Cosmology with the SKA

Dominik J. Schwarz
Universität Bielefeld

Image credit: SKA South Africa

Structure of lecture

- What is the SKA?
- Short introduction to cosmology
- The extragalactic radio sky
- Cosmology opportunities with the SKA
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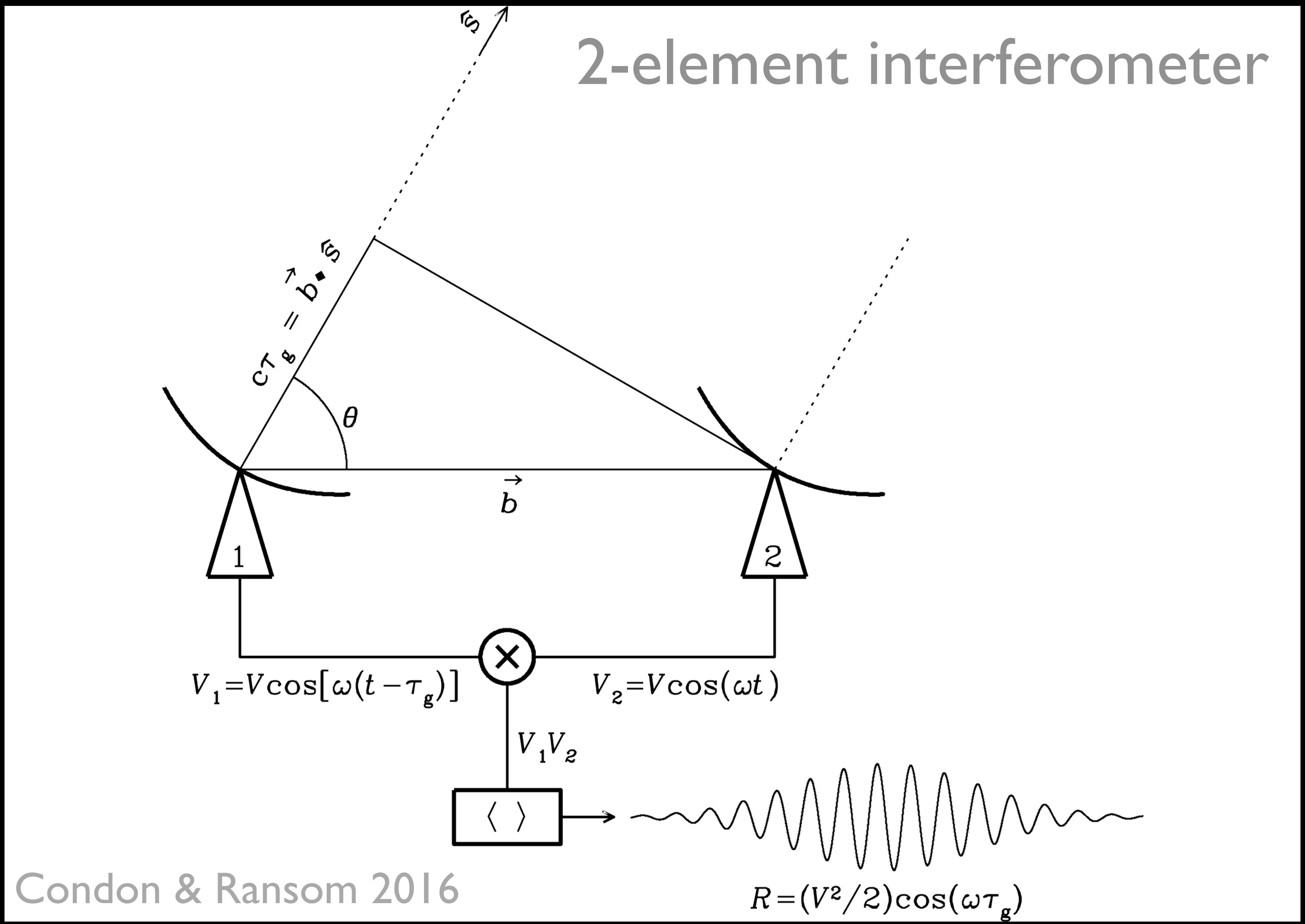
Square Kilometre Array

- global research facility with sites on three continents (Australia, Africa, Europe)
- two interferometers that observe southern radio sky across three decades in frequency
- top radio facility in the combination of sensitivity, resolution and survey speed
- science cases go well beyond classical field of radio astronomy, e.g. the origin of Life

Principle of a Radio Interferometer



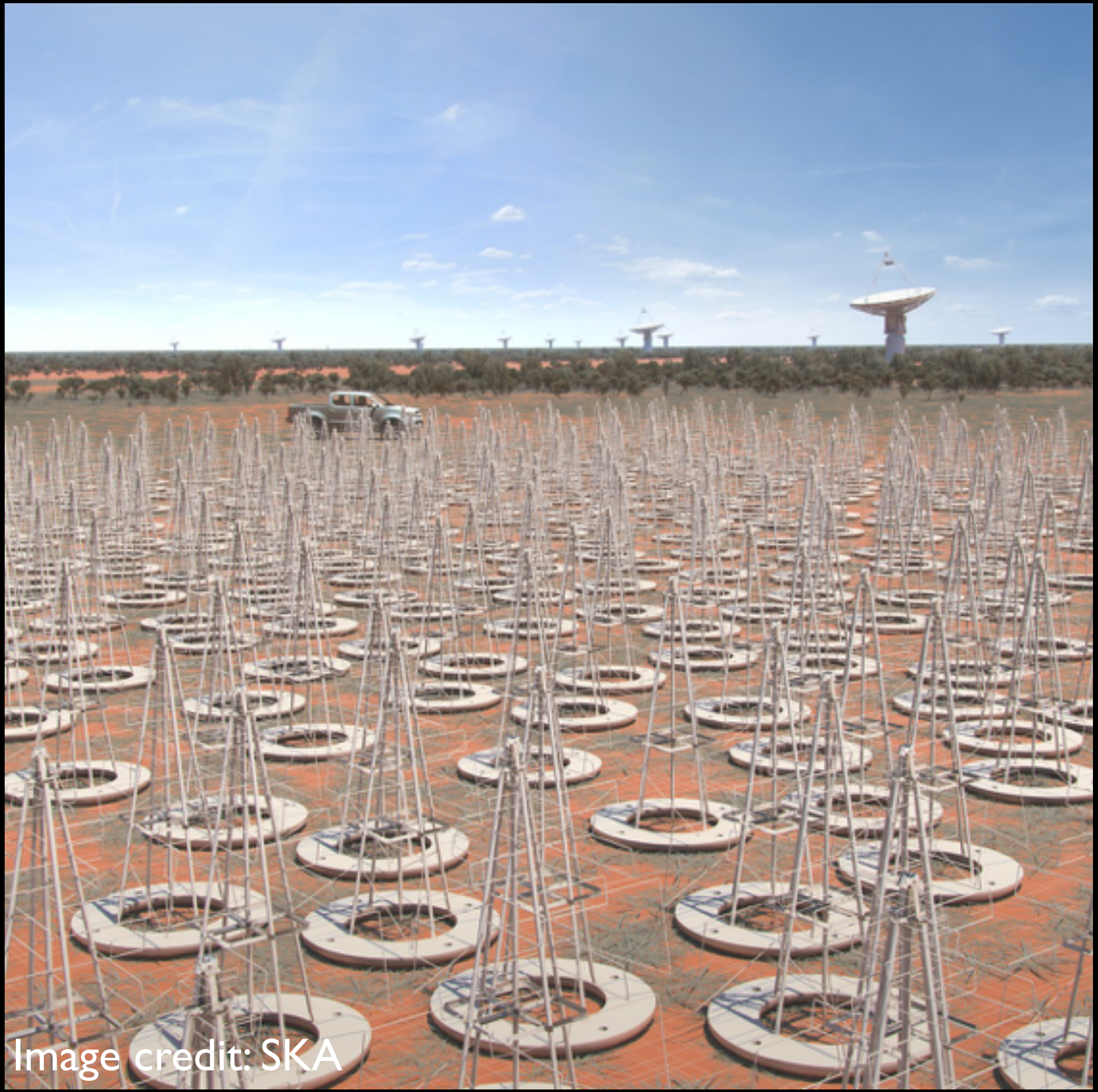
signals from two antennas (1,2) on baseline b are correlated (multiplied and averaged) and show oscillations as Earth or antennas move

N antennas provide N(N-1)/2 independent baselines

The averaged products of voltages are called visibilities. They are Fourier components of the image folded by the antenna beams.

SKA1-low

SKA Low Frequency Aperture Array



location: Western Australia

frequency: 50 - 350 MHz

number of stations:
476 (512)

number of antennas:
140,000 (150,000)

max. baseline: 40 (65) km

raw data rate: 146 (157) TB/s

deployment (baseline) design

SKA1-mid

SKA Mid Frequency Aperture Array


Image credit: SKA

location: South Africa

frequency: 350 MHz — 14 GHz

available bands: 1, 2, half of 5

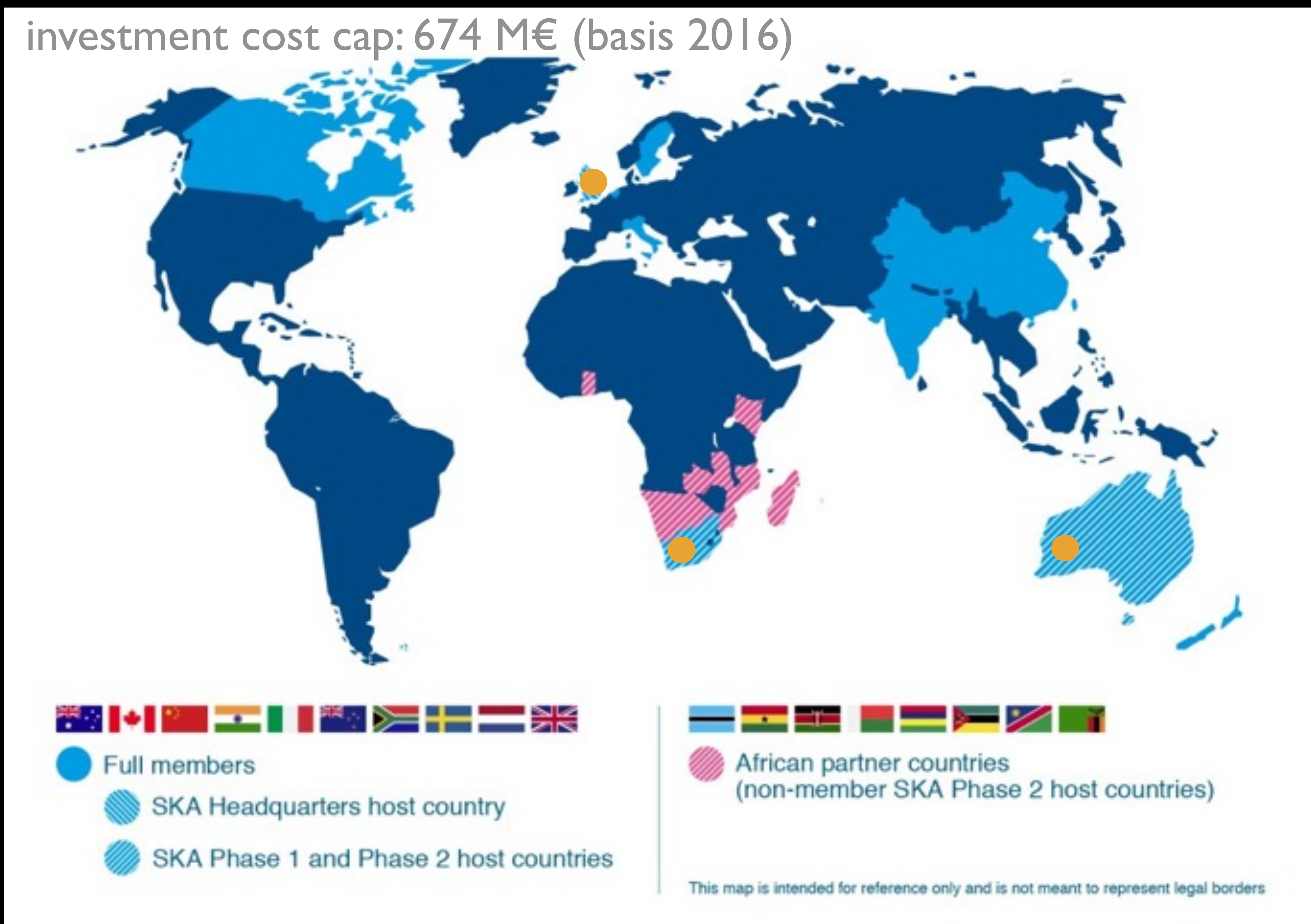
number of dishes:
130 (133)

max. baseline: 120 (150) km

raw data rate: 2 TB/s

deployment (baseline) design

SKA Observatory



Interested countries: France, Germany, Japan, Korea, Malta, Portugal, Spain, Switzerland, USA; Contacts: Brasil, Mexico, Ireland, Russia

SKAO will be founded as IGO (plan: IGO 2018, construction approval 2019)

Germany plans to become an associated member

SKA HQ: Jodrell Bank, UK

SKA1-mid: Karoo, ZA

SKA1-low: Murchison, Aus

SKA1 High Priority Science

- Cosmic Dawn/EoR: imaging & P(k)
- Pulsars: galactic population & test gravity
- HI: galaxy formation, ISM studies
- Transients: missing baryon problem
- Cradle of Life: planet formation at 100 pc
- Magnetism: interstellar and intergalactic
- Cosmology: gravity, initial conditions & matter dipole
- Continuum: star formation history

More in: Advancing Astrophysics with the SKA, PoS 2015

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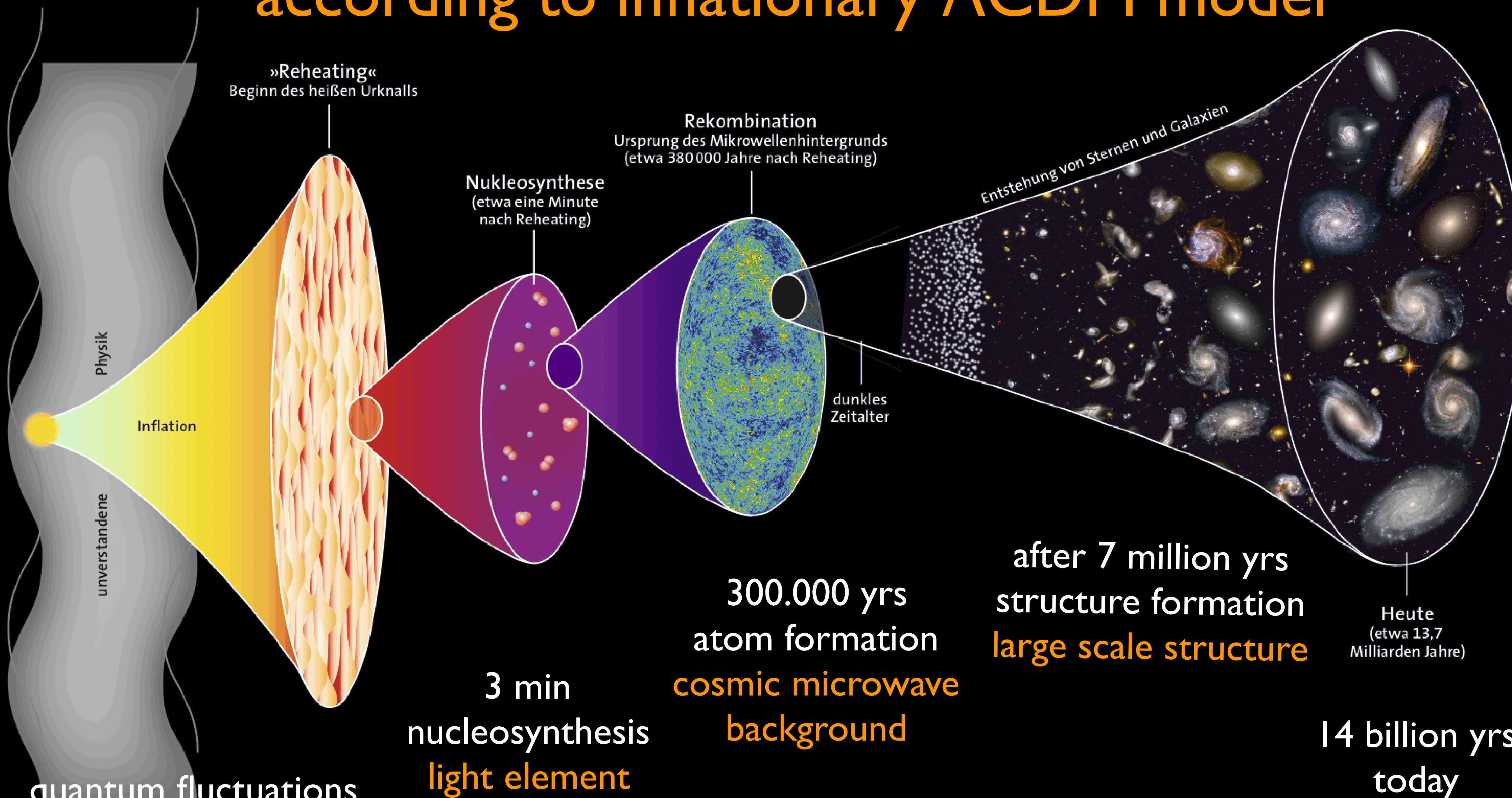
Physical Cosmology

- based on physical theories, experiments and observations
- standard model of cosmology is based on general relativity (dynamics of space-time) and standard model of particle physics (matter content of the Universe),
- but also postulates several dark components and initial conditions, which must be tested by experiment/observation

History of the Universe

according to inflationary ΛCDM model



quantum fluctuations
cosmological inflation
geometry & fluctuations

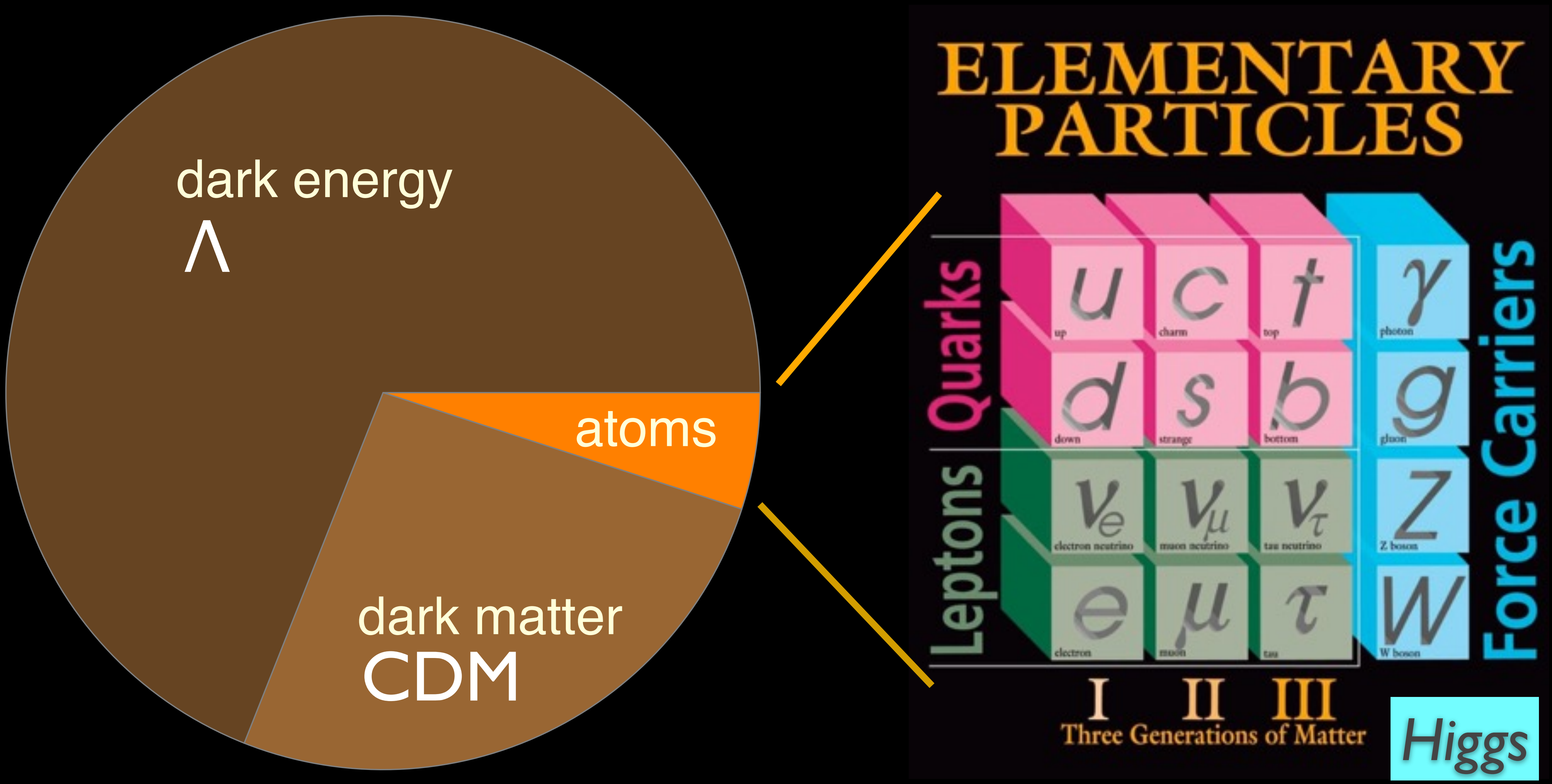
3 min
nucleosynthesis
light element
abundance

300.000 yrs
atom formation
cosmic microwave
background

after 7 million yrs
structure formation
large scale structure

14 billion yrs
today
cosmic clocks

Composition of the Universe

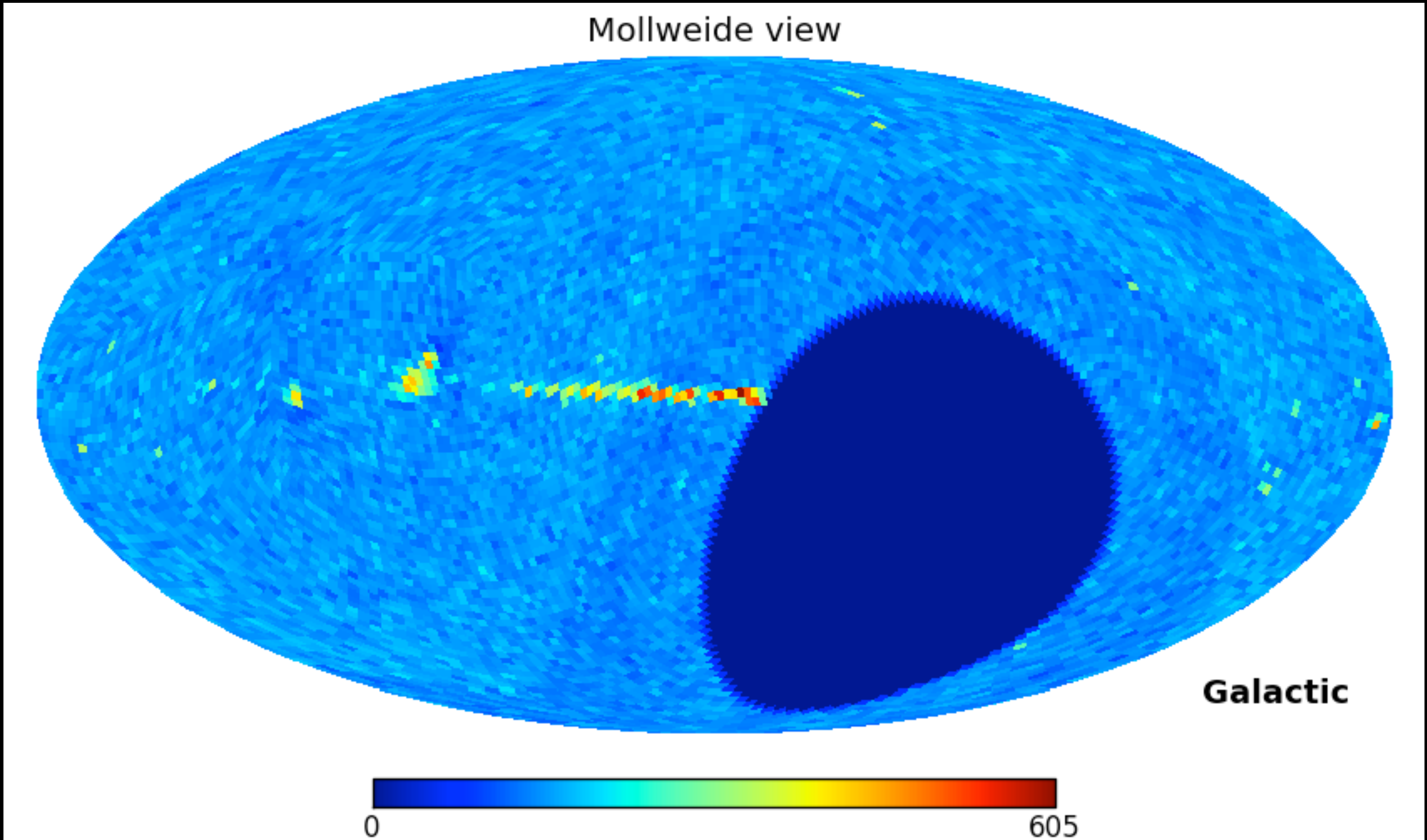


What is established?

- expansion of the Universe (Hubble rate > 0)
- hot primeval epoch (25% He, T = 2.7 K)
- isotropy of the Universe (radio, CMB, …, GRBs, ..)
- spatial flatness of the Universe (CMB fluctuations)
- only 4%-5% of known matter (BBN & CMB)
- large scale structure grows from small seeds via gravitational instability

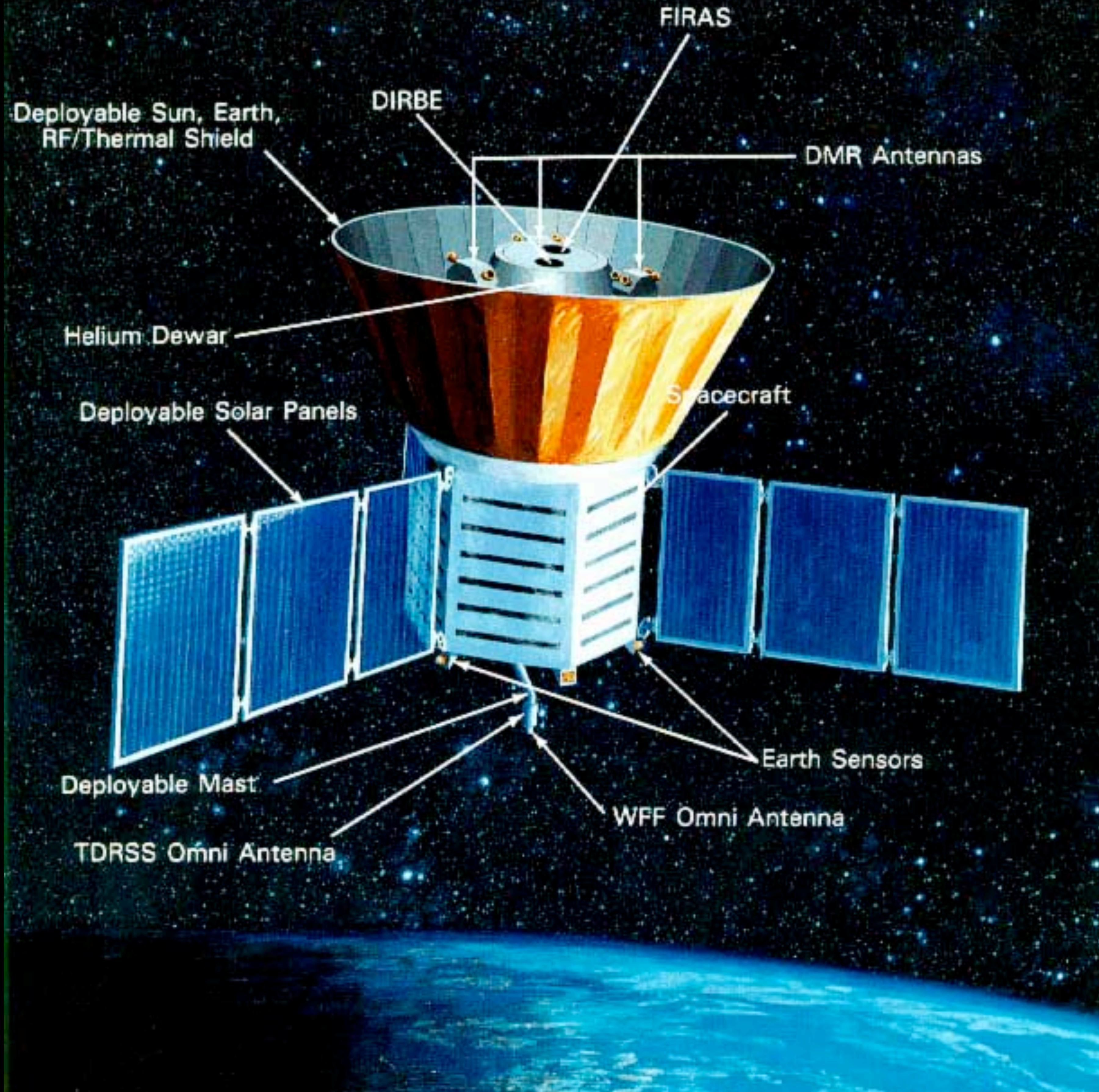
Very Large Array, NRAO

Isotropic radio sky (NVSS)

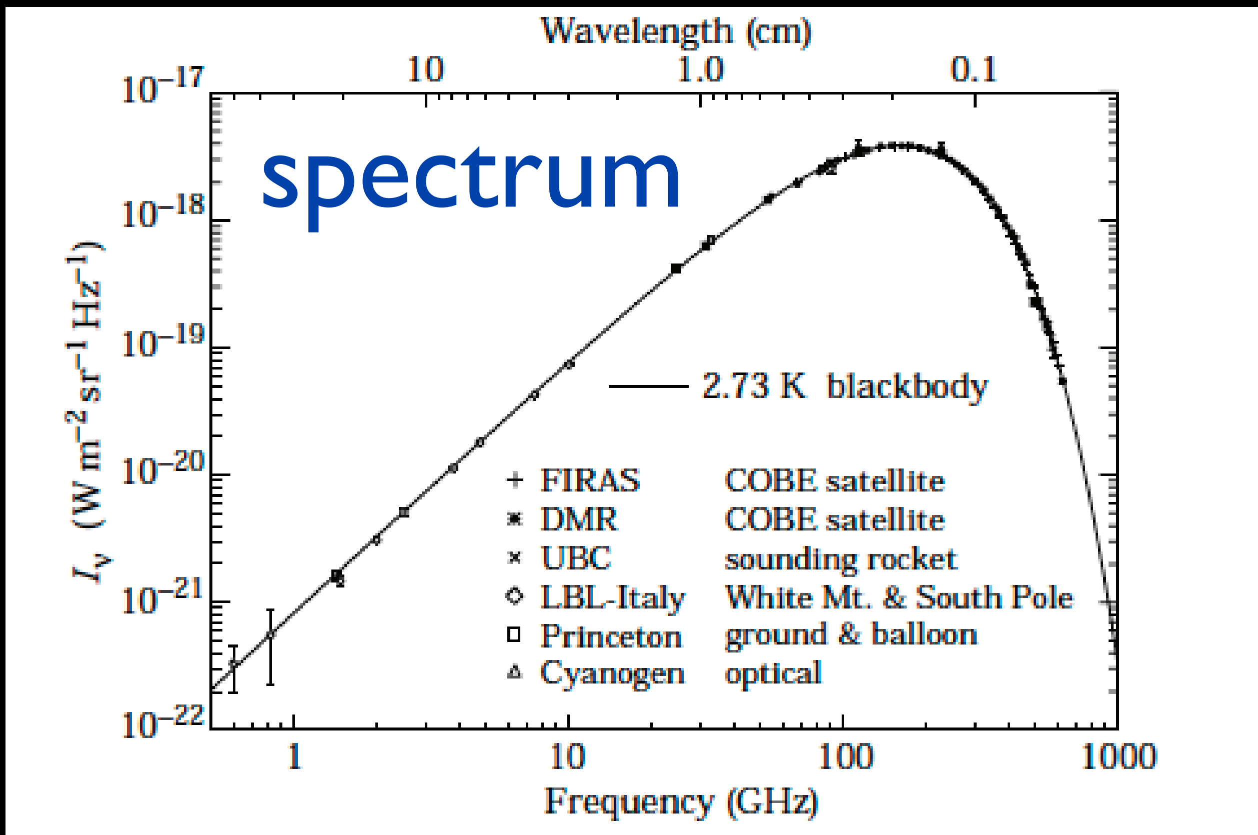


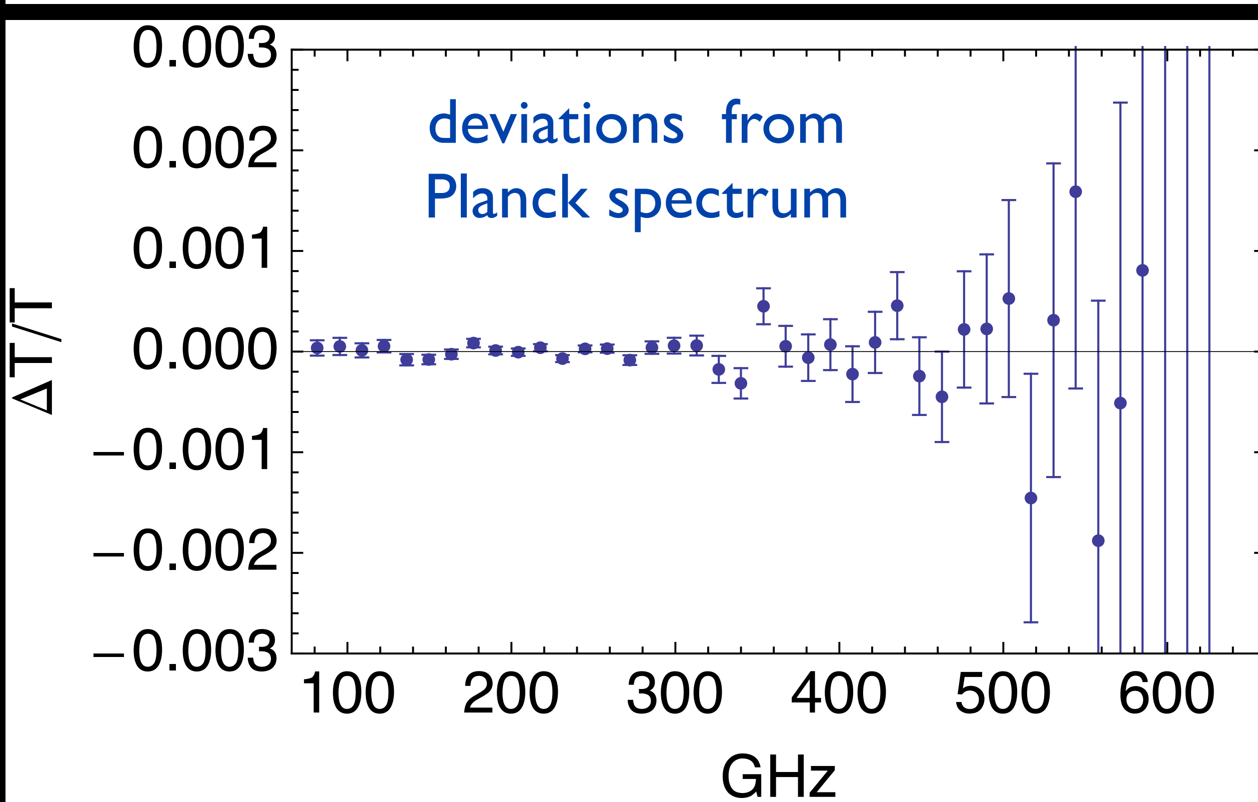
radio point sources per pixel

COBE COsmic Background Explorer



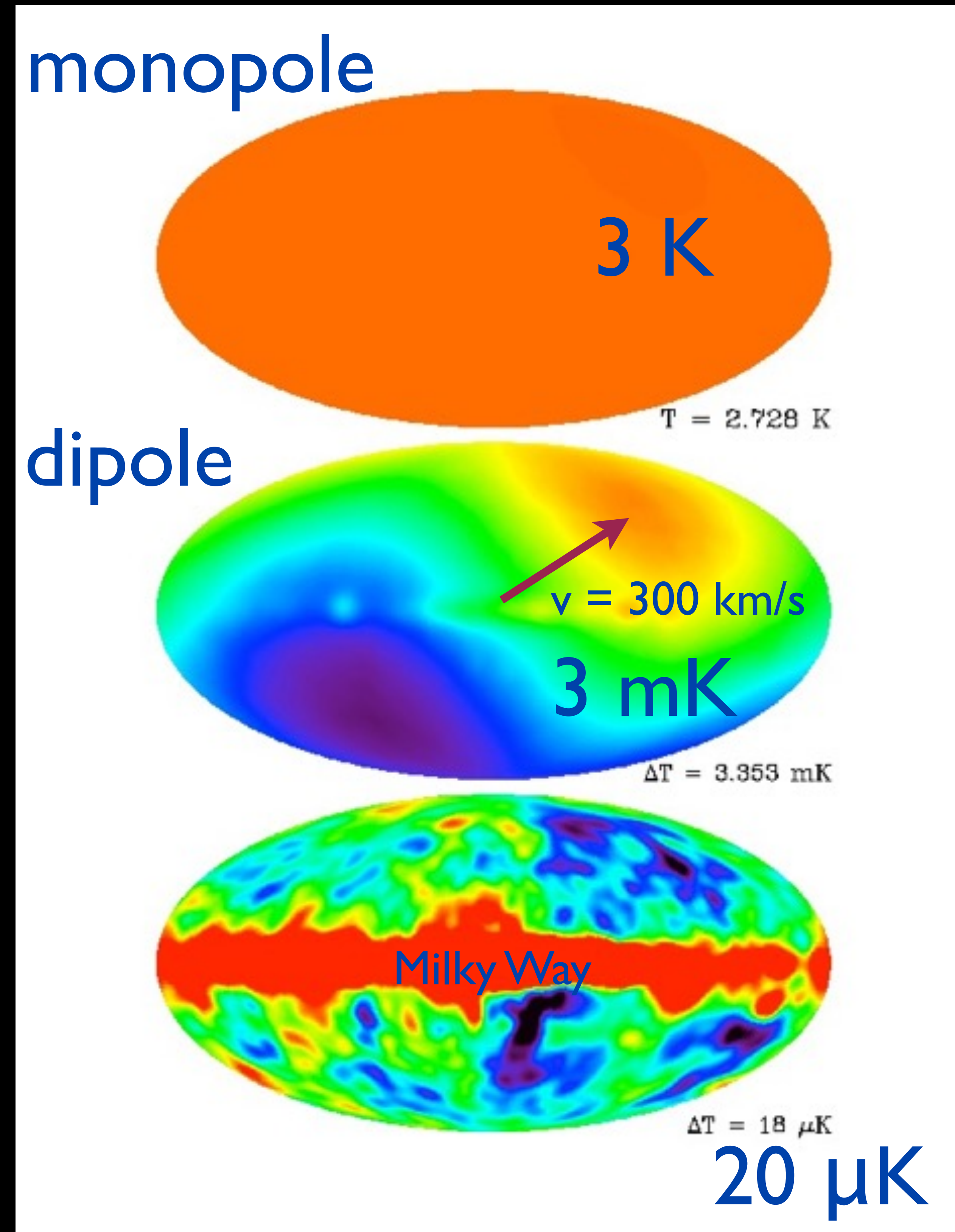
Microwave Sky





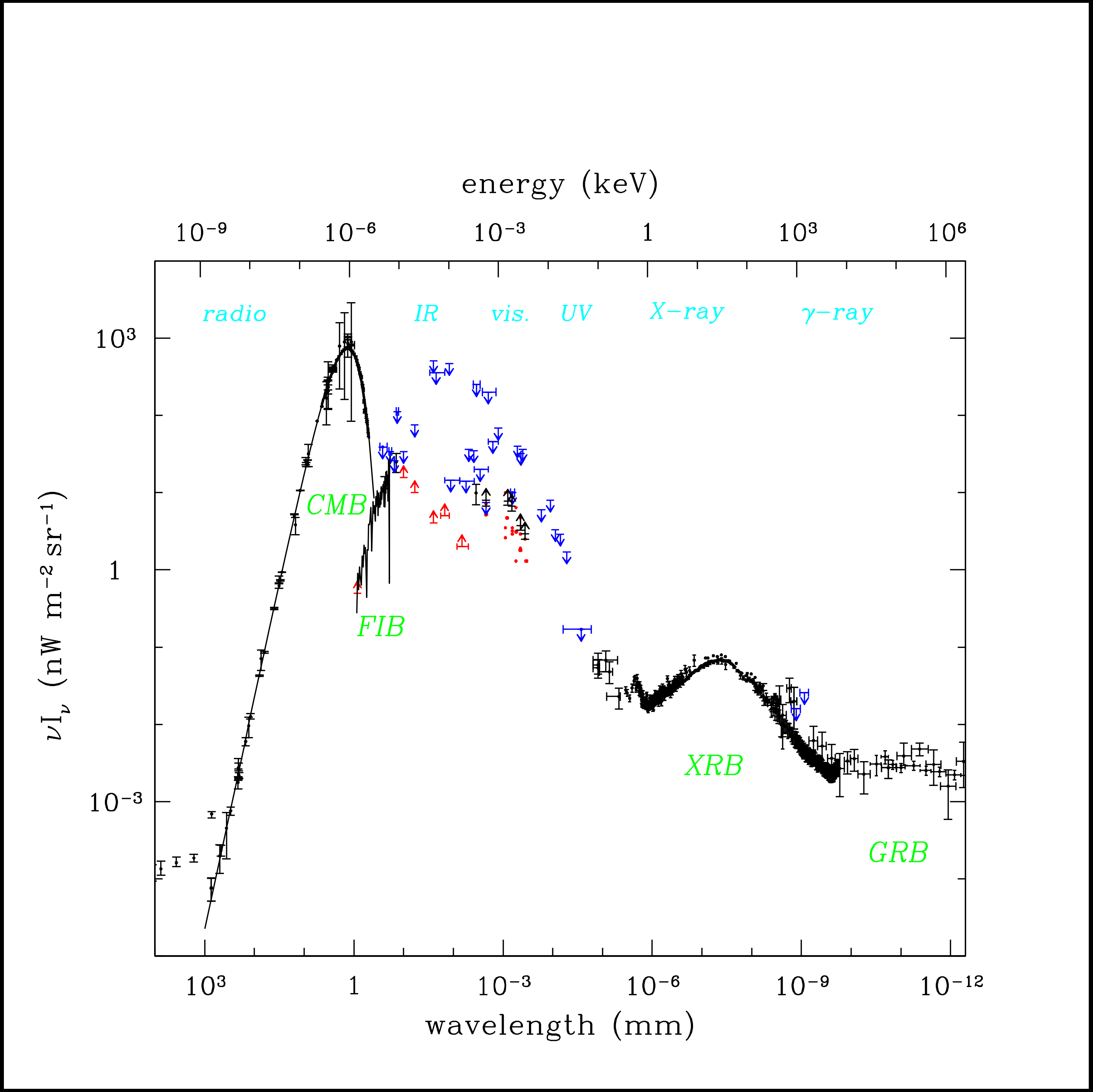
COBE - FIRAS

temperatur map



COBE - DMR

Why is the CMB so important?

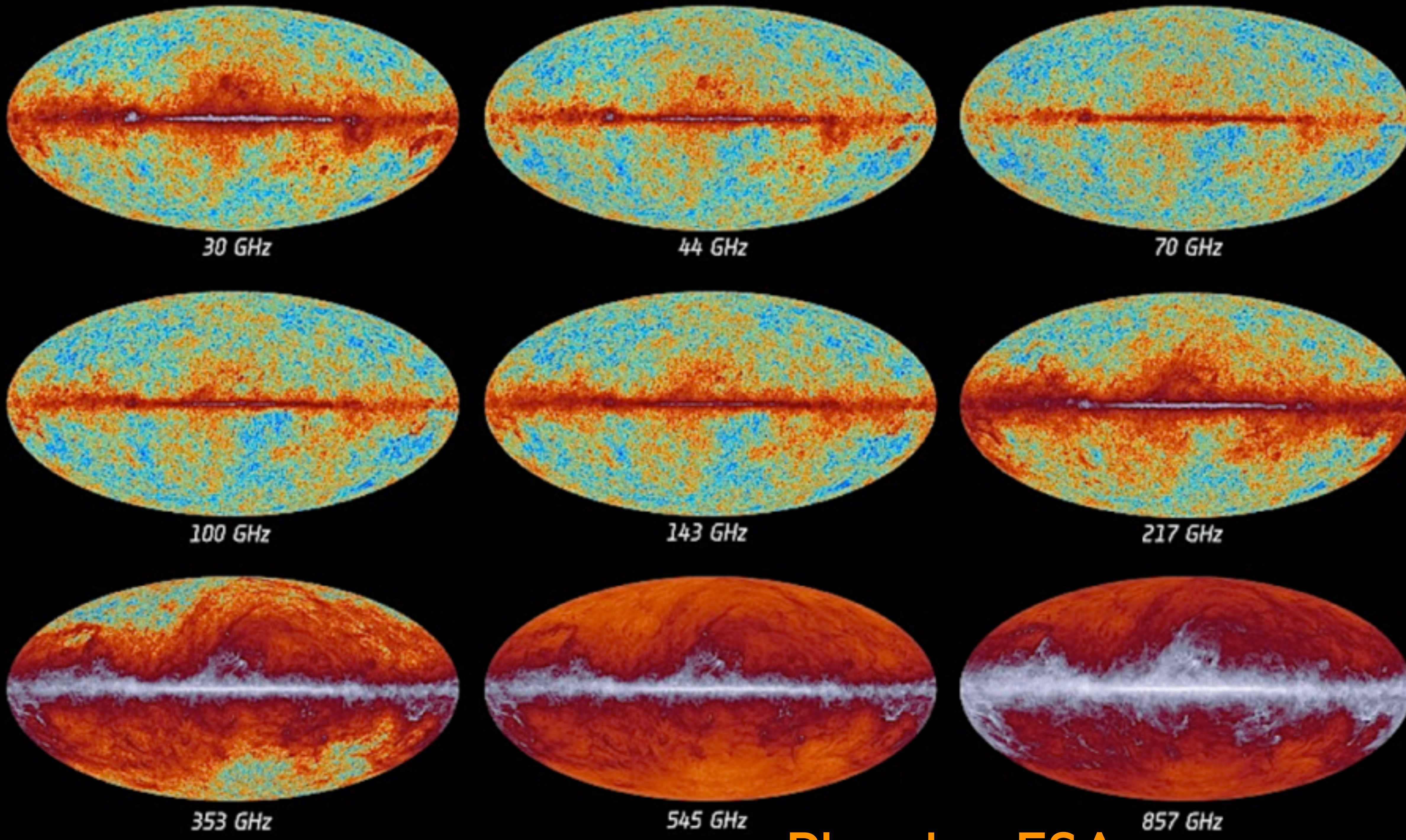


diffuse all sky spectrum
(don't look into LED/Sun/Moon/MW)

Halpern & Scott 1999

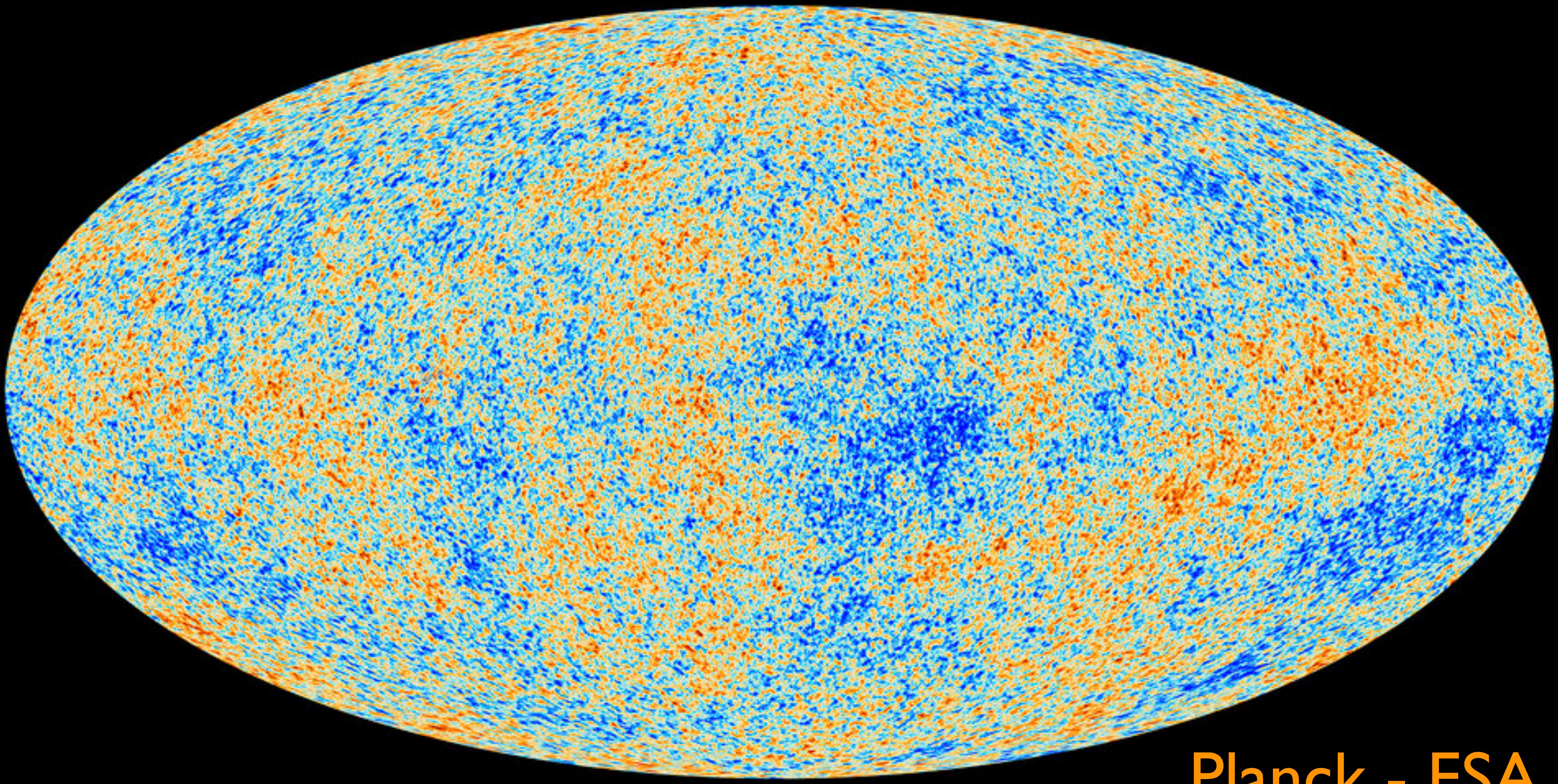
Intensity Maps of Mikrowave Sky

9 frequency channels



Planck - ESA

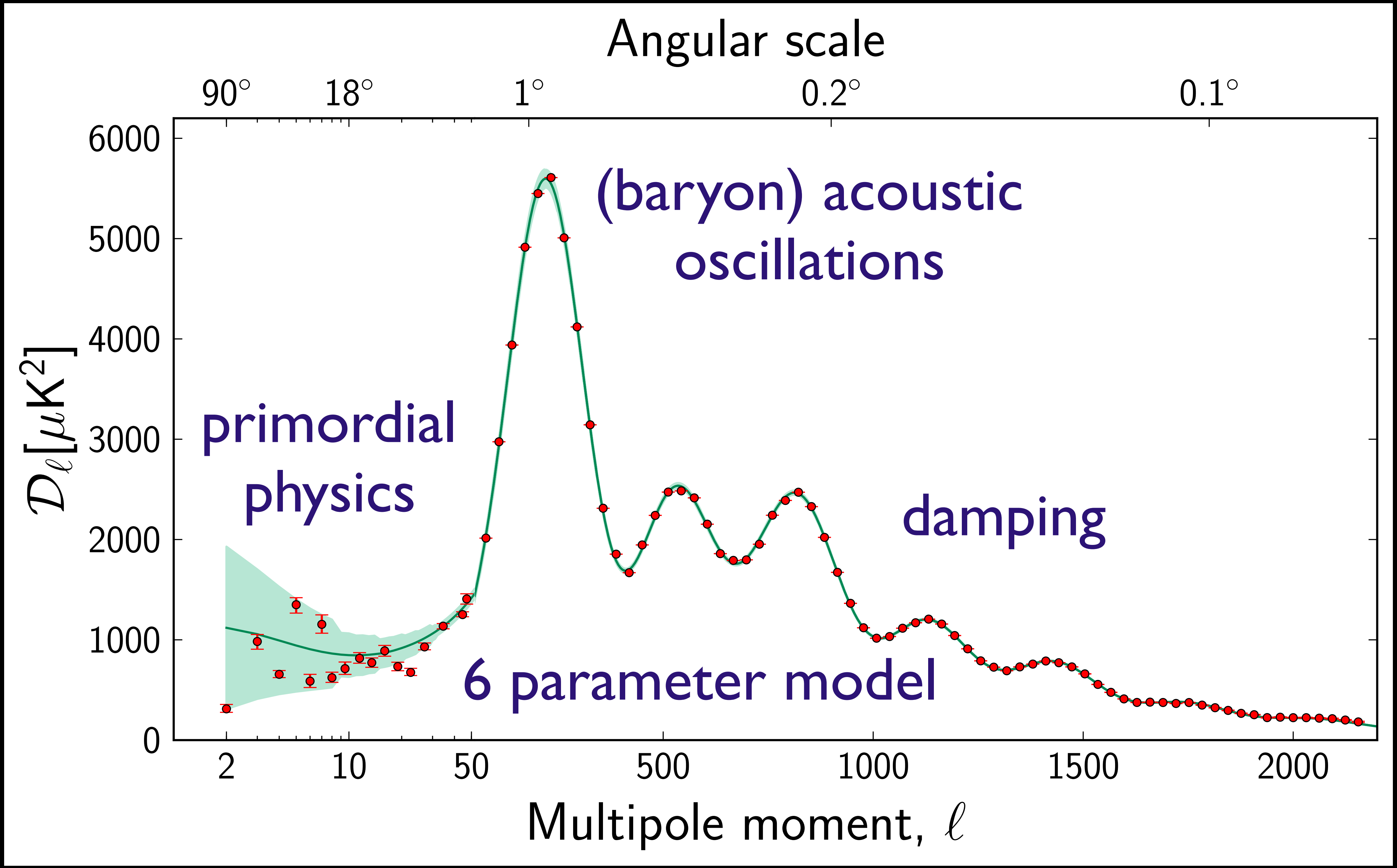
Temperature anisotropies



SMICA map

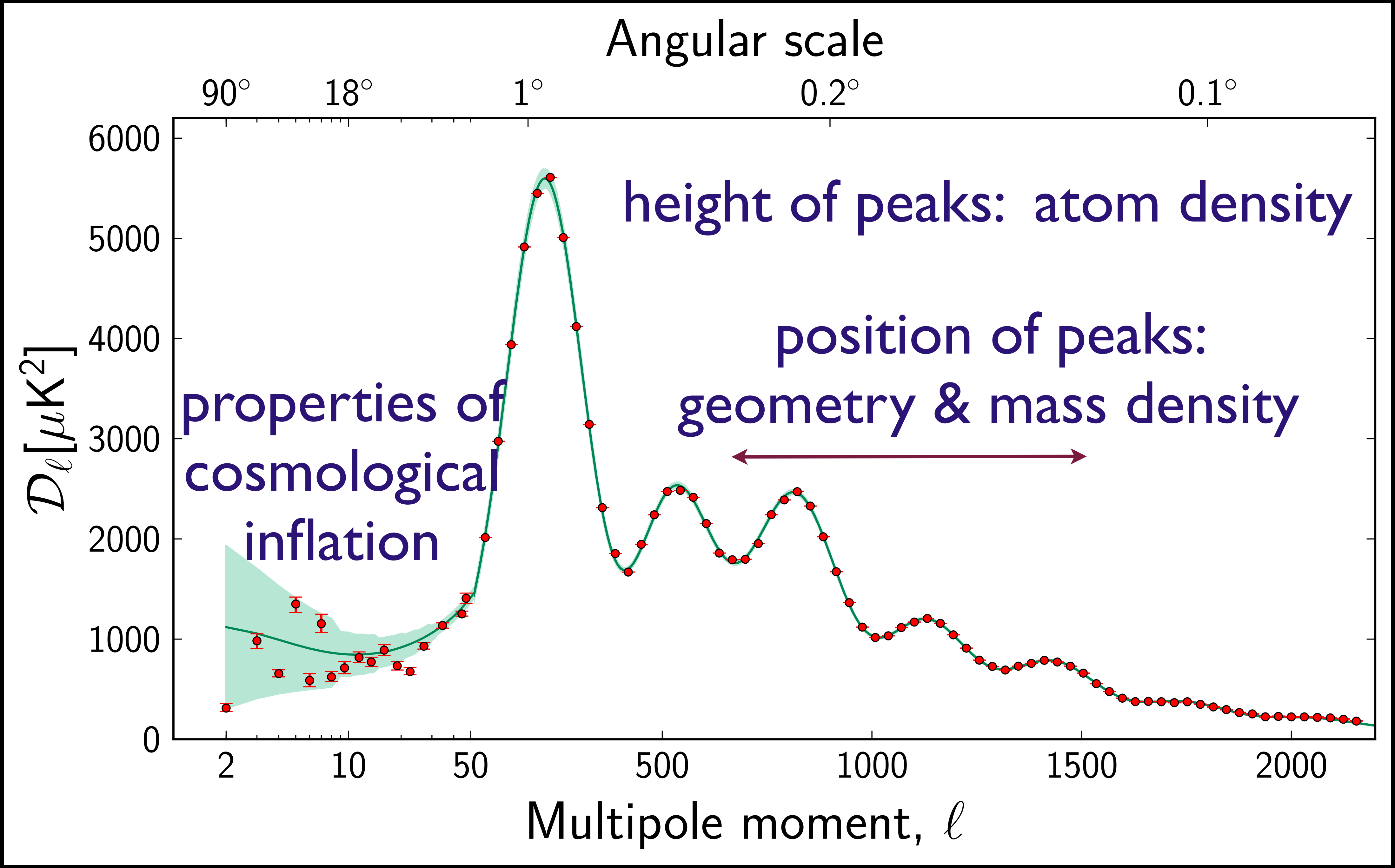
Planck - ESA

Band power



Planck 2013

Band power



Angular scale
90°
18°
1°
0.2°
0.1°
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell [\mu K^2]$
height of peaks: atom density
position of peaks:
geometry & mass density
properties of
cosmological
inflation
2
10
50
500
1000
1500
2000
Multipole moment, ℓ

Cosmological Parameters

Table 3. Parameters of the base ΛCDM cosmology computed from the 2015 baseline *Planck* likelihoods illustrating the consistency of parameters determined from the temperature and polarization spectra at high multipoles. Column [1] uses the TT spectra at low and high multipoles and is the same as column [6] of Table 1. Columns [2] and [3] use only the TE and EE spectra at high multipoles, and only polarization at low multipoles. Column [4] uses the full likelihood. The last column lists the deviations of the cosmological parameters determined from the TT+lowP and TT,TE,EE+lowP likelihoods.

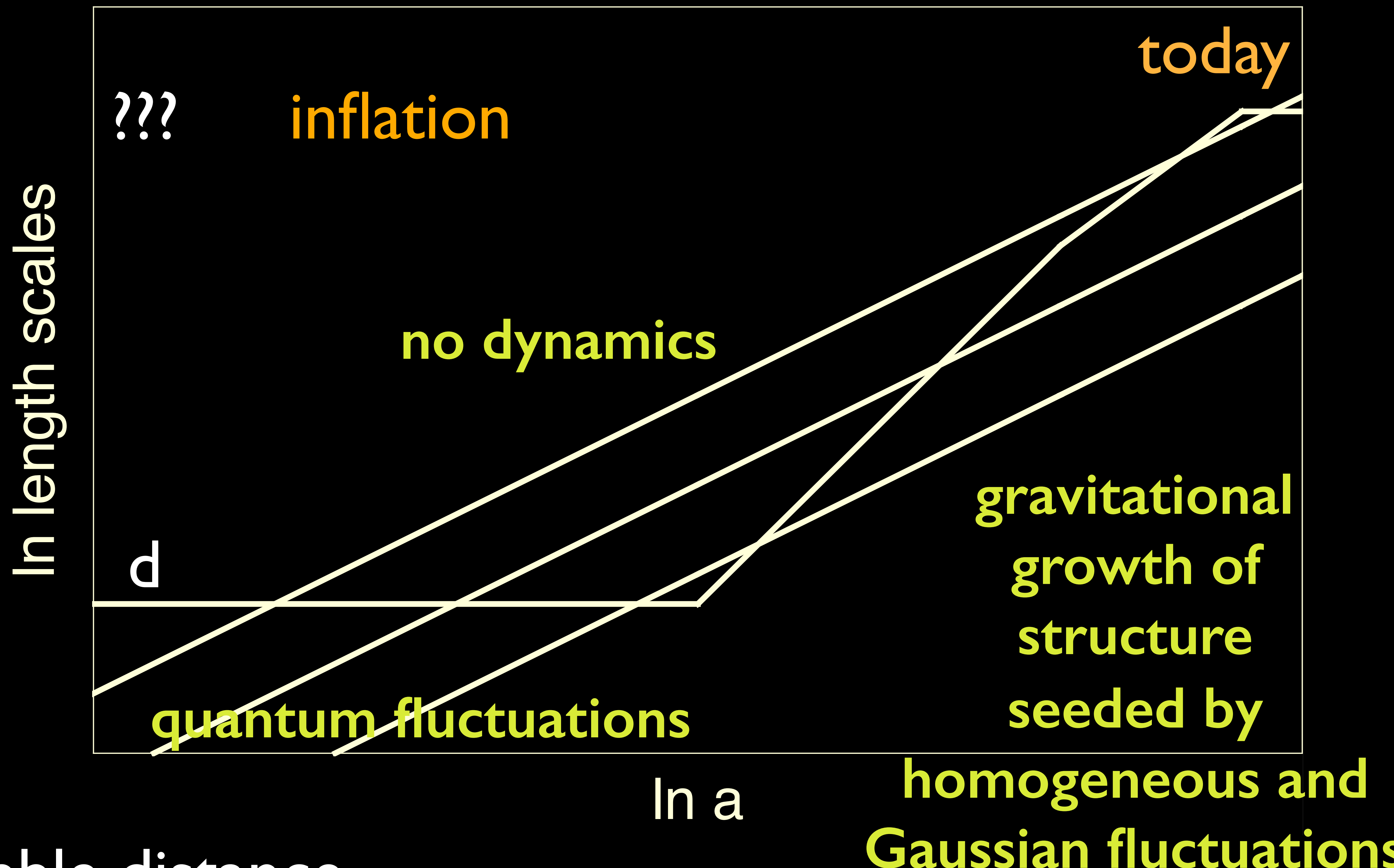
Parameter	[1] *Planck* TT+lowP	[2] *Planck* TE+lowP	[3] *Planck* EE+lowP	[4] *Planck* TT,TE,EE+lowP	$([1]-[4])/\sigma_{[1]}$
$\Omega_b h^2$	0.02222 ± 0.00023	0.02228 ± 0.00025	0.0240 ± 0.0013	0.02225 ± 0.00016	-0.1
$\Omega_c h^2$	0.1197 ± 0.0022	0.1187 ± 0.0021	$0.1150^{+0.0048}_{-0.0055}$	0.1198 ± 0.0015	0.0
$100\theta_{MC}$	1.04085 ± 0.00047	1.04094 ± 0.00051	1.03988 ± 0.00094	1.04077 ± 0.00032	0.2
τ	0.078 ± 0.019	0.053 ± 0.019	$0.059^{+0.022}_{-0.019}$	0.079 ± 0.017	-0.1
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.031 ± 0.041	$3.066^{+0.046}_{-0.041}$	3.094 ± 0.034	-0.1
n_s	0.9655 ± 0.0062	0.965 ± 0.012	0.973 ± 0.016	0.9645 ± 0.0049	0.2
H_0	67.31 ± 0.96	67.73 ± 0.92	70.2 ± 3.0	67.27 ± 0.66	0.0
Ω_m	0.315 ± 0.013	0.300 ± 0.012	$0.286^{+0.027}_{-0.038}$	0.3156 ± 0.0091	0.0
σ_8	0.829 ± 0.014	0.802 ± 0.018	0.796 ± 0.024	0.831 ± 0.013	0.0
$10^9 A_s e^{-2\tau}$	1.880 ± 0.014	1.865 ± 0.019	1.907 ± 0.027	1.882 ± 0.012	-0.1

Planck 2016

6-parameter fit to flat ΛCDM model with primordial power-law spectrum of density perturbations:

$\Omega_m = \Omega_b + \Omega_c$; $\Omega_m + \Omega_\Lambda = 1$; $H_0 = 100\ h$ km/s/Mpc; $P(k) = A\ k^{n-1}$; τ

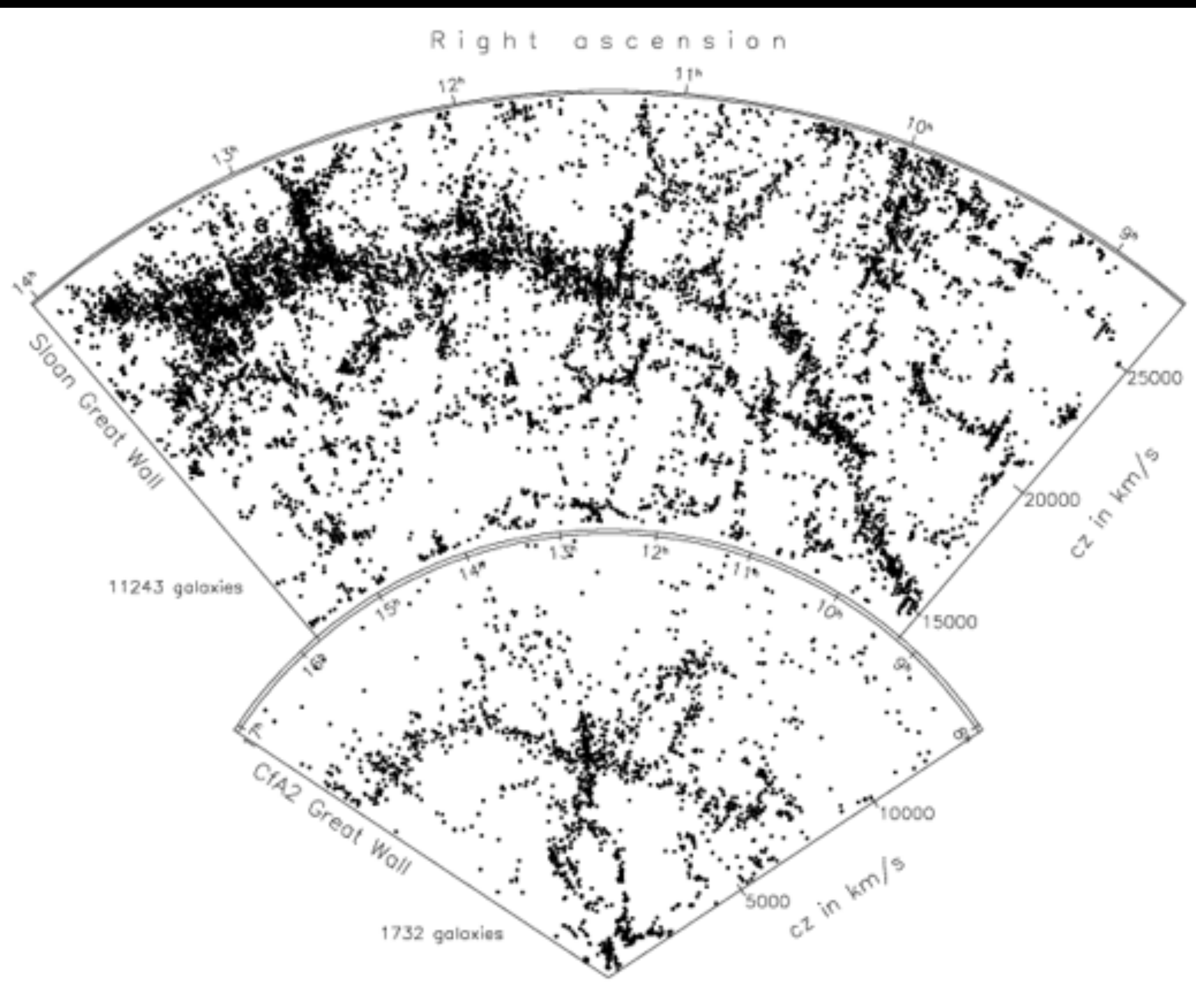
Quantum to Classical



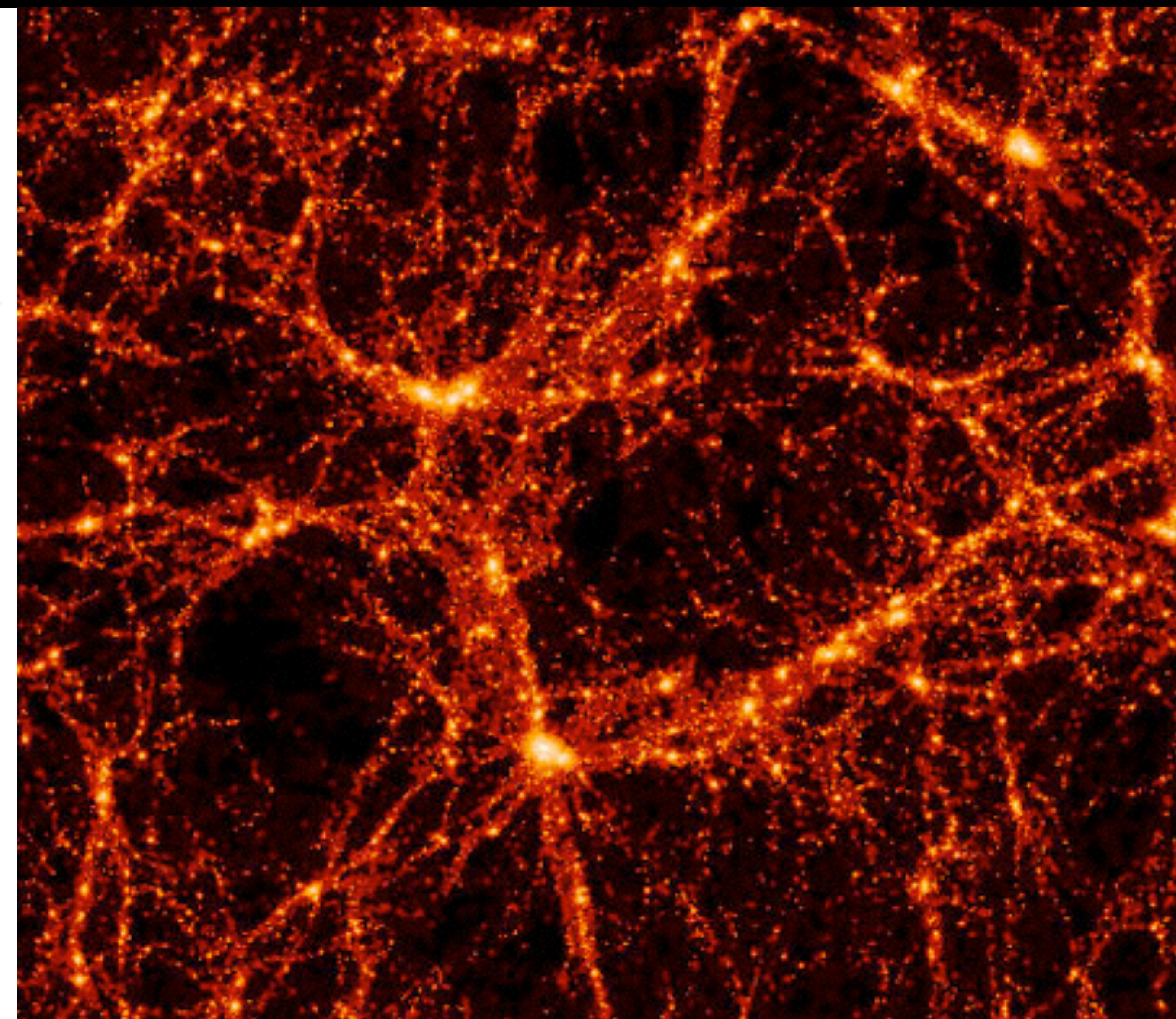
d Hubble distance

Large Scale Structure

Observation of galaxy distribution



Simulation of mass distribution



Cosmology questions

- initial conditions: isotropy, gaussianity, curvature, ...
- constituents: dark matter, dark energy, role of neutrinos in cosmology, ...
- laws of physics: modified gravity, time varying fundamental constants, ...

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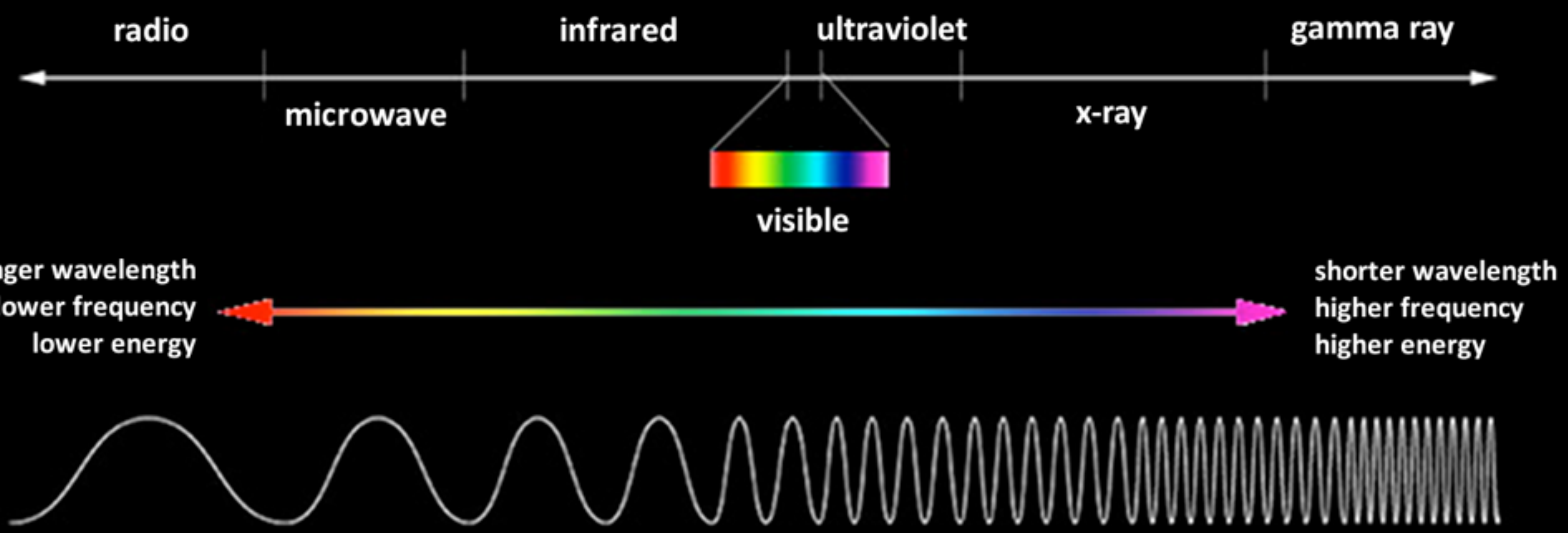
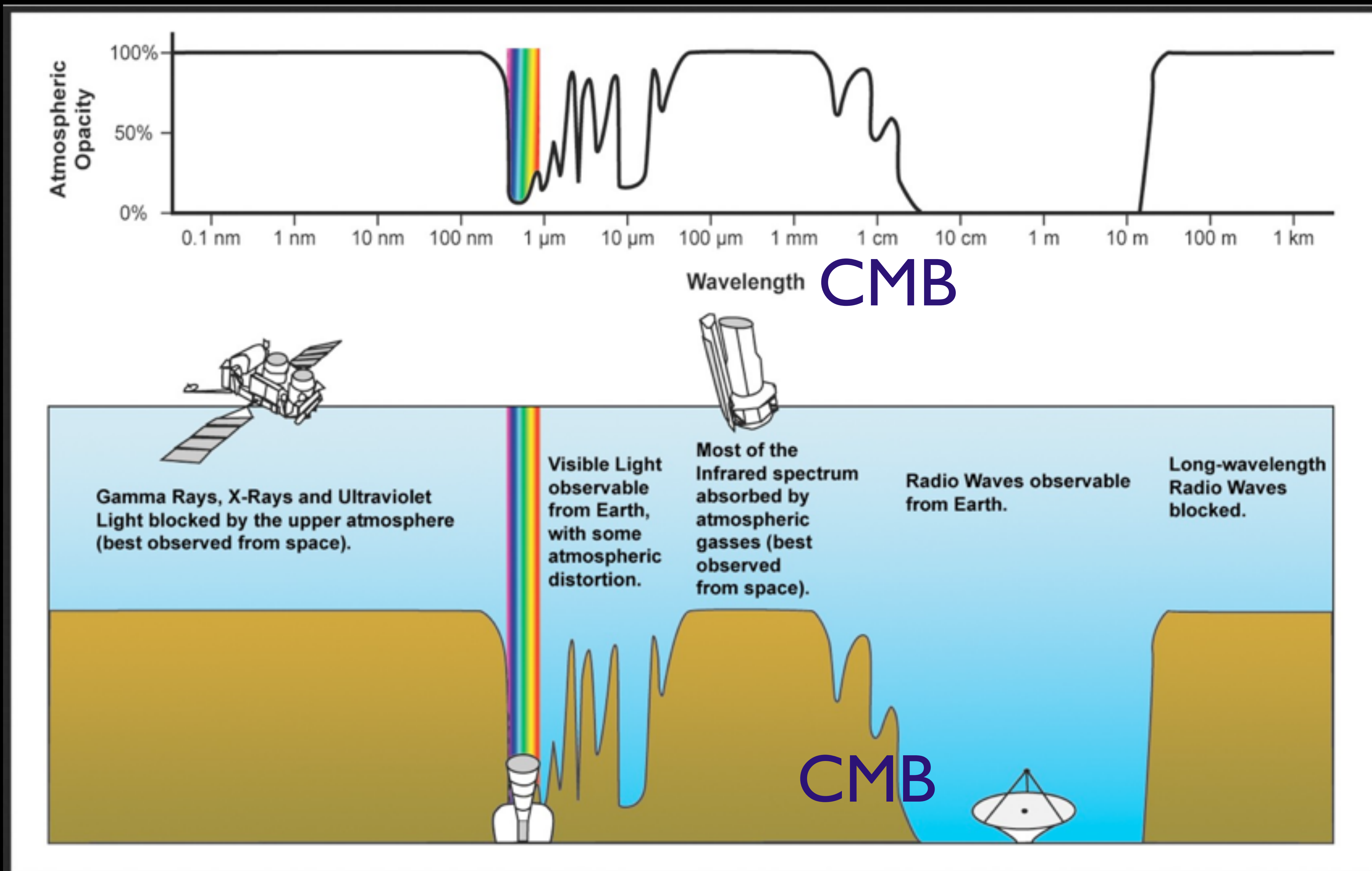
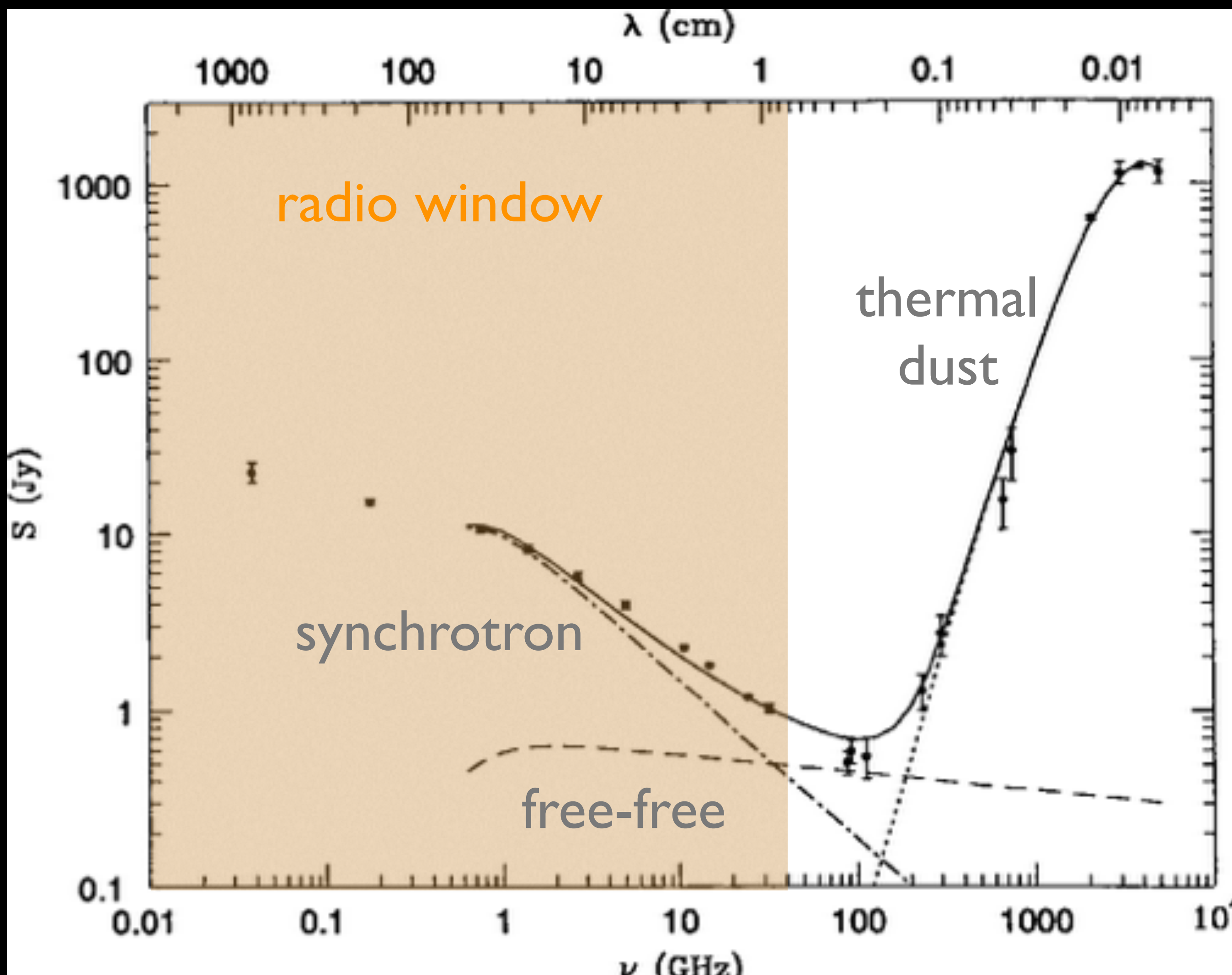
Electromagnetic Spectrum



Transparency of Atmosphere/Ionosphere



Emission of radio waves



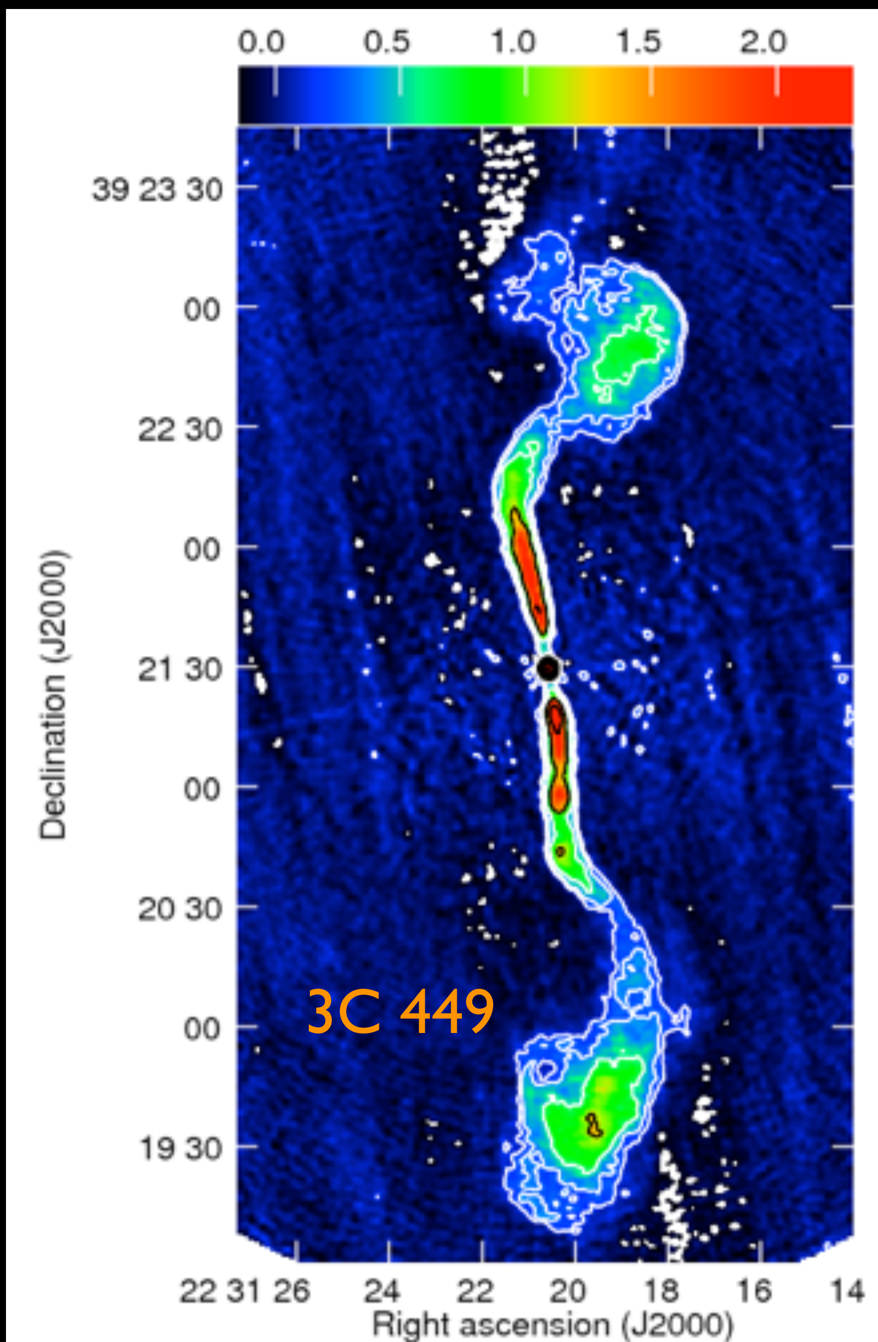
Condon 1992

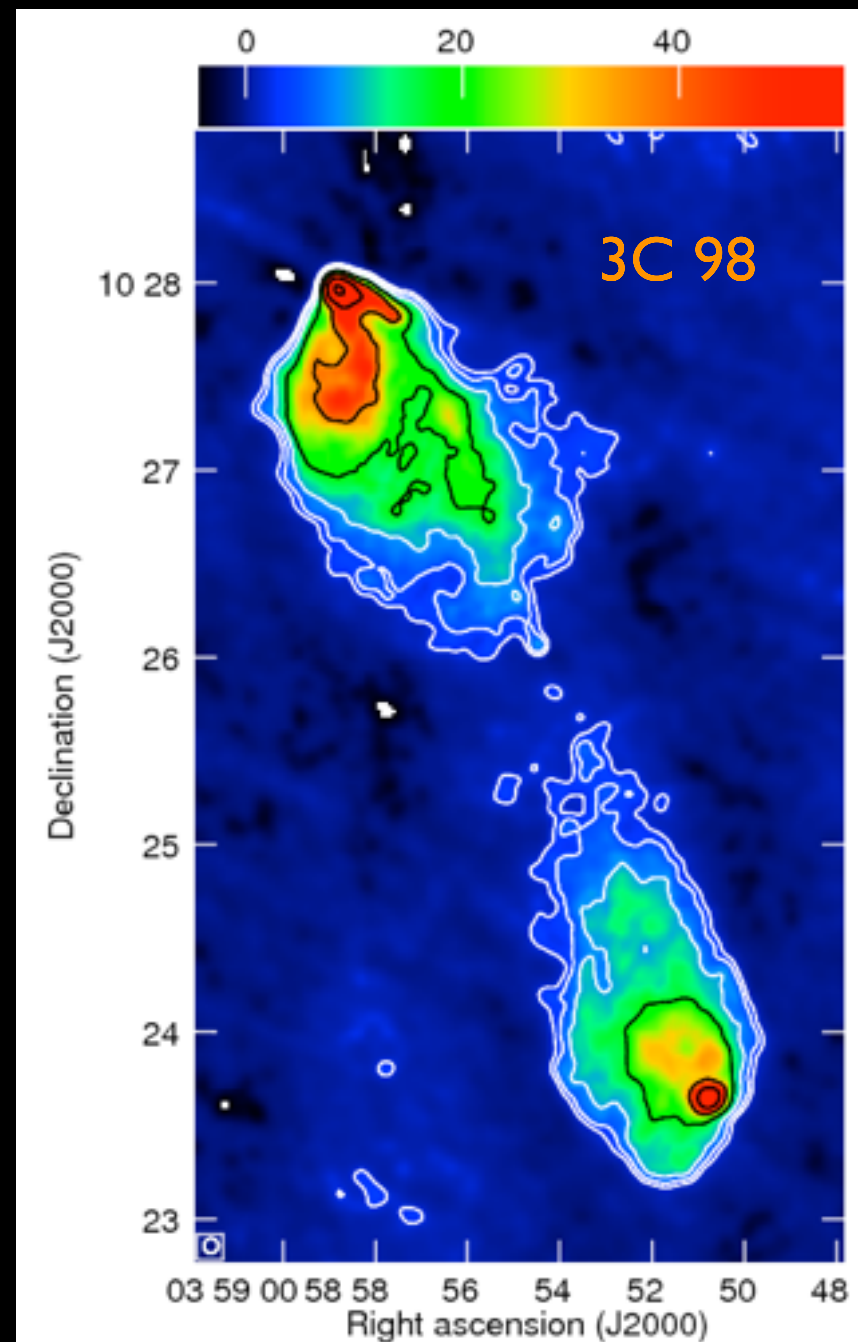
spectrum of the starburst galaxy M82
(10 x SFR of Milky Way)

- synchrotron radiation from electrons in magnetic field
- free-free emission from electrons in ionised regions (HII)

galaxies are sources of radio continuum emission

Types of extragalactic radio sources





1. Active Galactic Nuclei (AGNs)

brightest radio sources visible throughout the universe

supermassive galactic black holes emit jets which are dumped in the intergalactic material

Faranoff-Riley (FR) type I and type II

images from Kharb et al. 2015

Types of extragalactic radio sources

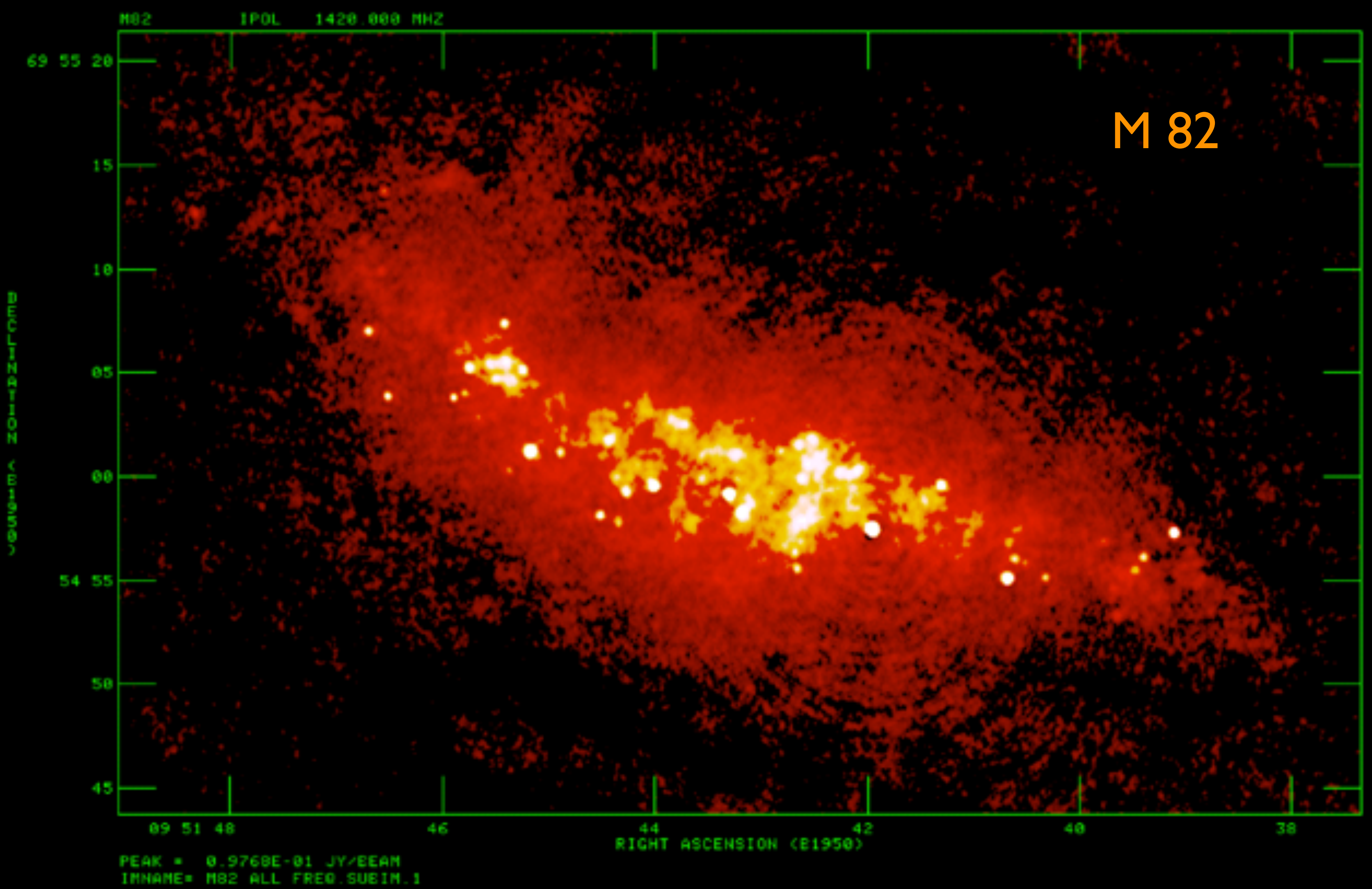


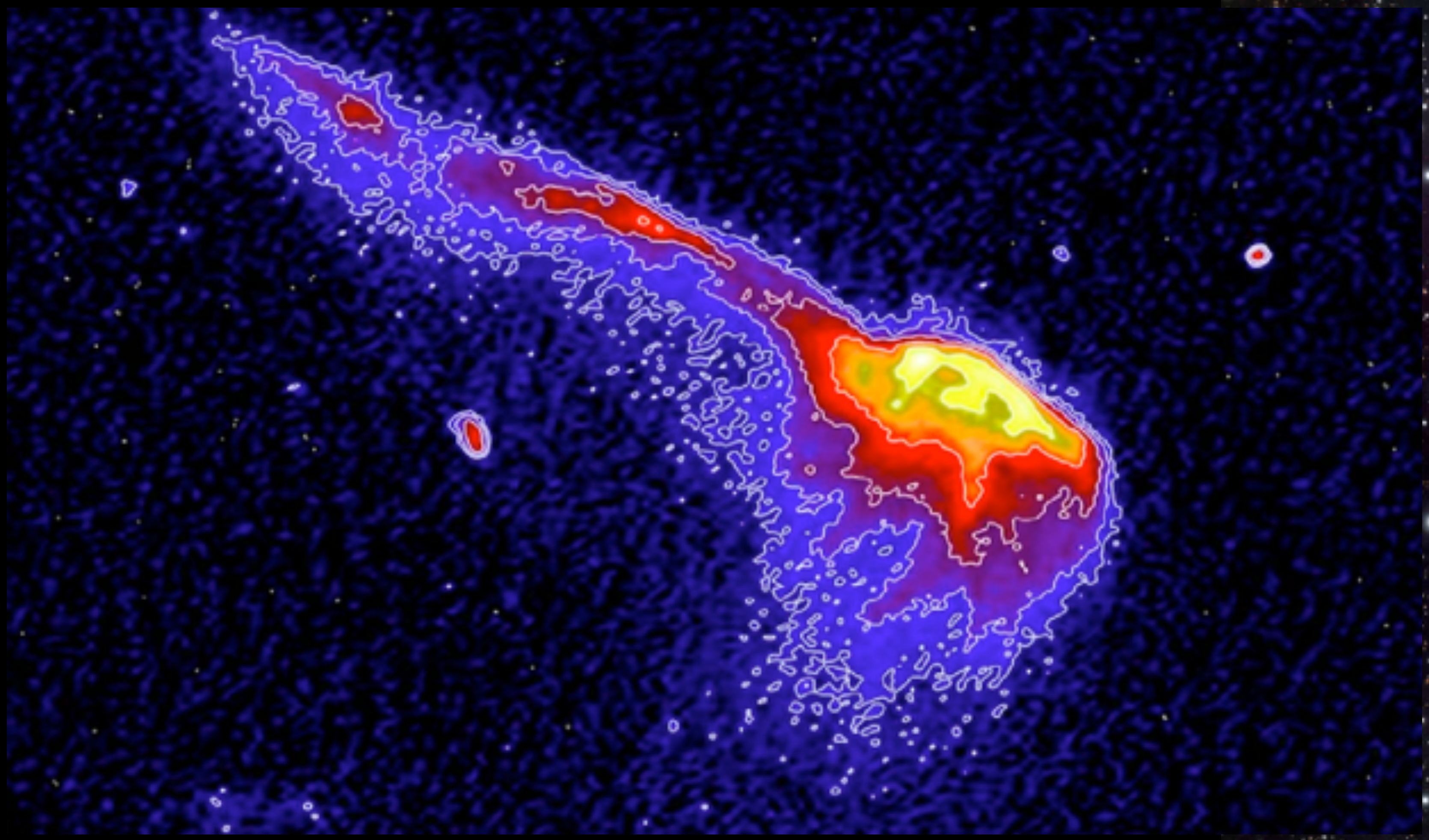
image from Muxlow et al. 1996

2. Starforming Galaxies

not as bright, but
majority of radio sources

Hubble image

Diffuse emission — radio relics



LOFAR 120 - 180 MHz: van Weeren et al. 2016

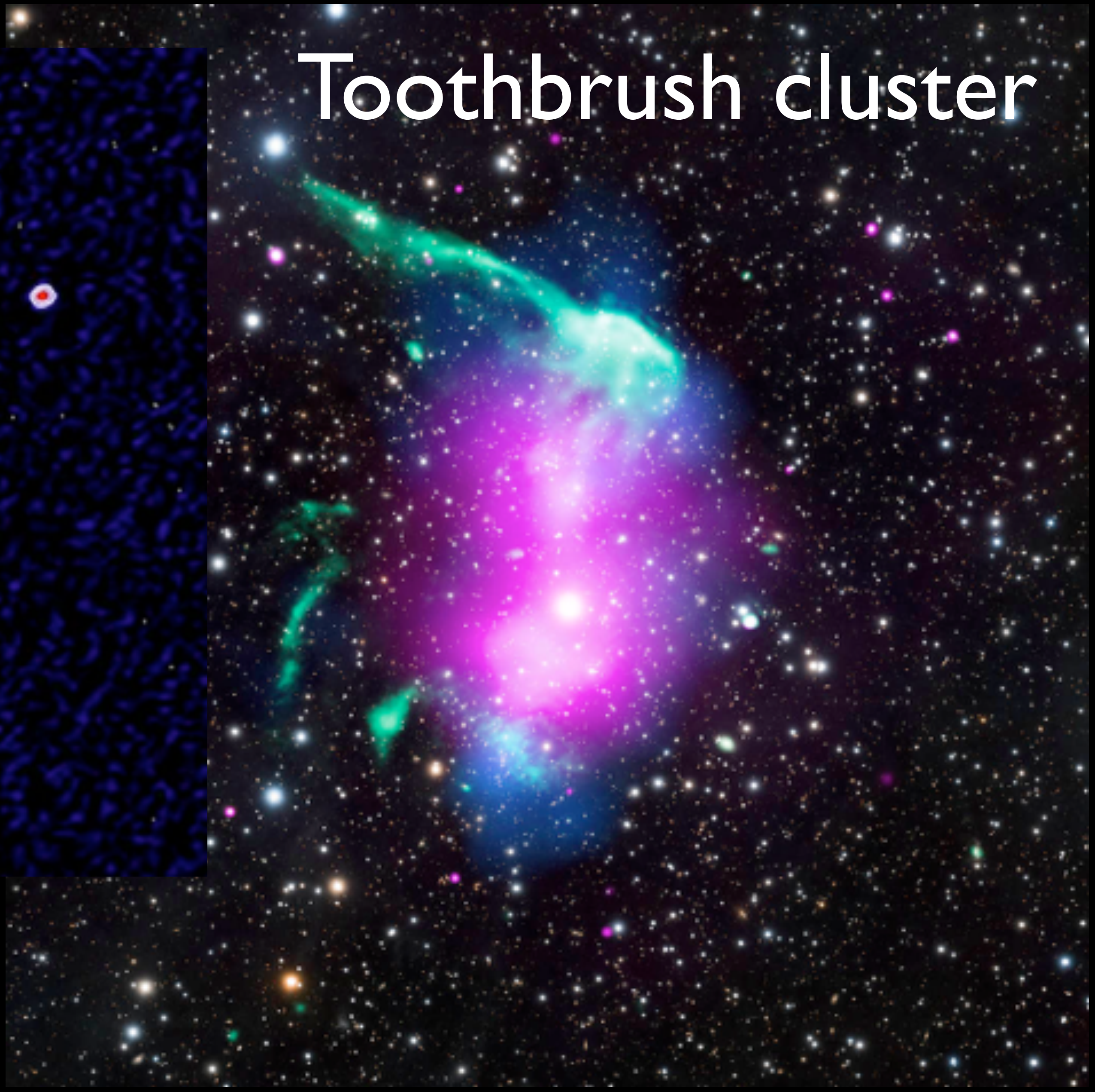
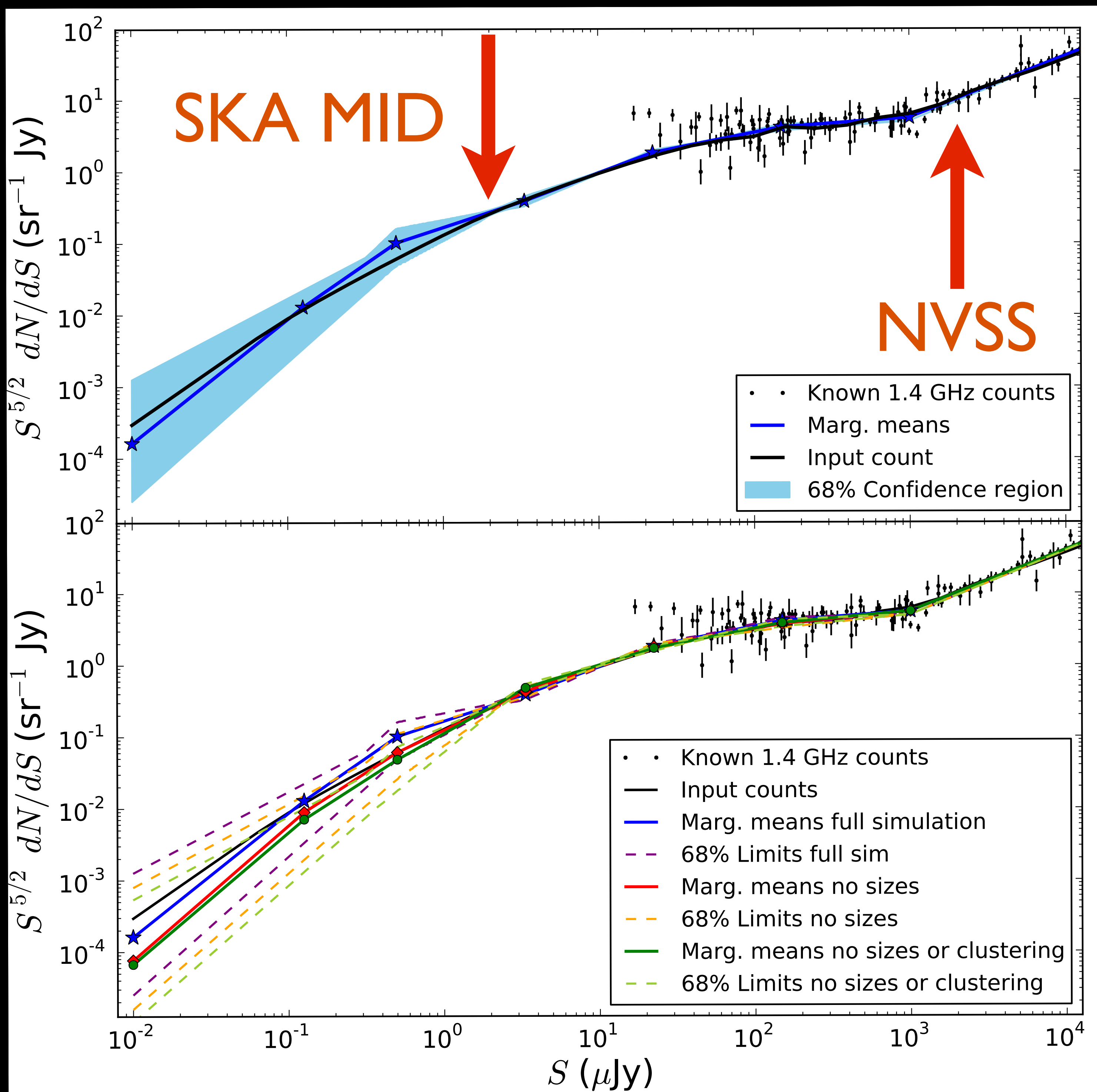


image credit: NASA
combinded from radio (green), X-ray (purple), IR (white), gravitational lensing (blue)

believed to be a relic of a past merger of two galaxy clusters

Cosmic Radio Source Counts



JVLA, Vernstrom et al. 2013

two populations:

* AGNs (FRI-II, RQQ)

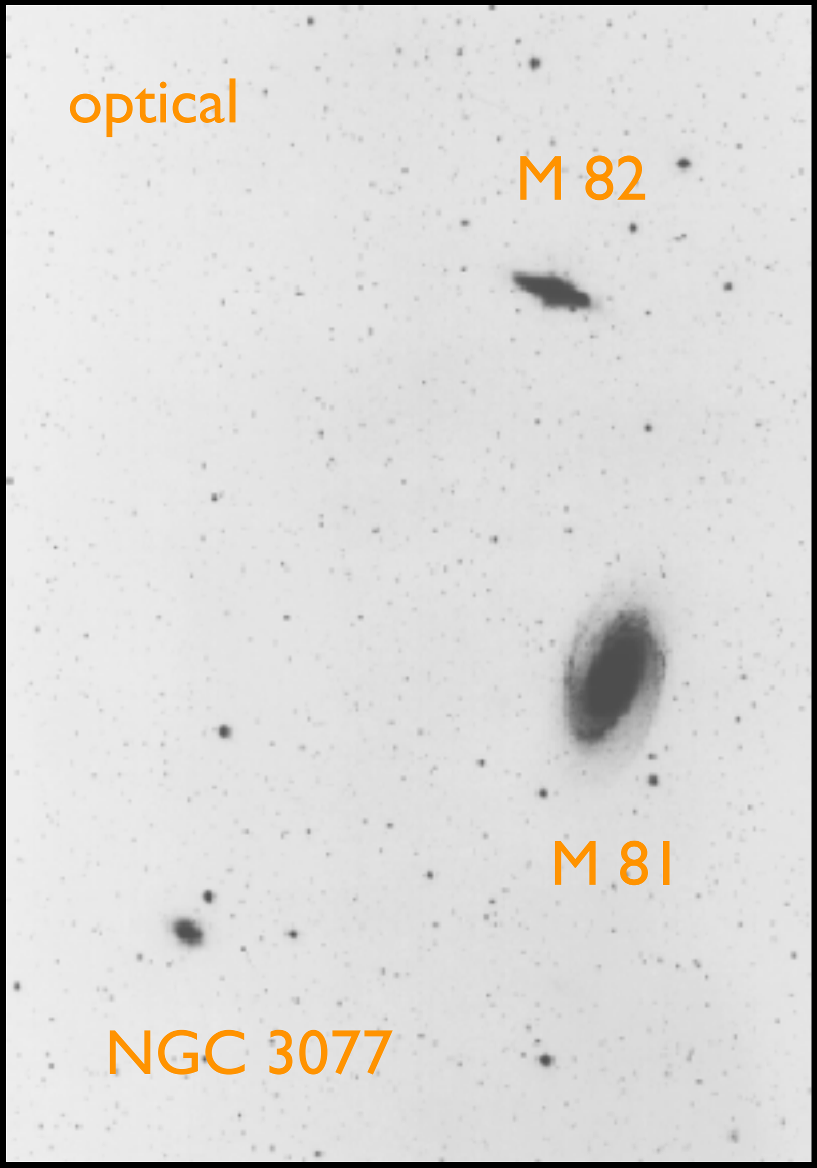
* galaxies (SFG, SBG)

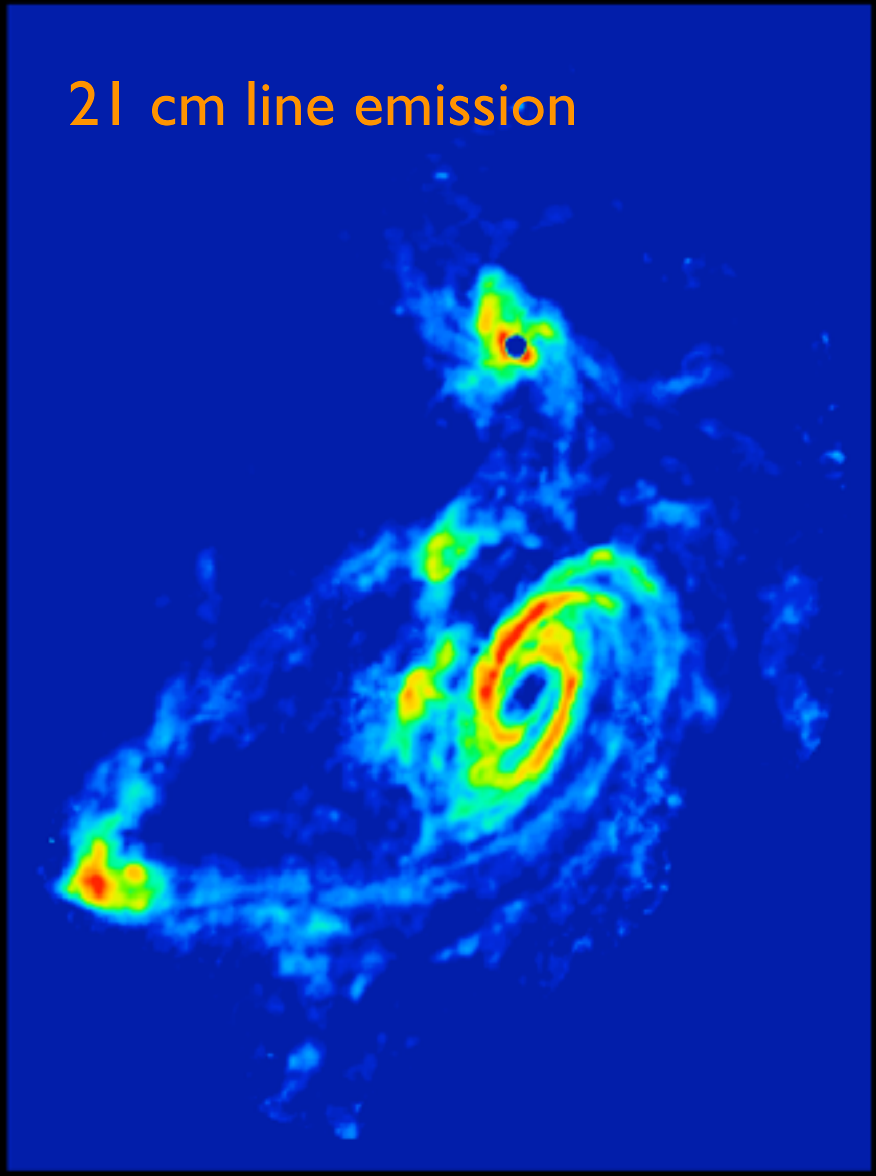
AGNs dominate at large fluxes

star forming galaxies dominate below ~ 1 mJy

identification of morphology for angular resolution 0.5”

Emission of radio waves





images from Yun et al. 1994

all galaxies contain atoms and molecules

neutral hydrogen (HI) is visible due to its hyperfine structure at 21 cm

other important lines are recombination lines and molecular lines (e.g. CO)

an important aspect are masers, which serve as standard rulers (Hubble constant)

galaxies are sources of line emission

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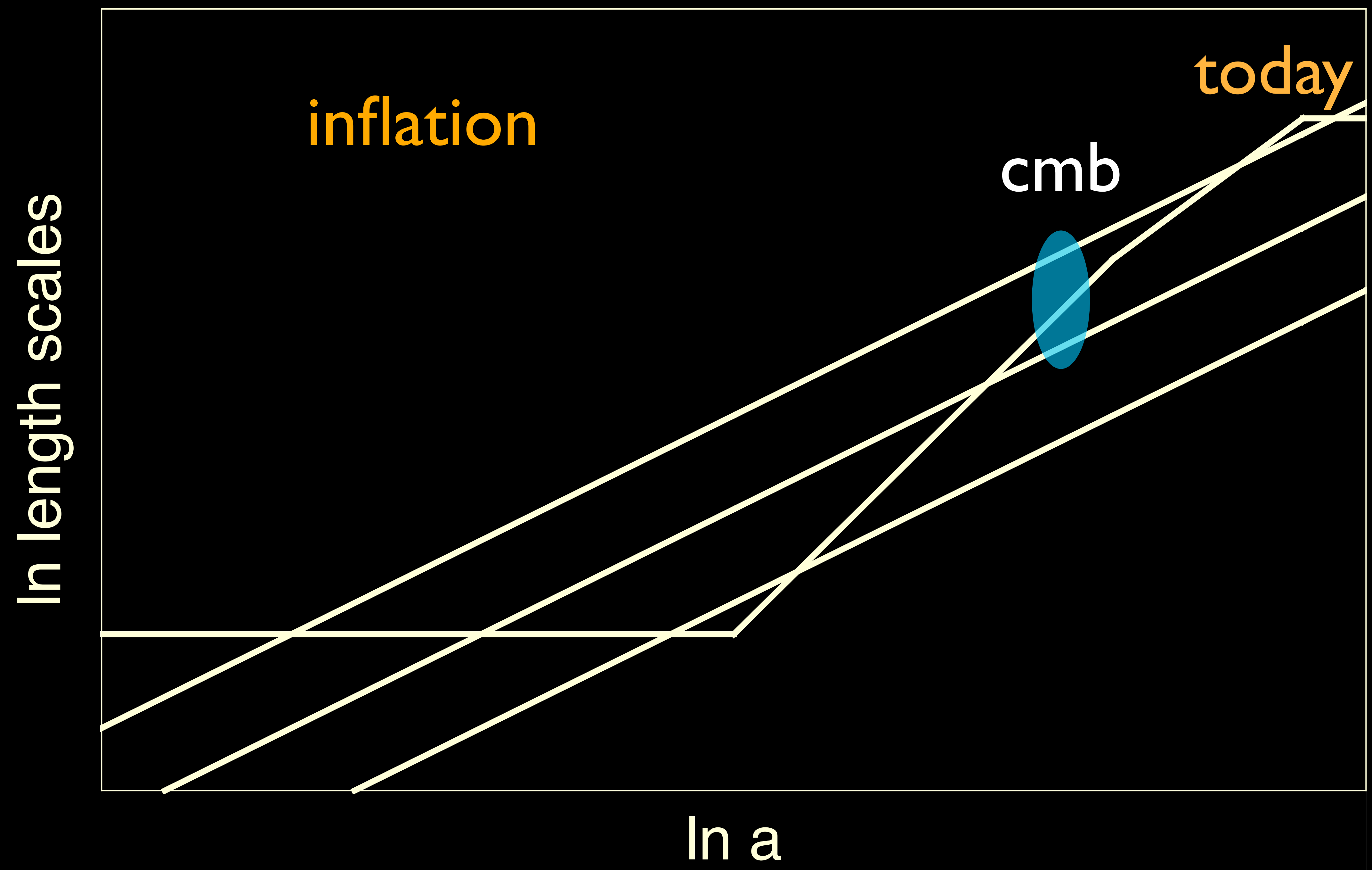
3 Types of Targets

- Discoveries: Epoch of Reionisation, Cosmic Dawn, Dark Ages; direct observation of acceleration via redshift drift
- Precision cosmology: BAO, P(k), weak lensing, etc.
- Fundamental tests: radio dipole, isotropy, non-Gaussianity, etc.

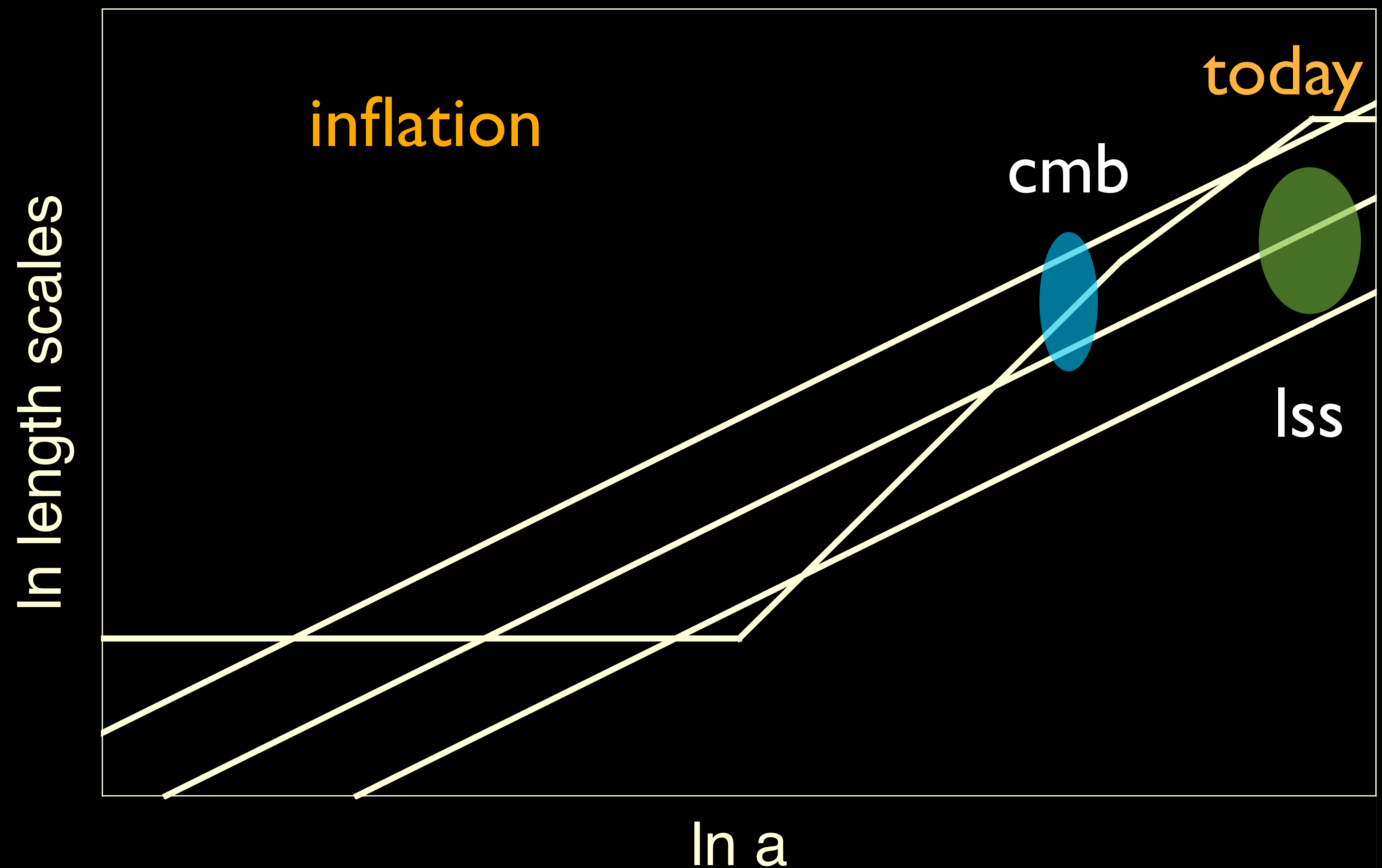
Probe cosmology across times and scales

d Hubble distance

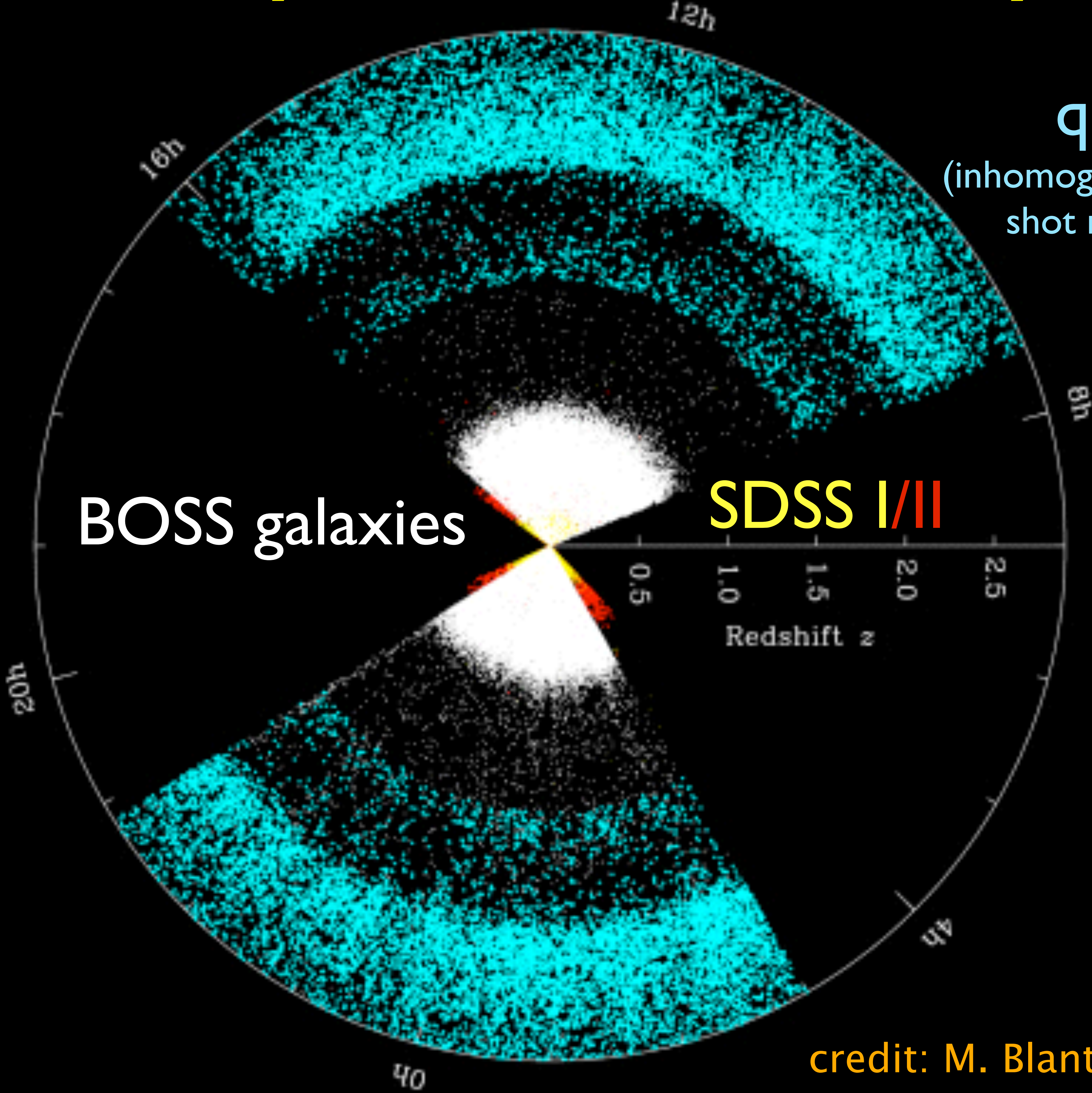
Probe cosmology across times and scales



Probe cosmology across times and scales



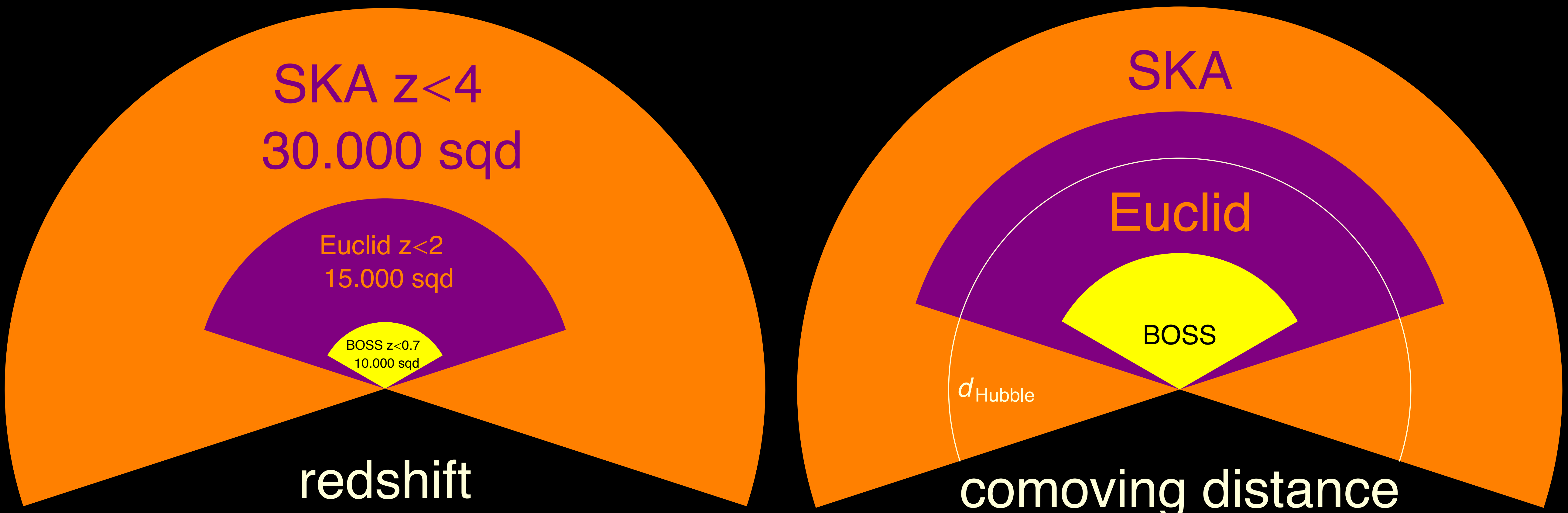
Galaxy redshift surveys



credit: M. Blanton 2011

Cosmic volumes probed

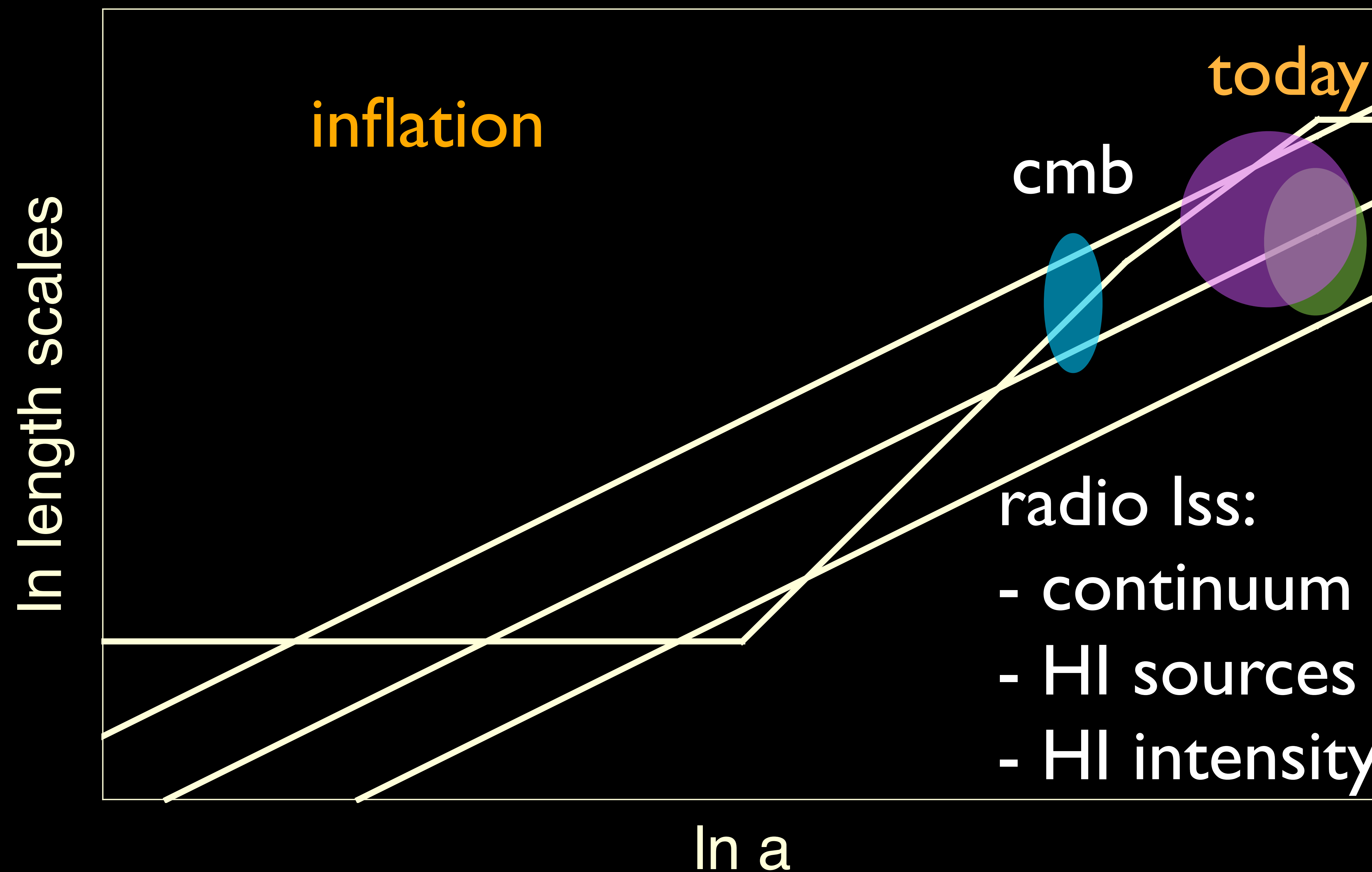
with continuum and HI galaxy surveys



Key advantages of radio continuum and HI surveys:

* more independent modes that optical/ir/cmb
* different systematics from optical/ir

Probe cosmology across times and scales



SKA's unique cosmology potential

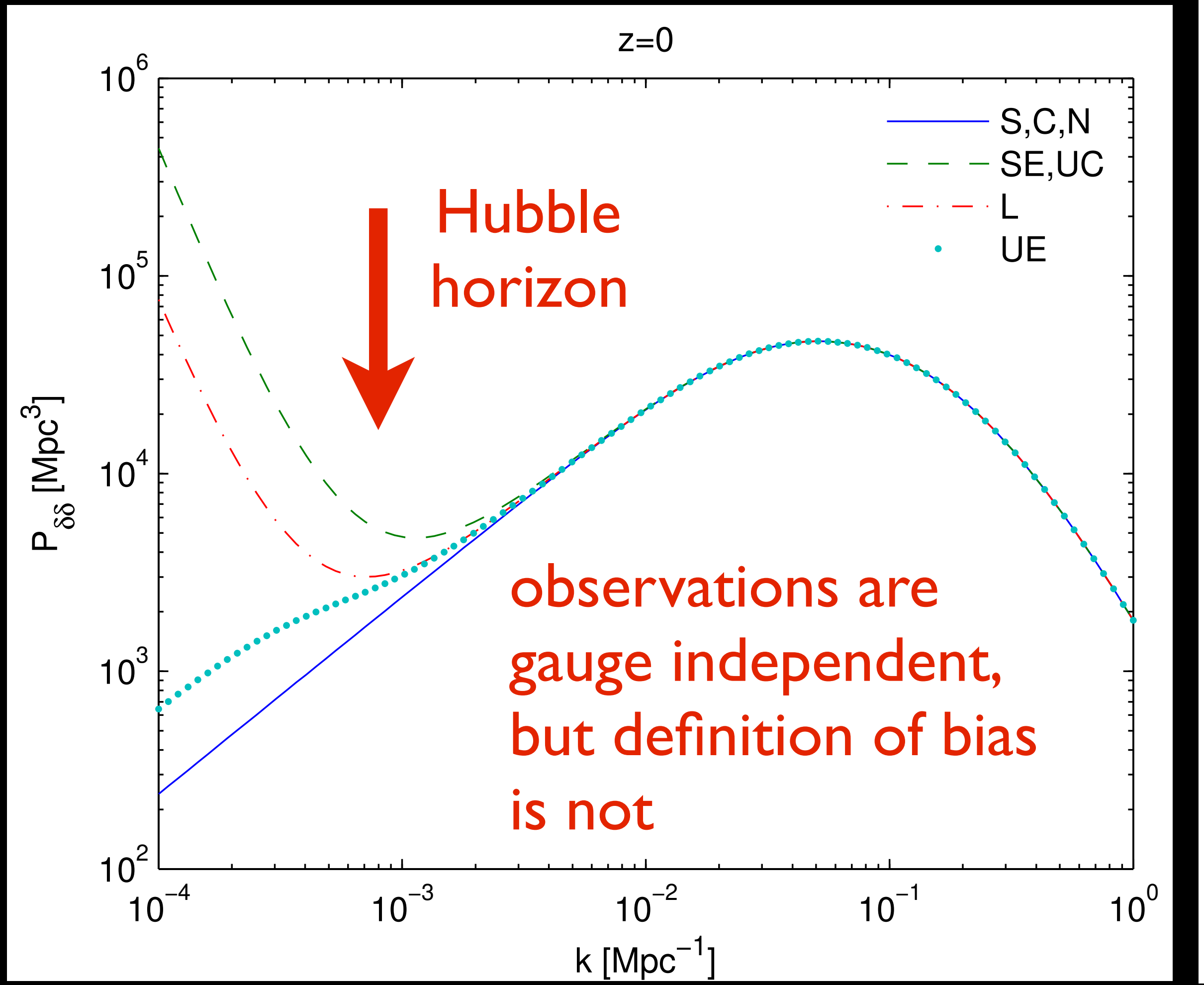
* access super-horizon scales at z = 1 to ~ 20 (H1 intensity mapping)
* see "all" H1 in the Universe
* huge number of independent modes (more than CMB!)
* different systematics as optical/infra-red/cmb
* morphology identification (continuum survey) breaks bias degeneracies and reduces cosmic variance at largest scales

SKA phase 1

- epoch of reionisation and cosmic dawn: images and P(k,z) at z = 5 to ~ 20 (a statistical detection might happen before SKA1 starts with MWA or LOFAR)
- continuum survey (650 - 1100 MHz, 0.5”, all sky at >2 μJy): isotropy, autocorrelation, integrated Sachs-Wolfe, cosmic magnification
- HI galaxy survey (0.2 < z < 4, all sky): P(k), bao, f(z), weak lensing, …
- HI intensity mapping: bao most powerful

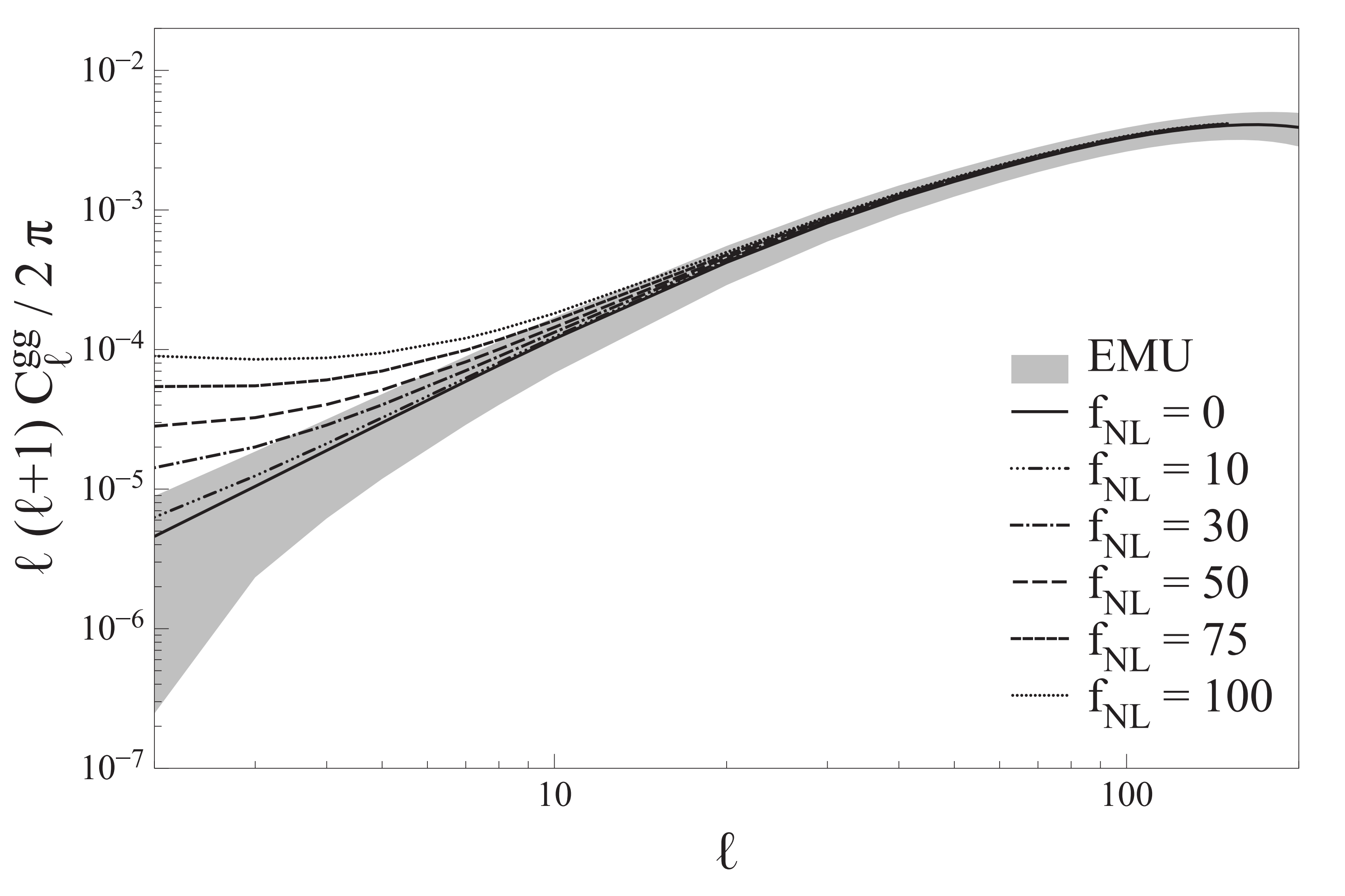
Physics at large scales

Relativistic effects



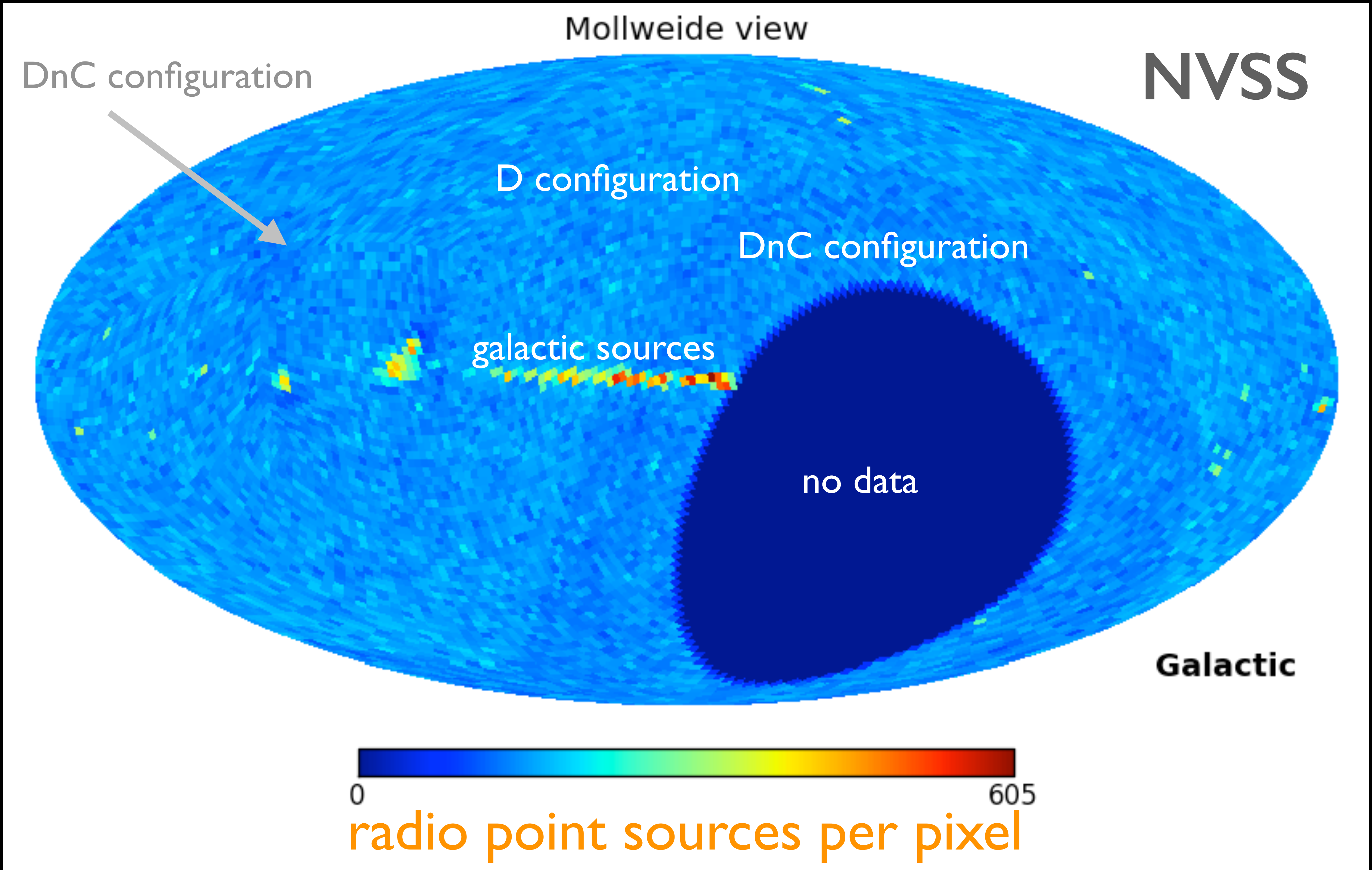
Flender and Schwarz 2013

Non-Gaussianity

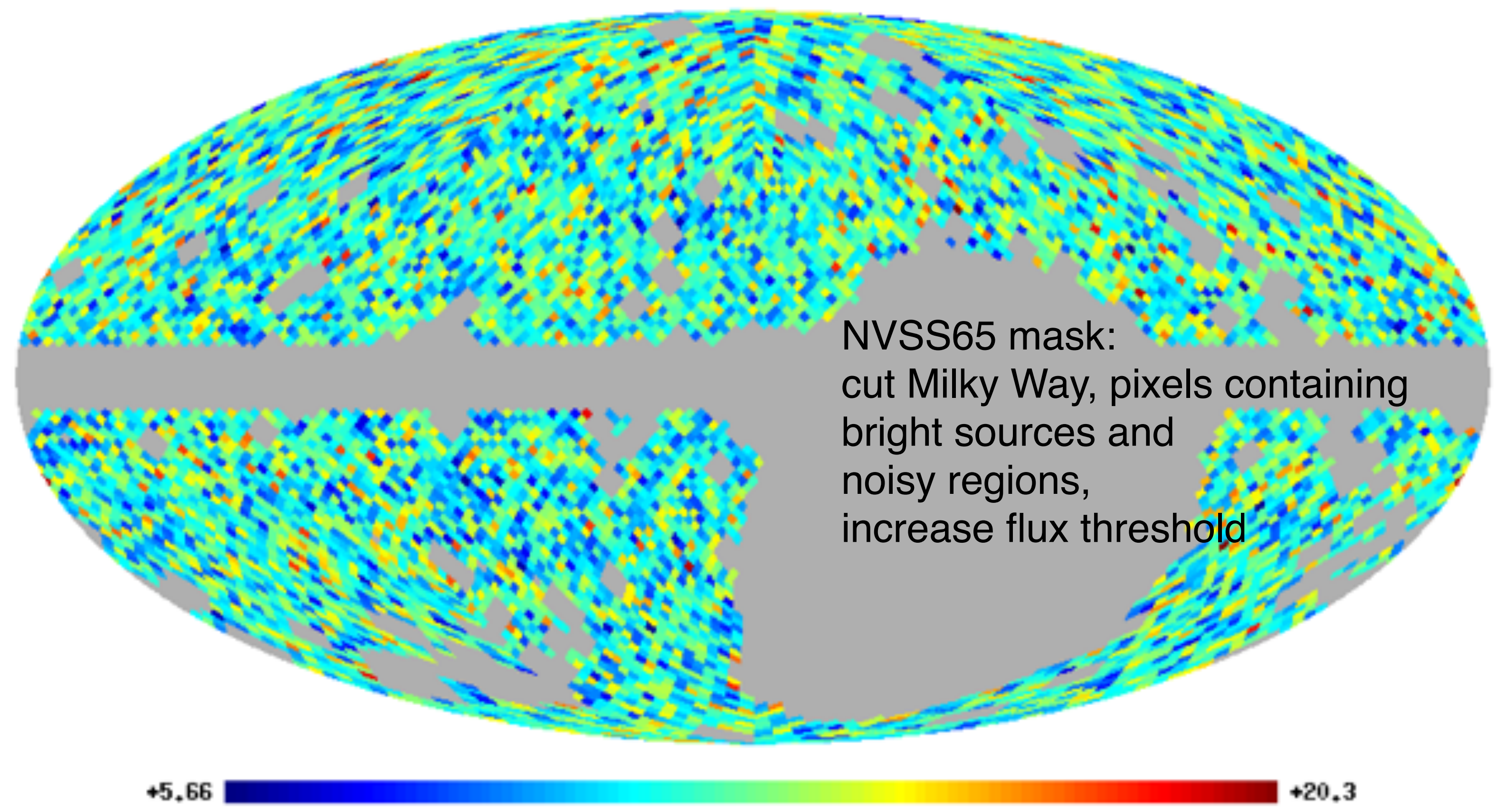


Raccanelli et al. 2013

Radio continuum survey
(NVSS, f = 1.4 GHz, S > 2 mJy)



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



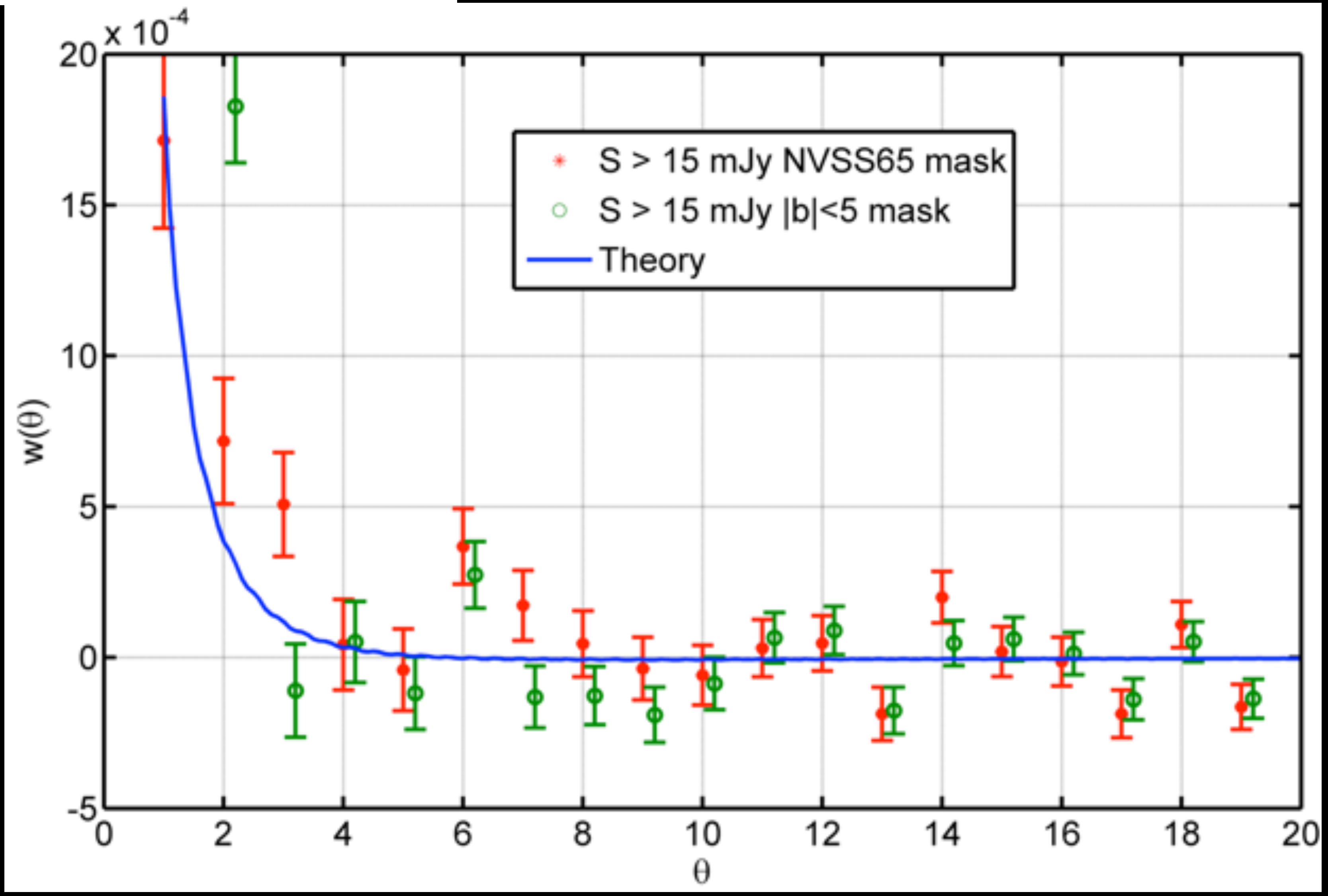
NVSS map of surface density

S > 15 mJy
f = 1.4 GHz

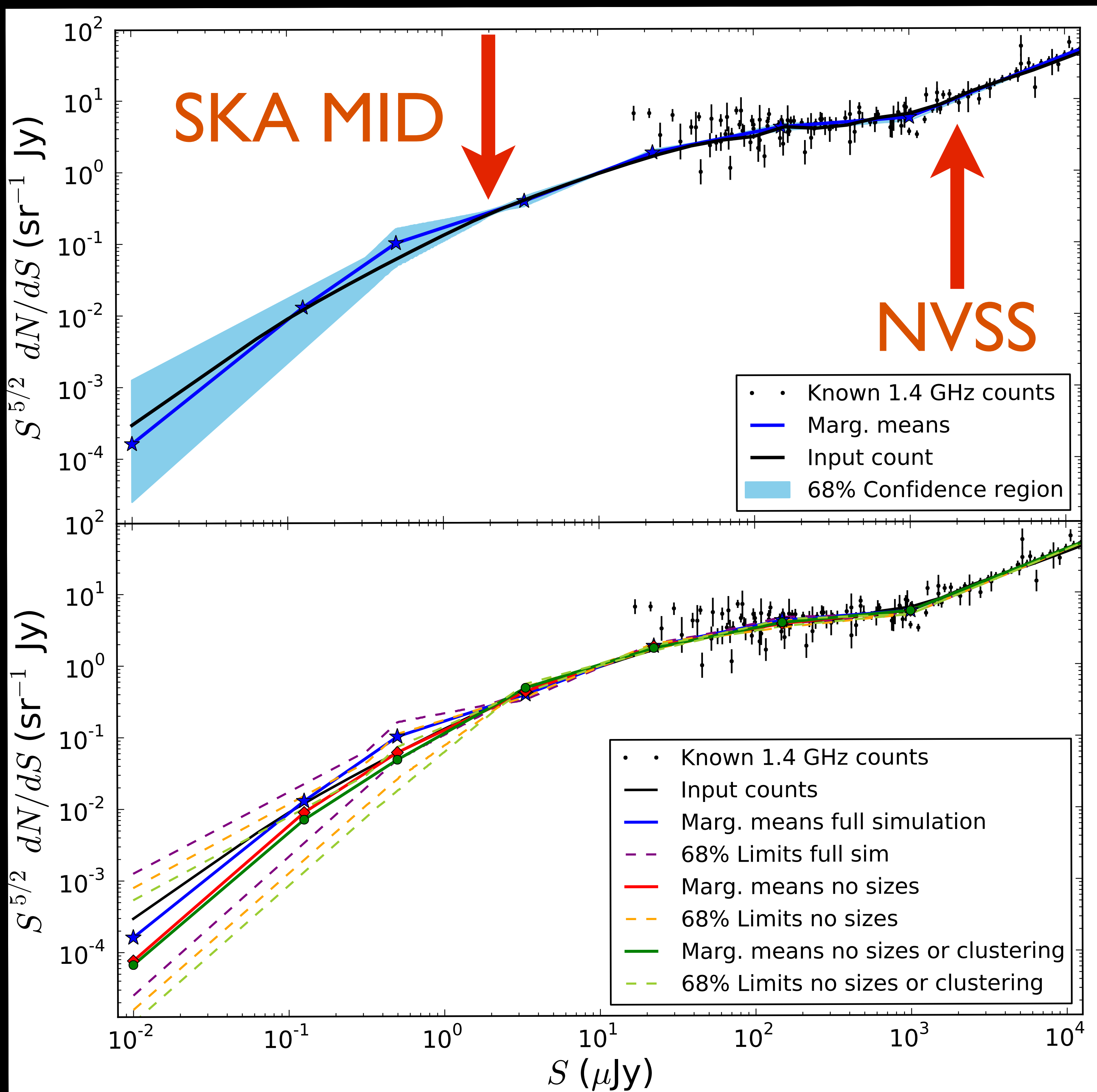
Chen & Schwarz 2015

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



Cosmic Radio Source Counts



JVLA, Vernstrom et al. 2013

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star forming galaxies
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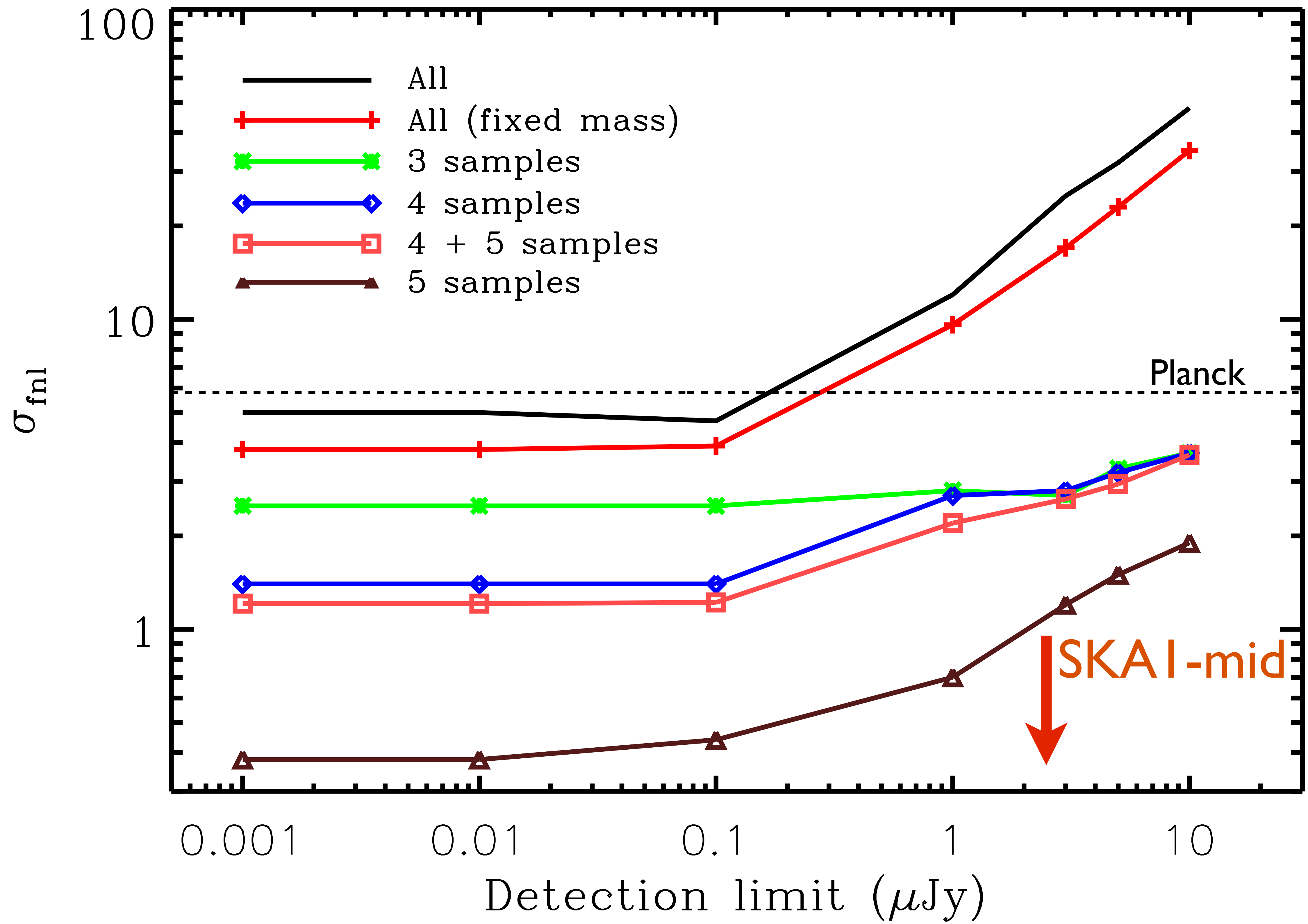
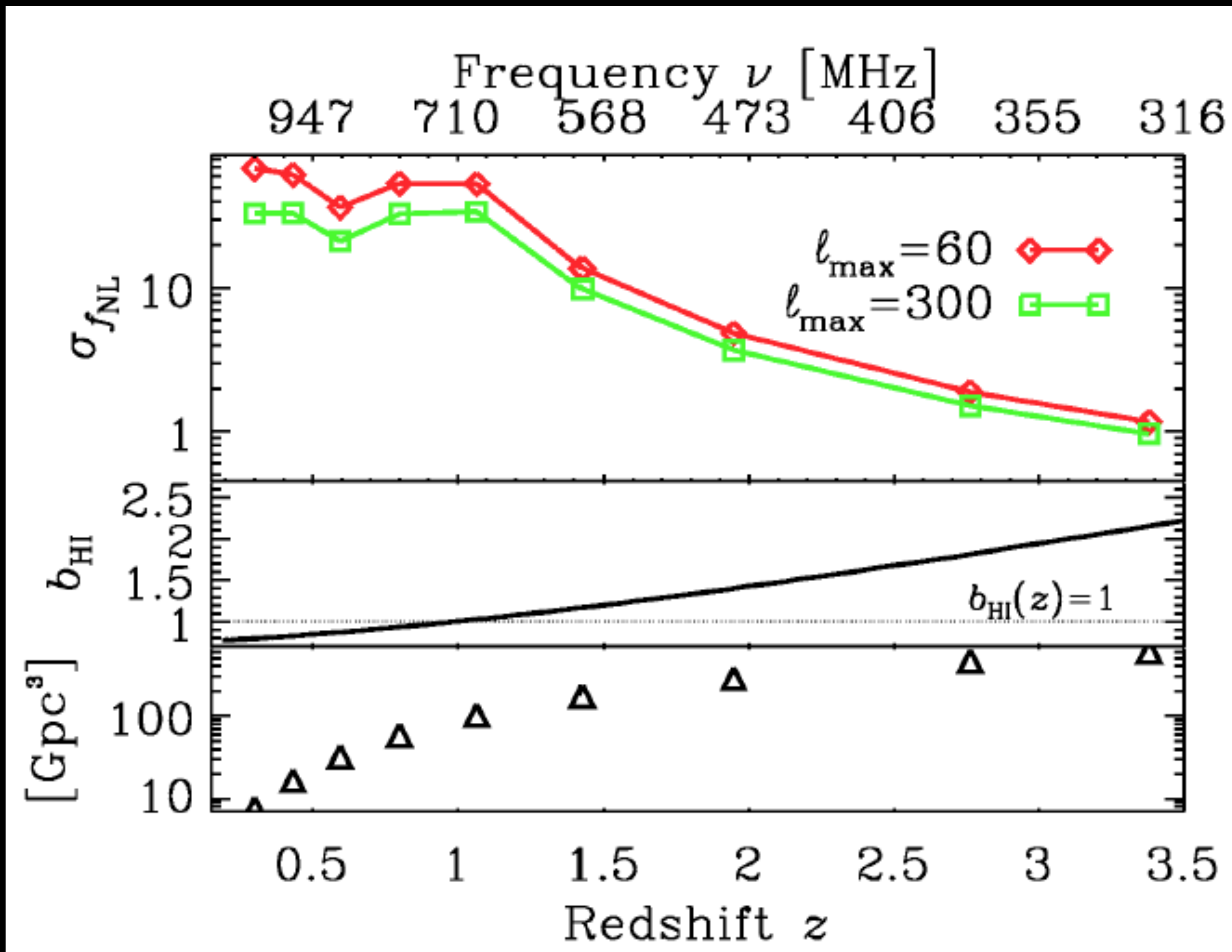
identification of morphology
for angular resolution 0.5”

Constraints on non-Gaussianity with SKA (continuum)



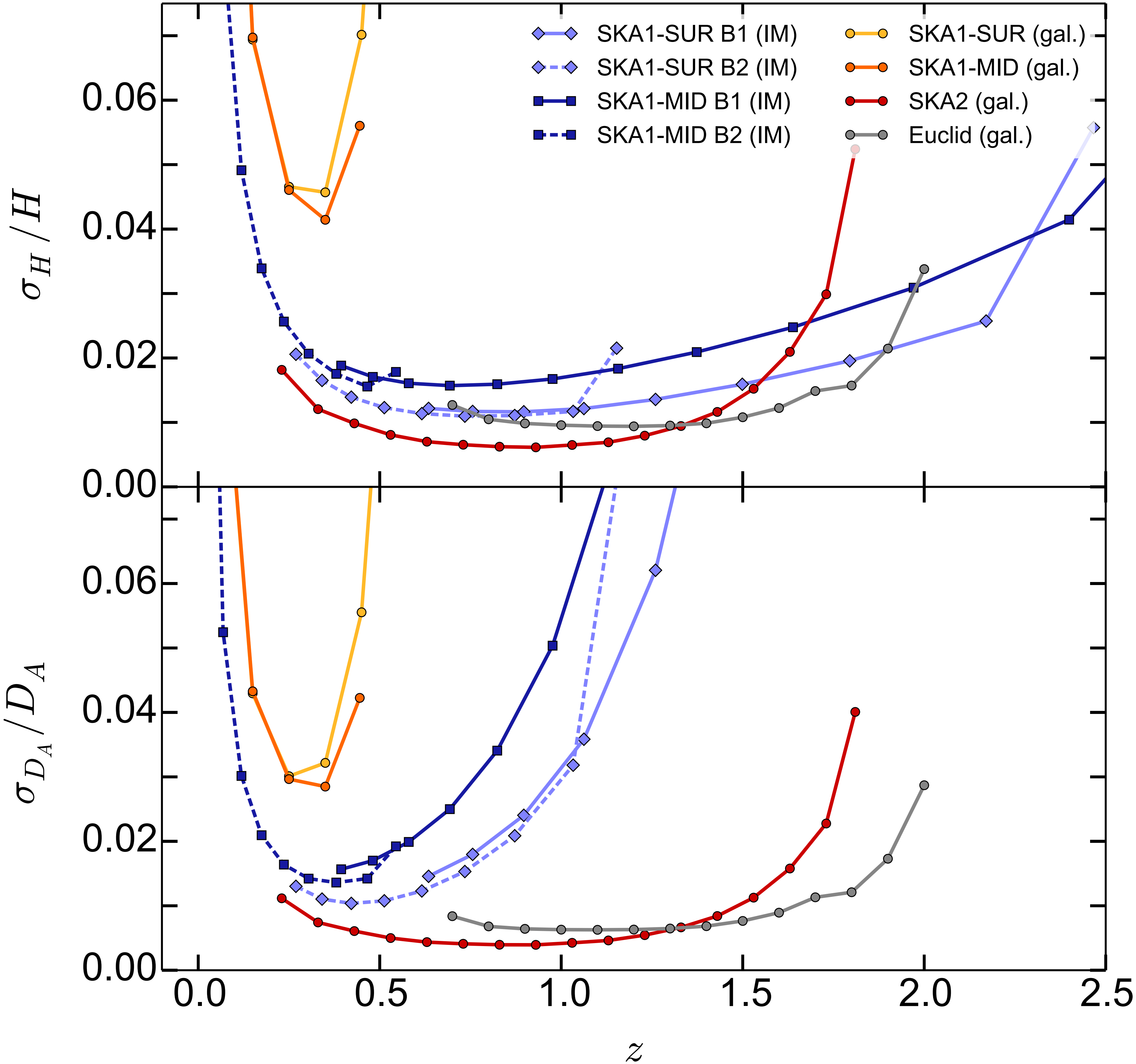
Camera et al., 2015, SKA Science Book

Non-Gaussianity (HI intensity)



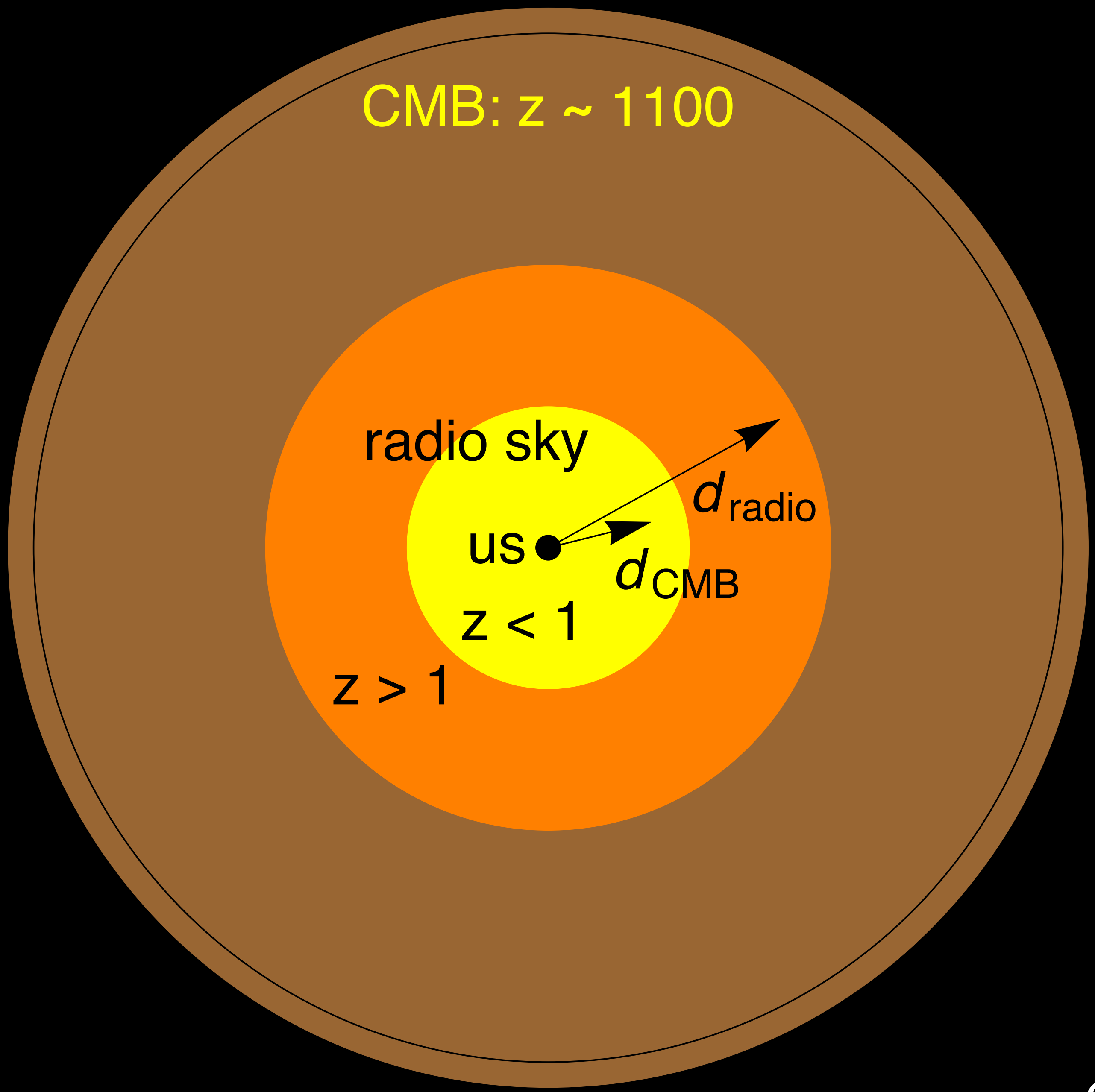
Camera et al. 2013

Baryon Acoustic Oscillations with SKA



Bull et al., 2015, SKA Science Book

Cosmic Radio Dipole



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

radio galaxies: **mean z > 1**

d_{matter} expected to be small

kinetic dipole

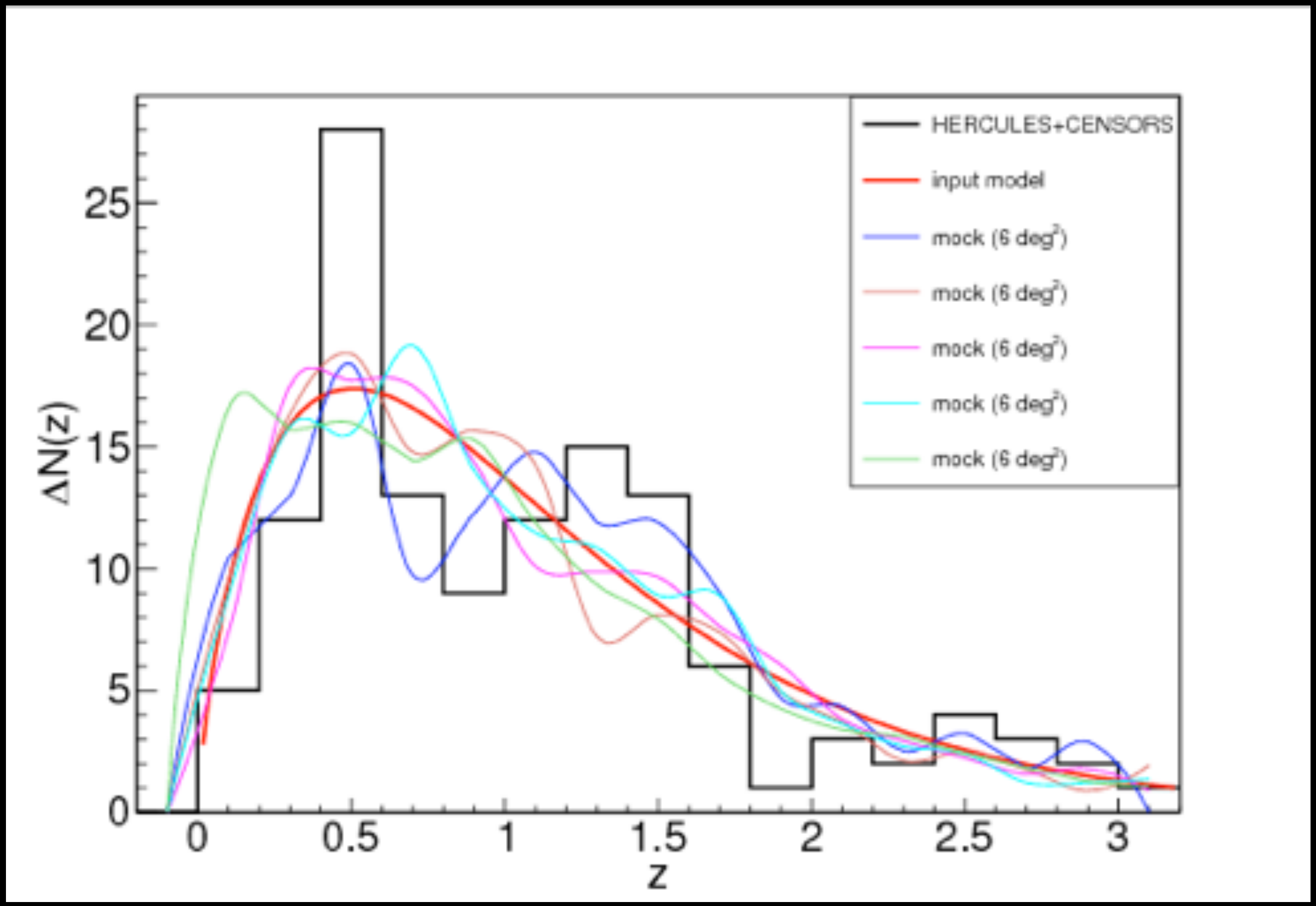
Ellis & Baldwin 1984

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

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

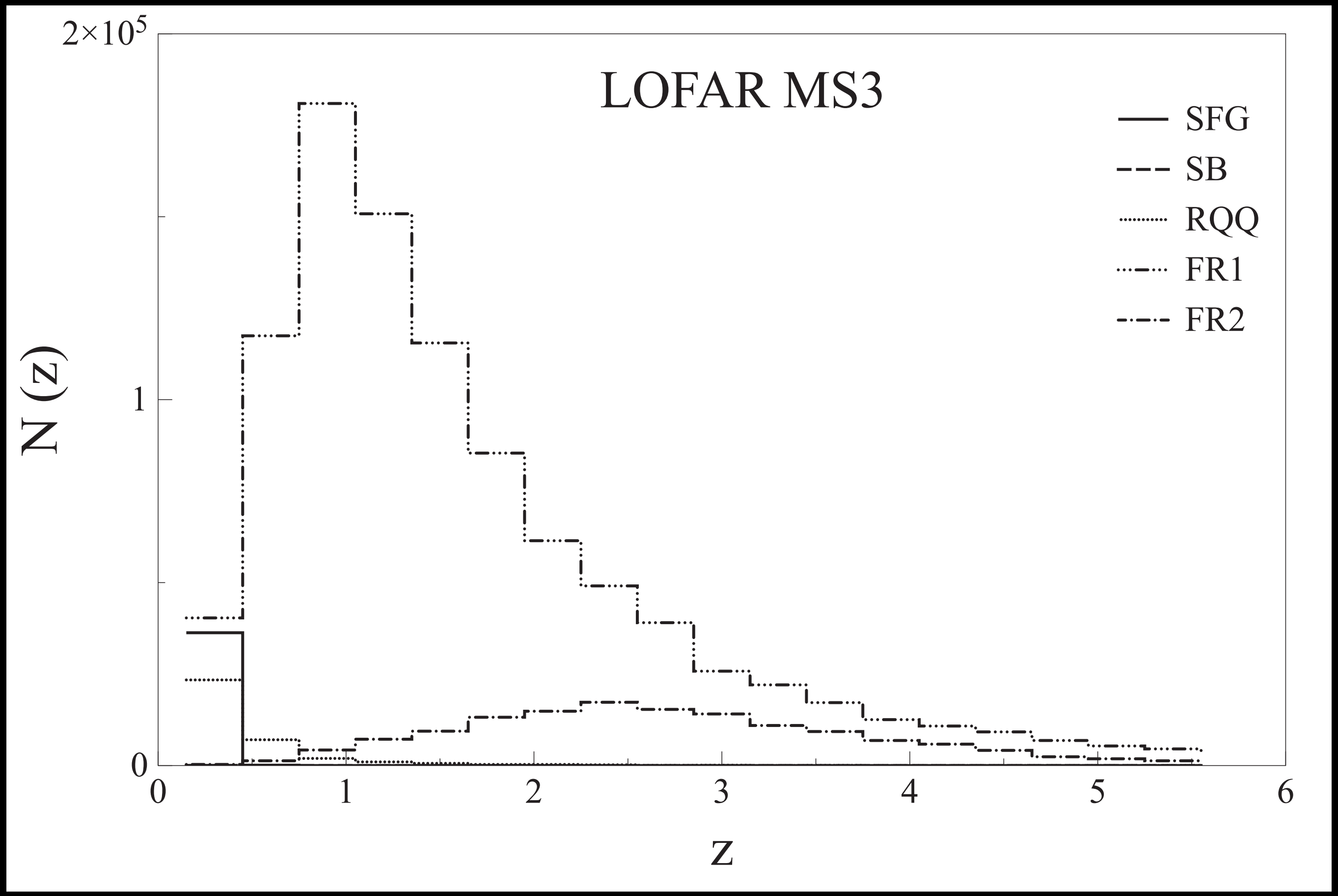
aberration & Doppler shift

Redshift distribution of radio sources



distribution of measured redshifts to NVSS radio sources and models

Tiwari et al. 2016



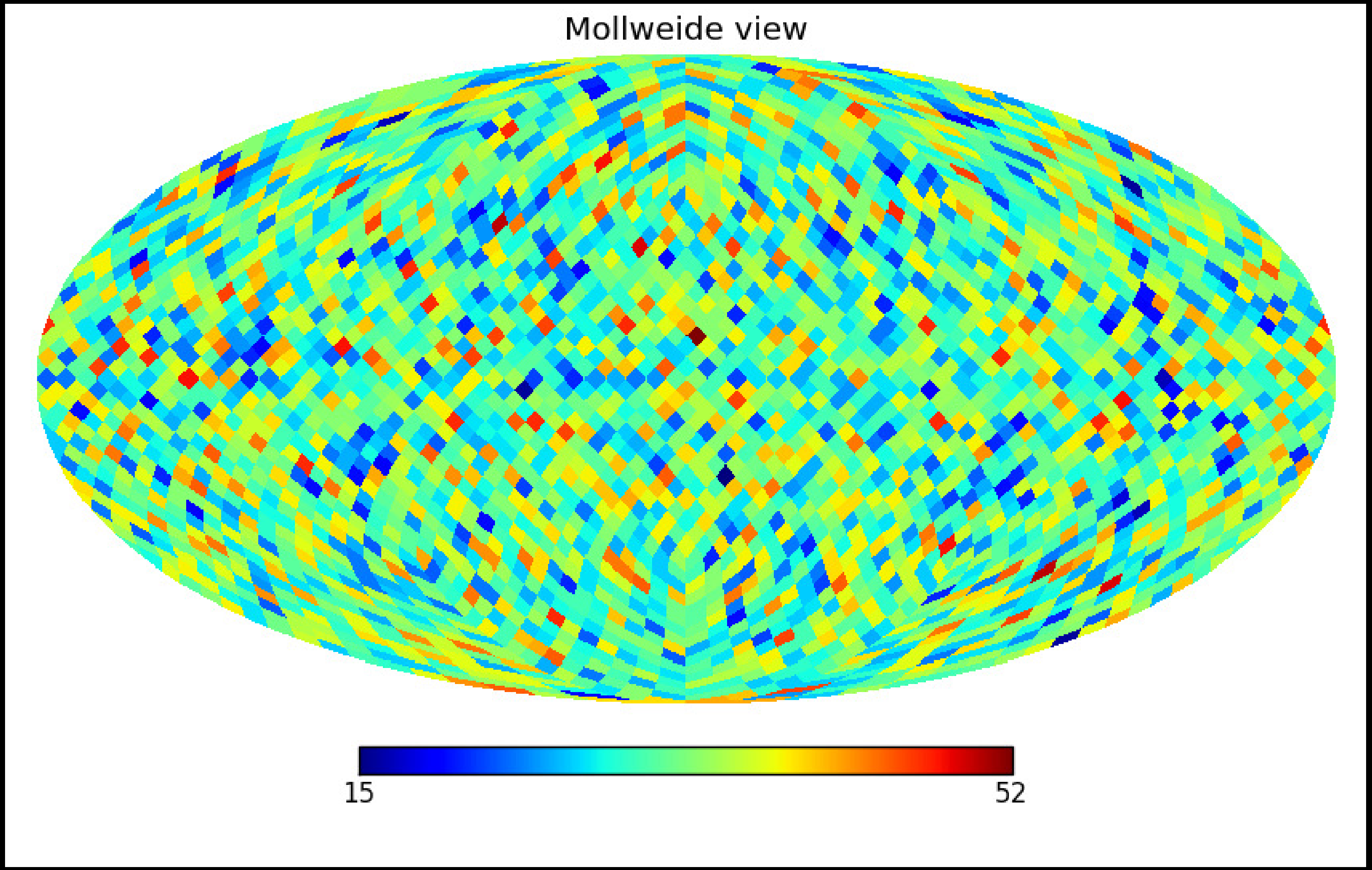
forecasted redshift distribution of radio sources in LOFAR MSSS

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

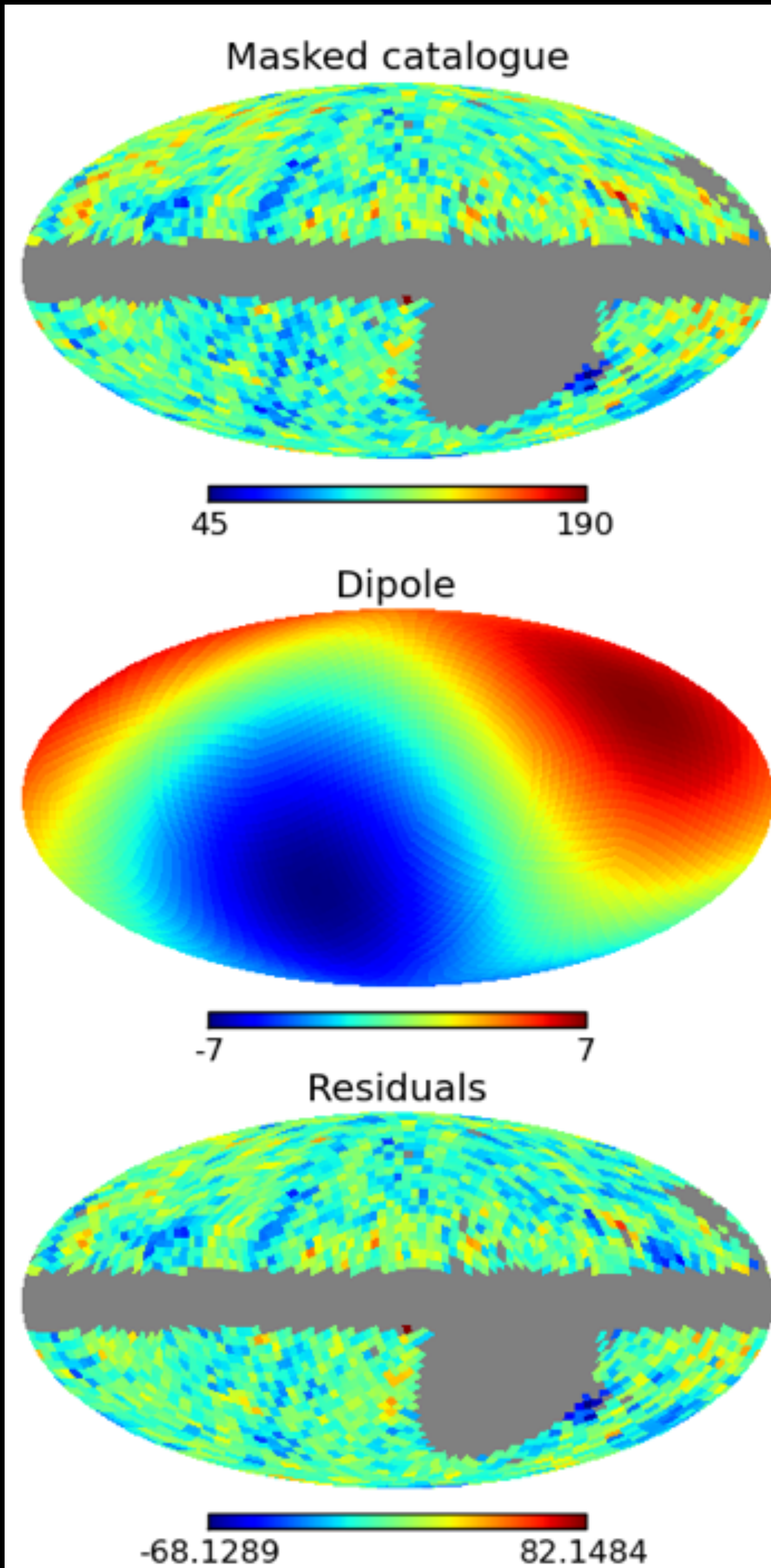
our Hubble patch is expected to be at rest wrt the cmb

The Challenge

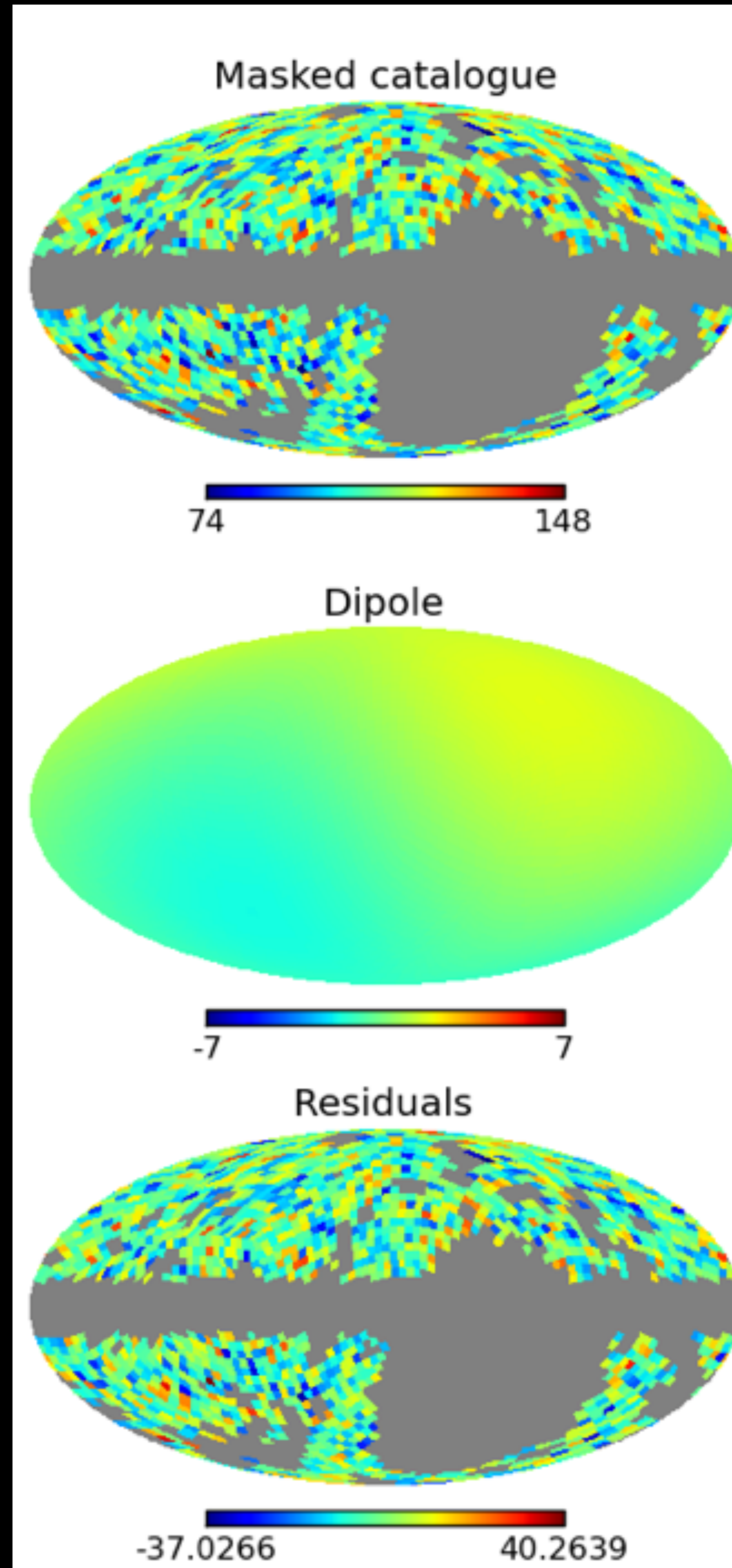


Simulated pixelated sky map of 100,000 sources
including expected kinetic dipole:
shot noise dominated
➔ need huge catalogues (> 10^6 sources)
and large sky coverage (> 20.000 sqdeg)

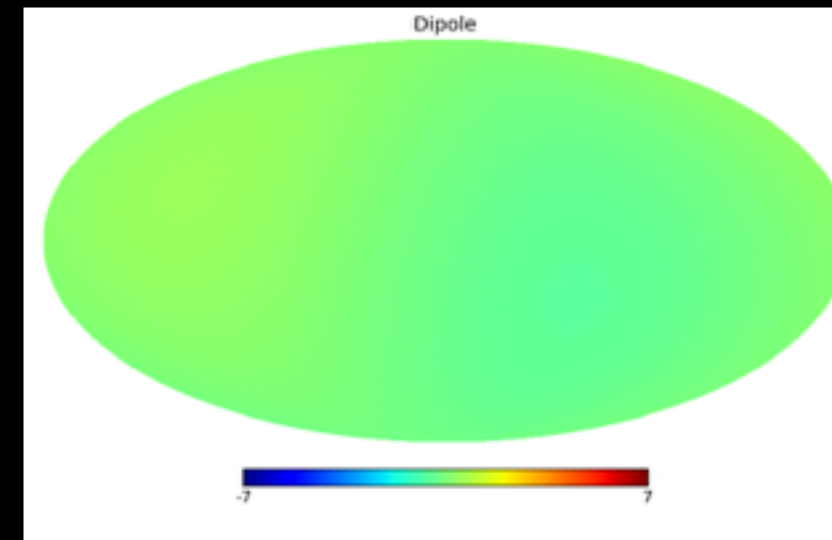
TGSS 151 MHz



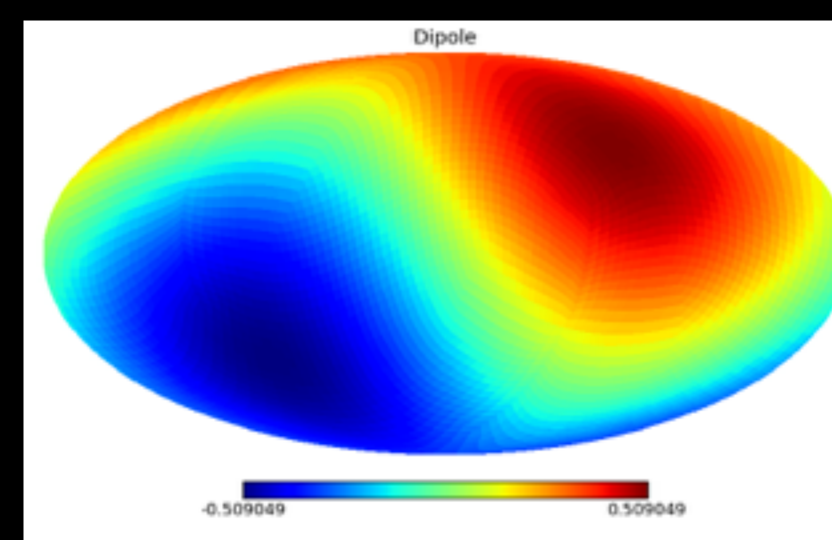
NVSS 1.4 GHz



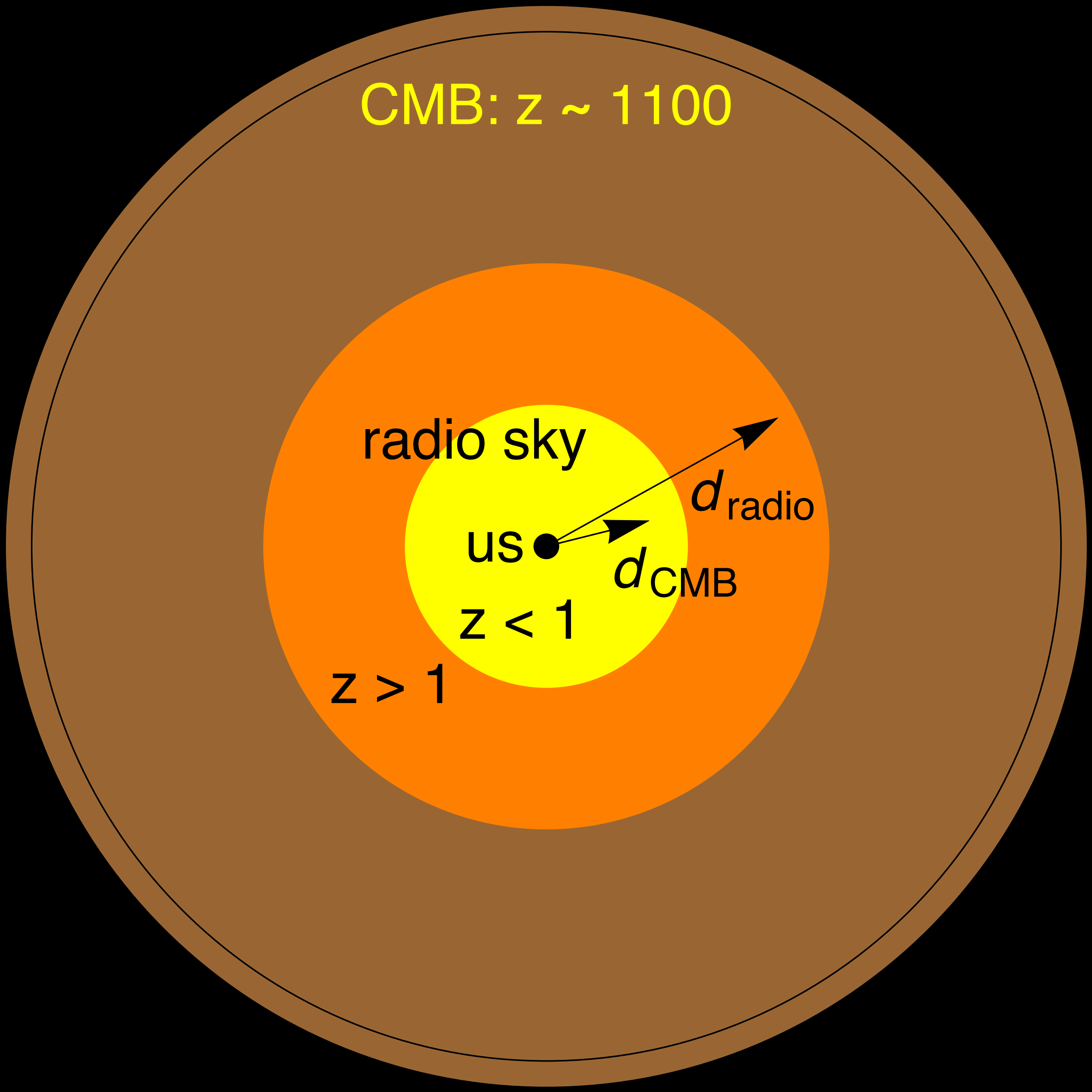
expected kinetic
radio dipole
same color scale



expected kinetic
radio dipole
adjusted scale
factor 14



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

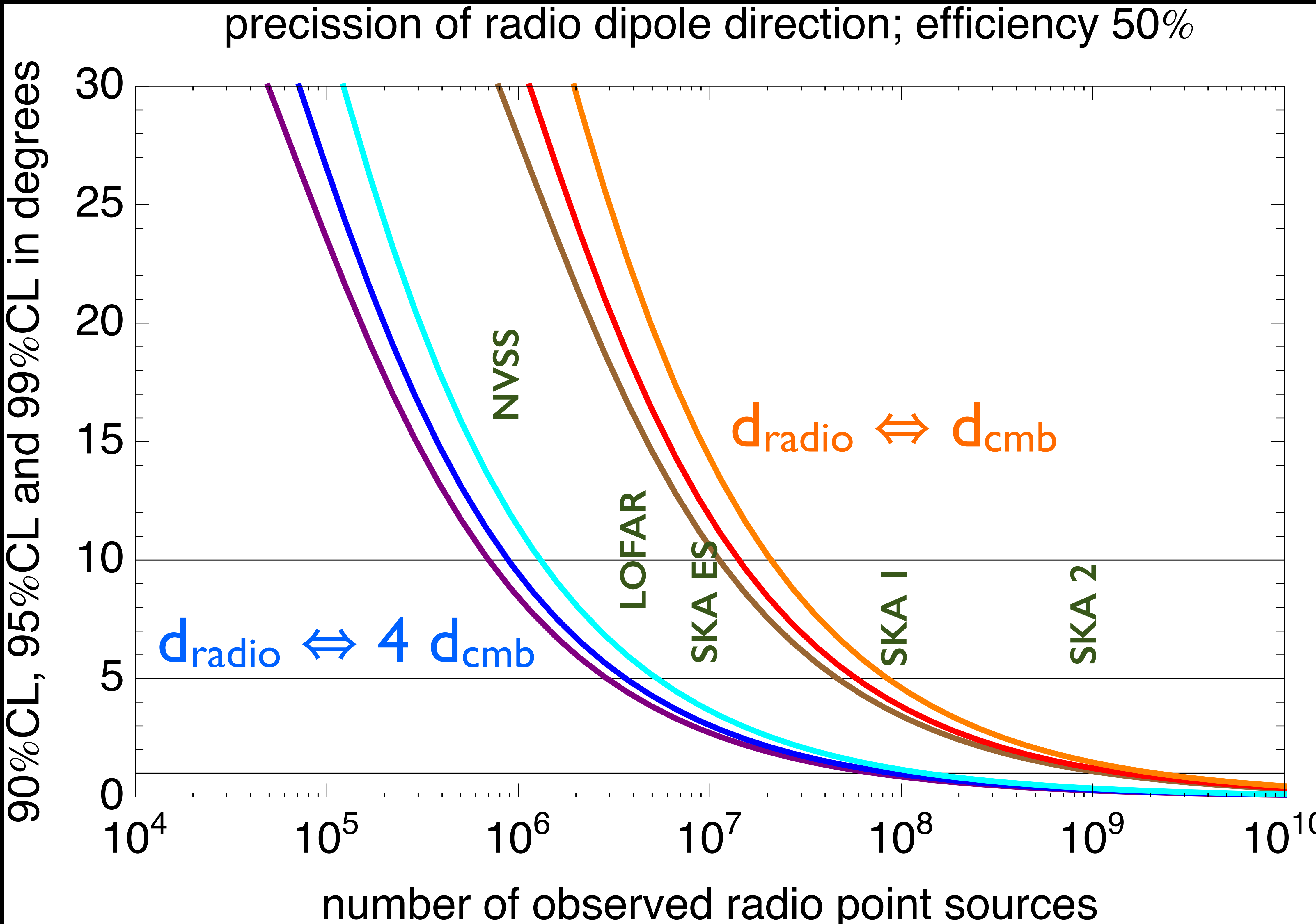
local bulk flows?

Watkins & Feldman 2014
Atrio-Barandela et al. 2014

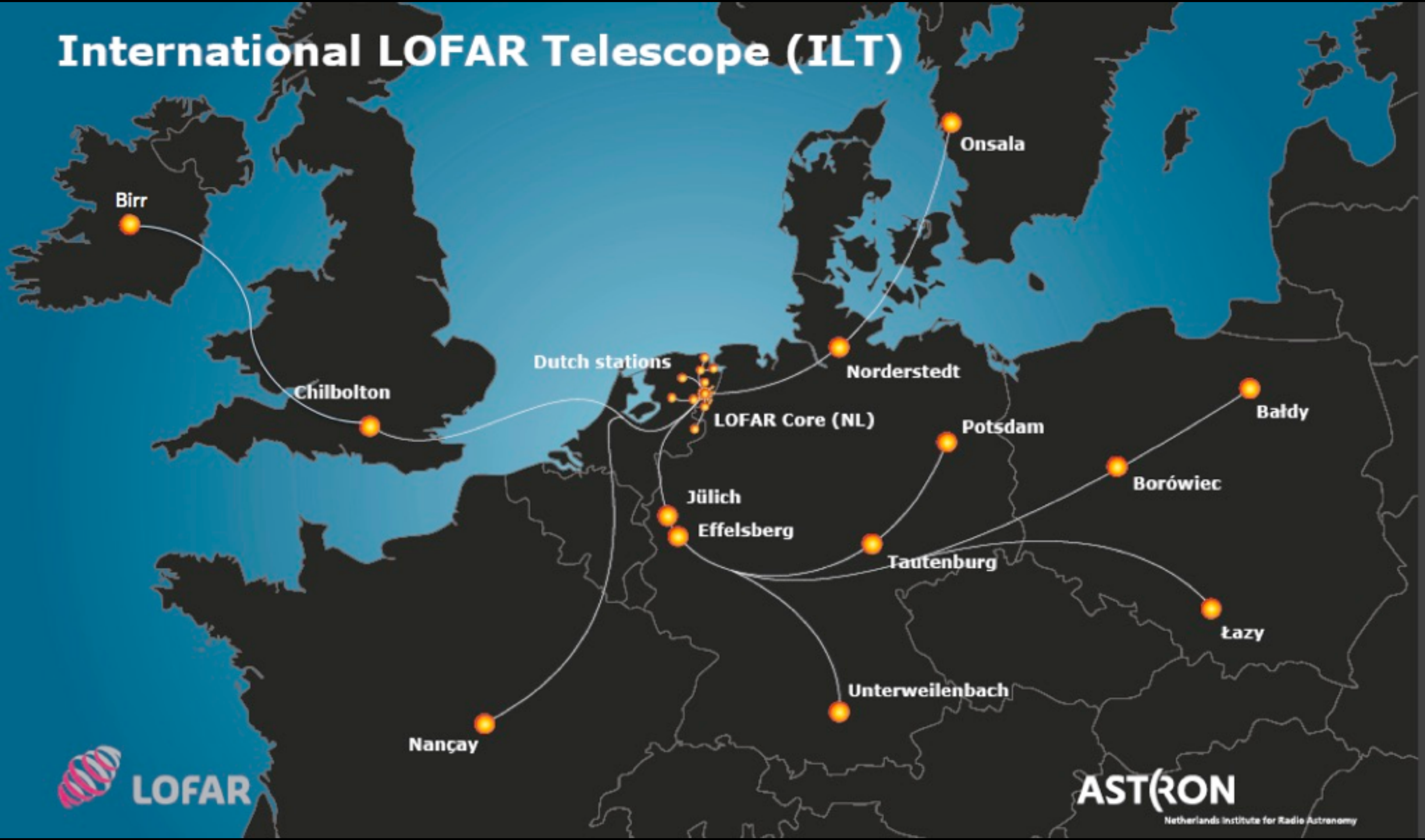
local structure dipole?

Rubart, Bacon & Schwarz 2014
Nusser & Tiwari 2016

Cosmic radio dipole



Schwarz et al., 2015, SKA Science Book



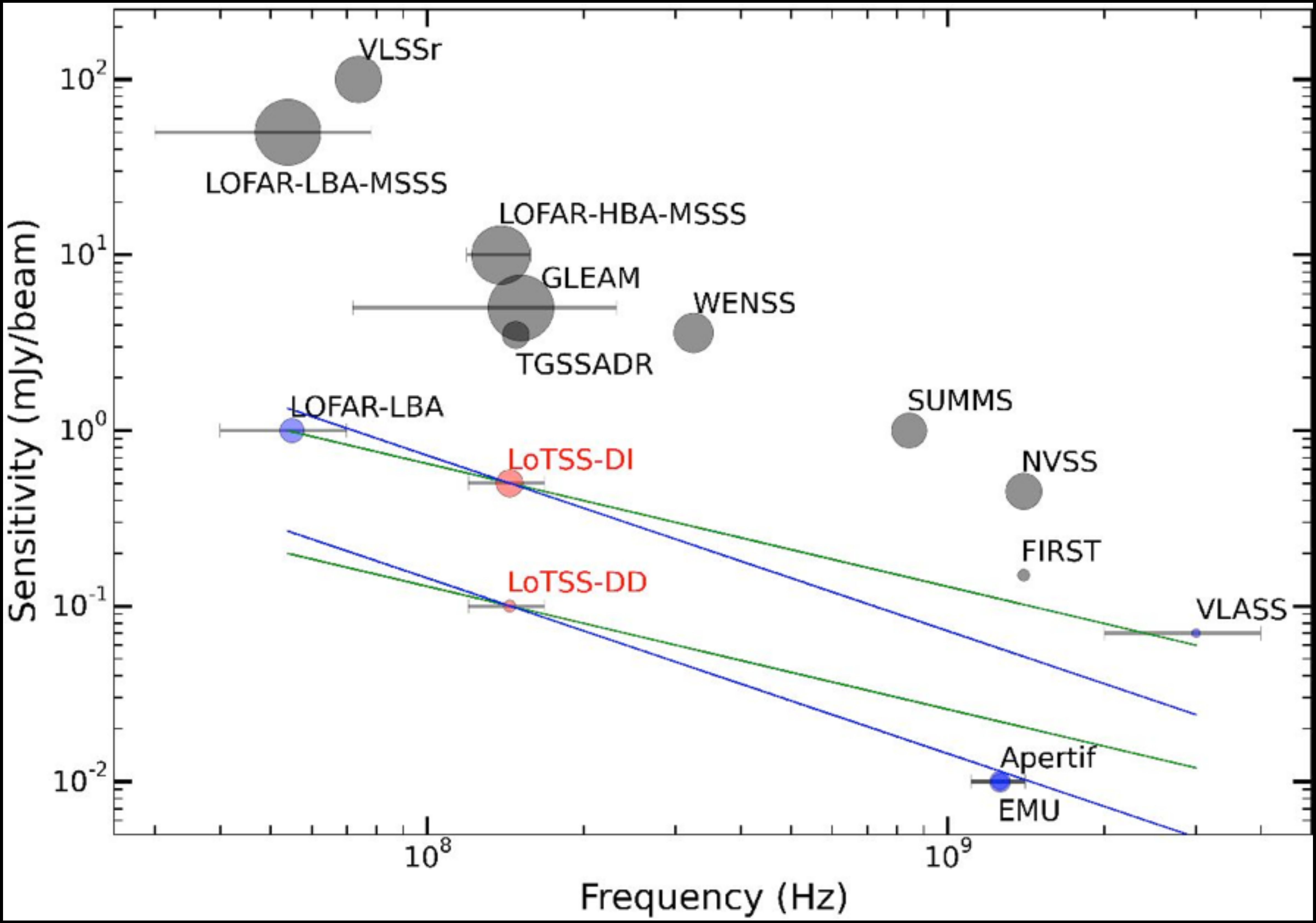
LOw Frequency ARray

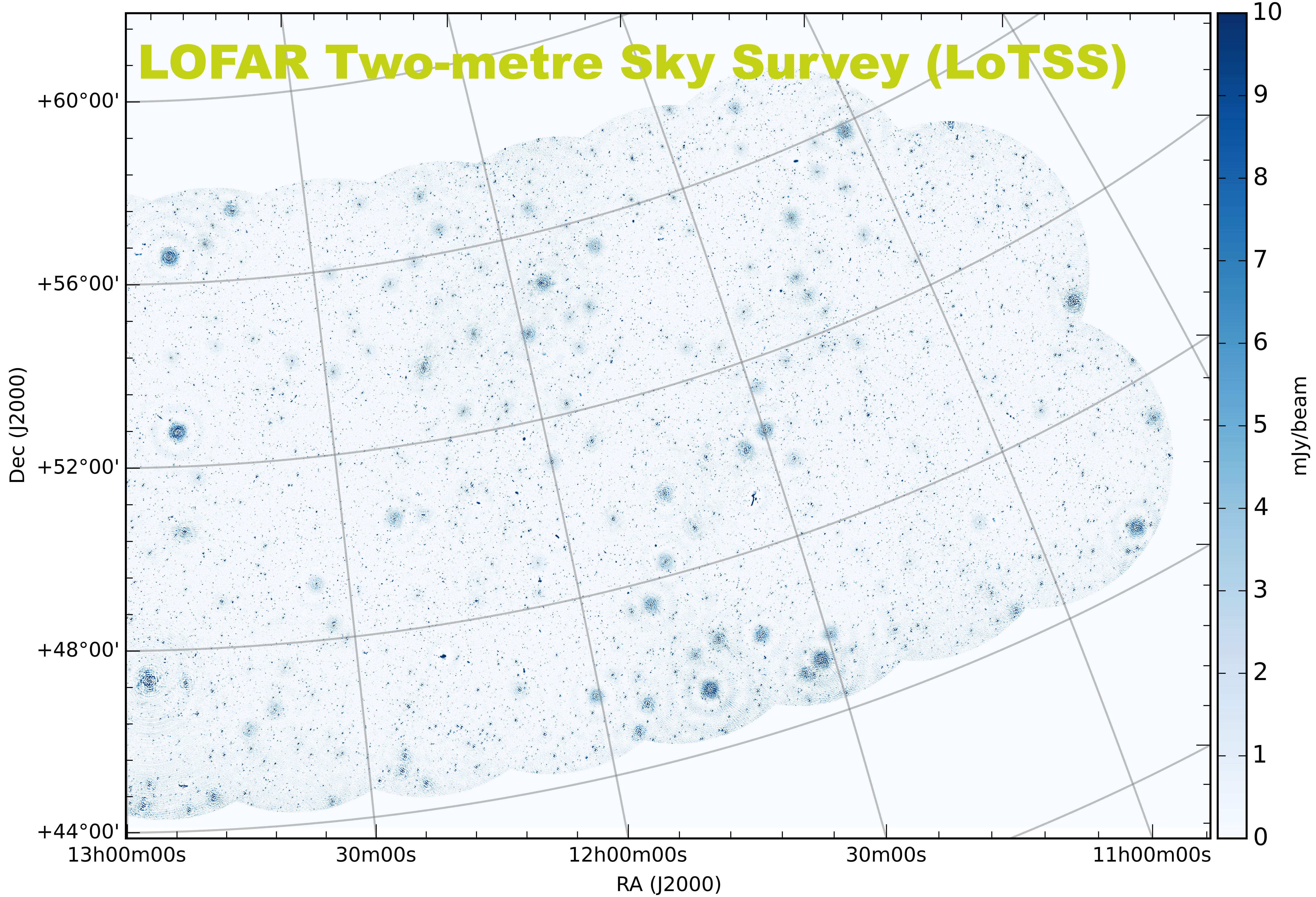
51 stations in NL (38), D (6), PL (3), F, IR, S, UK

2019-2025: LOFAR2.0 complementary to SKA1; new stations in Latvia and Italy, cover frequencies below 50 MHz, cover large baselines, northern sky

LOFAR Two-metre Sky Survey (LoTSS)

Shimwell et al. 2017

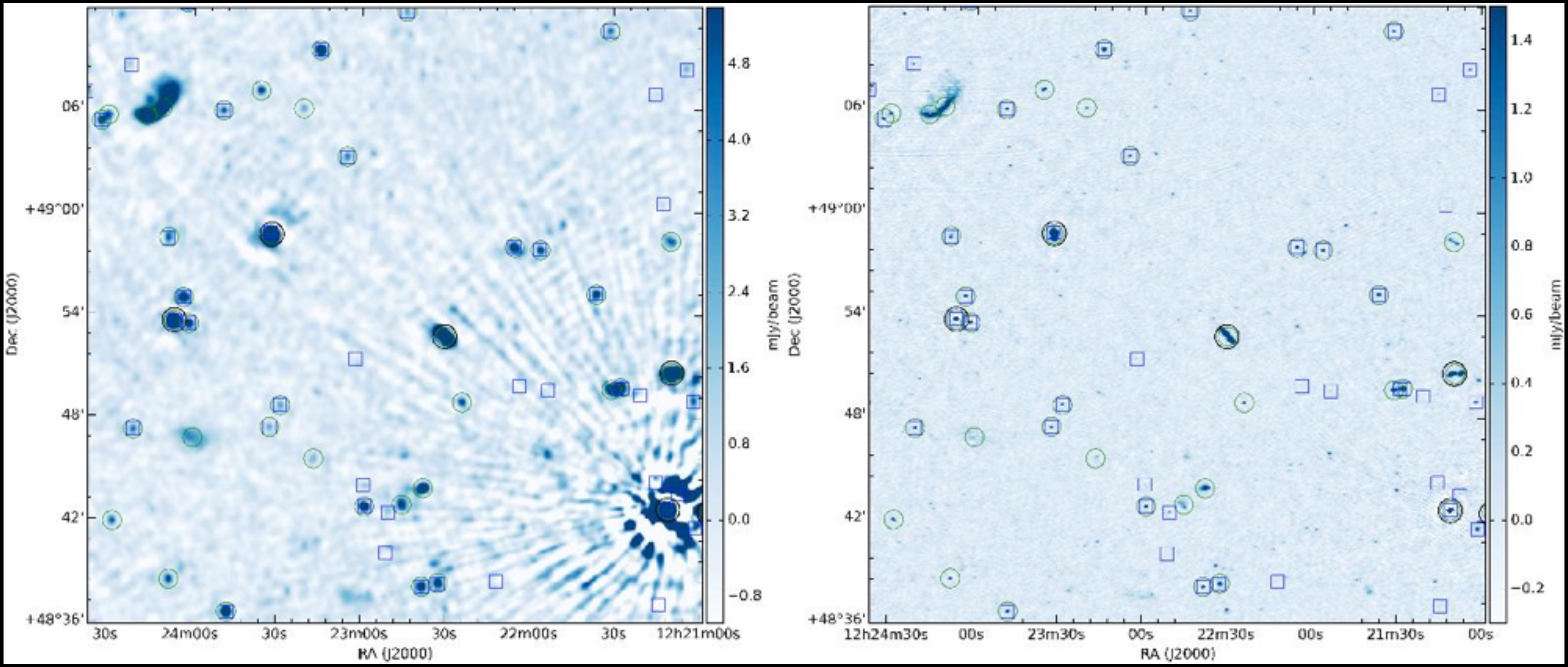




half of first 350 sqdeg, plan to do half sky: Shimwell et al. 2017

LOFAR Two-metre Sky Survey (LoTSS)

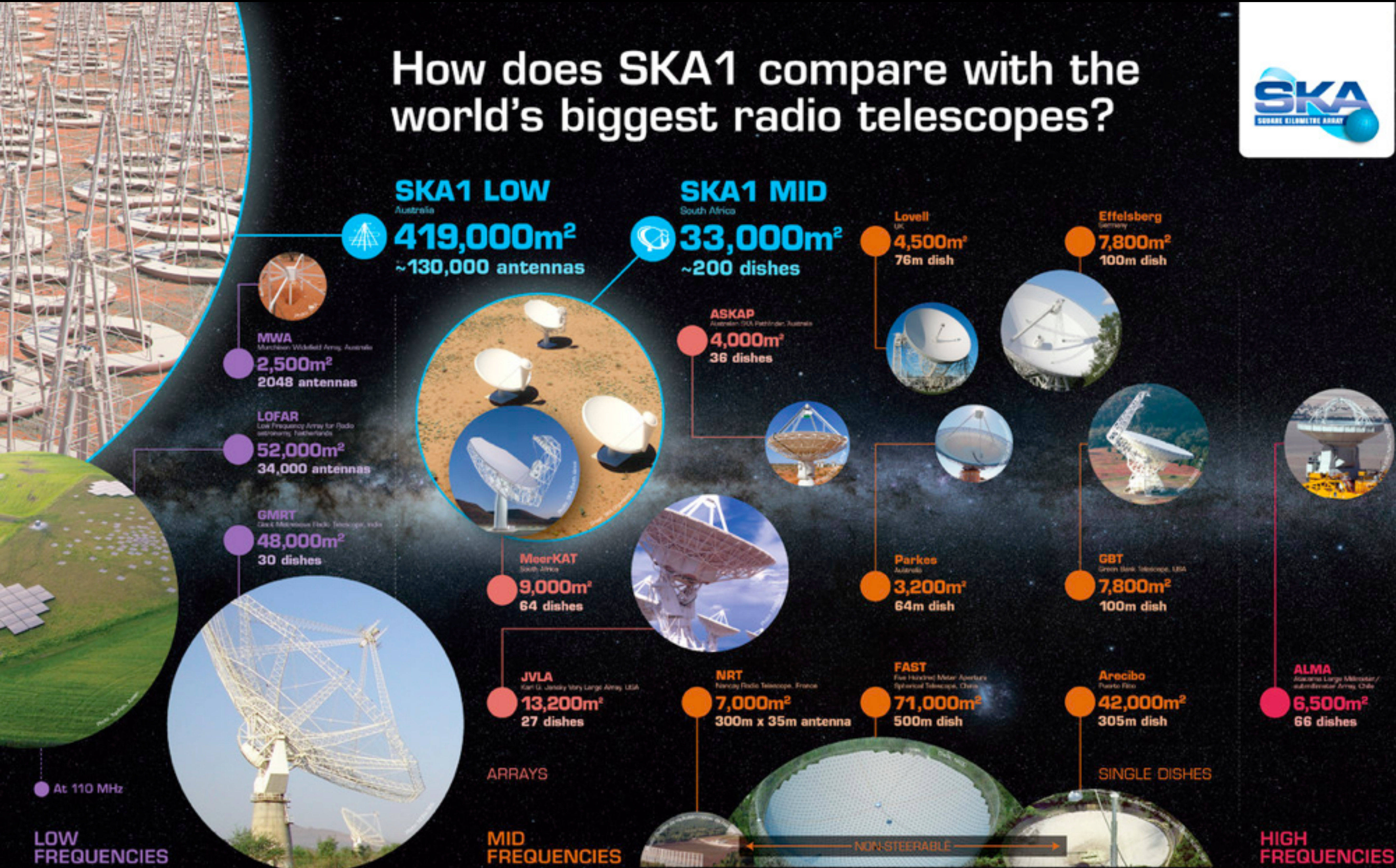
Shimwell et al. 2017



direction independent vs direction dependent calibration

Structure of lecture

- What is the SKA?
- Short introduction to cosmology
- The extragalactic radio sky
- Cosmology opportunities with the SKA
- Summary



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 The Square Kilometre Array

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.

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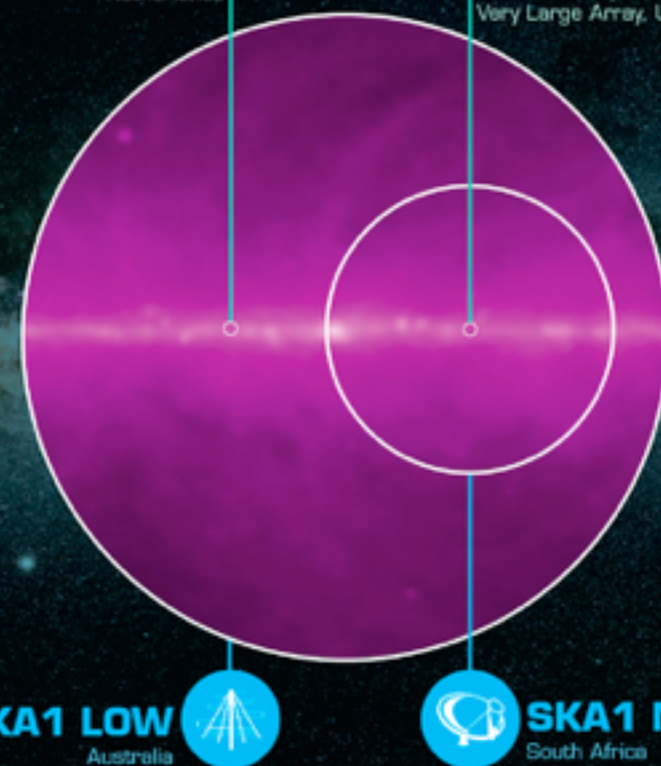
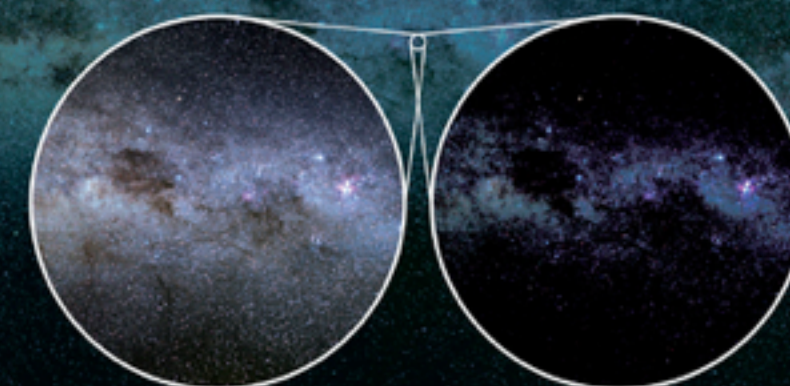
WITH THE SKA

WITH CURRENT RADIO TELESCOPES





WITH THE SKA

WITH CURRENT RADIO TELESCOPES

RESOLUTION

SKA1 LOW x1.2 LOFAR NL

SKA1 MID x4 JVLA

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

SURVEY SPEED

SKA1 LOW x135 LOFAR NL

SKA1 MID x60 JVLA

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.

SENSITIVITY

SKA1 LOW x8 LOFAR NL

SKA1 MID x5 JVLA

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 YouTube 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.

Cosmology Opportunities of the SKA

- Discoveries: Epoch of Recombination, Cosmic Dawn, Dark Ages; direct observation of acceleration via redshift drift
- Precision cosmology: BAO, P(k), weak lensing, etc.
- Fundamental tests: radio dipole, isotropy, non-Gaussianity, etc.

Why should we invest in SKA?

largest scales test fundamental assuptions of modern cosmology:

- initial conditions and symmetries
- relativistic effects
- evolution

radio surveys will probe largest volumes

- in solid angle
- in redshift
- frequency range
- complementary systematics to optical/ir

JVLA, LOFAR, ASKAP, MeerKAT, and SKA