International School of Space Science

Non-standard Physics in Light of CMB Experiments

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Introduction

- New Physics in Neutrino sector: the Neutrino Background Anisotropies as constrained by Planck
- New Physics in Inflation sector: the blue tensor spectrum as constrained by BICEP2
- Conclusions

Neutrino Anisotropies

$$\dot{\delta}_\nu = \frac{\dot{a}}{a}\left(1 - 3c^2_{\rm eff}\right)\left(\delta_\nu + 3\frac{\dot{a}}{a}\frac{q_\nu}{k}\right) - k\left(q_\nu + \frac{2}{3k}\dot{h}\right)$$ Density contrast

$$\dot{q}_\nu = k\,c^2_{\rm eff}\left(\delta_\nu + 3\frac{\dot{a}}{a}\frac{q_\nu}{k}\right) - \frac{\dot{a}}{a}q_\nu - \frac{2}{3}k\pi_\nu$$ Euler equation

$$\dot{\pi}_\nu = 3\,c^2_{\rm vis}\left(\frac{2}{5}q_\nu + \frac{8}{15}\sigma\right) - \frac{3}{5}kF_{\nu,3}$$ Anisotropic stress

$$\frac{2l+1}{k}\dot{F}_{\nu,l} - lF_{\nu,l-1} = -(l+1)\,F_{\nu,l+1} \quad l \geq 3$$ Higher-order distribution function moments

Effective sound speed

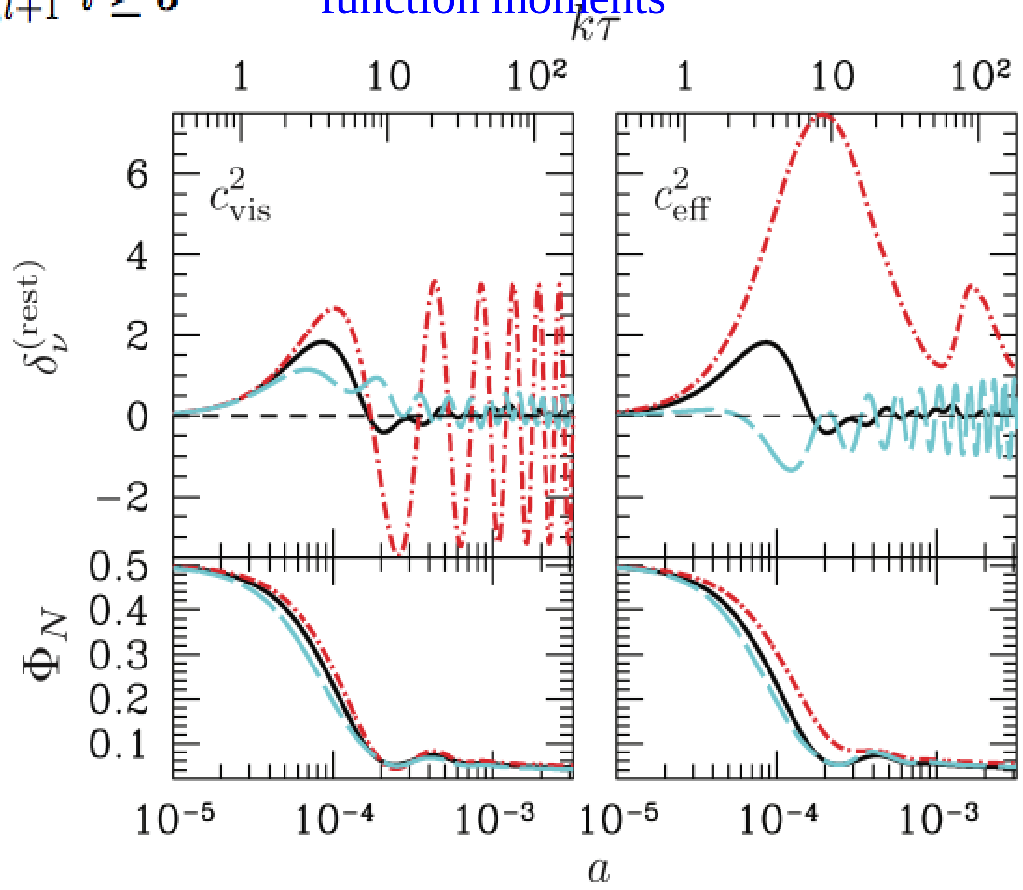
Viscosity parameter

Expected values for standard, non-interacting NRB:

$$c^2_{eff} = \frac{1}{3}$$

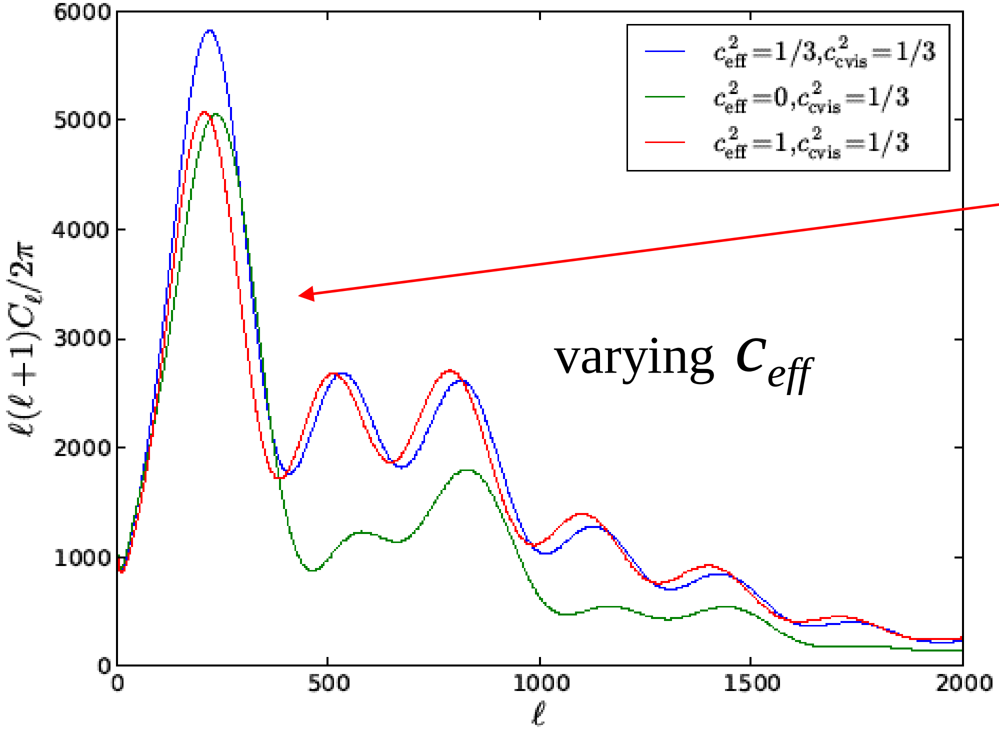
$$c^2_{vis} = \frac{1}{3}$$

W. Hu, Astrophys. J. 506, 485 (1998)
R. Trotta and A. Melchiorri, Phys. Rev. Lett. 95 (2005) 011305
M. Archidiacono, E. Calabrese and A. Melchiorri, Phys. Rev. D 84, 123008 (2011)

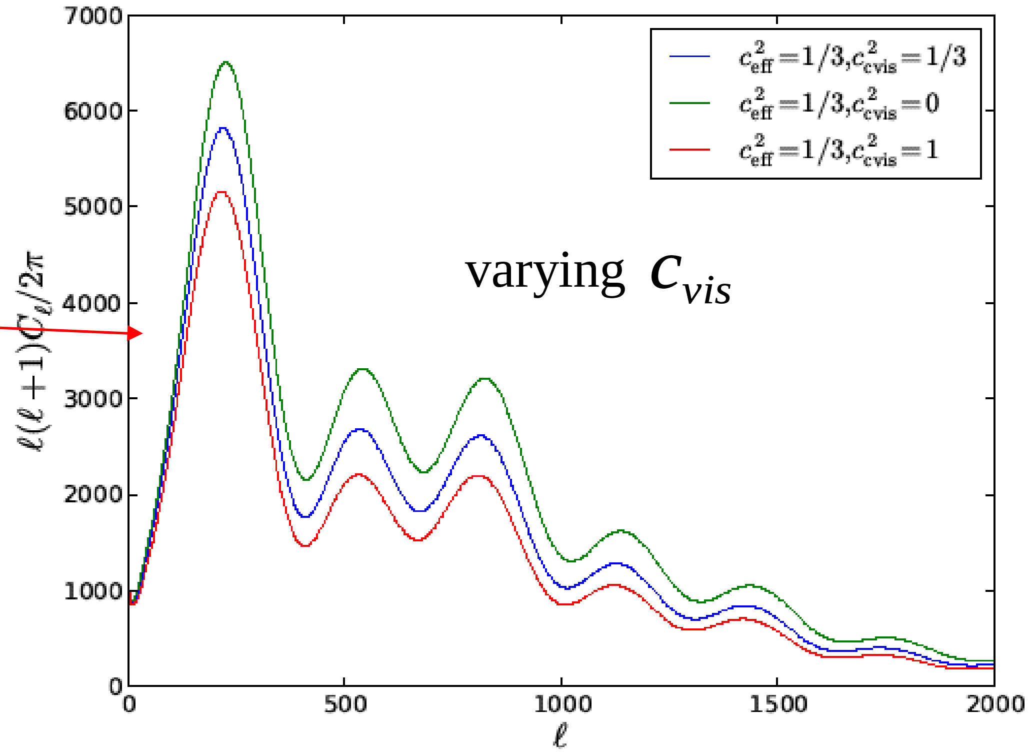


T. L. Smith, S. Das and O. Zahn, Phys. Rev. D 85 (2012) 023001

Impact on TT power spectrum



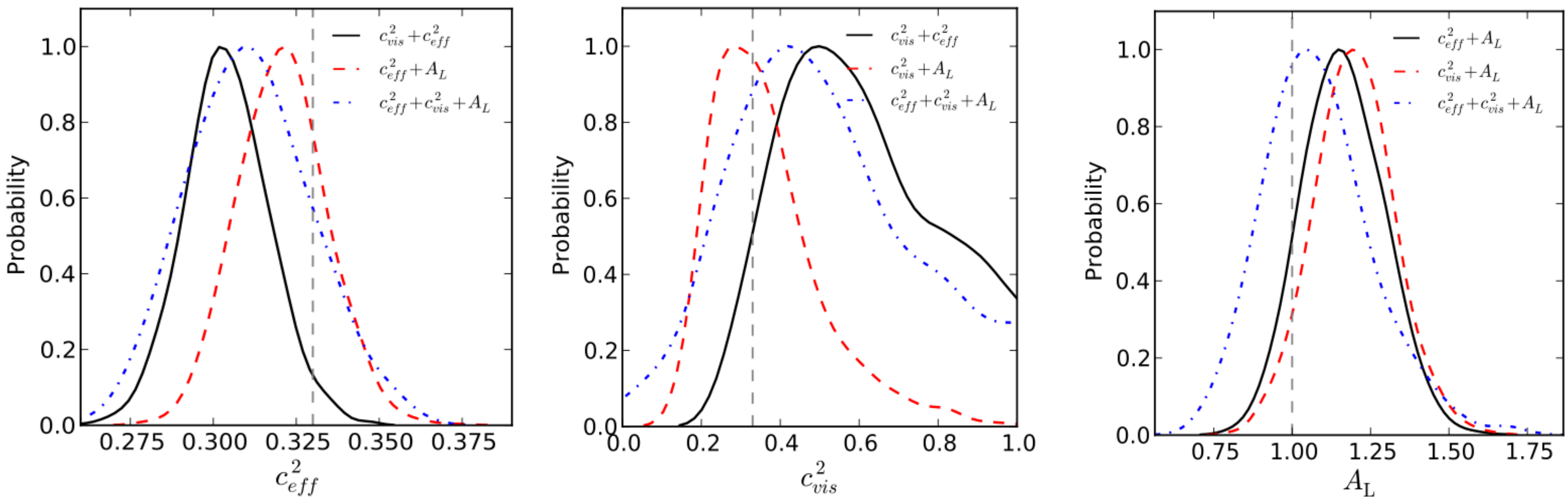
- Scale dependence
- Slight correlation with other parameters
- Tighter constraints



- Scale-free modifications
- Strong correlation with other parameters
- Milder constraints

Constraints from Planck

Parameter	ΛCDM	$+c^2_{\rm vis} + c^2_{\rm eff}$	$+c^2_{\rm eff} + A_{\rm L}$	$+c^2_{\rm vis} + A_{\rm L}$	$+c^2_{\rm eff} + c^2_{\rm vis} + A_{\rm L}$
$100\,\Omega_b h^2$	2.206 ± 0.028	2.118 ± 0.047	2.219 ± 0.045	2.236 ± 0.053	2.162 ± 0.095
$\Omega_c h^2$	0.1199 ± 0.0027	0.1157 ± 0.0038	0.1177 ± 0.0032	0.1170 ± 0.0034	0.1159 ± 0.0036
$100\,\theta$	1.0413 ± 0.0006	1.0412 ± 0.0014	1.0428 ± 0.0012	1.0421 ± 0.0019	1.0420 ± 0.0020
$\log[10^{10} A_S]$	3.089 ± 0.025	3.173 ± 0.052	3.086 ± 0.028	3.08 ± 0.05	3.141 ± 0.078
τ	0.090 ± 0.013	0.089 ± 0.013	0.088 ± 0.013	0.087 ± 0.013	0.089 ± 0.014
n_S	0.9606 ± 0.0073	0.998 ± 0.018	0.9732 ± 0.0099	0.970 ± 0.014	0.989 ± 0.023
$A_{\rm L}$	$\equiv 1$	$\equiv 1$	1.16 ± 0.13	1.20 ± 0.12	1.08 ± 0.18
$c^2_{\rm vis}$	$\equiv 0.33$	0.60 ± 0.18	$\equiv 0.33$	0.35 ± 0.12	0.51 ± 0.22
$c^2_{\rm eff}$	$\equiv 0.33$	0.304 ± 0.013	0.321 ± 0.014	$\equiv 0.33$	0.311 ± 0.019
H_0	67.3 ± 1.2	68.0 ± 1.3	68.7 ± 1.5	68.9 ± 1.5	68.6 ± 1.7



G.M., Di Valentino E. And Said N., Phys.Rev. D88 (2013) 063538

Degeneracy with inflationary parameters

Parameter	ΛCDM	$+c^2_{\rm vis}+c^2_{\rm eff}$	$+c^2_{\rm eff}+A_{\rm L}$	$+c^2_{\rm vis}+A_{\rm L}$	$+c^2_{\rm eff}+c^2_{\rm vis}+A_{\rm L}$
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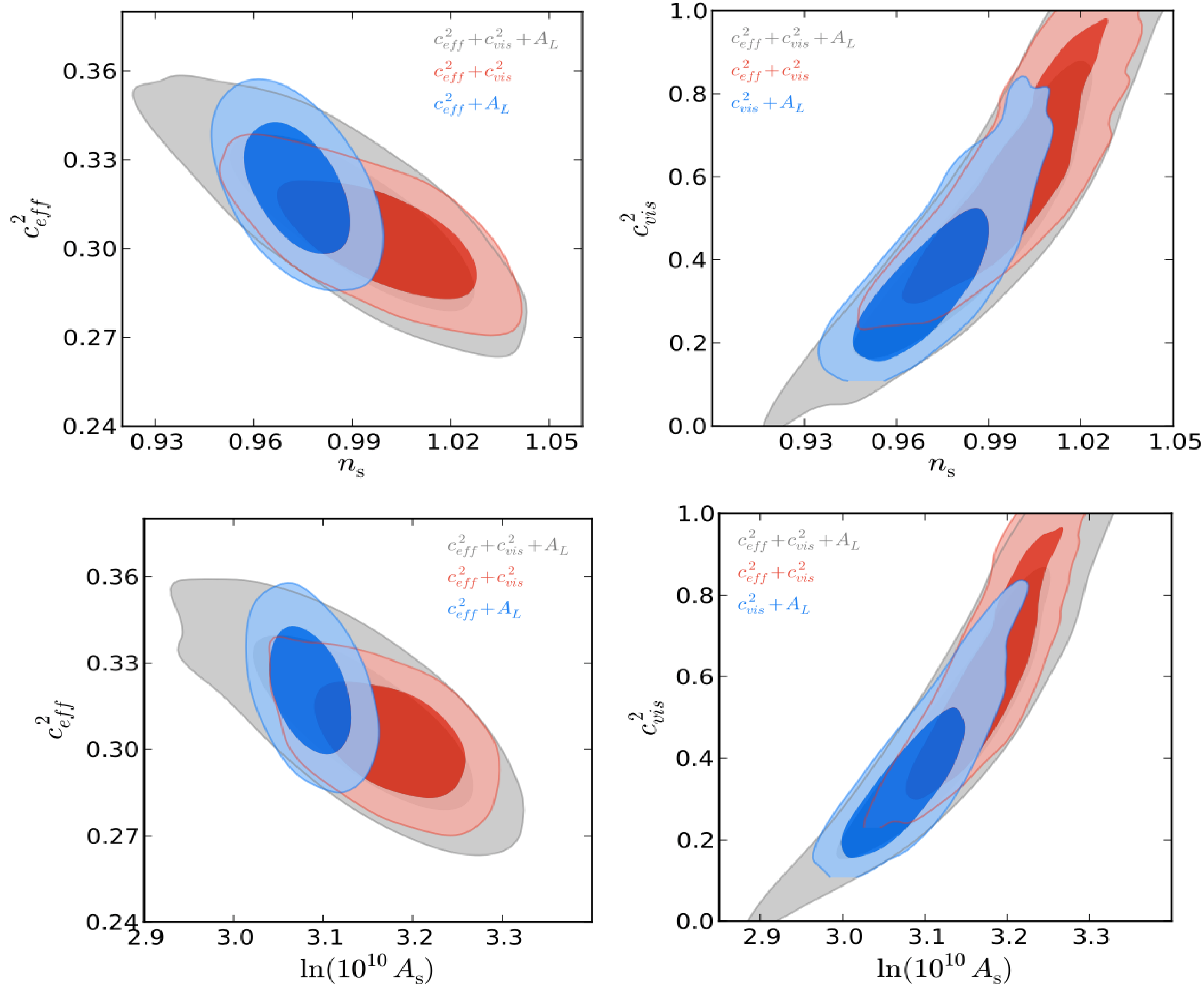
$c^2_{\rm eff}$	$\equiv 0.33$	0.304 ± 0.013	0.321 ± 0.014	$\equiv 0.33$	0.311 ± 0.019
H_0 $^{(a)}$	67.3 ± 1.2	68.0 ± 1.3	68.7 ± 1.5	68.9 ± 1.5	68.6 ± 1.7

- Worse constraints on inflationary parameters when varying c^2_{eff}, c^2_{vis}
- Scale-free spectrum at 1σ when varying jointly c^2_{eff}, c^2_{vis}



$c^2_{eff}+c^2_{vis}+A_L$
$c^2_{eff}+c^2_{vis}$
$c^2_{eff}+A_L$
$c^2_{vis}+A_L$
c^2_{eff}
c^2_{vis}
n_s
$\ln(10^{10} A_s)$
0.24
0.27
0.30
0.33
0.36
0.0
0.2
0.4
0.6
0.8
1.0
0.93
0.96
0.99
1.02
1.05
2.9
3.0
3.1
3.2
3.3

Tensor power spectrum

$$P_T = A_T \left(\frac{k}{k_0}\right)^{n_T}$$

Inflation predicts a stochastic background of gravity waves

Overall normalization amplitude

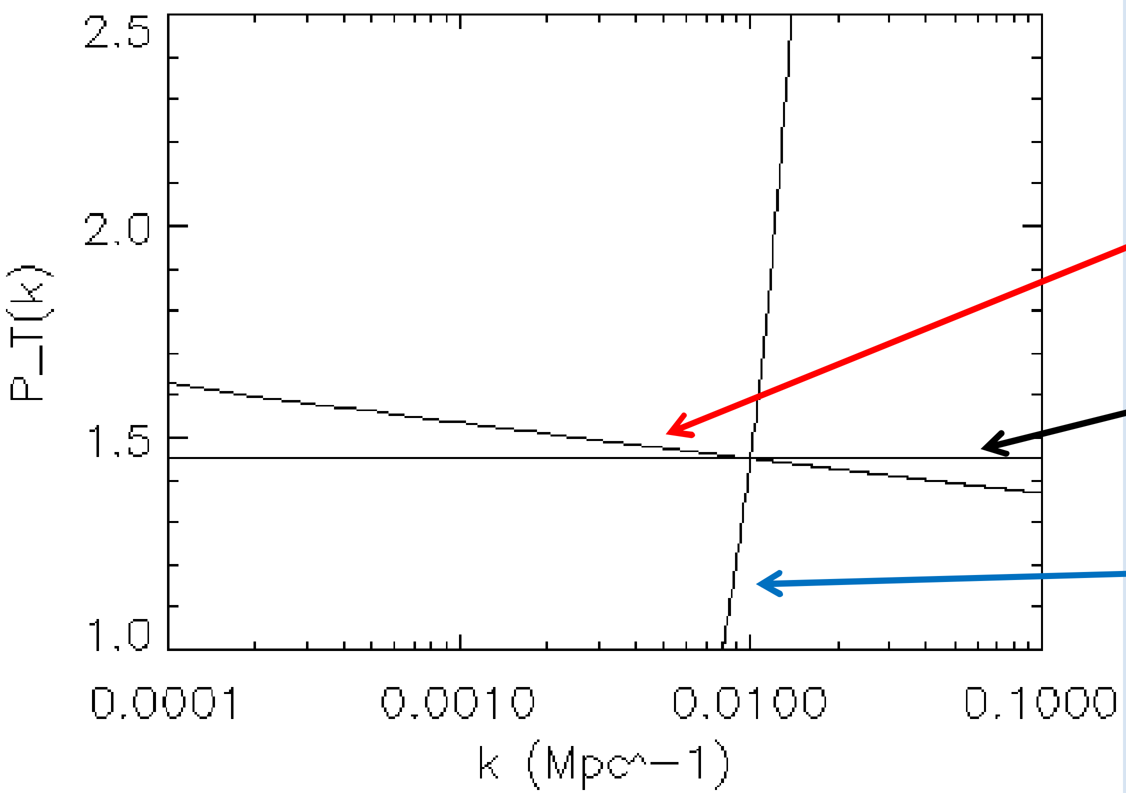
$$r = \left.\frac{P_T}{P_S}\right|_{k=k_0}$$

Inflation consistency relation

$$n_T = -r/8$$

Tensor spectral index

$$n_T = -2\epsilon, \;\; \epsilon = -\frac{\dot{H}}{H^2}$$

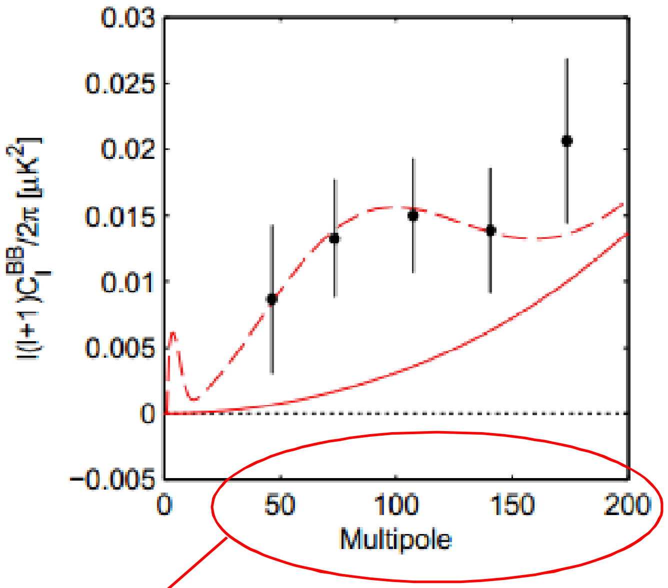


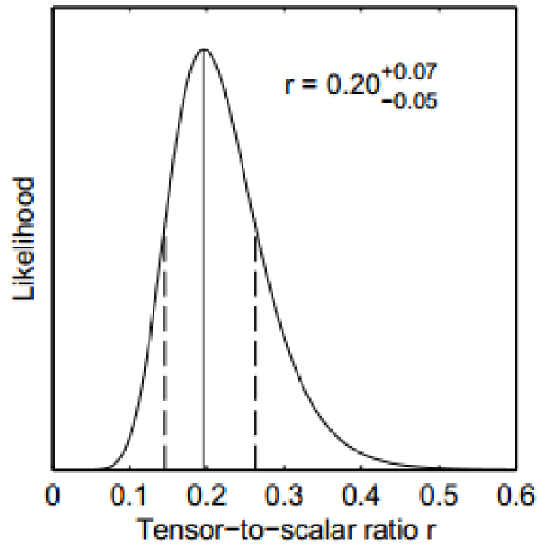
Red spectrum: nt<0
Slow-roll prediction

Scale-free spectrum: nt=0

Blue spectrum: nt>0
Non standard models,
NEC violation

Why Blue Gravity Waves?





BICEP2 detection
BICEP2 collaboration,
arXiv:1403.3985

k0≈0.01 Mpc^-1

VS

$$r_{0.002} < 0.11 \ (95\%)$$

Planck (and others) indirect constraint from TT power spectrum
Planck collaboration XVI, arXiv:1303.5076

The angular scales tested by BICEP2 are smaller than the angular scales used by Planck for constraining r!!!

Need for more power at smaller angular scales

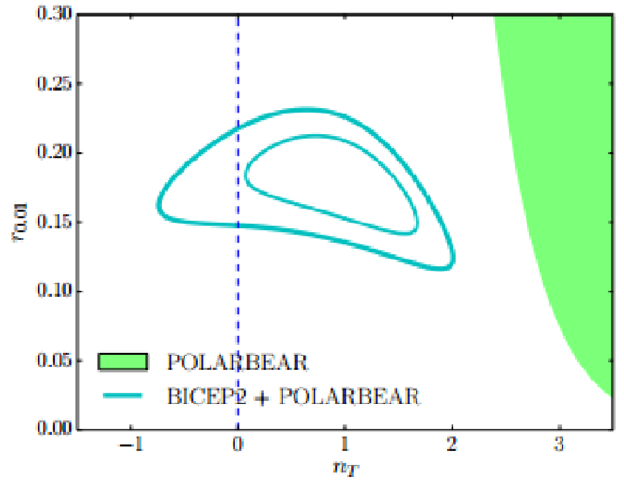
Fitting BICEP2 data with a blue tensor power spectrum

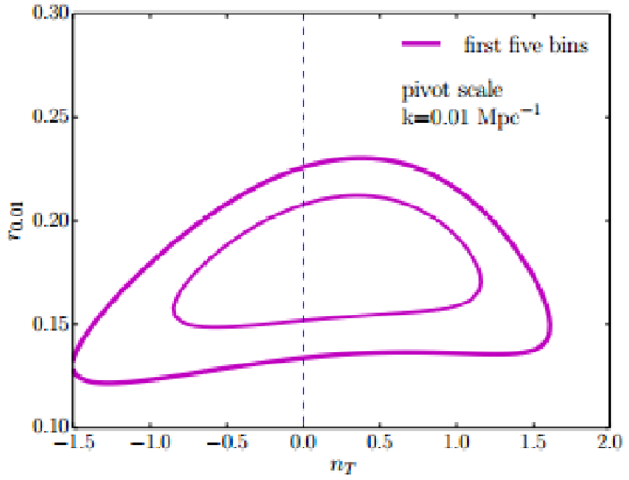
Case	$r_{0.01}$	n_T
n_T free	0.19 ± 0.06	1.36 ± 0.83
TT prior+n_T free	0.18 ± 0.05	1.67 ± 0.53
$n_T < 0$	0.22 ± 0.06	$n_T > -0.76$
TT prior+$n_T < 0$	0.15 ± 0.03	$n_T > -0.09$

MG,Marchini,Pagano,Salvati,Di Valentino, Melchiorri, arXiv:1403.5732

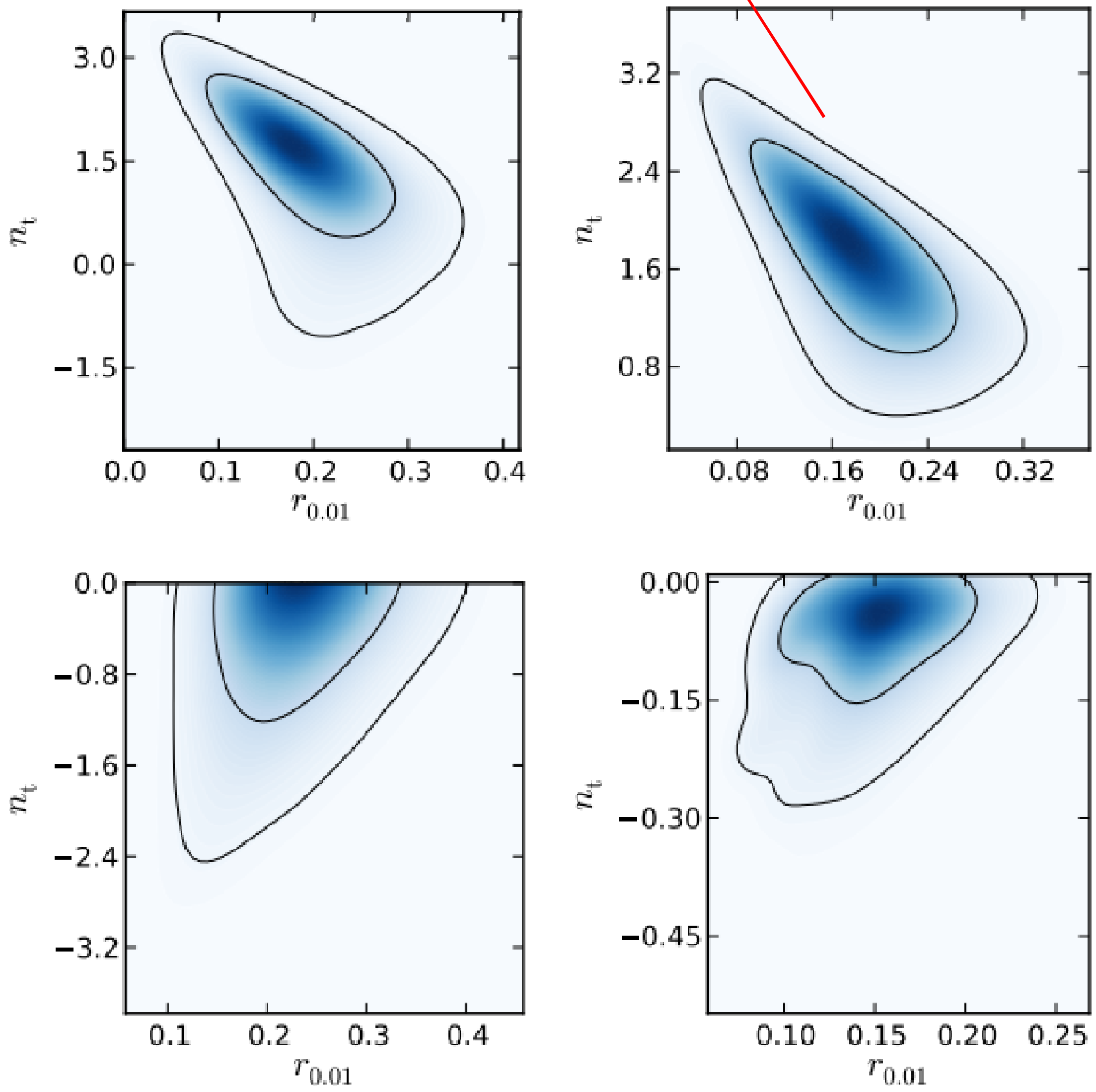
nt=0 excluded
at more than 95%

r<0.11 at k=0.002 Mpc^-1





Wang and Xue, arXiv:1403.5817

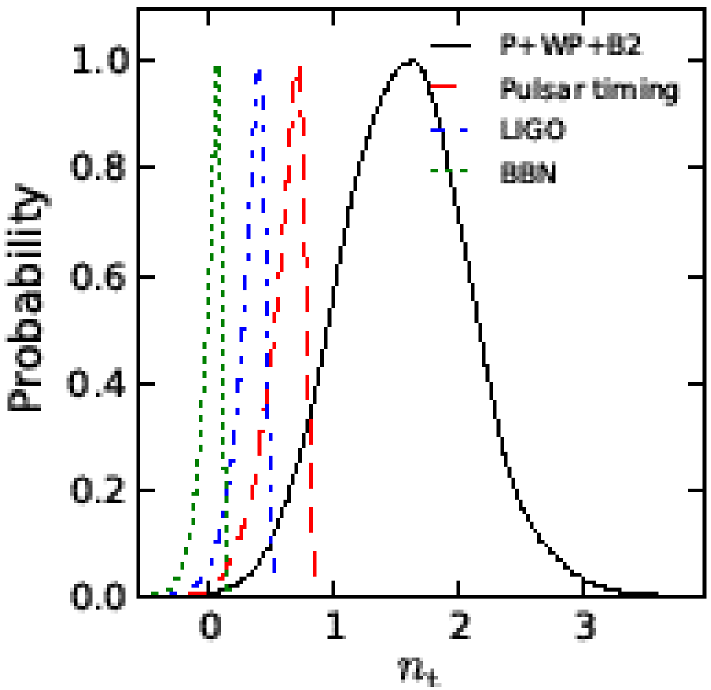


Is it the right answer?

Combination with direct upper limits from

- Pulsar timing
  h^2Ωgw<2 10^-8 @ 4 10^-9 Hz
- LIGO experiment
  Ωgw<6.9 10^-6 @100Hz
- Big Bang Nucleosynthesis
  ∫Ωgw d(lnf)<1.1 10^-5 (Nν-3)

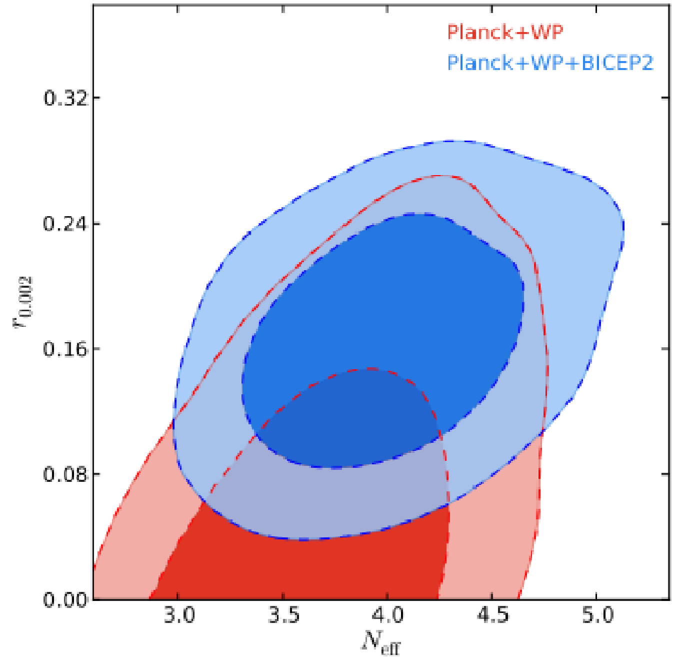
MG,Marchini,Pagano,Salvati,Di Valentino,Melchiorri,arXiv:1403.5732
LIGO collaboration, *Nature* **460**, 990-994
Stewart and Brandenberger, JCAP 0808, 012 (2008)



Dataset	Parameter	HZ $+n_S+r+n_{\rm run}$
eSPT	$100\,\Omega_b h^2$	2.272 ± 0.036
	$\Omega_c h^2$	0.1178 ± 0.0018
	$100\,\theta$	1.0424 ± 0.0009
	$\log[10^{10} A_S]$	3.04 ± 0.07
	τ	0.095 ± 0.015
	n_S	1.107 ± 0.045
	r	0.28 ± 0.16
	$n_{\rm run}$	-0.051 ± 0.015
	H_0 [a]	69.51 ± 0.78
	$-2\log\mathcal{L}$ [b]	7615.9
	$\Delta\chi^2$ [c]	-37.5

Benetti M., GM. et al, 2013 *1475-7516* 2013 030

nt>0
could not be the only answer
A hint for need
for extra parameters



Giusarma,Di Valentino,Lattanzi,Melchiorri,Mena,
arXiv: 1403.4852

Conclusions

1) Era of precision cosmology: we can test non standard physics with high accuracy

2) Neutrino anisotropies: expected values restored if parameters are varied jointly; degeneracy between clustering and inflationary parameters is a hint for new physics or unaccounted systematics?

3) BICEP2 measurements at odds with current CMB constraints on r: need for revising standard models (blue gravity waves? Extra degrees of freedom? Runnig of spectral index?)

For further questions:
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