University of Chinese Academy of Sciences

The Inflation Trilogy and Primordial Black Holes

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Nov. 2rd, 2024

Based on arXiv: 2410.10996 (Paulo B. Ferraz, João G. Rosa)

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Outline

Overview of cosmological inflation

Motivation

The Model

Primordial Black Holes

Conclusion

Overview of Cosmological Inflation

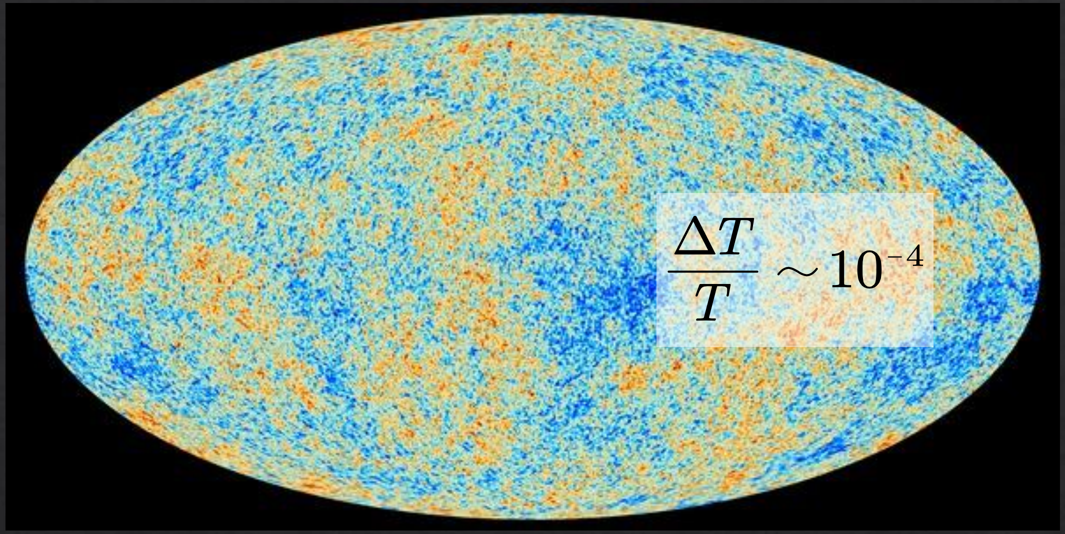
Why Inflation?

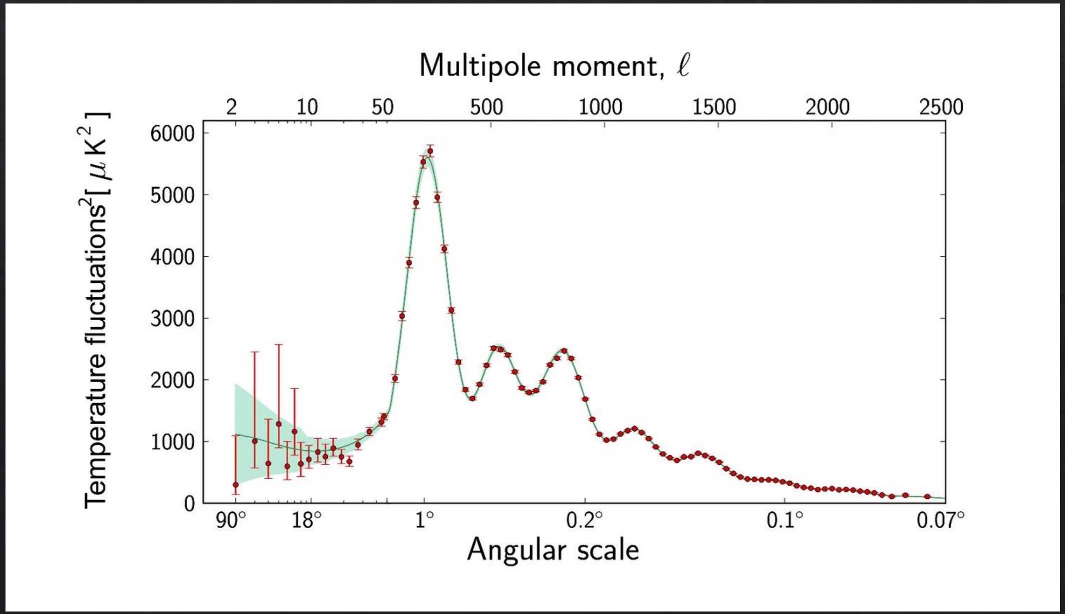
- Flatness problem

- Horizon problem

- Origin of primordial density fluctuation

(Primordial) density fluctuations are:
- small
- scale-invariant
- Gaussian
- ...



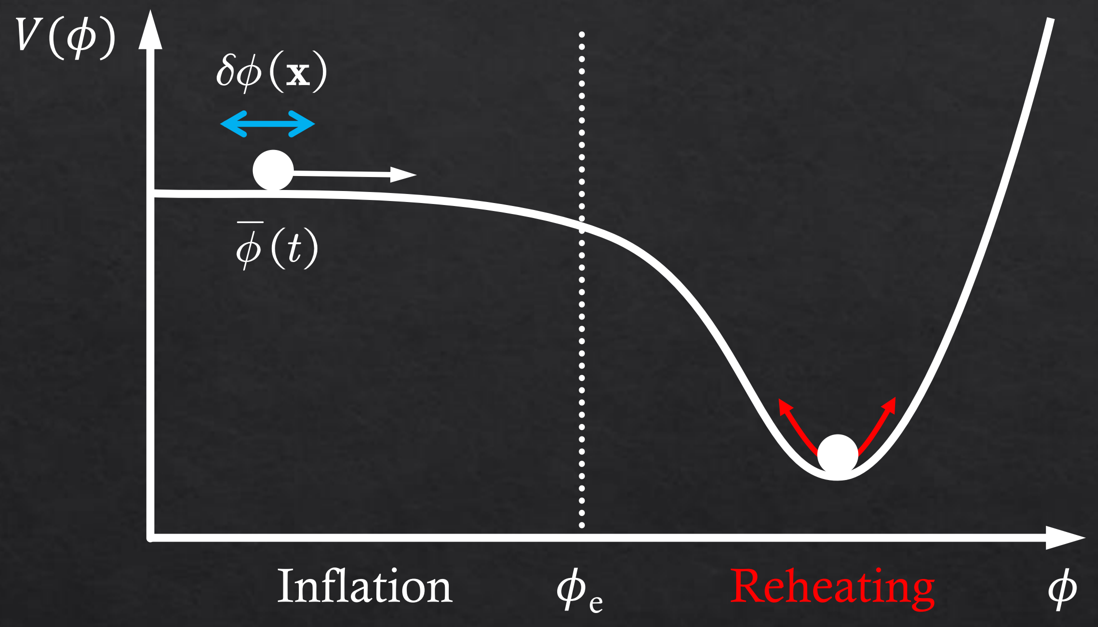


[Planck 2013]

Cold Inflation

$$H^2 \approx \frac{V}{3M_{\rm pl}^2}$$

Slow-roll Inflation



EOM:

$$\cancel{\ddot{\phi}} + 3H\dot{\phi} + V'(\phi) = 0$$

Slow-roll conditions:

$$\boxed{\epsilon_V = \frac{M_{\rm pl}^2}{2}\left(\frac{V'}{V}\right)^2 \ll 1, \quad \eta_V = M_{\rm pl}^2 \frac{V''}{V} \ll 1}$$

- In cold inflation, interactions of the inflaton with other fields are considered negligible:

$$\dot{\rho}_r + 4H\rho_r = 0 \Rightarrow \rho_r \sim 1/a^4 \Rightarrow \text{Universe supercools}$$

"Radiation density redshifts away"

Cold Inflation

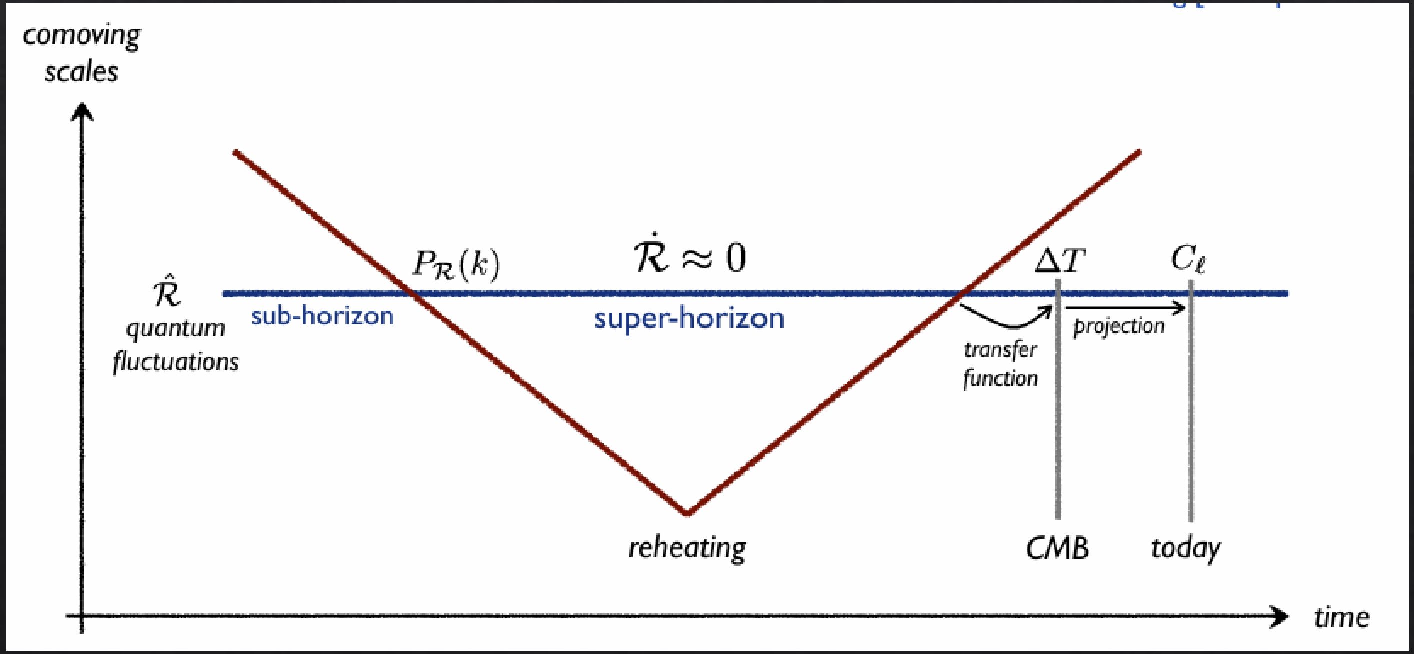
- Quantum fluctuations:

$$\boxed{\delta\phi(\mathbf{x}) \sim H}$$

- Primordial curvature power spectrum:

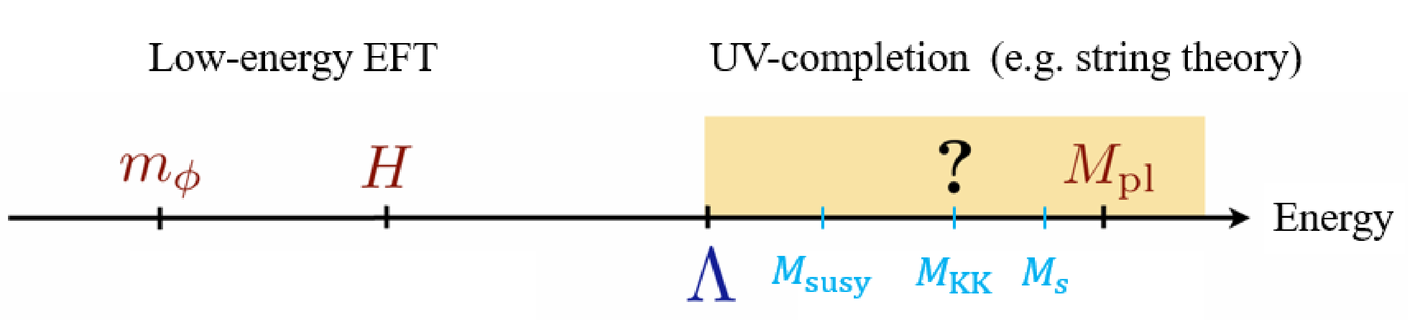
$$\boxed{\Delta^2_{\mathcal{R}}(k) = \frac{k^3}{2\pi^2} P_{\mathcal{R}}(k) = A_s(k_\star)\left(\frac{k}{k_\star}\right)^{n_s - 1}, \quad A_s(k_\star) \simeq 10^{-9}\,,\, n_s \simeq 0.968}$$

- nearly scale-invariant
- slightly red-tilted spectrum



Cold Inflation

- Shortcoming: eta-problem



Successful inflation requires that the inflaton mass is smaller than the Hubble scale

$$\eta = \frac{m_\phi^2}{3H^2} \sim \mathcal{O}(0.01)\,.$$

Integrating out the massive particles yields

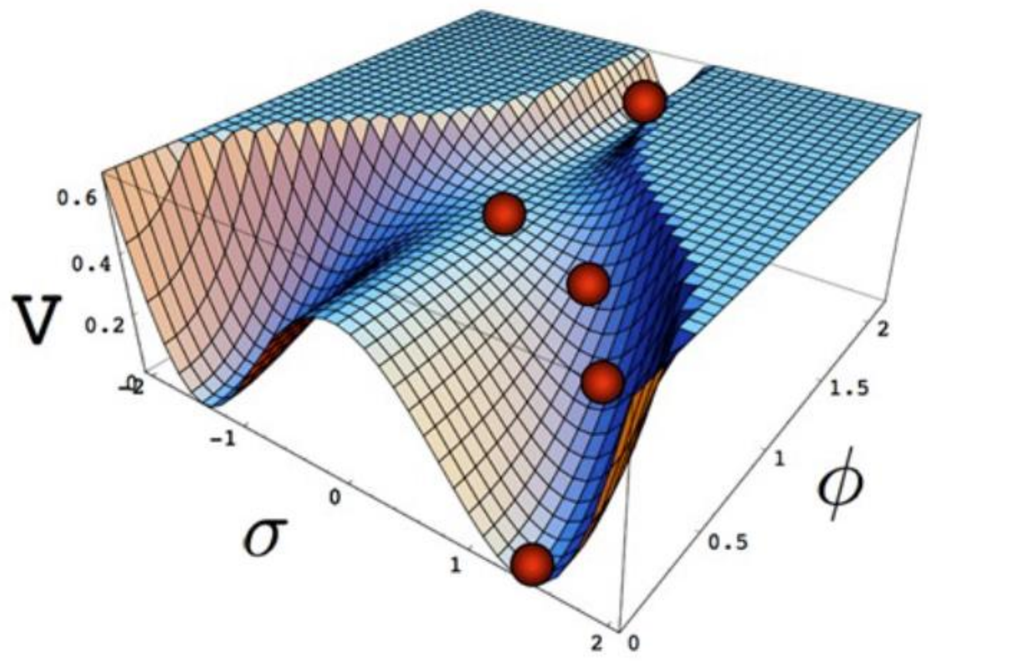
$$\Delta V = c_1 V(\phi)\frac{\phi^2}{\Lambda^2}\,,$$

$$\Rightarrow \Delta\eta_V = \frac{M_{\rm pl}^2}{V}(\Delta V)'' \approx 2c_1\left(\frac{M_{\rm pl}}{\Lambda}\right)^2 > 1\,.$$

Cold Inflation

A sample of hybrid inflation

$$V(\sigma,\phi) = \frac{1}{4\lambda}(M^2 - \lambda\sigma^2)^2 + \frac{m^2}{2}\phi^2 + \frac{g^2}{2}\phi^2\sigma^2$$



ϕ: inflaton σ: waterfall field

Warm Inflation

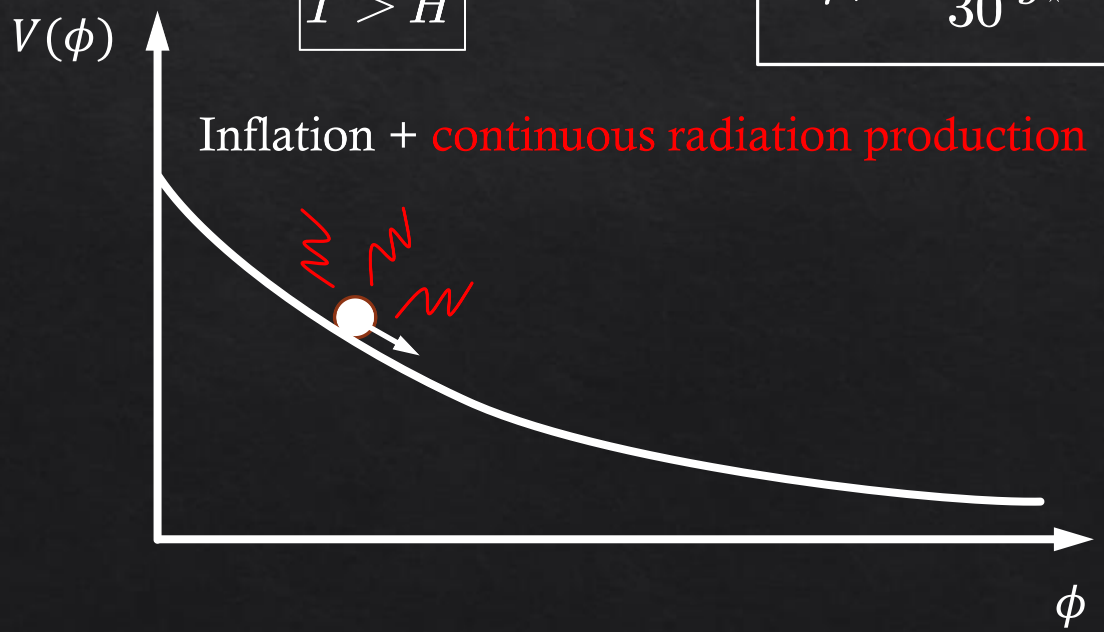
- Interactions of the inflaton with other d.o.f. are important during inflation, (generate dissipation terms) small fraction of vacuum energy density can be converted to radiation

$$\cancel{\ddot{\phi}} + (3H + \Upsilon)\dot{\phi} + V'(\phi) = 0$$

$$\cancel{\dot{\rho}_r} + 4H\rho_r = \Upsilon\dot{\phi}^2$$

$$\rho_r = \frac{\pi^2}{30} g_\star T^4$$

$\boxed{T > H}$



$$\boxed{\frac{\Upsilon}{3H} \equiv Q > 1}$$

$$\epsilon_H = -\frac{\dot{H}}{H^2} \simeq \frac{1+Q}{2M_{\rm pl}^2}\frac{\dot{\phi}^2}{H^2} \simeq \frac{\epsilon_V}{1+Q} < 1 \Rightarrow \epsilon_V < 1+Q$$

$$\eta_H = \frac{\dot{\epsilon}_H}{H\epsilon_H} < 1 \Rightarrow \eta_V < 1+Q$$

Warm Inflation

- Eta-problem can be alleviated in warm inflation due to the additional dissipative friction.
- Primordial density fluctuations are sourced by thermal fluctuations:

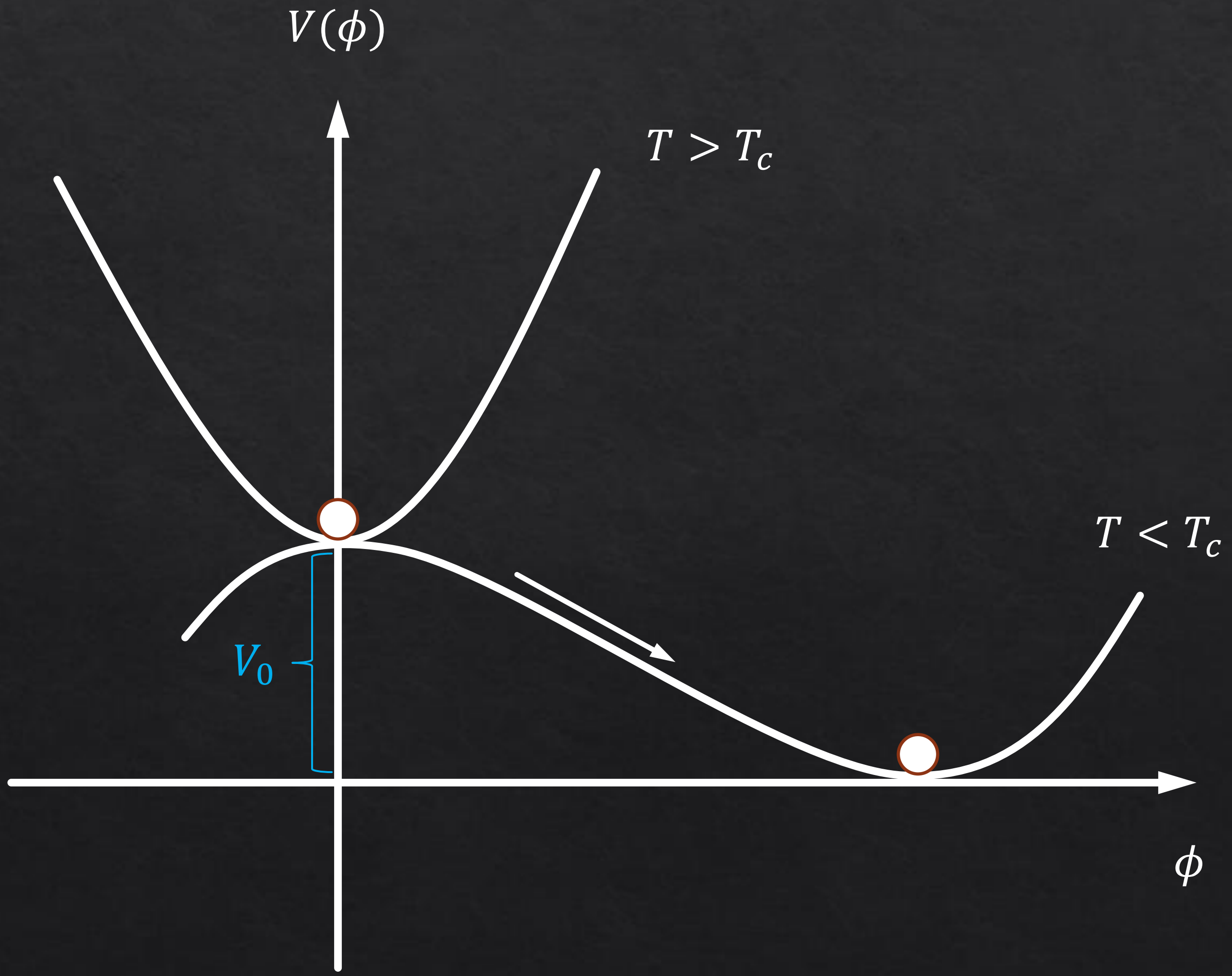
$$\delta\phi \sim H + \sqrt{HT} + \sqrt{\Upsilon T}$$

- Strong dissipative effects lead to a blue-tilted primordial spectrum

$$\boxed{\Delta_R^2(k) = A_s \left(\frac{k}{k_\star}\right)^{n_s - 1}, \quad n_s > 1}$$

Thermal inflation [Lyth and Stewart, 1995]

- Occurs after reheating.
- Dilute the unwanted cosmological relics.



$$V(\phi, T) = V_0 + \frac{1}{2}(g^2T^2 - m^2)\phi^2 + \frac{\lambda^2\phi^6}{M_{\mathrm{p}}^2}$$

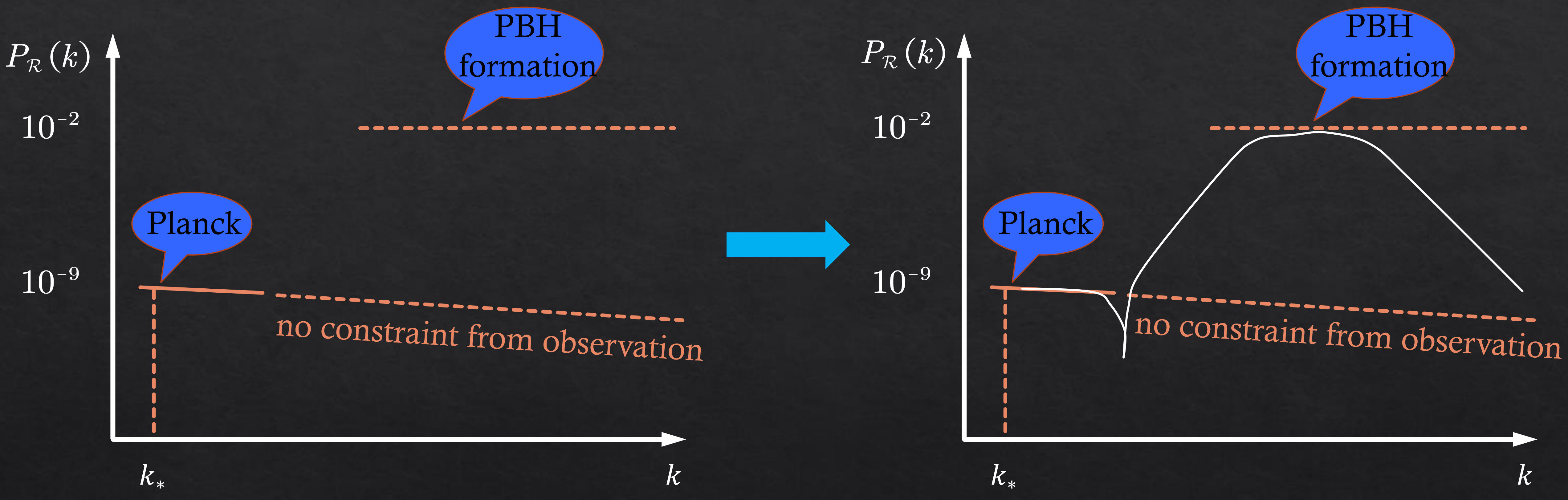
$$T_t = \left(\frac{30}{\pi^2 g_\star}\right)^{1/4} V_0^{1/4}, \quad T_{\mathrm{c}} \equiv m/g$$

$$N = \log\frac{T_t}{T_{\mathrm{c}}}$$

Motivation

- Requiring a single field to drive the full 50-60 e-folds of inflationary expansion may be too much to ask for in a theory
- Avoid eta-problem
- Explain all of the dark matter by PBHs

Motivation



$P_{\mathcal{R}}(k)$
PBH formation
10^{-2}
Planck
10^{-9}
no constraint from observation
k_*
k
$P_{\mathcal{R}}(k)$
PBH formation
10^{-2}
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k

Inflationary Trilogy

- Inflationary trilogy: undergoes three distinct stages of inflation – cold, warm and thermal – driven by three different scalar fields

Cold Inflation → Warm Inflation → Thermal Inflation

- Cold inflation contributes most of the e-folds
- Warm inflation avoids eta-problem and produces PBHs
- Thermal inflation dilutes the unwanted relics

Inflationary Trilogy

Cold Inflation → Warm Inflation → Thermal Inflation

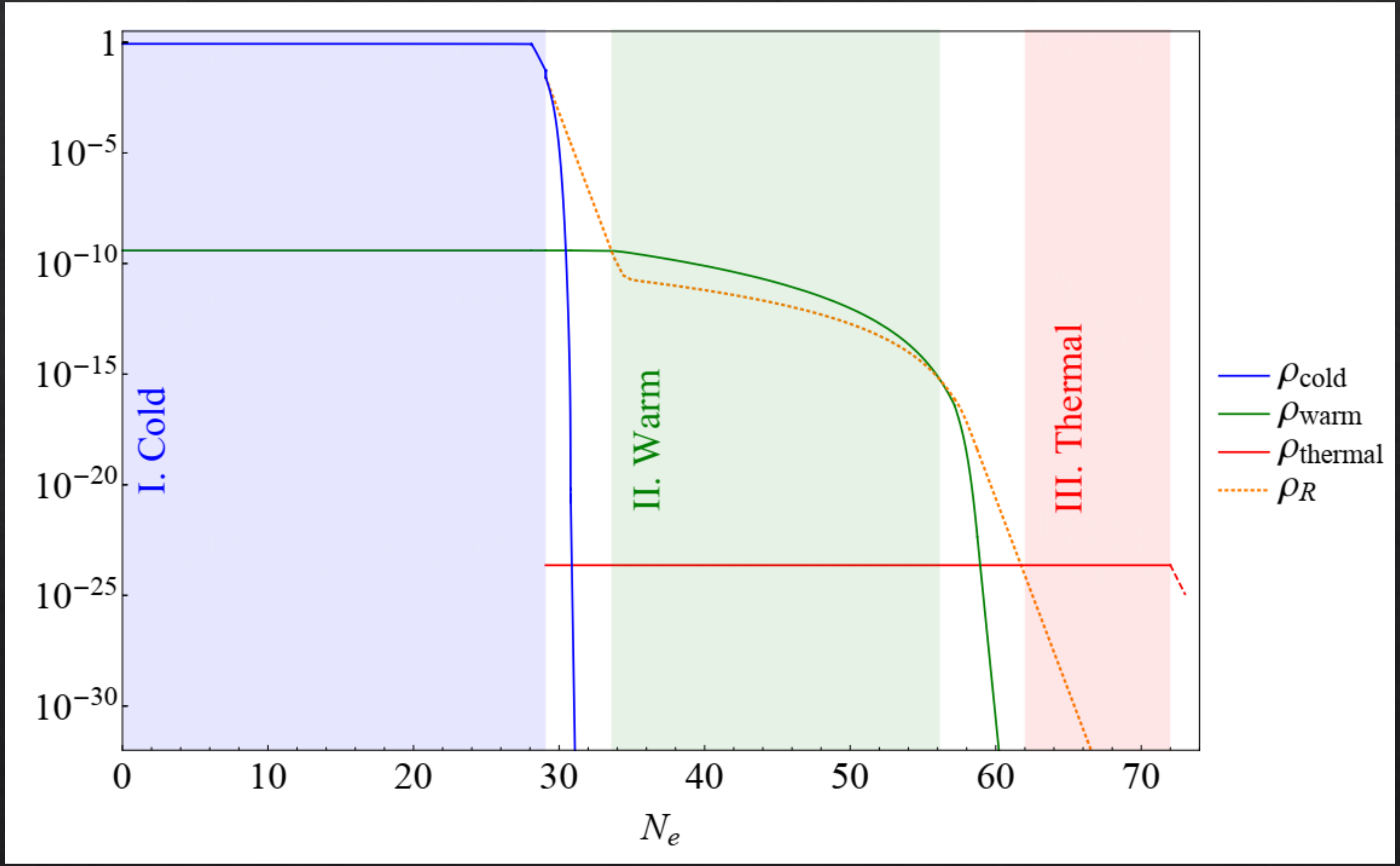


Fig. Evolution of the energy density of the relevant scalar fields and radiation fluid

The Model - Cold inflation

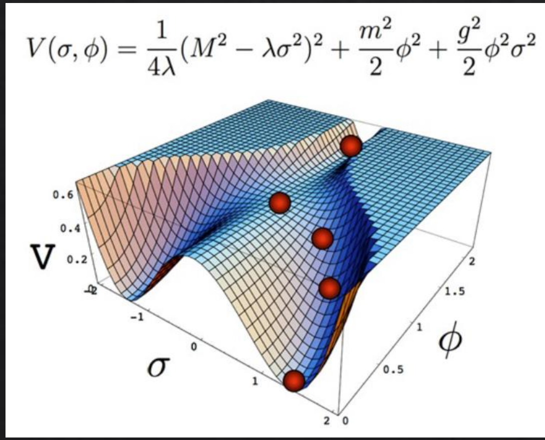
- The tree-level scalar potential in a SUSY hybrid inflation model is given by

$$V_0 = 2\kappa^2|\phi_c|^2|\sigma|^2 + \kappa^2(|\sigma|^2 - M_c^2)^2 .$$

ϕ_c: singlet chiral superfield – cold inflaton

σ , $\overline{\sigma}$: a pair of conjugate superfields — waterfall field

- After taking radiative corrections into account, and at 1-loop order these are given by



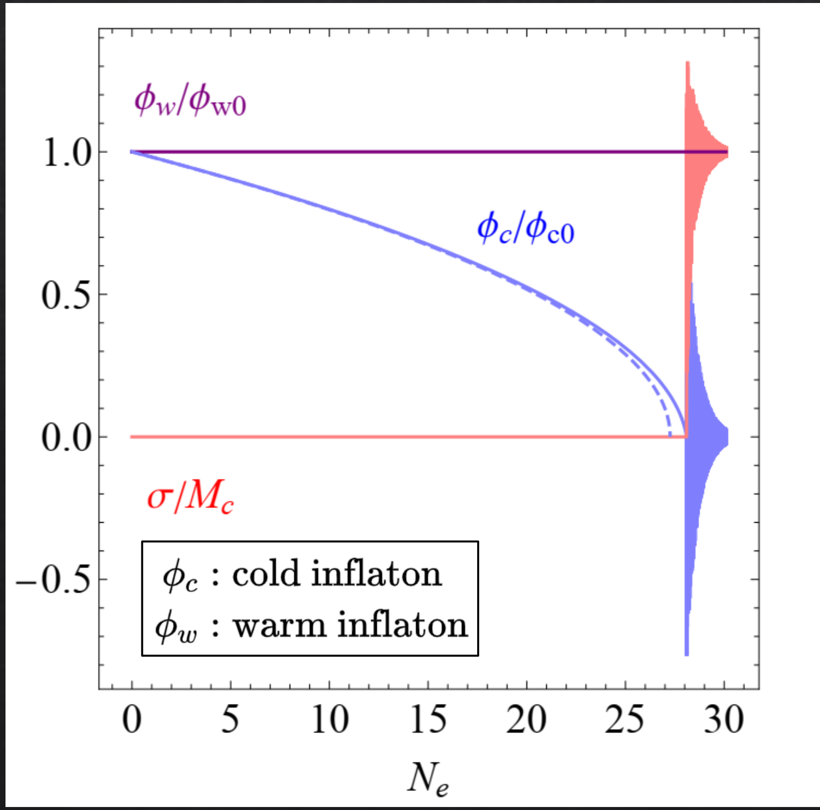
$$\Delta V_1 \simeq \frac{(\kappa M_c)^4}{8\pi^2}\mathcal{N} f[x] , \; x = \frac{|\phi_c|}{M_c} ,$$

$$f[x] = \frac{1}{4}\left((x^4+1)\log\frac{x^4-1}{x^4} + 2x^2\log\frac{x^2+1}{x^2-1} + 2\log\frac{\kappa^2 M_c^2 x^2}{Q^2} - 3\right)$$

The Model - Cold inflation

- The evolution of the cold, warm and waterfall scalar fields

$$\ddot{\phi}_i + 3H\dot{\phi}_i + \frac{\partial V}{\partial \phi_i} = 0\,, \quad H^2 = \frac{\sum_i \frac{1}{2}\dot{\phi}_i^2 + V(\phi_c, \phi_w, \sigma)}{3M_{\rm pl}^2}$$



$$\boxed{A_s(k_\star) \simeq 2.1\times 10^{-9}, \quad n_s(k_\star) \simeq 0.965\,, \quad k_\star \simeq 0.005\,\mathrm{Mpc}^{-1}}$$

$$\Downarrow$$

$$n_s \simeq 1 - \frac{1}{N_c} \Rightarrow N_c \simeq 28$$

Parameters setting:

$M_c = 6.6\times 10^{15}\,\mathrm{GeV},\ \lambda = 7\times 10^{-16},\ \kappa = 1\,,\ \mathcal{N} = 1$

Initial conditions for the fields:

$\phi_{c,0} = 266 M_c,\ \phi_{w,0} \simeq 27 M_c$

The Model - Warm inflation

- **Warm Little Inflaton:** [Phys.Rev.Lett. 117 (2016) 15, 151301]

  The warm inflaton ϕ_w is the resultant singlet scalar field from the collective spontaneous breaking of a $U(1)$ gauge symmetry:

$$\boxed{\Phi_1 = \frac{M_w}{\sqrt{2}} e^{i(\alpha+\phi_w)/M_w}, \quad \Phi_2 = \frac{M_w}{\sqrt{2}} e^{i(\alpha-\phi_w)/M_w}}$$

$\langle\Phi_1\rangle = \langle\Phi_2\rangle = M_w/\sqrt{2}$,

M_w is the symmetry breaking scale.

- Consider interactions between the warm inflaton and other d.o.f. consistent with the gauge symmetry, we may build the interaction Lagrangian:

$$\begin{aligned} -\mathcal{L}_{\phi\psi} &= \frac{g}{\sqrt{2}}(\Phi_1+\Phi_2)\overline{\psi}_{1L}\psi_{1R} - i\frac{g}{\sqrt{2}}(\Phi_1-\Phi_2)\overline{\psi}_{2L}\psi_{2R} \\ &= gM_w\cos(\phi_w/M_w)\overline{\psi}_{1L}\psi_{1R} + gM_w\sin(\phi_w/M_w)\overline{\psi}_{2L}\psi_{2R} \end{aligned}$$

The Model - Warm inflation

$$Q \equiv \frac{\Upsilon}{3H}$$

- Warm inflation dynamics:

$$\dot{\rho}_R + 4H\rho_R = \Upsilon\dot{\phi}_w^2\,,$$
$$\ddot{\phi}_w + (3H+\Upsilon)\dot{\phi}_w + V'(\phi_w) = 0\,,$$
$$\rho_R = \frac{\pi^2}{30}g_\star T^4\,,\quad H^2 = \frac{\rho_w+\rho_R}{3M_{\rm pl}^2}\,.$$

$$\xrightarrow[\epsilon_w < 1+Q]{\text{Slow-roll approx.}}$$

$$4H\rho_R \simeq \Upsilon\dot{\phi}_w^2\,,$$
$$(3H+\Upsilon)\dot{\phi}_w + V'(\phi_w) = 0\,.$$

with

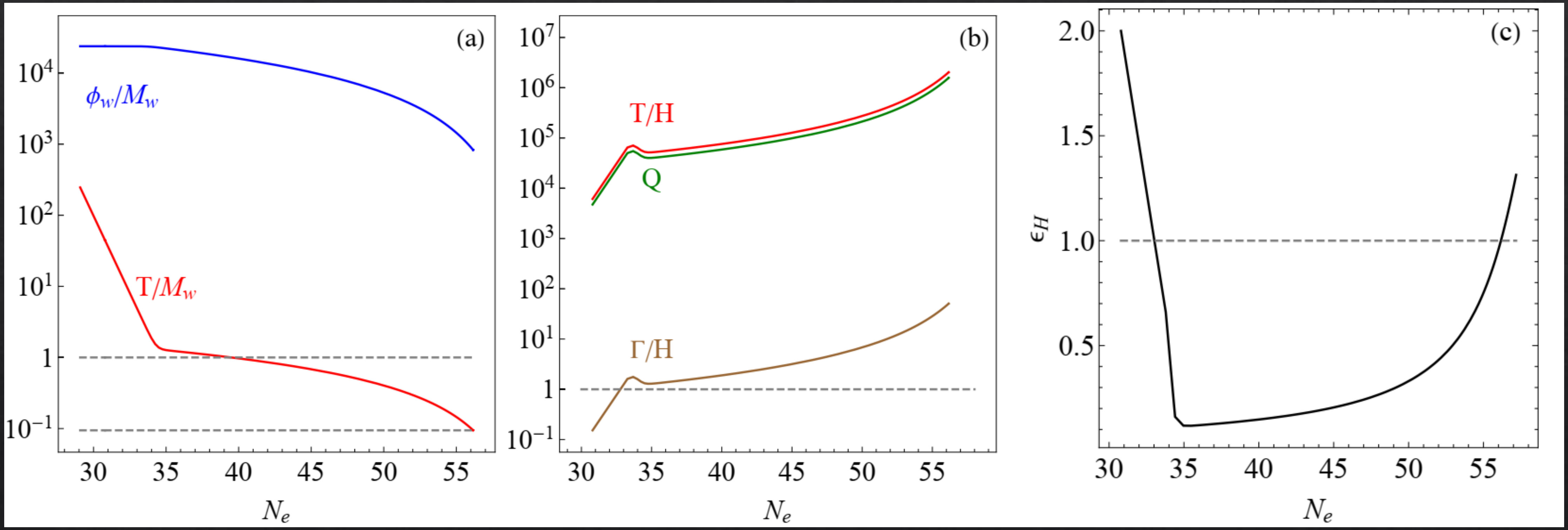
$$V_w(\phi_w) = \lambda\phi_w^4\,,\quad \Upsilon \simeq C_T T\,,\quad C_T = \frac{g^2}{h^2}\frac{3}{1-0.34\,\mathrm{loh}\,h}$$

- After reheating, radiation is initially diluted as $\rho_R \sim a^{-4}$ until the dissipative source term becomes comparable. When Q ≫ 1, we can see form $\varepsilon_w < 1 + Q$ that the radiation smoothly takes over as the dominant component:

$$\frac{\rho_R}{\rho_w} \simeq \frac{\epsilon_w}{2}\frac{Q}{(1+Q)^2} \simeq \frac{\epsilon_H}{2}\frac{Q}{1+Q}$$

The Model - Warm inflation

- Dynamics of the second stage of warm inflation:



Parameters setting: $M_w = 5.36 \times 10^{12}\,\mathrm{GeV},\ g \simeq 0.13,\ h \simeq 0.21\ (C_T \simeq 0.77),\ g_\star \simeq 12.5$

$$\boxed{N_w = 22,\ N_1 = 3}$$

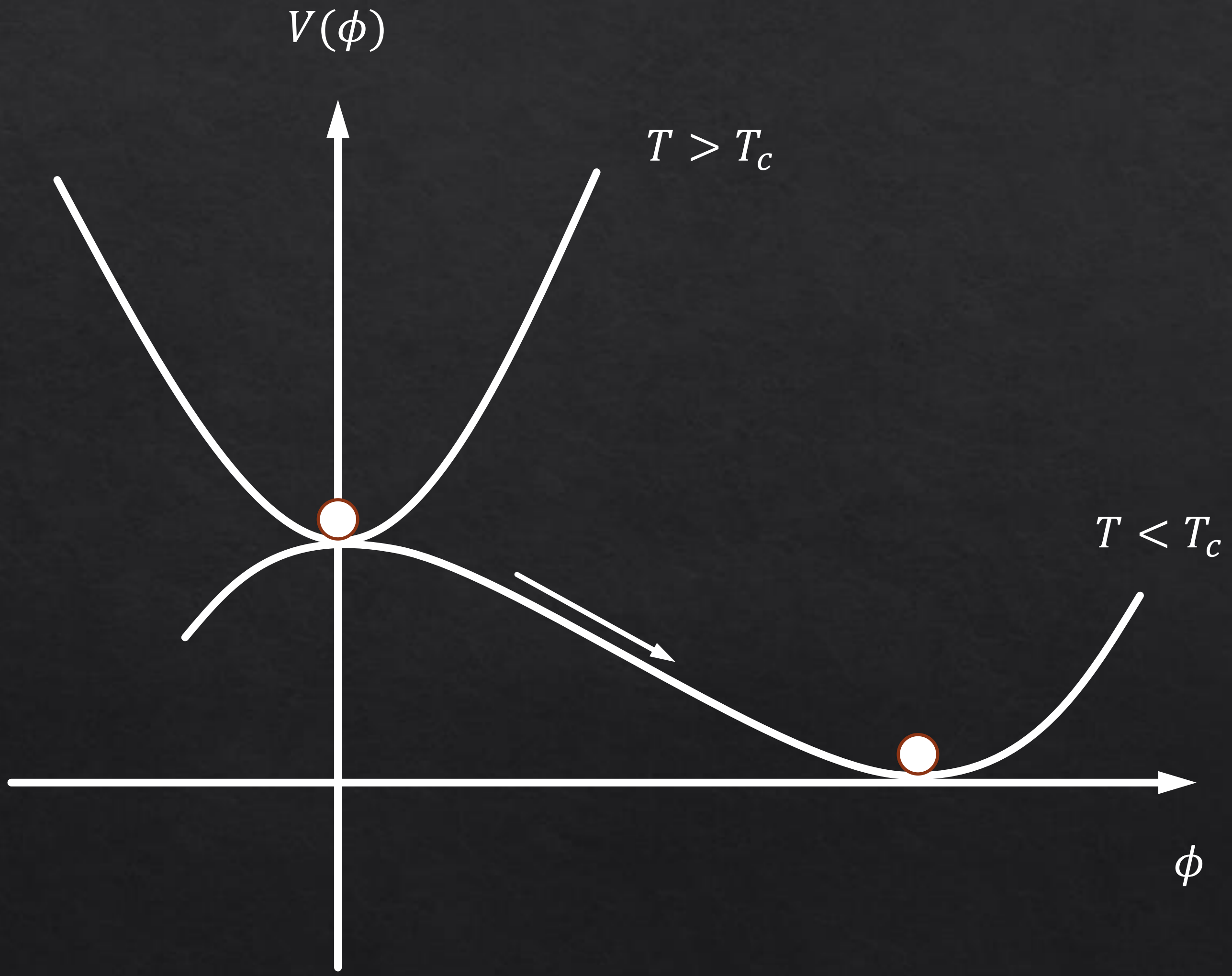
The Model - Warm inflation

- The dimensionless curvature power spectrum is:

$$\Delta_{\mathcal{R}}^2 = \frac{V_w (1+Q)^2}{24\pi^2 M_{\rm pl}^4 \epsilon_w}\left(1 + 2n + \frac{2\sqrt{3}Q}{\sqrt{3+4\pi Q}}\frac{T}{H}\right) G(Q)\,, \quad G(Q) \simeq 1 + 0.0185 Q^{2.315} + 0.335 Q^{1.364}\,.$$

- For $Q \sim T/H \gg 1$, the power spectrum is enhanced by nearly a factor Q^4 relative its quantum counterpart.
- In our example we find $\Delta_R^2 \sim 10^{-2}$ on scales crossing the horizon during warm inflation. This offers a natural setting for producing a significant abundance of PBHs that may potentially explain all of the dark matter.

The Model - Thermal inflation



$$V(\phi_t, T) \simeq V_0 + \frac{1}{2}(\alpha^2 T^2 - m^2)\phi_t^2 + \cdots$$

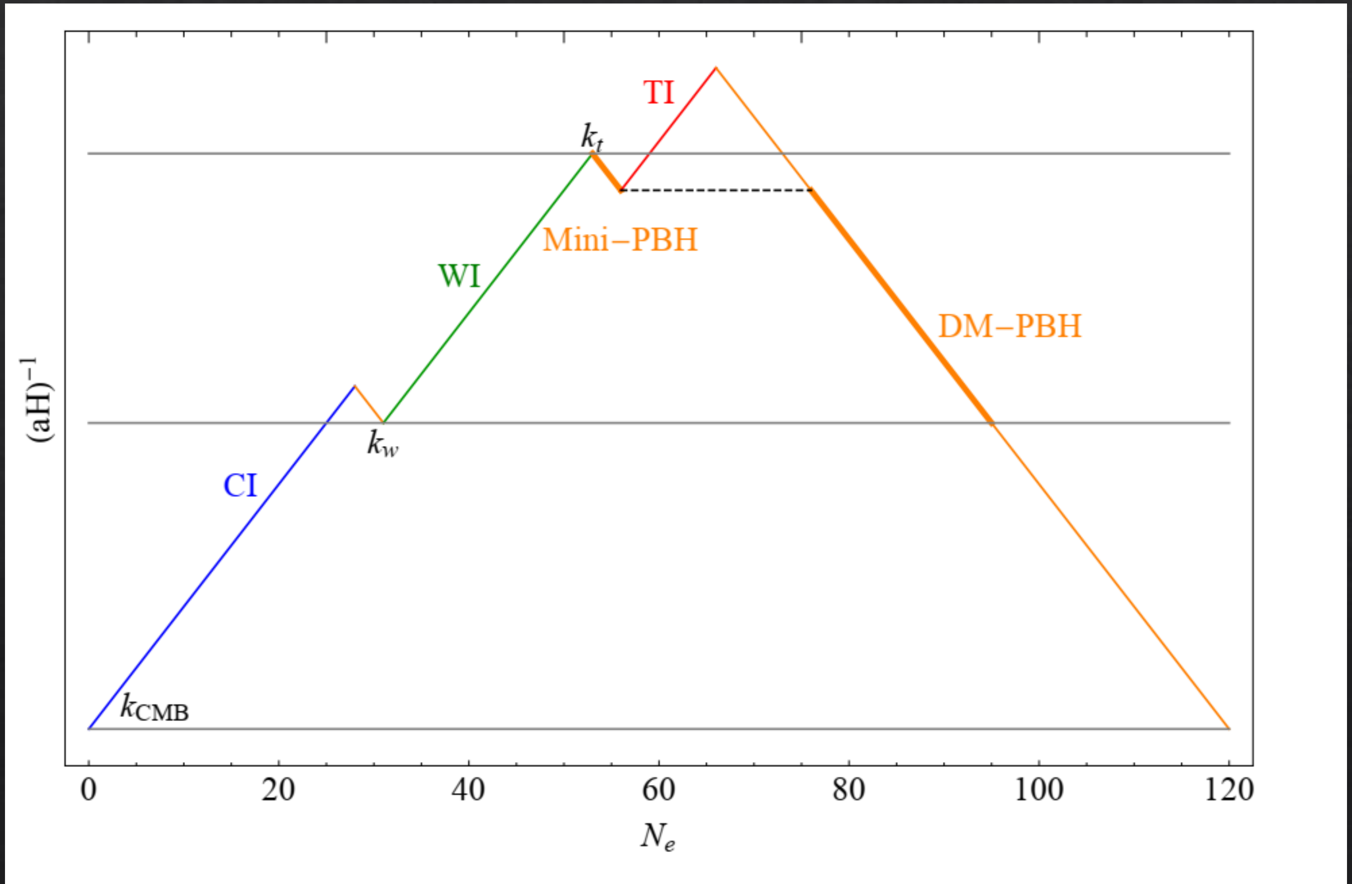
$$T_t = \left(\frac{30}{\pi^2 g_\star}\right)^{1/4} V_0^{1/4}, \quad T_{\rm crit} \equiv m/\alpha$$

$$N_t \simeq \log \frac{T_t}{T_{\rm crit}} = \log \frac{V_0^{1/4}}{m} + \frac{1}{4}\log\left(\frac{30}{\pi^2 g_\star}\right) + \log \alpha$$

$$N_t \approx 10$$

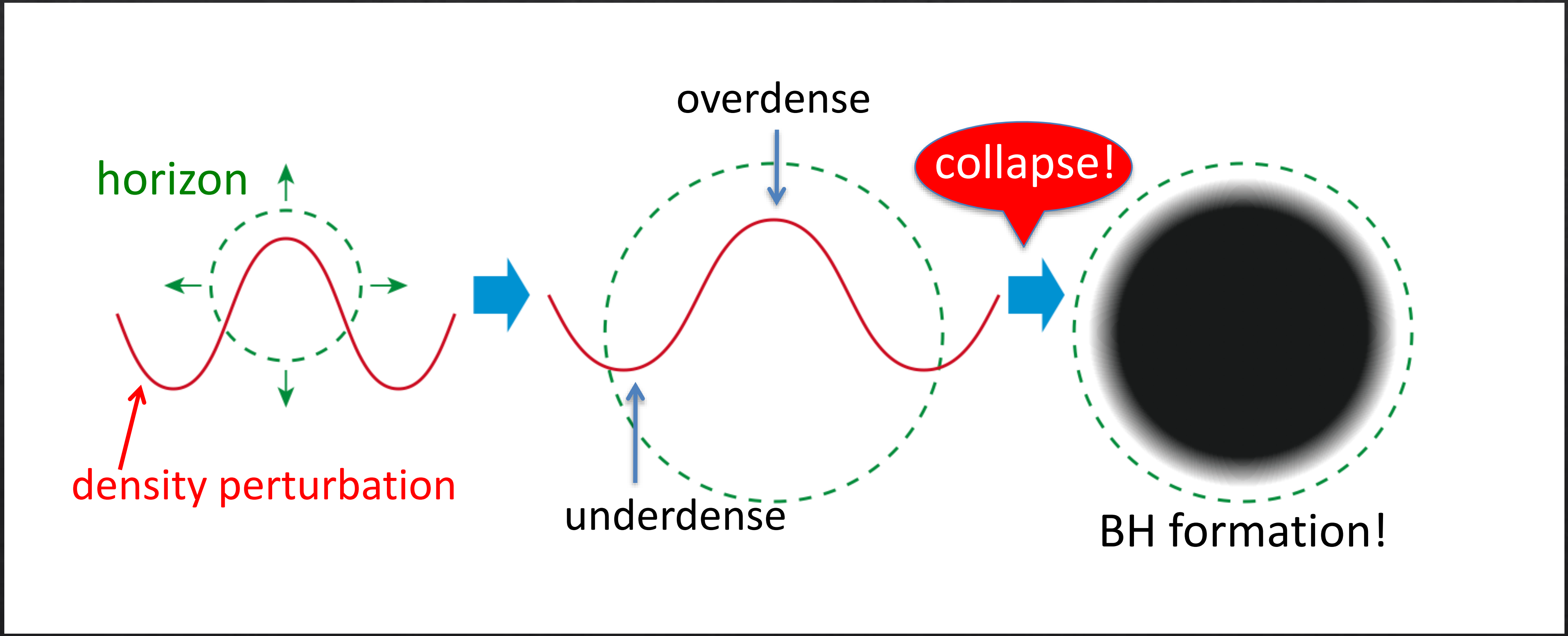
Primordial Black Holes

- Evolution of the Hubble horizon in this inflationary trilogy scenario:



Primordial Black Holes

- PBHs are formed by collapse of overdense regions in radiation dominated universe.



[copied from Kitajima's slides]

PBH mass ≈ horizon mass at the formation: $M_{\rm PBH} \sim \frac{4\pi}{3}\rho(t_{\rm PBH})H^{-3}(t_{\rm PBH})$

Primordial Black Holes

$$\boxed{\gamma \simeq 0.2}$$

$$\boxed{\Delta_\delta^2 = \frac{4(1+w)^2}{(5+3w)^2}\left(\frac{k}{aH}\right)^4 \Delta_{\mathcal{R}}^2}$$

- The mass of a PBH:

$$\boxed{M_{\rm PBH} = 1.55\times 10^{24} M_\odot \left(\frac{\gamma}{0.2}\right)\left(\frac{g_\star}{106.75}\right)^{1/6} (1+z)^{-2}\xi^2 ,} \quad \xi = \begin{cases} 1, & \mathrm{DM-PBHs} \\ e^{N_t}, & \mathrm{mini-PBHs} \end{cases}$$

- The present fraction of dark matter in the form of PBHs:

$$\boxed{f_{\rm PBH} = 1.68\times 10^{8}\left(\frac{\gamma}{0.2}\right)^{1/2}\left(\frac{g_\star}{106.75}\right)^{-1/4}\left(\frac{M_{\rm PBH}}{M_\odot}\right)^{-1/2}\beta_{\rm PBH}\,\xi^{-3} .}$$

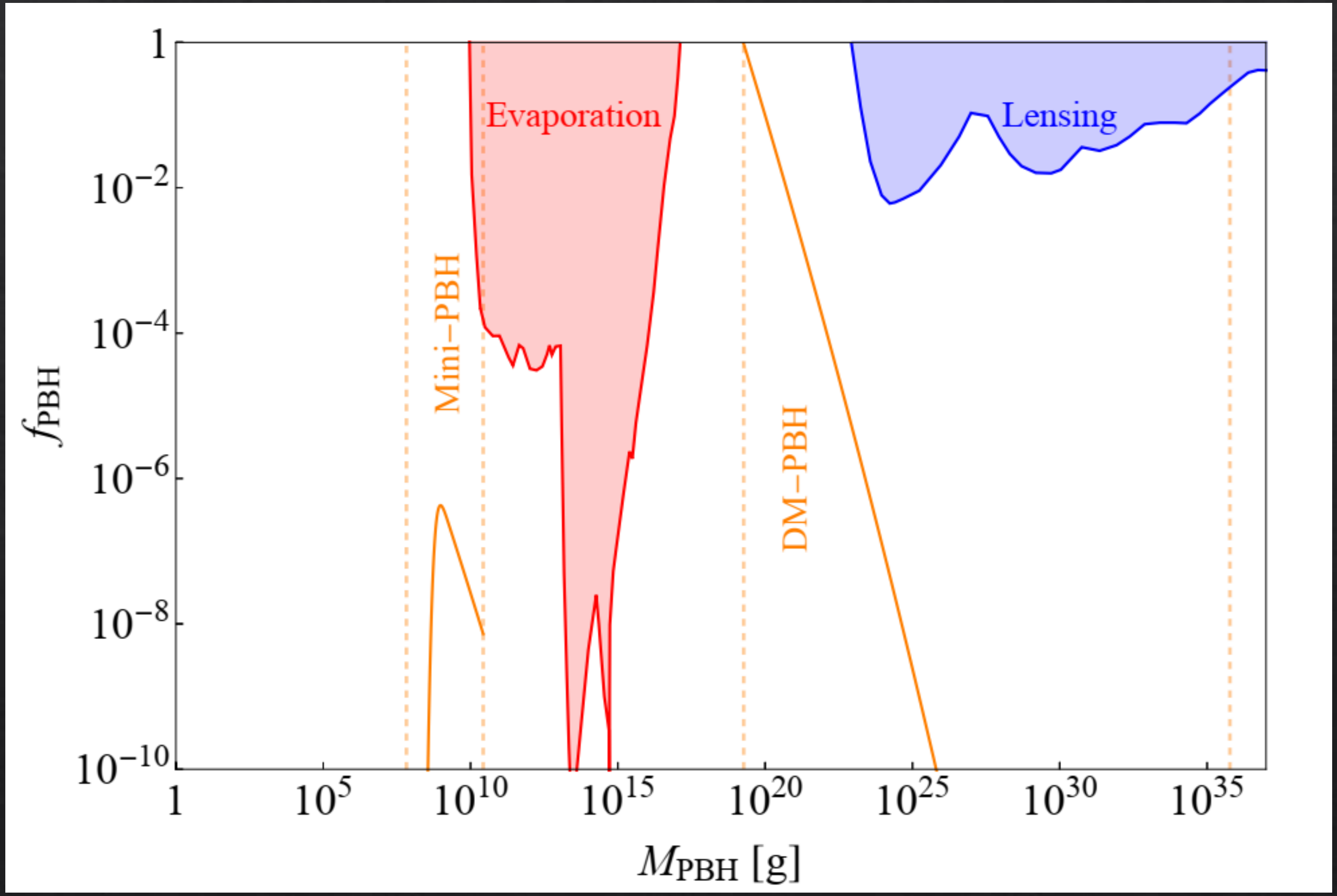
with

$$\beta_{\rm PBH} = \gamma\int_{\delta_c}^{1} P(\delta)\,d\delta \simeq \gamma\frac{\sigma}{\sqrt{2\pi}\,\delta_c} e^{-\frac{\delta_c^2}{2\sigma^2}} ,$$

$$\sigma^2 = \frac{8}{81} A_s \left(\frac{k_{\rm PBH}}{k_w}\right)^{n_s-1}\left(\Gamma\left[\frac{n_s+3}{2},\left(\frac{k_w}{k_{\rm PBH}}\right)^2\right] - \Gamma\left[\frac{n_s+3}{2},\left(\frac{k_t}{k_{\rm PBH}}\right)^2\right]\right).$$

Primordial Black Holes

- PBH redictions of the inflation trilogy scenario:



Thanks for your attention!

Backup

$$f_{\mathrm{PBH}} = \Omega_{\mathrm{DM},0}^{-1}\left(\frac{H}{H_0}\right)^2 (1+z)^{-3}\beta_{\mathrm{PBH}}\,.$$

$$M_{\mathrm{PBH}} = \gamma\frac{4\pi}{3}H^{-3}(t_{\mathrm{PBH}})\rho(t_{\mathrm{PBH}}) = 4\pi M_{\mathrm{pl}}^2 H^{-1}(t_{\mathrm{PBH}})$$

$$M_{\mathrm{PBH}} = \gamma\frac{4\pi M_{\mathrm{pl}}^2}{H}\,, \quad H \propto a^{-2} = (1+z)^2$$

$$f_{\mathrm{PBH}} = \frac{\rho_{\mathrm{PBH},0}}{\rho_{\mathrm{DM},0}} \qquad \beta_{\mathrm{PBH}} = \frac{\rho_{\mathrm{PBH}}}{\rho_{\mathrm{tot}}} = \frac{\rho_{\mathrm{PBH}}}{3M_{\mathrm{pl}}^2 H^2}$$

$$f_{\mathrm{PBH}} = \frac{\rho_{\mathrm{PBH},0}}{\rho_{\mathrm{DM},0}}$$

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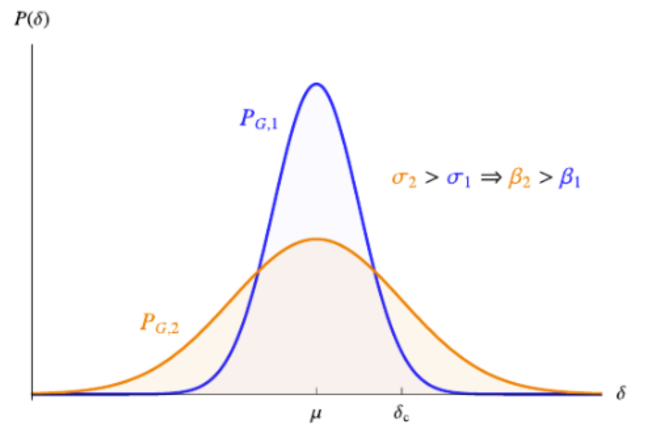
$$\beta_{\mathrm{PBH}} = \frac{\rho_{\mathrm{PBH}}}{\rho_{\mathrm{tot}}}$$

$$\Delta_{\mathcal{R}}^2(k) = A_s(k/k_w)^{n_s-1}$$

$$\sigma^2 = \int \mathrm{d}\log k\, \Delta_\delta^2(k) W^2(k, k_{\mathrm{PBH}})\,,$$



Gaussian window function: $W = \exp(-k^2/2k_{\mathrm{PBH}}^2)$

Cold Inflation

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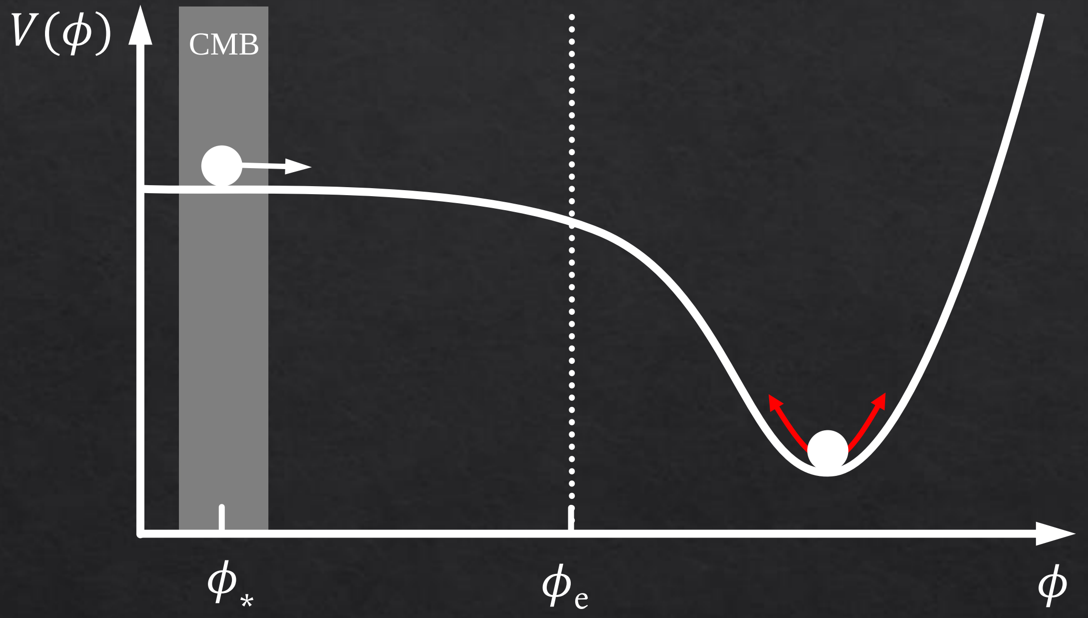
Slow-roll Inflation



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- In cold inflation, interactions of the inflaton with other fields are considered negligible during inflation:

$$\dot{\rho}_r + 4H\rho_r = 0 \Rightarrow \rho_r \sim 1/a^4 \Rightarrow \text{Universe supercools}$$

"Radiation density redshifts away"

Cold Inflation

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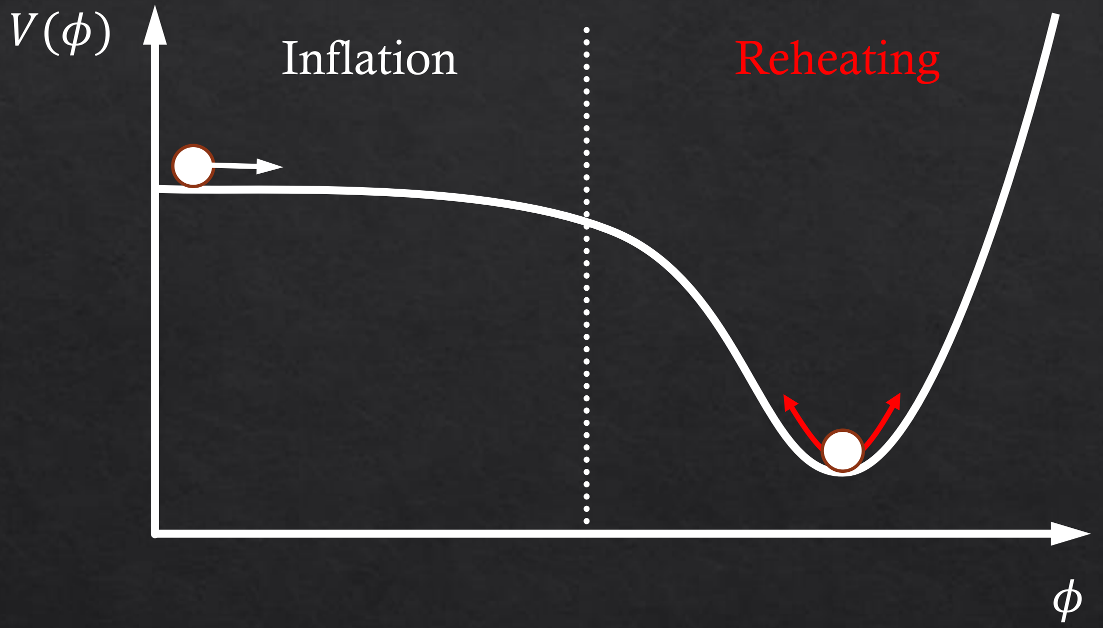

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“Radiation density redshifts away”

Cold Inflation

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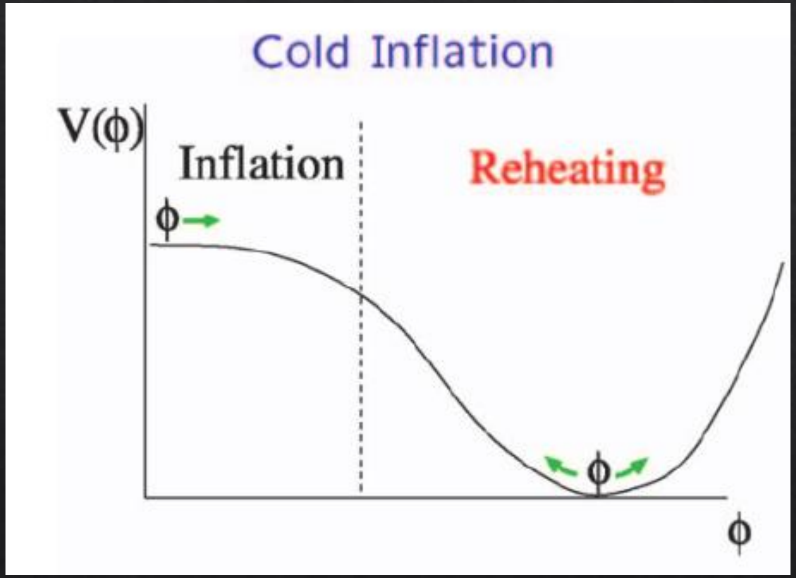


$$\dot{\rho}_r + 4H\rho_r = \Upsilon\dot{\phi}^2$$

$\Rightarrow$ The radiation density redshifts away: $\rho_r \sim 1/a^4$

$\Rightarrow$ Universe supercools during inflation

- Curvature perturbations: $\Phi = H\delta\phi/\dot{\phi}, \quad \delta\phi(\mathbf{x},t) = \phi(\mathbf{x},t) - \phi(t)$

$$P_R^2 = \frac{k^3}{2\pi^2}\int_{k'}\langle\Phi(k)\Phi(k')\rangle = P_R^2(k_0)\left(\frac{k}{k_0}\right)^{n_s-1}, \quad \text{amplitude} = P_R^2(k_0)$$

→nearly scale-invanrint, but slightly red-tilted, \sigma~As~10^-9, no chance to get PBHs

- Shortcoming: eta-problem

Warm Inflation

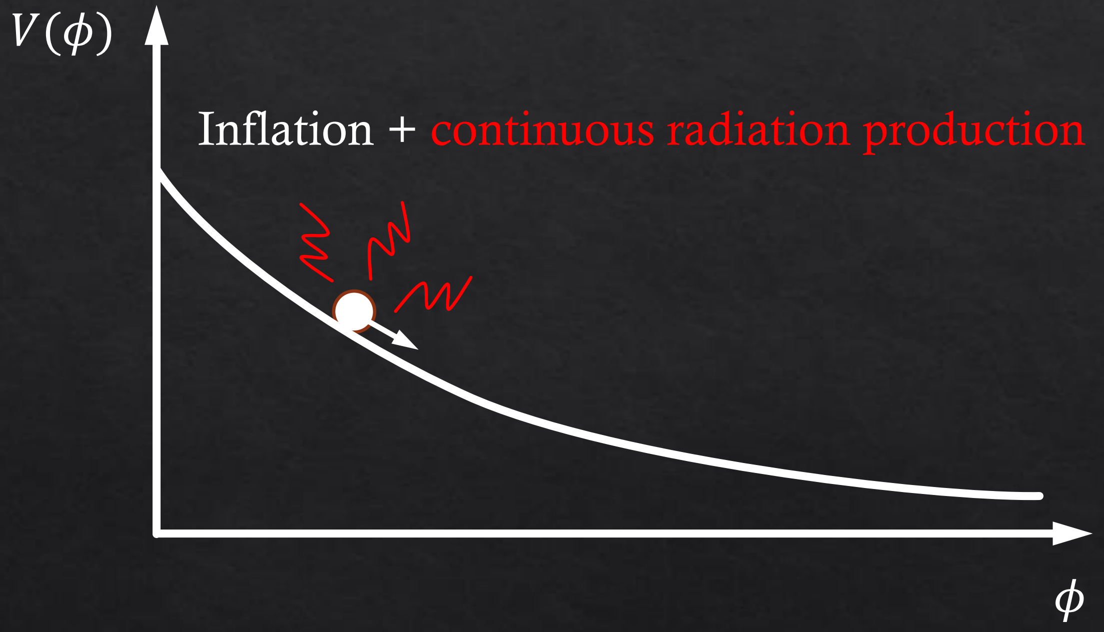
$$\boxed{\frac{\Upsilon}{3H} \equiv Q > 1}$$

- Strong dissipative effects lead to a blue-tilted primordial spectrum

$$H^2 \simeq \frac{V(\phi)}{3M_{\rm pl}^2}$$

$$\ddot{\phi} + (3H + \Upsilon)\dot{\phi} + V'(\phi) = 0$$

$$\dot{\rho}_r + 4H\rho_r = \Upsilon\dot{\phi}^2 \qquad H^2 = \frac{\rho_r + \dot{\phi}^2/2 + V(\phi)}{3M_{\rm pl}^2}$$



$$3H(1+Q)\dot{\phi} \simeq -V'$$

$$4H\rho_r \simeq \Upsilon\dot{\phi}^2 \;\Rightarrow\; \rho_r = \frac{3}{4}Q\dot{\phi}^2$$

$$\rho_r = \frac{\pi^2}{30}g_\star T^4$$

$$\epsilon_H = -\frac{\dot{H}}{H^2} \simeq \frac{1+Q}{2M_{\rm pl}^2}\frac{\dot{\phi}^2}{H^2} \simeq \frac{\epsilon_V}{1+Q} < 1 \Rightarrow \epsilon_V < 1+Q$$

$$\eta_H = \frac{\dot{\epsilon}_H}{H\epsilon_H} < 1 \Rightarrow \eta_V < 1+Q$$

Warm Inflation

- Eta-problem can be alleviated in warm inflation due to the additional dissipative friction
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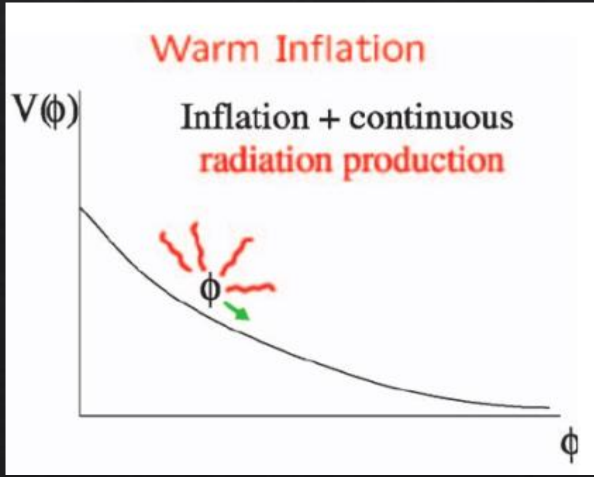
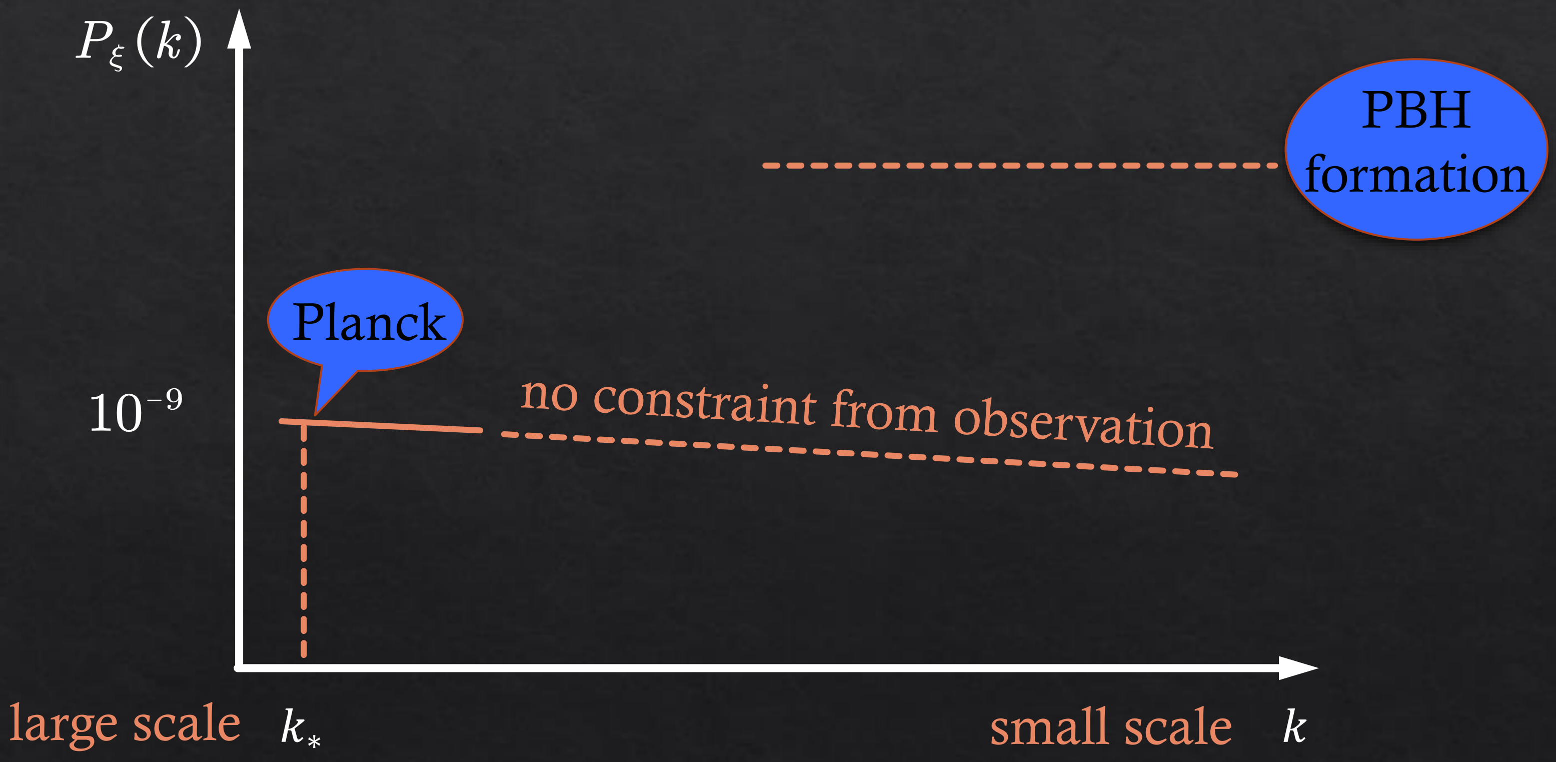


→nearly scale-invanrint, but slightly blue-tilted, PR gets enhanced by large Q, get chance to get PBHs

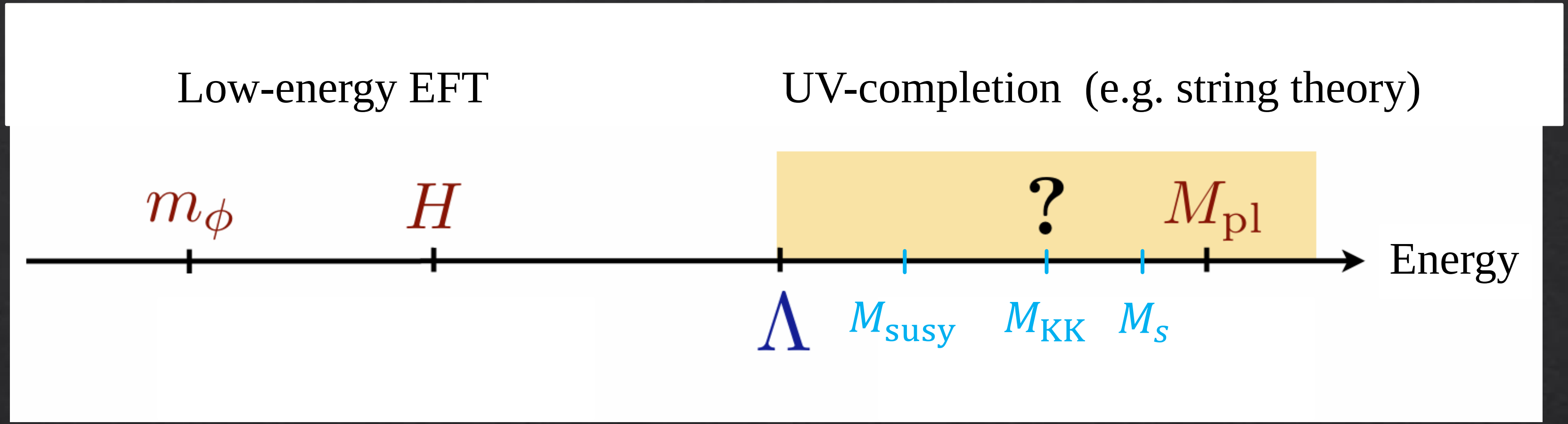
Primordial Black Holes

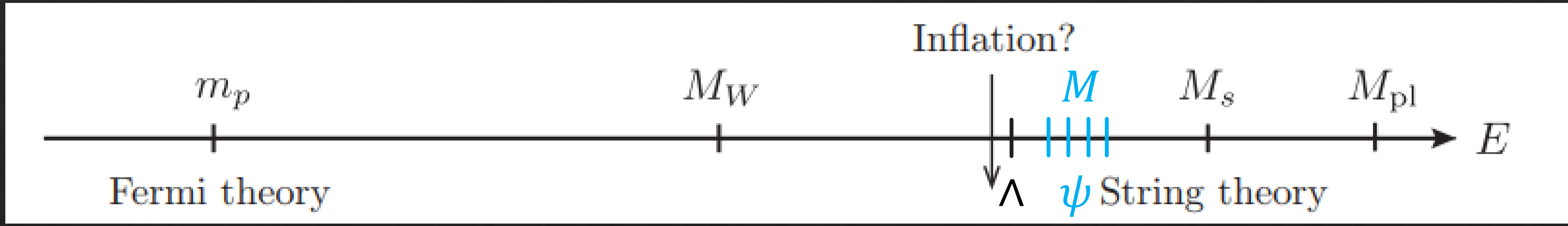
The power spectrum of curvature perturbation :

$P_\xi \sim 2 \times 10^{-9}$ with nearly scale-invariant [Planck obs.]



Cold Inflation





$$\mathcal{L}_{\rm eff} = -\frac{1}{2}(\partial_\mu\phi)^2 - V(\phi) - \sum_n c_n V(\phi)\frac{\phi^{2n}}{\Lambda^{2n}} - \sum_n d_n \frac{(\partial\phi)^{2n}}{\Lambda^{4n}} + \cdots$$

Cold Inflation

- Quantum fluctuations:

$$\delta\phi(\mathbf{x}) \sim H$$

- Primordial curvature power spectrum:

$$\boxed{\Delta^2_{\mathcal{R}}(k) = \frac{k^3}{2\pi^2} P_{\mathcal{R}}(k) = A_s(k_\star)\left(\frac{k}{k_\star}\right)^{n_s - 1}, \quad A_s(k_\star) \simeq 10^{-9}\, , n_s \simeq 0.968}$$

- nearly scale-invariant
- slightly red-tilted spectrum

$$\langle \mathcal{R}_{\mathbf{k}} \mathcal{R}_{\mathbf{k}'} \rangle = (2\pi)^3 \delta(\mathbf{k} + \mathbf{k}') P_{\mathcal{R}}(k), \quad \Delta^2_{\mathcal{R}}(k) = \frac{k^3}{2\pi^2} P_{\mathcal{R}}(k)\, .$$

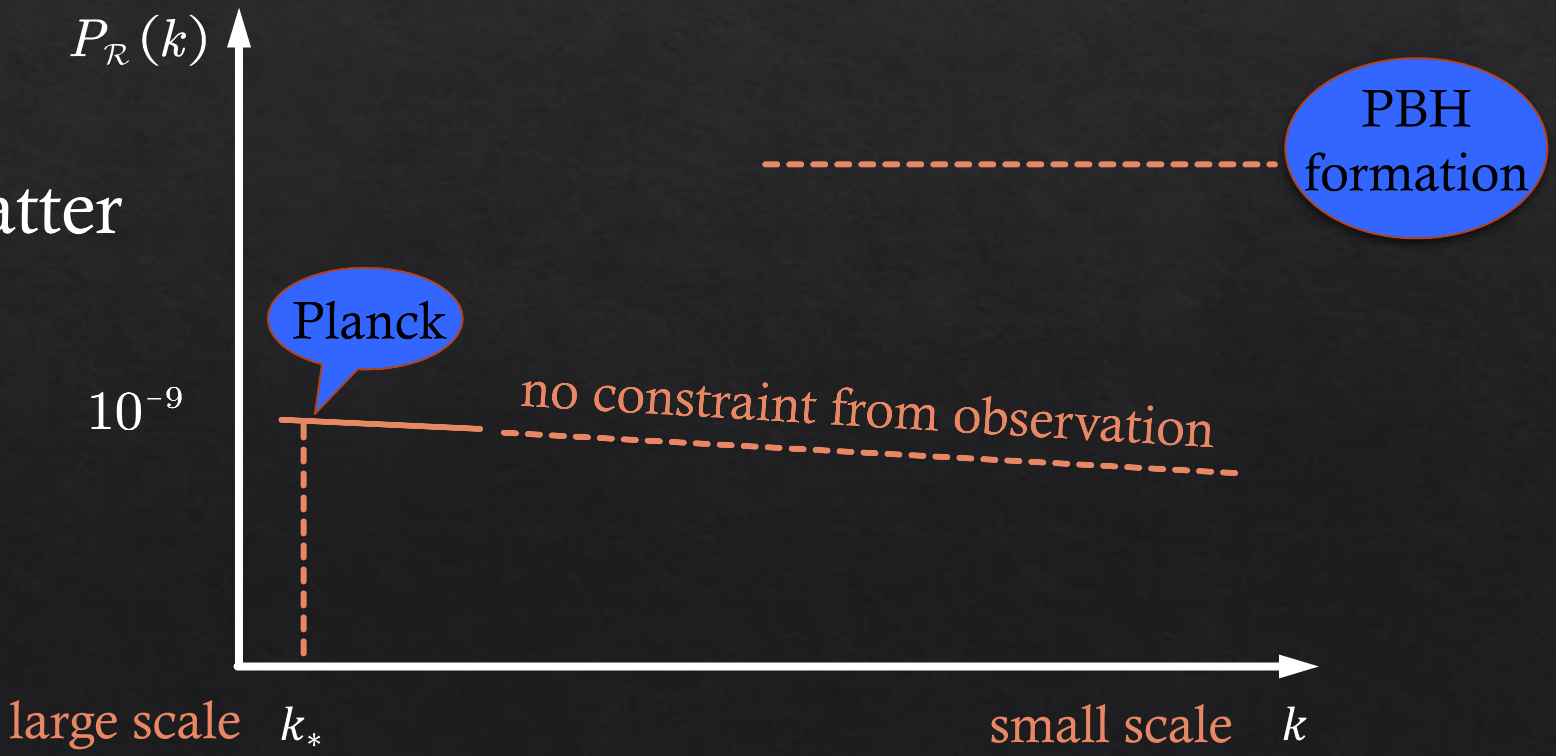
$$\langle \mathcal{R}_{\mathbf{k}} \mathcal{R}_{\mathbf{k}'} \rangle = \left(\frac{H}{\dot{\phi}}\right)^2 \langle \delta\phi_{\mathbf{k}} \delta\phi_{\mathbf{k}'} \rangle$$

$$\langle \delta\phi_{\mathbf{k}} \delta\phi_{\mathbf{k}'} \rangle = (2\pi)^3 \delta(\mathbf{k} + \mathbf{k}') \frac{2\pi^2}{k^3} \left(\frac{H}{2\pi}\right)^2, \quad \Delta^2_{\delta\phi} = \left(\frac{H}{2\pi}\right)^2 .$$

$$\Delta^2_{\mathcal{R}}(k) = \frac{H_\star^2}{(2\pi)^2} \frac{H_\star^2}{\dot{\phi}_\star^2}\, .$$

Motivation

- Requiring a single field to drive the full 50-60 e-folds of inflationary expansion may be too much to ask for in a theory
- Avoid eta-problem
- Explain all of the dark matter




Thanks for your attention!