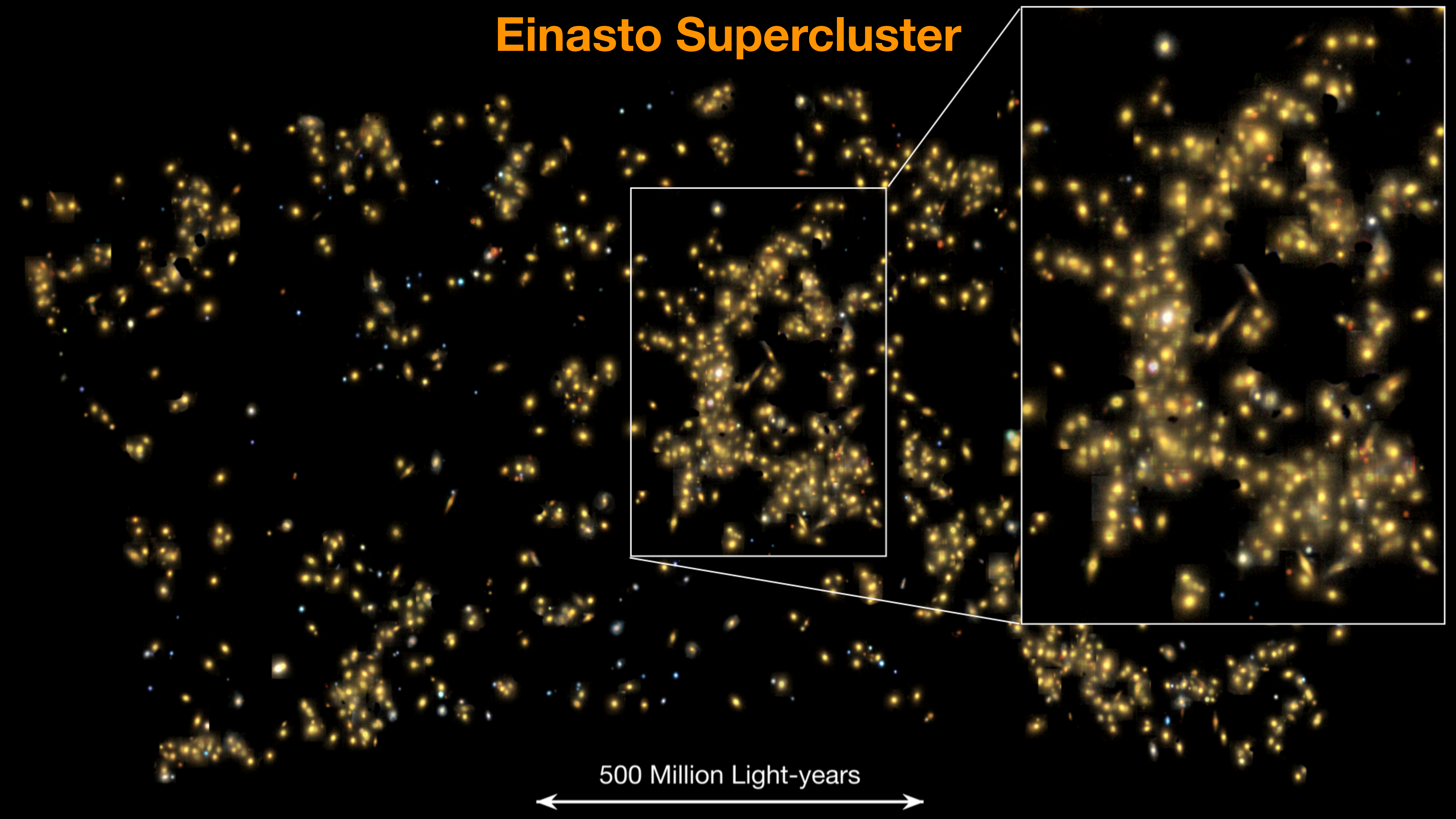
H. Lietzen[1,2], E. Tempel[3], L. J. Liivamägi[3], A. Montero-Dorta[4], M. Einasto[3], A. Streblyanska[1,2], C. Maraston[5], J. A. Rubiño-Martín[1,2], and E. Saar[3]

Saraswati Supercluster

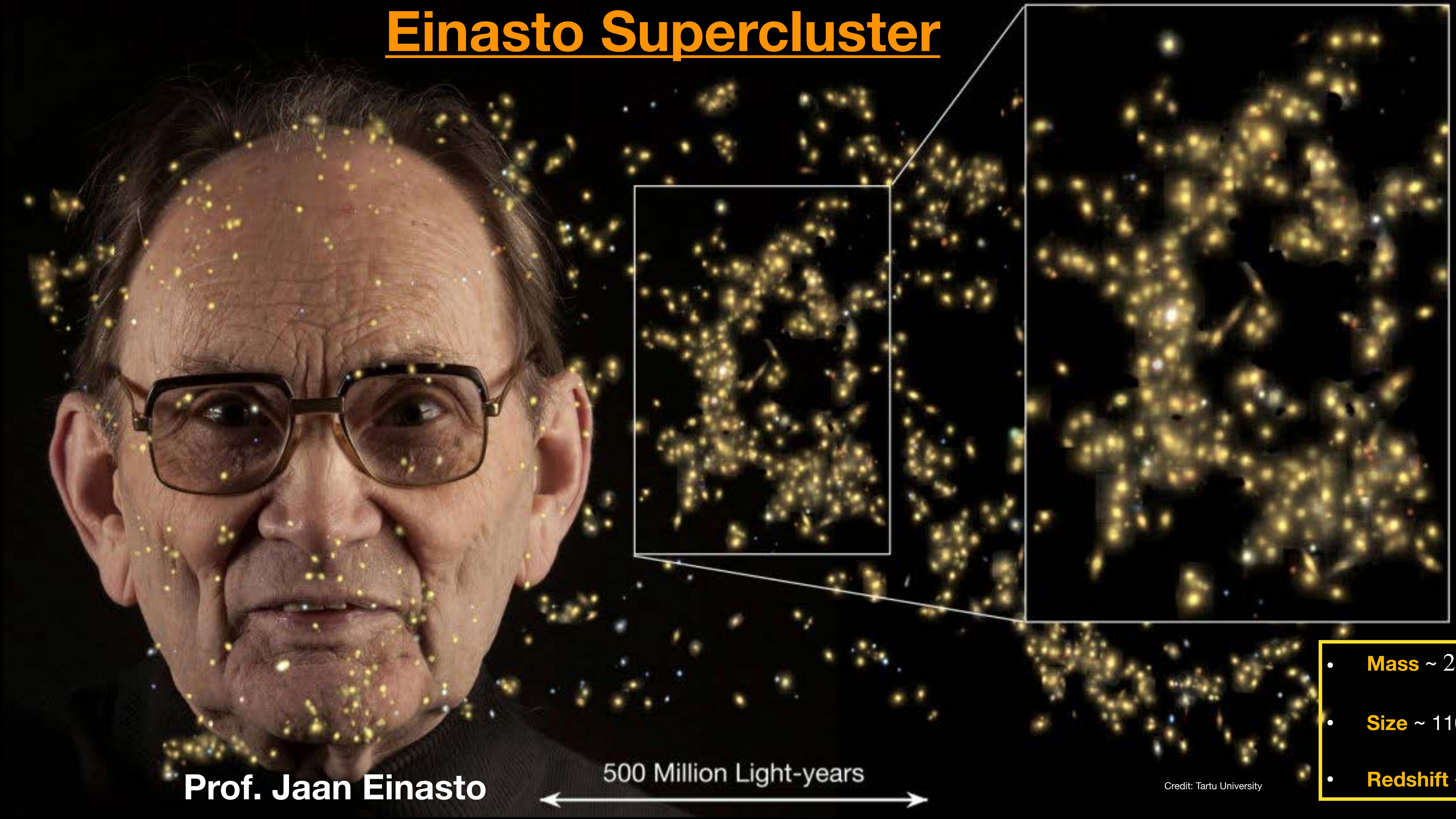
Size ~ 200 Mpc
Distance ~ 4 billion lightyears
Mass ~ $2 \times 10^{16}\ M_{\odot}$



Bagchi et al. (2017)


Einasto Supercluster
500 Million Light-years

Einasto Supercluster



- **Mass** ~ $2 \times 10^{16} M_{\odot}$
- **Size** ~ 110 Mpc
- **Redshift** ~ 0.25

Einasto in the sky! ⟶ Anagram ⟶ **Estonia in the sky!**

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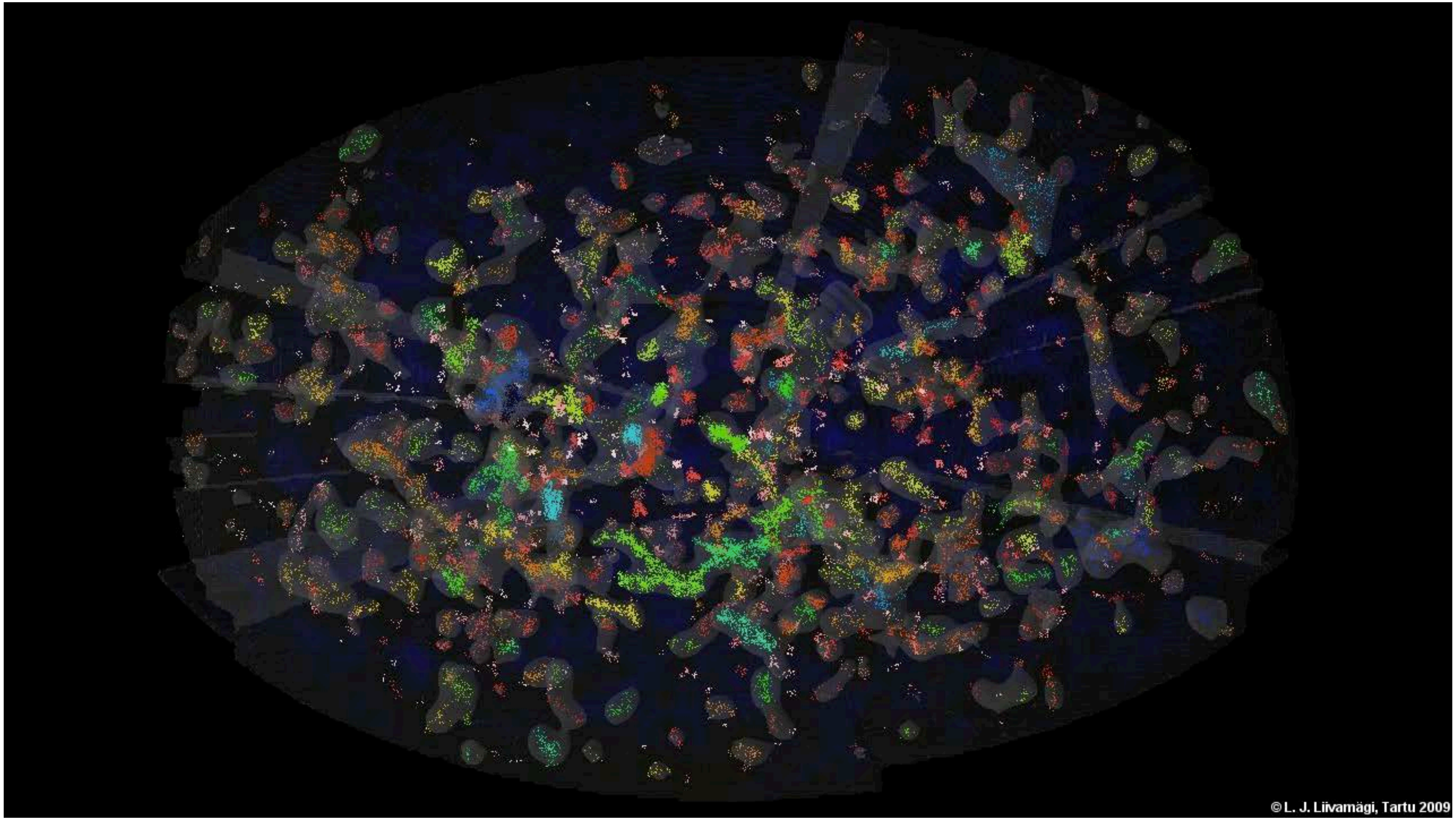
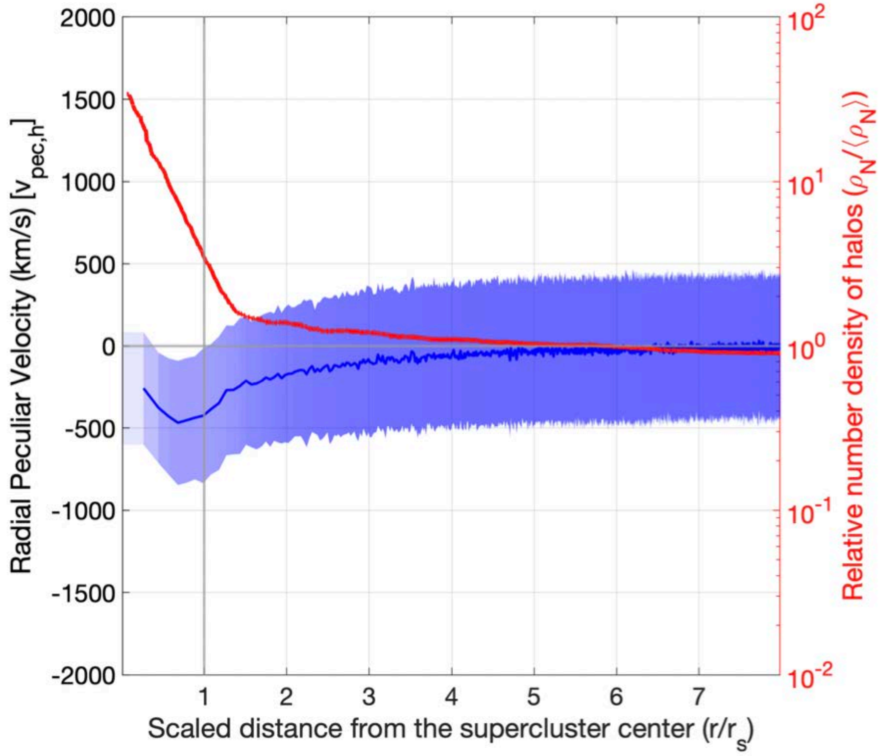
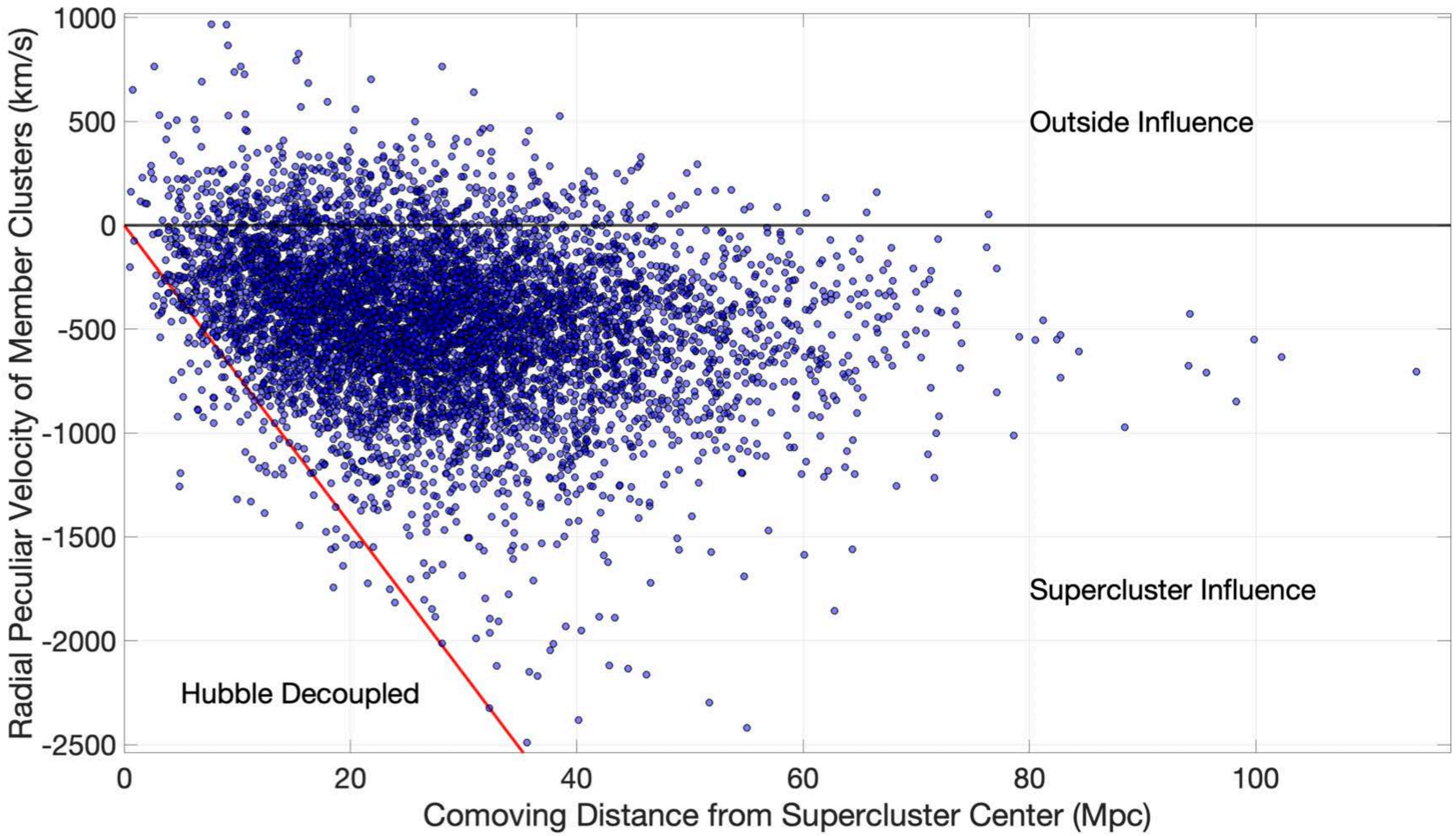
Superclusters in the Universe



Liivamägi, Tempel, Saar (2011)





Superclusters are not dynamically bound structures

How to map Universe?

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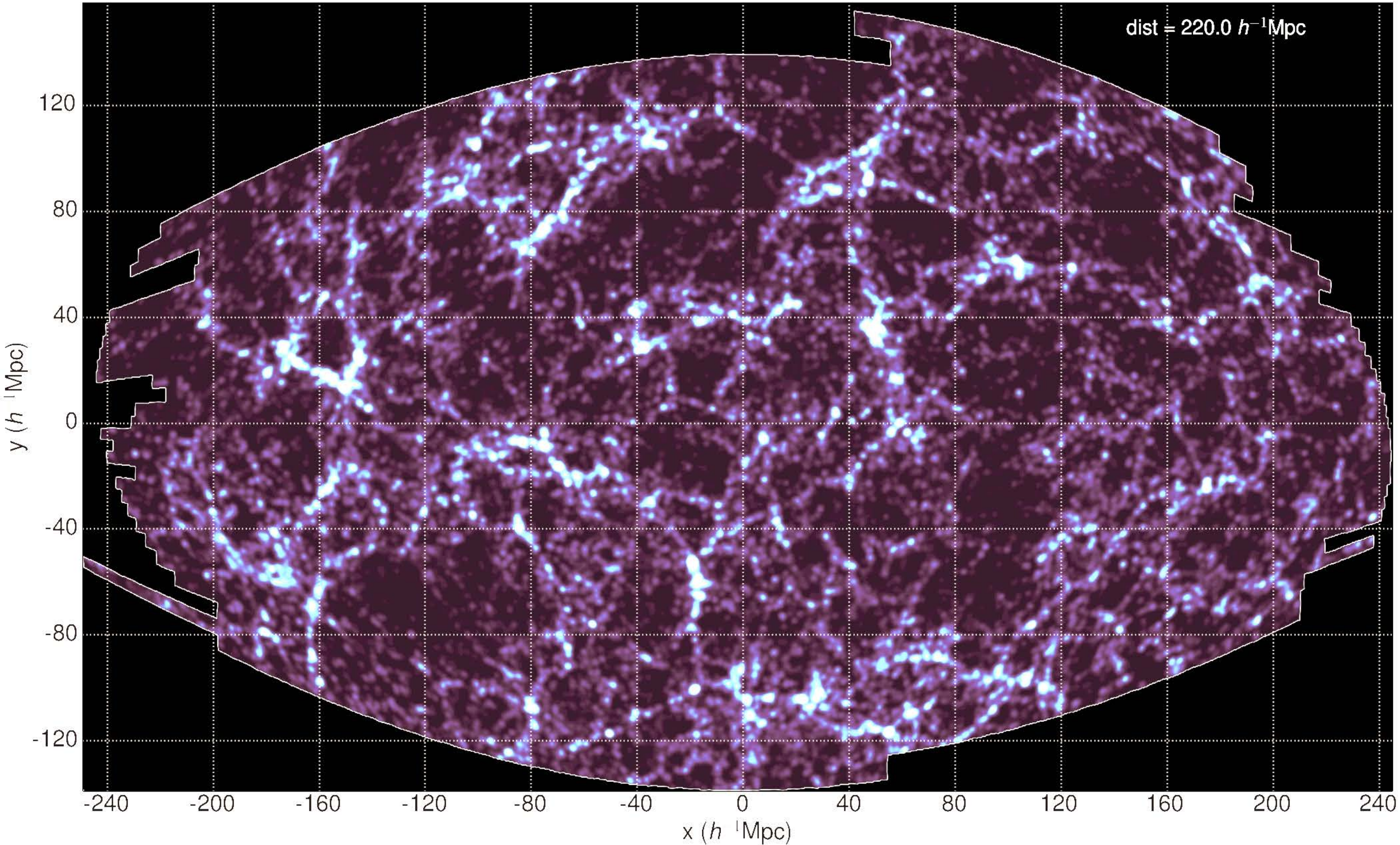
Source: PlanetSAT, NASA

Light follows population
Starlight follows matter

SDSS galaxy redshift survey



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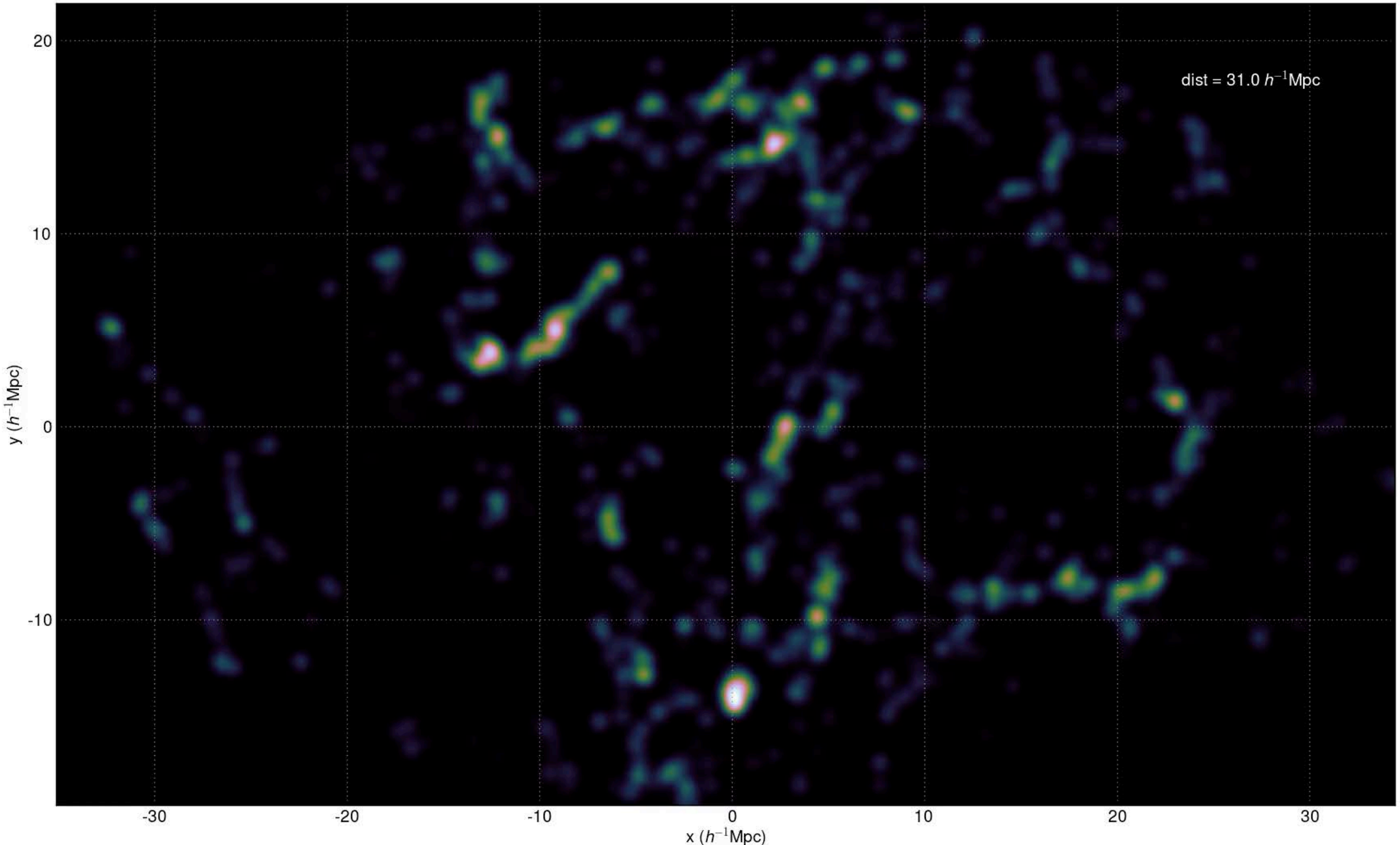
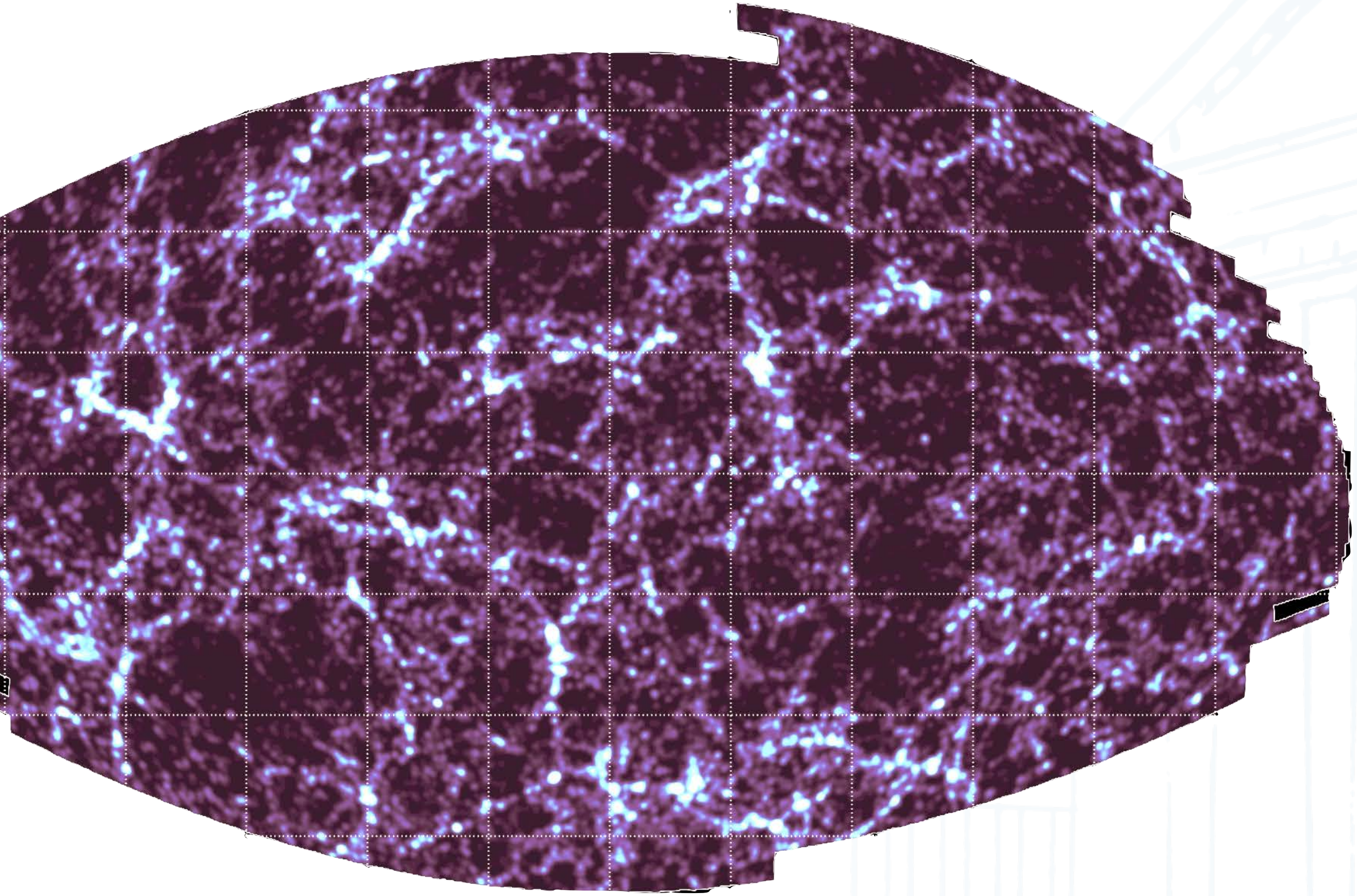
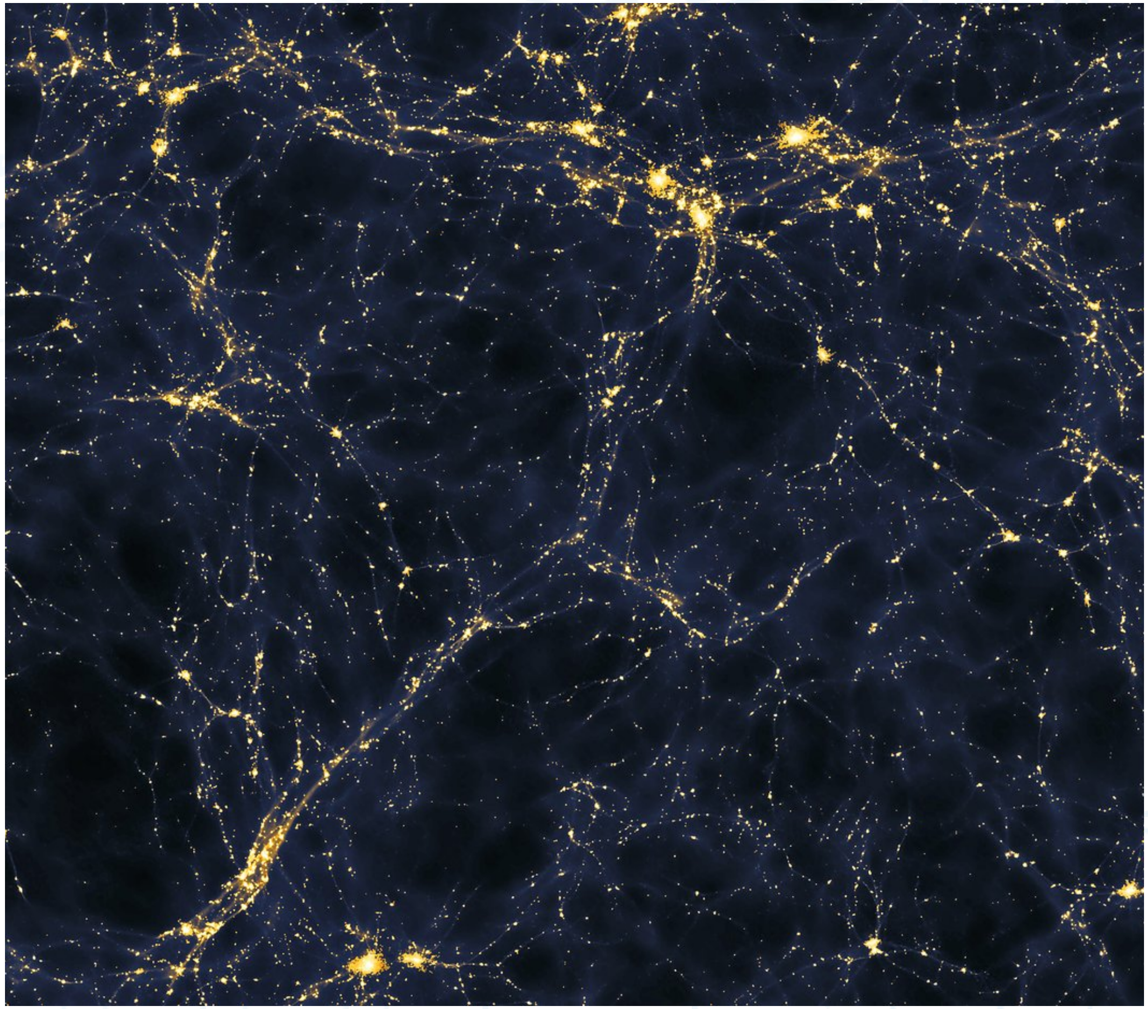
SDSS galaxy redshift survey



Observed vs simulated cosmic web



Credit: L. J. Liivamägi



Credit: Andrew Pontzen & Fabio Governato

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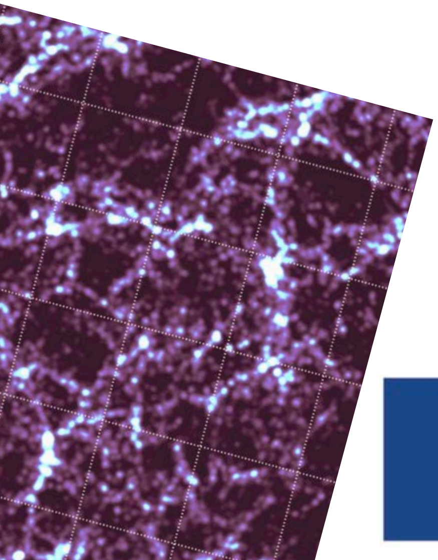
Galaxy redshift surveys - biased overview



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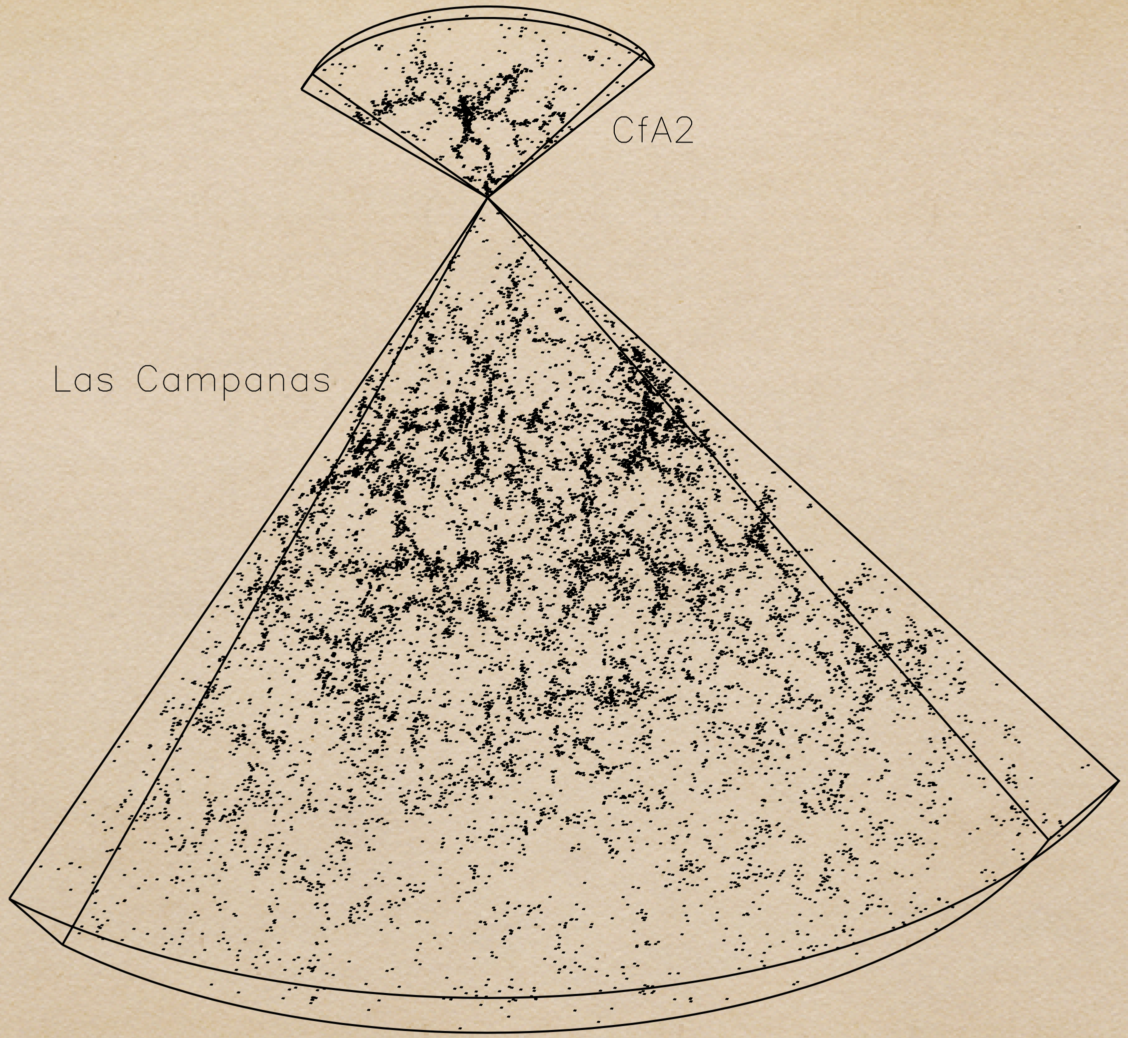
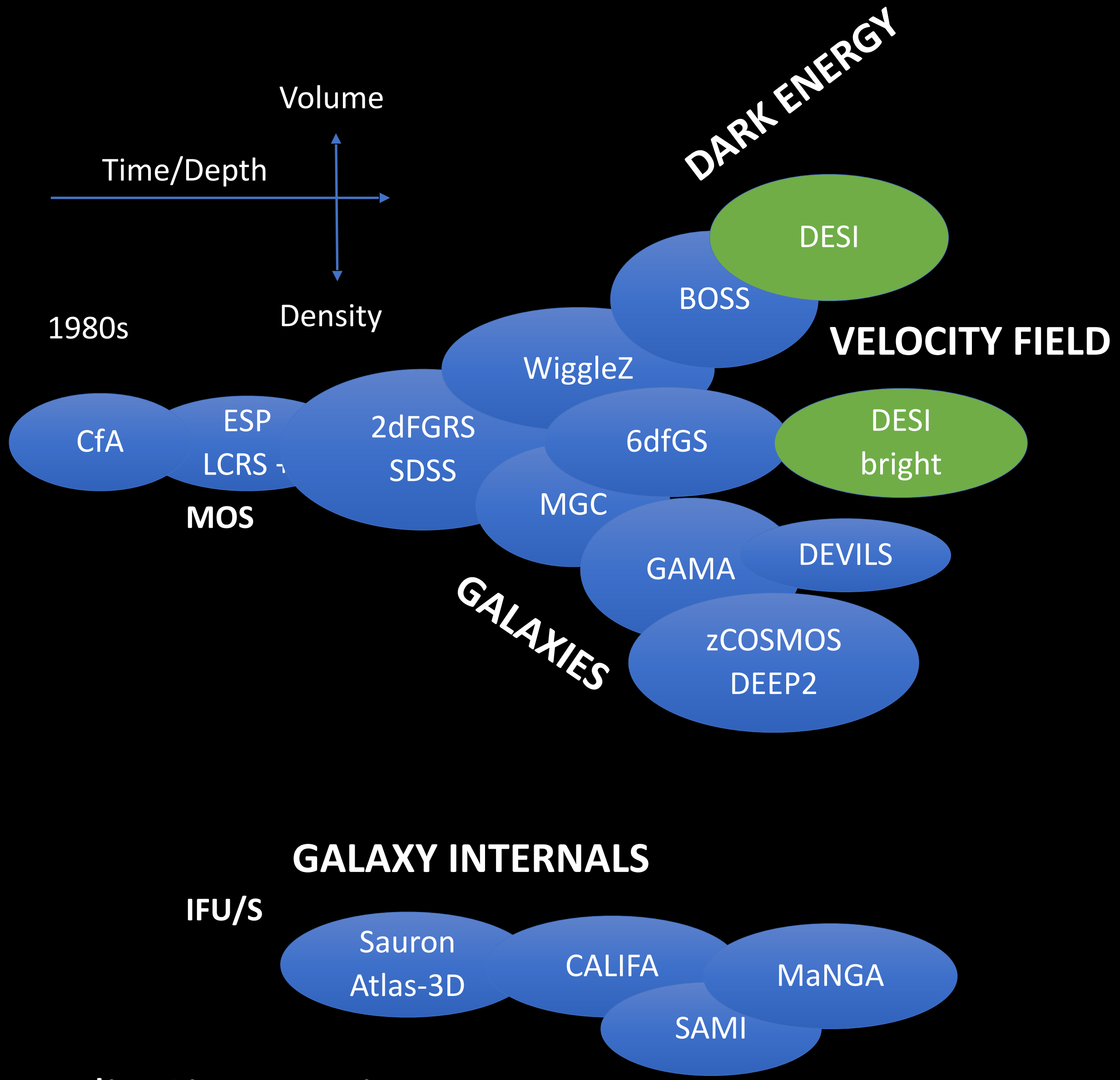
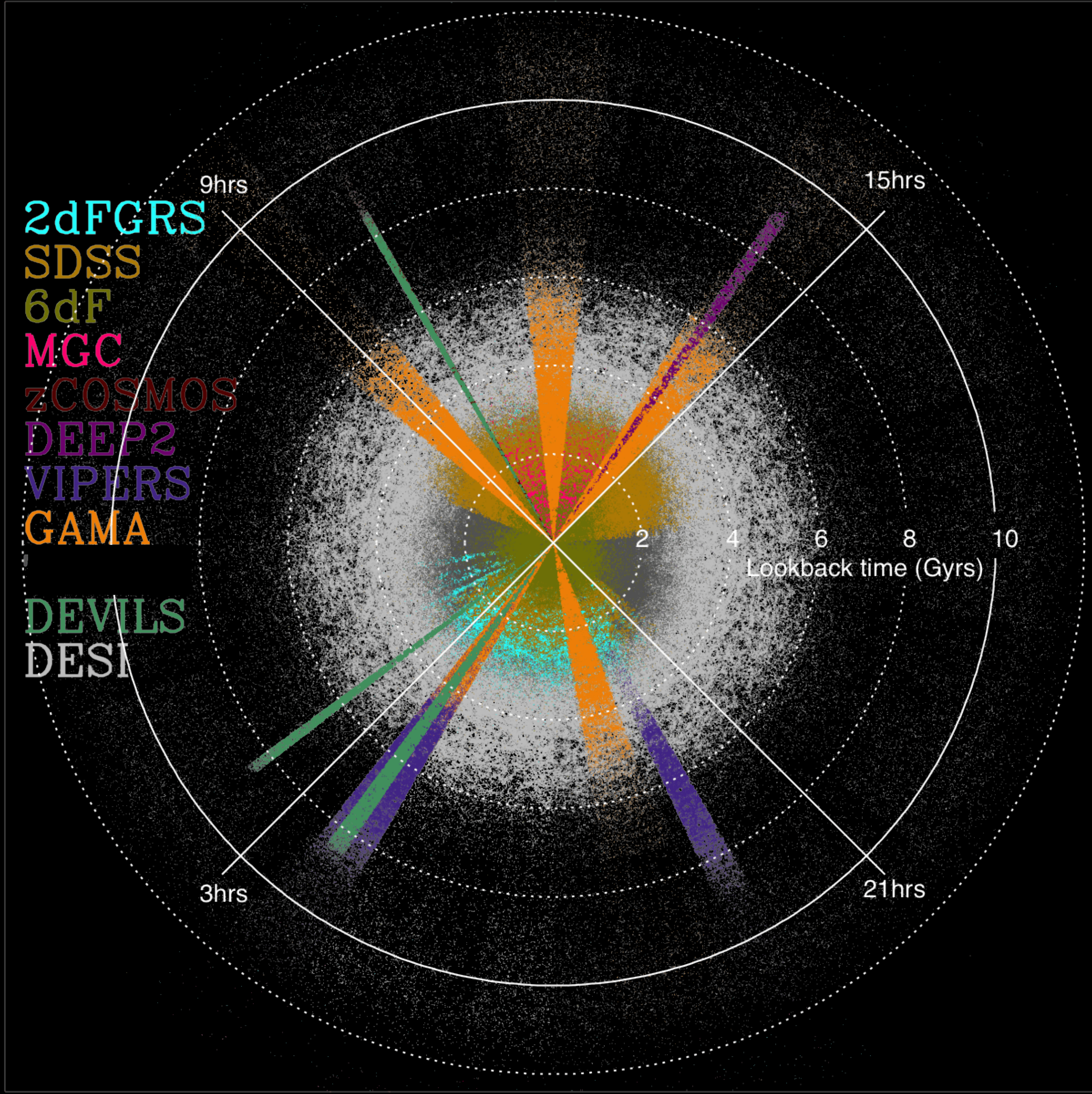

CfA2
Las Campanas

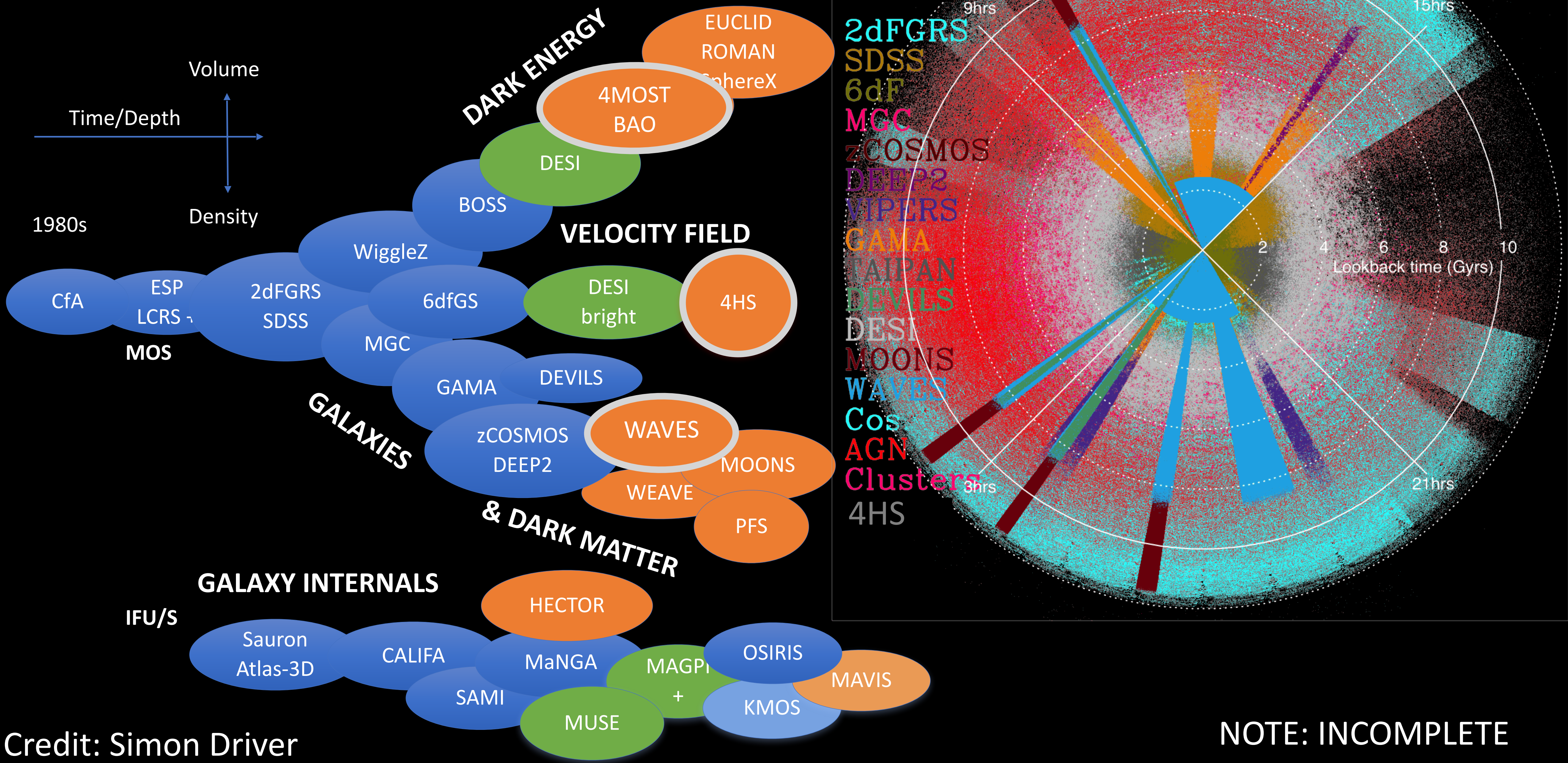
The tuning fork of galaxy redshift surveys





Credit: Simon Driver

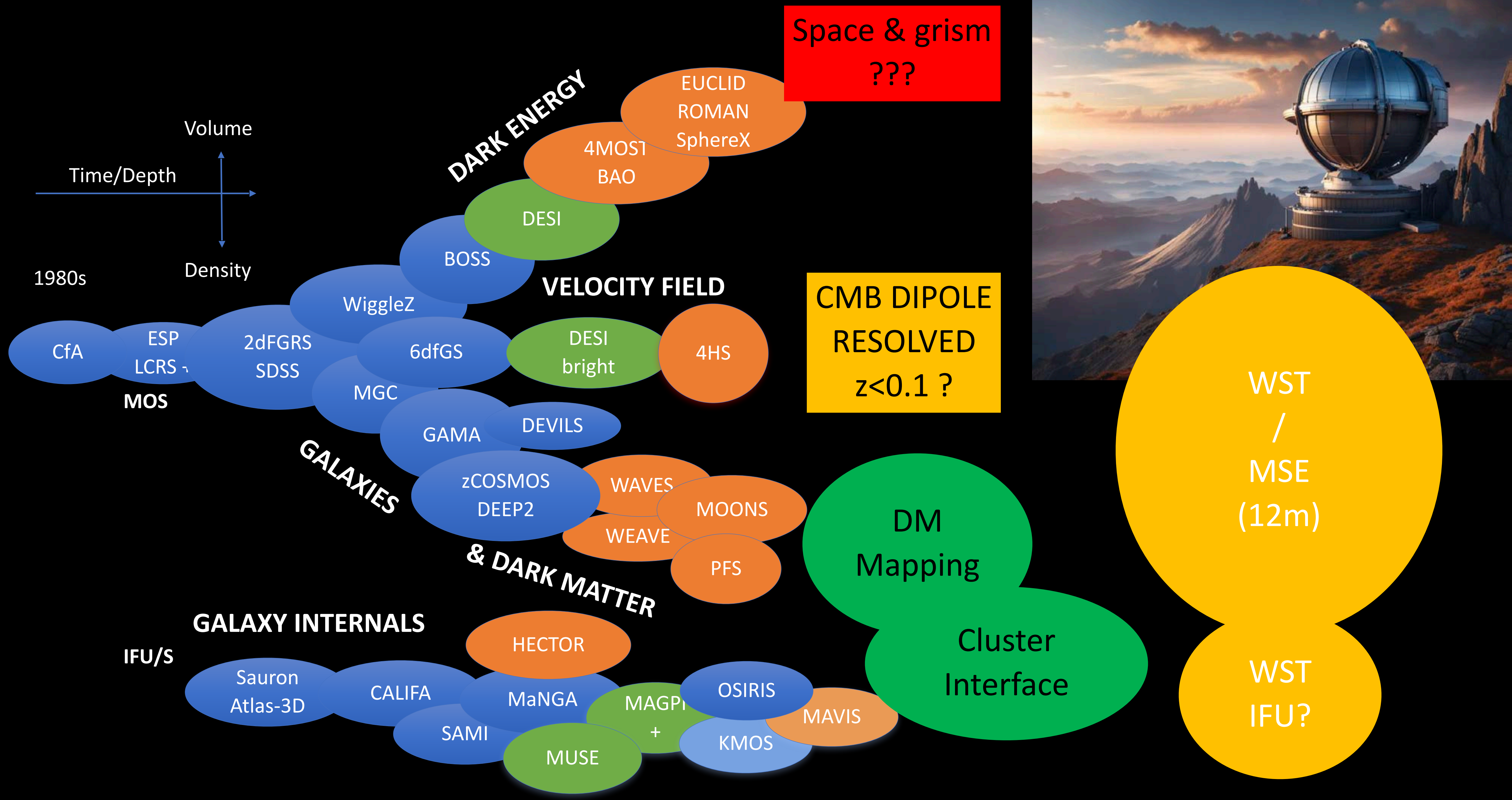
The tuning fork of galaxy redshift surveys



Credit: Simon Driver

NOTE: INCOMPLETE

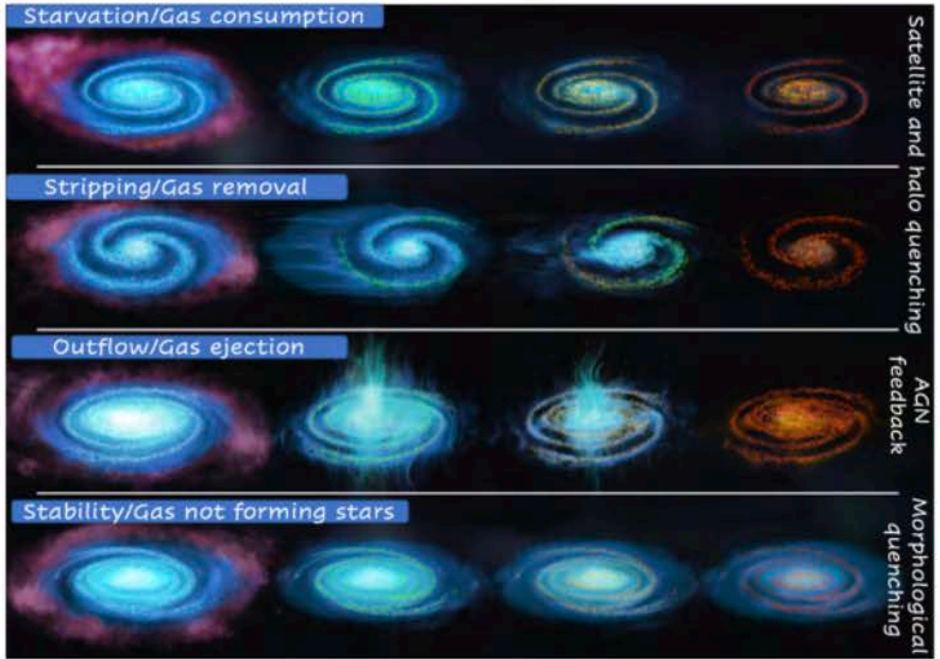
The tuning fork of MOS surveys !

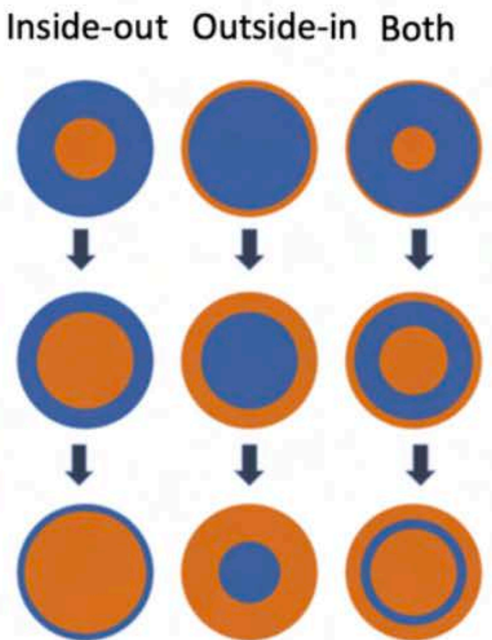


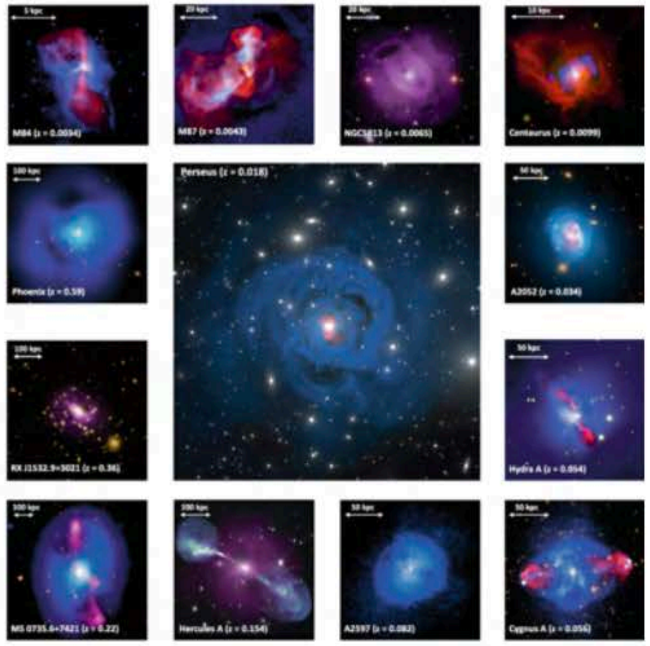
KateMOSS (KMOS ATlas & Environment MultiObject Spectroscopic Survey)

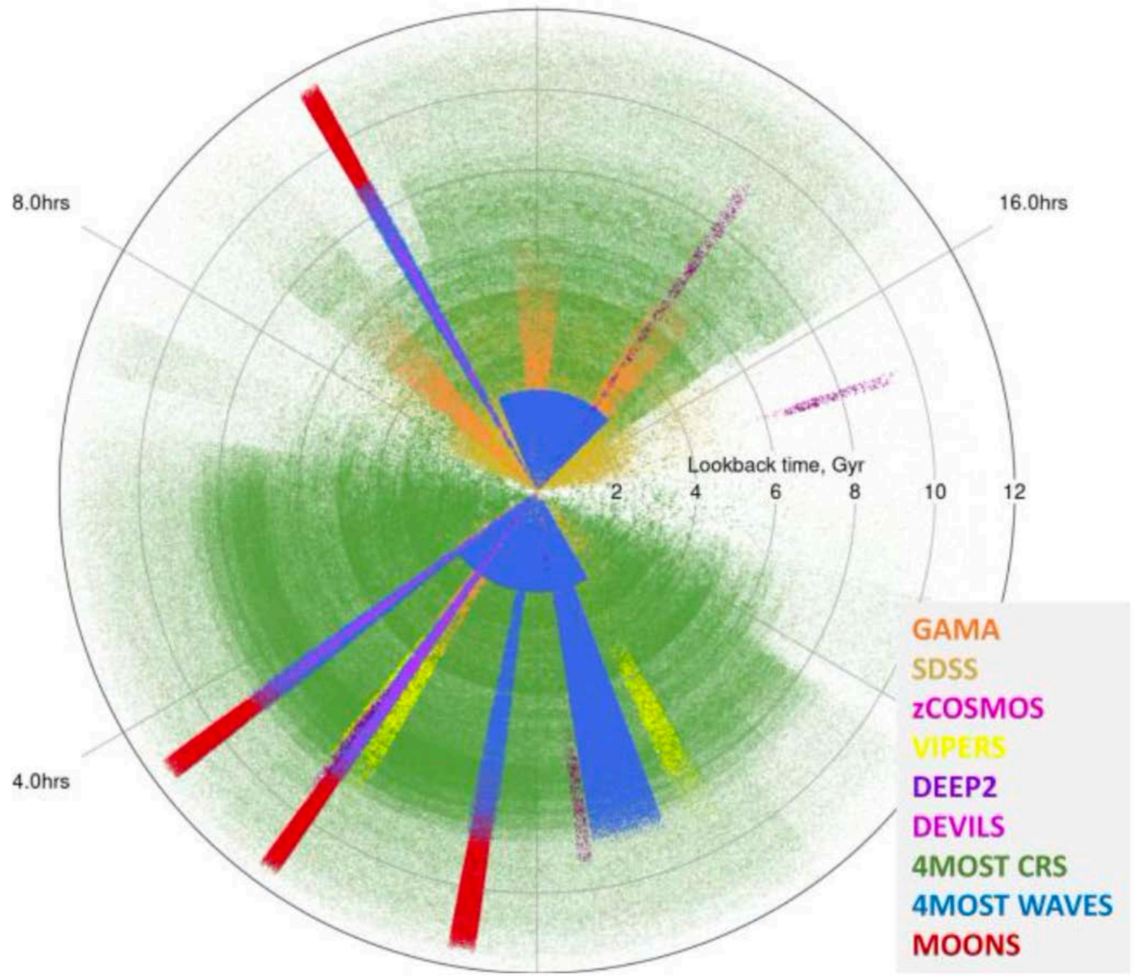
This ambitious IFU campaign will target ~900 galaxies with $M^*>10^{10}$ M_sun across three key epochs at z~0.75, z~1.6, and z~2.3, which span the decline, peak, and early rise of cosmic star formation rate density.

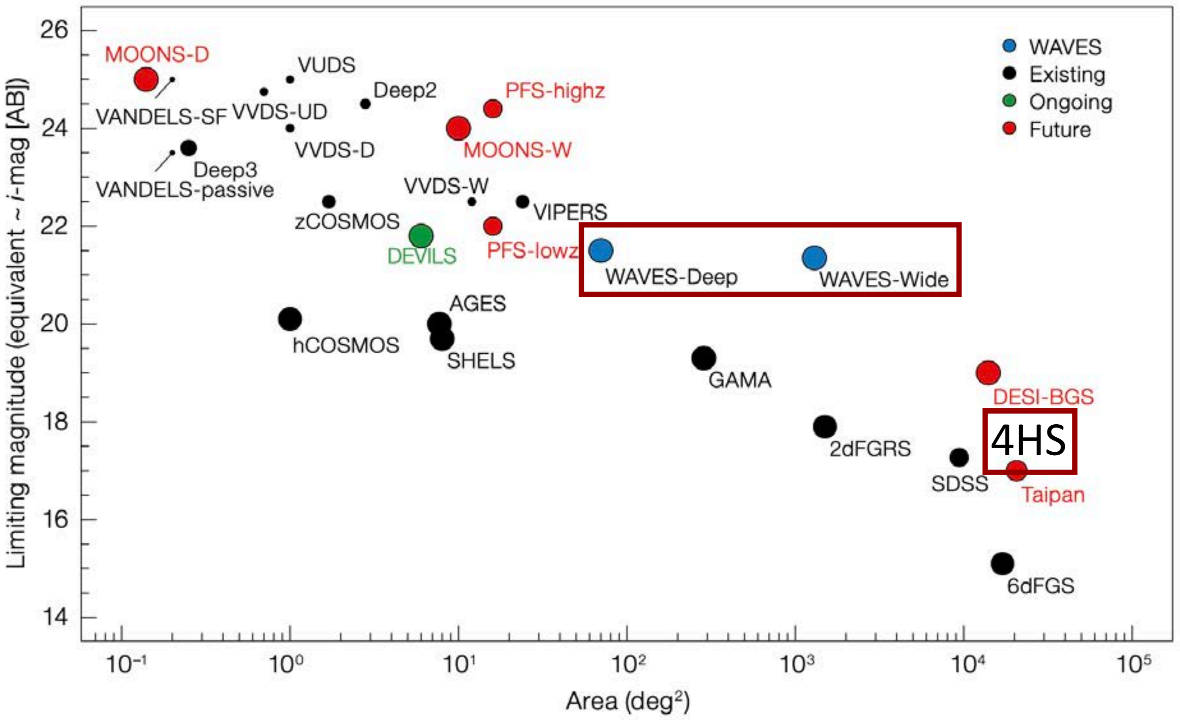
KateMOSS is designed to answer fundamental questions in galaxy evolution:
When and where do galaxies quench their star formation (SF)?
What roles do mass, AGN feedback, and environment play in regulating SF?
How does the cosmic web shape these processes across cosmic time?

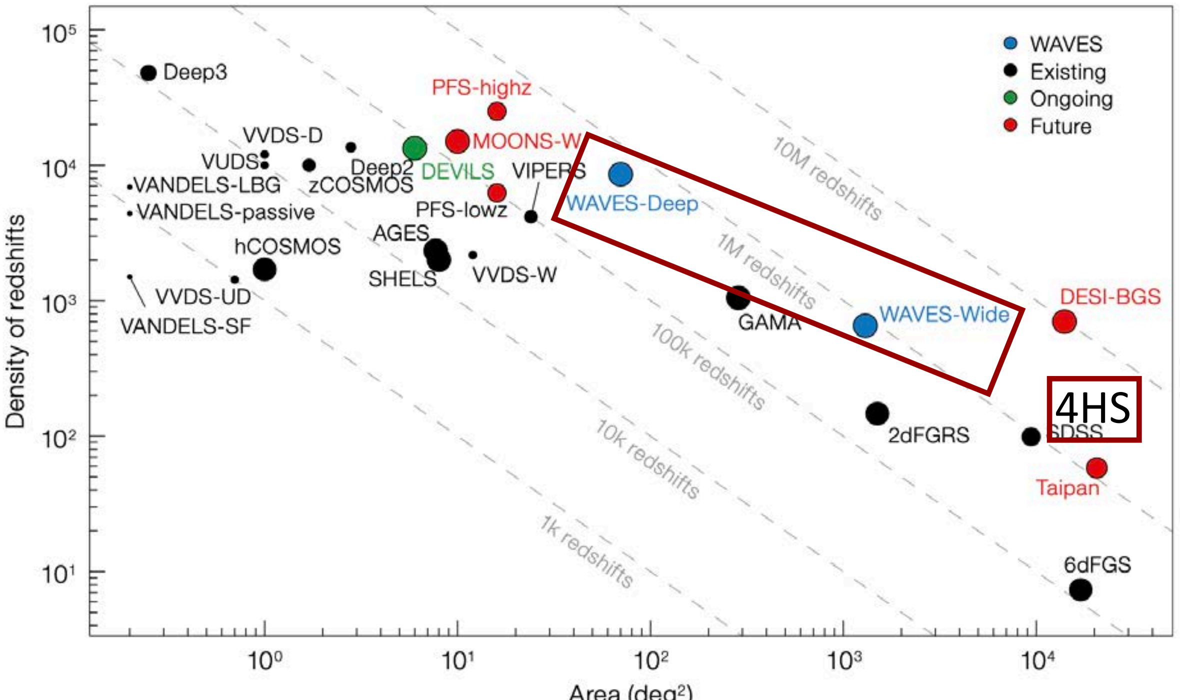








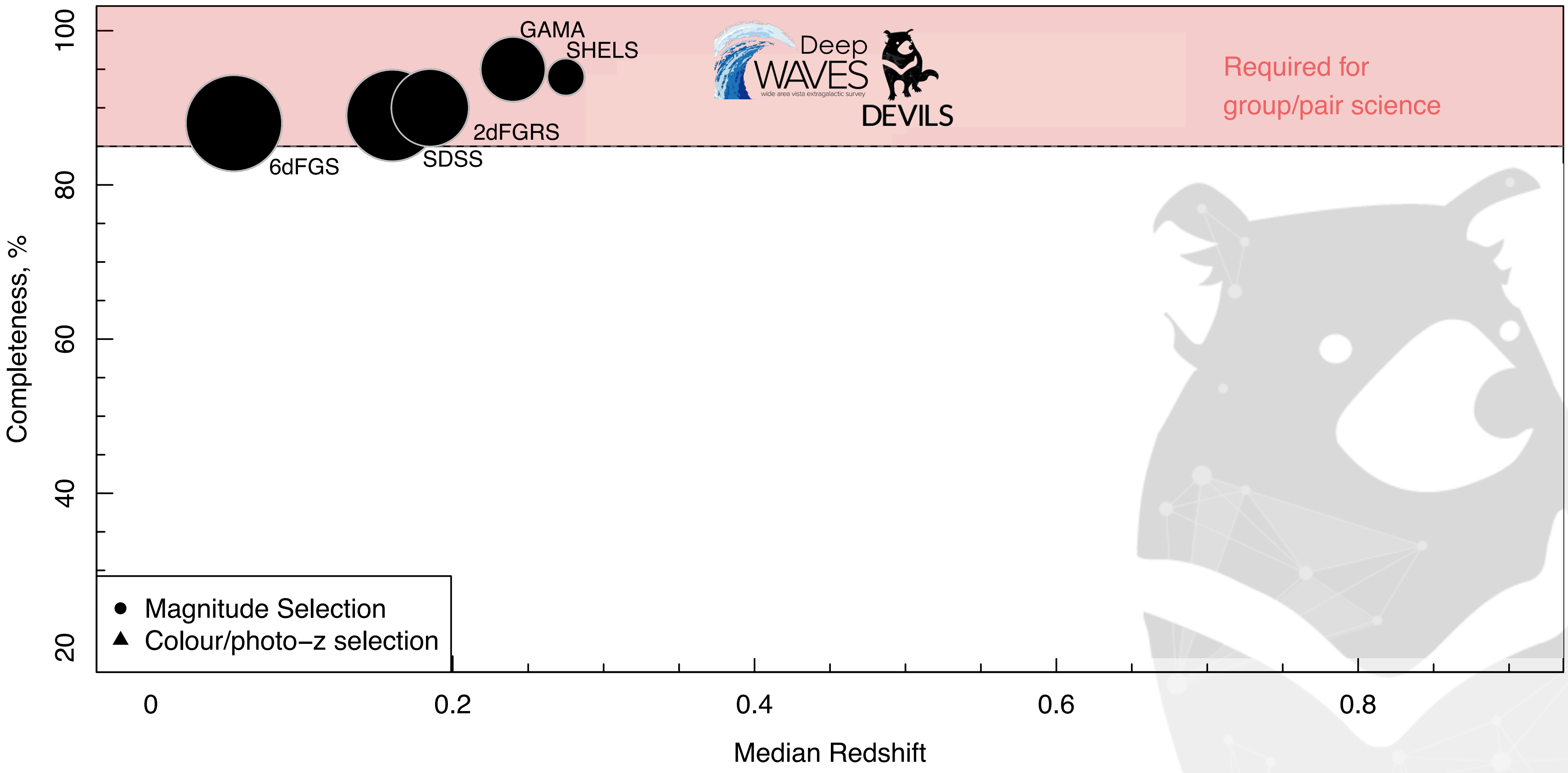




WAVES+4HS survey

Galaxy evolution in low redshift (z<0.2)

Existing surveys at earlier epochs



Where do we go next?

2dFGRS

GAMA

SDSS

Larger samples size/area, similar selection → Reduced errors & cosmic variance, find outliers → DESI, 4HS (THE 4MOST HEMISPHERE SURVEY)

Lower mag, stellar mass, halo mass → New populations/ physics, extend all relations → WAVES (wide area vista extragalactic survey) Wide

Earlier epochs → Larger evolutionary baseline, new populations → DEVILS, WAVES (wide area vista extragalactic survey) Deep, MOONS

Where do we go next?

Go beyond 'typical' galaxies and halos

Lower Stellar/Halo Mass

Wide WAVES
wide area vista extragalactic survey

Determine the **causation** of the local **correlations**

GAMA

&

Higher Redshifts

Deep WAVES
wide area vista extragalactic survey

(G23 & DDFs)

Probe 'rarer' environments and improve statistics

SDSS

Larger area

4HS
THE 4MOST HEMISPHERE SURVEY

+

Combine with multi-phase medium

(Arecibo, VLA, GMRT, ALMA and others...)

Synergy with other facilities

WAVES
wide area vista extragalactic survey
+ SKAO
(and precursors)
(and others...)

What WAVES will give us

Robustly measured galaxy properties for all of the galaxies involved

This will include state-of-the-art data from...

VERA C. RUBIN OBSERVATORY · WEBB SPACE TELESCOPE · SKAO · eROSITA · esa euclid · NANCY GRACE ROMAN SPACE TELESCOPE

and physical properties derived state-of-the-art software...

Stellar Mass

Size

Component SFH

Gas mass/ distribution

Star Formation History

Bulge-to-Total

AGN classifications

Star Formation Rate

Morphology

Metallicity

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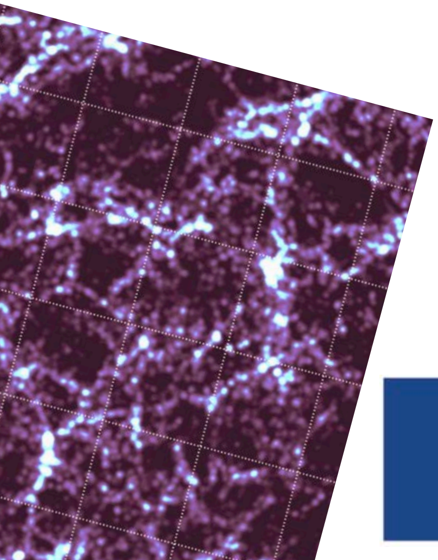
4MOST WAVES and 4HS surveys - mapping the Universe



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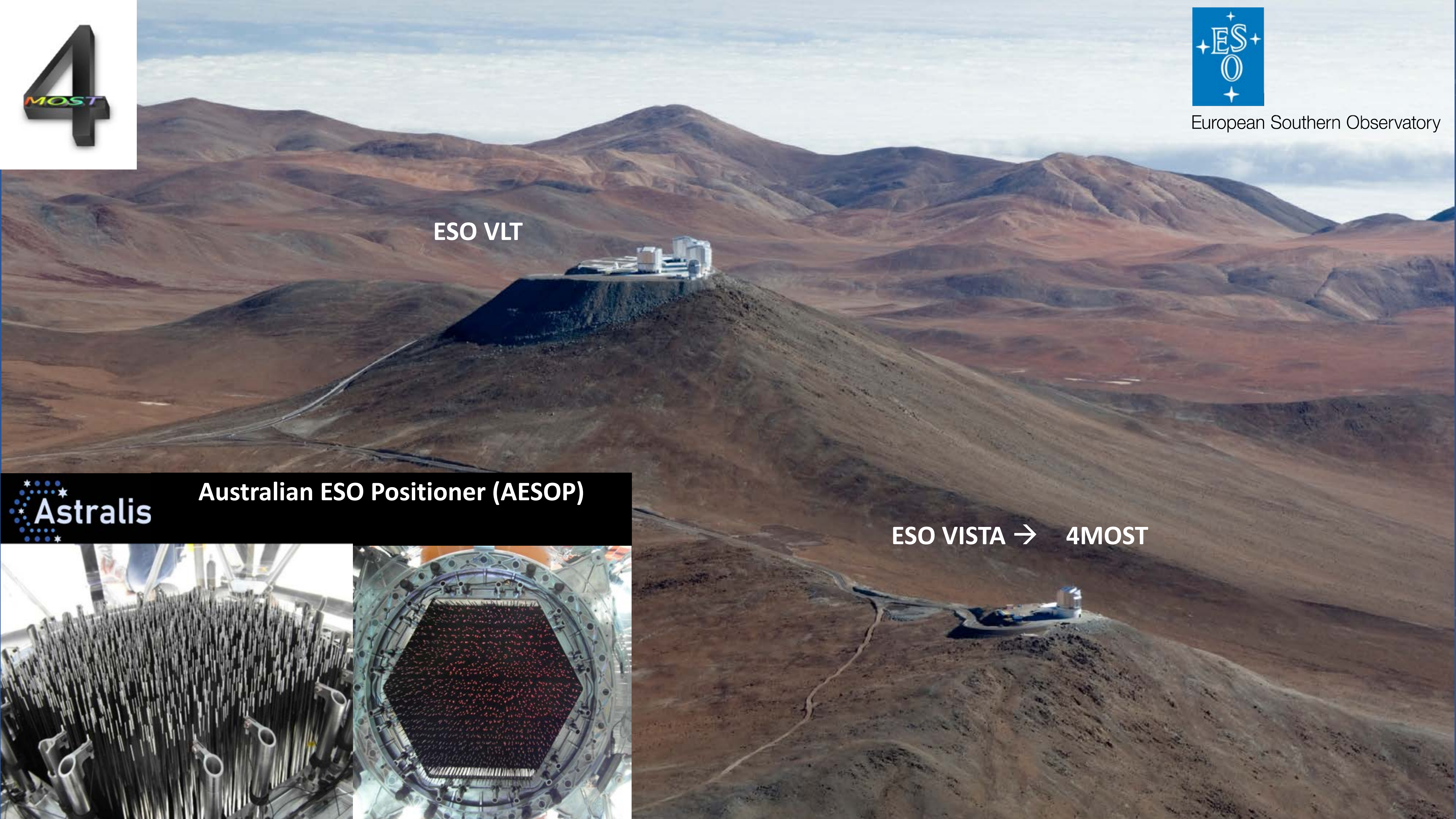
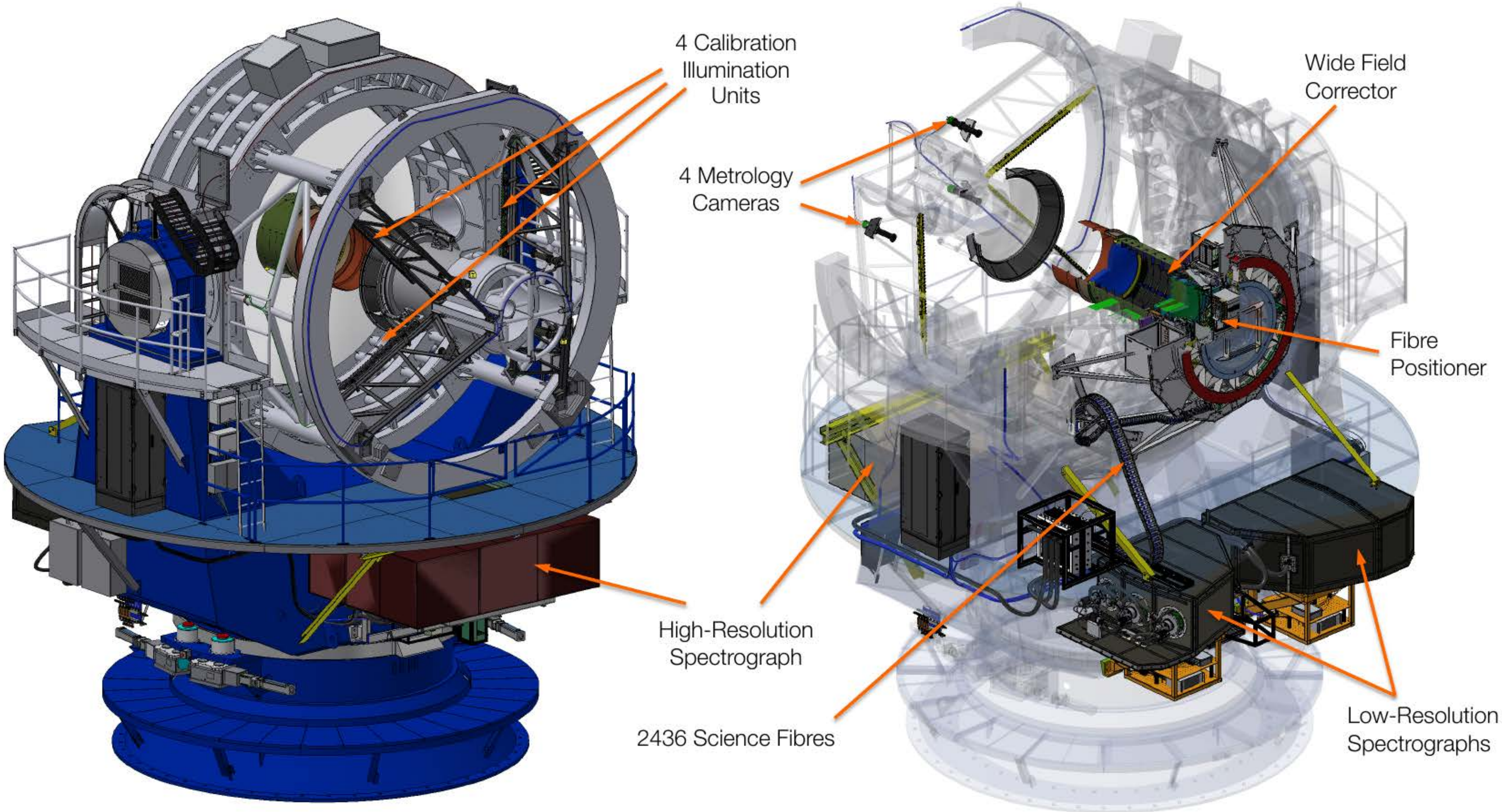
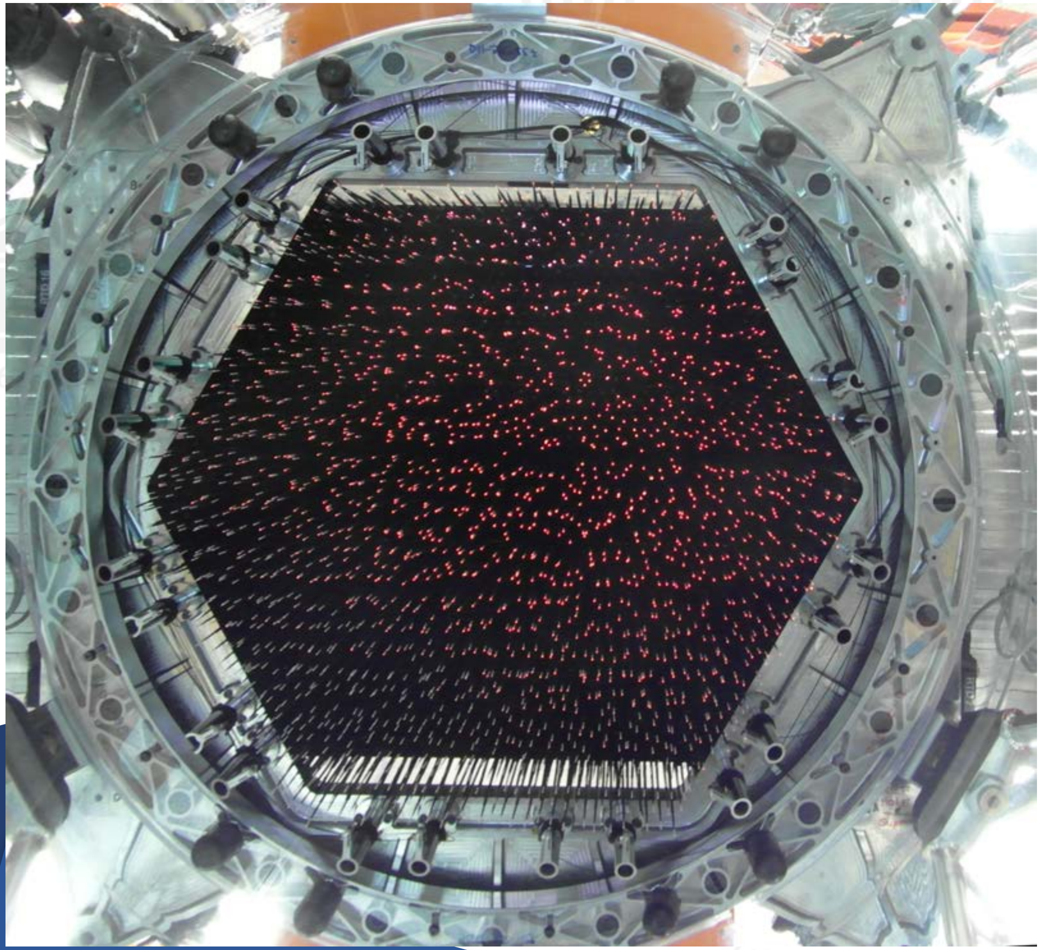

European Southern Observatory
ESO VLT
Astralis
Australian ESO Positioner (AESOP)
ESO VISTA → 4MOST

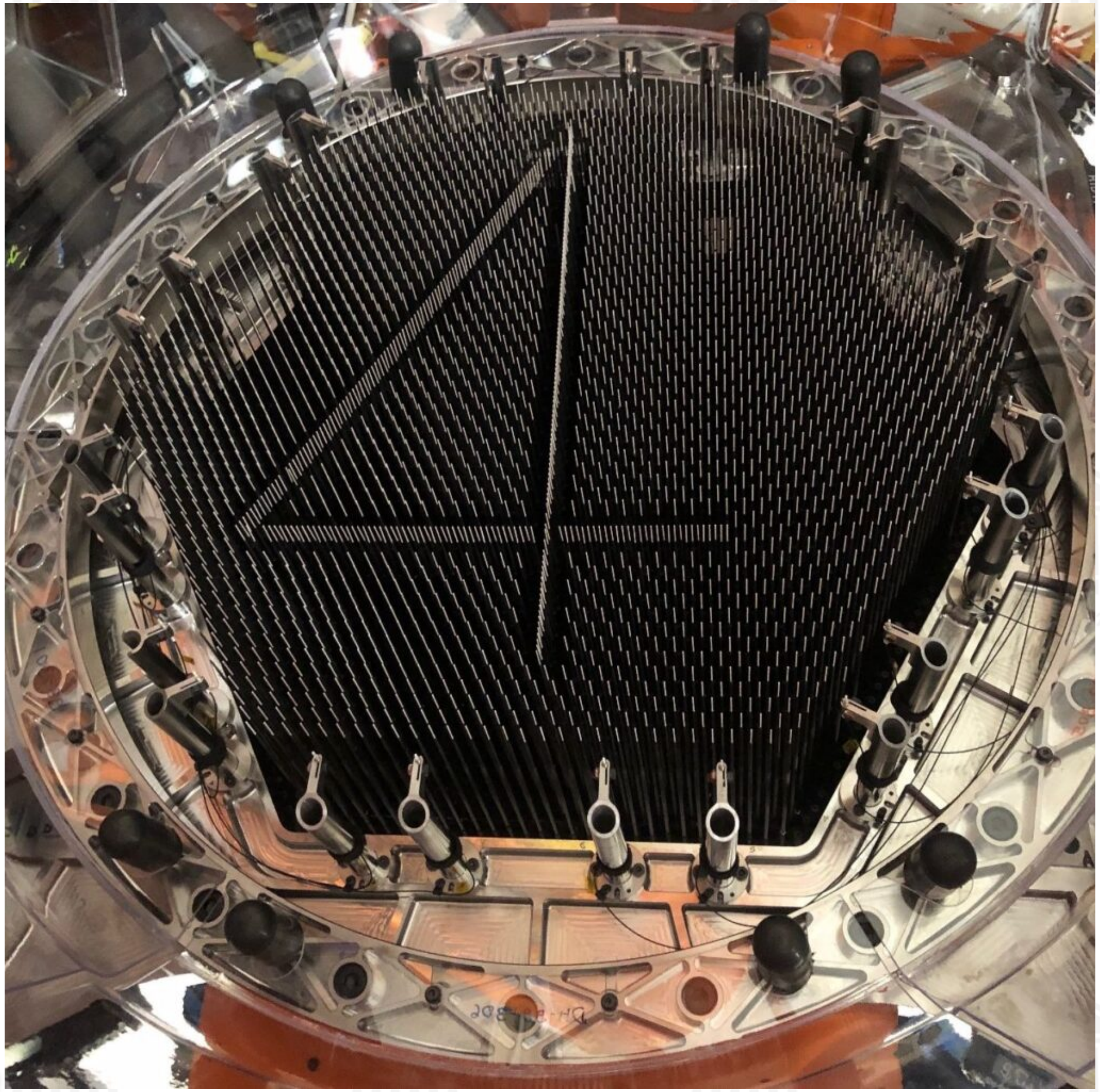


4MOST

ESO/VISTA 4-metre telescope

Credit: 4MOST





4MOST

AESOP fibre positioner

Credit: 4MOST

4MOST

Wide science program - 18 surveys

Credit: 4MOST

4MOST: ESO's DESI

- €60 Million upgrade to the 4m VISTA telescope to become large field of view fibre-fed spectroscopic survey facility
- Consortium of Universities/Institutes working with ESO (approved June 2015). 17 full members & 9 minor participatns. **PI: Roelof de Jong**
- Operations start Q1 2026 (at least 2x5 year surveys)
- Simultaneously run 10 consortium surveys (70% time) and community proposed surveys (30% time) contiguously over 5yrs
- 10+ surveys will share the focal plane in a given pointing

18 independent surveys on 1 telescope embedded in 1 observing program

WAVES is the largest of the extragalactic programs

4HS

THE 4MOST HEMISPHERE SURVEY

SURVEY

Mapping mass and motion across the southern sky

Edward (ned) Taylor

Cosmic Ecosystems in Radio and Optical, 9/12/24

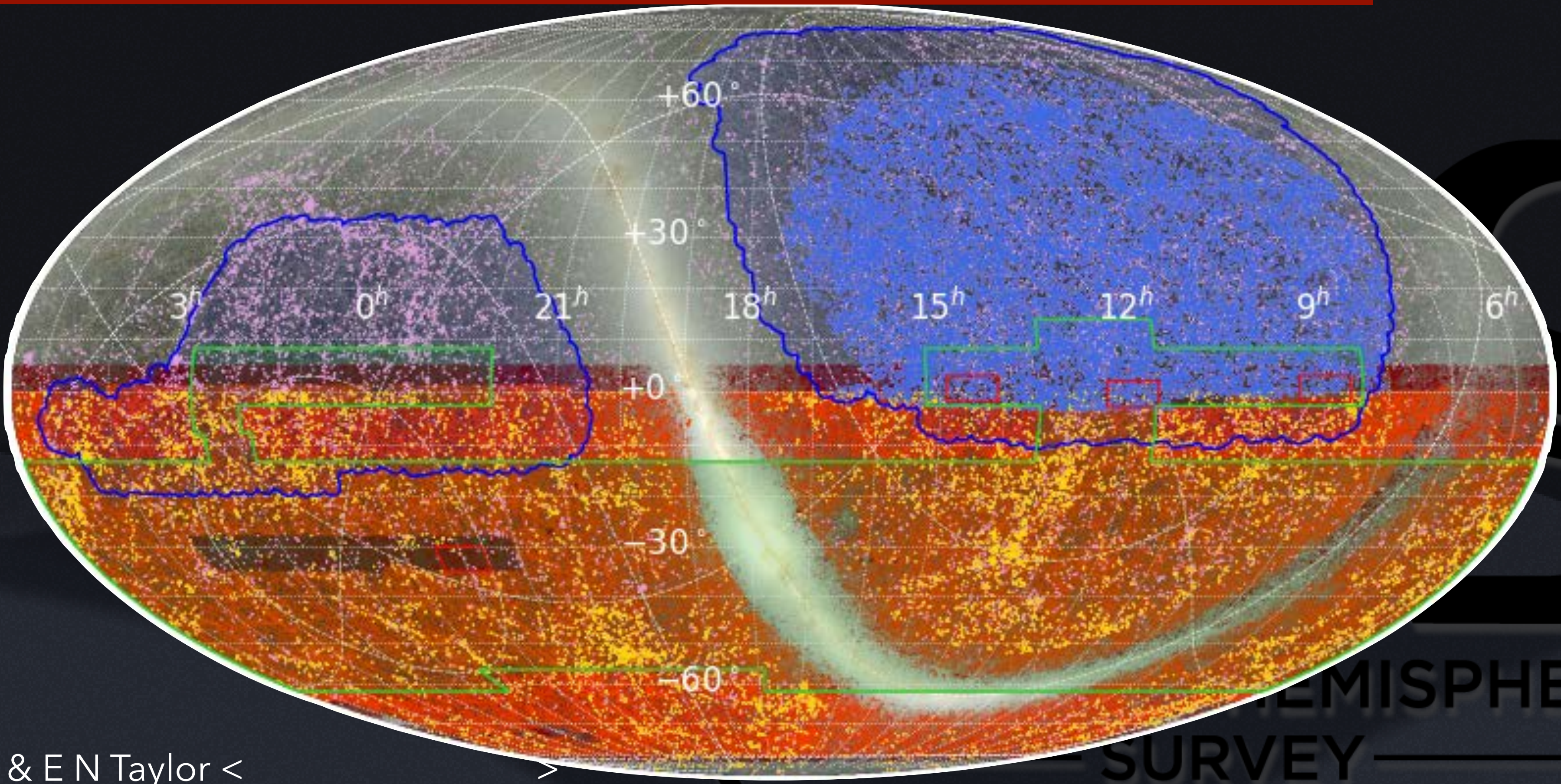
4HS: The 4MOST Hemisphere Survey

See ENT, MC, et al. 2023, Msngr 190, 46

Spectroscopy and redshifts for ~4.5 M galaxies over ~17.500 deg^2 with high and unbiased completeness for $z < 0.15$.

- ***PV cosmology sample: J < 16.5 and (J-K) < 0.3 --> ~65 / deg^2 x ~17.500 deg^2***
  ~500.000+ PV measurements over the largest possible area/volume.

CF4
6dFGS
SDSS
DESI
Wallaby
4HS PV



4HS PIs: M Cluver & E N Taylor < >

4HS: The 4MOST Hemisphere Survey

See ENT, MC, et al. 2023, Msngr 190, 46

Spectroscopy and redshifts for ~4.5 M galaxies over ~17.500 deg^2 with high and unbiased completeness for z < 0.15.

- No (strong) sample pre-selection:
  we will observe everything and then down-select.
- Will re-observe all of 6dFGS, plus GAMA/SDSS/DESI overlap.
- Baseline strategy equiv. to 18 min in nominal gray conditions
  (cf. ~5 min in nominal dark conditions for DESI-BGS).
- very high and unbiased completeness: >90 % globally.
  < 2% bias against separations < 15 arcsec (yes, arcsec!!)
- Feedback prescription to maximise yield with S/N > 10;
  expectation to have repeat observations for ~5+% of targets.
- R ~ 6000 => velocity dispersion limit ~25 km/s
  (cf. DESI: R ~4500 => ~45 km/s; SDSS R ~2000 => ~60 km/s).

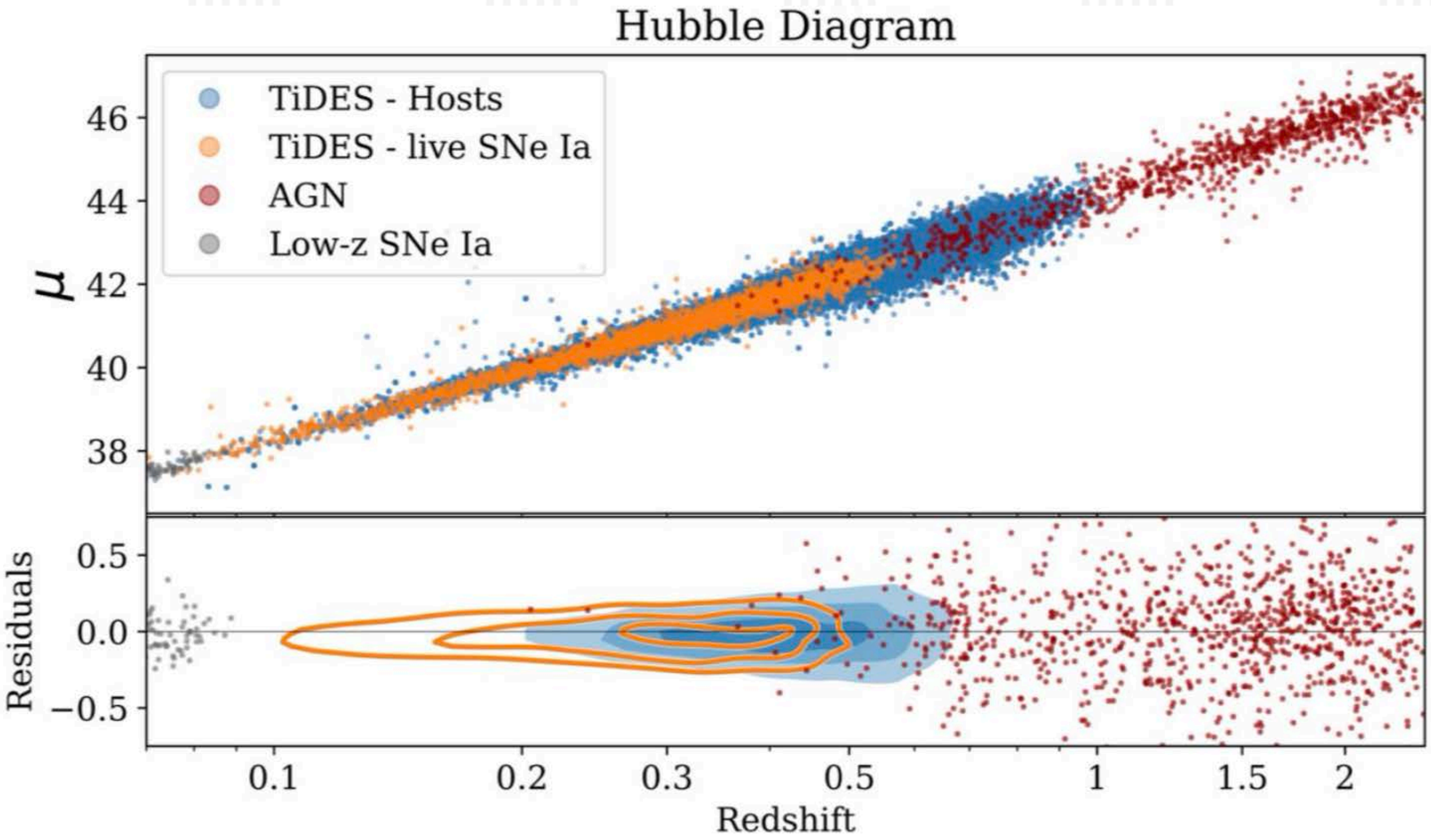
4HS PIs: M Cluver & E N Taylor < >

4HS: The 4MOST Hemisphere Survey

See ENT, MC, et al. 2023, Msngr 190, 46

- ***Whatever the astrophysics, low-z science is driven – or limited – by the availability of spectroscopic redshifts.***
    - ~4.5 M galaxy redshifts for Dec < 0.
    - ~800,000 redshift independent D/PV measures.
    - 650,000 galaxy groups with N > 3.
    - Group-averaged redshifts for all of these.
    - Group-averaged D/PV measures for ~65,000 groups.
    - Complete, all-sky flow modelling to convergence with CMB.
    - ***An essential complement to all low-z cosmology … esp. SNe and GW!***

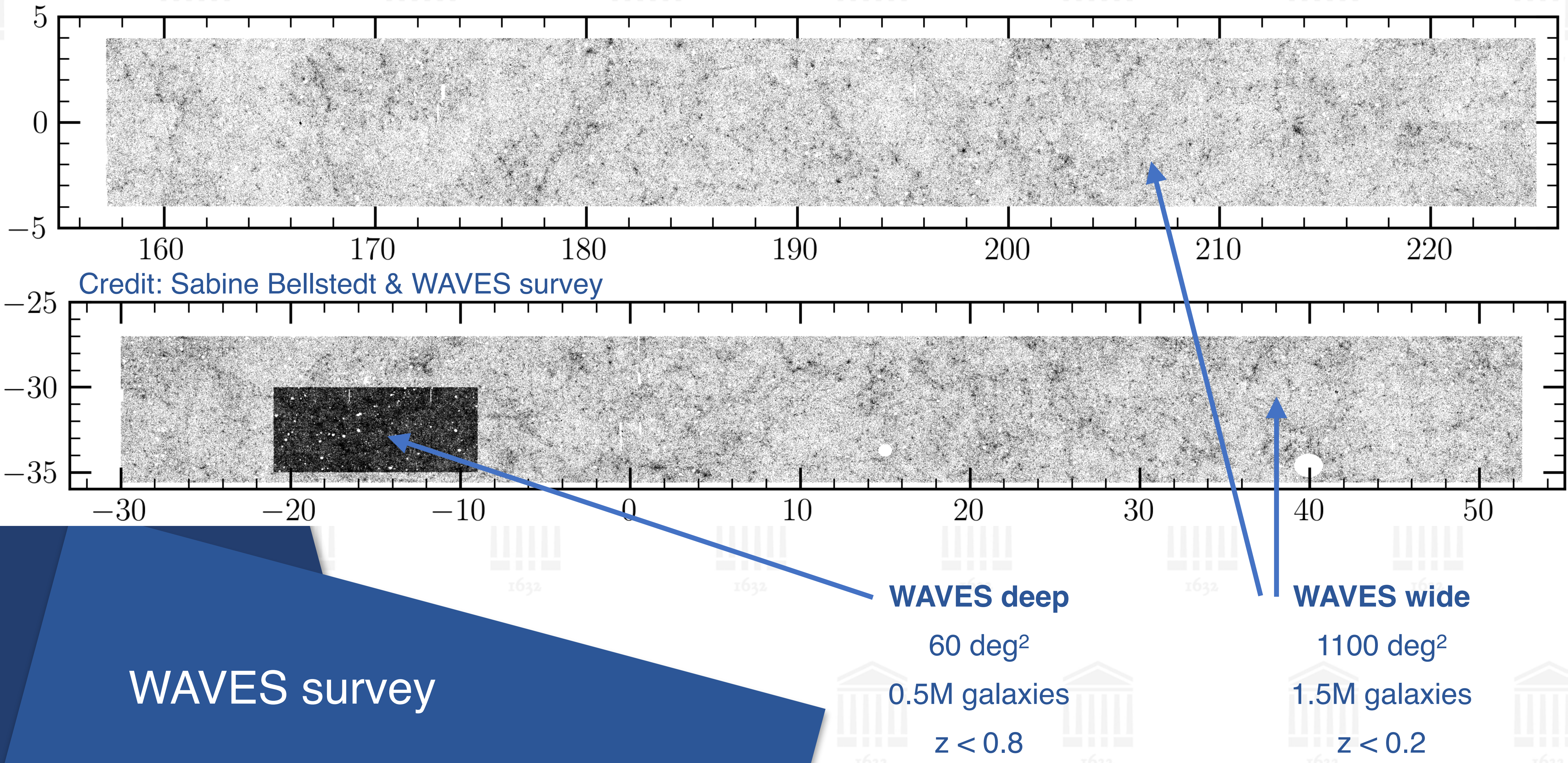
4HS PIs: M Cluver & E N Taylor < >



arXiv:2501.16311

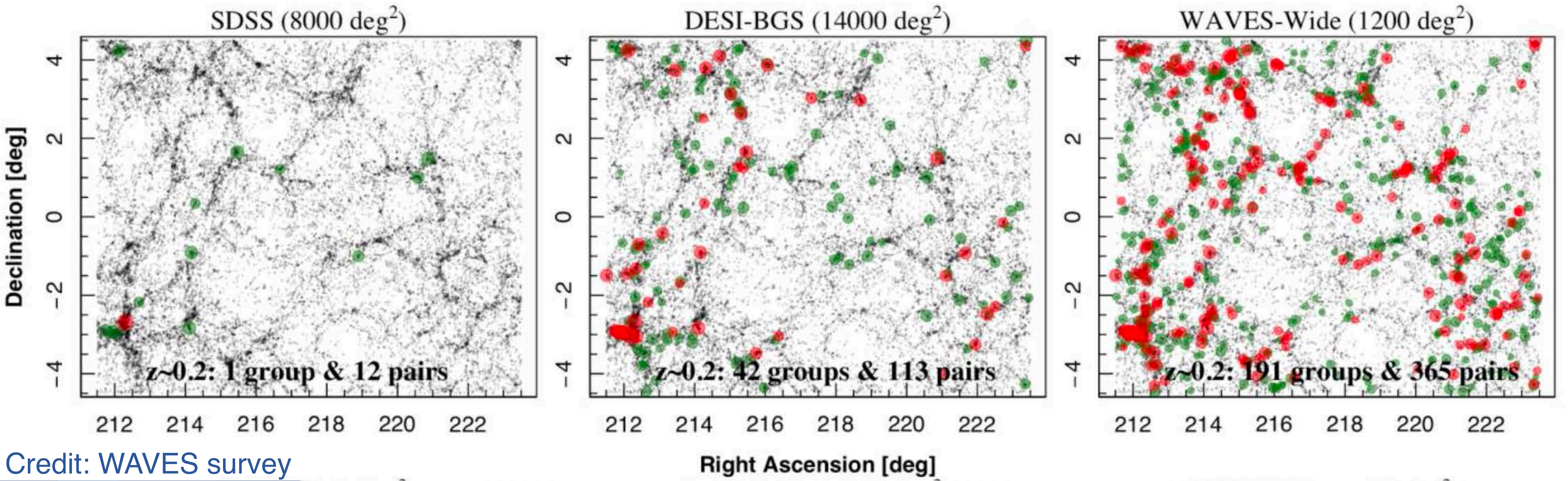
TiDES (LSST transients) supernovae

Credit: 4MOST



WAVES survey

Photometry is based on VISTA KiDS



Credit: WAVES survey

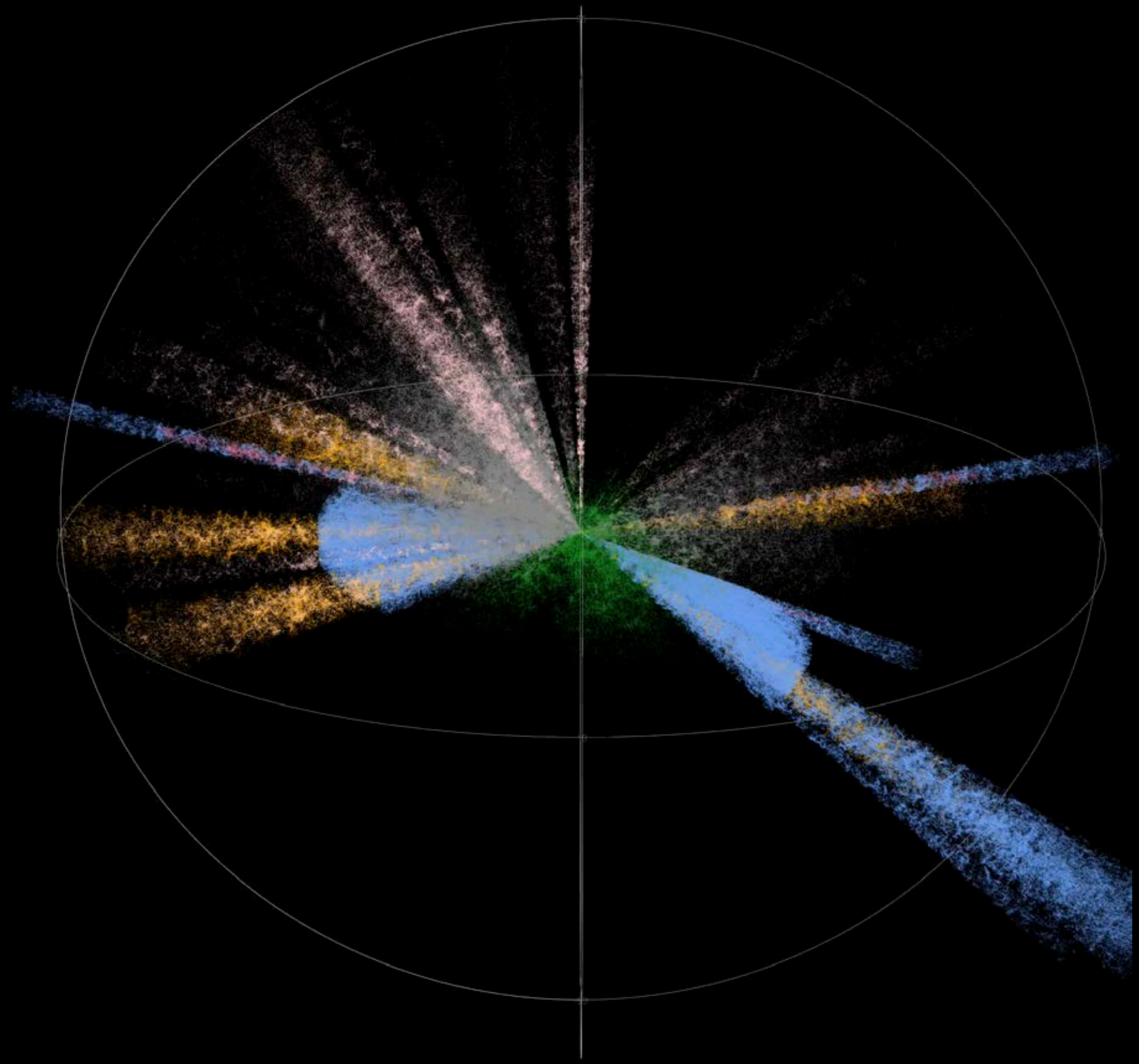
WAVES survey

Galaxy density in WAVES is ~10 times higher than in SDSS

SDSS main	WAVES wide	
7200 deg^2	1200 deg^2	6x smaller
0.5M galaxies	1.5M galaxies	3x redshifts
mag_r < 17.77	mag_i < ~22	more than 10 times denser
z < 0.2	z < 0.2	

Wide Area VISTA Extragalactic Survey

SDSS
GAMA
DEVILS
DESI
WAVES

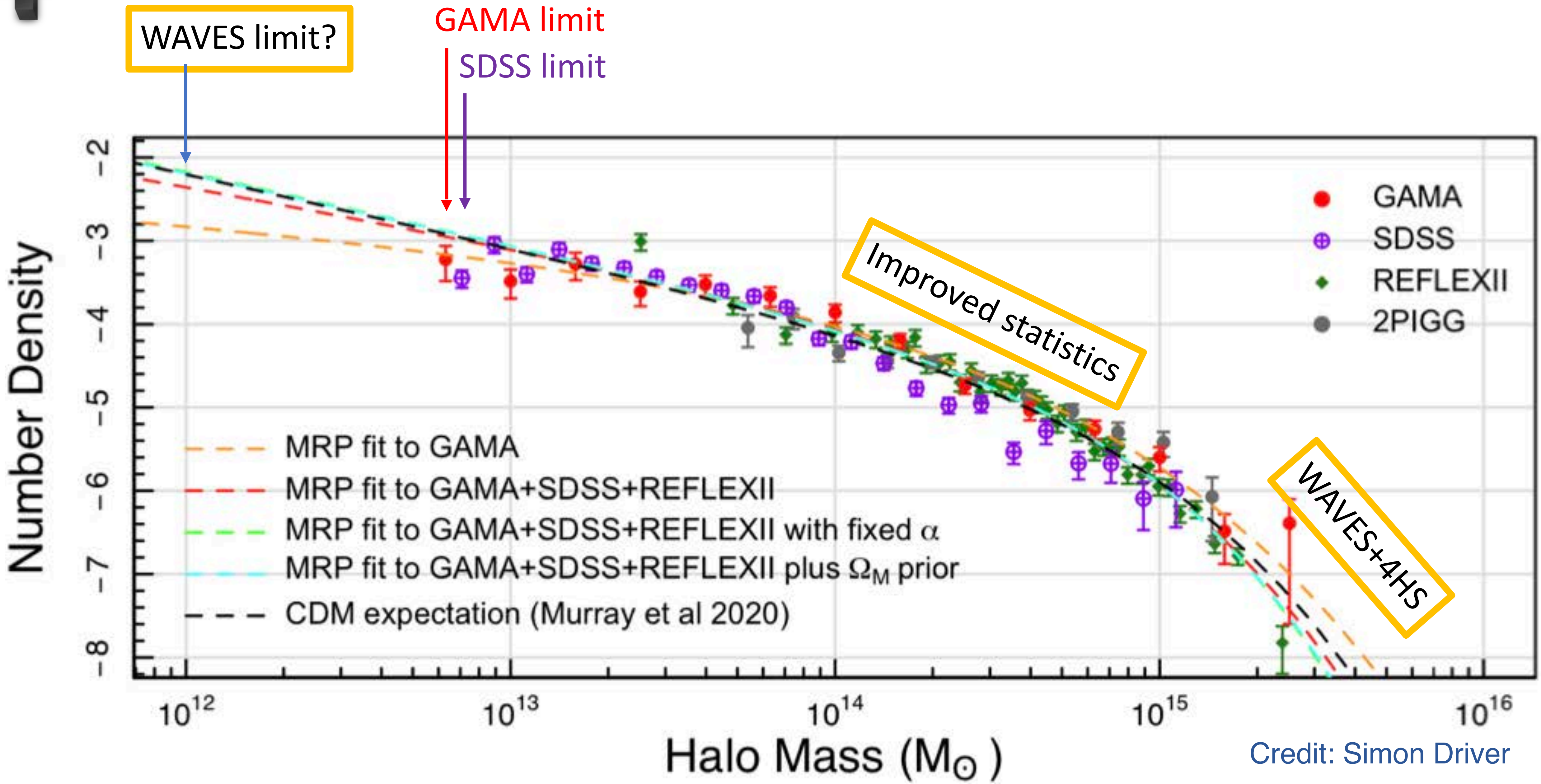


~850 clusters with $>10^{14}$ M_{sol} out to z<0.8 from the deep surveys.

Extra depth in WAVES will mean GAMA groups with ~2 members will have around 10 in WAVES – substantially improving halo masses.

sabine-bellstedt sabine.bellstedt@uwa.edu.au

The halo mass function from REFLEXII+SDSS+GAMA



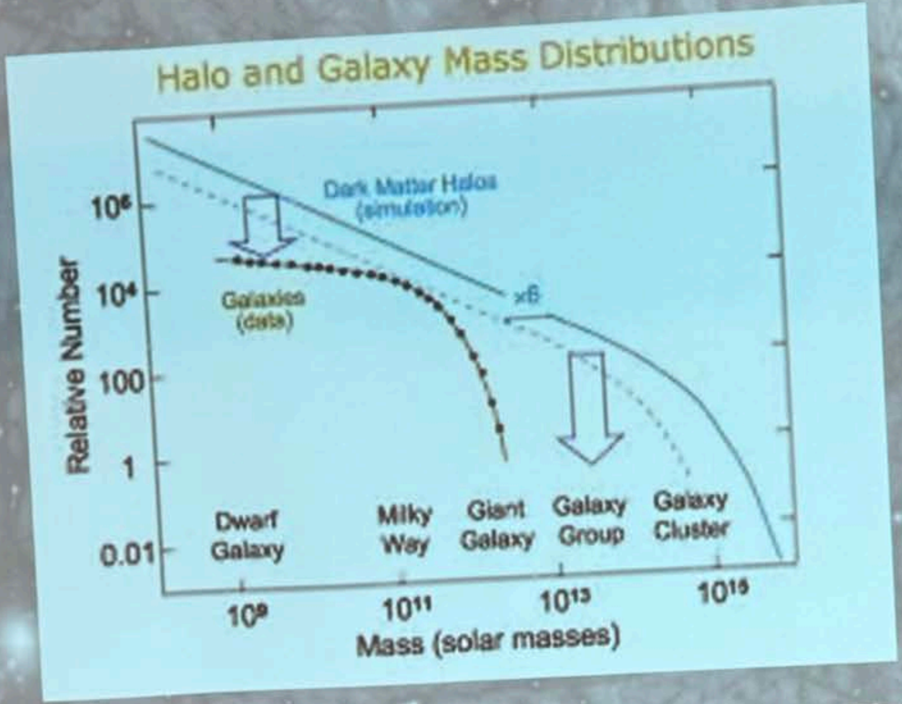
Credit: Simon Driver

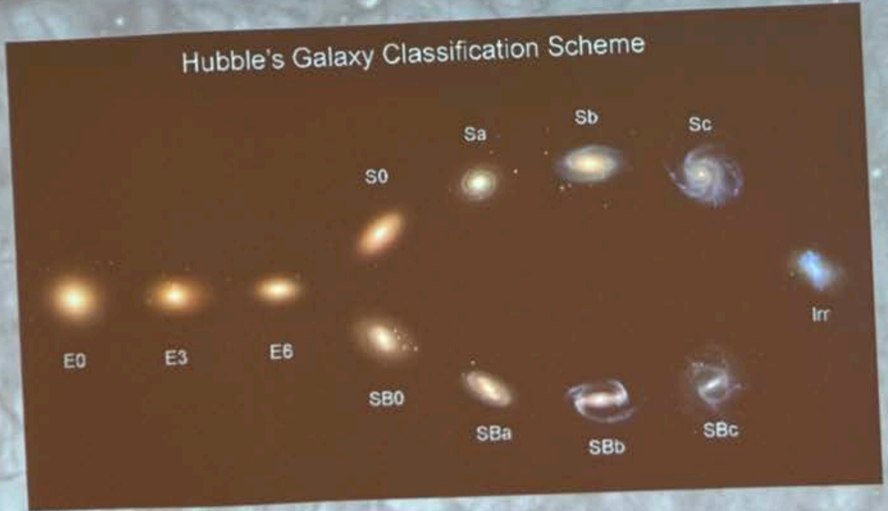
The central questions of cosmology:

Given the initial conditions from the CMB:

how did structure in the universe form?

How did galaxies form?





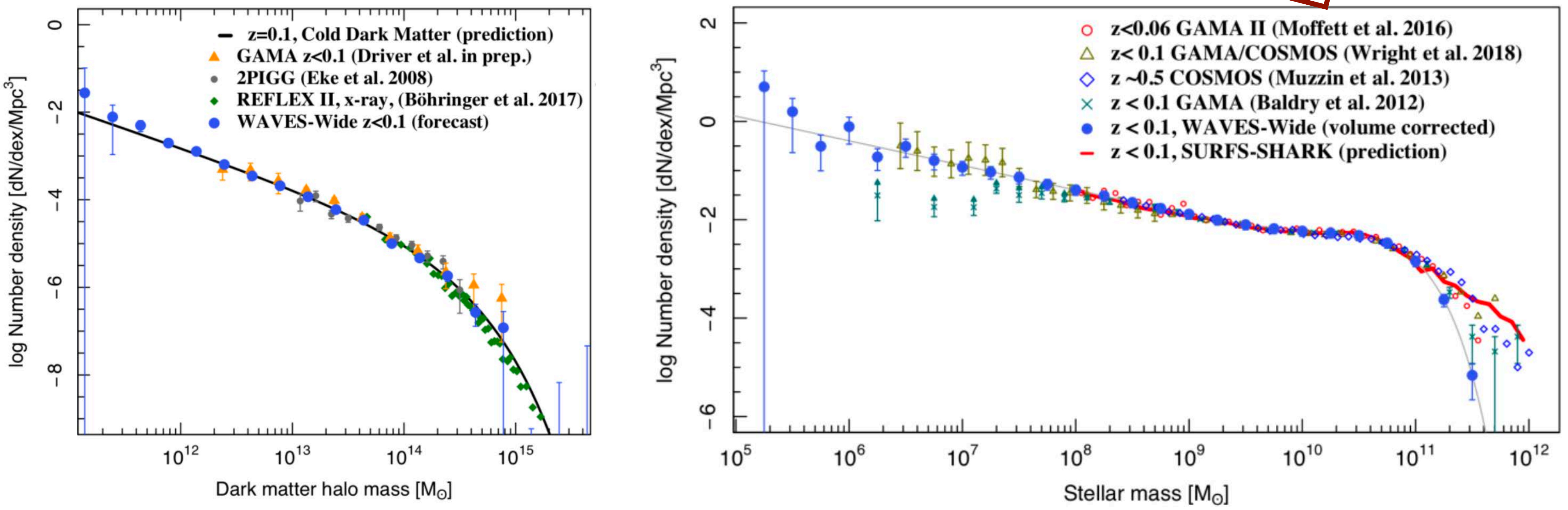
All of galaxy formation can be simplified as:

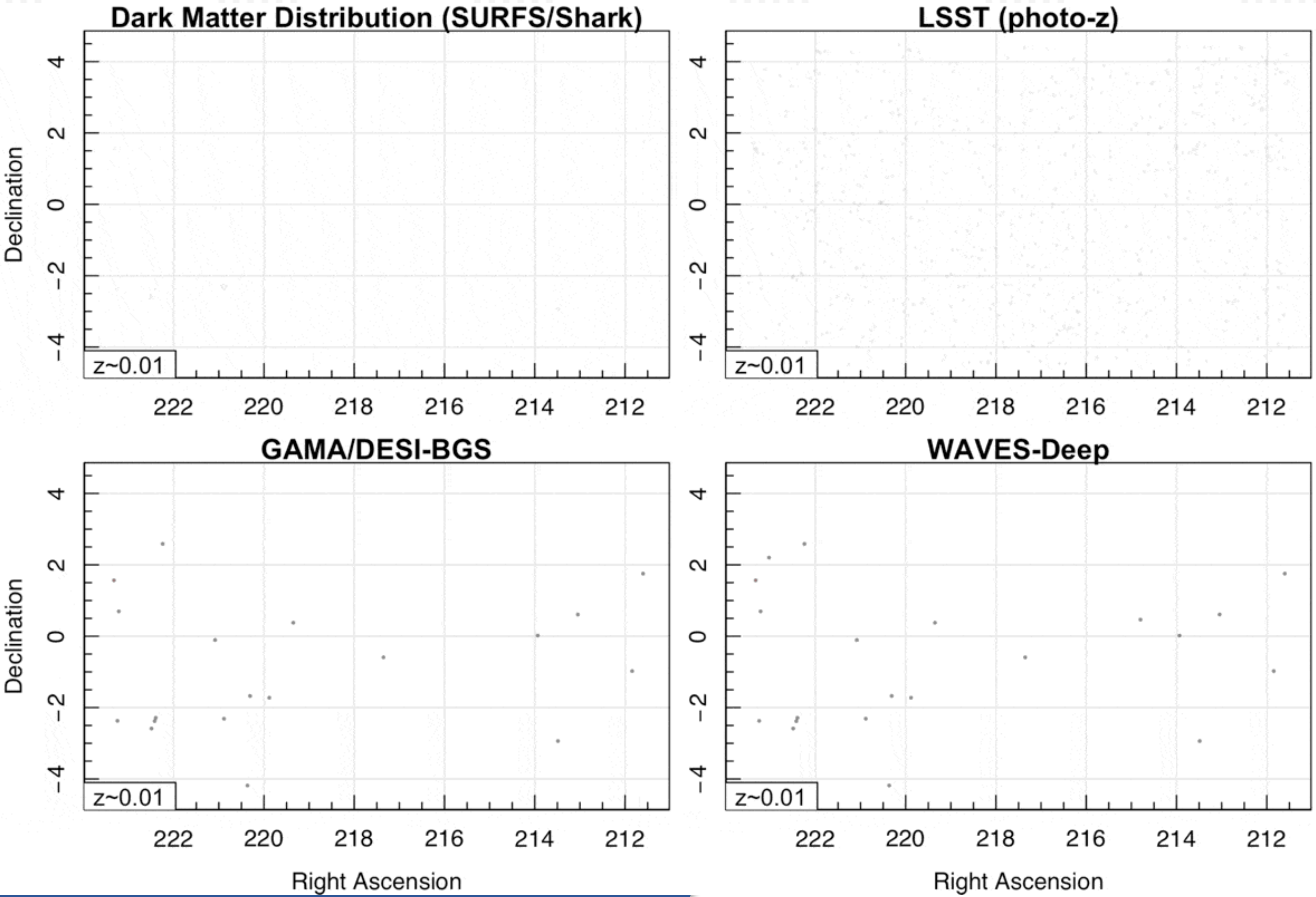
How do you turn the halo mass function into the galaxy luminosity function?

Credit: Noam Libeskind

WAVES

LMC like DM haloes
dwarf galaxies

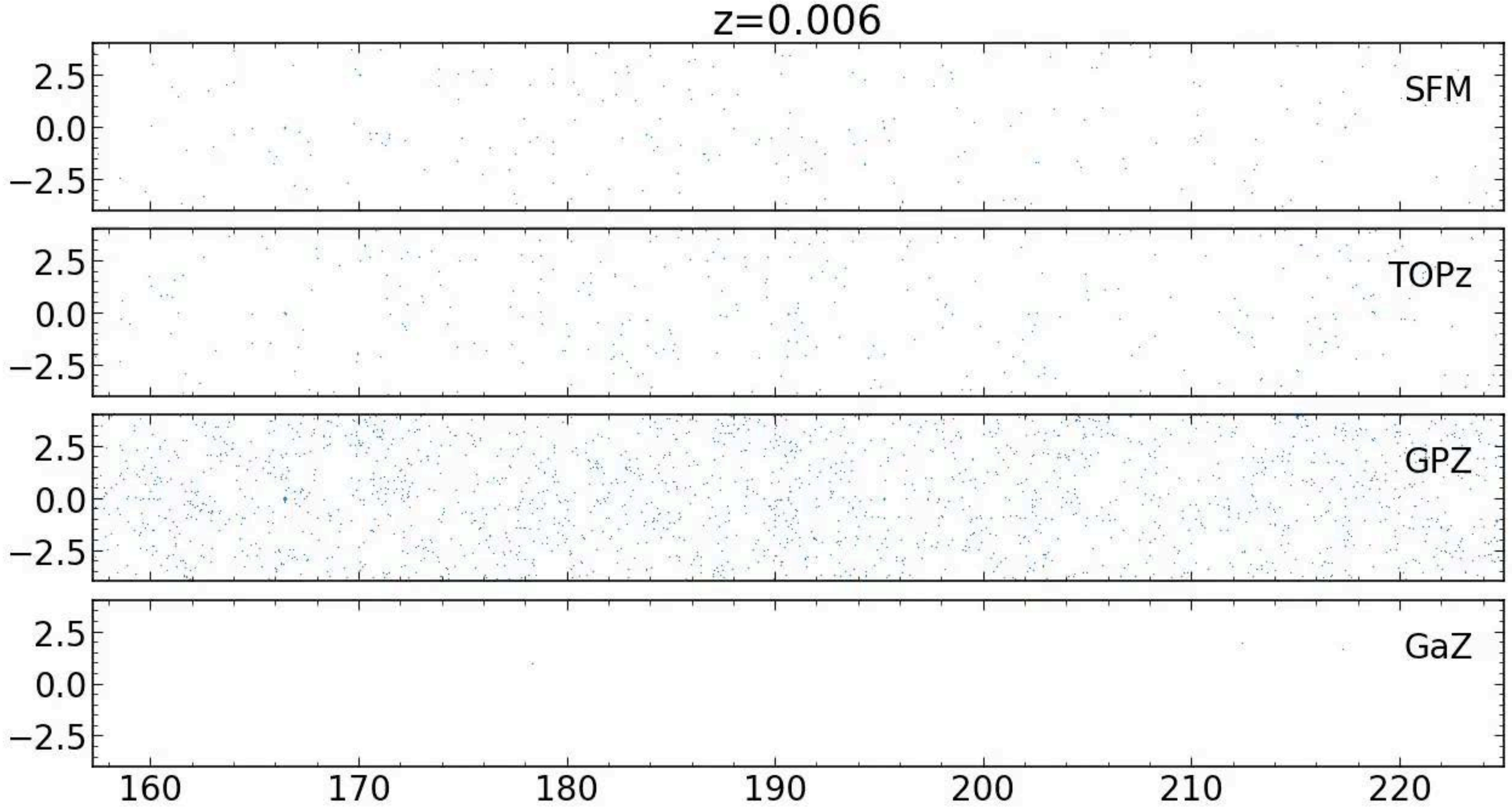


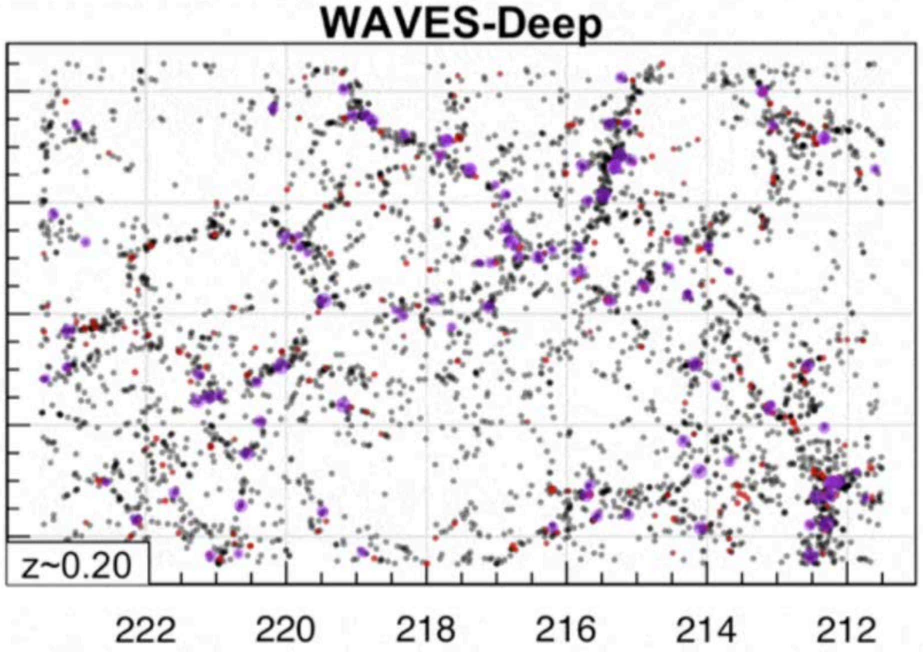


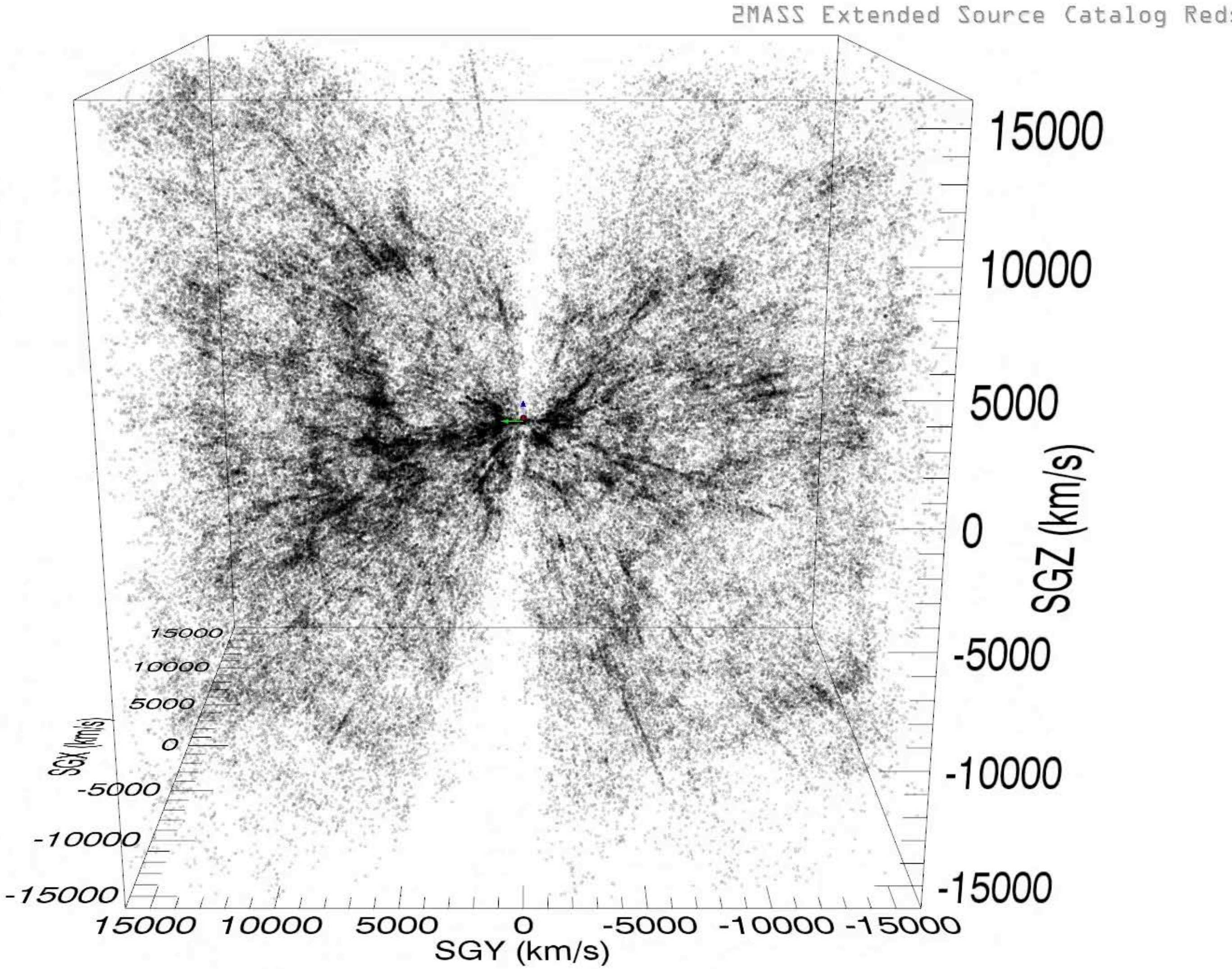
Cosmic Web in WAVES

Credit: Simon Driver

Same dataset, different photo-z methods







Cosmic Web in 3D

Cosmic web in the Local Universe

Galaxy/AGN science

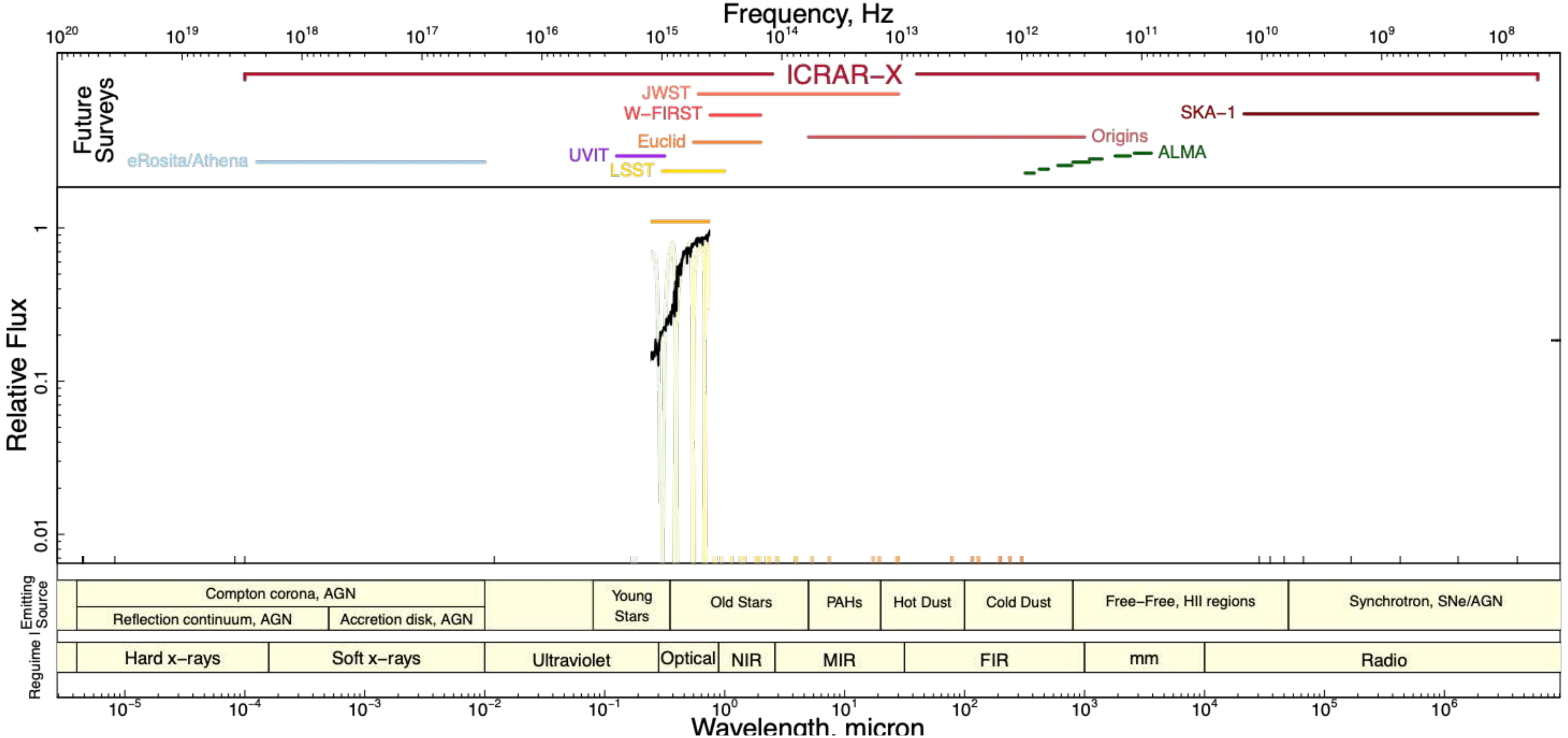
Galaxy/AGN unification

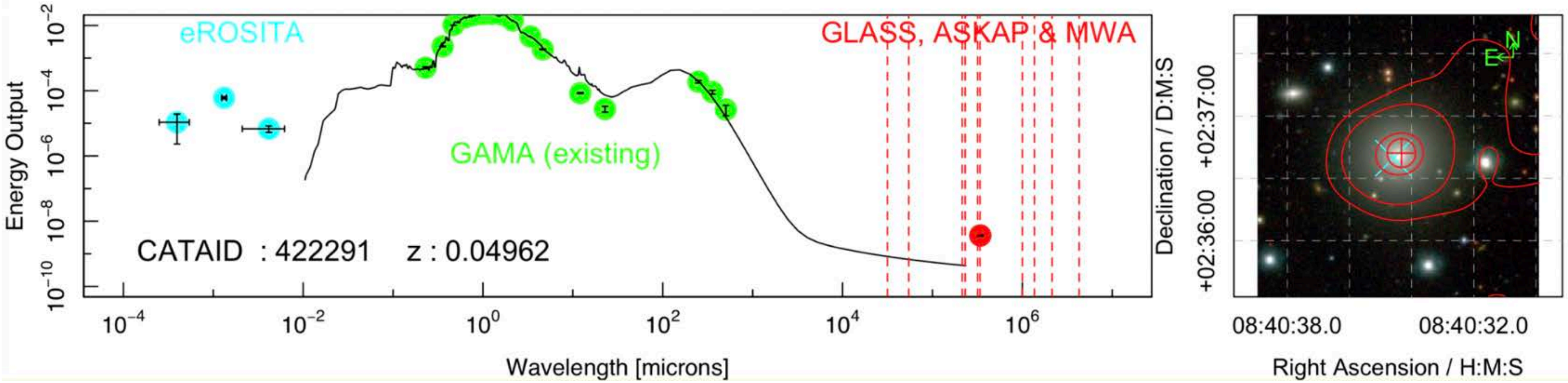
Galaxy SEDs and SFHs (ProSpect)

Joint SED+structural decomps (ProFuse)

10 radio continuum channels plus eROSITA

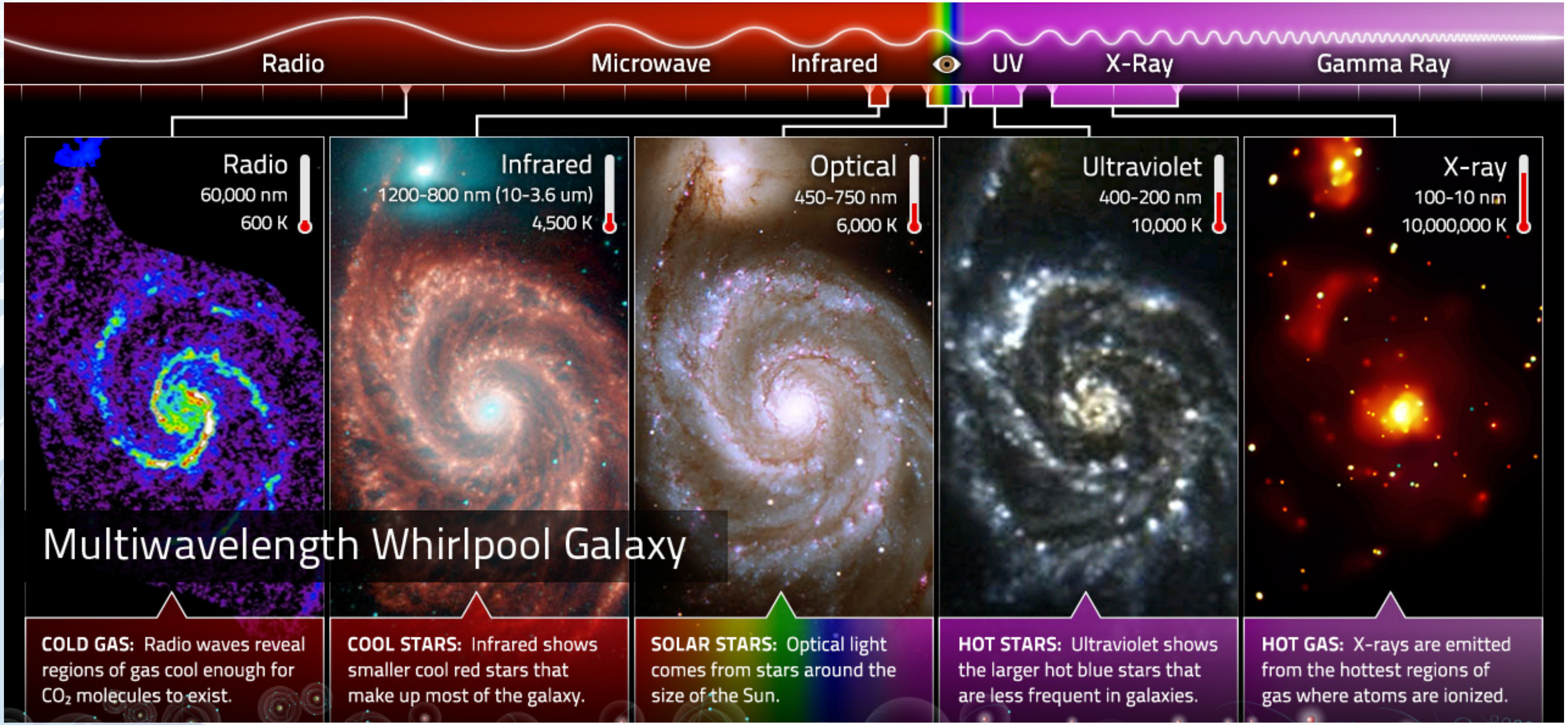
LSST+Euclid





Why is this useful?

- The source of the light emitted changes with wavelength – Thus the use of data collected across the wavelength region allows us to build a fuller picture of the structure of AGN/Galaxies, and probe the emission from stars, dust and gas.



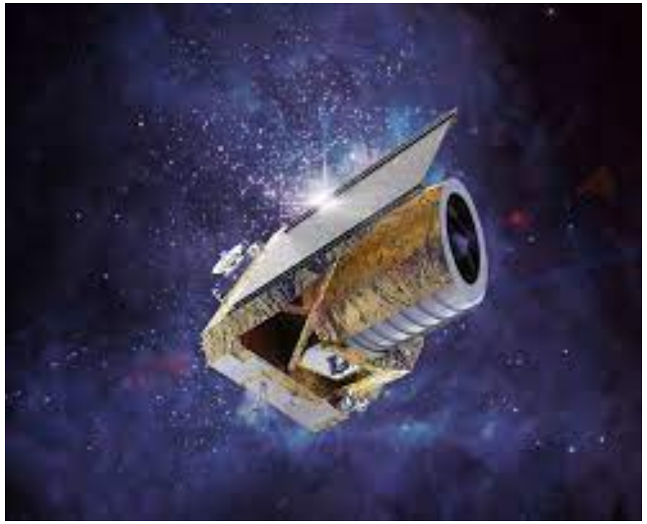
https://ecuip.lib.uchicago.edu/multiwavelength-astronomy/astrophysics/05.html

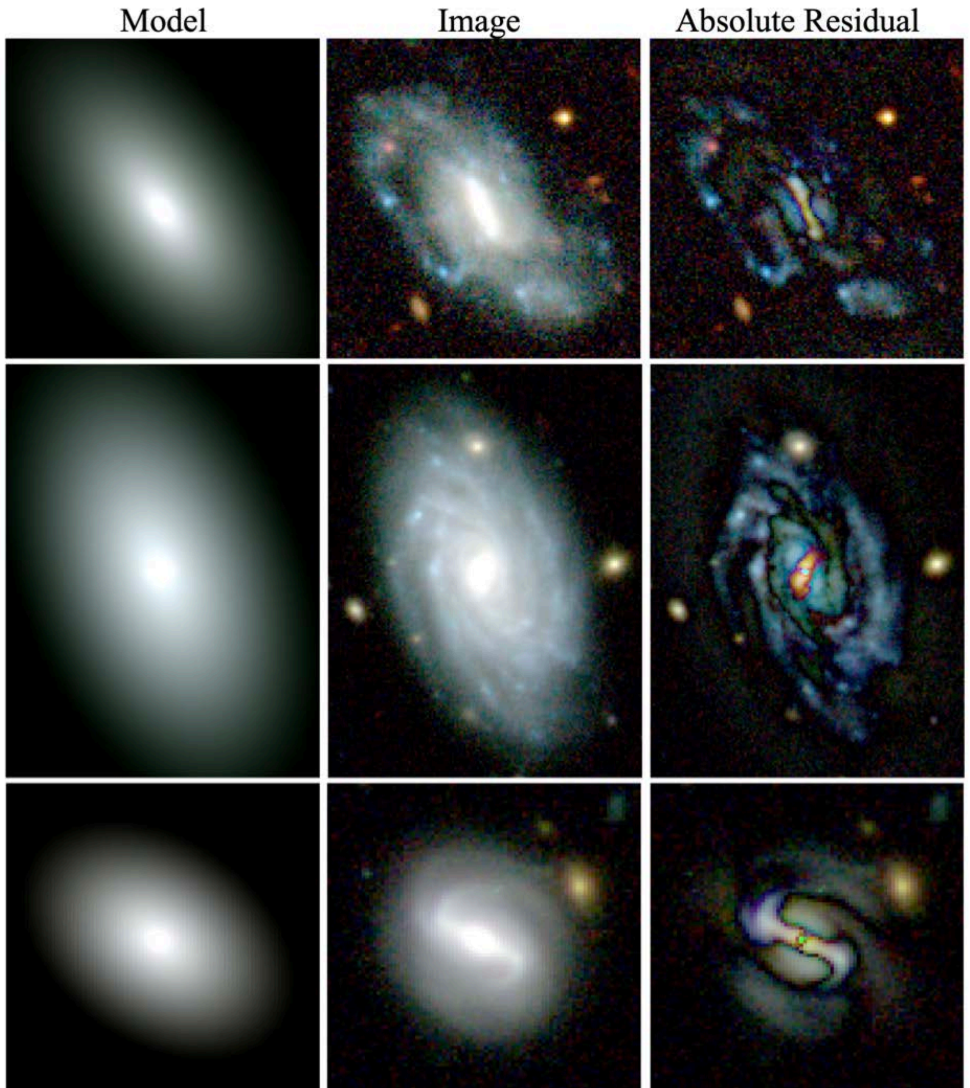
Identify the physical mechanisms behind kpc structures

Inclusion of Euclid allows for **Simultaneous SED and spatial fitting with ProFuse (Robotham et al 2022)!**

LSST photo-z + Euclid spatial resolution + multiband photometry

Euclid will cover all of WAVES-Wide South providing exquisite HST resolution data



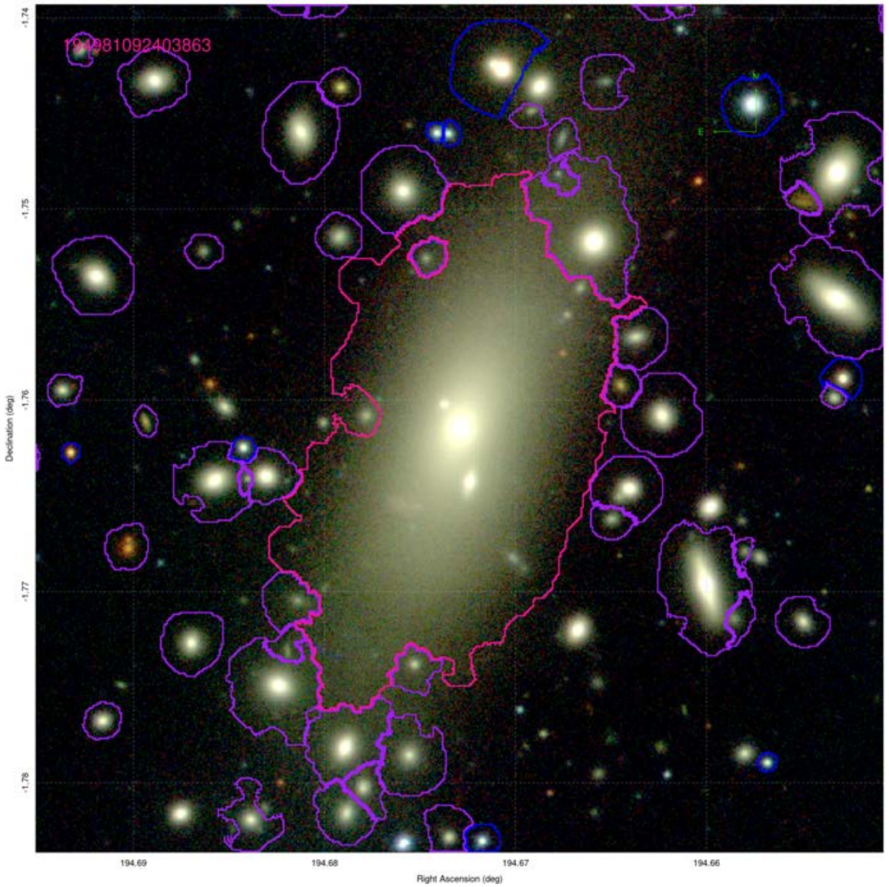


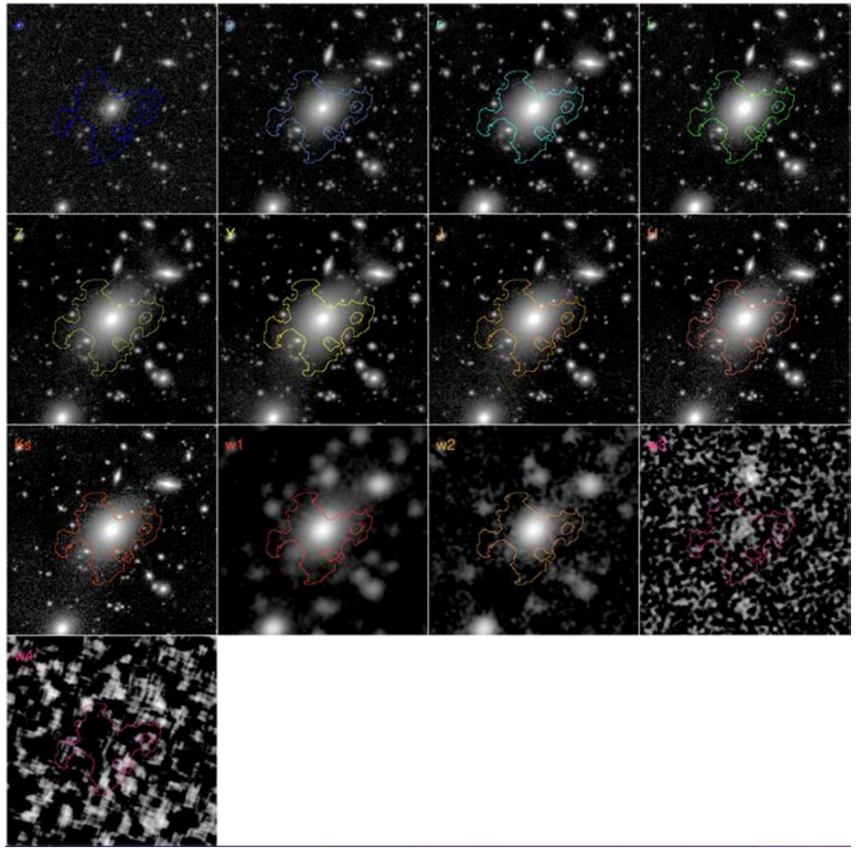
Bellstedt et al (2023)

WAVES Input Catalogues: ESO VST & VISTA

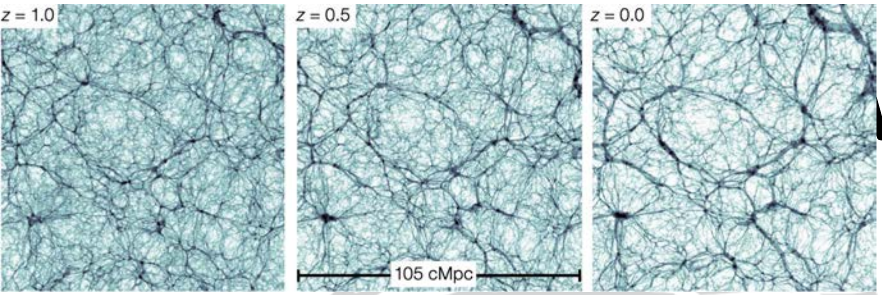
All data and catalogues available via: https://wavessegview.icrar.org
Data Engineer to be employed to improve tool and incorporate into Data Central
(currently too slow and frequently disconnects outside UWA)

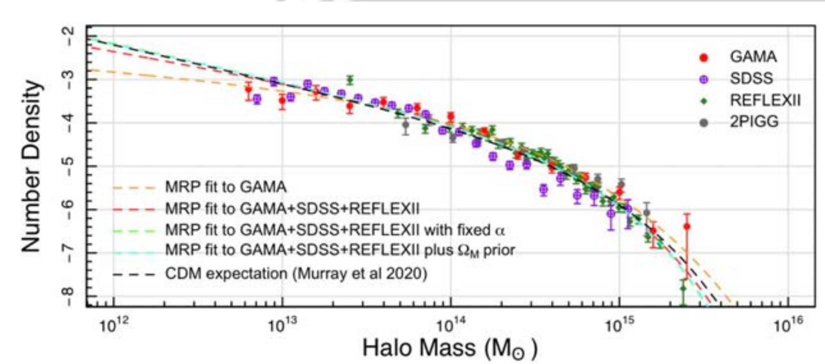
~70 million objects
over 1300 sq degrees
in 13 bands:
ugri ZYJHK $WISE_{1234}$

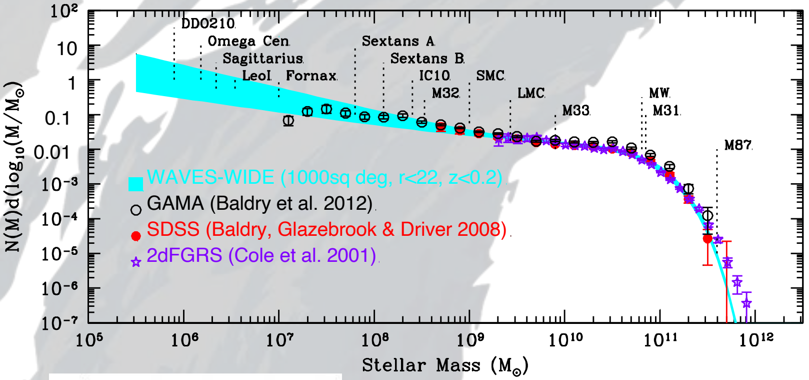


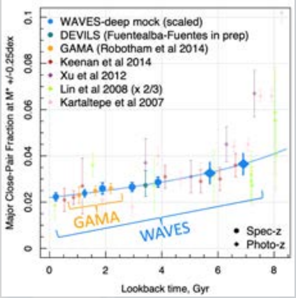


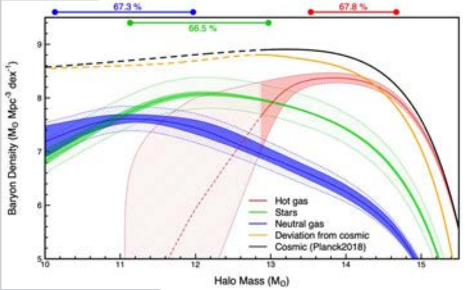
WAVES Headline Science Goals











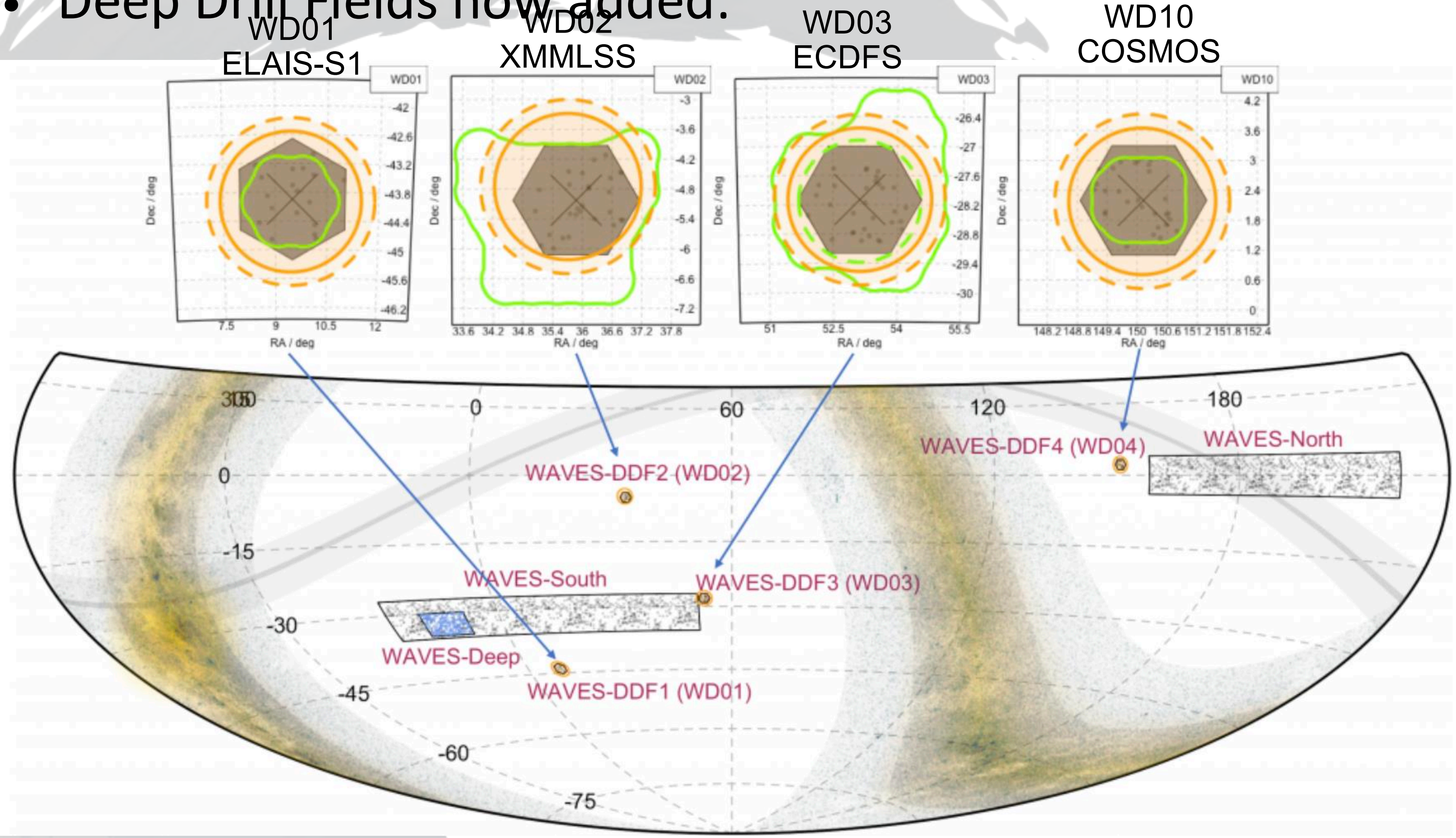
See Talks this afternoon, but:

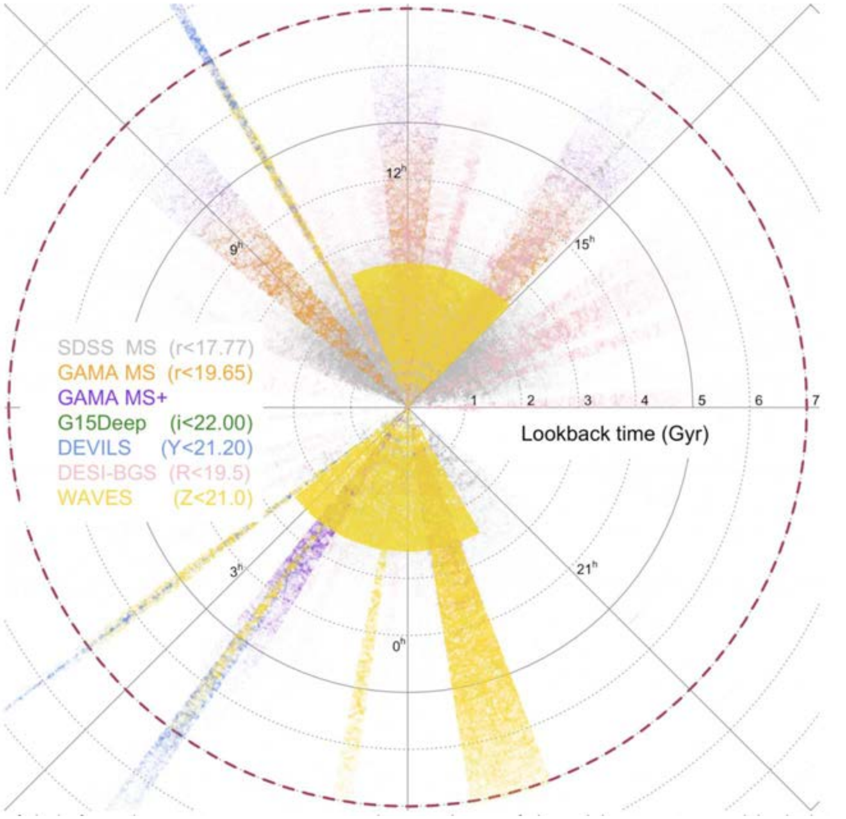
- **The Halo Mass Function and its evolution since z=0.8**
- **The Galaxy Stellar Mass Function to the very lowest mass limits**
- Evolution of the galaxy stellar mass function
- The galaxy major merger rate since z=0.8
- The forensic and core CSFH and CAGNH
- Evolution of galaxy components (simultaneous structure and SED modelling)
- Halo properties: plasma, stars, gas, dust and intra halo light
- **Mapping the Dark Matter distribution: high fidelity LSS**
- Disentangling AGN and galaxy flux
- The EBL and energy production at all redshifts
- The very very faint and dim nearby Universe (Crouching Giants and LSBGs)

https://wavesurvey.org

WAVES Survey Design

- Essentially unchanged since 2014 except for minor tweaks in flux limits and footprints edges:
- Deep Drill Fields now added:





WAVES science, but really open ended (GAMA++)

Mapping the Dark Matter distribution
WAVES website: https://wavesurvey.org

Wide:

- The z=0 galaxy halo mass function to $10^{11.5}$ M
- The galaxy stellar mass function to 10^{5} M
- Void/Filament/Cluster/Group studies
- Galaxy SEDs, SFHs, components, shapes, morphologies and environmental dependencies
- Galaxy/AGN unification

Deep:

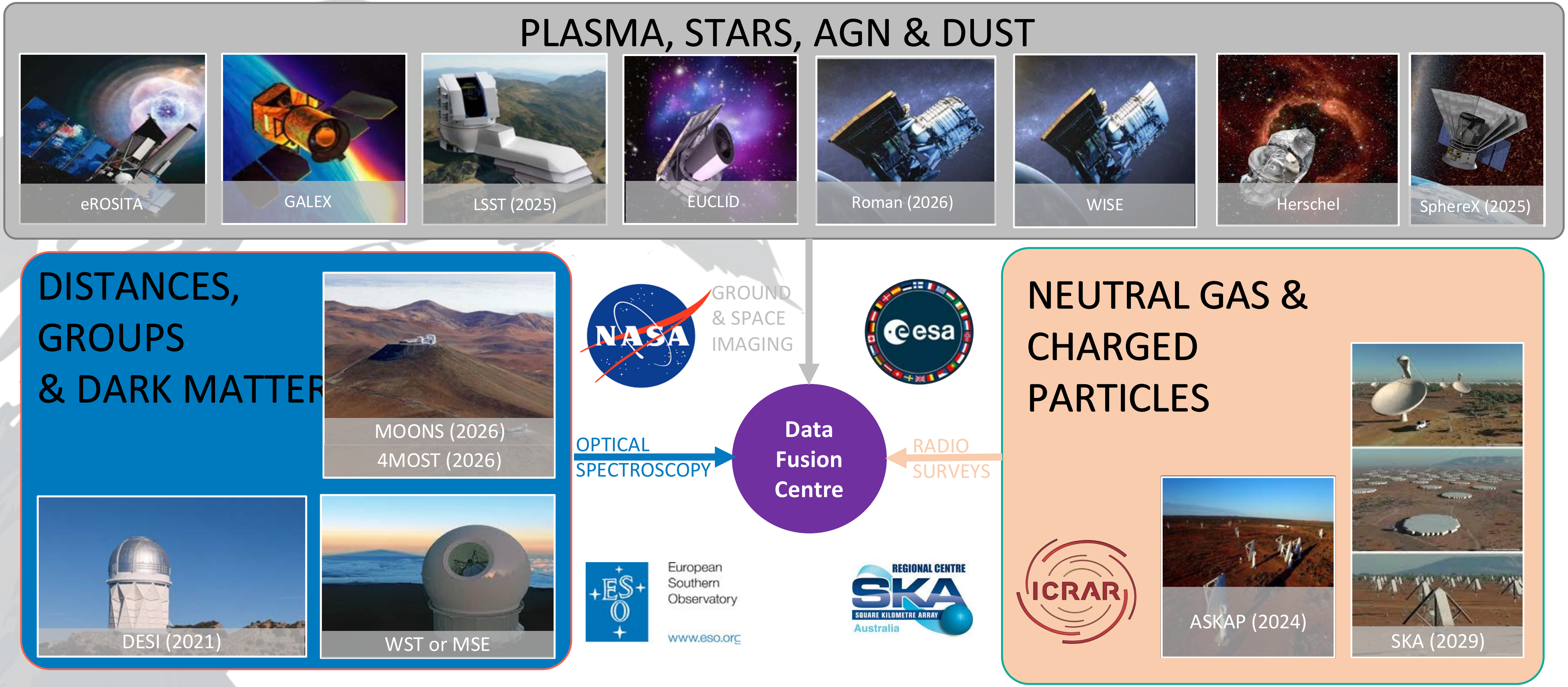
- Evolution of the Halo Mass function since z=0.8
- Evolution of filaments/voids/clusters/groups and galaxies since z=0.8
- Measurement of major, minor and micro merger rates
- The role of environment on galaxy evolution

DDF:

- As for deep but with auxillary radio (MeerKat) and space-based (JWST/Euclid) deep data

plus legacy, legacy, legacy i.e., environmental and panchromatic launchpad for follow-on surveys

Building the ultimate database ?



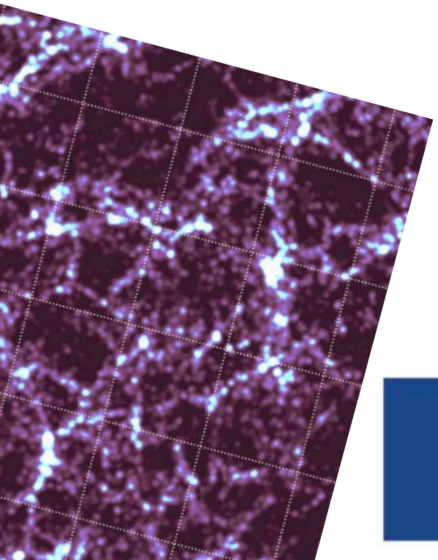
Ongoing LEGACY that builds on SDSS/GAMA/DEVILS → 4MOST/LSST/Euclid/SKA

UNIVERSITY OF TARTU
1632

Co-funded by the European Union

Investing in your future

Preparing and optimising the 4MOST survey



Funded by the European Union

4MOST

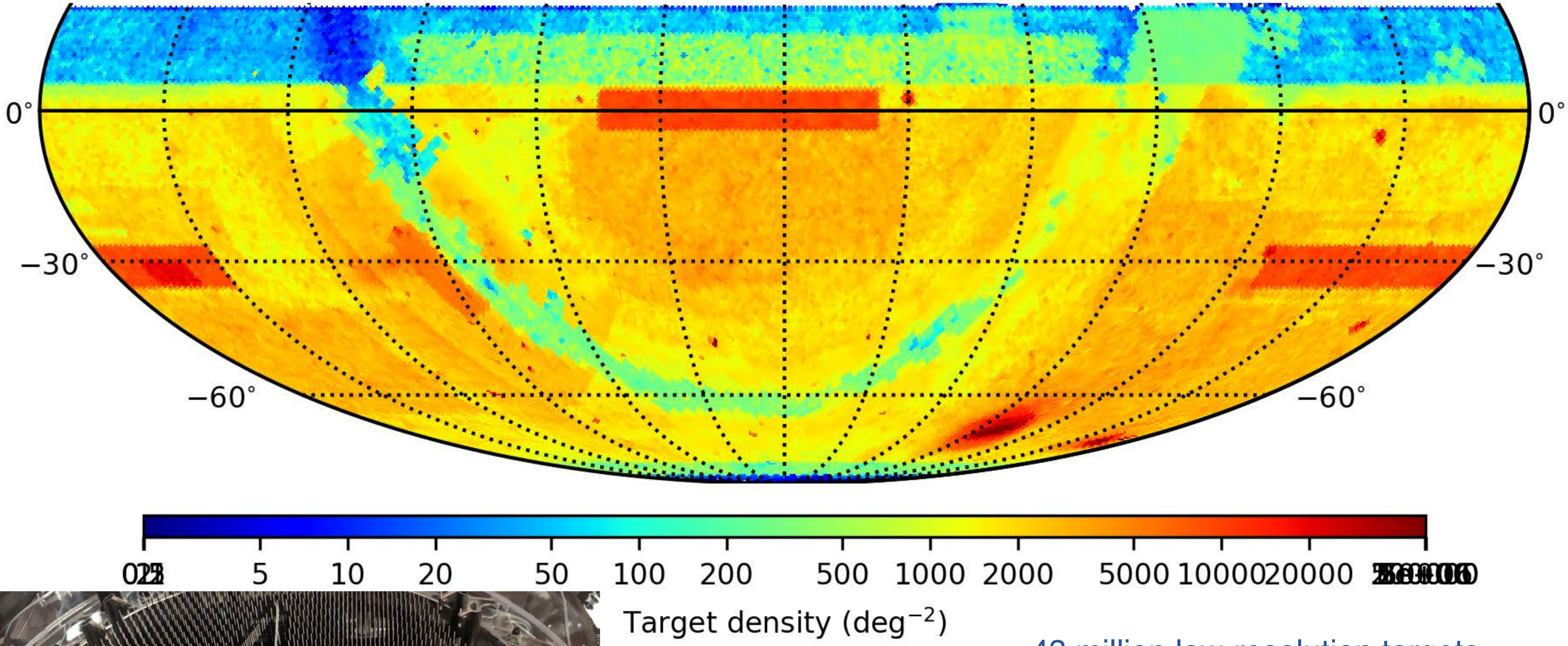
Wide science program - 18 surveys

Credit: 4MOST

Operations model

- 4MOST will be the only instrument on VISTA
- 4MOST will be operated in survey mode only, no “regular” observations
- 4MOST will execute a 5-year **Public Survey** programme
  - Surveys need to be of legacy value to the wider community
  - Raw data (L0) public immediately
  - Reduced data (L1) and derived data products (L2) to be published on a pre-determined, timely schedule
- Extension to another 5-year period likely (with a new survey programme)
- Surveys will be executed **in parallel**, sharing the focal plane
- Survey programme:
  - 10 4MOST Consortium Survey ← 70% of observing time
  - 15 Community Surveys ← 30% of observing time

4MOST is a statistical survey: understanding observational selection function is a key for many science cases

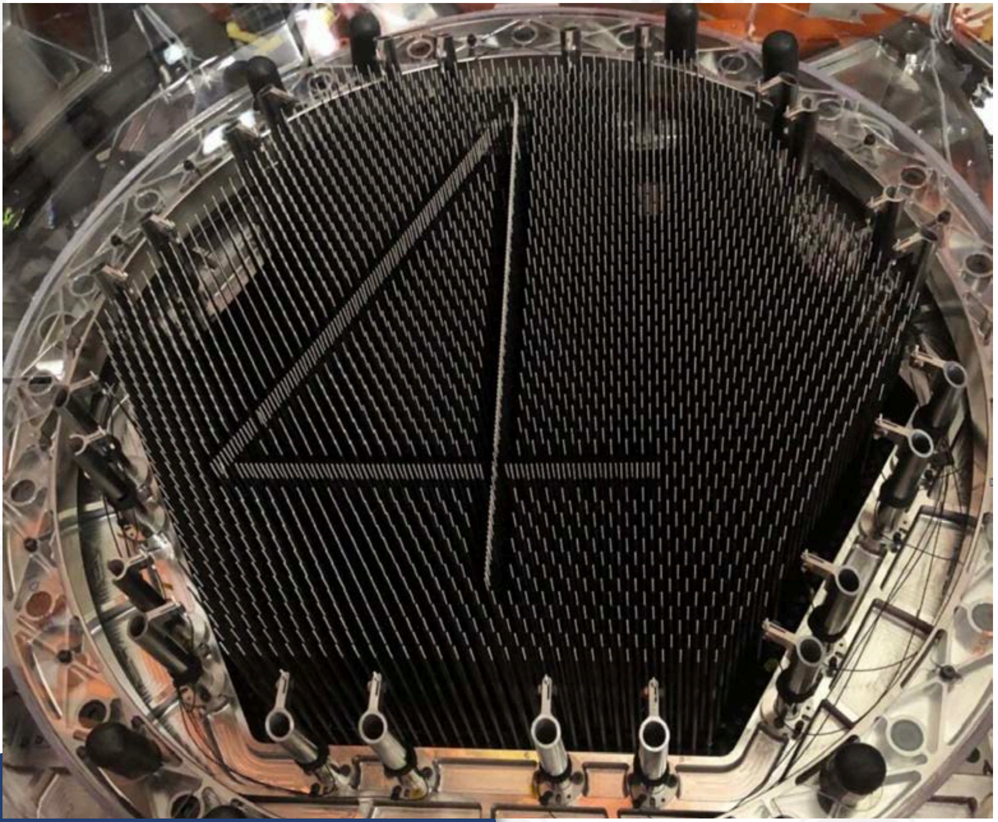


43 million low-resolution targets

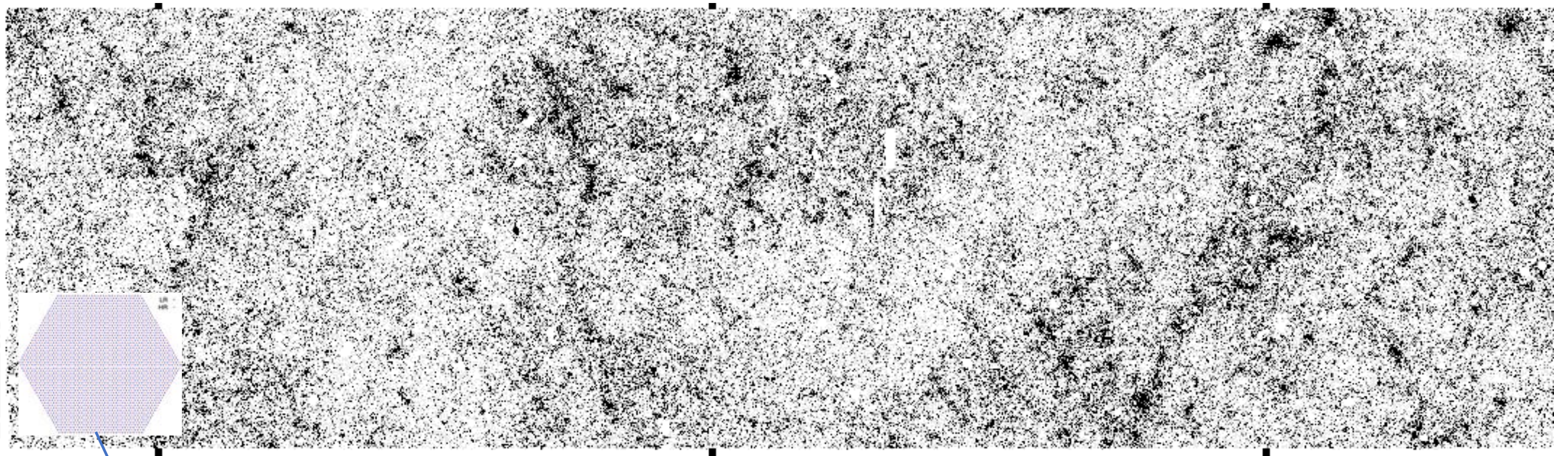
9 million high-resolution targets

How to observe those targets most efficiently?
How to model observational selection function?

Credit: 4MOST



4MOST WAVES-Wide survey



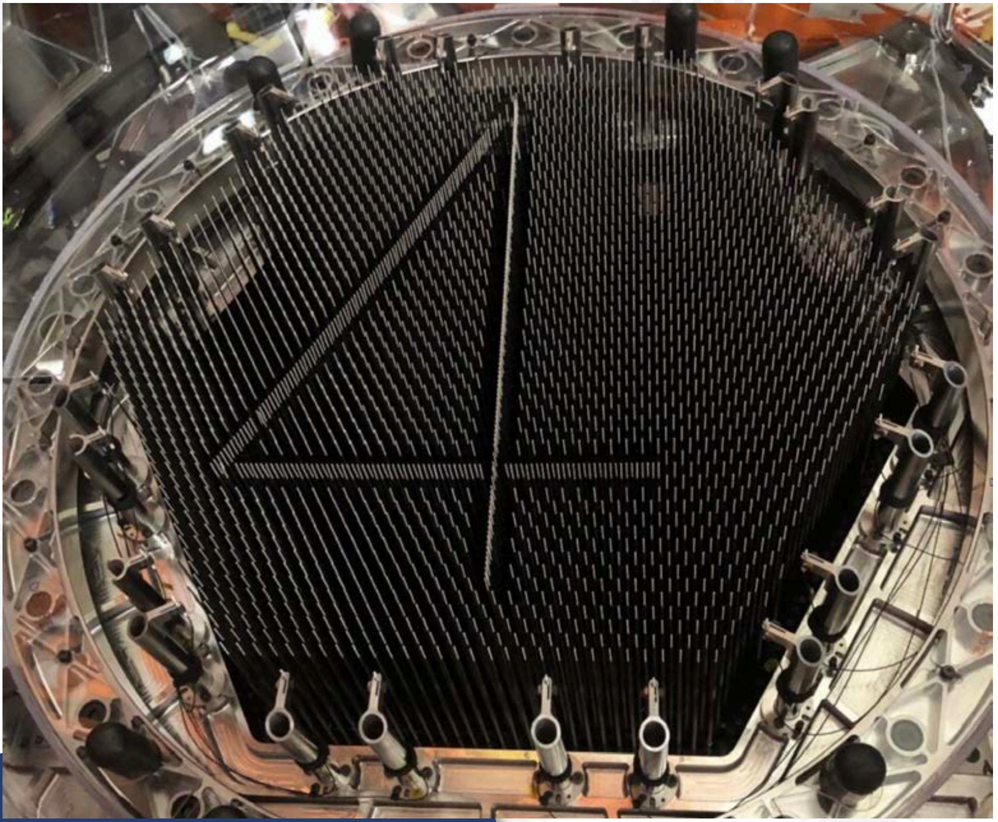
4MOST field of view

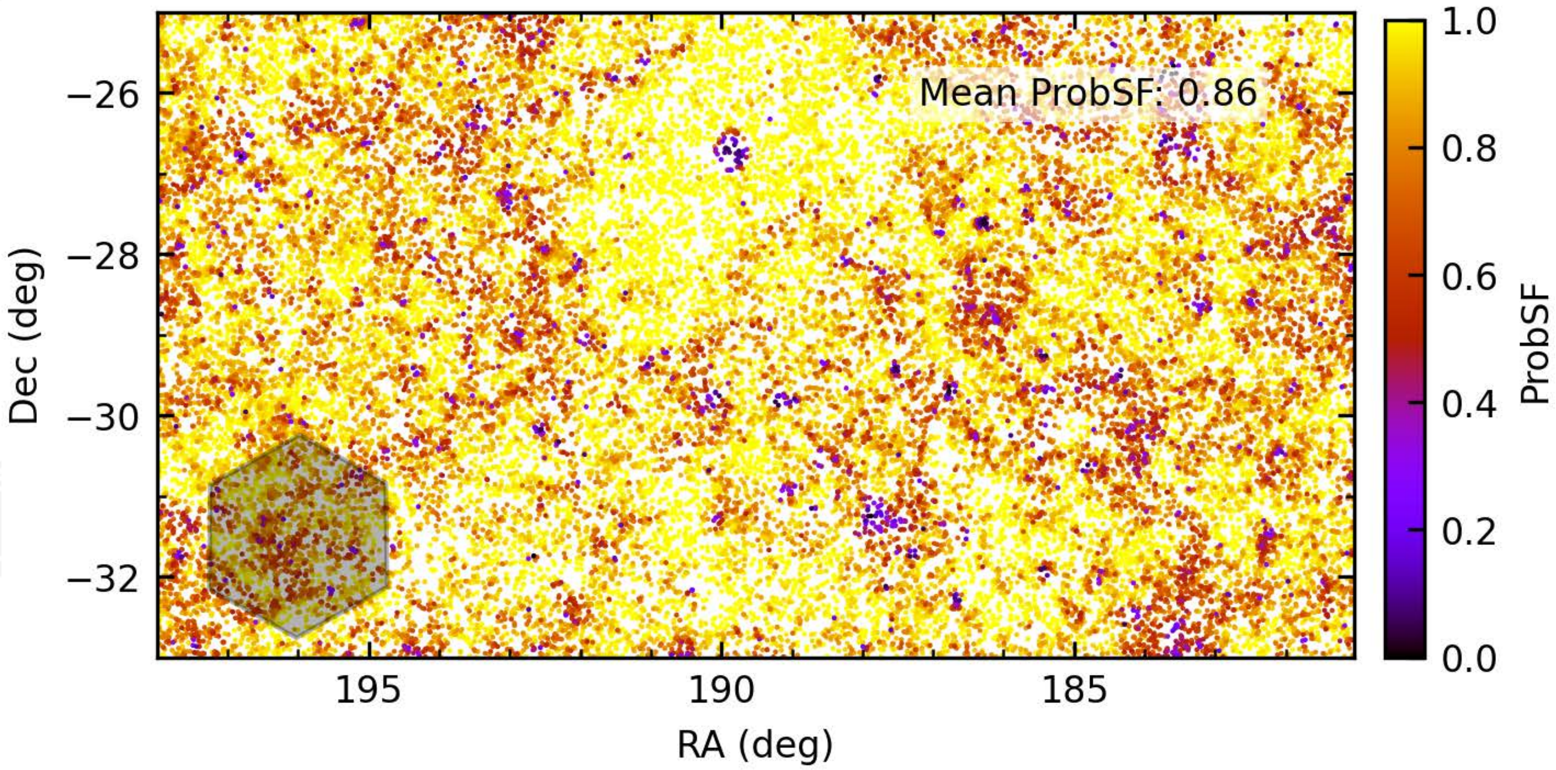
Fixed fibre pattern

Limited patrol area for each fibre

Efficiency vs completeness

Efficiency	completeness
• all fibres are used • not all targets are observed	• all targets are observed • many fibres are empty





Fixed fibre pattern

Limited patrol area for each fibre

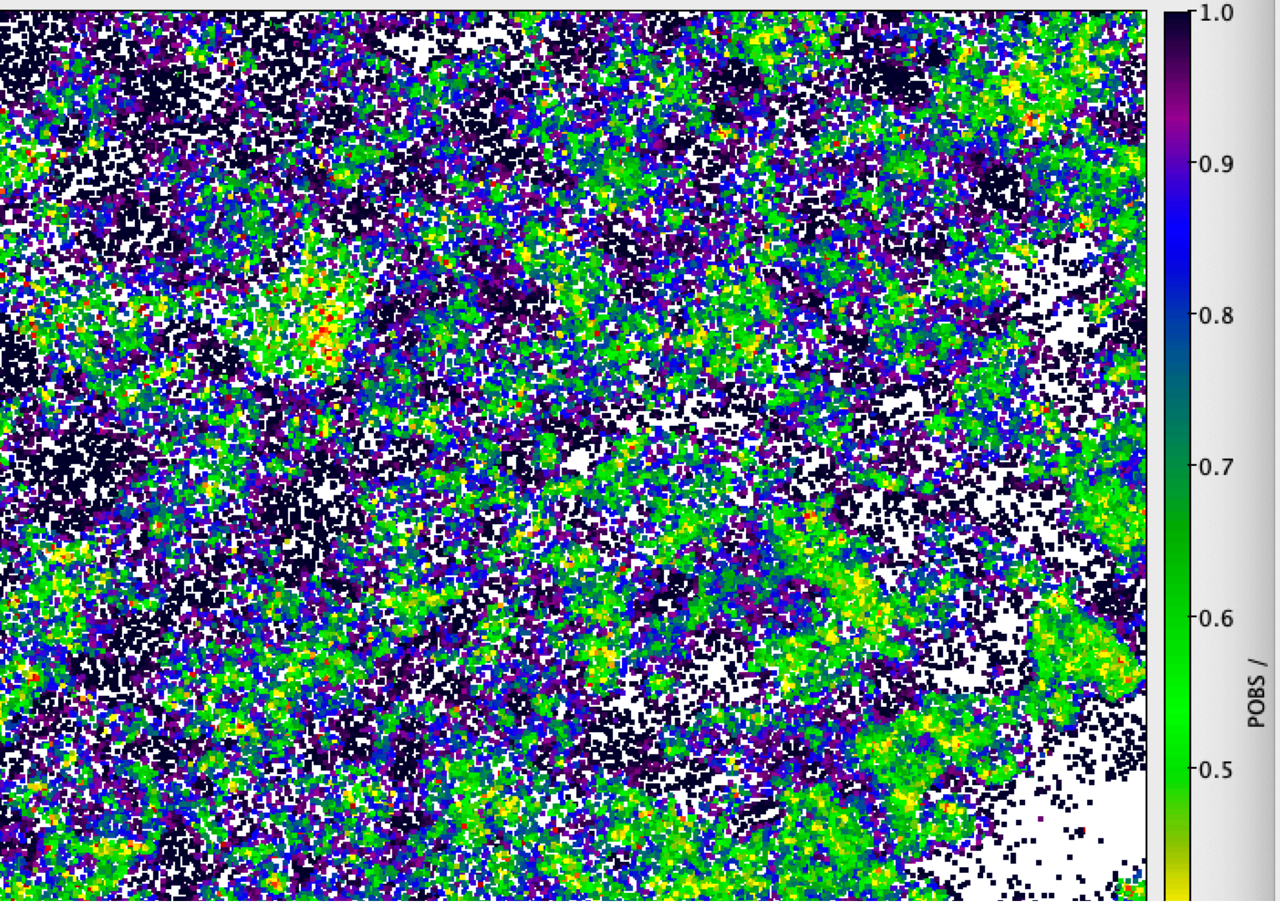
Efficiency vs completeness

- all fibres are used
- not all targets are observed

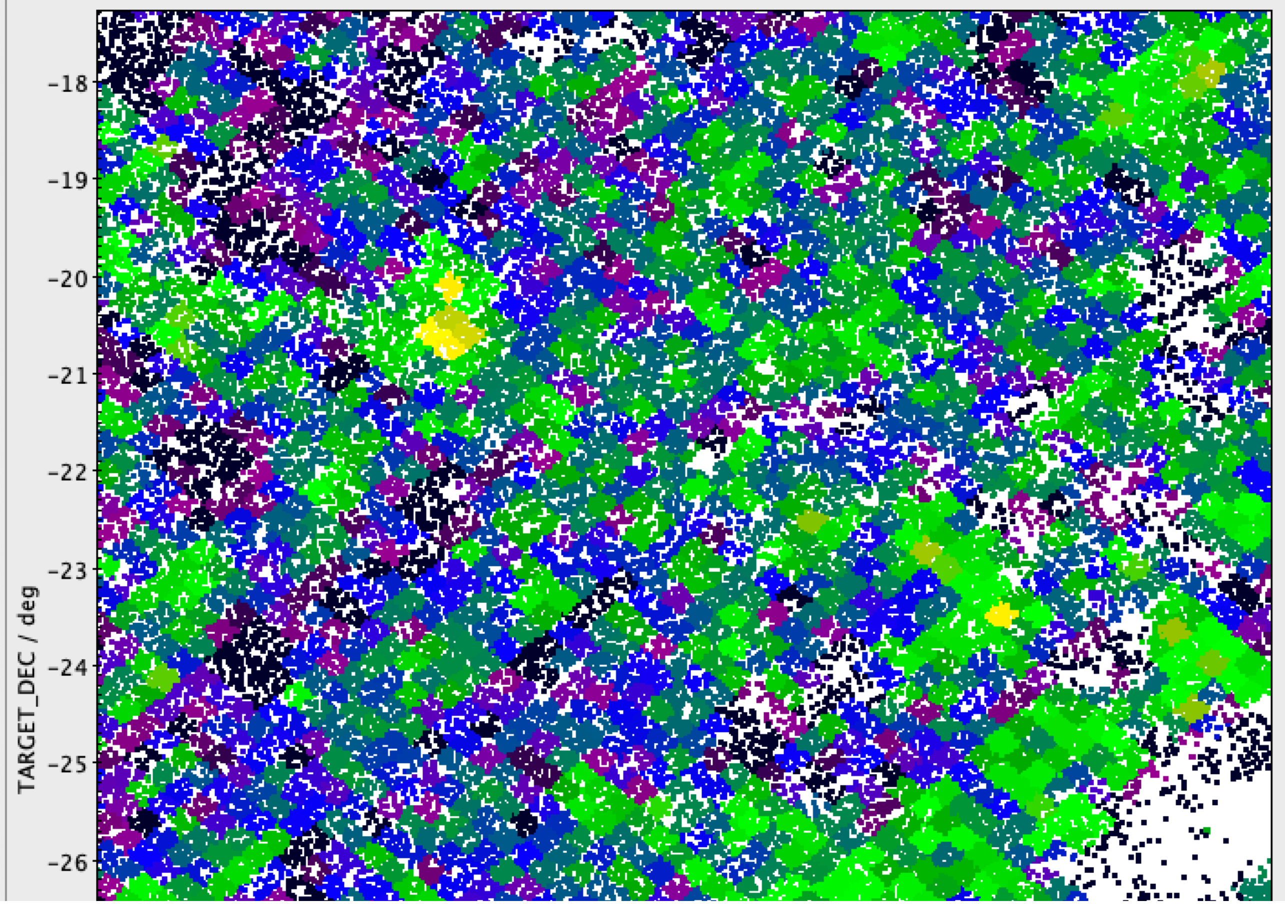
- all targets are observed
- many fibres are empty

Probabilistic Selection Function

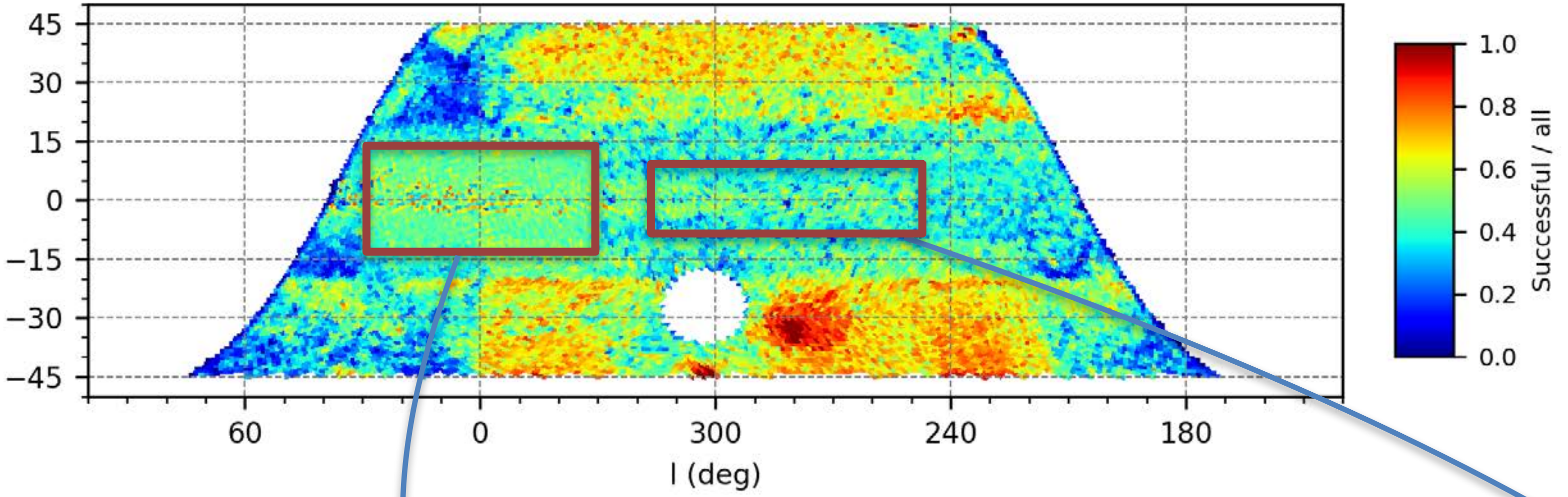
- Probabilistic SF



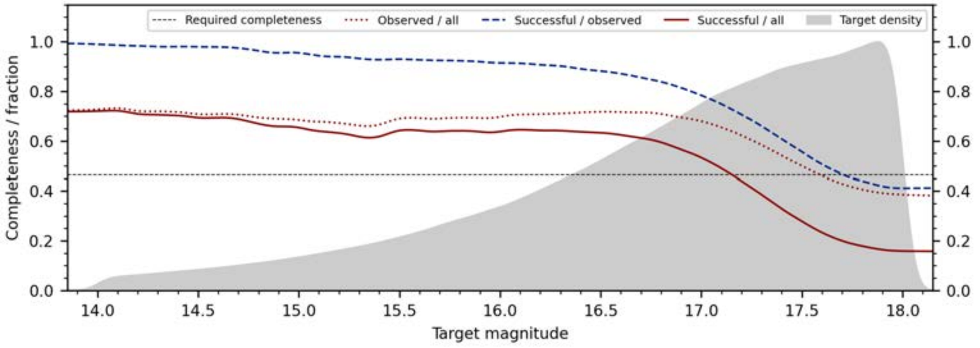
- Counting targets



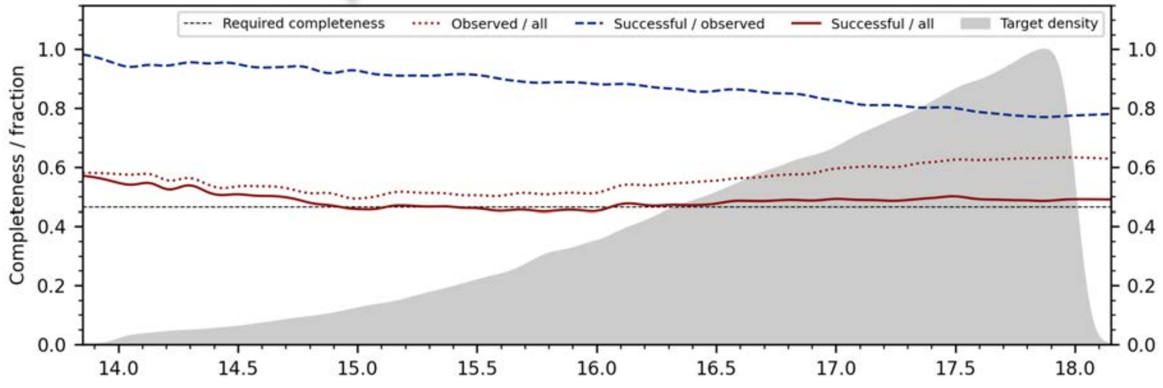
Example: Completeness for a single subsurvey



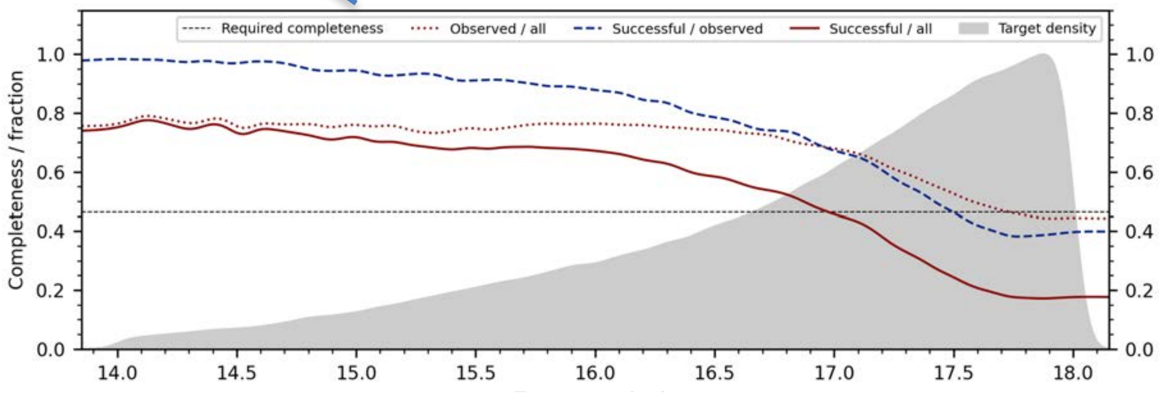
- Overall completeness



- Target magnitude

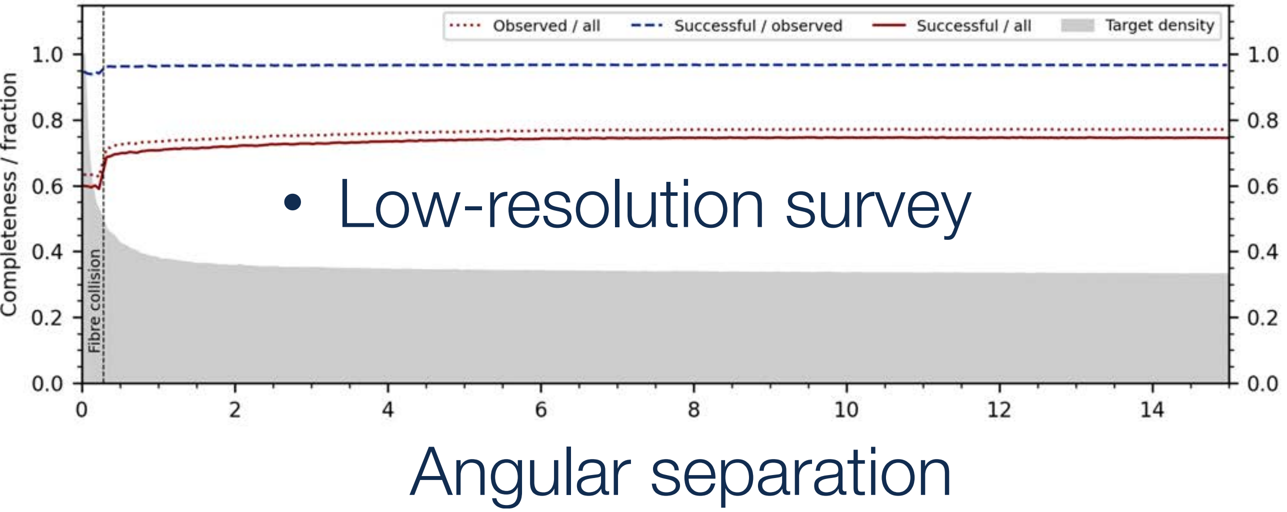


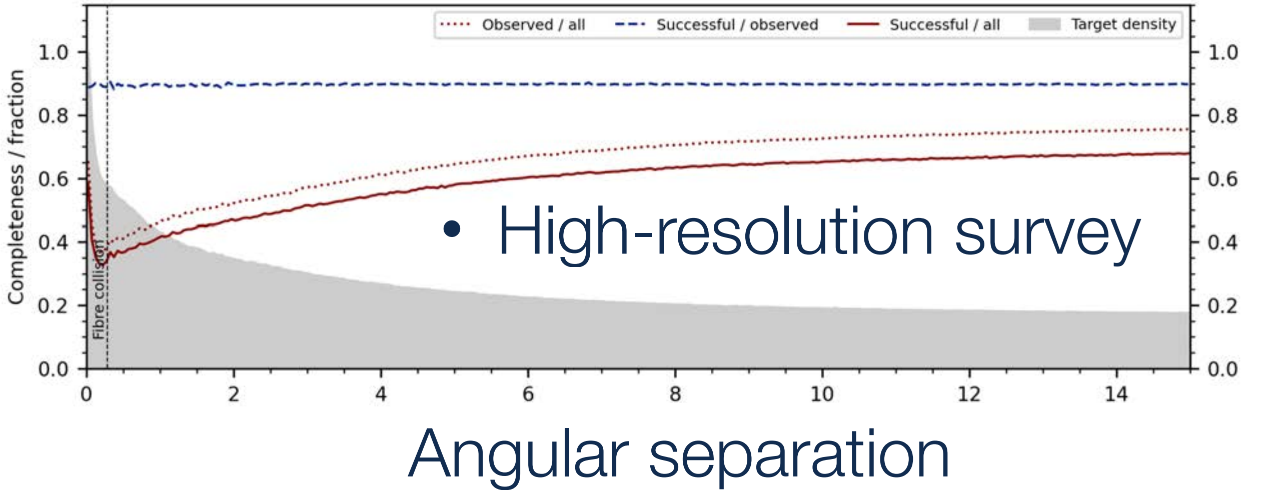
- Target magnitude

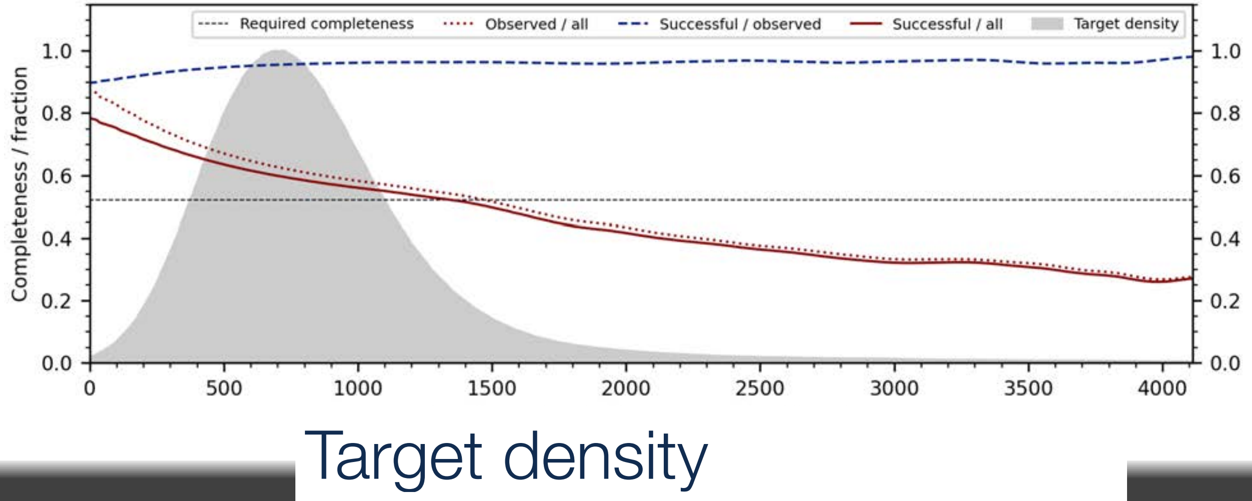


- Target magnitude

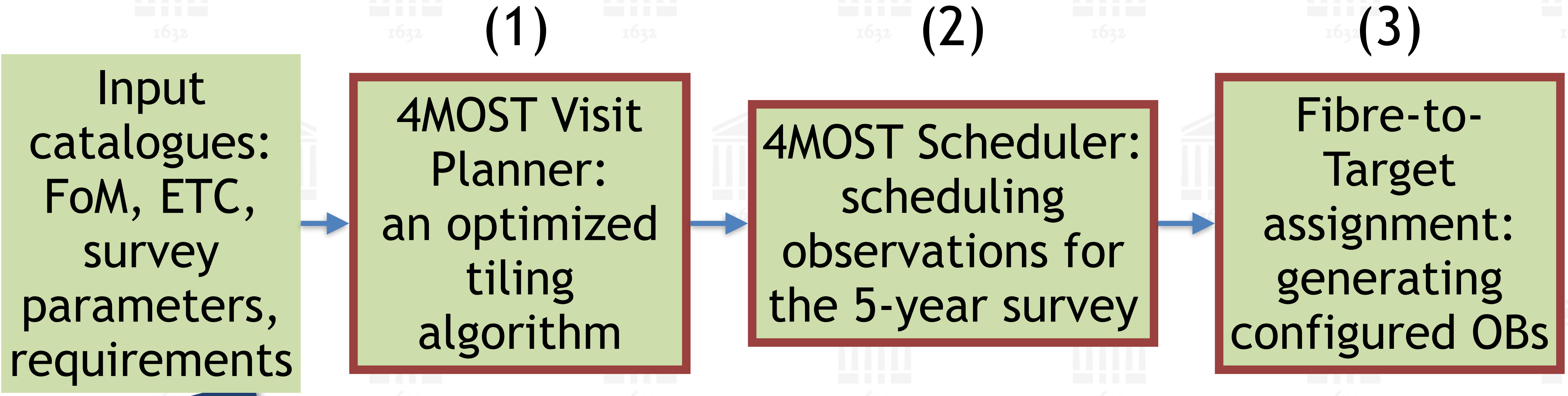
Completeness as a function of target separation







- Due to the fixed fibre density, the completeness depends on the target density



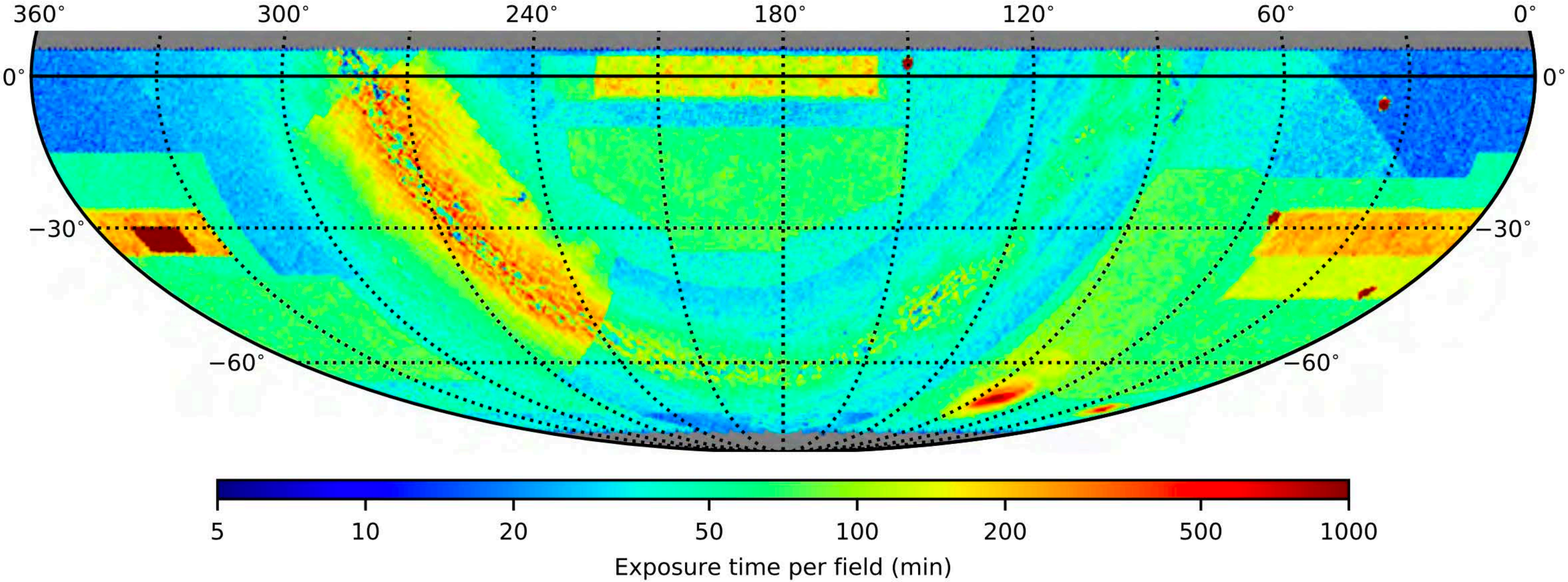
(1) ET et al. (2020) “An optimised tiling pattern for multi-object spectroscopic surveys: application to the 4MOST survey”

(2) paper in prep

(3) ET et al. (2020) “Probabilistic fibre-to-target assignment algorithm for multi-object spectroscopic surveys”

Preparing observations

General flowchart



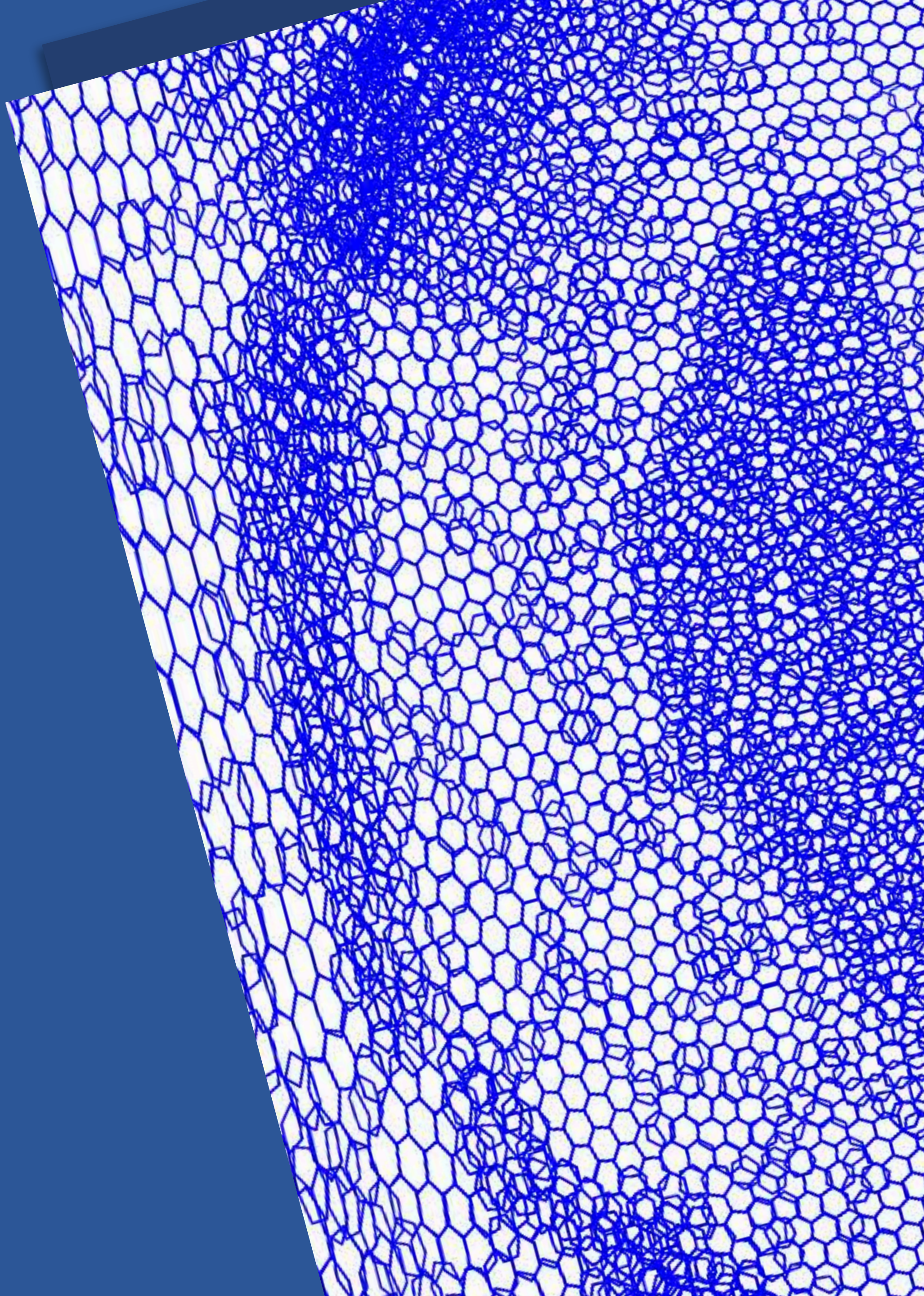
4MOST Visit Planner

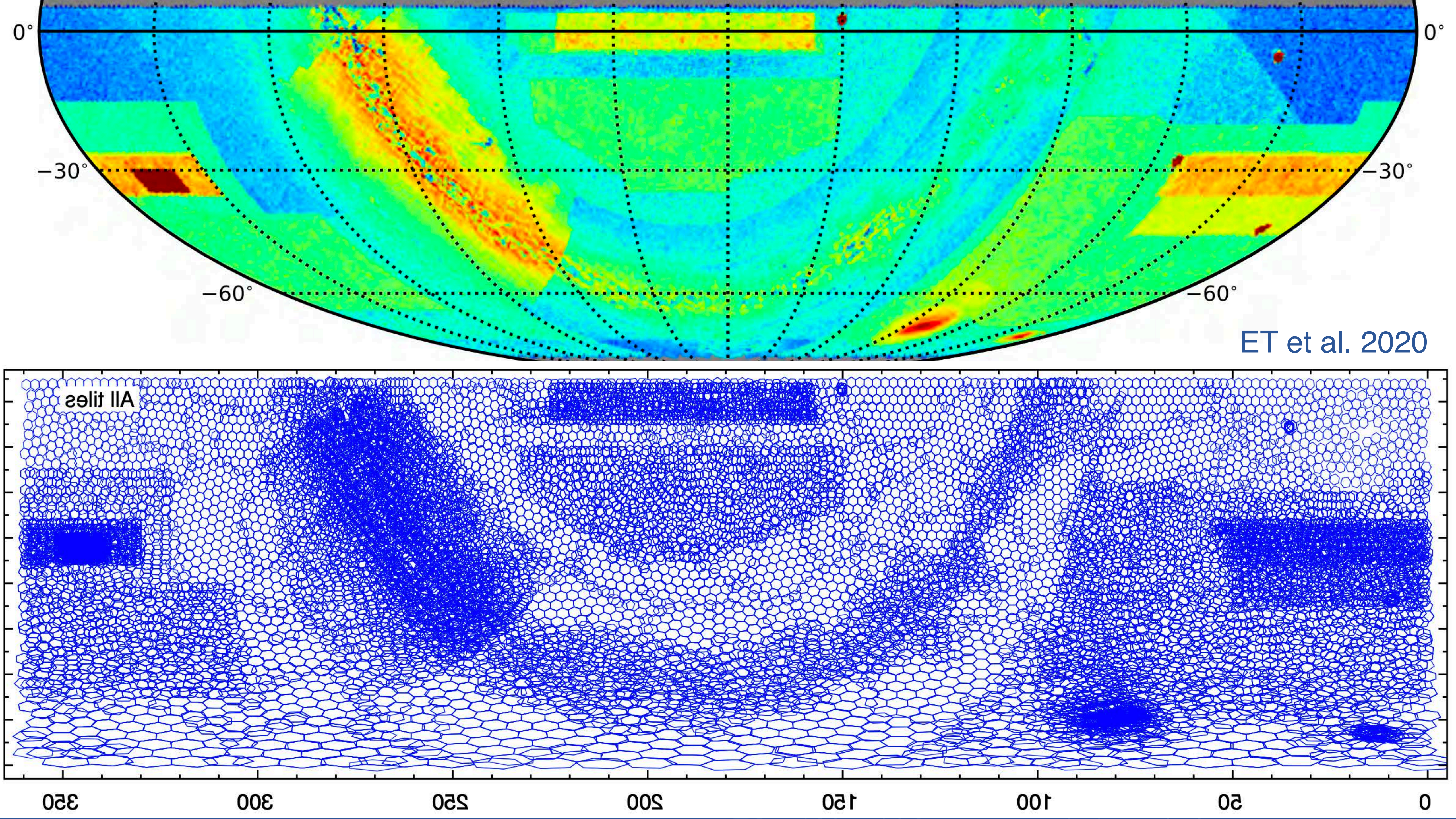
Why do we need a Visit Planner?

ET et al. 2020

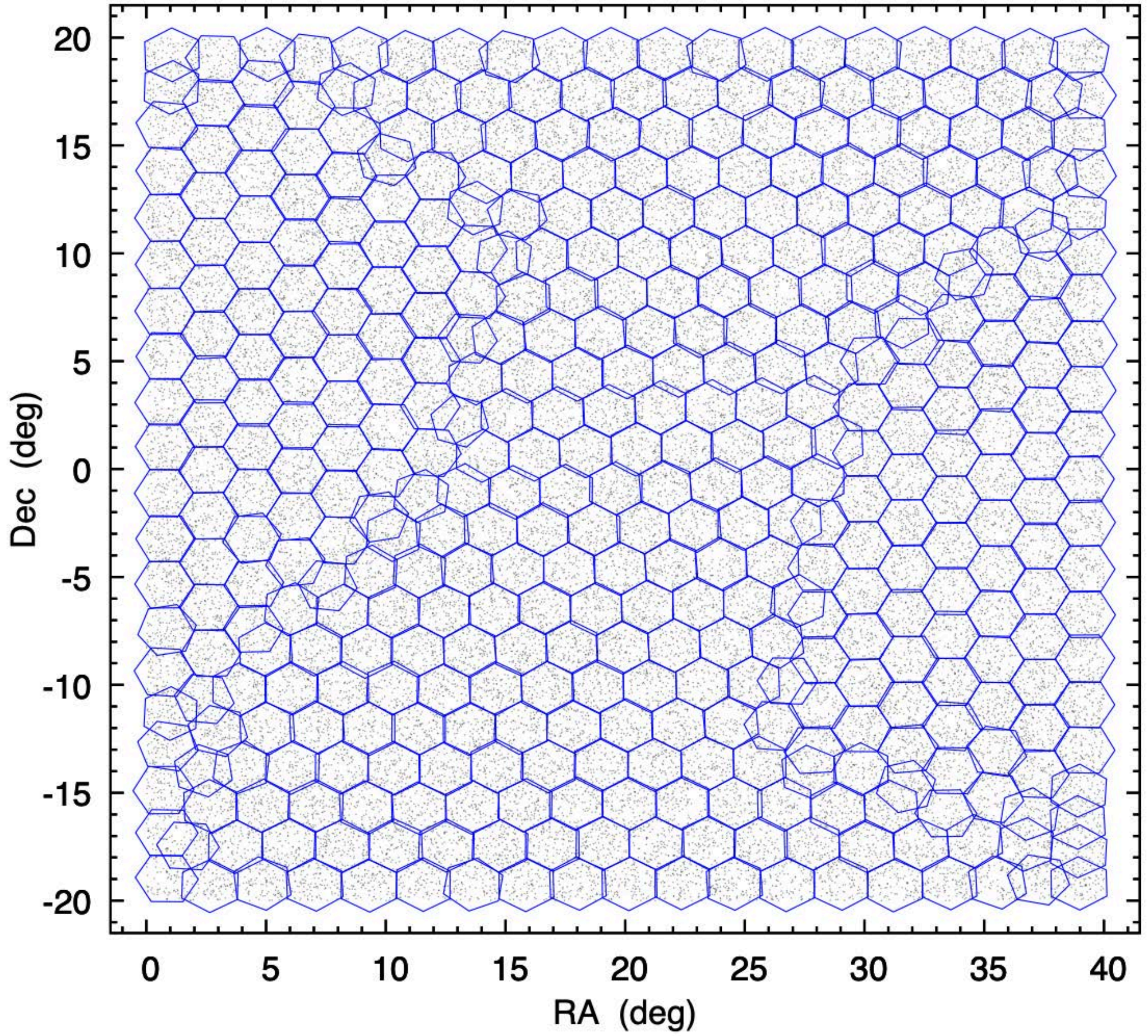
Tiling challenge

- Where to point the telescope? The list of tile centres and orientation angles that are needed to effectively observe the given list of targets.
- What is the exposure time of each tile? Attach an exposure time for each tile so that the targets are observed efficiently.
- Divide the tiles between D/G/B sky conditions.
- Include survey requirements, e.g. contiguous area (no gaps between tiles).

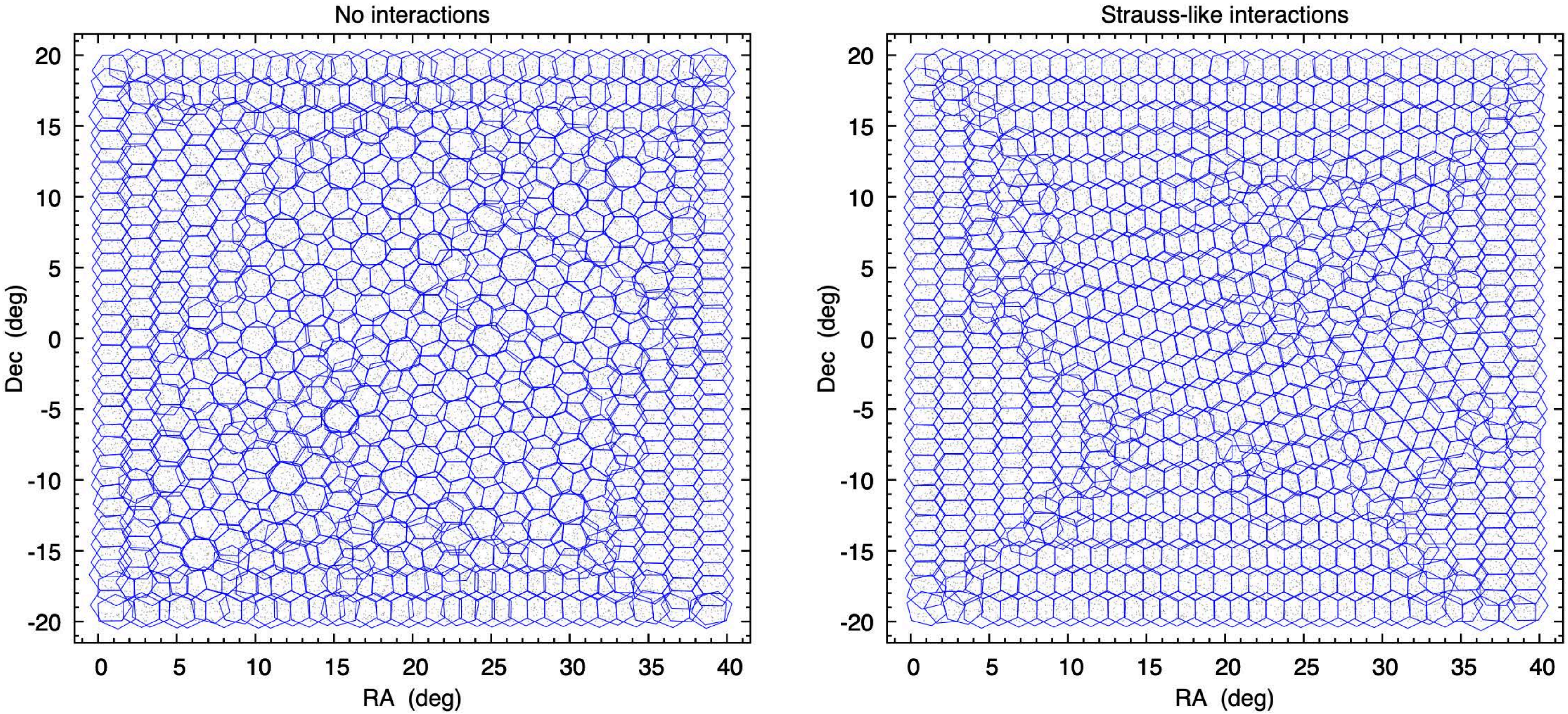



0°
0°
−30°
−30°
−60°
−60°
ET et al. 2020
All tiles
350
300
250
200
150
100
50
0

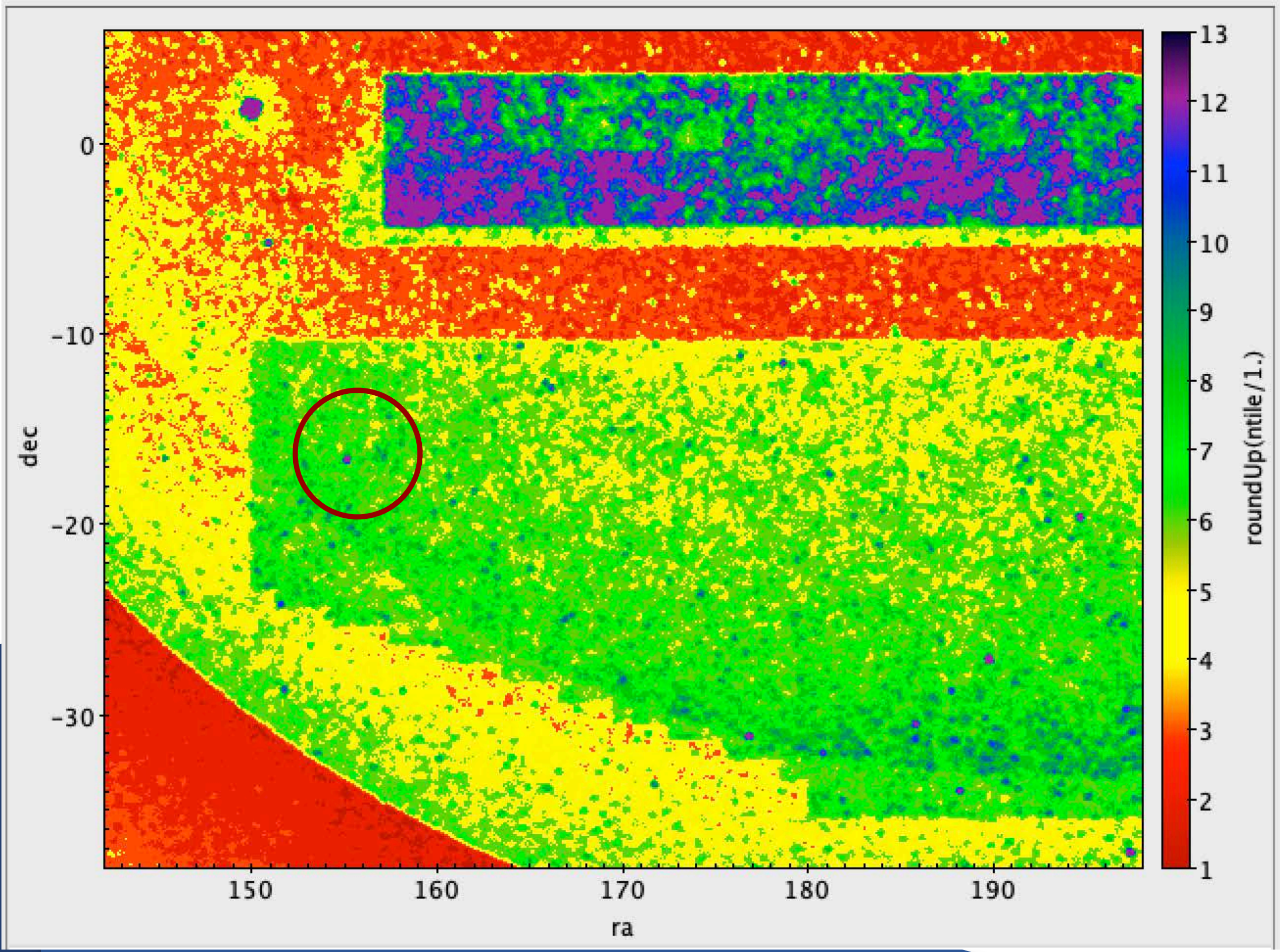
Tiles in a single layer (one visit)



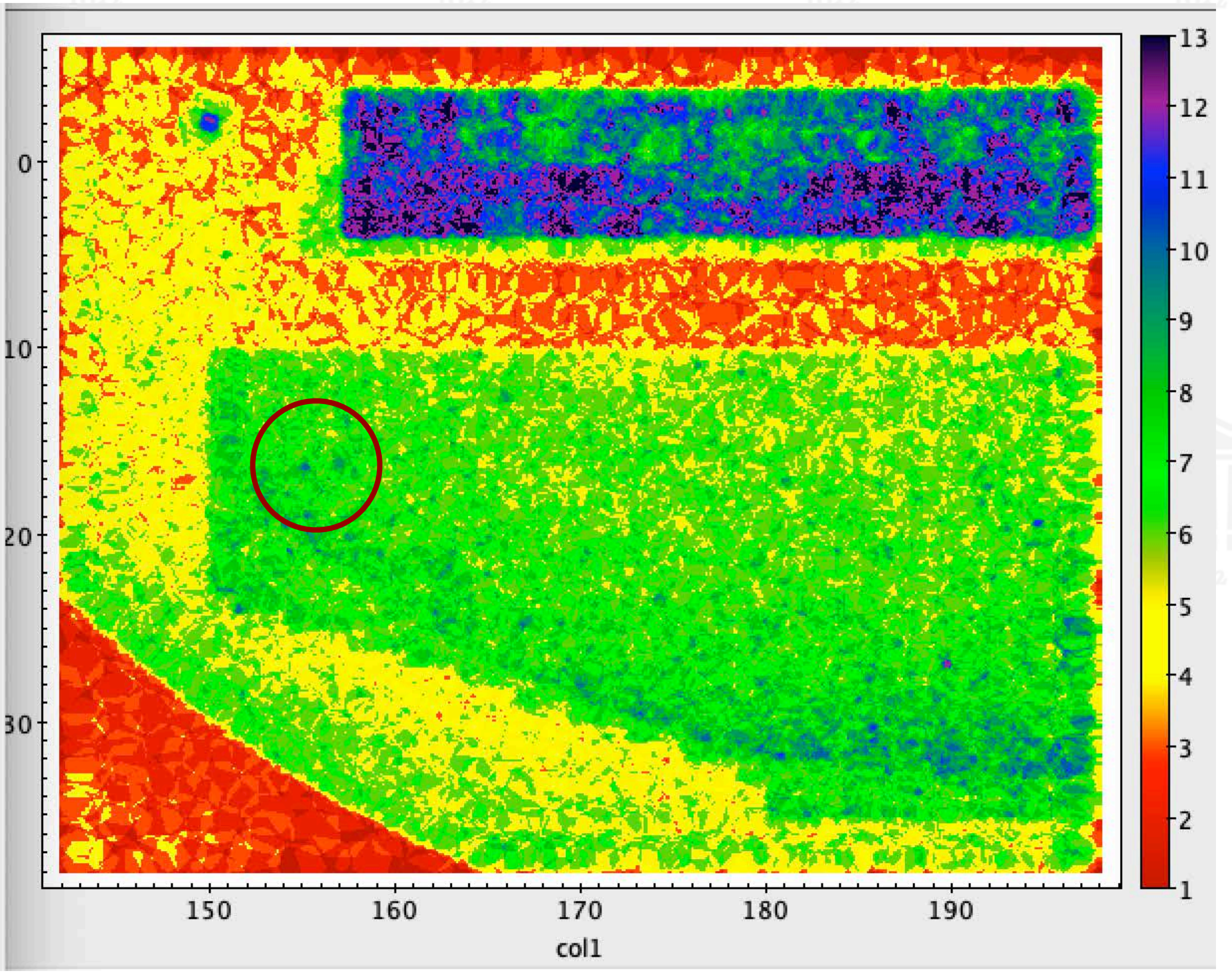
Tiles in two layers (two visits)



Required exposure time



Exposure time from tiling



4MOST Visit Planner

A small sky area

ET et al. 2020

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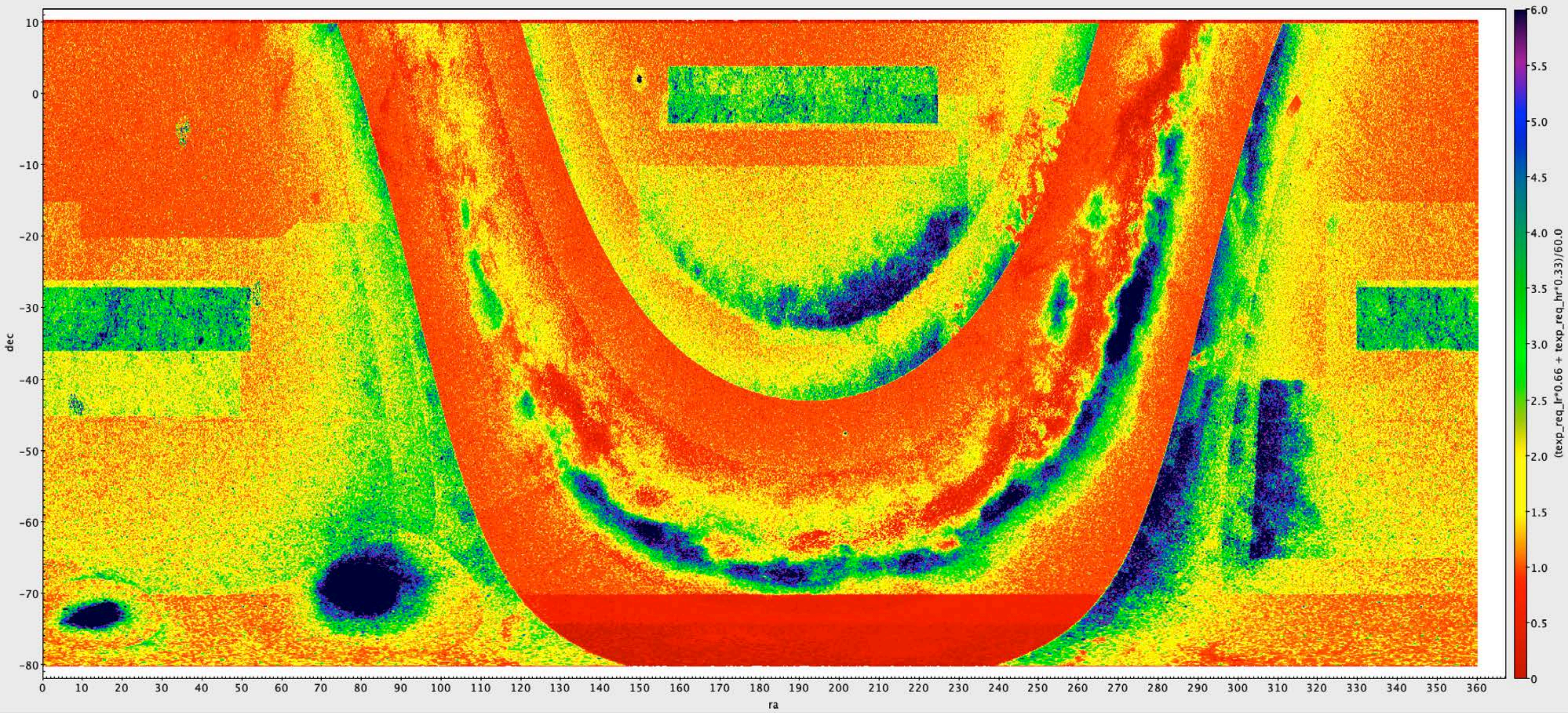
4MOST — objektid taevas



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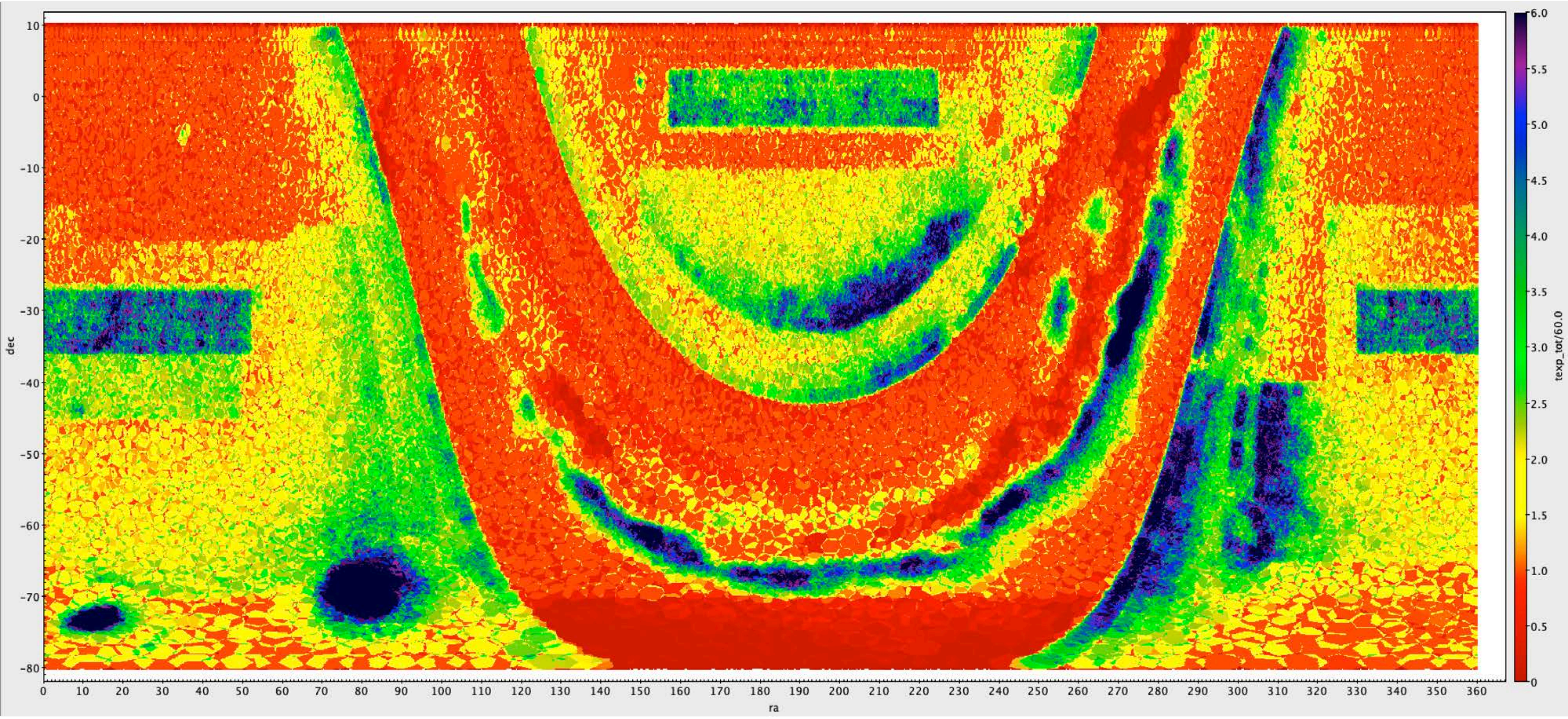
4MOST — planeeritud vaatlused



Metropolis-Hastings algorithm with simulated annealing

$$p(\mathbf{y}\,|\,\theta) \propto \exp\left[-U(\mathbf{y}\,|\,\theta)\right],$$

→

$$(\hat{\mathbf{y}}, \hat{\theta}) = \arg\max_{\Omega\times\Theta} p(\mathbf{y}, \theta) = \arg\max_{\Omega\times\Theta} p(\mathbf{y}\,|\,\theta)p(\theta),$$

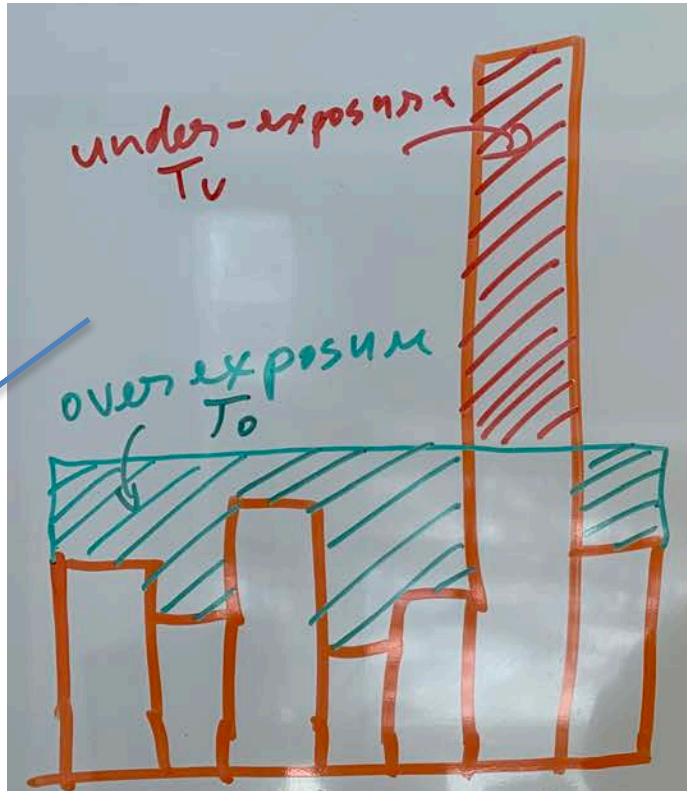
Energy function $U(\mathbf{y}\,|\,\theta)$ is constructed as following:

$$U(\mathbf{y}\,|\,\theta) = U_{\text{targets}}(\mathbf{y}\,|\,\theta) + U_{\text{overhead}}(\mathbf{y}\,|\,\theta) + \quad (6)$$

$$+U_{\text{tiles}}(\mathbf{y}\,|\,\theta) + U_{\text{BGD}}(\mathbf{y}\,|\,\theta), \quad (7)$$

where each component in the energy function takes into account different aspects in the optimal tiling pattern.

$$U_{\text{targets}}(\mathbf{y}\,|\,\theta) = \sum_{s\in S}\left[c_{\text{missing}}T^{s}_{\text{missing}} + c_{\text{wasted}}T^{s}_{\text{wasted}}\right],$$

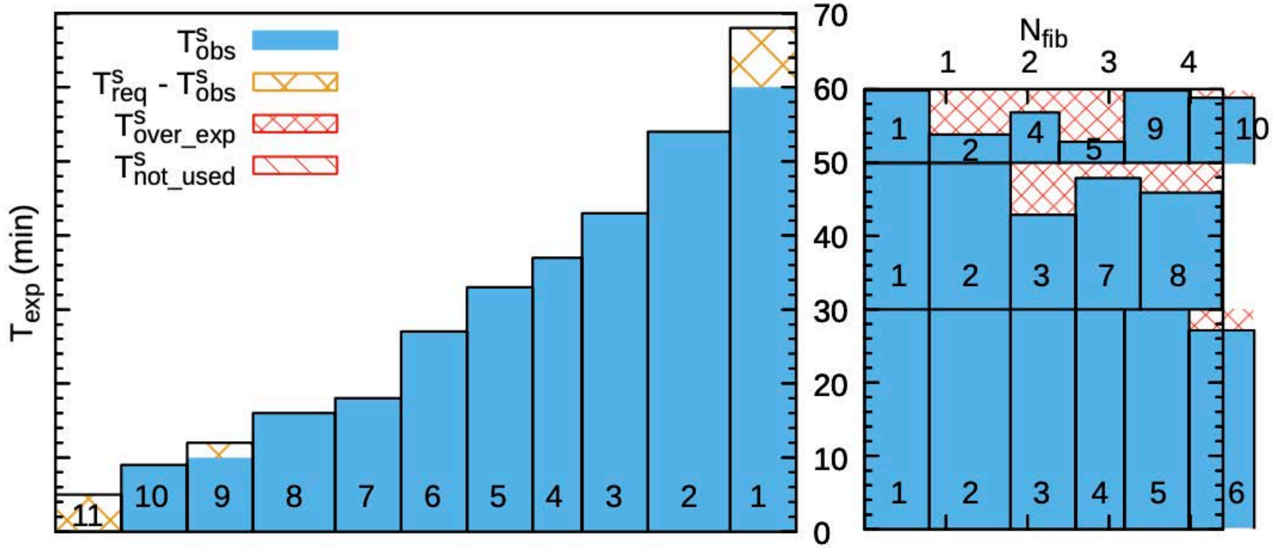


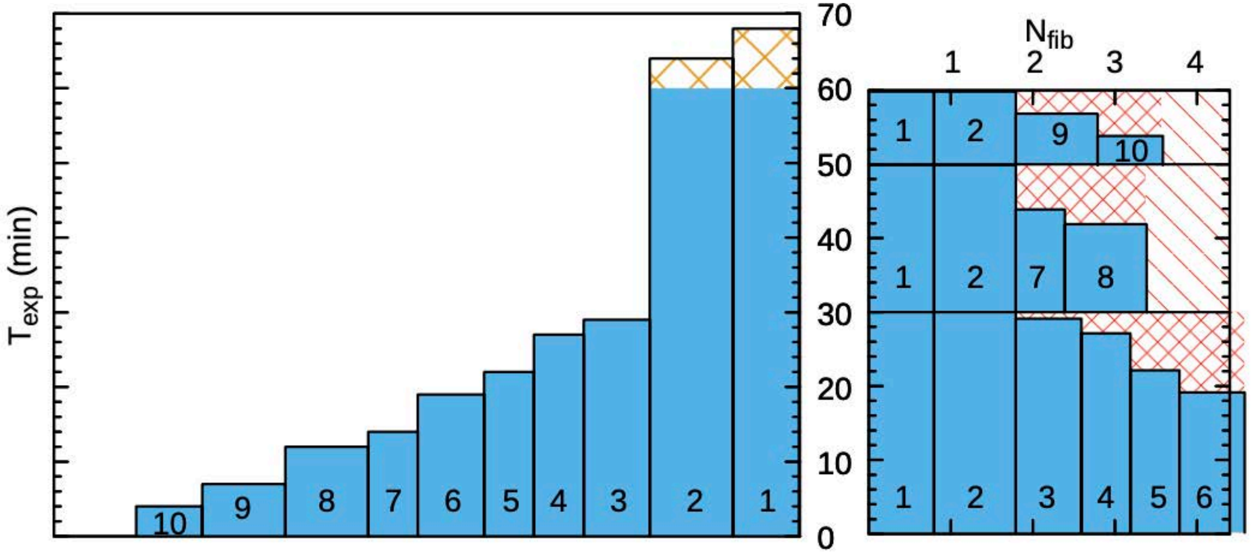
$$U(\mathbf{y}\,|\,\theta) = \boxed{U_{\text{targets}}(\mathbf{y}\,|\,\theta)} + U_{\text{overhead}}(\mathbf{y}\,|\,\theta) + \\ + U_{\text{tiles}}(\mathbf{y}\,|\,\theta) + U_{\text{BGD}}(\mathbf{y}\,|\,\theta), \qquad (5)$$

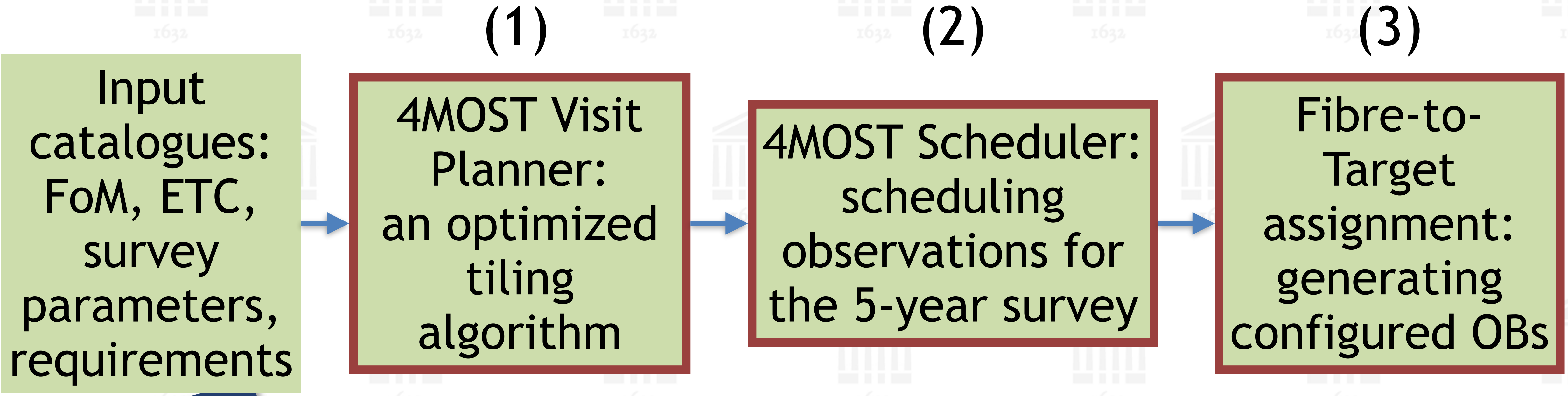
$$U_{\text{targets}}(\mathbf{y}\,|\,\theta) = \frac{1}{A(\text{FoV})} \iint_{S} U^{s}_{\text{targets}}(\mathbf{y}\,|\,\theta)\,\mathrm{d}s, \qquad (6)$$

$$U^{s}_{\text{targets}}(\mathbf{y}\,|\,\theta) \; = \; \left[c_{\text{miss}} T^{s}_{\text{miss}} + c_{\text{wasted}} T^{s}_{\text{wasted}}\right] \\ \text{for} \quad \{t \in \mathbf{t} : \|t - s\| < s_{\max}\}, \qquad (7)$$

Simplified/statistical
fibre-to-target assignment







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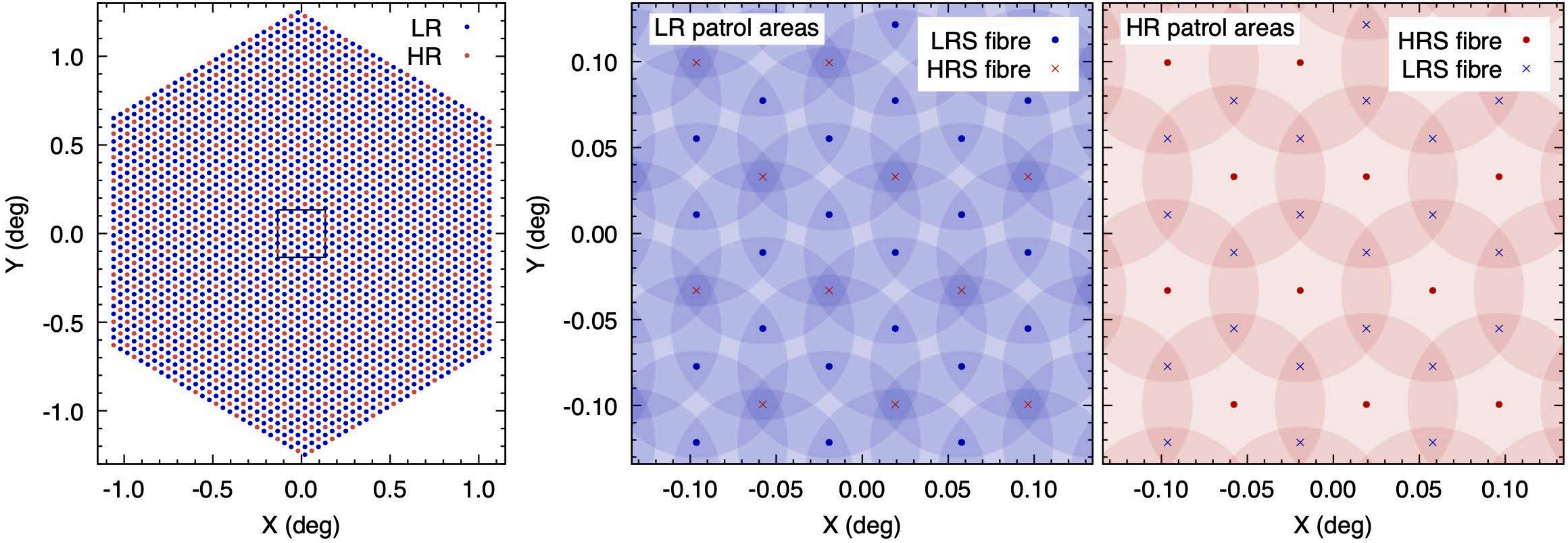
(2) paper in prep

(3) ET et al. (2020) “Probabilistic fibre-to-target assignment algorithm for multi-object spectroscopic surveys”

Preparing observations

Where to point and when?

What targets to select?

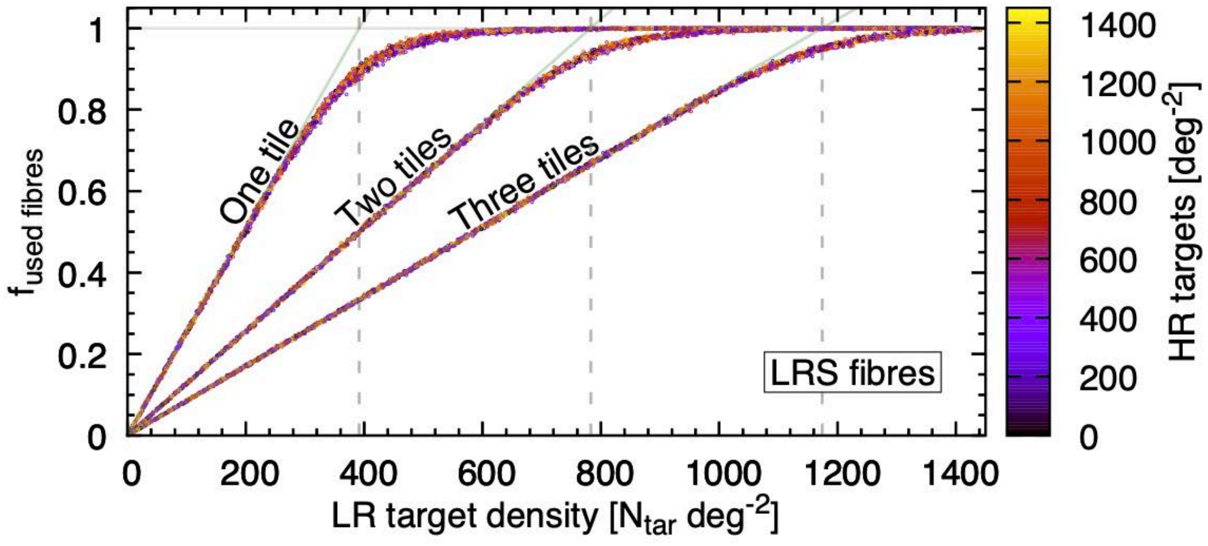


4MOST fibre pattern

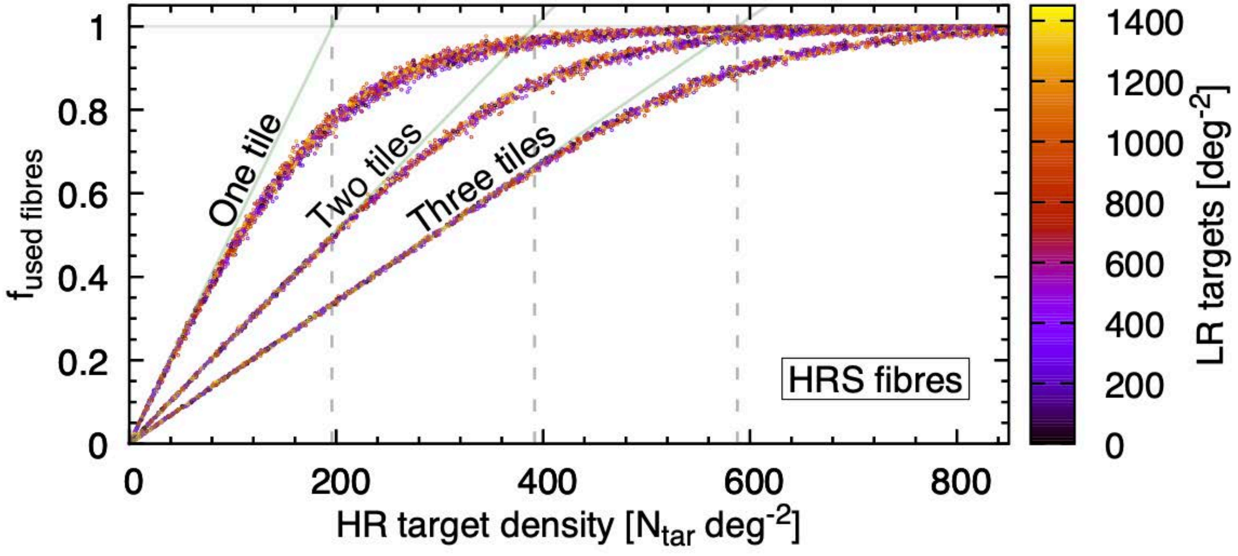
2/3 low-resolution and 1/3 high-resolution fibres

ET et al. 2020

Low-resolution fibres



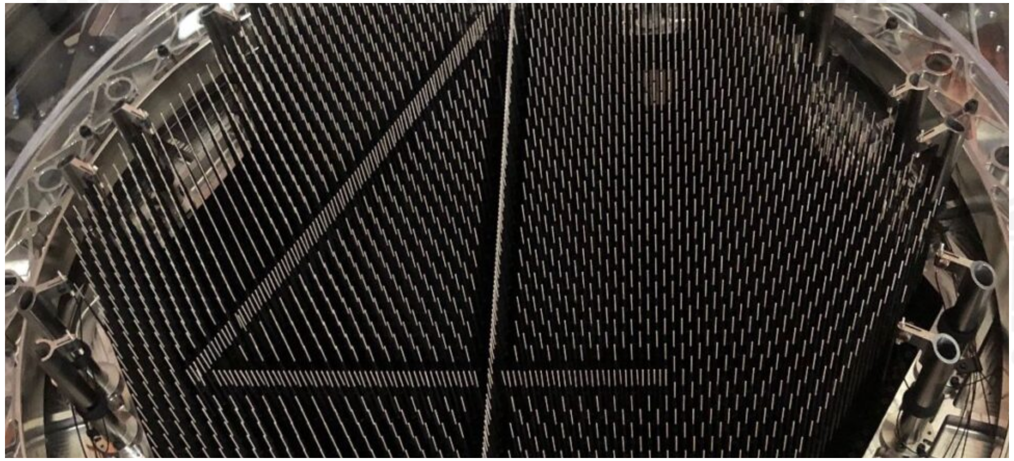
High-resolution fibres



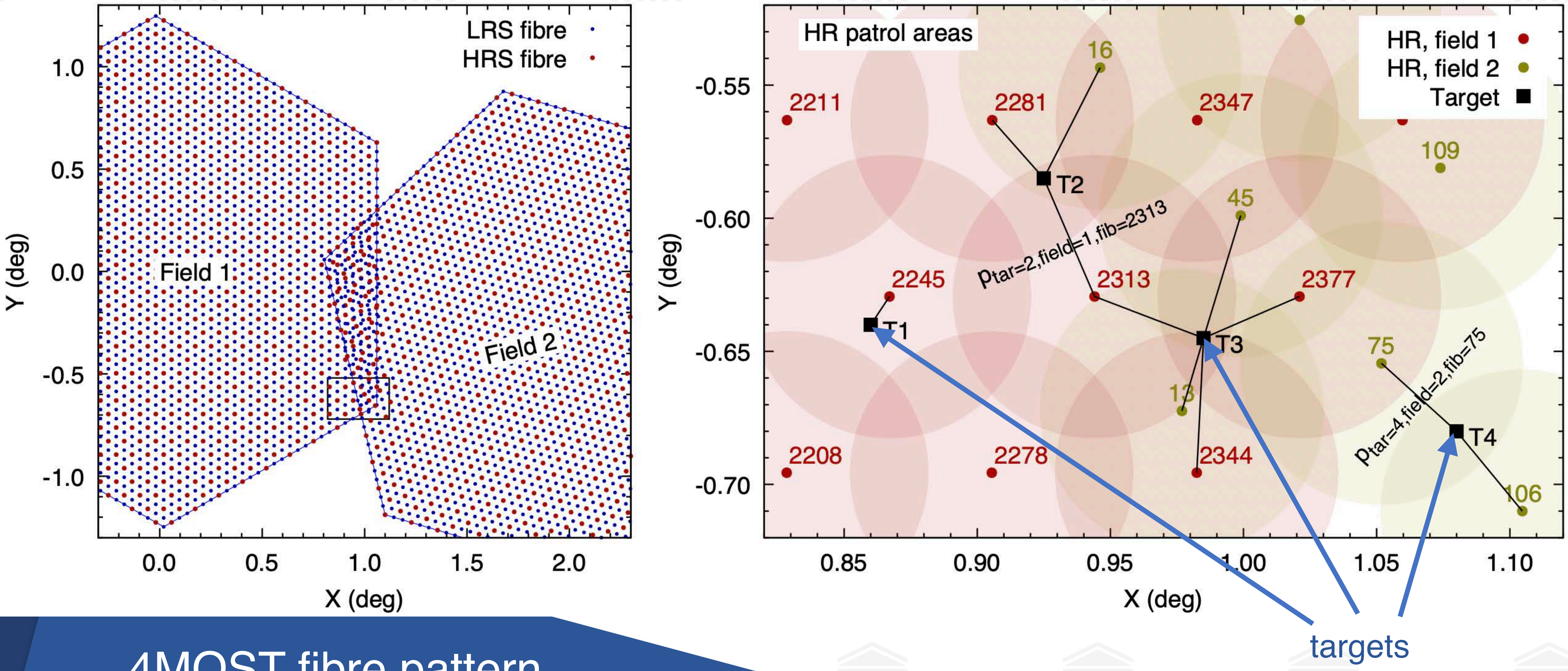
For efficient survey, it is important to have more targets in the catalog than are required for the science goals

4MOST fibre pattern

fibre assignment efficiency



ET et al. 2020

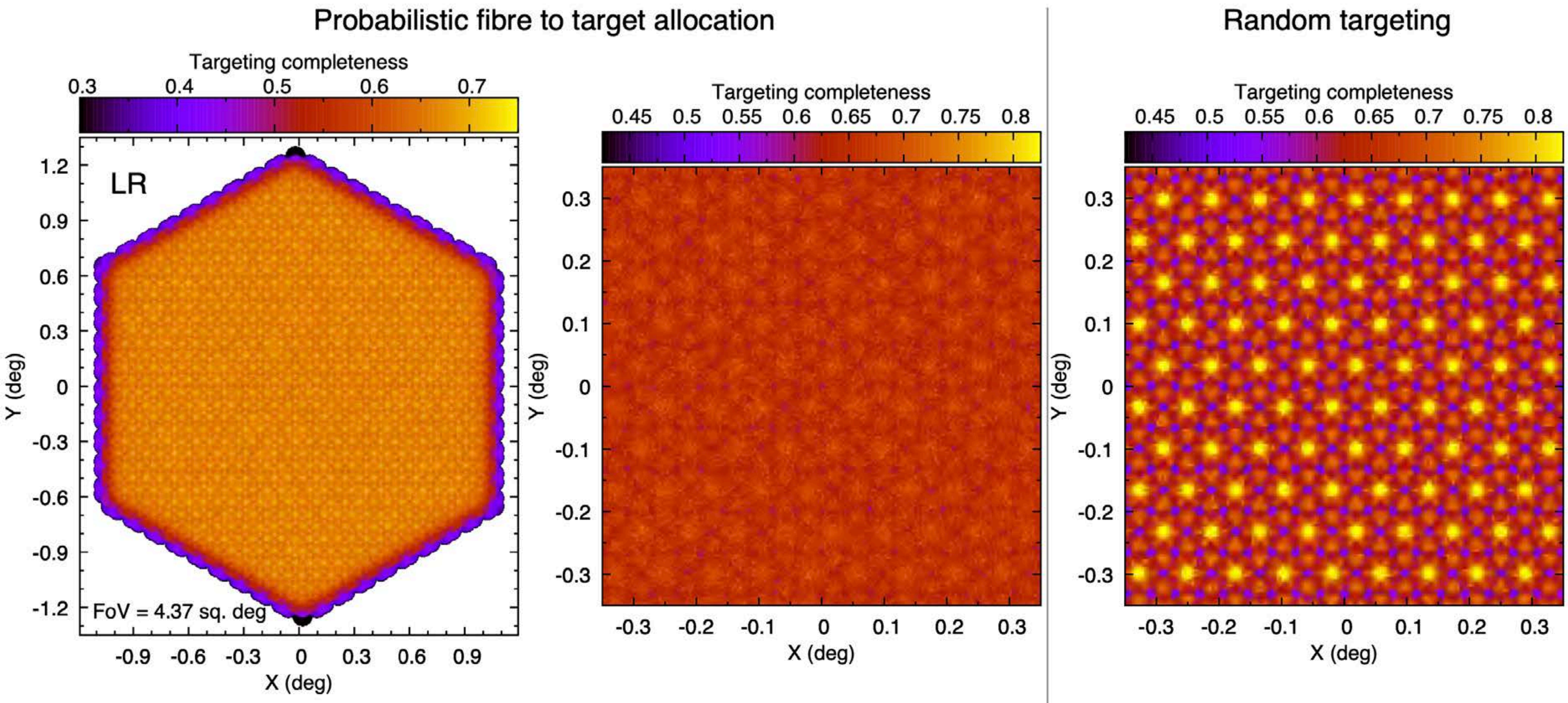


4MOST fibre pattern

Probabilistic fibre-to-target assignment

We assign a probability for each fibre-target pair

ET et al. 2020



4MOST fibre pattern

Random vs probabilistic targeting

ET et al. 2020

4MOST FTA steps

Targets/Positions (science, calibration, sky, etc) in the focal plane (X, Y coordinates)

For each fibre, find potential targets that can be allocated

Assign Fibre-Target probabilities (FTP) for each fibre-target pair

How this is done depends on the target type (science, calibration, sky)

Select fibre (randomly or following other rules)

Fibre selection depends on the target type (science, calibration, sky)

Assign target/position to selected fibre using FTP

Stop criteria depends on the target type. Monte-Carlo (Metropolis Hastings) assignment for science targets

Repeat (Monte-Carlo) as necessary

Configured tile — fibres assigned positions (X, Y)

Features included in current OpSim

- Target progress is estimated as: f_obs = Texp_observed / Texp_requested
- Simplistic weather, fixed observing conditions (dark, grey, bright)
- 2D and 3D fibre collision avoidance.
- Probabilistic fibre-to-target assignment that takes into account target exposure times and expected completeness.
- Monte-Carlo algorithm to minimise the number of empty fibres in each tile.
- Some sky regions can be prioritised over other sky regions

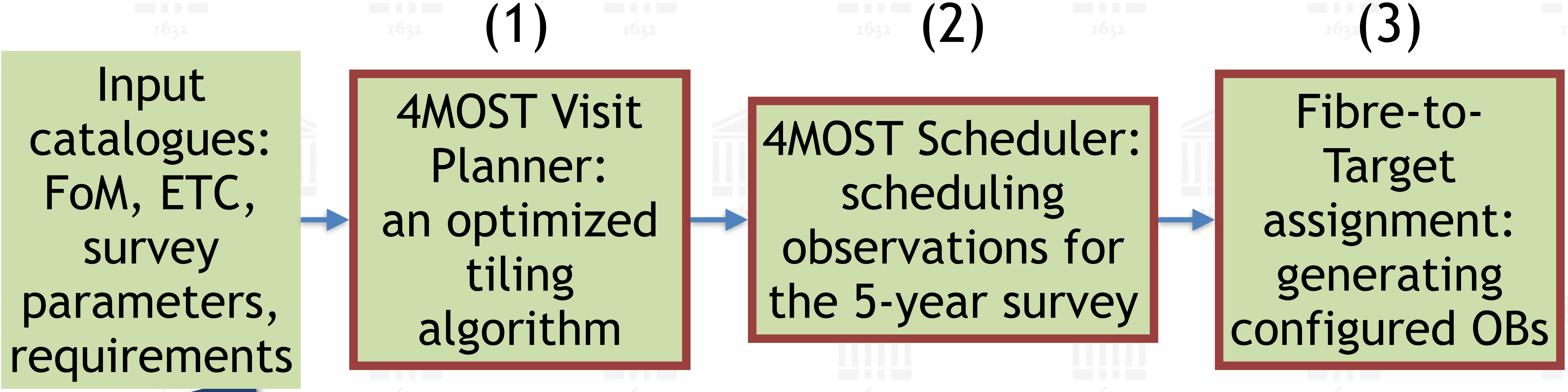
Tempel et al. (2020) “An optimised tiling pattern for multi-object spectroscopic surveys: application to the 4MOST survey”, MNRAS, 497, 4626 (arXiv:2007.03307)
Tempel et al. (2020) “Probabilistic fibre-to-target assignment algorithm for multi-object spectroscopic surveys”, A&A, 635, A101 (arXiv:2001.09348)

Specific features implemented in SELFIE

- **Each target can have independent selection probability (required completeness).**
- **For each target you can specify texp-factor (default 1.0) that mimics the template assignment (ETC exposure time) uncertainty. ETC exposure times multiplied by texp-factor is considered as required exposure time to successfully complete target.**
- **For each tile exposure you can add uncertainty and bias that is added to the VP tile exposures. This mimics the fact that real obseravations (per tile) can be more or less efficient than initially planned by the VP.**
- **For each tile you can specify when DMS feedback arrives for all targets in that tile.**
- **During simulated observations, initial guess of target progress is based on ETC exposure times. After DMS feedback has been arrived, the actual target progress is updated while including texp-factor per target.**
- **2D and 3D fibre collisions are avoided during fibre-target assignment.**
- **You can specify maximum target magnitude difference between neighbouring fibres in a CCD. Target is not allocated if magnitude difference is larger than this limiting value.**
- **Fibre-target assignment uses Monte-Carlo algorithm to maximise the fibre usage.**
- **Target for each fibre is selected based on Tile-Target Probabilities (TTP).**
- **TTP can be precalculated using SELFIE-TTP algorithm or using OpSys TTP algorithm.**
- **Tile-Target Probabilities are adjusted during FTA to take into account maximum Target Value, which is estimated based on the total remaining time for a given target.**
- **Tile-Target Probabilities can be adjusted for each subsurvey, i.e. to boost the completeness of some subsurveys.**
- **Tile-Target Probabilities can be adjusted based on probabilistic selection function output. It helps surveys that require high completeness (e.g. WAVES, 4HS).**
- **To estimate target progress, SELFIE includes fibre-to-fibre throughput variations and fibre tilt angle dependent throughput.**
- **To estimate target progress, for each fibre-target pair SELFIE adds additional scatter to mimick uncertainties related with e.g. fibre misalignment.**
- **For each target, you can specify the rules for target reobservations. At the moment targets that need reobservations are prioritised.**
- **5-year survey can be simulated as a sum of smaller periods: visit planner can be rerun between periods, target catalog can be updated, etc.**
- **Sky fibres can be allocated randomly or according to some predefined rules.**
- **Per target cadence flags are taken into account in FTA.**

Preparing observations

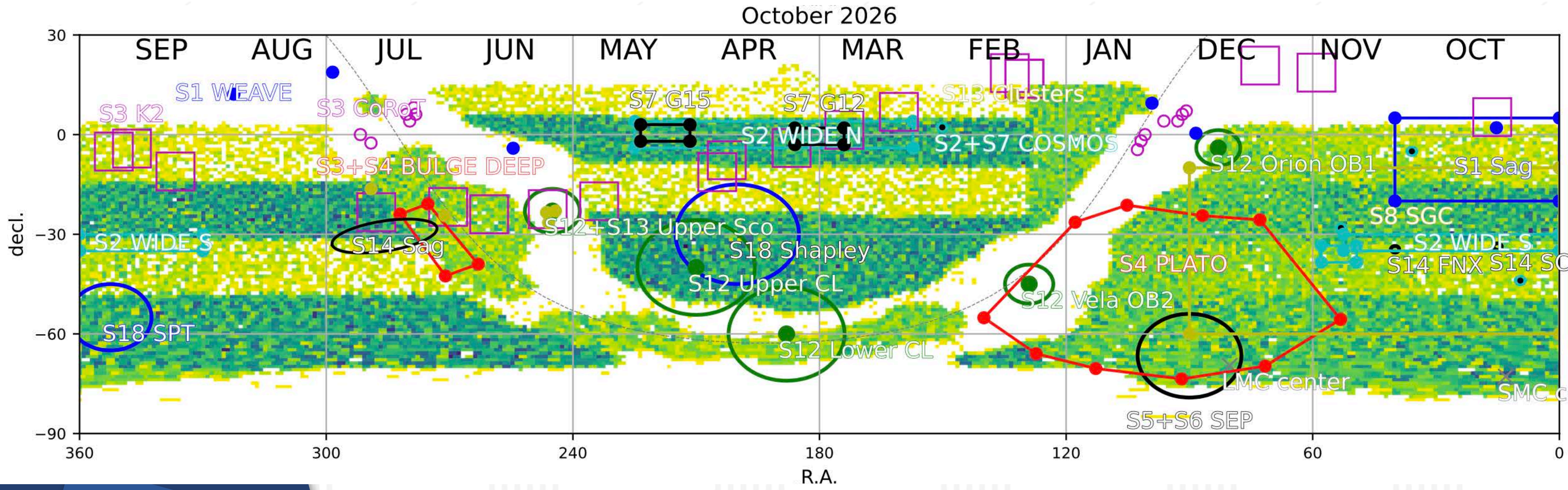
General flowchart



(1) ET et al. (2020) “An optimised tiling pattern for multi-object spectroscopic surveys: application to the 4MOST survey”

(2) paper in prep

(3) ET et al. (2020) “Probabilistic fibre-to-target assignment algorithm for multi-object spectroscopic surveys”

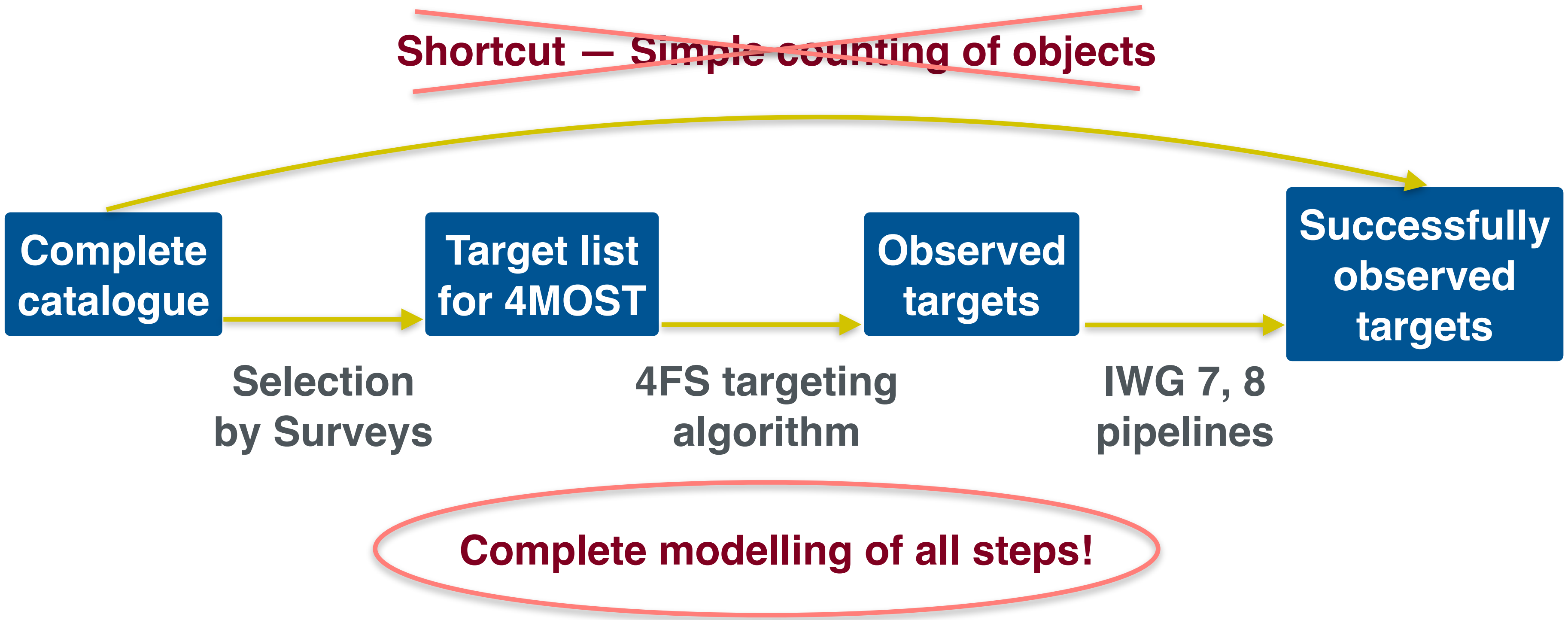


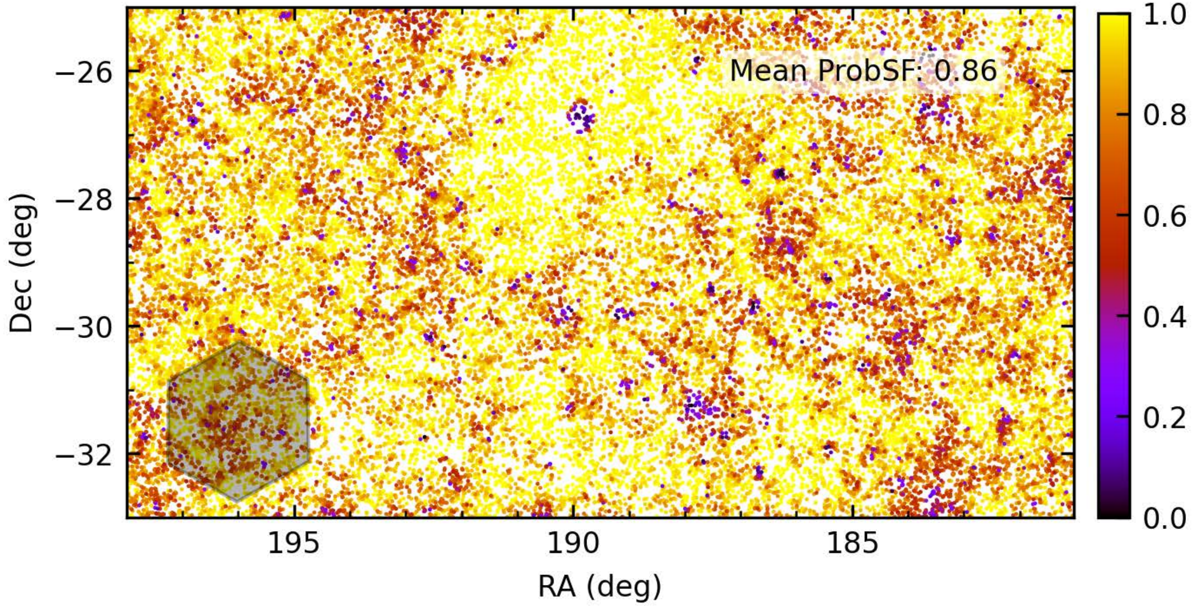
LSST rolling cadence

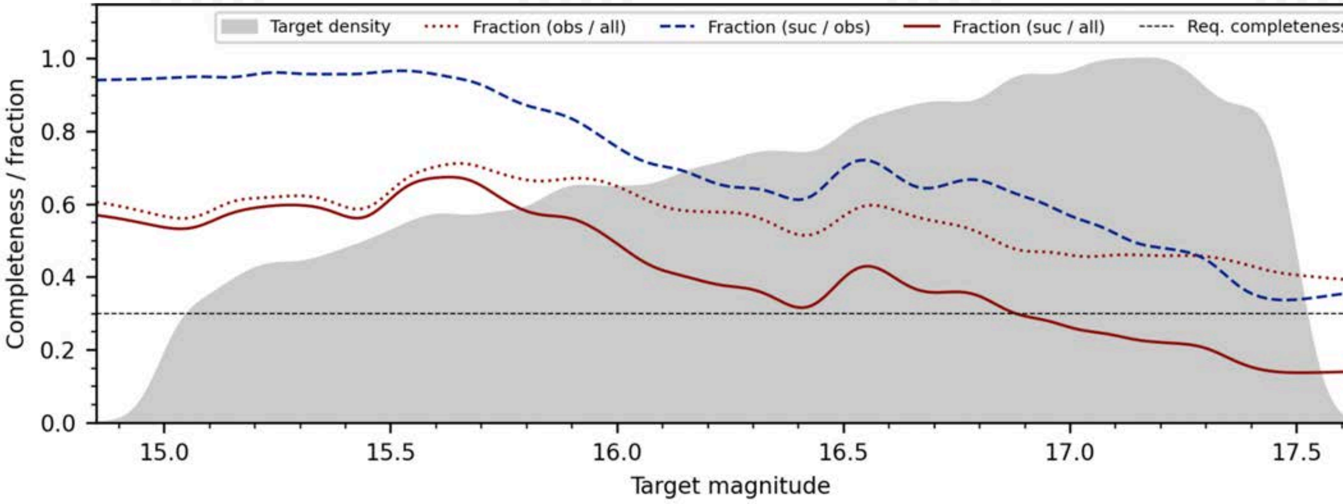
Input to Long-Term Scheduler

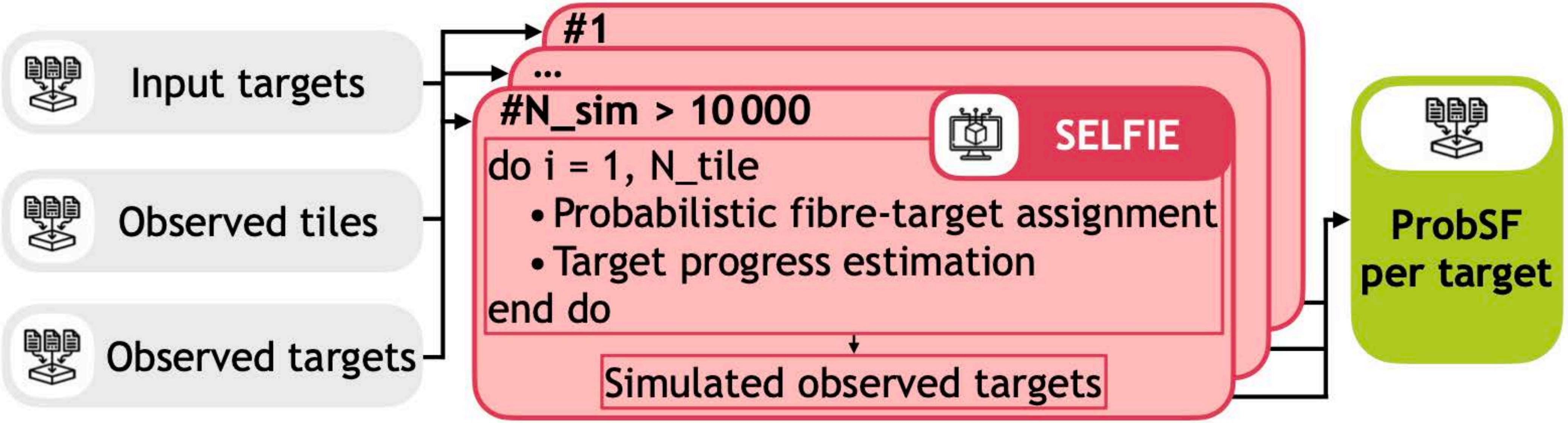
4MOST will try to follow LSST schedule as much as possible, while taking into account other observational constraints

From complete catalogue to observed targets



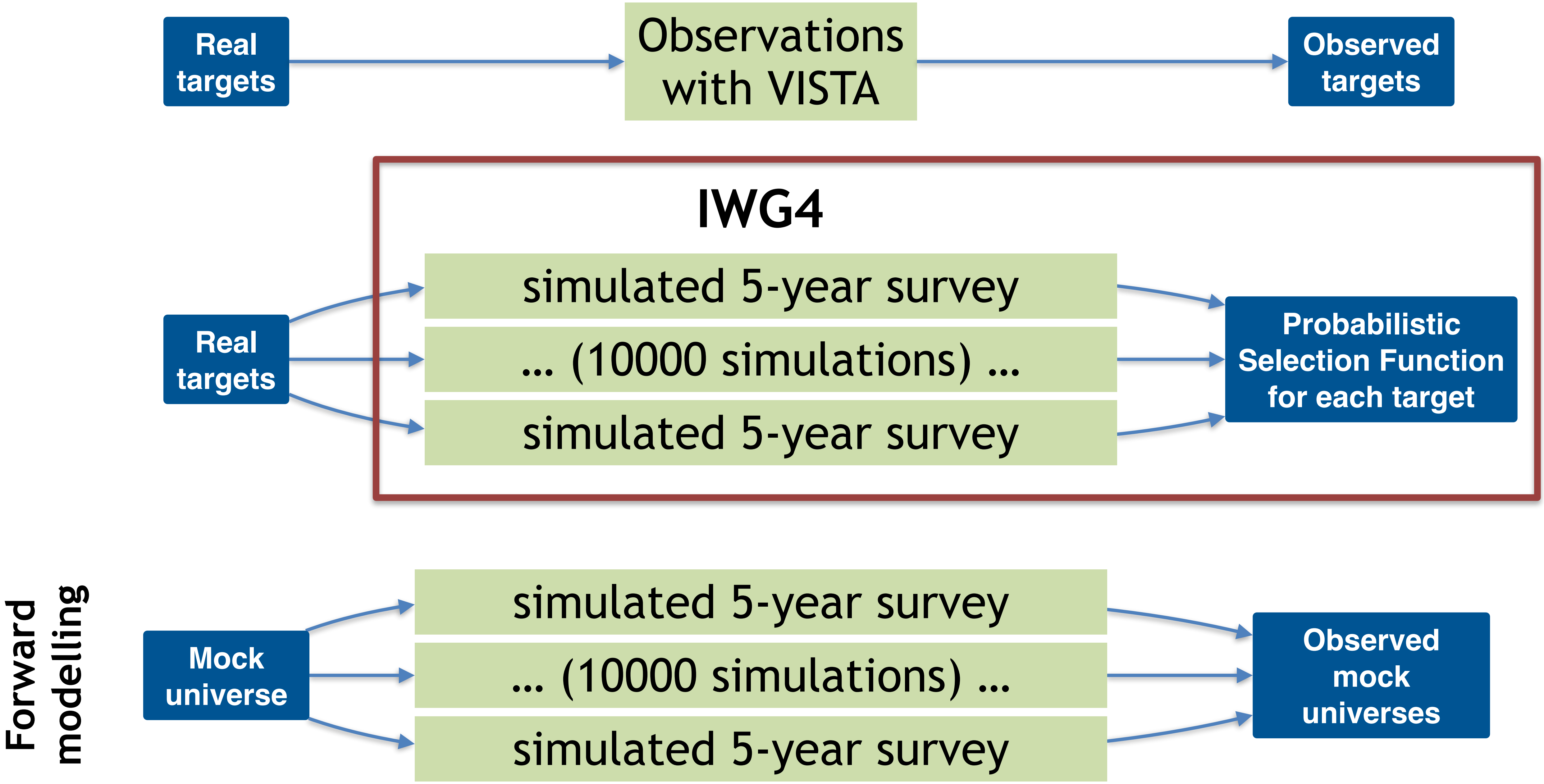


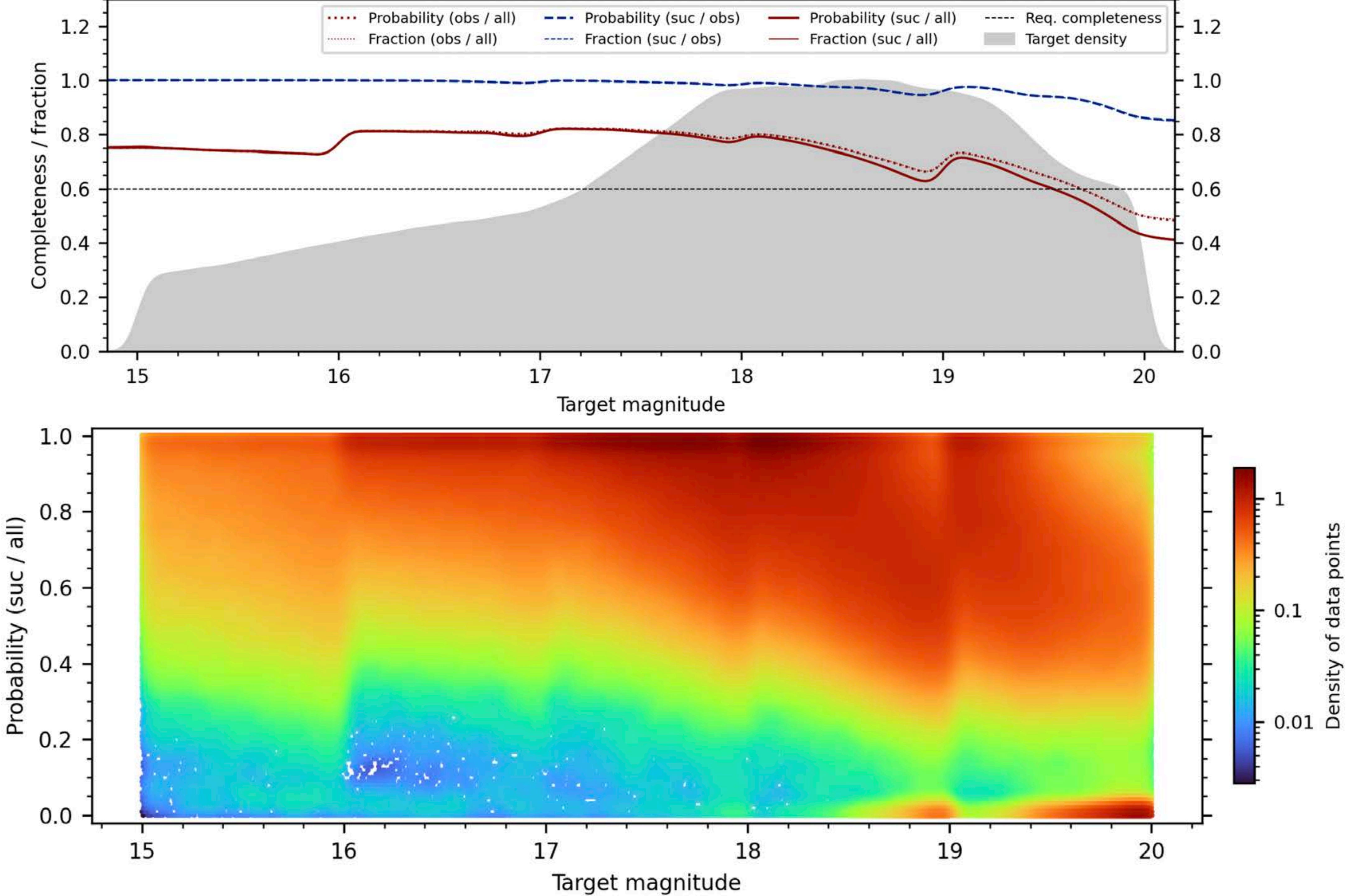




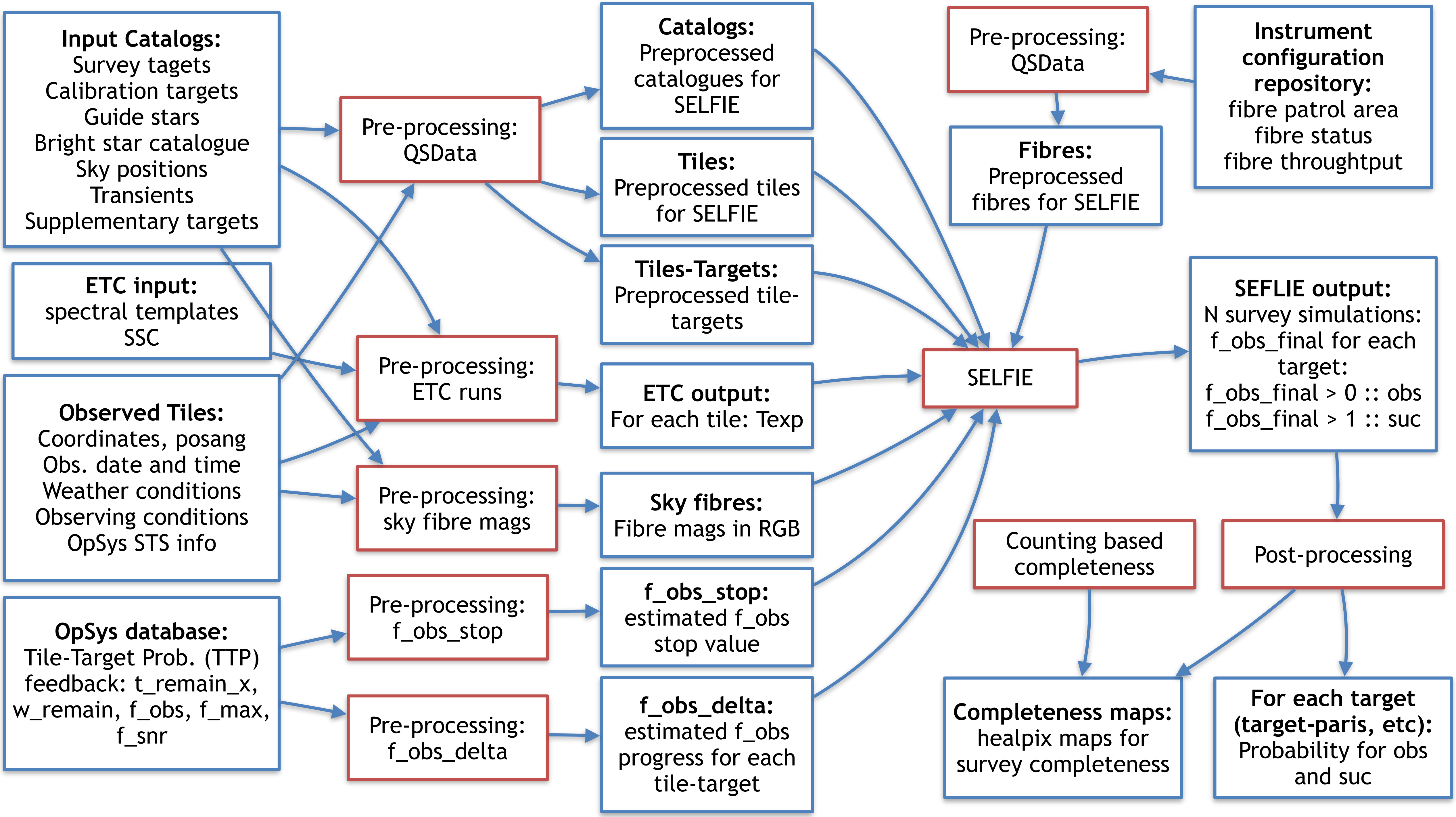
Probabilistic selection function

4MOST survey simulations

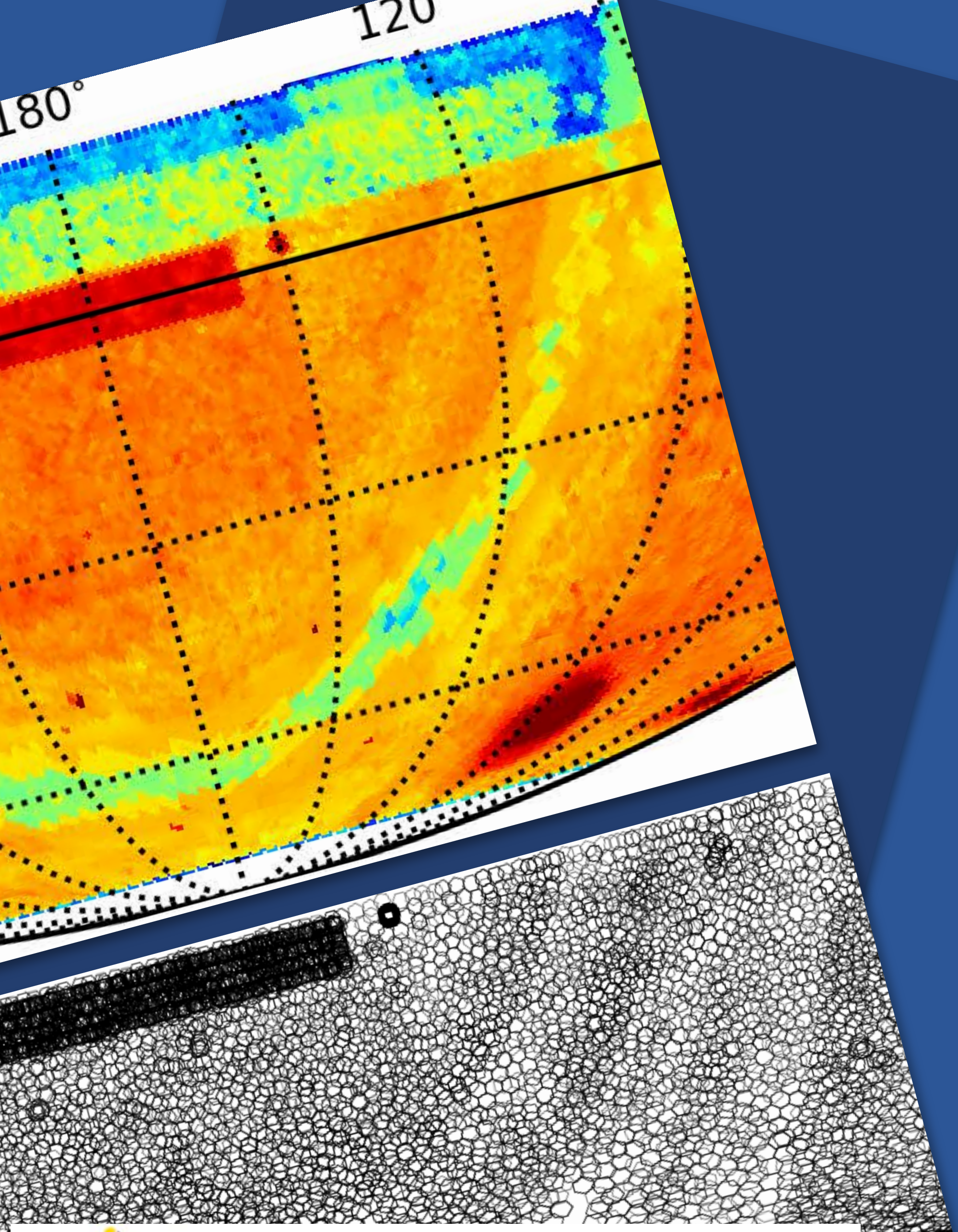

Real targets
Observations with VISTA
Observed targets
IWG4
Real targets
simulated 5-year survey
… (10000 simulations) …
simulated 5-year survey
Probabilistic Selection Function for each target
Forward modelling
Mock universe
simulated 5-year survey
… (10000 simulations) …
simulated 5-year survey
Observed mock universes



Probability (obs / all)
Fraction (obs / all)
Probability (suc / obs)
Fraction (suc / obs)
Probability (suc / all)
Fraction (suc / all)
Req. completeness
Target density
Completeness / fraction
Target magnitude
Probability (suc / all)
Density of data points
Target magnitude



Input Catalogs:
Survey tagets
Calibration targets
Guide stars
Bright star catalogue
Sky positions
Transients
Supplementary targets
ETC input:
spectral templates
SSC
Observed Tiles:
Coordinates, posang
Obs. date and time
Weather conditions
Observing conditions
OpSys STS info
OpSys database:
Tile-Target Prob. (TTP)
feedback: t_remain_x,
w_remain, f_obs, f_max,
f_snr
Pre-processing:
QSData
Pre-processing:
ETC runs
Pre-processing:
sky fibre mags
Pre-processing:
f_obs_stop
Pre-processing:
f_obs_delta
Catalogs:
Preprocessed
catalogues for
SELFIE
Tiles:
Preprocessed tiles
for SELFIE
Tiles-Targets:
Preprocessed tile-
targets
ETC output:
For each tile: Texp
Sky fibres:
Fibre mags in RGB
f_obs_stop:
estimated f_obs
stop value
f_obs_delta:
estimated f_obs
progress for each
tile-target
Pre-processing:
QSData
Instrument
configuration
repository:
fibre patrol area
fibre status
fibre throughtput
Fibres:
Preprocessed
fibres for SELFIE
SELFIE
SEFLIE output:
N survey simulations:
f_obs_final for each
target:
f_obs_final > 0 :: obs
f_obs_final > 1 :: suc
Counting based
completeness
Post-processing
Completeness maps:
healpix maps for
survey completeness
For each target
(target-paris, etc):
Probability for obs
and suc



Summary

- 4MOST 4HS and TiDES surveys will contribute to the peculiar velocity science. In coming years, peculiar velocity datasets will increase significantly.
- Developing an optimal operations strategy for 4MOST is challenging, but it allows to maximise the scientific return of the instrument.
- Probabilistic Selection Function to understand the targeting selection effects (incompleteness).
- Uncertainties in our analysis are not limited by the size of the available datasets. Scientific analyses are limited by our understanding of systematics and biases in our data.

EXCOSM
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