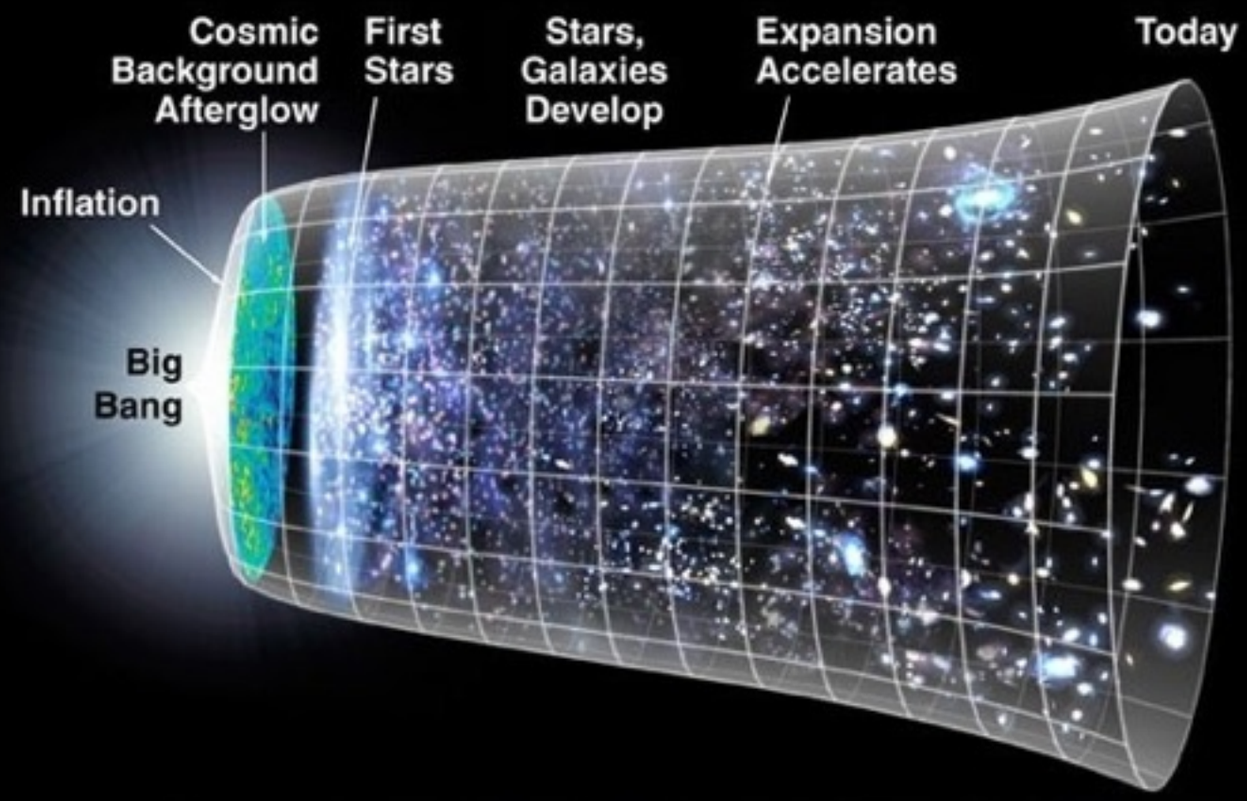
Primordial Gravitational Waves and Inflation



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April 6th 2023

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Inflation

Simplest realization: single-scalar field in slow-roll

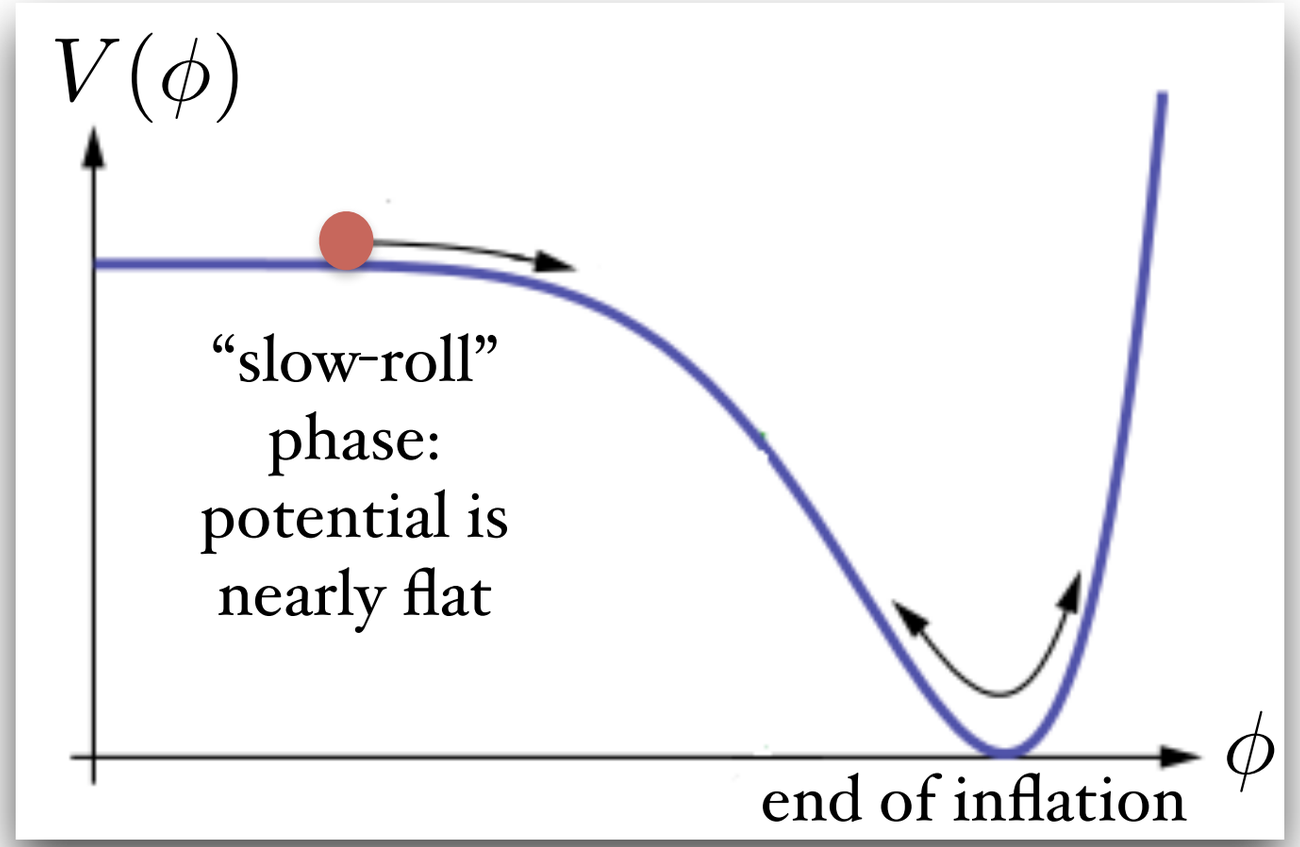
- Scalar field :

$$p_\phi = \frac{\dot\phi^2}{2} - V(\phi) \approx -V(\phi)$$

$$\rho_\phi = \frac{\dot\phi^2}{2} + V(\phi) \approx V(\phi)$$

$$\dot\phi^2 \ll V$$

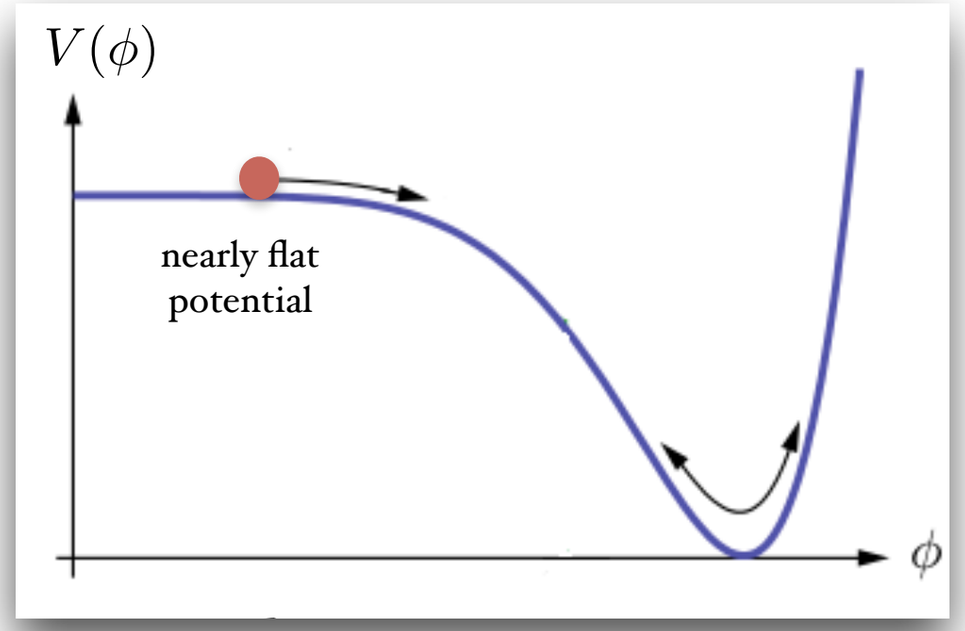
$$p_\phi \approx -\rho_\phi$$



Slow-roll

start flat

$$\epsilon \equiv -\frac{\dot{H}}{H^2} \simeq \frac{M_{\rm P}^2}{2}\left(\frac{V'}{V}\right)^2 \simeq \frac{3}{2}\frac{\dot{\phi}^2}{V} \ll 1$$



stay flat

$$|\eta| \equiv \frac{|\dot{\epsilon}|}{H\epsilon} \simeq -\frac{2}{3}\left(\frac{V''}{H^2}\right) + 4\epsilon \ll 1$$

Metric Fluctuations

$$ds^2 = (-dt^2 + a(t)^2[e^{2\zeta}\delta_{ij} + \gamma_{ij}]dx^i dx^j)$$

scalar fluctuations

tensor perturbations

Observables

(in the minimal scenario)

$$ds^2 = (-dt^2 + a(t)^2[e^{2\zeta}\delta_{ij} + \gamma_{ij}]dx^i dx^j)$$

scalar fluctuations

$$\mathcal{P}_\zeta(k) = \frac{1}{8\pi^2}\frac{1}{\epsilon}\frac{H^2}{M_{\rm pl}^2}\left(\frac{k}{k_*}\right)^{n_s-1}$$

$$n_s - 1 \simeq -2\epsilon - \eta$$

2.2×10^{-9}

0.9649 ± 0.0042

$[k_* = 0.05\,\mathrm{Mpc}^{-1}, 68\%\mathrm{C.L.}]$

from Planck measurements of CMB anisotropies

tensor perturbations

$$\mathcal{P}_\gamma^{\rm vacuum}(k) = \frac{2}{\pi^2}\frac{H^2}{M_{\rm pl}^2}\left(\frac{k}{k_*}\right)^{n_T}$$

proxy "energy" scale of inflation

red tilt

$$n_T \simeq -2\epsilon \simeq -r/8$$

tensor-to-scalar ratio $r \equiv \dfrac{\mathcal{P}_\gamma}{\mathcal{P}_\zeta}$

bounds

current

$r < 0.032$ $(95\%, \mathrm{Planck} + \mathrm{BICEP/Keck})$

future

$r < 0.01$ (CMB-S3); $r < 0.001$ (-S4)

Energy Scale of Inflation

(in the minimal scenario)

$$V^{1/4} \simeq 10^{16}\mathrm{GeV}\left(\frac{r}{0.01}\right)^{1/4}$$

The Cosmological “Collider” and the desert in between

10^3GeV

Beyond SF-SR, r <=x=> E_{inf} , but thorough **characterization** of the signal across the scales can go a long way!

spectral shape

chirality

non-Gaussianity

GW anisotropies

Guaranteed Scientific Returns I

Planckian field range and Symmetries

$$\frac{\Delta\phi}{M_{\rm P}} \gtrsim \left(\frac{r_*}{8}\right)^{1/2} \mathcal{N}_* \gtrsim \left(\frac{r}{0.01}\right)^{1/2}$$

r ~ 0.01 detection

Planckian field range ⟶ d.o.f.s other than the inflaton would become relevant

matter + GR generally has $\Lambda_{\rm UV}^{\rm cutoff} < M_{\rm P}$ ⟶ e.g. massive fields become light

↓

not the smooth SF-SR potential one started with

unless

there is a symmetry protecting e.g. couplings

Guaranteed Scientific Returns II

Ruling in (out) simple & compelling Models

r ~ 0.001 detection

Notice $n_s(\mathcal{N}) - 1 = -\dfrac{p+1}{\mathcal{N}}$ for typical $\mathcal{N}$ is about right

If $\epsilon \ll 1$ then $r(\mathcal{N}) = \dfrac{8p}{\mathcal{N}} \dfrac{1}{1 + (\mathcal{N}/\mathcal{N}_{\rm eq})^p}$

$\dfrac{8p}{\mathcal{N}} \simeq 0.01$ monomial potentials

$\dfrac{8p}{\mathcal{N}} \left(\dfrac{N_{\rm eq}}{\mathcal{N}}\right)^p \simeq 0.001$ hilltop & plateau

Starobinsky inflation (R^2)

Higgs inflation

fibre inflation

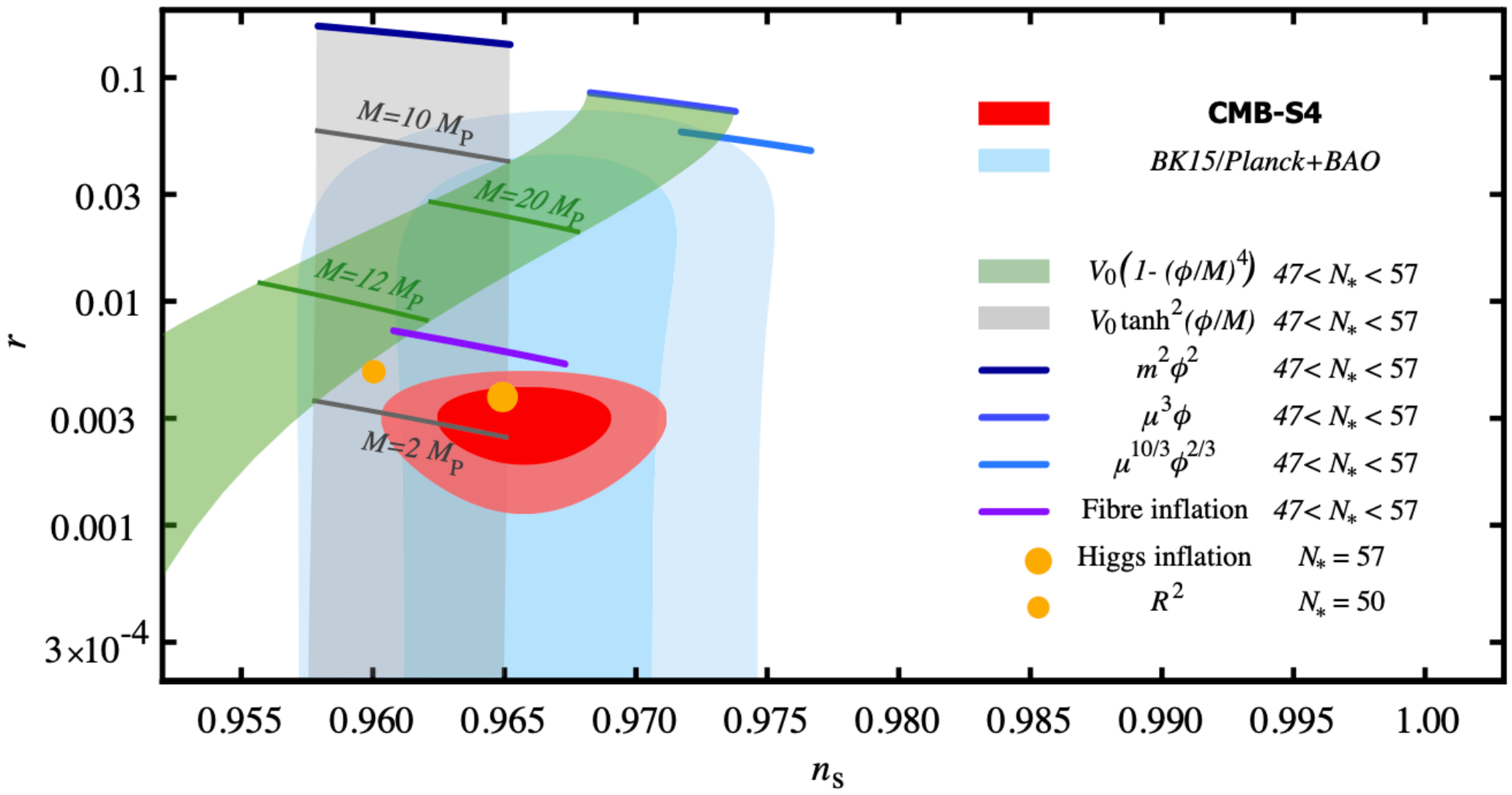
α-attractors

(for benchmark values of α)

Compelling also because these models are easily embedded in e.g. supergravity & string theory constructions!

Guaranteed Scientific Returns II

Ruling in (out) simple & compelling Models



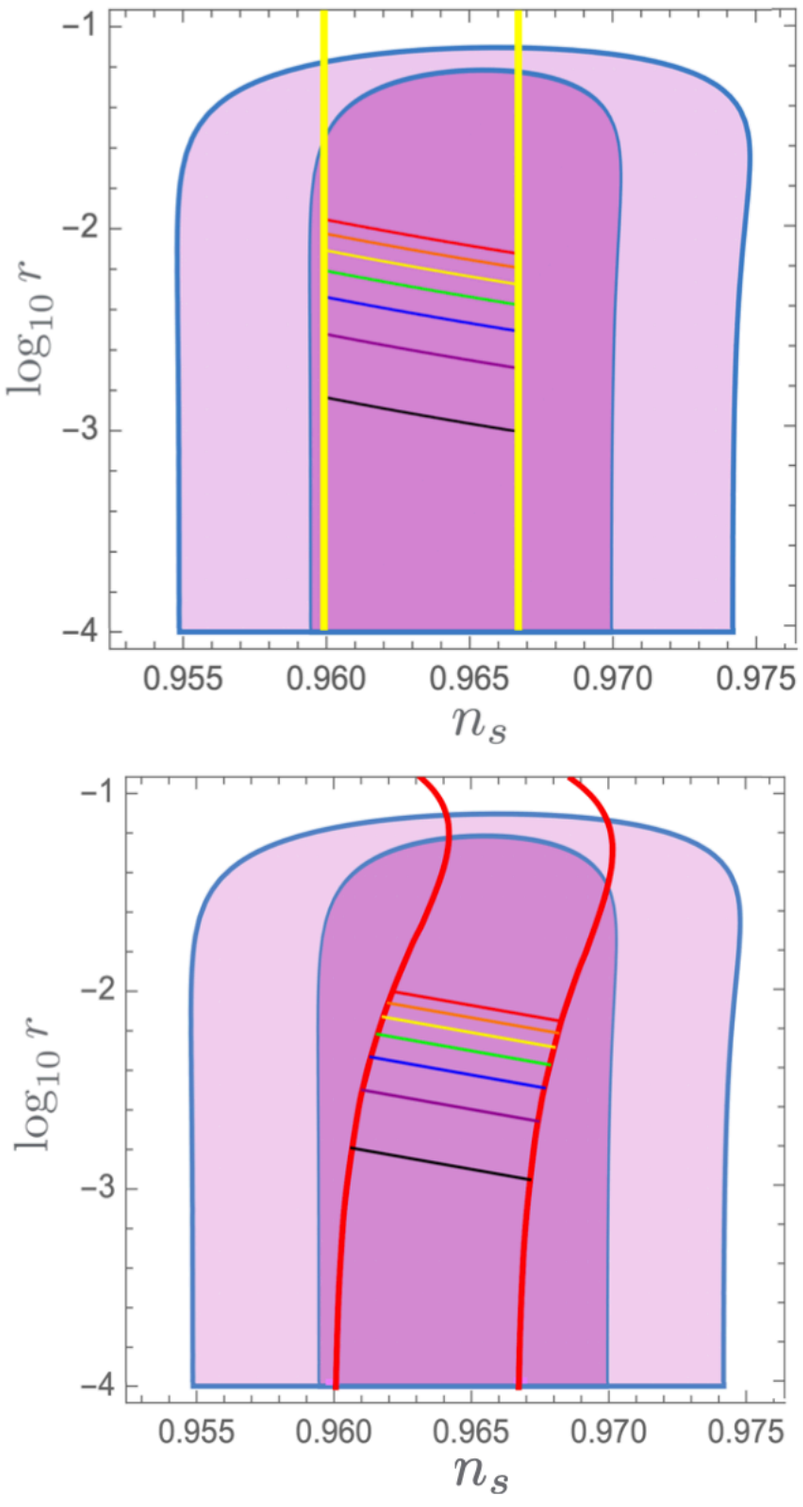
Guaranteed Scientific Returns II

Ruling in (out) simple & compelling Models

U-duality benchmarks

$3\alpha \in \{1, 2, 3, 4, 5, 6, 7\}$

in alpha-attractor inflationary models originating from theories with maximal supersymmetry: M-theory, string theory, maximal supergravity



$$1 - n_s = \frac{2}{\mathcal{N}}$$

$$r = \frac{12\alpha}{\mathcal{N}^2}$$

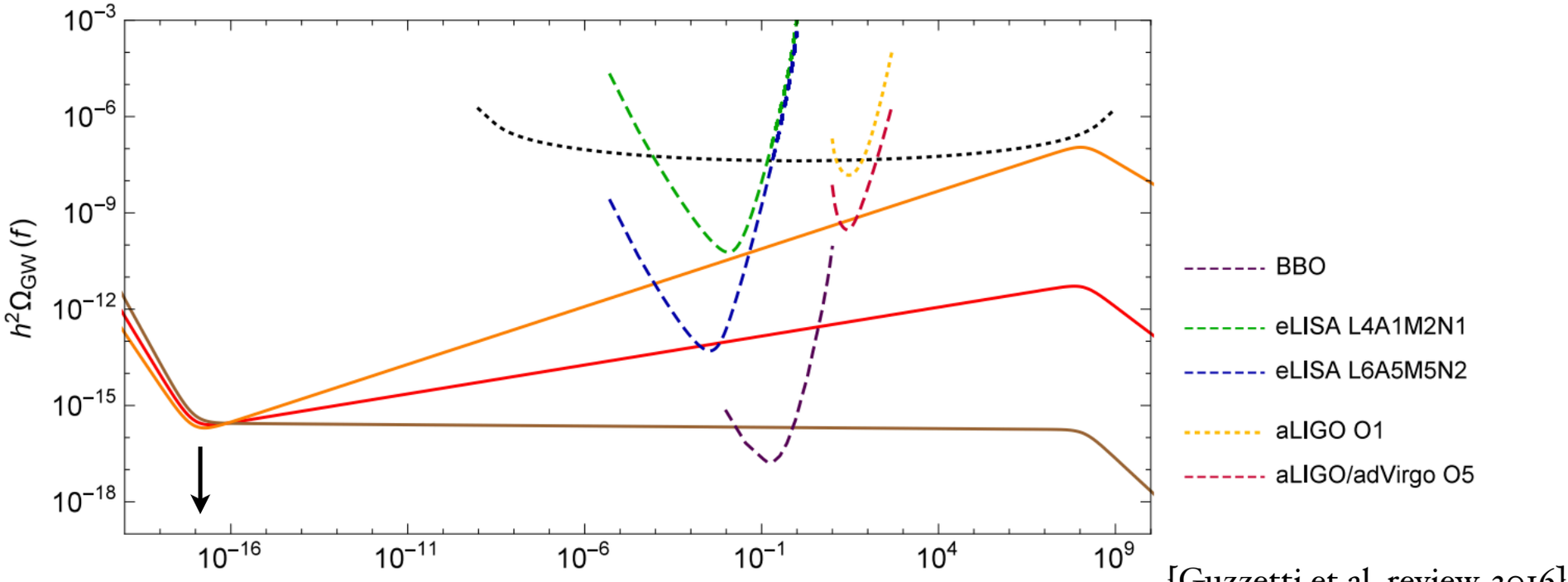
[Kallosh, Linde, 2019]

(Indirect yet) Guaranteed Scientific Returns III

Lowering bound on r very hard to satisfy for models generating observable GW at small scales

==>

rules out massive parameter (and model) space chunks in theories with blue spectrum



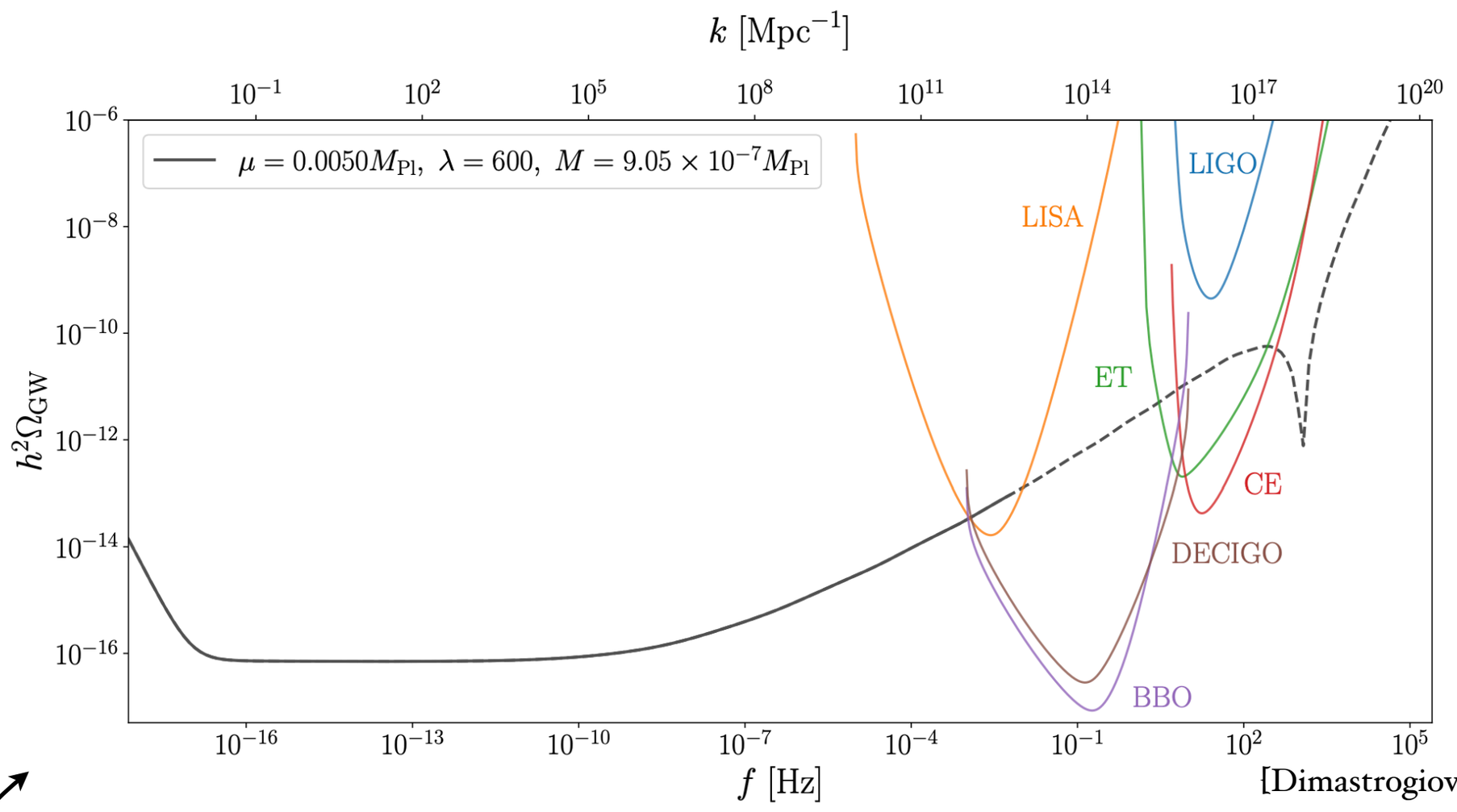
[Guzzetti et al, review, 2016]

(i) Saturate CMB bound on r
(ii) Detectable by LISA/ET/CE <u>yet not by</u> LIGO/VIRGO

} very hard for n_T =const!

(Indirect yet) Guaranteed Scientific Returns III

Axion-inflation (with gauge fields) models:
large, blue, chiral GW spectrum at small scales, yet impactful constraints from CMB-S3,4



[Dimastrogiovanni et al 2023]

How generic? Typical in classes of models with Chern-Simons couplings between inflaton and gauge sector

$$\frac{\lambda}{f}\phi F\tilde{F} \longrightarrow \frac{\lambda\dot{\phi}}{f}\ldots$$

Last 3 weeks
- [Dimastrogiovanni et al], SU(2)
- [Garcia-Belllido et al], U(1)
- [Figueroa et al], U(1) on the lattice

Conclusions

Planckian field range and Symmetries ✔

Ruling in (out) simple & compelling Models ✔

Starobinsky, Higgs, fiber, benchmark alpha-attractors +...

- ⭐ Full characterisation crucial (and extremely effective) to draw conclusions beyond single-field slow-roll ❗

- ⭐ CMB-S3,4 benchmarks very consequential even for classes of inflationary models whose signatures are typically most striking at smaller scales ✔

Thank you!