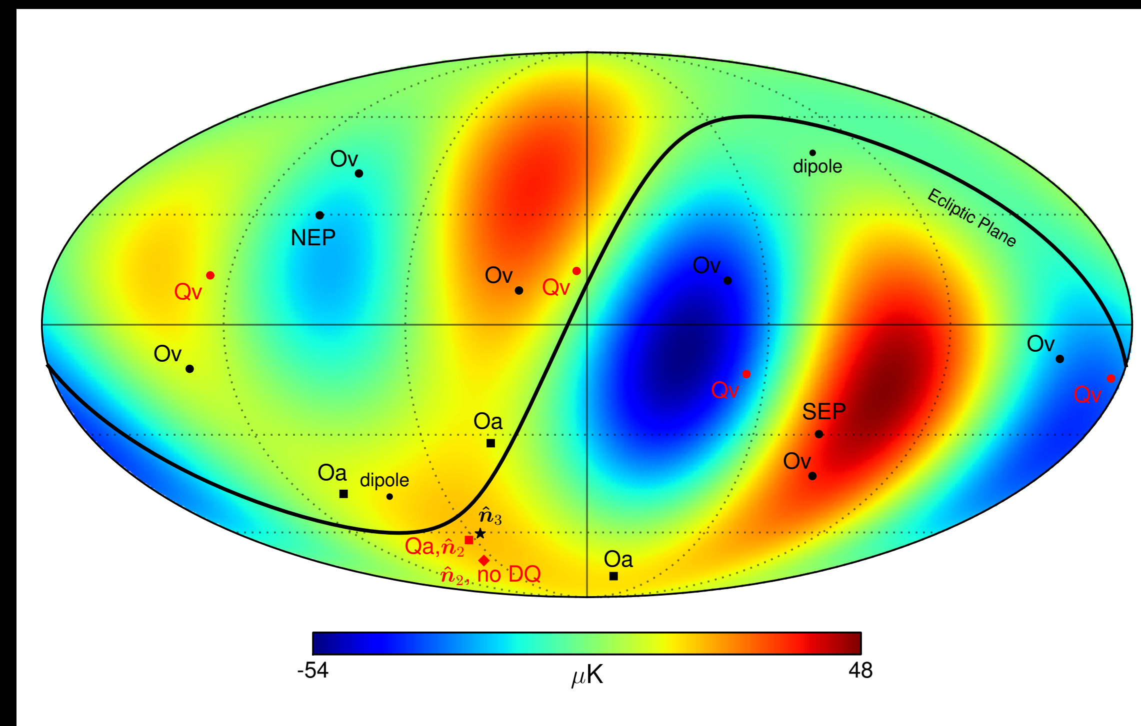
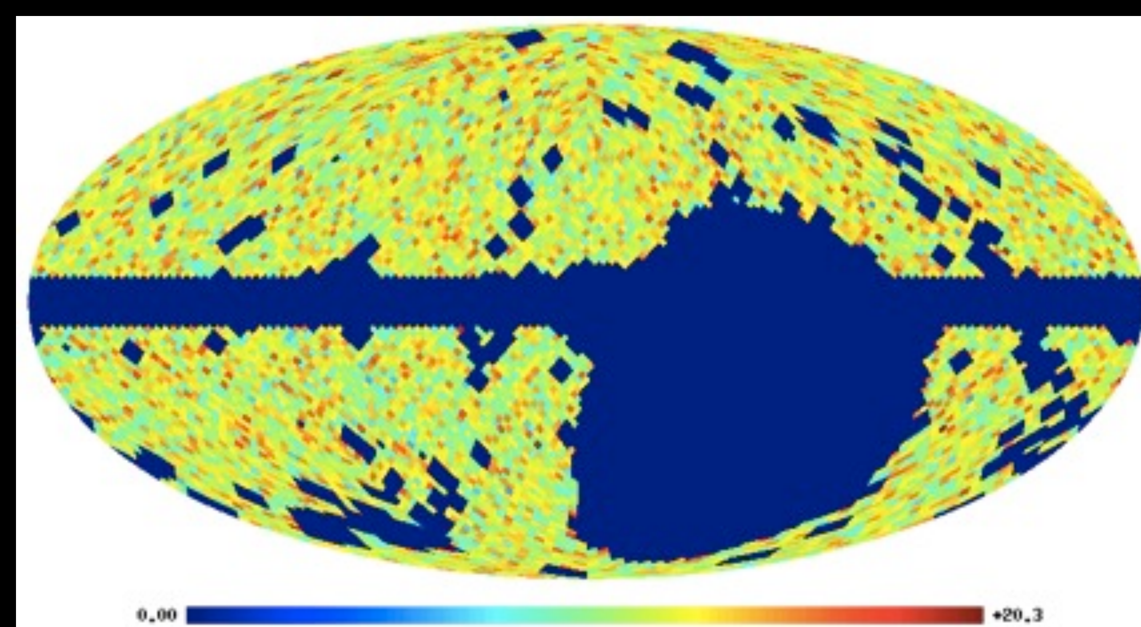
Cosmology at the largest scales

Dominik J. Schwarz
Universität Bielefeld

- principles
- inflation
- CMB
- radio sky
- LOFAR/SKA



Copi et al. 2015



Chen & Schwarz 2015

Heidelberg, October 2015

Physical Cosmology

any physical model/theory requires

1- equations of motion

➜ general relativity & energy/matter content
(or modification of GR)

➜ at large scales just GR (or modification)

2- initial/boundary conditions

for the Universe ➜ ??? (inflation, QG???)

or

extra symmetry principles to avoid initial/boundary data

➜ cosmological principle(s) !!!

Cosmological principle(s)

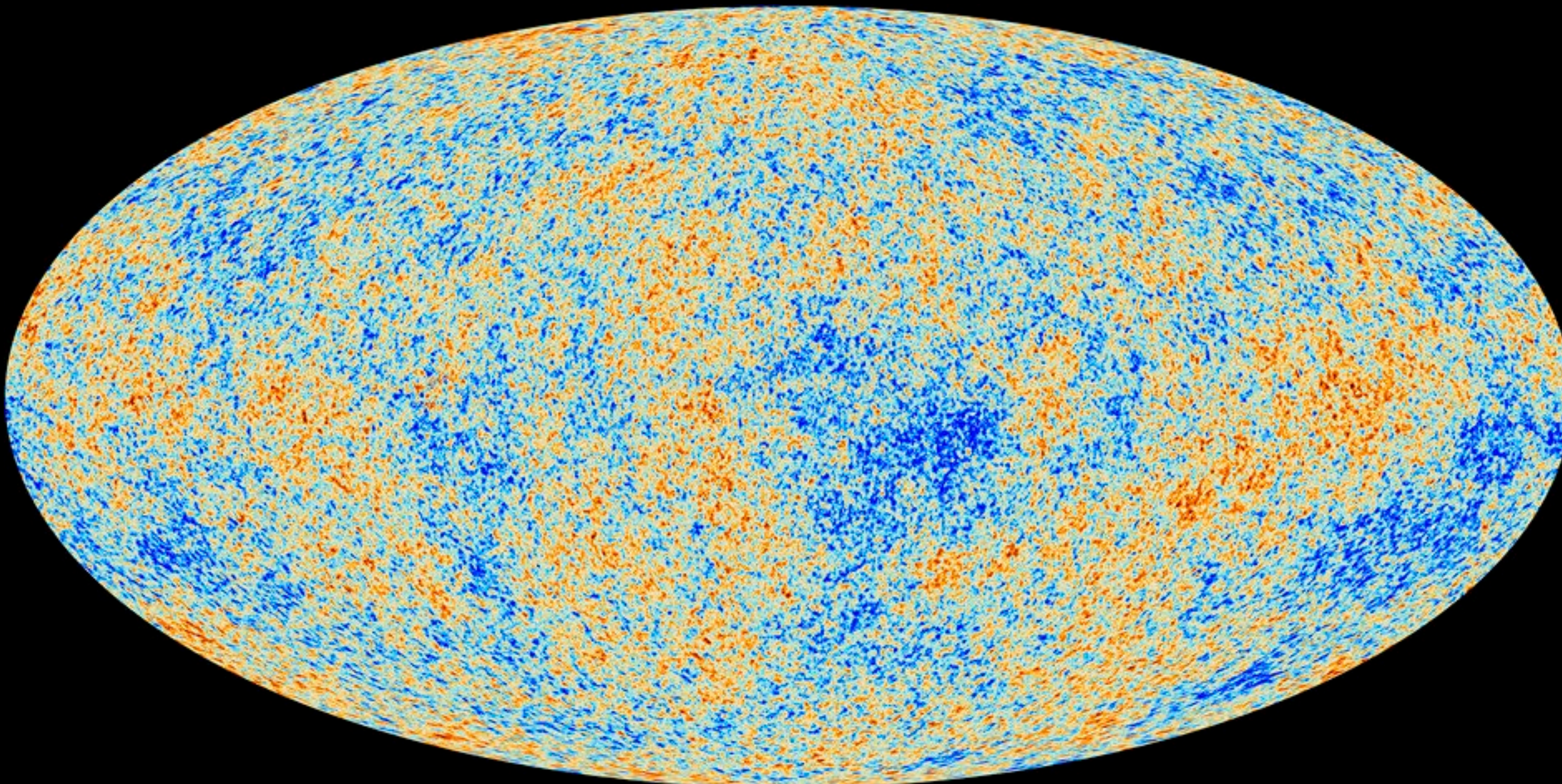
Exact: The Universe is spatially isotropic and homogeneous.

ruled out by the fact that we see cosmic structures, reasonable 1st approximation

Statistical: The distribution of mass and light in the Universe is statistically isotropic and homogeneous.

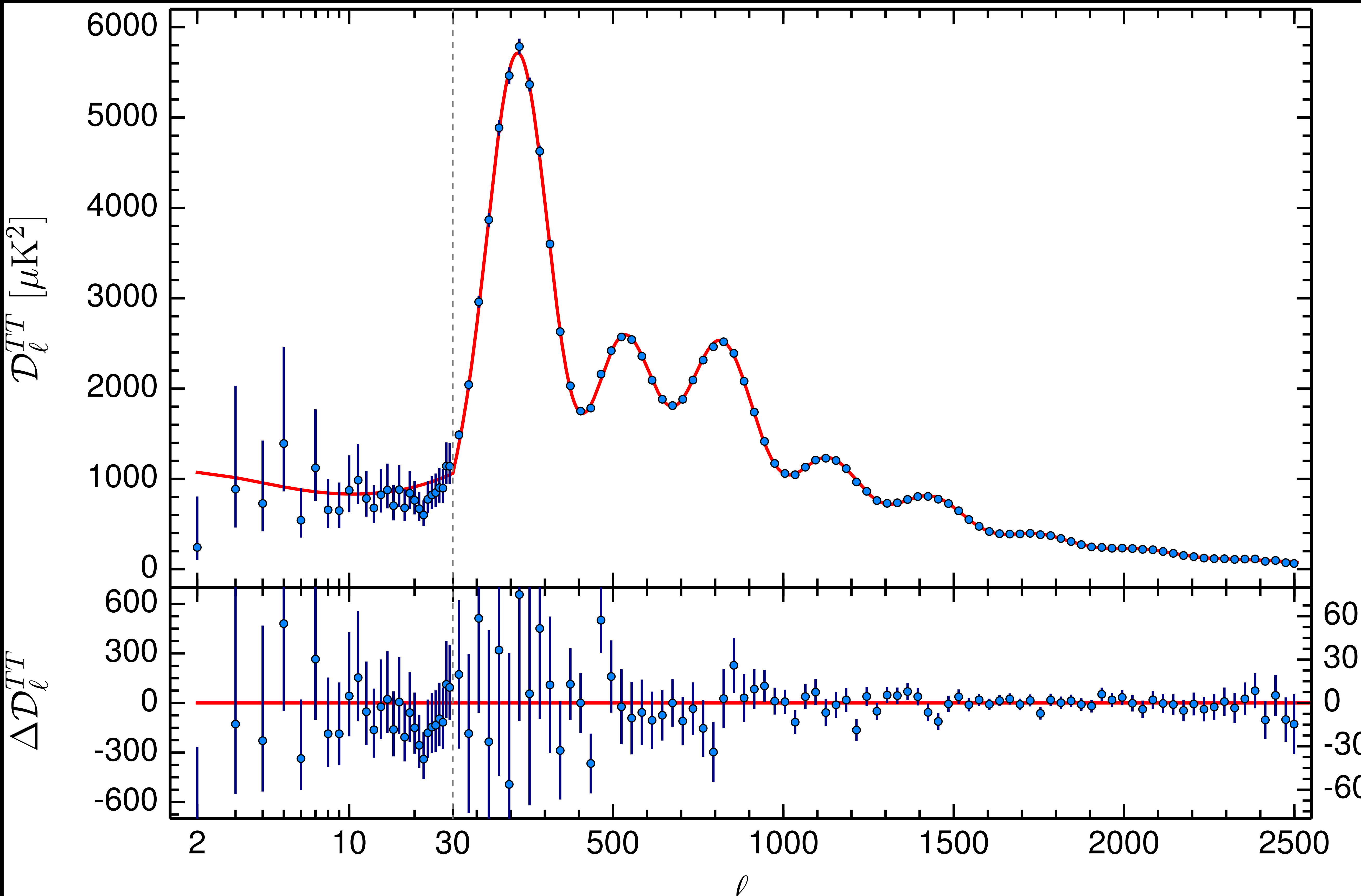
➜ TEST the statistical cosmological principle

Cosmic microwave sky



z ~ 1100

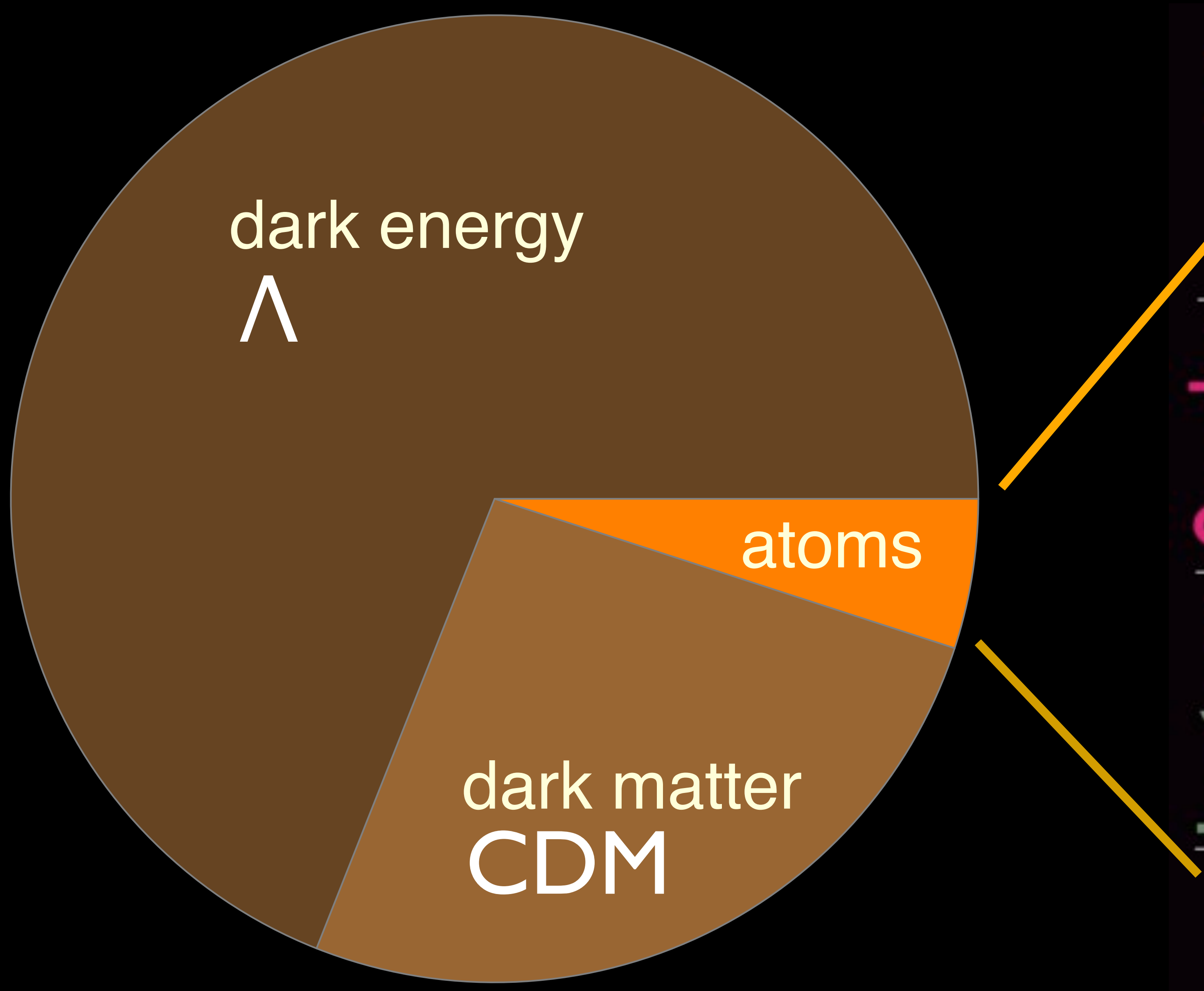
Planck - ESA

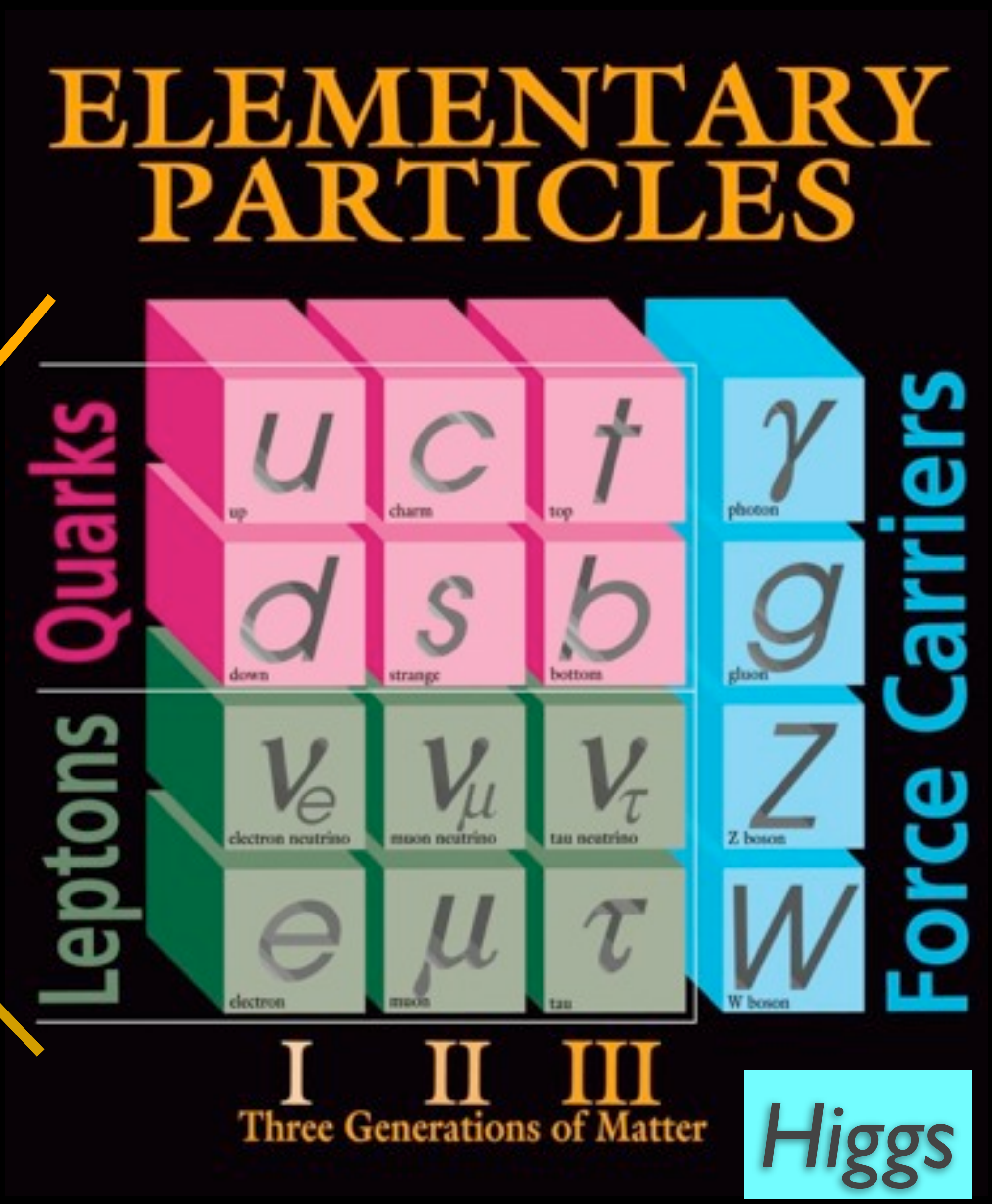


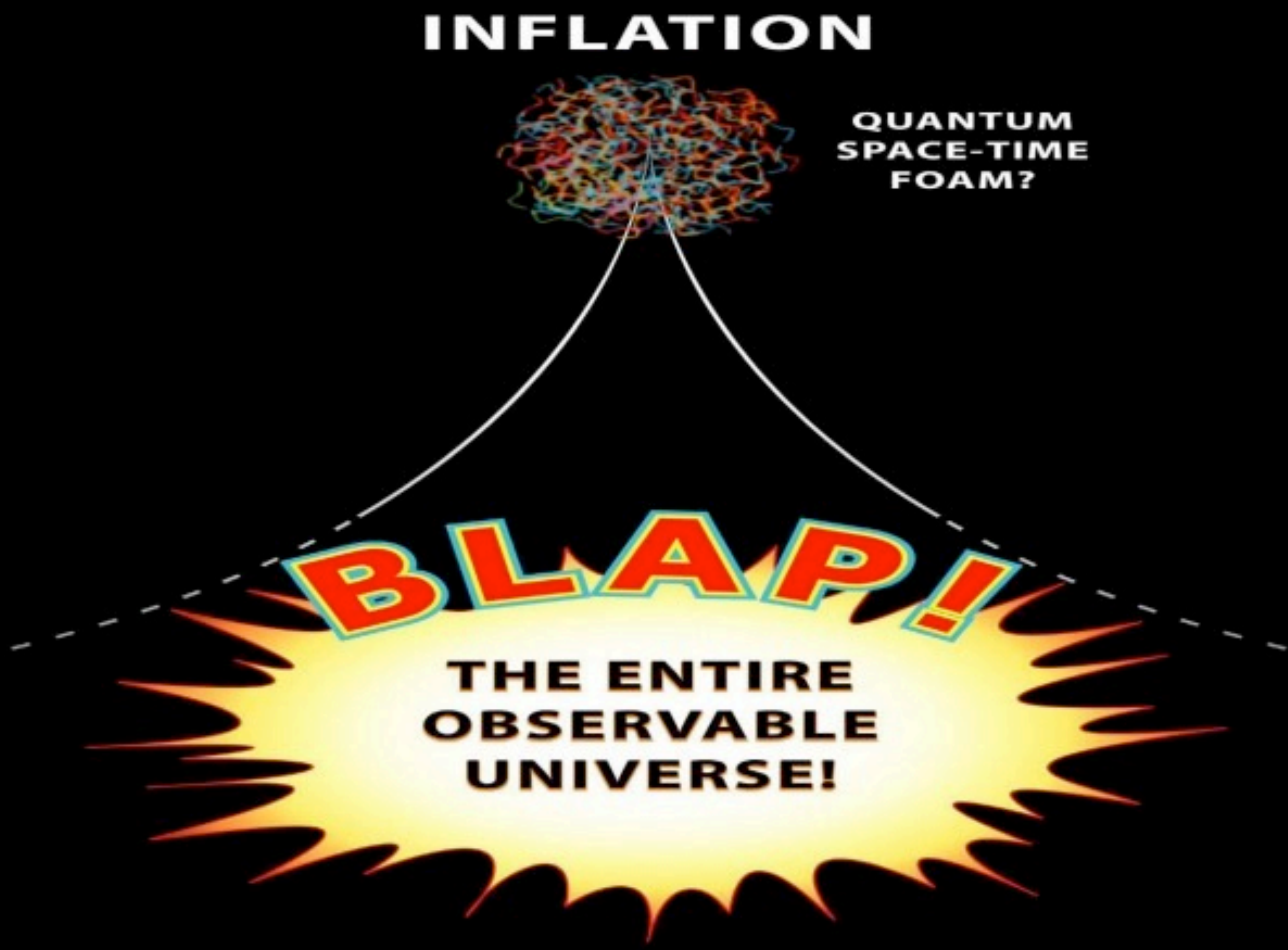
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell^{TT}$ [μK^2]
600
300
0
-300
-600
$\Delta\mathcal{D}_\ell^{TT}$
60
30
0
-30
-60
2
10
30
500
1000
1500
2000
2500
ℓ

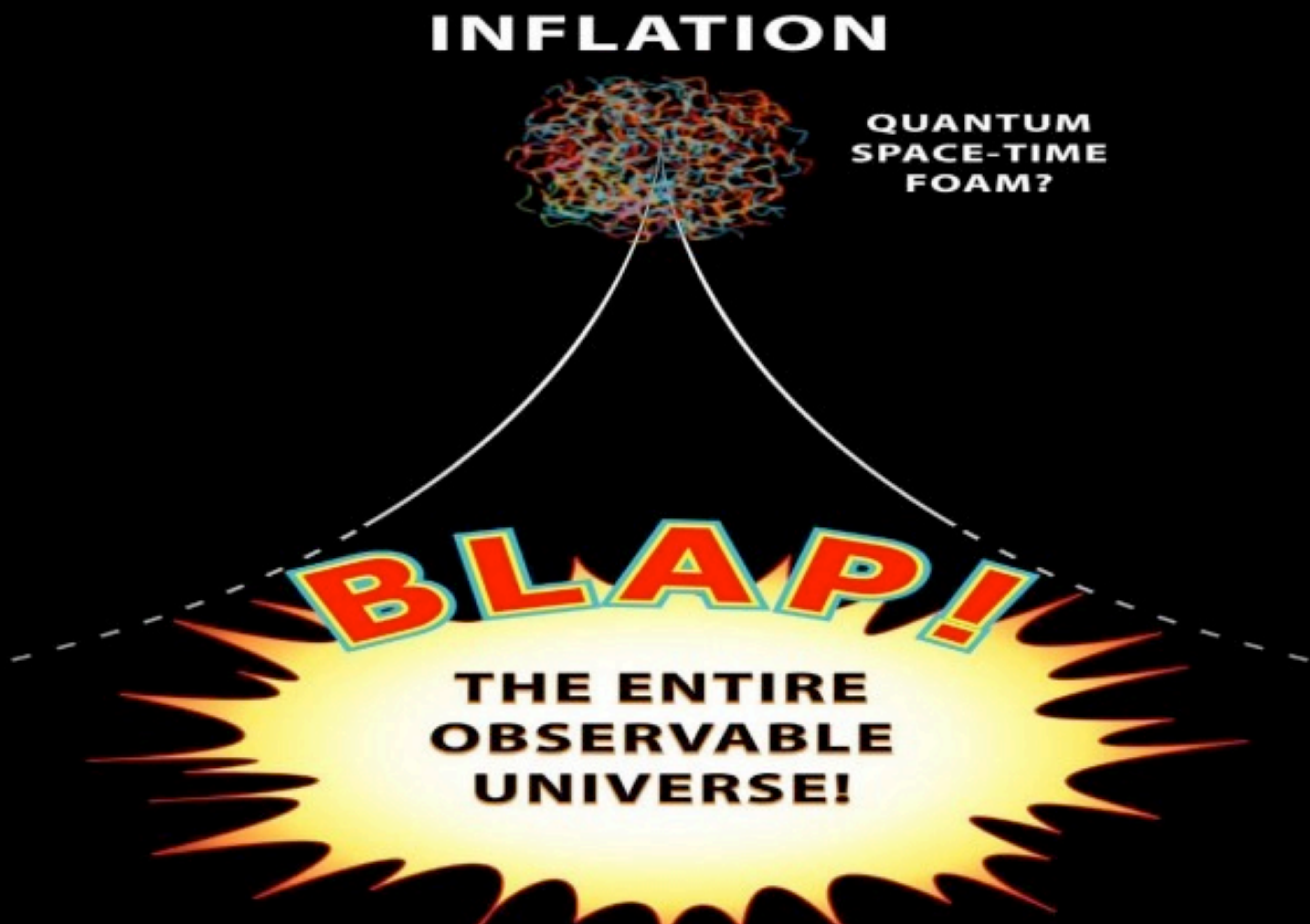
Planck 2015

Composition of the Universe



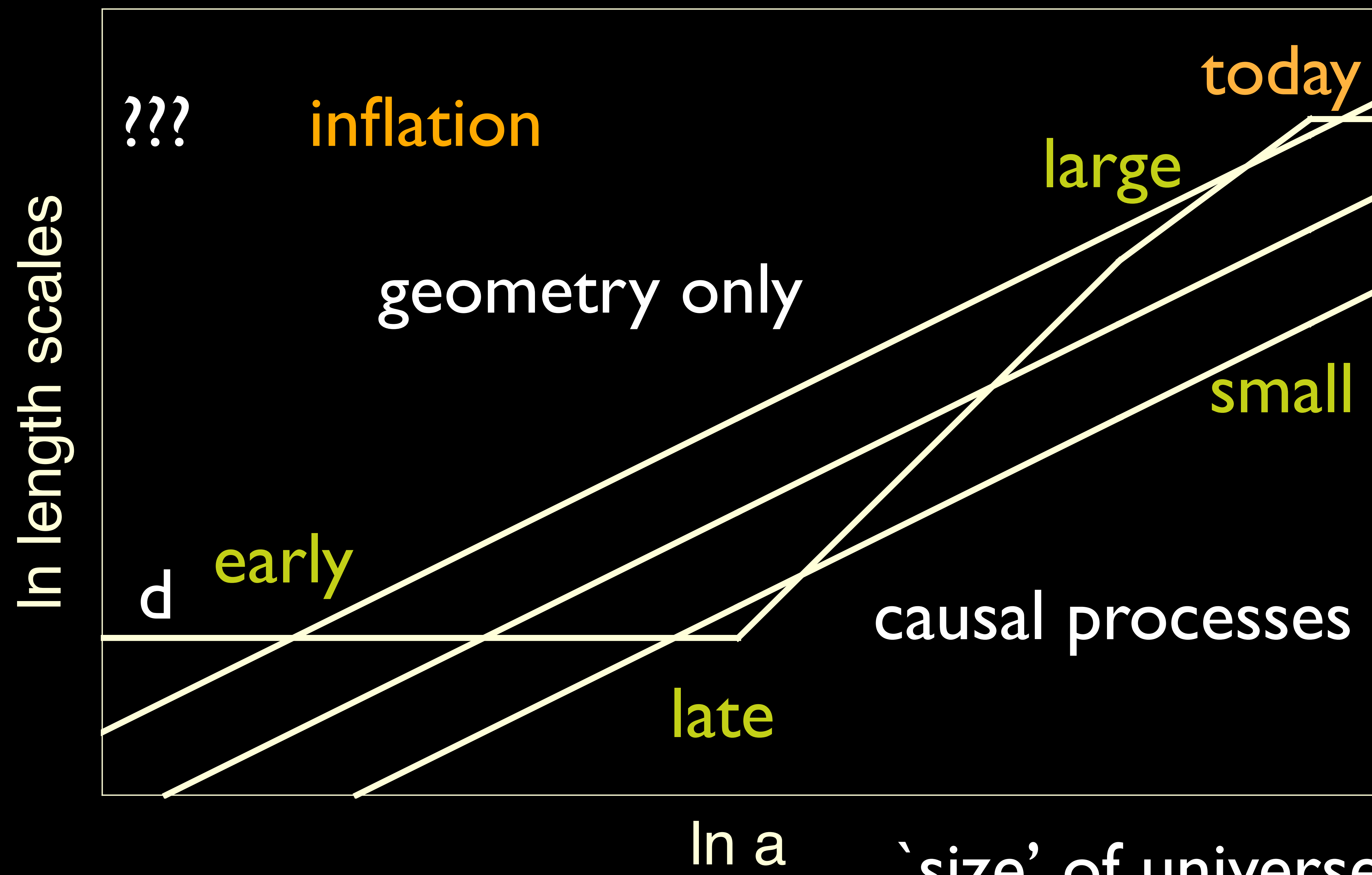



INFLATION
QUANTUM SPACE-TIME FOAM?
BLAP!
THE ENTIRE OBSERVABLE UNIVERSE!



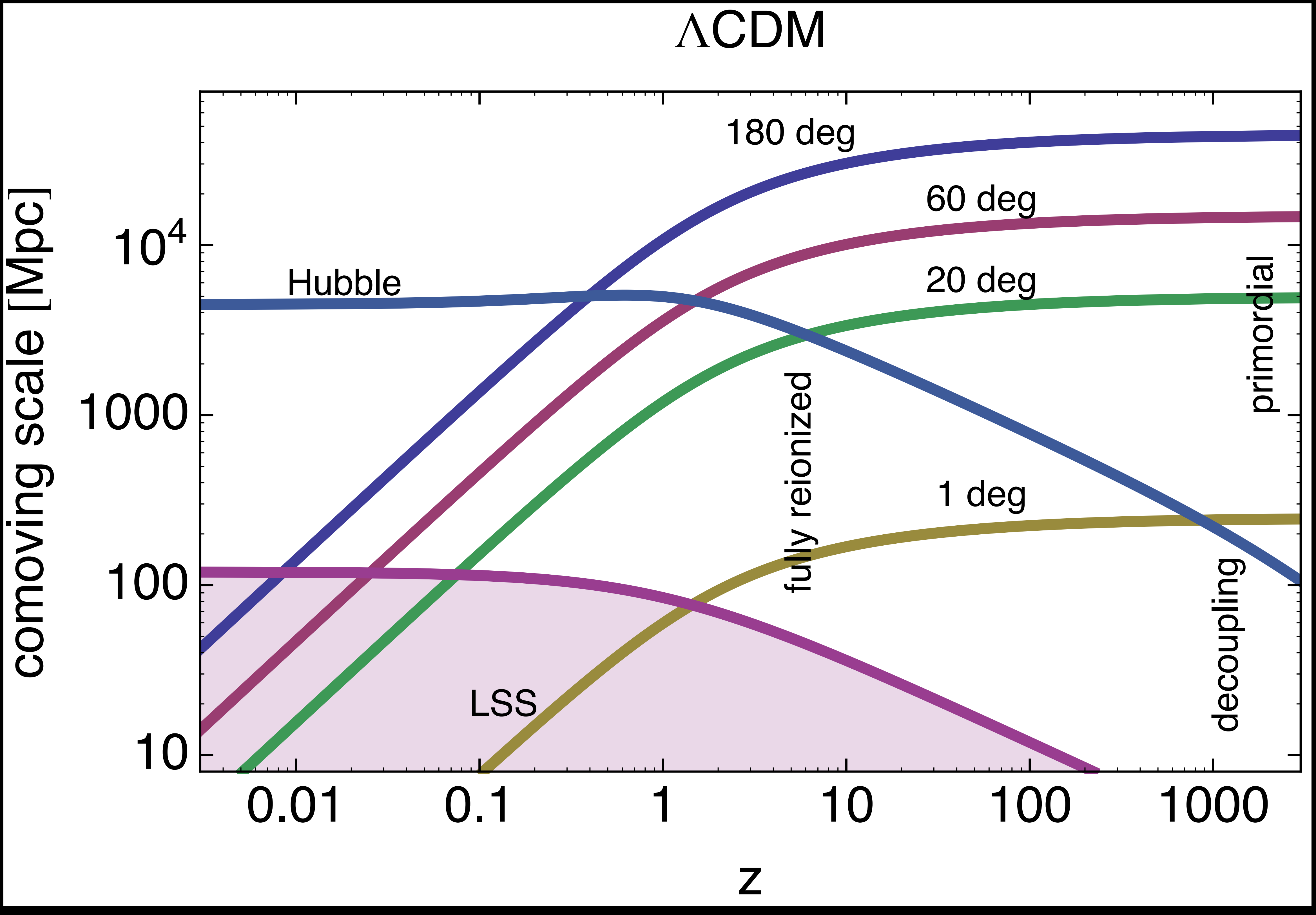
predicts flatness, coherence, ~ scale invariance, Gaussianity
Does it also predict a statistical cosmological principle?

Cosmological Inflation

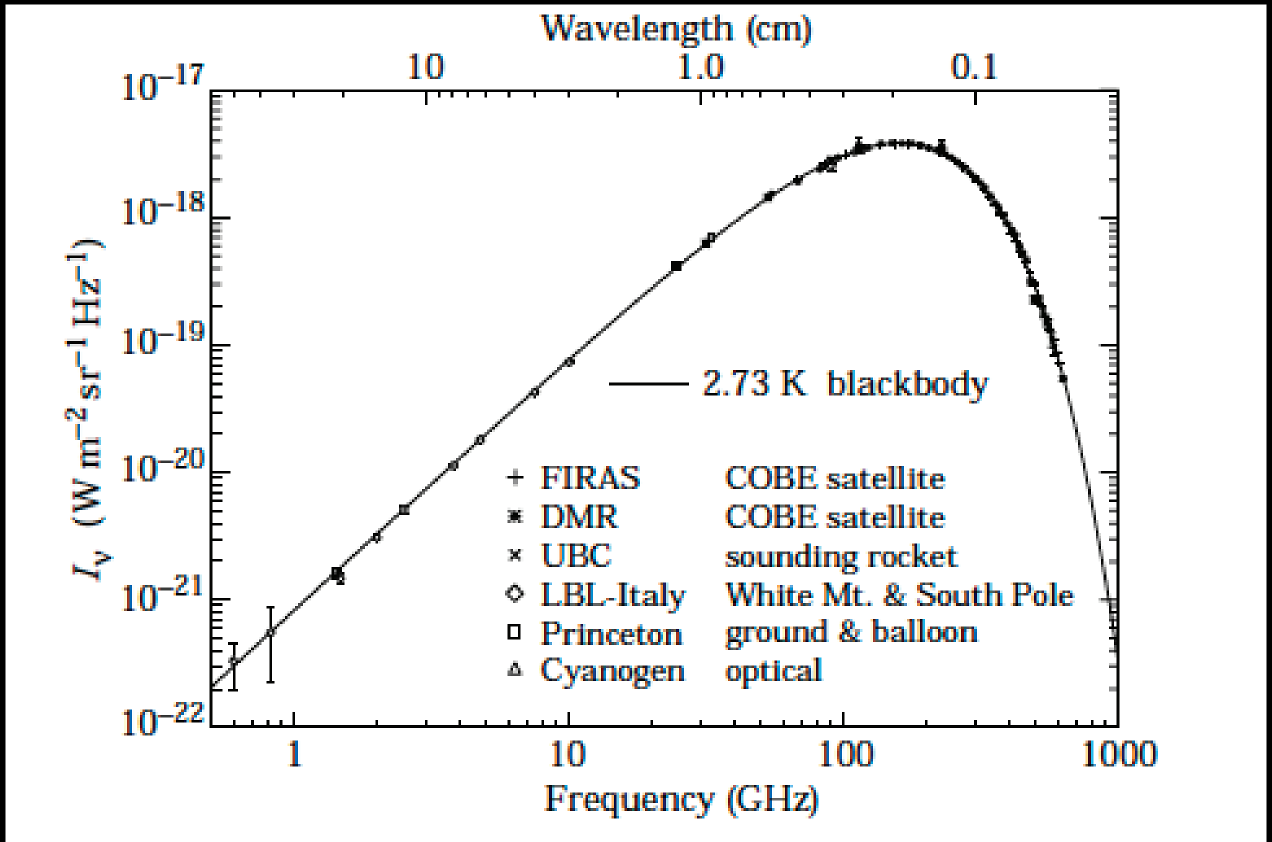


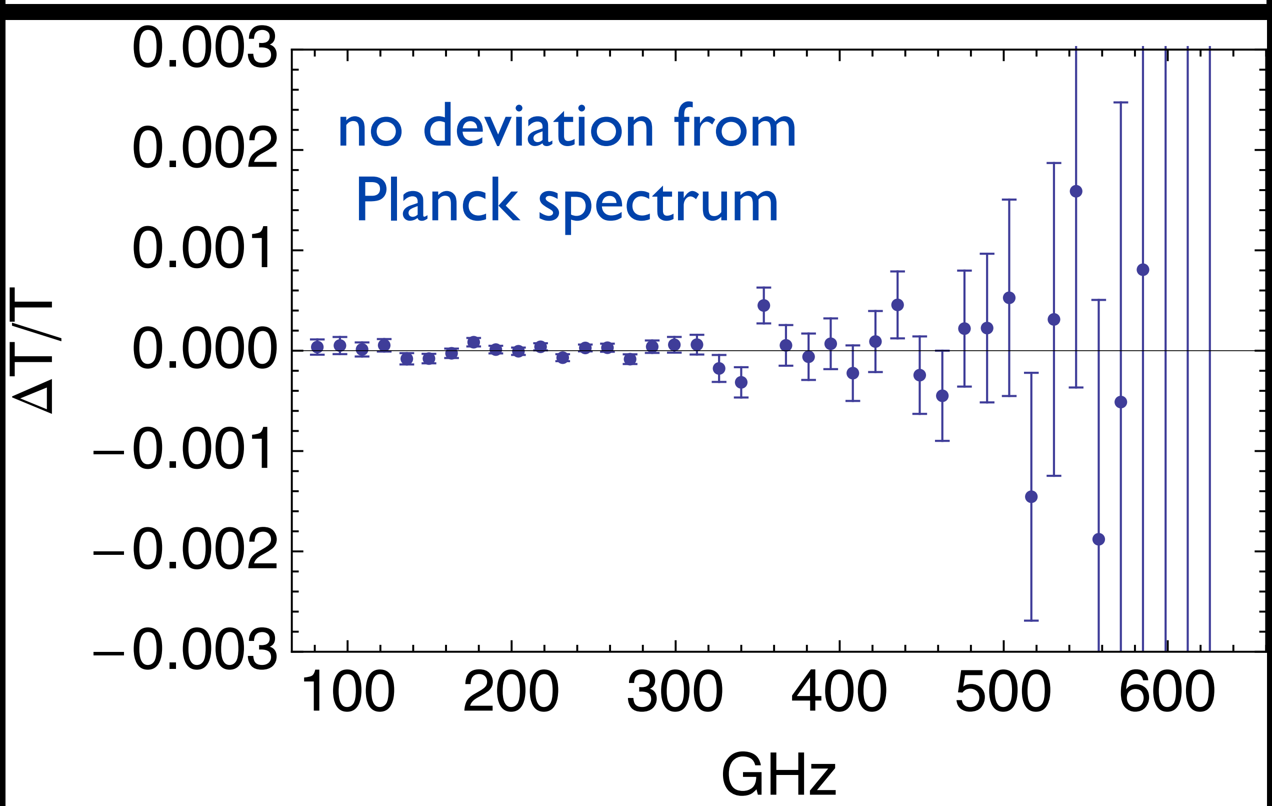
d Hubble distance

Why look at the largest scales?



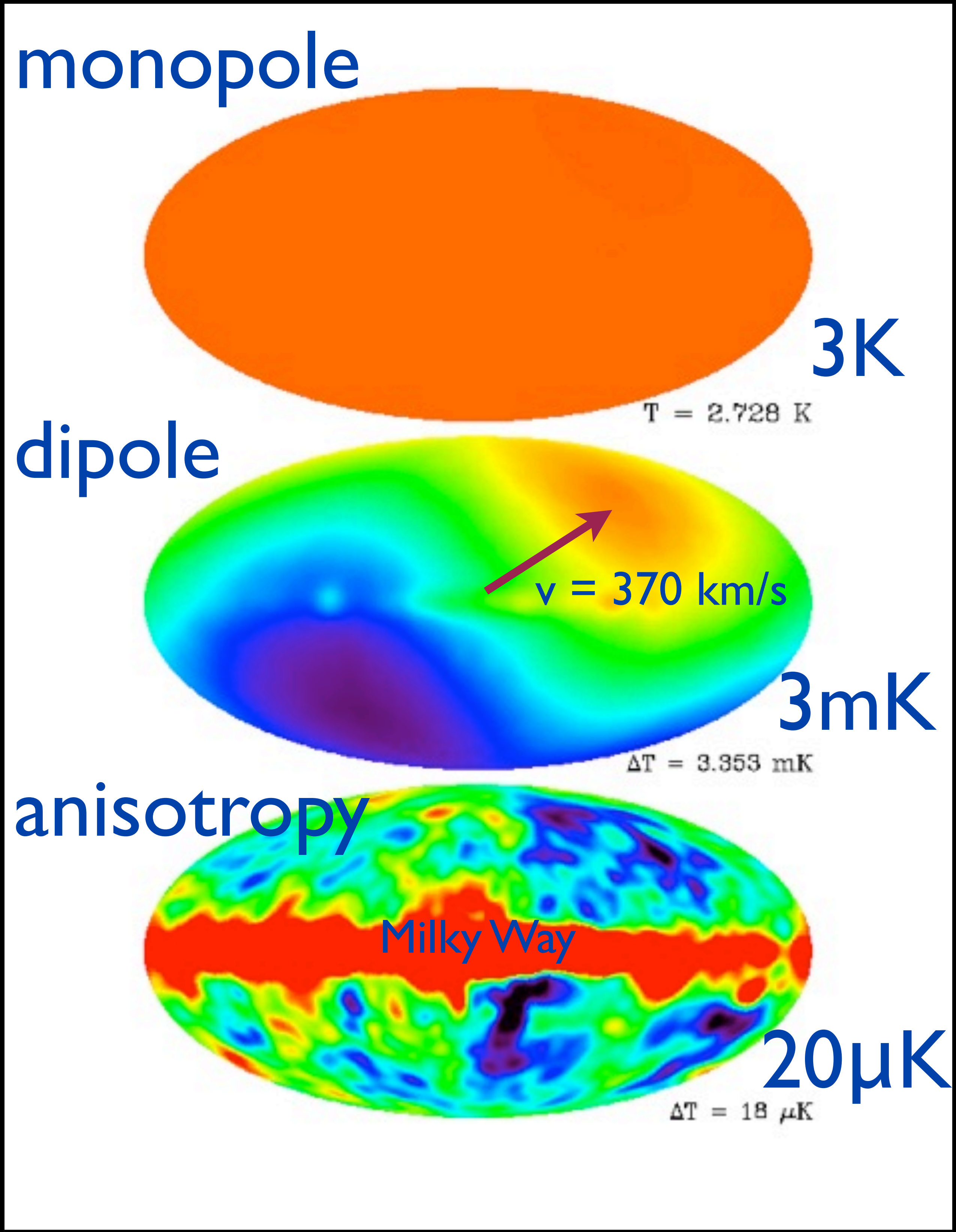
Thermal spectrum





COBE - FIRAS

Temperature anisotropy



COBE - DMR

Is the CMB statistically isotropic?

hypothesis: cmb dipole is due to peculiar motion
$v = (369 \pm 0.9)$ km/s

prediction:

Doppler shift and aberration

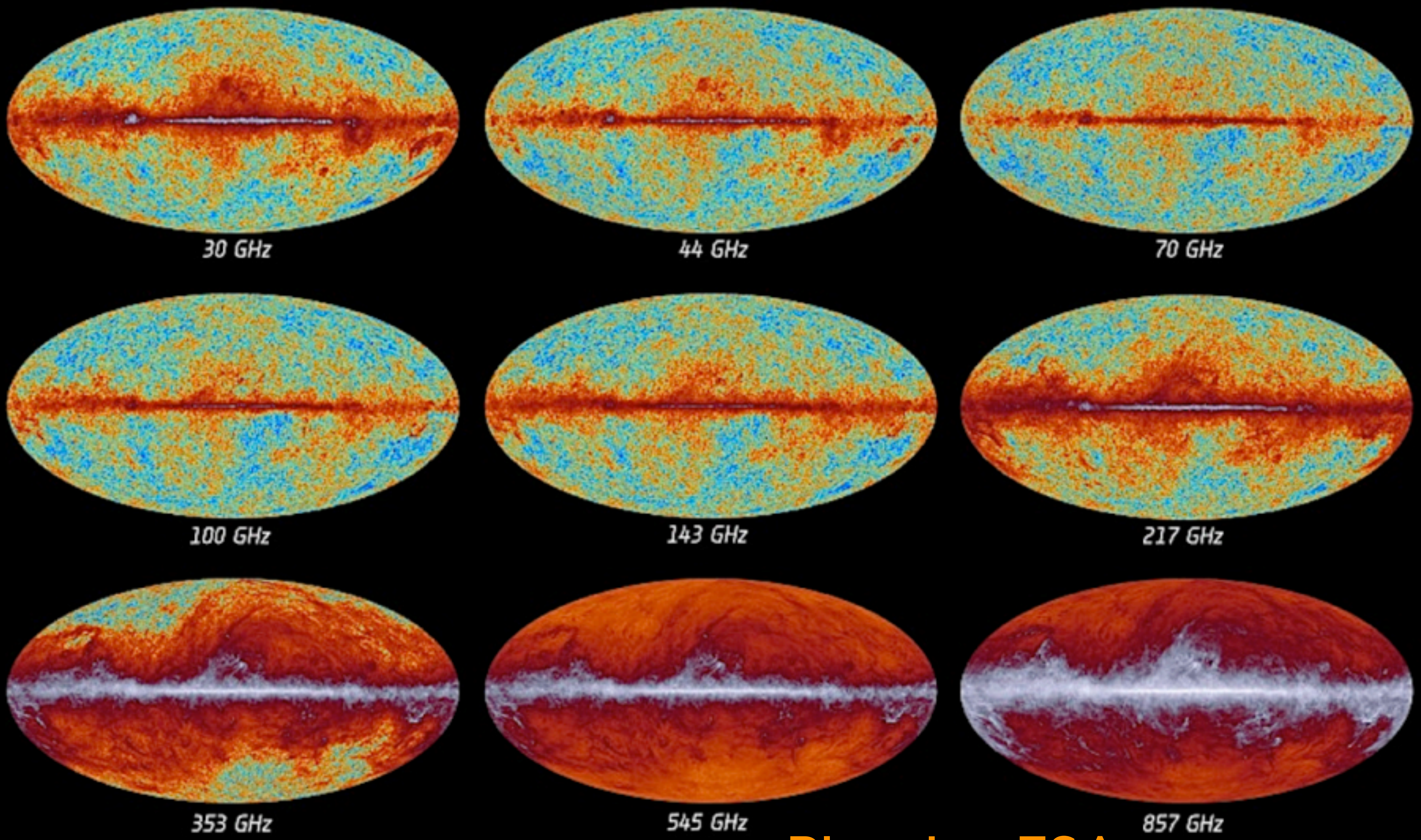
(for all objects at any frequency)

test with high l multipoles in CMB Planck 2013/2015

test with radio sky

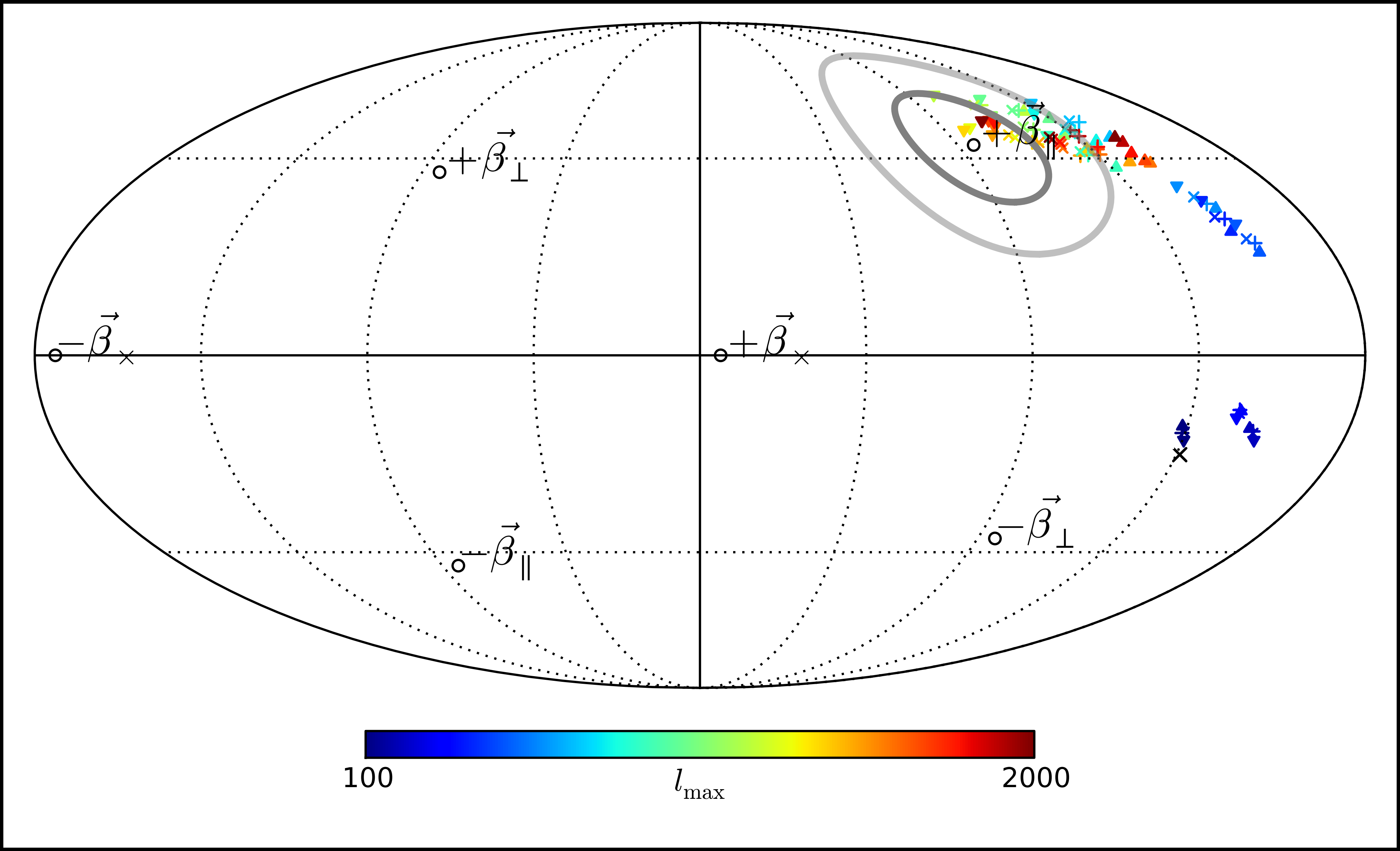
Cosmic Microwaves

frequency bands



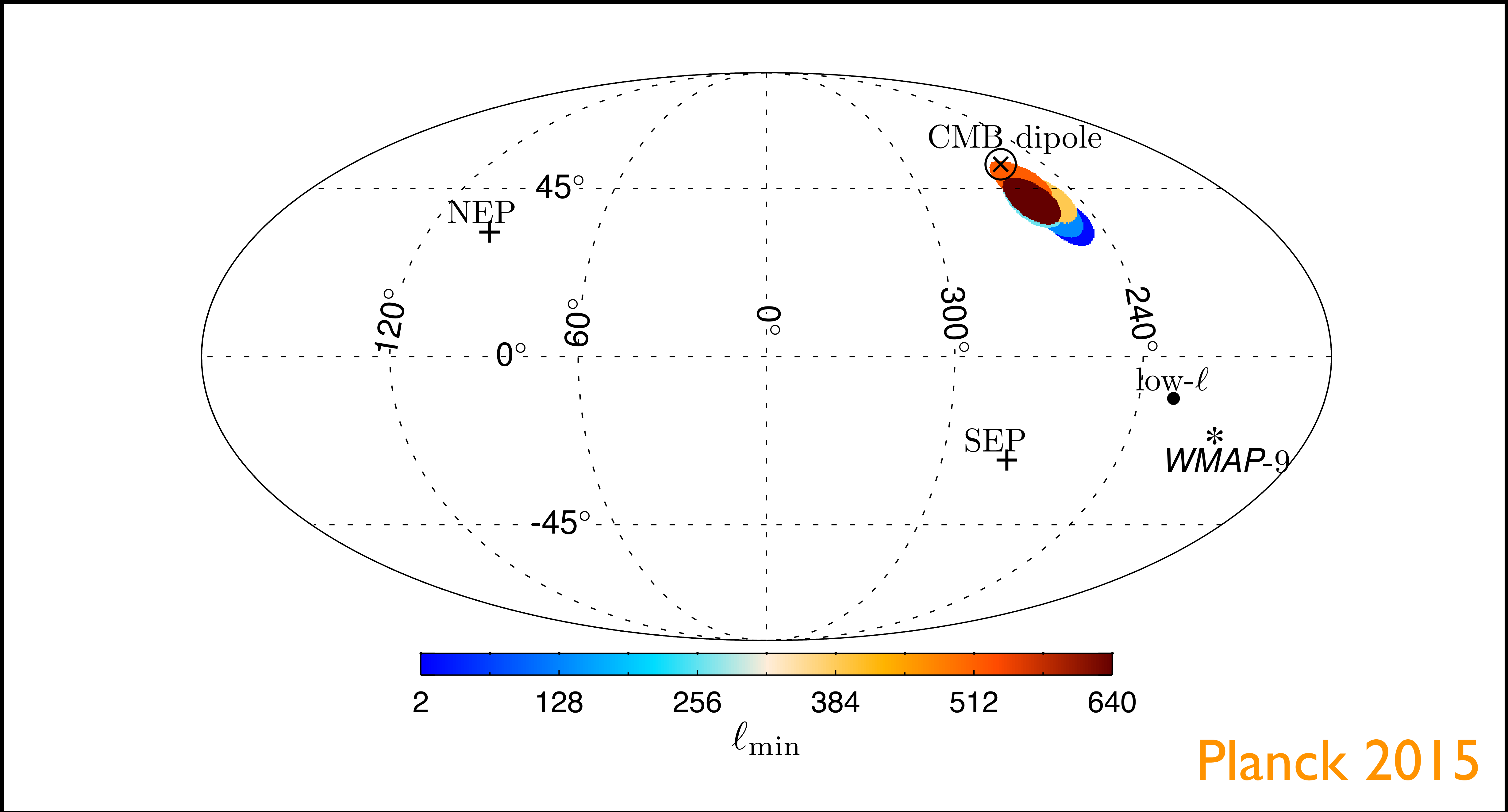
Planck - ESA

Kinetic CMB dipole



v = 384 km/s ± 78 km/s (stat.) ± 115 km/s (sys.) Planck 2013

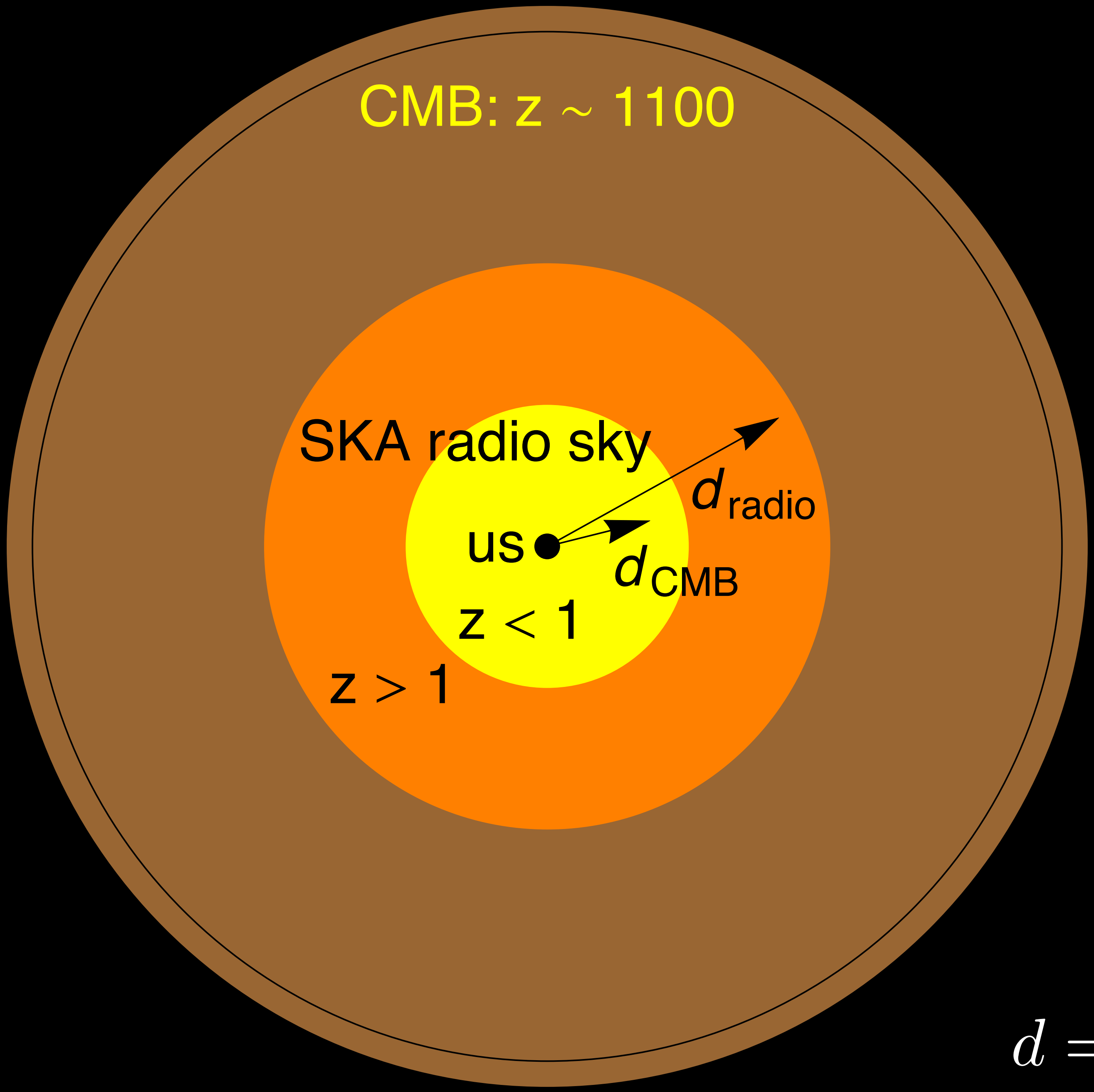
CMB proper motion test



Bipolar Spherical Harmonics

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

Cosmic radio dipole



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

kinetic dipole

Ellis & Baldwin 1984

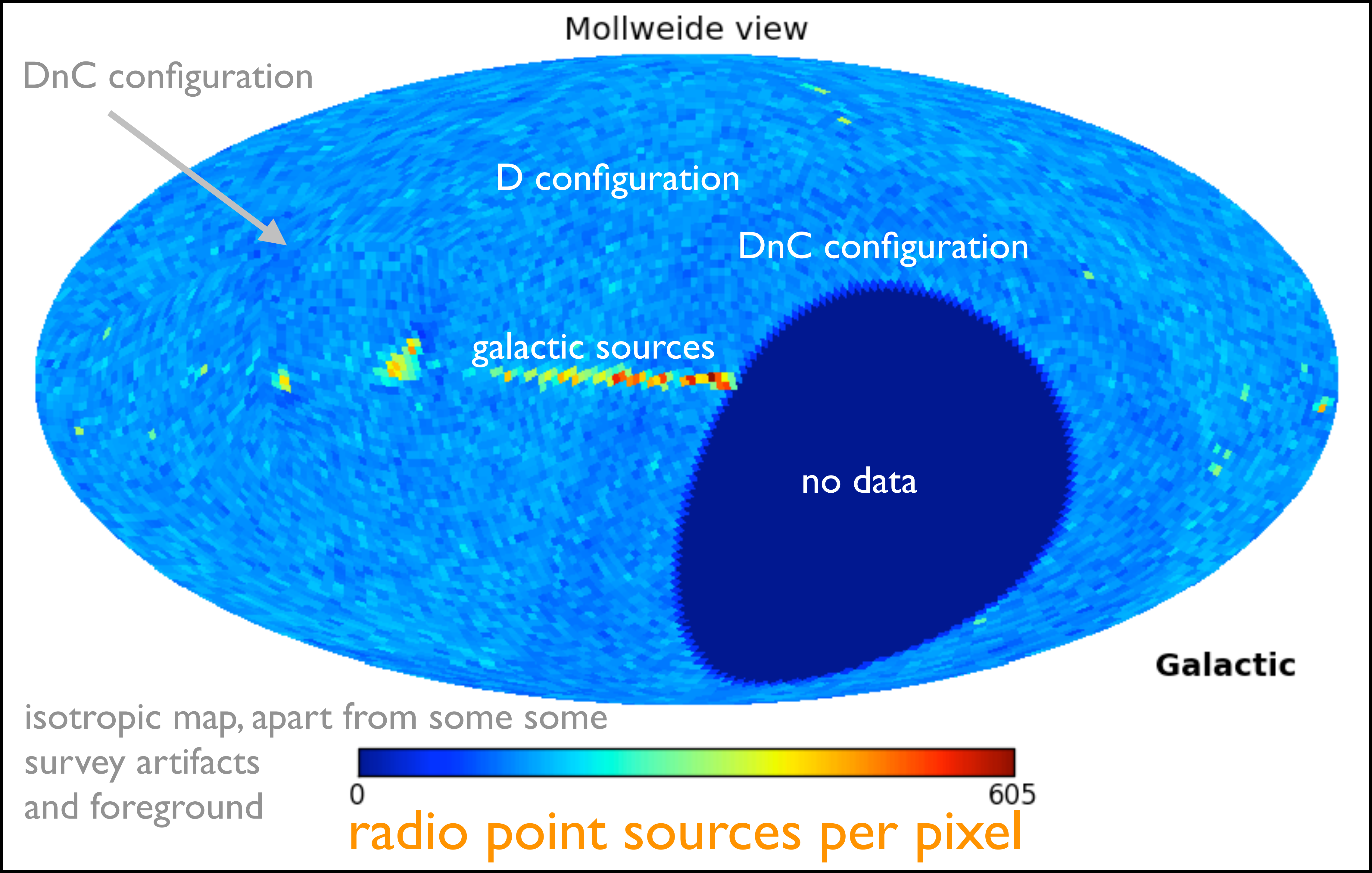
mean z of radio galaxy catalogues > 1, unlike for optical or IR galaxies

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

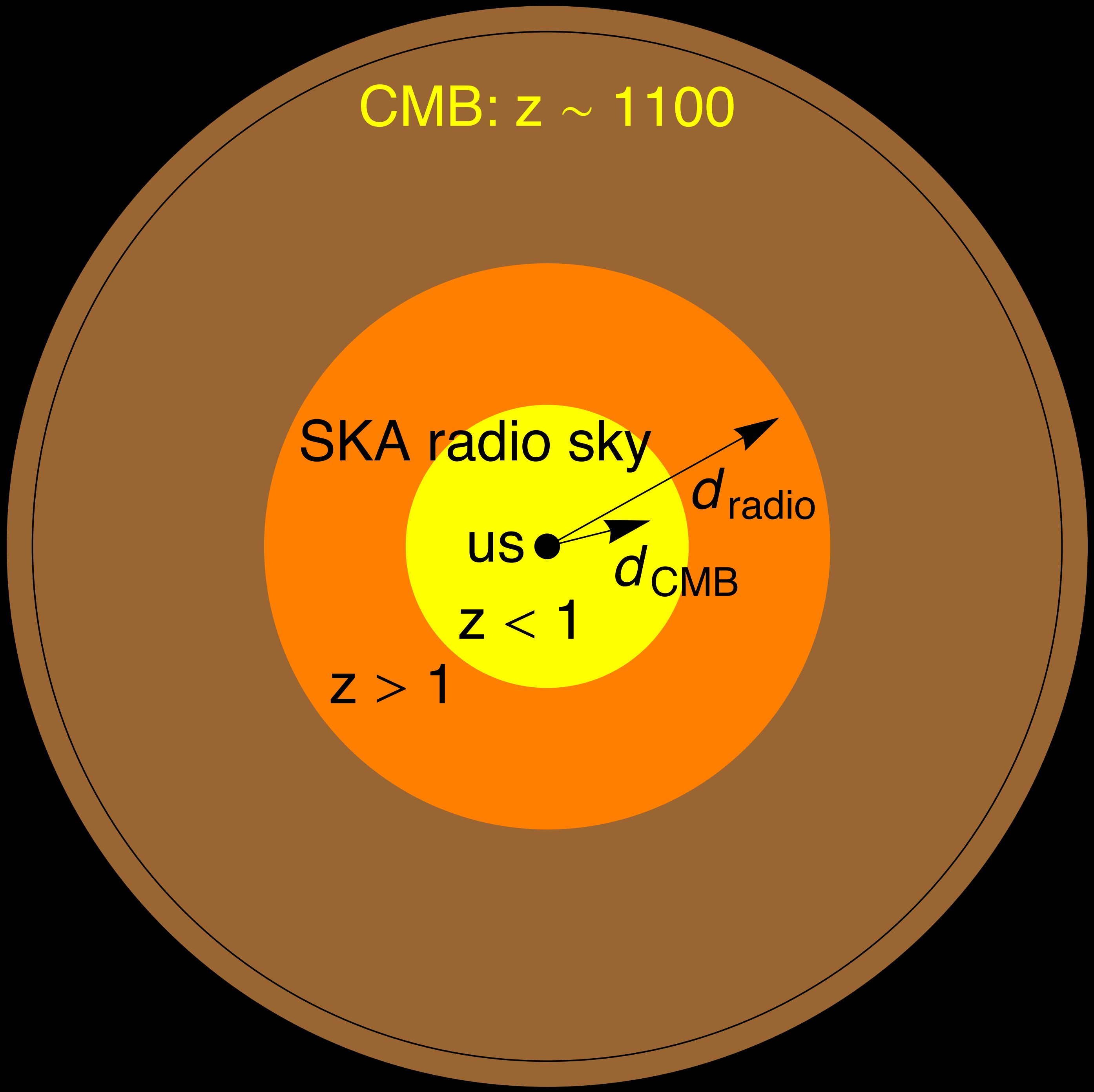
$$d = [2 + x(\alpha + 1)]\frac{v}{c}, \quad S \propto \nu^{-\alpha}$$

(Jansky) Very Large Array, NRAO

Isotropic radio sky (NVSS)



Cosmic radio dipole



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

NVSS (1.4 GHz) & WENSS (345 MHz): directions consistent, amplitude 2 - 4 times too large

Blake & Wall 2002
Rubart & Schwarz 2013

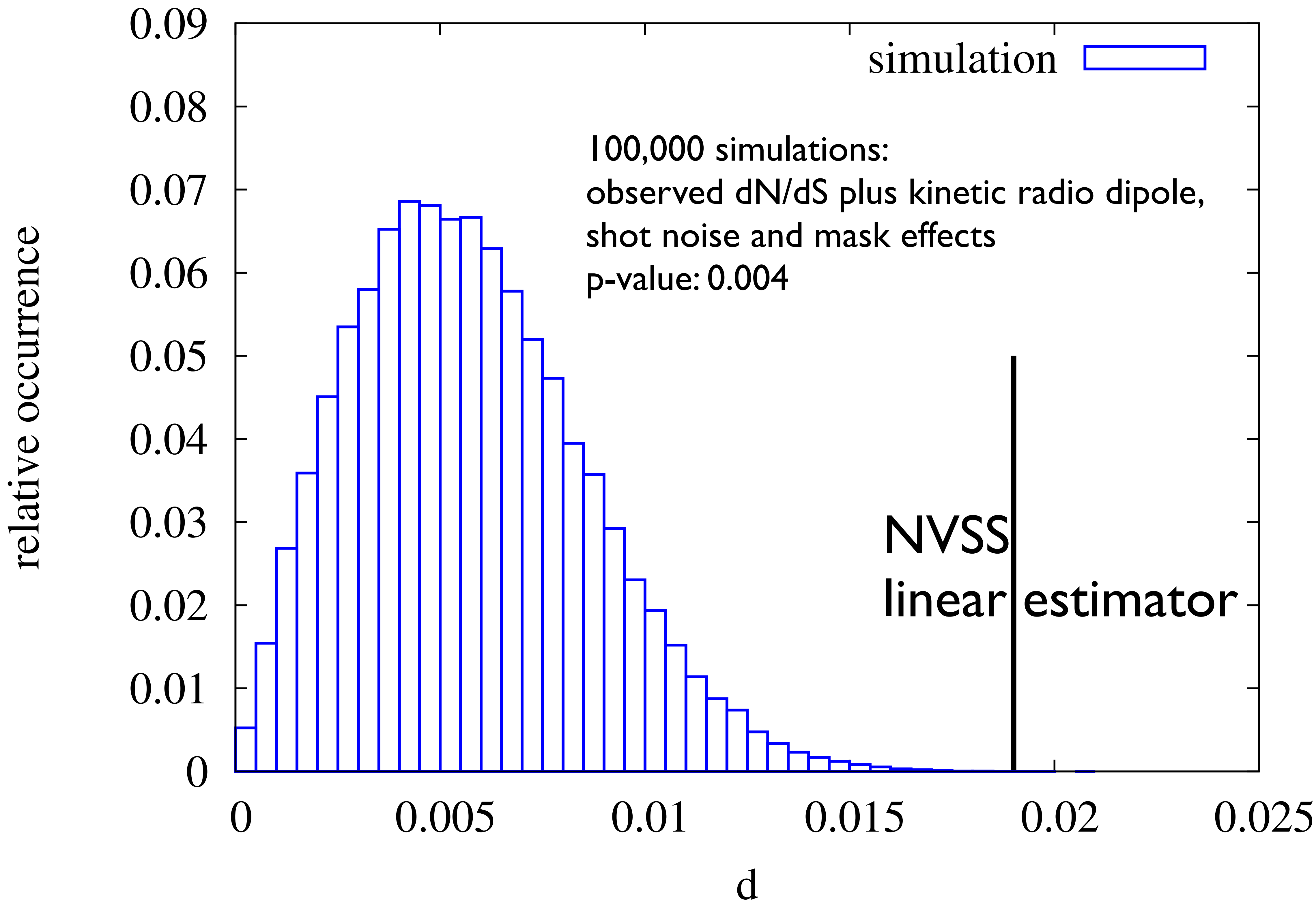
bulk flows?

Watkins & Feldman 2014
Atrio-Barandela et al. 2014

local structure dipole?

Rubart, Bacon & Schwarz 2014

Statistical significance



Rubart & Schwarz 2013

Is the CMB statistically isotropic?

hypothesis: cmb dipole is due to peculiar motion

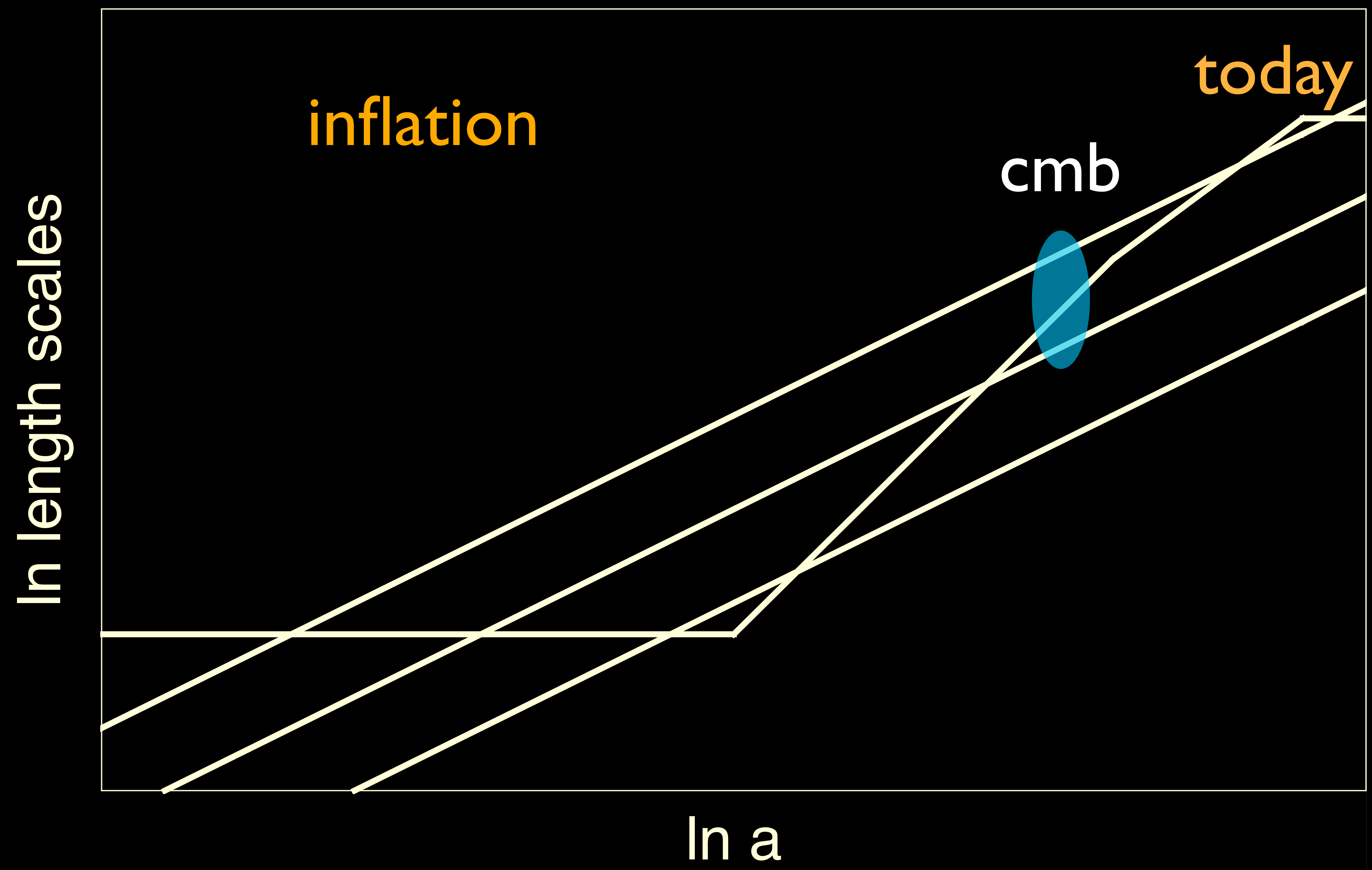
preliminary conclusion from
CMB high l and radio sky:

hypothesis is ok, but cmb dipole may include structure dipole of comparable order of magnitude

warning: systematic issues with radio surveys

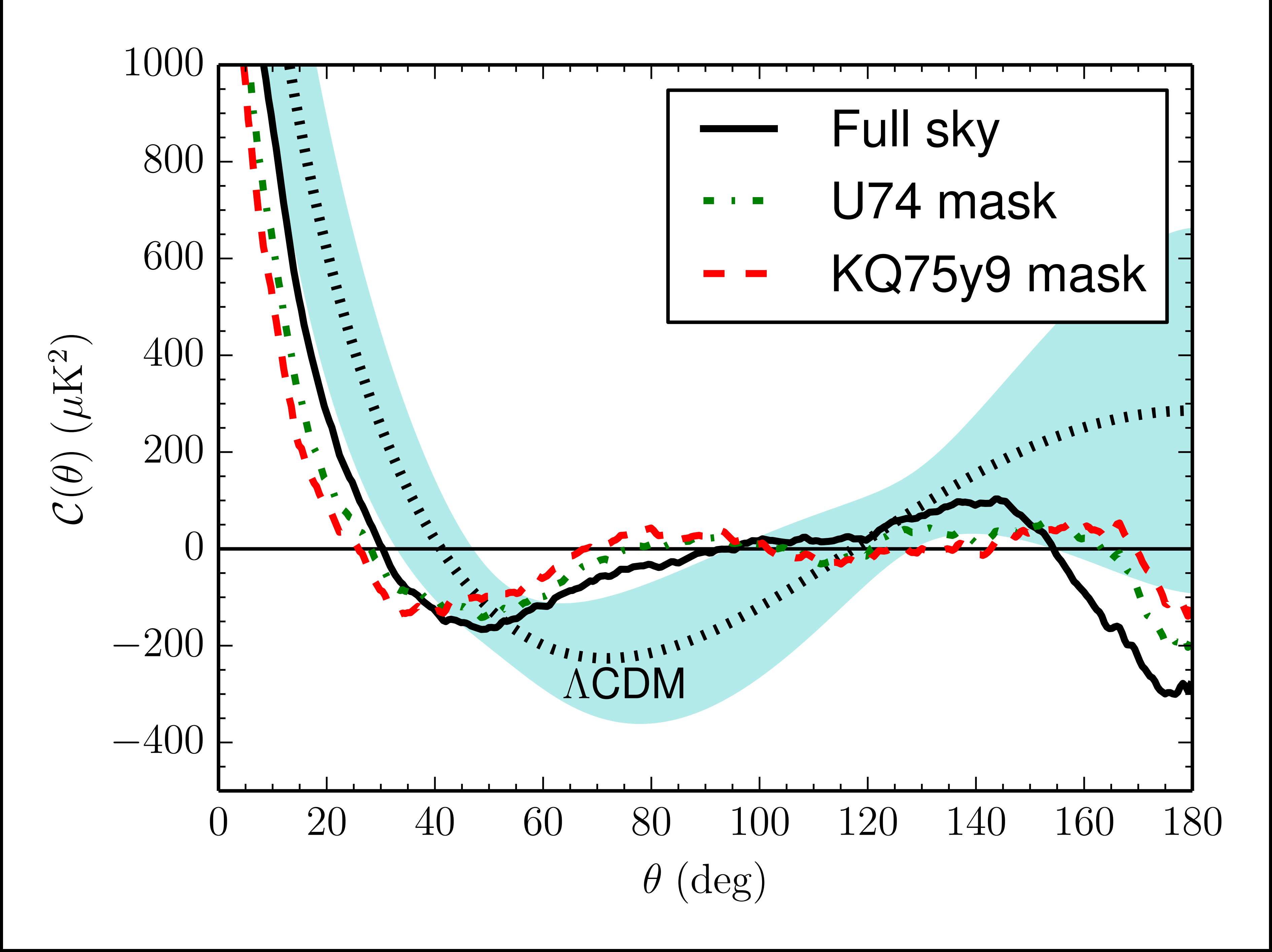
study CMB multipoles $l > 1$

Cosmological Inflation



CMB anomalies (WMAP & Planck)

lack of angular correlation at > 60 degrees

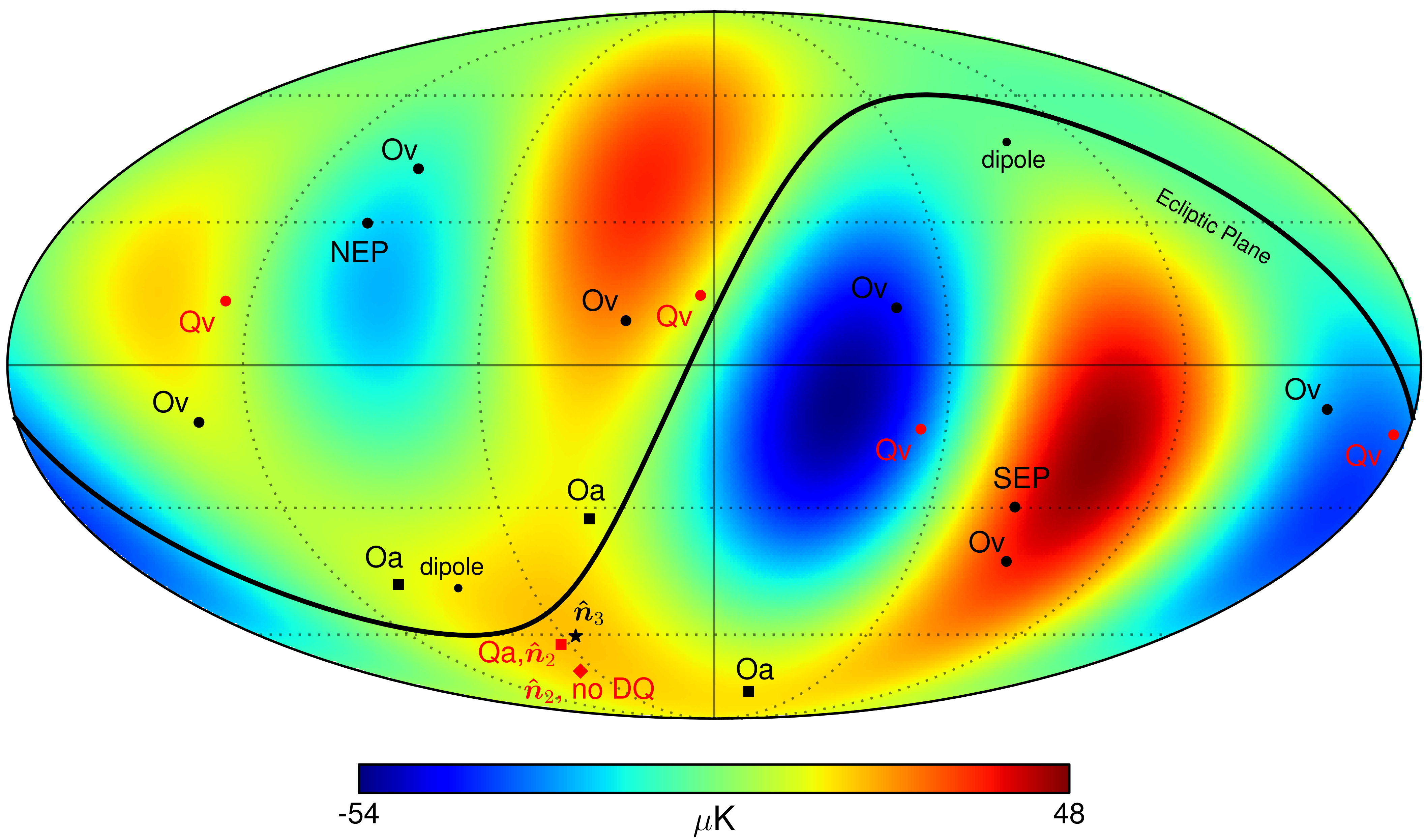


violation of scale invariance and isotropy

Copi et al. 2015

CMB anomalies (WMAP & Planck)

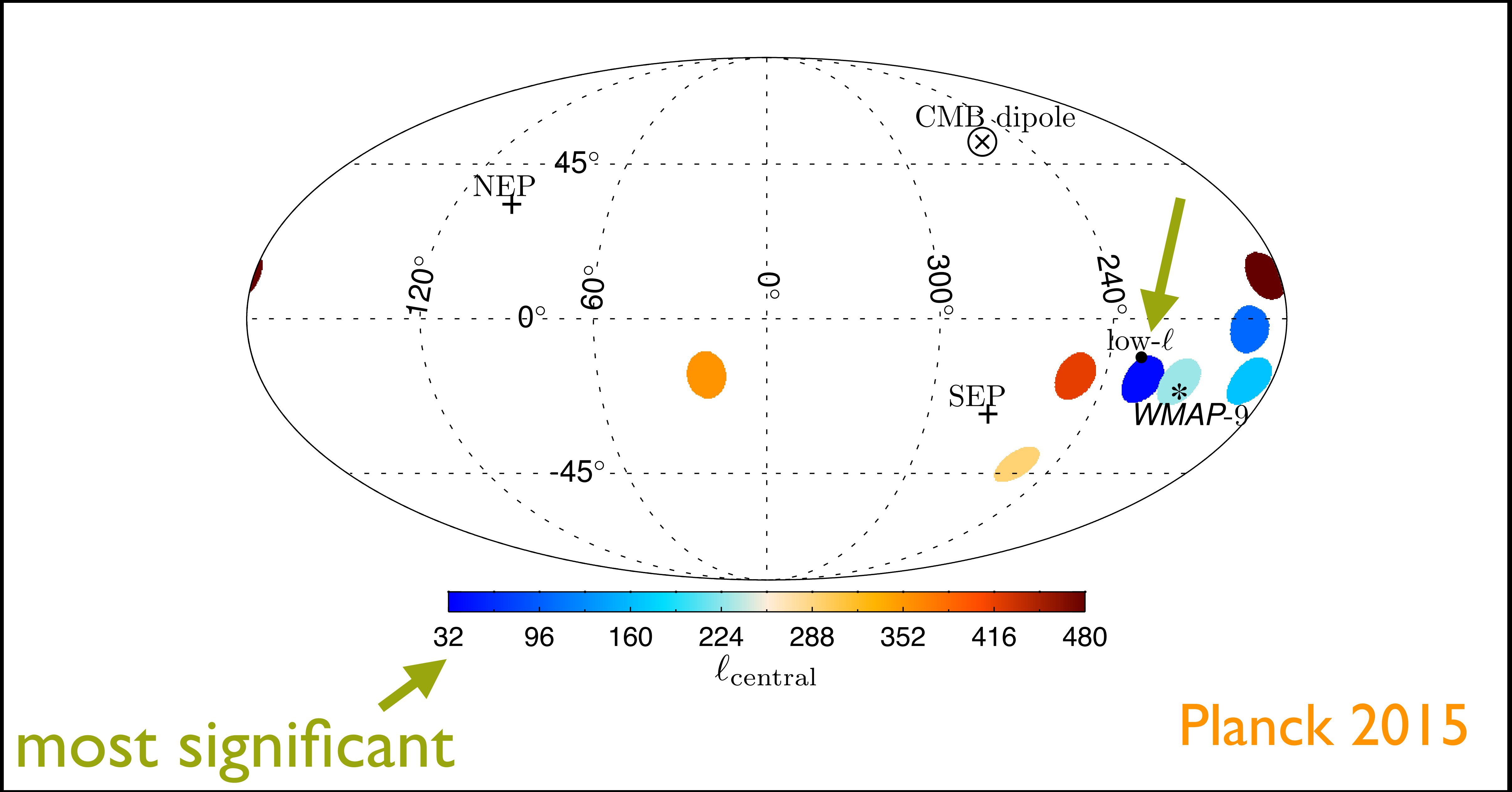
alignment of low-l multipoles



Copi et al. 2015

CMB anomalies (WMAP & Planck)

dipolar modulation of CMB angular power



ideas: cosmic structure, anisotropic cosmology, foreground, ...

CMB anomalies (WMAP & Planck)

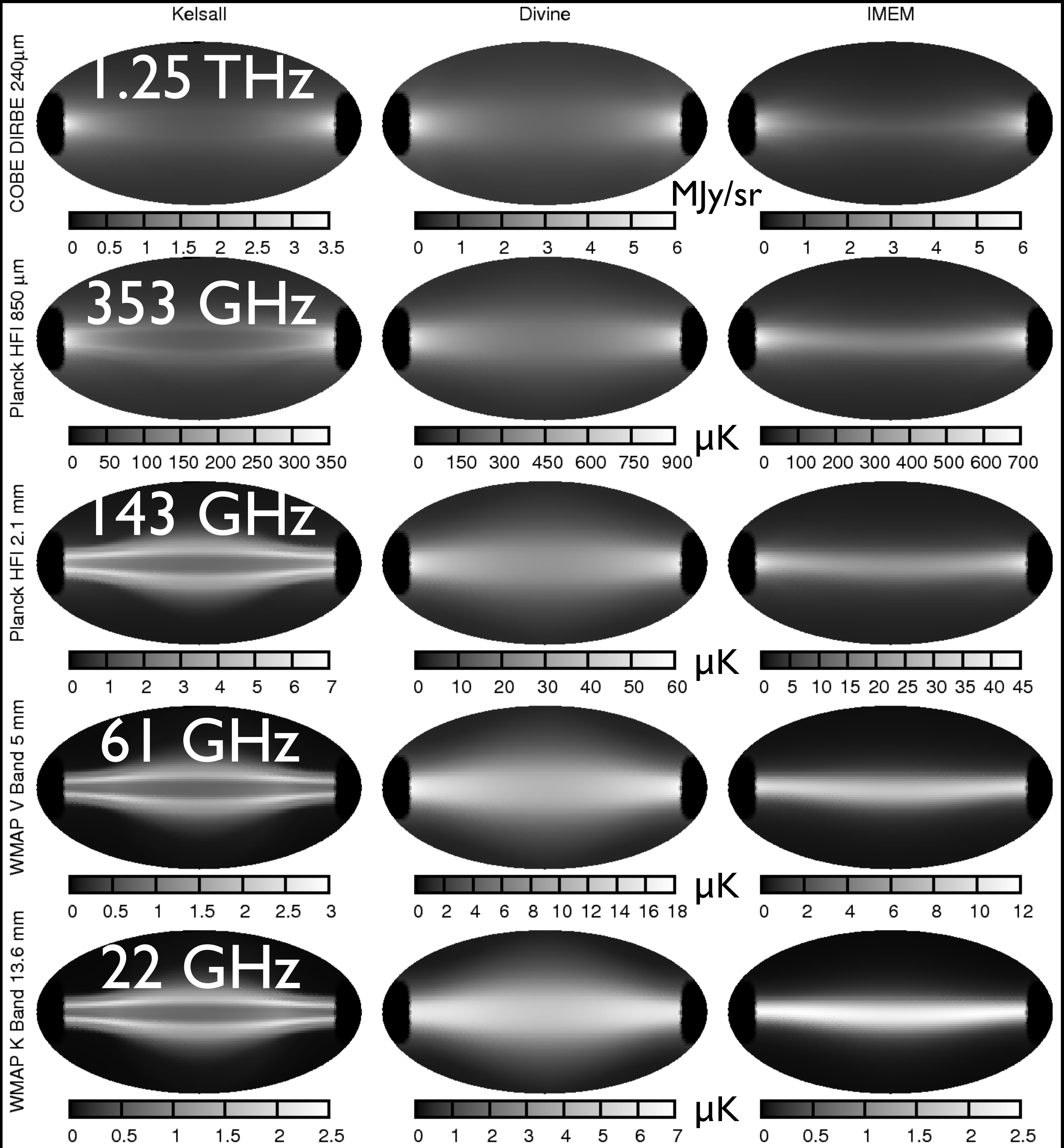
- low variance
- low 2-pt correlation
- low-l alignments
- parity asymmetry
- dipolar power modulation, extending to higher l
- cold spot

all indicate a violation of statistical isotropy at ~ 3 σ

BUT no indication for non-Gaussianity or curvature

CQG special Planck issue: Schwarz et al. 2015

Solar System dust



Planck uses Kelsall model based on COBE DIRBE, no dust dynamics

Divine model based on meteorite size and flux measurements, dust dynamics

IMEM model based on both, used by ESA to predict hazard when launching spacecraft

Dikarev & Schwarz 2015

The largest observable scales

initial conditions:

- isotropy and homogeneity
- curvature
- (almost) scale invariance
- gaussianity

cosmic reference frame:

- kinetic vs. structure dipole

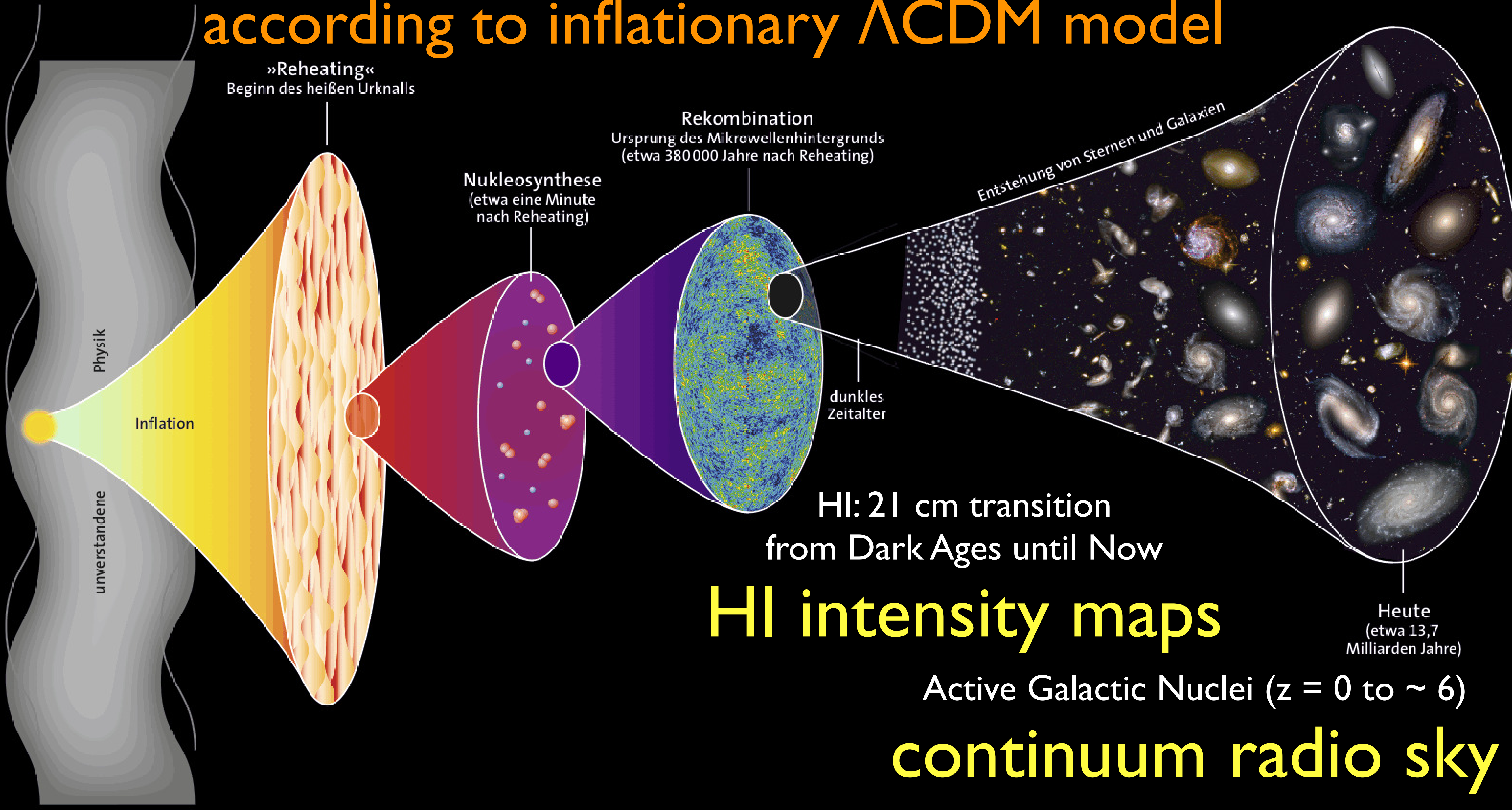
large scale structure:

- linear regime
- relativistic effects
- bias and cosmic variance

WHAT'S NEXT?

Cosmic History

according to inflationary ΛCDM model



HI: 21 cm transition
from Dark Ages until Now

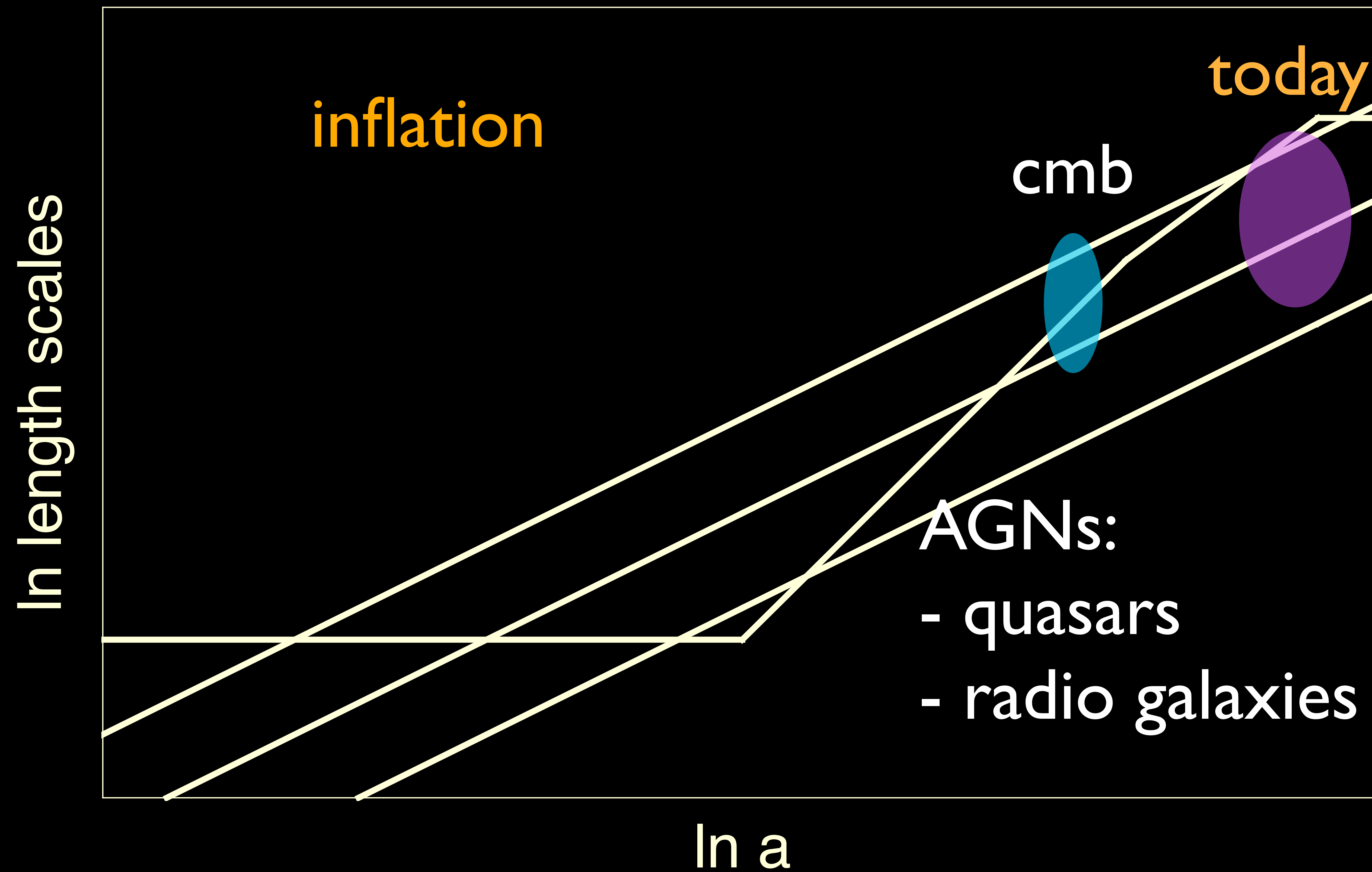
HI intensity maps

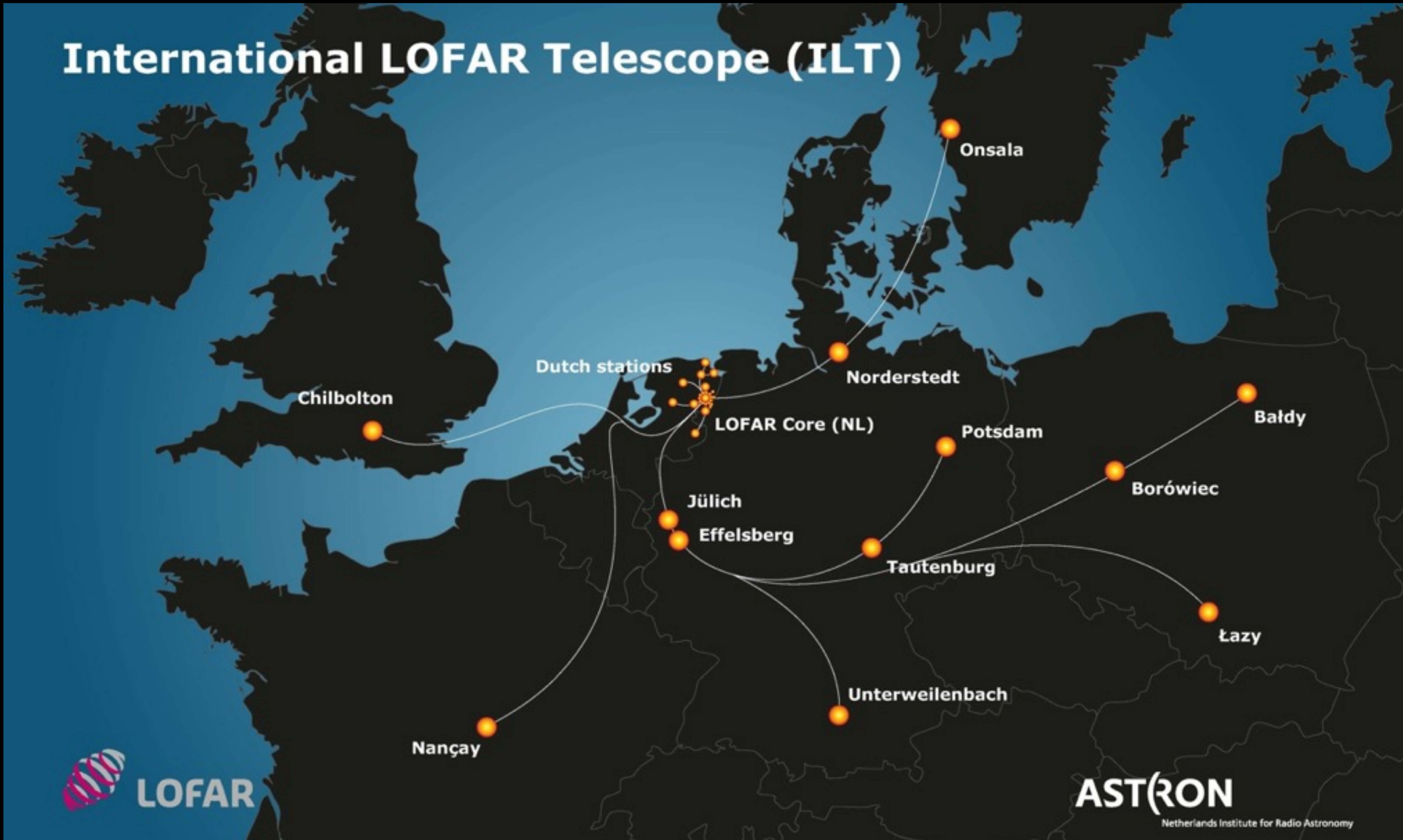
Active Galactic Nuclei (z = 0 to ~ 6)

continuum radio sky

quasars

Cosmological Inflation



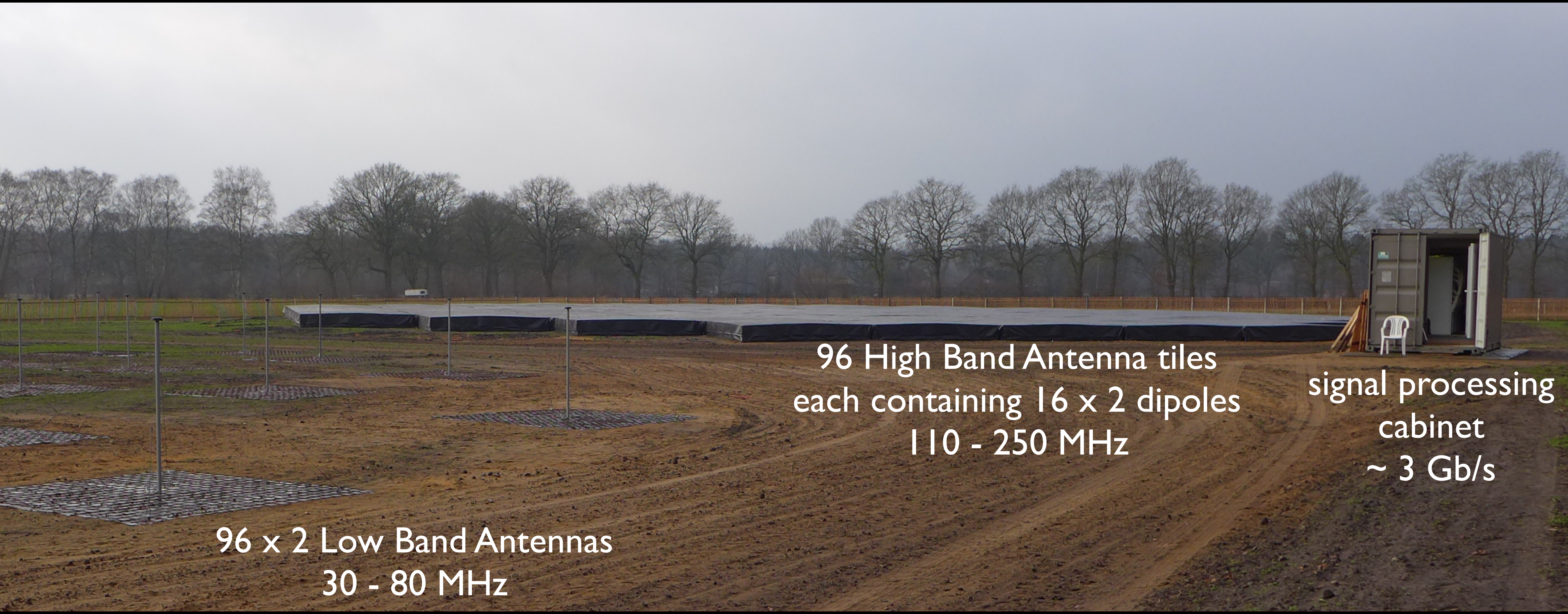


LOw Frequency ARray

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

International LOFAR Station DE609 Norderstedt

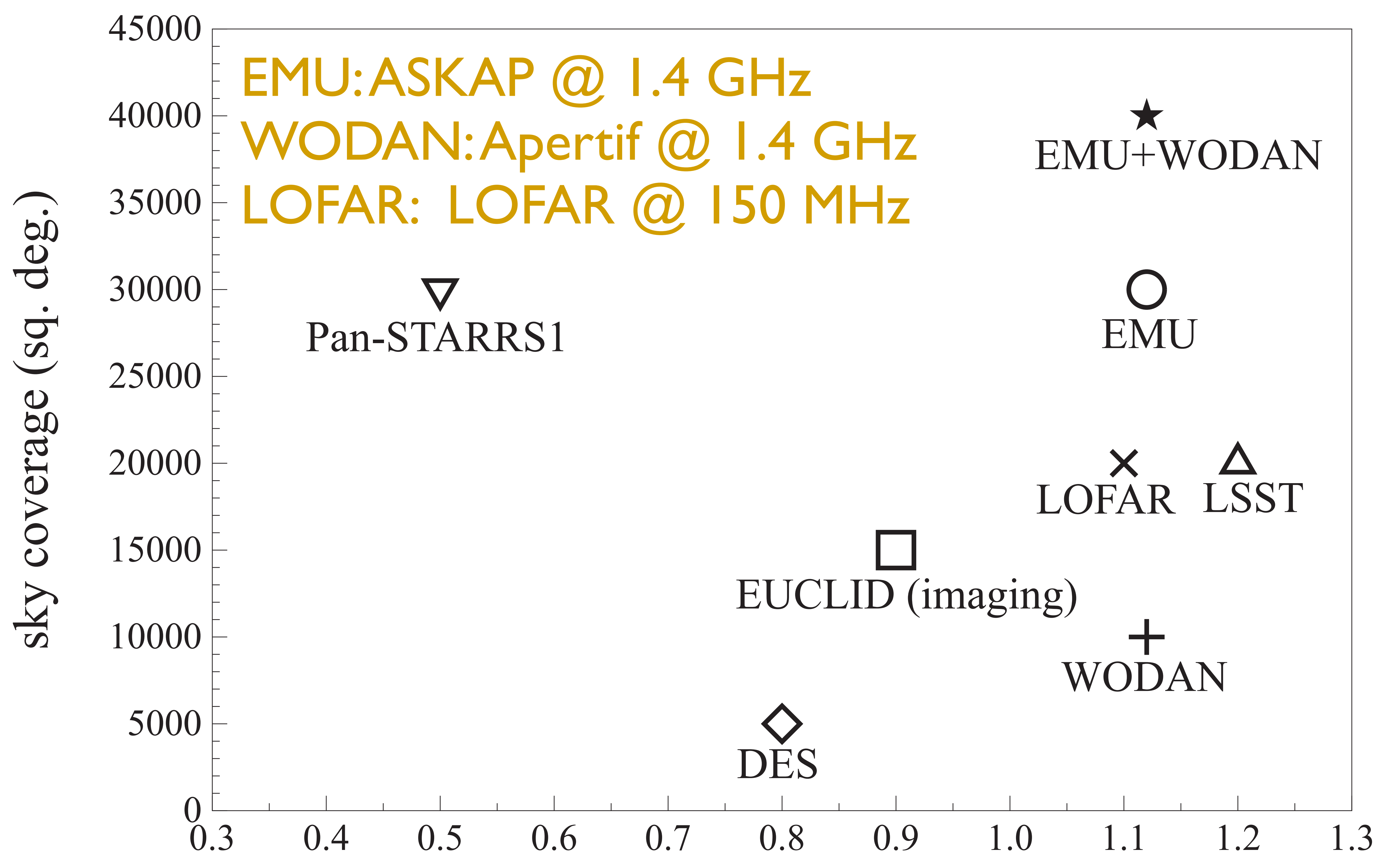
completed December 2014, funded by BMBF/HH/NRW



data archives in Amsterdam,
Groningen and Jülich (by now ~14 PB)

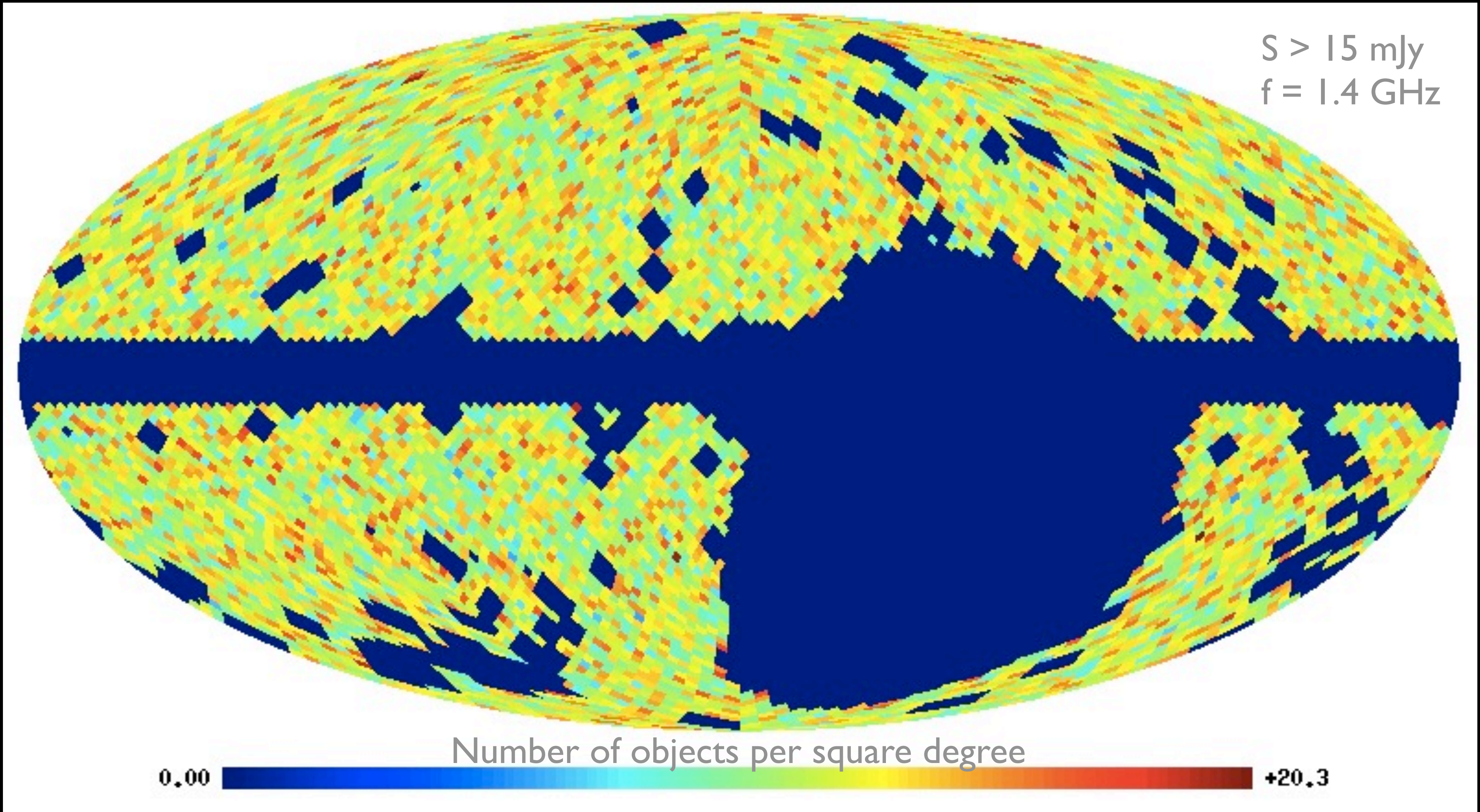
10 GbE fiber connection (via JSC, FZ Jülich) to
high performance computer in Groningen, NL

Radio continuum surveys

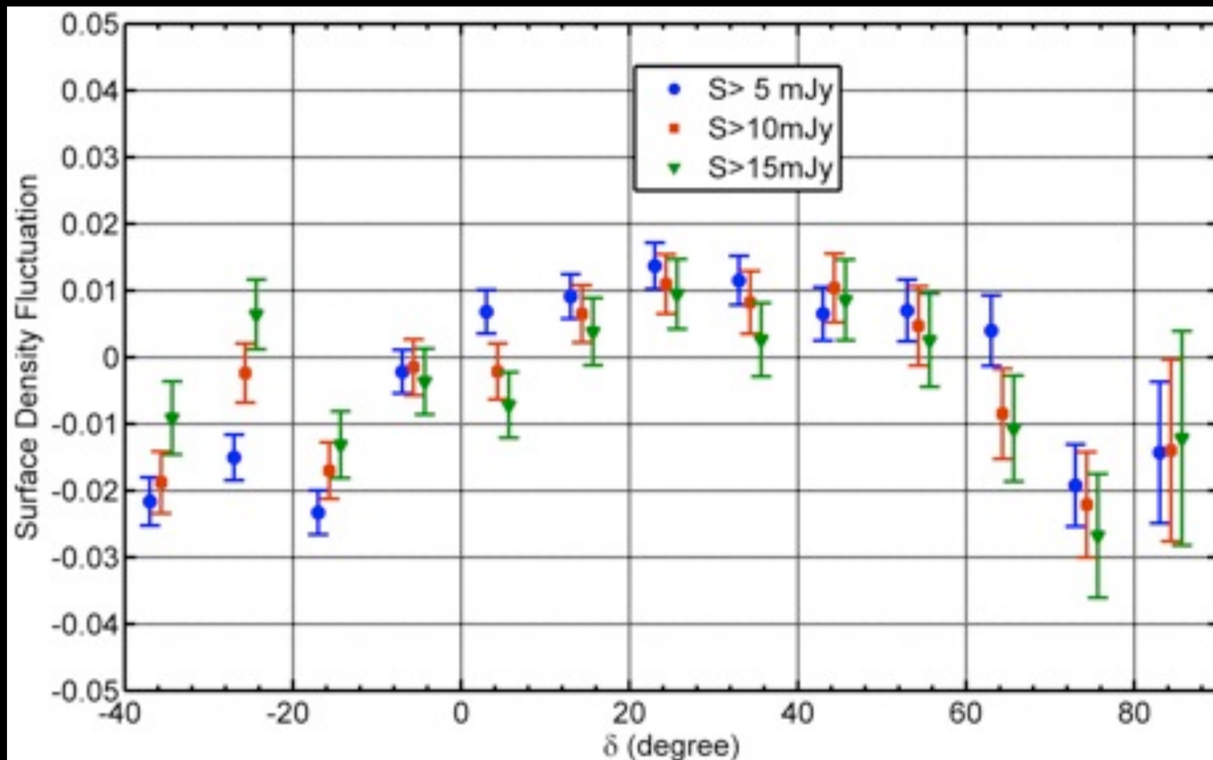


Raccanelli et al. 2013

NVSS surface density fluctuations



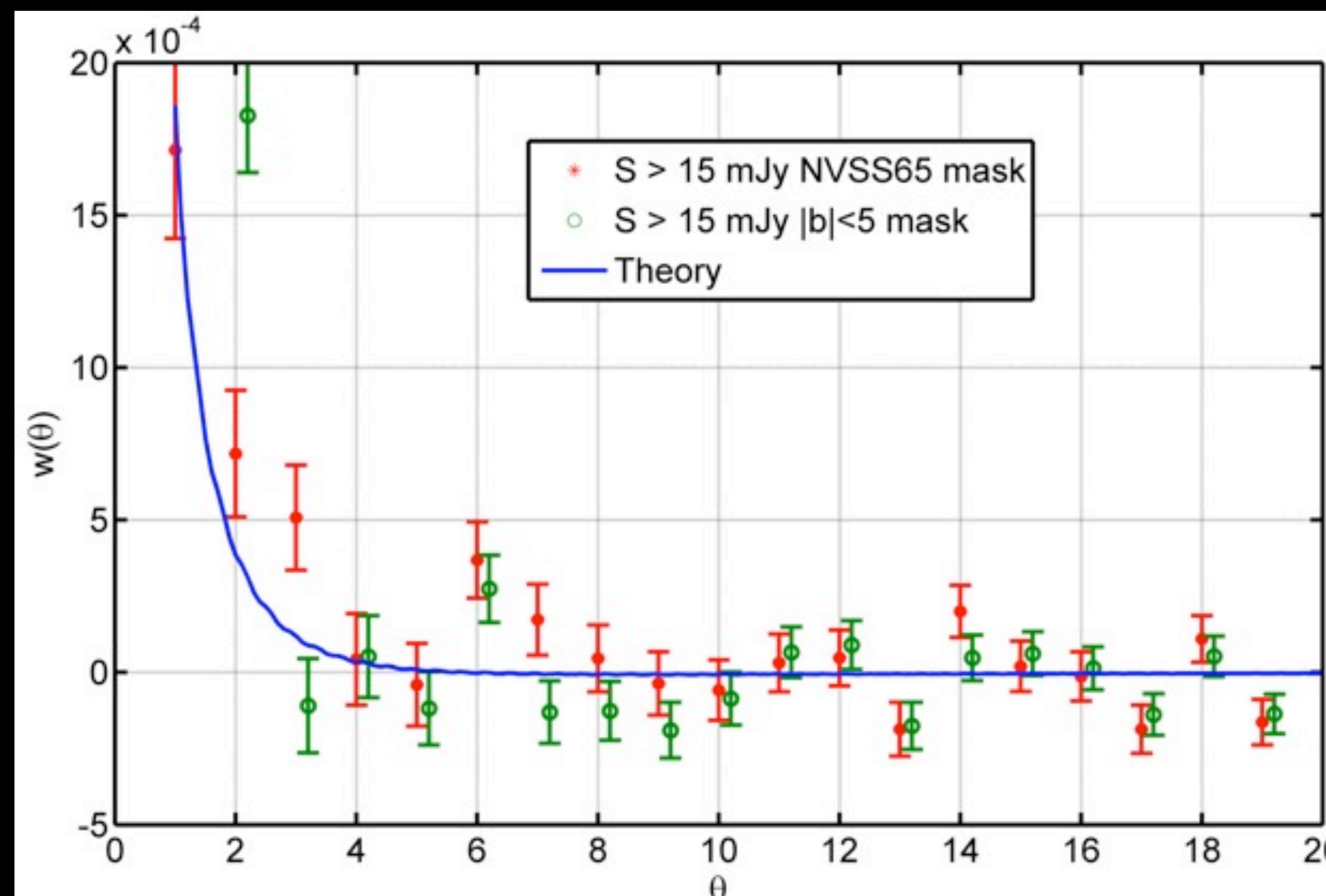
Chen & Schwarz 2015



systematic effects:
- direction dependent effects
- strong point sources
- foregrounds
- remove radio dipole

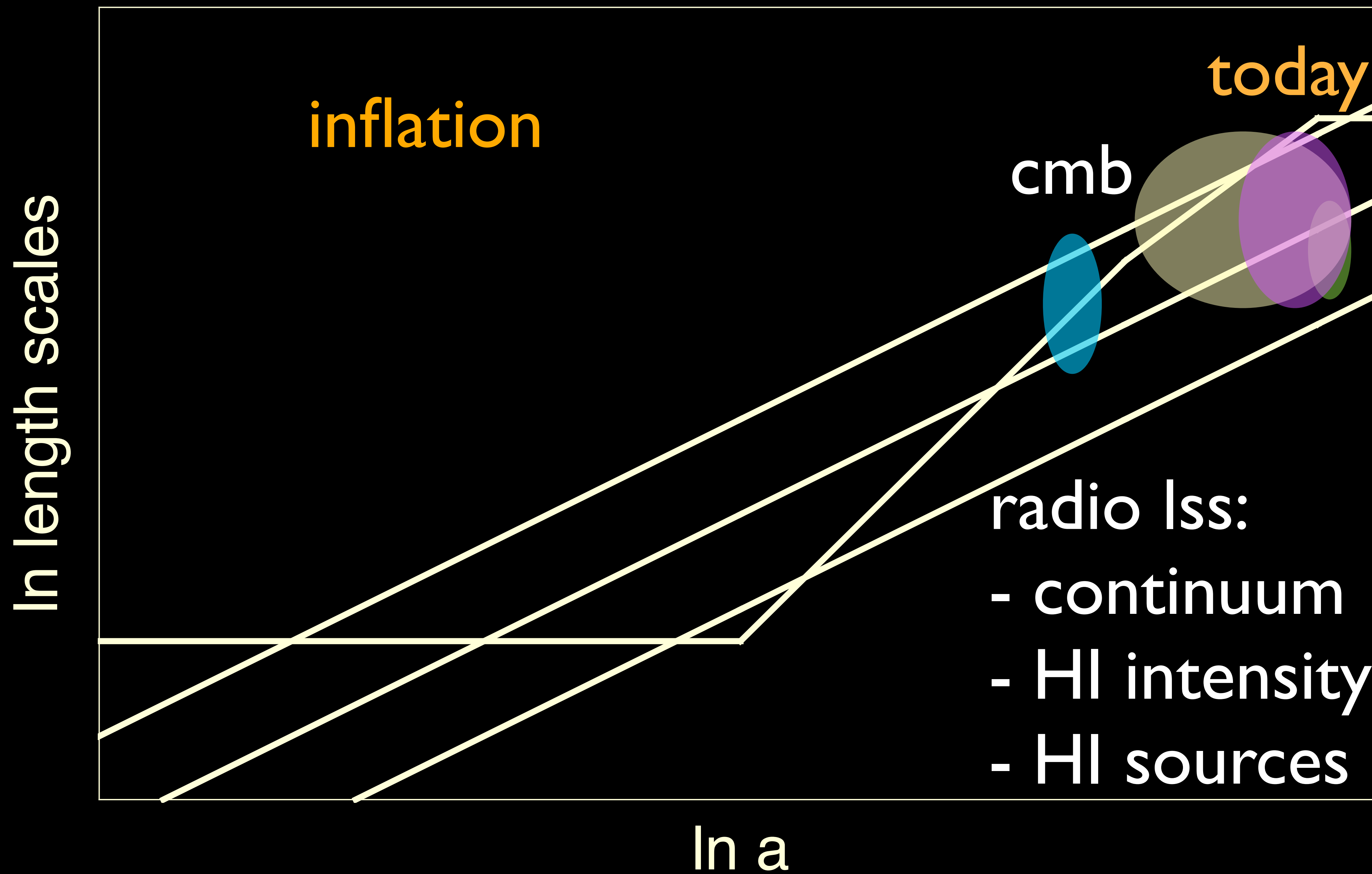
2pt correlation: consistent with Planck best-fit model and CENSOR redshift distribution

claims on Non-Gaussianity (Xia et al.) can be explained by systematic effects of NVSS data



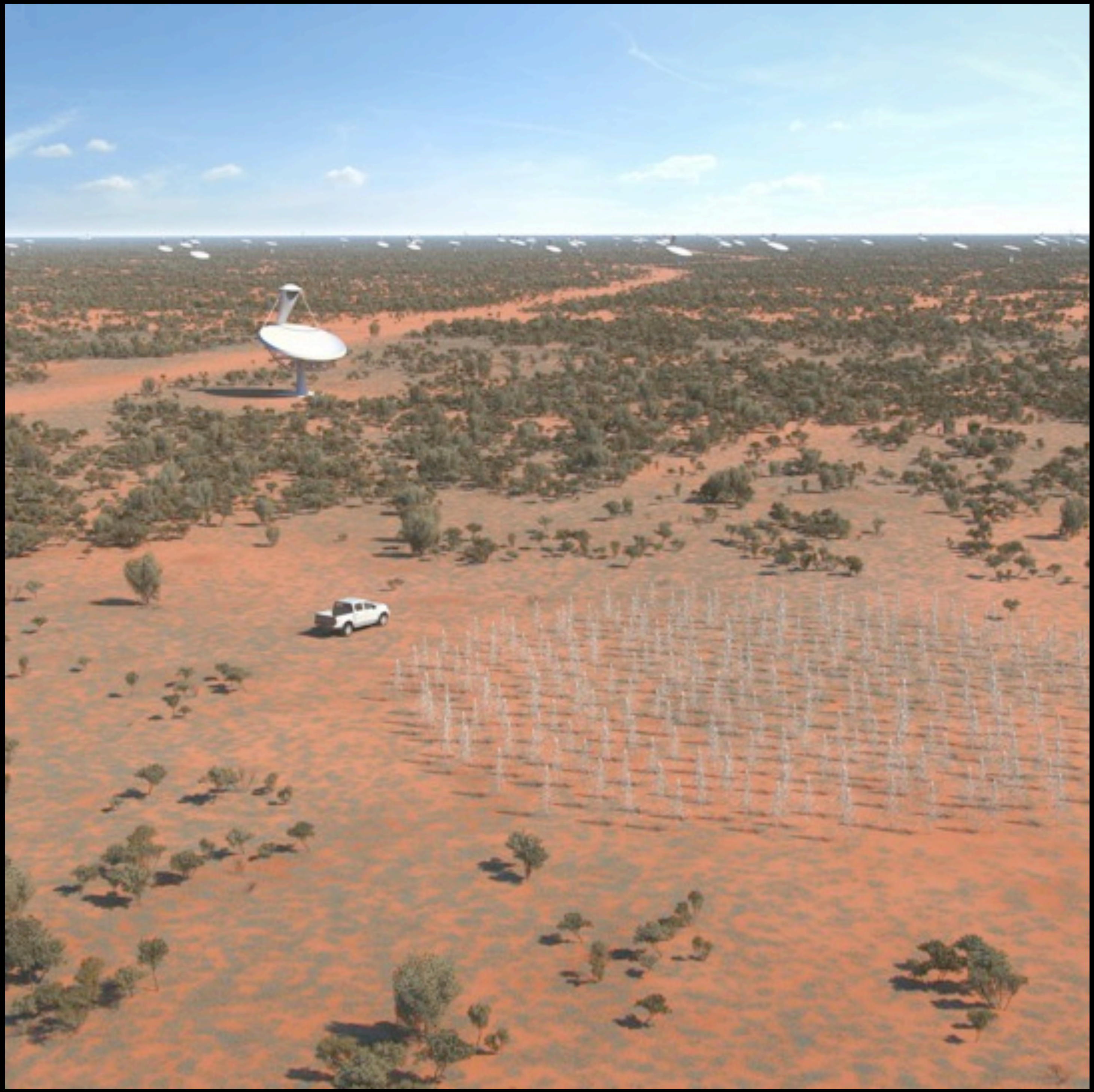
Chen & Schwarz 2015

Cosmological Inflation



SKA Square Kilometre Array, Early Science in 2020+

will be biggest telescope for decades



Science Goals:

- Cosmic Dawn
- General Relativity
- Cosmology
- Cosmic Magnetism
- Craddle of Life

3 decades in frequency
high resolution
high sensitivity

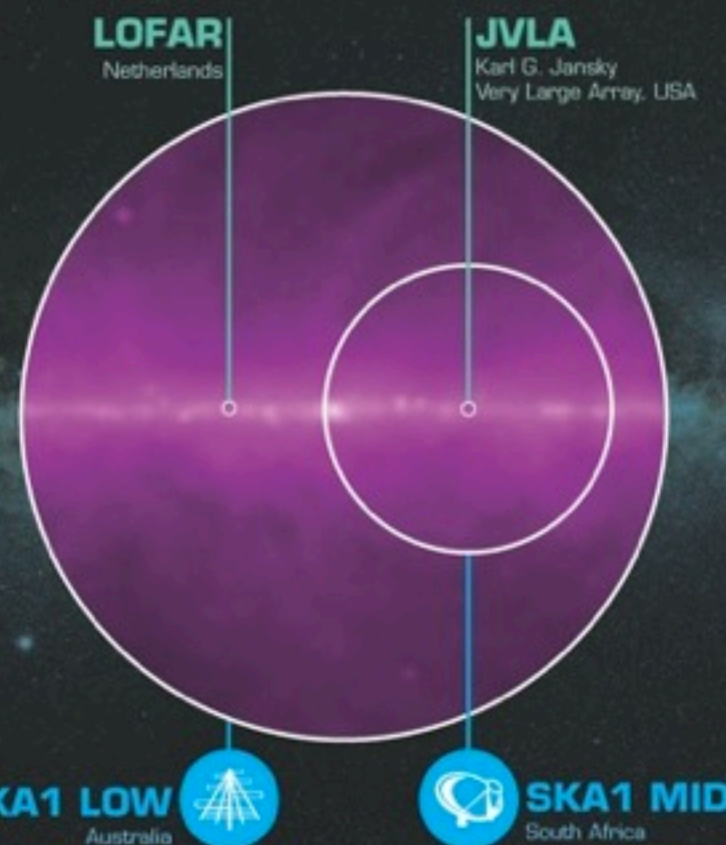
redshift for billions of galaxies

Africa & Australia; 2 Phases (construction phase I: 2018 - 2023; II: 2025+)

How will SKA1 be better than today's best radio telescopes?

Astronomers assess a telescope's performance by looking at three factors - **resolution**, **sensitivity**, and **survey speed**. With its sheer size and large number of antennas, the SKA will provide a giant leap in all three compared to existing radio telescopes, enabling it to revolutionise our understanding of the Universe.

The **Square Kilometre Array** (SKA) will be the world's largest radio telescope. It will be built in two phases - SKA1 and SKA2 - starting in 2018, with SKA1 representing a fraction of the full SKA. SKA1 will include two instruments - **SKA1 MID** and **SKA1 LOW** - observing the Universe at different frequencies.



SKA1 LOW **x1.2** LOFAR NL

SKA1 MID **x4** JVLA

RESOLUTION

Thanks to its size, the SKA will see smaller details, making radio images less blurry, like reading glasses help distinguish smaller letters.

SKA1 LOW **x135** LOFAR NL

SKA1 MID **x60** JVLA

SURVEY SPEED

Thanks to its sensitivity and ability to see a larger area of the sky at once, the SKA will be able to observe more of the sky in a given time and so map the sky faster.

SKA1 LOW **x8** LOFAR NL

SKA1 MID **x5** JVLA

SENSITIVITY

Thanks to its many antennas, the SKA will see fainter details, like a long-exposure photograph at night reveals details the eye can't see.

www.skatelescope.org Square Kilometre Array @SKA_telescope The Square Kilometre Array

As the SKA isn't operational yet, we use an optical image of the Milky Way to illustrate the concepts of increased sensitivity and resolution.

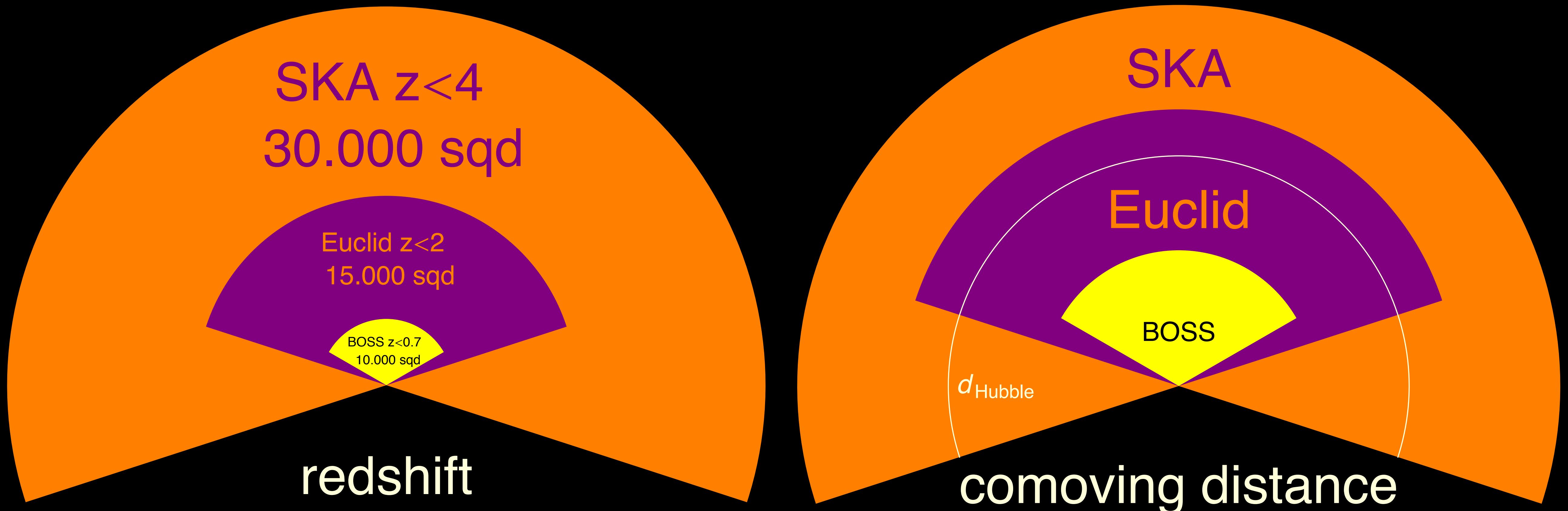
The Square Kilometre Array (SKA) will be the world's largest radio telescope, revolutionising our understanding of the Universe. The SKA will be built in two phases - SKA1 and SKA2 - starting in 2018, with SKA1 representing a fraction of the full SKA. SKA1 will include two instruments - SKA1 MID and SKA1 LOW - observing the Universe at different frequencies.

A telescope's capacity to receive faint signals - called sensitivity - depends on its collecting area, the bigger the better. But just like you can't compare radio telescopes and optical telescopes, comparison only works between telescopes working in similar frequencies, hence the different categories above.

The collecting area is just one aspect of a telescope's capability though. Arrays like the SKA have an advantage over single dish telescopes: by being spread over long distances, they simulate a virtual dish the size of that distance and so can see smaller details in the sky, this is called resolution.

www.skatelescope.org | Square Kilometre Array | @SKA_telescope | YouTube The Square Kilometre Array

Cosmic volumes probed

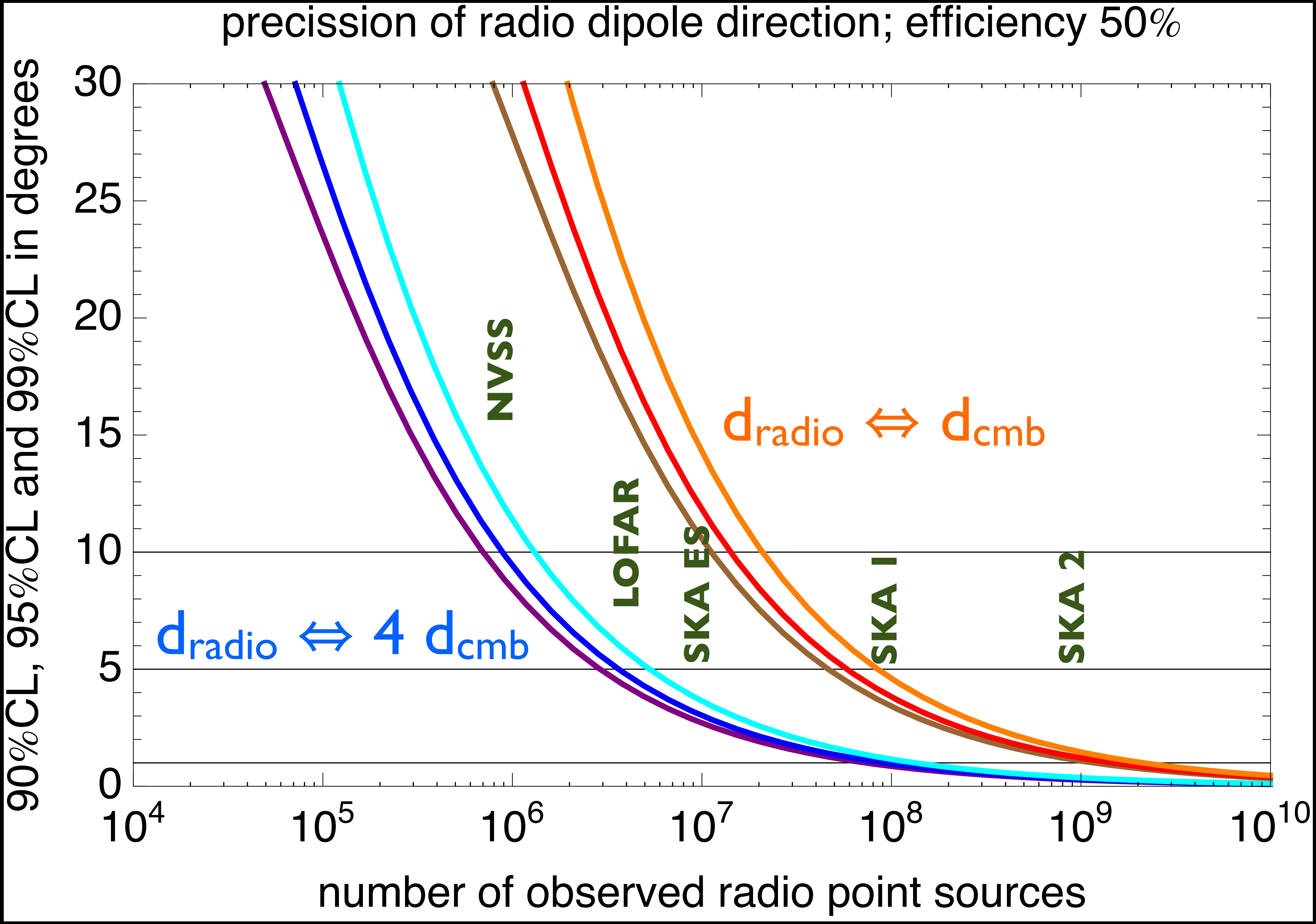


Key advantages of radio continuum and HI surveys:

* more independent modes that optical/ir/cmb

* different systematics from optical/ir

Cosmic radio dipole



Schwarz et al., 2015, SKA Science Book

Conclusion

largest observable scales reflect
initial conditions and symmetries of Universe

deviations from inflationary LCDM at largest scales:
high radio dipole & CMB anomalies

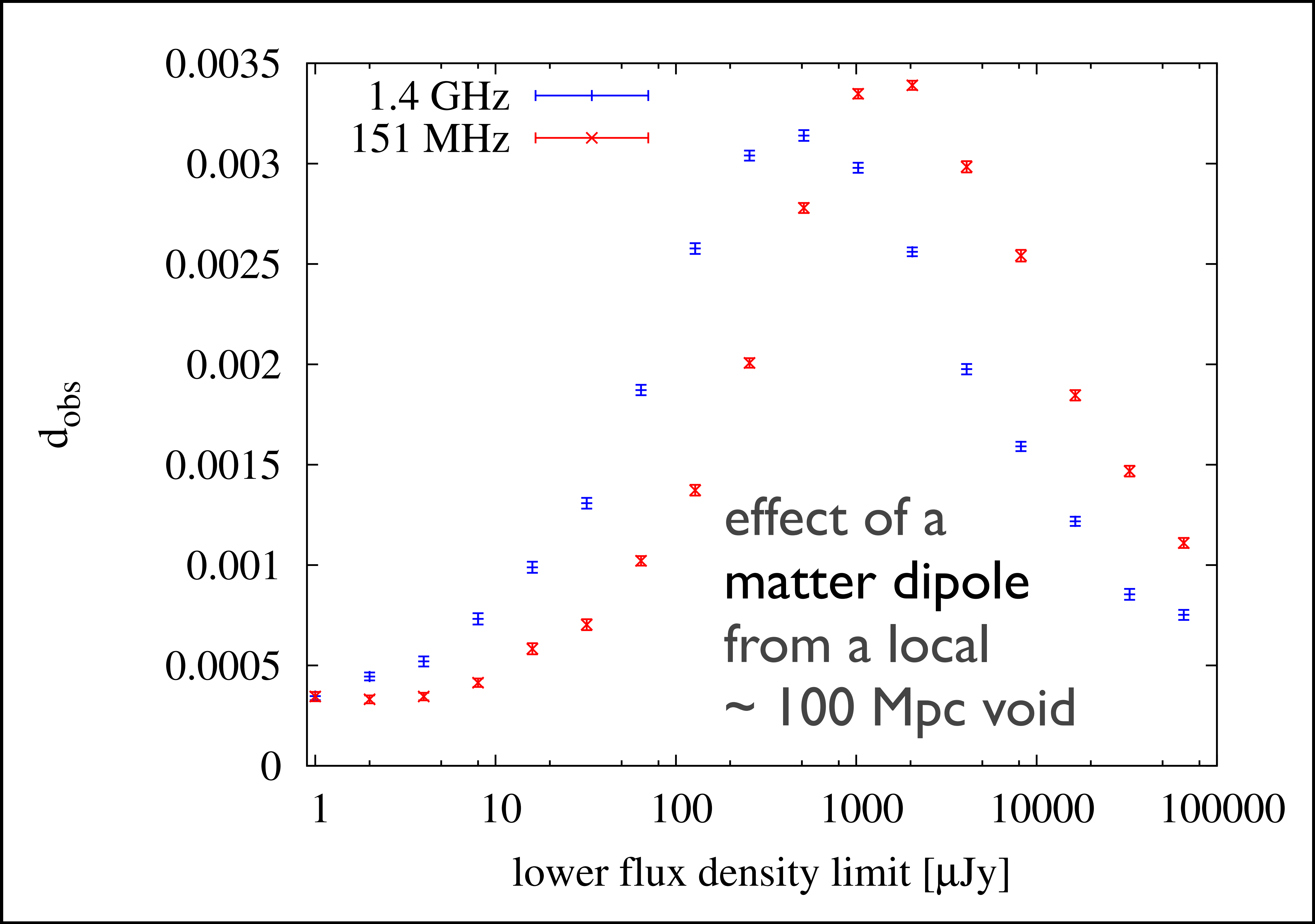
unclear how to explain (e.g. short or anisotropic inflation)

to improve systematics and statistics
new generation of radio surveys with
SKA & pathfinders probe largest volumes ever

LOFAR MSSS will be out soon, LOFAR Tier1 started

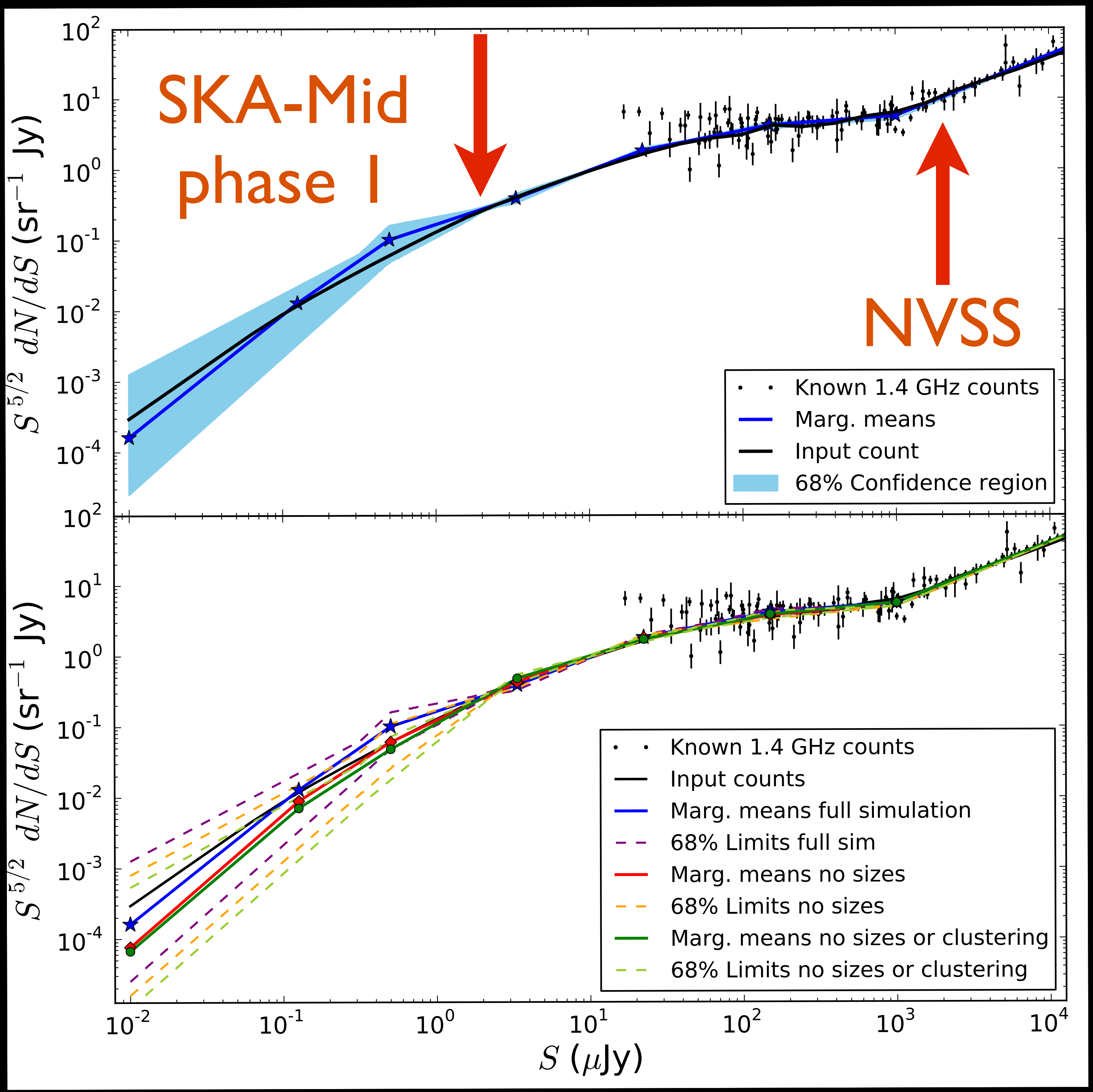
Support a German participation in the SKA:
GLOW SKA: www.glowconsortium.de

Dipole tomography



Rubart, Bacon & Schwarz 2014

Radio source counts



JVLA, Vernstrom et al. 2013

two populations:

* AGNs (FRI-II, RQQ)

* galaxies (SFG, SBG)

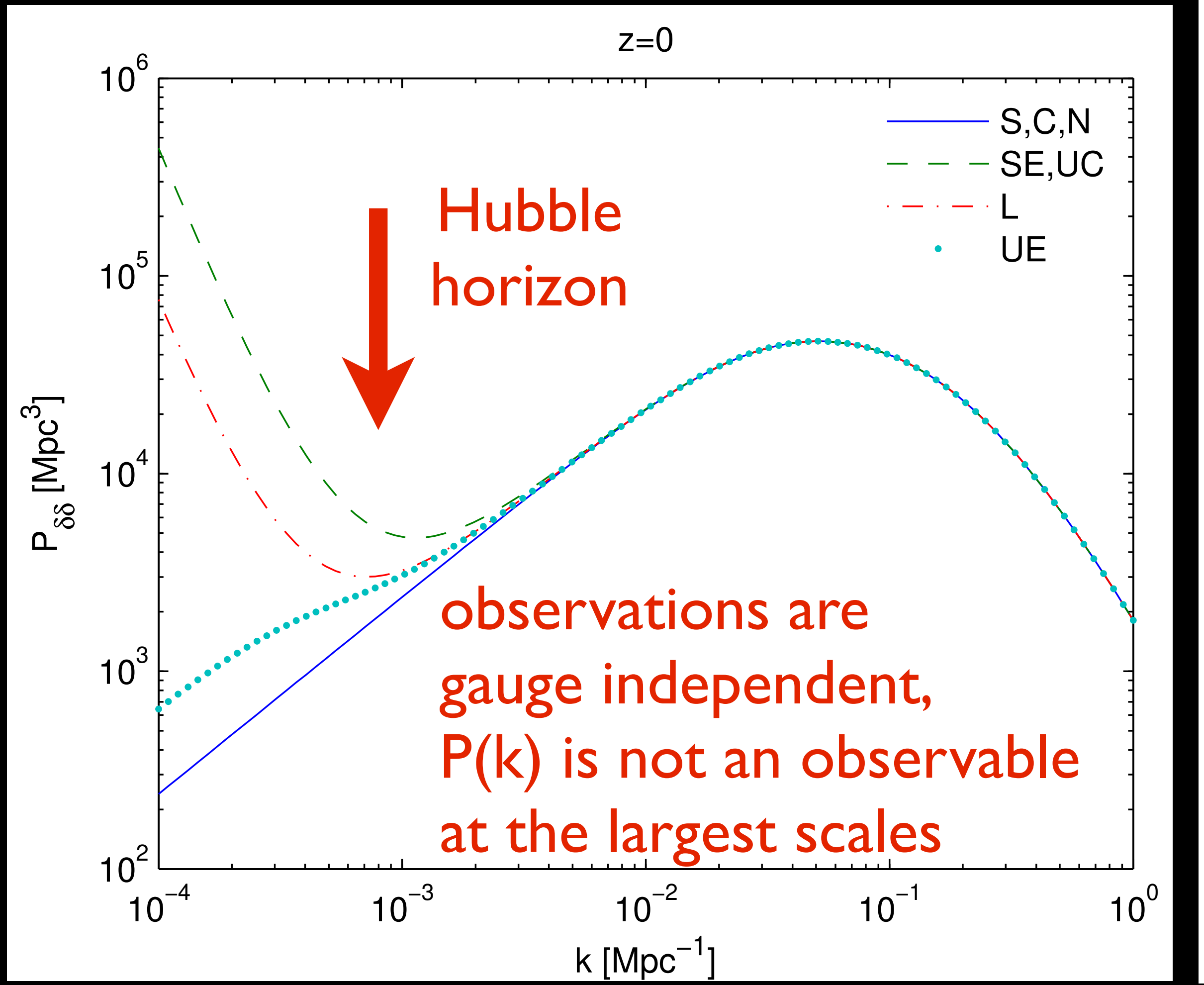
AGNs dominate at large fluxes

star forming galaxies dominate below ~ 1 mJy

identification of morphology for angular resolution 0.5”

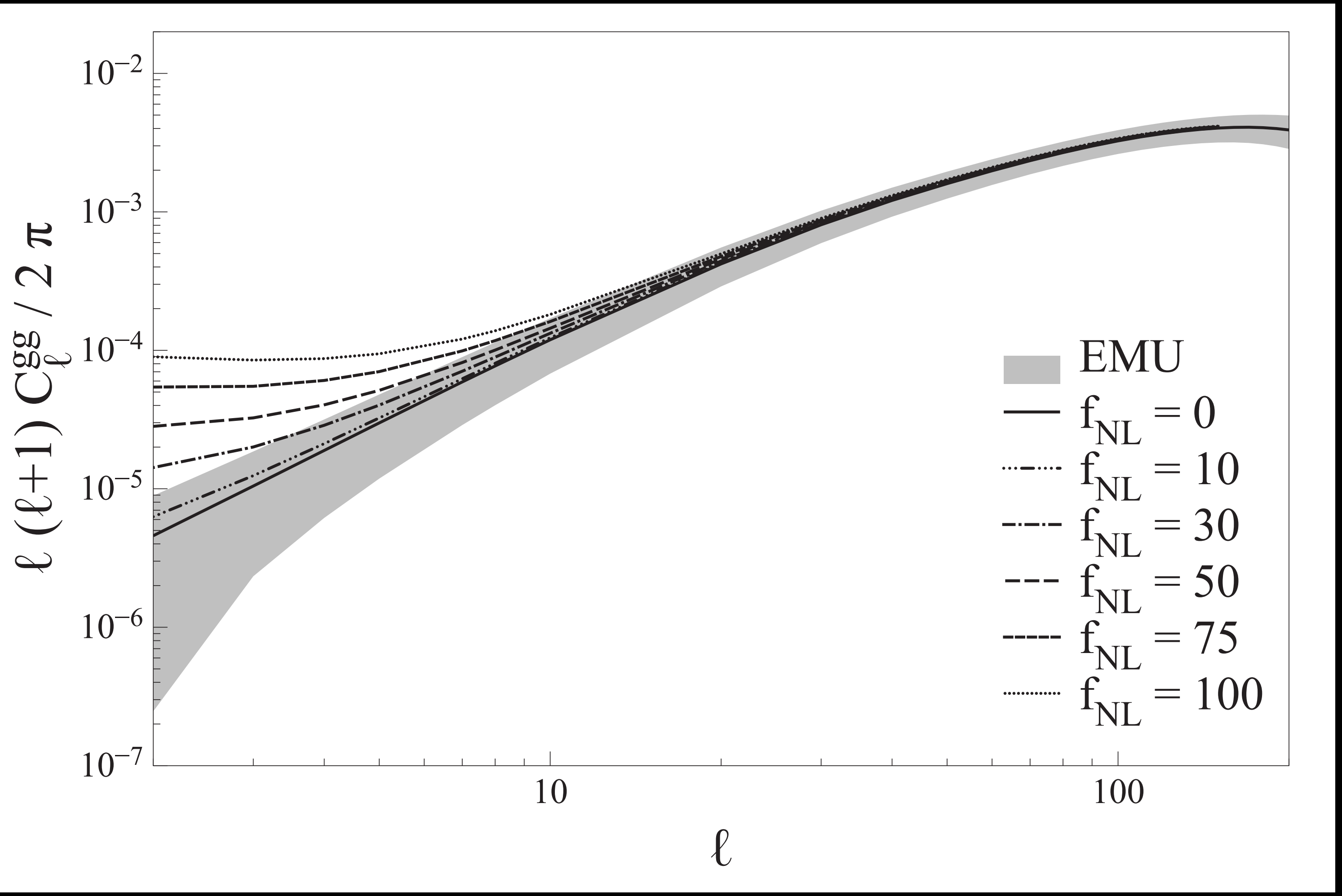
Physics at large scales

Relativistic effects



Yoo 2009, Bonvin and Durrer 2011,
Flender and Schwarz 2013,
Chen and Schwarz 2014

Non-Gaussianity



Raccanelli et al. 2013

$\frac{d^2 N}{d\Omega dS}(\mathbf{e}, \nu, S)$ and $\frac{d^2 N}{d\Omega dz}(\mathbf{e}, \nu, z)$ are gauge independent

SKA cosmology probes

- continuum survey (0.5", morphology resolved, all sky): dipole, autocorrelation, ISW, cosmic magnification, non-Gaussianity, ...
- HI galaxy survey ($0.2 < z < 4$, all sky): P(k), BAO, f(z), weak lensing, ...
- HI intensity mapping (interferometer and/or dish survey): BAO most powerfull