CENTER FOR PHYSICAL SCIENCES AND TECHNOLOGY

Research Council of Lithuania

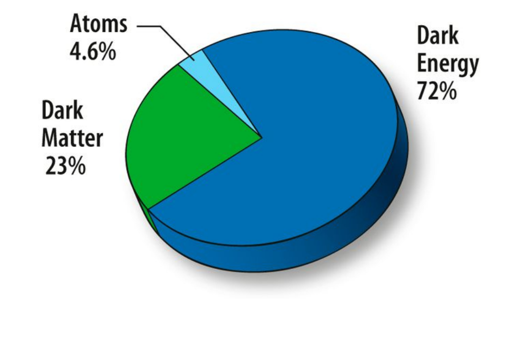
Primordial Black Holes from Resonances in the Running-Mass-Inflation Model

Mindaugas Karčiauskas

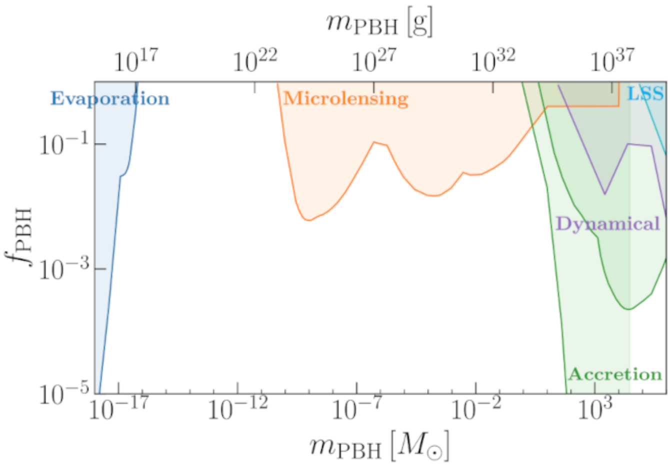
Center for Physical Sciences and Technology,
Vilnius, Lithuania

Furuta, MK, Kohri, Sáez (2511.23182)

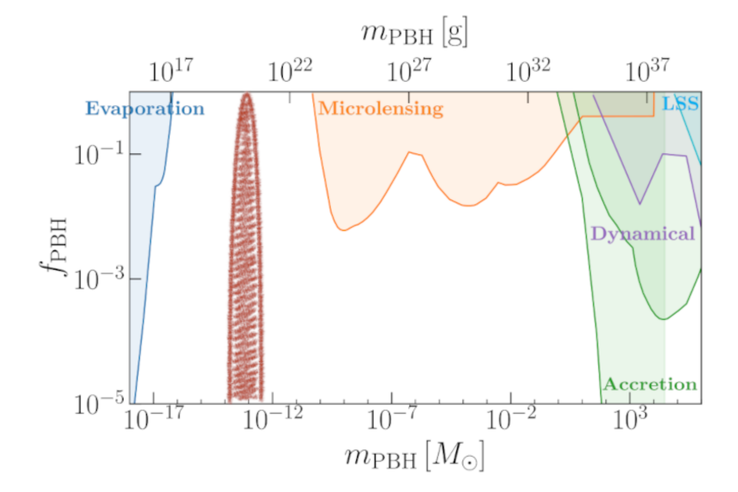
Dark Matter



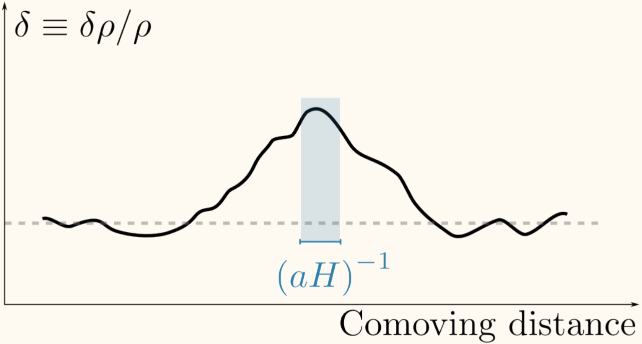
Primordial Black Holes as Dark Matter



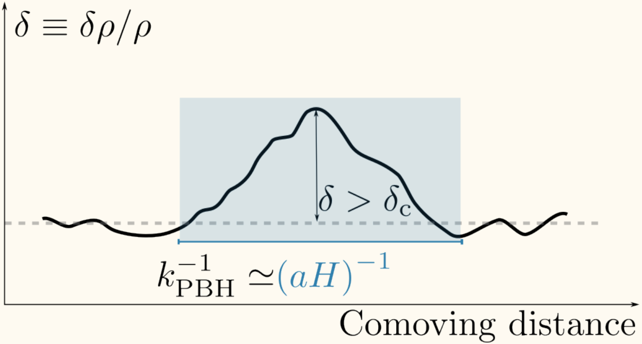
Primordial Black Holes as Dark Matter



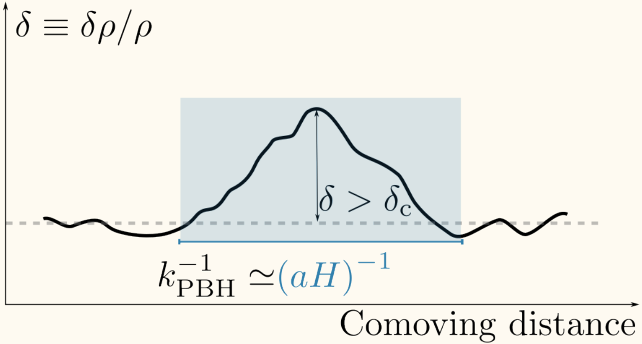
Overdensities into Black Holes



Overdensities into Black Holes



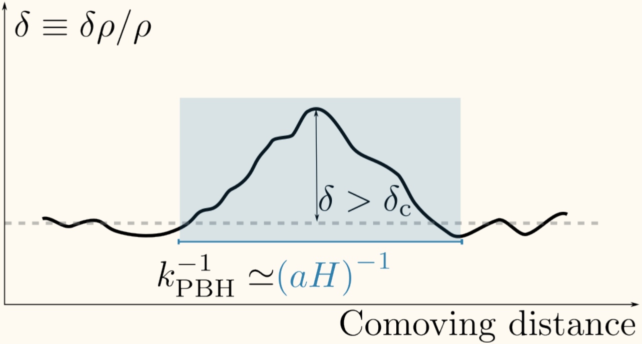
Overdensities into Black Holes



Musco (2019), Escrivà (2022)

$$0.4 < \delta_c < 0.66$$

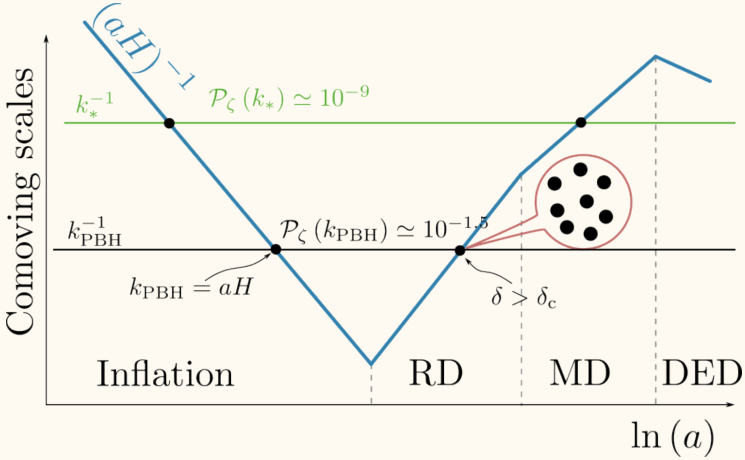
Overdensities into Black Holes



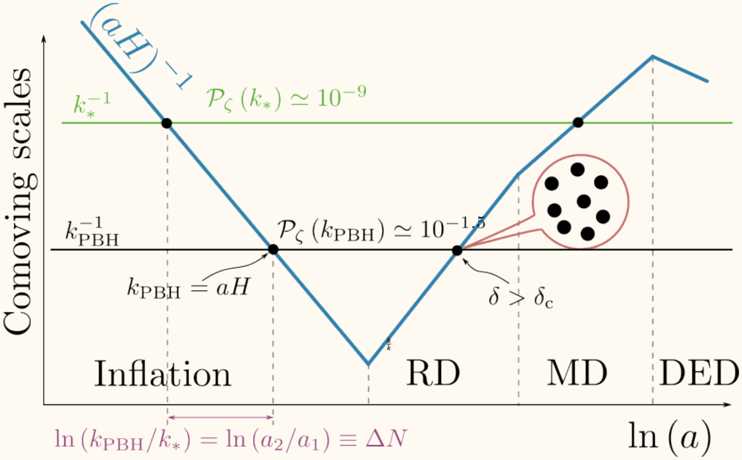
$$m_{\rm PBH}(k_{\rm PBH}) \simeq \gamma M_H(k_{\rm PBH})$$

where $\gamma = \mathcal{O}(0.1)$

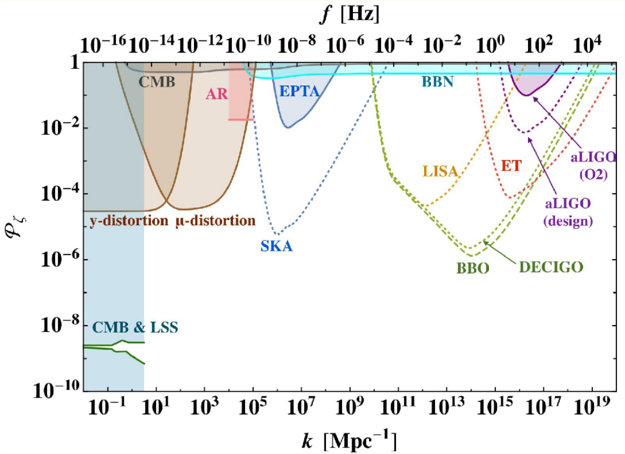
Inflation Produces Overdensities



Inflation Produces Overdensities

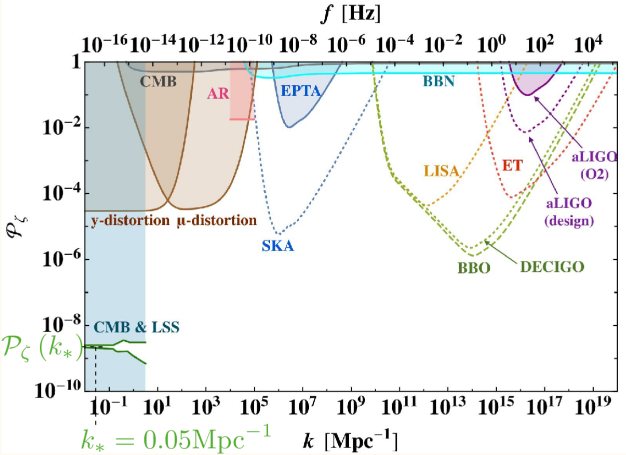


Primordial Perturbation Spectrum



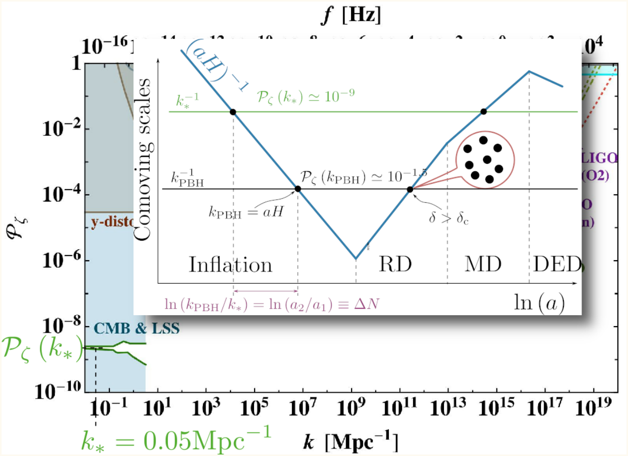
Adapted from Inomata and Nakama (2019)

Primordial Perturbation Spectrum



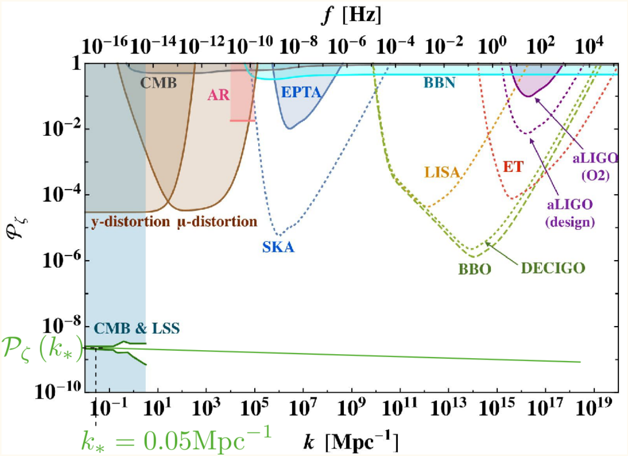
Adapted from Inomata and Nakama (2019)

Primordial Perturbation Spectrum



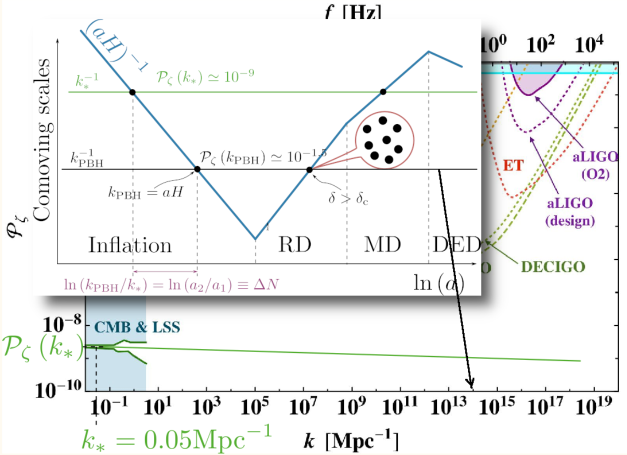
Adapted from Inomata and Nakama (2019)

Primordial Perturbation Spectrum



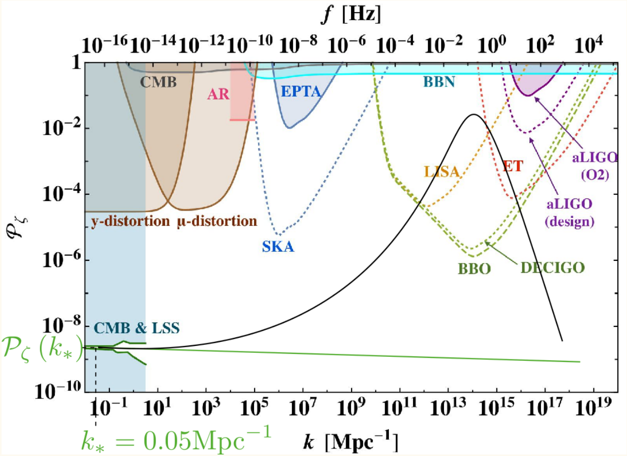
Adapted from Inomata and Nakama (2019)

Primordial Perturbation Spectrum



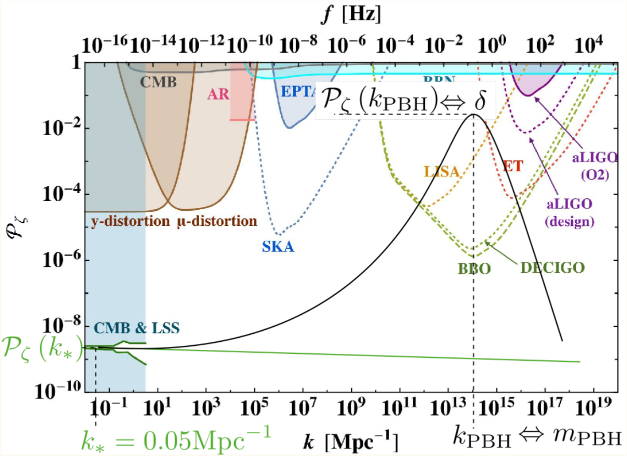
Adapted from Inomata and Nakama (2019)

Primordial Perturbation Spectrum



Adapted from Inomata and Nakama (2019)

Primordial Perturbation Spectrum



Adapted from Inomata and Nakama (2019)

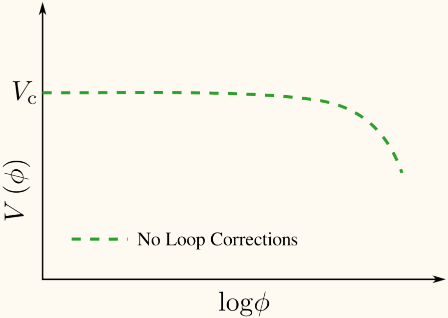
$\mathcal{P}_{\zeta\max} \simeq 10^{-1.5}$ at $\sim 30 - 35$ e-folds after the pivot scale exits the horizon.

Running-Mass-Inflation

Running-Mass Inflation

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

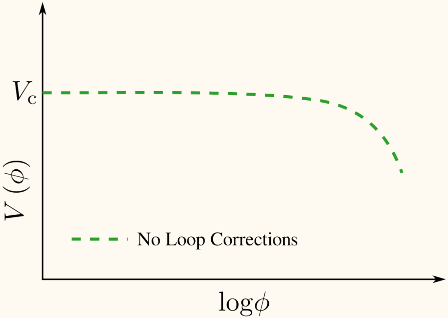
$$V \simeq V_{\rm c} \left[1 - \frac{1}{2} \mu^2 \frac{\phi^2}{m_{\rm Pl}^2} + \ldots \right]$$



Running-Mass Inflation

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

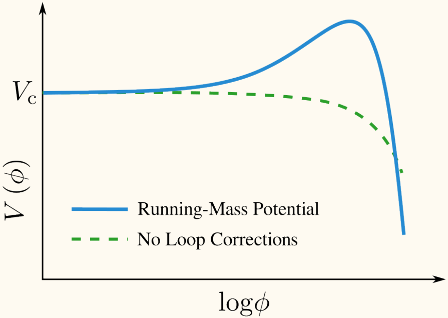
$$\mu = \mu\left[\mu_0, A, \alpha \ln \frac{\phi}{m_{\rm Pl}}\right]$$



Running-Mass Inflation

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

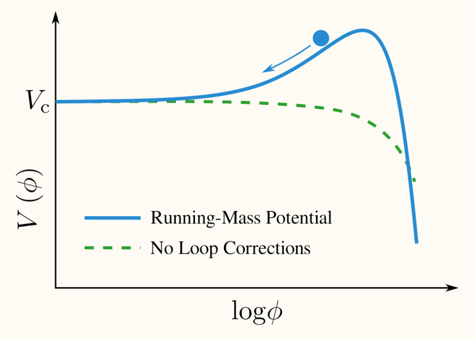
$$V(\phi) = V_{\mathrm{c}} \left[1 - \frac{1}{2} \frac{\phi^2}{m_{\mathrm{Pl}}^2} \left(B - \frac{A}{\left(1 + \alpha \ln \frac{\phi}{m_{\mathrm{Pl}}}\right)^2} \right) \right]$$



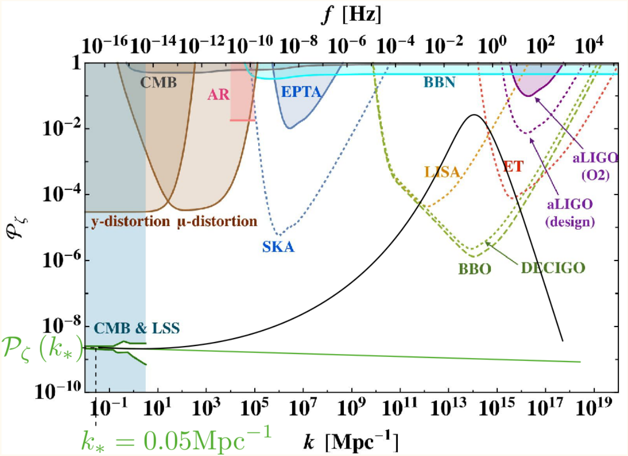
Running-Mass Inflation

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

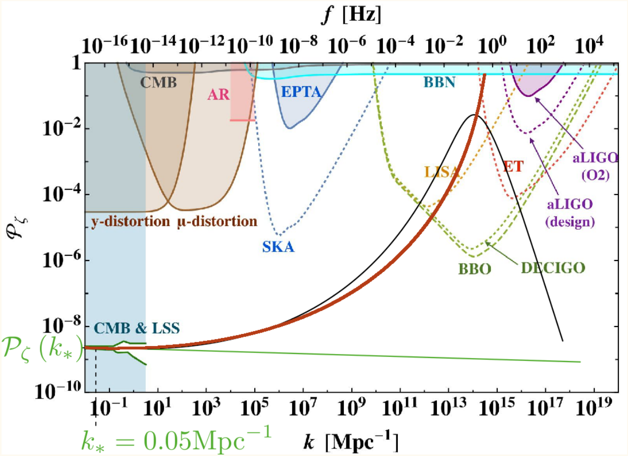
$$V(\phi) = V_{\mathrm{c}} \left[1 - \frac{1}{2} \frac{\phi^2}{m_{\mathrm{Pl}}^2} \left(B - \frac{A}{\left(1 + \alpha \ln \frac{\phi}{m_{\mathrm{Pl}}} \right)^2} \right) \right]$$



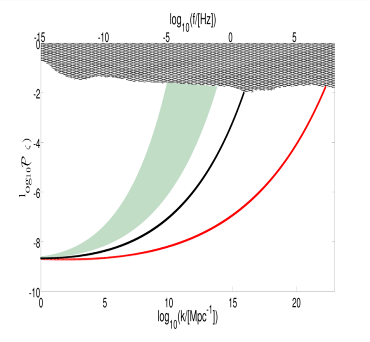
PBH Overproduction and Graceful Exit



PBH Overproduction and Graceful Exit



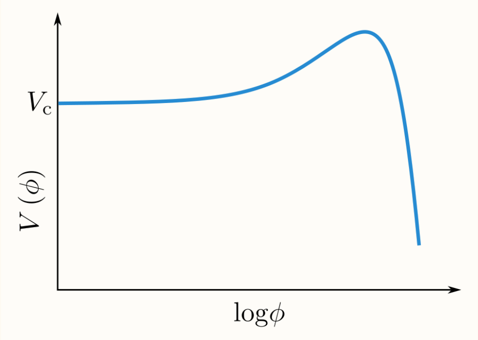
PBH Overproduction and Graceful Exit



Alabidi+ (2012)

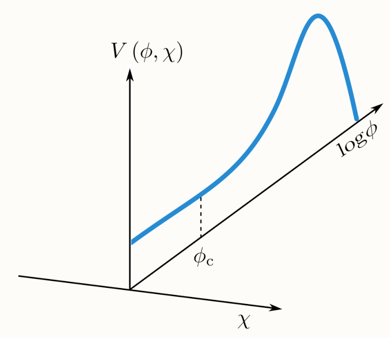
PBH Overproduction and Graceful Exit

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



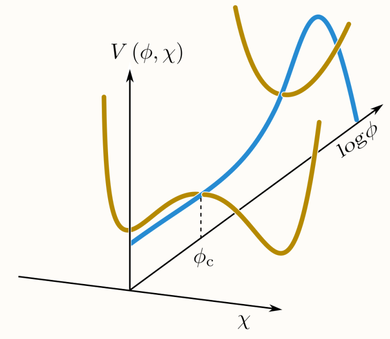
PBH Overproduction and Graceful Exit

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



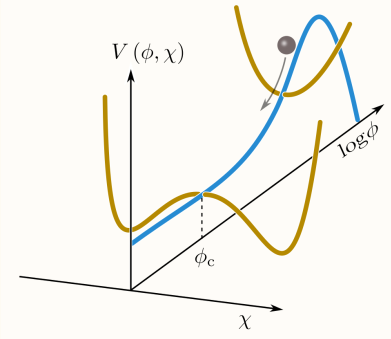
PBH Overproduction and Graceful Exit

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



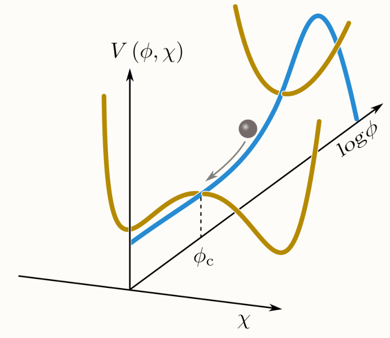
PBH Overproduction and Graceful Exit

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



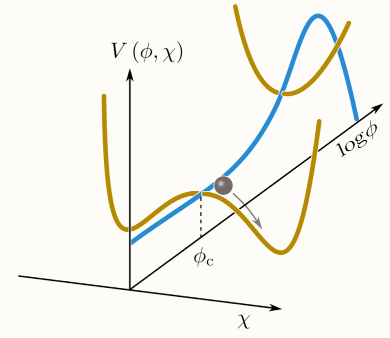
PBH Overproduction and Graceful Exit

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



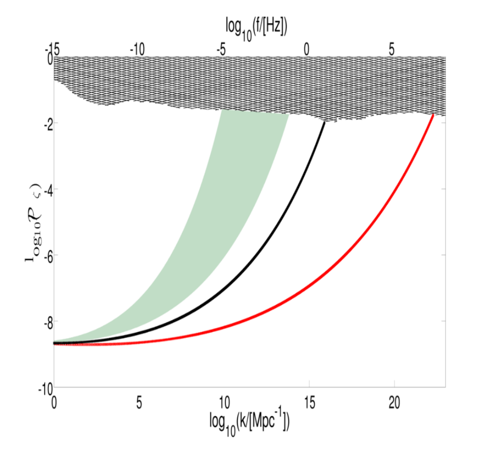
PBH Overproduction and Graceful Exit

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



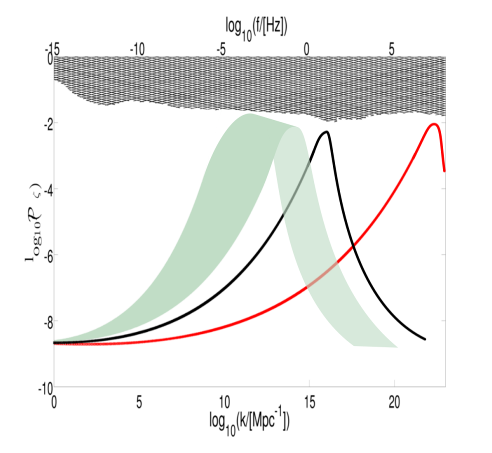
PBH Overproduction and Graceful Exit

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



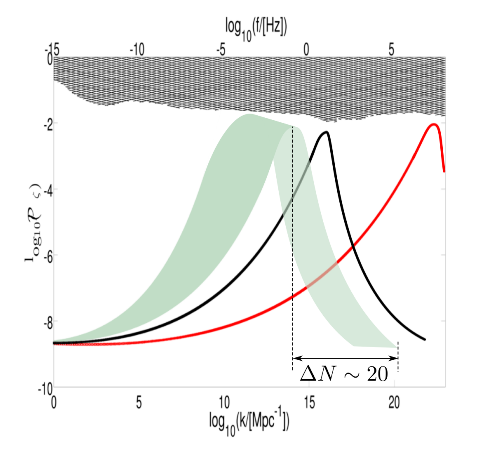
PBH Overproduction and Graceful Exit

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



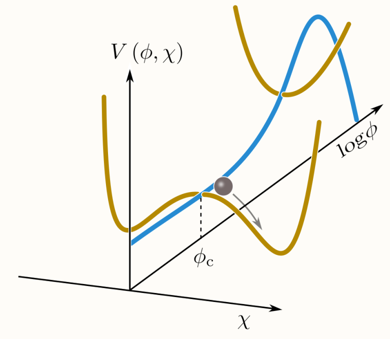
PBH Overproduction and Graceful Exit

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



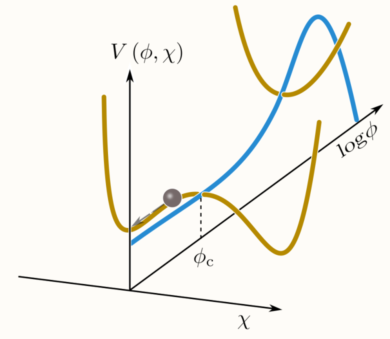
PBH Overproduction and Graceful Exit

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



PBH Overproduction and Graceful Exit

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

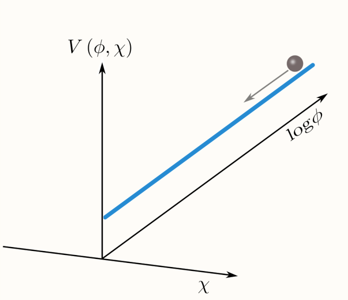


Tachyonic Trap

Beauty is Attractive

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

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

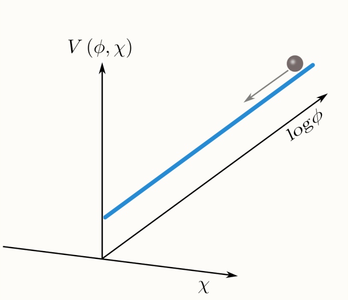


Beauty is Attractive

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

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

$$\phi \simeq \dot{\phi}_c t$$

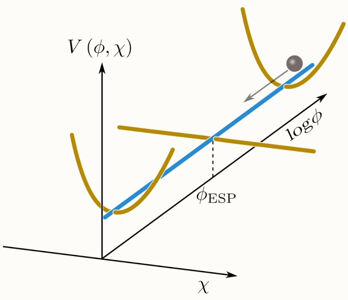


Beauty is Attractive

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

$$\mathcal{L} = -\partial_\mu \phi \partial^\mu \phi + V_c - \partial_\mu \chi \partial^\mu \chi - \frac{1}{2} g^2 \chi^2 (\phi - \phi_{\mathrm{ESP}})^2$$

$$\phi \simeq \dot{\phi}_c t$$

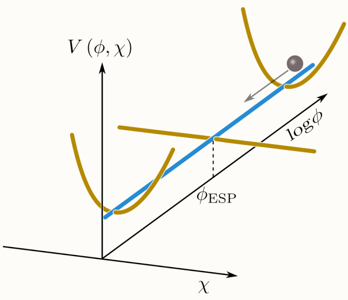


Beauty is Attractive

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

$$\mathcal{L} = -\partial_\mu\phi\partial^\mu\phi + V_c - \partial_\mu\chi\partial^\mu\chi - \frac{1}{2}g^2\chi^2\left(\phi - \phi_{\mathrm{ESP}}\right)^2$$

$$\chi \simeq 0 \quad \Rightarrow \quad \phi \simeq \dot{\phi}_c t$$

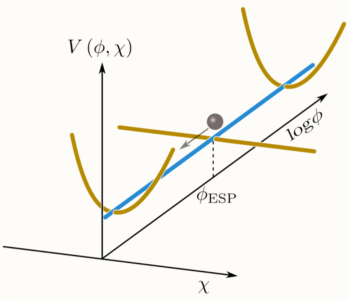


Beauty is Attractive

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

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

$$\chi \simeq 0 \quad \Rightarrow \quad \phi \simeq \dot{\phi}_{\mathrm{c}} t$$

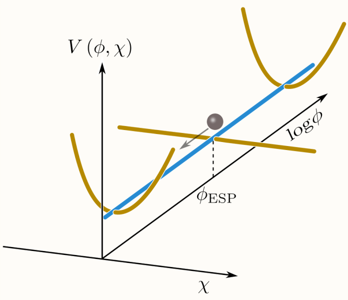


Beauty is Attractive

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

$$\mathcal{L} = -\partial_\mu \phi \partial^\mu \phi + V_c - \partial_\mu \chi \partial^\mu \chi - \frac{1}{2} g^2 \chi^2 \left(\phi - \phi_{\mathrm{ESP}}\right)^2$$

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

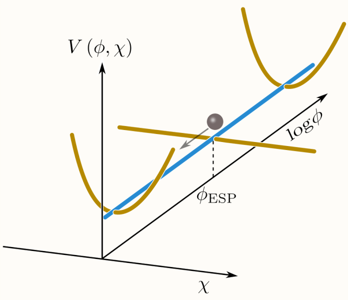


Beauty is Attractive

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

$$\mathcal{L} = -\partial_\mu\phi\partial^\mu\phi + V_c - \partial_\mu\chi\partial^\mu\chi - \frac{1}{2}g^2\chi^2\left(\phi - \phi_{\mathrm{ESP}}\right)^2$$

$$\delta\ddot{\chi}_k + \omega_k^2\delta\chi_k = 0; \qquad \omega_k^2 = k^2 + g^2\left(\phi - \phi_{\mathrm{SBP}}\right)^2 \;\Rightarrow\; \frac{|\dot{\omega}_k|}{\omega_k^2} \gg 1$$

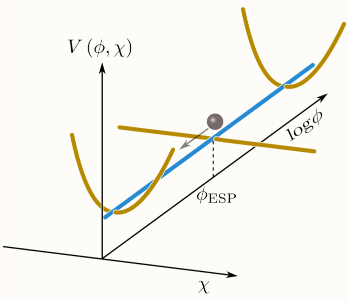


Beauty is Attractive

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

$$\mathcal{L} = -\partial_\mu\phi\partial^\mu\phi + V_{\rm c} - \partial_\mu\chi\partial^\mu\chi - \frac{1}{2}g^2\chi^2\left(\phi - \phi_{\rm ESP}\right)^2$$

$$\delta\ddot{\chi}_k + \omega_k^2\delta\chi_k = 0; \qquad \omega_k^2 = k^2 + g^2\left(\phi - \phi_{\rm SBP}\right)^2 \;\Rightarrow\; \frac{|\dot{\omega}_k|}{\omega_k^2} \gg 1$$

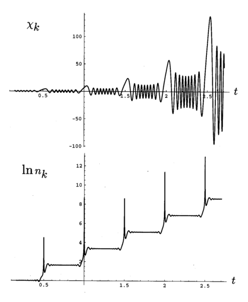


Beauty is Attractive

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

$$\mathcal{L} = -\partial_\mu\phi\partial^\mu\phi + V_c - \partial_\mu\chi\partial^\mu\chi - \frac{1}{2}g^2\chi^2\left(\phi - \phi_{\rm ESP}\right)^2$$

$$\delta\ddot{\chi}_k + \omega_k^2\delta\chi_k = 0; \qquad \omega_k^2 = k^2 + g^2\left(\phi - \phi_{\rm SBP}\right)^2 \Rightarrow \frac{|\dot{\omega}_k|}{\omega_k^2} \gg 1$$



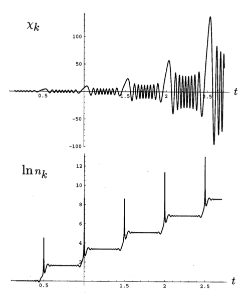
Kofman+ (1997)

Beauty is Attractive

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

$$\mathcal{L} = -\partial_\mu \phi \partial^\mu \phi + V_c - \partial_\mu \chi \partial^\mu \chi - \frac{1}{2} g^2 \langle \chi^2 \rangle (\phi - \phi_{\rm ESP})^2$$

$$\delta \ddot{\chi}_k + \omega_k^2 \delta \chi_k = 0; \qquad \omega_k^2 = k^2 + g^2 (\phi - \phi_{\rm SBP})^2 \ \Rightarrow \ \frac{|\dot{\omega}_k|}{\omega_k^2} \gg 1$$



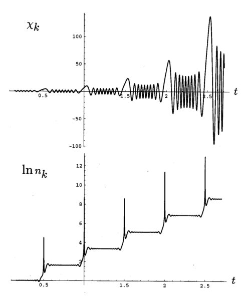
Kofman+ (1997)

Beauty is Attractive

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

$$\mathcal{L} = -\partial_\mu \phi \partial^\mu \phi + V_c - \partial_\mu \chi \partial^\mu \chi - \frac{1}{2} g^2 \langle \chi^2 \rangle (\phi - \phi_{\rm ESP})^2$$

$$\phi \simeq \dot{\phi}_c t \qquad \longrightarrow \qquad \ddot{\phi} + g^2 n_\chi \frac{\phi}{|\phi|} \quad \simeq \quad 0$$



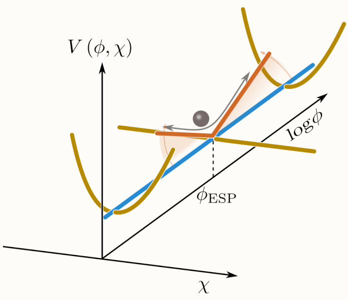
Kofman+ (1997)

Beauty is Attractive

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

$$\mathcal{L} = -\partial_\mu \phi \partial^\mu \phi + V_c - \partial_\mu \chi \partial^\mu \chi - \frac{1}{2} g^2 \langle \chi^2 \rangle (\phi - \phi_{\rm ESP})^2$$

$$\phi \simeq \dot{\phi}_c t \qquad \longrightarrow \qquad \ddot{\phi} + g^2 n_\chi \frac{\phi}{|\phi|} \quad \simeq \quad 0$$

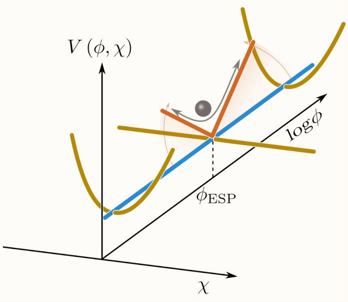


Beauty is Attractive

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

$$\mathcal{L} = -\partial_\mu \phi \partial^\mu \phi + V_c - \partial_\mu \chi \partial^\mu \chi - \frac{1}{2} g^2 \langle \chi^2 \rangle (\phi - \phi_{\rm ESP})^2$$

$$\phi \simeq \dot{\phi}_c t \qquad \longrightarrow \qquad \ddot{\phi} + g^2 n_\chi \frac{\phi}{|\phi|} \quad \simeq \quad 0$$

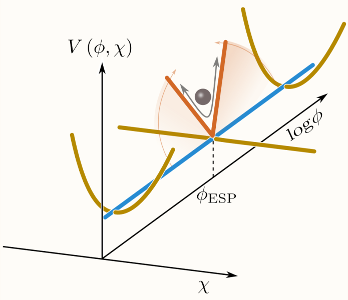


Beauty is Attractive

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

$$\mathcal{L} = -\partial_\mu \phi \partial^\mu \phi + V_c - \partial_\mu \chi \partial^\mu \chi - \frac{1}{2} g^2 \langle \chi^2 \rangle (\phi - \phi_{\rm ESP})^2$$

$$\phi \simeq \dot{\phi}_c t \qquad \longrightarrow \qquad \ddot{\phi} + g^2 n_\chi \frac{\phi}{|\phi|} \quad \simeq \quad 0$$

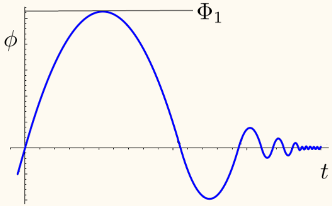


Beauty is Attractive

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

$$\mathcal{L} = -\partial_\mu \phi \partial^\mu \phi + V_c - \partial_\mu \chi \partial^\mu \chi - \frac{1}{2} g^2 \langle \chi^2 \rangle (\phi - \phi_{\mathrm{ESP}})^2$$

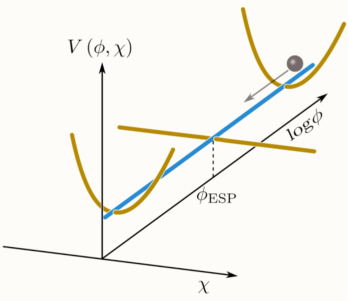
$$\phi \simeq \dot{\phi}_c t \qquad \longrightarrow \qquad \ddot{\phi} + g^2 n_\chi \frac{\phi}{|\phi|} \quad \simeq \quad 0$$



Tachyonic Trap

Dimopoulos+ (2019), Karčiauskas+ (2022)

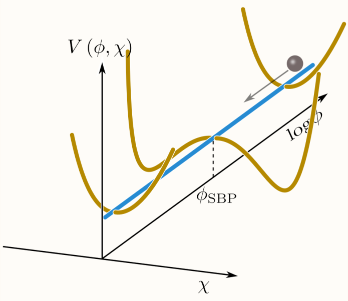
$$\mathcal{L} = -\partial_\mu\phi\partial^\mu\phi + V_c - \partial_\mu\chi\partial^\mu\chi - \frac{1}{2}g^2\chi^2\left(\phi - \phi_{\rm ESP}\right)^2$$



Tachyonic Trap

Dimopoulos+ (2019), Karčiauskas+ (2022)

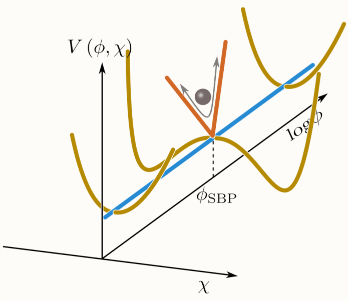
$$\mathcal{L} = -\partial_\mu\phi\partial^\mu\phi + V_c - \partial_\mu\chi\partial^\mu\chi - \frac{1}{2}g^2\chi^2\left(\phi - \phi_{\rm SBP}\right)^2 - \frac{1}{4}\lambda^2\left(\chi^2 - f^2\right)^2$$



Tachyonic Trap

Dimopoulos+ (2019), Karčiauskas+ (2022)

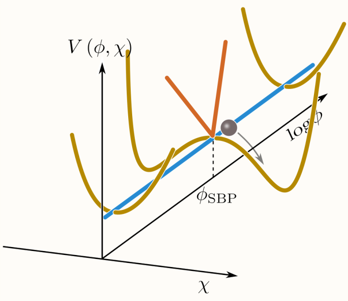
$$\mathcal{L} = -\partial_\mu\phi\partial^\mu\phi + V_c - \partial_\mu\chi\partial^\mu\chi - \frac{1}{2}g^2\chi^2\left(\phi - \phi_{\rm SBP}\right)^2 - \frac{1}{4}\lambda^2\left(\chi^2 - f^2\right)^2$$



Tachyonic Trap

Dimopoulos+ (2019), Karčiauskas+ (2022)

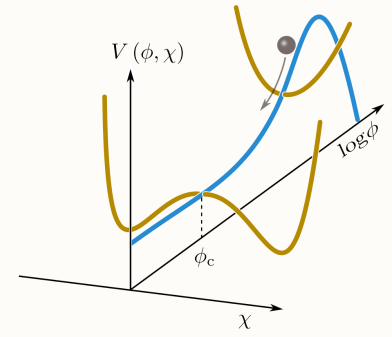
$$\mathcal{L} = -\partial_\mu\phi\partial^\mu\phi + V_c - \partial_\mu\chi\partial^\mu\chi - \frac{1}{2}g^2\chi^2\left(\phi - \phi_{\rm SBP}\right)^2 - \frac{1}{4}\lambda^2\left(\chi^2 - f^2\right)^2$$



Running-Mass-Inflation

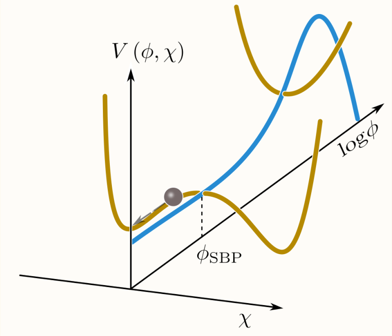
Running-Mass-Inflation

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



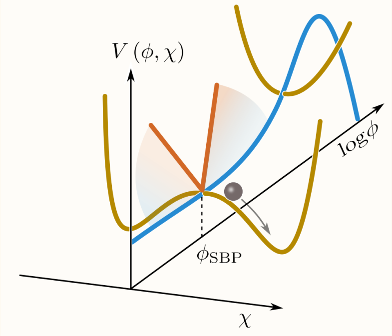
Running-Mass-Inflation

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



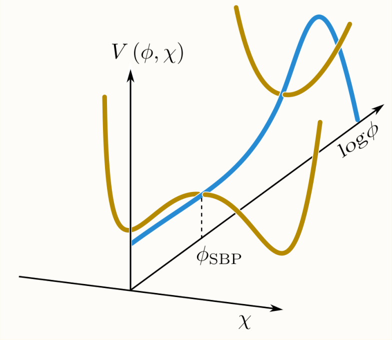
Running-Mass-Inflation

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



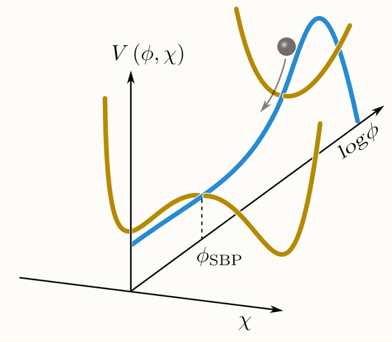
The Plan

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



CMB Constraints

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



CMB Constraints

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

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

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

and

$$r = 16\epsilon$$

CMB Constraints

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

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 (Akrami+ (2020))

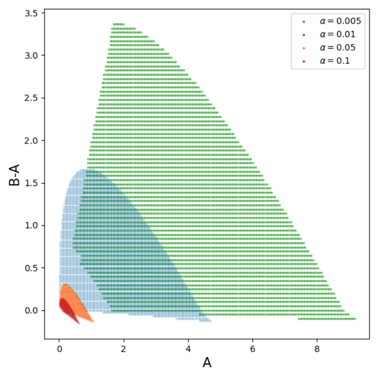
$$\begin{aligned} A_s &= 3.044 \\ n_s &= 0.9587 \pm 0.0056 \\ \alpha_s &= 0.013 \pm 0.012 \\ \beta_s &= 0.022 \pm 0.012 \end{aligned}$$

and (Ade+ (2021))

$$r < 0.036$$

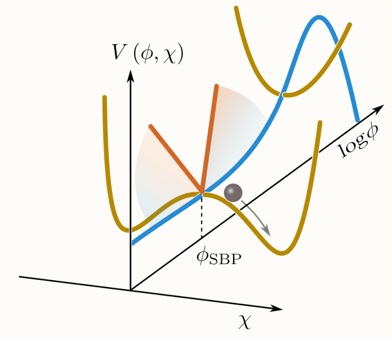
CMB Constraints

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



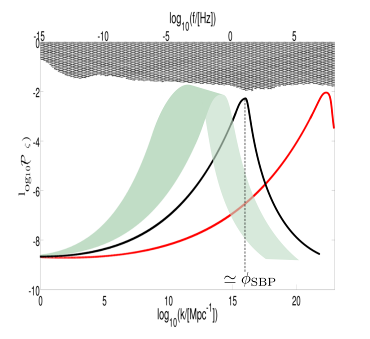
Perturbations

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



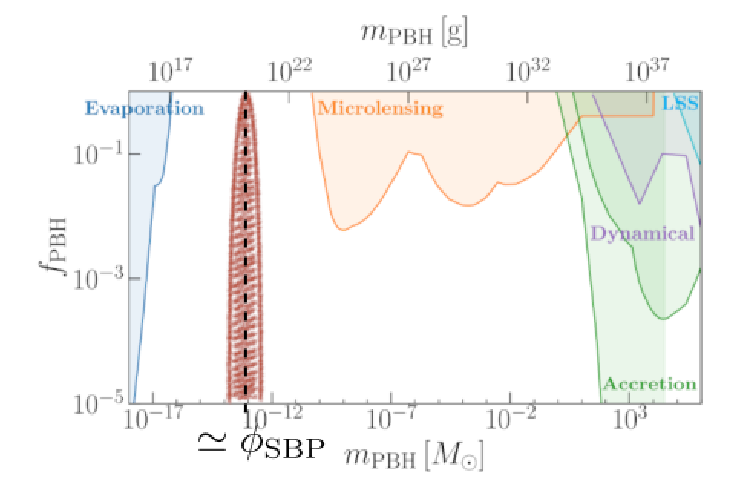
Perturbations

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



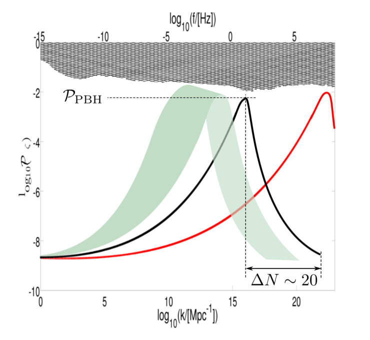
Perturbations

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



Perturbations

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



Perturbations

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

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

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

Hartree approximation

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

Perturbations

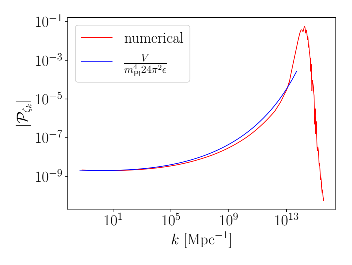
$$V(\phi,\chi) = V(\phi) - \frac{1}{2}m^2\chi^2 + \frac{1}{2}g^2\chi^2(\phi-\phi_{\rm SBP})^2 + \ldots$$

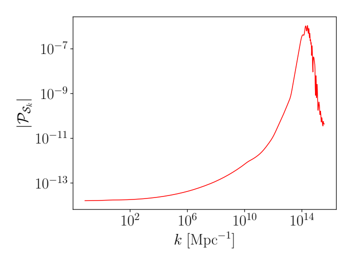
Curvature and isocurvature perturbations:

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

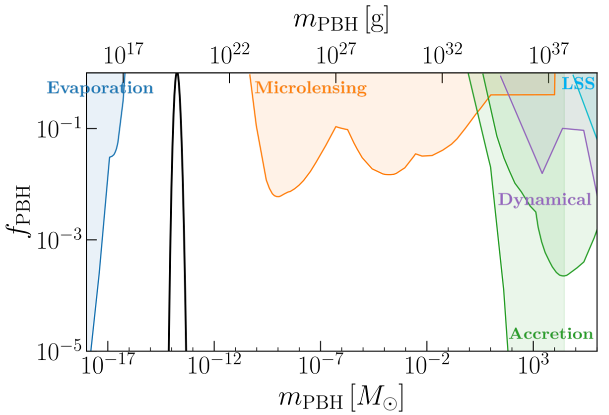
$$\mathcal{S}_k = \frac{2}{3}\frac{\delta V\left[3H\left(\dot\phi^2+\dot\chi^2\right)+\dot V\right]+\left[\dot\phi\delta\dot\phi_k+\dot\chi\delta\dot\chi_k+\Phi_k\left(\dot\phi^2+\dot\chi^2\right)\right]\dot V}{\left(\dot\phi^2+\dot\chi^2\right)\left[3H\left(\dot\phi^2+\dot\chi^2\right)+2\dot V\right]}$$

Simulation Results



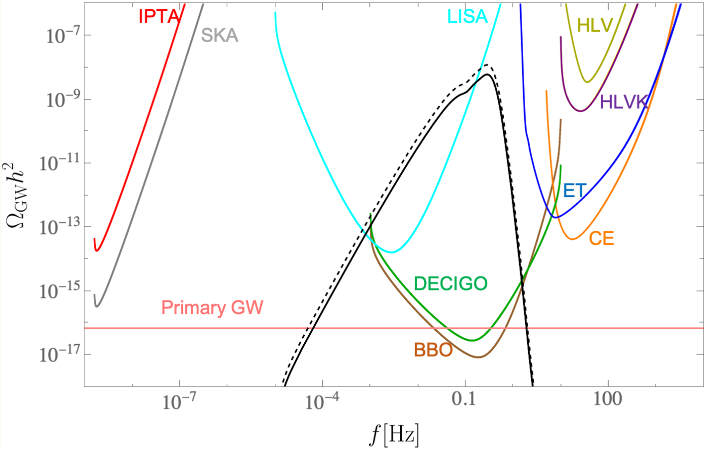


Simulation Results



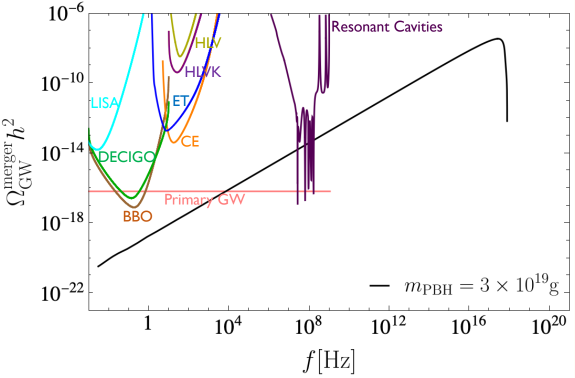
Gravitational Waves

Induced Gravitational



Binary Mergers

Merging PBH binaries produce a stochastic GW background
Sasaki+ (2018), Wang+ (2020), Kohri+ (2025)



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
- Observable gravitational waves:
  - Scalar induced
  - Black Hole mergers

Furuta, MK, Kohri, Sáez (2511.23182)