Cosmological probes of additional field content during inflation

XX/05/2022
Hot Topics in Modern Cosmology
SW 14

O.Ö, arXiv: 2005.10280
O.Ö, arXiv: 2106.14895
P. Campeti, O.Ö, I. Obata, M. Shiraishi, arXiv: 2203.03401

O.Ö, Z. Lalak, arXiv: 2008.07549

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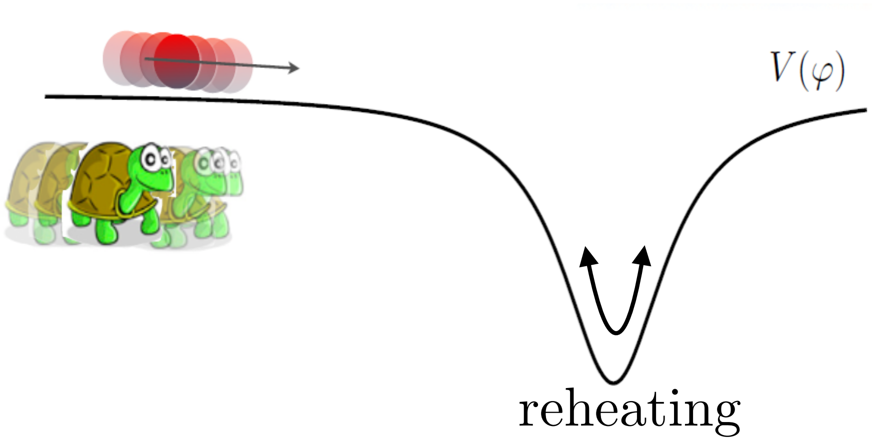
FZU

Ogan Özsoy

Recap: Inflation (Single field slow-roll)

- Simplest realization: single scalar field in slow-roll motion!

$$\left.\begin{aligned} P_\varphi &= \dot{\varphi}^2/2 - V(\varphi), \\ \rho_\varphi &= \dot{\varphi}^2/2 + V(\varphi). \end{aligned}\right\} \quad \dot{\varphi}^2/2 \ll V(\varphi) \Rightarrow P_\varphi \approx -\rho_\varphi$$



$$\mathrm{slow-roll}: \quad \begin{aligned} \epsilon &\equiv -\frac{\dot{H}}{H^2} \simeq \frac{M_{\rm pl}}{2}\left(\frac{V'}{V}\right)^2 \ll 1 \\ \eta &= \frac{\dot{\epsilon}}{\epsilon H} \simeq -\frac{2}{3}\frac{V''}{H^2} + \mathcal{O}(\epsilon) \ll 1 \end{aligned}$$

→ Needs to stay flat to solve puzzles of Hot Big Bang cosmology!

Single field slow-roll @ CMB

- Scalar power spectra:

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

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

$\mathcal{A}_s \simeq 2.1\times10^{-9}$ $\quad n_s = 0.9649 \pm 0.0042$

at $k = k_{\rm CMB} = 0.05\ {\rm Mpc}^{-1}$, %68 CL

by $\langle \delta T\,\delta T\rangle$

Agreement beyond 2-pt statistics, $f_{\rm NL} \simeq \mathcal{O}(\epsilon,\eta)$ $\quad f_{\rm NL}^{\rm local} = -0.9 \pm 5.1$

- Tensor power spectra:

Not observed yet!

$$\mathcal{P}_h^{\rm vac}(k) = \frac{2H^2}{\pi^2 M_{\rm pl}^2}\left(\frac{k}{k_{\rm CMB}}\right)^{n_t}$$

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

$$r \equiv \frac{\mathcal{P}_h}{\mathcal{P}_{\mathcal{R}}} < 0.056$$

→

$r \lesssim 0.001$ CMB S-4

Future bounds LiteBIRD

☆ Single field slow-roll agrees well with CMB observations !

Beyond Single field slow-roll (@ CMB) ?

- To re-evaluate the implications of GW observations

Lyth ‘97

$$\underbrace{h''_{ij} + 2\frac{a'(\tau)}{a(\tau)}h'_{ij} + k^2 h_{ij}}_{\equiv 0 \text{ for vacuum}} = \frac{2}{M_{\rm pl}^2} T_{ij}^{TT} \qquad H_{\rm inf} \overset{?}{\simeq} 2.4 \times 10^{-5} \left(\frac{r}{0.056}\right)^{1/2} M_{\rm pl}$$

(Namba et. al, ’15). (Dimastrogiovanni et.al, ’16)
(Biagetti et. al. ’13) (Fujita et.al, ’17)

- Additional field content is likely outcome from top-down perspective.

String Theory → 4D EFT with many moduli fields, axions & gauge fields

- Extra d.o.f’s have testable predictions
  - Chiral, scale dependent, non-Gaussian GWs of non-vacuum origin.
  - Mixed tensor - scalar non-Gaussianities, …

Axion-GF dynamics as a source of GWs

$$\frac{\mathcal{L}_m}{\sqrt{-g}} = -\frac{1}{2}\partial_\mu a\,\partial^\mu a - V_{\rm sb}(a) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{c_a}{4f}\,a\,F_{\mu\nu}\tilde{F}^{\mu\nu} + \dots$$

Approximate shift symmetry: $a \to a + c$

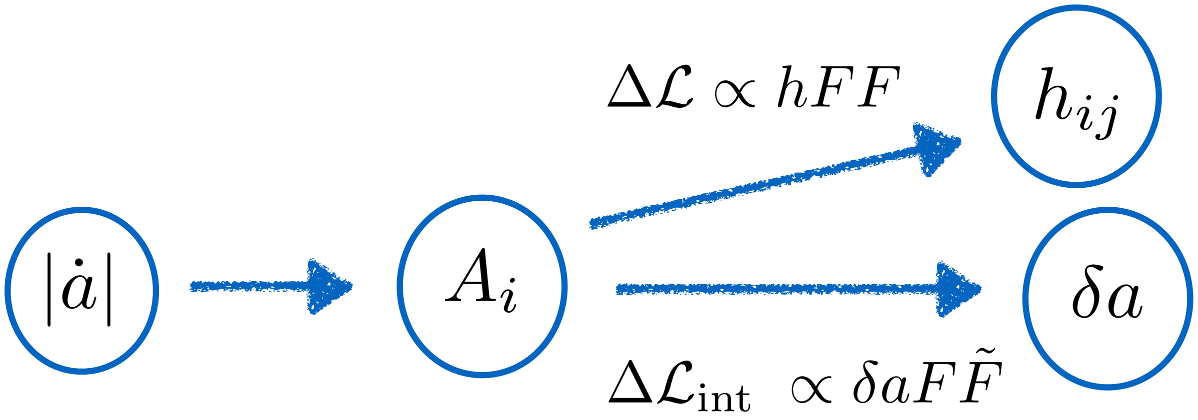
- They are light and can roll a significant amount of time during inflation:

$$\dot{a}^2 \gg \rho_h^{\rm vac} \simeq H^4$$

(A resourceful Dinamo/reservoir!)

- Natural couplings to matter sector where they can dump their energy into:

$$\Delta\mathcal{L}_{\rm int} = \frac{c_a}{4f} aF\tilde{F} \equiv -\frac{c_a}{2f}\,\epsilon^{\mu\nu\rho\sigma}\,\partial_\mu a\,\partial_\rho A_\sigma\,A_\nu$$



$\Delta\mathcal{L} \propto hFF$

h_{ij}

$|\dot{a}|$

A_i

δa

$\Delta\mathcal{L}_{\rm int} \;\propto \delta a F\tilde{F}$

$a = \phi$ case is problematic,

Too much NG's restricting

$h_{\rm sourced} \ll h_{\rm vacuum}$

(N. Barnaby & M. Peloso, '10)
(OÖ, K. Sinha & S.Watson '14)

Extended model with a spectator axion

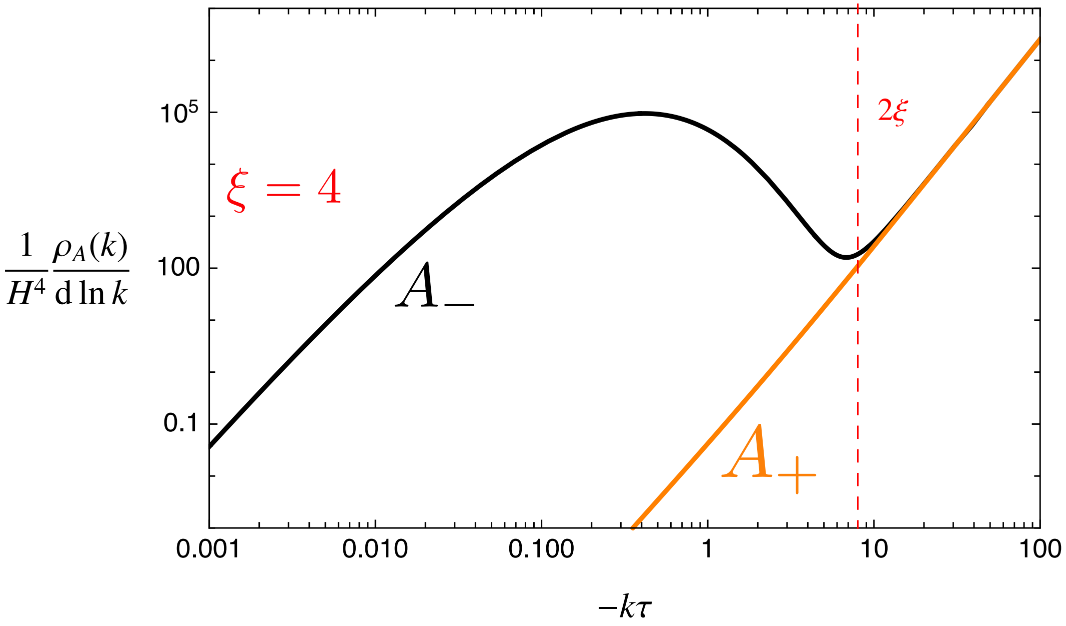
To decouple the GW source (GFs) as much as possible: Spectator axion σ !

$$\frac{\mathcal{L}_m}{\sqrt{-g}} = -\frac{1}{2}(\partial\phi)^2 - V_\phi(\phi) - \frac{1}{2}(\partial\sigma)^2 - V_\sigma(\sigma) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{\alpha_c}{4f}\,\sigma\,F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Barnaby et.al '12

$$A''_\pm + k^2\left(1 \pm \frac{2\xi}{x}\right)A_\pm = 0$$

$$\xi \equiv \frac{\alpha_c|\dot{\sigma}|}{2Hf}$$



- Parity breaking!
- Exponential sensitivity to

$$A_- \propto \exp\left[\frac{\pi\alpha_c|\dot{\sigma}|}{Hf}\right]$$

- ρ_A is diluted at late times

Extended model with a spectator axion

To decouple the GW source (GFs) as much as possible: Spectator axion σ !

$$\frac{\mathcal{L}_m}{\sqrt{-g}} = -\frac{1}{2}(\partial\phi)^2 - V_\phi(\phi) \boxed{- \frac{1}{2}(\partial\sigma)^2 - V_\sigma(\sigma) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{\alpha_c}{4f}\,\sigma\, F_{\mu\nu}\tilde{F}^{\mu\nu}}$$

Barnaby et.al '12

1) $\Delta\mathcal{L}_{\rm int} \propto h_{ij}FF \longrightarrow A_- + A_- \to h_-^{(s)}$ GW emission!

2) $\Delta\mathcal{L}_{\rm int} \propto \sigma F\tilde{F} \longrightarrow A_- + A_- \to \delta\sigma^{(s)} \underset{\downarrow\, |\dot{\sigma}| \neq 0}{\to} \delta\phi^{(s)} \propto \mathcal{R}^{(s)}$

Ferreira&Sloth, '14

Tensor to scalar ratio reduces due to NG constraints, the key difficulty here: Generating observable GWs without overproducing NG density perturbations

Ferreira&Sloth, '14, O.Ö, '17

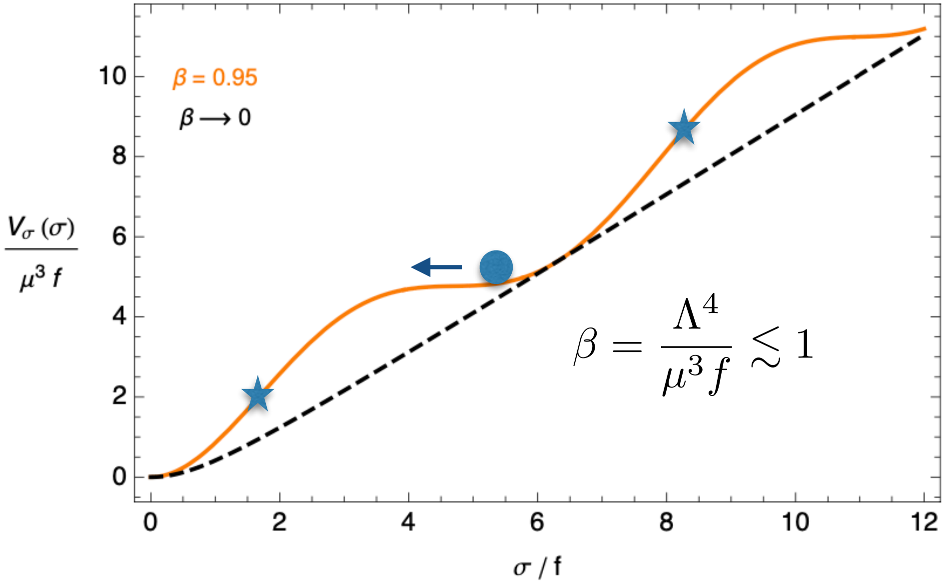
*To keep channel (2) under control, we need to switch of gauge field production, e.g through a localized roll of σ !

*R. Namba, M. Peloso, M. Shiraishi, L. Sorbo, C. Ünal arXiv:1509.07521

Localized signal (spectator axion-GF dynamics)

$$\frac{\mathcal{L}_m}{\sqrt{-g}} = -\frac{1}{2}(\partial\phi)^2 - V_\phi(\phi) \boxed{- \frac{1}{2}(\partial\sigma)^2 - V_\sigma(\sigma) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{\alpha_c}{4f}\,\sigma\, F_{\mu\nu}\tilde{F}^{\mu\nu}}$$

Signal is sensitive to $V_\sigma(\sigma)$ → $A_- \propto e^{|\dot\sigma|}$



$$\beta = \frac{\Lambda^4}{\mu^3 f} \lesssim 1$$

↓

Localized emission of GWs
and Scalar perturbations

$$A_- + A_- \to h_-^{(s)}$$

$$A_- + A_- \to \delta\sigma^{(s)} \to \delta\phi^{(s)} \propto \mathcal{R}^{(s)}$$

$\dot\sigma \neq 0$ for a finite amount of time

$$V_\sigma(\sigma) = \mu^3\sigma + \Lambda^4\left[1 - \cos\left(\frac{\sigma}{f}\right)\right]$$

Scale dependent bumps in the
scalar and tensor spectra!

(McAllister et.al, '08)
(Silverstein & Westphal, '08)

Axion Monodromy!

arXiv: 2005.10280-O.Ö

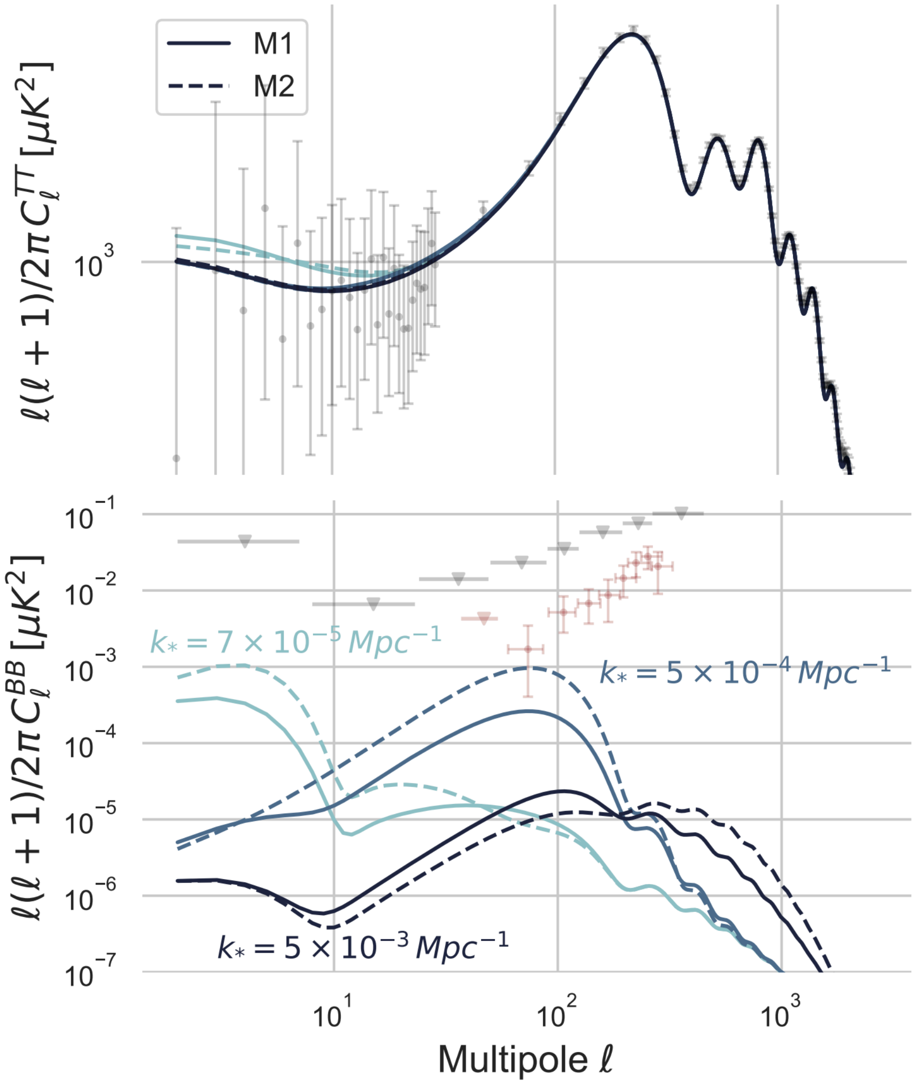
Localized signal (spectator axion-GF dynamics)

$r_{\mathrm{vac}} = 10^{-4}$ $\quad m_\sigma^2 = 0.6H^2$

$$\mathcal{P}_{\mathcal{R}} = \mathcal{P}_{\mathcal{R}}^{(\mathrm{vac})} + \mathcal{P}_{\mathcal{R}}^{(\mathrm{s})}\left(m_\sigma, \frac{k}{k_*}, \dot{\sigma}_*\right)$$

$$\mathcal{P}_h = \mathcal{P}_h^{(\mathrm{vac})} + \mathcal{P}_h^{(\mathrm{s})}\left(m_\sigma, \frac{k}{k_*}, \dot{\sigma}_*\right)$$

$k_* = \{7\times10^{-5}, 5\times10^{-4}, 5\times10^{-3}\}\,[\mathrm{Mpc}^{-1}]$



$$\left(\frac{r_*}{0.056}\right)^{1/2} \simeq \left(\frac{H_{\mathrm{inf}}/M_{\mathrm{pl}}}{2.4\times10^{-5}}\right)^2 e^{1.58\pi(\xi_*-4.05)}$$

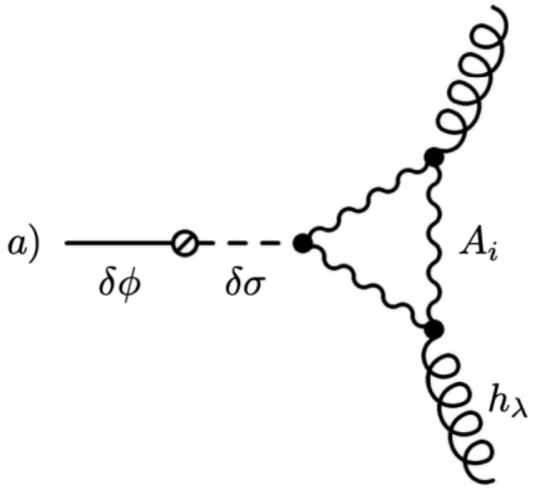
Distinguishable via tensor running, or TB and BBB*

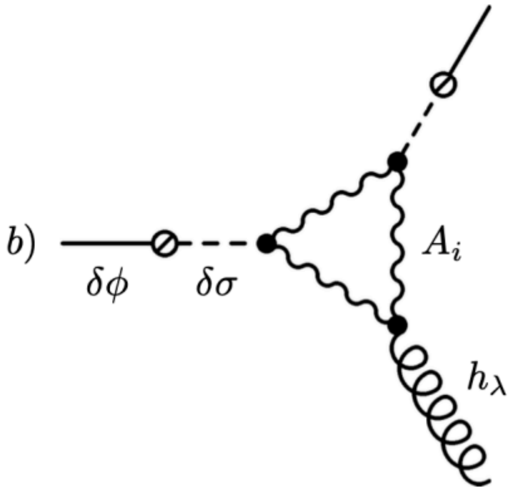
arXiv: 2203.03401-P. Campeti O.Ö, I. Obata, M. Shiraishi

*M. Shirashi et. al. 1606.06082

Spectator axion-GF dynamics

Other signals for distinguishability:





$$\langle \mathcal{R} h_- h_- \rangle \gg \langle \mathcal{R} h_+ h_+ \rangle$$

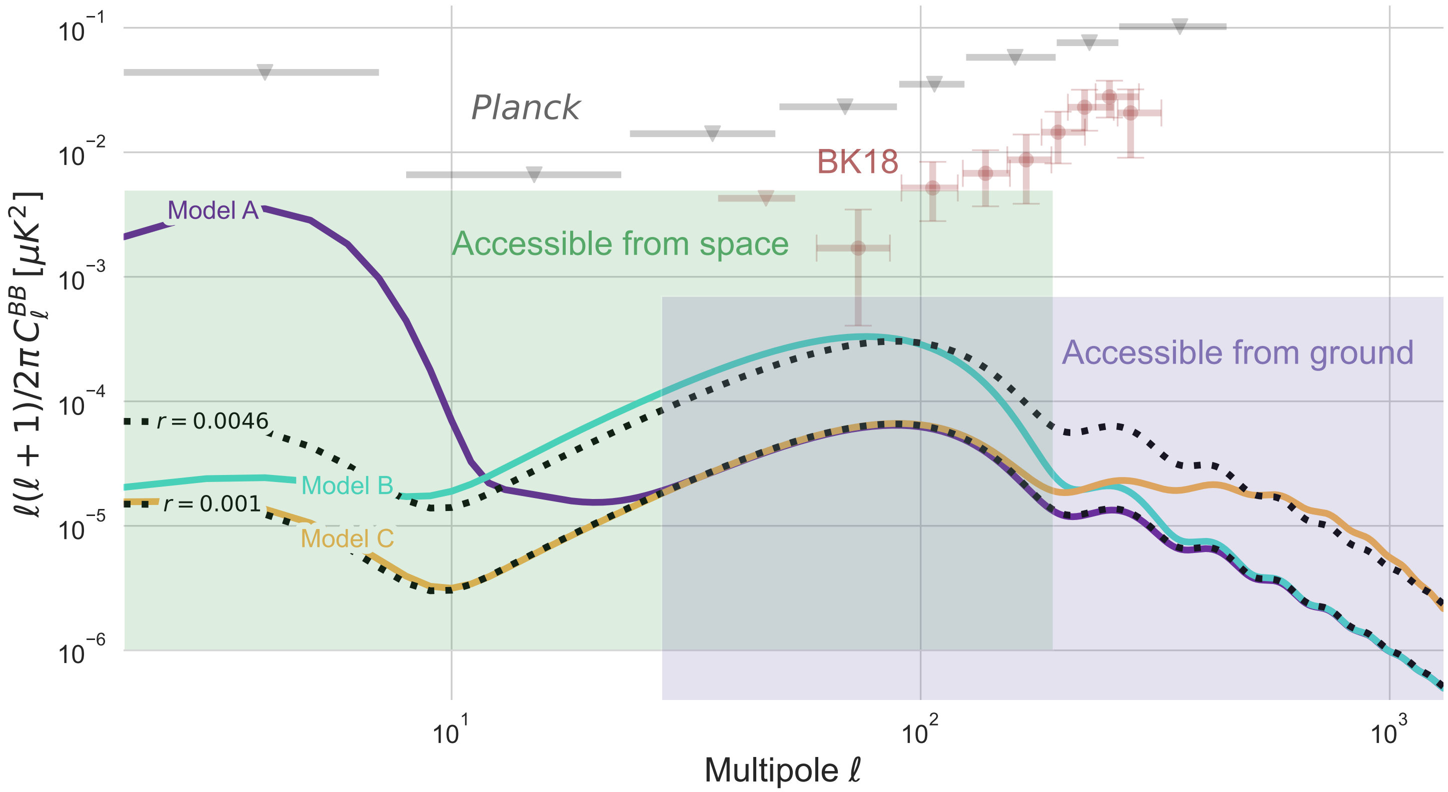
$$\langle h_- \mathcal{R}\mathcal{R} \rangle \gg \langle h_+ \mathcal{R}\mathcal{R} \rangle$$

$$f_{\rm NL} \sim \mathcal{O}(1-10) \left(\frac{r_*}{0.01}\right)^{3/2}$$

Parity violating mixed non-Gaussianity!

arXiv:2106.14895-O.Ö

Conclusions (Part 1)

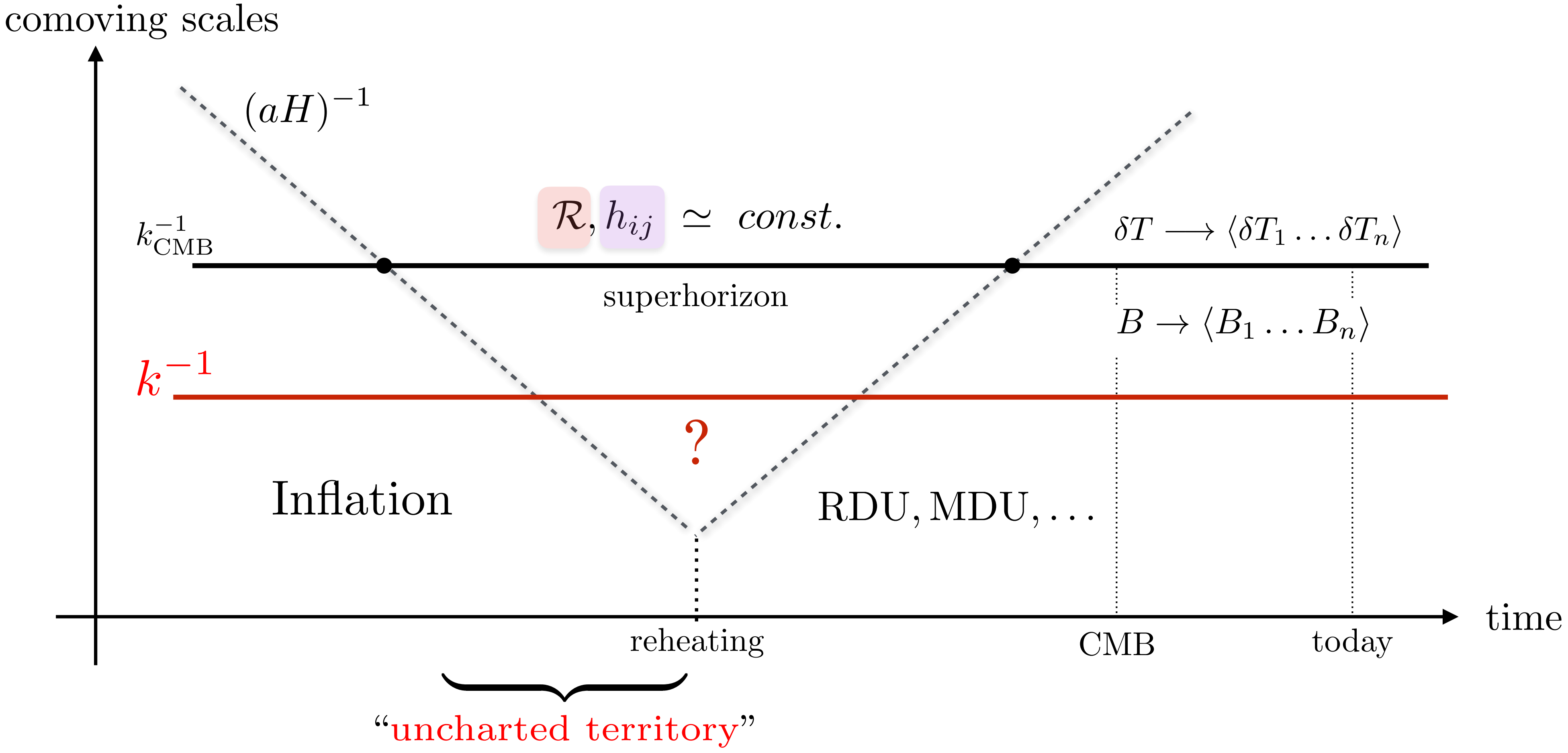


- Observable synthetic GWs with low scale of inflation and sub-planckian field excursion is possible but one needs to try hard to shake the standard view on inflation: i.e r vs H
- Nevertheless, additional field content have interesting implications: chiral, scale dependent, non-Gaussian GWs.

✓ Any departure from the standard predictions on tensor fluctuations: scale free, parity conserving and high degree Gaussianity, have the potential to inform us about the inflationary field content.

✓ B-modes and their properties are expected to be measured by forthcoming experiments: CMB-S4 and LiteBIRD. Accessing the whole range of multipoles is important to establish vacuum vs non-vacuum origin of GWs: CMB-S4 + LiteBIRD

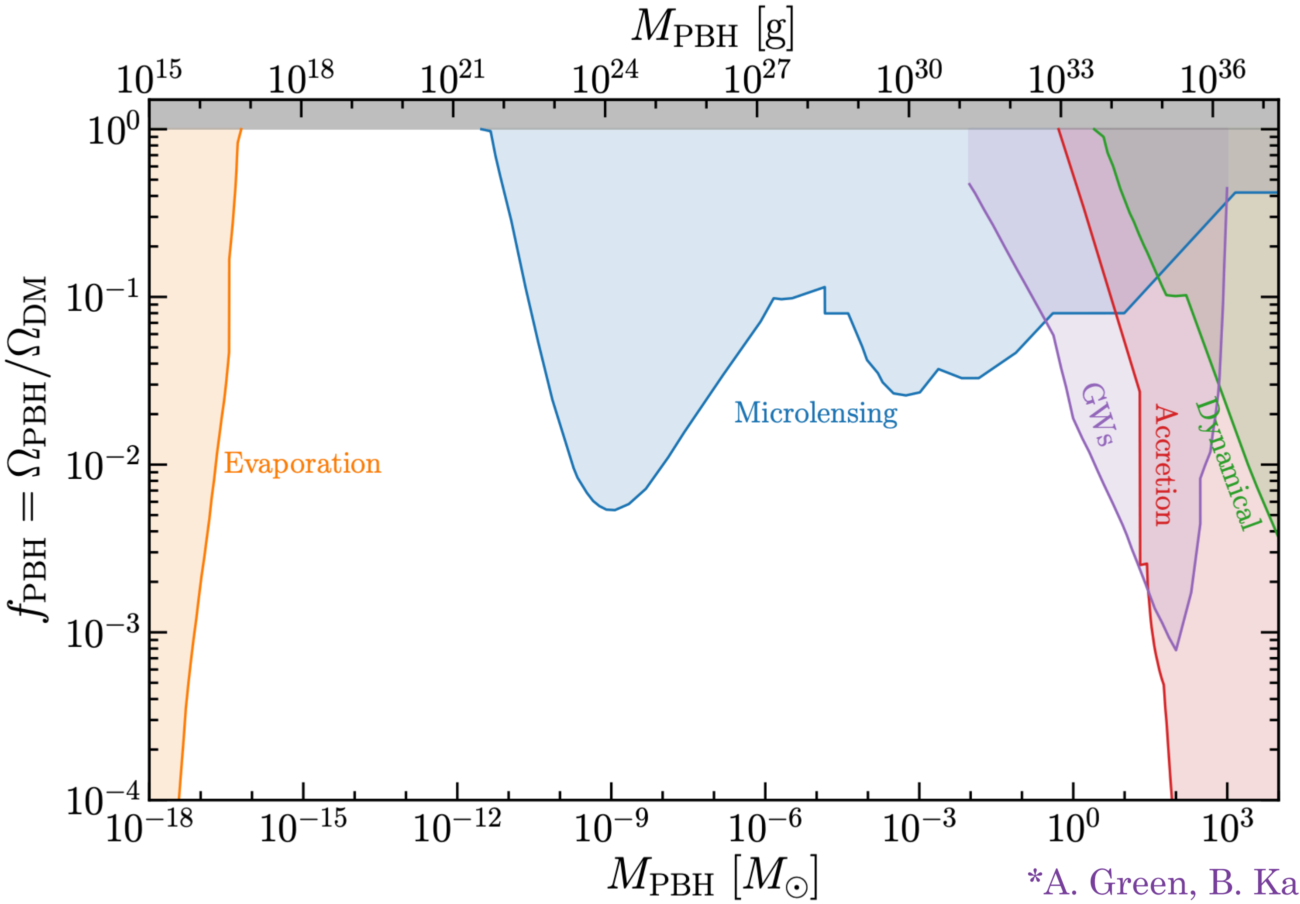
Small scale probes of inflation (Motivations)



CMB and LSS (& Spectral Dist.) → limited access to Early Universe Phyiscs

$10^{-4} \lesssim k[\mathrm{Mpc}^{-1}] \lesssim 10^4 \ \rightarrow$ 60-42 e-folds before the end of inflation

Small Scale Probes of Inflation - PBHs



*A. Green, B. Kavanagh , arXiv: 2007.10722,

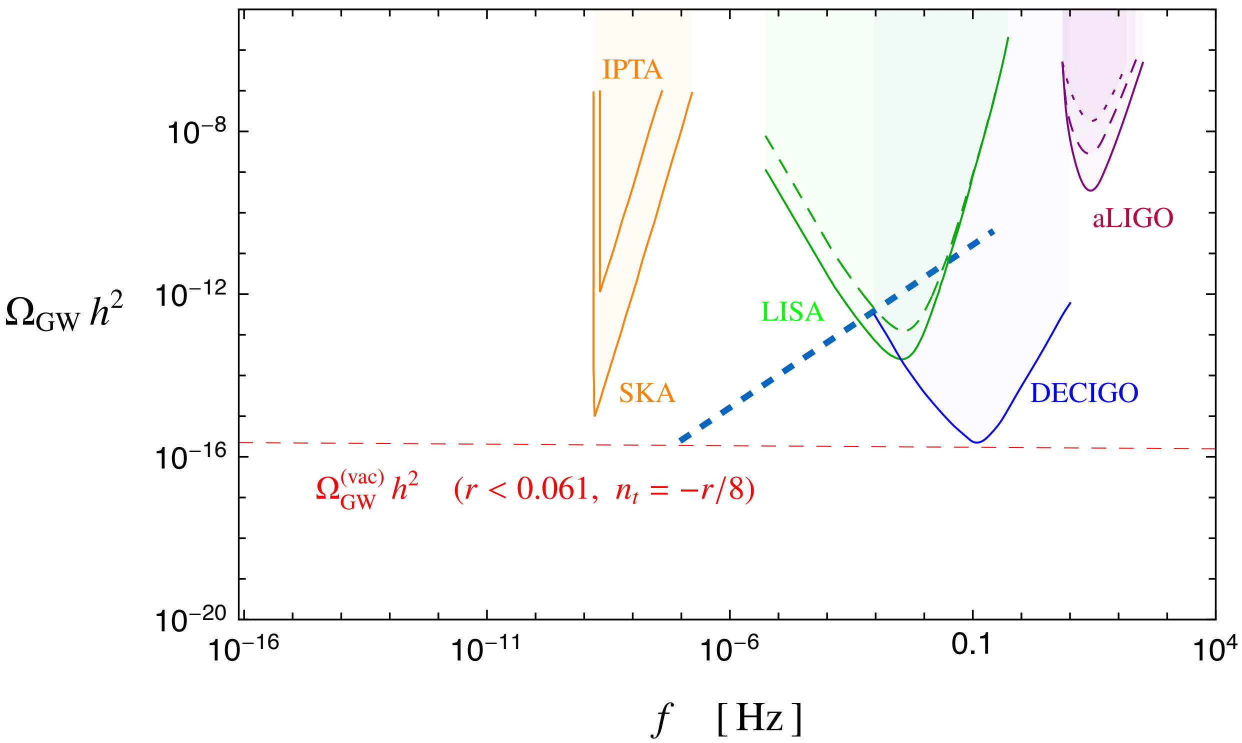
- Primordial Black Holes (PBHs)
- (Depending on their mass) PBHs can (maybe !) account for all or a fraction of DM abundance

S. Bird et.al, “Did LIGO detect dark matter ?”, arXiv: 1603.00464

- Indirect access to a large range scales $10^{-18} M_\odot < M_{\rm PBH} < 10^2 M_\odot$

$$\mathcal{P}_{\mathcal{R}}(k_{\rm PBH}) \gg \mathcal{P}_{\mathcal{R}}(k_{\rm CMB})$$

Small Scale Probes of Inflation-SGWB



Blue tilted spectrum is required at interferometers!

(J. Cook & L. Sorbo, ’11)

(N. Barnaby, E.Pajer&M.Peloso ’11)

(V. Domcke, M. Pieroni & Binetruy, ’16)

(Iacconi et.al ’19)

- GWs at interferometer scales
  - Induced GWs: inevitable part of SGWB due to non-linear nature of gravity!

$$\Omega_{\rm GW}(k) \sim \int dp\, \mathcal{P}_{\mathcal{R}}(|\vec{k}-\vec{p}|)\mathcal{P}_{\mathcal{R}}(p) \longrightarrow \text{Potential probe of } \mathcal{P}_{\mathcal{R}}(k)$$

  - Direct enhancement of tensor perturbations during inflation:

$$\underbrace{h''_{ij} + 2\frac{a'(\tau)}{a(\tau)}h'_{ij} + k^2 h_{ij}}_{\equiv 0 \text{ for vacuum}} = \frac{2}{M_{\rm pl}^2}T_{ij}^{TT}$$

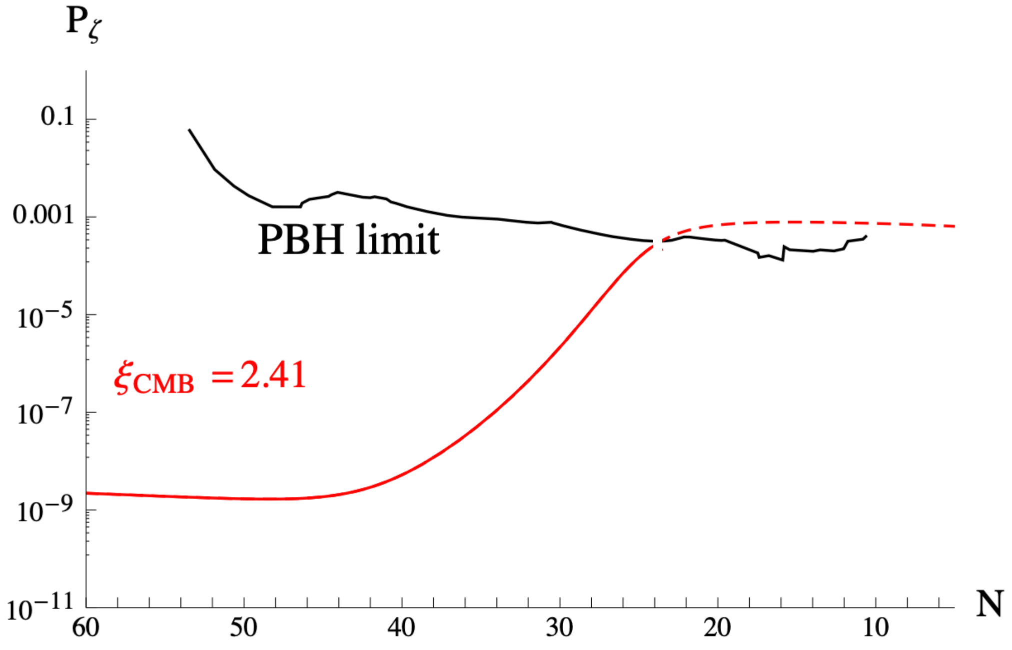
Axion-Gauge field Inflation @ sub-CMB scales

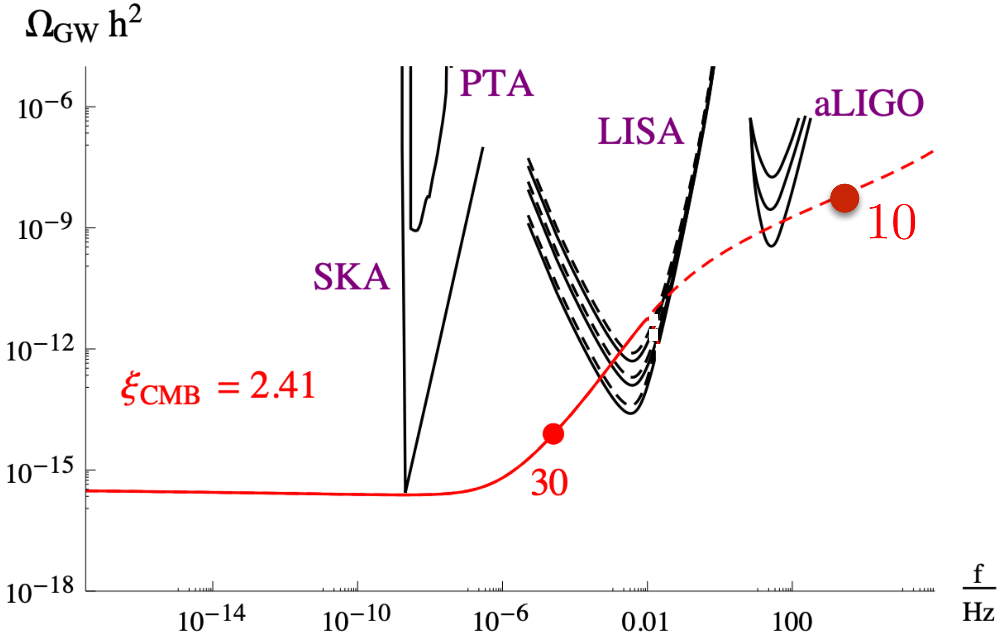
$$\frac{\mathcal{L}_m}{\sqrt{-g}} = -\frac{1}{2}(\partial\phi)^2 - V(\phi) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{\alpha_c}{4f}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$|\dot{\phi}|$ is increasing: possibility to probe late stages of inflation

$$A_- + A_- \rightarrow \delta\phi^{(s)} \propto \mathcal{R}^{(s)}$$

$$A_- + A_- \rightarrow h_-^{(s,p)}$$





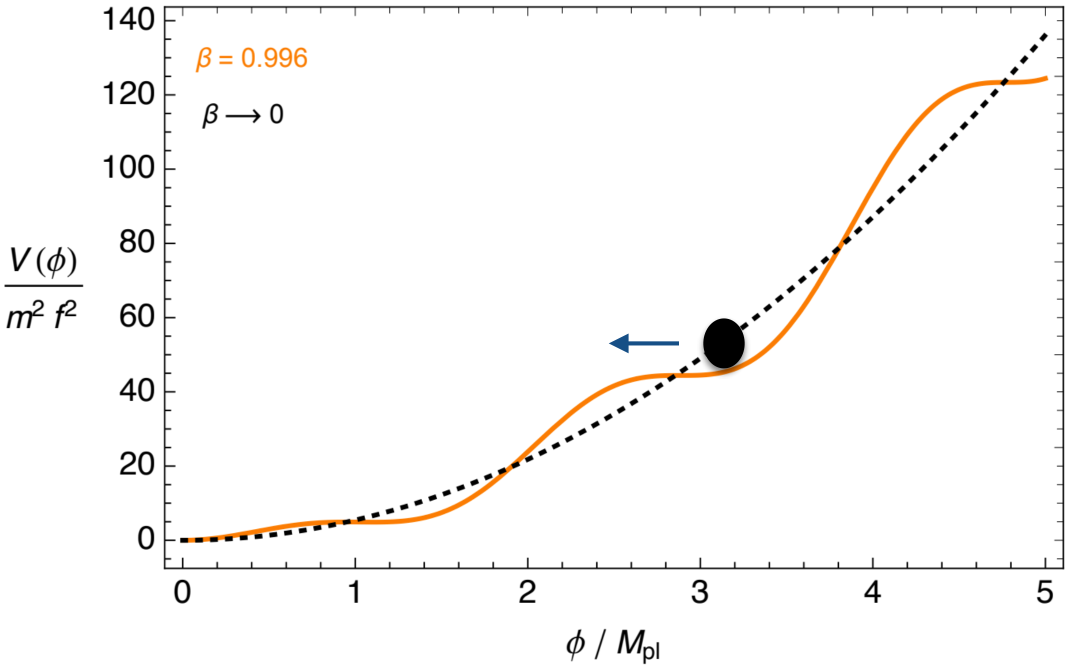
PBH limits are stricter since scalar fluctuations are strongly non-Gaussian*: $\mathcal{P}_{\mathcal{R}(\chi^2)} \simeq \frac{2}{\mathcal{R}_c^2}\mathcal{P}^2_{\mathcal{R}(G)}$

(M. Peloso, C. Unal & G. Bellido, '16, A. Linde, S. Mooij, E.Pajer arXiv:1212.1693)

*See However, arXiv: 2204.12874, Caravano et. Al.

Axion-Gauge field Inflation

$$\frac{\mathcal{L}_m}{\sqrt{-g}} = -\frac{1}{2}(\partial\phi)^2 - V(\phi) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{\alpha_c}{4f}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$$



$$V(\phi) = \frac{1}{2}m^2\phi^2 + \Lambda^4 \frac{\phi}{f}\sin\left(\frac{\phi}{f}\right)^*$$

*Kobayashi et. al. arXiv: 1510.08768, Kallosh et.al. arXiv: 1404.6244, McAllister et. al. 0808.0706, Flauger et. al. arXiv: 1412.1814.

Interested in "Bumpy" Regime ⟶

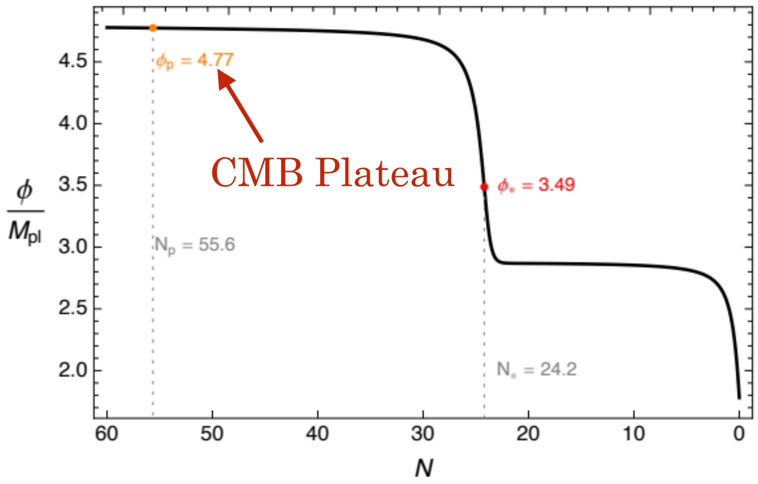
$$\boxed{\beta = \frac{\Lambda^4}{m^2 f^2} \lesssim 1}$$

S-L. Cheng, W. Lee, K-W. Ng, arXiv: 1801.09050

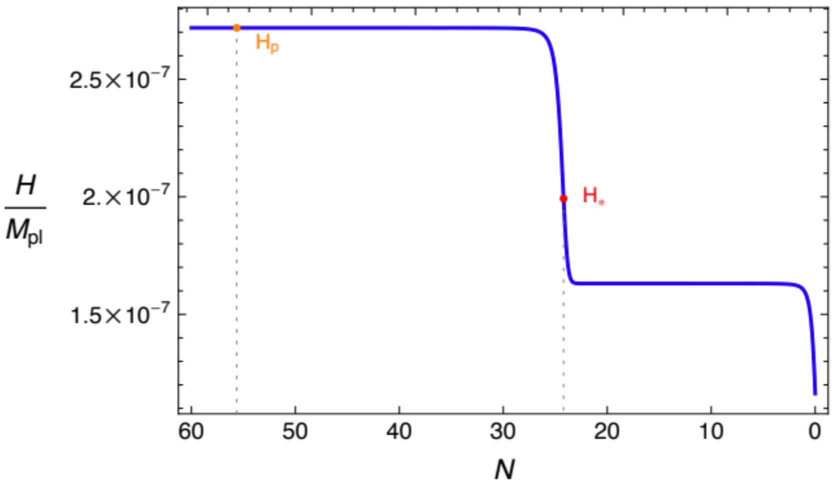
O.Ö. Z. Lalak, arXiv: 2008.07549

Axion Inflation in the Bumpy Regime

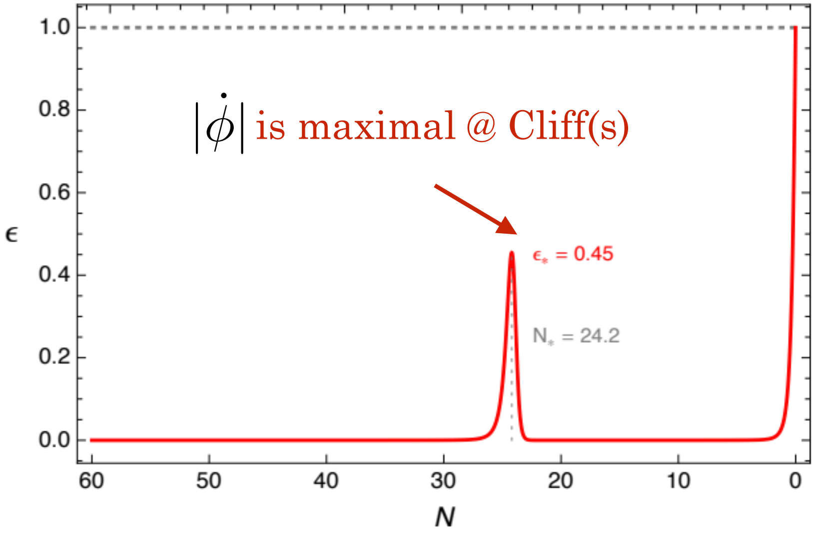
$$\Delta\phi \simeq 3M_{\rm pl} \left\{ \right.$$



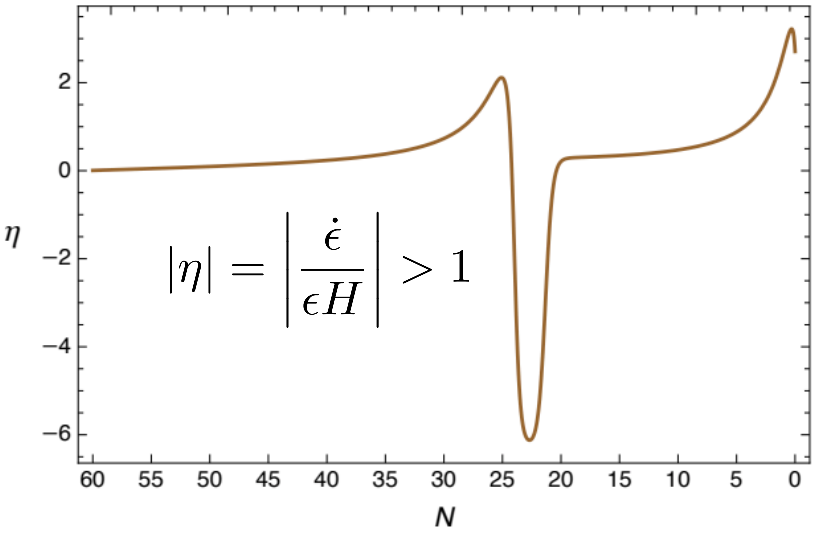
CMB Plateau



- Hubble drag in the plateau regions of $V(\phi)$ is pretty efficient to sustain enough inflation for an intermediate field range and energy scale! ($r \simeq 10^{-5}$)



$|\dot{\phi}|$ is maximal @ Cliff(s)



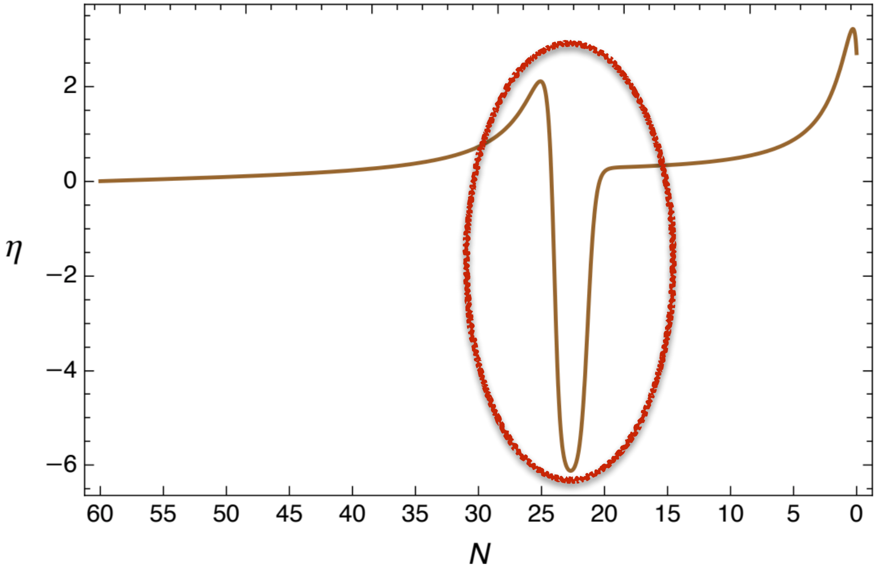
$$|\eta| = \left|\frac{\dot{\epsilon}}{\epsilon H}\right| > 1$$

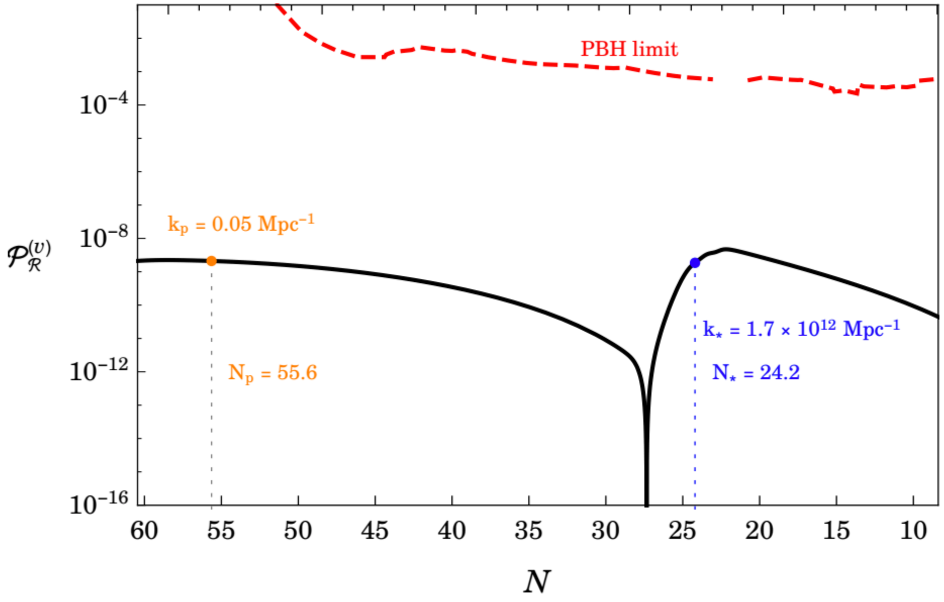
- Temporary speed up of inflaton at the cliff like regions of $V(\phi)$ and slow-roll violation

*S. Parameswaran, G.Tasinato, I. Zavala, arXiv:1602.02812.
O.Ö et.al arXiv: 1803.07626

O.Ö, Z. Lalak, arXiv: 2008.07549

Axion Inflation in the Bumpy Regime (without GFs)





$$\mathcal{R}_k'' + 2aH \underbrace{\left[1 + \frac{\eta}{2}\right]} \mathcal{R}_k' + k^2 \mathcal{R}_k \simeq 0$$

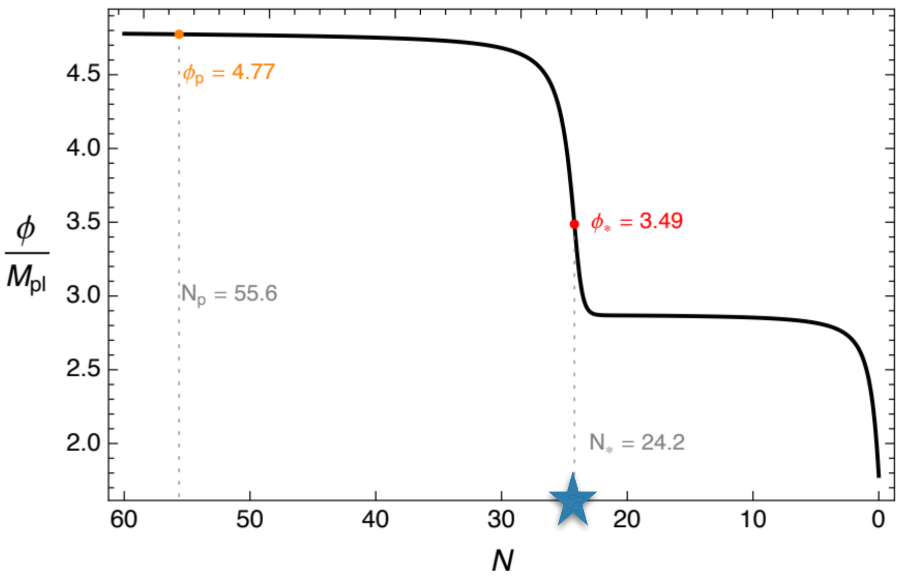
Damping term becomes a driving term

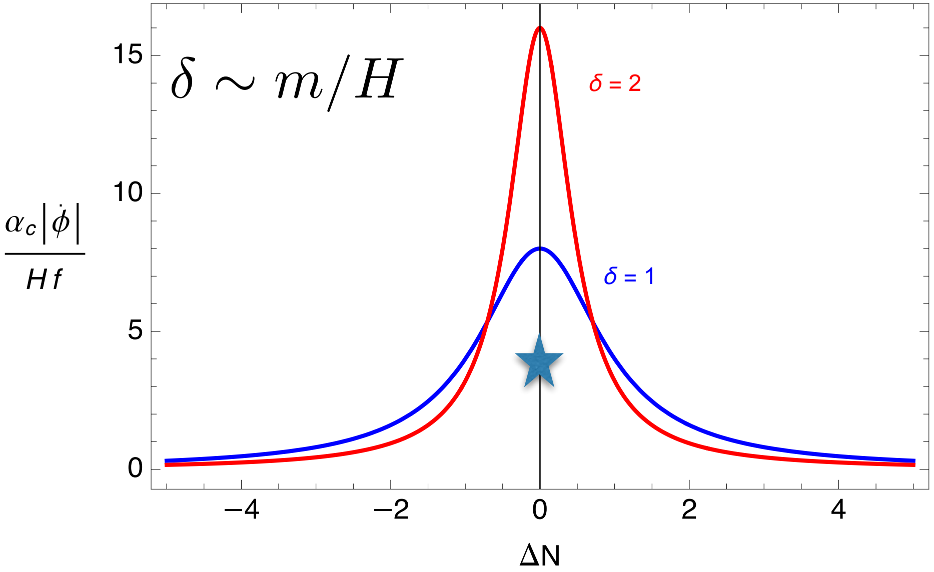
- Duration of negative η phase determines the enhancement in the power spectrum*

*O.Ö, G. Tasinato, arXiv: 1912.01061

O.Ö, Z. Lalak, arXiv: 2008.07549

Gauge field production at the cliff(s)





Faster roll through the cliffs
for heavier inflaton! (larger δ)

$$A''_-(\tau,k) + k^2\left(1 - \frac{aH}{k}\frac{\alpha_c|\dot{\phi}|}{Hf}\right)A_-(\tau,k) = 0$$

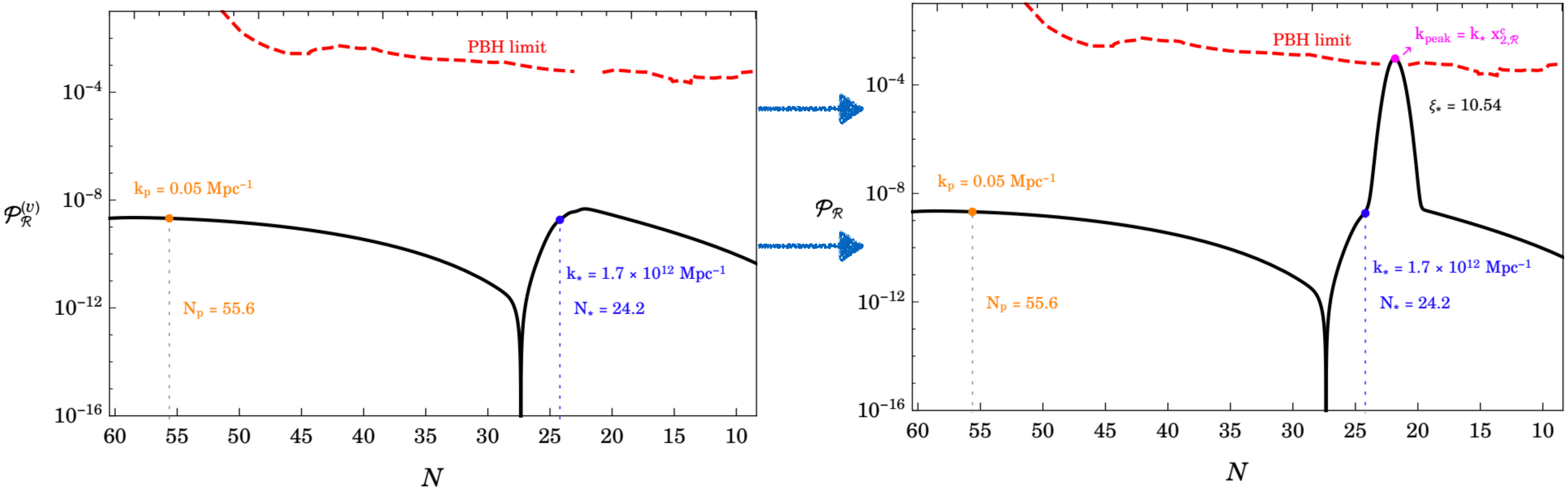
$$\left.\frac{k}{aH}\right|_{t=t_*} \equiv \frac{k}{k_*} \qquad \left.\frac{\alpha_c|\dot{\phi}|}{Hf}\right|_{t=t_*} = 2\xi_*$$

Gauge field production is localized and scale dependent.

O.Ö, Z. Lalak, arXiv: 2008.07549

Echoes of GF production (PBH as DM)

$$\mathcal{P}_{\mathcal{R}}^{\text{vac}} \qquad\qquad A_- + A_- \to \delta\phi^{(s)} \propto \mathcal{R}^{(s)}$$



Scalar Power spectrum:

$$\mathcal{P}_{\mathcal{R}}(k) = \mathcal{P}_{\mathcal{R}}^{(v)}(k)\left[1 + \frac{H^2}{64\pi^2 M_{\rm pl}^2} f_{2,\mathcal{R}}\left(\xi_*, \frac{k}{k_*}, \delta\right)\right]$$

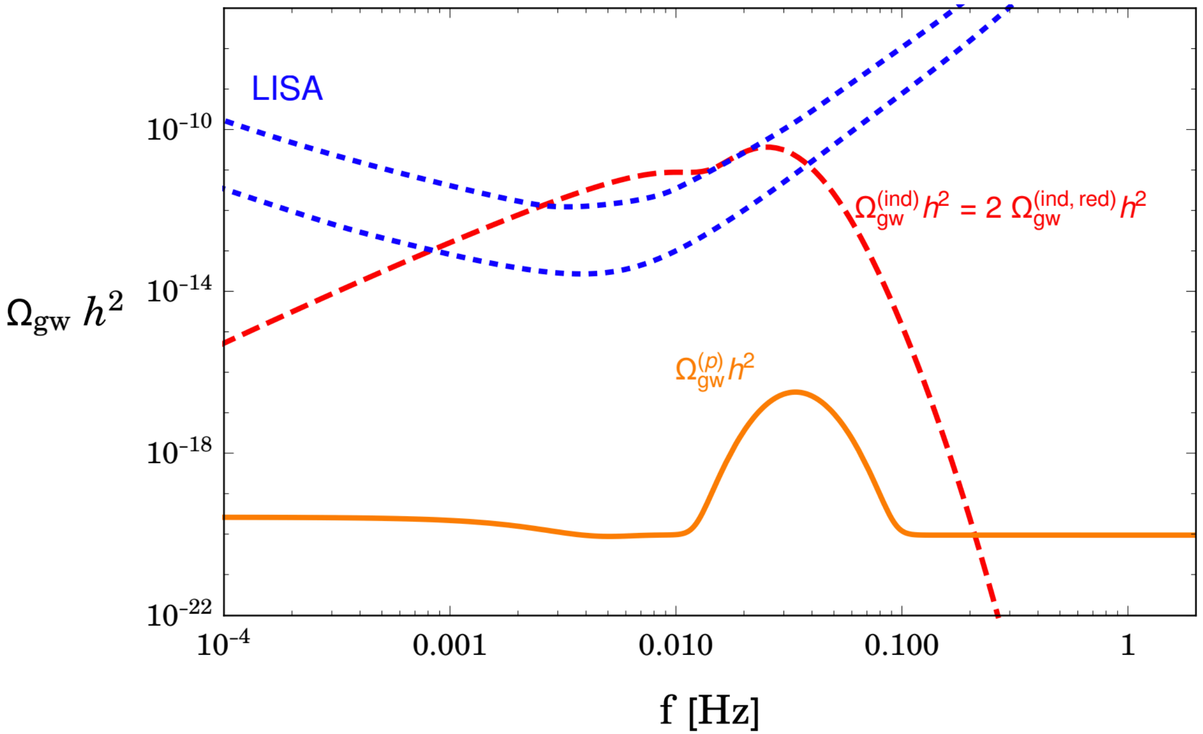
Fraction of regions collapsing to PBHs at their formation is modified due to non-Gaussianity:

$$\beta(N) = \text{Erfc}\left(\sqrt{\frac{1}{2} + \frac{\mathcal{R}_c}{\sqrt{2P_{\mathcal{R}}(N)}}}\right)$$

*A. Linde, S. Mooij, E.Pajer arXiv:1212.1693

O.Ö, Z. Lalak, arXiv: 2008.07549

Für LISA



During RDU:

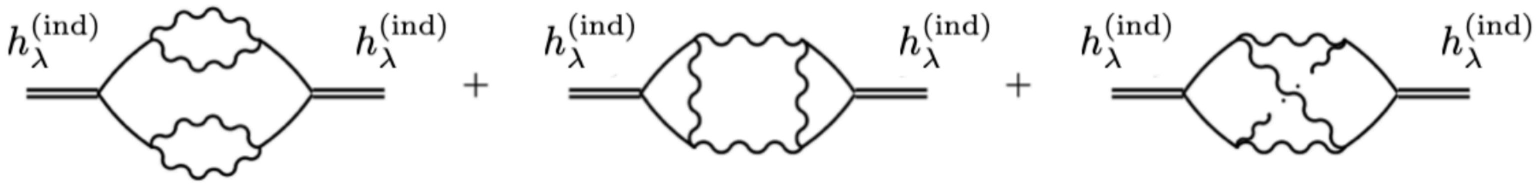
$2A_- + 2A_- \to \mathcal{R} + \mathcal{R} \to h_\pm^{\rm (ind\ )}$

During inflation

$A_- + A_- \to h_-$ (Chiral!)

Total SGWB:

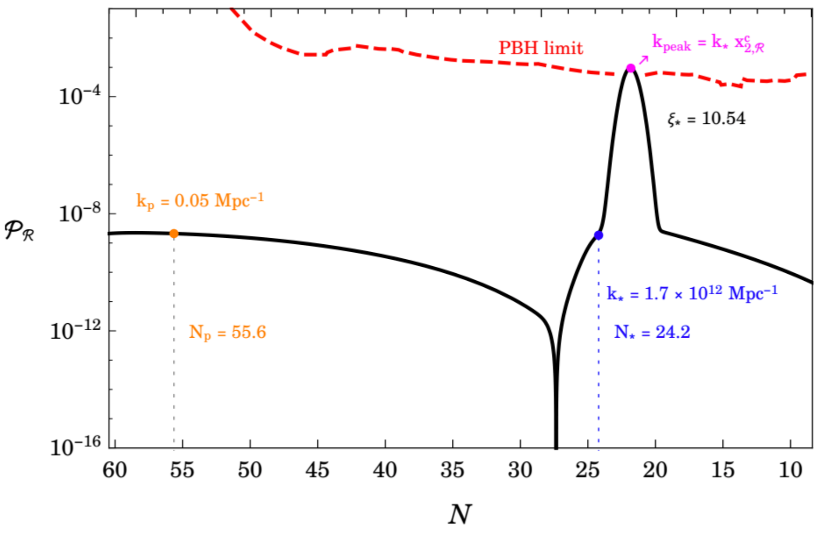
$$\Omega_{\rm gw}^{\rm (tot)}\left(\tau_0, k\right) h^2 \simeq \frac{\Omega_{r,0}h^2}{24}\left\{\sum_\lambda \mathcal{P}_\lambda^{(v,{\rm p})} + \mathcal{P}_-^{(s,{\rm p})}\left(\tau_i, k\right) + \sum_\lambda \left(\frac{k}{\mathcal{H}\left(\tau_f\right)}\right)^2 \overline{\mathcal{P}_\lambda^{\rm (ind)}\left(\tau_f, k\right)}\right\}$$

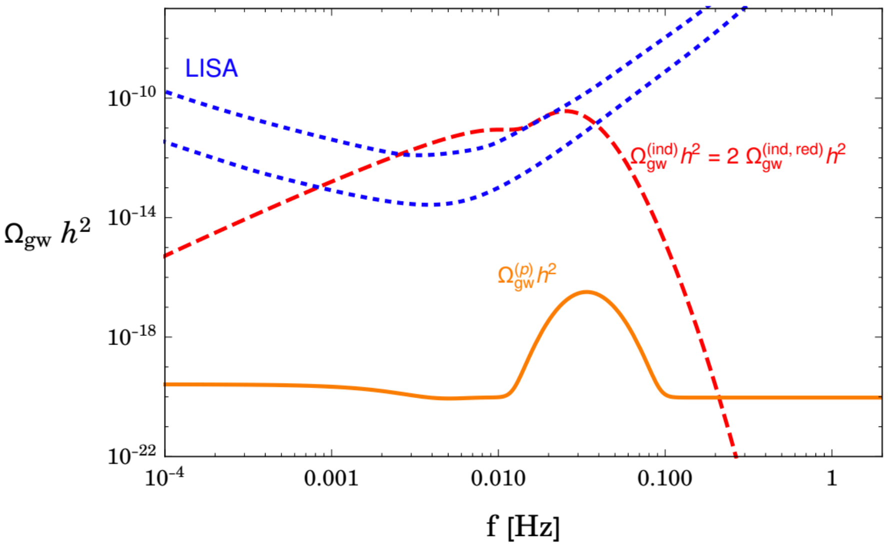


*J. Garcia-Bellido, M. Peloso, C. Ünal arXiv: 1707.02441

O.Ö, Z. Lalak, arXiv: 2008.07549

Conclusions (Part 2)





"Roller-Coaster" Axion Gauge-Field dynamics:

i) realization of inflation with an intermediate field range $\Delta\phi \simeq \mathcal{O}(1)M_{\rm pl}$ and energy scale with $r \simeq 10^{-5}$ @ CMB scales.

ii) presence of feature(s) in the potential leads to a pronounced peak (non-Gaussian) in the curvature perturbation that can lead to a significant population of PBHs.

iii) This in turn generates an induced observable SGWB (@ LISA) that inherits the properties of the curvature perturbation such as its shape and non-Gaussianity.

*Chirality of the SGWB at interferometers: a non-planar network of interferometers *Smith & Caldwell, '17

*Signal reconstruction methods developed for LISA can be used to distinguish GW signal compared to other early universe mechanisms and astrophysical backgrounds.

*Caprini et. al., arXiv:1906.09244, Flaguer et. al., arXiv: 2009.11845 (LISA Working Group)

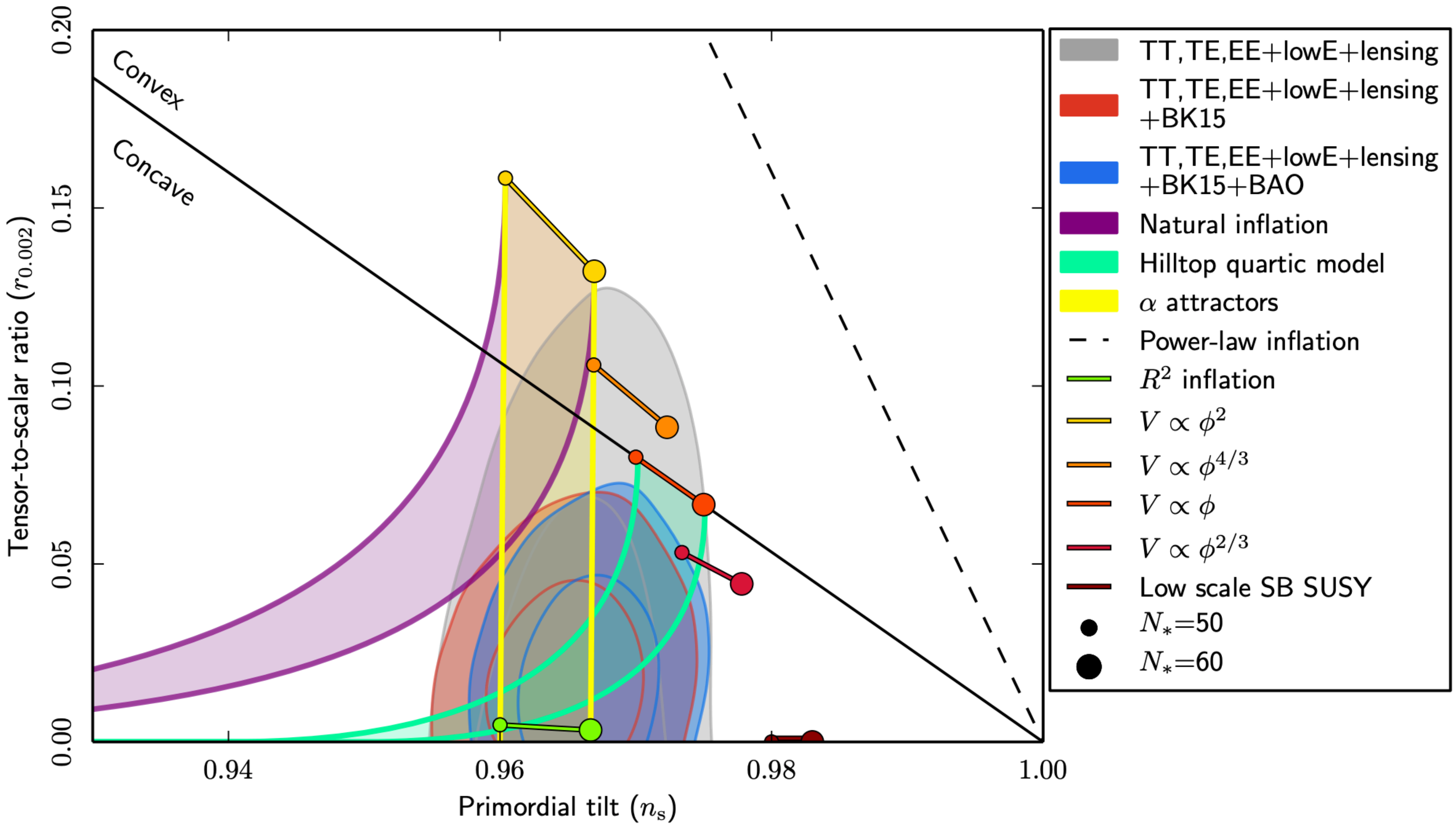
Thank you !

ceico

FZU

European Structural and Investment Funds and the Czech Ministry of Education, Youth and Sports (Project CoGraDS-CZ.02.1.01/0.0/0.0/15003/0000437)

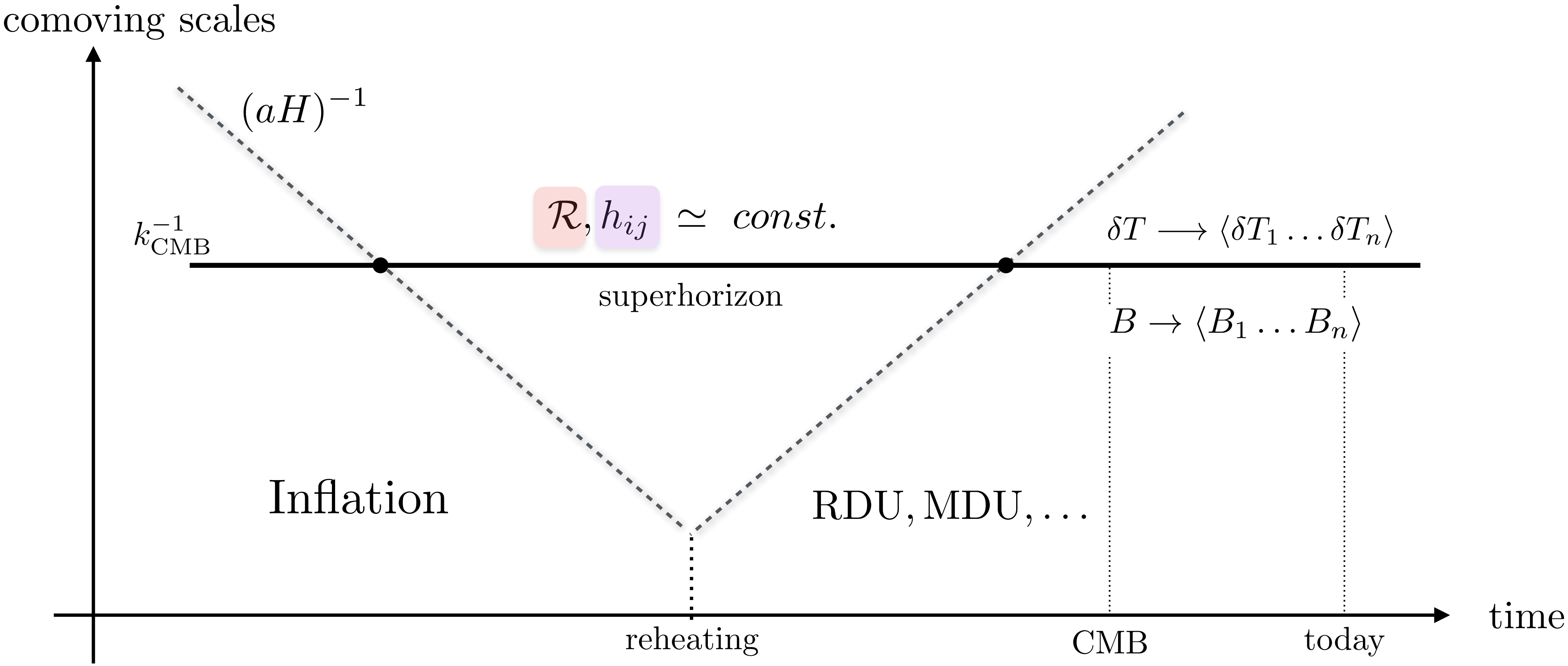
Single field slow-roll @ CMB



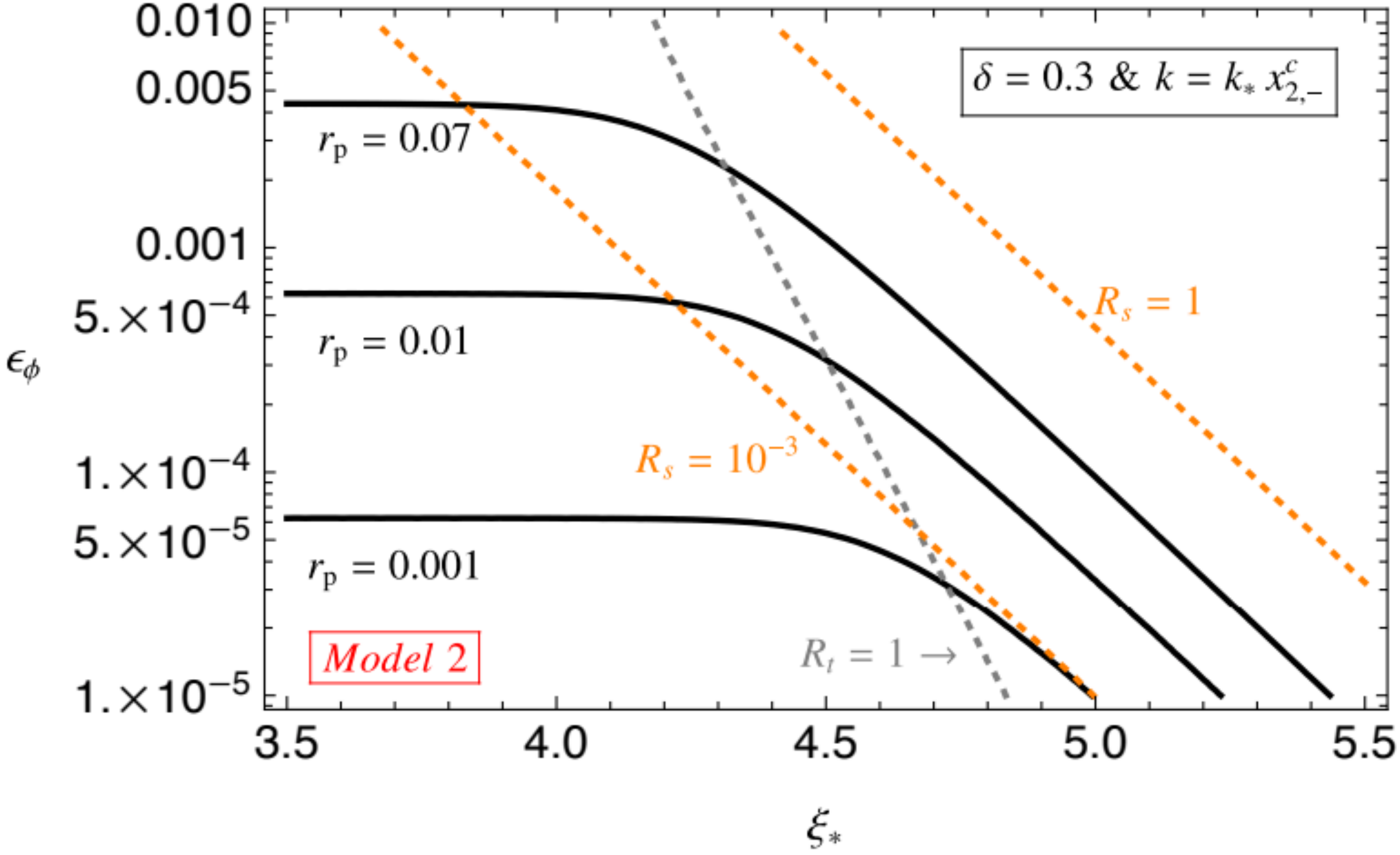
Future bounds ⟶ $r \lesssim 0.001$ CMB S-4 LiteBIRD

Cosmological collider (Inflationary universe)

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + a^2(t)\left[e^{\underbrace{-2\mathcal{R}}_{\text{scalar}}}\delta_{ij} + \underbrace{h_{ij}}_{\text{tensor}}\right]\mathrm{d}x^i\mathrm{d}x^j$$



Observable GWs at CMB scales (non-vacuum)

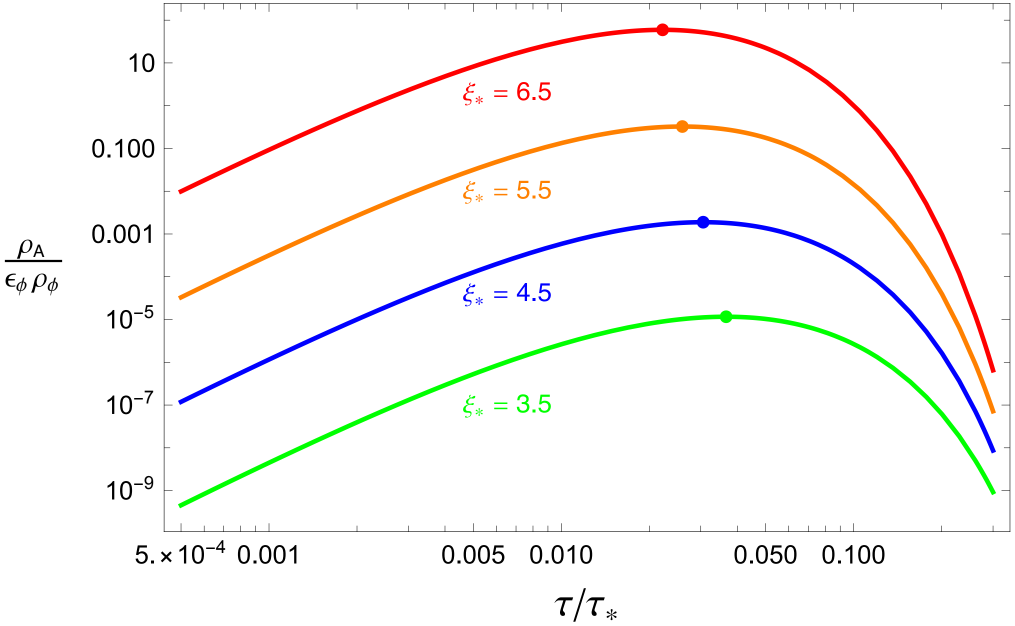


on the r.h.s of $R_t = 1$,

$$r_{\rm vac} = 16\epsilon_\phi \ll r^{(s)}$$

arXiv: 2005.10280-O.Ö

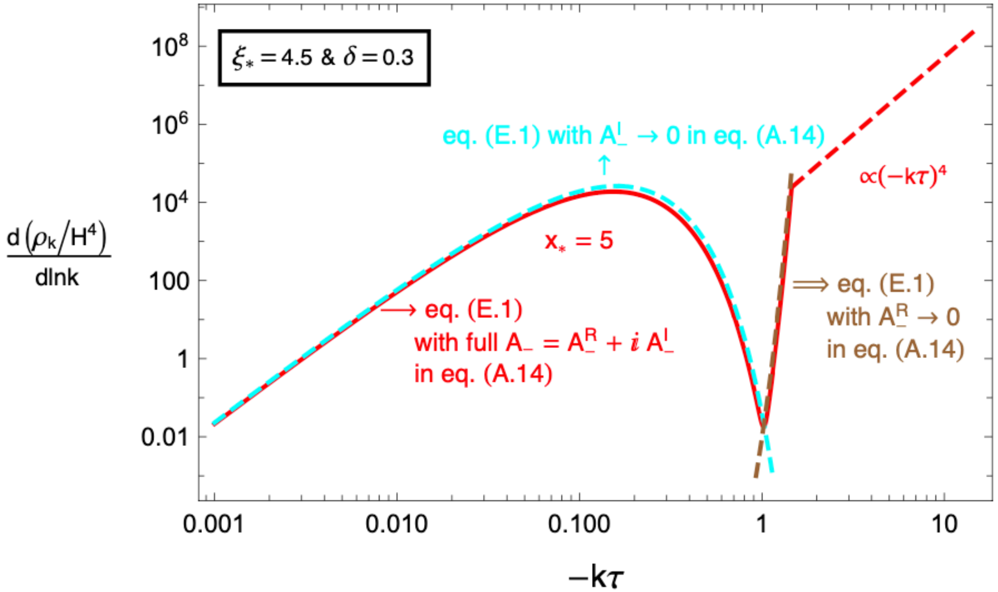
Energy density in the gauge fields (transient roll)

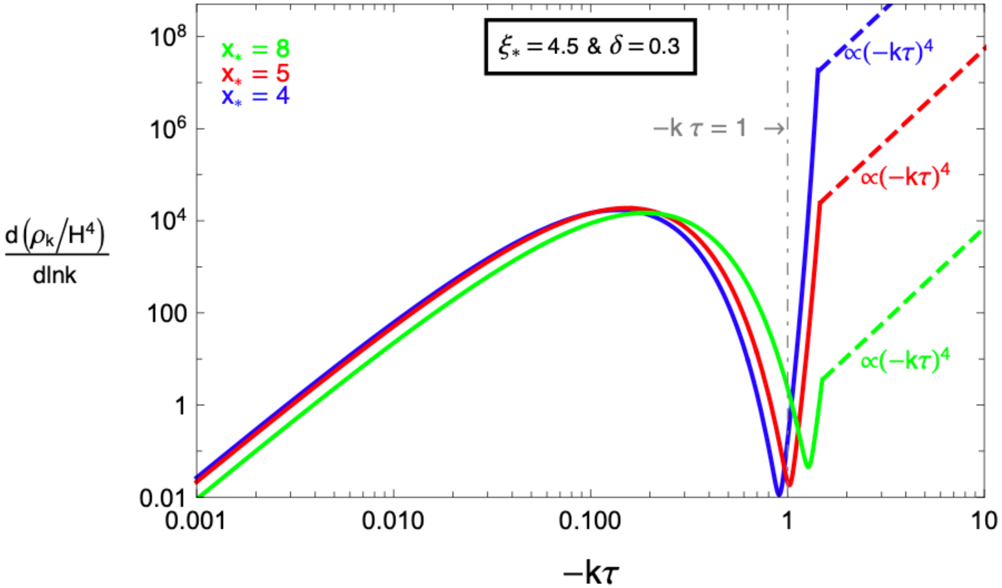


$$\frac{\rho_A}{\epsilon_\phi \rho_\phi} = \frac{\mathcal{P}_\mathcal{R}^{(v)} y^{7/2} N^{c2} \sqrt{2\xi(y)}}{3} \int_0^\infty \mathrm{d}x_* x_*^{5/2} \exp\left[-\frac{4\sqrt{2\xi_* y} x_*^{1/2}}{\delta |\ln(y)|} - \frac{\ln\left(x_*/q_c\right)}{\sigma^2}\right] \left(1 + \frac{x_* y}{2\xi(y)}\right)$$

✓ IR safe mechanism!

Energy density per mode (transient roll)





$$\frac{\mathrm{d}\left(\rho_{k,A}/H^4\right)}{\mathrm{d}\ln k}=\frac{x^4}{8\pi^2}\left(\left|\frac{\mathrm{d}\tilde{A}_-}{\mathrm{d}x}\right|^2+\left|\tilde{A}_-\right|^2\right)$$

Constraints on Model building

Back-reaction:

$$\rho_A = \frac{1}{2}\langle \vec{E}^2 + \vec{B}^2 \rangle \ll \frac{\dot{\sigma}_*^2}{2}$$

$$\boxed{2.4 \times 10^{-6} \sqrt{\epsilon_\phi}\, e^{2.42\,\xi_*} < \frac{f}{M_{\rm pl}}.}$$

Perturbativity:

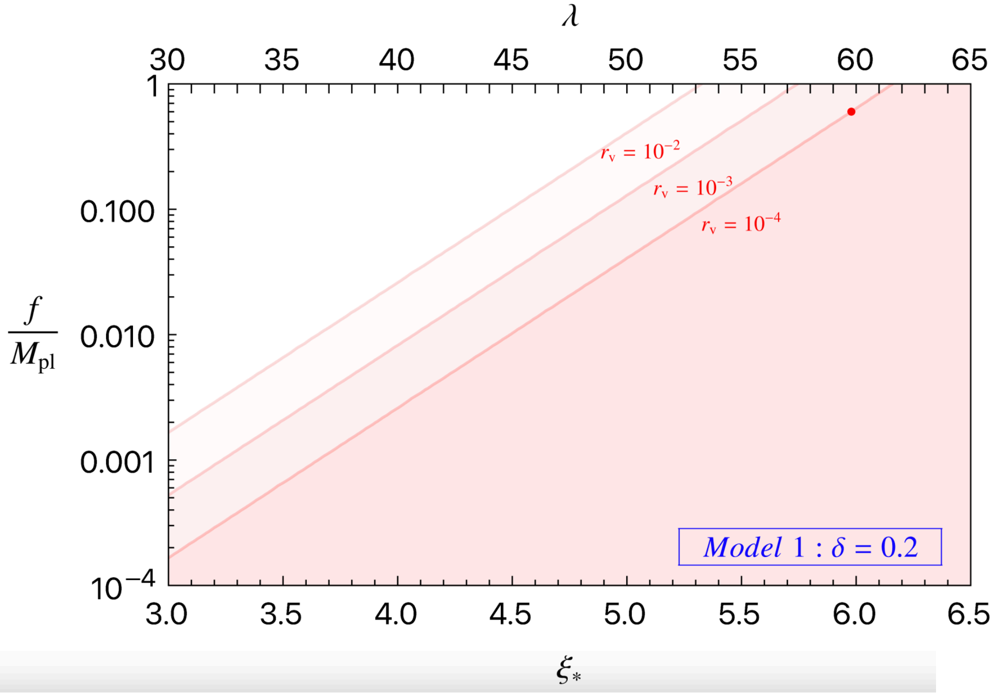
$$P_A \equiv \left| \frac{\delta^{(1)} \langle\, \hat{A}_-(\tau,\vec{k})\hat{A}_-(\tau,\vec{k}')\,\rangle'}{\langle\, \hat{A}_-(\tau,\vec{k})\hat{A}_-(\tau,\vec{k}')\,\rangle'} \right| \ll 1,$$

$$\boxed{5.6 \times 10^{-7} \sqrt{\epsilon_\phi}\; e^{2.71\xi_*} < \frac{f}{M_{\rm pl}},}$$

$$P_\sigma \equiv \frac{\sqrt{\langle \delta\hat{\sigma}^{(1)}(\tau,\vec{x})\delta\hat{\sigma}^{(1)}(\tau,\vec{x})\rangle}}{\sigma_{\rm cl}} = \frac{\sqrt{\int {\rm d}\ln k\, \mathcal{P}_\sigma^{(1)}(\tau,k)}}{\sigma_{\rm cl}} \ll 1,$$

* M. Peloso, L. Sorbo, C. Ünal, arXiv: 1606.00459

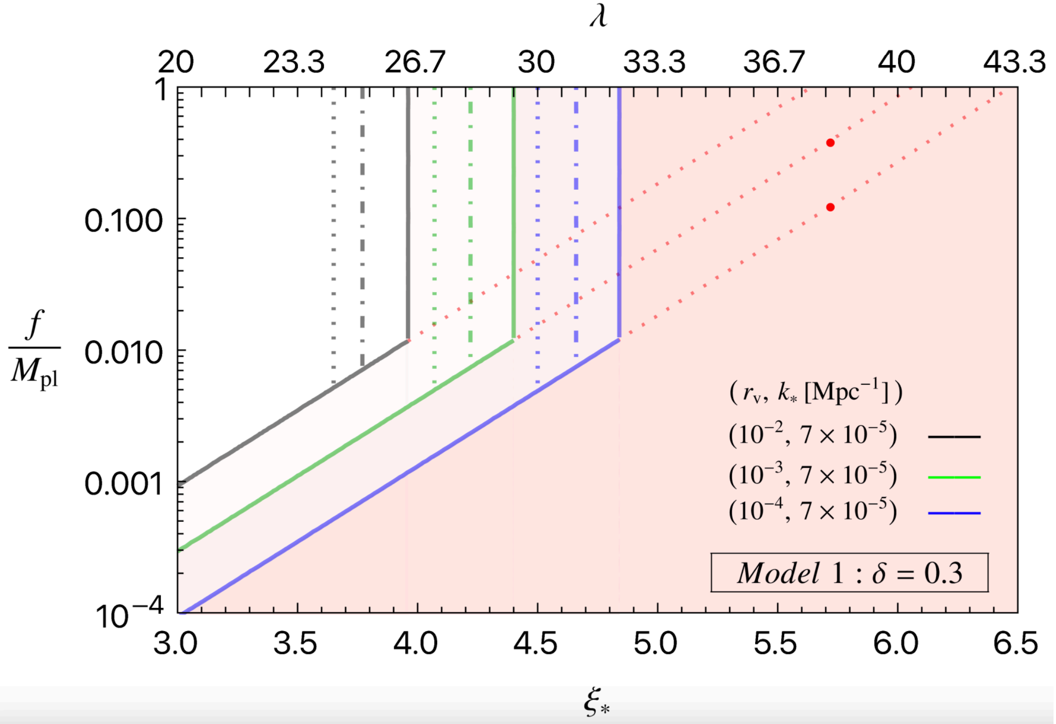
Backreaction and perturbativity limits (spectator)



$$m_\sigma^2 = 0.6H^2$$

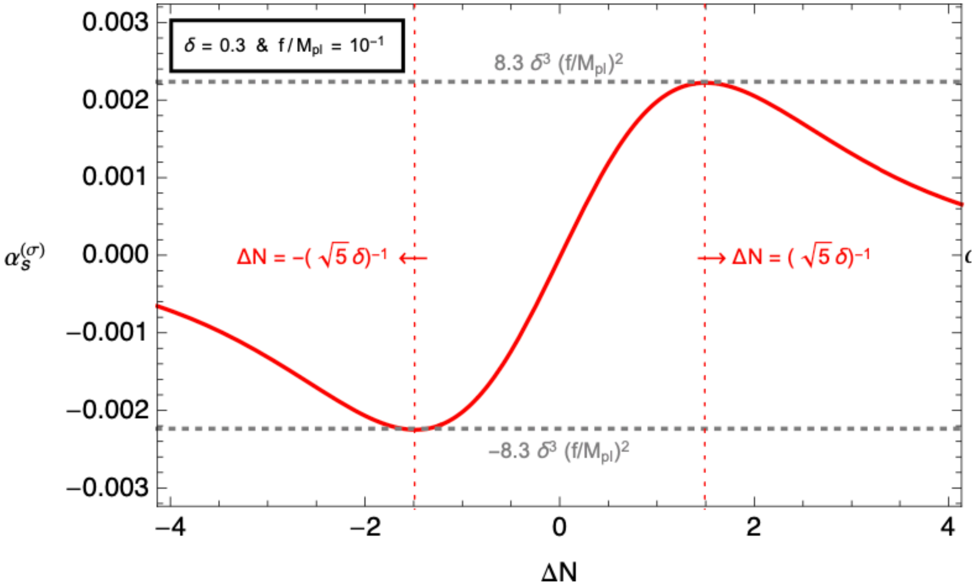
$$\Delta\mathcal{L}_{\rm int} = \frac{\lambda}{4f}\left[\bar{\sigma} + \delta\sigma\right] F\tilde{F}$$

$$m_\sigma^2 = 0.9H^2$$



Constraints on Model building

Running @CMB scales: $\alpha_s^{\sigma} \equiv -4\frac{\mathrm{d}\epsilon_\sigma}{\mathrm{d}\ln k} \simeq 8\epsilon_\sigma\left(\eta_\sigma - \epsilon_\phi - \epsilon_\sigma\right),$

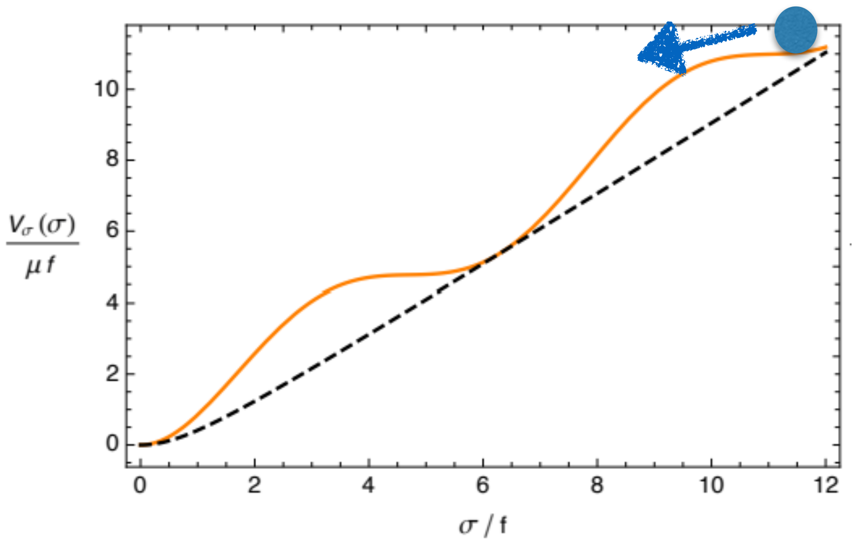


Summary of upper bounds:

$$\boxed{\frac{f}{M_{\rm pl}} \lesssim 0.6 \;\; \text{@Interferometer scales,} \qquad \frac{f}{M_{\rm pl}} \lesssim 0.18 \;\; \text{@CMB scales}\,.}$$

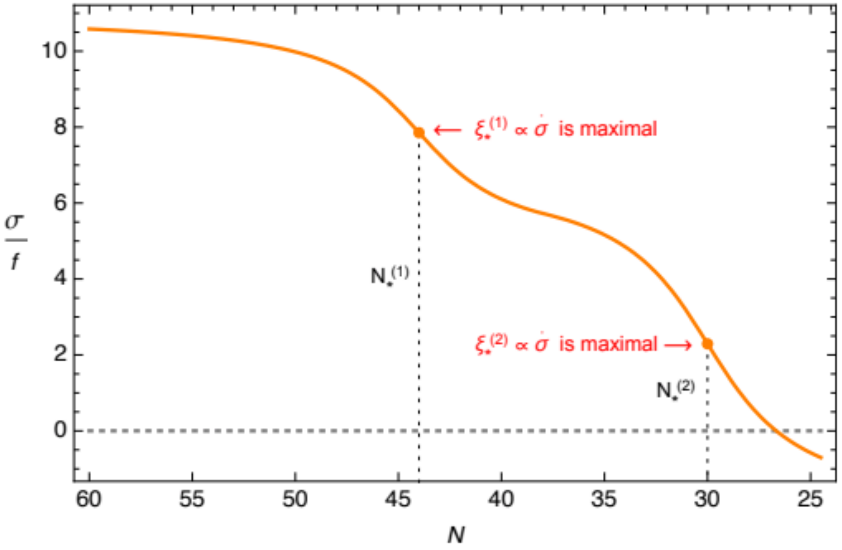
$\rho_\sigma \ll 3H^2 M_{\rm pl}^2$ @sub-CMB scales:

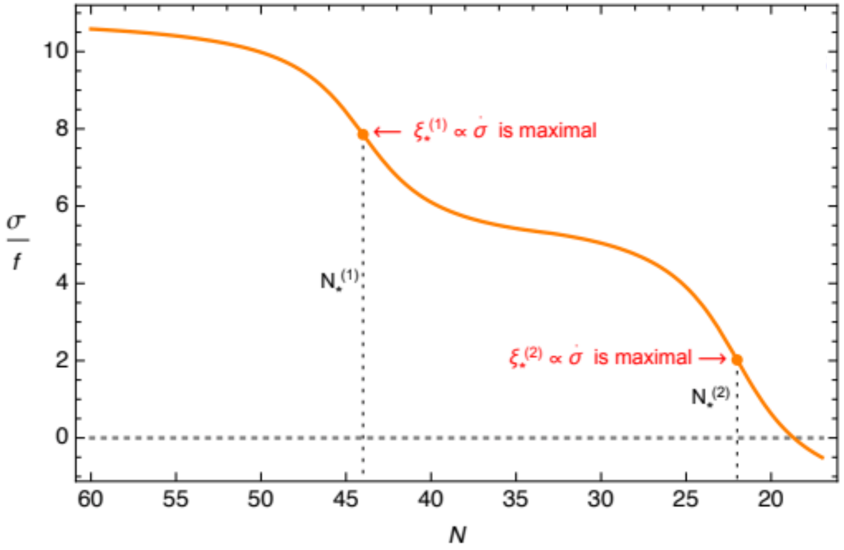
Observable GWs at interferometers (non-vacuum)



✓ Consider a scenario where spectator σ traverses multiple wiggles in its pot.

✓ Tune model parameters such that $|\dot{\sigma}|$ is maximal during the time(s) where scales associated with spatial and ground based interferometers exit the horizon





$N_*^{(1)} = 44$ $N_*^{(2)} = 30$

(PTA-SKA) —— (LISA)

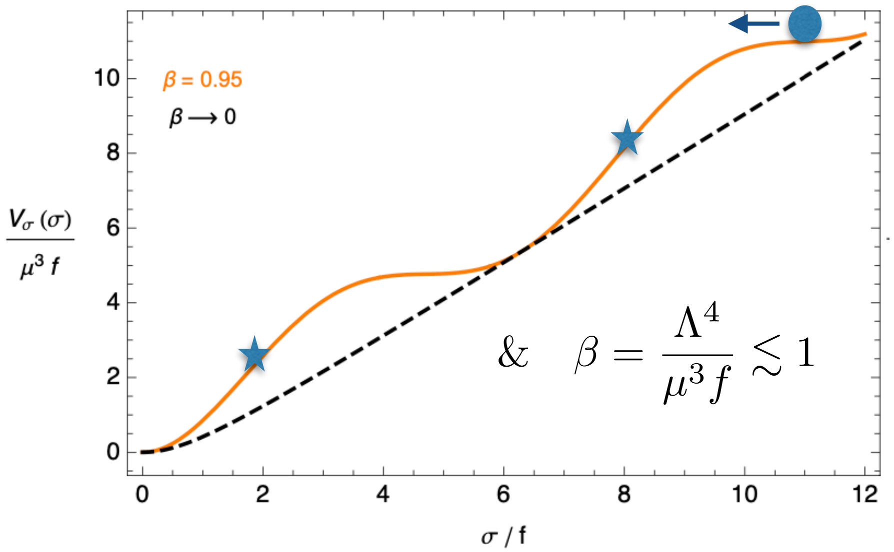
$N_*^{(1)} = 44$ $N_*^{(2)} = 22$

(PTA-SKA) —— (AdvLIGO)

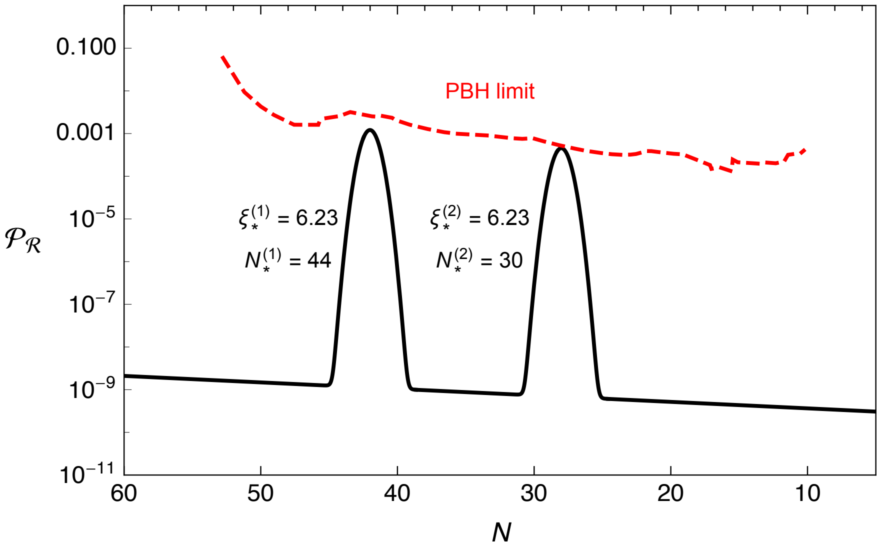
Spectator axion model (PBH production)

$$\frac{\mathcal{L}_m}{\sqrt{-g}} = -\frac{1}{2}(\partial\phi)^2 - V_\phi(\phi) - \frac{1}{2}(\partial\sigma)^2 - V_\sigma(\sigma) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{\alpha_c}{4f}\,\sigma\, F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Signal is sensitive to $V_\sigma(\sigma)$



$$\& \quad \beta = \frac{\Lambda^4}{\mu^3 f} \lesssim 1$$

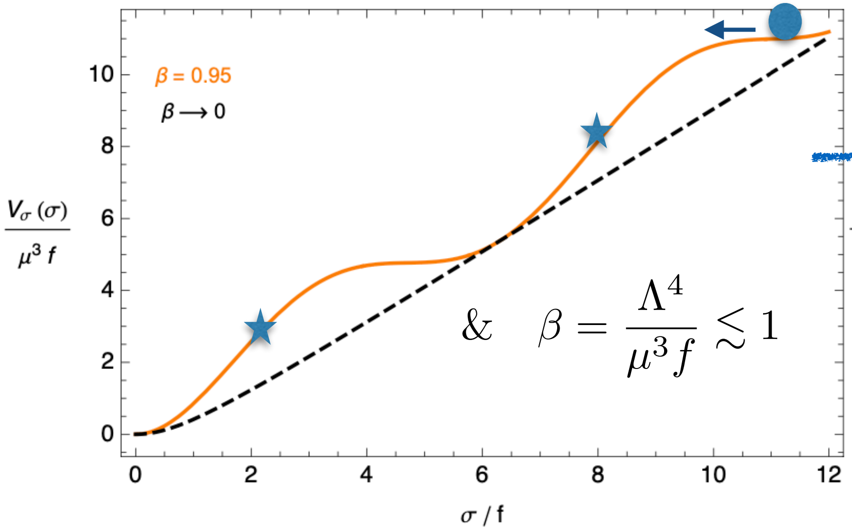


arXiv: 2005.10280-O.Ö

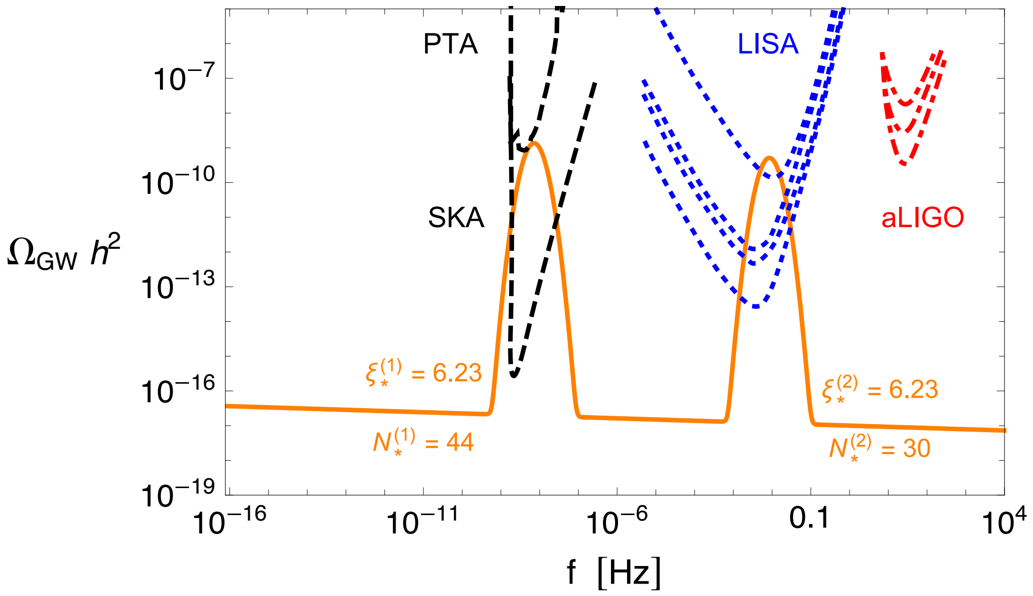
Spectator model (GWs @ interferometers)

$$\frac{\mathcal{L}_m}{\sqrt{-g}} = -\frac{1}{2}(\partial\phi)^2 - V_\phi(\phi) \boxed{- \frac{1}{2}(\partial\sigma)^2 - V_\sigma(\sigma) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{\alpha_c}{4f}\,\sigma\, F_{\mu\nu}\tilde{F}^{\mu\nu}}$$

Signal is sensitive to $V_\sigma(\sigma)$



$$\& \quad \beta = \frac{\Lambda^4}{\mu^3 f} \lesssim 1$$



$$\boxed{\Omega_{\rm GW}\, h^2 = \frac{\Omega_{r,0}\, h^2}{24}\mathcal{P}_h(k)}$$

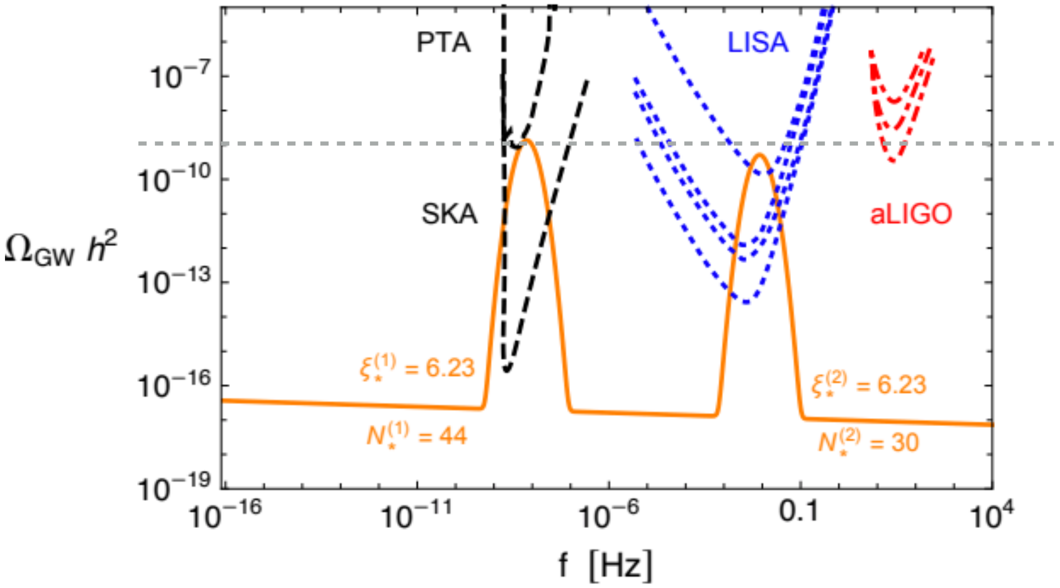
arXiv: 2005.10280-O.Ö

Summary of Model Buiding Constraints

$$\boxed{5.6 \times 10^{-7} \sqrt{\epsilon_\phi}\, e^{2.71\xi_*} < \frac{f}{M_{\rm pl}} \lesssim \{0.18, 0.6\},}$$

$$0.0017 \left(\frac{r_*}{0.063}\right)^{1/4} e^{0.23\,\xi_*} < \frac{f}{M_{\rm pl}} \lesssim 0.18, \qquad \text{@CMB scales},$$

$$0.07 \left(\frac{\Omega_{\rm GW}\, h^2}{10^{-9}}\right)_*^{1/4} e^{0.23\,\xi_*} < \frac{f}{M_{\rm pl}} \lesssim 0.6, \qquad \text{@Interferometer scales.}$$



Full expression for curvature perturbation

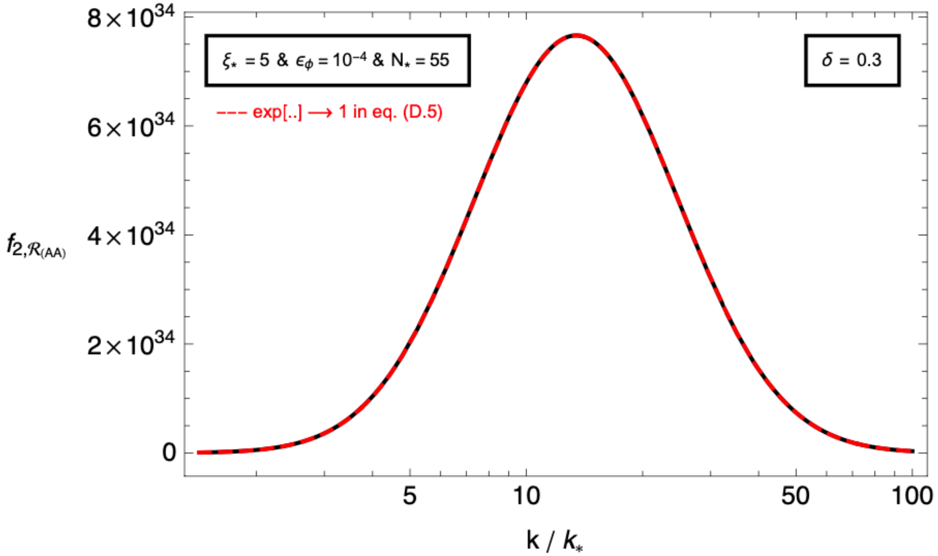
$$\mathcal{R}(\tau,\vec{k}) = \frac{H}{a\left(\dot{\phi}^2+\dot{\sigma}^2\right)}\left(\dot{\phi}Q_\phi + \dot{\sigma}Q_\sigma - a\delta q_{(AA)}(\tau,\vec{k})\right)$$

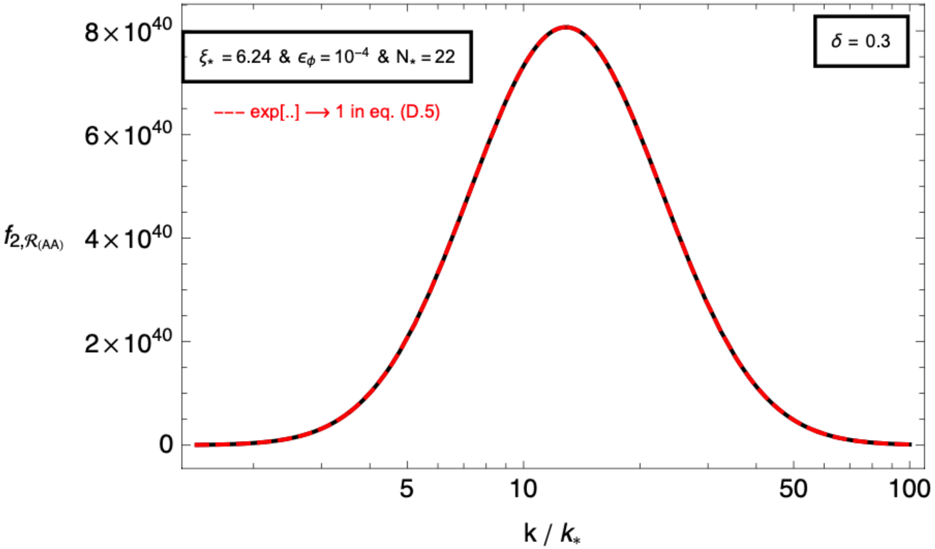
Direct contribution from gauge fields:

$$\delta q_{(AA)}(\tau,\vec{k}) = -a\frac{i\hat{k}_i}{k}\epsilon_{ijk}\int\frac{\mathrm{d}^3q}{(2\pi)^{3/2}}E_j(\tau,\vec{k}-\vec{q})B_k(\tau,\vec{q})$$

Check if it can contribute significantly to the correlators:

$$\mathcal{P}_{\mathcal{R}_{(AA)}}(k) = \left[\epsilon_\phi\mathcal{P}_{\mathcal{R}}^{(v)}\right]^2\left(\frac{\tau_{\rm end}}{\tau_*}\right)^6 f_{2,\mathcal{R}_{(AA)}}\left(\xi_*,\frac{k}{k_*},\delta\right)$$





Echoes of particle production (Bumpy ride)

Scalar and tensor correlators are sourced by Gauge fields, so n-point correlators inherit the similar parametric dependence in terms of the set $\left\{\frac{k}{k_*}, \xi_*, \delta\right\}$

$$\mathcal{P}_{\mathcal{R}}(k) = \mathcal{P}_{\mathcal{R}}^{(v)}(k) + \mathcal{P}_{\mathcal{R}}^{(s)}(k), \quad \mathcal{P}_{\lambda}(k) = \mathcal{P}_{\lambda}^{(v)}(k) + \mathcal{P}_{\lambda}^{(s)}(k)$$

$$\mathcal{P}_{\mathcal{R}}^{(v)}(k) = \frac{H^2}{8\pi^2 \epsilon_\phi M_{\rm pl}^2}, \quad \mathcal{P}_{\lambda}^{(v)}(k) = \frac{H^2}{\pi^2 M_{\rm pl}^2}$$

→ Controlled by inflaton!

$$\mathcal{P}_{\mathcal{R}}^{(s)}(k) = \left[\epsilon_\phi \mathcal{P}_{\mathcal{R}}^{(v)}(k)\right]^2 f_{2,\mathcal{R}}\left(\xi_*, \frac{k}{k_*}, \delta\right) \qquad \mathcal{P}_{\lambda}^{(s)}(k) = \left[\epsilon_\phi \mathcal{P}_{\mathcal{R}}^{(v)}(k)\right]^2 f_{2,\lambda}\left(\xi_*, \frac{k}{k_*}, \delta\right)$$

controlled by σ and A_μ !

$$\mathcal{B}_{\mathcal{R}}^{(s)}(k_1, k_2, k_3) = \frac{\left[\epsilon_\phi \mathcal{P}_{\mathcal{R}}^{(v)}(k)\right]^3}{k_1^2 k_2^2 k_3^2} f_{3,\mathcal{R}}\left(\xi_*, \frac{k_1}{k_*}, \frac{k_2}{k_*}, \frac{k_3}{k_*}, \delta\right) \qquad \mathcal{B}_{\lambda\lambda\lambda}^{(s)}(k_1, k_2, k_3) = \frac{\left[\epsilon_\phi \mathcal{P}_{\mathcal{R}}^{(v)}(k)\right]^3}{k_1^2 k_2^2 k_3^2} f_{3,\lambda}\left(\xi_*, \frac{k_1}{k_*}, \frac{k_2}{k_*}, \frac{k_3}{k_*}, \delta\right)$$

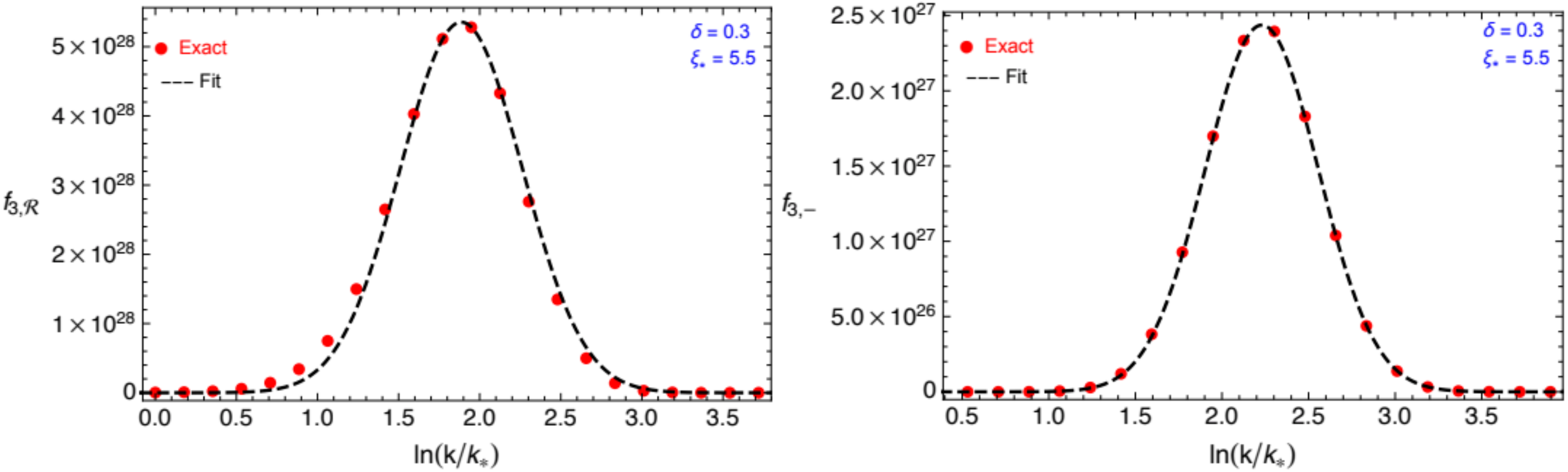
Bispectra is maximal for equilateral triangles ! $k_1 \approx k_2 \approx k_3 = k$

Echoes of particle production (Bumpy ride)

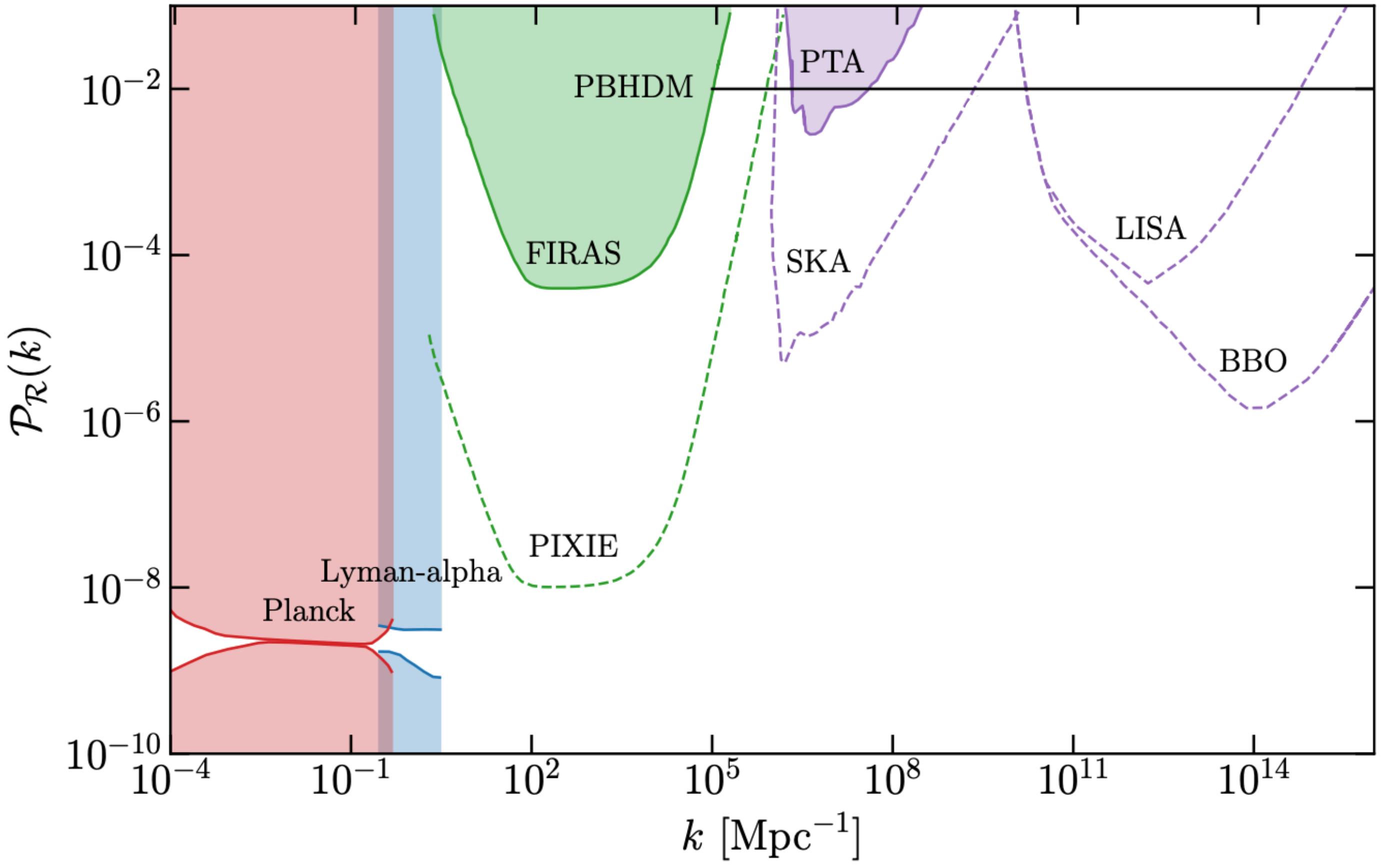
$$f_{i,j}\left(\frac{k}{k_*},\xi_*,\delta\right) \simeq f^c_{i,j}\left[\xi_*,\delta\right]\exp\left[-\frac{1}{2\sigma^2_{i,j}\left[\xi_*,\delta\right]}\ln^2\left(\frac{k}{k_* x^c_{i,j}\left[\xi_*,\delta\right]}\right)\right]$$

$3 \leq \xi_* \leq 6.5$

$\{i,j\}$	$\ln(\lvert f^c_{i,j}\rvert) \simeq$	$x^c_{i,j} \simeq$	$\sigma_{i,j} \simeq$
$\{2,\mathcal{R}\}$	$-15.13+10.09\,\xi_*+0.0389\,\xi_*^2$	$6.63-0.403\,\xi_*+0.0856\,\xi_*^2$	$0.89-0.101\,\xi_*+0.0066\,\xi_*^2$
$\{2,-\}$	$-14.78+9.91\,\xi_*+0.0487\,\xi_*^2$	$7.78-0.166\,\xi_*+0.0992\,\xi_*^2$	$0.83-0.110\,\xi_*+0.0070\,\xi_*^2$
[redacted]	[redacted]	[redacted]	[redacted]
$\{3,\mathcal{R}\}$	$-19.03+15.18\,\xi_*+0.0561\,\xi_*^2$	$6.21-0.377\,\xi_*-0.0814\,\xi_*^2$	$0.68-0.086\,\xi_*+0.0055\,\xi_*^2$
$\{3,-\}$	$-20.81+14.83\,\xi_*+0.0773\,\xi_*^2$	$7.43-0.209\,\xi_*+0.0996\,\xi_*^2$	$0.67-0.095\,\xi_*+0.0061\,\xi_*^2$



Limits on Power spectrum at small scales



→ Threshold for sizeable PBH abundance for a Gaussian power spectrum

- Constraints depend on the details of the primordial scalar fluctuations: i.e shape of the power spectrum, non-Gaussianity…

*A. Green, B. Kavanagh , arXiv: 2007.10722,

Gauge field production at the cliff(s)

$$\frac{\mathrm{d}^2 A_-}{\mathrm{d}x^2}+\underbrace{\left(1-\frac{2}{x}\,\frac{\xi_*}{1+\ln[(x_*/x)^{\delta}]^2}\right)}_{V_{\rm eff}(x)}A_-=0$$

$$V_{\rm eff}(x)=\begin{cases} p(x)^2, & x>x_{\rm c} \\ -\kappa(x)^2, & x<x_{\rm c}\end{cases}$$

IN region

OUT region

$$V_{\rm eff}(x_c)=0 \quad\longrightarrow\quad x_c=x_c(\xi_*,\delta,x_*)$$

INTERMEDİATE region

1) $A_-\,(x>x_{\rm c})\simeq\frac{\alpha}{\sqrt{p(x)}}\cos\left(\int_{x_{\rm c}}^{x}p\,(x')\,\mathrm{d}x'-\frac{\pi}{4}\right)-\frac{\beta}{\sqrt{p(x)}}\sin\left(\int_{x_{\rm c}}^{x}p\,(x')\,\mathrm{d}x'-\frac{\pi}{4}\right)$ IN region

2) $A_-\,(x\approx x_{\rm c})\propto c_1\,\mathrm{Ai}[x-x_{\rm c}]+c_2\,\mathrm{Bi}[x-x_{\rm c}]$ INTERMEDİATE region

3) $A_-\,(x<x_{\rm c})\simeq\frac{\alpha/2}{\sqrt{\kappa(x)}}\exp\left(-\int_{x}^{x_{\rm c}}\kappa\,(x')\,\mathrm{d}x'\right)+\frac{\beta}{\sqrt{\kappa(x)}}\exp\left(\int_{x}^{x_{\rm c}}\kappa\,(x')\,\mathrm{d}x'\right)$ OUT region

$$\boxed{\alpha=\frac{1}{\sqrt{2k}}\qquad \beta=-\frac{i}{\sqrt{2k}}}$$

Fixed by Bunch-Davies

Gauge field production at the cliff(s)

$$A_-\left(x<x_{\mathrm{c}}\right)\simeq\frac{\alpha/2}{\sqrt{\kappa(x)}}\exp\left(-\int_x^{x_{\mathrm{c}}}\kappa\left(x'\right)\mathrm{d}x'\right)+\underbrace{\frac{\beta}{\sqrt{\kappa(x)}}\exp\left(\int_x^{x_{\mathrm{c}}}\kappa\left(x'\right)\mathrm{d}x'\right)}$$

Growing Mode

$$\int_x^{x_{\mathrm{c}}}\kappa\left(x'\right)\mathrm{d}x'=\underbrace{\int_0^{x_{\mathrm{c}}}\kappa\left(x'\right)\mathrm{d}x'}_{\ln N(\xi_*,x_*,\delta)}-\underbrace{\int_0^{x}\kappa\left(x'\right)\mathrm{d}x'}_{\frac{2\sqrt{2\xi_* x}}{\delta|\ln(x/x_*)|}}$$

$$x_c=x_c\left(\xi_*,\delta,x_*\right)$$

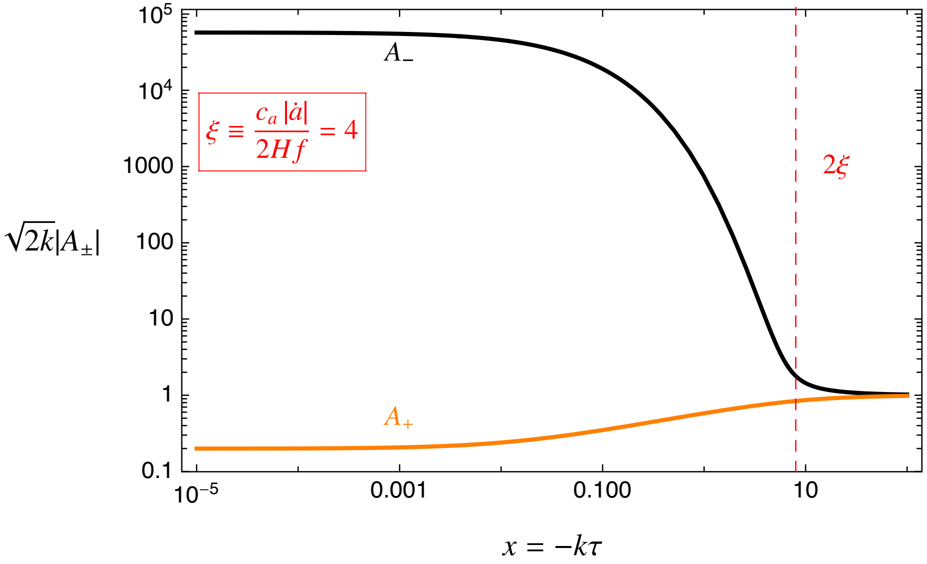
$$A_-(\tau,\vec{k})=\frac{1}{\sqrt{2k}}\left(\frac{-k\tau}{2\xi(\tau)}\right)^{1/4}N\left(\xi_*,x_*,\delta\right)\exp\left[-\frac{2\sqrt{2\xi_*}(-k\tau)^{1/2}}{\delta\left|\ln\left(\tau/\tau_*\right)\right|}\right]$$

Normalization factor that parametrizes the scale dependent growth

$$\boxed{N\left(\xi_*,x_*,\delta\right)\simeq N^c\left[\xi_*,\delta\right]\exp\left(-\frac{1}{2\sigma^2\left[\xi_*,\delta\right]}\ln^2\left(\frac{x_*}{q^c\left[\xi_*,\delta\right]}\right)\right)}$$

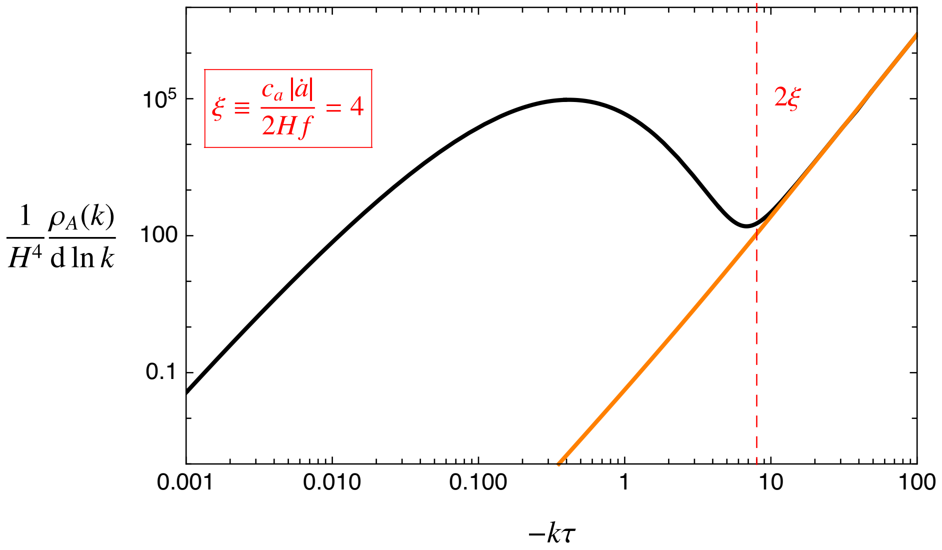
Gauge field production (Review)

$$\frac{\mathcal{L}_m}{\sqrt{-g}} = -\frac{1}{2}\partial_\mu a\,\partial^\mu a - V_{\rm sb}(a) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{c_a}{4f}\,a\,F_{\mu\nu}\tilde{F}^{\mu\nu} + \ldots$$



$$A''_\pm + k^2\left(1 \pm \frac{2\xi}{x}\right)A_\pm = 0$$

$$\xi \equiv \frac{c_a\,|\dot{a}|}{2H\,f}$$



- Parity breaking!
- Exponential sensitivity to field velocity

$$A_- \propto \exp\left[\frac{\pi c_a|\dot{a}|}{H\,f}\right]$$

- ρ_A is diluted at late times

(M. Anber & L. Sorbo, '09)