Universität Bielefeld

Do we understand the cosmic dipole?

Dominik J. Schwarz
Universität Bielefeld

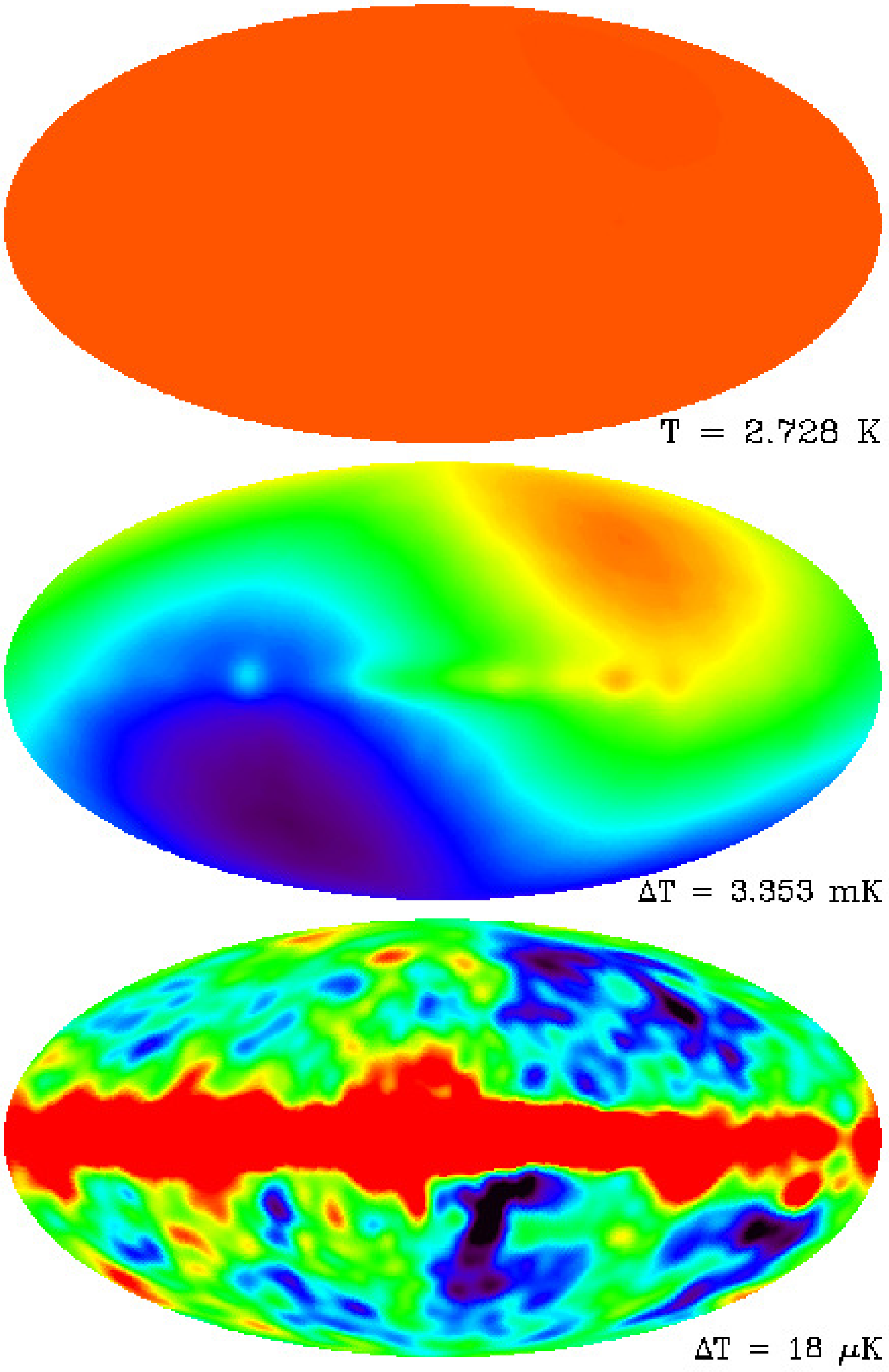
- CMB dipole
- Why bother?
- Radio dipole
- SKA forecast

Ferrara 2018

Cosmic microwave sky

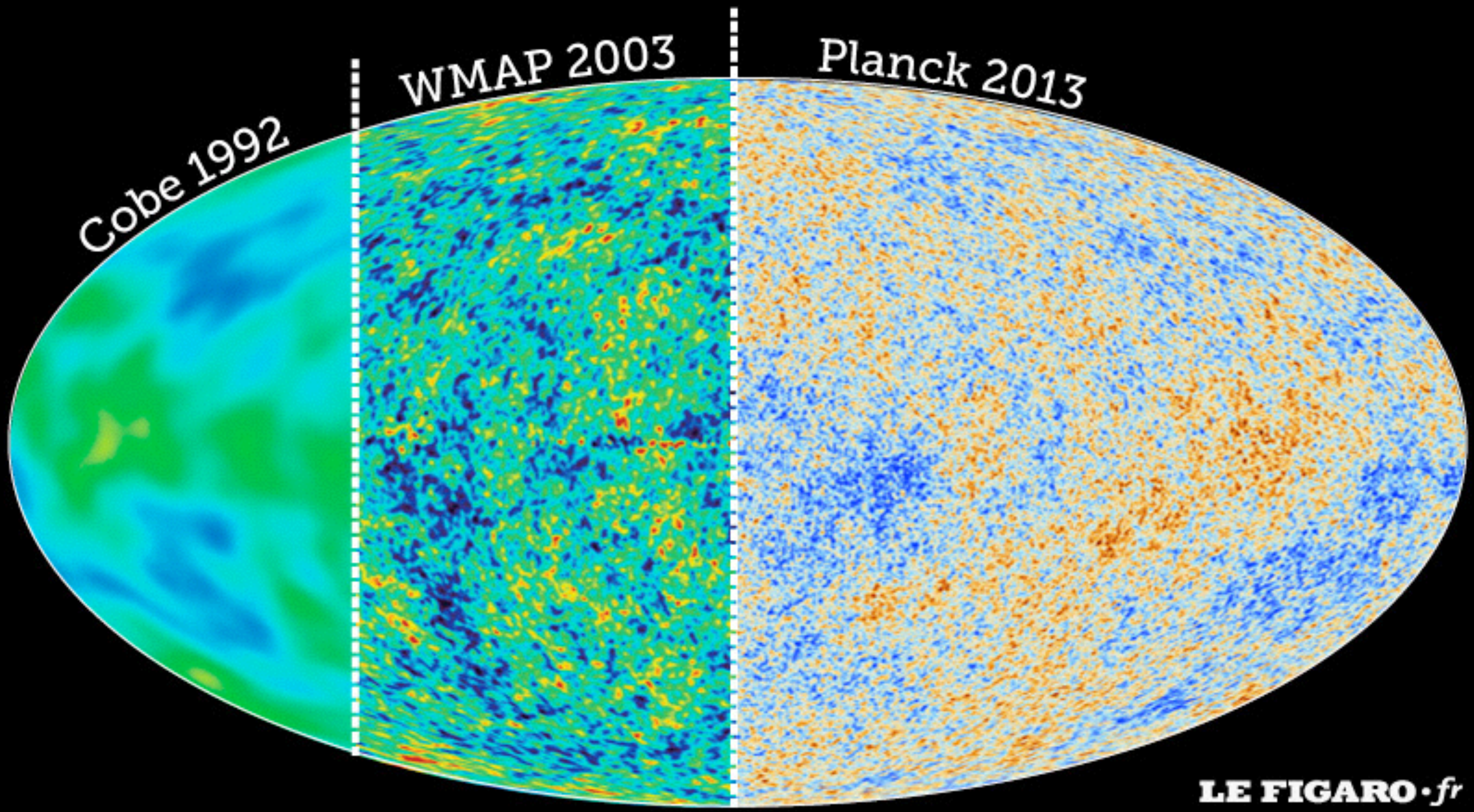
most photons in the Universe are primordial — dominant features:

- isotropic & thermal
- dipole Conklin 1969
- galactic foreground



COBE-DMR

CMB Missions



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

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

Peebles & Wilkinson 1968

CMB dipole

The proper motion hypothesis makes a prediction:

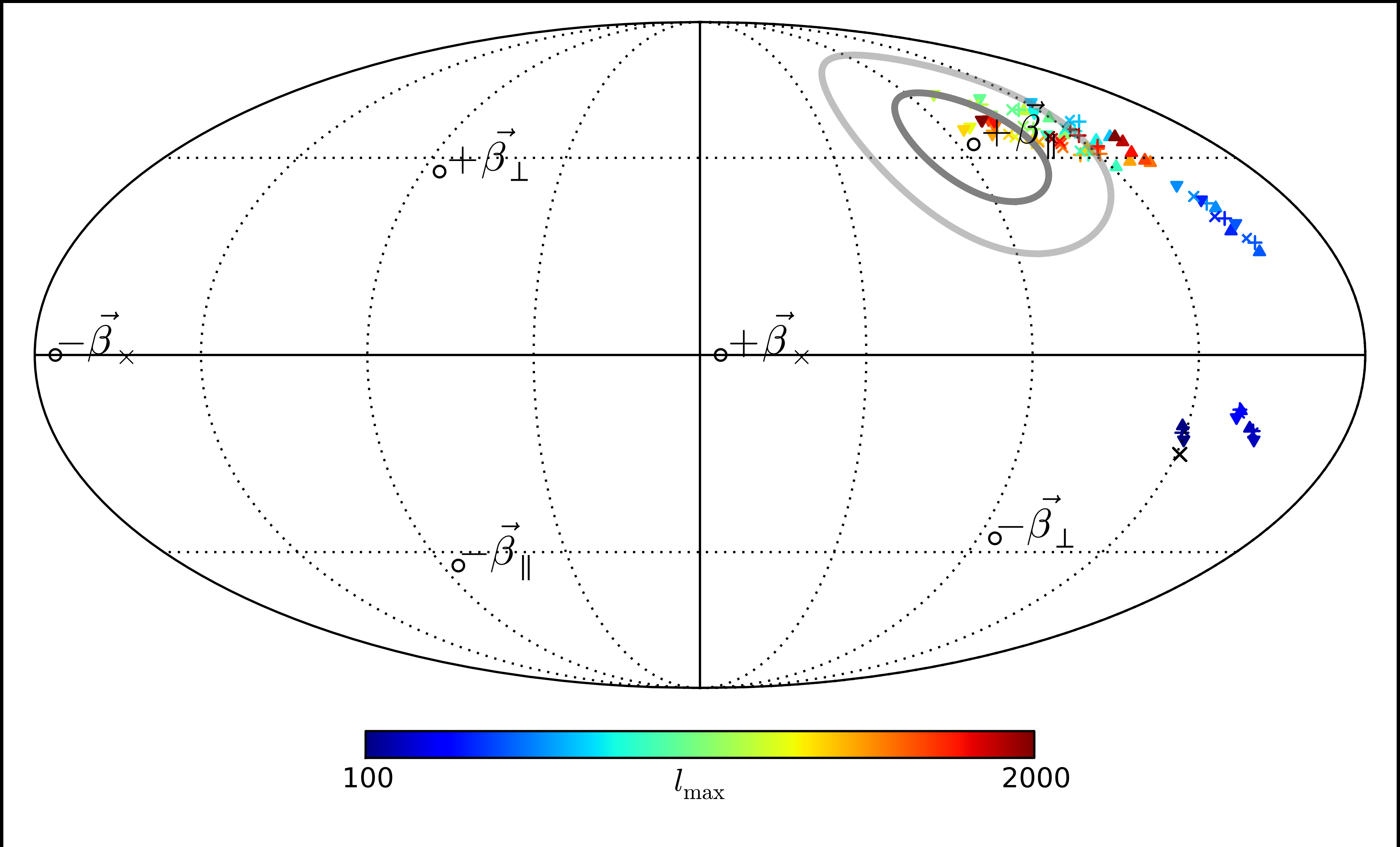
Doppler shift and aberration
for all objects at cosmological distances and at any frequency

➜ 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)

CMB proper motion test



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

Planck 2013

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

Cosmological standard model is formulated in CMB dipole frame, i.e. for comoving observers

Why bother?

1. Bulk flows and Hubble rate

CMB dipole defines cosmic reference frame

Hubble expansion rate

- ➜ H_0 = (66.88 ± 0.91) km/s/Mpc (CMB: Planck XLVI 2017)
  H_0 = (73.52 ± 1.62) km/s/Mpc (SN1a: Riess et al. 2018) … 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:

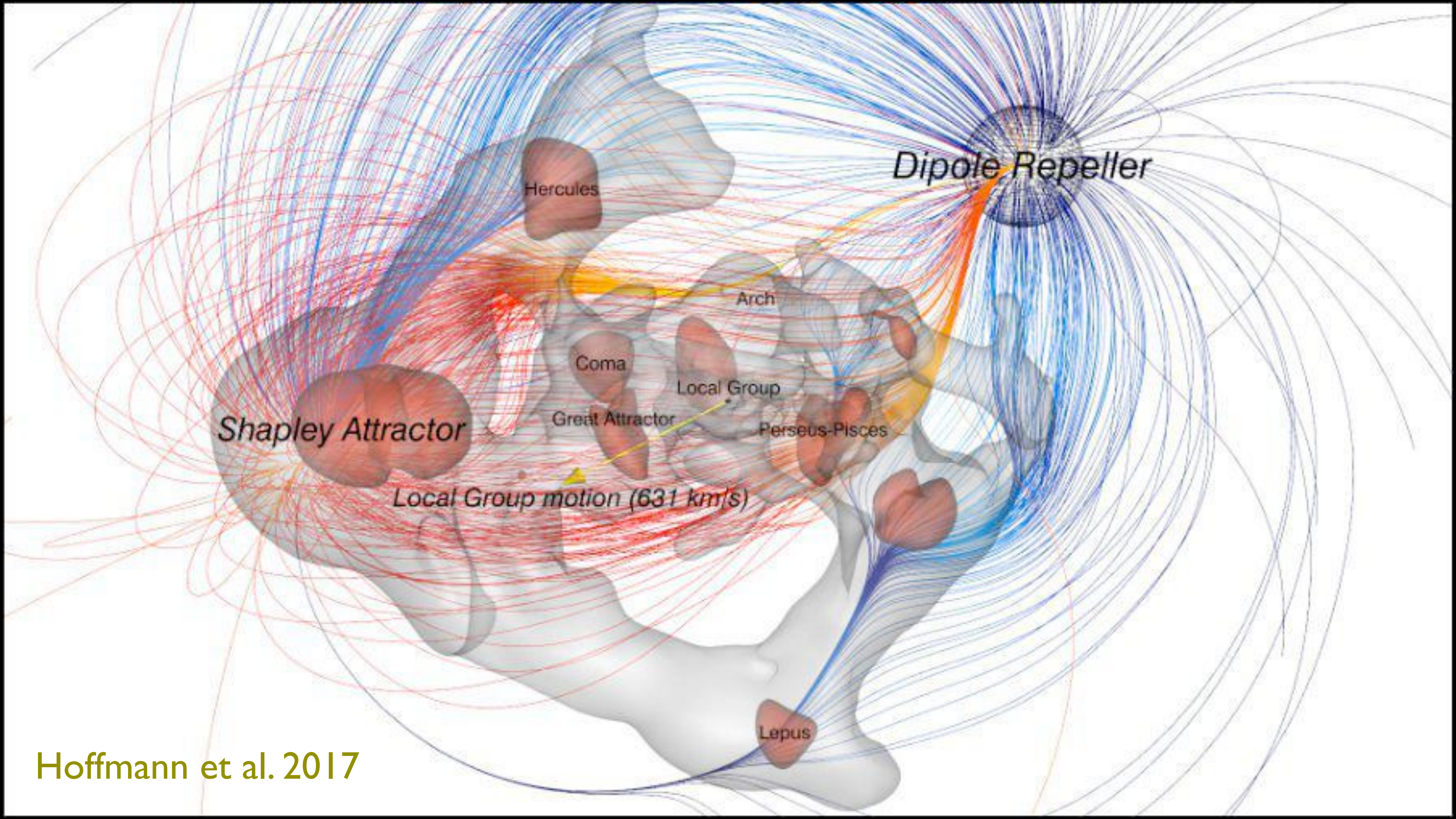
$$\text{if } \Delta v_p = 100 \text{ km/s} \Rightarrow \frac{\Delta H_i}{H_0} \sim \frac{h^{-1}\text{Mpc}}{d_i}$$

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

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

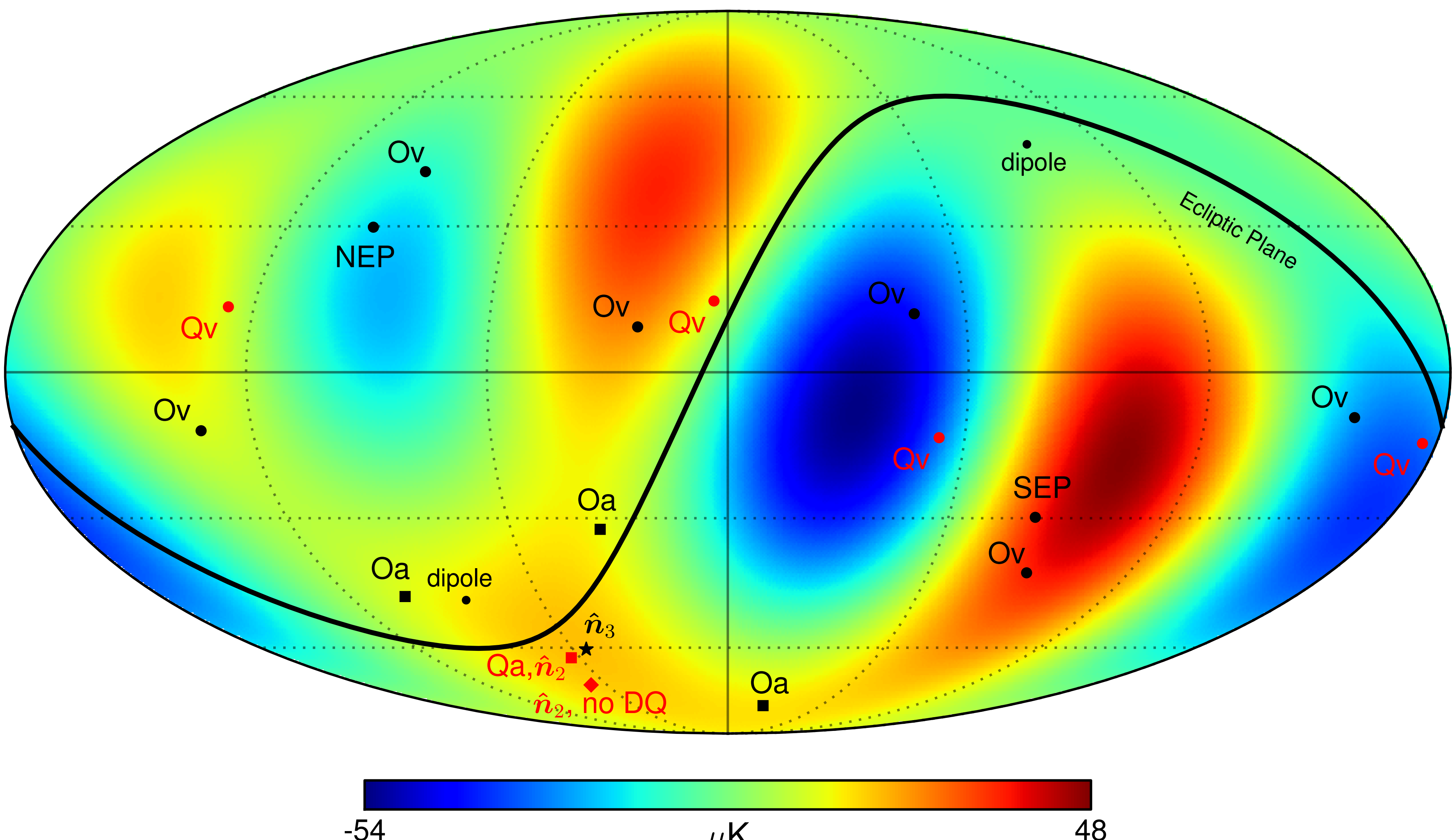
important for precision cosmology,
cannot explain local vs. global (or early vs. late) conflict, but will eventually matter

Why bother?
2. The local Universe



Hoffmann et al. 2017

Why bother?
3. CMB anomalies

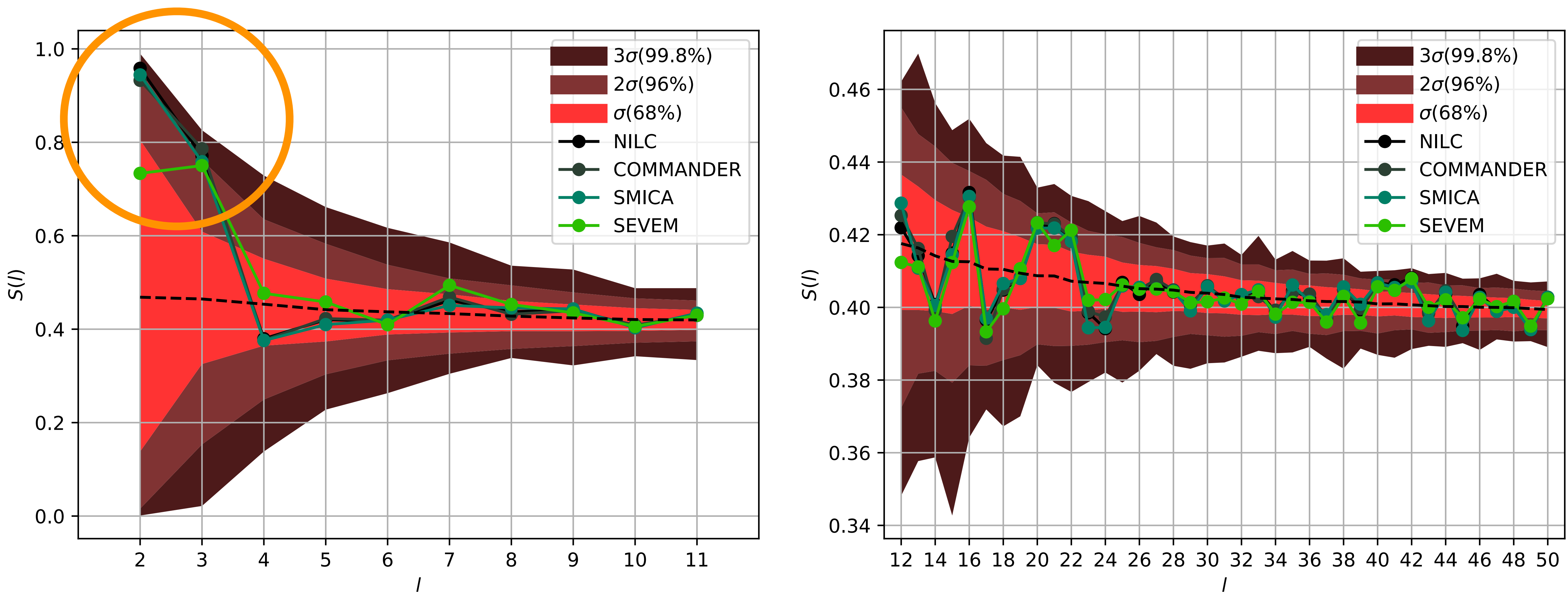


Schwarz et al. 2004, Copi et al. 2013

alignment of ℓ = **1,2,3** multipoles — kinematic quadrupole (!)

Why bother?
3. CMB anomalies

Pinkwart & Schwarz, 2018



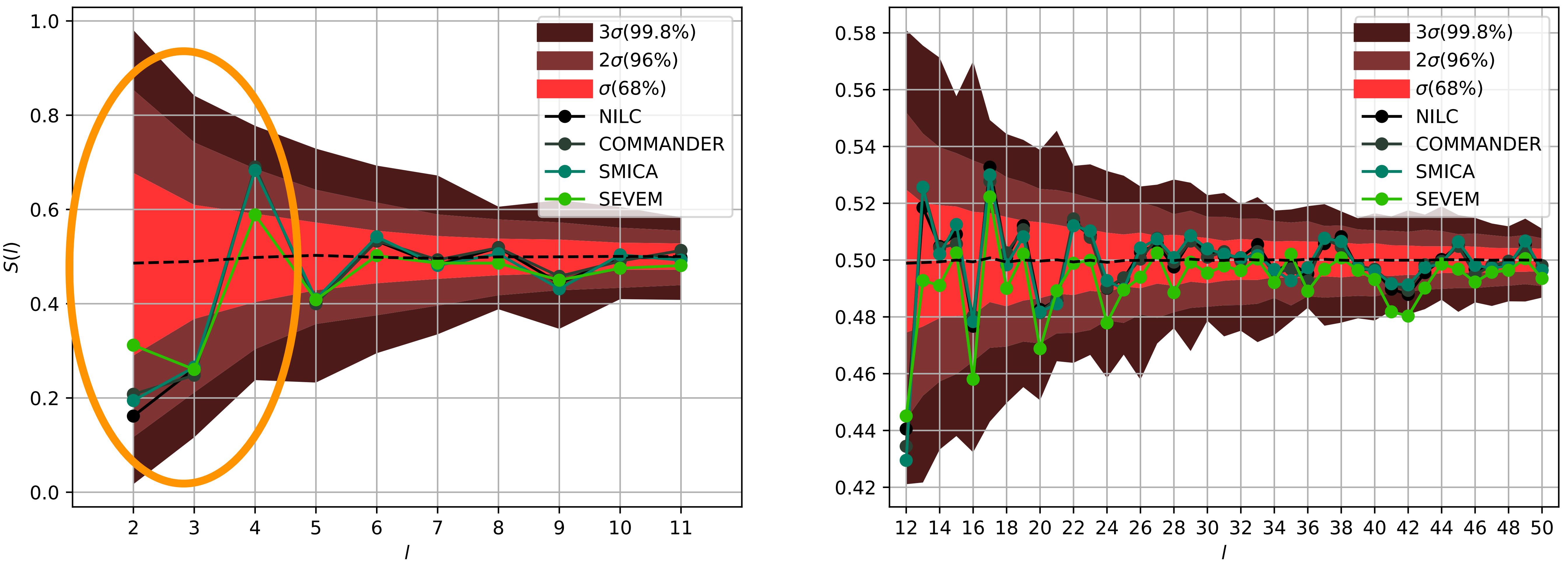
How orthogonal is the dipole to a given multipole?

p-value of quadrupole and octopole < 0.04 each and < 0.002 together

higher moments show expected behaviour

Why bother?
3. CMB anomalies

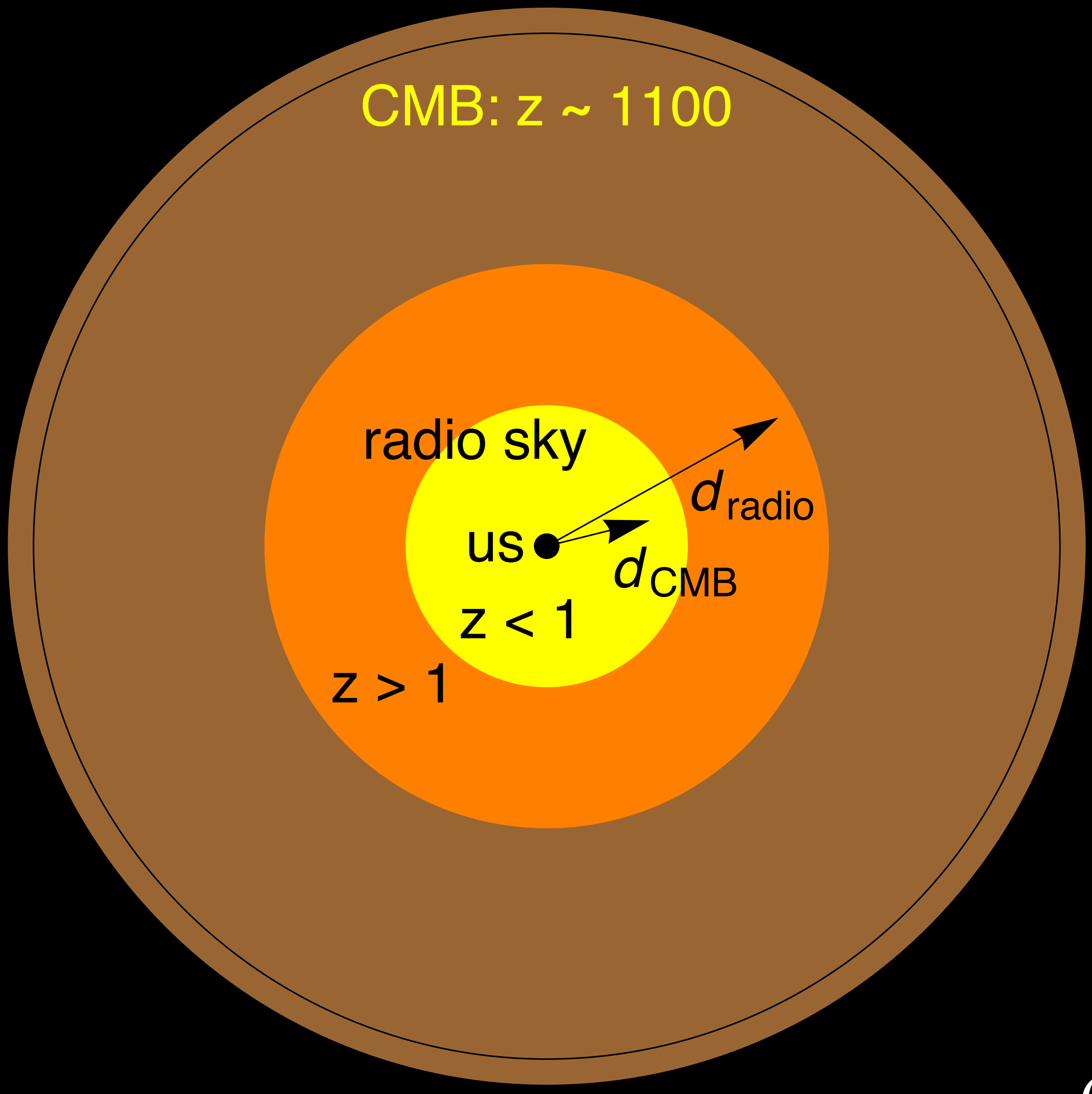
Pinkwart & Schwarz, 2018



How parallel is the dipole to a given multipole?

for l = 2,3,4,5 p-value < 0.004

Cosmic Radio Dipole



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

in LCDM = O(0.005) + O(0.001)

radio galaxies: **mean z > 1**

d_{matter} expected to be small

kinetic dipole

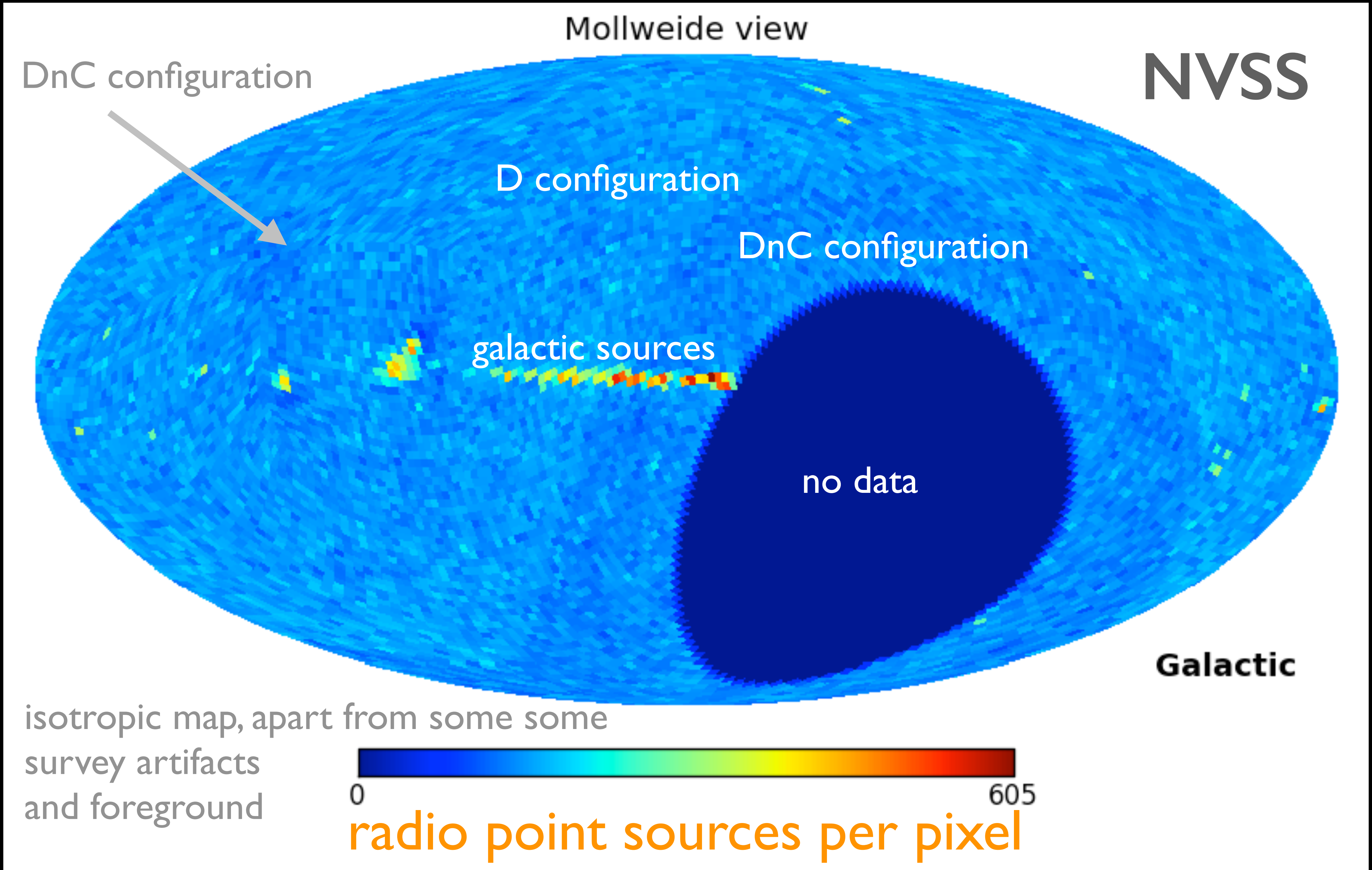
Ellis & Baldwin 1984

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

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

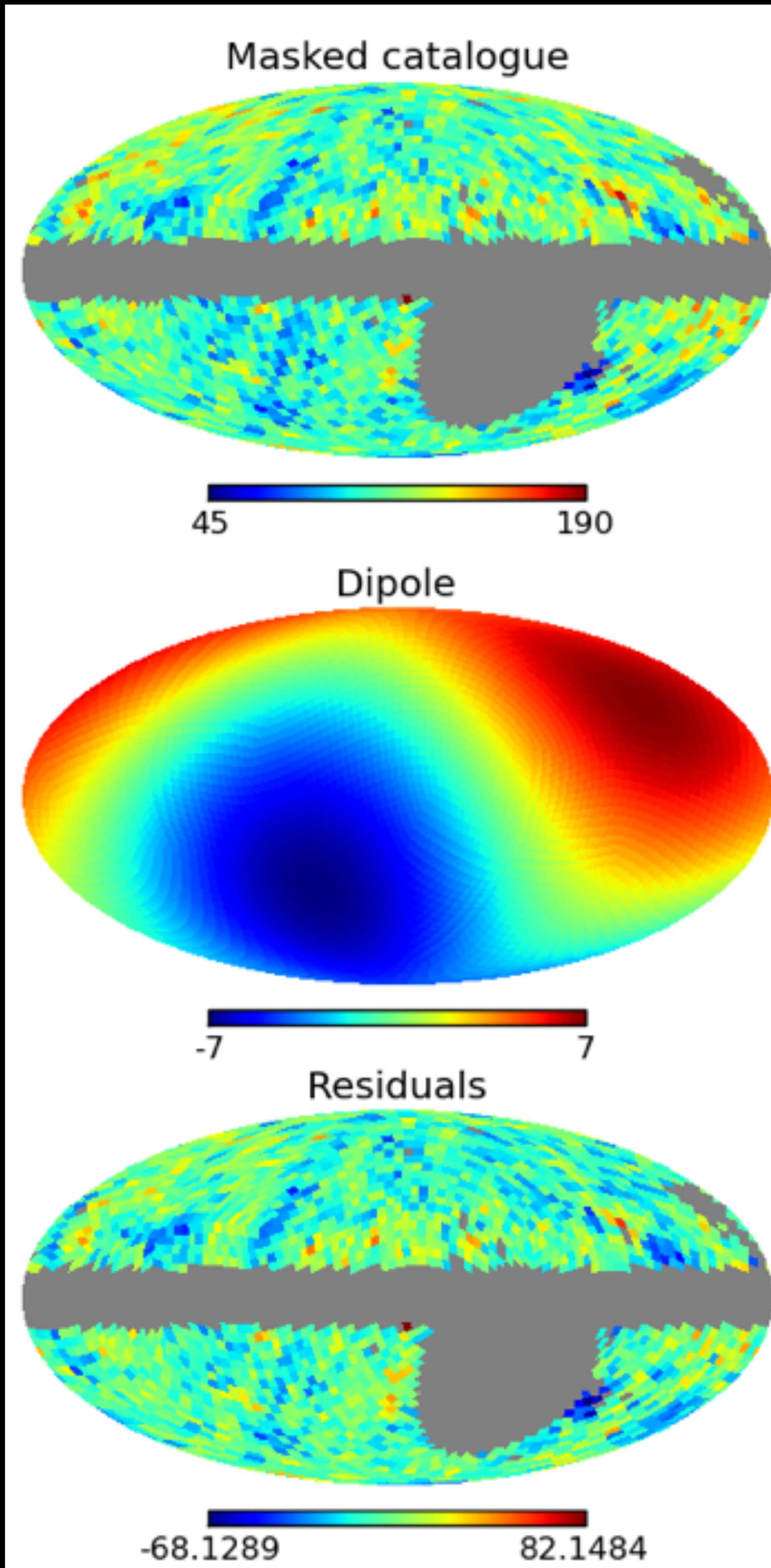
aberration & Doppler shift

Isotropic Radio Sky

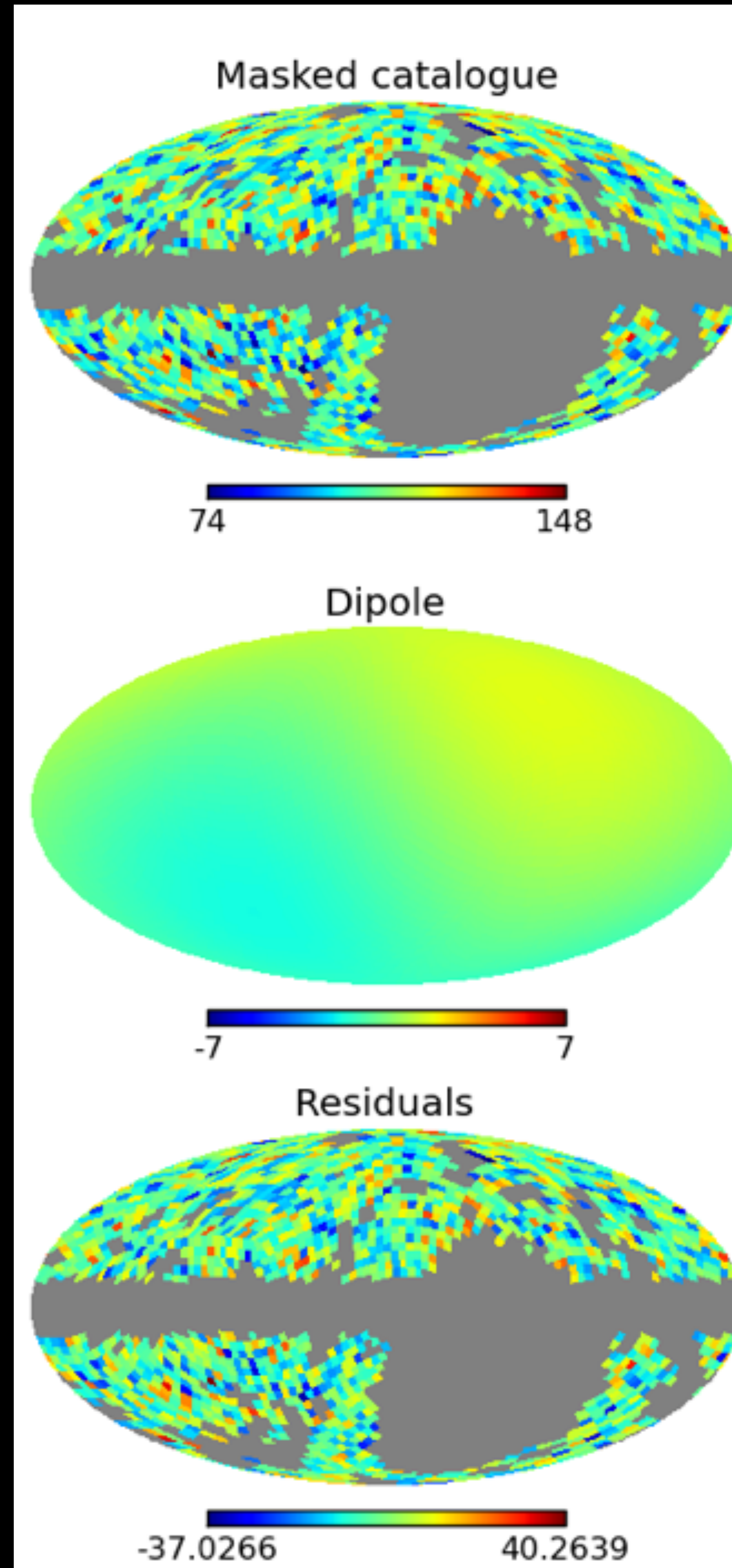


NVSS = NRAO VLA Sky Survey, Condon et al. 2002

TGSS 151 MHz



NVSS 1.4 GHz



dipole DIRECTIONS AGREE with expectation for

TGSS/WENSS/SUMSS/NVSS
(4 frequencies with 4 instruments)

BUT

dipole AMPLITUDES DISAGREE with expectation for all 4 catalogues

frequency dependence ?

Rubart, Schwarz & Siewert, in prep.

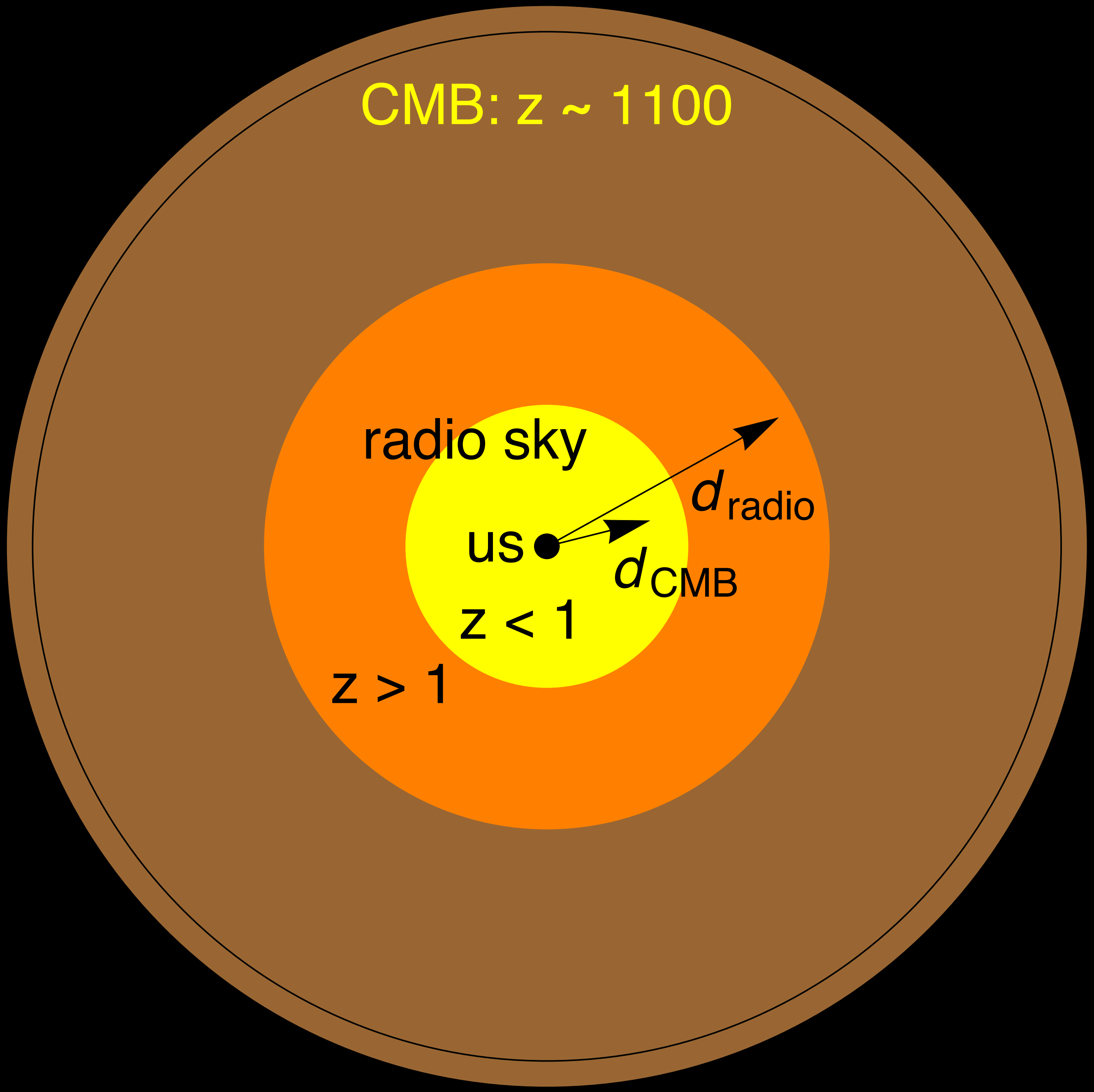
See also:
Colin et al. 2017
Bengaly et al. 2018

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.
WENSS	25	92,600	117±40	—	2.9±1.9	lin.
WENSS	25	85,285	118±39	-7±24	1.6±0.8	*quad.
aTGSS	100	229,235	146±13	2±19	5.6±0.4	*quad.
expect.	—	—	168	-7	0.4-0.5	—

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

Cosmic radio dipole



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

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

directions consistent, amplitudes too large

Blake & Wall 2002
Rubart & Schwarz 2013
Colin et al. 2017
Bengaly et al. 2018

local bulk flows?

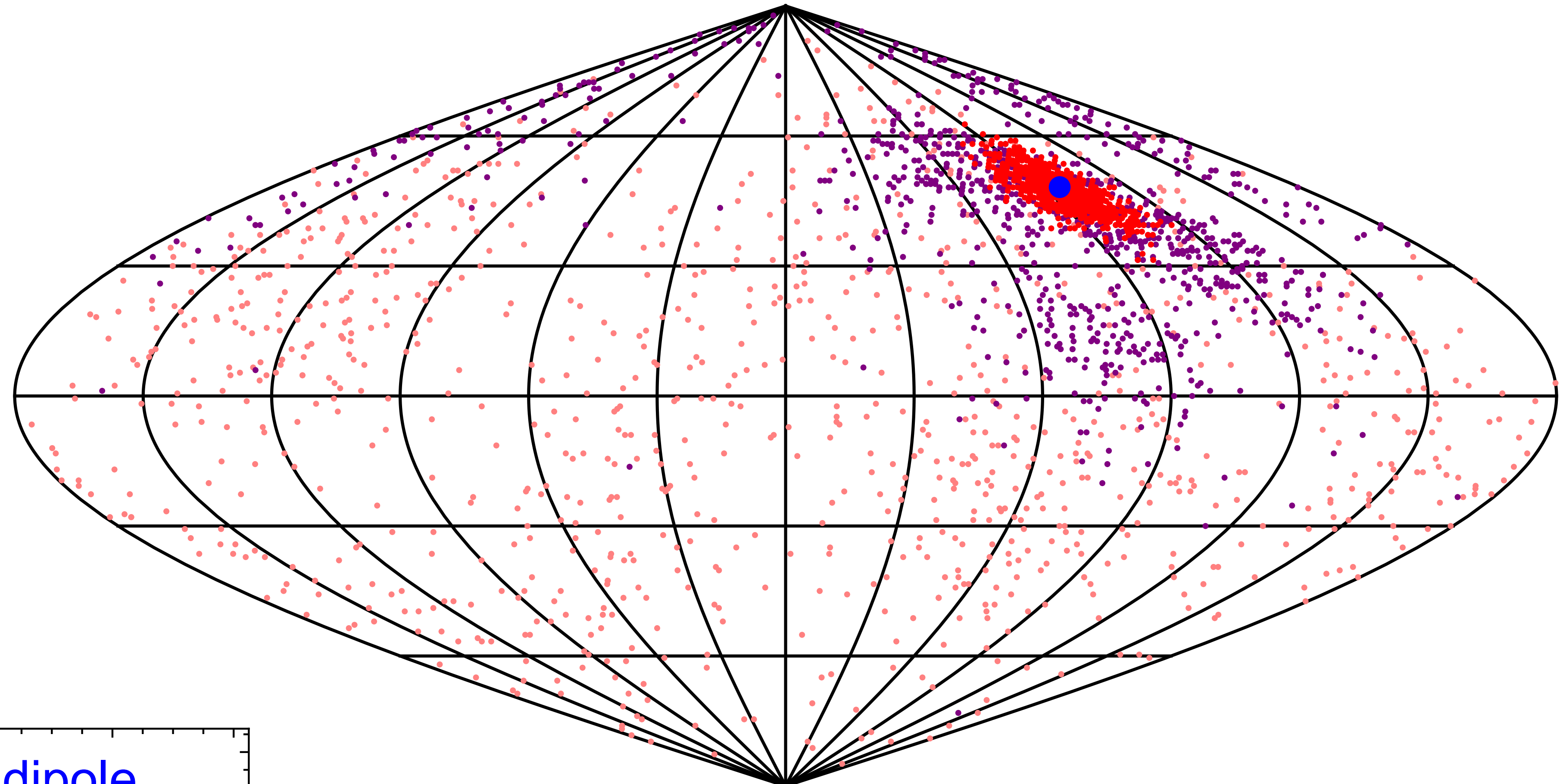
Watkins & Feldman 2014
Atrio-Barandela et al. 2014

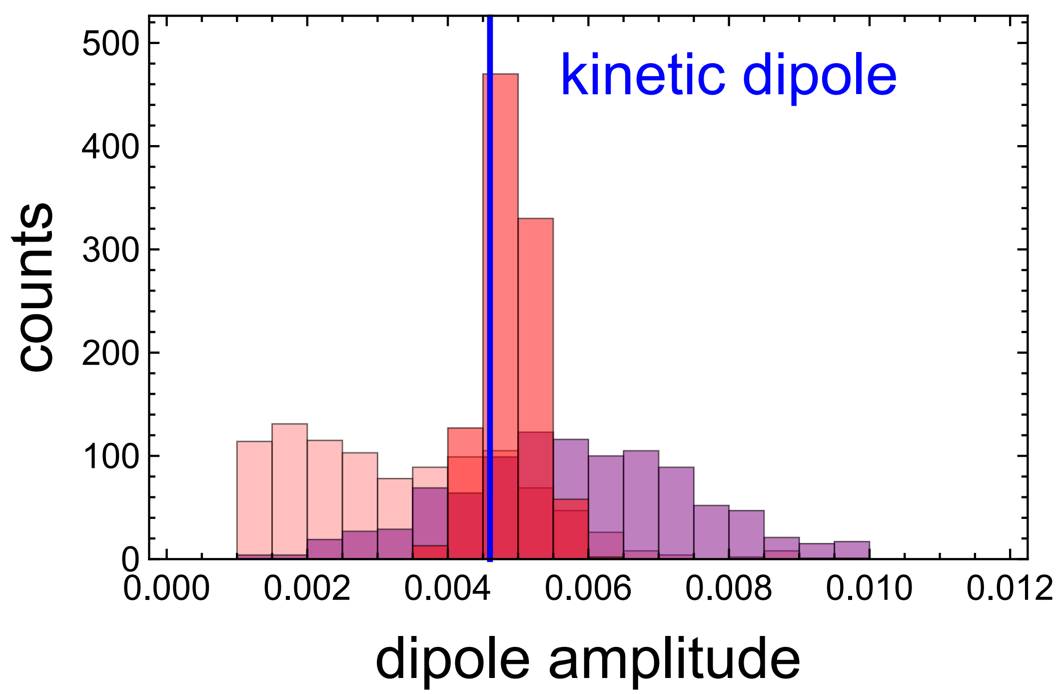
local structure dipole?

Rubart, Bacon & Schwarz 2014
Nusser & Tiwari 2016

SKA Forecast

- CMB dipole
- structure dipole
- kinematic & structure dipole
- kinematic & structure dipole, w/o local structure





SKA-Mid band 1 wide survey with lower flux density threshold of 20 μJy

local structure: $z < 0.5$

CMB foregrounds: SKA prototype dish

Karoo, SA (next to MeerKAT)

MT Mechatronics (dish)
Max Planck Institute for Radio Astronomy (S-band)
construction 2018, start of all-sky survey mid 2019

diameter: 15 m

S-Band:

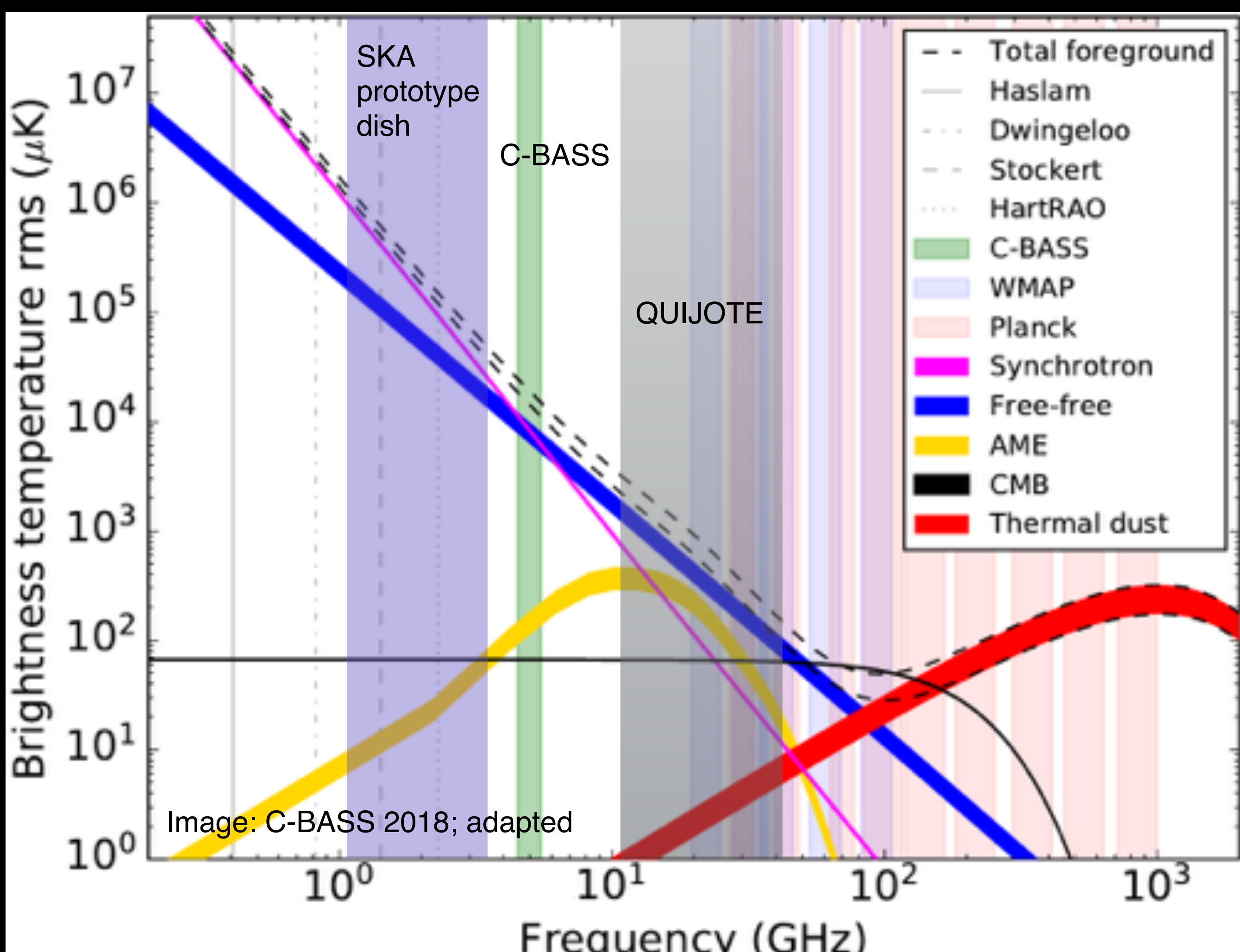
T_{sys}/η: 25 — 30 K
frequency: 1.6 — 3.5 GHz
beam: 50 — 25 arcmin
full polarisation: IQUV
confusion noise I: 70 — 300 mJy
confusion noise P: ~ 0.06 mJy

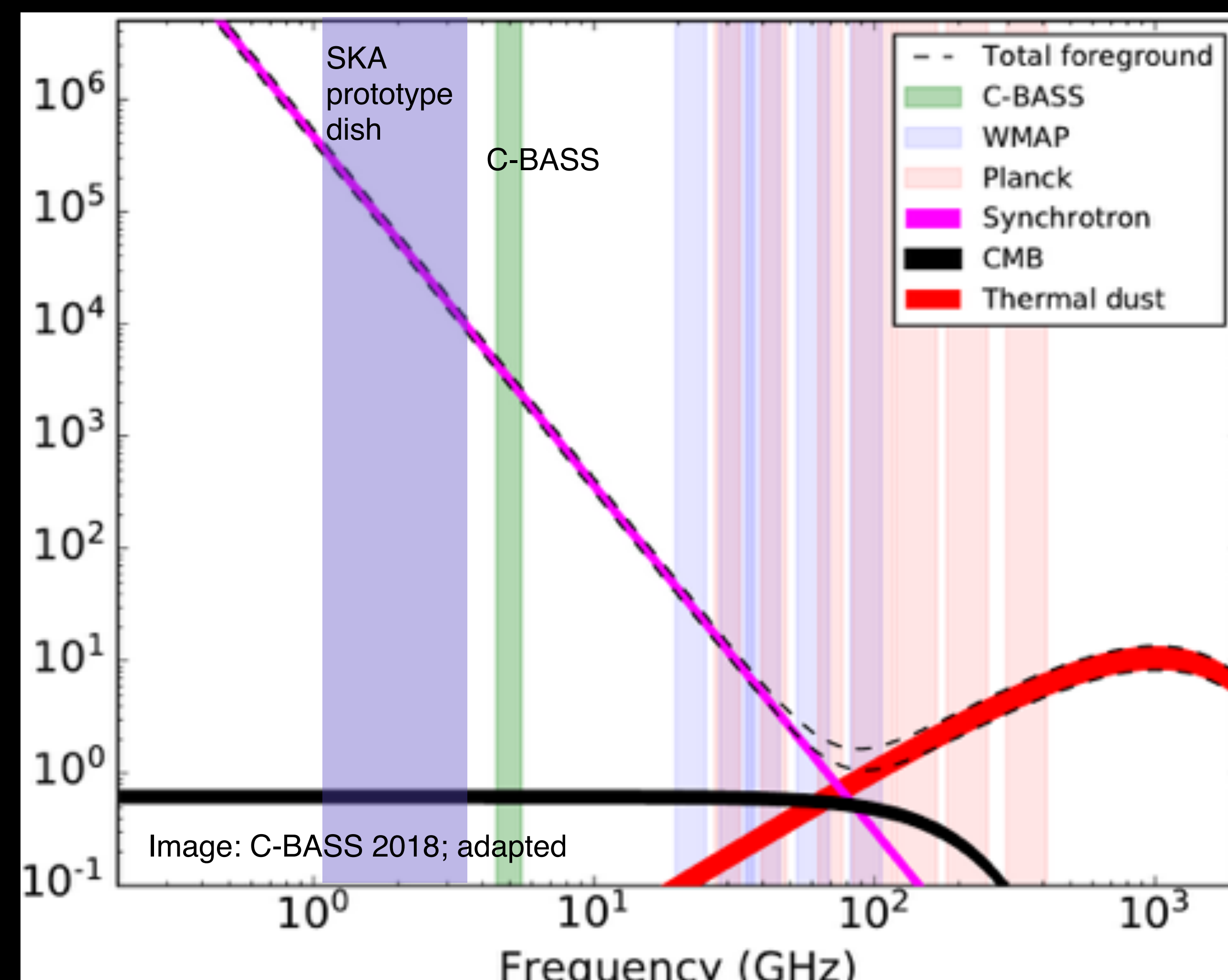
All-sky S-band survey

Max-Planck-Institut für Radioastronomie

Universität Bielefeld

project scientist SKA
prototype dish: H.-R. Klöckner (MPIfR)
survey design: A. Basu (Bielefeld)
funding: MPG & BMBF (D-MeerKAT)





SKA prototype antenna S-band all-sky survey (~ 30,000 sqdeg)
QU fitting to predict amount of polarised synchrotron emission at CMB frequencies
looking for partners that help in data analysis; email: dschwarz@physik.uni-bielefeld.de

Conclusion

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

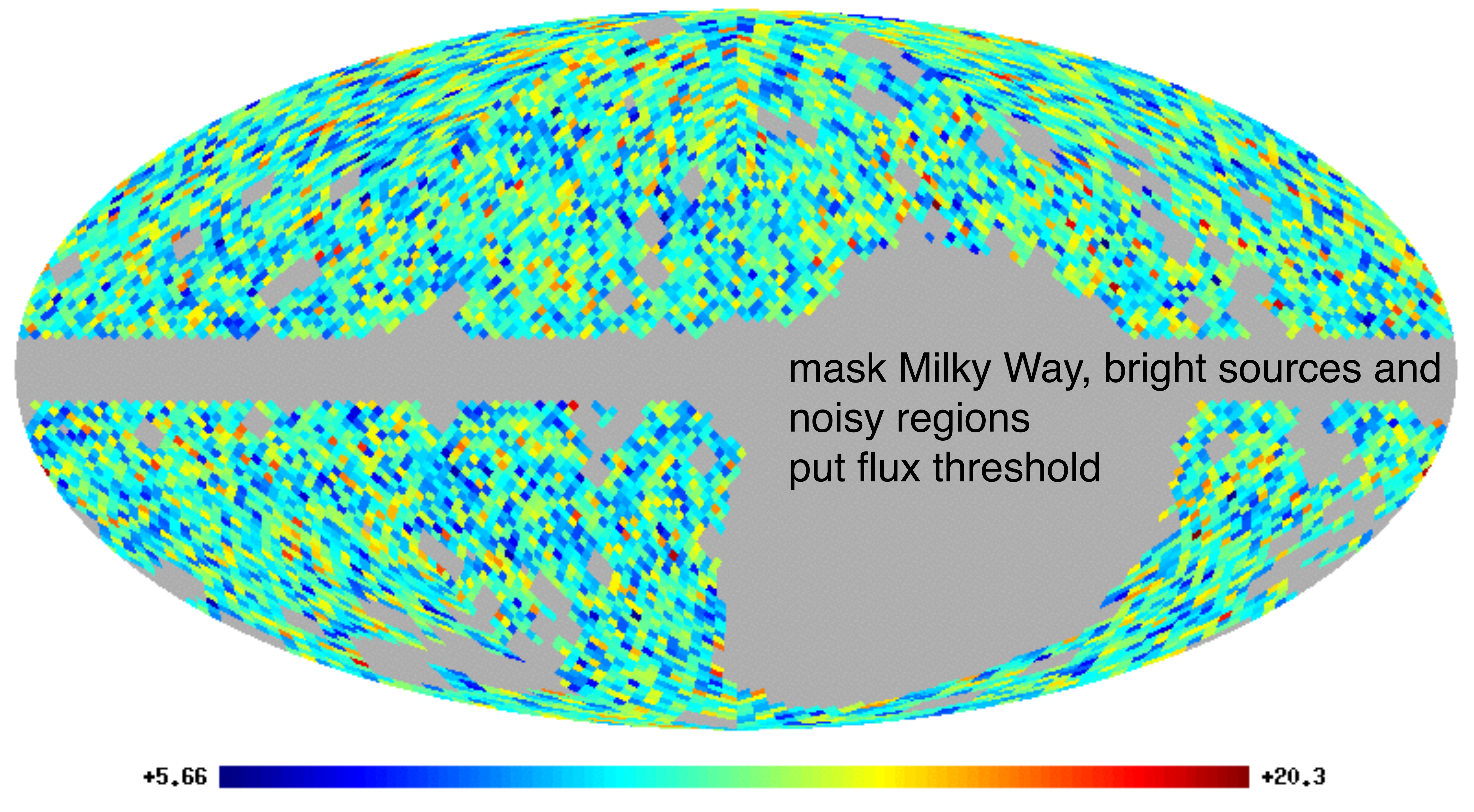
- firmly establish a cosmic rest frame

- test fundamental assumptions in cosmology

- improve measurement of cosmic expansion rate

- may help to resolve some puzzles (CMB anomalies)

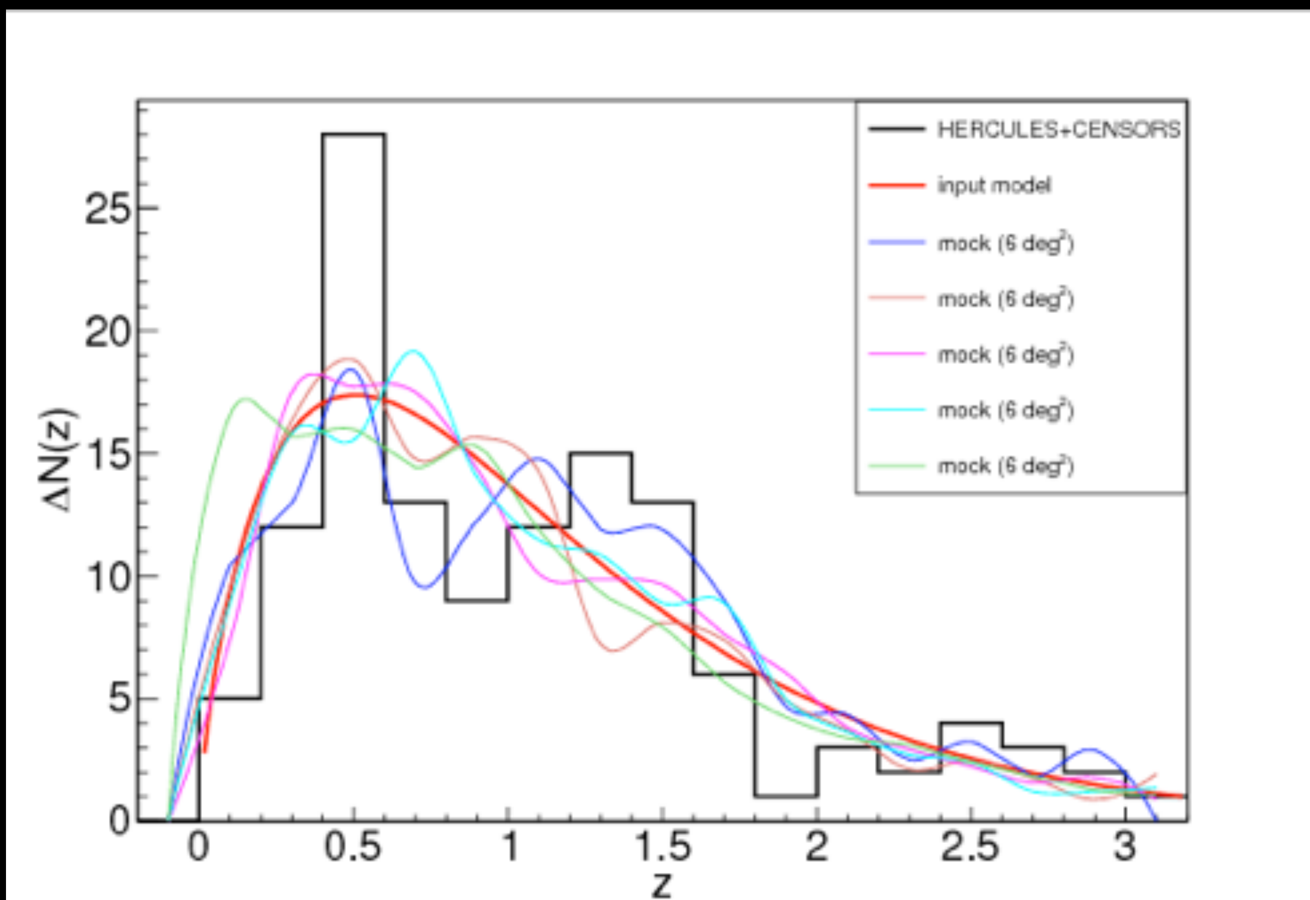
NVSS @ 1.4 GHz



S > 15 mJy

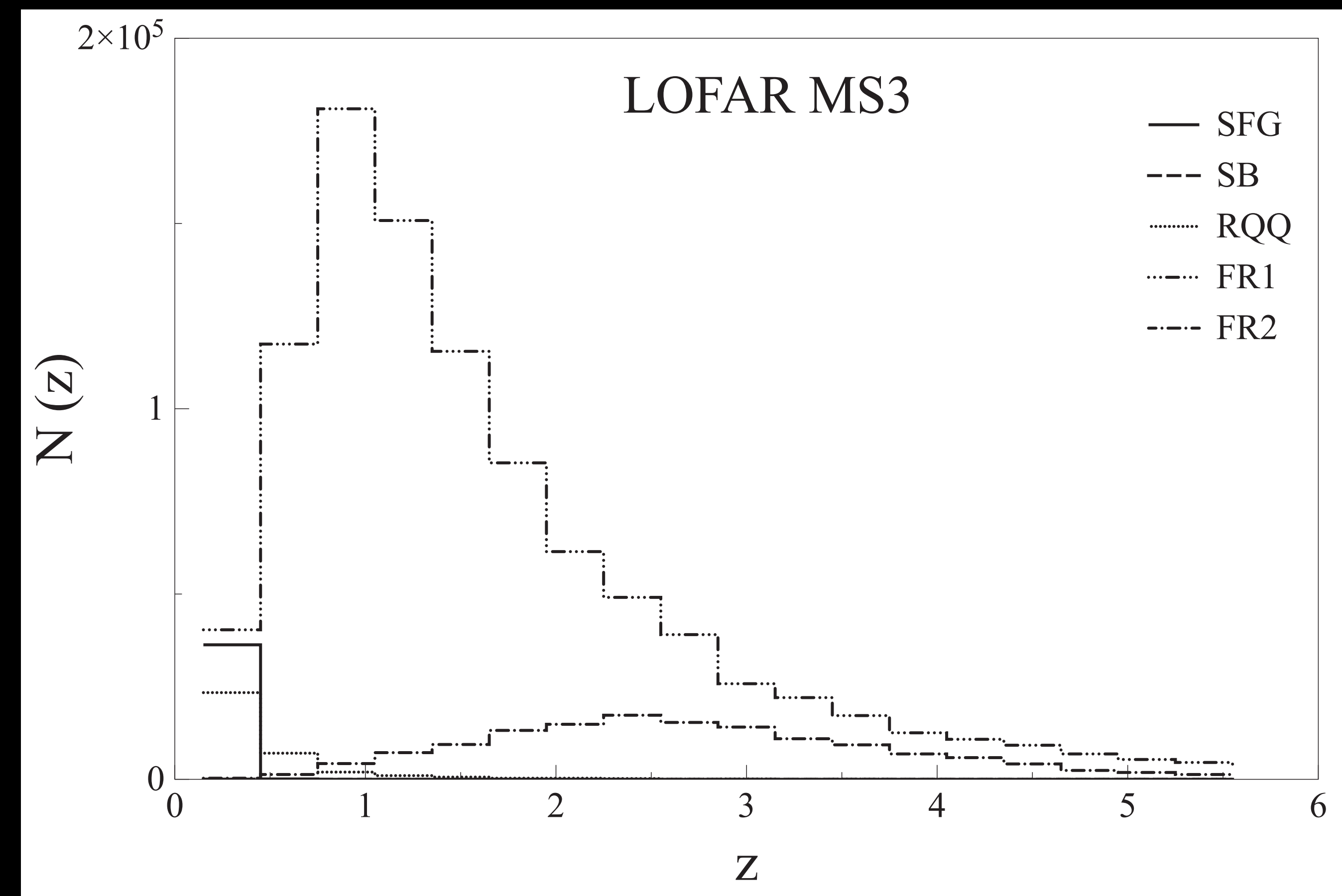
Chen & Schwarz 2016

Redshift distribution of radio sources



distribution of measured redshifts to NVSS radio sources and models

Tiwari et al. 2016

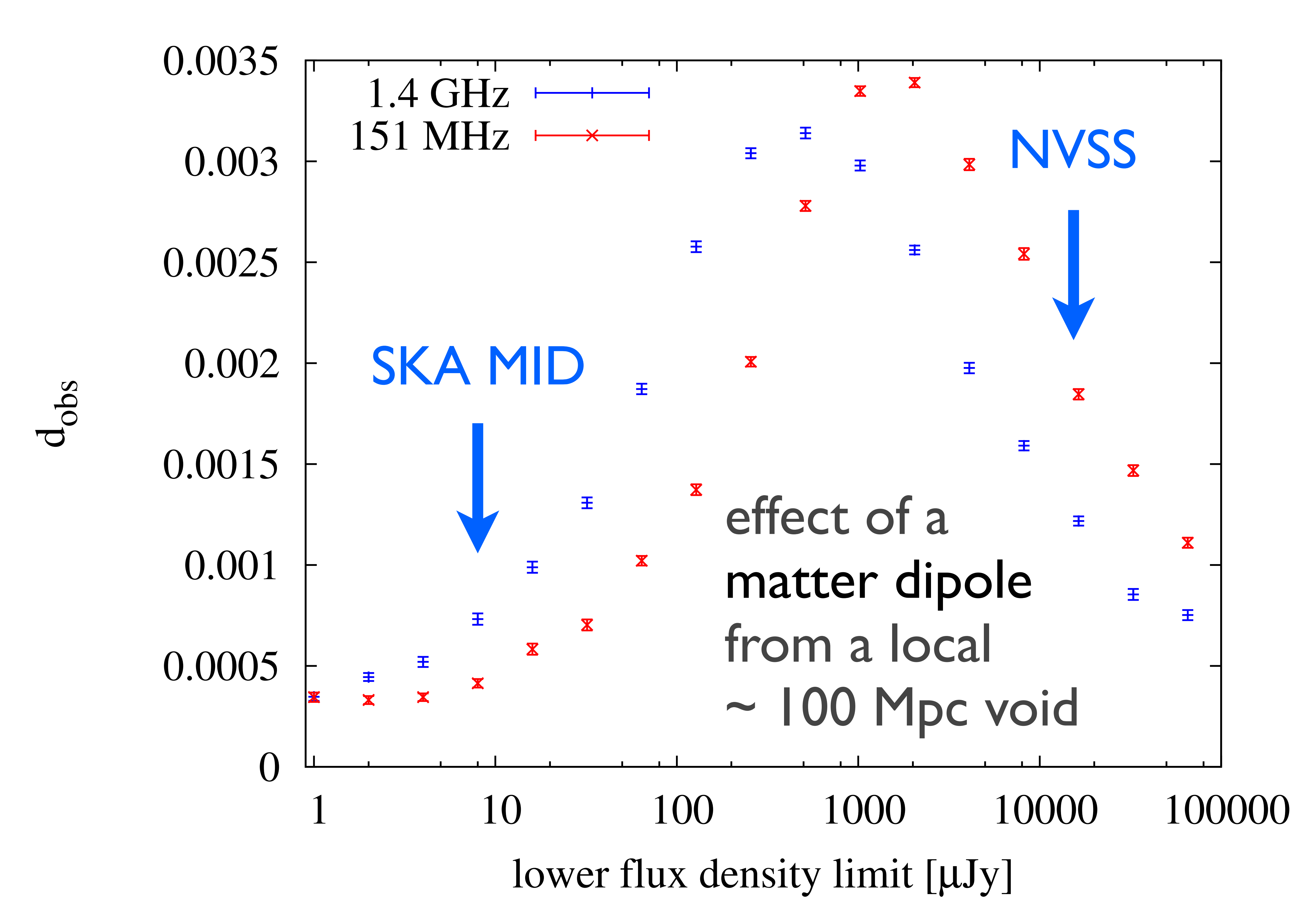


forecasted redshift distribution of radio sources in LOFAR MSSS

Raccanelli et al. 2012

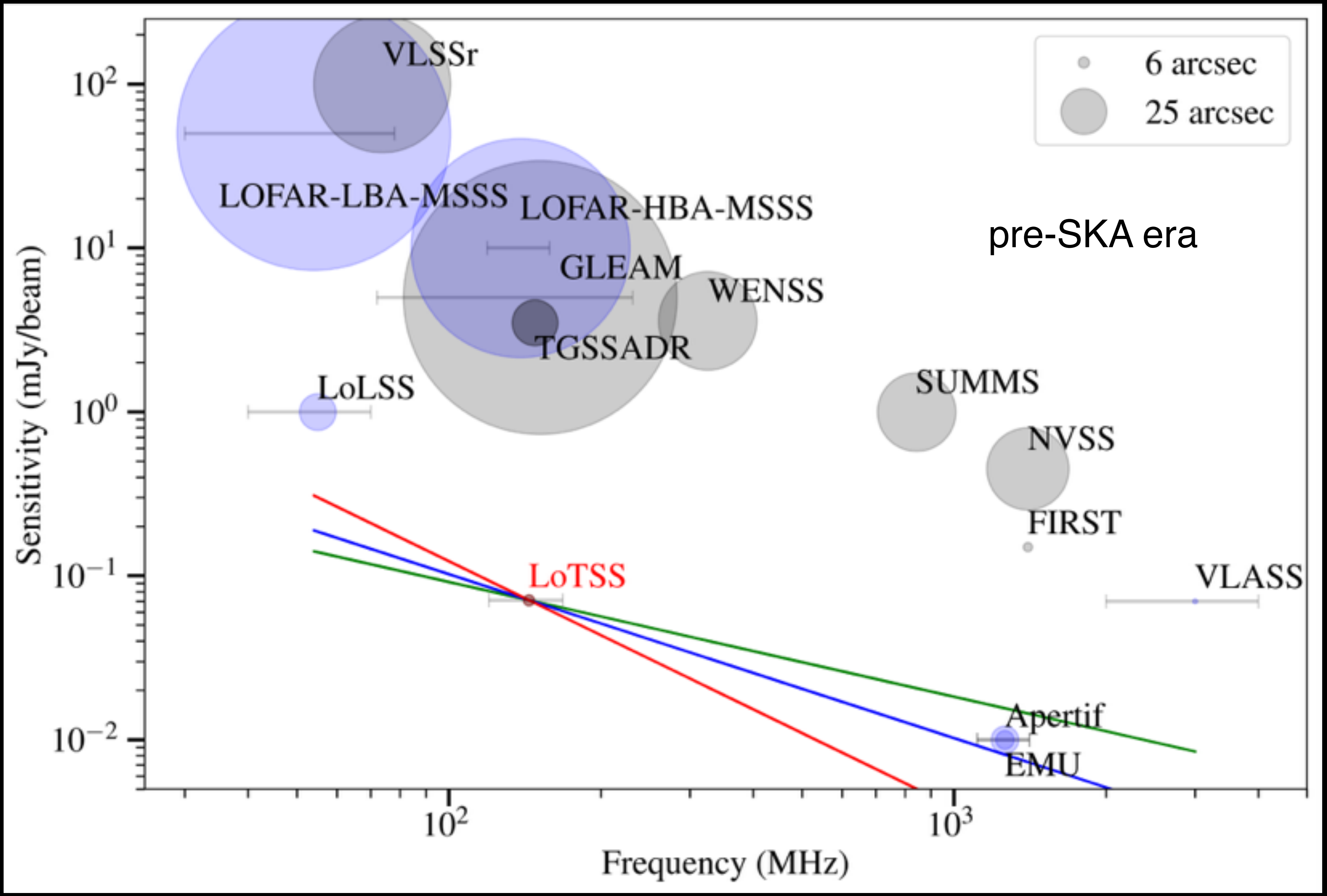
in isoptropic and homogeneous cosmologies coherent peculiar velocities are expected to vanish on distance scales larger than the matter-radiation equality scale
our Hubble patch is expected to be at rest wrt the cmb

Dipole tomography



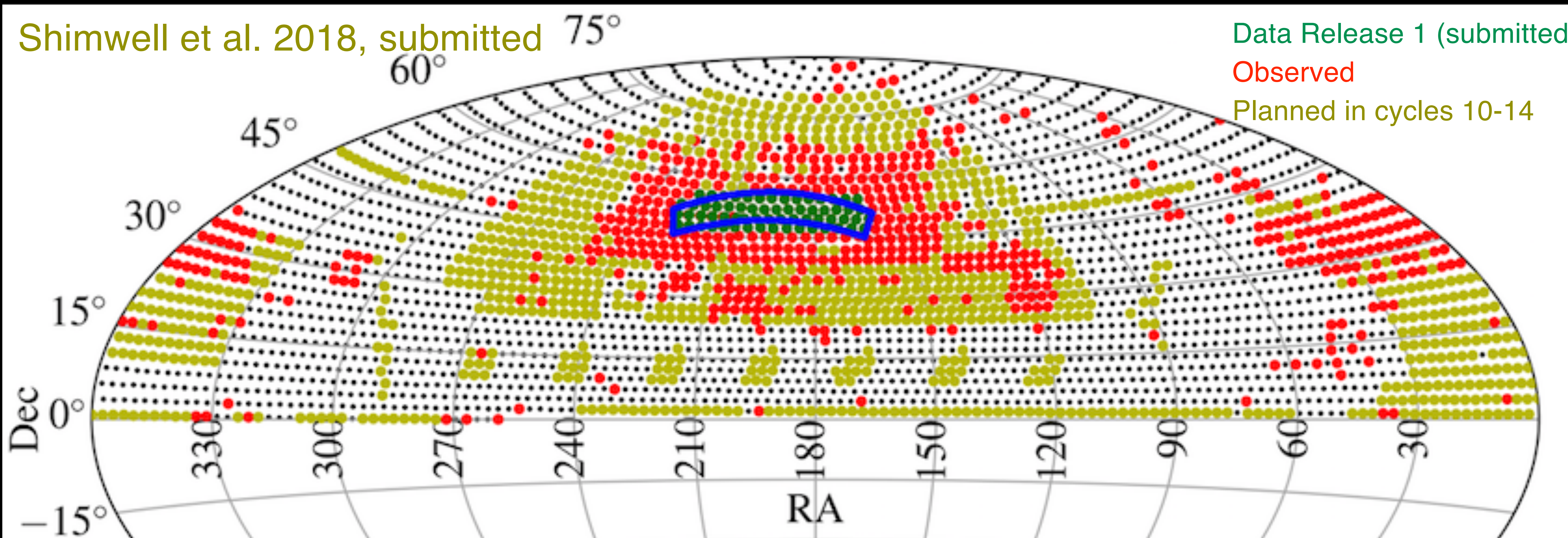
Rubart, Bacon & Schwarz 2014

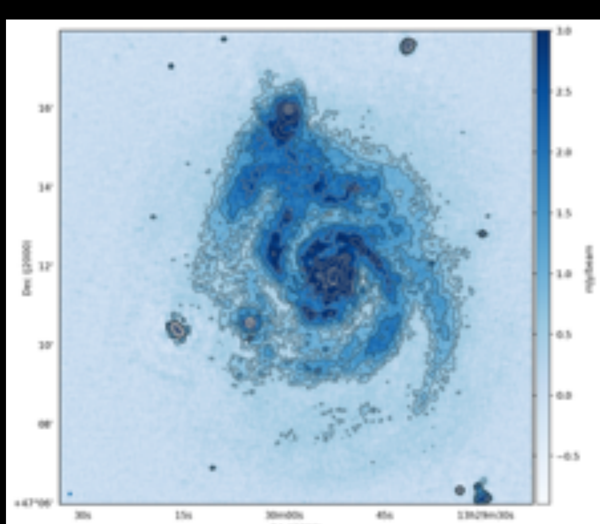
Continuum Radio Surveys

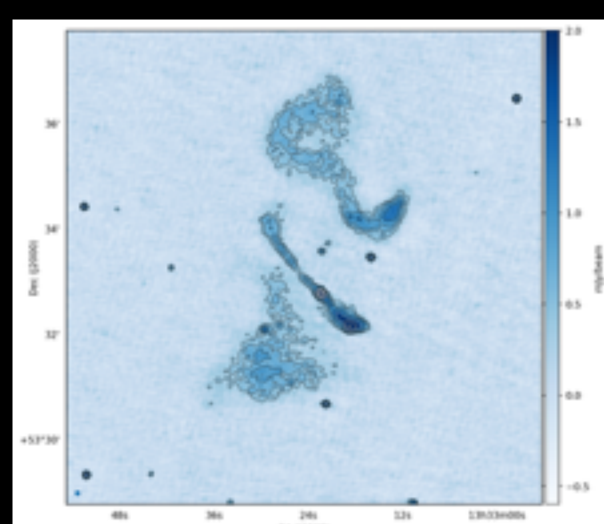


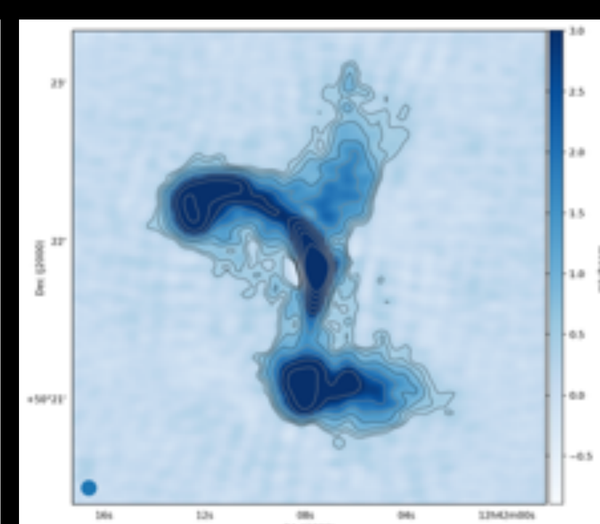
Shimwell et al 2018

LOFAR Two-metre Sky Survey (LoTSS)









- Northern hemisphere
- expect ~ 15 M sources
- rms noise 0.07 mJy/beam
- angular resolution 6”
- optical/ir id and photo-z for large fraction of sources