Do we understand the Cosmic Dipole?

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- CMB temperature and dipole anisotropy define cosmic rest frame
- peculiar motion of Milky Way is only partially understood
- tension between local and global H_0
- controversial claims on bulk flows
- CMB anomalies (tiny intrinsic dipole?)

MITP workshop QVG 2017, Mainz

Do we understand the Cosmic Dipole?

Dominik J. Schwarz
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based on work with
Craig Copi, Dragan Huterer, Glenn Starkman
David Bacon, Song Chen, Marvin Pinkwart,
Matthias Rubart, Thilo Siewert
SKA Cosmology WG & LOFAR Survey KSP

MITP workshop QVG 2017, Mainz

CMB Dipole

T_0 = (2.7255 ± 0.0006) K Fixsen 2009
T_1 = (3364.5 ± 2.0) μK
l = (264.00 ± 0.03) deg, b = (48.24 ± 0.02) deg Planck 2015

hypothesis: cmb dipole is due to peculiar motion of Solar system with v = (369 ± 0.9) km/s Planck 2015

$$T(\mathbf{e},\mathbf{v}) = \frac{\sqrt{1-\mathbf{v}^2/c^2}}{1-\mathbf{e}\cdot\mathbf{v}/c} T_0 = T_0 \left[(1 - \frac{v^2}{6c^2}) + \frac{v}{c} P_1(\mu) + \frac{2v^2}{3c^2} P_2(\mu) + \dots \right]$$

Peebles & Wilkinson 1968

CMB Dipole: Impact

The proper motion hypothesis makes a prediction:

Doppler shift and aberration
for all objects at cosmological distances and at any frequency

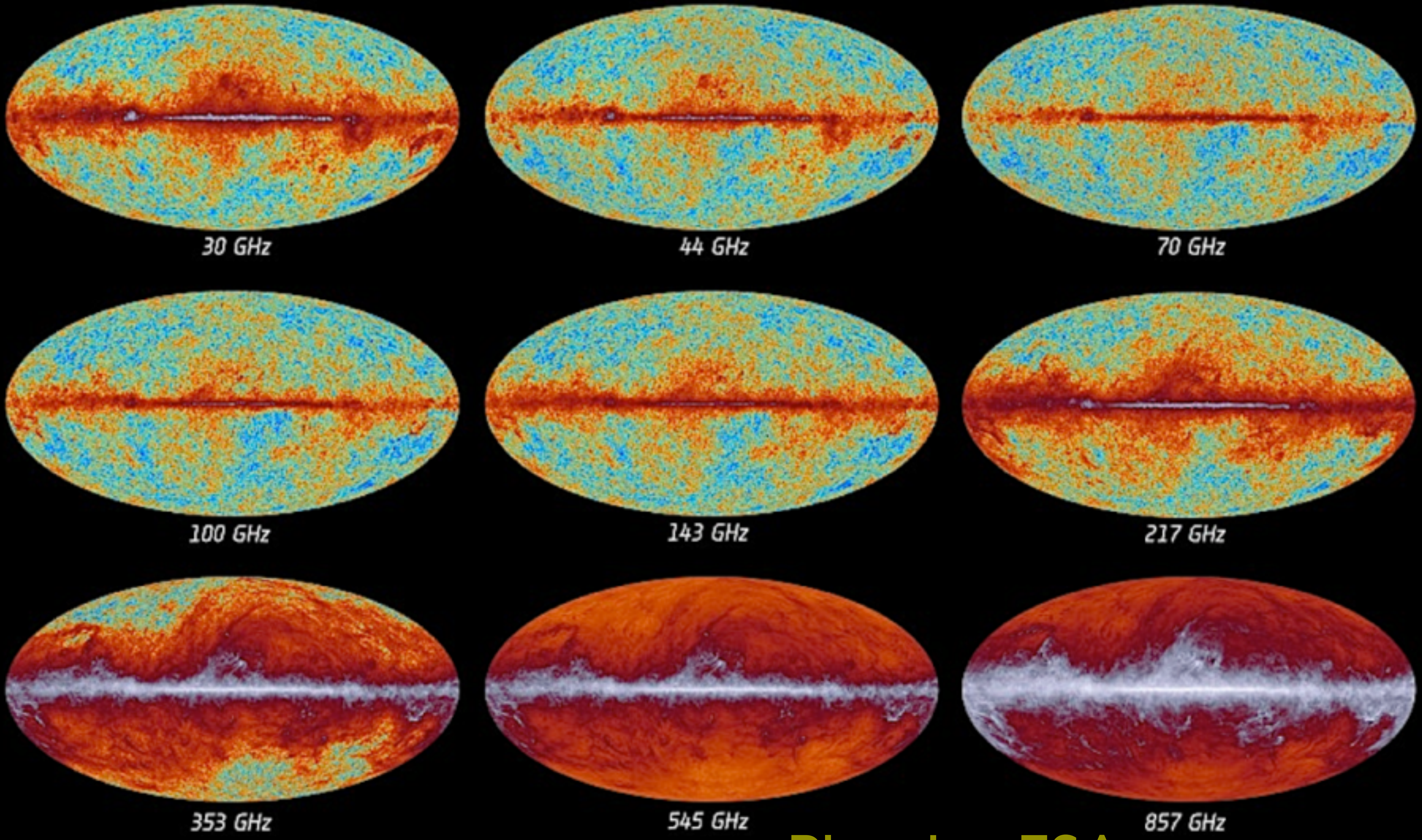
➜ test with high-ℓ multipoles in CMB Planck 2013/2015
(coupling of ℓ to $\ell \pm 1$ multipoles)

➜ test with radio sky (as $\langle z \rangle > 1$, unlike IR or optical)

➜ identify corresponding structures
(e.g. SN1a bulk flow, IR galaxy distribution)

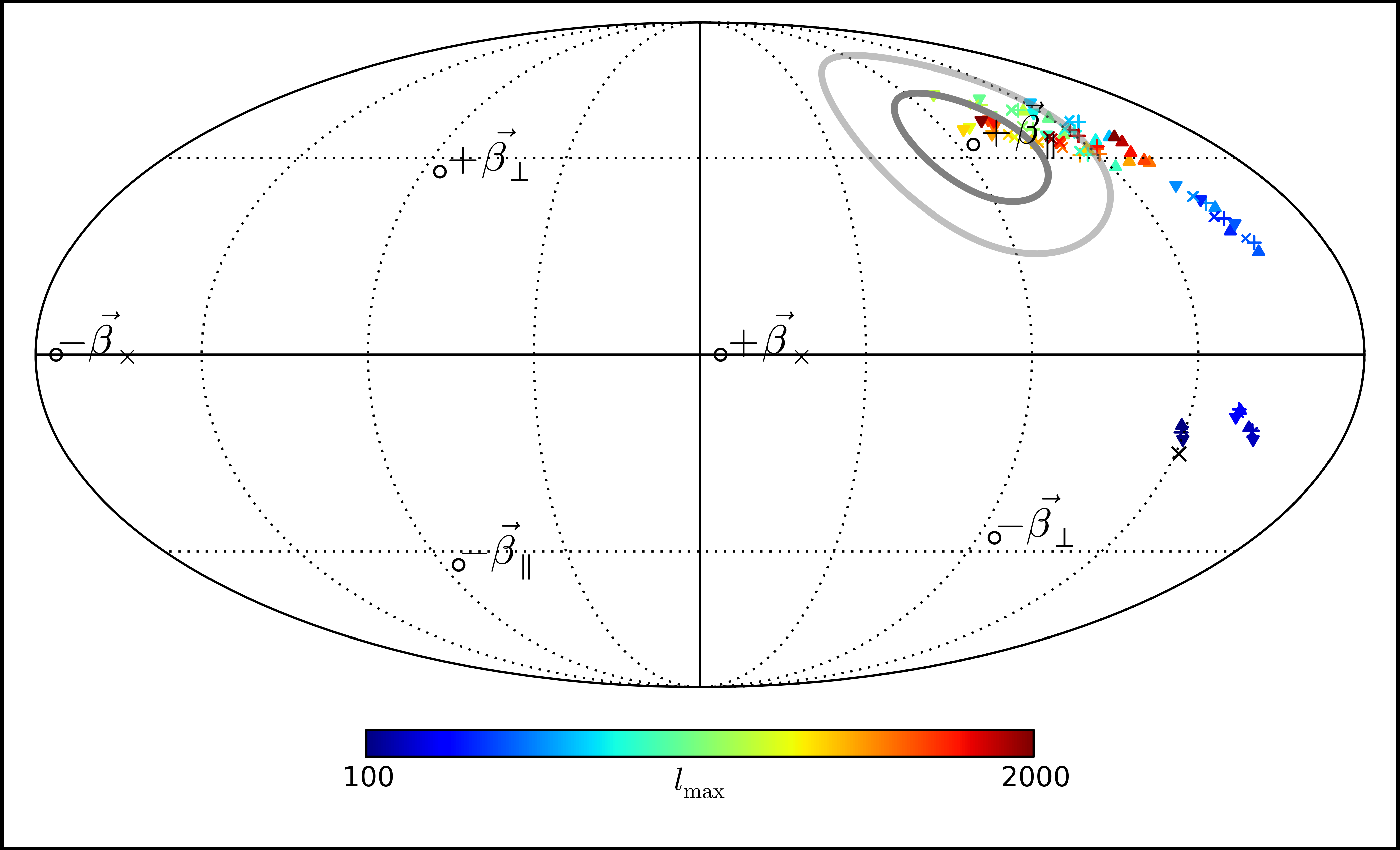
Cosmic Microwaves

frequency bands



Planck - ESA

CMB proper motion test

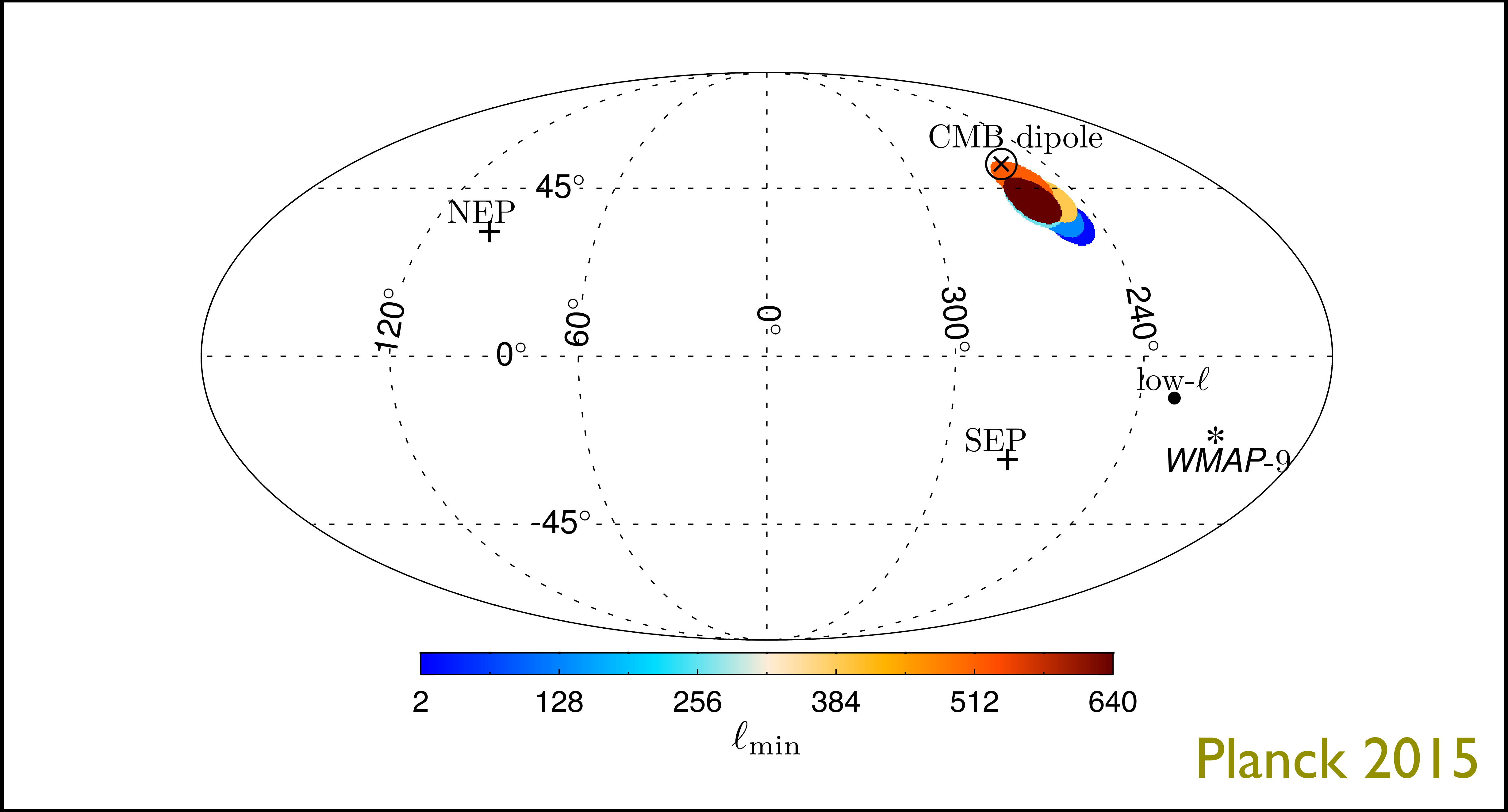


v = 384 km/s ± 78 km/s (stat.) ± 115 km/s (sys.)

compare with CMB dipole: v = (369 ± 0.9) km/s; analysis fixes direction

Planck 2013

CMB proper motion test



Bipolar Spherical Harmonics

allows for 40% non-kinetic contribution to CMB-dipole

Hubble expansion rate

- ➜ H_0 = (67.8 ± 0.9) km/s/Mpc (CMB: Planck 2015)
  H_0 = (73.0 ± 2.4) km/s/Mpc (SN1a: Riess et al. 2011) … debated conflict

- ➜ measurement of H_0 assumes that redshifts of cepheids and SN1a are given in comoving cmb frame

ideal situation
(isotropic
source distribution)

$$H_0 = \frac{1}{N}\sum_{i=1}^{N}\frac{cz_i + v_{pi}}{d_i} = \frac{1}{N}\sum_{i=1}^{N}\frac{cz_i}{d_i} + O(\frac{1}{\sqrt{N}})$$

- ➜ error in determination of comoving frame:

$$\text{if } \Delta v_p = 100 \text{ km/s} \Rightarrow \frac{\Delta H_i}{H_0} \sim \frac{h^{-1}\text{Mpc}}{d_i}$$

- ➜ realistic N/S anisotropic sample with ⟨d⟩ = 150 Mpc:

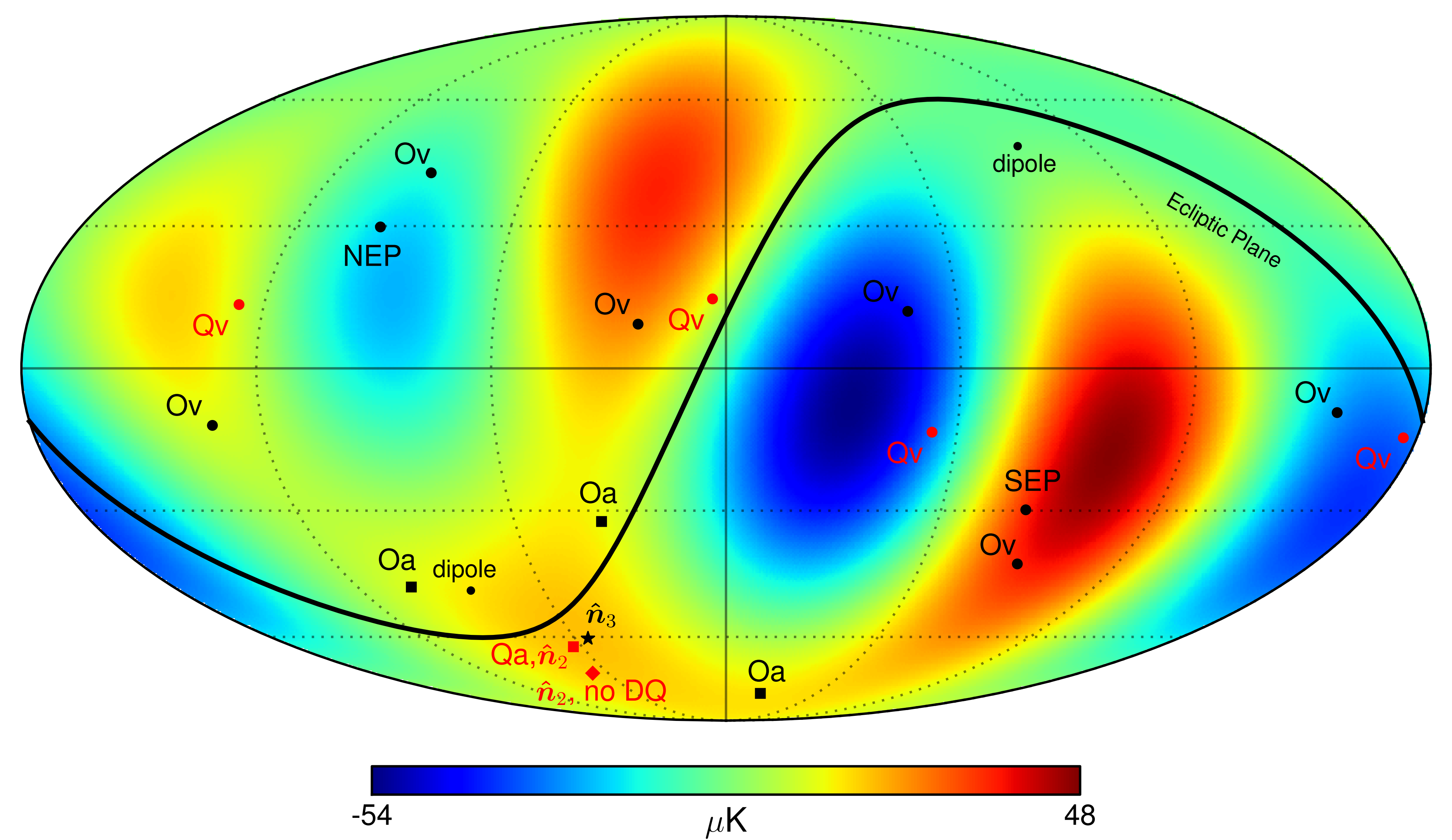
important for
precision cosmology,

$$\Delta H_0 \sim \frac{1}{2}\frac{h^{-1}\text{ Mpc}}{150\text{ Mpc}}H_0 \sim 0.3\text{ km/s/Mpc}$$

larger effect on cepheid callibrators (luminosity distance is not boost invariant)

Why bother?

2. CMB anomalies (WMAP & Planck)

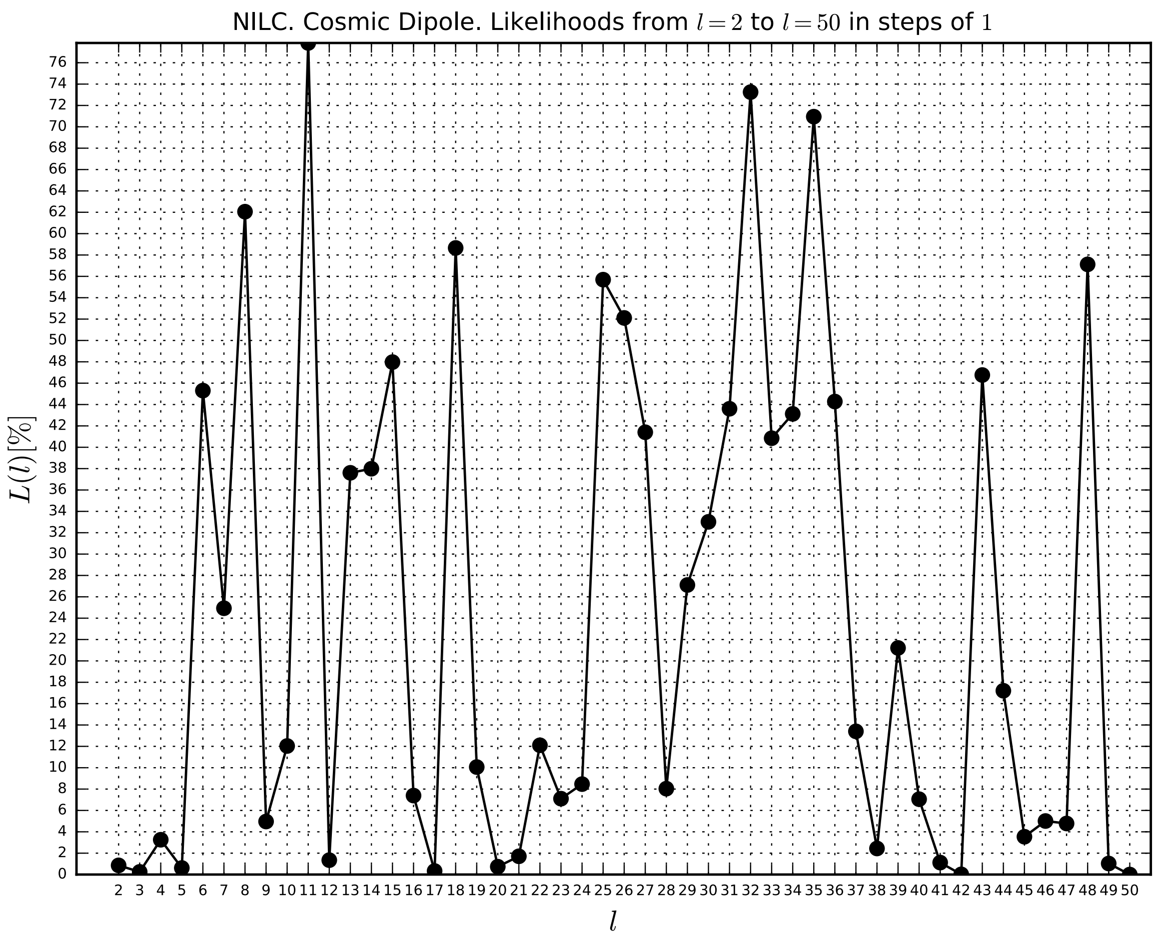


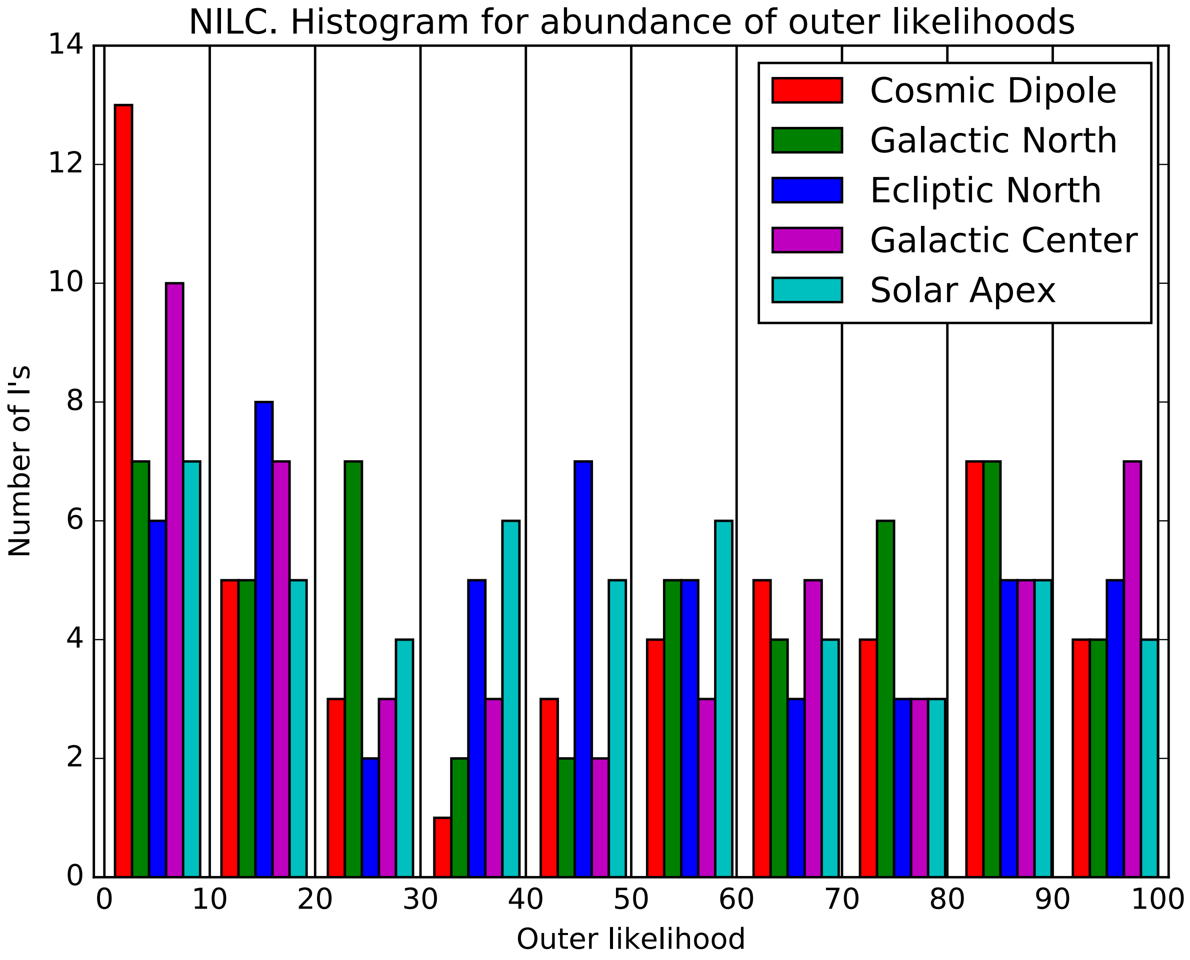
Copi et al. 2013, Schwarz et al. 2016

alignment of low-ℓ multipoles with CMB dipole

CMB anomalies (WMAP & Planck)

alignment extends to ℓ = 50 with CMB dipole

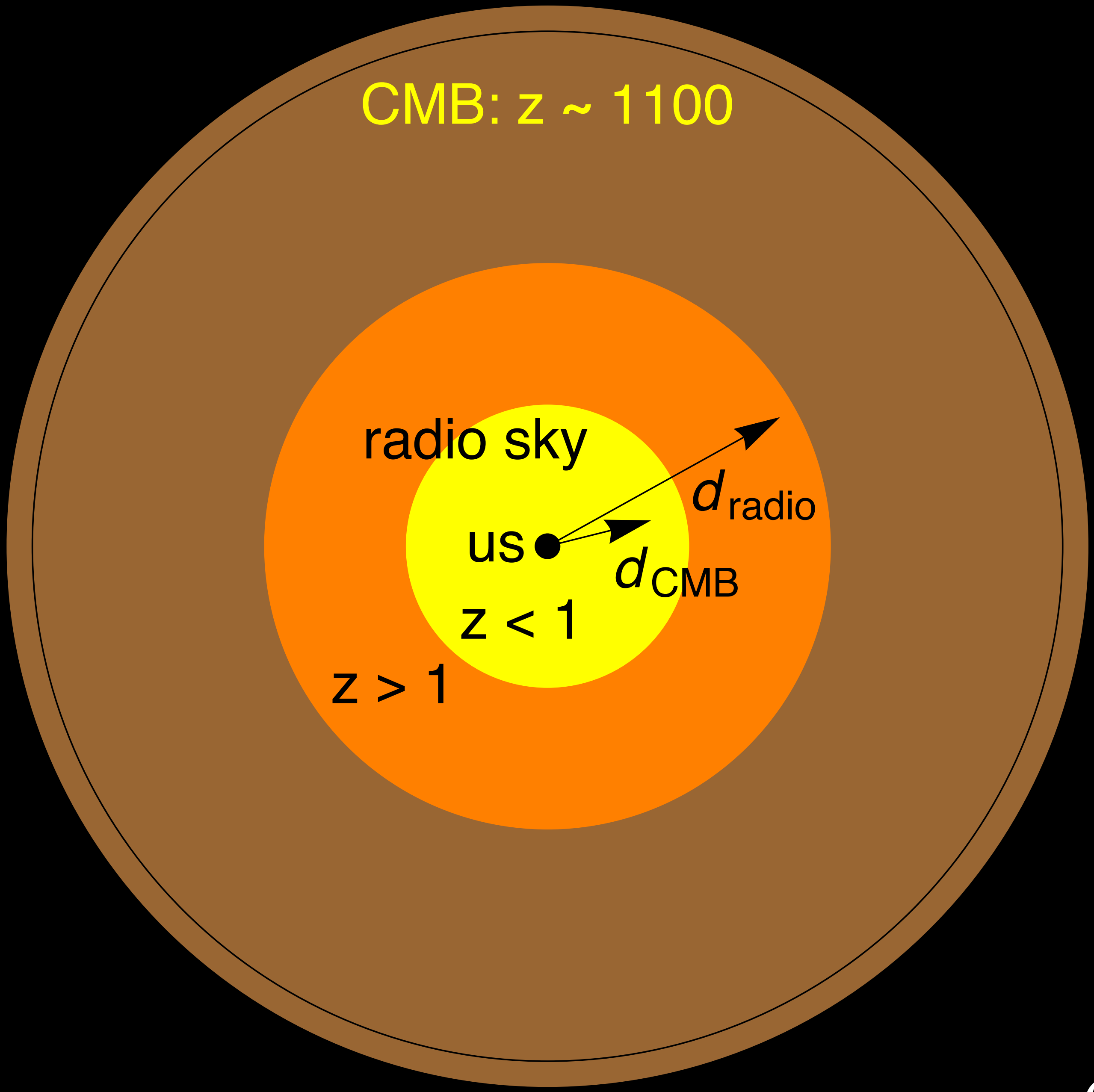




11 out of the 49 lowest multipoles are aligned with the dipole at less than 2% likelihood (expected is 2-3)

Pinkwart & Schwarz, in prep.

Cosmic Radio Dipole



$d_{\text{radio}} = d_{\text{kin}} + d_{\text{matter}}$

radio galaxies: **mean z > 1**

d_{matter} expected to be small

kinetic dipole

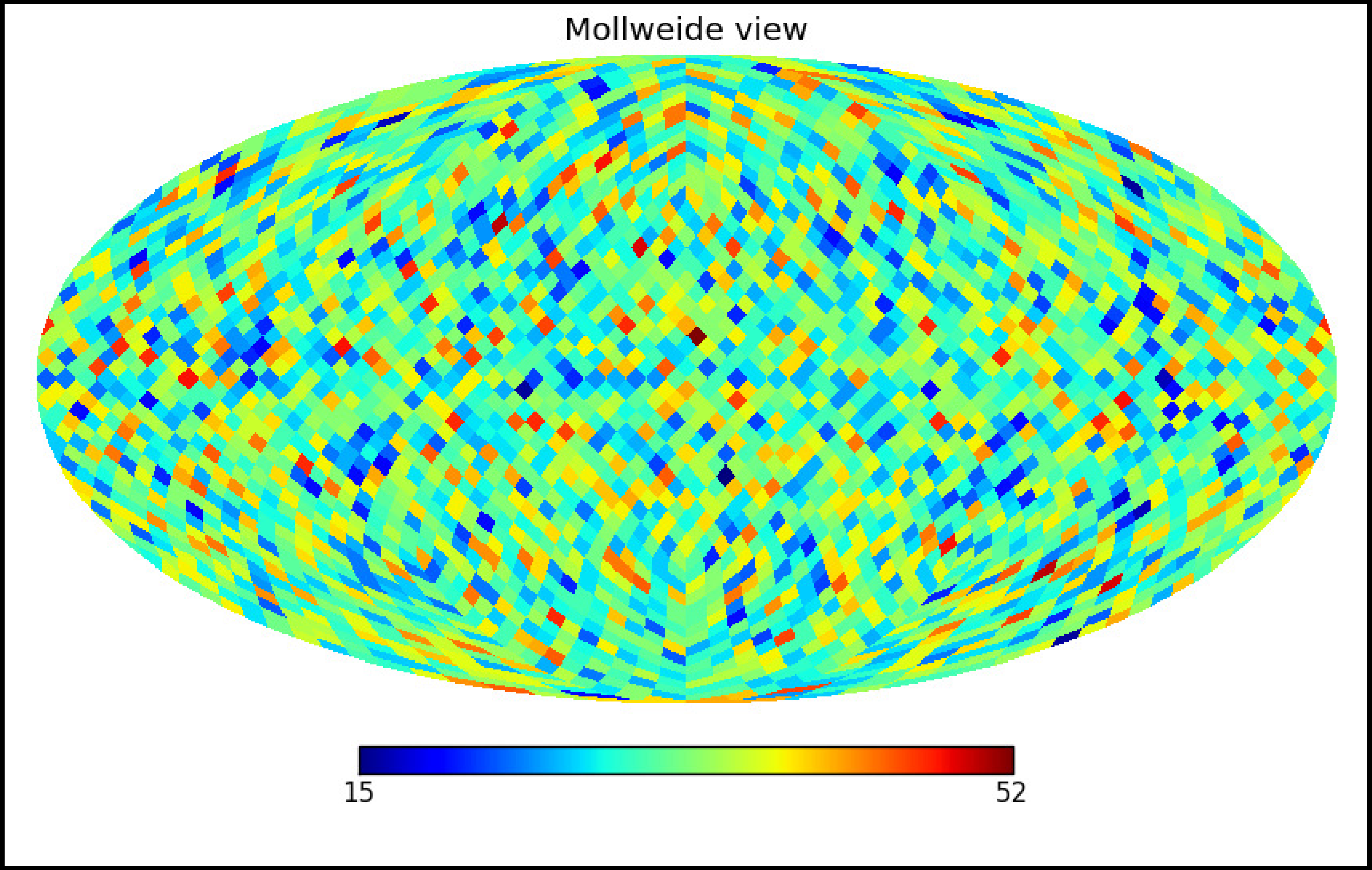
Ellis & Baldwin 1984

$$\frac{\mathrm{d}N}{\mathrm{d}\Omega}(>S) = aS^{-x}[1 + d\cos\theta + ...]$$

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

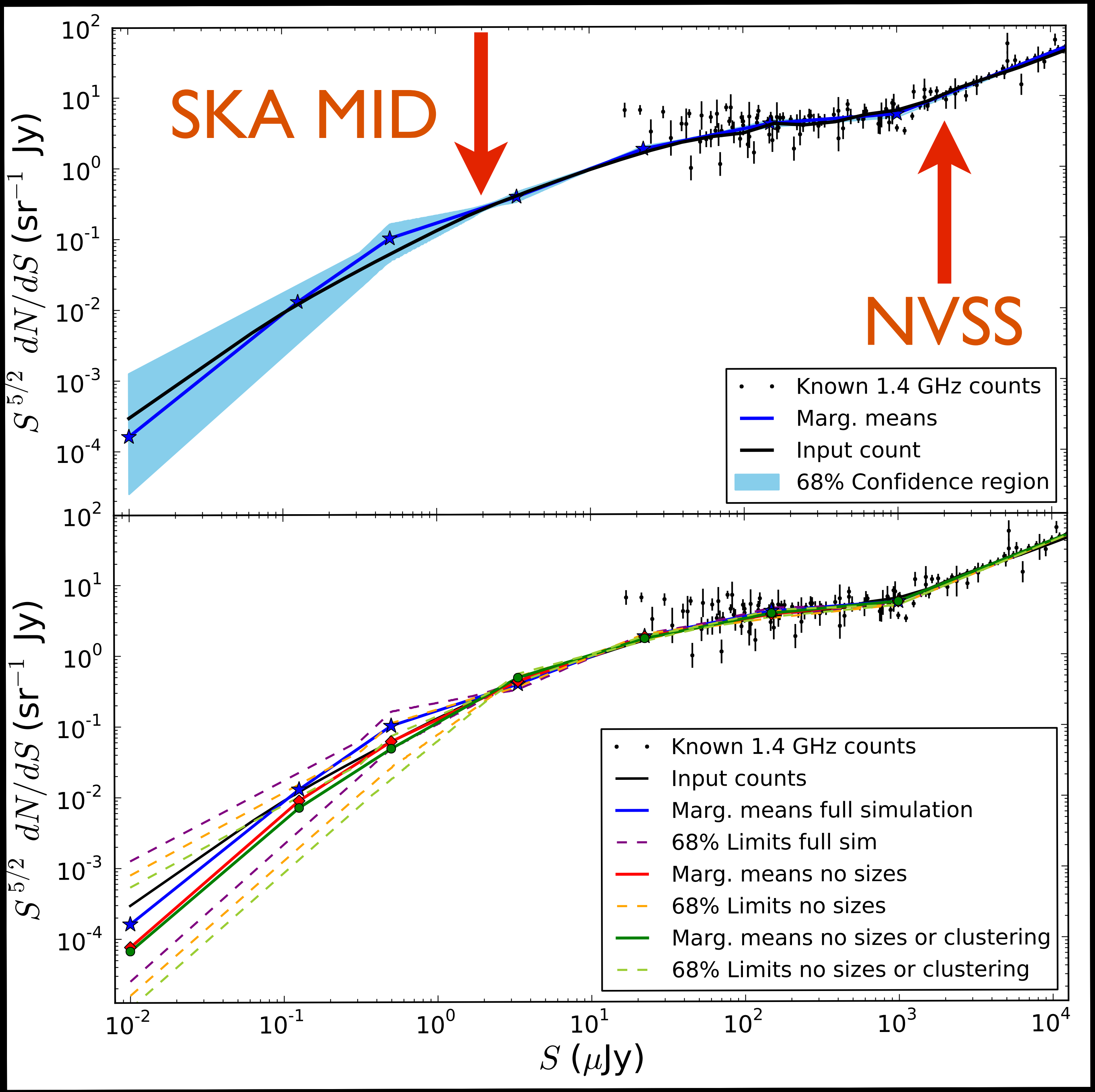
aberration & Doppler shift

The Challenge



Simulated pixelated sky map of 100,000 sources
including expected kinetic dipole:
shot noise dominated
➔ need huge catalogues (> 10^6 sources)
and large sky coverage (> 20.000 sqdeg)

Cosmic Radio Sources



JVLA, Vernstrom et al. 2013

two populations:

* AGNs (FRI-II, RQQ)

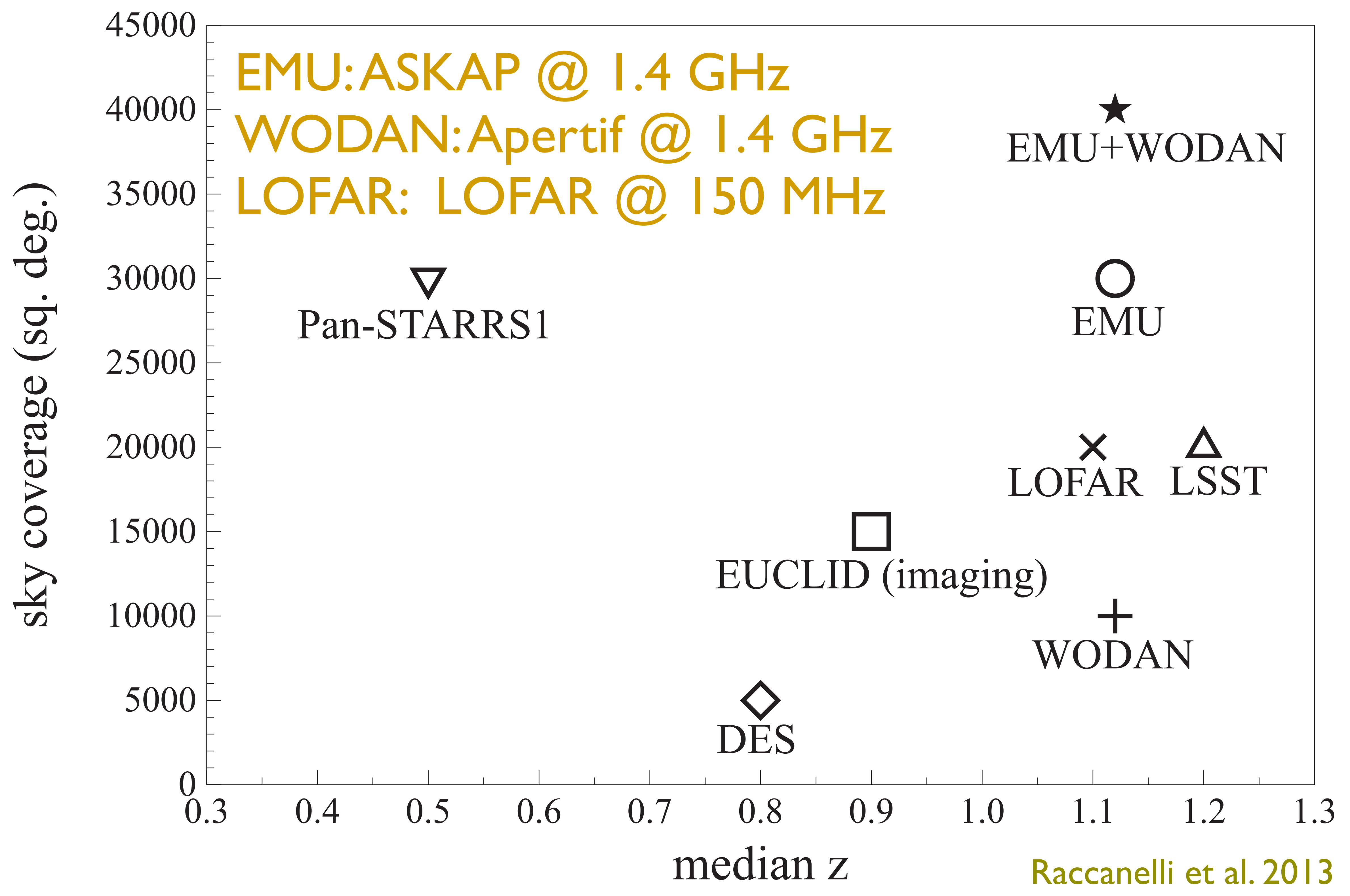
* galaxies (SFG, SBG)

AGNs dominate at large fluxes

star forming galaxies
dominate below ~ 1 mJy

identification of morphology
for angular resolution 0.5”

Radio Continuum Surveys



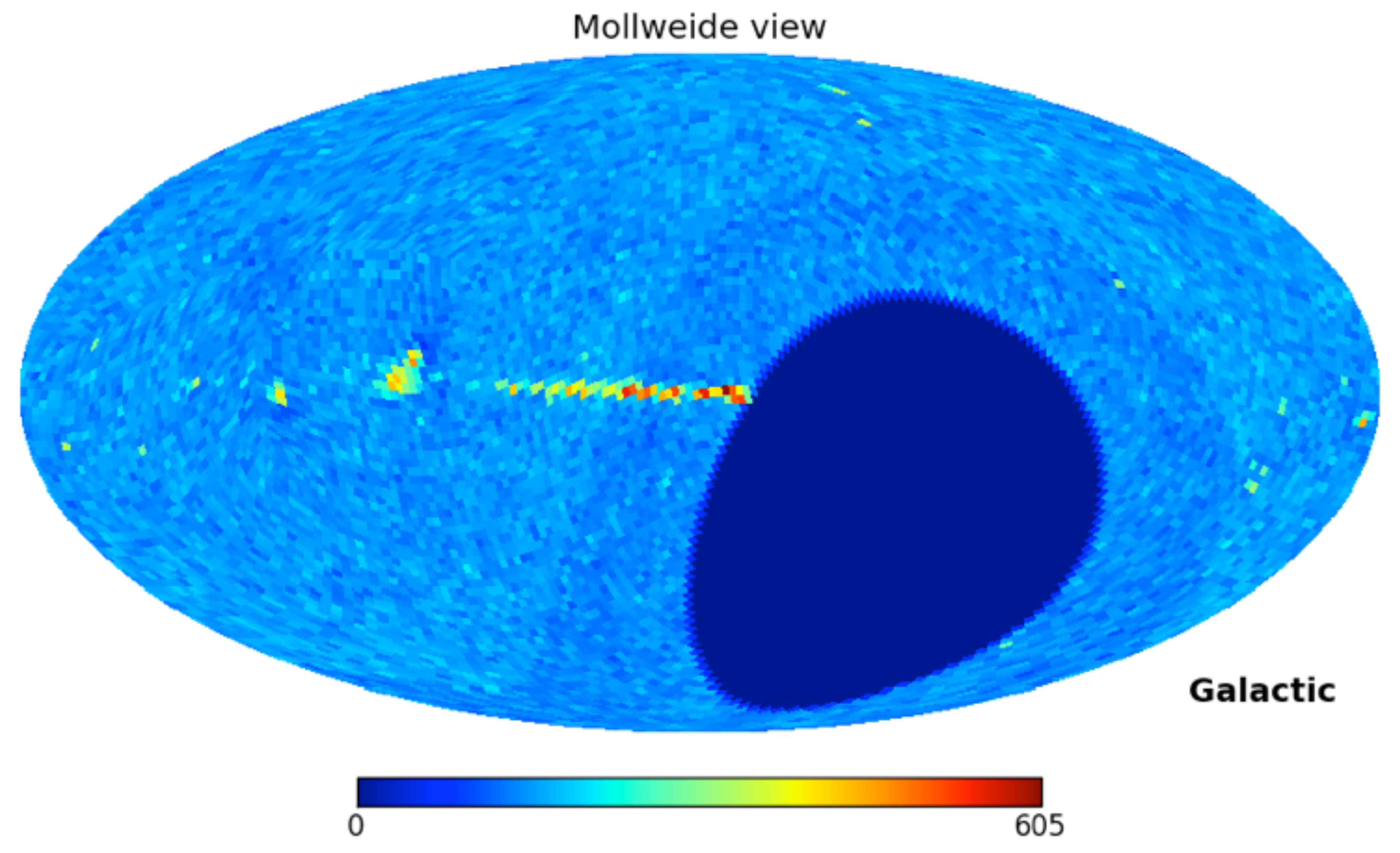
EMU: ASKAP @ 1.4 GHz

WODAN: Apertif @ 1.4 GHz

LOFAR: LOFAR @ 150 MHz

Raccanelli et al. 2013

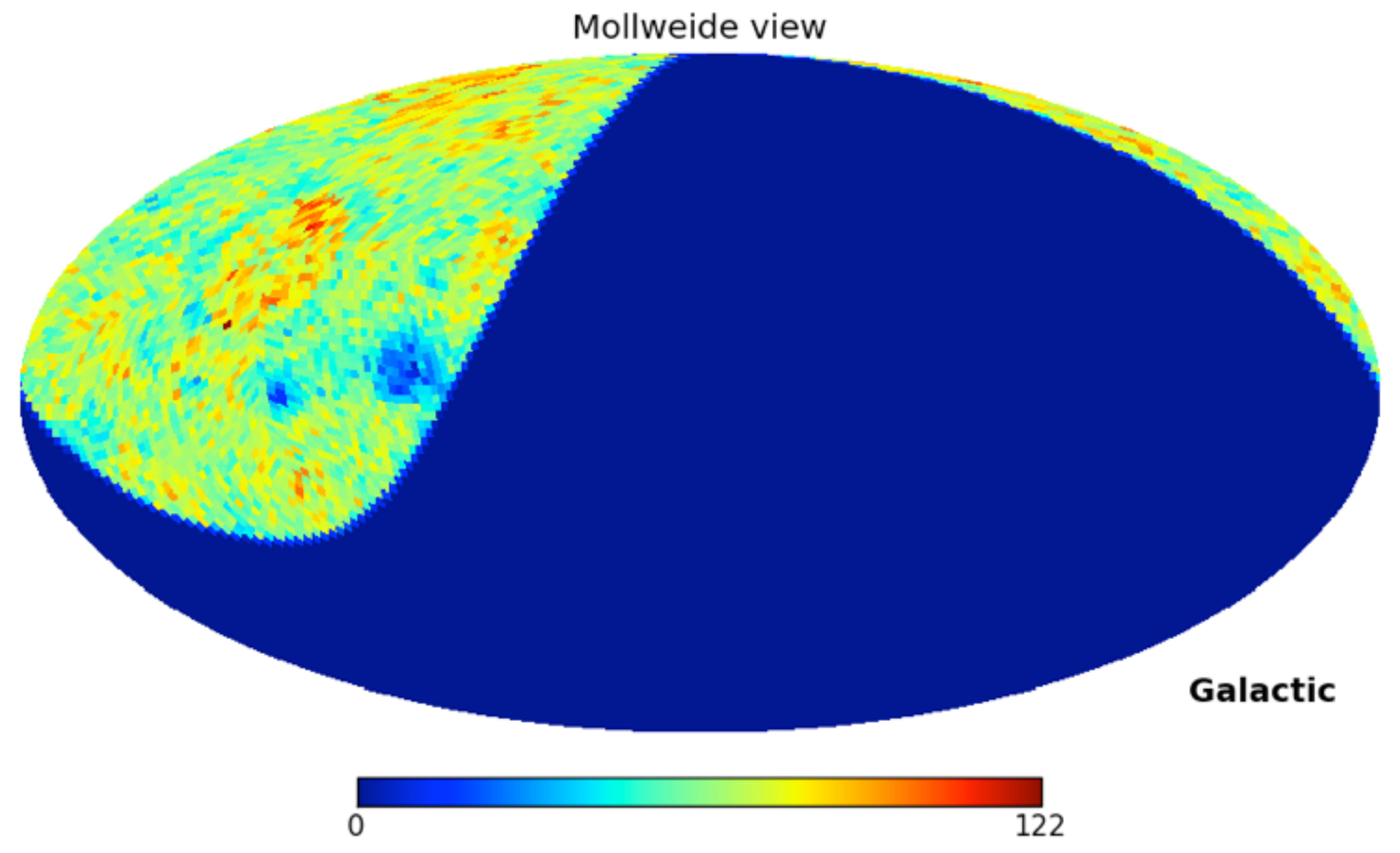
NVSS @ 1.4 GHz



S > 25 mJy

Condon et al. 2002

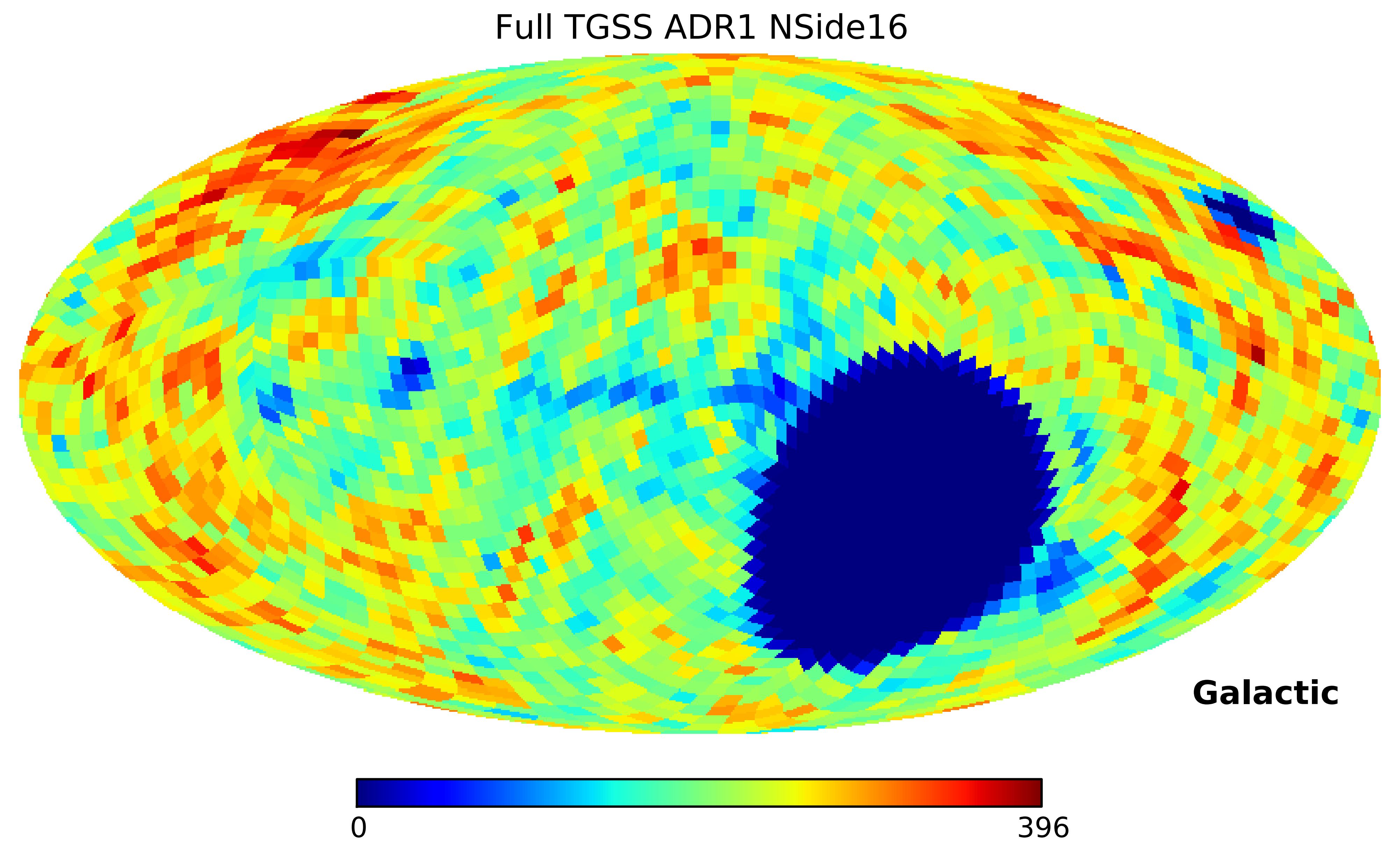
WENSS @ 325 MHz



S > 25 mJy

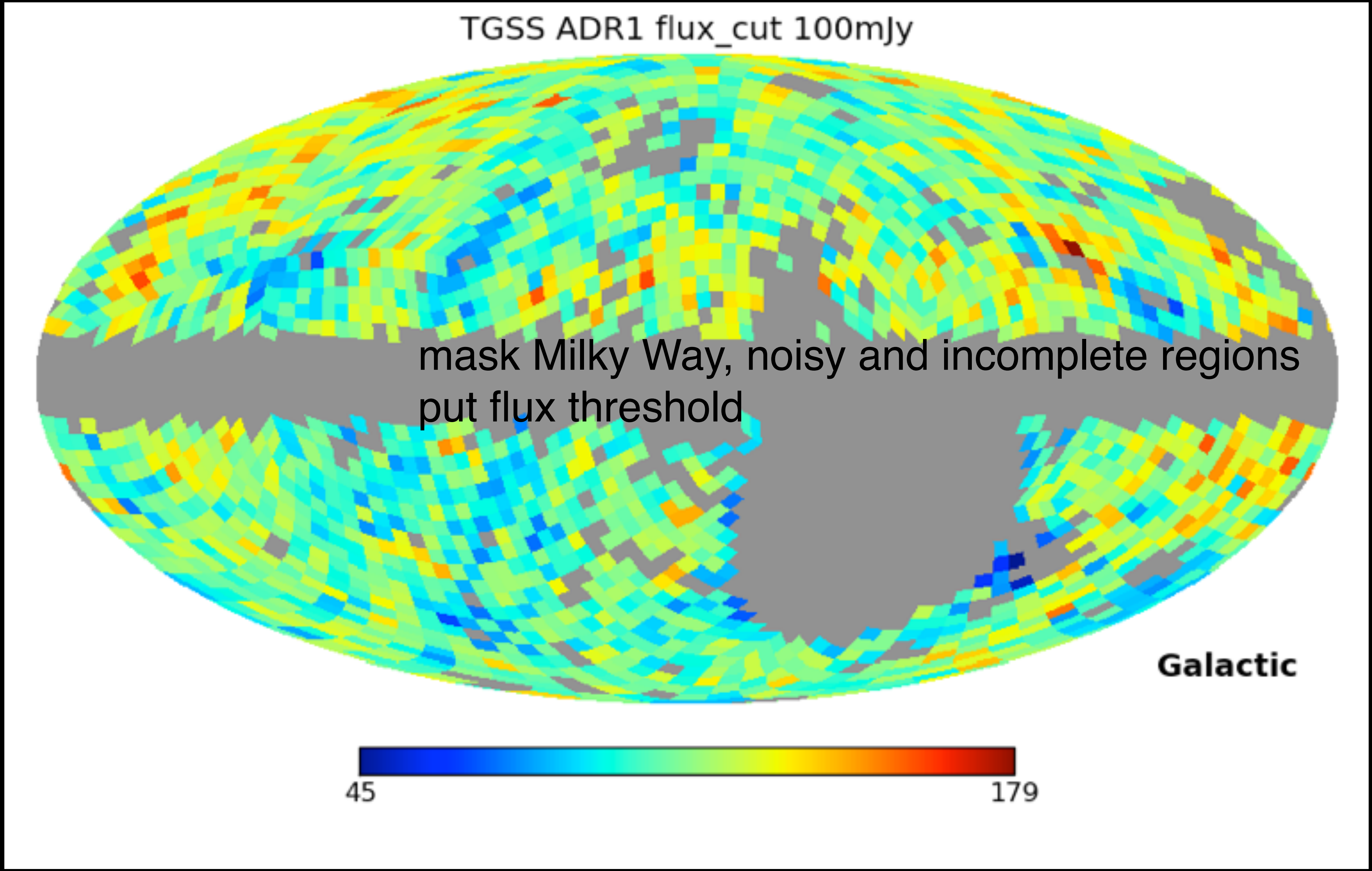
Rengelink et al. 1997

aTGSS @ 150 MHz



Intema et al. 2016

aTGSS (alternative DR1 TIFR GMRT SS)
90% of sky @ 150 MHz



mask Milky Way, noisy and incomplete regions
put flux threshold

S > 100 mJy

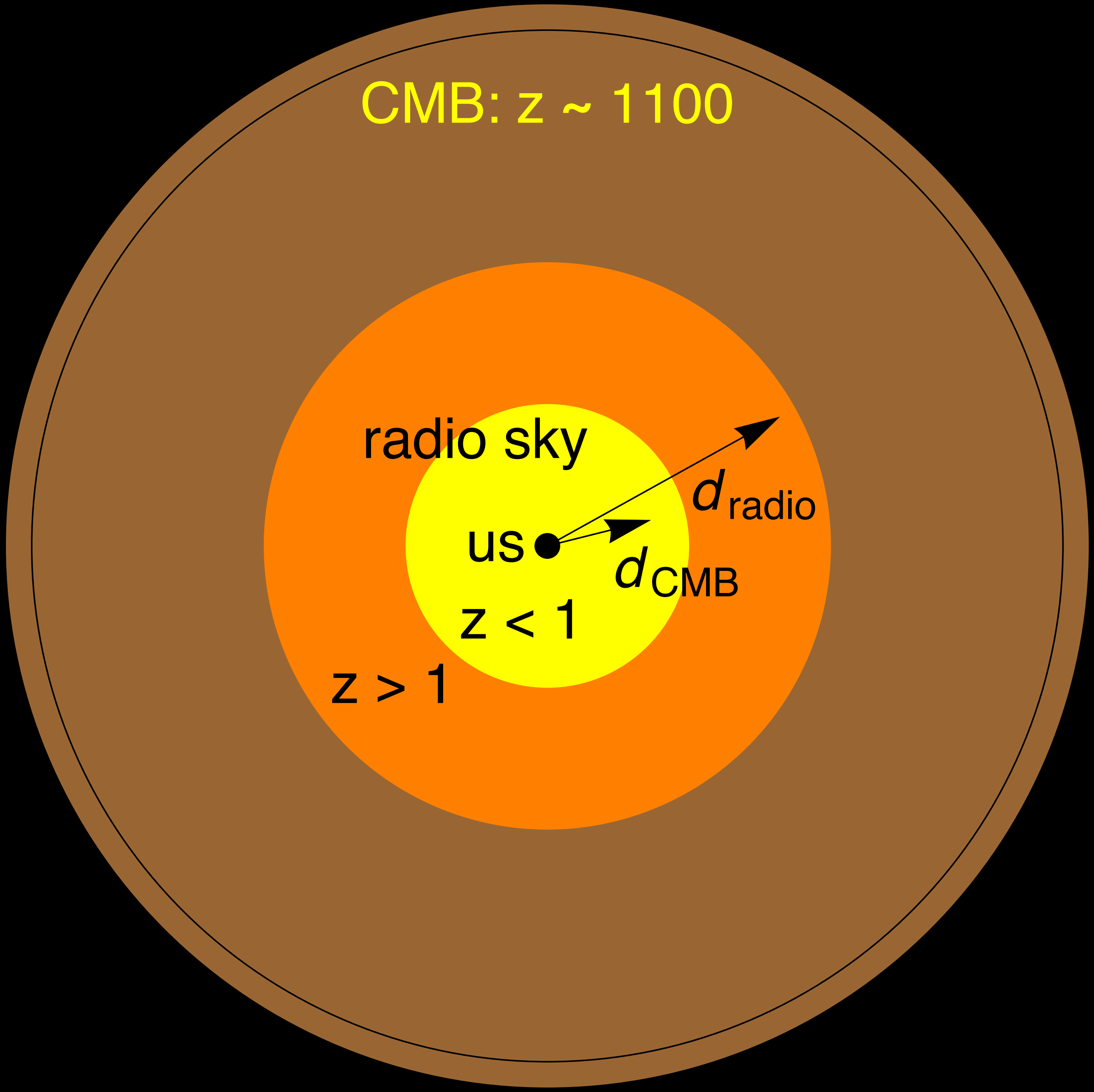
Rubart, Schwarz & Siewert, in prep.

Cosmic dipole @ 3 freq.

	Smin [mJy]	N	α [deg]	δ [deg]	d [0.01]	est.
NVSS	25	197.998	153±30	-4±34	1.1±0.3	**quad. harm.
NVSS	25	185.649	158±21	-2±21	1.6±0.6	lin.
NVSS	25	220.237	143±12	-11±15	1.8±0.5	*quad.
NVSS	15	298.289	149±19	17±19	1.4±0.5	lin.
WENSS	25	92.600	117±40		2.9±1.9	lin.
aTGSS	200	118.287	141±15	12±20	6.8±0.6	*quad.
aTGSS	100	229.235	141±13	7±18	6.2±0.4	*quad.
expect.	-	-	168	-7	0.4	

*preliminary **Blake & Wall 2002 Rubart & Schwarz 2013 & in prep.

Cosmic radio dipole



$d_{\text{cmb}} \Leftrightarrow d_{\text{radio}}$?

NVSS (1.4 GHz),
WENSS (345 MHz),
aTGSS (150 MHz):

directions consistent, amplitudes 2 - 10 times too large

Blake & Wall 2002
Rubart & Schwarz 2013

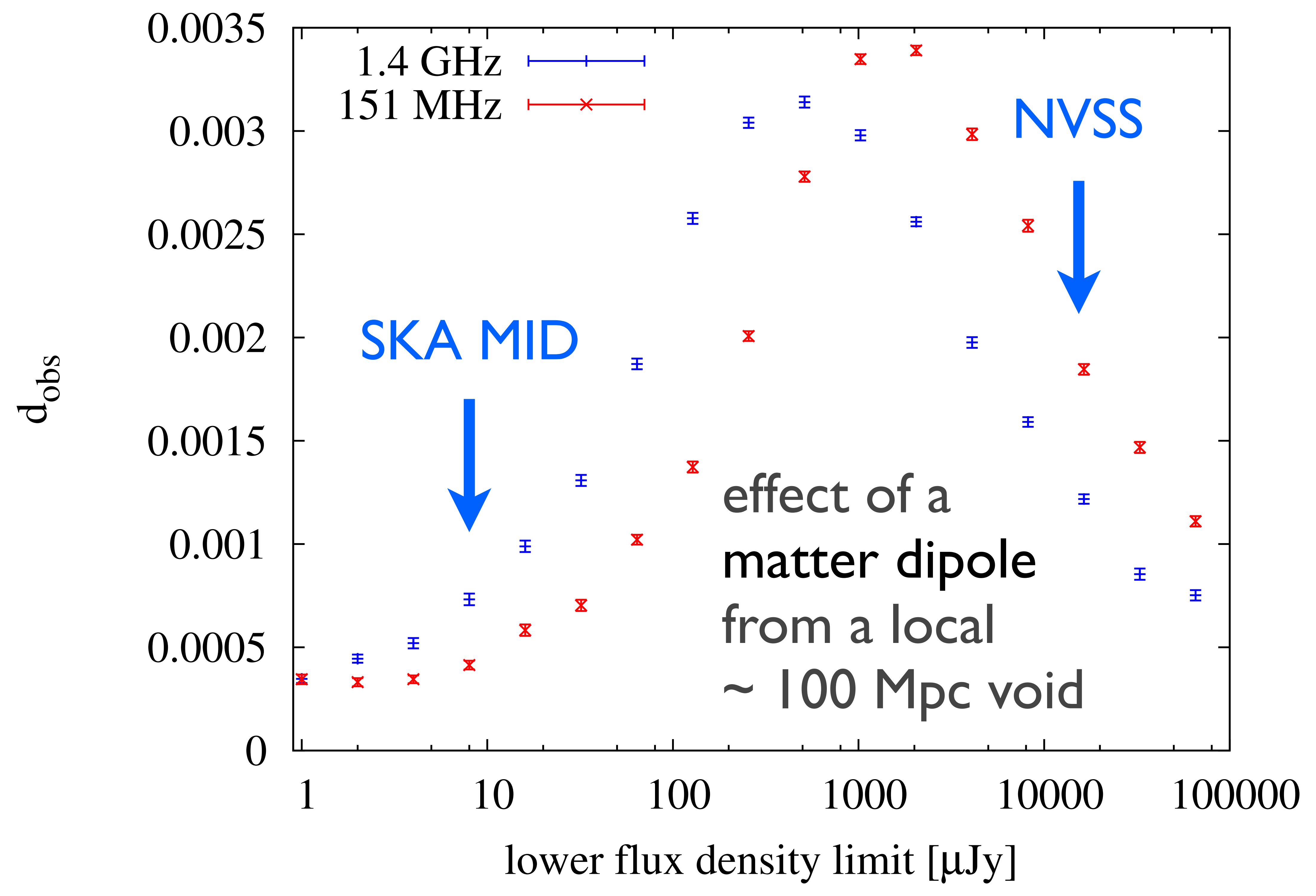
local bulk flows?

Watkins & Feldman 2014
Atrio-Barandela et al. 2014

local structure dipole?

Rubart, Bacon & Schwarz 2014
Nusser & Tiwari 2016

Dipole tomography



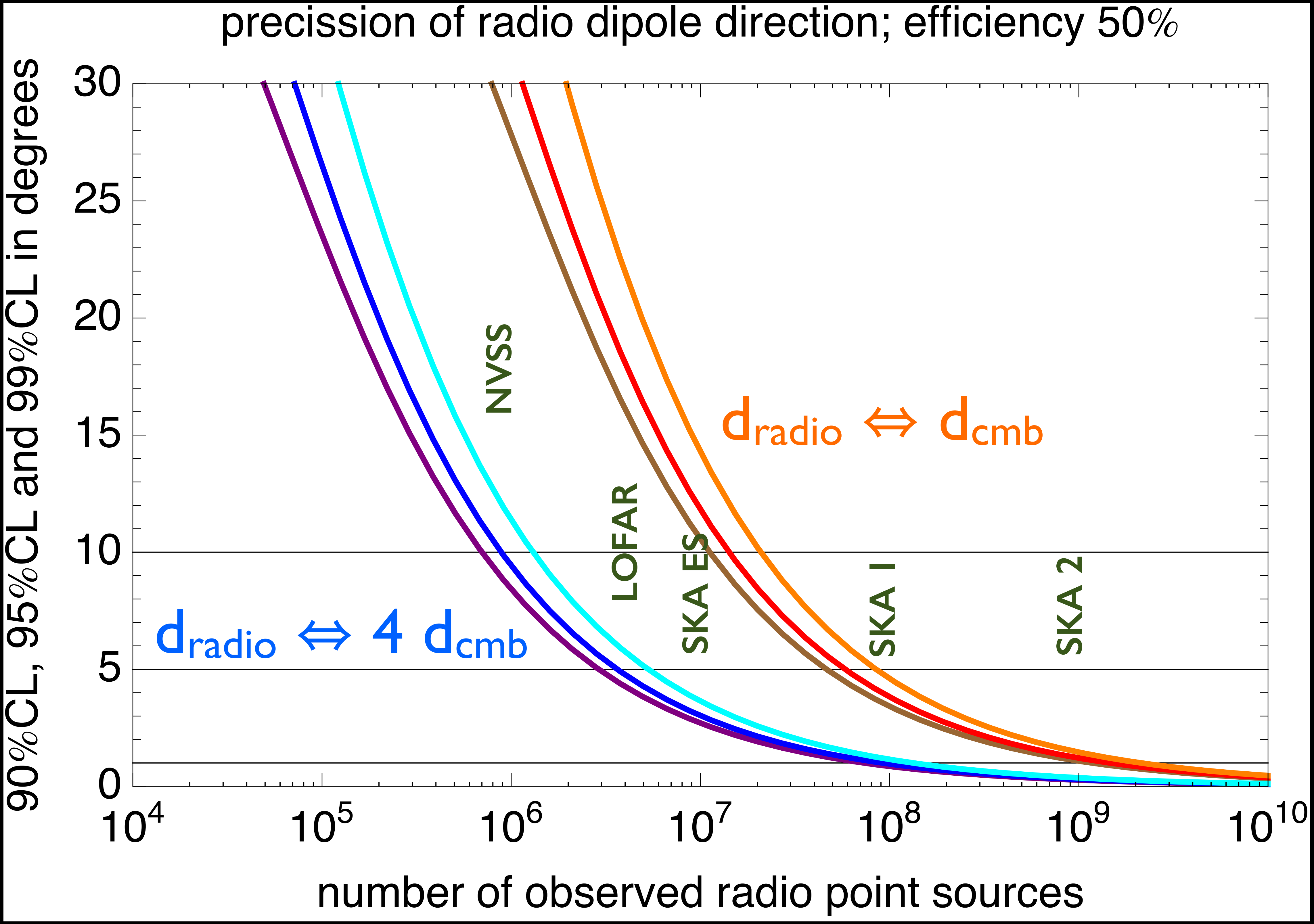
SKA MID

NVSS

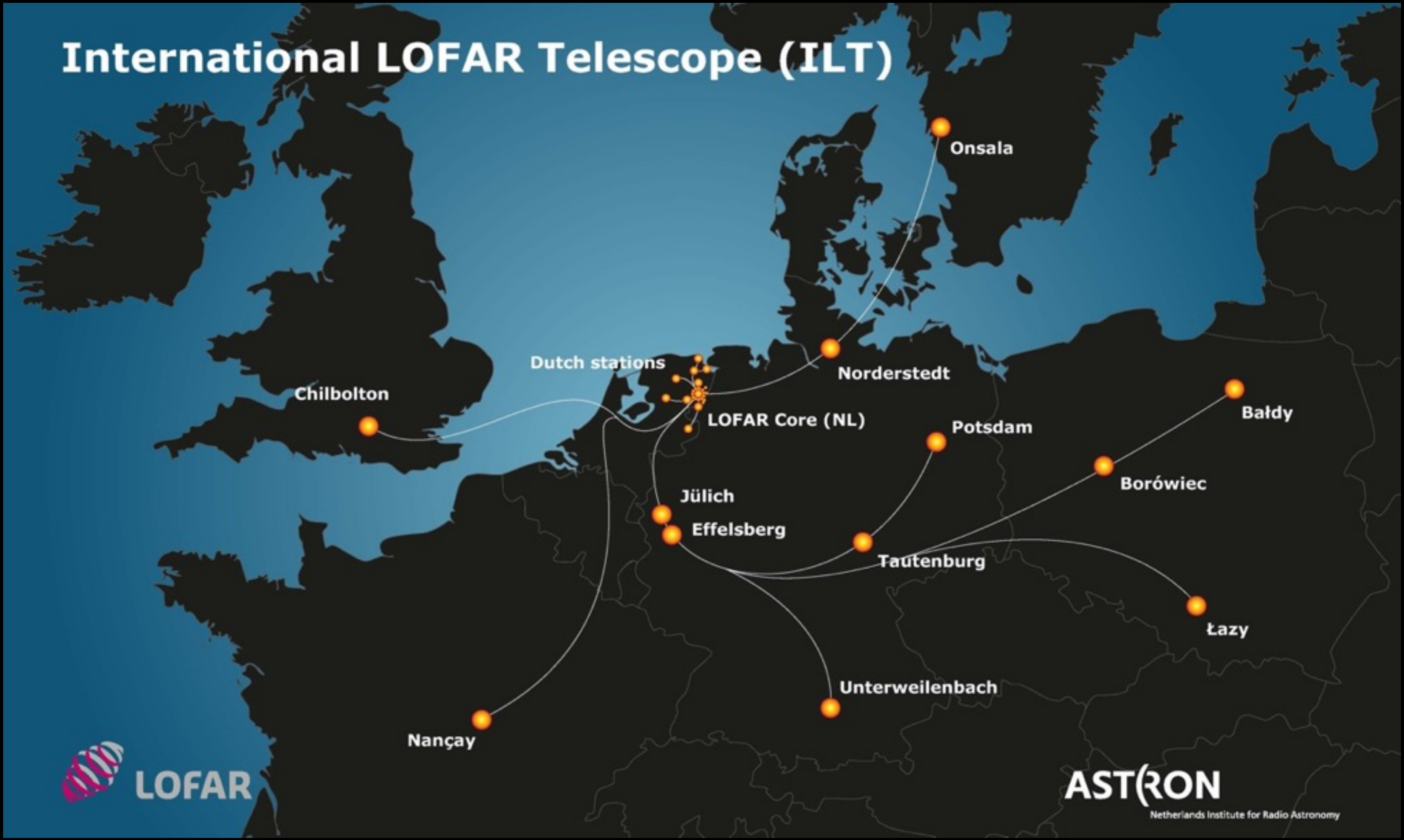
effect of a **matter dipole** from a local ~ 100 Mpc void

Rubart, Bacon & Schwarz 2014

Cosmic radio dipole



Schwarz et al., 2015, SKA Science Book

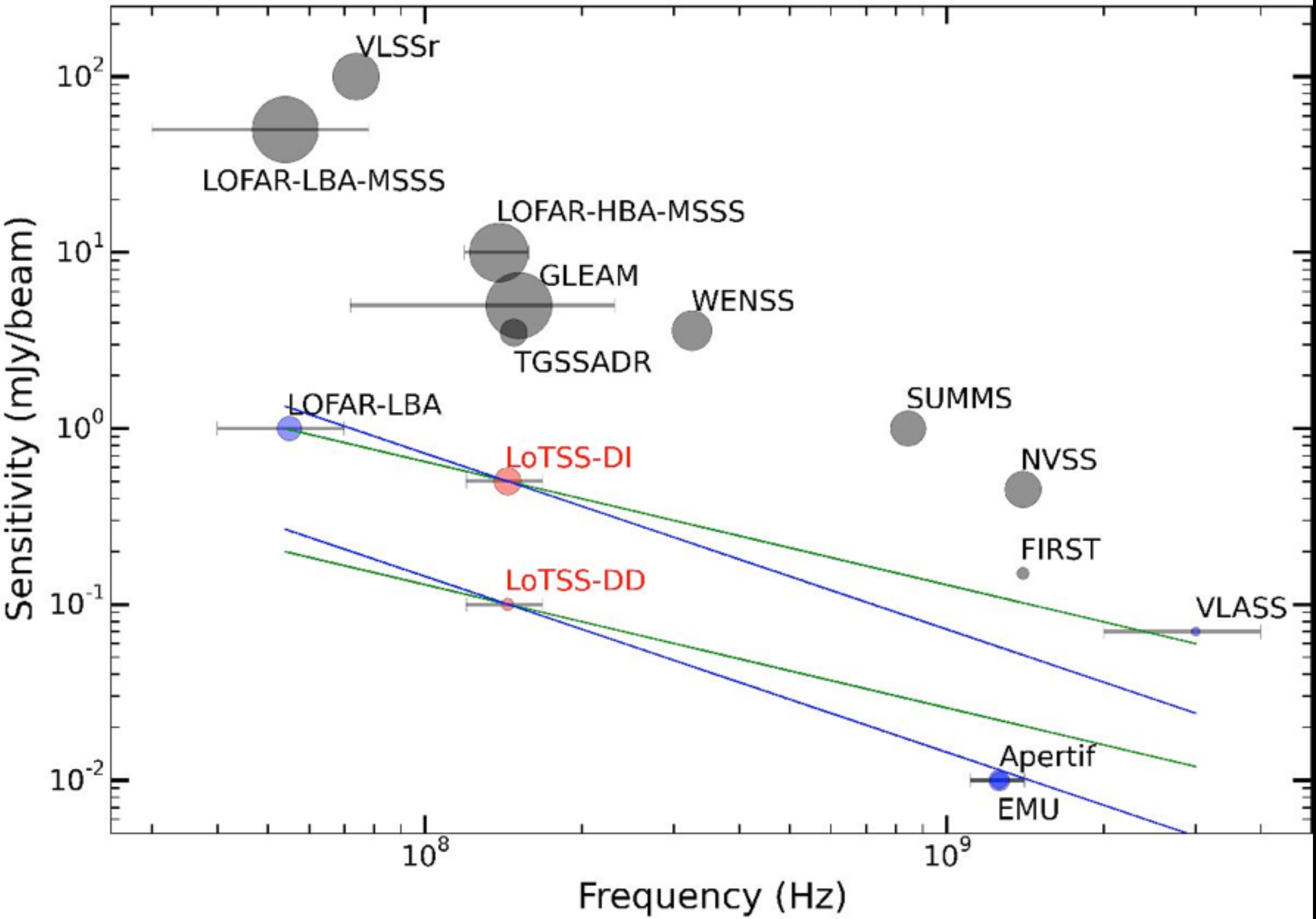


LOw Frequency ARray

50 stations in NL (38), D (6), PL (3), F, S, UK

LOFAR Two-metre Sky Survey (LoTSS)

Shimwell et al. 2017



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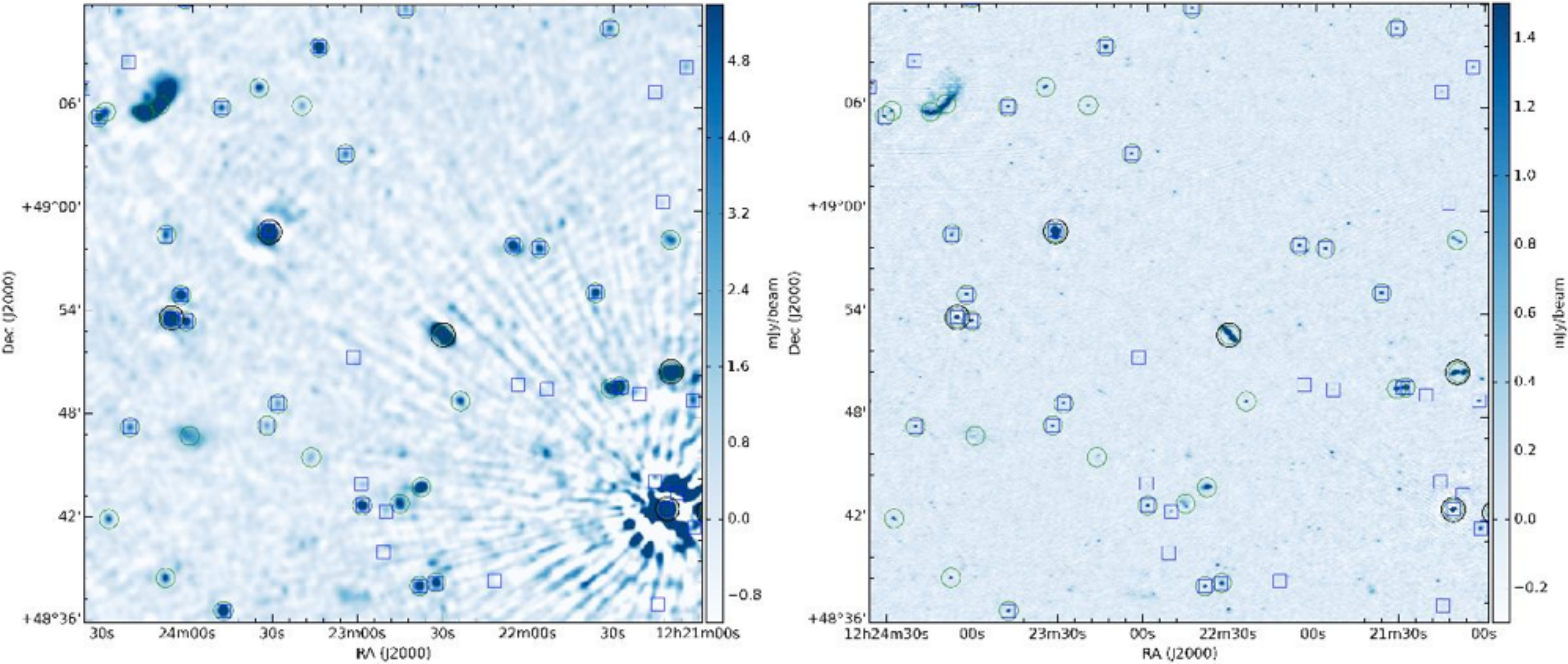
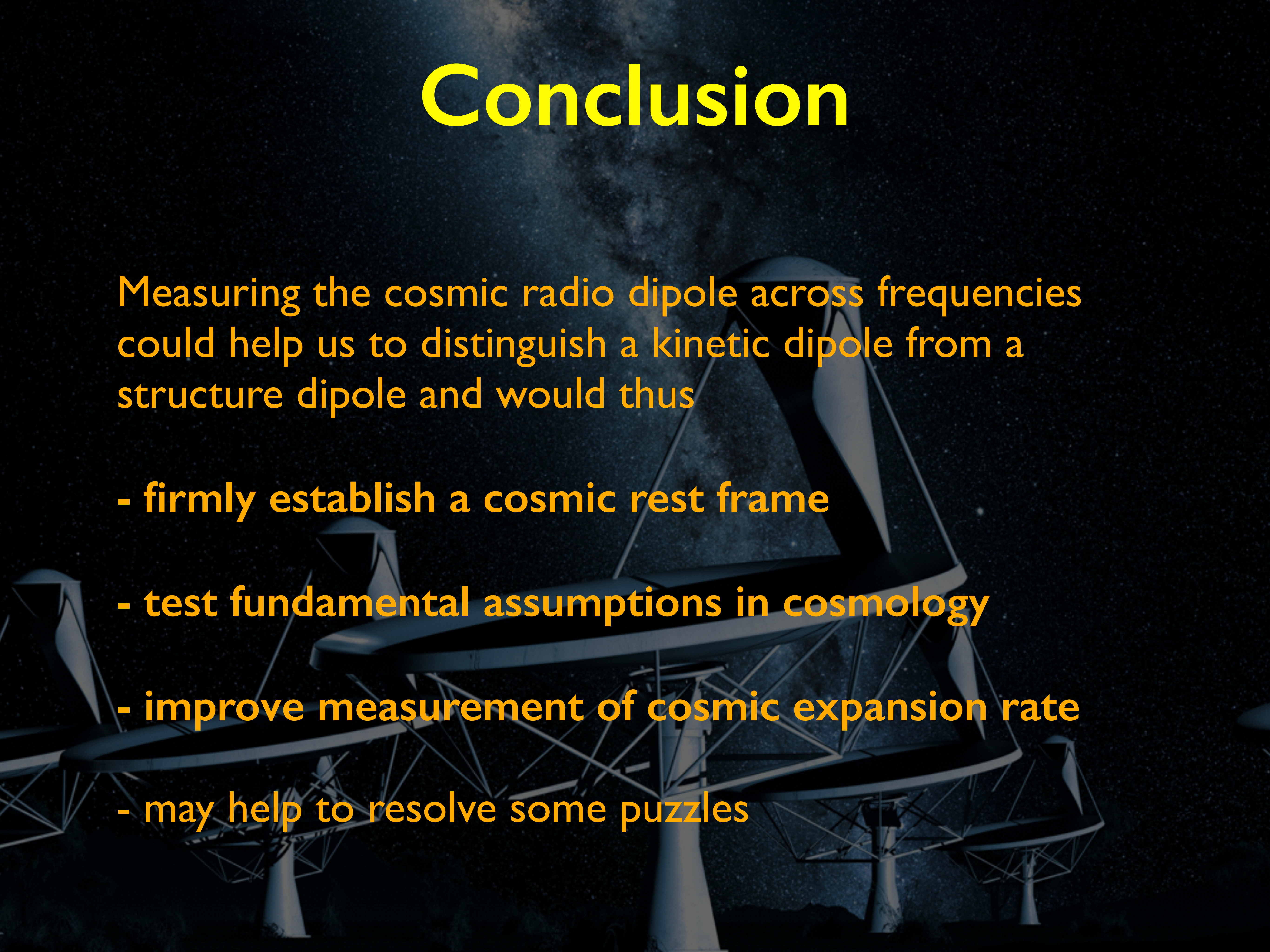


direction independent vs **direction dependent calibration**

Conclusion



Measuring the cosmic radio dipole across frequencies could help us to distinguish a kinetic dipole from a structure dipole and would thus

- **firmly establish a cosmic rest frame**

- **test fundamental assumptions in cosmology**

- **improve measurement of cosmic expansion rate**

- may help to resolve some puzzles