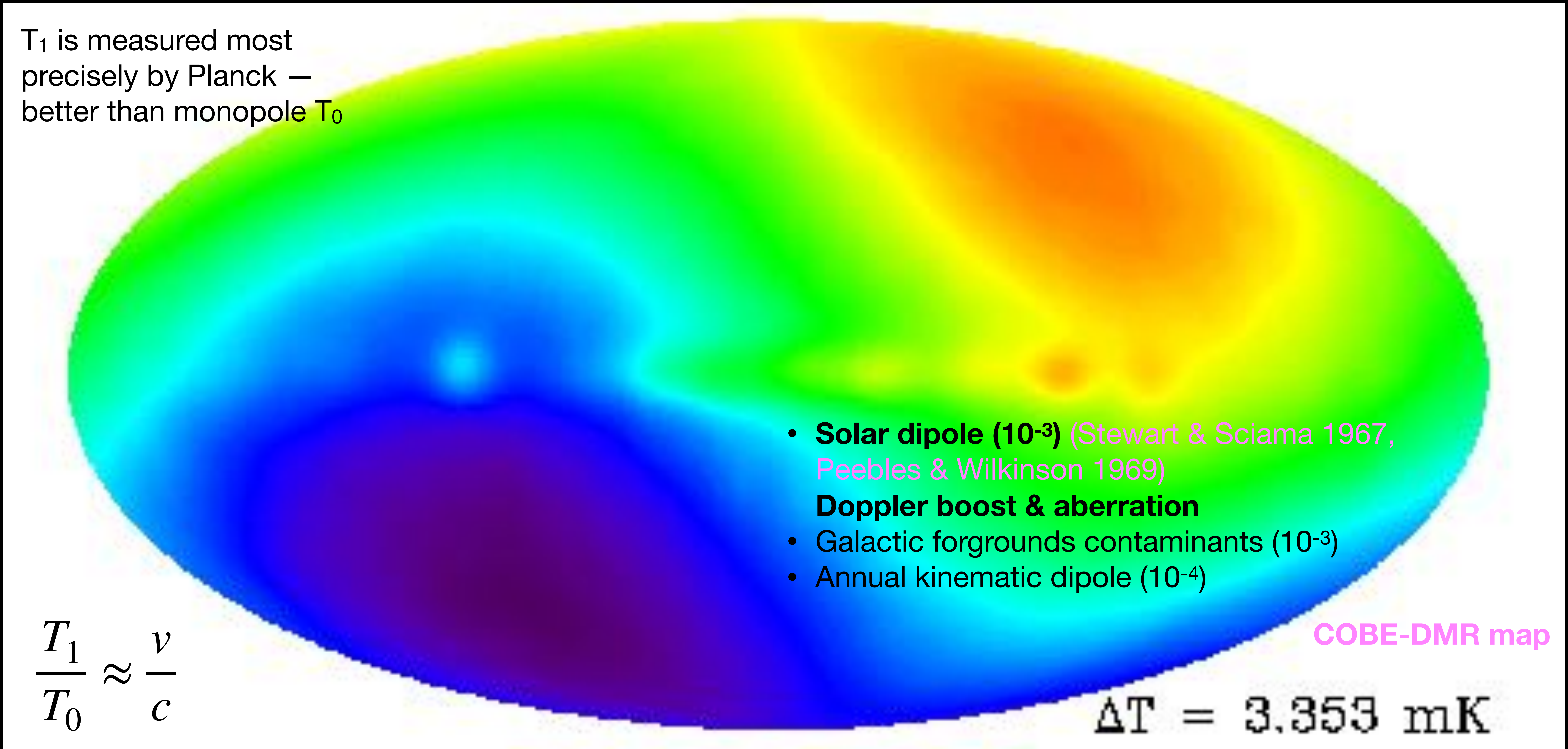
Cosmic dipole(s)

Why are they of interest ?

Cosmic radio dipole and Gaussianity are one of SKA's 14 highlight science cases
Schwarz et al. 2014 (AASKA14), Bacon et al. 2020 (Red Book)

Dominik Schwarz (Bielefeld University) **SKA Cosmology Working Group Meeting** **January 2023**

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})

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

COBE-DMR map

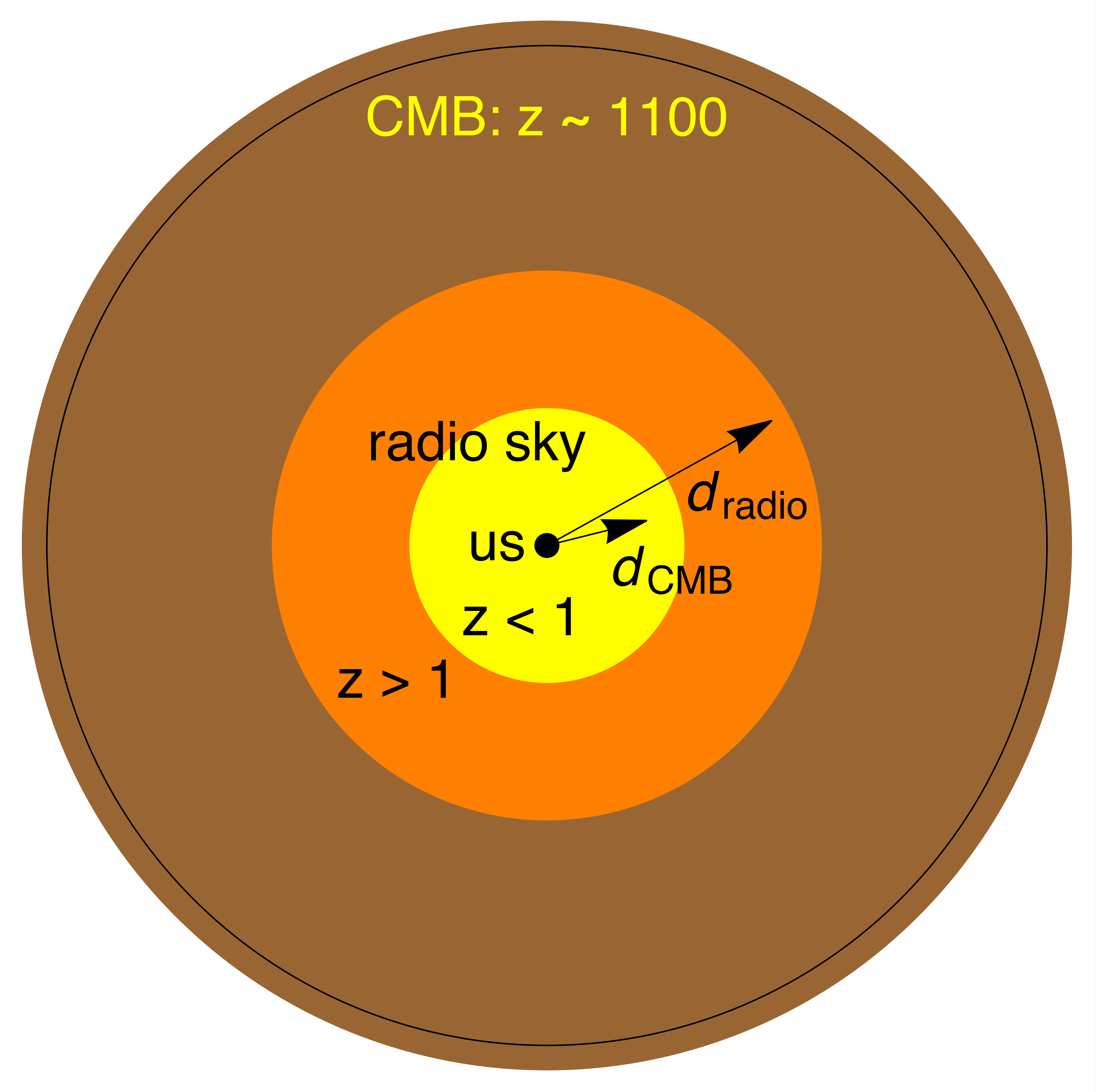
Assumed to be due to motion of Sun w.r.t. cosmic 2.7 K background radiation

Nature of the CMB dipole?

Cosmological principle
(statistical isotropy and homogeneity)
implies the existence of a
preferred rest frame and of comoving observers

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

But CMB dipole could in principle be (partly) a primordial fluctuation



How to probe the nature of the CMB dipole?

Can we establish CMB dipole is kinematic?

Higher multipole moments of CMB show that high-ℓ modes are consistent with kinematic origin of CMB dipole

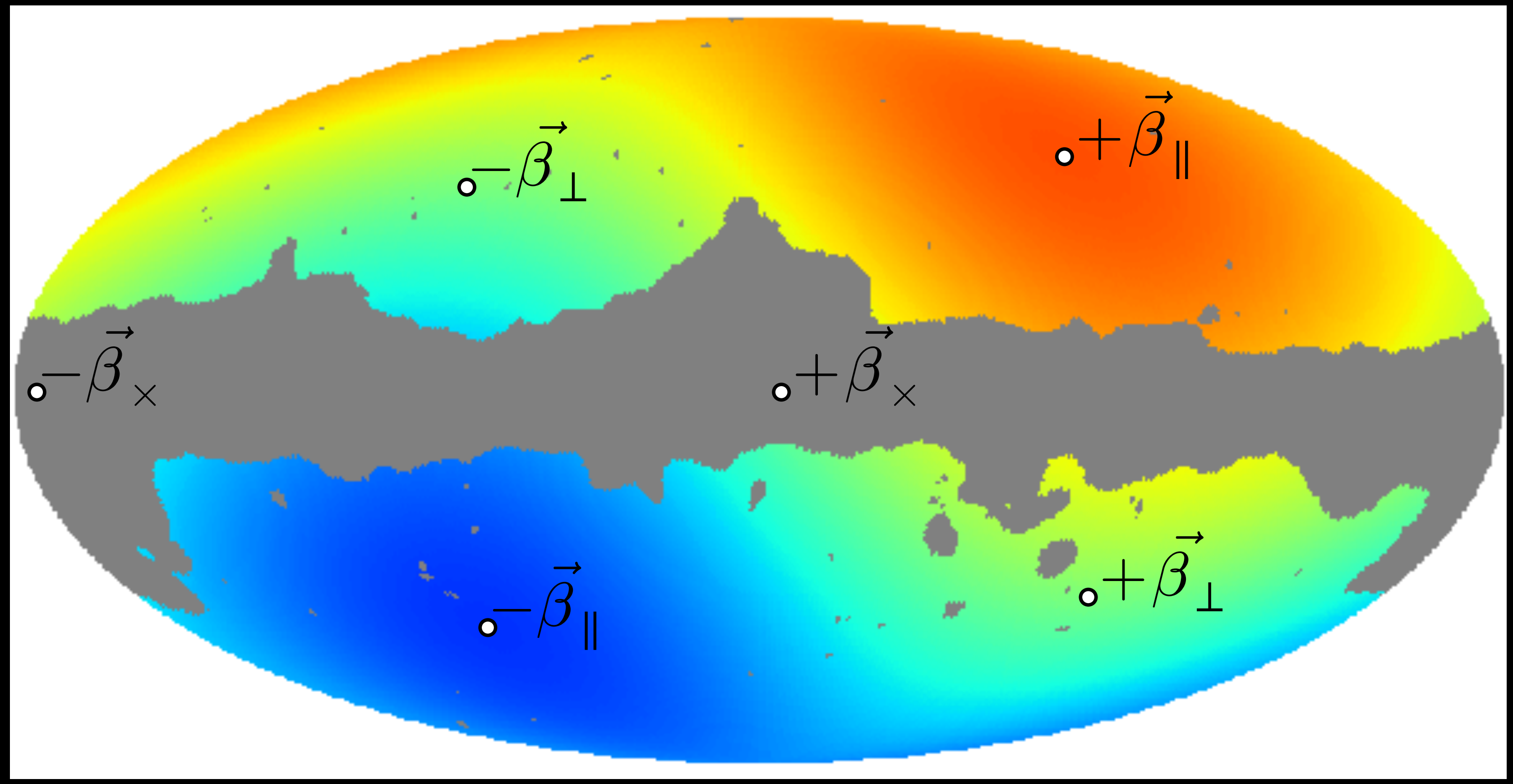
$$\ell = 1 : v = (1.23356 \pm 0.00045) \times 10^{-3} c$$

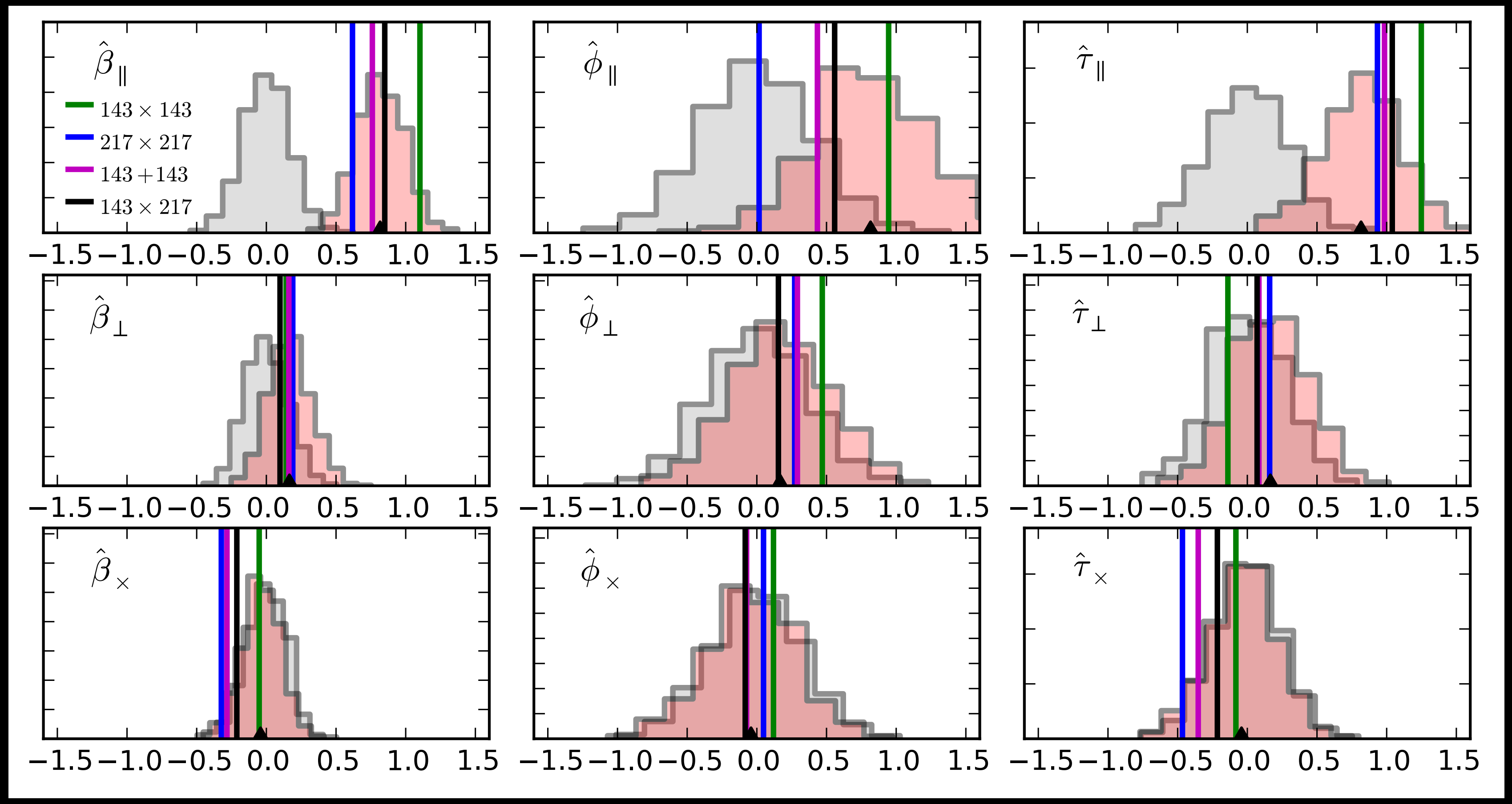
Planck 2020

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

Planck 2014, Saha et al. 2020

could only be improved by even better full sky maps (foregrounds!)





Planck 2014

A cosmic rest frame?

Supernovae Ia

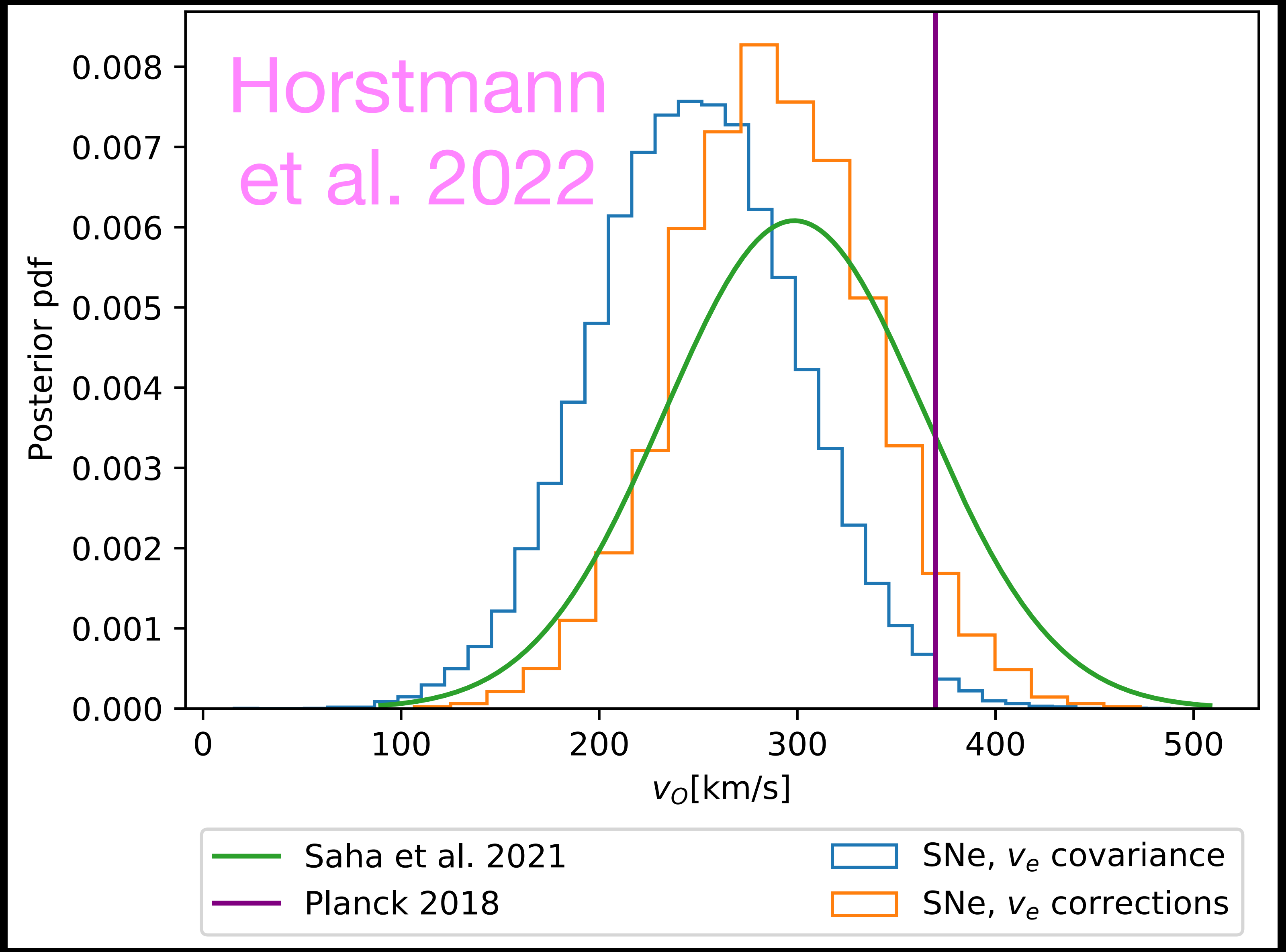
SN1a magnitude is coherently modulated by proper motion of Solar system
Sasaki 1985, Horstmann et al. 2022

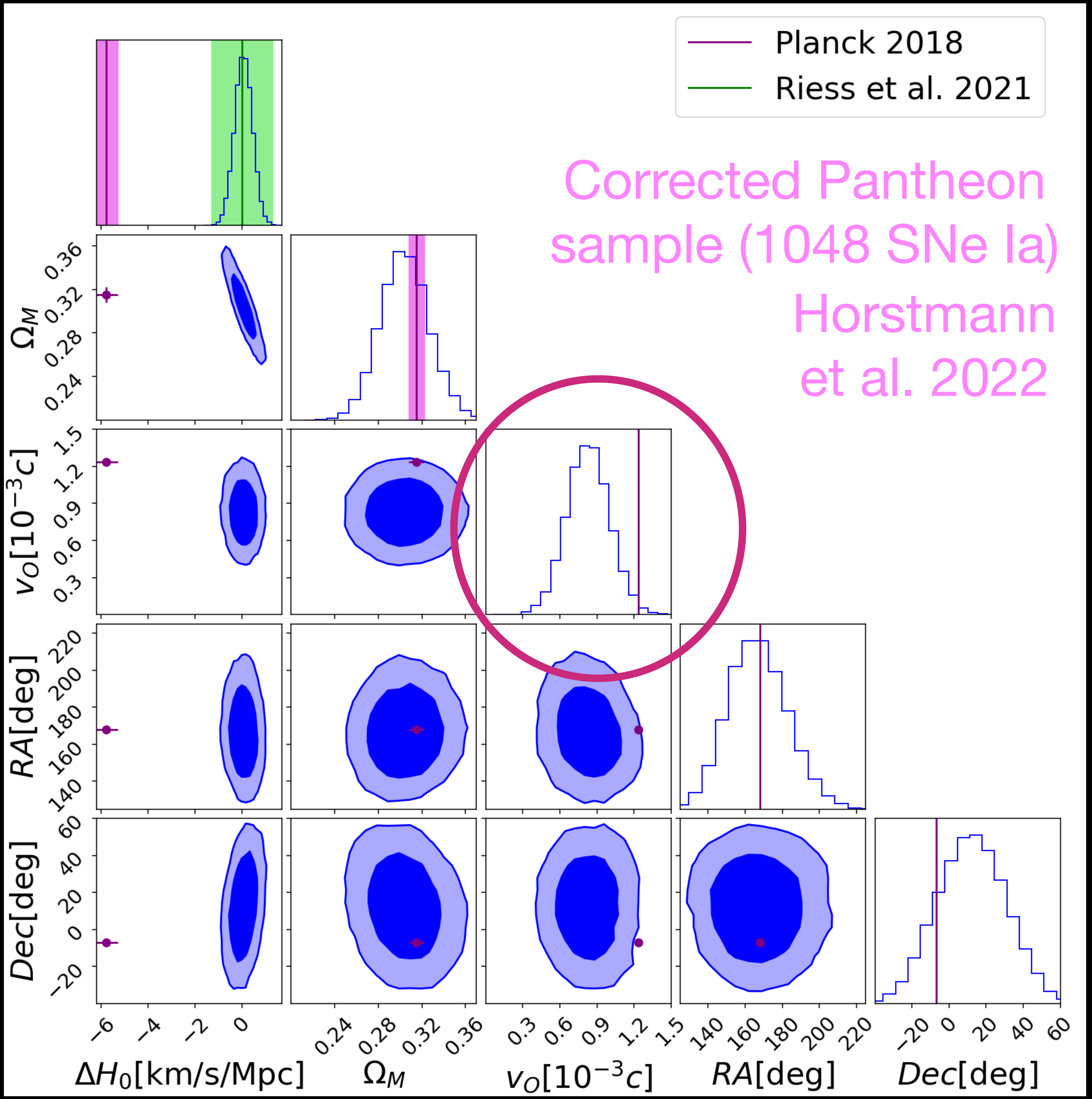
$$\mu(z, \mathbf{e}) = \mu_{\rm com}(z) + 5\log_{10}(1 - \mathbf{e}\cdot\mathbf{v}/c)$$

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





Other probes of the rest frame

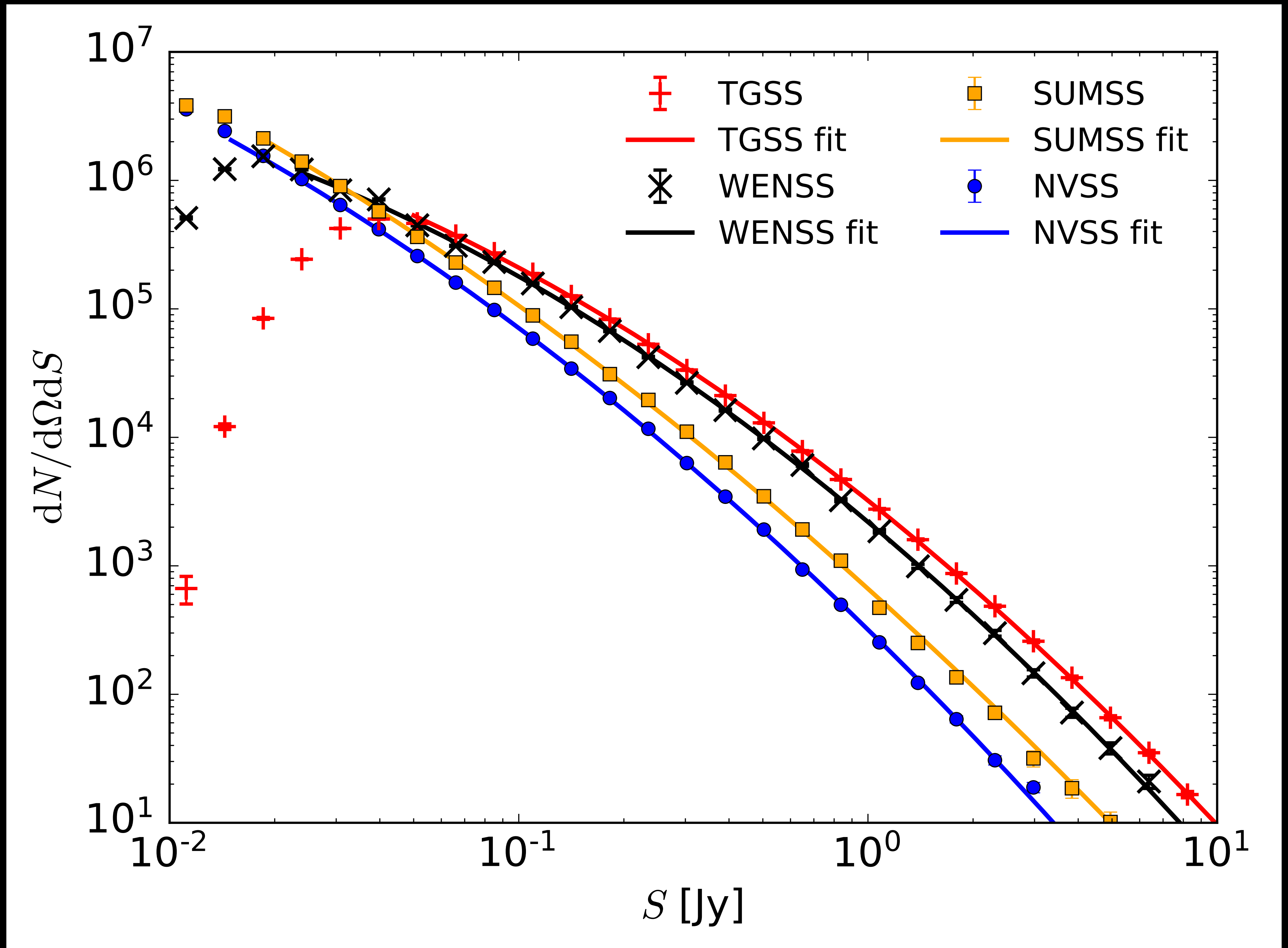
Radio and quasar dipoles

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

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

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

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



x in various radio surveys: Siewert et al. 2021

Other probes of the rest frame

Radio and quasar dipoles

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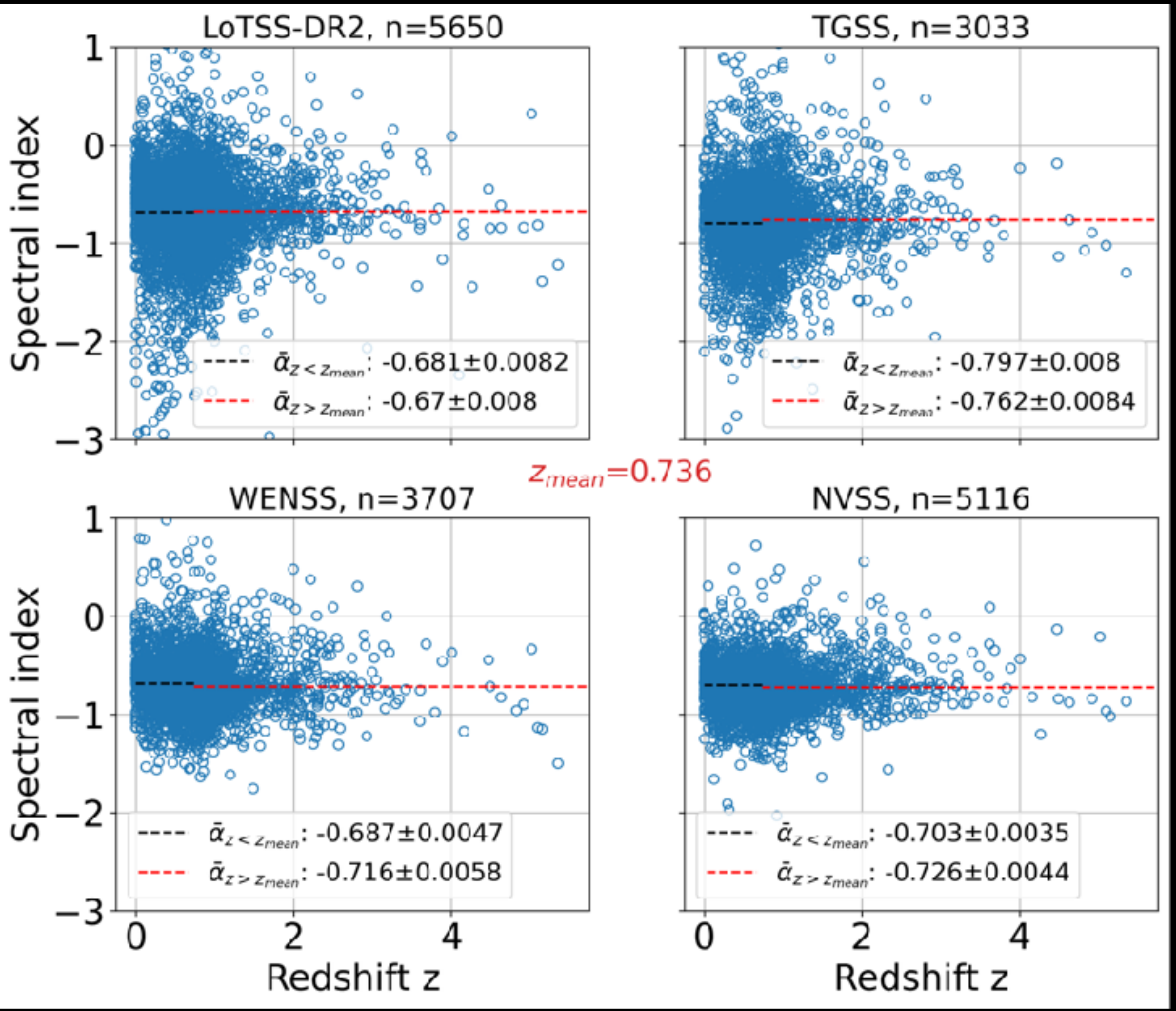
$$\frac{\mathrm{d}N}{\mathrm{d}\Omega}(>S, \mathbf{e}) = \frac{\mathrm{d}N}{\mathrm{d}\Omega}_{\mathrm{com}}(>S)\ (1 + \mathbf{d}\cdot\mathbf{e} + \ldots),$$

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

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

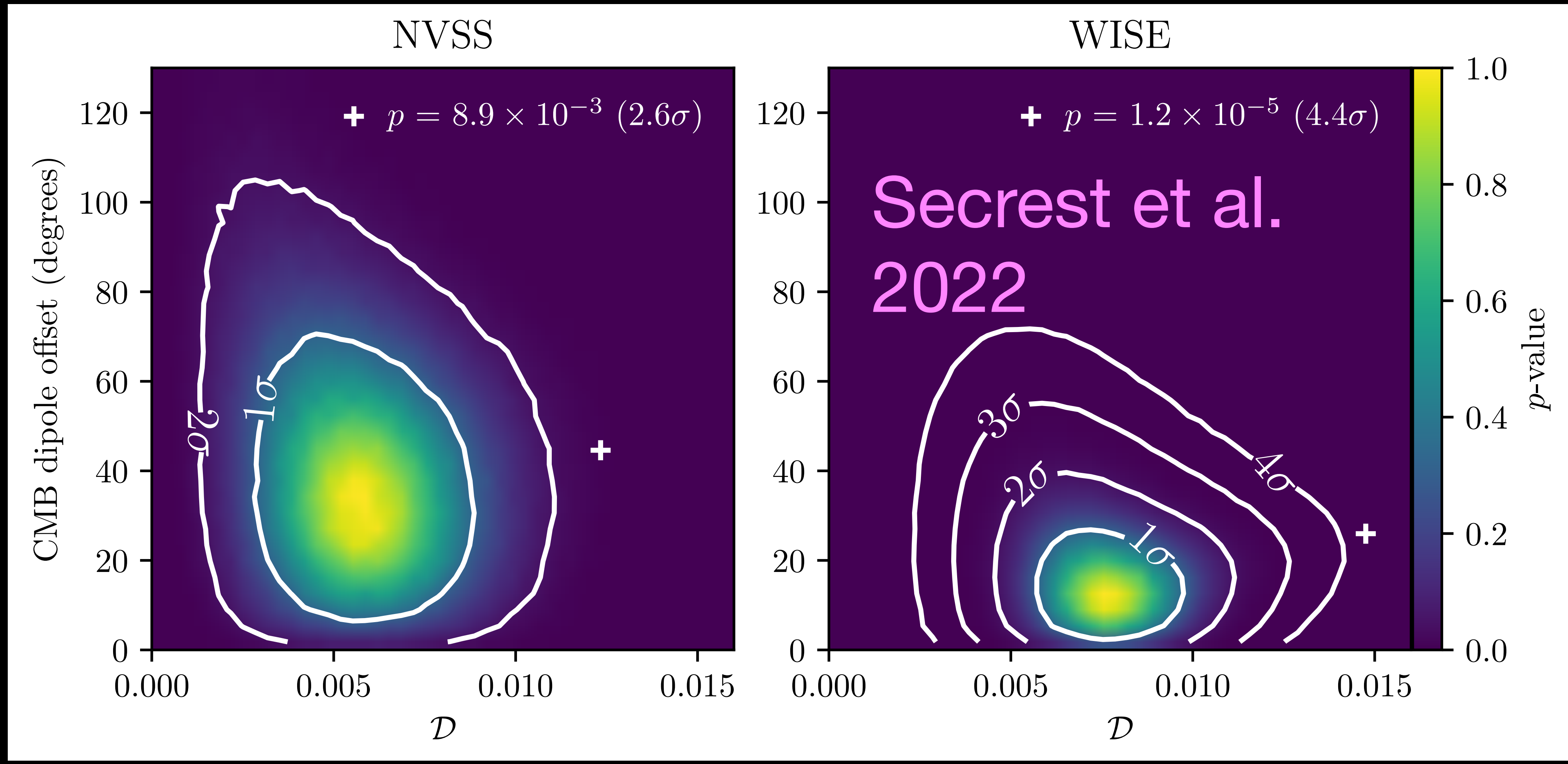
No indication for evolution of α (for radio galaxies), but huge scatter



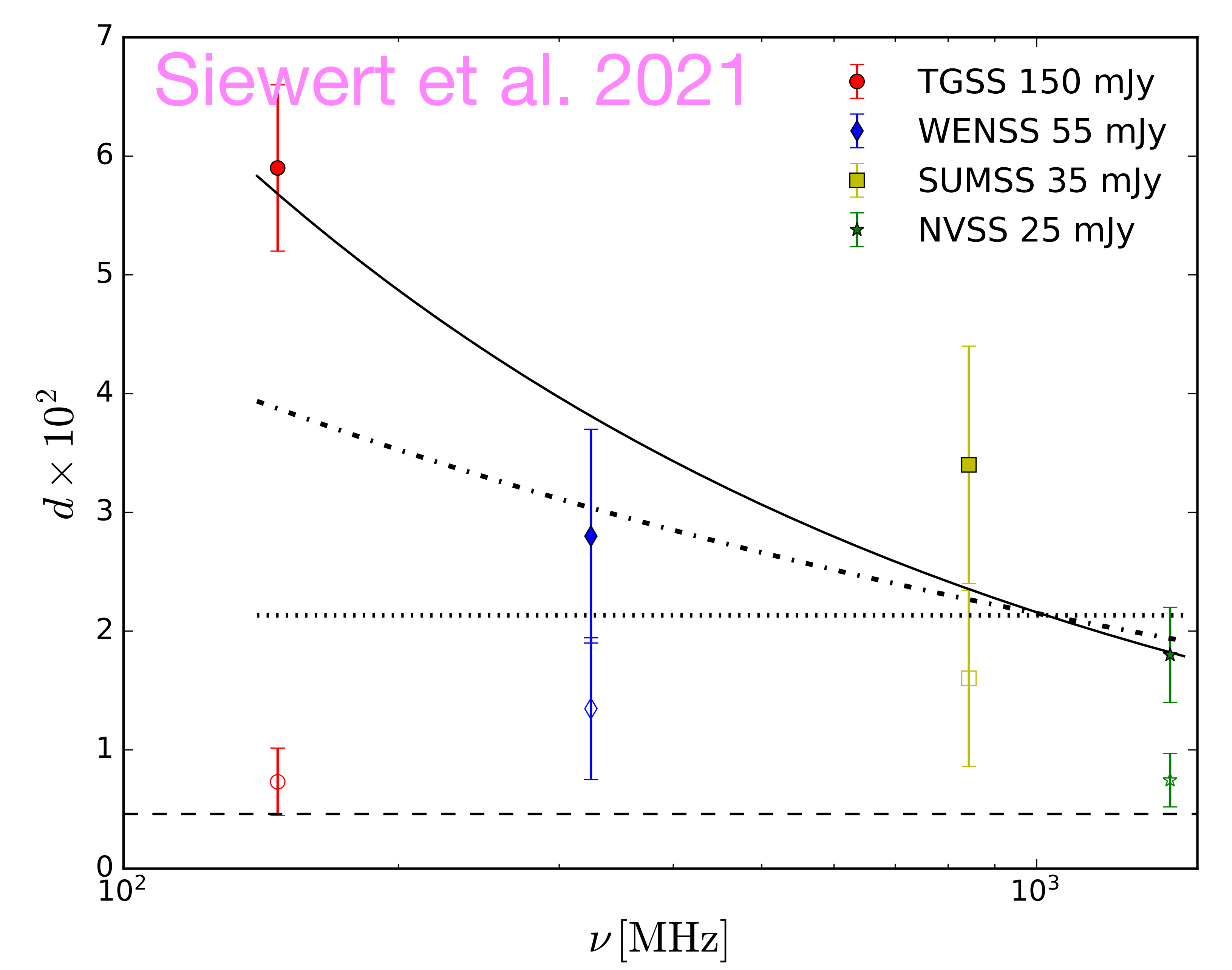
α(z) from LoLSS cross-matched with other radio surveys and photo-z from LoTSS VAC
Böhme et al. (submitted)

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)



Possible caveats:
Sample selection — completeness & reliability
Estimators and masks (Siewert et al. 2021, Dam et al. 2022)
Evolution effects (Dalang & Bonvin 2022, Guandalin et al. 2022)
Large Scale Structure Dipole (Rubart et al. 2014, Bengaly et al. 2019, Dam et al. 2022)



To establish existence of a cosmic rest frame:
demonstrate that different kinematic dipoles agree with each other (not done so far!)

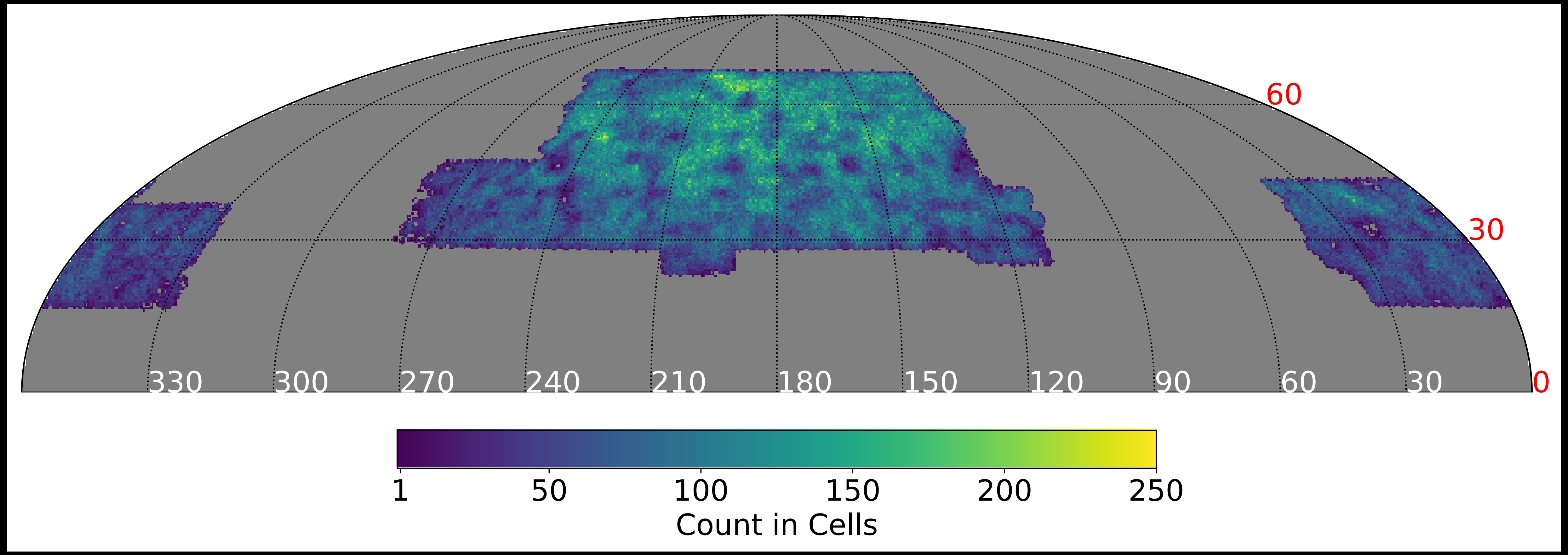
Preliminary LOFAR radio dipole result

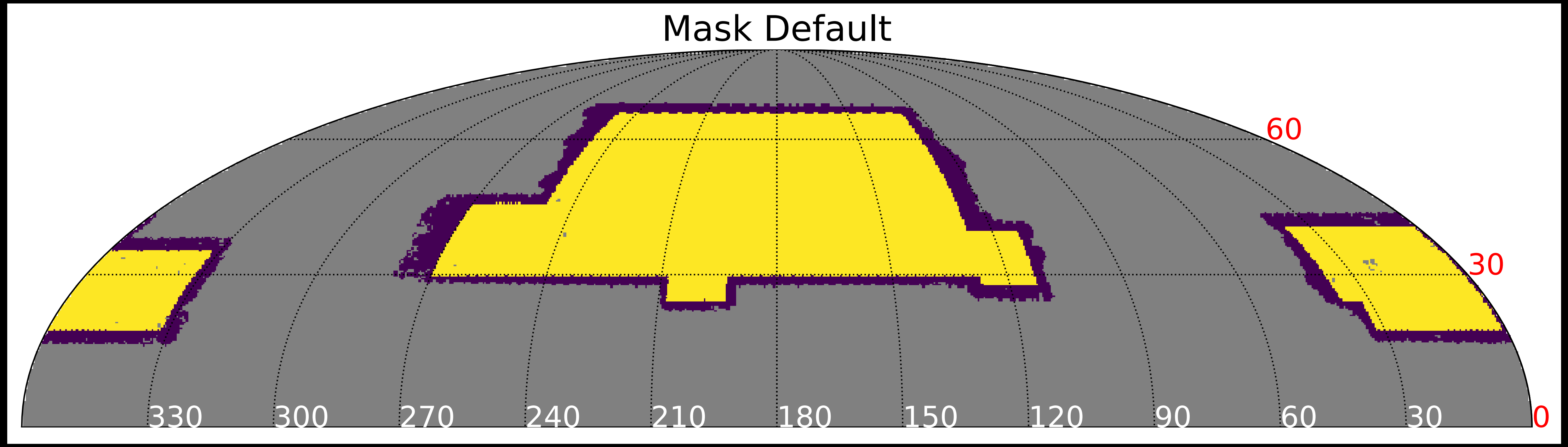
LoTSS-DR2: mask survey area, S > 1.5 mJy, SNR > 7.5 (Hale et al. in prep.)

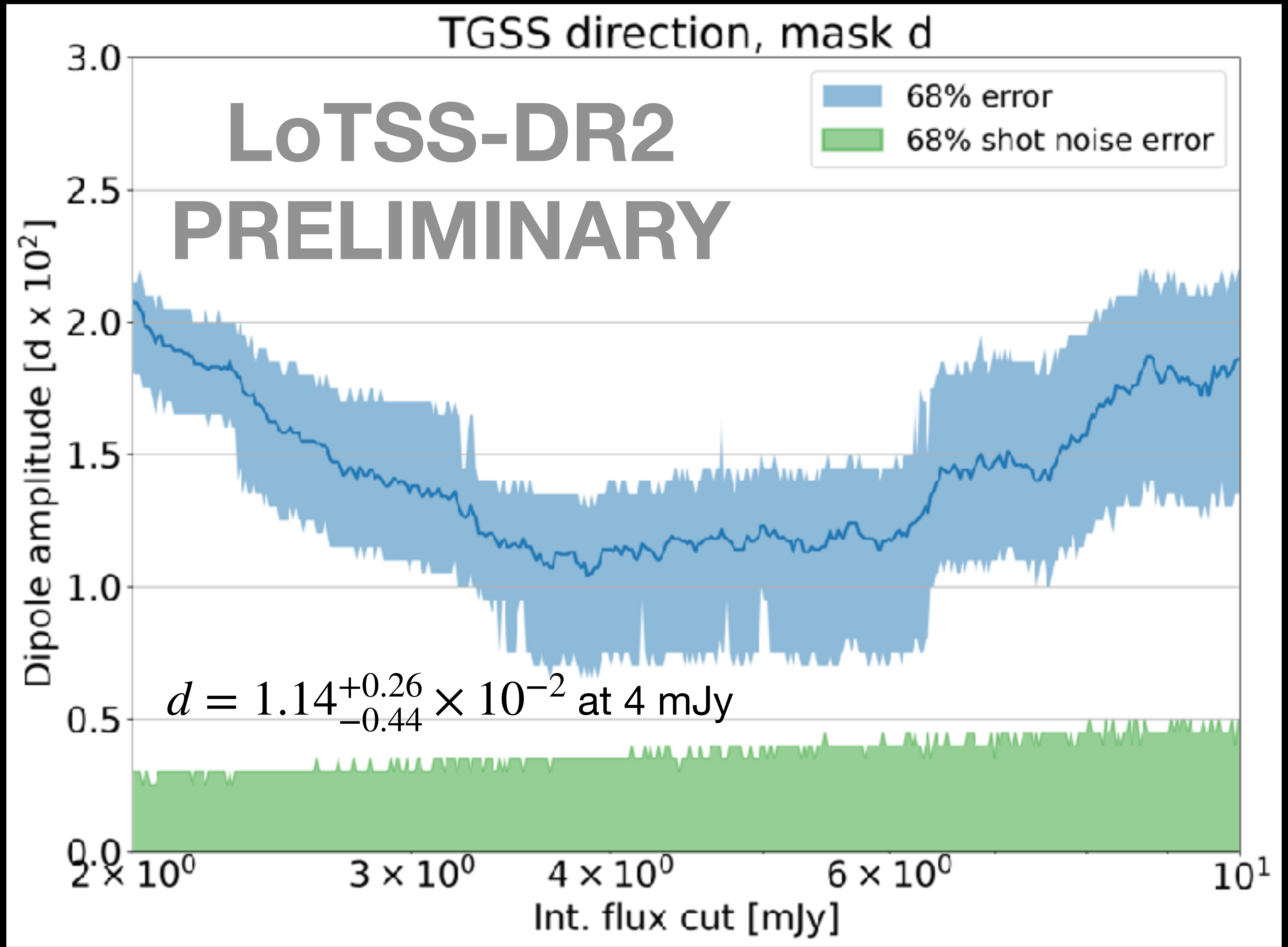
Significant detection of dipole (d > 0: p = 0.9998 @ 4 mJy; large scale issues at S < 3 mJy)

TGSS dipole (d ~ 0.06) is ruled out; LoTSS dipole consistent with NVSS & WISE

BUT: p = 0.02 to agree with CMB expected value





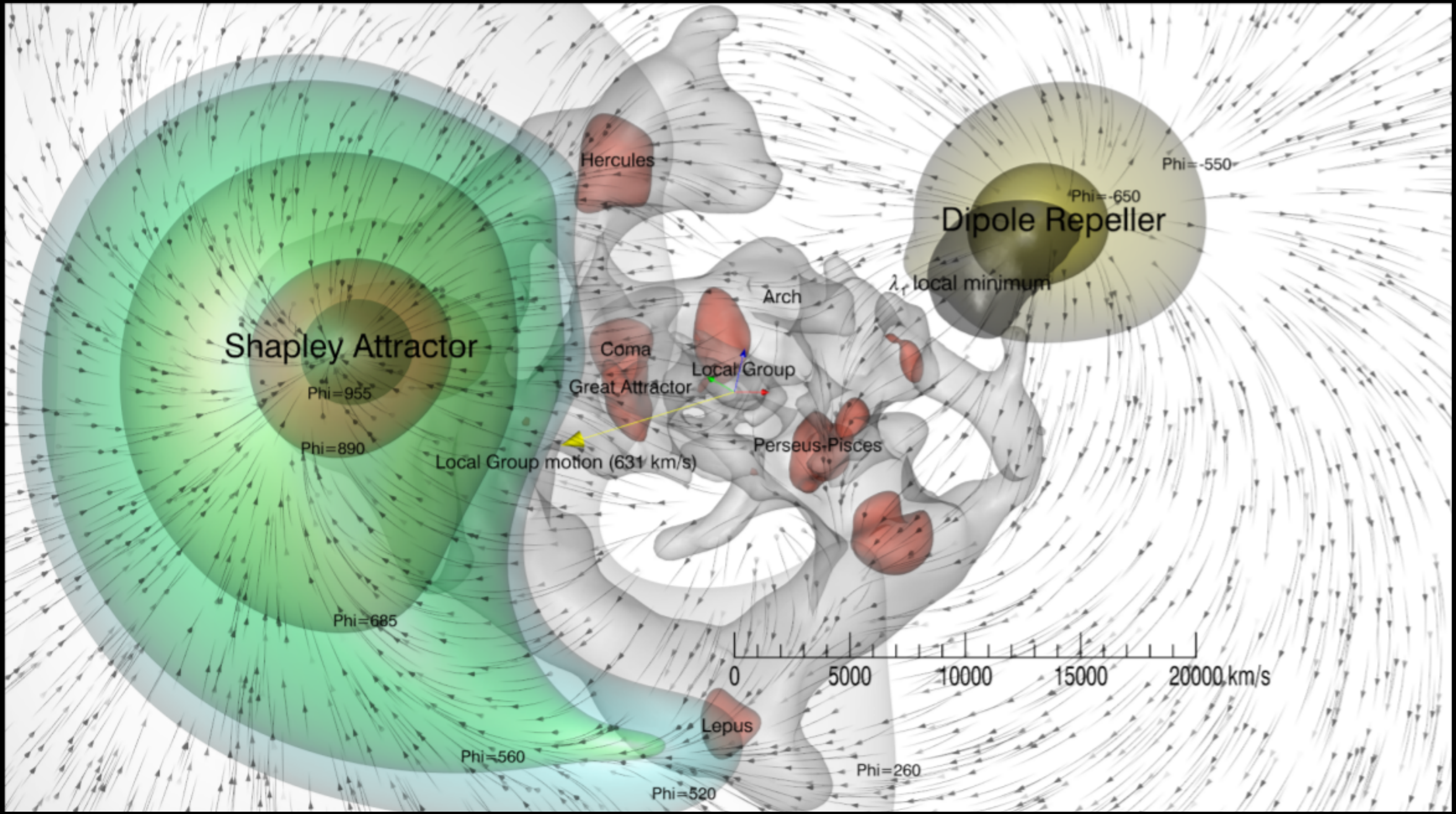


Hale et al., Pashapourahmanabadi et al. (in prep.)

How to explain the CMB dipole?

Can we link CMB dipole to local structure(s), like great attractor, dipole repeller, bulk flows, etc.?

See e.g. Cosmic Flows programme by Tully et al.



Hoffman et al. 2017

Local structure and the cosmic radio dipole

- Simulations include: Poisson noise, cosmic structure, proper motion, survey geometry
- Not included: multi-component aspect, multi-tracer aspect, galactic foregrounds, calibration systematics, errors on photo-z's
- Forecasting exercise for Square Kilometre Array surveys

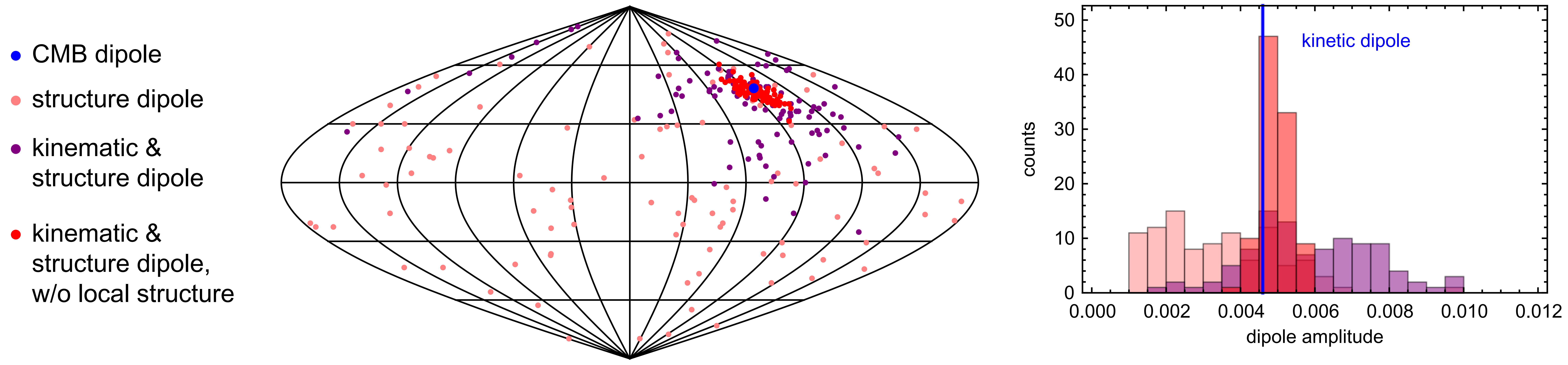


Figure 10. Dipole directions (left) and histogram of dipole amplitudes (right) based on 100 LSS simulations each for a flux density threshold of 22.8μJy at 700 MHz without kinetic dipole (pink), with kinetic dipole (purple) and with the contribution from the local structure dipole removed (red). The 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

How to prepare for SKA surveys

- Astrophysics of various tracers (AGNs, SFGs):
  evolution/correlation of α and x, redshift distribution, b(z), luminosity and density evolution
- Flux calibration: Only very few primary calibrators in Southern hemisphere, establish more calibrators and characterise them very well, potential identify issues transfering solutions across elevation (atmosphere)
- Blending and source identification as a function of flux density in nJy regime?
  Identify issues and identify requirements, e.g. pointing accuracy & wind
- Are galactic foregrounds an issue for the measurement of the cosmic dipole?
- How to obtain multifrequency data over large area? Will Rubin and Euclid be good enough for what we will need? Need to identify ALL local objects ($z < 0.1 - 0.3$)
- Is the theoretical ground sound? See e.g. recent work by Krishan et al. 2022 on tilt instability of CP

Status and Summary of Cosmic Radio Dipole

Kinematic interpretation of CMB dipole agrees with CMB at small angular scales and with observations of SN1a magnitudes

Radio and quasar dipole directions agree with each other and the CMB dipole direction within errors

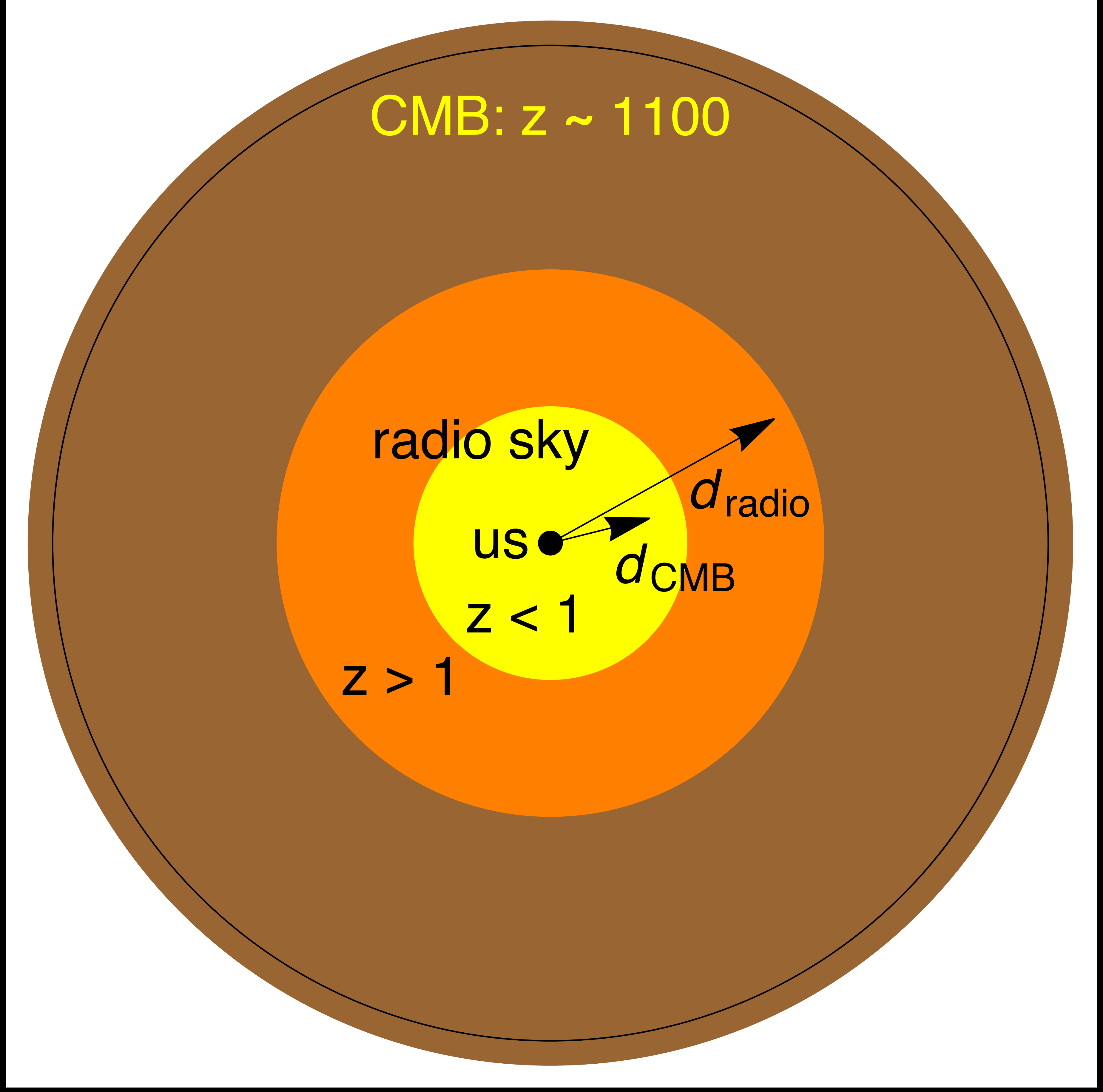
Cosmic radio and quasar dipoles exceed expectations based by factor of 2 - 4

X-ray clusters (kSZ) also disagree with CMB Kashlinsky et al. 2010

THE PROBLEM IS REAL & SERIOUS ! Peebles 2022

Pre-SKA: LoLSS/LoTSS/MALS/RACS/EMU

Major challenges: calibration over largest scales & sample selection



Multi-wavelength & multi-probe questions

- Radio (AGN) & Quasars (AGN)
  + large statistics, wide area & mean z > 1, dominate at $S > 1$ mJy (L-band)
  - precision on individual objects poor, local structure, incomplete sky, typically poor photo-z

- Radio (SFG)
  + even larger statistics, wide area, at least at z < 1 robust photo-z, dominate at $S < 100\mu$Jy (L-band)
  - smaller mean redshift, precision on individual objects poor, incomplete sky

- Cosmic infrared background
  + bright
  - no good fully sky survey so far -> Euclid/Roman, contamination by galactic foreground, incomplete sky

- Supernovae
  + very precise, much smaller samples needed
  - hard to double sample size, degenerate with local bulk flows, incomplete sky

- X-ray clusters (e.g. Kashlinsky et al. 2010: 1000 km/s out to 800 Mpc)
  + direct measurement of motion (kSZ), all sky (in principle)
  - limited by shot noise, local structures, incomplete sky