Near-future Large Scale Radio surveys

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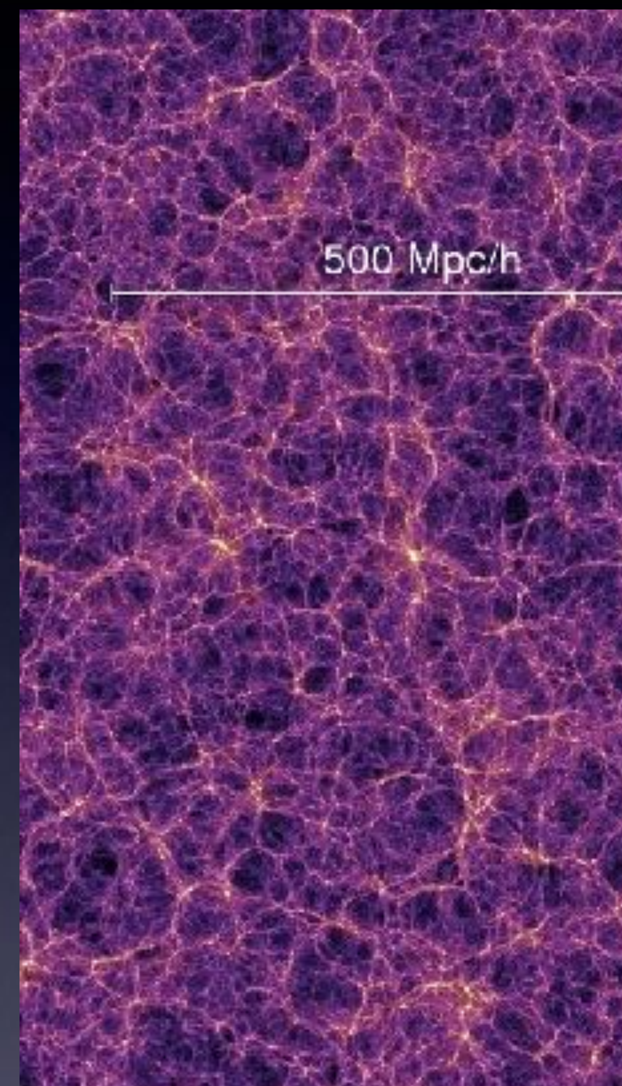
Outline

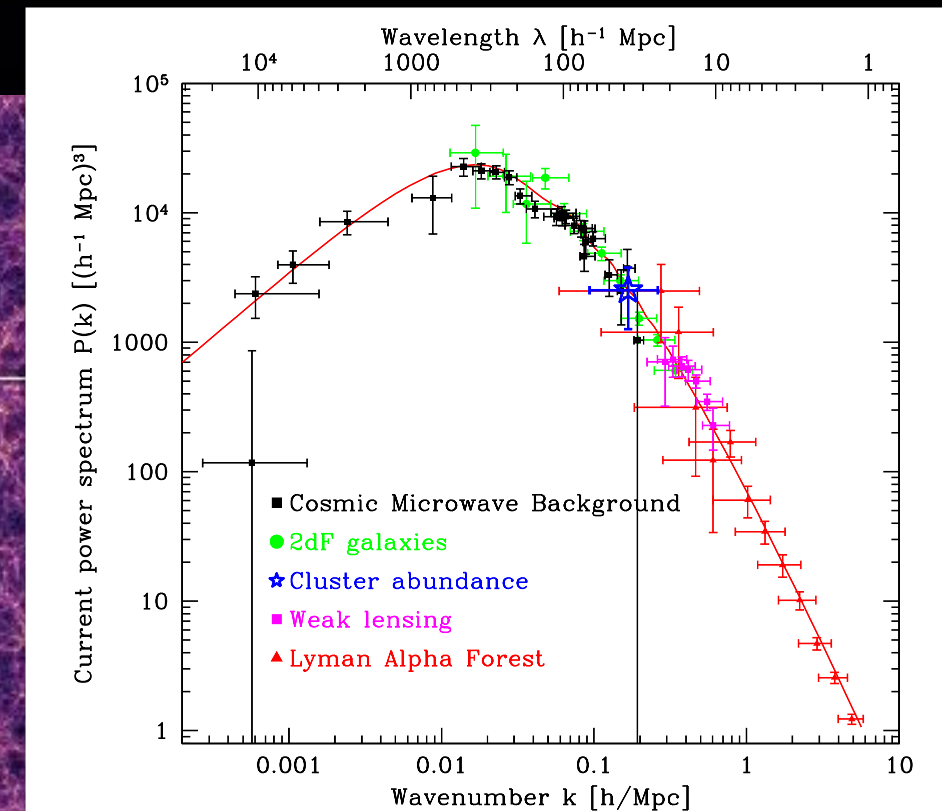
- Introduction
- All-sky radio surveys
  - Continuum
  - Intensity Mapping
- Cross-correlations
- Summary

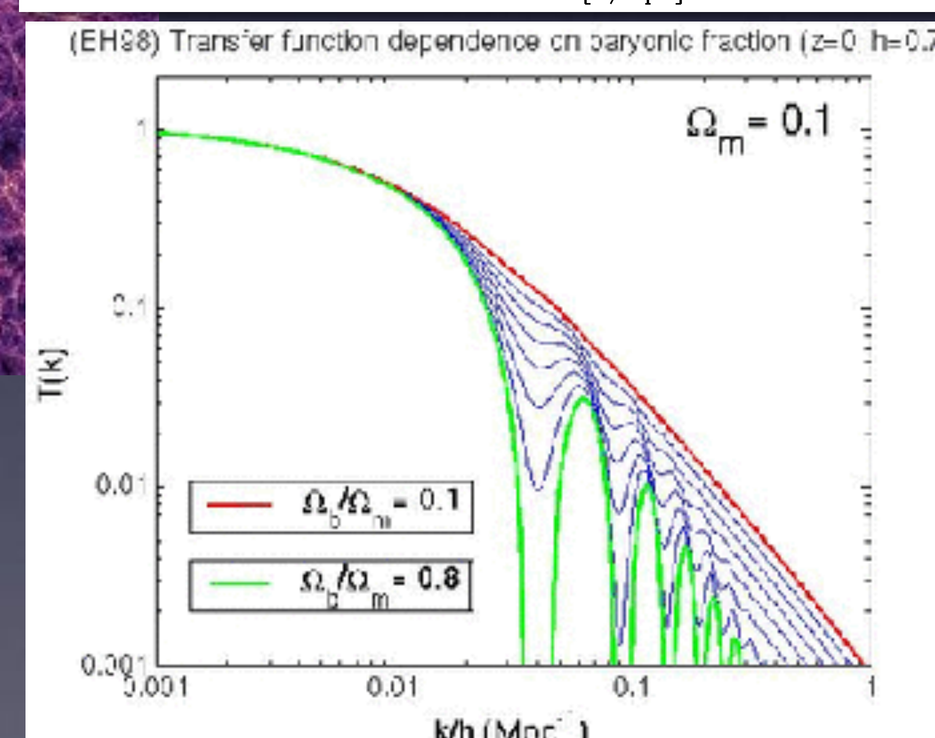
1.Introduction

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

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

Other experiments

- Canadian Hydrogen Intensity Mapping Experiment (CHIME)
    - Four 100 x 20 metre semi-cylinders, 400-800 MHz
- Tianlai
    - 3 (15x40m) cylinders, 400-800 MHz
    - 16 (6m) dishes (800-1500 MHz)
- The Hydrogen Intensity and Real-time Analysis eXperiment (HIRAX)
    - 1000 6-m dishes, 400-800 MHz
- LOFAR
    - Dipole antenna - Low Band Antenna (LBA) 10-80 MHz and High Band Antenna (HBA) 120-240 MHz
    - 24 core stations, 14 remote stations, and 12 international stations

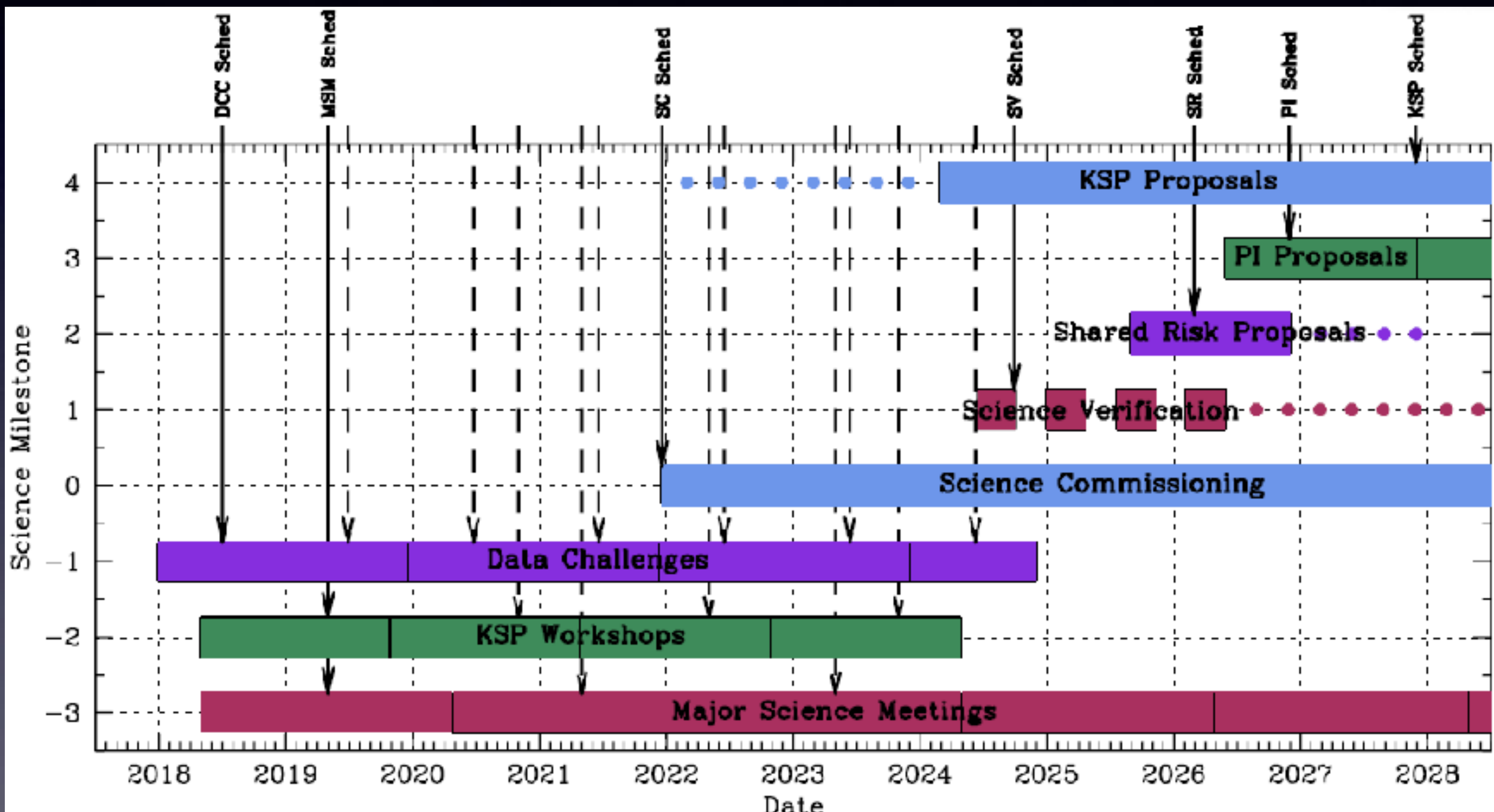
Credit: L. Zhang

The Tianlai Project – A Dark Energy Radio Observation Experiment

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

SKA timeline



Cosmology SWG

Chairs:

- Richard Battye & Laura Wolz

Focus group coordinators:

- Intensity mapping (Santos & Wolz)
- Weak lensing (Brown & Harrison)
- HI galaxies (Bull & Maddox)
- Continuum (Jarvis & Parkinson)
- Joint probes (Bacon & Camera)
- SKA-LOW cosmology (Pourtsidou & Pritchard)
- Simulations (Alonso & Villaescusa-Navarro)

3. All-sky radio surveys

a. Continuum

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

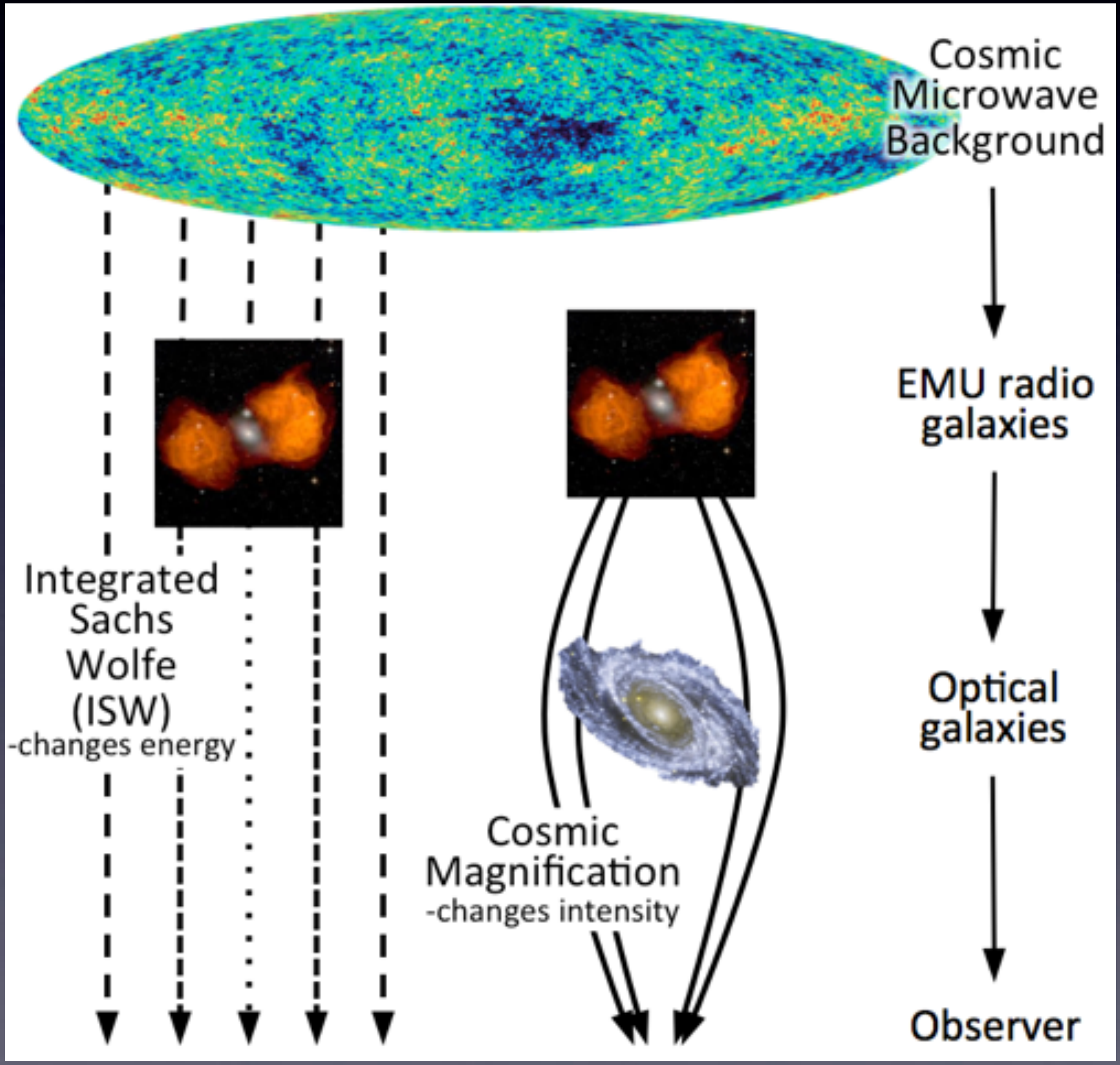


Image credit: Tamara Davis

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

Cosmic Magnification

- Measured density field has correction due to gravitational lensing magnification

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

- Effect takes the form of some ‘magnification bias’

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

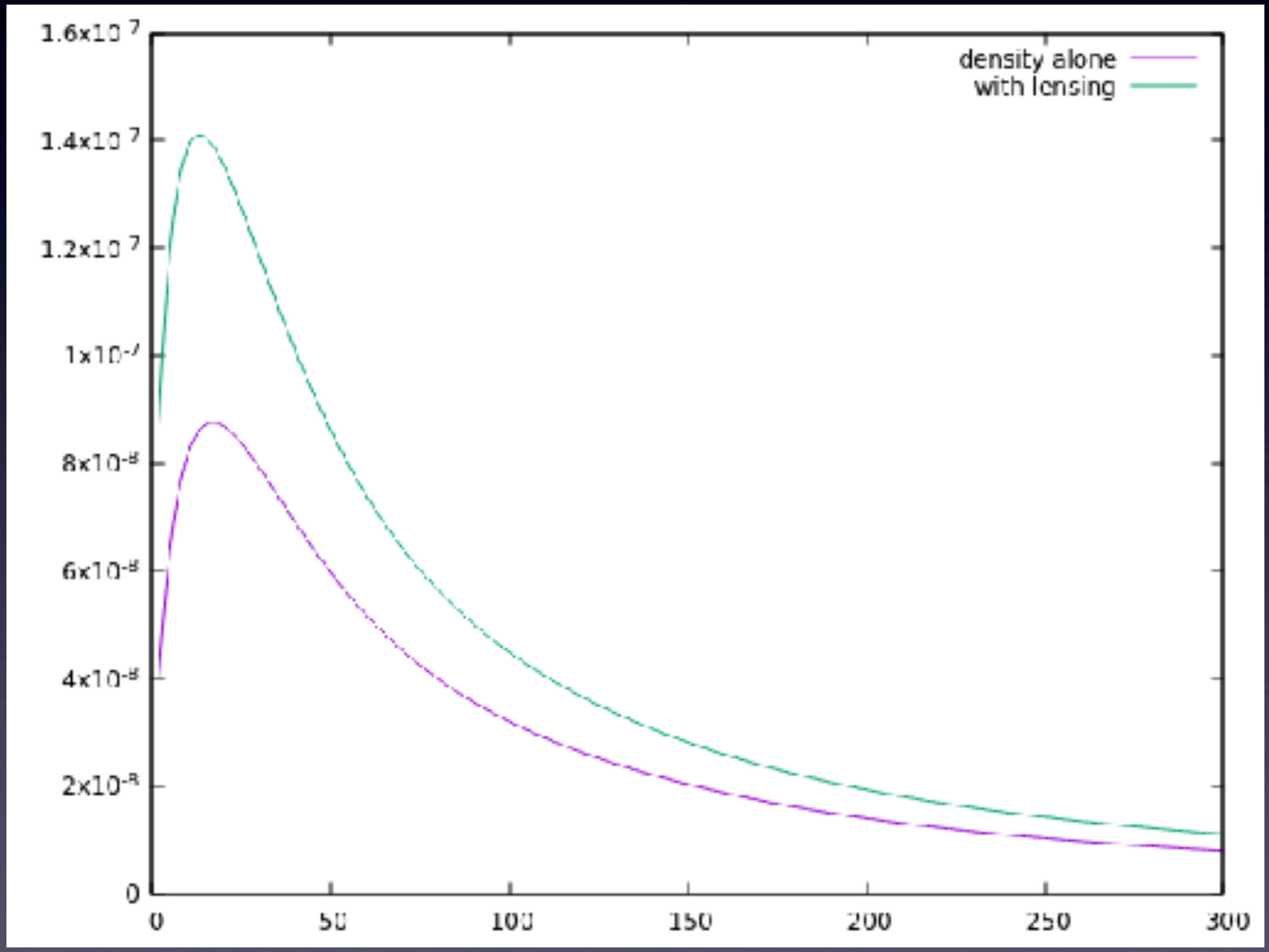
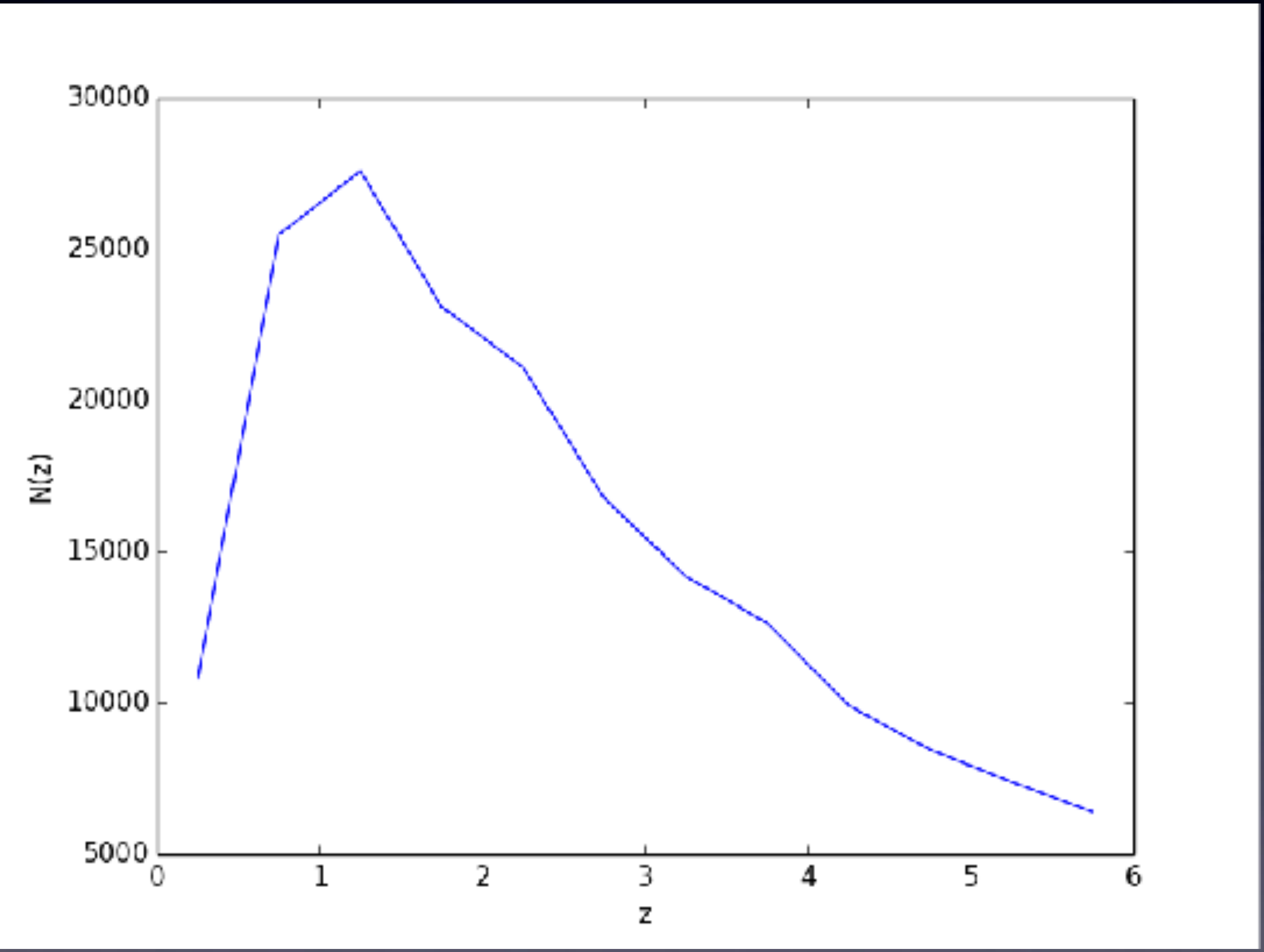
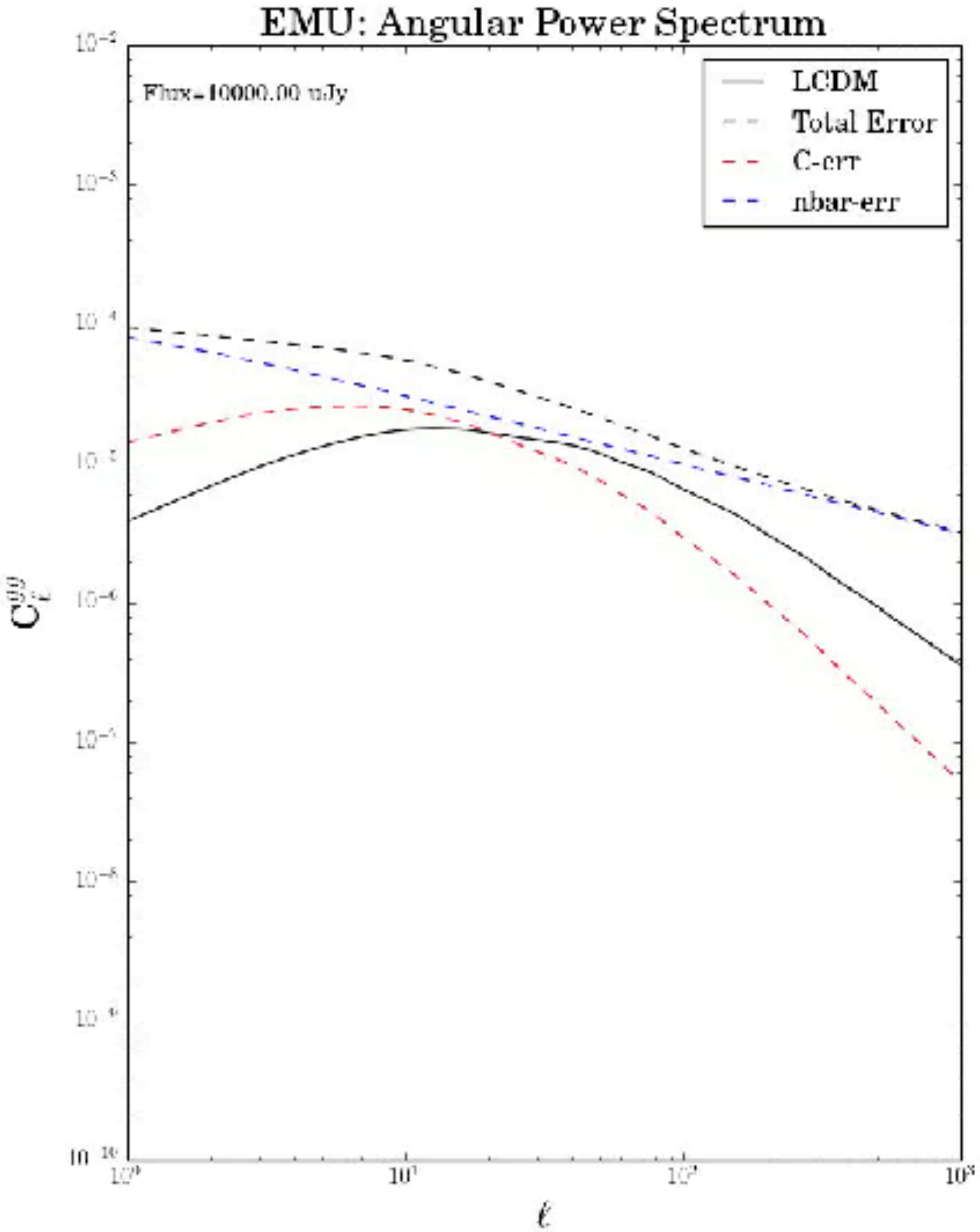


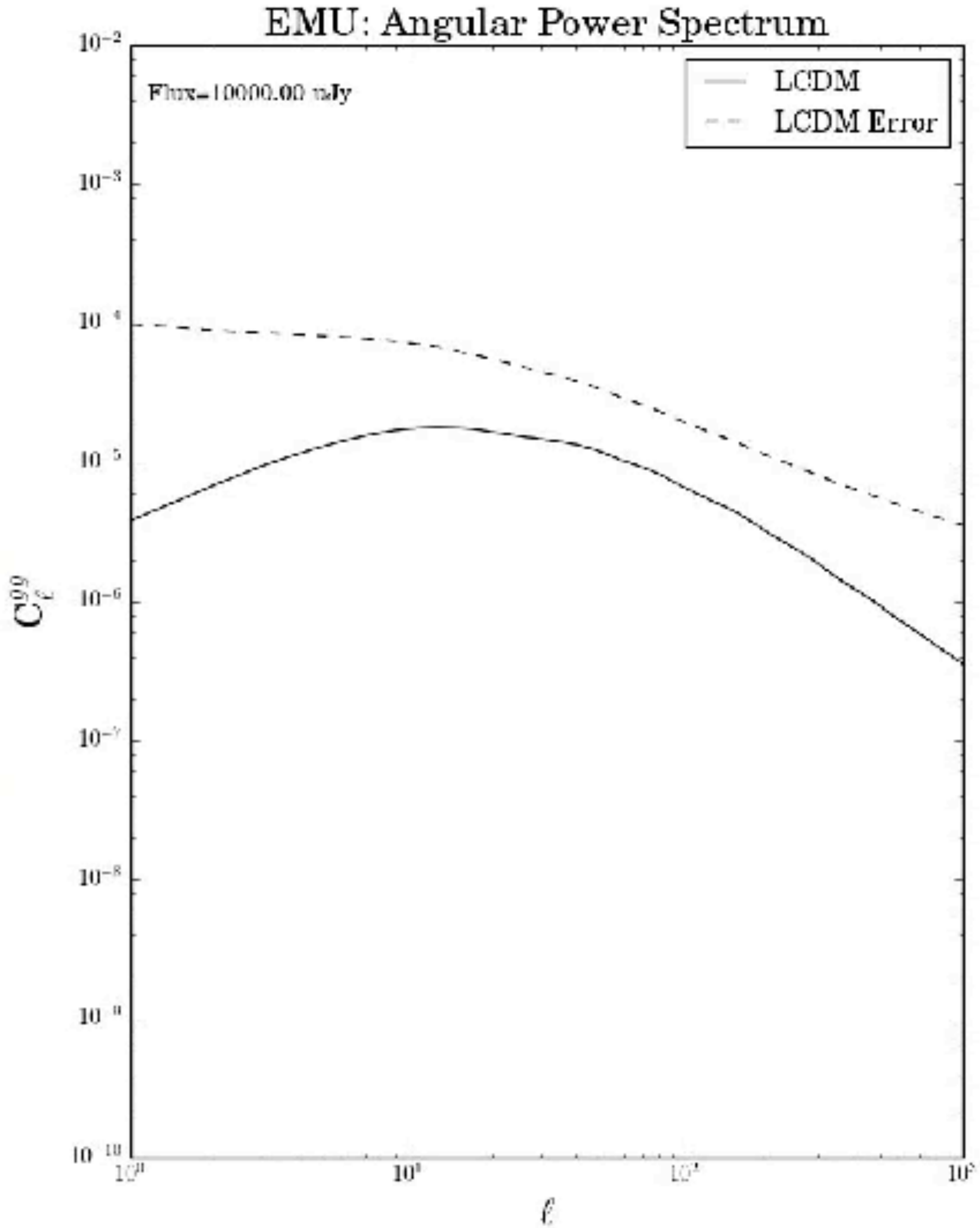
Image credit: Song Chen

Long-tail bin

- 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)



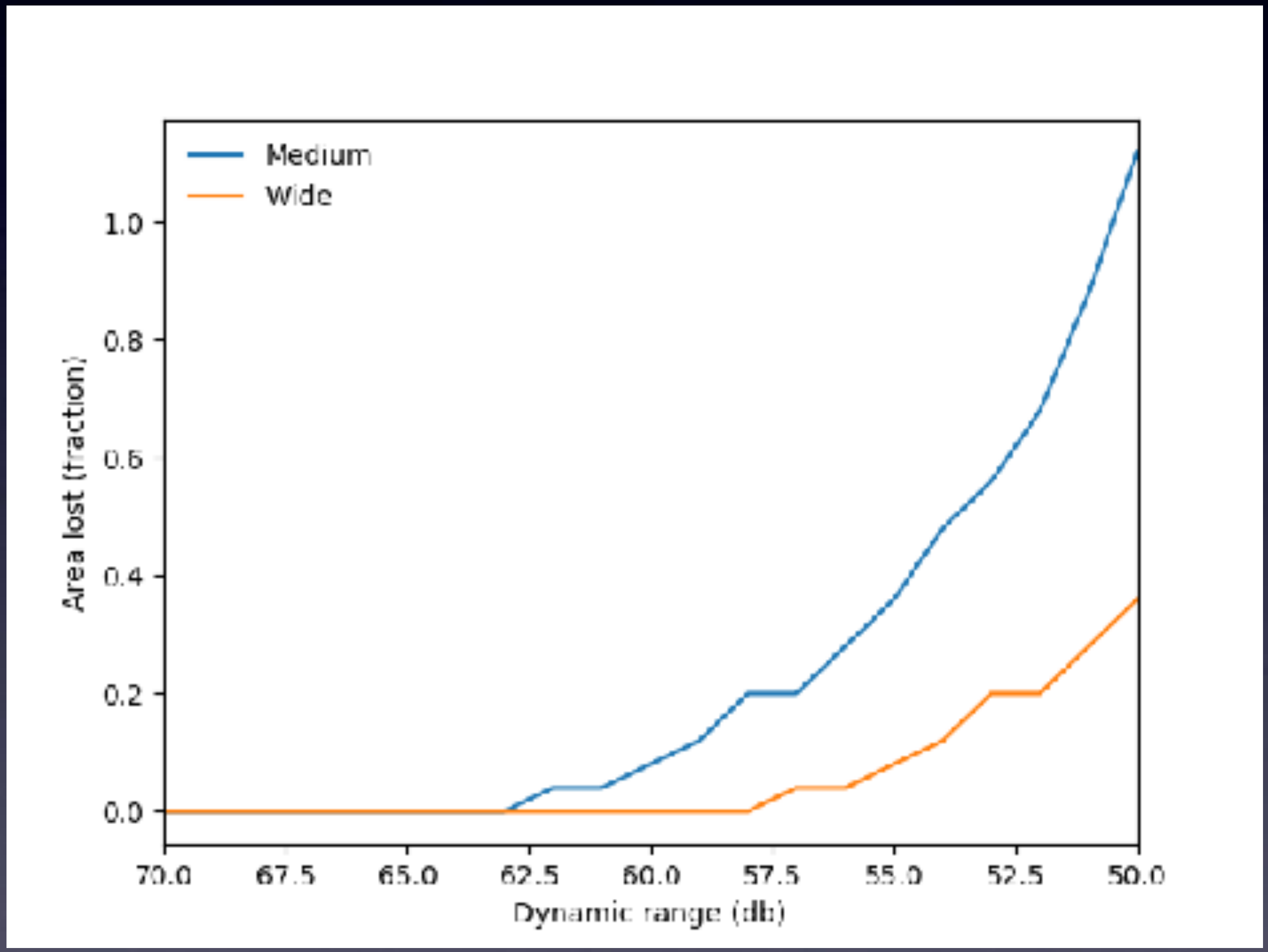




Video credit: Glen Rees

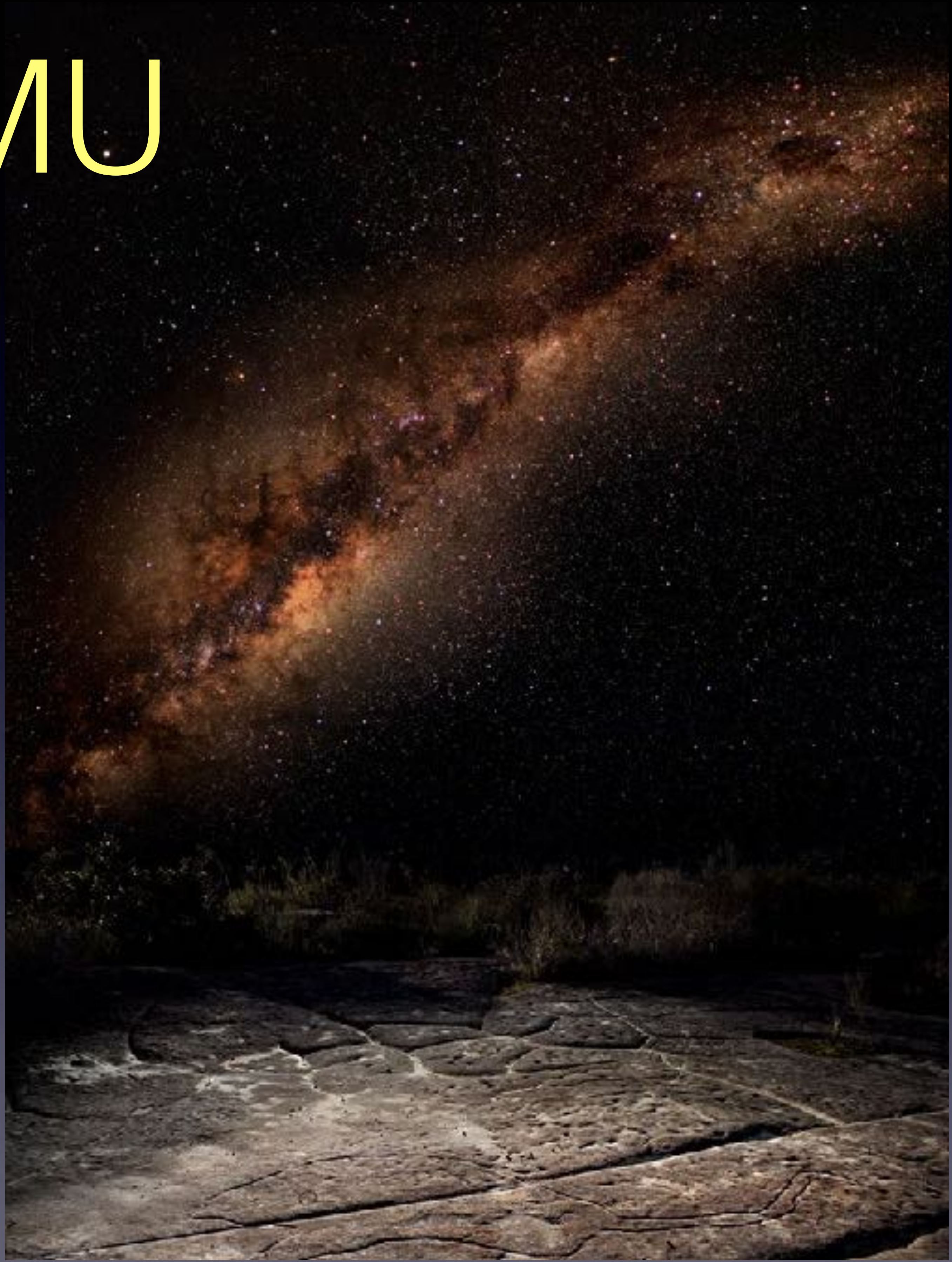
Confusion noise and dynamic range

- Numerous unresolved faint extragalactic sources create “confusion” noise in sensitive survey images
- “Natural confusion” happens as the sources themselves start to overlap
- For SKA to operate at the confusion limit for continuum sources, a dynamic range of 73 dB is required (Condon 2009), but for a brighter, large area survey, D>63 dB is needed to avoid significant area loss.



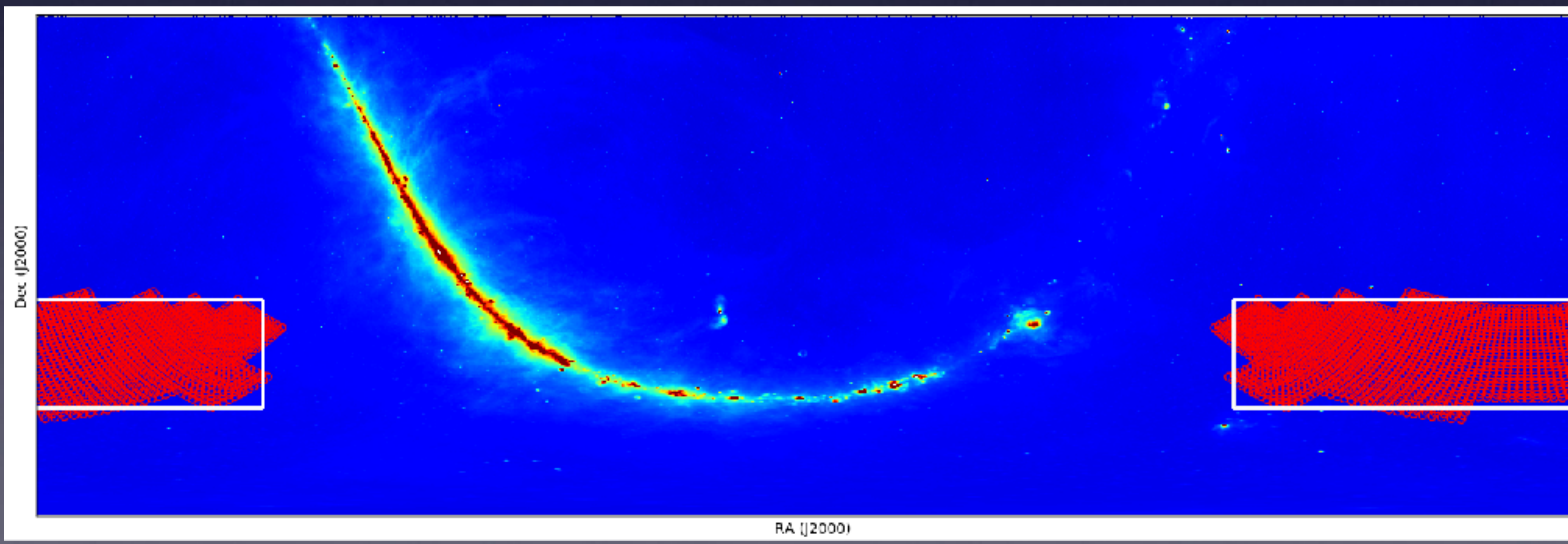
EMU

- 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

- Area: 2000 sq. degs
- Freq: 800-1100 MHz
- Limit: 100 uJy
- Time: 200 hours (60 pointings)
- Number density: 150 sources/deg2
- Region: 20<RA<5, -65<dec<-40
- Good coverage of DES and SPT surveys



Radio Continuum Surveys: area vs. sensitivity

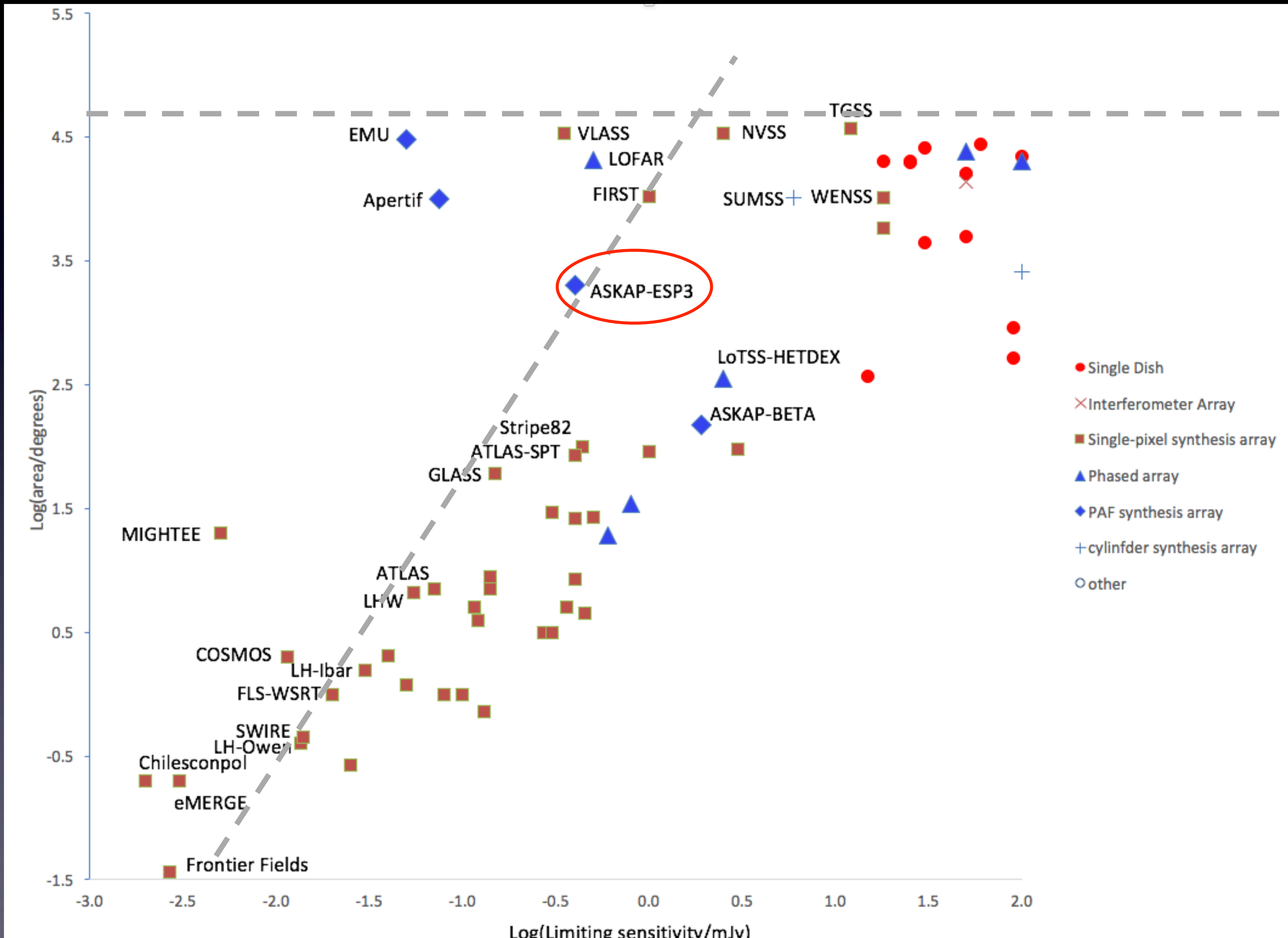
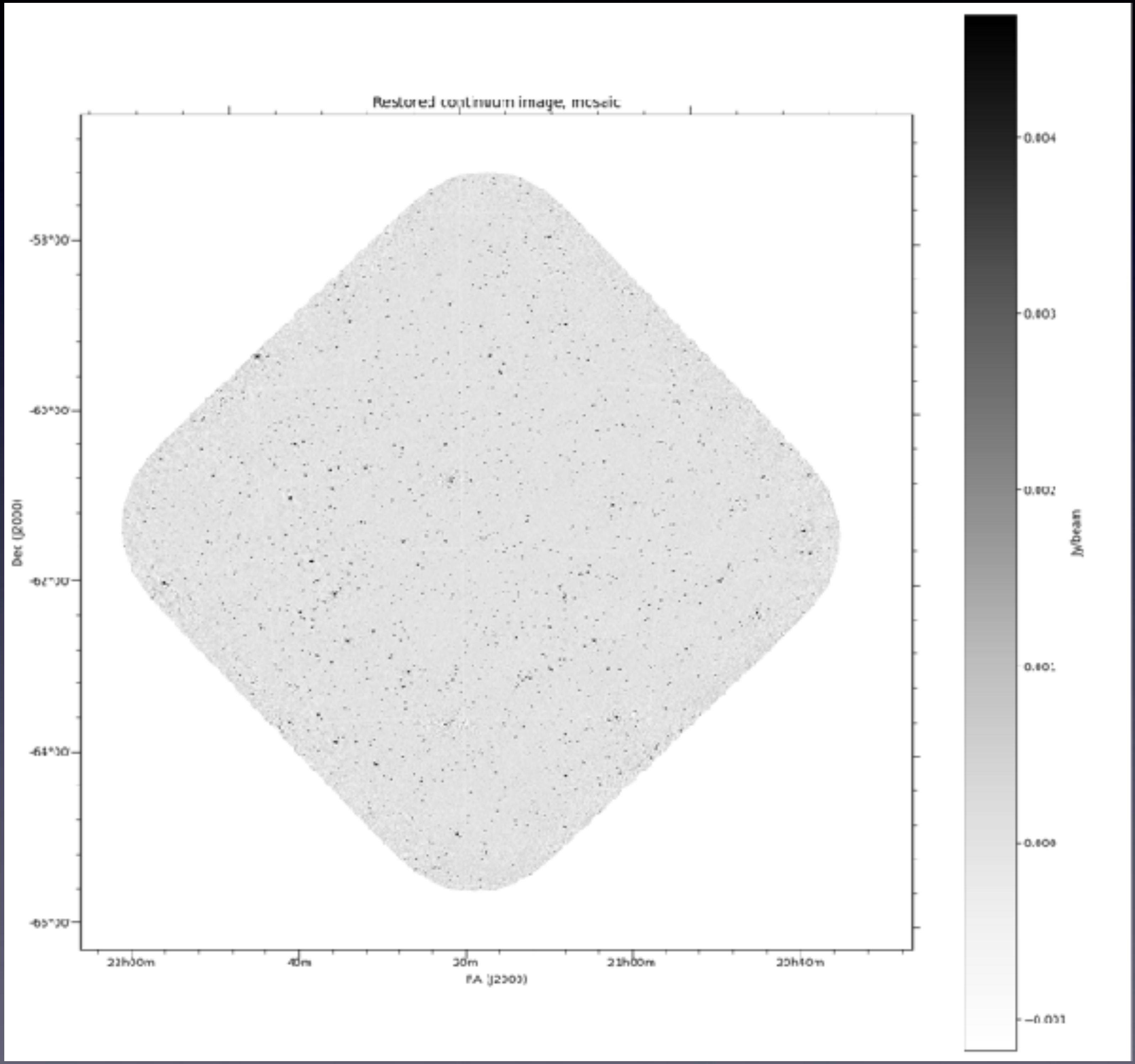


Image credit: Ray Norris

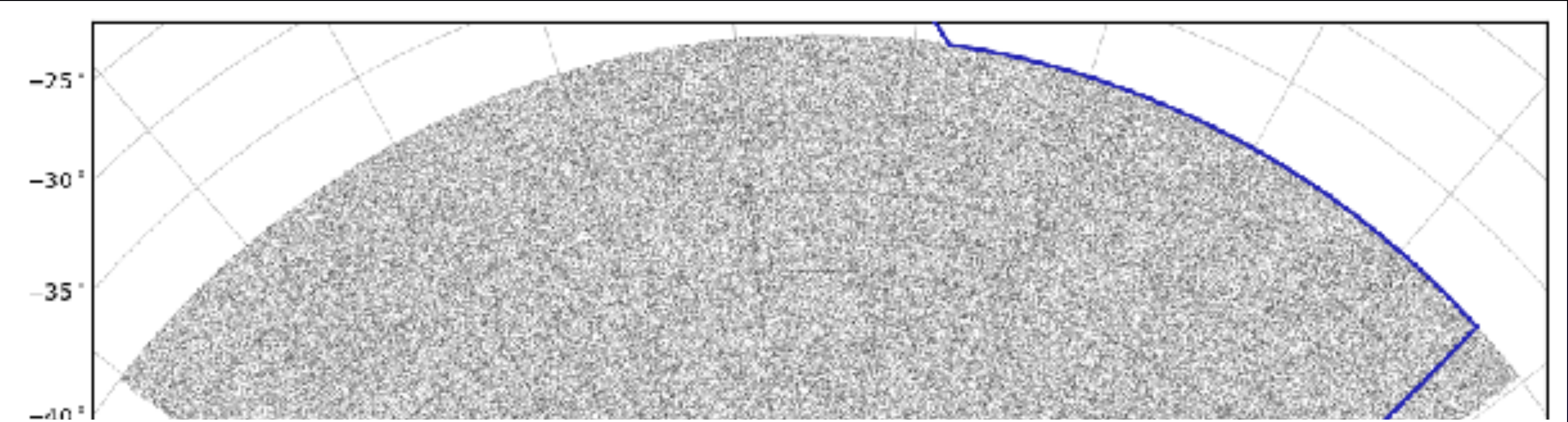
Observations

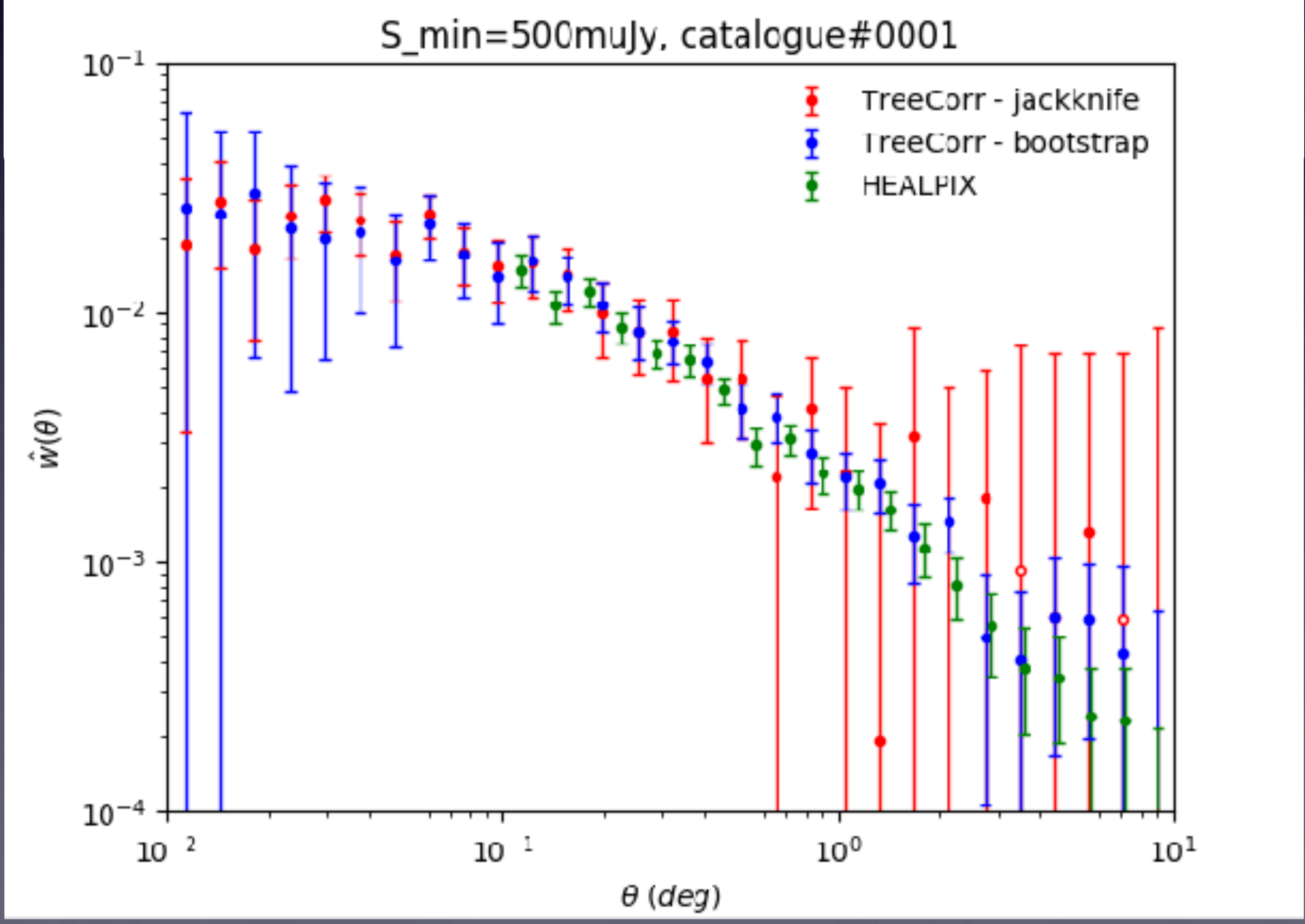
- Observations of the EMU early science cosmology region has already started
- Of the 68 ASKAP pointings, 16 integrations have been taken.
- Reduction of the data is still in the testing phase, as the ASKAPsoft data reduction pipeline (A2D output to images and catalogues) is still also being developed



Cosmology pipeline

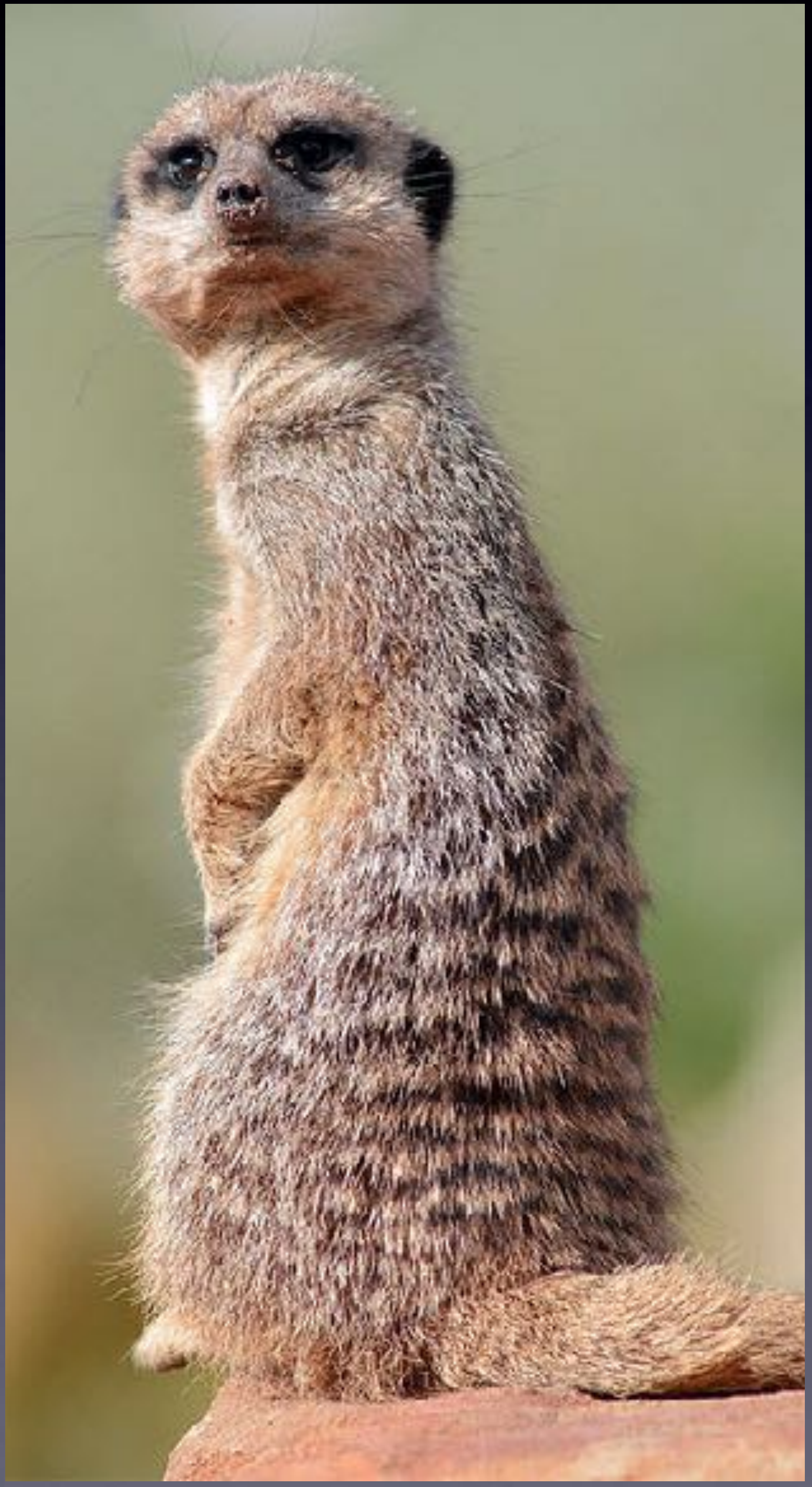
- Full-sky Lognormal Astro-fields Simulation Kit (Xavier et al 2016)
    - Assumes n(z) and takes correlation function as input
- Generate random catalogues, for testing data analysis & pipeline
- Use TreeCorr to measure angular correlation function
- Finally fit with boltzmann code





MeerKLASS

- MeerKLASS (MeerKAT Large Area Synoptic Survey) is an large area radio survey using MeerKAT
  - 4000 deg^2 in 4000 hours, over the DES region
- Frequency range: 900-1670 MHz (L-band)
- 80 x deeper than NVSS
  - 5.3 μJy rms across the region
- Similar angular resolution to NVSS (16 arcsec) for HI, better for continuum (interferometer)
- Will detect and image large number of sources, down to 5μJy (10 million galaxies)
- Not as fast or as wide as EMU, with worse angular resolution, but will produce redshifts (21cm)



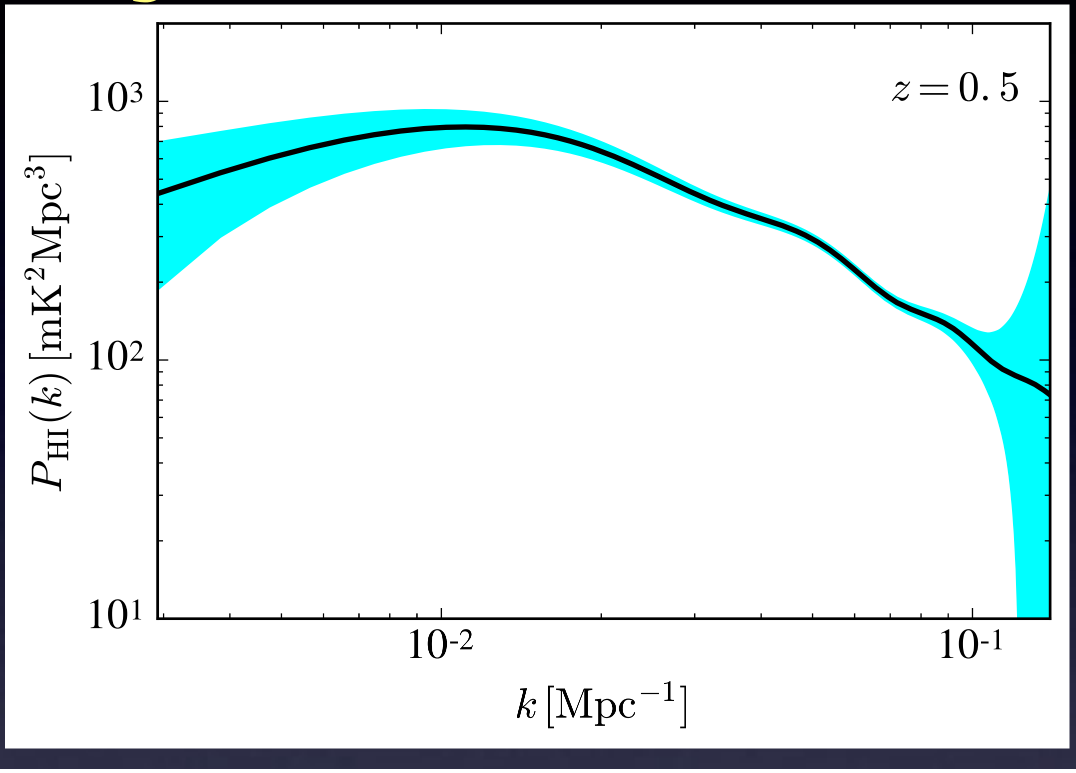
SKA continuum surveys

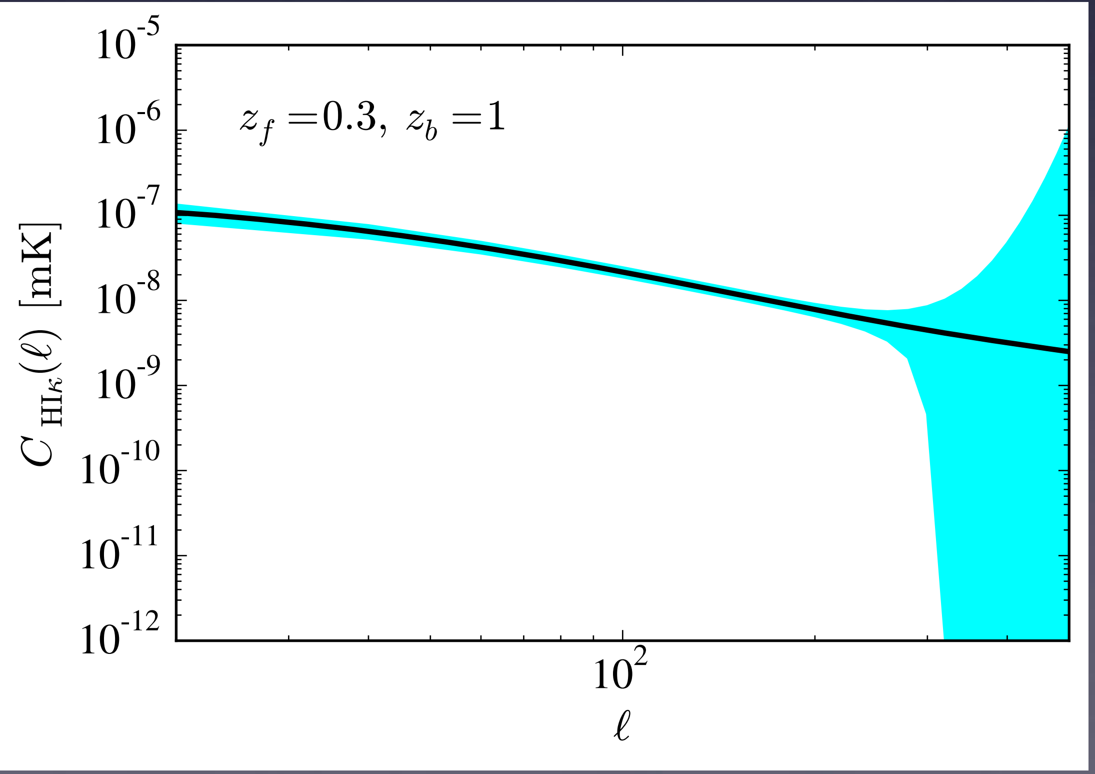
Survey	Area (deg^2)	Flux-limit	N
NVSS	26,800	10 mJy	4×10^5
EMU-early	2000	100 μJy	3.5×10^5
MeerKLASS	4000	5 μJy	7.2×10^8
EMU-full	30,000	10 μJy	7.2×10^7
SKA-2	30,000	100 nJy	5.5×10^9

b. Intensity Mapping

21cm physics

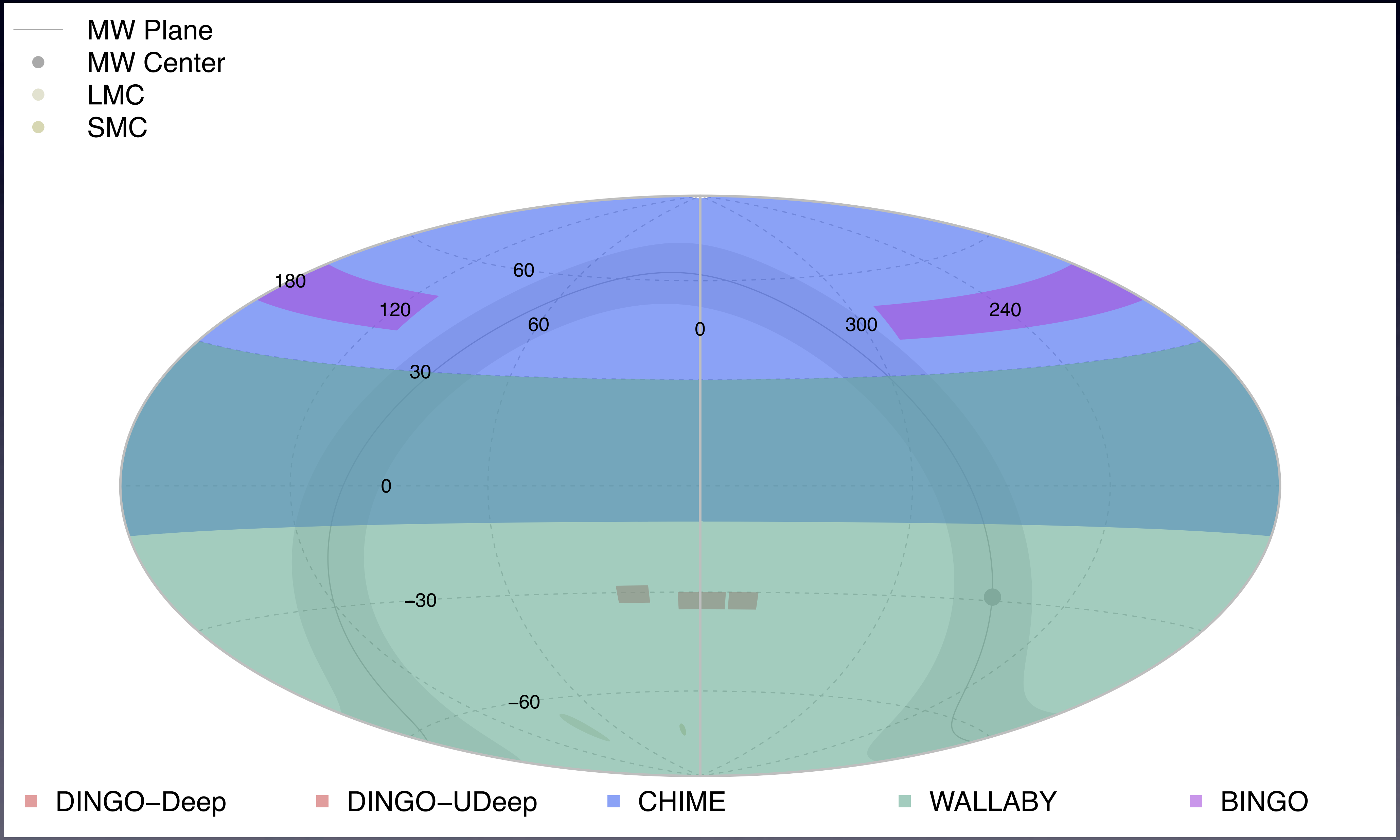
- 21cm intensity mapping is an accurate redshift, but delocalised in sky position
- Can be used to measure BAO and RSD
- Very weak signal, can be swamped by foregrounds
  - Large dynamic range needed, as foregrounds ~10^3 x signal
- Need to minimise spectral structure from bandpass cal. uncertainties
  - Also: Need accurate model of (polarised) beam sidelobes
  - RFI from satellites is a pain





From Santos et al 2016

HI surveys



MW Plane
MW Center
LMC
SMC
180
120
60
60
0
300
240
30
0
-30
-60
DINGO–Deep
DINGO–UDeep
CHIME
WALLABY
BINGO

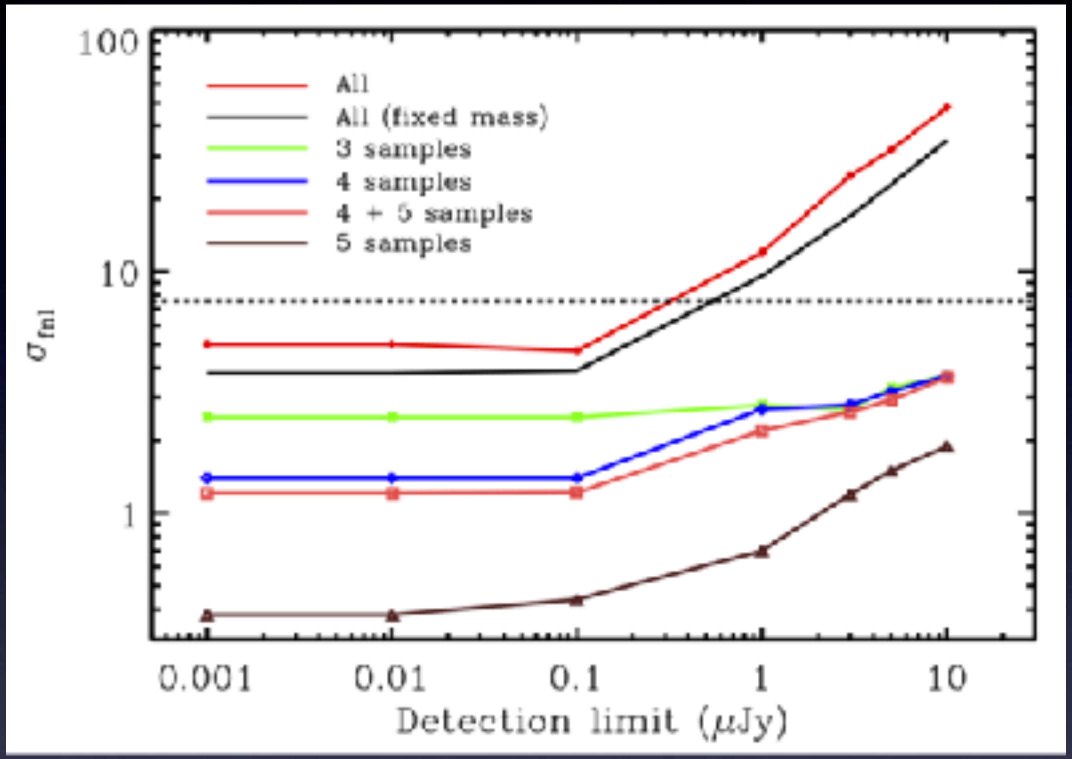
HI Surveys

Name	Redshift range	Number of sources	Area (sq deg)	Hemisphere	Start date
WALLABY	0-0.26	500,000	30,000	south	2018
DINGO	0-0.43		150	south	2018
CHIME	0.8-2.5		30,000	north	2017
MeerKLASS	0-0.58 (L) 0.4-1.5 (UHF)	100,000	4000	south	2019
BINGO	0.13-0.48		2000	north	2019
HIRAX	0.8-2.5		15,000	south	
SKA – stage 1	0-0.5	10M	5000	south	2025
SKA – stage 2	0-2	900M	30,000	south	?

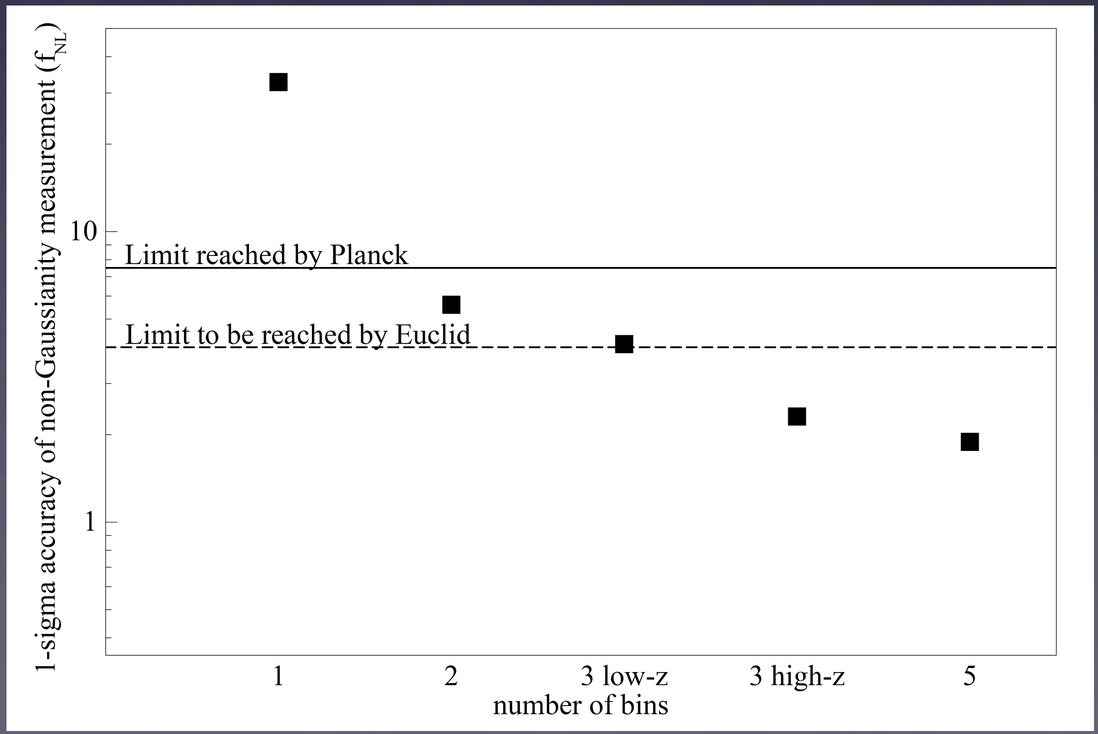
4. Cross-correlations

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

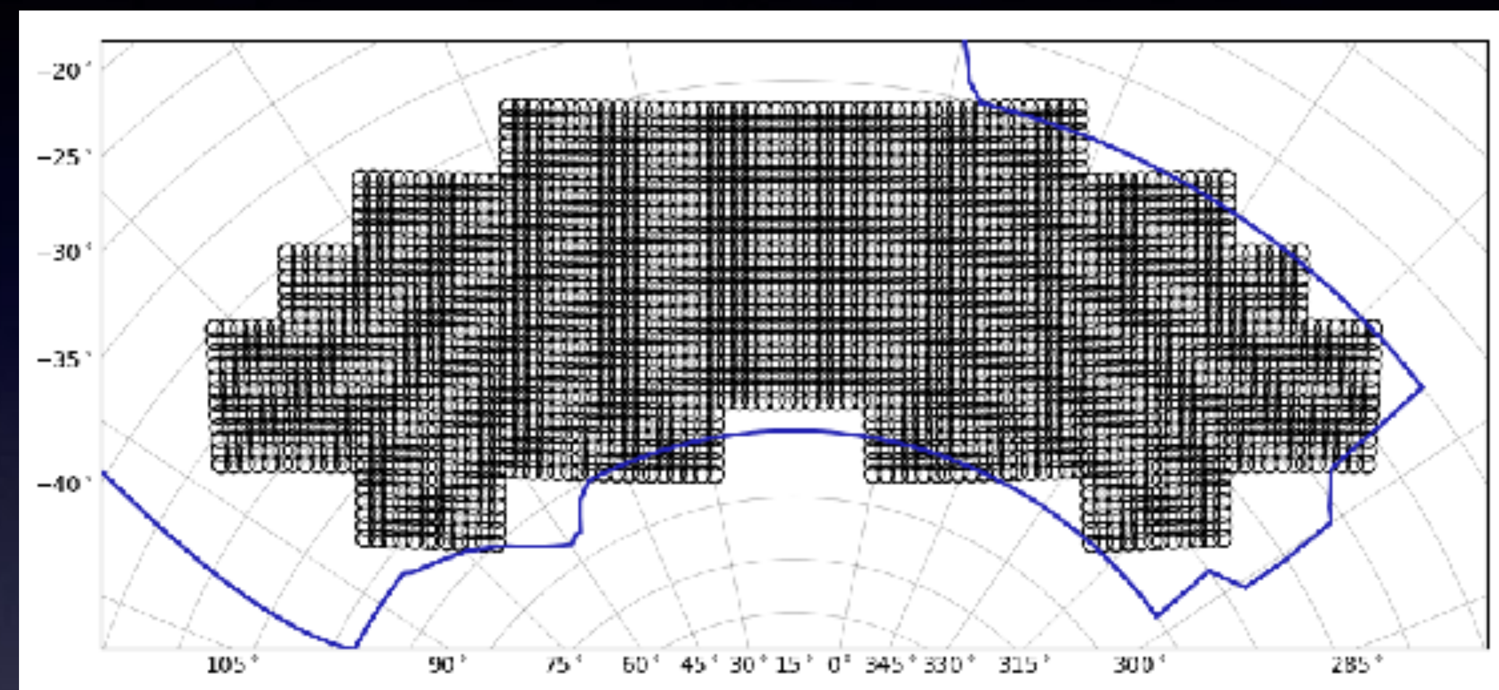


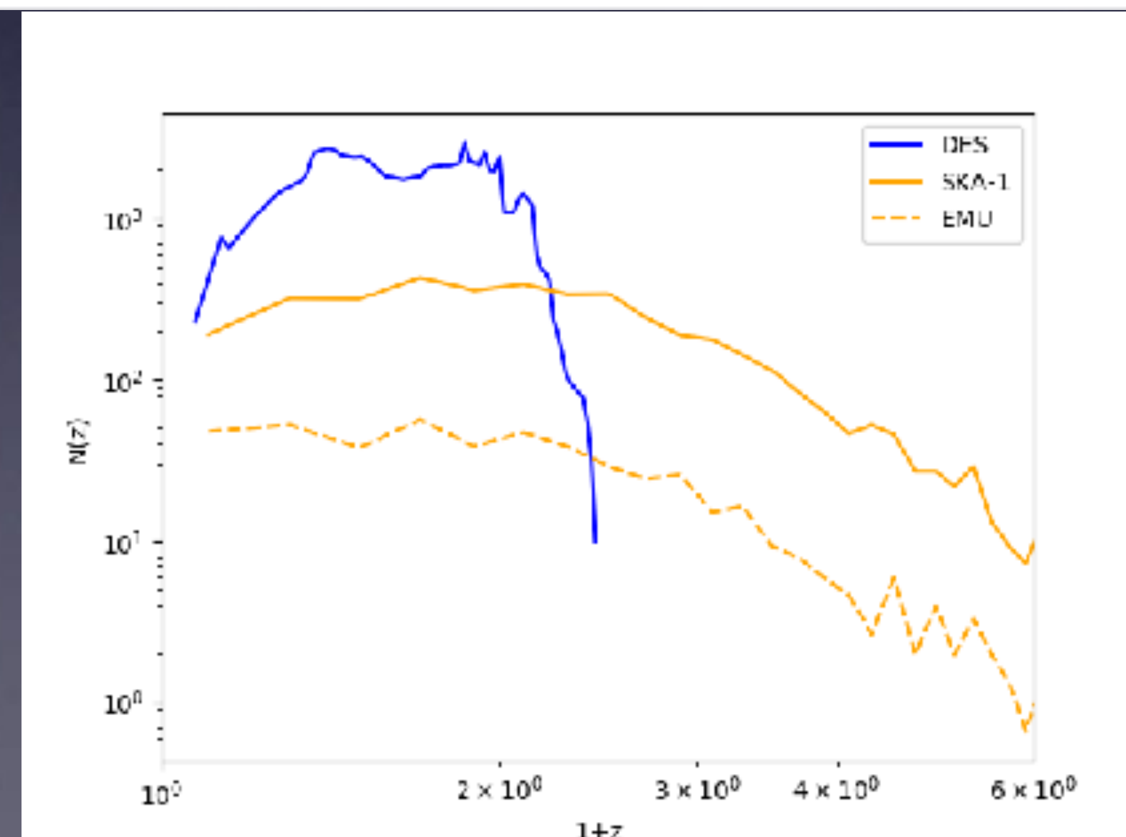
Ferramacho et al. (2014)



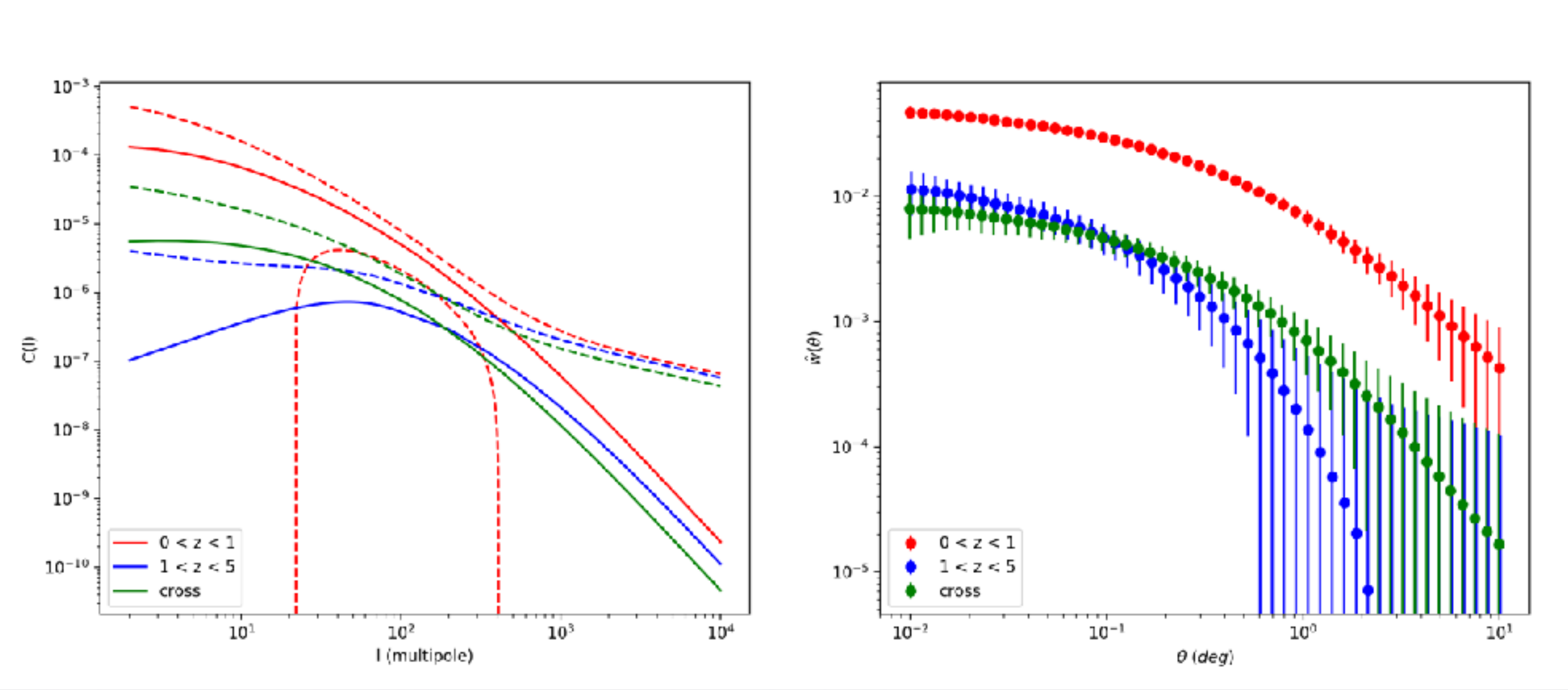
EMU & DES

- 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



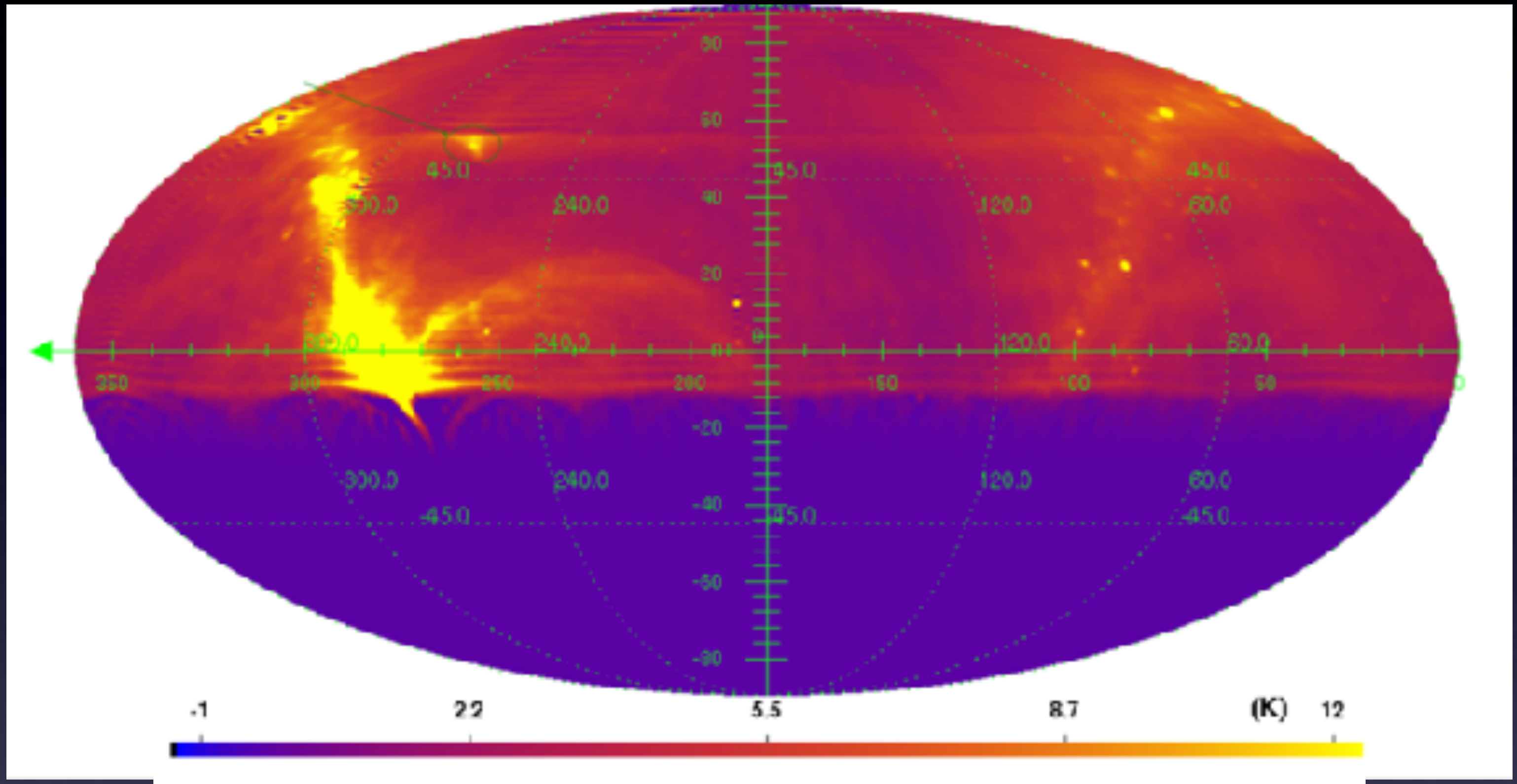


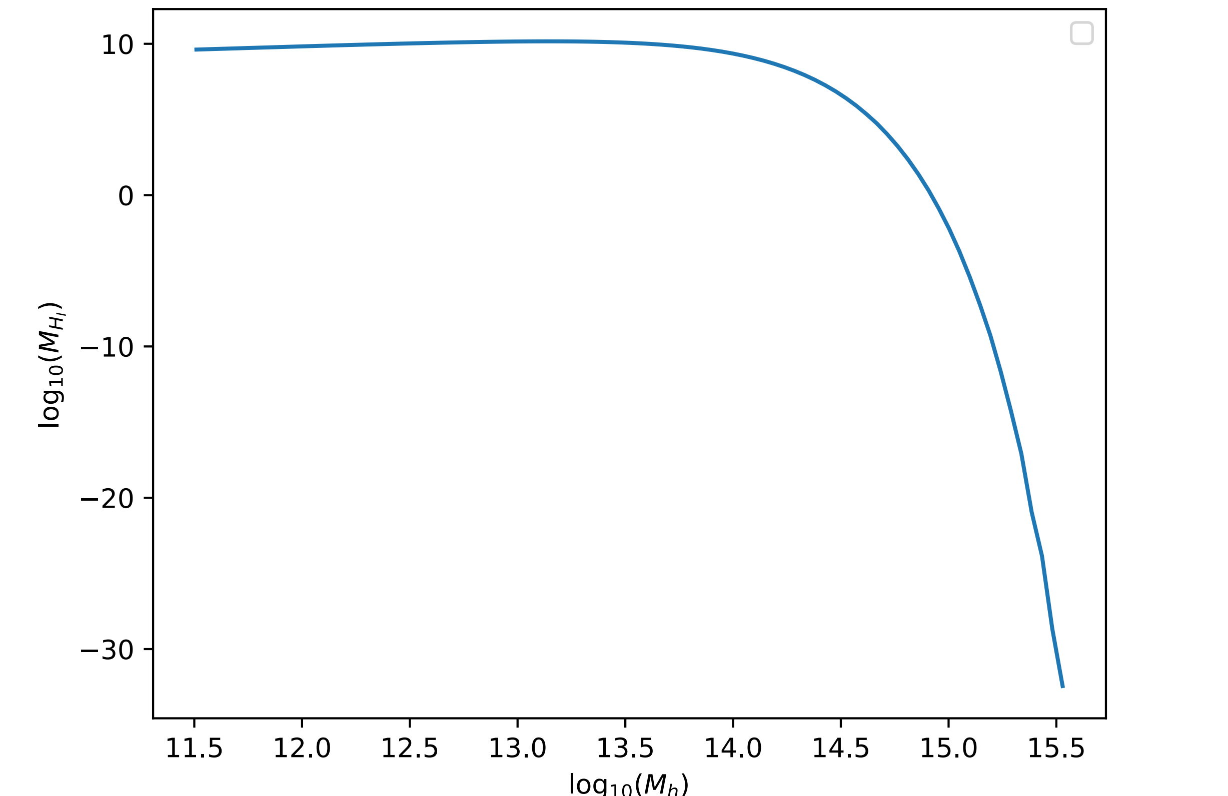
Magnification



Tianlai & DESI

- Getting past foregrounds
  - Brightness temperature signal weak, and delocalized in angular position
  - Cross-correlation enhances HI signal, allowing for better determination of power spectra
- Cross-correlation at low redshift (ELGs, LRGS)
  - Dipole (Hall and Bonvin, 2017)
- Cross-correlation at high-redshift (LBGs)
  - 21cm detection, 21cm bias (Villaescusa-Navarro et al 2014)





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
  - HI intensity mapping will be possible over a wide area
- Large dynamic range needed, to detect faint anisotropies
  - data processing issue
- Cross-correlation, with optical/IR data, will increase the detection and utility of the anisotropic map
  - Cosmic magnification
  - Large-scale non-Gaussianity/GR effects
- This is a good time to be involved in large radio projects!

Extra: Simulations

Dark Energy

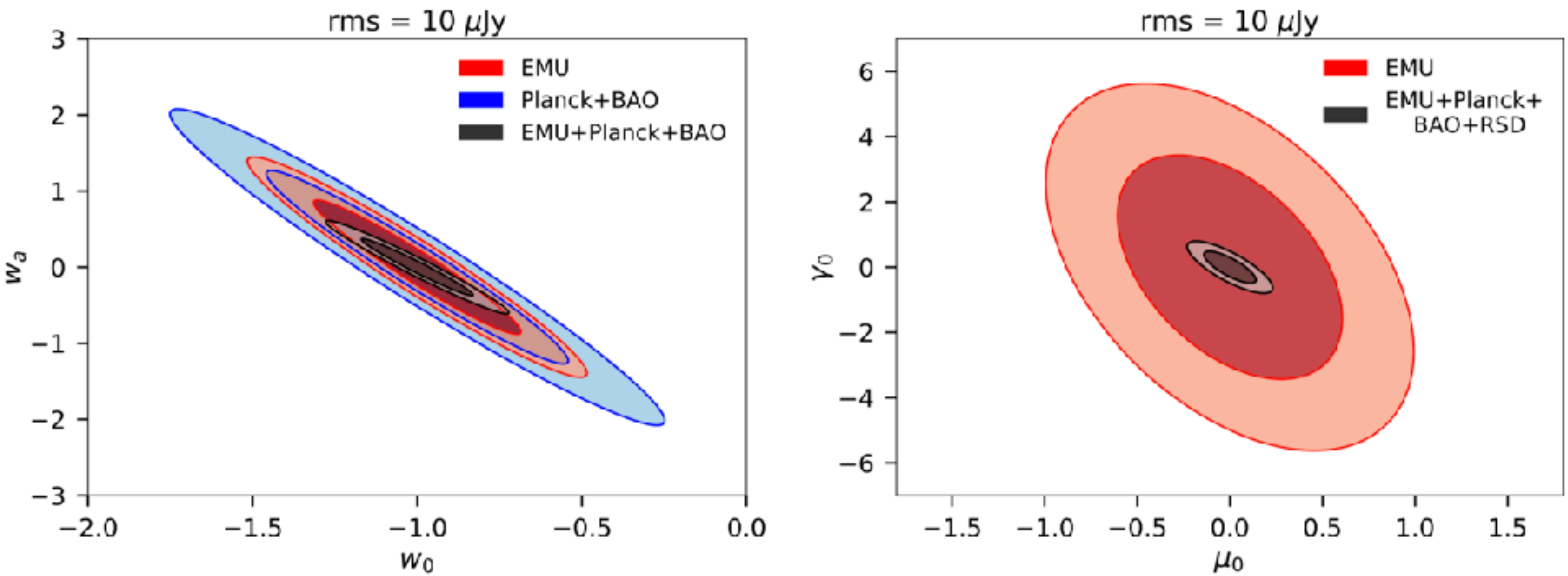


Image credit: Jose Luis Bernal

Non-Gaussianity