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AstroParticle Symposium

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Primordial Black Holes from Dissipation During Inflation

Marcos A. G. García

+ G. Ballesteros, A. Pérez Rodríguez, M. Pierre and J. Rey

arXiv:2208.14978 [astro-ph.CO]

Universidad Nacional Autónoma de México

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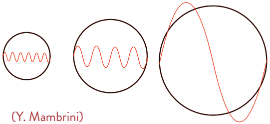
Black holes from inflation

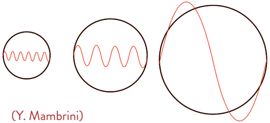


(Y. Mambrini)

Quantum fluctuations in ϕ, g, are strechted by expansion

$$\langle \mathcal{R}(k)\mathcal{R}^*(k')\rangle = \frac{2\pi^2}{k^3}\mathcal{P}_{\mathcal{R}}\delta(k-k') \qquad \longrightarrow \qquad \text{single field:} \quad \mathcal{P}_{\mathcal{R}}(k_*) \simeq \frac{H_*^4}{4\pi^2\dot{\phi}_*^2}$$

Black holes from inflation



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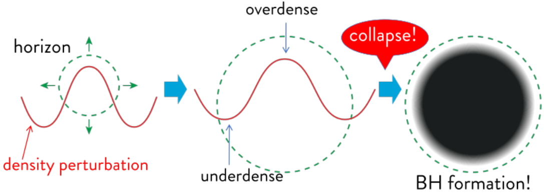


(N. Kitajima)

1. PBHs from inflation

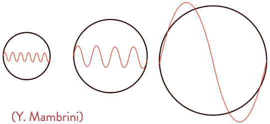
2. Background

3. (Random) fluctuations

4. GWs

5. Conclusion

Black holes from inflation



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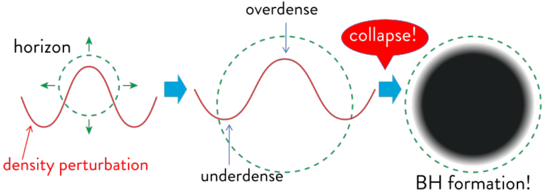
$$\langle \mathcal{R}(k)\mathcal{R}^*(k')\rangle = \frac{2\pi^2}{k^3}\mathcal{P}_\mathcal{R}\delta(k-k') \longrightarrow \text{single field:} \quad \mathcal{P}_\mathcal{R}(k_*) \simeq \frac{H_*^4}{4\pi^2\dot{\phi}_*^2}$$

Given critical threshold, $\delta_c \approx 0.5$, the fraction of BHs of mass M is

$$\beta(M) = \int_{\delta_c}^{\infty} d\delta\, P(\delta, M)$$

Typically $P \propto e^{-\delta^2/2\sigma^2(M)}$, and

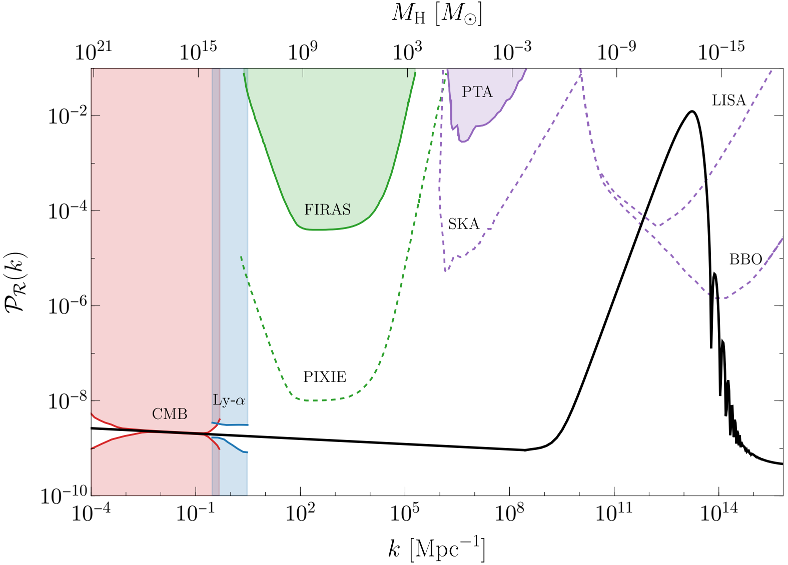
$$\sigma^2(M(k)) = \frac{16}{81}\int \frac{dq}{q}\left(\frac{q}{k}\right)^4 \mathcal{P}_\mathcal{R}(q)\, W(q/k)^2$$



(N. Kitajima)

W. Press, P. Schechter, Astrophys. J. 187 (1974), 425

Peaks in the power spectrum



A. Green, B. Kavanagh, J. Phys. G 48 (2021), 043001

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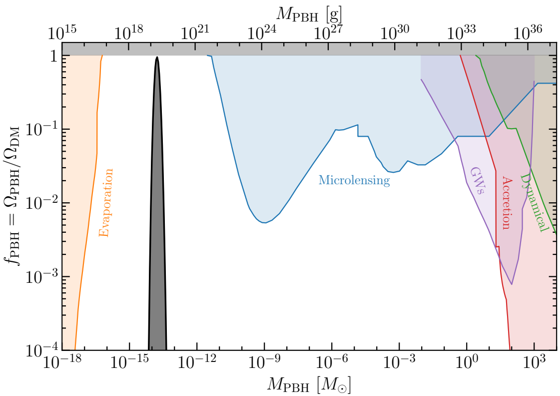


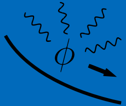
A. Green, B. Kavanagh, J. Phys. G 48 (2021), 043001

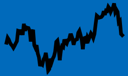
$$M(k) \approx 10^{18}\,\mathrm{g}\left(\frac{k}{7\times 10^{13}\,\mathrm{Mpc}^{-1}}\right)^{-2}$$

$$\frac{\Omega_{\rm PBH}(M)}{\Omega_{\rm DM}} \simeq \frac{\beta(M)}{8\times 10^{-16}}\left(\frac{M}{10^{18}\,\mathrm{g}}\right)^{-1/2}$$

$$\Omega_{\rm PBH} = \int d\log M\;\Omega_{\rm PBH}(M)$$

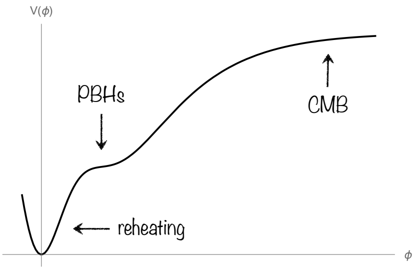
Simplest mechanism: *ultra* slow-roll, $\mathcal{P}_\mathcal{R} \propto \dot\phi^{-2}$





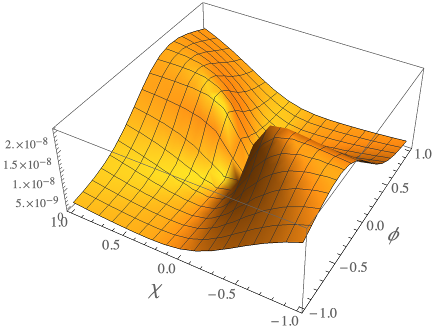
Peaks in the power spectrum

Single field



G. Ballesteros, M. Taoso, PRD 97 (2018), 023501

Multifield

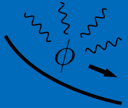


S. Geller *et al.*, PRD 106 (2022), 063535

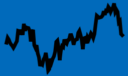
Simplest mechanism: *ultra* slow-roll, $\mathcal{P}_\mathcal{R} \propto \dot{\phi}^{-2}$

1. PBHs from inflation

2. Background



3. (Random) fluctuations

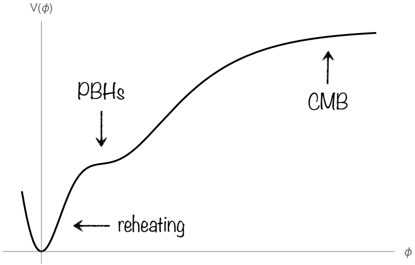


4. GWs

5. Conclusion

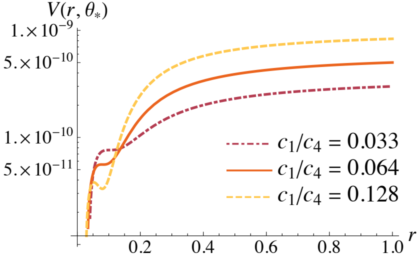
Peaks in the power spectrum

Single field



G. Ballesteros, M. Taoso, PRD 97 (2018), 023501

"Multifield"



S. Geller *et al.*, PRD 106 (2022), 063535

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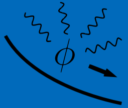
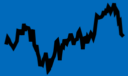
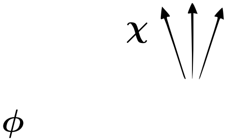




Slow roll from particle production

Non-adiabatic, non-thermalized production

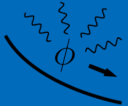
$$\mathcal{L} \supset -\frac{1}{2} g^2 \sum_i (\phi - \phi_i)^2 \chi_i^2$$

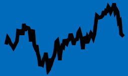


(trapped inflation)

D. Green *et al.*, PRD 80 (2009), 063533

L. Pearce, M. Peloso, L. Sorbo, JCAP 11 (2016), 058





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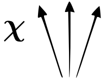
Non-adiabatic, non-thermalized production

$$\mathcal{L} \supset -\frac{1}{2} g^2 \sum_i (\phi - \phi_i)^2 \chi_i^2$$

$$\downarrow$$



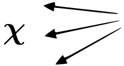
$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) + \int^t \frac{g^{5/2}}{\Delta(2\pi)^3} (\dot{\phi}(t'))^{5/2} \frac{a(t')^3}{a(t)^3} \, dt' = 0$$

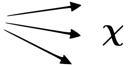
ϕ

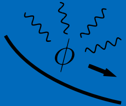
(trapped inflation)

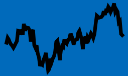
D. Green *et al.*, PRD 80 (2009), 063533

L. Pearce, M. Peloso, L. Sorbo, JCAP 11 (2016), 058





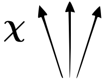




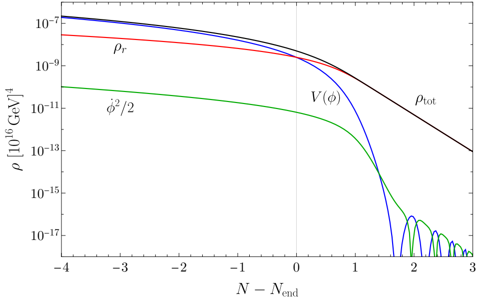
Slow roll from particle production

Adiabatic, thermalized production

$$\ddot{\phi} + (3H + \Gamma)\dot{\phi} + V_\phi = 0$$



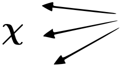
ϕ

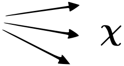


(warm inflation)

A. Berera, PRL 75 (1995), 3218

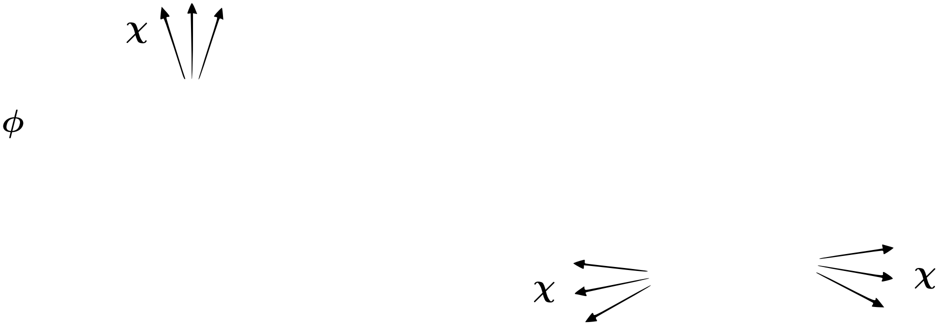
A. Berera, I. Moss, R. Ramos, Rept. Prog. Phys. 72 (2009), 026901





Curvature perturbations from particle production

background dynamics $\longrightarrow$ particle production $\langle \chi_{\boldsymbol{k}_1} \chi_{\boldsymbol{k}_2} \cdots \rangle$ $\longleftrightarrow$ curvature fluctuations $\langle \mathcal{R}_{\boldsymbol{k}_1} \mathcal{R}_{\boldsymbol{k}_2} \cdots \rangle$



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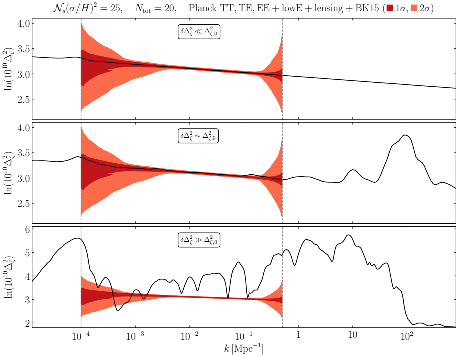
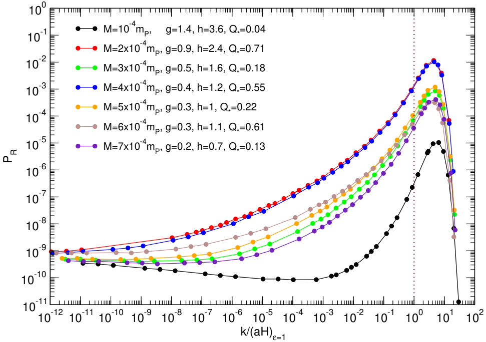
Curvature perturbations from particle production

background dynamics $\longrightarrow$ particle production $\longleftrightarrow$ curvature fluctuations





$$\pi'' + 2\mathcal{H}\pi' - \nabla^2\pi = -\frac{a}{2c}\frac{dm^2}{d\tau}\chi^2$$

$$\delta\ddot{\phi}_{\boldsymbol{k}} + (3H+\Gamma)\delta\dot{\phi}_{\boldsymbol{k}} = \xi_{\boldsymbol{k}} + \cdots$$

MG, M. Amin, D. Green, JCAP 06 (2020), 039

M. Bastero-Gil, M. Díaz-Blanco, JCAP 12 (2021), 052

Dissipation during inflation

The total (inflaton+radiation) stress-energy tensor is conserved, $\nabla_\mu T^{\mu\nu} = 0$, but individually,

$$\nabla_\mu T^{\mu\nu}_{(\phi)} = Q^\nu$$
$$\nabla_\mu T^{\mu\nu}_{(r)} = -Q^\nu$$

where

(M. Gleiser, R. Ramos, PRD 50 (1994) 2441; M. Bastero-Gil *et.al.*, JCAP 05 (2014) 004)

$$Q_\mu = \underbrace{-\Gamma\, u^\nu \nabla_\nu \phi \nabla_\mu \phi}_{\text{dissipation}} + \underbrace{\sqrt{\frac{2\Gamma\, T}{a^3}}\,\xi_t \nabla_\mu \phi}_{\text{fluctuation}}$$

ξ_t denotes a normalized white-noise process, $\xi_t = dW_t/dt$, with dW_t a Wiener increment,

$$\langle \xi_t(\mathbf{x})\xi_{t'}(\mathbf{x}')\rangle = \delta^{(3)}(\mathbf{x}-\mathbf{x}')\delta(t-t')$$

Only dissipation affects the background

1. PBHs from inflation
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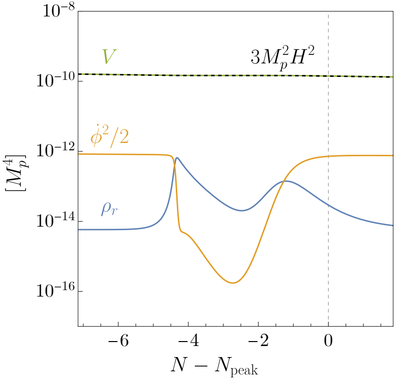
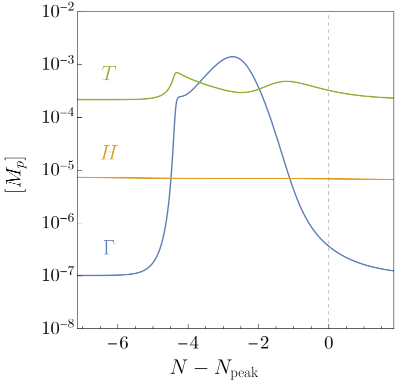
Background dynamics

$$\begin{aligned} \ddot{\phi} + (3H + \Gamma)\dot{\phi} + V_\phi &= 0 \\ \dot{\rho}_r + 4H\rho_r &= \Gamma\dot{\phi}^2 \\ \rho_r + \frac{1}{2}\dot{\phi}^2 + V &= 3M_P^2 H^2 \end{aligned}$$

$$\begin{aligned} V &= \frac{1}{4}\lambda\phi^4 \\ \Gamma &= \frac{T^3}{m^2 + M^2 \tanh^2\left(\frac{\phi-\phi^*}{\Lambda}\right)} \\ \rho_r &= \frac{\pi^2}{30} g_\star T^4 \end{aligned}$$





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Localized dissipation?

Inflaton coupled to a d.o.f. χ connected or part of the thermal bath

$$V(\phi,\chi) \;=\; V(\phi) + f(\phi)g(\chi)$$

Integration over χ and an ensamble averaging,

$$\partial_\mu \frac{\partial \mathcal{L}_{\rm eff,r}[\phi]}{\partial(\partial_\mu \phi)} - \frac{\partial \mathcal{L}_{\rm eff,r}[\phi]}{\partial \phi}$$
$$- i\frac{\partial f}{\partial \phi}\int d^4x'\,\theta(t-t')\;[f(\phi(x')) - f(\phi(x))]\,\langle[g(\chi(x)) - g(\chi(x'))]\rangle \;=\; 0$$

$\downarrow$ adiabaticity $\dot\phi/\phi \ll \tau^{-1} \longrightarrow$ locality

$$\ddot\phi + (3H+\Gamma)\dot\phi + \frac{\partial V_{\rm eff}}{\partial \phi} \;=\; 0$$

with

$$\Gamma \;=\; -i\int d^4x \left(\frac{\partial f}{\partial \phi}\right)^2 \theta(t-t')\,\langle[g(\chi(x)) - g(\chi(x'))]\rangle\,(t-t')$$

A. Hosoya, M. Sakagami, PRD 29 (1984), 2228; M. Bastero-Gil, A. Berera, R. Ramos, JCAP 09 (2011), 033

Localized dissipation?

Thermal corrections to the potential can be suppressed via heavy field exchange, $\phi \to \chi \to \sigma$

$$\mathcal{L} \;=\; \frac{1}{2\mathcal{K}(\varphi)}\partial^\mu\varphi\partial_\mu\varphi + \frac{1}{2}\partial^\mu\chi\partial_\mu\chi + \frac{1}{2}\partial^\mu\sigma\partial_\mu\sigma - \frac{1}{2}g^2\varphi^2\chi^2 - \frac{1}{2}\tilde{g}^2\varphi\chi\sigma^2 - V(\varphi)$$

With ϕ the canonically normalized field,

$$\begin{aligned}\Gamma \;&=\; \frac{g^4(\partial_\phi\varphi^2)^2}{2T}\int\frac{d^4p}{(2\pi)^4}\,n(\omega)\left[n(\omega)+1\right]\rho_\chi^2(\omega)\\ &\simeq\; \frac{40g^4(\partial_\phi\varphi^2)^2\Gamma_{\chi,0}^2T^3}{(2\pi)^3m_\chi^6}\qquad (T \ll m_\chi)\end{aligned}$$

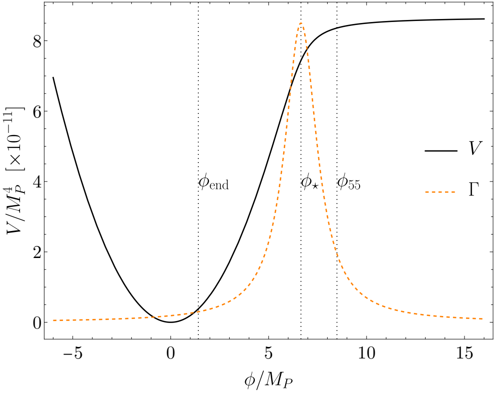
where

$$\begin{aligned}\rho_\chi \;&=\; \frac{4\omega_p\Gamma_\chi}{(\omega^2-\omega_p^2)^2+4\omega_p^2\Gamma_\chi^2}\\ n(\omega) \;&=\; \left(e^{\omega T}-1\right)^{-1}\\ \Gamma_\chi \;&\simeq\; \frac{\tilde{g}^4\varphi^2}{8\pi\omega_p(\mathbf{p})}\end{aligned}$$

Localized dissipation?

Thermal corrections to the potential can be suppressed via heavy field exchange, $\phi \to \chi \to \sigma$

$$\mathcal{L} = \frac{1}{2\mathcal{K}(\varphi)}\partial^\mu\varphi\partial_\mu\varphi + \frac{1}{2}\partial^\mu\chi\partial_\mu\chi + \frac{1}{2}\partial^\mu\sigma\partial_\mu\sigma - \frac{1}{2}g^2\varphi^2\chi^2 - \frac{1}{2}\tilde{g}^2\varphi\chi\sigma^2 - V(\varphi)$$



$$\mathcal{K}(\varphi) = \frac{4\varphi^4}{(1+\varphi^2)^2}$$

$$V(\varphi) = \lambda(\varphi+\beta)^2$$

$$\downarrow$$

$$V(\phi) = \lambda\left(\phi - \sqrt{(\phi-\phi_\star)^2+1} + \sqrt{1+\phi_\star^2}\right)^2$$

$$\Gamma = \frac{5}{16\pi^5}\left(\frac{\tilde{g}}{g}\right)^4 \frac{T^3}{1+(\phi-\phi_\star)^2}$$

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Scalar fluctuations

Introduce the set of linear fluctuations in the Newtonian gauge, $\delta\phi$, $\delta\rho_r$, $\delta q_r = \frac{4}{3}\rho_r \delta v_r$, and

$$ds^2 = (1+2\psi)\,dt^2 - a^2(1-2\psi)\delta_{ij}\,dx^i dx^j$$

Einstein's equations lead to

$$\begin{aligned}
3H(\dot\psi + H\psi) + \frac{k^2}{a^2}\psi &= -\frac{1}{2M_p^2}\left[\delta\rho_r + \dot\phi(\delta\dot\phi - \dot\phi\psi) + V_\phi\delta\phi\right] \\
\dot\psi + H\psi &= -\frac{1}{2M_p^2}\left(\delta q_r - \dot\phi\delta\phi\right) \\
\ddot\psi + 4H\dot\psi + (2\dot H + 3H^2)\psi &= \frac{1}{2M_p^2}\left[\frac{1}{3}\delta\rho_r + \dot\phi(\delta\dot\phi + \dot\phi\psi) - V_\phi\delta\phi\right]
\end{aligned}$$

Scalar fluctuations

Introduce the set of linear fluctuations in the Newtonian gauge, $\delta\phi,\ \delta\rho_r,\ \delta q_r = \frac{4}{3}\rho_r \delta v_r$, and

$$ds^2 = (1+2\psi)dt^2 - a^2(1-2\psi)\delta_{ij}dx^i dx^j$$

Continuity equations in turn give (M. Bastero-Gil *et.al.*, JCAP 05 (2014) 004)

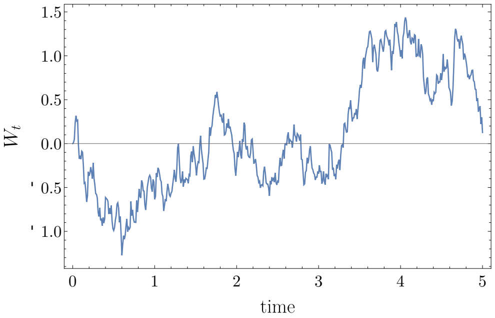
$$\begin{aligned}
\delta\ddot{\phi} + (3H+\Gamma)\delta\dot{\phi} + \left(\frac{k^2}{a^2} + V_{\phi\phi} + \dot{\phi}\Gamma_\phi\right)\delta\phi + \Gamma_T \frac{\dot{\phi}T}{4\rho_r}\delta\rho_r - 4\dot{\psi}\dot{\phi} + (2V_\phi + \Gamma\dot{\phi})\psi &= \sqrt{\frac{2\Gamma T}{a^3}}\,\xi_t \\
\delta\dot{\rho}_r + \left(4H - \Gamma_T \frac{\dot{\phi}^2 T}{4\rho_r}\right)\delta\rho_r - \frac{k^2}{a^2}\delta q_r + \Gamma\dot{\phi}^2\psi - 4\rho_r\dot{\psi} - (\Gamma_\phi\delta\phi - 2\Gamma\delta\dot{\phi})\dot{\phi} &= -\sqrt{\frac{2\Gamma T}{a^3}}\,\dot{\phi}\,\xi_t \\
\delta\dot{q}_r + \frac{4}{3}\rho_r\psi + 3H\delta q_r + \frac{1}{3}\delta\rho_r + \Gamma\dot{\phi}\delta\phi &= 0
\end{aligned}$$

Solutions reach an attractor, so initial conditions may be chosen as

$$\delta q_r = 0, \qquad \delta\rho_r = 0, \qquad \psi = 0, \qquad \delta\phi = -\frac{\dot{\phi}e^{-ik\tau}}{2M_p\, aH\sqrt{k\epsilon}}$$

Difficult to find their gauge-invariant versions!

Frequentist vs deterministic



W_t is continuous but not differentiable

$$W_{t+\Delta t} - W_t \sim \mathcal{N}(0, \Delta t)$$

Take $\boldsymbol{\Phi} \equiv \left(\psi, \delta\rho_r, \delta\dot{\phi}, \delta\phi\right)^{\mathrm{T}}$

$$\dot{\boldsymbol{\Phi}} + \boldsymbol{A}\boldsymbol{\Phi} = \boldsymbol{B}\,\xi_t$$

$$\approx \boldsymbol{B}\sum_i \xi_i\,\delta(t - t_i)$$

with $\langle \xi_i \rangle = 0,\ \langle \xi_i \xi_j^* \rangle = \Delta t\,\delta(t - t')$

$$\int_{t_i^-}^{t_i^+} dt\,\left(\dot{\boldsymbol{\Phi}} + \boldsymbol{A}\boldsymbol{\Phi}\right) = \boldsymbol{\Phi}_i^+ - \boldsymbol{\Phi}_i^- = \boldsymbol{B}_i\,\xi_i$$

$$\Rightarrow \qquad \boldsymbol{\Phi}(t + \Delta t) \simeq \boldsymbol{A}(t)\boldsymbol{\Phi}(t)\Delta t + \boldsymbol{B}(t)\,\xi_i$$

(Euler-Maruyama)

(we use a stochastic RK method)

Frequentist vs deterministic

Itô's lemma:

$$\begin{aligned} dX &= a\,X\,dt + b\,dW_t \\ dX^2 &= (2a\,X^2 + b^2)\,dt + 2b\,X\,dW_t \end{aligned} \quad \Rightarrow \quad \begin{aligned} \frac{d\langle X\rangle}{dt} &= a\langle X\rangle \\ \frac{d\langle X^2\rangle}{dt} &= 2a\langle X^2\rangle + b^2 \end{aligned}$$

For cosmological perturbations,

$$\frac{d\langle \boldsymbol{\Phi}\boldsymbol{\Phi}^\dagger\rangle}{dt} = -\boldsymbol{A}\langle \boldsymbol{\Phi}\boldsymbol{\Phi}^\dagger\rangle - \langle \boldsymbol{\Phi}\boldsymbol{\Phi}^\dagger\rangle \boldsymbol{A}^{\mathrm{T}} + \boldsymbol{B}\boldsymbol{B}^{\mathrm{T}}$$

The curvature power spectrum is

$$\langle \mathcal{P}_{\mathcal{R}}\rangle = \frac{k^3}{2\pi^2}\boldsymbol{C}^{\mathrm{T}}\langle \boldsymbol{\Phi}\boldsymbol{\Phi}^\dagger\rangle \boldsymbol{C}\Big|_{k\ll aH}$$

with $\mathcal{R} = \boldsymbol{C}^T\,\boldsymbol{\Phi}$

1. PBHs from inflation

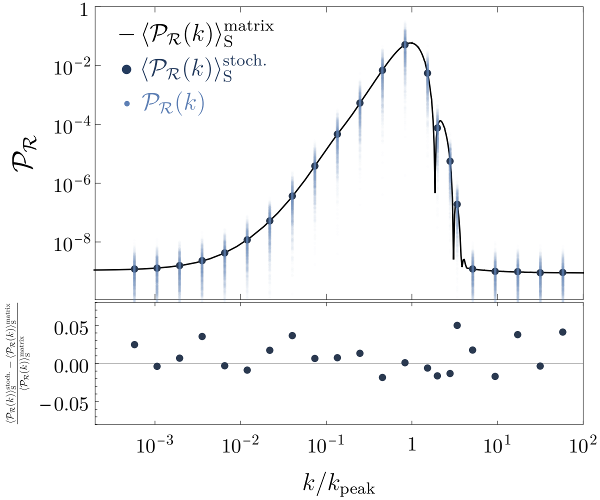
2. Background

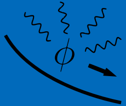
3. (Random) fluctuations

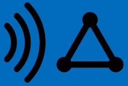
4. GWs

5. Conclusion

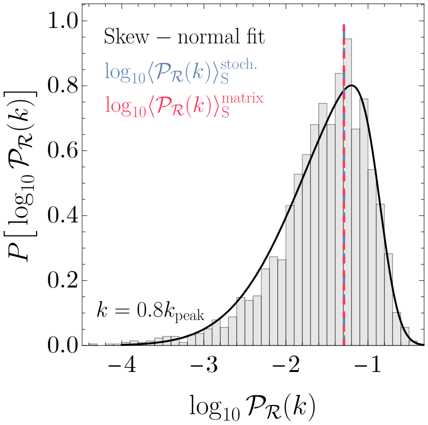
Frequentist vs deterministic

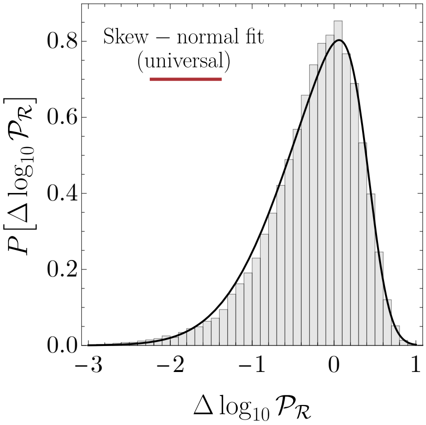






Distribution of the power spectrum





$$P_{\mathsf{SKN}}(x\,|\,\mu,\sigma,\alpha) \;=\; \frac{1}{\sqrt{2\pi}\sigma}\, e^{-\frac{(x-\mu)^2}{2\sigma^2}}\,\mathrm{erfc}\left[-\frac{\alpha(x-\mu)}{\sqrt{2}\sigma}\right]$$

$$\Delta\log_{10}\mathcal{P}_\mathcal{R} \equiv \log_{10}\mathcal{P}_\mathcal{R} - \log_{10}\langle\mathcal{P}_\mathcal{R}\rangle$$

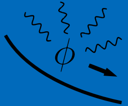
$$\{\mu,\sigma,\alpha\} = \{0.42, 0.87, -4.15\}$$

Analytical approximation

- Decouple $\delta\phi$: $\quad \ddot{\delta\phi} + (\dot{\delta\phi}, \delta\phi, \text{background}) \;=\; f_\phi(t)\xi_t$
- Approximate $\mathcal{R} \approx -\dfrac{\delta\phi}{\phi'}$
- Parametrize background as piecewise constants
- Solve homogeneous equation, $\ddot{\delta\phi} + (\dot{\delta\phi}, \delta\phi, \text{background}) \;=\; 0\,,$ and find Green's function
- Formally solve, $\delta\phi(t) \;=\; \delta\phi^{(h)}(t) + \int dt'\; G(t,t')\, f_\phi(t')\xi_{t'}$
- $\mathcal{P}_{\delta\phi} \;=\; \mathcal{P}^{(h)}_{\delta\phi}(t) + \int dt'\; G(t,t')^2\, f_\phi(t')^2 \qquad \longrightarrow \qquad \mathcal{P}_{\mathcal{R}}$

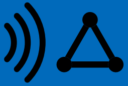
1. PBHs from inflation

2. Background



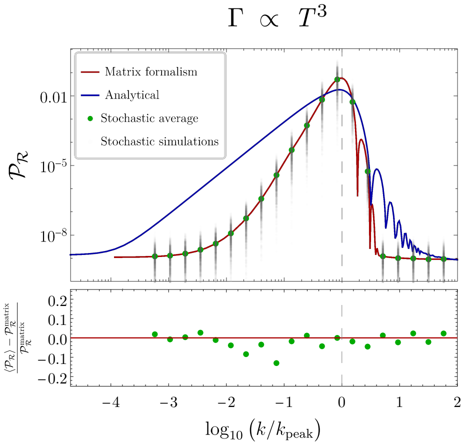
3. (Random) fluctuations

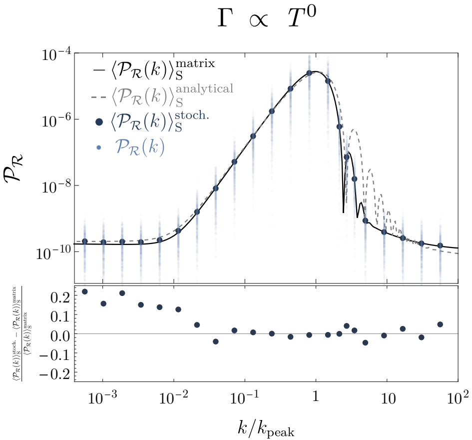
4. GWs



5. Conclusion

Analytical approximation





Induced gravitational waves

Second order induced GWs, $(s = (+, \times))$

$$h_k^{s\prime\prime} + 2\mathcal{H} h_k^{s\prime} + k^2 h_k^s \; = \; S_k^s$$

$$S_k^s \; = \; \int \frac{3p}{(2\pi)^3} \mathbf{e}_{ij}^s(\boldsymbol{k}) p_i p_j \left[8\psi_p \psi_{k-p} + \frac{16\rho}{3(\rho+p)} \left(\psi_p + \frac{1}{\mathcal{H}} \psi_p' \right) \left(\psi_{k-p} + \frac{1}{\mathcal{H}} \psi_{k-p}' \right) \right]$$

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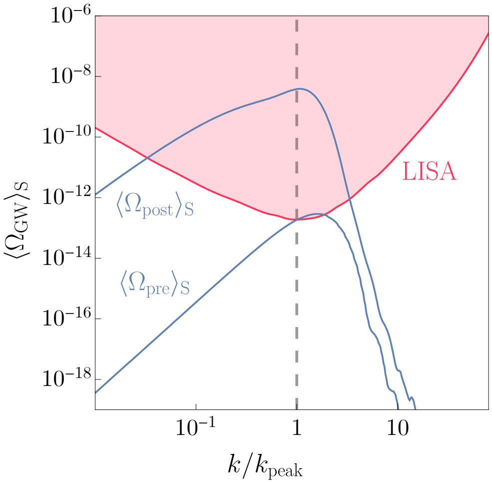
The source needs to be tracked during and after inflation,

$$S^s_{k(\mathrm{pre})} \; = \; \frac{4}{3} \left(\frac{\rho}{\rho + p} \right) \left(\frac{\phi'^2}{\mathcal{H}^2 M_p^4} \right) \int \frac{3p}{(2\pi)^3} \mathbf{e}^s(\boldsymbol{k}, \boldsymbol{p}) \delta\phi_p \delta\phi_{k-p}$$

$$S^s_{k(\mathrm{post})} \; = \; \int \frac{3p}{(2\pi)^3} \mathbf{e}^s(\boldsymbol{k}, \boldsymbol{p}) \left[8\psi_p \psi_{k-p} + 4 \left(\psi_p + \frac{1}{\mathcal{H}} \psi_p' \right) \left(\psi_{k-p} + \frac{1}{\mathcal{H}} \psi_{k-p}' \right) \right]$$

Signals



$$\langle h_k(\eta) h_{k'}(\eta) \rangle = \frac{2\pi^2}{k^3} \mathcal{P}_h(k,\eta) \delta(k - k')$$

$$\langle \mathcal{P}_h(k,\eta) \rangle = \langle \mathcal{P}_{\rm pre}(k,\eta) \rangle + 2 \langle \mathcal{P}_{\rm mix}(k,\eta) \rangle + \langle \mathcal{P}_{\rm post}(k,\eta) \rangle$$

$$\langle \Omega_{\rm GW}(T_0, k) \rangle_{\rm S} = \frac{\Omega_\gamma(T_0)}{24} \frac{g_{\star,T}}{g_{\star,T_0}} \left(\frac{g_{\star s,T_0}}{g_{\star s,T}} \right)^{4/3} \times \left(\frac{k}{\mathcal{H}} \right)^2 \overline{\langle \mathcal{P}_h(\eta,k) \rangle}_{\rm S}$$

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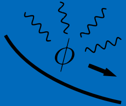

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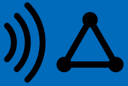

5. Conclusion

Conclusion

- Localized dissipation can be realized with non-minimal kinetic terms
- Dissipation affects the background, but does not drive the enhancement in $\mathcal{P}_\mathcal{R}$
- Thermal fluctuations are the main source for a peaked $\mathcal{P}_\mathcal{R}$
- Thermal attractor allows for analytical estimates
- First full determination of the stochastic GW signal
- Induced growth of fluctuations during reheating?

Thank you