GWs from Axion-Gauge Field Dynamics during inflation

O.Ö, Z. Lalak, arXiv: 2008.07549 O.Ö, arXiv: 2005.10280

Prague Relativity Group Meeting

03/12/2021

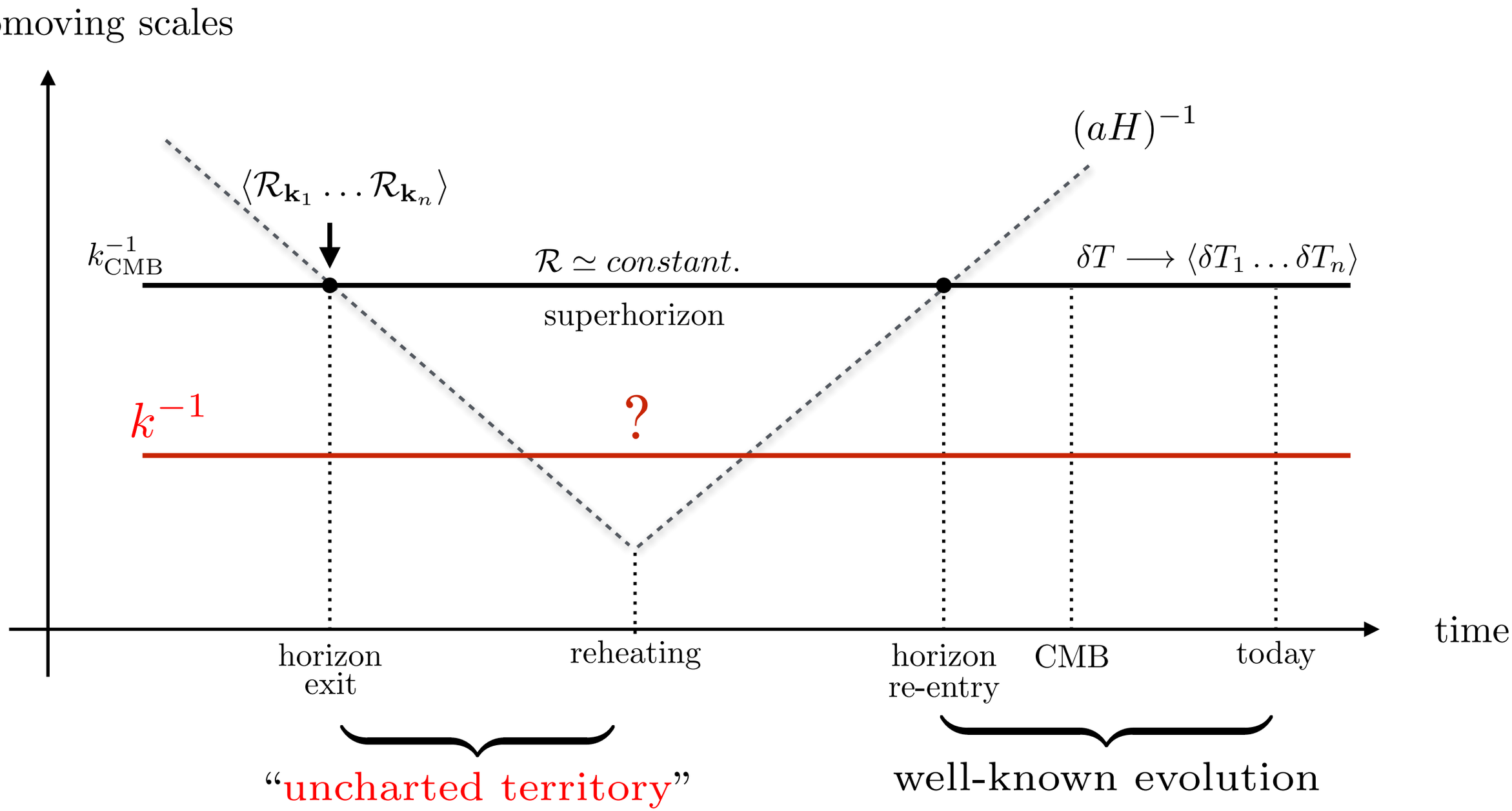
Ogan Özsoy-CEICO

EUROPEAN UNION
European Structural and Investment Funds
Operational Programme Research,
Development and Education

MINISTRY OF EDUCATION,
YOUTH AND SPORTS

FZU

Poor man's collider



CMB and LSS (& Spectral Dist.) $\rightarrow$ 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

- Primordial Black Holes (PBHs)

  - (Depending on their mass) PBHs can (maybe !) account for all or significant fraction of DM abundance

    Simeon Bird et.al, "Did LIGO detect dark matter ?", arXiv: 1603.00464

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

    requires large $\mathcal{P}_\mathcal{R}(k)$ at $k \gg k_{\rm CMB}$

- GWs at interferometer scales

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

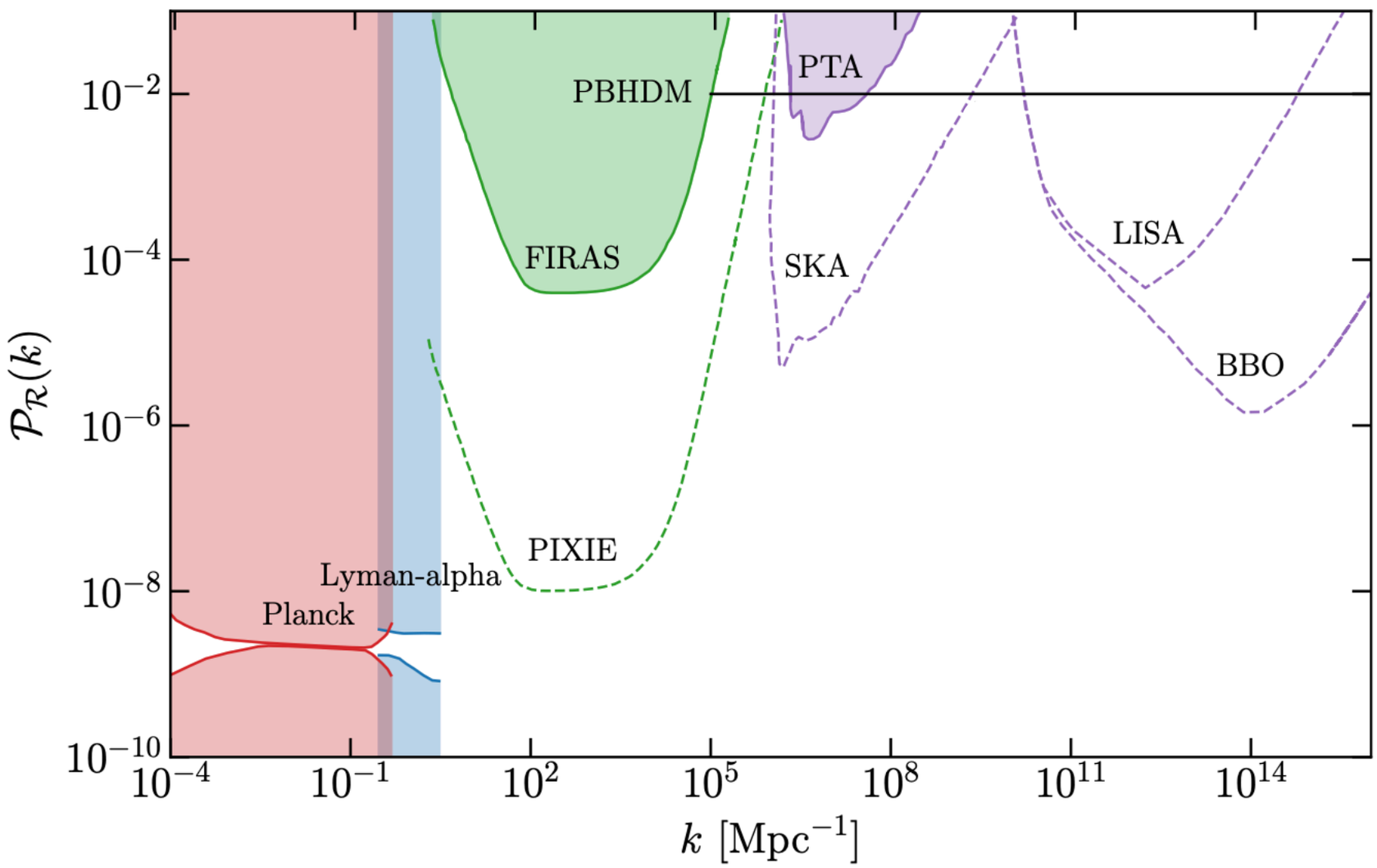
    $\Omega_{\rm GW}(k) \sim \int dp\, \mathcal{P}_\mathcal{R}(|\vec{k} - \vec{p}|)\mathcal{P}_\mathcal{R}(p)$ → Potential probe of $\mathcal{P}_\mathcal{R}(k)$

    Strong Bending of trajectory in multi-scalar inflation, J. Fumagalli, S. Renaux-Petel, L. Witkowski, arXiv: 2012.02761

  - Direct enhancement of tensor perturbations during inflation:

    Multi-field: Axion-Gauge field dynamics, N. Barnaby, E. Pajer, M. Peloso, arXiv: 1110.3327.

Limits on Power spectrum at small scales

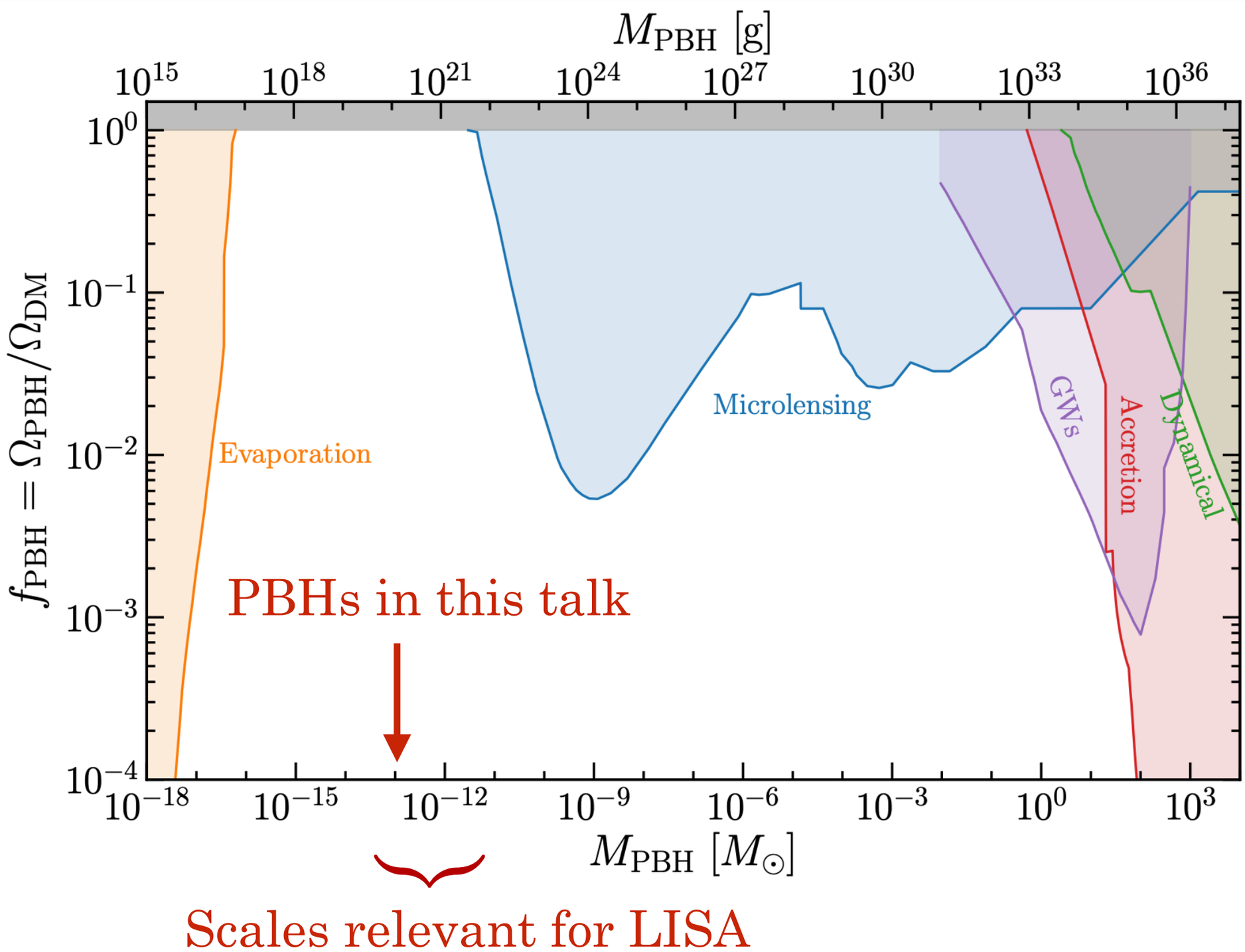


Threshold for sizeable PBH abundance for a Gaussian power spectrum

- 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,

Limits on PBH as Dark Matter

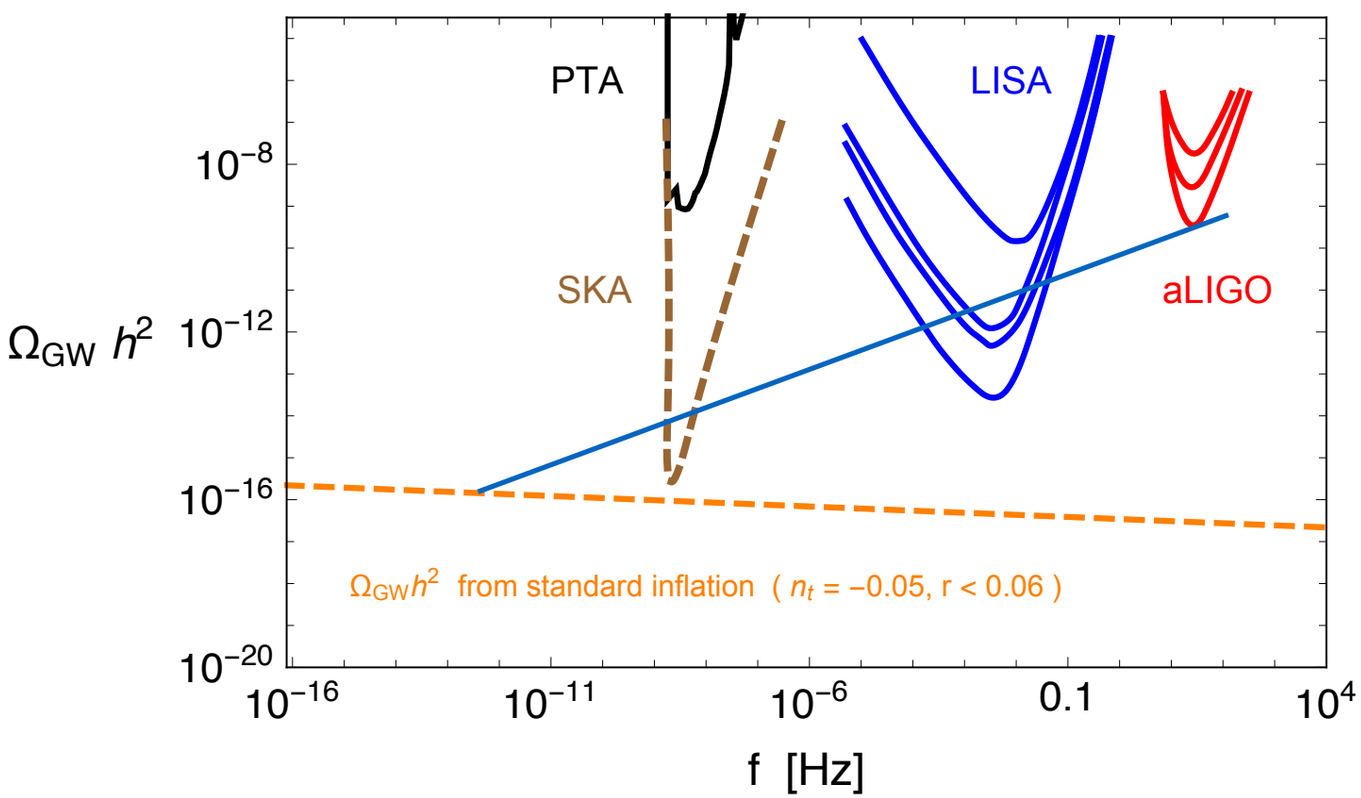


*A. Green, B. Kavanagh , arXiv: 2007.10722,

Alternative sources of GW's

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

Amplification of vacuum modes is an irreducible configuration during inflation but too small to be detected at interferometer scales*



Produced GWs must be blue tilted to be observable at interferometers!

(J. Cook & L. Sorbo, '11)
(N. Barnaby, E.Pajer&M.Peloso '11)
(V. Domcke, M. Pieroni & Binetruy, '16)
(Iacconi et.al '19)

*Exception to this: transient non-attractor phases during single field inflation (localized blue tilt).
arXiv: 1808.10475, 1902.04976, OÖ, M. Mylova, G.Tasinato, I. Zavala, S. Parameswaran

Rolling Axion as a reservoir

Axions have approximate shift symmetry: $X \to X + c$

As a consequence:

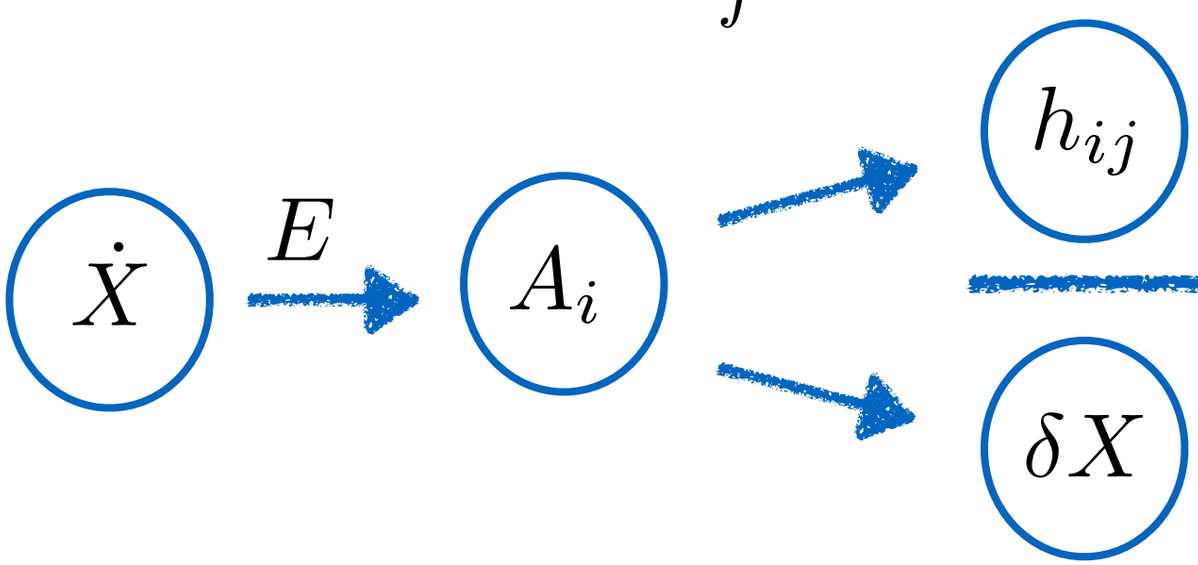
i) they are light and can roll a significant amount of time during inflation,

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

(A resourceful Dinamo/reservoir!)

ii) natural couplings to gauge fields where they can dump their kinetic energy:

$$\Delta\mathcal{L}_{\rm int} = \frac{\alpha_{\rm c}}{f} X F\tilde{F} = -4\alpha_{\rm c}\frac{\partial_\mu X}{f}\epsilon_{\mu\nu\rho\sigma}A_\nu\partial_\rho A_\sigma$$



GWs through inverse decay of gauge fields.

$X = \phi$ case is typically problematic if we insist sourced GWs > vacuum GWs at CMB scales (N. Barnaby & M. Peloso, '10)

(OÖ, K. Sinha & S.Watson '14)

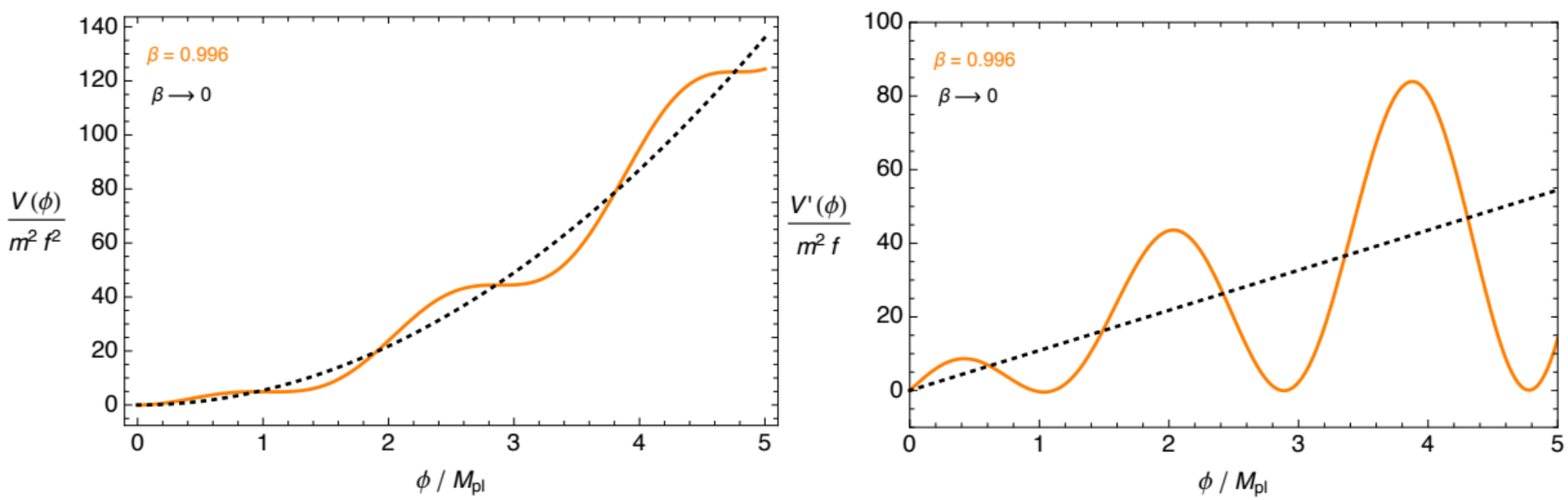
Axion-Gauge field Inflation

$$\frac{\mathcal{L}}{\sqrt{-g}} = \frac{M_{\rm pl}^2}{2}R - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{\alpha_{\rm c}}{4f}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}{}^{*}$$

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

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

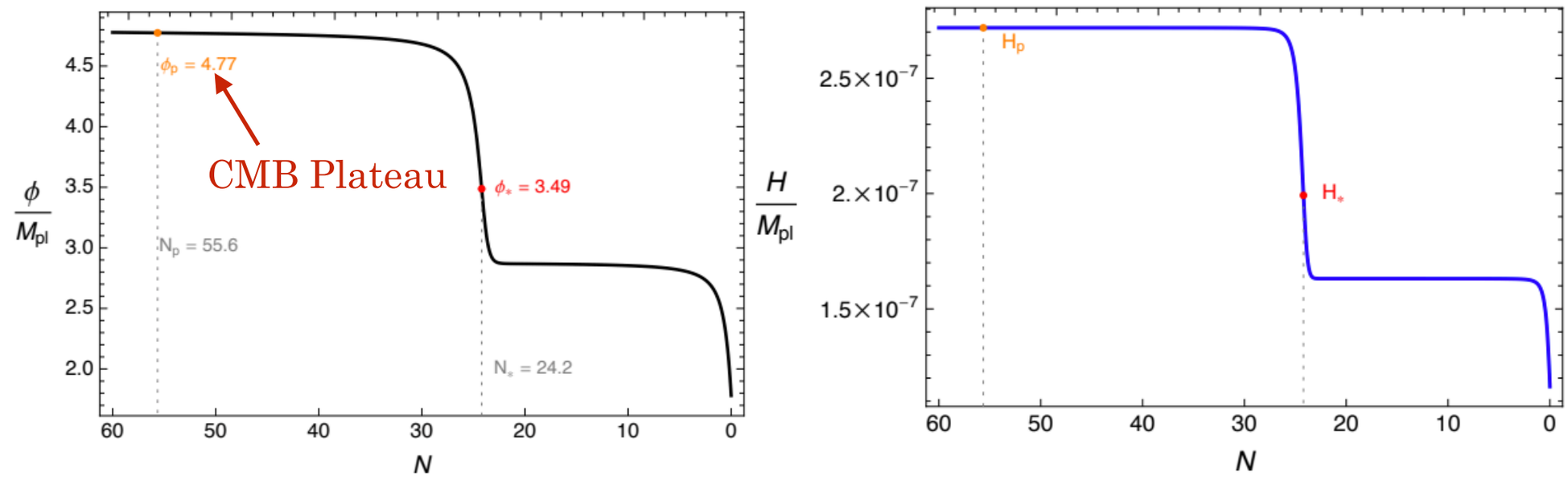
Interested in "Bumpy" Regime → $\beta = \frac{\Lambda^4}{m^2 f^2} \lesssim 1$



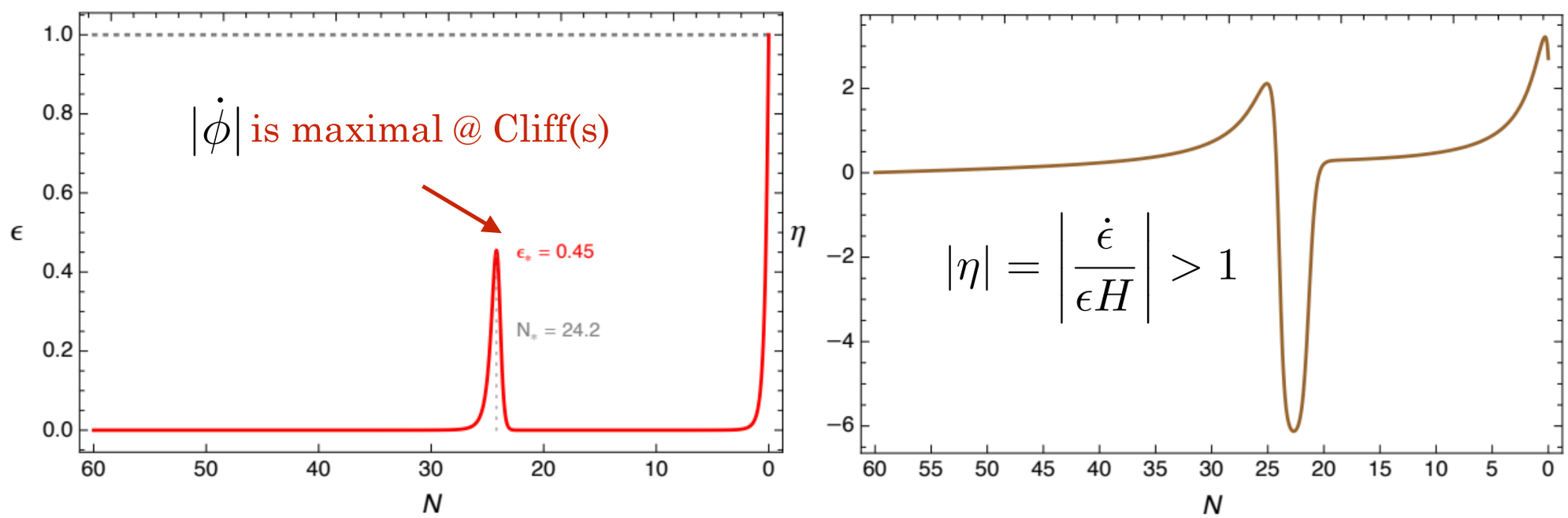
*M. Anber, L. Sorbo, arXiv: 0908.4089, A. Linde, S. Mooij, E.Pajer arXiv:1212.1693, J. Garcia-Bellido, M. Peloso, C. Ünal arXiv: 1610.03763, S-L. Cheng, W. Lee, K-W. Ng, arXiv: 1801.09050

Axion Inflation in the Bumpy Regime

$\Delta\phi \simeq 3M_{\rm pl}$



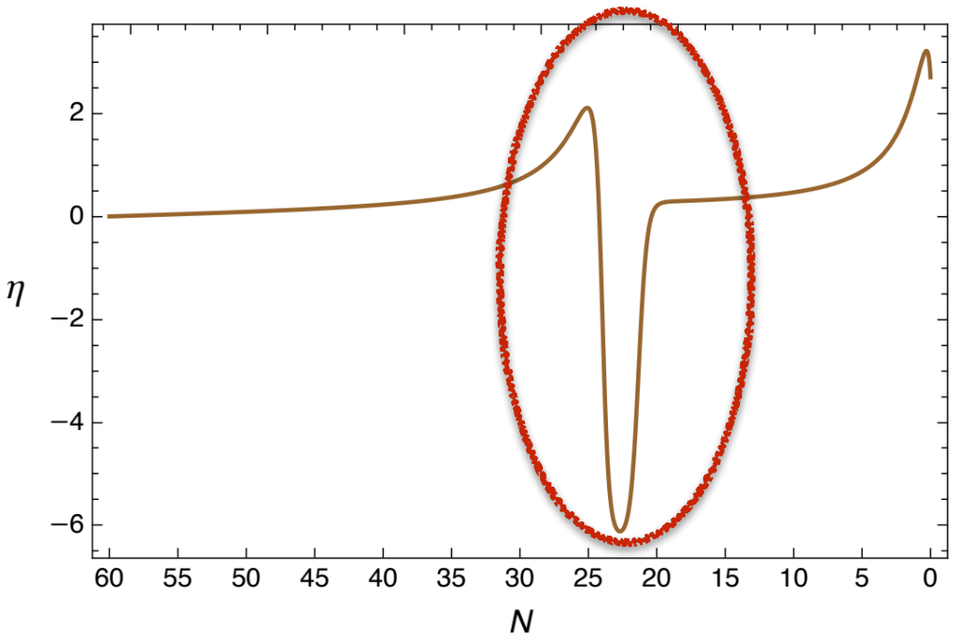
- Hubble drag in the plateau regions of $V(\phi)$ is pretty efficient to sustain enough inflation for an intermediate field range and energy scale! ($r \simeq 10^{-5}$)



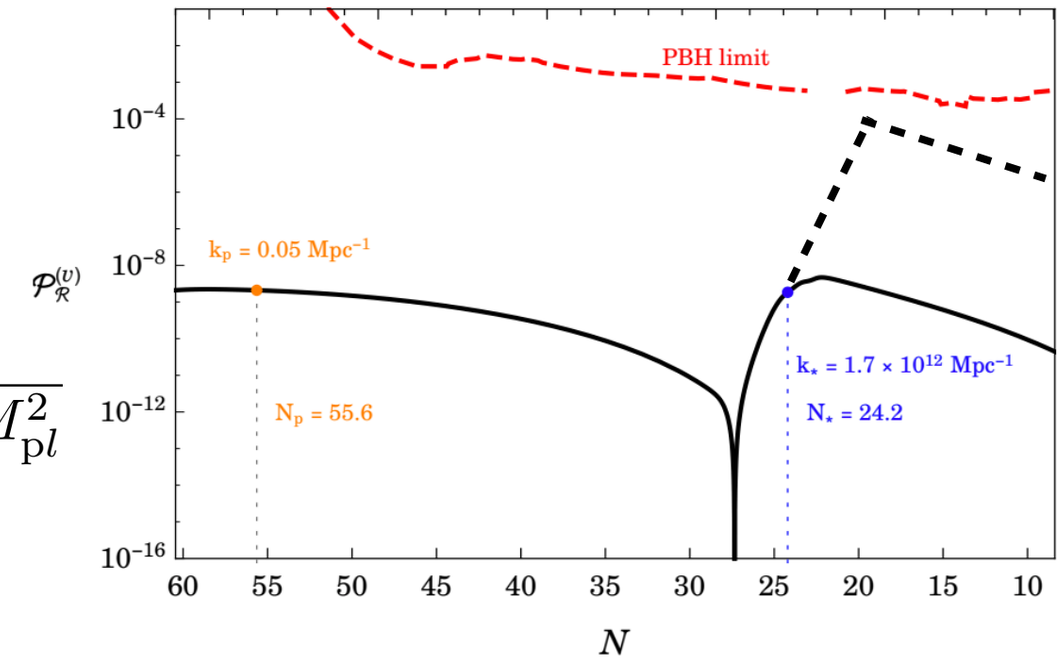
- Temporary speed up of inflaton at the cliff like regions of $V(\phi)$ and slow-roll violation

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

Axion Inflation in the Bumpy Regime



$$\mathcal{P}_{\mathcal{R}}^{(v)} \overset{!}{=} \frac{H^2}{8\pi^2 \epsilon\, M_{\rm pl}^2}$$

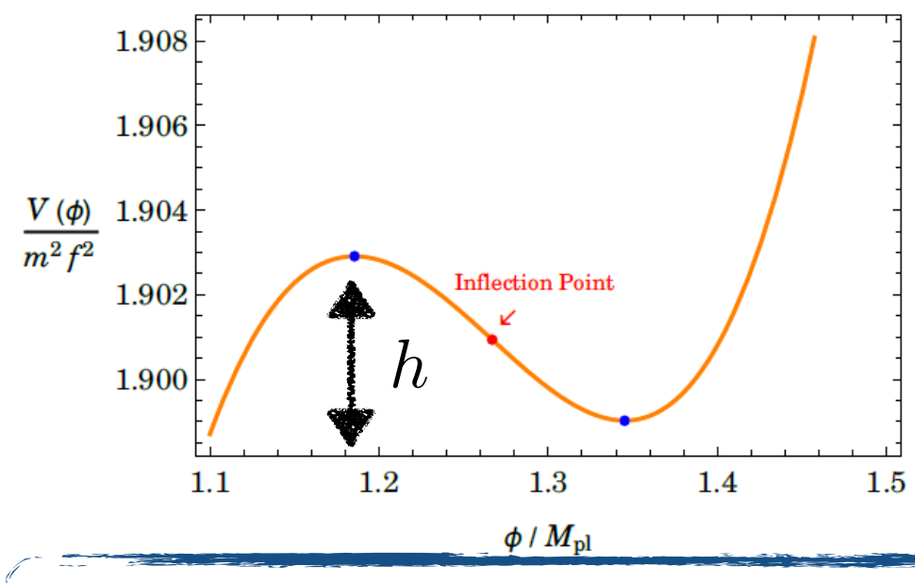


- Large positive η phase (fast-roll) followed by negative η phase (non-attractor) : $\epsilon \propto e^{\eta N}$

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

Damping term becomes a driving term

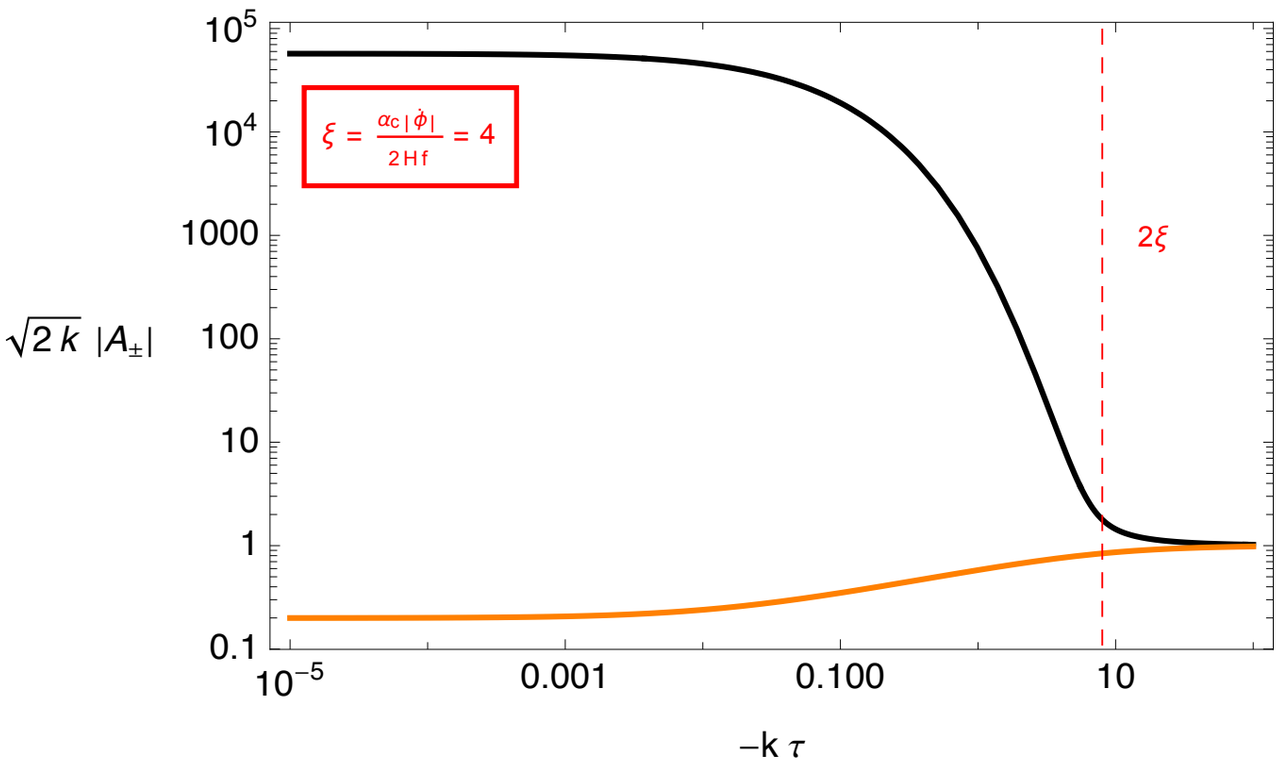
- Duration of negative η phase determines the enhancement in the power spectrum*

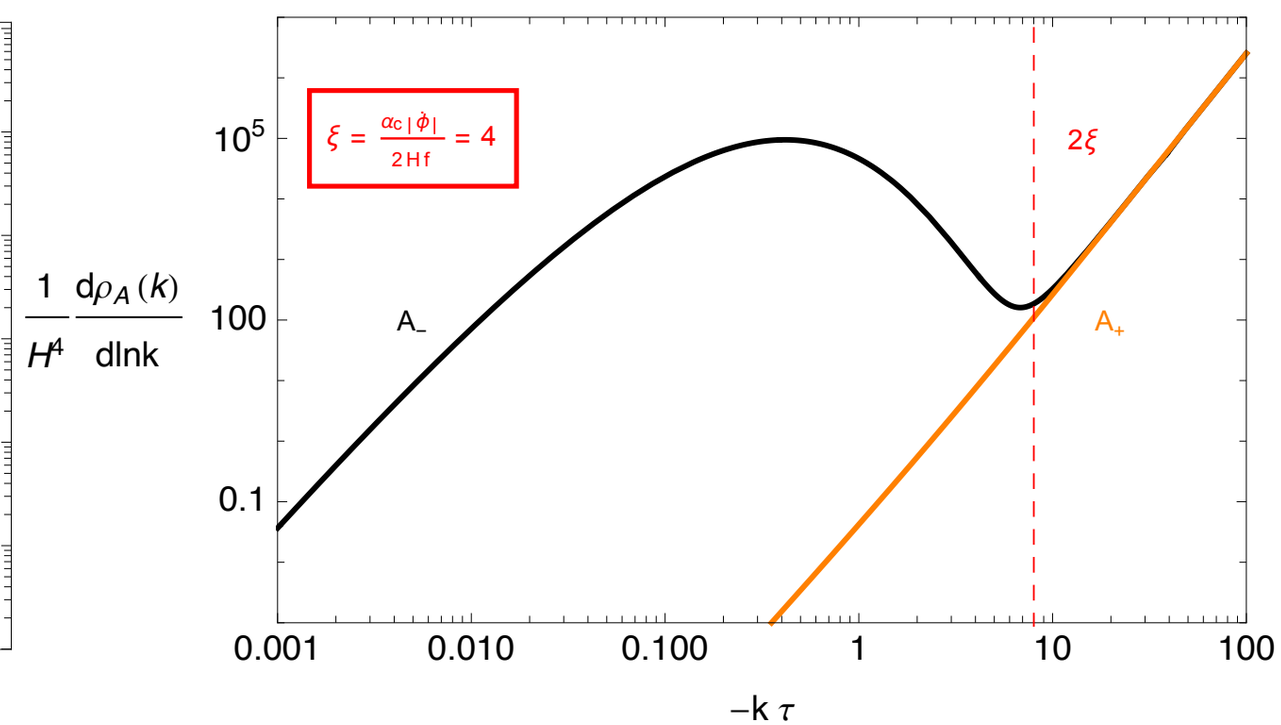


Fine tuning of model parameters is required to get a larger enhancement: e.g by adjusting the height h of the barrier

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

Gauge field production (Review)





$$\frac{\mathcal{L}}{\sqrt{-g}} = \frac{M_{\rm pl}^2}{2}R - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi) \underbrace{-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{\alpha_c}{4f}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}}$$

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

Constant $|\dot\phi|$ case

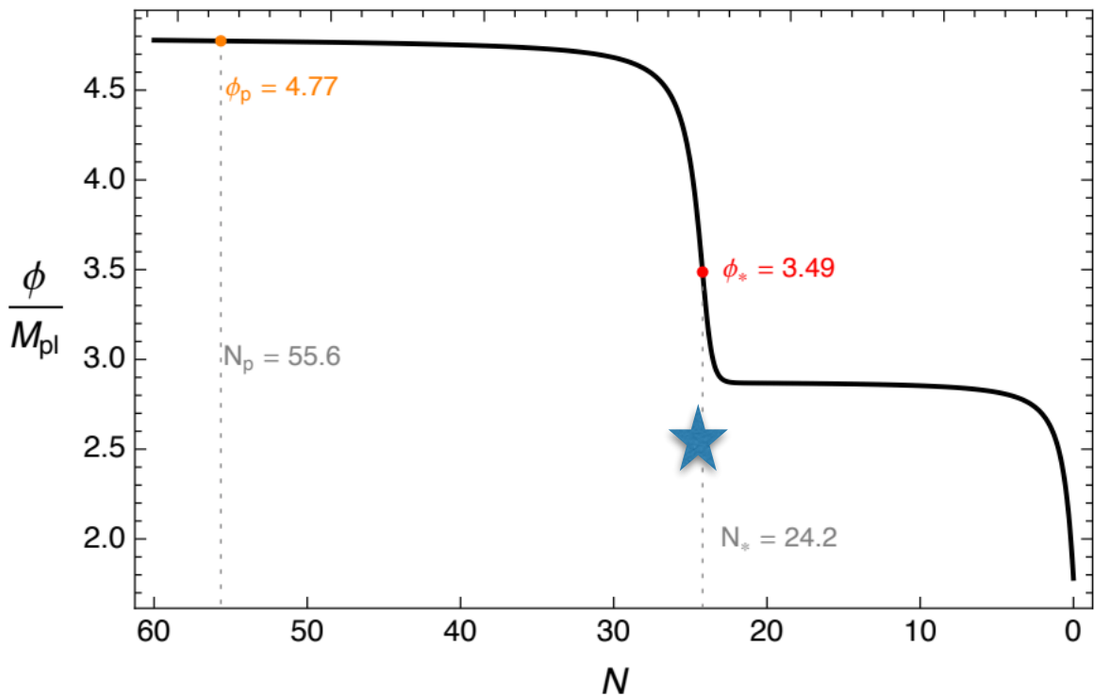
i) Only A_- is amplified: parity breaking due to $\Delta\mathcal{L}_{\rm int} = -\frac{\alpha_c}{4f}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$

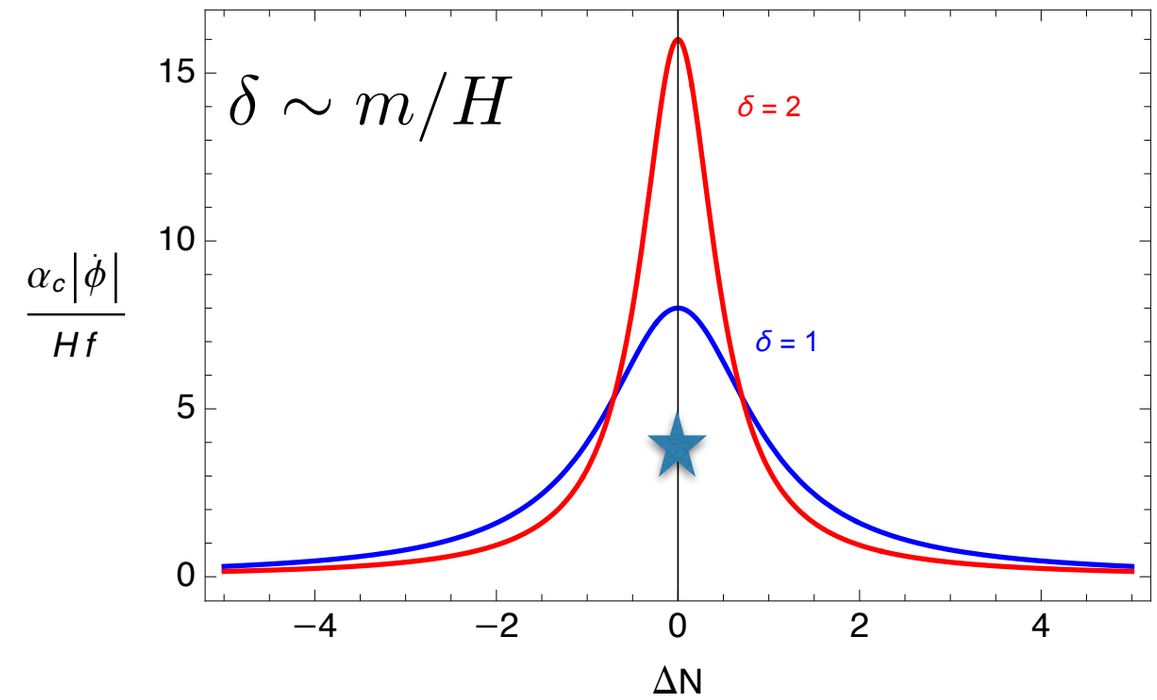
ii) ρ_A is diluted at late times

iii) Exponential sensitivity to $A_- \propto e^{\frac{\alpha_c|\dot\phi|}{Hf}}$

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

Gauge field production at the cliff(s)





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

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

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

Amplification of the will be maximal for modes that exits the horizon

When the velocity of the of spectator is maximal → Scale dependence

Gauge field production is localized and parametrized by → $\left\{\frac{k}{k_*}, \xi_*, \delta\right\}$

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

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

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

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

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

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

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

Normalization factor that parametrizes the scale dependent growth

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

Echoes of gauge field production

Scalar fluctuations: $\Delta\mathcal{L}_{\rm int} = -\frac{\alpha_{\rm c}}{f}\delta\phi\, F\tilde{F}$

(i) Amplified A_- sources $\mathcal{R}$ through: $A_- + A_- \to \delta\phi^{(s)} \propto \mathcal{R}^{(s)}$

Tensor fluctuations:

(i) Amplified A_- generates GWs through: $A_- + A_- \to h_-^{(s,p)}$

(ii) Induced GWs at horizon re-entry by the amplified scalar perturbations:

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

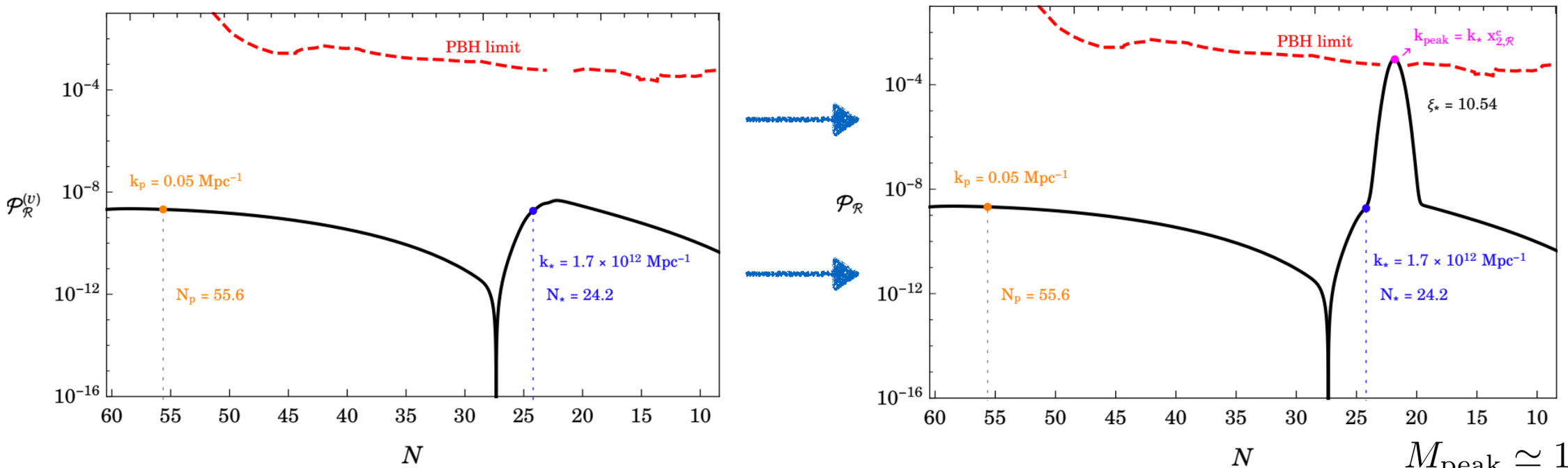
Scalar Power spectrum:

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

SGWB:

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

PBH as Dark Matter



$M_{\rm peak} \simeq 10^{-13} M_\odot$

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

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

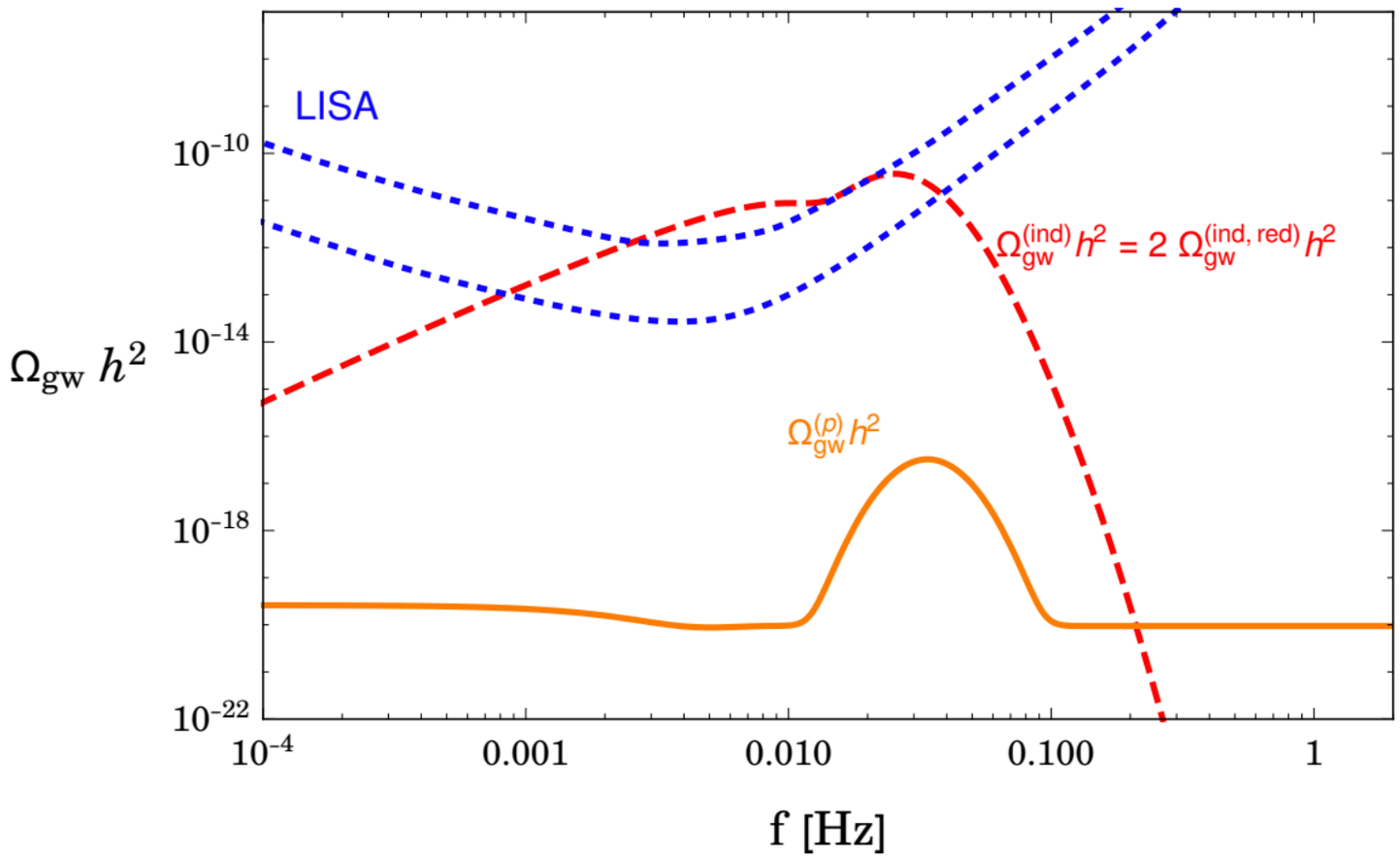
$$\beta(N) = \mathrm{Erfc}\left(\sqrt{\frac{1}{2} + \frac{\mathcal{R}_c}{\sqrt{2P_\mathcal{R}(N)}}}\right)$$

Relation between power spectra that leads to the same fraction:

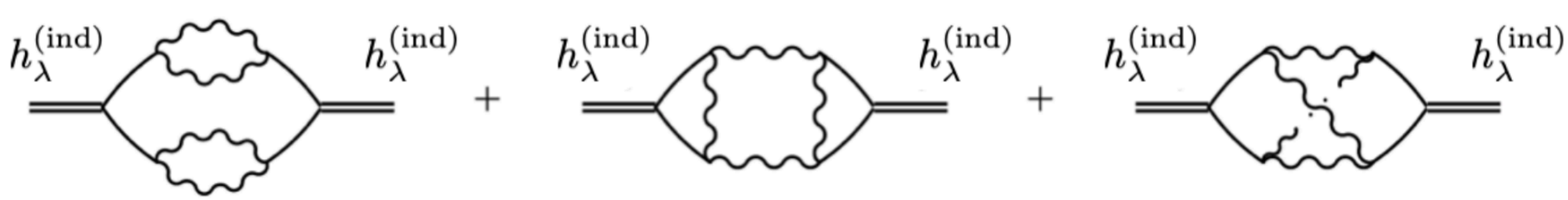
$$\mathcal{P}_{\mathcal{R}(\chi^2)} \simeq \frac{2}{\mathcal{R}_c^2}\mathcal{P}^2_{\mathcal{R}(\mathrm{G})}$$

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

Für eLISA

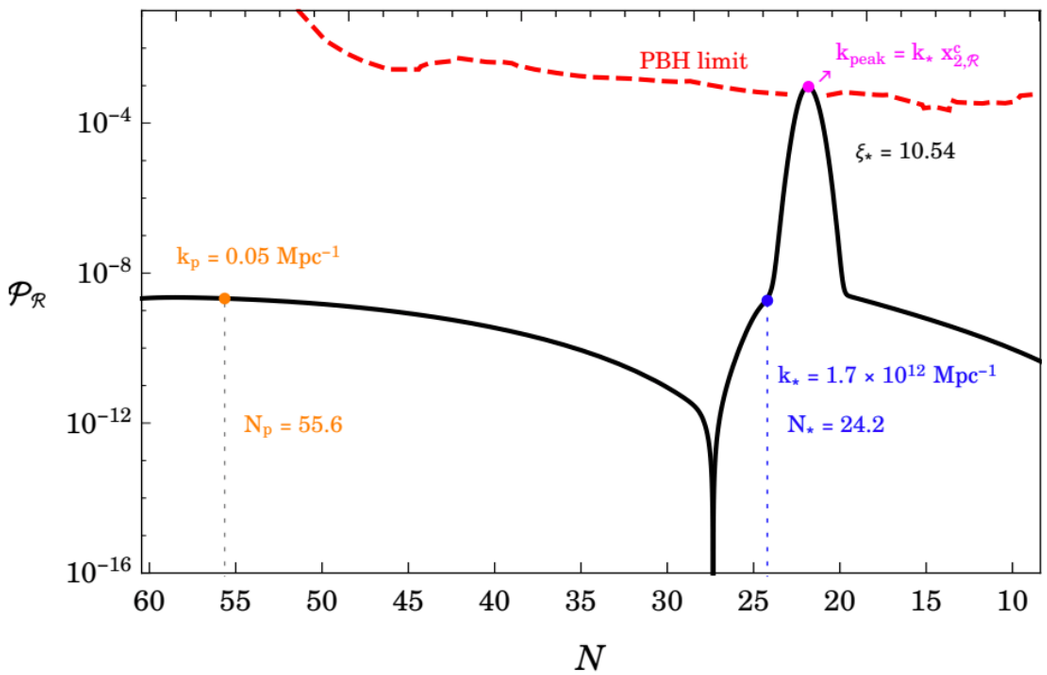


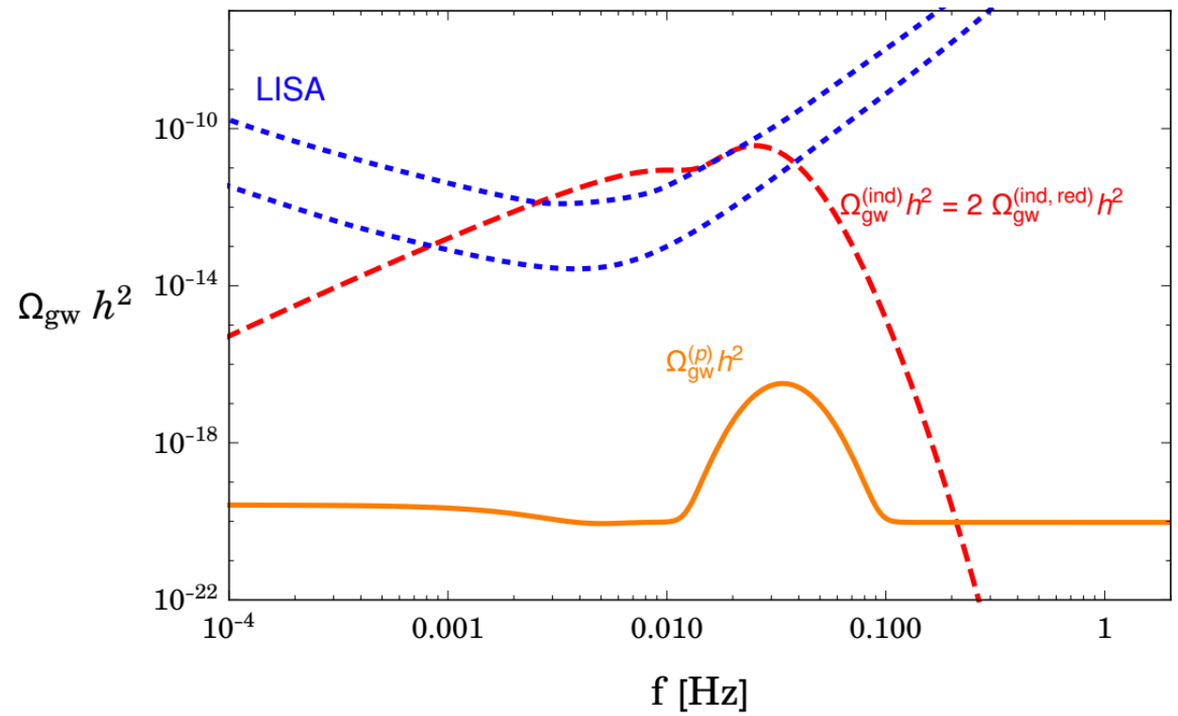
$$\Omega_{\rm gw}^{(\rm tot)}(\tau_0, k)\, h^2 \simeq \frac{\Omega_{r,0} h^2}{24} \left\{ \sum_\lambda \mathcal{P}_\lambda^{(v,\rm p)} + \mathcal{P}_-^{(s,\rm p)}(\tau_i, k) + \sum_\lambda \left(\frac{k}{\mathcal{H}(\tau_f)} \right)^2 \overline{\mathcal{P}_\lambda^{(\rm ind)}(\tau_f, k)} \right\}$$



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

Recap





"Bumpy" 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.

*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)

GW's as a probe of inflation (@ CMB scales)

- GW's are generic predictions of inflation:

$$r < 0.063\,(95\,\%\mathrm{CL})$$ tensor-to-scalar ratio

- Future CMB missions (LiteBIRD, CMB-S4) are expected to probe a tensor-to-scalar ratio at the level of $r \lesssim 10^{-3}$
- LiteBIRD is expected to be sensitive $f_{\mathrm{NL}}^{\mathrm{tens}} = 1$

GW's as a direct measure of inflationary energy scale (?)

$$H_{\mathrm{inf}} \simeq 2.5 \times 10^{-5} \left(\frac{r}{0.063}\right)^{1/2} M_{\mathrm{pl}}$$

Quantum vacuum fluctuations of the metric is proportional to in Hubble rate during inflation!

An observation of B-modes in this context can be considered as a first hint on the quantum nature of gravity (at the linearised level) (?)

Alternative sources of GW's

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

Energetic enough field configs can lead to GW emission that can compete with vacuum fluctuations of the metric at CMB scales

$$H_{\rm inf} \simeq 2.5 \times 10^{-5}\left(\frac{r}{0.063}\right)^{1/2} M_{\rm pl}$$

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

The model

Identify X as a spectator during inflation: $X \to \sigma$

(to evade bounds from CMB)

$$\frac{\mathcal{L}}{\sqrt{-g}} = \frac{M_{\rm pl}^2 R}{2} - \underbrace{\frac{1}{2}(\partial\phi)^2 - V_\phi(\phi)}_{\text{Inflaton Sector}} - \underbrace{\frac{1}{2}(\partial\sigma)^2 - V_\sigma(\sigma) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{\alpha_{\rm c}\sigma}{4f}F_{\mu\nu}\tilde{F}^{\mu\nu}}_{\text{Hidden Sector}}$$

$\rho_\sigma \ll \rho_\phi$ Spectator axion σ !

$$3H^2 M_{\rm pl}^2 = \rho_\phi + \rho_\sigma \quad \longrightarrow \quad 3H^2 M_{\rm pl}^2 \simeq V_\phi(\phi)$$

Echoes of particle production

$\Delta\mathcal{L}_{\rm int} \propto \sigma F\tilde{F}$

(1) Produced A_- sources $\delta\phi$ through: $A_- + A_- \to \delta\sigma^{(s)} \xrightarrow{|\dot{\sigma}| \neq 0} \delta\phi^{(s)} \propto \mathcal{R}^{(s)}$

$\Delta\mathcal{L}_{\rm int} \propto h_{ij}FF$

(2) Amplified A_- also generates GWs through: $A_- + A_- \to h_-^{(s)}$

*Due to $\Delta\mathcal{L}_{\rm int} \propto \sigma\tilde{F}F$, scalar modes are highly non-Gaussian at CMB scales, only $r < 10^{-3} - 10^{-4}$ is allowed for a featureless potential $V_\sigma(\sigma)$

(Ferreira&Sloth, '14, OÖ, '17)

Key difficulty here: Generating observable GWs without overproducing density perturbations (channel (1) is active as long as $|\dot{\sigma}| \neq 0$)

*To keep channel (1) under control, we need to switch of gauge field production, e.g through a localized roll of σ !

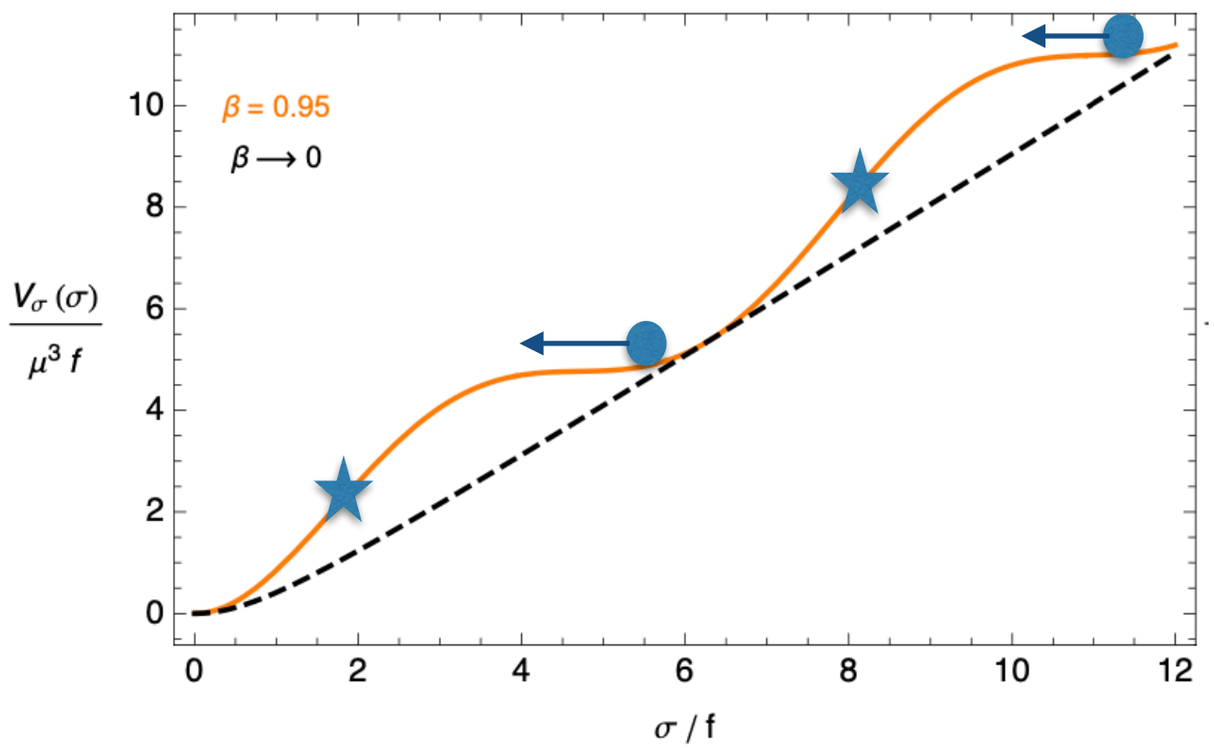
*R. Namba, M. Peloso, M. Shiraishi, L. Sorbo, C. Ünal arXiv:1509.07521

Localized signal ?

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

An example: Axion Monodromy! (Silverstein & Westphal, '08) (McAllister et.al, '08)

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



Bumpy ride of a spectator axion

arXiv: 2005.10280-O.Ö

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 !

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

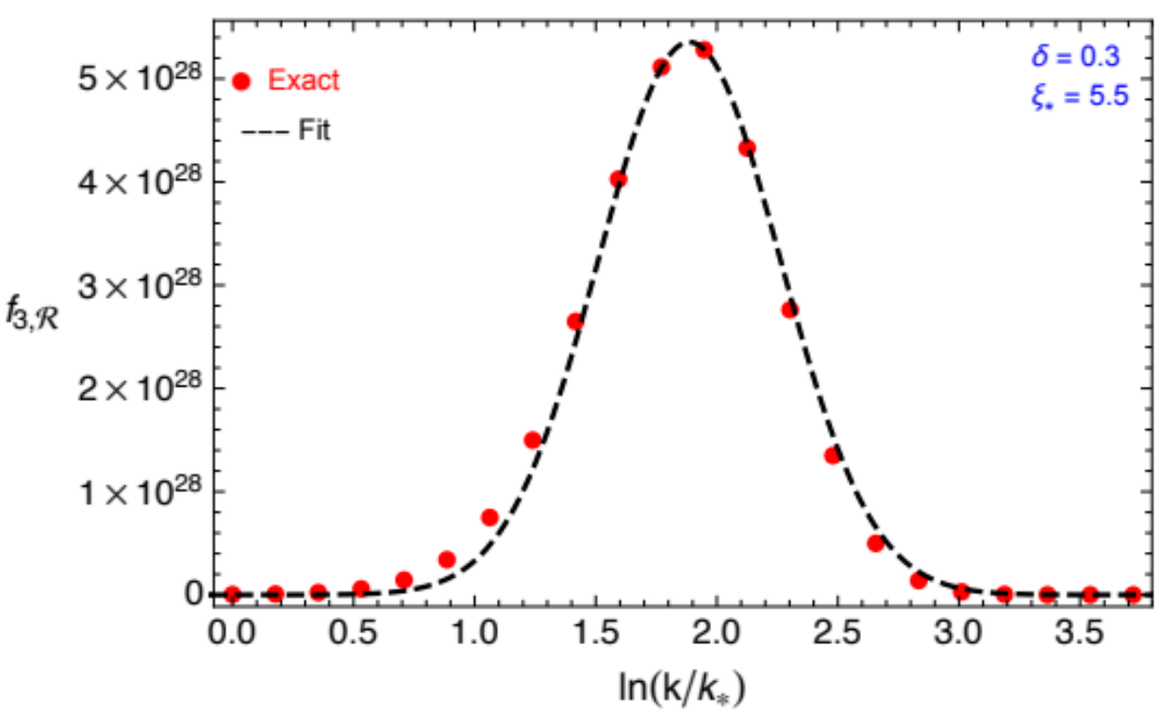
Bispectra is maximal for equilateral triangles ! $k_1 \approx k_2 \approx k_3 = k$

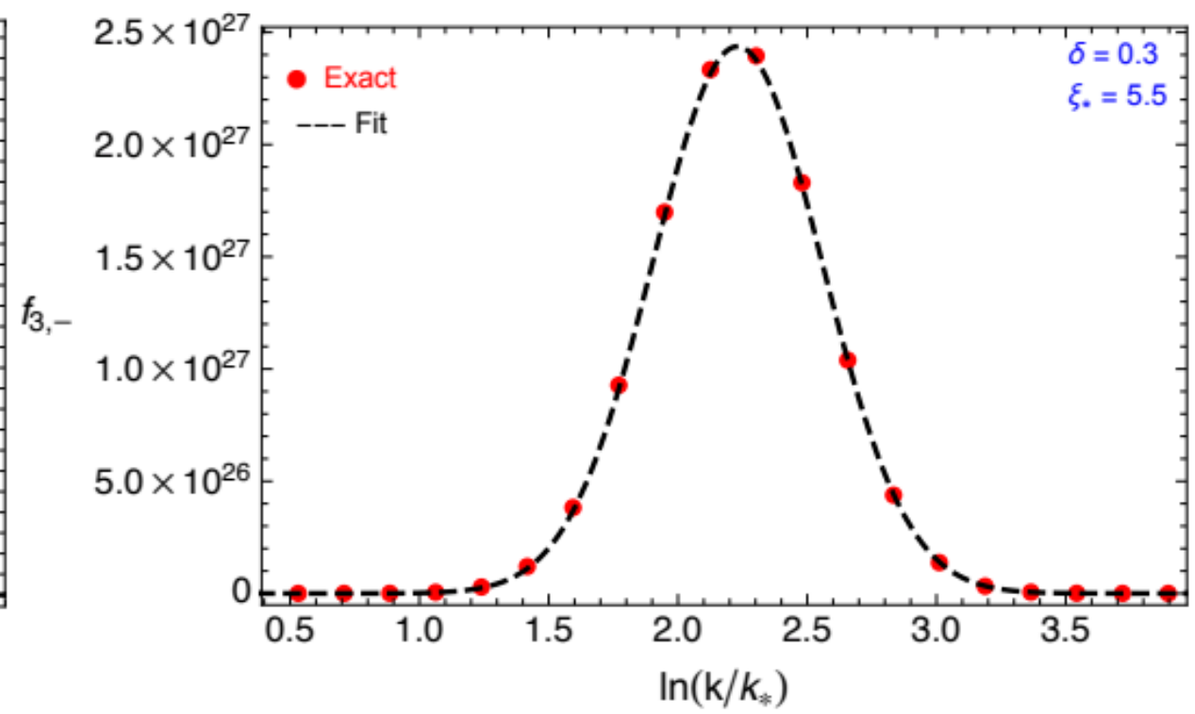
Echoes of particle production (Bumpy ride)

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

$3 \leq \xi_* \leq 6.5$

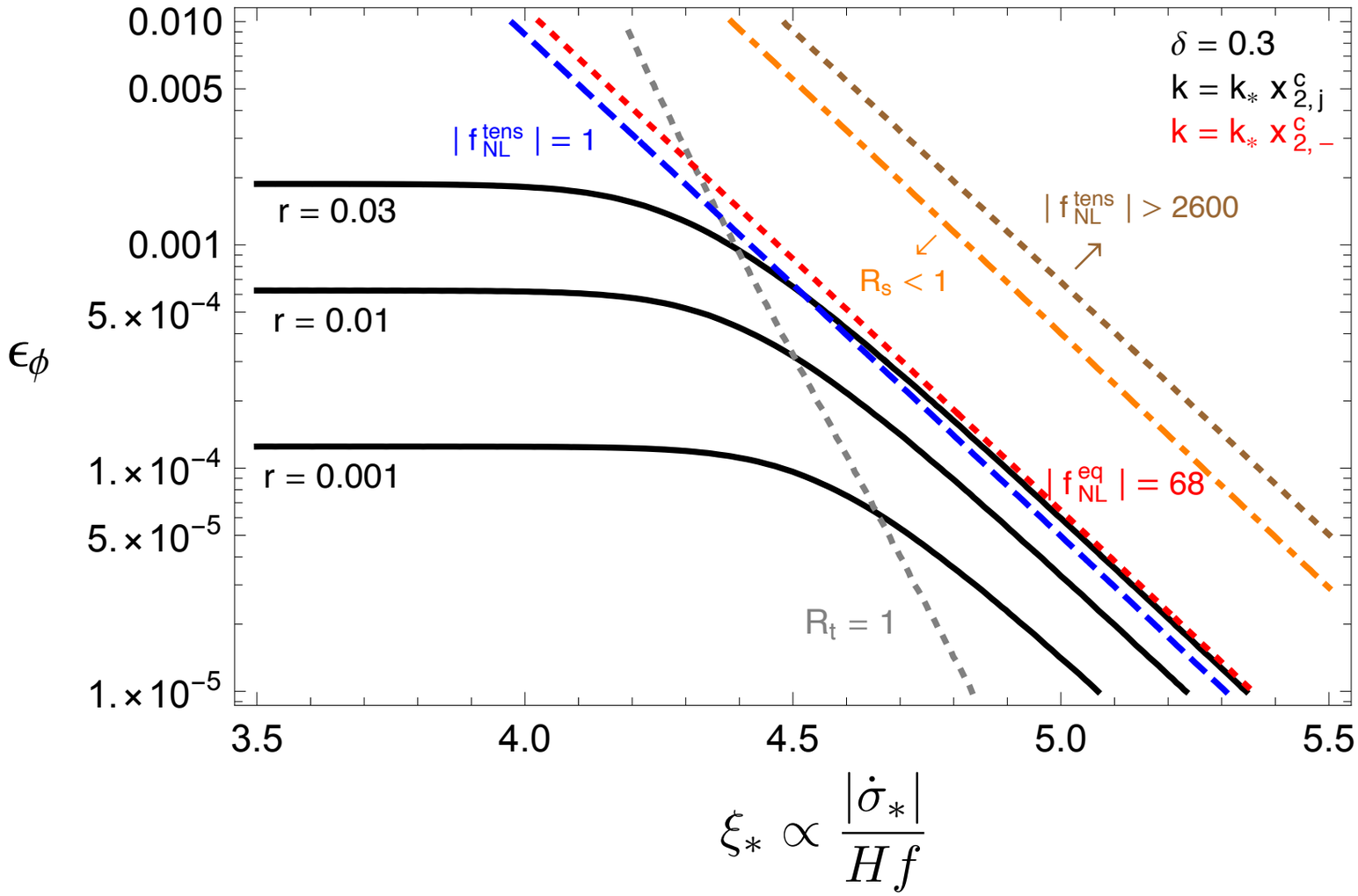
$\{i,j\}$	$\ln(\lvert f^c_{i,j}\rvert) \simeq$	$x^c_{i,j} \simeq$	$\sigma_{i,j} \simeq$
$\{2,\mathcal{R}\}$	$-15.13 + 10.09\,\xi_* + 0.0389\,\xi_*^2$	$6.63 - 0.403\,\xi_* + 0.0856\,\xi_*^2$	$0.89 - 0.101\,\xi_* + 0.0066\,\xi_*^2$
$\{2,-\}$	$-14.78 + 9.91\,\xi_* + 0.0487\,\xi_*^2$	$7.78 - 0.166\,\xi_*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





Observable GWs at CMB scales (non-vacuum)

Assume the signal peaks at CMB scales !



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

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

$$\left(\frac{r_*}{0.063}\right)^{1/2} \simeq \left(\frac{H_{\rm inf}/M_{\rm pl}}{2.5\times10^{-5}}\right)^2 e^{1.58\pi(\xi_*-4.05)}$$

vs.

$$H_{\rm inf} \simeq 2.5\times10^{-5}\left(\frac{r}{0.063}\right)^{1/2} M_{\rm pl}$$

Observable GWs are allowed even for a low scale of inflation!

arXiv: 2005.10280-O.Ö

Recap-2

- ✓ B-modes and their properties are expected to be measured by forthcoming experiments: CMB-S4 and LiteBIRD. Therefore its timely to search for alternatives mechanisms that can generate observable GWs in order to revisit our standard view on the early universe physics

- ✓ The transient motion of non-compact axion-like spectator field in its wiggly potential can lead to efficient production of its gauge fields which in turn generate GWs that can be parametrically larger than vacuum fluctuations: observable GWs with low scale of inflation and sub-planckian field excursion is possible!

  ☆ Scale dependent, parity violating, non-Gaussian GW signal at CMB!

- ✓ Any departure from the standard predictions on tensor fluctuations: scale free, parity conserving and high degree Gaussianity, would give us clues about the energy density contained in the hidden sectors, or more broadly might inform us about the inflationary field content.

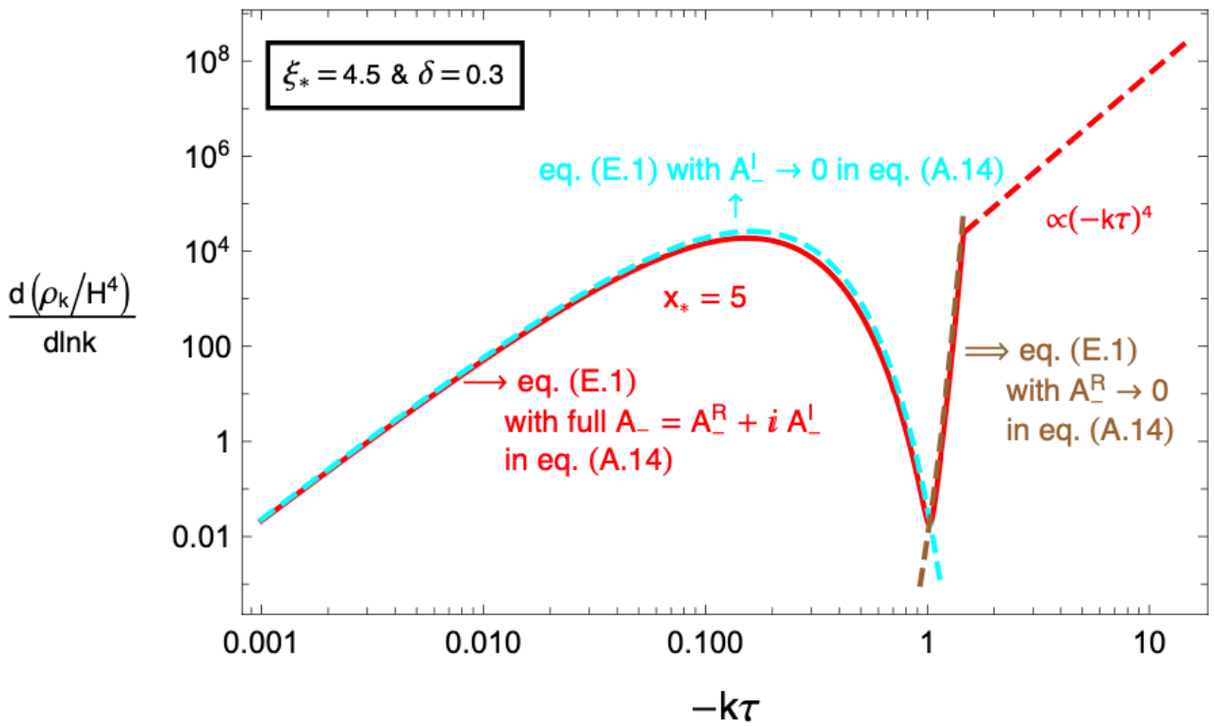
Thank you !

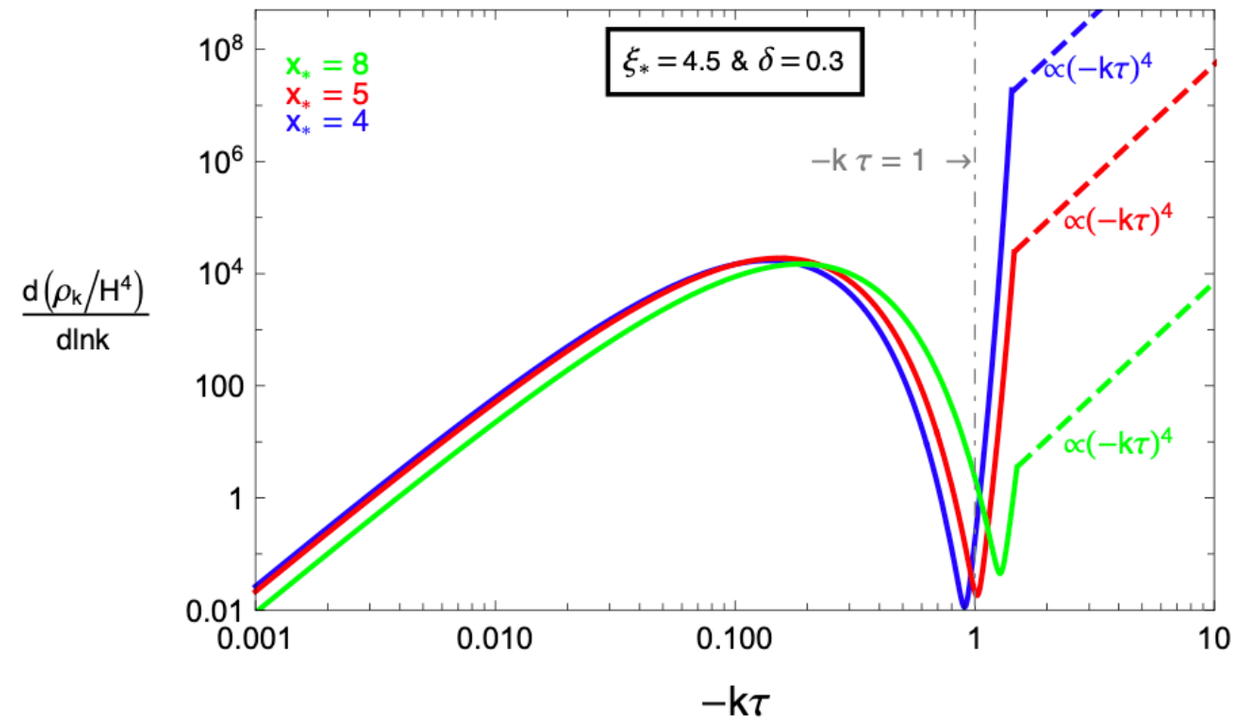
arXiv: 2008.07549

arXiv: 2005.10280

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)

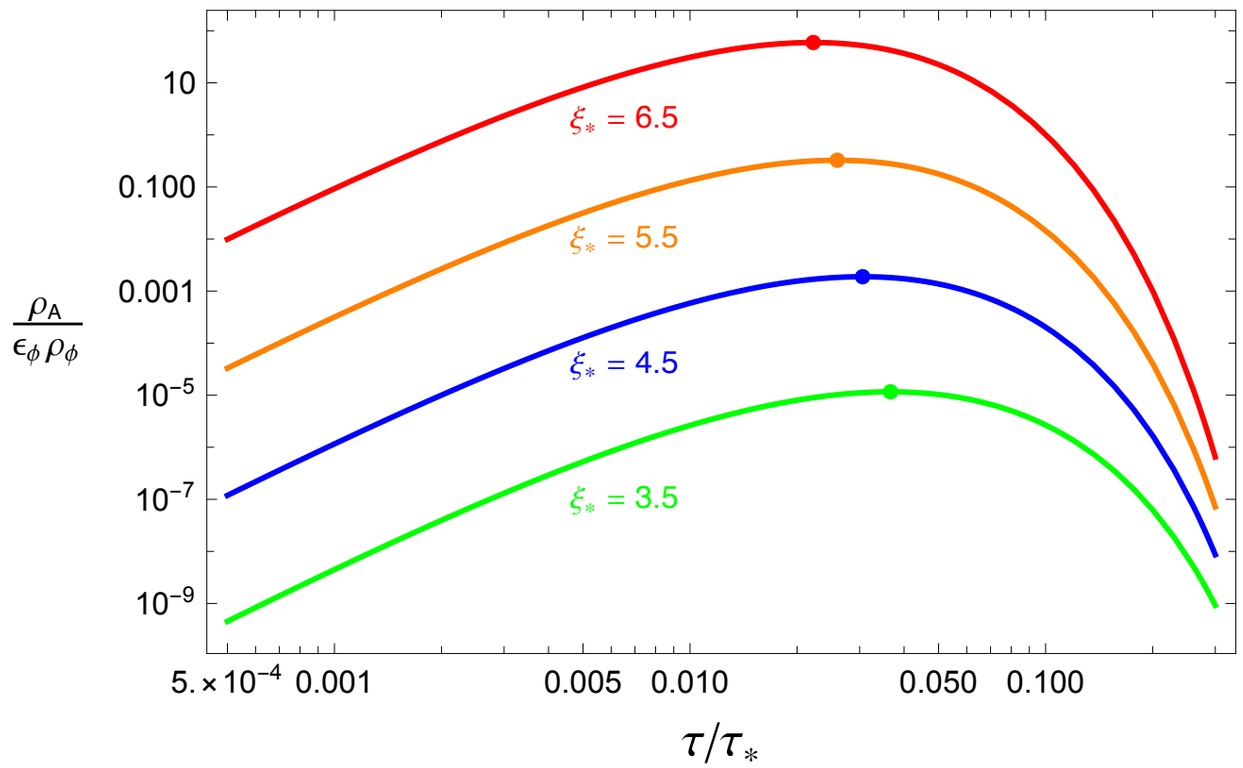
Energy density per mode (transient roll)





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

Energy density in the gauge fields (transient roll)



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

✓ IR safe mechanism!

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:

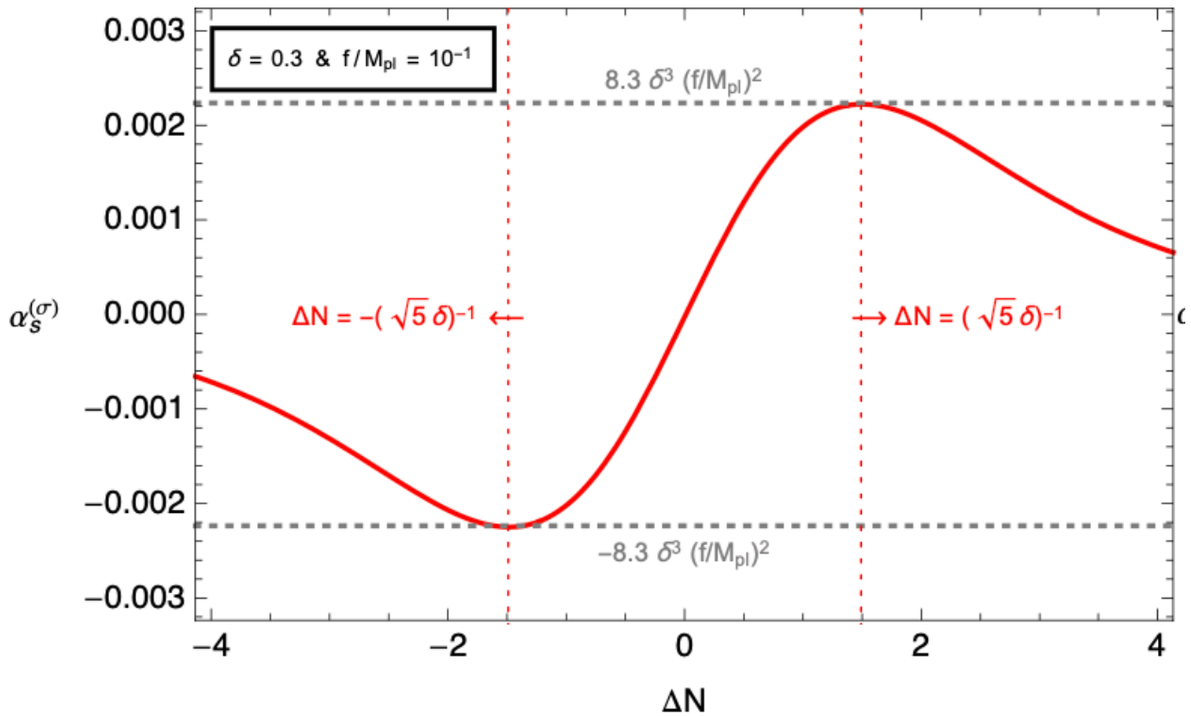
$$P_A \equiv \left| \frac{\delta^{(1)} \langle\, \hat{A}_-(\tau,\vec{k}) \hat{A}_-(\tau,\vec{k}') \,\rangle'}{\langle\, \hat{A}_-(\tau,\vec{k}) \hat{A}_-(\tau,\vec{k}') \,\rangle'} \right| \ll 1, \qquad P_\sigma \equiv \frac{\sqrt{\langle \delta\hat{\sigma}^{(1)}(\tau,\vec{x}) \delta\hat{\sigma}^{(1)}(\tau,\vec{x})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

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

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

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:

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

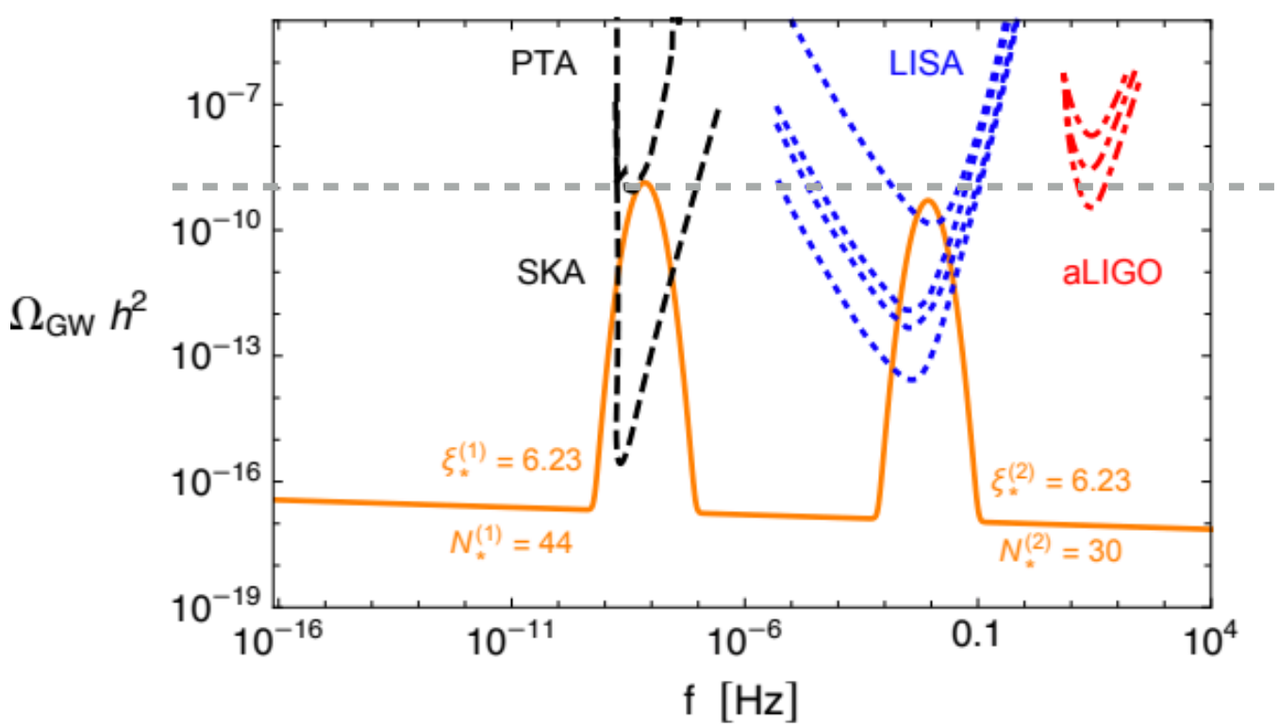
$\rho_\sigma \ll 3H^2 M_{\rm pl}^2$ @sub-CMB scales:

Summary of Model Buiding Constraints

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

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

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



Full expression for curvature perturbation

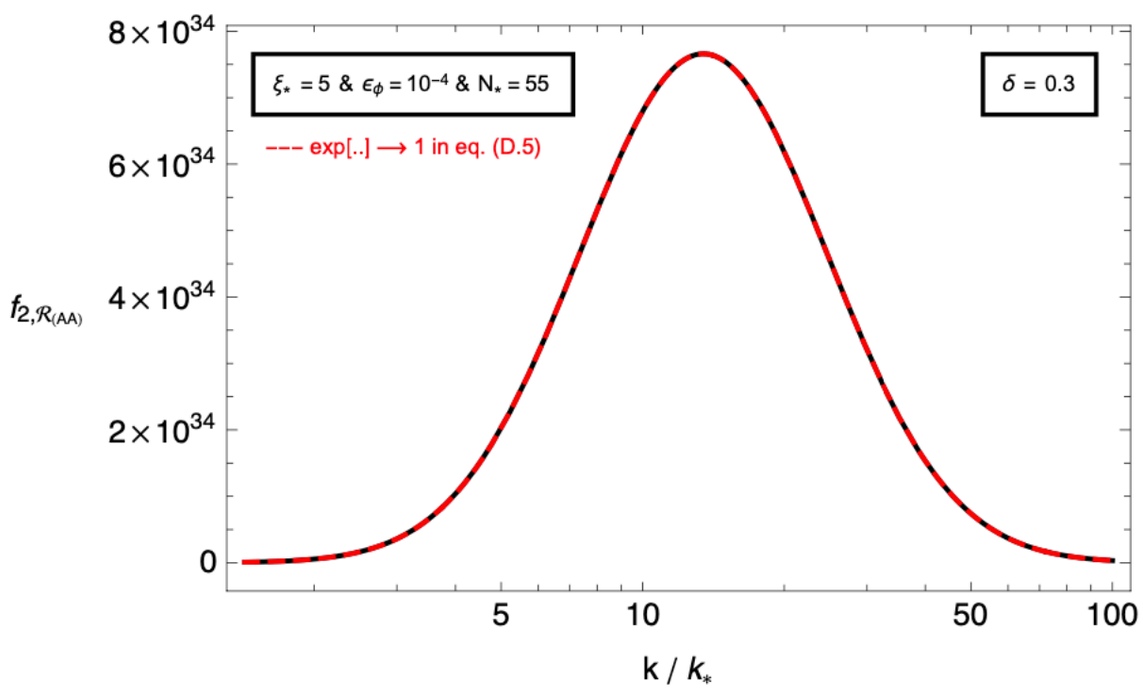
$$\mathcal{R}(\tau,\vec{k}) = \frac{H}{a\left(\dot{\phi}^2+\dot{\sigma}^2\right)}\left(\dot{\phi}Q_\phi + \dot{\sigma}Q_\sigma - a\delta q_{(AA)}(\tau,\vec{k})\right)$$

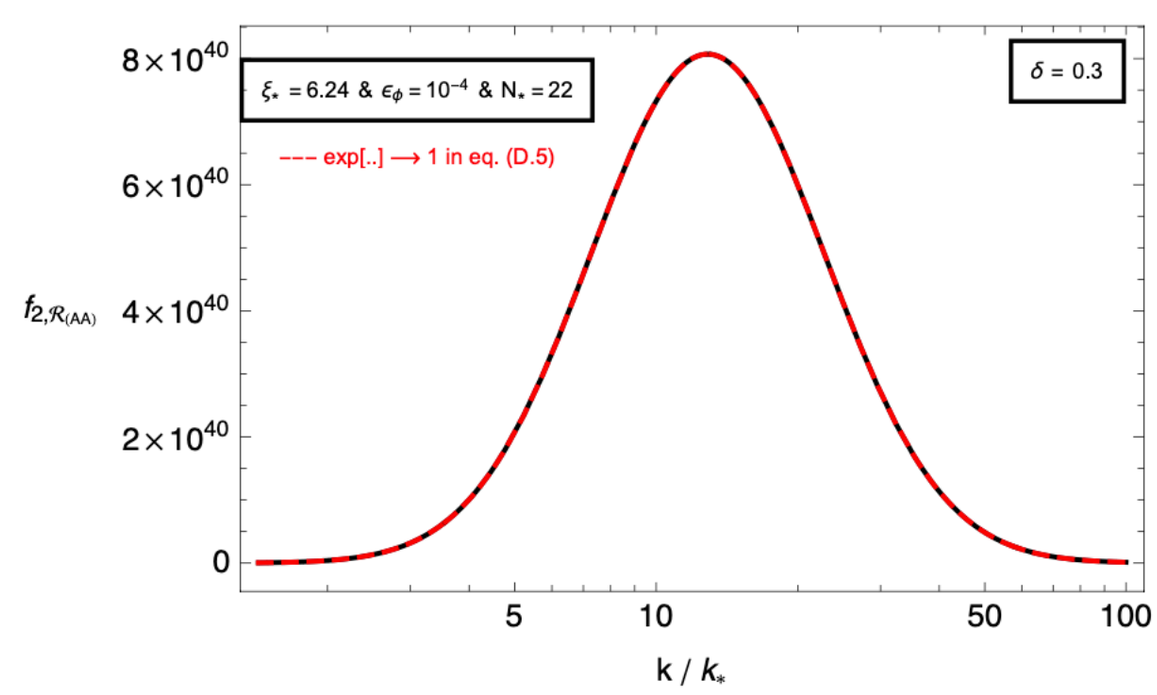
Direct contribution from gauge fields:

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

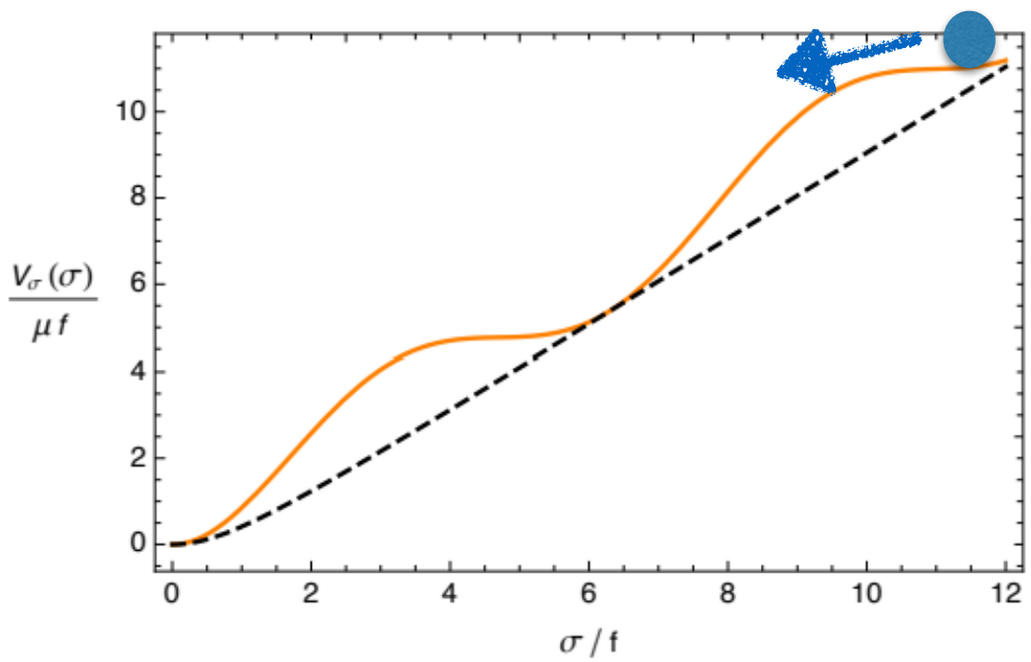
Check if it can contribute significantly to the correlators:

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

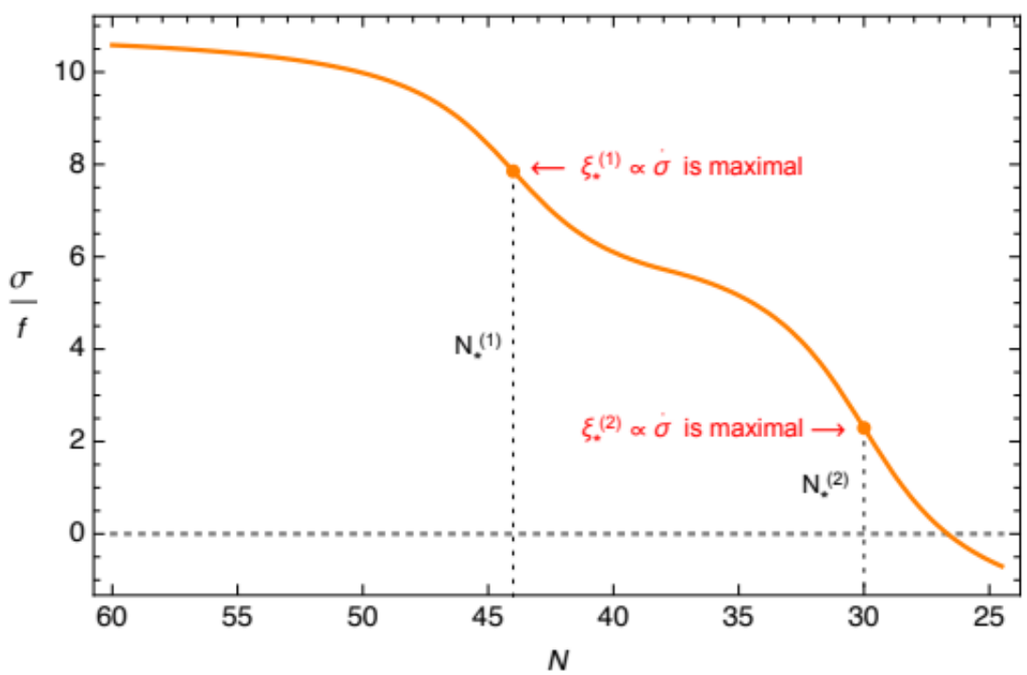




Observable GWs at interferometers (non-vacuum)

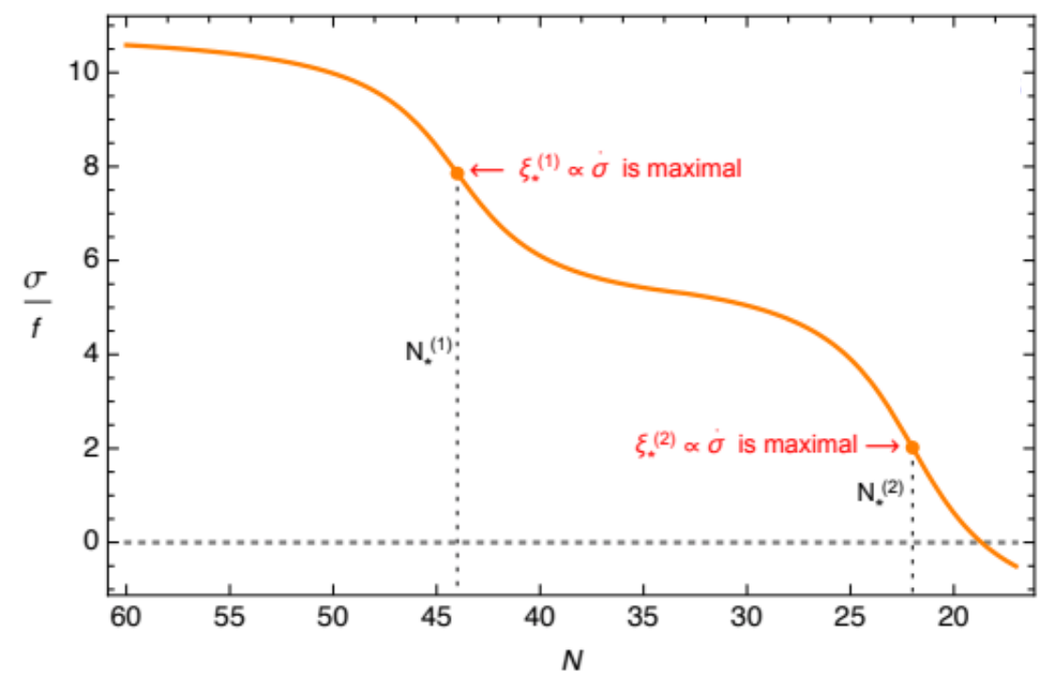


- ✓ Consider a scenario where spectator σ traverses multiple wiggles in its pot.
- ✓ Tune model parameters such that $|\dot{\sigma}|$ is maximal during the time(s) where scales associated with spatial and ground based interferometers exit the horizon



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

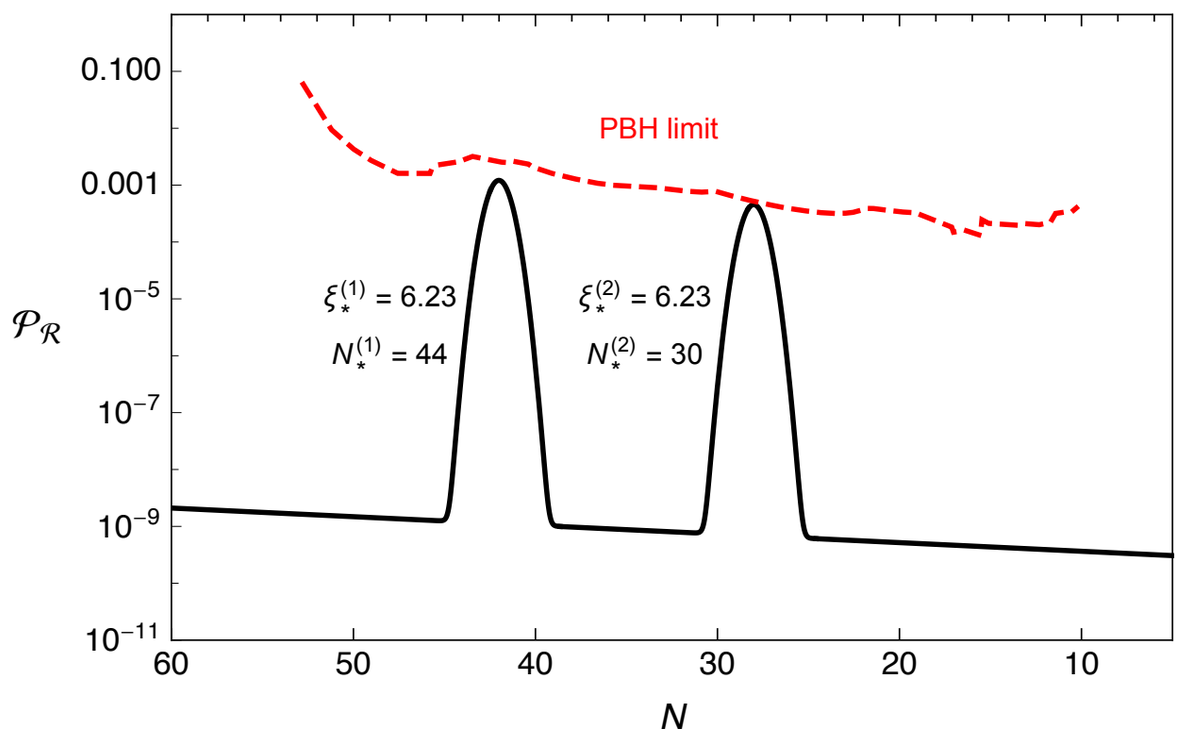
(PTA-SKA) —— (LISA)

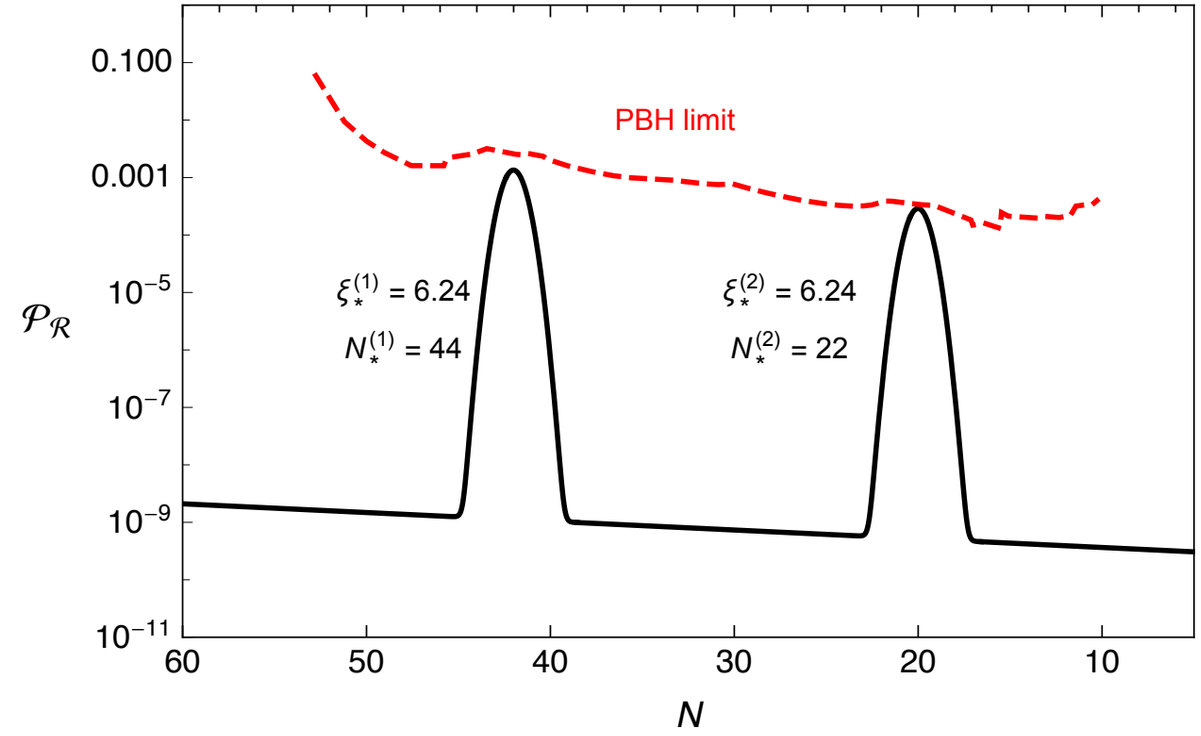


$N_*^{(1)} = 44$ $N_*^{(2)} = 22$

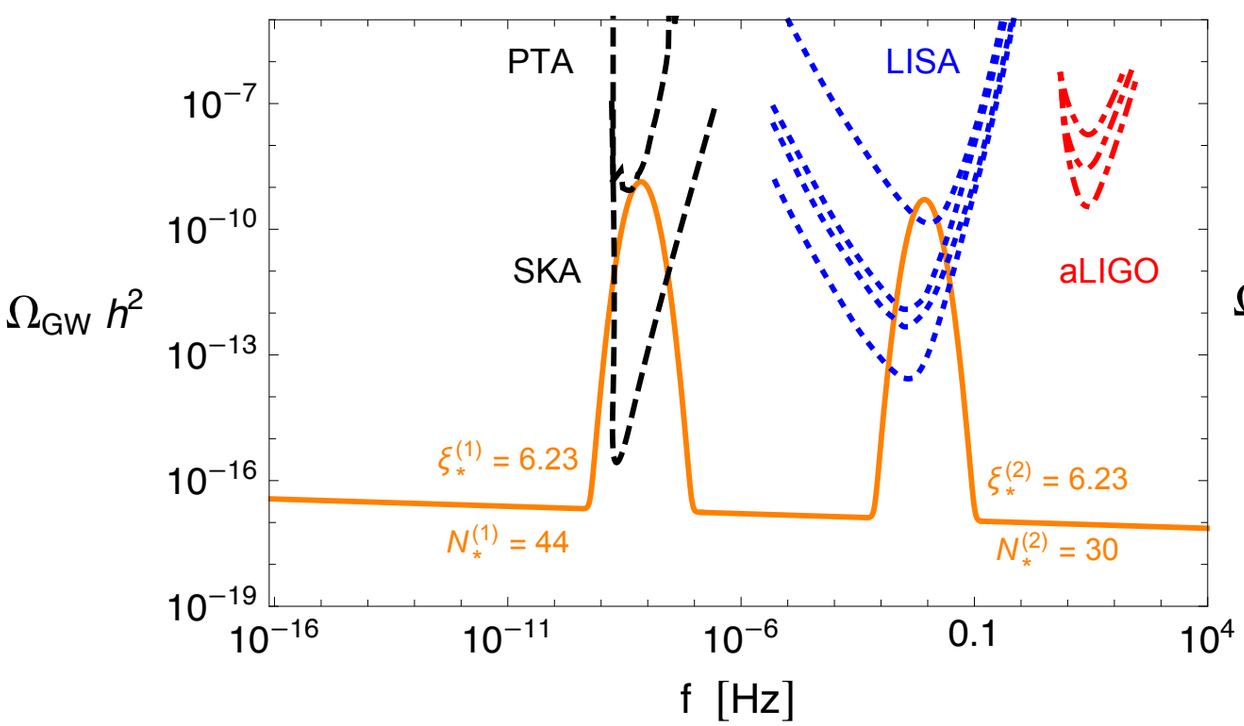
(PTA-SKA) —— (AdvLIGO)

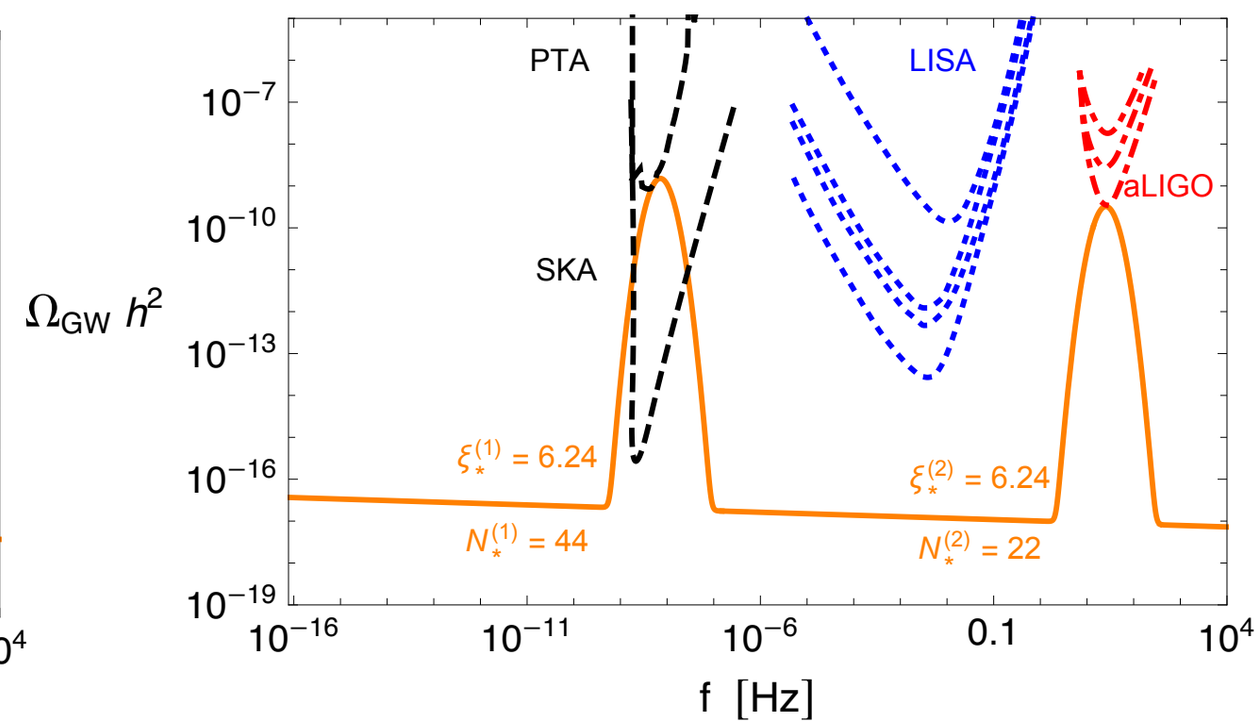
Observable GWs at interferometers (non-vacuum)



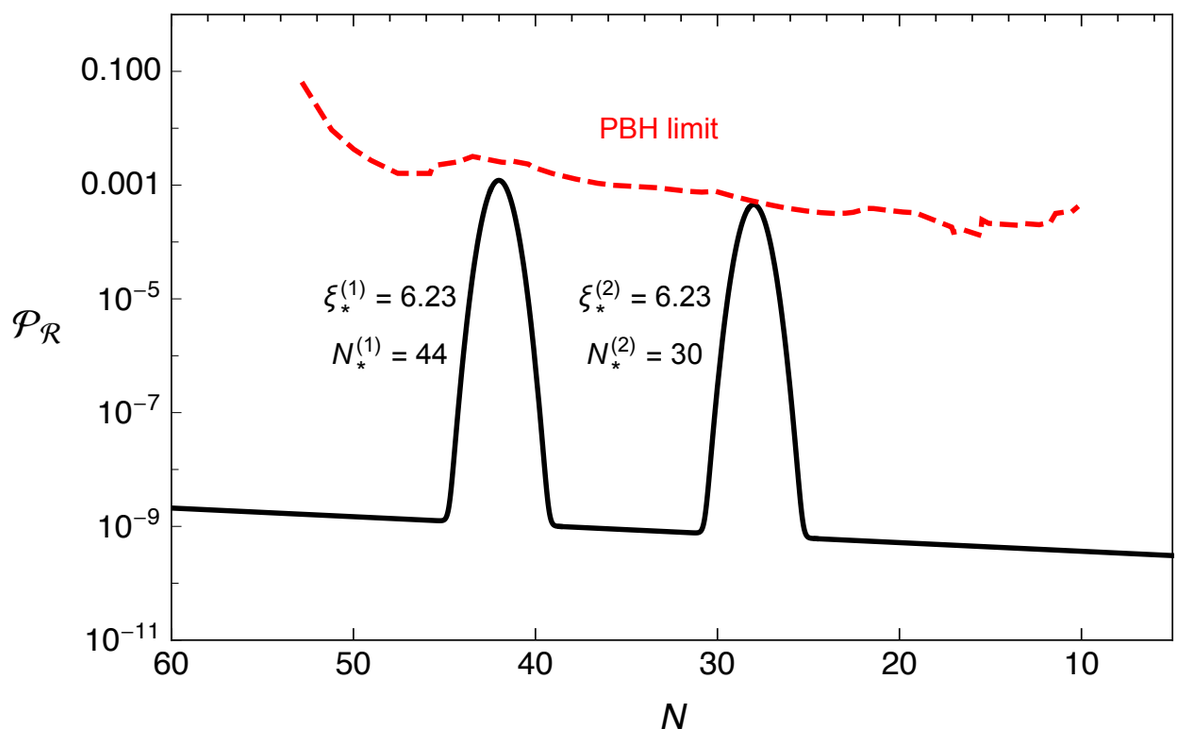


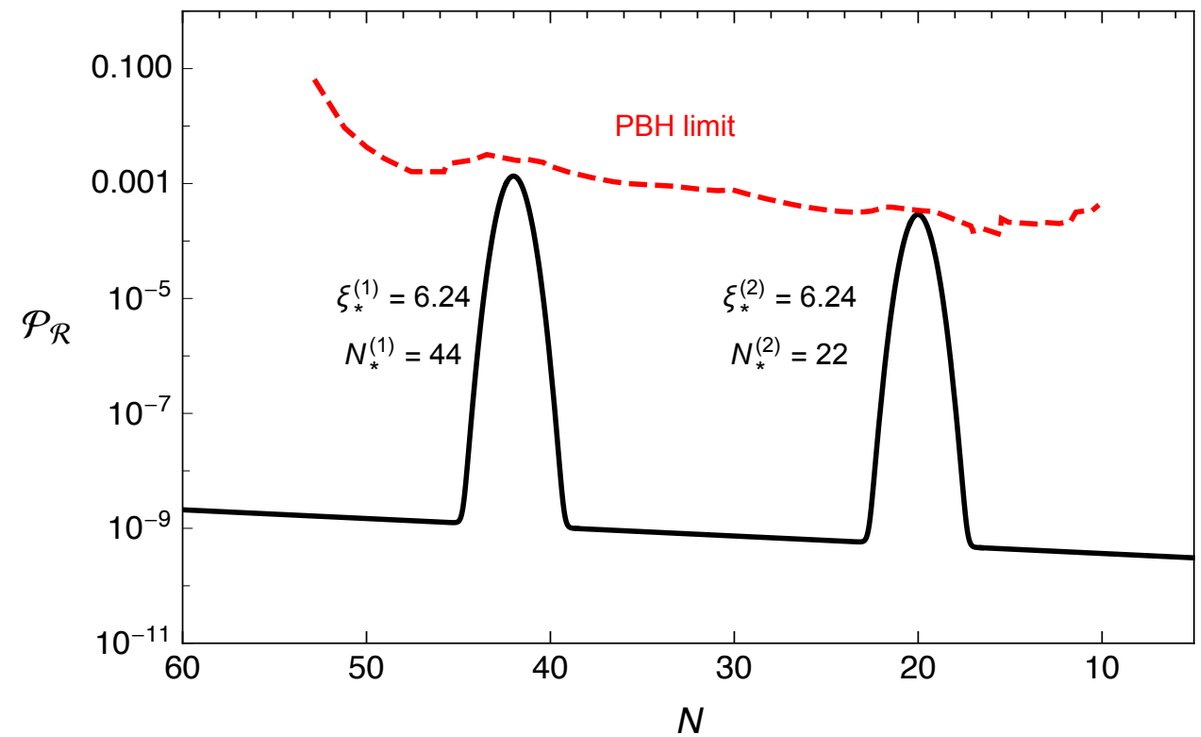
Limits on PBH abundance constraints the maximum height of the signal!





Constraints of PBH abundance

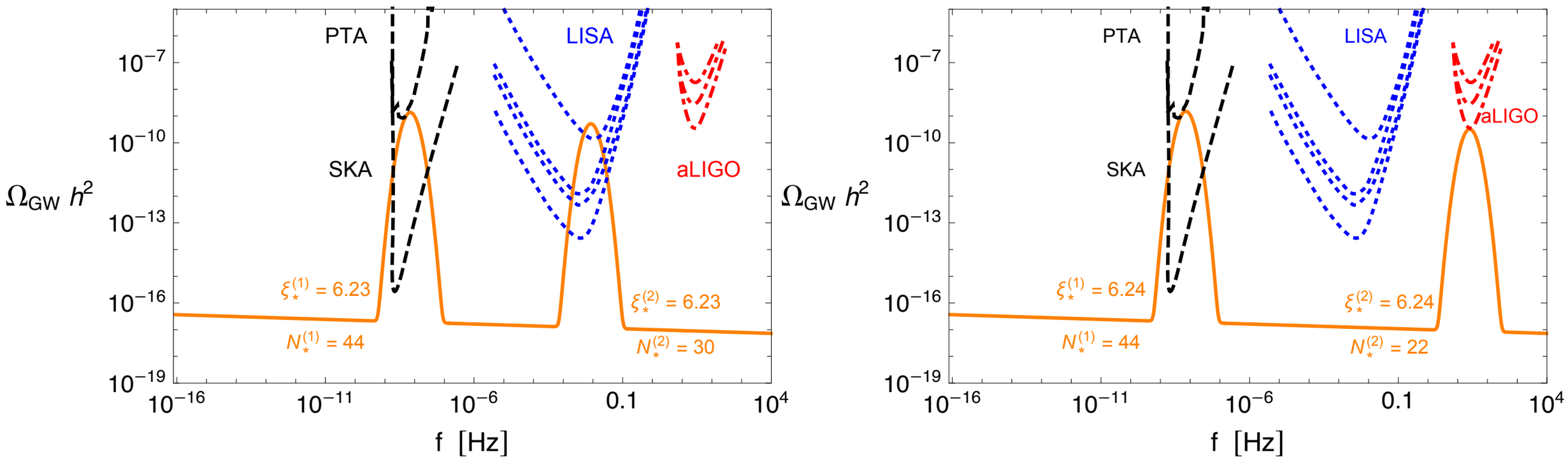




$$\mathcal{P}_\mathcal{R}(k) = \mathcal{P}_\mathcal{R}^{(v)}(k) + \left[\epsilon_\phi \mathcal{P}_\mathcal{R}^{(v)}(k)\right]^2 \sum_{i=1,2} f_{2,\mathcal{R}}^{(i)}\left(\xi_*, k/k_*, \delta\right)$$

$$\mathcal{P}_\mathcal{R}^{(v)}\left(k_N\right) = \mathcal{P}_\mathcal{R}^{(v)}\left(k_p\right) e^{-(1-\epsilon_\phi)(1-n_s)(N_p-N)}$$

GWs at interferometers



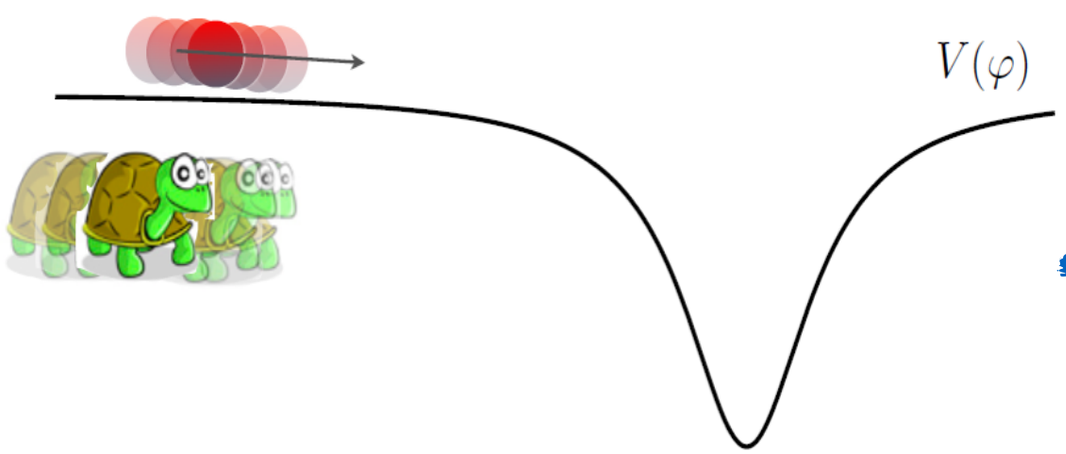
$$\mathcal{P}_h(k) = 16\epsilon_\phi \mathcal{P}_{\mathcal{R}}^{(v)}(k) + \left[\epsilon_\phi \mathcal{P}_{\mathcal{R}}^{(v)}(k)\right]^2 \sum_{i=1,2} f_{2,-}^{(i)}\left(\xi_*, k/k_*, \delta\right)$$

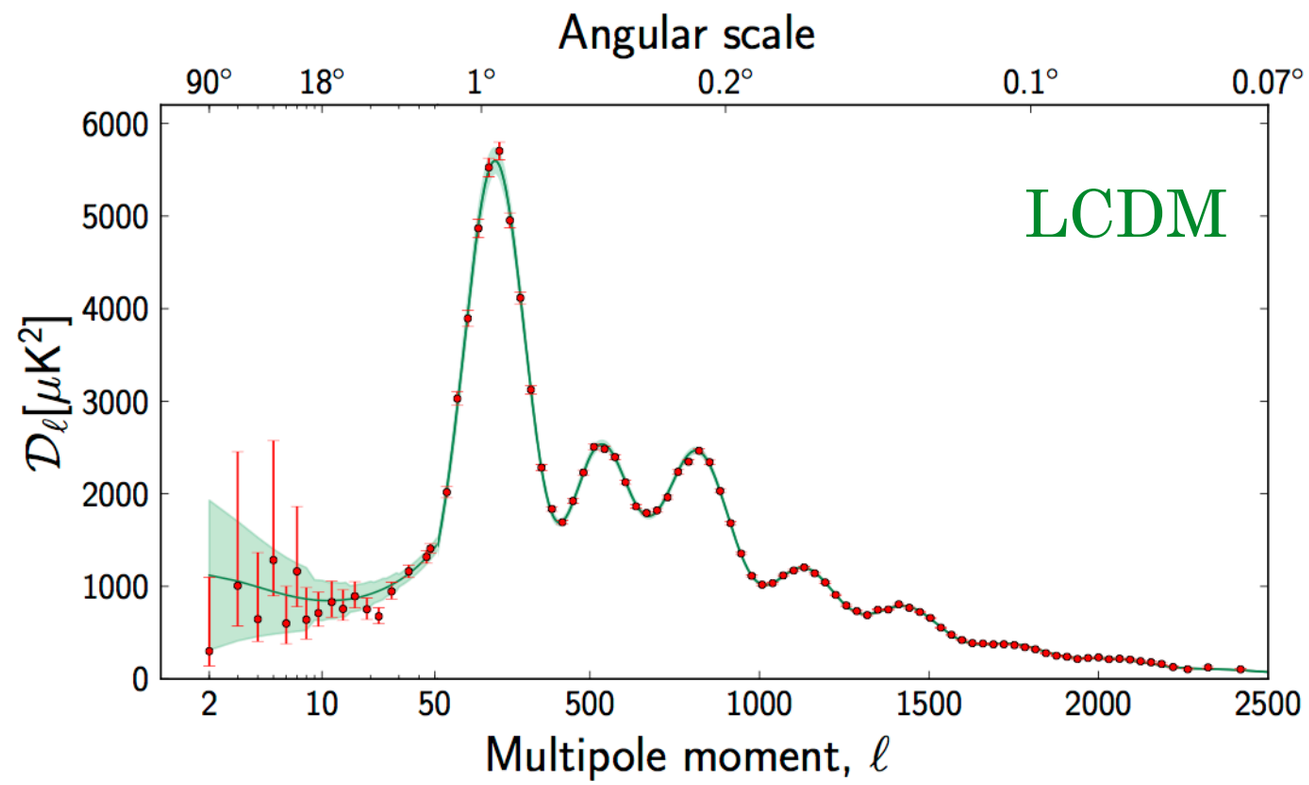
$$\Omega_{\rm GW}\, h^2 = \frac{\Omega_{r,0}\, h^2}{24} \mathcal{P}_h(k)$$

Recap: CMB as a probe of inflation

- Observed density fluctuations are in excellent agreement with simplest realizations of inflation:

Nearly Gaussian, adiabatic scalar fluctuations with a small red tilt





$$\mathcal{P}_{\mathcal{R}}(k) = \mathcal{A}_s \left(\frac{k}{k_p}\right)^{n_s - 1}$$

$$\mathcal{A}_s \simeq 2.1 \times 10^{-9}$$

$$|n_s - 1| \ll 1$$

$$f_{\rm NL}^{\rm local} = -0.9 \pm 5.1$$

(Planck, 2018)