Primordial Black Holes from Resonances in the Running-Mass-Inflation Model

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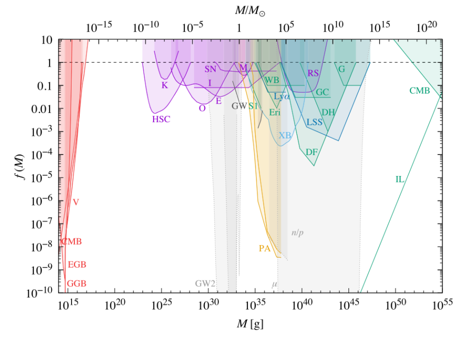
Primordial Black Holes as Dark Matter



Carr+ (2021)

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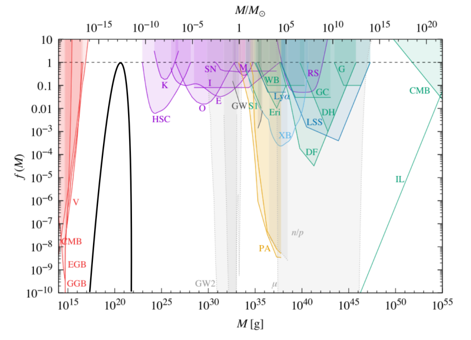

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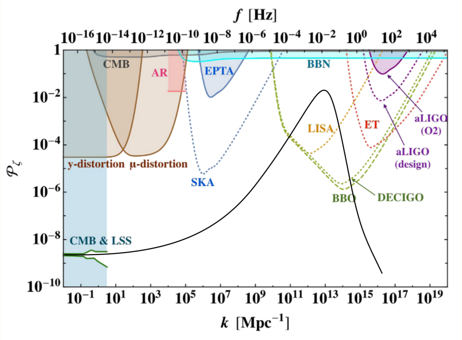


Adapted from Inomata and Nakama (2019)

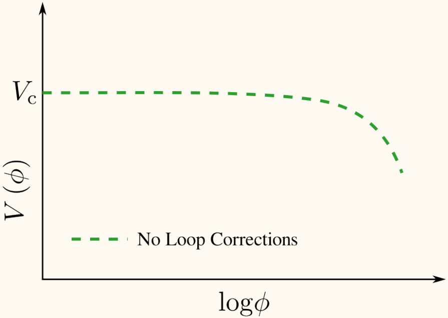
$\mathcal{P}_{\zeta\max} \simeq 10^{-1.5}$ at $\sim 30 - 35$ e-folds after the pivot scale exits the horizon.

Running-Mass-Inflation

Running-Mass Inflation

Stewart (1997), Covi+ (1999, 2004), Leach+ (2000), Alabidi+ (2006, 2009, 2012)

$$V \simeq V_{\rm c}\left[1 - \frac{1}{2}\mu^2\frac{\phi^2}{m_{\rm Pl}^2} + \dots\right]$$



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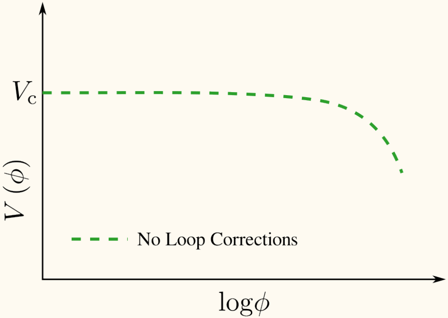
$$\mu = \mu \left[\mu_0, A, \alpha \ln \frac{\phi}{m_{\rm Pl}} \right]$$



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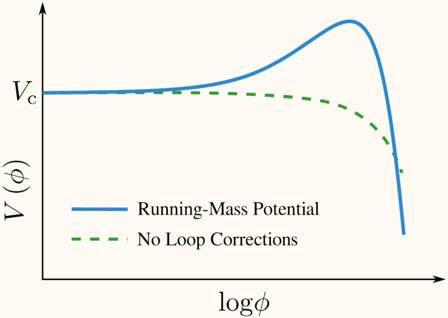
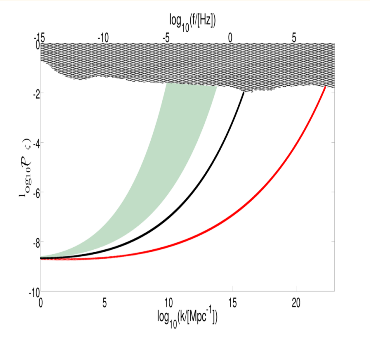
$$V(\phi) = V_{\mathrm{c}} \left[1 - \frac{1}{2} \frac{\phi^2}{m_{\mathrm{Pl}}^2} \left(B - \frac{A}{\left(1 + \alpha \ln \frac{\phi}{m_{\mathrm{Pl}}}\right)^2} \right) \right]$$

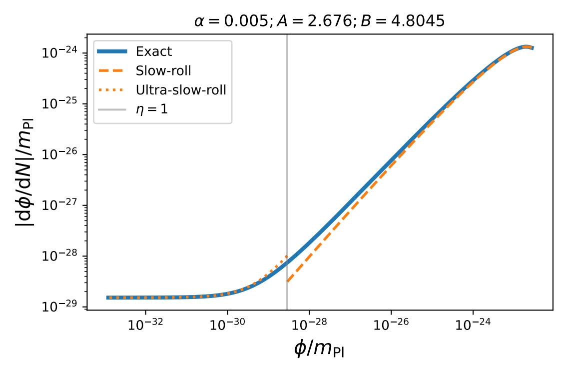


Earlier Works

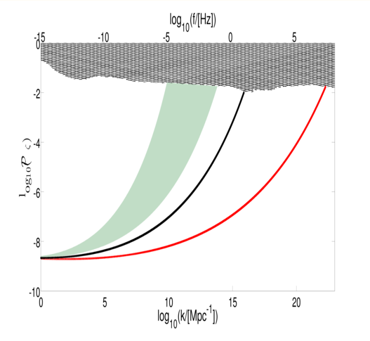


Alabidi+ (2012)

Homogeneous Dynamics of RMI



Graceful Exit



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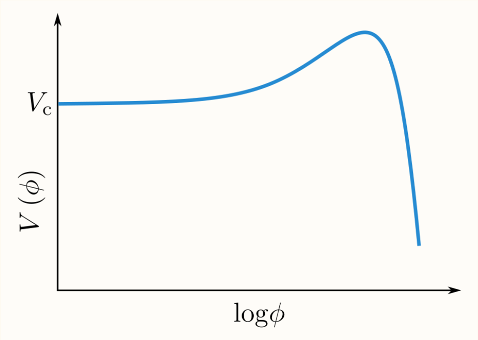

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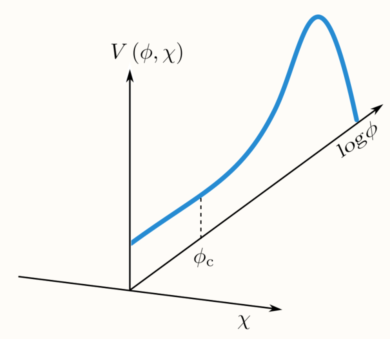
$$V(\phi,\chi) \quad = \quad V(\phi) - \frac{1}{2}m^2\chi^2 + \frac{1}{2}g^2\chi^2(\phi-\phi_c)^2 + \ldots$$



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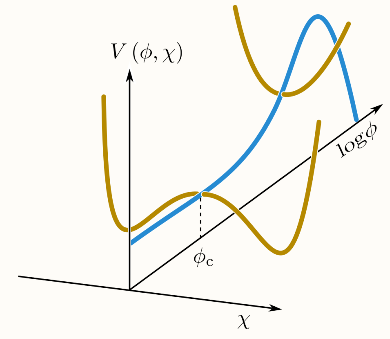

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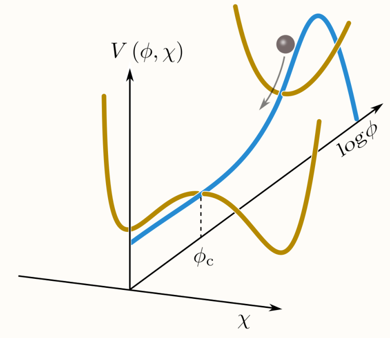

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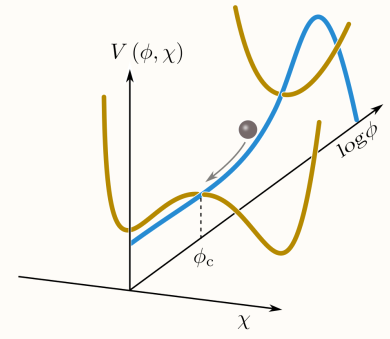

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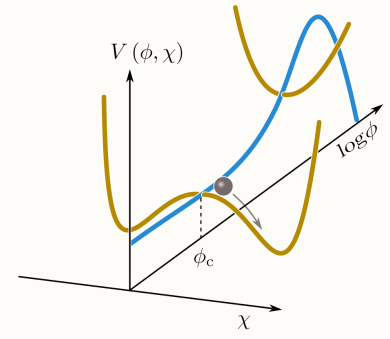

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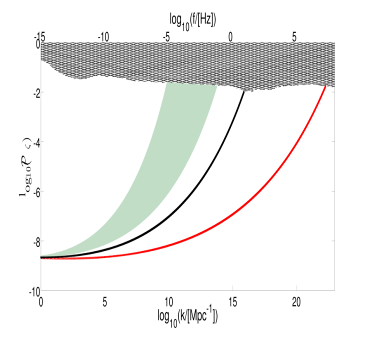

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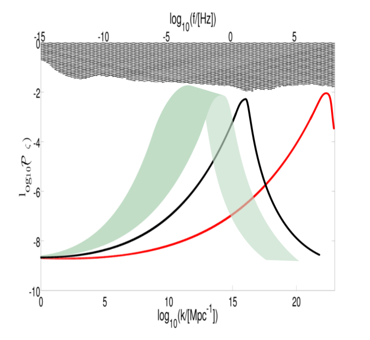

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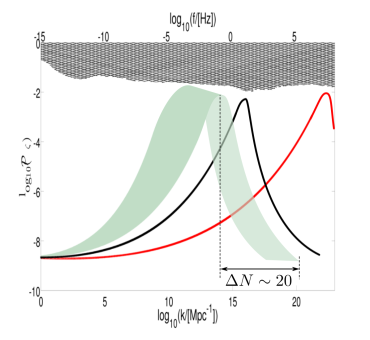

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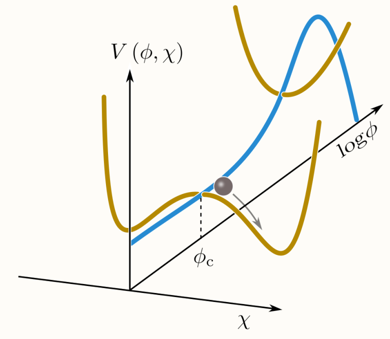

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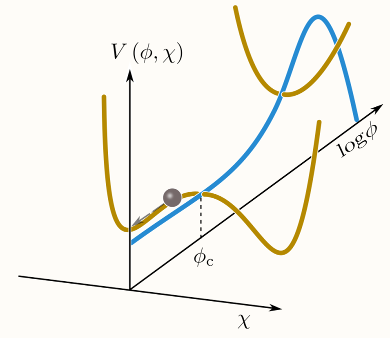
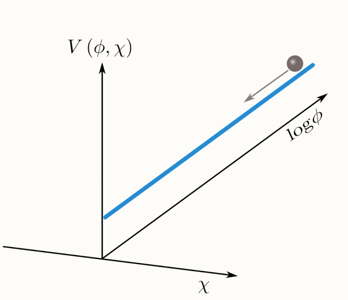


Tachyonic Trap

Beauty is Attractive

Kofman +, "Beauty is attractive: Moduli trapping at enhanced symmetry points" (2004)

$$\mathcal{L} = -\partial_\mu \phi \partial^\mu \phi + V_c$$



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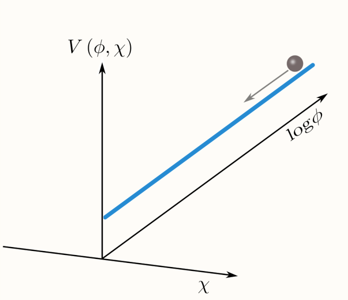

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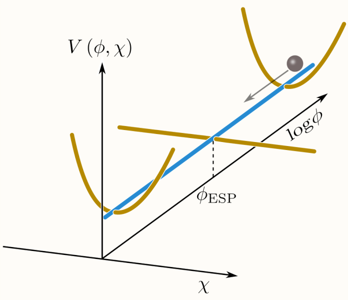

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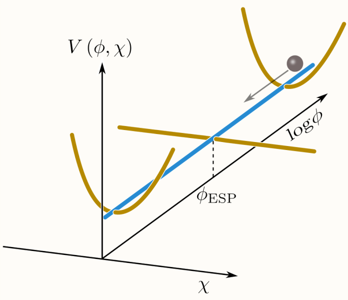

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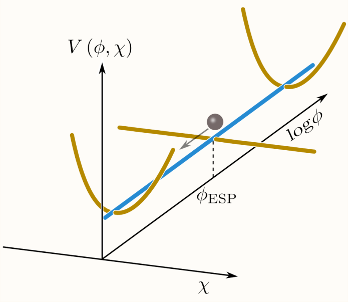

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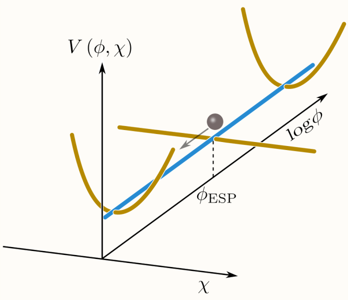

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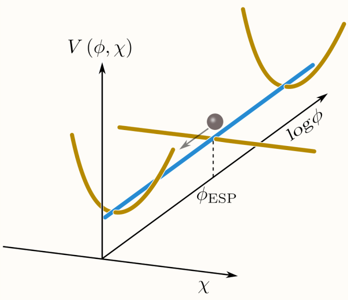

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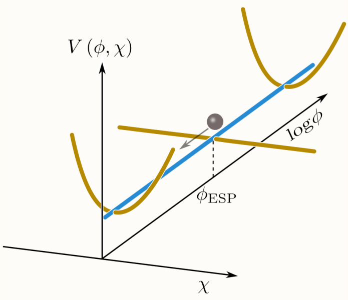

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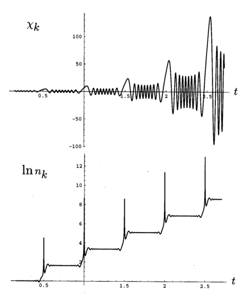

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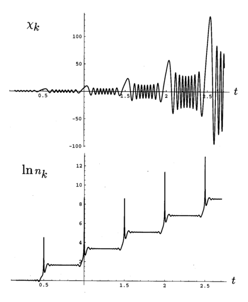

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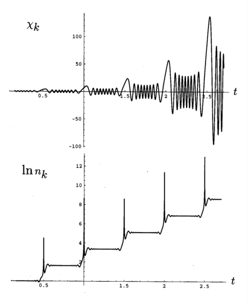

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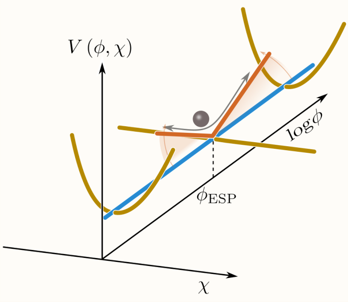

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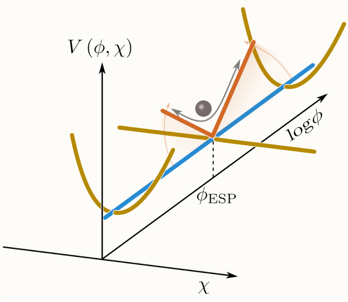

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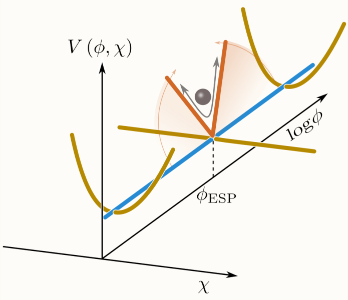

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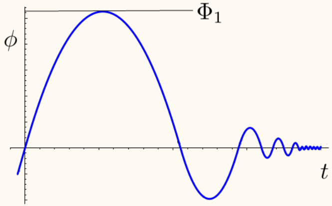

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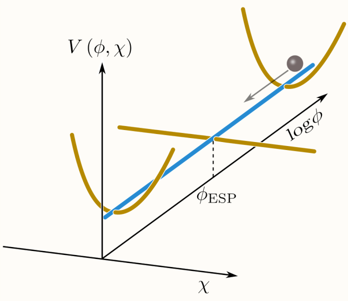

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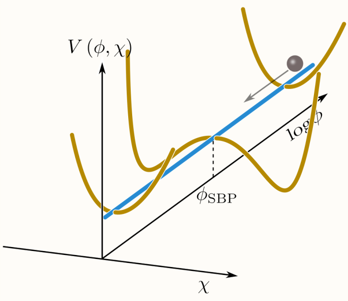

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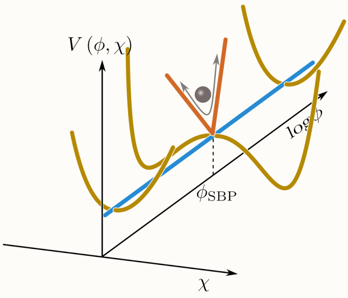

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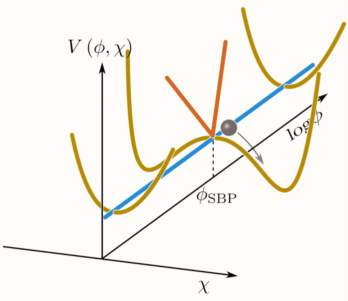

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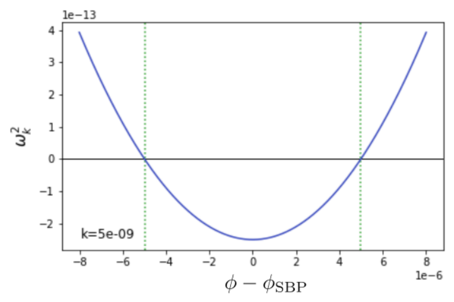
$$\mathcal{L} = -\partial_\mu\phi\partial^\mu\phi - \partial_\mu\chi\partial^\mu\chi - \frac{1}{2}g^2\chi^2\left(\phi - \phi_{\mathrm{SBP}}\right)^2 - \frac{1}{4}\lambda^2\left(\chi^2 - f^2\right)^2 + V_{\mathrm{c}}$$

$$\delta\ddot{\chi}_k + \omega_k^2\delta\chi_k = 0; \qquad \omega_k^2 = k^2 + g^2\left(\phi - \phi_{\mathrm{SBP}}\right)^2 - \lambda f^2 + 3\lambda\left\langle\chi^2\right\rangle$$

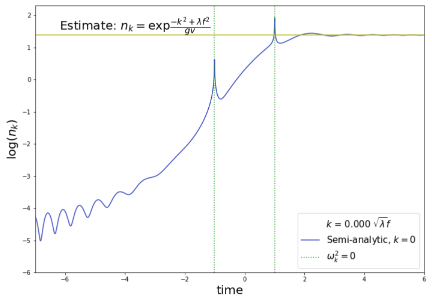


Tachyonic Trap

Dimopoulos+ (2019), Karčiauskas+ (2022)

$$\mathcal{L} = -\partial_\mu \phi \partial^\mu \phi - \partial_\mu \chi \partial^\mu \chi - \frac{1}{2} g^2 \chi^2 (\phi - \phi_{\mathrm{SBP}})^2 - \frac{1}{4} \lambda^2 \left(\chi^2 - f^2\right)^2 + V_{\mathrm{c}}$$

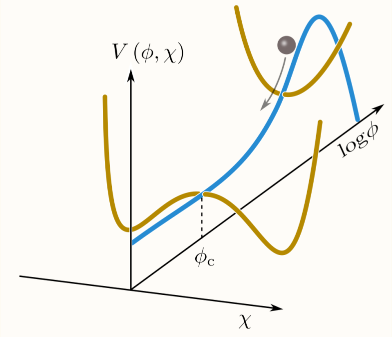
$$n_{k1} = \mathrm{e}^{\pi \frac{-k^2 + \lambda f^2}{g v}}$$



Running-Mass-Inflation

Running-Mass-Inflation

$$V(\phi,\chi) \quad = \quad V(\phi) - \frac{1}{2}m^2\chi^2 + \frac{1}{2}g^2\chi^2(\phi-\phi_c)^2 + \ldots$$



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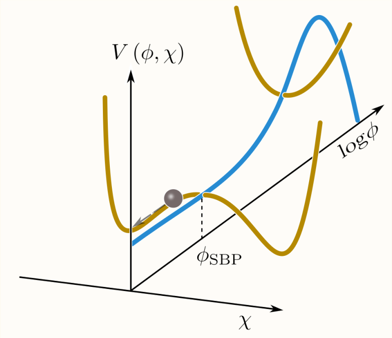

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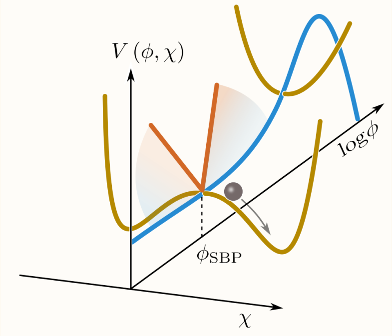
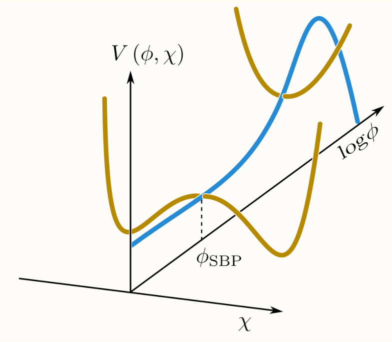


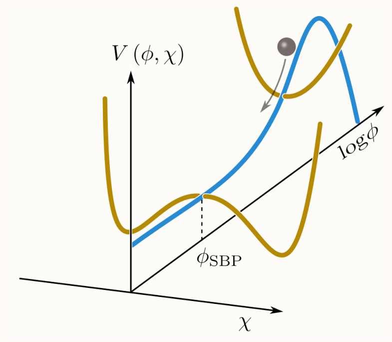
The Plan

1. Find models consistent with CMB observations;
2. Find parameters for PBHs



CMB Constraints

$$V(\phi_*) = V_c \left[1 - \frac{1}{2}\frac{\phi_*^2}{m_{\rm Pl}^2}\left(B - \frac{A}{\left(1+\alpha \ln \frac{\phi_*}{m_{\rm Pl}}\right)^2}\right)\right]$$



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$$V\left(\phi_*\right) = V_c\left[1-\frac{1}{2}\frac{\phi_*^2}{m_{\rm Pl}^2}\left(B-\frac{A}{\left(1+\alpha\ln\frac{\phi_*}{m_{\rm Pl}}\right)^2}\right)\right]$$

Slow-roll approximation:

$$\mathcal{P}_\zeta = A_s\left(\frac{k}{k_*}\right)^{n_s-1+\frac{1}{2}\alpha_s(\ln k/k_*)+\frac{1}{6}\beta_s(\ln k/k_*)^2}$$

where

$$\begin{aligned} A_s &= V/\left(24m_{\rm Pl}^2\epsilon\right) \\ n_s &= 1-6\epsilon+2\eta \\ \alpha_s &= -16\epsilon\eta+24\epsilon^2+2\xi^2 \\ \beta_s &= -192\epsilon^3+192\epsilon^2\eta-32\epsilon\eta^2-24\epsilon\xi^2+2\eta\xi^2+2\omega^3 \end{aligned}$$

and

$$r = 16\epsilon$$

CMB Constraints

$$V(\phi_*) = V_c \left[1 - \frac{1}{2}\frac{\phi_*^2}{m_{\rm Pl}^2}\left(B - \frac{A}{\left(1+\alpha \ln \frac{\phi_*}{m_{\rm Pl}}\right)^2}\right)\right]$$

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where (Akrami+ (2020))

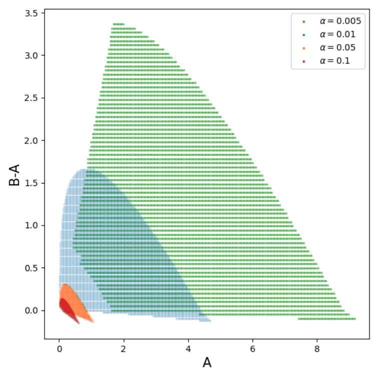
$$\begin{aligned} A_s &= 3.044 \\ n_s &= 0.9587 \pm 0.0056 \\ \alpha_s &= 0.013 \pm 0.012 \\ \beta_s &= 0.022 \pm 0.012 \end{aligned}$$

and (Ade+ (2021))

$$r < 0.036$$

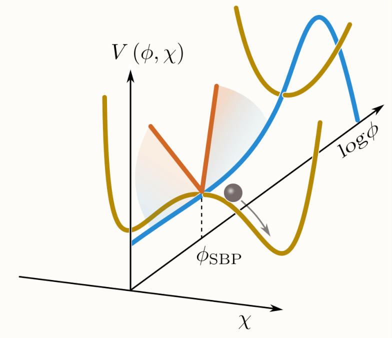
CMB Constraints

$$V(\phi_*) = V_c \left[1 - \frac{1}{2}\frac{\phi_*^2}{m_{\rm Pl}^2}\left(B - \frac{A}{\left(1+\alpha \ln \frac{\phi_*}{m_{\rm Pl}}\right)^2}\right)\right]$$



Perturbations

$$V(\phi, \chi) \quad = \quad V(\phi) - \frac{1}{2} m^2 \chi^2 + \frac{1}{2} g^2 \chi^2 (\phi - \phi_{\mathrm{SBP}})^2 + \dots$$



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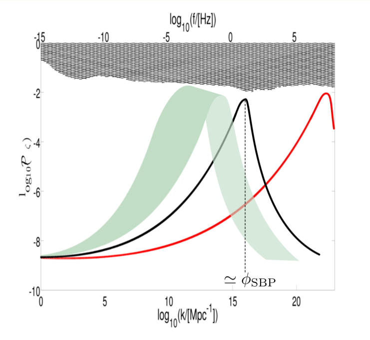

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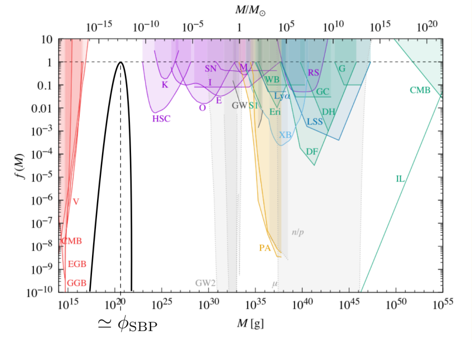

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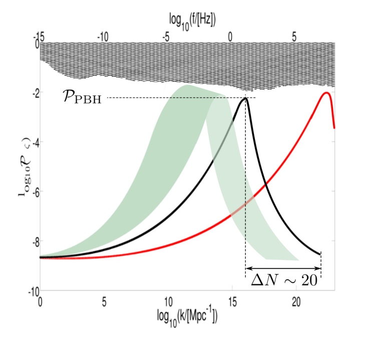


Perturbations

$$V(\phi,\chi) = V(\phi) - \frac{1}{2}m^2\chi^2 + \frac{1}{2}g^2\chi^2(\phi-\phi_{\mathrm{SBP}})^2 + \dots$$

Newtonian gauge:

$$\mathrm{d}s^2 = -(1+2\Phi)\,\mathrm{d}t^2 + a^2(t)(1+2\Phi)\,\delta_{ij}\mathrm{d}x^i\mathrm{d}x^j$$

Perturbations:

$$\delta\ddot{\phi}_k + 3H\delta\dot{\phi}_k + \left(\frac{k^2}{a^2} + V_{,\phi\phi}\right)\delta\phi_k = 2\left(2\dot{\phi}\dot{\Phi}_k - V_{,\phi}\Phi_k\right) - V_{,\phi\chi}\delta\chi_k$$

$$\delta\ddot{\chi}_k + 3H\delta\dot{\chi}_k + \left(\frac{k^2}{a^2} + V_{,\chi\chi}\right)\delta\chi_k = 2\left(2\dot{\chi}\dot{\Phi}_k - V_{,\chi}\Phi_k\right) - V_{,\phi\chi}\delta\phi_k$$

$$\dot{\Phi}_k + H\Phi_k = \frac{1}{2}\left(\dot{\phi}\delta\phi_k + \dot{\chi}\delta\chi_k\right)$$

Perturbations

$$V(\phi,\chi) \quad = \quad V(\phi) - \frac{1}{2} m^2 \chi^2 + \frac{1}{2} g^2 \chi^2 (\phi - \phi_{\mathrm{SBP}})^2 + \ldots$$

Hartree approximation

$$\chi^2 \quad \to \quad \langle \chi^2 \rangle$$

where

$$\langle \chi^2 \rangle (t) \quad = \quad \frac{1}{2\pi^2} \int_0^\infty k^2 \left[|\delta\chi_k(t)|^2 - \frac{1}{2\,|\omega_k(t)|} \right] \mathrm{d}k$$

Perturbations

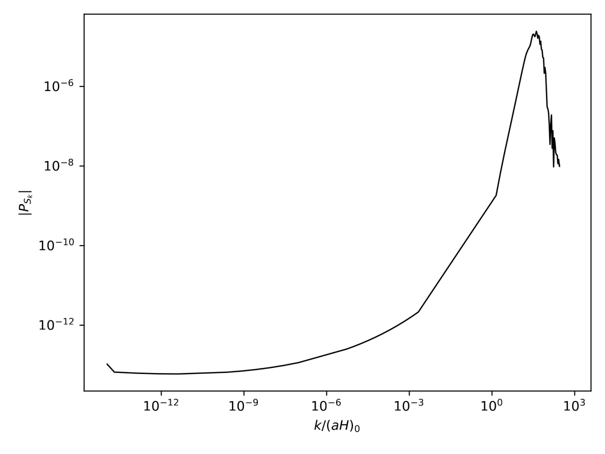
$$V(\phi,\chi) = V(\phi) - \frac{1}{2} m^2 \chi^2 + \frac{1}{2} g^2 \chi^2 (\phi - \phi_{\mathrm{SBP}})^2 + \ldots$$

Curvature and isocurvature perturbations:

$$\zeta_k = \Phi_k + 2H \frac{\dot{\Phi}_k + H\Phi_k \left(1 + \frac{1}{3}\frac{k^2}{a^2 H^2}\right)}{\dot{\phi}^2 + \dot{\chi}^2}$$

$$\mathcal{S}_k = \frac{2}{3} \frac{\delta V \left[3H\left(\dot{\phi}^2 + \dot{\chi}^2\right) + \dot{V}\right] + \left[\dot{\phi}\delta\dot{\phi}_k + \dot{\chi}\delta\dot{\chi}_k + \Phi_k\left(\dot{\phi}^2 + \dot{\chi}^2\right)\right]\dot{V}}{\left(\dot{\phi}^2 + \dot{\chi}^2\right)\left[3H\left(\dot{\phi}^2 + \dot{\chi}^2\right) + 2\dot{V}\right]}$$

Simulation Results



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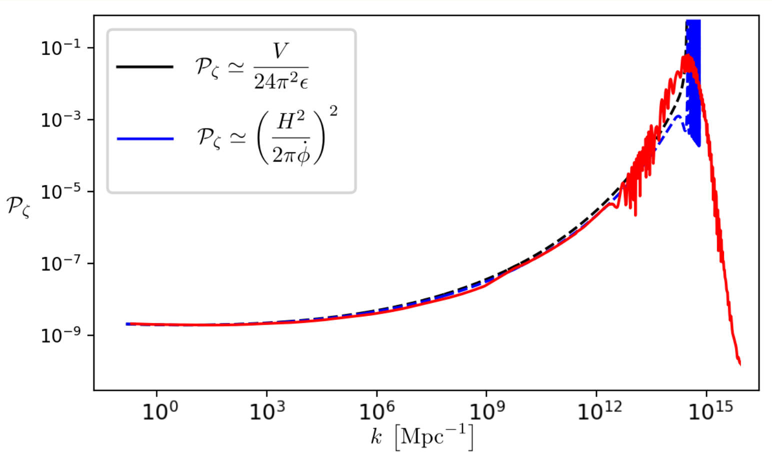

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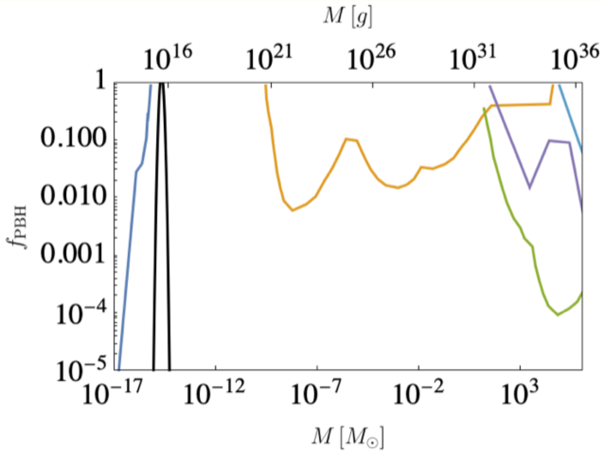

Scale and Duration of Inflation

This particular model: $V_{\mathrm{c}}^{1/4} = 2.5 \times 10^{-7} m_{\mathrm{Pl}}$

$N = 41.2$

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$$N = 41.2$$

$$N \simeq 56 - \frac{2}{3} \ln \frac{10^{16}\ \mathrm{GeV}}{\rho_*^{1/4}} - \frac{1}{3} \ln \frac{10^{9}\ \mathrm{GeV}}{T_{\mathrm{reh}}}$$

Scale and Duration of Inflation

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$$T_{\rm BBN} < T_{\rm reh}$$
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$$5 \times 10^{-19} \mathrm{e}^{4(N-56)} < V_{\mathrm{c}} < 3 \times 10^{14} \cdot \mathrm{e}^{6(N-56)}$$

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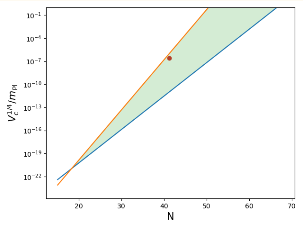
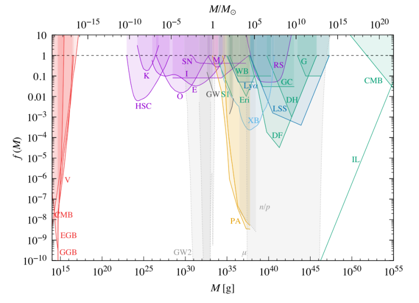


Conclusions

- Running-mass-inflation naturally gives a large running of the spectrum $\Rightarrow$ PBHs
- Non-perturbative processes at SBP provide:
  - grateful exit
  - the viable spectrum for PBH formation
- To do:
  - Non-gaussianity
  - Gravitational waves

Bounds on PBHs



- red: evaporation (γ rays)
- magenta: lensing
- green: dynamical effects
- black: gravitational waves
- light blue: accretion
- orange: CMB distortions
- dark blue: large-scale structure
- grey: background effects