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Inflationary GW: prospects [for] measurement in the near future

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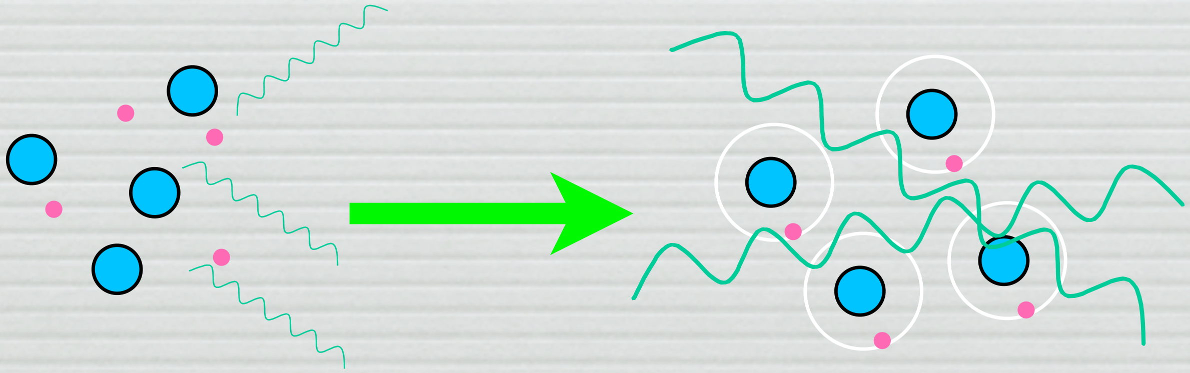
eLISA Cosmology 2015
CERN

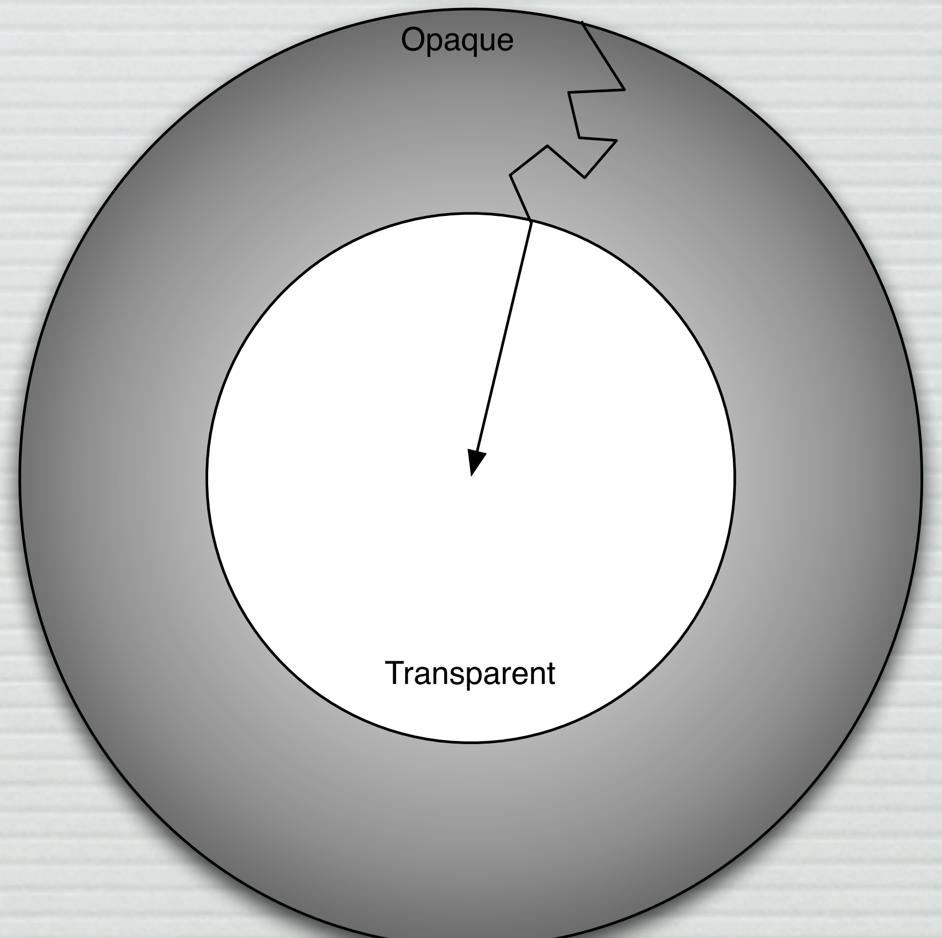
Inflationary GW: prospects for measurement in the near future

- Background: polarization and gravitational radiation
- State of the art: Planck, BICEP, Polarbear, etc.
- The next generation
- The next decade
- Beyond detection: characterising inflation

Evidence & Observations: Cosmic Microwave Background

- 400,000 years after the Big Bang, the temperature of the Universe was $T \sim 3{,}000$ K
- Hot enough to keep hydrogen atoms *ionized* until this time
  - ***proton + electron → Hydrogen*** + *photon* $[p^+ + e^- \rightarrow H + \gamma]$
  - ***charged plasma → neutral gas***
    - depends on *entropy* of the Universe
- Photons (light) can't travel far in the presence of charged particles
  - ***Opaque → transparent***



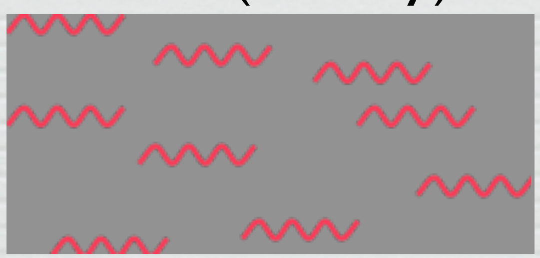


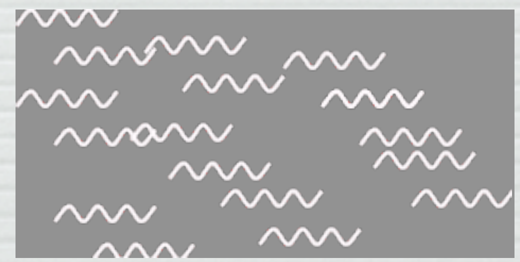
What affects the CMB temperature?

$$\frac{\Delta T}{T}(\hat{x}) \simeq \frac{1}{4}\frac{\delta \rho_\gamma}{\rho_\gamma} + v \cdot \hat{x} + \int_{\eta_{rec}}^{\eta_0} d\eta \, \dot{h}_{ij} \hat{x}_i \hat{x}_j$$

- Initial temperature (density) of the photons

Cooler





Hotter

- Doppler shift due to movement of baryon-photon plasma
- Gravitational red/blue-shift as photons climb out of potential wells or fall off of underdensities

- Photon path from LSS to today
- All linked by initial conditions ⇒ 10^{-5} fluctuations

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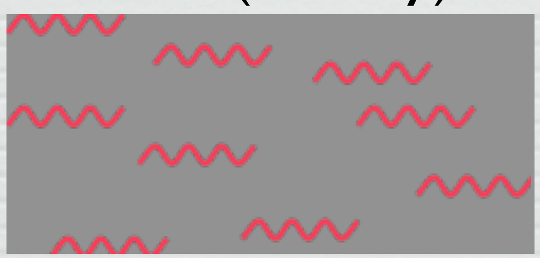

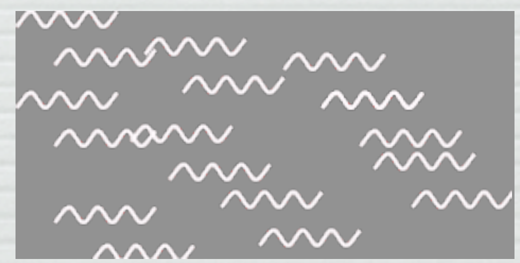

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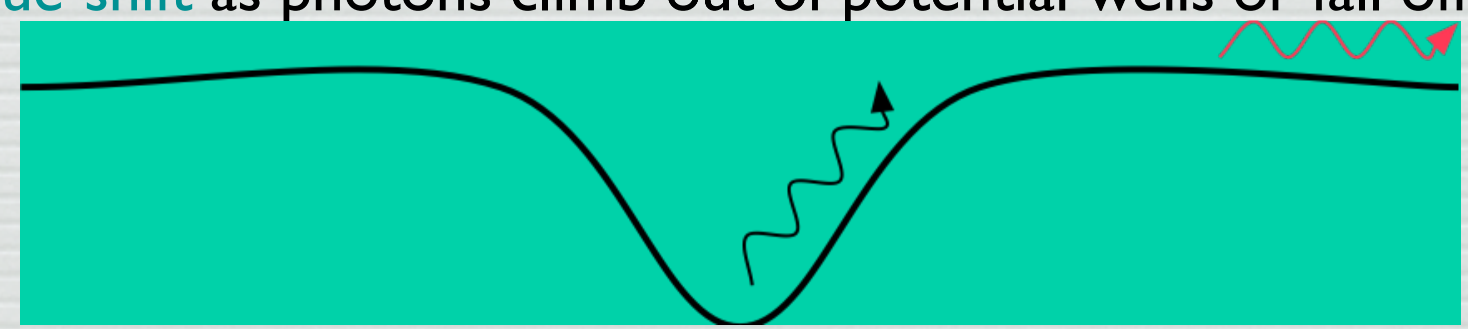

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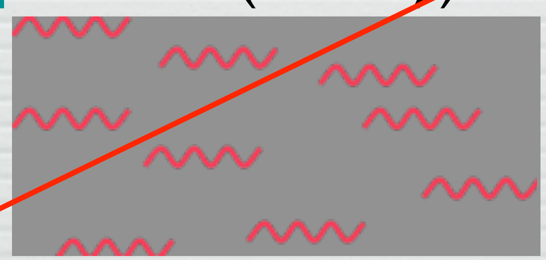

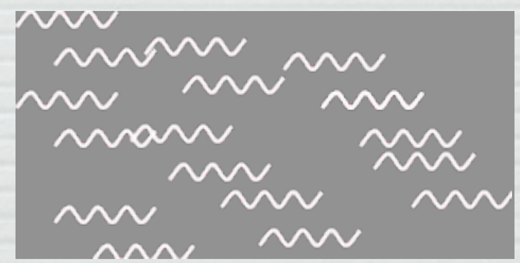

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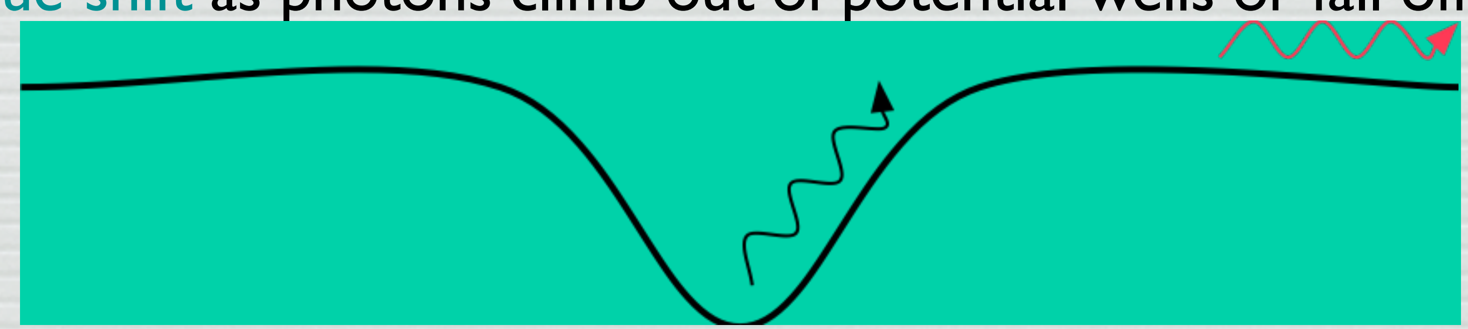

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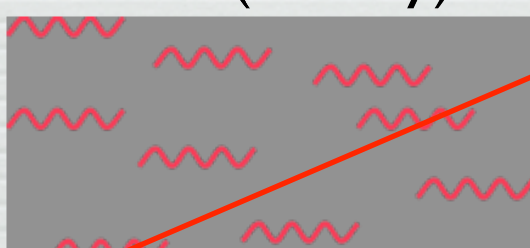

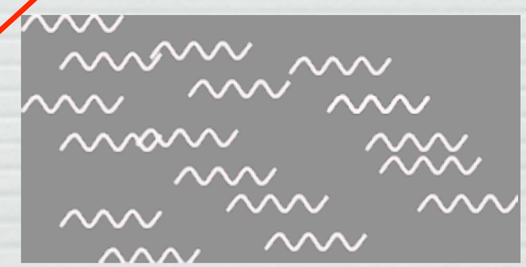

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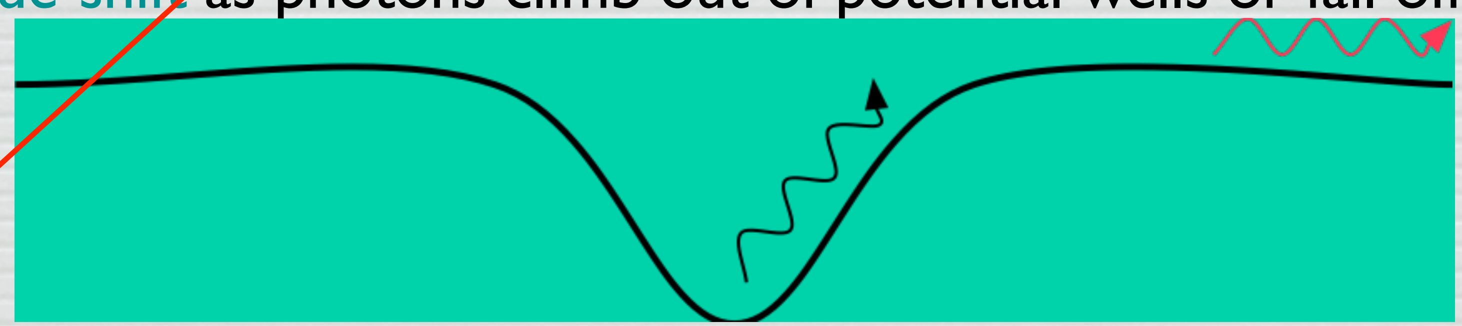

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CMB Statistics

z~1300: p+e→H & Universe becomes transparent.

$$\frac{T(\hat{x}) - \bar{T}}{\bar{T}} \equiv \frac{\Delta T}{T}(\hat{x}) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\hat{x})$$

i.e., Fourier Transform, but on a sphere

Determined by **temperature**, **velocity** and **metric** on the last scattering surface.

Power Spectrum:

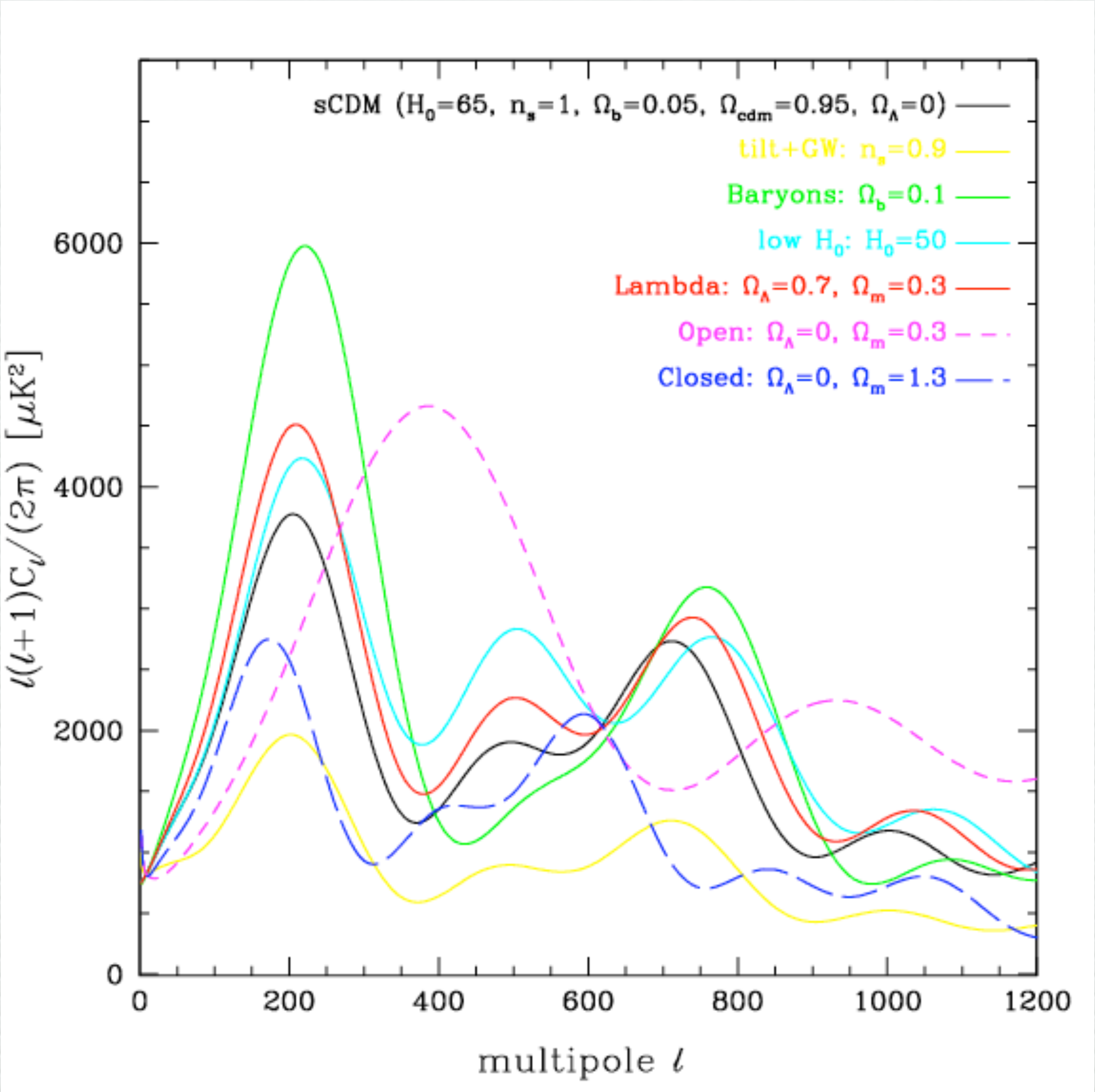
$$\langle a^*_{\ell m} a_{\ell' m'} \rangle = \delta_{\ell\ell'} \delta_{mm'} \, C_\ell$$

Multipole ℓ ~ angular scale $180°/\ell$

For a **Gaussian** theory, C_ℓ completely determines the statistics of the temperature.

Theoretical Predictions

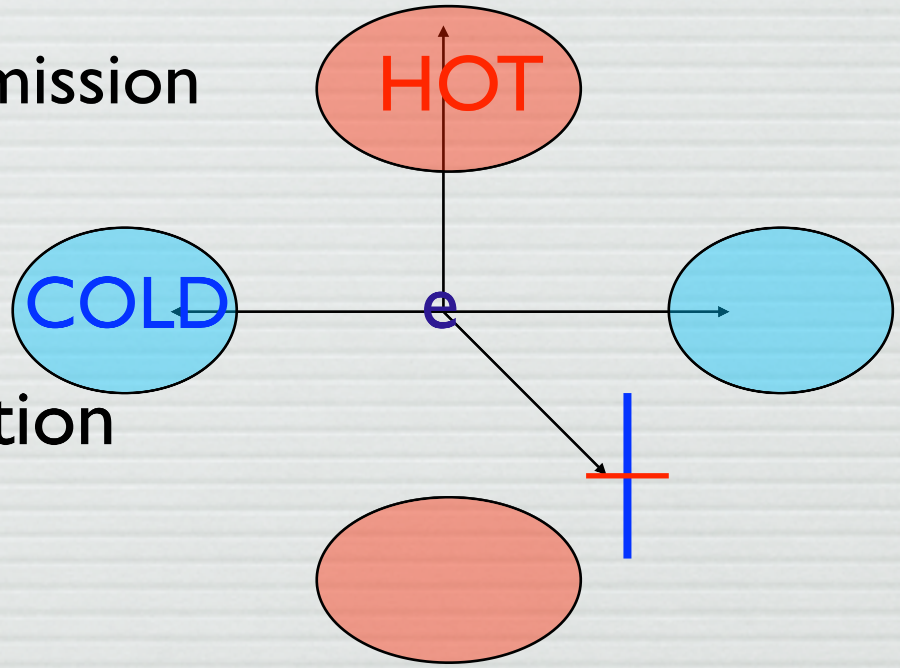
Mean square fluctuation amplitude



~180°/Angular scale

CMB Polarization: Generation

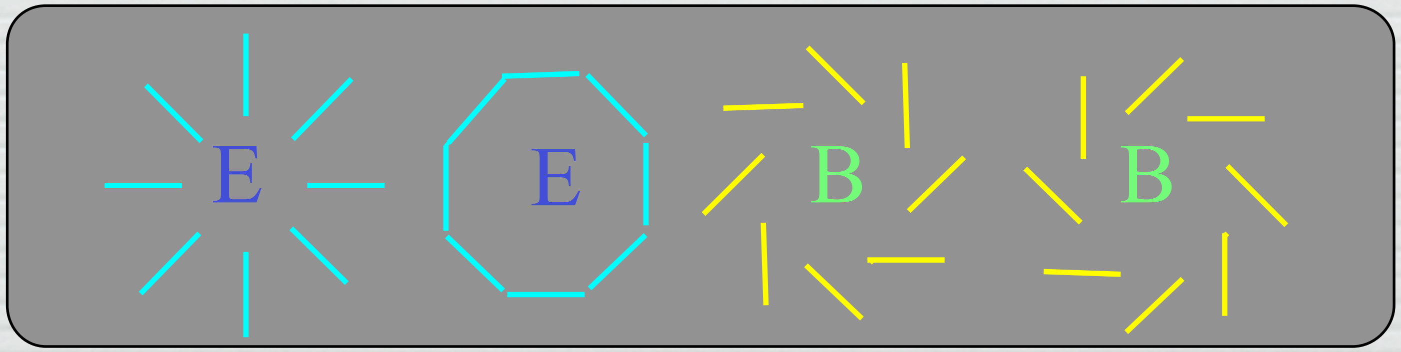
- Ionized plasma + quadrupole radiation field:
  - Thomson scattering ⇒ [linearly] polarized emission



- Unlike intensity, only generated when ionization fraction, $0<x<1$ (*i.e.*, during transition)
- *Scalar* perturbations: traces ~gradient of velocity
  - same initial conditions as temperature and density fluctuations
- *Tensor* perturbations: independent of density fluctuations
  - +,× patterns of quadrupoles (impossible to form via linear scalar perturbations)
  - at last-scattering, from primordial background of gravitational radiation, *predicted by inflation*

CMB Polarization: E/B Decomposition

- 2-d (headless) vector field on a sphere
- Spin-2/tensor spherical harmonics
- grad/scalar/E + curl/pseudoscalar/B patterns



- NB. From polarization pattern ⇒ E/B decomposition requires integration (*non-local*) or differentiation (*noisy*)
  - *Lewis et al; Bunn et al; Smith & Zaldarriaga; Grain et al; Bowyer & AJ; …*
  - (data analysis problems)

E/B decomposition: the math

- Scalar and tensor modes are isotropic, parity-symmetric fields on the sky.
- T is a scalar, E is the "gradient" of a scalar, B is the "curl" of a pseudoscalar

$$Q(\hat{n}) = -\frac{1}{2}\sum_{lm}\left(a^E_{lm}\left[{}_2Y_{lm}(\hat{n}) + {}_{-2}Y_{lm}(\hat{n})\right] + i a^B_{lm}\left[{}_2Y_{lm}(\hat{n}) - {}_{-2}Y_{lm}(\hat{n})\right]\right)$$

Spin-weighted spherical harmonics

$$U(\hat{n}) = -\frac{1}{2}\sum_{lm}\left(a^B_{lm}\left[{}_2Y_{lm}(\hat{n}) + {}_{-2}Y_{lm}(\hat{n})\right] + i a^E_{lm}\left[{}_2Y_{lm}(\hat{n}) - {}_{-2}Y_{lm}(\hat{n})\right]\right)$$

$$e(\hat{n}) = \sum_{lm}\sqrt{\frac{(l-2)!}{(l+2)!}}\,a^E_{lm}Y_{lm}(\hat{n}) \qquad b(\hat{n}) = \sum_{lm}\sqrt{\frac{(l-2)!}{(l+2)!}}\,a^B_{lm}Y_{lm}(\hat{n})$$

Newman-Penrose derivative

$$\nabla^4 e = -\frac{1}{2}[\bar{\eth}^2(Q+iU) + \eth^2(Q-iU)] \qquad \nabla^4 b = \frac{i}{2}[\bar{\eth}^2(Q+iU) - \eth^2(Q-iU)]$$

  - everything except scalar perturbations sources B
  - parity: expect $\langle EB\rangle = \langle TB\rangle = 0$
  - try to measure $\langle TT\rangle$, $\langle BB\rangle$, $\langle EE\rangle$, $\langle TE\rangle$

Gravitational Radiation from Inflation

- Gravitational radiation produced during inflation
- Characterized by ratio of amplitudes of tensor perturbation power (GWs) to scalar power (density), $r=T/S$
  - ⇒Energy scale of inflation: $V^{1/4}/M_{Pl} \approx 3\times10^{-3} r^{1/4}$
- Contributes to *all* CMB power spectra (T, E, B)
- In single-field, "slow-roll" models, *r* is further related to the scalar and tensor spectral indices:
  - $P_{\mathrm{t}}(k) \propto k^{n_{\mathrm{t}}}$ $\quad P_{\mathrm{S}}(k) \propto k^{1-n_{\mathrm{s}}}$

Models of inflation

- Scalar & tensor spectra:

$$\mathcal{P}_{\mathcal{R}}(k) = A_{\mathrm{s}} \left(\frac{k}{k_*}\right)^{n_{\mathrm{s}}-1+\frac{1}{2}\,\mathrm{d}n_{\mathrm{s}}/\mathrm{d}\ln k\,\ln(k/k_*)+\frac{1}{6}\,\mathrm{d}^2 n_{\mathrm{s}}/\mathrm{d}\ln k^2 (\ln(k/k_*))^2+\ldots} \qquad \mathcal{P}_{\mathrm{t}}(k) = A_{\mathrm{t}} \left(\frac{k}{k_*}\right)^{n_{\mathrm{t}}+\frac{1}{2}\,\mathrm{d}n_{\mathrm{t}}/\mathrm{d}\ln k\,\ln(k/k_*)+\ldots}$$

  - Energy scale of inflation $\quad V^{1/4}/M_{Pl} \approx 3\times 10^{-3}\, r^{1/4}$

- Single-field Slow-roll

$$\epsilon_V = \frac{M_{\mathrm{pl}}^2 V_{,\phi}^2}{2V^2} \ll 1 \qquad \eta_V = \frac{M_{\mathrm{pl}}^2 V_{,\phi\phi}}{V} \qquad |\eta_V| \ll 1$$

$$\begin{aligned} n_{\mathrm{s}} - 1 &\approx 2\eta_V - 6\epsilon_V, \\ n_{\mathrm{t}} &\approx -2\epsilon_V, \\ \mathrm{d}n_{\mathrm{s}}/\mathrm{d}\ln k &\approx +16\epsilon_V\eta_V - 24\epsilon_V^2 - 2\xi_V^2, \\ \mathrm{d}n_{\mathrm{t}}/\mathrm{d}\ln k &\approx +4\epsilon_V\eta_V - 8\epsilon_V^2, \end{aligned}$$

$$A_{\mathrm{s}} \approx \frac{V}{24\pi^2 M_{\mathrm{pl}}^4 \epsilon_V}, \quad \text{(measured by } C_\ell\text{)}$$

$$A_{\mathrm{t}} \approx \frac{2V}{3\pi^2 M_{\mathrm{pl}}^4},$$

  - Consistency: $\displaystyle r = \frac{A_{\mathrm{t}}}{A_{\mathrm{s}}} \approx 16\epsilon_{\mathrm{V}} \approx -8n_{\mathrm{t}}$

- Beyond slow-roll: model-dependent
  - large derivatives of *V*
  - multiple fields
  - non Bunch-Davies vacuum
  - non-standard kinetic term
  - not inflation: pre-BB, string gas, …

(Also, GWs from preheating, etc—see Arttu's, Enrico's, … talks)

[1] List of available inflation models – non exhaustive : eternal inflation, hybrid inflation, chaotic, Ghost inflation, Tilted Ghost inflation, DBI inflation, brane inflation, N-flation, bubble inflation, extended inflation, false vacuum inflation, power law inflation, k-inflation, hyperextended inflation, supersymmetric inflation, Quintessential inflation, Natural inflation, Super inflation, Supernatural inflation, D-term inflation, B -inflation, Thermal inflation, discrete inflation, Assisted inflation, Polar cap inflation, Open inflation, Topological inflation, Double inflation, Multiple inflation, Induced-gravity inflation, Warm inflation, stochastic inflation, Generalized assisted inflation, self-sustained inflation, Graduated inflation, Local inflation, Singular inflation, Slinky inflation, locked inflation, Elastic inflation, Mixed inflation, Phantom inflation, Boundary inflation, Non-commutative inflation, Tachyonic inflation, Tsunami inflation, Lambda inflation, Steep inflation, Oscillating inflation, Mutated Hybrid inflation, intermediate inflation, Inhomogeneous inflation.

CMB Signals from inflation

- Want to probe inflaton potential V(φ)
- Induce scalar and tensor power spectra
  - Observables:
    - temperature and polarization CMB spectra
    - functionally linear relationships

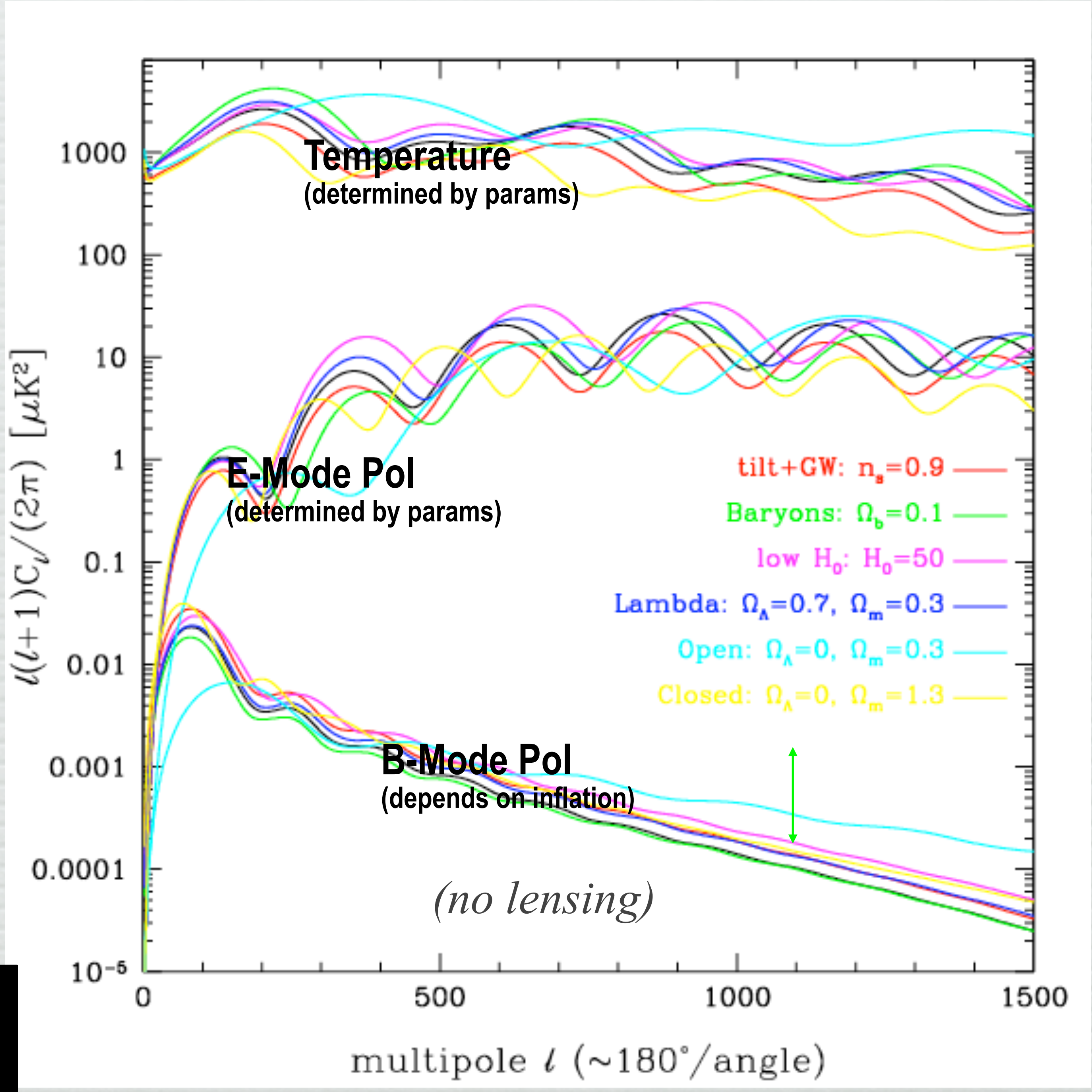
$$C_\ell^{BB} = \int dk\, T_\ell^{hB}(k) P_h(k)$$

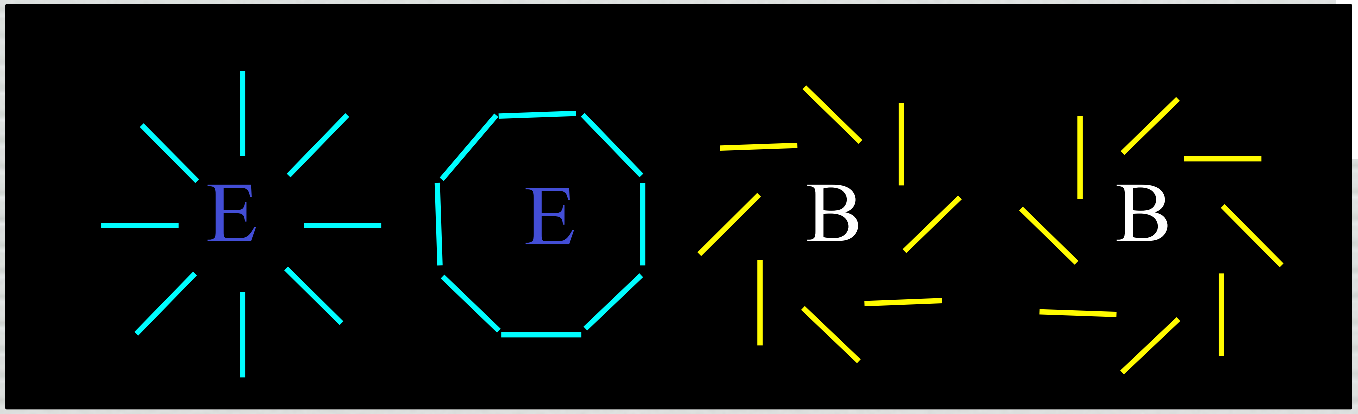
$$C_\ell^{TT} = \int dk\, \left[T_\ell^{hT}(k) P_h(k) + T_\ell^{RT}(k) P_R(k)\right]$$

    - Transfer functions T depend on cosmological parameters
    - Amplitude ($r=T/S$) and shape (n_s, n_T) of the spectra probe the inflaton potential
- Non-gaussianity:
  - specific inflationary models $\Rightarrow$ departures from Gaussianity
  - e.g., $f_{NL} \sim 1$ (in reach of Planck, but not [yet] detected)

The Polarization of the CMB

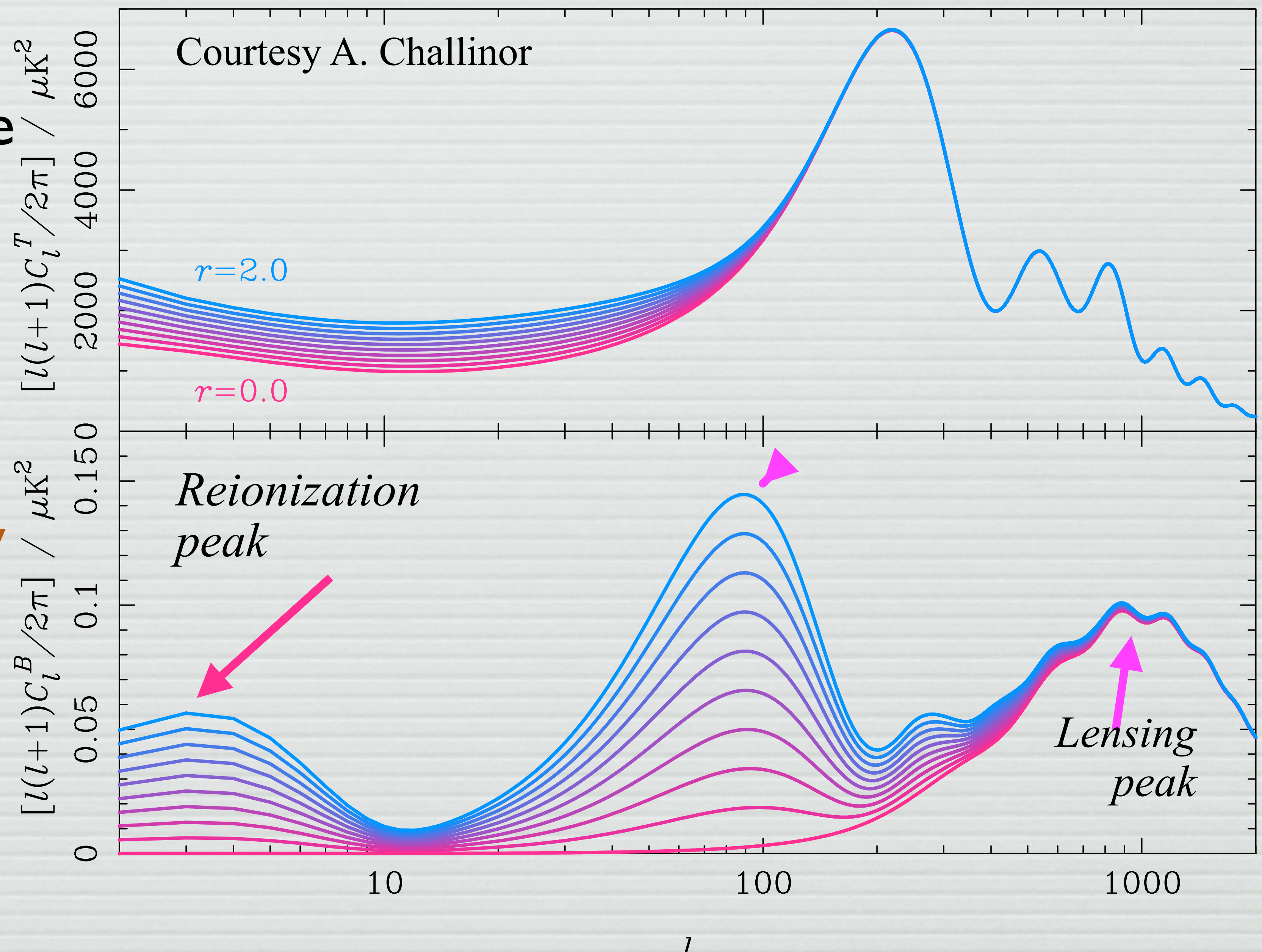
- Anisotropic radiation field at last scattering → polarization
- "Grad" or *E* mode
  - Breaks degeneracies
  - New parameters:
    - reionization
- "Curl" or *B* sensitive to gravity waves
  - "Smoking gun" of inflation?
  - Very low amplitude
- Need [better] handle on
  - systematics,
  - lensing
  - polarized foregrounds





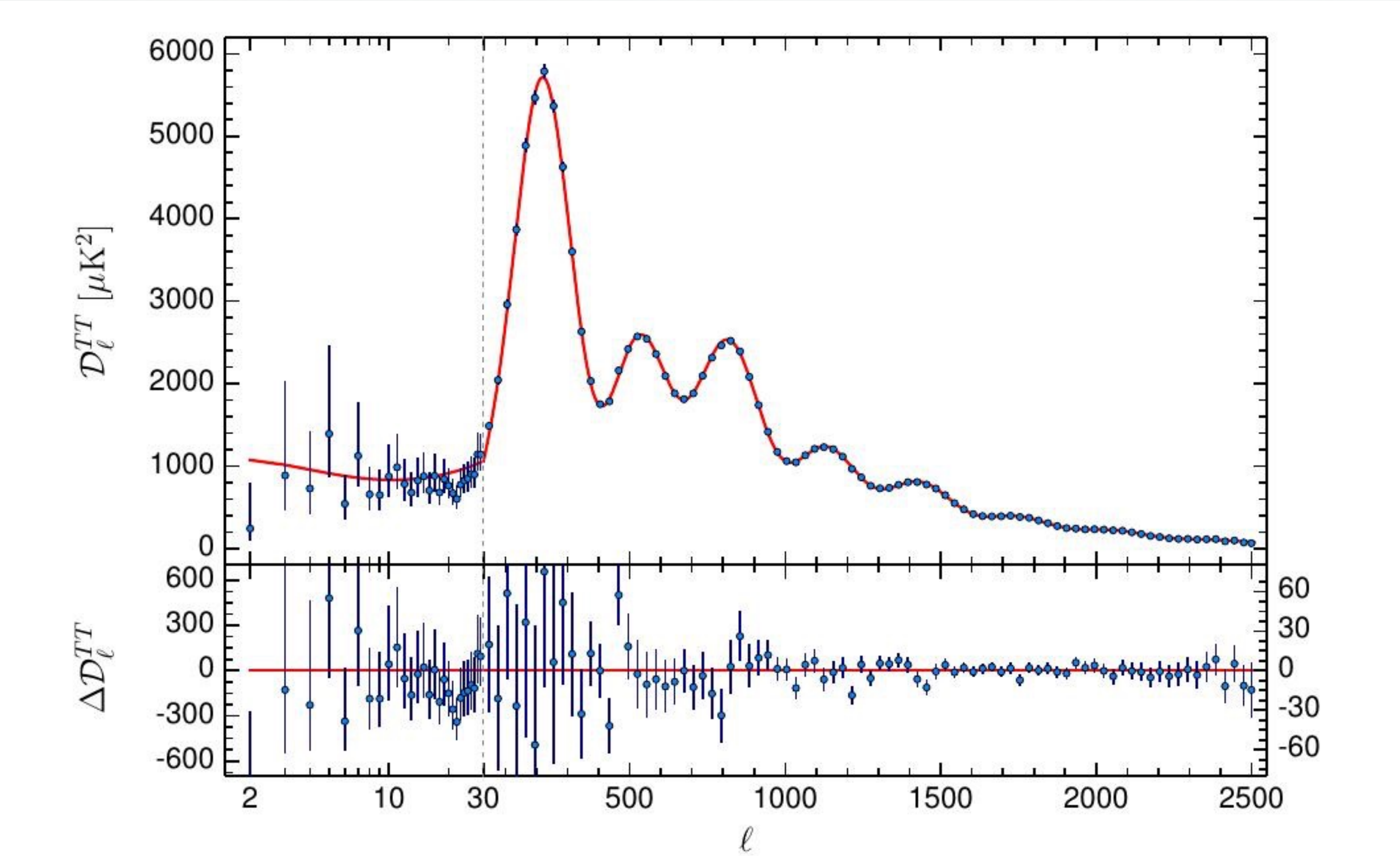
Gravitational Radiation & CMB

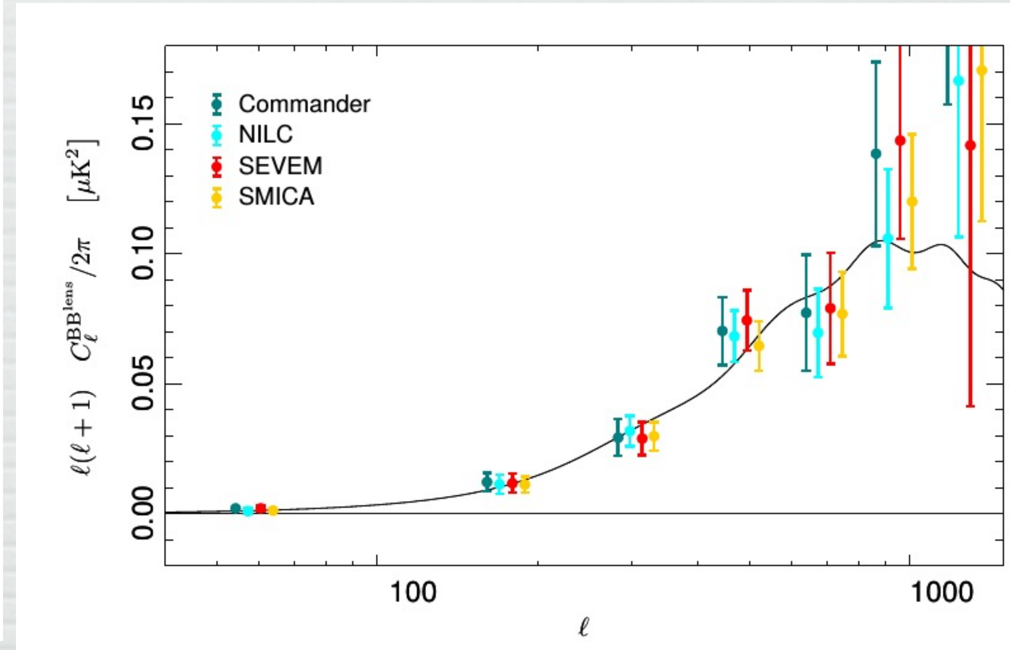
- Last scattering: "direct" effect of tensor modes (primordial GWs) on the primordial plasma
  - inflationary potential
- dominated by *lensing of E ⇒ B* for $\ell \gtrsim 200$
  - [sensitive to $m_\nu \lesssim 0.06$eV
    - (i.e., hot dark matter)]
- Reionization peak $\ell \lesssim 20$
  - need ~full-sky. Difficult for single suborbital experiments
  - Planck 2015: $\tau \approx 0.07$ — low
- *Limits depend on full set of parameters*

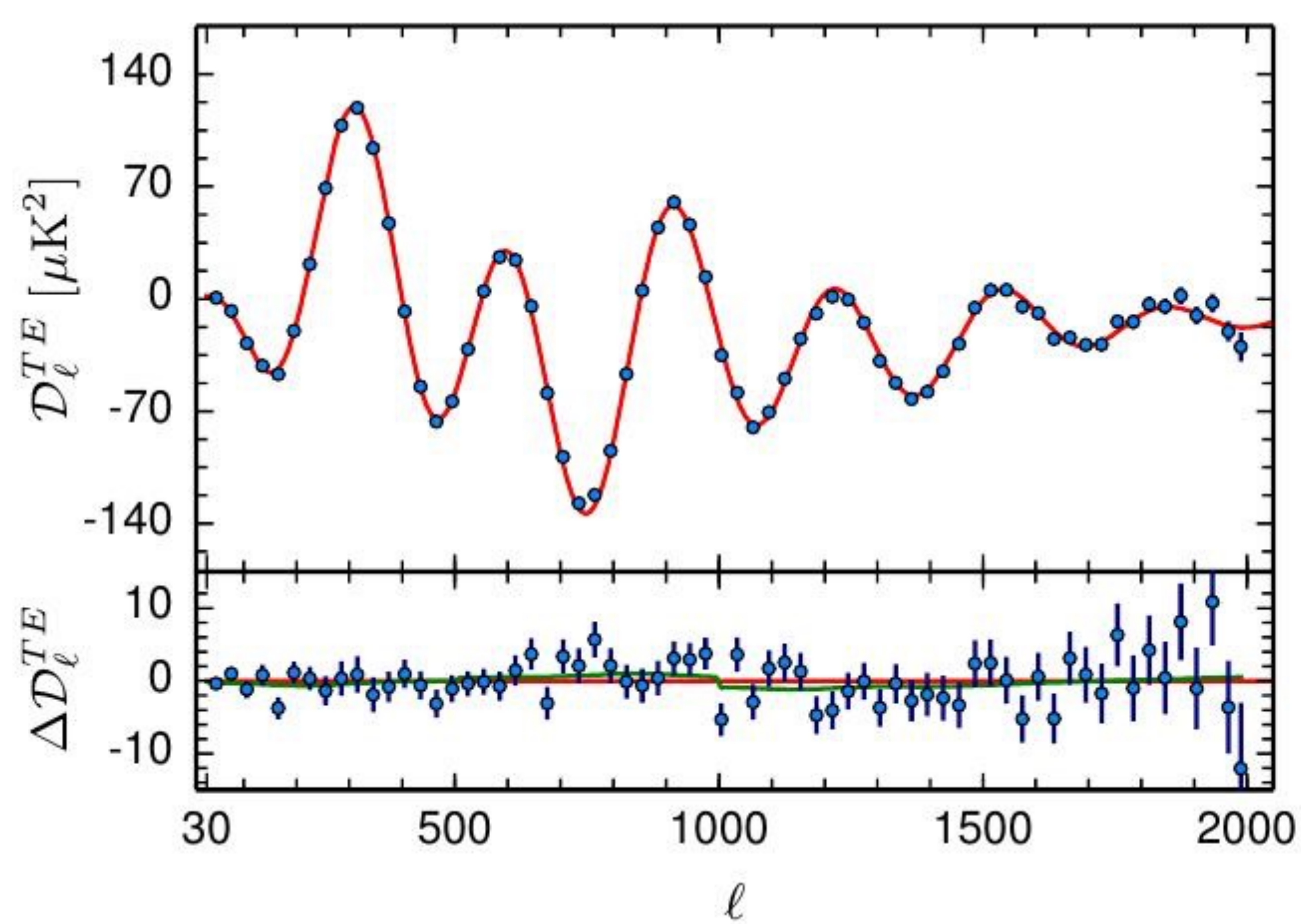


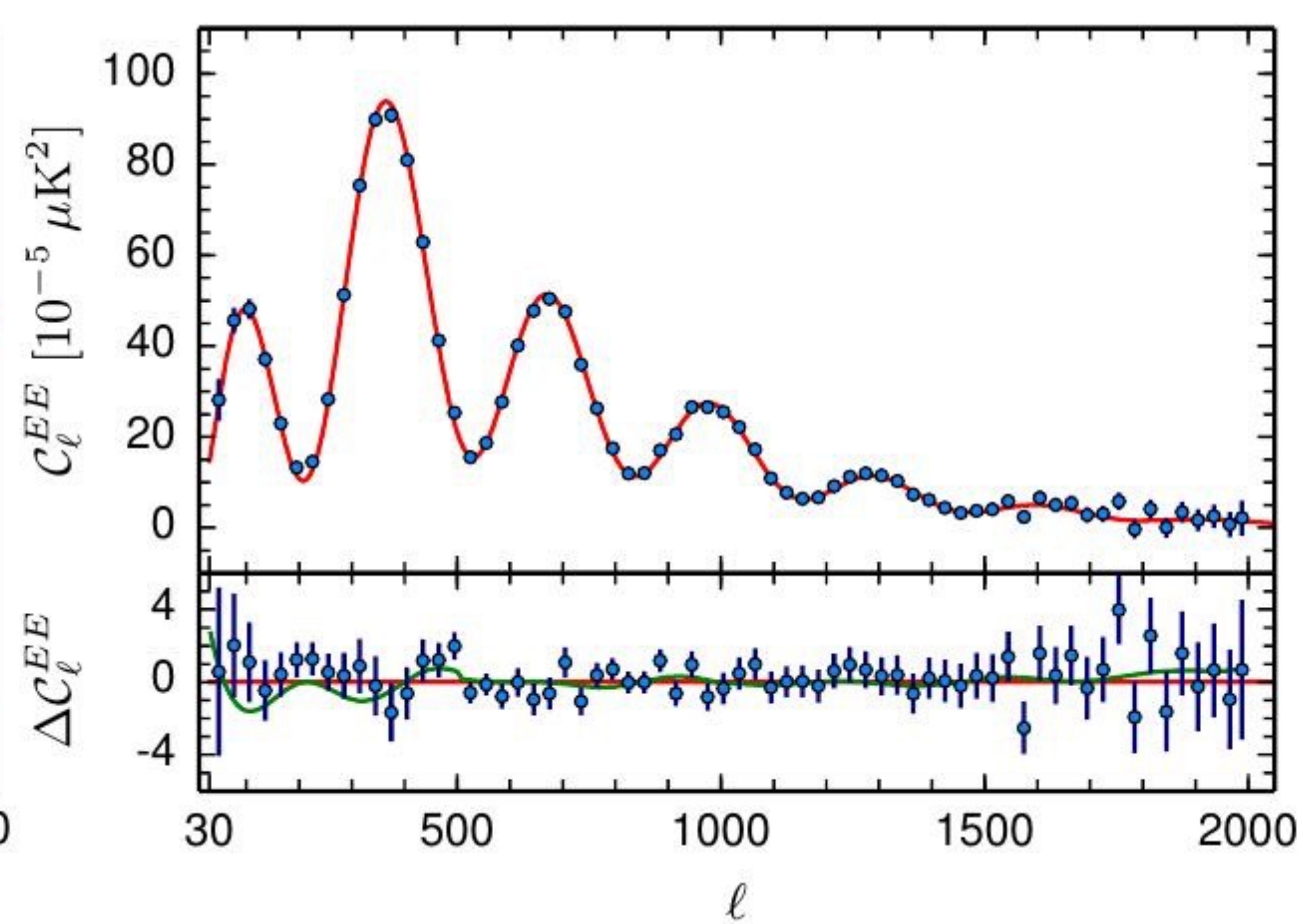
Suborbital experiments target $\ell \sim 100$ peak: kilopixel telescopes give order-of-magnitude increase in sensitivity over Planck

Planck 2015


$\mathcal{D}_\ell^{TT}$ [μK^2]
$\Delta\mathcal{D}_\ell^{TT}$
6000
5000
4000
3000
2000
1000
0
600
300
0
-300
-600
60
30
0
-30
-60
2
10
30
500
1000
1500
2000
2500
ℓ


Commander
NILC
SEVEM
SMICA
$\ell(\ell+1)$ $C_\ell^{\mathrm{BB^{lens}}}/2\pi$ [μK^2]
0.00
0.05
0.10
0.15
100
1000
ℓ


$\mathcal{D}_\ell^{TE}$ [μK^2]
$\Delta\mathcal{D}_\ell^{TE}$
140
70
0
-70
-140
10
0
-10
30
500
1000
1500
2000
ℓ

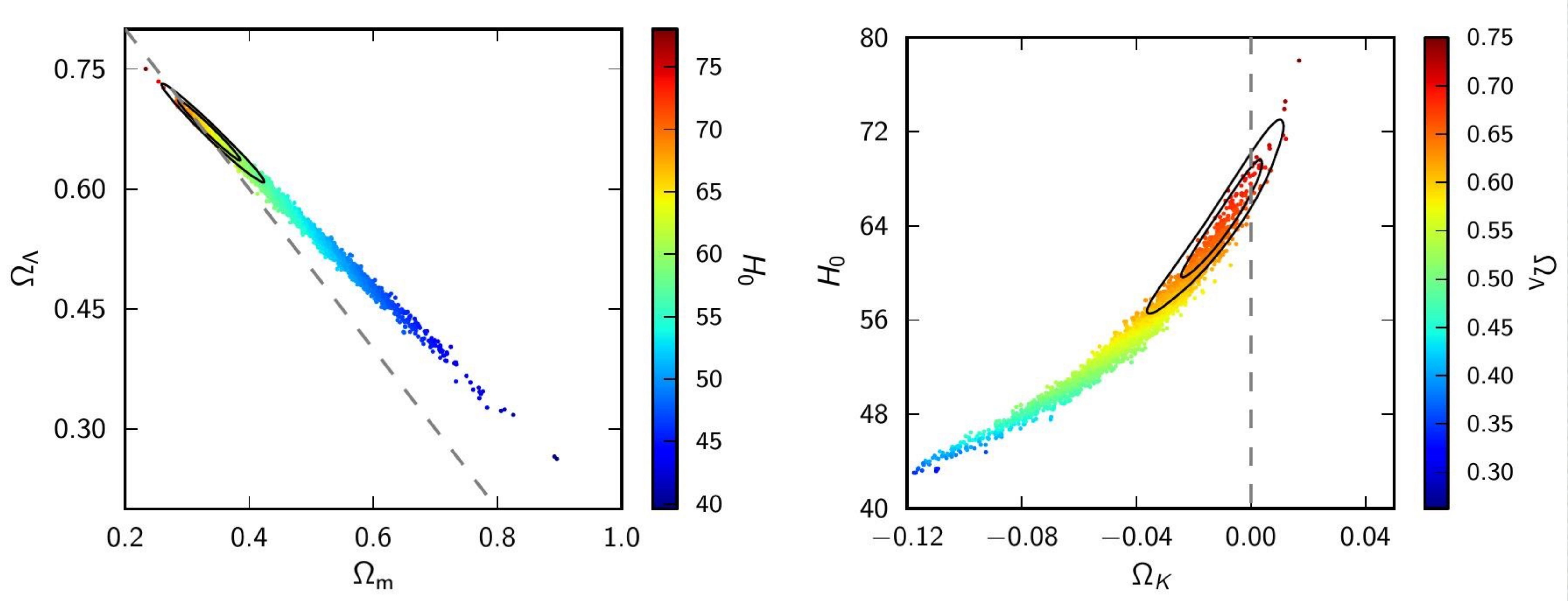

C_ℓ^{EE} [10^{-5} μK^2]
ΔC_ℓ^{EE}
100
80
60
40
20
0
4
0
-4
30
500
1000
1500
2000
ℓ

Planck 2015-2016

- 2015 data release
  - To be completed ~June 2015 (with likelihood code)
  - Temperature: all
  - Polarization: full high-ℓ data, only 70 GHz low-ℓ
    - polarization is hard: differencing sensitive to detector drifts (low-frequency noise/systematics)
    - temperature remains baseline
- 2016 data release
  - full-mission temperature and polarization
  - better measurements of τ, reionization history

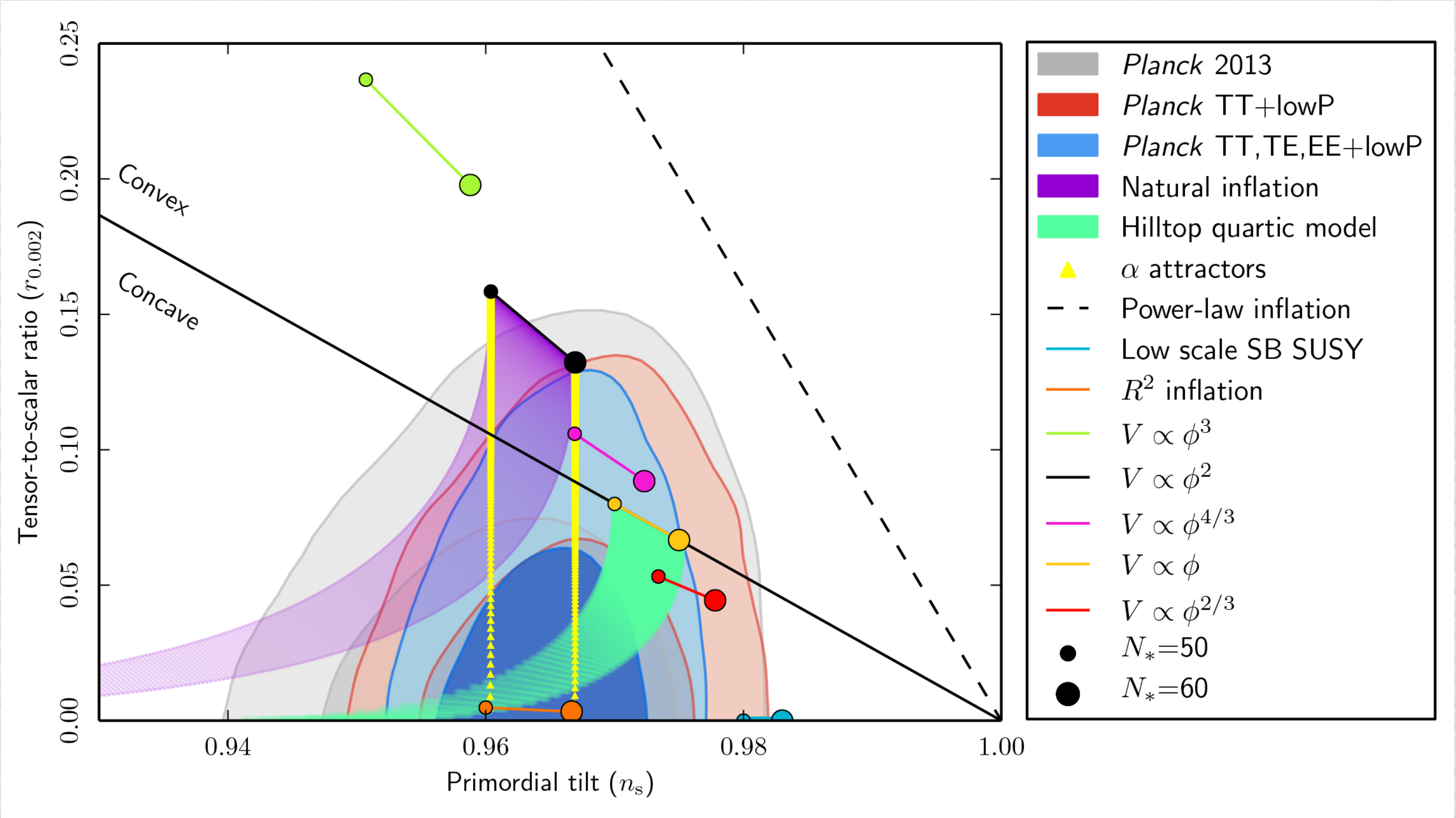
Evidence for inflation?

- A flat universe



Inflation: Models

- Slightly redder than scale-invariant ($n_s \lesssim 1$)
- Simplest models: scalar field φ w/very flat potential $V(\varphi)$
- *Planck* constrains specific models of inflation
- No evidence of gravitational radiation in the early universe



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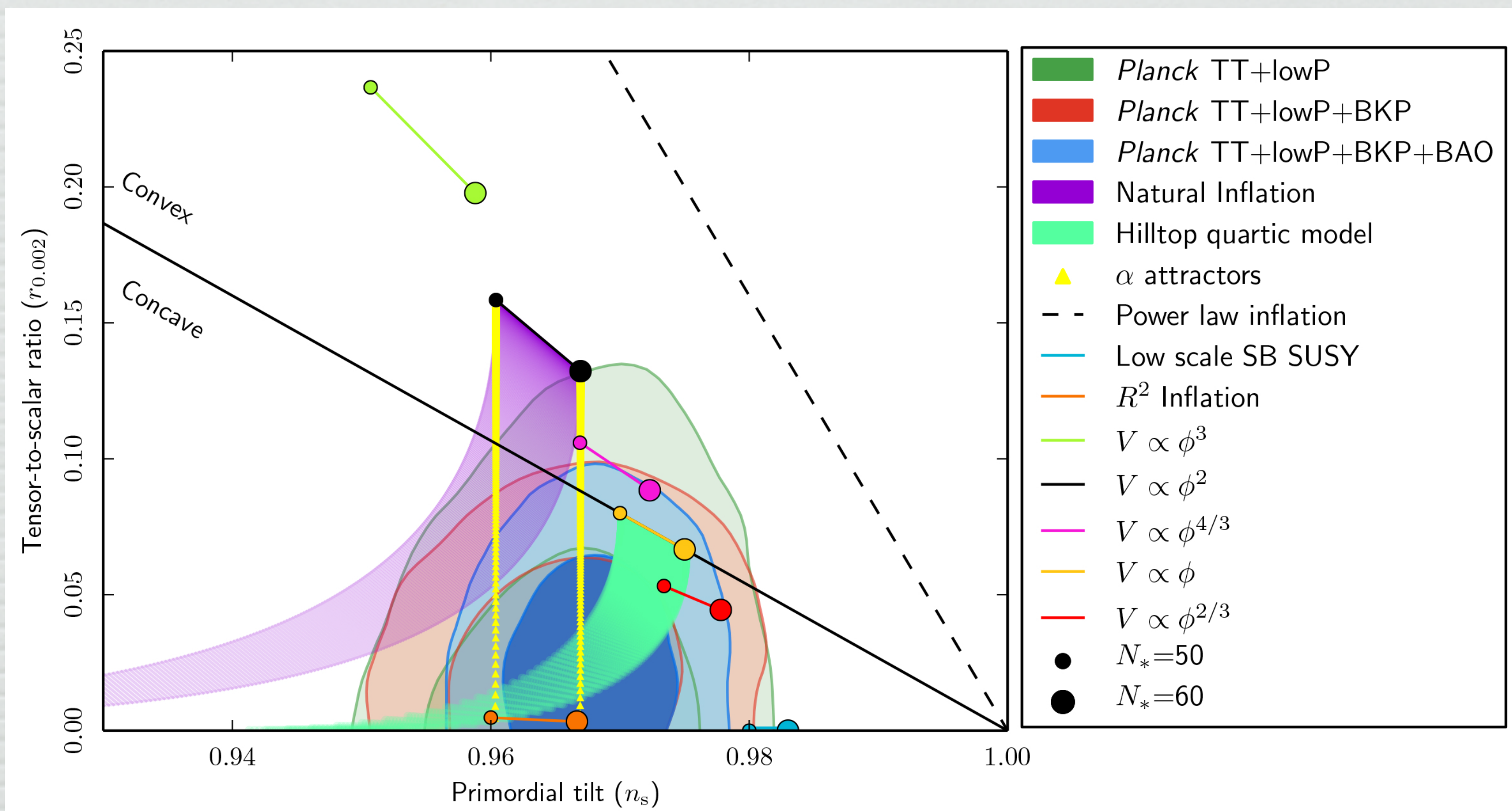
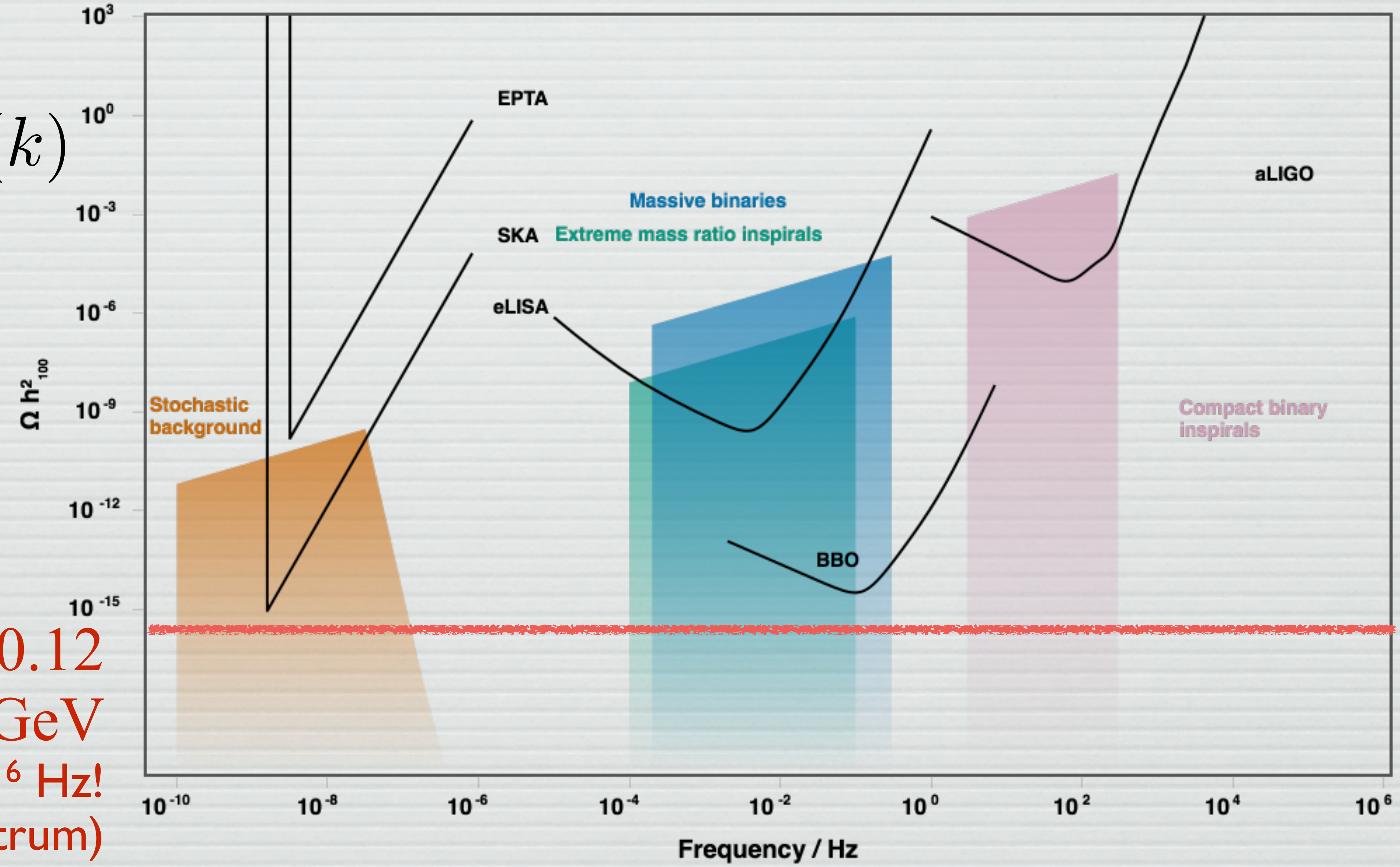


From low frequency to high: Future and Current limits

$$\Omega_{\rm GW}(k) \propto P_{\rm t}(k) \propto V \propto r$$



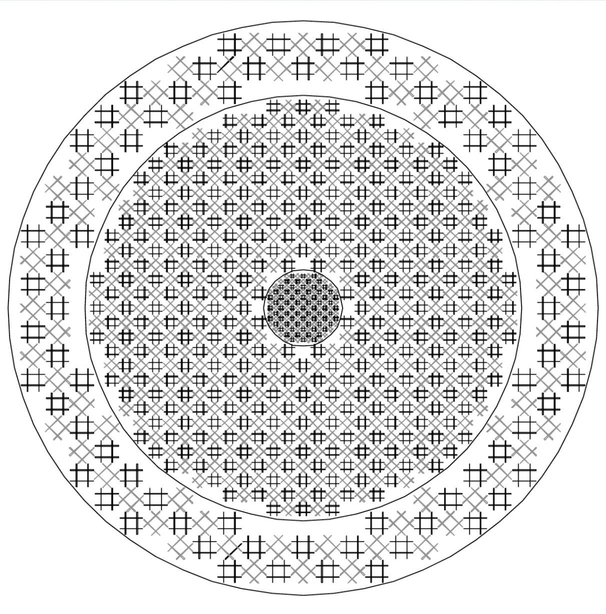
current CMB: $r<0.12$
$\rightarrow V^{1/4}<2\times10^{16}$ GeV
extrapolated from 10^{-16} Hz!
(assuming non-blue spectrum)

- courtesy http://rhcole.com/apps/GWplotter/
- (see Moore, Cole & Berry 2014, arXiv:1408.0740)
- nb. Joe Romano's caveats on these figures...

Post-Planck CMB

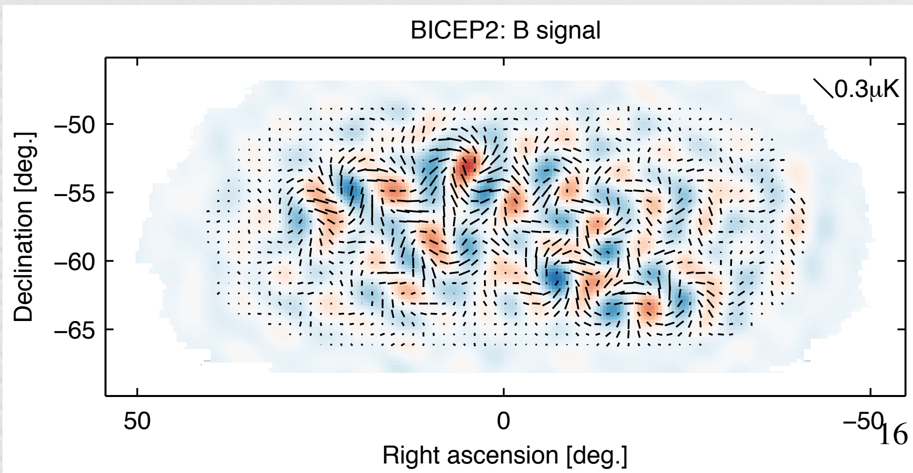
- Since late 1990s, (bolometric) detectors at ~ quantum limits
  - need many detectors (low noise)
    - Can only improve by $\sqrt{N}$
  - … at many frequencies (discriminate foregrounds)
    - narrow bands (or even Fourier-transform spectroscopy)
    - (fewer photons per band, so see above — many detectors)

- e.g., lithography
  + antenna coupling



Original Polarbear design, c. 2000

BICEP2



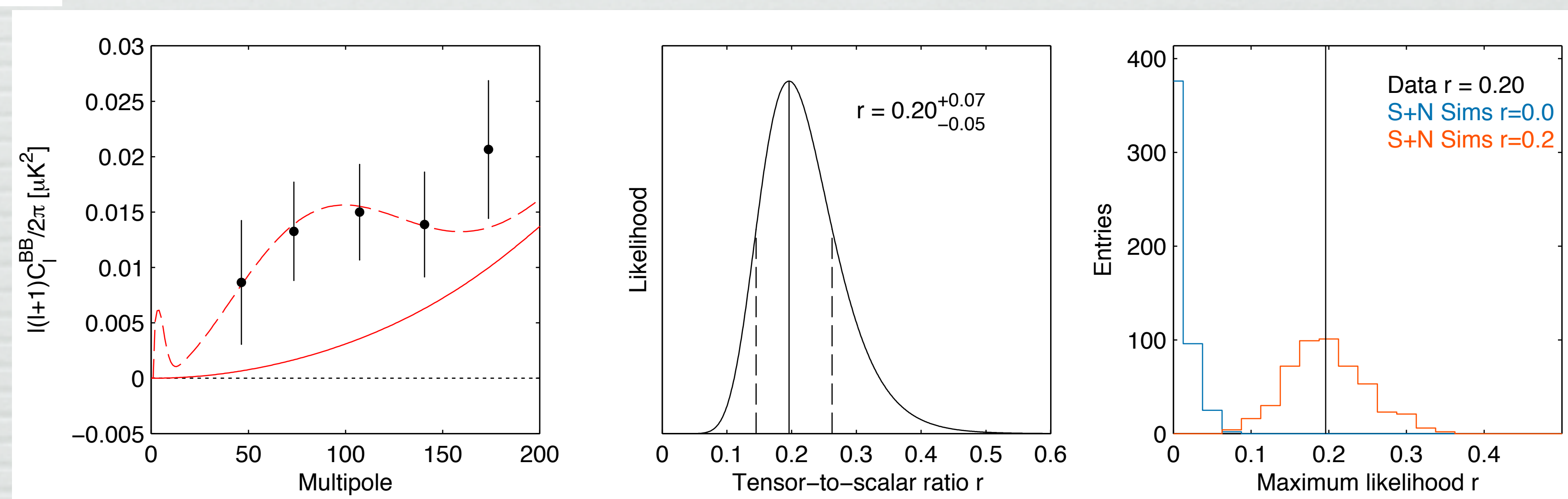
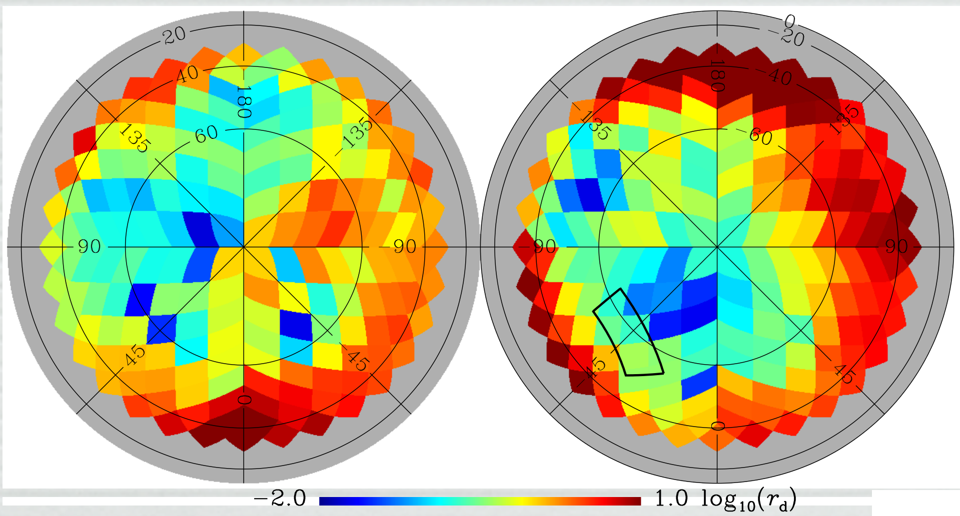


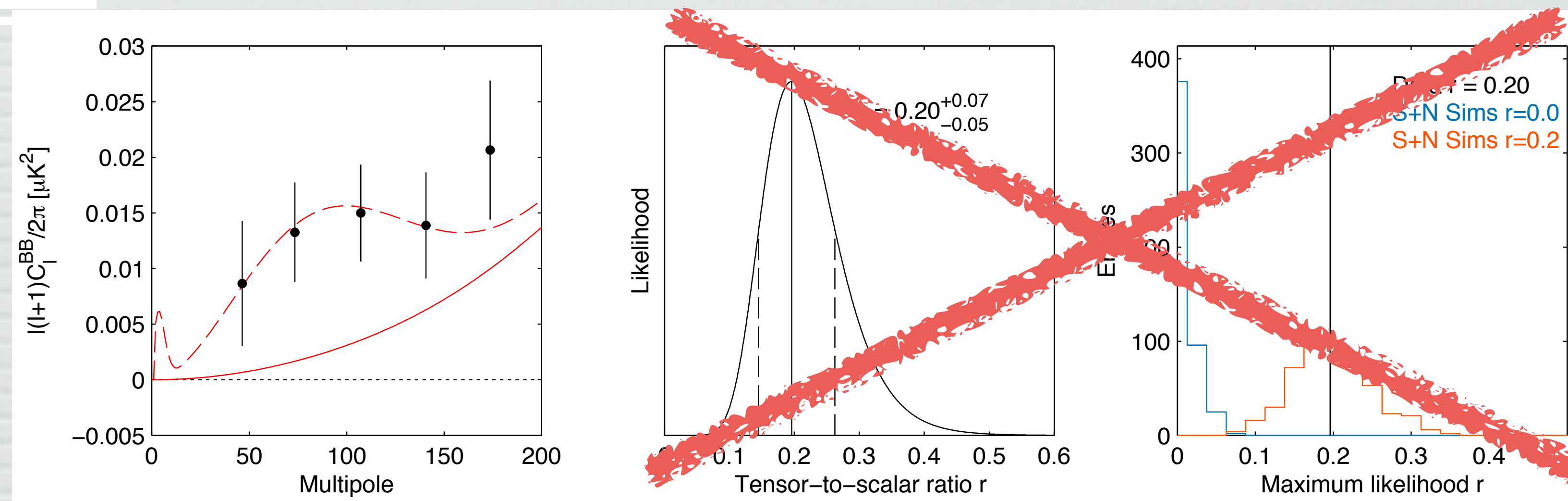
FIG. 10.— *Left:* The BICEP2 bandpowers plotted with the maximum likelihood lensed-ΛCDM+$r = 0.20$ model. The uncertainties are taken from that model and hence include sample variance on the r contribution. *Middle:* The constraint on the tensor-to-scalar ratio r. The maximum likelihood and $\pm 1\,\sigma$ interval is $r = 0.20^{+0.07}_{-0.05}$, as indicated by the vertical lines. *Right:* Histograms of the maximum likelihood values of r derived from lensed-ΛCDM+noise simulations with $r = 0$ (blue) and adding $r = 0.2$ (red). The maximum likelihood value of r for the real data is shown by the vertical line.

- 256×2 = 512 TES bolos @150GHz
- 0.5 deg FWHM
- Strategy: large sky area 380 deg^2 (AJ et al ’00)

BICEP2



BICEP2 Collaboration



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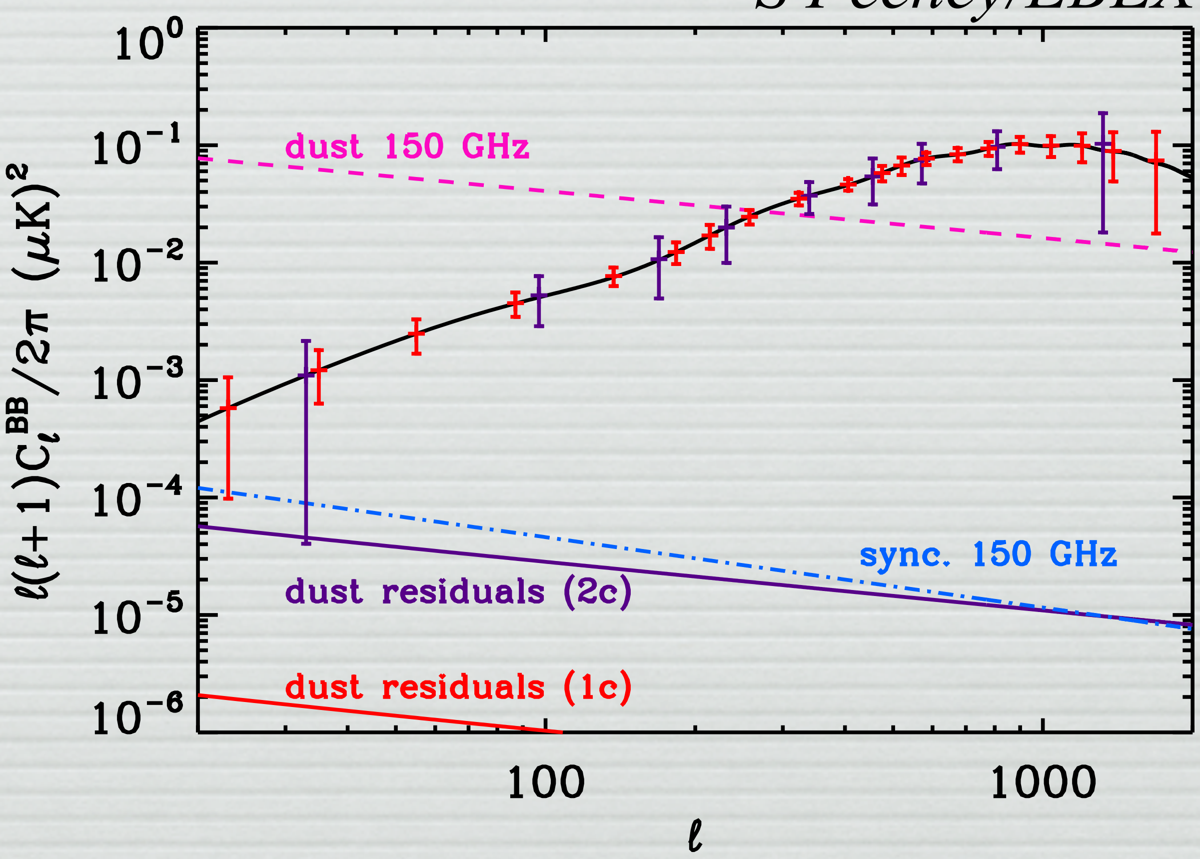
Foreground modelling

- The Planck/BICEP2 experience has shown that foregrounds dominate even “clean” areas of sky
  - low dust intensity ≠ low dust polarisation
- need enough frequency coverage to measure dust (&c) properties on small patches.
  - e.g. two-temperature grey-body models, galactic magnetic field
  - traced better at higher (dust) and lower (synch, free-free) frequencies than 100-200 GHz where CMB dominates.

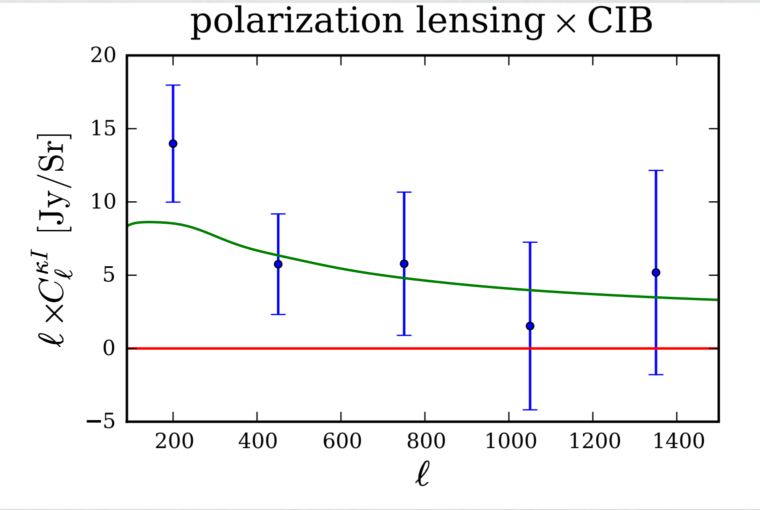
S Feeney/EBEX



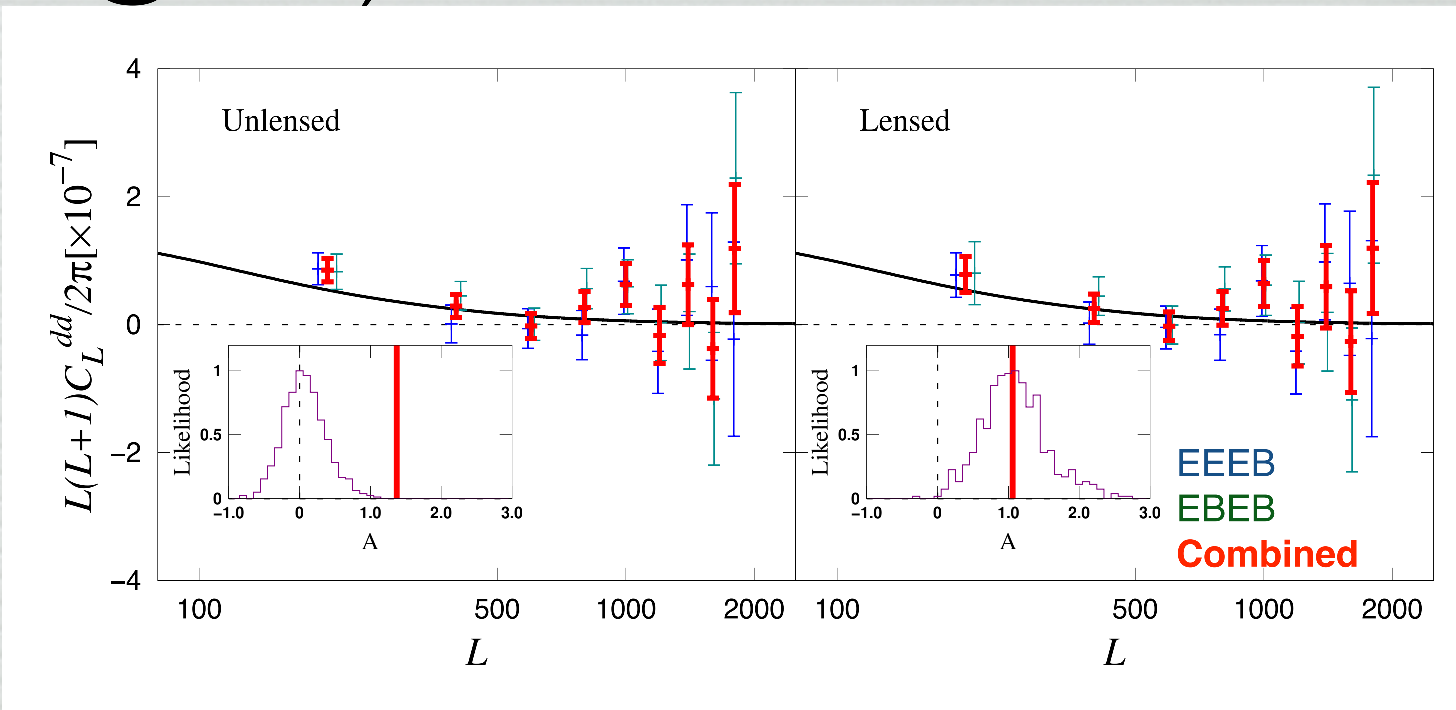
The Post-Planck generation: Lensing

- Polarization: Starting to get the first results from kilo-pixel CMB detector arrays — sufficient to detect lensing conversion of E→B
  - Sensitive to growth of structure (e.g., neutrinos)
  - Cross-correlation with *large-scale structure* (SPTPol: Hanson et al; ACT: Hand et al; Polarbear @ ~4σ)

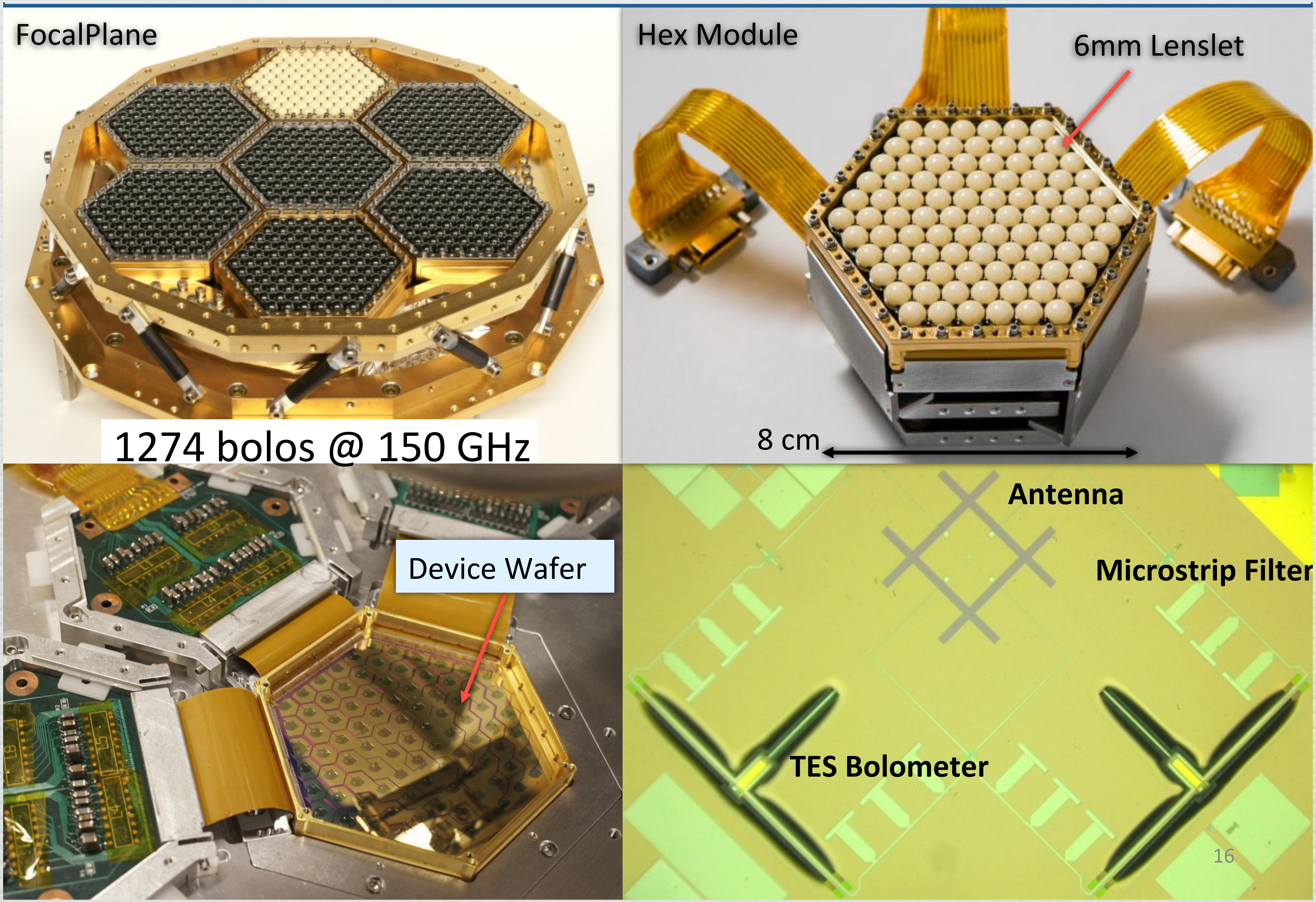
PB x Herschel H-Atlas CIB measurement



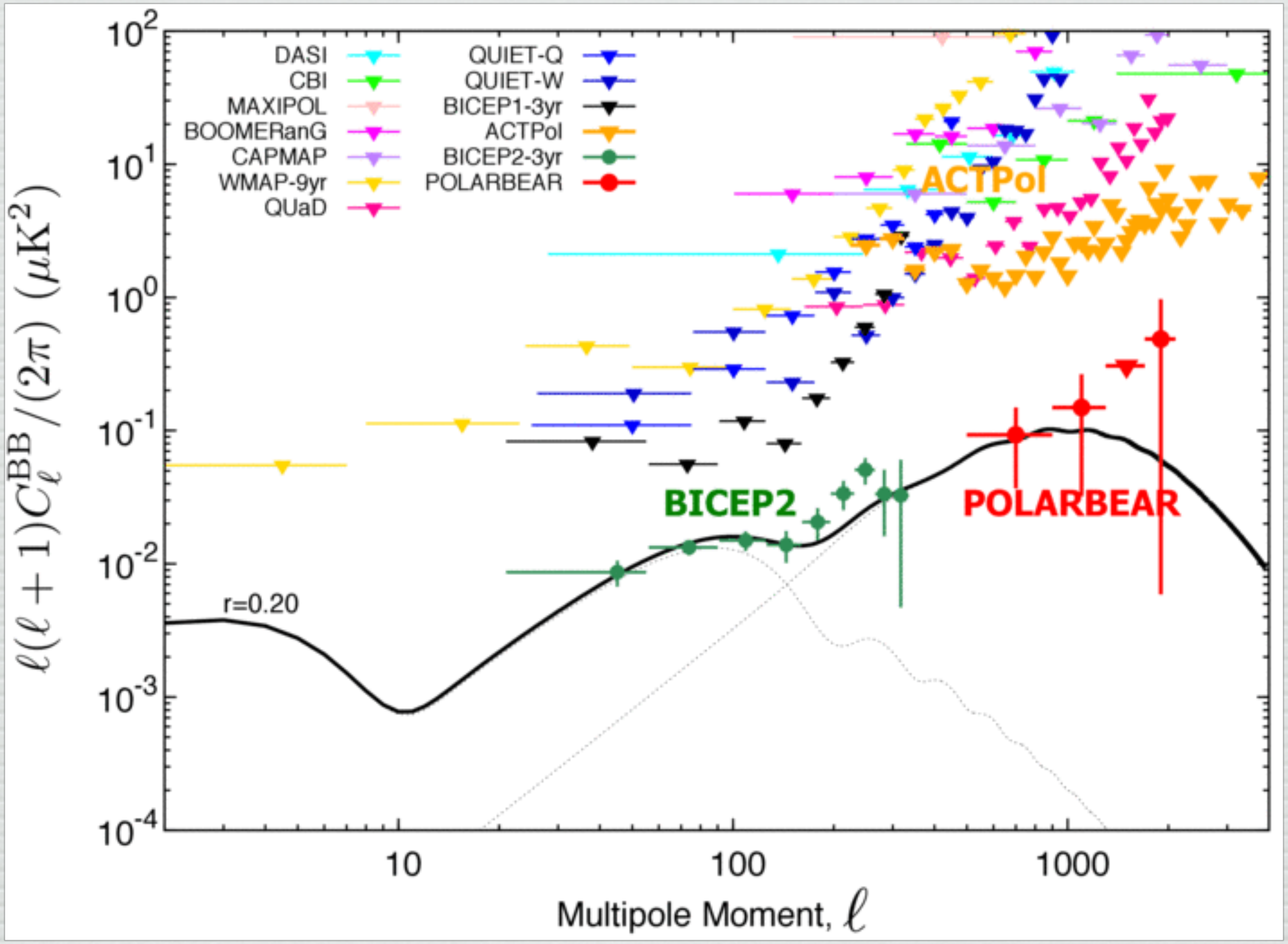
  - ⟨EEEB⟩ & ⟨EBEB⟩ (Polarbear @ ~4σ)
  - These are *not* primordial B modes (gravitational radiation)



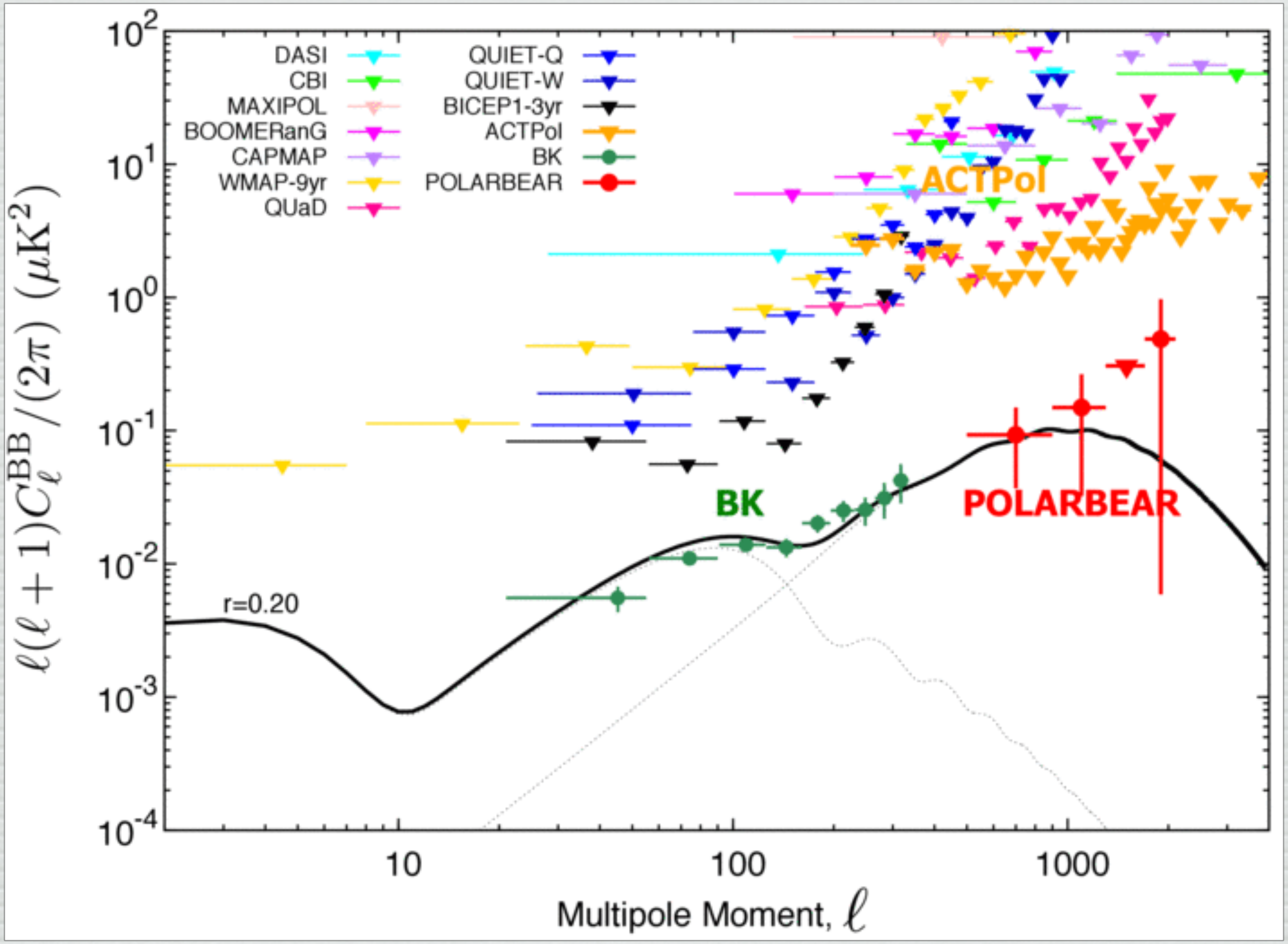
The Polarbear focal plane



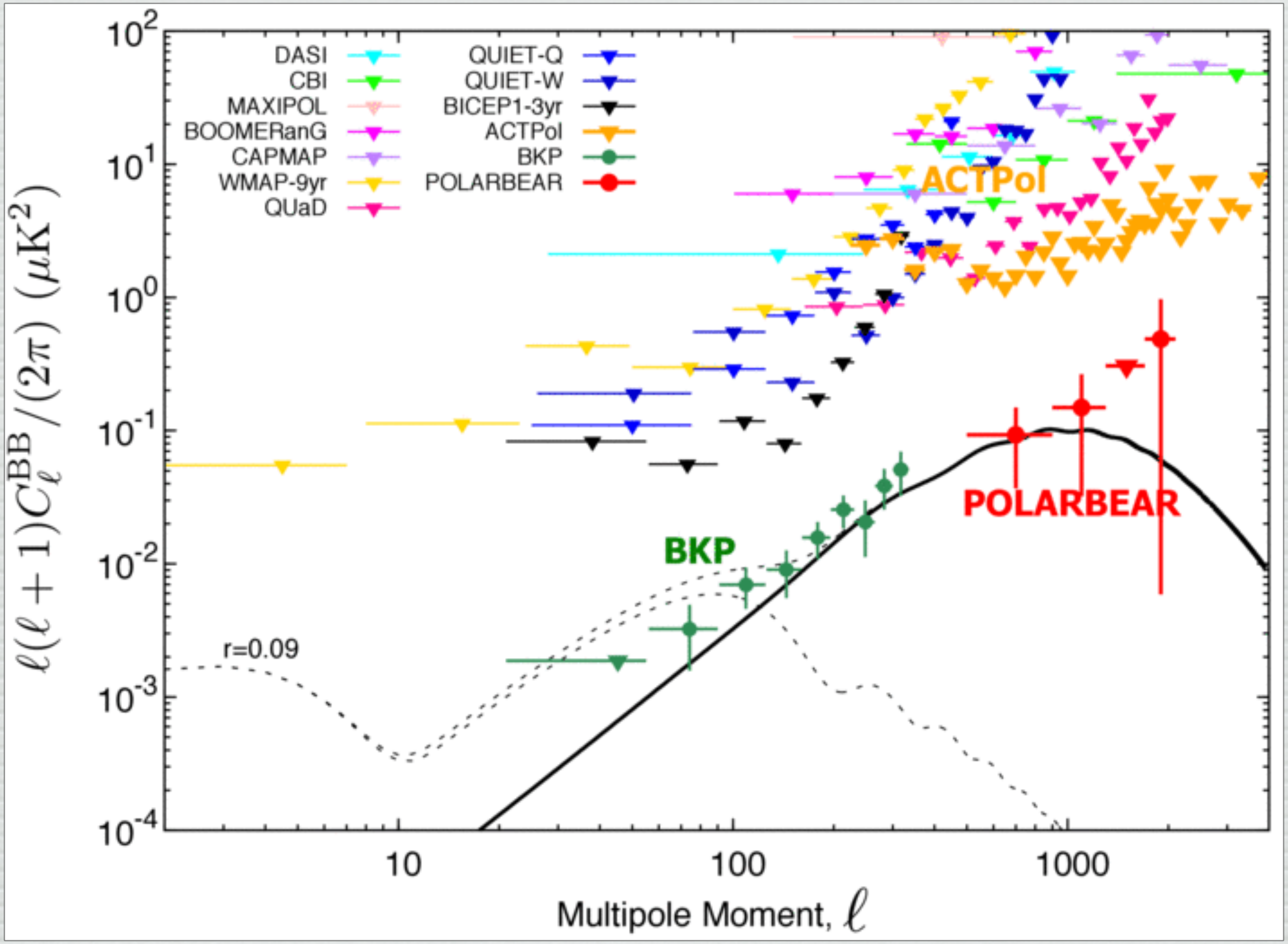
State of the art



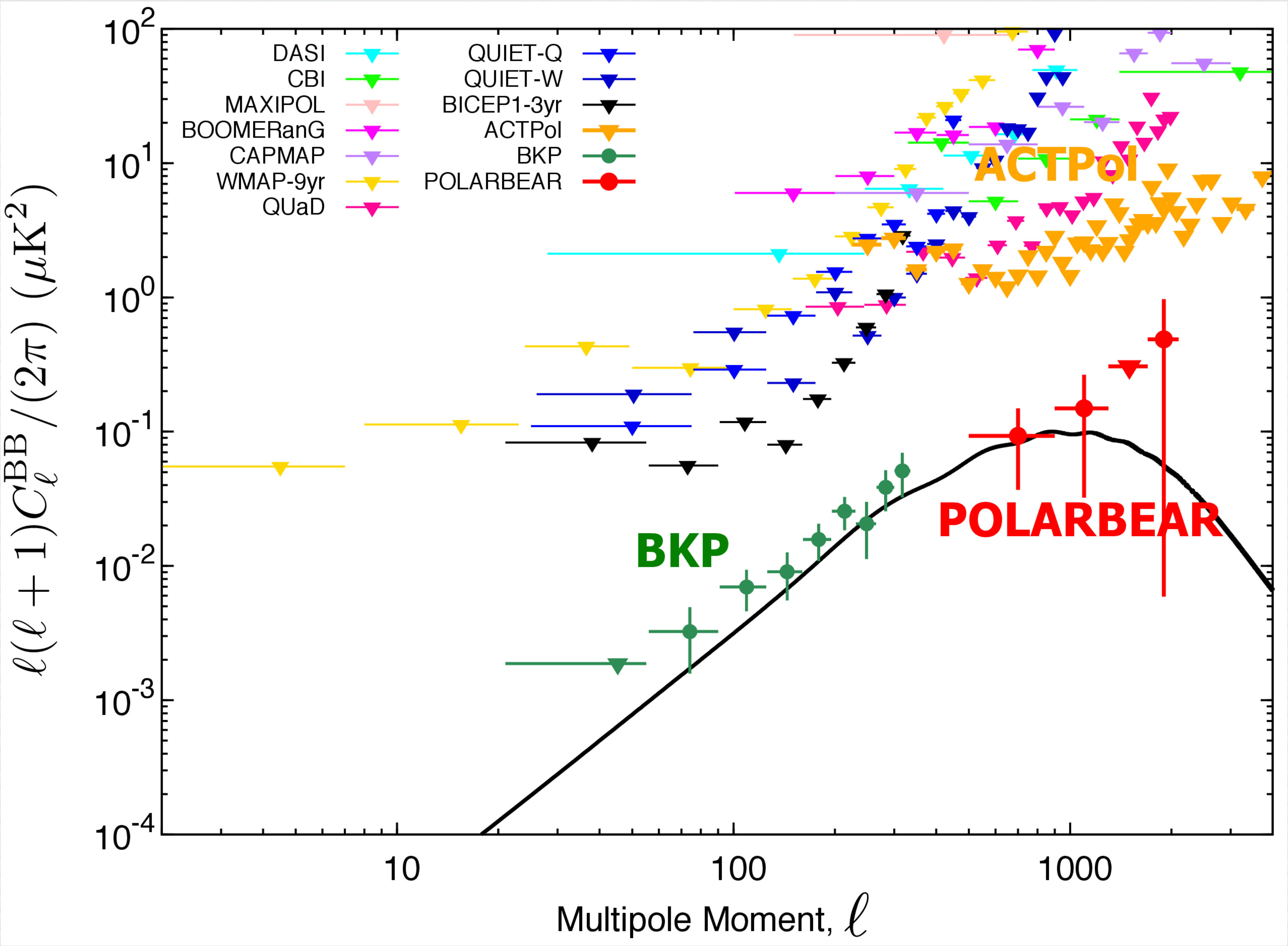
State of the art



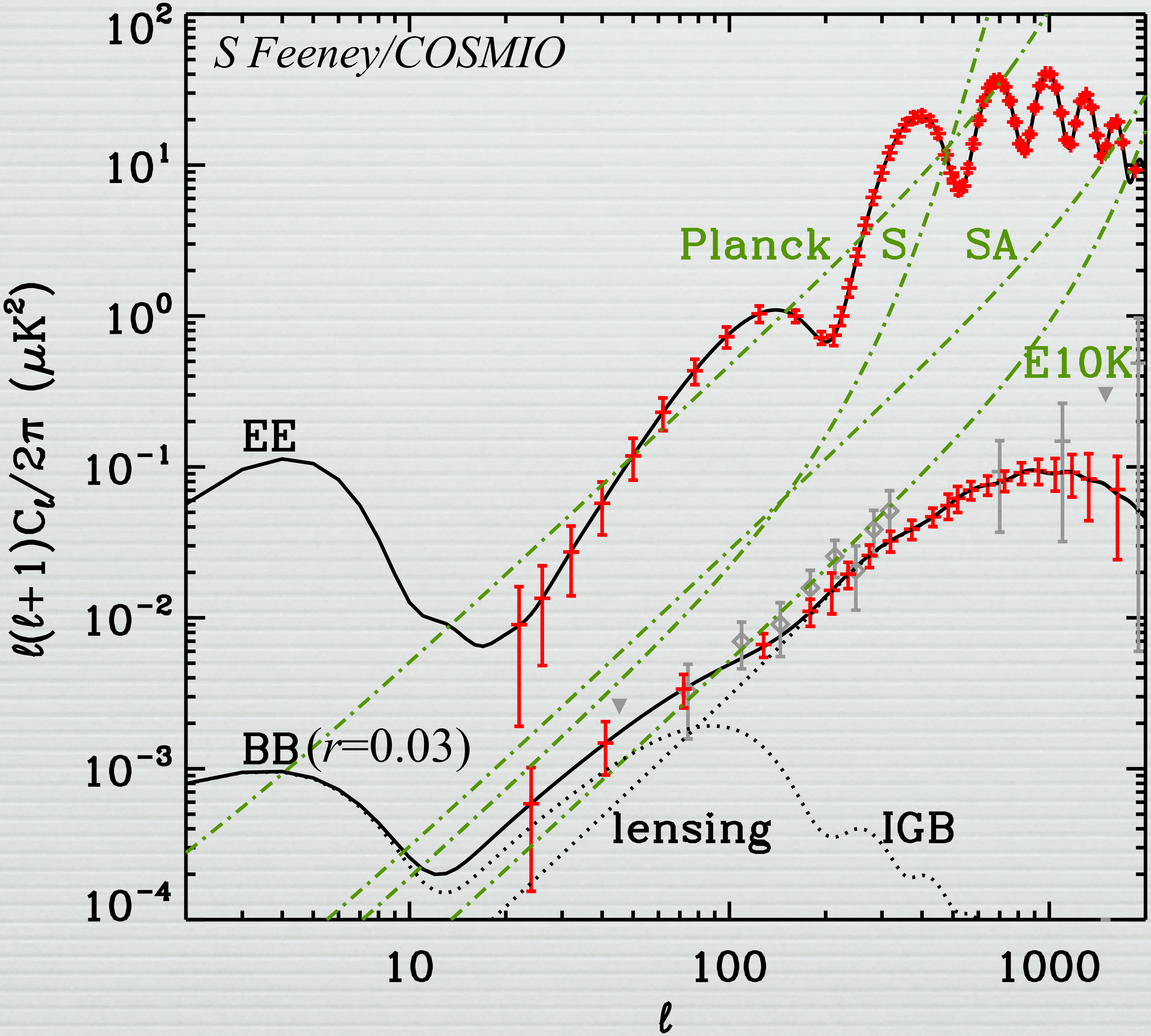
State of the art



State of the art



The near future



Noise levels

Planck

S: *Spider*

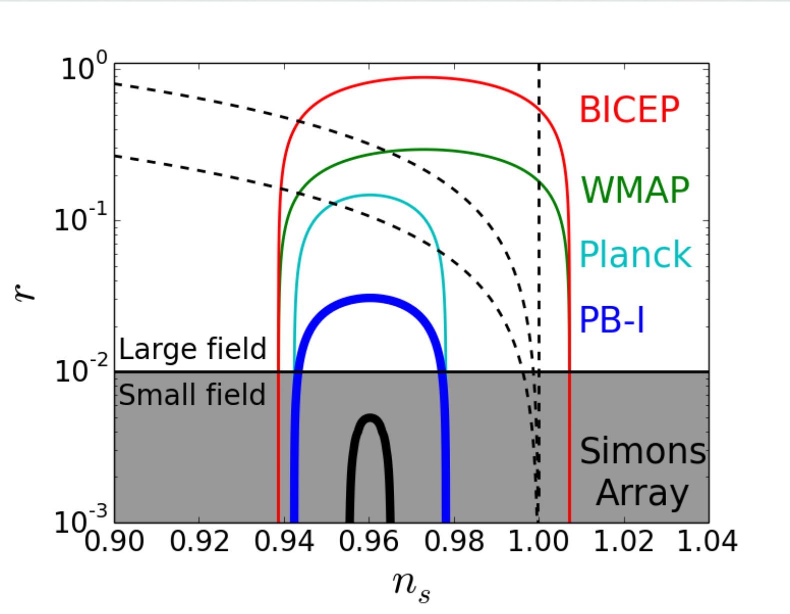
SA: *Simons Array* (Polarbear)

E10K: *EBEX*

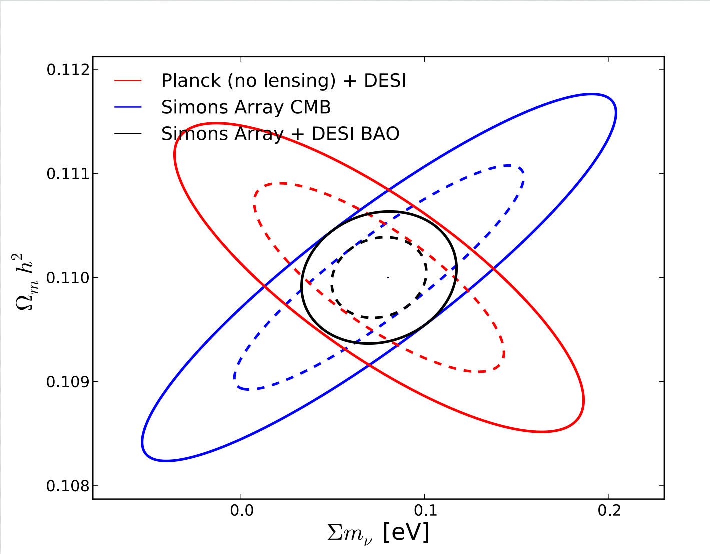
Similar performance expected from other 3d-gen experiments: Keck Array, LSPE, SPT3G …

Beyond detections

- already done: $\Omega_k = 1$, $n_s \neq 1$
- detection: $r \neq 0$
- characterisation:
  - measure r to a "few sigma"
  - measure running
  - measure shape of tensor power spectrum, n_T
    - for single-field inflation these essentially give derivatives of the potential V(φ)
  - (also, detect non-Gaussianity, isocurvature modes)
  - other physics, e.g., neutrino mass



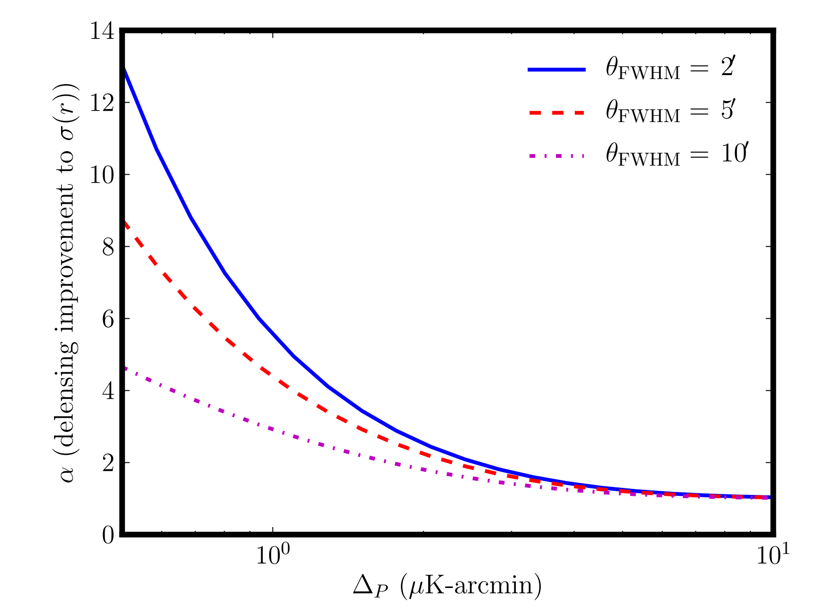
Polarbear/Simons Array



Polarbear/Simons Array

delensing

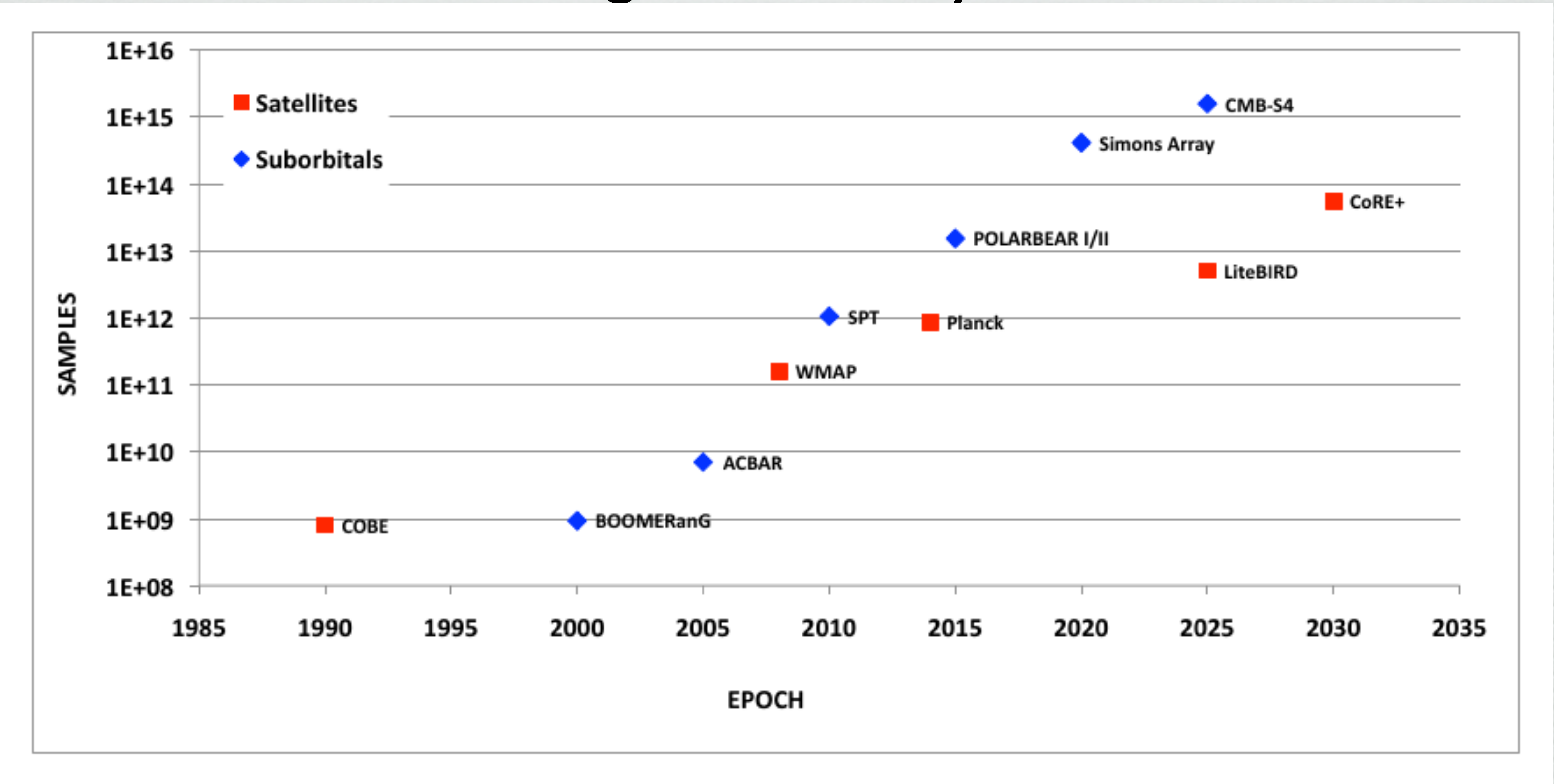
- Matter along the line sight shifts photon trajectories E→B (and B→E)
- Already observed in CMB alone and in cross-correlation with LSS observations
  - modifies the distribution function of temperature and polarisation
    - induces non-Gaussianity (Hu and Okamoto)
    - use high-resolution observations to de-lens low-l spectra
  - correlates signal with ρ along line of sight (Smith et al)
    - with LSS obs'ns, not as powerful as CMB-only; 21cm a possibility
    - What about "mass maps" from GW sirens?
  - In principal, can use these to separate the lensing effect from the primordial contribution.



Smith et al 2012

The next (last?) generation: S4

- Currently planning/funding 10^4-detector experiments — need another order of magnitude to take full advantage of the sky



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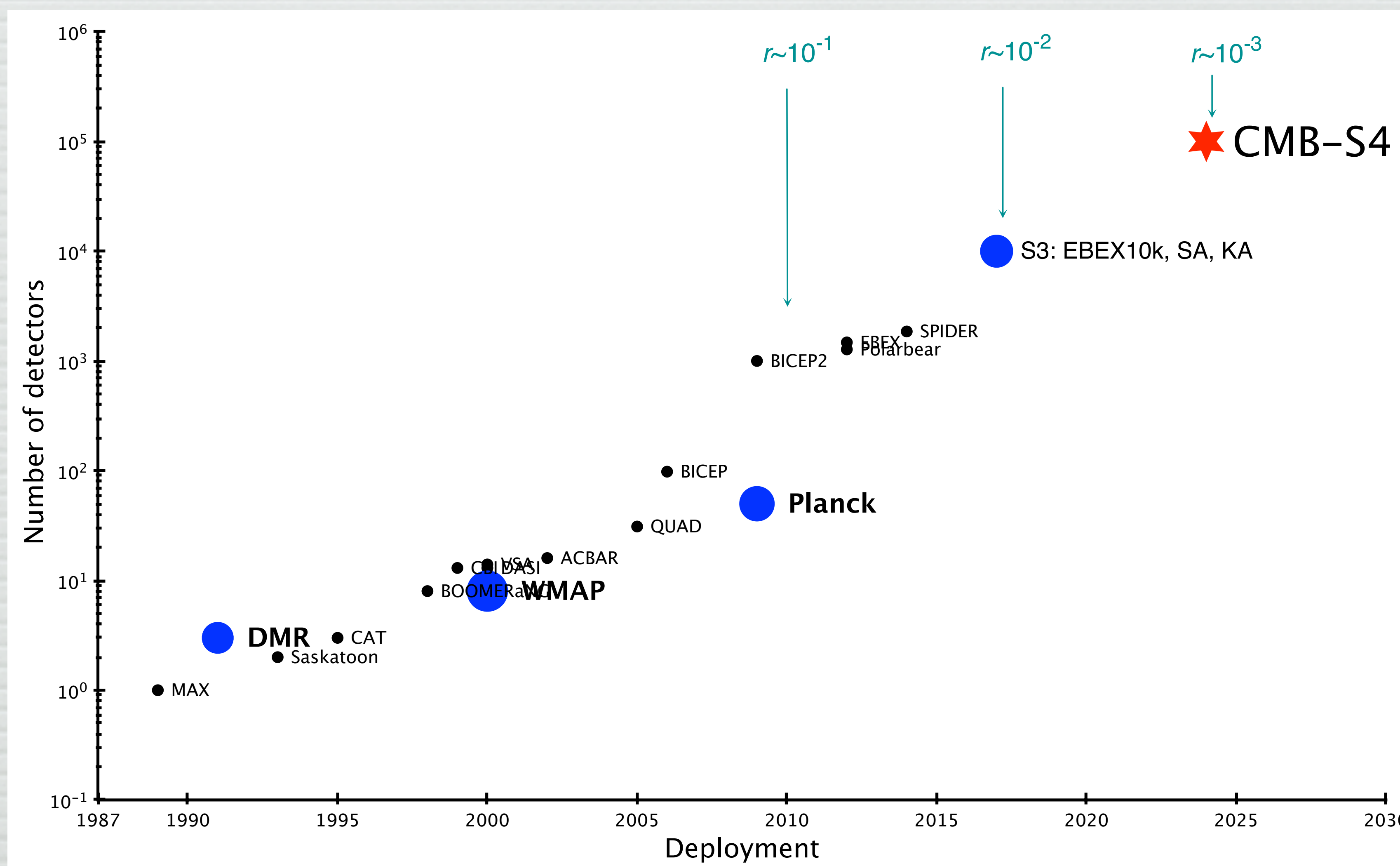
Parts of this talk based on data & papers released 2013-15 by the 400-person Planck Collaboration

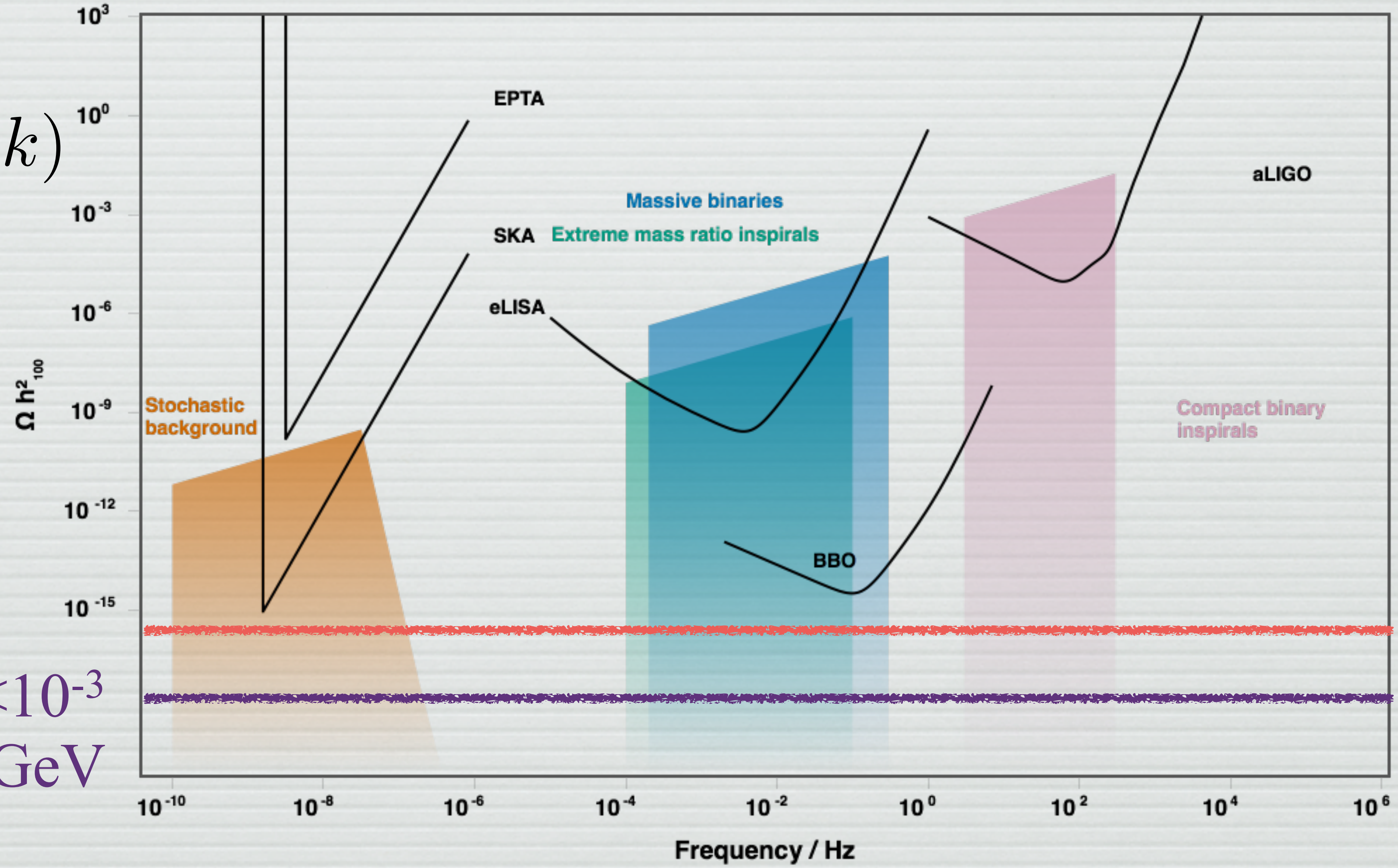
Moore's law for CMB experiments?

- Goal $r \sim 10^{-3}$
  - Starobinsky, Higgs
  - trans-Planckian excursions
  - (*Creminelli et al* 2015)
  - also $n_t \sim 0.1$
- Multiple ground-based telescopes
- $>10^5$ detectors
- 50% sky
- 40-240 GHz for foreground removal
- 1 μK arcm sensitivity
- TES bolos
- 1 TB/day
- (supplemented by balloons for >300 GHz?)
- similar to a future satellite (!)



Prospects for the coming decade+

$$\Omega_{\rm GW}(k) \propto P_{\rm t}(k)$$
$$\propto V$$
$$\propto r$$



CMB goal: $r<10^{-3}$
$\rightarrow V^{1/4}<6\times10^{15}$ GeV

- Still have 1-2 more orders of magnitude in *r* to observe
- Interesting models to see or rule out.
- Technical challenges — 100k detector arrays, foregrounds, lensing