Cosmology from SKA Observatory pathfinders

Jacobo Asorey
Universidad Complutense de Madrid

In collaboration with:
Benedict Bahr-Kalus (KASI), Stefano Camera (UoT), Catherine Hale (ROE), David Parkinson (KASI), Ignacio Sevilla-Noarbe (Ciemat), Fei Qin (KASI) and members of the EMU and RACS collaborations

B. Bahr-Kalus, D. Parkinson D., JA, S. Camera, C. Hale, F. Qin, 2022, MNRAS

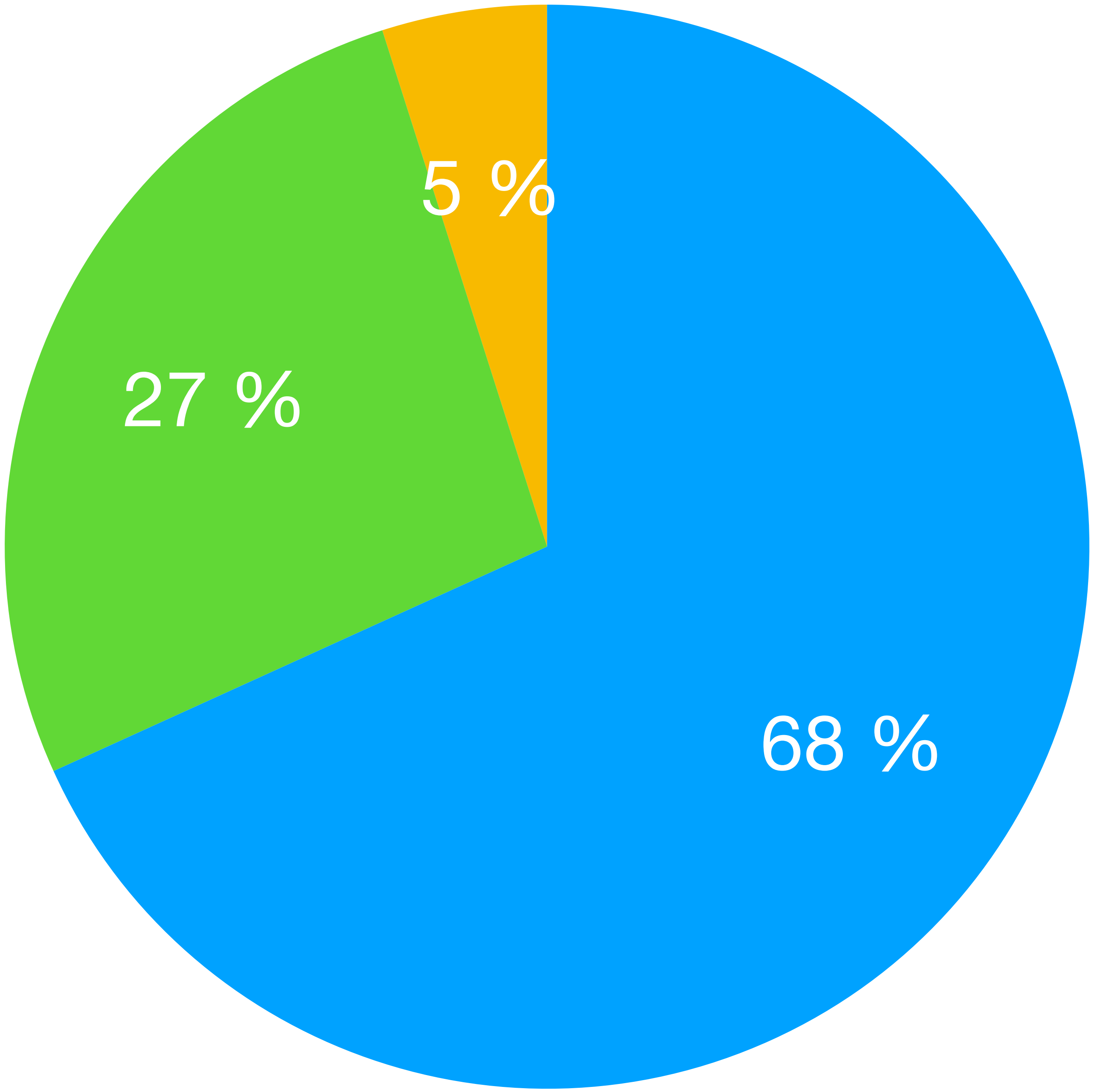
UNIVERSIDAD COMPLUTENSE MADRID
GOBIERNO DE ESPAÑA
MINISTERIO DE UNIVERSIDADES
Plan de Recuperación, Transformación y Resiliencia
Financiado por la Unión Europea
NextGenerationEU

Saturnalia 2022, Universidad de Zaragoza, 20/11/2022

Cosmological Standard Model

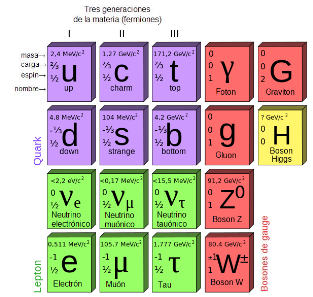
- Isotropic and homogeneous Universe at large scales described by GR and a cosmological constant.

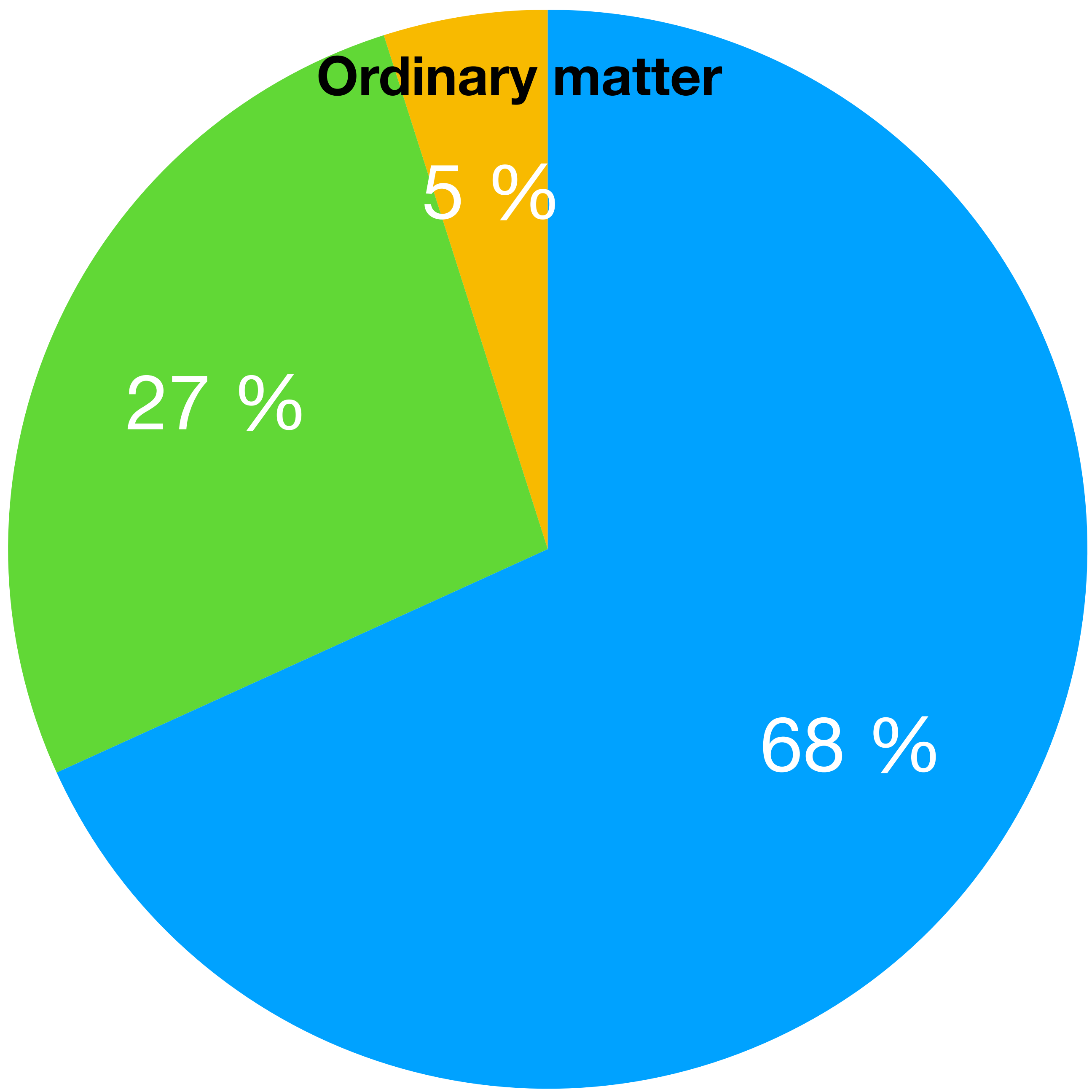
Cosmological Standard Model



- Isotropic and homogeneous Universe at large scales described by GR and a cosmological constant.

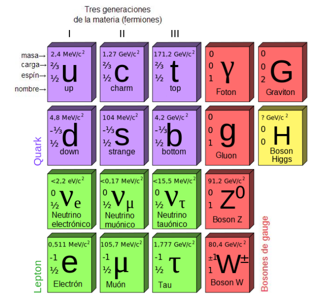
Cosmological Standard Model

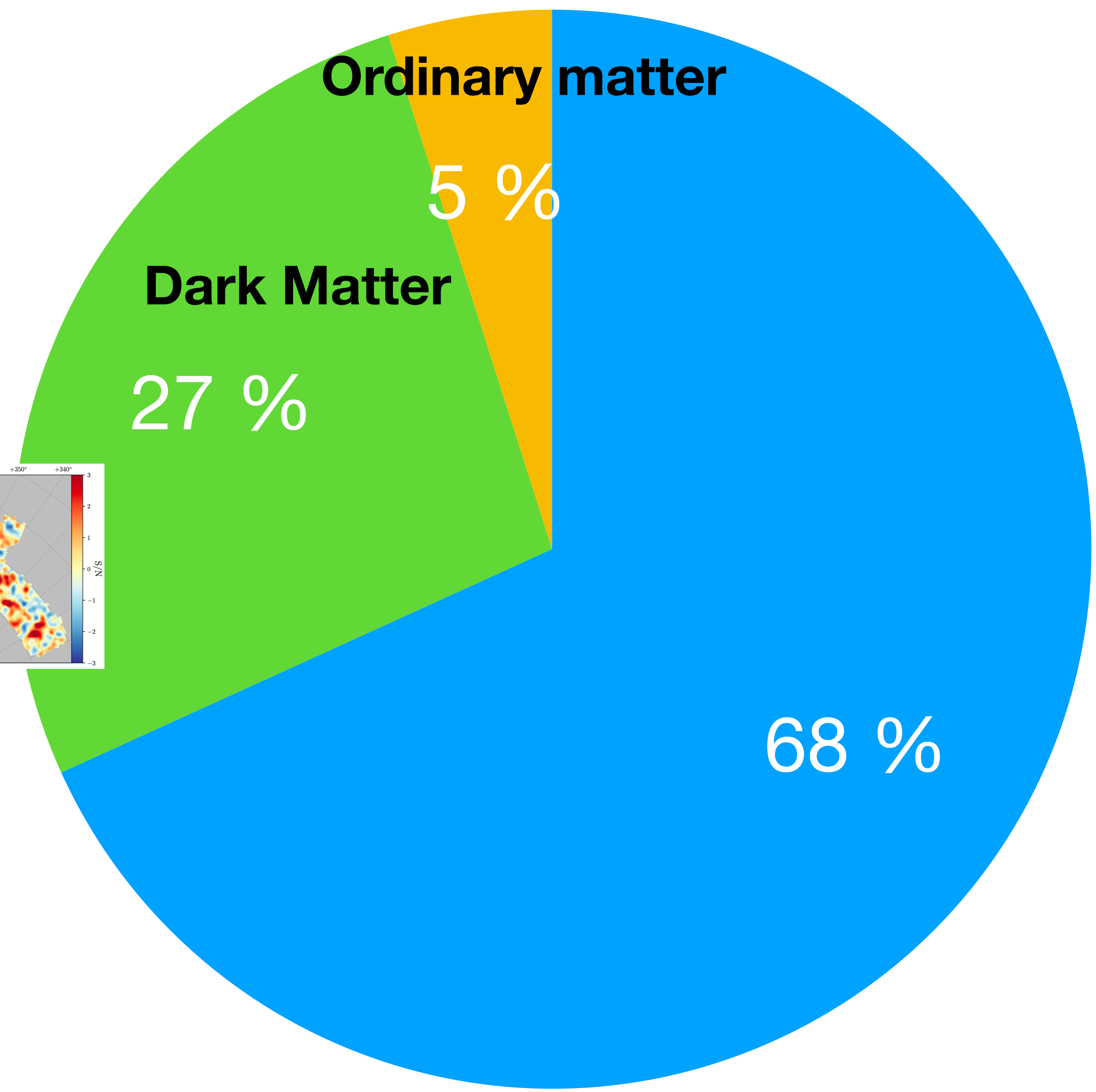


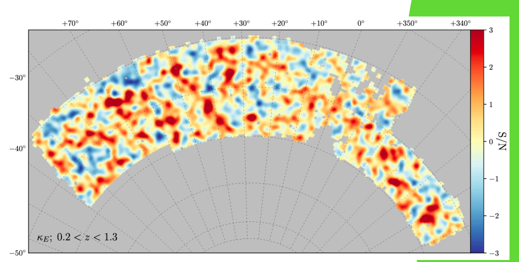


- Isotropic and homogeneous Universe at large scales described by GR and a cosmological constant.

Cosmological Standard Model

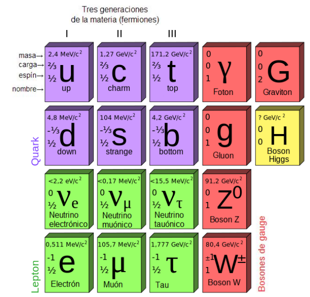


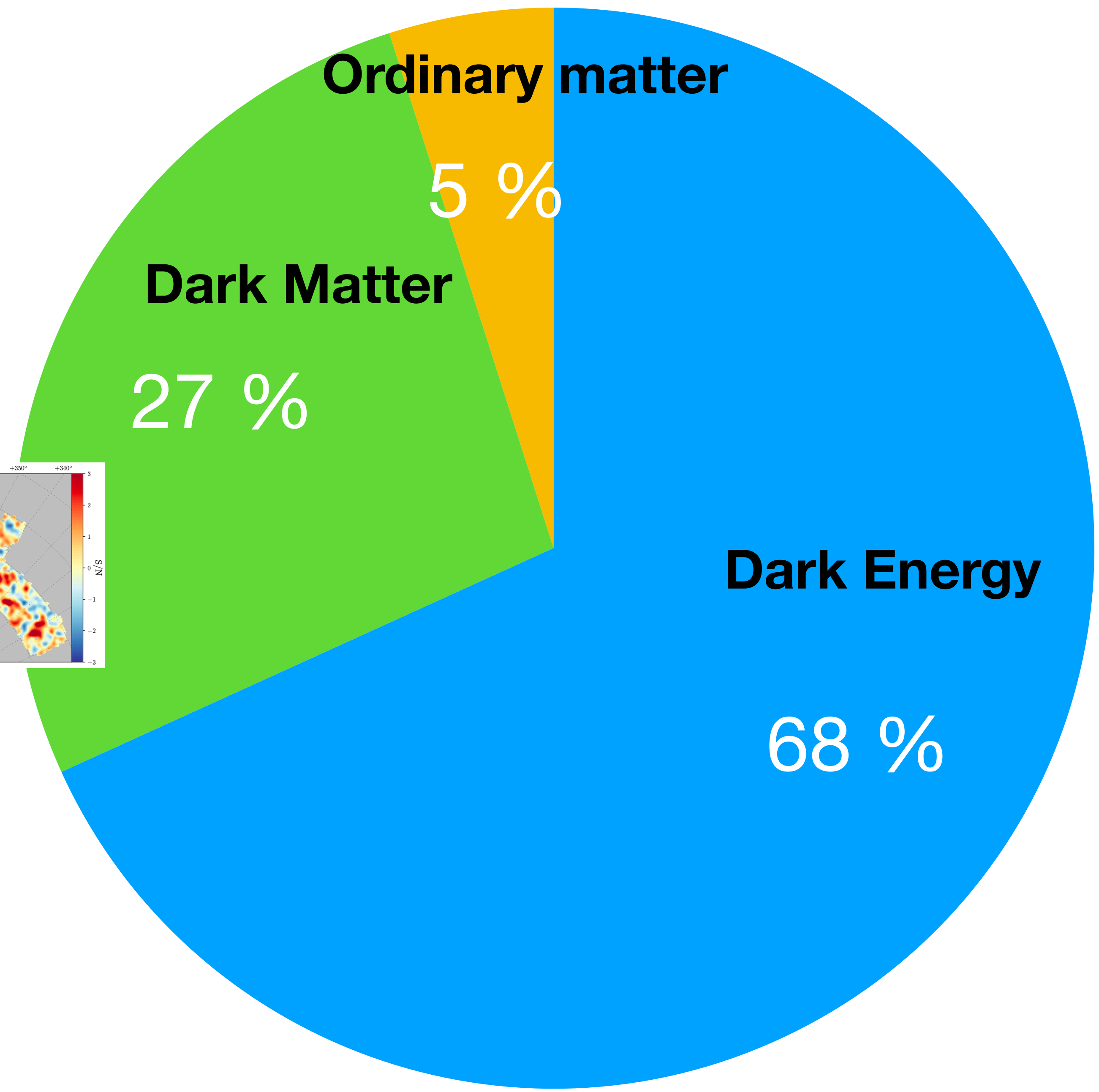


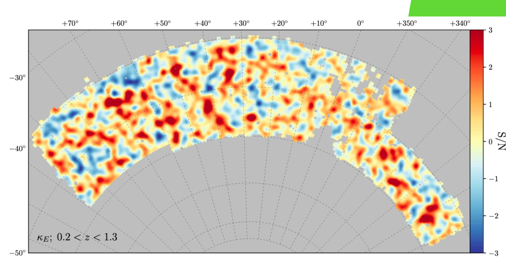


- Isotropic and homogeneous Universe at large scales described by GR and a cosmological constant.

Cosmological Standard Model



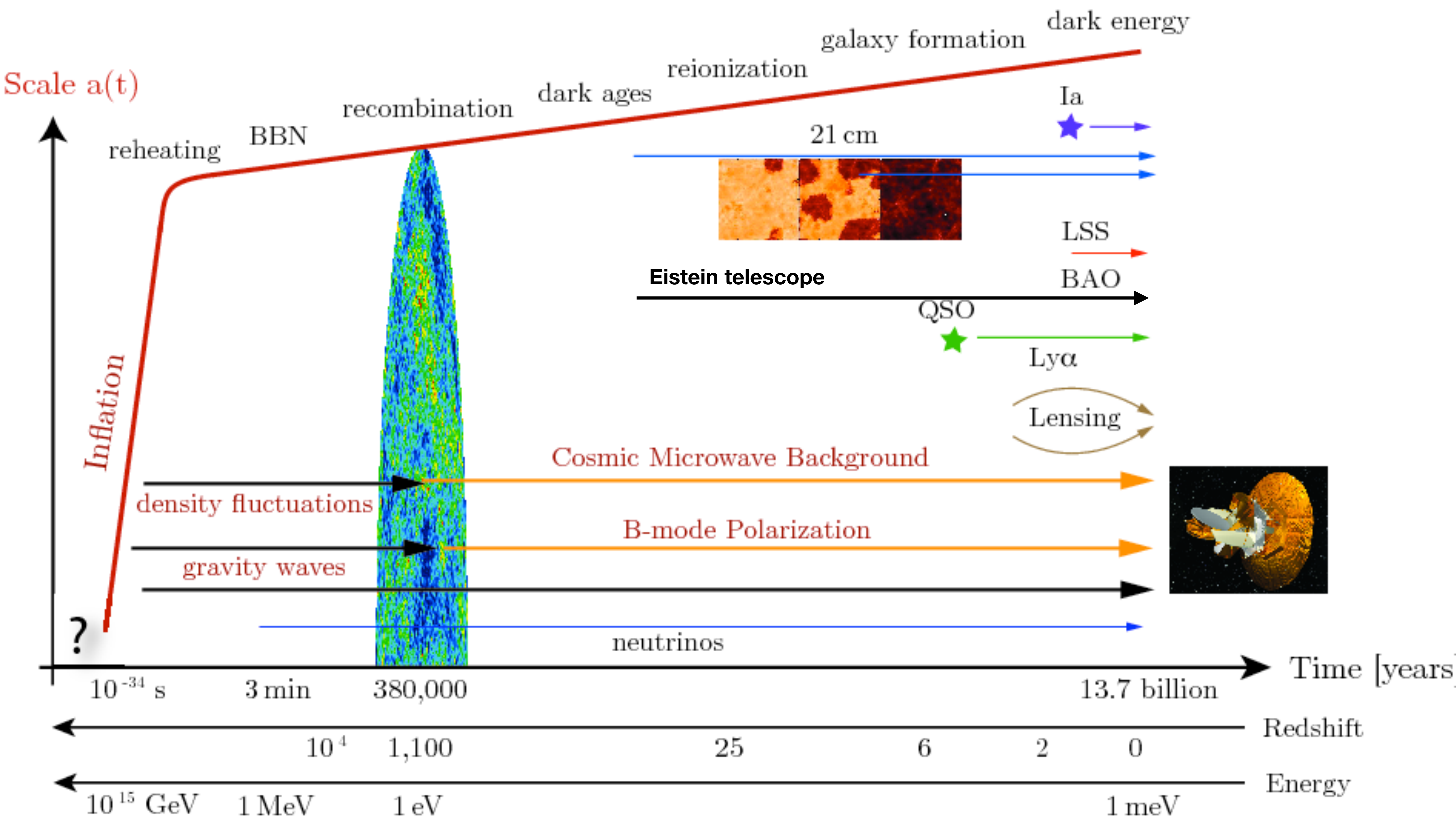




Λ

- Isotropic and homogeneous Universe at large scales described by GR and a cosmological constant.

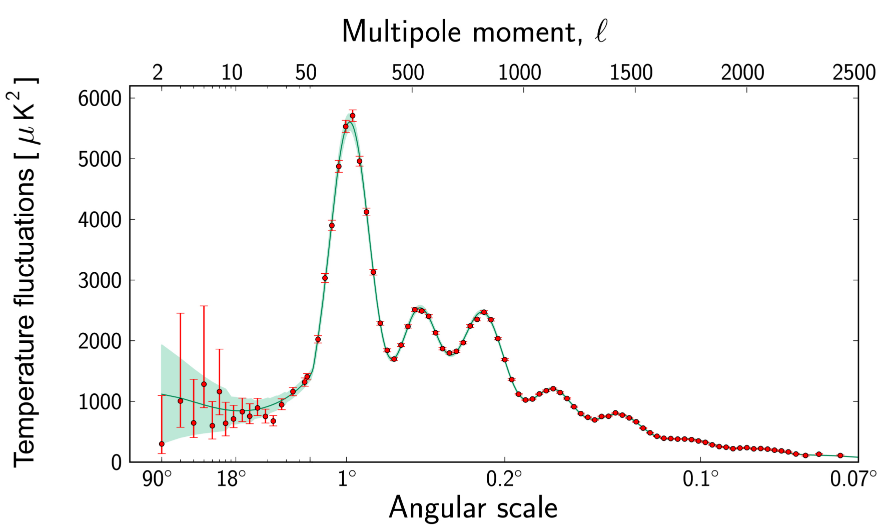
Timeline



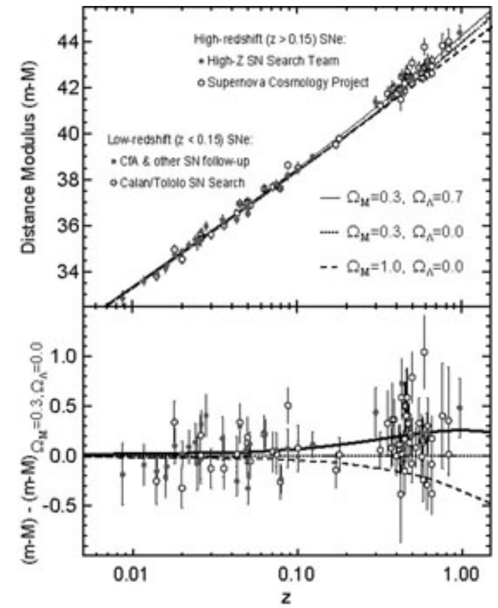
D. Baumann, 2009, arXiv:0907.5424

Cosmological archeology

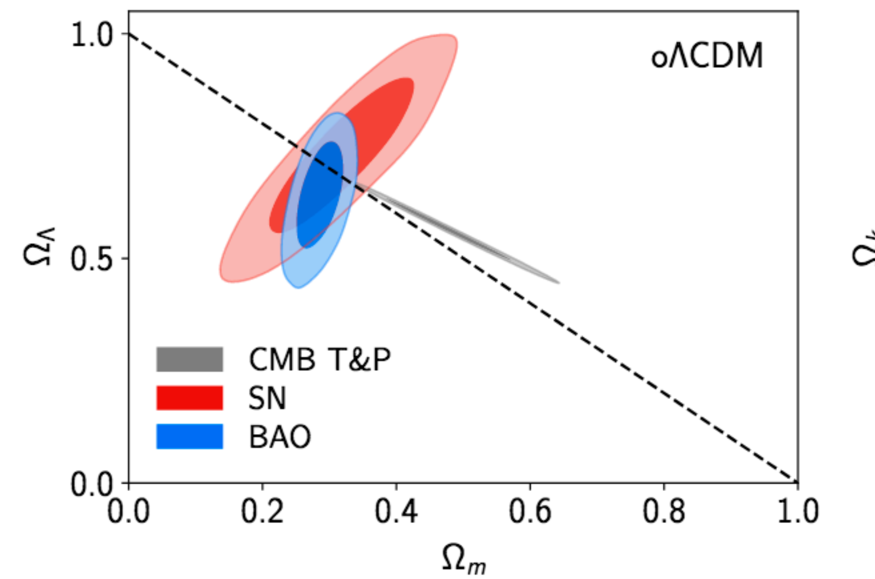
- 100 years of cosmological observations have lead us to establish the standard ΛCDM model, based on 6 parameters (Ω_b, Ω_m, n_s, A_s, τ, H_0).



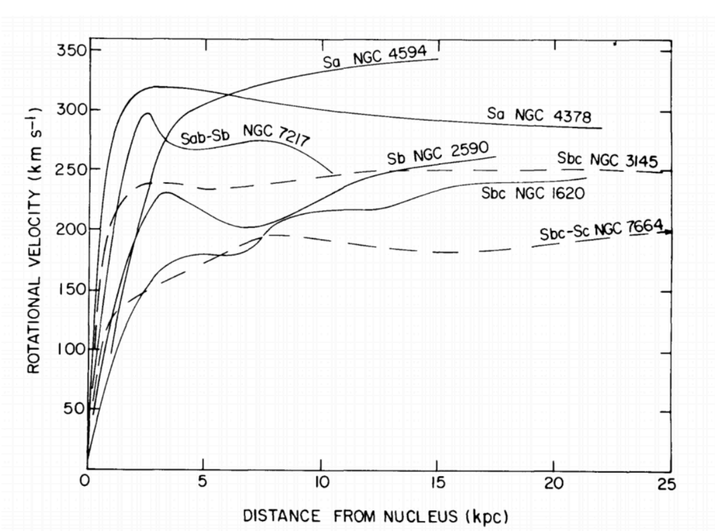
Planck Collaboration



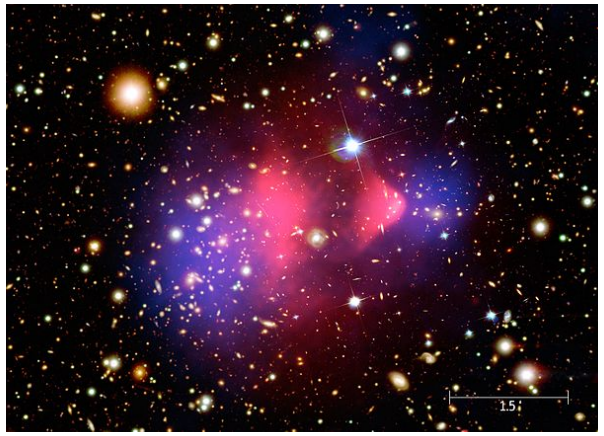
Riess et al., 1998, Perlmutter et al. 1999



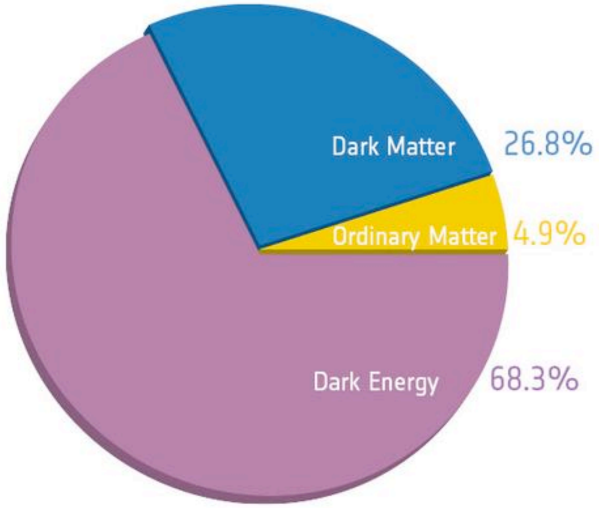
eBOSS Collaboration



V. Rubin et al. 1978

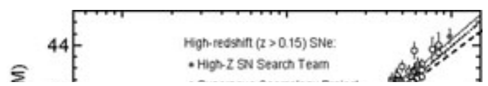


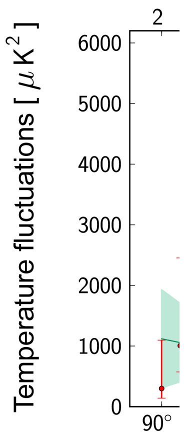
Bullet Cluster



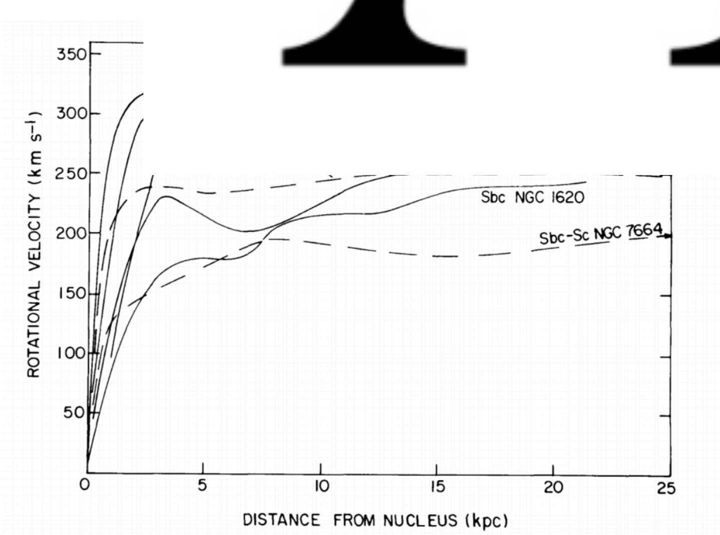
Cosmological archeology

- 100 years of cosmological observations have lead us to establish the standard ΛCDM model, based on 6 parameters (Ω_b, Ω_m, n_s, A_s, τ, H_0).



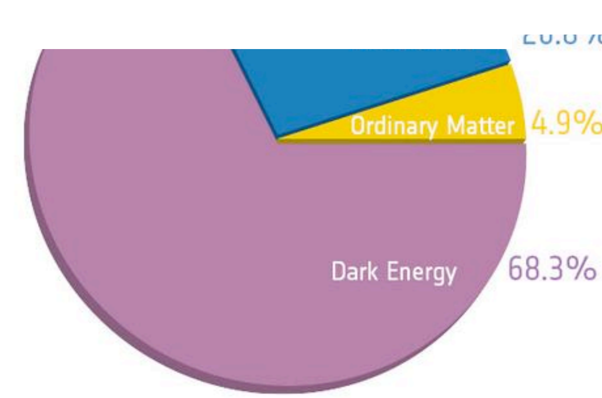


Λ or not Λ



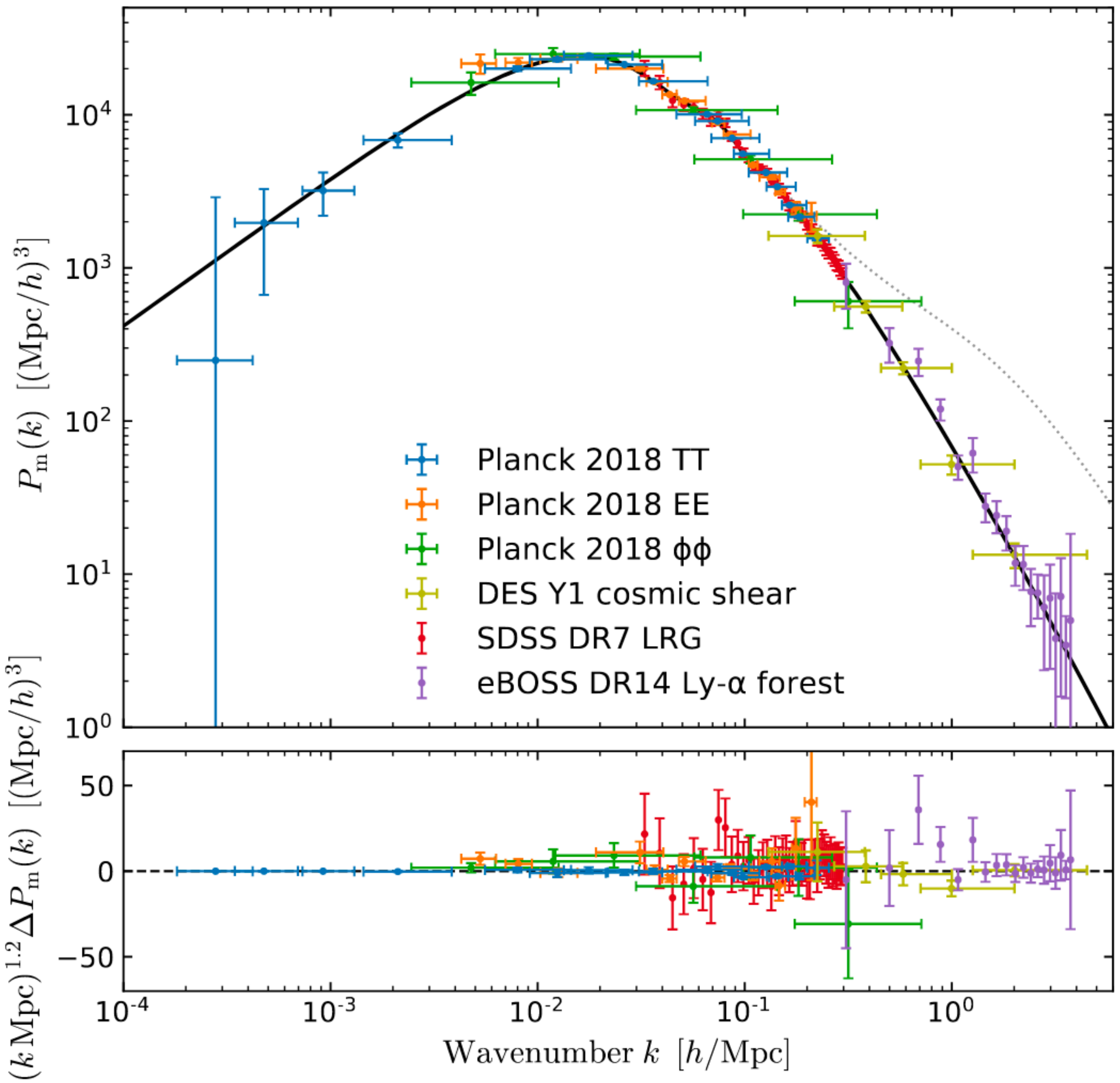
V. Rubin et al. 1978

Bullet Cluster



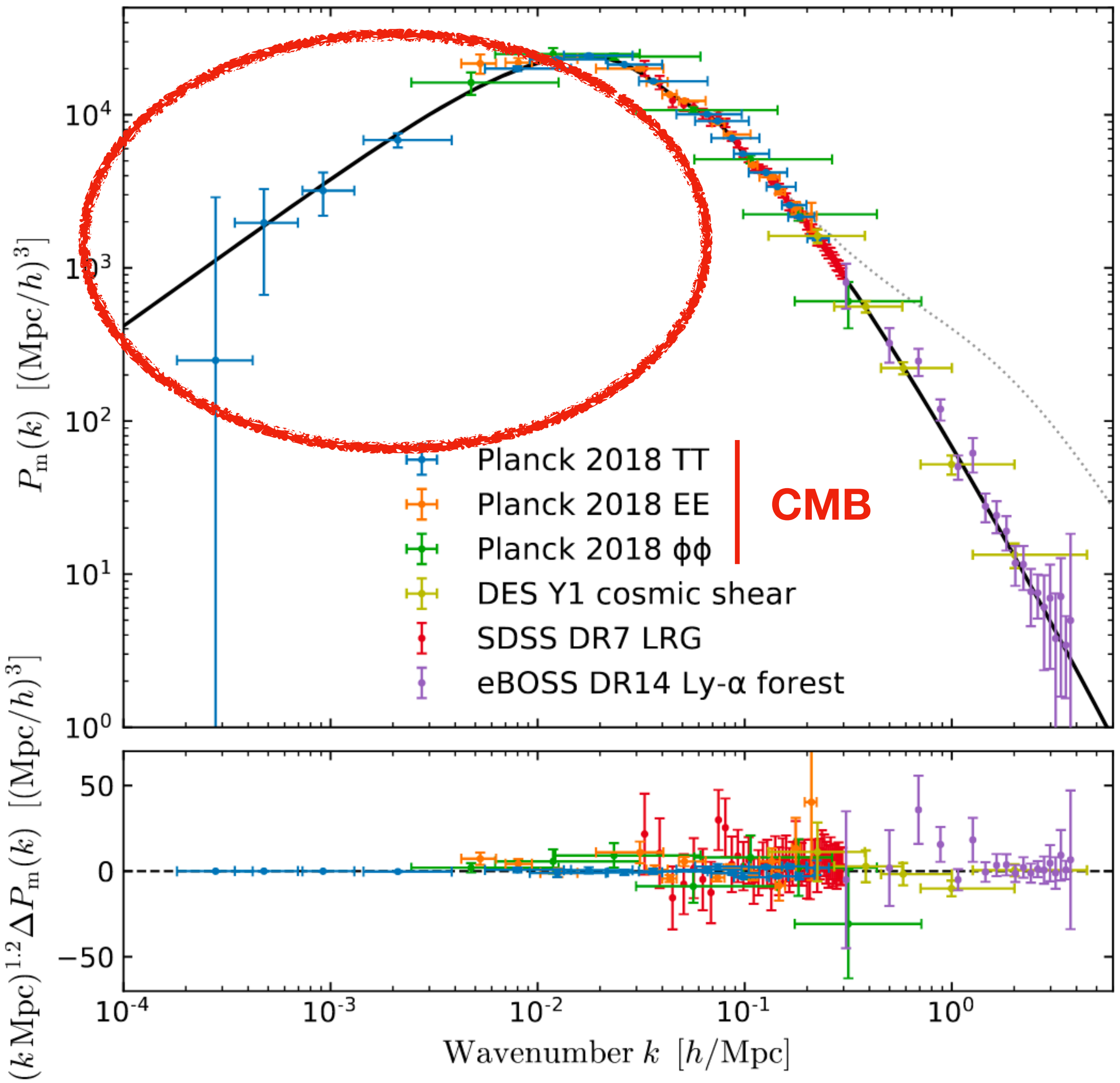
Large-scale structure

- Universe filled with density fluctuations
- Structure only only visible through galaxies (distribution) and photons (weak lensing)
- Galaxies and photons here are functioning as test particles - tracing out the gravitational field
- Most low-redshift surveys have measured the transfer function.
- Need very large volumes to measure primordial power spectrum and determine initial conditions (independently from CMB)



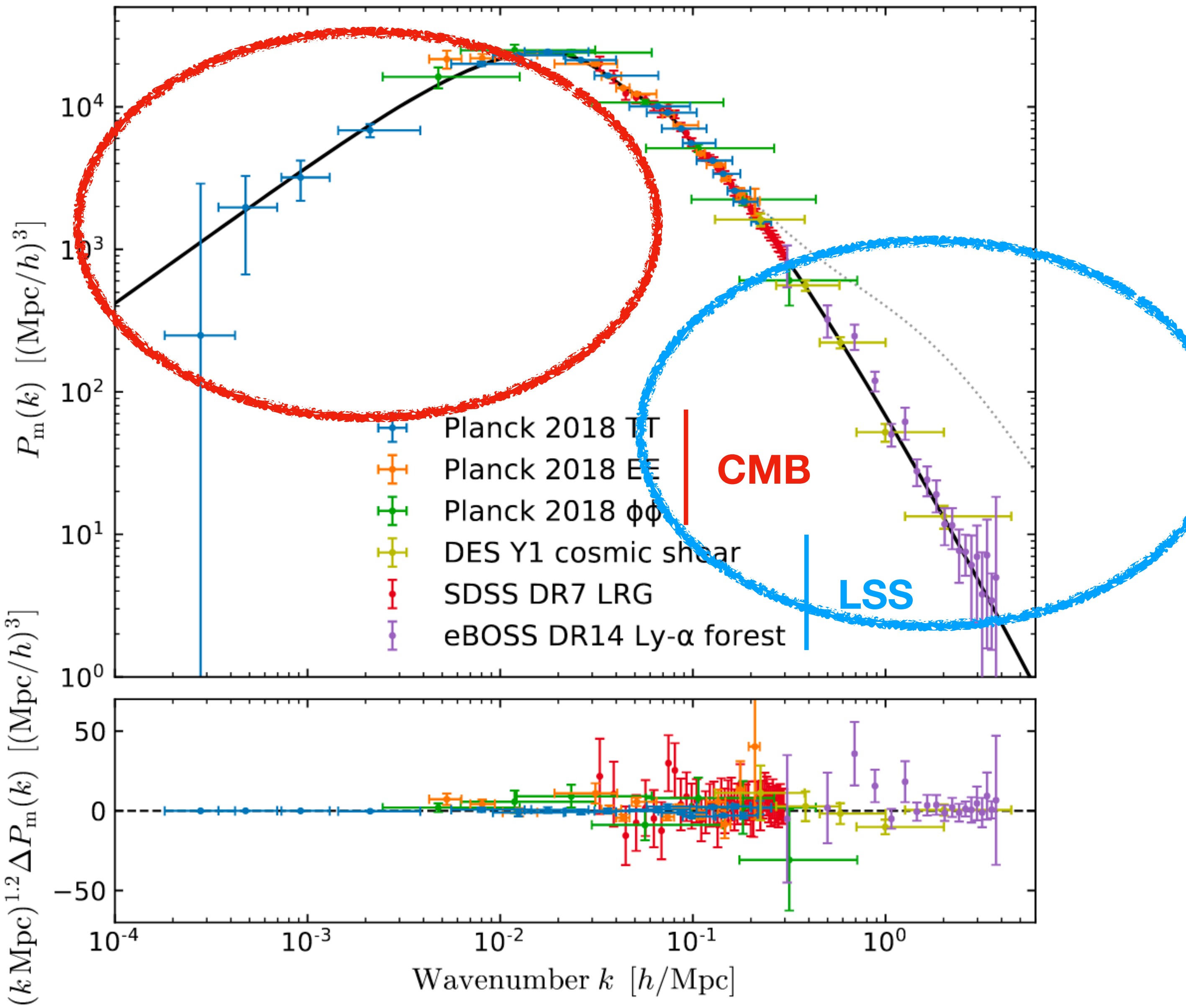
Large-scale structure

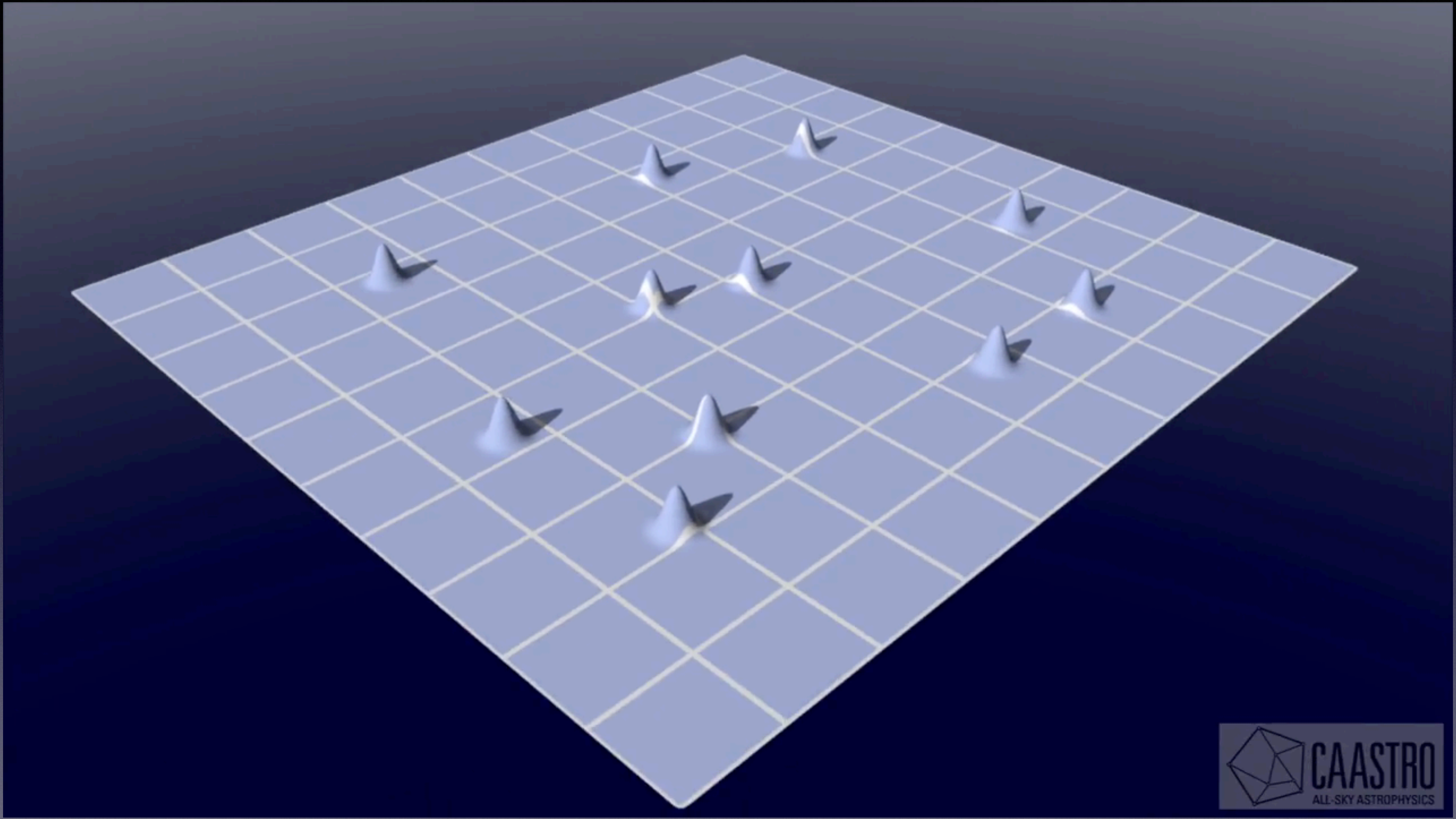
- Universe filled with density fluctuations
- Structure only only visible through galaxies (distribution) and photons (weak lensing)
- Galaxies and photons here are functioning as test particles - tracing out the gravitational field
- Most low-redshift surveys have measured the transfer function.
- Need very large volumes to measure primordial power spectrum and determine initial conditions (independently from CMB)

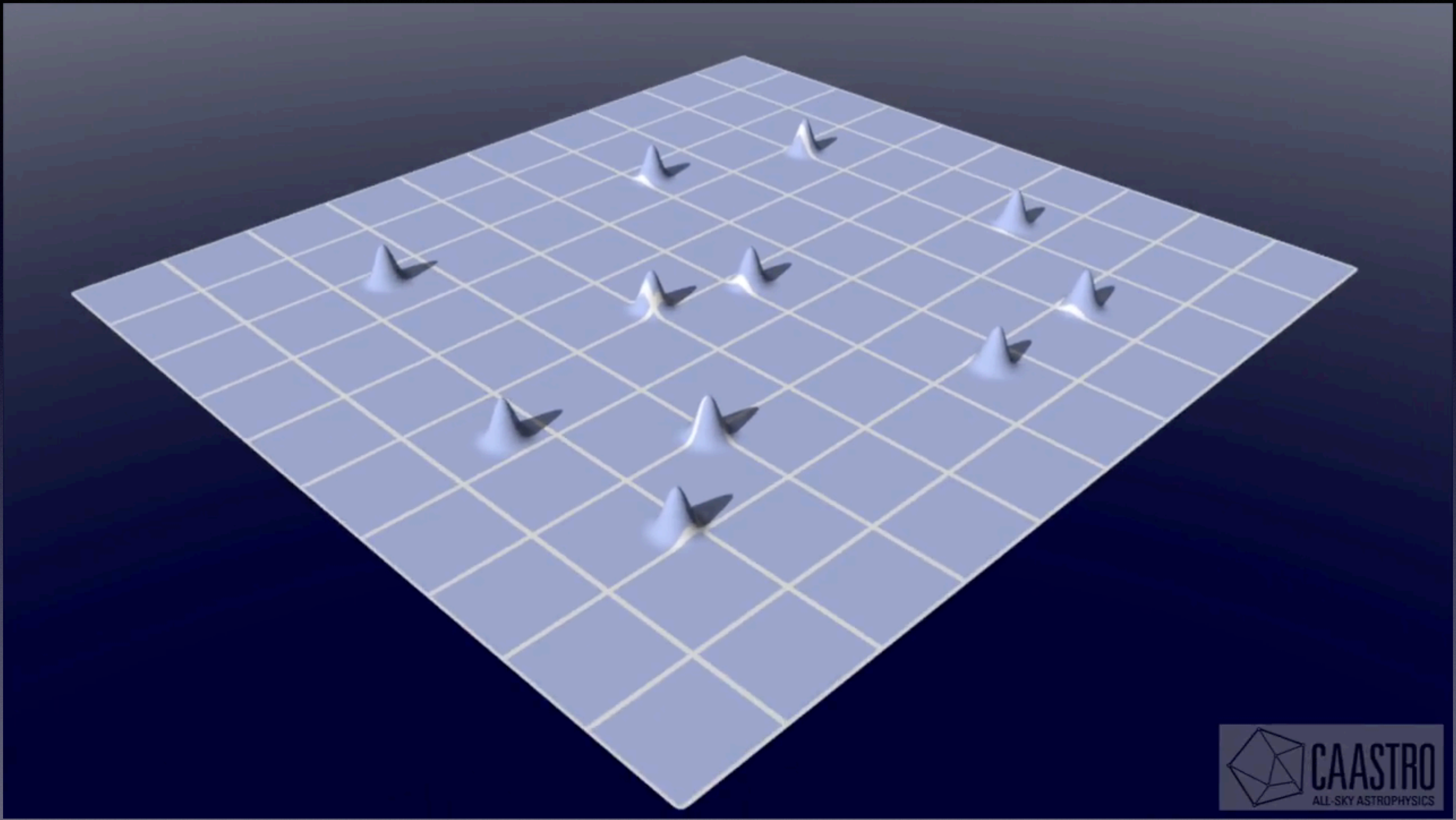


Large-scale structure

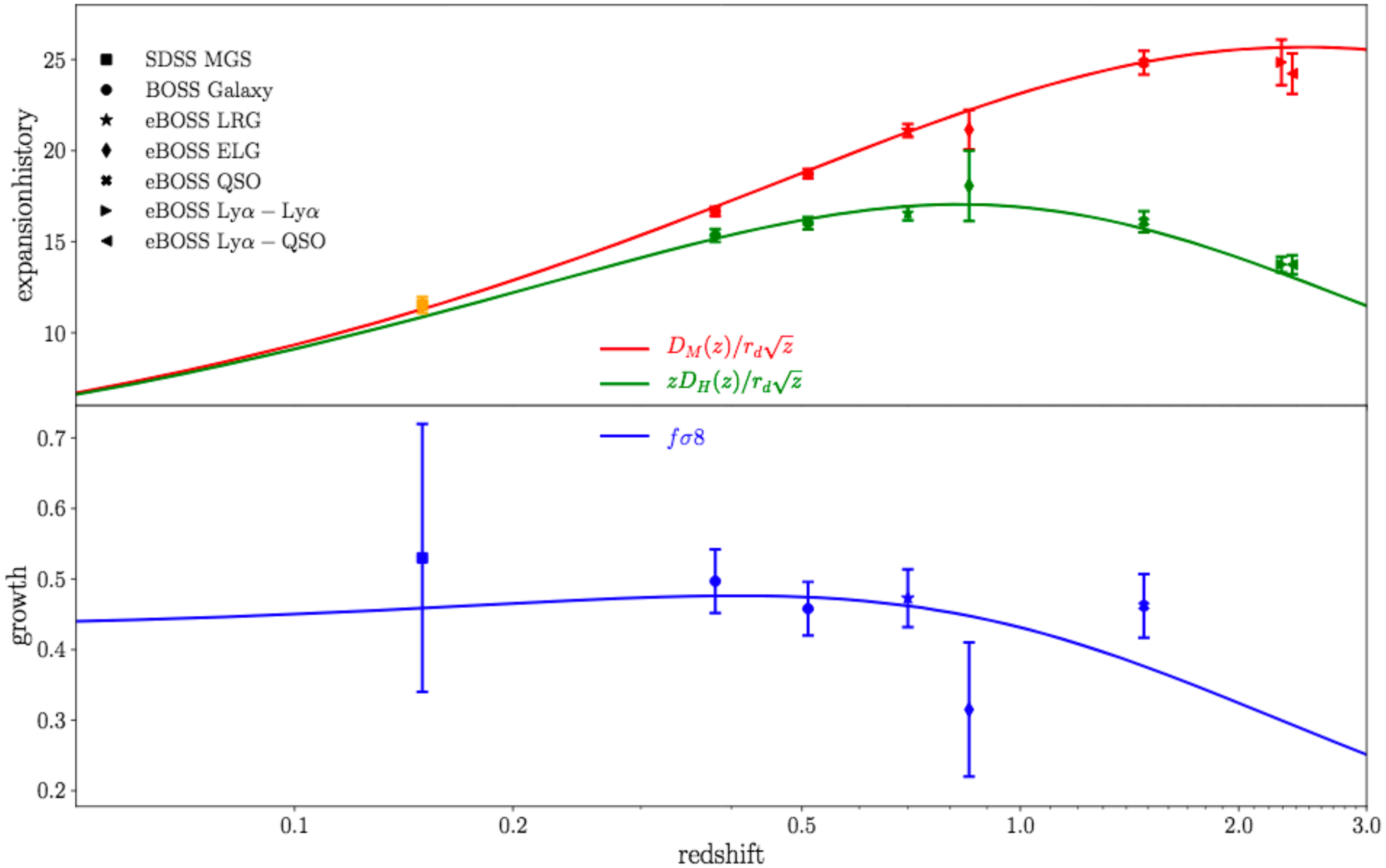
- Universe filled with density fluctuations
- Structure only only visible through galaxies (distribution) and photons (weak lensing)
- Galaxies and photons here are functioning as test particles - tracing out the gravitational field
- Most low-redshift surveys have measured the transfer function.
- Need very large volumes to measure primordial power spectrum and determine initial conditions (independently from CMB)



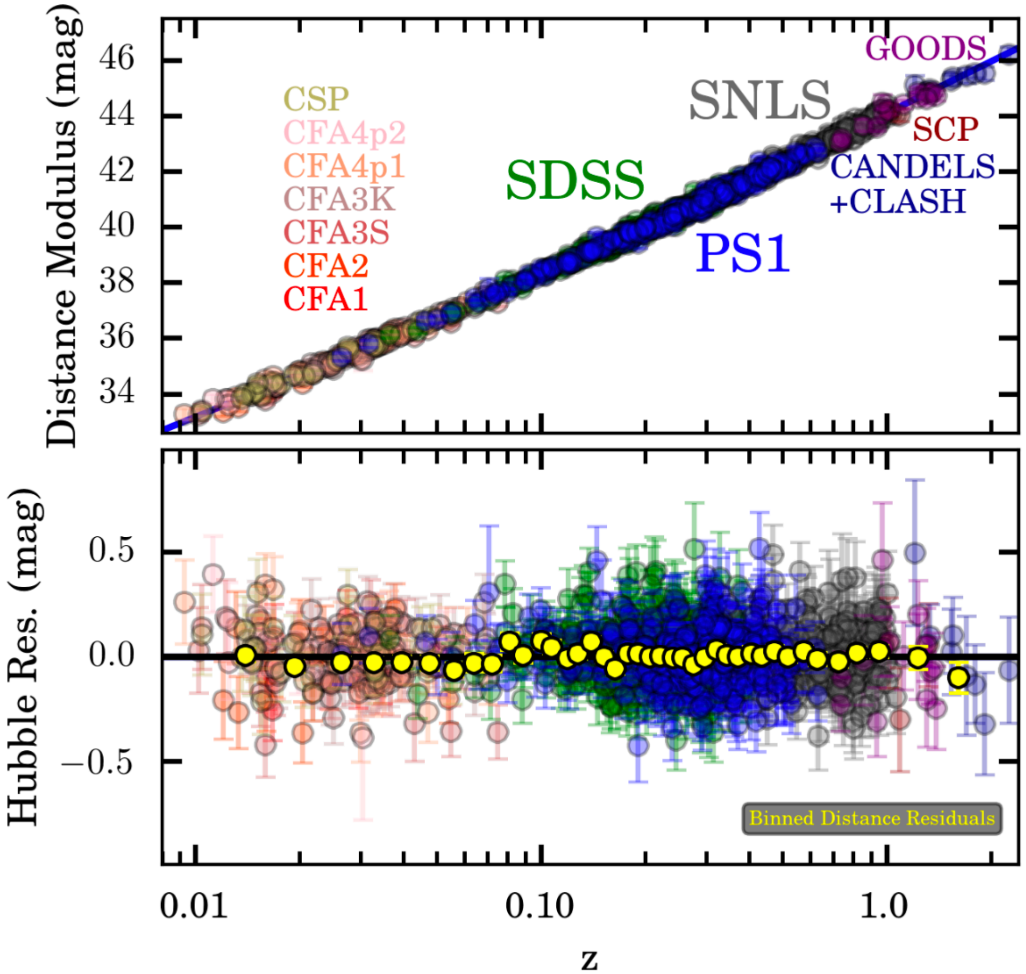

CAASTRO
ALL-SKY ASTROPHYSICS


CAASTRO
ALL-SKY ASTROPHYSICS

ΛCDM confirmation (Standard rulers and candles)



eBOSS Collaboration (2020)

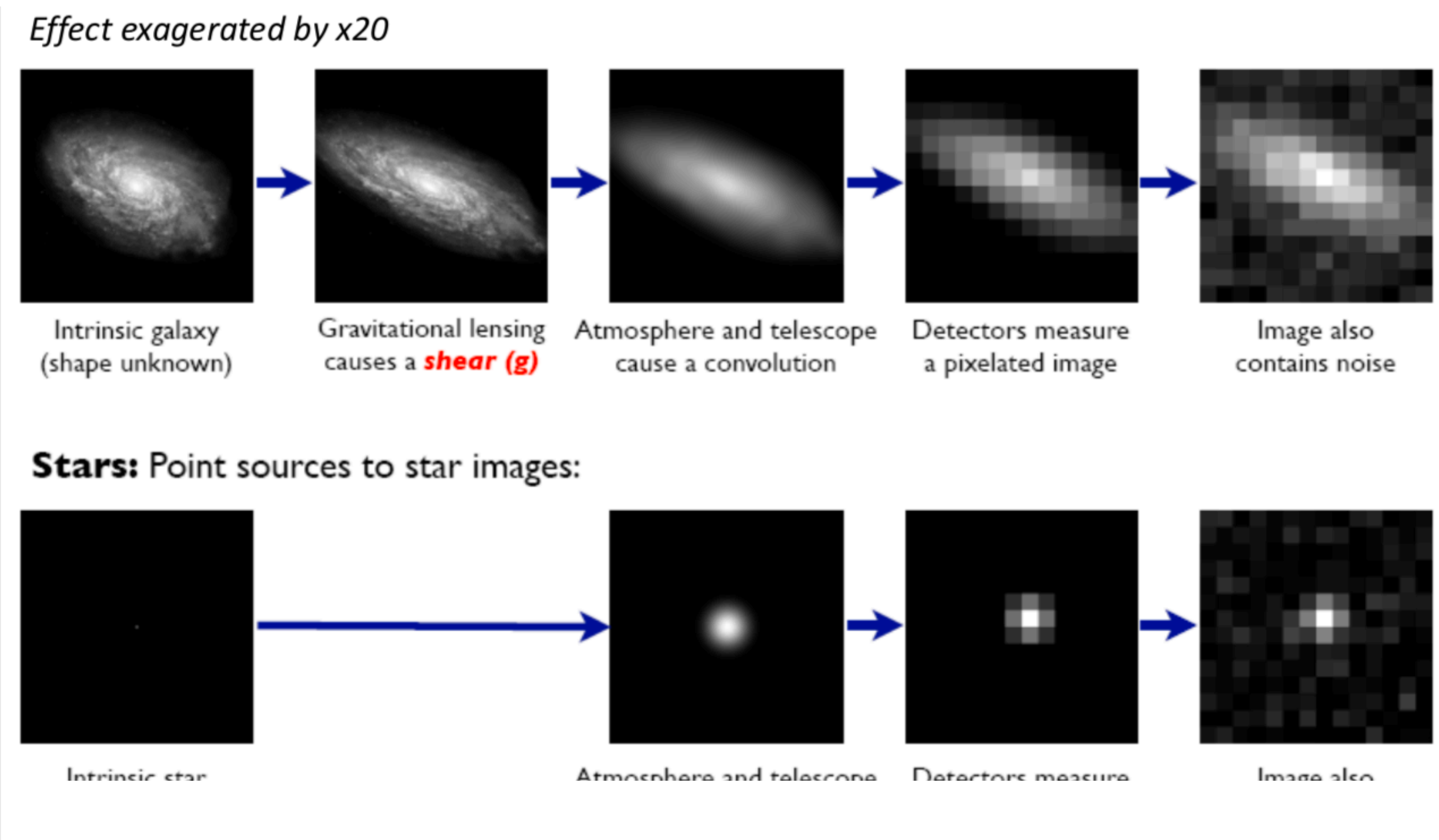


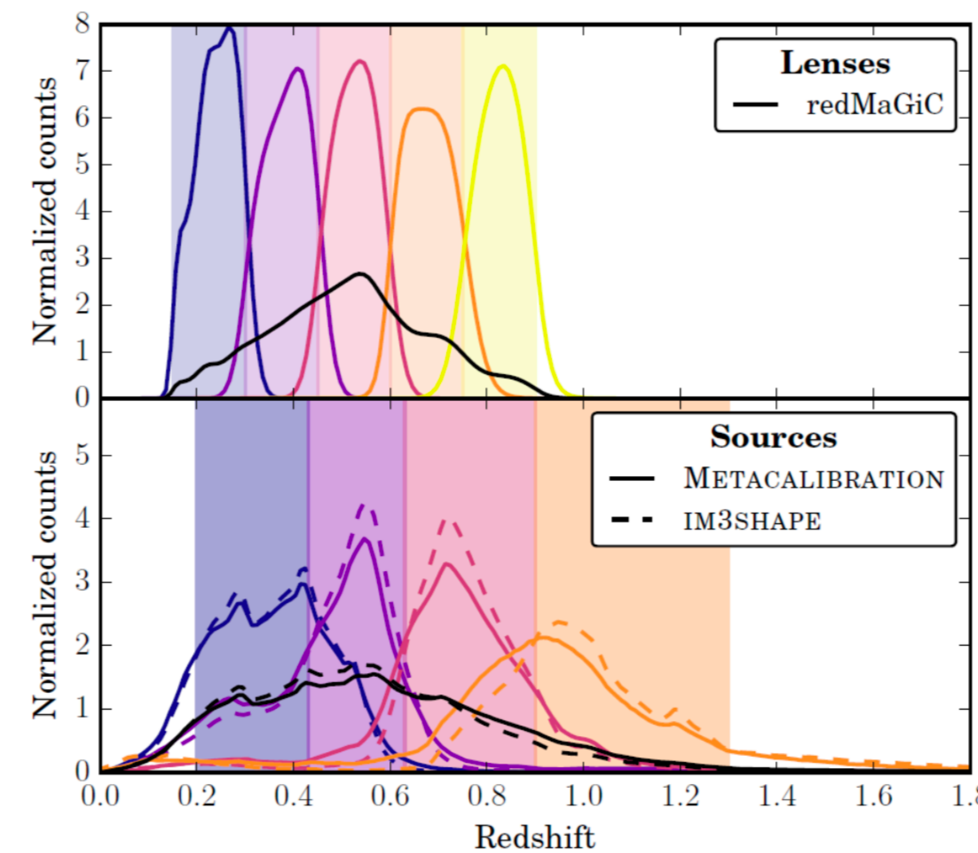
Scolnic et al. (2017)

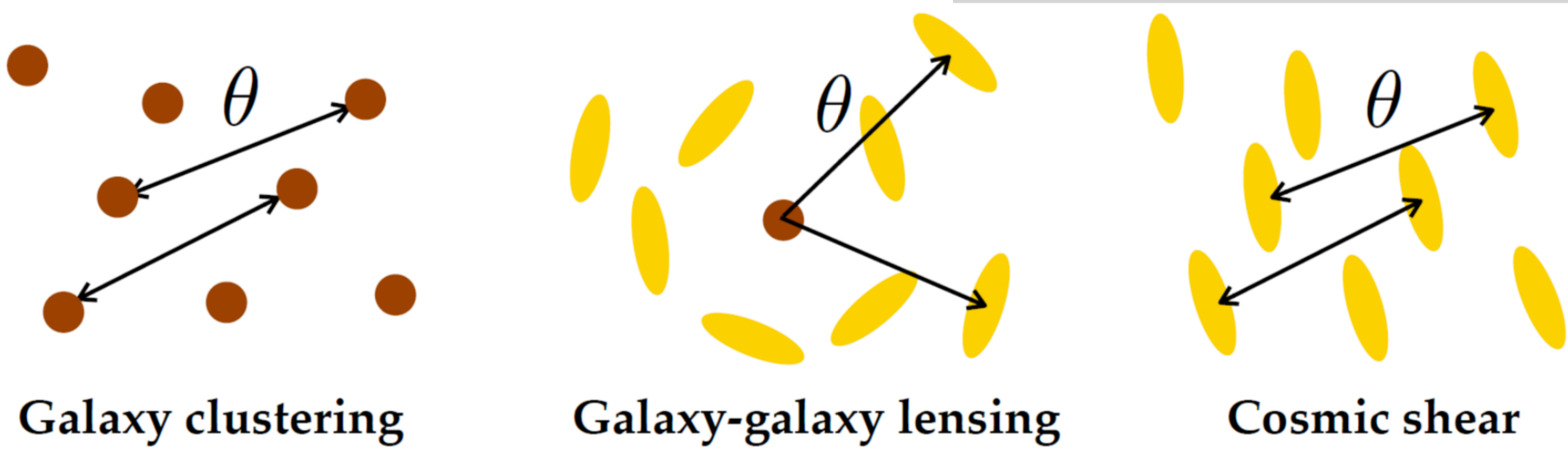
- Supernovae and Baryonic Acoustic Oscillations results are consistent with the ΛCDM.

3x2pt Weak Lensing

- Combined correlations of galaxy clustering and shear distortion caused by weak gravitational lensing







ΛCDM confirmation (3x2pt Weak Lensing)

- Weak lensing surveys are also supporting ΛCDM (3x2pt analysis)

Joint constraints

Combining all these data sets we find:

In ΛCDM:

$$S_8 = 0.812^{+0.008}_{-0.008} \quad (0.815)$$

$$\Omega_\mathrm{m} = 0.306^{+0.004}_{-0.005} \quad (0.306)$$

$$\sigma_8 = 0.804^{+0.008}_{-0.008} \quad (0.807)$$

$$h = 0.680^{+0.004}_{-0.003} \quad (0.681)$$

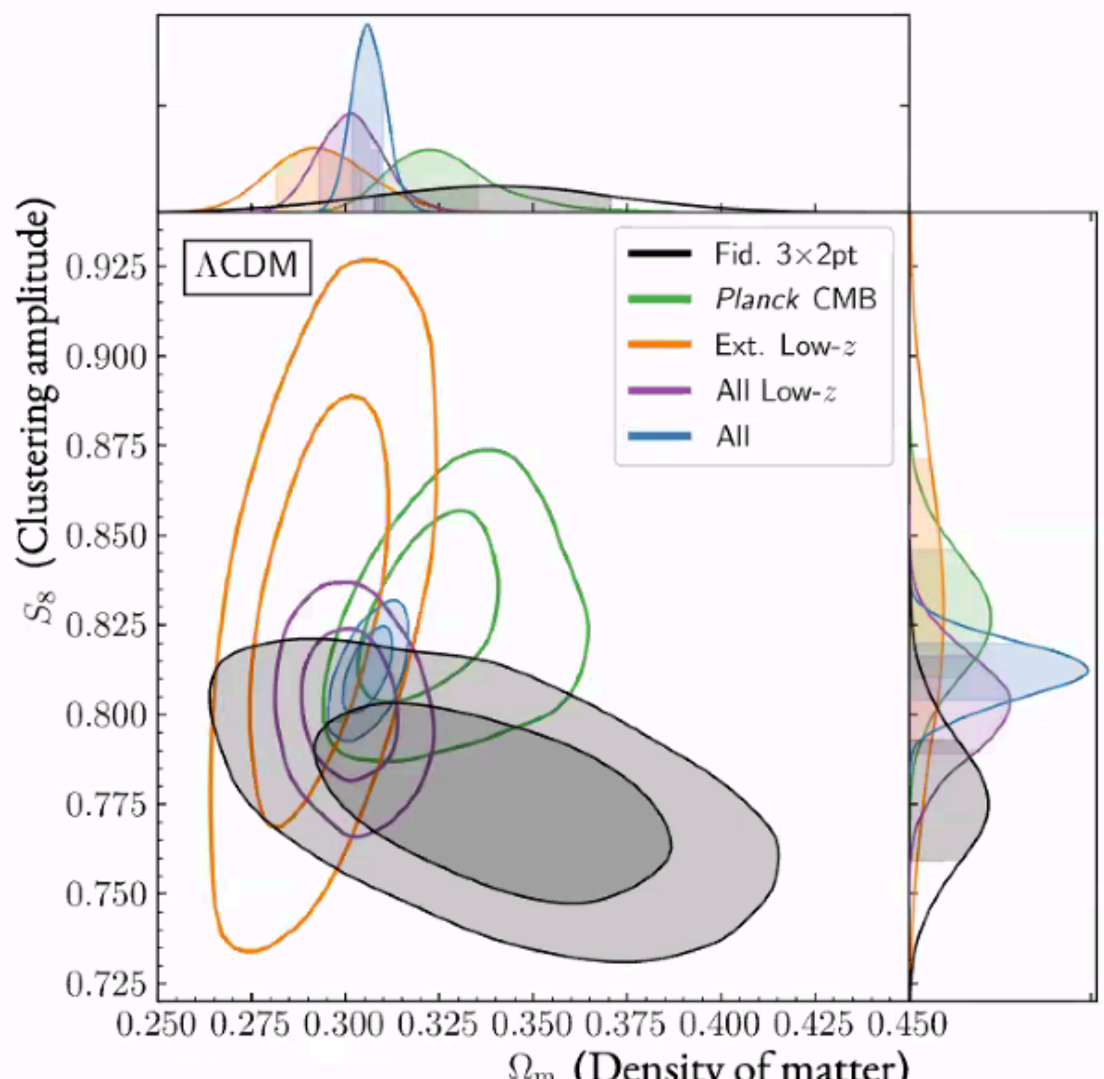
$$\sum m_\nu < 0.13 \text{ eV } (95\% \text{ CL})$$

In wCDM:

$$\sigma_8 = 0.810^{+0.010}_{-0.009} \quad (0.804)$$

$$\Omega_\mathrm{m} = 0.302^{+0.006}_{-0.006} \quad (0.298)$$

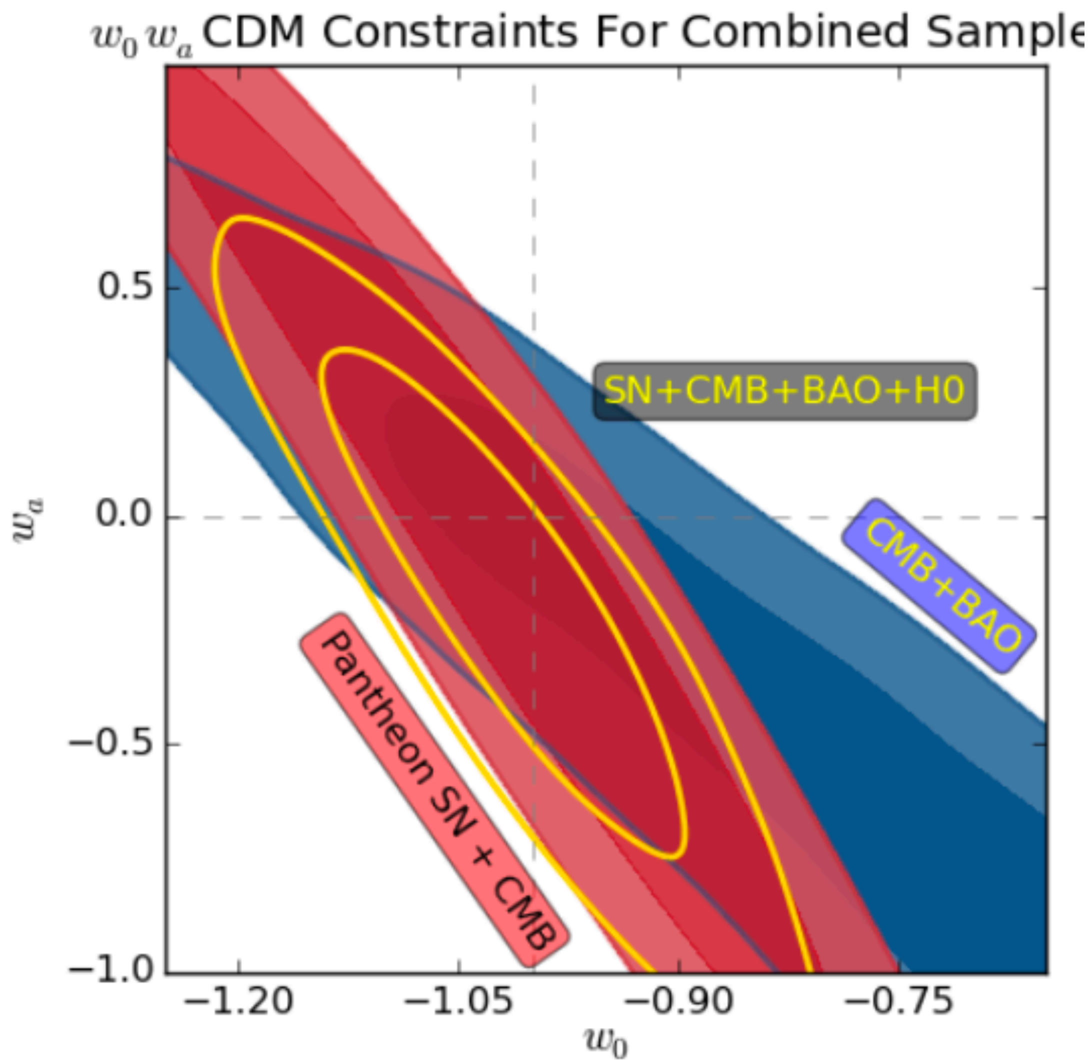
$$w = -1.03^{+0.03}_{-0.03} \quad (-1.00)$$



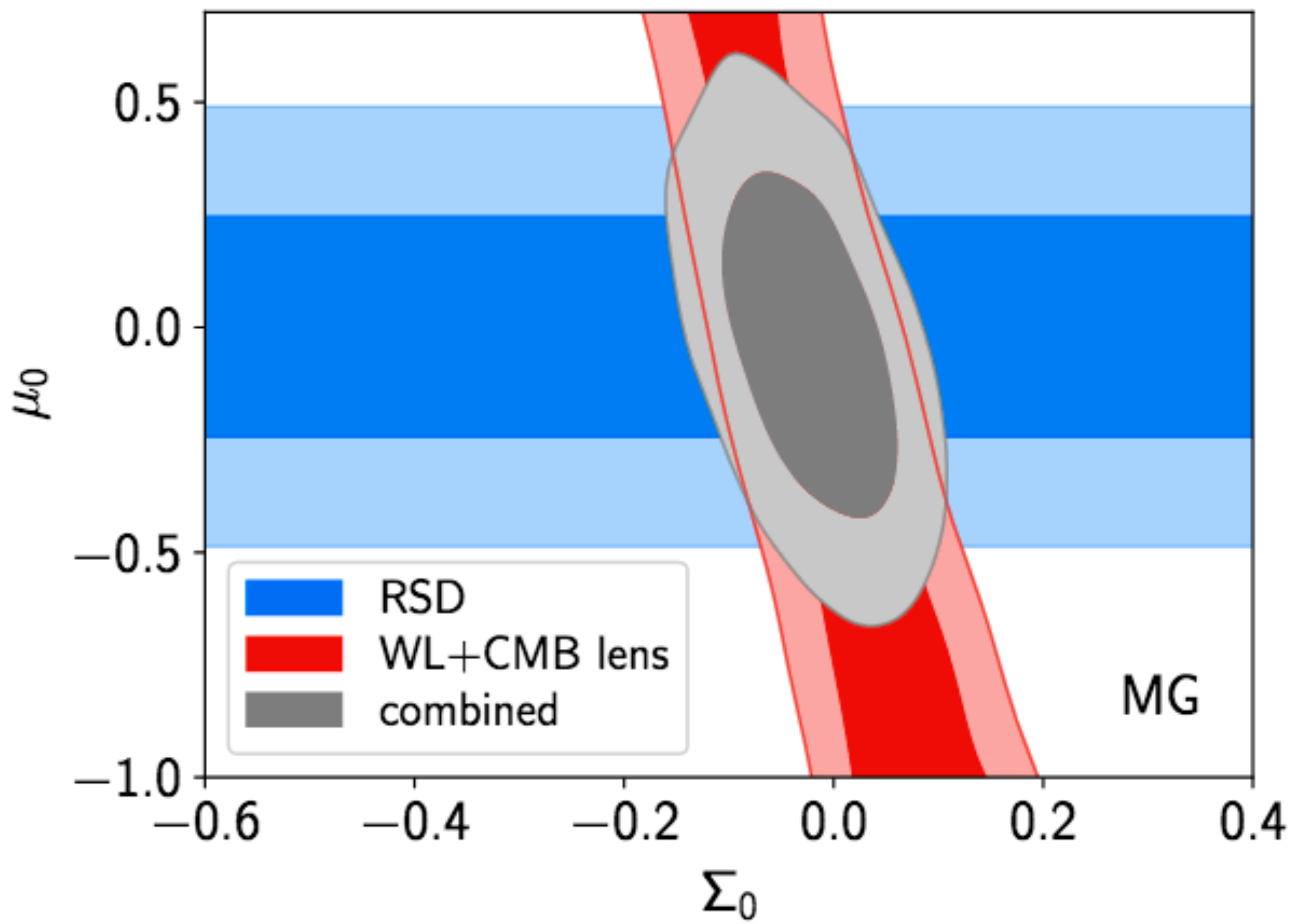
70

DES Collaboration (2021)

Modelling DE



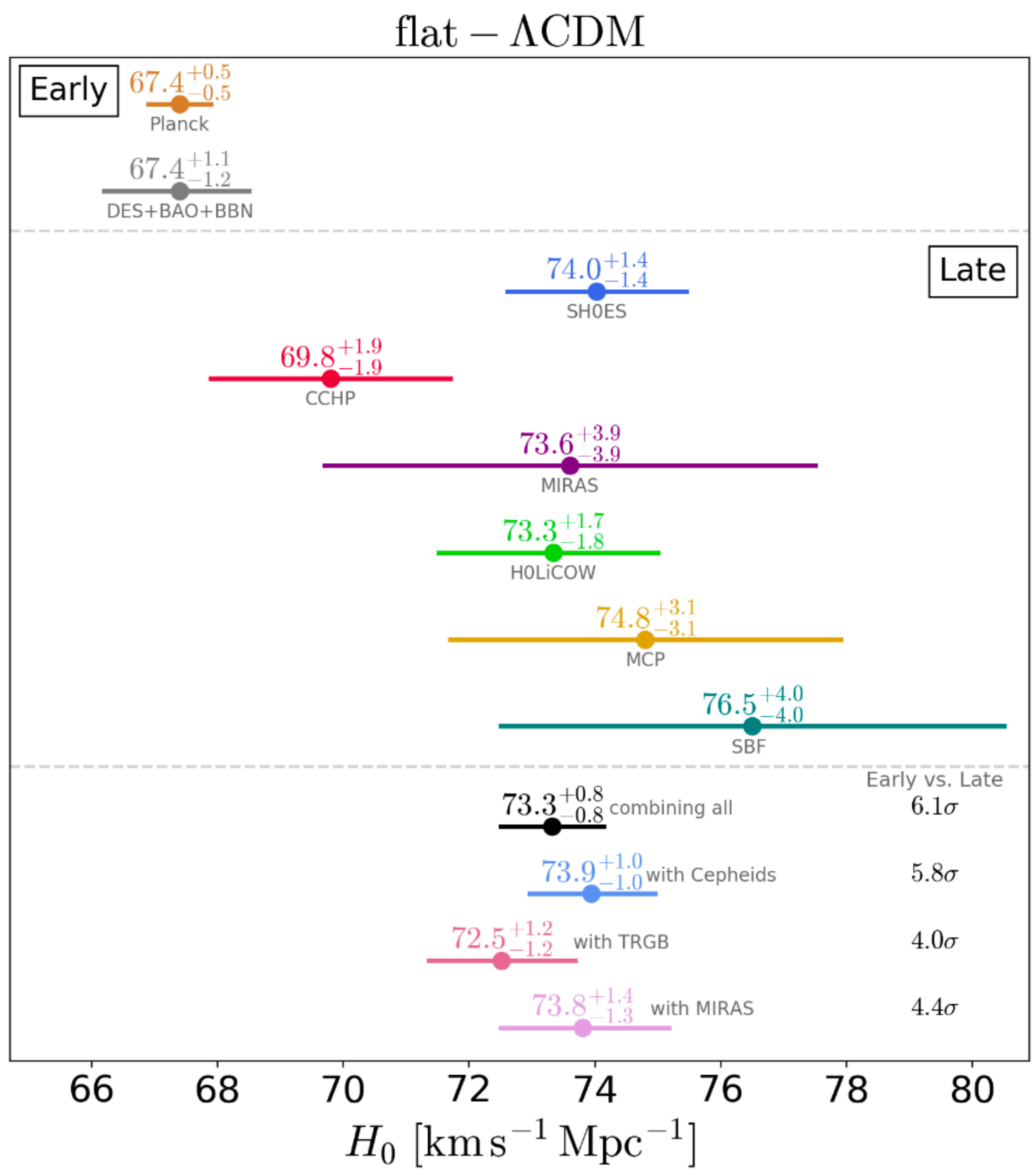
Scolnic et al. (2017)



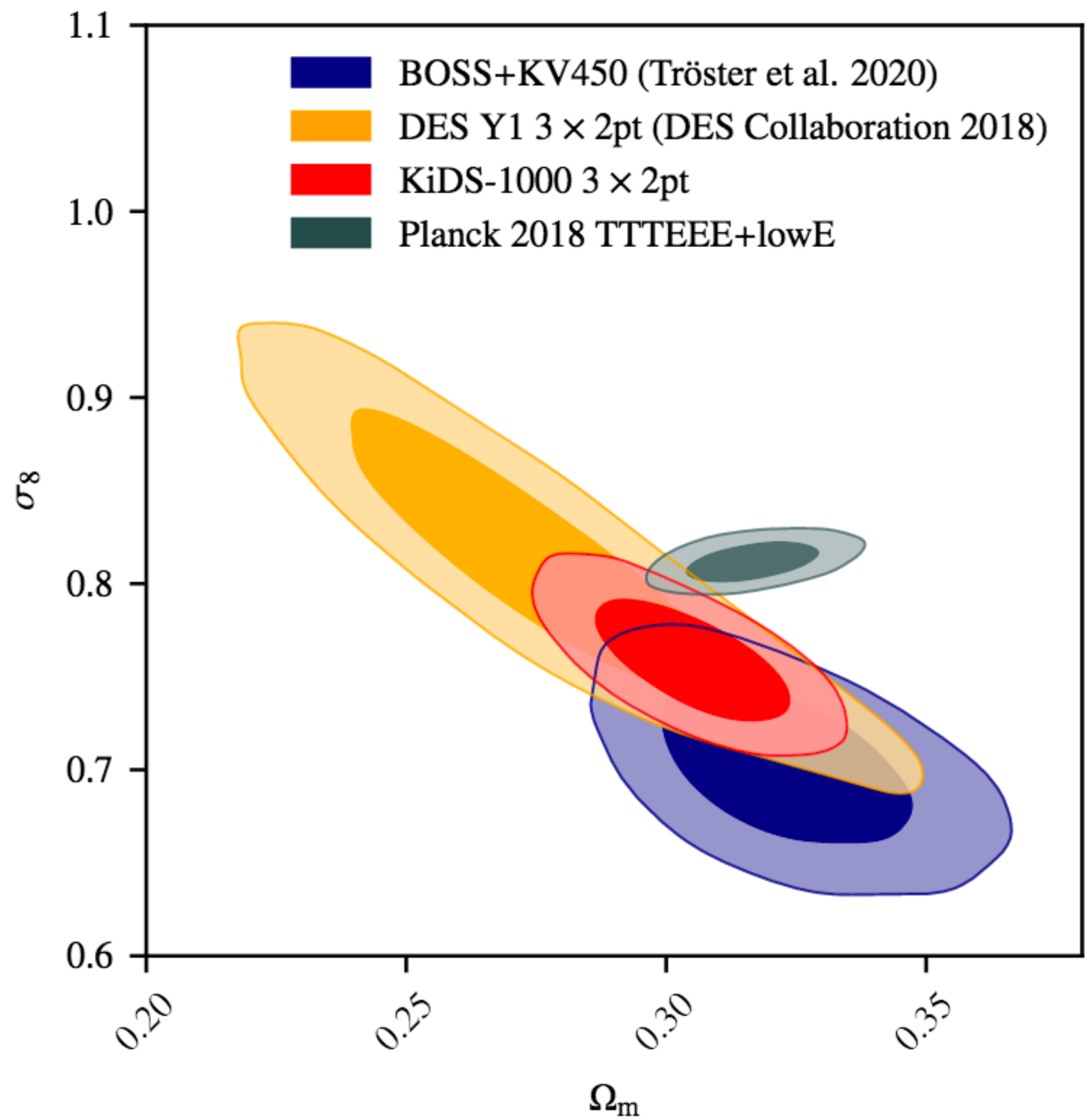
eBOSS Collaboration (2020)

- Evolution of the equation of state of DE and deviations of GR are not favoured by the data.

Tensions: New Physics or systematics?

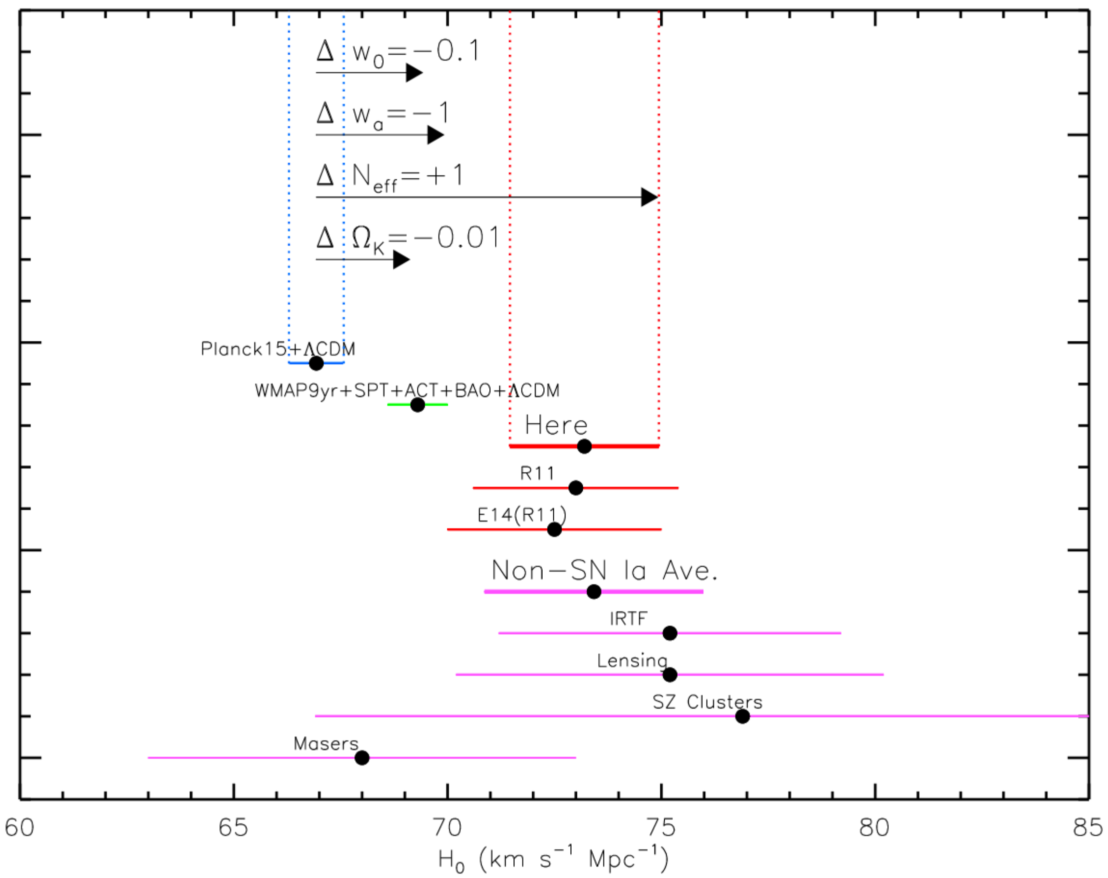


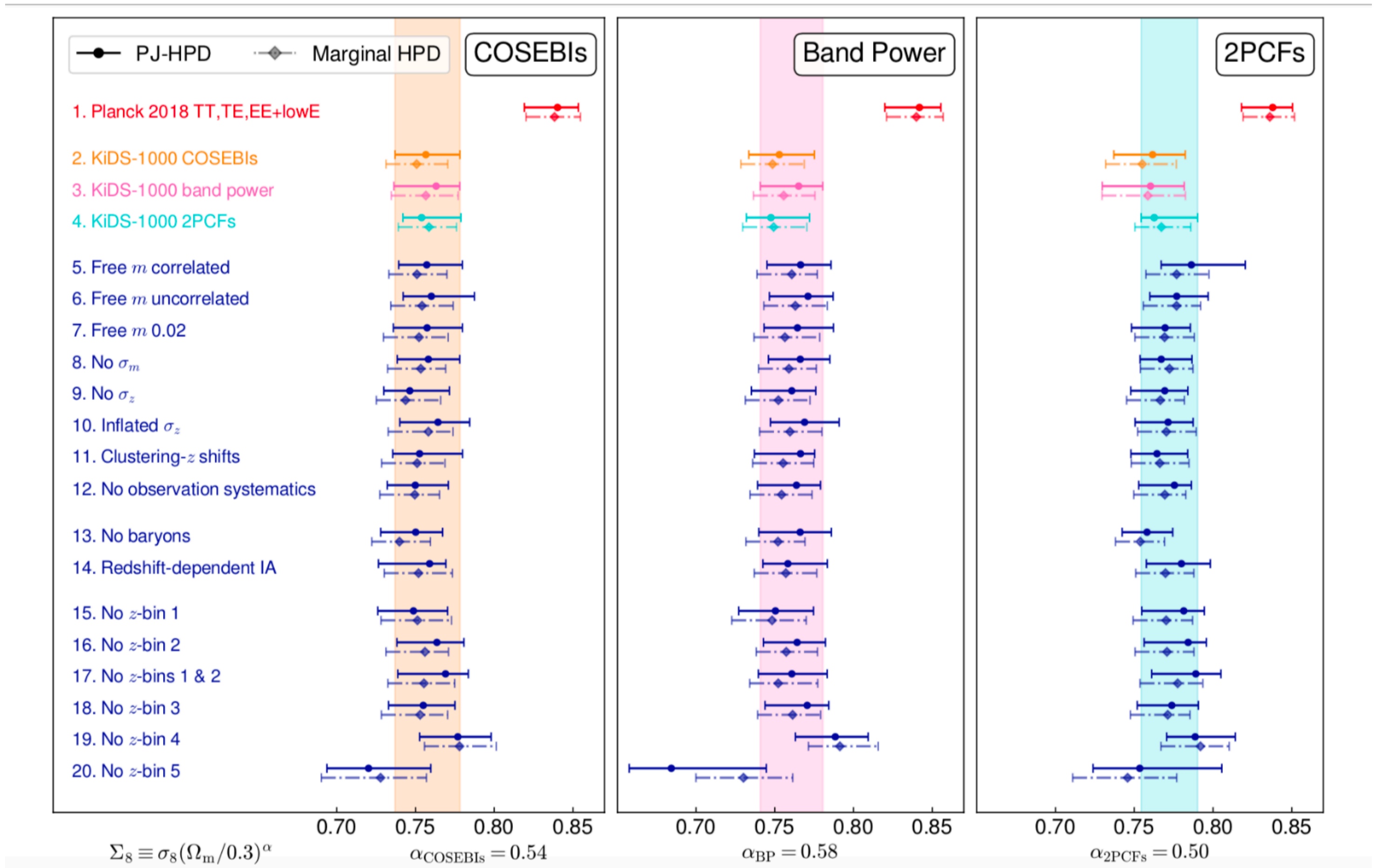
Verde, Riess, Treu (2019)



Heynmans et al. (2020)

Tensions: New Physics or systematics?





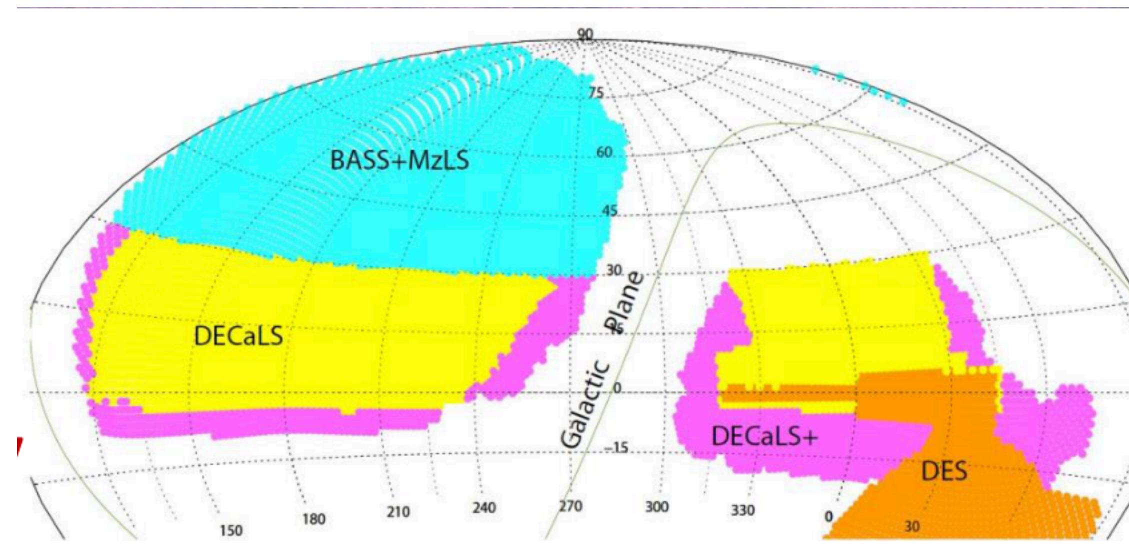
Riess et al. (2016)

Asgari et al. (2020)

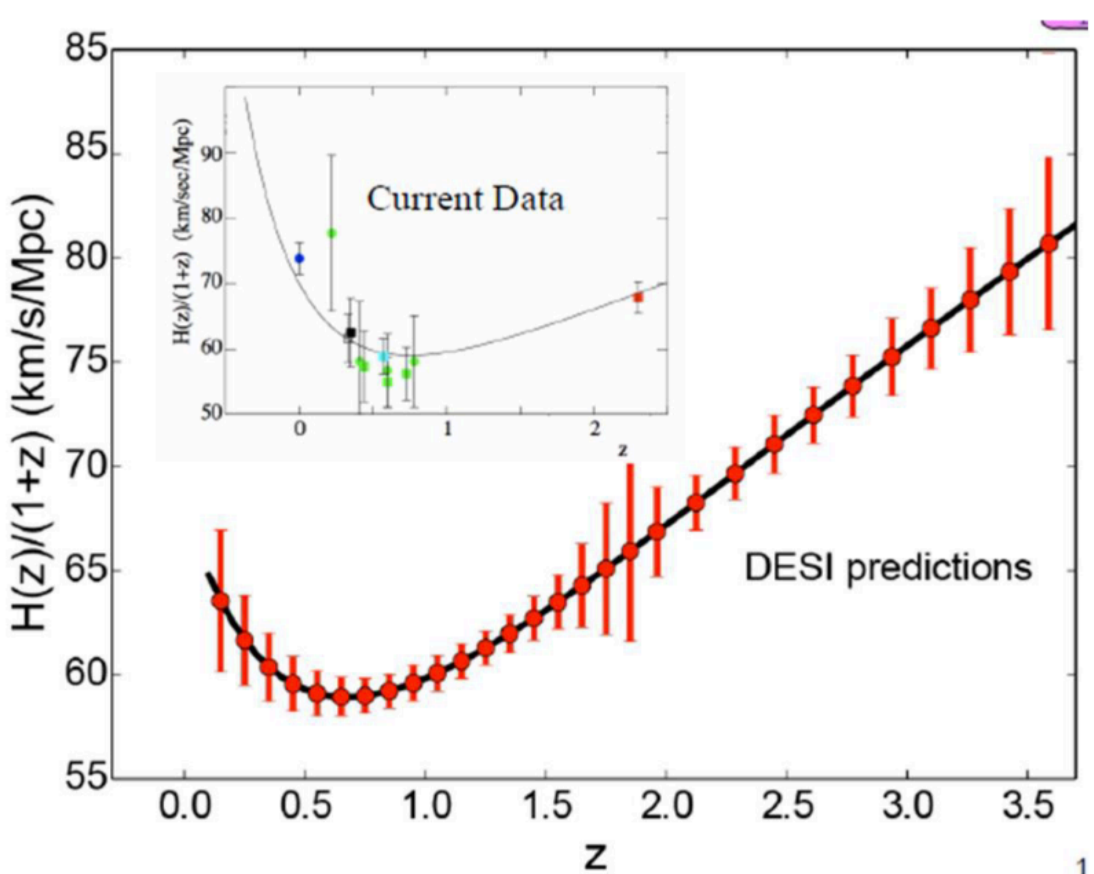
- Simple model extensions or current checks on systematics are alleviating the tension.

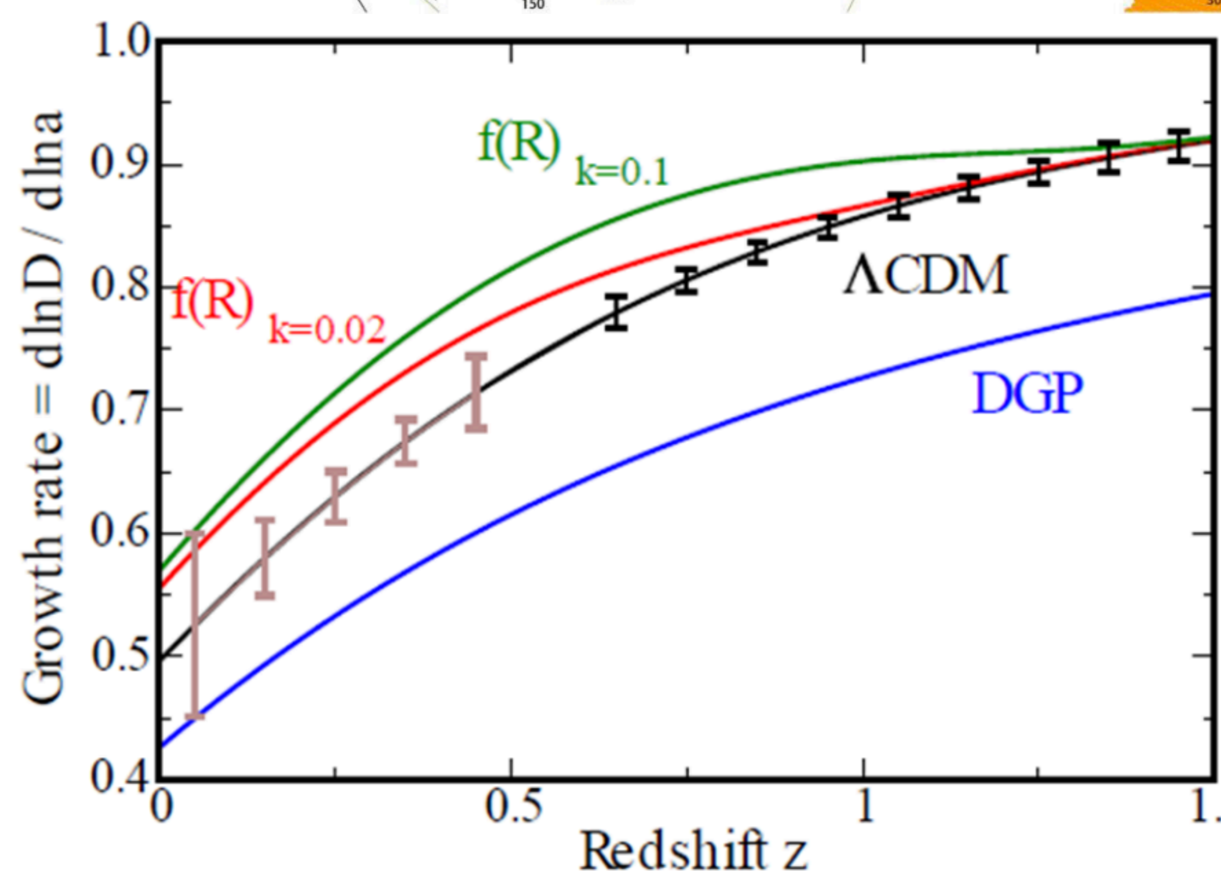
Dark Energy Spectroscopic Instrument (DESI)

DESI survey (@ 4m Mayall):
- 5000 fibre multi-object
- Footprint of 14000 sq. degs:
  - 35 million ELGs
  - 4 million LRGs
  - 2.4 million QSOs



- DESI will measure the BAO with 0.3%
- Growth factor: 1% precision.
- Perfect for LCDM discrimination

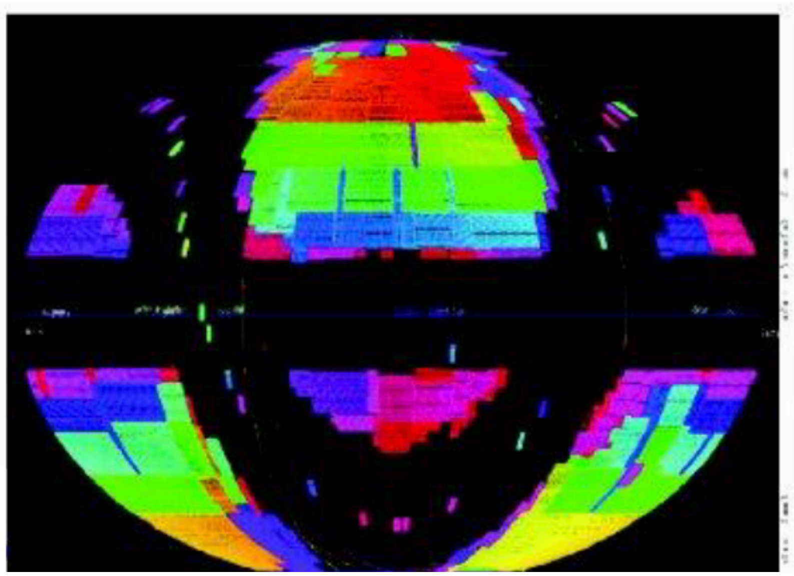




Future of optical surveys

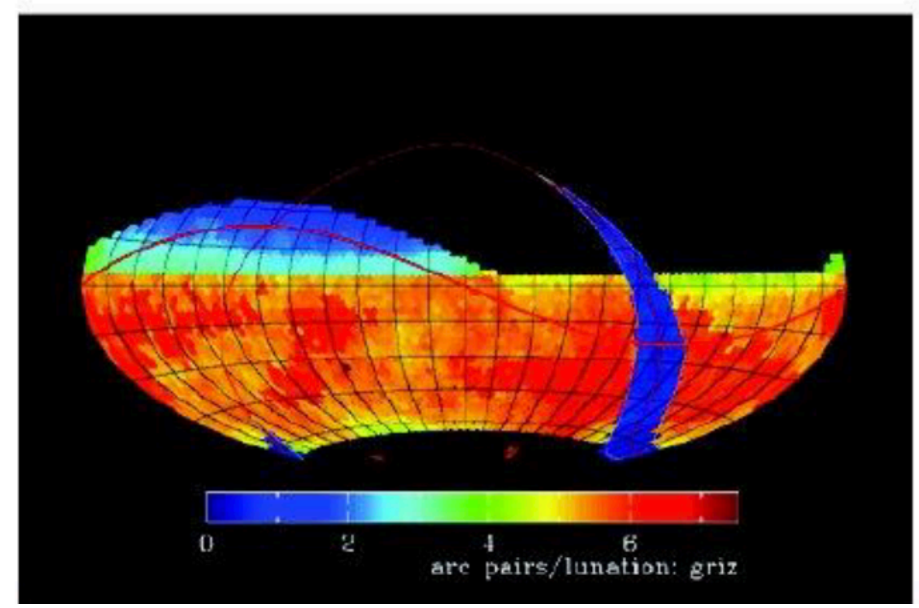
Euclid Consortium

FoM ~ 1500 , -4000 (all)
Main probes: WL & Galaxie clustering (BAO,RSD) (spectro))
European lead project / ESA
Participation of NASA
~ 1000 members
Space telescope / 1.2 m mirror
Launch : **Q4 2023**
Mission length : 6 years
1 exposure depth : 24 mag
Survey Area : 15 000 sq deg (.36 sky)
Filters : 1 Visible(550-900nm)+ 3 IR (920-2000 nm) + NIR spectroscopy (1100 – 2000 nm)

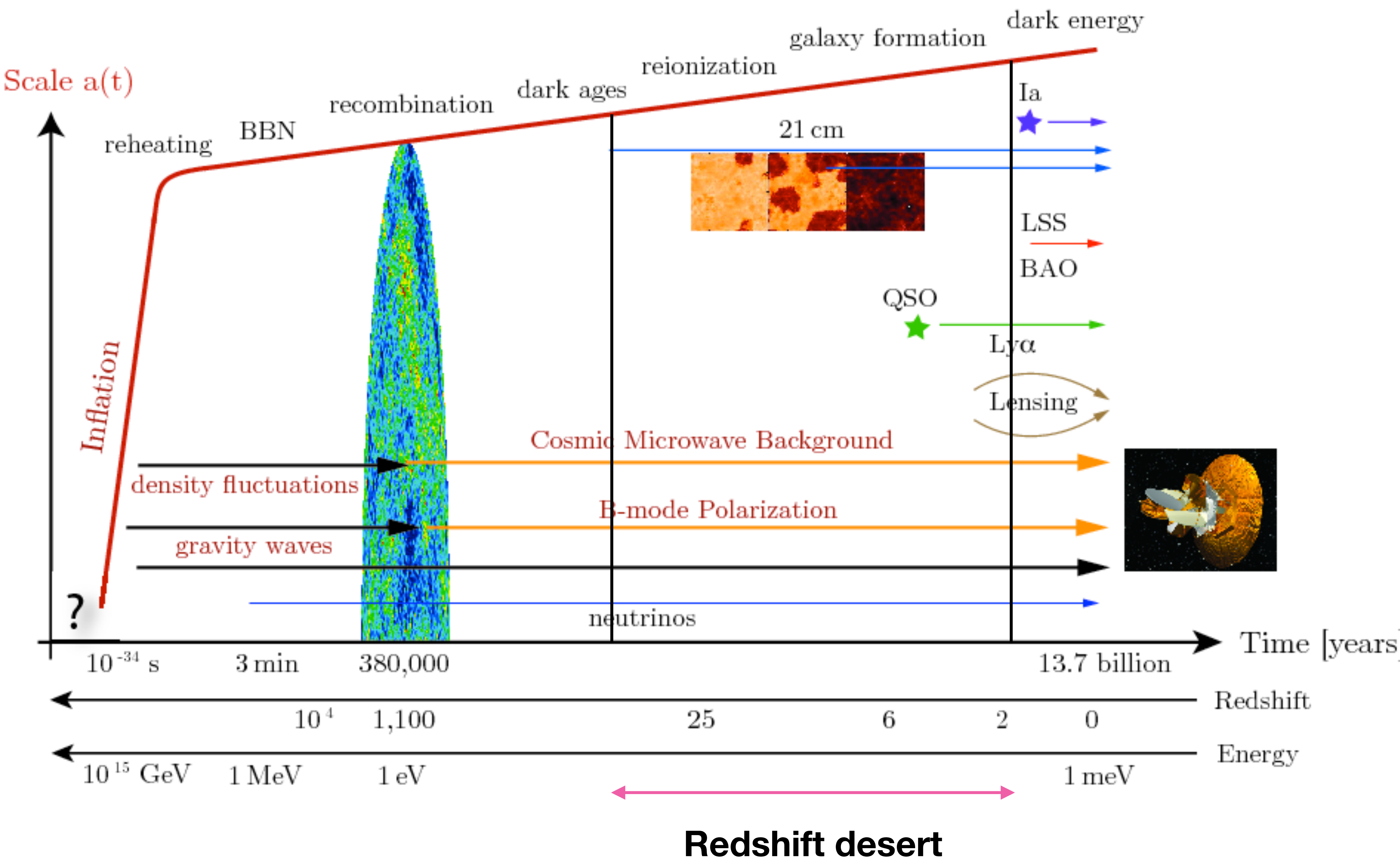


LSST – Large Synoptic Survey Telescope

FoM > 800
Main probes : **WL, CL, SN, BAO (photo)…**
US lead project / NSF-DOE
Participation of France/In2P3
~ 450 Core members + 450 to come
Ground Telescope / 6.5 m effective mirror
1st light : **2023**
Observation length : 10 years
1 exposure depth : 24 mag (i)
Survey Area : 20 000 sq dg (.48 sky)
Filters : 6 filters (320-1070 nm)

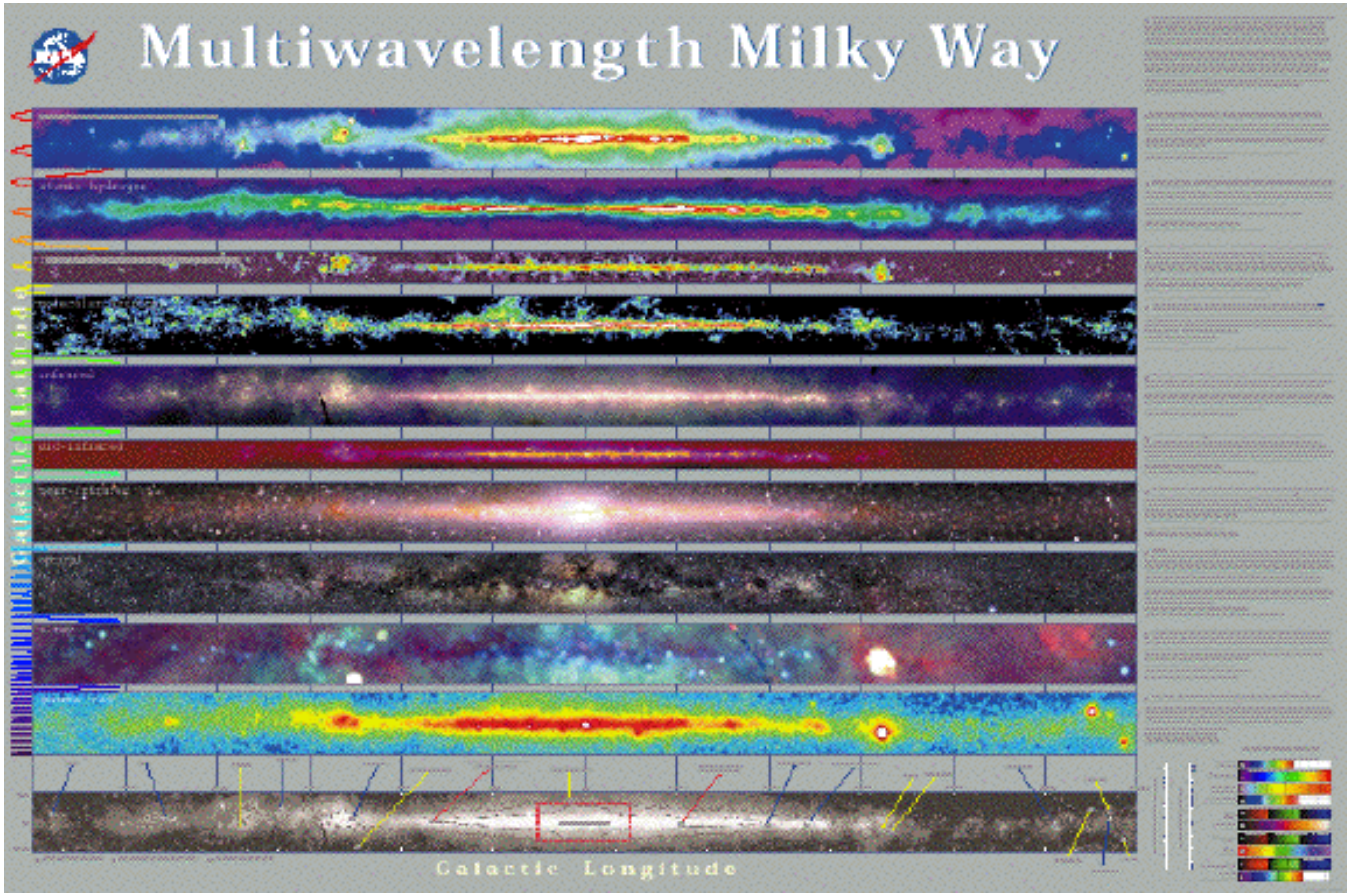


“The redshift desert”



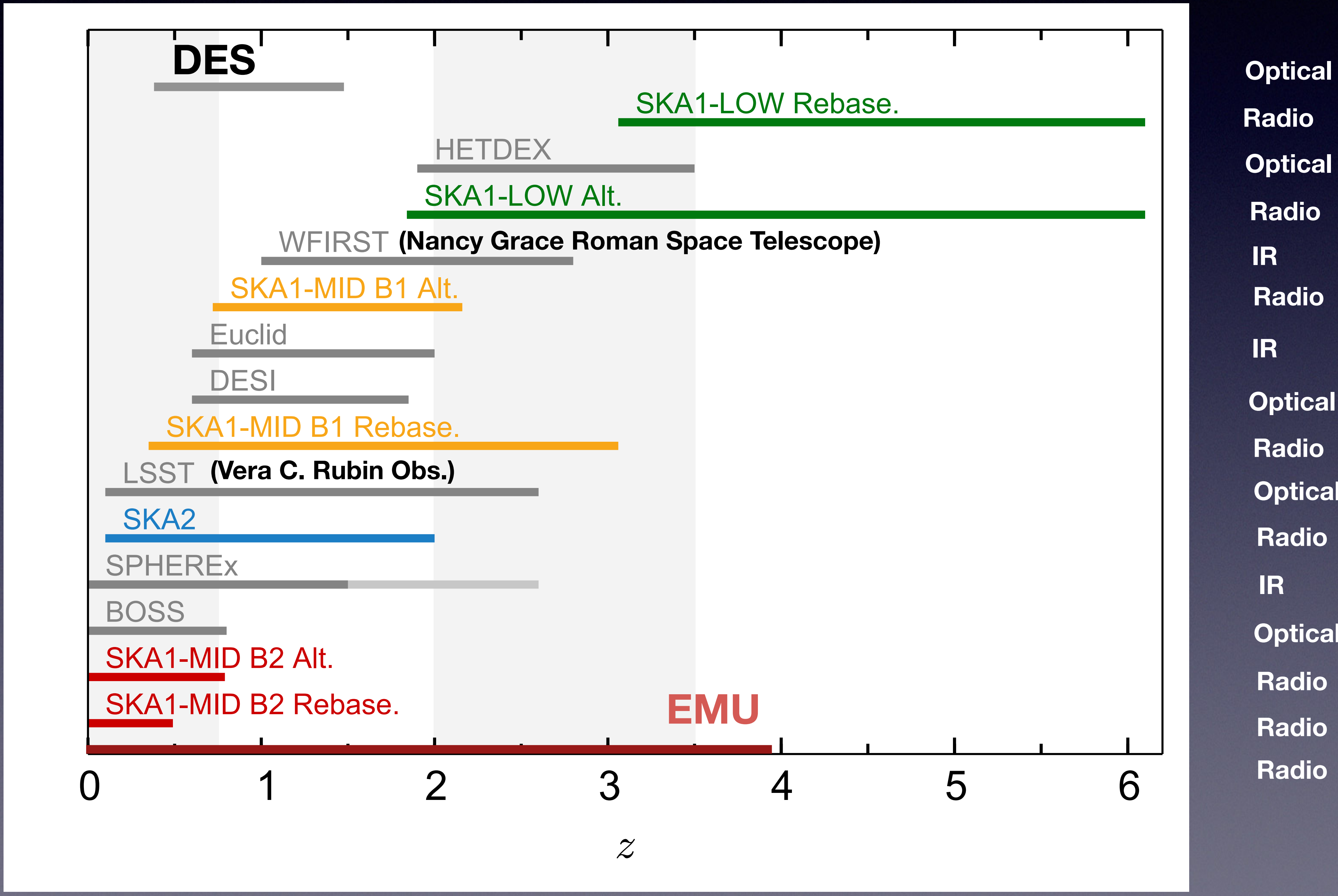
- We need to access higher redshifts in order to complete the picture.

Beyond optical …



Sampling the redshift desert

- In the near future, we will sample the "redshift desert" with different missions and surveys.



Bull (2016)

Radio Cosmology

HI galaxy

(like spectroscopic surveys)

[e.g., HIPASS, ALFALFA]

Continuum galaxy

(like photometric) surveys)

[e.g., EMU]

HI intensity mapping

(like 3D CMB)

[e.g., CHIME, TIANLAI]

Radio Cosmology

HI galaxy

(like spectroscopic surveys)

[e.g., HIPASS, ALFALFA]

Continuum galaxy

(like photometric) surveys)

[e.g., EMU]

HI intensity mapping

(like 3D CMB)

[e.g., CHIME, TIANLAI]

Radio Cosmology

HI galaxy

(like spectroscopic surveys)

[e.g., HIPASS, ALFALFA]

Continuum galaxy

(like photometric) surveys)

[e.g., EMU]

HI intensity mapping

(like 3D CMB)

[e.g., CHIME, TIANLAI]

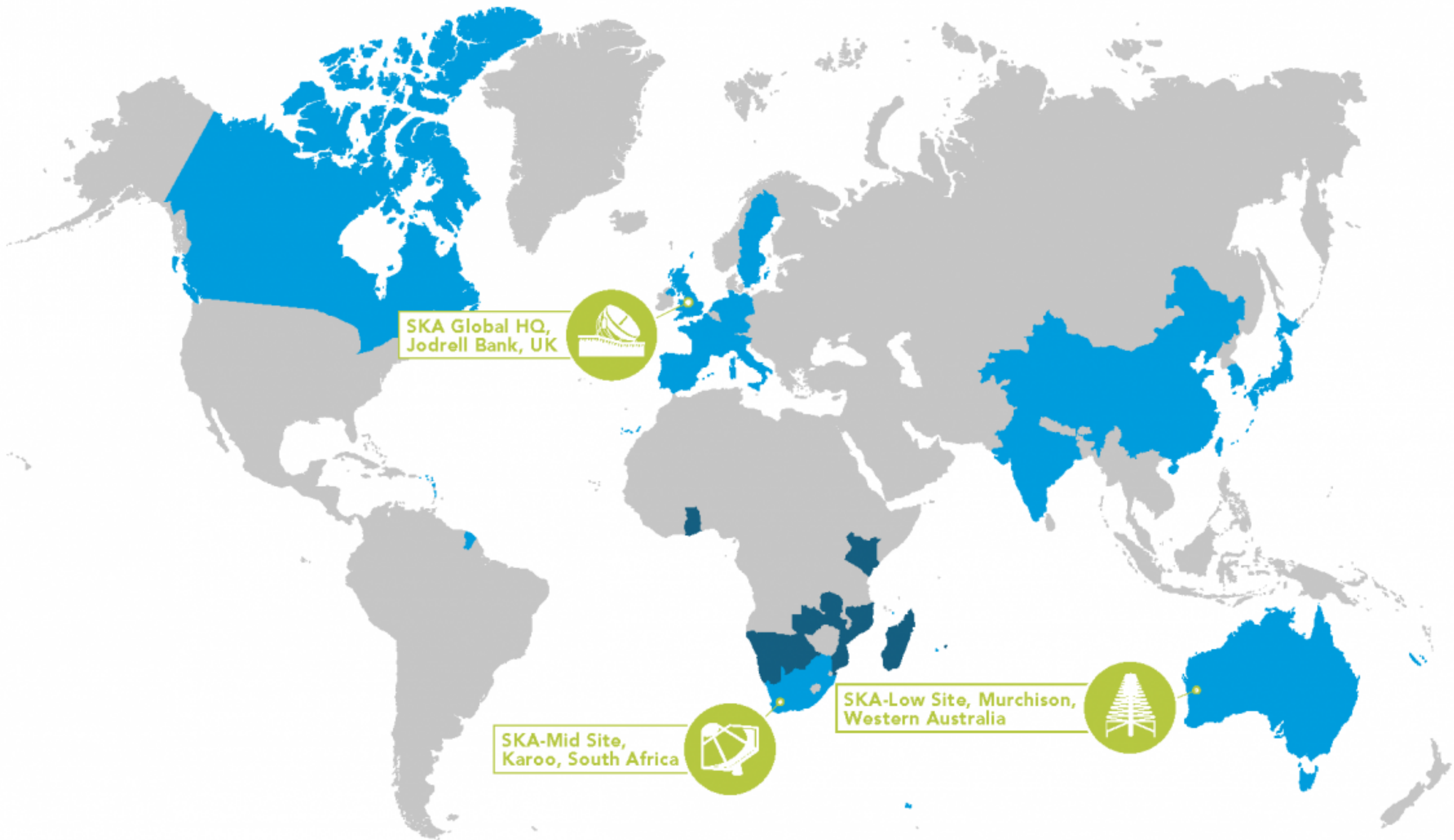
Radio Cosmology

HI galaxy
(like spectroscopic surveys)
[e.g., HIPASS, ALFALFA]

Continuum galaxy
(like photometric) surveys)
[e.g., EMU]

HI intensity mapping
(like 3D CMB)
[e.g., CHIME, TIANLAI]

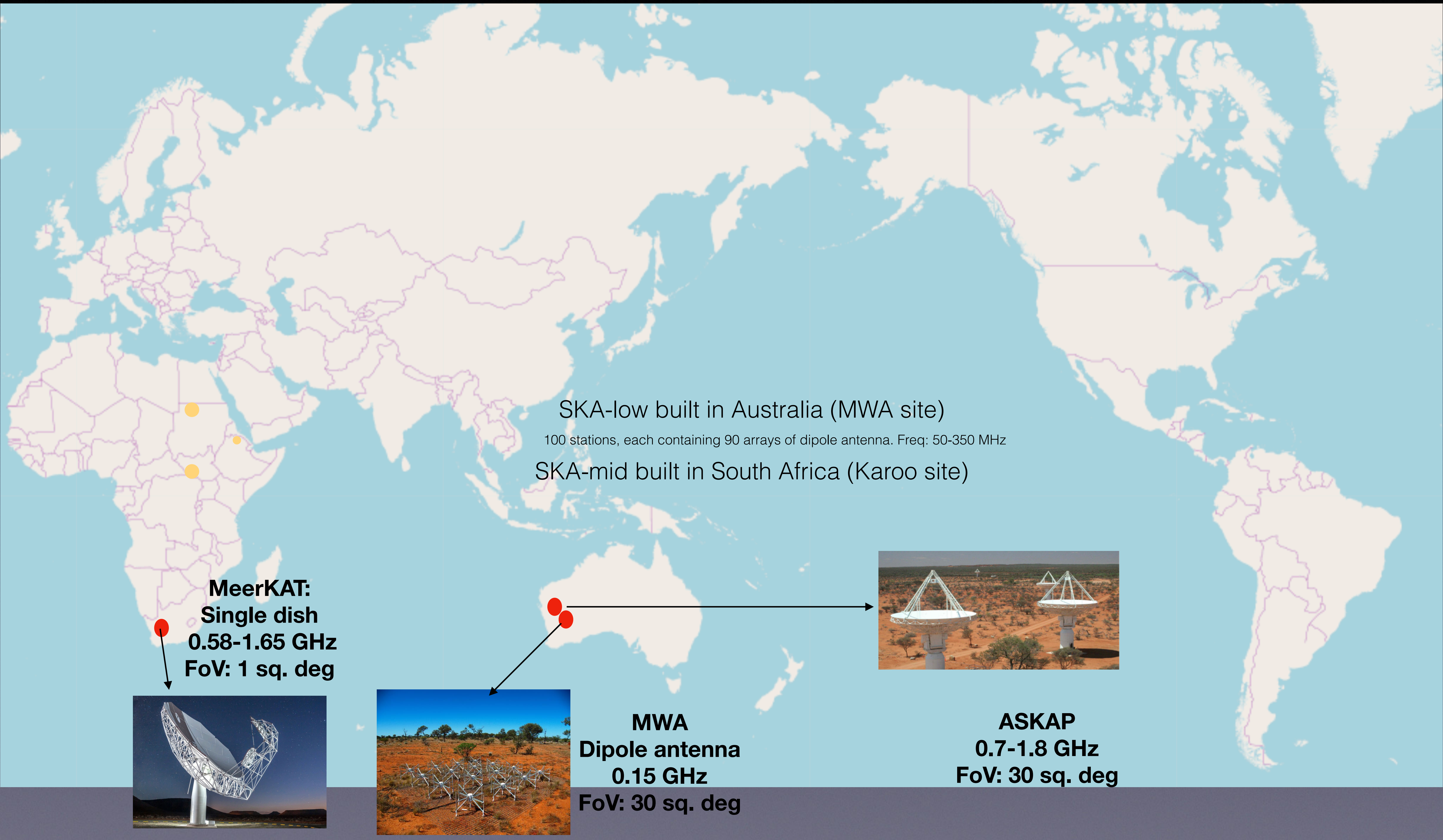
SKA Observatory (SKAO)



SKA Partners – includes Members of the SKA Organisation – precursor to the SKAO –, current SKAO Member States*, and SKAO Observers (as of June 2021)

African Partner Countries

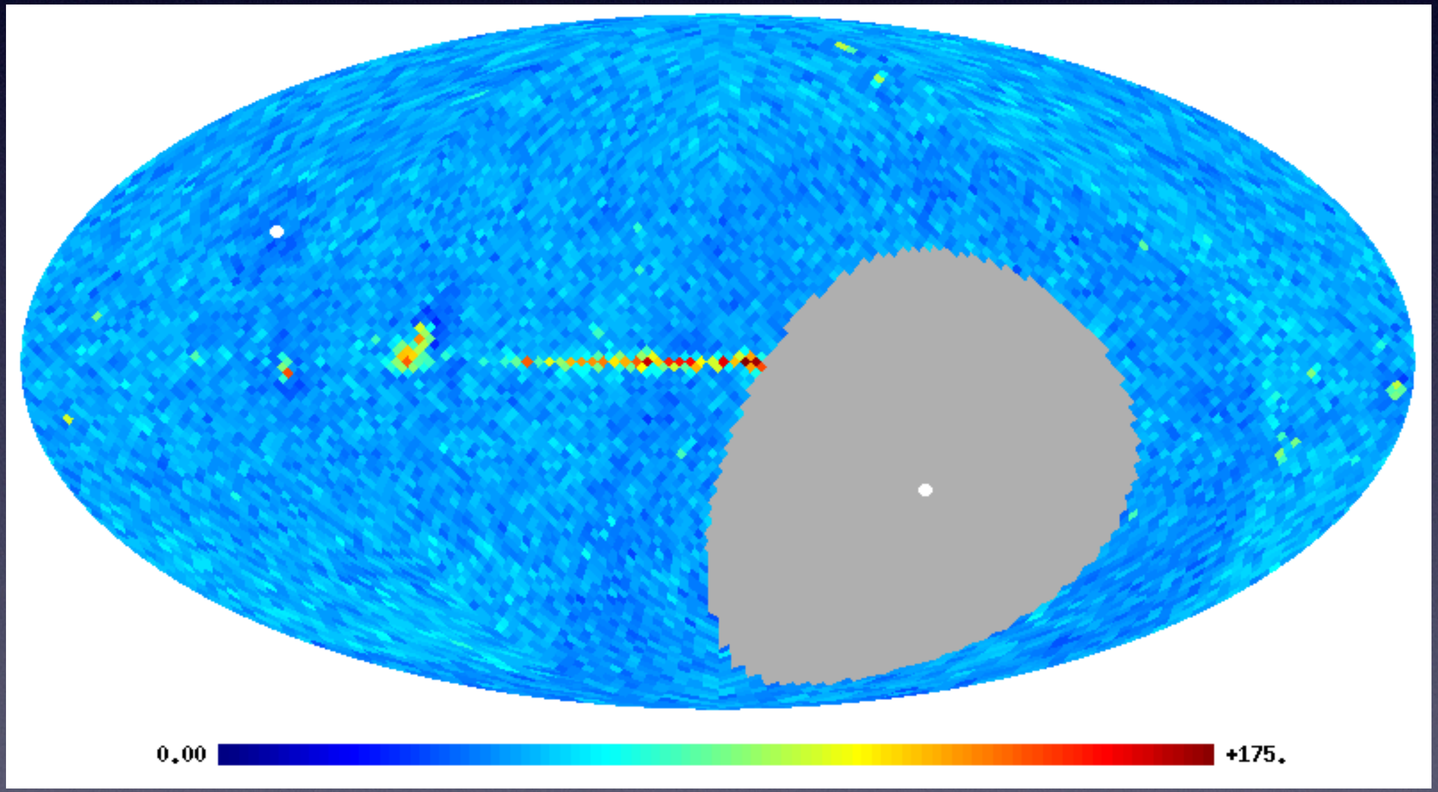
SKA precursors



Radio Continuum Surveys

- Continuum surveys measure intensity of total radio emission, across waveband
- Emission dominated by synchrotron, so spectrum (almost) featureless
- Measure **RA** and **Dec** of sources, but need other information for redshift

NVSS Healpix map



Chen & Schwartz (2016)

Australian Square Kilometre Array Pathfinder (ASKAP)

- 36 12-metre antennas spread over a region 6 km in diameter
- frequency band of 700–1800 MHz, with an instantaneous bandwidth of 300 MHz
- FoV ~ 30deg^2, pointing accuracy > 30 arcsec
- Angular resolution ~ 10 arcsec
- **75% of the time: Survey projects**

EMU: Continuum

RACS: Continuum

WALLABY: Spectroscopy 21cm

DINGO: HI evolution

POSSUM: MW magnetic fields

FLASH: HI absorption

CRAFT: Fast transients

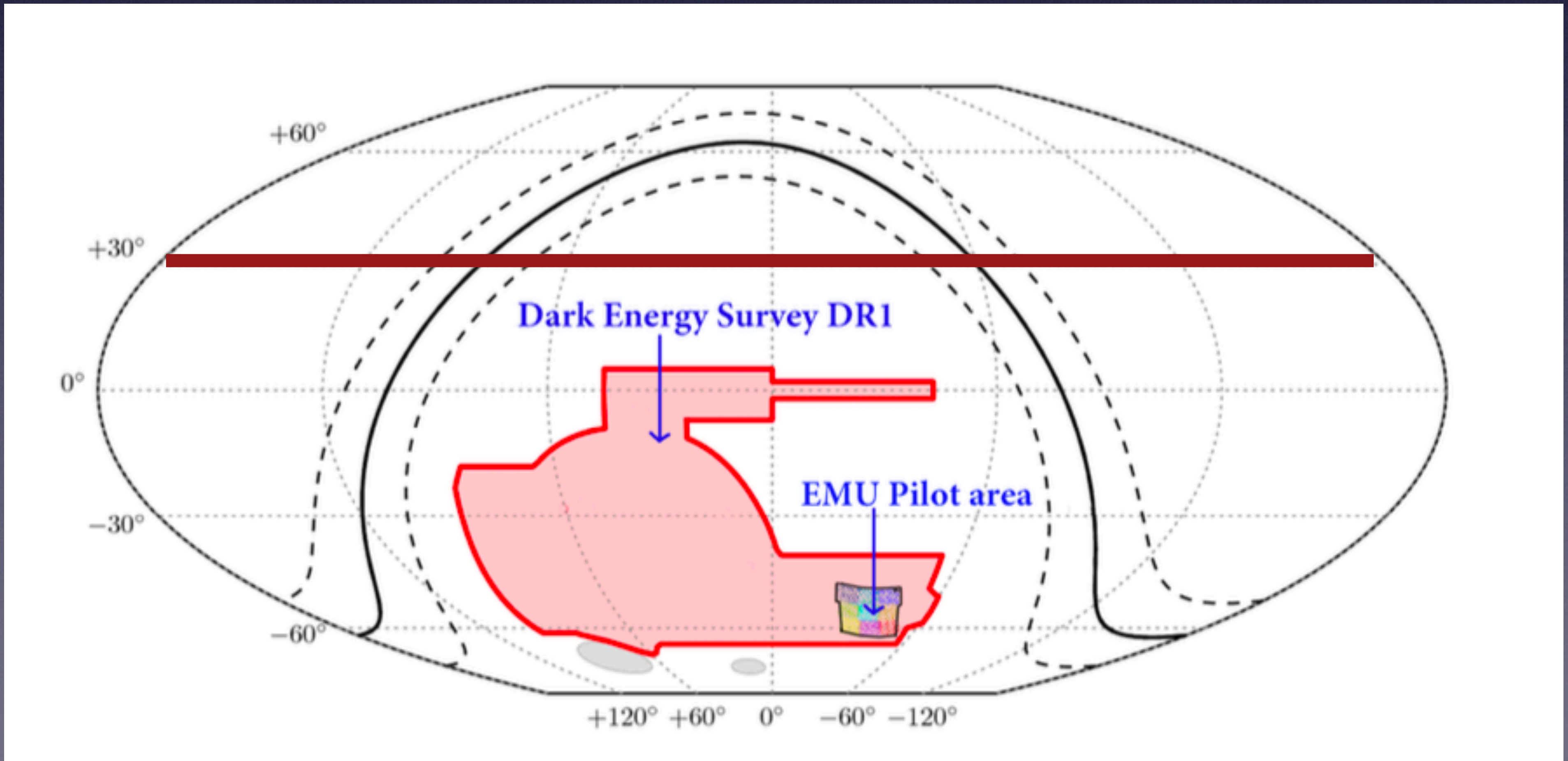
COAST: PTA

VAST: Slow transients

VLBI: long baseline

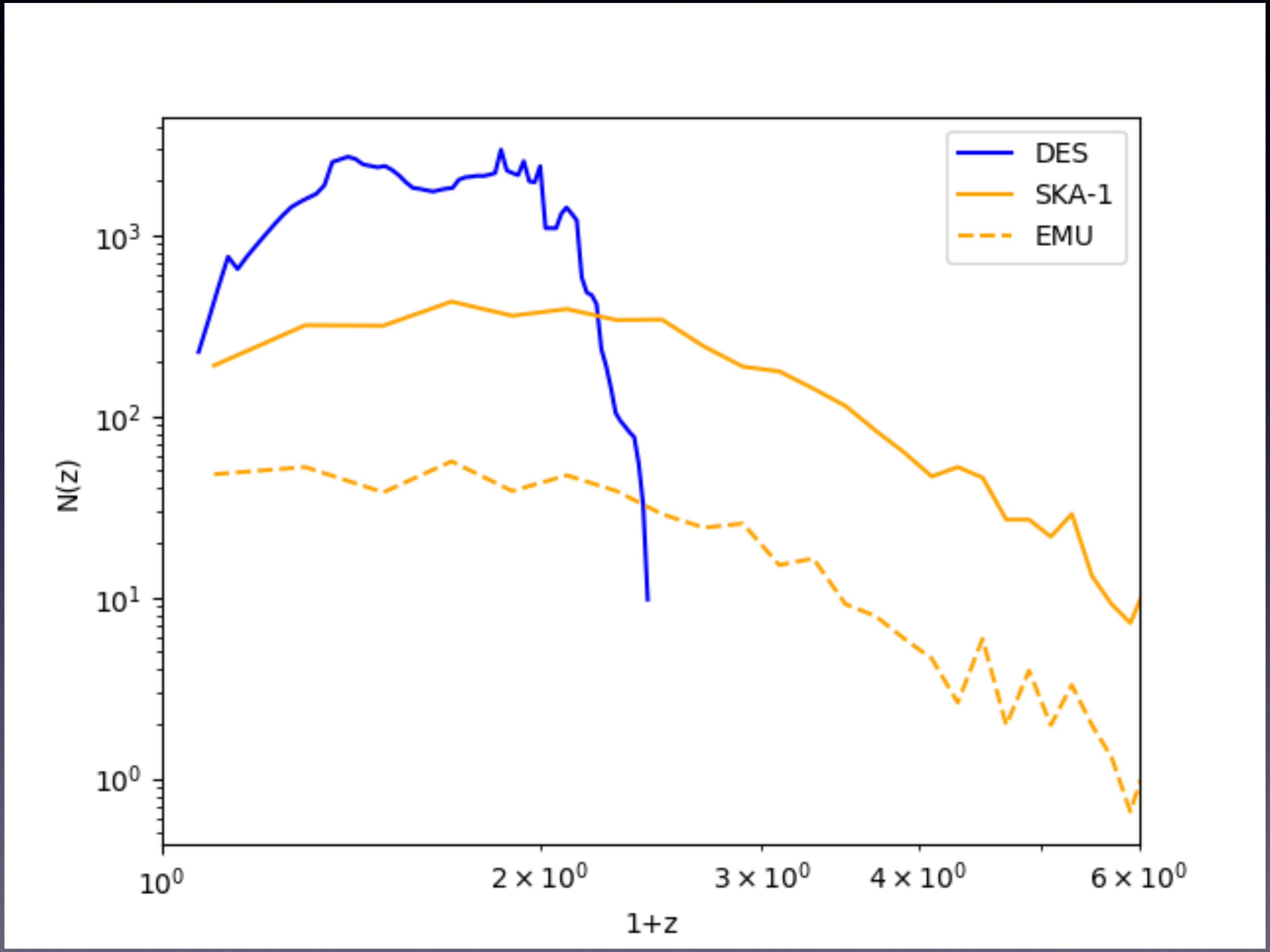
Evolutionary Map of the Universe (EMU)

- Main continuum survey with ASKAP
- Covering up to declination +30 degrees (30000 sq. deg)
- Expected noise of 15 μJy.
- Resolution of ~12″ to 15″ FWHM
- Expected 70 million sources



Long tail distributions

- Large-area and deep surveys give access to largest scales (modes larger than k_{eq}), both in radial and tangential directions
  - Early universe (non-Gaussianity)
  - Dark energy/modified gravity
  - large-scale features (dipole/anisotropy)



Cosmological observables

1. Angular correlation function of radio galaxies
2. Cosmic Magnification of high-z radio galaxies by low-z optical foreground galaxies
3. Cosmic Magnification of CMB by radio galaxies
   - Cross-correlation between radio density and CMB on small scales
4. Integrated Sachs-Wolfe effect
   - Cross-correlation between radio density and CMB on large scales

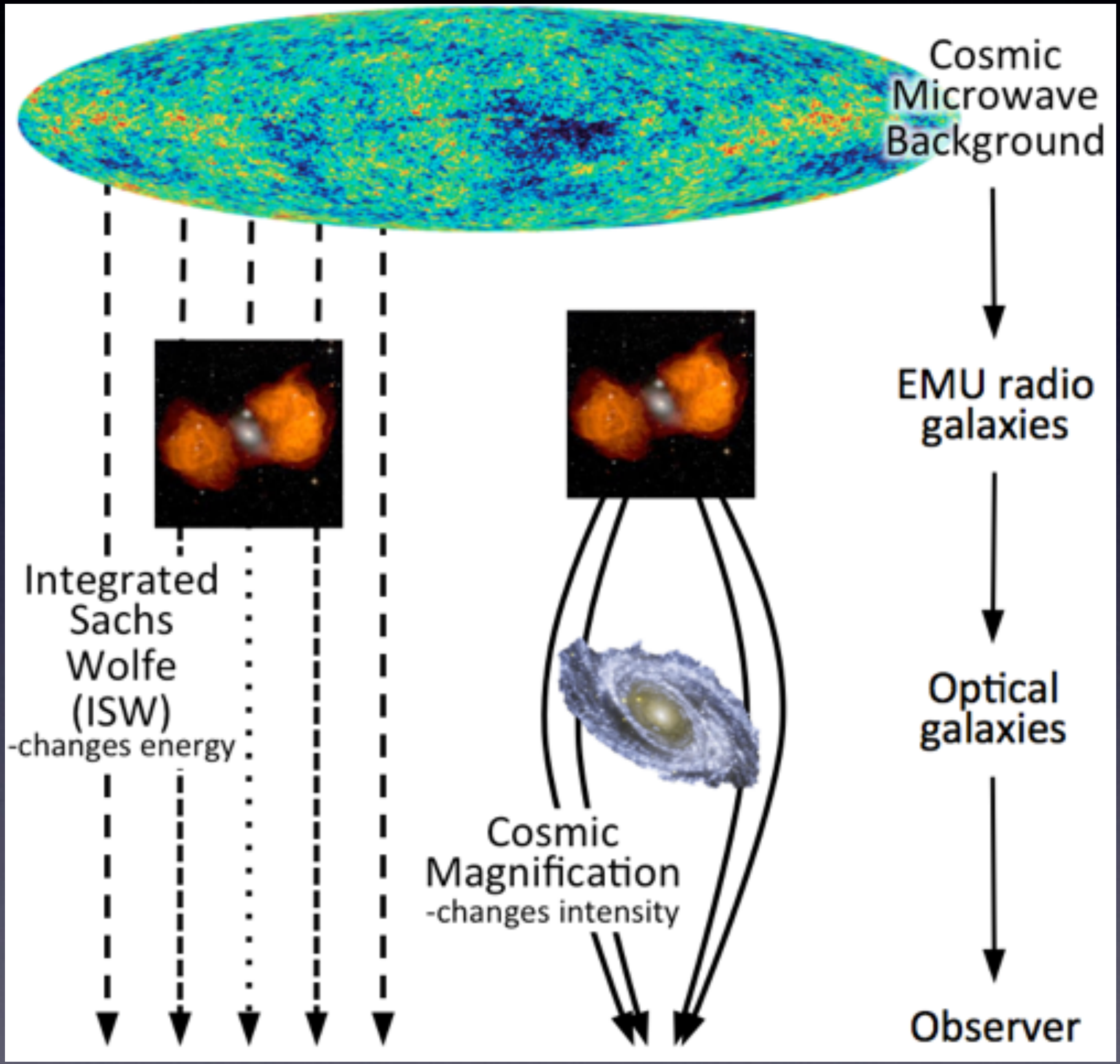
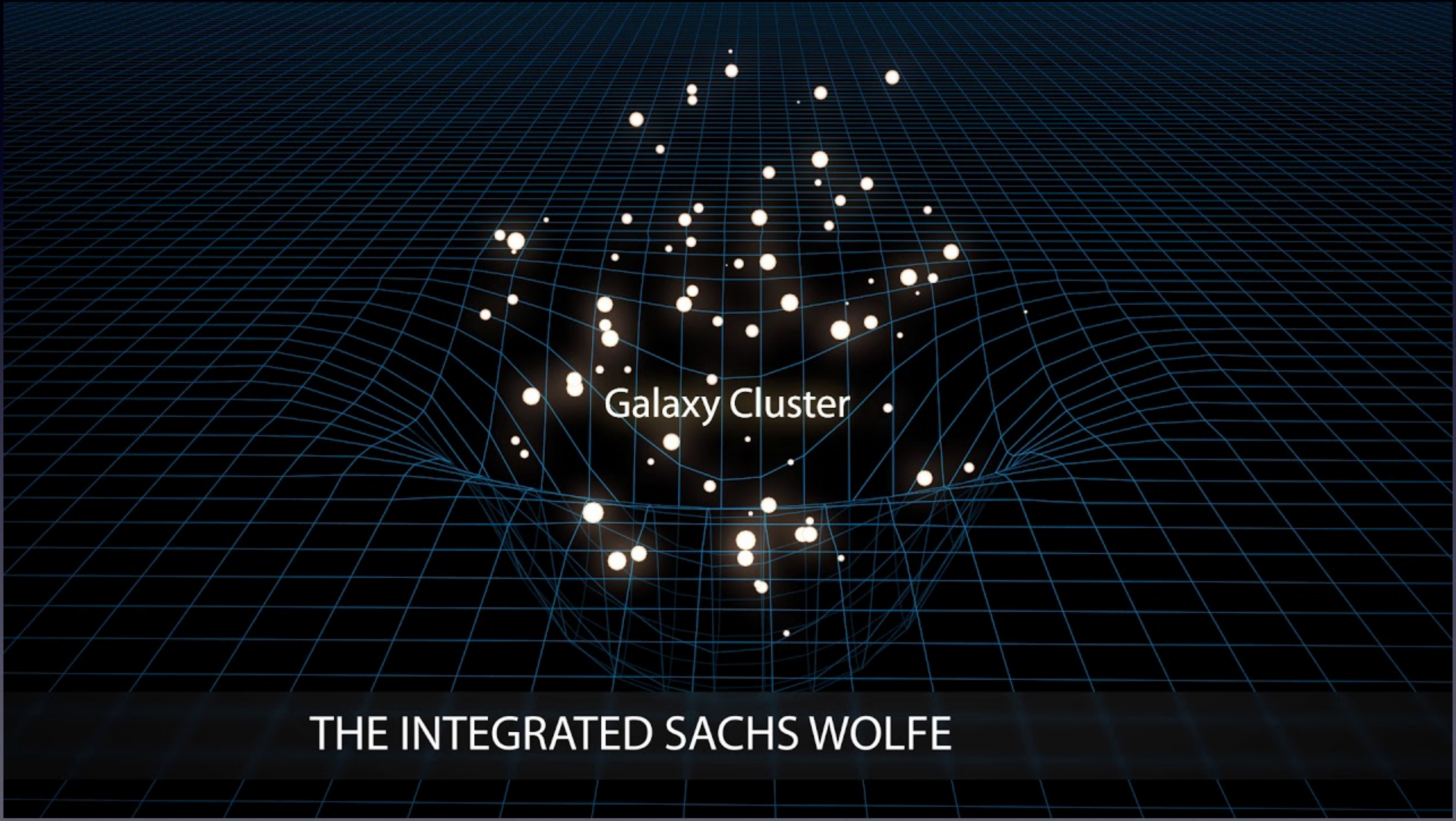


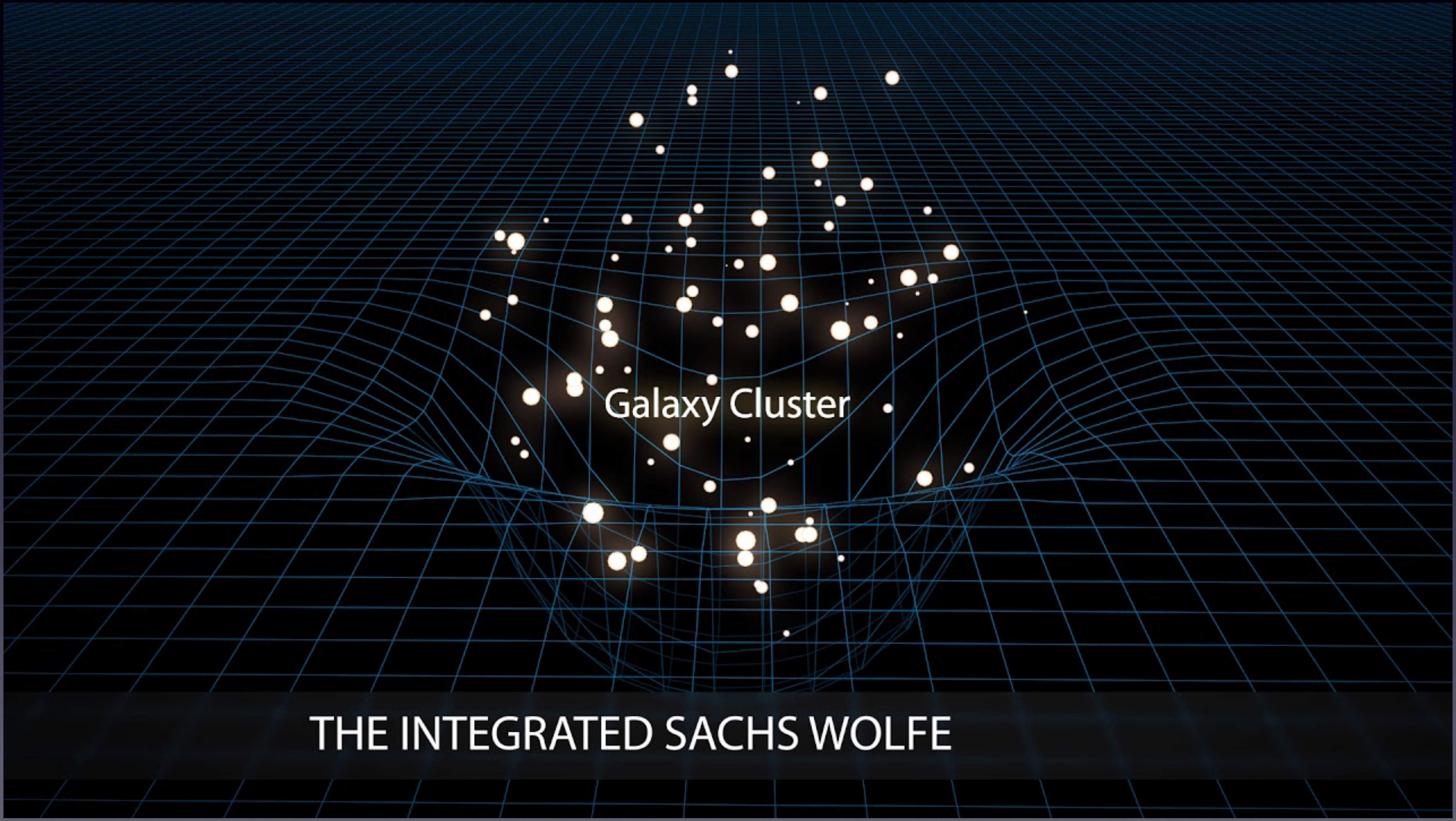
Image credit: Tamara Davis

The Integrated Sachs Wolfe Effect



Credit: CAASTRO

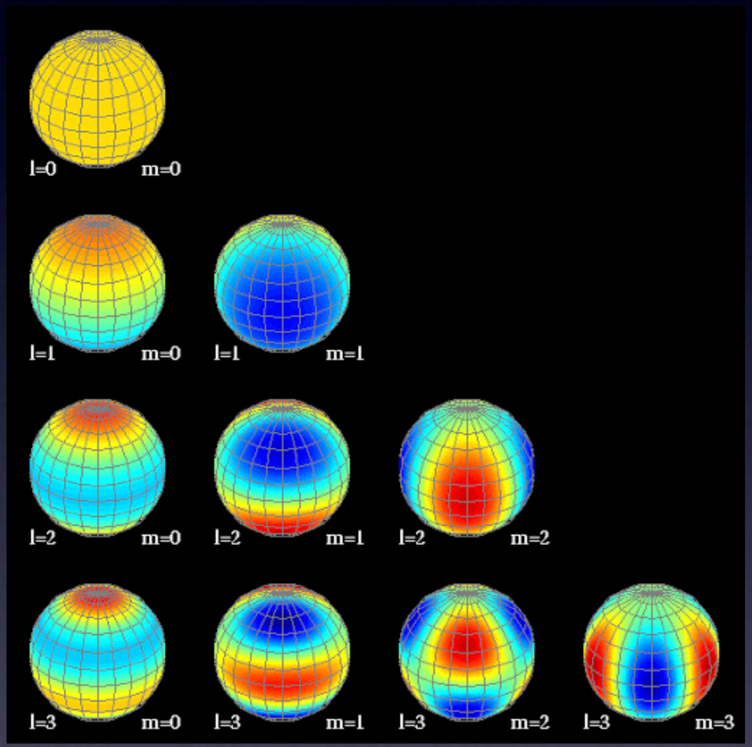
The Integrated Sachs Wolfe Effect



Credit: CAASTRO

Statistics and correlations

- An individual galaxy is not enough, need a measure of the *distribution* of galaxies
- For radio continuum, don't have accurate redshift information
  - Everything in 2D (angular)
- We describe distribution of galaxies through σ(θ) displacement field
  - Here θ is a particular direction
- σ(θ) decomposed into its multiple moment using spherical harmonics
- Compute either *angular power spectrum* (same as the CMB) or *angular correlation function*



$$a_{\ell m} = \int d\vec{\theta} Y^*_{\ell m} \sigma(\vec{\theta})$$

Power spectrum: assume isotropy and average

$$\langle a^*_{\ell m} a_{\ell' m'} \rangle = \delta_{\ell \ell'} \delta_{m m'} C_\ell$$

Connection to theory

- How can we connect measured correlations to cosmological parameters (e.g. density of matter, Hubble parameter today)?
- We infer the underlying matter power spectra P(k)

$$C_\ell^{ij} = \frac{2}{\pi} \int W_\ell^i(K) W_\ell^j(k) P(k) k^2 dk$$

- But need to understand the window function $W_\ell(k)$ of underlying populations

$$W_\ell(k) = \int j_\ell(kr) b(z) \frac{dN(z)}{dz} dr$$

  - CMB Window function easy – localised at z_{rec}.
  - Galaxy window function more difficult – signal can be confused with number or bias evolution

- Shopping list for cosmology:
- (Observations)
  - a large sample (N) of galaxies
  - over a large area (A),
  - with few holes/gaps
  - that can be sub-divided by redshift into bins
- (Theory understanding)
  - with known population number evolution n(z)
  - and known bias b(z)
  - and a known luminosity distribution L(z)
  - and a known evolutionary rate
- Of course, we may need to estimate the theoretic quantities ourselves at the same time as we do cosmology

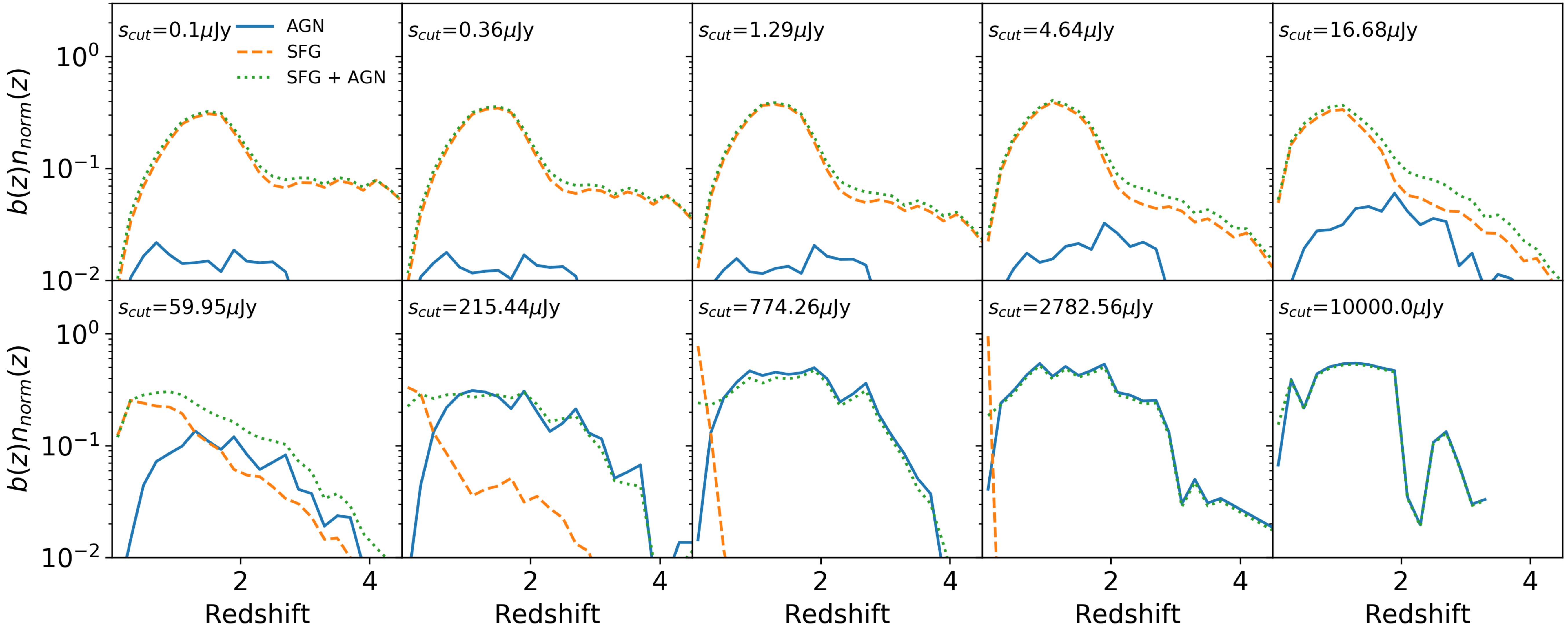
Clustering statistics

- The error depends on the sample variance and on the shot noise.
- Angular clustering depends on the redshift distribution N(z) and the galaxy bias.
- N(z) from T-RECS simulation (Bonaldi et al., 2016) and theoretical prescription for the bias.

Angular power spectrum:

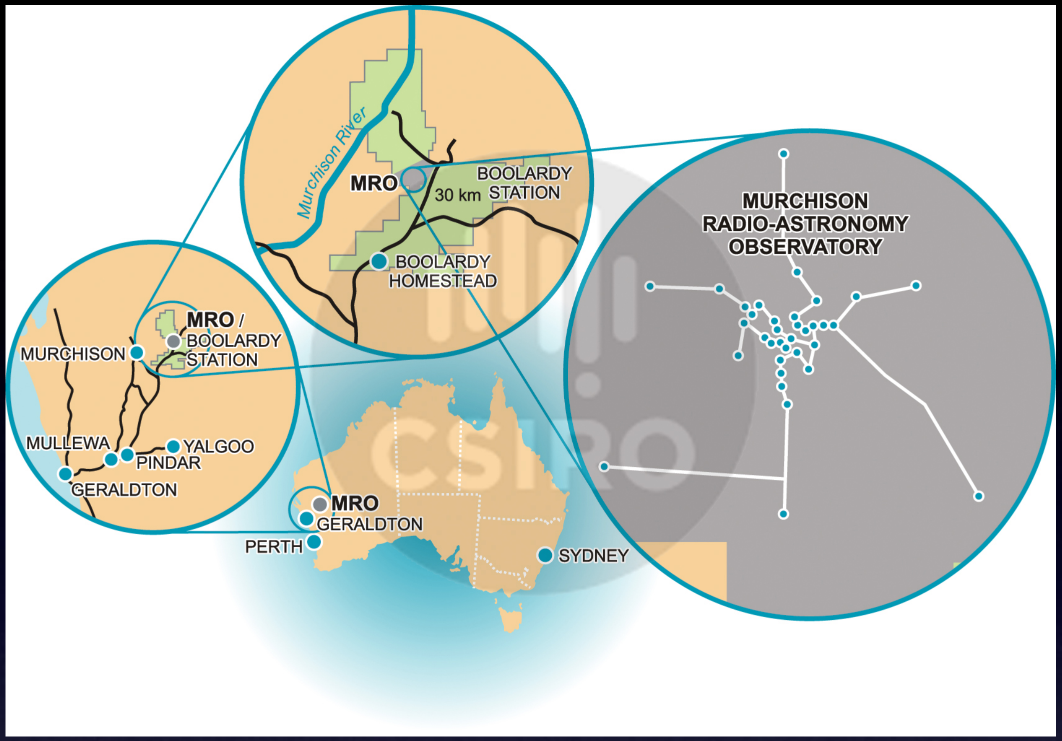
$$C_\ell = 4\pi \int \frac{dk}{k} \Delta^2(k) [W_\ell^g(k)]^2 ,$$

$$W_\ell(k) = \int \frac{dN(\chi)}{d\chi} b(z) D(z) j_\ell [k\chi] d\chi .$$



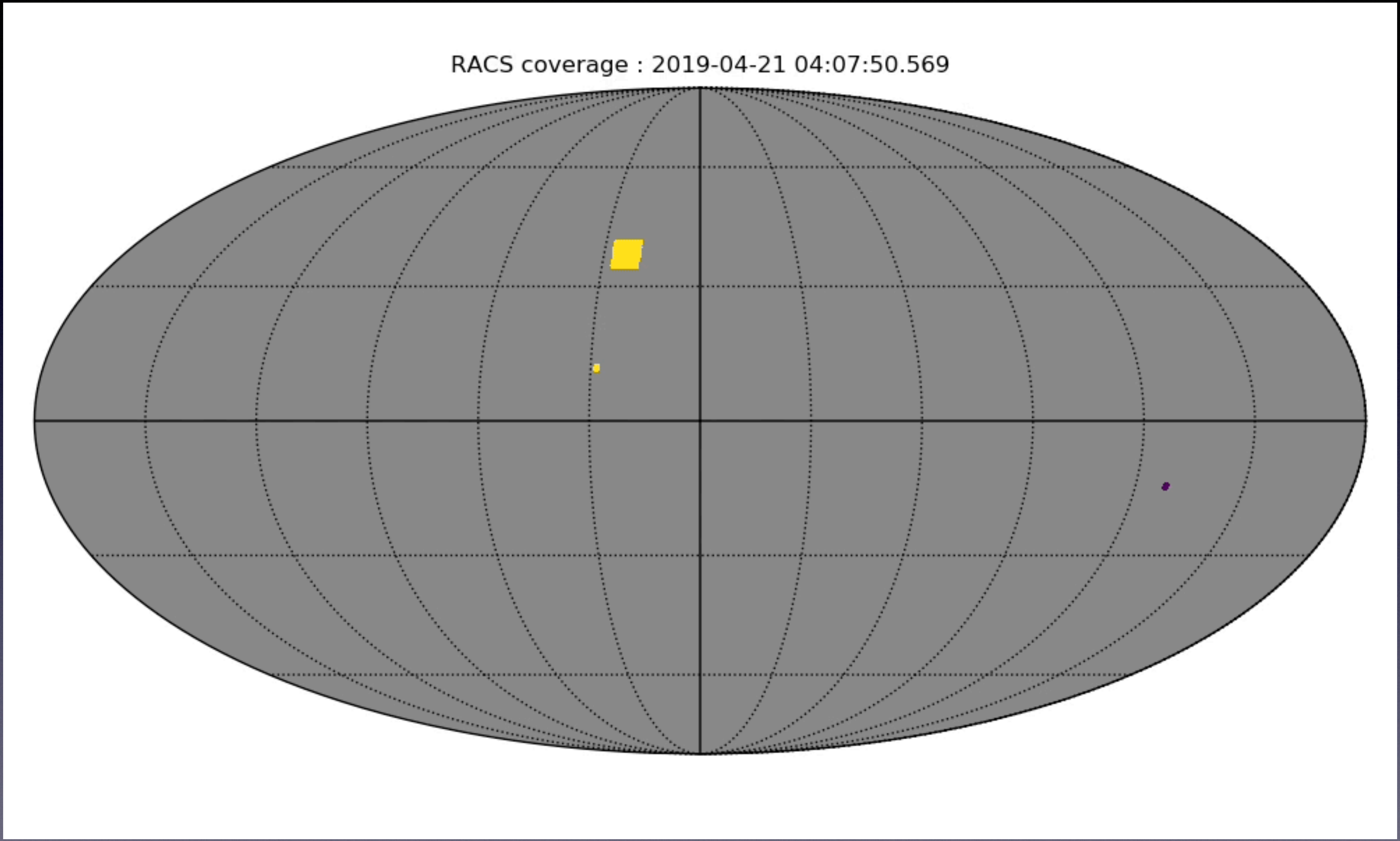
Asorey & Parkinson 2021, MNRAS

Rapid ASKAP Continuum Survey (RACS)

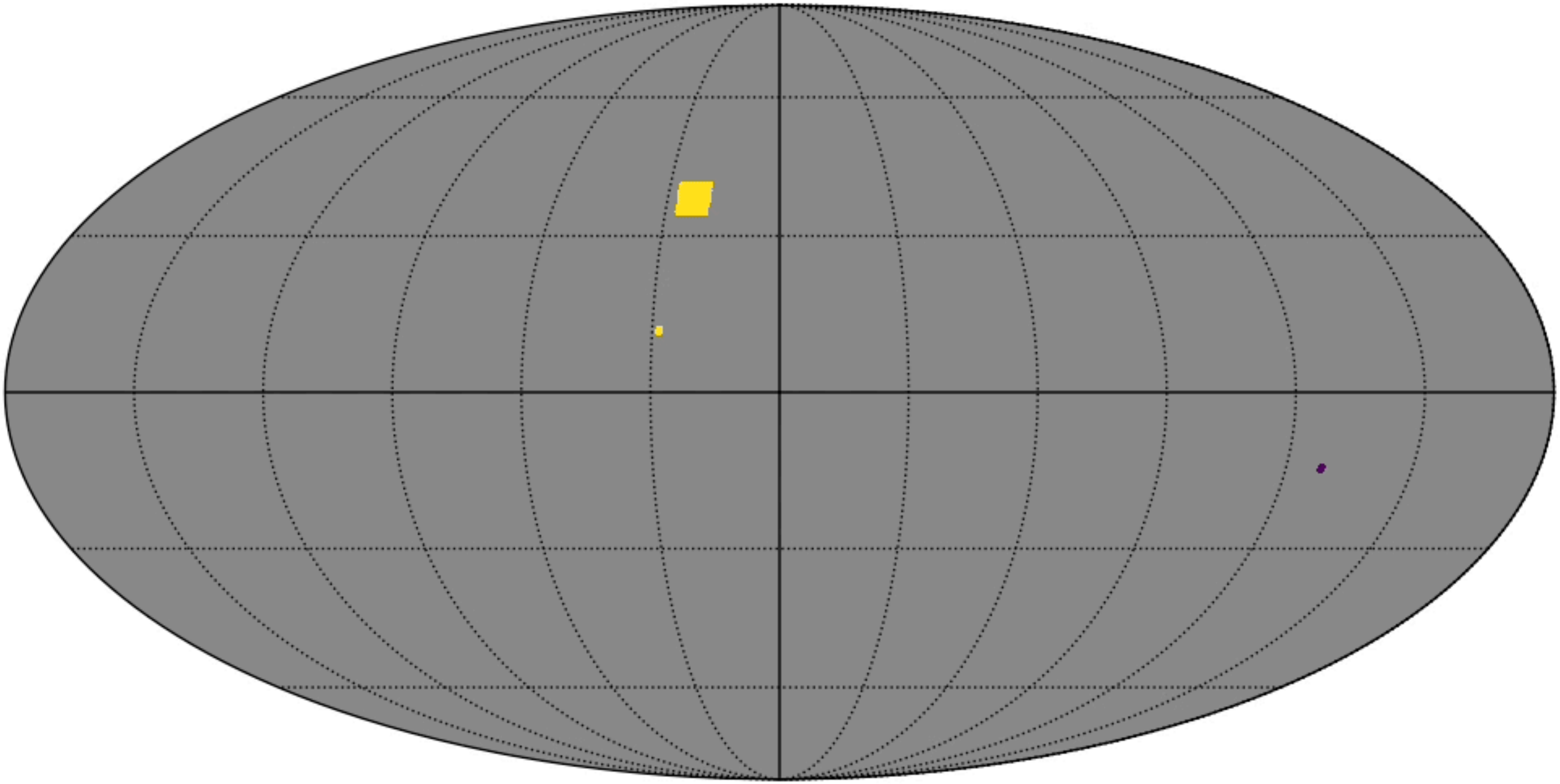


- Rapid ASKAP Continuum Survey (RACS, fast)
  - Technology demonstration, no major science goals
- We acknowledge the Wajarri Yamatji people as the traditional owners of the Observatory site.

Baselines	22m - 6400m	All 36 antennas
Resolution	15 arcsec	
Frequencies	700-1800 MHz	288 MHz bandwidth
Integration	15 minutes	
Polarization	I, Q, U, V	
Image noise	~250 μJy	
Sky coverage	$-90° < \delta < +40°$	903 tiles

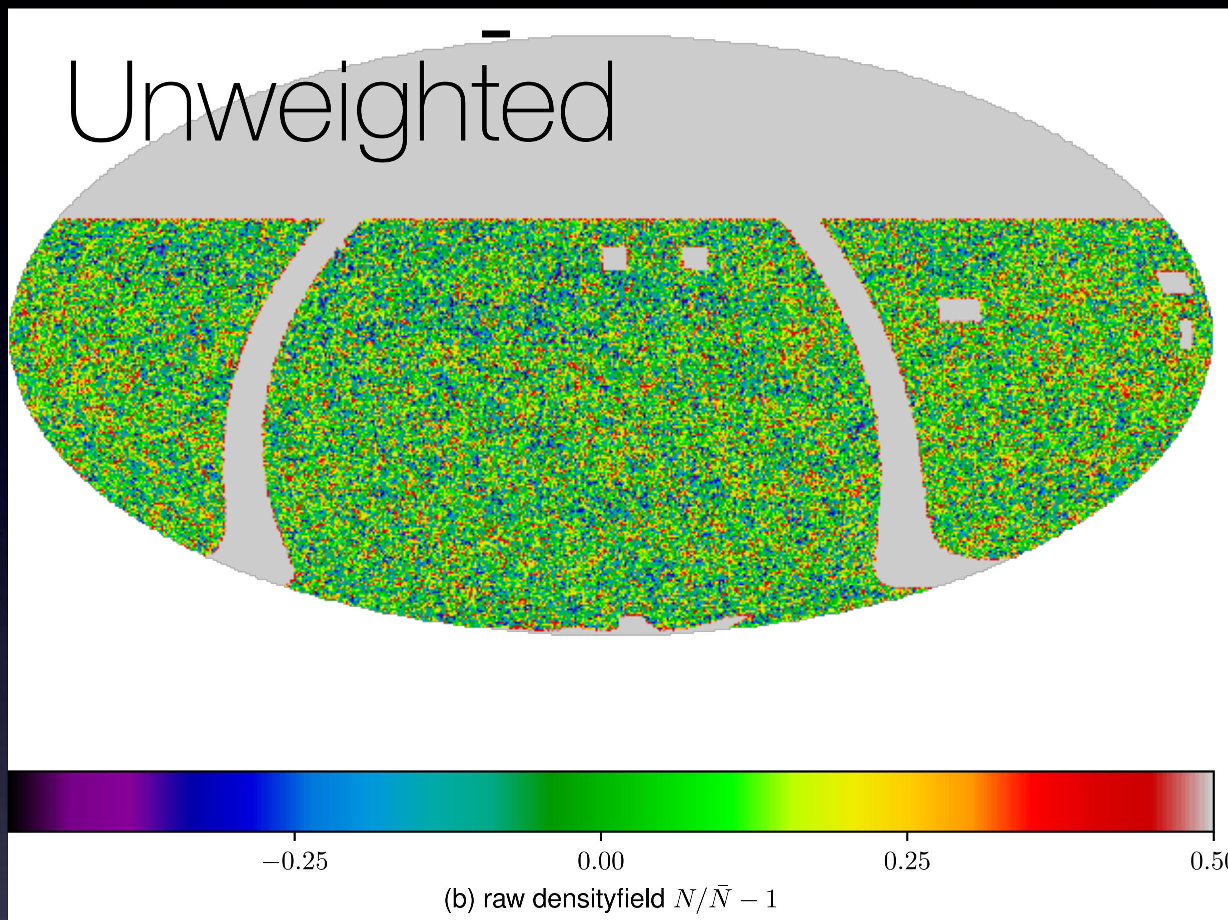

RACS coverage : 2019-04-21 04:07:50.569

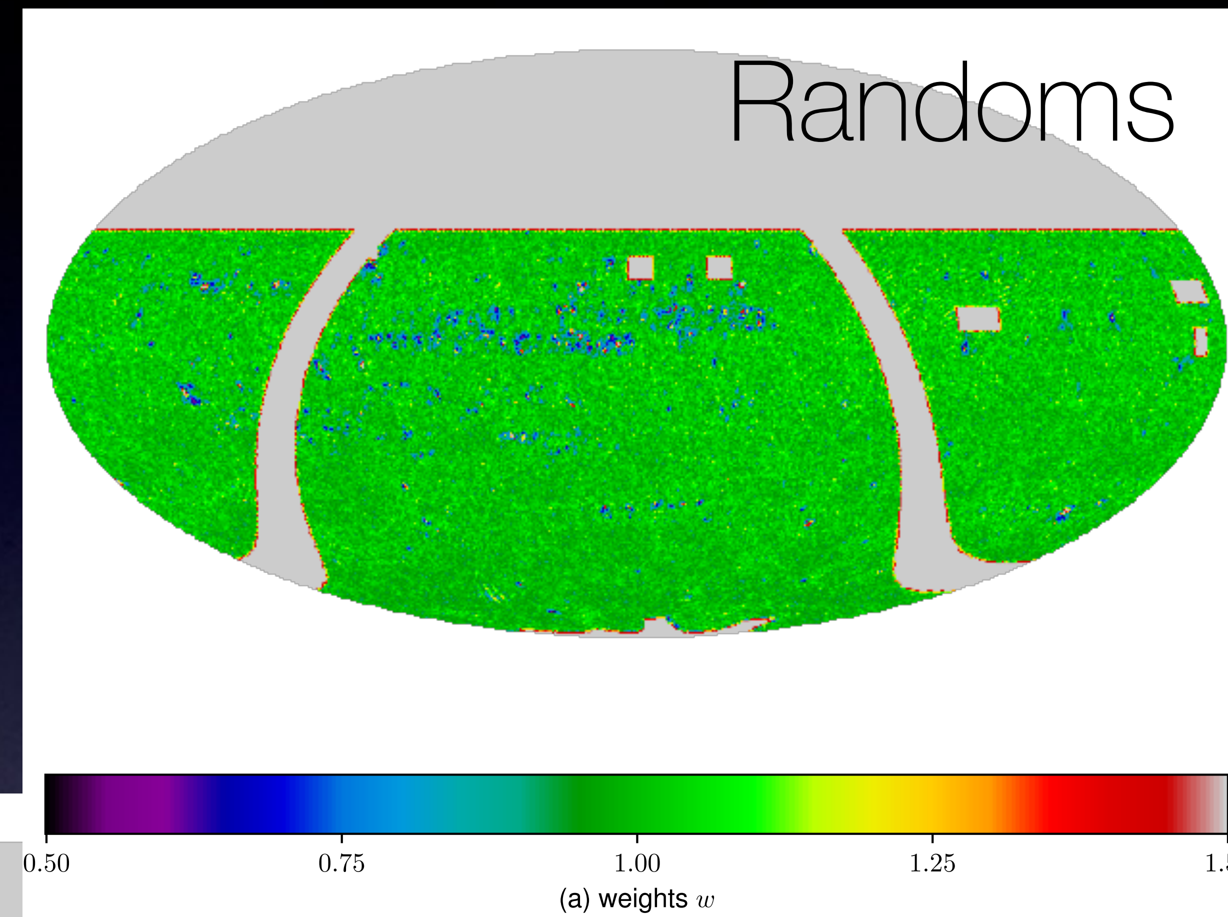
RACS coverage : 2019-04-21 04:07:50.569



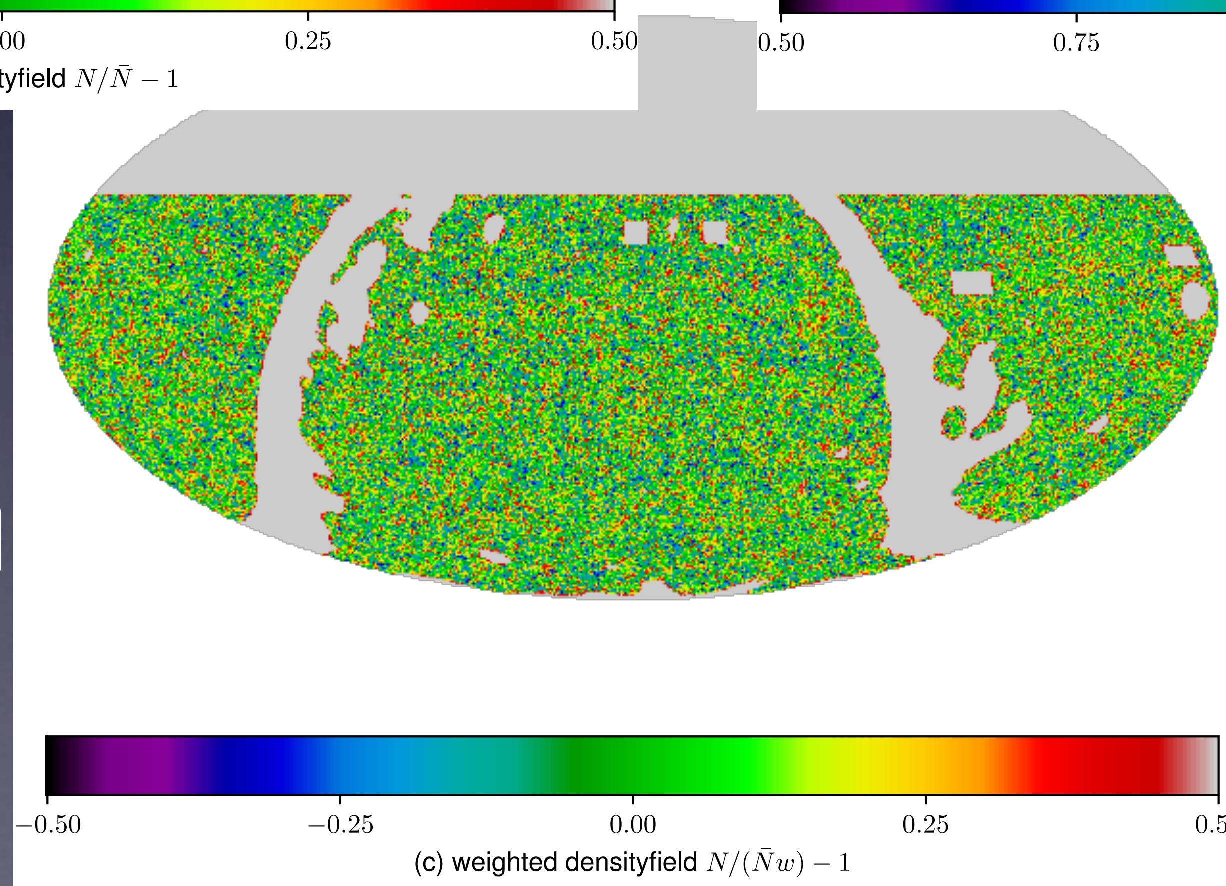
RACS Source density

1.26 Million galaxies (EMU will have 40 Million).

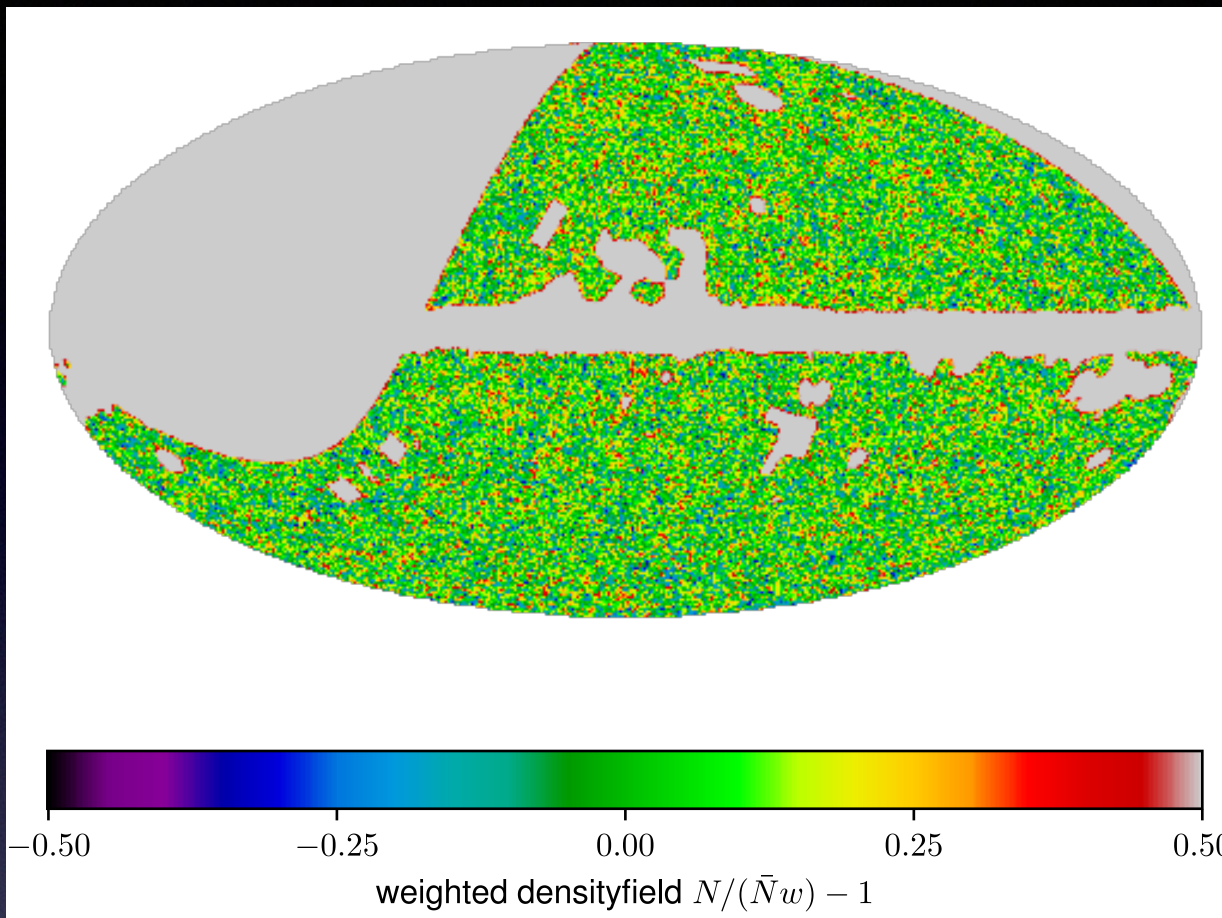


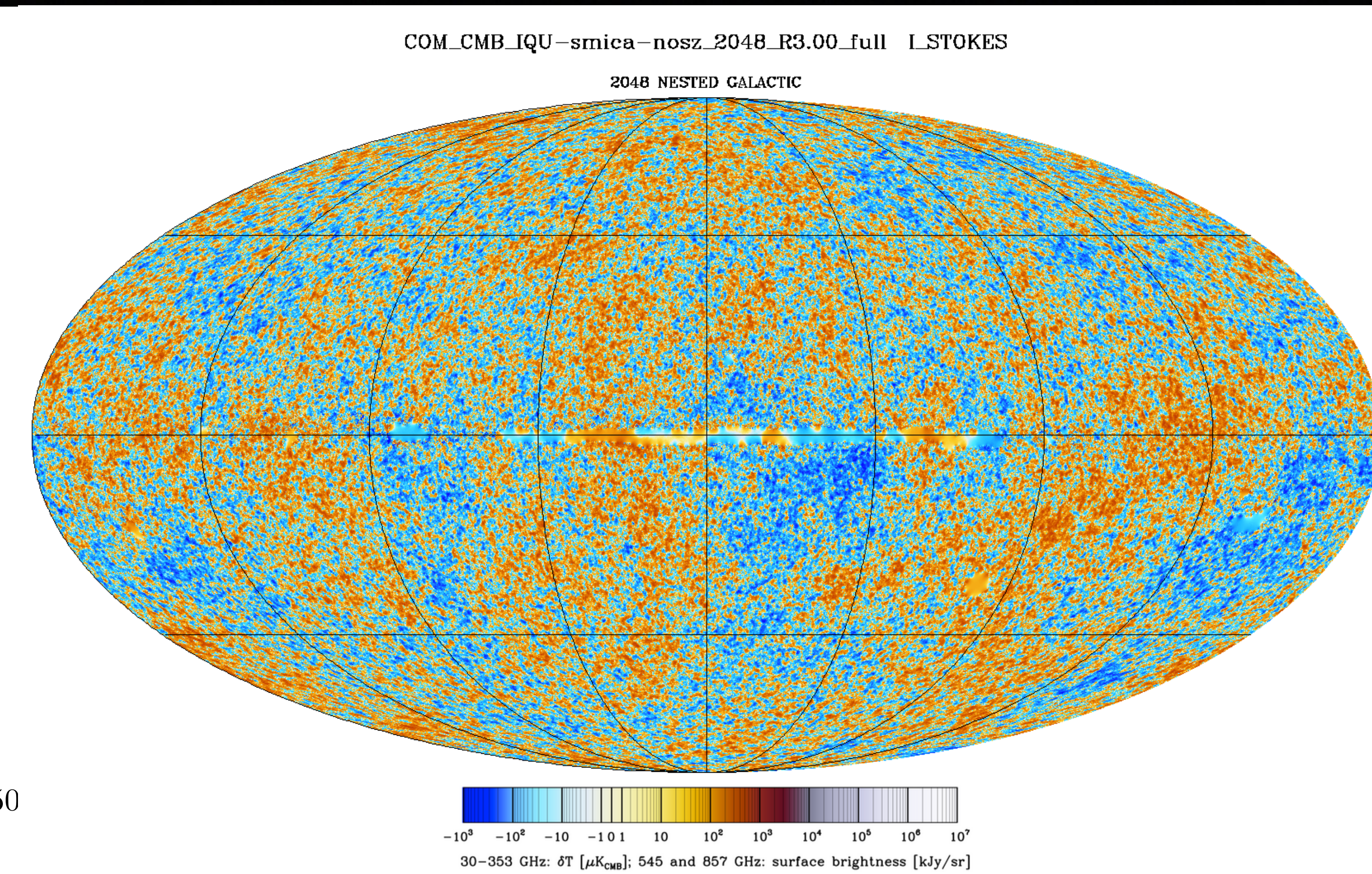


Weighted, and CMB mask applied



RACS x Planck SMICA R3

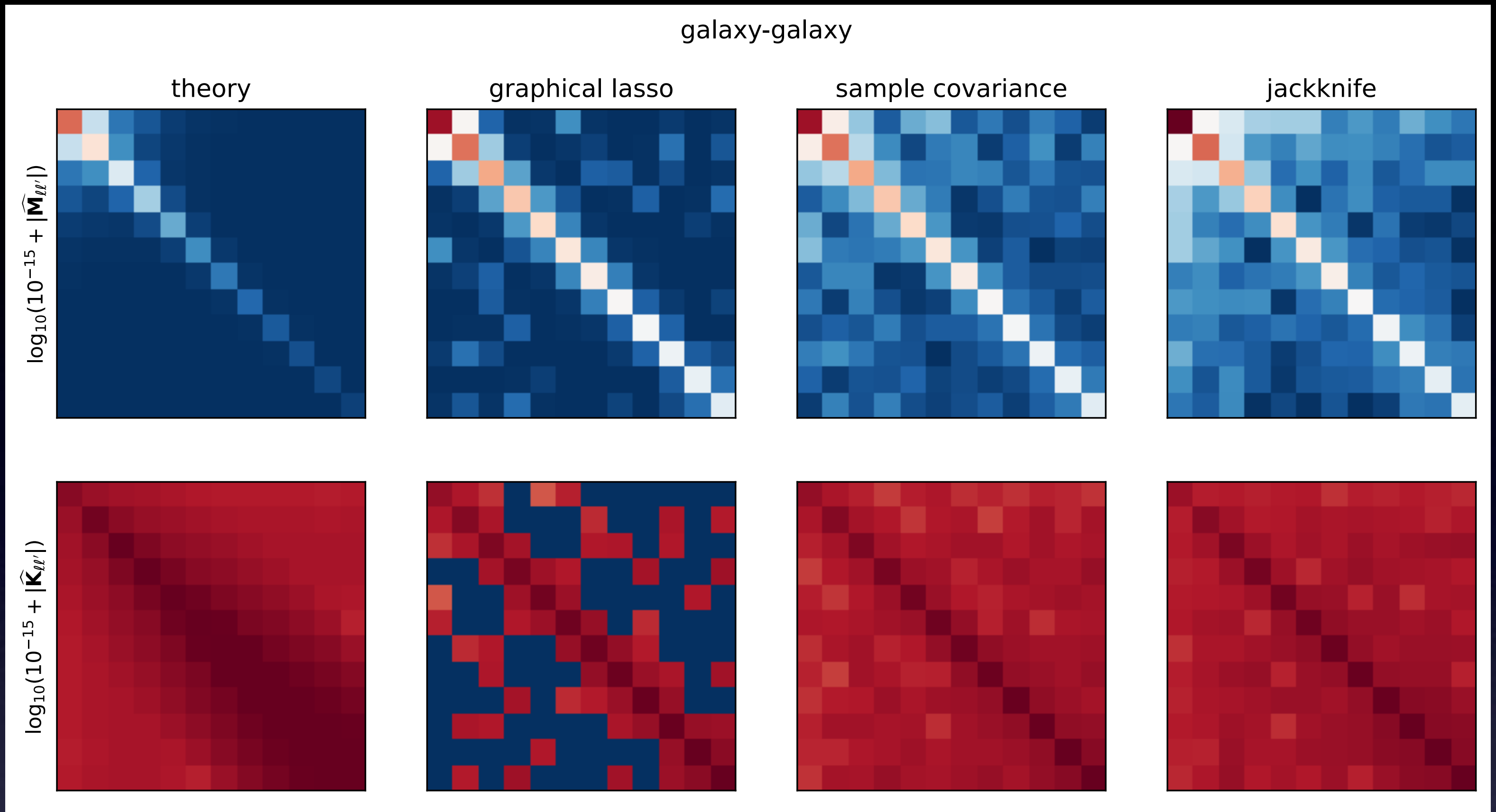




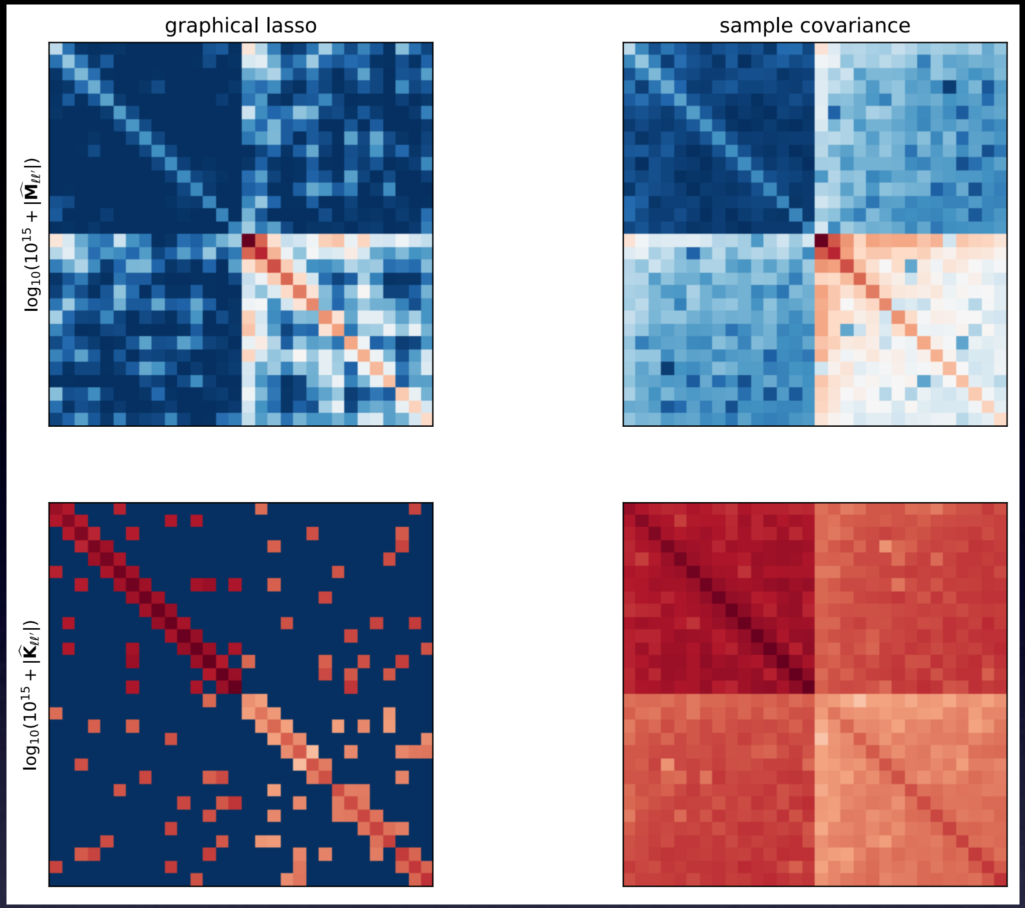
- Removed Galactic plane ($|b| < 5°$)
- Flux cut of 4 mJy
- Construct weight map w using SKADS simulations
- Apply Planck mask
- Cut regions with w < 0.5
- Apply weights to number count and obtain over-density field

Covariance matrices

gg



$\mathrm{gg} \times \mathrm{gT}$

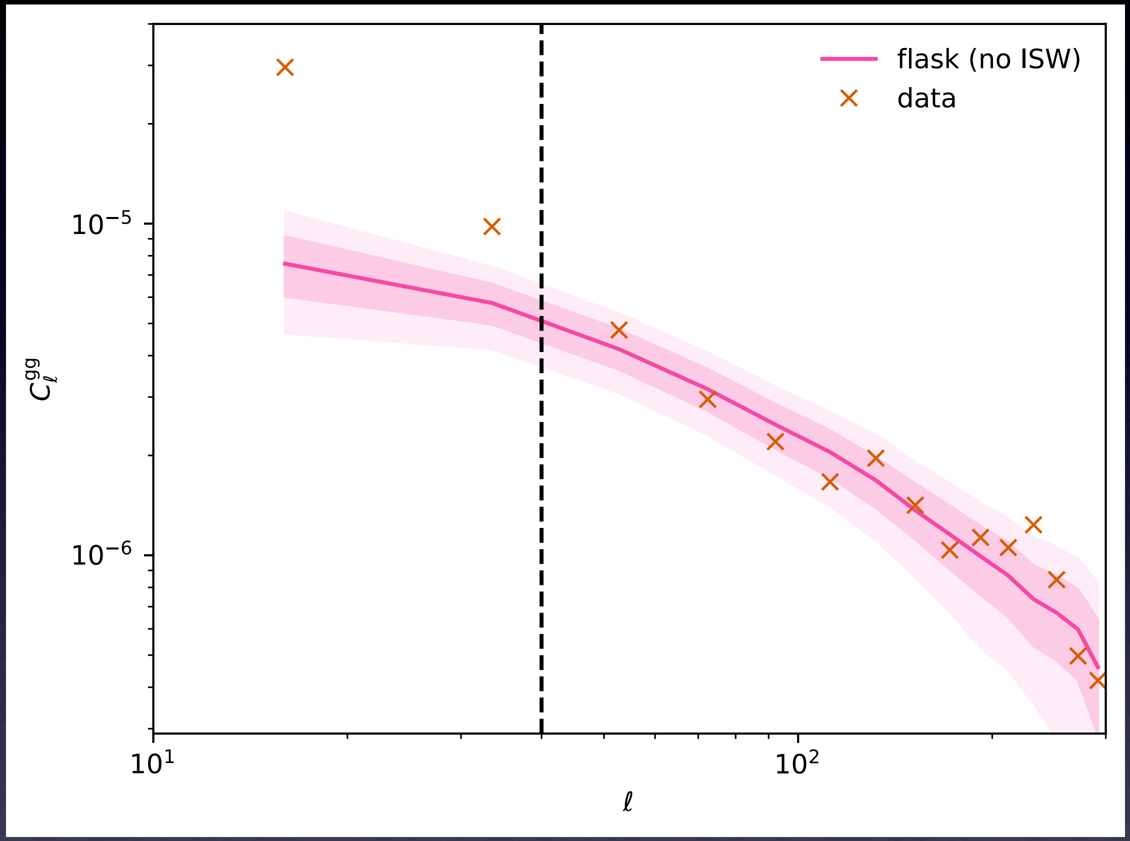


- We use 4 different methods to obtain the gg covariance matrix: analytic, graphical lasso, sample covariance from 3000 Flask simulations and jackknife resampling from the data.

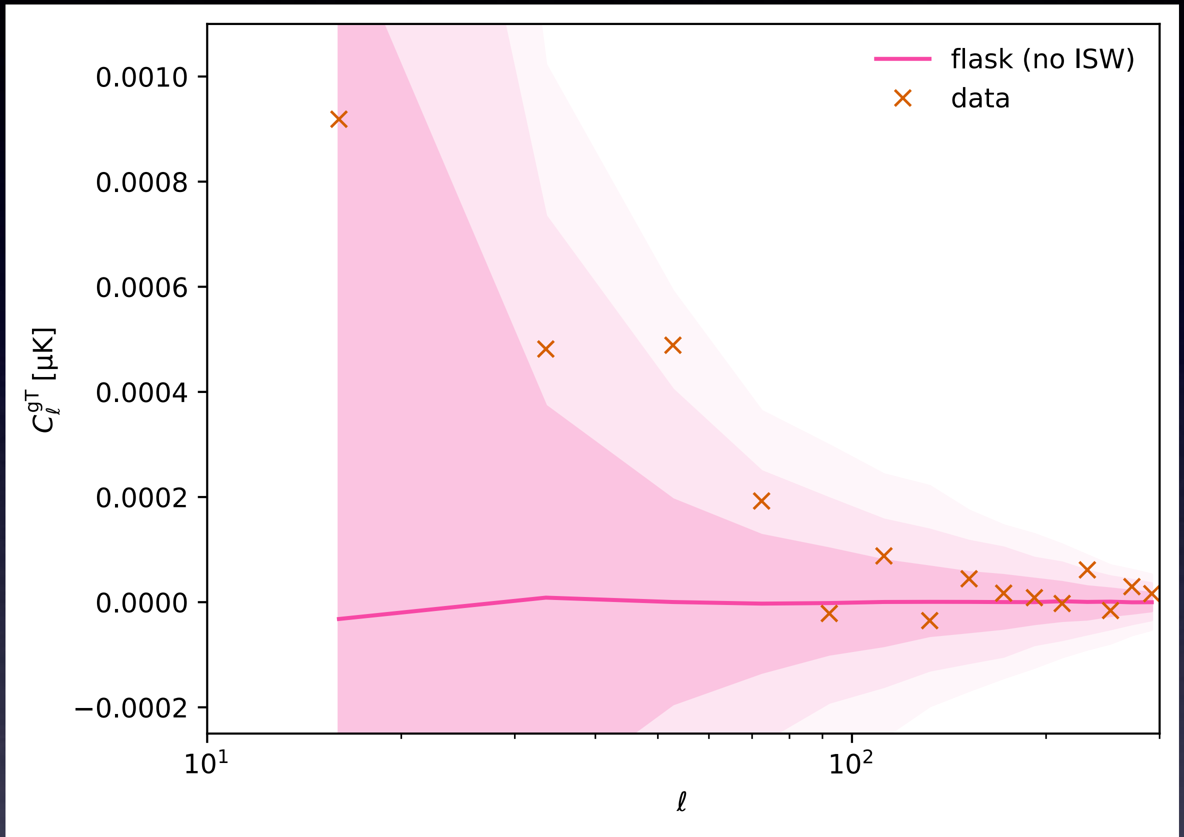
- Same for **gT** spectrum
- $\mathrm{gg} \times \mathrm{gT}$ from mocks only
- Use of sample cov for the main results
- $\mathrm{gg} \times \mathrm{gT}$ cov does not contribute to χ^2

RACS measurements

gg



gT



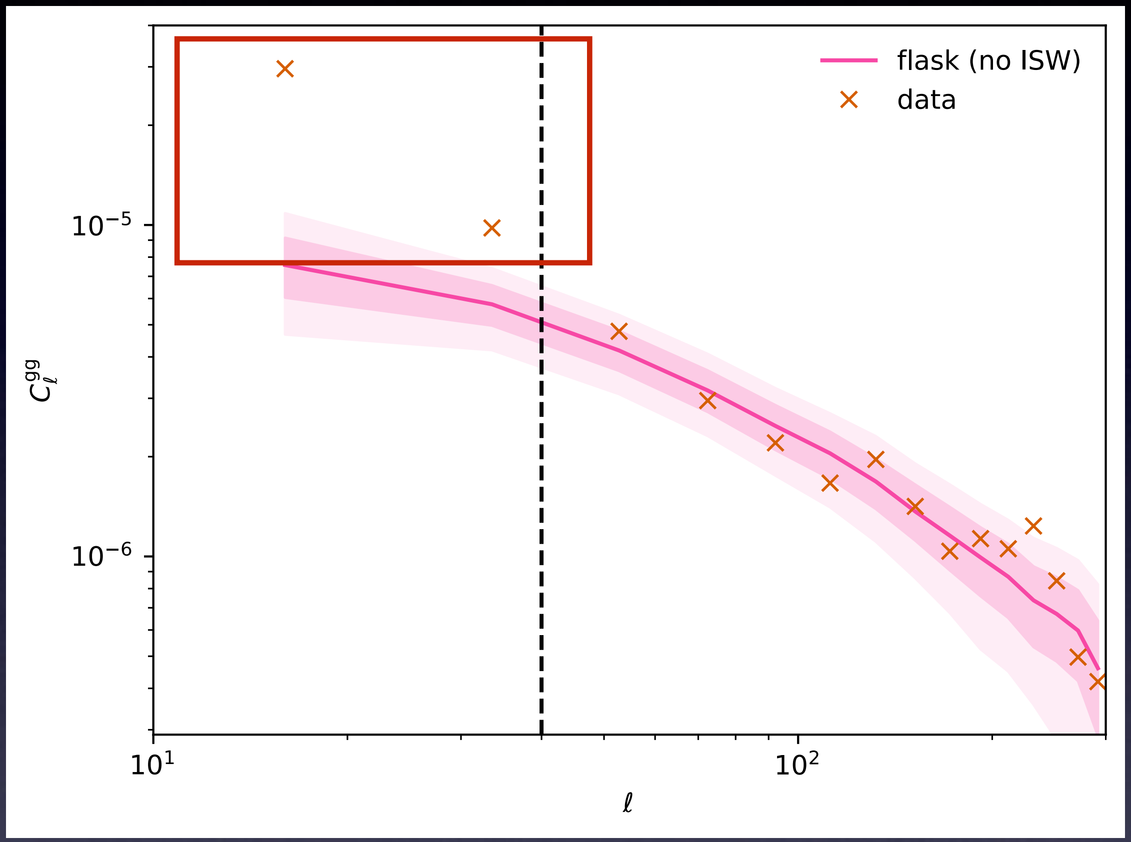
Good agreement at small scales,
Large scale power offset
(Galaxy power spectra information at $\ell >$ 40 not included in analysis)

$$\frac{S}{N} = \frac{\sum_{\ell,\ell'} C_\ell^{(\text{data})} \mathbf{K}_{\ell\ell'} C_{\ell'}^{(\text{model})}}{\sqrt{\sum_{\ell,\ell'} C_\ell^{(\text{model})} \mathbf{K}_{\ell\ell'} C_{\ell'}^{(\text{model})}}} \approx 2.8$$

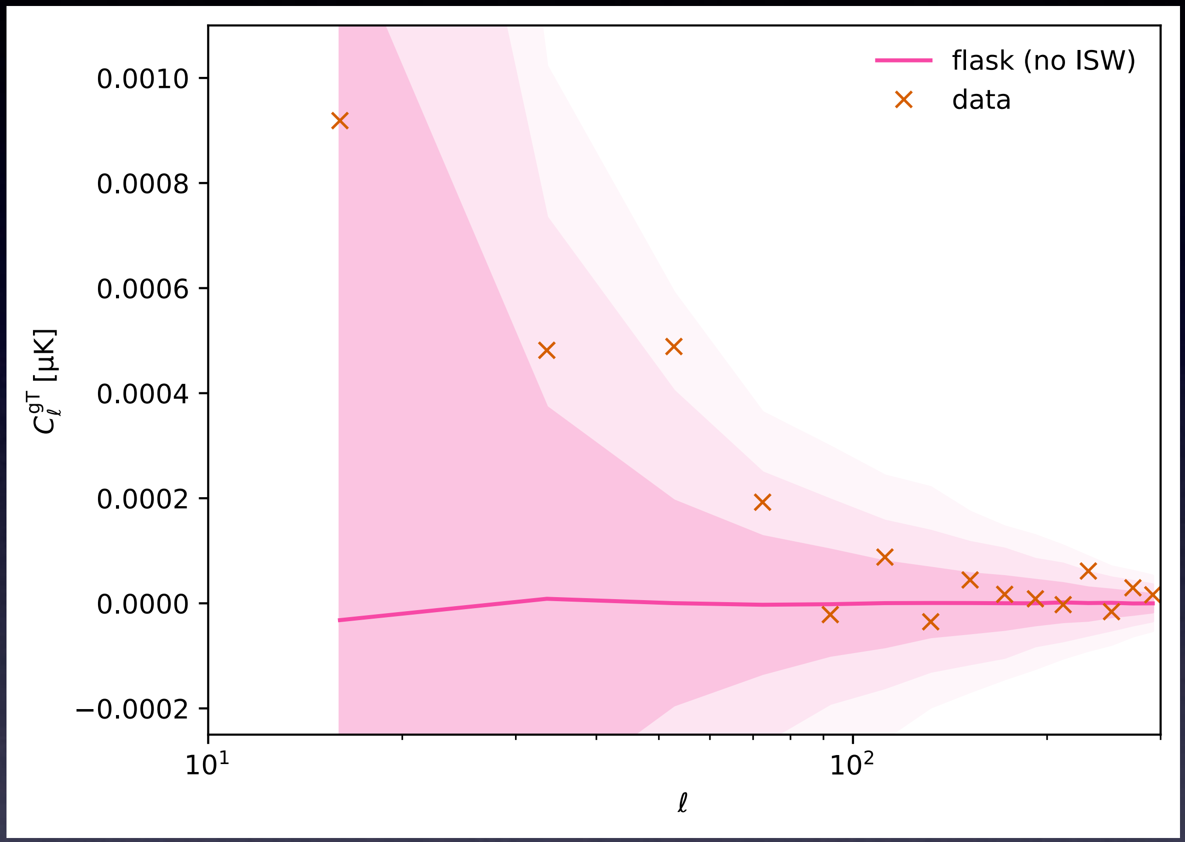
relative to null hypothesis of no correlation

RACS measurements

gg



gT



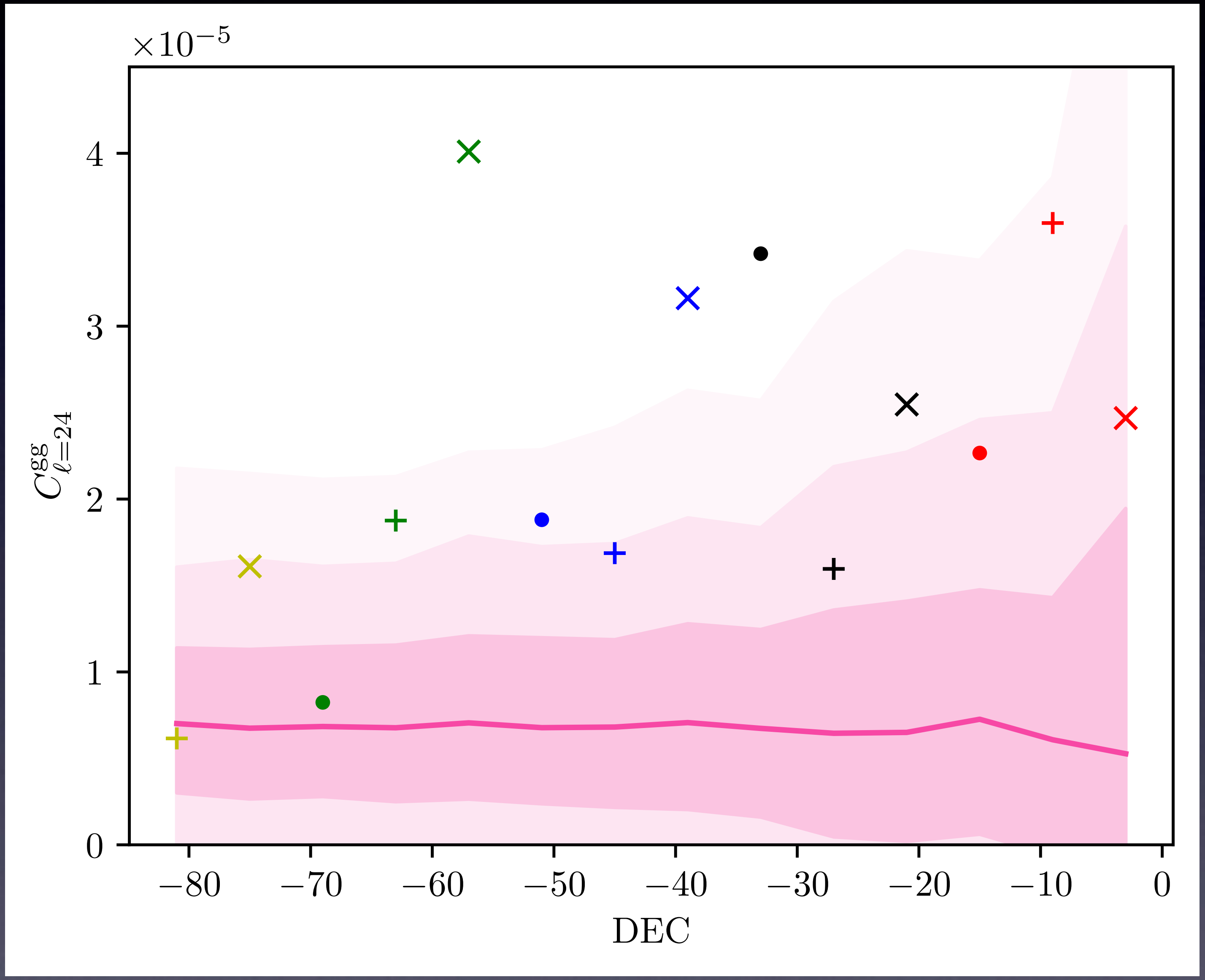
Good agreement at small scales,
Large scale power offset
(Galaxy power spectra information at $\ell >$ 40 not included in analysis)

$$\frac{S}{N} = \frac{\sum_{\ell,\ell'} C_\ell^{(\mathrm{data})} \mathbf{K}_{\ell\ell'} C_{\ell'}^{(\mathrm{model})}}{\sqrt{\sum_{\ell,\ell'} C_\ell^{(\mathrm{model})} \mathbf{K}_{\ell\ell'} C_{\ell'}^{(\mathrm{model})}}} \approx 2.8$$

relative to null hypothesis of no correlation

Some systematics

- Large scale power excess seems to be correlated with declination
  - Close to south pole errors smaller, and mean close to predicted value
  - Close to equator number of counts smaller and sky noise large, power is higher than expected
- Hypothesis is that power excess is **not** non-Gaussianity causing scale-dependent bias, but a systematic caused by data reduction procedure

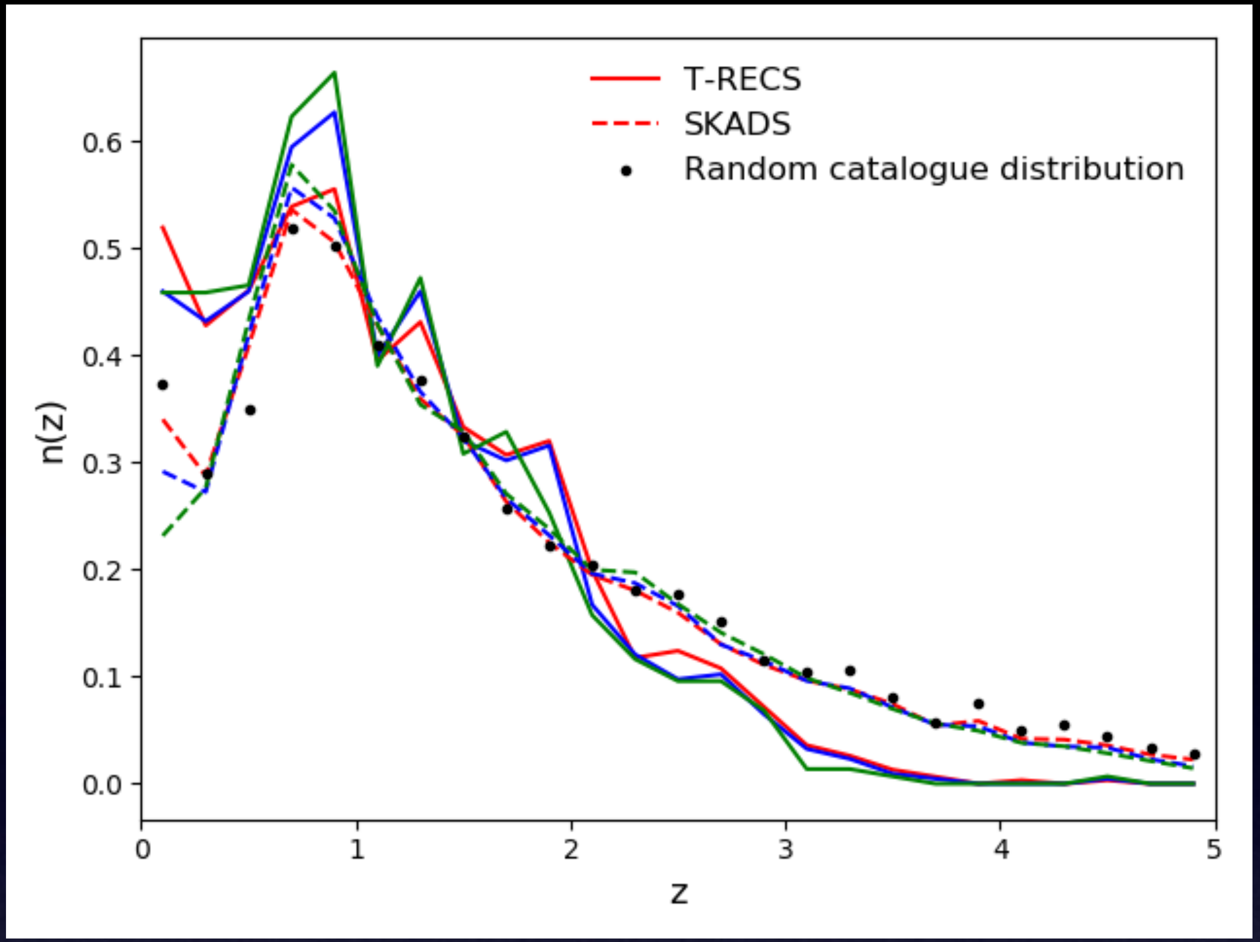


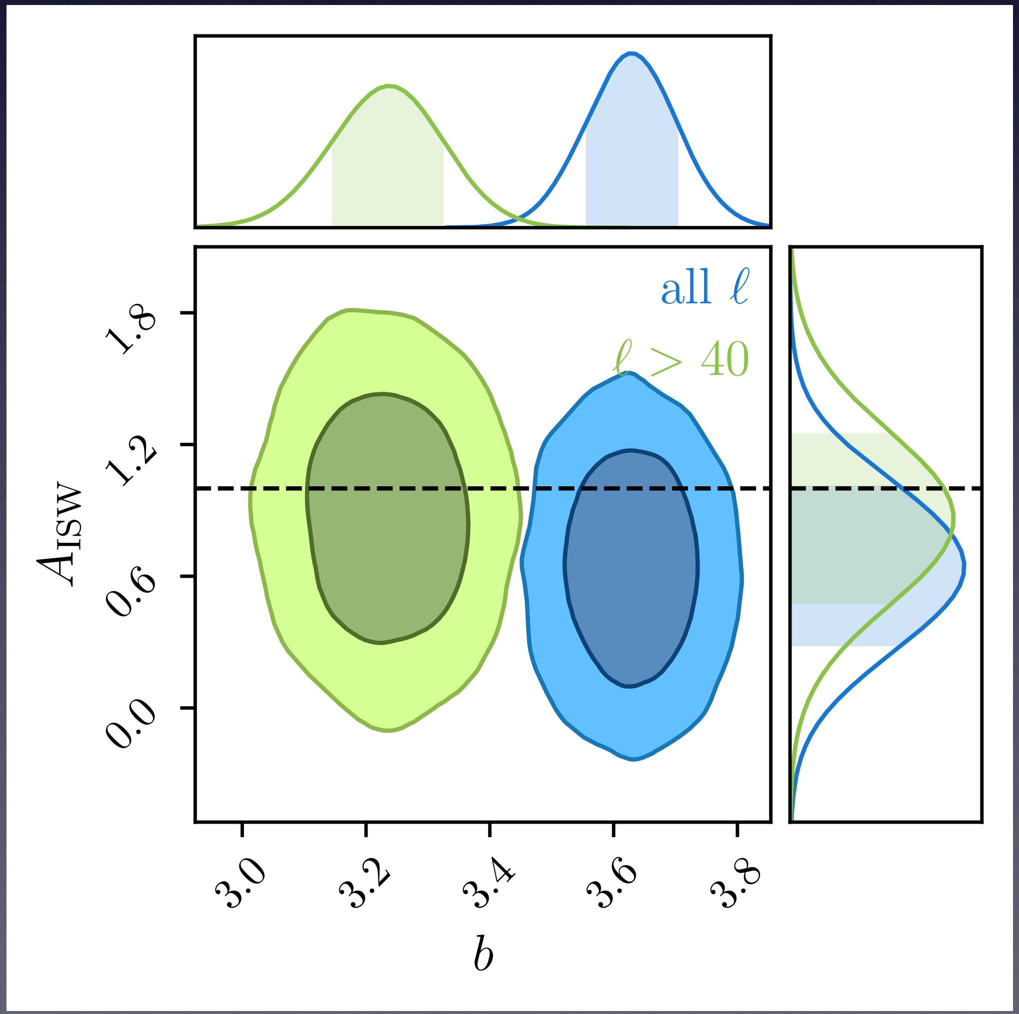
Cosmological constraints

- We vary $b(z)$ and define $A_{\rm ISW}$ such that $C^{gT}_{\ell,\rm measured} = A_{\rm ISW} C^{gT}_{\ell,\rm model}$
- more Bayesian approach to quantify significance of ISW detection
- $A_{\rm ISW}$ and $b(z)$ degenerate in C^{gT}_ℓ, broken in combined C^{gg}_ℓ and C^{gT}_ℓ analysis
- $b(z)$ also degenerate with $\dfrac{dN(z)}{dz}$,
- analysis with $N(z)$ inferred from **SKADS**, as well as from **T-RECS**

$$C^{ij}_\ell = \frac{2}{\pi}\int W^i_\ell(K) W^j_\ell(k) P(k) k^2 dk$$

$$W_\ell(k) = \int j_\ell(kr) b(z) \frac{dN(z)}{dz} dr$$

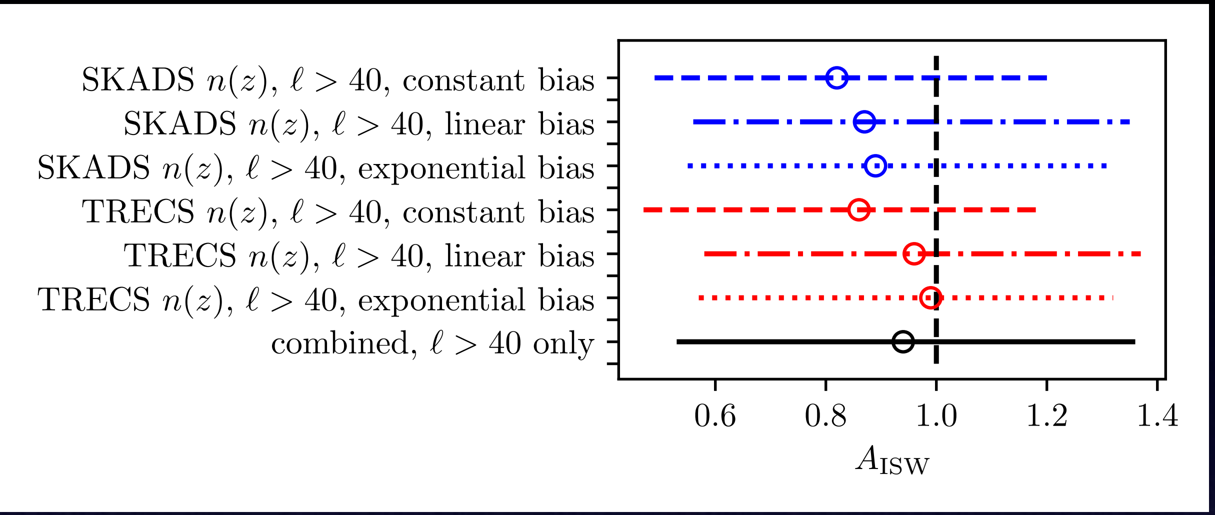


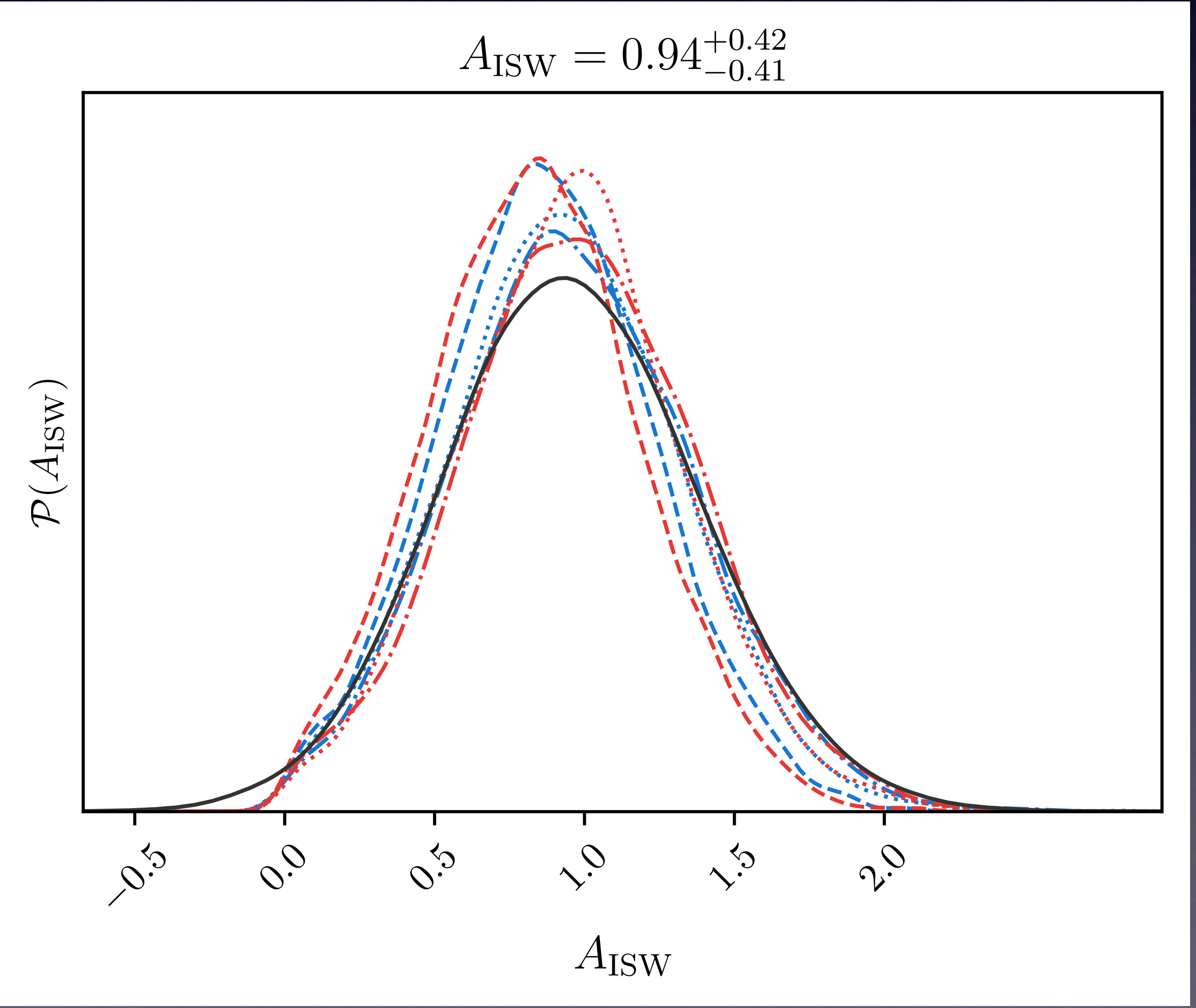


Cosmological constraints

- Consider three bias parameterisations:
  - $b(z)$ constant
  - $b(z) = b_0 + b_1 z$
  - $b(z) = b_0 \exp(\beta z)$
- Always take full ℓ-range into account for C_ℓ^{gT}
- Repeat C_ℓ^{gg} analysis with and without $\ell < 40$
- Use scatter to estimate systematic uncertainty

2.3σ detection of ISW effect with more conservative Bayesian analysis
Probability of $A_{\rm ISW} > 0$ is 98.9%





Summary

- Measurements of the clustering of radio galaxies can be used to determine the bias of radio populations and the cosmological parameters
- The effect of anisotropic noise (location-dependent completeness) can be modelled when generating randoms, to remove any potential bias
- We used FLASK to generate mock catalogues with the same clustering power spectrum as our fiducial cosmology, to test our pipeline and estimate covariance matrix
- We measured angular power spectrum of radio continuum sources detected by RACS at 888 MHz, in auto-and cross-correlation with Planck CMB maps
- Angular power spectra of RACS galaxies consistent with prediction from ΛCDM, except on large scales where we detect an excess.
- Detect cross-correlation between galaxy distribution and CMB temperature distributions. Significant at 2.8σ relative to null hypothesis.
- Parameterise ISW amplitude as $A_{\rm ISW}$. Combining the angular auto- and cross-power spectra, and combining measurements obtained under different assumptions in conservative Bayesian way, we get $A_{\rm ISW} = 0.94^{+0.42}_{-0.41}$ $(2.3\sigma/98.9\%)$

¡Thank you!