Doppler boosting the CMB

Based on "*Planck* 2013 Results. XXVII. Doppler boosting of the CMB"

Douglas Scott
on behalf of the Planck Collaboration

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"Eppur si mouve"
[And yet it moves]

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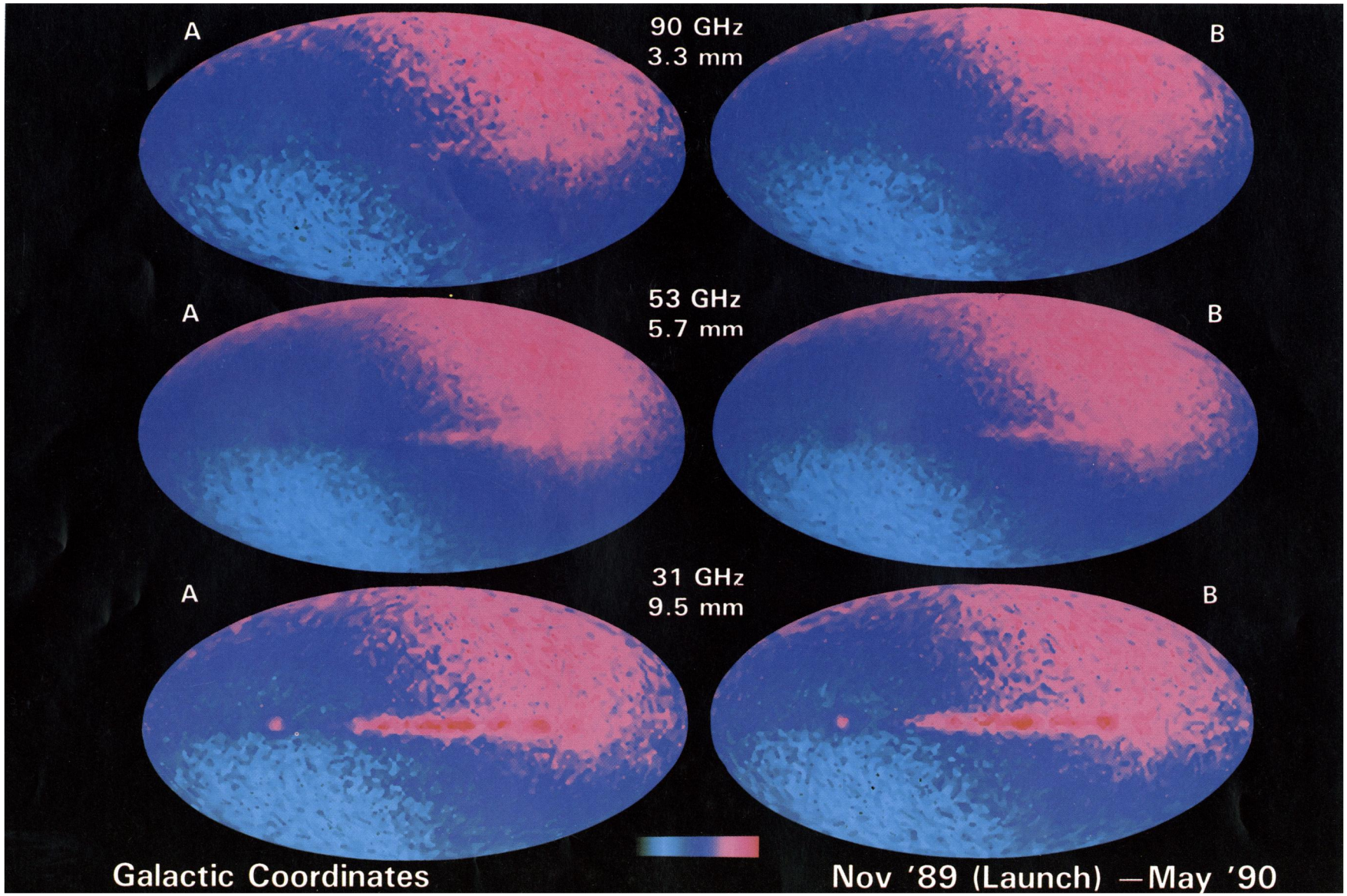
HAPPY
EASTER


HAPPY
EASTER

CMB dipole is well known



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

Monopole and dipole from *COBE* FIRAS and DMR (*Planck*'s dipole will come later)

- Monopole: $T_0=(2.7255\pm0.0006)K$

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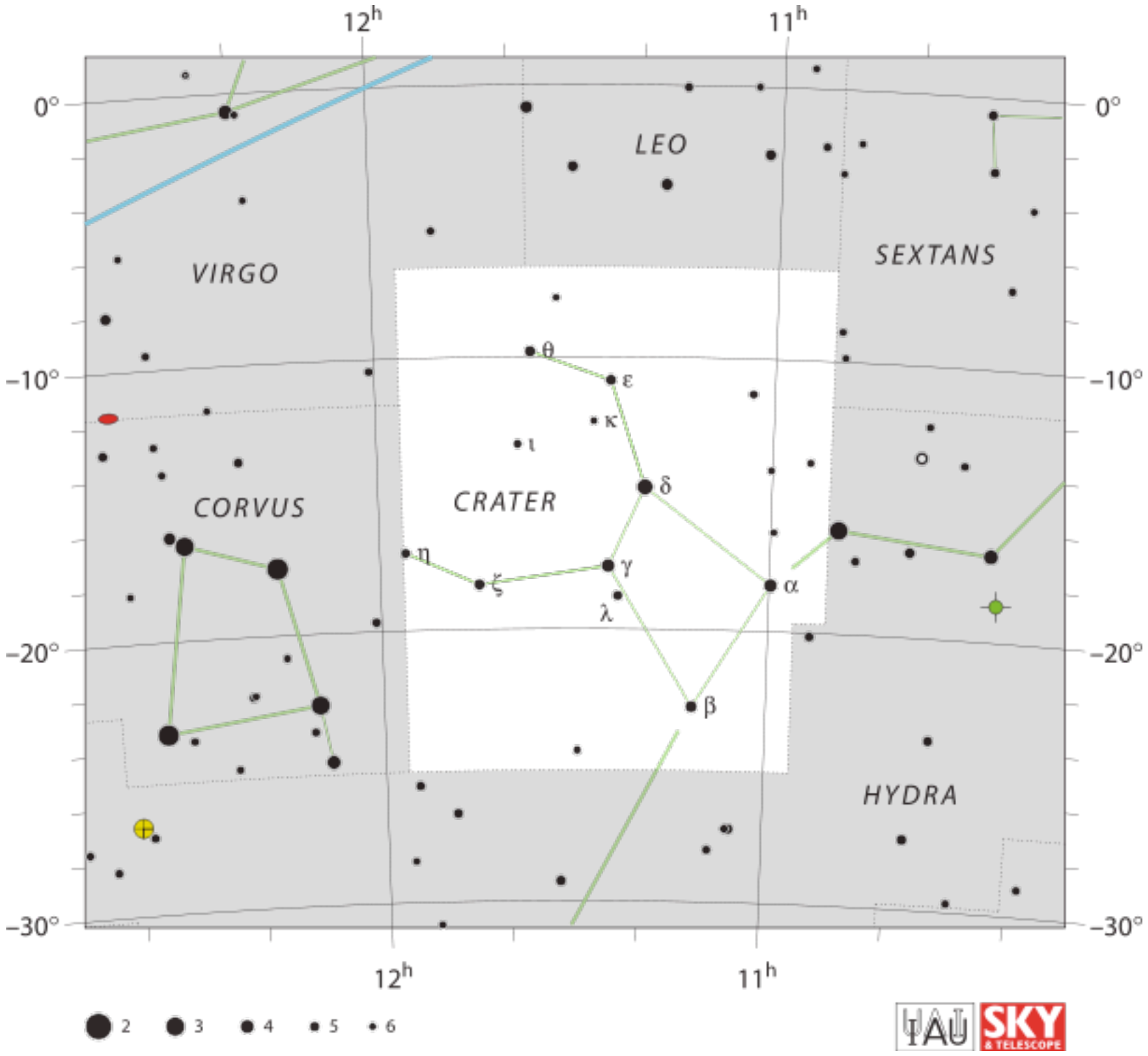
- β=0.00123 towards the constellation Crater
- And there are other effects…

Monopole and dipole from *COBE* FIRAS and DMR (*Planck*'s dipole will come later)


12h
11h
0°
−10°
−20°
−30°
LEO
VIRGO
SEXTANS
CORVUS
CRATER
HYDRA
θ
ε
κ
ι
δ
η
ζ
γ
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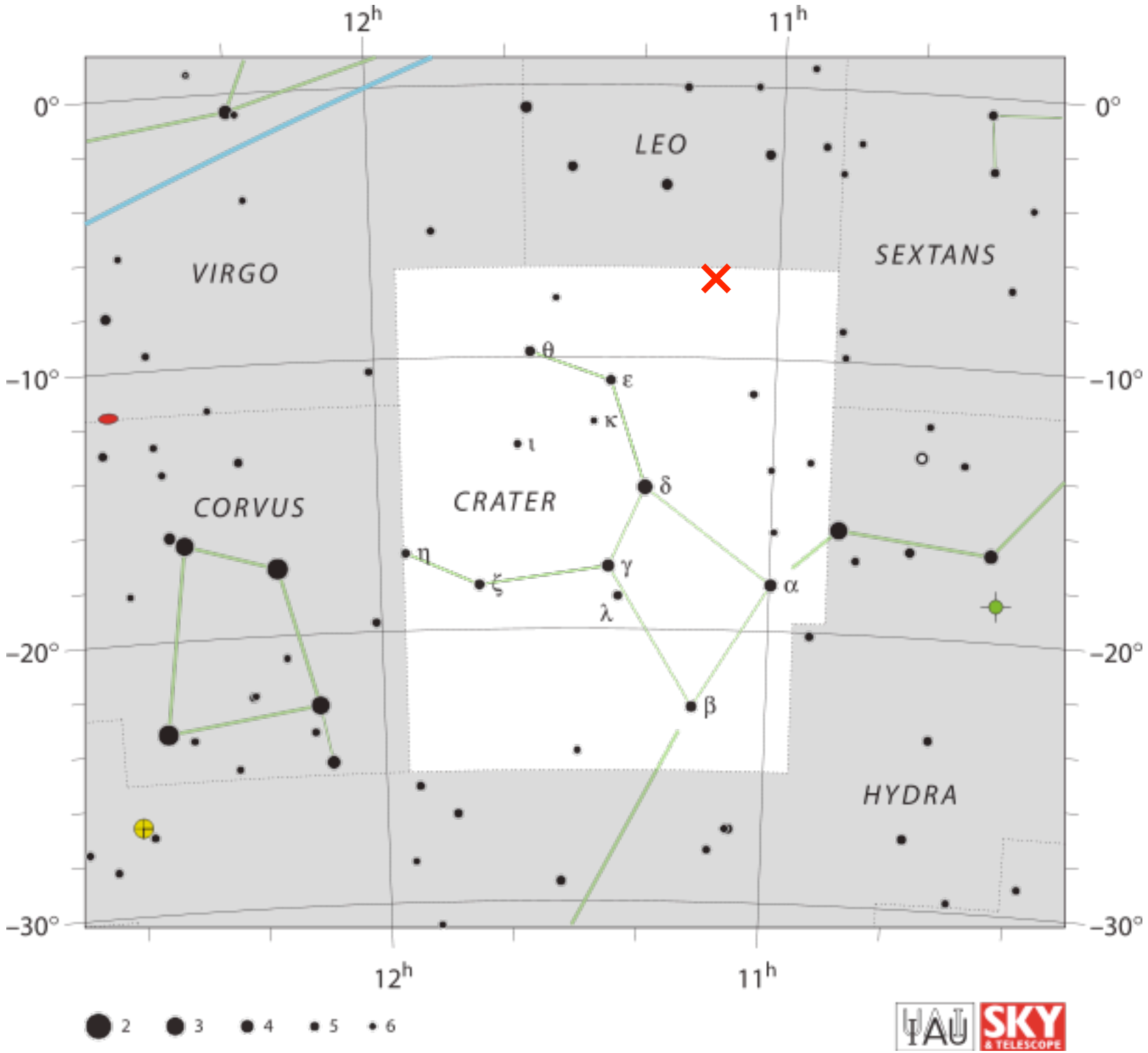
α
β
ο
2
3
4
5
6
IAU
SKY
& TELESCOPE


12h
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LEO
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5 boosting effects

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

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5 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
• Generation of $O(\beta^2)$ quadrupole	Too hard!

Peebles & Wilkinson (1968); Challinor & van Leeuwen (2002);
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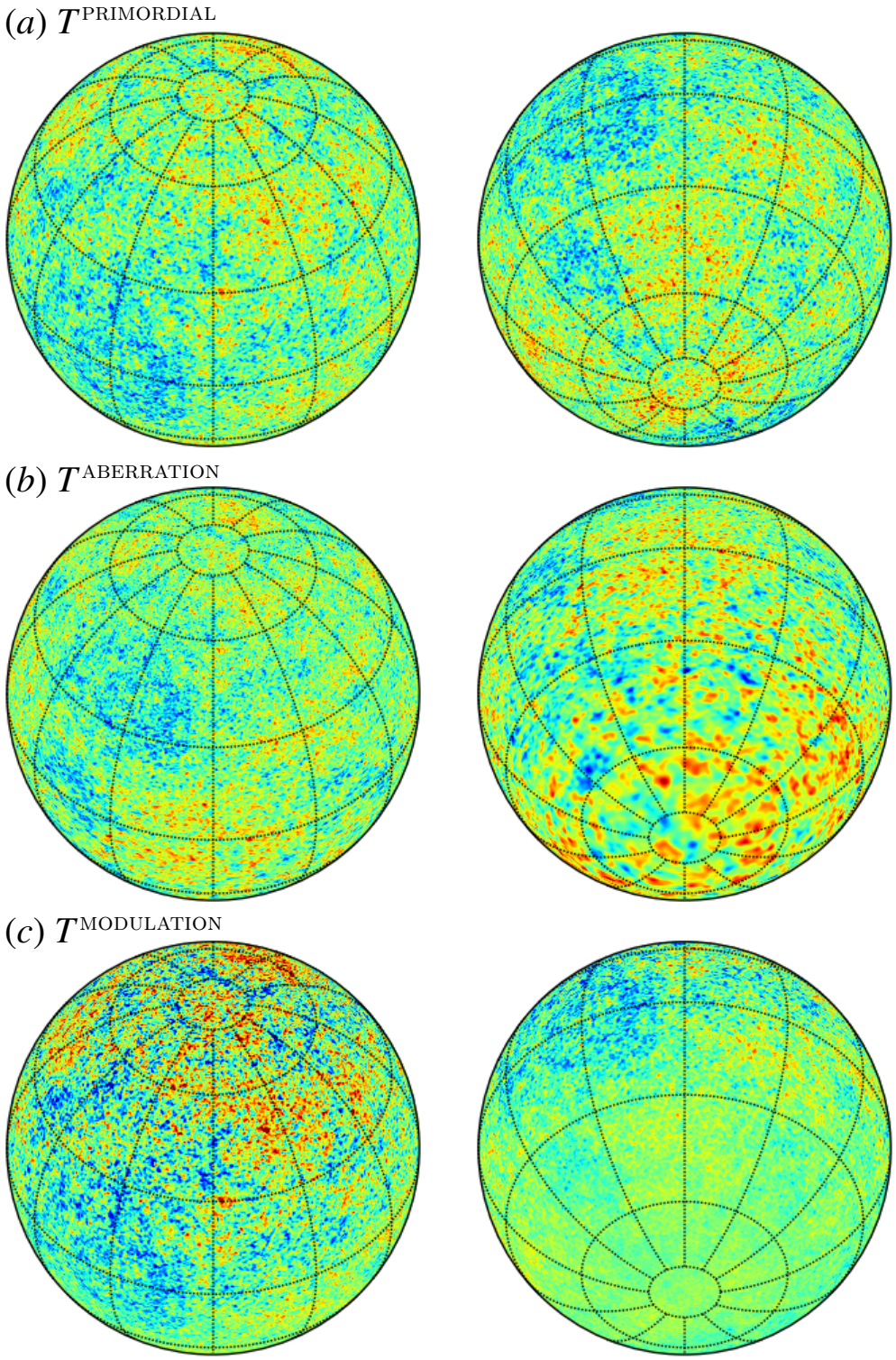
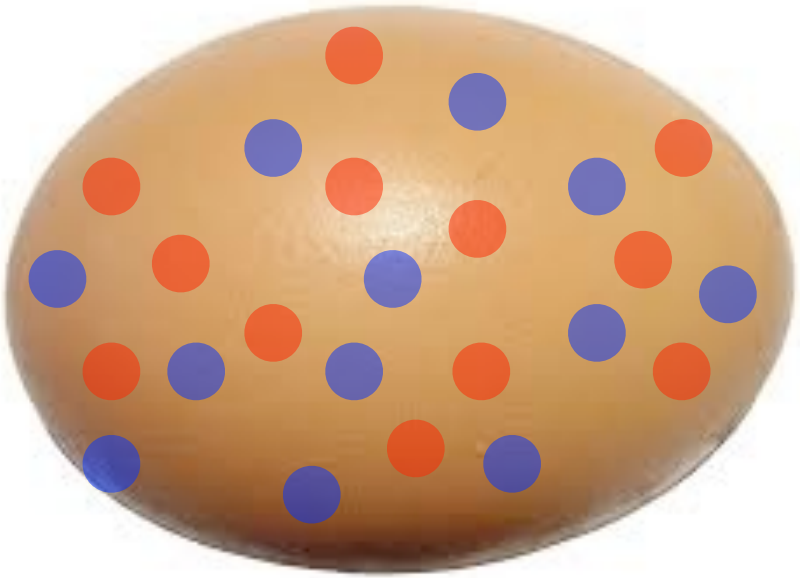
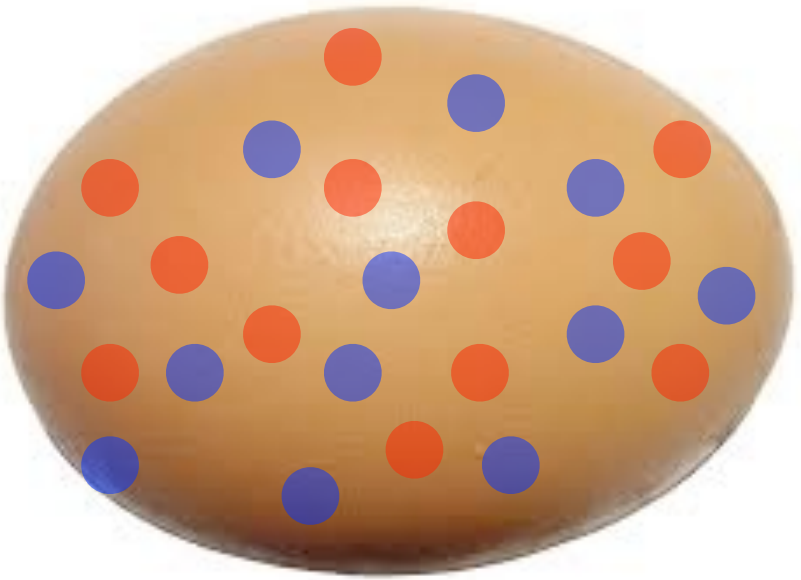


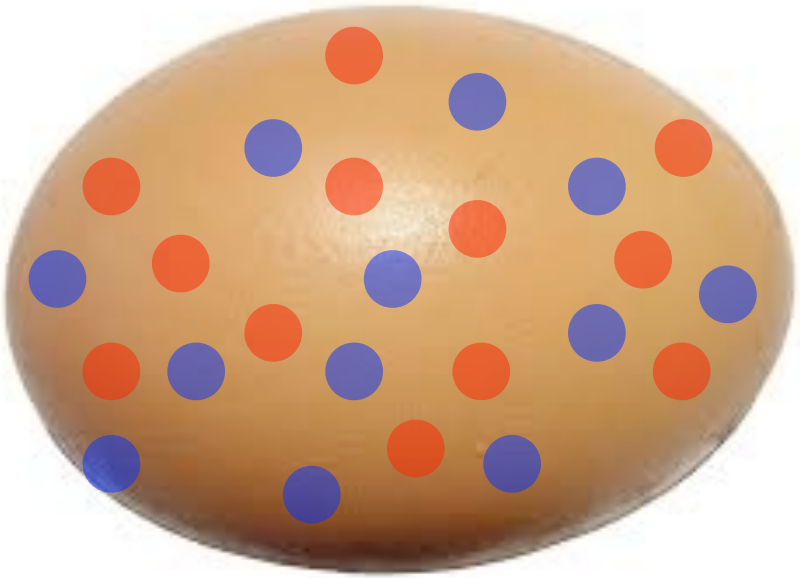
Simulated CMB

Aberration
for β=0.85

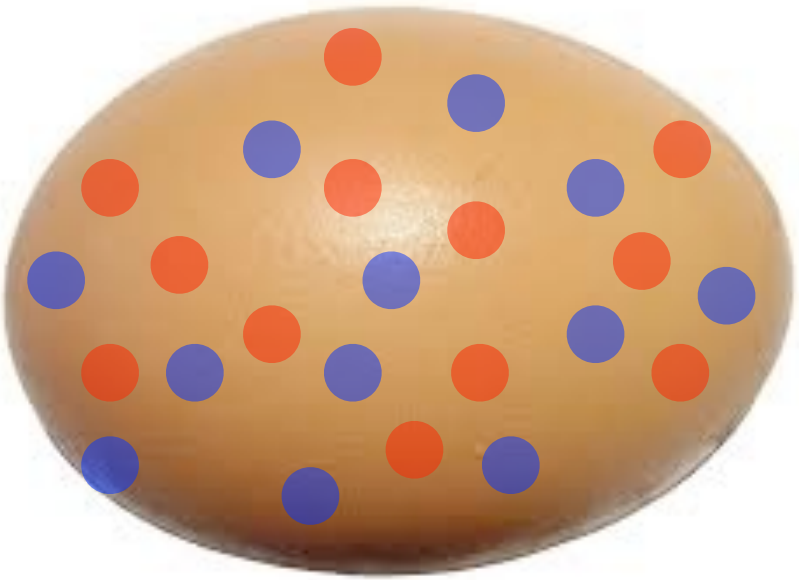
Modulation
for β=0.85

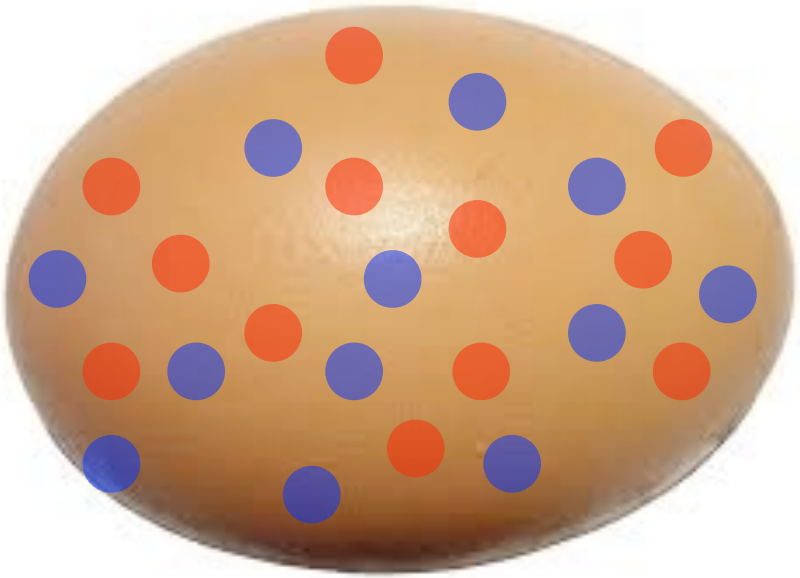






Aberration





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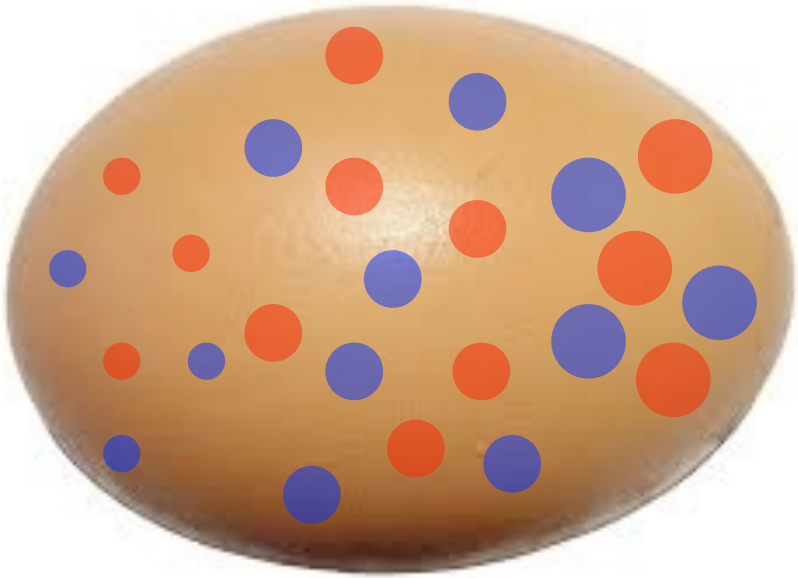

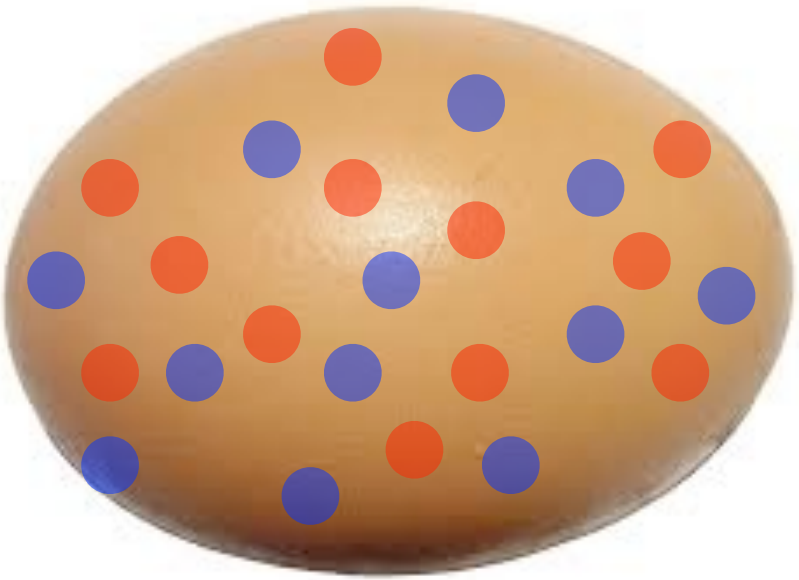

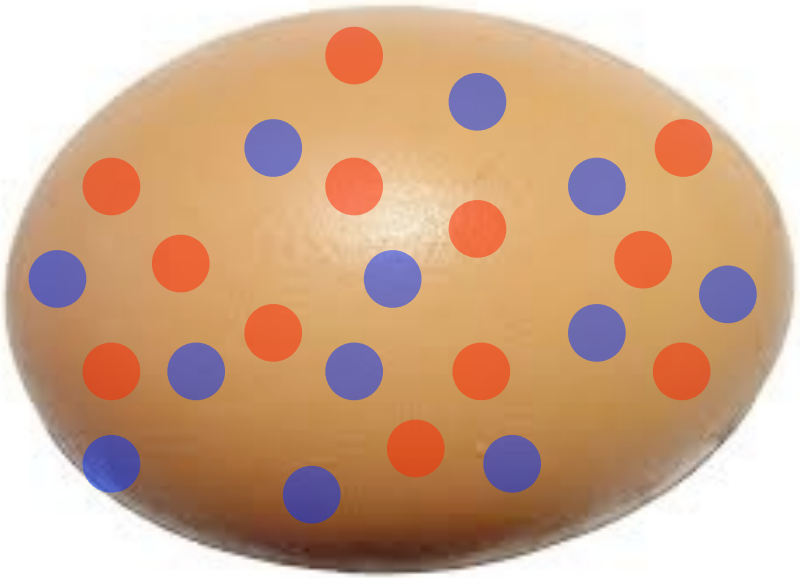

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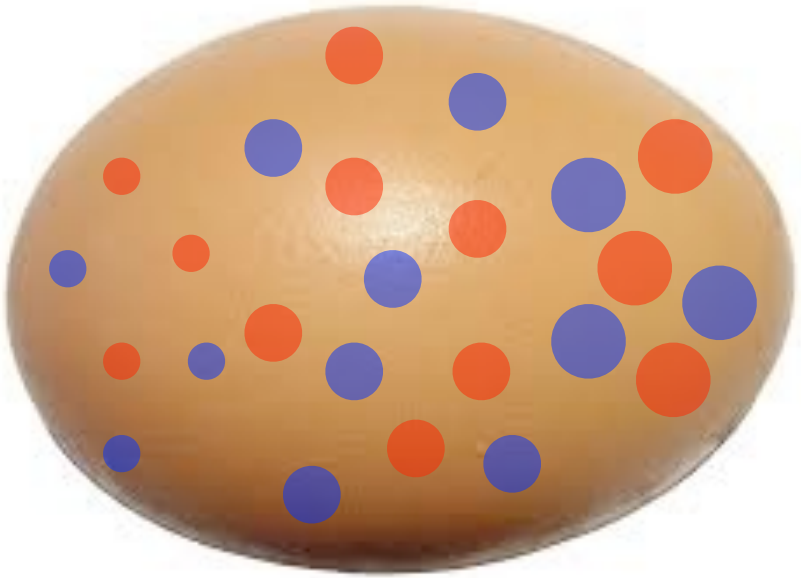
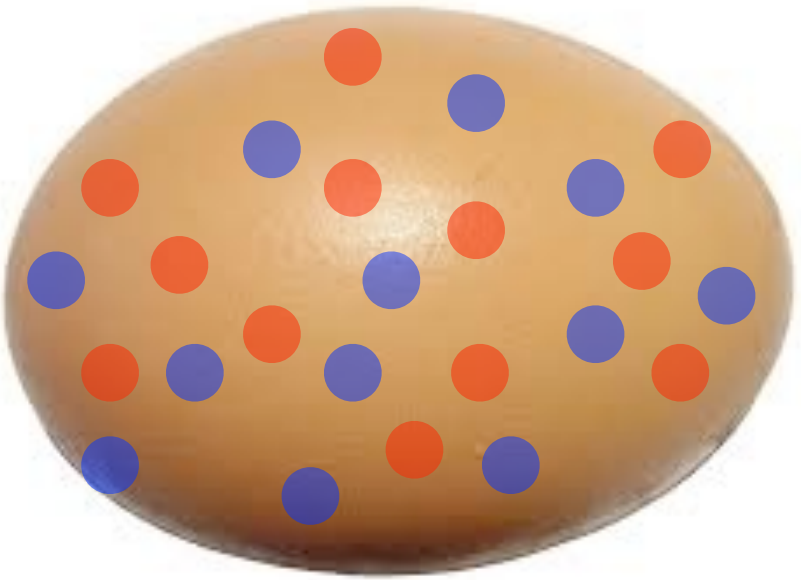
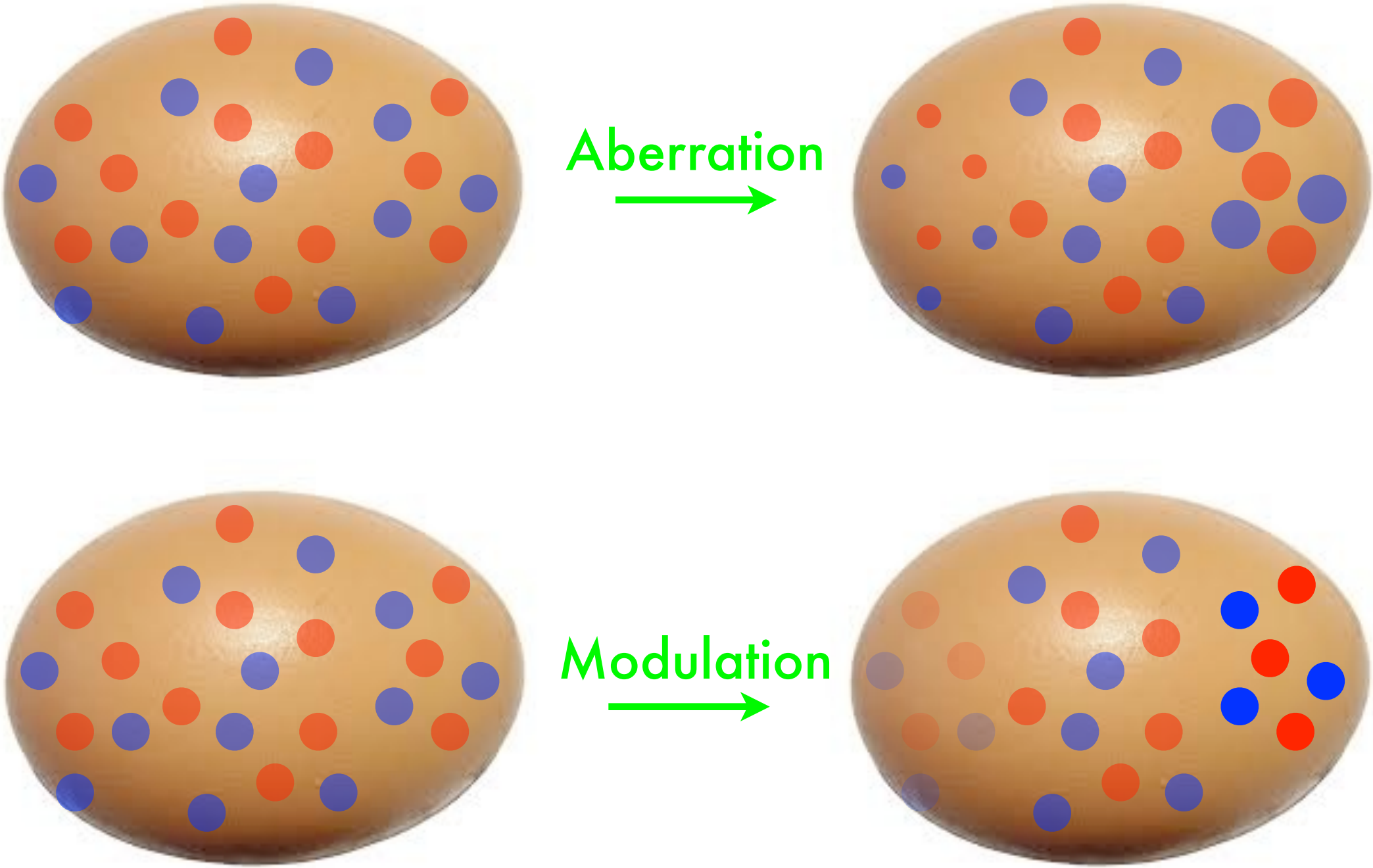




Modulation


Aberration
Modulation

Boosting frames

Boosting frames

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

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observed frame

CMB frame

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v/c

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

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To 1st order in β:

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

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So finally:

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

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This could be done either in map space or harmonic space

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

Boosting frames

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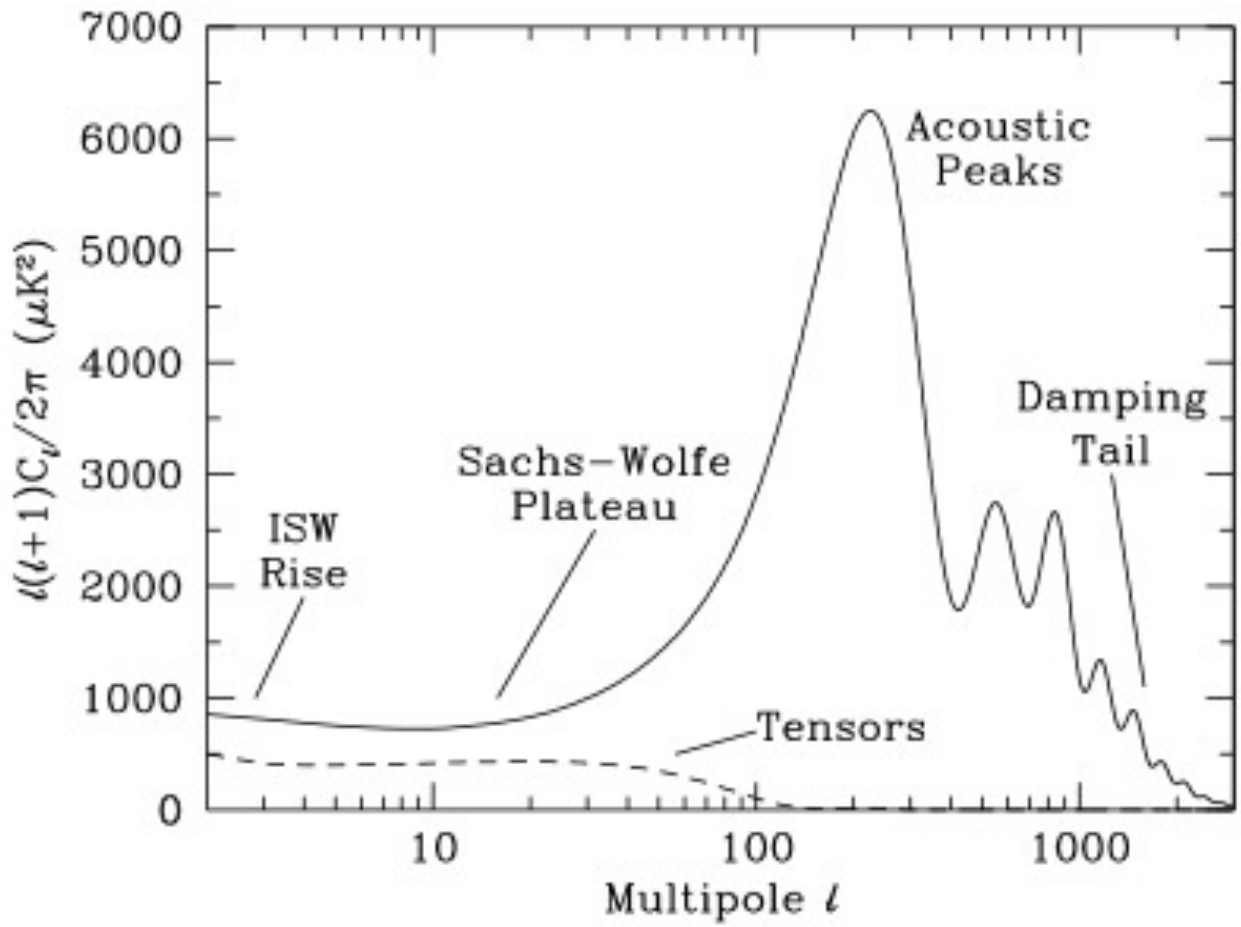

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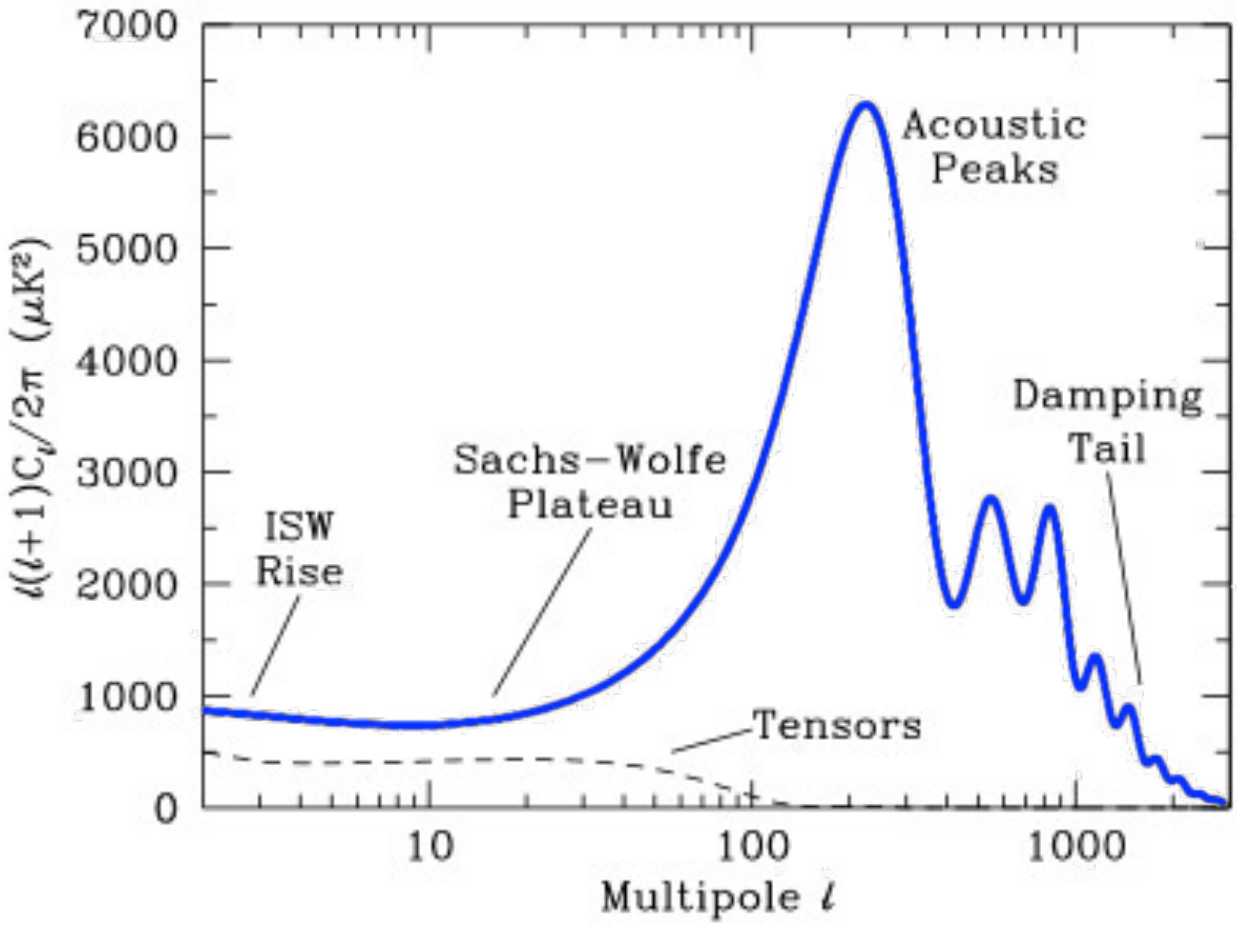

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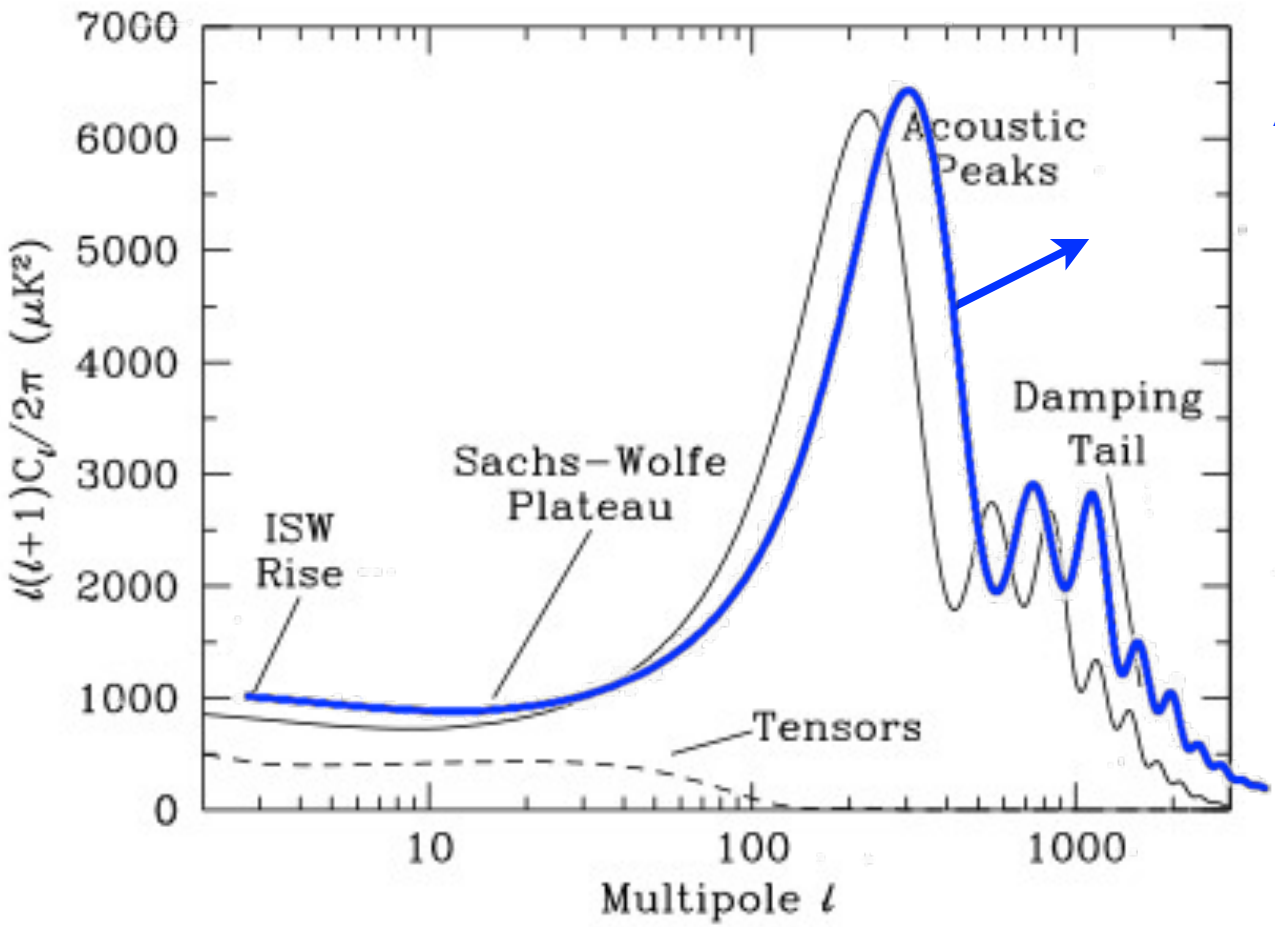
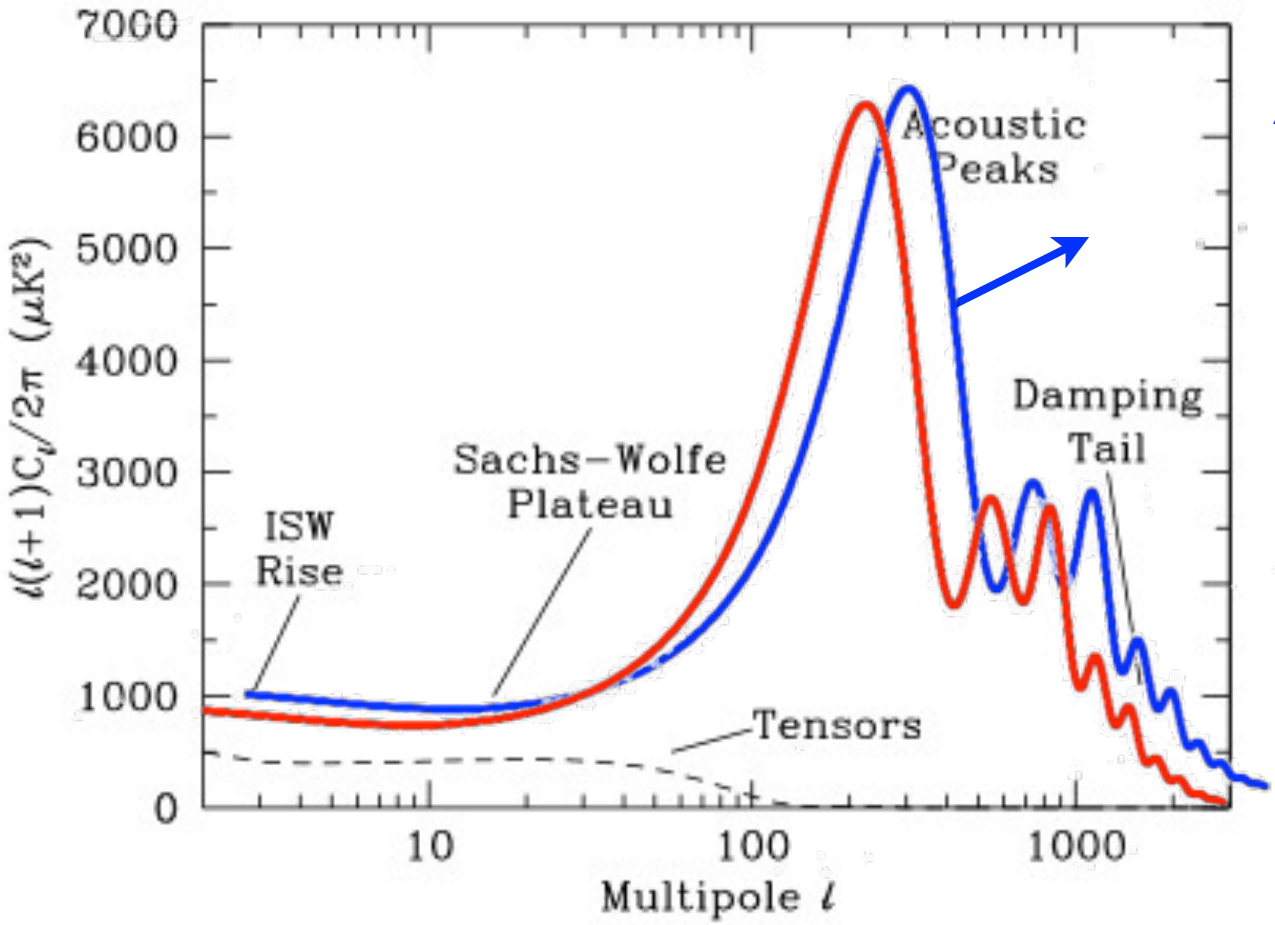


Angles squashed and anisotropies boosted in +ve direction

Boosting frames



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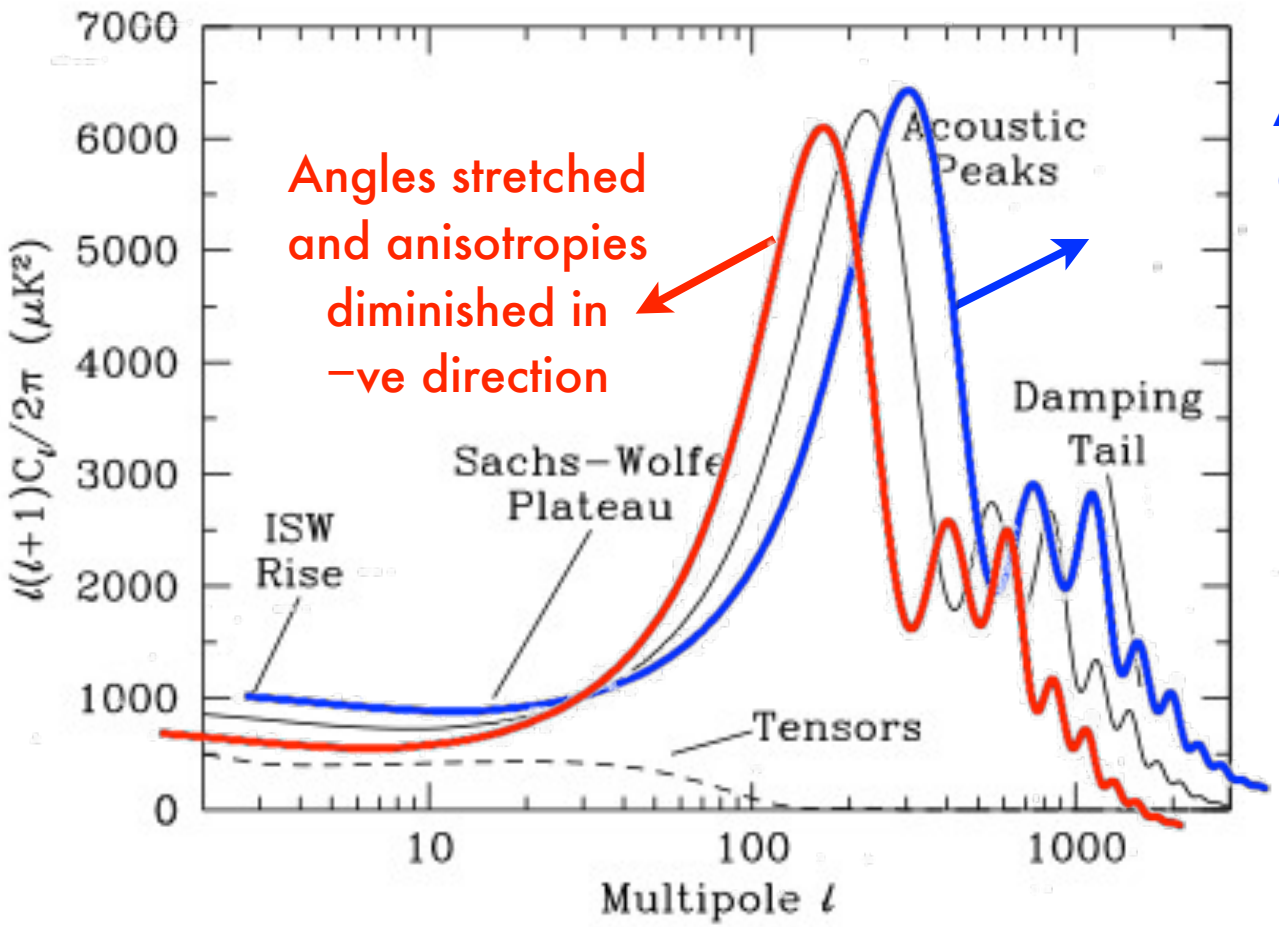

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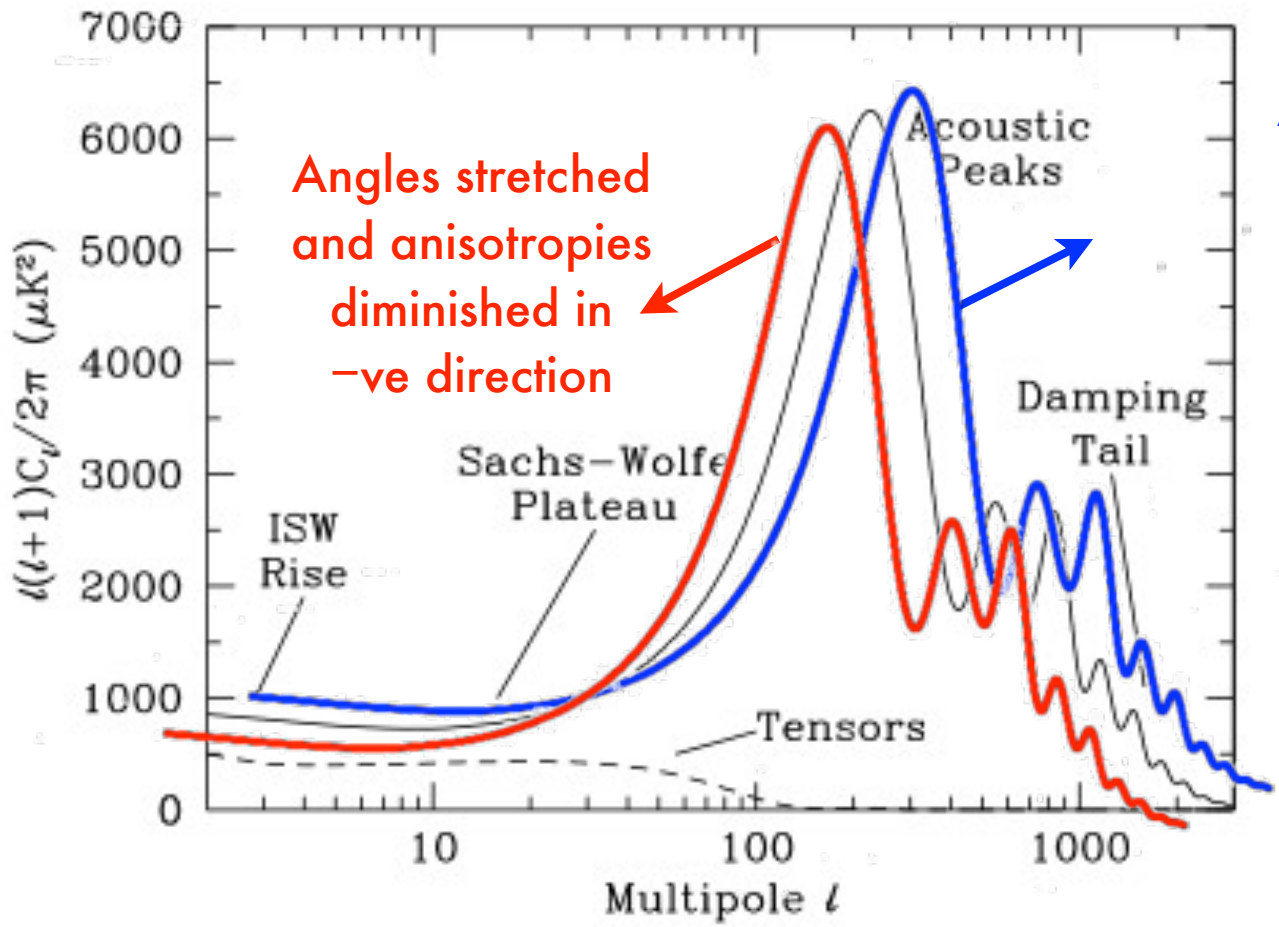

Or can consider this as an effect which couples harmonics

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

Figure by Joel Hutchinson

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

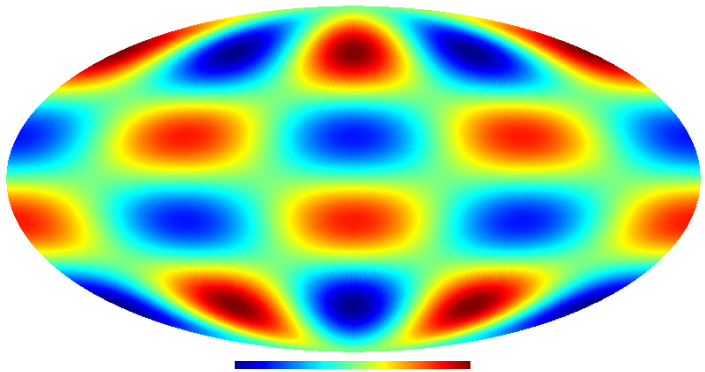

Figure by Joel Hutchinson

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

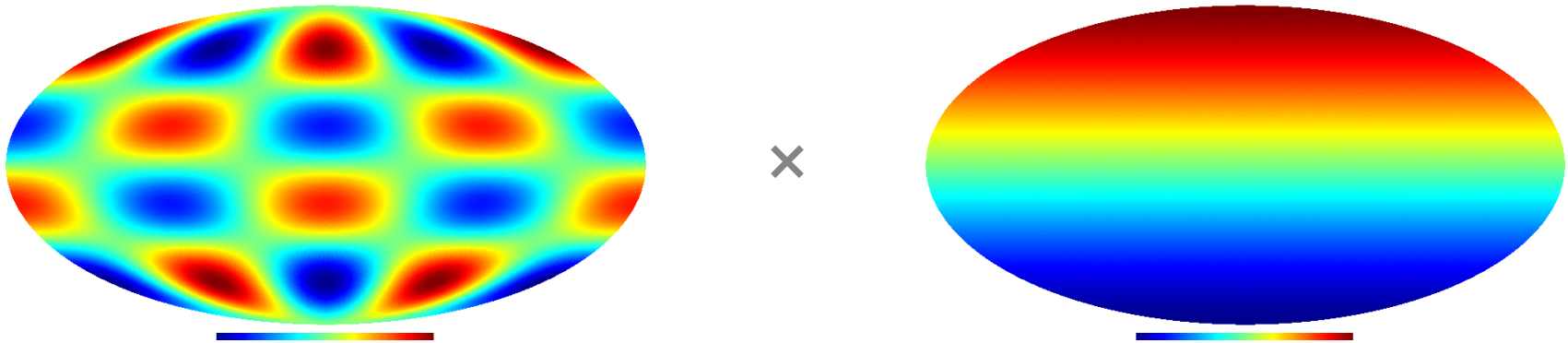

Figure by Joel Hutchinson

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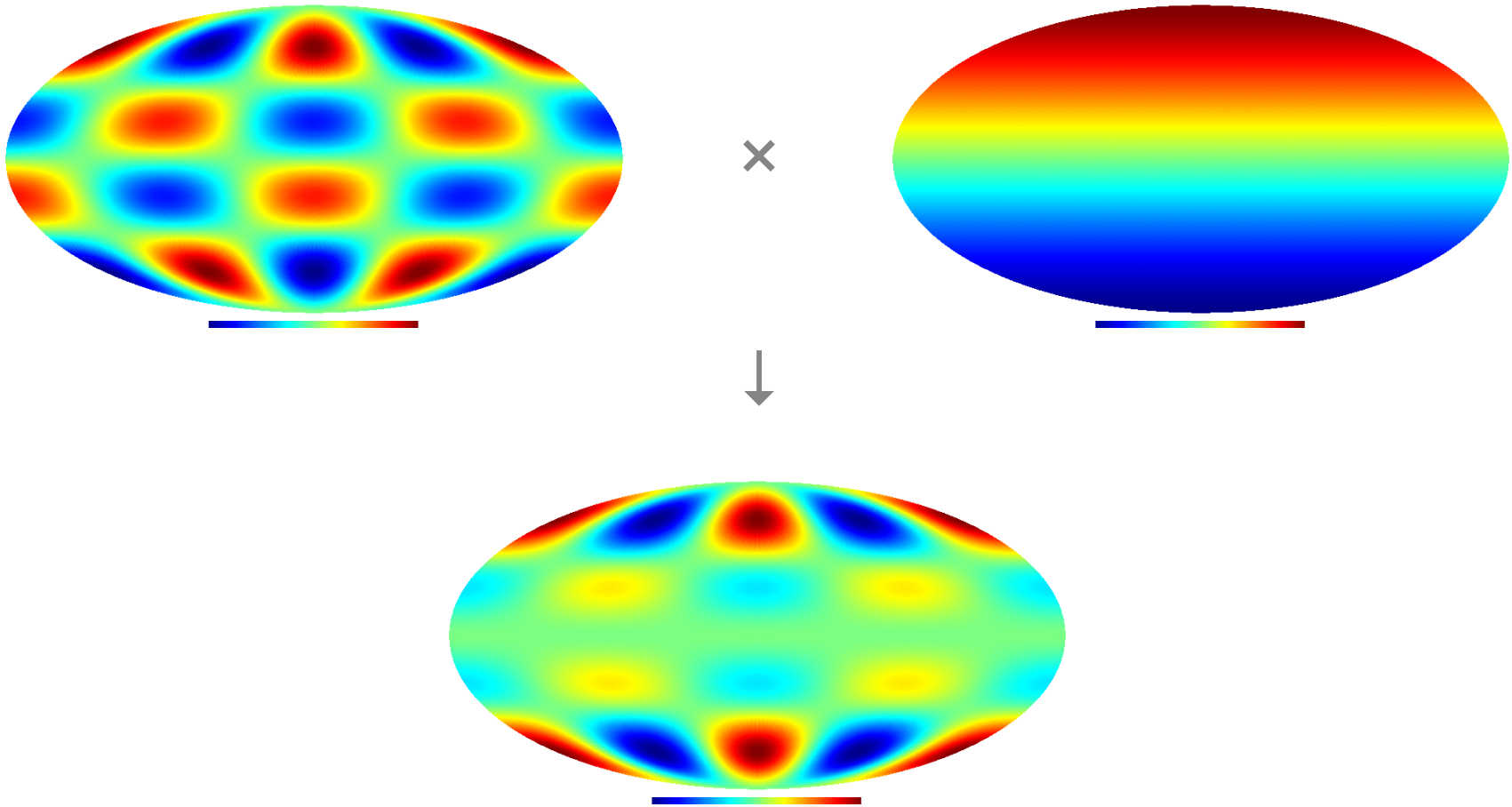

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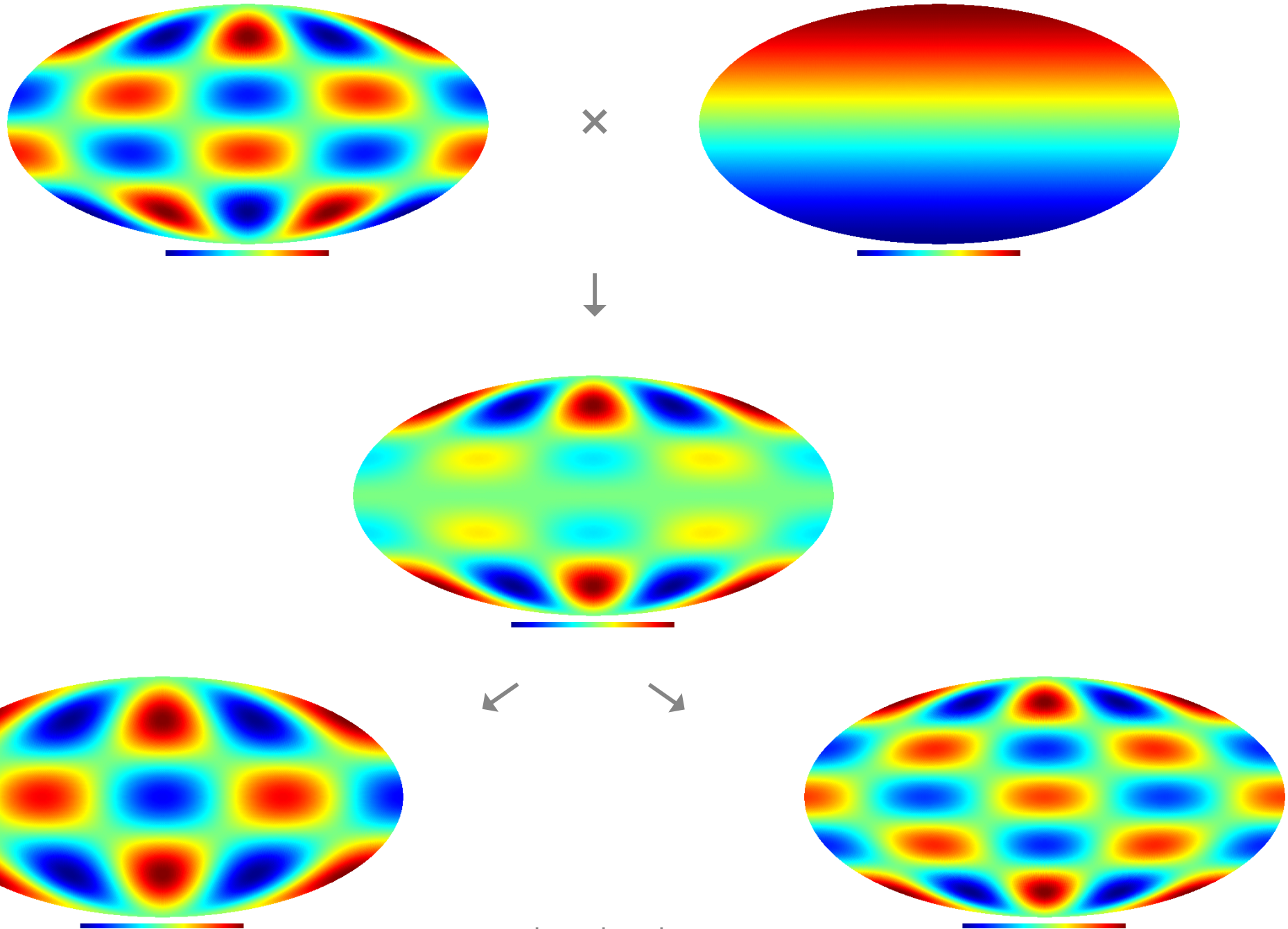

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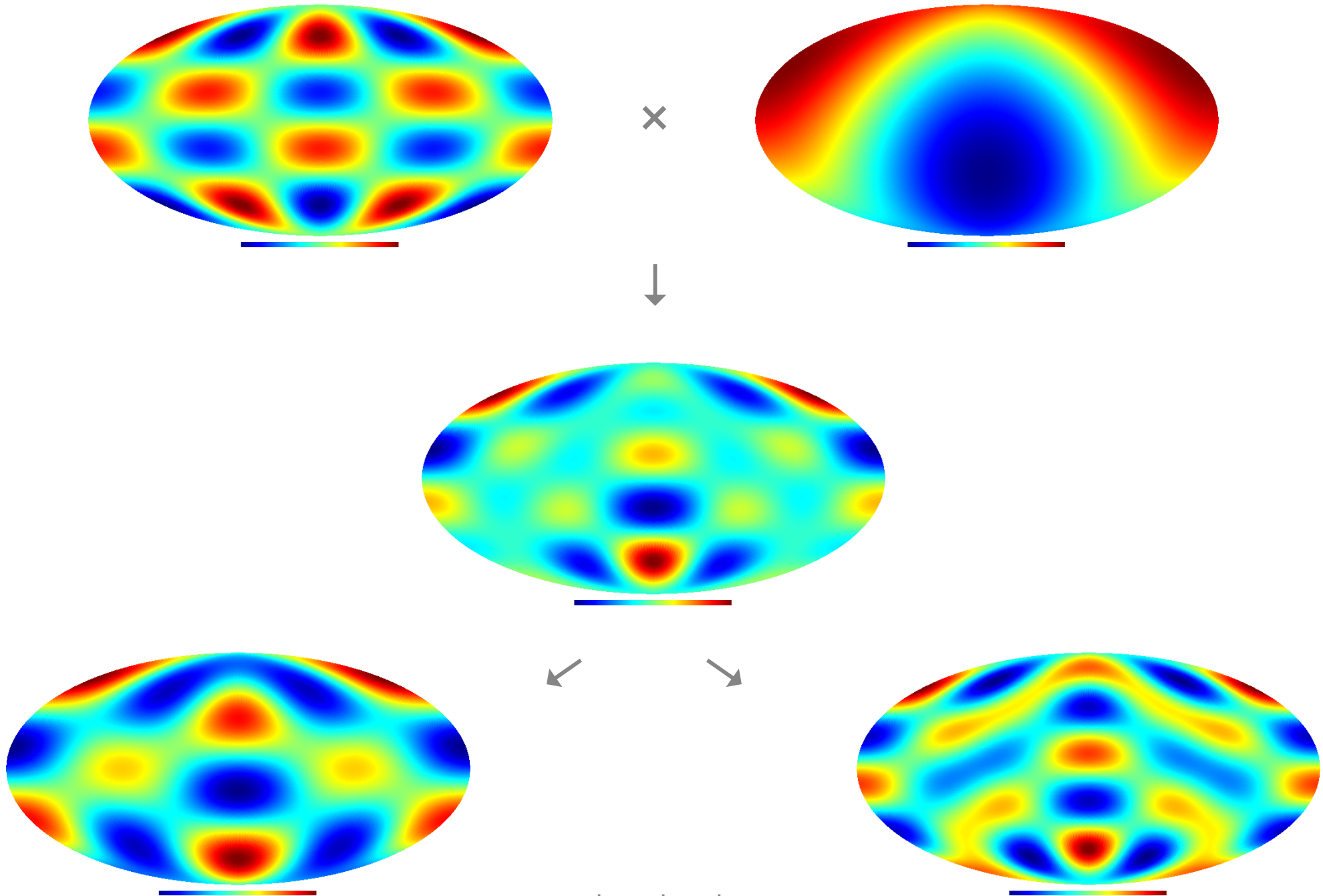

Figure by Joel Hutchinson

Calculations

See Hanson & Lewis (2009) and Planck Collaboration XXVII (2013)

Calculations

- We use quadratic estimators

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- We use quadratic estimators
- Summing over covariance matrix

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Calculations

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- And repeat for simulations (with and without velocity effects)

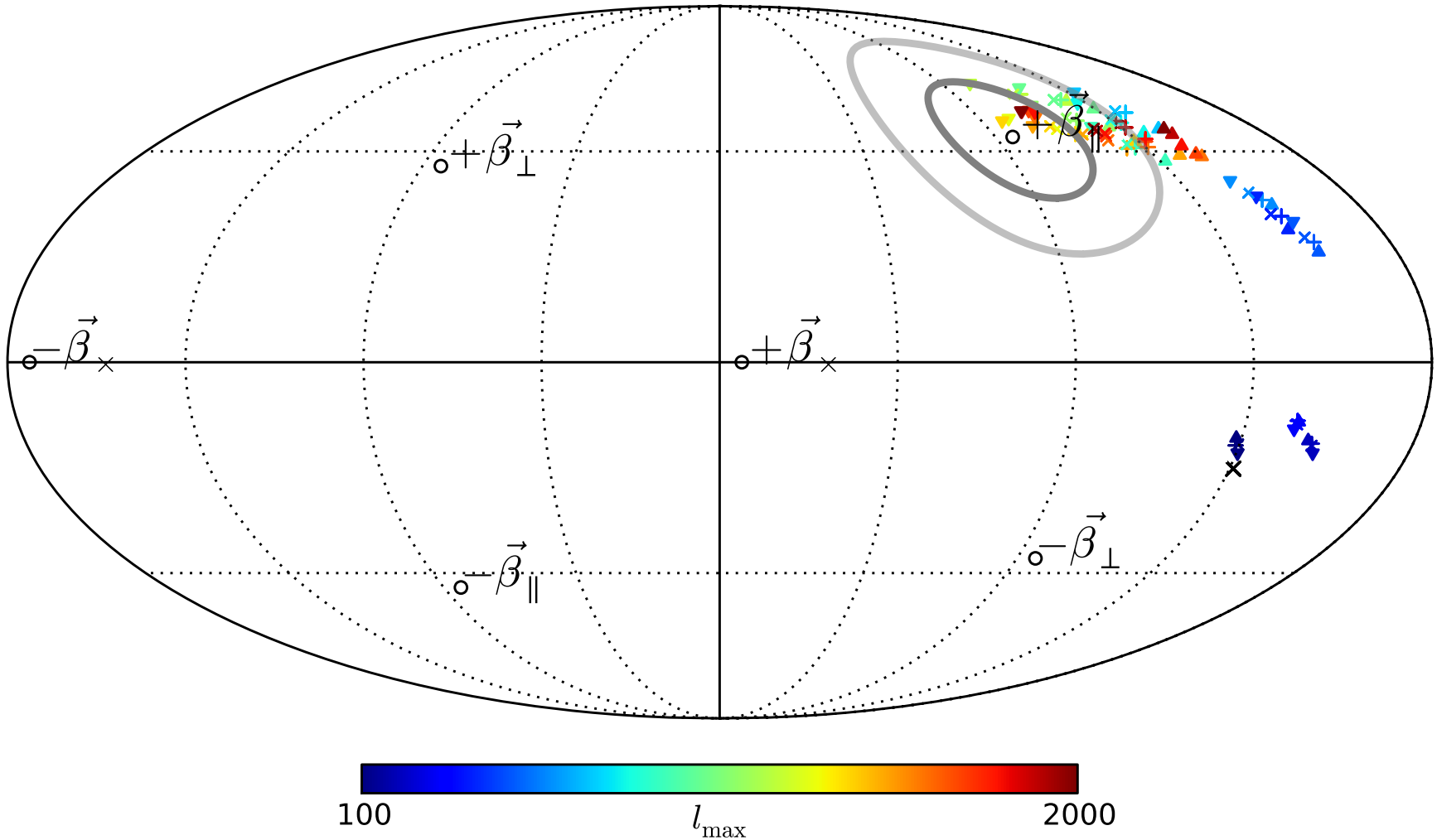
See Hanson & Lewis (2009) and Planck Collaboration XXVII (2013)

Calculations

- We use quadratic estimators
- Summing over covariance matrix
- With weights designed for β
- And repeat for simulations (with and without velocity effects)
- For several data combinations from 143GHz and 217GHz (857 subtracted)

See Hanson & Lewis (2009) and Planck Collaboration XXVII (2013)

Results



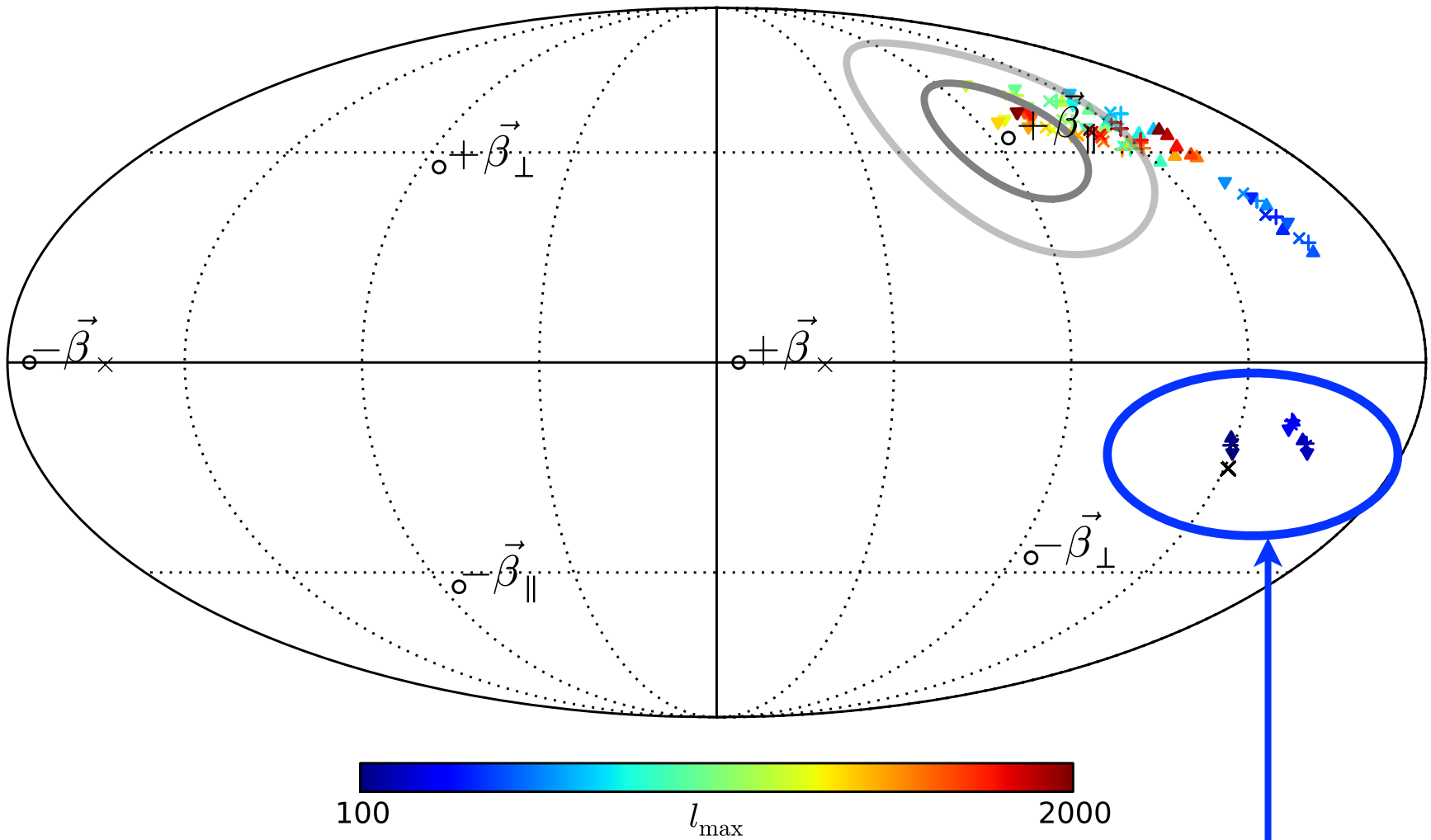
▼ : 143x143

▲ : 217x217

× : 143x217

\+ : 143+217

Results



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

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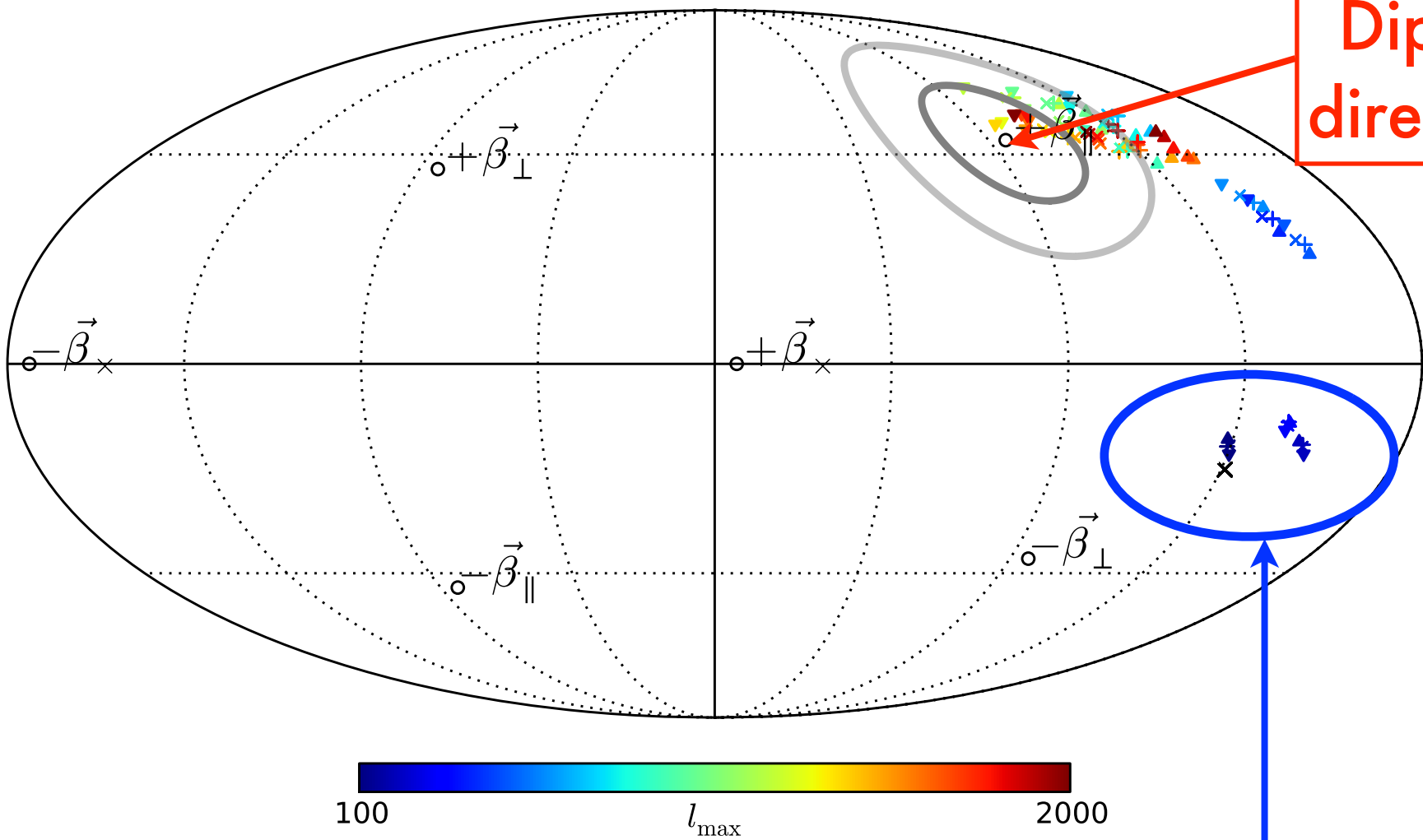

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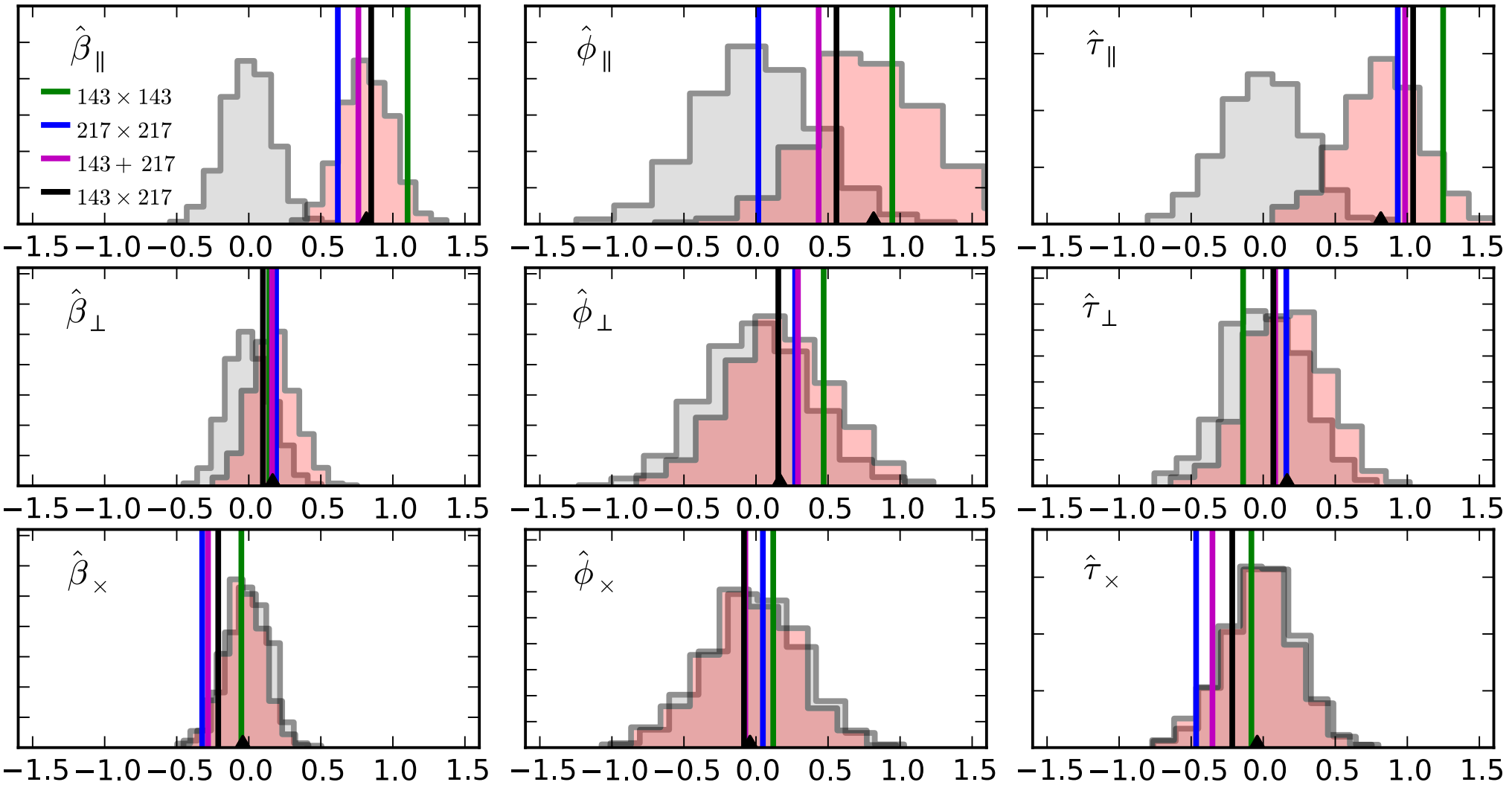
$\hat{\beta}_{\parallel}$
$\hat{\phi}_{\parallel}$
$\hat{\tau}_{\parallel}$
$\hat{\beta}_{\perp}$
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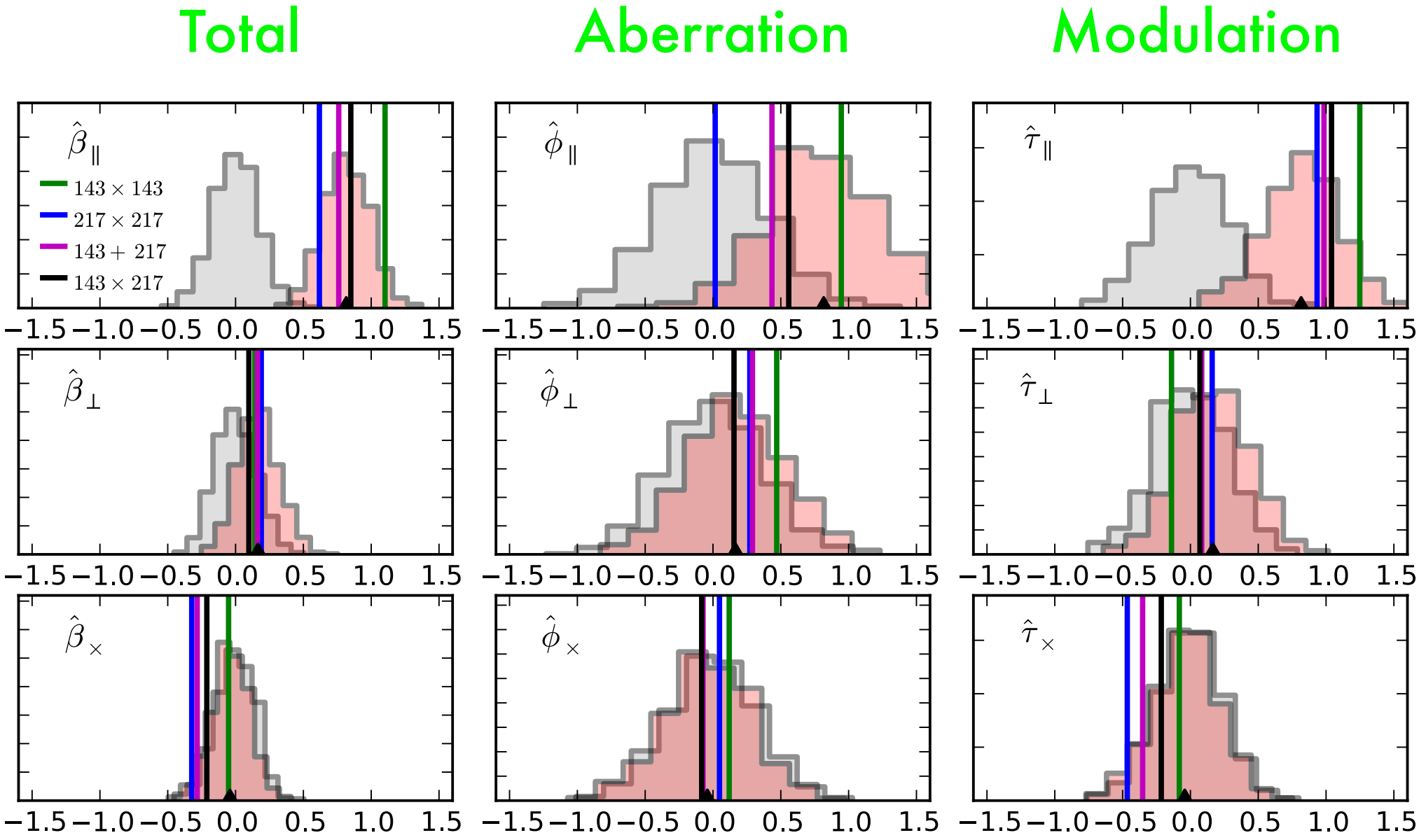
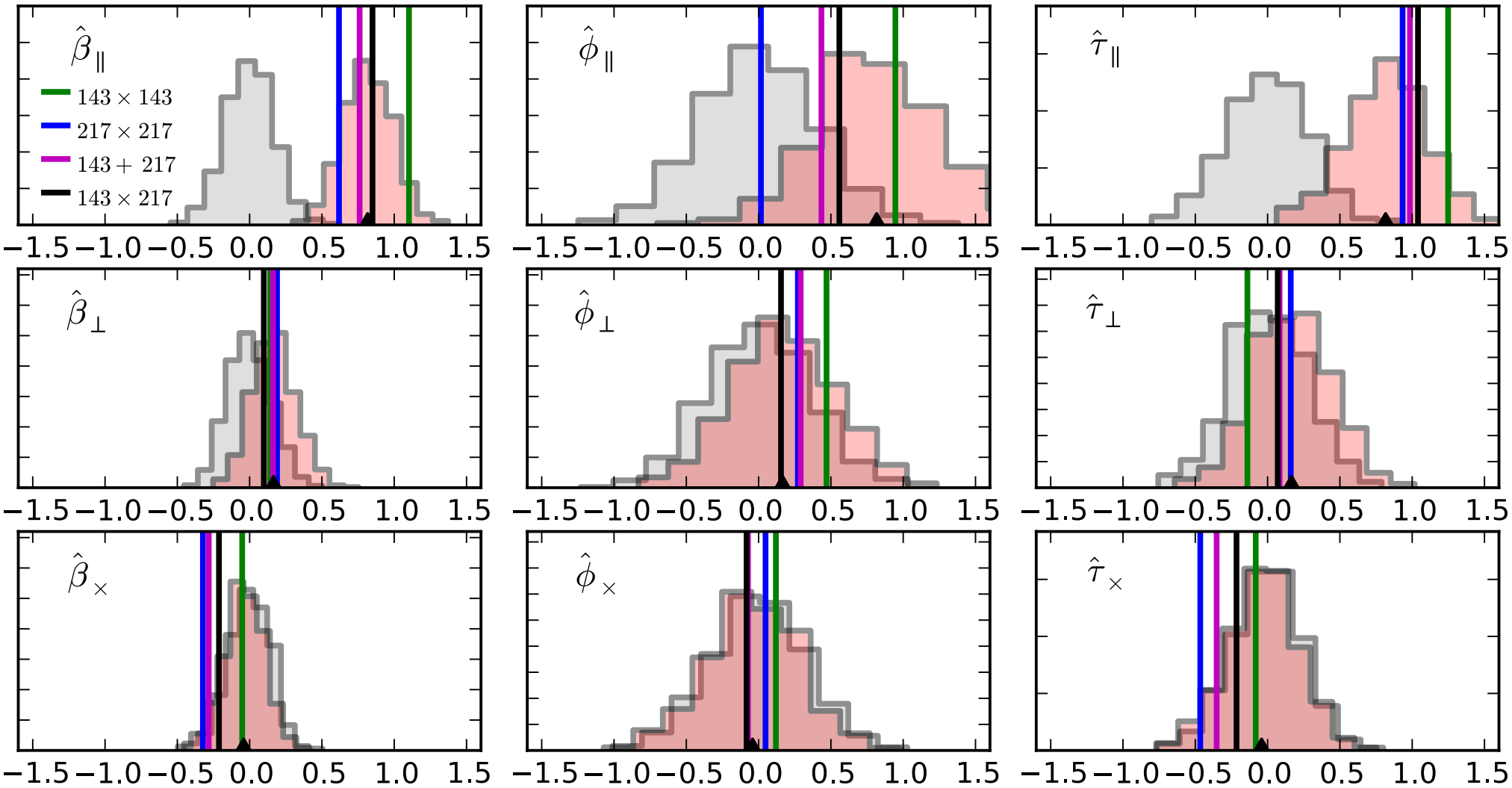
$\hat{\tau}_{\perp}$
$\hat{\beta}_{\times}$
$\hat{\phi}_{\times}$
$\hat{\tau}_{\times}$
143 × 143
217 × 217
143 + 217
143 × 217
−1.5 −1.0 −0.5 0.0 0.5 1.0 1.5


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

Total Aberration Modulation



Grey histogram: without Pink histogram: with β effects

Vertical lines are different data combinations

Concluding remarks

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- Masking means velocity effects are ≈25% of θ error – that's how well *Planck* constrains anisotropies
- Only possible to measure velocity with *Planck*!

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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