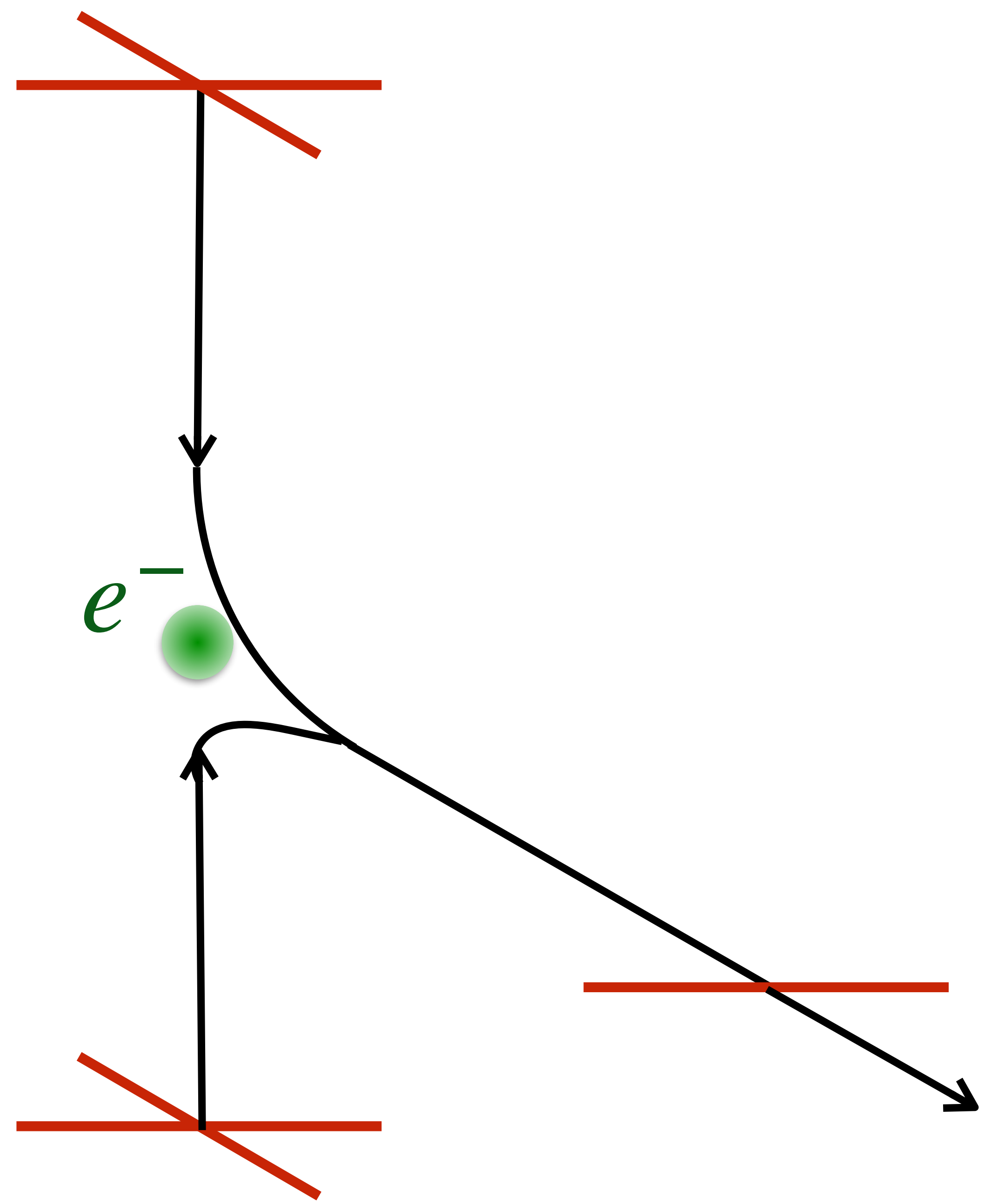
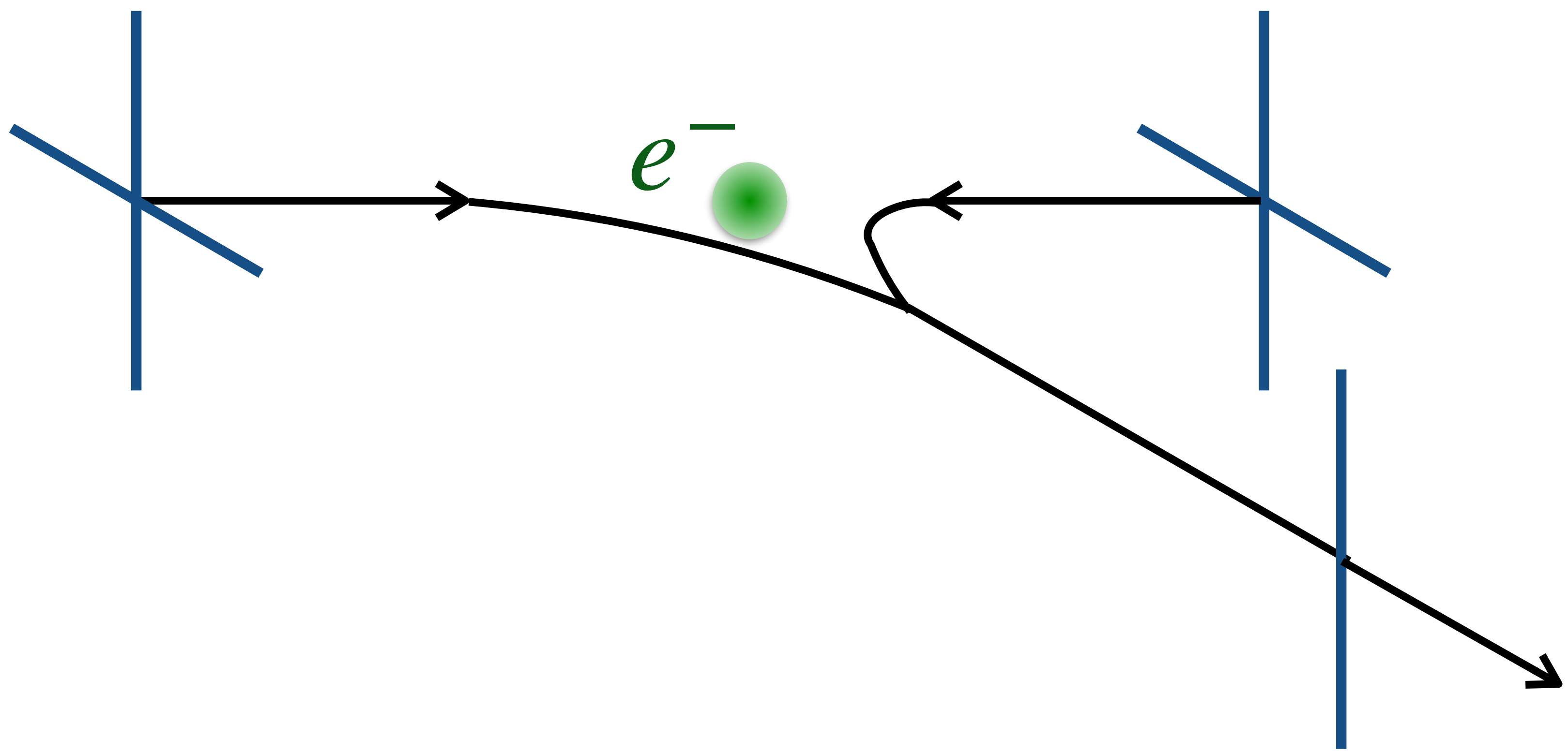
CMB polarisation

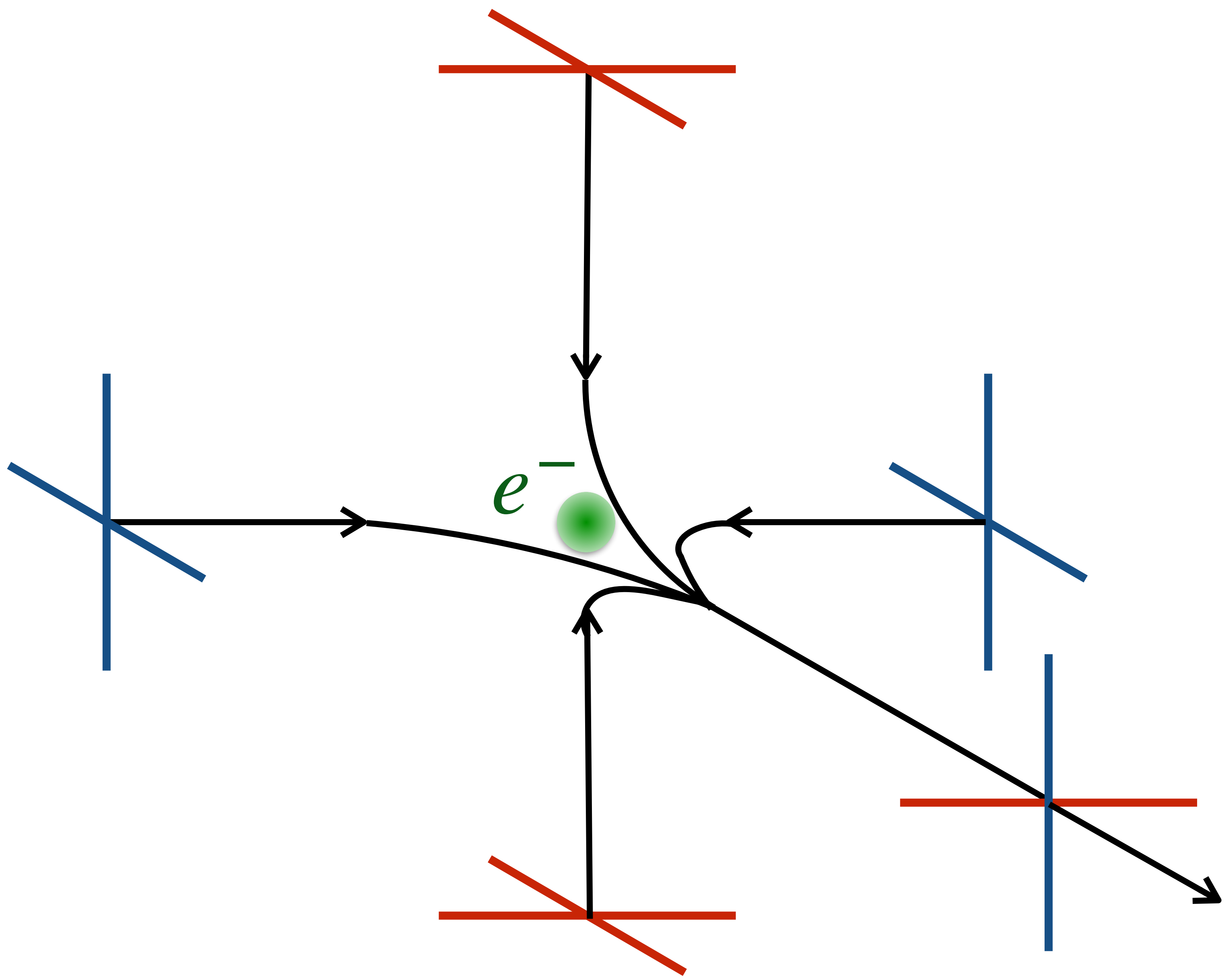
CMB polarisation



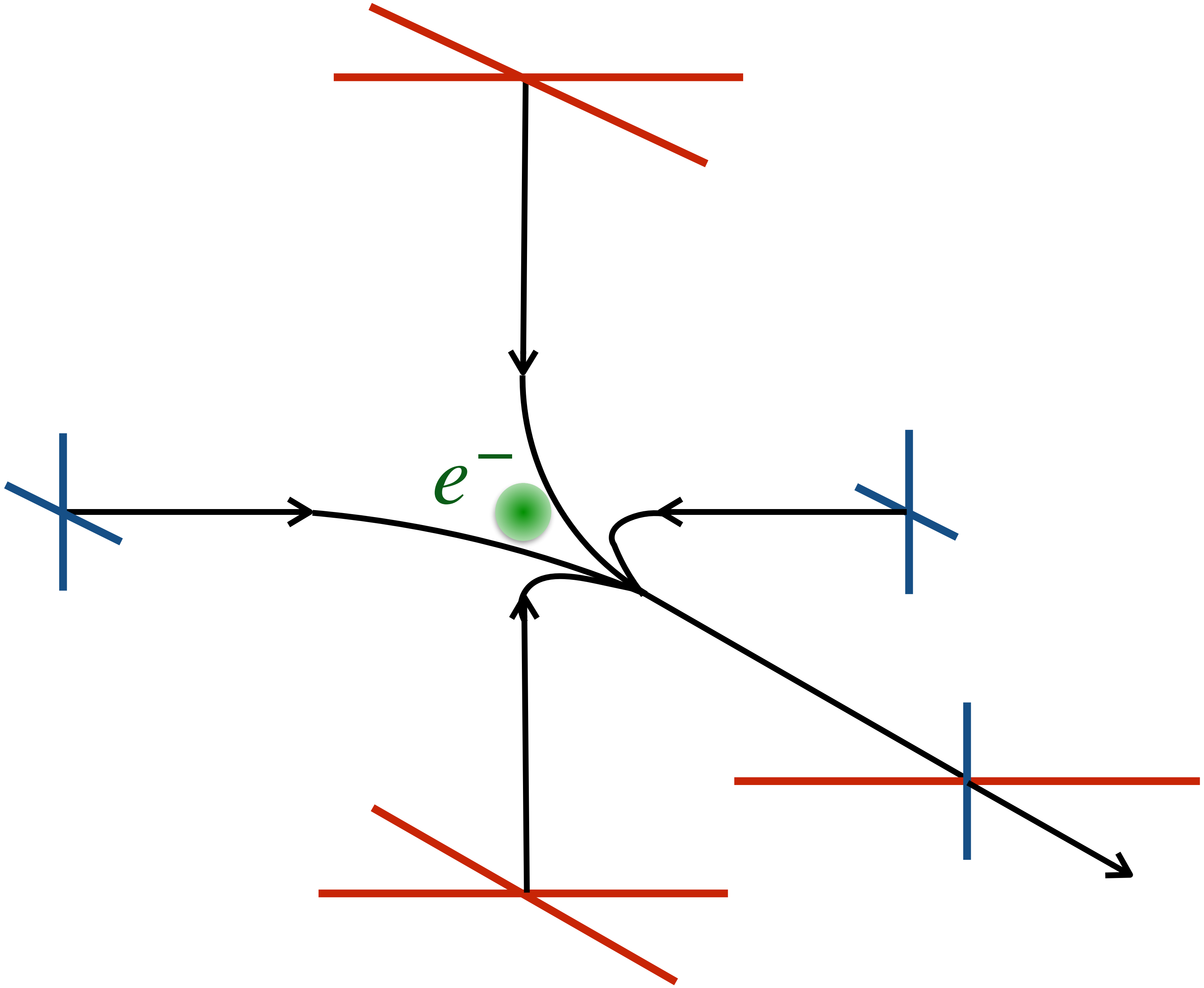
CMB polarisation



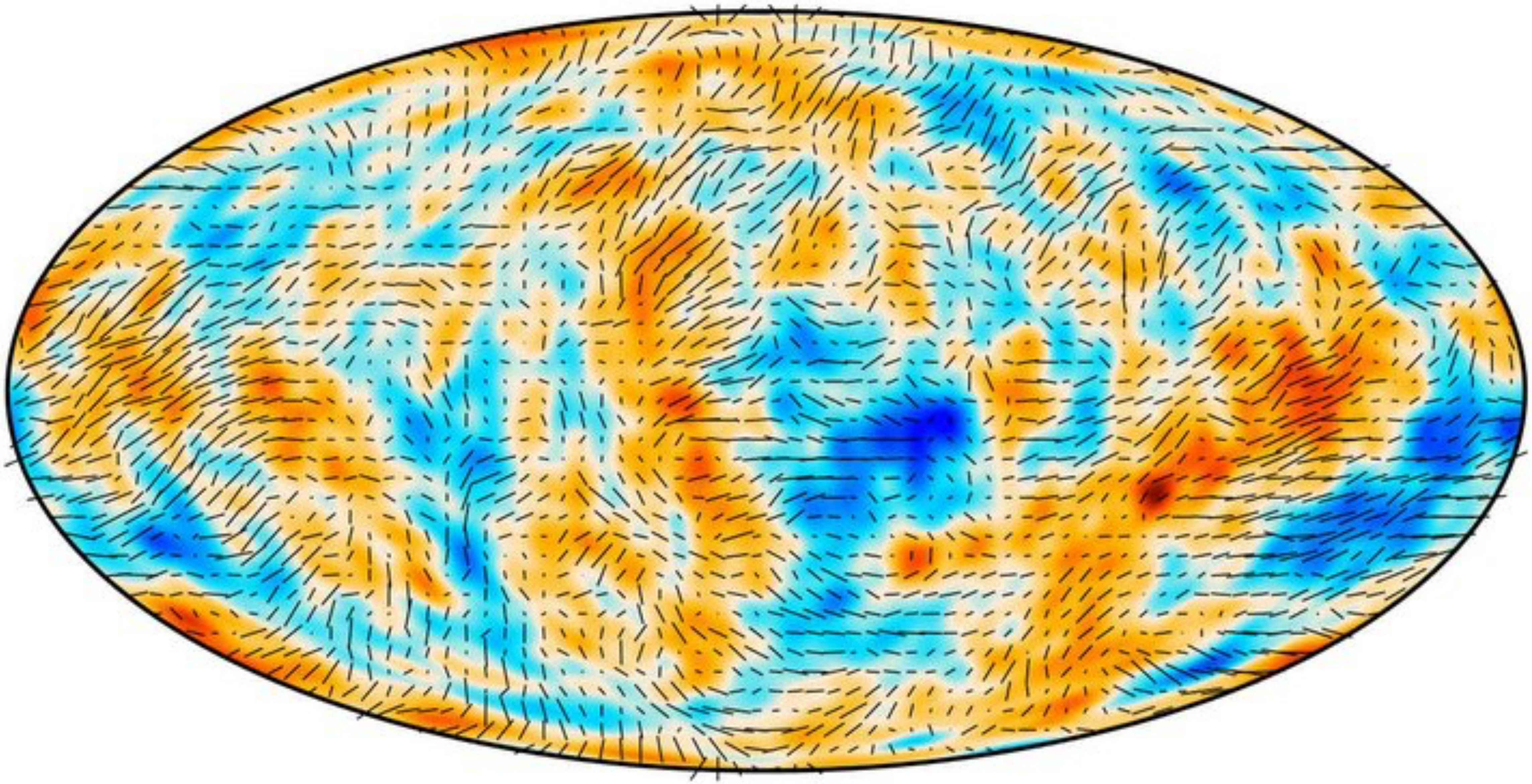
CMB polarisation



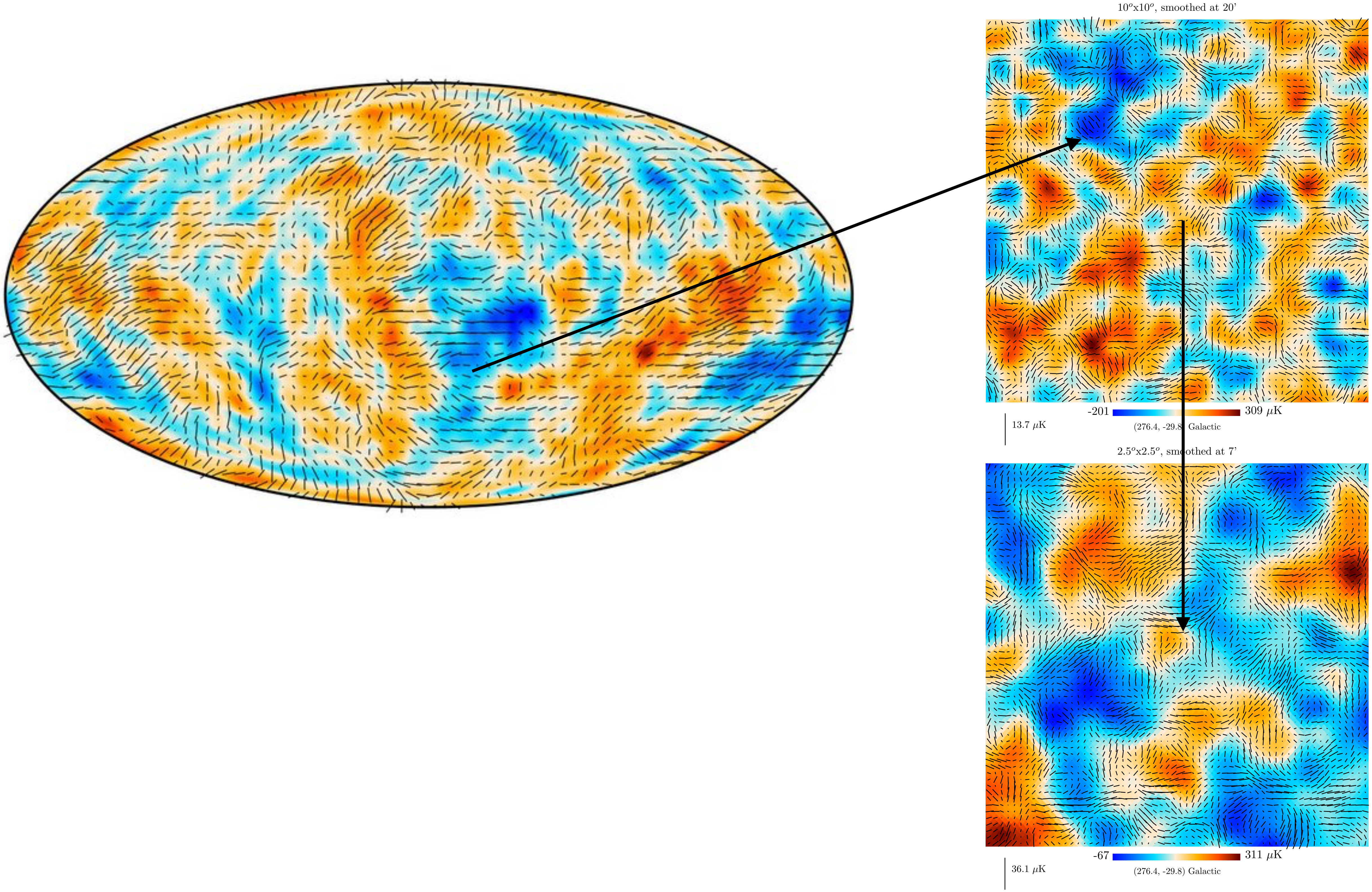
CMB polarisation



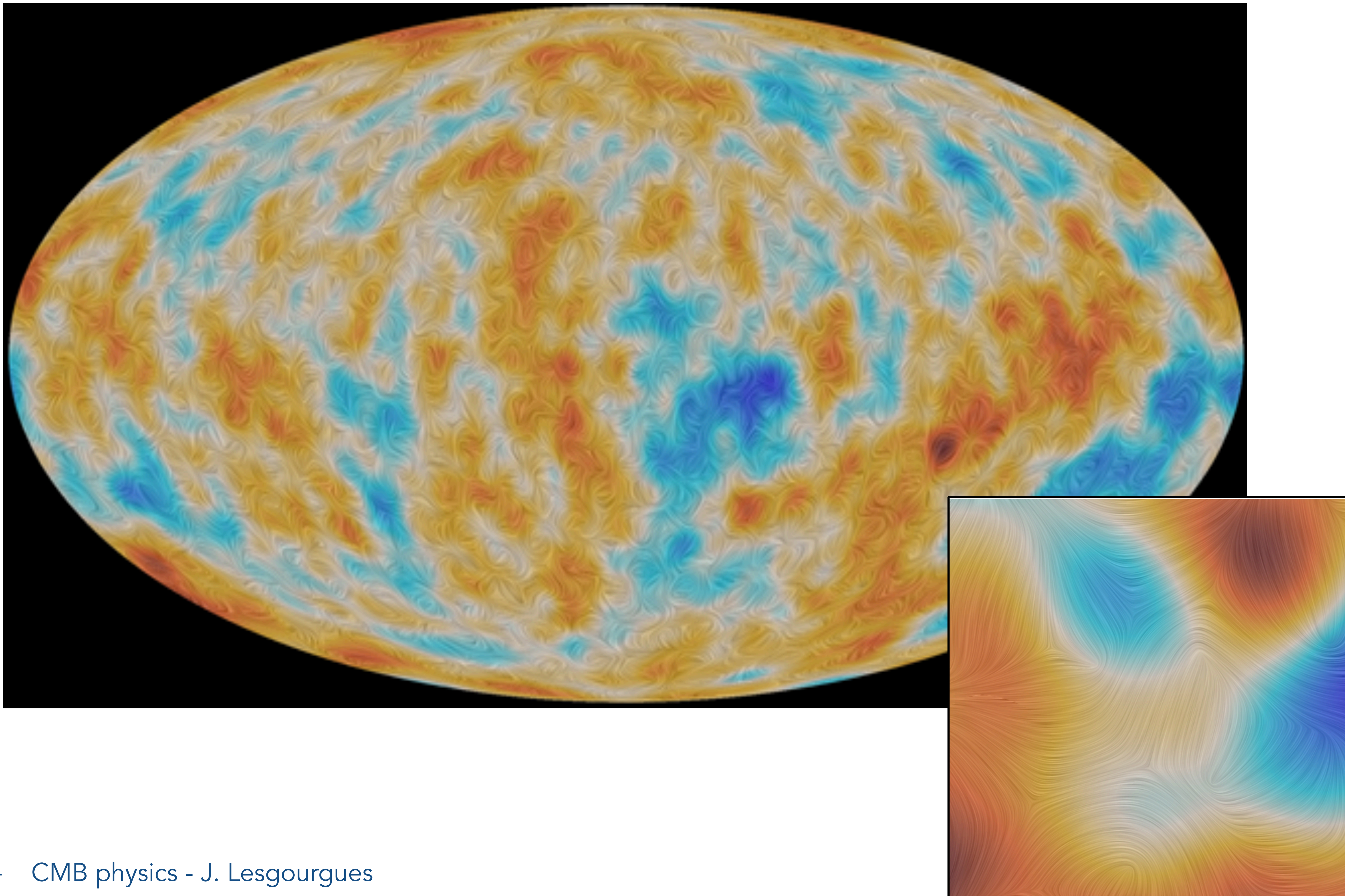
CMB polarisation



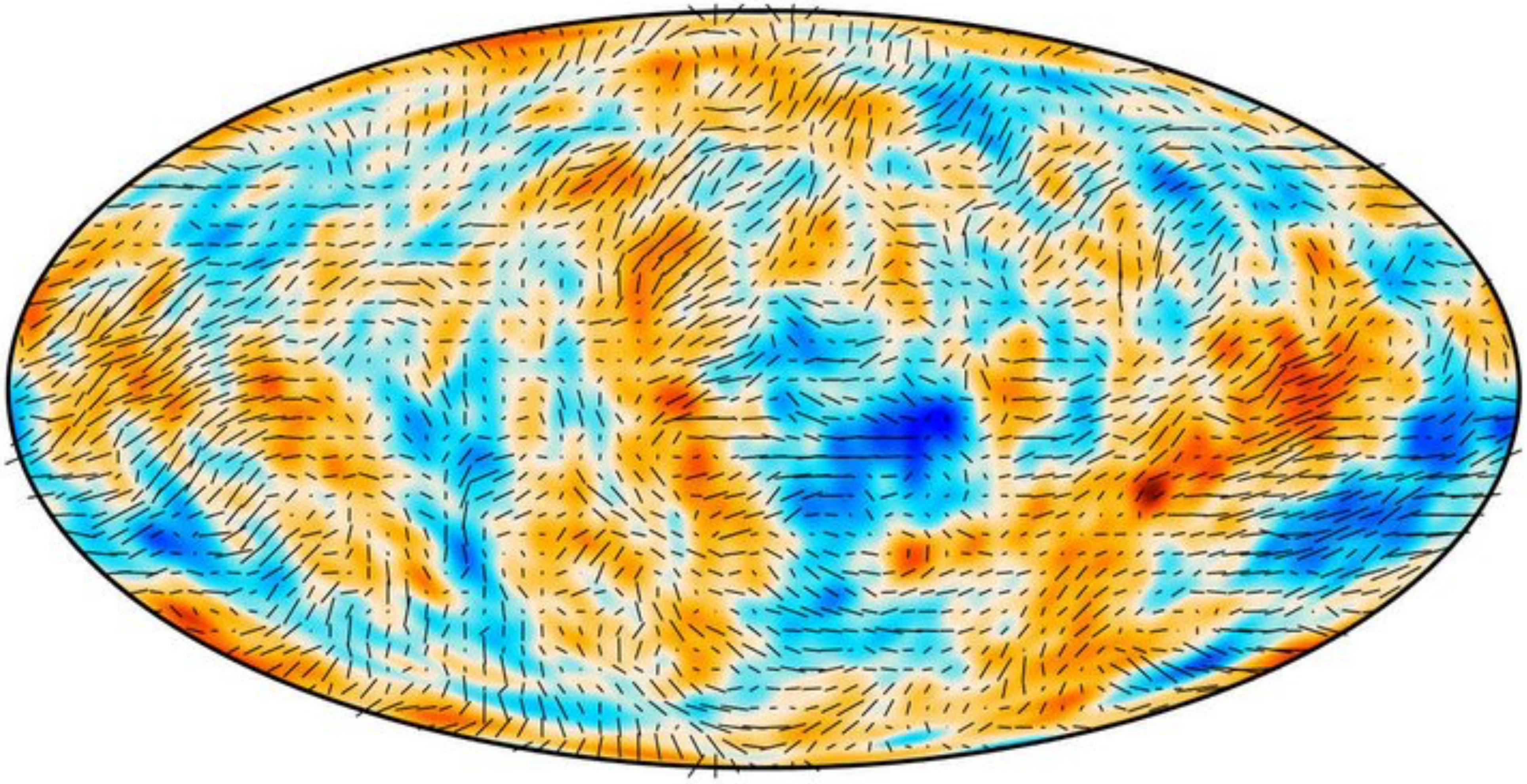
CMB polarisation



CMB polarisation



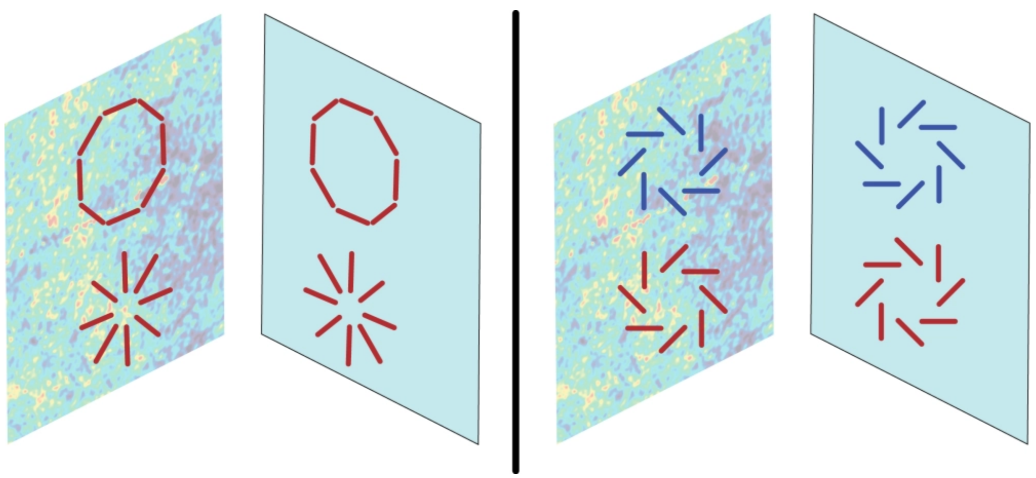
CMB polarisation

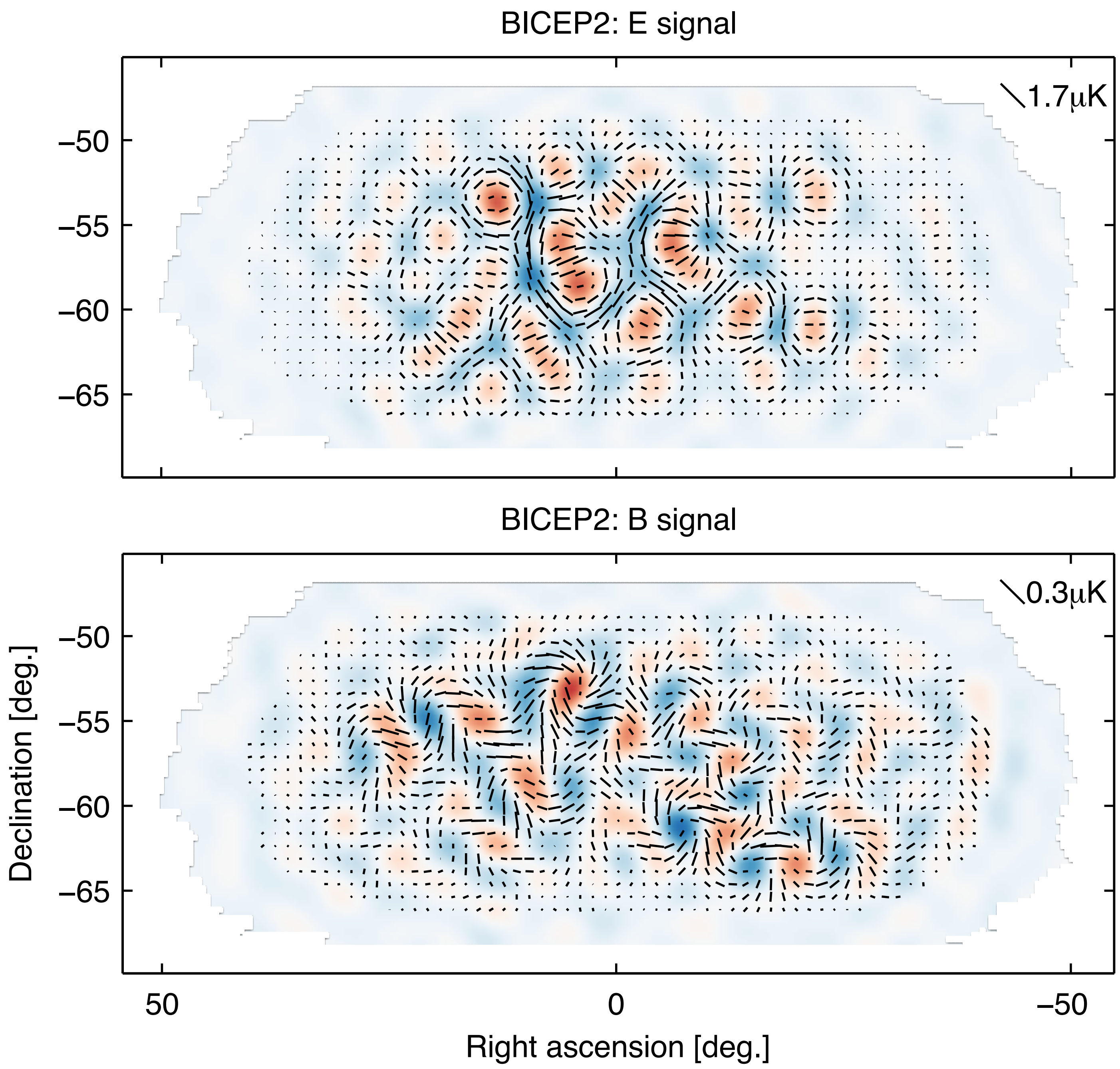


1 spin-two map ⇔ 2 scalar maps (E = gradient field, B = rotation field), but:

scalar modes → gradients → B-mode vanish

CMB polarisation





CMB polarisation

Temperature spectrum: $C_\ell^{TT} = \langle a_{lm}^T a_{lm}^{T*} \rangle = \frac{2}{\pi} \int dk\, k^2 [\Theta_\ell(\eta_0, k)]^2 \;\; P_{\mathscr{R}}(k)$

with transfer function
$$\Theta_l(\eta_0,k) = \int_{\eta_{\rm ini}}^{\eta_0} d\eta \,\{ g\,(\Theta_0 + \psi)\; j_l(k(\eta_0 - \eta)) + g\, k^{-1}\theta_{\rm b}\; j_l'(k(\eta_0 - \eta)) + e^{-\tau}(\phi' + \psi')\, j_l(k(\eta_0 - \eta))\}$$

For polarisation:

Kosowsky 1996; Seljak & Zaldarriaga astro-ph/9609170; Hu & White astro-ph/9702170

CMB polarisation

Temperature spectrum: $C_\ell^{TT} = \langle a^T_{lm} a^{T*}_{lm} \rangle = \frac{2}{\pi} \int dk\, k^2 [\Theta_\ell(\eta_0, k)]^2 \;\; P_{\mathcal{R}}(k)$

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$$\Theta_l(\eta_0,k) = \int_{\eta_{\rm ini}}^{\eta_0} d\eta \, \{ g \, (\Theta_0 + \psi) \; j_l(k(\eta_0 - \eta)) + g \, k^{-1}\theta_{\rm b} \; j_l'(k(\eta_0 - \eta)) + e^{-\tau} (\phi' + \psi') \, j_l(k(\eta_0 - \eta)) \}$$

For polarisation:

Kosowsky 1996; Seljak & Zaldarriaga astro-ph/9609170; Hu & White astro-ph/9702170

E-mode polarisation spectrum: $C_\ell^{EE} = \langle a^E_{lm} a^{E*}_{lm} \rangle = \frac{2}{\pi} \int dk\, k^2 [\Delta^E_\ell(\eta_0, k)]^2 \;\; P_{\mathcal{R}}(k)$

E

with transfer function $\Delta^E_l(\eta_0, k) = \int_{\eta_{\rm ini}}^{\eta_0} d\eta \;\; g \;\; \{\Theta_2 + \ldots\} \; (\ldots) \; j_l(k(\eta_0 - \eta))$

CMB polarisation

Temperature spectrum: $C_\ell^{TT} = \langle a_{lm}^T a_{lm}^{T*} \rangle = \frac{2}{\pi} \int dk\, k^2 [\Theta_\ell(\eta_0, k)]^2 \;\; P_{\mathcal{R}}(k)$

with transfer function $\Theta_l(\eta_0,k) = \int_{\eta_{\rm ini}}^{\eta_0} d\eta \, \{ g\,(\Theta_0 + \psi)\; j_l(k(\eta_0 - \eta))$

$+\, g\, k^{-1}\theta_{\rm b}\; j_l'(k(\eta_0 - \eta))$

$+\, e^{-\tau}(\phi' + \psi')\, j_l(k(\eta_0 - \eta)) \} \;\; + \ldots$

For polarisation:

Kosowsky 1996; Seljak & Zaldarriaga astro-ph/9609170; Hu & White astro-ph/9702170

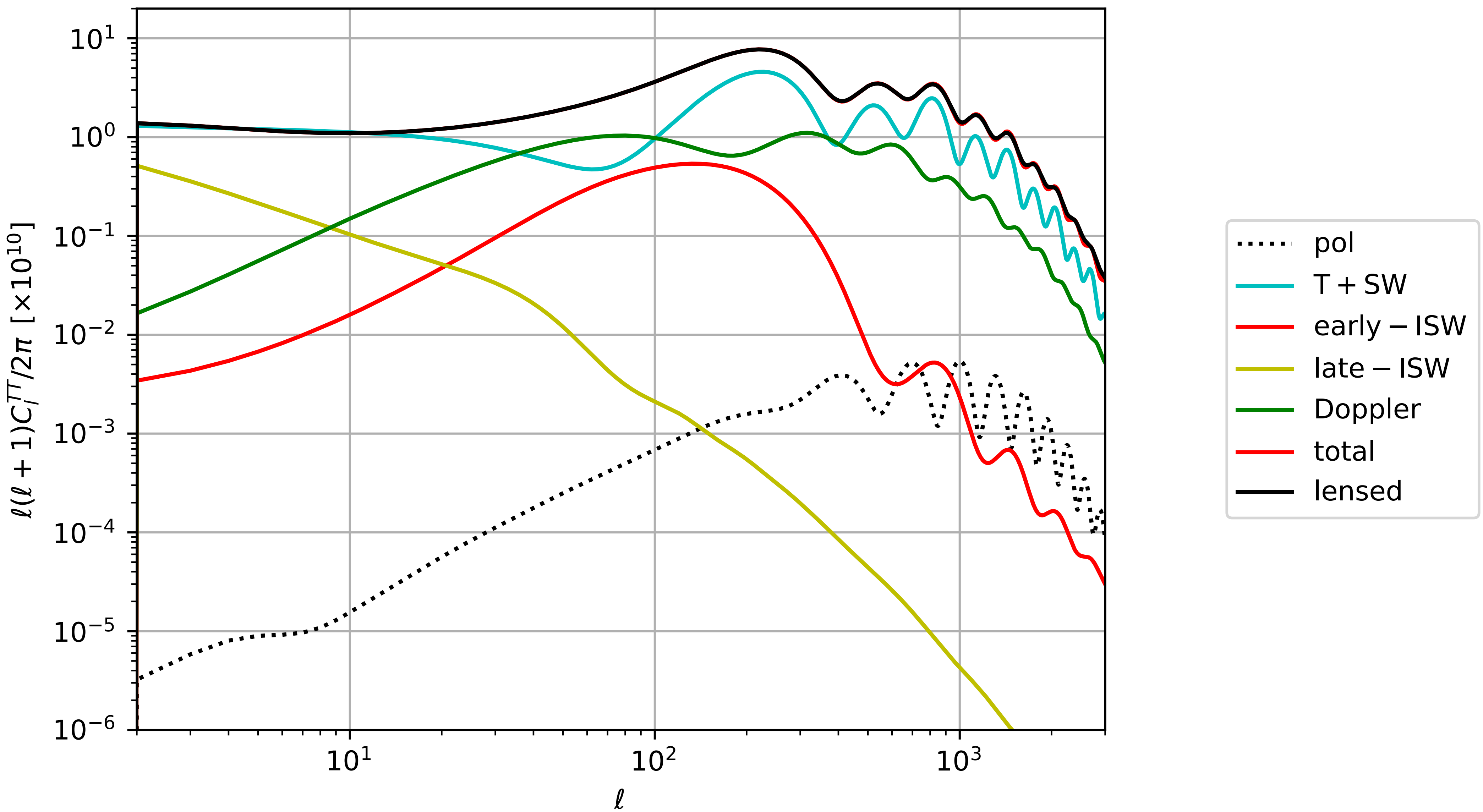
E-mode polarisation spectrum: $C_\ell^{EE} = \langle a_{lm}^E a_{lm}^{E*} \rangle = \frac{2}{\pi} \int dk\, k^2 [\Delta_\ell^E(\eta_0, k)]^2 \;\; P_{\mathcal{R}}(k)$

E

with transfer function $\Delta_l^E(\eta_0, k) = \int_{\eta_{\rm ini}}^{\eta_0} d\eta \;\; g \;\; \{\Theta_2 + \ldots\} \; (\ldots)\, j_l(k(\eta_0 - \eta))$

CMB polarisation

Corrections to temperature spectrum taking into account polarisation anisotropies



notebooks/cltt_terms.ipynb + loglog + 'temperature_contributions':'pol'

CMB polarisation

Temperature spectrum: $C_\ell^{TT} = \langle a^T_{lm} a^{T*}_{lm} \rangle = \frac{2}{\pi} \int dk\, k^2 [\Theta_\ell(\eta_0, k)]^2 \;\; P_{\mathcal{R}}(k)$

with transfer function $$\Theta_l(\eta_0,k) = \int_{\eta_{\rm ini}}^{\eta_0} d\eta \, \{ g\, (\Theta_0 + \psi)\; j_l(k(\eta_0 - \eta)) + g\, k^{-1}\theta_{\rm b}\; j_l'(k(\eta_0-\eta)) + e^{-\tau}(\phi' + \psi')\, j_l(k(\eta_0-\eta)) \} \; + \ldots$$

For polarisation:

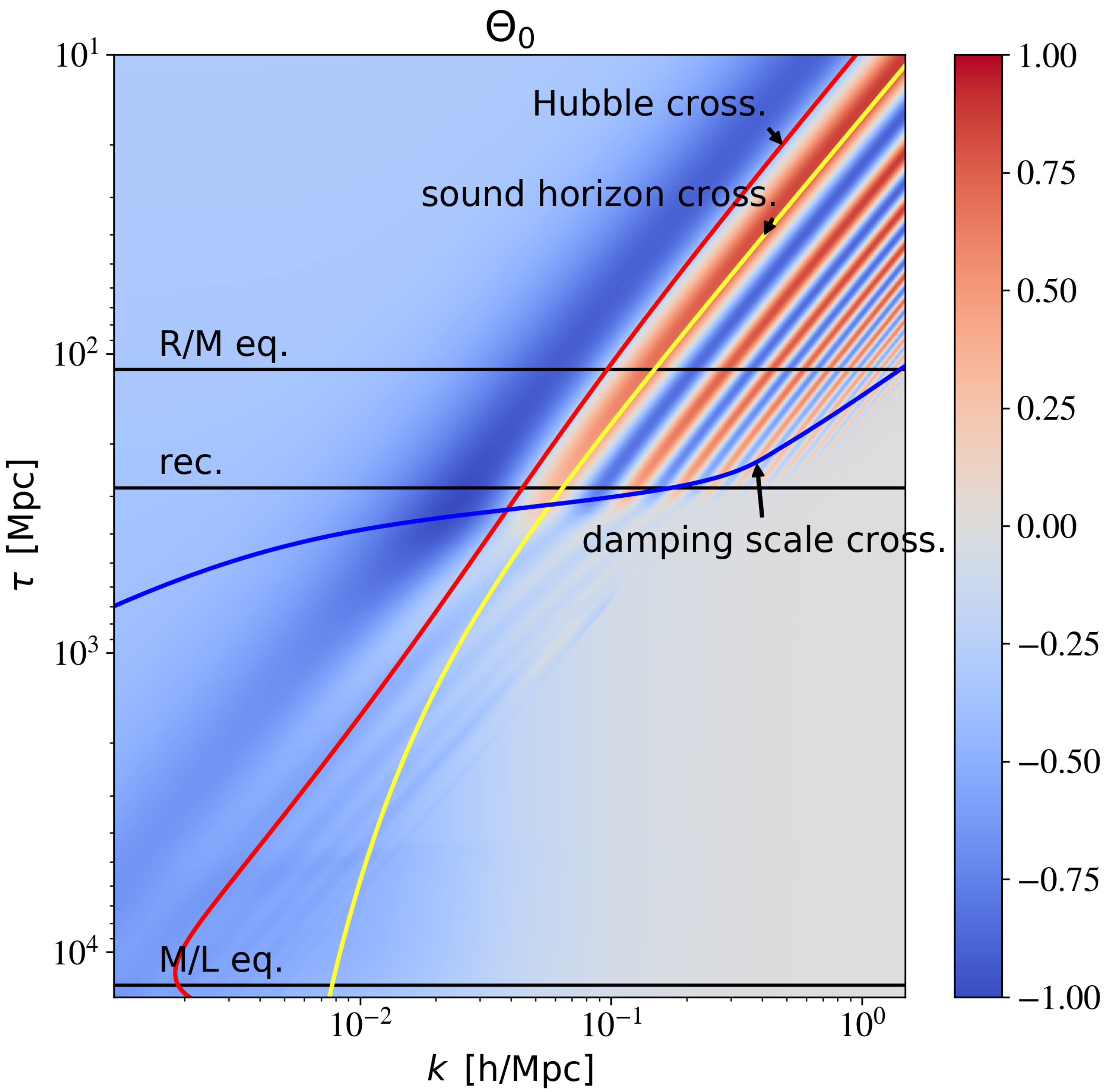
Kosowsky 1996; Seljak & Zaldarriaga astro-ph/9609170; Hu & White astro-ph/9702170

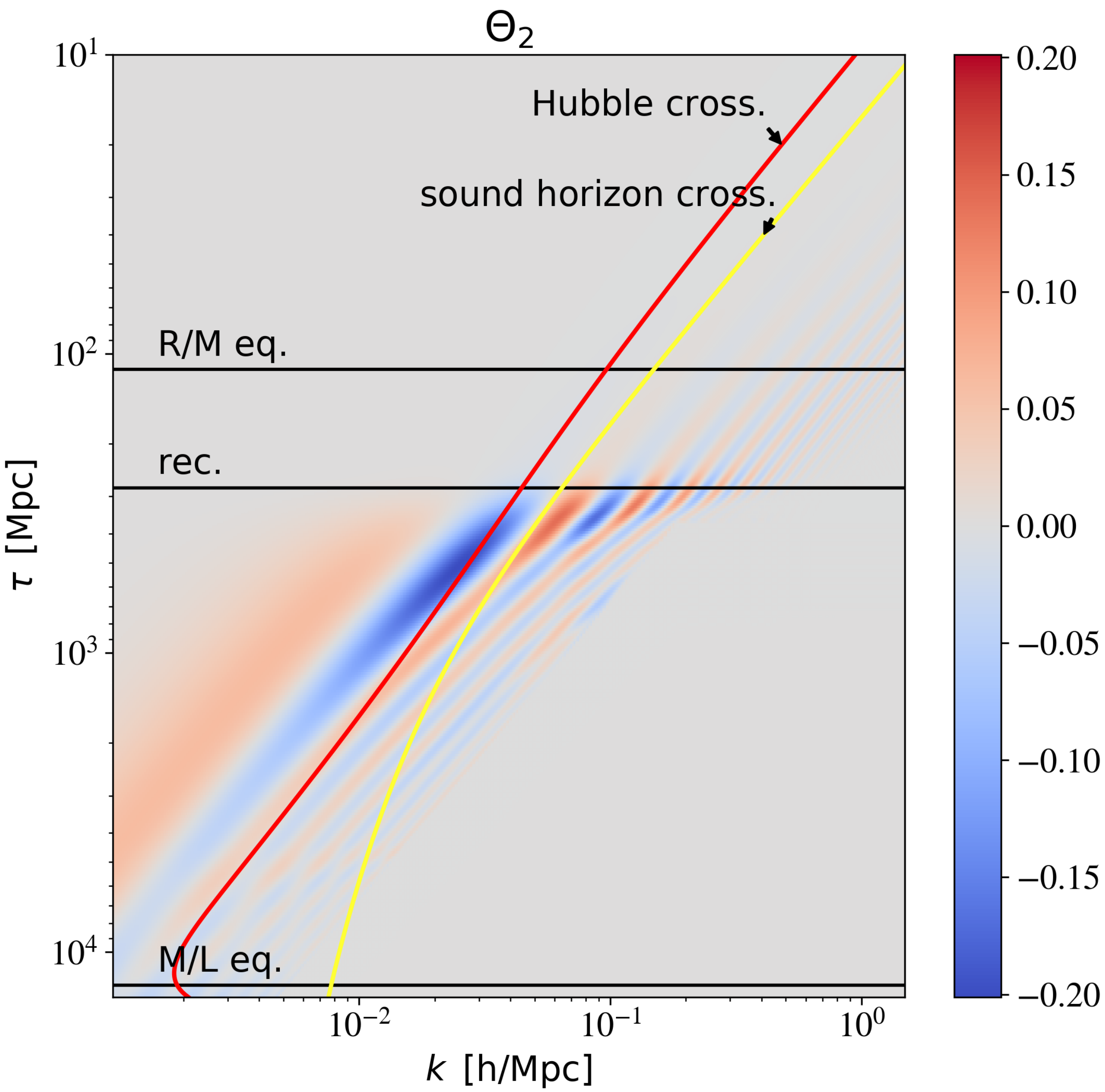
E-mode polarisation spectrum: $C_\ell^{EE} = \langle a^E_{lm} a^{E*}_{lm} \rangle = \frac{2}{\pi} \int dk\, k^2 [\Delta^E_\ell(\eta_0, k)]^2 \;\; P_{\mathcal{R}}(k)$
E

with transfer function $$\Delta^E_l(\eta_0, k) = \int_{\eta_{\rm ini}}^{\eta_0} d\eta \;\; g \;\; \{\Theta_2 + \ldots\} \; (\ldots)\, j_l(k(\eta_0 - \eta))$$

… no Doppler … no Sachs-Wolfe … no ISW …

CMB polarisation





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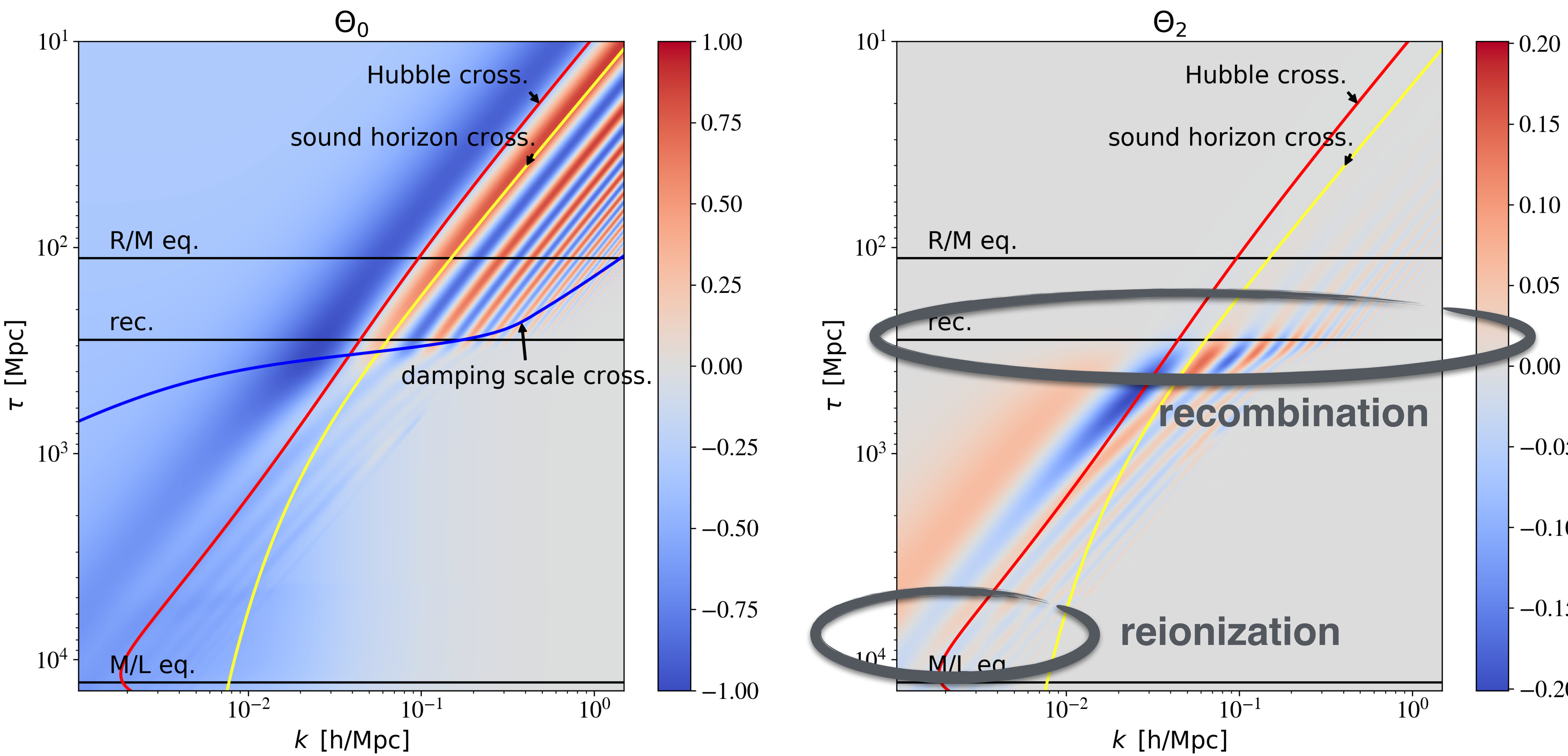
CMB polarisation



$$\Delta_l(\eta_0, k) = \int_{\eta_{\rm ini}}^{\eta_0} d\eta \;\; g \;\{\Theta_2 + \ldots\}\; (\ldots)\; j_l(k(\eta_0 - \eta))$$

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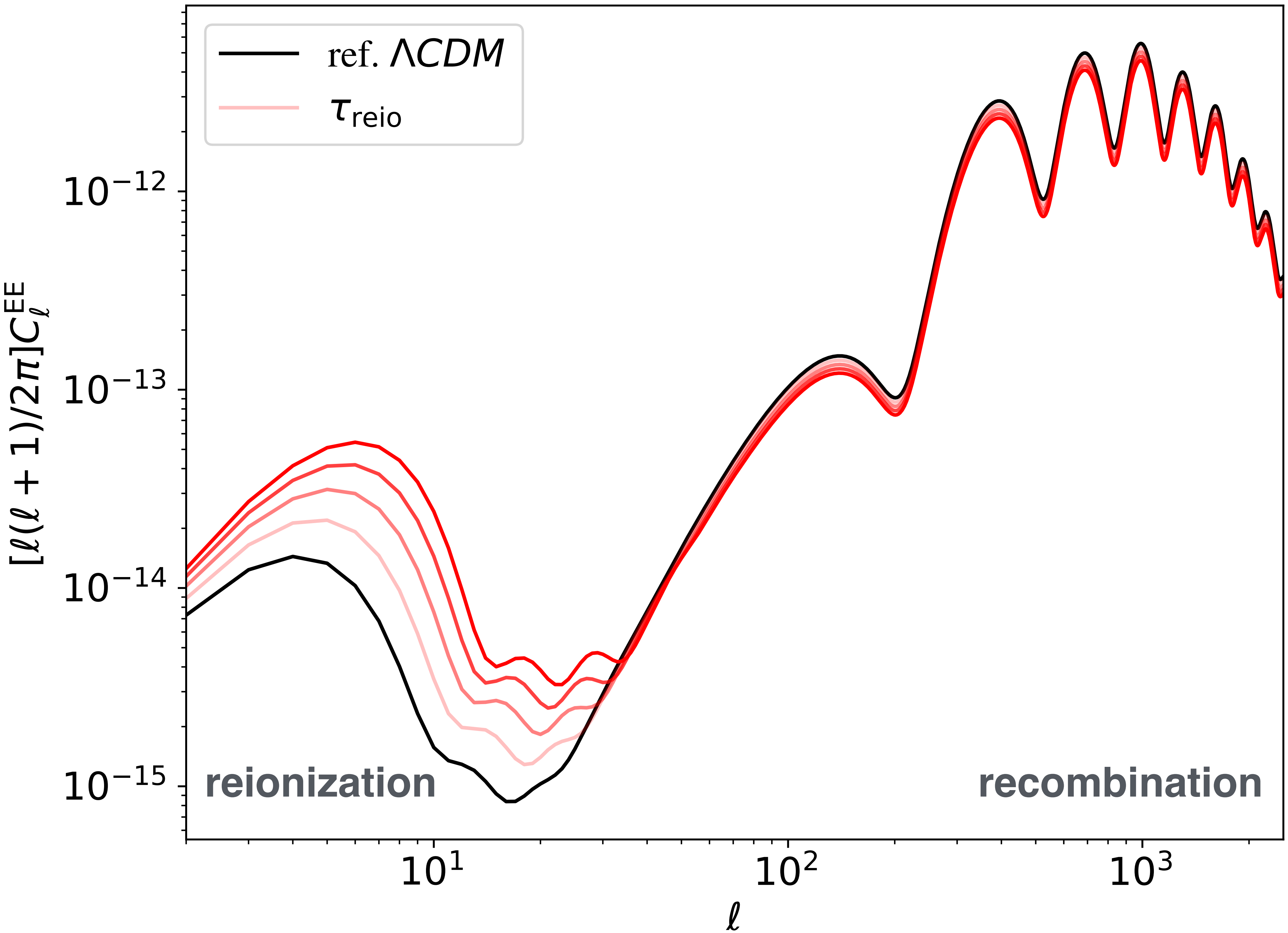
CMB polarisation



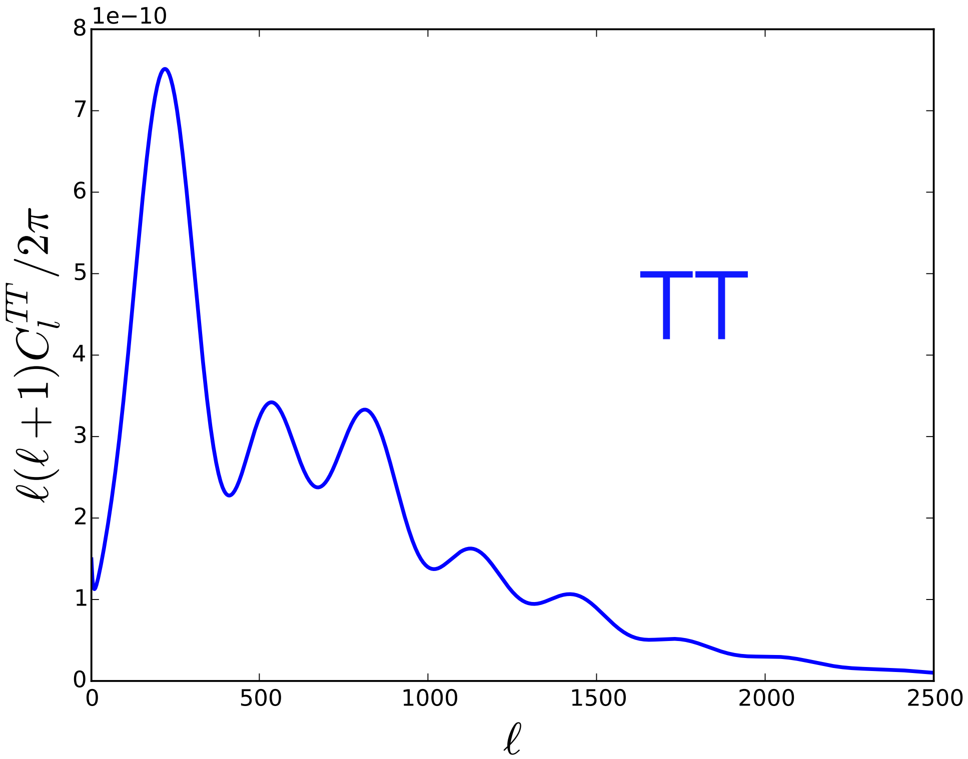
CMB polarisation

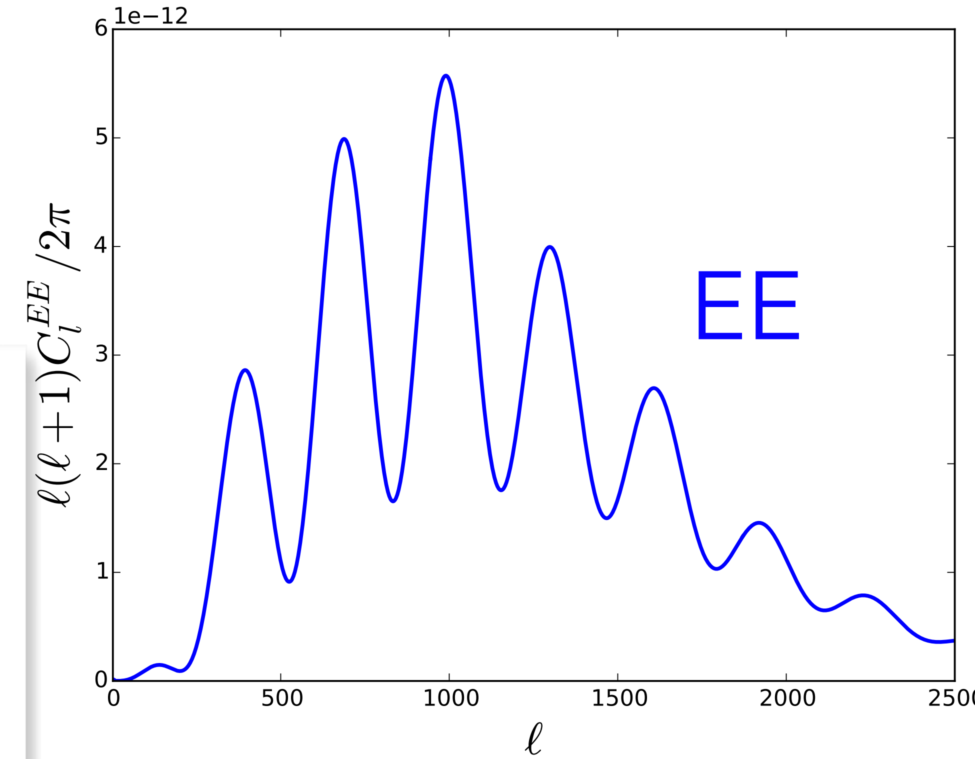
Cross spectrum: $$C_\ell^{TE} = \left\langle \frac{a_{lm}^T a_{lm}^{E*} + a_{lm}^E a_{lm}^{T*}}{2} \right\rangle = \frac{2}{\pi} \int dk\, k^2\, \Theta_\ell(\eta_0, k)\, \Delta_\ell^E(\eta_0, k)\;\; P_{\mathcal{R}}(k)$$

with transfer function $$\Theta_l(\eta_0,k) = \int_{\eta_{\rm ini}}^{\eta_0} d\eta \,\{g\, (\Theta_0 + \psi)\; j_l(k(\eta_0 - \eta)) + g\, k^{-1}\theta_{\rm b}\; j_l'(k(\eta_0 - \eta)) + e^{-\tau}(\phi' + \psi')\, j_l(k(\eta_0 - \eta))\} \;+ \ldots$$

and $$\Delta_l^E(\eta_0, k) = \int_{\eta_{\rm ini}}^{\eta_0} d\eta \;\; g\; \{\Theta_2 + \ldots\}\; (\ldots)\; j_l(k(\eta_0 - \eta))$$

CMB polarisation





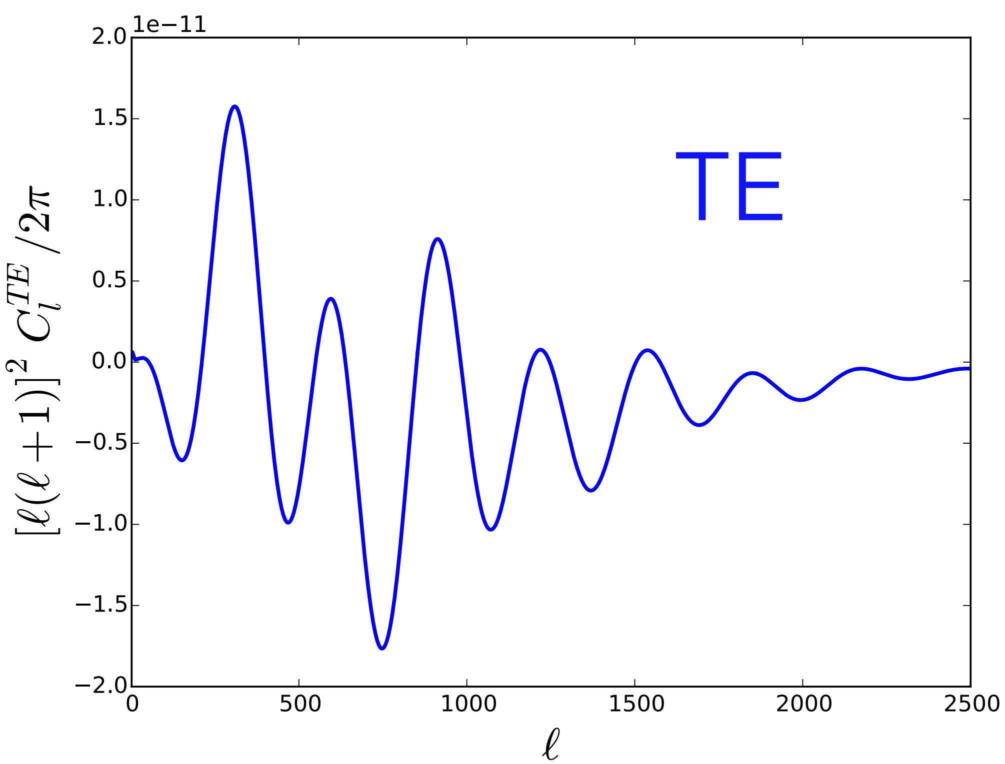
Bardeen scalars

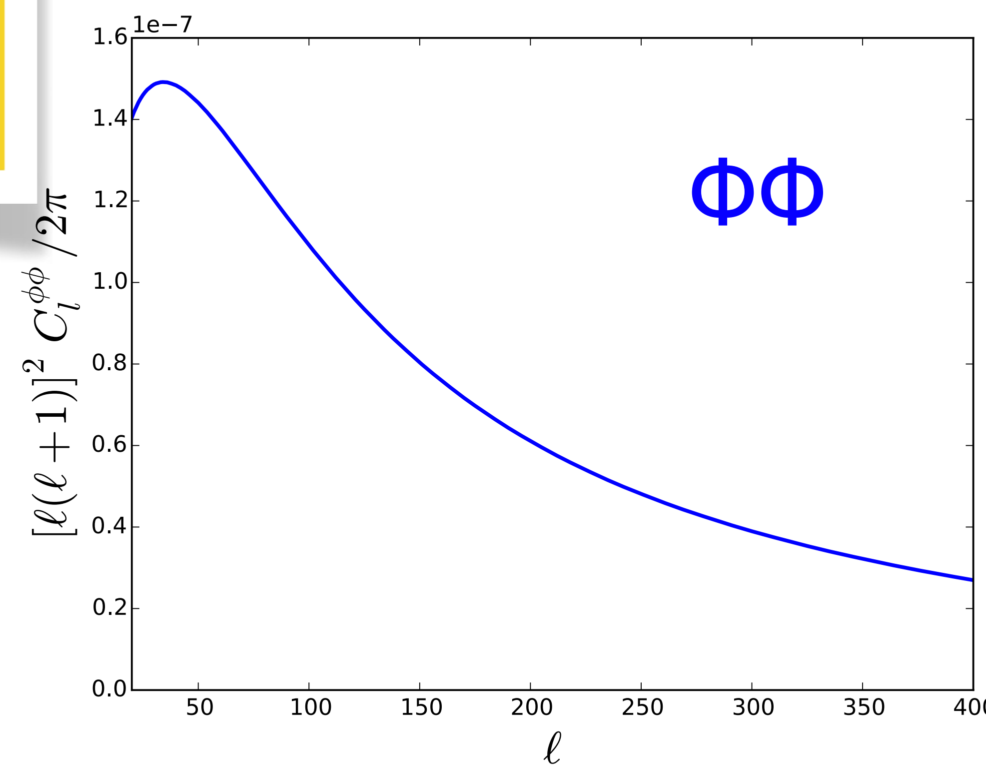
⇓

CMB information

stored in 4 spectra

C_l^{XY}





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Tensor modes

Tensor modes

$$g_{\mu\nu} = a^2(\eta_{\mu\nu} + h_{\mu\nu})$$

Bardeen scalars (spin-0)

$$h_{\mu\nu} = \begin{pmatrix} -2\psi & 0 & 0 & 0 \\ 0 & -2\phi & 0 & 0 \\ 0 & 0 & -2\phi & 0 \\ 0 & 0 & 0 & -2\phi \end{pmatrix}$$

(Newtonian gauge)

Bardeen tensors (spin-2)

$$h_{\mu\nu} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_1 & h_2 & 0 \\ 0 & h_2 & -h_1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

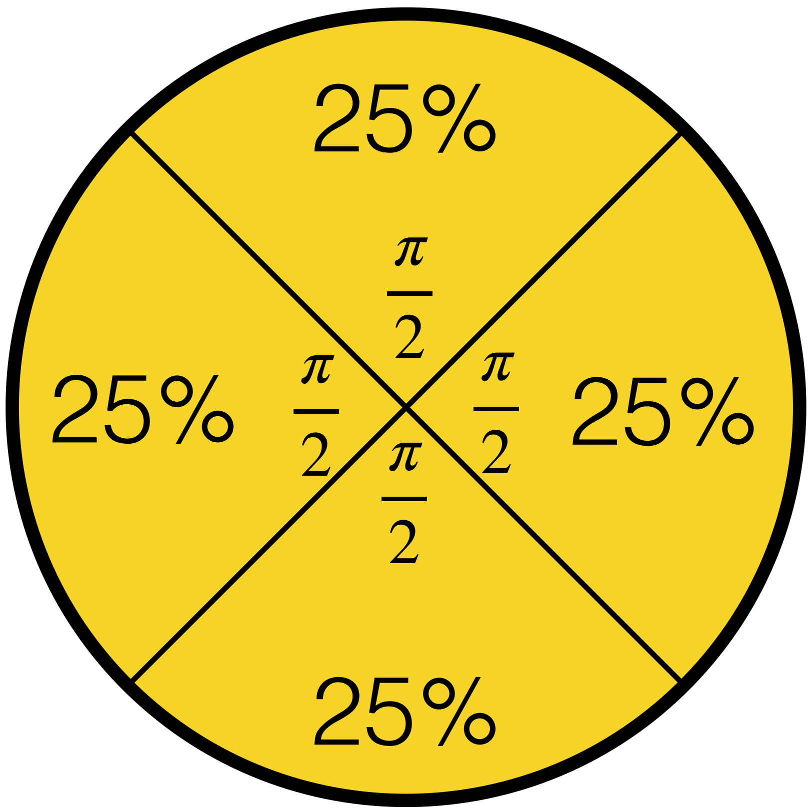
(for GWs along x^3)

Boltzmann with scalars: $\Theta' + \hat{n} \cdot \vec{\nabla}\Theta = \hat{n} \cdot \vec{\nabla}\psi - \phi' + [\mathrm{Thomson}]$

grav. Dop. dilation

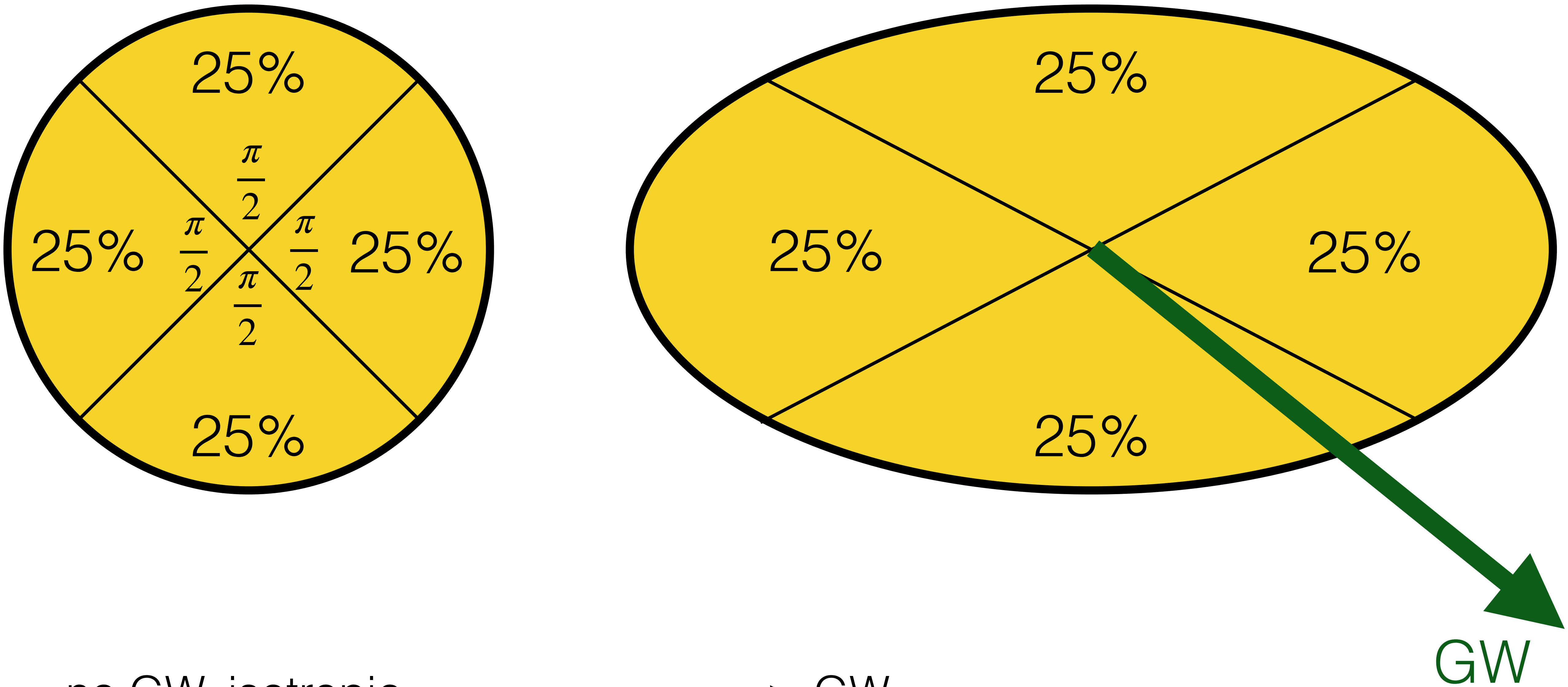
Boltzmann with tensors: $\Theta' + \hat{n} \cdot \vec{\nabla}\Theta = -\frac{1}{2}h'_{ij}\hat{n}^i\hat{n}^j$ + [Thomson]

Tensor modes



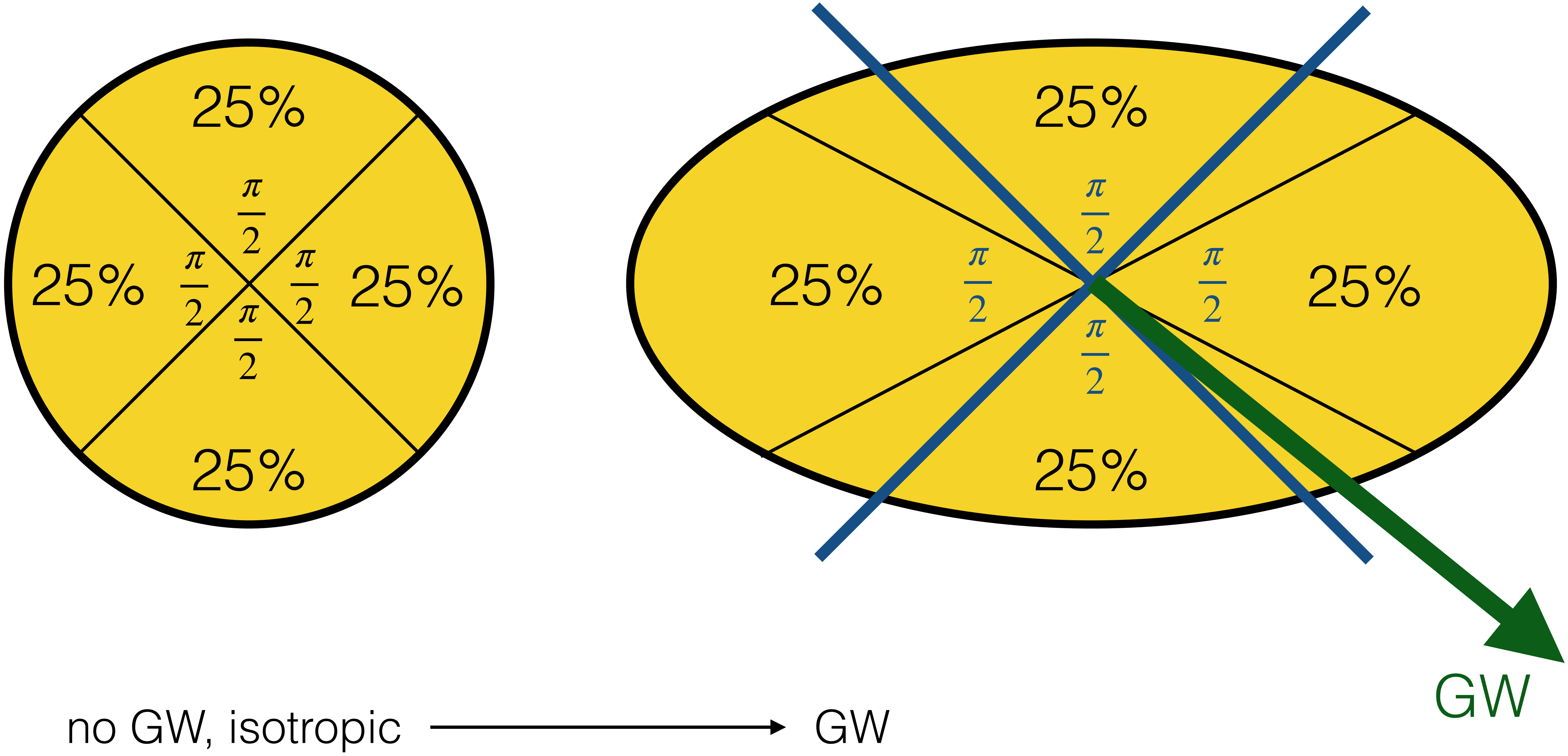
no GW, isotropic

Tensor modes



no GW, isotropic → GW

Tensor modes



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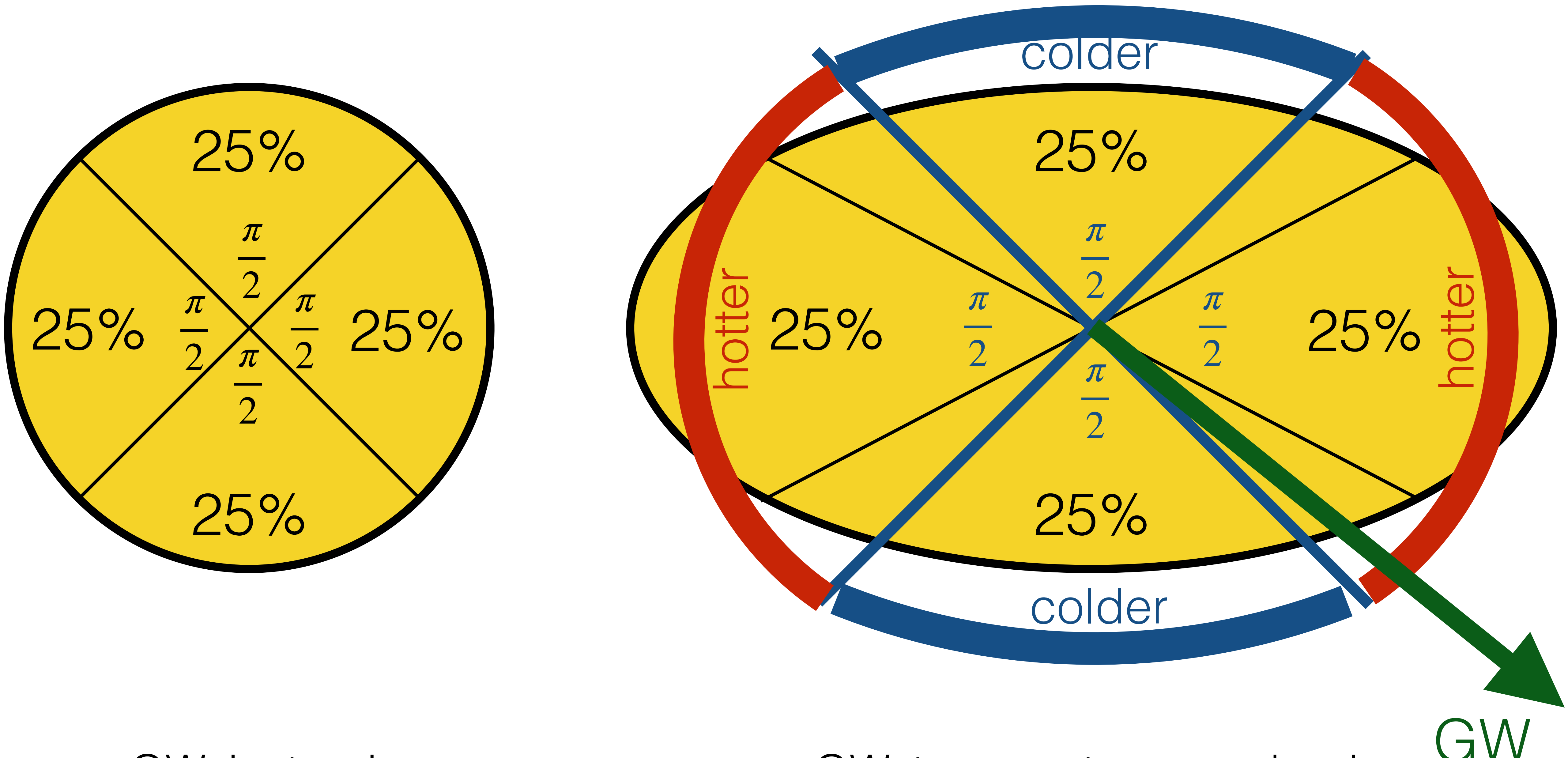
Tensor modes



no GW, isotropic → GW, temperature quadruple

Tensor modes

Scalar Boltzmann: $\Theta' + \hat{n} \cdot \vec{\nabla}\Theta = \hat{n} \cdot \vec{\nabla}\psi - \phi' + [\mathrm{Thomson}]$

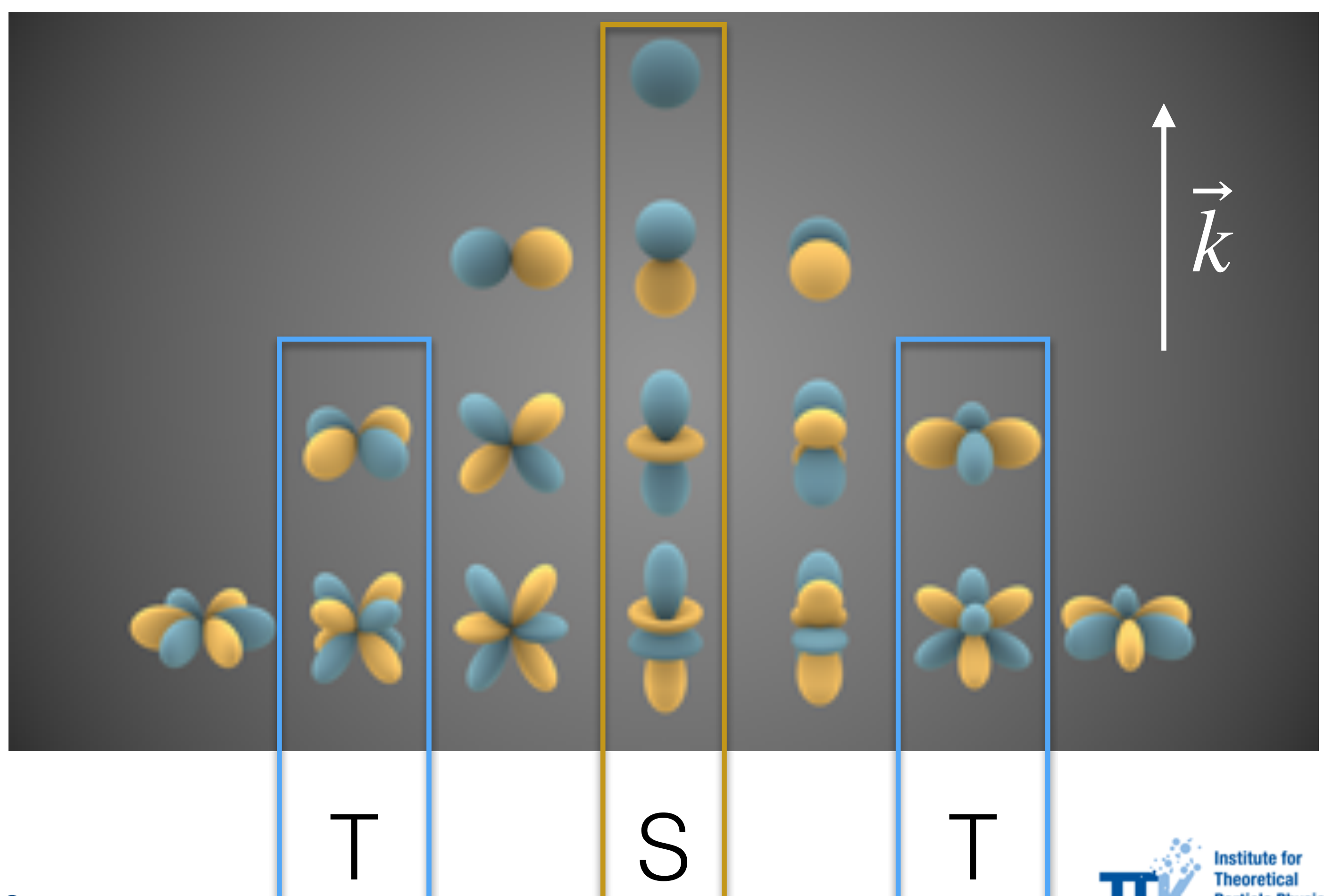
Tensor Boltzmann: $\Theta' + \hat{n} \cdot \vec{\nabla}\Theta = -\frac{1}{2} h'_{ij} \hat{n}^i \hat{n}^j$ +[Thomson]

Tensor modes

Scalar Boltzmann: $\Theta' + \hat{n}\cdot\vec{\nabla}\Theta = \hat{n}\cdot\vec{\nabla}\psi - \phi' + [\mathrm{Thomson}]$

Tensor Boltzmann: $\Theta' + \hat{n}\cdot\vec{\nabla}\Theta = -\frac{1}{2}h'_{ij}\hat{n}^i\hat{n}^j$ +[Thomson]

General expansion: $\Theta(\eta,\vec{x},\hat{n}) \longrightarrow \Theta(\eta,\vec{k},\hat{n}) = \sum_{lm}\Theta_{lm}(\eta,\vec{k})Y_{lm}(\hat{n})$



Tensor modes

GW h'_{ij}

↓

Tensor temperature quadrupole

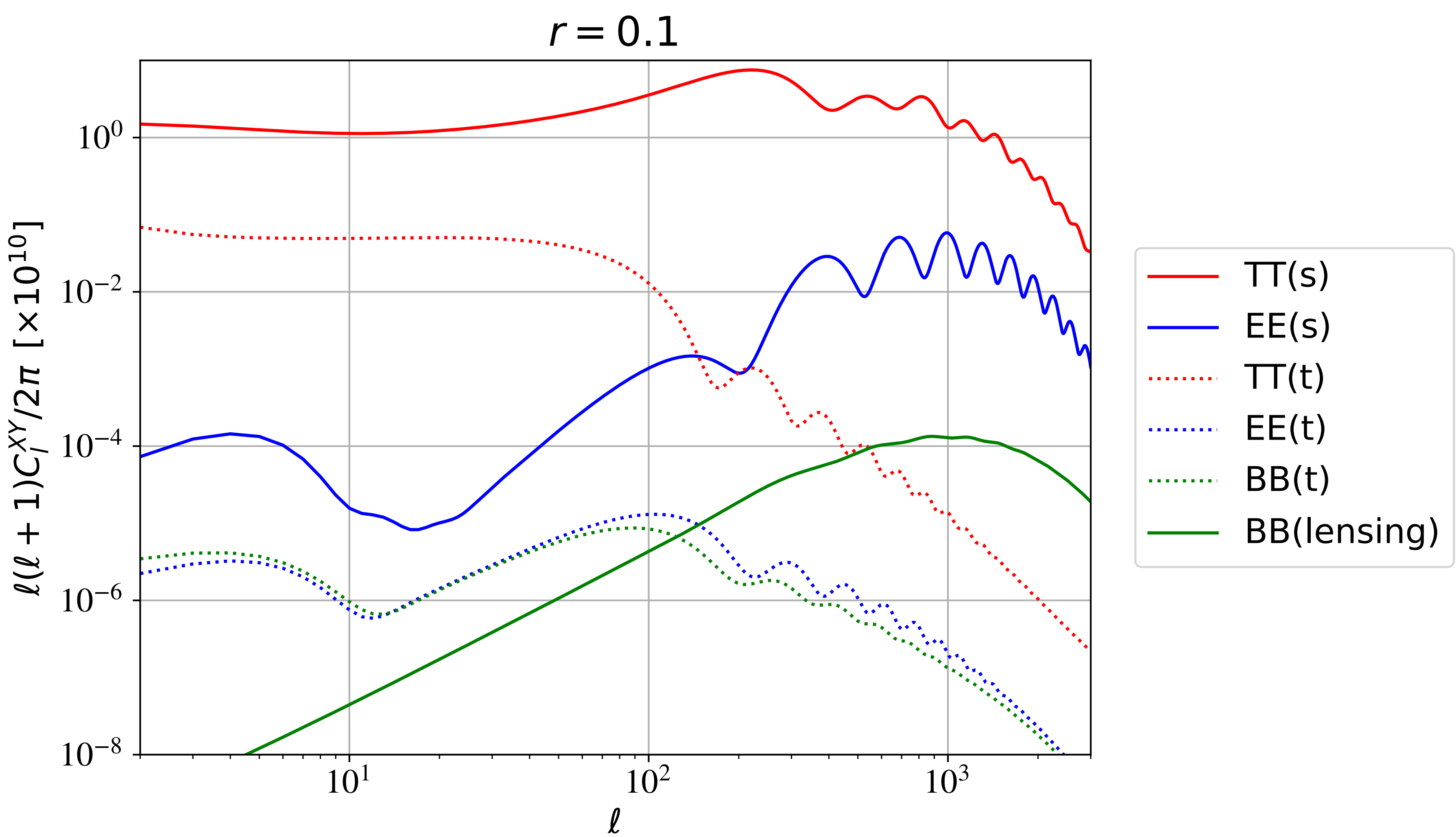
↙ ↘

Other tensor temperature multipoles → T-anisotropies

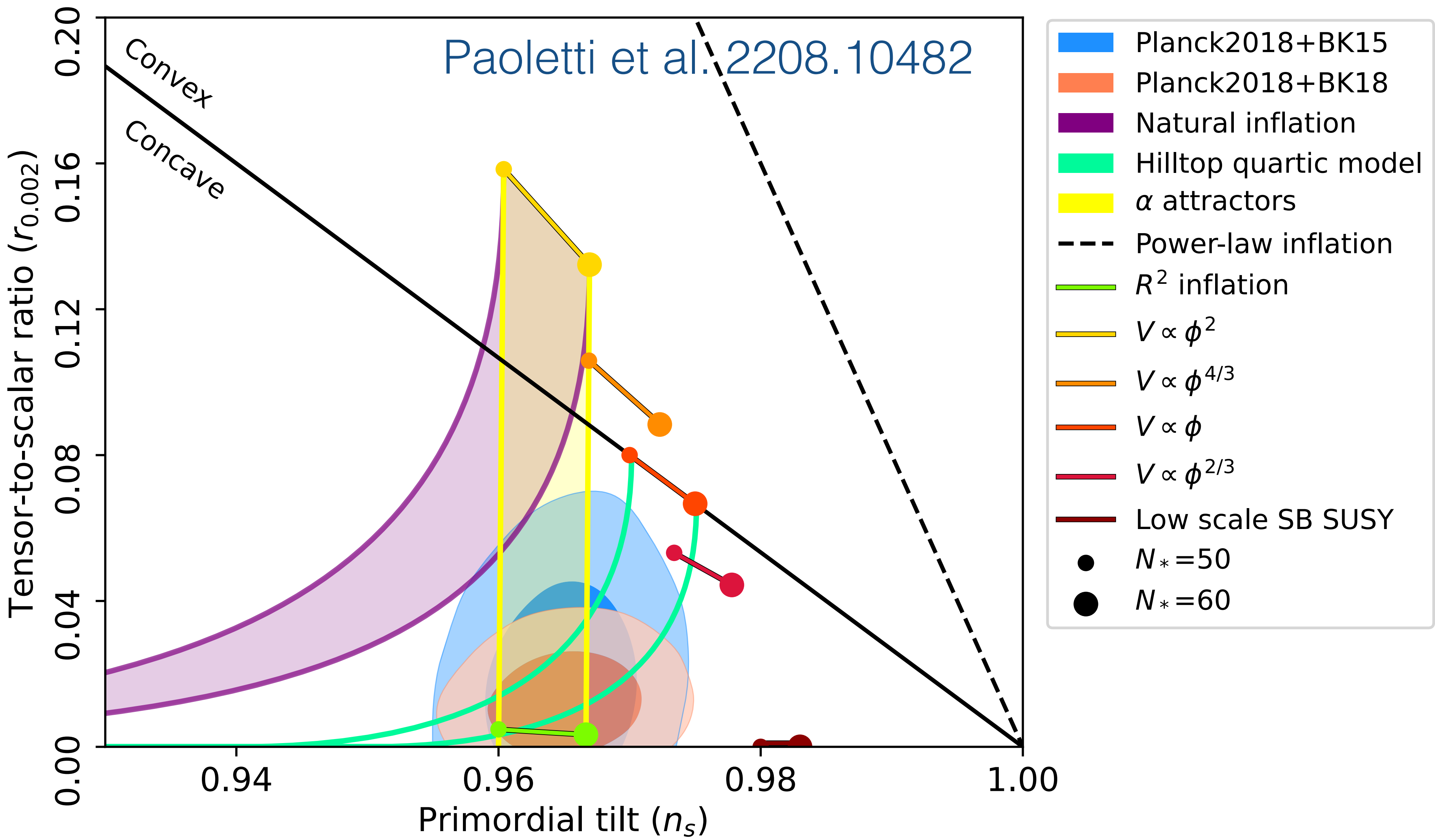
Tensor polarisation multipoles → E and B-anisotropies

Scalar and tensor sector statistically independent, solved independently,

$$C_l^{TT} = C_l^{TT(s)} + C_l^{TT(t)}$$
$$C_l^{EE} = C_l^{EE(s)} + C_l^{EE(t)}$$
$$C_l^{TE} = C_l^{TE(s)} + C_l^{TE(t)}$$
$$C_l^{BB} = 0 + C_l^{BB(t)}$$



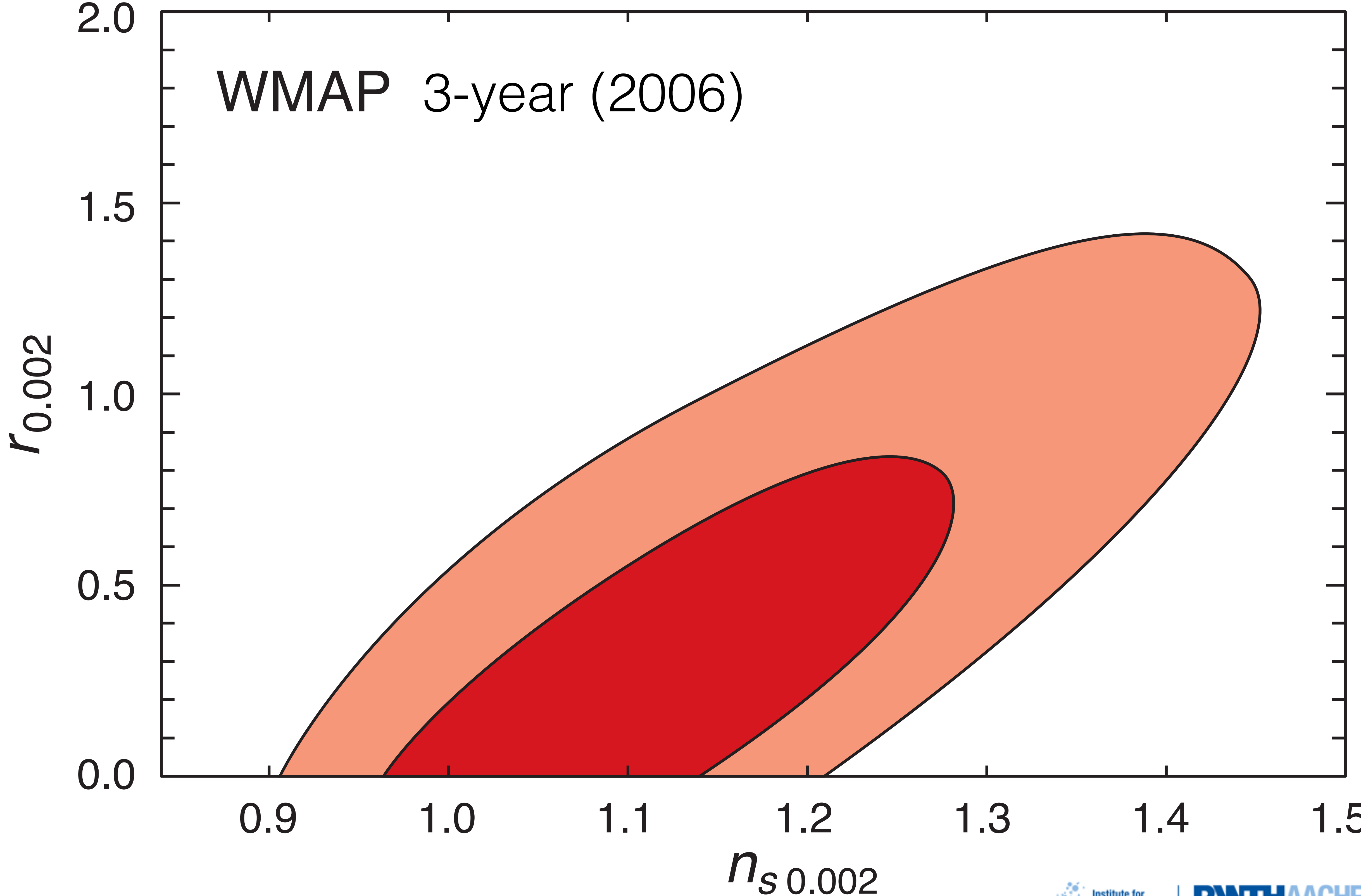
Observational constraints on ΛCDM + r



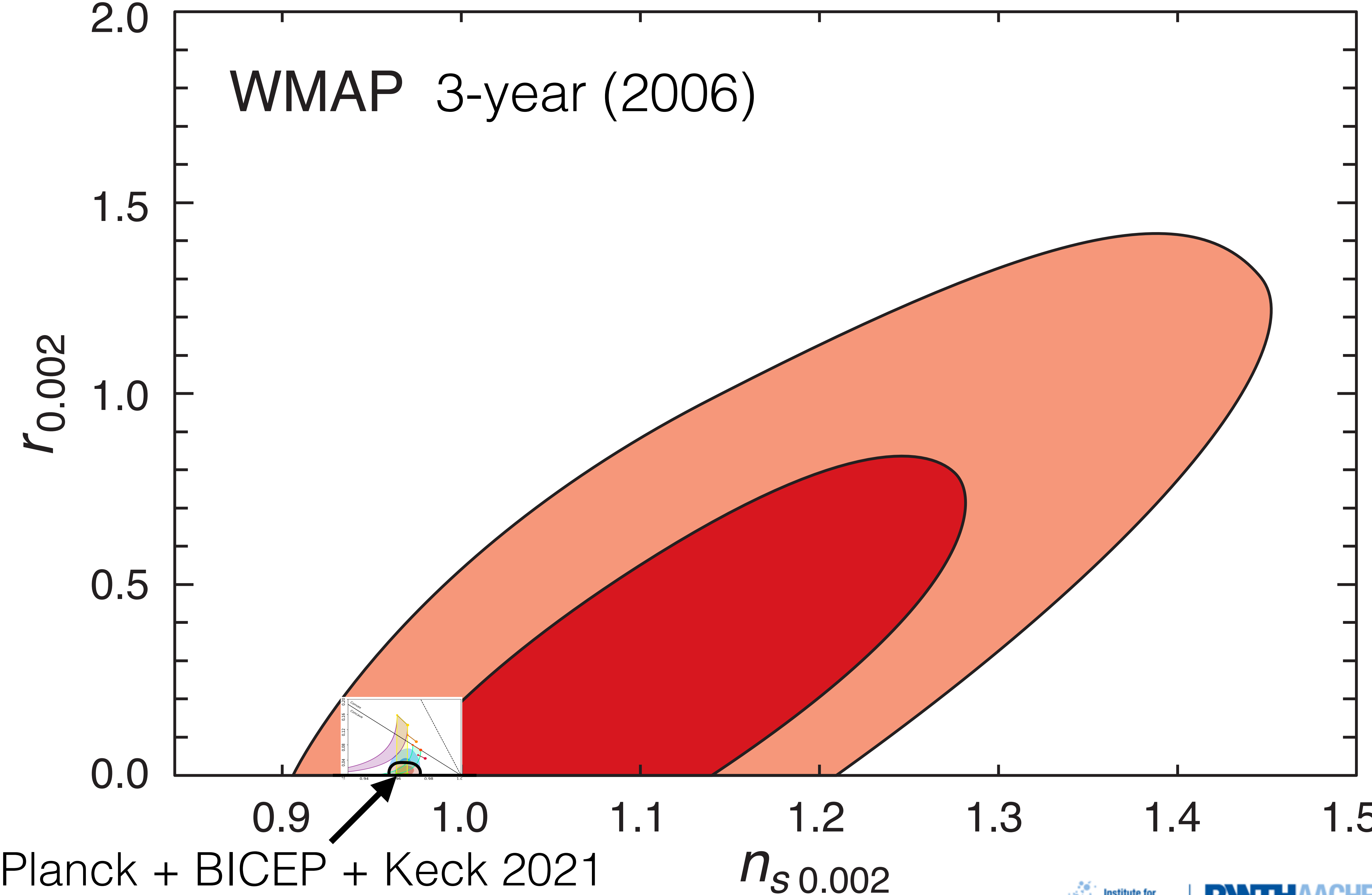
Energy scale of inflation V_*

$$V_* = \frac{3\pi^2 A_s}{2}\, r\, M_{\rm Pl}^4 < (1.4 \times 10^{16}\ \mathrm{GeV})^4 \quad (95\%\ \mathrm{CL})$$

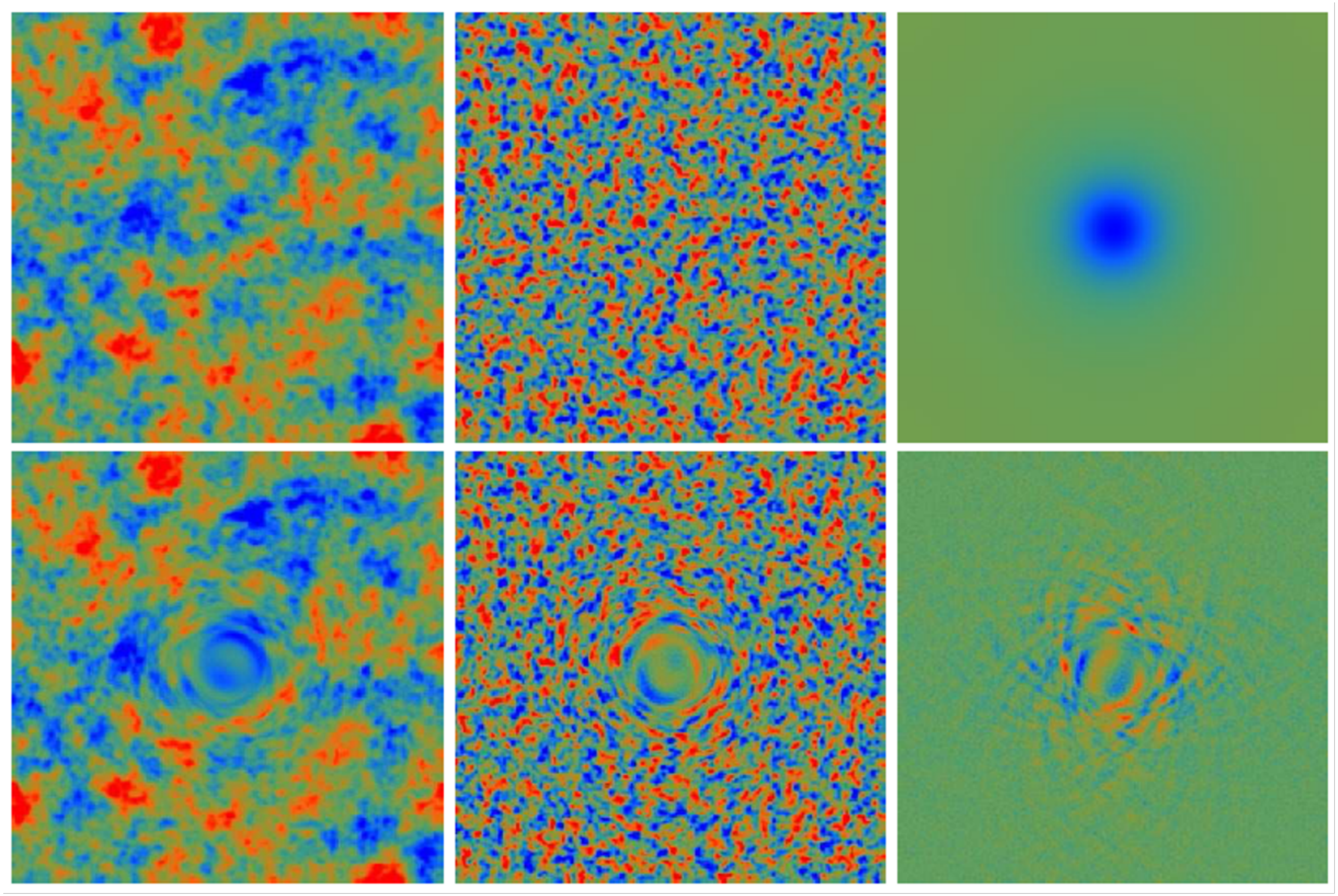
Observational constraints on ΛCDM + r



Observational constraints on ΛCDM + r



CMB lensing



from W. Hu

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Basic math

Deflection field

typically ~ arc minutes

$$\frac{\delta T^{\rm obs}}{T}(\hat{n}) = \frac{\delta T^{\rm raw}}{T}\left(\hat{n} + \vec{d}(\hat{n})\right) = \frac{\delta T^{\rm raw}}{T}\left(\hat{n} + \vec{\nabla}\Phi(\hat{n})\right)$$

CMB lensing potential

$$\Phi(\hat{n}) = \int_{\eta_0}^{\eta_{\rm dec}} d\eta\ W(\eta)\ \phi\left(\eta, \vec{r}(\eta)\right) = \sum_{lm} \Phi_{lm} Y_{lm}(\hat{n})$$

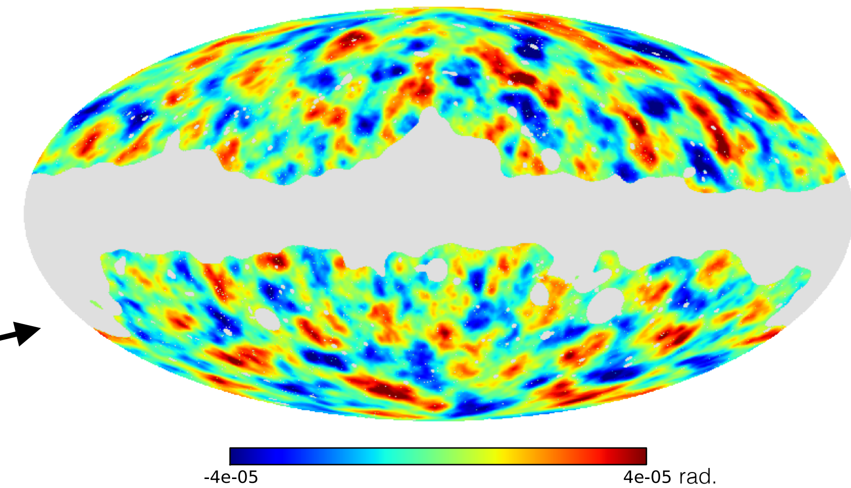
CMB lensing spectrum

$$C_\ell^{\Phi\Phi} = \langle |\Phi_{lm}|^2 \rangle$$

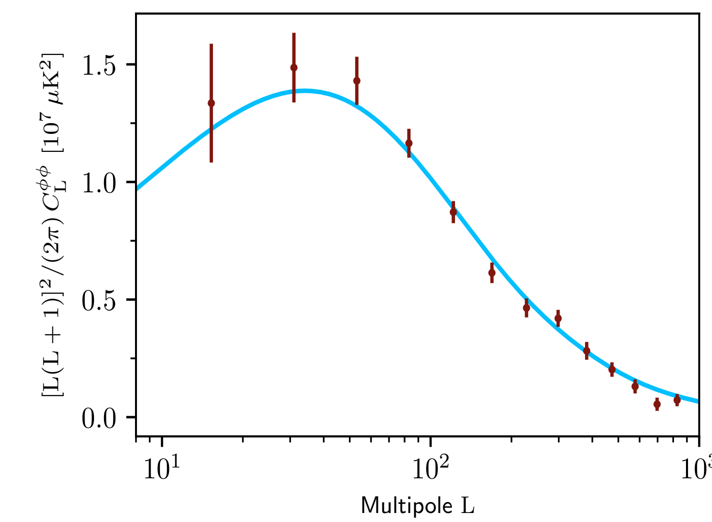
easy to predict with EBS (linear pert.)

Many important goals

1. How are observable $C_\ell^{TT}, C_\ell^{EE}, C_\ell^{TE}, C_\ell^{BB}$ affected? (needed for fitting theory)

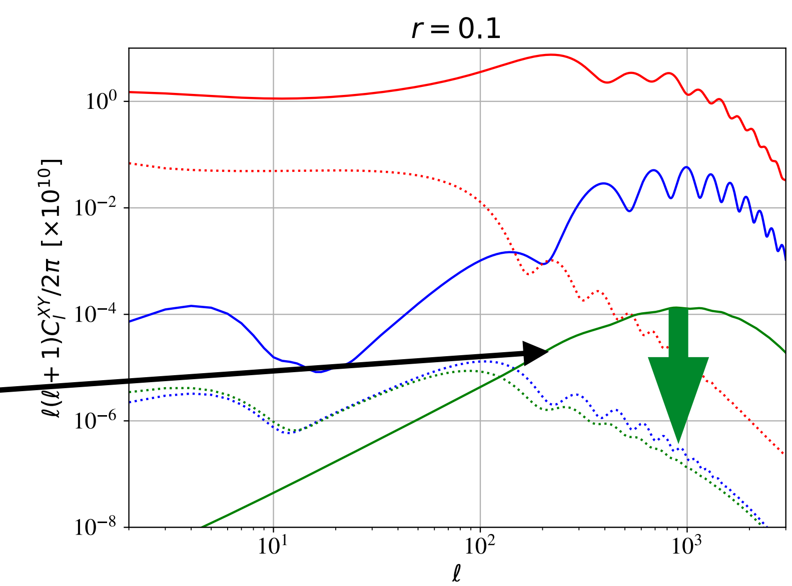


2. Infer map $\Phi(\hat{n})$ from data



3. Infer the $C_\ell^{\Phi\Phi}$ from data and fit theory (more information than in 1)

4. Delens temperature and polarisation maps



5. Delens spectra $C_\ell^{TT}, C_\ell^{EE}, C_\ell^{TE}, C_\ell^{BB}$

Basic method

Taylor

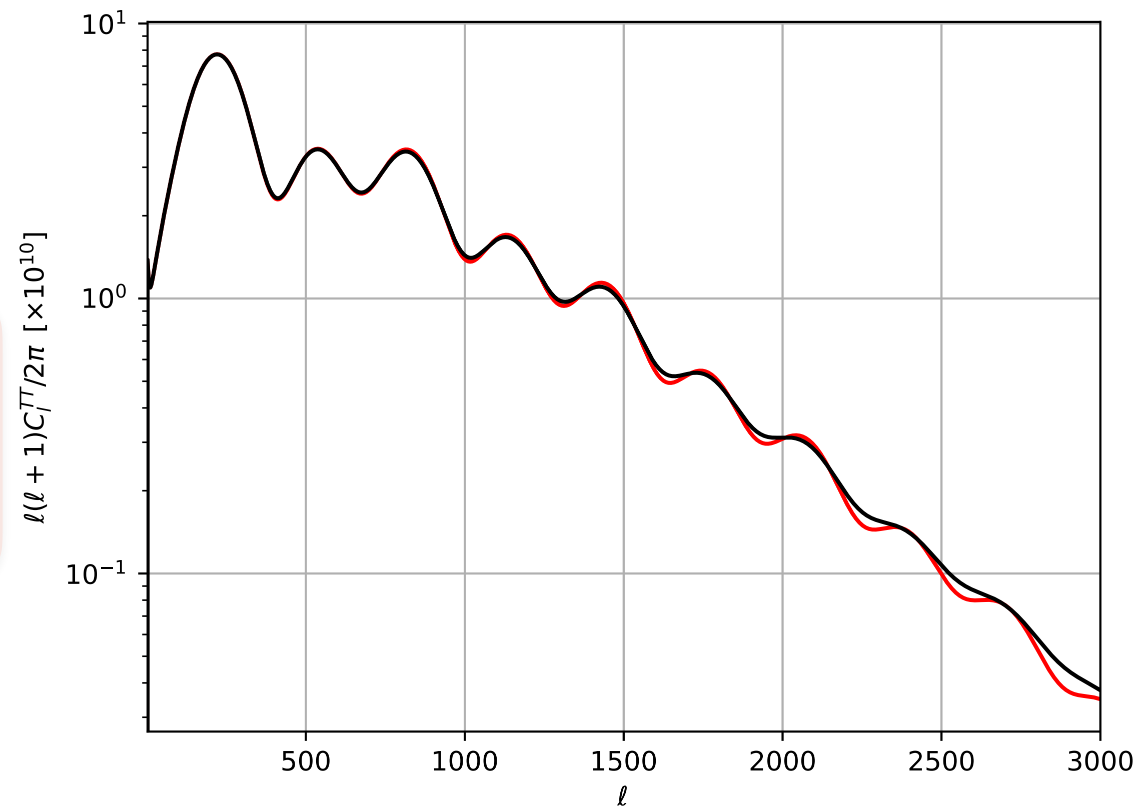
$$X^{\rm obs}(\hat{n}) = X^{\rm raw}\left(\hat{n} + \vec{\nabla}\Phi(\hat{n})\right) = X^{\rm raw} + D_i\Phi\ D^iX^{\rm raw} + \frac{1}{2}D_i\Phi\ D_j\Phi\ D^iD^jX^{\rm raw} + \dots$$

Harmonic

$$X^{\rm obs}_{lm} = X^{\rm raw}_{lm} + I^{l_1m_1l_2m_2}_{lm}\Phi_{l_1m_1}X^{\rm raw}_{l_2m_2} + J^{l_1m_1l_2m_2l_3m_3}_{lm}\Phi_{l_1m_1}\Phi_{l_2m_2}X^{\rm raw}_{l_3m_3} + \dots$$

1. How are observable $C_\ell^{TT}, C_\ell^{EE}, C_\ell^{TE}, C_\ell^{BB}$ affected?

Compute $\langle\, | X^{\rm obs}_{lm} |^2 \rangle$ with $X^{\rm raw}_{lm}$ and Φ_{lm} seen as gaussian independent variables:



$C_\ell^{XY,\rm obs} = C_\ell^{XY,\rm raw}$ smoothed by kernel that depends on $C_\ell^{\Phi\Phi}$.

Both I and J matter!

Basic method

Taylor

$$X^{\rm obs}(\hat{n}) = X^{\rm raw}\left(\hat{n} + \overrightarrow{\nabla}\Phi(\hat{n})\right) = X^{\rm raw} + D_i\Phi\ D^iX^{\rm raw} + \frac{1}{2}D_i\Phi\ D_j\Phi\ D^iD^jX^{\rm raw} + \ldots$$

Harmonic

$$X^{\rm obs}_{lm} = X^{\rm raw}_{lm} + I^{l_1m_1l_2m_2}_{lm}\Phi_{l_1m_1}X^{\rm raw}_{l_2m_2} + J^{l_1m_1l_2m_2l_3m_3}_{lm}\Phi_{l_1m_1}\Phi_{l_2m_2}X^{\rm raw}_{l_3m_3} + \ldots$$

2. Infer map $\Phi(\hat{n})$ from data

Neglect J-term. Previous relation cannot be just inverted… exploit non-Gaussianity of $X^{\rm obs}_{lm}$!

$$X^{\rm obs}_{lm}Y^{\rm obs}_{l'm'} = X^{\rm raw}_{lm}Y^{\rm raw}_{l'm'} + K^{l_1m_1l_2m_2l_3m_3}_{lml'm'}\ \Phi_{l_1m_1}\ X^{\rm raw}_{l_2m_2}\ Y^{\rm raw}_{l_3m_3}$$

Imagine "average over realisations" for $l \neq l', m \neq m'$:

$$\langle X^{\rm obs}_{lm}Y^{\rm obs}_{l'm'}\rangle_{\rm CMB} = K^{l_1m_1l_2m_2l_3m_3}_{lml'm'}\delta_{l_2l_3}\delta_{m_2m_3}C^{XY,{\rm raw}}_{l_2}\ \ \Phi_{l_1m_1}$$

Linear combinations of many $X^{\rm obs}_{lm}Y^{\rm obs}_{l'm'}$ reveals one $\Phi_{l_1m_1}$ up to some "cosmic variance":

quadratic estimator of Hu & Okamoto astro-ph/0301031

CMB spectral distortions

Blackbody radiation in early Universe

Elastic and inelastic scattering, $\Gamma > H$

$\downarrow$

Momentum exchange

$\downarrow$

Thermal/kinetic equilibrium

Bose-Einstein / Fermi-Dirac

$$f(p) = \frac{1}{e^{(E-\mu)/T} - 1}$$

$\downarrow$

for massless particles

$$f(p) = \frac{1}{e^{(p-\mu)/T} - 1}$$

Inelastic scattering, $\Gamma > H$

$\downarrow$

Chemical equilibrium

$$\Sigma \mu_i |_{\text{left}} = \Sigma \mu_i |_{\text{right}}$$

$\downarrow$

For particle without conserved numbers:

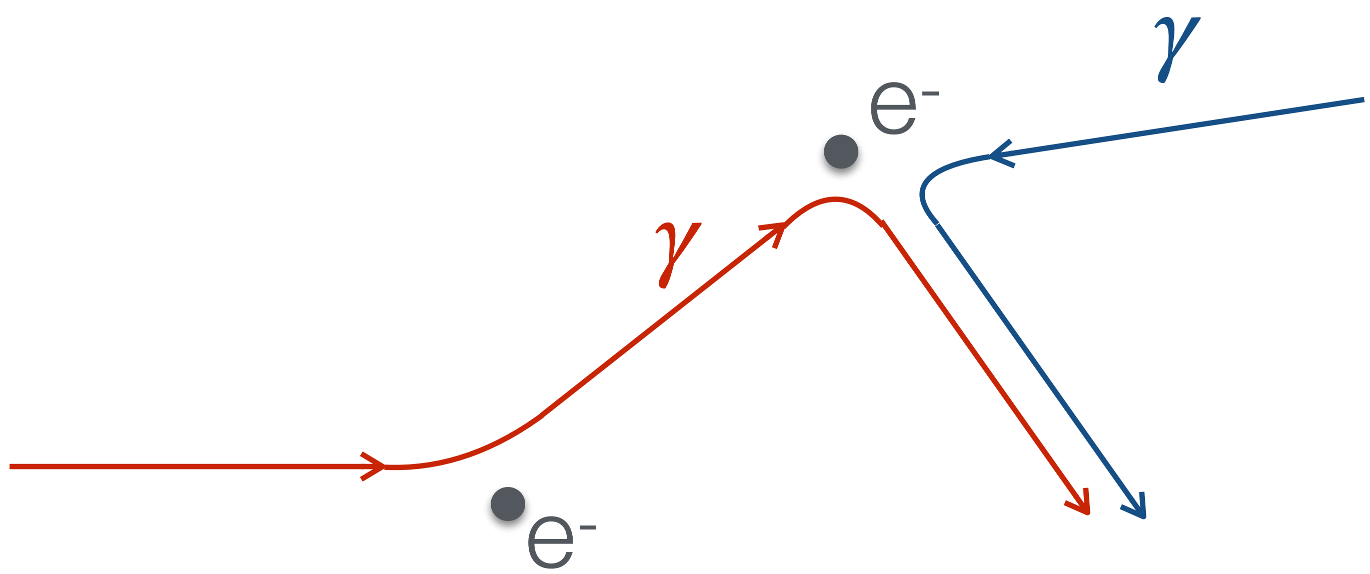
Number-changing reactions

$\downarrow$

$$\mu = 0$$

Photons: $f(p) = \dfrac{1}{e^{p/T} - 1}$ = blackbody/Planck spectrum

Blackbody radiation in early Universe



Redshifting along geodesics: $$\frac{d\ln(a\,p)}{d\eta} = \phi' - \hat{n}\cdot\vec{\nabla}\psi$$

Gravity preserves blackbody, but what about late interactions?

Blackbody radiation in early Universe

- Compton scattering (CS):

$\gamma + e^- \longrightarrow \gamma + e^-$ (number conserving)

$$\frac{\partial f}{\partial t} = \dot{\tau} \frac{T_e}{m_e} \frac{1}{x^2} \frac{\partial}{\partial x} \left(x^4 \left[\frac{\partial f}{\partial x} + \frac{T_z}{T_e} f(1+f) \right] \right)$$

Kompaneyets equation

(solution: BE with arbitrary μ)

- double Compton scattering (DC):

$\gamma + e^- \longrightarrow \gamma + \gamma + e^-$ (non-number conserving)

- Bremsstrahlung (BR):

$e^- \longrightarrow e^- + \gamma$ (non-number conserving)

Blackbody radiation in early Universe

- $z > 3 \times 10^6$: CS, DC, BR efficient: BE with $\mu = 0$ = blackbody

  energy injection-> no distortion

- $z > 4 \times 10^4$: only CS: BE with arbitrary mu, Kompaneyets can only impose

$$f(p;T,\mu=0) \rightarrow f(p;T',\mu) \simeq f_{BE}(p;T,0)\left\{1+\mu\left[0.4561-\frac{T}{p}\right]\right\}$$

  energy injection-> μ-distortion

- $z > 10^3$: CS not efficient: Kompaneet at next-to-leading order in H/Γ can only impose

$$f(p;T,\mu=0) \rightarrow f_{BE}(p;T,0)\left\{1+y\left[\frac{p}{T}\frac{e^{p/T}+1}{e^{p/T}-1}-4\right]\right\}$$

  energy injection-> y-distortion

- $z \sim 10^3$: additional residuals

- Even later: CMB photons decoupled anyway
- Reionization: CS again, possible y-distortions (Sunyaev-Zel'dovitch 1970)

Source of distortions in standard cosmology

Lucca, Schöneberg, Hooper, JL, Chluba 1910.04619

- Adabatic cooling of electrons and photons:
  - UR particles in equilibrium with themselves: $T \propto a^{-1}$
  - NR particles in equilibrium with themselves: $T \propto a^{-2}$
  - Efficient CS: $T_e = T_b = T_\gamma \propto a^{-1}$
  - Inefficient CS: $T_e = T_b < T_\gamma$

    → energy extracted from photon, $\mu = -3 \times 10^{-9}, \; y = -5 \times 10^{-10}$

- Dissipation of acoustic waves:
  - Diffusion damping → superposition of BB with different temperature,

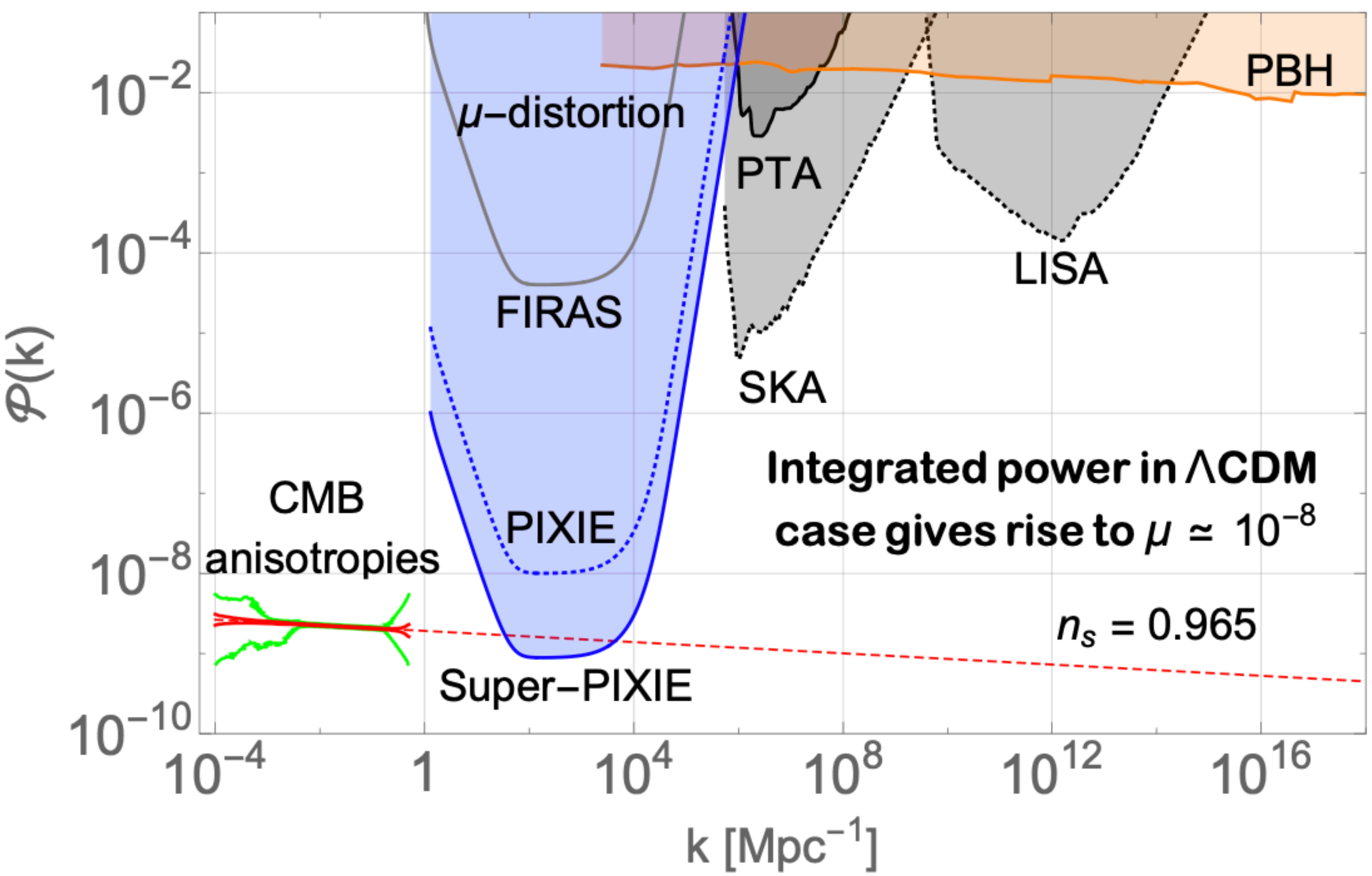
    → reprocessed as $\mu = 2 \times 10^{-8}, \; y = 4 \times 10^{-9}$
  - Transfer of energy from small-scale anisotropies to spectral distortions
  - Accurately computed by CLASS
  - Probe of $P_{\mathscr{R}}(k)$ on very small scales

- Emission/absorption lines during H and He recombination: y-distorsions + small residuals

- Sunyaev-Zel'dovitch effect from hot electrons during reionization → $y \sim 10^{-6}$

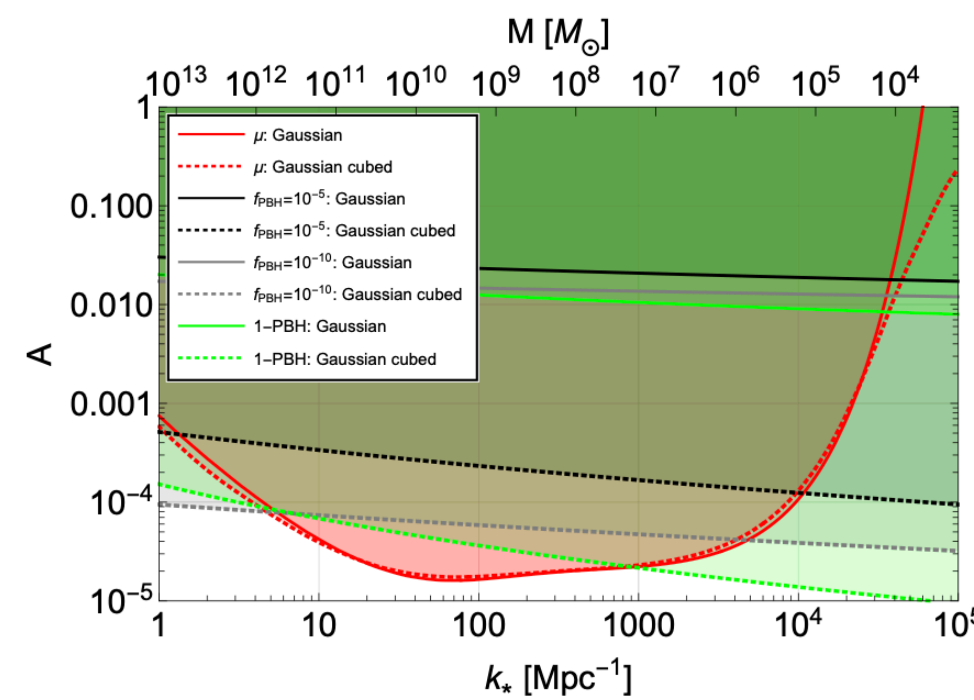
Source of distortions in non-minimal cosmology

- Extra power in small-scale $P_{\mathcal{R}}(k)$



J. Chluba et al., BAAS 51, 184 (2019), 1903.04218

Exclusion plots on peaks producing PBH



Pritchard, Byrnes, JL, Sharma 2505.08442

Source of distortions in non-minimal cosmology

- DM annihilation or decay: products end up heating electrons

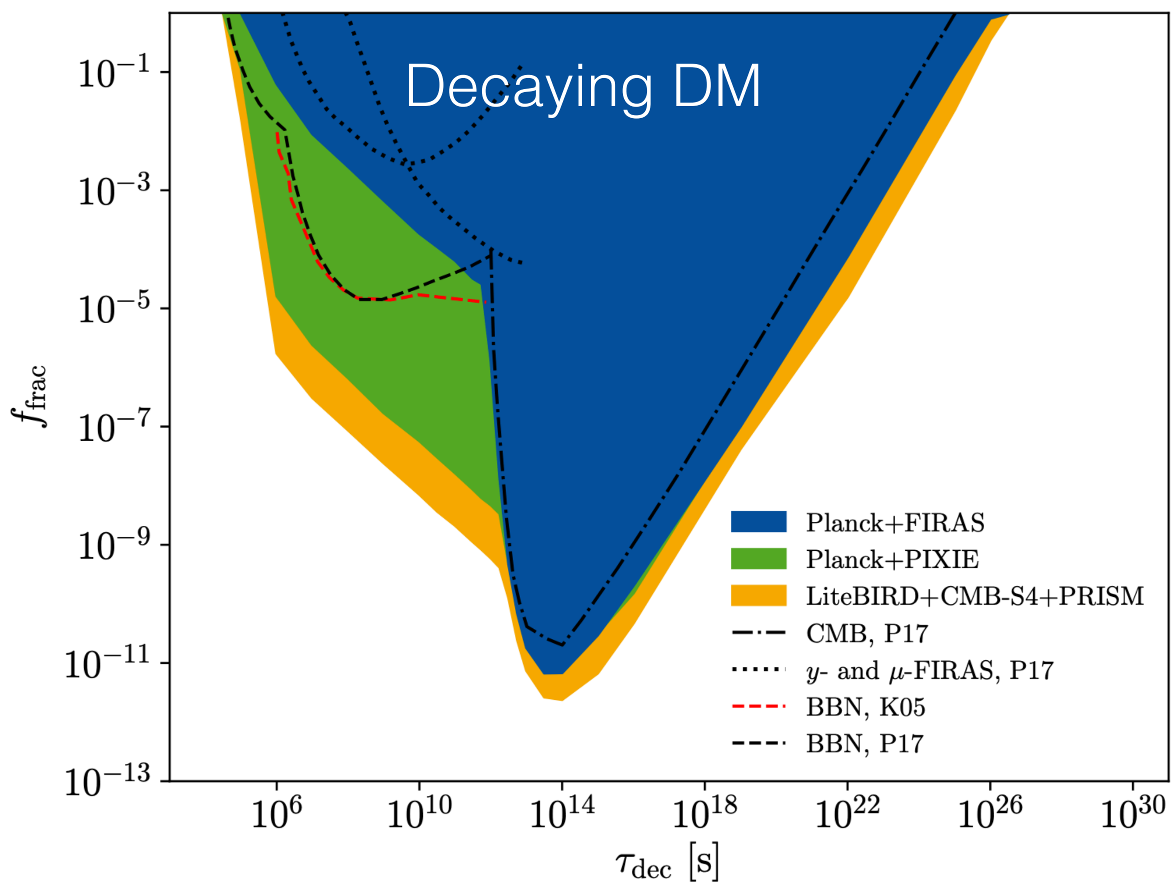
Lucca, Schöneberg, Hooper, JL, Chluba 1910.04619

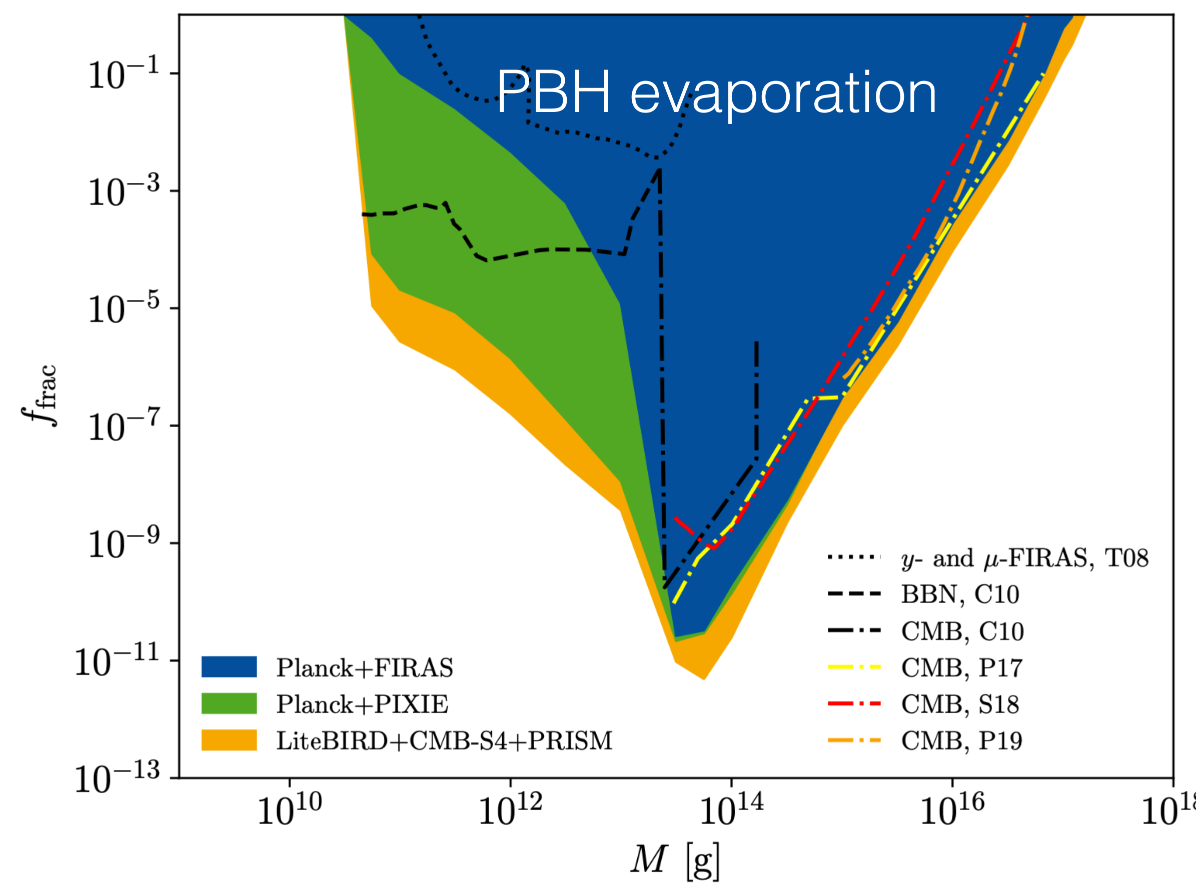
- PBH accretion or evaporation

- Other exotic energy injection mechanisms in dark sector

- also produces change in recombination, and thus CMB anisotropies…

→ anisotropy/distortion synergy → distorsion module in CLASS, ExoCLASS branch

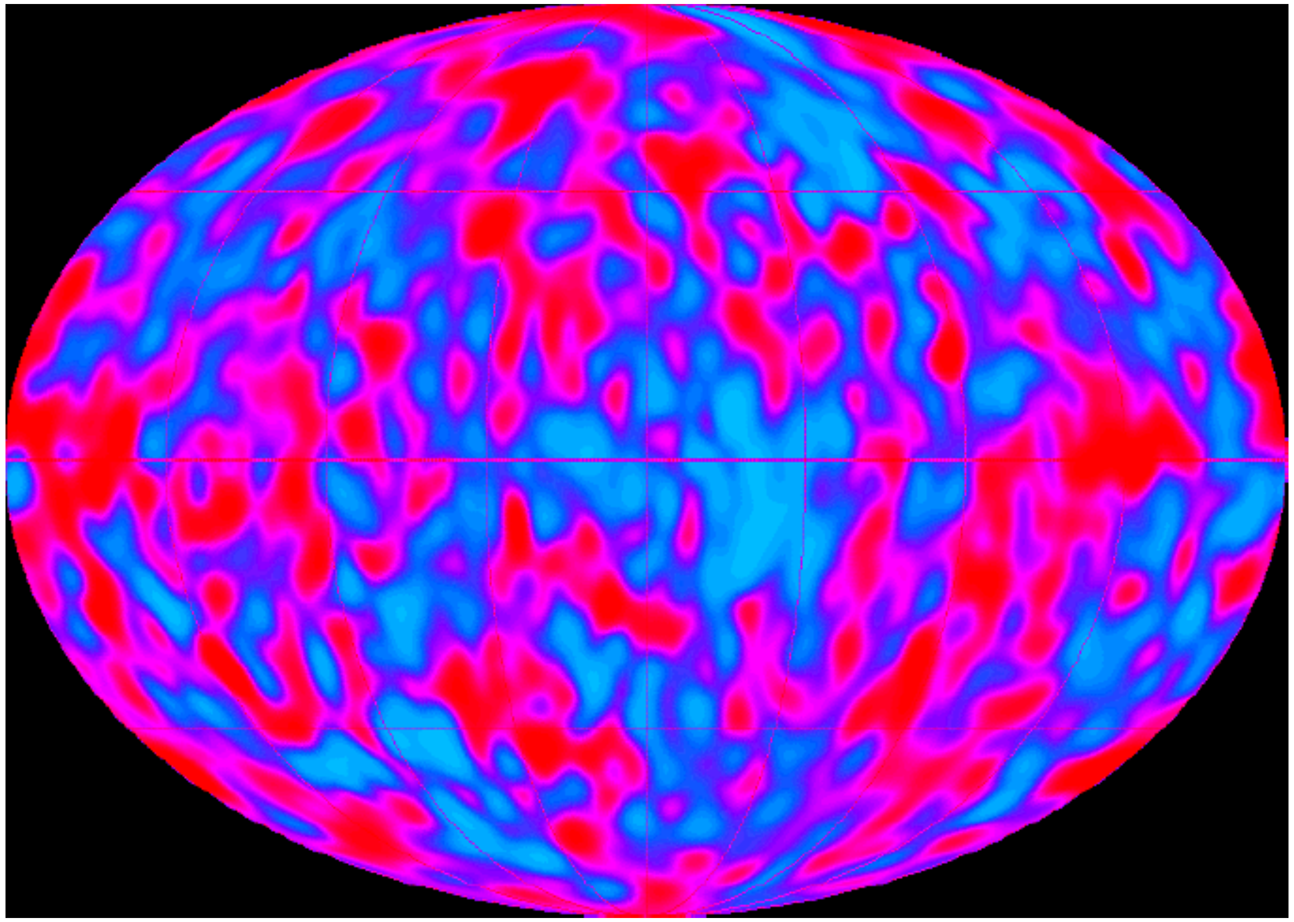




Observations

From COBE to Planck

- CMB anisotropies:
  - 1992-94 : COBE confirms roughly flat spectrum for l<20
  - 2000 : Boomerang
  - 2003 -2011 : WMAP
  - 2013-2015 : Planck



CMB lensing

- CMB anisotropies:
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  - 2000 : Boomerang
  - 2003 -2011 : WMAP
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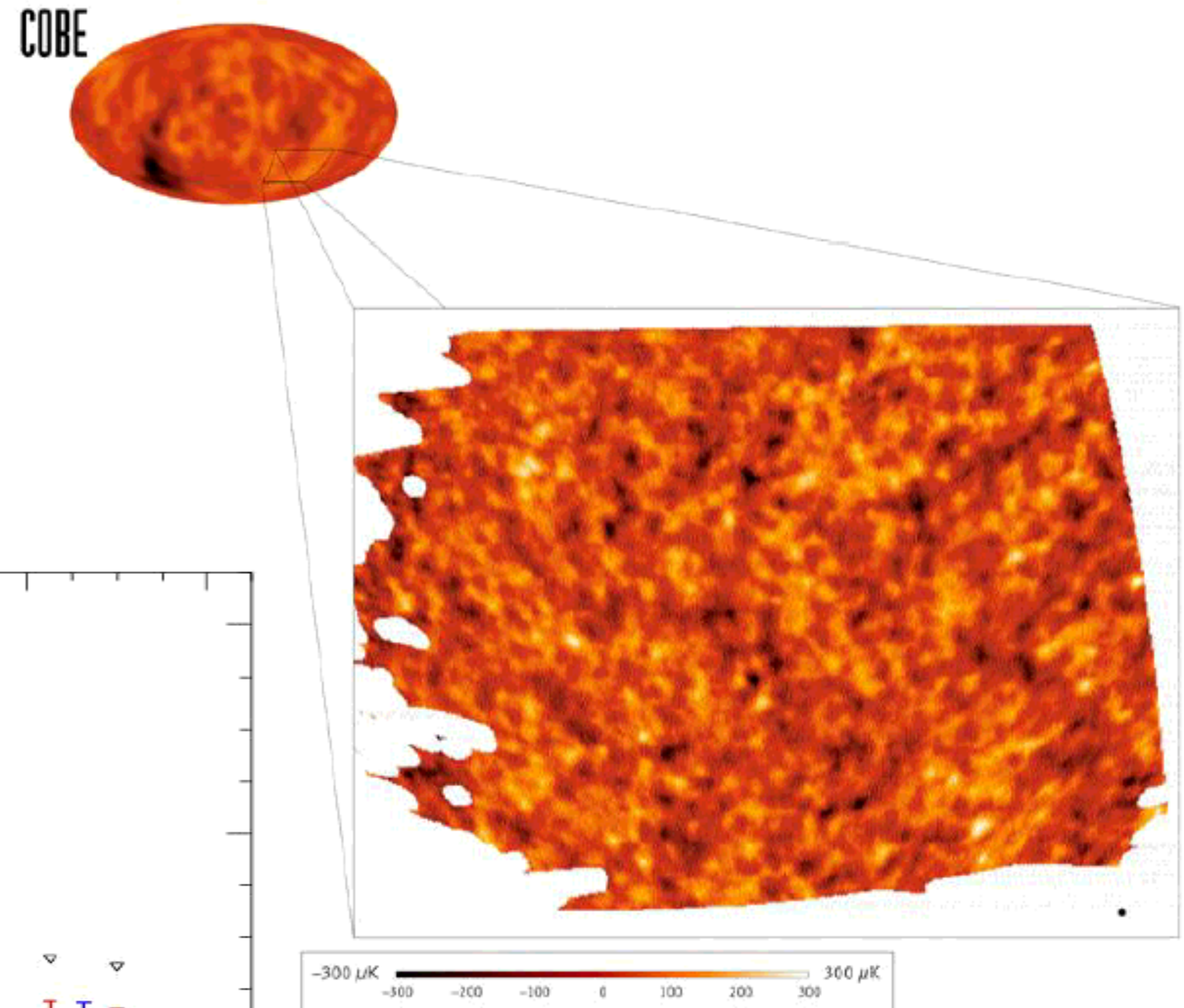

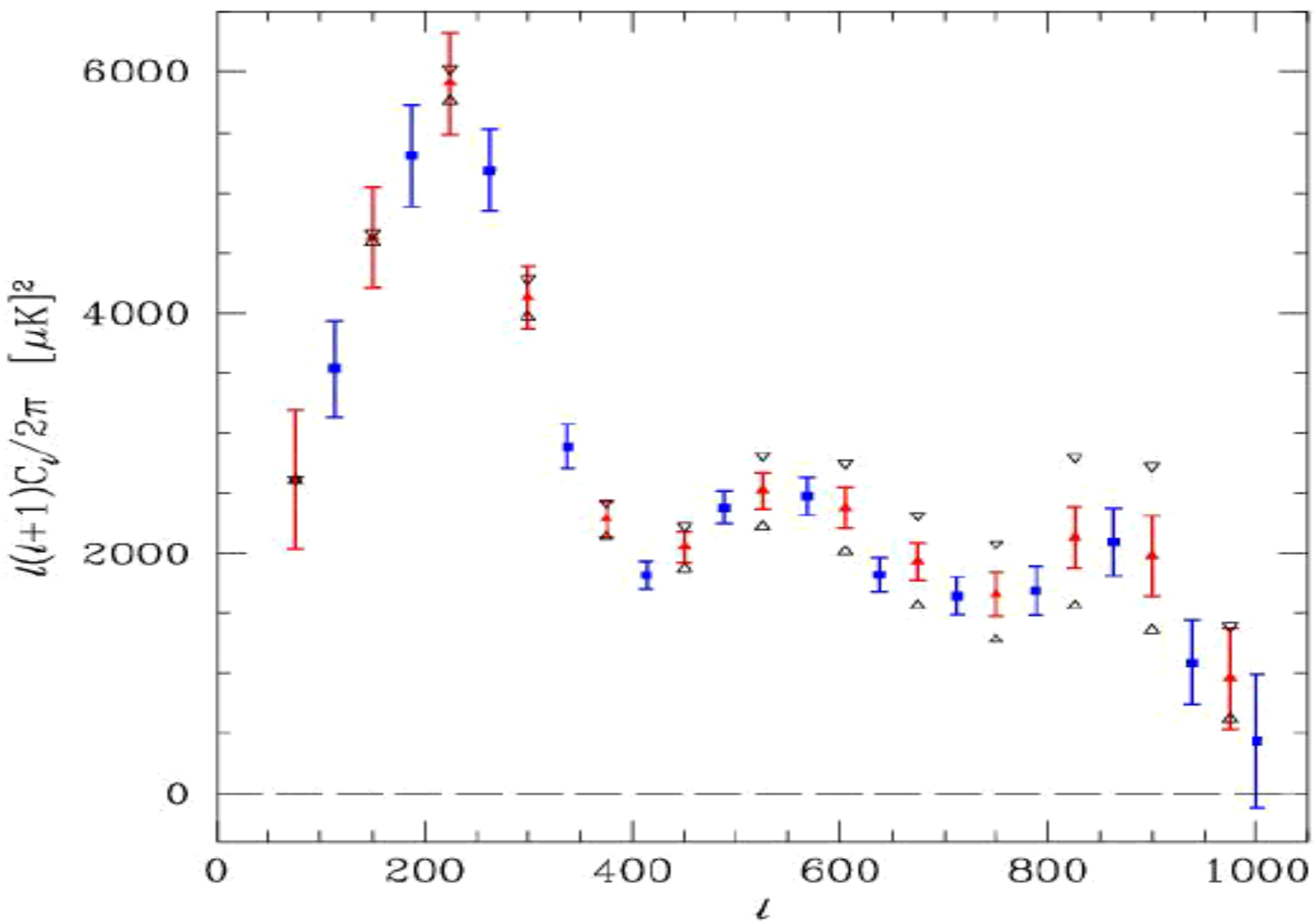

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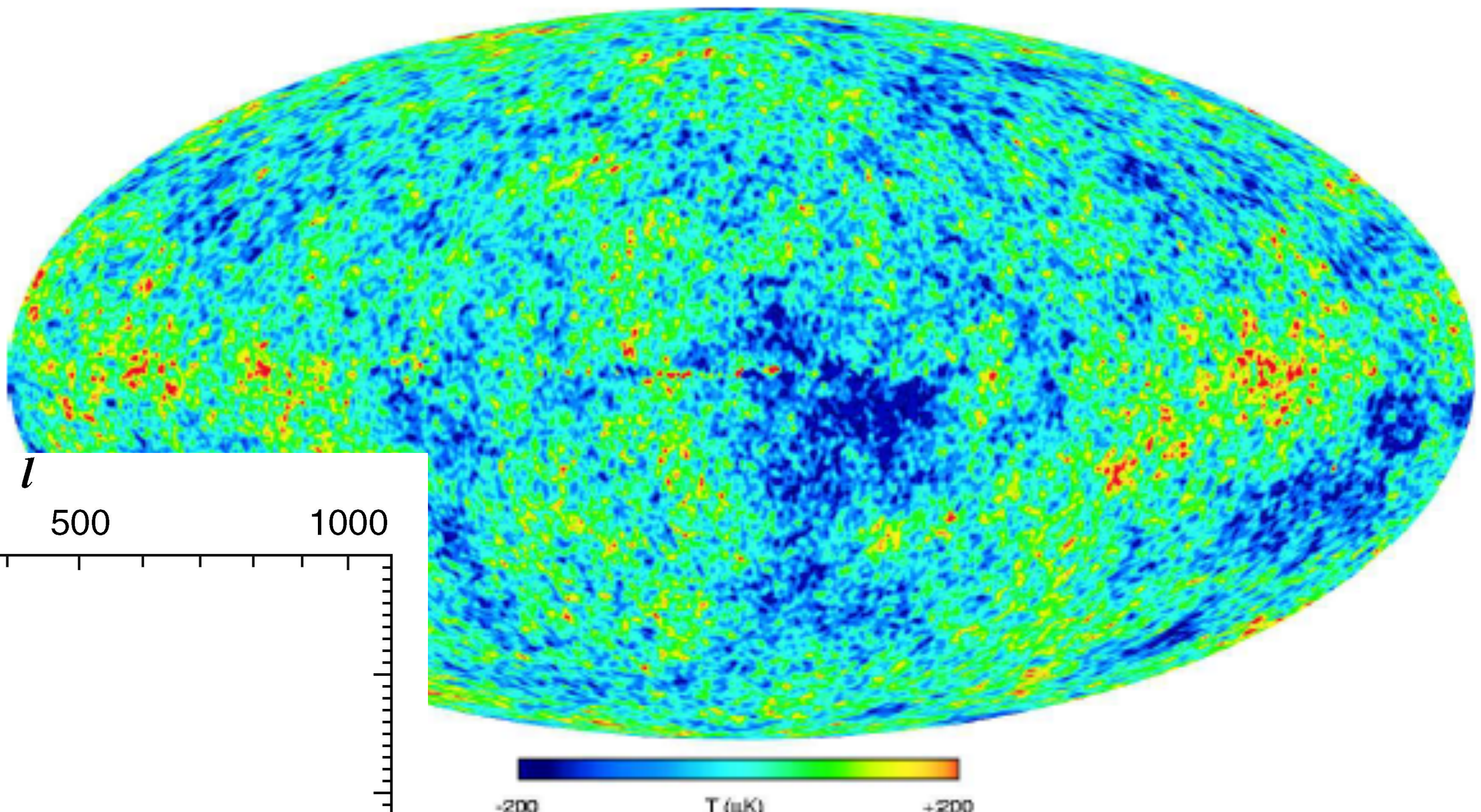

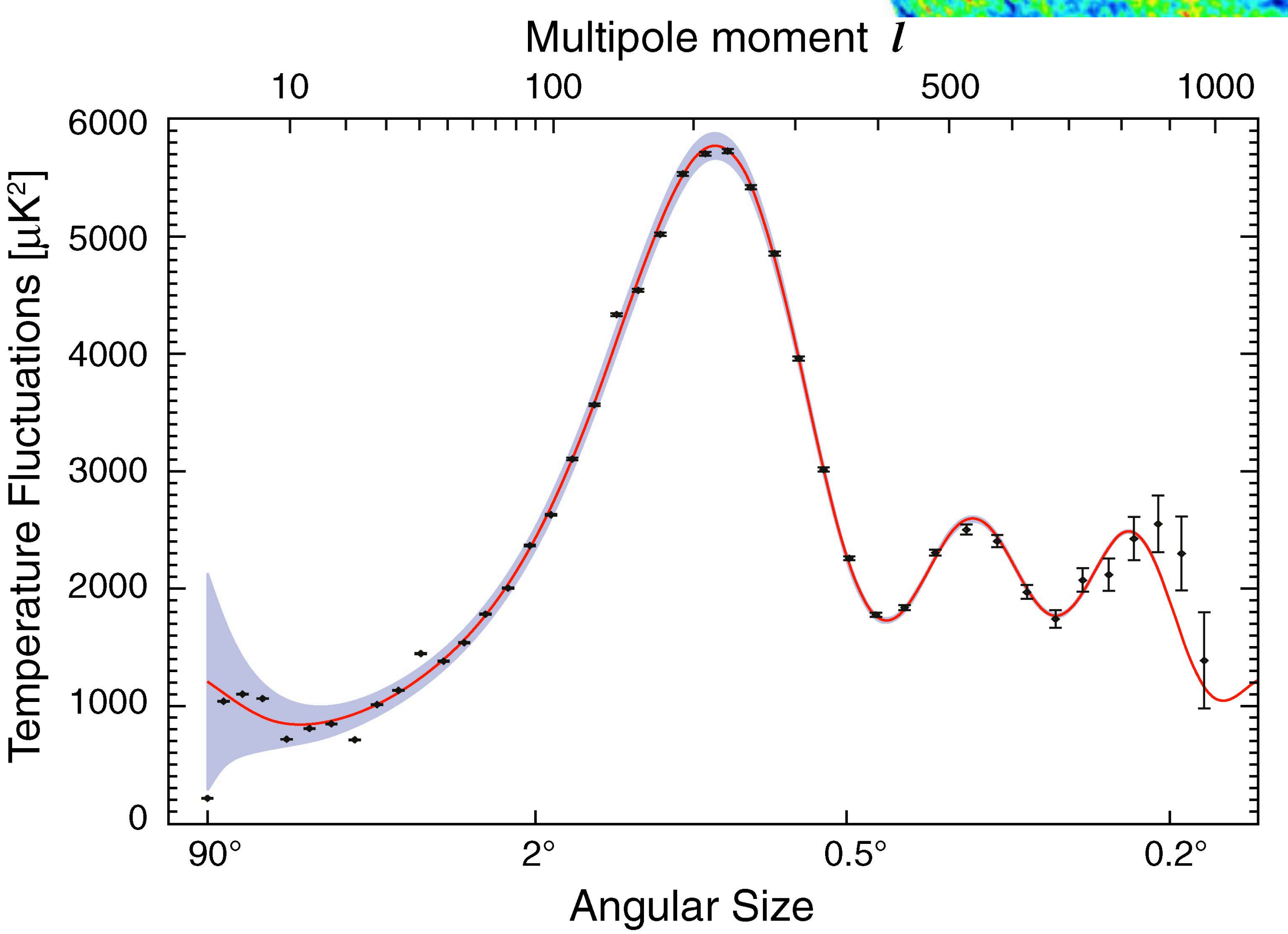

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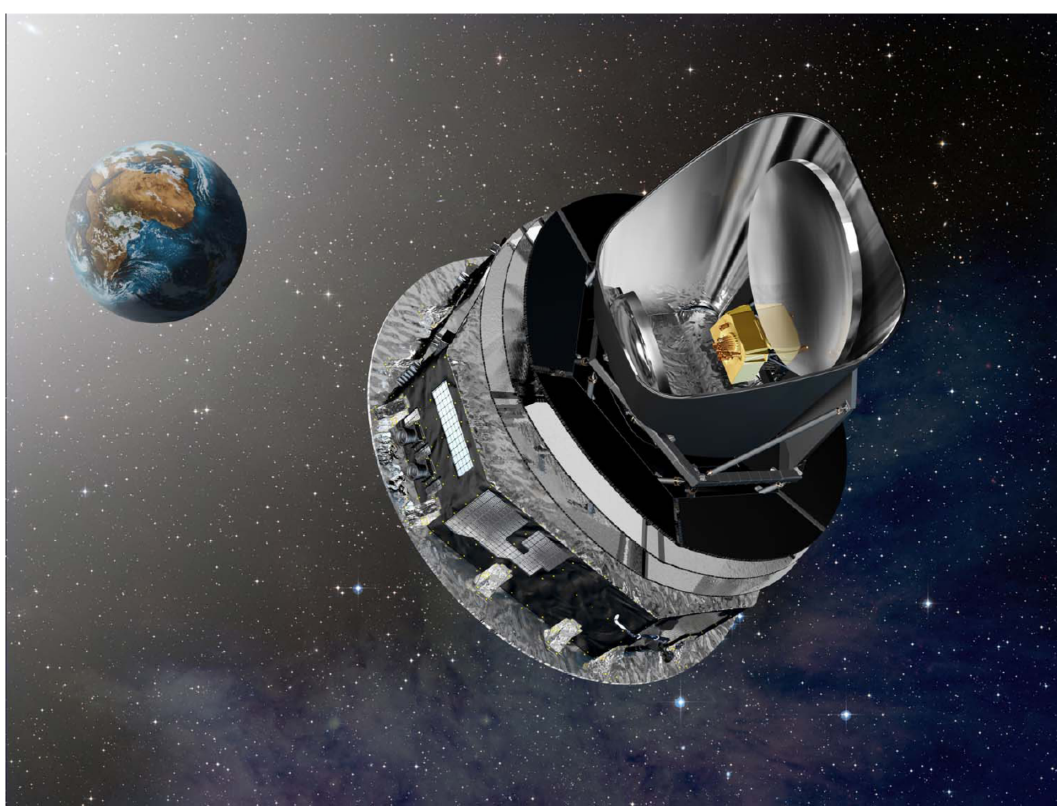
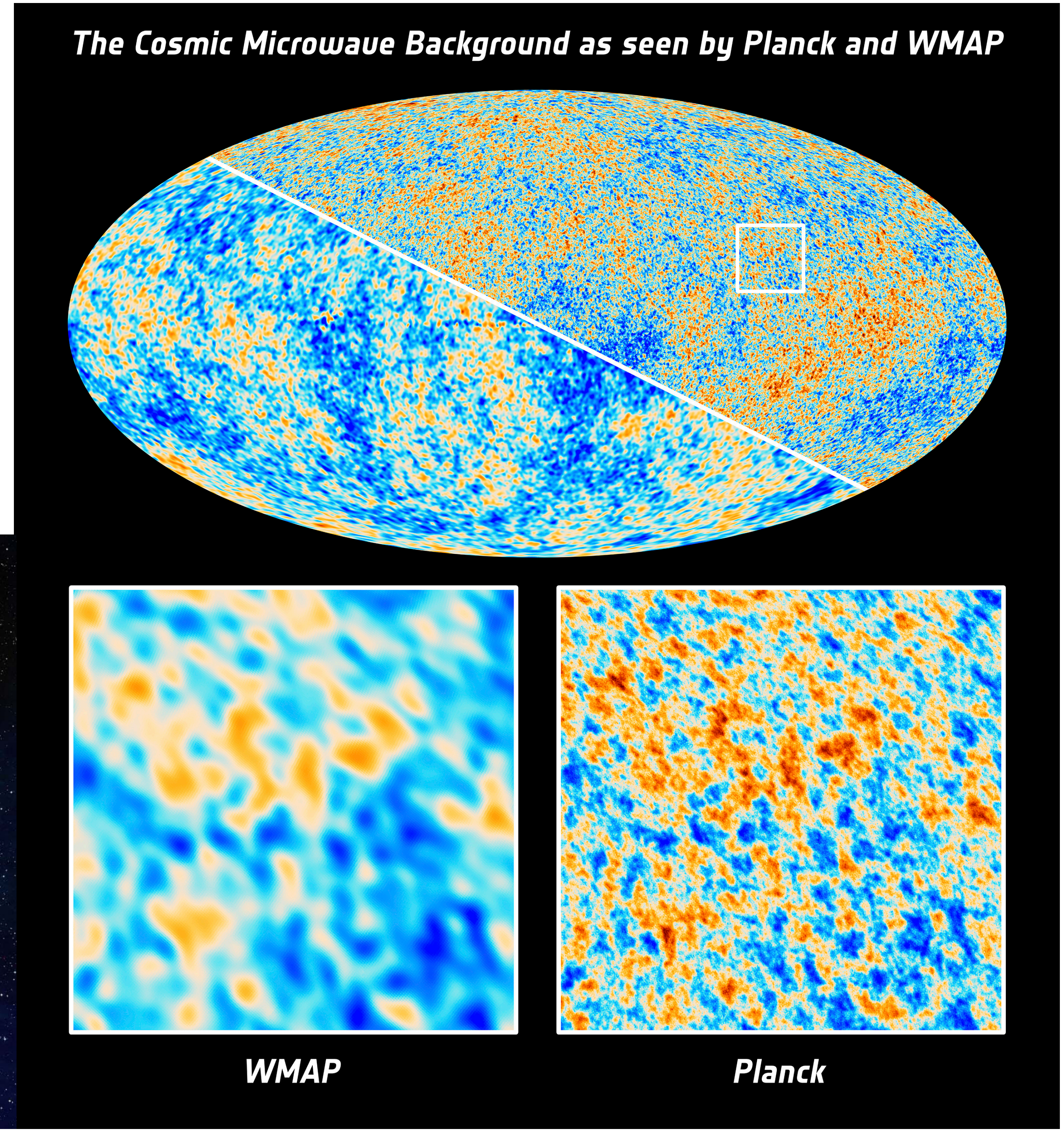
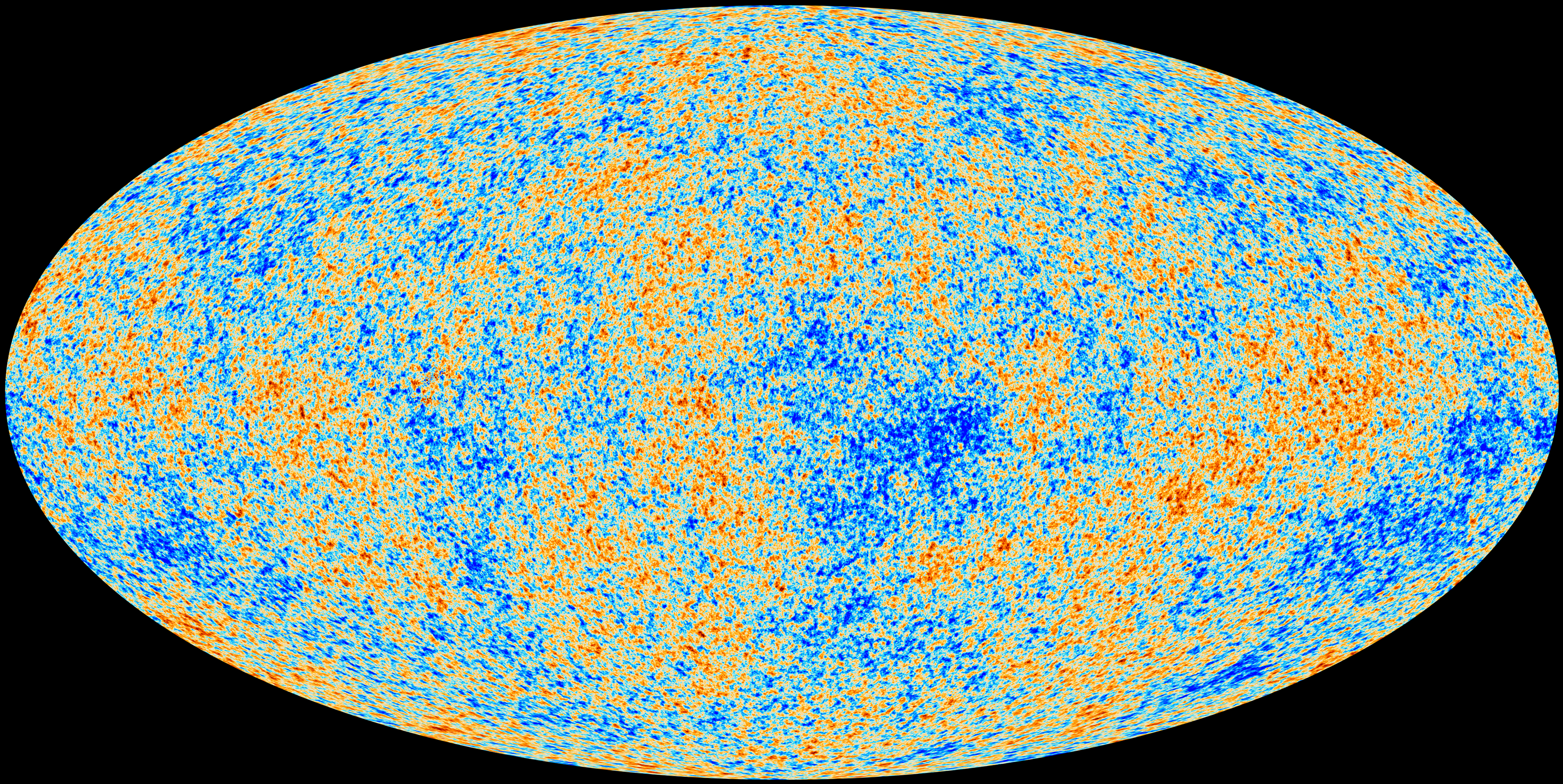
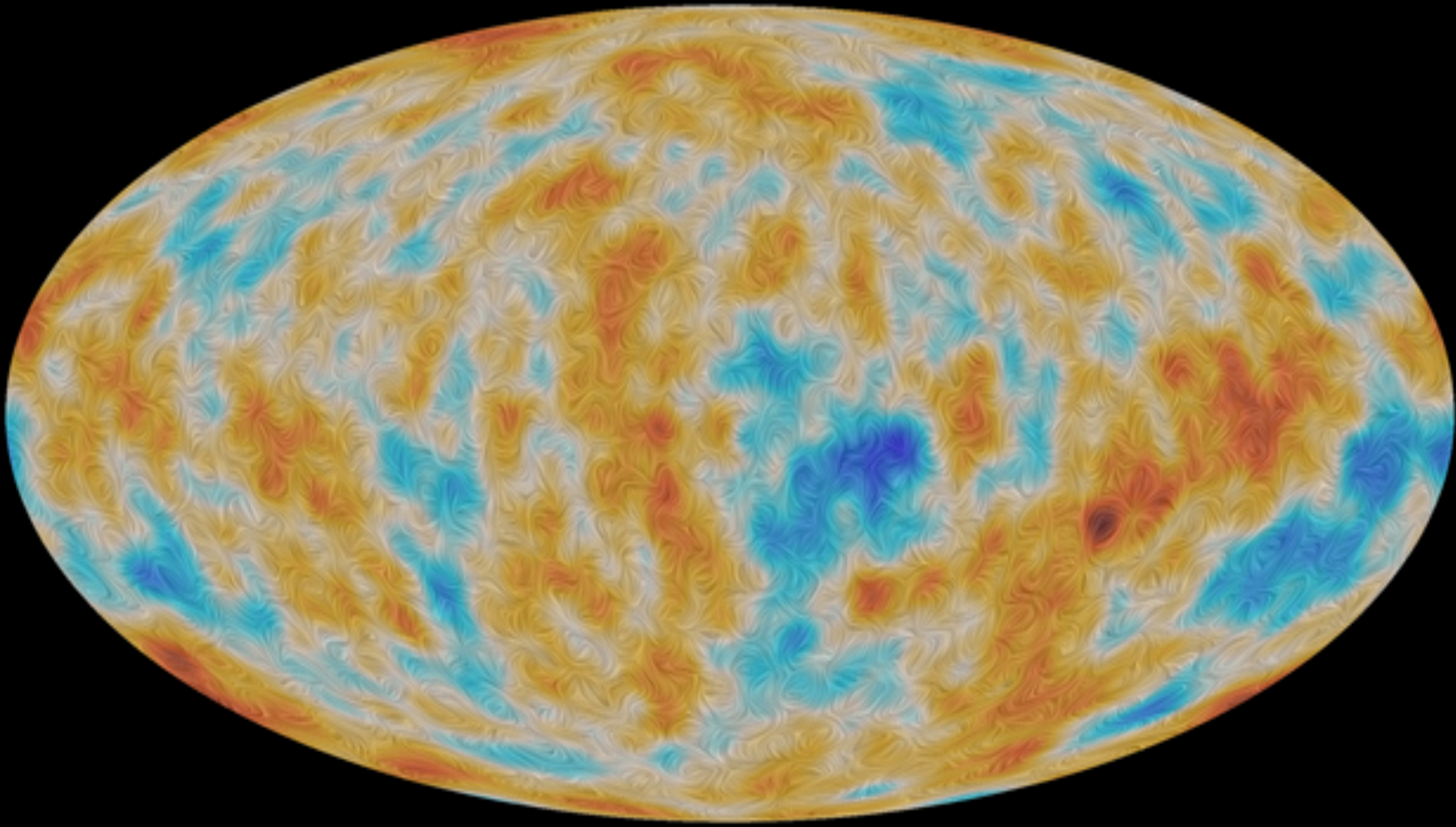




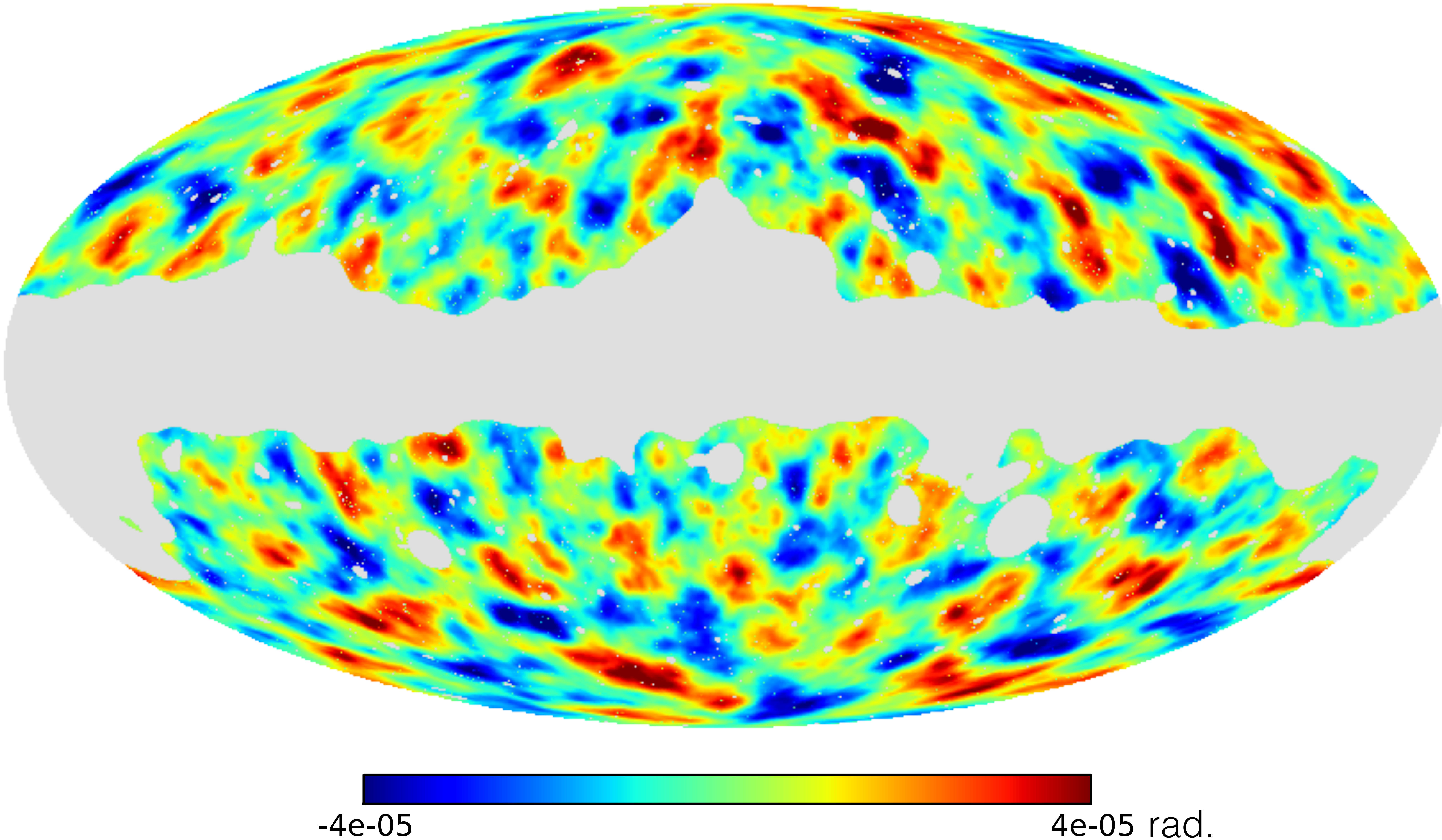
Three main observables



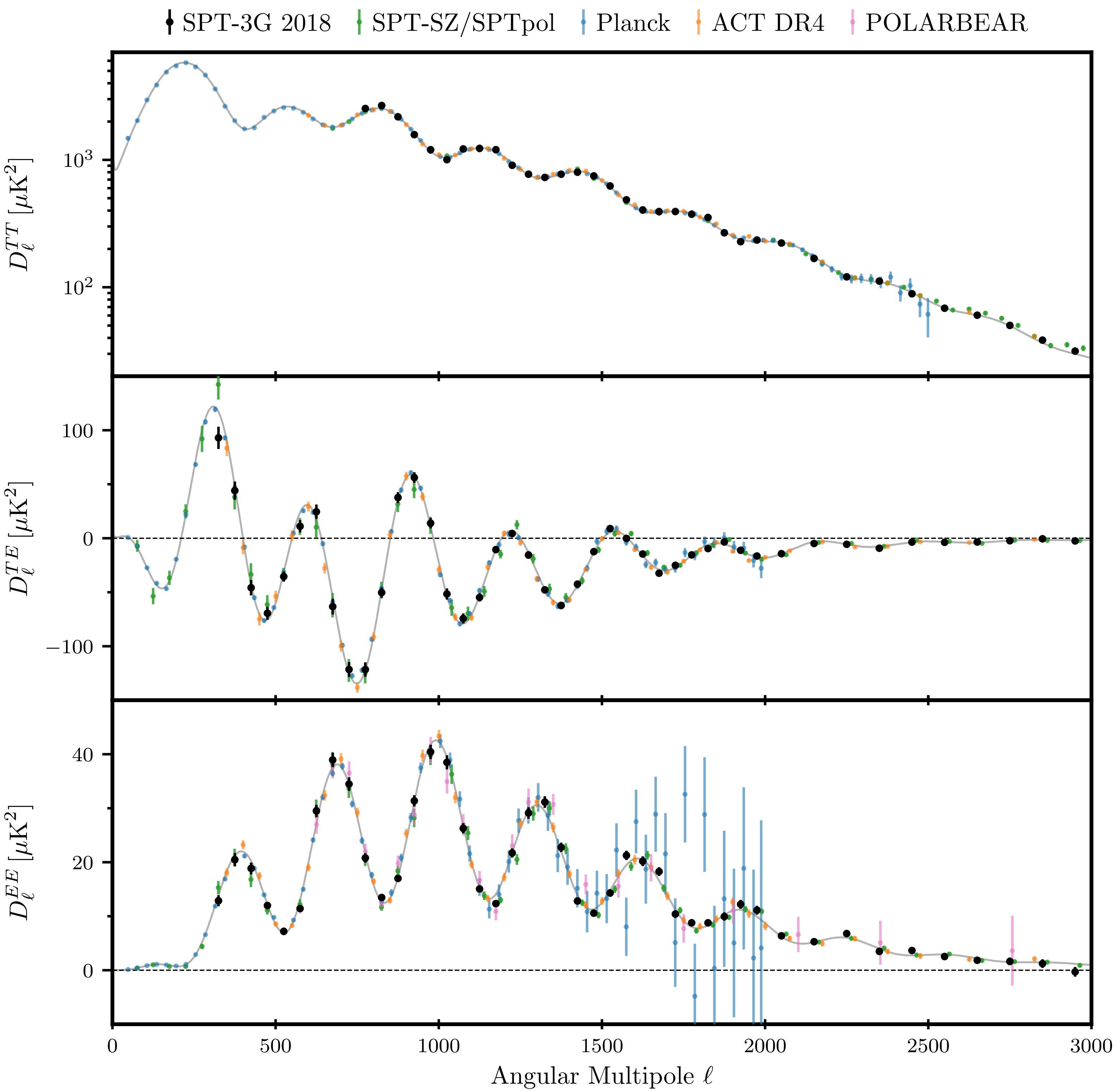
Three main observables



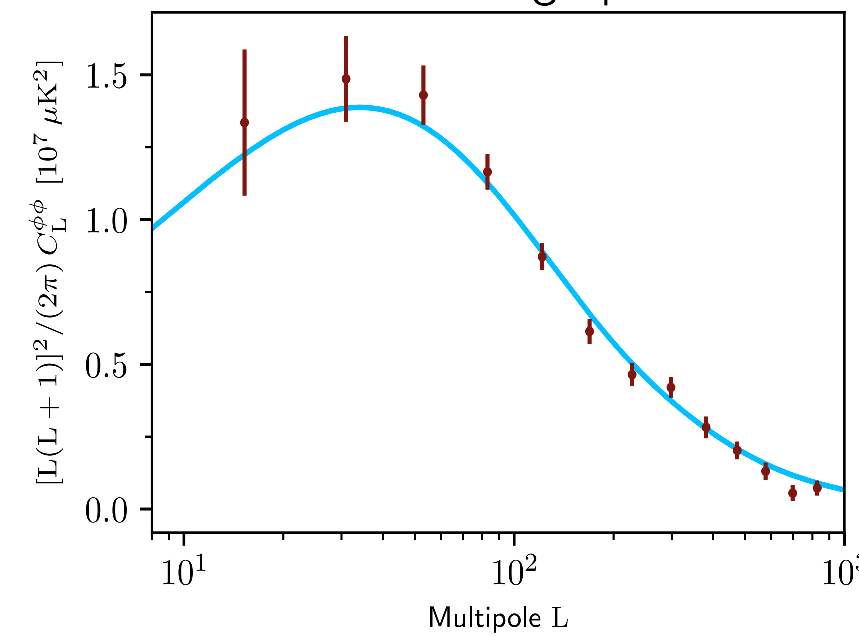
Three main observables

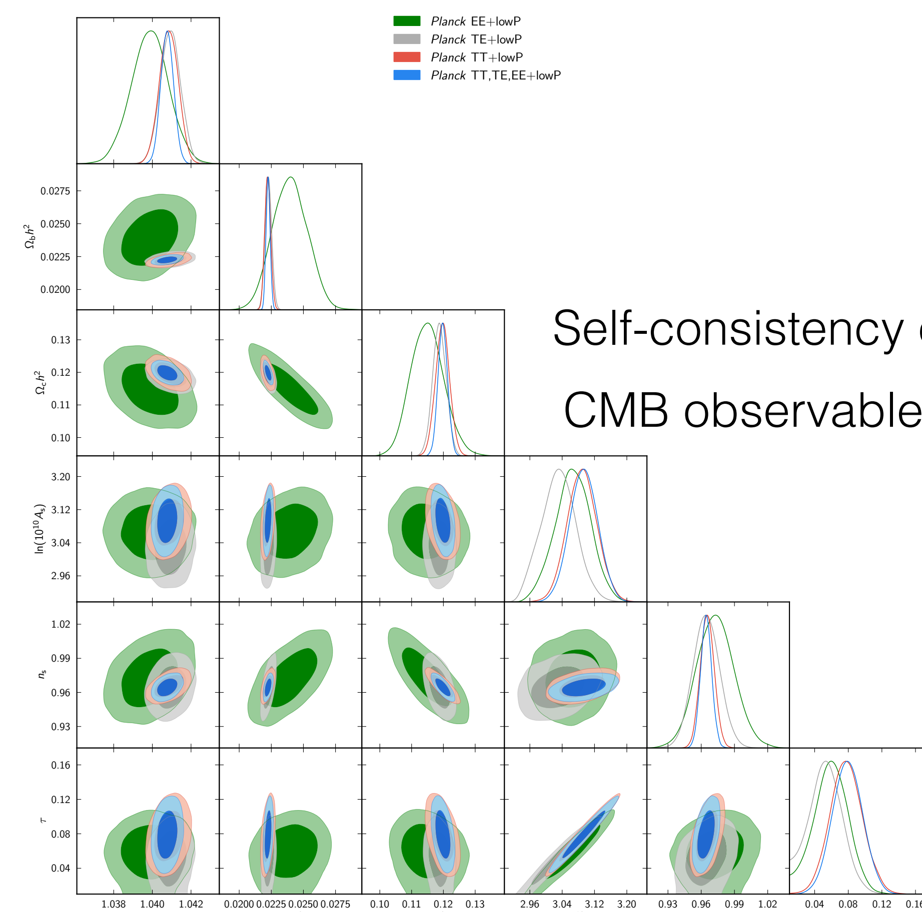


Most recent results



+ *Planck* lensing spectrum





Self-consistency of CMB observables

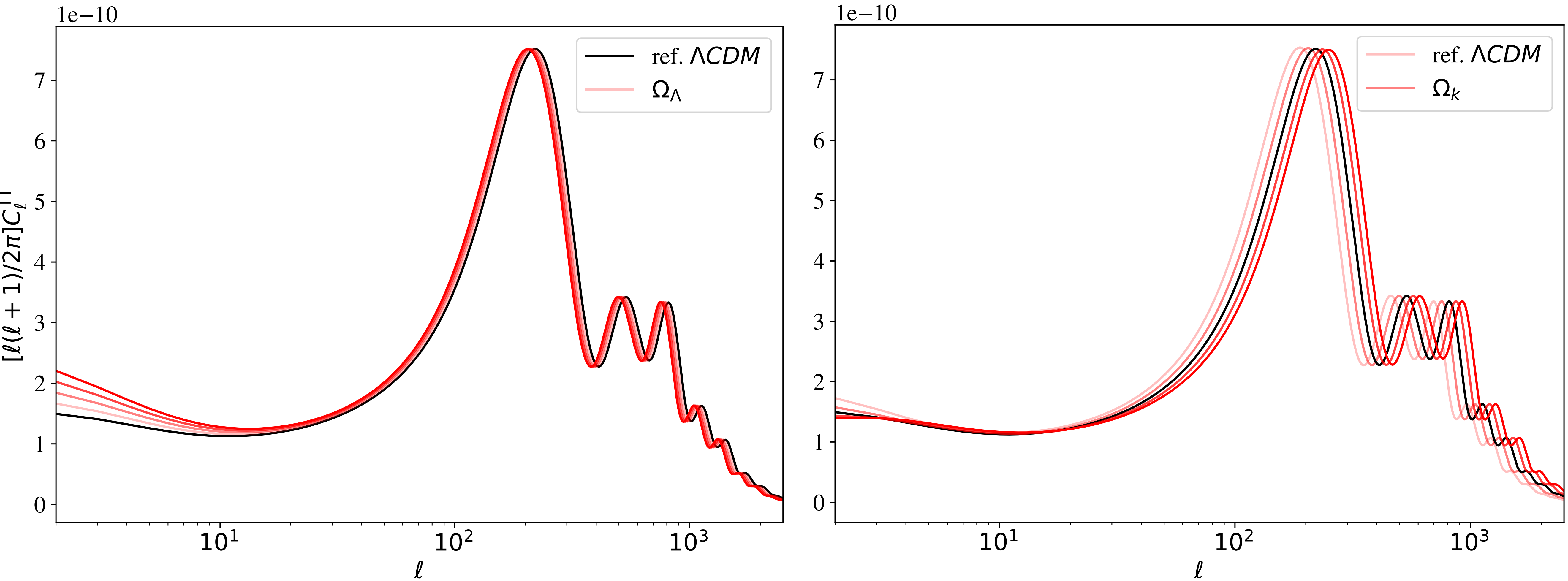
Most recent ΛCDM results from Planck 2018 + SPT-3G

Flat, M_ν fixed to 0.06eV, 68%CL

$\tau_{\rm reio}$ (Planck only)	0.0540 ± 0.0074	← consistent with quasars (Gunn-Peterson, …)
	SPT-3G 2018 + *Planck*	
$\Omega_{\rm b}h^2$	0.02233 ± 0.00013	← consistent with BBN
$\Omega_{\rm c}h^2$	0.1201 ± 0.0012	← 100σ detection
$100\theta_{\rm MC}$	1.04075 ± 0.00028	
$10^9 A_{\rm s}e^{-2\tau}$	1.884 ± 0.010	
$n_{\rm s}$	0.9649 ± 0.0041	← consistent with inflation
H_0 [km s^{-1} Mpc^{-1}]	67.24 ± 0.54	← consistent with BAO+BBN but not with distance ladder
σ_8	0.8099 ± 0.0067	
$S_8 \equiv \sigma_8\sqrt{\Omega_{\rm m}/0.3}$	0.832 ± 0.014	← small tension with weak lensing?
Ω_Λ	0.6835 ± 0.0075	← consistent with remote SNIa
Age/Gyr	13.807 ± 0.021	← consistent with age data

Results beyond ΛCDM

- spatial curvature Ω_k

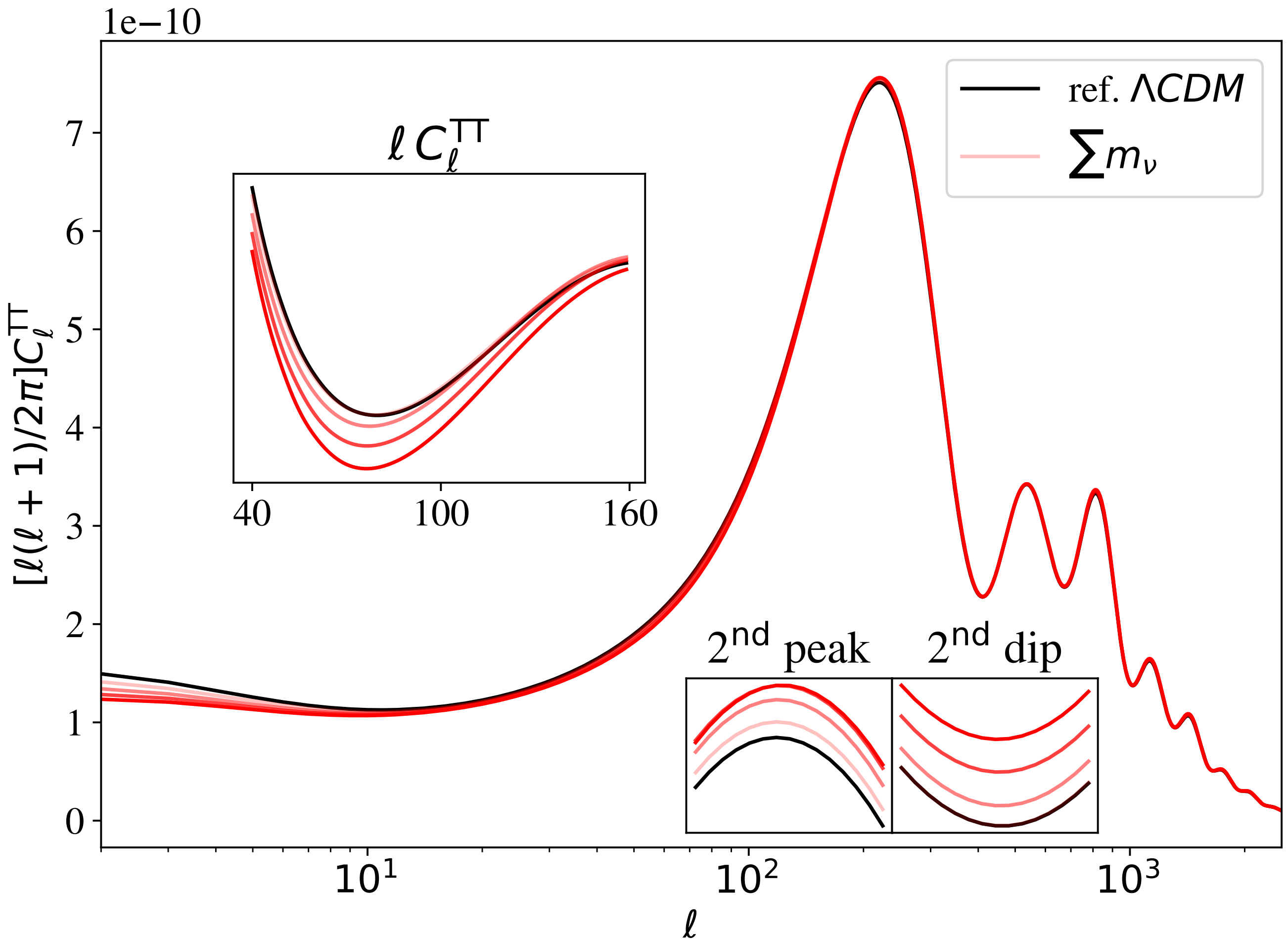


In ΛCDM + Ω_k, same 8 effects only, but tight to 7 parameters: CMB also mesures Ω_k

Parameter	*Planck* alone	*Planck* + BAO	
Ω_K	-0.0096 ± 0.0061	0.0007 ± 0.0019	95% CL

Results beyond ΛCDM

- Total neutrino mass M_ν



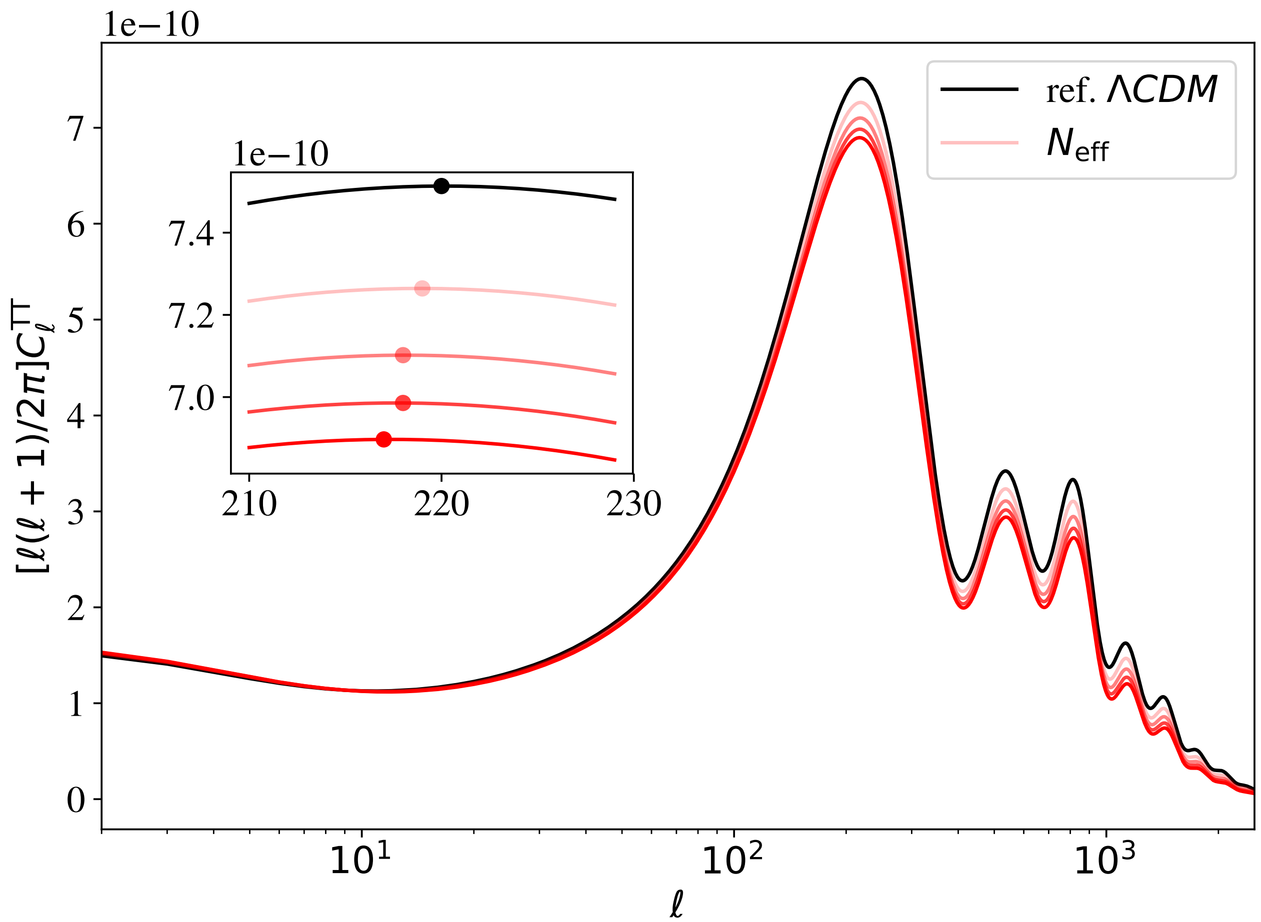
In ΛCDM + M_ν , new effects (early ISW, extra lensing)

Parameter	*Planck* alone	*Planck* + BAO
Σm_ν [eV]	< 0.241	< 0.120

95% CL

Results beyond ΛCDM

- Density of relativistic relics in units of neutrino density, $N_{\rm eff}$

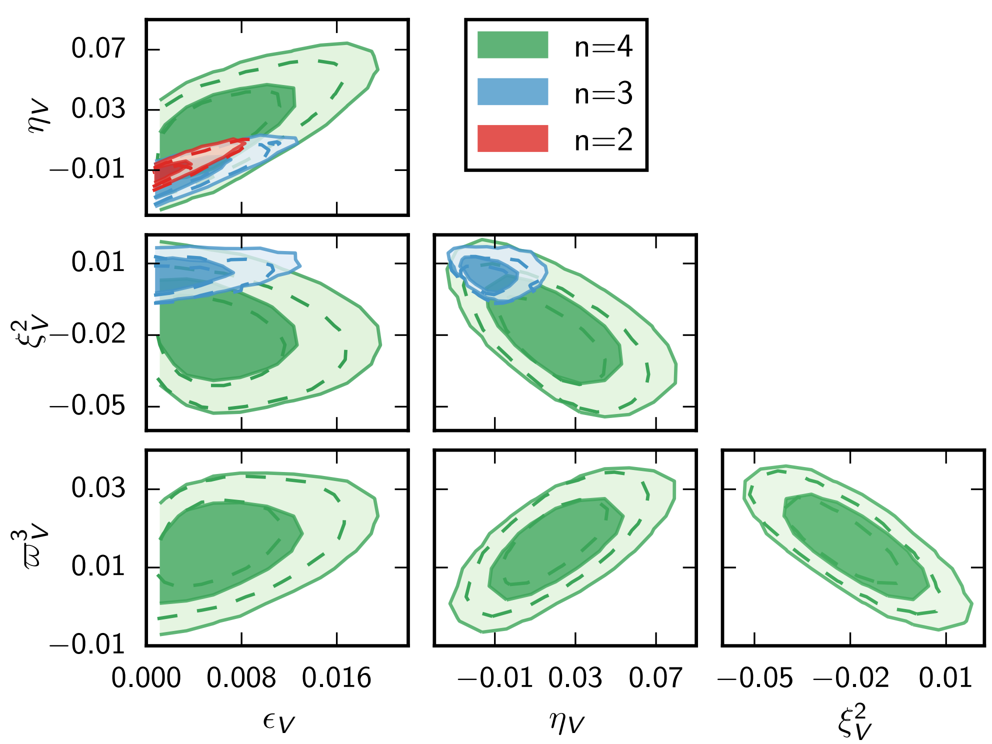


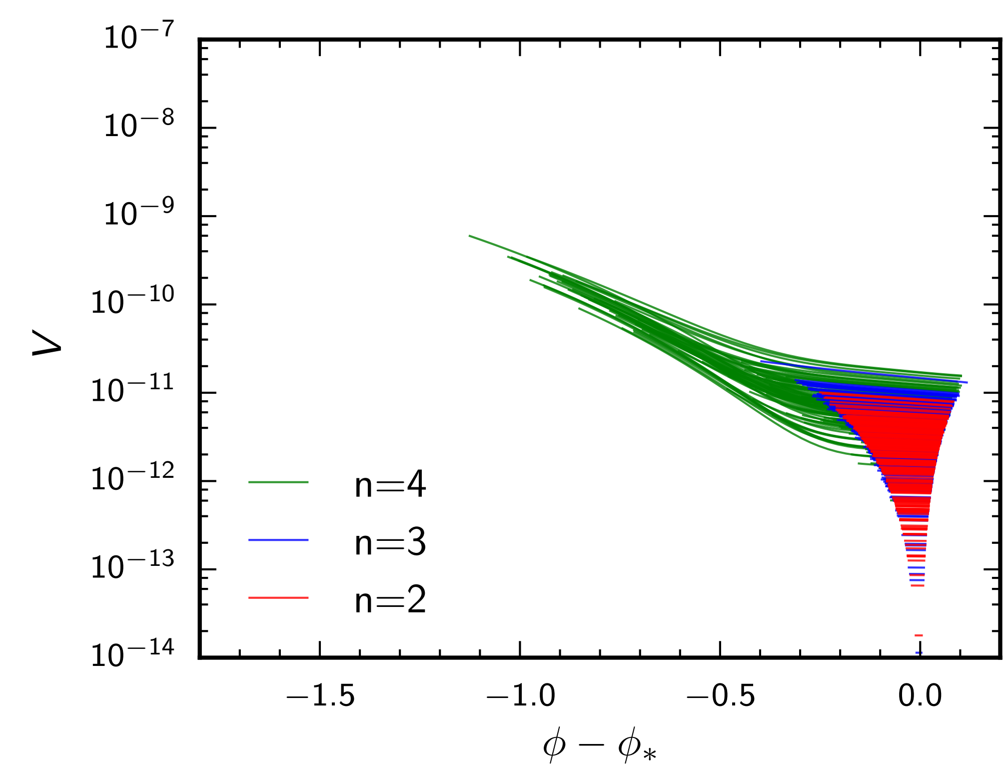
In ΛCDM + $N_{\rm eff}$, new effects (peak shift, damping scale relative to sound scale)

Parameter	*Planck* alone	*Planck* + BAO	
$N_{\rm eff}$	$2.89^{+0.36}_{-0.38}$	$2.99^{+0.34}_{-0.33}$	95% CL

Observational constraints on ΛCDM + r

ΛCDM + r
ΛCDM + r + running
ΛCDM + r + running + running of the running
ΛCDM + r + primordial spectra with parametrised features
ΛCDM + r + binned primordial spectra
ΛCDM + r + <u>parametrised inflation potential</u>
ΛCDM + r + isocurvature modes
etc.





Planck 2015 XX constraints on inflation 1502.02114 (see also 1807.06211)

Future observations

Targets and future observations

- Current status with **Planck, ACT, SPTpol**…
  - temperature error bar below C.V. till $l \sim 1800$
  - polarisation error bar below C.V. till $l \sim 700$
- Future objectives:
  - Low-l polarisation:
    - primordial B-mode, r , inflation, $\tau_{\rm reio}$, reionisation
    - **LiteBIRD** (JAXA) ($\sigma(r_{0.01}) \sim 0.003$)
  - High-l polarisation:
    - polarisation peak scale and damping tail, $N_{\rm eff}$, exotic models (EDE, shifted recombination, etc.)
    - lensing, M_ν , exotic models (non-standard neutrino/DM, modified gravity, EDE, shifted recombination, etc.)
    - **Simons Observatory**, **CMB-S4** ($\sigma(N_{\rm eff}) \sim 0.04$)

THE END

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Books:

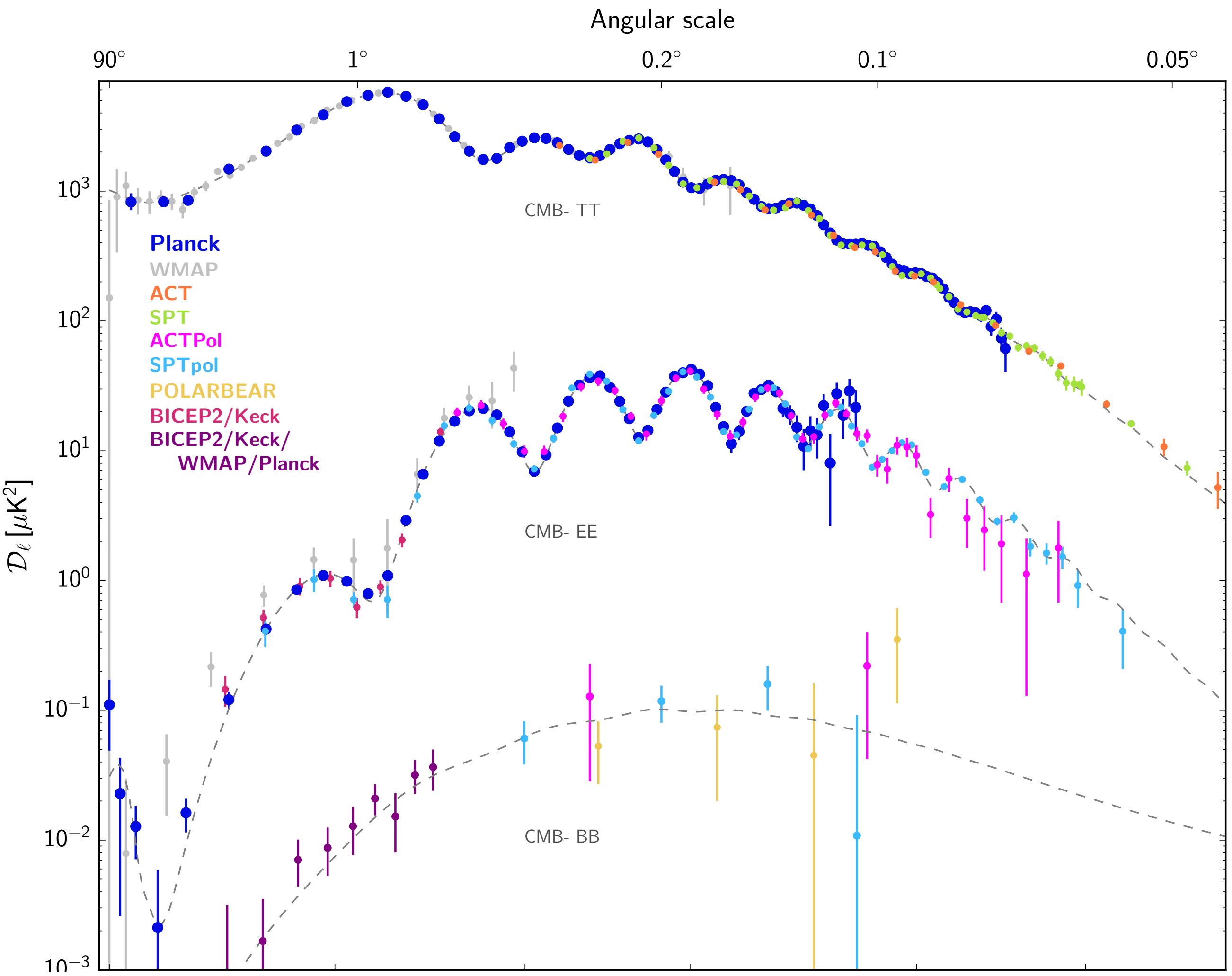
- *The Young Universe: Primordial Cosmology,*
  edited by R. Taillet (John Wiley & Sons, 2022) ISBN : 1789450322
  → Chapter 2: Cosmological Microwave Background, by JL

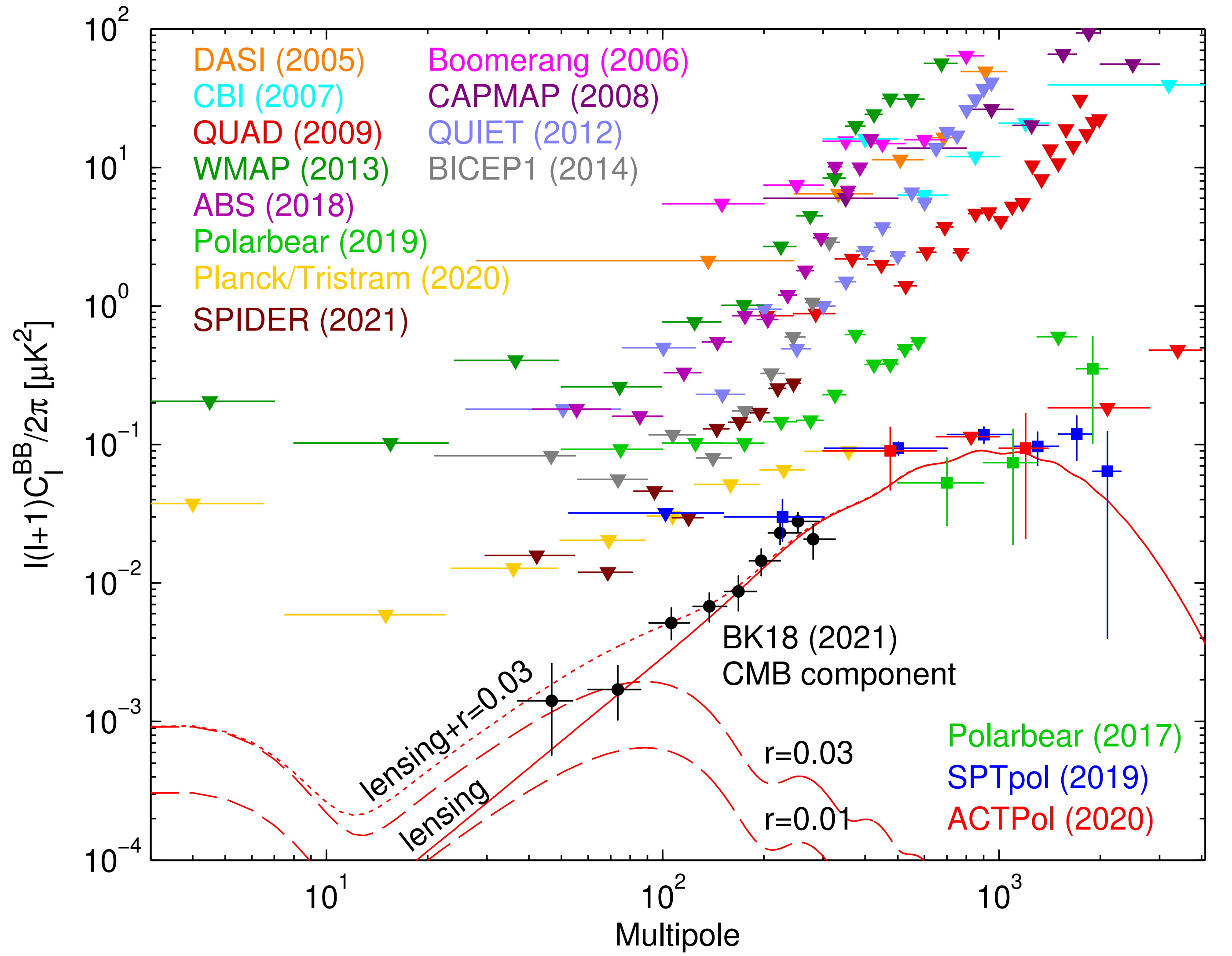
- *Neutrino cosmology,*
  JL, G. Mangano, G. Miele, S. Pastor (Cambridge University Press 2013)
  → Chapter 5: Cosmological Microwave Background, by JL

Notes from Master course on advanced Cosmology:

- *The Ingredients of the Universe,* -> link on Indico page of this school
  JL, course at RWTH Aachen University
  1. Recalls on homogeneous cosmology
  2. Thermal history of the Universe
  3. Linearised gravity
  4. Inflation
  5. CMB anisotropies
  6. Large Scale Structure

Scalar versus tensor spectra





data summary on TT, EE, BB

small-l BB measurements

(Bicep/Keck 2110.00483)

Tensor-to-scalar ratio r:

$$\left.\begin{array}{r} r_{0.005} < 0.030 \\ r_{0.02} < 0.098 \end{array}\right\} \text{(95\% CL, \textit{Planck} TT,TE,EE +lowE+lensing+BK18).}$$

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