The largests cosmic scales and the source count dipole

Radio source count dipole and Gaussianity have been among SKA's 14 highlight science cases and there is even more reason than in 2014 to make the largest scales a prime traget for the SKA

Fonseca et al. 2014, Schwarz et al. 2014 (AASKA14), Bacon et al. 2020 (Red Book)

Dominik J. Schwarz (Bielefeld University)

SKA Science Working Group Meeting

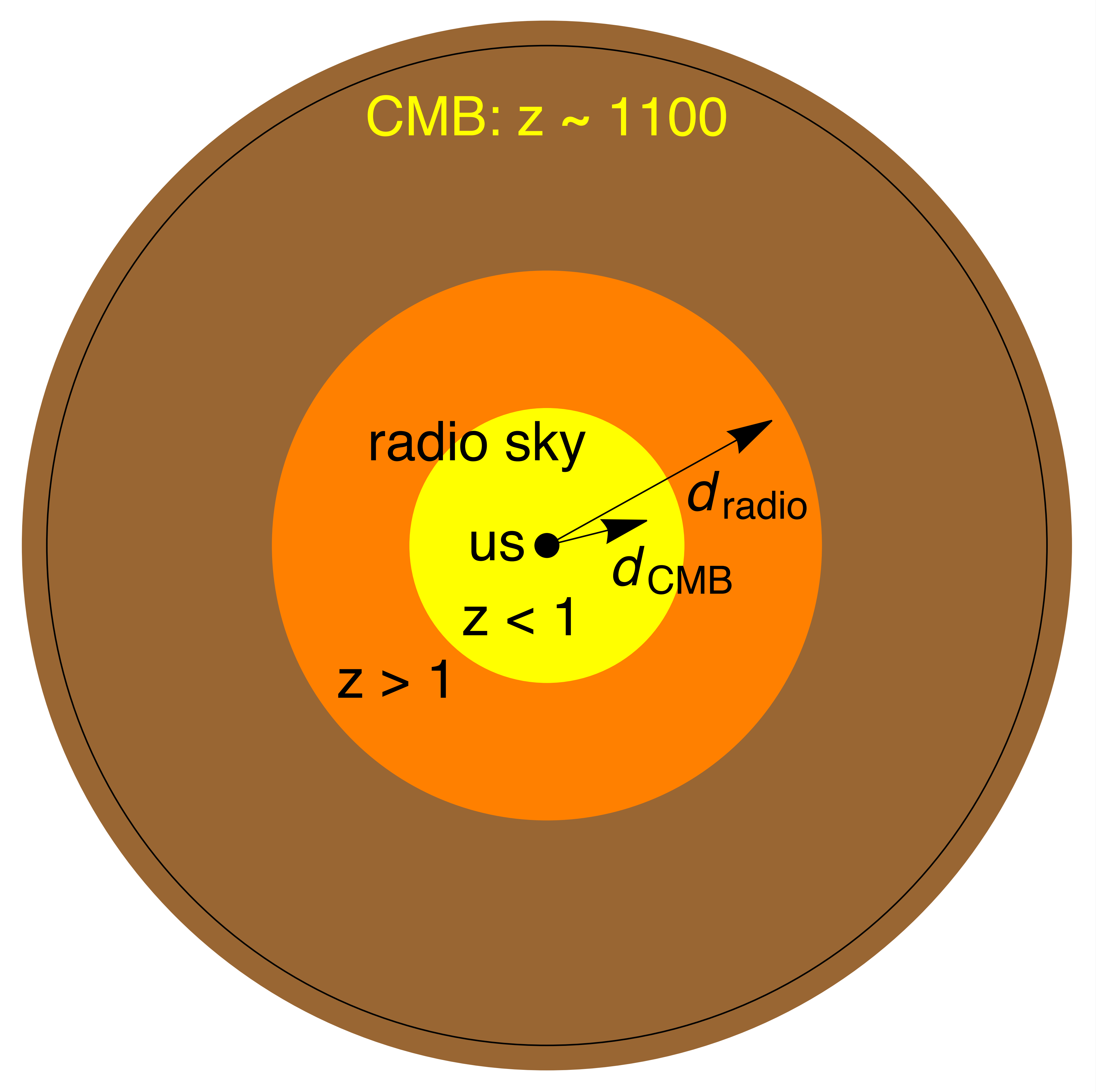
November 2024

Nature of cosmic dipoles

Cosmological principle
(statistical isotropy and homogeneity)
implies the existence of **cosmic time**,
preferred rest frame, and **comoving observers**

This **cosmic rest frame** must be universal, i.e. the same at different redshifts (z = 0, 1 or 1000) and the same for all probes (CMB, AGNs, clusters, SNe, …)

Can we find this common cosmic redshift in different cosmological probes?



How to probe the nature of the CMB dipole?

Is the CMB dipole purely kinematic?

CMB itself shows that high-ℓ modes are consistent with kinematic origin of CMB dipole

$$\ell = 1 : v = (1.23356 \pm 0.00045) \times 10^{-3} c$$

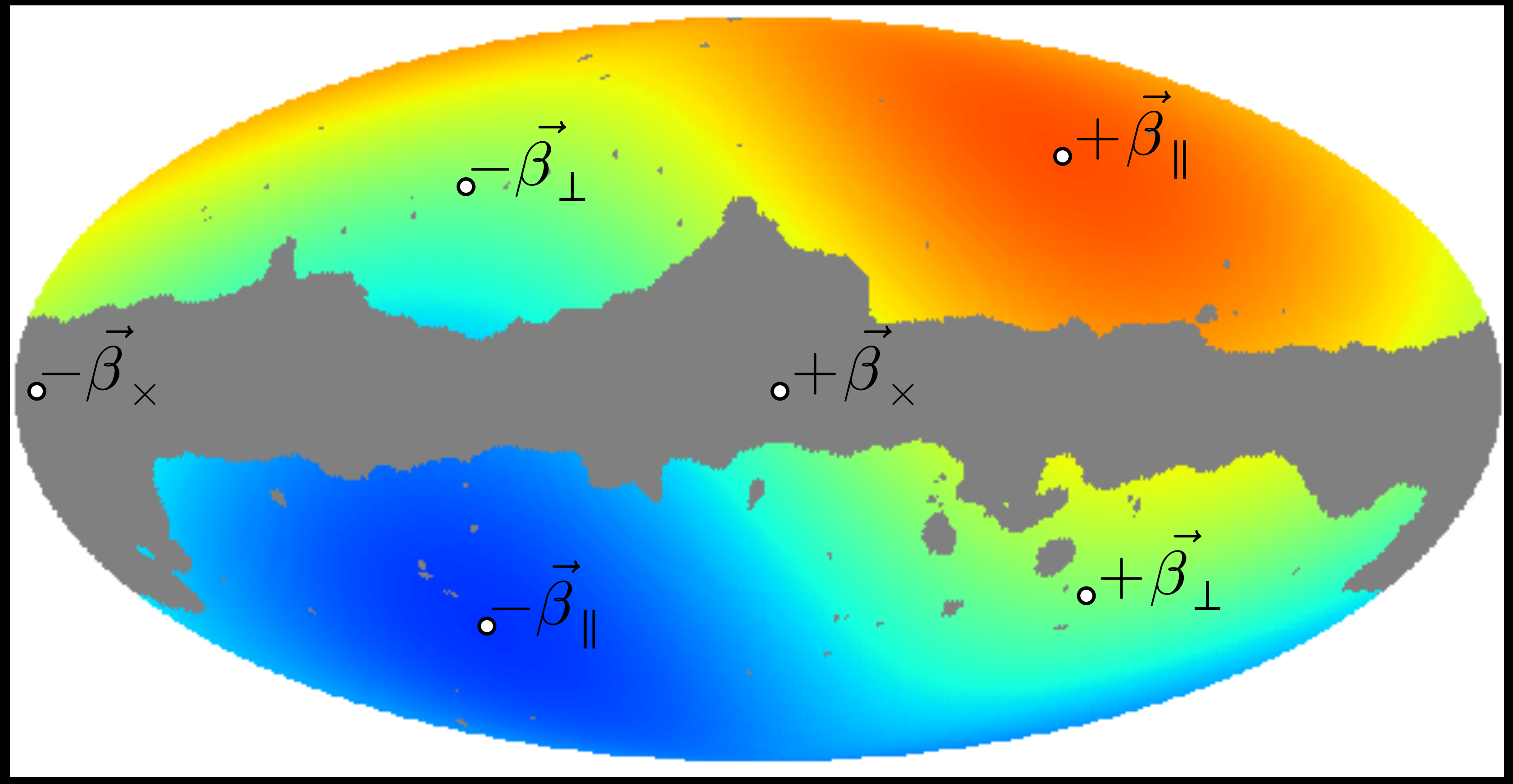
Planck 2020

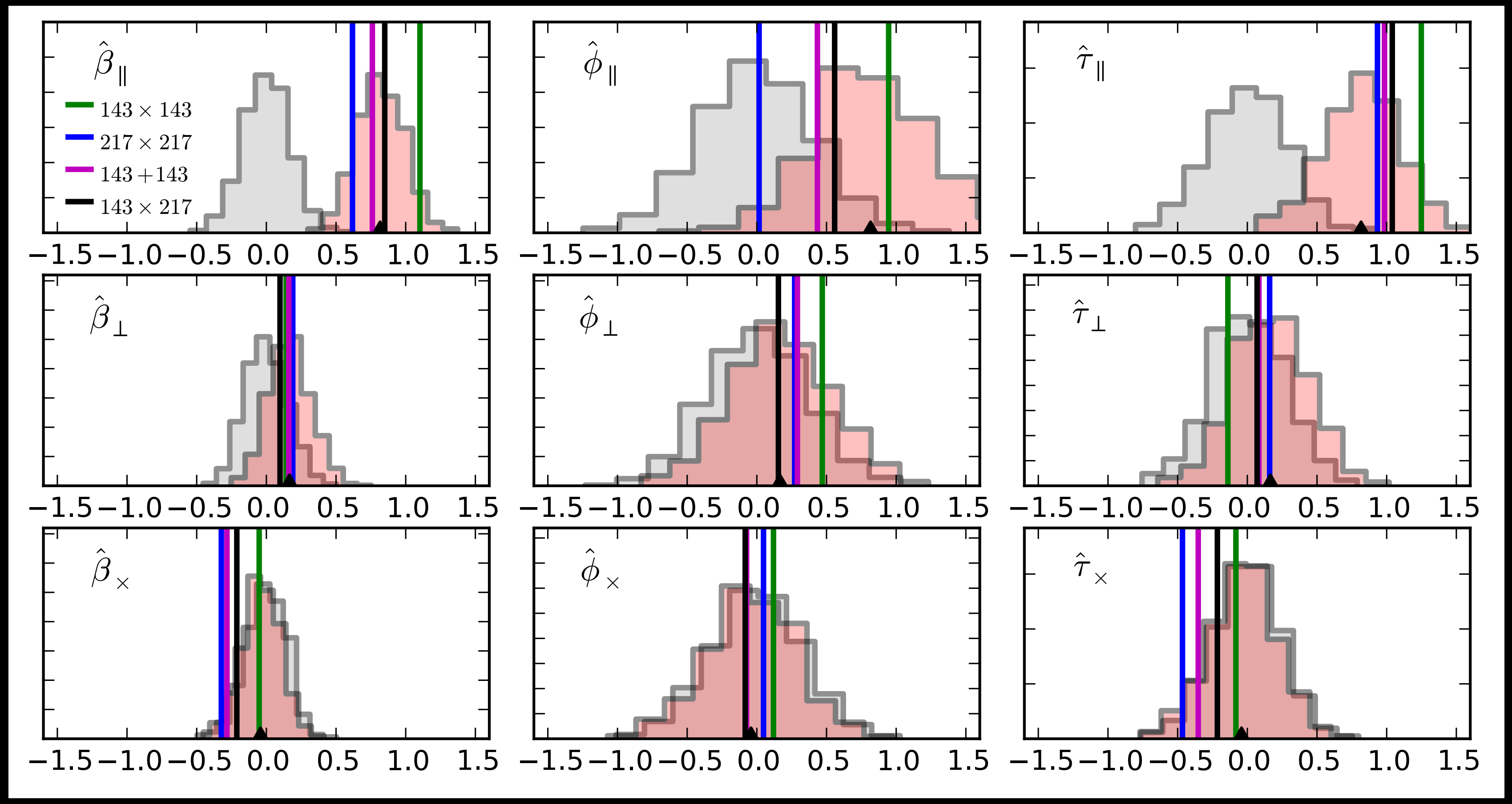
$$\ell \gg 1 : v = (0.996 \pm 0.219) \times 10^{-3} c$$

Planck 2014, Saha et al. 2020

improve via better full sky maps (foregrounds!)

should be done by LiteBIRD, CMB-S4 lacks sky coverage





Planck 2014

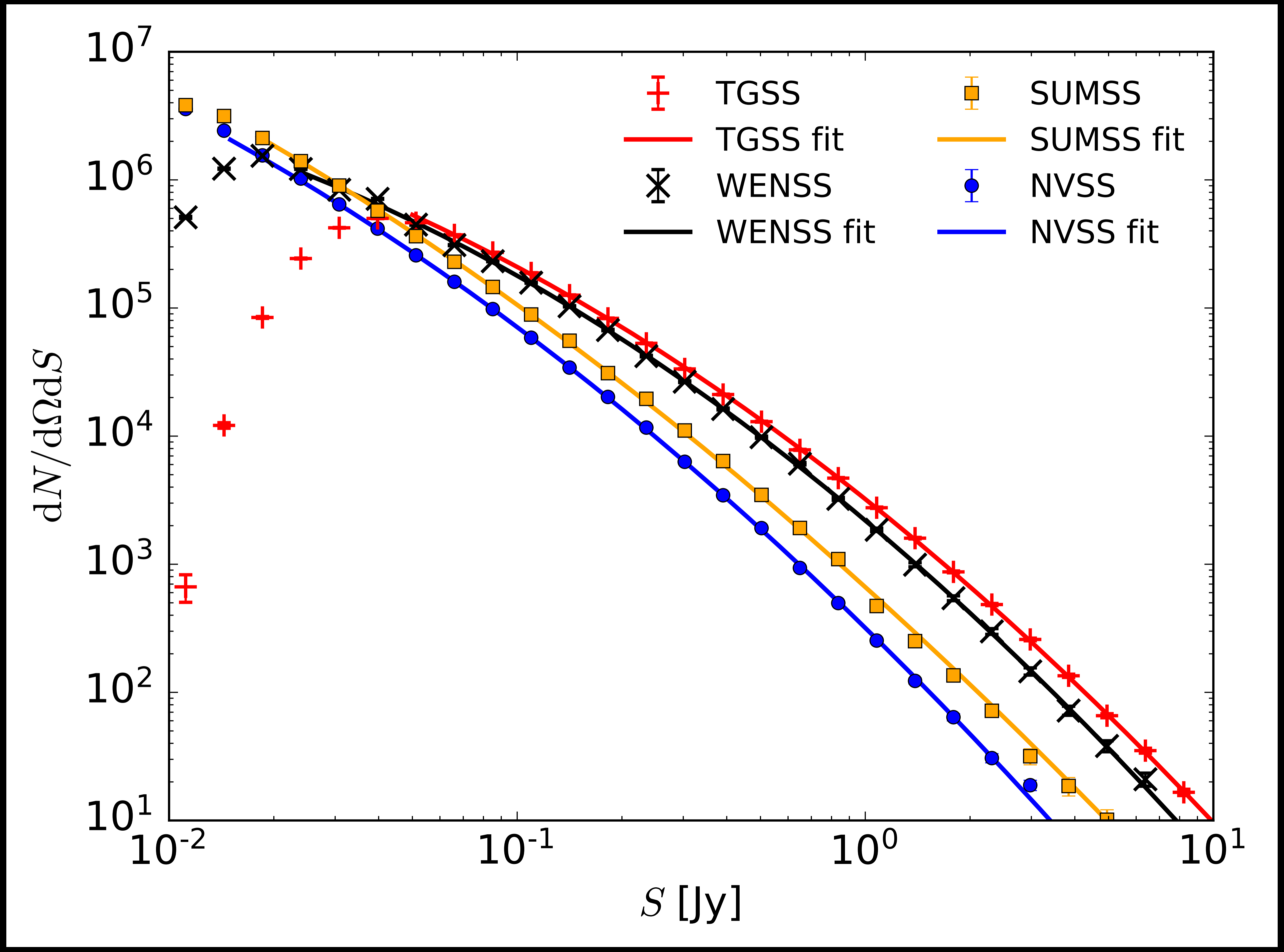
Kinematic source count dipole

For extragalactic sources at $z_{\mathrm{median}} > 1$:

Counts-in-cell from surveys covering large areas
Ellis & Baldwin 1984

$$\frac{\mathrm{d}N}{\mathrm{d}\Omega}(>S, \mathbf{e}) = \frac{\mathrm{d}N}{\mathrm{d}\Omega}_{\mathrm{com}}(>S)\ (1 + \mathbf{d}\cdot\mathbf{e} + \ldots),$$

$$\mathbf{d} = [2 + x(1-\alpha)]\mathbf{v}/c, \quad S \propto \nu^{\alpha}, \quad \frac{\mathrm{d}N}{\mathrm{d}\Omega} \propto S^{-x}$$



x in various radio surveys: Siewert et al. 2021

Power-law ansatz for x is not quite correct,
but can be easily corrected (Tiwari et al. 2015)

Local structure and the cosmic radio dipole

- Simulations for SKA-MID Baseline Design included:
  Cosmic structure (LCDM), simple bias model, proper motion of observer, survey geometry
- Not included: multi-component aspect, multi-tracer aspect, bias evolution, galactic foregrounds, calibration systematics, errors on photo-z's

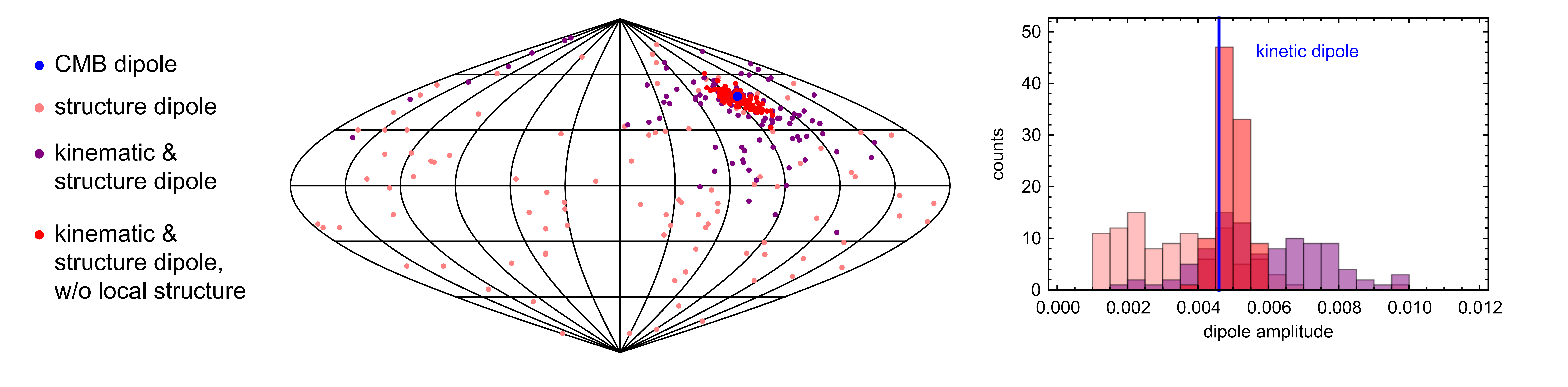


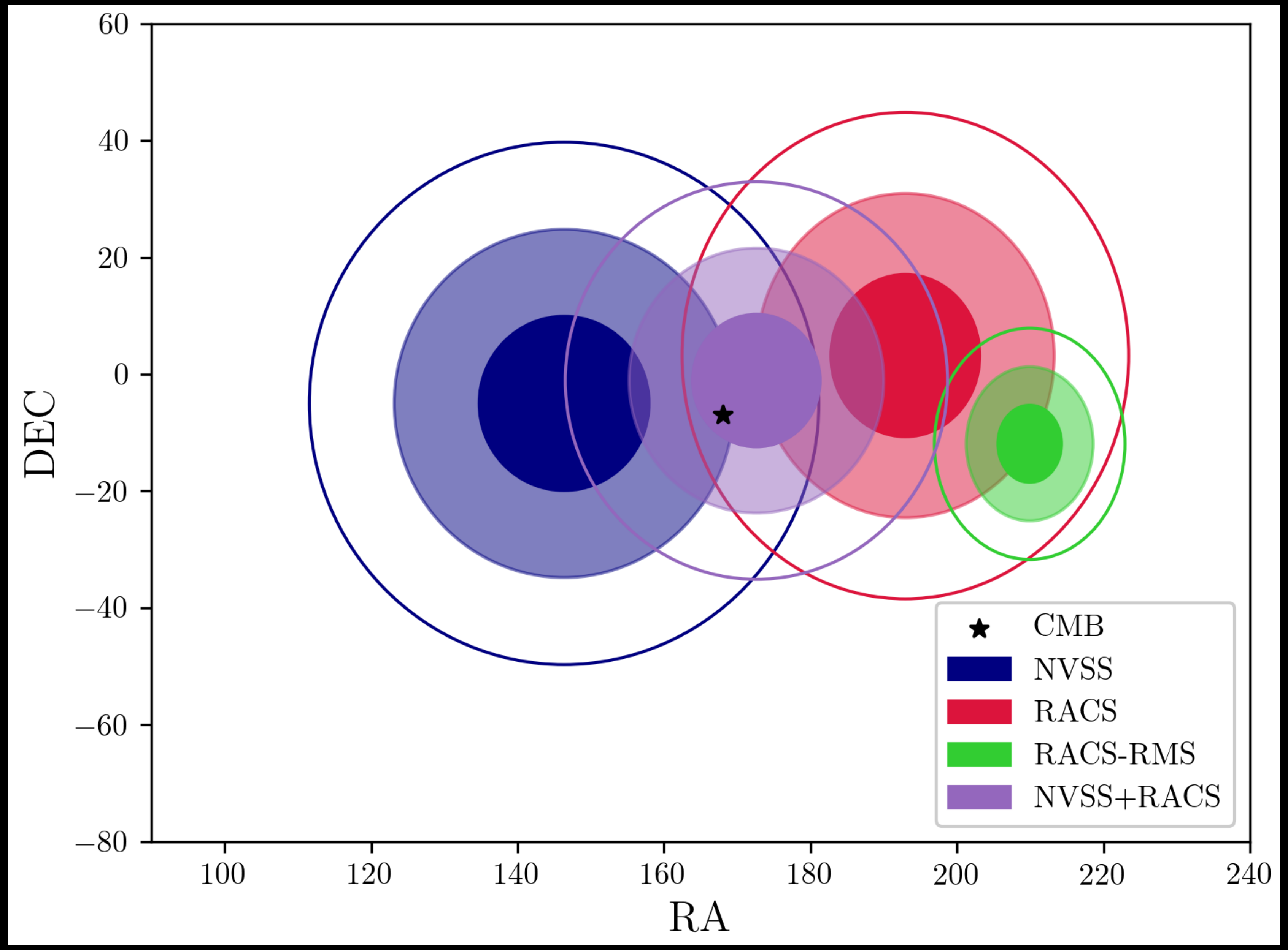
Figure 10. Dipole directions (left) and histogram of dipole amplitudes (right) based on 100 LSS simulations each for a flux density threshold of 22.8μJy at 700 MHz without kinetic dipole (pink), with kinetic dipole (purple) and with the contribution from the local structure dipole removed (red). The blue dot shows the direction of the CMB dipole. The results are displayed in galactic coordinates and in stereographic projection.

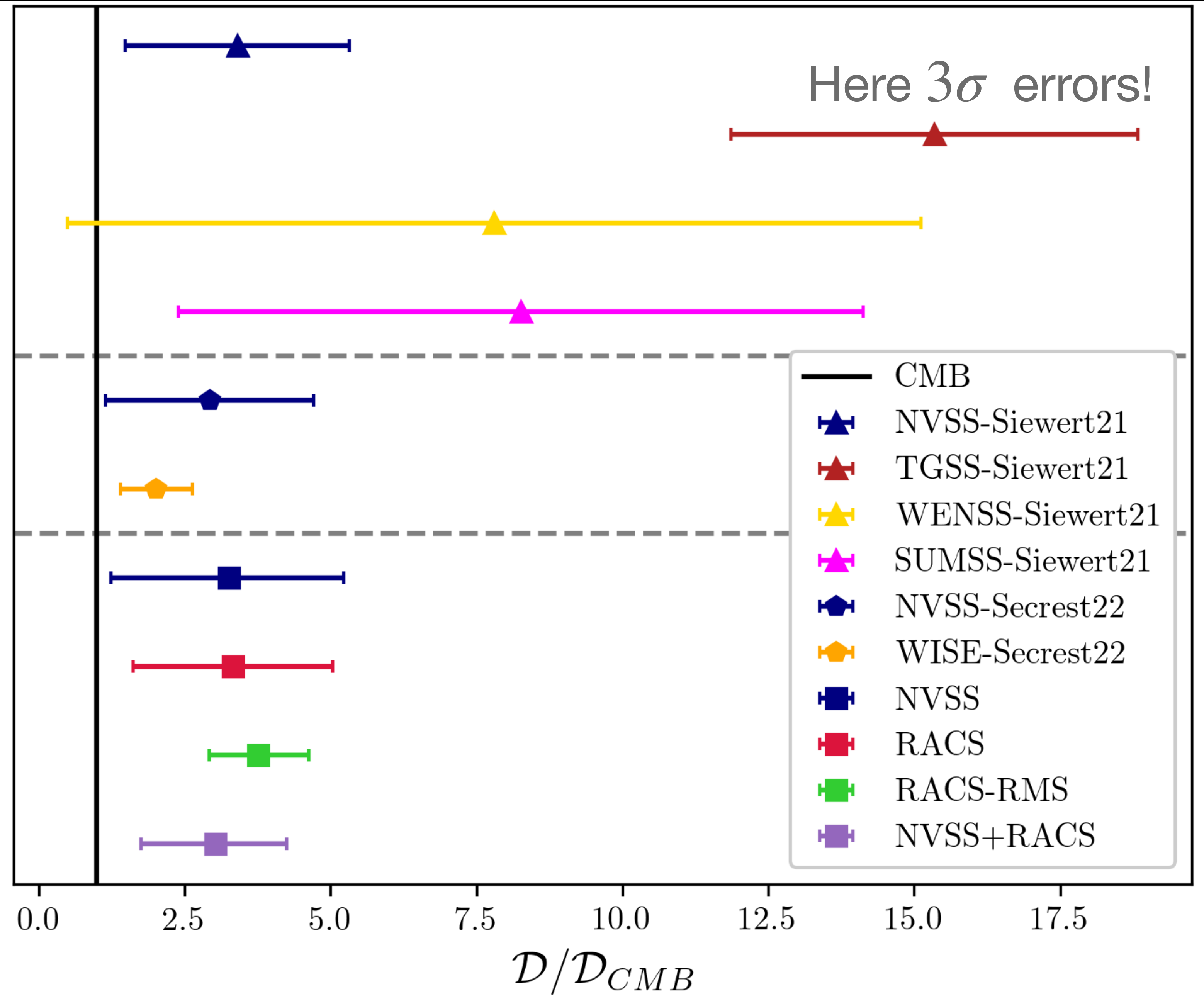
Bengaly et al. 2019; SKA Cosmology Science Working Group: Bacon et al. 2020

Radio and quasar dipoles

Radio and quasar dipoles show excess dipole

(Blake & Wall 2002, Singal 2011, Rubart & Schwarz 2013, Tiwari et al. 2015, Singal 2019, Siewert et al. 2021, Secrest et al. 2021, 2022, Dam et al. 2022, Wagenveld et al. 2023, Mittal et al. 2024, …)



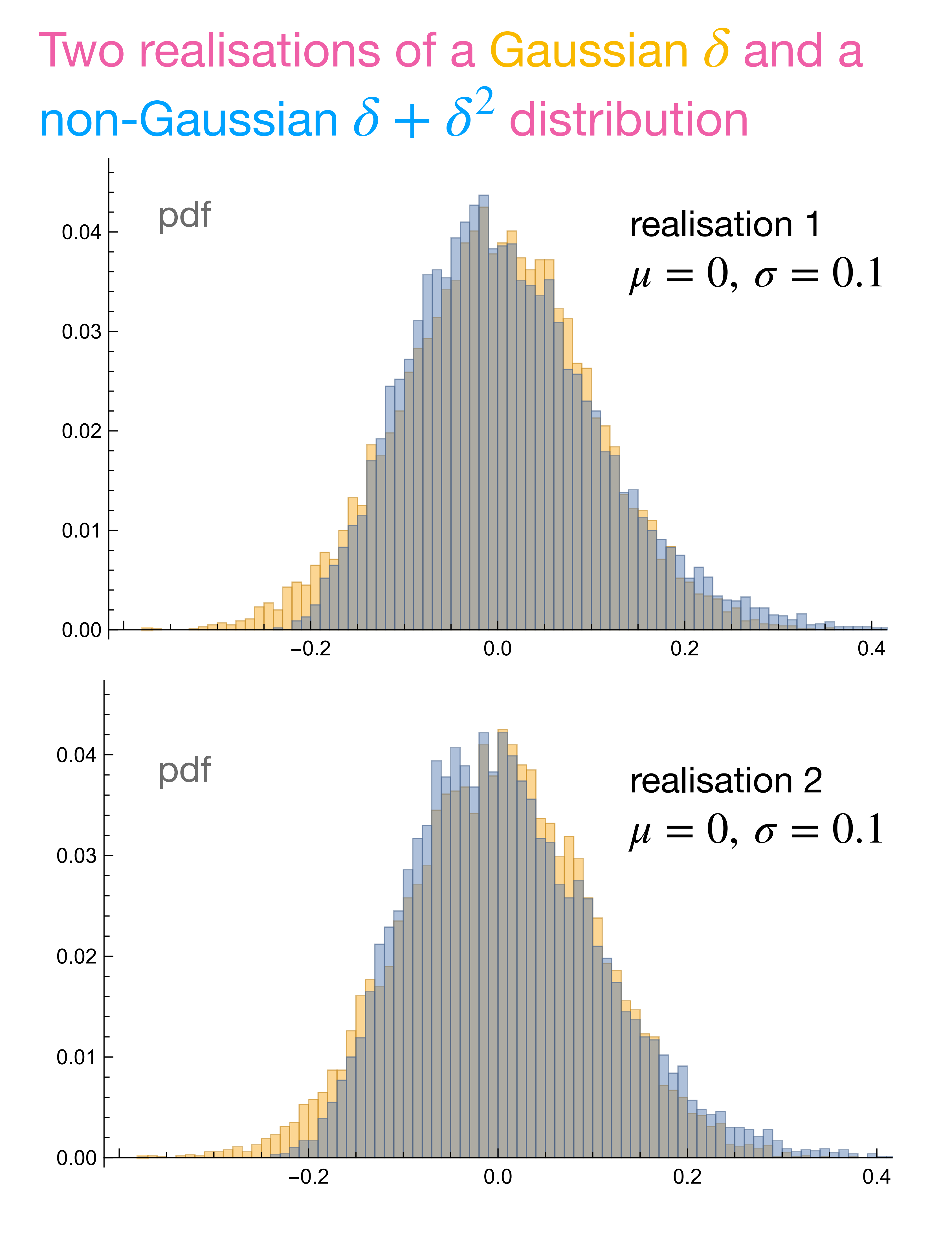


Wagenveld et al. 2023

Task: **distinguish clustering dipole from kinematic dipole** and **demonstrate that different kinematic dipoles agree with each other**

Nature of primordial perturbations

Cosmological inflation
(early epoch of accelerated expansion)
implies the existence of almost **scale invariant** and close to **Gaussian** primordial fluctuations of matter and space time

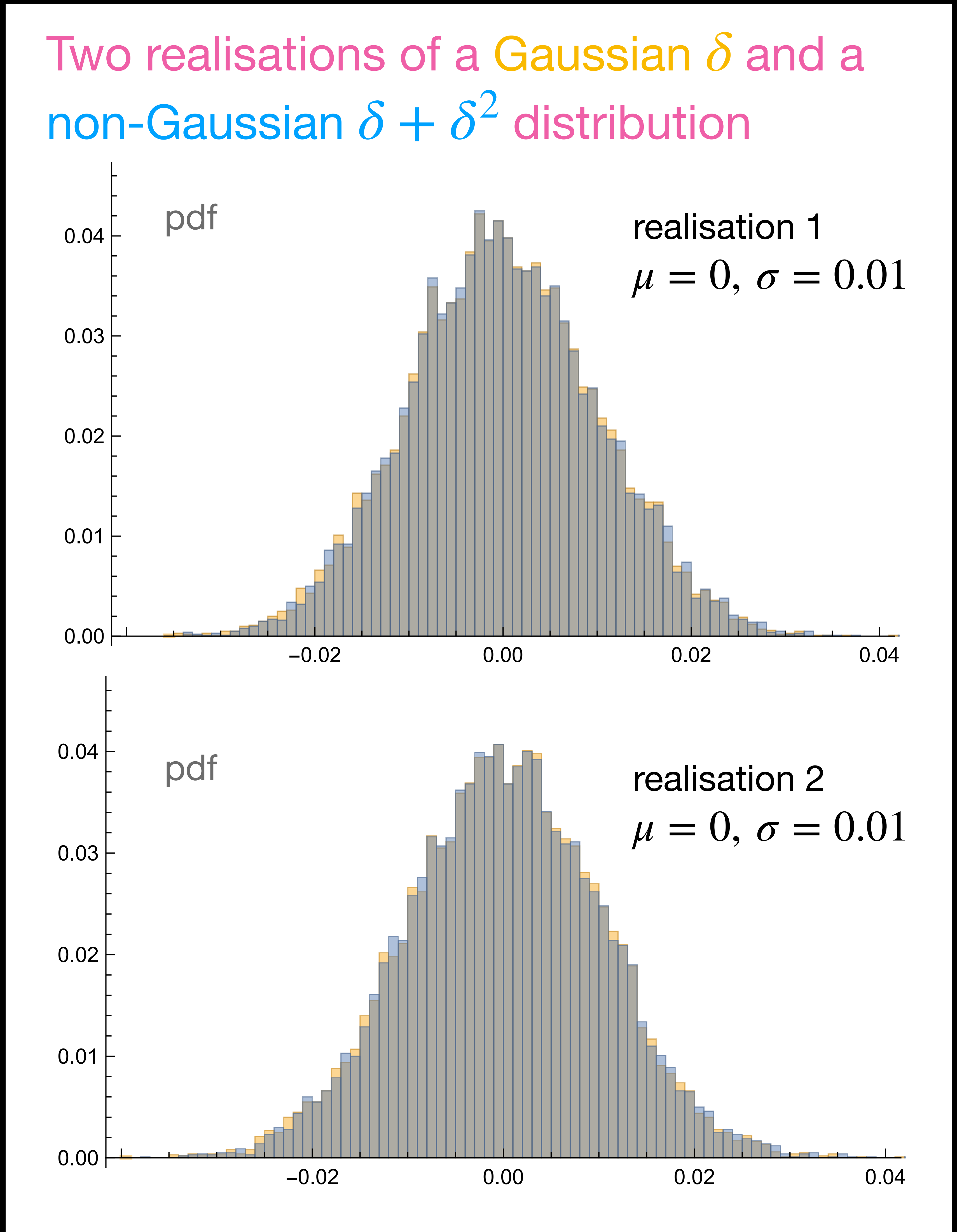


Nature of primordial perturbations

Cosmological inflation
(early epoch of accelerated expansion)
implies the existence of almost **scale invariant** and close to **Gaussian** primordial fluctuations of matter and space time

So far, all observations agree with Gaussianity

The minimally expected non-Gaussian effects are tiny
The examples show $f_{\mathrm{nl}} \sim 1$ for 10 000 draws and $\delta = \mathcal{O}(0.1)$ and $\mathcal{O}(0.01)$



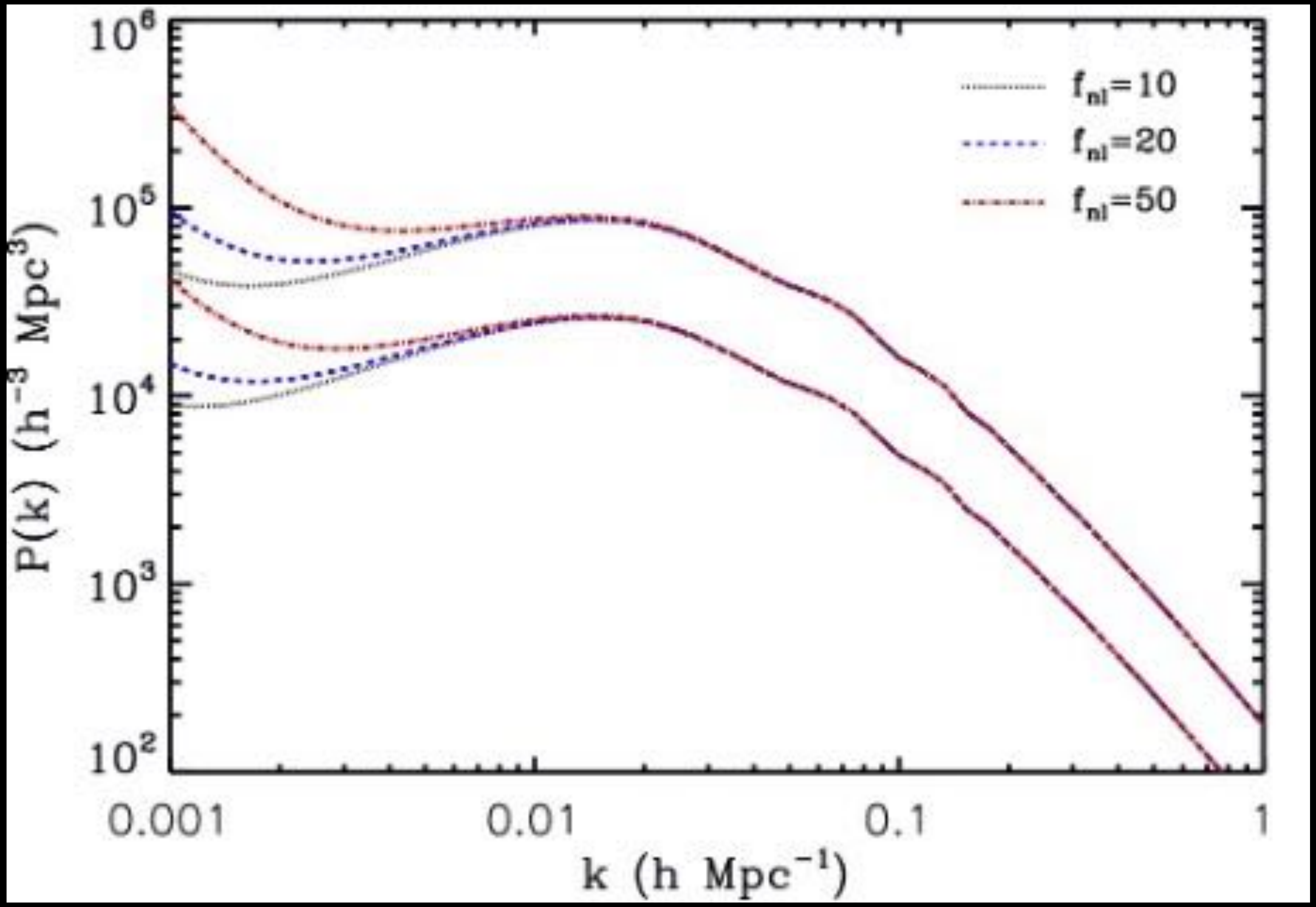
Nature of primordial perturbations

- Boost of power at largest scales due to influence of non-Gaussianity on halo bias Matarese et al. 2000, Dalal et al 2008, Matarese & Verde 2008, Slosar et al. 2008

- multi-tracer technique to reduce cosmic variance Seljak 2009

- Several forcasts for SKA-MID Raccanelli et al. 2012, Ferramacho et al. 2014, Alonso & Ferreira 2015, Raccanelli et al. 2018, Gomes et al. 2020 claim that $f_{\rm nl} \sim 5$ could be reached

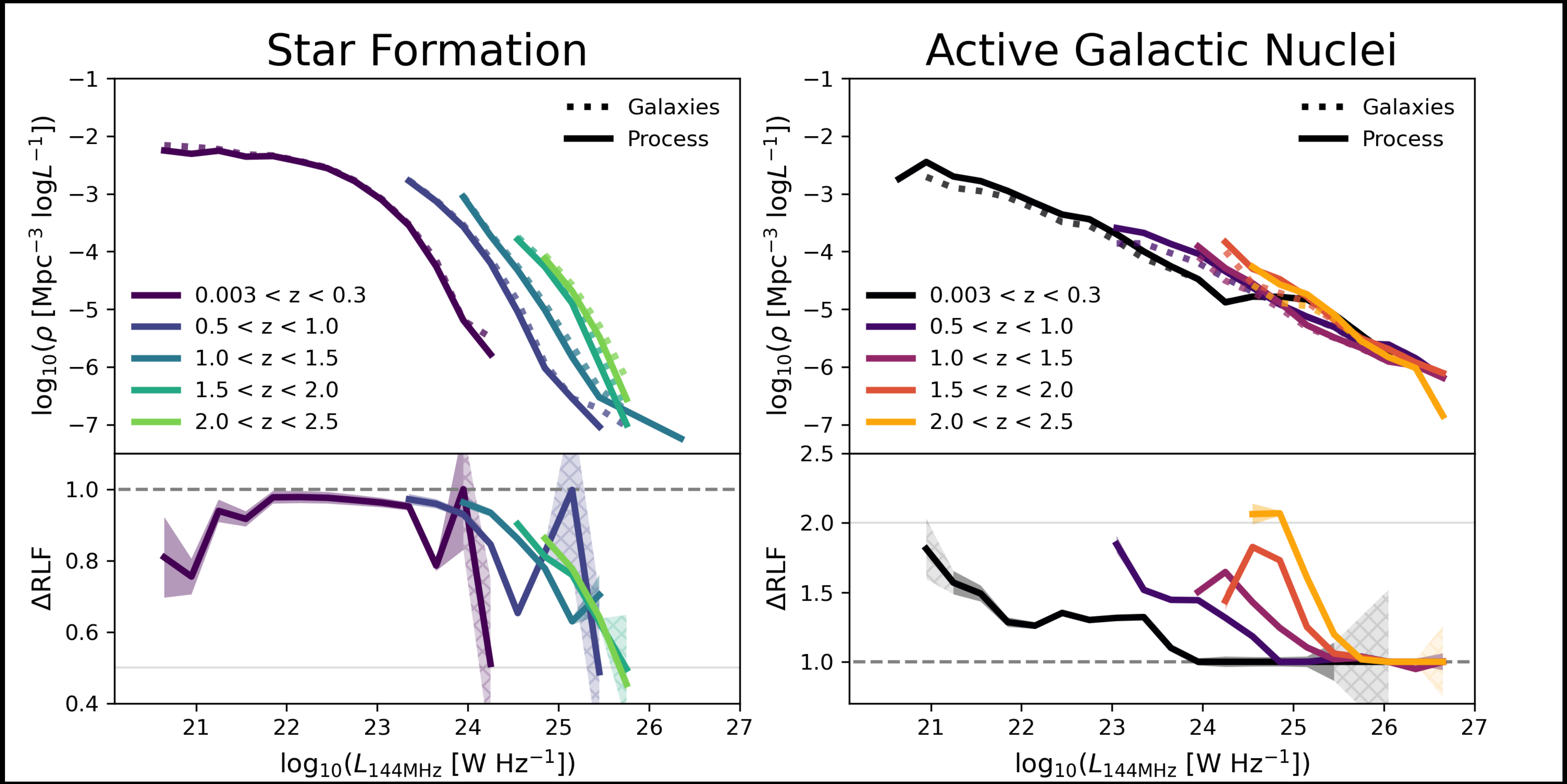
- Assumptions should be updated



Ferramacho et al. 2014

Radio luminosity functions

- Process based (surface brightness) compared to galaxy morphology based radio luminosity function of SFGs and AGNs from LOFAR international baselines deep fields
- Shows that AGN luminosity has been underestimated (up to factors of 2) and SFG slightly overestimated
- Impact on differential source counts, redshift distribution and bias needs to be further investigated



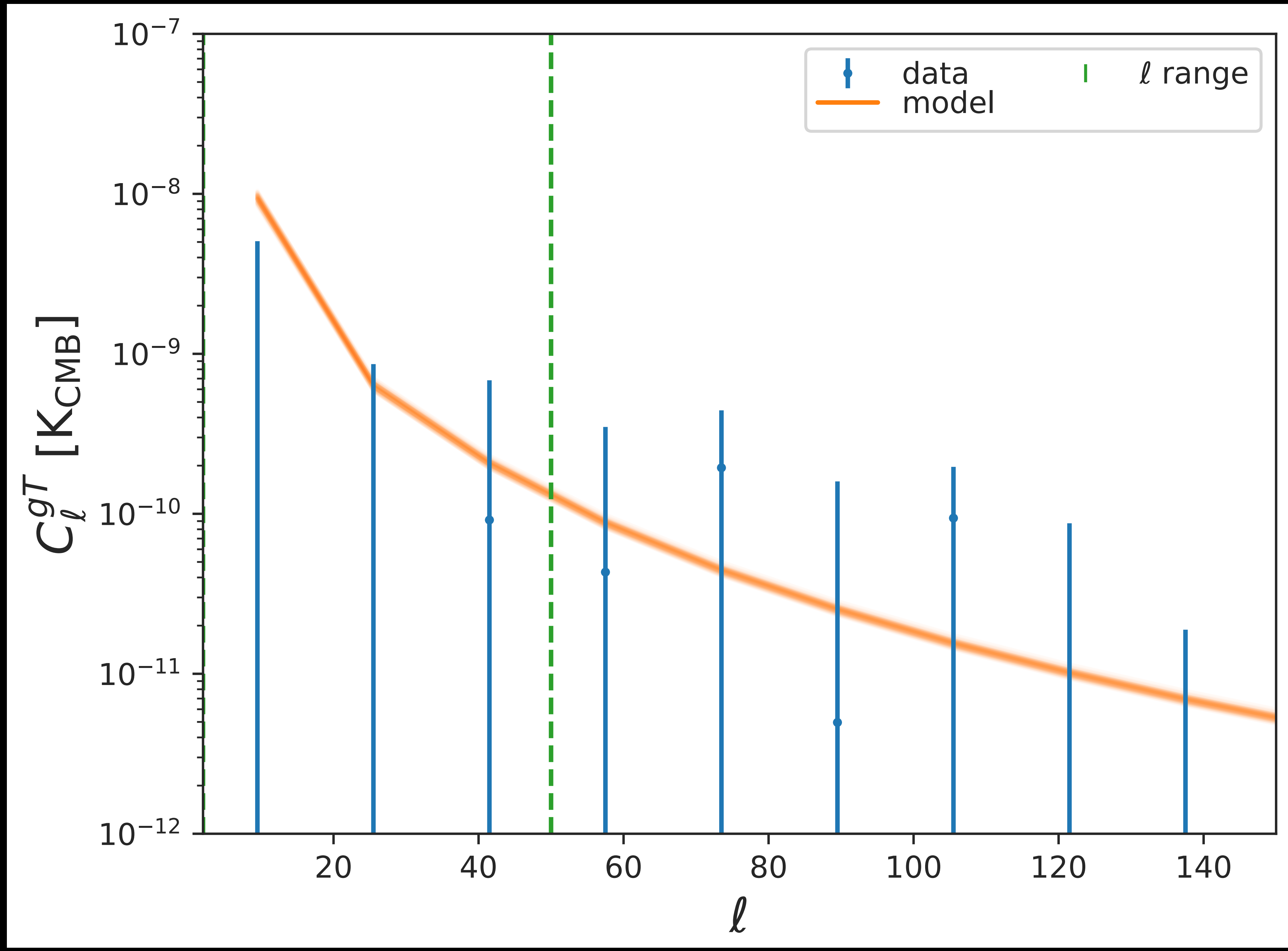
Morabito et al. submitted

Nature of dark energy

Late time accelerated expansion leads to late time **integrated Sachs-Wolfe effect**

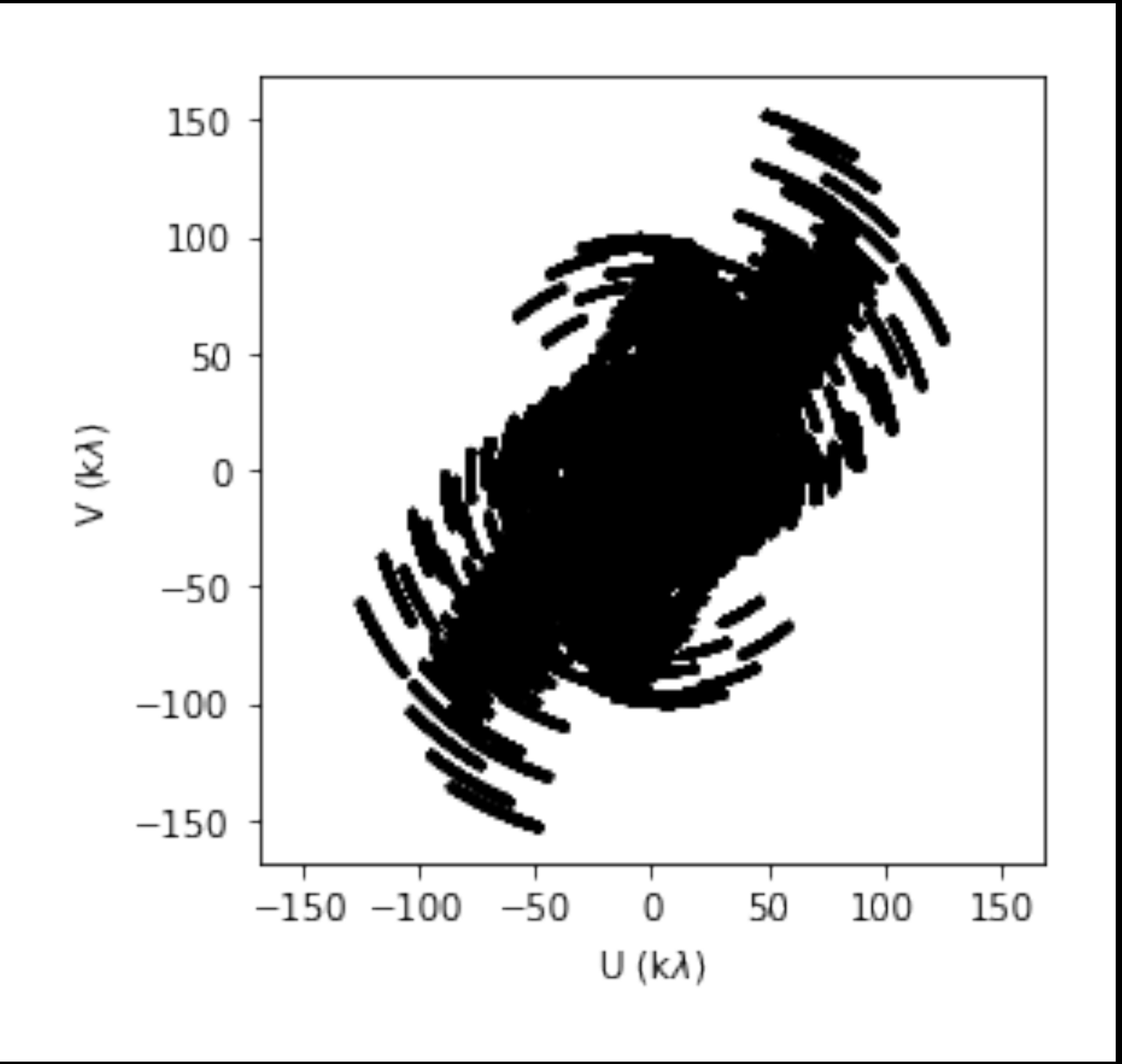
Probes LCDM and other dark energy models

Yet, only weak significance ($2.6\sigma/2.8\sigma$) for ISW from CMB-radio (NVSS/RACS-low), but these are still the largest non-CMB ISW signals
Planck 2016, Bahr-Kalus et al. 2022
In LoTSS DR2 less than 2σ
(wide area is essential) Nakonecny et al. 2024

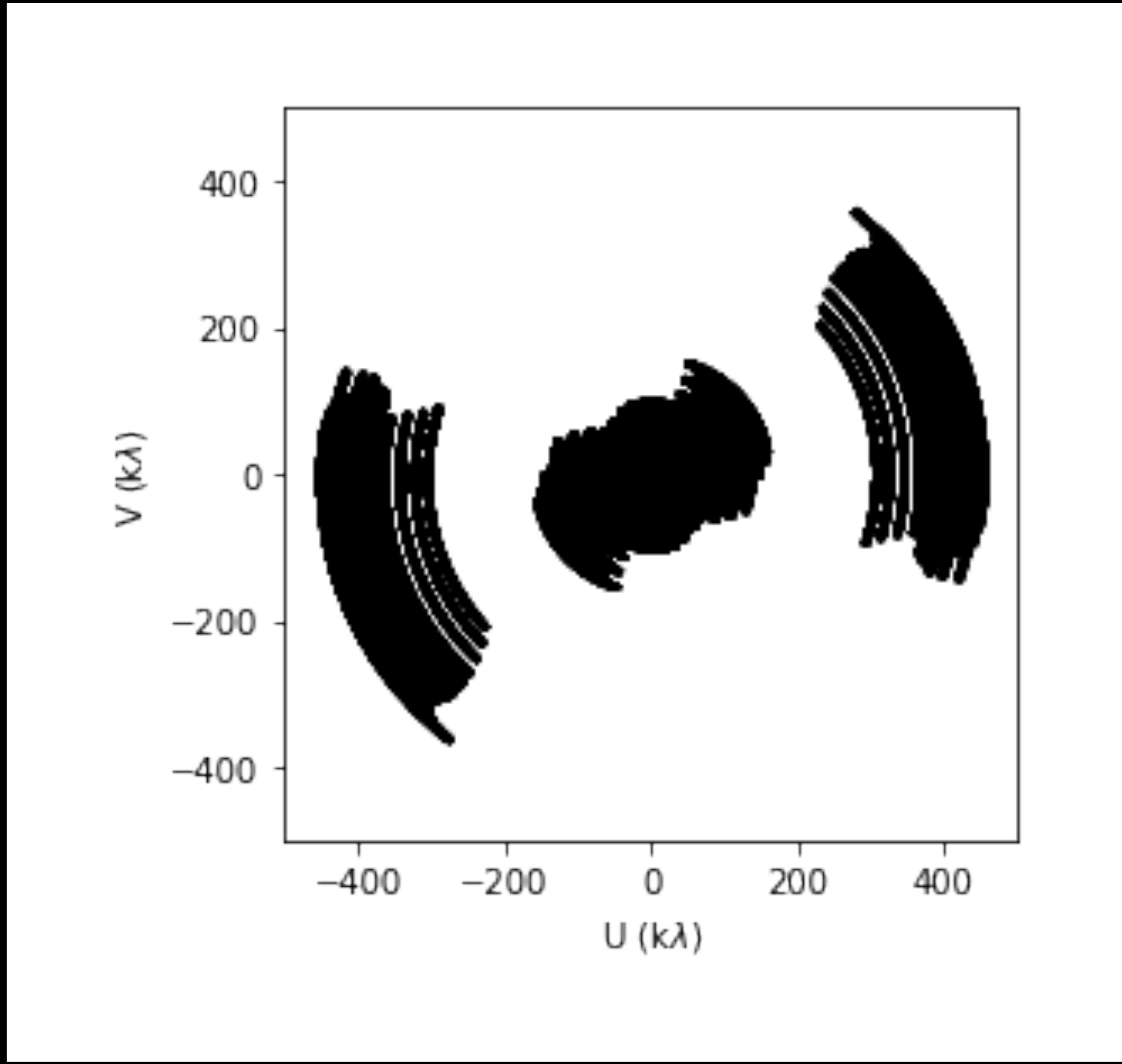


Nakonecny et al. 2024

SKA-MID Array Assembly



uv coverage of AA* - SKA008 for 4h track at 1.4 GHz



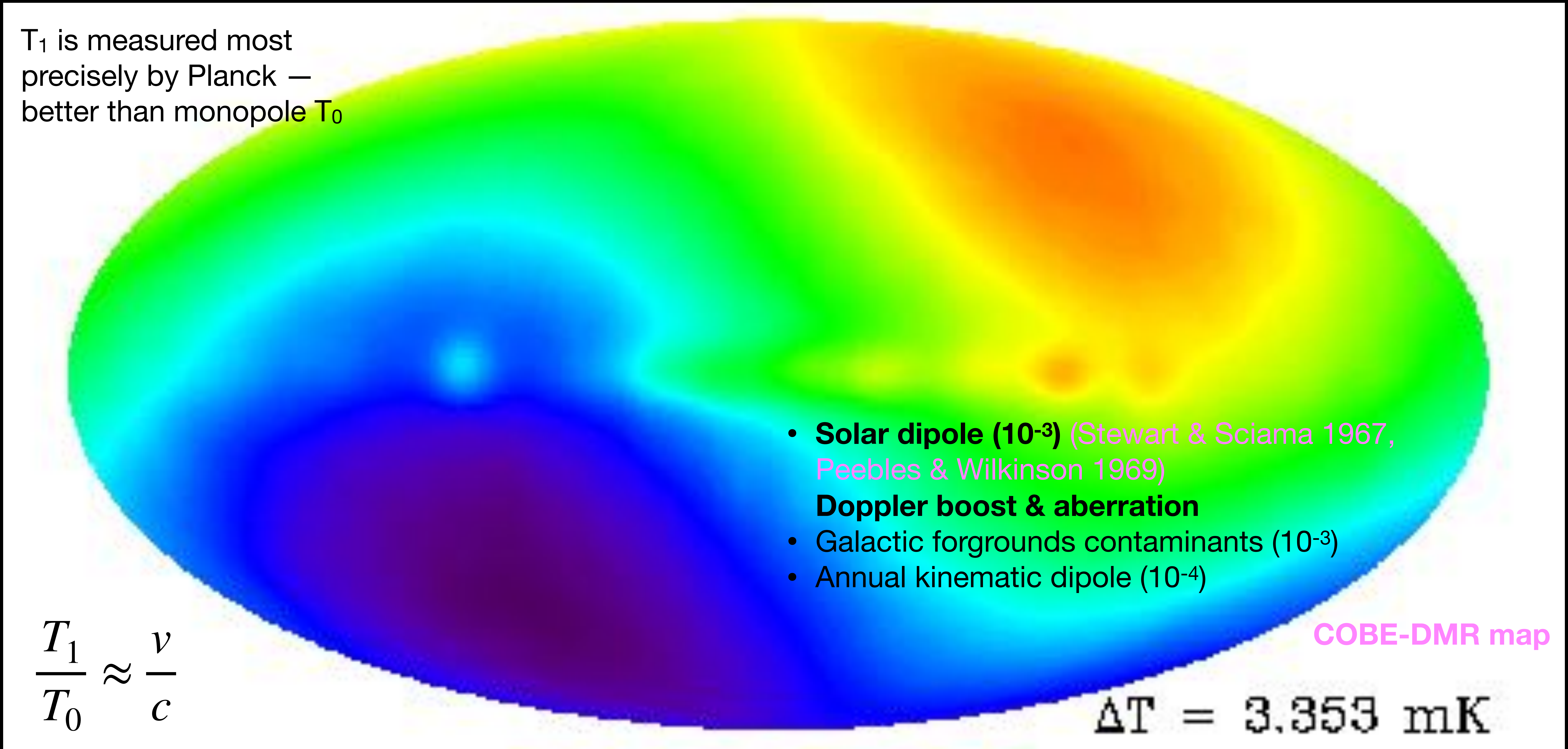
uv coverage after adding single
150 km baseline of AA* does not look good

Which goals can be achieved with such a lower angular resolution — harder to get good multi-wavelength cross identification— go to higher frequencies — but not of interest for HI

Cosmology with SKA

- Target fundamental questions
- Unique opportunities at large and ultra-large cosmological scales due to combination of sensitivity and survey speed (and angular resolution AA4)
- Cosmic dipoles (and other higher multipoles) -> Cosmological principle
- Non-Gaussianity -> Quantum fluctuations and non-linear structure
- Integrated Sachs-Wolfe -> Dark energy
- All need to cover largest anglar scales at several bands and photo-z

CMB dipole



T_1 is measured most precisely by Planck — better than monopole T_0

- **Solar dipole (10^{-3})** (Stewart & Sciama 1967, Peebles & Wilkinson 1969)
  Doppler boost & aberration
- Galactic forgrounds contaminants (10^{-3})
- Annual kinematic dipole (10^{-4})

$$\frac{T_1}{T_0} \approx \frac{v}{c}$$

Assumed to be due to motion of Sun w.r.t. cosmic 2.7 K background radiation

Other probes of the rest frame

Radio and quasar dipoles

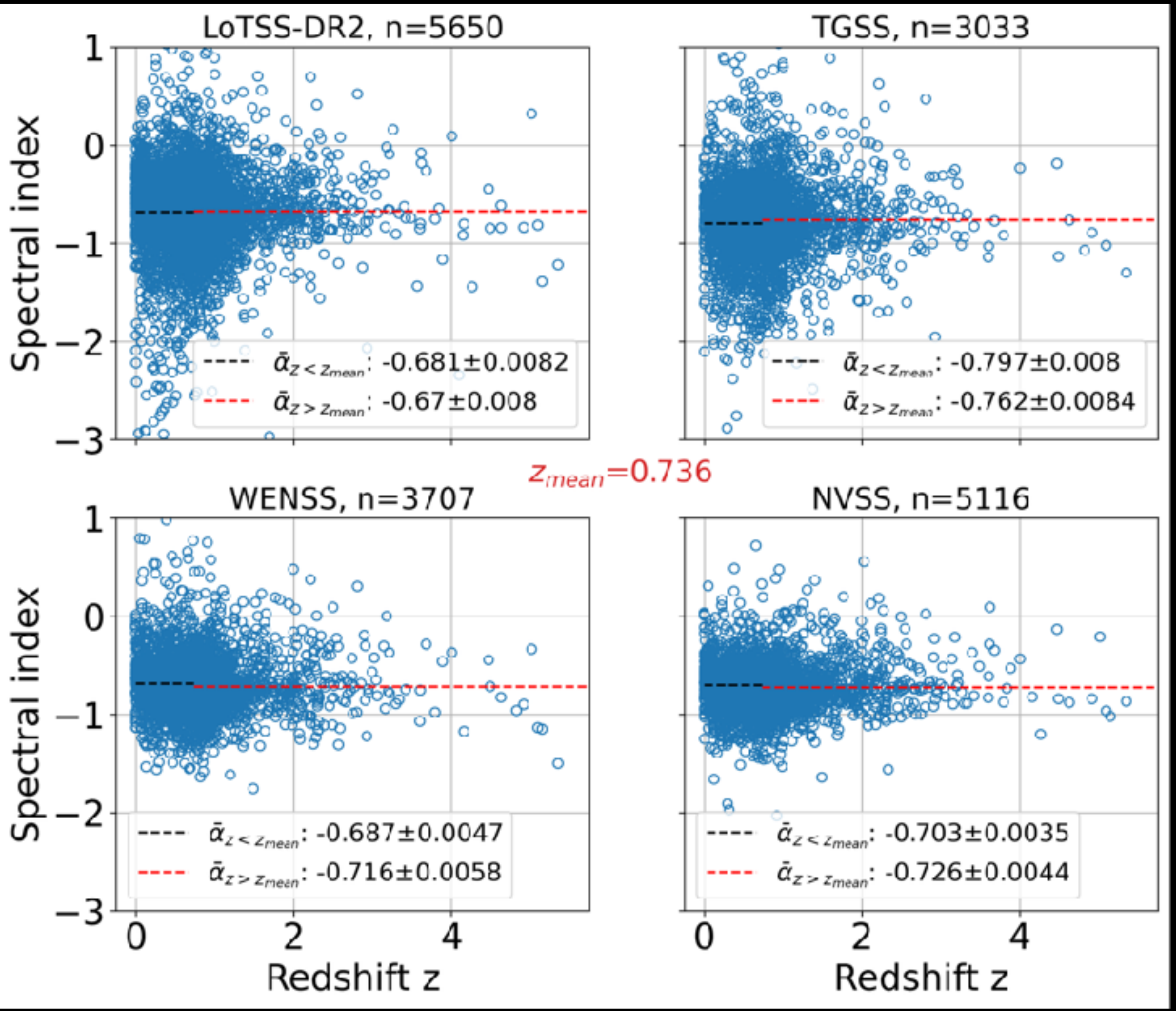
Use counts-in-cell from wide area surveys
Ellis & Baldwin 1984

$$\frac{\mathrm{d}N}{\mathrm{d}\Omega}(>S,\mathbf{e}) = \frac{\mathrm{d}N}{\mathrm{d}\Omega}_{\mathrm{com}}(>S)\;(1+\mathbf{d}\cdot\mathbf{e}+\ldots),$$

$$\mathbf{d} = [2+x(1-\alpha)]\mathbf{v}/c, \quad S \propto \nu^{\alpha}, \quad \frac{\mathrm{d}N}{\mathrm{d}\Omega} \propto S^{-x}$$

More complicated if x AND α evolve with z
Chen & Schwarz 2016, Nadolny et al. 2021, Dalang & Bonvin 2022, von Hausegger 2024

No indication for evolution of α (for radio galaxies), but huge scatter



α(z) from LoLSS cross-matched with other radio surveys and photo-z from LoTSS VAC
Böhme et al. 2023

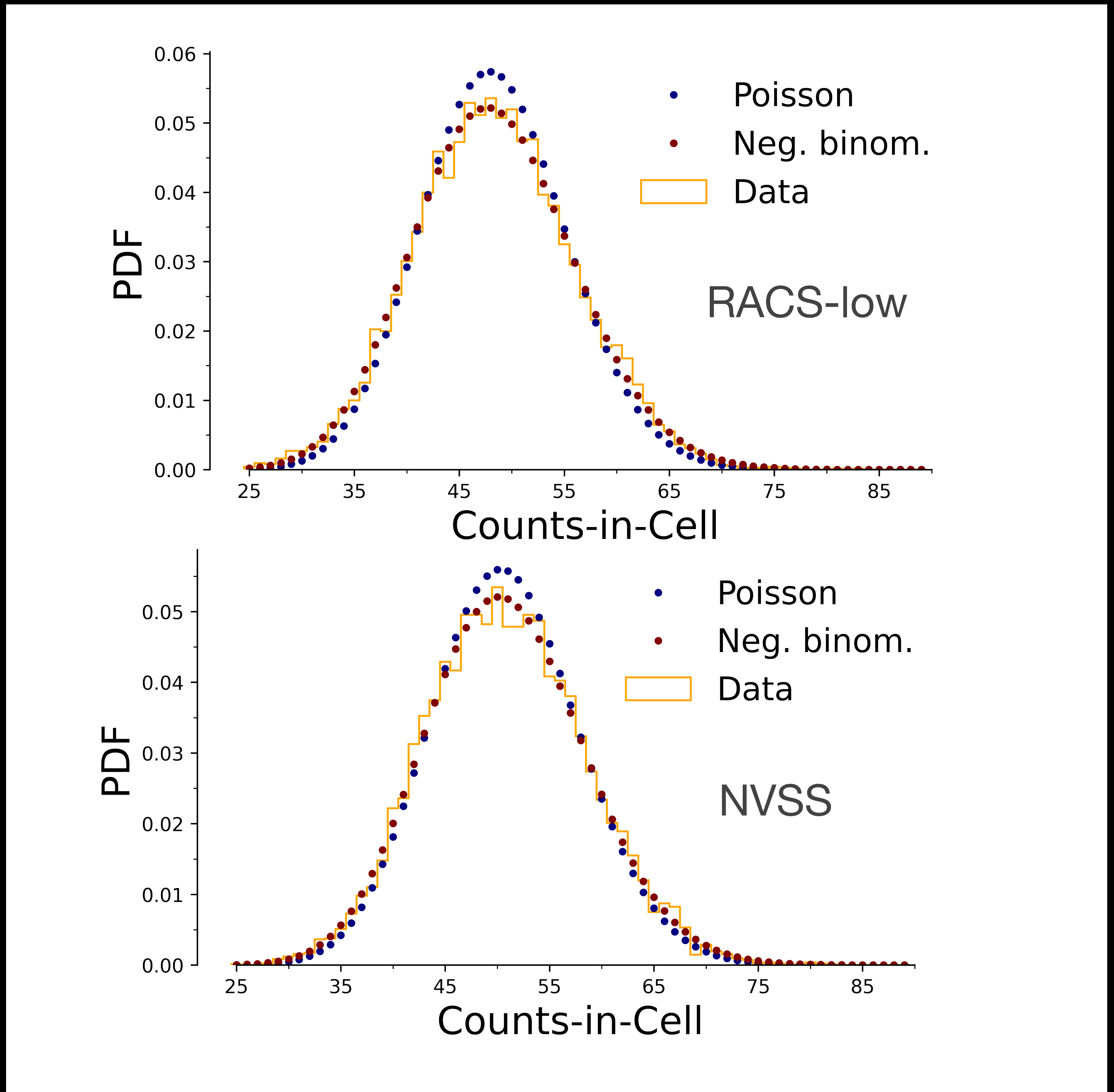
Radio and quasar dipoles

Photometry and calibration
(do we know the flux densities at required accuracy and precission?)

Estimators and masks
(Siewert et al. 2021, Dam et al. 2022, Böhme et al. in prep.)

Evolution effects
(Dalang & Bonvin 2022, Guandalin et al. 2022, von Hausegger 2024)

Clustering Dipole
(Rubart et al. 2014, Bengaly et al. 2019, Dam et al. 2022, Wagenveld et al. in prep.)



Böhme et al. in prep.

Task: **distinguish clustering dipole from kinematic dipole** and **demonstrate that different kinematic dipoles agree with each other**

Other probes for kinematic dipole

Supernovae Ia

SN1a magnitude is coherently modulated by proper motion of Solar system
Sasaki 1985, Horstmann et al. 2022

$$\mu(z, \mathbf{e}) = \mu_{\text{com}}(z) + 5\log_{10}(1 - \mathbf{e}\cdot\mathbf{v}/c)$$

Can be degenerate with large scale bulk flows

Agreement!

But see also
Sorrenti et al. 2022
they find larger velocity and a tension in dipole direction for Pantheon+ sample (but Pantheon+ contains more local and less high-z SNe)