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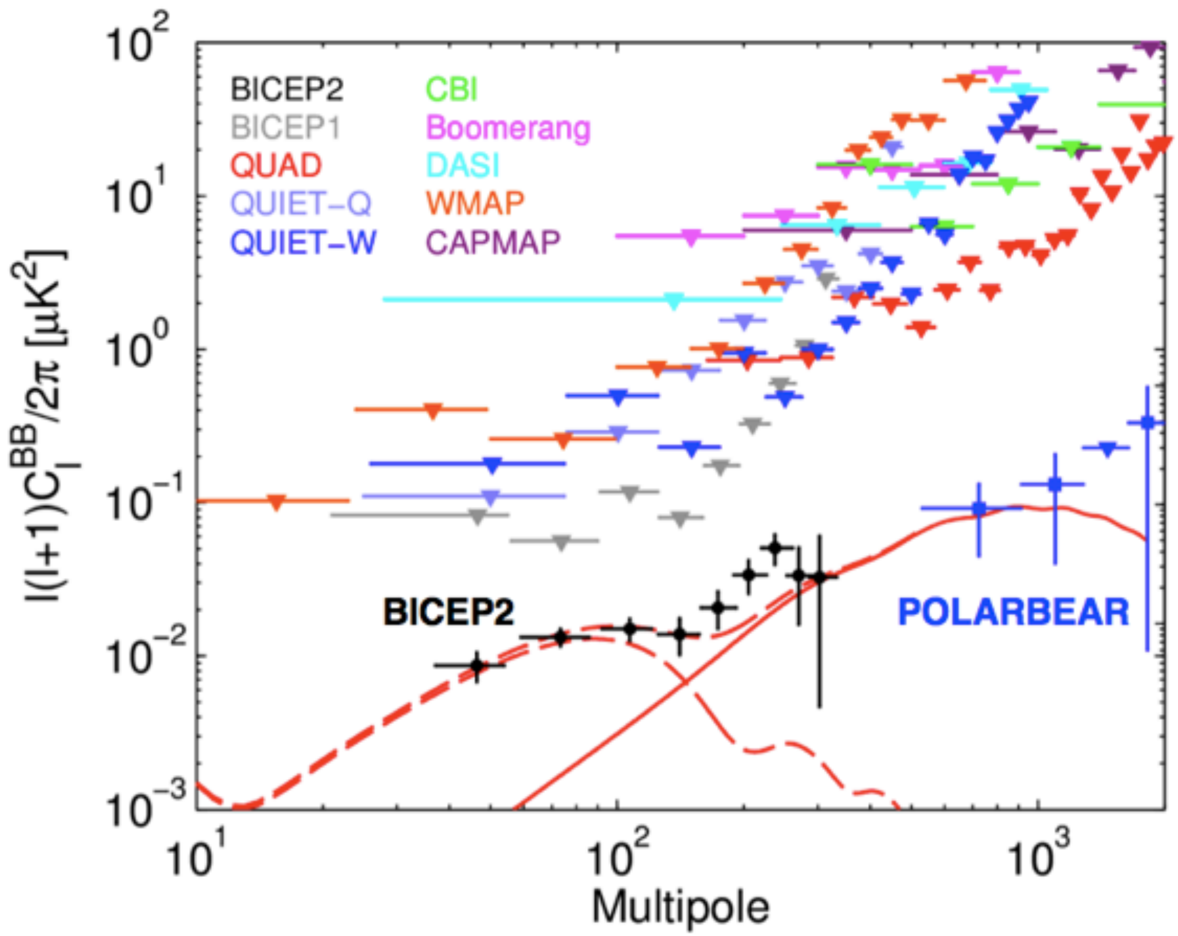
B - mode cosmology

Quy Nhon - August 20th 2015

The new era of B-modes

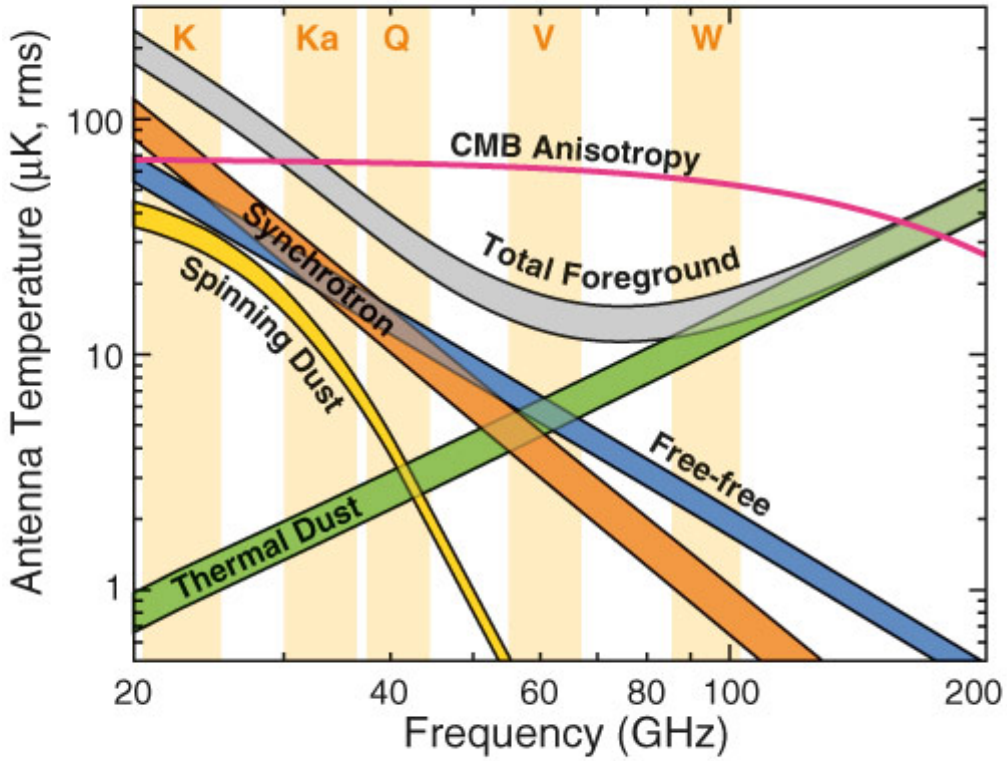


- Amazing improvement in exp sensitivity

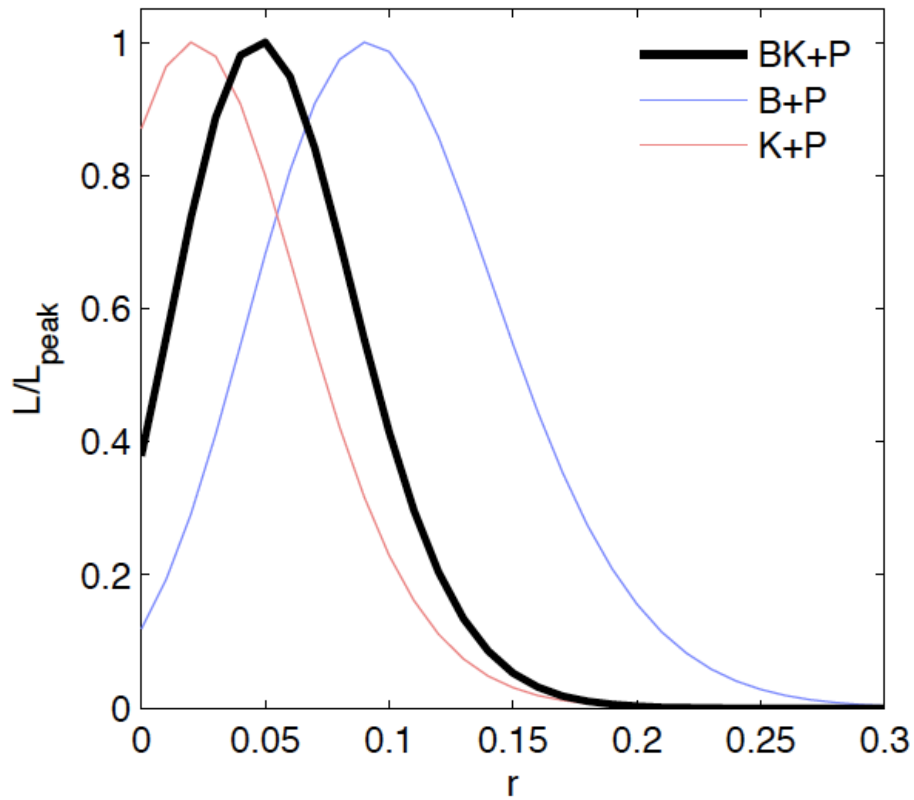
  ΔP ~ 3.4 μK arcmin
  (Planck ΔP ~ 45 μK arcmin)

- Theoretically motivated region

Dust under the carpet



BICEP2/Keck + Planck:
signal is compatible with being only dust




GRAVITATIONAL
WAVES

Robust signature

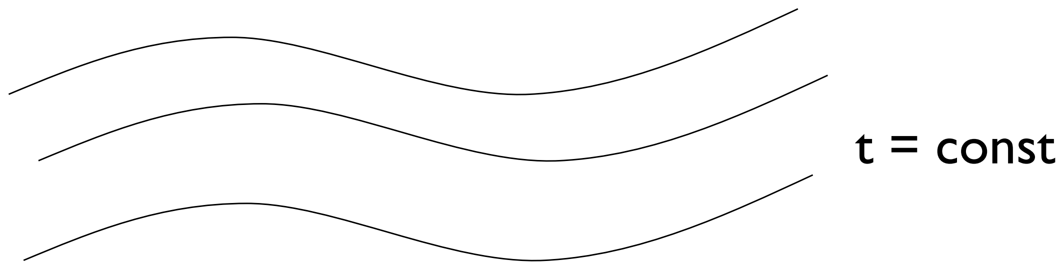
- It is easy to play with scalar perturbations:

    1. choice of potential
    2. many scalars (effects on late Universe)
    3. speed of propagation c_S

- It is not easy to play with gravity ! GWs are direct probes of H

Speed of gravity

Effective field theory of inflation:



Parametrize the most general dynamics compatible with symmetries

Cheung, PC, Fitzpatrick, Kaplan, Senatore 07

$$S = \int \mathrm{d}^4x \sqrt{-g}\,\frac{M_{\mathrm{Pl}}^2}{2}\left[R - 2\left(\dot{H} + 3H^2\right) + 2\dot{H} g^{00} - \underline{\underline{\left(1 - c_T^{-2}(t)\right)\left(\delta K_{\mu\nu}\delta K^{\mu\nu} - \delta K^2\right)}}\right]$$

$$K_{ij} = \frac{1}{2N}\left(\dot{h}_{ij} - \nabla_i N_j - \nabla_j N_i\right)$$

$$S_{\gamma\gamma} = \frac{M_{\mathrm{Pl}}^2}{8}\int \mathrm{d}^4x\, a^3 c_T^{-2}\left[\dot{\gamma}_{ij}^2 - c_T^2 \frac{(\partial_k \gamma_{ij})^2}{a^2}\right] \longrightarrow \Delta_T^2 = \frac{2}{\pi^2}\frac{H^2}{M_{\mathrm{Pl}}^2}\cdot\frac{1}{c_T(t)}$$

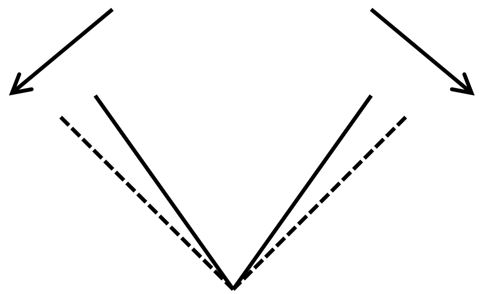
Disformed away

PC, Gleyzes, Noreña, Vernizzi 14

$$\Delta_T^2 = \frac{2}{\pi^2}\frac{H^2}{M_{\rm Pl}^2}\cdot\frac{1}{c_T(t)}$$

- Scale invariance without H ~ const.
- P_T does not measure energy scale
- $n_T \neq 2\dot H/H^2 < 0$

$$\boxed{g_{\mu\nu} \mapsto g_{\mu\nu} - (1-c_T^2)\partial_\mu\phi\partial_\nu\phi/(\partial\phi)^2}$$



$$g_{\mu\nu} \mapsto c_T^{-1}(t)\, g_{\mu\nu}$$

$$\tilde t \equiv \int c_T^{1/2}(t){\rm d}t\,, \qquad \tilde a(\tilde t) \equiv c_T^{-1/2}a(t)$$

$$\dot c_T = 0$$

$$\int {\rm d}^4x\sqrt{-\tilde g}\frac{M_{\rm Pl}^2}{2}\left\{\tilde R - 2(\dot{\tilde H} + 3\tilde H^2) + 2\dot{\tilde H}\tilde g^{00} + 2(1-c_T^2)\dot{\tilde H}\times\left(1-\sqrt{-\tilde g^{00}}\right)^2\right\}$$

$\tilde c_s = 1/c_T$

NG in original frame beyond decoupling!

Disformed away

$$S = \int \mathrm{d}\tilde{t}\mathrm{d}^3x\sqrt{-\tilde{g}}\frac{M_{\rm Pl}^2}{2}\Big\{\tilde{R} - 2(\dot{\tilde{H}} + 3\tilde{H}^2) + 2\dot{\tilde{H}}\tilde{g}^{00} + \Big[2(1-c_T^2)\dot{\tilde{H}} - \quad \tfrac{3}{2}\alpha^2 - c_T^2\left(\dot{\alpha} + \tilde{H}\alpha + \frac{1}{2}\alpha^2\right)\Big] \times \left(1 - \sqrt{-\tilde{g}^{00}}\right)^2 + 2\alpha\,\delta\tilde{K}\left(1 - \sqrt{-\tilde{g}^{00}}\right)\Big\}$$

$$\alpha \equiv \dot{c_T}/c_T$$

Blue tilt using c_T → Stable NEC violation with operator $\delta N \delta K$

PC, Luty, Nicolis, Senatore 06

No loss of generality in taking $c_T = 1$
(even multifield or alternatives to inflation)

Exceptions: 1. Different symmetry pattern (solid inflation, gauge-flation…)
2. GWs not produced as vacuum fluctuations

Spectrum and 3pf corrections

- Corrections to spectrum start with 3 derivative operators:

$$\varepsilon^{ijk}\partial_i\dot{\gamma}_{jl}\dot{\gamma}_{lk}\ , \qquad \varepsilon^{ijk}\partial_i\partial_m\gamma_{jl}\partial_m\gamma_{lk}$$

$$4\int \mathrm{d}^4x\ \varepsilon^{0ijk}\nabla_i\delta K_{jl}\delta K_{lk} \qquad\qquad -4\int \mathrm{d}^4x\ \varepsilon^{ijk}\left(\frac{1}{2}{}^3\Gamma^p_{iq}\partial_j{}^3\Gamma^q_{kp}+\frac{1}{3}{}^3\Gamma^p_{iq}{}^3\Gamma^q_{jr}{}^3\Gamma^r_{kp}\right)$$

Parity violation: different power spectrum for each elicity

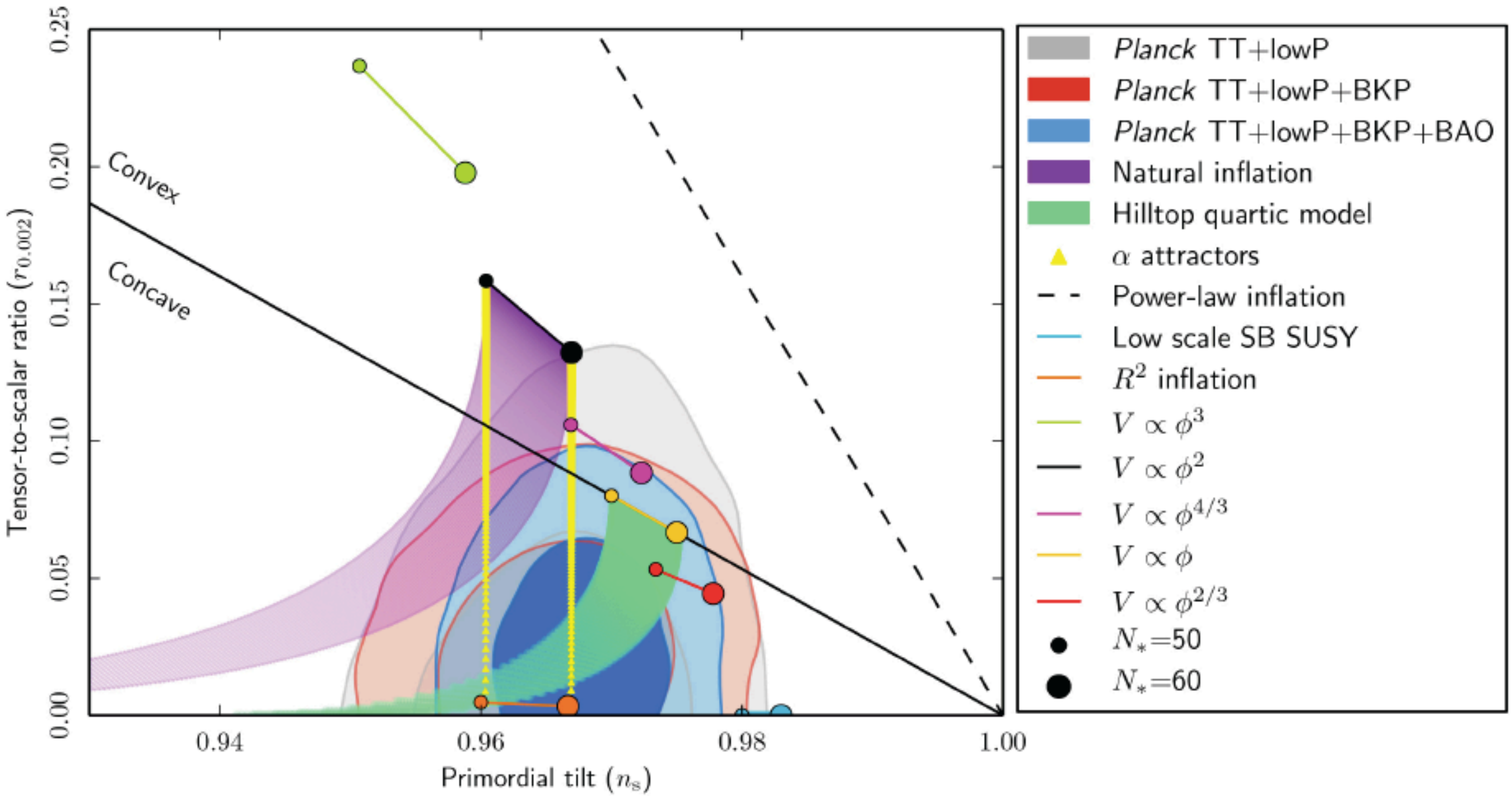
$$\langle\gamma^{\pm}_{\vec{k}}\gamma^{\pm}_{\vec{k}'}\rangle=(2\pi)^3\delta(\vec{k}+\vec{k}')\frac{H^2}{2M^2_{\mathrm{Pl}}k^3}\left(1\pm\beta\frac{\pi}{2}\frac{H}{\Lambda}\right)$$

For r ~ 0.1 we can observe a 50% difference between the two polarizations

Gluscevic, Kamionkowski 10
Ferte, Grain 14

- Not only spectrum, also $\langle\gamma\gamma\gamma\rangle$ cannot be modified at leading order in derivatives

The plane



$$P_\zeta = A \cdot k^{-3+(n_s-1)}$$

We will measure V, V' and V''

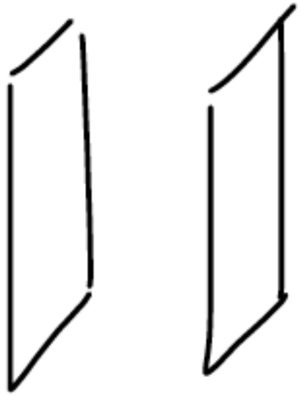
The scalar tilt

Planck: $n_s - 1 = -0.0348 \pm 0.0047 \quad (\gtrsim 7\sigma)$ It is of order 1/N (~ 0.02)

Did we expect that? Can we learn something on r?

True in many cases: $V = \frac{1}{2} m^2 \phi^2$ $\quad n_s - 1 = -\frac{2}{N}$

Brane inflation

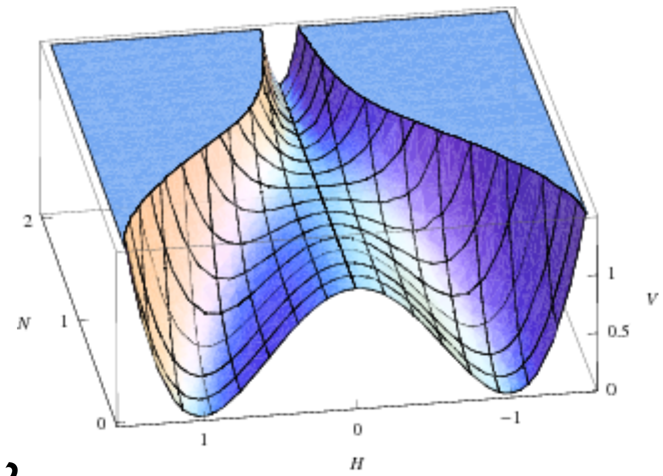


$$V = V_0 \left(1 - \left(\frac{\phi}{\mu}\right)^{-4}\right) \qquad n_s - 1 = -\frac{5}{3} \cdot \frac{1}{N}$$

Starobinsky, Higgs inflation… $V \sim V_0 (1 - e^{-\phi/M})$ $\quad n_s - 1 = -\frac{2}{N}$

and not in others…

- Hybrid: $V = \frac{1}{2}m^2\phi^2 + \frac{1}{4}\lambda(\psi^2 - M^2)^2 + \frac{1}{2}\psi^2\phi^2$



$n_s - 1 = 2M_P^2 m^2/V_0$ independent of N

Small but not so small because of SUGRA corrections (η-problem)?

Why not n_s -1 ~ 0.1 ?

- Natural inflation: $V = V_0\left[1 - \cos\left(\frac{\phi}{f}\right)\right]$

$$n_s - 1 = -a^2\left(1 + \frac{4}{(2+a^2)e^{a^2 N} - 2}\right) \qquad a \equiv \frac{M_P}{f}$$

It scales like 1/N only for a << 1

Let us take it seriously

PC, Dubovsky, Nacir, Simonović, Trevisan, Villadoro, Zaldarriaga 14

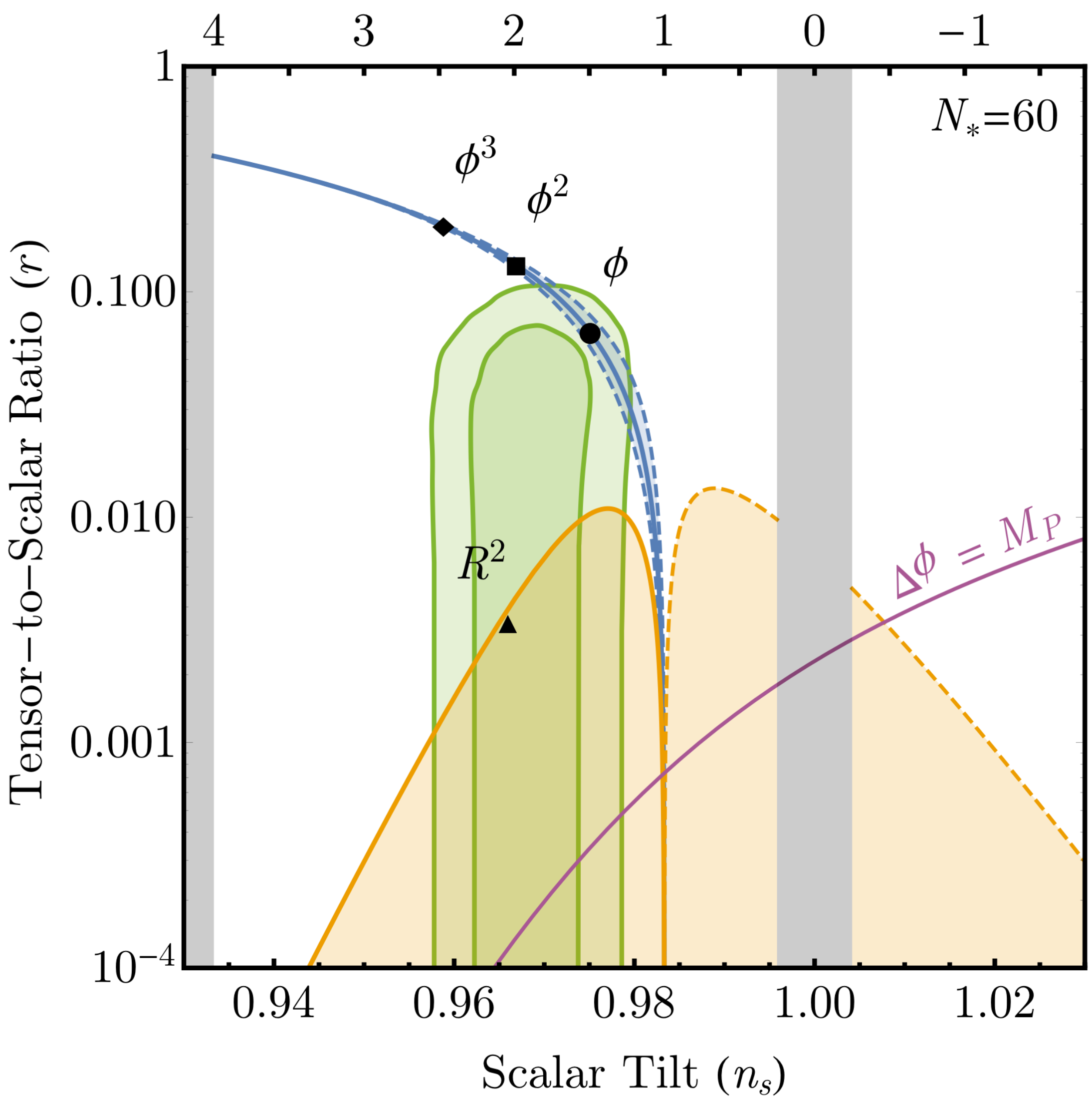
n_s -1 scales as 1/N in a window (larger than observable one)

$$n_s - 1 = -2\epsilon + \frac{\mathrm{d}\log\epsilon}{\mathrm{d}N} = -\frac{\alpha}{N}$$

$$\downarrow$$

$$\epsilon(N) = \frac{1}{2(\alpha-1)^{-1}N + AN^{\alpha}}$$

I assume one of the two scalings wins in the window



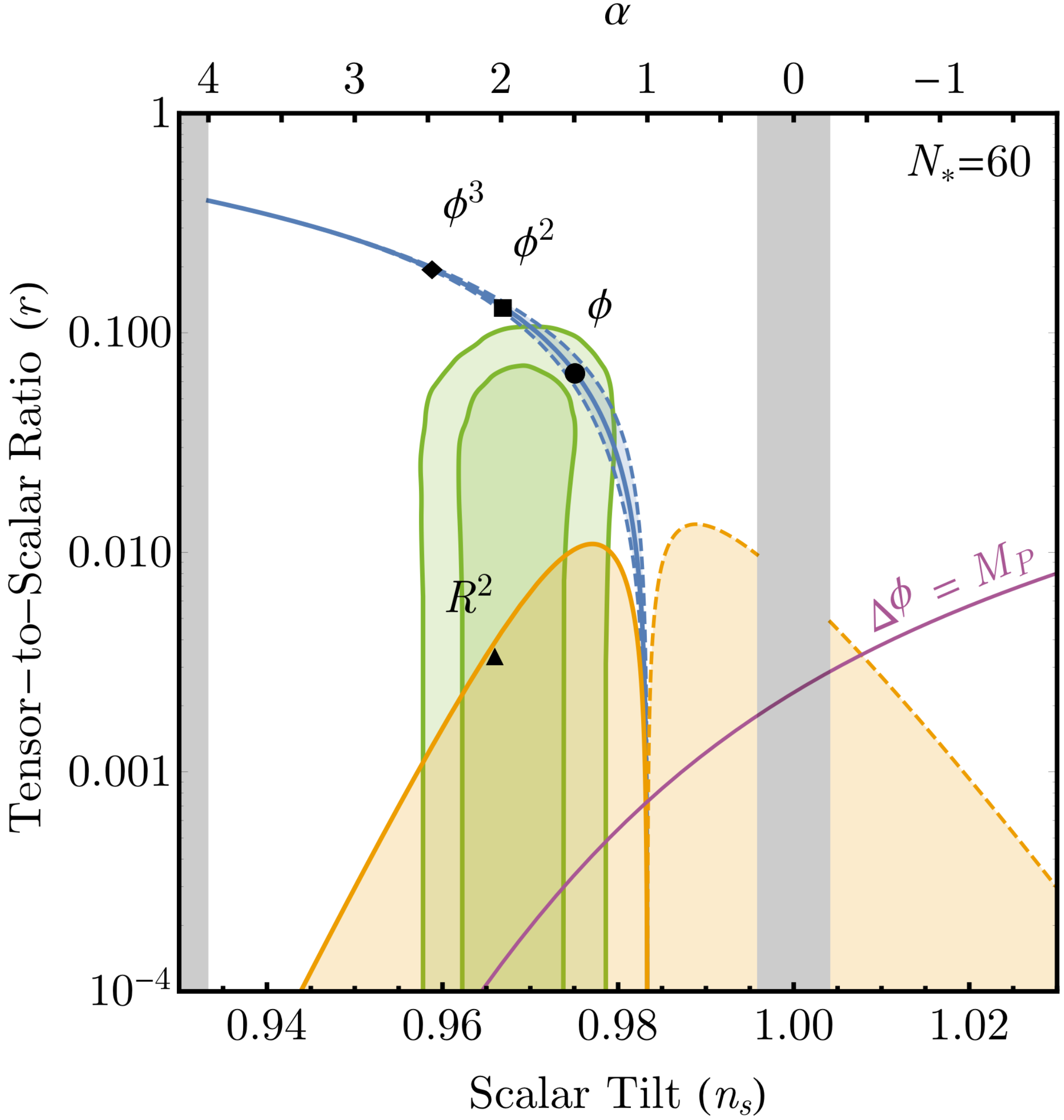
Similar to Mukhanov 13 and Roest 13

- Running α $\quad \frac{d\epsilon^{-1}}{d\log N} - \alpha(N)\epsilon^{-1} = -2N$

$$\epsilon^{-1}(N) = -2e^{\int_1^N \frac{d\tilde{N}}{\tilde{N}}\alpha(\tilde{N})}\int_1^N d\tilde{N} e^{-\int_1^{\tilde{N}} \frac{d\hat{N}}{\hat{N}}\alpha(\hat{N})} + Ae^{\int_1^N \frac{d\tilde{N}}{\tilde{N}}\alpha(\tilde{N})} .$$

- No lower bound on r
- "Forbidden" region: exp target
- Relevance of tilt
- Running $-\alpha/N_*^2 \simeq -7 \cdot 10^{-4}$
  can we measure it ?
- c_S opens degeneracies

Zavala 14



Future: some motivated threshold ?

There are various ways to argue for an interesting threshold:

$r \sim 2 \times 10^{-3}$

- Typical for exponential approach to a constant (with M_P) : $V \propto \exp\left(-\phi/M_P\right)$
  (Starobinsky, Higgs-inflation, …)

- 1/N argument

- Transplanckian displacement (Lyth bound)
  assuming increasing r:

$$\frac{\Delta\phi}{M_{\rm P}} = \int {\rm d}N \sqrt{\frac{r}{8}}$$

$$r = 8N^{-2} \simeq 2 \times 10^{-3}$$

Future: how far can we get ?

PC, Nacir, Simonović, Trevisan, Zaldarriaga 15

Now that we know better the enemies (dust) we can forecast:

$$S_{\ell,\nu} = \left(W_\nu^S\right)^2 C_\ell^S = \left(W_\nu^S\right)^2 A_S \left(\frac{\ell}{\ell_S}\right)^{\alpha_S}, \qquad W_\nu^S = \left(\frac{\nu}{\nu_S}\right)^{\beta_S},$$

$$D_{\ell,\nu} = \left(W_\nu^D\right)^2 C_\ell^D = \left(W_\nu^D\right)^2 A_D \left(\frac{\ell}{\ell_D}\right)^{\alpha_D}, \qquad W_\nu^D = \left(\frac{\nu}{\nu_D}\right)^{1+\beta_D} \frac{e^{h\nu_D/kT}-1}{e^{h\nu/kT}-1}$$

Cross-correlation:

$$g\sqrt{S_{\ell,\nu_i} D_{\ell,\nu_j}}$$

Parameter	**Synchrotron**	**Dust (EE, BB)**
$A_{72\%}$ $[\mu\mathrm{K}^2]$	2.1×10^{-5}	$0.318, 0.169$
$A_{53\%}$ $[\mu\mathrm{K}^2]$	2.1×10^{-5}	$0.120, 0.065$
$A_{24\%}$ $[\mu\mathrm{K}^2]$	2.1×10^{-5}	$0.036, 0.019$
$A_{11\%}$ $[\mu\mathrm{K}^2]$	4.2×10^{-6}	$0.024, 0.013$
$A_{1\%}$ $[\mu\mathrm{K}^2]$	4.2×10^{-6}	$0.012, 0.006$
ν [GHz]	65	353
ℓ	80	80
α	-2.6	-2.42
β	-2.9	1.59
T [K]	–	19.6

Future: how far can we get ?

$$\boxed{\mathcal{L}(D,p) \propto \; e^{-\frac{1}{2}\sum_{\ell,m} D^T \cdot \left(W \cdot C \cdot W^T + N\right)^{-1} \cdot D}}$$

Frequencies, noises, beams for each exp

Marginalized over A_{S}, A_{D}, β_{S}, β_{D}, g, τ

- Dust and Sync are comparable at 90 GHz in the cleanest 1%
- Prior: 50% on A_S and A_D, 10% on β_S, 10-50 % on β_D
- 10% delensing in exp with sufficient ang resolution: 4.4 → 1.4 μK'

Ground and balloons

1 sigma

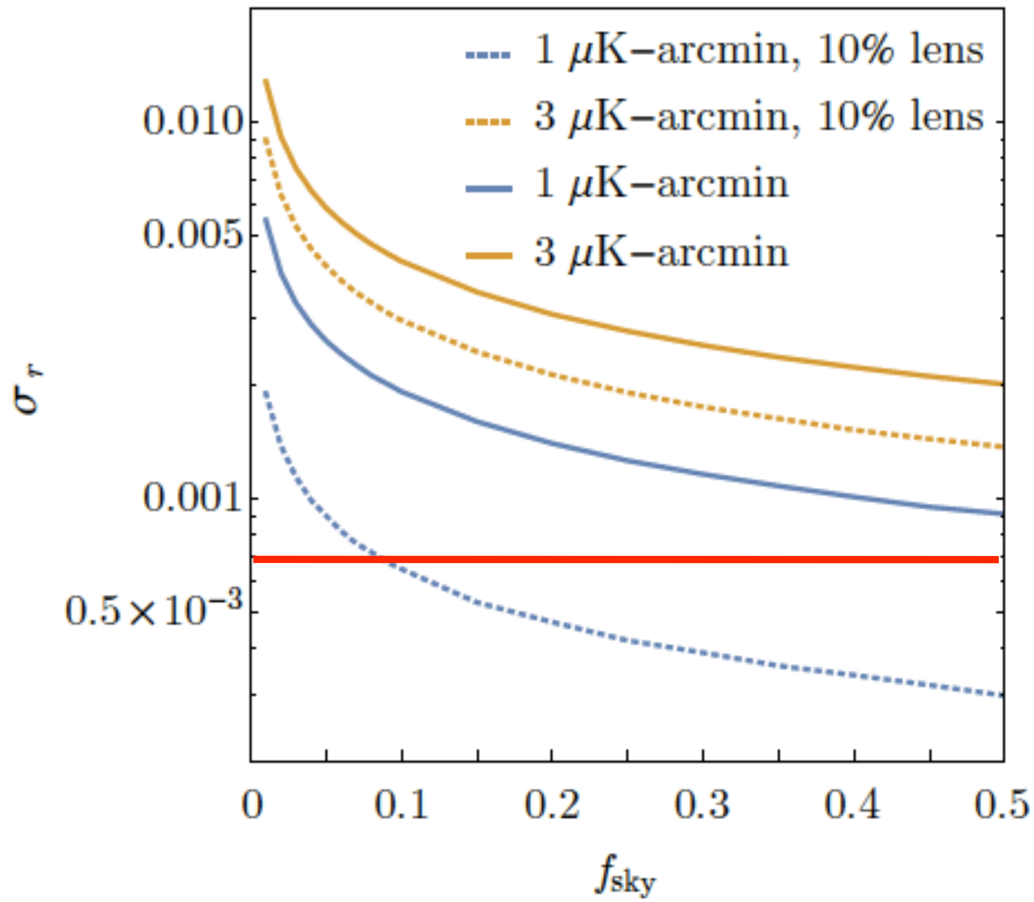
	r	Keck/BICEP3	Simons Array	AdvACT	CLASS	SPT-3G
CS	0.1	2.2×10^{-2}	7.6×10^{-3}	5.4×10^{-3}	6.5×10^{-3}	9.0×10^{-3}
	0.01	—	5.0×10^{-3}	3.1×10^{-3}	3.4×10^{-3}	4.2×10^{-3}
	0.001	—	—	—	—	—
	0	9.1×10^{-3}	3.4×10^{-3}	1.4×10^{-3}	9.0×10^{-4}	3.7×10^{-3}
FG 1%	0.1	1.9×10^{-2}	1.1×10^{-2}	7.8×10^{-3}	6.0×10^{-3}	8.1×10^{-3}
	0.01	7.8×10^{-3}	8.1×10^{-3}	4.8×10^{-3}	3.5×10^{-3}	4.1×10^{-3}
	0.001	—	—	—	—	—
	0	6.4×10^{-3}	7.8×10^{-3}	4.6×10^{-3}	3.3×10^{-3}	3.7×10^{-3}

	r	EBEX 10k	Spider
CS	0.1	1.5×10^{-2}	1.8×10^{-2}
	0.01	7.4×10^{-3}	—
	0.001	—	—
	0	6.4×10^{-3}	1.3×10^{-2}

New dust level only changes ~ factor of 2 in reach

Trust foreground model at 1%

Ground: future



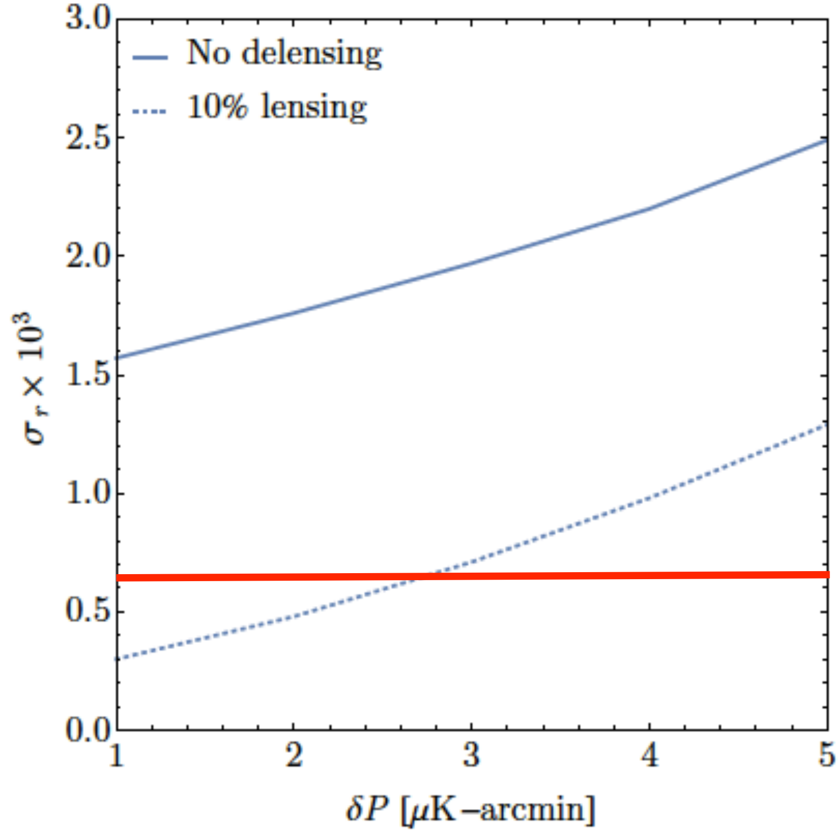
Stage IV

Can get to 2×10^{-3} but very challenging

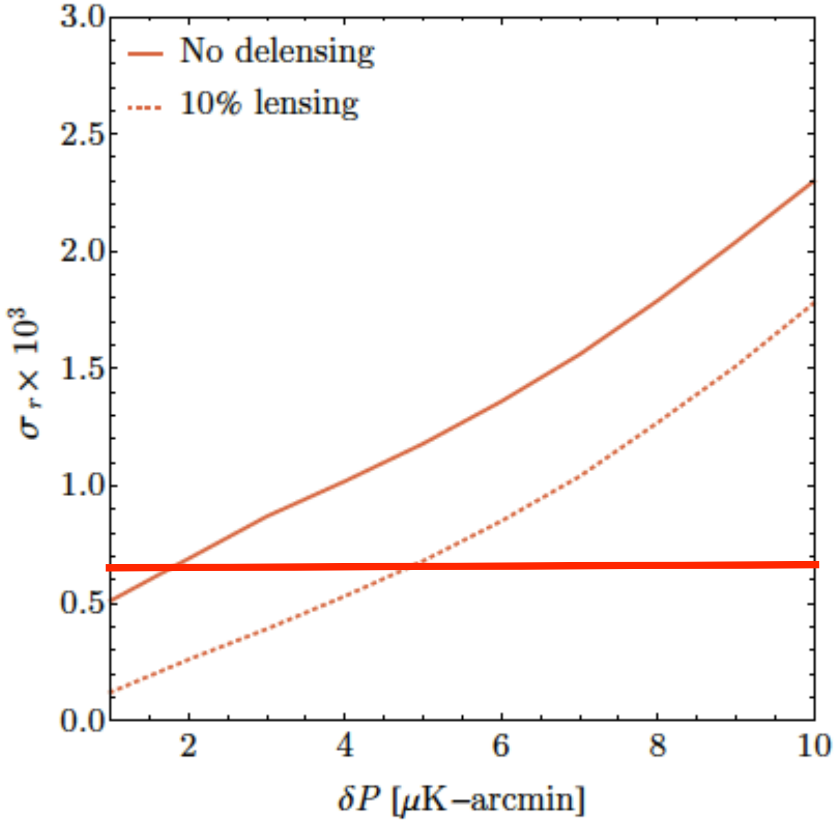
Beam 5' and 100, 150, 220 GHz

$r = 2 \times 10^{-3}$

Balloons: future



(a) BAL covering 5% of the sky.



(b) ULDB covering 60% of the sky.

Beam 5' and 150, 220, 280, 350 GHz

Space

	r	CMBPol	COrE	LiteBIRD
CS	0.1	1.2×10^{-3}	1.3×10^{-3}	1.9×10^{-3}
	0.01	2.7×10^{-4}	3.3×10^{-4}	5.9×10^{-4}
	0.001	1.1×10^{-4}	1.5×10^{-4}	2.5×10^{-4}
	0	1.4×10^{-5}	2.1×10^{-5}	8.3×10^{-5}

r ~ 10^{-3} (5σ) is achievable from space

New dust level only changes ~ factor of 2 in reach

How do we avoid a new BICEP2 roller-coaster?

How can we say it is not some extra dust component ?

- Homogeneity over the sky (needs large f_{sky} or more patches)
- Gaussianity
- l-dependence and frequency dependence: fit also for α_{CMB} and β_{CMB}

	r	σ_r	$\sigma_{\alpha_{CMB}}$	$\sigma_{\beta_{CMB}}$
AdvACT	0.1	8.8×10^{-3}	7.8×10^{-2}	1.3×10^{-1}
	0.01	6.8×10^{-3}	2.9×10^{-1}	1.1
CLASS	0.1	1.4×10^{-2}	7.2×10^{-2}	1.1×10^{-1}
	0.01	—	—	—
Keck/BICEP3	0.1	2.9×10^{-2}	5.5×10^{-1}	4.0×10^{-1}
	0.01	—	—	—
Simons Array	0.1	2.9×10^{-2}	4.0×10^{-1}	4.0×10^{-1}
	0.01	—	—	—
CMBPol	0.1	1.3×10^{-3}	1.9×10^{-2}	6.3×10^{-3}
	0.01	3.2×10^{-4}	4.0×10^{-2}	2.4×10^{-2}
	0.001	1.7×10^{-4}	1.0×10^{-1}	1.0×10^{-1}

Bumps

Not clear the level of foregrounds on large scales.
Detection of reionization bump is very relevant for discovery:

E.g. COrE (r=0): 2 x 10^{-5} → 2 x 10^{-4} removing first multipoles

The recombination bump if detected would be a strong evidence

	Simons Array	AdvACT	CLASS	GRD	CMBPol
r_{min}	0.08	0.045	0.095	0.005	0.003

Minimum value of r for a 3 σ evidence of the bump

Conclusions

- Robustness of $\Delta_h^2(k) = \frac{2}{\pi^2}\frac{H^2}{M_{\rm pl}^2}$
- 1/N scaling: "forbidden region"
- Forecasts: down to 10^{-3} (not changed too much by dust)
- How to avoid a new BICEP roller-coaster?

Backup slides

Instrumental specifications:

Experiment	f_{sky} [%]	ν [GHz]	θ_{FWHM} [′]	δP [μK′]
AdvACT	50	90	2.2	7.8
		150	1.3	6.9
		230	0.9	25
CLASS	70	38	90	39
		93	40	13
		148	24	15
		217	18	43
EBEX 10k	2	150	6.6	5.5
		220	4.7	11
		280	3.9	25
		350	3.3	52
Keck/BICEP3	1	95	30	9.0
		150	30	2.3
		220	30	10
Simons Array	65	95	5.2	13.9
		150	3.5	11.4
		220	2.7	30.1
Spider	7.5	94	49	17.8
		150	30	13.6
		280	17	52.6
SPT-3G	6	95	1	6.0
		150	1	3.5
		220	1	6.0
BAL	5	150, 220, 280, 350	5	[1,5]
ULDB	60	150, 220, 280, 350	5	[1,10]
GRD	[1,50]	100, 150, 220	5	1, 3

Instrumental specifications:

Experiment	ν [GHz]	θ_{FWHM} [$'$]	δP [μK$'$]
CMBPol (EPIC-2m)	30	26	19.2
	45	17	8.3
	70	11	4.2
	100	8	3.2
	150	5	3.1
	220	3.5	4.8
	340	2.3	21.6
COrE	45	23	9.1
	75	14	4.7
	105	10	4.6
	135	7.8	4.6
	165	6.4	4.6
	195	5.4	4.5
	225	4.7	4.6
	255	4.1	10.5
	285	3.7	17.4
	315	3.3	46.6
	375	2.8	119
LiteBIRD	60	32	10.3
	78	58	6.5
	100	45	4.7
	140	32	3.7
	195	24	3.1
	280	16	3.8