Inflation and GWs @ IV LISA workshop

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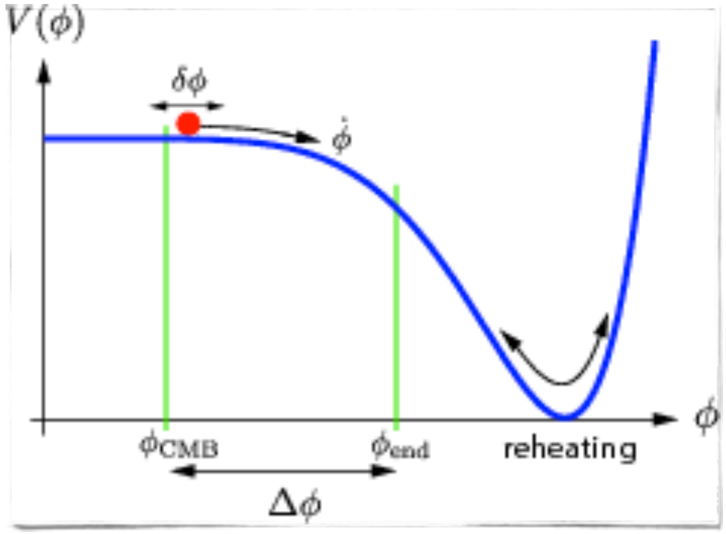
MAINZ

Observational windows of inflation



	k $[\mathrm{Mpc}^{-1}]$	$N_{\rm estim.}$
CMB / LSS	$10^{-4} - 10^{-1}$	$56 - 63$
$y-$ & $\mu-$distortions	$10^{-1} - 10^{4}$	$45 - 56$
$P_\zeta \to$ PBH $\to$ GW @ PTA	$10^{4} - 10^{5}$	$41 - 44$
$P_\zeta \to$ PBH $\to$ GW @ LISA	$10^{5} - 10^{7}$	$38 - 41$
$P_\zeta \to$ PBH $\to$ GW @ AdvLIGO	$10^{7} - 10^{8}$	$35 - 37$
$P_{\delta g} \to$ GW @ PTA	$10^{6} - 10^{8}$	$36 - 40$
$P_{\delta g} \to$ GW @ LISA	$10^{11} - 10^{14}$	$22 - 28$
$P_{\delta g} \to$ GW @ AdvLIGO	$10^{16} - 10^{17}$	$15 - 17$

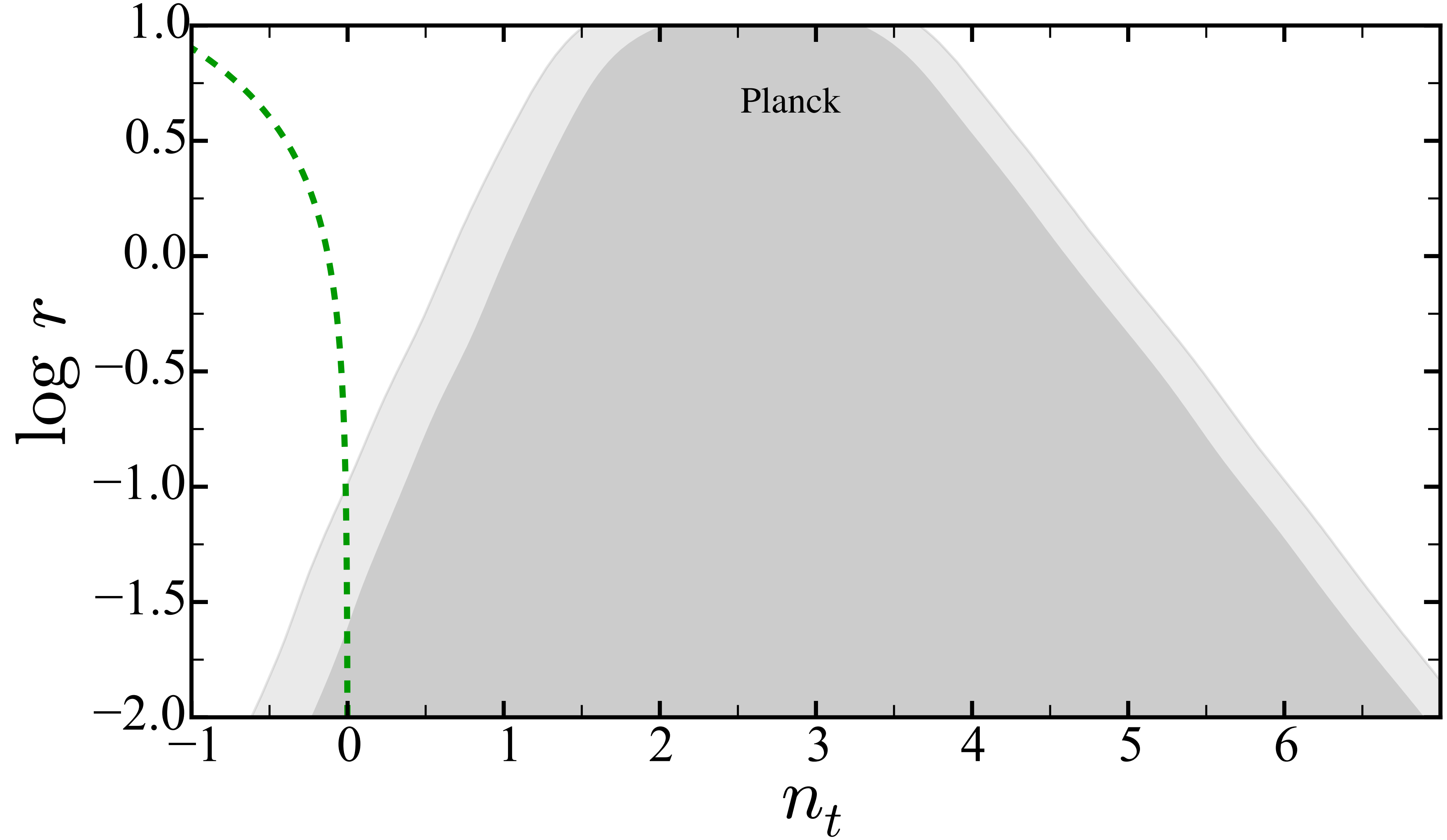
$$N \equiv \int_{t_i}^{t_f} H \mathrm{d}t$$

e-folding number

[J. Garcia-Bellido, M. Peloso, C. Unal '16]

LISA=>Possibility to test regions for which we have poor information

Importance of measuring the Tensor PS (at different scales)



$n_T \lesssim 5$ only with CMB

[P. D. Lasky et al., (1511.05994)]

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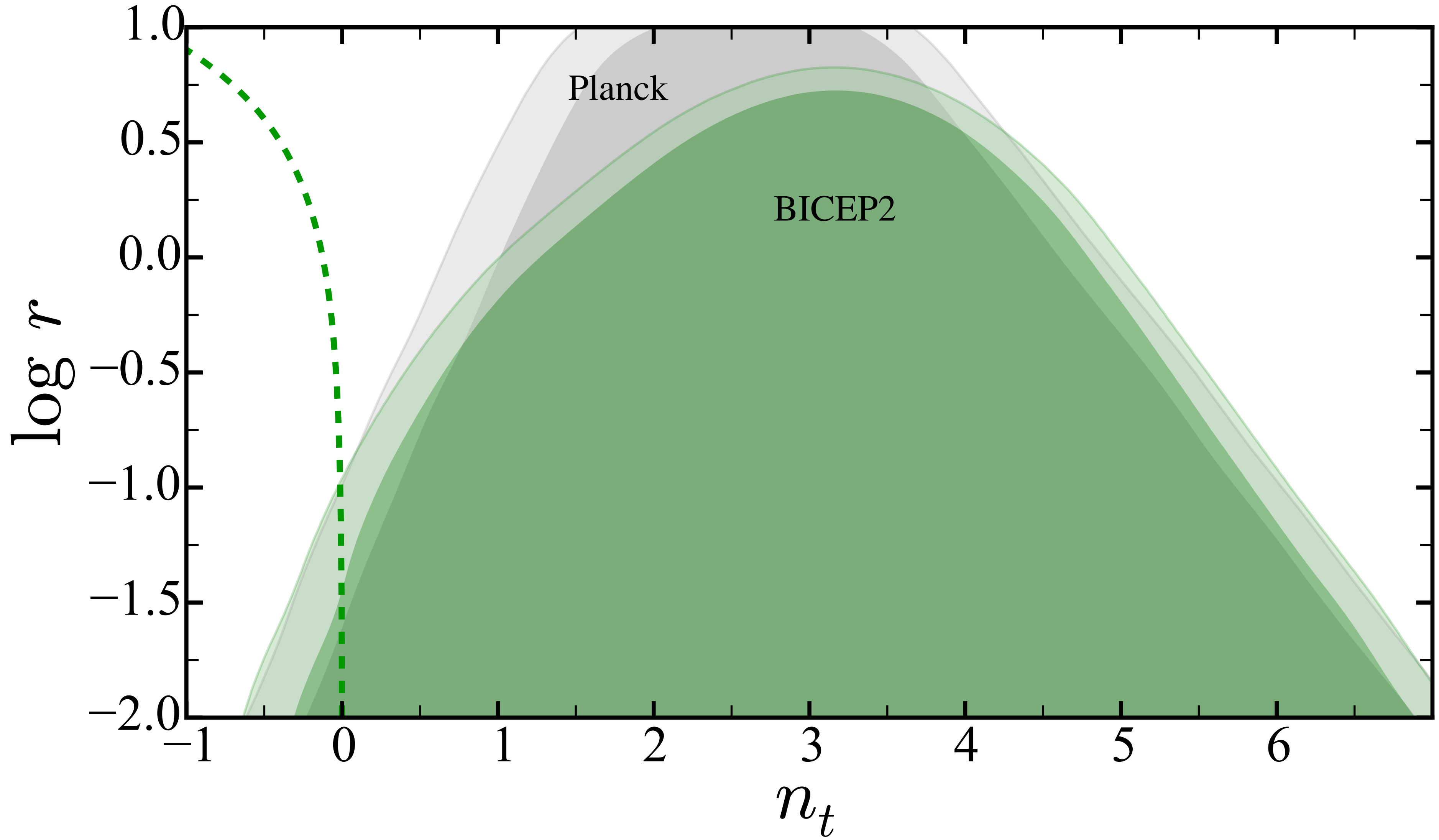

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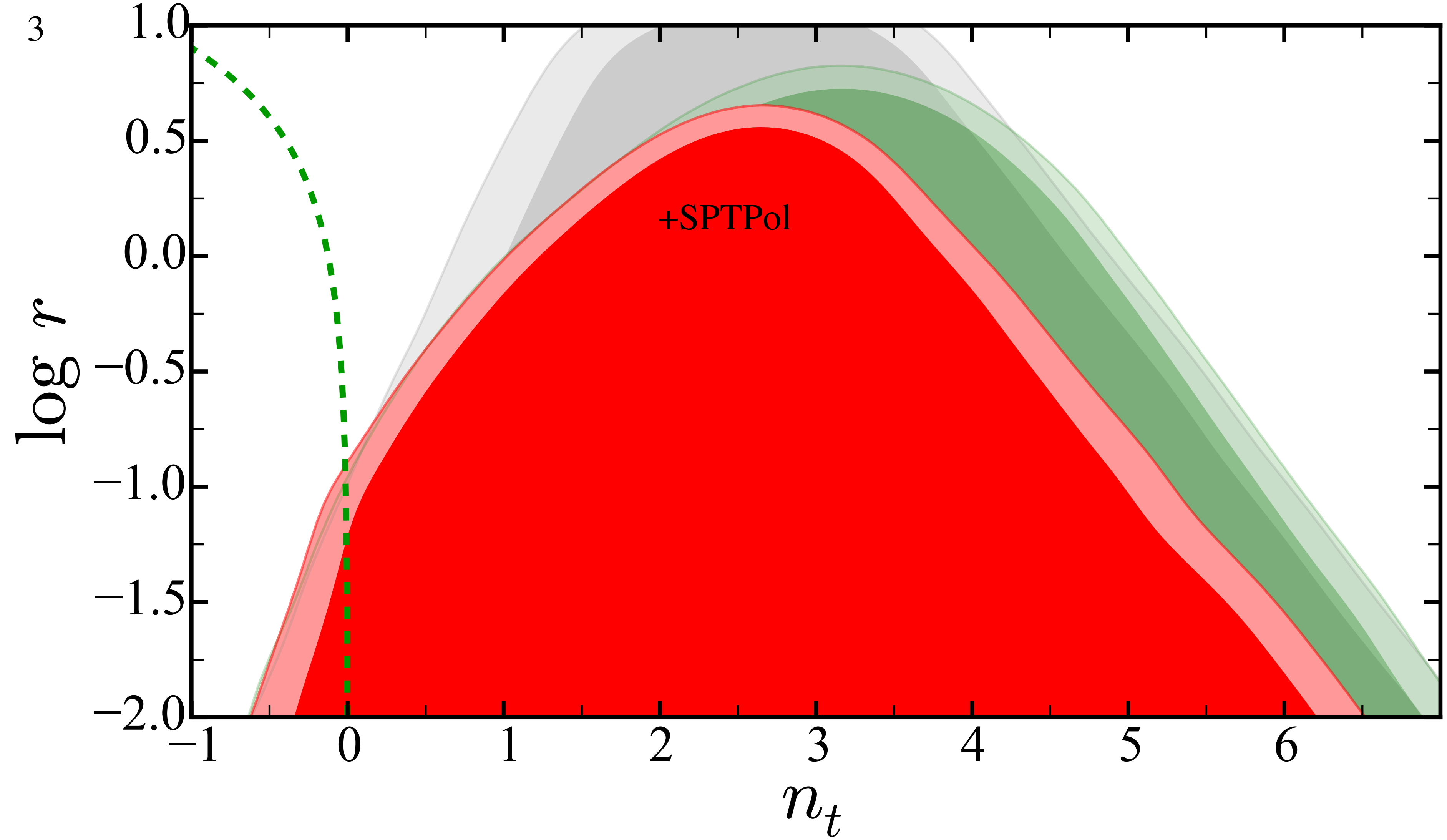

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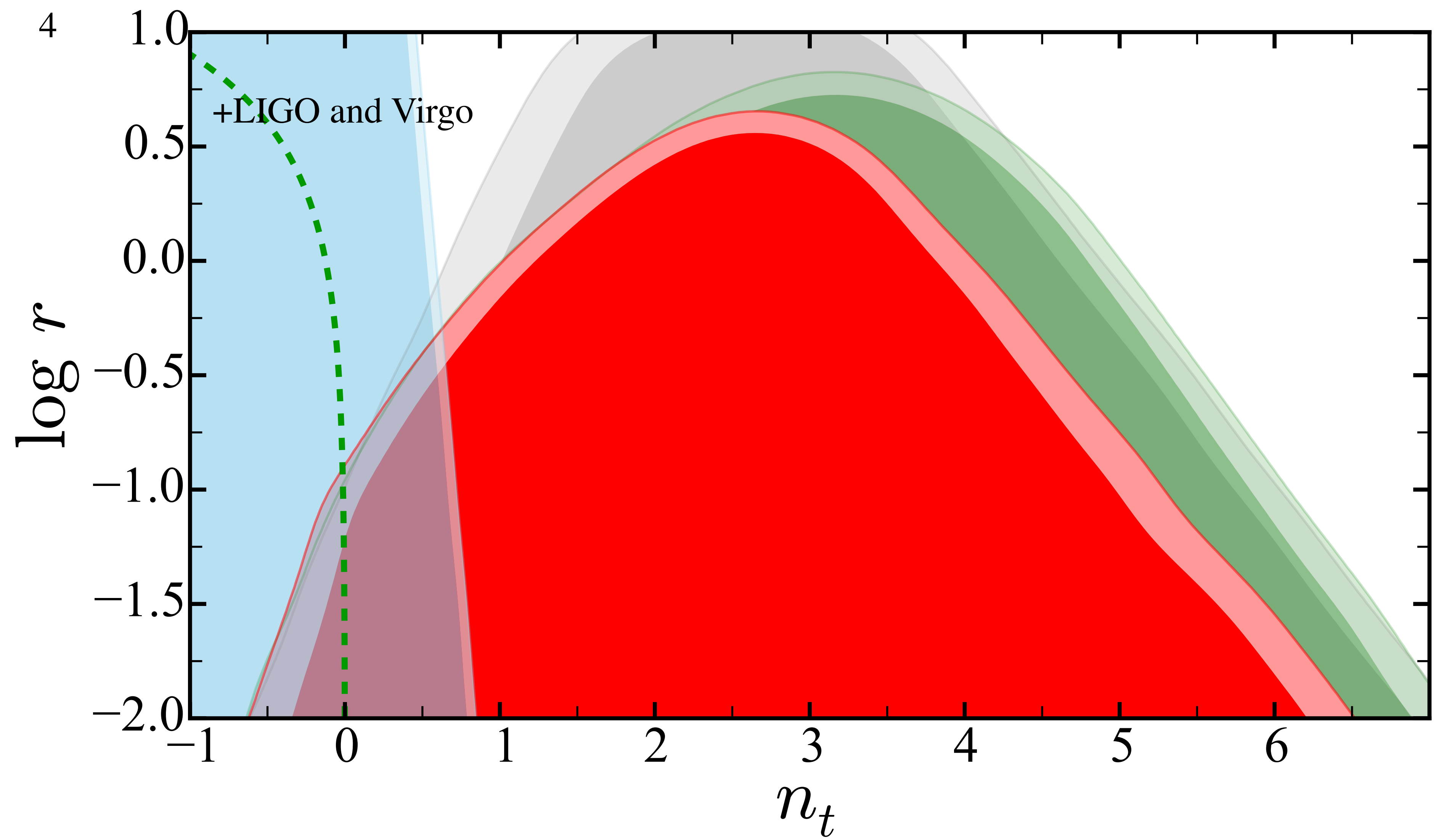

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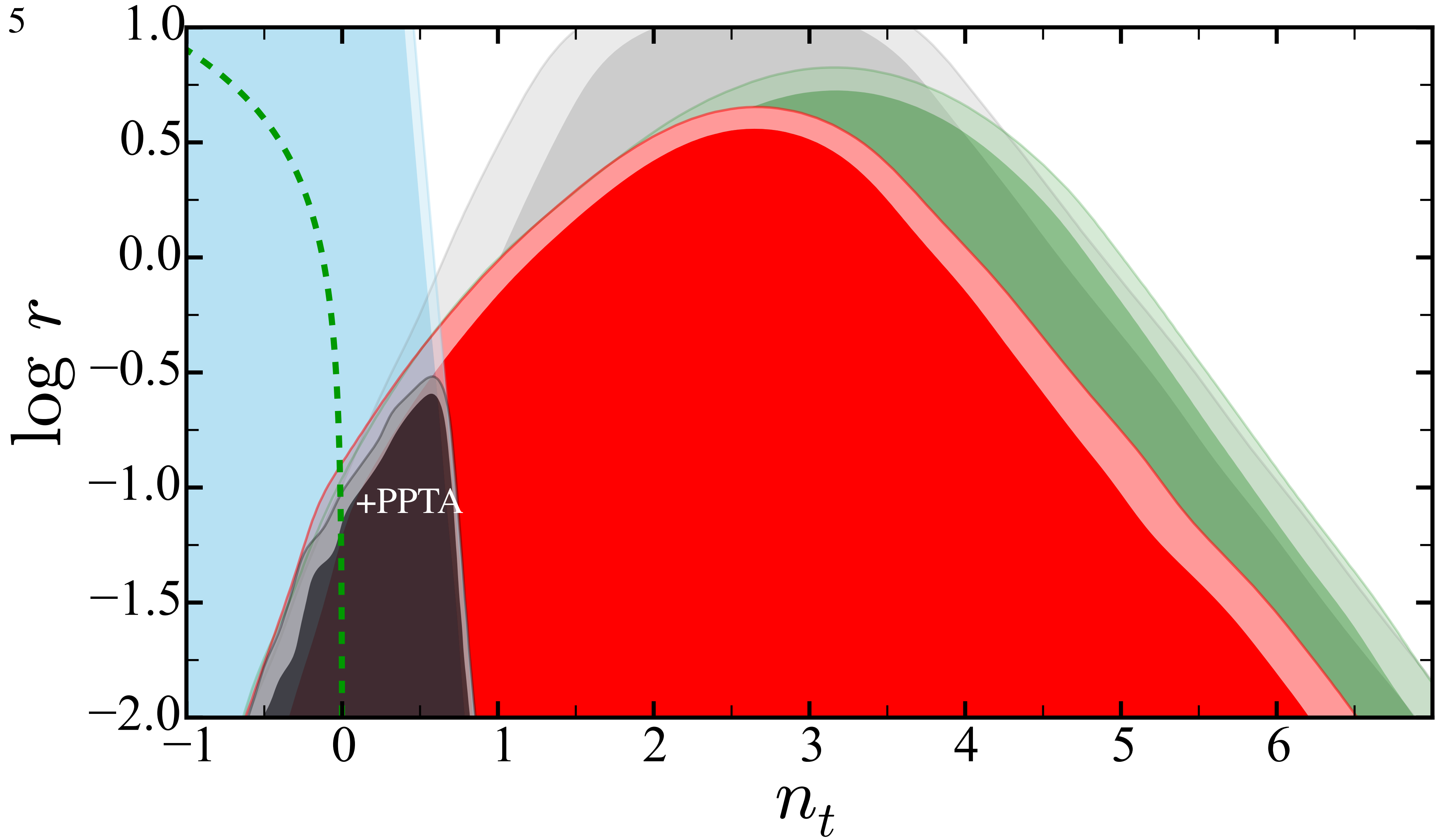

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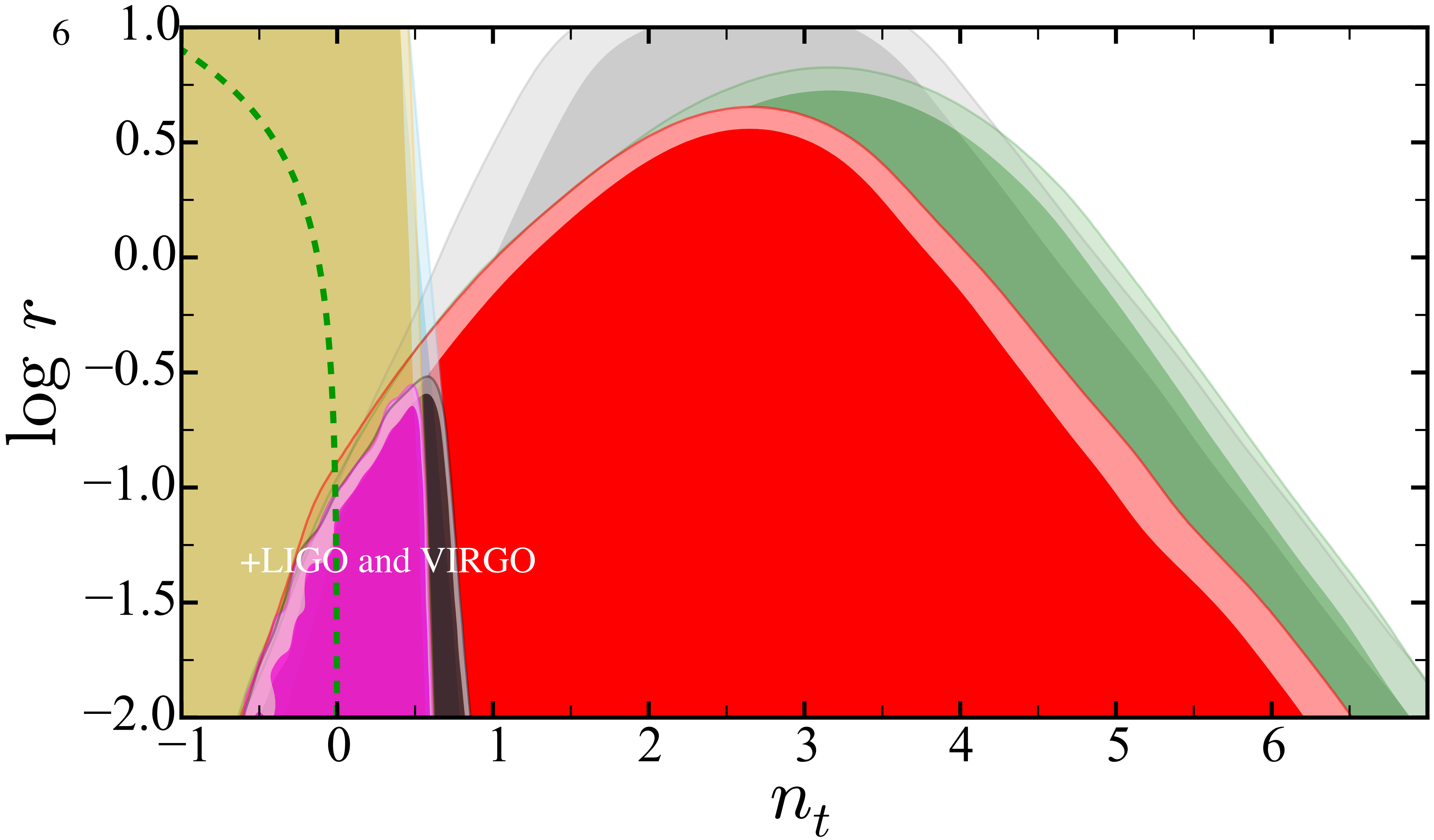

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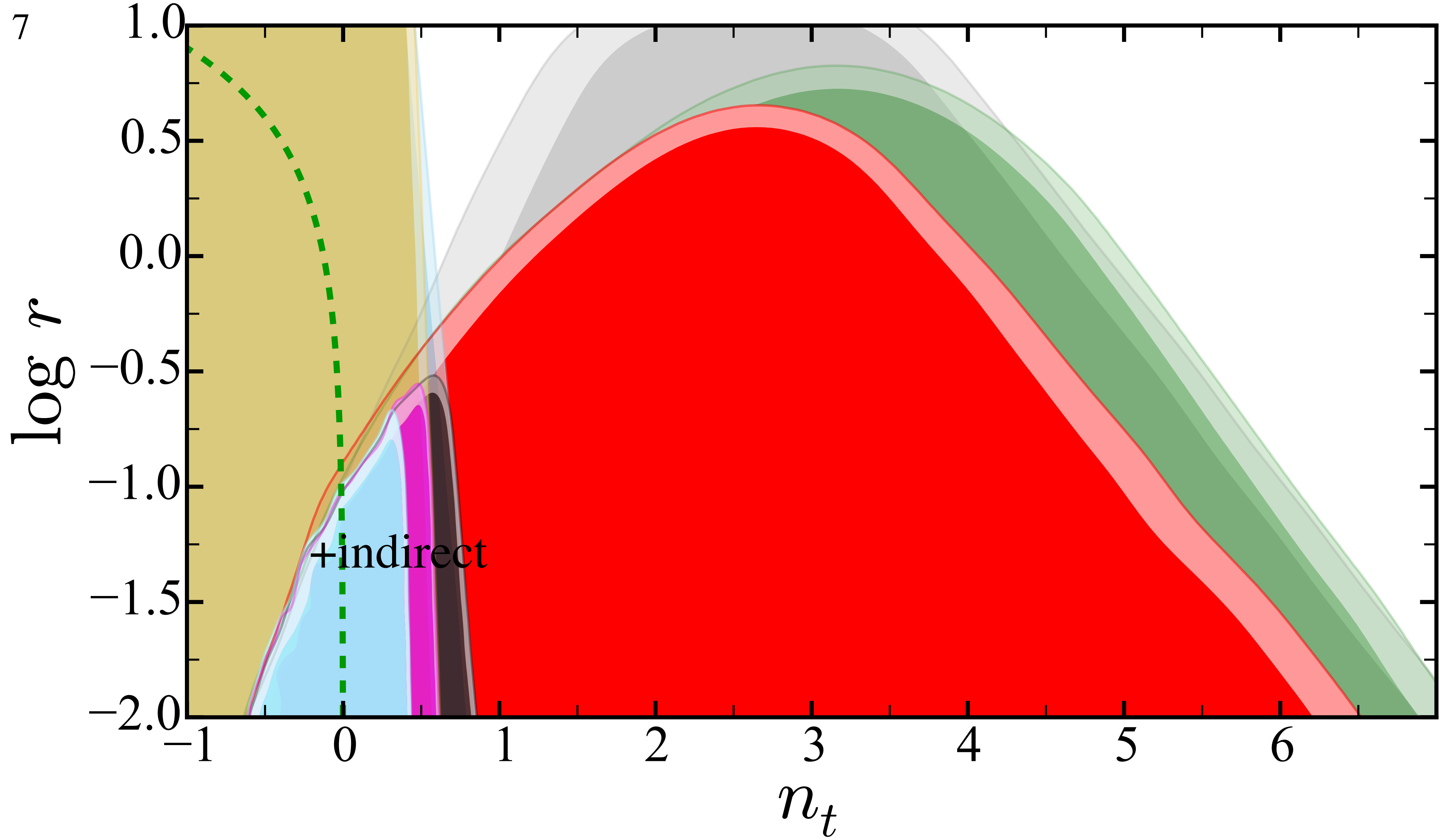
7



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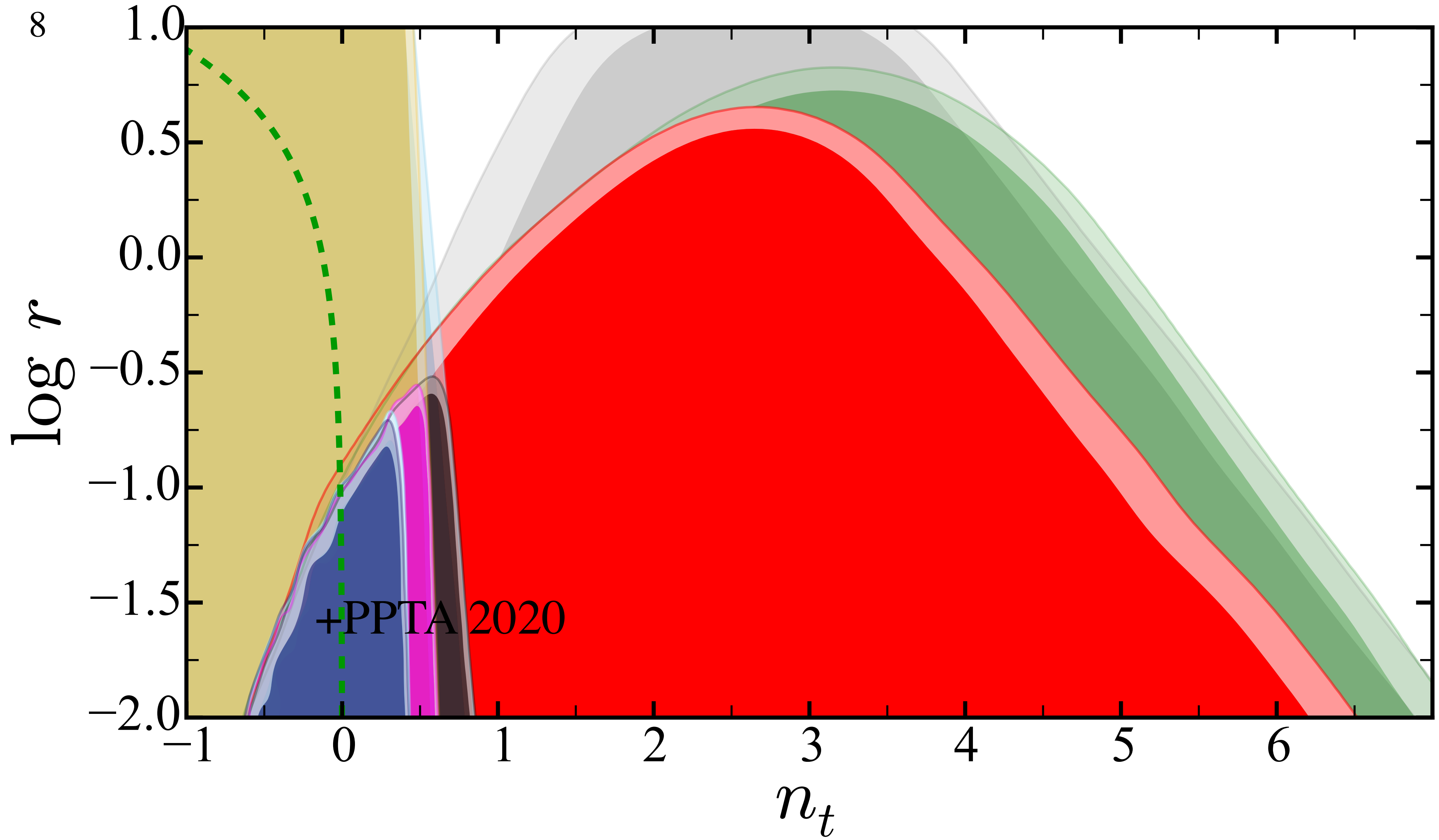

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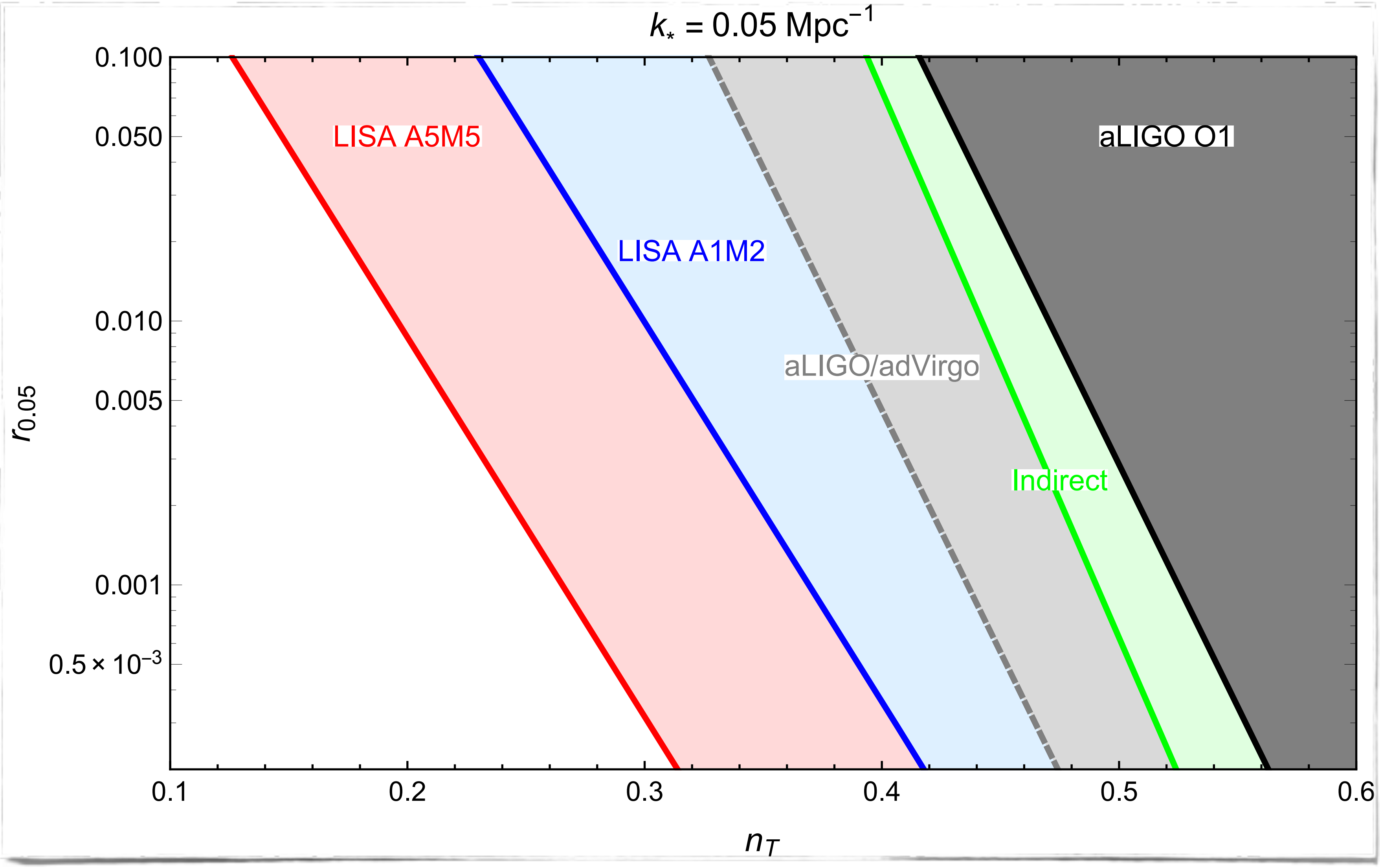
[P. D. Lasky et al., (1511.05994)]

$$\Omega_{GW}(f) = \Omega_{GW}^{CMB} \left(\frac{f}{f_{CMB}} \right)^{n_T}$$

[Bartolo N. et al '16]



$$r \overset{?}{=} -8 n_T$$

$$r \equiv \frac{A_T(k_*)}{A_S(k_*)}$$

Test for single-field consistency relation

Potentially interesting scenarios

Inflationary GWs generated by the amplification of the vacuum fluctuations
have an amplitude OUT of LIGO and LISA range

- Presence of extra degrees of freedom during inflation

- New patterns of symmetry during inflation

- Merging of Primordial BHs after inflation

- ...

MODEL INDEPENDENT PARAMETRIZATION

It allows to study a model within a given observational window (frequency band of LISA)
agnostic about the potential at field values that not impact these scales

$$\mathcal{L} \supset -\frac{\varphi}{4f} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$\xi \equiv \frac{\dot{\varphi}}{2fH}$$

$$h^2\Omega_{\rm gw} = A_* \left(\frac{f}{f_*}\right)^{n_T}$$

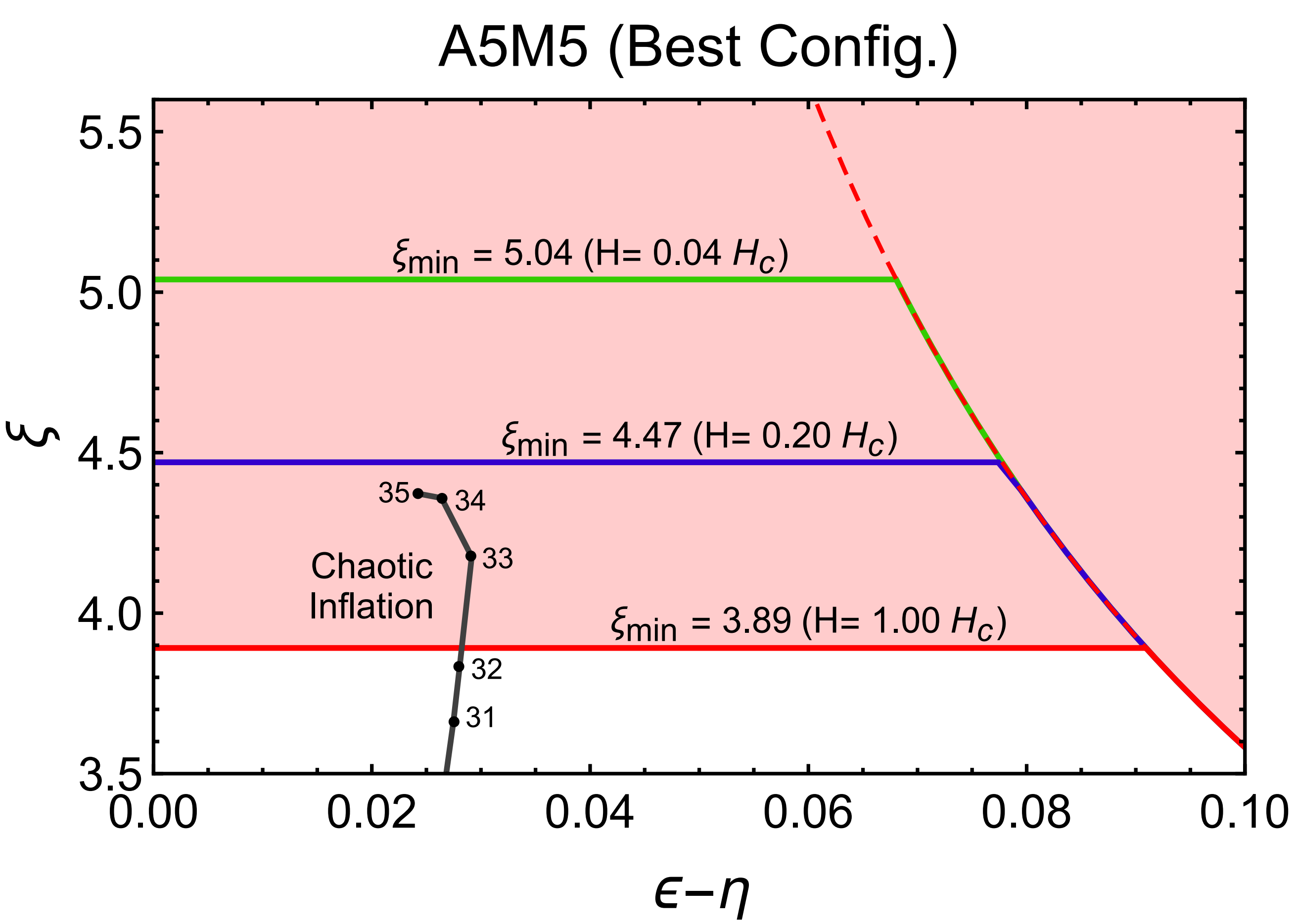
$$n_T \simeq (4\pi\xi - 6)(\epsilon_H - \eta)$$

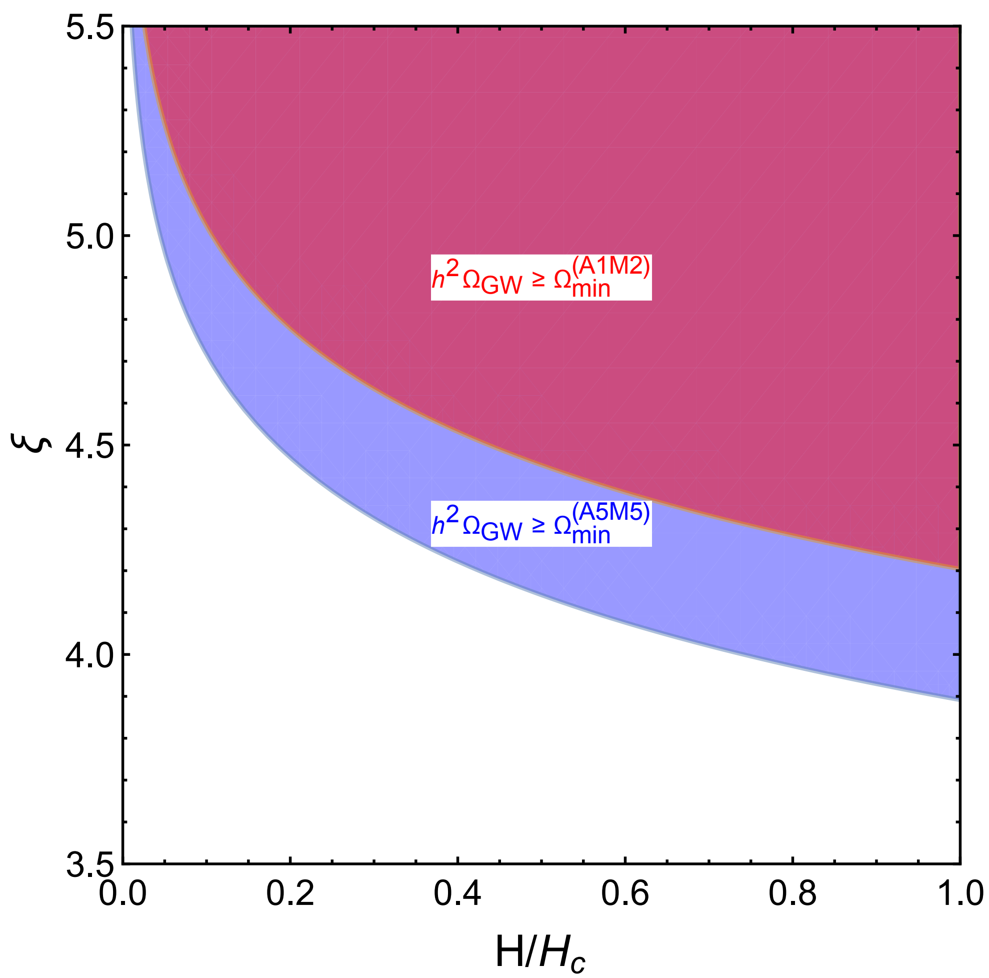
3 parameters

$$H,\ \xi,\ \epsilon_H - \eta$$

$$\epsilon_H \equiv -\frac{\dot{H}}{H^2}\ ,\quad \eta \equiv -\frac{\ddot{\phi}}{H\dot{\phi}}$$

[Bartolo N. et al '16]





$H_c \sim 2.6 \cdot 10^{-5} M_{Pl} \simeq 6.4 \cdot 10^{13} GeV$

GLOBAL PARAMETRIZATION

Specify the potential and combine all the scales in the **observable** 60 efolds of inflation

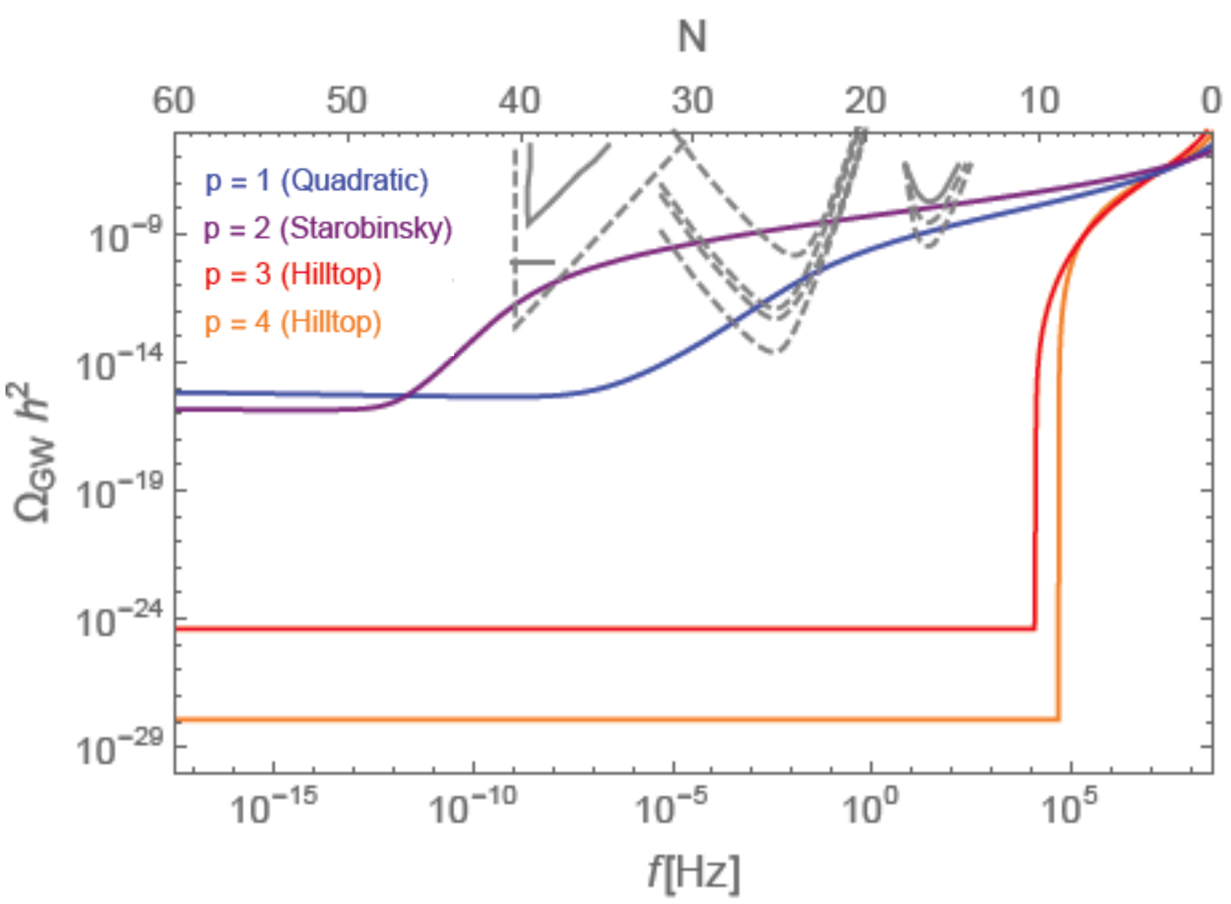
A simple (global) parametrization of the scalar potential:

$$\epsilon_V = \frac{1}{2}\left(\frac{V_{,\phi}}{V}\right)^2 = \frac{\beta}{N^p}$$

Mukhanov '13

3 parameters

$\alpha,\ \beta,\ p$



Binetruy, Domcke, Pieroni '16

$$\xi \simeq \frac{M_{Pl}}{\sqrt{2}\,f}\sqrt{\epsilon_V} \propto N^{-p/2}$$

$$n_s \simeq 1 - \frac{p}{N+1}$$

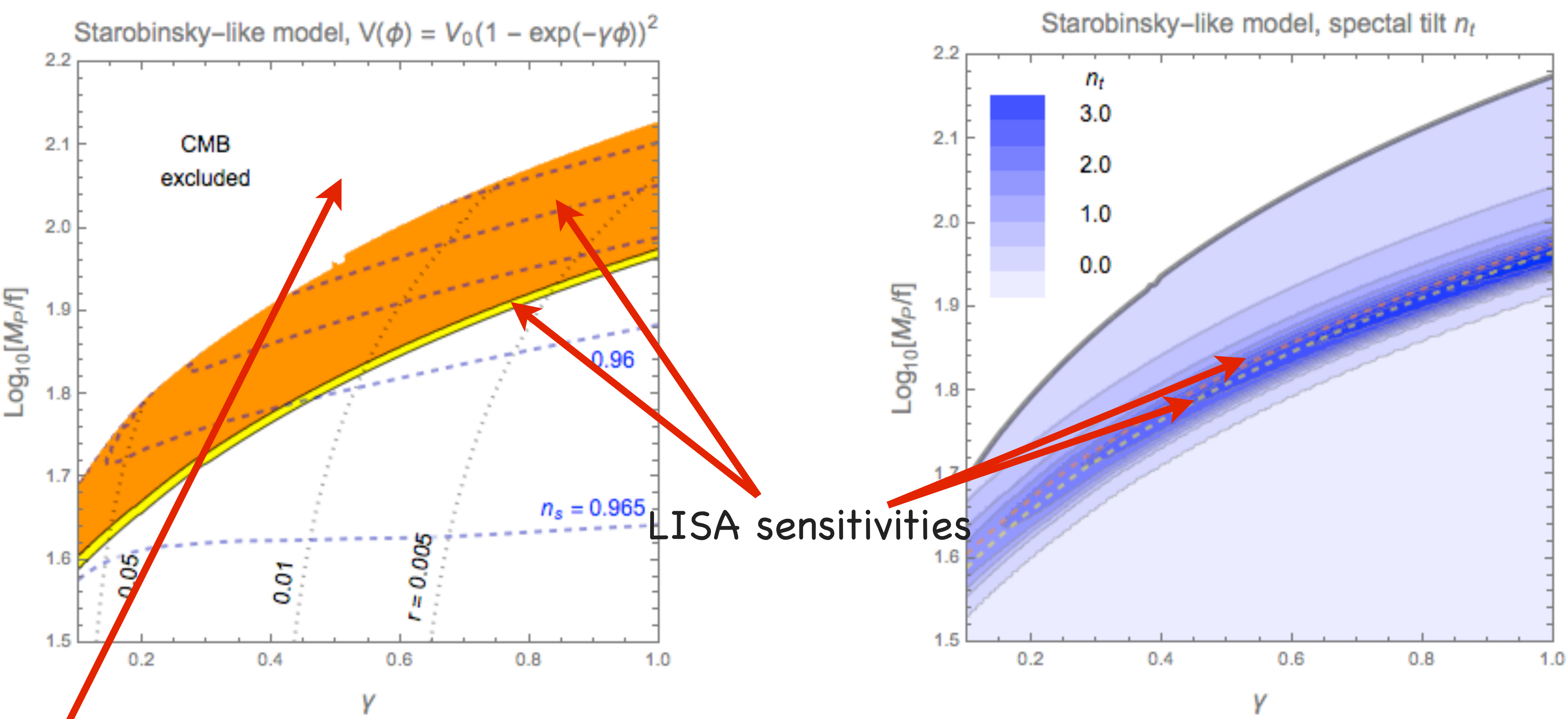
$p = 2$ => largest GW contribution

STAROBINSKY-TYPE POTENTIAL

3 parameters
$\alpha/\Lambda,\ \beta,\ p$

$$V(\phi) = V_0(1 - e^{-\gamma\phi})^2 \rightarrow p = 2 \ \text{ vary } \quad \beta = 1/(2\gamma^2) \text{ and } \ \alpha$$

[Bartolo N. et al '16]



non-Gaussianity, mu-distorsion (+LIGO)

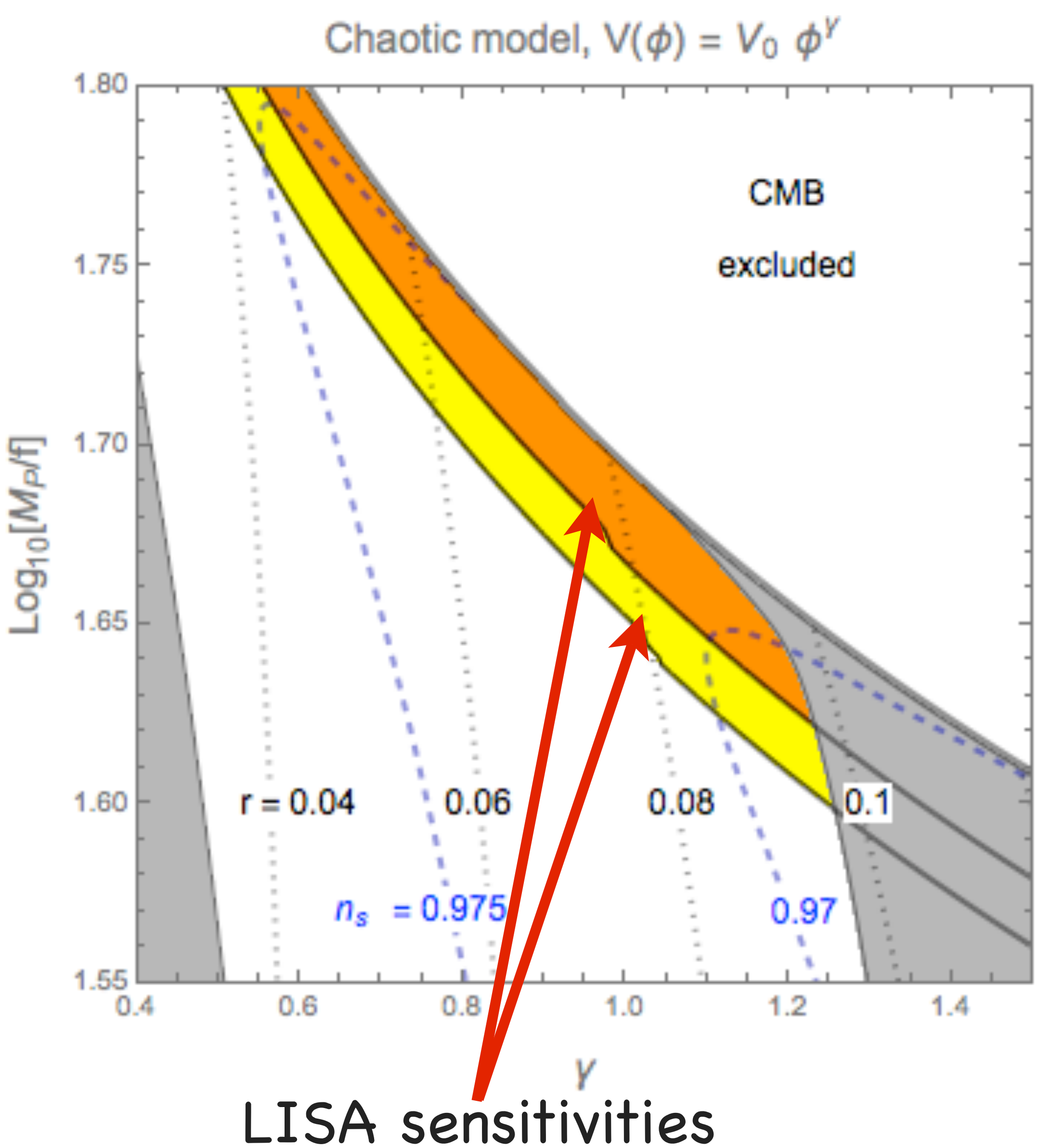
complementarity between CMB and direct GW observations

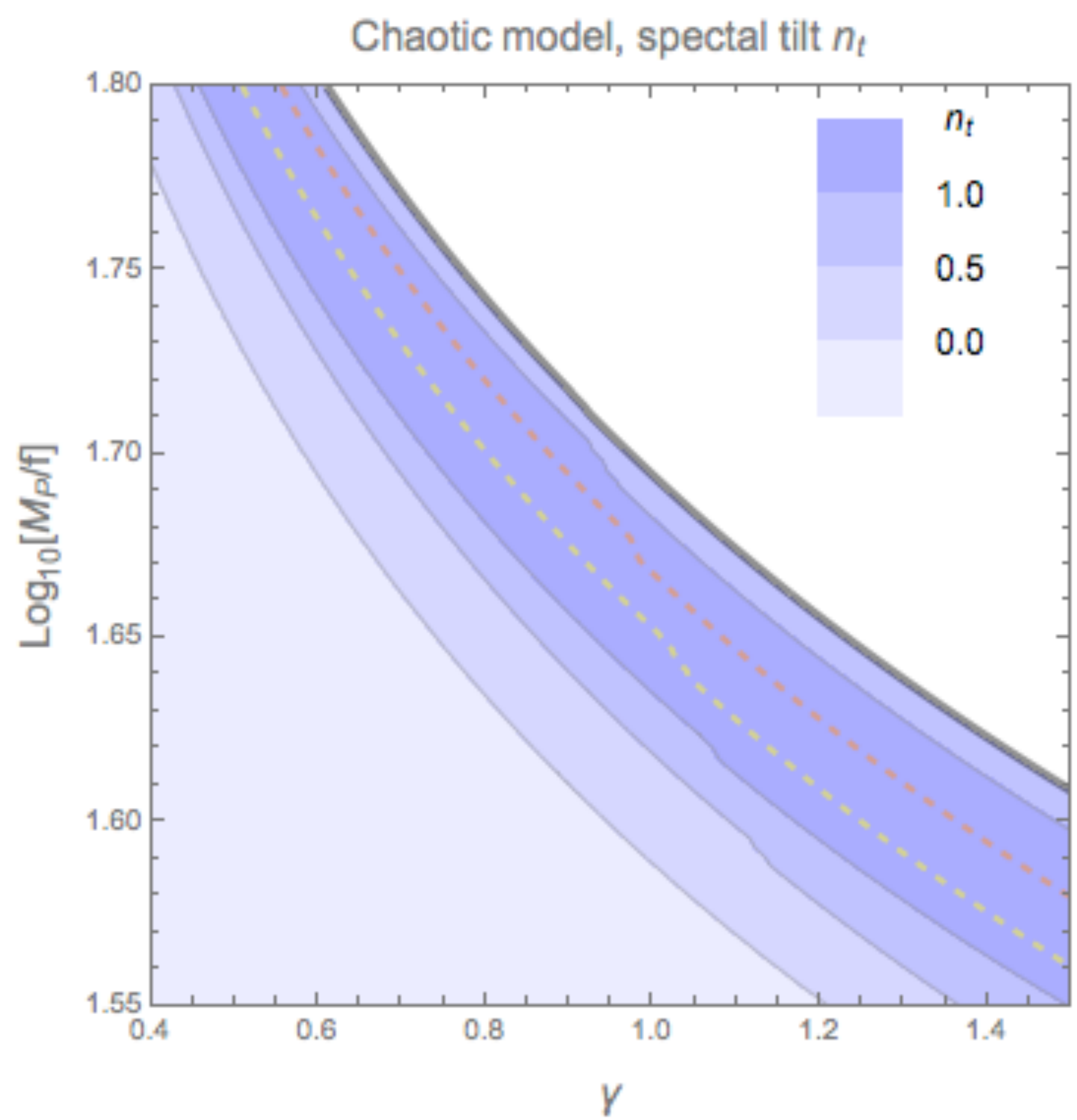
CHAOTIC POTENTIAL

3 parameters
$$\alpha/\Lambda,\ \beta,\ p$$

$$V(\phi) = V_0 \phi^{\gamma} \rightarrow p = 1 \ \text{ vary } \ \ \beta = \gamma/4 \text{ and } \ \alpha$$

Bartolo et al ‘16



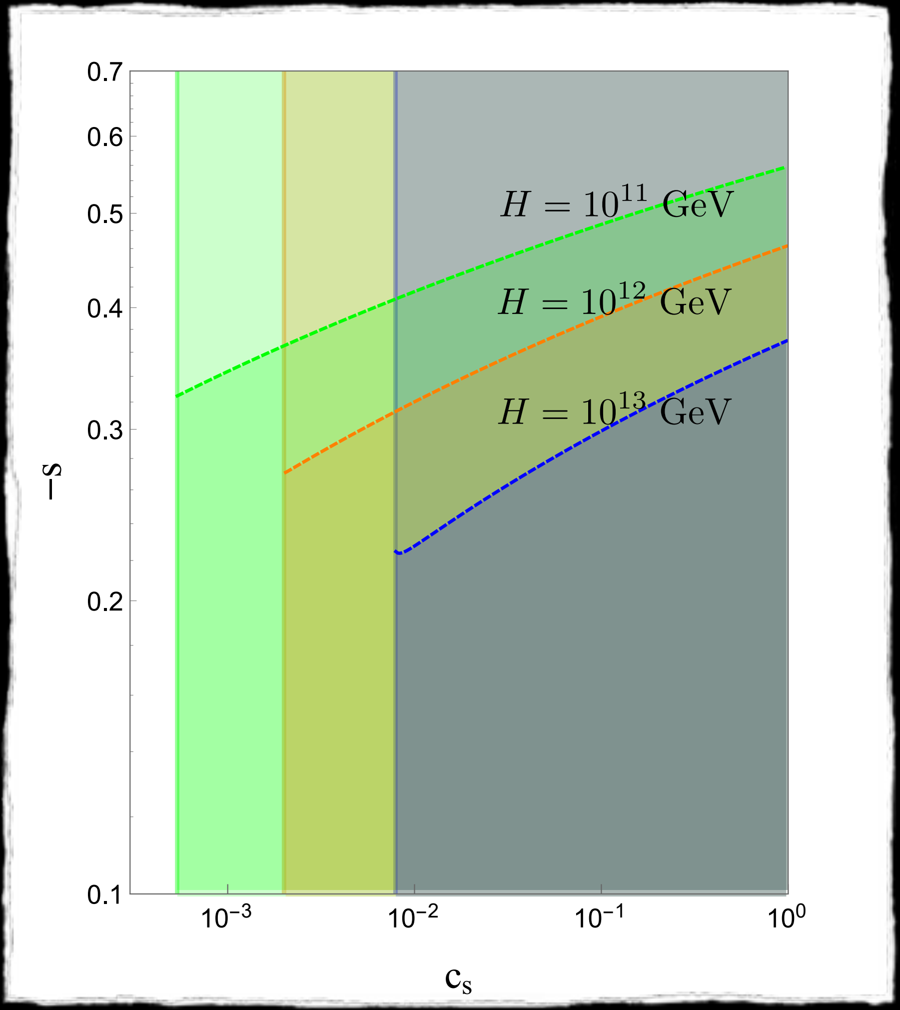


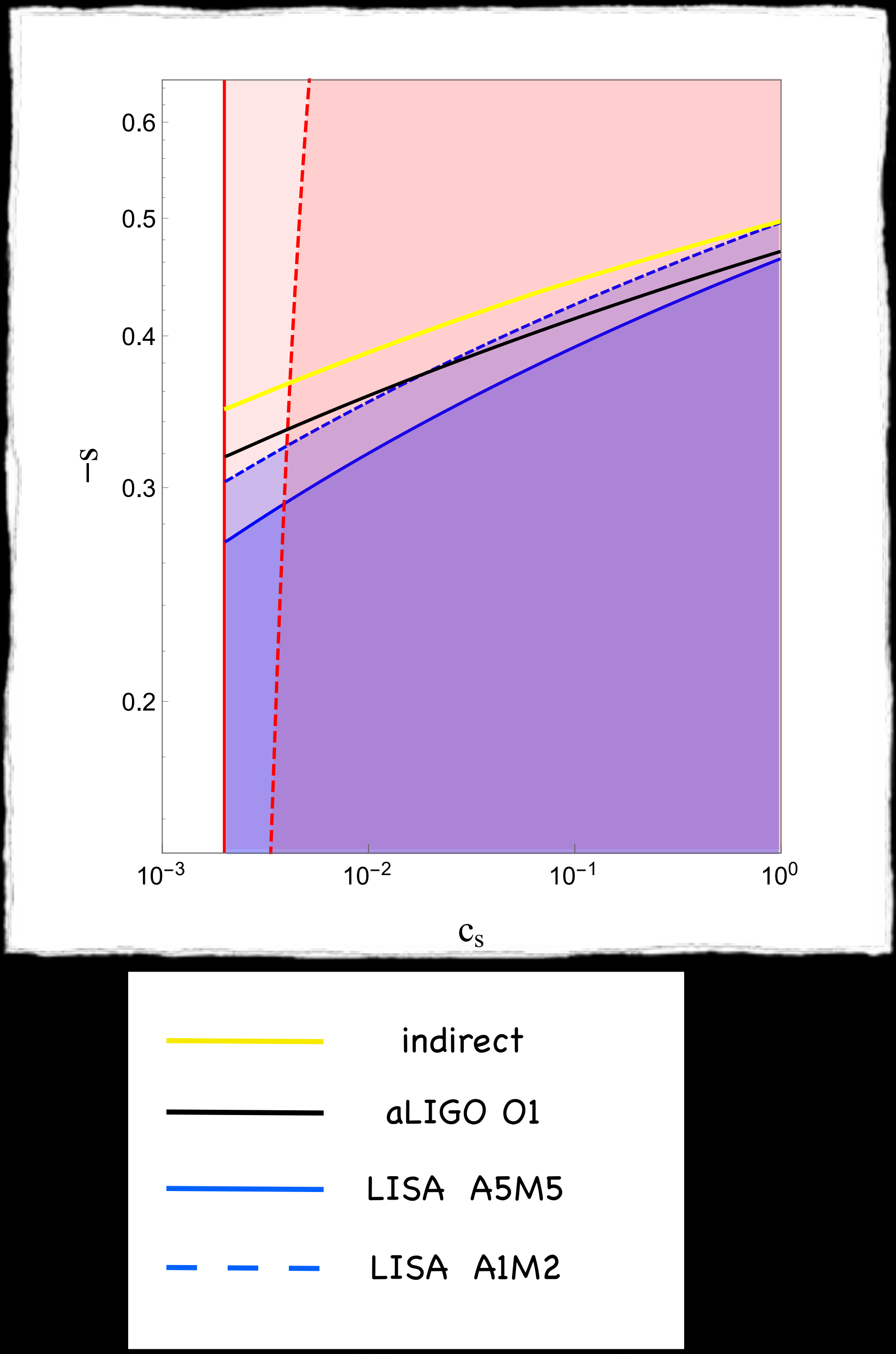
Spectral tilt as a model discriminator

Extra (spectator) scalar field during inflation

$$\mathcal{L} \supset P(X, \sigma)$$ $$X = \frac{1}{2}\partial_\mu \sigma \partial^\mu \sigma$$ $$c_s \neq 0$$ $$s \equiv \frac{\dot{c}_s}{H c_s} \neq 0$$

Bartolo et al '16





$$A^{(S)}_{0.05} = 2.21 \times 10^{-9} \ \ (65\% \, CL)$$

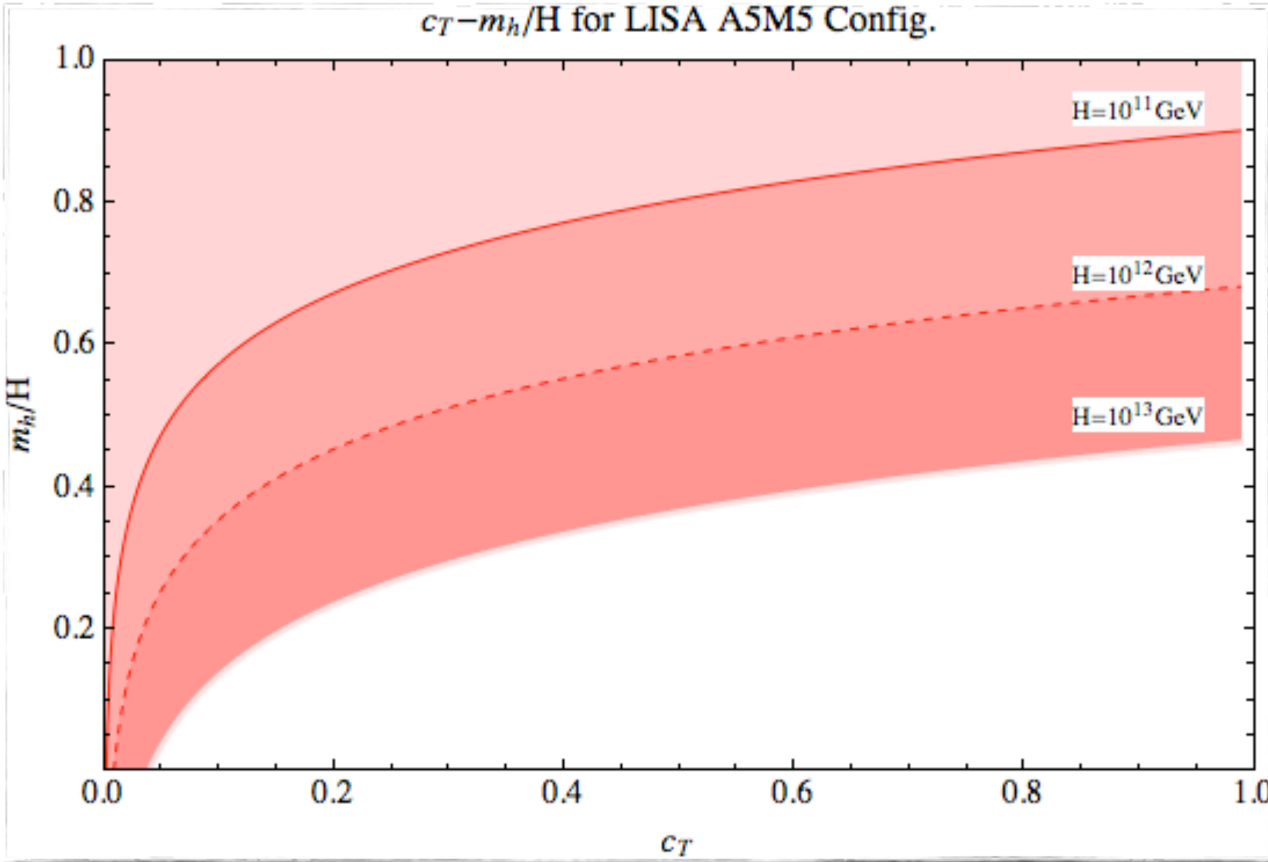
[Planck 2013 XVI]

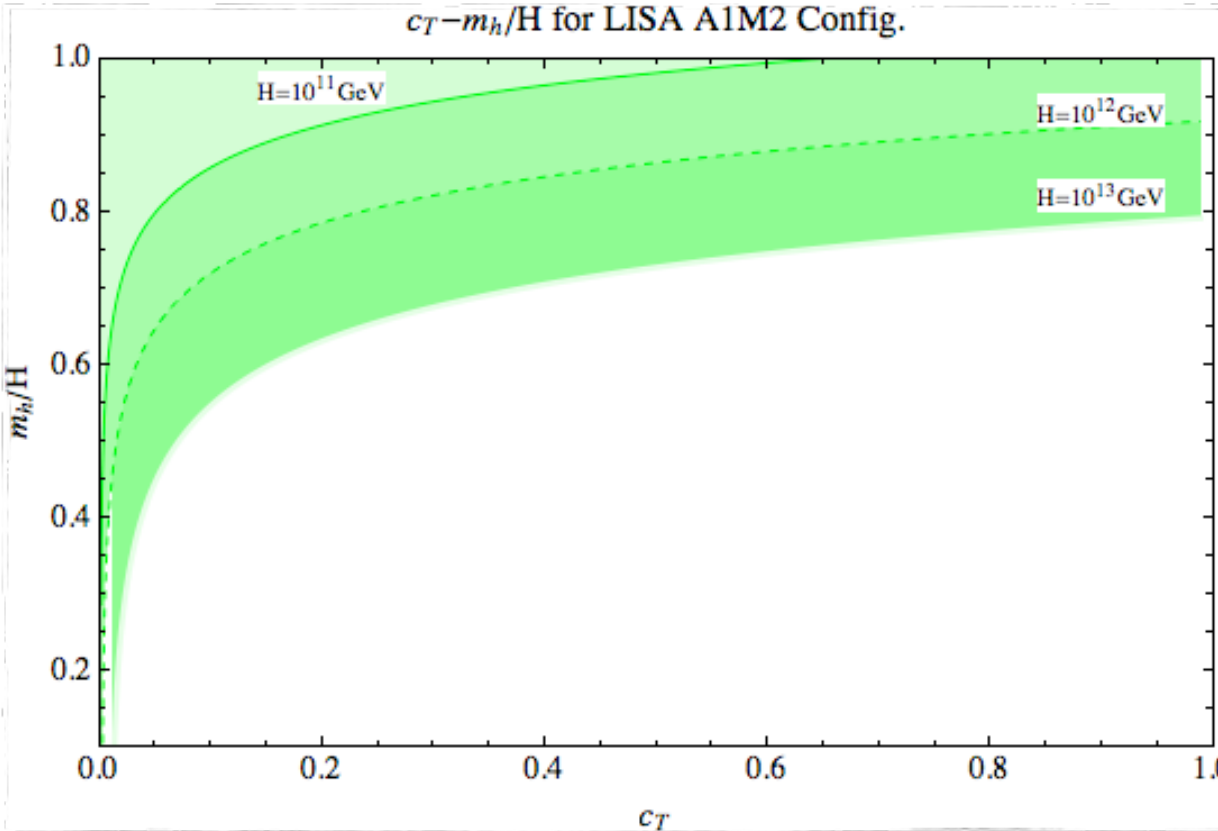
$$\epsilon = 0.0068 \ \ (95\% \, CL) \ \ (\text{PlanckTT} + \text{lowP})$$

$$r_{0.05} < 0.09 \ \ (95\% \, CL)$$ [BICEP2 / Keck Array VI]

Deserves analysis about PBHs and non-G

Effective theory for (massive) tensor during inflation





c_T -> tensor sound speed

$$S_h = \frac{M_{Pl}^2}{4} \int d\eta\, d^3x\, a^2(\eta) \left\{ \left(h'_{ij}\right)^2 - c_T^2 \left(\partial_l h_{ij}\right)^2 - m^2 h_{ij}^2 \right\} .$$

[Bartolo et al '16]

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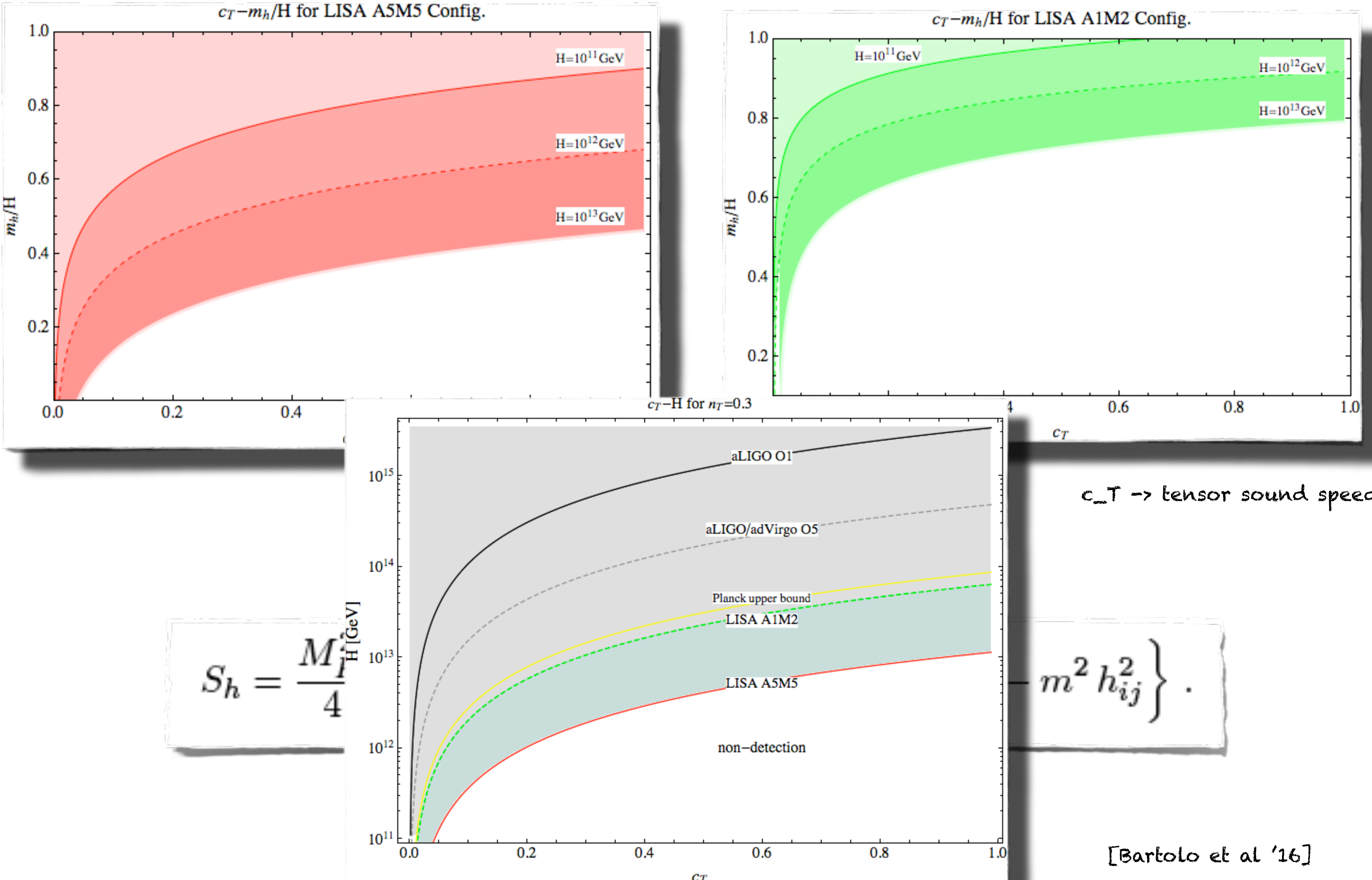


c_T -> tensor sound speed

[Bartolo et al '16]

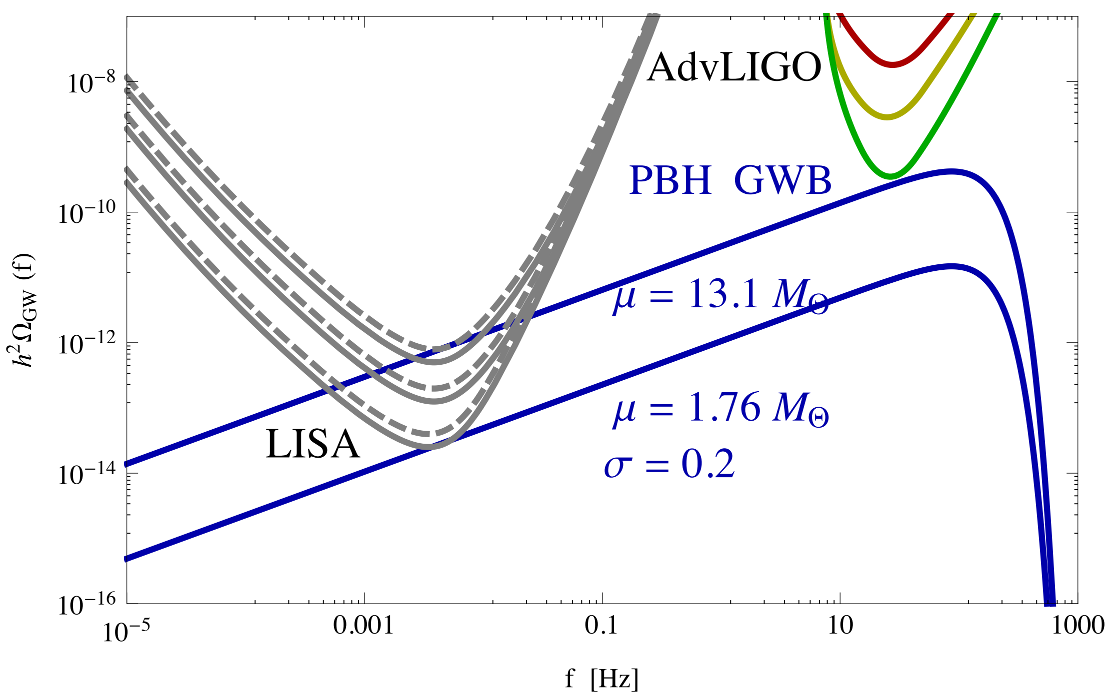
GWs from "post"-inflationary processes

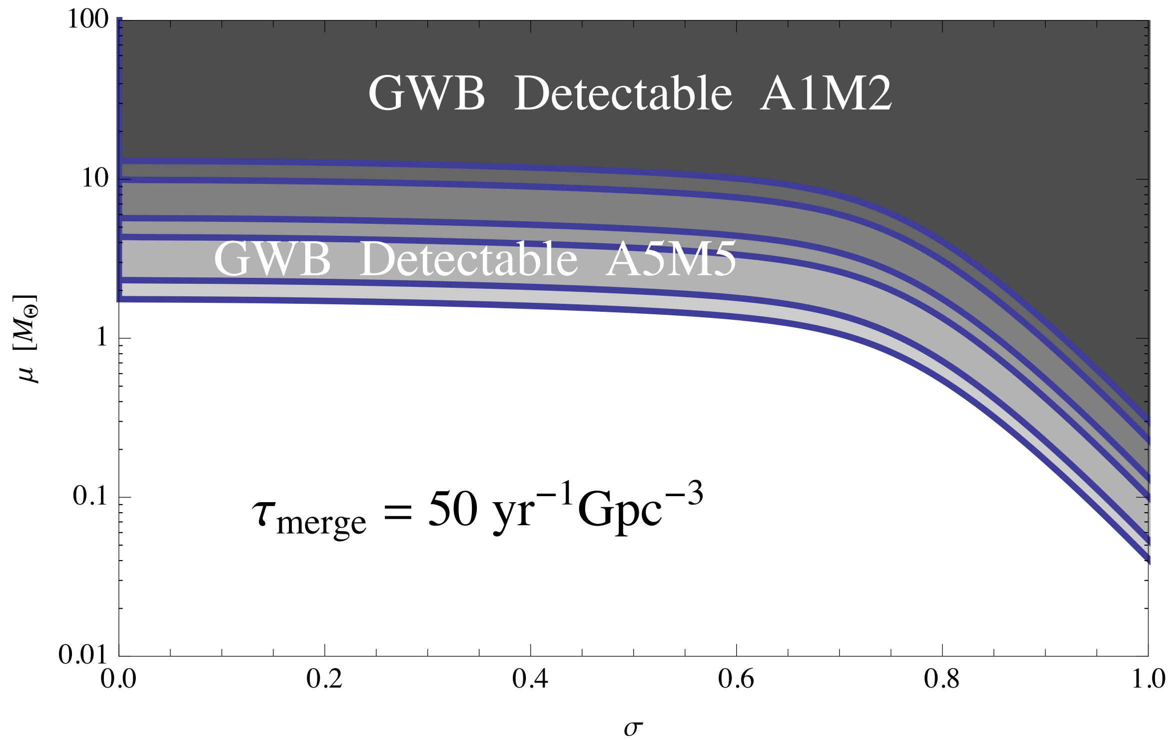
Large peaks in the matter PS => PBHs

merging of PBHs => stochastic bg of GWs

$$V(\phi,\psi) = \Lambda[\left(1-\frac{\psi^2}{v^2}\right)^2 + \frac{(\phi-\phi_c)}{\mu_1} - \frac{(\phi-\phi_c)^2}{\mu_2^2} + \frac{2\phi^2\psi^2}{\phi_c^2 v^2}]$$

Two-fields waterfall hybrid potential





[Bartolo et al '16]

PBHs as dark matter in the Universe

GWs “Beyond” inflation

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GWs from (p)reheating through parametric effects

GWs from (p)reheating through spinodal instabilities

Large Amplitude but High frequency

$\Omega_{GW}^{(o)} \sim 10^{-11}$ $f_o \sim 10^8 - 10^9$ Hz

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$\Omega_{GW}^{(o)} \sim 10^{-11}$ $f_o \sim 10^8 - 10^9$ Hz

2nd order GWs $h''_{ij} + 2\mathcal{H}h'_{ij} + k^2 h_{ij} = S_{ij}^{TT}$ $S_{ij}^{TT} \sim \Phi * \Phi$

IF $\Delta^2_{\mathcal{R}} \gg \Delta^2_{\mathcal{R}}|_{CMB} \sim 3 \times 10^{-9}$ @ small scales

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BBN $\Omega_{gw,0} < 1.5 \times 10^{-5}$ ⟶ $\Delta^2_{\mathcal{R}} < 0.1 \left(\frac{F_{rad}}{30}\right)^{-\frac{1}{2}}$

LIGO $\Omega_{gw,0} < 6.9 \times 10^{-6}$ ⟶ $\Delta^2_{\mathcal{R}} < 0.07 \left(\frac{F_{rad}}{30}\right)^{-\frac{1}{2}}$

PTA $\Omega_{gw,0} < 4 \times 10^{-8}$ ⟶ $\Delta^2_{\mathcal{R}} < 5 \times 10^{-3} \left(\frac{F_{rad}}{30}\right)^{-\frac{1}{2}}$

LISA $\Omega_{gw,0} < 10^{-13}$ ⟶ $\Delta^2_{\mathcal{R}} < 1 \times 10^{-5} \left(\frac{F_{rad}}{30}\right)^{-\frac{1}{2}}$

BBO $\Omega_{gw,0} < 10^{-17}$ ⟶ $\Delta^2_{\mathcal{R}} < 3 \times 10^{-7} \left(\frac{F_{rad}}{30}\right)^{-\frac{1}{2}}$

D. Wands et al, 2006-2010

GWs "Beyond" inflation

GWs from (p)reheating through parametric effects

GWs from (p)reheating through spinodal instabilities

Large Amplitude but High frequency

$\Omega^{(o)}_{GW} \sim 10^{-11}$ $f_o \sim 10^8 - 10^9$ Hz

2nd order GWs $h''_{ij} + 2\mathcal{H}h'_{ij}$

PBH

(see Garcia-Bellido, Peloso's talks)

IF $\Delta^2_{\mathcal{R}} \gg \Delta^2_{\mathcal{R}}|_{CMB} \sim 3 \times$

BBN	$\Omega_{gw,0} < 1.5 \times 10^{-5}$	⟶	$\Delta^2_{\mathcal{R}} < 0.1 \left(\frac{F_{rad}}{30}\right)^{-\frac{1}{2}}$
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D. Wands et al, 2006-2010

GWs from String Gas Cosmology

[Brandenberger et al '14]

$$n_T \simeq -(1 - n_s)$$

Planck: $n_s = 0.968 \pm 0,006$ => NO GWs @ LISA scales

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GWs from Kination Domination after inflation

[B. Spokoiny arXiv:gr-qc/9306008]
[M. Joyce arXiv:hep-ph/9606223]

$$w = (K - V)/(K + V) \simeq +1$$

It does not affect CMB modes

GWs ???

GWs from String Gas Cosmology

[Brandenberger et al '14]

$$n_T \simeq -(1 - n_s)$$

Planck: $n_s = 0.968 \pm 0,006$ => NO GWs @ LISA scales

GW... ...tion

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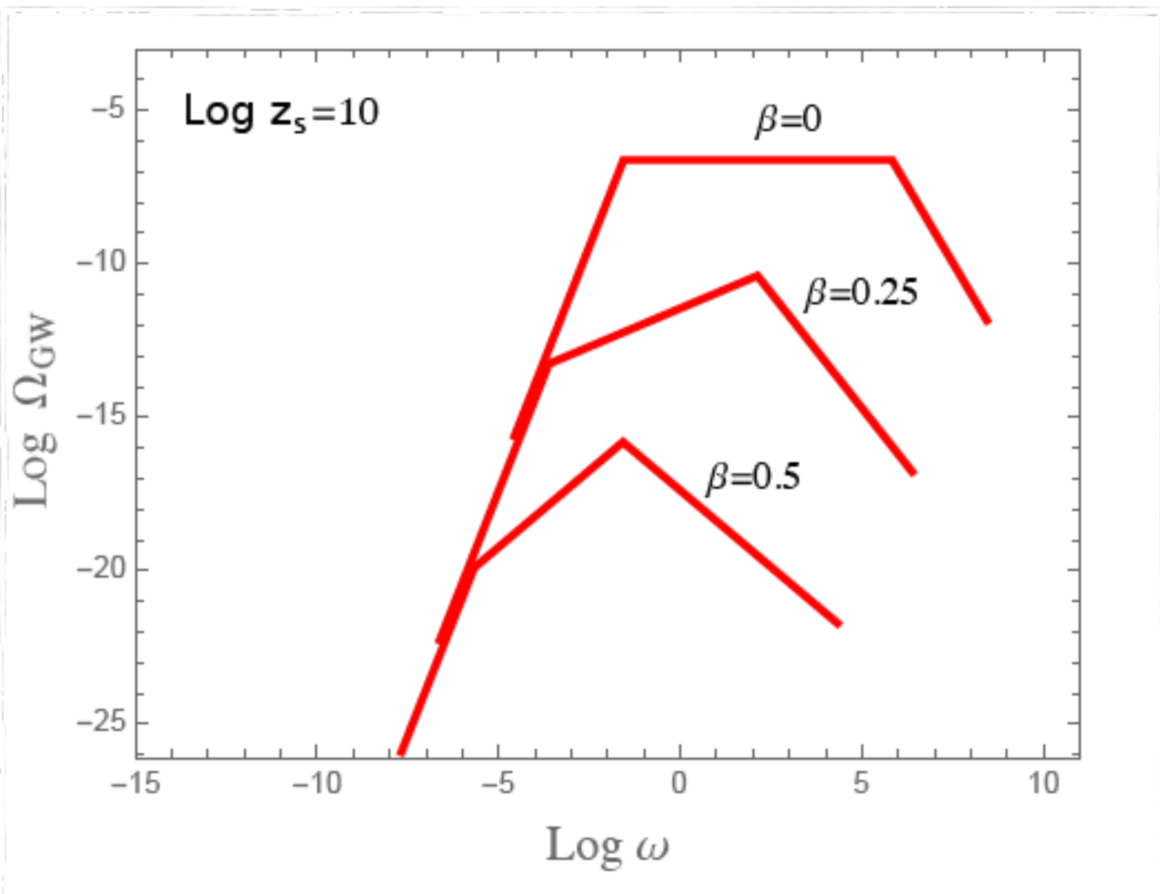
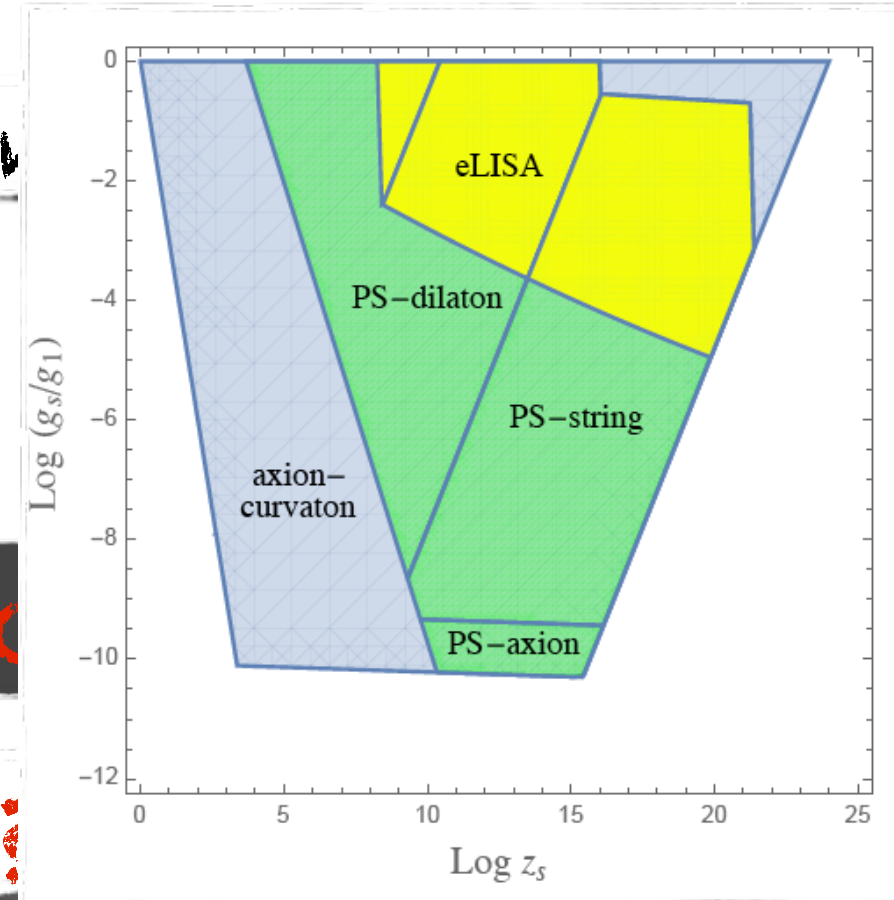




GWs from Pre-Big Bang model

[Gasperini '16]

axion-curvaton mechanism

β string parameter

g string coupling

Possible future directions

non-Gaussianity

(scalar sector)

$$\langle \zeta(\mathbf{k}_1)\zeta(\mathbf{k}_2)\zeta(\mathbf{k}_3)\rangle \equiv (2\pi)^3\delta^{(3)}(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3)B_\zeta(k_1,k_2,k_3)$$

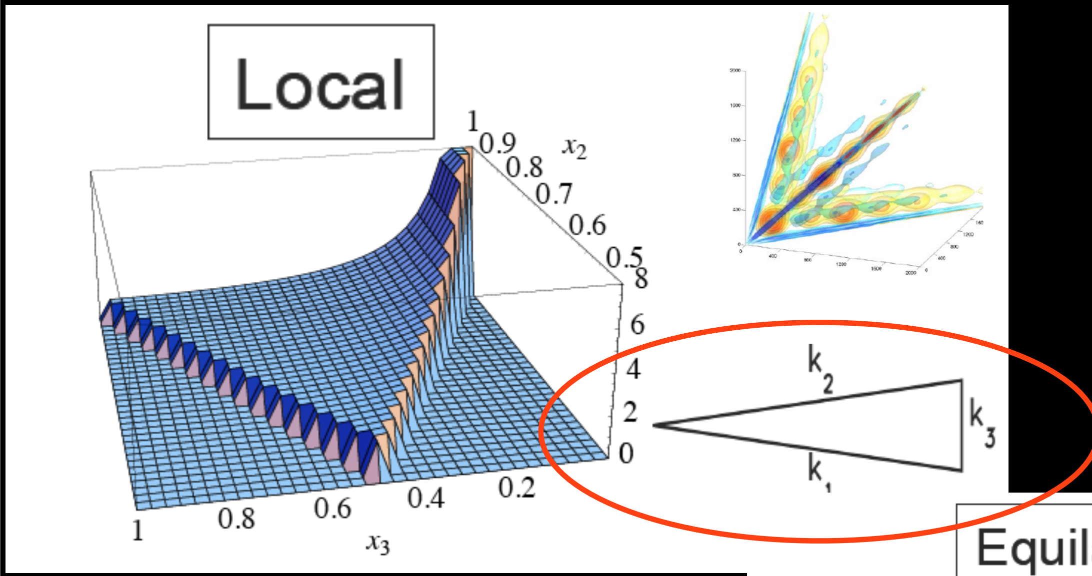
$\frac{\Delta T}{T} = -\frac{\Phi}{3} = -\frac{1}{5}\zeta$ on S-H scales

$$B_\zeta(k_1,k_2,k_3) = f_{NL} F(k_1,k_2,k_3)$$

Amplitude (f_{NL}) Shape ($F(k_1,k_2,k_3)$)

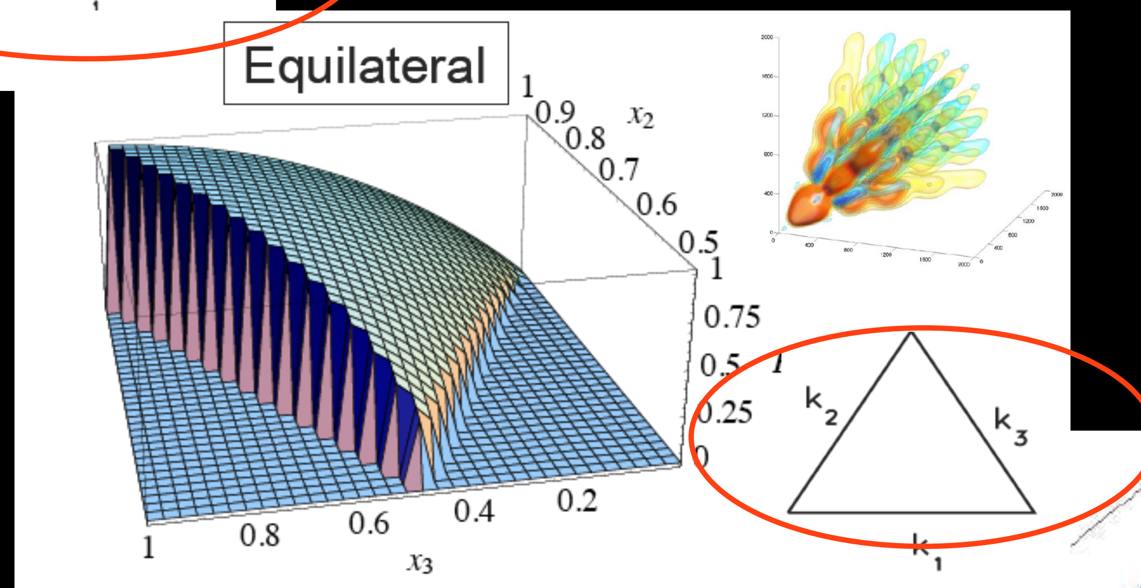
Different inflationary models predict different <u>amplitudes</u> and <u>shapes</u> of the bispectrum

CMB Bispectrum Shapes

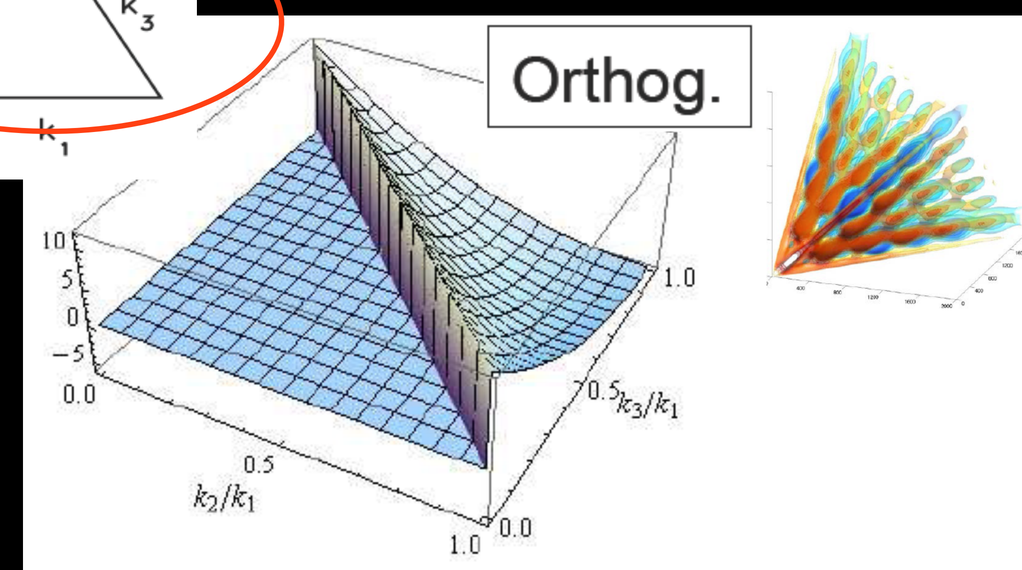


- Multi-field models
- Curvaton
- Ekpyrotic/cyclic models

Planck 2015 results. XVII

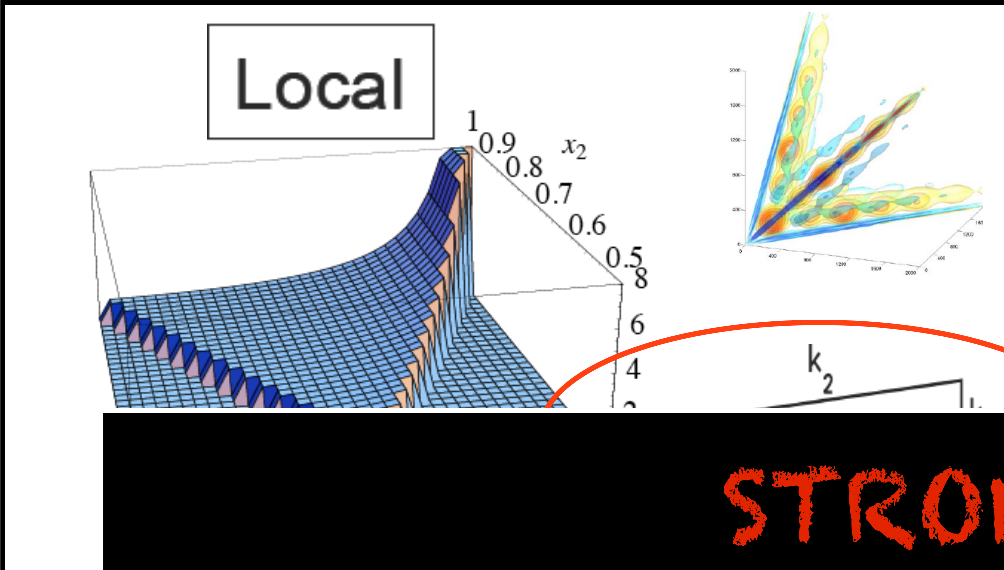


- (K-Inflation, DBI)
- Effective Field Theory



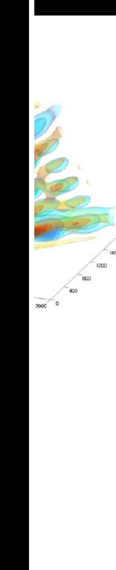
- Higher derivative interaction
- Galileon inflation

CMB Bispectrum Shapes



Planck 2015 results. XVII

- N
- C
- E



STRONG constraints on scalar non-Gaussianity

Planck 2015

Shape and method	f_{NL}(KSW) Independent	f_{NL}(KSW) ISW-lensing subtracted
SMICA (T)		
Local	9.5 ± 5.6	**1.8 ± 5.6**
Equilateral	−10 ± 69	**−9.2 ± 69**
Orthogonal	−43 ± 33	**−20 ± 33**
SMICA (T+E)		
Local	6.5 ± 5.1	**0.71 ± 5.1**
Equilateral	−8.9 ± 44	**−9.5 ± 44**
Orthogonal	−35 ± 22	**−25 ± 22**

Planck 2015 results. XVII

Tensor non-Gaussianity?

$$\langle h^{s_1}(\mathbf{k}_1) h^{s_2}(\mathbf{k}_2) h^{s_3}(\mathbf{k}_3)\rangle \equiv (2\pi)^3 \delta^{(3)}(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3) B_h^{s_1 s_2 s_3}(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3)$$

s= polarization

$$B_h(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3) = f_{NL}^T F(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3)$$

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CMB constraints only about EQUILATERAL CONFIGURATION

$$f_{\rm NL}^{tens} = \frac{5}{18}\frac{B_h^{++\pm}(k,k,k)}{P_\zeta^2(k)}$$

$10^{-2} \times f_{\rm NL}^{tens}(\texttt{parity even}) = 4 \pm 16$

$10^{-2} \times f_{\rm NL}^{tens}(\texttt{parity odd}) = 80 \pm 110$

[Shiraishi et al '15]

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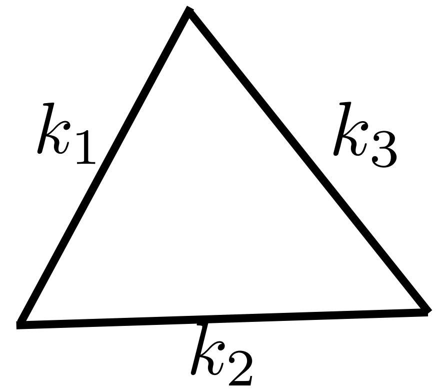
[Shiraishi et al '15]

what about tensor nG @ LISA scales?

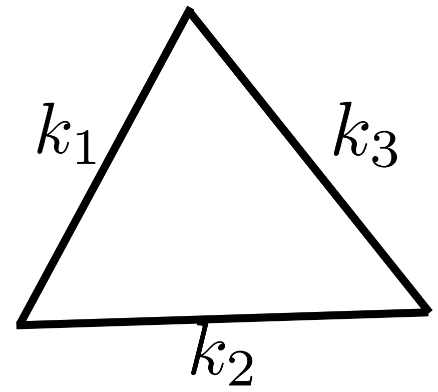
"Equilateral shape": NO IDEA

typical of particle production models



$$k_1 \sim k_2 \sim k_3 = k$$

“Equilateral shape”:



NO IDEA

typical of particle production models

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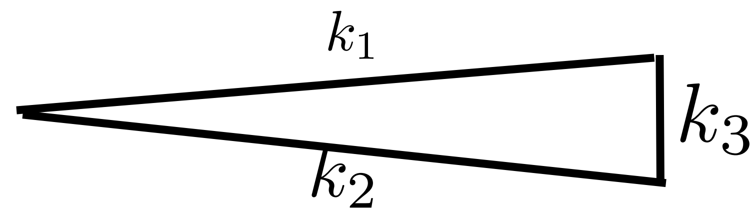

$$k_1 \sim k_2 \gg k_3$$

$$\langle h^{s_1}_{\vec{q}}\, h^{s_2}_{\vec{k}}\, h^{s_3}_{-\vec{k}} \rangle'_{q\to 0} \,=\, \delta^{s_2\, s_3}\, \mathcal{P}_h(q)\, \mathcal{P}_h(k)\, \left(\frac{3}{2} + f^{T}_{\rm NL}\right)\, \epsilon^{(s_1)}_{ij}(\vec{q})\, \frac{k^i\, k^j}{k^2}$$

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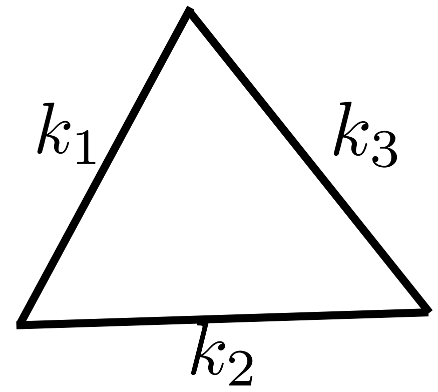

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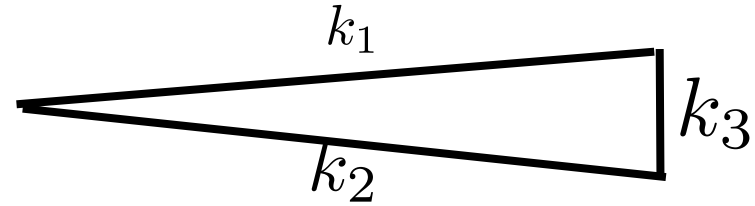

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Then the GWs Power Spectrum...

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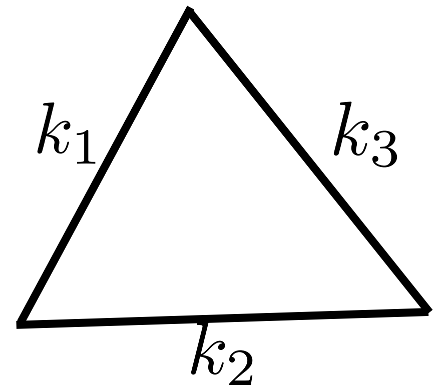

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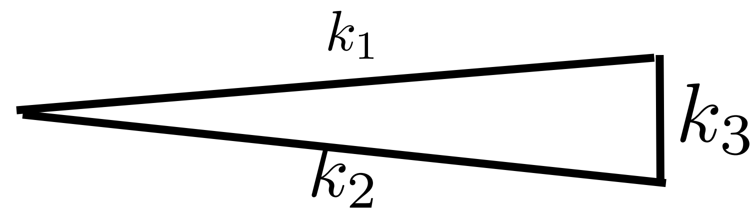

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see Tasinato's Talk

Chiral GWs

[Smith & Caldwell '16]

[B. Thorne et al '17]

For a GW in n = z direction

$$h_{xx}(t,z) = -h_{yy}(t,z) = \mathrm{Re}[B_+ \mathrm{e}^{-iw(t-z)}]$$

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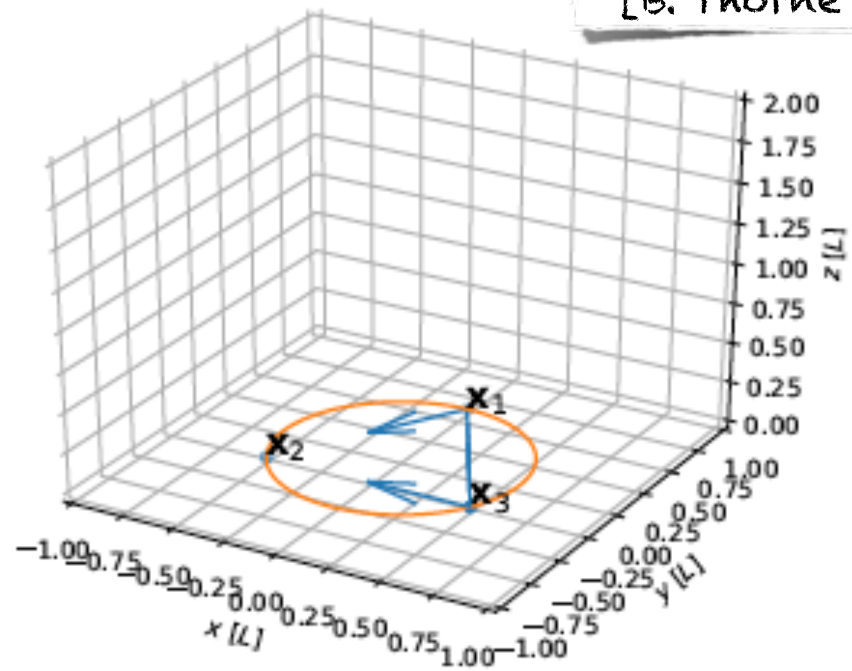

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$$I = |B_R|^2 + |B_L|^2$$

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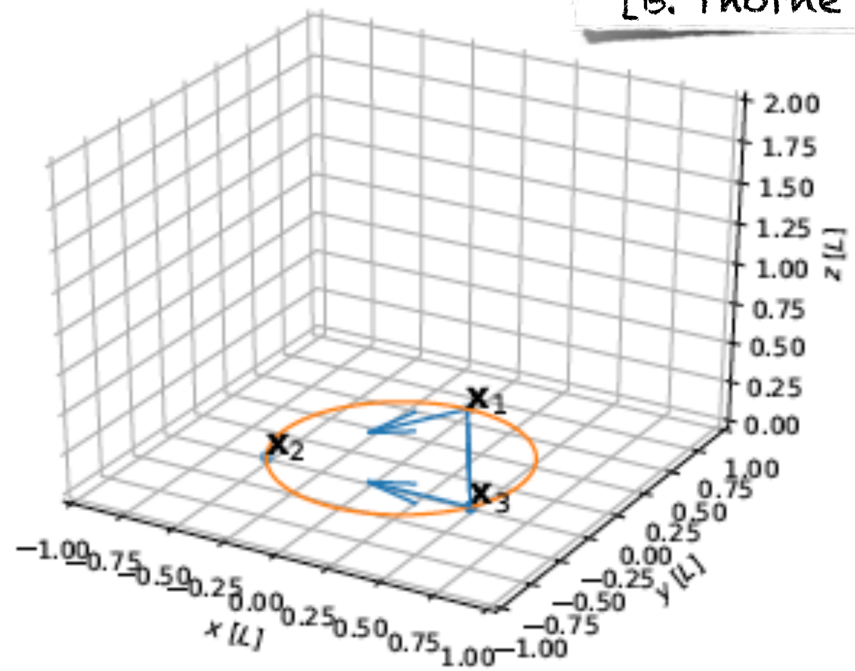

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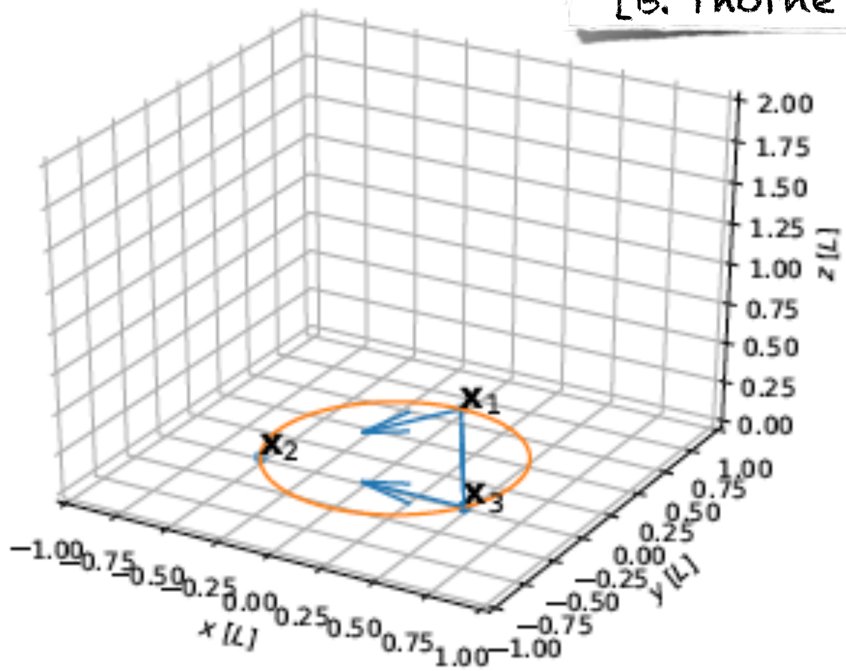

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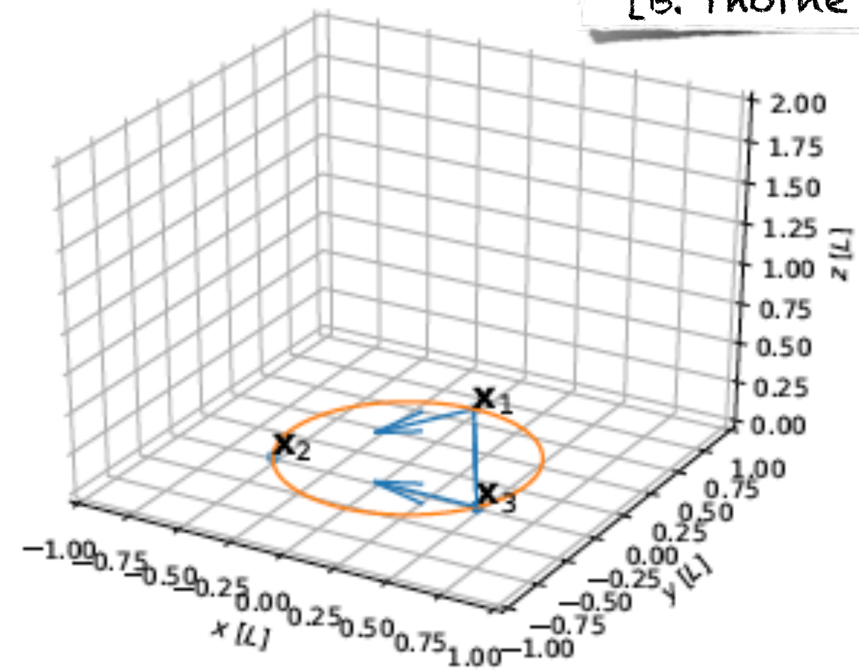

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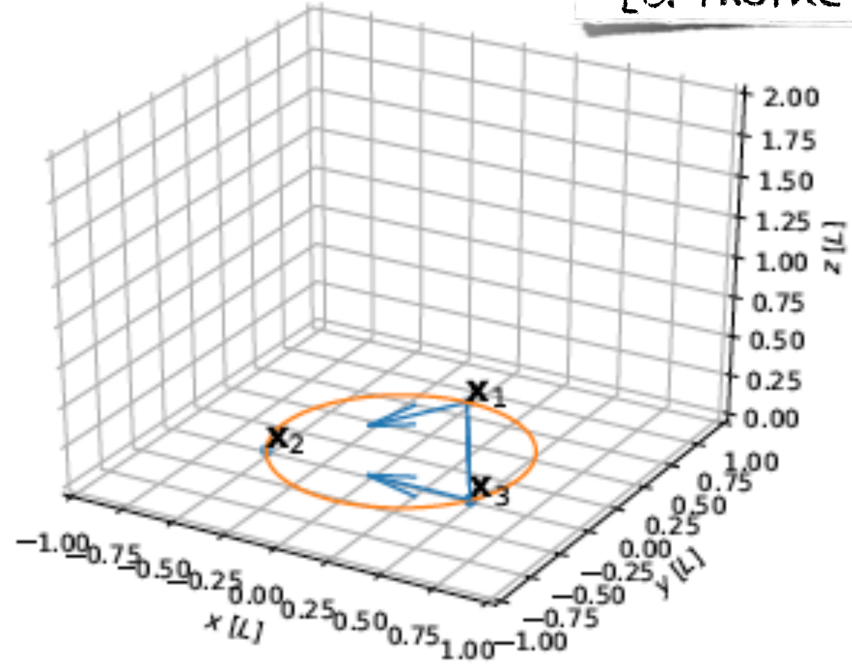

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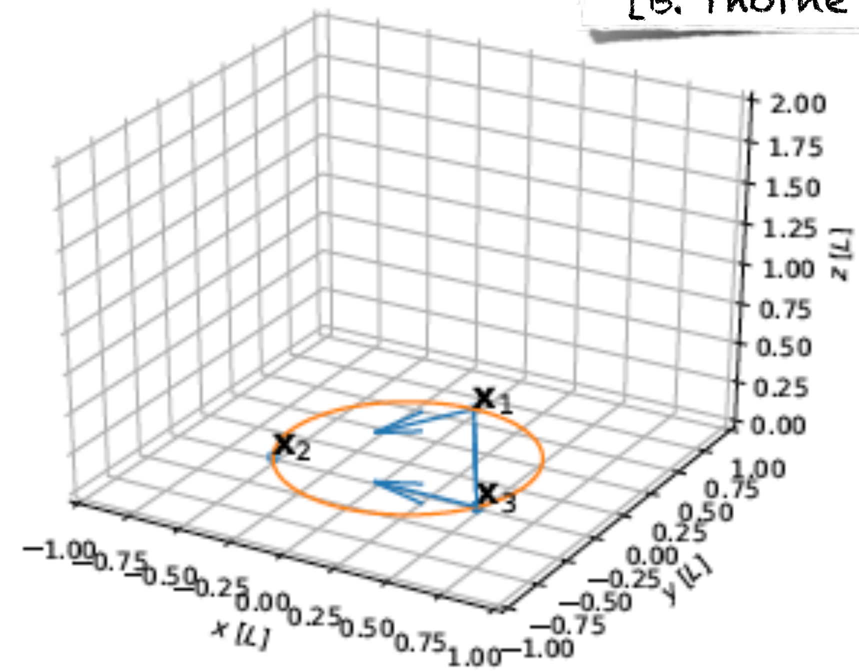

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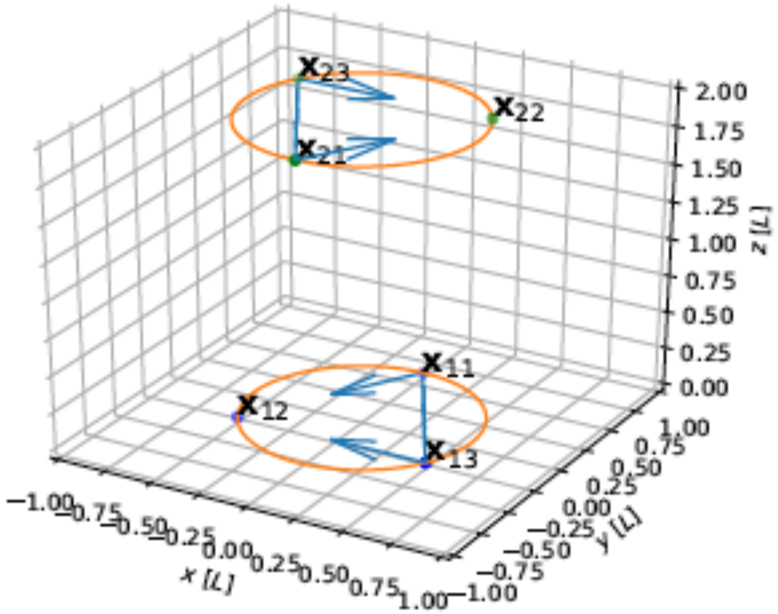

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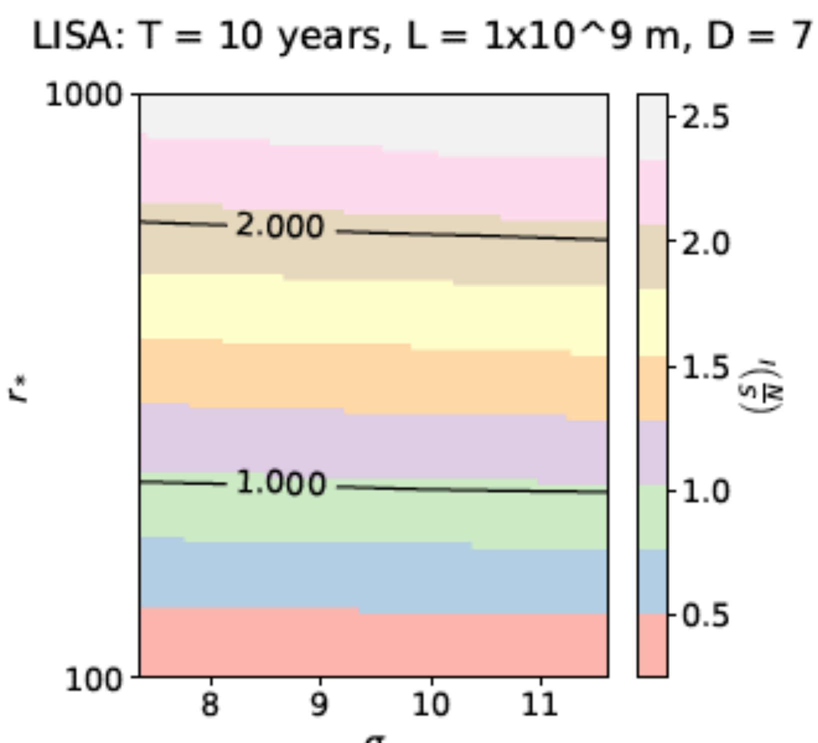

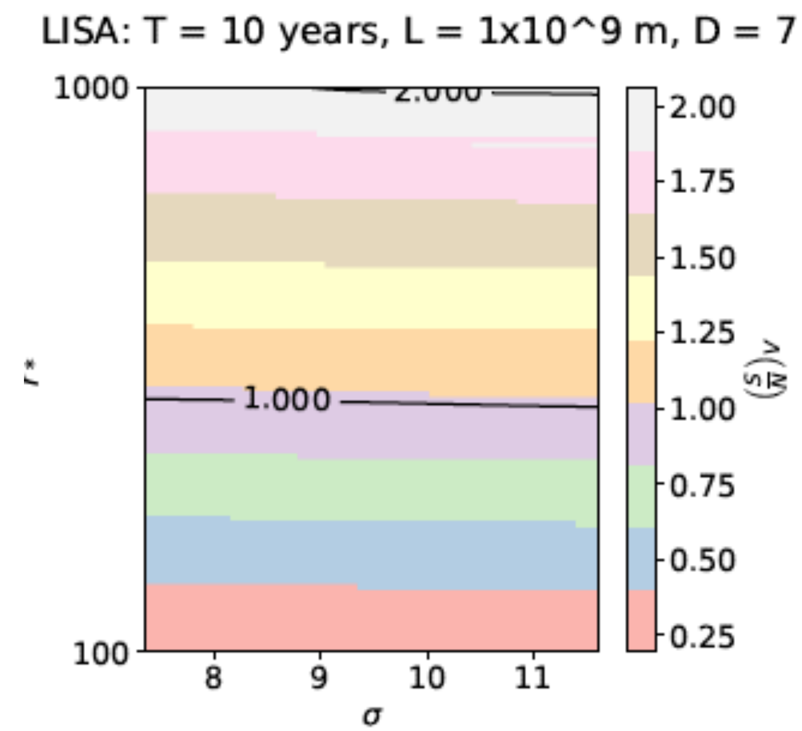

GWs from PBHs

Conditions to generate

- ★ inflection in the potential
- ★ multi-fields
- ★ bubble collisions (?)
- ★ . . .

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Distinguish PHB from astrophys.

- ★ eccentricity
- ★ spin
- ★ mass function
- ★ spatial distribution?
- ★ . . .

} How are they related to inflation?

see Garcia-Bellido and Peloso's Talks

The detection or NOT of primordial GWs with LISA, constrains inflationary cosmological parameters complementary to CMB

- Next steps?

Forecast the ability of LISA to constrain "inflationary-related" scenarios

Ability of LISA to constrain other "cosmological" observables (n-G, extra polarizations ...)

LISA abilities for PBHs phenomenology