Are primordial black holes formed during reheating after R^2 inflation?

Yuki Watanabe
NIT, Gunma College

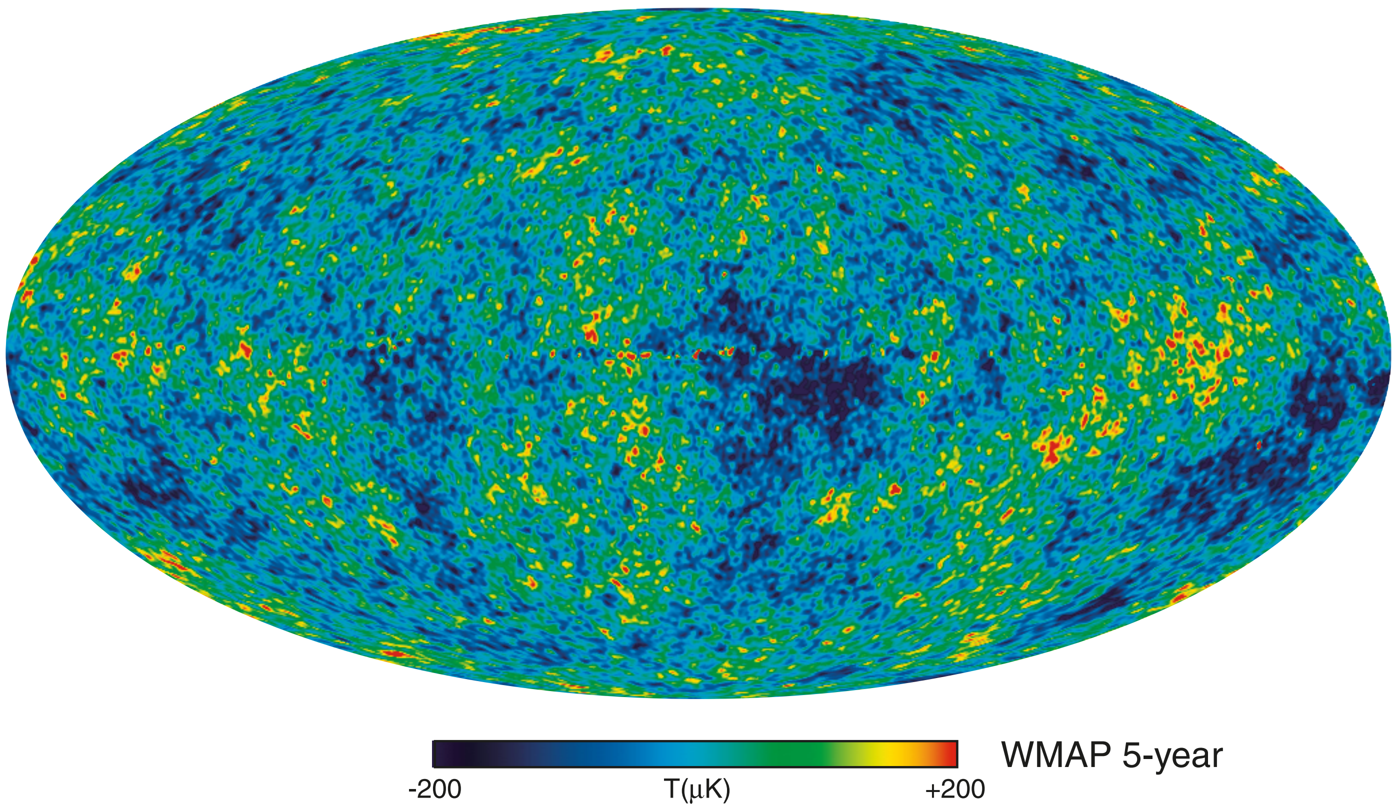
Based on Work with H. Jeong, R. Jinno, J. Yokoyama

The Dark Side of the Universe (DSU 2024)

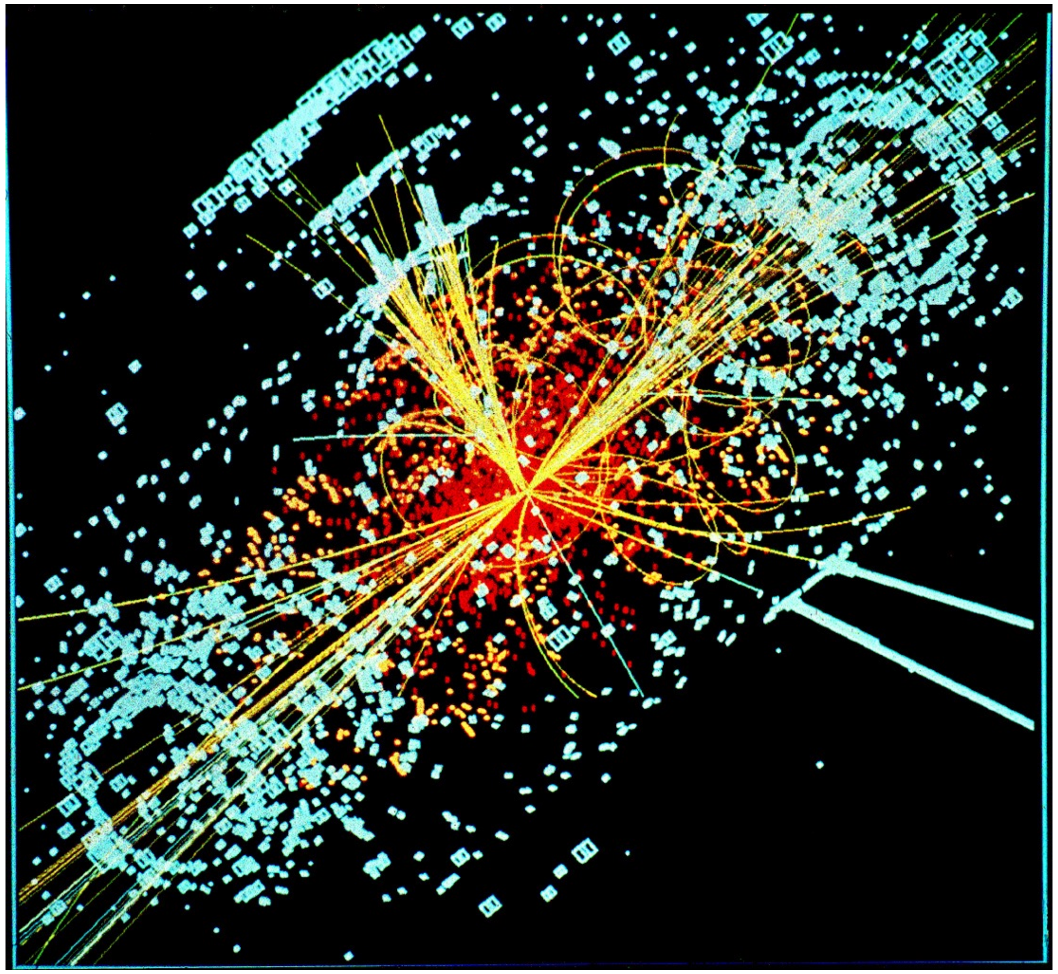
Mon-Repos, Corfu, Greece
Sep. 11, 2024

CMB observations and BSM physics

- (n_s, r) precision measurements from CMB
- No signal of physics beyond the Standard Model (BSM) at the LHC

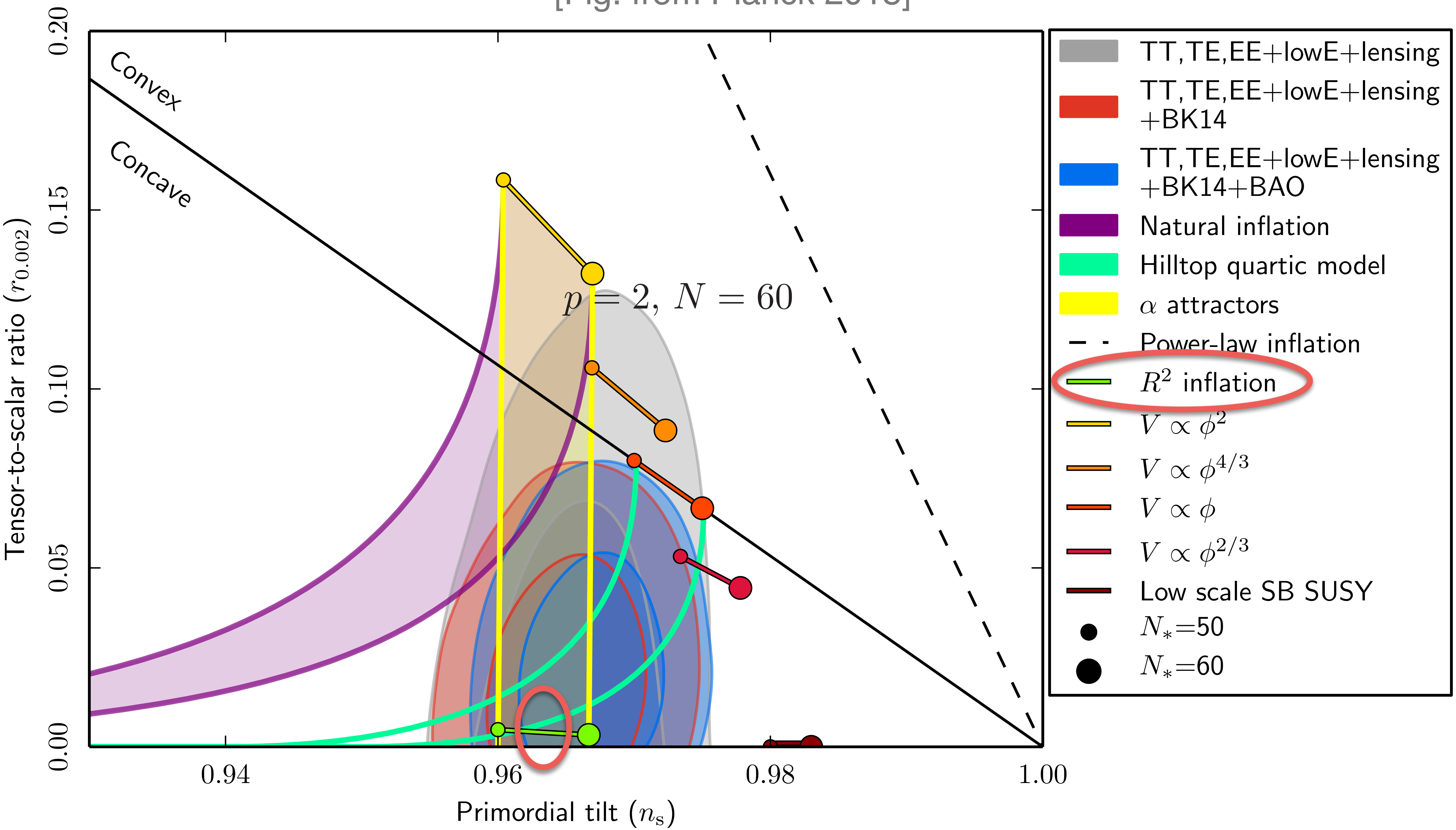


credit: NASA



CMB constraint on inflation models

[Fig. from Planck 2018]



- Monomial potentials (p ≧ 2) in GR are disfavored.
- What if we could nail down to further precision?

Starobinsky R^2 Inflation

[Starobinsky 1980; Mukhanov & Chibisov 1981]

$$S = \frac{1}{2\kappa^2}\int d^4x\sqrt{-g}\left(R + \frac{R^2}{6M^2}\right) + S_m$$

$$S_m = \int d^4x\sqrt{-g}\left[-\frac{1}{2}(\nabla\sigma)^2 - V(\sigma)\right] \quad \leftarrow \textbf{Higgs}$$

+ minimally coupled SM, RHN
+ "*desert*" or BSM

- One of the oldest models of Inflation, before models of Sato and Guth
- A single parameter **M** characterizes the model.

R^2 Inflation as scalar-tensor theory

[Whitt 1984; Maeda 1988]

$$S_J = \frac{1}{2\kappa^2}\int d^4x\sqrt{-\hat{g}}\left(\hat{R} + \frac{\hat{R}^2}{6M^2}\right) + S_m$$

$$S_m = \int d^4x\sqrt{-\hat{g}}\left[-\frac{1}{2}(\hat{\nabla}\hat{\sigma})^2 - V(\hat{\sigma})\right]$$

R^2 Inflation as scalar-tensor theory

[Whitt 1984; Maeda 1988]

$$S_J = \frac{1}{2\kappa^2}\int d^4x\sqrt{-\hat{g}}\left(\hat{R} + \frac{\hat{R}^2}{6M^2}\right) + S_m$$

$$S_m = \int d^4x\sqrt{-\hat{g}}\left[-\frac{1}{2}(\hat{\nabla}\hat{\sigma})^2 - V(\hat{\sigma})\right]$$

Jordan frame $\hat{g}_{\mu\nu}$

↓

Einstein frame $g_{\mu\nu}$

$$g_{\mu\nu} = \hat{g}_{\mu\nu}\Omega^2$$

$$\Omega^2 = 2\kappa^2\left|\frac{\partial\mathcal{L}_J}{\partial\hat{R}}\right| = 1 + \frac{\hat{R}}{3M^2} \equiv e^{\sqrt{\frac{2}{3}}\kappa\varphi}$$

$$\hat{R} = \Omega^2[R + 3\Box(\ln\Omega^2) - \frac{3}{2}g^{\mu\nu}\partial_\mu(\ln\Omega^2)\partial_\nu(\ln\Omega^2)]$$

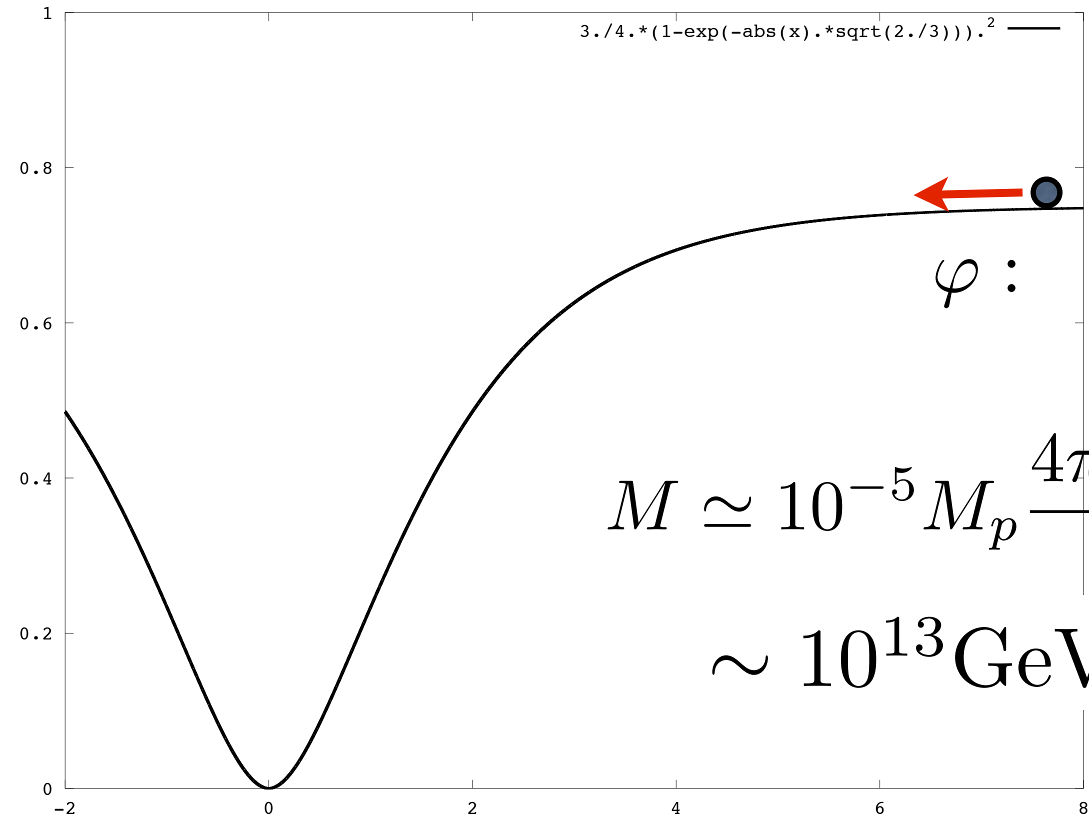
$$S_E = \int d^4x\sqrt{-g}\left[\frac{1}{2\kappa^2}R - \frac{1}{2}(\nabla\varphi)^2 - U(\varphi) - \frac{1}{2}e^{-\sqrt{\frac{2}{3}}\kappa\varphi}(\nabla\hat{\sigma})^2 - e^{-\sqrt{\frac{8}{3}}\kappa\varphi}V(\hat{\sigma})\right]$$

$$U(\varphi) = \frac{3}{4}M^2M_p^2\left(1 - e^{-\sqrt{\frac{2}{3}}\kappa\varphi}\right)^2 = \begin{cases}\frac{3}{4}M^2M_p^2 & \text{for} \quad \varphi \gg \varphi_f \\ \frac{1}{2}M^2\varphi^2 & \text{for} \quad \varphi \ll \varphi_f\end{cases}$$

$$\varphi : \quad \text{Scalaron} = \text{Inflaton}$$

Starobinsky R^2 Inflation

[Starobinsky 1980; Mukhanov & Chibisov 1981]



φ : Scalaron = Inflaton

$$M \simeq 10^{-5} M_p \frac{4\pi\sqrt{30}}{N_*} \left(\frac{\mathcal{P}_\zeta(k_*)}{2 \times 10^{-9}} \right)^{1/2}$$

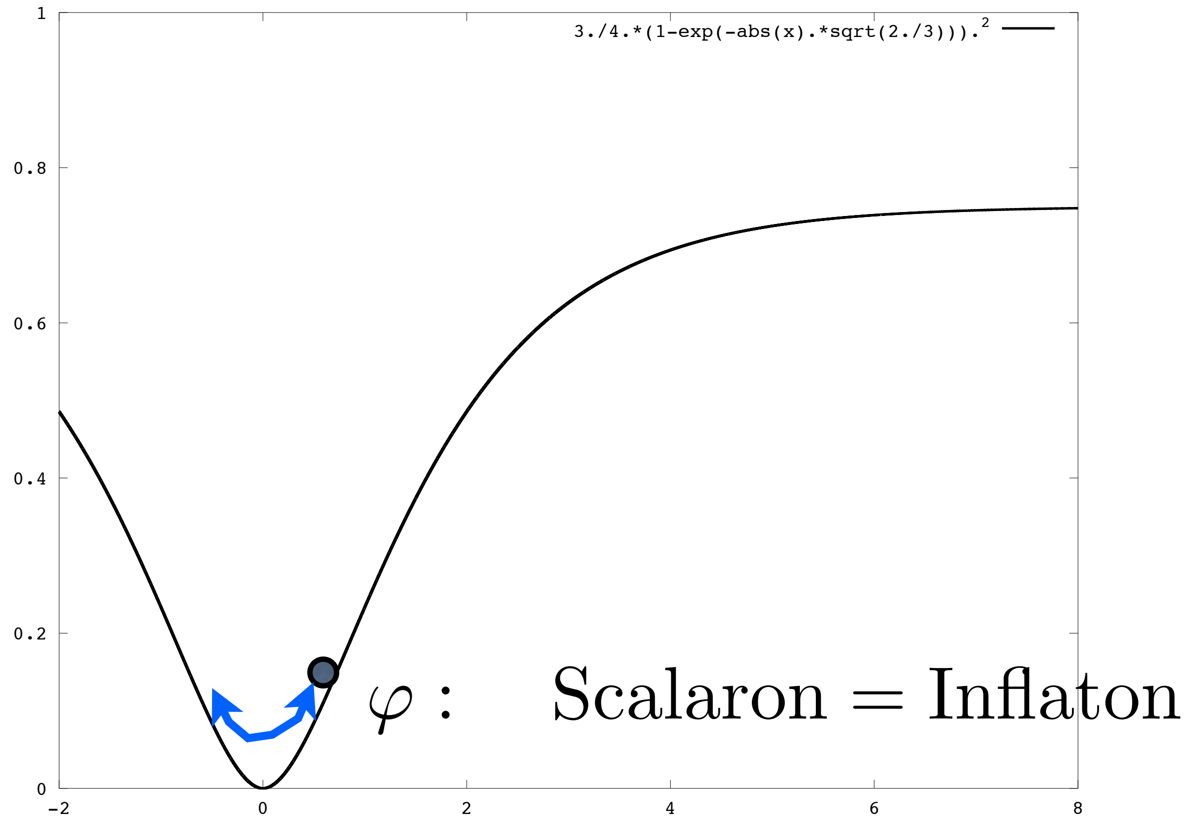
$$\sim 10^{13} \mathrm{GeV}$$

Scalaron mass M is fixed by CMB temp. anisotropy

$$U(\varphi) = \frac{3}{4} M^2 M_p^2 \left(1 - e^{-\sqrt{\frac{2}{3}}\kappa\varphi}\right)^2 = \begin{cases} \frac{3}{4} M^2 M_p^2 & \text{for} \quad \varphi \gg \varphi_f \\ \frac{1}{2} M^2 \varphi^2 & \text{for} \quad \varphi \ll \varphi_f \end{cases}$$

Starobinsky R² Inflation

[Starobinsky 1980; Mukhanov & Chibisov 1981]



$$U(\varphi) = \frac{3}{4} M^2 M_p^2 \left(1 - e^{-\sqrt{\frac{2}{3}}\kappa\varphi}\right)^2 = \begin{cases} \frac{3}{4} M^2 M_p^2 & \text{for} \quad \varphi \gg \varphi_f \\ \frac{1}{2} M^2 \varphi^2 & \text{for} \quad \varphi \ll \varphi_f \end{cases}$$

Gravitational reheating by scalaron decay

[YW & Komatsu gr-qc/0612120; YW 1011.3348; YW & White 1503.08430]

$$\sigma \equiv e^{-\frac{\kappa}{\sqrt{6}}\varphi}\hat{\sigma}$$

$$\mathcal{L}_{\rm scalar} = -\frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \frac{\kappa\sigma}{\sqrt{6}}\partial_\mu\sigma\partial^\mu\varphi - \frac{\kappa^2\sigma^2}{12}\partial_\mu\varphi\partial^\mu\varphi - \frac{m_\sigma^2}{2}e^{-\frac{2}{\sqrt{6}}\kappa\varphi}\sigma^2$$

$$\psi \equiv e^{-\frac{3\kappa}{2\sqrt{6}}\varphi}\hat{\psi}$$

$$\mathcal{L}_{\rm fermion} = -\bar{\psi}\not{D}\psi - e^{-\frac{1}{\sqrt{6}}\kappa\varphi}m_\psi\bar{\psi}\psi$$

Gravitational reheating by scalaron decay

[YW & Komatsu gr-qc/0612120; YW 1011.3348; YW & White 1503.08430]

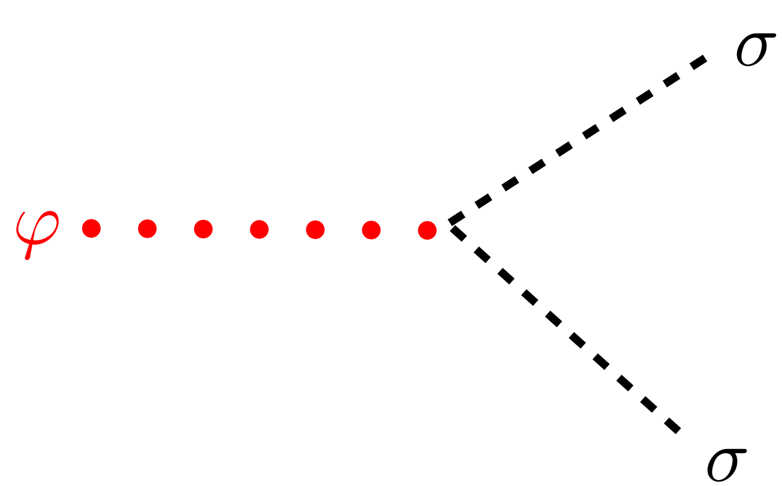
$$\sigma \equiv e^{-\frac{\kappa}{\sqrt{6}}\varphi}\hat{\sigma}$$

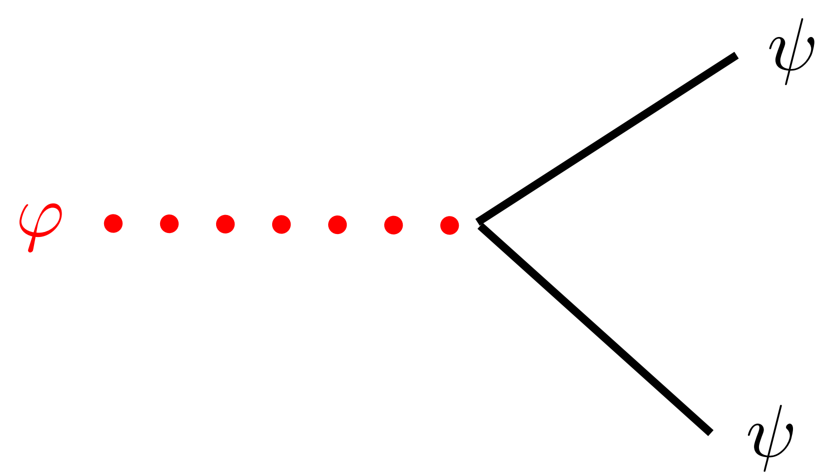
$$\mathcal{L}_{\rm scalar} = -\frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \frac{\kappa\sigma}{\sqrt{6}}\partial_\mu\sigma\partial^\mu\varphi - \frac{\kappa^2\sigma^2}{12}\partial_\mu\varphi\partial^\mu\varphi - \frac{m_\sigma^2}{2}e^{-\frac{2}{\sqrt{6}}\kappa\varphi}\sigma^2$$

$$\psi \equiv e^{-\frac{3\kappa}{2\sqrt{6}}\varphi}\hat{\psi}$$

$$\mathcal{L}_{\rm fermion} = -\bar{\psi}\not{D}\psi - e^{-\frac{1}{\sqrt{6}}\kappa\varphi}m_\psi\bar{\psi}\psi$$

$$\mathcal{L}_{\rm 3leg} = \frac{1}{\sqrt{6}M_{\rm Pl}}\varphi\partial^\mu\sigma\partial_\mu\sigma + \frac{2m_\sigma^2}{\sqrt{6}M_{\rm Pl}}\varphi\sigma^2 + \frac{m_\psi^2}{\sqrt{6}M_{\rm Pl}}\varphi\bar{\psi}\psi$$





Gravitational reheating by scalaron decay

[YW & Komatsu gr-qc/0612120; YW 1011.3348; YW & White 1503.08430]

$$\Gamma(\varphi \to \sigma\sigma) = \frac{\mathcal{N}_\sigma (M^2 + 2m_\sigma^2)^2}{192\pi M_{\rm Pl}^2 M}$$

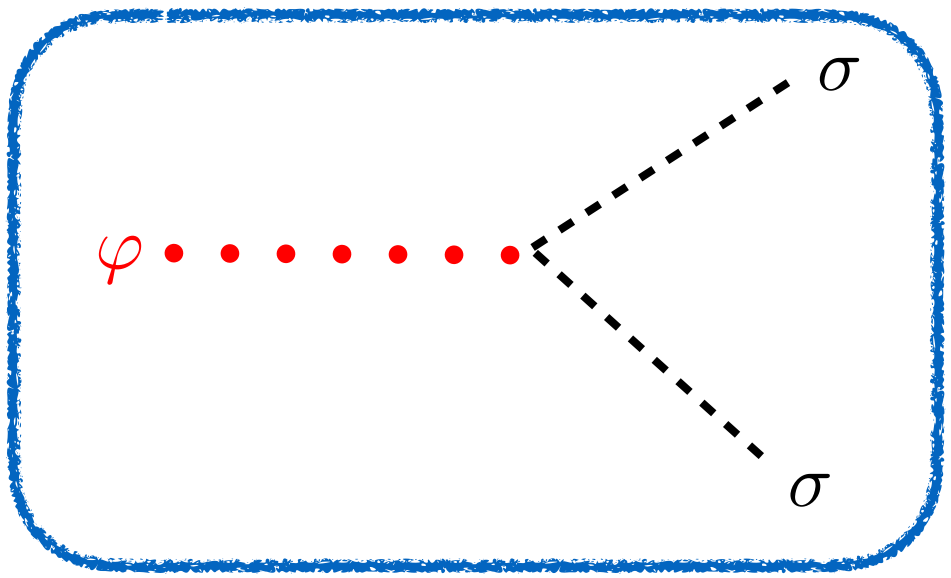
$$\simeq \frac{\mathcal{N}_\sigma M^3}{192\pi M_{\rm Pl}^2} + \frac{\mathcal{N}_\sigma m_\sigma^2 M}{48\pi M_{\rm Pl}^2}$$

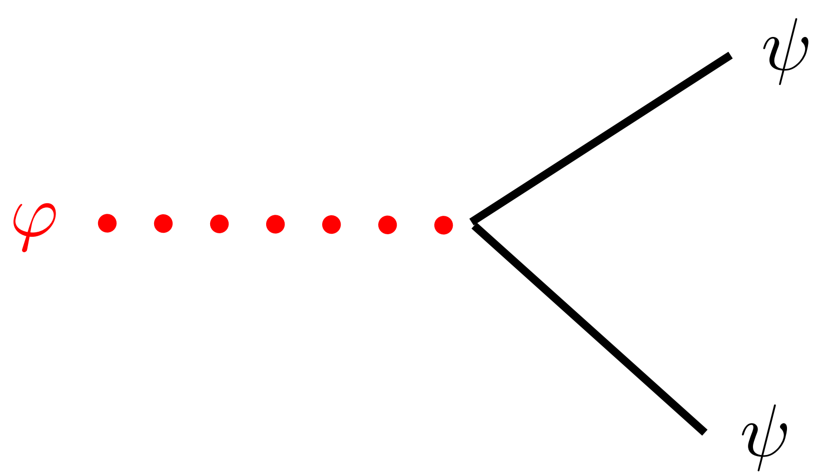
$$\Gamma(\varphi \to \bar{\psi}\psi) = \frac{\mathcal{N}_\psi m_\psi^2 M}{48\pi M_{\rm Pl}^2}$$

Leading term

$$H_{\rm rh} = \Gamma$$

$$T_{\rm rh} \simeq 0.1\sqrt{\Gamma_{\rm tot} M_p}\left(\frac{\mathcal{N}_{\rm tot}}{100}\right)^{-1/4}$$





Gravitational reheating by scalaron decay

[YW & Komatsu gr-qc/0612120; YW 1011.3348; YW & White 1503.08430]

$$\Gamma(\varphi \to \sigma\sigma) = \frac{\mathcal{N}_\sigma (M^2 + 2m_\sigma^2)^2}{192\pi M_{\rm Pl}^2 M}$$

$$\simeq \frac{\mathcal{N}_\sigma M^3}{192\pi M_{\rm Pl}^2} + \frac{\mathcal{N}_\sigma m_\sigma^2 M}{48\pi M_{\rm Pl}^2}$$

$$\Gamma(\varphi \to \bar{\psi}\psi) = \frac{\mathcal{N}_\psi m_\psi^2 M}{48\pi M_{\rm Pl}^2}$$

Leading term

$$T_{\rm rh} \simeq 0.1\sqrt{\Gamma_{\rm tot} M_p} \left(\frac{\mathcal{N}_{\rm tot}}{100}\right)^{-1/4} \sim 10^{-9} M_p,$$

$$N_* \simeq 54 + \frac{1}{3} \ln\left(\frac{T_{\rm rh}}{10^9\ {\rm GeV}}\right),$$

If we know the matter sector (e.g. SM minimally coupled to gravity), inflationary predictions can be made without uncertainty.

Predictions depend on reheating temperature

e-folds of inflation

$$N_* \simeq 54 + \frac{1}{3} \ln \left(\frac{T_{\rm rh}}{10^9 \ \rm GeV} \right),$$

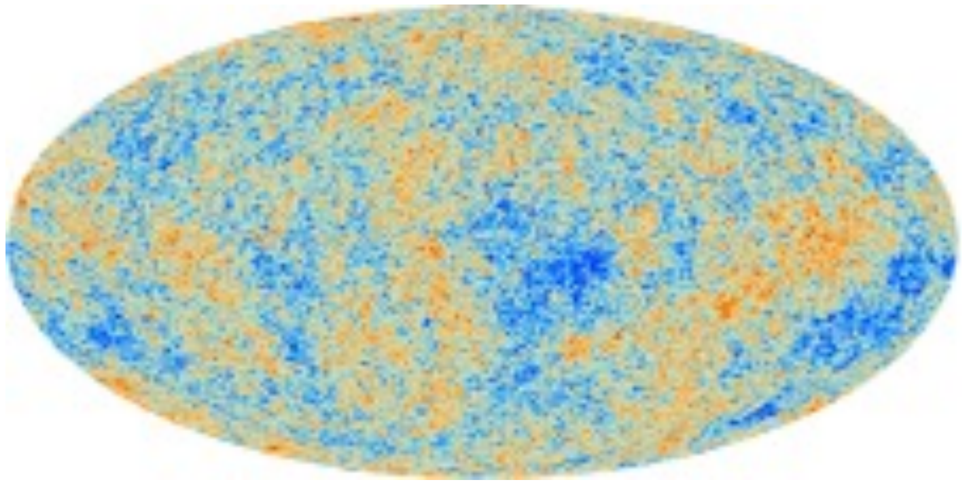
scalaron mass

$$M \simeq 10^{-5} M_p \frac{4\pi\sqrt{30}}{N_*} \left(\frac{\mathcal{P}_\zeta(k_*)}{2 \times 10^{-9}} \right)^{1/2}$$

$$\sim 10^{13} \rm GeV$$

grav. waves

$$r = \frac{\mathcal{P}_\gamma(k)}{\mathcal{P}_\zeta(k)} \simeq 16\epsilon \simeq \frac{12}{N_*^2}.$$



tilt and running of spectra

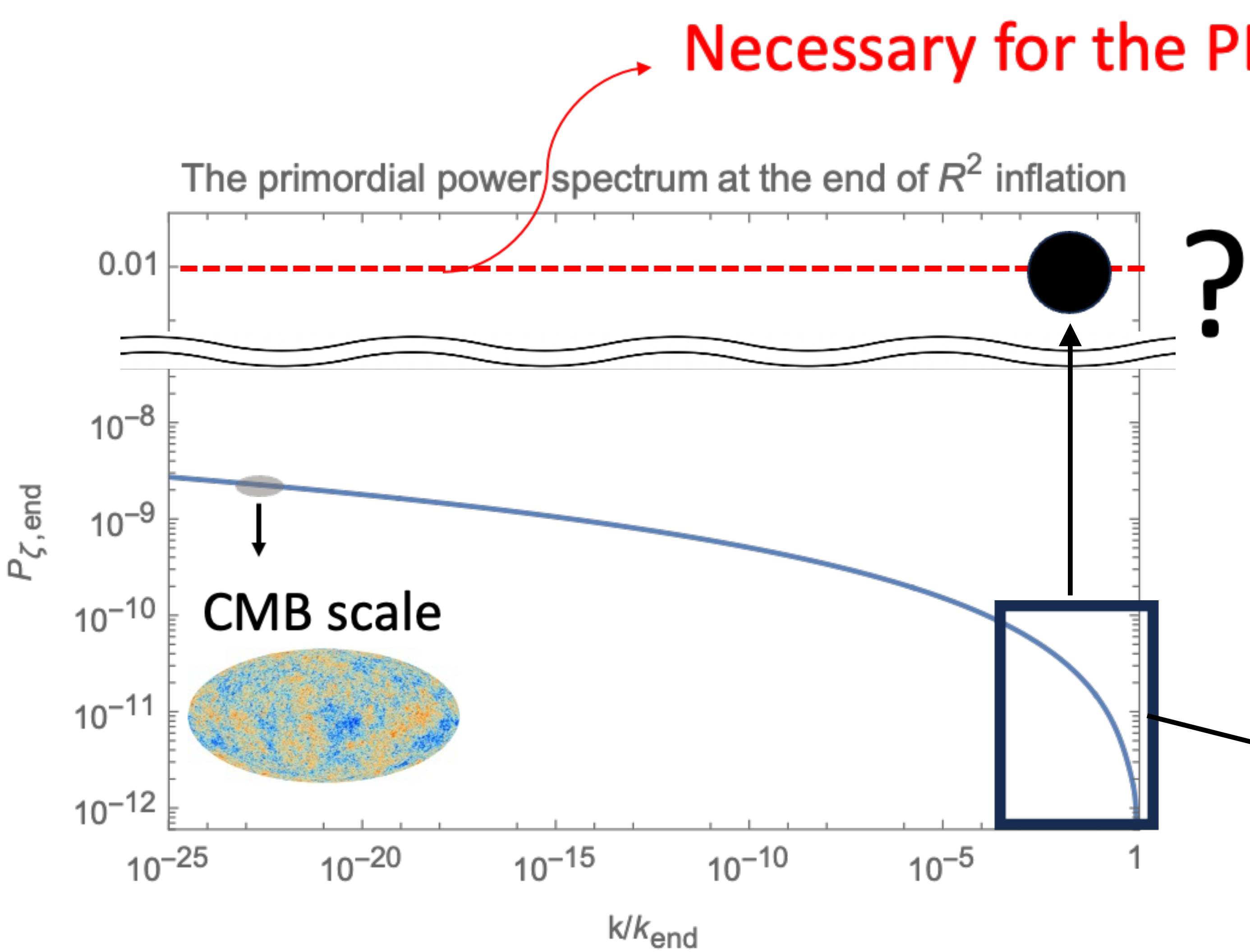
$$n_s - 1 = \frac{d \ln \mathcal{P}_\zeta(k)}{d \ln k} \simeq -6\epsilon_V + 2\eta_V \simeq -\frac{2}{N_*},$$

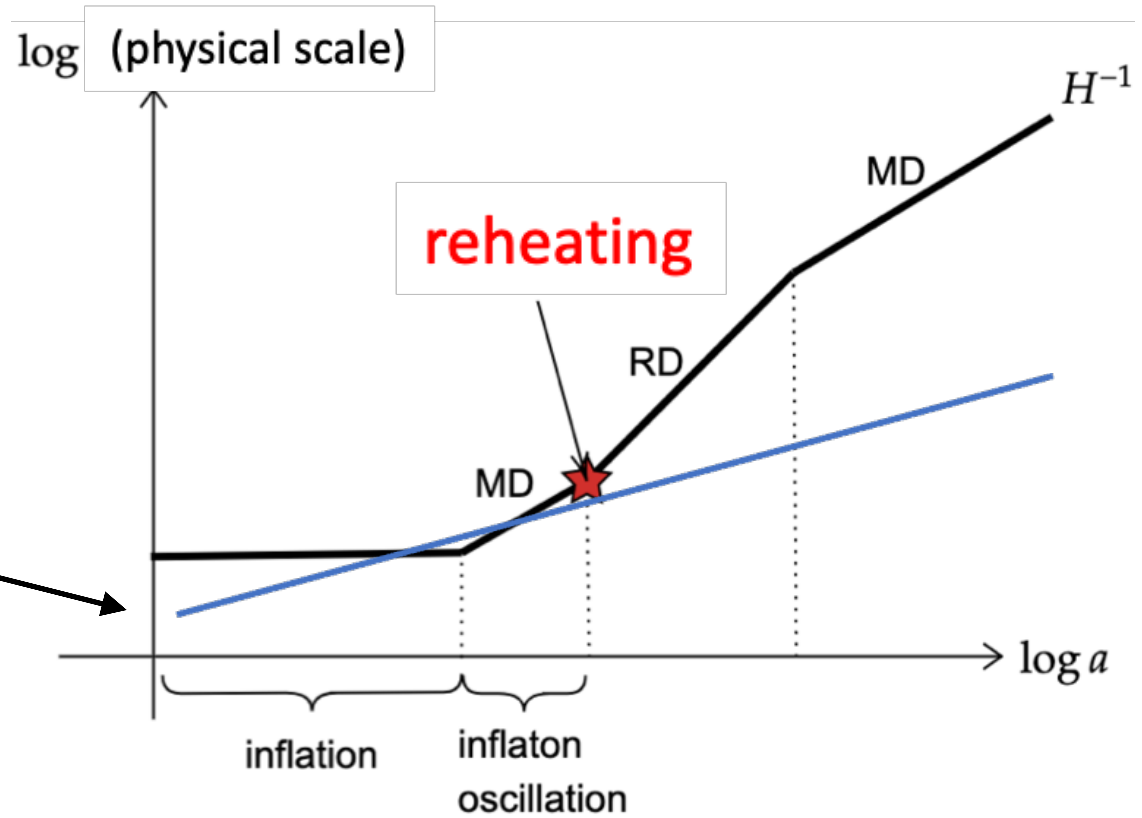
$$n_t = \frac{d \ln \mathcal{P}_\gamma(k)}{d \ln k} \simeq -2\epsilon_V \simeq -\frac{3}{2N_*^2},$$

$$\frac{dn_s}{d \ln k} \simeq 16\epsilon_V \eta_V - 24\epsilon_V^2 - 2\xi_V^2 \simeq -\frac{2}{N_*^2},$$

$$\frac{dn_t}{d \ln k} \simeq 4\epsilon_V \eta_V - 8\epsilon_V^2 \simeq -\frac{3}{N_*^3},$$

PBH formation after R² inflation?





These modes **re-enter** the horizon

& **grow** during the long inflaton-oscillation epoch

Perturbations during the inflaton-oscillation era

[Finelli, Brandenberger 1999; Jedamzik, Lemoine, Martin 2010]

Background

$\phi(t) \propto a(t)^{-3/2} \sin Mt$

→ Effective MD

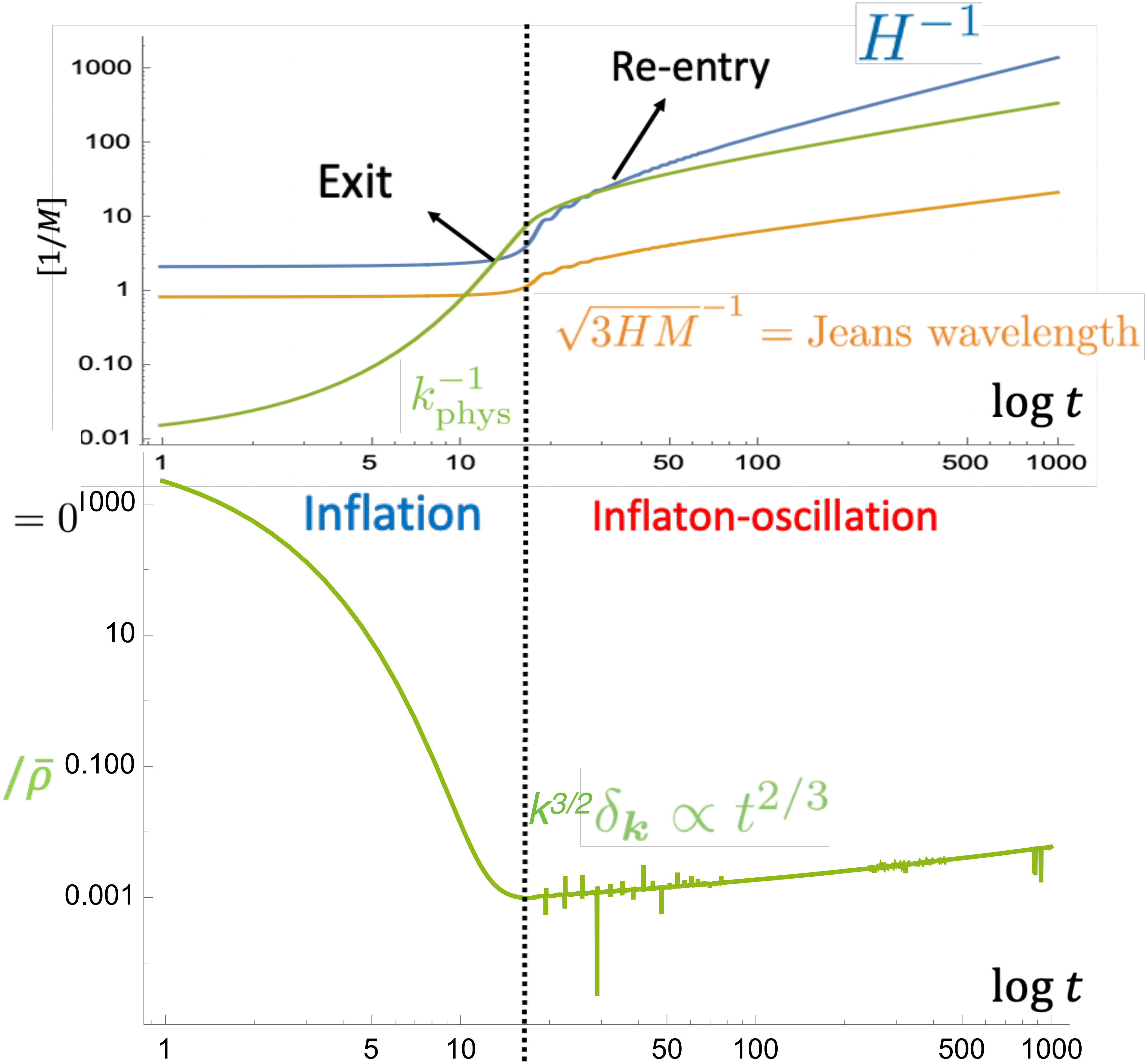
Perturbation

Mukhanov-Sasaki Eq.

$$v_{\boldsymbol{k}}'' + \left(k^2 - \frac{\left(a\sqrt{\epsilon\left[\phi(t)\right]}\right)''}{a\sqrt{\epsilon\left[\phi(t)\right]}} \right) v_{\boldsymbol{k}} = 0$$

→ Mathieu Eq.

Linear growth of $\delta = (\rho - \bar{\rho})/\bar{\rho}$ due to Jeans instability



Perturbations during the inflaton-oscillation era

[Finelli, Brandenberger 1999; Jedamzik, Lemoine, Martin 2010]

Background

$\phi(t) \propto a(t)^{-3/2} \sin Mt$

→ Effective MD

Perturbation

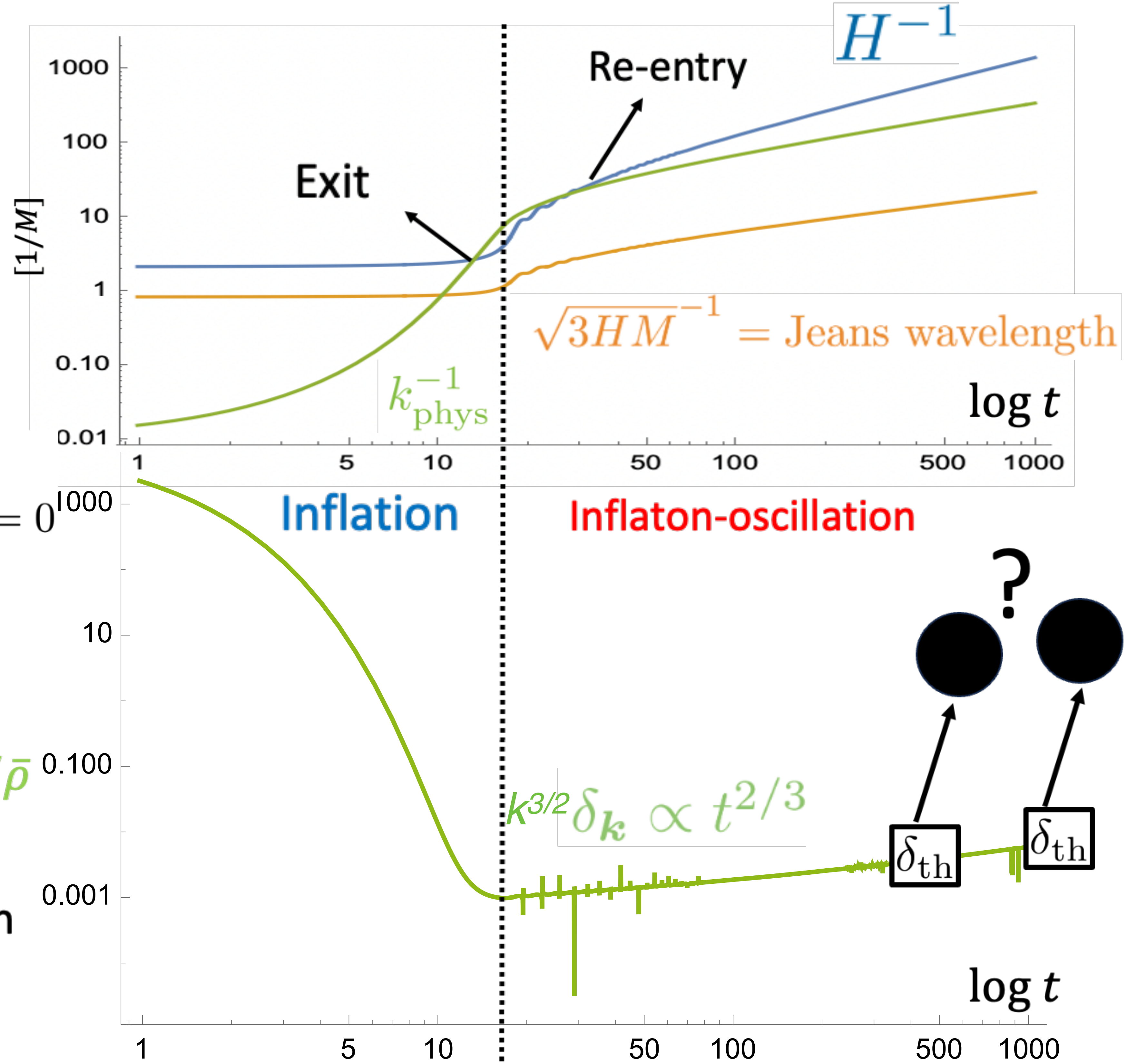
Mukhanov-Sasaki Eq.

$$v_{\boldsymbol{k}}'' + \left(k^2 - \frac{\left(a\sqrt{\epsilon\,[\phi(t)]}\right)''}{a\sqrt{\epsilon\,[\phi(t)]}} \right) v_{\boldsymbol{k}} = 0$$

→ Mathieu Eq.

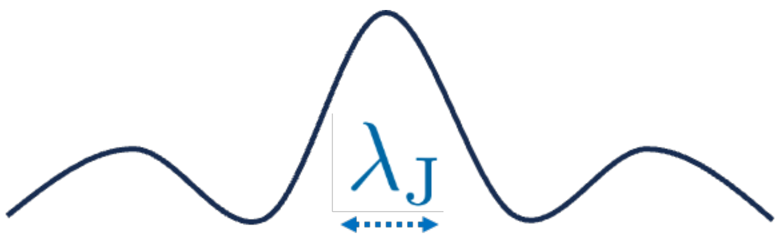
Linear growth of $\delta = (\rho - \bar{\rho})/\bar{\rho}$
due to Jeans instability

Long inflaton-ocsillation epoch
⇨ δ grows large ⇨ PBH?

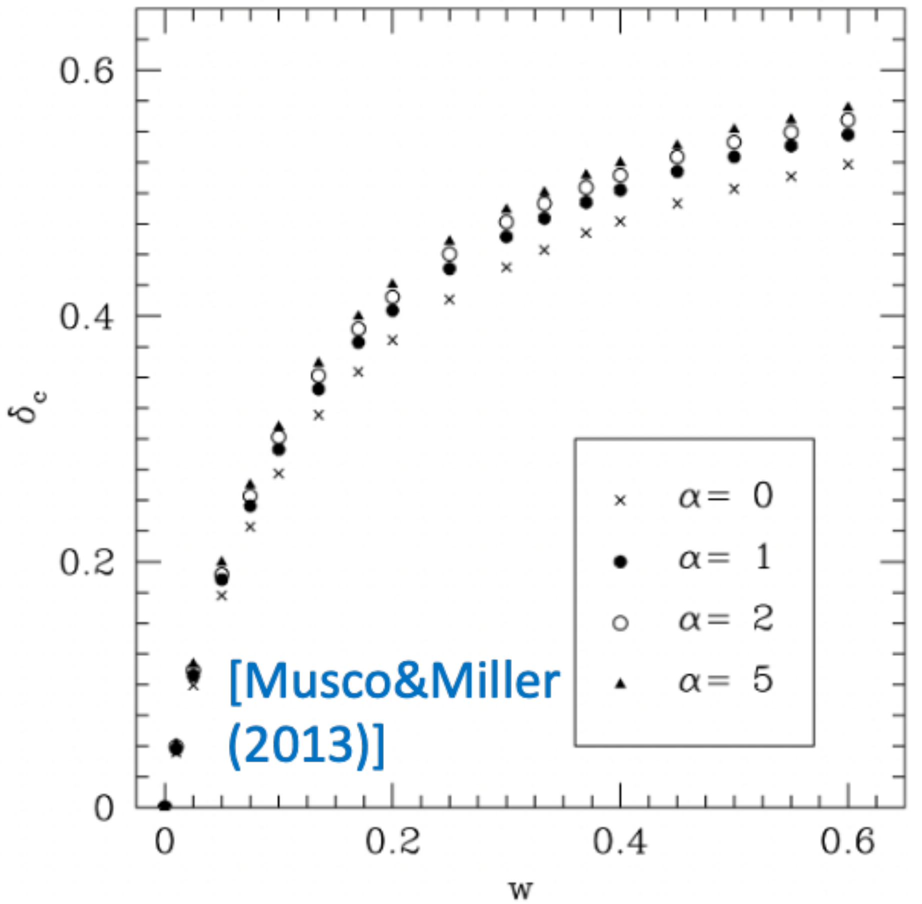


PBH formation condition: Jeans criterion $\delta > \delta_{\rm th}$

RD($w = 1/3$)



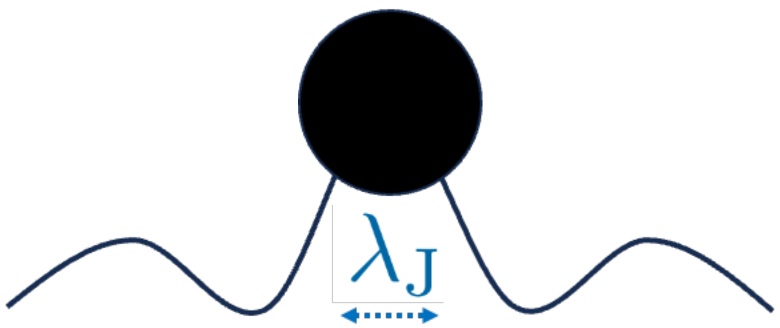
$1/3 > w > 0$



MD($w = 0$)

PBH formation condition: Jeans criterion $\delta > \delta_{\rm th}$

RD($w = 1/3$)



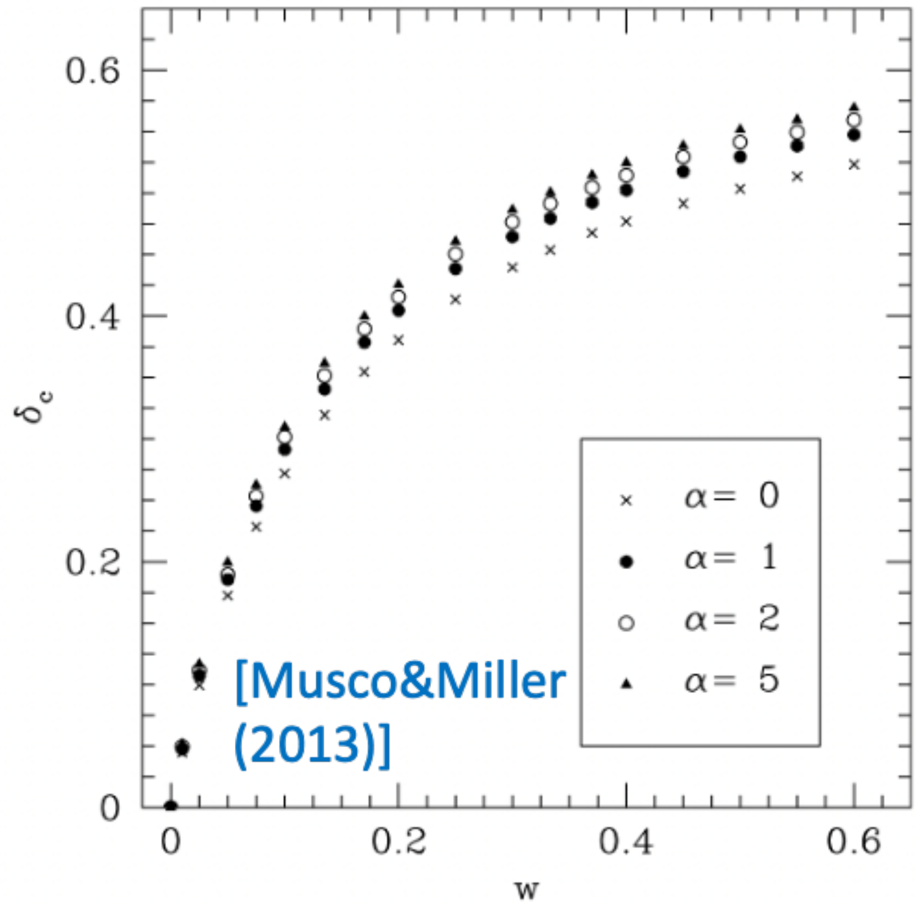
Jeans condition

$$\lambda > \lambda_{\rm J}$$

$$\Rightarrow \quad \delta_{\rm th} \simeq 0.33$$

[B. J. Carr 1975]

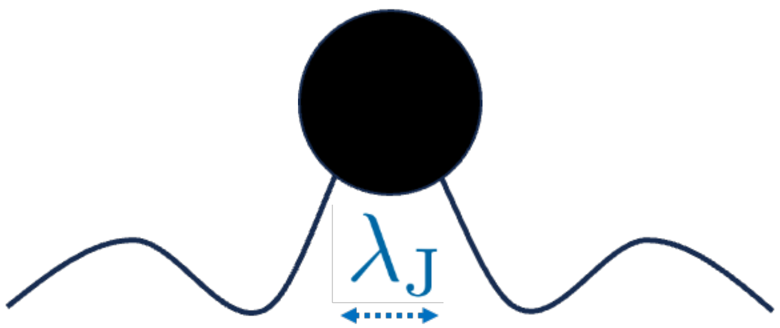
1/3> w > 0



MD($w = 0$)

PBH formation condition: Jeans criterion $\delta > \delta_{\rm th}$

RD($w = 1/3$)



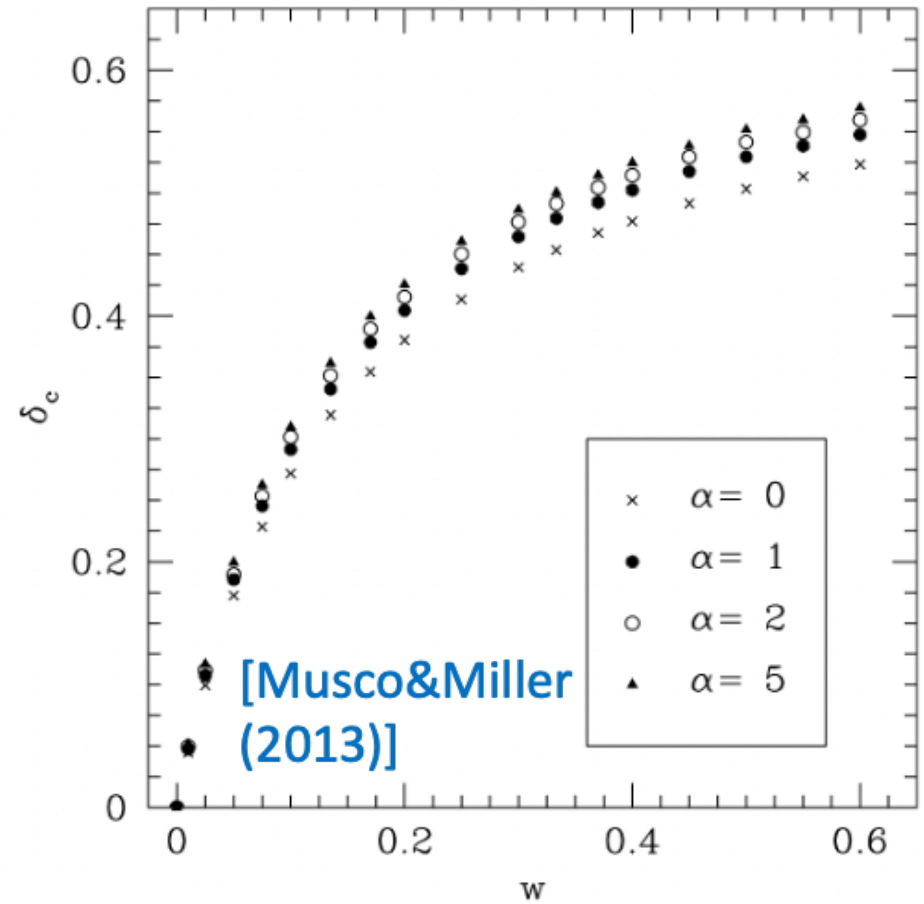
Jeans condition

$$\lambda > \lambda_{\rm J}$$

$$\Rightarrow \quad \delta_{\rm th} \simeq 0.33$$

[B. J. Carr 1975]

1/3> $w > 0$



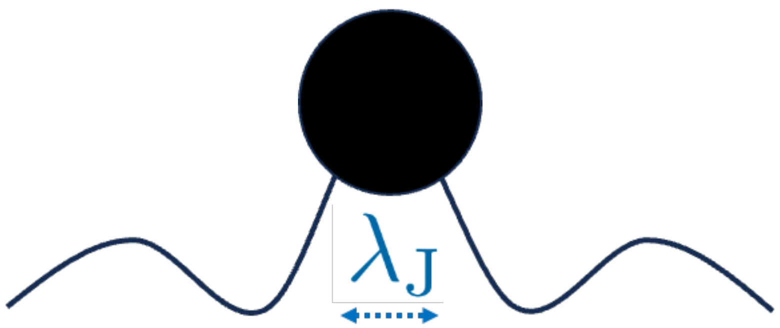
$$\delta_{\rm th} = \frac{3(1+w)}{5+3w} \sin^2 \left[\frac{\pi\sqrt{w}}{1+3w} \right]$$

[T. Harada et al. 2013]

MD($w = 0$)

PBH formation condition: Jeans criterion $\delta > \delta_{\rm th}$

RD($w = 1/3$)



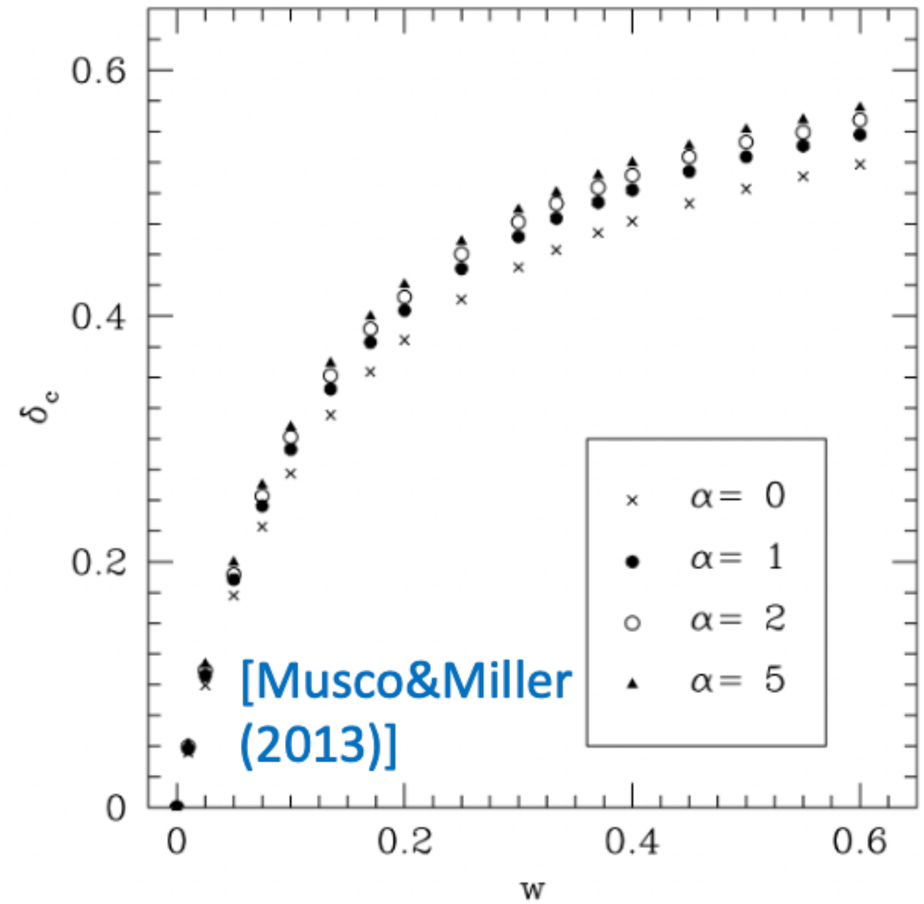
Jeans condition

$$\lambda > \lambda_{\rm J}$$

$$\Rightarrow \quad \delta_{\rm th} \simeq 0.33$$

[B. J. Carr 1975]

1/3> $w > 0$



$$\delta_{\rm th} = \frac{3(1+w)}{5+3w} \sin^2\left[\frac{\pi\sqrt{w}}{1+3w}\right]$$

[T. Harada et al. 2013]

MD($w = 0$)

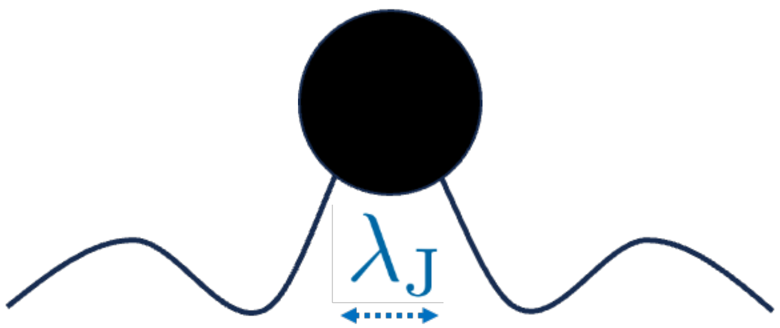
naive

extrapolation

$$\delta_{\rm th} = 0$$

PBH formation condition: Jeans criterion $\delta > \delta_{\rm th}$

RD($w = 1/3$)



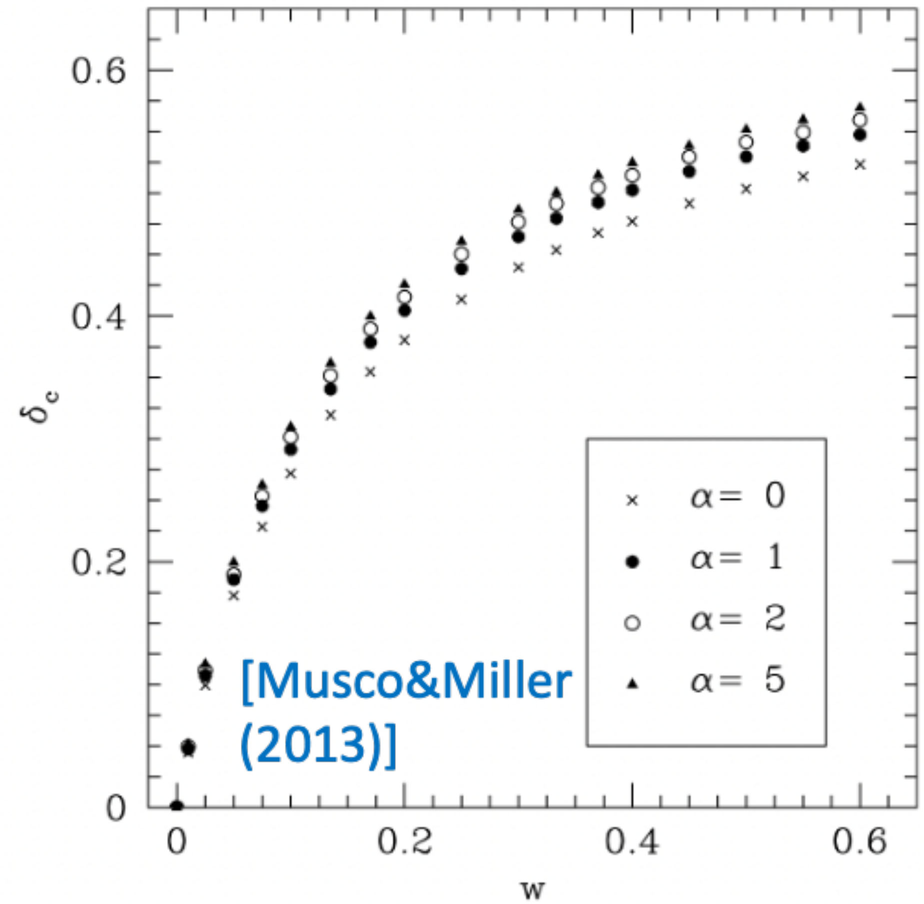
Jeans condition

$$\lambda > \lambda_J$$

$$\Rightarrow \quad \delta_{\rm th} \simeq 0.33$$

[B. J. Carr 1975]

1/3> $w > 0$

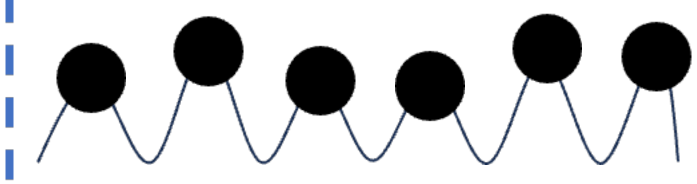


$$\delta_{\rm th} = \frac{3(1+w)}{5+3w}\sin^2\left[\frac{\pi\sqrt{w}}{1+3w}\right]$$

[T. Harada et al. 2013]

MD($w = 0$)

crazy



?

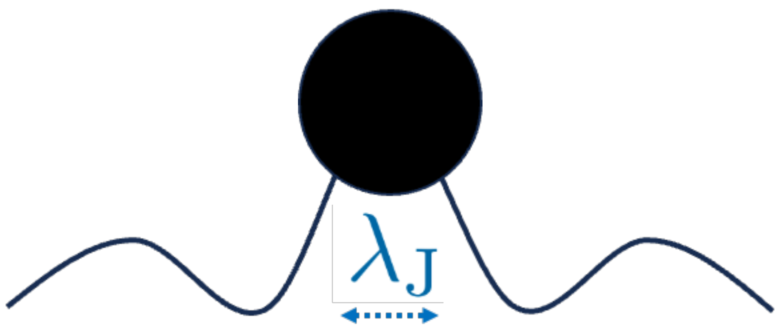
naive extrapolation

$$\delta_{\rm th} = 0$$

Untrustable

PBH formation condition: Jeans criterion $\delta > \delta_{\rm th}$

RD($w = 1/3$)



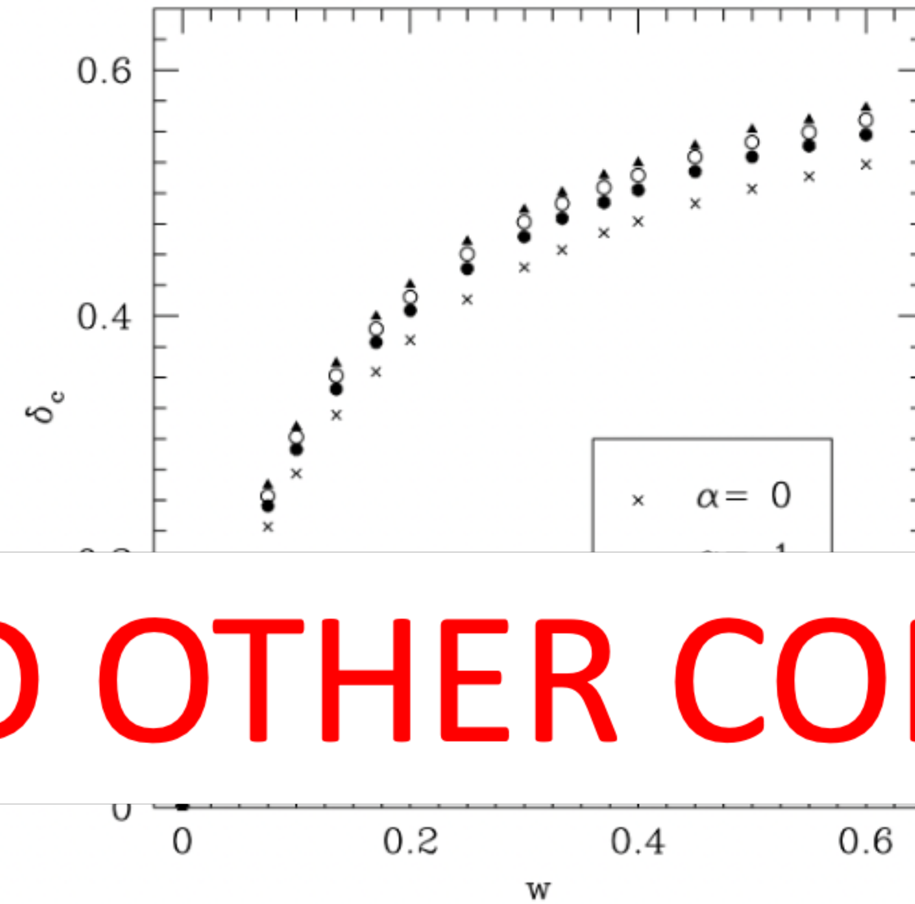
Jea

$\lambda > \lambda_J$

$\Rightarrow$ $\delta_{\rm th} \simeq 0.33$

[B. J. Carr 1975]

$1/3 > w > 0$

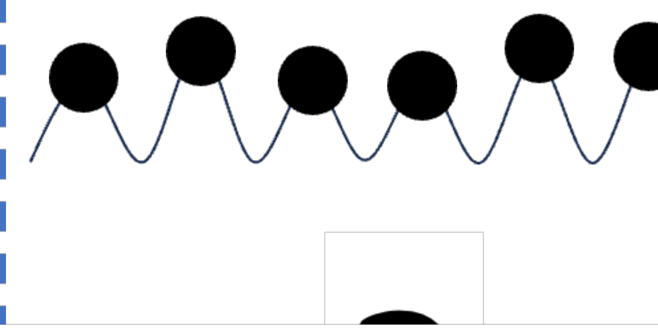


$$\delta_{\rm th} = \frac{3(1+w)}{5+3w} \sin^2 \left[\frac{\pi\sqrt{w}}{1+3w} \right]$$

[T. Harada et al. 2013]

MD($w = 0$)

crazy



naive extrapolation

$\delta_{\rm th} = 0$

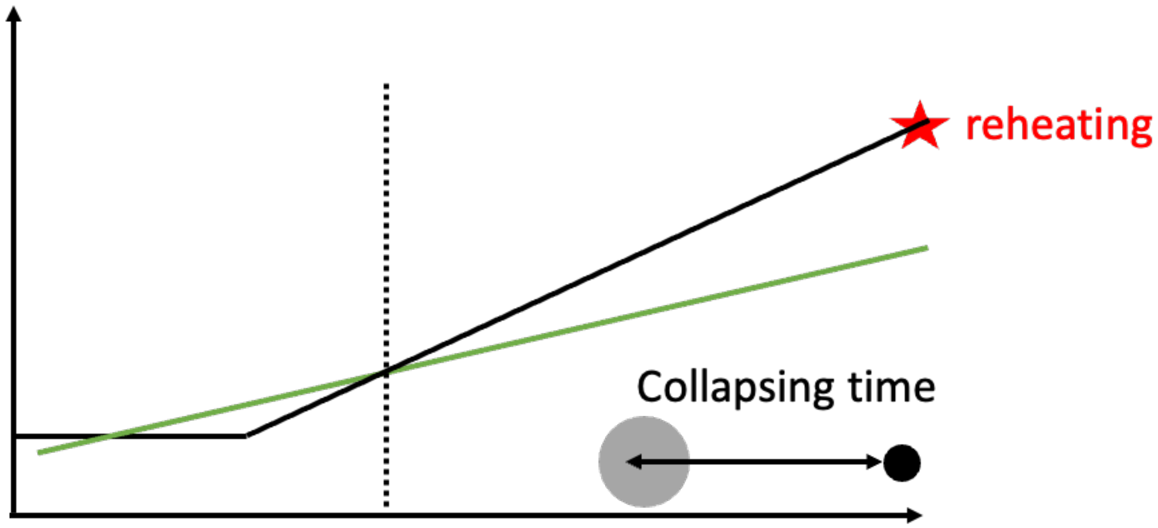
Untrustable

WE NEED OTHER CONDITION

Overproduction of PBHs during oscillation era

[Martin, Papanikolaou, Venin 2020]

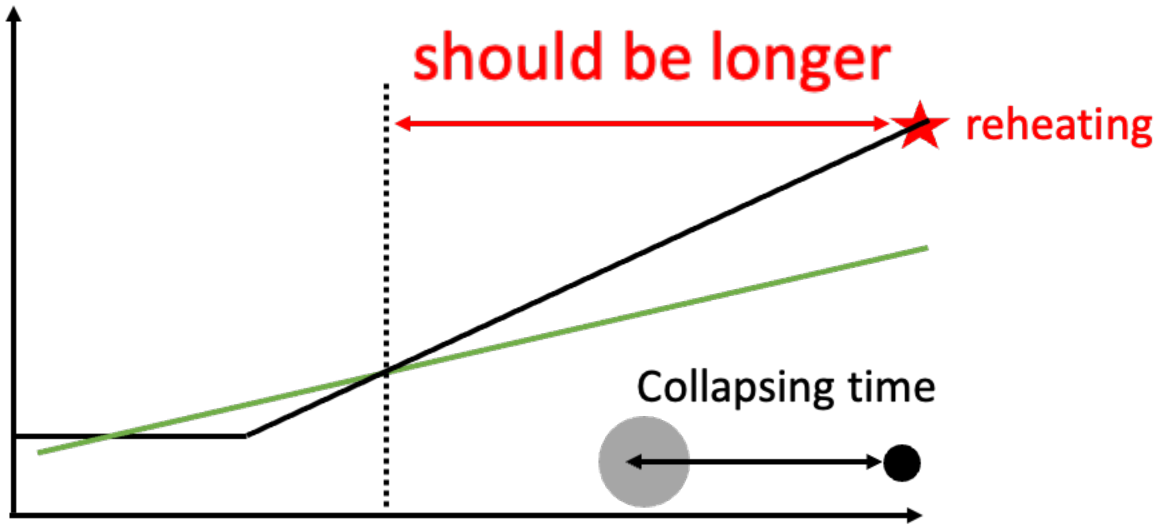
Another condition



Overproduction of PBHs during oscillation era

[Martin, Papanikolaou, Venin 2020]

Another condition

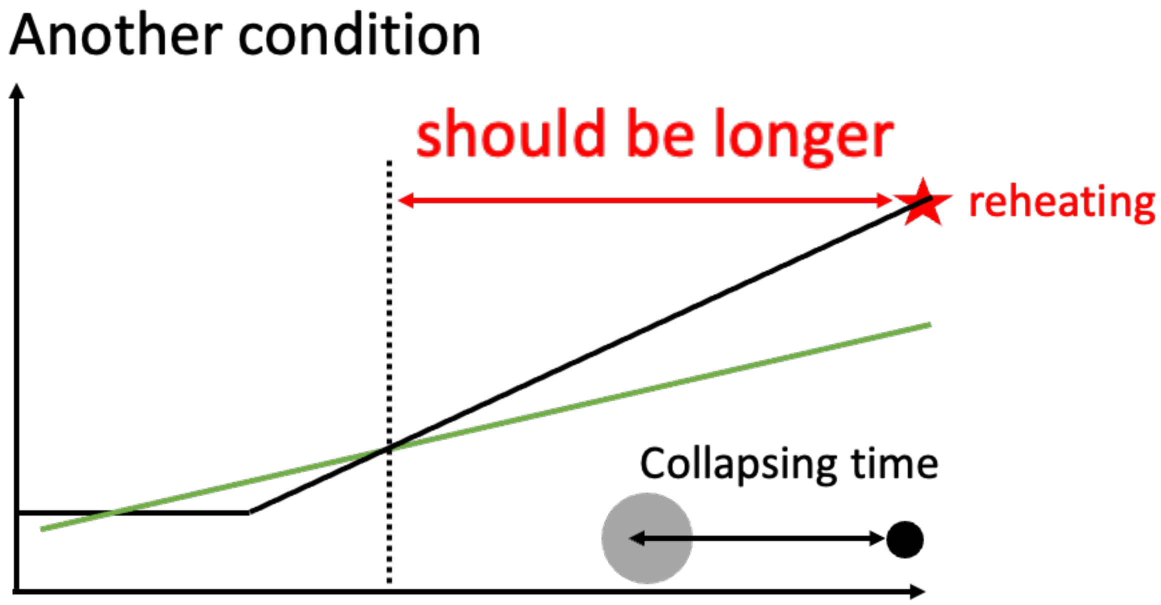


Mass fraction of PBHs

$$\beta(k(M)) = 2\int_{\delta_{\rm th}}^{\infty} P(\delta)d\delta$$

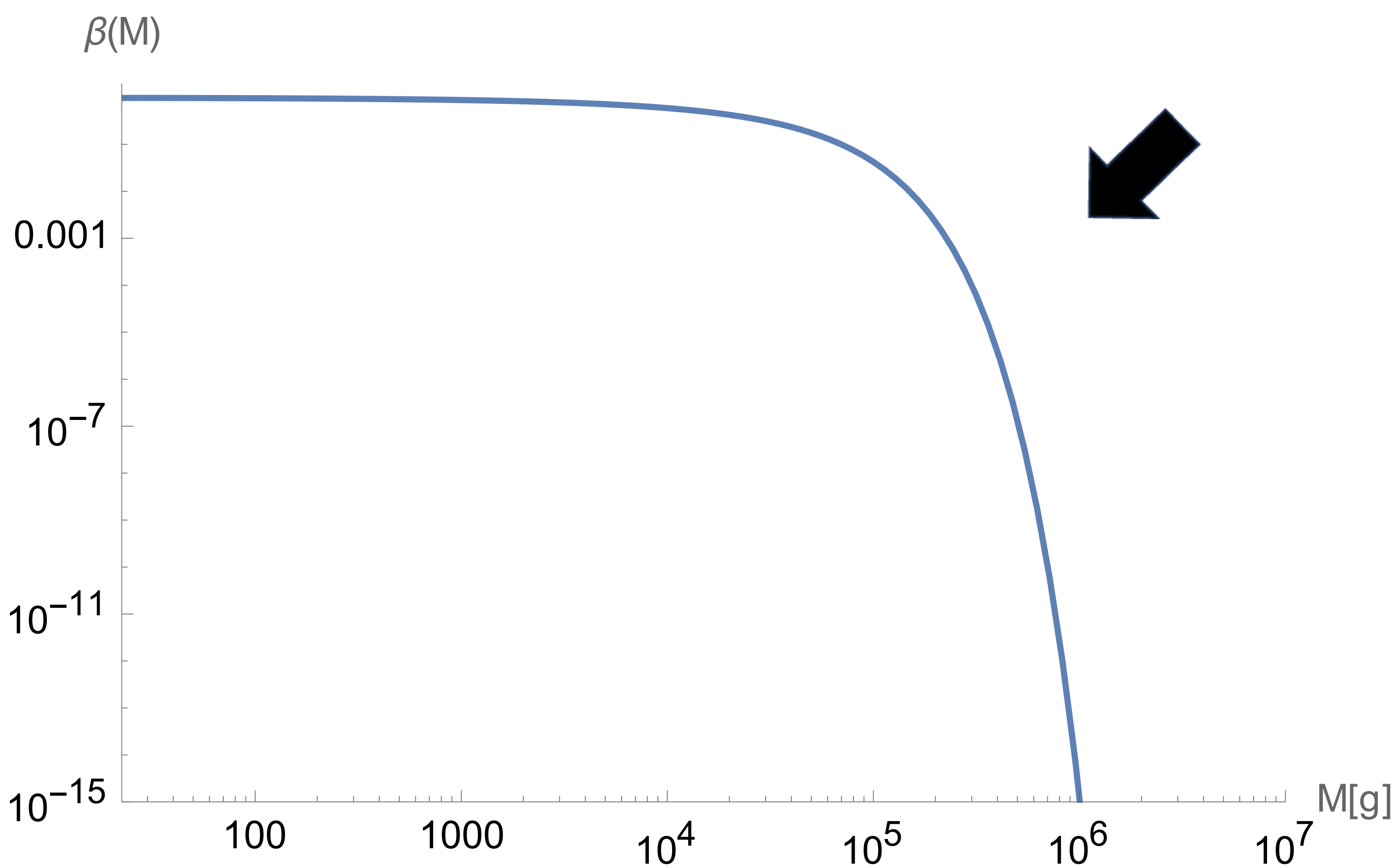
Overproduction of PBHs during oscillation era

[Martin, Papanikolaou, Venin 2020]



Mass fraction of PBHs

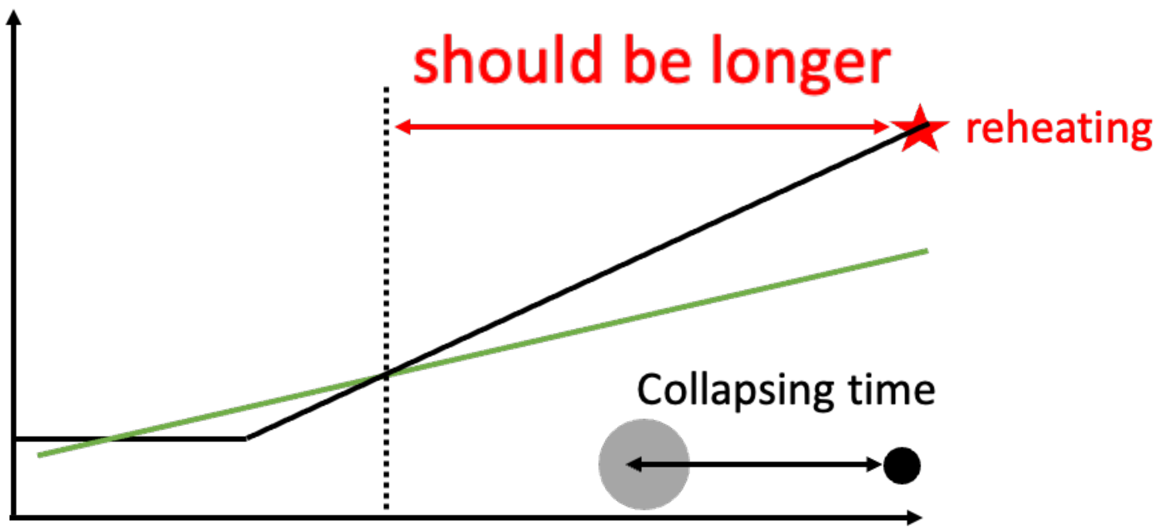
$$\beta(k(M)) = 2\int_{\delta_{\rm th}}^{\infty} P(\delta)d\delta$$



Overproduction of PBHs during oscillation era

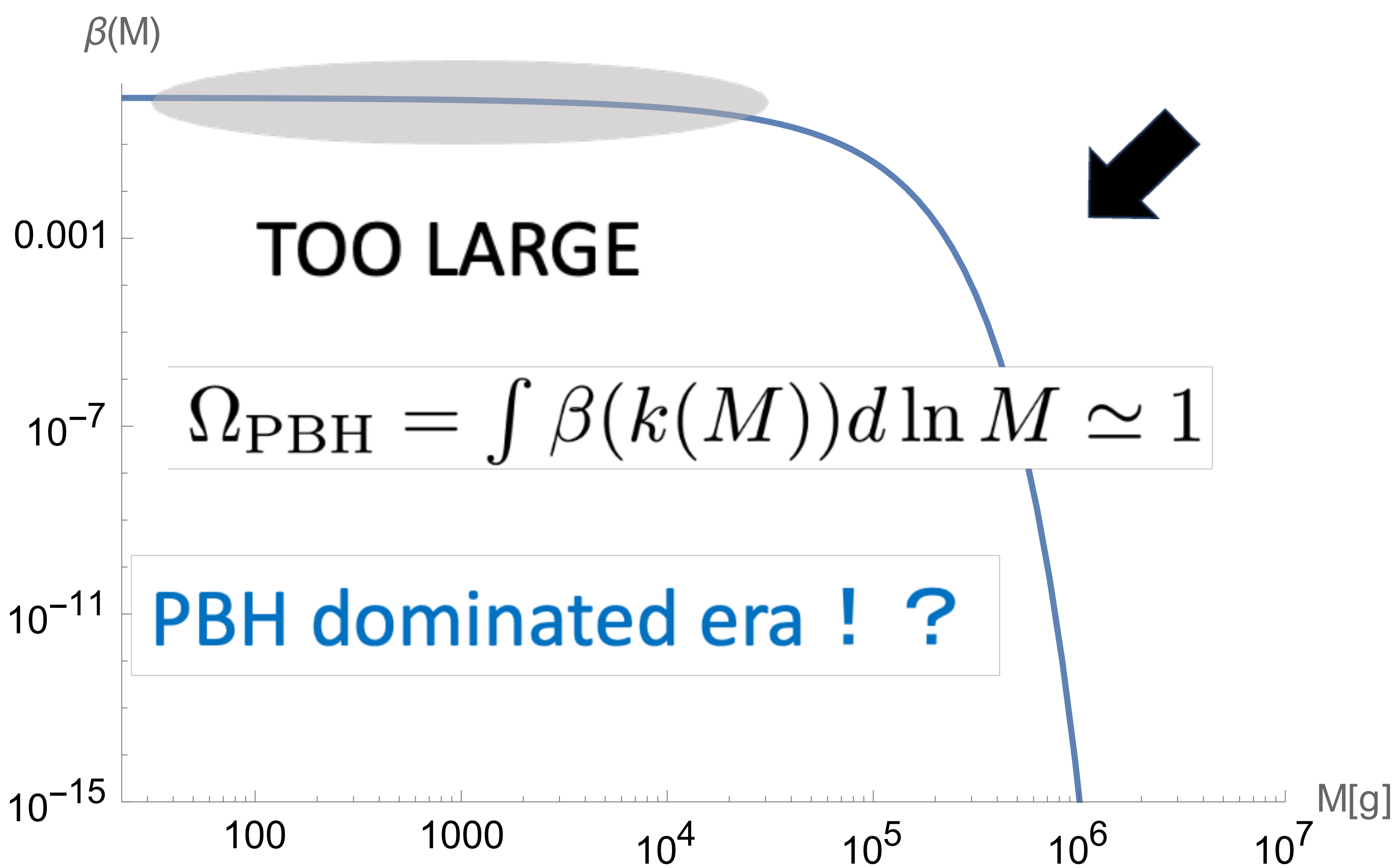
[Martin, Papanikolaou, Venin 2020]

Another condition



Mass fraction of PBHs

$$\beta(k(M)) = 2\int_{\delta_{\rm th}}^{\infty} P(\delta)d\delta$$



TOO LARGE

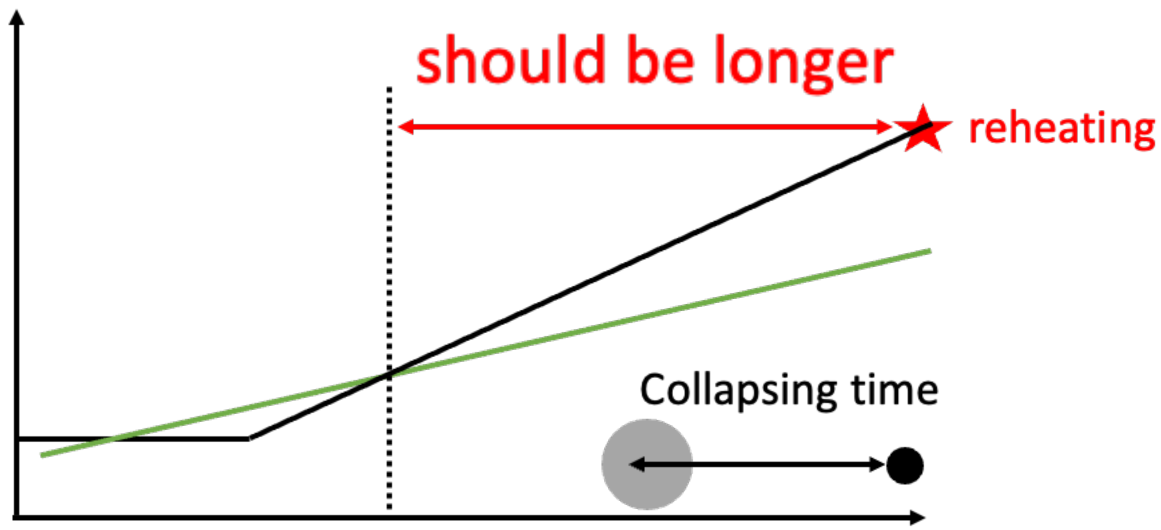
$$\Omega_{\rm PBH} = \int \beta(k(M))d\ln M \simeq 1$$

PBH dominated era！？

Overproduction of PBHs during oscillation era

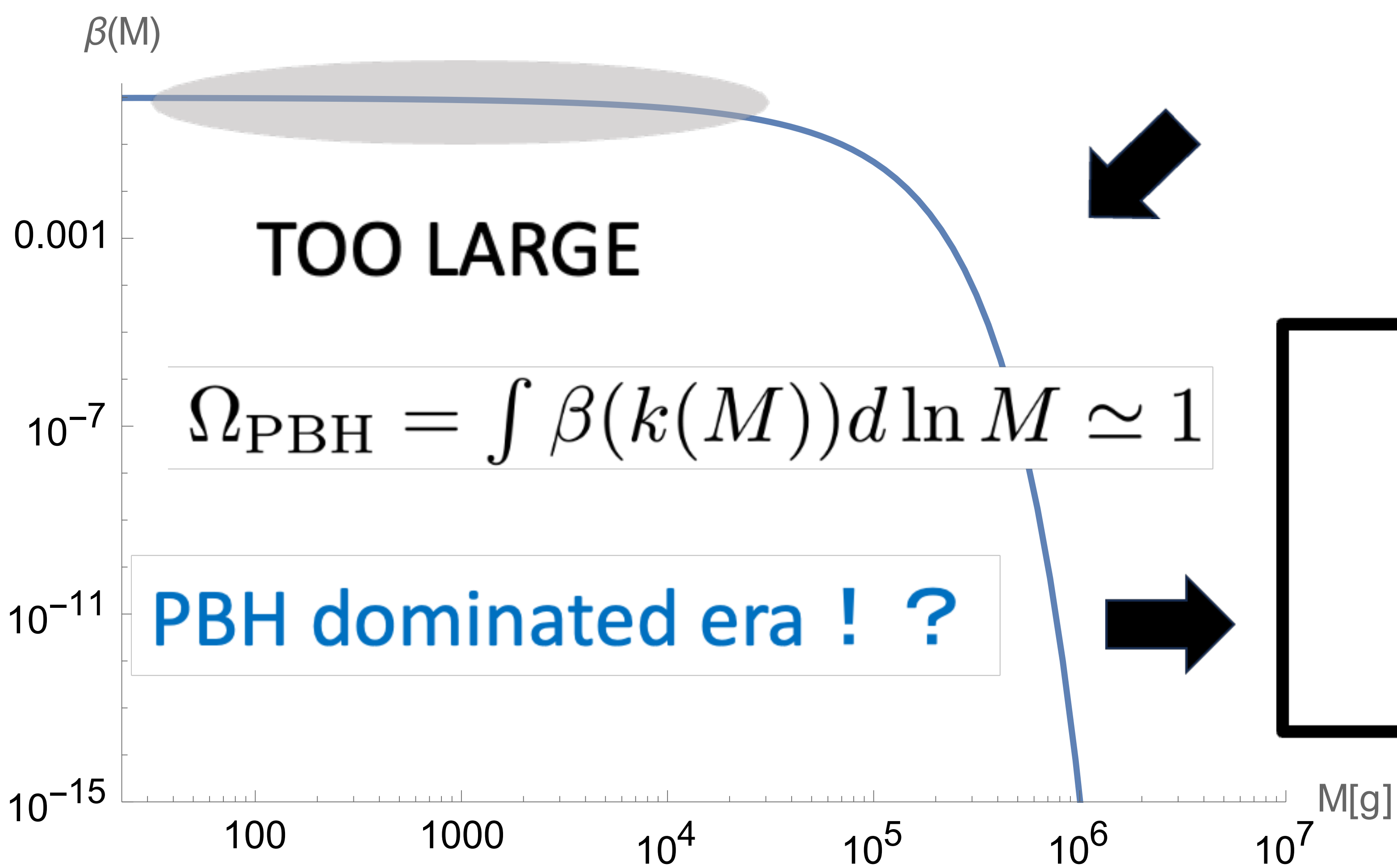
[Martin, Papanikolaou, Venin 2020]

Another condition



Mass fraction of PBHs

$$\beta(k(M)) = 2\int_{\delta_{\rm th}}^{\infty} P(\delta)d\delta$$



TOO LARGE

$$\Omega_{\rm PBH} = \int \beta(k(M))d\ln M \simeq 1$$

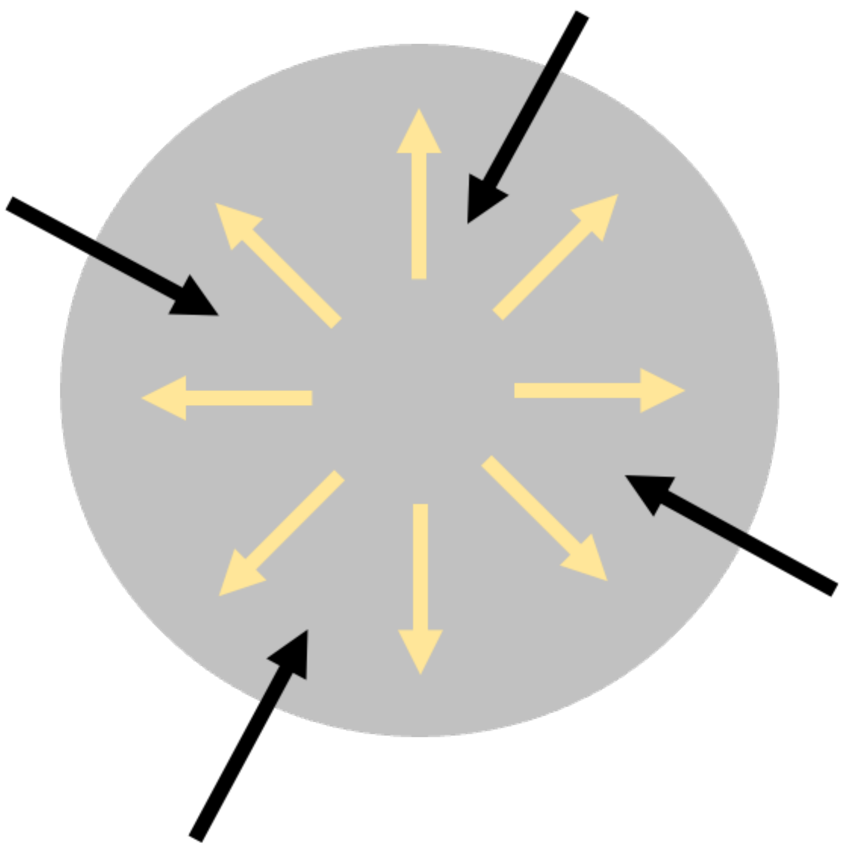
PBH dominated era！？

Other important effects:
Pancake collapse effect
&
Spin effect

Our viewpoint

The evolution of the anisotropy

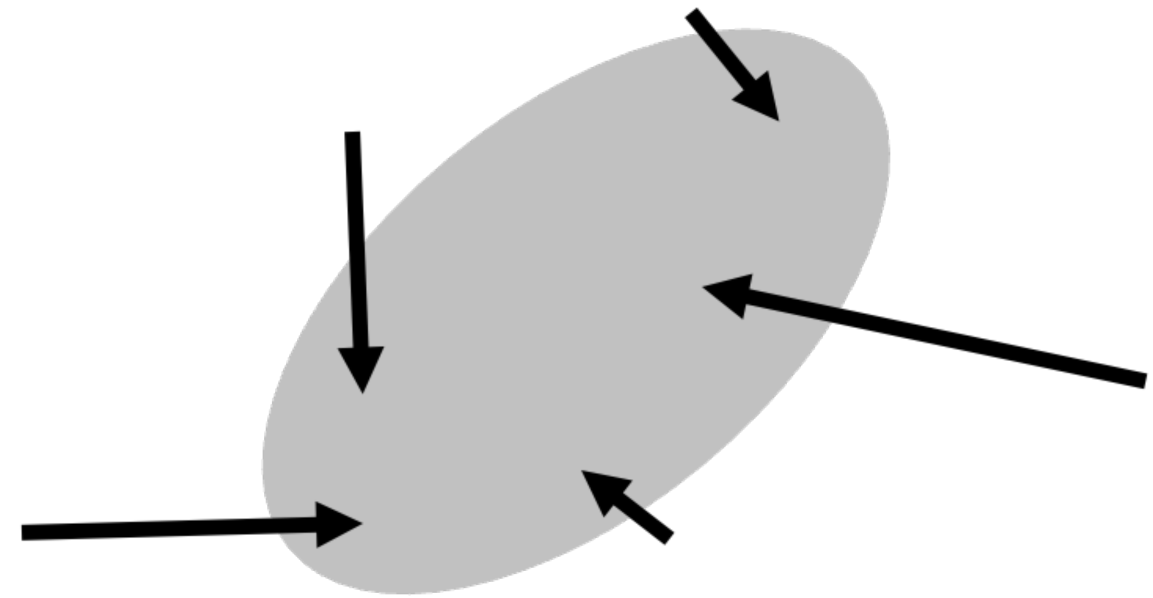
Radiation Dominated



Spherical Collapse

Matter Dominated

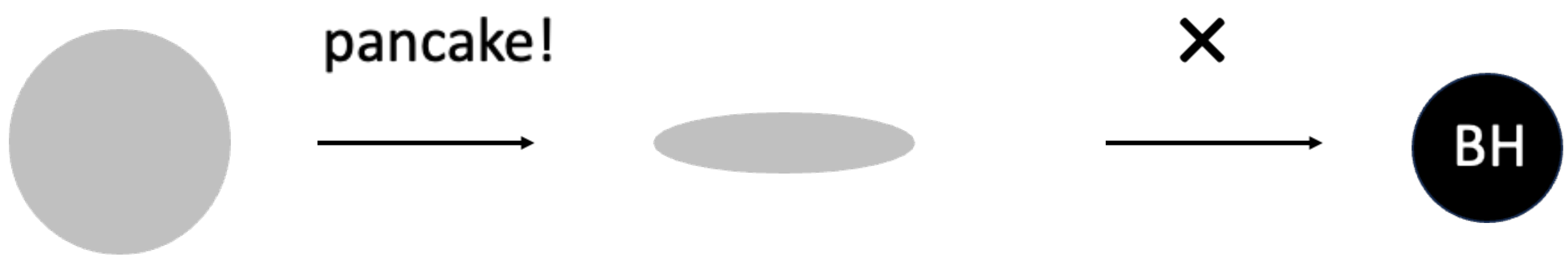
w/o Pressure gradient force



Non-Spherical Collapse

Pancake Collapse Effect

[Khlopov, Polnarev 1980; Harada, Yoo, Kohri, Jhingan 2016]



Hoop Conjecture [K. Thorne 1972]

If ∃ perimeter > $2\pi\times$(Schwarzchild radius) → cannot collapse

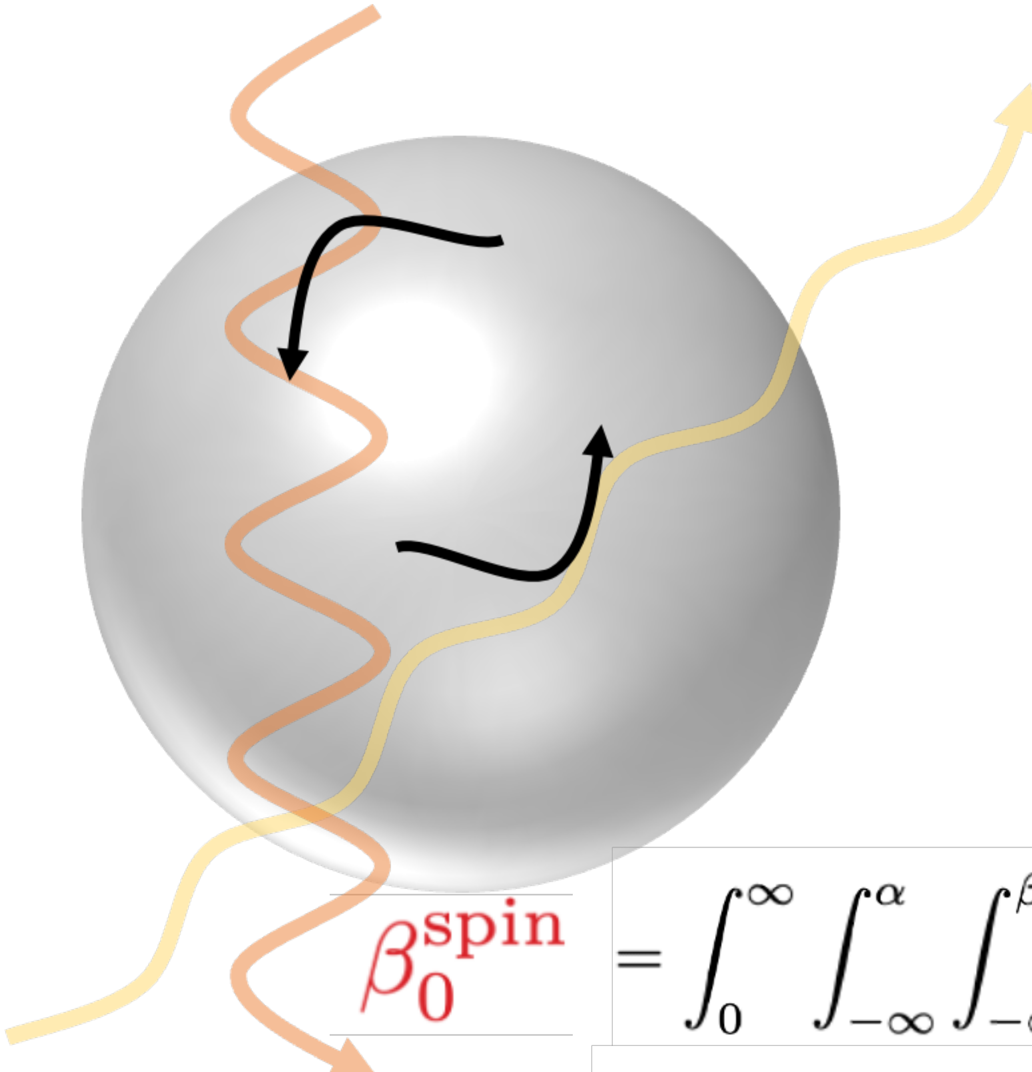
$$\beta_0^{\text{pancake}} = \int_0^\infty d\alpha \int_{-\infty}^{\alpha} d\beta \int_{-\infty}^{\beta} d\gamma\, \theta(1 - h(\alpha,\beta,\gamma))w(\alpha,\beta,\gamma)$$

$$\simeq 0.071\sigma_H^5$$

$$\sigma_H = \sqrt{\mathcal{P}_\delta}$$

The Spin Effect

[Harada, Yoo, Kohri, Nakao 2017]



Two modes couples to produce the torque

↓

Centrifugal force prevents the collapsing

↓

Kerr parameter ≤ 1 determines the threshold

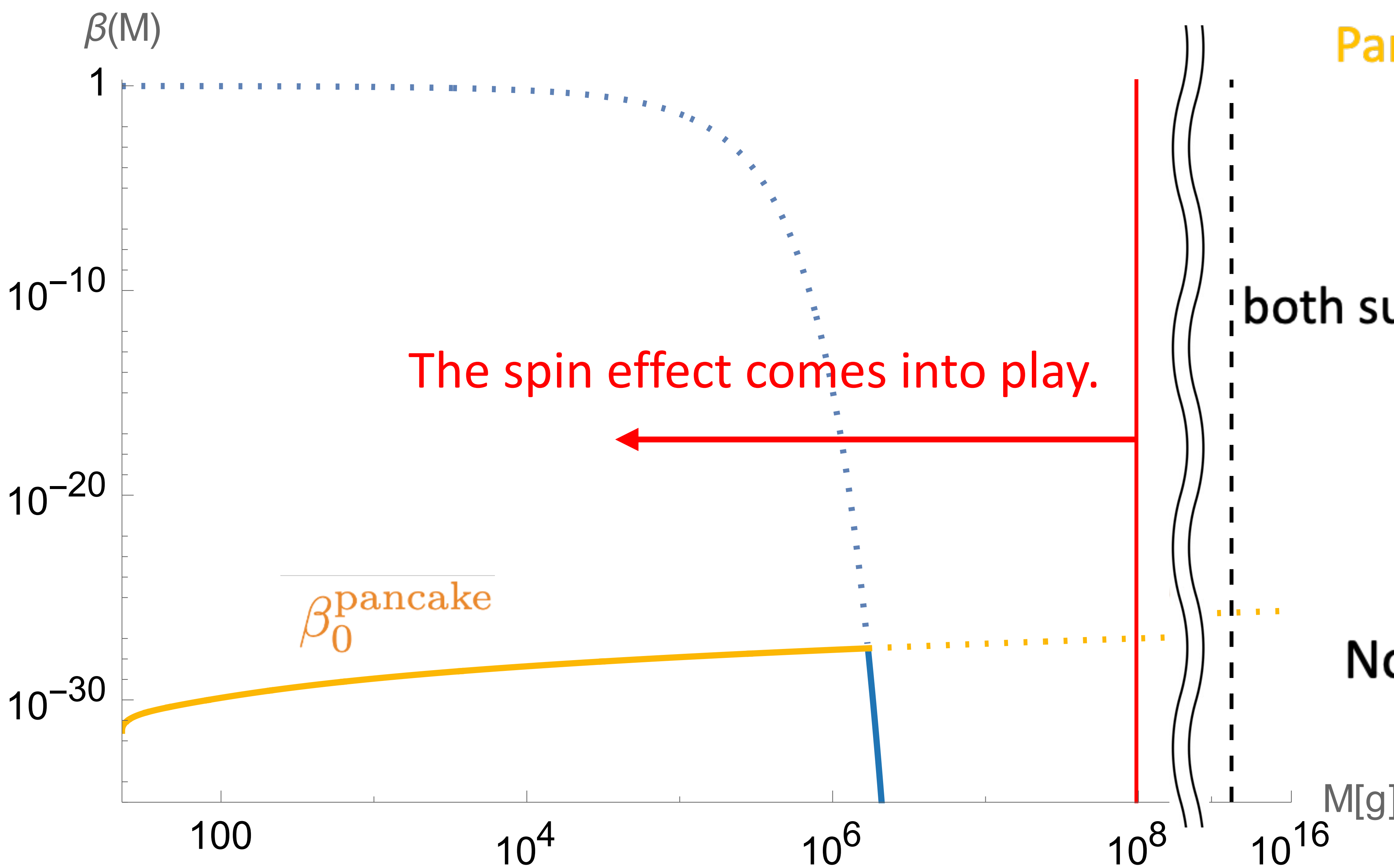
$$\beta_0^{\mathrm{spin}} = \int_0^{\infty}\int_{-\infty}^{\alpha}\int_{-\infty}^{\beta} \theta(\delta_H(\alpha,\beta,\gamma) - \delta_{\mathrm{th}}) \times \theta(1 - h(\alpha,\beta,\gamma)) w(\alpha,\beta,\gamma)$$

$$\simeq 1.921 \times 10^{-7} f_q(q_c)\mathcal{I}^6 \sigma_{\mathrm{H}}^2 \times \exp\left[-0.1474 \times \frac{\mathcal{I}^{4/3}}{\sigma_{\mathrm{H}}^{2/3}}\right]$$

$$\sigma_{\mathrm{H}} \sim 10^{-5}$$

PBH production is suppressed very very very much!!!

Result: No PBH dominant era



Pancake collapse effect

&

Spin effect

both suppresses PBH formation

↓

No PBH dominated era！

Conclusion

MODEL: R^2 inflation model

FOCUS: The density perturbation @ inflaton-oscillation epoch

Previous work

The possibility of PBH over-production
→PBH dominated era [J. Martin, Papanikolau, Venin 2020]

However

This Talk

Pancake-like collapse effect
&Spin effect

We show **the anisotropic effect**
suppresses the production of PBH
→NO PBH dominated era

$$T_{\rm rh} \sim 10^9\ {\rm GeV}$$

Appendix: SUSY Scenarios

Higher derivative SUGRA [Cecotti 1987; Ferrara & Porrati 2014]

R is the supercurvature
ϕ, V are the matter sector

$$S=\int \mathrm{d}^4x\mathrm{d}^4\theta E\left(N(\mathcal{R},\bar{\mathcal{R}})+J\left(\phi,\bar{\phi}e^{gV}\right)\right)$$
$$+\left[\int \mathrm{d}^4x\mathrm{d}^2\Theta 2\mathscr{E}\left(F(\mathcal{R})+P(\phi)+\frac{1}{4}h_{AB}(\phi)W^AW^B\right)+\mathrm{H.c.}\right]$$

↓ duality trans. by T, S (T is the Lagrange multiplier)

$$S=\int d^4xd^2\Theta 2\mathscr{E}\frac{3}{8}\left(\bar{\mathscr{D}}\bar{\mathscr{D}}-8\mathcal{R}\right)e^{-K/3}+W+\frac{1}{4}h_{AB}W^AW^B+\mathrm{H.c.}$$

Kahler pot: $K=-3\ln\left(\frac{T+\bar{T}-N(S,\bar{S})-J(\phi,\bar{\phi}e^{gV})}{3}\right),$

Superpot: $W=2TS+F(S)+P(\phi).$

Starobinsky SUGRA R2 inflation

[Terada, YW, Yamada, Yokoyama 1411.6746; Dalianis & YW 1801.05736]

$$\mathcal{L} = -3M_P^2 \int d^4\theta\, E \left[1 - \frac{4}{m_\Phi^2}\mathcal{R}\bar{\mathcal{R}} + \frac{\zeta}{3m_\Phi^4}\mathcal{R}^2\bar{\mathcal{R}}^2\right]$$

$$N(S,\bar{S}) = -3 + \frac{12}{m_\Phi^2}S\bar{S} - \frac{\zeta}{m_\Phi^4}\left(S\bar{S}\right)^2$$

$$F(S) = 0,$$

↓ ***S, ImT*** **are stabilized.**

Real part of T becomes the inflaton Φ: $V = \frac{3m_\Phi^2}{4}\left(1 - e^{-\sqrt{2/3}\widehat{\mathrm{Re}T}}\right)^2$

$$S = \int d^4x d^2\Theta 2\mathscr{E}\frac{3}{8}\left(\bar{\mathscr{D}}\bar{\mathscr{D}} - 8\mathcal{R}\right)e^{-K/3} + W + \frac{1}{4}h_{AB}W^A W^B + \mathrm{H.c.}$$

$$K = -3\ln\left(\frac{T + \bar{T} - N(S,\bar{S}) - J(\phi, \bar{\phi}e^{gV})}{3}\right),$$

$$W = 2TS + F(S) + P(\phi).$$

↓ **Grav. coupling to matter** ϕ**,** V

Starobinsky SUGRA R2 inflation

[Terada, YW, Yamada, Yokoyama 1411.6746; Dalianis & YW 1801.05736]

$$\mathcal{L} = -3M_P^2 \int d^4\theta \, E \left[1 - \frac{4}{m_\Phi^2}\mathcal{R}\bar{\mathcal{R}} + \frac{\zeta}{3m_\Phi^4}\mathcal{R}^2\bar{\mathcal{R}}^2\right]$$

$$N(S,\bar{S}) = -3 + \frac{12}{m_\Phi^2}S\bar{S} - \frac{\zeta}{m_\Phi^4}\left(S\bar{S}\right)^2$$

$$F(S) = 0,$$

Real part of T becomes the inflaton Φ: $V = \frac{3m_\Phi^2}{4}\left(1 - e^{-\sqrt{2/3}\widehat{\mathrm{Re}T}}\right)^2$

SUSY breaking field:

$$J(z,\bar{z}) = |z|^2 - \frac{|z|^4}{\Lambda^2},$$

$$P(z) = \mu^2 z + W_0,$$

Z may dominate after inflation.

Inflaton decay after SUGRA R2 inflation

[Terada, YW, Yamada, Yokoyama 1411.6746; Dalianis & YW 1801.05736]

Scalars:

$$\Gamma(T \to \phi^i \bar{\phi}^{\bar{i}}) = \frac{3m_i^4}{8\pi M_P^2 m_\Phi}, \quad \Gamma(T \to \phi^i \phi^j) = \frac{m_\Phi^3}{96\pi M_P^2} |J_{ij}|^2.$$

Fermions:

$$\Gamma(T \to \chi^i \bar{\chi}^{\bar{i}}) = \frac{m_i^2 m_\Phi}{192\pi M_P^2},$$

Gauge fields & gauginos:

$$\Gamma(T \to AA) + \Gamma(T \to \lambda\lambda) \simeq \frac{3N_g \alpha^2 m_\Phi^3}{128\pi^3 M_P^2} \left(T_G - \frac{1}{3}T_R\right)^2$$

Gravitinos: (Φ is inflaton)

$$\Gamma(\Phi_{R\pm} \to \psi_{3/2}\psi_{3/2}) \simeq \frac{m_\Phi^3}{48\pi M_P^2} \times \begin{cases} 16\left(\frac{m_{3/2}}{m_\Phi}\right)^2 & (m_z^2 \ll m_\Phi m_{3/2}) \\ \left(\frac{m_z}{m_\Phi}\right)^4 & (3m_\Phi m_{3/2} \ll m_z^2 \ll m_\Phi^2) \\ 1 & (m_\Phi^2 \ll m_z^2) \end{cases}$$

Constraints from gravitino abundance

[Terada, YW, Yamada, Yokoyama 1411.6746]

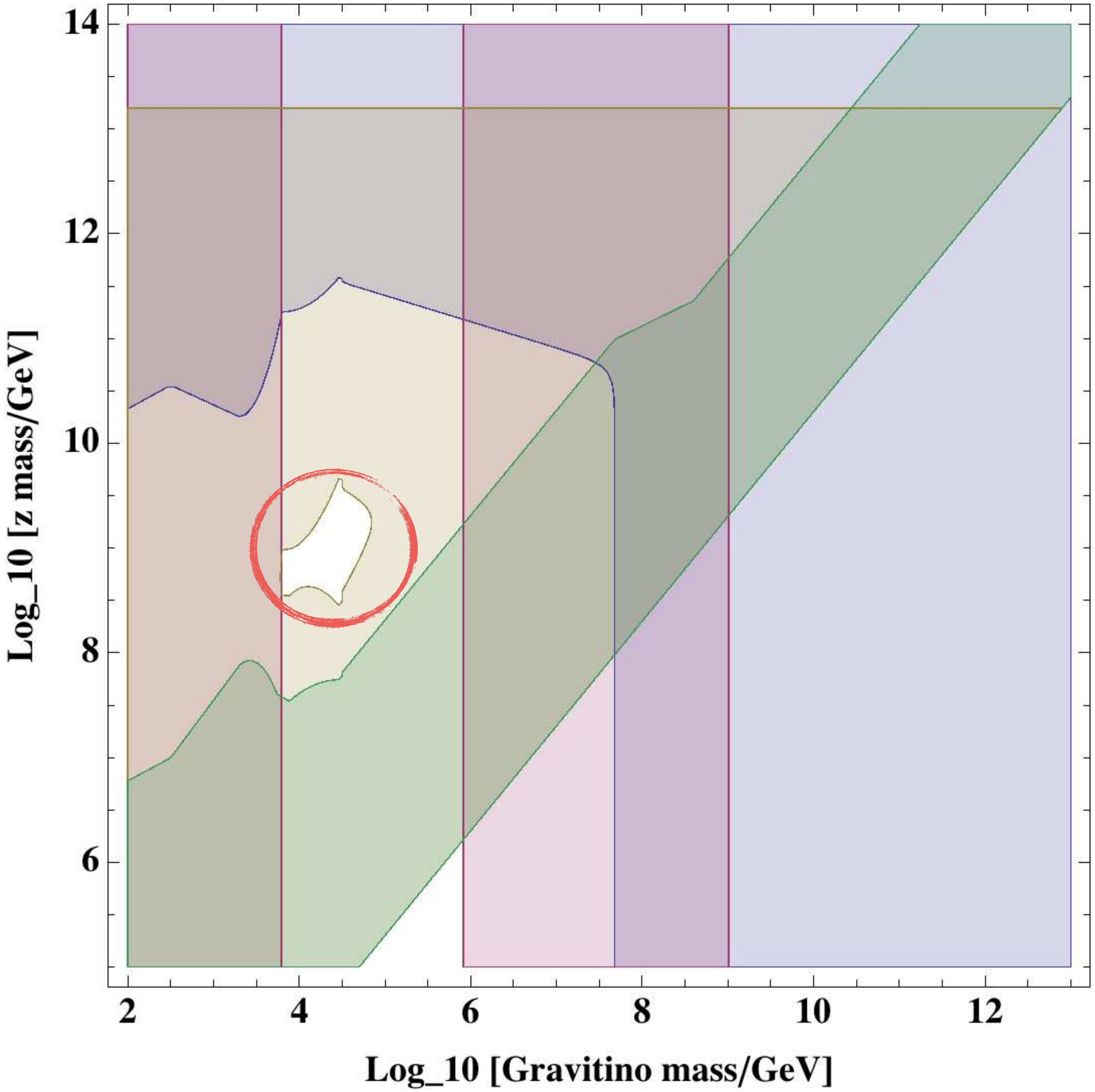
Gravitinos generated from:

1) inflaton decay
2) thermal scatterings
3) decay of particles
4) decay of oscillating Z

Neutralino LSP (~TeV WIMP) is assumed for:

gravitino mass > 10^4.5 GeV
→ anomaly mediation

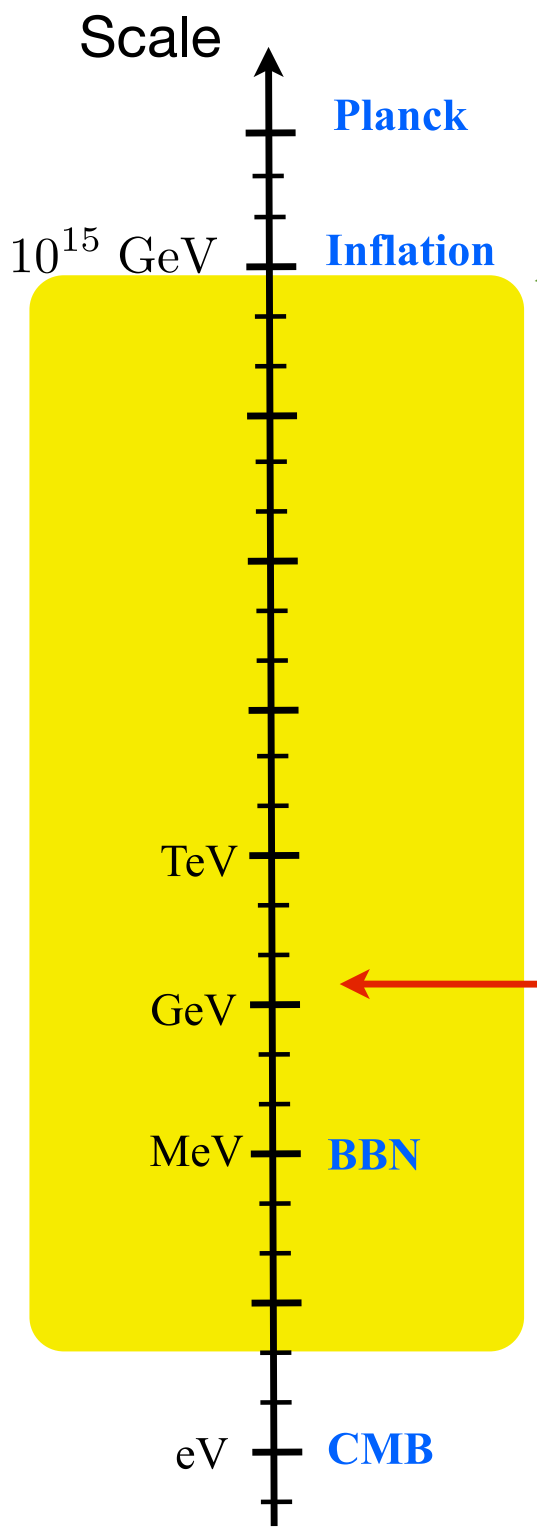
gravitino mass < 10^4.5 GeV
→ gravity mediation



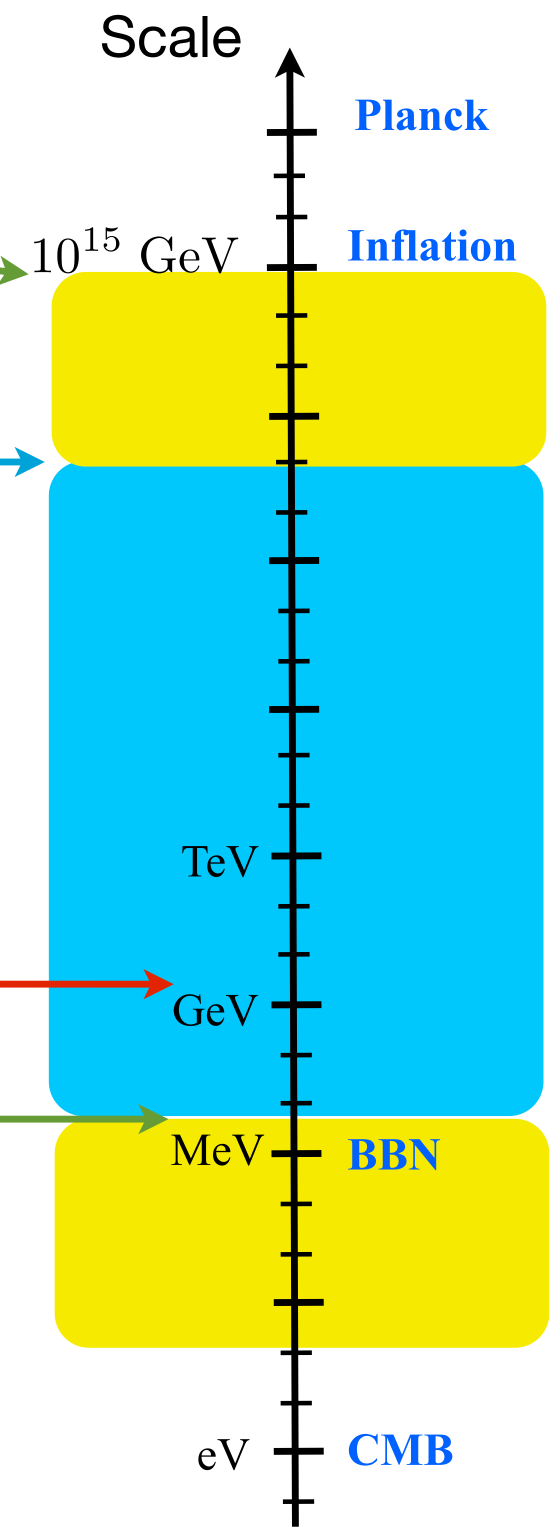
CMB uncertainties from the post-inflationary evolution

[Easther, Galvez, Ozsoy, Watson 2013]

Thermal History



Alternative History



$$N_* \equiv \int_{t_*}^{t_{\rm end}} H dt = \ln(a_{\rm end}/a_*)$$

Radiation Phase (instant reheating)

Scalar Oscillations Dominate

$$n_s(k_*) = 1 - \frac{\alpha}{N_*}$$

$$\Delta n_s = \alpha \frac{\Delta N}{N^2} = \frac{(1-n_s)^2}{\alpha} \Delta N$$

Thermal DM Freeze-out

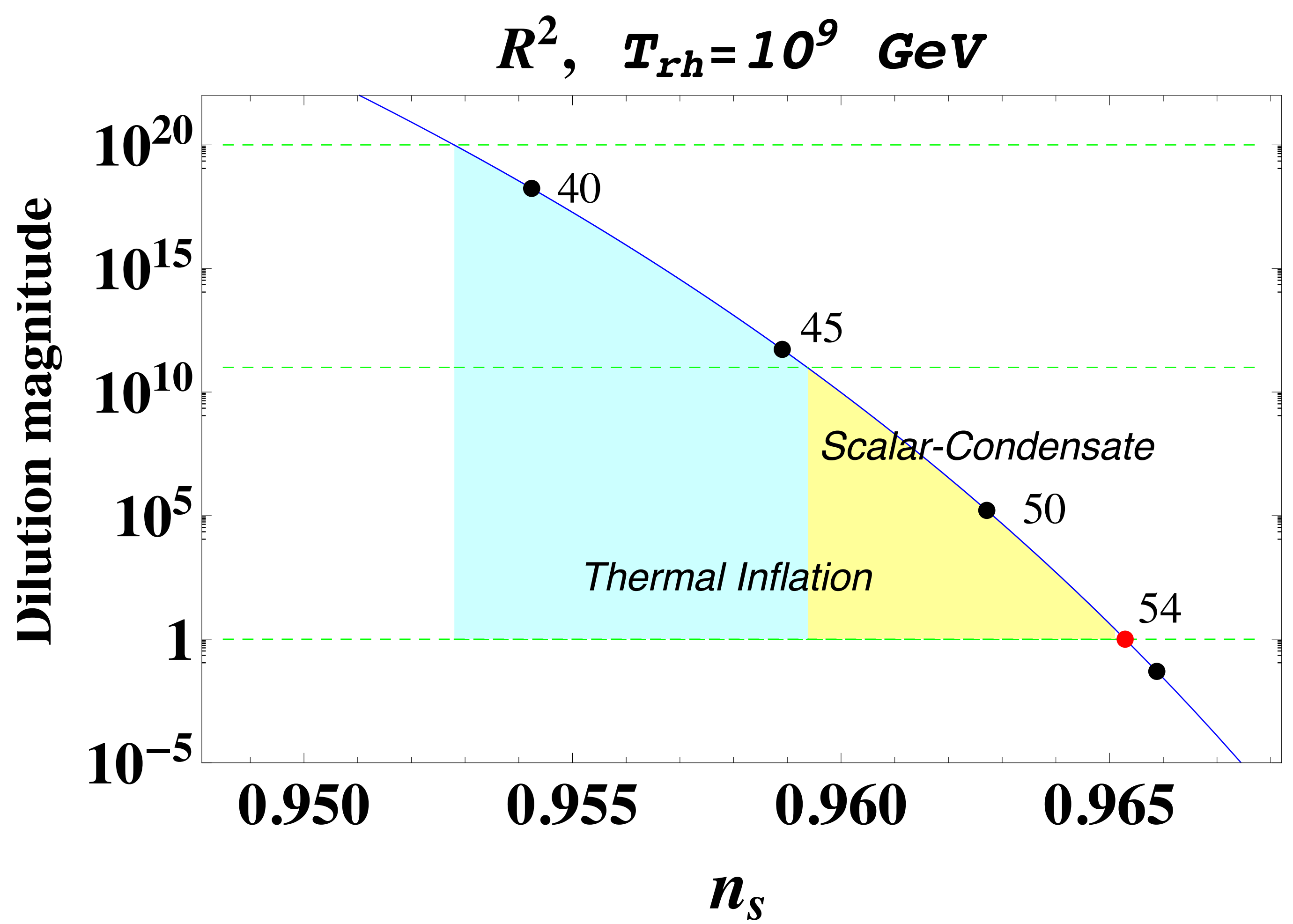
Particles Decay and Reheat

Shift in (ns, r) due to late entropy production

- After inflaton decay, a diluter field X (modulus, flaton) may dominate the universe until BBN. Decays of X produce **entropy**:

$$\Delta N_X = \frac{1}{3}\ln\left[\left(\frac{g_*(T_X^{\rm dom})}{g_*(T_X^{\rm dec})}\right)^{1/4} D_X\right] \equiv \frac{1}{3}\ln \tilde{D}_X$$

$$D_X \equiv \frac{S_{\rm after}}{S_{\rm before}} = 1 + \frac{g_s(T_X^{\rm dec})}{g_*(T_X^{\rm dec})}\frac{g_*(T_X^{\rm dom})}{g_s(T_X^{\rm dom})}\frac{T_X^{\rm dom}}{T_X^{\rm dec}} \simeq \frac{T_X^{\rm dom}}{T_X^{\rm dec}} \geq 1$$



Supersymmetric dark matter scenarios

Merits: Gauge coupling unification, stable dark matter, baryogenesis, stringy UV completion, …

1. Gravitino LSP
2. Neutralino LSP (WIMP)

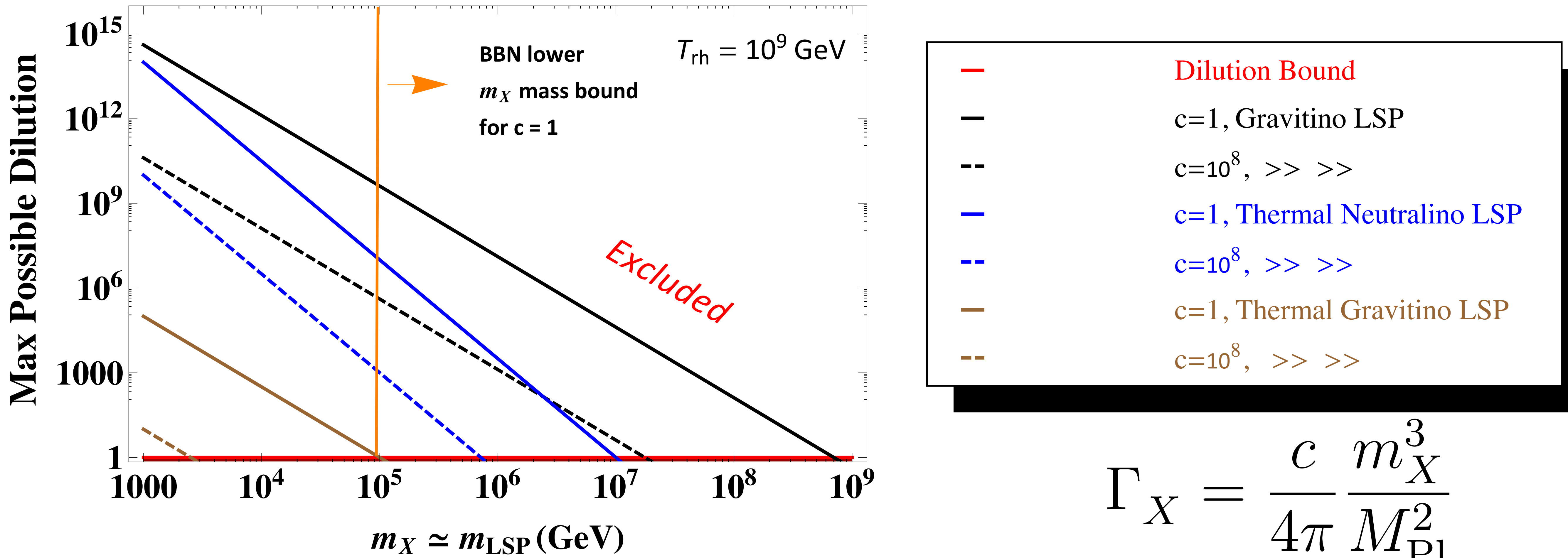
- Thermal DM (freeze out): thermal scatterings with the MSSM, messenger fields
- Non-thermal DM (freeze in): decays, thermal scatterings

Light WIMP mass is disfavored by the LHC.
$\Omega_{DM}h^2$ is severely constrained when **sparticle masses increase**:

$$\Omega_{3/2} \propto m_{3/2}^{\alpha} \left(\frac{m_{\tilde{g}}}{m_{3/2}}\right)^{\beta} \left(\frac{m_{\tilde{f}}}{m_{3/2}}\right)^{\gamma} T_{\rm rh}^{\delta} \,, \qquad m_{3/2} < m_{\tilde{g}}, m_{\tilde{f}} \,,$$

$$\Omega_{\tilde{\chi}^0} \propto m_{\tilde{\chi}^0}^{\tilde{\alpha}} \, m_{3/2}^{\tilde{\beta}} \left(\frac{m_{\tilde{f}}}{m_{3/2}}\right)^{\tilde{\gamma}} T_{\rm rh}^{\tilde{\delta}} \,, \qquad m_{\tilde{\chi}^0} < m_{3/2}, m_{\tilde{f}}$$

Alternative cosmic histories and SUSY



$$\Gamma_X = \frac{c}{4\pi}\frac{m_X^3}{M_{\rm Pl}^2}$$

★ High reheating temp. generally overproduce light LSP

→ Dilution of DM abundance is necessary: **diluter field X**

- If $D_X = 1$ then $T_{\rm rh} \lesssim \tilde{m}$ or $\tilde{m} \sim \text{TeV}$
- If $\mathcal{O}(\text{TeV}) < (m_{\rm LSP}, \tilde{m}) < T_{\rm rh}$ then $D_X \geq D_X^{\rm min} \equiv \frac{\Omega_{\rm LSP}^{<}}{0.12\, h^{-2}}$

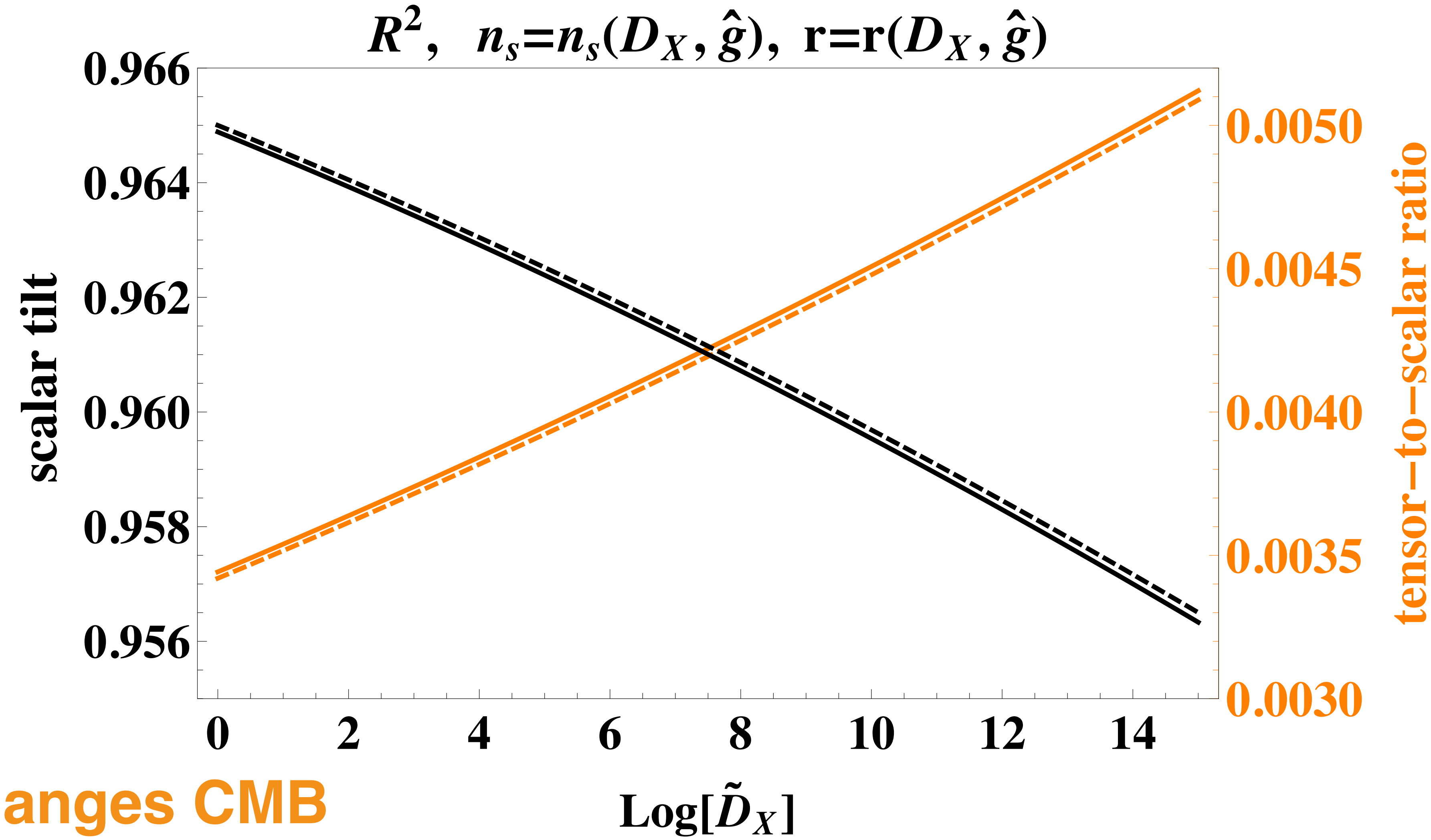
where $\tilde{m}$ the sparticle mass scale.

CMB observables: SUGRA R2 inflation

$$n_s^{(\mathrm{th})}\Big|_{R^2} = 0.965\,,$$

$$r^{(\mathrm{th})}\Big|_{R^2} = 0.0034$$

$$N^{(\mathrm{th})} = 54$$



★ **Dilution factor D_X changes CMB observables:** $\Delta N_X = \dfrac{1}{3}\ln \tilde{D}_X$

$$N_*\big|_{R^2} = 55.9 + \frac{1}{4}\ln\epsilon_* + \frac{1}{4}\ln\frac{V_*}{\rho_{\mathrm{end}}} + \frac{1}{12}\ln\left(\frac{g_{*\mathrm{rh}}}{100}\right) + \frac{1}{3}\ln\left(\frac{T_{\mathrm{rh}}}{10^9\ \mathrm{GeV}}\right) - \Delta N_X$$

CMB observables: SUGRA R2 inflation

[Dalianis & YW 1801.05736]

$$\mathcal{L} = -3M_P^2 \int d^4\theta \, E \left[1 - \frac{4}{m^2}\mathcal{R}\bar{\mathcal{R}} + \frac{\zeta}{3m^4}\mathcal{R}^2\bar{\mathcal{R}}^2 \right]$$

+ MSSM, Z, X, (messengers)

Gravitino DM (in GeV units)

#	m_Z	$m_{\tilde{g}}$	$m_{\tilde{f}}$	$m_{3/2}$ (LSP)	D_X	N_*	n_s	r	Origin
4	10^3	10^3	10^4	10	1	54	**0.965**	**0.0034**	Th

Alternative history after reheating

Neutralino (WIMP) DM

#	m_Z	$m_{3/2}$	$m_{\tilde{f}}$	$m_{\tilde{\chi}^0}$ (LSP)	$D_{(X)}$	N_*	n_s	r	Origin
4	10^5	10^5	10^5	10^3	1	54	**0.965**	**0.0034**	Th

Alternative history after reheating

CMB observables: SUGRA R2 inflation

[Dalianis & YW 1801.05736]

$$\mathcal{L} = -3M_P^2 \int d^4\theta\, E\left[1 - \frac{4}{m^2}\mathcal{R}\bar{\mathcal{R}} + \frac{\zeta}{3m^4}\mathcal{R}^2\bar{\mathcal{R}}^2\right]$$

+ MSSM, Z, X, (messengers)

Gravitino DM (in GeV units)

#	m_Z	$m_{\tilde{g}}$	$m_{\tilde{f}}$	$m_{3/2}$ (LSP)	D_X	N_*	n_s	r	Origin
1	10^4	10^4	10^4	10^2	$10^4\vert_{\min}$	$51\vert_{\max}$	$\mathbf{0.963}\vert_{\max}$	$\mathbf{0.0038}\vert_{\min}$	Th
2	10^4	10^4	10^5	10^3	$10^{10}\vert_{\min}$	$46\vert_{\max}$	$\mathbf{0.960}\vert_{\max}$	$\mathbf{0.0044}\vert_{\min}$	Th
3	10^6	10^5	10^6	10^4	$10^6\vert_{\min}$	$49\vert_{\max}$	$\mathbf{0.962}\vert_{\max}$	$\mathbf{0.0041}\vert_{\min}$	Non-th
4	10^3	10^3	10^4	10	1	54	**0.965**	**0.0034**	Th

Neutralino (WIMP) DM

#	m_Z	$m_{3/2}$	$m_{\tilde{f}}$	$m_{\tilde{\chi}^0}$ (LSP)	$D_{(X)}$	N_*	n_s	r	Origin
1	10^7	10^6	10^6	10^3	$10^2\vert_{\min}$	$52\vert_{\max}$	$\mathbf{0.964}\vert_{\max}$	$\mathbf{0.0036}\vert_{\min}$	Non-th
2	10^9	10^8	10^8	10^3	$10^2\vert_{\min}$	$52\vert_{\max}$	$\mathbf{0.964}\vert_{\max}$	$\mathbf{0.0036}\vert_{\min}$	Th
3	10^8	10^7	10^7	10^5	$10^8\vert_{\min}$	$48\vert_{\max}$	$\mathbf{0.961}\vert_{\max}$	$\mathbf{0.0042}\vert_{\min}$	Non-th
4	10^5	10^5	10^5	10^3	1	54	**0.965**	**0.0034**	Th

CMB observables: SUGRA R2 inflation

[Dalianis & YW 1801.05736]