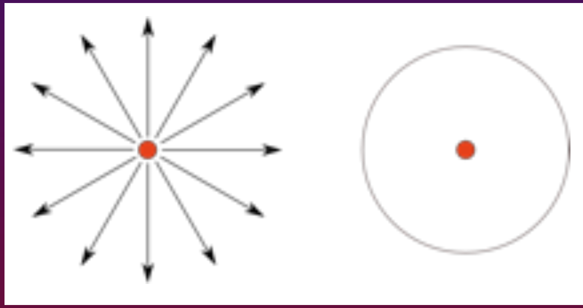
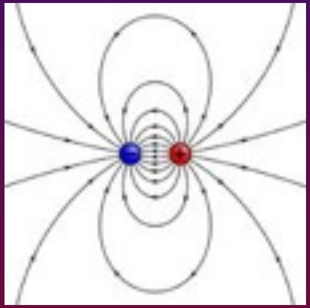
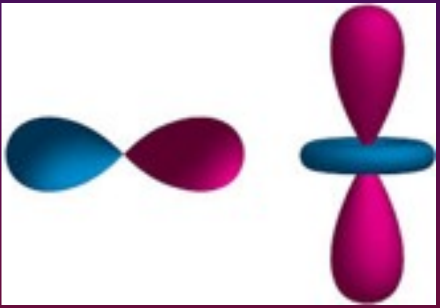
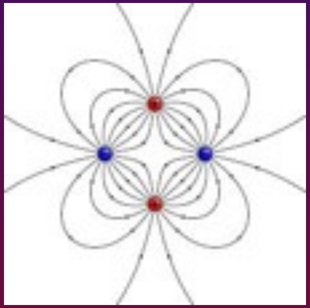
The CMB's lowest-order multipoles

Douglas Scott
(with Dago Contreras & Jim Zibin)
UBC

CMB@50

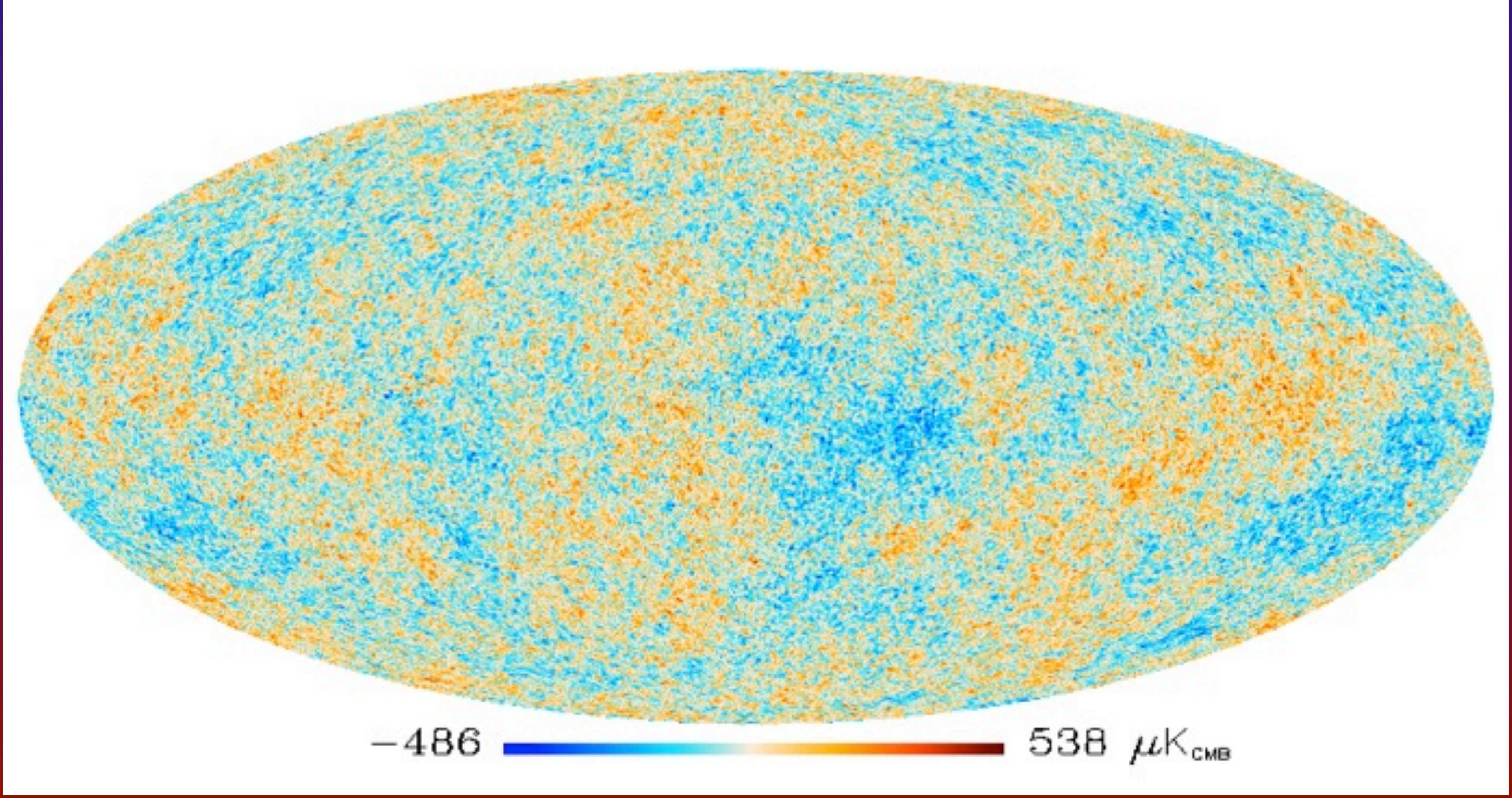
Princeton University, June 2015

CMB History

- CMB “predicted”/“detected” in 1940s
- Discovered by Penzias & Wilson 1965
- Spectrum measured 1970s
  (Precisely blackbody by 1990)
- Dipole measured 1970s
- Anisotropies predicted 1970s & 1980s
  (often focused on the quadrupole)
- Anisotropies detected early 1990s
- Lots of experiments followed
- Joined now by Planck

The CMB Sky

Temperature anisotropies at ~400,000 years



Statistical description of anisotropies

Expand sky in spherical harmonics

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

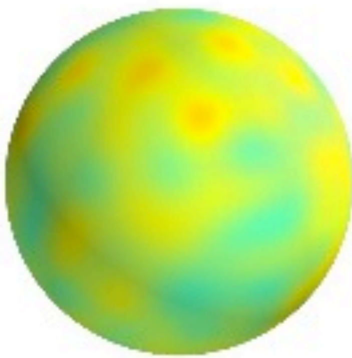
Monopole is T_0 (=a_{00})

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*

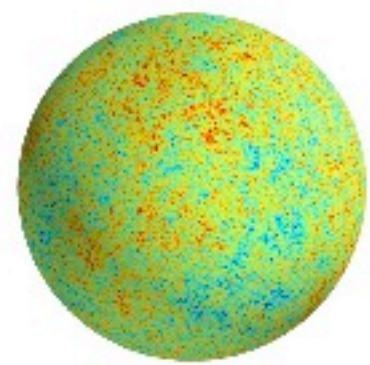
$$(2\ell+1)C_\ell/4\pi$$ is power at each ℓ



+

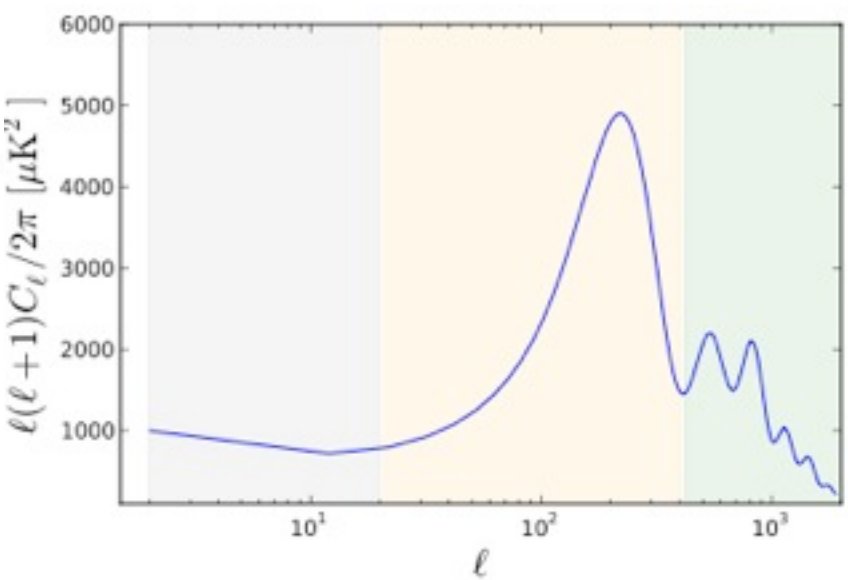
+

=



Temp. variance

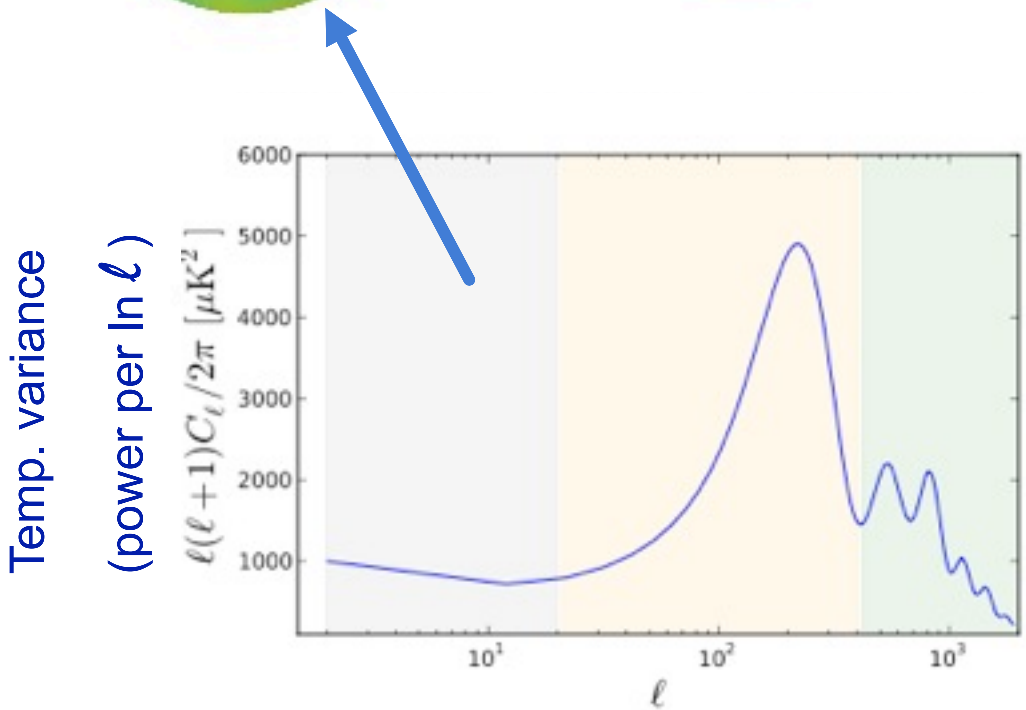
(power per ln ℓ)



ℓ = oscillations per ~180 degrees

Large-scale modes

=



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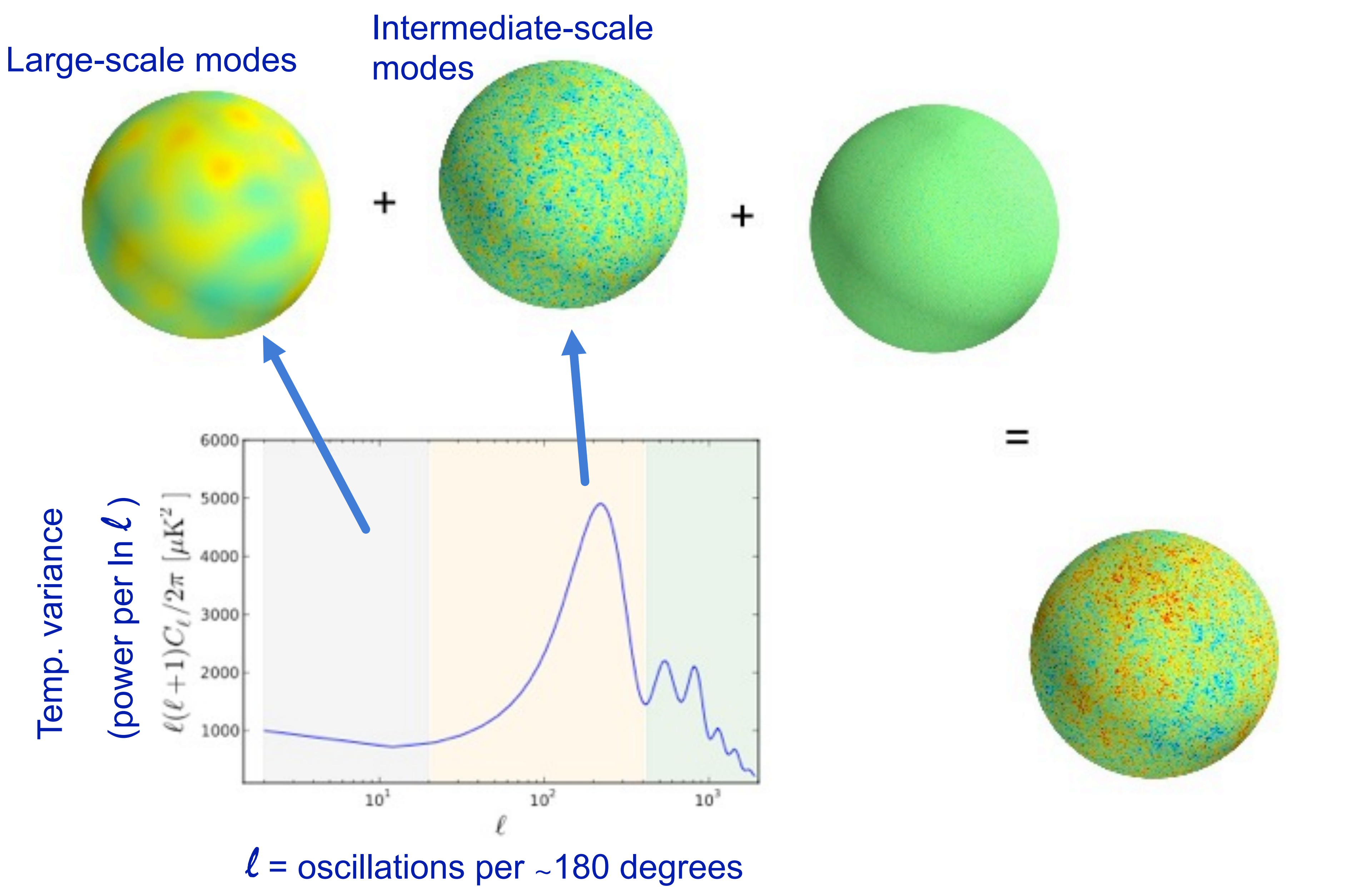
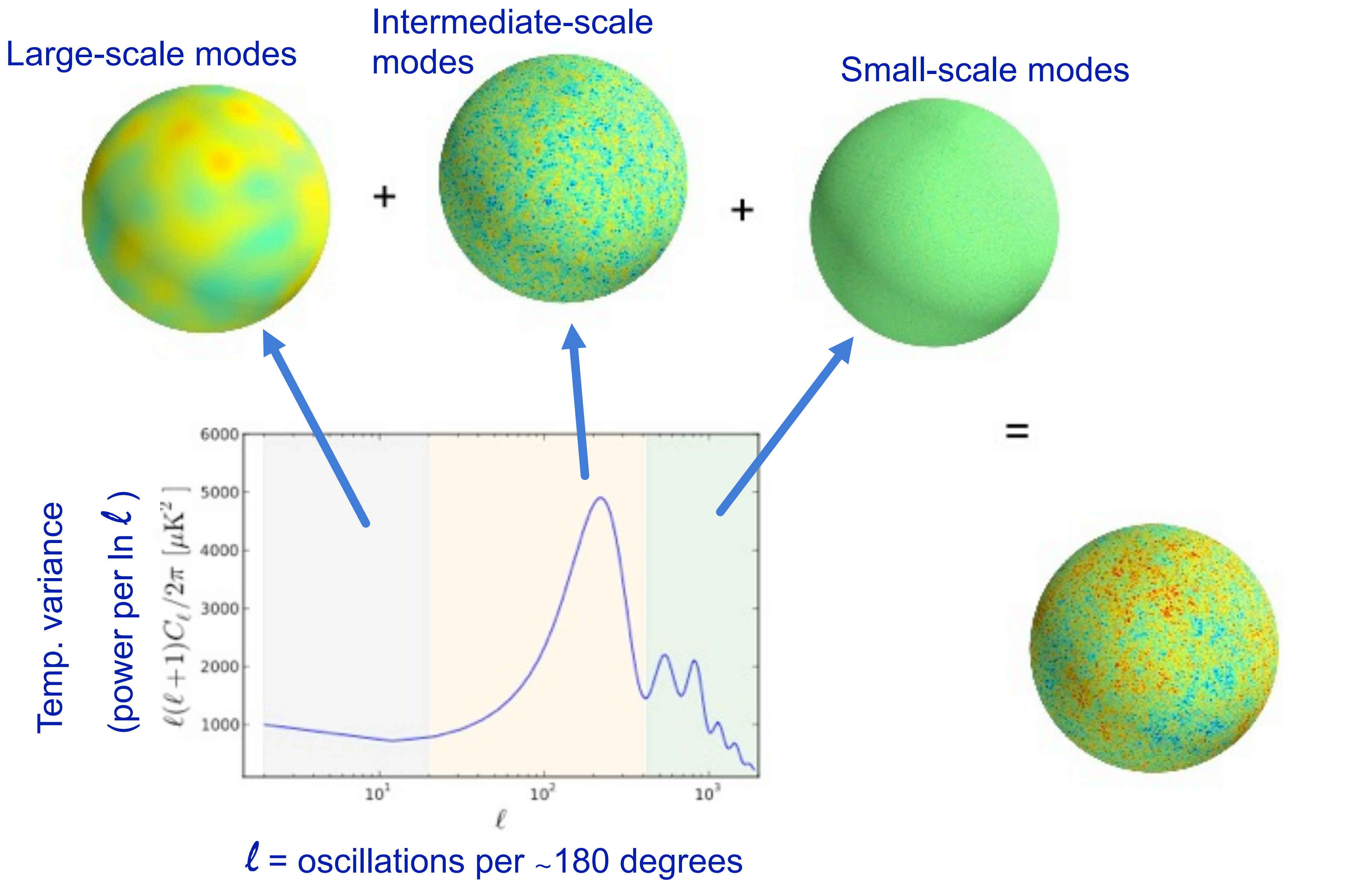
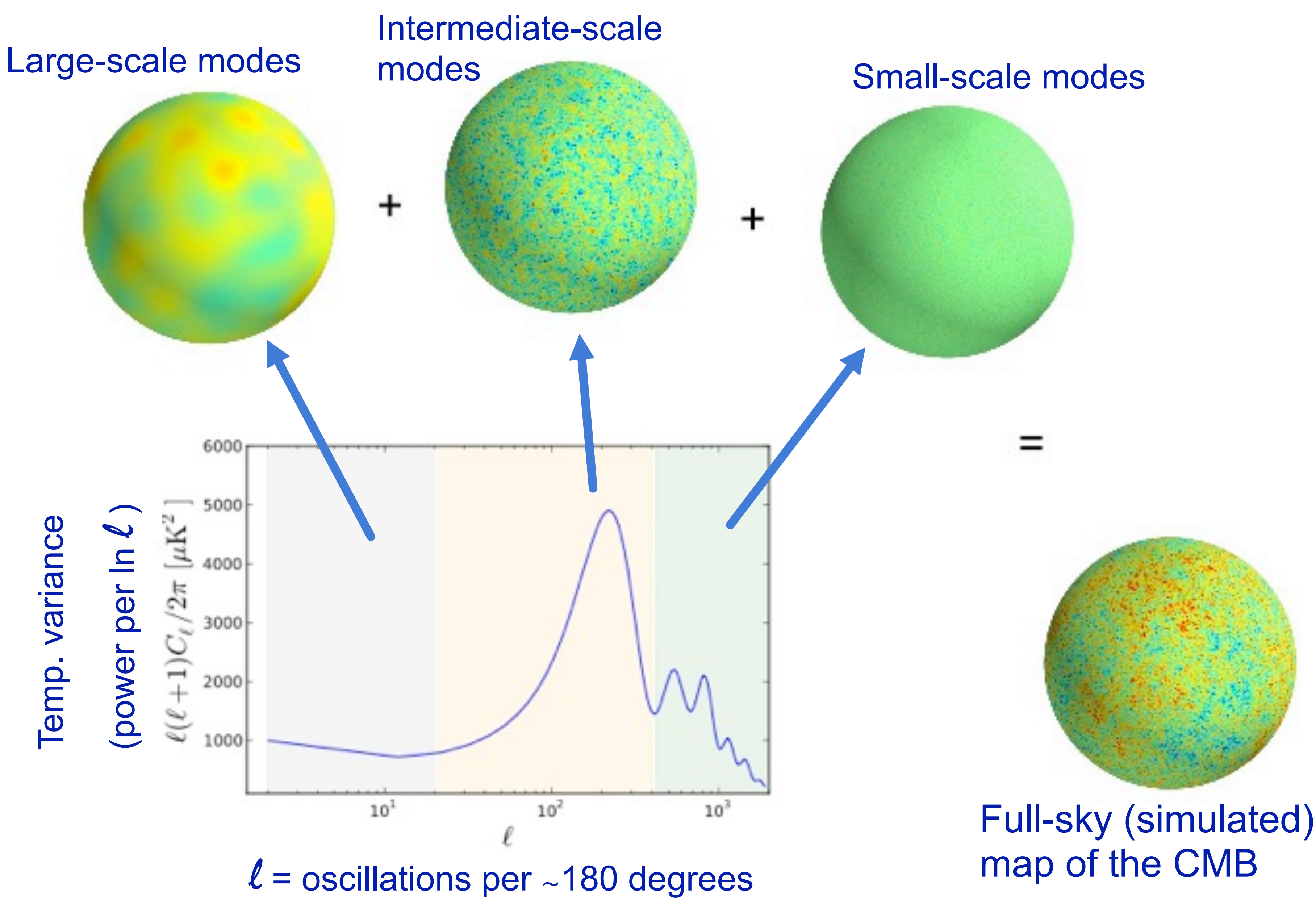


Large-scale modes
Intermediate-scale modes
+
+
=
Temp. variance
(power per ln ℓ)
$\ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
6000
5000
4000
3000
2000
1000
10^1
10^2
10^3
ℓ
ℓ = oscillations per ~180 degrees



Large-scale modes
Intermediate-scale modes
Small-scale modes
+
+
=
Temp. variance
(power per ln ℓ)
ℓ(ℓ+1)C_ℓ/2π [μK²]
6000
5000
4000
3000
2000
1000
10¹
10²
10³
ℓ
ℓ = oscillations per ~180 degrees



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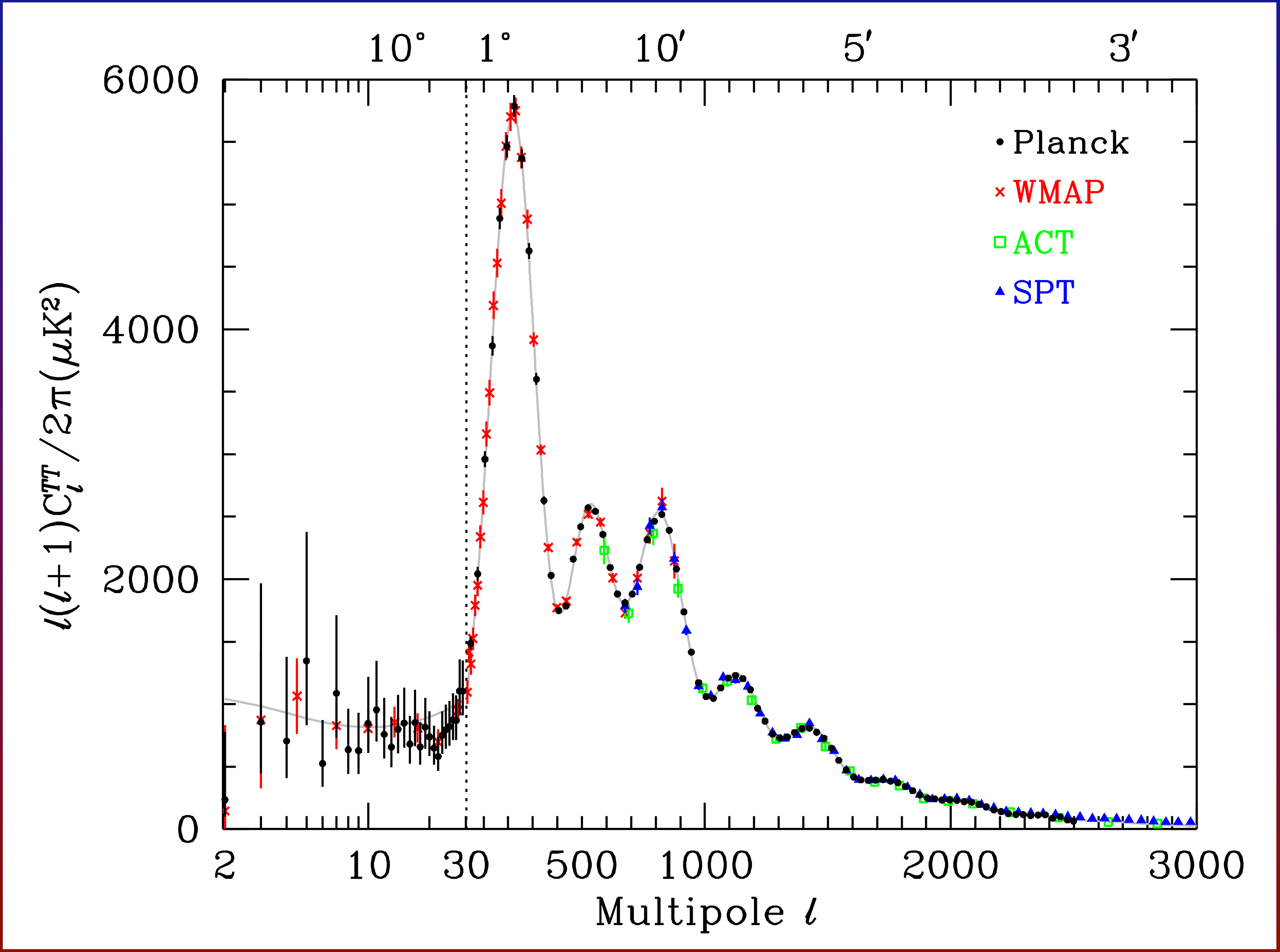
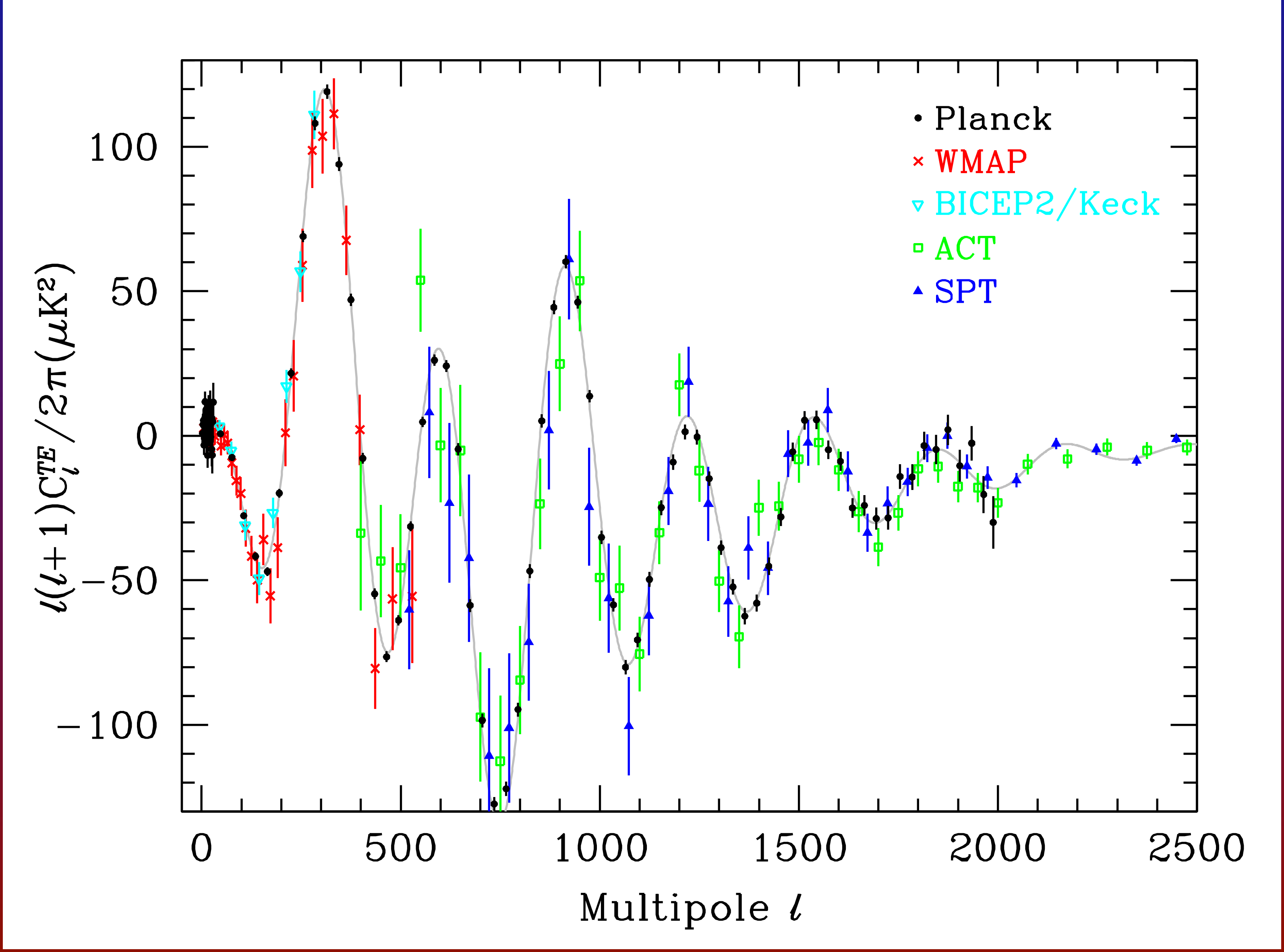
6000
5000
4000
3000
2000
1000
10^1
10^2
10^3
ℓ
ℓ = oscillations per ~180 degrees
Full-sky (simulated) map of the CMB

“Precision era” of cosmology

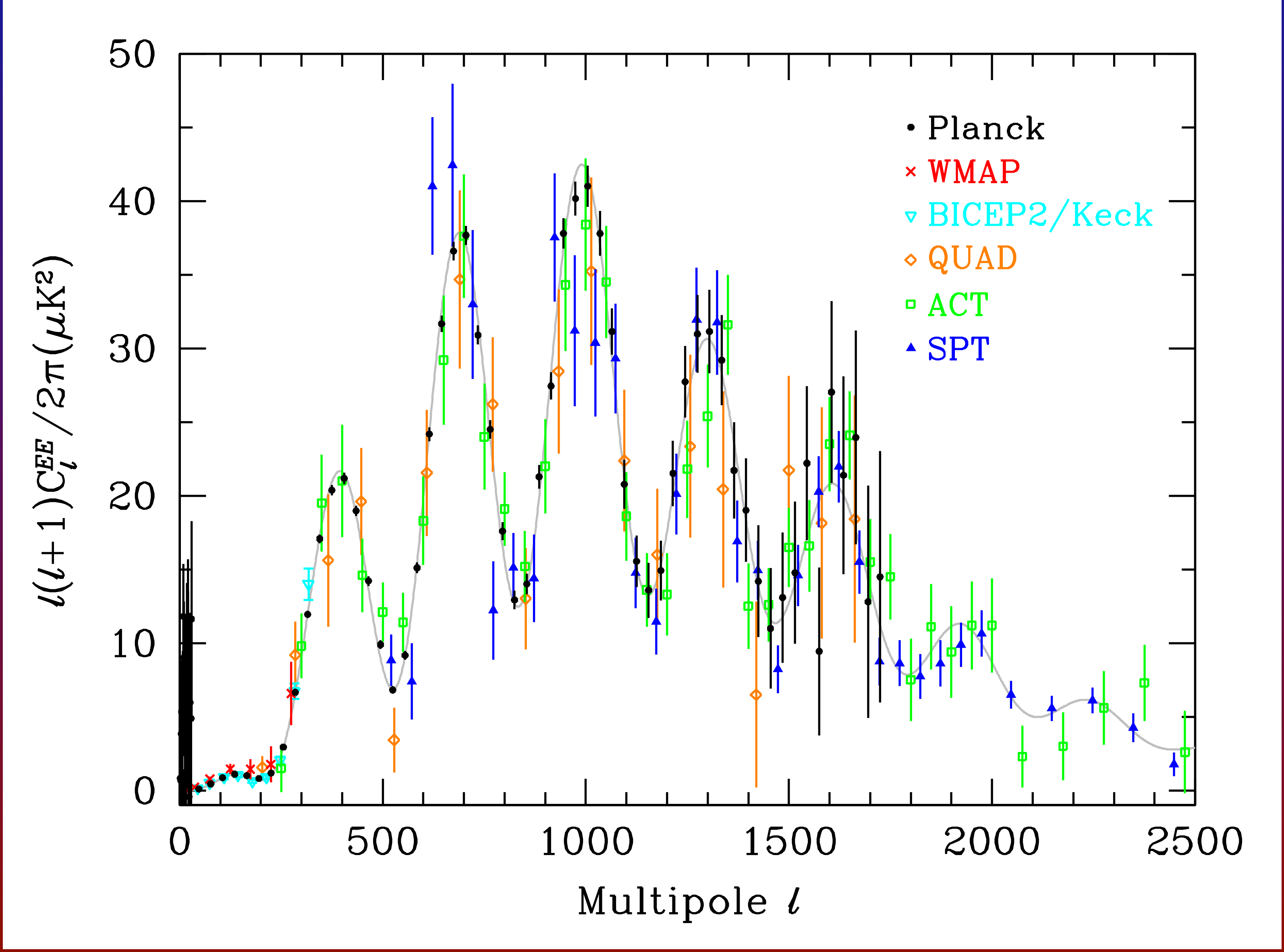


TE



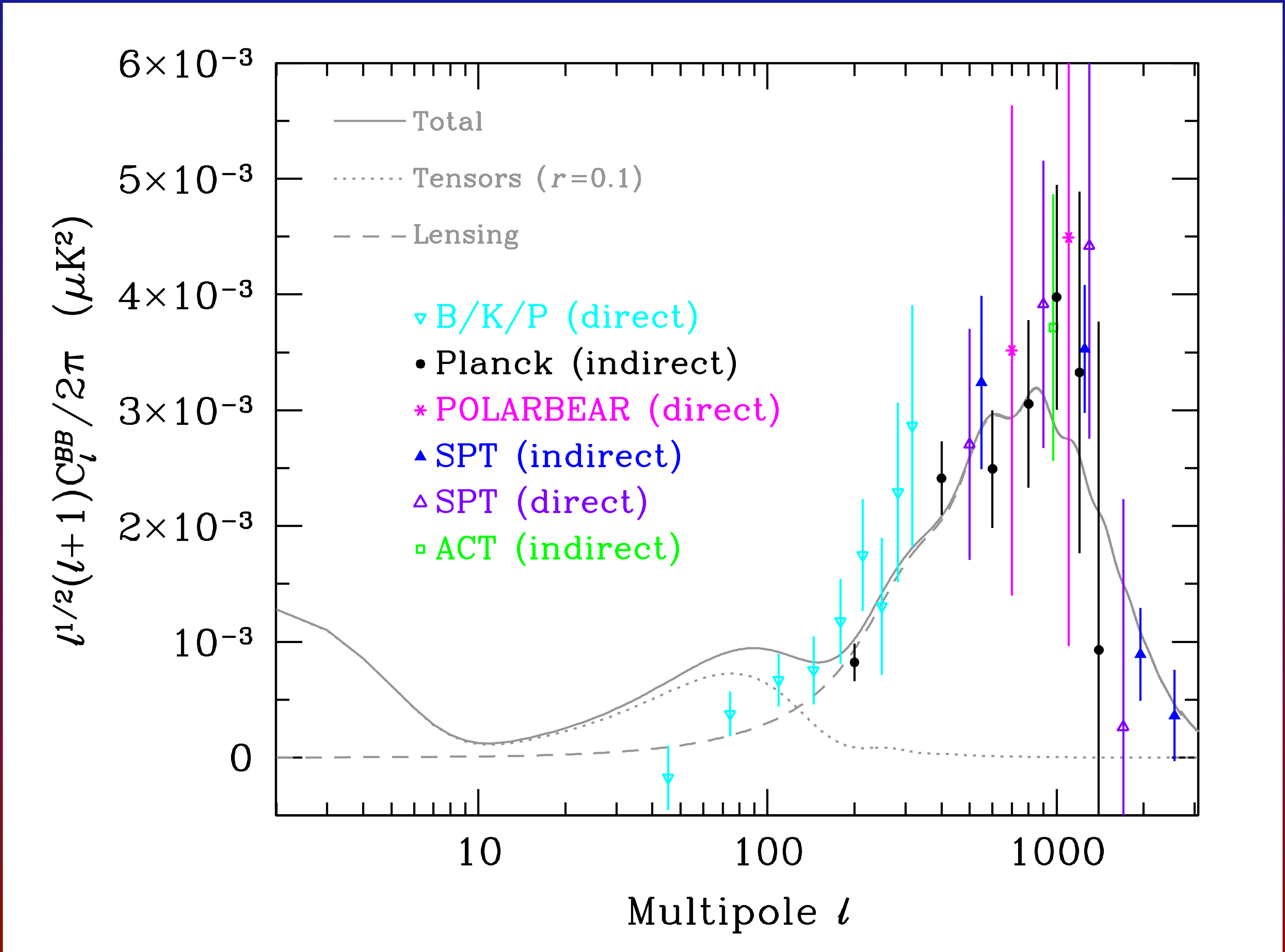
Planck
WMAP
BICEP2/Keck
ACT
SPT
100
50
0
−50
−100
0
500
1000
1500
2000
2500
Multipole ℓ
$\ell(\ell+1)C_\ell^{TE}/2\pi(\mu K^2)$

EE



Planck
WMAP
BICEP2/Keck
QUAD
ACT
SPT
$\ell(\ell+1)C_\ell^{EE}/2\pi(\mu K^2)$
Multipole ℓ
0
10
20
30
40
50
0
500
1000
1500
2000
2500

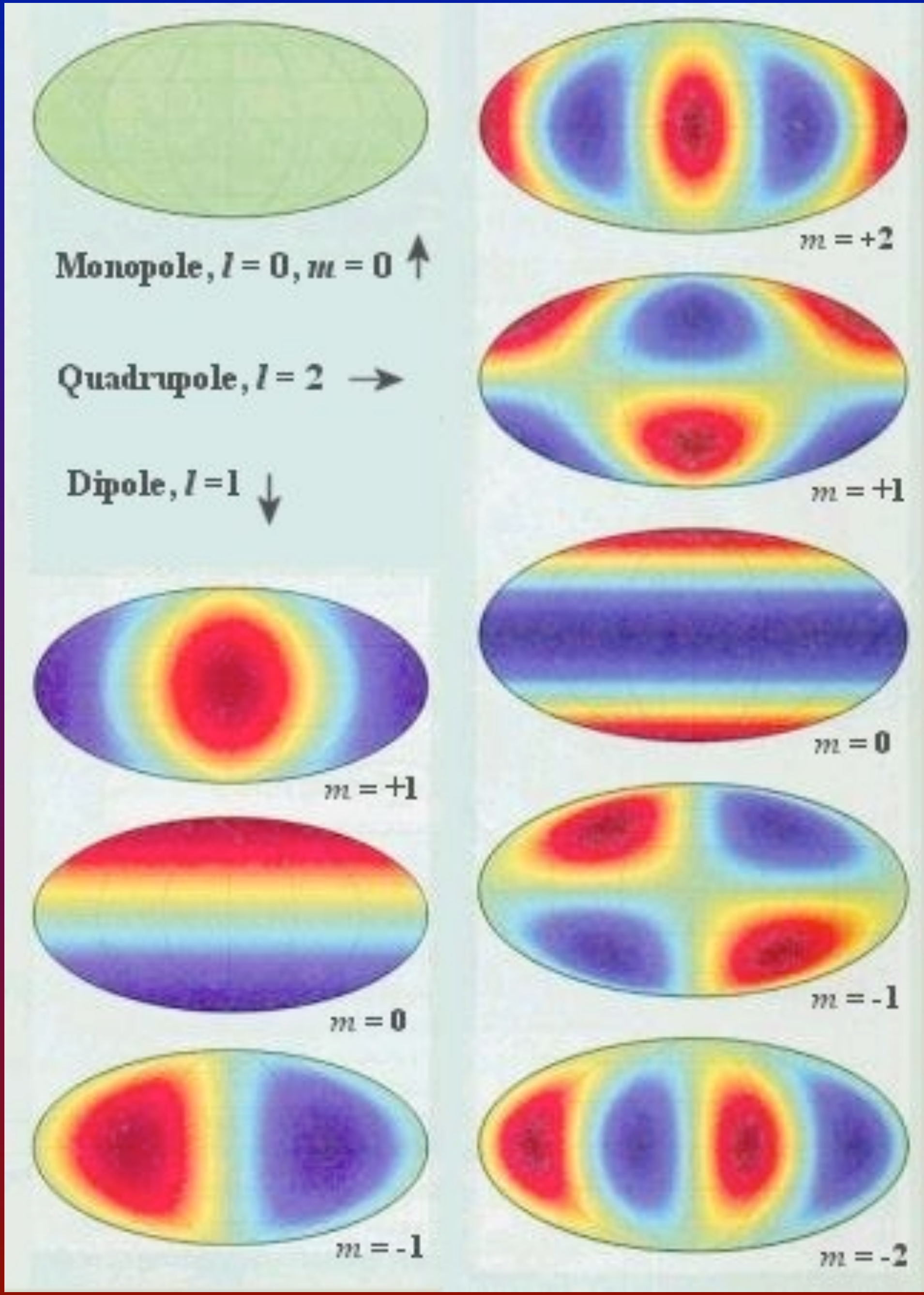
BB



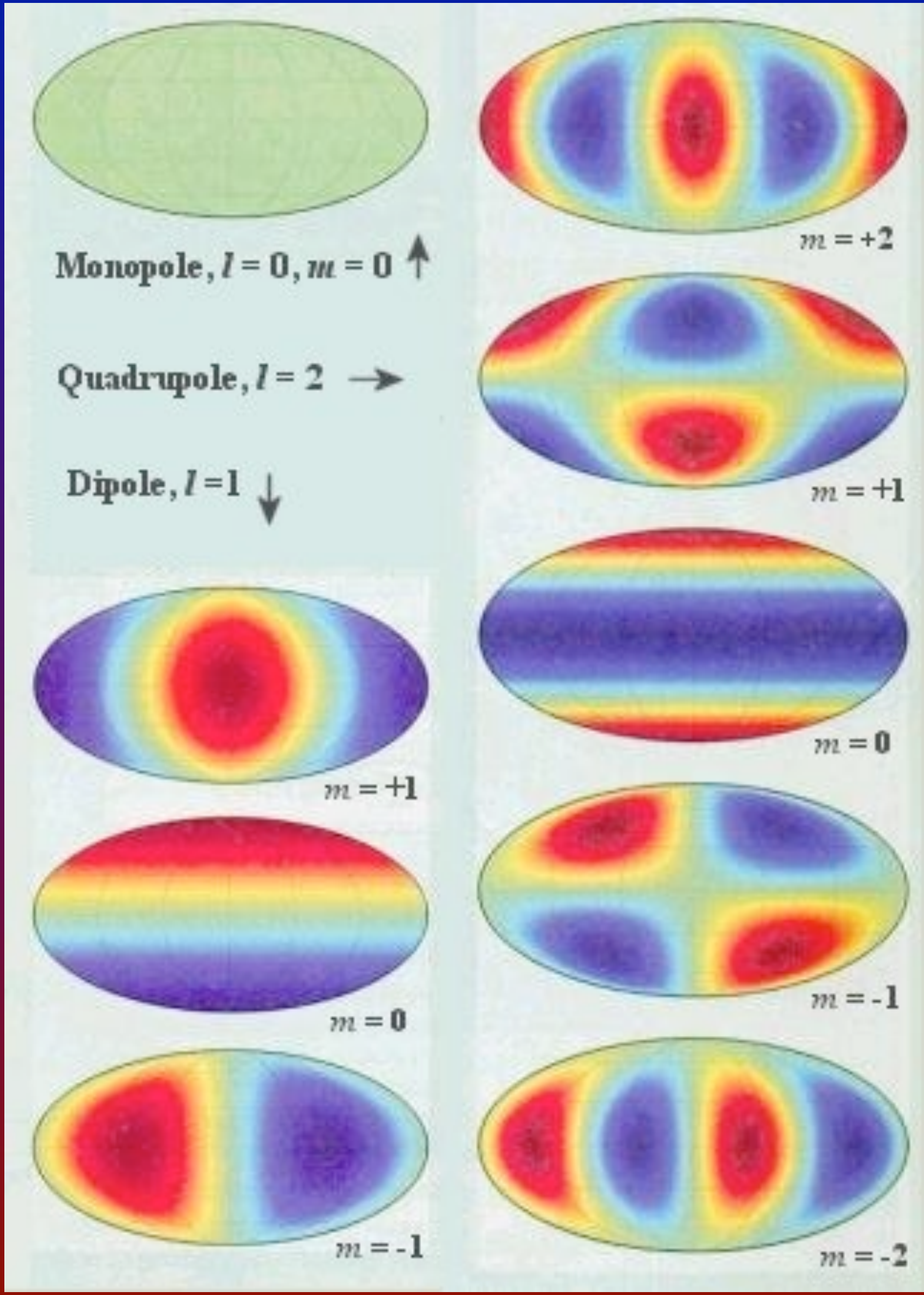
6×10⁻³
5×10⁻³
4×10⁻³
3×10⁻³
2×10⁻³
10⁻³
0
10
100
1000
Multipole ℓ
ℓ^{1/2}(ℓ+1)C_ℓ^{BB}/2π (μK²)
Total
Tensors (r=0.1)
Lensing
B/K/P (direct)
Planck (indirect)
POLARBEAR (direct)
SPT (indirect)
SPT (direct)
ACT (indirect)

But let's ignore all that beauty and precision!

And talk about the very lowest multipoles!



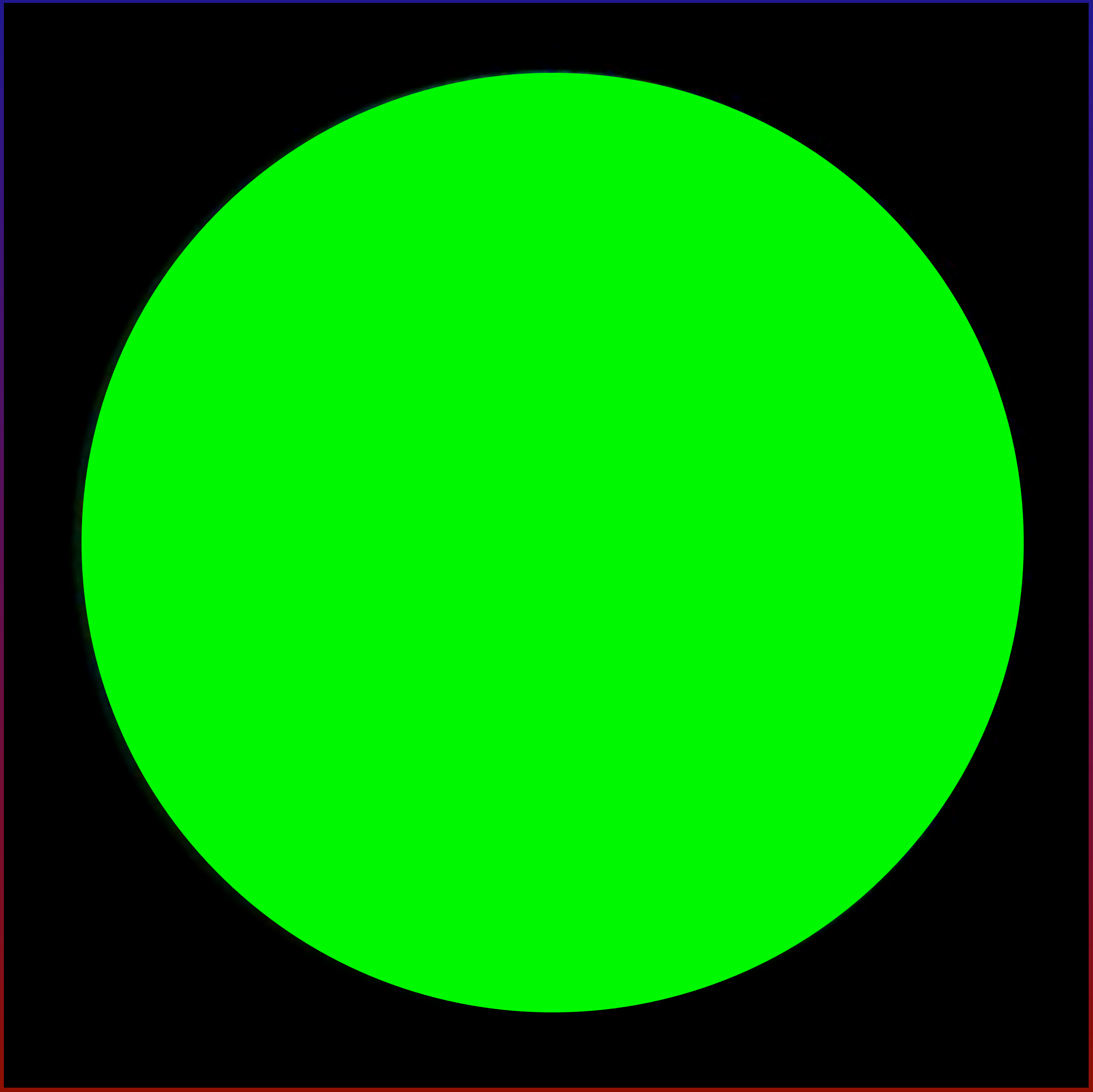
Lowest-order spherical harmonics



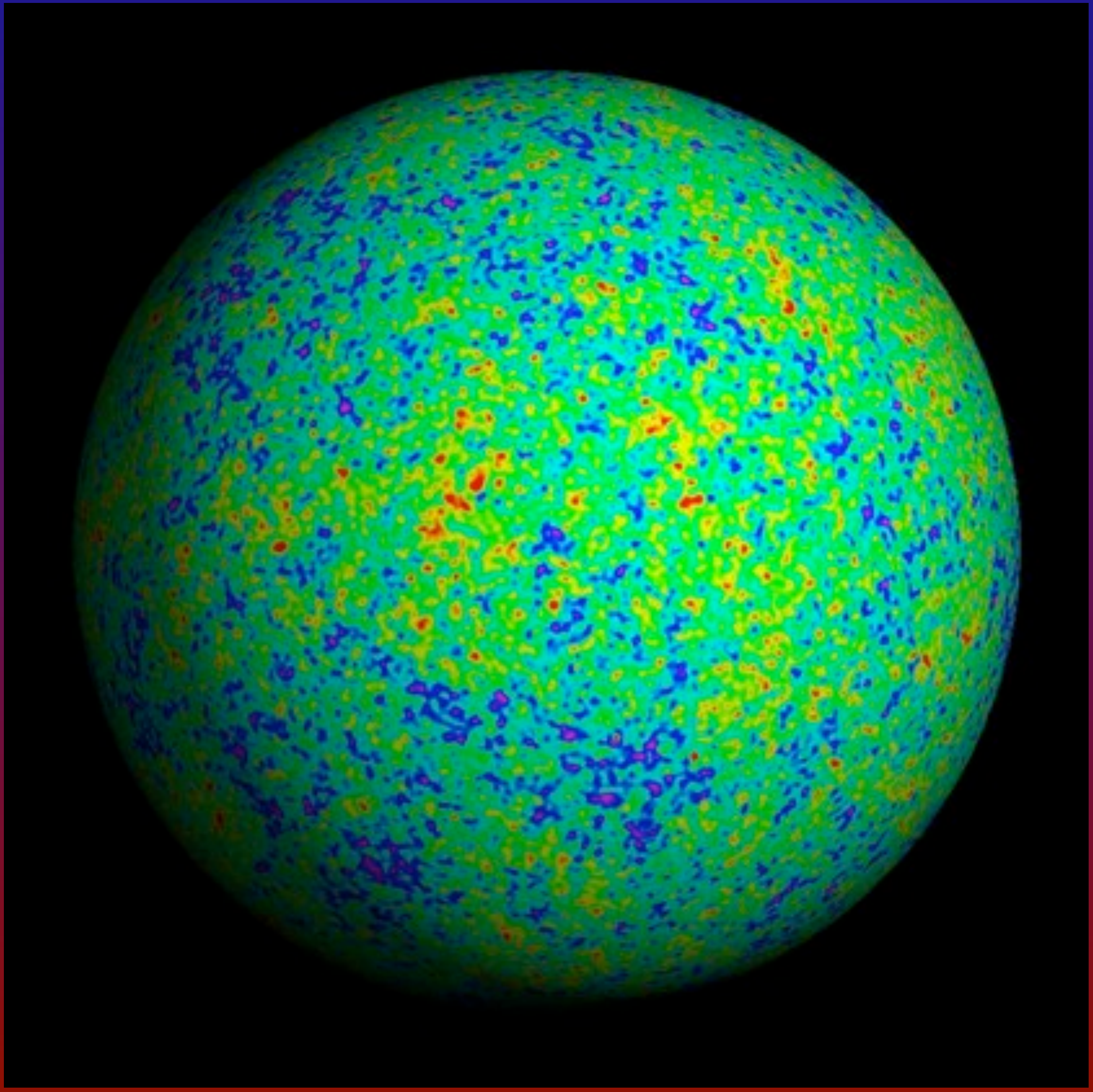
Lowest-order spherical harmonics

Let's start with the monopole

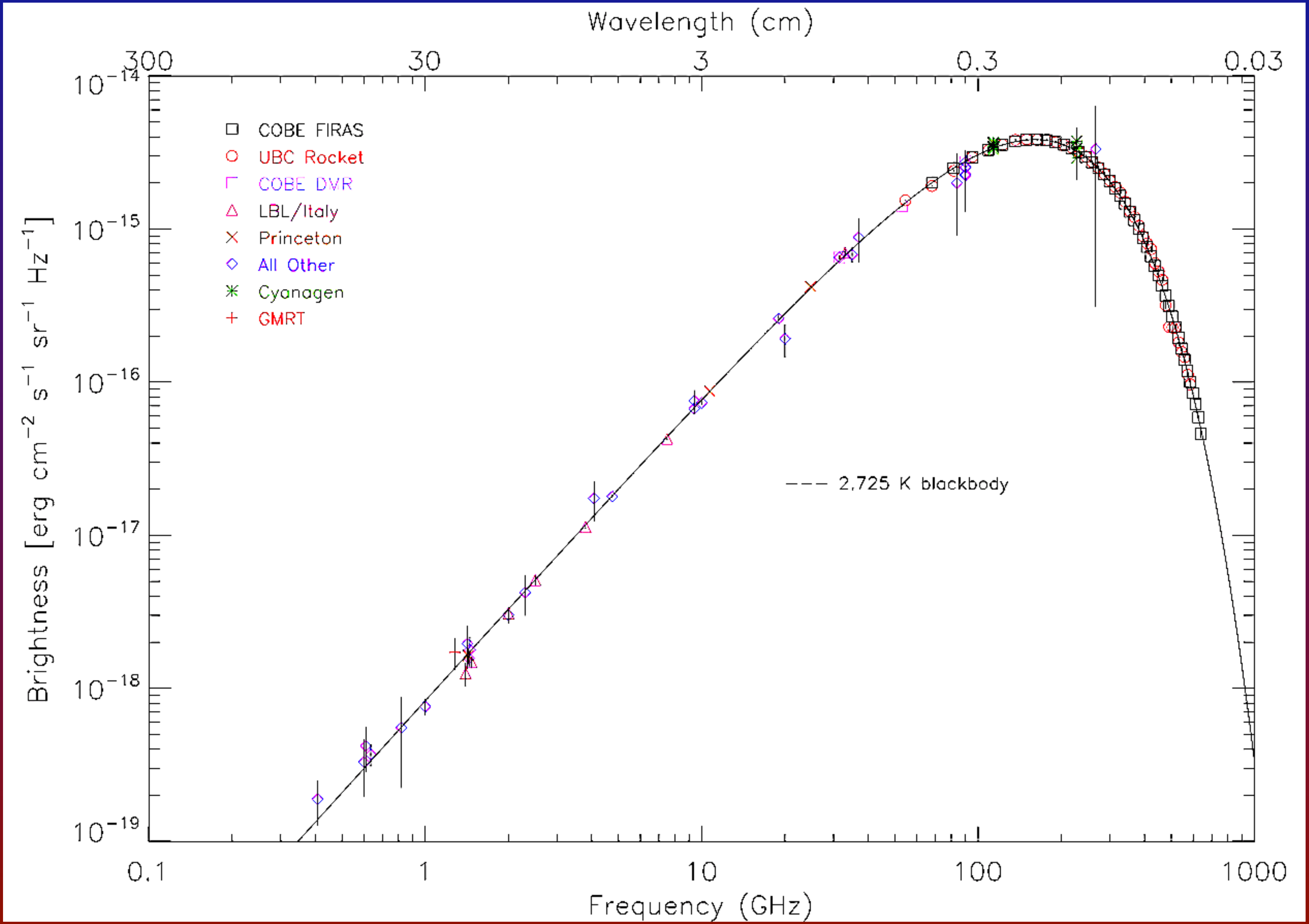
CMB Sky



CMB Sky



CMB Spectrum



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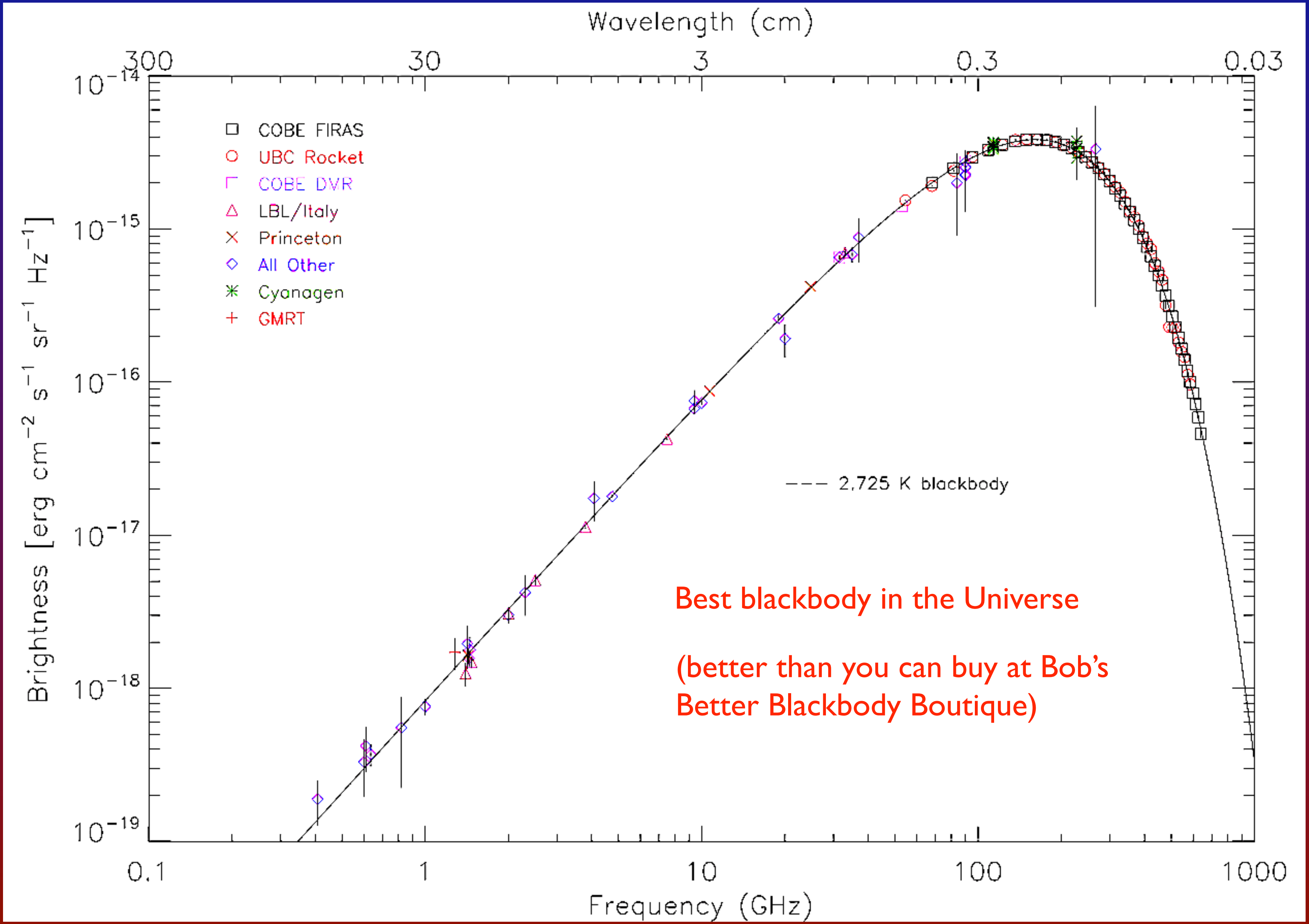

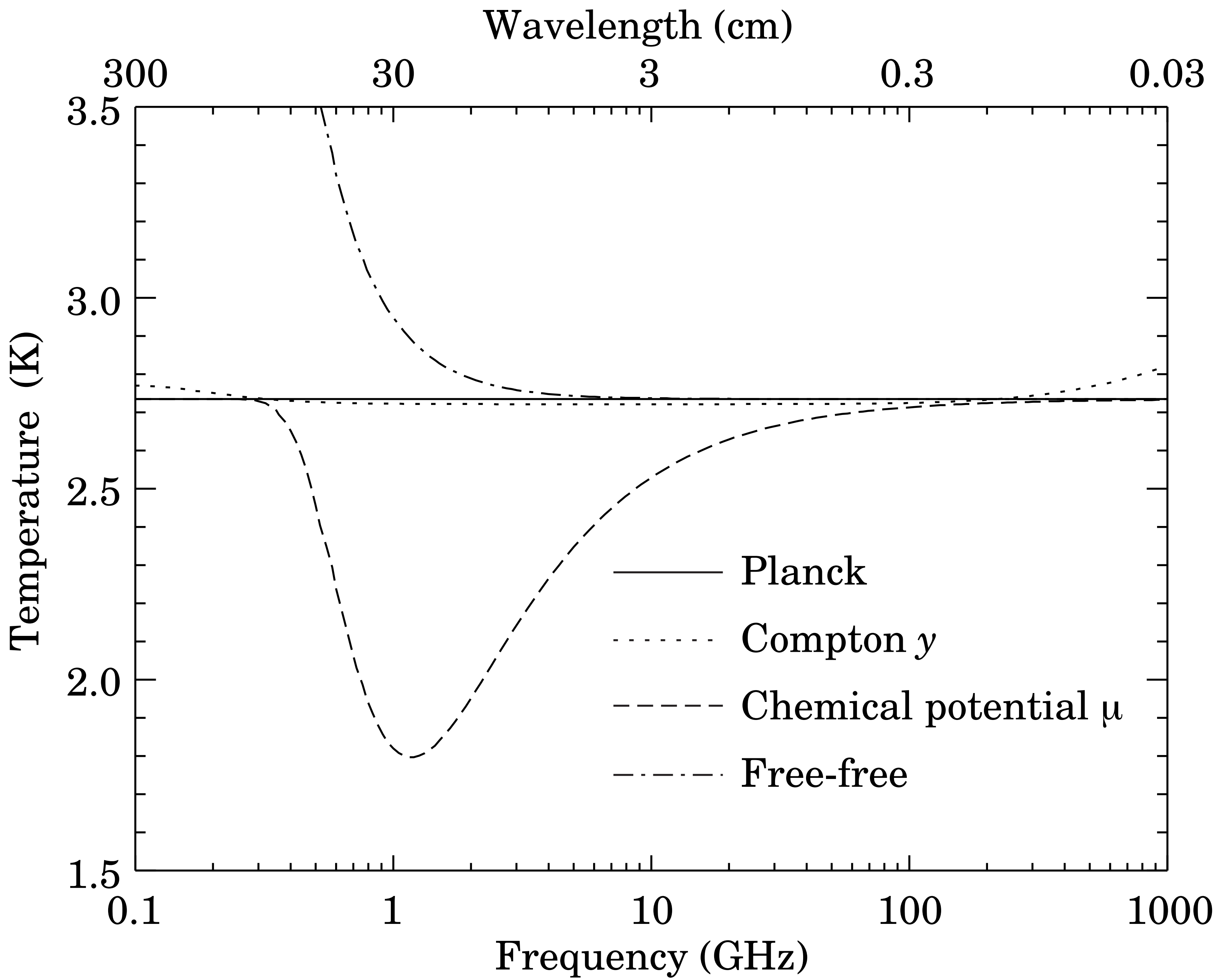

Wavelength (cm)
300
30
3
0.3
0.03
3.5
3.0
2.5
2.0
1.5
Temperature (K)
Planck
Compton y
Chemical potential μ
Free-free
0.1
1
10
100
1000
Frequency (GHz)

CMB Spectrum

T_0 = 2.7255±0.0006 K

n_0 = 410.1 cm^{-3}

ε_0 = 0.2605 eV cm^{-3}

ν_{peak} = 160.24 GHz

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

Tight constraints on distortions
But expected distortions smaller still

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(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)

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

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

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

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

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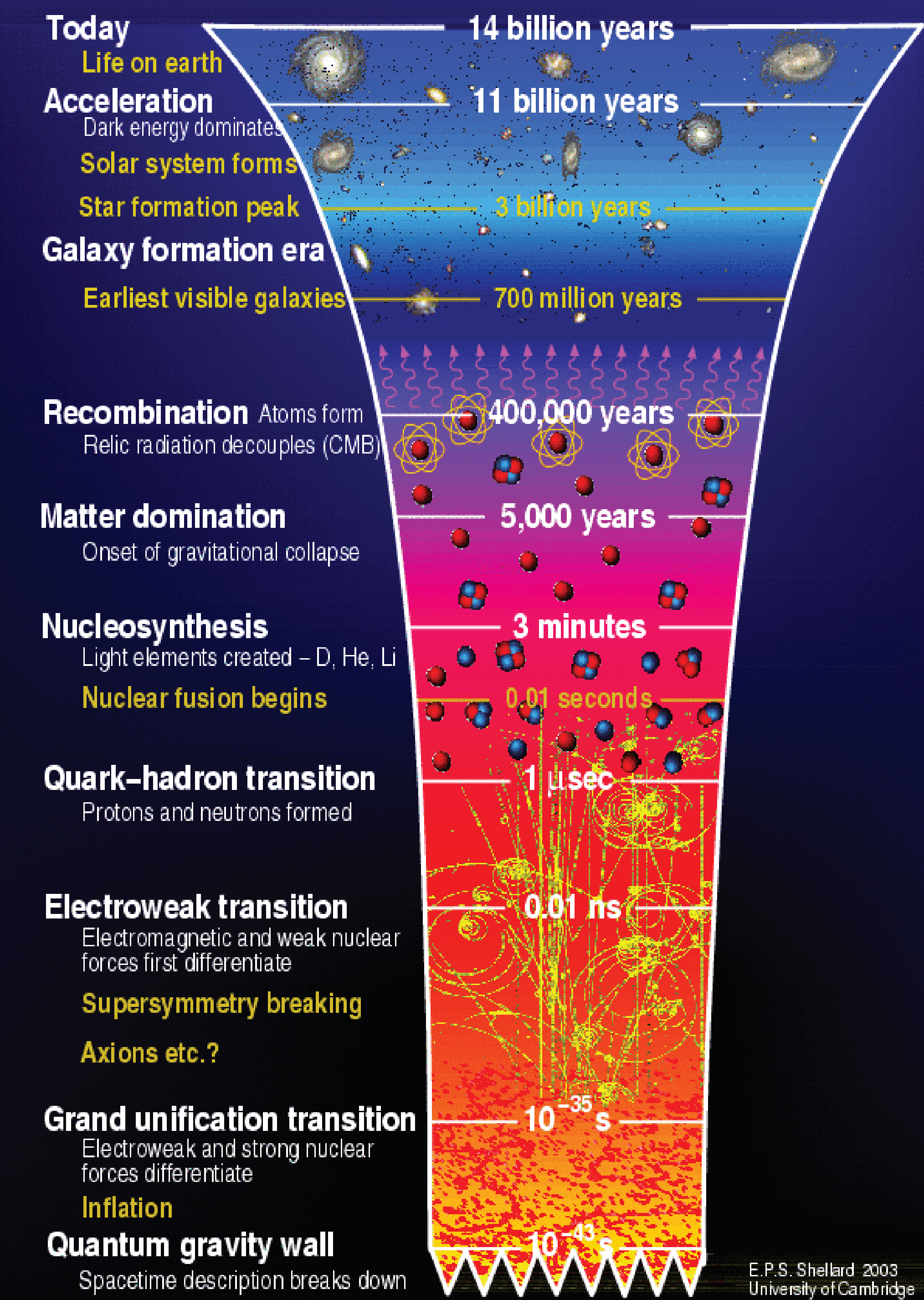
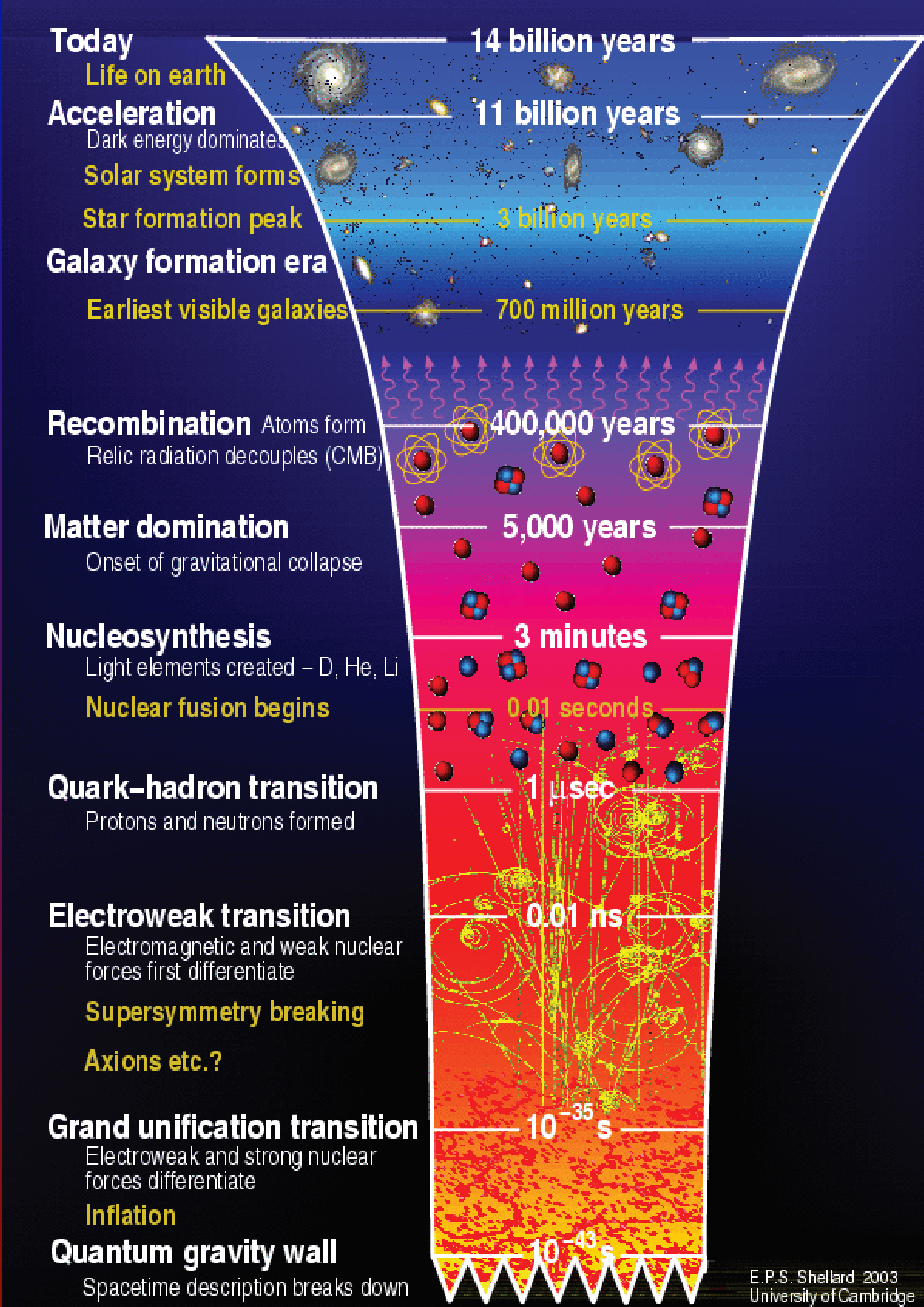
$$[\pi \mathrm{e}^{\pi} \simeq 73] \quad \mathrm{e}^{-73} T_{\mathrm{Pl}}\ (= 2.805\,\mathrm{K})$$

The Hot Big Bang



The Hot Big Bang

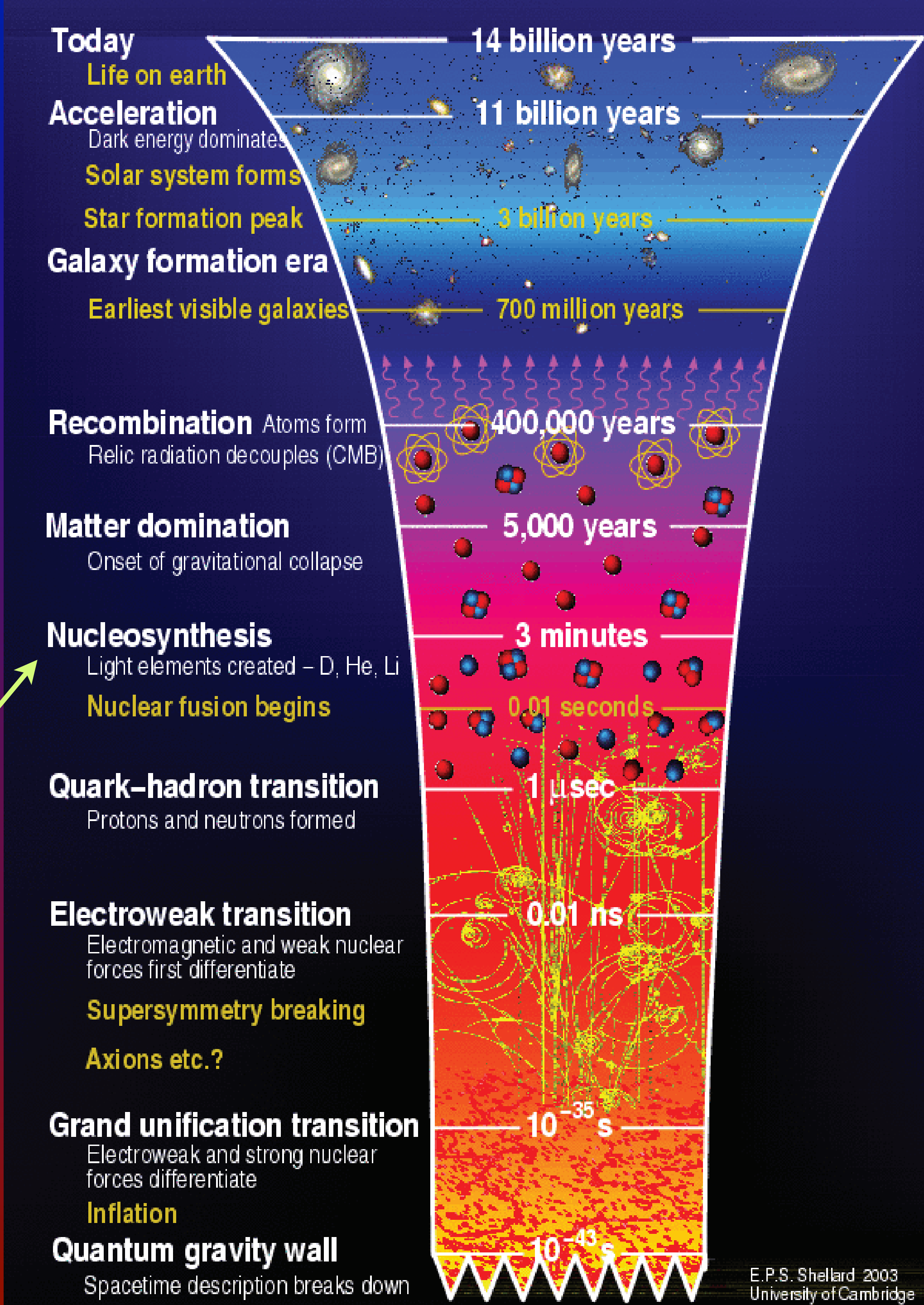
Where did the CMB really come from?



The Hot Big Bang

Where did the CMB <u>really</u> come from?

Photons made at this epoch



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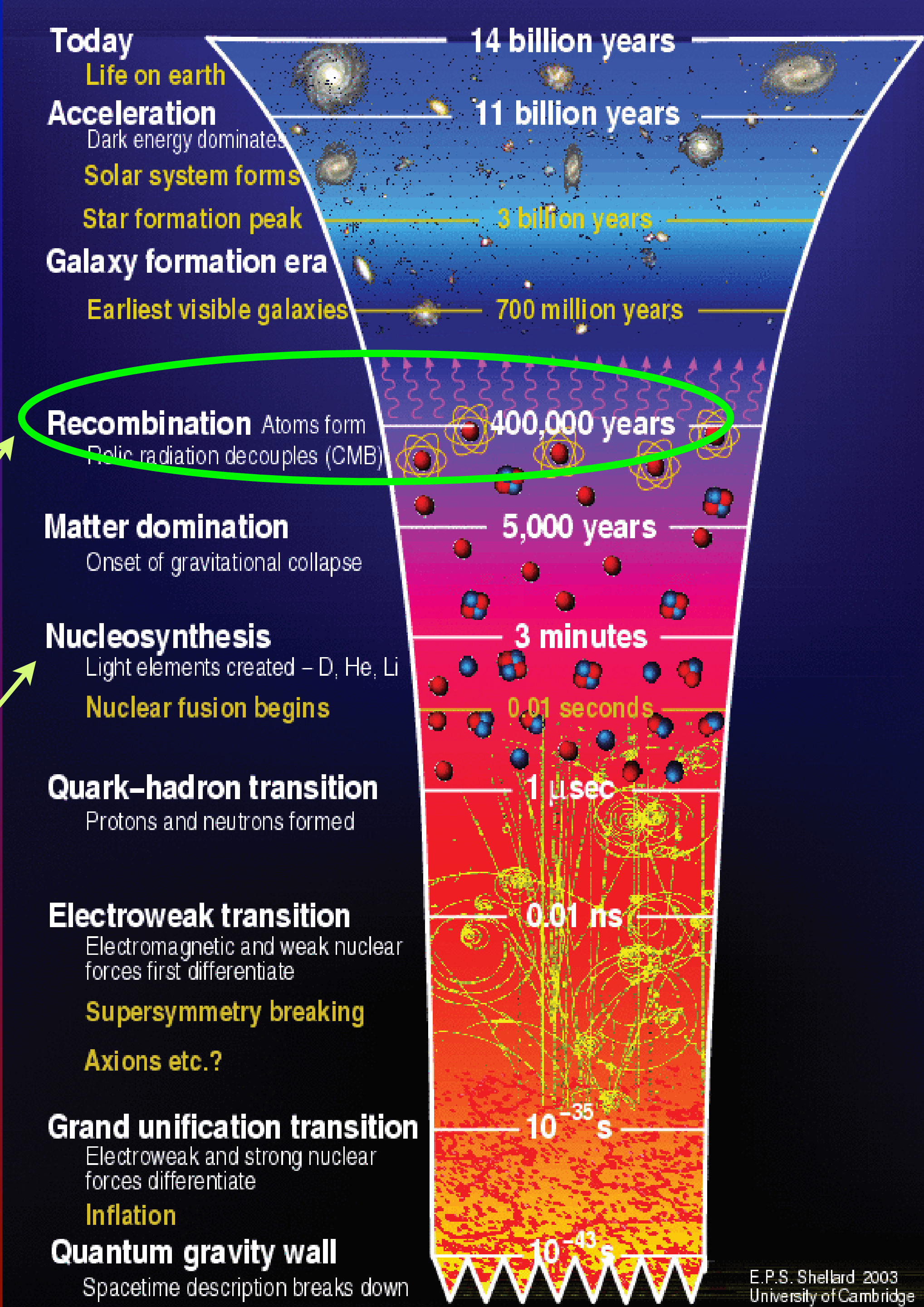


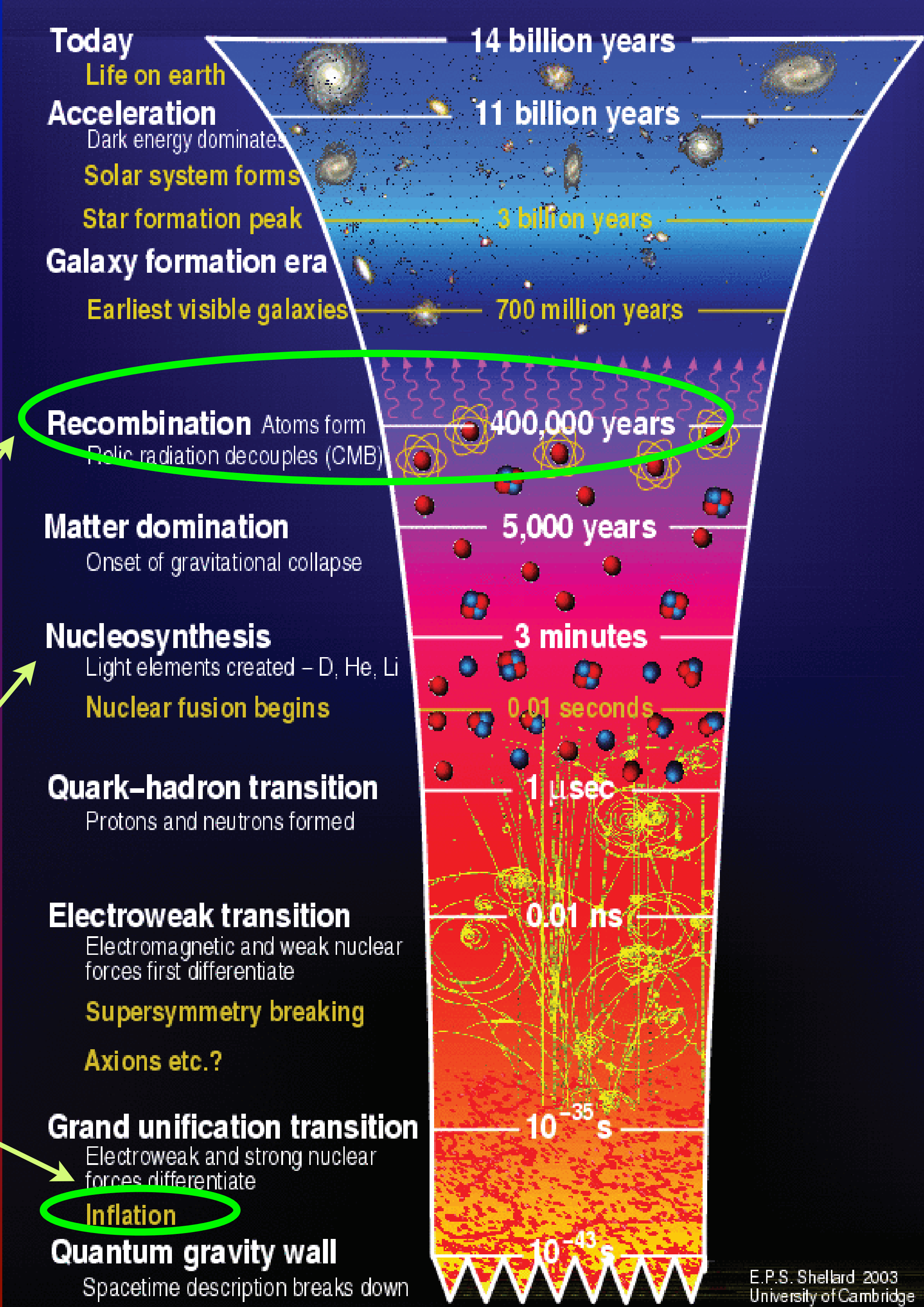
The Hot Big Bang

Where did the CMB <u>really</u> come from?

Last scattered at this epoch

Photons made at this epoch

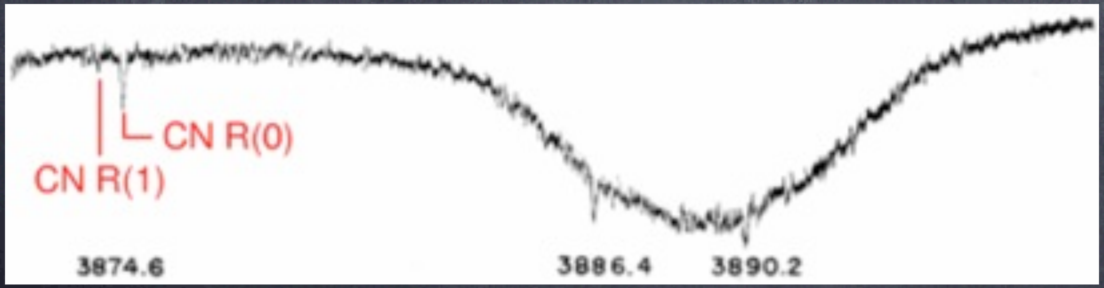
Deriving from physics at this epoch



CMB history (eh)

Andrew McKellar

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



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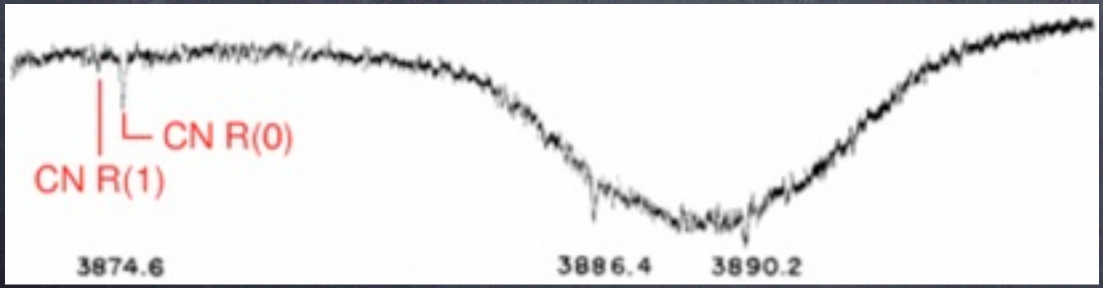
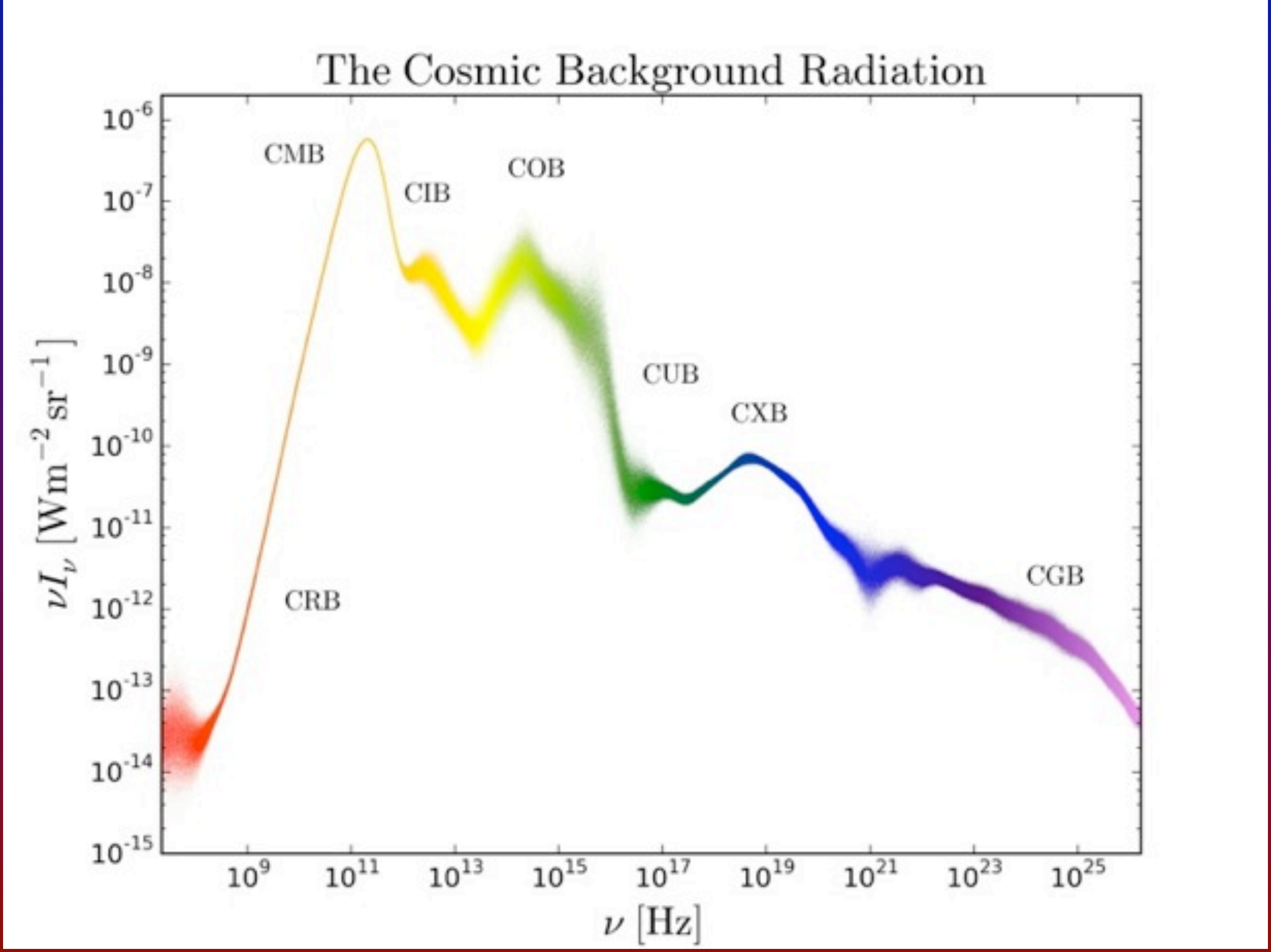


Herzberg (1950): "...only a very restricted meaning"

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 ΔT/T~0.00001 on all scales including our Hubble patch!

So if we could live in a ~3 σ 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

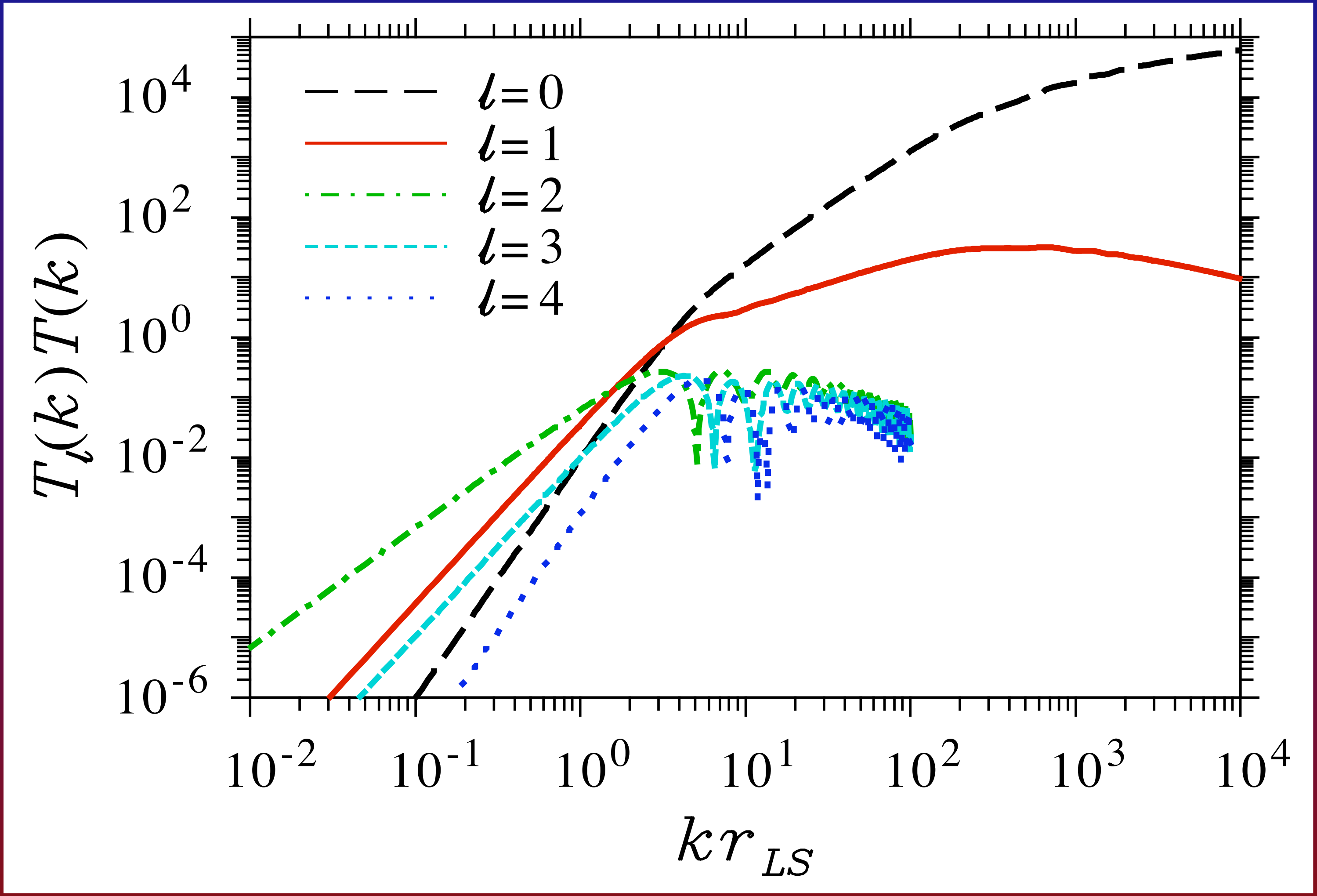
Obvious choice is uniform matter slice
Or equivalently uniform energy density

Can calculate the transfer function

What do you call the study of the monopole?

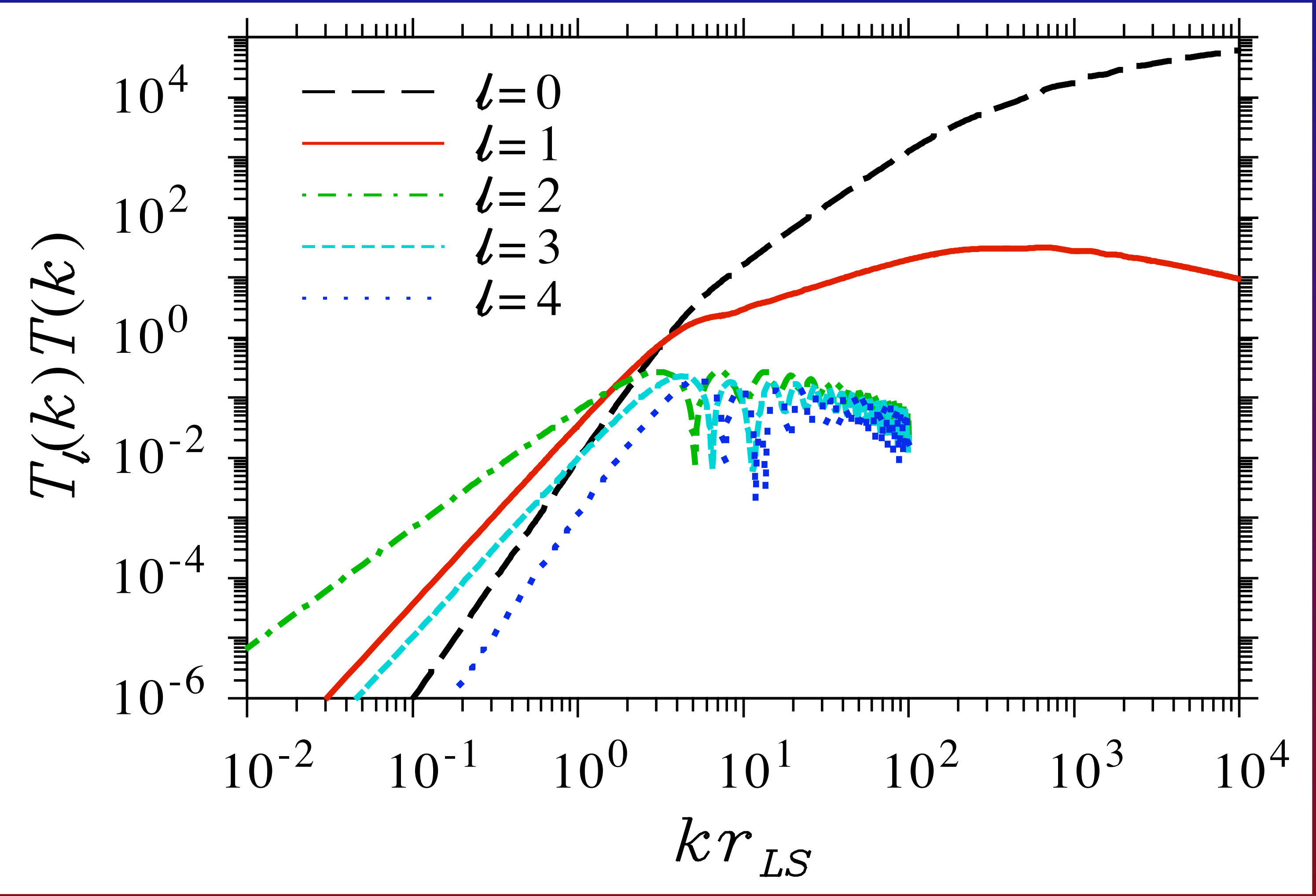
What do you call the study of the monopole?

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



Zibin & Scott arXiv:0808.2047

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

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

Defining the dipole

"Extrinsic" dipole comes from our motion

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In principle estimate "real" motion with aberration

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Or determine motion from accelerations due to local lumps of matter

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

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In principle estimate "real" motion with aberration

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

Not in adiabatic models!

The dipole is just our velocity relative to the CMB LSS

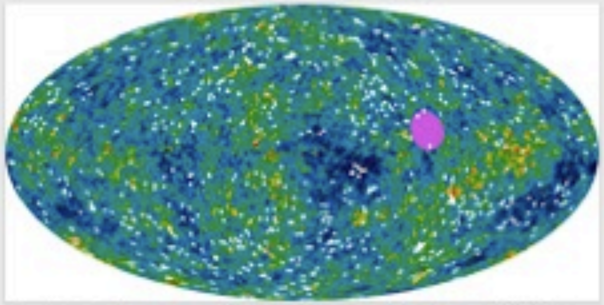
Defining the dipole

Scientists Detect Cosmic 'Dark Flow' Across Billions of Light Years **09.23.08**

Francis Reddy / Rob Gutro
Goddard Space Flight Center, Greenbelt, Md.
301-286-4453 / 4044
francis.j.reddy@nasa.gov / robert.j.gutro@nasa.gov

Release No. 08-83

WASHINGTON – Using data from NASA's Wilkinson Microwave Anisotropy Probe (WMAP), scientists have identified an unexpected motion in distant galaxy clusters. The cause, they suggest, is the gravitational attraction of matter that lies beyond the observable universe.



Hot gas in moving galaxy clusters (white spots) shifts the temperature of cosmic microwaves. Hundreds of distant clusters seem to be moving toward one patch of sky (purple ellipse). **Credit:** NASA/WMAP/A. Kashlinsky et al.
> Larger image

"The clusters show a small but measurable velocity that is independent of the universe's expansion and does not change as distances increase," says lead researcher Alexander Kashlinsky at NASA's Goddard Space Flight Center in Greenbelt, Md. "We never expected to find anything like this."

Kashlinsky calls this collective motion a "dark flow" in the vein of more familiar cosmological mysteries: dark energy and dark matter. "The distribution of matter in the observed universe cannot account for this motion," he says.

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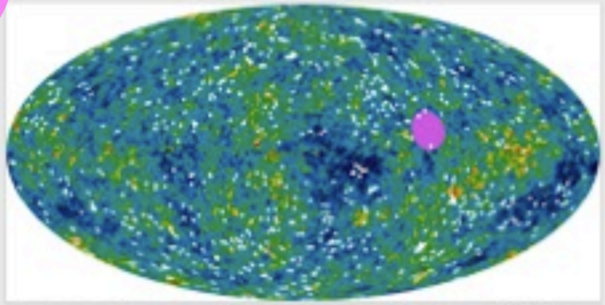

Hot gas in moving galaxy clusters (white spots) shifts the temperature of cosmic microwaves. Hundreds of distant clusters seem to be moving toward one patch of sky (purple ellipse). **Credit:** NASA/WMAP/A. Kashlinsky et al.
> Larger image

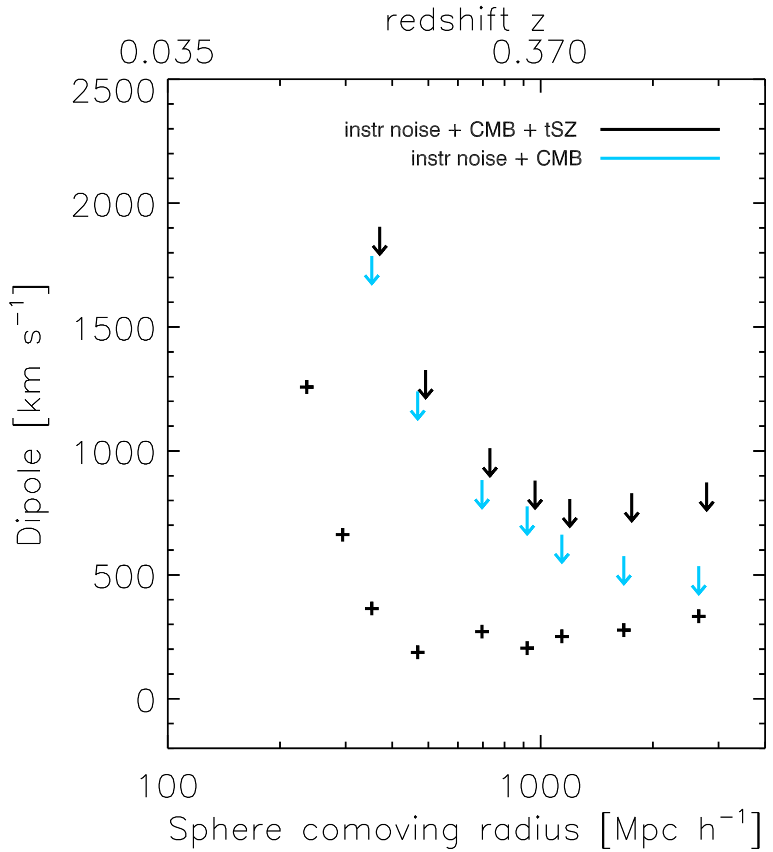

Fig. 9. Bulk flow amplitude measured in *Planck* data with the all-sky method, after subtraction (vectorially) of the Galactic contribution (black crosses), compared with 95 % upper limits derived from simulations containing CMB and instrumental noise only (blue arrows) or also including tSZ signal (black 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

What about Planck's dipole?

Now the "orbital dipole" is used to calibrate

So the "solar dipole" can be independently measured

This is the currently most precise dipole

Dipole calibration: Planck vs WMAP

- 2015: Orbital dipole calibration for both LFI and HFI

	Amplitude (μK)	Latitude (deg)	Longitude (deg)
LFI	3365.5±2	48.26	264.01
HFI	3364.1±2	48.23±0.1	263.96±0.03
Planck (LFI+HFI)	3364.5±2	48.24±0.1	264.00±0.03
WMAP	3355±8	48.26±0.03	263.99±0.14

PRELIMINARY

- Accuracy ~0.05%, limited by foregrounds
- Residual dipoles from component separation: ~1μK
- Very good agreement with WMAP

  (1σ, 0.3% amplitude, 3′ direction)

Dipole calibration: Planck vs WMAP

planck

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PRELIMINARY

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- Residual dipoles from component separation: ~1μK
- Very good agreement with WMAP

  (1σ, 0.3% amplitude, 3′ direction)

esa

PLANCK LFI

HFI PLANCK

Dipole calibration: Planck vs WMAP

- 2015: Orbital dipole calibration for both LFI and HFI

	Amplitude (μK)	**Latitude** (deg)	**Longitude** (deg)
LFI	3365.5±2	48.26	264.01
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WMAP	3355±8	48.26±0.03	263.99±0.14

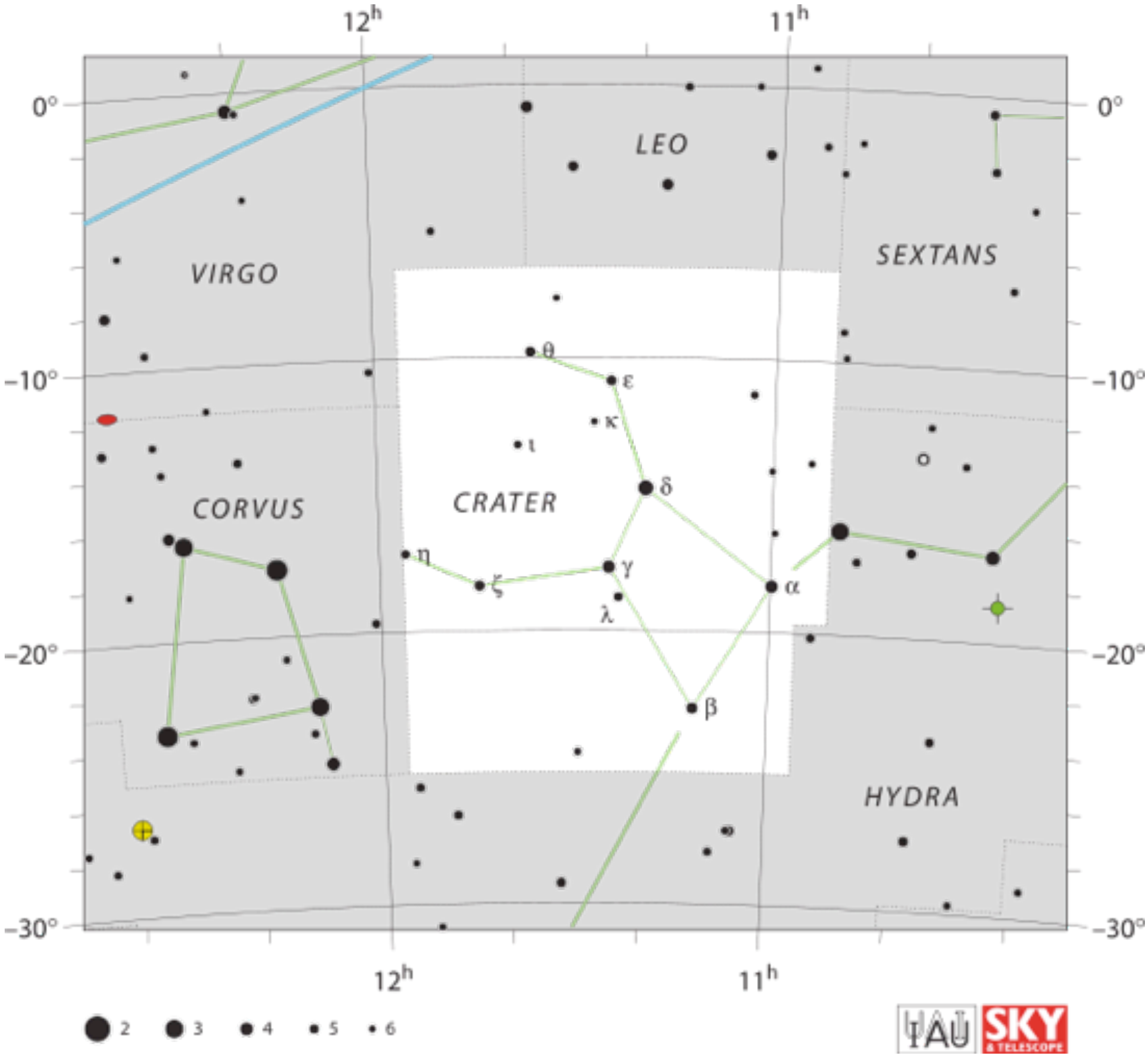
PRELIMINARY NOT!

- Accuracy ~0.05%, limited by foregrounds
- Residual dipoles from component separation: ~1μK
- Very good agreement with WMAP

(1σ, 0.3% amplitude, 3′ direction)

Planck’s new dipole amplitude:

$v = 0.12345\%\ c$!


12h
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SEXTANS
VIRGO
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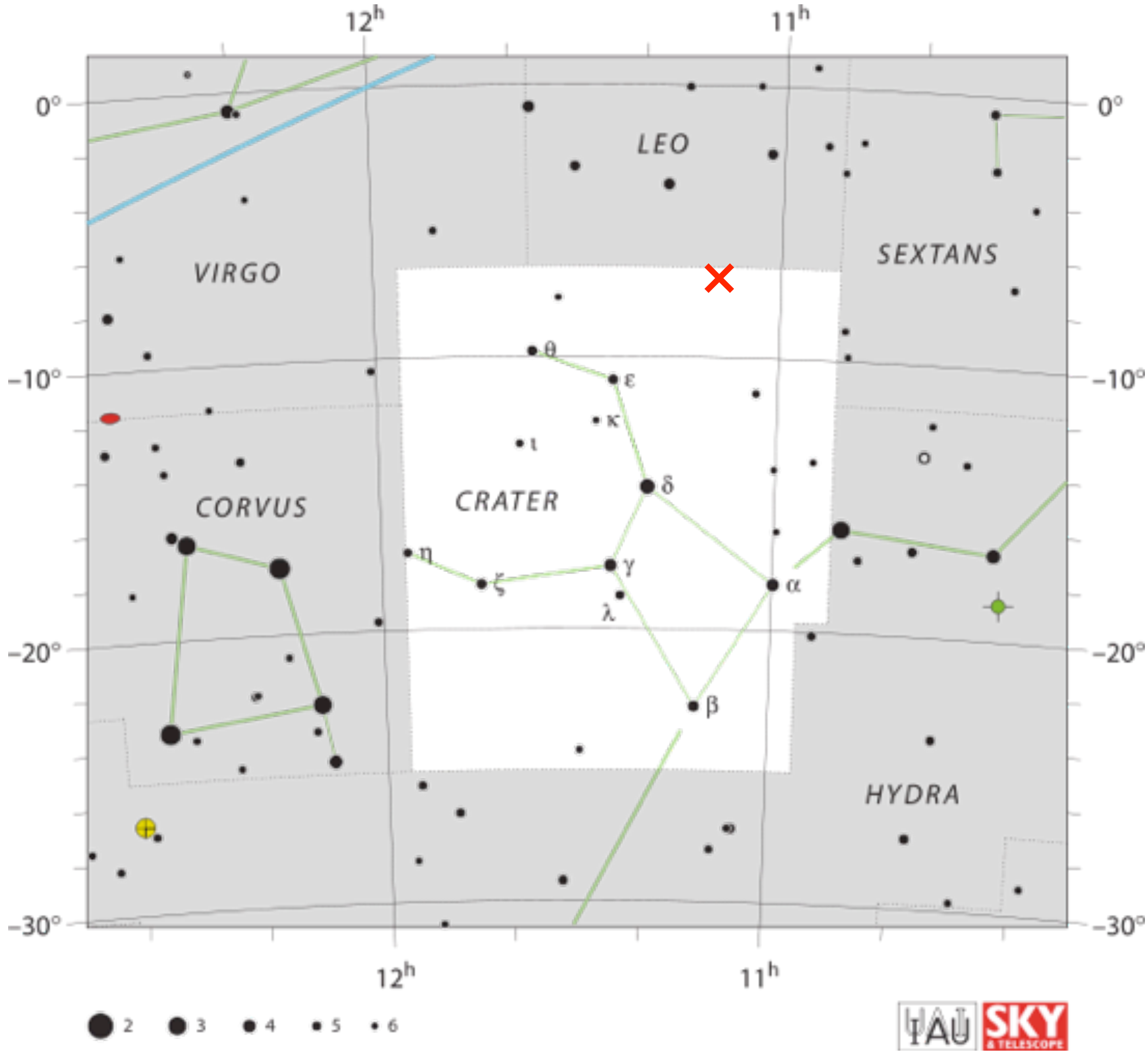
IAU
SKY & TELESCOPE



12h
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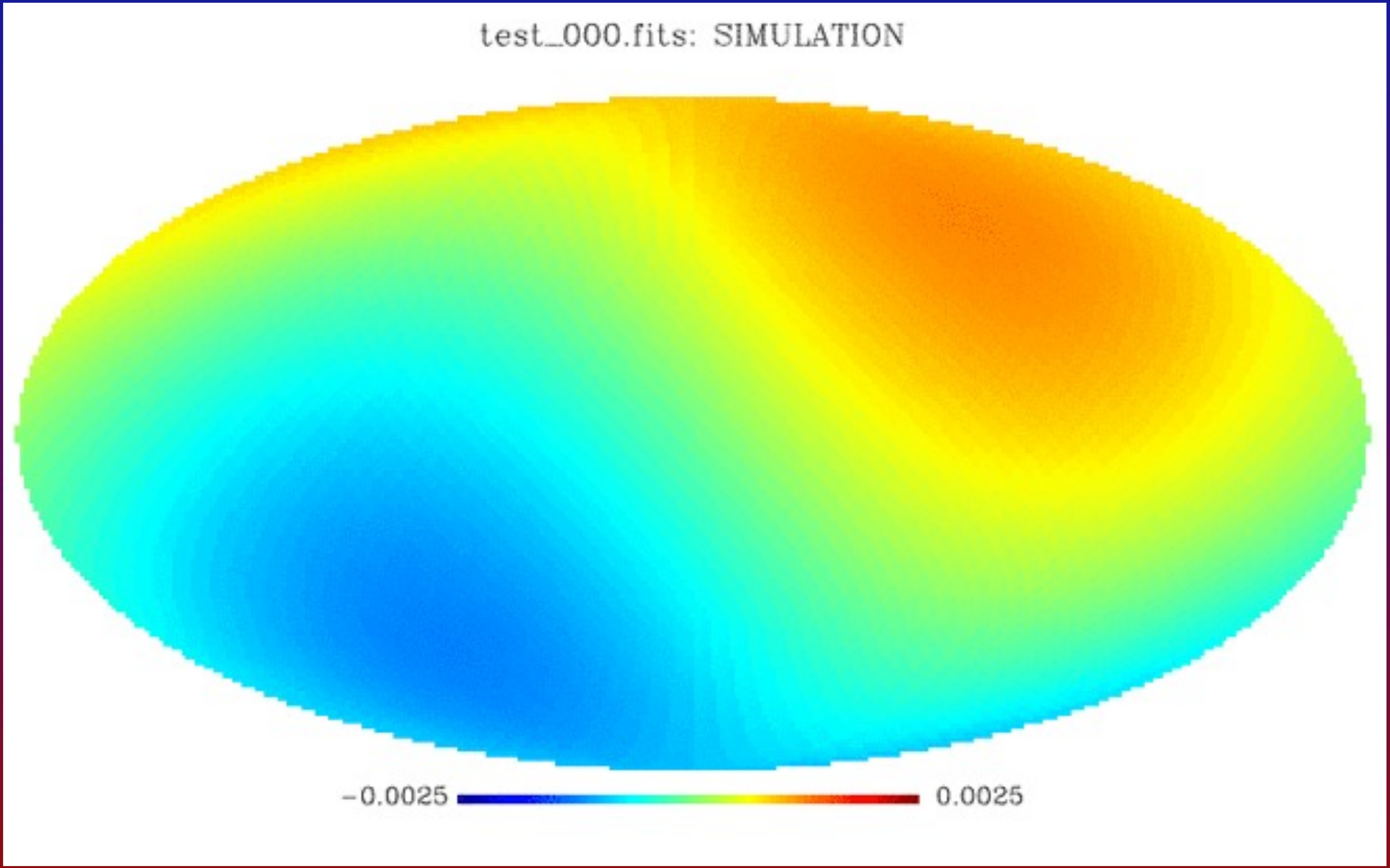
SKY & TELESCOPE

Dipole evolves as we circle the Galaxy

Moss, Scott & Zibin arXiv:0706.4482 & 0709.4040

Dipole evolves as we circle the Galaxy



Moss, Scott & Zibin arXiv:0706.4482 & 0709.4040

Doppler boosting the CMB

Based on this paper:

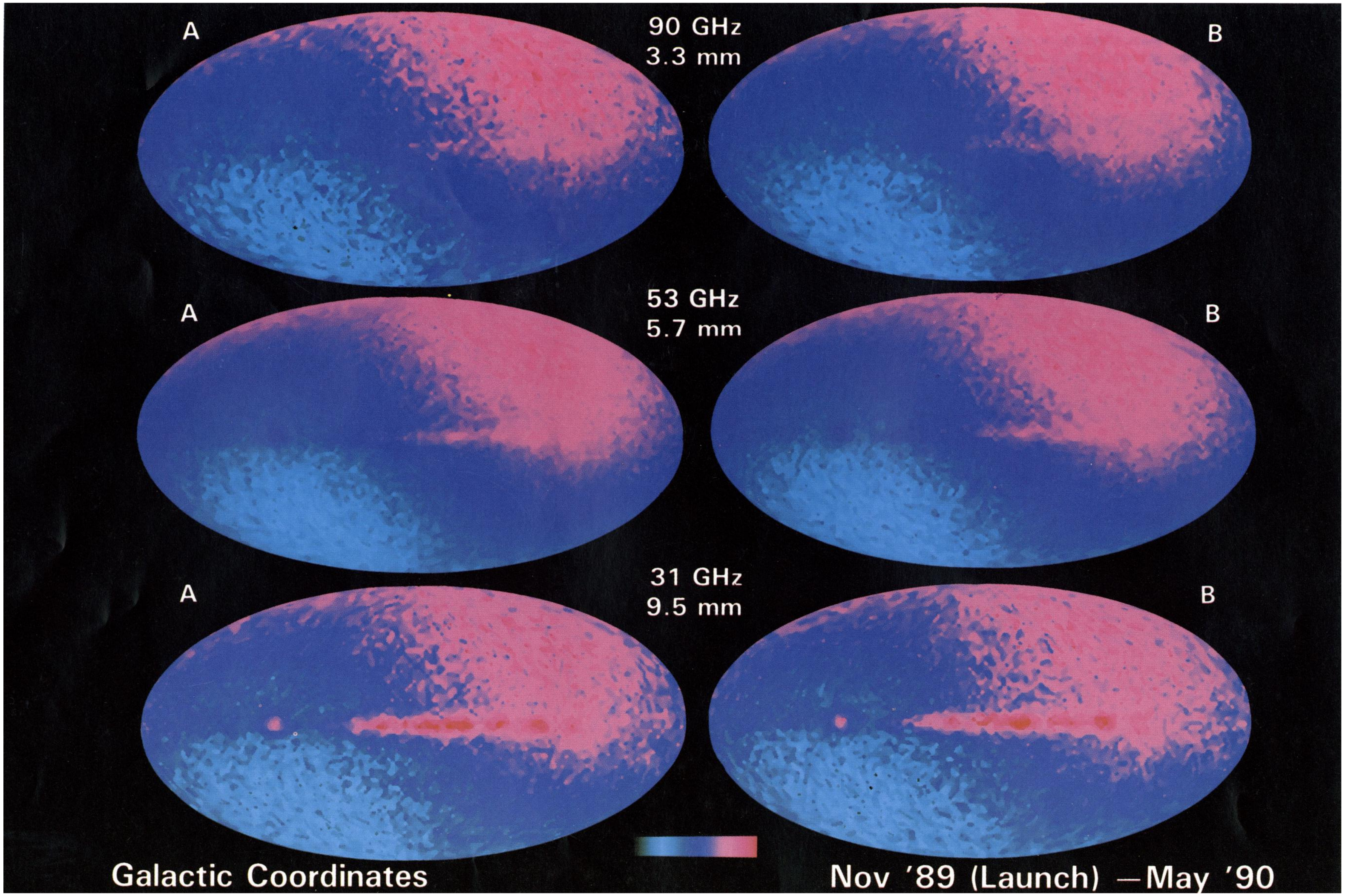
Planck 2013 results. XXVII. Doppler boosting of the CMB: Eppur si muove★

Planck Collaboration: N. Aghanim[52], C. Armitage-Caplan[81], M. Arnaud[65], M. Ashdown[62,5], F. Atrio-Barandela[15], J. Aumont[52], A. J. Banday[83,8], R. B. Barreiro[59], J. G. Bartlett[1,60], K. Benabed[53,82], A. Benoit-Lévy[21,53,82], J.-P. Bernard[8], M. Bersanelli[32,44], P. Bielewicz[83,8,75], J. Bobin[65], J. J. Bock[60,9], J. R. Bond[7], J. Borrill[11,79], F. R. Bouchet[53,82], M. Bridges[62,5,56], C. Burigana[43,30], R. C. Butler[43], J.-F. Cardoso[66,1,53], A. Catalano[67,64], A. Challinor[56,62,10], A. Chamballu[65,12,52], L.-Y Chiang[55], H. C. Chiang[24,6], P. R. Christensen[72,35], D. L. Clements[50], L. P. L. Colombo[20,60], F. Couchot[63], B. P. Crill[60,73], F. Cuttaia[43], L. Danese[75], R. D. Davies[61], R. J. Davis[61], P. de Bernardis[31], A. de Rosa[43], G. de Zotti[40,75], J. Delabrouille[1], J. M. Diego[59], S. Donzelli[44], O. Doré[60,9], X. Dupac[37], G. Efstathiou[56], T. A. Enßlin[70], H. K. Eriksen[57], F. Finelli[43,45], O. Forni[83,8], M. Frailis[42], E. Franceschi[43], S. Galeotta[42], K. Ganga[1], M. Giard[83,8], G. Giardino[38], J. González-Nuevo[59,75], K. M. Górski[60,86], S. Gratton[62,56], A. Gregorio[33,42], A. Gruppuso[43], F. K. Hansen[57], D. Hanson[71,60,7], D. Harrison[56,62], G. Helou[9], S. R. Hildebrandt[9], E. Hivon[53,82], M. Hobson[5], W. A. Holmes[60], W. Hovest[70], K. M. Huffenberger[85], W. C. Jones[24], M. Juvela[23], E. Keihänen[23], R. Keskitalo[18,11], T. S. Kisner[69], J. Knoche[70], L. Knox[26], M. Kunz[14,52,3], H. Kurki-Suonio[23,39], A. Lähteenmäki[2,39], J.-M. Lamarre[64], A. Lasenby[5,62], C. R. Lawrence[60], R. Leonardi[37], A. Lewis[22], M. Liguori[29], P. B. Lilje[57], M. Linden-Vørnle[13], M. López-Caniego[59], P. M. Lubin[27], J. F. Macías-Pérez[67], M. Maris[42], D. J. Marshall[65], P. G. Martin[7], E. Martínez-González[59], S. Masi[31], S. Matarrese[29], P. Mazzotta[34], P. R. Meinhold[27], A. Melchiorri[31,46], L. Mendes[37], M. Migliaccio[56,62], S. Mitra[49,60], A. Moneti[53], L. Montier[83,8], G. Morgante[43], D. Mortlock[50], A. Moss[77], D. Munshi[76], P. Naselsky[72,35], F. Nati[31], P. Natoli[30,4,43], H. U. Nørgaard-Nielsen[13], F. Noviello[61], D. Novikov[50], I. Novikov[72], S. Osborne[80], C. A. Oxborrow[13], L. Pagano[31,46], F. Pajot[52], D. Paoletti[43,45], F. Pasian[42], G. Patanchon[1], O. Perdereau[63], F. Perrotta[75], F. Piacentini[31], E. Pierpaoli[20], D. Pietrobon[60], S. Plaszczynski[63], E. Pointecouteau[83,8], G. Polenta[4,41], N. Ponthieu[52,47], L. Popa[54], G. W. Pratt[65], G. Prézeau[9,60], J.-L. Puget[52], J. P. Rachen[17,70], W. T. Reach[84], M. Reinecke[70], S. Ricciardi[43], T. Riller[70], I. Ristorcelli[83,8], G. Rocha[60,9], C. Rosset[1], J. A. Rubiño-Martín[58,36], B. Rusholme[51], D. Santos[67], G. Savini[74], D. Scott[19]★★, M. D. Seiffert[60,9], E. P. S. Shellard[10], L. D. Spencer[76], R. Sunyaev[70,78], F. Sureau[65], A.-S. Suur-Uski[23,39], J.-F. Sygnet[53], J. A. Tauber[38], D. Tavagnacco[42,33], L. Terenzi[43], L. Toffolatti[16,59], M. Tomasi[44], M. Tristram[63], M. Tucci[14,63], M. Türler[48], L. Valenziano[43], J. Valiviita[39,23,57], B. Van Tent[68], P. Vielva[59], F. Villa[43], N. Vittorio[34], L. A. Wade[60], B. D. Wandelt[53,82,28], M. White[25], D. Yvon[12], A. Zacchei[42], J. P. Zibin[19], and A. Zonca[27]


HAPPY
EASTER


HAPPY
EASTER

CMB dipole is well known



e.g. first COBE results – Smoot et al. (1991)

Recall issues relevant to monopole and dipole

Monopole from *COBE* FIRAS (and ground-based experiments)

Dipole from *COBE* FIRAS/DMR and WMAP and now *Planck*

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
- And there are other effects...

Monopole from *COBE* FIRAS (and ground-based experiments)

Dipole from *COBE* FIRAS/DMR and WMAP and now *Planck*

6 boosting effects

- Dipole-modulate monopole → CMB dipole
- Dipole-modulation of all other multipoles
- Aberration of anisotropies
- Increase in monopole by $\beta^2/6$
- All-sky spectral (y) distortion
- Generation of $O(\beta^2)$ quadrupole

Peebles & Wilkinson (1968); Challinor & van Leeuwen (2002); Kamionkowski & Knox (2003); Burles & Rappaport (2006); Sollom (2010); Kosowsky & Kahniashvili 2010; Chluba (2011)

6 boosting effects

• Dipole-modulate monopole → CMB dipole	Well known!
• Dipole-modulation of all other multipoles	This talk
• Aberration of anisotropies	This talk
• Increase in monopole by $\beta^2/6$	Unmeasurable
• All-sky spectral (y) distortion	Uninteresting?
• Generation of $O(\beta^2)$ quadrupole	Spectrum?

Peebles & Wilkinson (1968); Challinor & van Leeuwen (2002); Kamionkowski & Knox (2003); Burles & Rappaport (2006); Sollom (2010); Kosowsky & Kahniashvili 2010; Chluba (2011)

Boosting frames

Boosting frames

Now $$T(\hat{\boldsymbol{n}}) = \frac{T'(\hat{\boldsymbol{n}}')}{\gamma(1 - \hat{\boldsymbol{n}} \cdot \boldsymbol{\beta})}$$

Boosting frames

CMB frame

observed frame

Now $$T(\hat{\boldsymbol{n}}) = \frac{T'(\hat{\boldsymbol{n}}')}{\gamma(1 - \hat{\boldsymbol{n}} \cdot \boldsymbol{\beta})}$$

Boosting frames

CMB frame

observed frame

v/c

Now

$$T(\hat{\boldsymbol{n}}) = \frac{T'(\hat{\boldsymbol{n}}')}{\gamma(1 - \hat{\boldsymbol{n}} \cdot \boldsymbol{\beta})}$$

Boosting frames

CMB frame

observed frame

Now $$T(\hat{\boldsymbol{n}}) = \frac{T'(\hat{\boldsymbol{n}}')}{\gamma(1 - \hat{\boldsymbol{n}} \cdot \boldsymbol{\beta})}$$

v/c

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

Boosting frames

CMB frame

observed frame

v/c

Now $$\underbrace{T(\hat{\boldsymbol{n}})}_{\text{observed frame}} = \frac{\overbrace{T'(\hat{\boldsymbol{n}}')}^{\text{CMB frame}}}{\gamma(1 - \hat{\boldsymbol{n}} \cdot \boldsymbol{\beta})}$$

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

To 1st order in β :

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

Boosting frames

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

v/c

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

To 1st order in β :

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

So finally:

$$\delta T(\hat{\boldsymbol{n}}) = T_0 \hat{\boldsymbol{n}} \cdot \boldsymbol{\beta} + \delta T'(\hat{\boldsymbol{n}} - \nabla(\hat{\boldsymbol{n}} \cdot \boldsymbol{\beta}))(1 + \hat{\boldsymbol{n}} \cdot \boldsymbol{\beta})$$

Boosting frames

CMB frame

observed frame

Now $$T(\hat{\boldsymbol{n}}) = \frac{T'(\hat{\boldsymbol{n}}')}{\gamma(1-\hat{\boldsymbol{n}}\cdot\boldsymbol{\beta})}$$

v/c

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

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

So finally:

dipole

$$\delta T(\hat{\boldsymbol{n}}) = T_0\hat{\boldsymbol{n}}\cdot\boldsymbol{\beta} + \delta T'(\hat{\boldsymbol{n}} - \nabla(\hat{\boldsymbol{n}}\cdot\boldsymbol{\beta}))(1+\hat{\boldsymbol{n}}\cdot\boldsymbol{\beta})$$

Boosting frames

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

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

To 1st order in β :

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

So finally:

$$\delta T(\hat{\boldsymbol{n}}) = \overset{\text{dipole}}{T_0\hat{\boldsymbol{n}}\cdot\boldsymbol{\beta}} + \delta T'(\hat{\boldsymbol{n}} - \overset{\text{deflections}}{\nabla(\hat{\boldsymbol{n}}\cdot\boldsymbol{\beta})})(1+\hat{\boldsymbol{n}}\cdot\boldsymbol{\beta})$$

Boosting frames

CMB frame

observed frame

Now $$T(\hat{\boldsymbol{n}}) = \frac{T'(\hat{\boldsymbol{n}}')}{\gamma(1-\hat{\boldsymbol{n}}\cdot\boldsymbol{\beta})}$$

v/c

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

To 1st order in β :

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

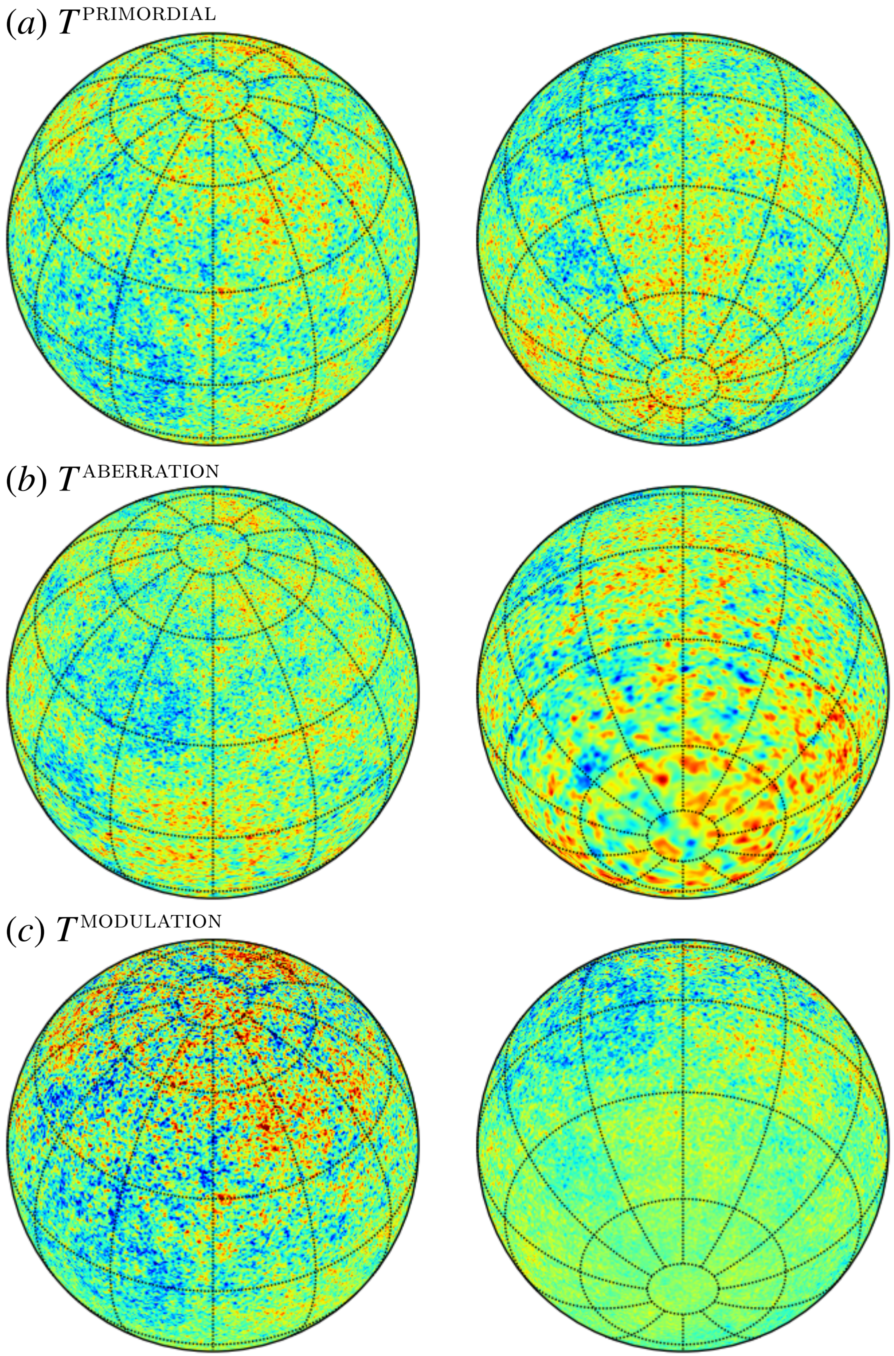
So finally:

dipole

deflections

modulation

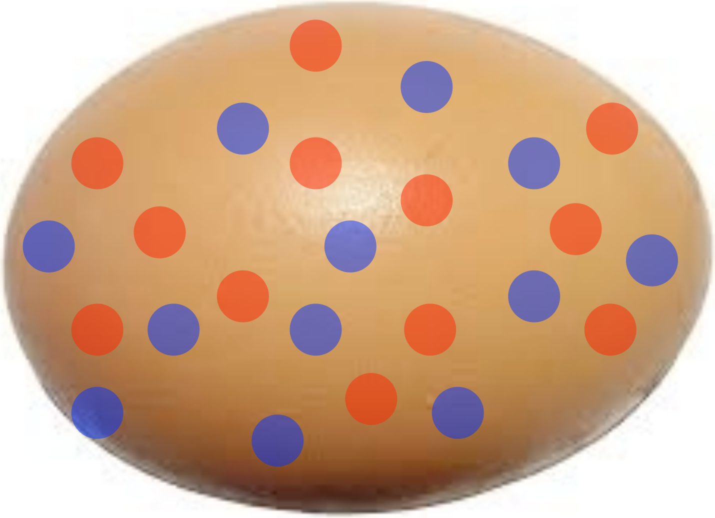
$$\delta T(\hat{\boldsymbol{n}}) = T_0\hat{\boldsymbol{n}}\cdot\boldsymbol{\beta} + \delta T'(\hat{\boldsymbol{n}} - \nabla(\hat{\boldsymbol{n}}\cdot\boldsymbol{\beta}))(1+\hat{\boldsymbol{n}}\cdot\boldsymbol{\beta})$$

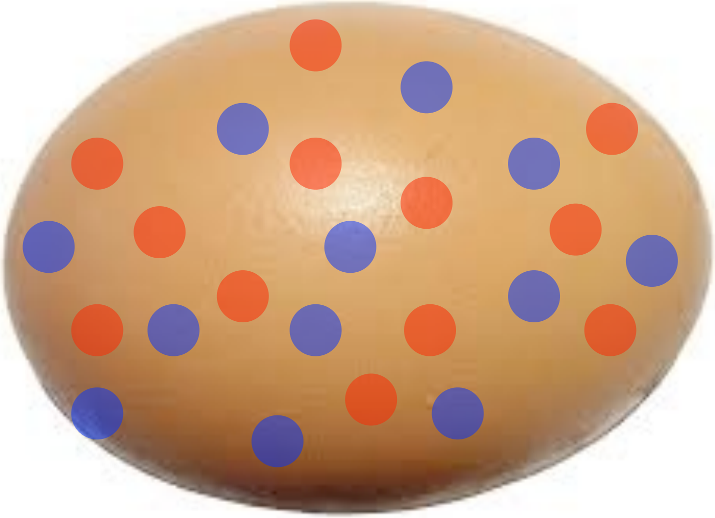


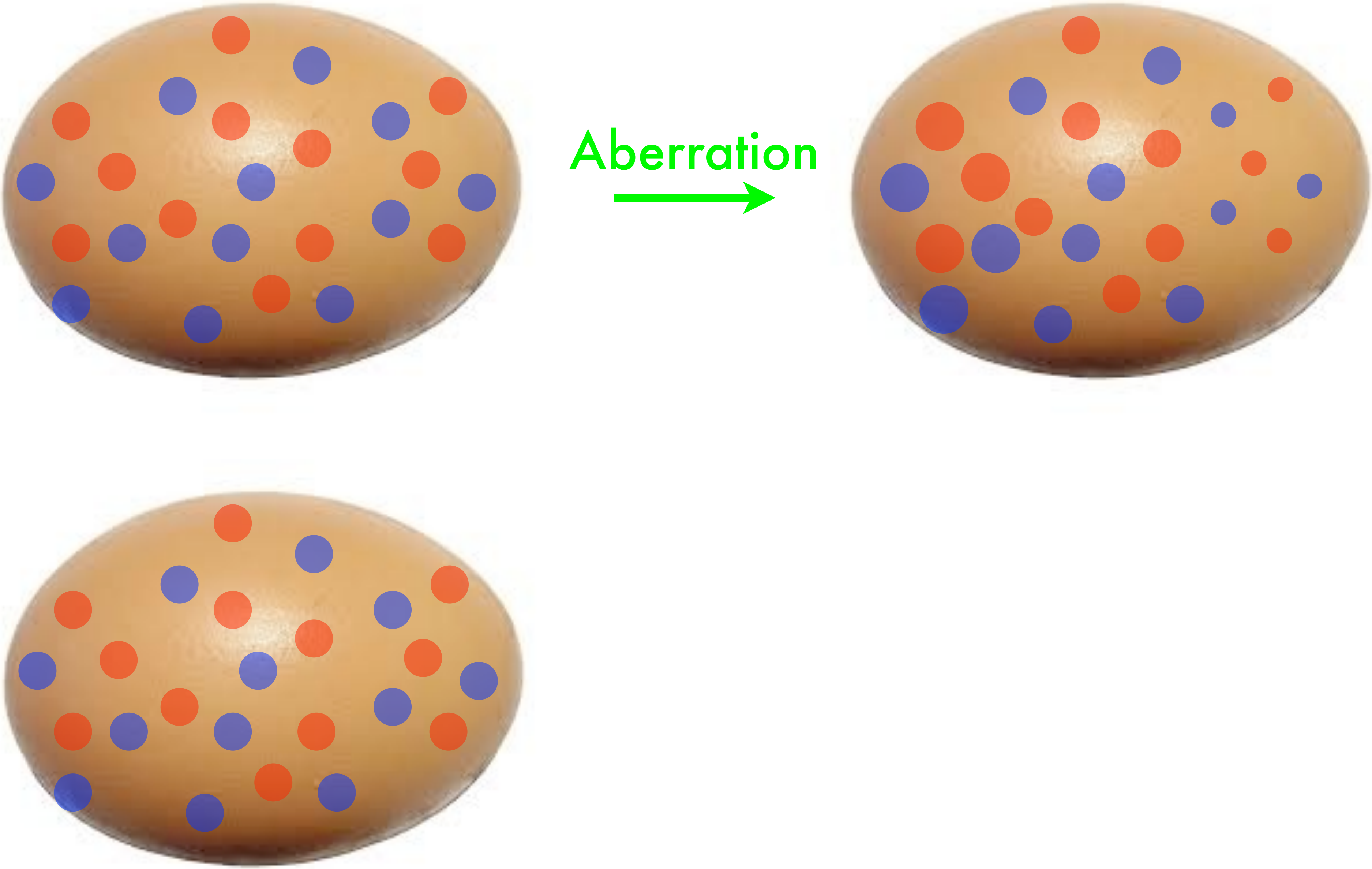
Simulated CMB

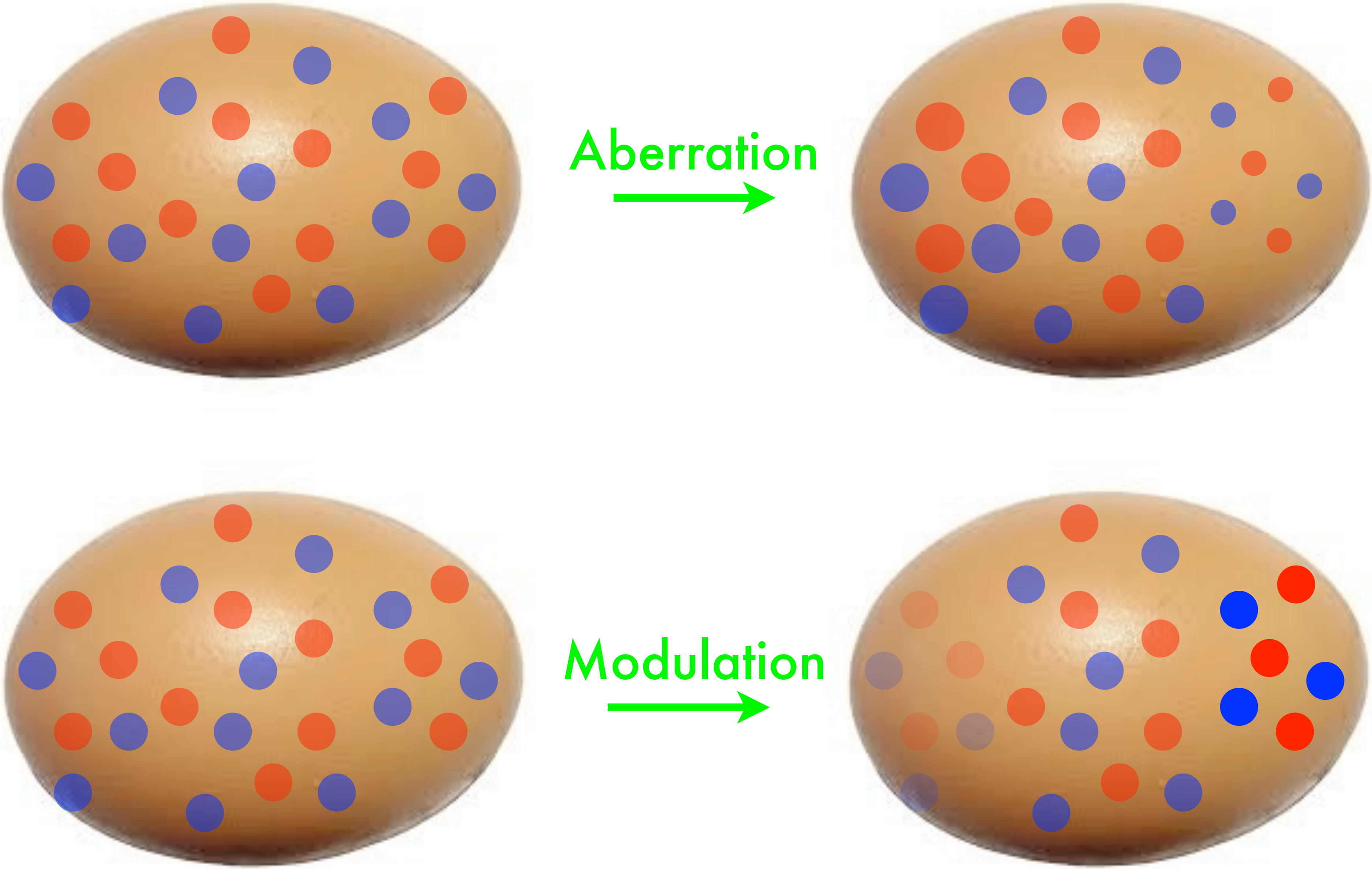
Aberration
for β=0.85

Modulation
for β=0.85






Aberration


Aberration
Modulation

Boosting frames

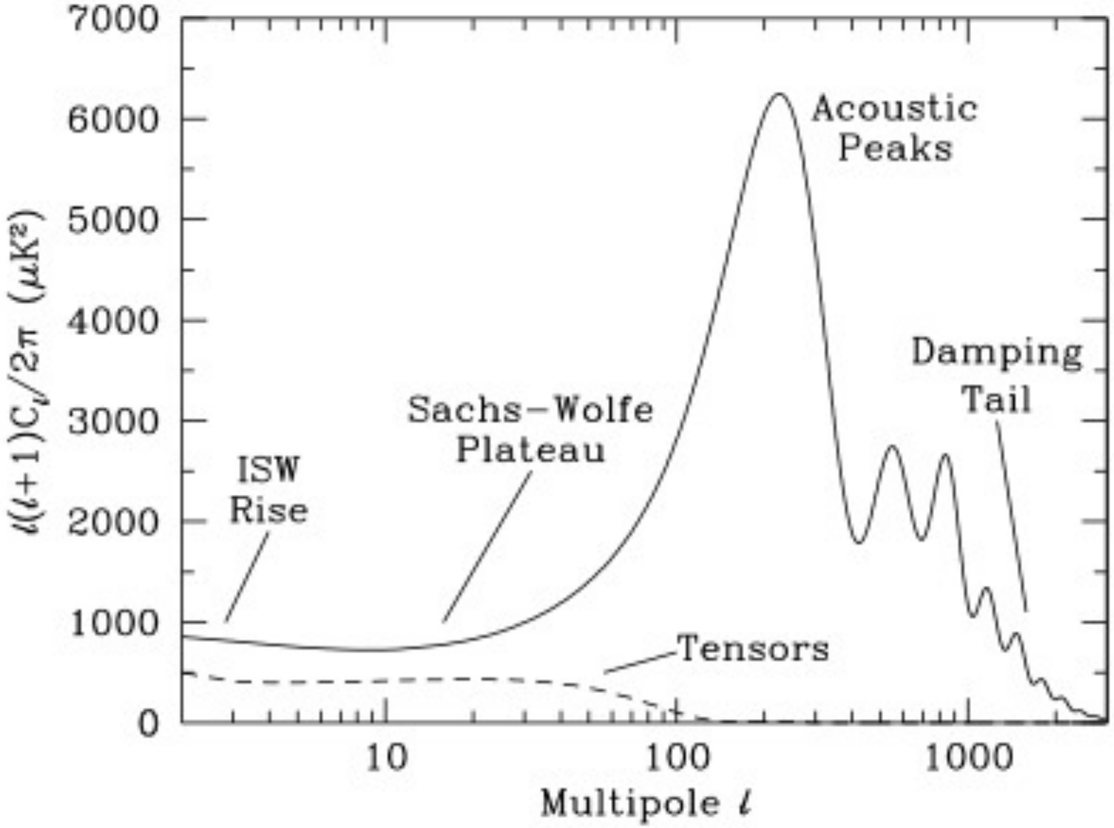
With *Planck* we can try to measure both the aberration and boosting effects

This could be done either in map space or harmonic space

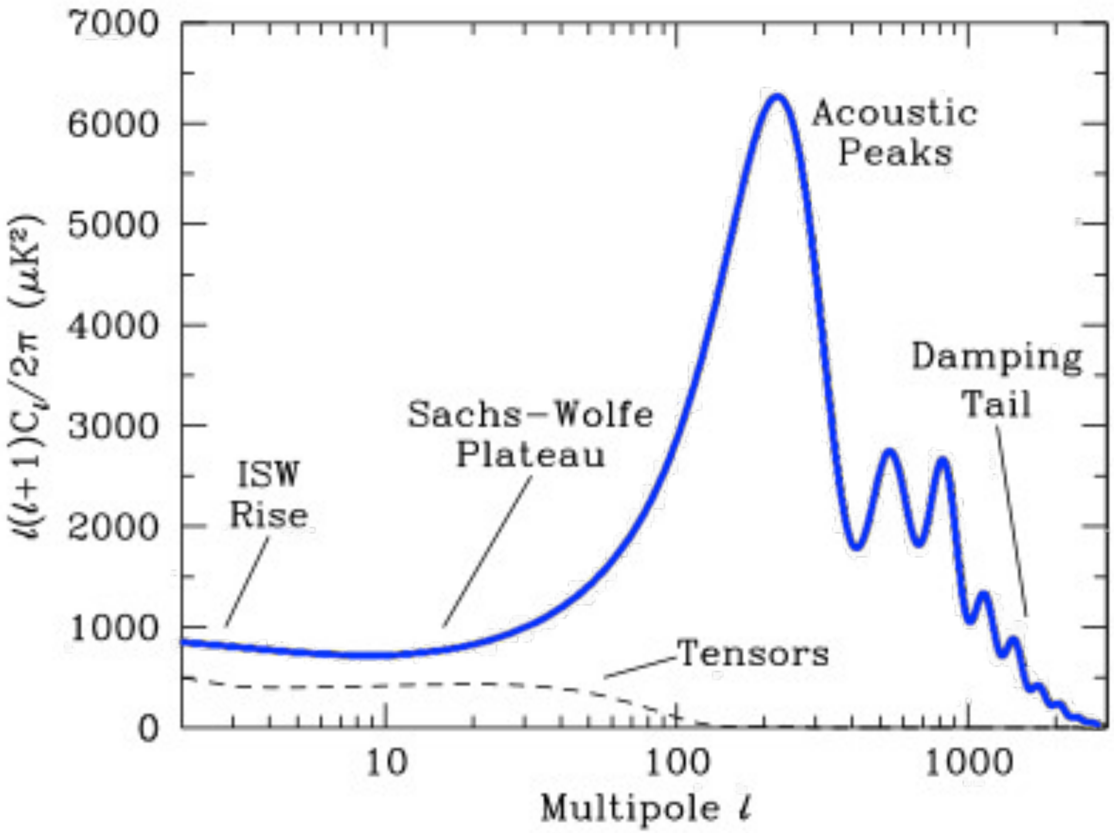
Harmonic space is more efficient and uses machinery of $\langle T_1 T_2 T_3 T_4 \rangle$

Boosting frames

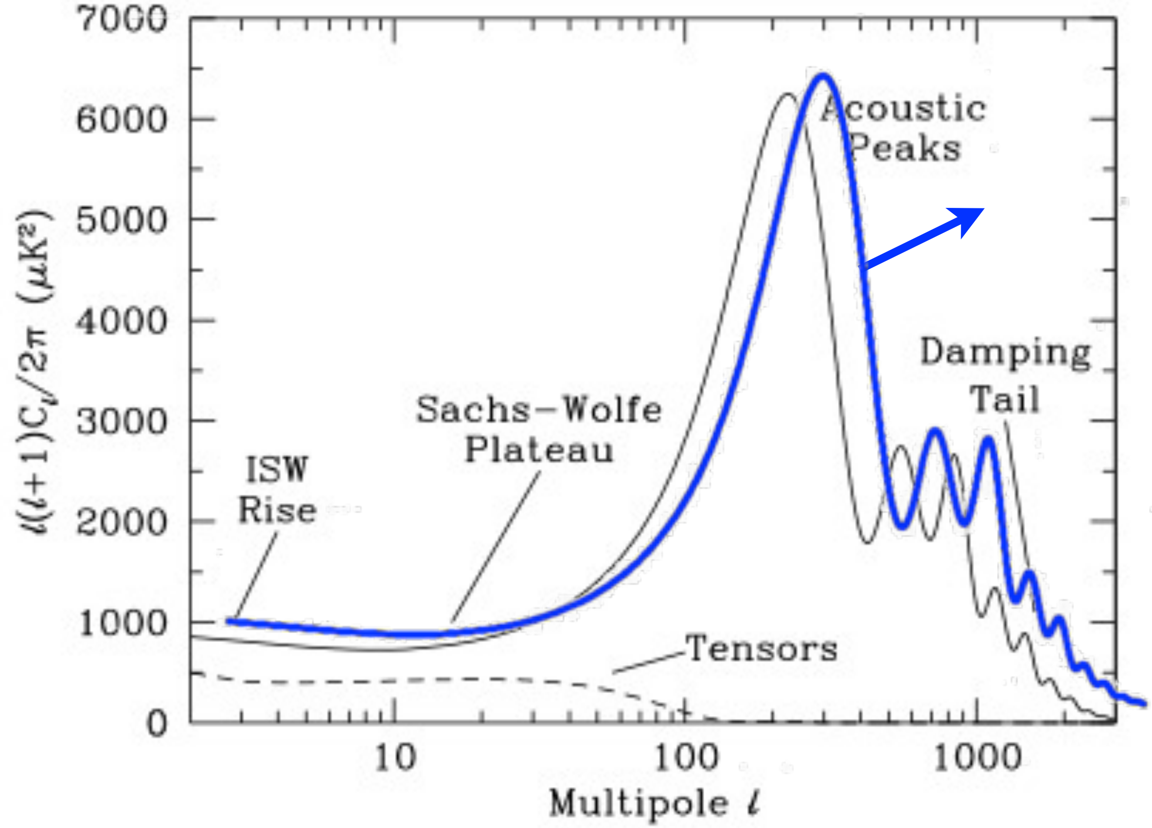
Boosting frames



Boosting frames

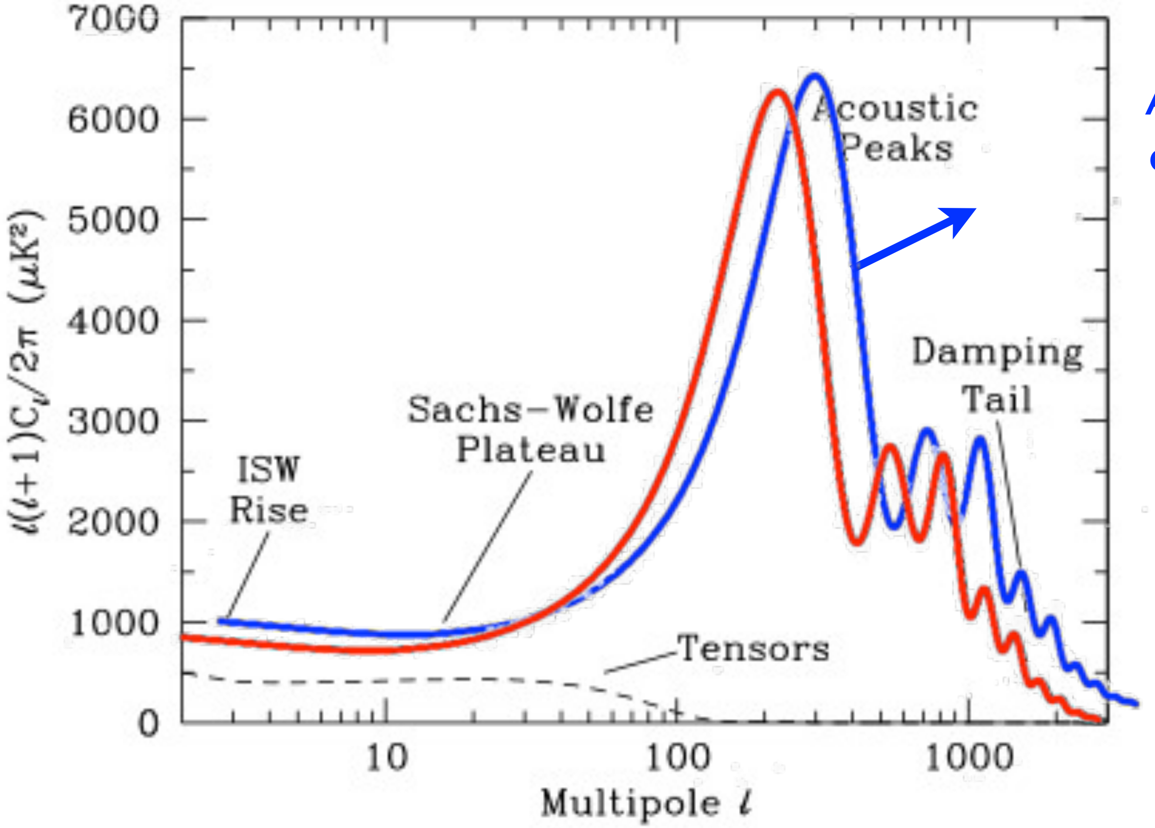


Boosting frames



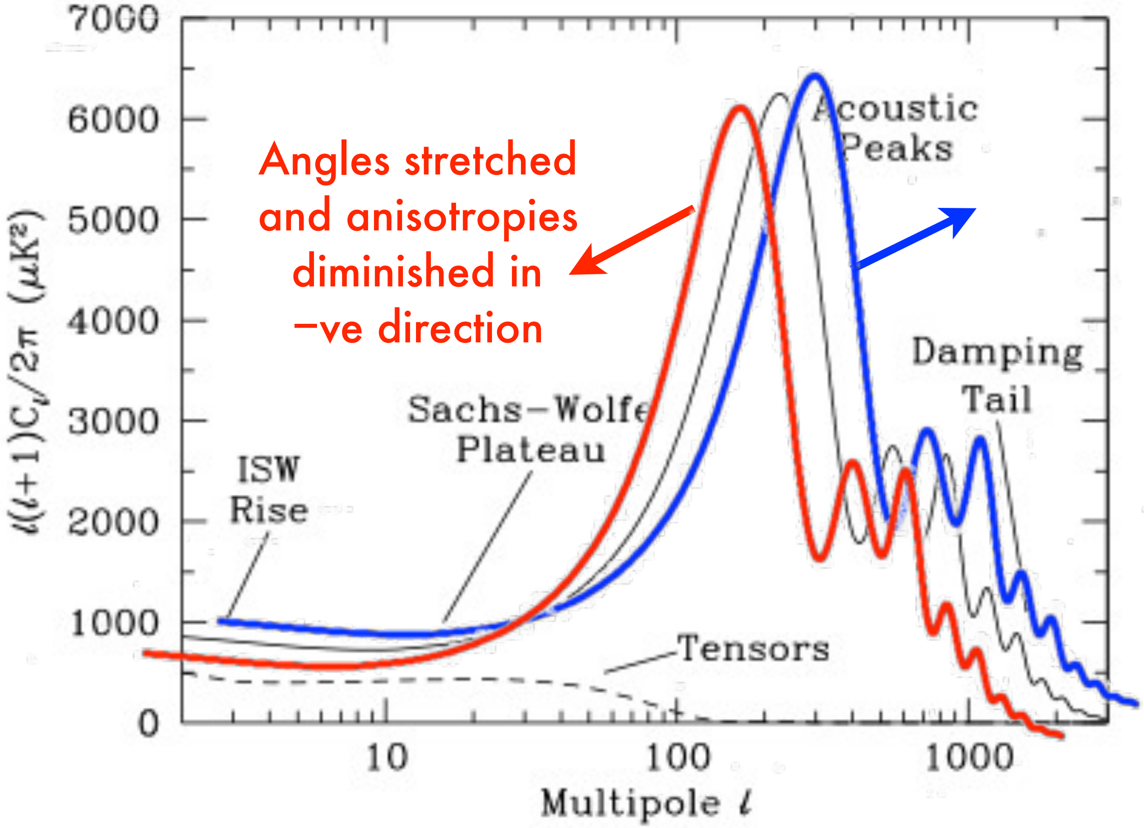
Angles squashed and anisotropies boosted in +ve direction

Boosting frames



Angles squashed and anisotropies boosted in +ve direction

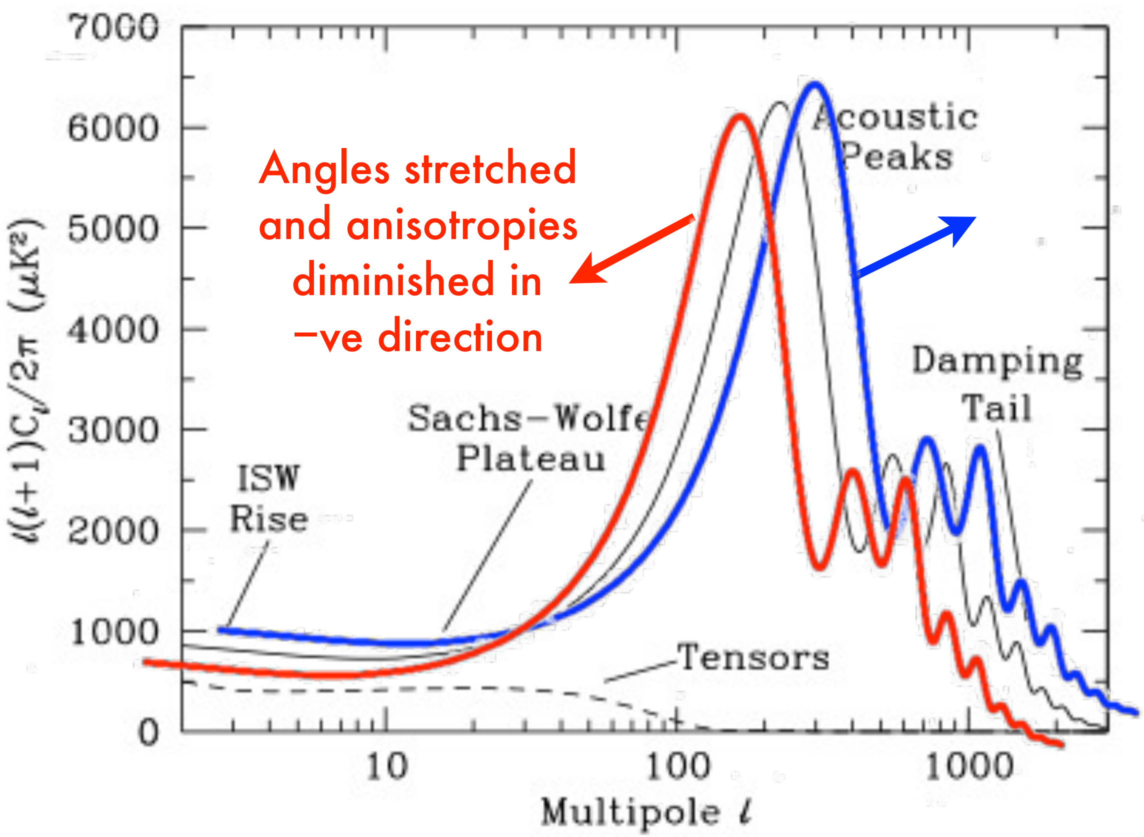
Boosting frames



Angles stretched and anisotropies diminished in −ve direction

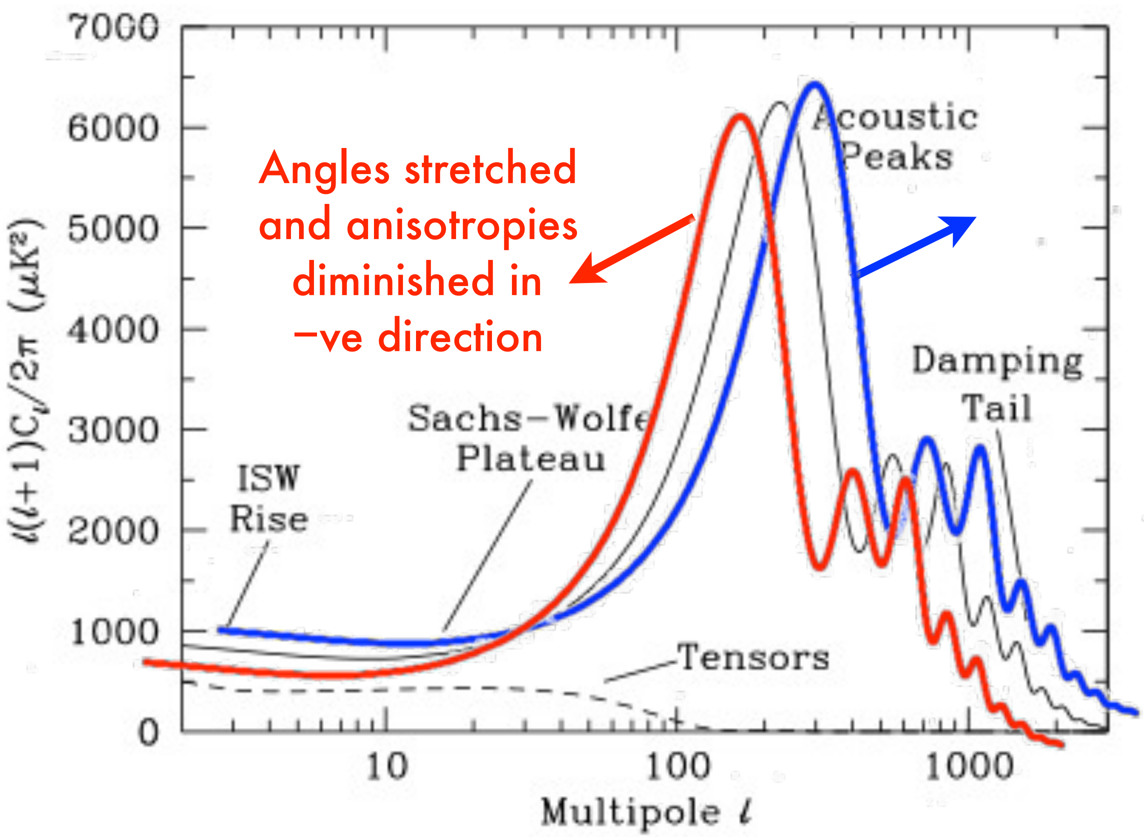
Angles squashed and anisotropies boosted in +ve direction

Boosting frames



Or can consider this as an effect which couples harmonics

Boosting frames



Angles squashed
and anisotropies
boosted in
+ve direction

Or can consider this as an effect which couples harmonics

This was measured convincingly in 2013 data set

Dipole modulation couples ℓ with $\ell \pm 1$

Figure by Joel Hutchinson

Dipole modulation couples ℓ with $\ell \pm 1$

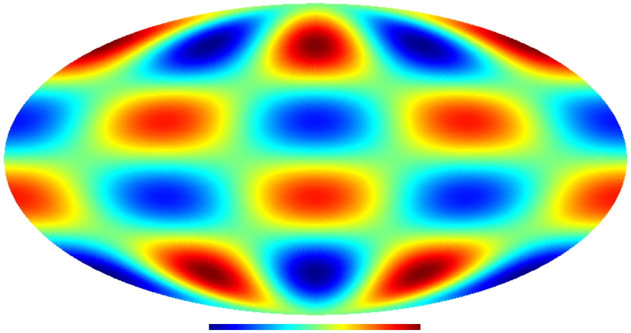


Figure by Joel Hutchinson

Dipole modulation couples ℓ with $\ell \pm 1$

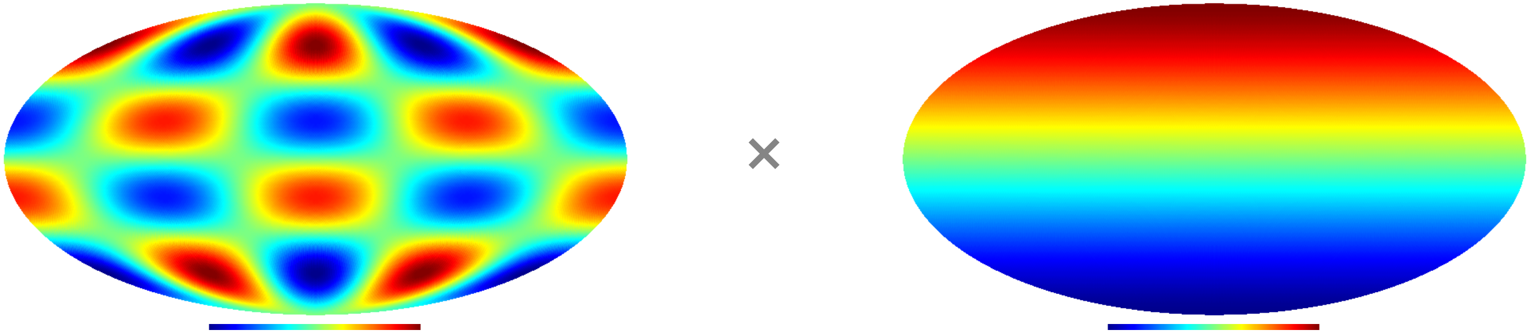


Figure by Joel Hutchinson

Dipole modulation couples ℓ with $\ell \pm 1$

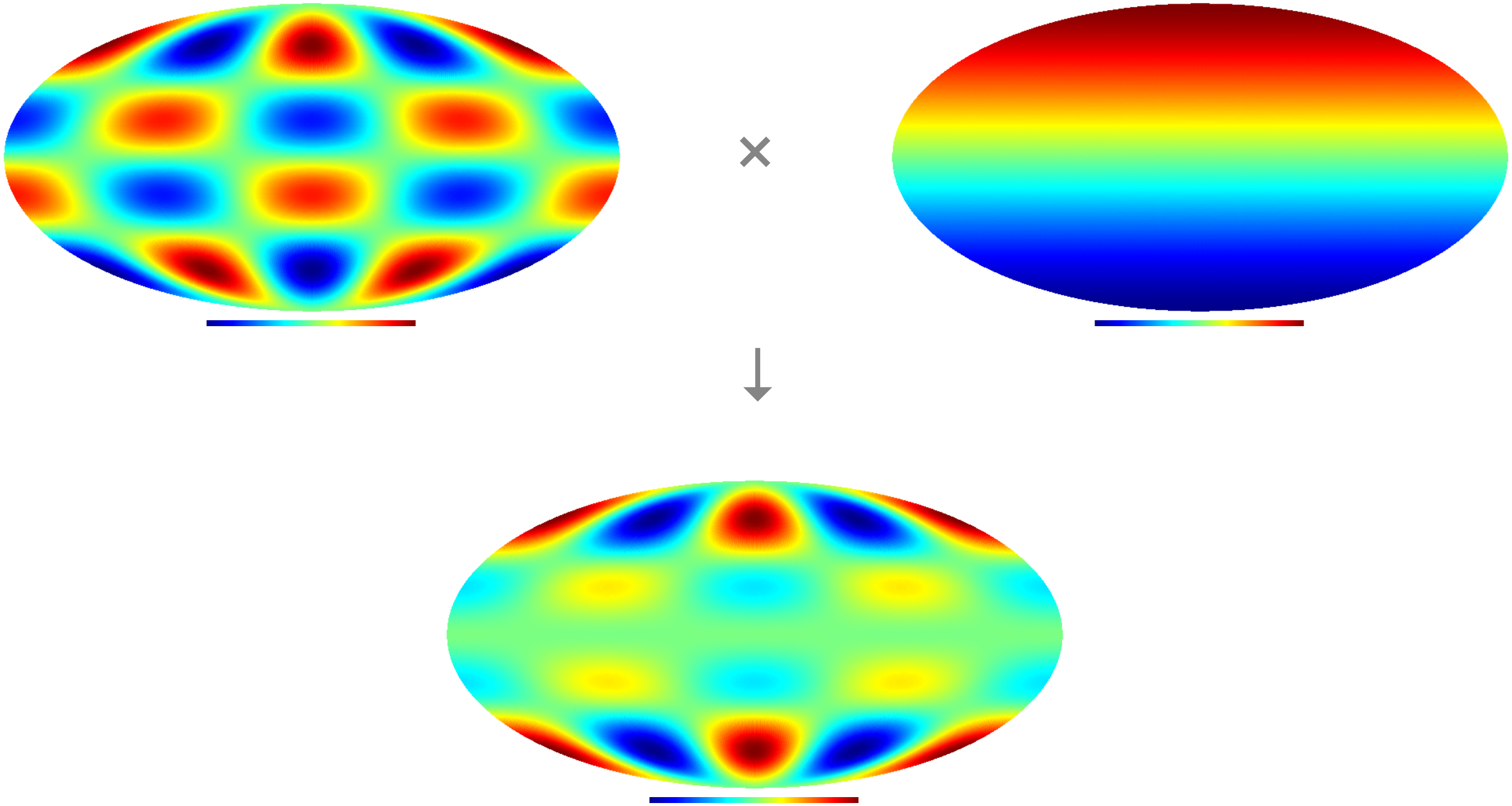


Figure by Joel Hutchinson

Dipole modulation couples ℓ with $\ell \pm 1$

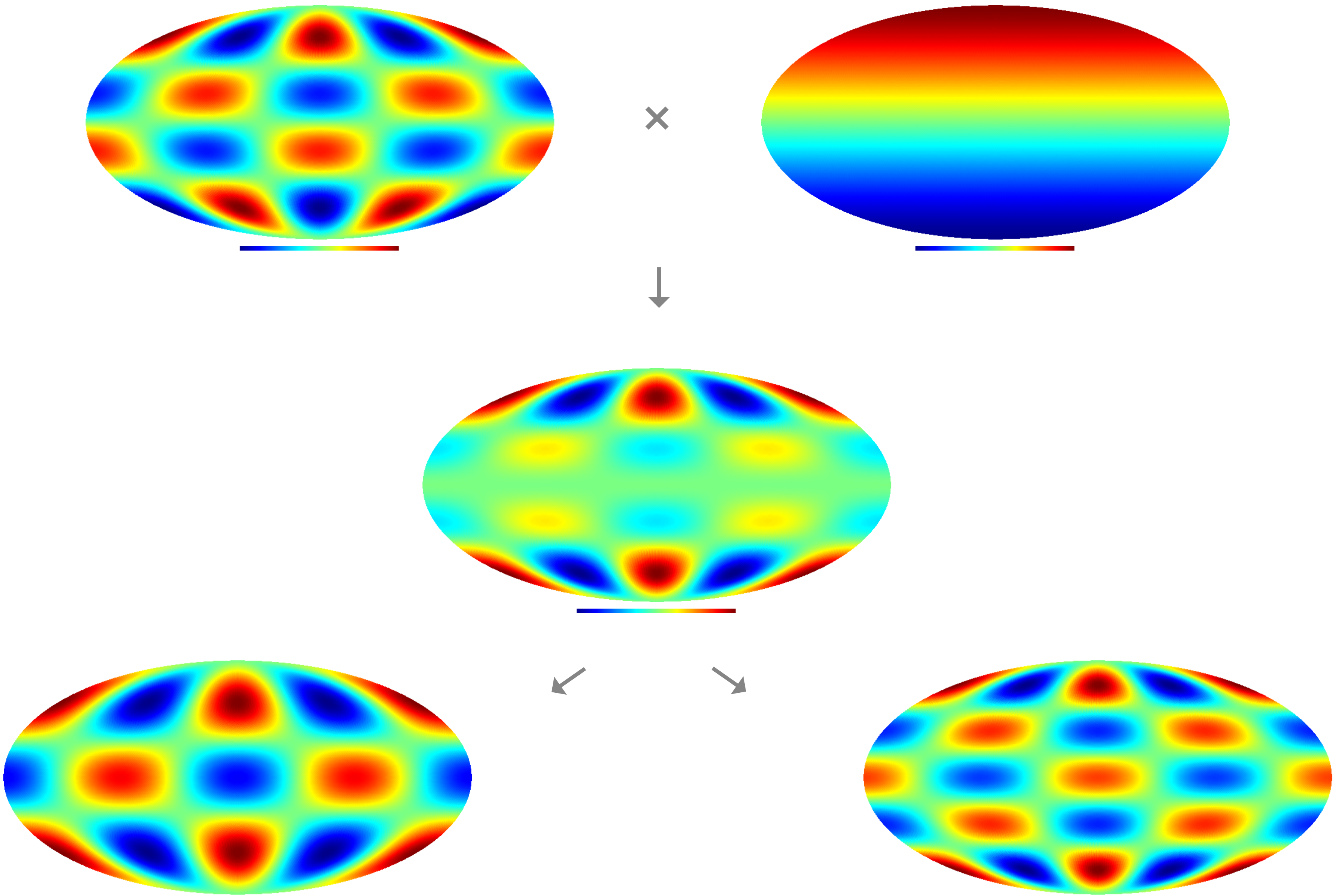


Figure by Joel Hutchinson

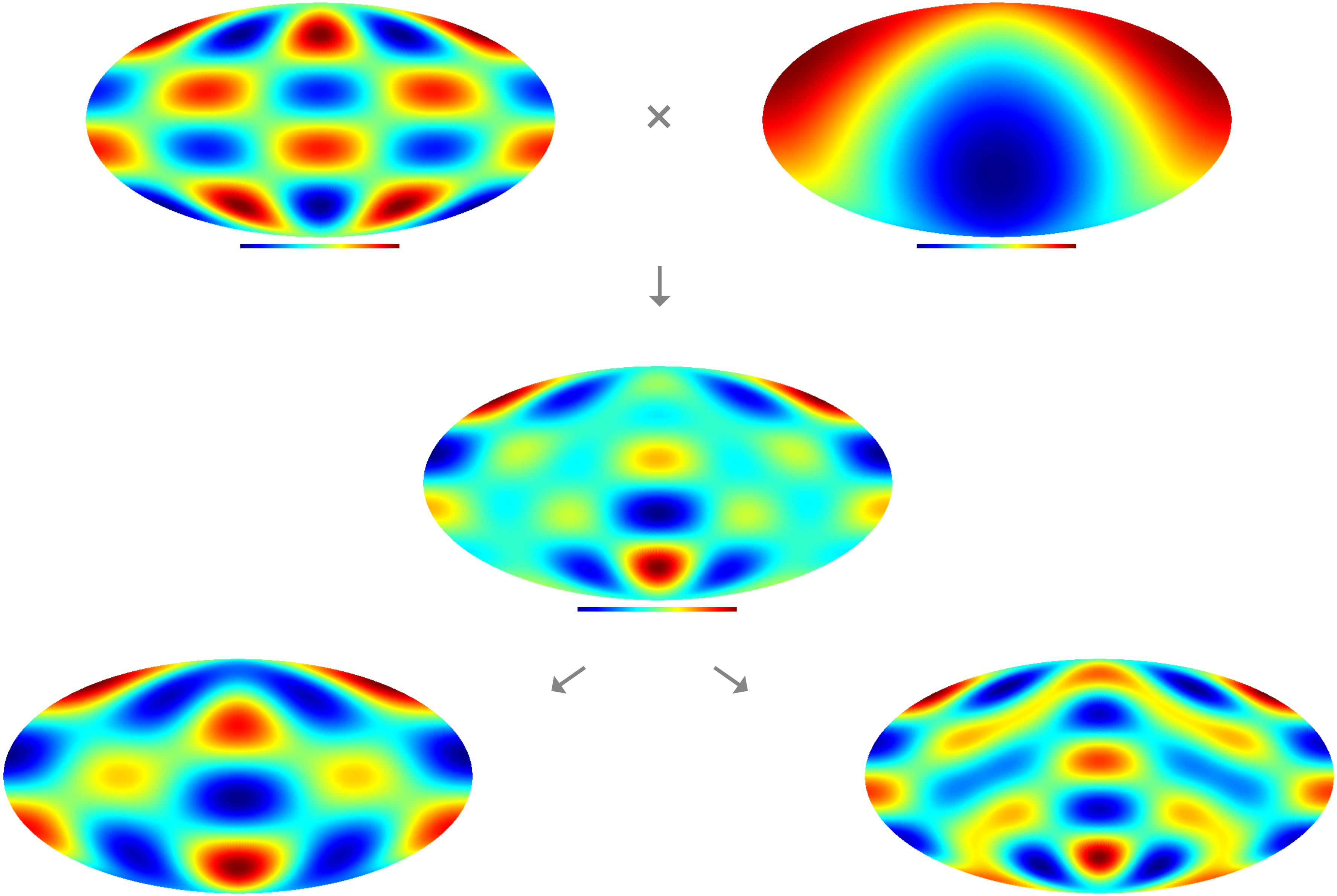
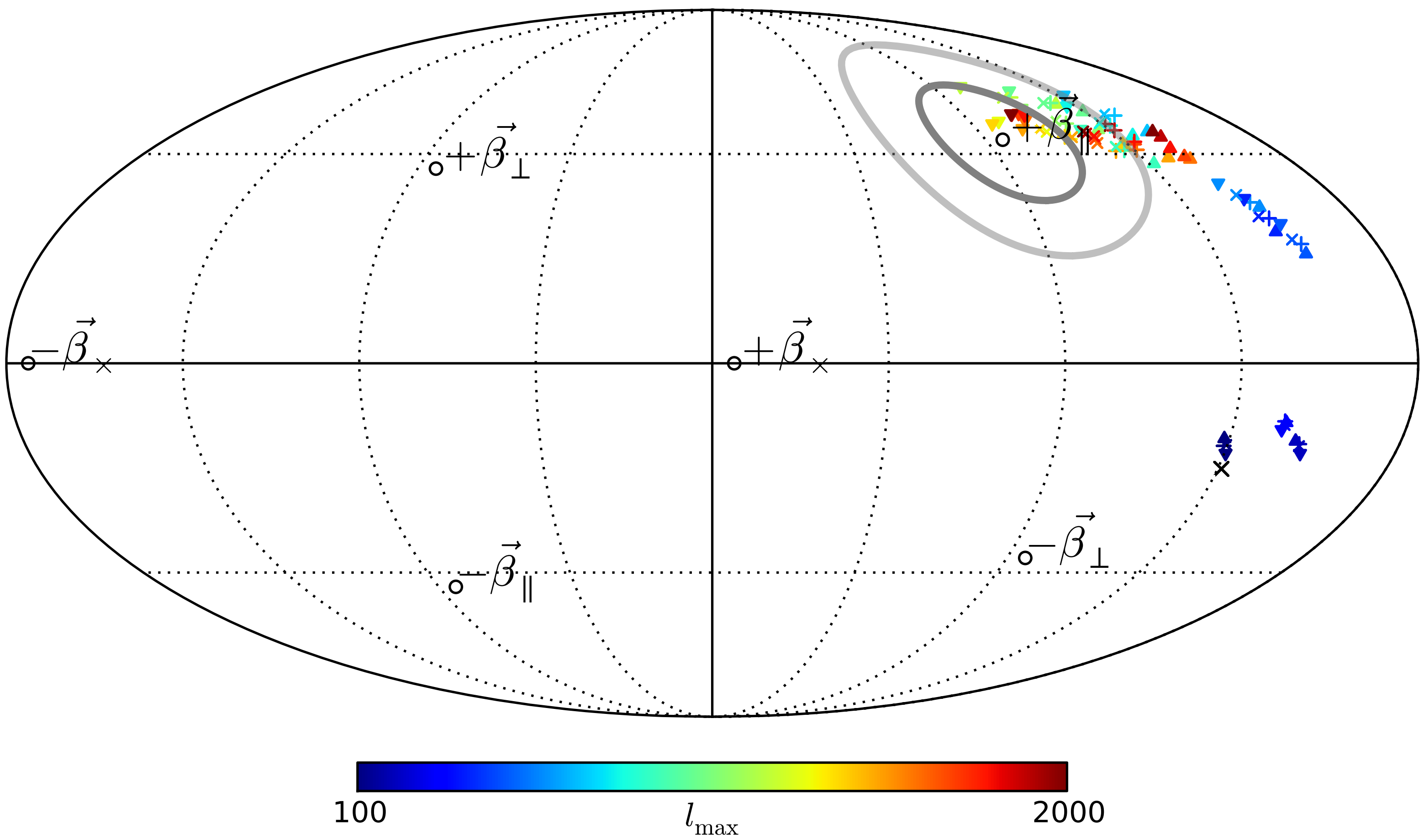


Figure by Joel Hutchinson

Results



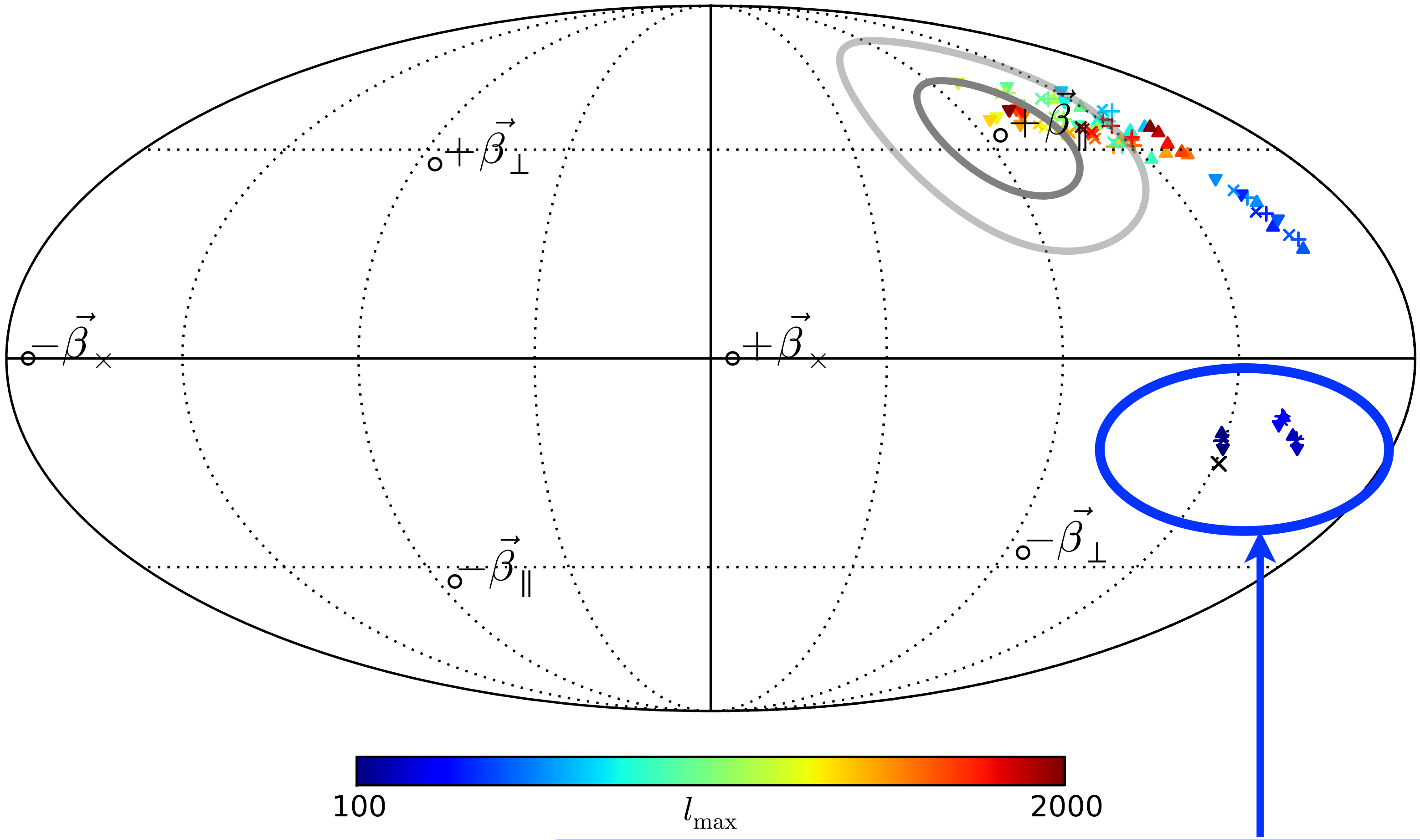
▼ : 143x143

▲ : 217x217

× : 143x217

+ : 143+217

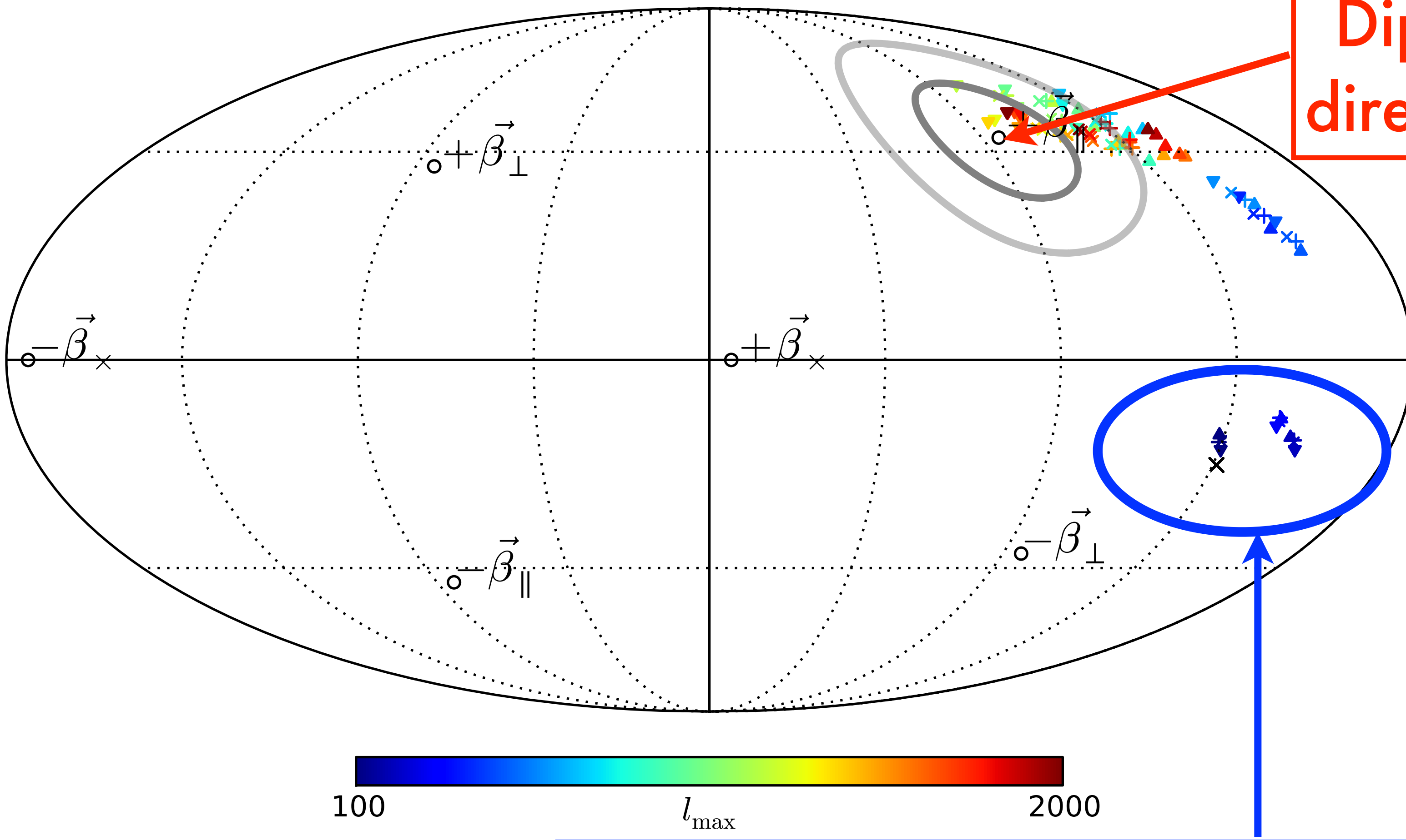
Results



▼ : 143x143
▲ : 217x217
× : 143x217
+ : 143+217

Hemispheric asymmetry anomaly dominates for lower multipoles (see Planck Collaboration XXIII)

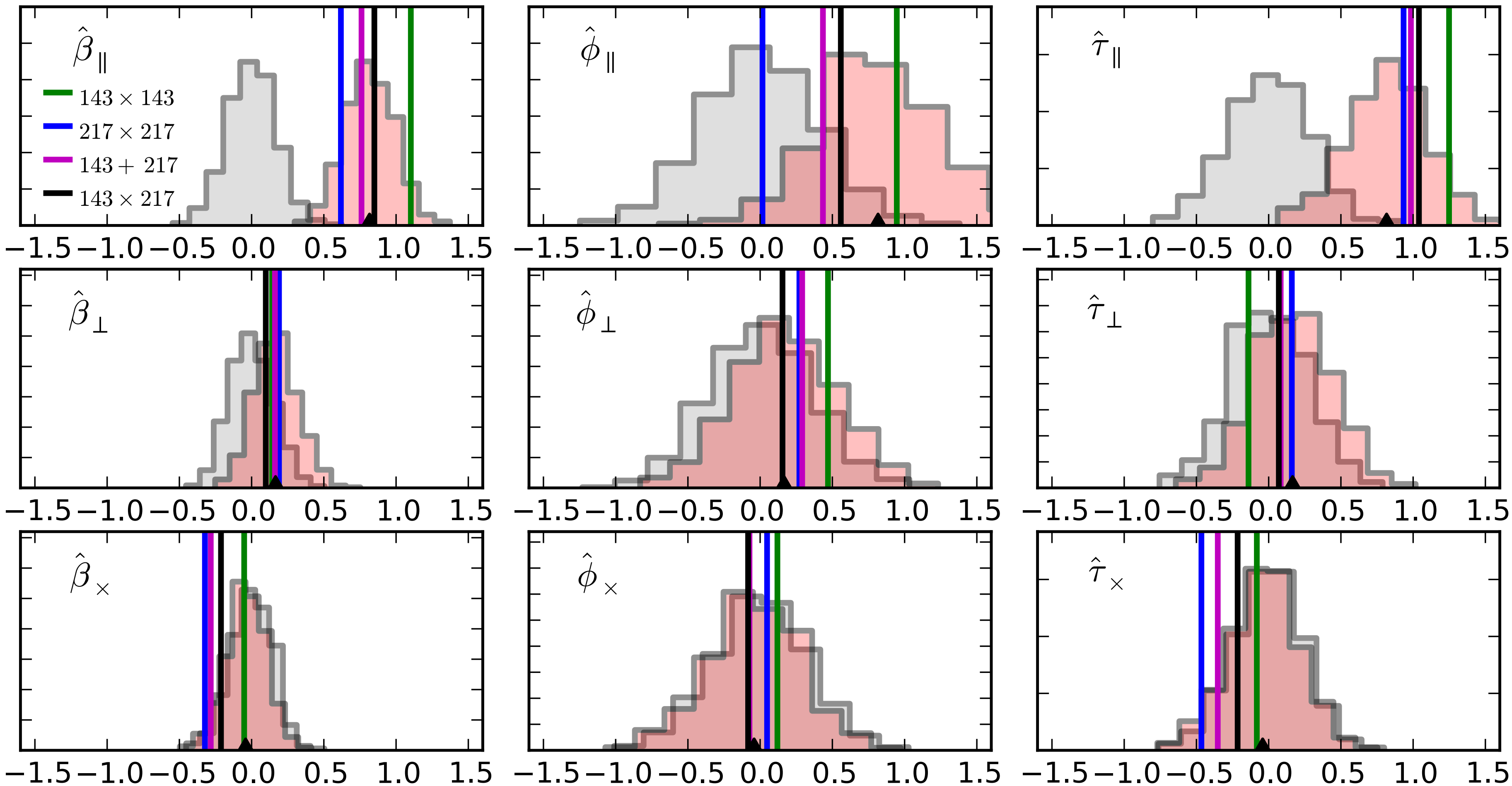
Results



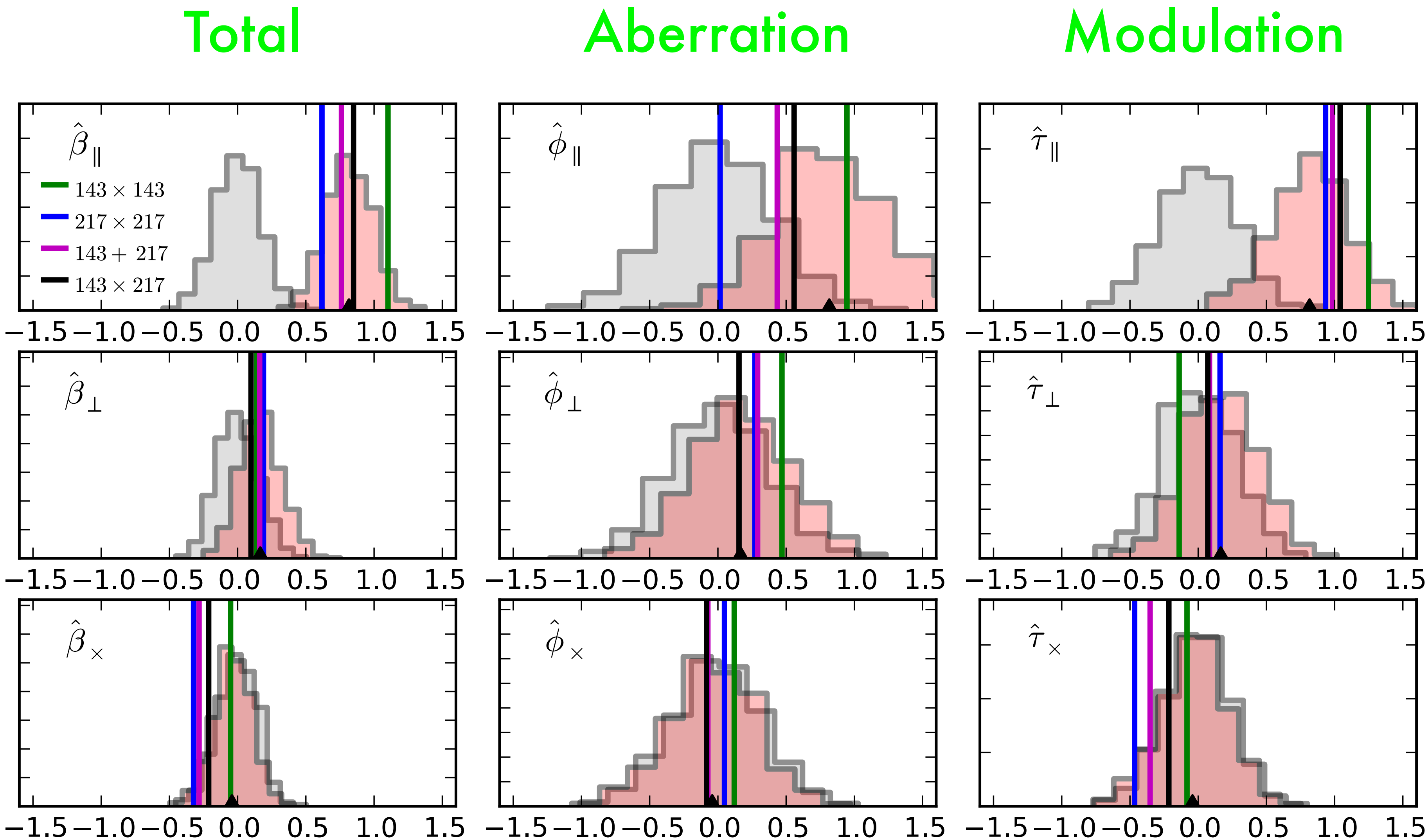
Dipole direction

▼ : 143x143
▲ : 217x217
× : 143x217
+ : 143+217

Hemispheric asymmetry anomaly dominates for lower multipoles (see Planck Collaboration XXIII)

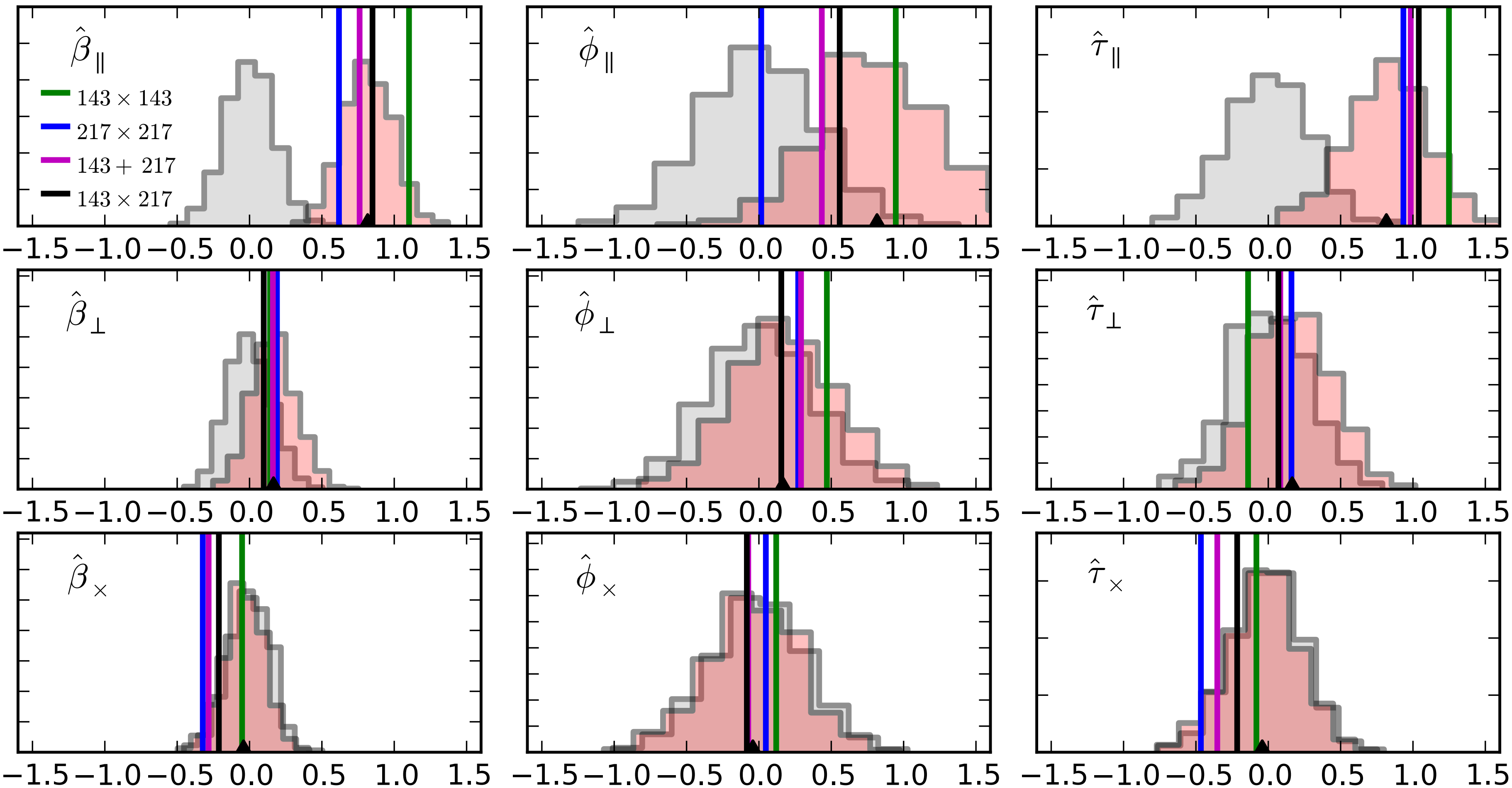


$\hat{\beta}_{\parallel}$
143×143
217×217
$143 + 217$
143×217
$\hat{\phi}_{\parallel}$
$\hat{\tau}_{\parallel}$
$\hat{\beta}_{\perp}$
$\hat{\phi}_{\perp}$
$\hat{\tau}_{\perp}$
$\hat{\beta}_{\times}$
$\hat{\phi}_{\times}$
$\hat{\tau}_{\times}$
−1.5 −1.0 −0.5 0.0 0.5 1.0 1.5



Total
Aberration
Modulation
$\hat{\beta}_{\parallel}$
143×143
217×217
$143 + 217$
143×217
$\hat{\phi}_{\parallel}$
$\hat{\tau}_{\parallel}$
$\hat{\beta}_{\perp}$
$\hat{\phi}_{\perp}$
$\hat{\tau}_{\perp}$
$\hat{\beta}_{\times}$
$\hat{\phi}_{\times}$
$\hat{\tau}_{\times}$
−1.5 −1.0 −0.5 0.0 0.5 1.0 1.5

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*!

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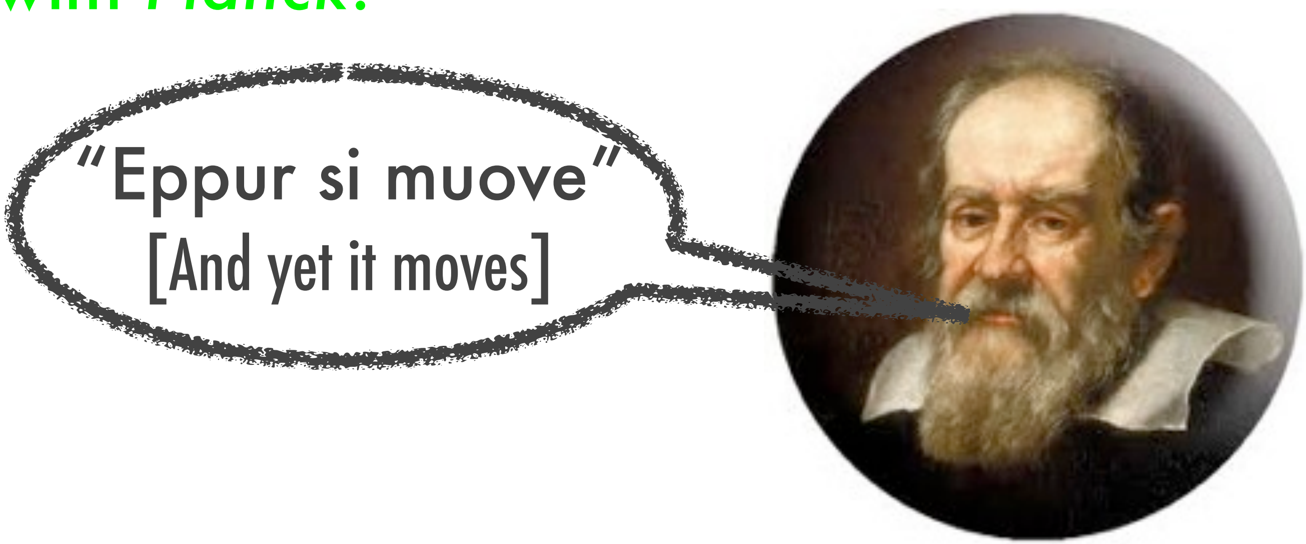
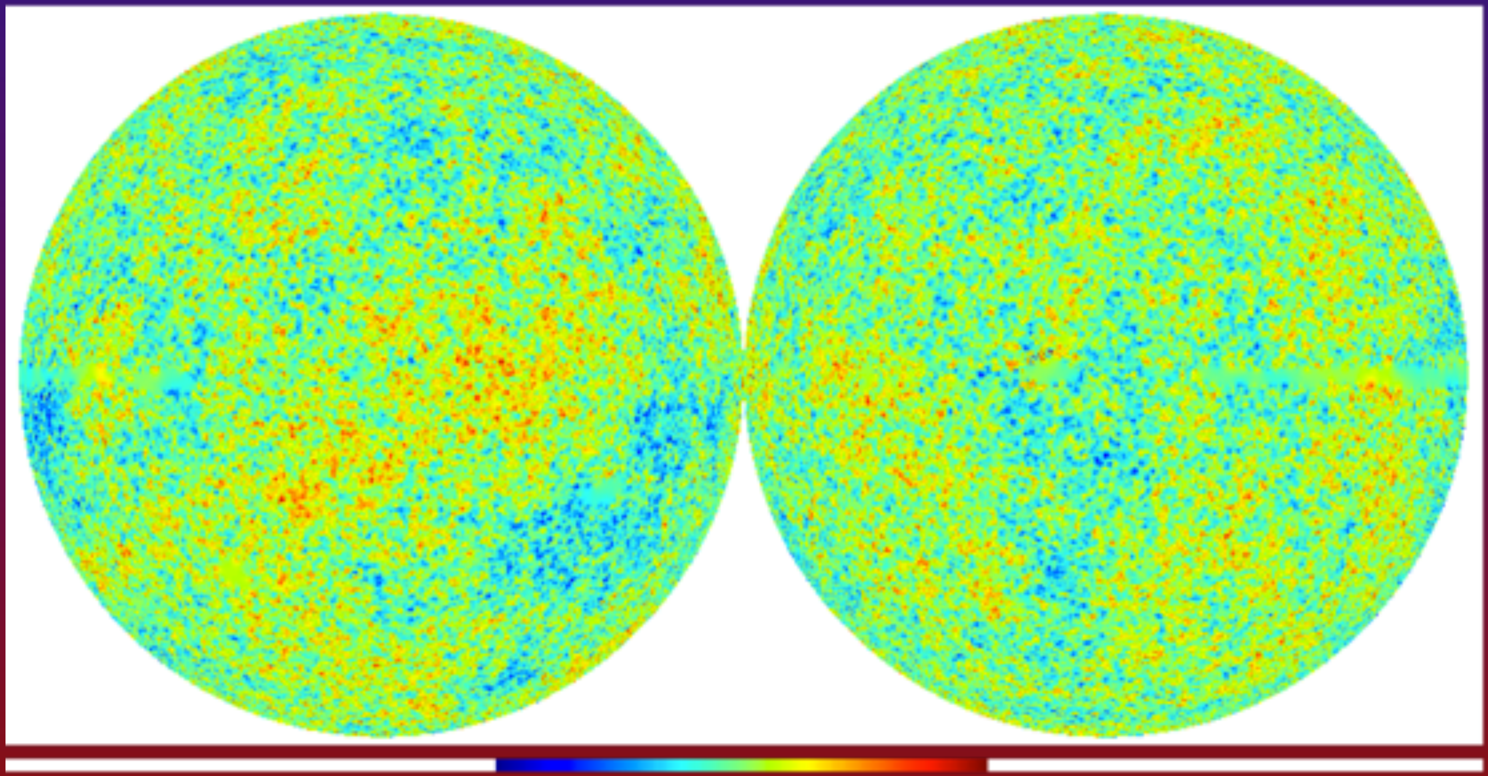
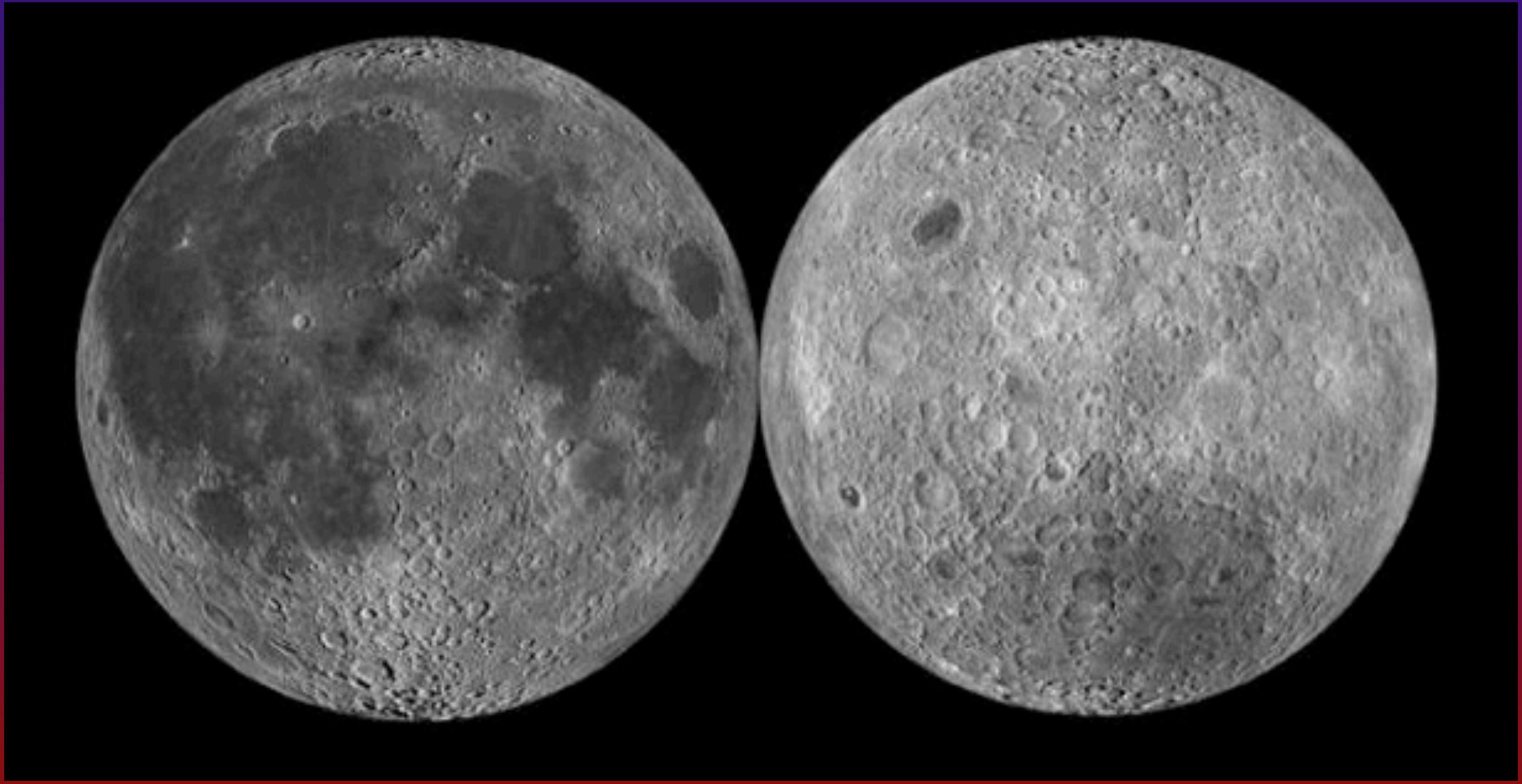


Sky appears dipole-modulated at <u>large</u> angular scales (see Planck 2015 I&S paper)

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 ≃6%, but only out to $\ell_{max} \simeq 64$

How do we assess whether this is statistically unlikely?

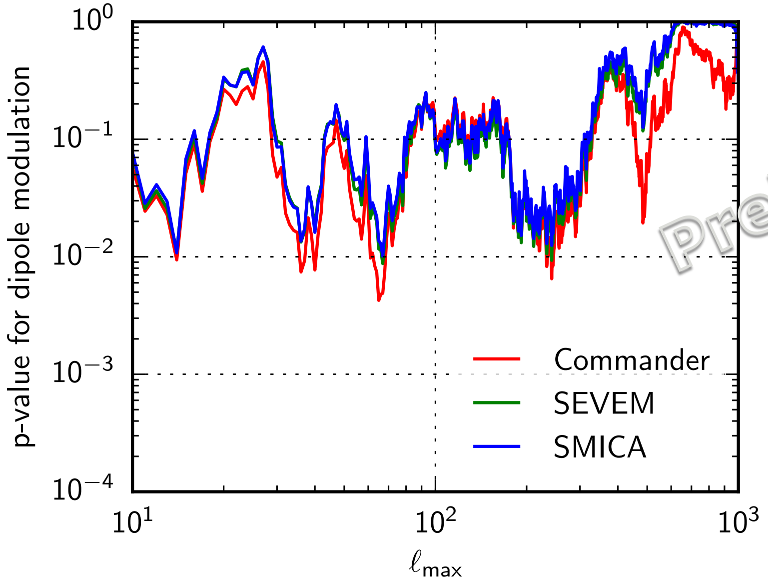
“Cosmic variance” expectation for dipole modulation to ℓ_{max} :

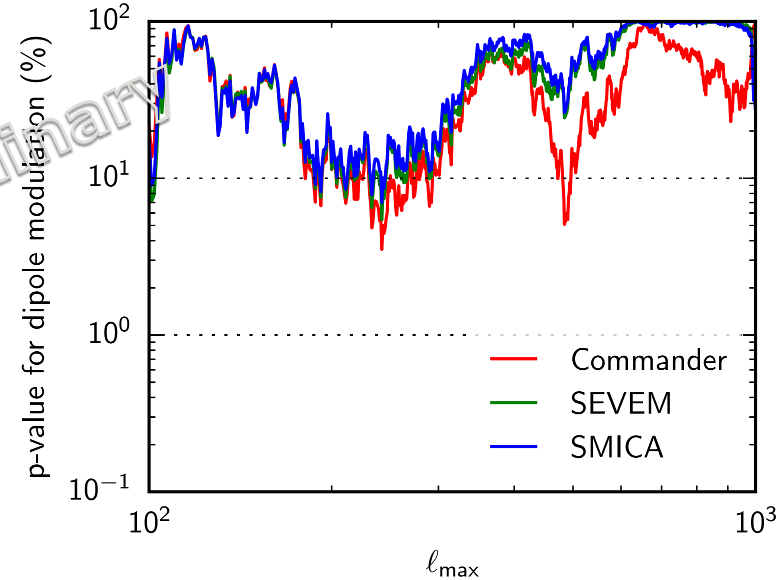
$$\left\langle \frac{\Delta A_{\mathrm{s}}}{A_{\mathrm{s}}} \right\rangle \simeq \sqrt{\frac{48}{\pi(\ell_{\mathrm{max}}+4)(\ell_{\mathrm{max}}-1)}}.$$

Map modulation is half of this, e.g. 2.9% for ℓ_{max}=67

Dipolar power modulation: harmonic analysis

planck





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.

Dipolar power modulation: harmonic analysis

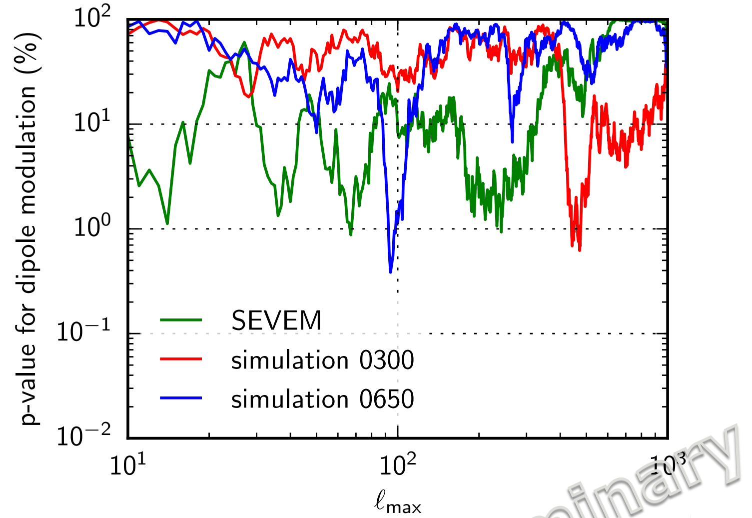
When analyzing (isotropic) simulations we found even more significant modulations, depending on the choice of $\ell_{\max}$.

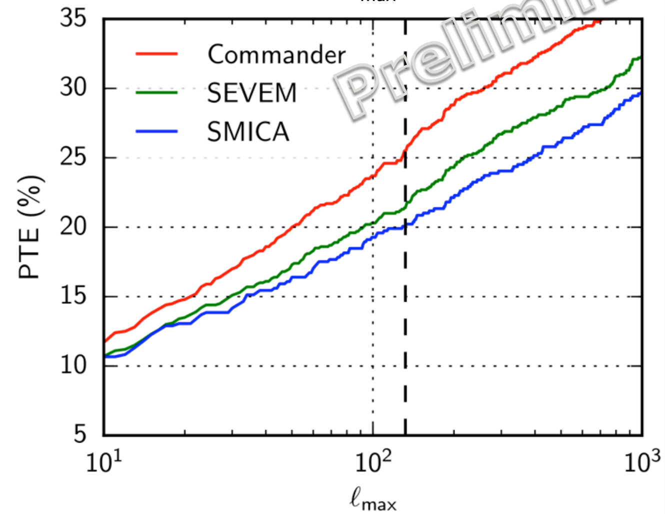
However, there is no *a priori* reason to adopt $\ell_{\max}$~65, and there is only the *a posteriori* observation that $\ell_{\max}$~65 provides the most significant detection.

Hence, we use simulations to derive the probability of finding a modulation as significant as in the *Planck* data as a function of $\ell_{\max}$.

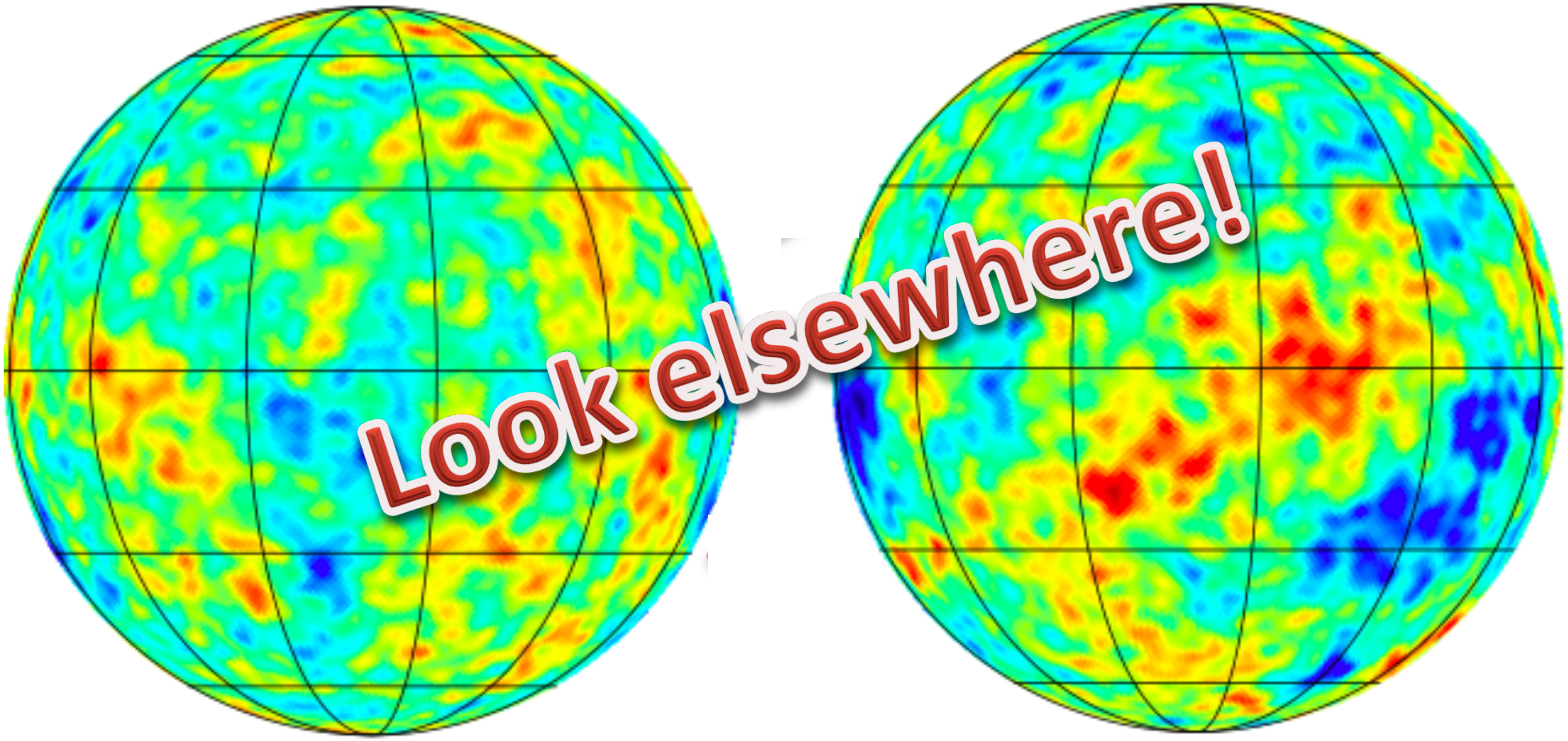
This is known as *multiplicity of tests*, *a posteriori correction*, or *look-elsewhere effect*.

Accounting for this reduces the significance of the modulation to PTE~15-20% at $\ell_{\max}$~65.





Large Angle Anomalies



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Large scales are special, so we should keep looking

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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 ...

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.

Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.