Title: "Primordial Black Holes and Gravitational Waves from Inflation "

Speakers: Ogan Ozsoy

Series: Cosmology & Gravitation

Date: May 23, 2023 - 11:00 AM

URL: https://pirsa.org/23050150

Abstract: Primordial black holes (PBHs), if they exist, may shed light on long-standing questions on the nature of dark matter and mechanism driving cosmic inflation. If we associate their origin to the presence of enhanced primordial scalar fluctuations generated during inflation, the underlying dynamics that populates these objects can also provide distinctive sources of gravitational waves (GWs), potentially detectable with current or forthcoming GW experiments. Therefore, their population, along with the associated GW signal offer promising opportunities to shed light on the nature of inflation, by opening up a unique window to its dynamics at scales inaccessible by conventional CMB probes. In this talk, I will review some of the compelling inflationary scenarios able to trigger the formation of such objects in the post-inflationary universe by enhancing the amplitude of the primordial scalar perturbations. In this context, I will discuss single and multi-field realizations with a focus on theoretical aspects of model building, discussing common themes shared among models in conjunction with their distinctive phenomenological implications in the form of a primordial GW background.

Zoom Link: https://pitp.zoom.us/j/98857635213?pwd=UGZoMXY4TnJBSmc1RlUvbGprSWlRQT09

PBH's and Gravitational Waves from Inflation

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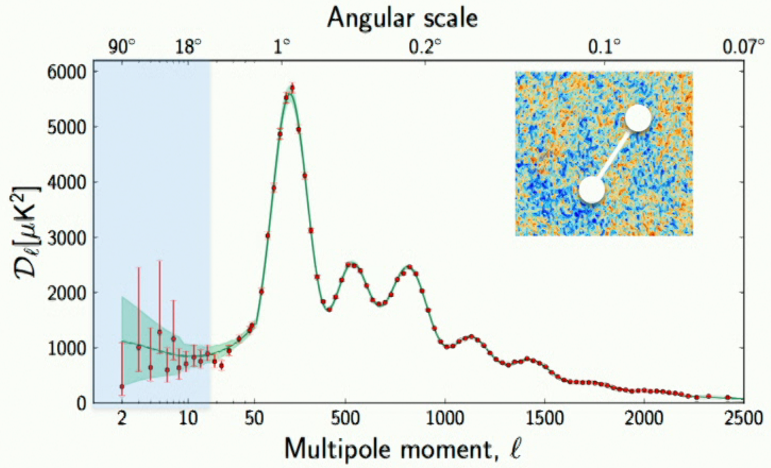
CSIC Consejo Superior de Investigaciones Científicas

Perimeter Institute for Theoretical Physics,
Cosmology and Gravitation Seminar

arXiv: 2301.03600,
O.Ö & G. Tasinato

Known Knowns

We observe correlations in the CMB temperature anisotropies!

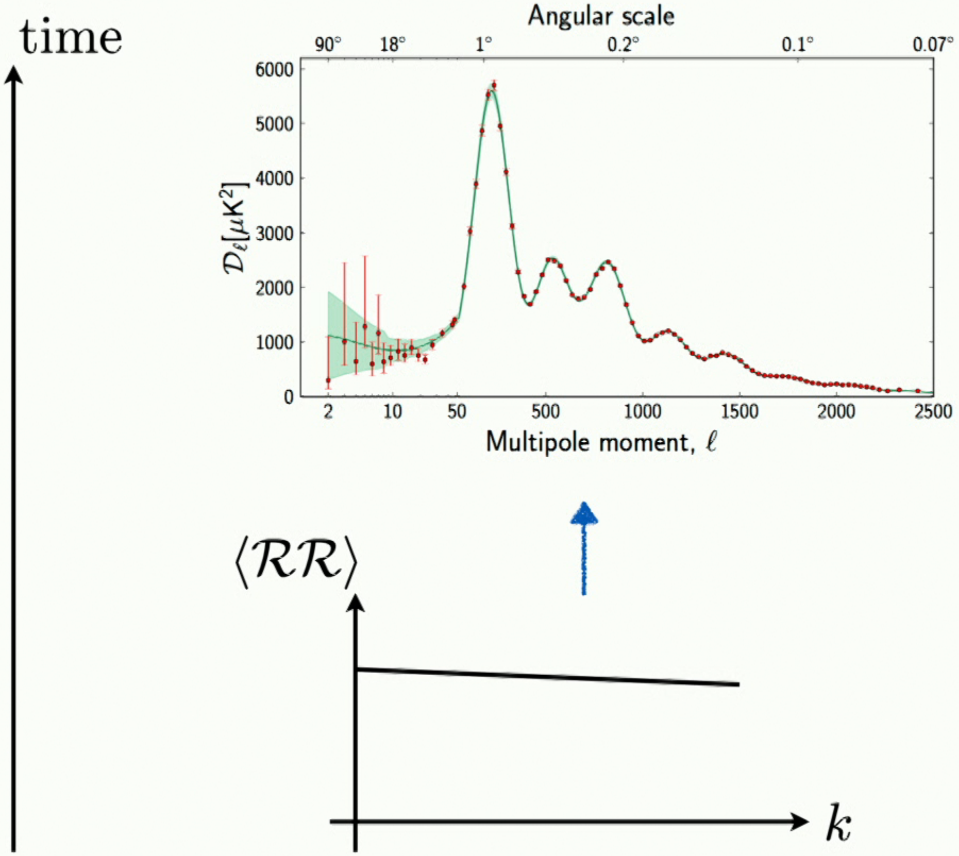


$$\langle \mathcal{R}_k \mathcal{R}_{k'} \rangle' = \underbrace{(2.098 \pm 0.1) \times 10^{-9}}_{\equiv \mathcal{A}_s} \left(\frac{k}{k_{\mathrm{cmb}}} \right)^{\underbrace{-0.0351 \pm 0.0042}_{\equiv n_s - 1}}$$

- Nearly scale invariant, Gaussian scalar fluctuations
- No sign of GWs yet (B-modes)
- Extremely uniform, super-horizon correlations (Horizon Problem)

These correlations must have been created before Hot Big Bang!

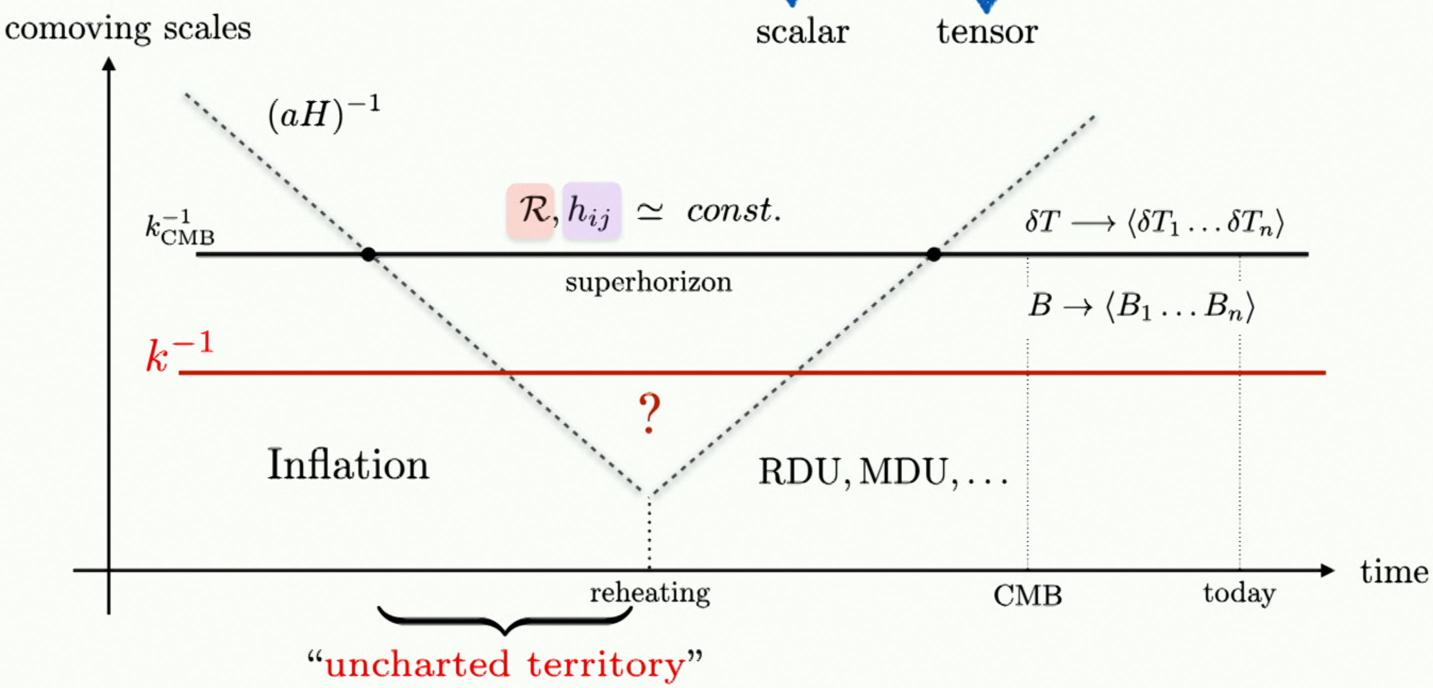
Scale invariance



Scale invariance is a natural prediction of inflation.

Small scale probes of inflation (Motivations)

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



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

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

Small Scale Probes of Inflation - PBHs

- Primordial Black Holes (PBHs)

- (Depending on their mass) PBHs can (maybe !) account for all or a fraction of DM abundance, economic explanation (SM + Inflation) to address DM paradigm

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

- May explain some of the current (LIGO) GW events

V. Luca et.al, arXiv: 2009.01728

- May play role in structure formation, i.e seeds of SMBH at the center of galaxies

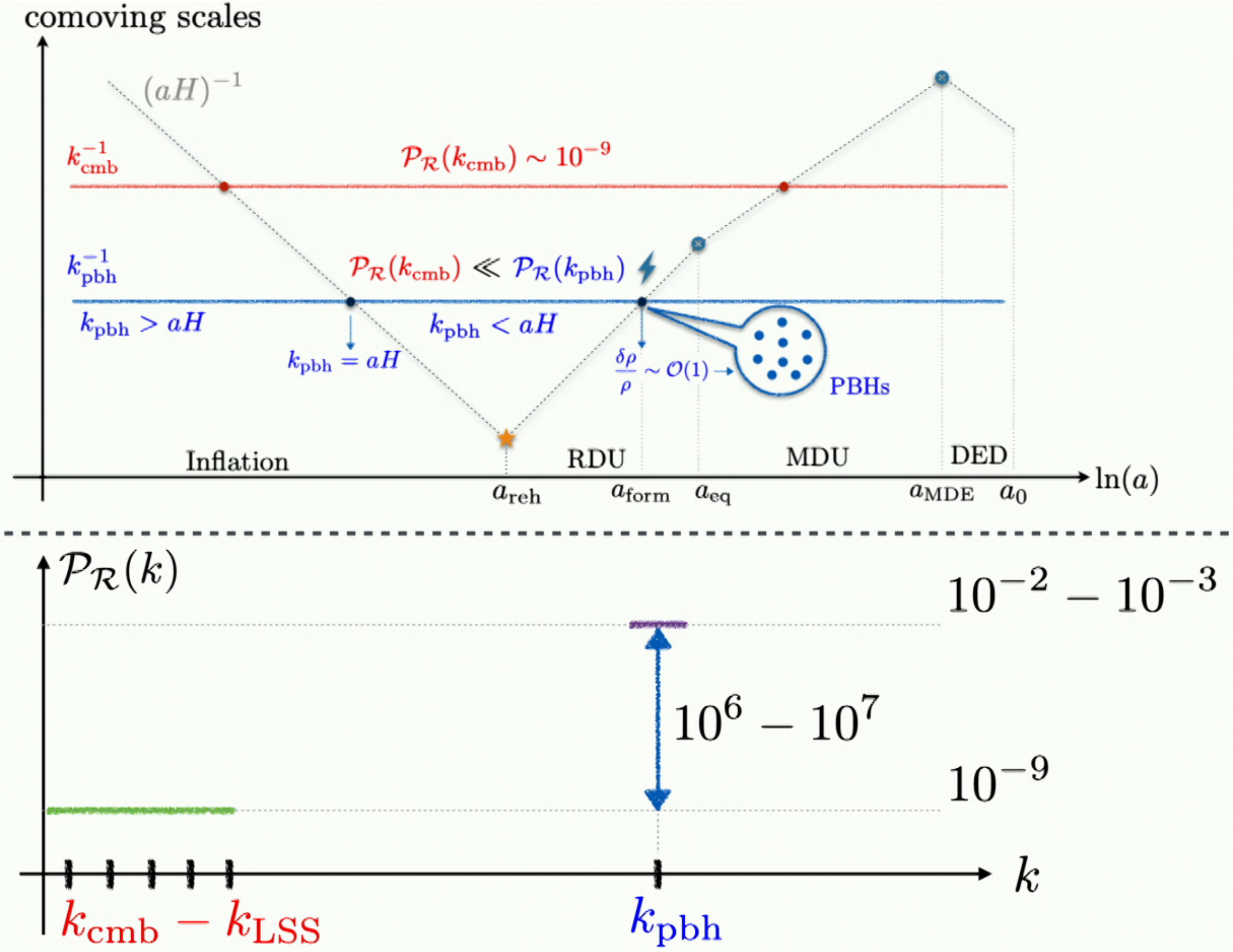
- Indirect access to a large range scales

$$10^{14} - 10^{15} < k\,[\mathrm{Mpc}^{-1}] < 10^{5} - 10^{6} \quad \longrightarrow \quad \mathcal{P}_{\mathcal{R}}(k_{\rm PBH}) \gg \mathcal{P}_{\mathcal{R}}(k_{\rm CMB})$$

$$10^{-18} < M_{\rm pbh}\,[M_{\odot}] < 10^{2}$$

$$\mathcal{P}_{\mathcal{R}}(k_{\rm pbh}) \sim 10^{-2} - 10^{-3}$$

Small Scale Probes of Inflation - PBHs



comoving scales

$(aH)^{-1}$

$k_{\rm cmb}^{-1}$

$\mathcal{P}_{\mathcal{R}}(k_{\rm cmb}) \sim 10^{-9}$

$k_{\rm pbh}^{-1}$

$\mathcal{P}_{\mathcal{R}}(k_{\rm cmb}) \ll \mathcal{P}_{\mathcal{R}}(k_{\rm pbh})$

$k_{\rm pbh} > aH$

$k_{\rm pbh} < aH$

$k_{\rm pbh} = aH$

$\frac{\delta\rho}{\rho} \sim \mathcal{O}(1) \rightarrow$

PBHs

Inflation

RDU

MDU

DED

$\ln(a)$

$a_{\rm reh}$

$a_{\rm form}$

$a_{\rm eq}$

$a_{\rm MDE}$

a_0

$\mathcal{P}_{\mathcal{R}}(k)$

$10^{-2} - 10^{-3}$

$10^6 - 10^7$

10^{-9}

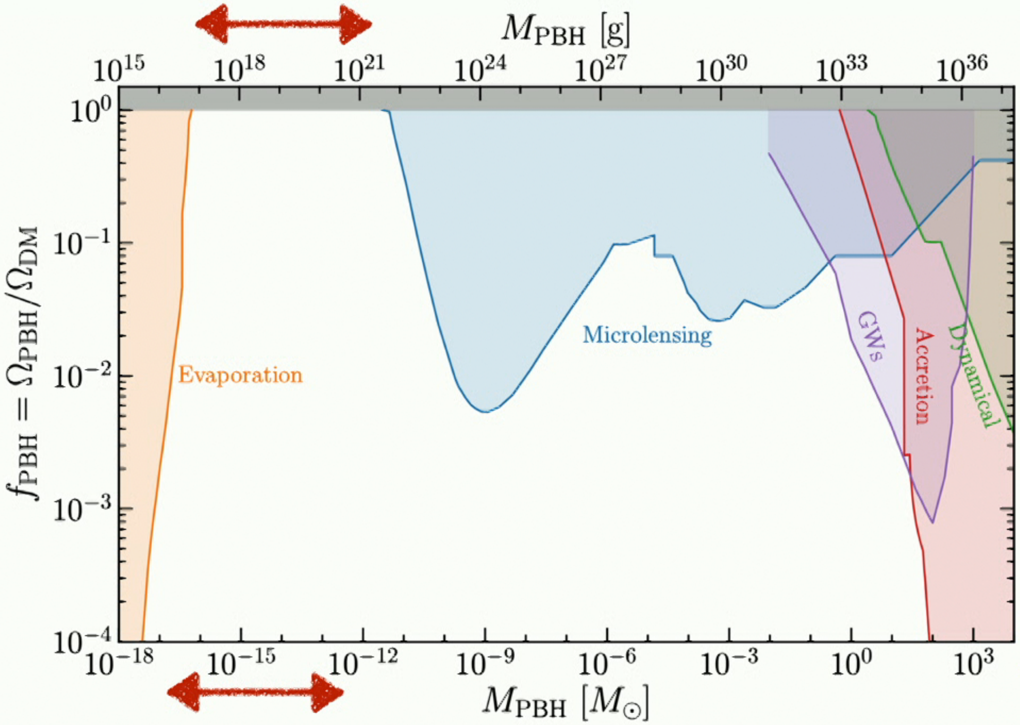
k

$k_{\rm cmb} - k_{\rm LSS}$

$k_{\rm pbh}$

PBHs as DM scenario

Tiny PBHs of (very) roughly "atomic size" $10^{-12} \lesssim r_s\,[\mathrm{cm}] \lesssim 10^{-7}$



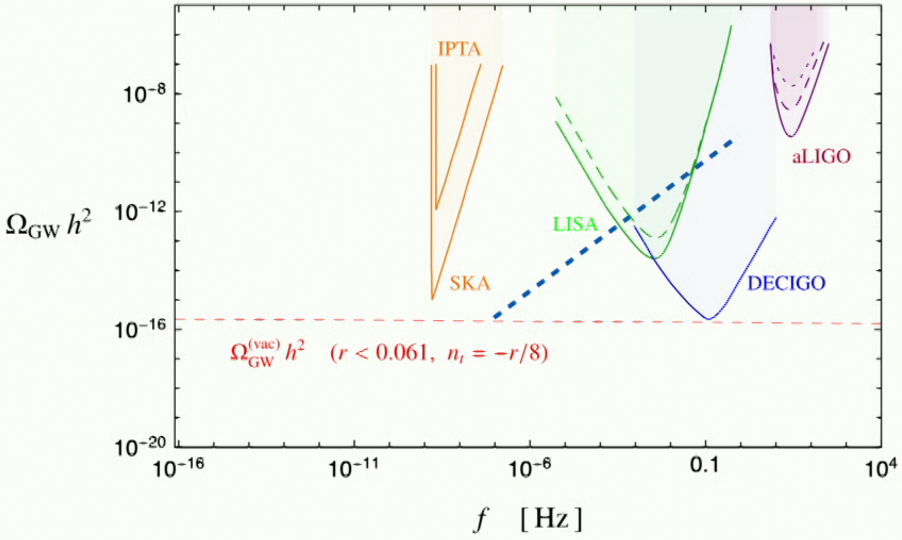
*(A. Green, B. Kavanagh , arXiv: 2007.10722)

"Sub-lunar mass range" $M_{\rm moon} \simeq 10^{-8} M_\odot$

A coincidence of scales: if PBH's with $M_{\rm PBH} \simeq 10^{-12} M_\odot$ produced by enhanced scalar perturbations, GWs observable at LISA can be produced*

*(Bartolo et. al., 2019)

Small Scale Probes of Inflation-SGWB



Broken scale invariance for tensor perturbations is required at interferometers!

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

- 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:

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

Plan for the rest of the talk

- Review of some of inflationary mechanisms that can break scale invariance of scalar and tensor perturbations during inflation, focusing on theoretical aspects of model building: strengths, weak points, phenomenological implications in the form of a SGWB.

  - Single field (SF) inflationary paradigm: broken scale invariance by slow-roll violation

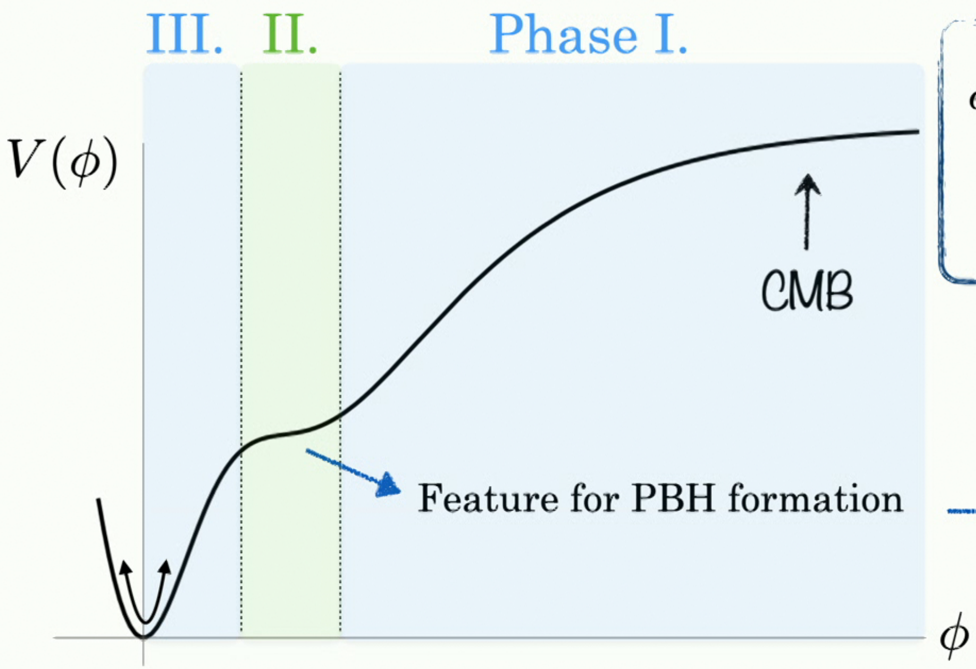
  - Multi-field scenarios: broken scale invariance by additional particle content during inflation

    1. Axion Inflation in the presence of Abelian gauge fields

    2. Spectator Axion - Gauge field dynamics

Collaborators: S. Parameswaran (Liverpool Uni.), G. Tasinato (Swansea Uni & Uni. Of Bologna), I. Zavala (Swansea Uni.)

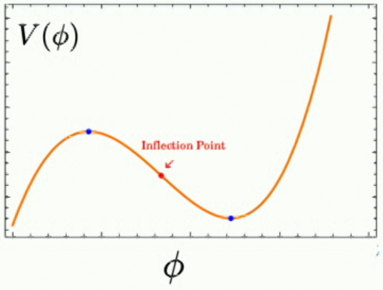
Slow-roll violation (SF) for PBH formation



Feature for PBH formation

$$\epsilon = -\frac{\mathrm{d}\ln H}{\mathrm{d}N} = \frac{\dot{\phi}^2}{2H^2 M_{\mathrm{pl}}^2}$$

$$\eta = \frac{\mathrm{d}\ln\epsilon}{\mathrm{d}N}$$

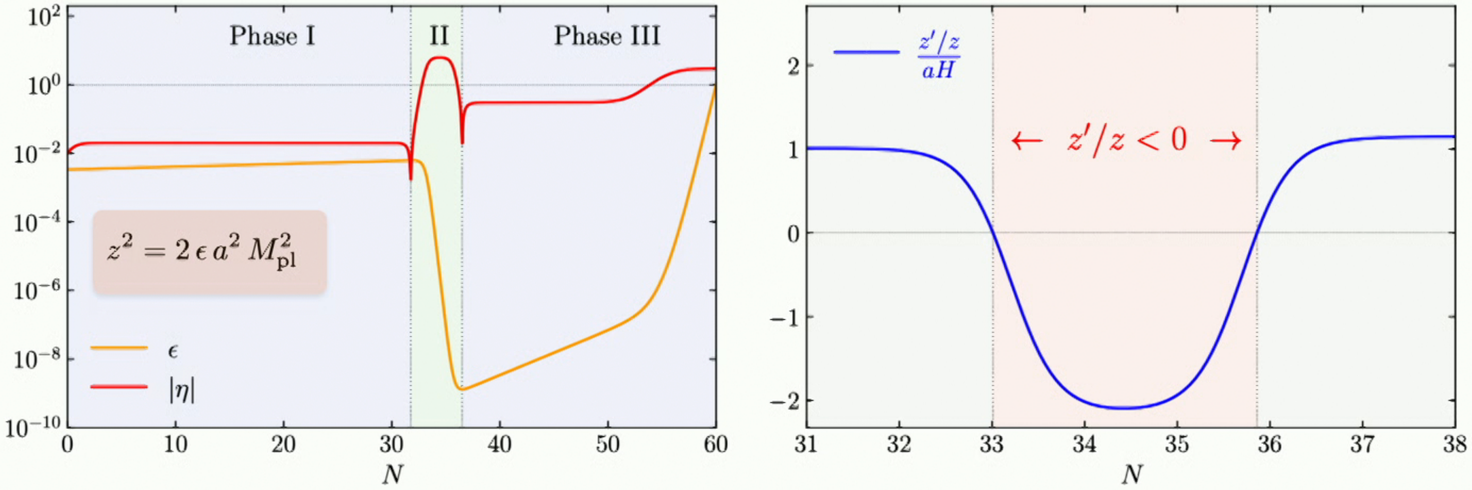


Phase I. ⟶ $\epsilon, \eta \ll 1$ (Slow-roll)

Phase II. ⟶ $\eta \leq -6$ (Non-attractor) $\epsilon \propto e^{\eta N}$

Phase III. ⟶ $\eta \gg \epsilon$ (Slow-roll)

Slow-roll violation for PBH formation



$$\mathcal{R}_k'' + \underbrace{2\frac{z'}{z}}\mathcal{R}_k' + k^2\mathcal{R}_k = 0$$

$$\boxed{\frac{z'}{z} = aH(1+\frac{\eta}{2})}$$

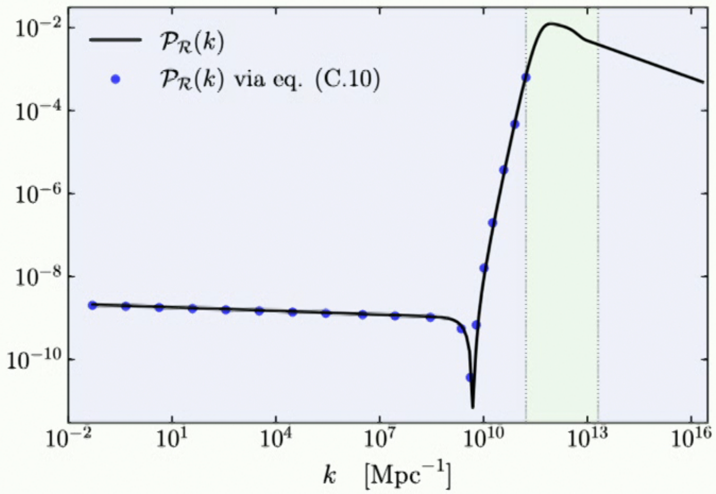
Damping term becomes a driving term in Phase II. $\eta \leq -6$

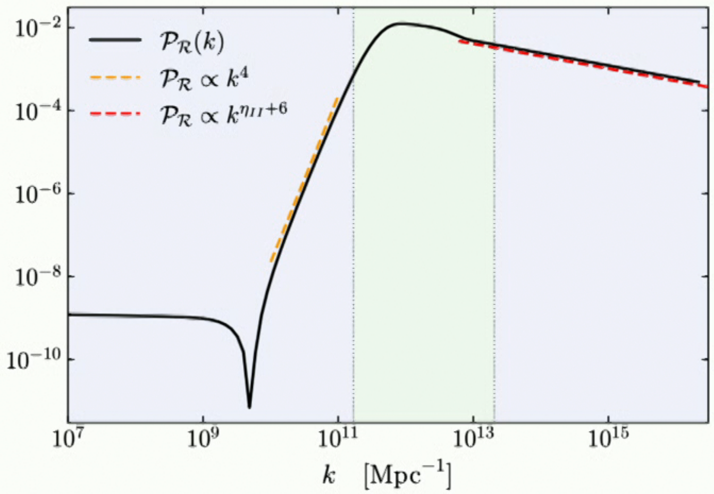
- Duration of negative η phase determines the enhancement in the power spectrum*

(O.Ö & G. Tasinato, 2019)
(O.Ö & G. Tasinato, 2023)

*Liddle&Leach, arXiv: astro-ph/0010082

Slow-roll violation and broken scale invariance





$$\frac{1}{z^2(\tau)}[z^2(\tau)\mathcal{R}_k'(\tau)]' = -k^2\mathcal{R}_k(\tau)$$

$$z^2 = 2\,\epsilon\,a^2\,M_{\rm pl}^2$$

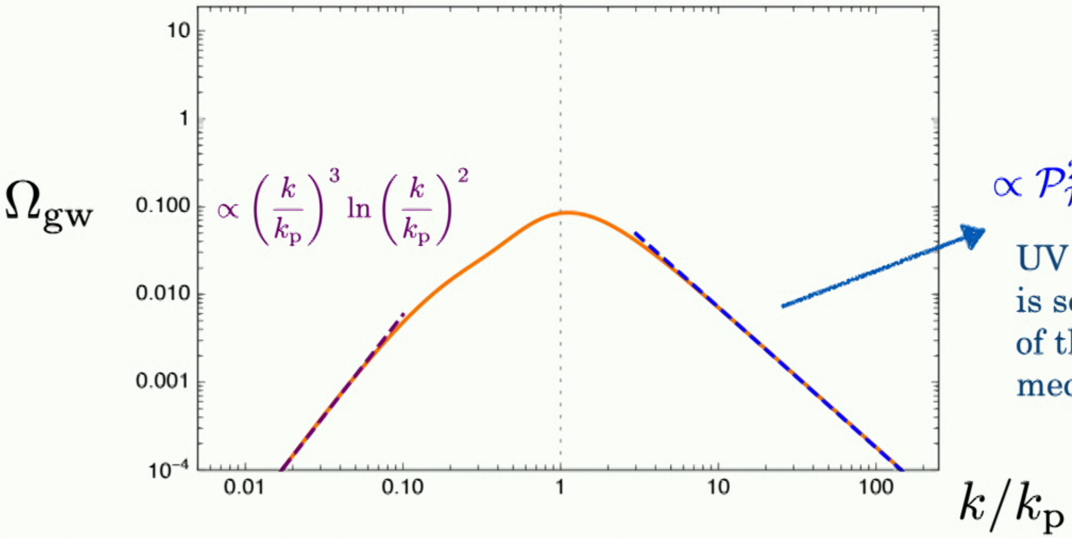
Solution at leading order in gradients (Phase 1):

$$\mathcal{R}_k(\tau) = \mathcal{R}_k^{(0)}\left[1 + \frac{\mathcal{R}_k^{(0)\,\prime}}{\mathcal{R}_k^{(0)}}\int_{\tau_0}^{\tau}\frac{d\tau'}{z^2(\tau')} - k^2\int_{\tau_0}^{\tau}\frac{d\tau'}{z(\tau')^2}\int_{\tau_0}^{\tau'}d\tau''\,z^2(\tau'')\right] \qquad \text{(C.10)}$$

(O.Ö & G. Tasinato, 2019)
(O.Ö & G. Tasinato, 2023)

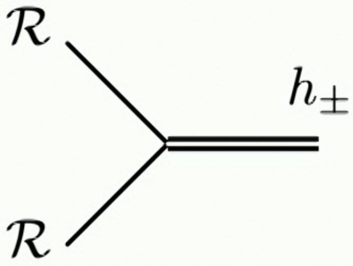
*Liddle&Leach, arXiv: astro-ph/0010082

Slow-roll violation and induced SGWB



$\propto \mathcal{P}_{\mathcal{R}}^2 \propto k^{2(6+\eta_{\rm II})} \propto k^{2\eta_{\rm III}}$

UV tail of induced SGWB is sensitive to the details of the inflationary mechanism*

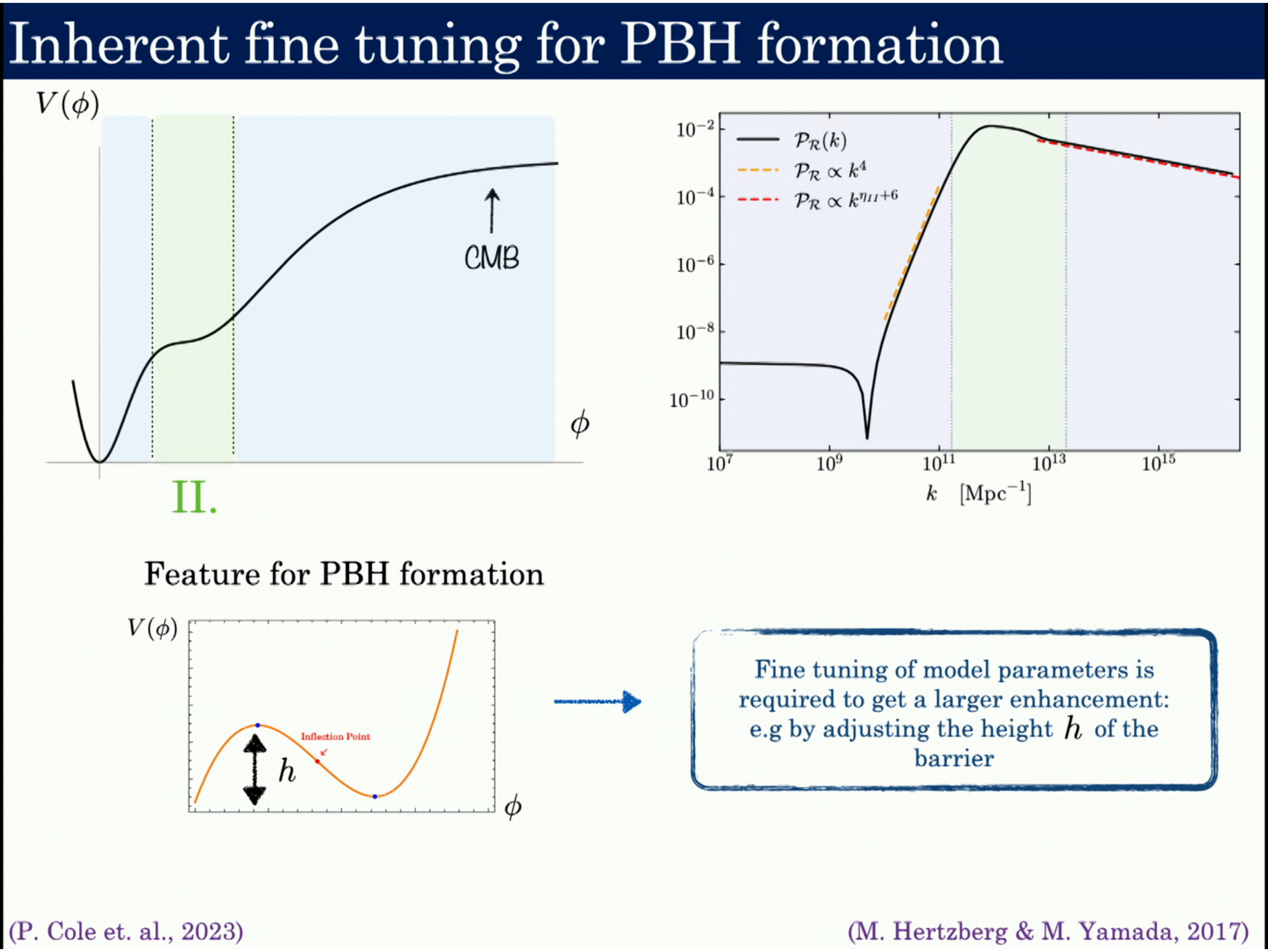


$$\longrightarrow \quad \Omega_{\rm GW}(k) \sim \int dp\, \mathcal{P}_{\mathcal{R}}(|\vec{k}-\vec{p}|)\mathcal{P}_{\mathcal{R}}(p)$$

Contribution to SGWB around the horizon re-entry during RDU!

(G. Domenech, 2021)

(O.Ö & G. Tasinato, 2019)



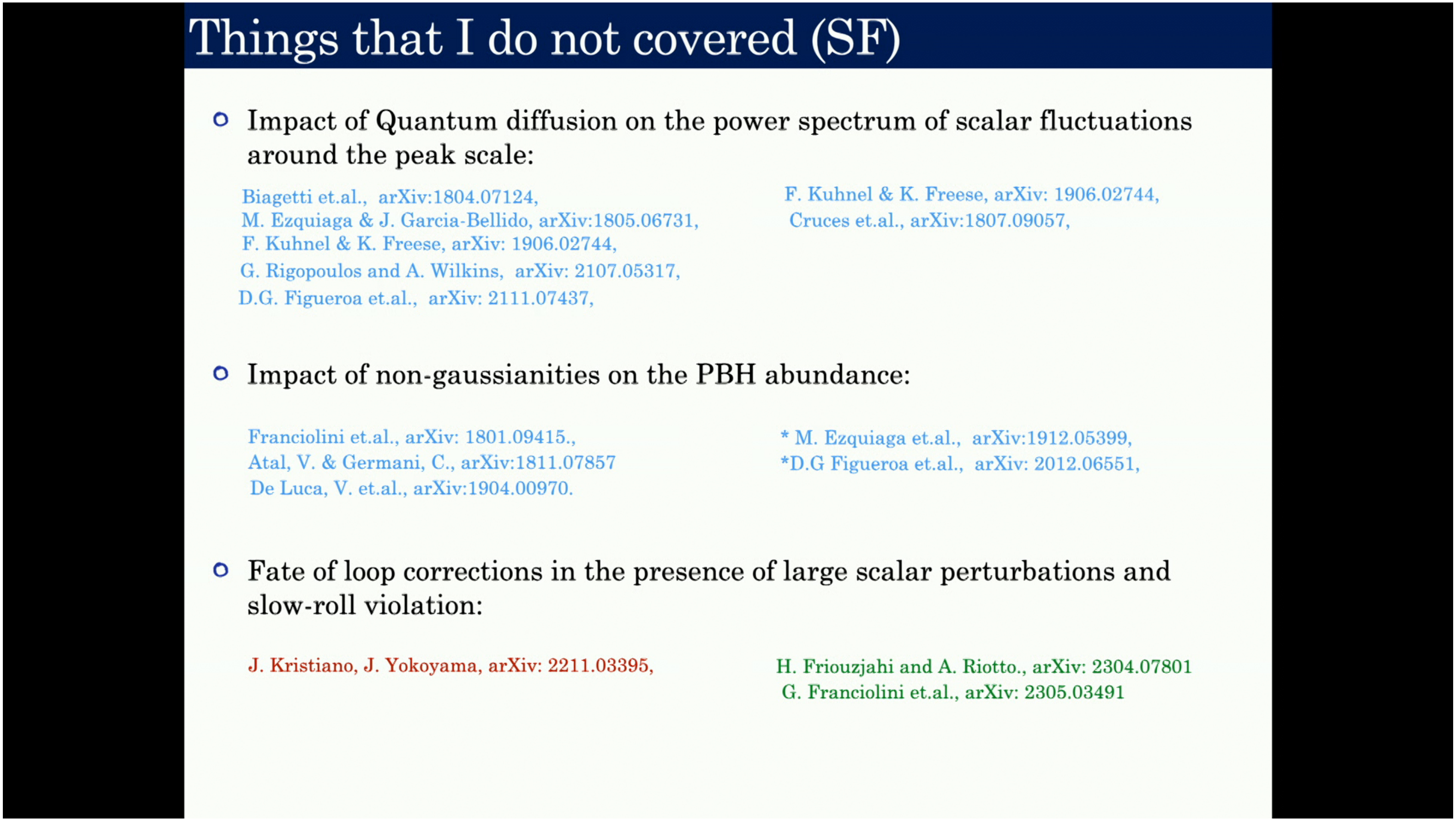
Inherent fine tuning for PBH formation

Feature for PBH formation

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

(P. Cole et. al., 2023)

(M. Hertzberg & M. Yamada, 2017)



Things that I do not covered (SF)

- Impact of Quantum diffusion on the power spectrum of scalar fluctuations around the peak scale:

Biagetti et.al., arXiv:1804.07124,
M. Ezquiaga & J. Garcia-Bellido, arXiv:1805.06731,
F. Kuhnel & K. Freese, arXiv: 1906.02744,
G. Rigopoulos and A. Wilkins, arXiv: 2107.05317,
D.G. Figueroa et.al., arXiv: 2111.07437,

F. Kuhnel & K. Freese, arXiv: 1906.02744,
Cruces et.al., arXiv:1807.09057,

- Impact of non-gaussianities on the PBH abundance:

Franciolini et.al., arXiv: 1801.09415.,
Atal, V. & Germani, C., arXiv:1811.07857
De Luca, V. et.al., arXiv:1904.00970.

* M. Ezquiaga et.al., arXiv:1912.05399,
*D.G Figueroa et.al., arXiv: 2012.06551,

- Fate of loop corrections in the presence of large scalar perturbations and slow-roll violation:

J. Kristiano, J. Yokoyama, arXiv: 2211.03395,

H. Friouzjahi and A. Riotto., arXiv: 2304.07801
G. Franciolini et.al., arXiv: 2305.03491

Axion-Inflation

$$\frac{\mathcal{L}_m}{\sqrt{-g}} = -\frac{1}{2}\partial_\mu\varphi\,\partial^\mu\varphi - V(\varphi) - \frac{1}{4}F_{\mu\nu}\,F^{\mu\nu} - \frac{g_{\rm cs}}{4f}\,\varphi\,F_{\mu\nu}\,\tilde{F}^{\mu\nu}.$$

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

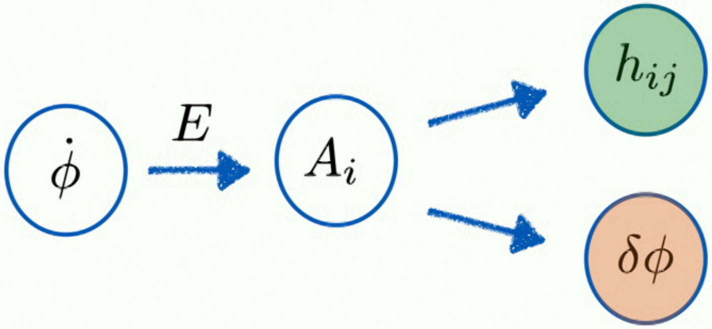
- They are light and can roll a significant amount of time during inflation:

  Axion-like fields are good candidates as inflatons!

  $$\varphi = \phi(t) + \delta\phi$$

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

$$\Delta\mathcal{L}_{\rm int} = -\frac{g_{\rm cs}}{4f}\,\varphi\,F\tilde{F} = -\frac{g_{\rm cs}}{2f}\,\epsilon^{\mu\nu\rho\sigma}\,\partial_\mu\varphi\,(A_\nu\,\partial_\rho A_\sigma)$$

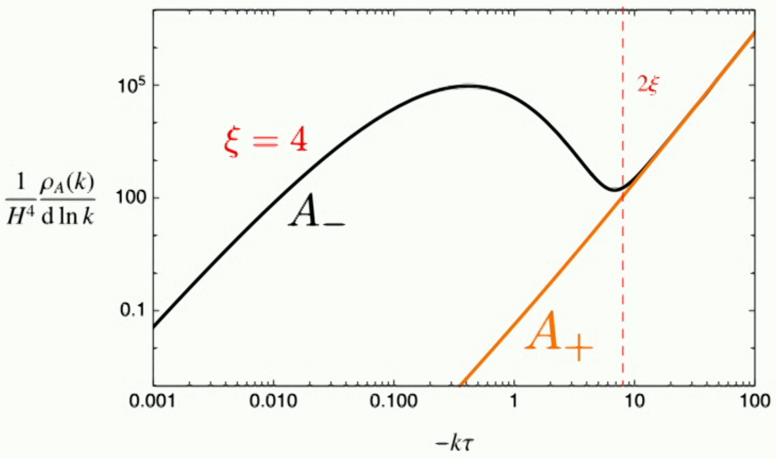


Axion-Inflation (Vector field production)

$$\frac{\mathcal{L}_m}{\sqrt{-g}} = -\frac{1}{2}\partial_\mu\varphi\,\partial^\mu\varphi - V(\varphi) - \frac{1}{4}F_{\mu\nu}\,F^{\mu\nu} - \frac{g_{\rm cs}}{4f}\,\varphi\,F_{\mu\nu}\,\tilde{F}^{\mu\nu}\,.$$

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

$$\xi \equiv \frac{g_{\rm cs}|\dot{\phi}|}{2H\,f}$$



Constant $|\dot{\phi}|$ case

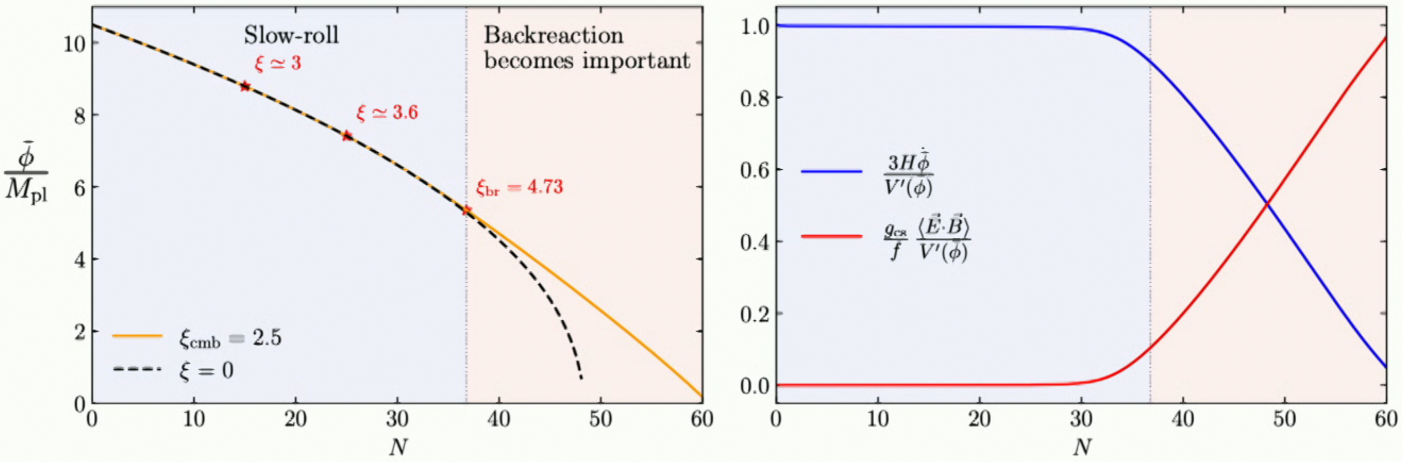
- Parity breaking!
- Exponential sensitivity to $|\dot{\phi}|$

$$A_- \propto \exp\left[\frac{\pi g_{\rm cs}|\dot{\phi}|}{H\,f}\right]$$

- ρ_A is diluted at late times

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

Axion-Inflation (Background)



$$\ddot{\bar\phi} + 3H\dot{\bar\phi} + V'(\bar\phi) = \frac{g_{\rm cs}}{f}\langle \vec{E}\cdot\vec{B}\rangle\ ,$$

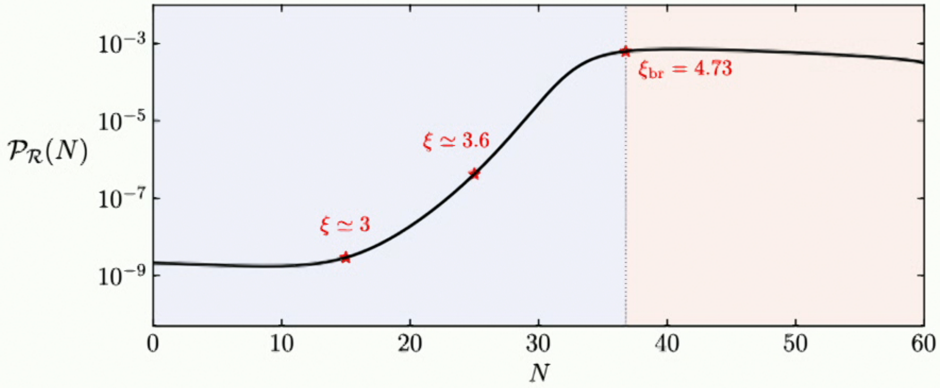
$$3H^2M_{\rm pl}^2 = \frac{1}{2}\dot{\bar\phi}^2 + V(\bar\phi) + \frac{1}{2}\left\langle \vec{E}^2+\vec{B}^2\right\rangle,$$

- Velocity of the inflation increases smoothly for a smooth scalar potential (so that inflation can end at some point).
- Larger the velocity, more the gauge field production, so that dynamics enter a back-reaction dominated regime which prolongs the duration of the inflation.

Broken scale inv. due to particle production

$$\frac{\mathcal{L}_m}{\sqrt{-g}} = -\frac{1}{2}\partial_\mu\varphi\,\partial^\mu\varphi - V(\varphi) - \frac{1}{4}F_{\mu\nu}\,F^{\mu\nu} - \frac{g_{\rm cs}}{4f}\,\varphi\,F_{\mu\nu}\,\tilde{F}^{\mu\nu}\,.$$

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



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

$$A_- \sim e^{|\dot{\phi}|}$$

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

$$\simeq \frac{H^2}{8\pi^2\epsilon M_{\rm pl}^2} + \left(\frac{g_{\rm cs}}{f}\frac{\langle\vec{E}\cdot\vec{B}\rangle}{3H\beta\dot{\phi}}\right)^2 \mathcal{F}^2\,.$$

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

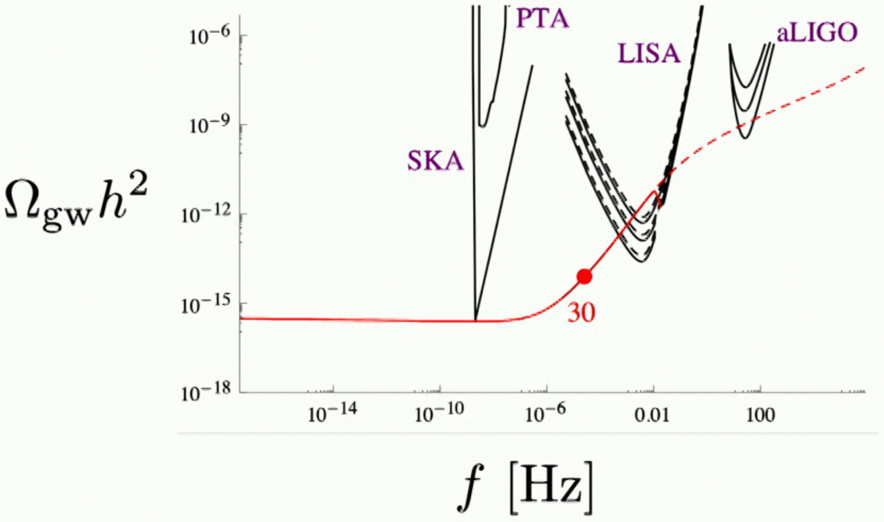
M. Peloso, C. Unal & G. Bellido, '16

arXiv: 2301.03600, O.Ö & G. Tasinato

SGWB due to particle production (during inflation)

$$\frac{\mathcal{L}_m}{\sqrt{-g}} = -\frac{1}{2}\partial_\mu\varphi\,\partial^\mu\varphi - V(\varphi) - \frac{1}{4}F_{\mu\nu}\,F^{\mu\nu} - \frac{g_{\rm cs}}{4f}\,\varphi\,F_{\mu\nu}\,\tilde{F}^{\mu\nu}\,.$$

$A_- + A_- \to h_-^{(s,p)}$ (Chiral!)



M. Peloso, C. Unal & G. Bellido, '16

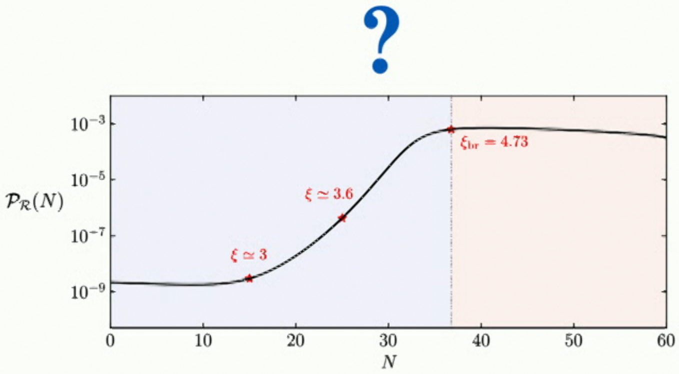
Smooth Axion-Inflation

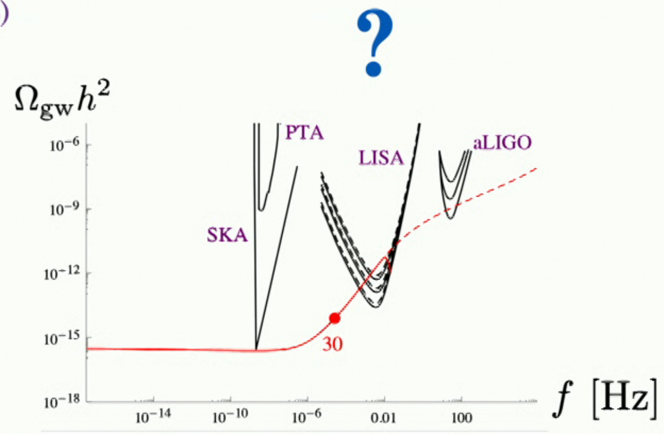
$$\frac{\mathcal{L}_m}{\sqrt{-g}} = -\frac{1}{2}\partial_\mu\varphi\,\partial^\mu\varphi - V(\varphi) - \frac{1}{4}F_{\mu\nu}\,F^{\mu\nu} - \frac{g_{\rm cs}}{4f}\,\varphi\,F_{\mu\nu}\,\tilde{F}^{\mu\nu}\,.$$

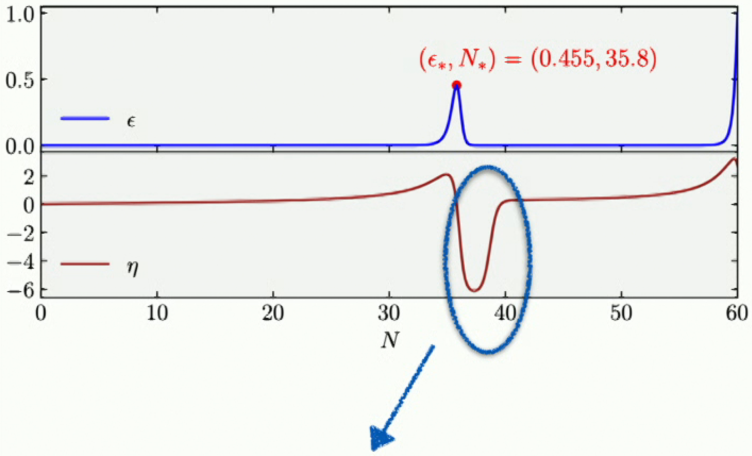
An instability in the strong back-reaction regime?

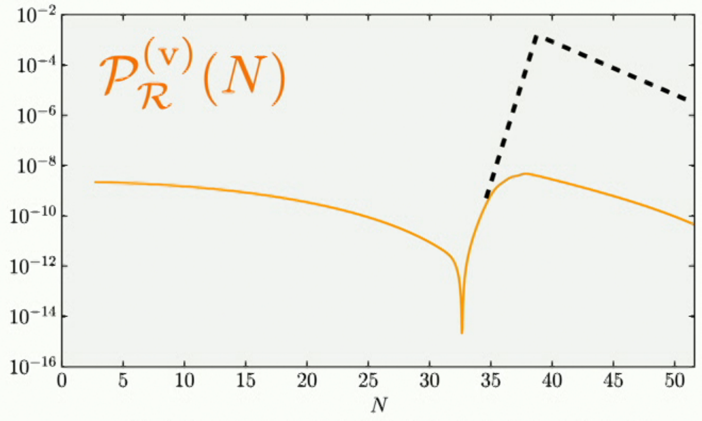
Recent numerical and analytical analysis show that $|\dot{\phi}|$ exhibit wild oscillations with growing amplitude!

(V. Domcke, V. Guidetti, Y. Welling, A. Westphal, 2020)
(A. Caravano, E. Komatsu, K. Lozanov, J. Weller, 2022)
(M. Peloso, L. Sorbo, 2023)
(D. Figuero, J. Lizarraga, A. Urio, J. Urestilla, 2023)

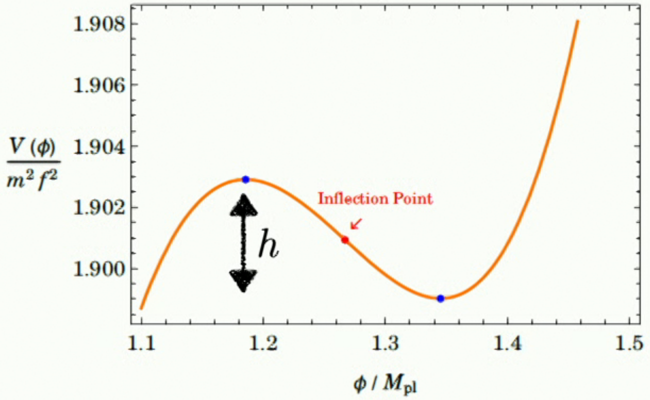








$$\mathcal{R}_k'' + 2aH\underbrace{\left[1+\frac{\eta}{2}\right]}_{\text{Damping term becomes a driving term}}\mathcal{R}_k' + k^2\mathcal{R}_k \simeq 0$$



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

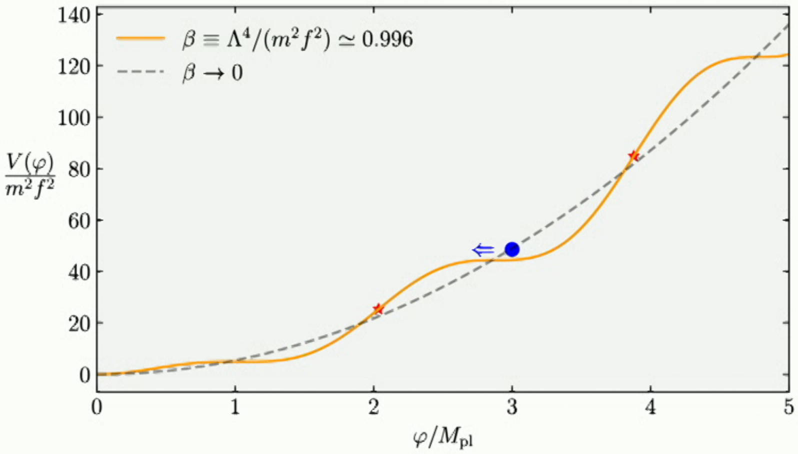
Fine tuning of model parameters is required to get a larger enhancement: e.g by adjusting the height h of the barrier.

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

O.Ö, Z. Lalak, arXiv: 2008.07549

Roller-Coaster Axion-Inflation

$$\frac{\mathcal{L}_m}{\sqrt{-g}} = -\frac{1}{2}\partial_\mu\varphi\,\partial^\mu\varphi - V(\varphi) - \frac{1}{4}F_{\mu\nu}\,F^{\mu\nu} - \frac{g_{\rm cs}}{4f}\,\varphi\,F_{\mu\nu}\,\tilde{F}^{\mu\nu}\,.$$



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

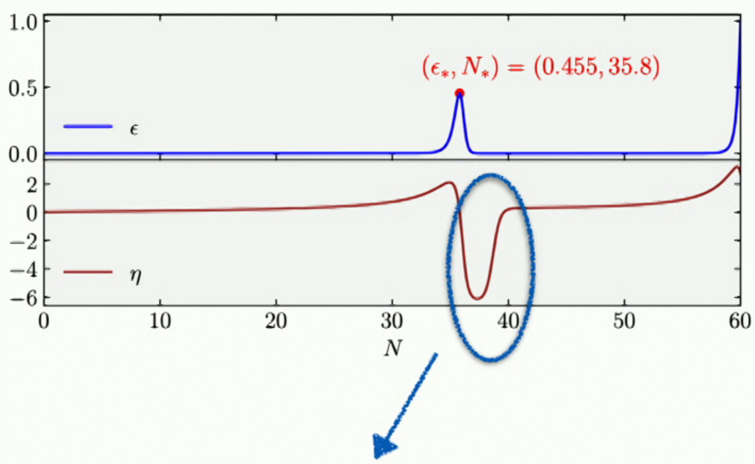
$$V(\varphi) = \frac{1}{2}m^2\varphi^2 + \Lambda^4\,\frac{\varphi}{f}\,\sin\left(\frac{\varphi}{f}\right)$$

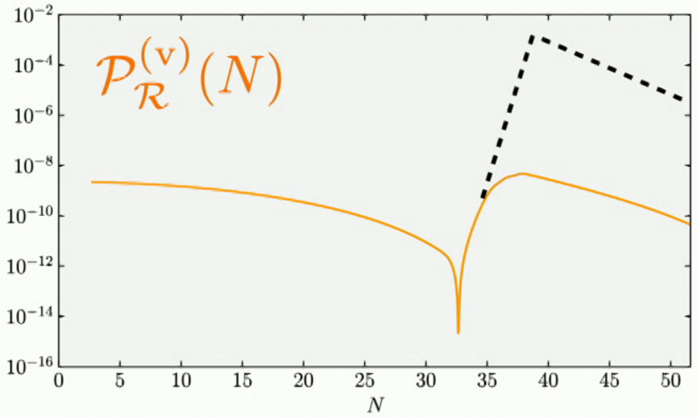
$$\beta = \frac{\Lambda^4}{m^2 f^2} \lesssim 1$$

Interested in the "Roller Coaster" Regime

O.Ö, S. Parameswaran, G.Tasinato, I. Zavala, arXiv:1803.07626
S-L. Cheng, W. Lee, K-W. Ng, arXiv: 1801.09050

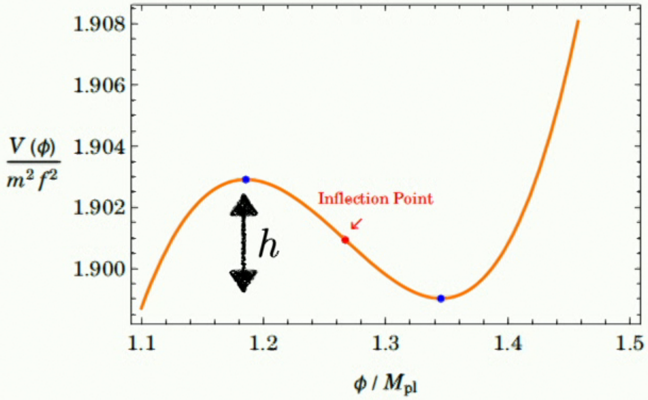
O.Ö, Z. Lalak, arXiv: 2008.07549





$$\mathcal{R}_k'' + 2aH\underbrace{\left[1+\frac{\eta}{2}\right]}_{\text{Damping term becomes a driving term}}\mathcal{R}_k' + k^2\mathcal{R}_k \simeq 0$$

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

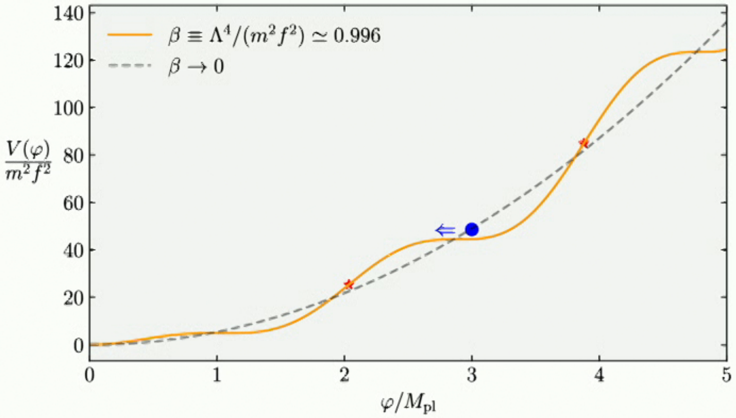


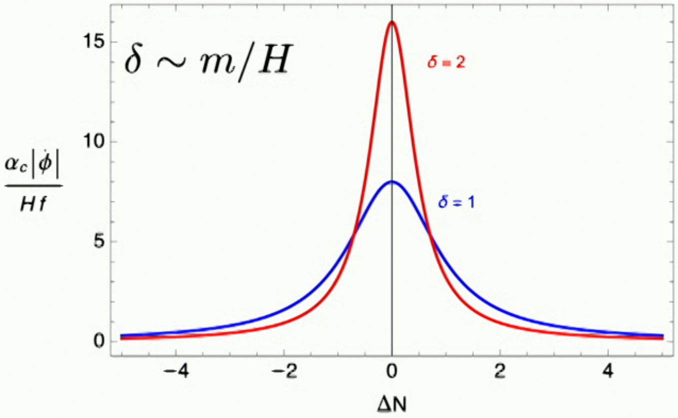
Fine tuning of model parameters is required to get a larger enhancement: e.g by adjusting the height h of the barrier.

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

O.Ö, Z. Lalak, arXiv: 2008.07549

Gauge field production at the cliff(s)





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

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

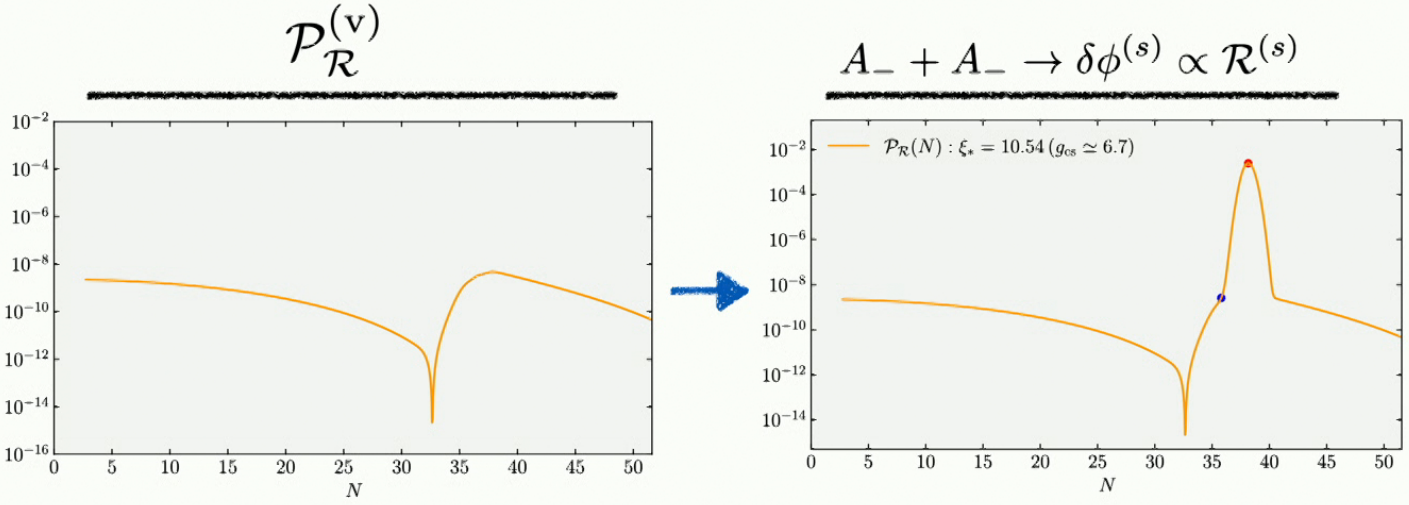
$$\left.\frac{k}{aH}\right|_{t=t_*} \equiv \frac{k}{k_*} \qquad \left.\frac{\alpha_c|\dot\phi|}{Hf}\right|_{t=t_*} = 2\xi_*$$

Amplification of vector fields 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 → $\left\{\frac{k}{k_*}, \xi_*, \delta\right\}$

O.Ö, Z. Lalak, arXiv: 2008.07549

Echoes of gauge field production (PBH as DM)



$\mathcal{P}_{\mathcal{R}}^{(\mathrm{v})}$

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

Scalar Power spectrum:

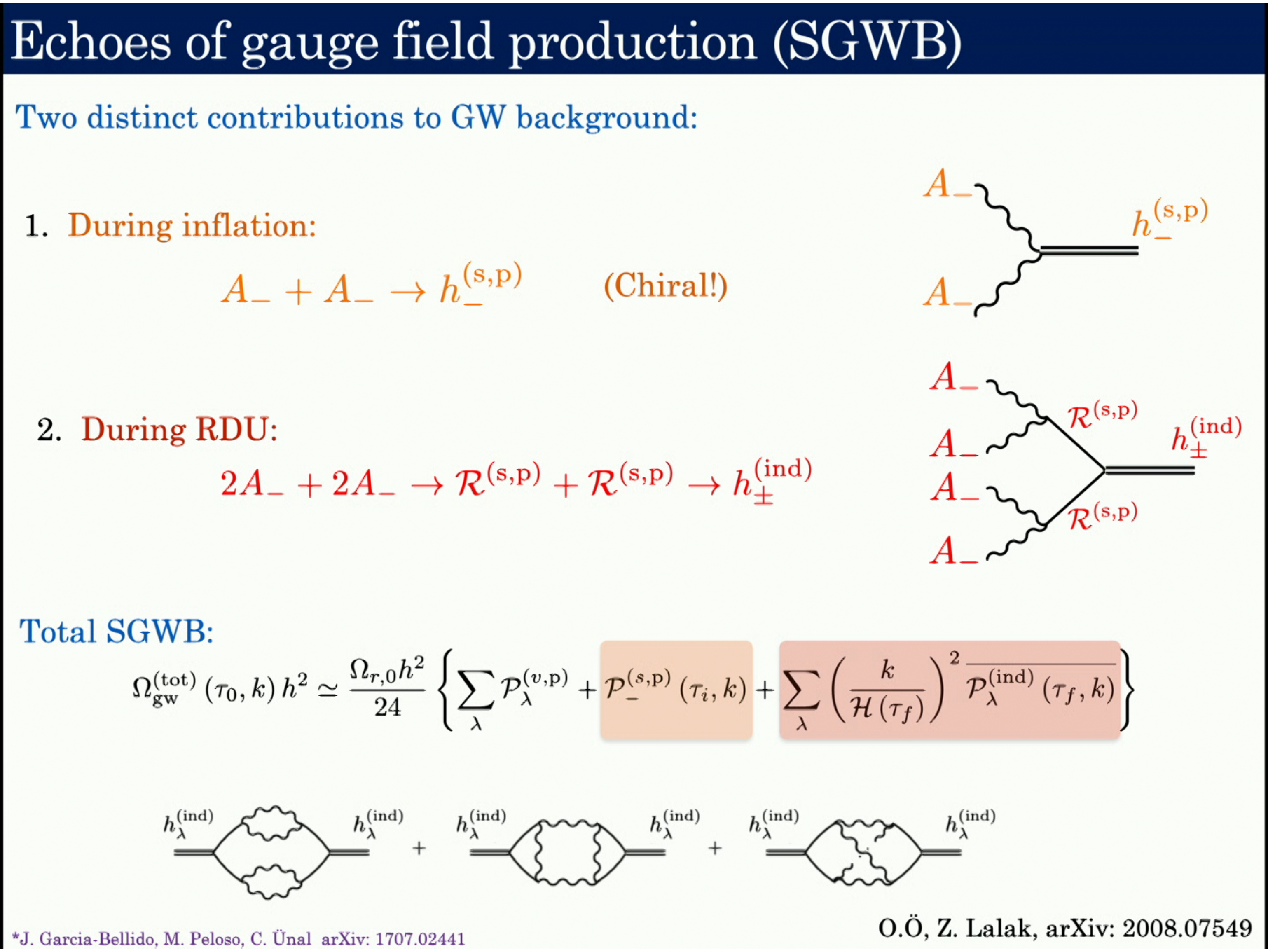
$$\mathcal{P}_{\mathcal{R}}(k) = \mathcal{P}_{\mathcal{R}}^{(v)}(k)\left[1 + \frac{H^2}{64\pi^2 M_{\mathrm{pl}}^2} f_{2,\mathcal{R}}\left(\xi_*, \frac{k}{k_*}, \delta\right)\right]$$

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

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

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

O.Ö, Z. Lalak, arXiv: 2008.07549



Echoes of gauge field production (SGWB)

Two distinct contributions to GW background:

1. During inflation:

$$A_- + A_- \to h_-^{(\rm s,p)} \qquad \text{(Chiral!)}$$

2. During RDU:

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

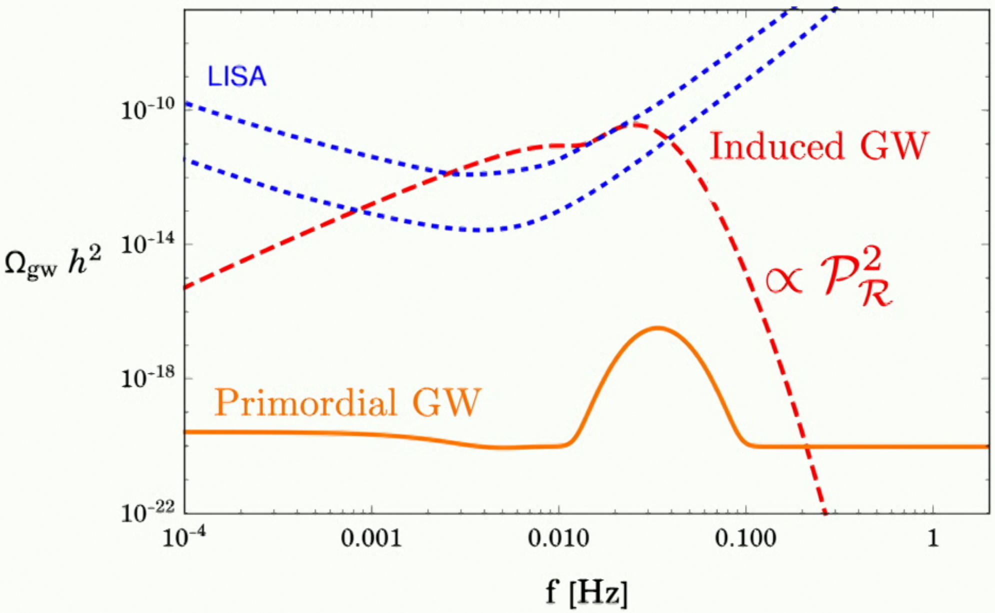
Total SGWB:

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

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

O.Ö, Z. Lalak, arXiv: 2008.07549

Echoes of gauge field production (SGWB)



- Induced spectrum has larger amplitude than the primordial one, because we have relatively small scale inflation that starts with a small H and due to limitations that PBHs do not over close the universe.
- IR behavior of induced GW is similar to the single field inflation, but UV tail is exponentially decreasing. (DECIGO?, BBO?)

Localized signal (spectator Axion-GF dynamics)

$$\frac{\mathcal{L}_{\rm m}}{\sqrt{-g}} = -\frac{1}{2}\partial_\mu\varphi\partial^\mu\varphi - V_\varphi(\varphi) - \frac{1}{2}\partial_\mu\sigma\,\partial^\mu\sigma - V_\sigma(\sigma) - \frac{1}{4}F_{\mu\nu}\,F^{\mu\nu} - \frac{g_{\rm cs}}{4f}\,\sigma\,F_{\mu\nu}\,\tilde{F}^{\mu\nu},$$

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

↓

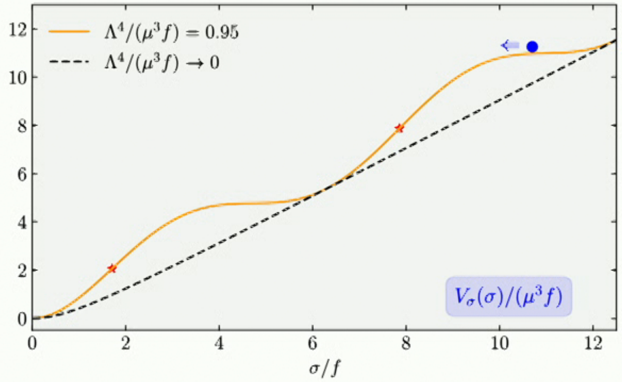
Localized emission of GWs
and Scalar perturbations

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

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

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

Scale dependent bumps in the
scalar and tensor spectra!



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

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

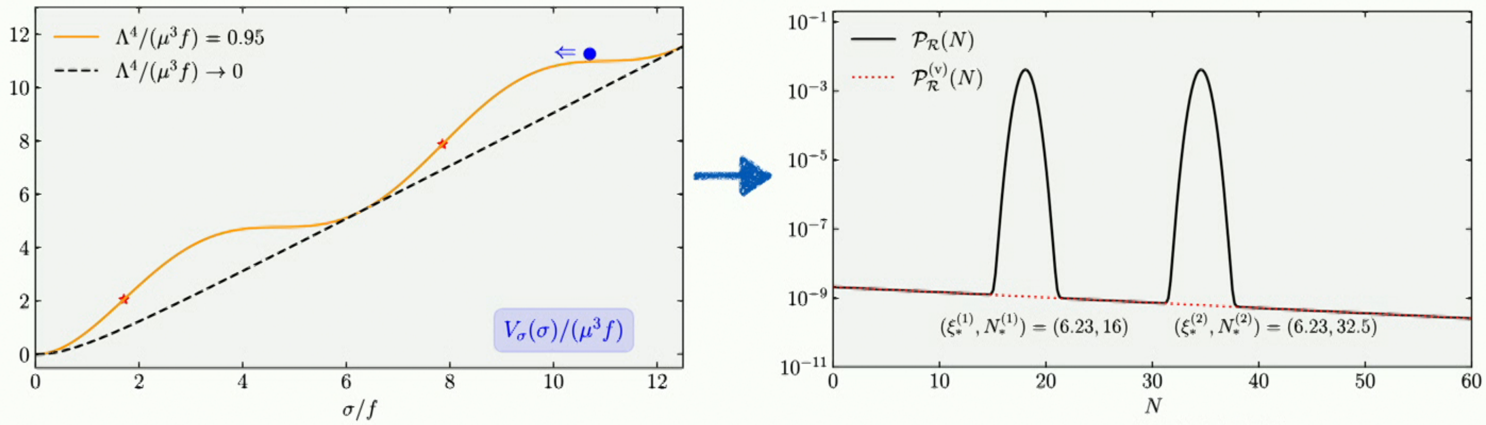
Axion Monodromy!

arXiv: 2005.10280-O.Ö

Broken scale inv. via particle production

$$\frac{\mathcal{L}_{\rm m}}{\sqrt{-g}} = -\frac{1}{2}\partial_\mu\varphi\partial^\mu\varphi - V_\varphi(\varphi) - \frac{1}{2}\partial_\mu\sigma\,\partial^\mu\sigma - V_\sigma(\sigma) - \frac{1}{4}F_{\mu\nu}\,F^{\mu\nu} \boxed{- \frac{g_{\rm cs}}{4f}\,\sigma\,F_{\mu\nu}\,\tilde{F}^{\mu\nu},}$$

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



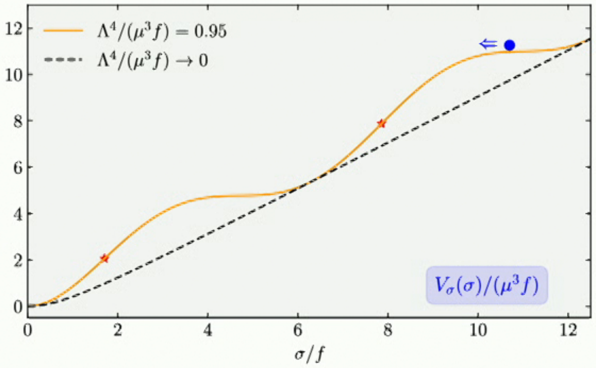
$$m_\sigma \simeq \mathcal{O}(1)H$$

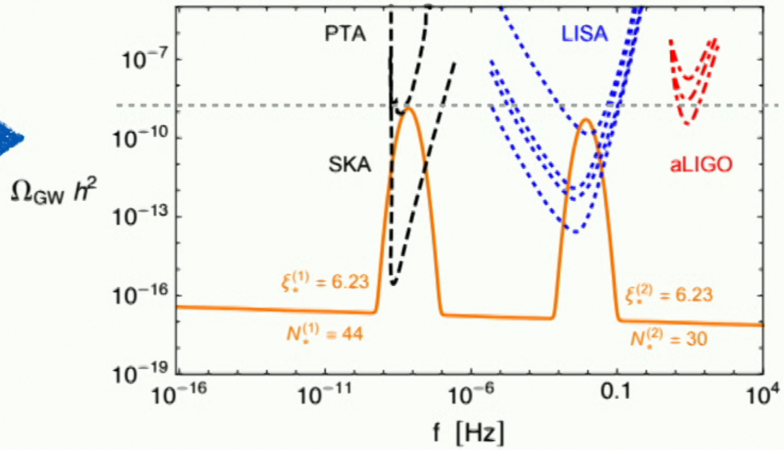
arXiv: 2005.10280-O.Ö

Broken scale inv. via particle production

$$\frac{\mathcal{L}_{\rm m}}{\sqrt{-g}} = -\frac{1}{2}\partial_\mu\varphi\partial^\mu\varphi - V_\varphi(\varphi) - \frac{1}{2}\partial_\mu\sigma\,\partial^\mu\sigma - V_\sigma(\sigma) - \frac{1}{4}F_{\mu\nu}\,F^{\mu\nu} - \frac{g_{\rm cs}}{4f}\,\sigma\,F_{\mu\nu}\,\tilde{F}^{\mu\nu},$$

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



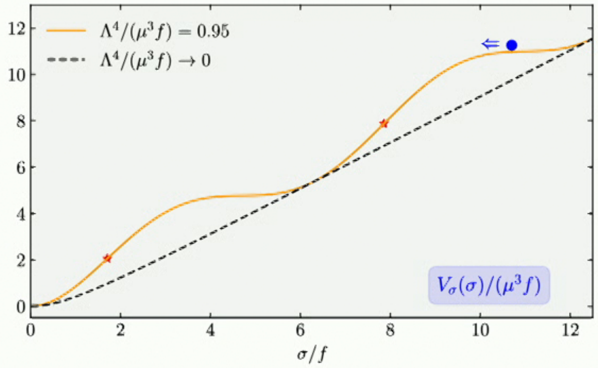


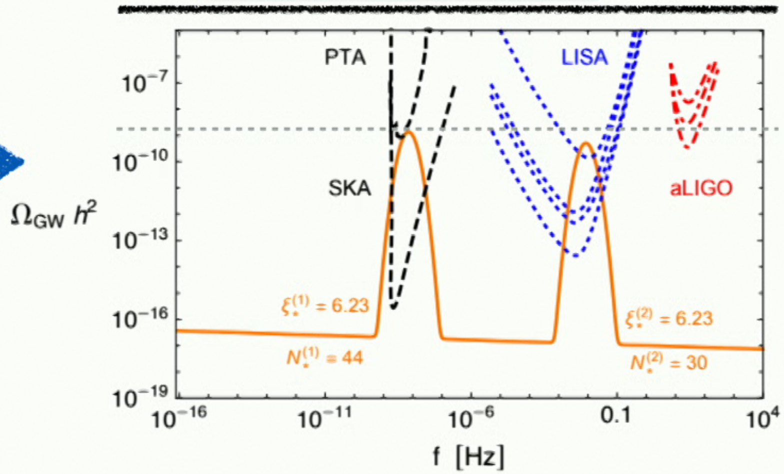
arXiv: 2005.10280-O.Ö

Broken scale inv. via particle production

$$\frac{\mathcal{L}_{\rm m}}{\sqrt{-g}} = -\frac{1}{2}\partial_\mu\varphi\partial^\mu\varphi - V_\varphi(\varphi) - \frac{1}{2}\partial_\mu\sigma\,\partial^\mu\sigma - V_\sigma(\sigma) \boxed{-\frac{1}{4}F_{\mu\nu}\,F^{\mu\nu}} - \frac{g_{\rm cs}}{4f}\,\sigma\,F_{\mu\nu}\,\tilde{F}^{\mu\nu},$$

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

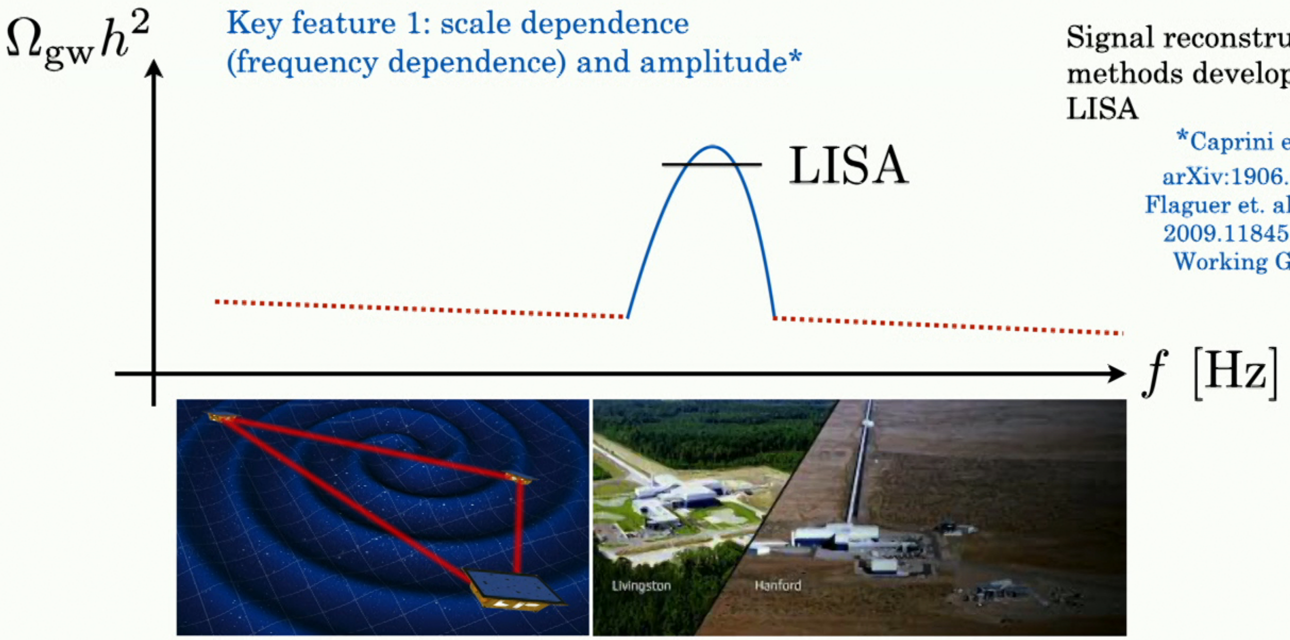




arXiv: 2005.10280-O.Ö

Clean probes of SGWBs @Interferometers

Key feature 1: scale dependence (frequency dependence) and amplitude*



Signal reconstruction methods developed for LISA

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

Key feature 2: chirality*

- Planar detectors cannot distinguish between a LH GW coming from up and a RH GW coming from down with the same amplitude.

Use kinematically induced dipole to break degeneracy in amplitude:
*Domcke et.al. 2019, arXiv: 1910.08052

Cross correlations between different interferometers : a non-planar network of interferometers *Smith & Caldwell, '17

Conclusions and Outlook

- Scale invariance of scalar perturbations during inflation can be broken to populate PBH's in the post-inflationary universe:

  1. In single field inflation: through the energy transfer from large gradients of homogeneous background quantities (slow-roll violation) into curvature perturbation.
  2. Multi-field inflation: Through the payback of the energy that the additional sectors borrowed from the homogeneous background quantities into the curvature perturbation.

- Fine tuning required in the model parameters and the level of model sophistication in realizing the enhancement can be demanding.

- Inf. Mechanisms of PBH formation is generically accompanied by distinct sources of GWs whose properties (e.g spectral shape, amplitude) depend on the statistics of the scalar perturbations and/or the particle content of inflation. Therefore future model building efforts are certainly worthwhile in providing insights on the nature of inflation through the model - GW observation mapping.

  - At the level of model building, it will be important to address challenges associated with fine tuning issues and to seek for more natural realizations of inflation that can generate interesting phenomenology at small scales.

    More soon…

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Thank you !

arXiv: 2301.03600, O.Ö & G. Tasinato
arXiv: 2008.07549, O.Ö & Z. Lalak
arXiv: 2005.10280-O.Ö
arXiv: 1803.07626, O.Ö, S. Parameswaran, G.Tasinato, I. Zavala,
arXiv: 1912.01061, O.Ö & G. Tasinato