AST 1430
Cosmology

IX

The Cosmic Microwave Background

Polarization

Announcements

- Feb 15th will be a 2hr session: 10am-12pm
- Presentations!
  - Anika – Baryogenesis
  - Caleb – CMB B-modes
  - Braden – Alternative DE
  - Anna – Higgs Mechanism
- Assignment #2 is posted, due Feb 28th

Week Index	Dates	Topics
~~**Week 1**~~	~~Jan 11, 13~~	~~logistics, introduction, basic observations~~
~~**Week 2**~~	~~Jan 18, 20~~	~~Basic GR, RW metric, Distances, coordinates, Friedmann equations, cosmological models~~
~~**Week 3**~~	~~Jan 25, 27~~	~~Consistency with observations, Early Hot Universe, BBN~~
Week 4	~~Feb 1, 3~~	~~Inflation, Perturbations & Structure pre-recombination~~
Week 5	Feb 8, 10	CMB: ~~basics~~, polarization, ~~secondaries~~
Week 6	Feb 15 (2h)	Early-Universe Presentations
Reading Week – No Class		
Week 7	Mar 1, 3	Post-recombination growth of structure, formation of dark matter halos, halo mass function
Week 8	Mar 8, 10	The relation between dark matter halos and galaxies
Week 9	Mar 15, 17	Probing the cosmic density field / clustering
Week 10	Mar 22, 24	Late-time cosmological observations: BAO, supernovae, weak lensing, etc.
Week 11	Mar 29, 31	H0 controversy: how fast exactly is the Universe expanding today?
Week 12	Apr 5	Late Universe Presentations + Review

Keith (Weeks 1–6)

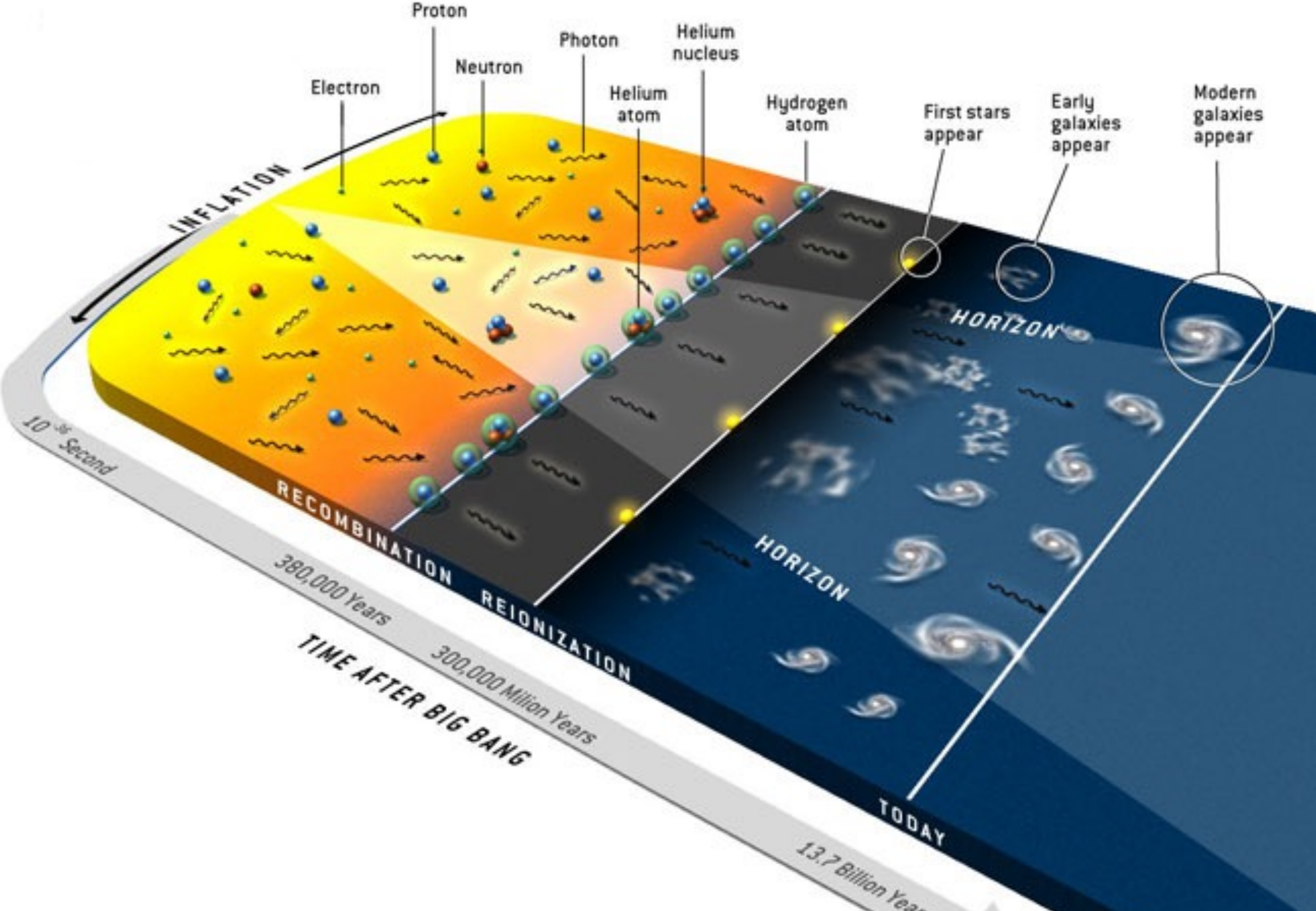
Jo (Weeks 7–12)

asst1 (Weeks 2–4)

asst2 (Weeks 6–7)

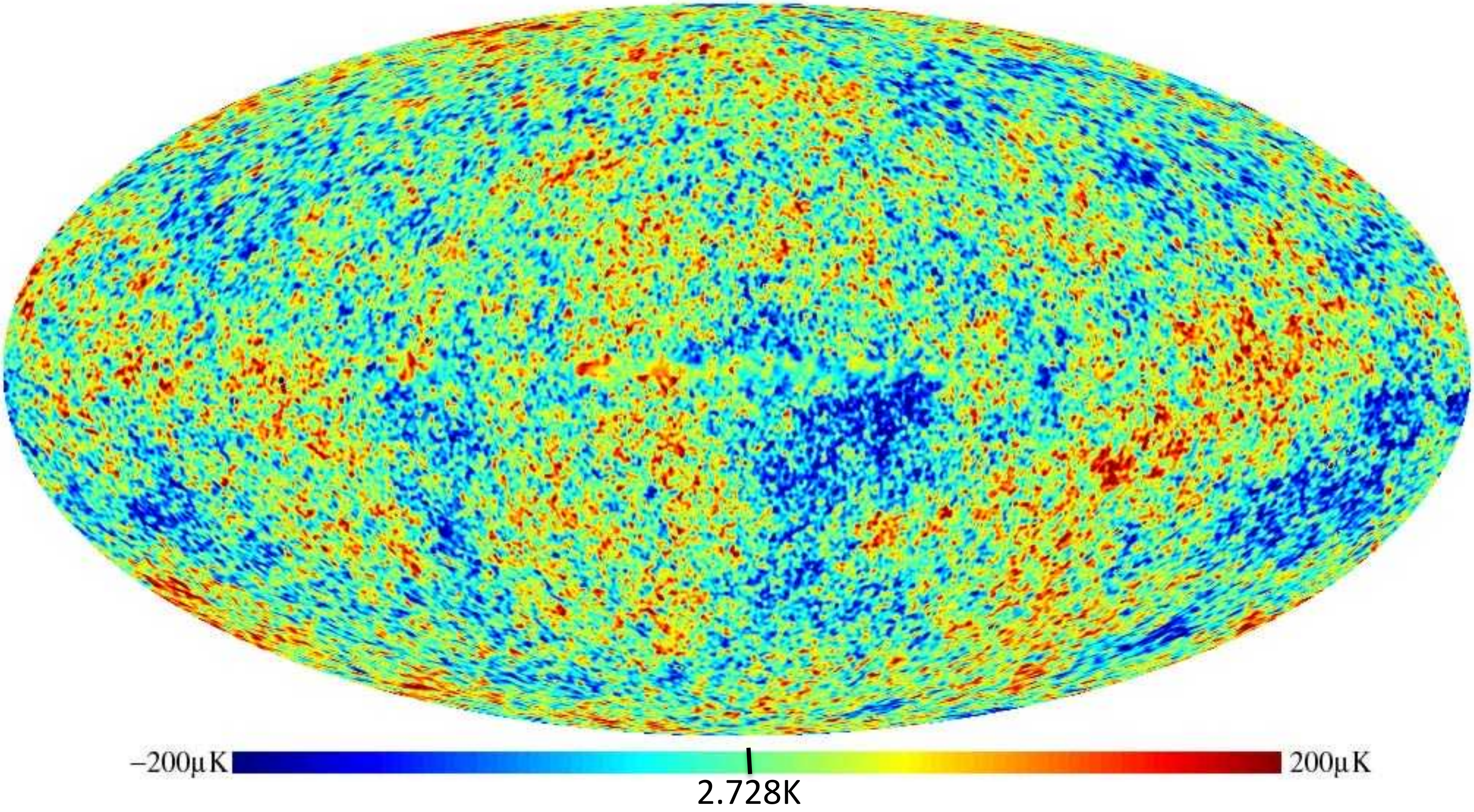
asst3 (Weeks 9–10)

Context Reminder

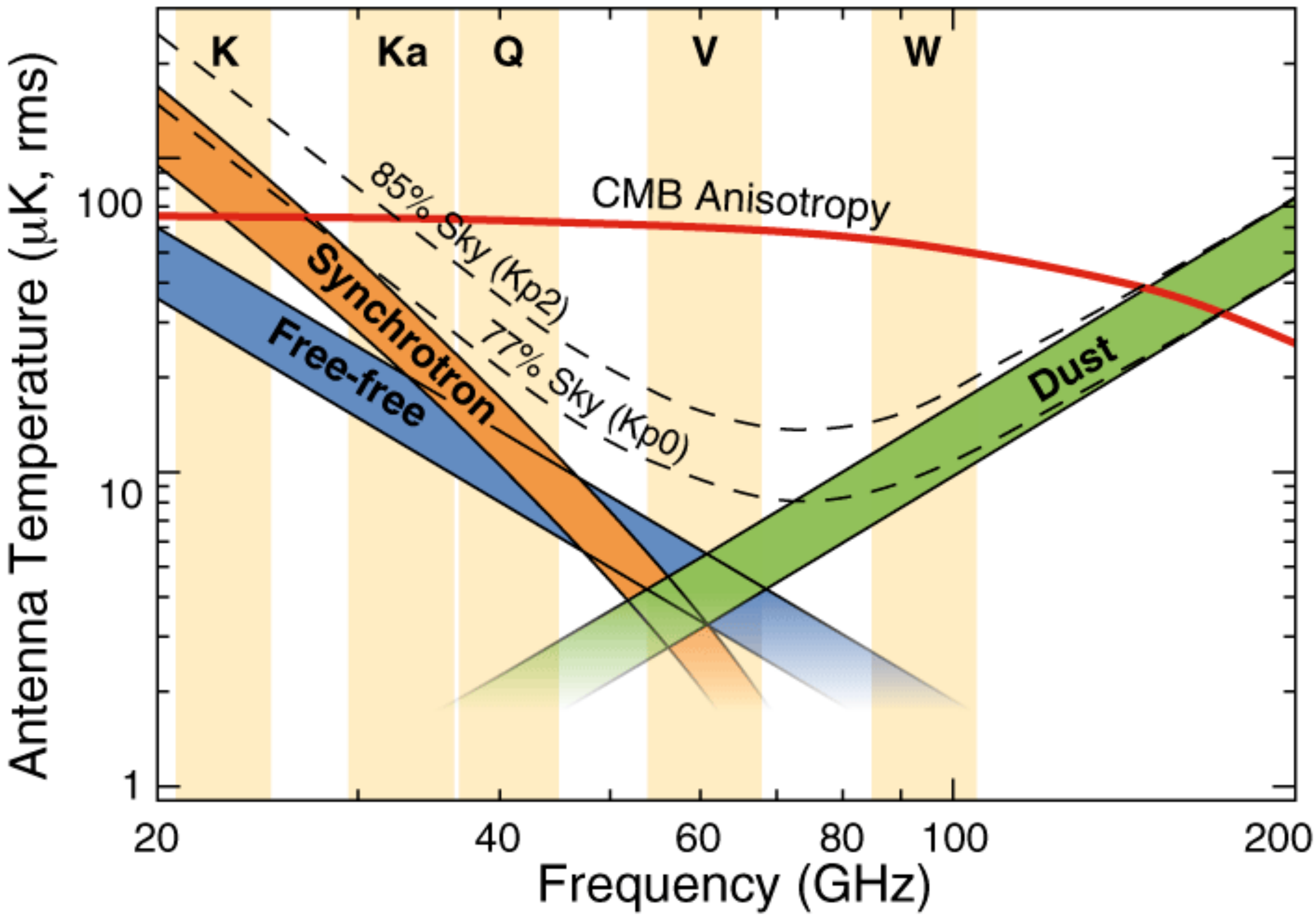


Hu & White, Scientific American, 2004

The Anisotropies

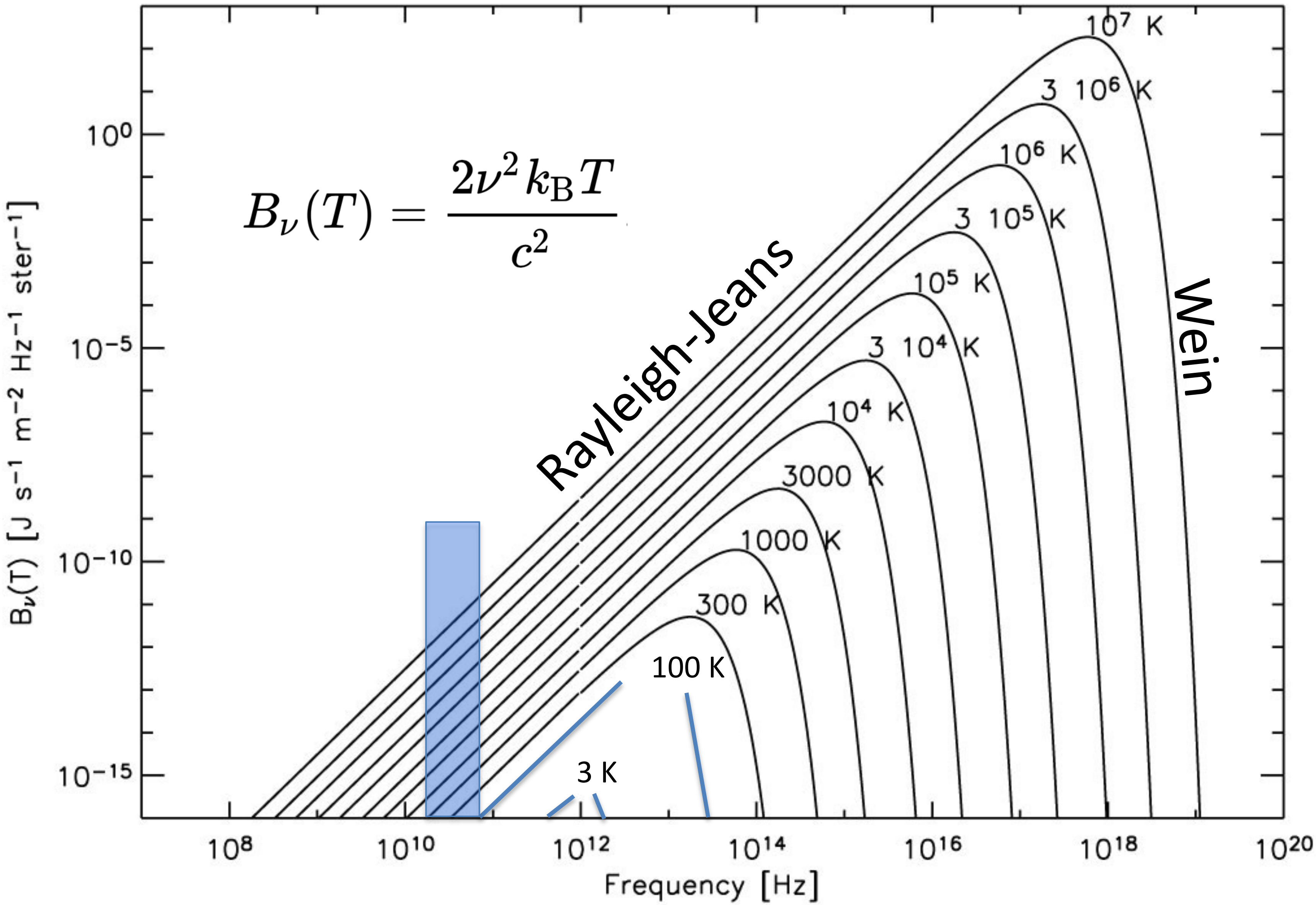


Foregrounds

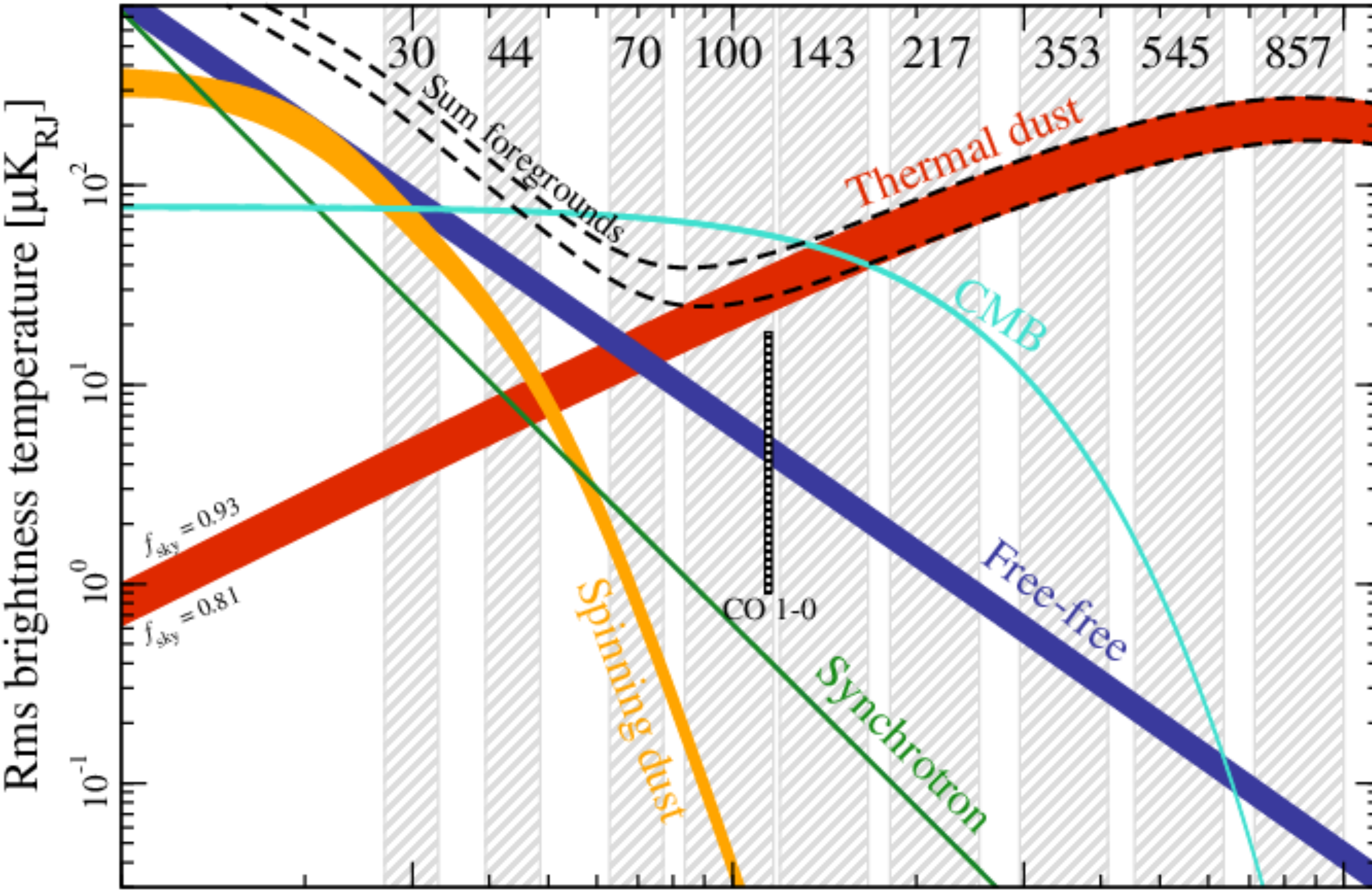


Rayleigh-Jeans Temperatures

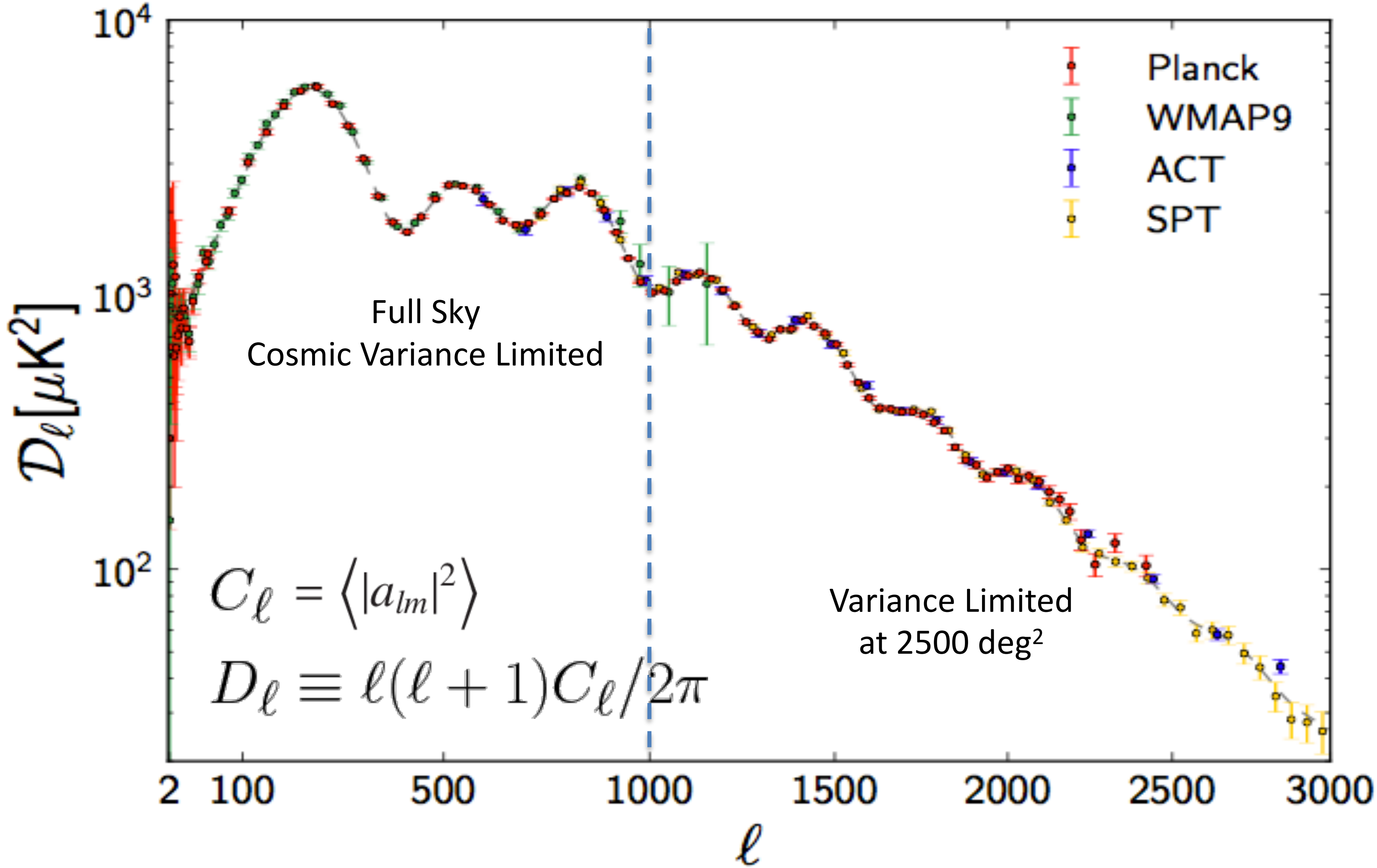
$$B_\nu(T) = \frac{2\nu^2 k_B T}{c^2}$$



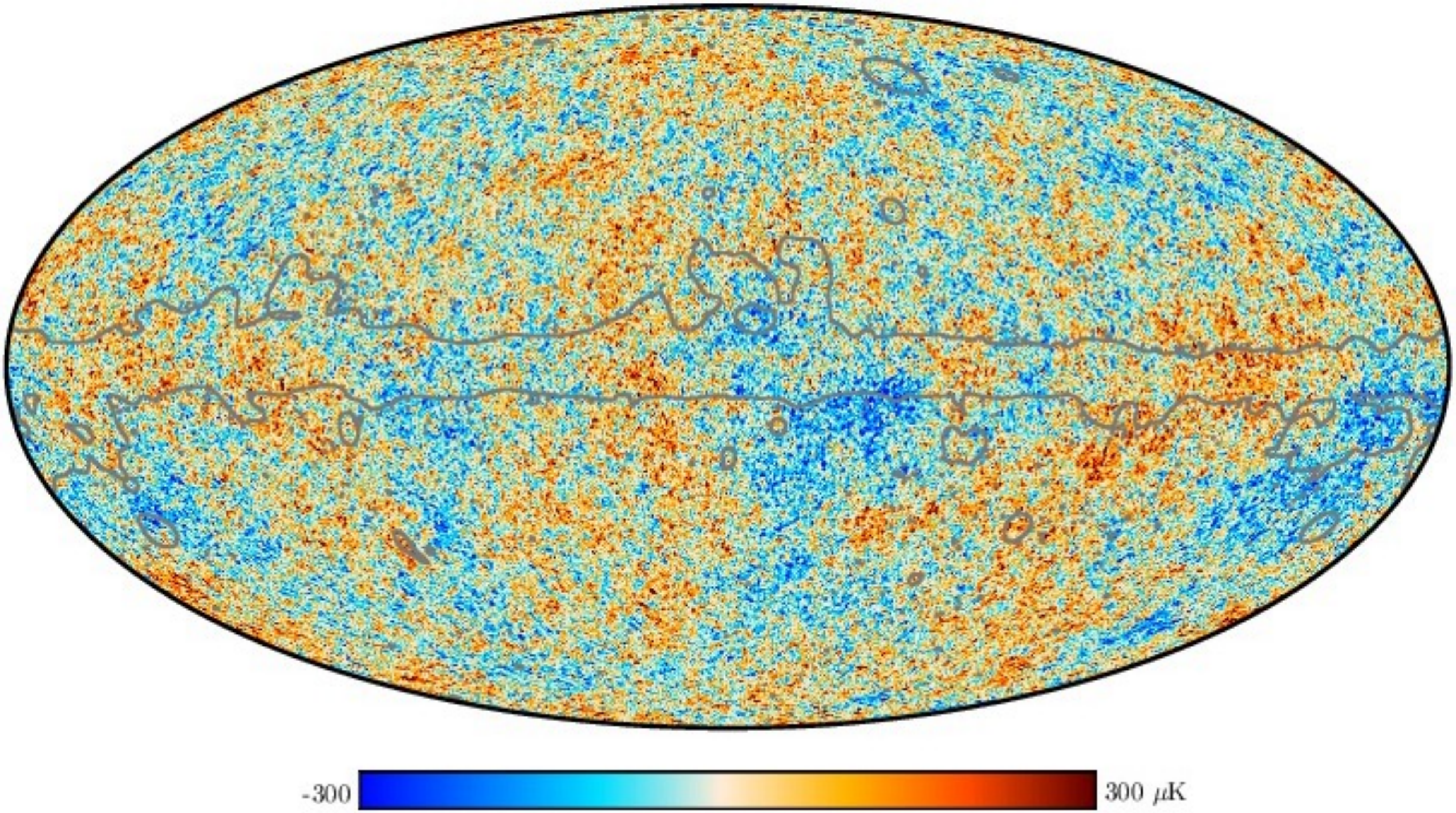
Foregrounds



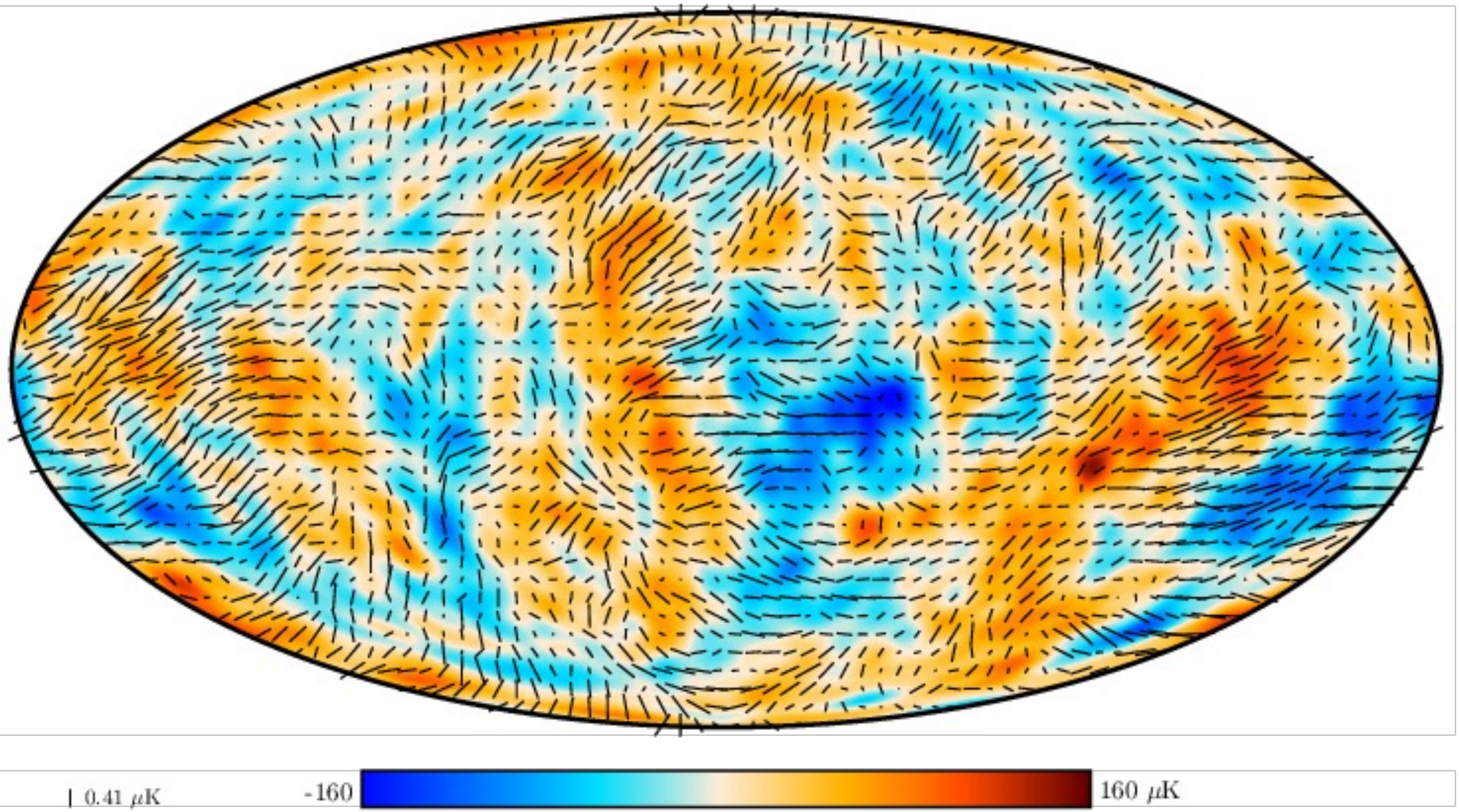
CMB Data Circa 2020



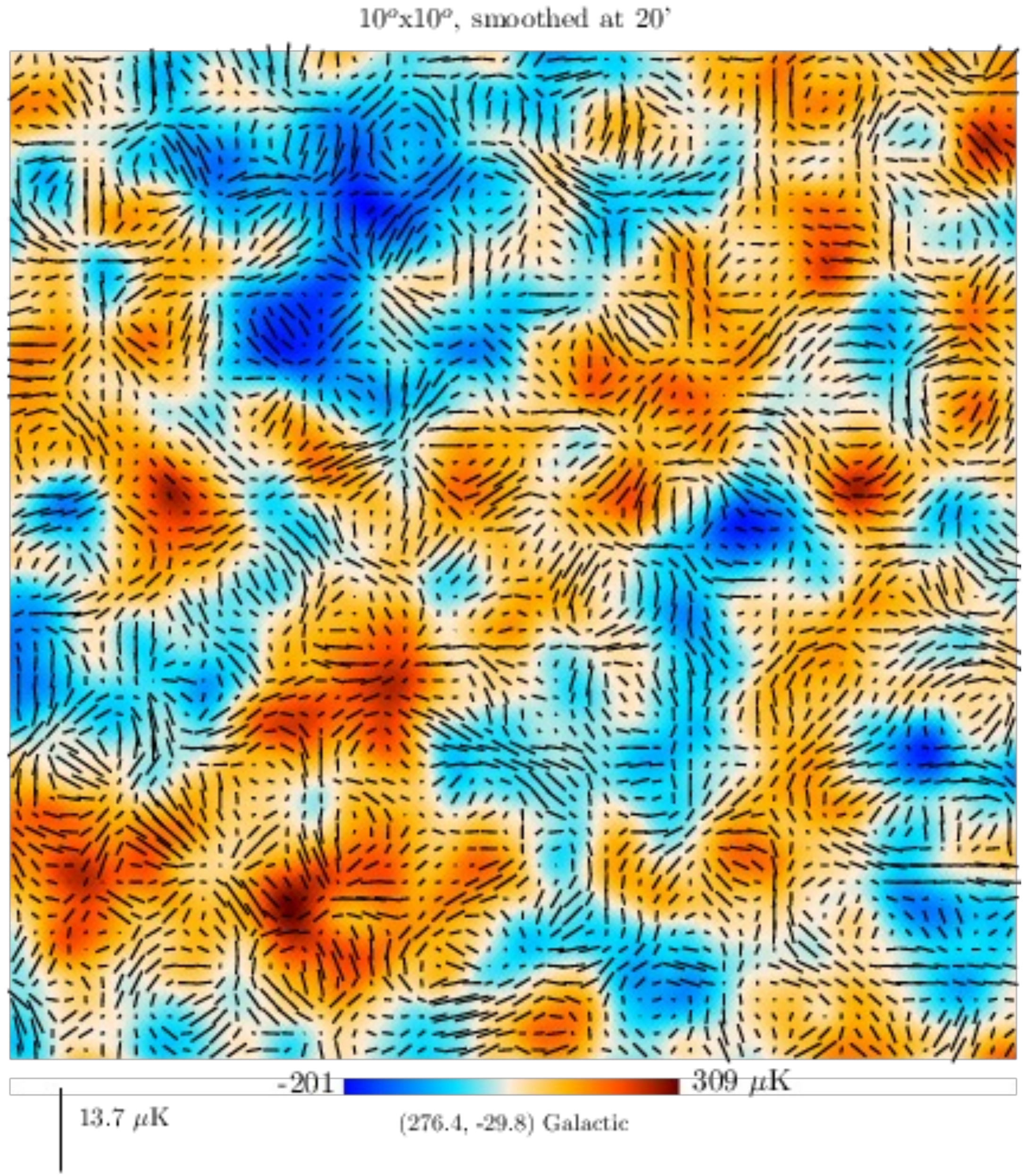
Planck Anisotropies



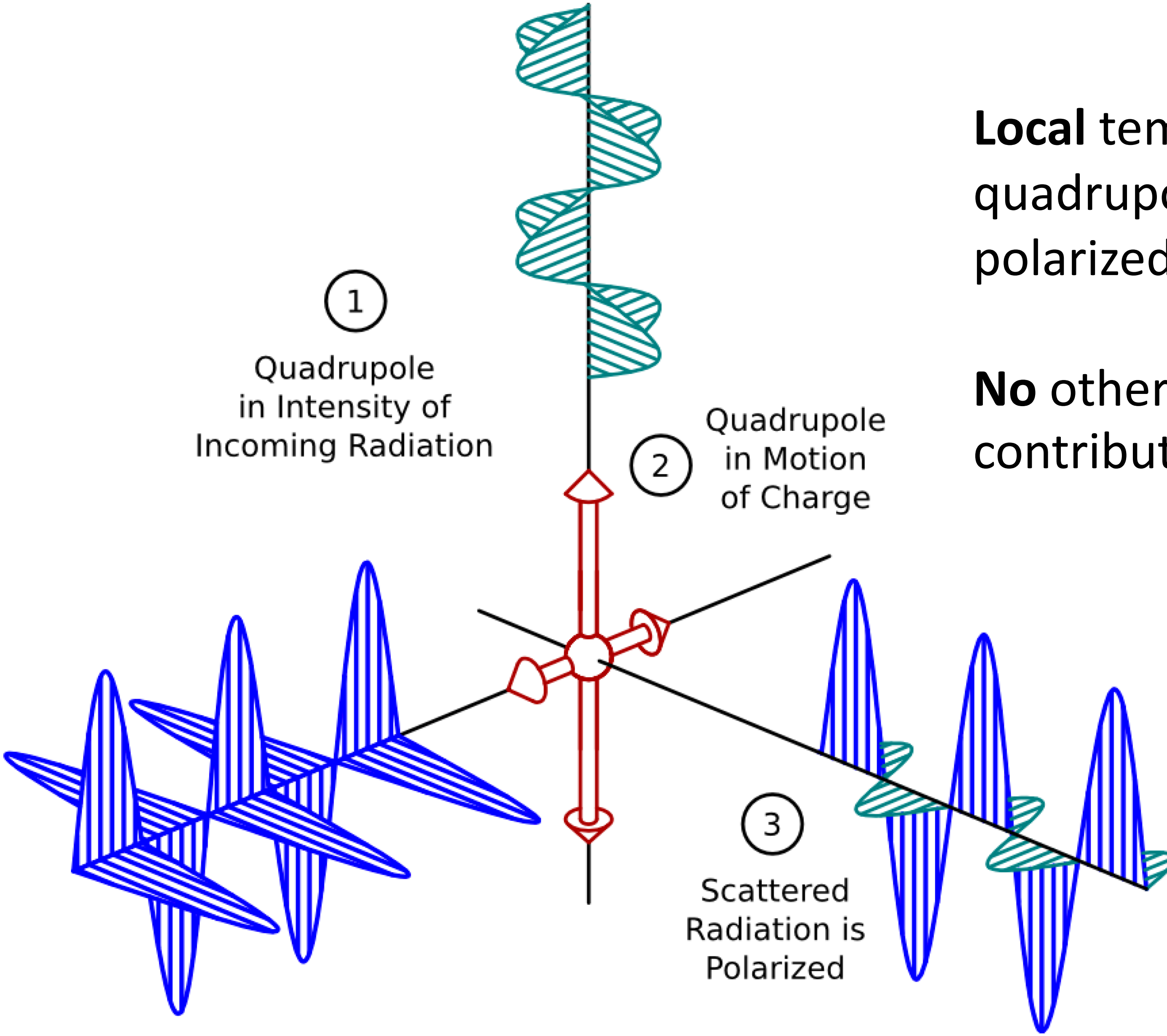
Planck Polarization



Planck Polarization



CMB: Polarized?



Local temperature quadrupole will yield polarized emission.

No other multipoles contribute!

Diffusion

→Polarization is generated by diffusion of photons.

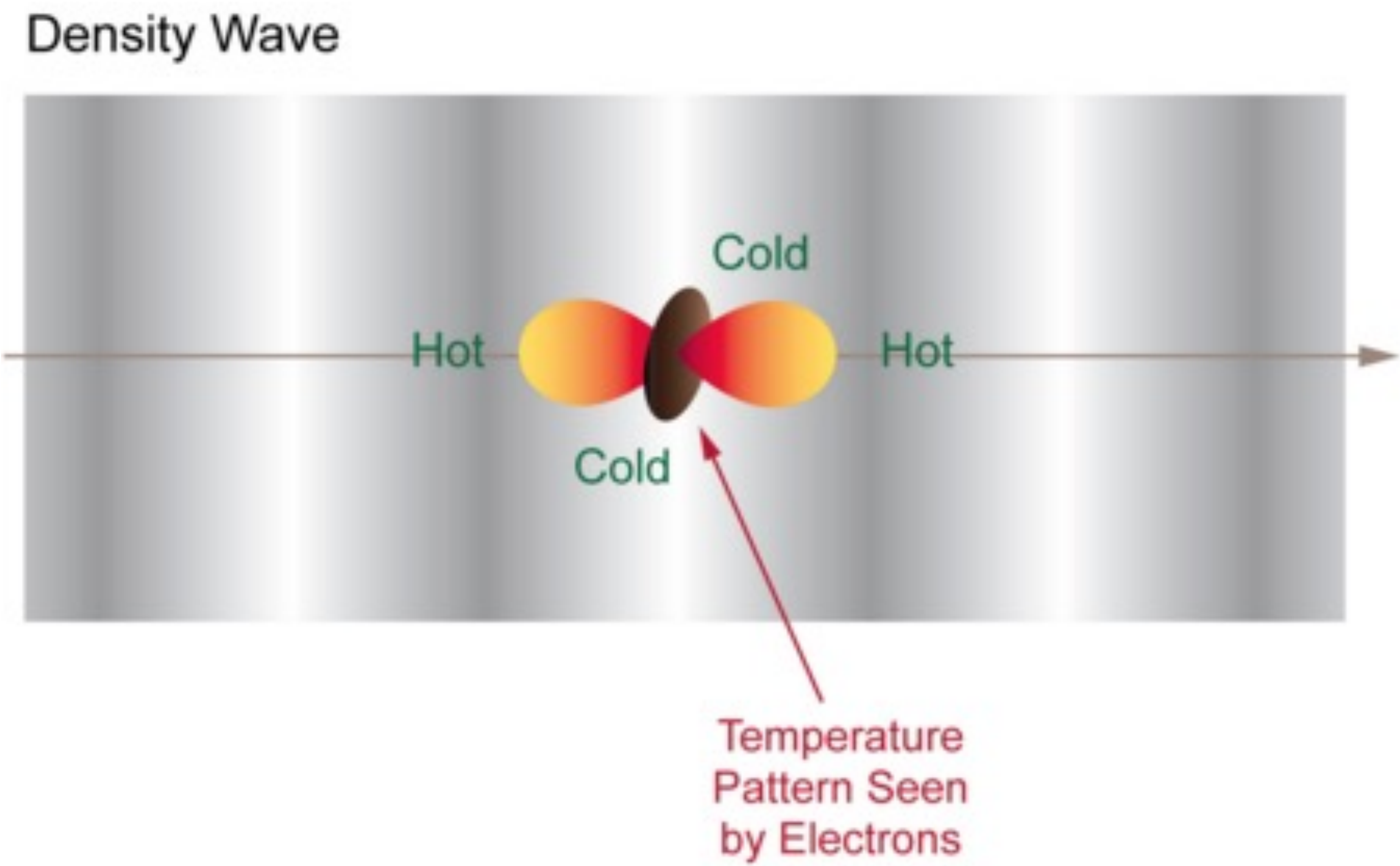
→ Photons can’t diffuse until free electrons are gone.

Polarization is only imprinted during
a brief time window: recombination.

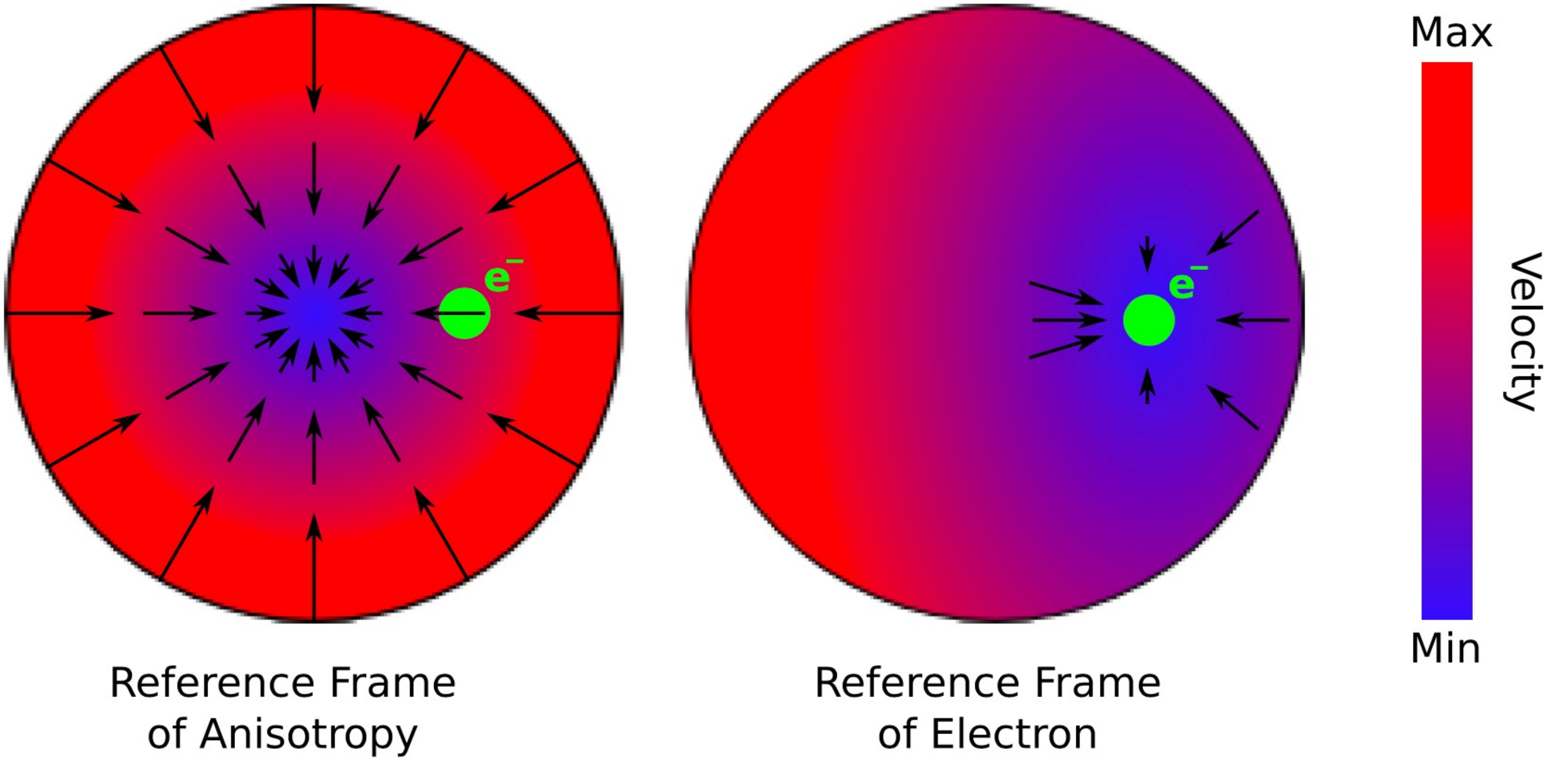
(Not true! Also imprinted by re-ionization!)

Primary CMB polarization peaks on the same scales damping kicks in → smaller scale, only ≈10% amp of T anisotropies

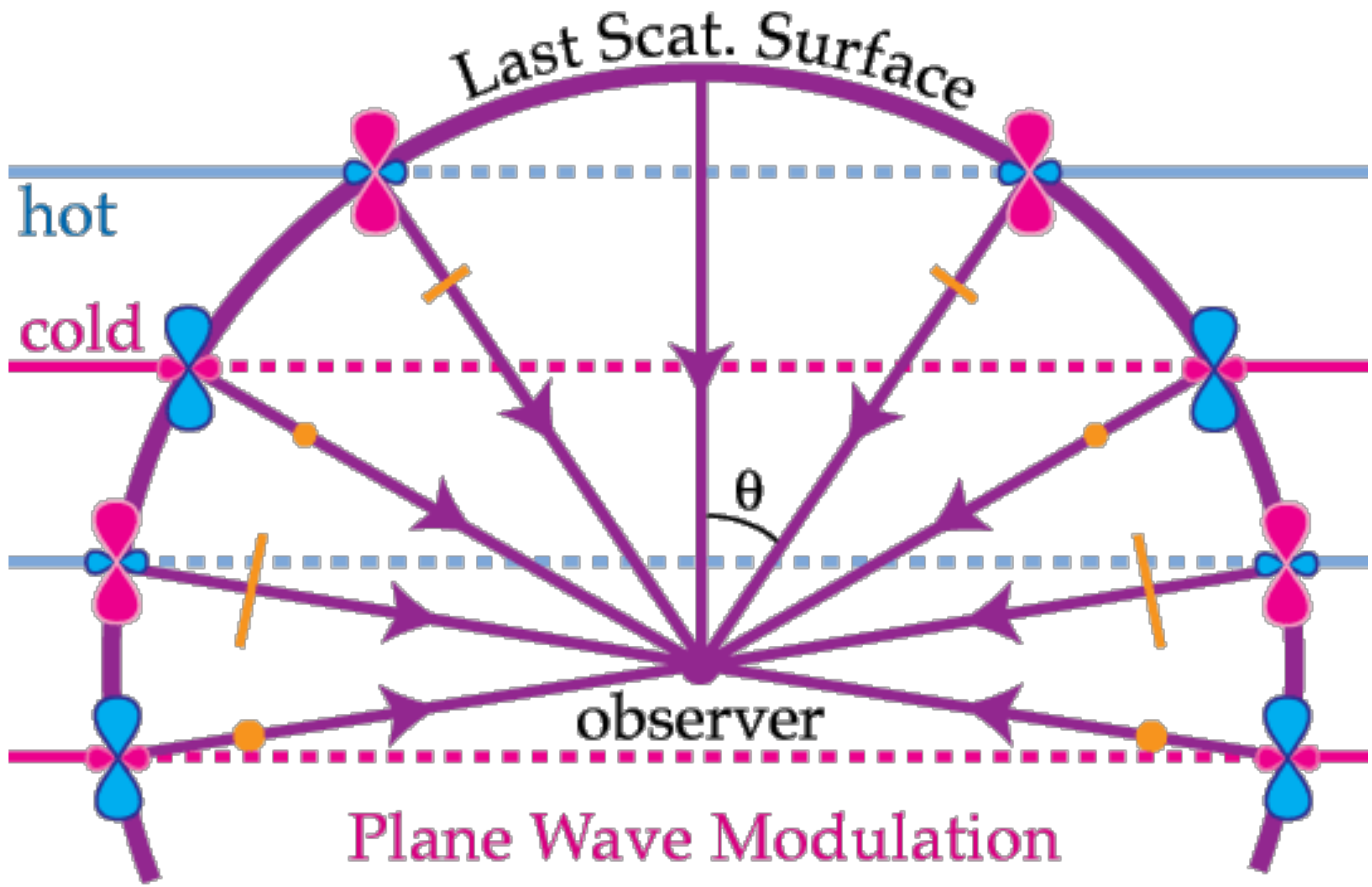
Of Plane Waves and Quadrupoles



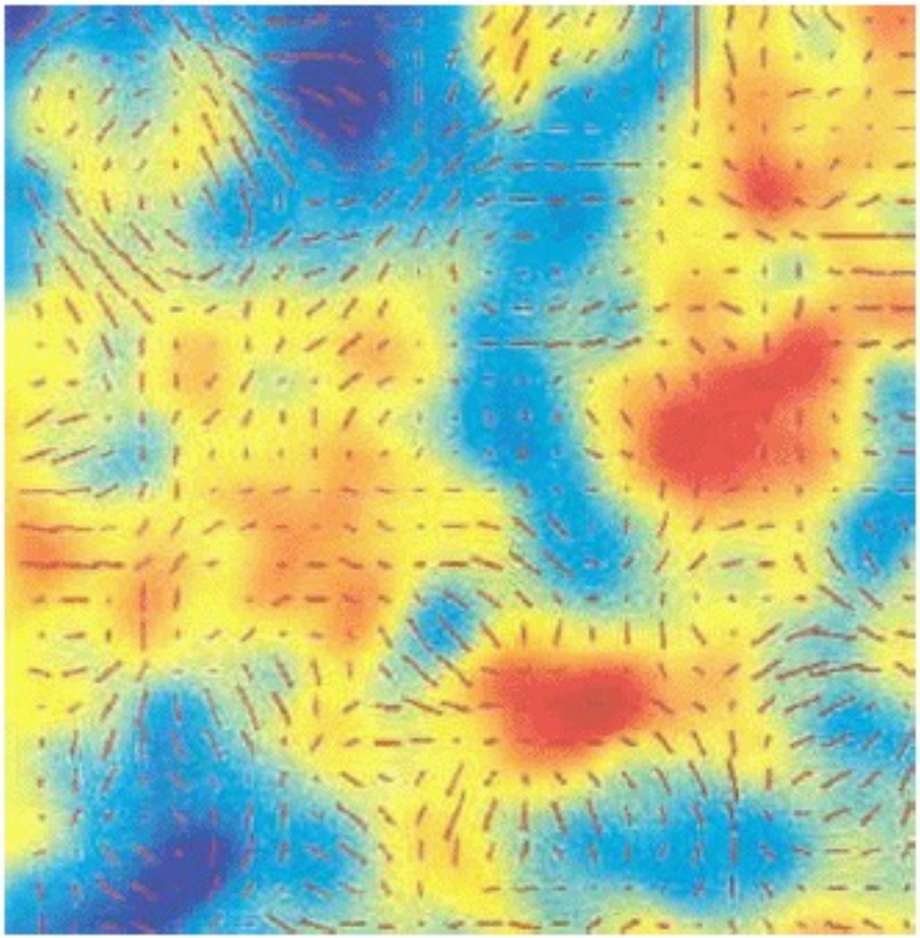
Doppler Shifted Temperature Field



Polarization Observed



From [pseudo] Vectors to Scalars



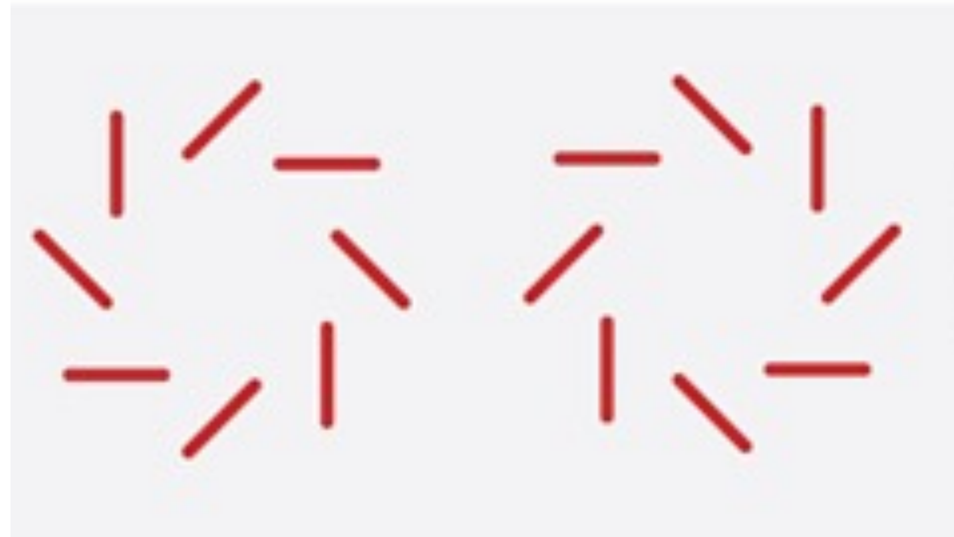
Scalar fields are a lot easier to work with.

Horizontal & vertical?
Stokes Q & U?

→ Too observer-dependent!

E-Modes

B-Modes



$E > 0$ $\quad$ $E < 0$ $\quad$ $B > 0$ $\quad$ $B < 0$

→ Nonlocal definition (!)

→ Independent of orientation

E-modes are symmetric. B-modes have “handedness.”

Formal Def'n

$$Q(\hat{n}) \pm iU(\hat{n}) = \sum_{\ell m} (a_{\ell m}^E \pm i a_{\ell m}^B)({}_{\pm 2}Y_{\ell m}(\hat{n}))$$

The basis functions $Y^{\mathrm{G}}_{(lm)ab}(\hat{\mathbf{n}})$ and $Y^{\mathrm{C}}_{(lm)ab}(\hat{\mathbf{n}})$ are given in terms of covariant derivatives of the spherical harmonics by [28]

$$Y^{\mathrm{G}}_{(lm)ab} = N_l \left(Y_{(lm):ab} - \frac{1}{2} g_{ab} Y_{(lm):c}{}^{c} \right), \tag{2.14}$$

(Where G ⇔ E ; C⇔ B)

and

$$Y^{\mathrm{C}}_{(lm)ab} = \frac{N_l}{2} \left(Y_{(lm):ac} \epsilon^{c}{}_{b} + Y_{(lm):bc} \epsilon^{c}{}_{a} \right), \tag{2.15}$$

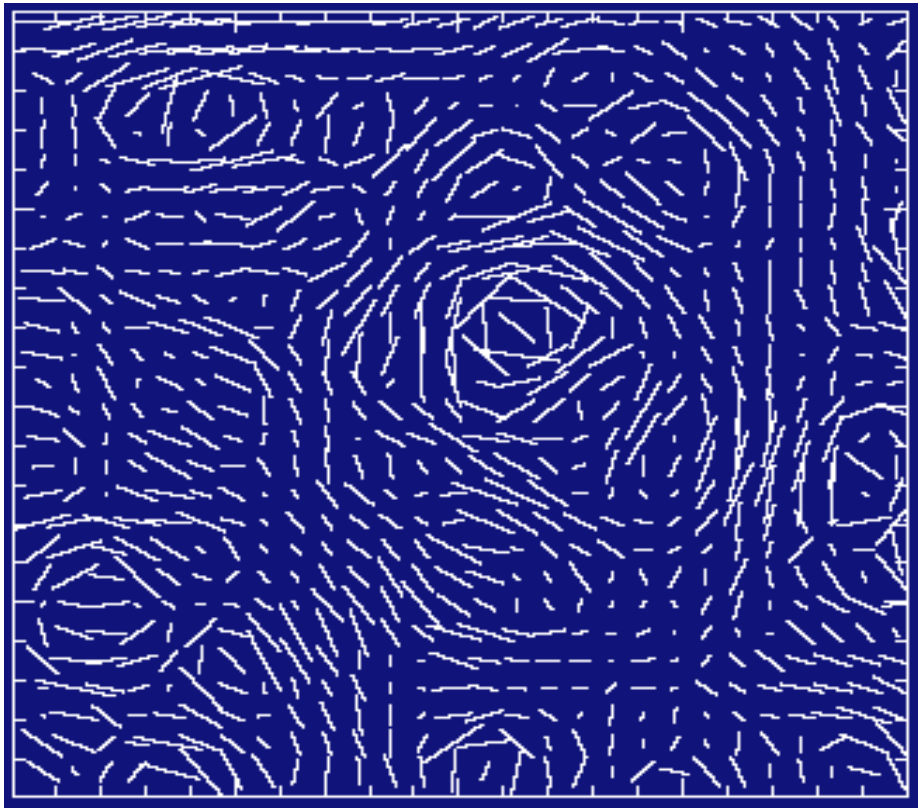
where ϵ_{ab} is the completely antisymmetric tensor, the ":" denotes covariant differentiation on the 2-sphere, and

$$N_l \equiv \sqrt{\frac{2(l-2)!}{(l+2)!}} \tag{2.16}$$

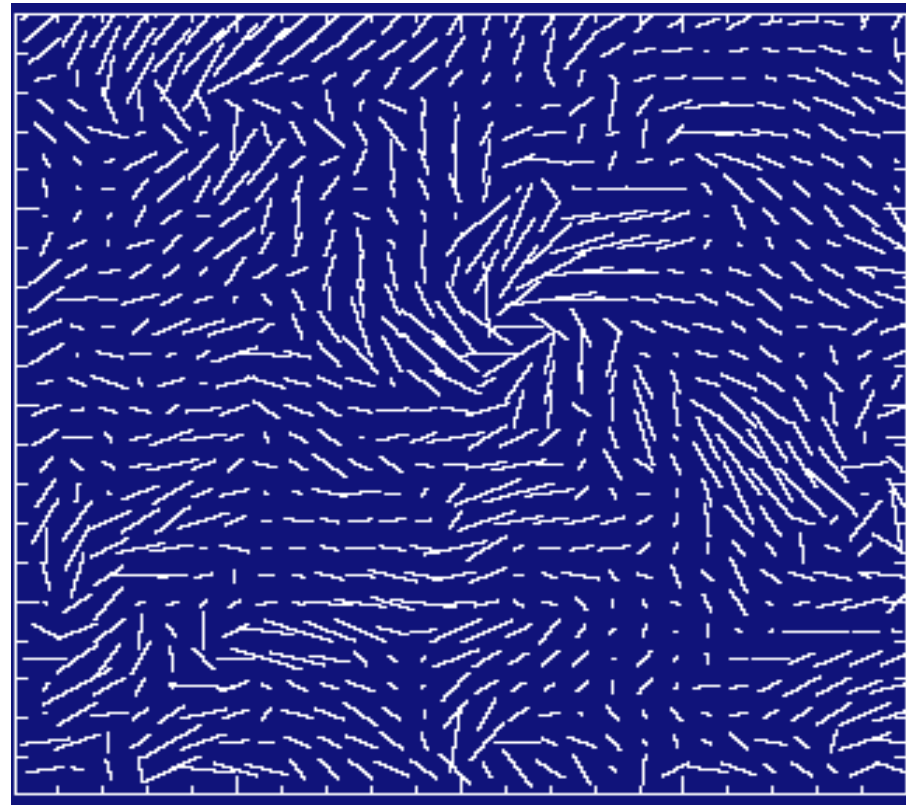
is a normalization factor.

Kamionkowski et al, 1996.

E- and B- modes

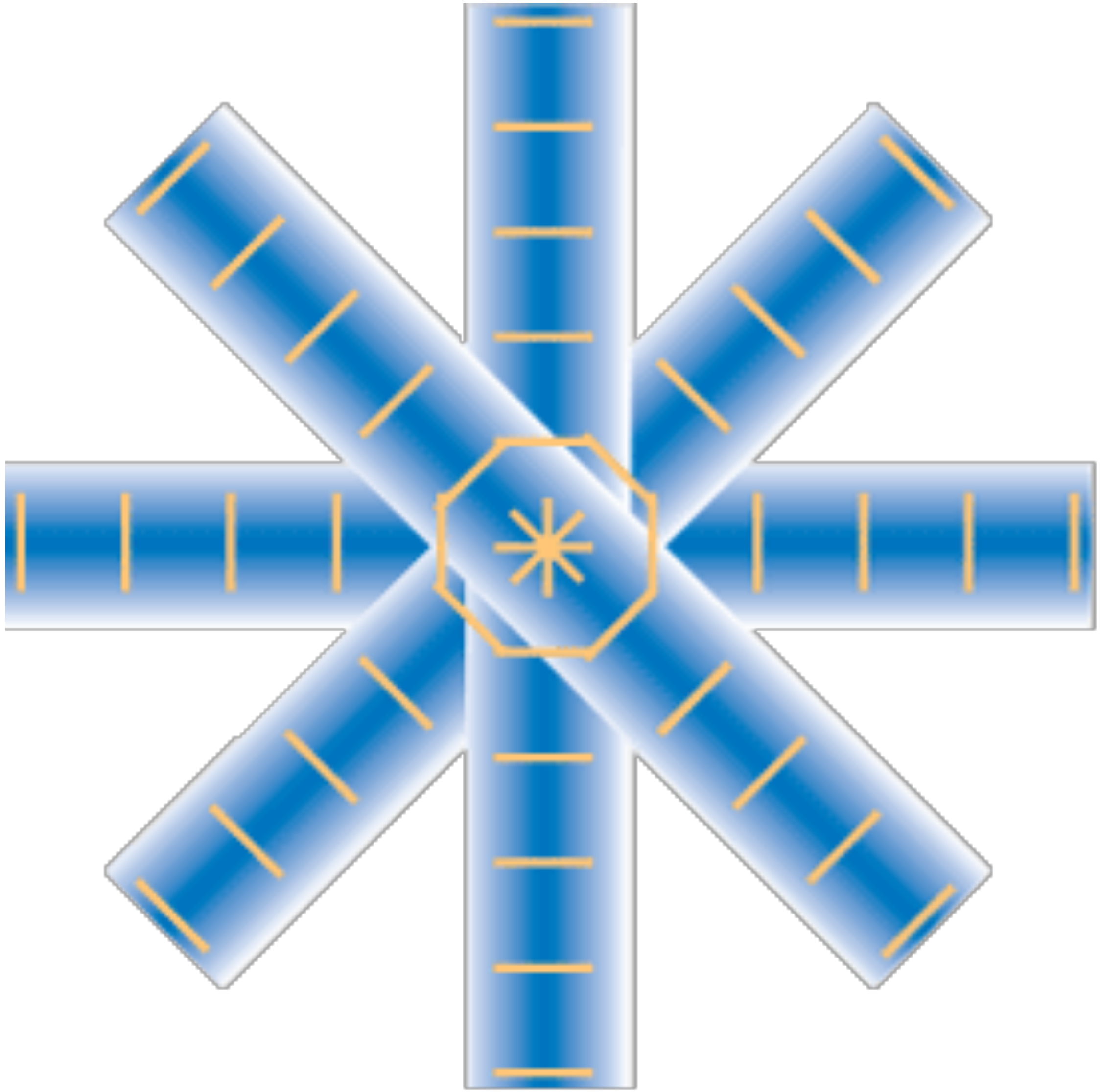


Polarization field composed only of E-modes



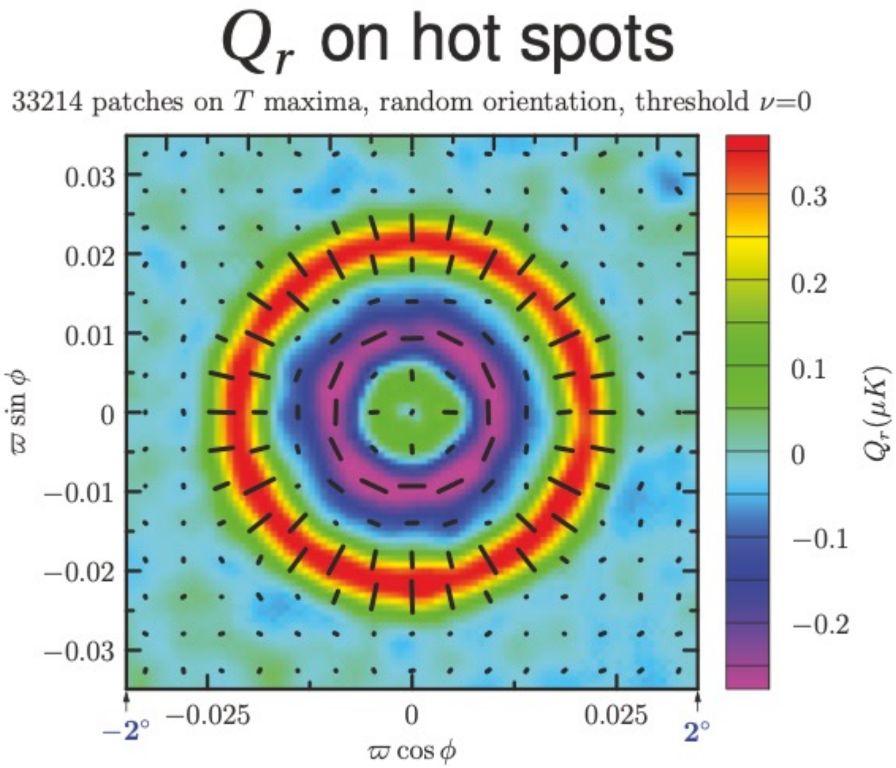
Polarization field composed only of B-modes

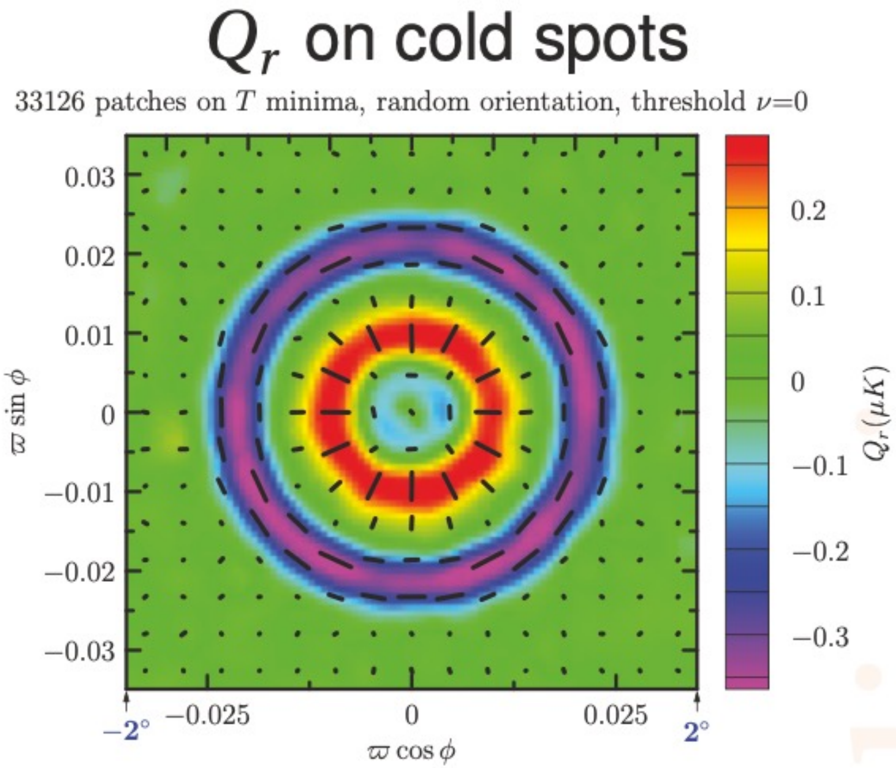
Hot Spots & Cold Spots



Scalar (density) perturbations generate ONLY E-mode polarization patterns!

Hot Spots & Cold Spots





Power Spectra

$$C_l \equiv \frac{1}{2l+1}\sum_m a_{lm}a_{lm}^* = \left\langle |a_{lm}|^2 \right\rangle$$

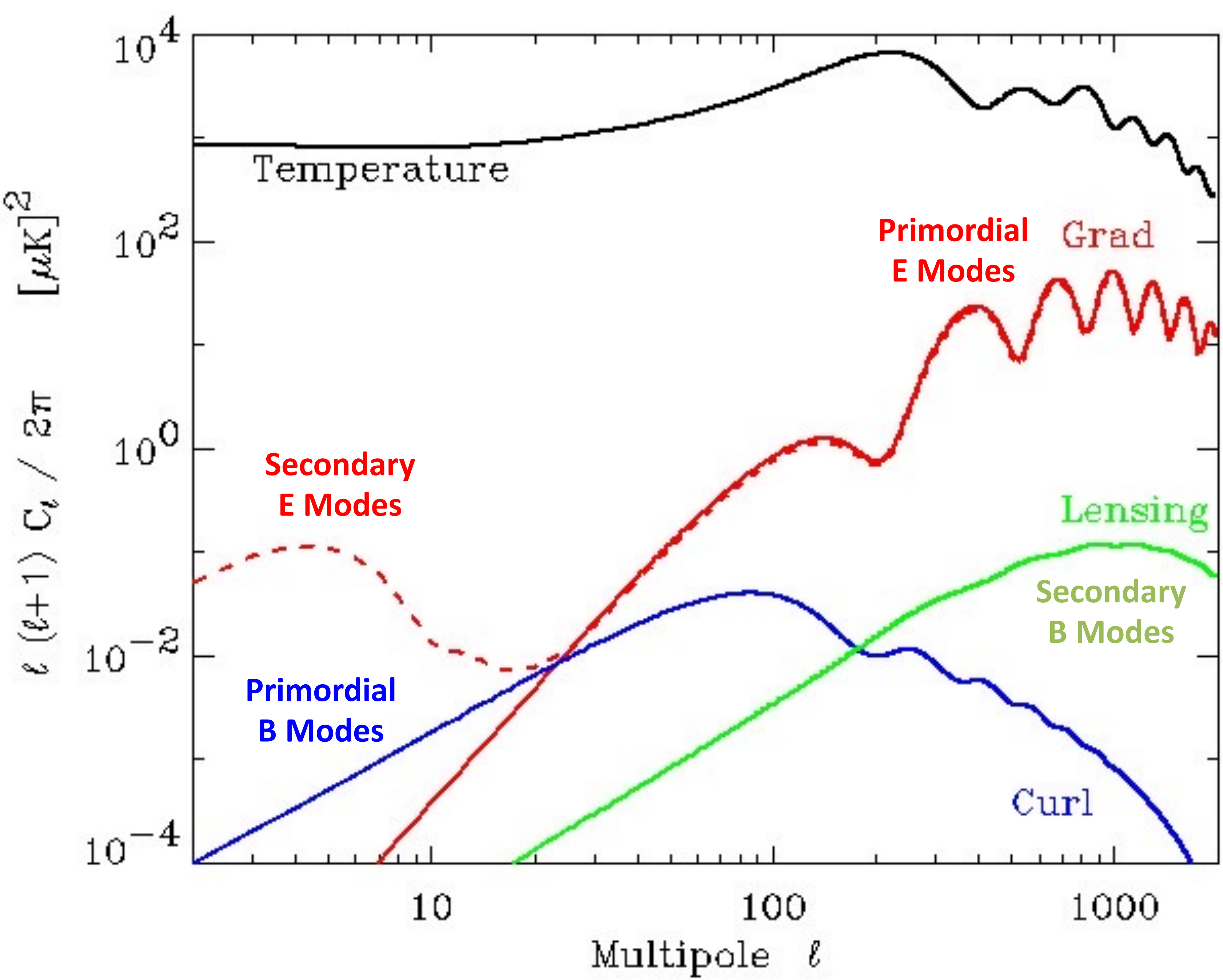
$$C_\ell^{TT} \equiv \frac{1}{2\ell+1}\sum a_{lm}^{T}a_{lm}^{T*} = \left\langle |a_{lm}^{T}|^2 \right\rangle$$

$$C_\ell^{EE} \equiv \frac{1}{2\ell+1}\sum a_{lm}^{E}a_{lm}^{E*} = \left\langle |a_{lm}^{E}|^2 \right\rangle$$

$$C_\ell^{BB} \equiv \frac{1}{2\ell+1}\sum a_{lm}^{B}a_{lm}^{B*} = \left\langle |a_{lm}^{B}|^2 \right\rangle$$

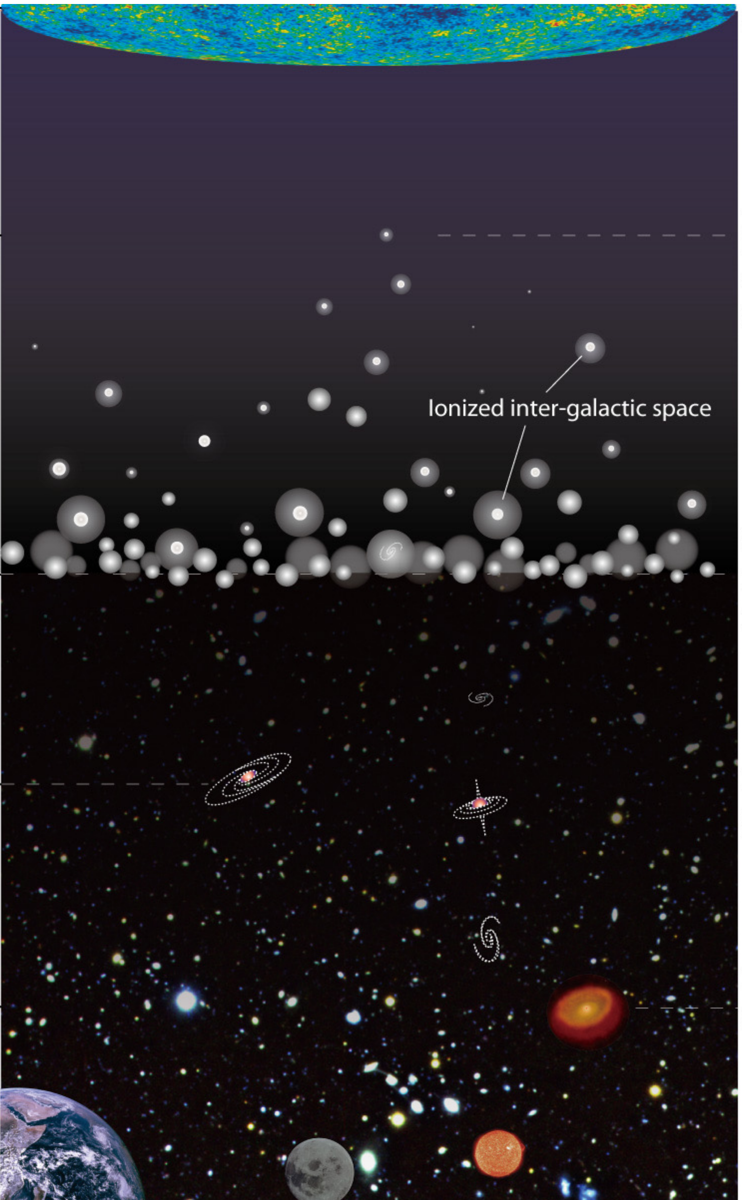
$$C_\ell^{TE} \equiv \frac{1}{2\ell+1}\sum a_{lm}^{T}a_{lm}^{E*}$$

$$\begin{aligned} C_\ell^{TB} &= \langle a_{lm}^{T}a_{lm}^{B*}\rangle = 0 \\ C_\ell^{EB} &= \langle a_{lm}^{E}a_{lm}^{B*}\rangle = 0 \end{aligned}$$



Temperature
Primordial E Modes
Grad
Secondary E Modes
Lensing
Secondary B Modes
Primordial B Modes
Curl
10^4
10^2
10^0
10^{-2}
10^{-4}
$\ell\,(\ell+1)\;C_\ell\;/\;2\pi\quad[\mu K]^2$
10
100
1000
Multipole ℓ

Reionization Bump



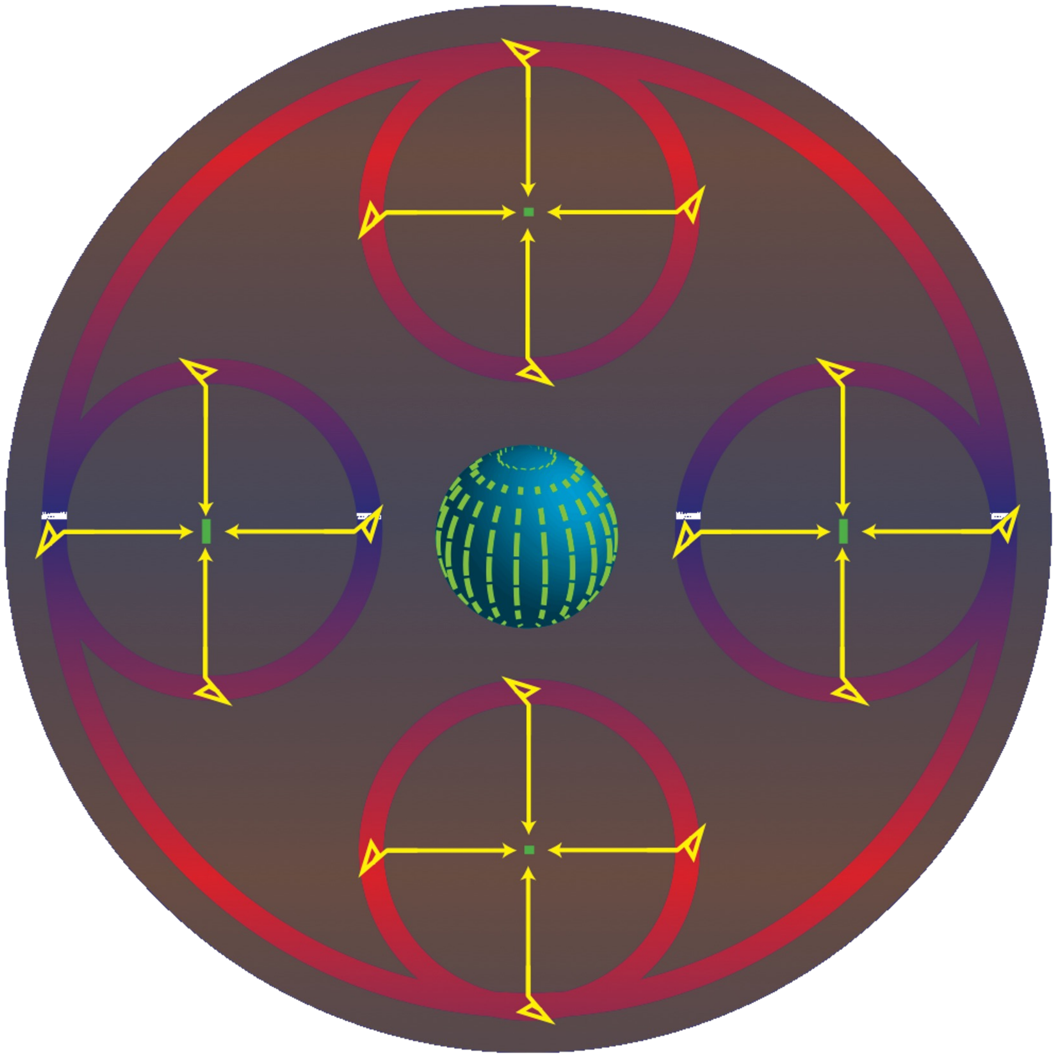
Last Scattering

Free Electrons & Photon Diffusion
→ Polarization Imprinted!

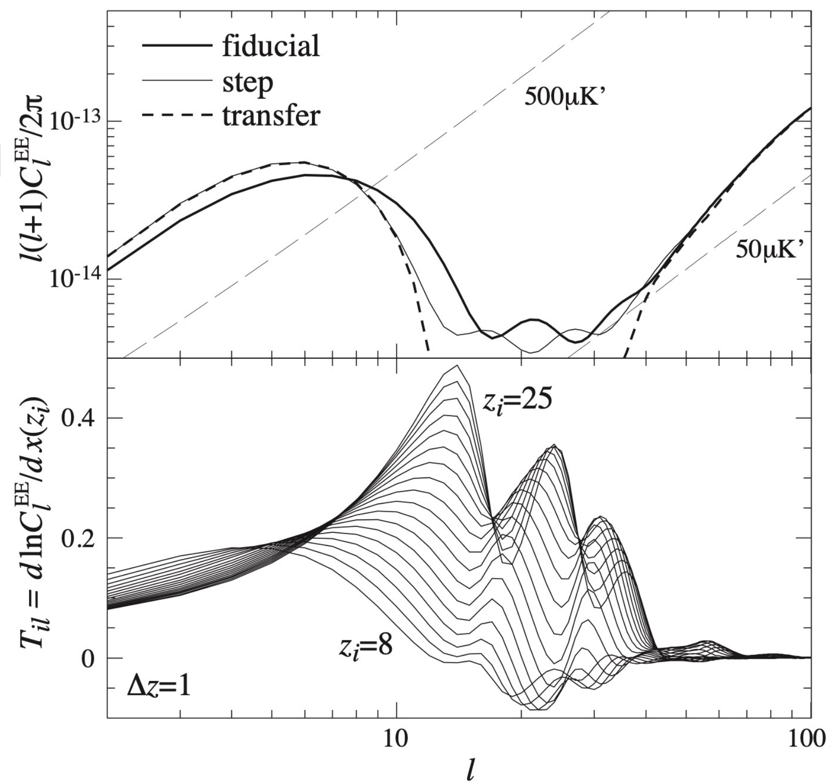
Reionization

Present Day

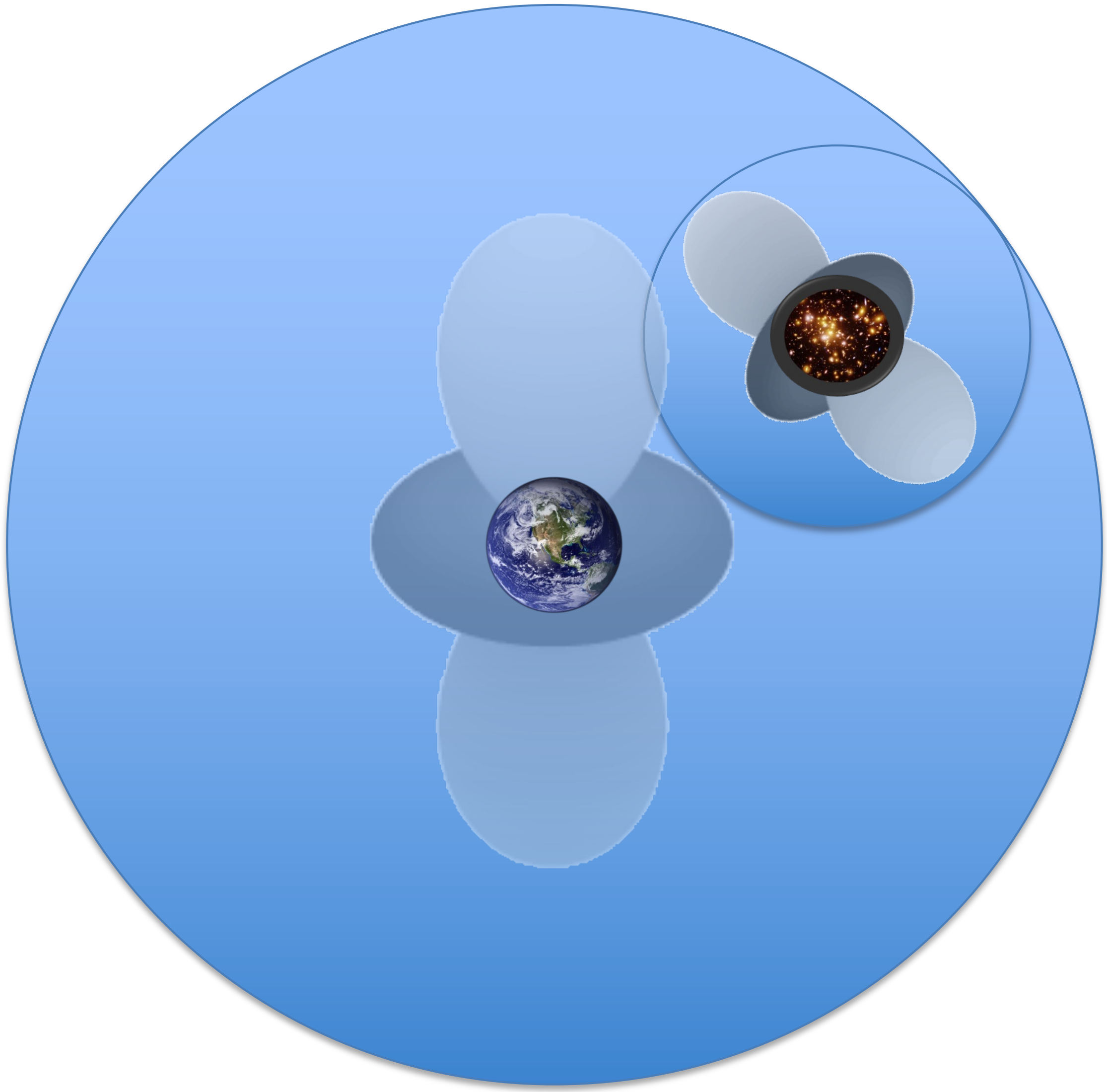
Reionization Bump



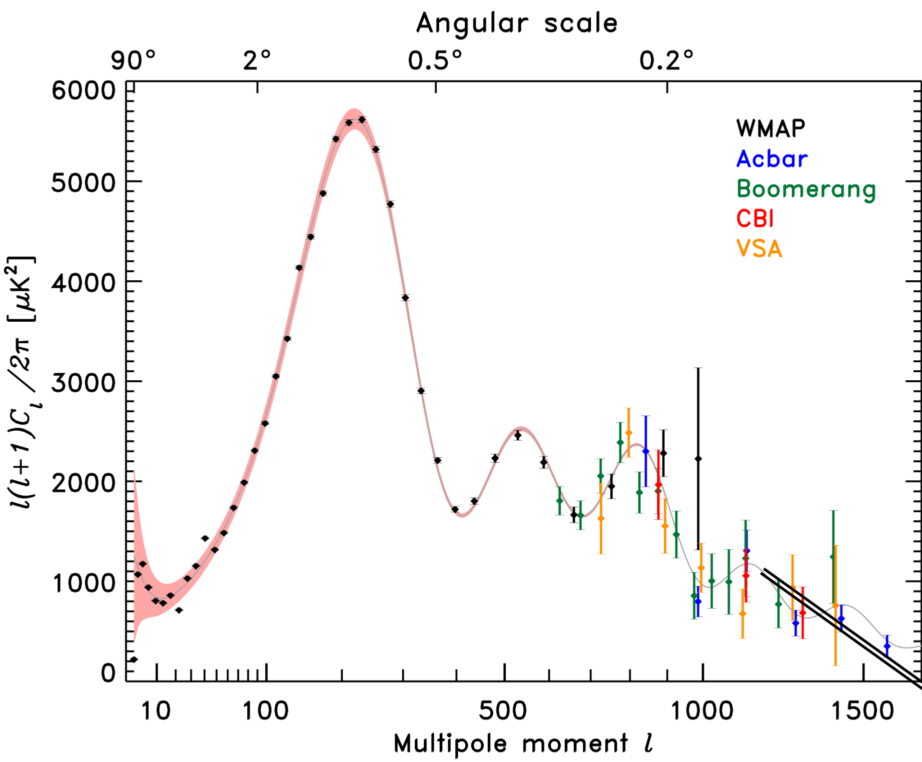
Generates E-modes at EoR Last Scattering scale: l ≈< 10



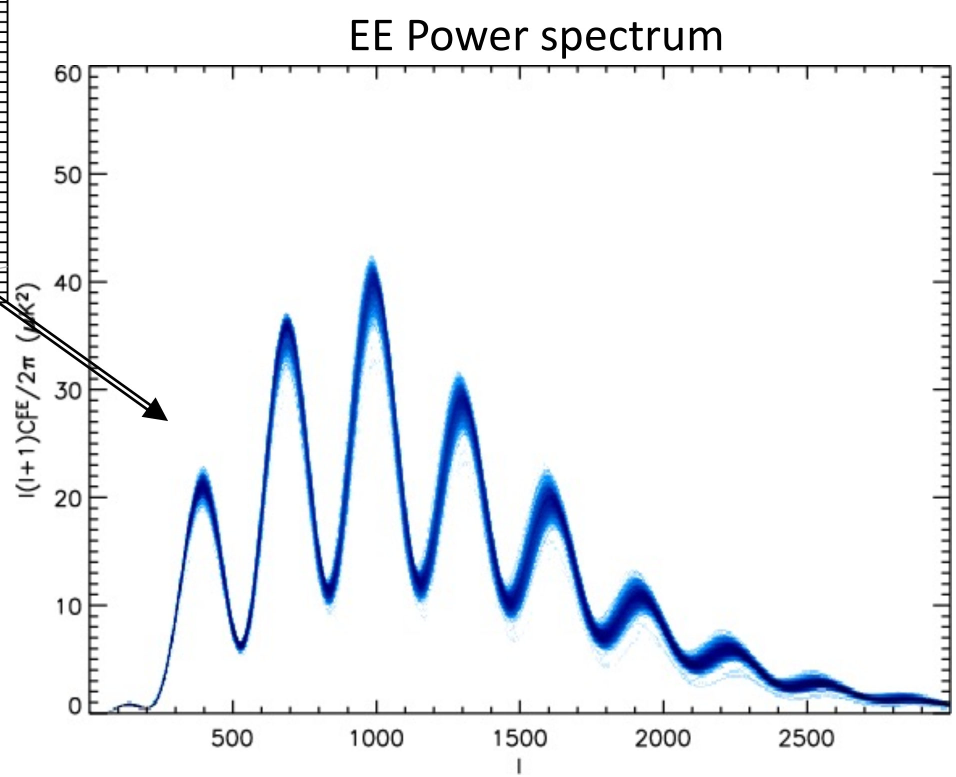
Observing someone else's Quadrupole



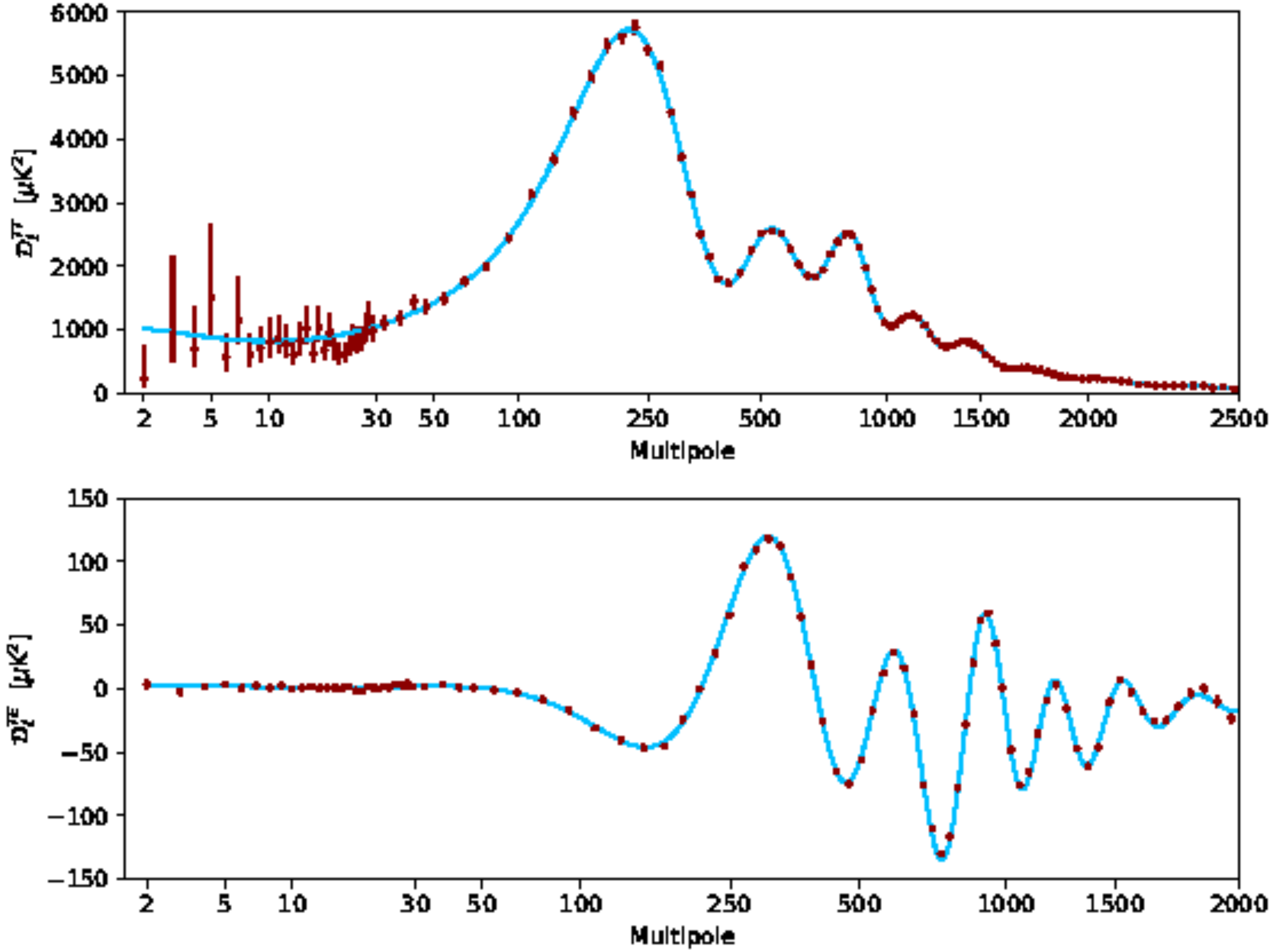
E-modes: Predicted from Temperature

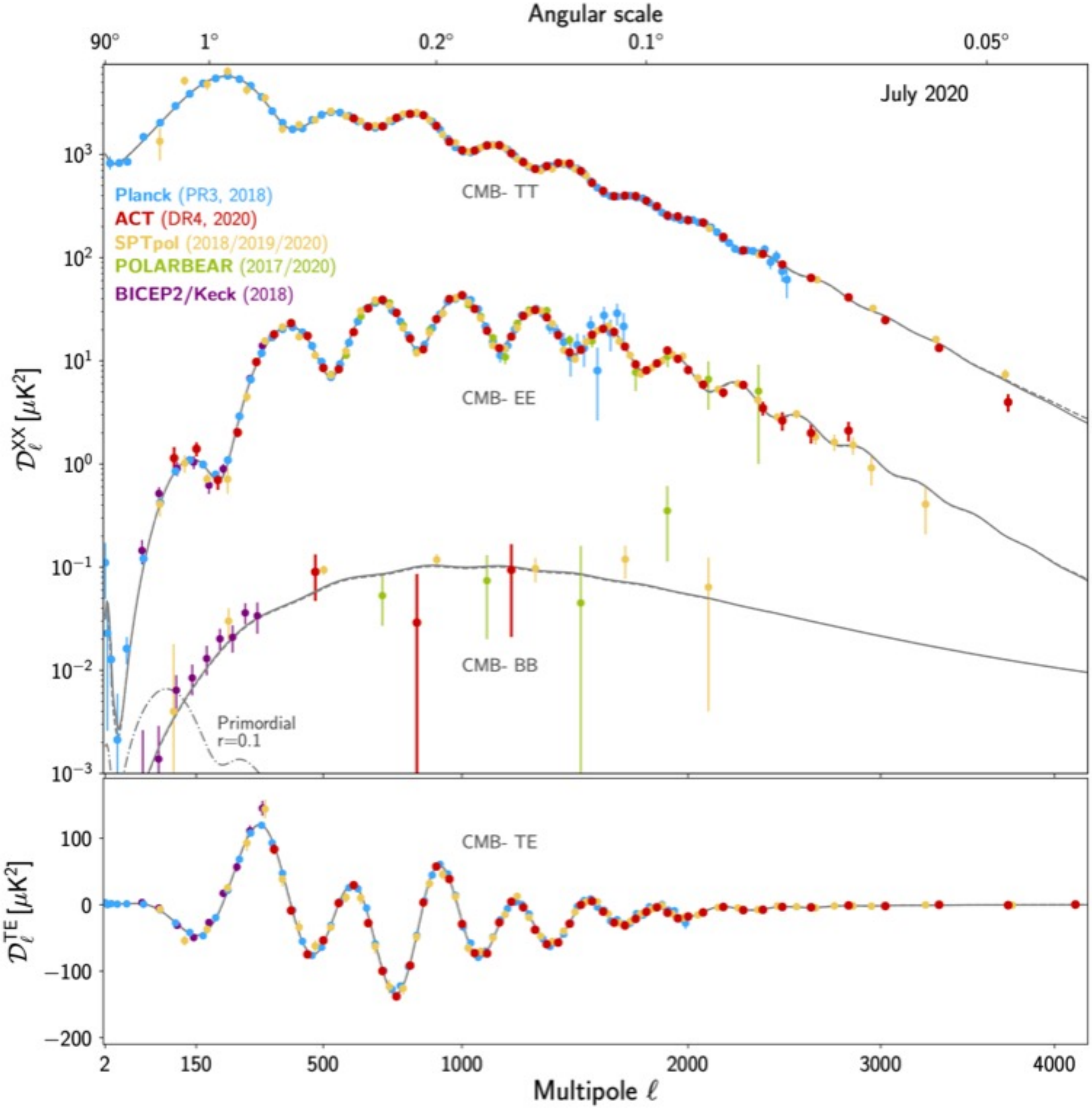


Excellent check on our understanding.
(Not post-hoc!)



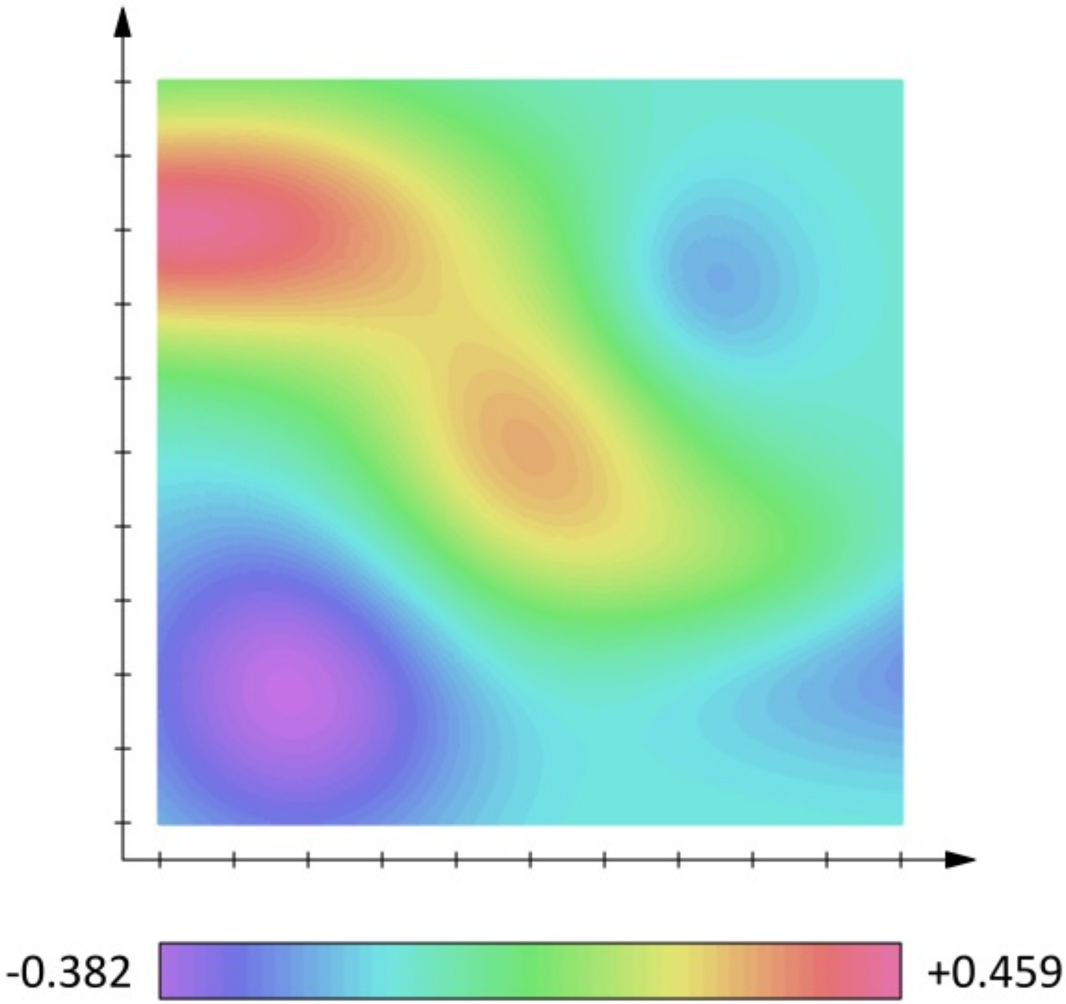
T-E correlation!





Angular scale
90°
1°
0.2°
0.1°
0.05°
July 2020
Planck (PR3, 2018)
ACT (DR4, 2020)
SPTpol (2018/2019/2020)
POLARBEAR (2017/2020)
BICEP2/Keck (2018)
CMB- TT
CMB- EE
CMB- BB
CMB- TE
Primordial
r=0.1
$\mathcal{D}_\ell^{XX}\,[\mu K^2]$
$\mathcal{D}_\ell^{TE}\,[\mu K^2]$
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
100
0
−100
−200
2
150
500
1000
2000
3000
4000
Multipole ℓ

Perturbations: Scalar



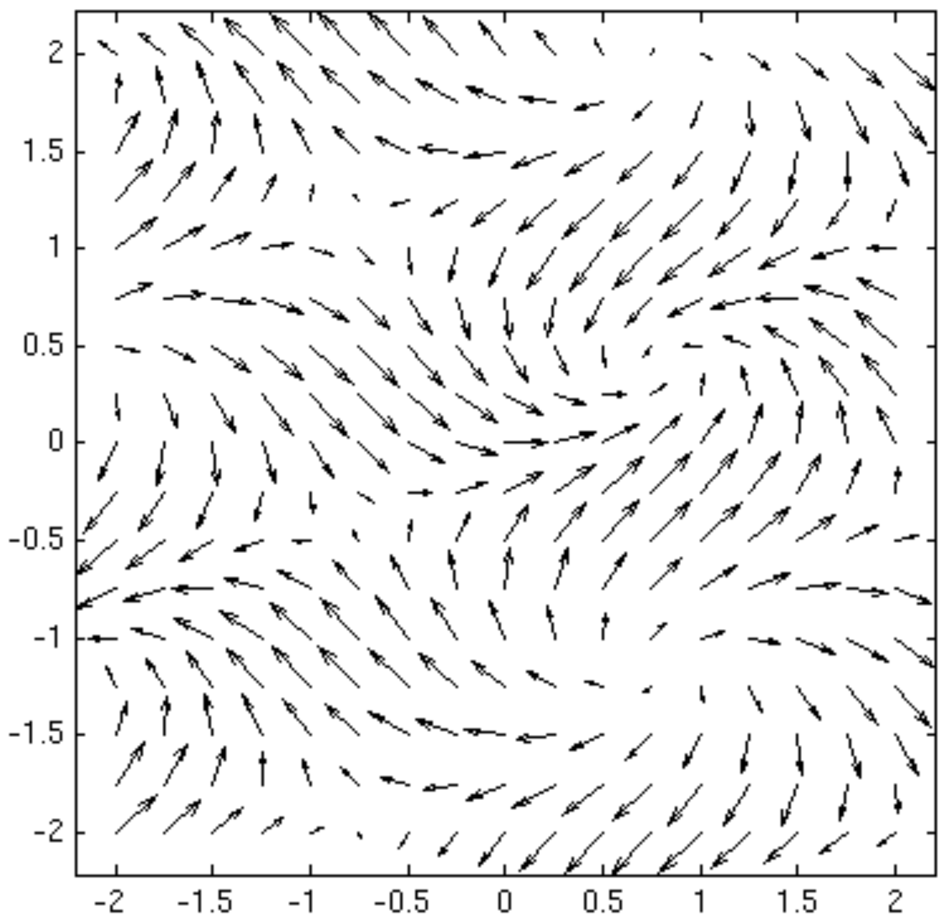
Perturbations in the energy density field. (Adiabatic)

Random Harrison-Zeldovich realization. (Scale invariant)

Evolve as discussed, into structure! E-mode pol only!

Described by amplitude (A_s) and tilt (n_s)

Perturbations: Vectors

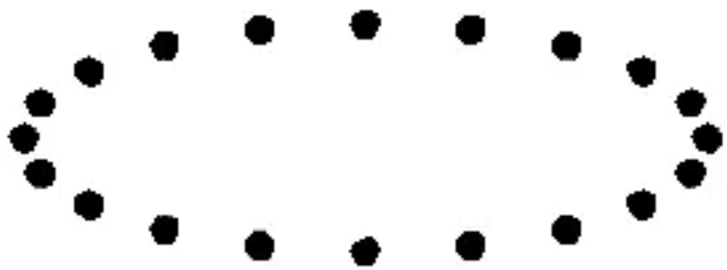


Perturbations in the velocity field.

Peculiar velocities damp out with the expansion!

Negligible by the time of decoupling. Not observable.

Perturbations: Tensors

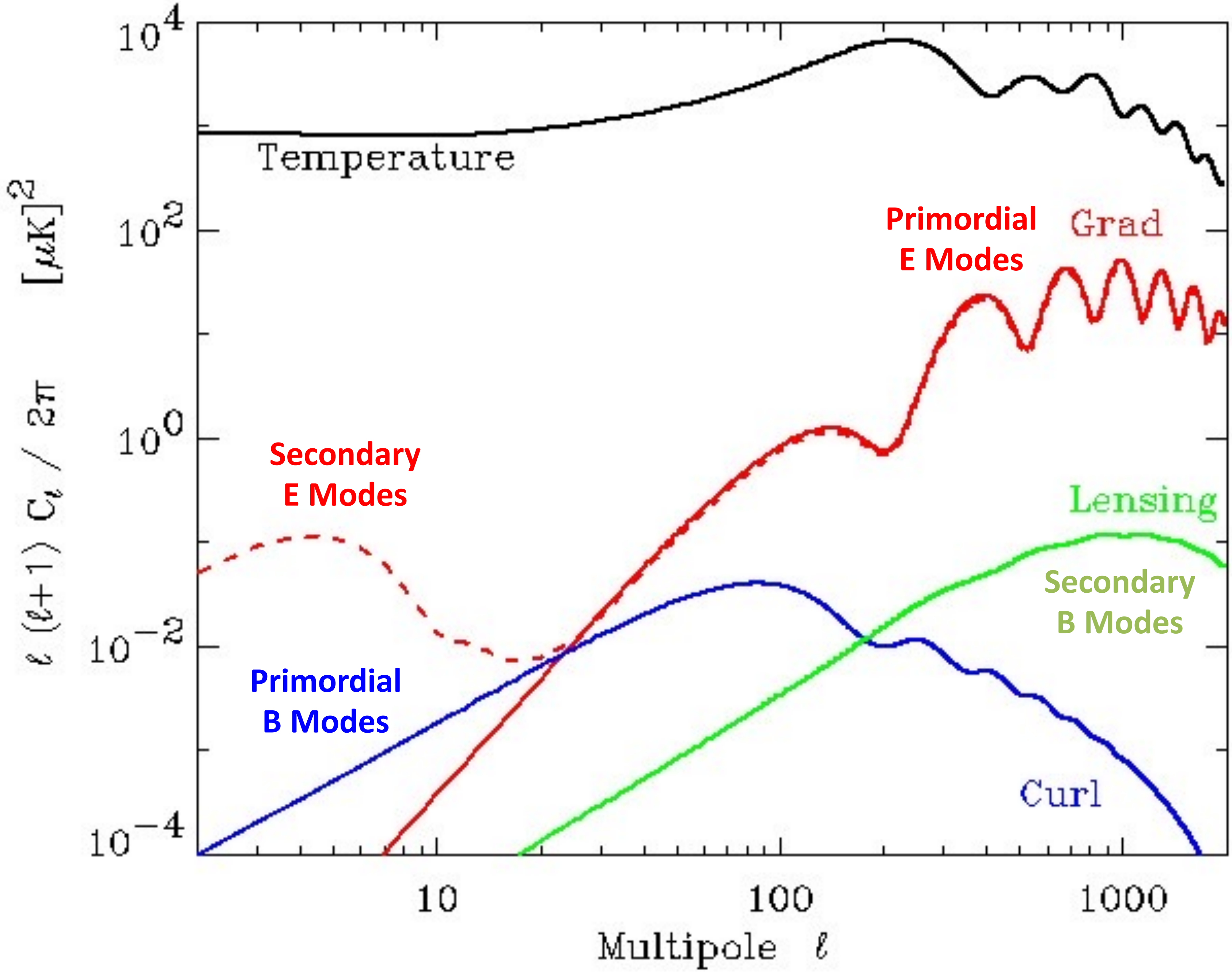


Gravitational waves!

Random realization.
(Scale invariant)

Random polarization at every point: E- and B-modes produced!

Described by amplitude relative to scalar
(r = $A_T^2 / 16A_S^2$) and tilt (n_T)



Temperature
Primordial E Modes
Grad
Secondary E Modes
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Secondary B Modes
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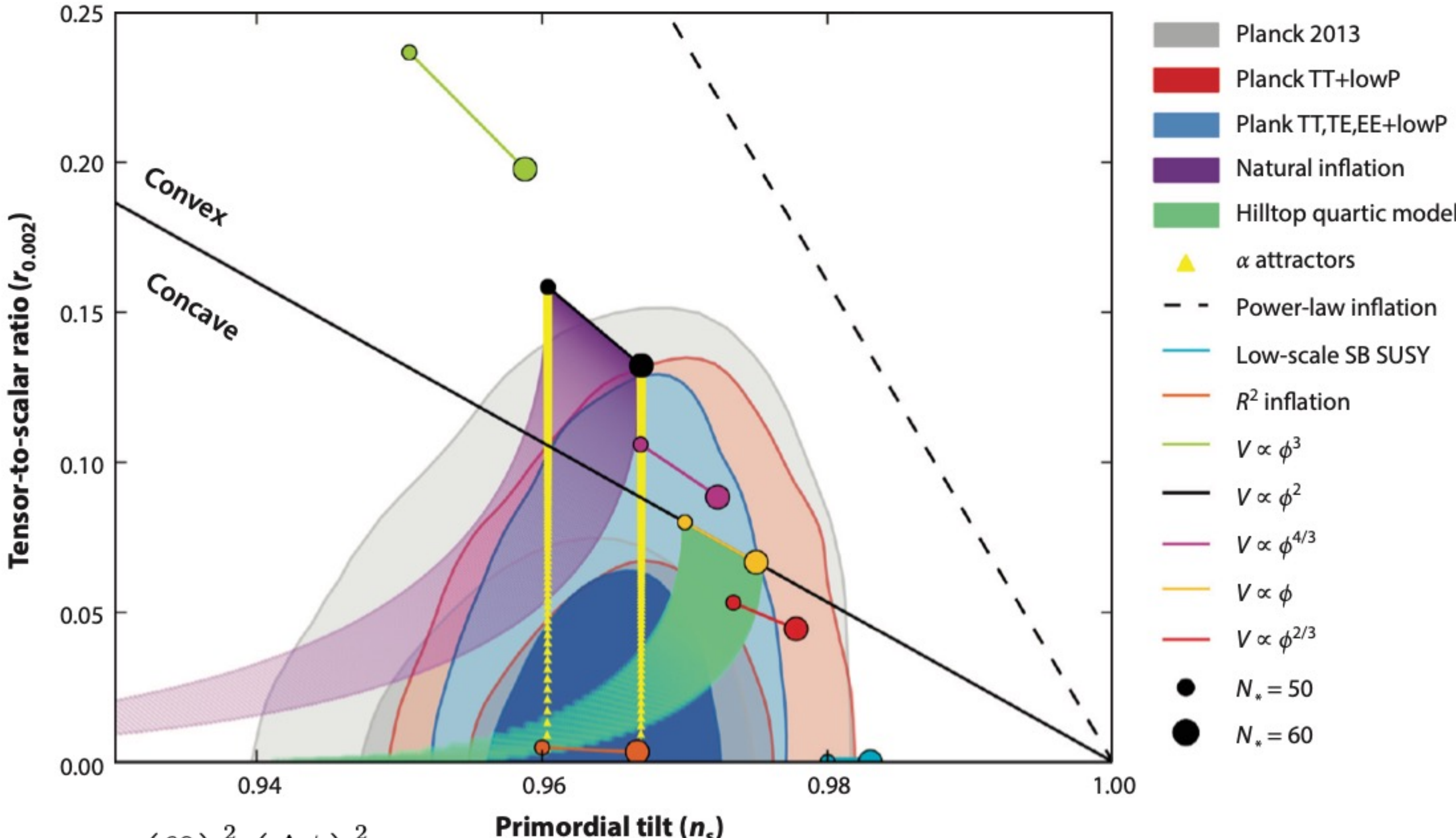
Curl
10^4
10^2
10^0
10^{-2}
10^{-4}
$\ell\ (\ell+1)\ C_\ell\ /\ 2\pi\ \ [\mu K]^2$
10
100
1000
Multipole ℓ

Inflation Potential



$$r \simeq 0.002 \left(\frac{60}{N}\right)^2 \left(\frac{\Delta\phi}{M_{\rm pl}}\right)^2$$

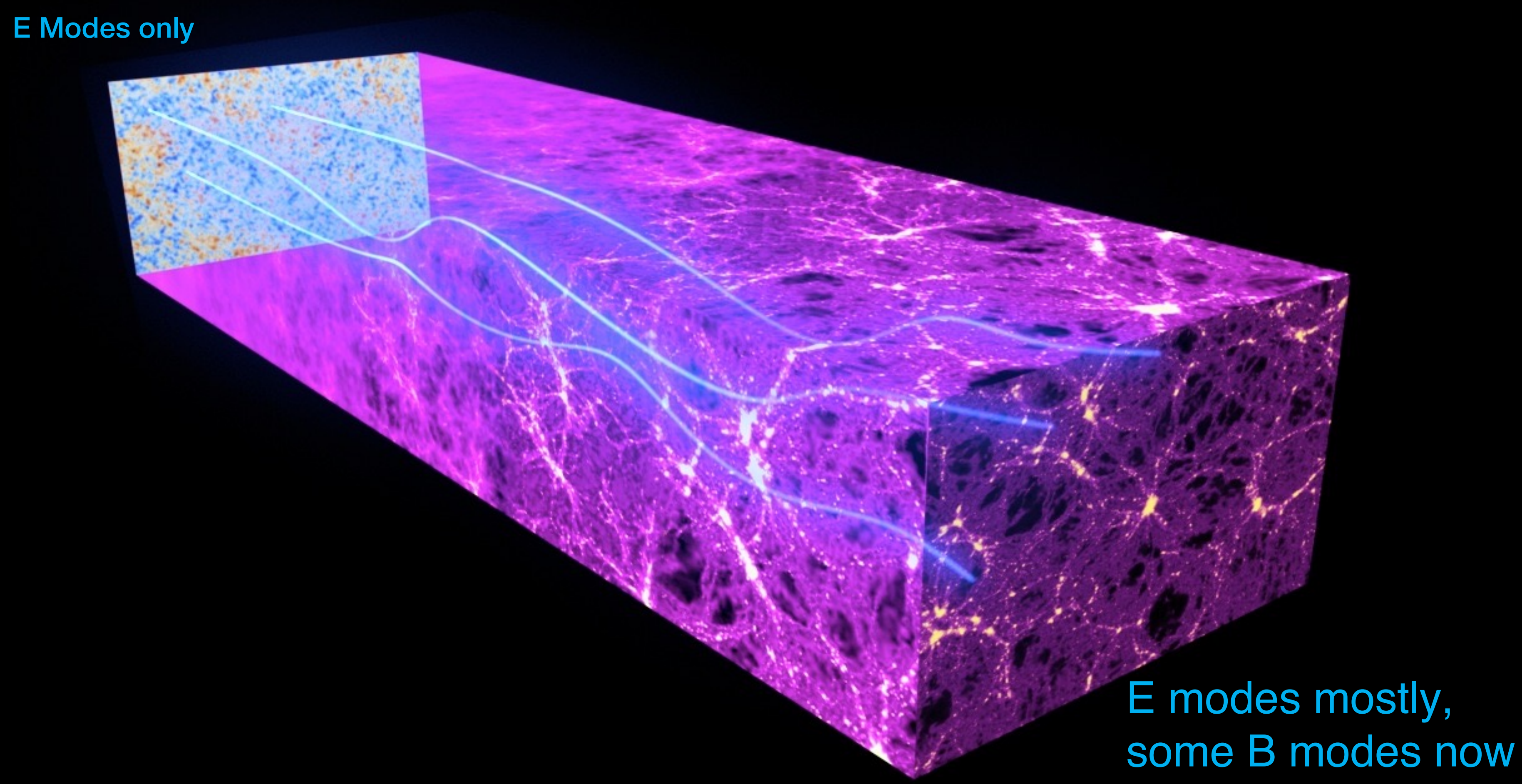
Consistency Relation

Why bother trying to measure Tensor Perturbations?

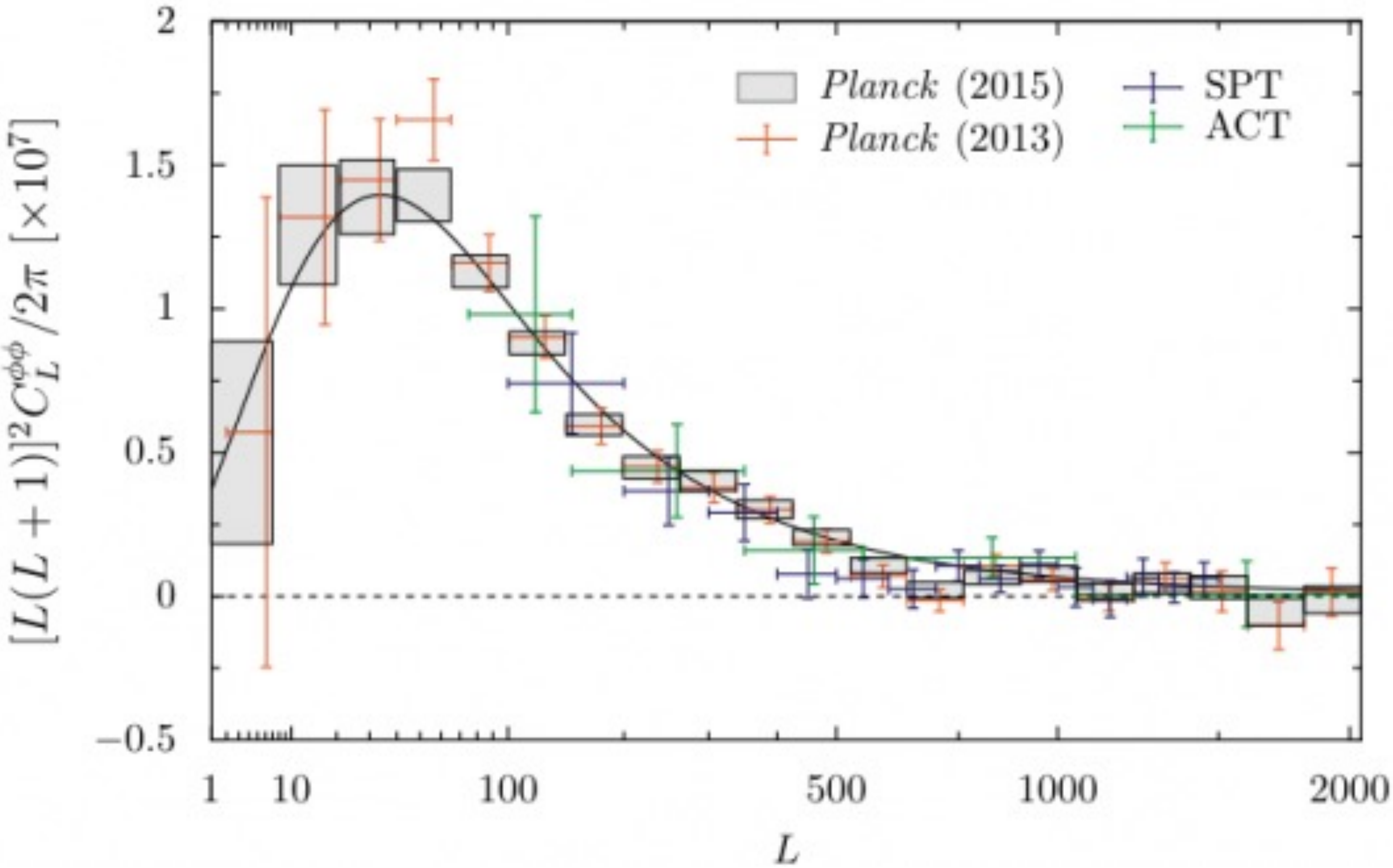
$$r = -\,8\; n_T$$

True for all slow-roll single-field inflation models!
A firm prediction!

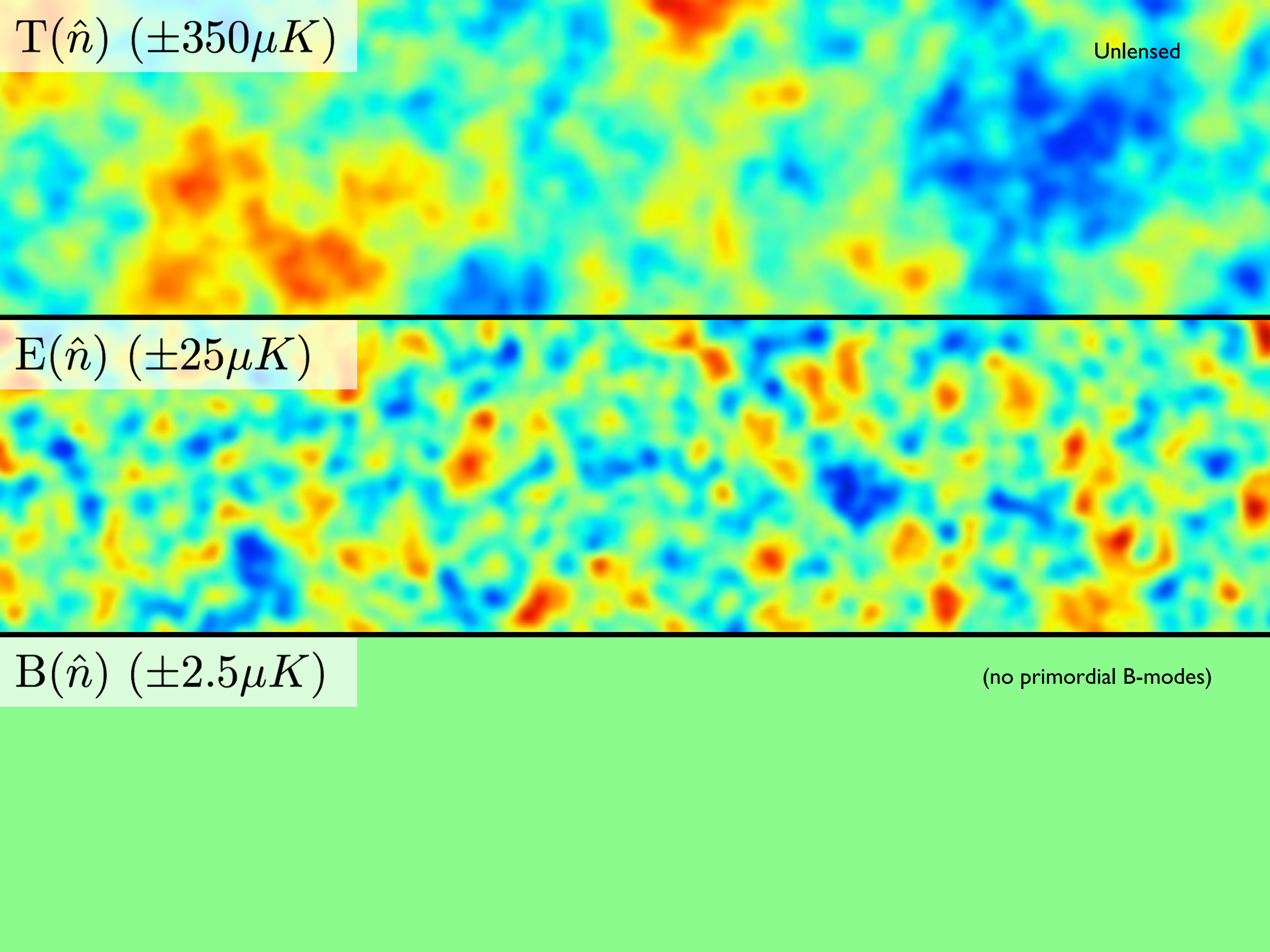
Gravitational Lensing



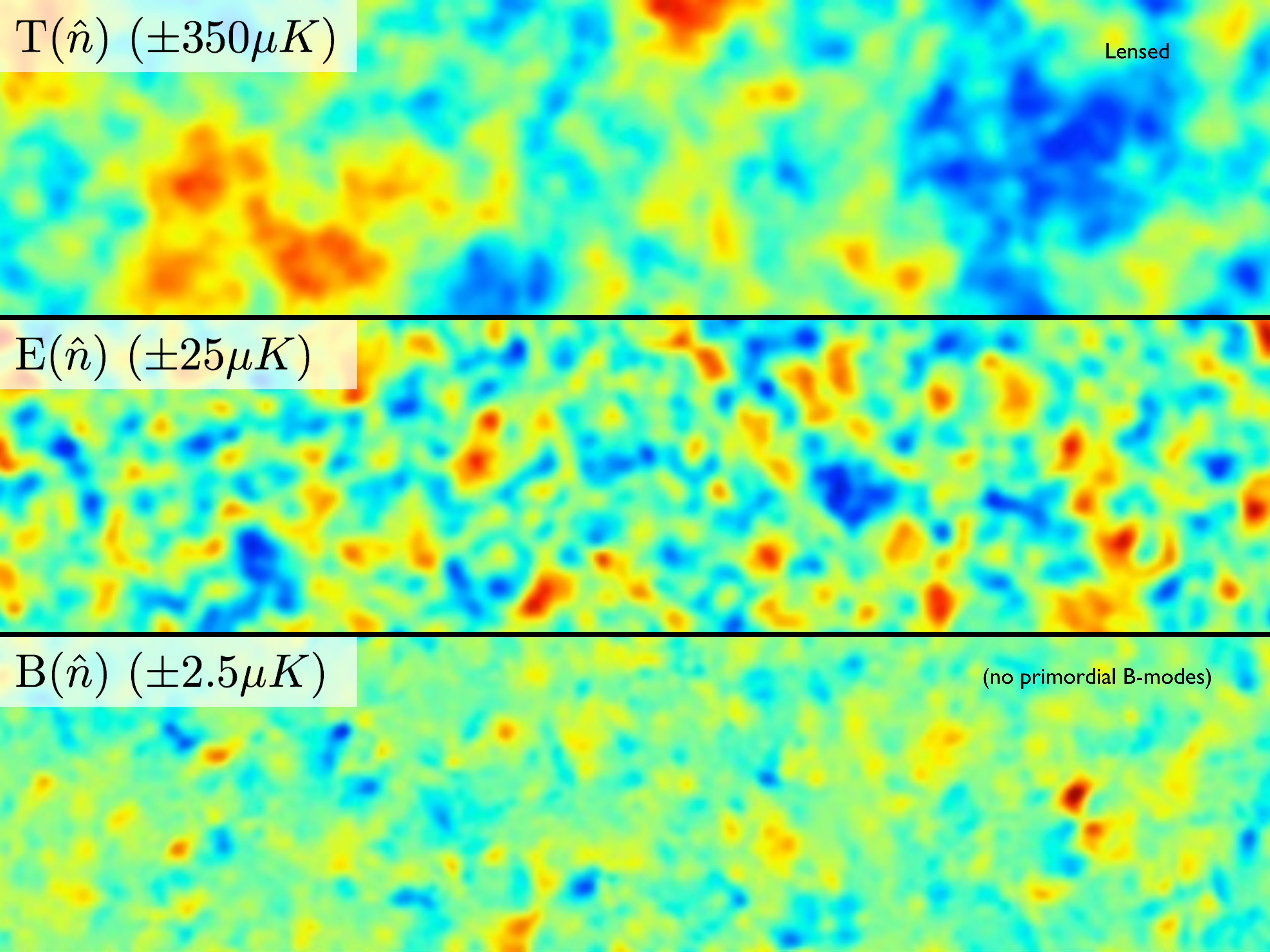
CMB Lensing



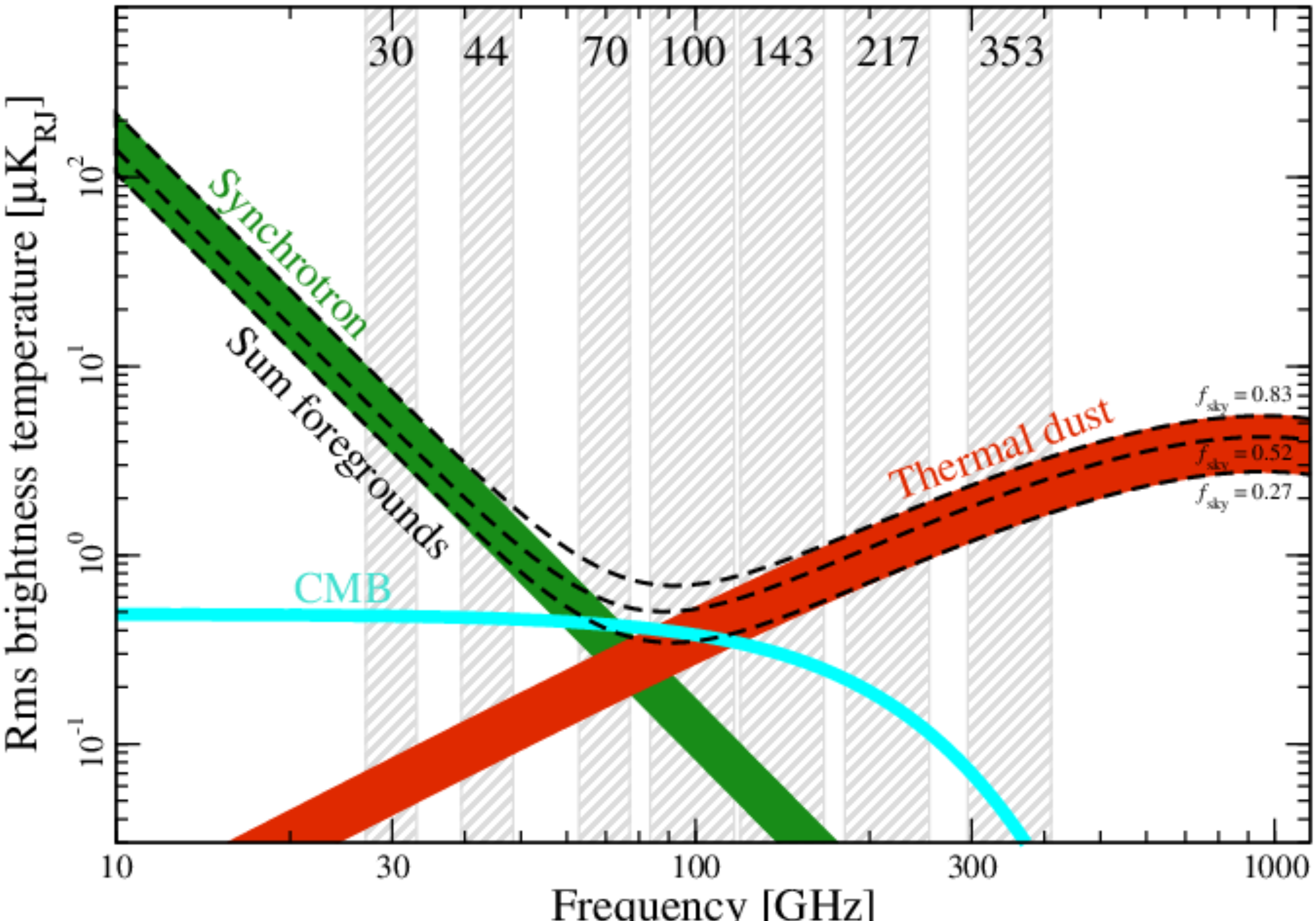
Planck (2015)
Planck (2013)
SPT
ACT
$[L(L+1)]^2 C_L^{\phi\phi}/2\pi\ [\times 10^7]$
2
1.5
1
0.5
0
−0.5
1
10
100
500
1000
2000
L



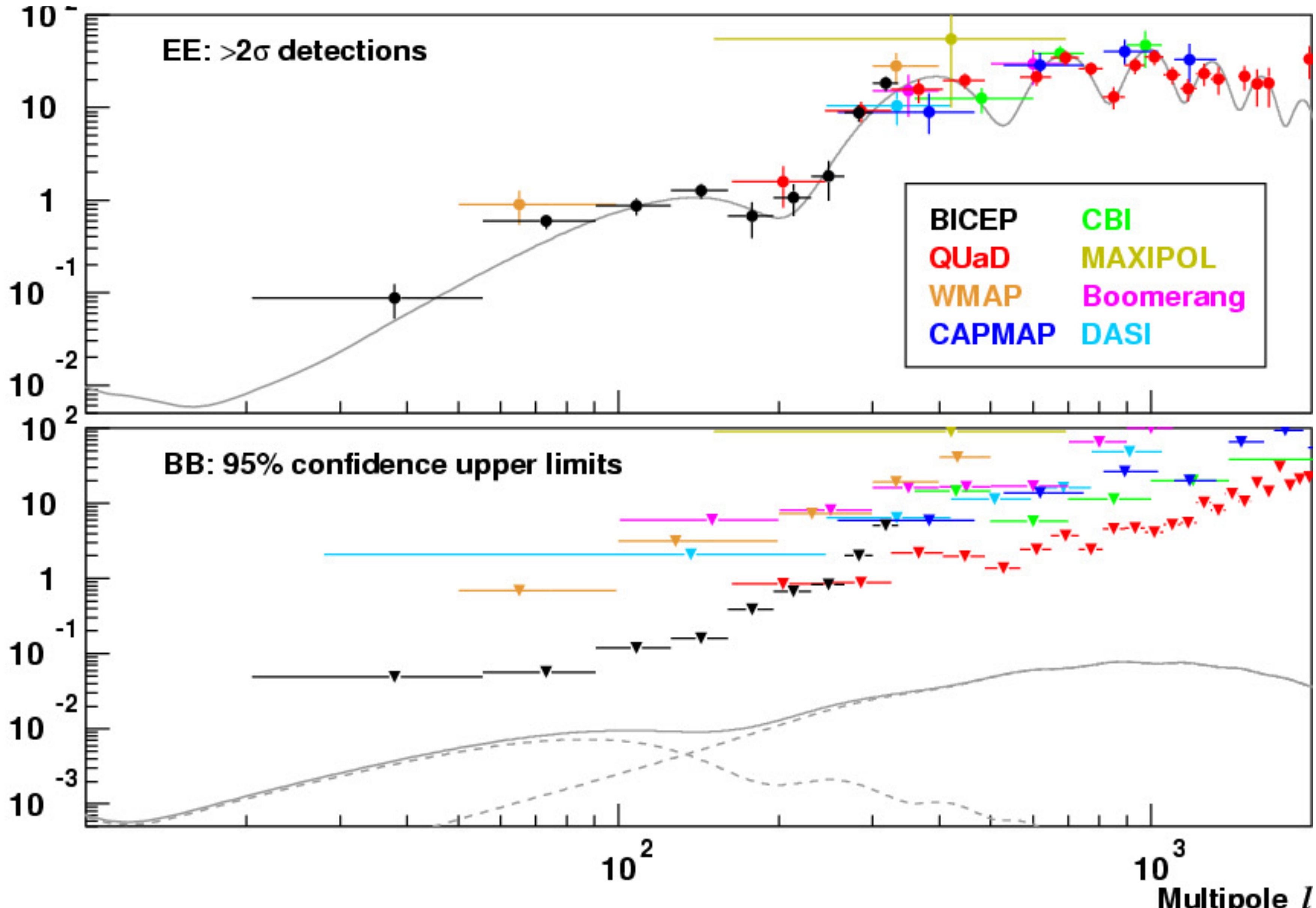
$T(\hat{n})$ $(\pm 350\mu K)$
Unlensed
$E(\hat{n})$ $(\pm 25\mu K)$
$B(\hat{n})$ $(\pm 2.5\mu K)$
(no primordial B-modes)


$T(\hat{n})$ $(\pm 350\mu K)$
Lensed
$E(\hat{n})$ $(\pm 25\mu K)$
$B(\hat{n})$ $(\pm 2.5\mu K)$
(no primordial B-modes)

Polarized Foregrounds

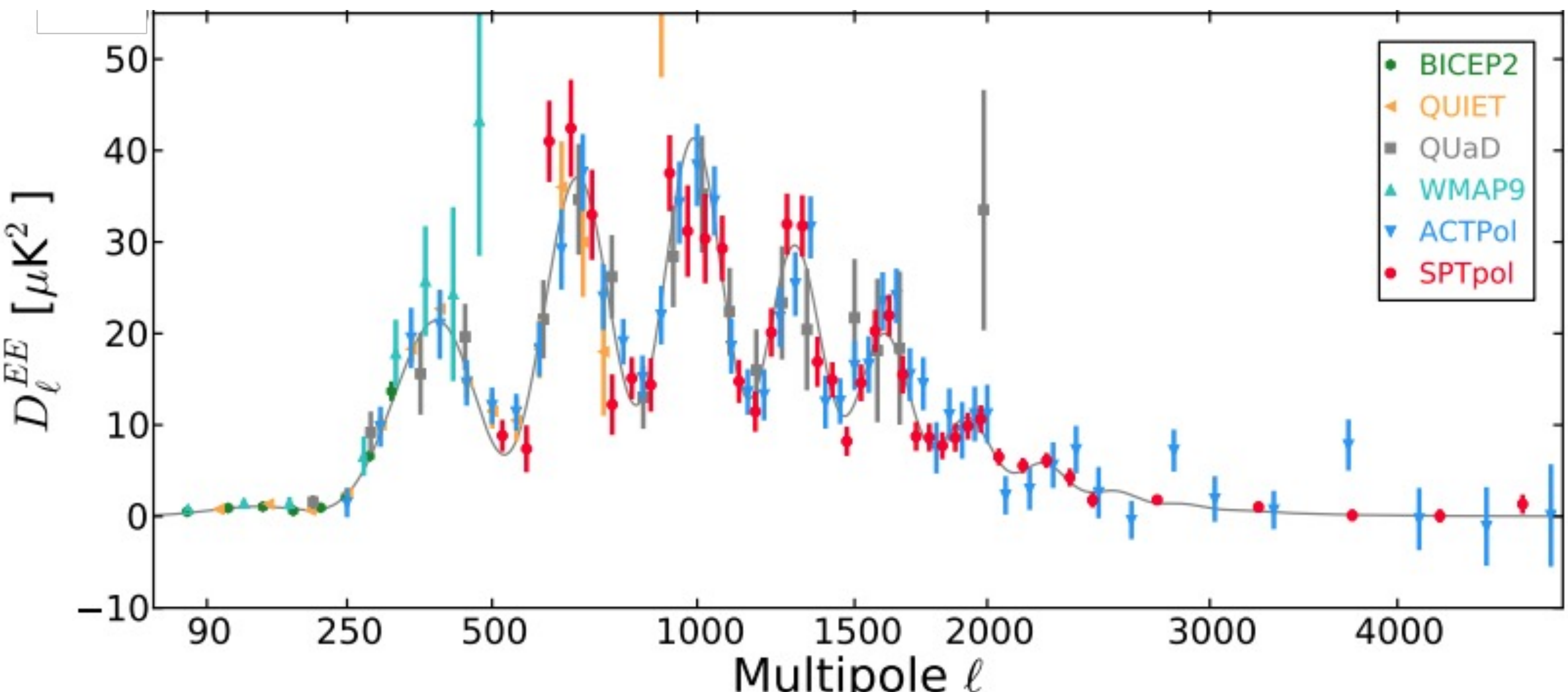


Circa 2009

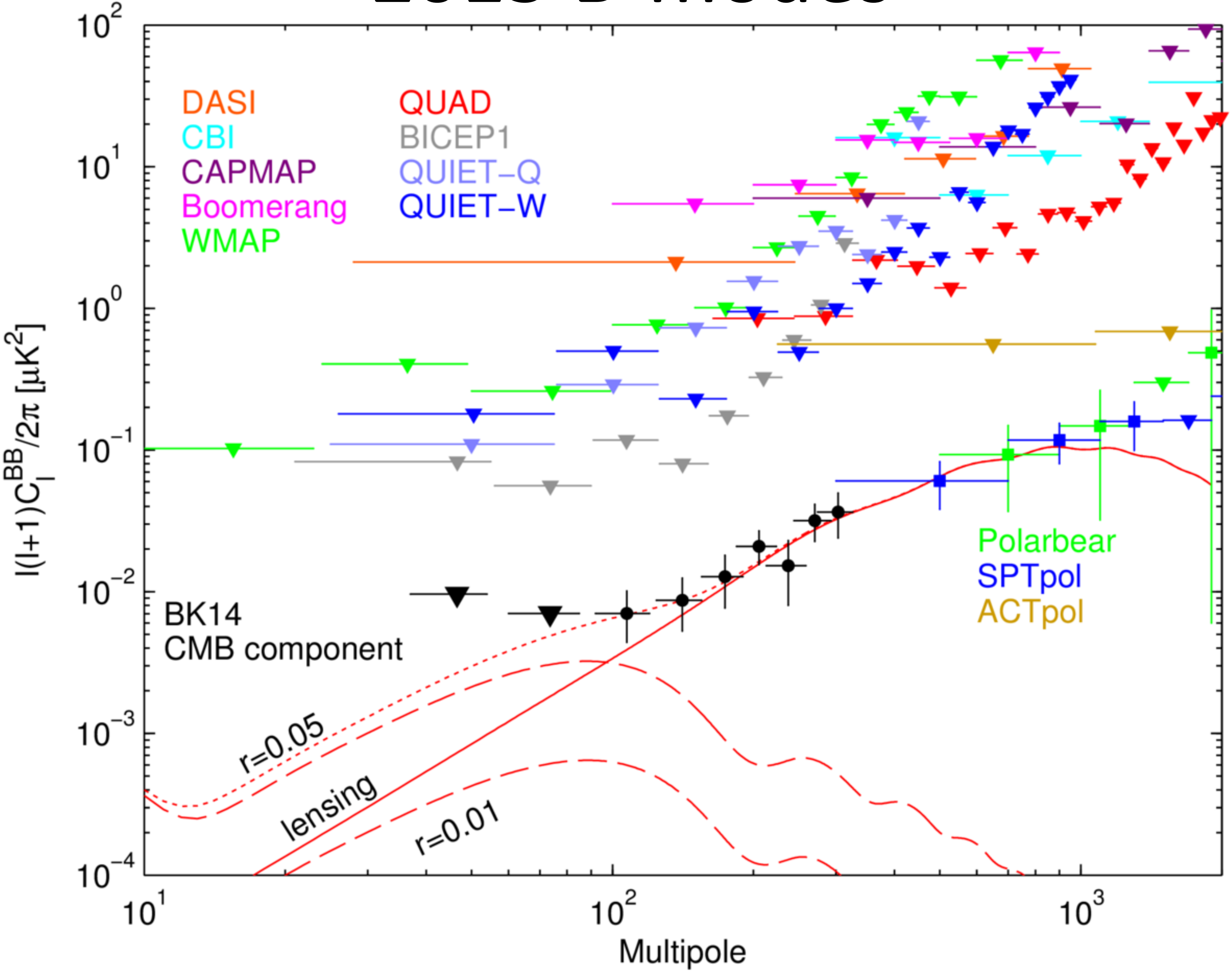


EE: >2σ detections
BB: 95% confidence upper limits
BICEP
CBI
QUaD
MAXIPOL
WMAP
Boomerang
CAPMAP
DASI
Multipole l

2015 E-modes


BICEP2
QUIET
QUaD
WMAP9
ACTPol
SPTpol
50
40
30
20
10
0
−10
90
250
500
1000
1500
2000
3000
4000
Multipole ℓ
D_ℓ^{EE} [μK^2]

2015 B-modes


DASI
CBI
CAPMAP
Boomerang
WMAP
QUAD
BICEP1
QUIET−Q
QUIET−W
Polarbear
SPTpol
ACTpol
BK14
CMB component
r=0.05
lensing
r=0.01
$l(l+1)C_l^{BB}/2\pi\ [\mu K^2]$
Multipole

Next Time:

Presentations!