Reconstruction of primordial spectra from CMB

Bin HU

Lorentz Institute, Leiden Univ

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outline

- Introduction of CMB physics
- Review of Planck
- Review of BICEP2
- Reconstruction of primordial spectra from Planck and BICEP2

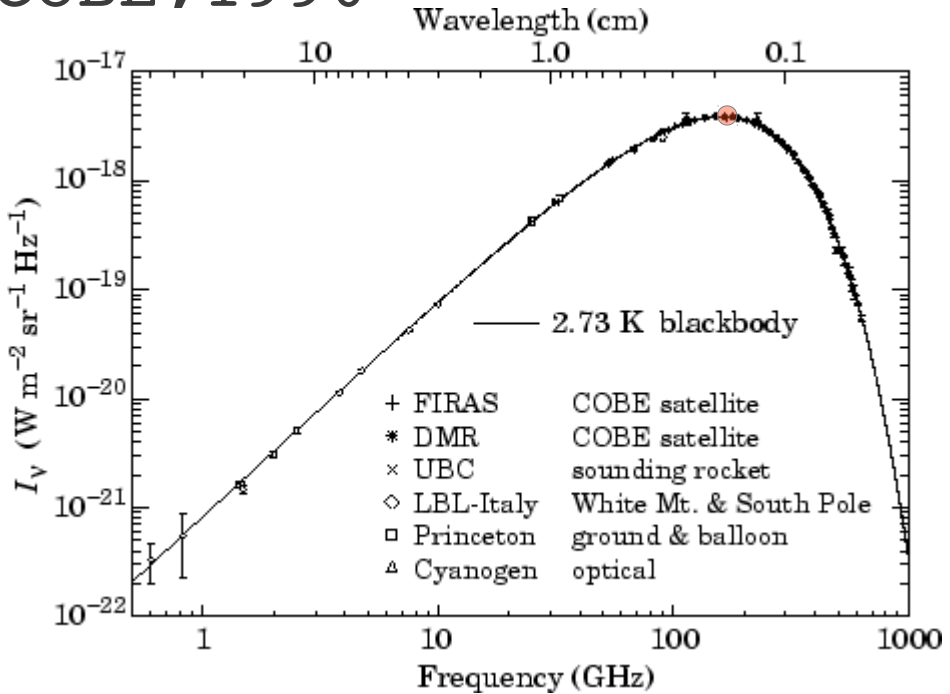
  (1404.3690: BH,Jian-Wei Hu,Zong-Kuan Guo,Rong-Gen Cai)

Introduction of CMB physics-black body spec

- Hot Big Bang,Gamow,1948,T~5K
- Black body spectrum

$$I_\nu = \frac{4\pi\hbar\nu^3/c^2}{\exp\{2\pi\hbar\nu/k_BT\} - 1}$$

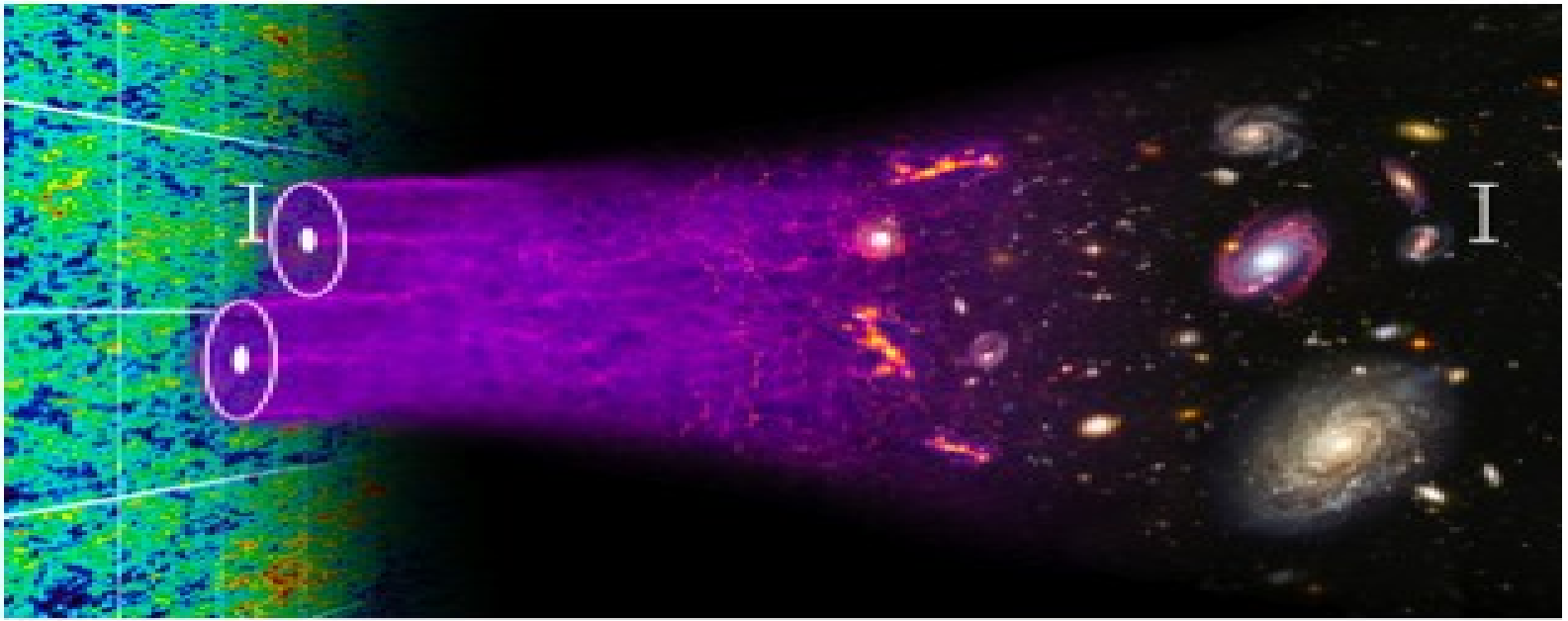
- T~3K,Penzias/Wilson,1965
- COBE,1990



Introduction of CMB physics-black body spec-II

- Red-shift z~1100,electron-proton-> hydrogen, T~3000K ~0.3 eV
- Before: electron-CMB photon

  tight coupling (Thomson scattering) -> plasma;
- After: almost free streaming

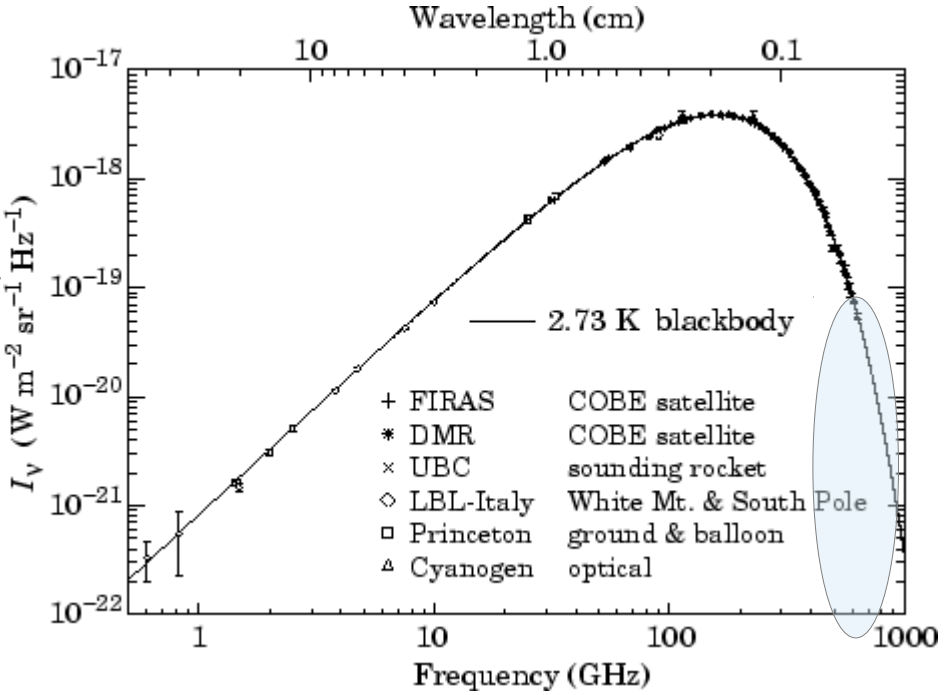


Introduction of CMB physics-black body spec-II

- Red-shift z~1100,electron-proton-> hydrogen, T~3000K ~0.3 eV
- Before: electron-CMB photon

  tight coupling (Thomson scattering) -> plasma;
- After: almost free streaming
- Earth: H bounding energy
- Baryon/photon ratio ~ 1E-

  13.6 eV/log(1E-10)~0.3 eV



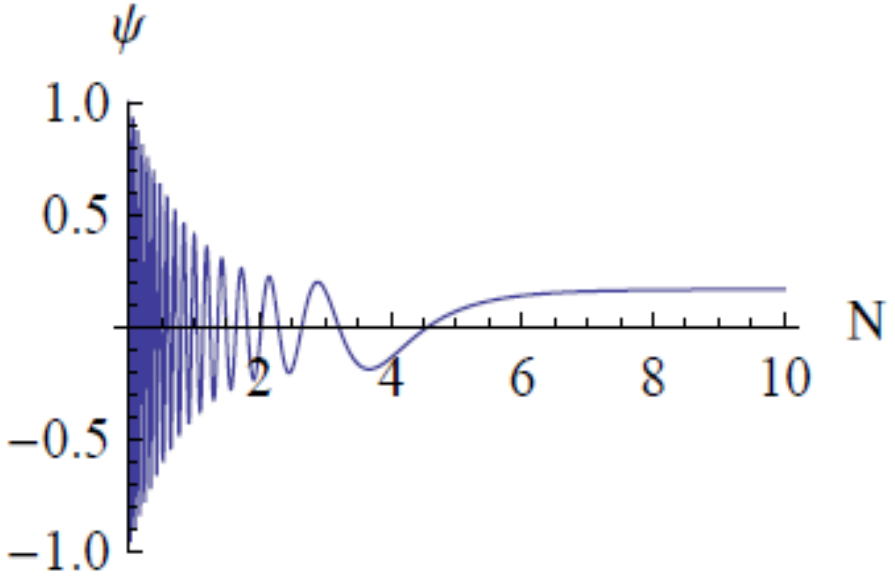
Inflation-scalar perturbation

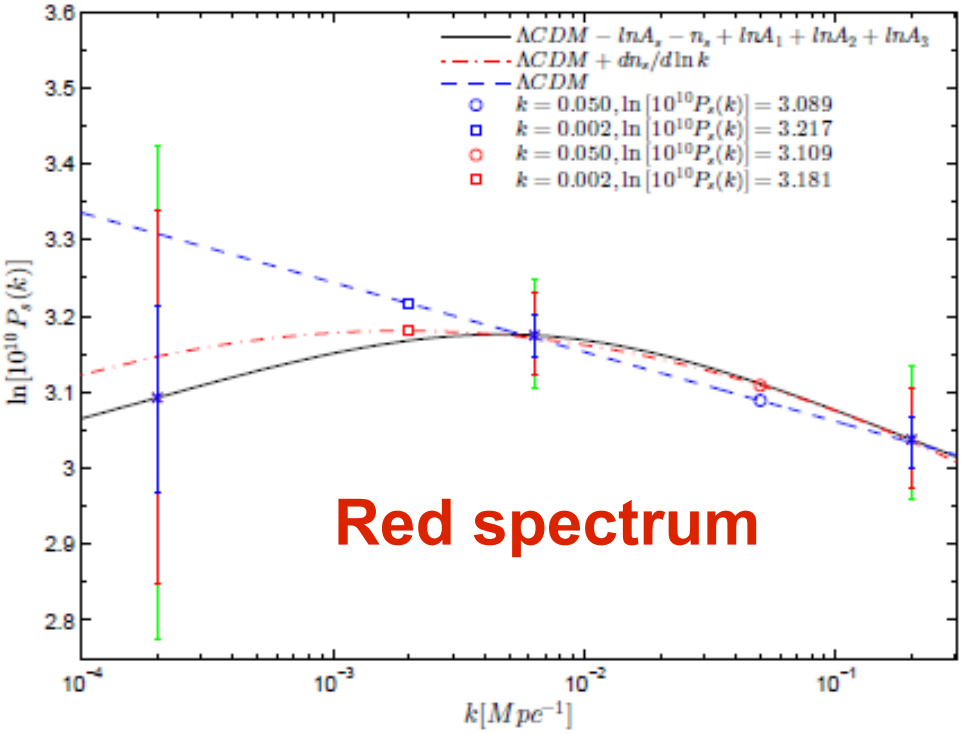
- Scalar Perturb Eq:

$$\delta\ddot{\phi}(t,k) + (k^2 - \frac{2}{\tau^2})\delta\phi = 0$$

- Scalar spectrum

$$P(k) \sim \langle \delta\phi(k)\delta\phi^*(k) \rangle \sim A_s k^{n_s - 1} \text{ , } Planck: \quad n_s \sim 0.9603 \pm 0.0073$$



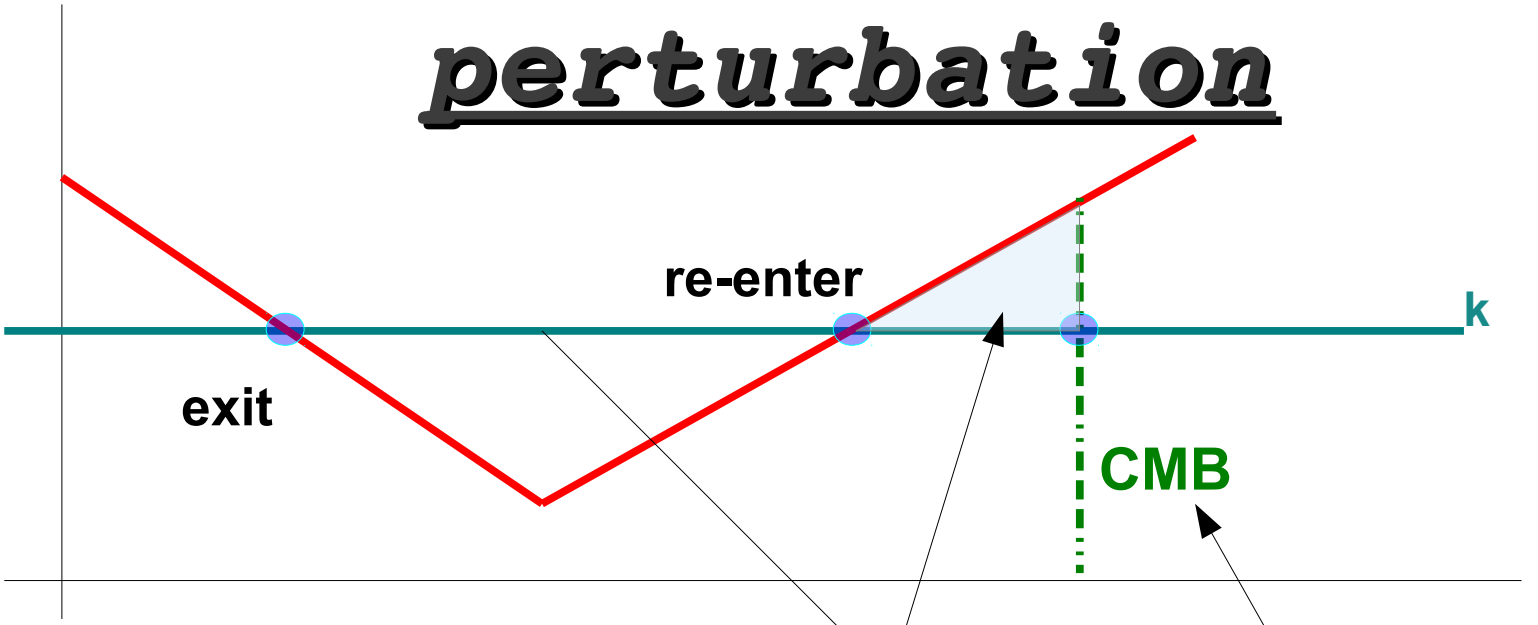


Inflation-tensor perturbation

- Metric perturb Eq: $ds^2 = a^2[-d\tau^2 + (\delta_{ij} + h_{ij})dx^i dx^j]$
- Tensor spectrum: $\ddot{h}_{ij}(t,k) + (k^2 - \frac{2}{\tau^2})h_{ij} = 0$

$P_t(k) \sim A_t k^{n_t}$, *Lyth bound* : $n_t = -r/8 < 0$ **Red spectrum**

Inflation-tensor perturbation

- 

- From Inflation to CMB:

Boltzmann Eq

$$\frac{\delta T(\hat{n},t)}{T(t)} = S(\hat{n},k,t)\delta\phi(k,t_*)$$

Transfer Function

$$\langle \frac{\delta T}{T}\frac{\delta T^*}{T}\rangle \sim \int dk|\Delta(k)|^2\langle\delta\phi(k)\delta\phi^*(k)\rangle \qquad \Delta(k) = \int dt S(k,t)$$

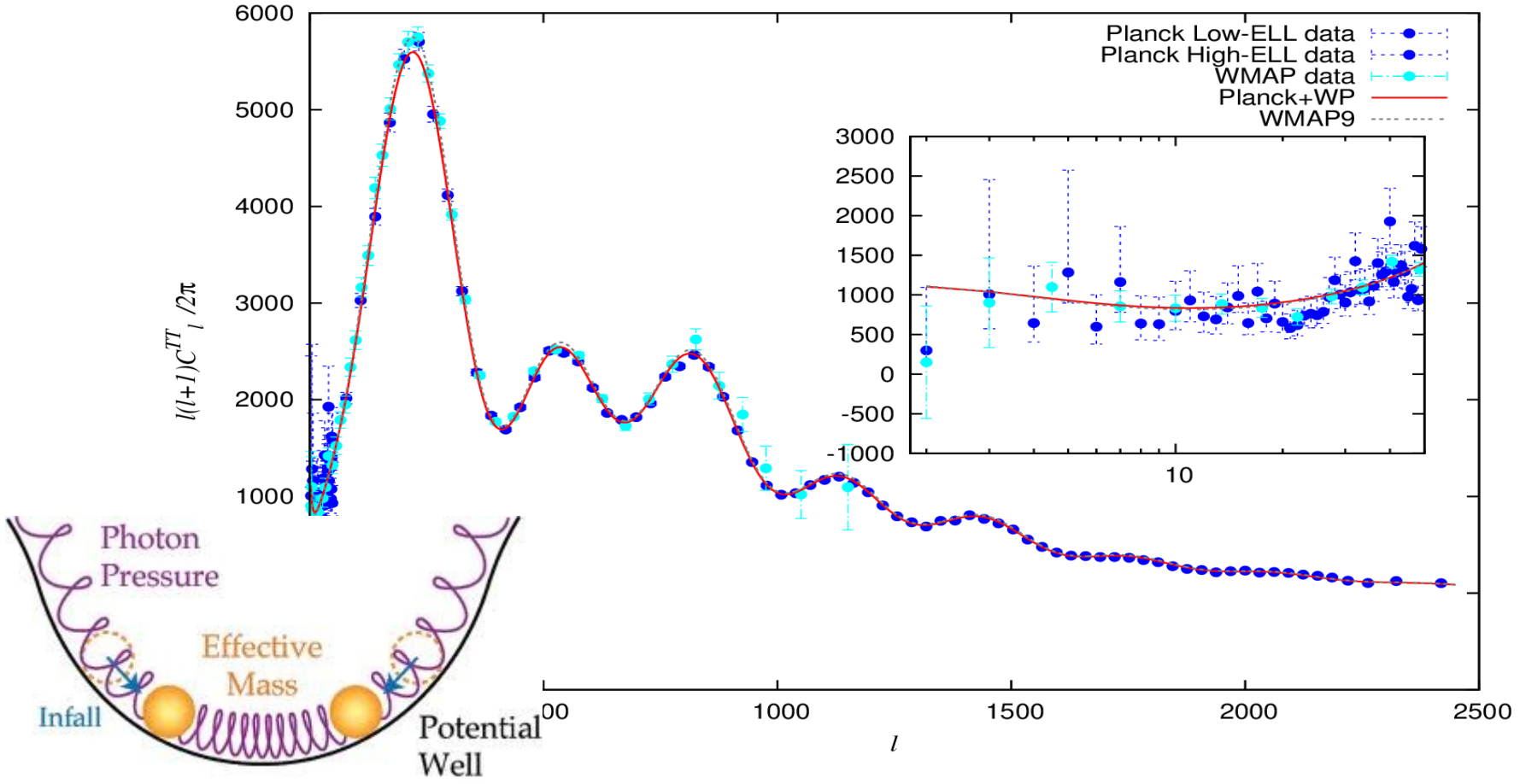
- Spherical harmo exp

$$\frac{\delta T(\hat{n},t)}{T(t)} = \sum_\ell \sum_m a_{\ell,m} Y_{\ell,m}(\hat{n})$$

CMB angular spectrum

- Angular spec:

$$C_\ell = \sum_m \frac{1}{2\ell+1} a_{\ell,m} a^*_{\ell,m}$$

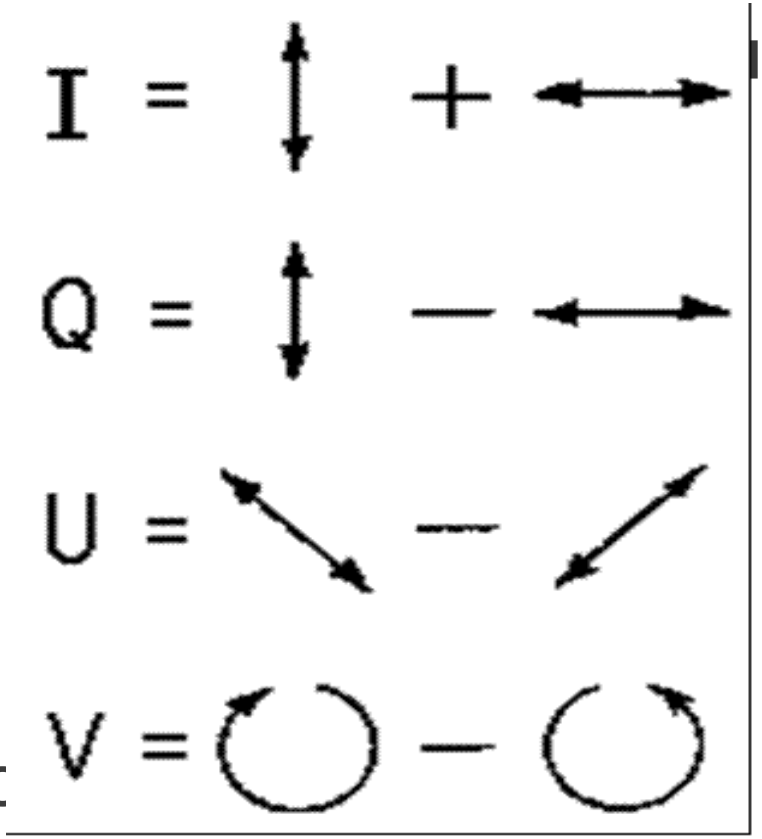


CMB polarization I

- Linear Polarization: Thomson Scattering
- Intensity tensor

$$I_{ij} = -\epsilon_0 E_i E_j - \frac{1}{\mu_0} B_i B_j \qquad I_{ij} = -\epsilon_0 E_i E_j$$

- Stokes parameter (4 co

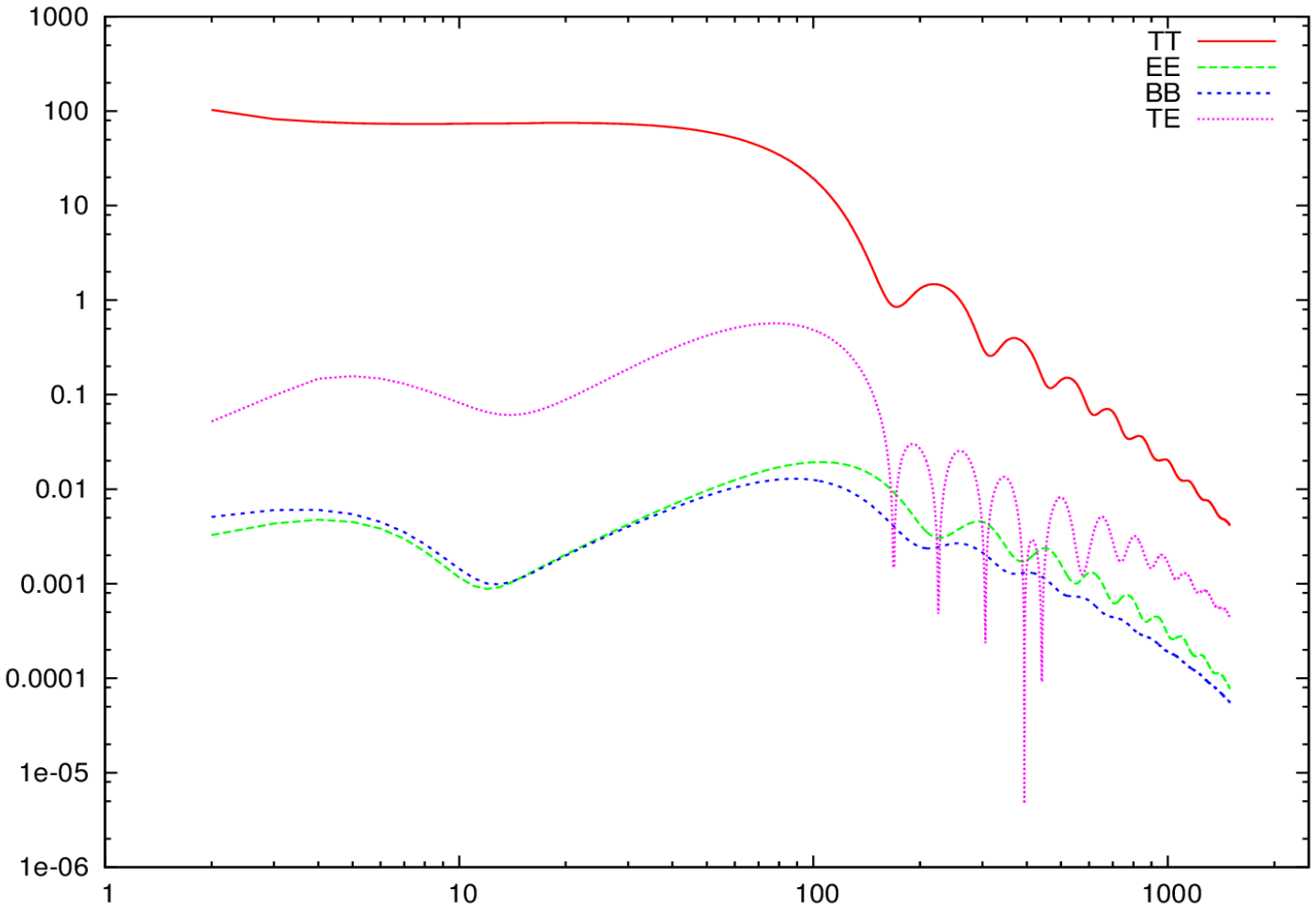


$$T = (I_{11} + I_{22})/4 \qquad Q = (I_{11} - I_{22})/4 \qquad U = I_{12}/2 \qquad V = 0$$

No filter **Lin Pol at 0 and 90** **Lin Pol at -45 and 45** **Cir Pol**

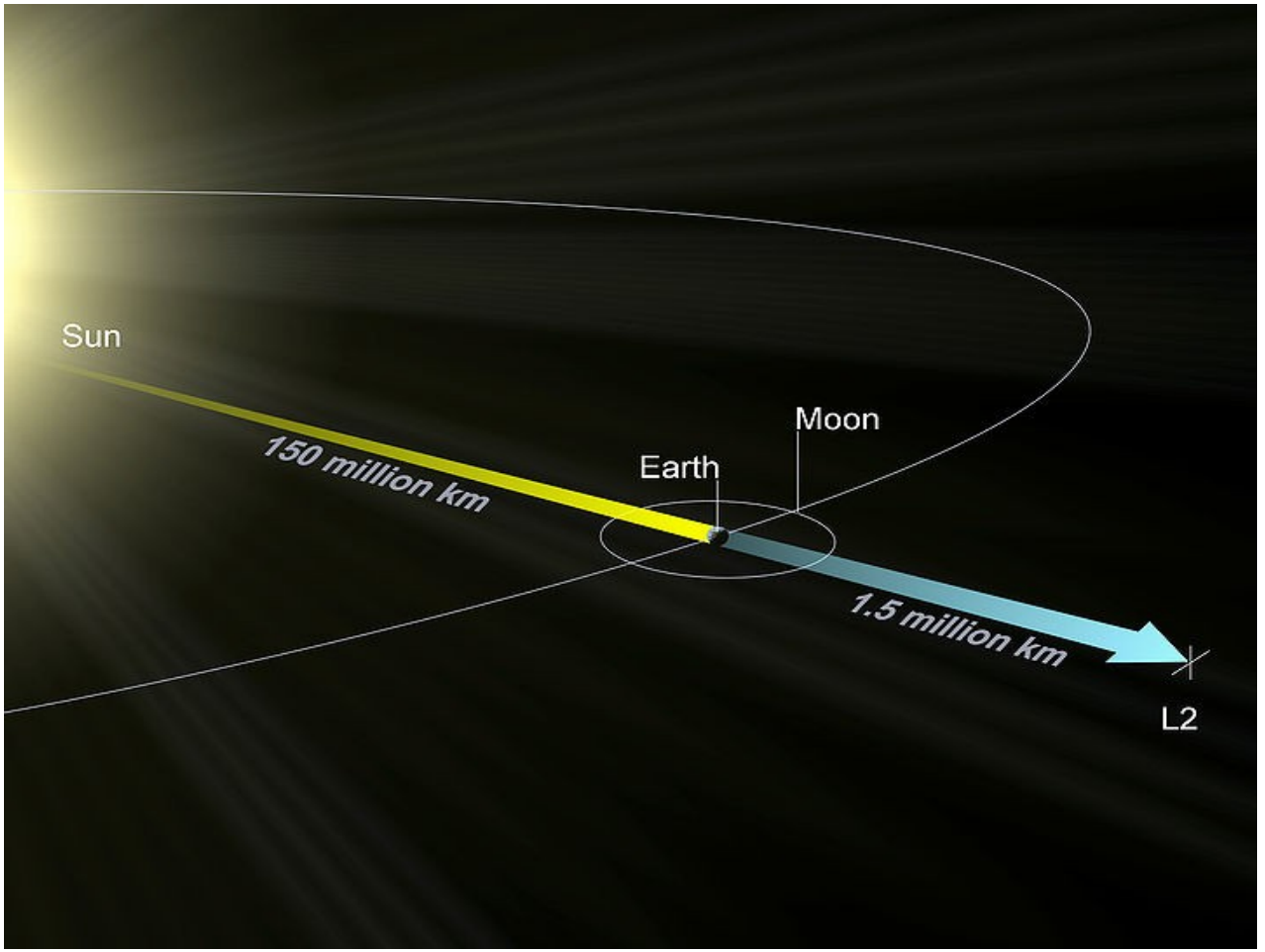
CMB polarization II

- Def
- $a_{E,\ell m}$
- $a_{B,\ell m}$
- 5%
- sqr



Review of Planck temperature results

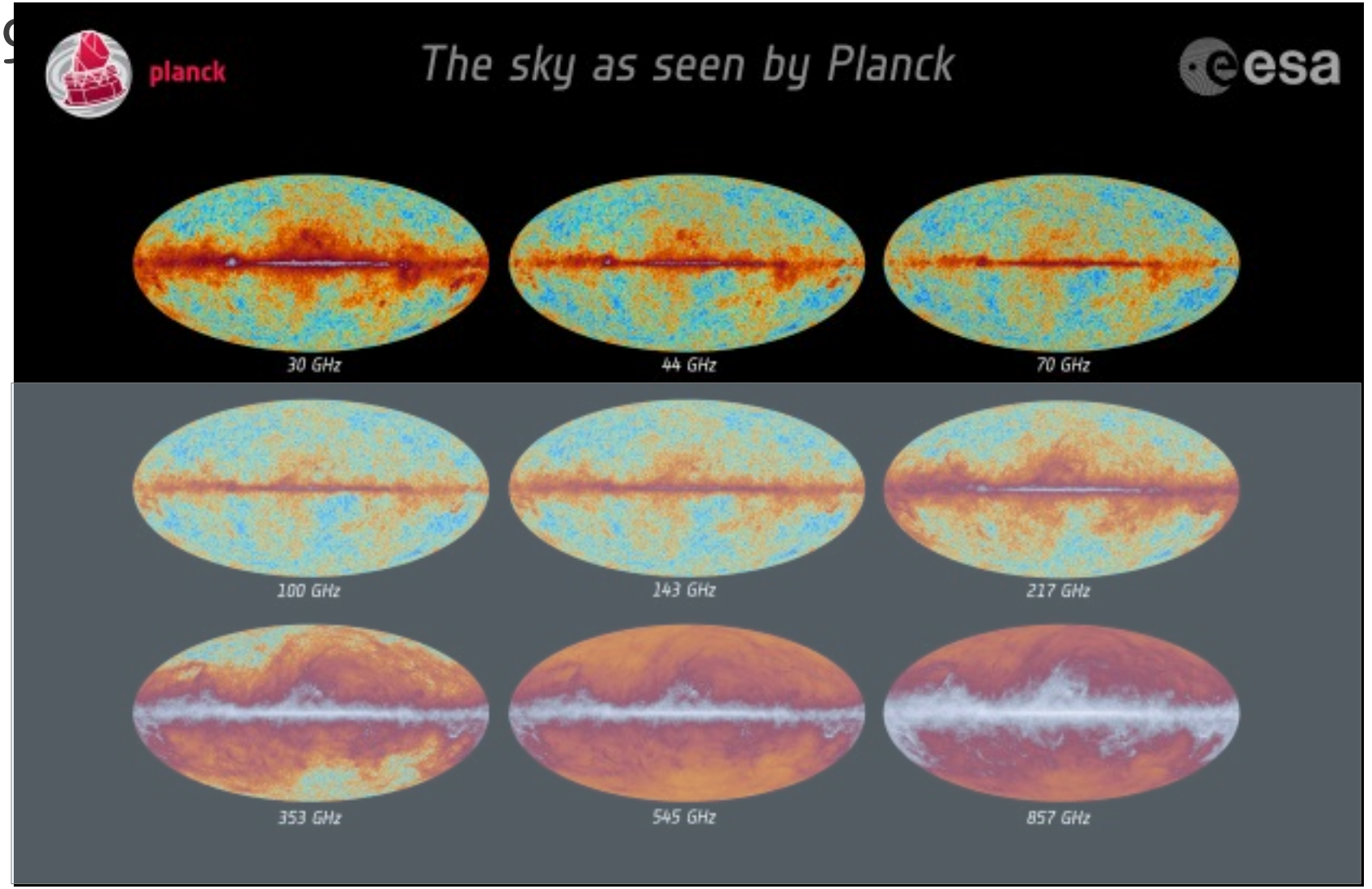
- Satellite: 2009/05 launched,L2 point



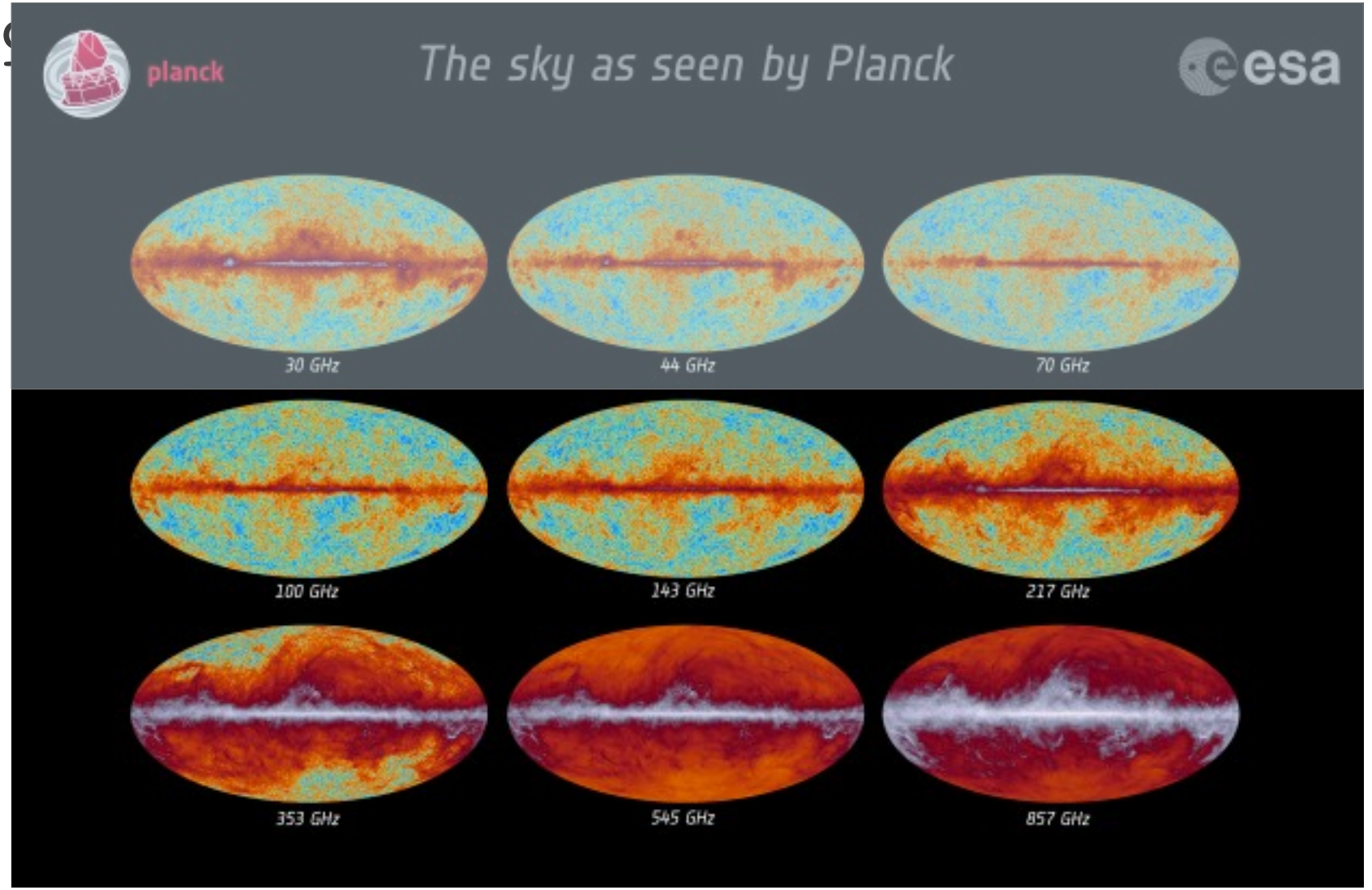
Review of Planck temperature results

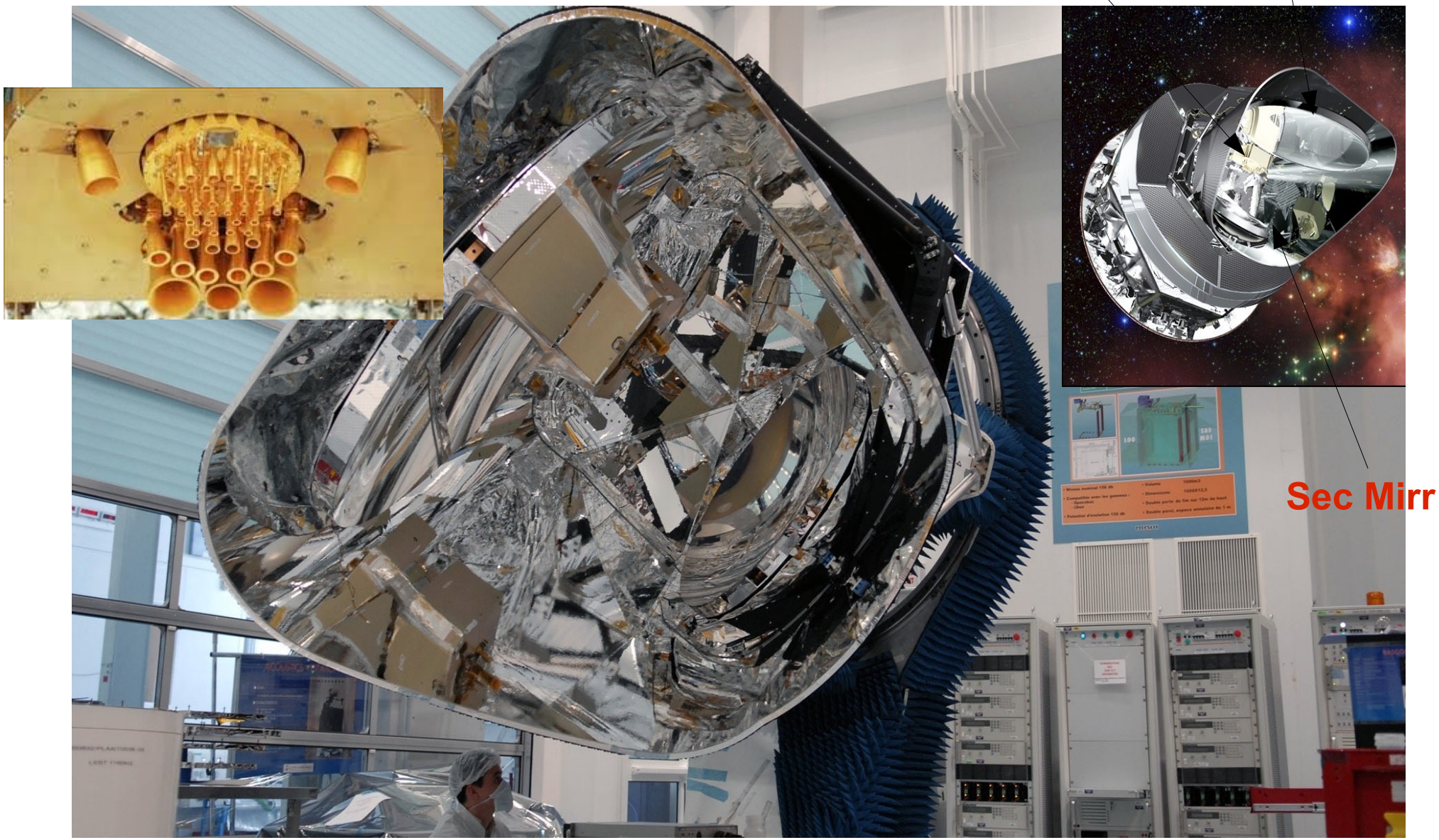
- Satellite: 2009/05 launched
- First data release: 2013/03 T-map
- Second data release: expected 2014/10~11, Pol-map
- Full sky
- Angular resolution: (~5')
- Sensitivity: $(\Delta T/T \sim 2 \times 10^{-6})$
- 9 frequency channels: LFI/HFI

Review of Planck temperature results

- 

Review of Planck temperature results

- 


Focal Plane
Primary Mirr
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Review of Planck temperature results

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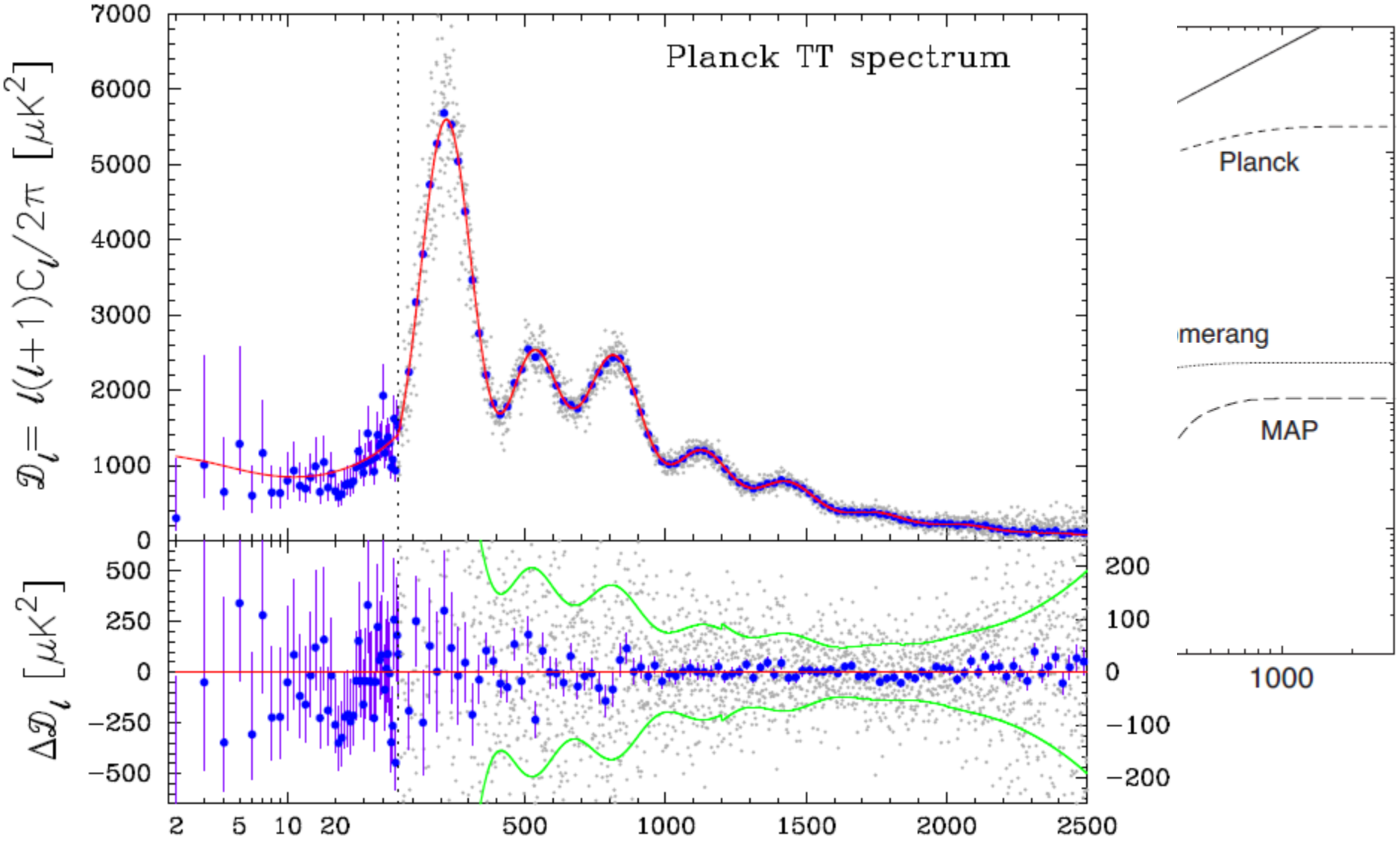
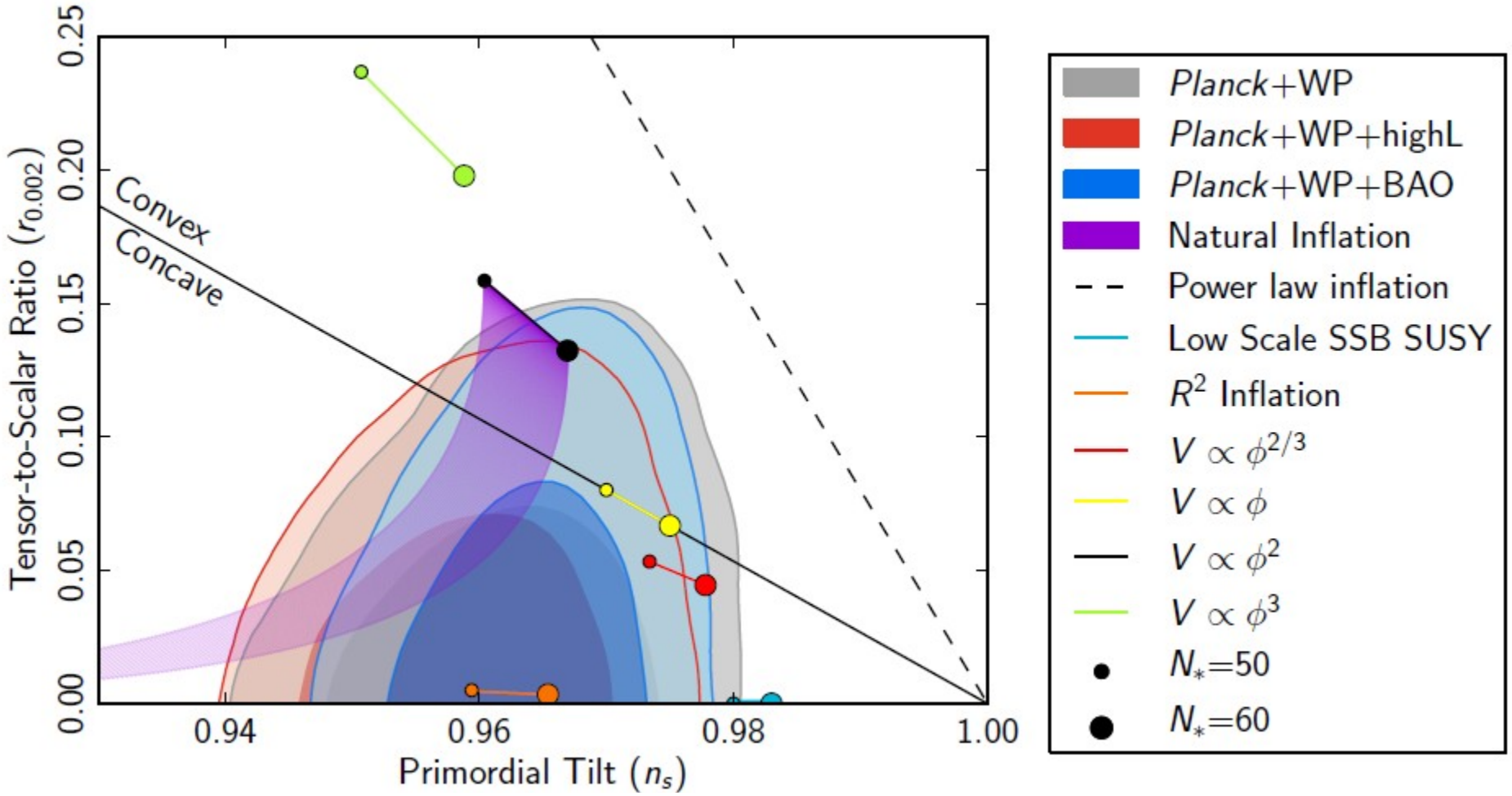


Review of Planck temperature results

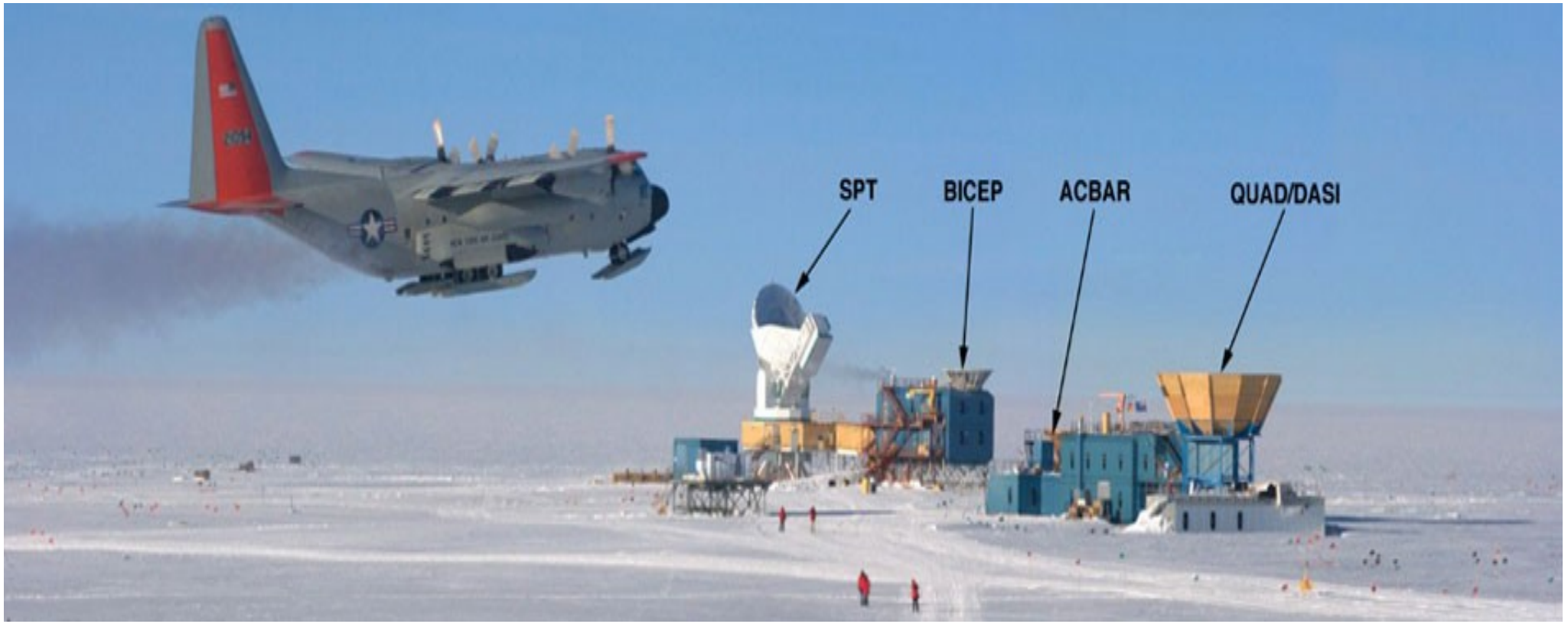


$P(k) =$

Model	Parameter	*Planck*+WP	*Planck*+WP+lensing	*Planck* + WP+high-ℓ	*Planck*+WP+BAO
ΛCDM + tensor	n_s	0.9624 ± 0.0075	0.9653 ± 0.0069	0.9600 ± 0.0071	0.9643 + 0.0059
	$r_{0.002}$	< 0.12	< 0.13	< 0.11	< 0.12
	$-2\Delta \ln \mathcal{L}_{max}$	0	0	0	-0.31

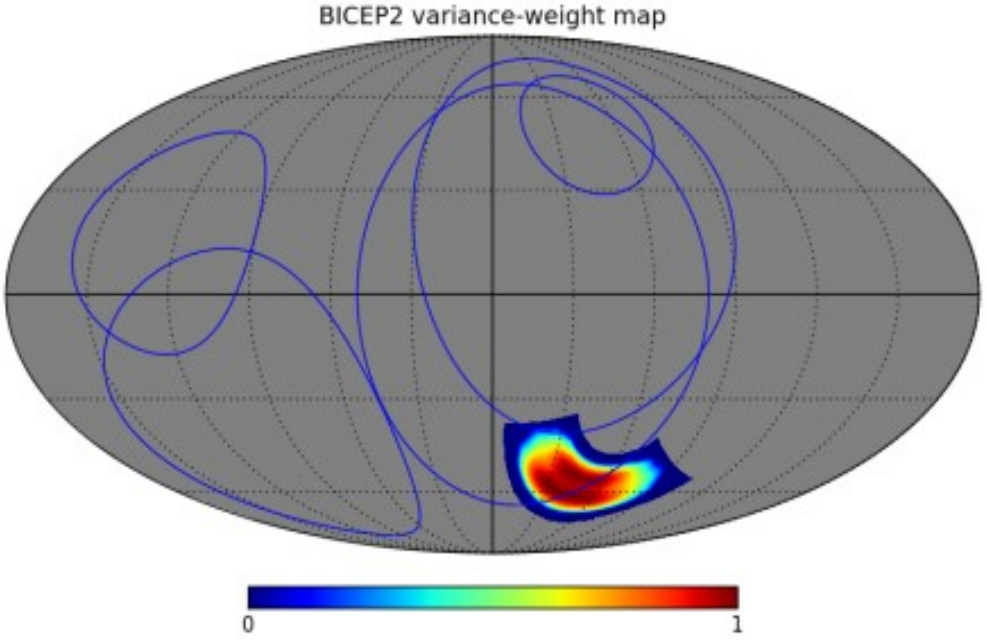
Review of BICEP2 polarization results

- Location: South Pole

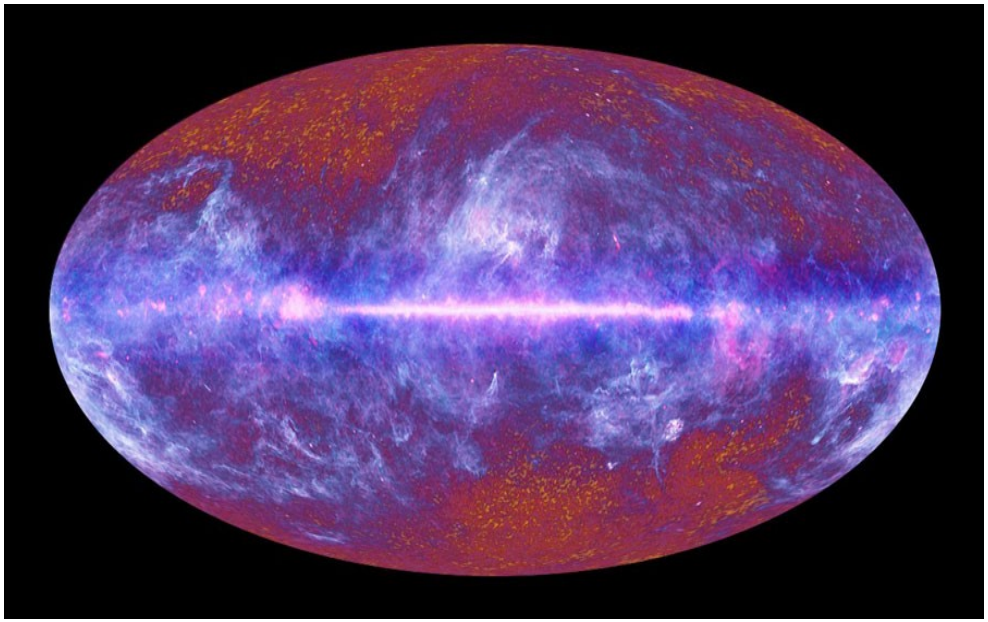


Review of BICEP2 polarization results

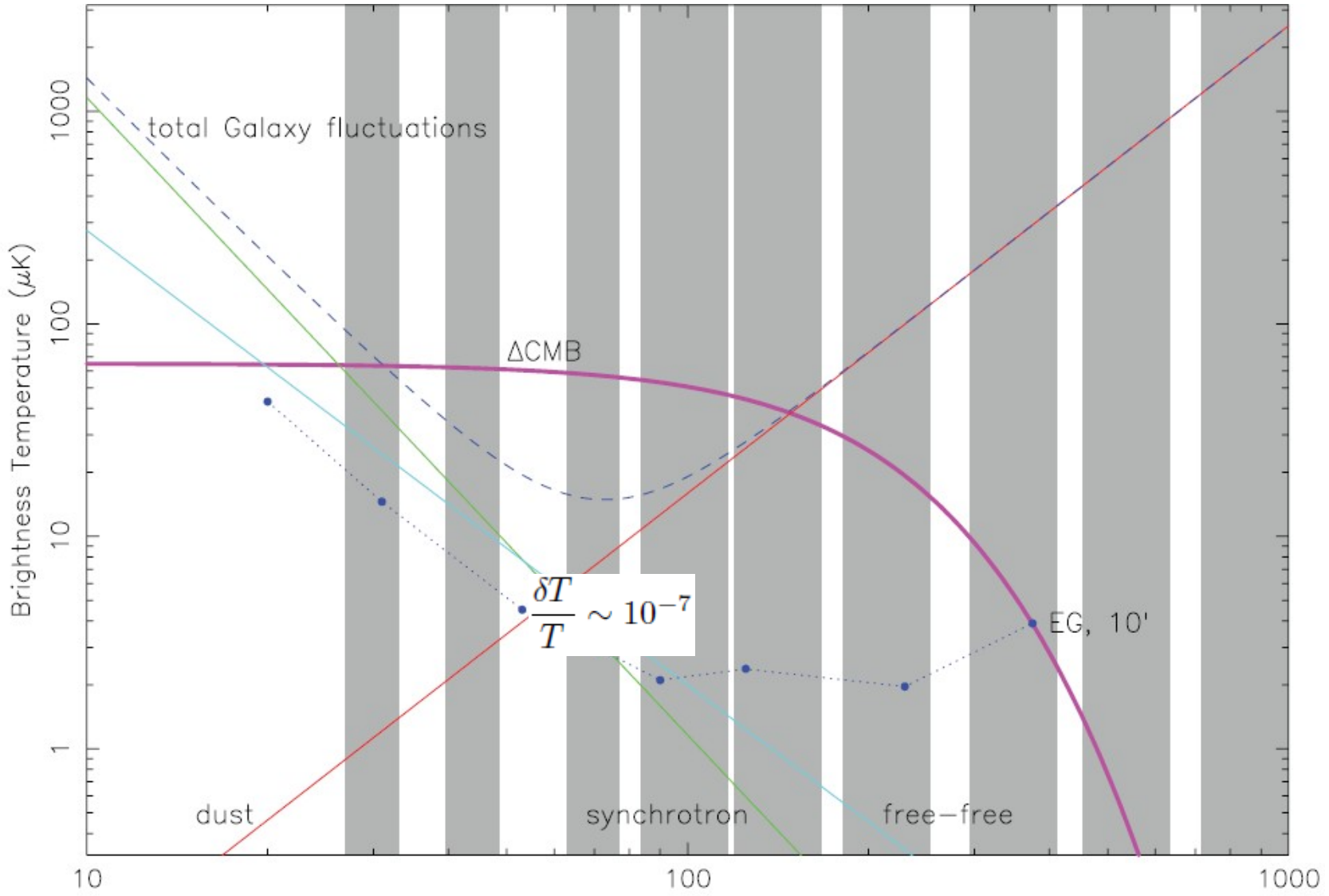
- Location: South Pole
- Ground base/ small patch of sky (foreground relatively clean)



Credit: P. Coles



Review of BICEP2 polarization results



Review of BICEP2 polarization results

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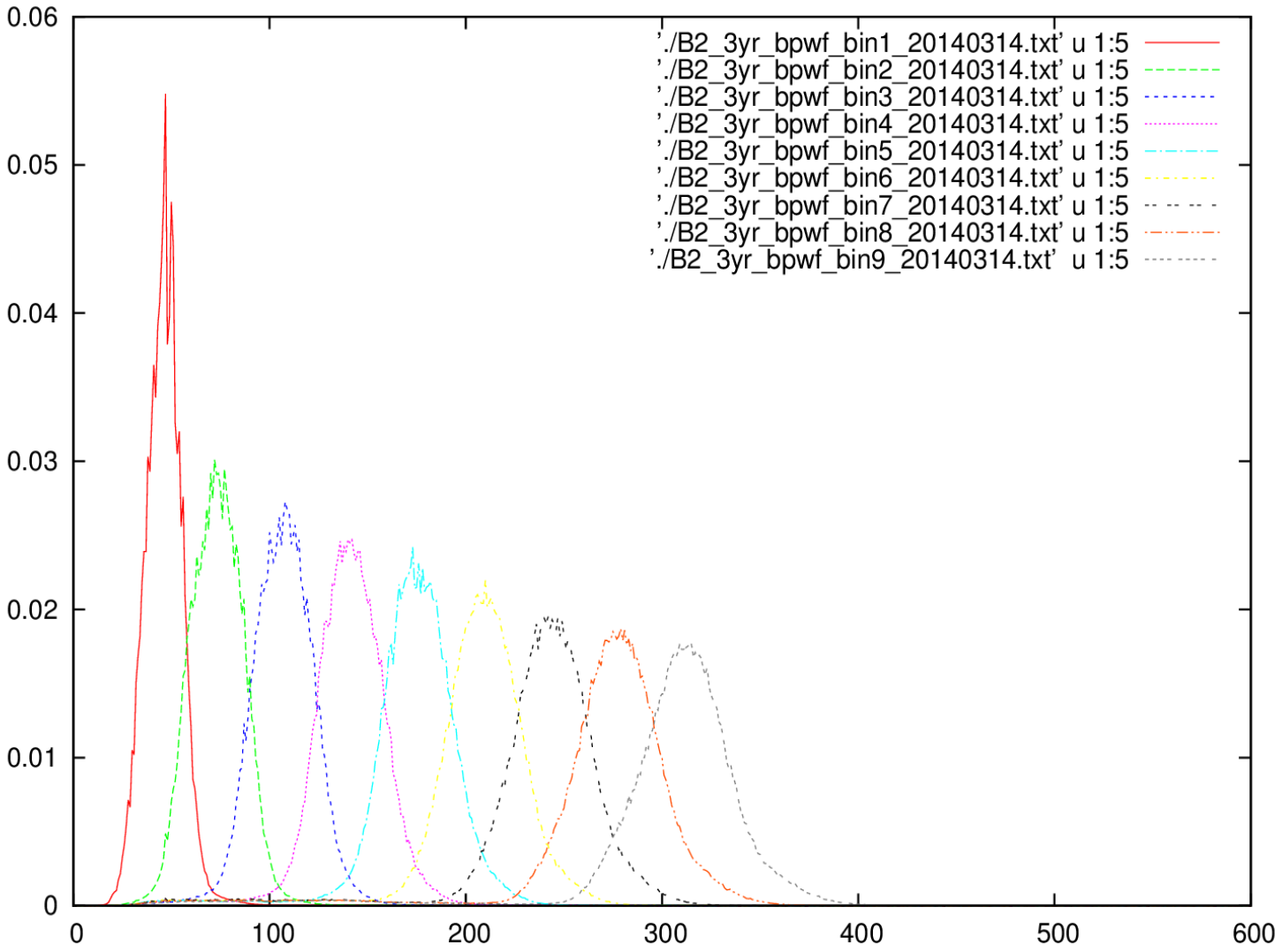
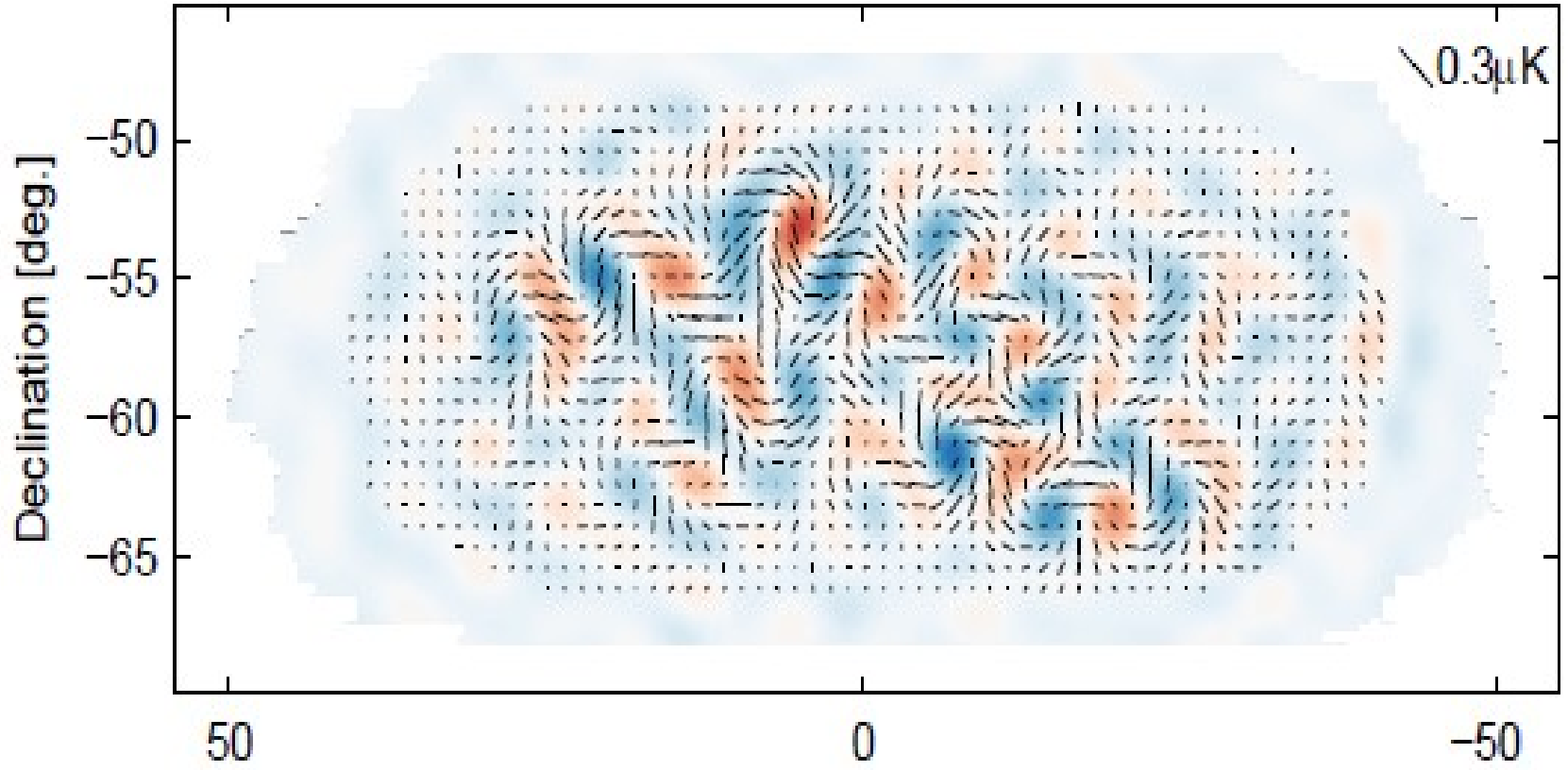


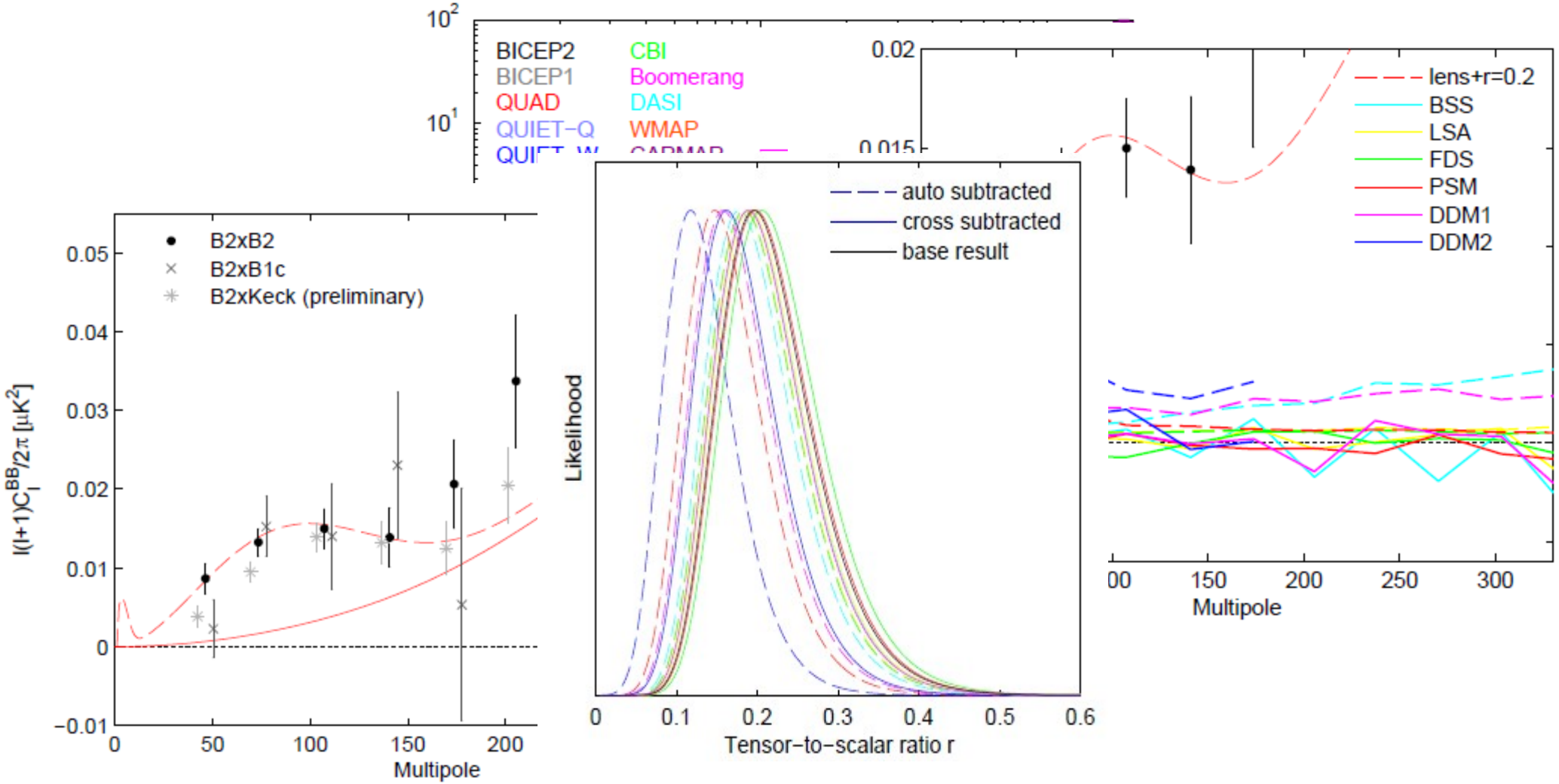
Review of BICEP2 polarization results

- Location: South Pole
- Ground base/a patch of sky



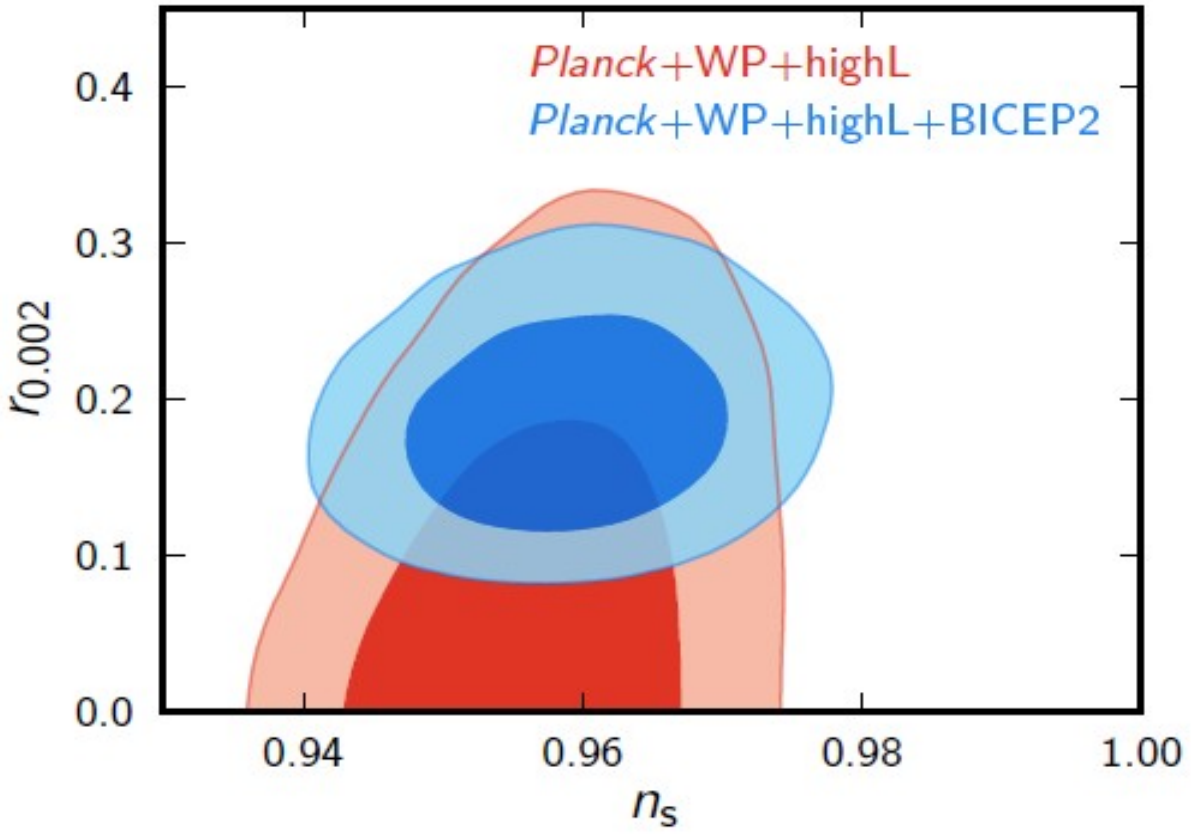
Review of BICEP2 polarization results

- BB spectrum



Review of BICEP2 polarization results

- BB spectrum
- Ns-r contour



$$r = 0.20^{+0.07}_{-0.05}$$

BICEP2 w foreground

$$r = 0.16^{+0.06}_{-0.05}$$

BICEP2 o foreground

$$r < 0.11$$ **(95%CL)**

Planck TT

Reconstruction of primordial spectra: Cubic spline method

- Cubic spline

arXiv:1404.3690

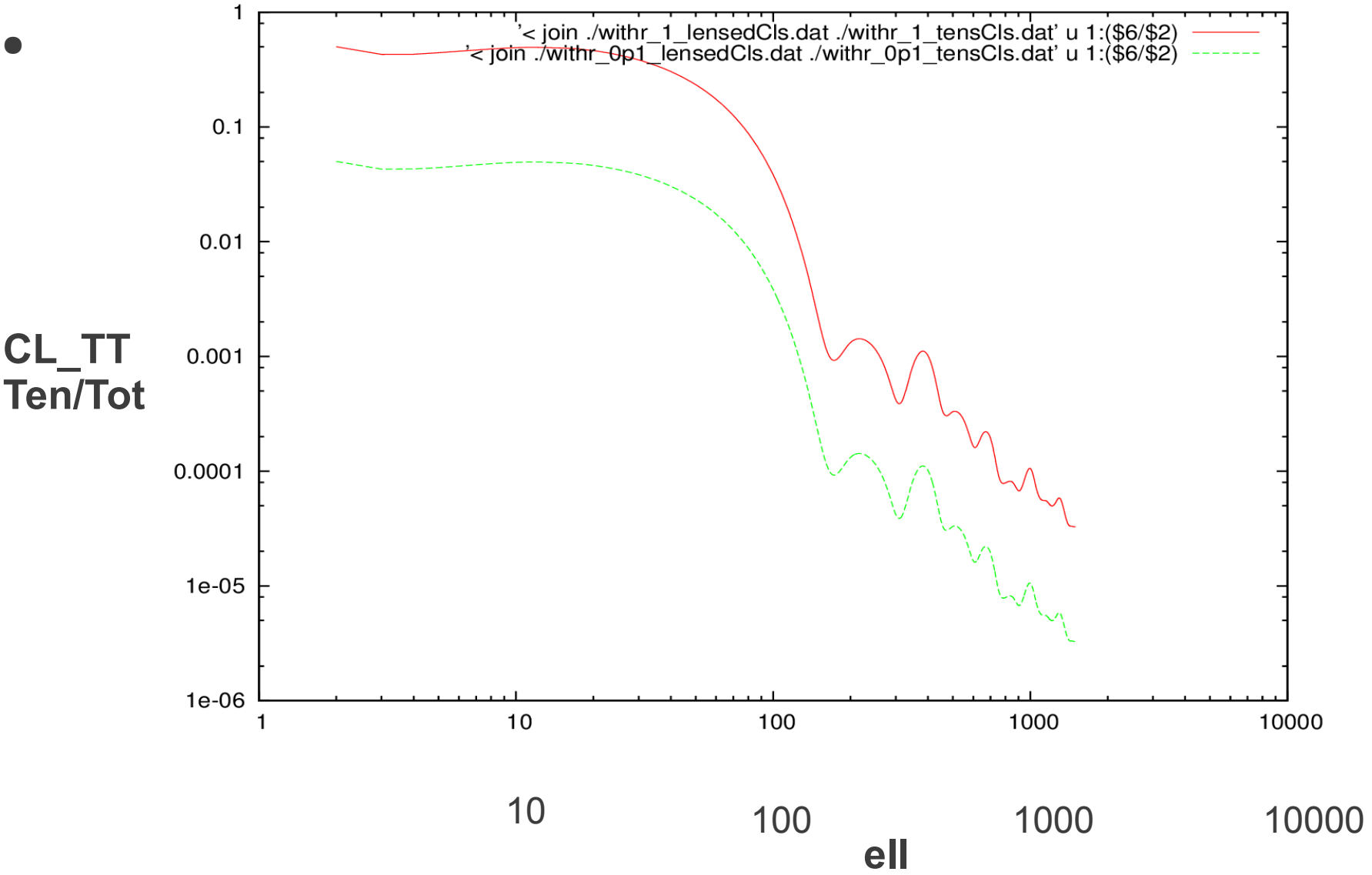
Bin Hu, Jian-Wei Hu, Zong-Kuan Guo, Rong-Gen Cai

$$\ln \mathcal{P}(k) = \begin{cases} \left.\frac{\mathrm{d}\ln \mathcal{P}(k)}{\mathrm{d}\ln k}\right|_{k_1} \ln\frac{k}{k_1} + \ln \mathcal{P}(k_1), & k < k_1; \\ \ln \mathcal{P}(k_i), & k \in \{k_i\}; \\ \text{cubic spline}, & k_i < k < k_{i+1}; \\ \left.\frac{\mathrm{d}\ln \mathcal{P}(k)}{\mathrm{d}\ln k}\right|_{k_{N_{\mathrm{bin}}}} \ln\frac{k}{k_{N_{\mathrm{bin}}}} + \ln \mathcal{P}(k_{N_{\mathrm{bin}}}), & k > k_{N_{\mathrm{bin}}}. \end{cases}$$

- Scalar spectrum: Power law $A_s k^{n_s - 1}$

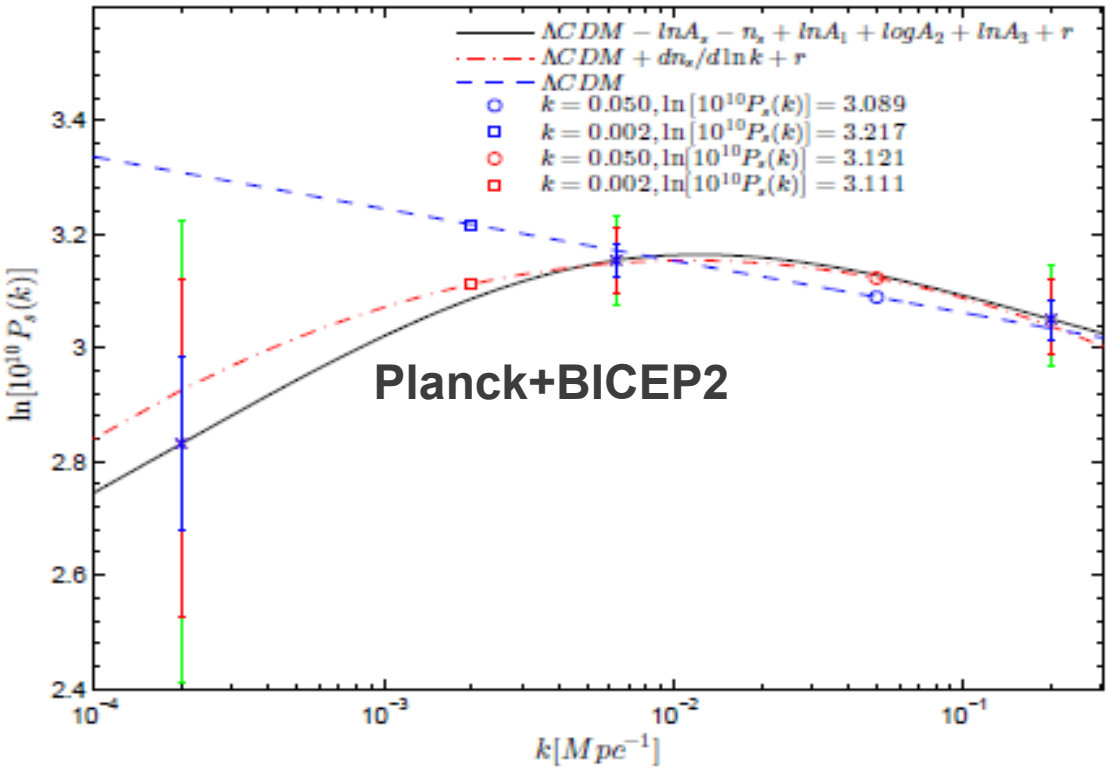
  log-log → straight line

Reconstruction of primordial spectra: Cubic spline method

- 

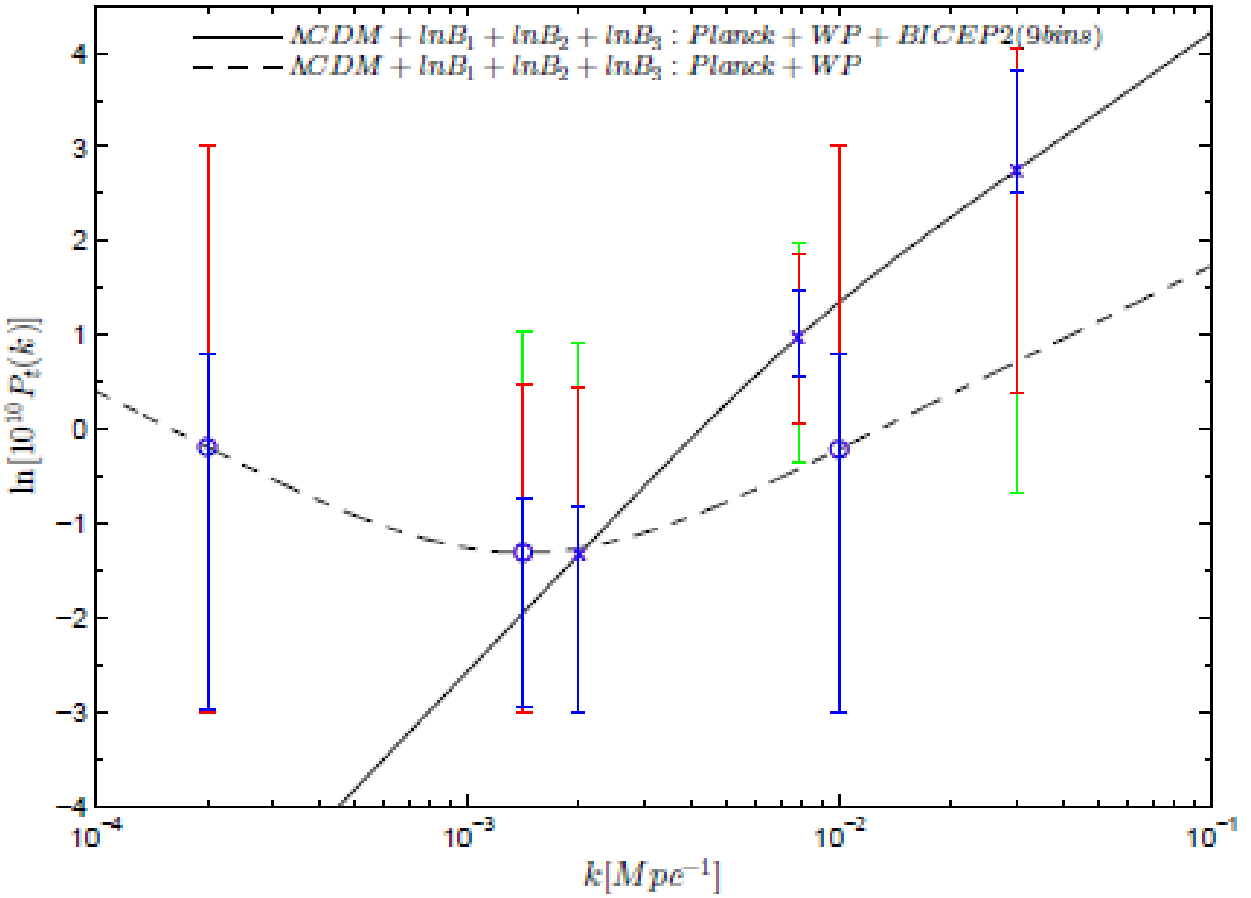
Reconstruction of primordial spectra: Cubic spline method

- Scalar spectrum reconstruction: Scalar index running $\mathrm{d}n_s/\mathrm{d}\ln k$



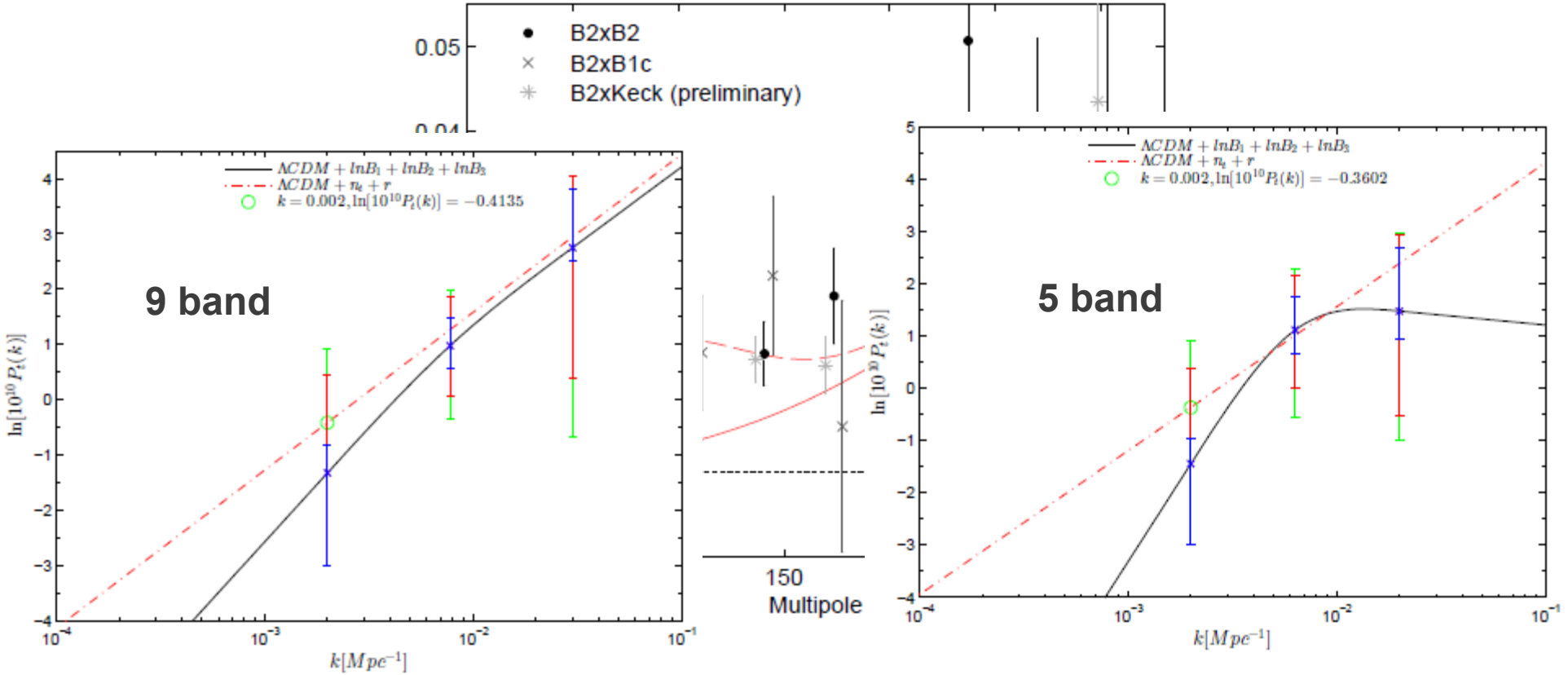
Reconstruction of primordial spectra: Cubic spline method

- Reconstruction of tensor spec $A_t k^{n_t}$



Reconstruction of primordial spectra: Cubic spline method

- 9 bandpower VS 5 bandpower



$n_t = 1.24^{+0.51}_{-0.58}$ (95%CL)

$n_t = 1.20^{+0.56}_{-0.64}$ (95%CL)

Reconstruction of primordial spectra: Cubic spline method

- Conclusion:

  1. Scalar spectrum: strong significance of non-zero running (3\sigma)

  2. Tensor spectrum: significant tension in Planck and BICEP2 (2~3 sigma)