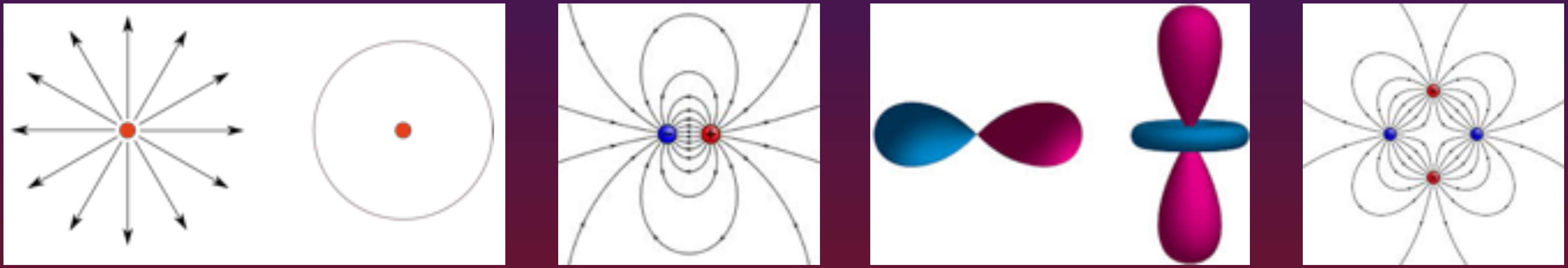
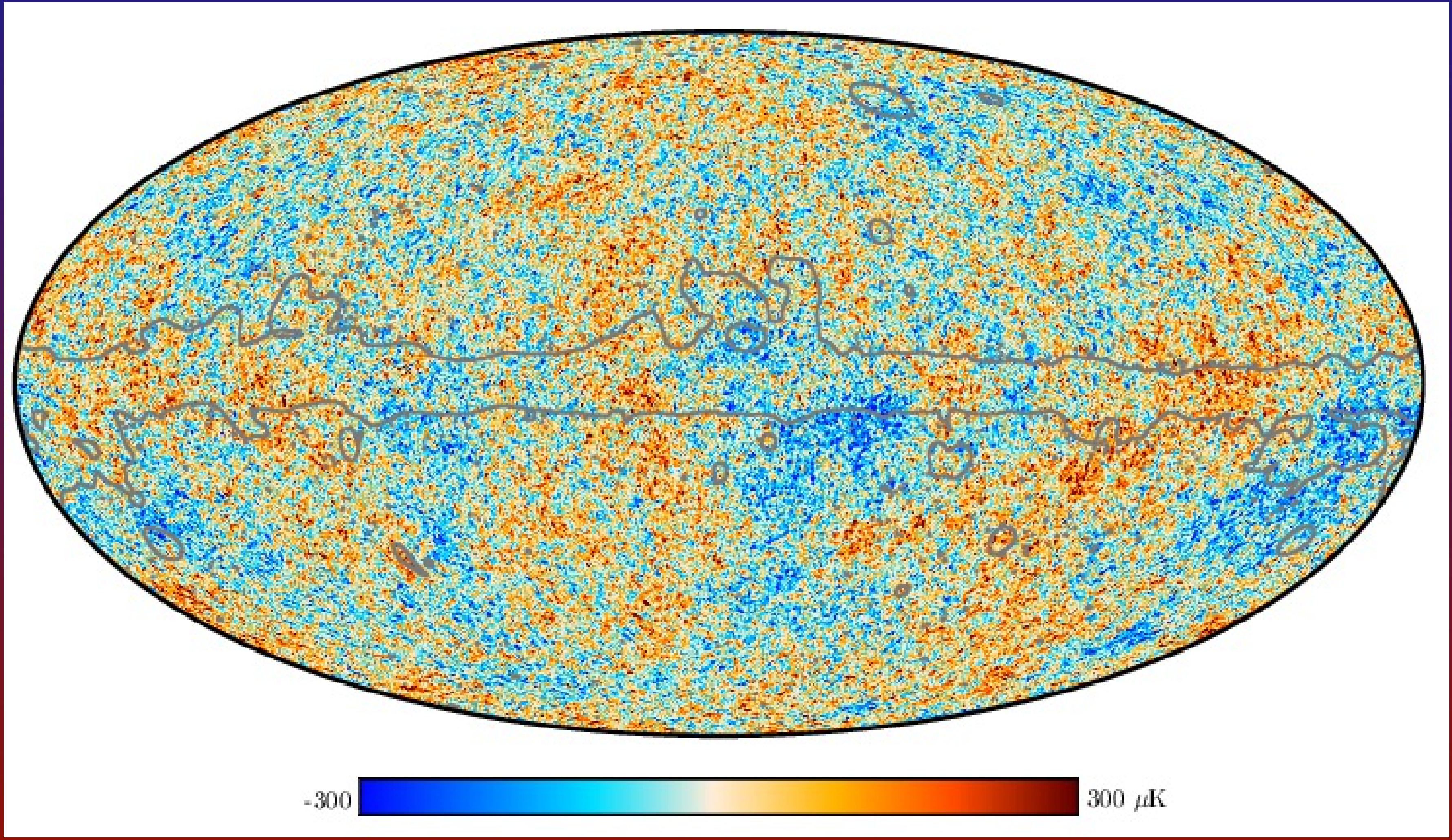
The CMB's lowest-order multipoles



Douglas Scott
UBC

The CMB Sky

Temperature anisotropies at ~400,000 years



Statistical description of anisotropies

Expand sky in spherical harmonics

$$T(\theta,\phi) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\theta,\phi)$$

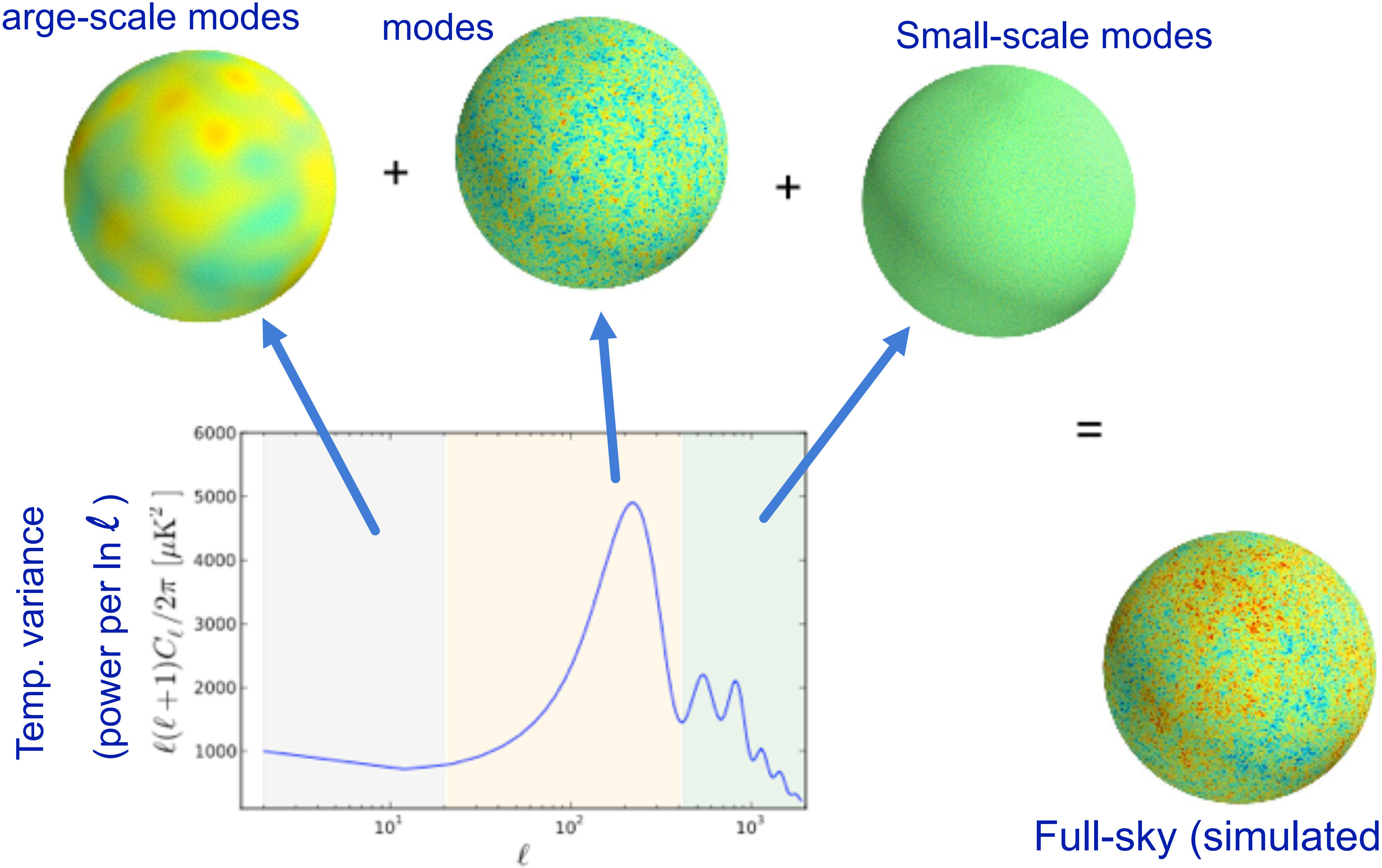
Monopole is T_0 (=a_{00})

Dipole is our “absolute motion”

$\ell \geq 2$ modes give info on perturbations

$C_\ell \equiv \left\langle |a_{\ell m}|^2 \right\rangle$ i.e. average over *ms*

$(2\ell + 1)C_\ell/4\pi$ is power at each ℓ



Large-scale modes

Intermediate-scale modes

Small-scale modes

\+

\+

=

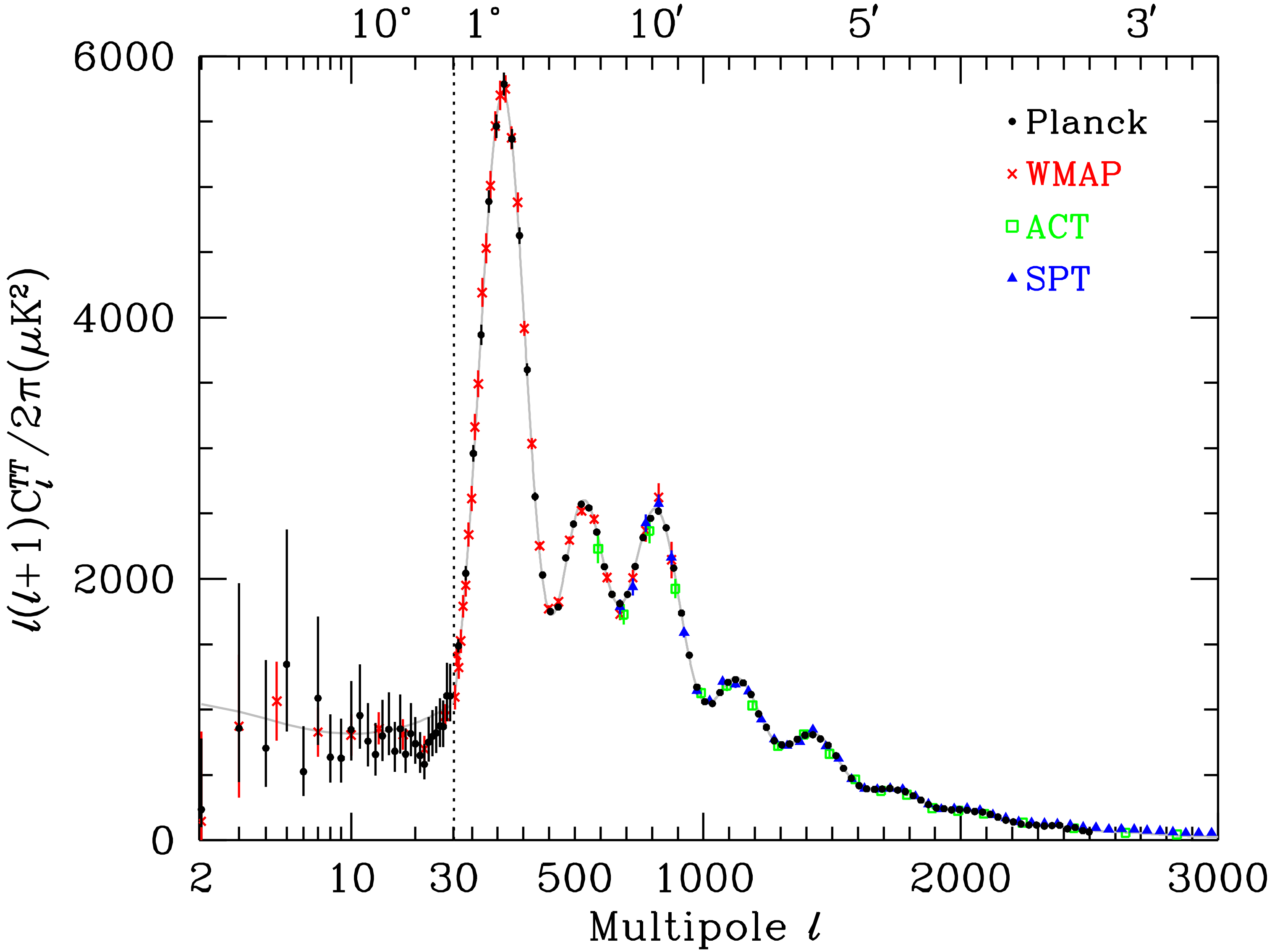
Temp. variance

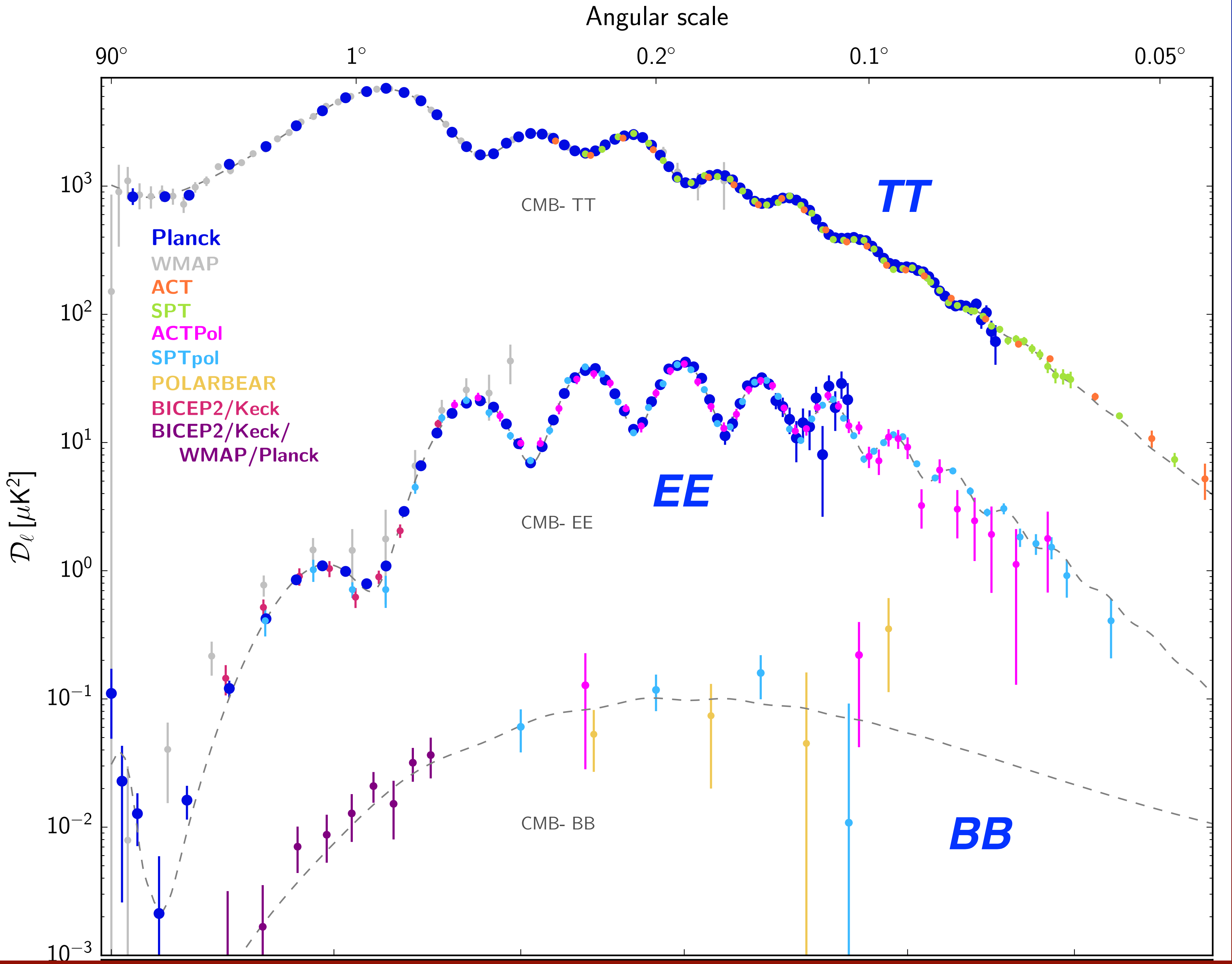
(power per ln ℓ)

ℓ = oscillations per ~180 degrees

Full-sky (simulated) map of the CMB

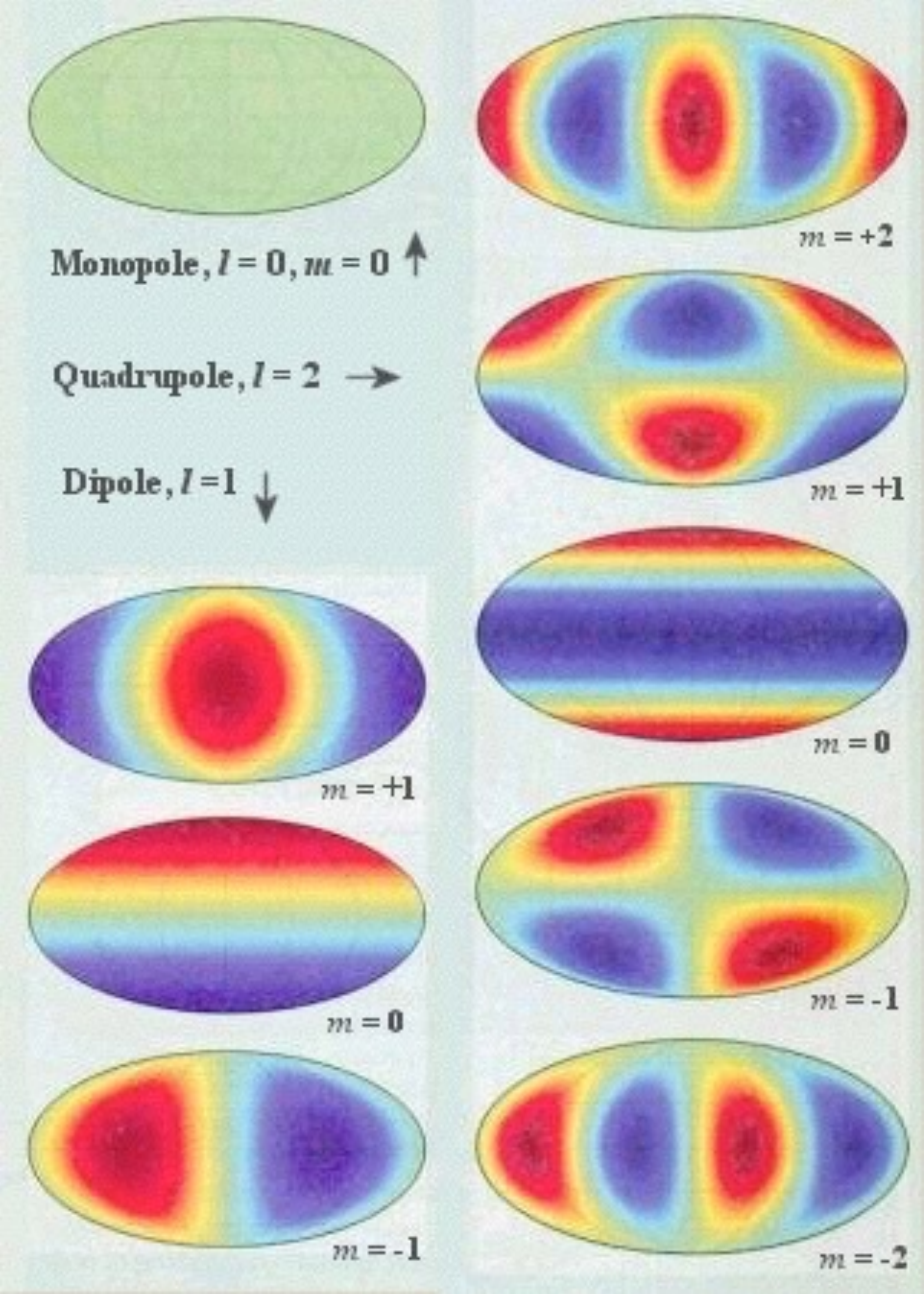
“Precision era” of cosmology




Angular scale
90°
1°
0.2°
0.1°
0.05°
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
$\mathcal{D}_\ell\,[\mu\mathrm{K}^2]$
Planck
WMAP
ACT
SPT
ACTPol
SPTpol
POLARBEAR
BICEP2/Keck
BICEP2/Keck/
WMAP/Planck
CMB- TT
TT
CMB- EE
EE
CMB- BB
BB

But let’s ignore all that beauty and precision!

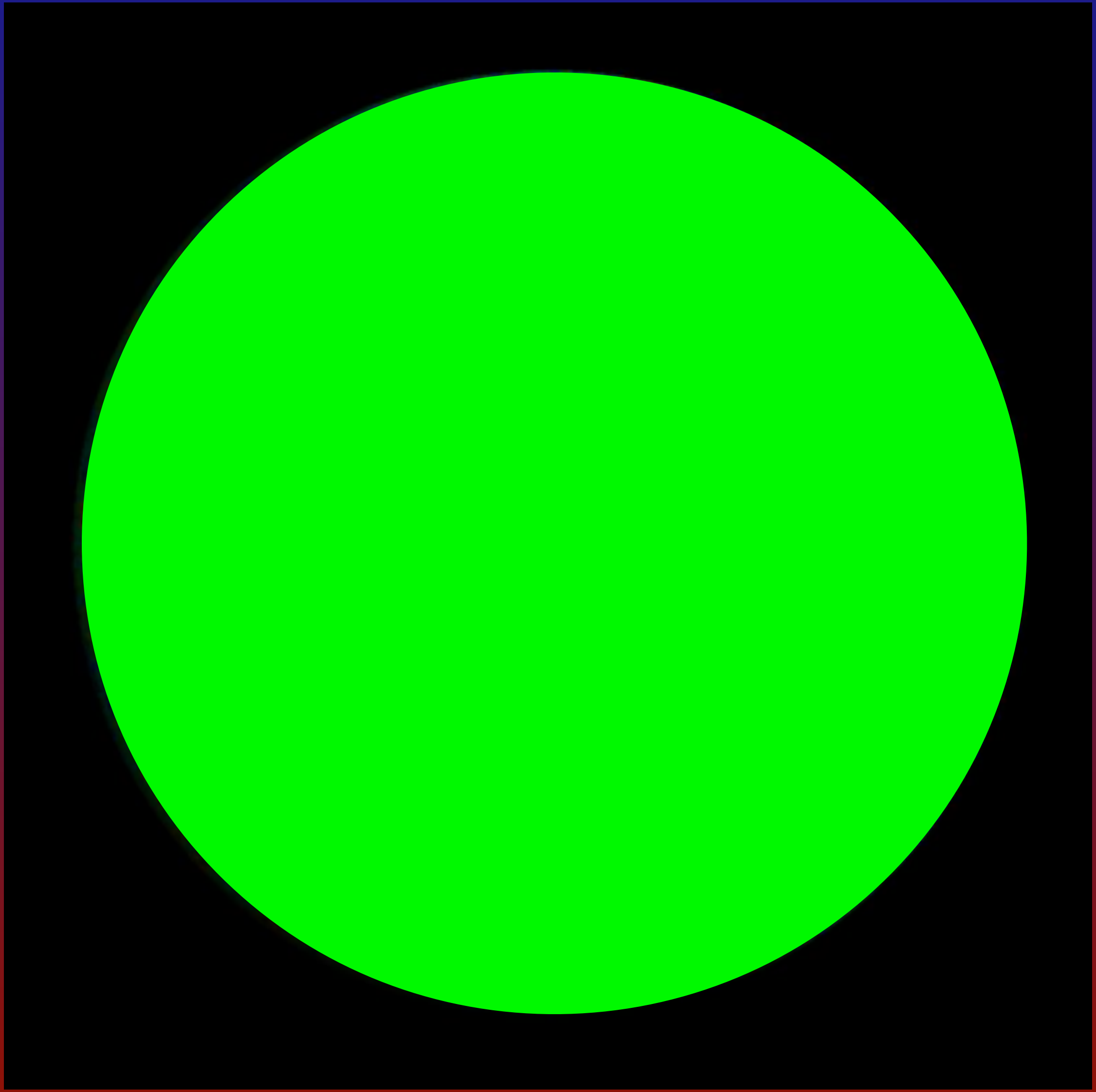
And talk about the very lowest multipoles!



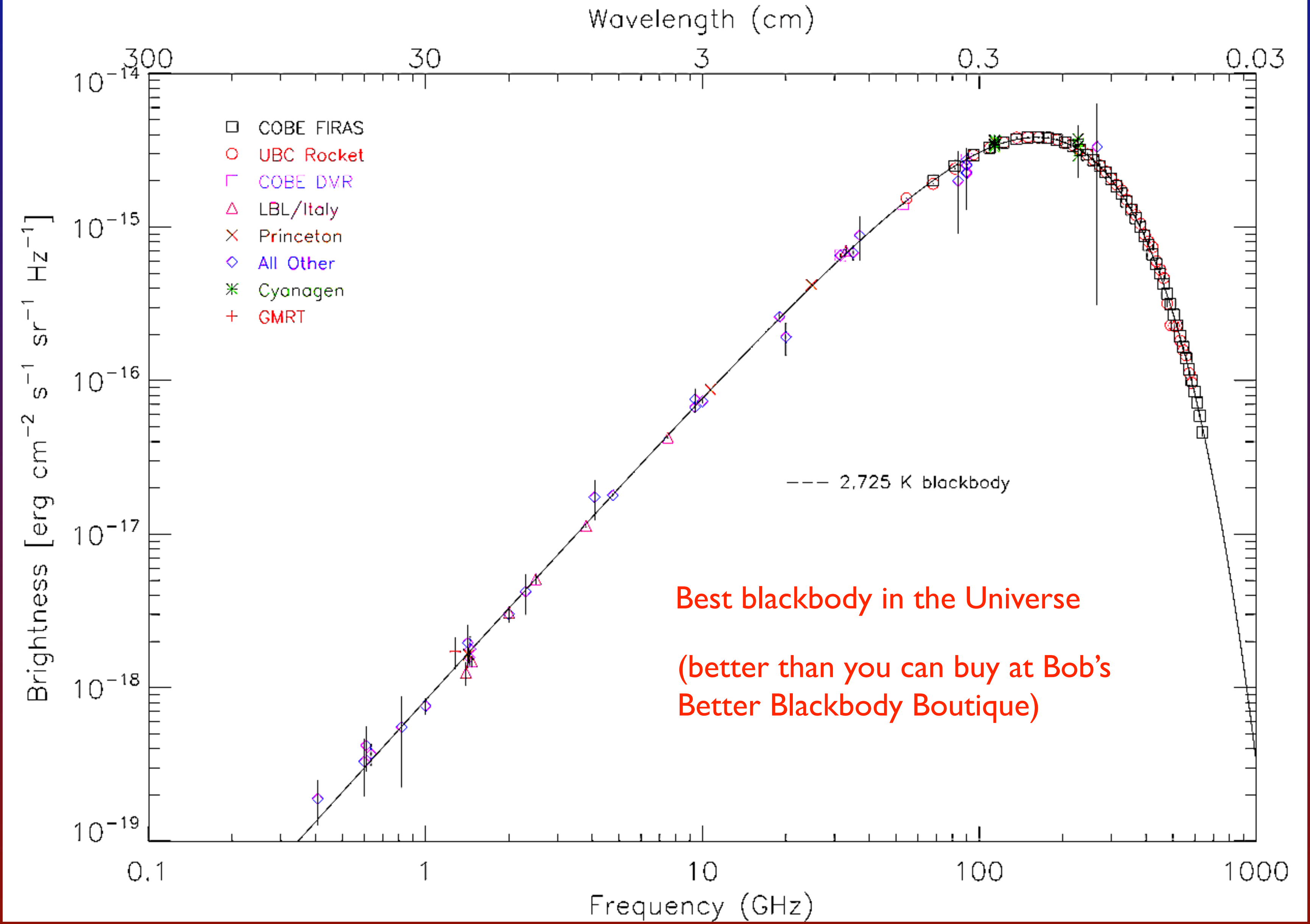
Lowest-order spherical harmonics

Let’s start with the monopole

CMB Sky

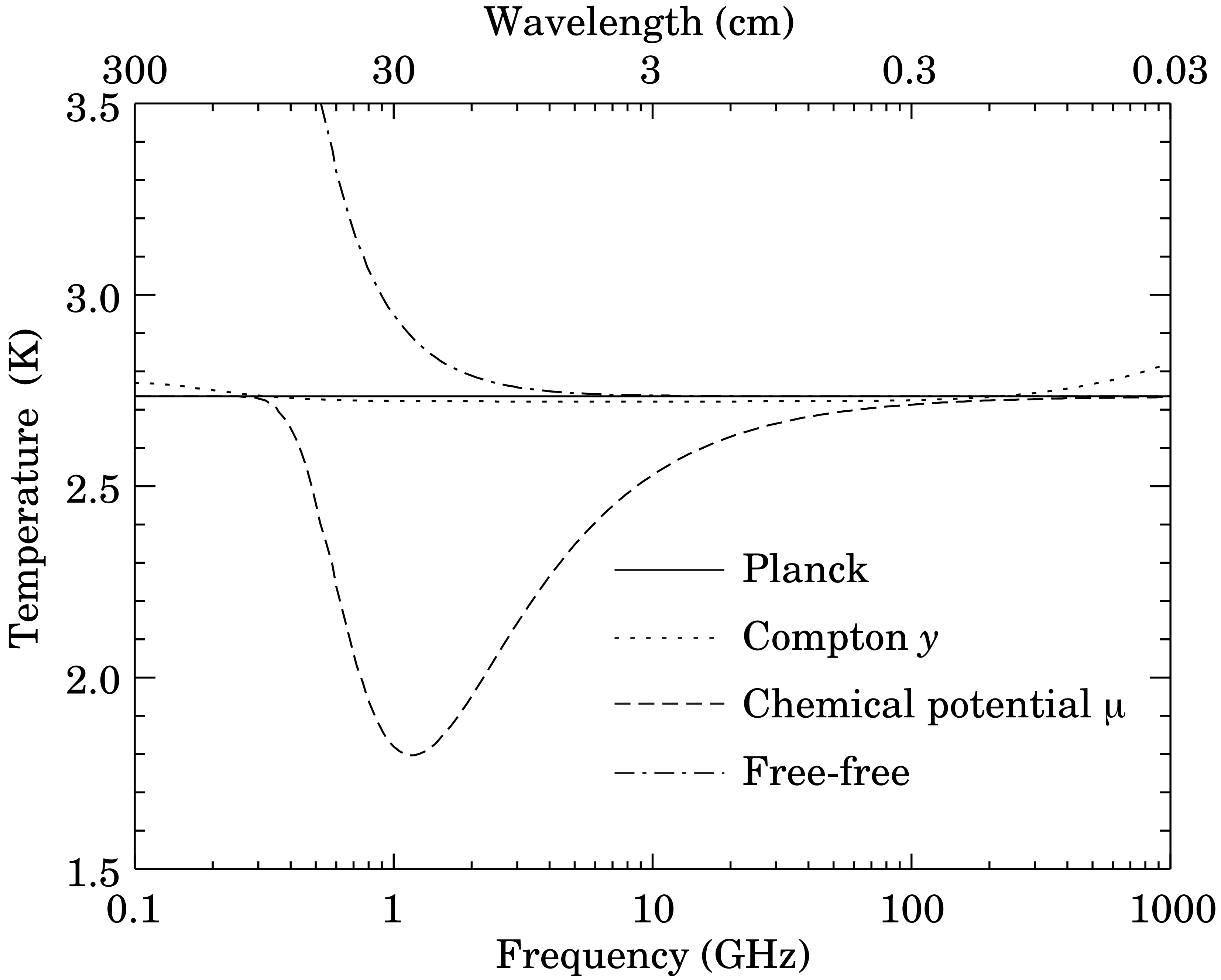


CMB Spectrum



Best blackbody in the Universe

(better than you can buy at Bob's Better Blackbody Boutique)


Wavelength (cm)
300
30
3
0.3
0.03
Temperature (K)
3.5
3.0
2.5
2.0
1.5
Planck
Compton y
Chemical potential μ
Free-free
0.1
1
10
100
1000
Frequency (GHz)

CMB Spectrum

$T_0 = 2.7255 \pm 0.0006$ K

$n_0 = 410.1$ cm^{-3}

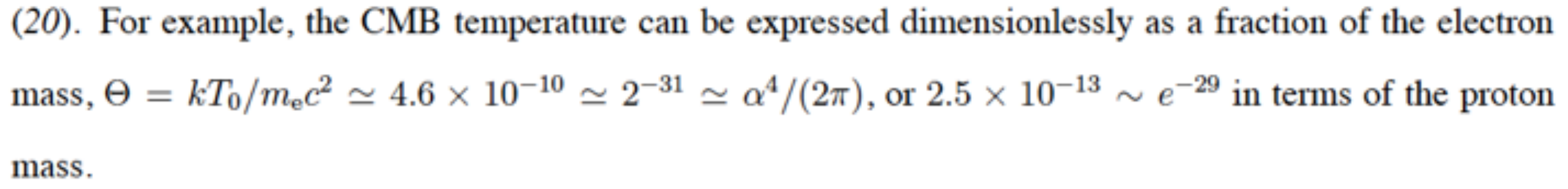
$\varepsilon_0 = 0.2605$ eV cm^{-3}

$\nu_{peak} = 160.24$ GHz

$$|y| < 1.2 \times 10^{-5} \quad (95\%\ \mathrm{CL})$$
$$|\mu_0| < 9 \times 10^{-5} \quad (95\%\ \mathrm{CL})$$
$$|Y_{ff}| < 1.9 \times 10^{-5} \quad (95\%\ \mathrm{CL})$$

$T_0 = -270.4245$ C

$T_0 = -454.7641$ F



(20). For example, the CMB temperature can be expressed dimensionlessly as a fraction of the electron mass, $\Theta = kT_0/m_ec^2 \simeq 4.6 \times 10^{-10} \simeq 2^{-31} \simeq \alpha^4/(2\pi)$, or $2.5 \times 10^{-13} \sim e^{-29}$ in terms of the proton mass.

Tight constraints on distortions

But expected distortions smaller still

Where did the CMB temperature come from?

$T_0 = 2.7255 \pm 0.0006$ K

(Fixsen 2009)

$$e\,\mathrm{Kelvin} (= 2.718\,\mathrm{K})$$

$$\sqrt{15/2}\,\mathrm{Kelvin} (= 2.739\,\mathrm{K})$$

$$30/11\,\mathrm{Kelvin} (= 2.727\,\mathrm{K})$$

$$-\ln(9\alpha)\,\mathrm{Kelvin} (= 2.723\,\mathrm{K})$$

$$\text{Triple point of water} \div 100 (= 2.7315\,\mathrm{K})$$

$$(2\alpha/\pi)^4 m_e c^2/k\ (= 2.762\,\mathrm{K})$$

$$(2/5)(\alpha_{\mathrm{G}} m_e/2\pi m_p)^{1/4} m_p c^2/k\ (= 2.719\,\mathrm{K})$$

$$[\alpha_{\mathrm{G}} \equiv G m_e^2/c\hbar] \qquad 16\sqrt{2}\pi\alpha_{\mathrm{G}}^{1/4} m_e c^2/k\ (= 2.727\,\mathrm{K})$$

$$(hc/k)\ \mu\mathrm{Leagues}^{-1} (= 2.98\,\mathrm{K})$$

$$[\pi \mathrm{e}^{\pi} \simeq 73] \qquad \mathrm{e}^{-73} T_{\mathrm{Pl}}\ (= 2.805\,\mathrm{K})$$

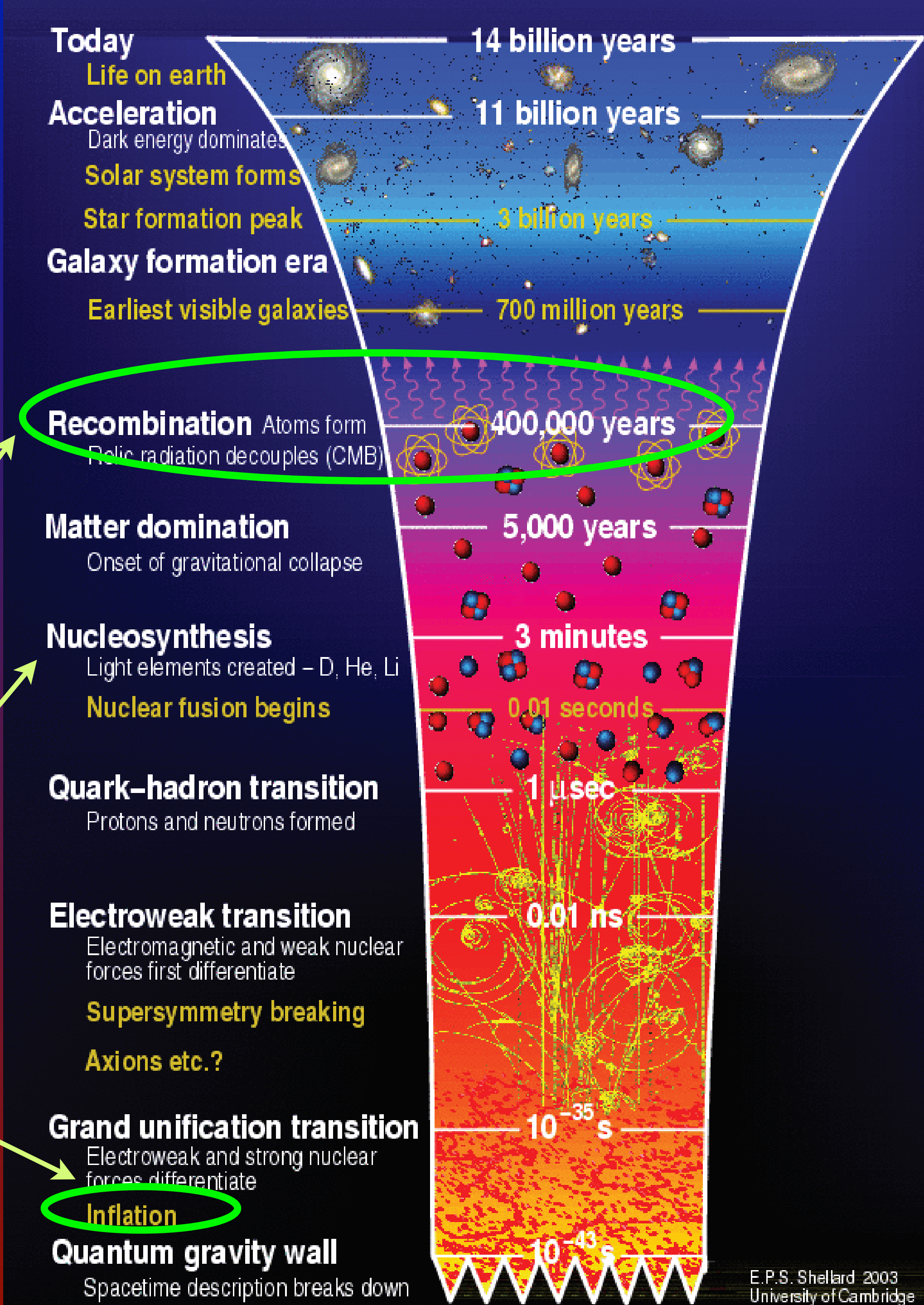
The Hot Big Bang

Where did the CMB really come from?

Last scattered at this epoch

Photons made at this epoch

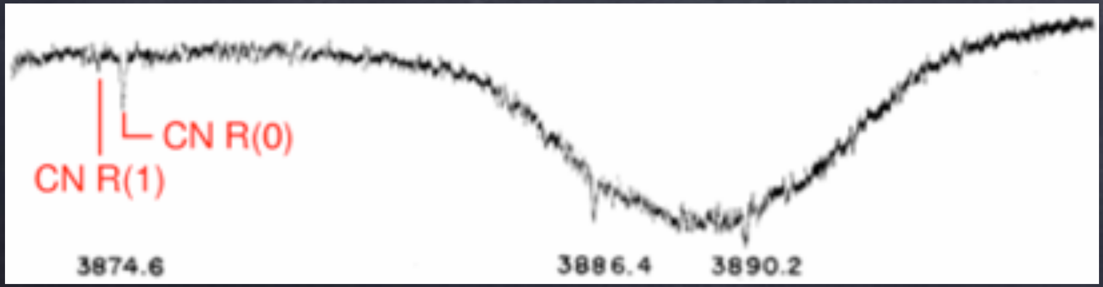
Deriving from physics at this epoch



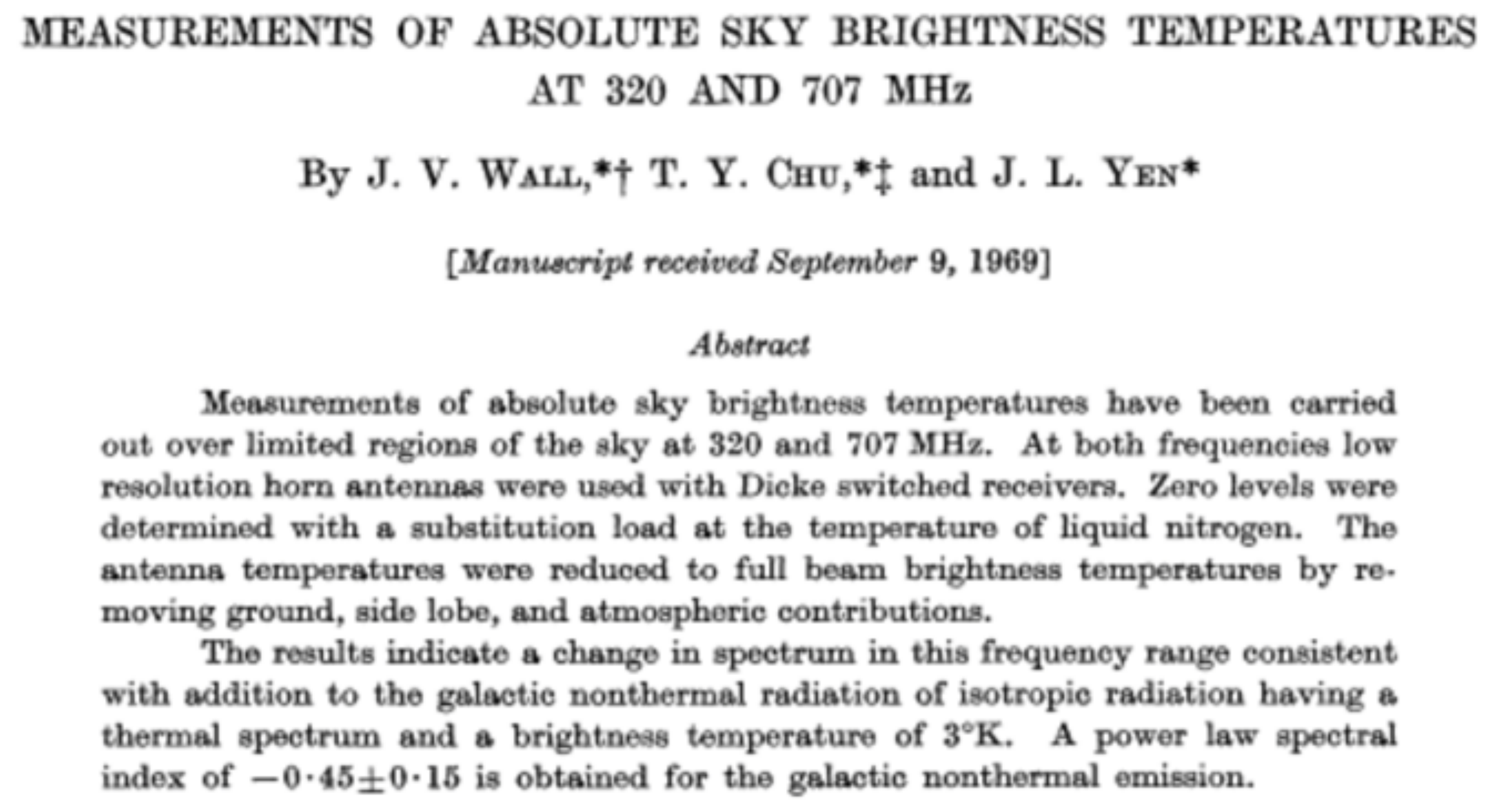
CMB history (eh)

Andrew McKellar

CN measurements at DAO (1940, 1941) ⇒ rotational temp ≈ 2.3K



Herzberg (1950): "...only a very restricted meaning"



MEASUREMENTS OF ABSOLUTE SKY BRIGHTNESS TEMPERATURES AT 320 AND 707 MHz

By J. V. Wall,*† T. Y. Chu,*‡ and J. L. Yen*

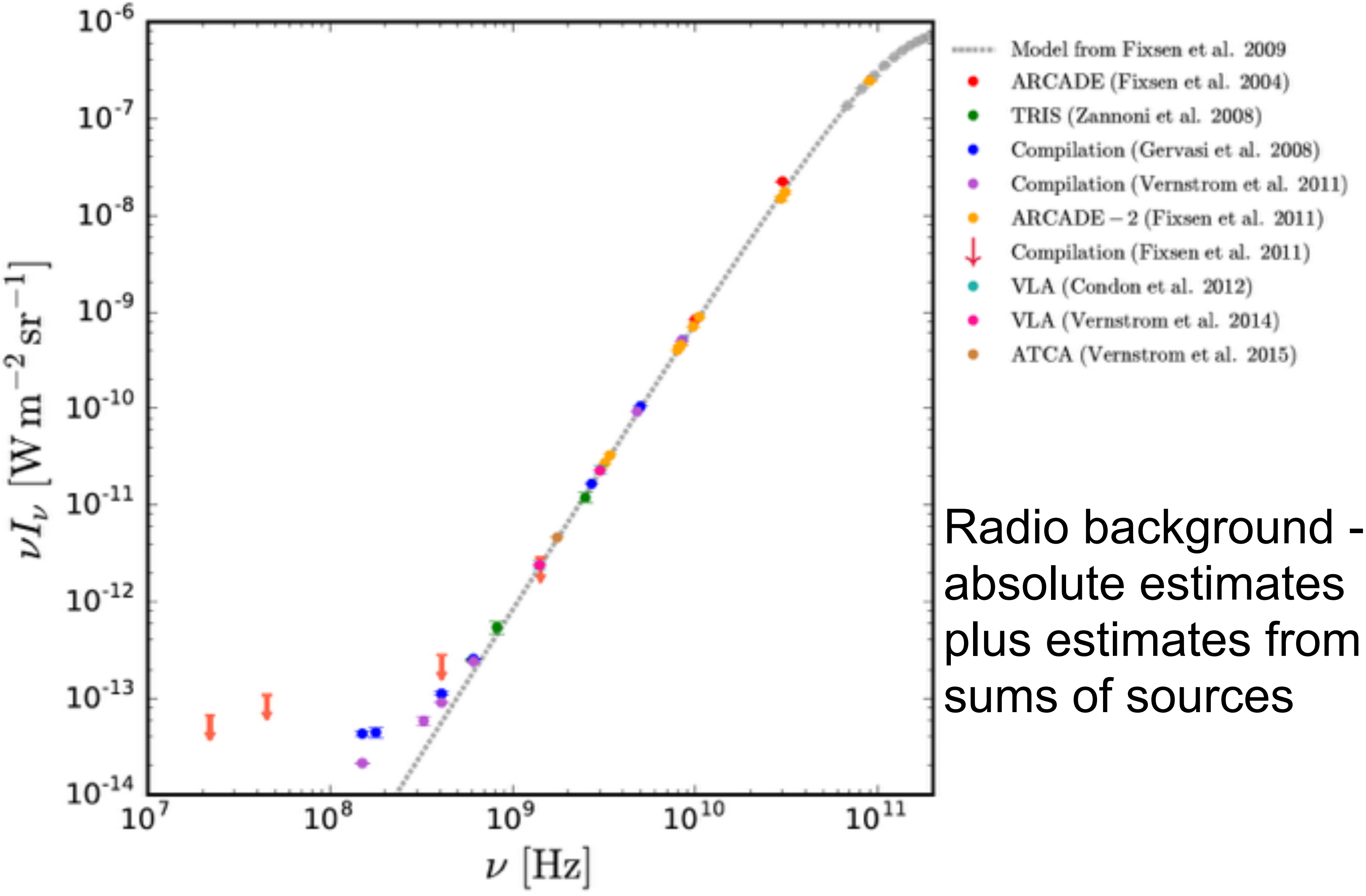
[*Manuscript received September 9, 1969*]

Abstract

Measurements of absolute sky brightness temperatures have been carried out over limited regions of the sky at 320 and 707 MHz. At both frequencies low resolution horn antennas were used with Dicke switched receivers. Zero levels were determined with a substitution load at the temperature of liquid nitrogen. The antenna temperatures were reduced to full beam brightness temperatures by removing ground, side lobe, and atmospheric contributions.

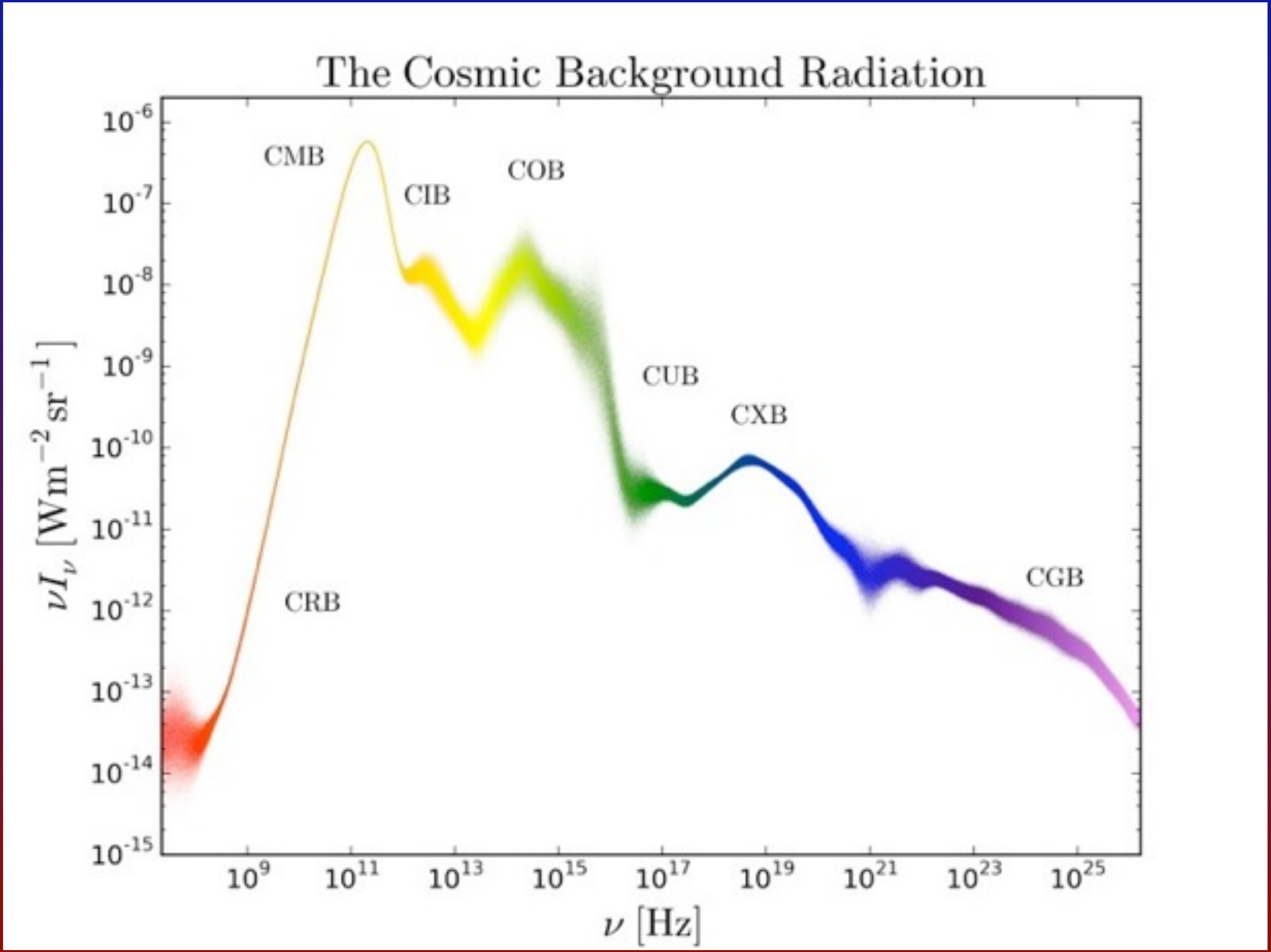
The results indicate a change in spectrum in this frequency range consistent with addition to the galactic nonthermal radiation of isotropic radiation having a thermal spectrum and a brightness temperature of 3°K. A power law spectral index of $-0{\cdot}45 \pm 0{\cdot}15$ is obtained for the galactic nonthermal emission.

Jasper’s contribution (data taken in 1965)



Radio background - absolute estimates plus estimates from sums of sources

The (extragalactic) monopole across the entire EM spectrum



with Ryley Hill and Kiyo Masui

The CMB monopole

Current measurement: T_0=2.7255±0.0006K (Fixsen 2009)

But $\Delta T/T$~0.00001 on all scales including our Hubble patch!

So if we could live in a ~3σ fluctuation then we're only ~10 from Cosmic Variance!

But isn't the monopole coordinate dependent?

The CMB monopole

But we live in a potential (which is in another potential ...)

So the “true” CMB monopole isn’t what we measure anyway

(But this is only of order v^2/c^2)

And this helps underscore that it’s coordinate-dependent

Defining the monopole

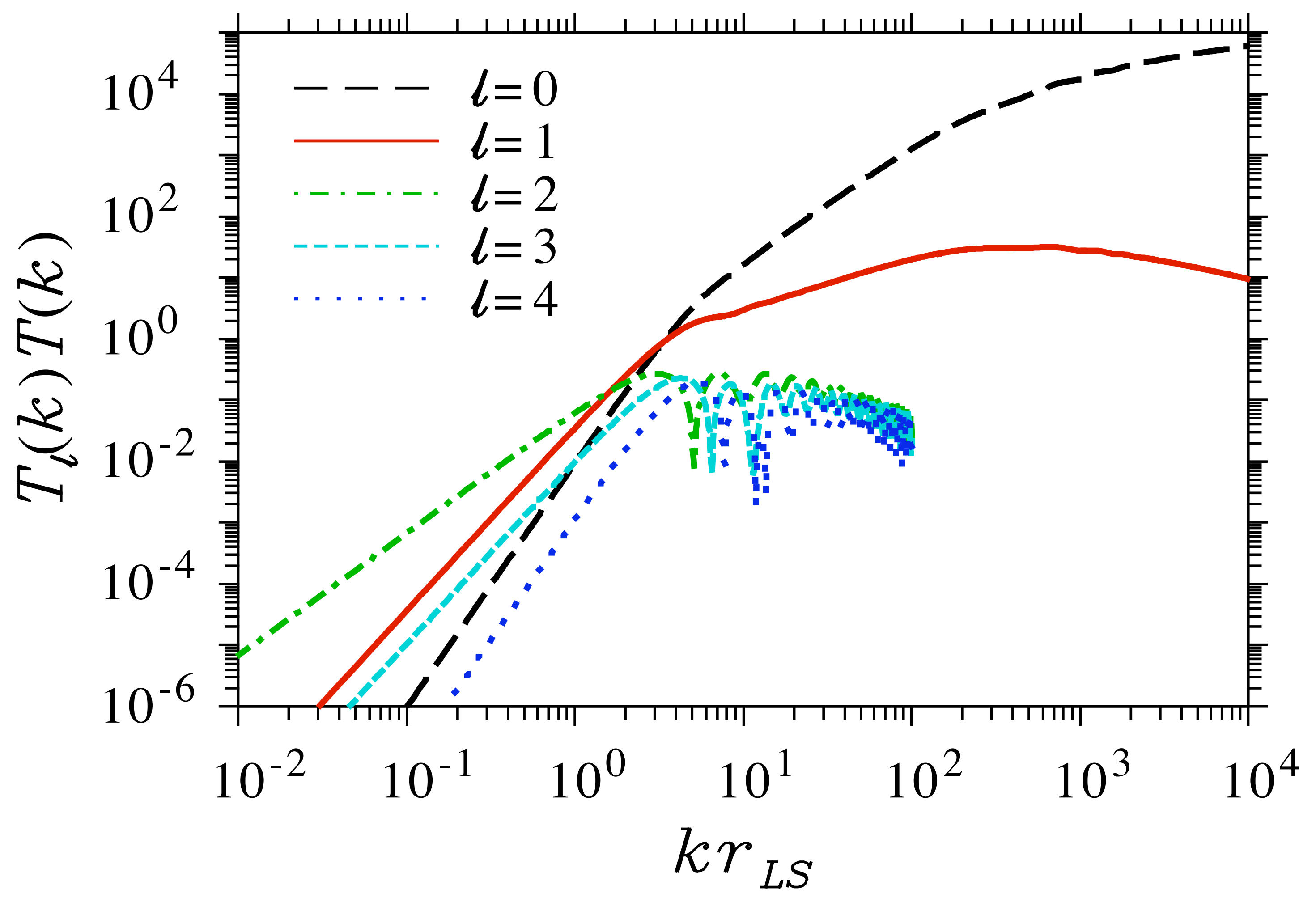
Monopole fluctuation is ambiguous -
depends on choice of hypersurface
(zero on constant radiation surface!)

Can still define monopole -
through sensible coordinate choice

Obvious choice is uniform matter slice
Or equivalently uniform energy density

Can calculate the transfer function
for the perturbations

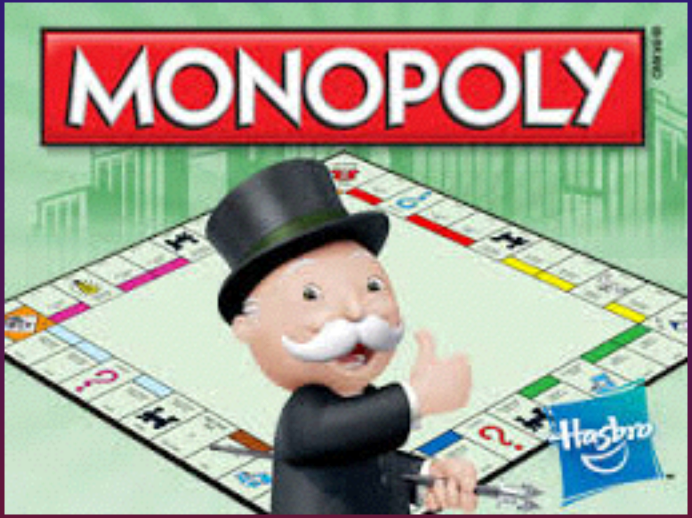
Even if monopole (and dipole) coordinate-dependent ... can still define the expected variance



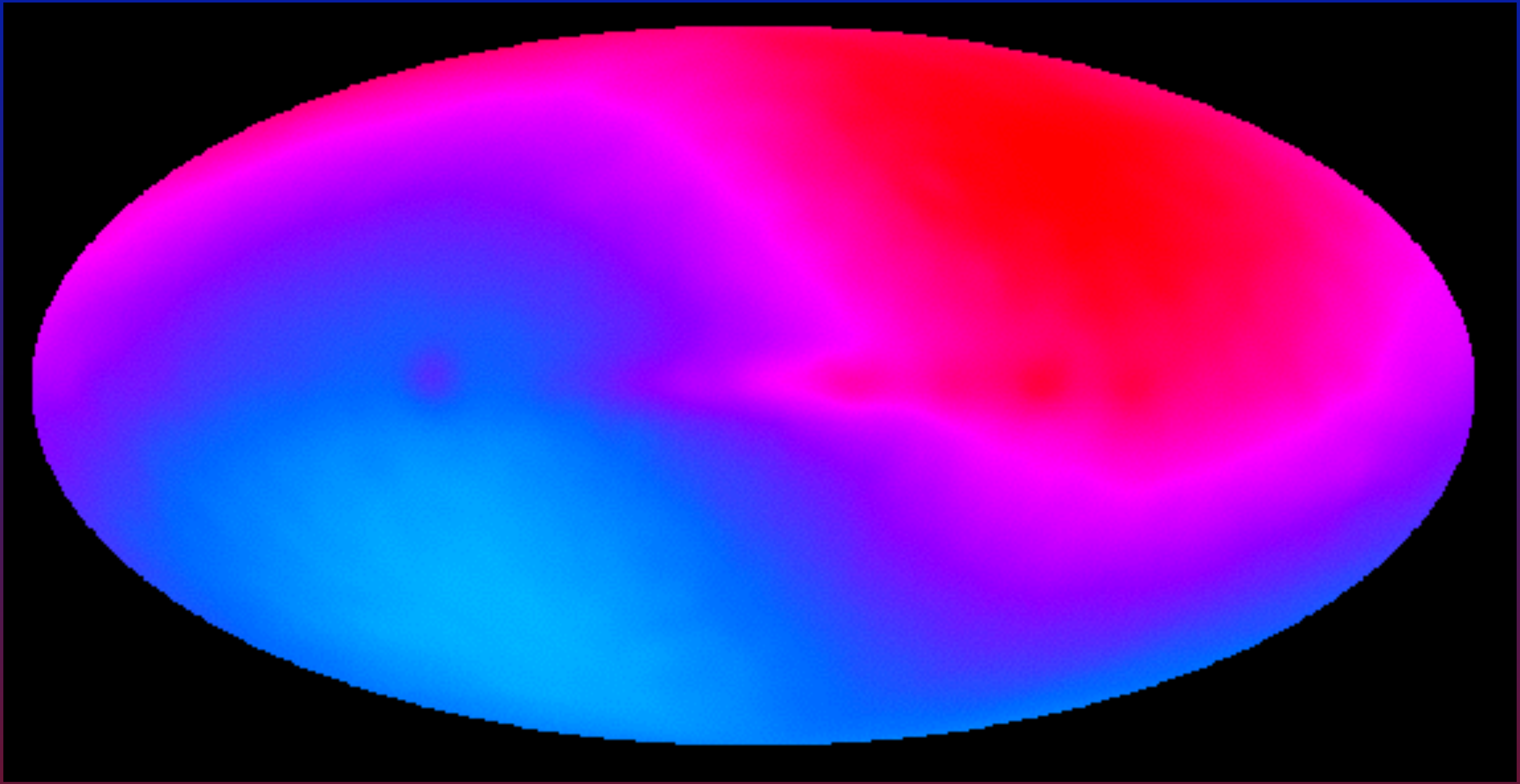
Find that monopole fluctuation is indeed ~10^{-5}

Zibin & Scott arXiv:0808.2047

What do you call the study of the monopole?



What about the dipole?
… diplomacy?



CMB dipole (from COBE satellite)

Defining the dipole

Dipole also ambiguous
(zero in “CMB rest frame”!)

Choose comoving matter field

Large contribution from small-scales, which are non-linear

(and Super-horizon contribution suppressed)

No “intrinsic dipole” for adiabatic perturbations
(since matter frame = CMB frame)

Defining the dipole

“Extrinsic” dipole comes from our motion

In principle estimate “real” motion with aberration

Or determine motion from accelerations due to local lumps of matter

Any deficit gives the dipole fluctuation (doesn’t it?)

Not in adiabatic models!
The dipole is just our velocity relative to the CMB LSS

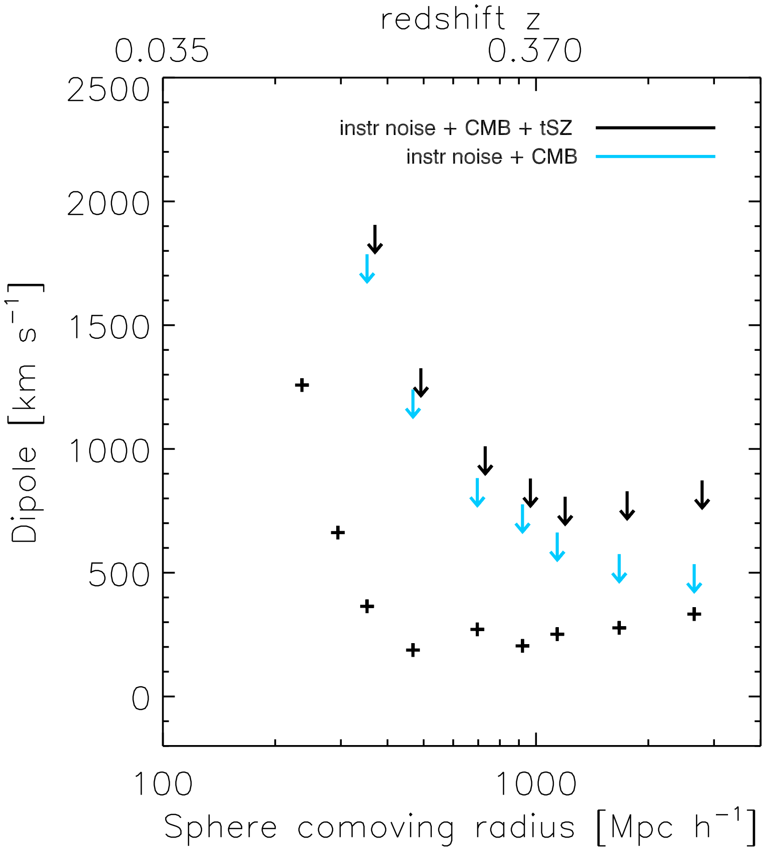


Fig. 9. Bulk flow amplitude measured in *Planck* data with the all-sky method, after subtraction (vectorially) of the Galactic contribution (black crosses), compared with 95 % upper limits derived from simulations containing CMB and instrumental noise only (blue arrows) or also including tSZ signal (black arrows). The fact that the crosses are below the arrows at all scales shows that there is no significant bulk flow detection.

Planck intermediate paper XIII (arXiv:1303.5090)

Kinetic Sunyaev-Zeldovich effect

Places limit on large bulk flows

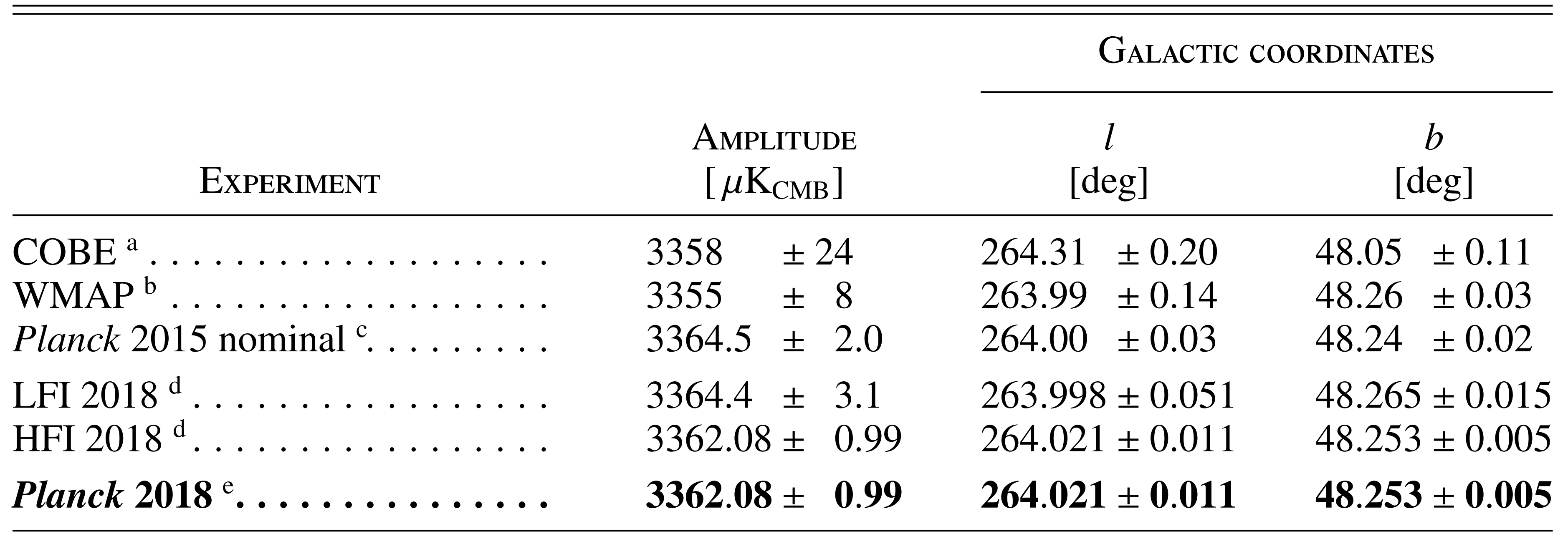
The matter and CMB frames are the same

What about Planck’s dipole?

The “orbital dipole” is used to calibrate
So the “solar dipole” can be independently measured
This is the currently most precise dipole

Hence the best estimate of our velocity relative to the distance “rest frame”

Planck's 2018 dipole



EXPERIMENT	AMPLITUDE [μK_{CMB}]	GALACTIC COORDINATES l [deg]	b [deg]
COBE [a]	3358 ± 24	264.31 ± 0.20	48.05 ± 0.11
WMAP [b]	3355 ± 8	263.99 ± 0.14	48.26 ± 0.03
Planck 2015 nominal [c]	3364.5 ± 2.0	264.00 ± 0.03	48.24 ± 0.02
LFI 2018 [d]	3364.4 ± 3.1	263.998 ± 0.051	48.265 ± 0.015
HFI 2018 [d]	3362.08 ± 0.99	264.021 ± 0.011	48.253 ± 0.005
***Planck* 2018** [e]	**3362.08** ± **0.99**	**264.021** ± **0.011**	**48.253** ± **0.005**

Position now known to ~30"

(uncertainties are systematics dominated)

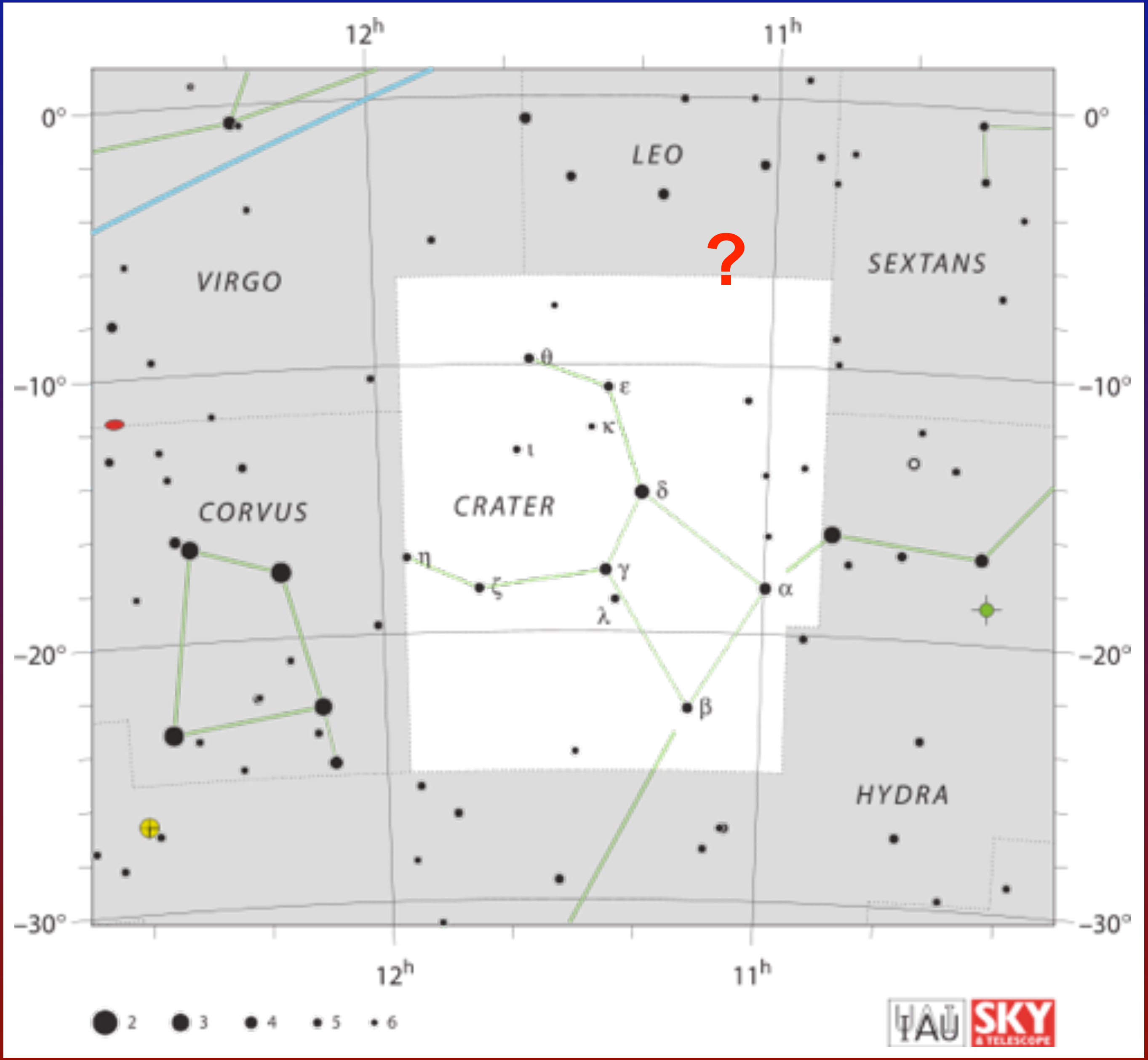
Planck's 2015 dipole amplitude:

$v = 0.12345\% \ c$!

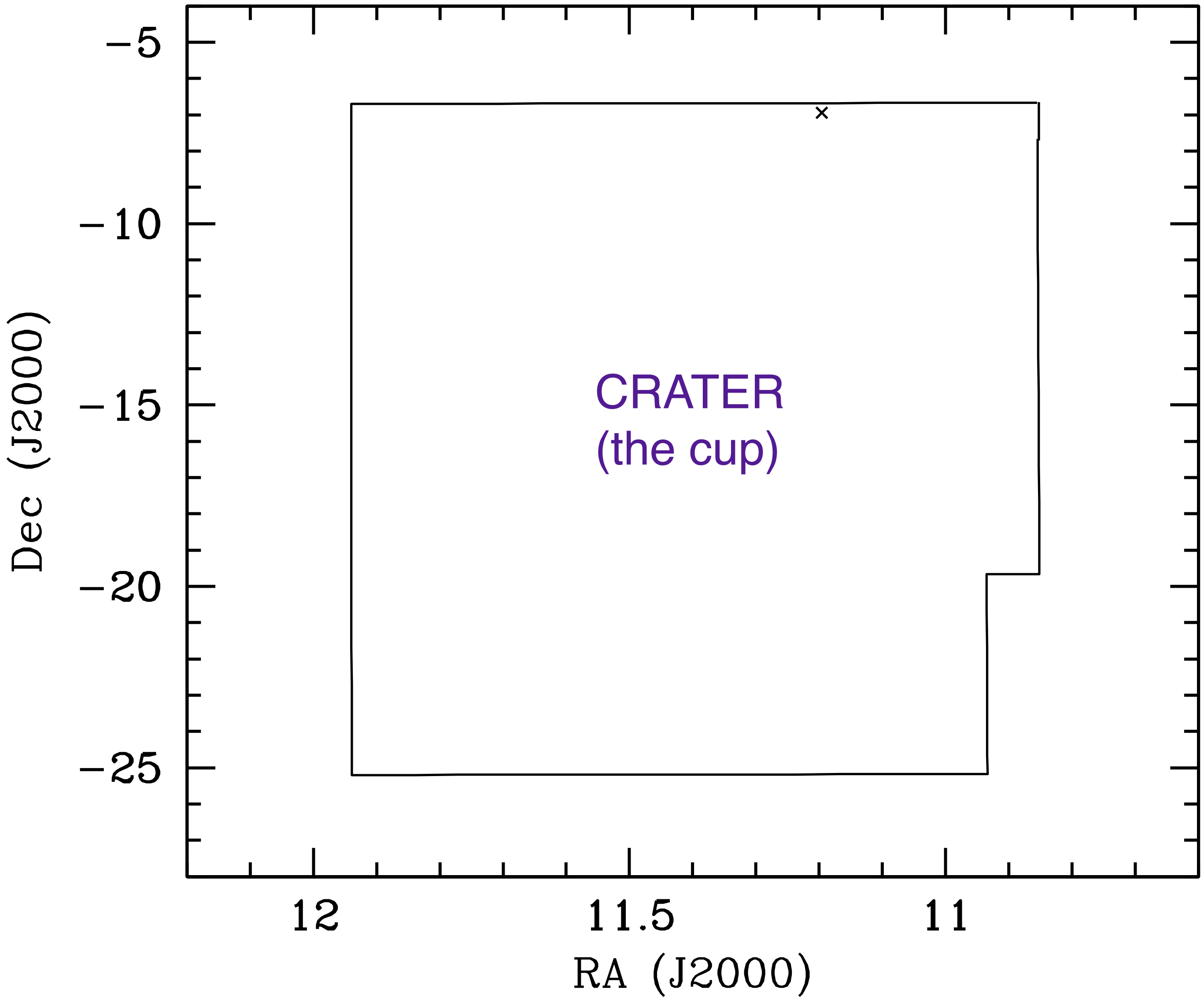
Planck's 2018 dipole amplitude:

$v = (0.12336 \pm 0.00004)\% \ c$

Where's the dipole direction?



What constellation am I in?



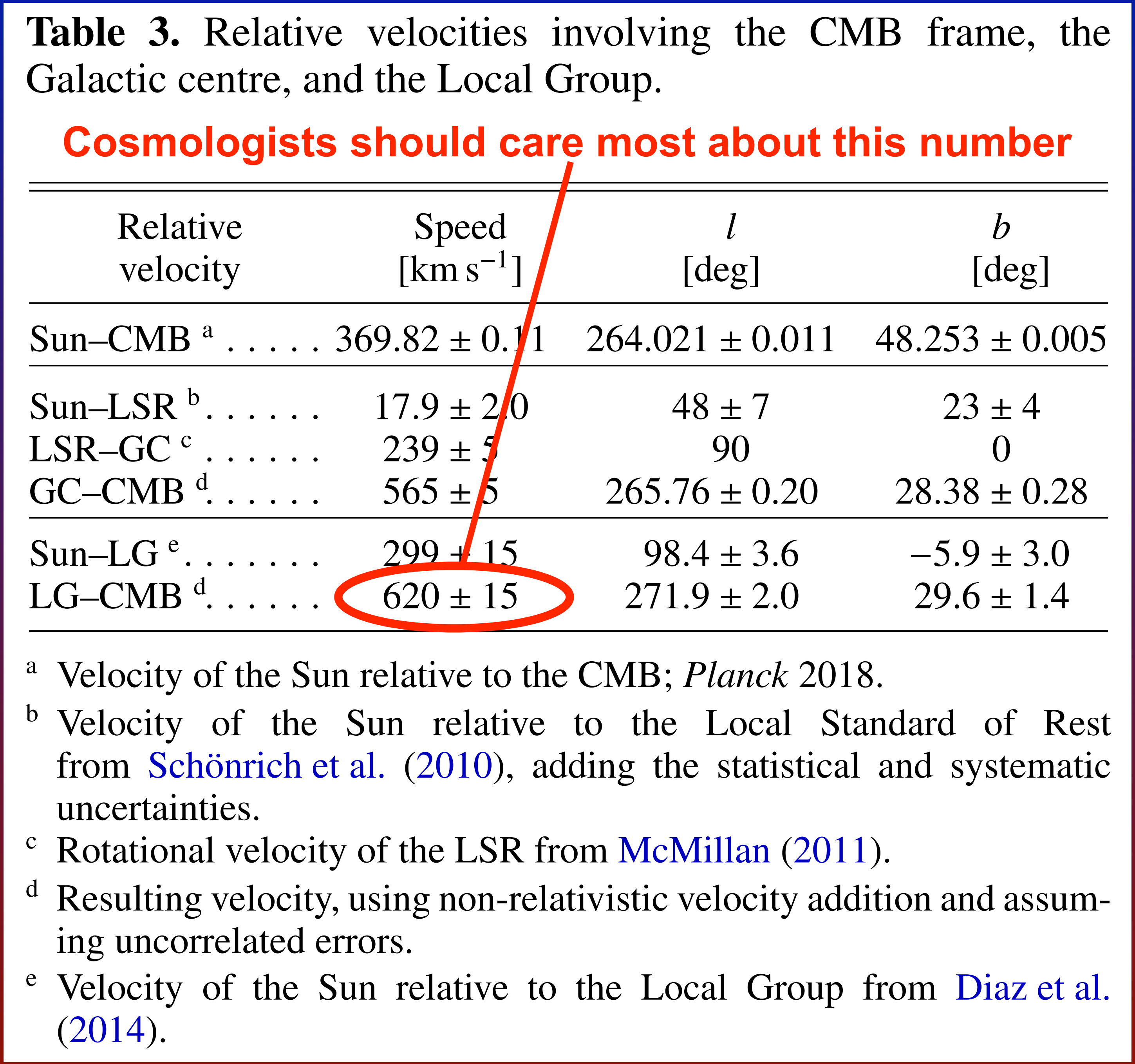


Table 3. Relative velocities involving the CMB frame, the Galactic centre, and the Local Group.

Cosmologists should care most about this number

Relative velocity	Speed [km s^{-1}]	l [deg]	b [deg]
Sun–CMB [a]	369.82 ± 0.11	264.021 ± 0.011	48.253 ± 0.005
Sun–LSR [b]	17.9 ± 2.0	48 ± 7	23 ± 4
LSR–GC [c]	239 ± 5	90	0
GC–CMB [d]	565 ± 5	265.76 ± 0.20	28.38 ± 0.28
Sun–LG [e]	299 ± 15	98.4 ± 3.6	−5.9 ± 3.0
LG–CMB [d]	620 ± 15	271.9 ± 2.0	29.6 ± 1.4

[a] Velocity of the Sun relative to the CMB; *Planck* 2018.

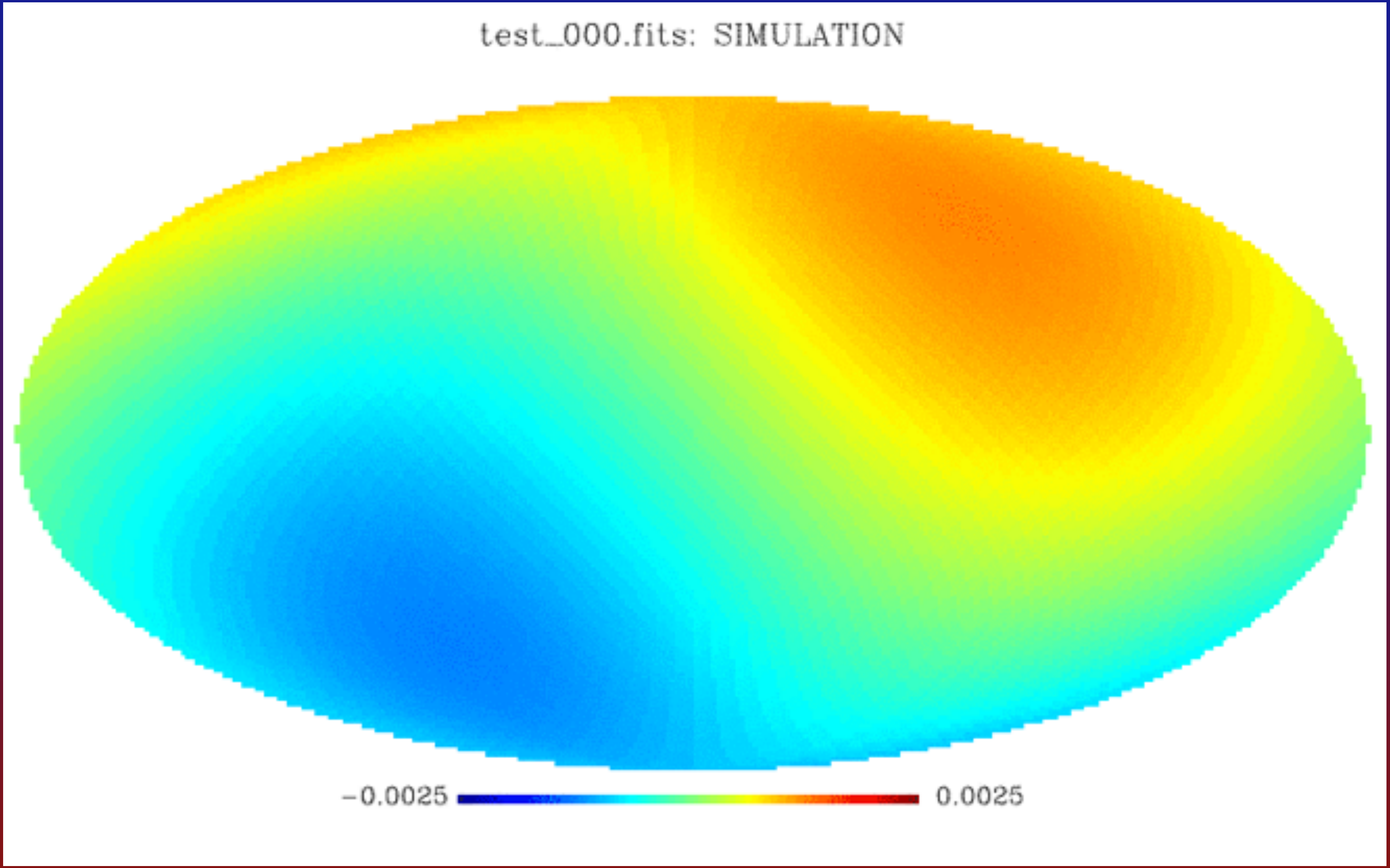
[b] Velocity of the Sun relative to the Local Standard of Rest from Schönrich et al. (2010), adding the statistical and systematic uncertainties.

[c] Rotational velocity of the LSR from McMillan (2011).

[d] Resulting velocity, using non-relativistic velocity addition and assuming uncorrelated errors.

[e] Velocity of the Sun relative to the Local Group from Diaz et al. (2014).

Dipole evolves as we circle the Galaxy



Moss, Scott & Zibin arXiv:0706.4482 & 0709.4040

Recall issues relevant to monopole and dipole

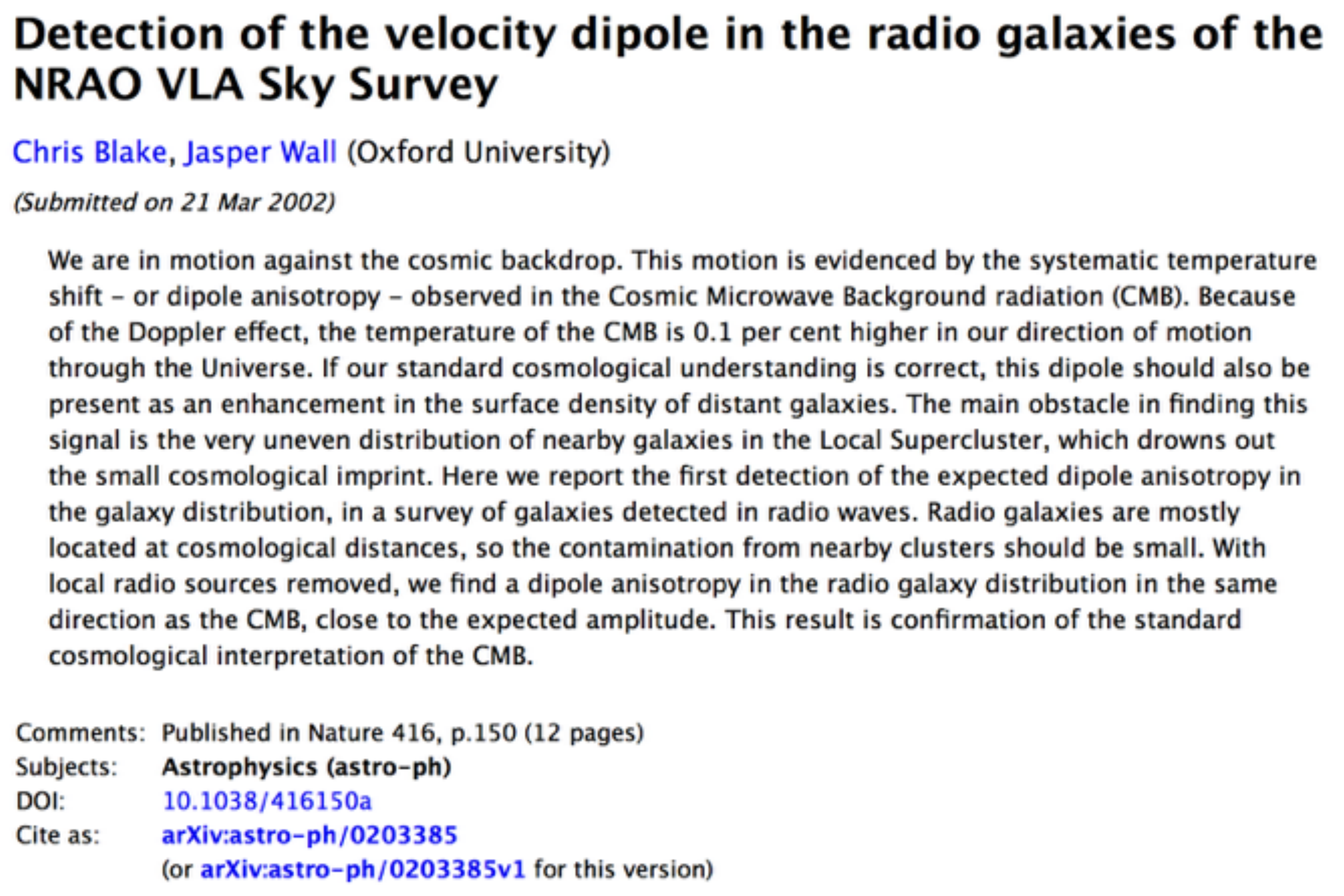
- Monopole: T_0=(2.7255±0.0006)K
- CMB last-scattering surface defines a rest frame
- It’s the frame with no observable dipole
- Relative to that frame we’re moving at ≈ 370km/s
- β=0.0012345 towards the constellation Crater
- Local Group 620km/s relative to CMB

And there are other effects…

And there are other effects…

Dipole-modulate monopole → CMB dipole	Well known!
Dipole-modulation of all other multipoles	Planck 2013
Aberration of anisotropies	Planck 2013
Increase in monopole by $\beta^2/6$	Unmeasurable
Generation of $O(\beta^2)$ quadrupole	y spectrum?

And related effects at other wavelengths, e.g. modulation of source counts



Detection of the velocity dipole in the radio galaxies of the NRAO VLA Sky Survey

Chris Blake, Jasper Wall (Oxford University)

(Submitted on 21 Mar 2002)

We are in motion against the cosmic backdrop. This motion is evidenced by the systematic temperature shift – or dipole anisotropy – observed in the Cosmic Microwave Background radiation (CMB). Because of the Doppler effect, the temperature of the CMB is 0.1 per cent higher in our direction of motion through the Universe. If our standard cosmological understanding is correct, this dipole should also be present as an enhancement in the surface density of distant galaxies. The main obstacle in finding this signal is the very uneven distribution of nearby galaxies in the Local Supercluster, which drowns out the small cosmological imprint. Here we report the first detection of the expected dipole anisotropy in the galaxy distribution, in a survey of galaxies detected in radio waves. Radio galaxies are mostly located at cosmological distances, so the contamination from nearby clusters should be small. With local radio sources removed, we find a dipole anisotropy in the radio galaxy distribution in the same direction as the CMB, close to the expected amplitude. This result is confirmation of the standard cosmological interpretation of the CMB.

Comments: Published in Nature 416, p.150 (12 pages)
Subjects: **Astrophysics (astro-ph)**
DOI: 10.1038/416150a
Cite as: **arXiv:astro-ph/0203385**
(or **arXiv:astro-ph/0203385v1** for this version)

Jasper (and Chris') dipole contribution

Boosting frames

Now $$\overset{\text{observed frame}}{T(\hat{\boldsymbol{n}})} = \frac{\overset{\text{CMB frame}}{T'(\hat{\boldsymbol{n}}')}}{\gamma(1-\hat{\boldsymbol{n}}\cdot\underset{\text{v/c}}{\boldsymbol{\beta}})}$$

with $$\hat{\boldsymbol{n}} = \frac{\hat{\boldsymbol{n}}' + \left[(\gamma-1)\hat{\boldsymbol{n}}'\cdot\hat{\boldsymbol{v}} + \gamma\beta\right.}{\gamma(1+\hat{\boldsymbol{n}}'\cdot\boldsymbol{\beta})}$$

To 1st order in β:

$$T'(\hat{\boldsymbol{n}}') = T'(\hat{\boldsymbol{n}} - \nabla(\hat{\boldsymbol{n}}\cdot\boldsymbol{\beta})) \equiv T_0 + \delta T'(\hat{\boldsymbol{n}} - \nabla$$

So finally:

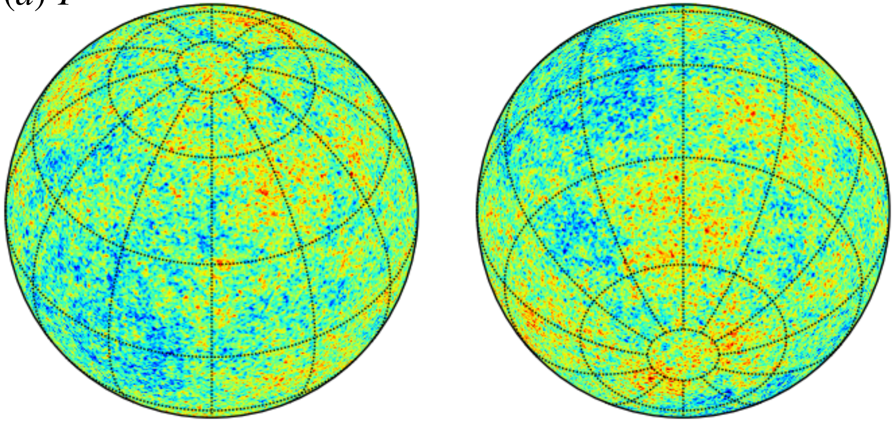
$$\delta T(\hat{\boldsymbol{n}}) = \overset{\text{dipole}}{\boxed{T_0\hat{\boldsymbol{n}}\cdot\boldsymbol{\beta}}} + \delta T'(\hat{\boldsymbol{n}} - \overset{\text{deflections}}{\boxed{\nabla(\hat{\boldsymbol{n}}\cdot\boldsymbol{\beta})}})($$

```
\def\mathbi#1{\textbf{\em #1}
T({\hat{\mathbi{n\,}}}) = {T^
\prime({\hat{\mathbi{n\,}}}^\pr
\over \gamma(1-{\hat{\mathbi
\,}}}^\prime\cdot\mbox{\boldr
$\beta$}
```

```
\def\mathbi#1{\text
{\hat{\mathbi{n\,}}}
 {{\hat{\mathbi{n\,}}
\left[(\gamma-1)
 {\hat{\mathbi{n\,}}}
\cdot{\hat{\mathbi{
 + \gamma\beta\rig
 {\hat{\mathbi{v\,}}}
 \gamma(1+{\hat{\m
\prime\cdot\mbox
{\boldmath$\beta$}
```

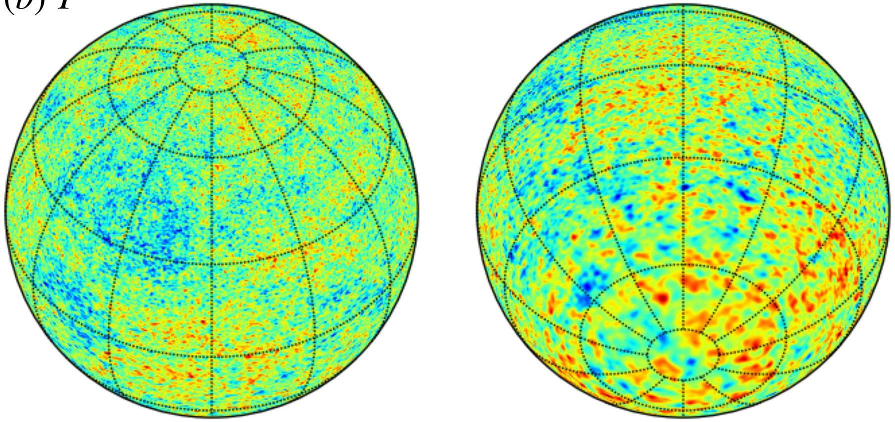
```
\def\mathbi#1{\textbf{\em
T^\prime({\hat{\mathbi{n\,
\prime) = T^\prime({\hat{\m
\,}}}-\nabla({\hat{\mathbi{n
\cdot\mbox{\boldmath$\b
\equiv T_0 + \delta T^
\prime({\hat{\mathbi{n\,}}}
\nabla({\hat{\mathbi{n\,}}}\
```

(*a*) $T^{\text{PRIMORDIAL}}$



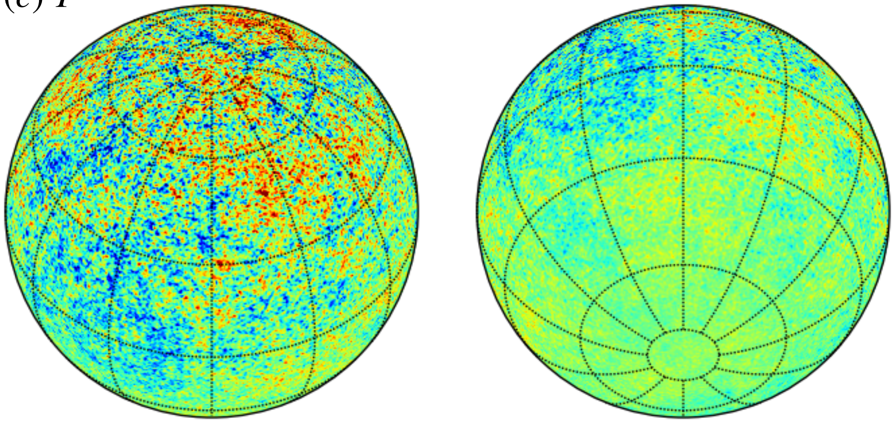
Simulated CMB

(*b*) $T^{\text{ABERRATION}}$

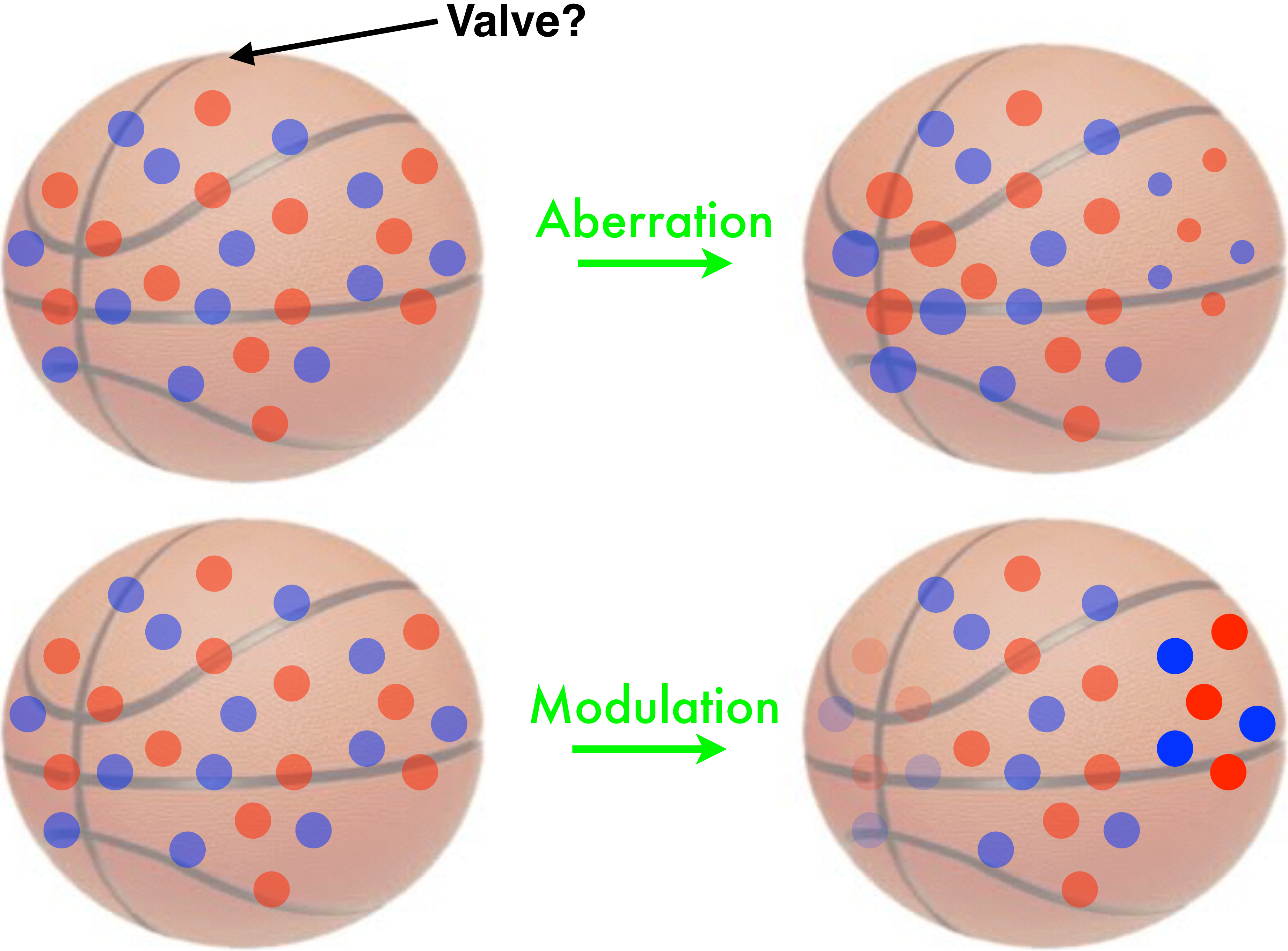


Aberration
for β=0.85

(*c*) $T^{\text{MODULATION}}$



Modulation
for β=0.85



Valve?

Aberration

Modulation

Boosting frames

With *Planck* we can try to measure both the aberration and boosting effects

This could be p space

or

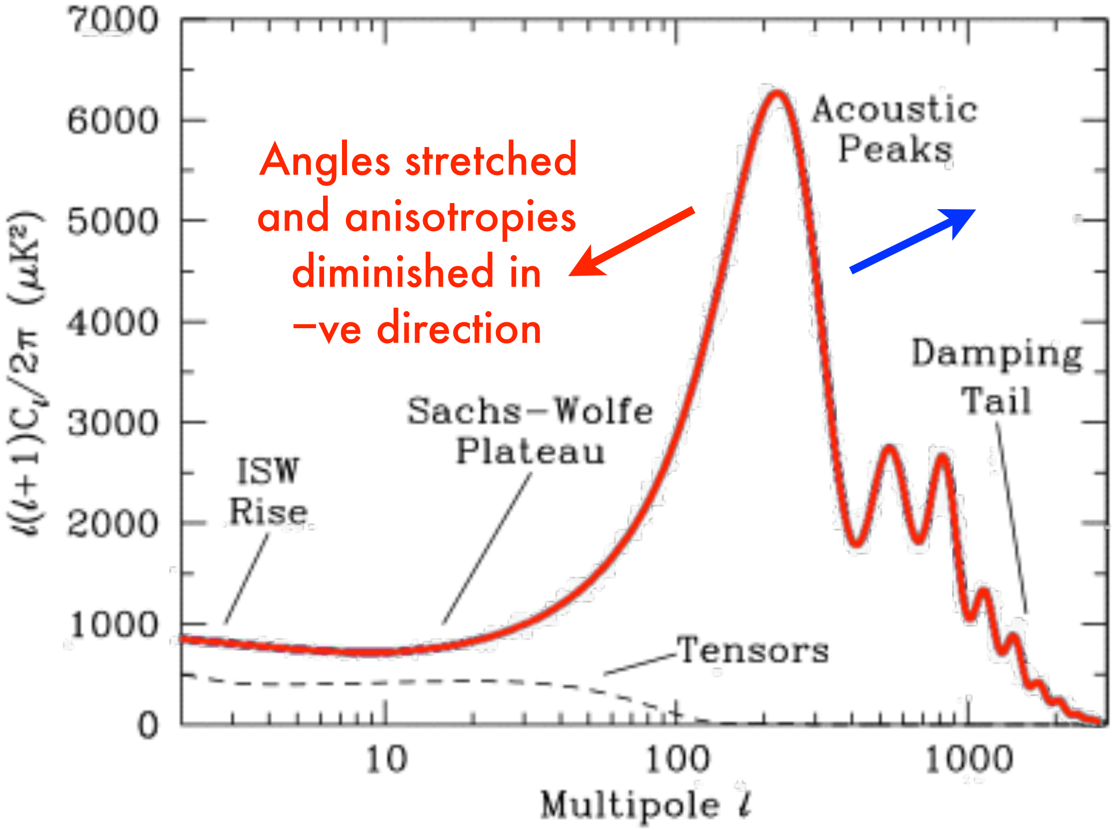
Harmonic space is more efficient

and uses machinery of $\langle T_1 T_2 T_3 T_4 \rangle$

```
\def\mathbi#1{\textbf{\em #1}}
{\hat{\mathbi{n\,}}} =
 {{\hat{\mathbi{n\,}}}^\prime +
\left[(\gamma-1)
 {\hat{\mathbi{n\,}}}^\prime
\cdot{\hat{\mathbi{v\,}}}
 + \gamma\beta\right]
 {\hat{\mathbi{v\,}}}\over
```

```
\def\mathbi#1{\textbf{
T({\hat{\mathbi{n\,}}})
\prime({\hat{\mathbi{n
\over \gamma(1-{\hat{
\,}}}^\prime\cdot\mbo
$\beta$})}
```

Boosting frames

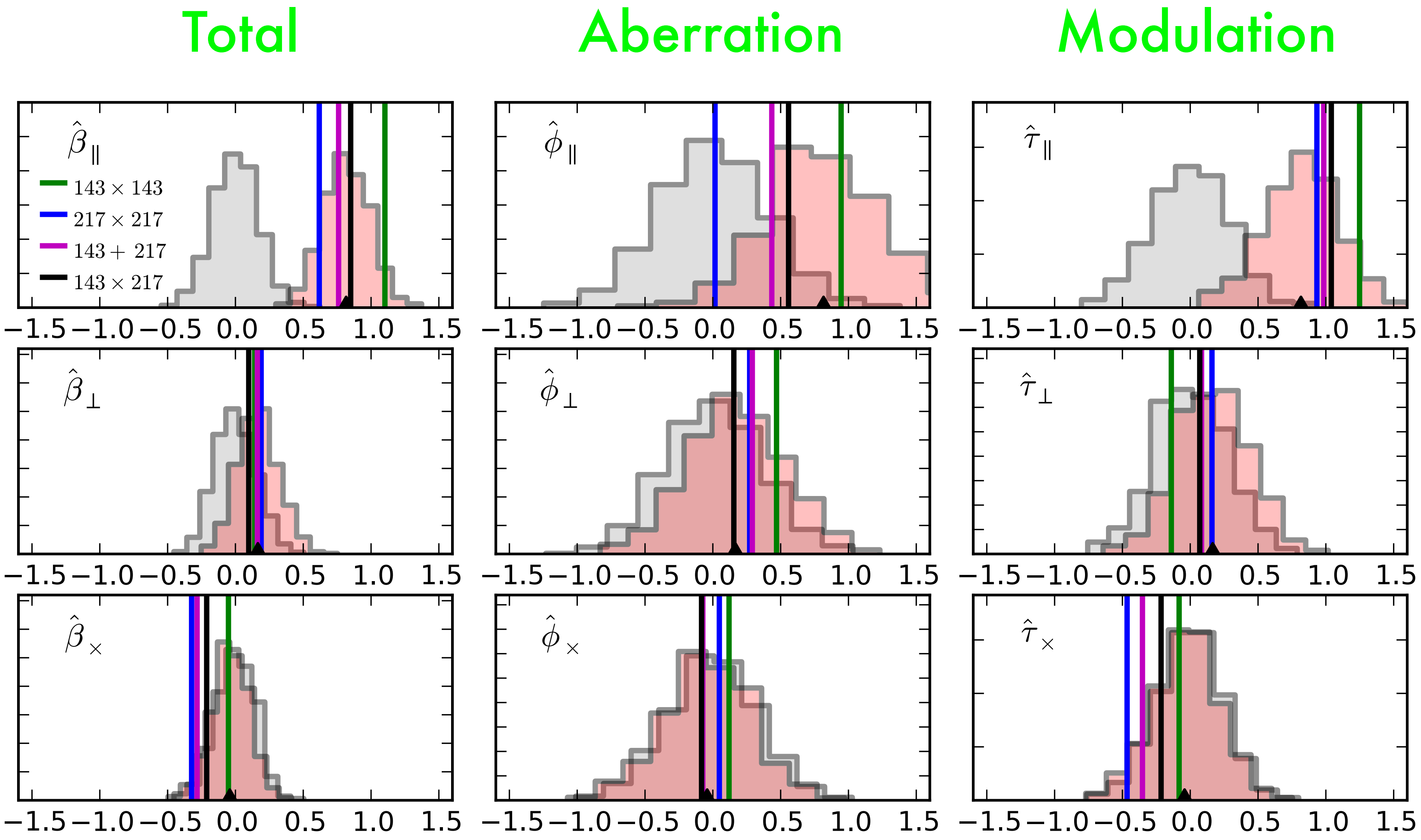


Angles stretched and anisotropies diminished in −ve direction

Angles squashed and anisotropies boosted in +ve direction

<u>Or</u> can consider this as an effect which couples harmonics

This was measured convincingly in 2013 Planck data set

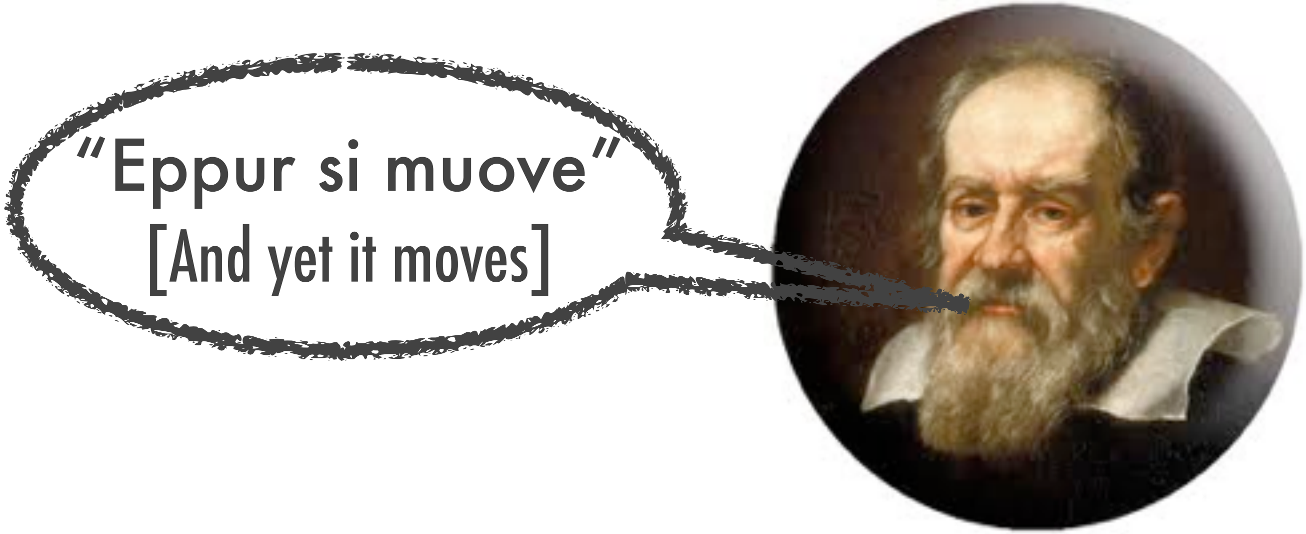

Total Aberration Modulation

Grey histogram: <u>without</u> Pink histogram: <u>with</u> β effects

Vertical lines are different data combinations

So what?

- Velocity Measured at 4−5σ
- (Complication with hemispheric asymmetry)
- Slightly biases parameters for partial sky coverage
- Probably doesn’t tell us anything new, but it’s cute!
- Only possible with *Planck*!



Are these “boosting” effects actually interesting?

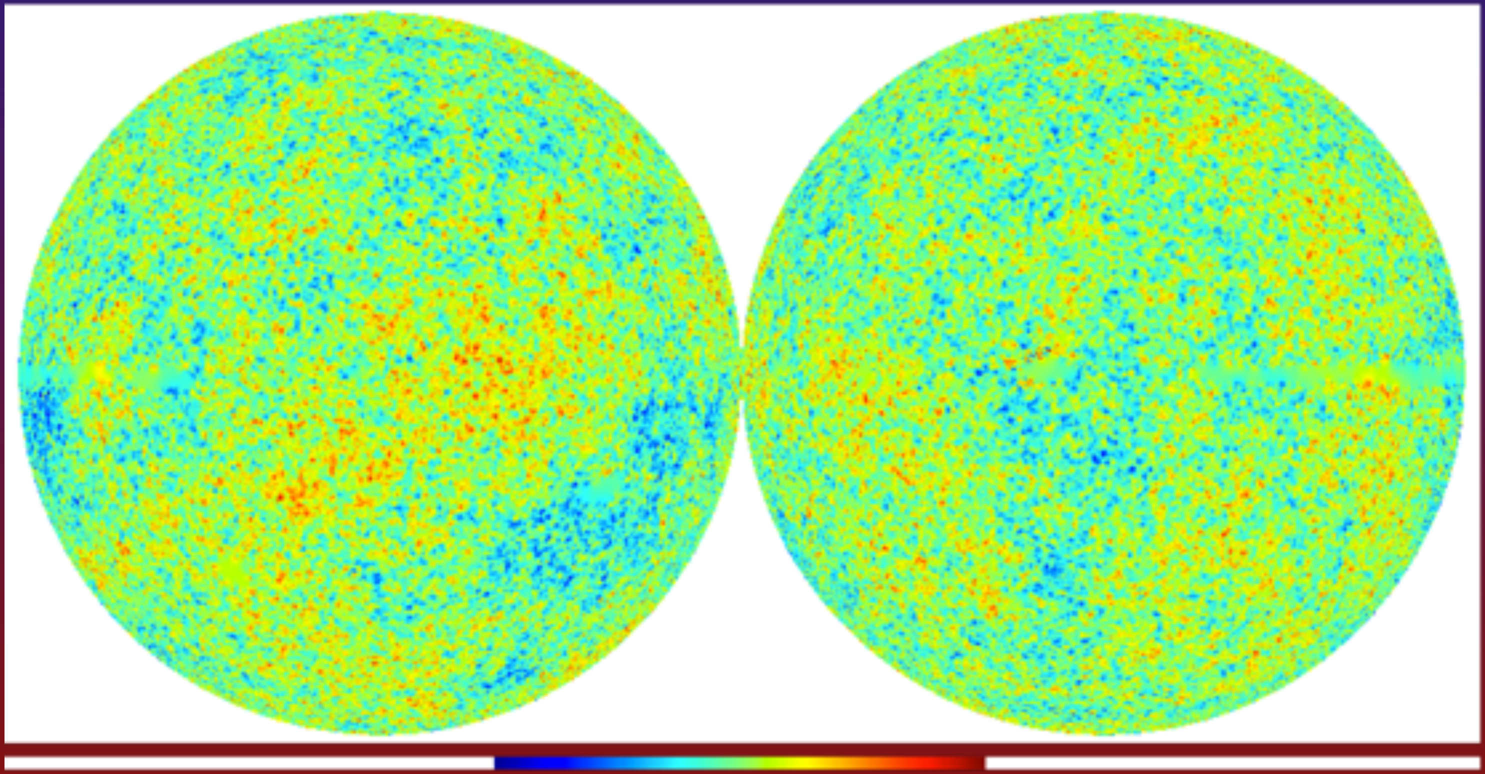
Could we tell about an “intrinsic dipole”?

No, because you’d get these effects with <u>any</u> dipole!

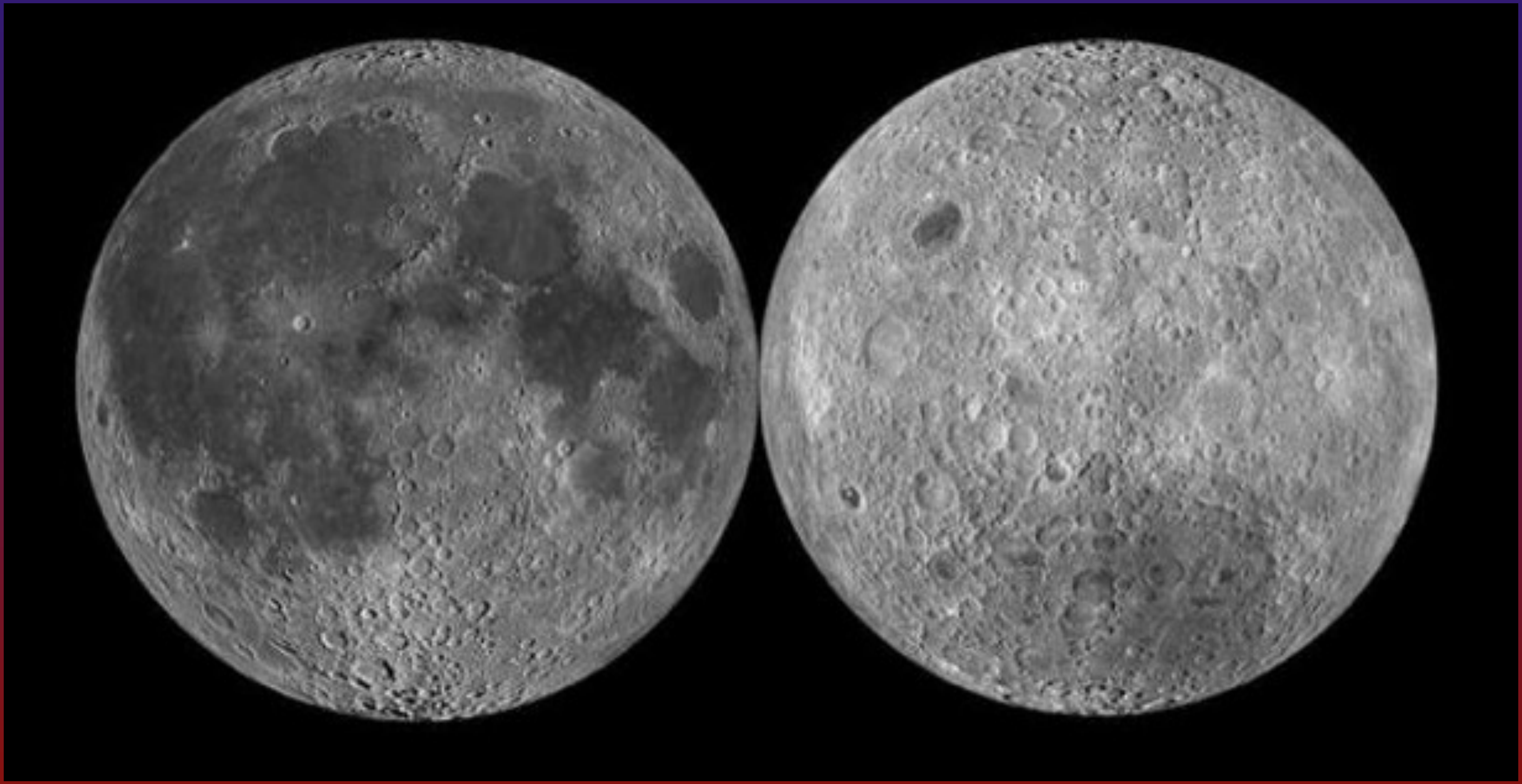
Sky appears dipole-
modulated
at <u>large</u> angular scales
(see Planck 2015 I&S paper)

Not caused by velocity
(only large scales)
- is it statistically significant?

Do the 2 sides of the CMB sky look alike?



Do the 2 sides of the Moon look alike?



Dipole modulation/ hemispheric asymmetry is real, but subtle

Maps modulated by $\simeq 6\%$,

but only out to $\ell_{\mathrm{max}} \simeq 64$

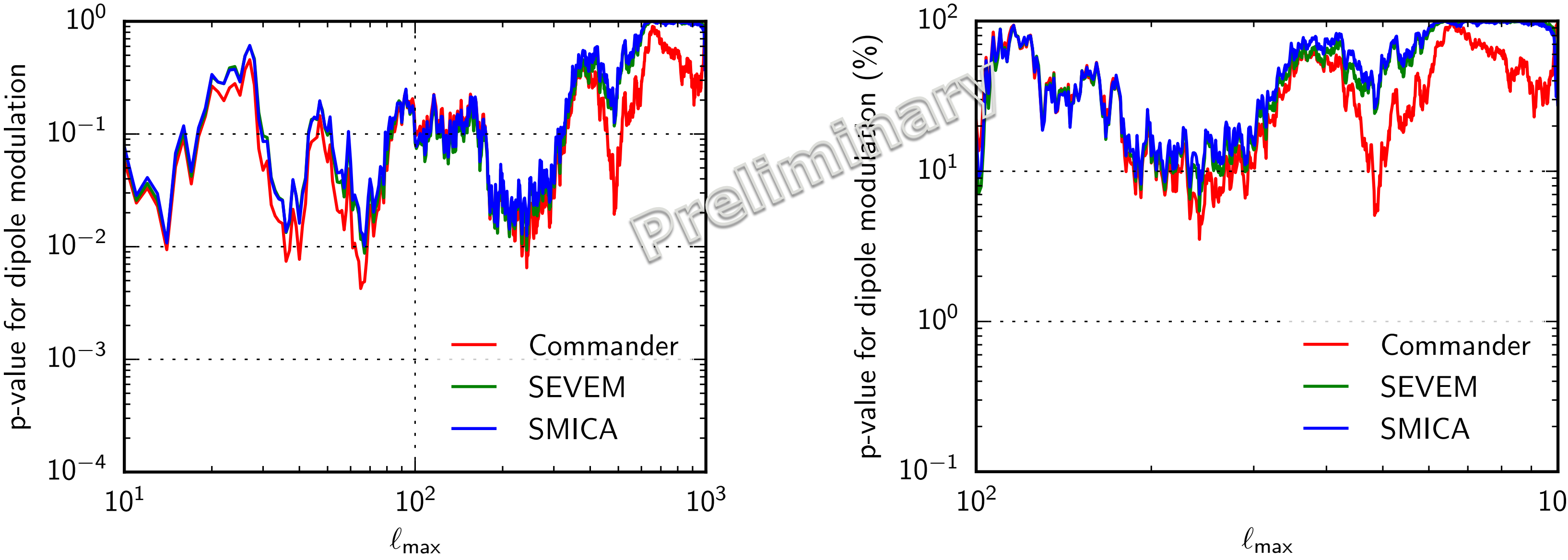
How do we assess whether this is statistically unlikely?

“Cosmic variance” expectation for dipole modulation to $\ell_{\rm max}$:

$$\left\langle \frac{\Delta A_{\rm s}}{A_{\rm s}} \right\rangle \simeq \sqrt{\frac{48}{\pi(\ell_{\rm max}+4)(\ell_{\rm max}-1)}}\,.$$

Map modulation is half of this, e.g. 2.9% for $\ell_{\rm max}$=67

Dipolar power modulation: harmonic analysis



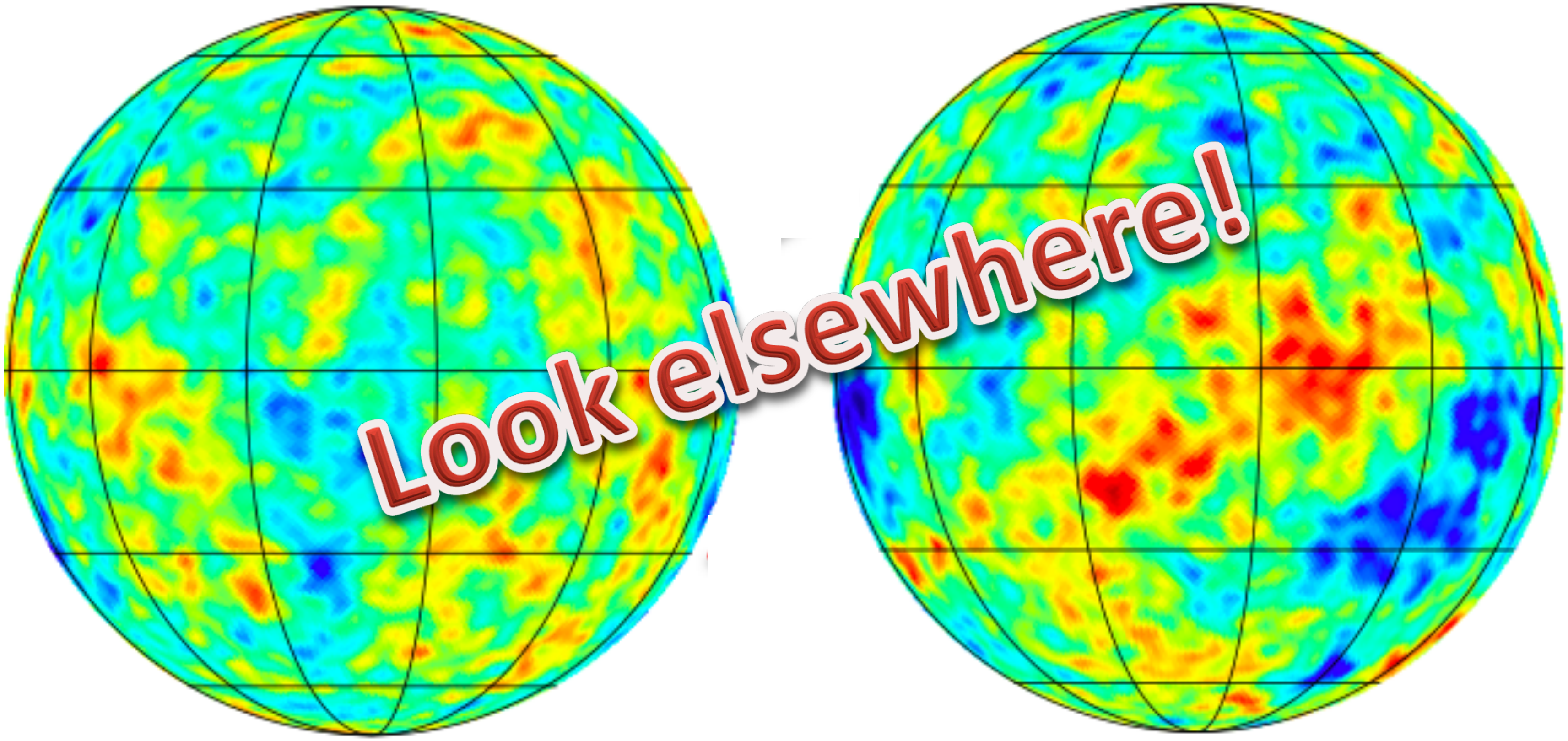
We use the harmonic QML estimator introduced in Moss et al 2011 (see also The Planck Collaboration, 2014, 571:A17-A27) to *Planck* intensity maps.

For $\ell_{\min}=2$ we found a ~3σ dipole modulation at $\ell_{\max}$~65 with a ~6.3% amplitude.

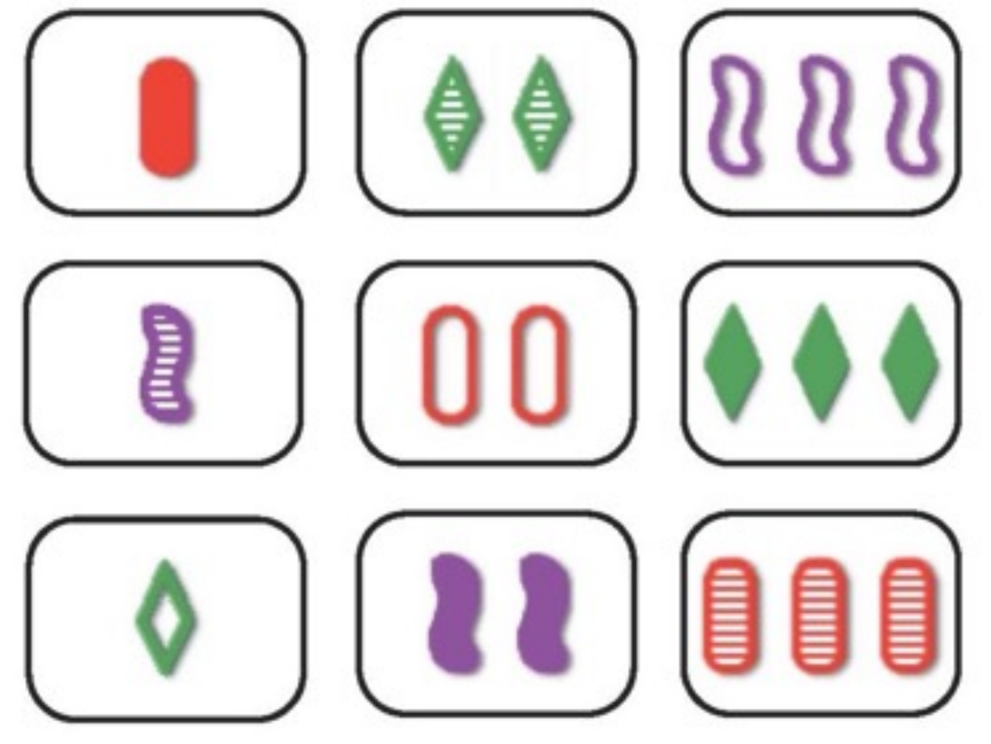
There is also evidence for modulations at $\ell_{\max}$~40, and $\ell_{\max}$~240.

However, the latter becomes much less significant when adopting $\ell_{\min}=100$, i.e. removing large angular scales.

Large Angle Anomalies



Our sky might look like this deal from the game “Set”



You should only get excited if it looks like this!

Right now the result doesn’t look very remarkable

But if we had a predictive model that would change everything

Large scales are special, so we should keep looking

Polarization offers the promise of an independent test

Quadrupole:
also some special issues
but out of time ...

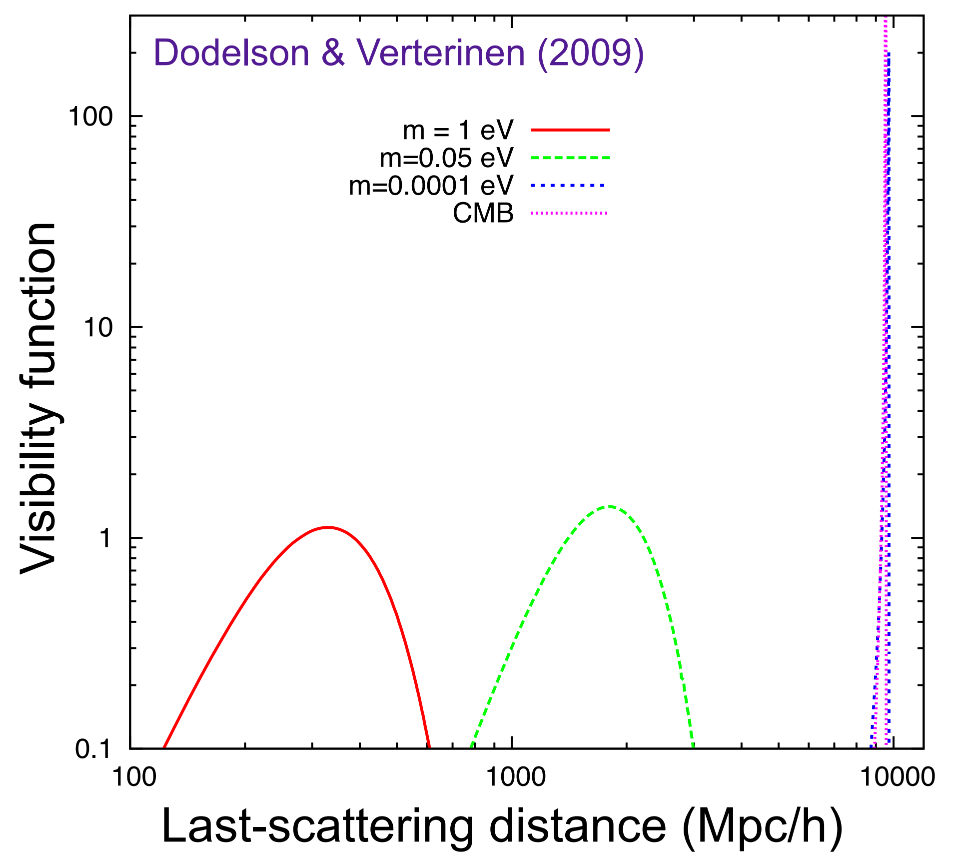
Other backgrounds
will also give dipoles

Depends on monopole
and spectral shape

Radio dipole, optical dipole,
and neutrino dipole?

Neutrino dipole?

Cosmic neutrino background is 1.9K (and F-D)
3 flavour states decoupled at about 1 second
But last-scattering surface(s) complicated!



Each mass state has a different LSS distance

And thick, because of momentum distribution

Dipole for lowest m could be affected by gravitational lensing

The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada.

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