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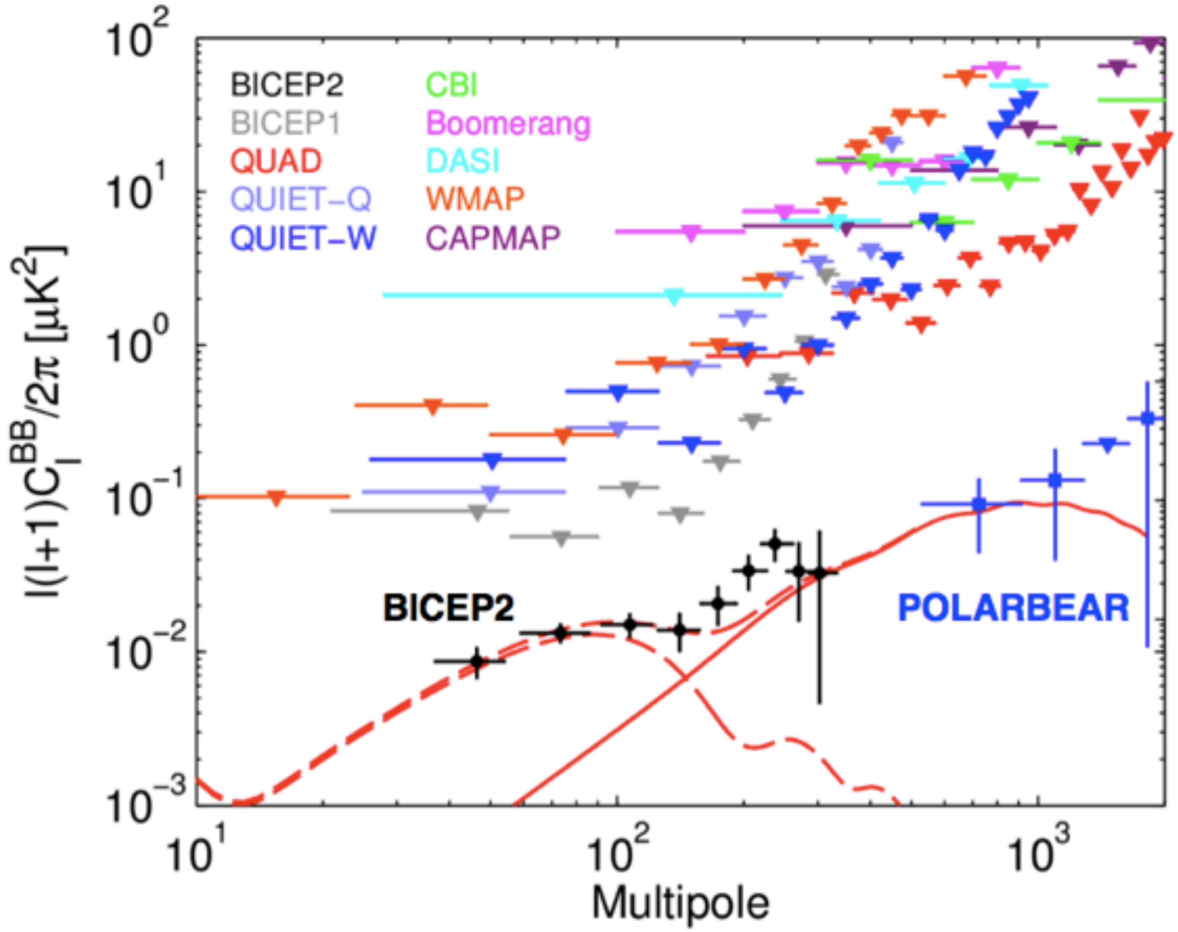
B - mode cosmology

CERN, January 9th 2015

The new era of B-modes

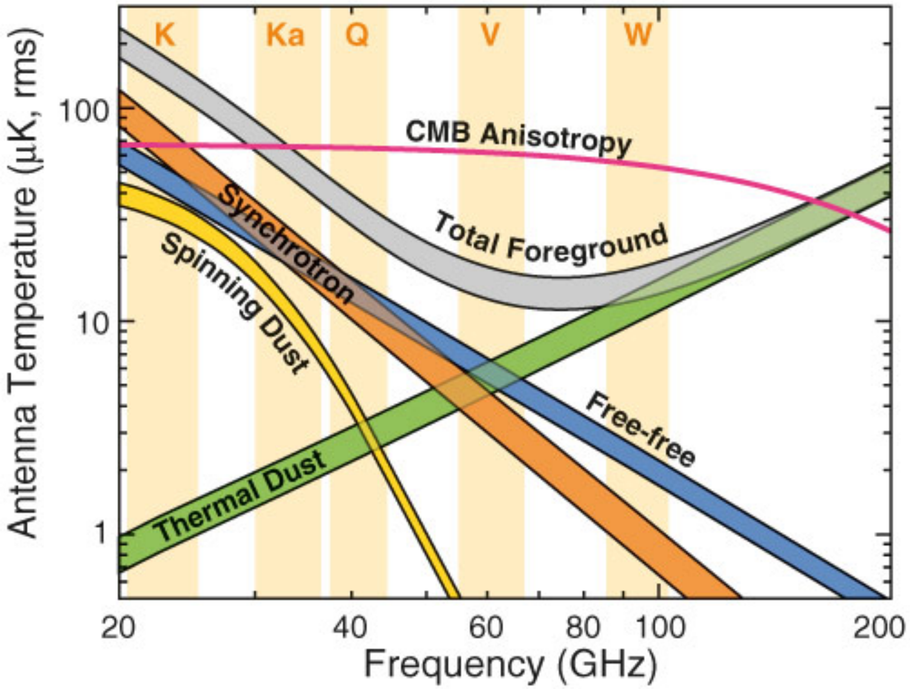


- Amazing improvement in exp sensitivity

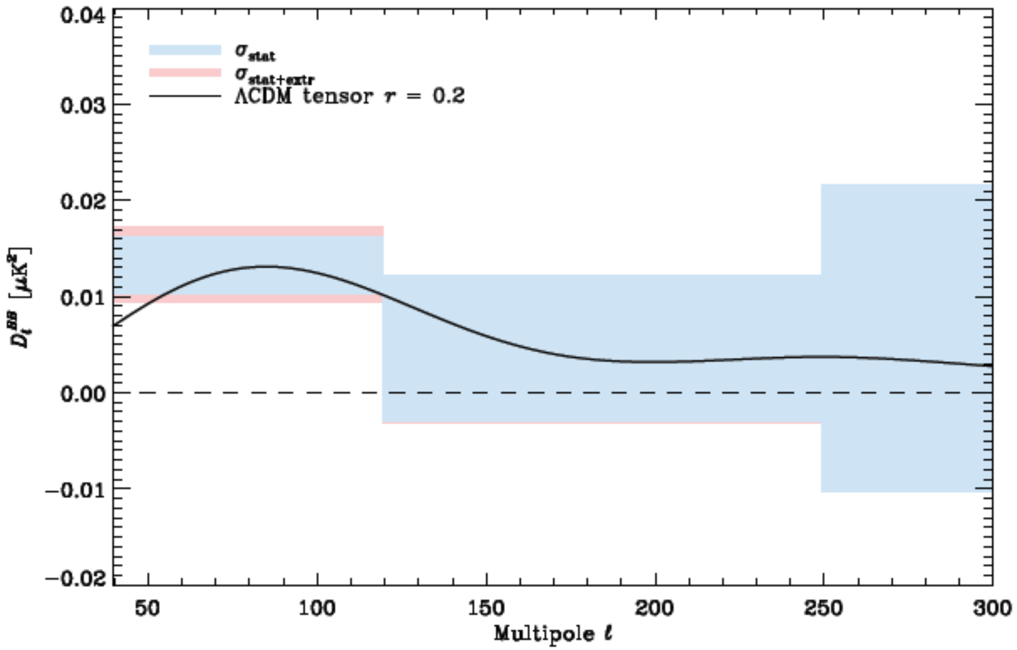
  ΔP ~ 5 μK arcmin
  (Planck ΔP ~ 45 μK arcmin)

- Theoretically motivated region

Dust under the carpet



Planck extrapolated from 353 GHz
1409.5738



BICEP2 signal is compatible with being only dust


GRAVITATIONAL
WAVES

Robust signature

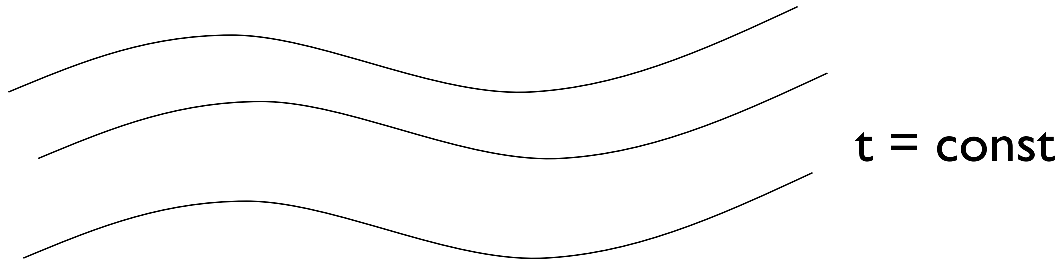
- It is easy to play with scalar perturbations:

  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

PC, Luty, Nicolis, Senatore 06
Cheung, PC, Fitzpatrick, Kaplan, Senatore 07

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

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

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

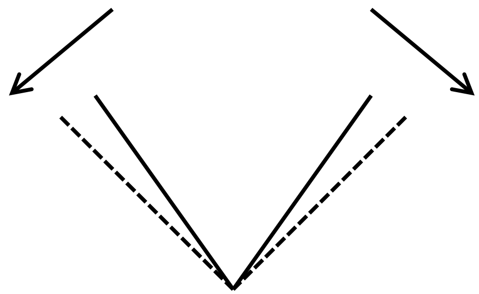
Disformed away

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
- $n_T \neq 2\dot H/H^2 < 0$

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



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

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

$\dot c_T = 0$

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

$\tilde c_s = 1/c_T$

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:

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

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

Parity violation: different power spectrum for each elicity

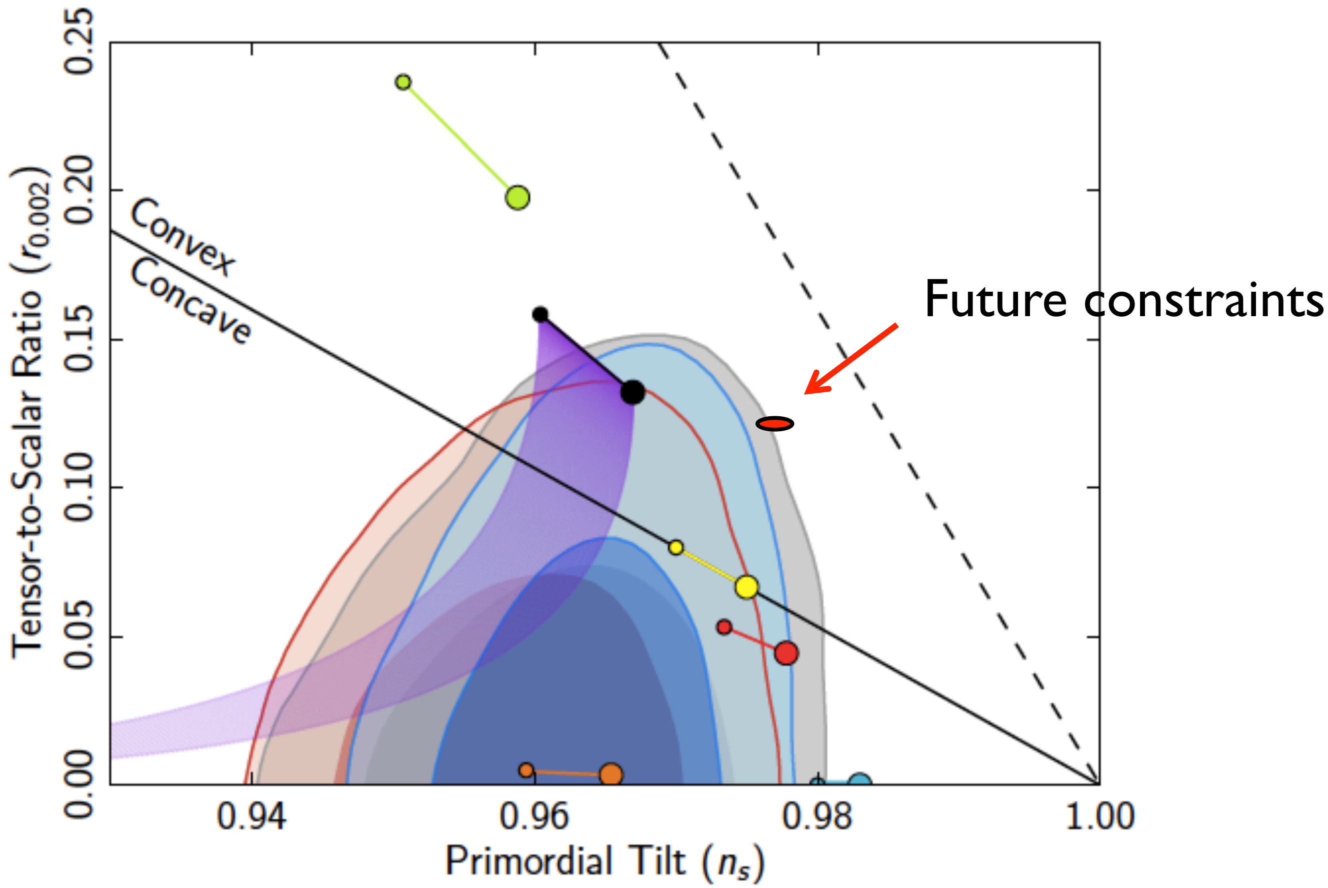
$$\langle\gamma^{\pm}_{\vec{k}}\gamma^{\pm}_{\vec{k}'}\rangle=(2\pi)^3\delta(\vec{k}+\vec{k}')\frac{H^2}{2M_{\rm Pl}^2k^3}\left(1\pm\beta\frac{\pi}{2}\frac{H}{\Lambda}\right)$$

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

Gluscevic, Kamionkowski 10
Ferte, Grain 14

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

The future



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

We will measure V, V' and V''

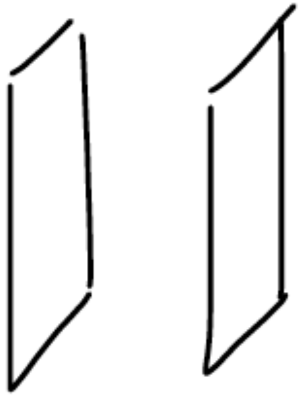
The scalar tilt

Planck: $n_s - 1 = -0.0397 \pm 0.0073 \quad (\gtrsim 5\sigma)$ It is of order 1/N (~ 0.02)

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

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

Brane inflation

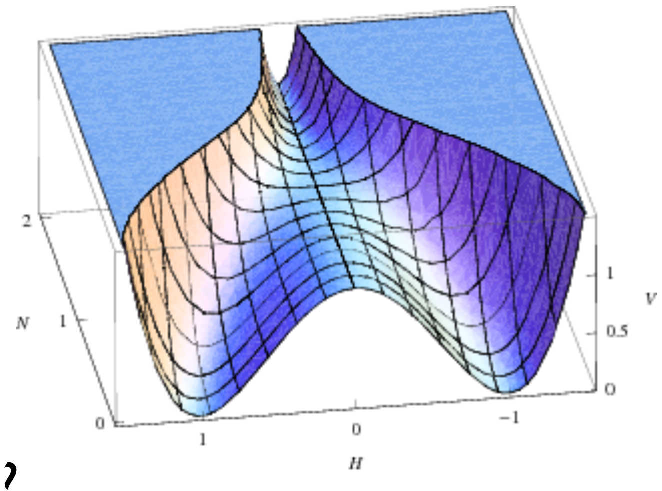


$$V = V_0 \left(1 - \left(\frac{\phi}{\mu}\right)^{-4}\right)$$ $$n_s - 1 = -\frac{5}{3} \cdot \frac{1}{N}$$

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

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

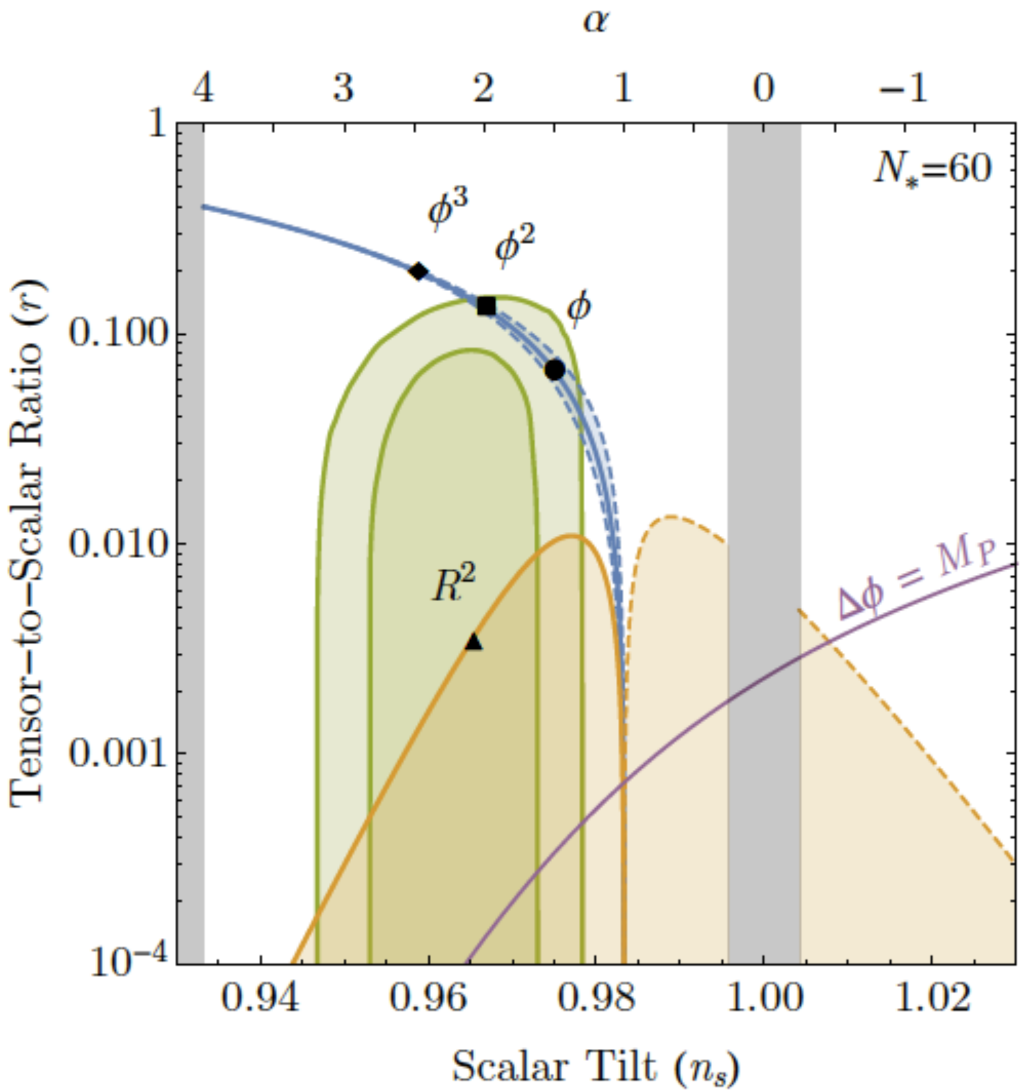
n_s -1 scales as 1/N in a window (larger than observable one)

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

↓

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

I assume one of the two scaling wins in the window

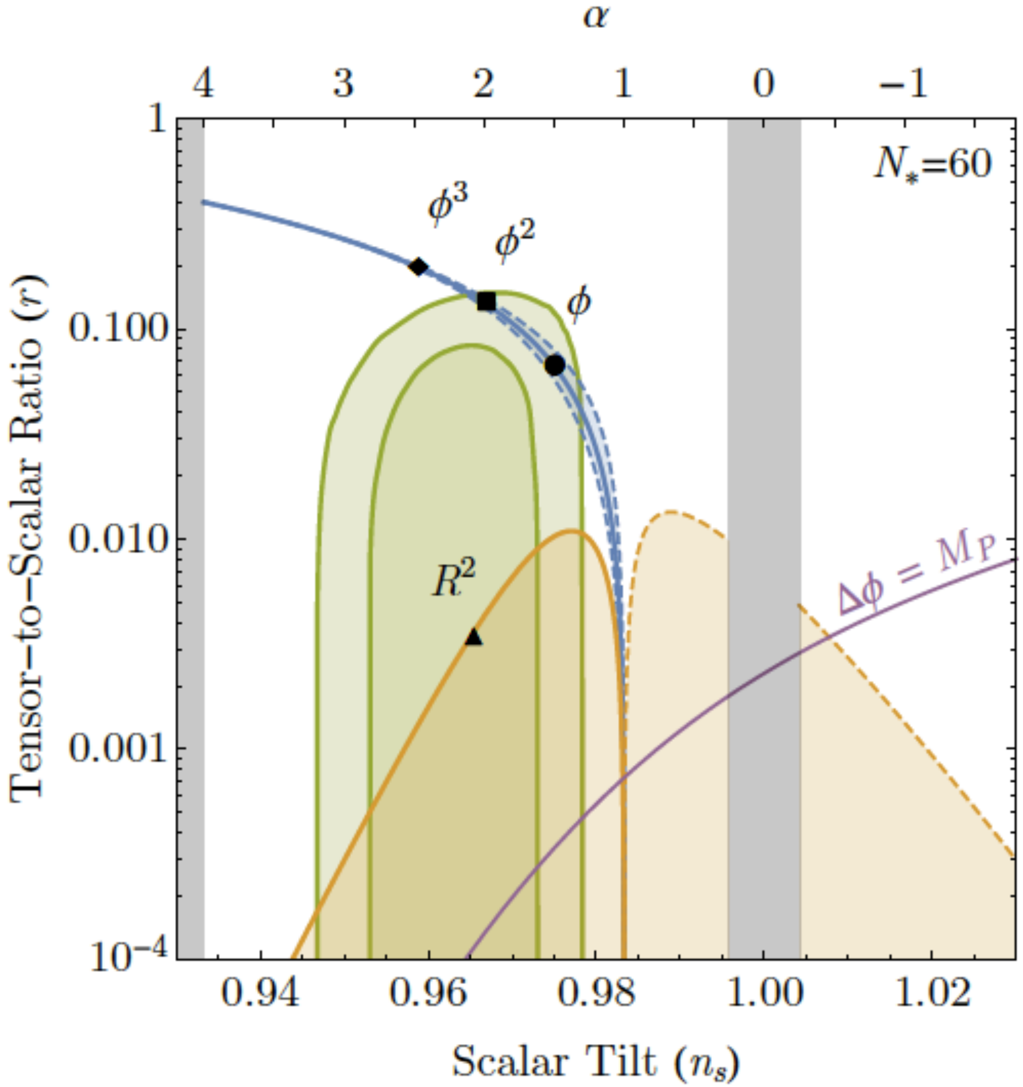


Similar to Mukhanov 13 and Roest 13

- Running α $\frac{d\epsilon^{-1}}{d\log N} - \alpha(N)\epsilon^{-1} = -2N$ $\epsilon^{-1}(N) = -2e^{\int_1^N \frac{d\tilde{N}}{\tilde{N}}\alpha(\tilde{N})} \int_1^N d\tilde{N} e^{-\int_1^{\tilde{N}} \frac{d\hat{N}}{\hat{N}}\alpha(\hat{N})} + Ae^{\int_1^N \frac{d\tilde{N}}{\tilde{N}}\alpha(\tilde{N})}$.
- No lower bound on r
- "Forbidden" region: exp target
- Relevance of tilt
- Running $-\alpha/N_*^2 \simeq -7 \cdot 10^{-4}$

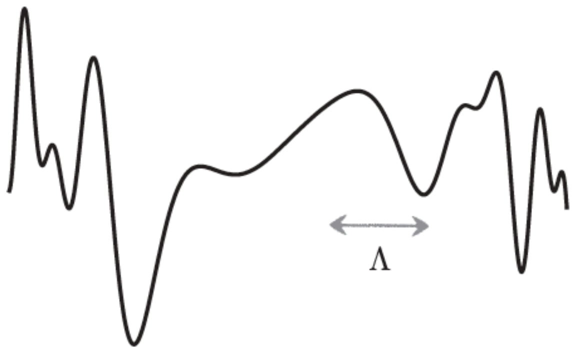
  can we measure it ?
- c_S opens degeneracies

Zavala 14

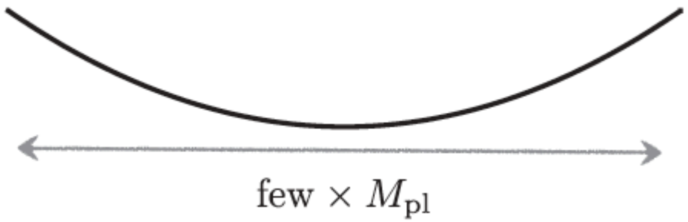


Mountains or hills ?

Landscape:



Around a minimum
all functions look
the same…



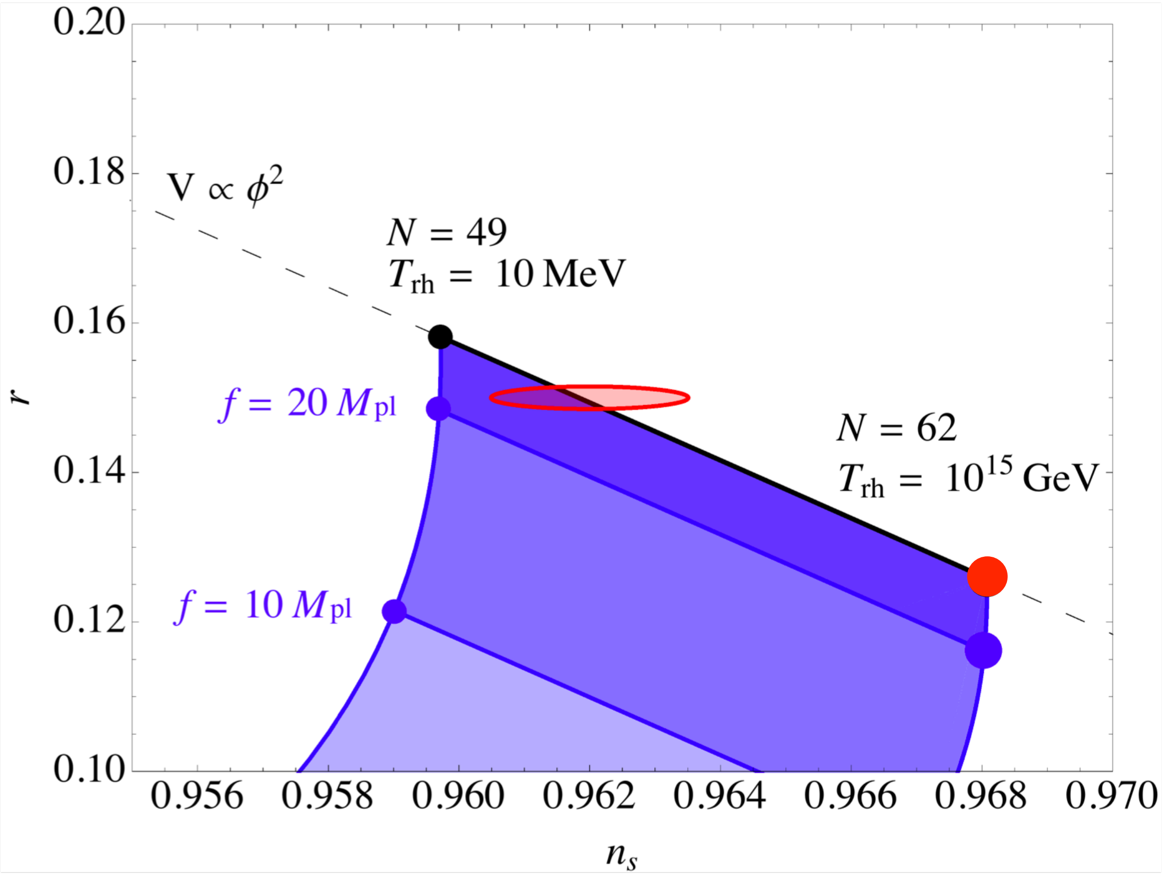
$$V = \frac{1}{2} m^2 \phi^2$$

We are probing this now!

Raphael ?

The simplest Universe

PC, Nacir, Simonović, Trevisan, Zaldarriaga 14



$$(n_s - 1) + \frac{r}{4} + \frac{11}{24}(n_s - 1)^2 = 0$$

Independently of N

Error dominated by n_S !

The most informative Universe

$$V(\phi) = \Lambda^4 \left[1 - \cos\left(\frac{\phi}{f}\right)\right]$$

$$(n_s - 1) + \frac{r}{4} + \frac{11}{24}(n_s - 1)^2 = -\left(\frac{M_{\rm pl}}{f}\right)^2$$

$$f \gtrsim 30 M_{\rm pl}$$

Scalar speed of sound:

$$(n_s - 1) + \frac{r}{4} + \frac{11}{24}(n_s - 1)^2 = -s + \frac{r}{4}\left(1 - \frac{1}{c_s}\right)$$

$$s \equiv \dot{c}_s / H c_s$$

$$|c_s - 1| \lesssim 3 \times 10^{-2}$$

Better than NGs or GWs consistency relation

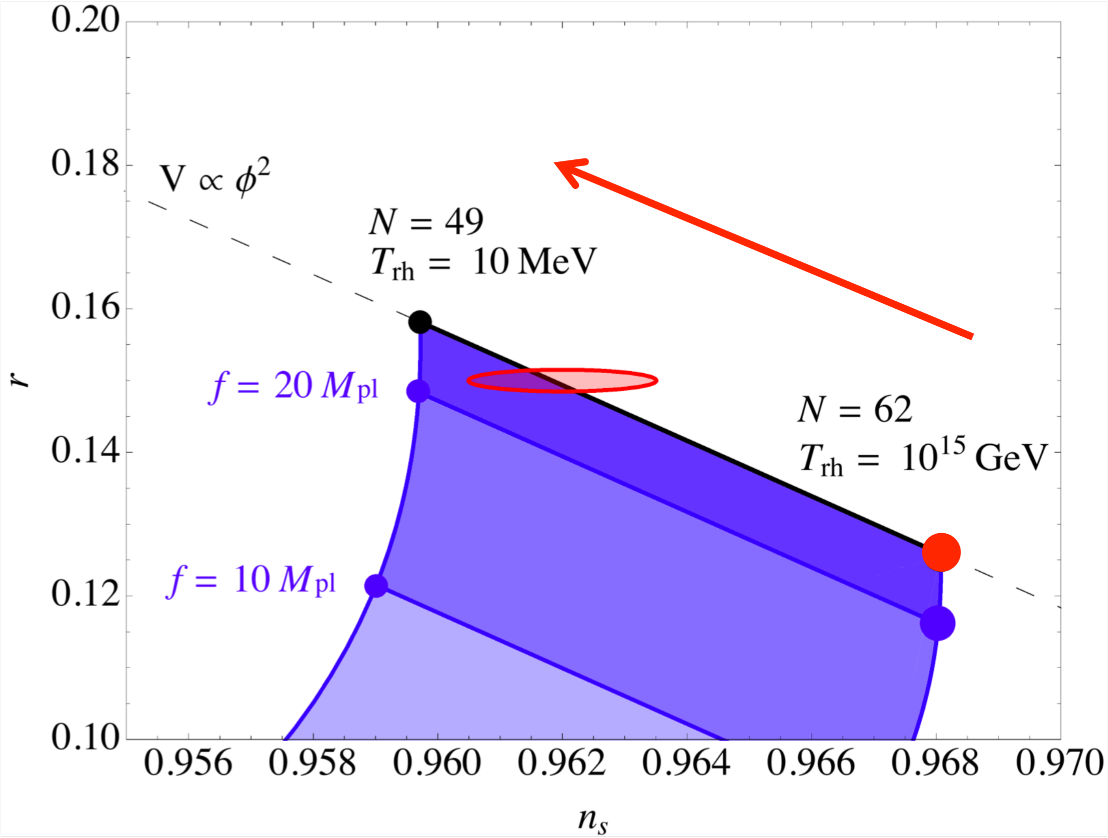
Reheating T:

$$\Delta N \simeq 0.4$$

$$\frac{\Delta T_{\rm rh}}{T_{\rm rh}} \simeq 1.2$$

The very simplest Universe

PC, Nacir, Simonović, Trevisan, Zaldarriaga 14



Everything non-minimal push to small N

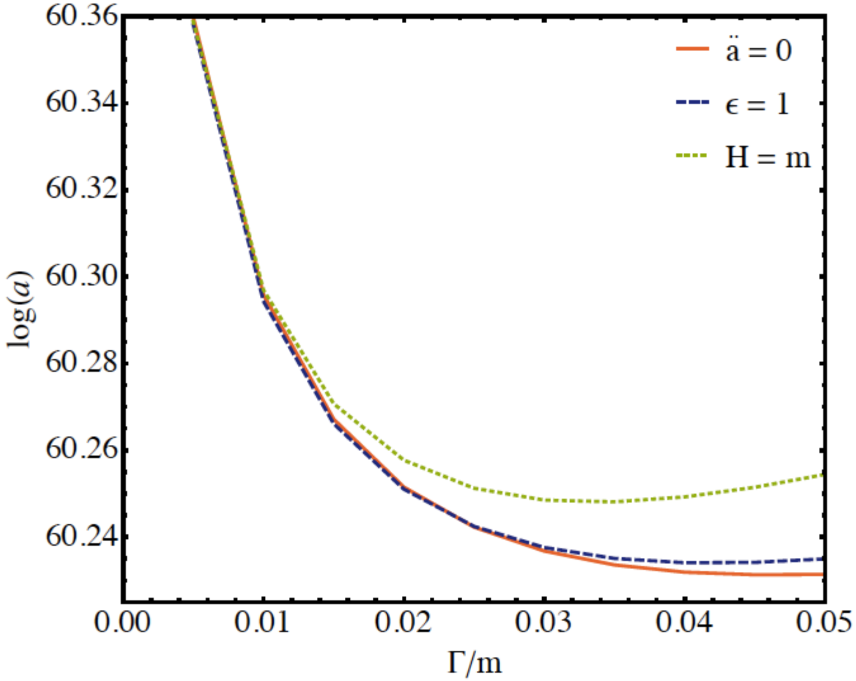
- Delayed reheating
- Late entropy injection
- Large g_*
- Additional matter dominance

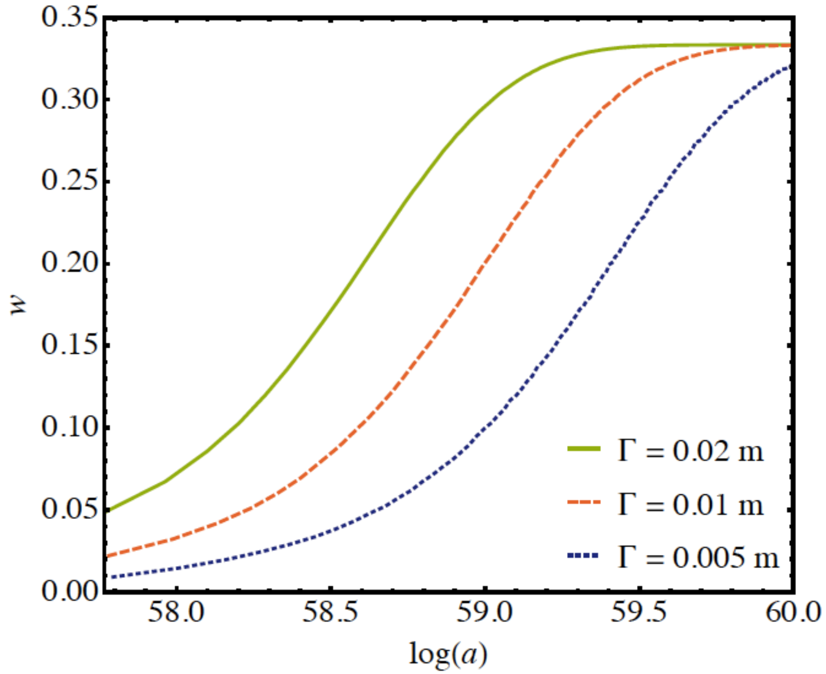
(Would need w > 1/3 to go the other way)

Eventually sensitive to % corrections

Required precision

- Here everything well defined
- Details of (p)reheating not relevant (provided fast enough)
- Transition among phases, 2nd order slow-roll…





$n_s = 0.9668 \pm 0.0003$, and $r = 0.131 \pm 0.001$ $\qquad k_* = 0.002\ \mathrm{Mpc}^{-1}$

How small can we get?

PC, Nacir, Simonović, Trevisan, Zaldarriaga
IN PROGRESS !

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

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

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

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

Marginalized over $\alpha_{S,}$ $\alpha_{D,}$ $\beta_{S,}$ $\beta_{D,}$

How small can we get?

Balloons

	r	EBEX	Spider
CS	0.1	2.2×10^{-2}	1.8×10^{-2}
	0.01	—	—
	0.001	—	—
	0	9.5×10^{-3}	1.3×10^{-2}
FG 1%	0.1	4.5×10^{-2}	2.5×10^{-2}
	0.01	—	—
	0.001	—	—
	0	1.8×10^{-3}	2.0×10^{-2}

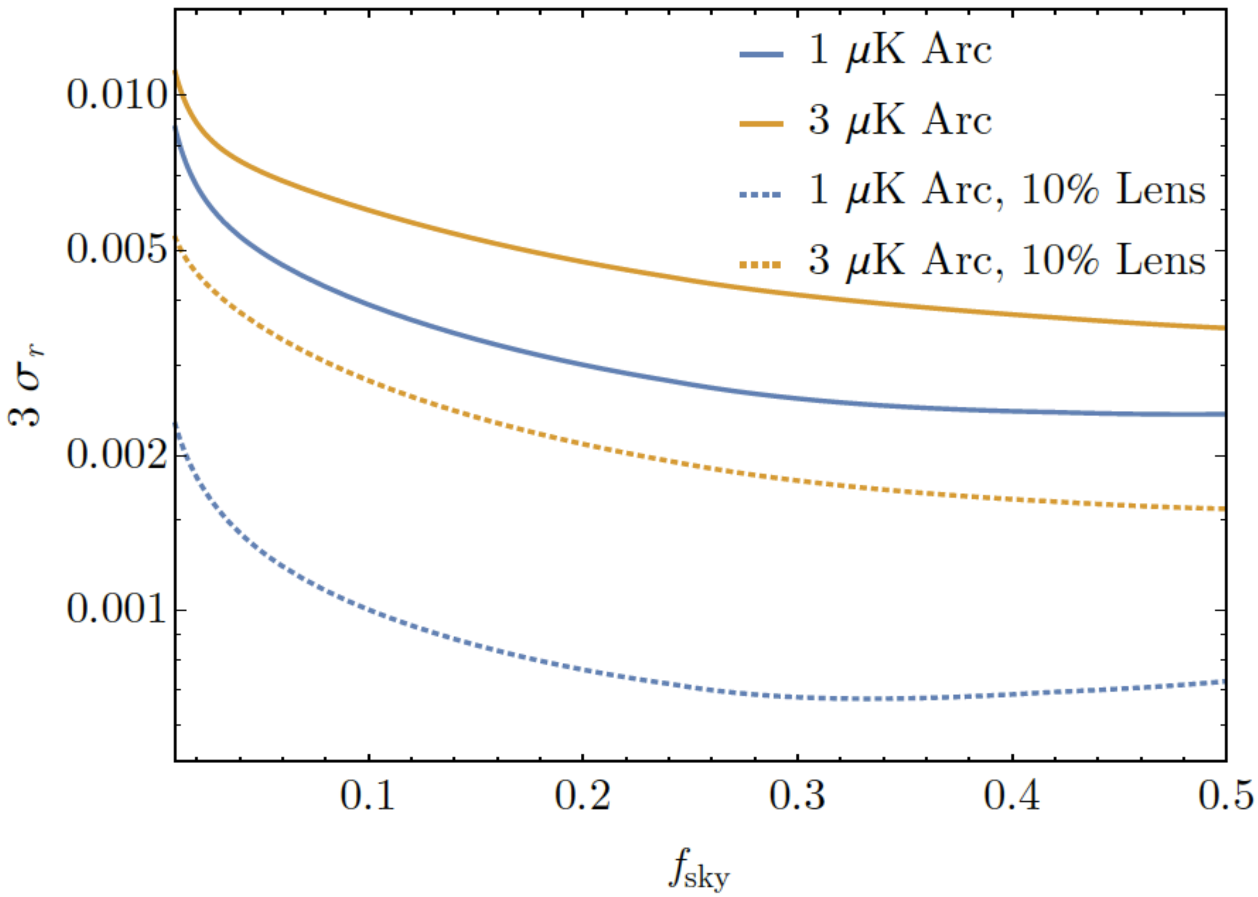
$r \sim 2\ 10^{-2}$ looks achievable

Ground

	r	AdvACT	Keck/BICEP3	Simon Array	SPT-3G
CS	0.1	6.6×10^{-3}	2.1×10^{-2}	2.1×10^{-2}	8.1×10^{-3}
	0.01	5.1×10^{-3}	—	—	4.0×10^{-3}
	0.001	—	—	—	—
	0	4.9×10^{-3}	8.9×10^{-3}	2.0×10^{-2}	3.5×10^{-3}
FG 1%	0.1	6.6×10^{-3}	1.8×10^{-2}	9.6×10^{-3}	7.1×10^{-3}
	0.01	4.1×10^{-3}	6.9×10^{-3}	7.5×10^{-3}	3.6×10^{-3}
	0.001	—	—	—	—
	0	3.6×10^{-3}	5.6×10^{-3}	7.3×10^{-3}	3.2×10^{-3}

How small can we get?

Ground, stage IV



Beam 5' and 100, 150, 220 GHz

How small can we get?

	r	COrE	EPIC-2m	LiteBIRD
CS	0.1	1.8×10^{-3}	1.7×10^{-3}	1.9×10^{-3}
	0.01	5.6×10^{-4}	5.0×10^{-4}	5.9×10^{-4}
	0.001	2.4×10^{-4}	2.2×10^{-4}	2.5×10^{-4}
	0	—	—	—
FG 1%	0.1	2.7×10^{-3}	2.3×10^{-3}	2.1×10^{-3}
	0.01	1.1×10^{-3}	8.6×10^{-4}	8.8×10^{-4}
	0.001	9.5×10^{-4}	6.9×10^{-4}	7.3×10^{-4}
	0	9.2×10^{-4}	6.7×10^{-4}	7.1×10^{-4}

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 ?

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

- With 3 frequencies we have 6 covariances : we can fit for r, $\alpha_{S,}$ $\alpha_{D,}$ $\beta_{S,}$ β_D and β_{CMB}
- Homogeneity over the sky (needs large f_{sky} or more patches)
- l-dependence

Conclusions

- Robustness of $\Delta_h^2(k) = \frac{2}{\pi^2}\frac{H^2}{M_{\rm pl}^2}$
- 1/N scaling: "forbidden region"
- ϕ^2 and ϕ^2 at the endpoint
- Forecasts: down to 10^{-3} ? How to avoid a new BICEP ?

Experiment	f_{sky} [%]	ν [GHz]	θ_{FWHM} [$'$]	$\sigma_{pix}\theta_{FWHM}$ [μK$'$]
AdvACT	50	90	2.2	7.8
		150	1.3	6.9
		230	0.9	25
EBEX	1	150	8	5.8
		250	8	17
		410	8	150
Keck/BICEP3	1	95	30	9.0
		150	30	2.3
		220	30	10
Simon Array	20	90	5.2	15.2
		150	3.5	12.3
		220	2.7	23.6
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, 250, 410	5	-
GRD	-	100, 150, 220	5	-