Cosmology with large-area radio and optical surveys

David Parkinson
한국천문연구원
Korea Astronomy and Space Science Institute

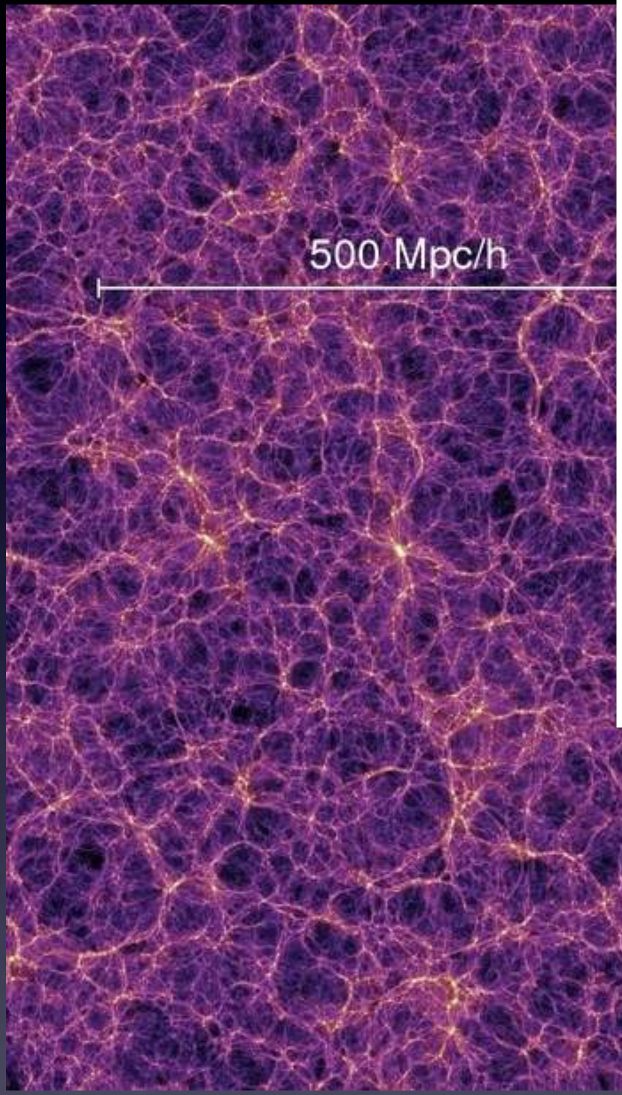
Outline

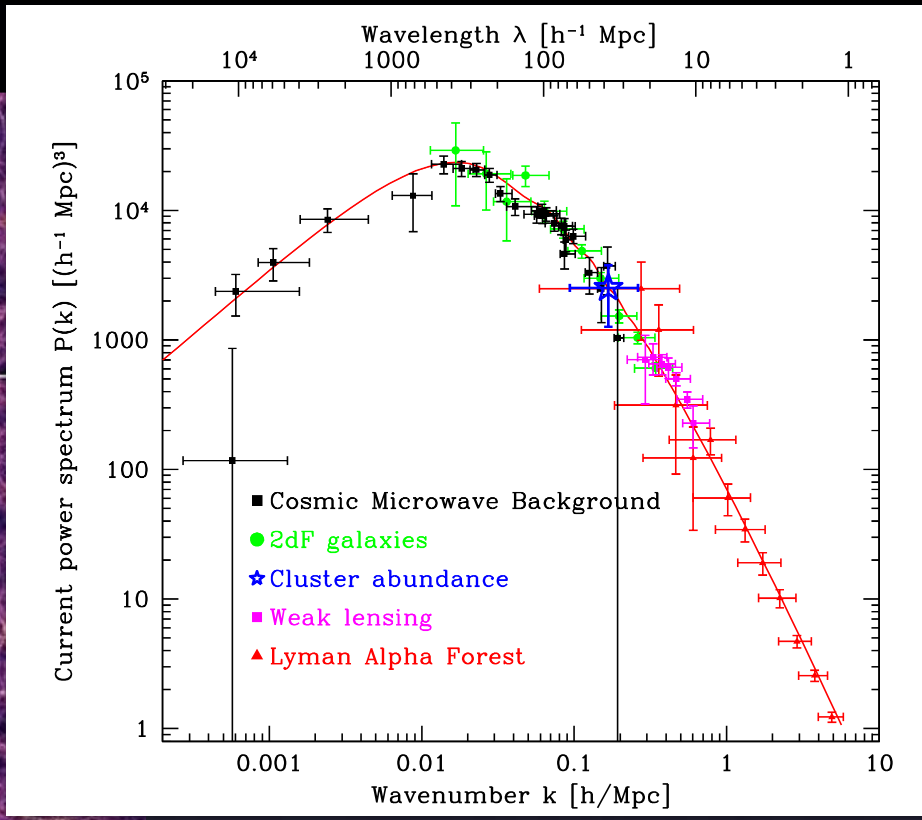
- Introduction
- All-sky radio surveys
- Cosmology with continuum
- Cross-correlations
- Summary

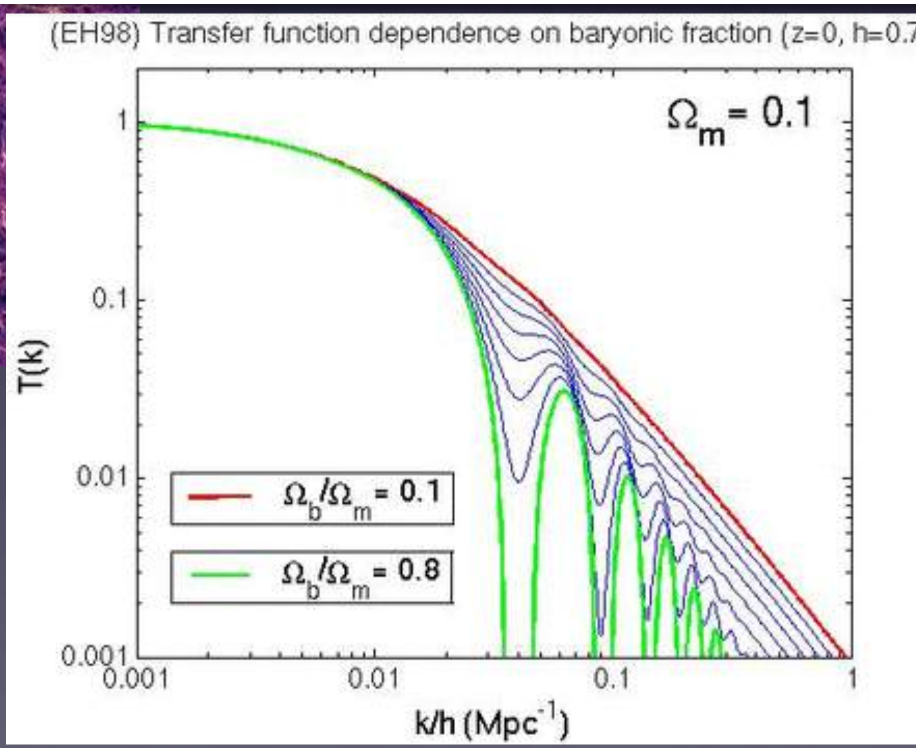
1.Introduction

Tracing 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 not measured spectrum of density fluctuations
    - Much more sensitive to transfer functions
- Need very large volumes to measure primordial power spectrum and determine initial conditions (independently from CMB)







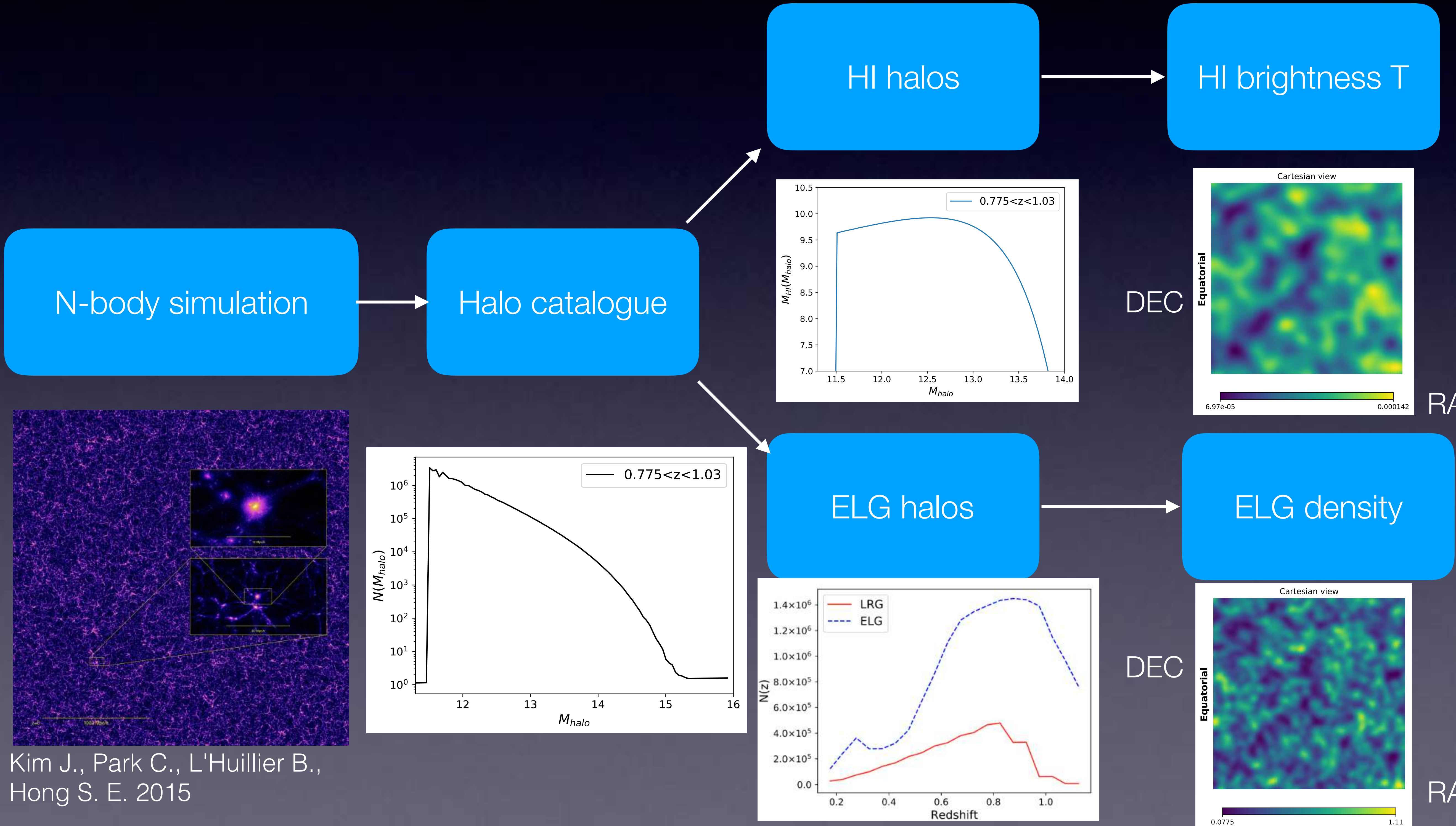
Radio cosmology era

- Most major results have come from CMB (continuous density field, high-redshift) and optical galaxy surveys (discrete density field, low-redshift)
  - Best cosmology experiment existing is still Planck, which is cosmic-variance limited at largest scales
- Radio (discrete and continuous density field, low- to medium-redshift) has lacked the number density to be a contender
  - Only 2 million extra-galactic radio sources currently known
- Radio has less of a problem with dust obscuration than optical, and observations can be faster
  - Access to very large-scale information, e.g. cosmic dipole, primordial non-Gaussianity
- Next generation of radio telescopes will provide large-scale structure data that will be independent and complimentary to optical and CMB experiments

Radio Surveys

- HI galaxy
  - Measures RA, Dec and redshift - Functions like an optical galaxy redshift survey
  - Can also measured peculiar velocities through Tully-Fisher relation
- Continuum galaxy
  - Measures RA, Dec, but not redshifts - Angular clustering survey
  - Cross-correlate with CMB and low-z sample for ISW and cosmic magnification
- HI intensity mapping
  - Measures RA, Dec, z, but no galaxies - delocalised in angular space
  - Can still use it like a spectroscopic survey (BAO & RSD) - competitive with Euclid
- Weak lensing shear
  - Shapes of continuum galaxies, need intensity mapping or similar for redshifts

H1R4: DESI x Tianlai simulations



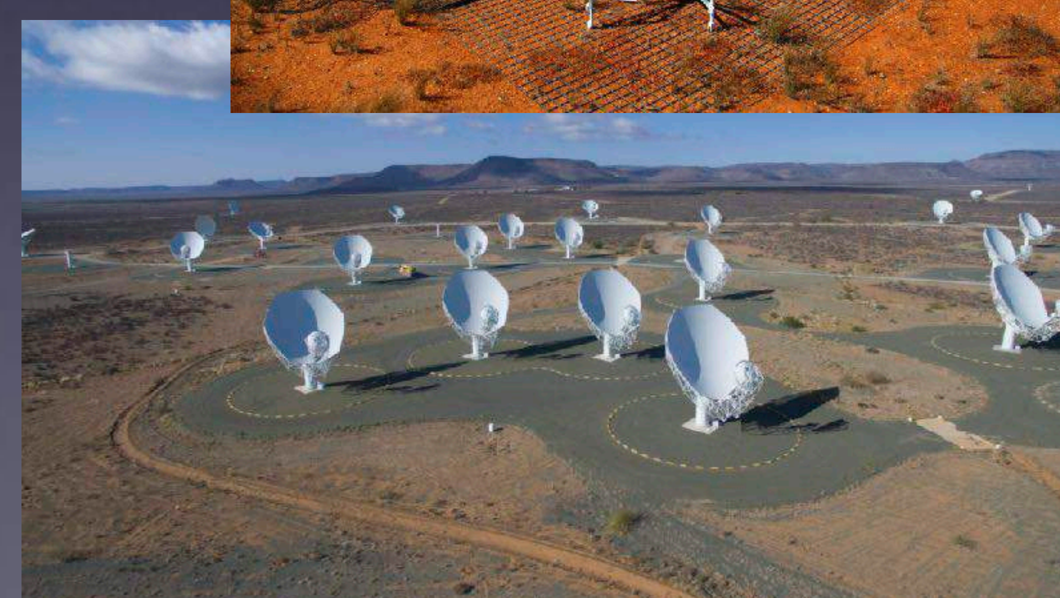
Kim J., Park C., L'Huillier B., Hong S. E. 2015

Precursors

- Australian Square Kilometre Array Pathfinder (ASKAP) - *SKA Survey*
    - 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

- Murchison Widefield Array (MWA) - *SKA low*
    - Tiles of 4x4 dipole antenna (150 MHz)
    - Core area has 50 antenna tiles uniformly distributed over a 100m diameter core, surrounded by 62 tiles, distributed over a 1.5 km diameter circle.
    - Drift-scan, FoV ~30 deg^2
    - Angular resolution ~ 2-3 arcmin

- MeerKAT (Karoo Array Telescope) - *SKA mid*
    - 64 13.5m dishes, with 48 concentrated in a 1km core
    - 580 MHz up to 1.65 GHz
    - Field of view ~ 1 deg^2



SKA

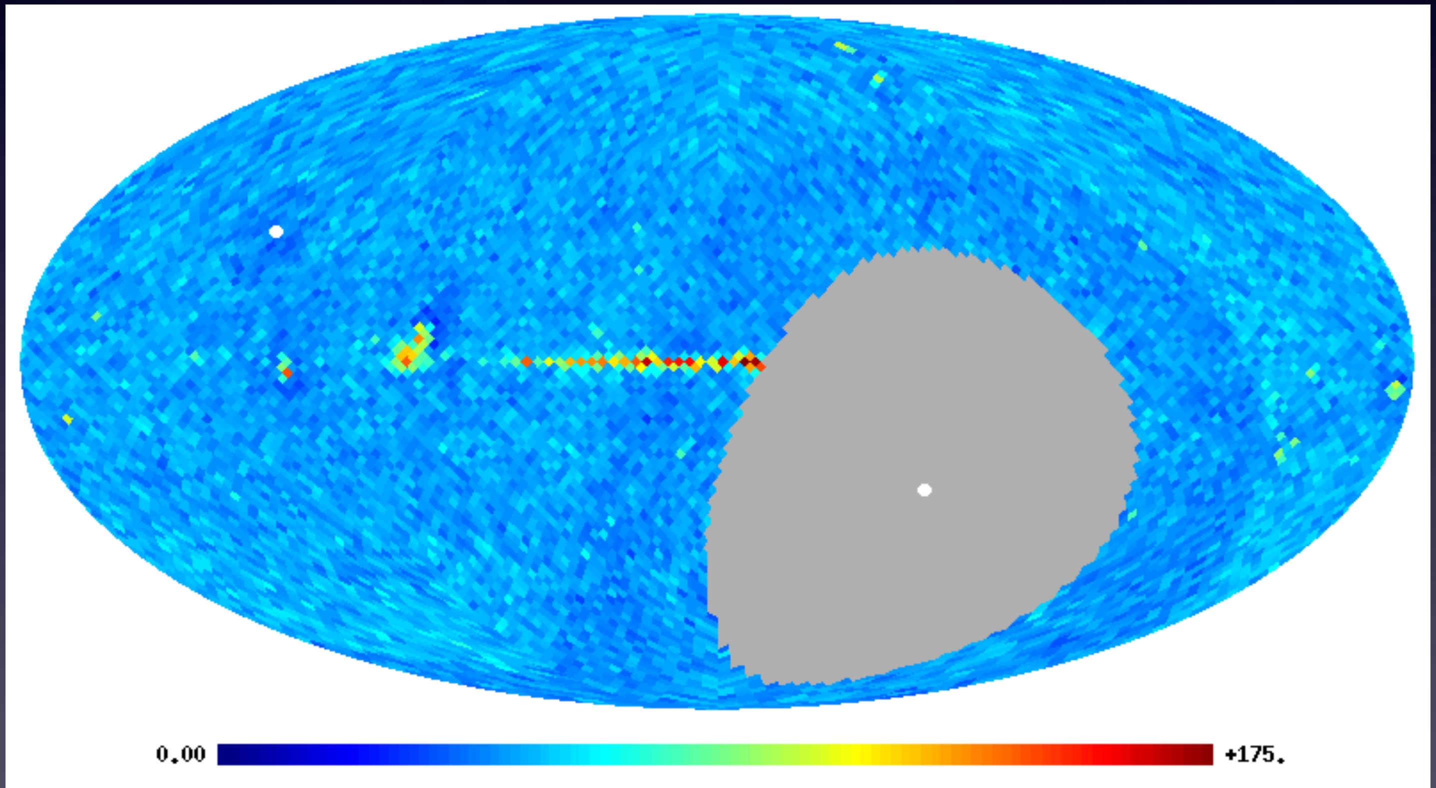
- SKA-low built in Australia (MWA site)
  - 100 stations, each containing 90 arrays of dipole antenna. Freq: 50-350 MHz
- SKA-mid built in South Africa (Karoo site)
  - 200 dishes, 13.5m diameter. Freq: 350 MHz to 1.76 GHz
- No SKA-survey as part of SKA-1

2. Cosmology in the continuum

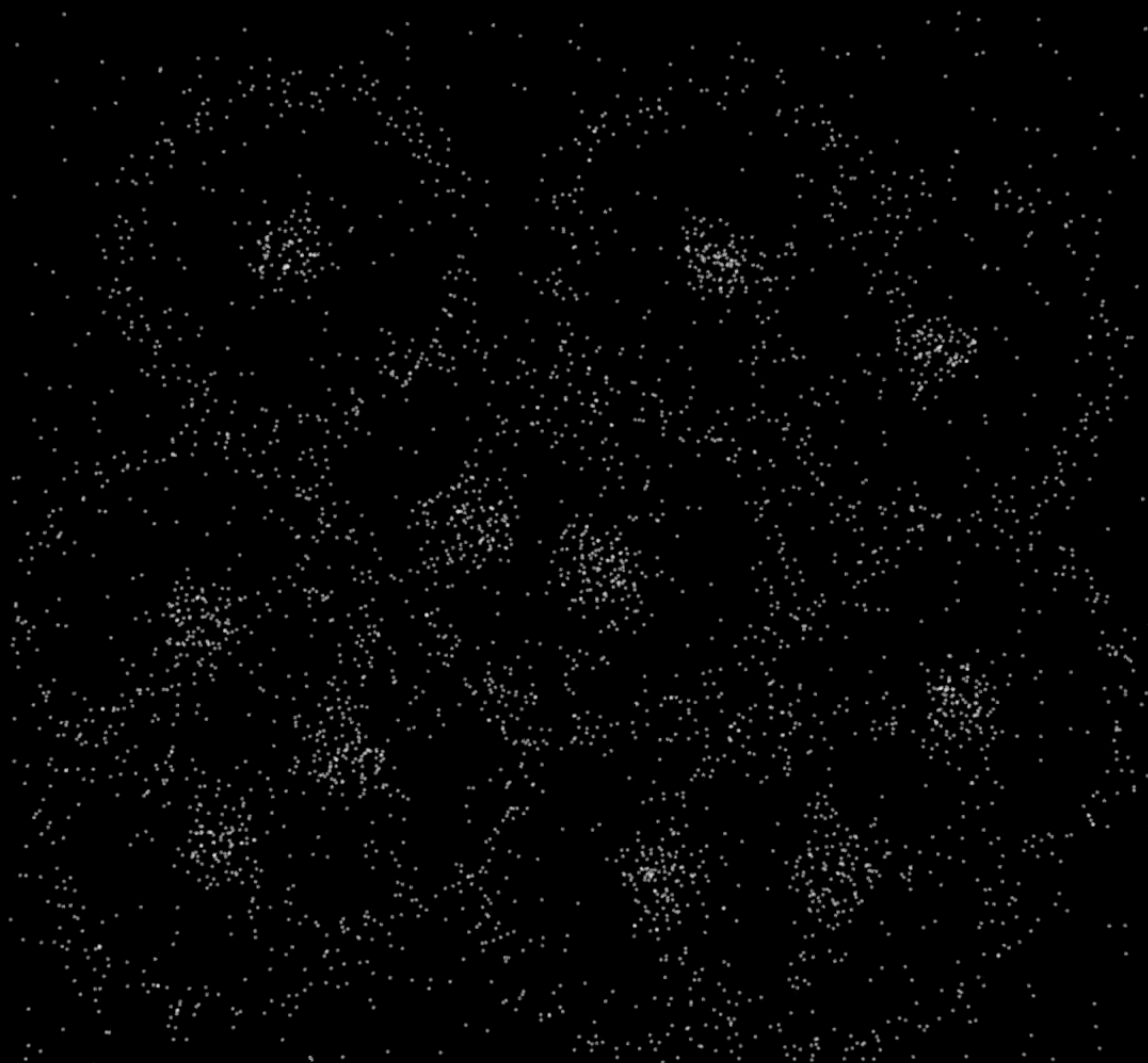
Continuum surveys

- 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 and Schwarz (2016)



CAASTRO
ALL-SKY ASTROPHYSICS

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

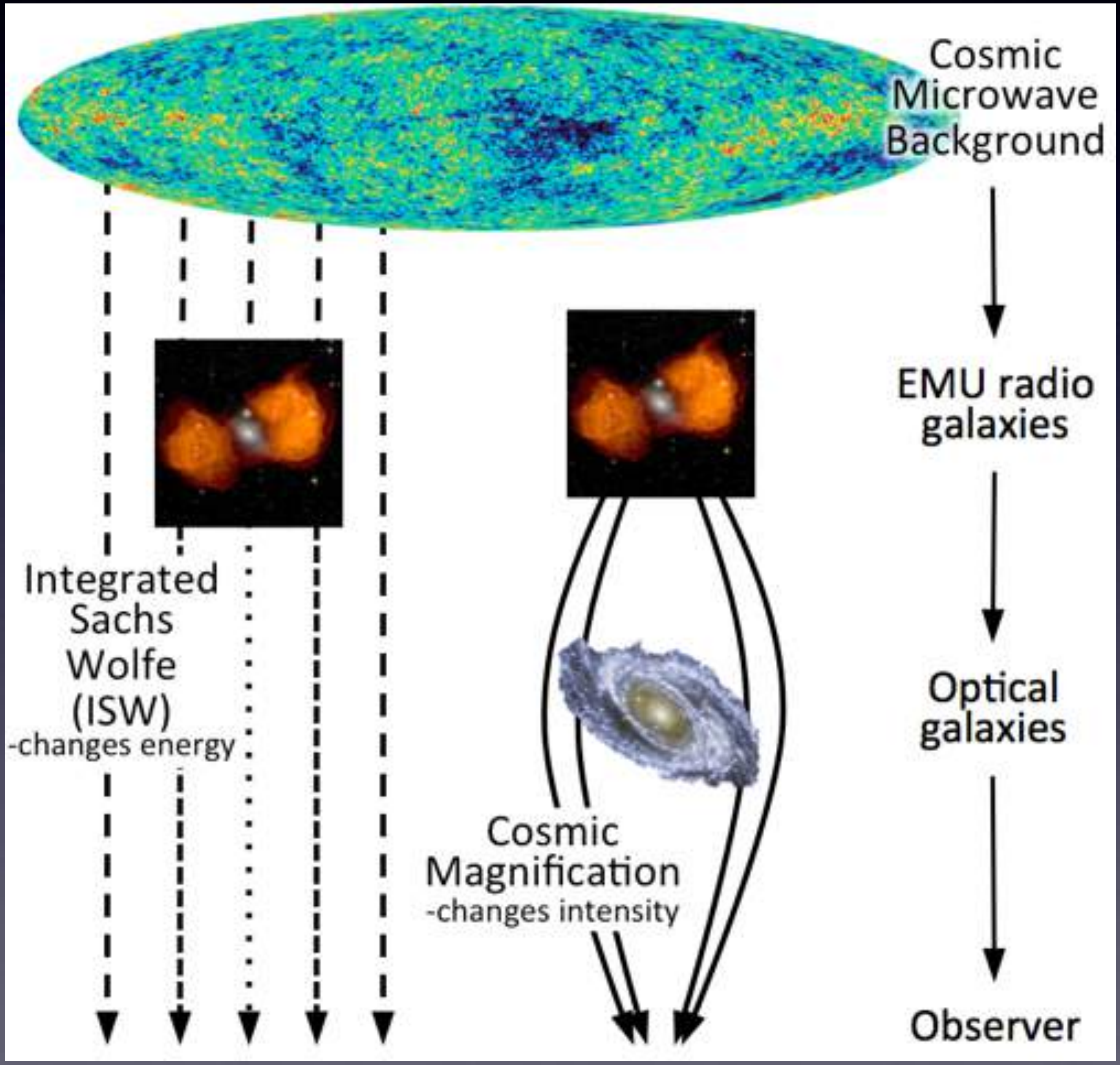


Image credit: Tamara Davis

Correlation functions

- All observables measured through correlations of objects
  - Angular power spectra = correlations of objects in the same bin
  - Magnification = correlations of objects in different bins, or objects with CMB
  - ISW = correlations of objects with CMB

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

- Need to understand the window function Wl(k) of different populations

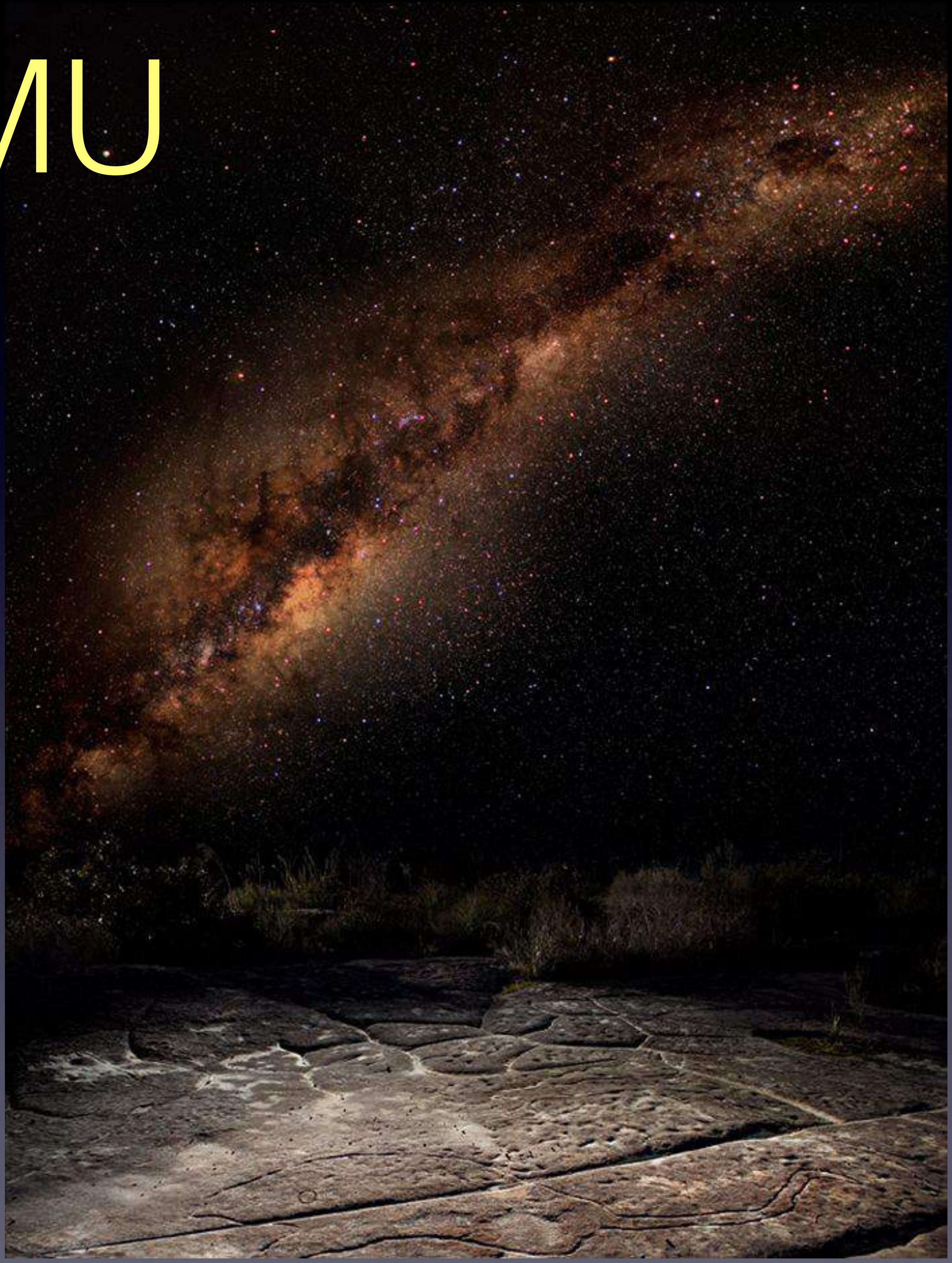
$$W_\ell(k) = \int j_\ell(kr) b(z) \frac{dN(z)}{dz} dr$$

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

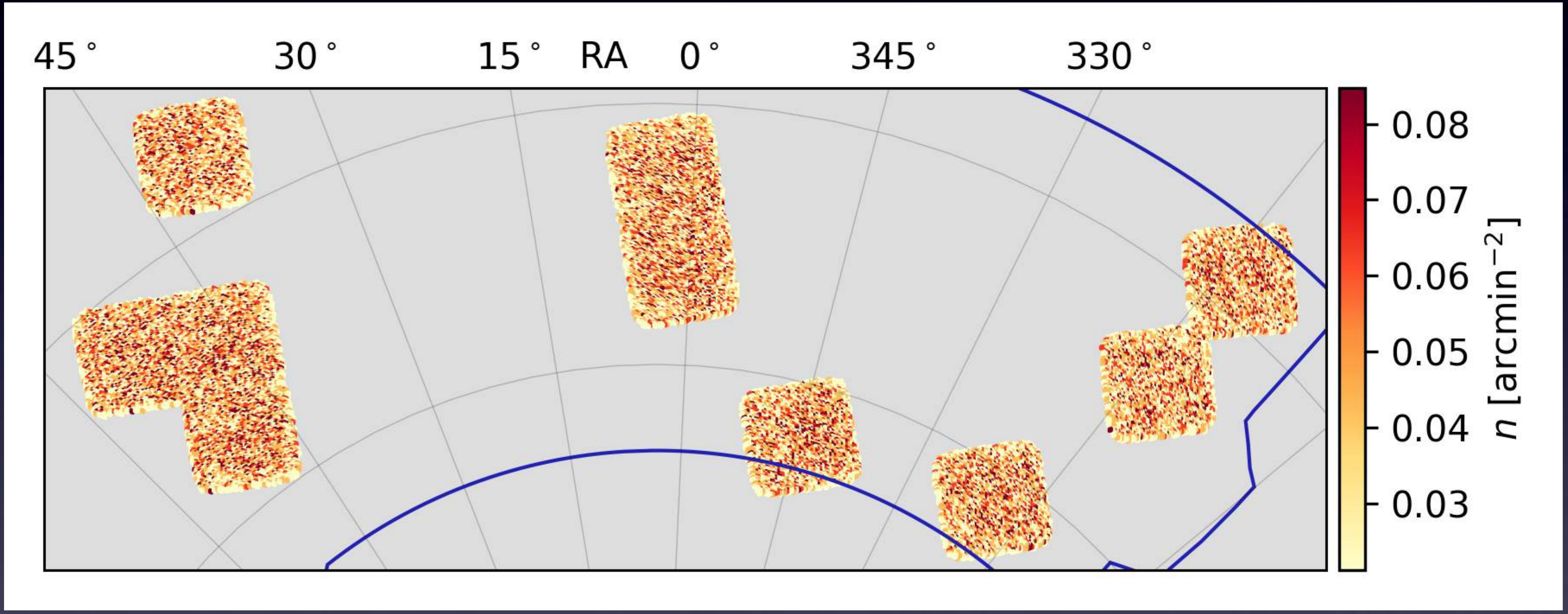
3. All-sky continuum surveys

EMU

- EMU (Evolutionary Map of the Universe) is an all-sky radio survey using ASKAP
  - 75% of the sky to declination +30°
- Frequency range: 1100-1400 MHz
  - Same as WALLABY, but EMU is continuum imaging, not 21cm spectroscopy
- 40 x deeper than NVSS
  - 10 μJy rms across the sky
- 5 x better angular resolution than NVSS (10 arcsec)
- Will detect and image ~70 million galaxies
  - All data to be processed in pipeline
  - Images, catalogues, cross-IDs, to be placed in public domain
- Survey starts end 2018
  - Early science has already started
- Total integration time: ~1.5 years

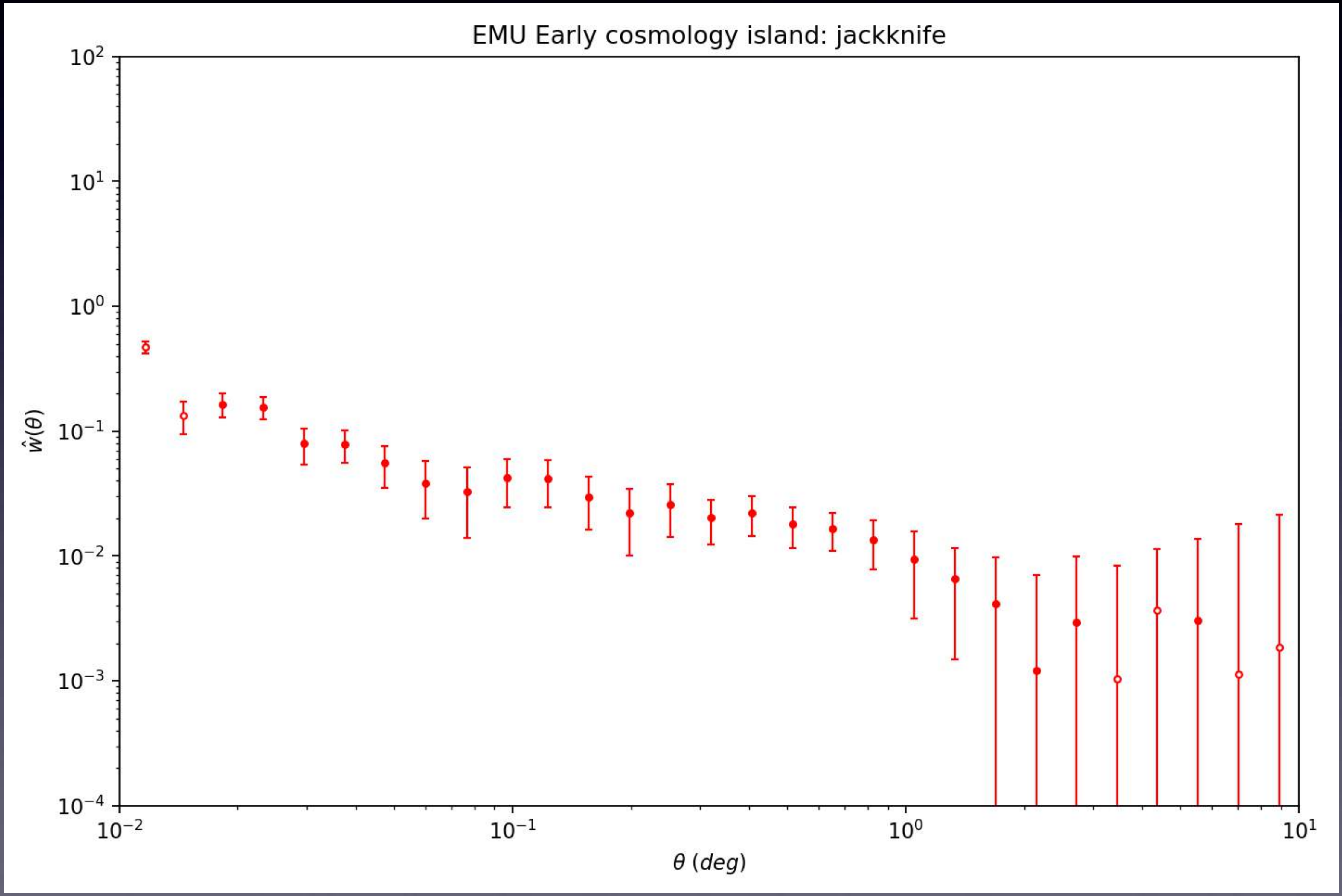


EMU Early Science Data

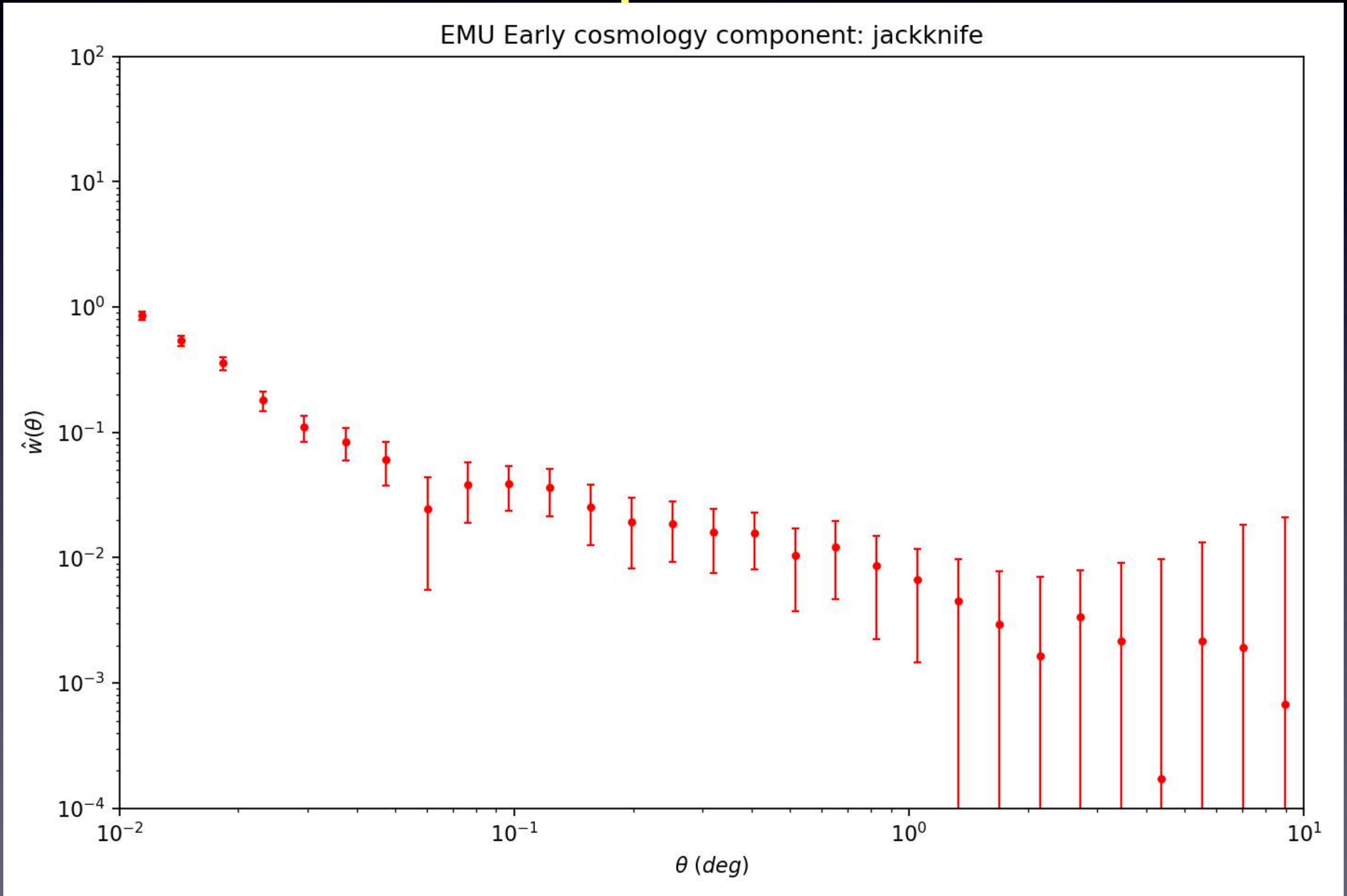


- Early Science Data from ASKAP-12, from 10 pointings
- Covers area inside Dark Energy Survey region
- Cross-identification using likelihood ratio between optical and radio sources (Sevilla-Noarbe, Seymour, Asorey and Parkinson, in progress)

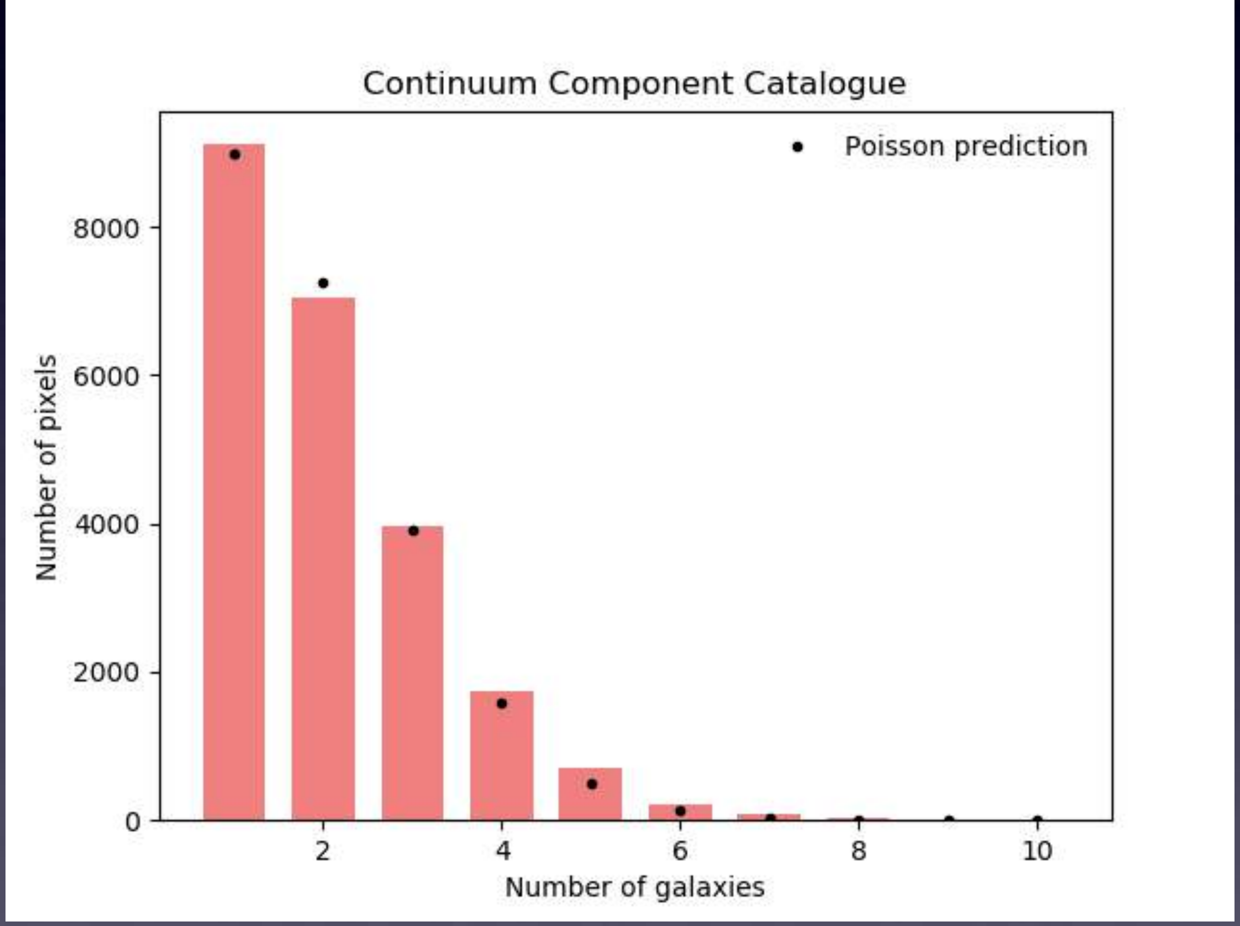
EMU Early Cosmology - Island

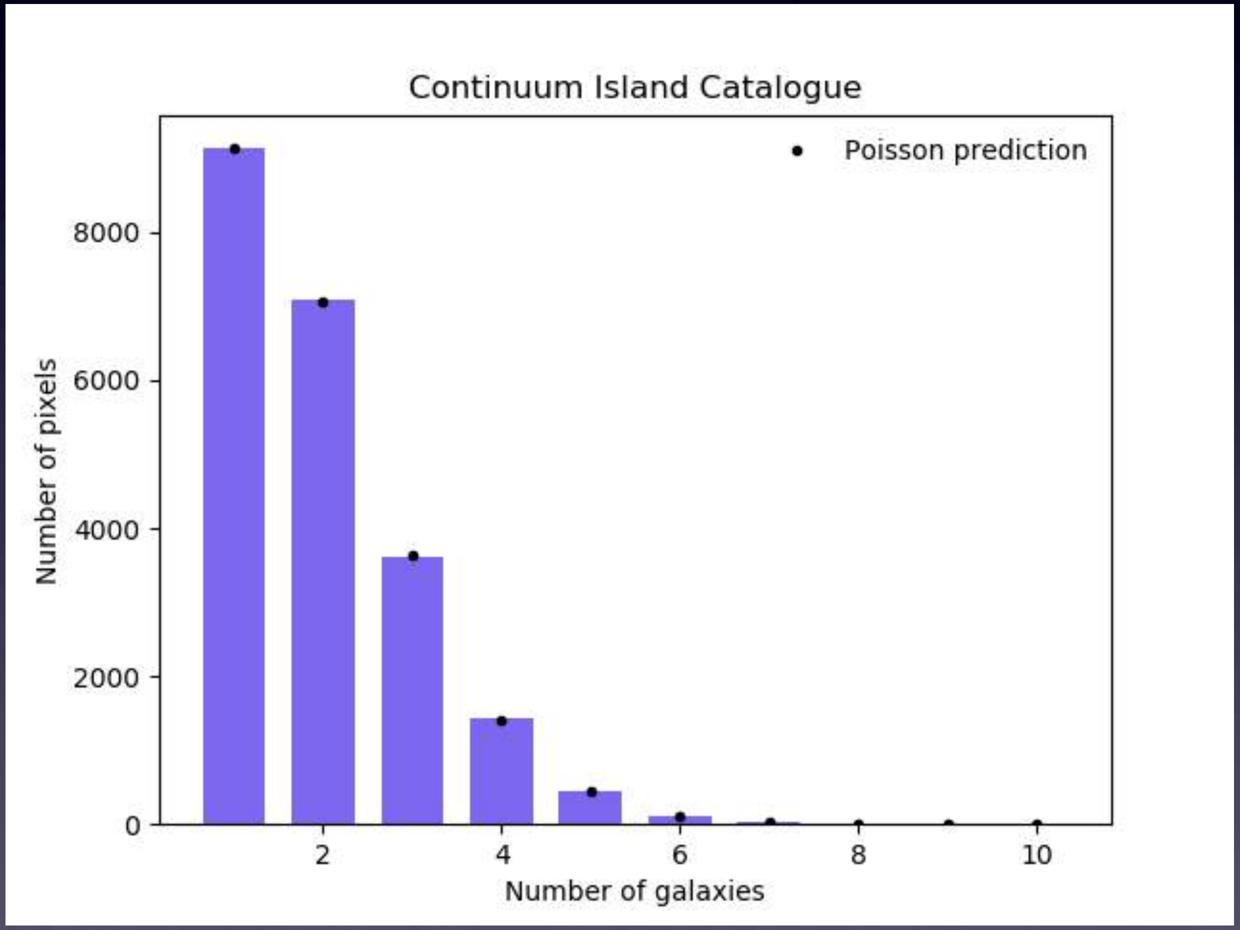


EMU Early Cosmology - Component



Histograms


Continuum Component Catalogue
Poisson prediction
Number of pixels
Number of galaxies
0
2000
4000
6000
8000
2
4
6
8
10


Continuum Island Catalogue
Poisson prediction
Number of pixels
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0
2000
4000
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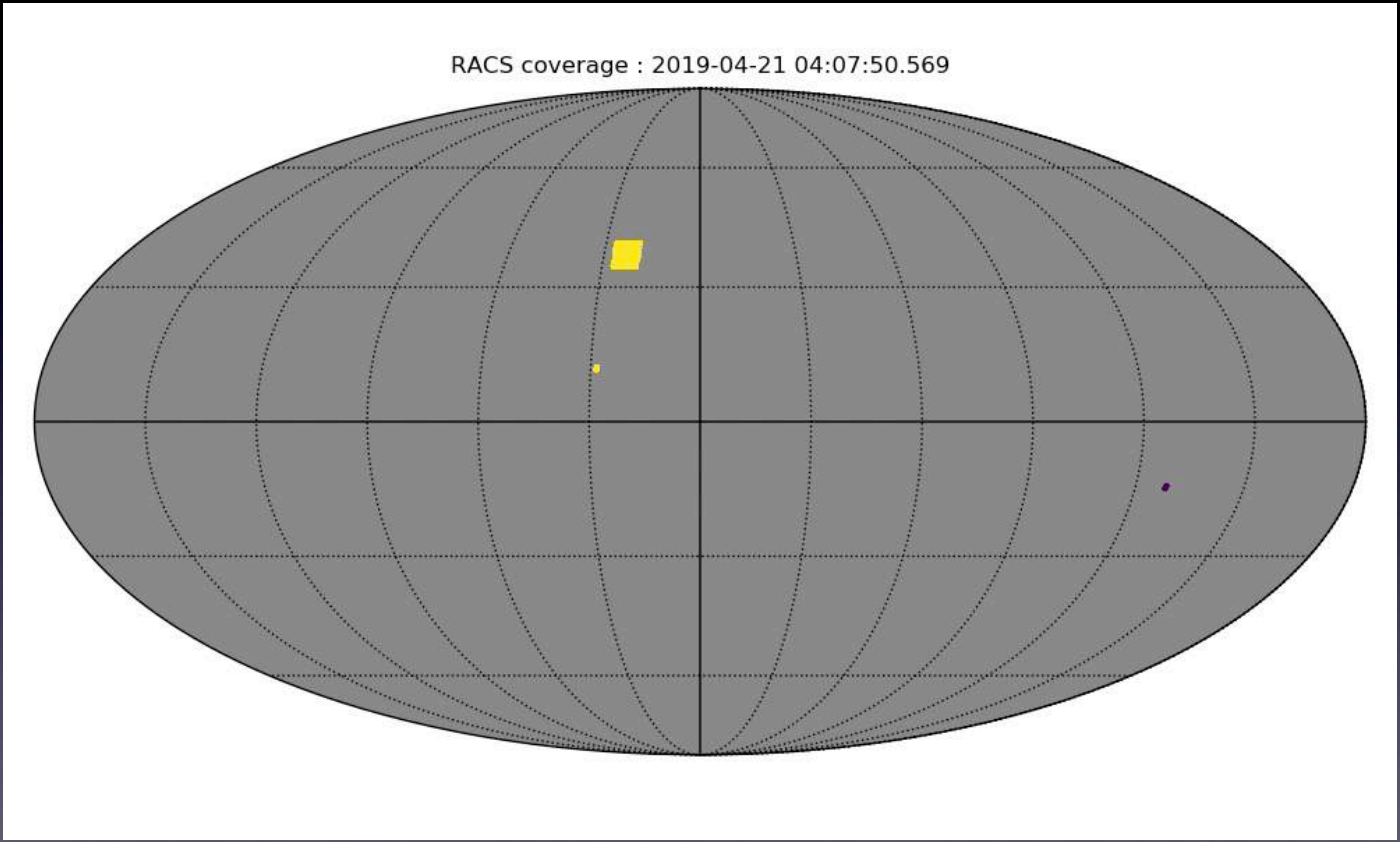
8000
2
4
6
8
10

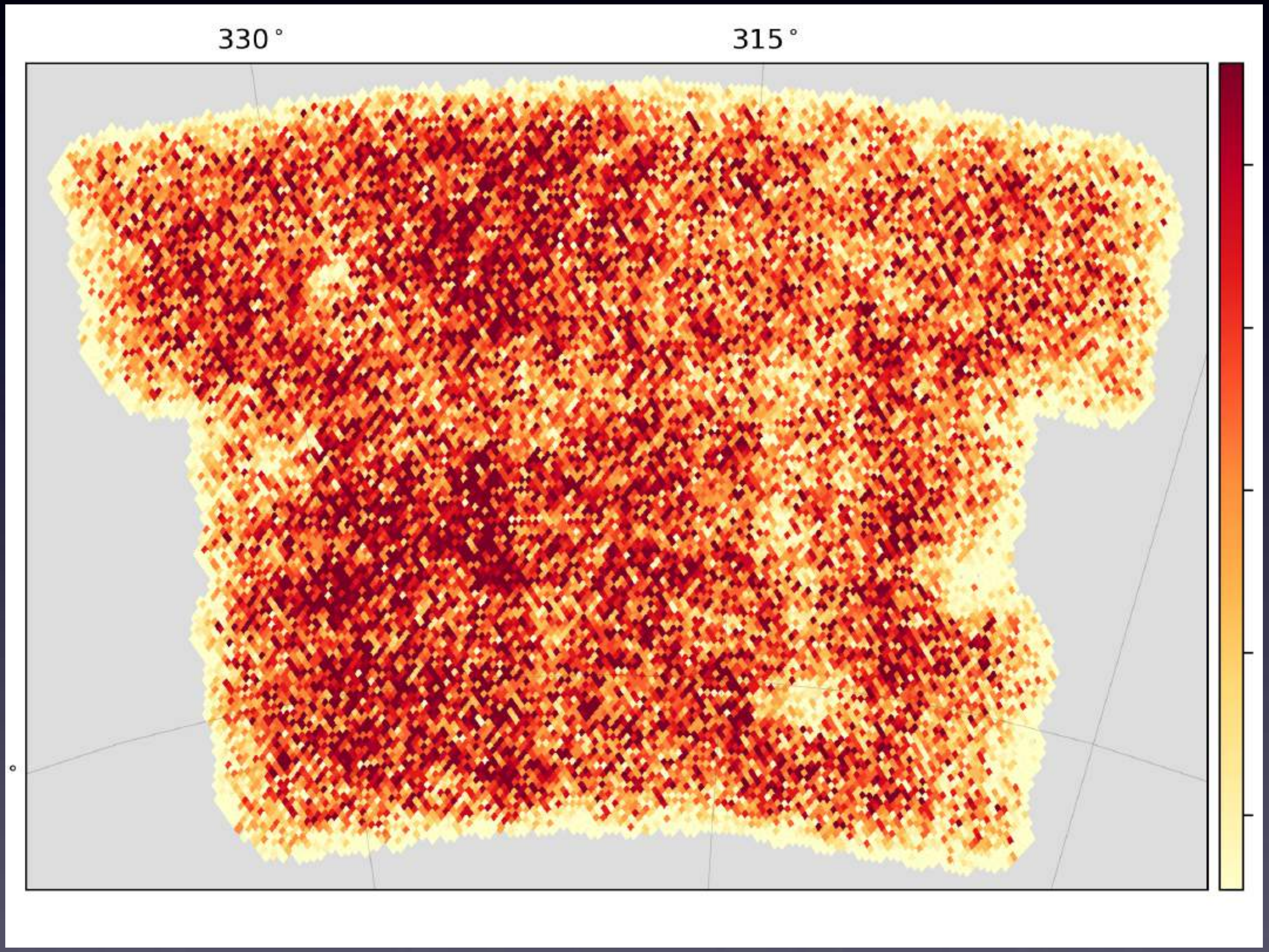
Estimators

- “Generally it is assumed that the variance of these estimators is the Poisson error of the bin counts” (Peebles 1980, Landy and Szalay 1993)
  - This is not true if there are double sources, as the bin counts will not be Poisson
- Landy-Szalay or similar is optimal estimator for Poissonian distribution - if not Poisson then not optimal
- Variance and bias of estimator may be under-estimated if points are not true tracers, but part of multi-component sources


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

EMU pilot data

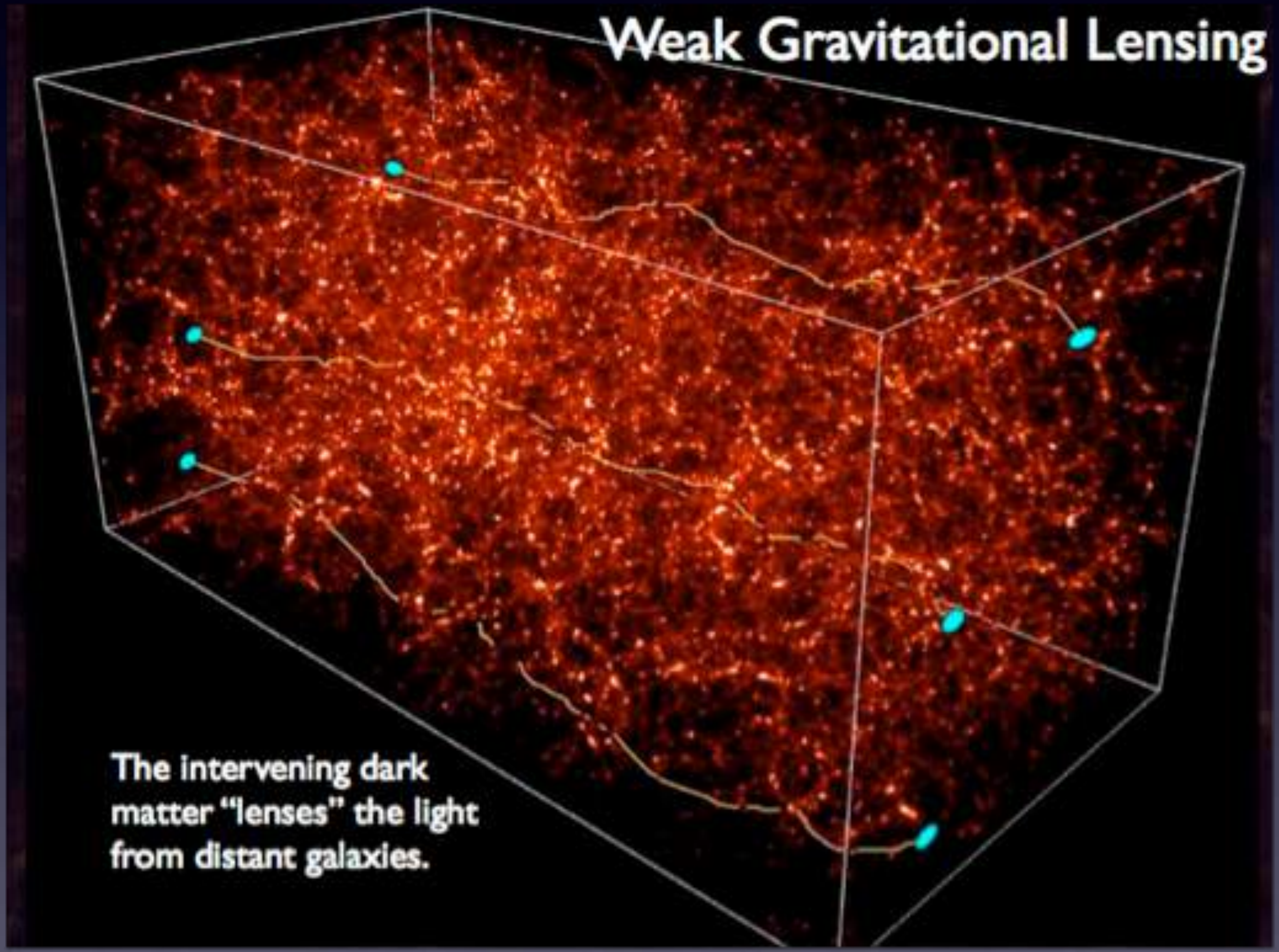
- New pilot data, over 10 fields (rough 270 sq. degs)
- Covers SPT deep field and part of DES
- ~250,000 sources
- Able to cross-correlate with DES and SPT lensing maps



4. Magnification

Cosmic Magnification

- The trajectories of photons are perturbed by the local gravitational potential
- This is gravitational lensing
- *Shear*: the ellipticities of galaxy shapes become correlated with the matter density, integrated over the whole photon trajectory
- *Magnification*: the brightness/ surface density of distant galaxies becomes correlated with the matter density integrated over the whole photon trajectory



Magnification and Density

- Measured density field has correction due to gravitational lensing magnification

$$\delta_n = \delta_g + \delta_\mu$$

- Effect takes the form of some 'magnification bias'

$$\delta_\mu(\theta, z_0) = (5s(z_0) - 2) \times \int_0^\infty dz \frac{c}{H(z)} g(z, z_0) \nabla_\perp^2 \phi(\chi(z)\theta, z_0)$$

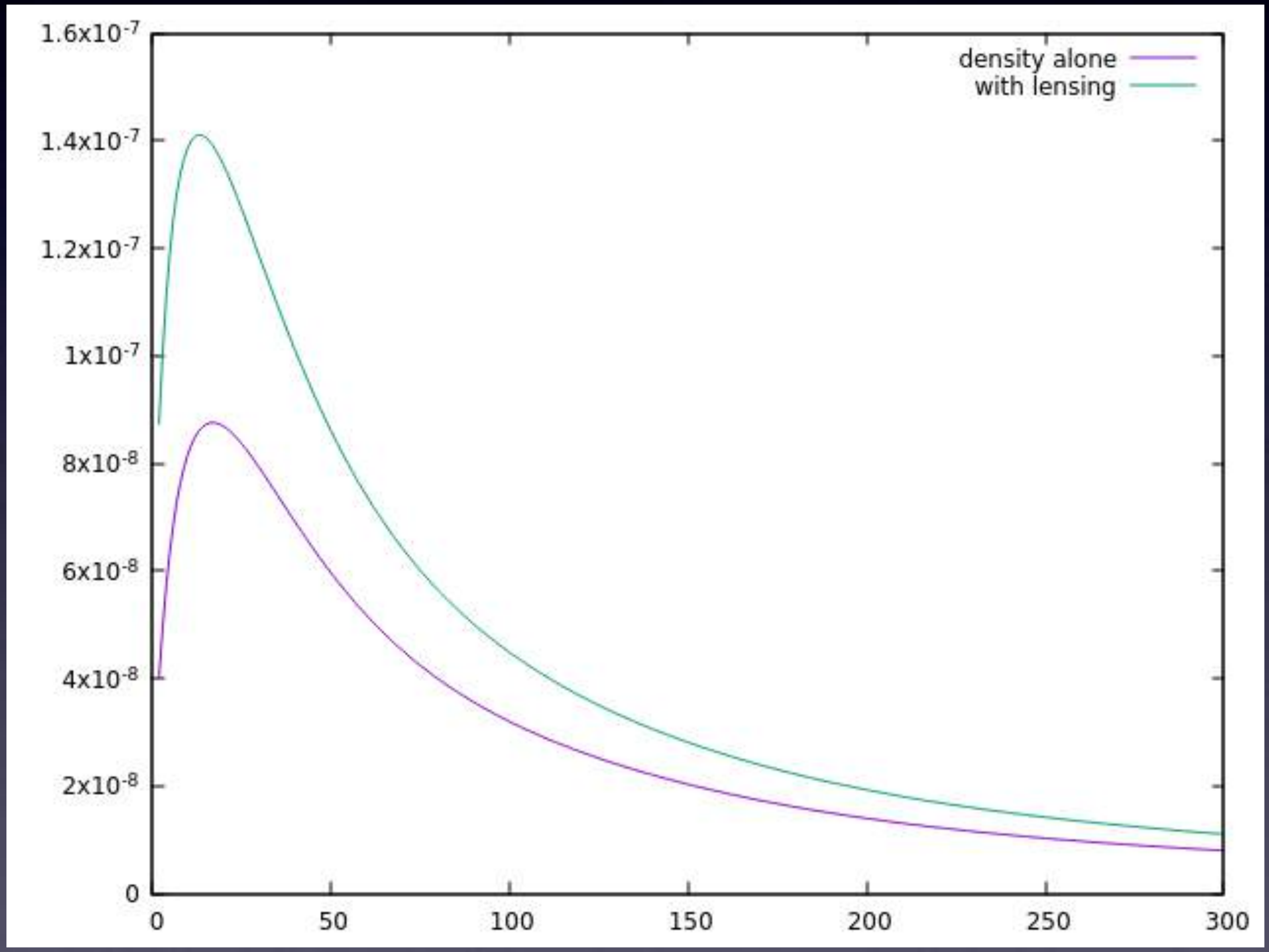
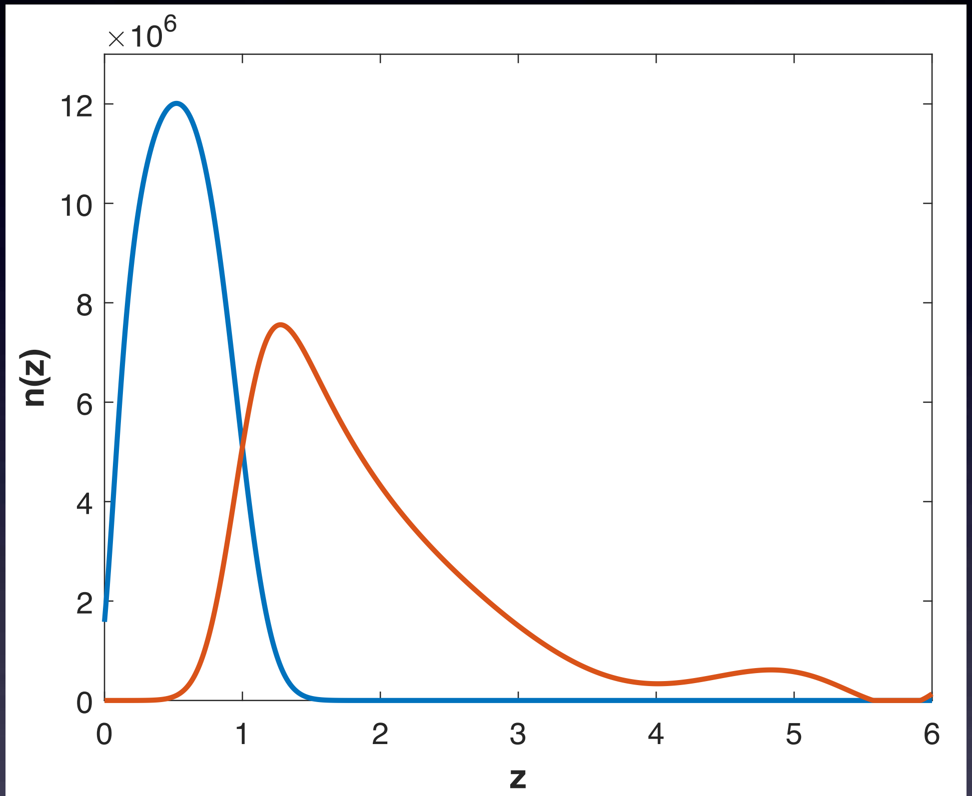
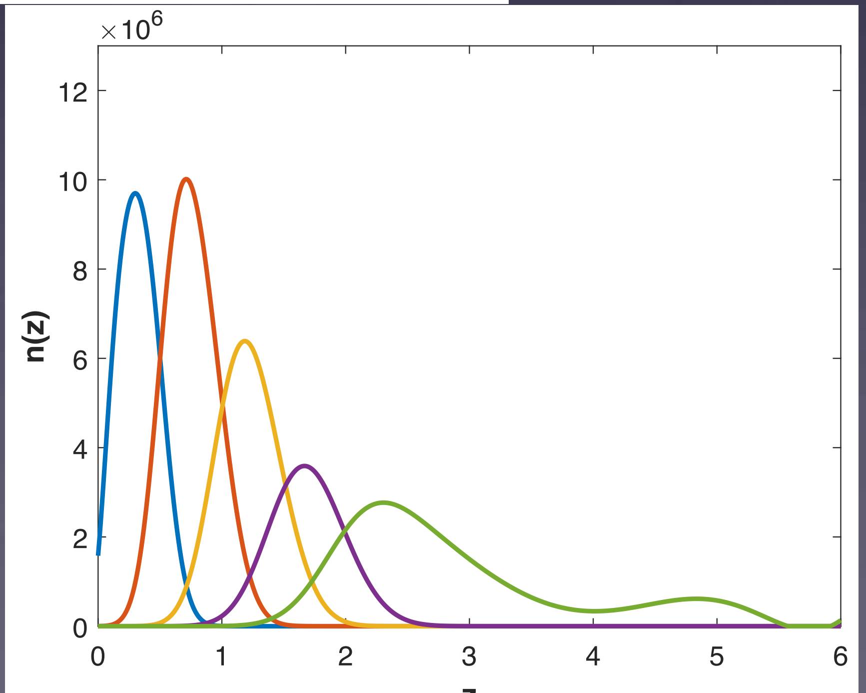


Image credit: Song Chen

EMU survey - photo-z bins

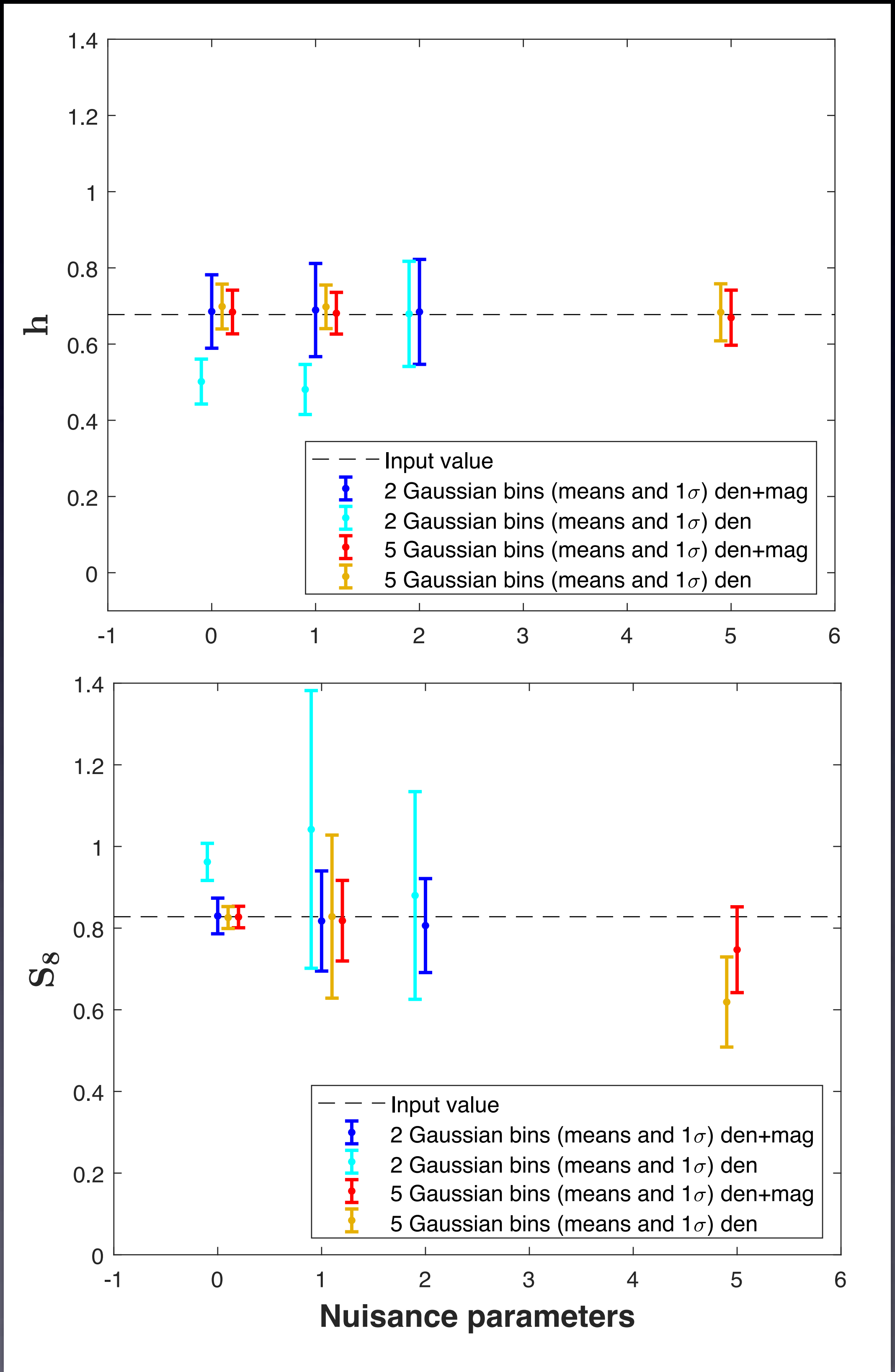
- We consider the EMU survey will a number of different photometric redshift bins
    - Two bins and five bins
- We compute auto- and cross-angular power spectra, and measure cosmology
- How biased is our result if we do not include magnification in cross-correlation?



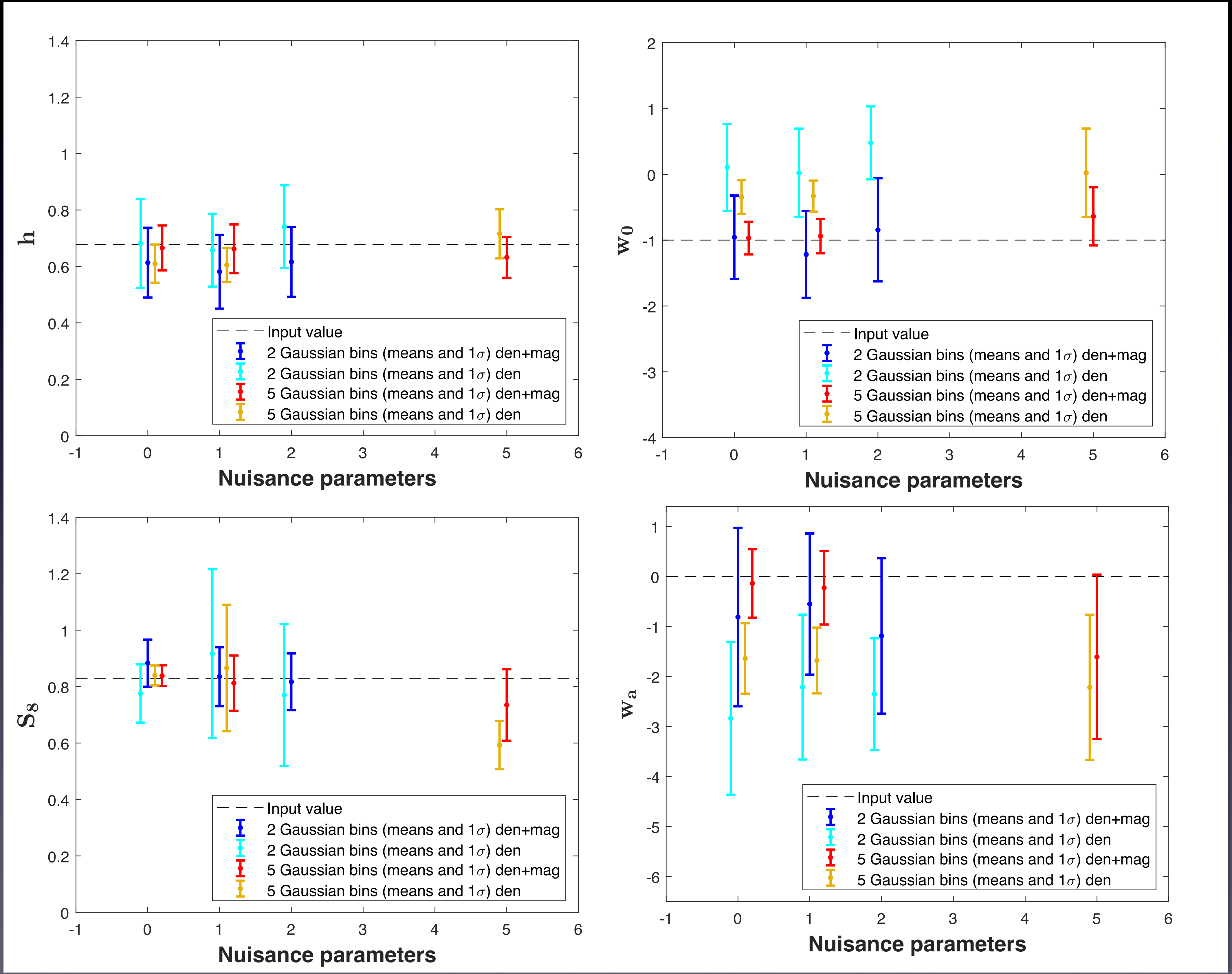


ΛCDM

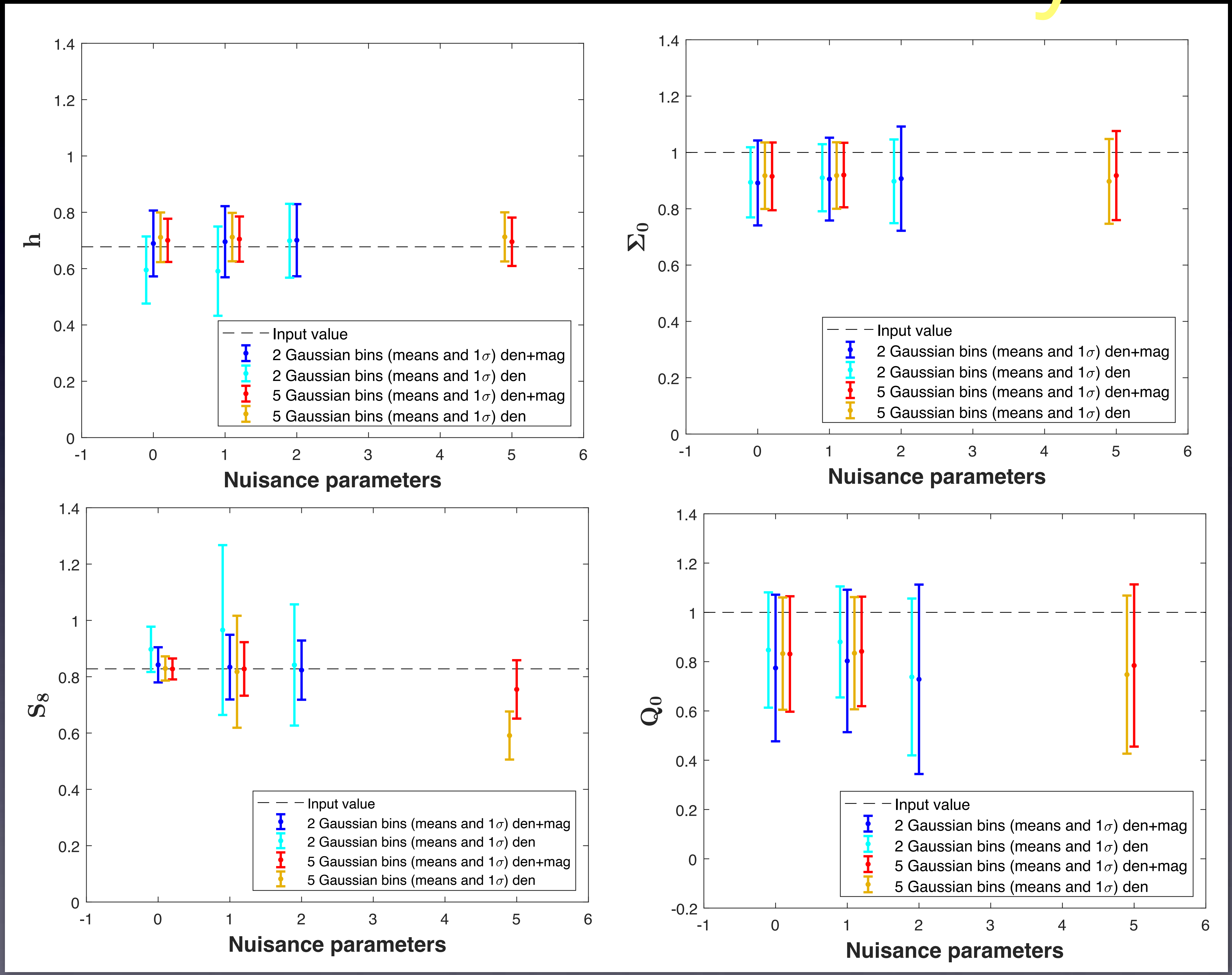
- In the two bin case not including magnification can introduce a offset (higher amplitude, lower hubble rate) compared to the input cosmology, to match the missing boost created by magnification.
- This can be reduced by introducing an evolving bias, which matches the data through the nuisance parameter
- The five bin case works in reverse, as an evolving bias can mimic magnification in the high redshift bins, which leads to a predicted power deficit at low redshift



wCDM


h
w_0
S_8
w_a
Nuisance parameters
Input value
2 Gaussian bins (means and 1σ) den+mag
2 Gaussian bins (means and 1σ) den
5 Gaussian bins (means and 1σ) den+mag
5 Gaussian bins (means and 1σ) den

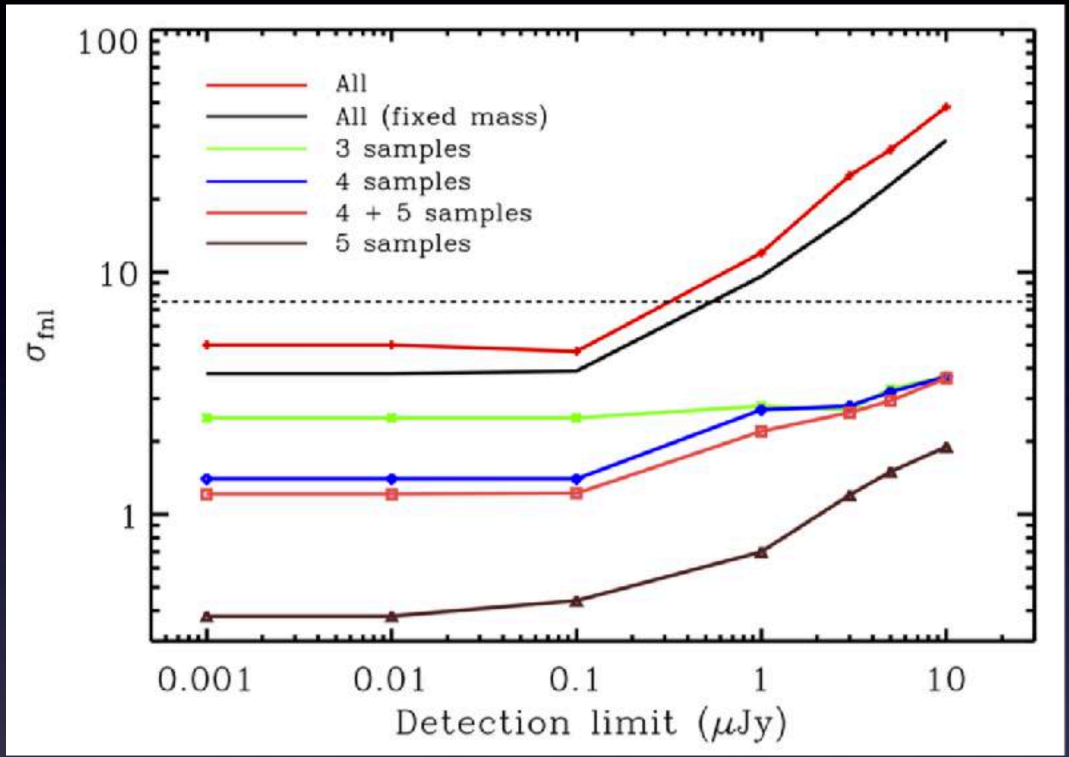
Modified Gravity



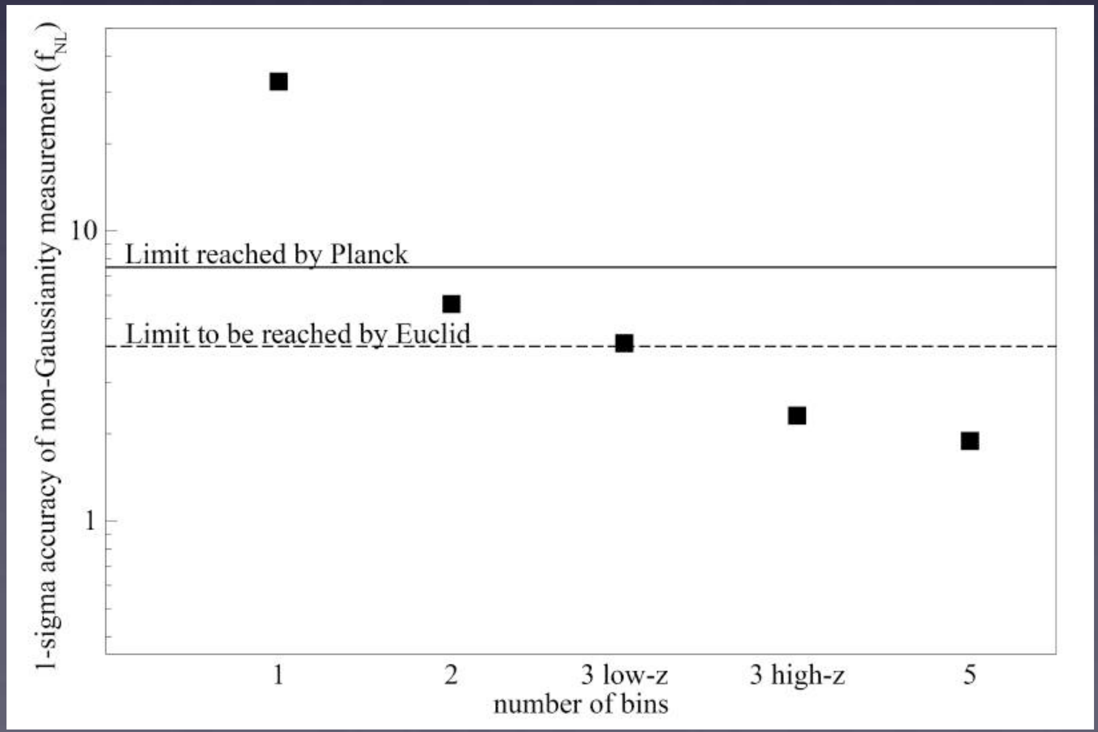
5. Cross-correlations

Cross-correlations

- Almost all LSS probes are systematic limited
- Combinations can remove systematics, as well as providing new cosmological tests
- Multi-tracer: Cross-correlating galaxy populations with different bias allows some quantities to be measured without cosmic variance
- Cross-correlating continuum/IM with large-area optical/IR (e.g. LSST) can improve measurement of primordial nonGaussianity/GR effects



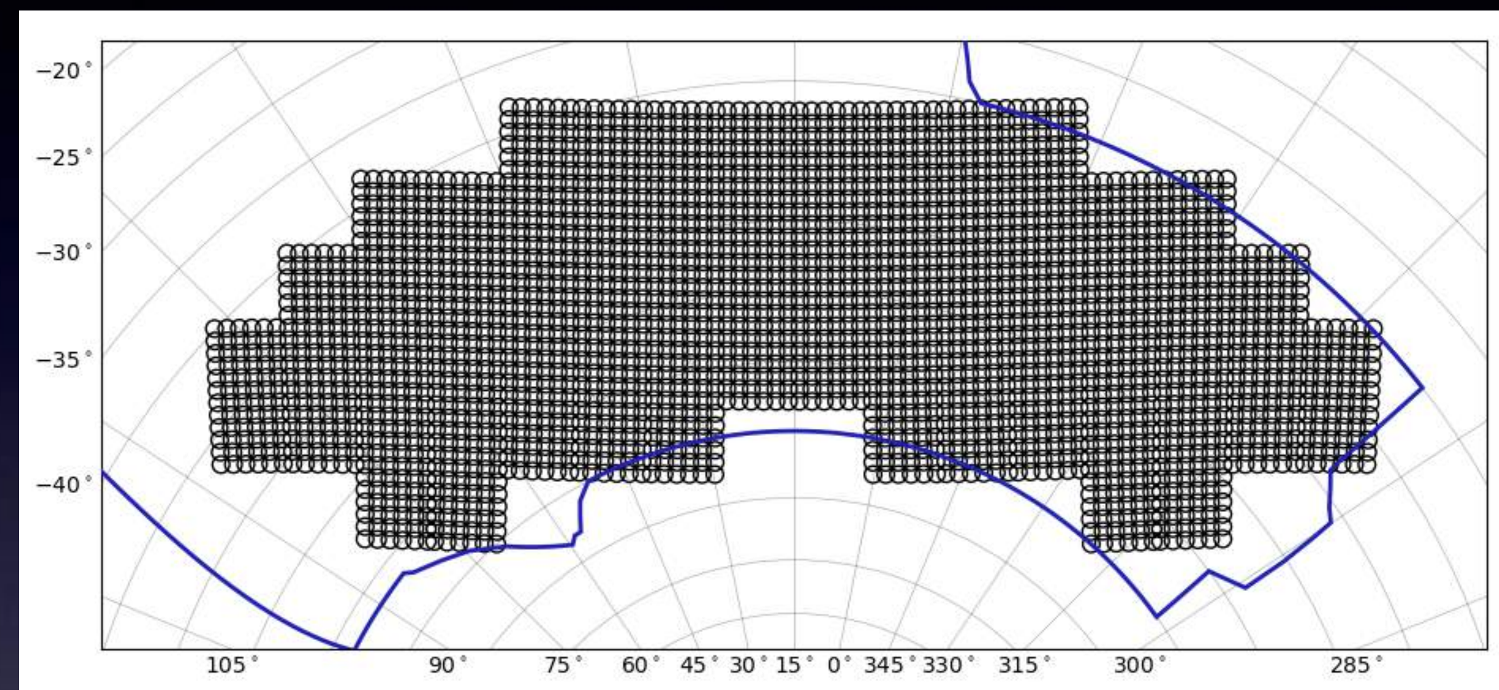
Ferramacho et al. (2014)

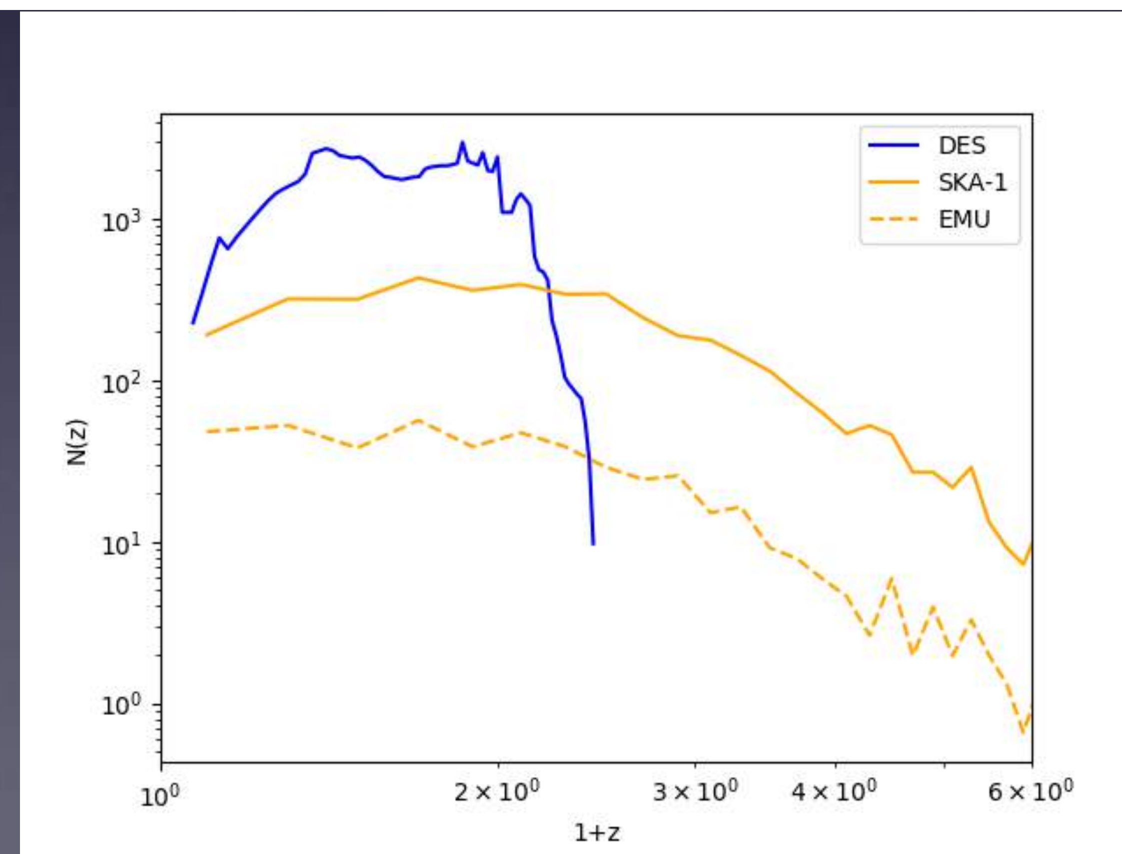


Raccanelli et al. (2015)

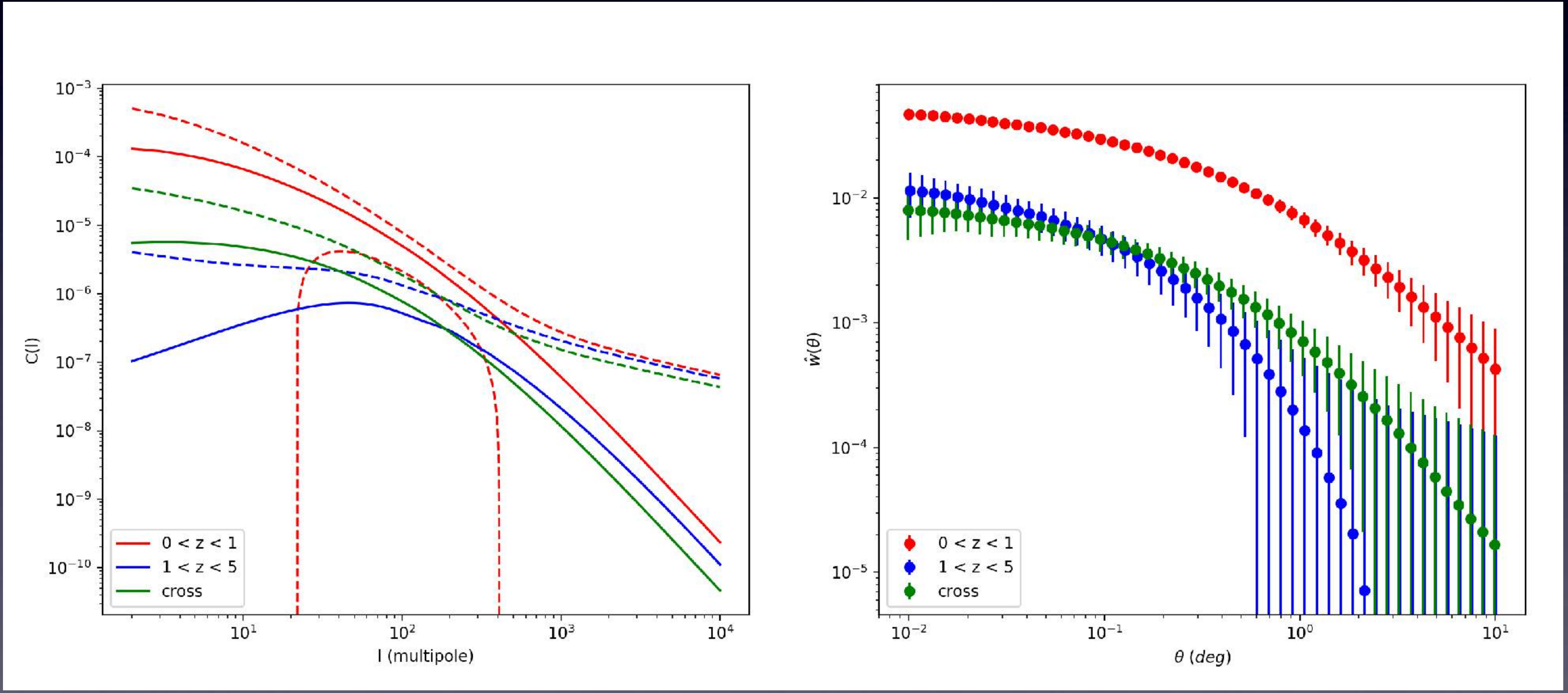
EMU-early & DES

- Improves the cosmology we can do
  - Cosmic magnification require cross-correlation between bins (i.e. two radio bins, high-z radio with low-z optical, high-z CMB with ‘low redshift’ radio sources)
  - ISW requires CMB information
- Improves our redshift estimates
  - Clustering redshifts, and photo-z information from optical/NIR counterparts
  - DES will provide photo-z information, to split the EMU sample into redshift bins





Magnification



Summary

- The next generation of radio surveys will make deep surveys over a wide area, approaching their confusion limit
  - Number of detected extra-galactic radio sources will increase to > 10^8
- The large volume will allow us to access the matter power spectrum of density fluctuations on the largest possible scales, detecting:
  - the imprint from the initial conditions of the Big Bang (non-Gaussianity)
  - the effect on the propagation of light over large-distances (magnification and ISW)
- This will deliver complementary and independent constraints on the cosmological parameters
- Cross-correlation, with optical/IR data, will increase the detection and utility of the continuum map
- This is a good time to be involved in large radio projects!