PBHs and GWs from an Early Matter Domination

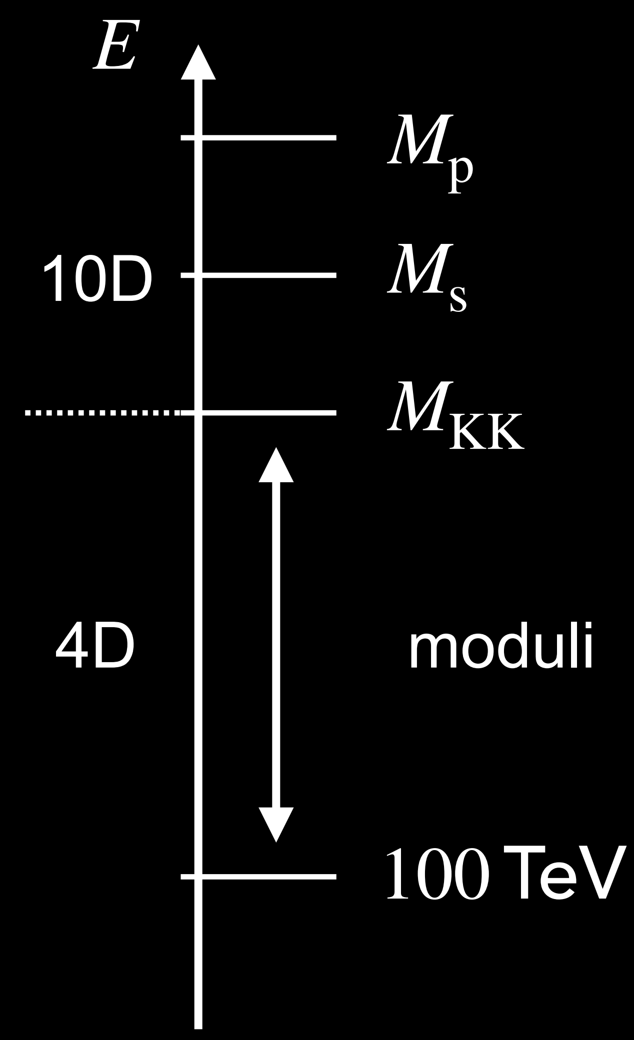
Francesco Muia

String Pheno 2022
05/07/2022

Based on 2112.11486, with Subinoy Das and Anshuman Maharana

Early Matter Domination

Moduli displaced from their late-time minimum during inflation



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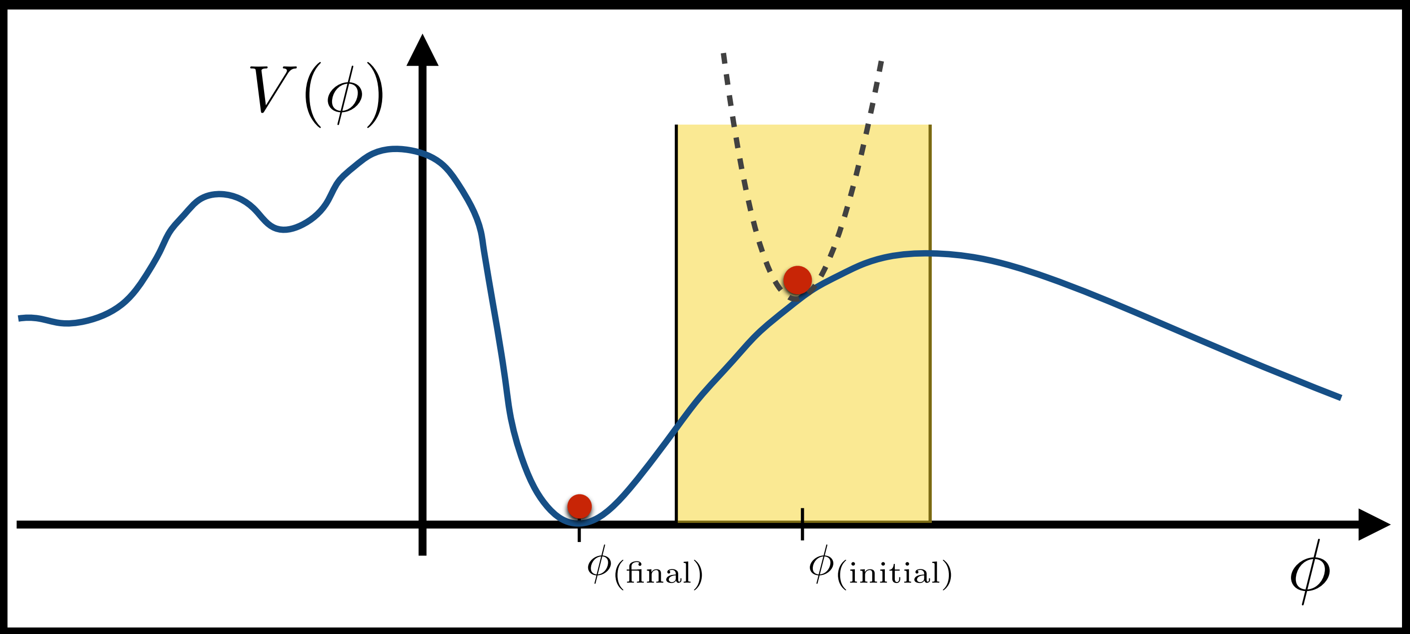
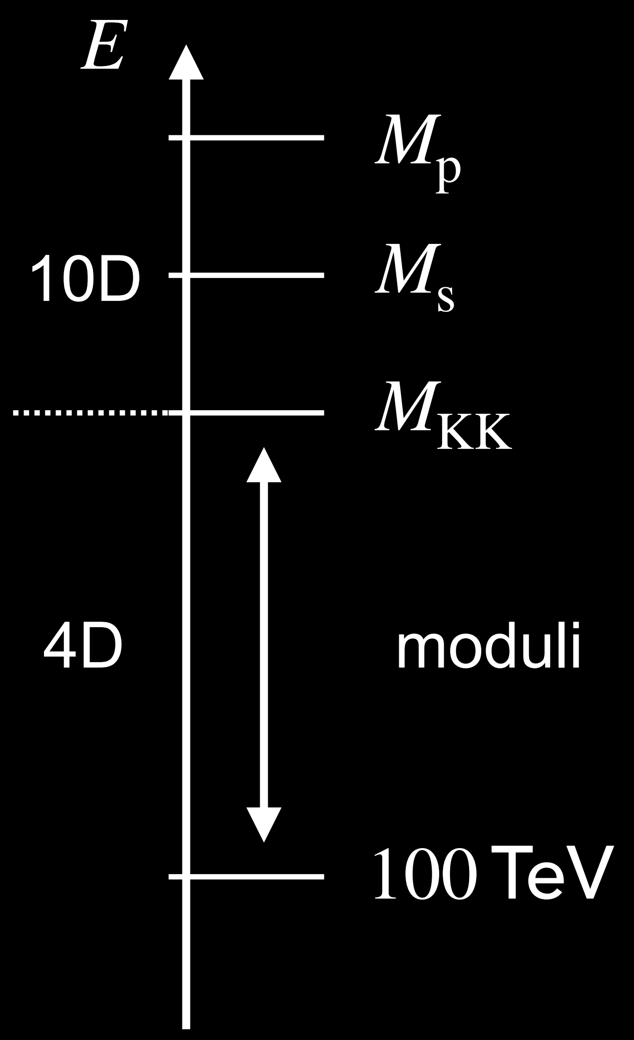


Modulus oscillates ⟶ early matter domination



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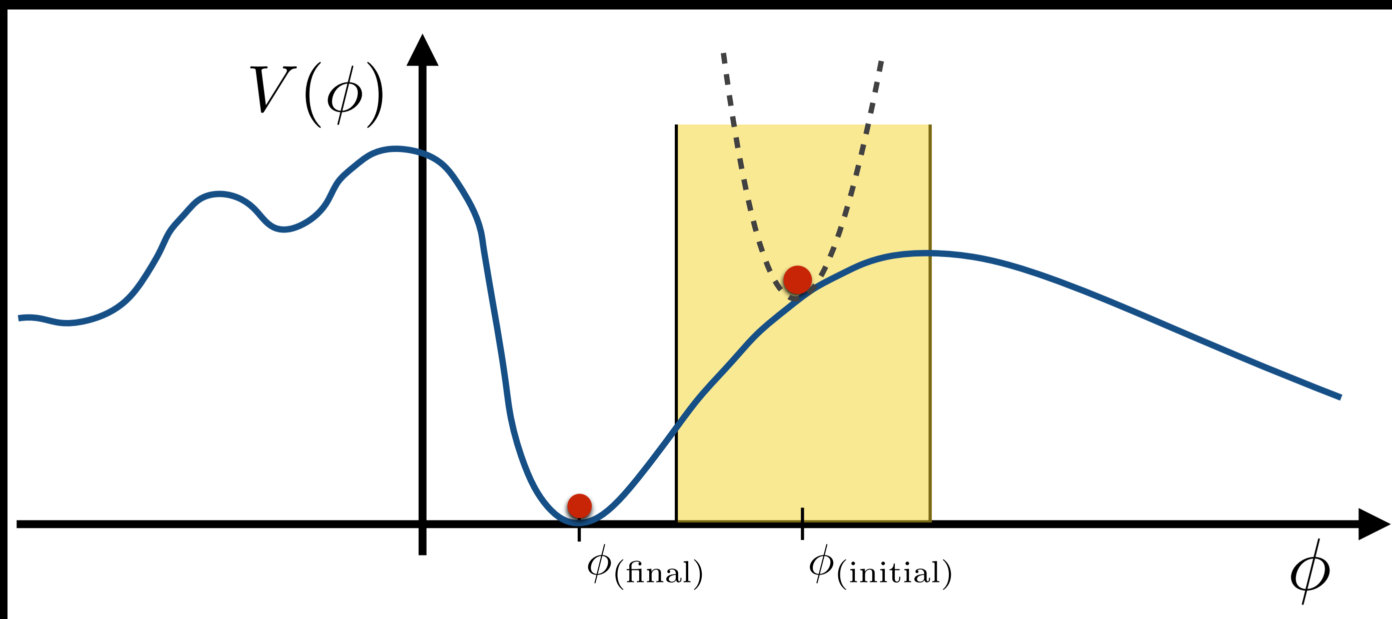

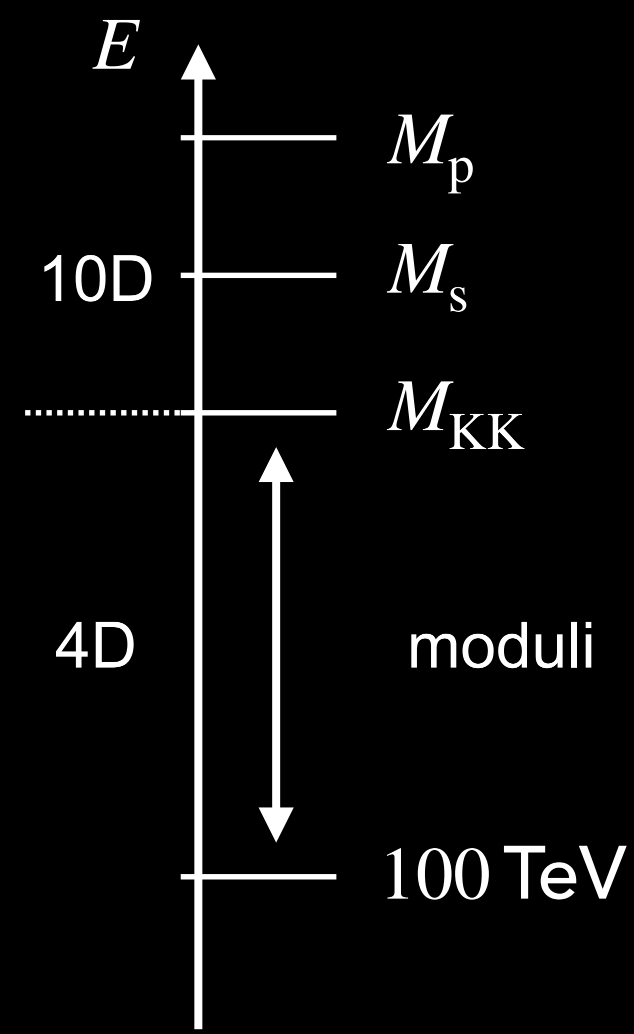

Modulus oscillates → early matter domination

Decay before onset of BBN → $m_\phi \gtrsim 30\,\mathrm{TeV}$

Early Matter Domination

+

additional ingredients

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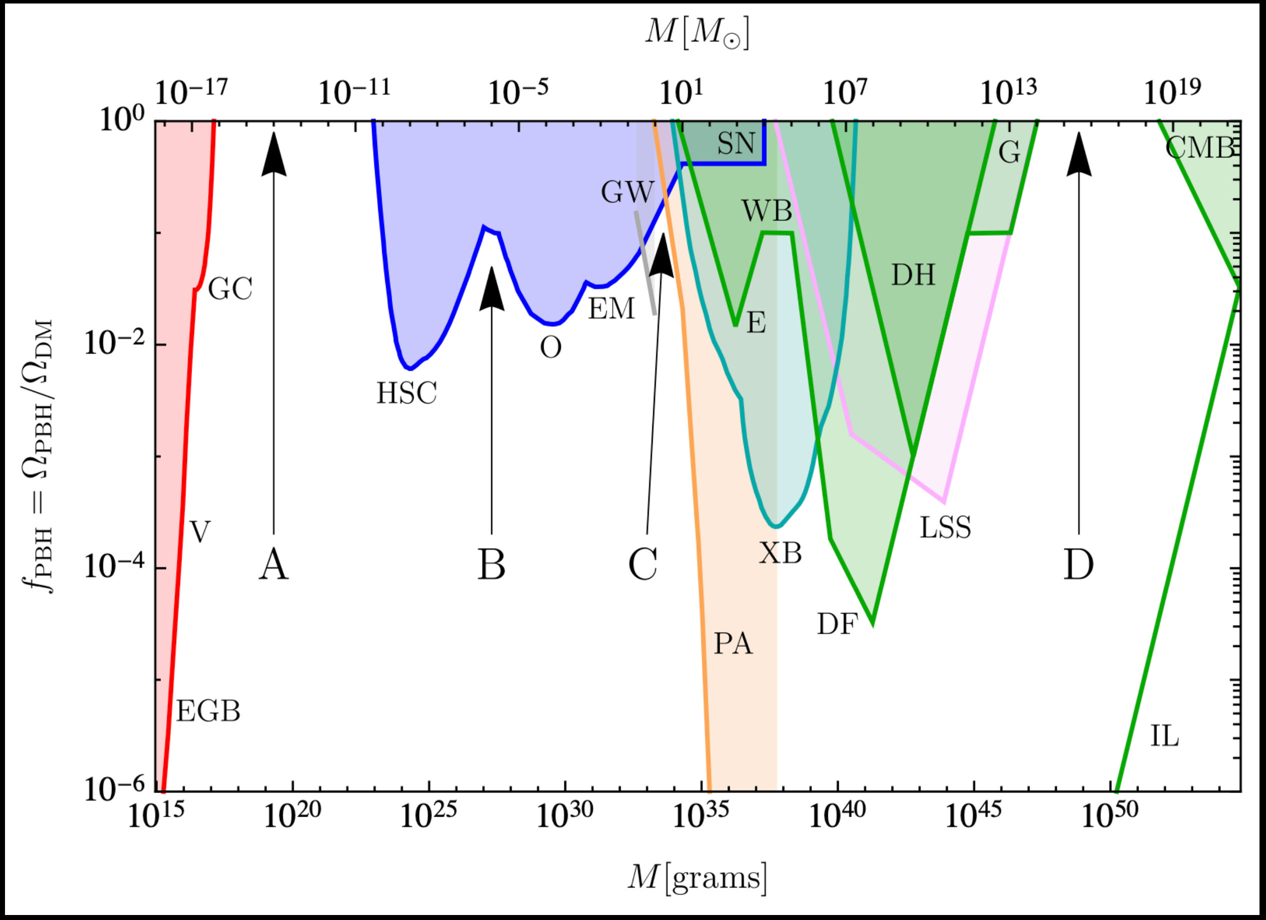
additional ingredients

PBH dark matter

[Carr, Kuhnel, 2021]

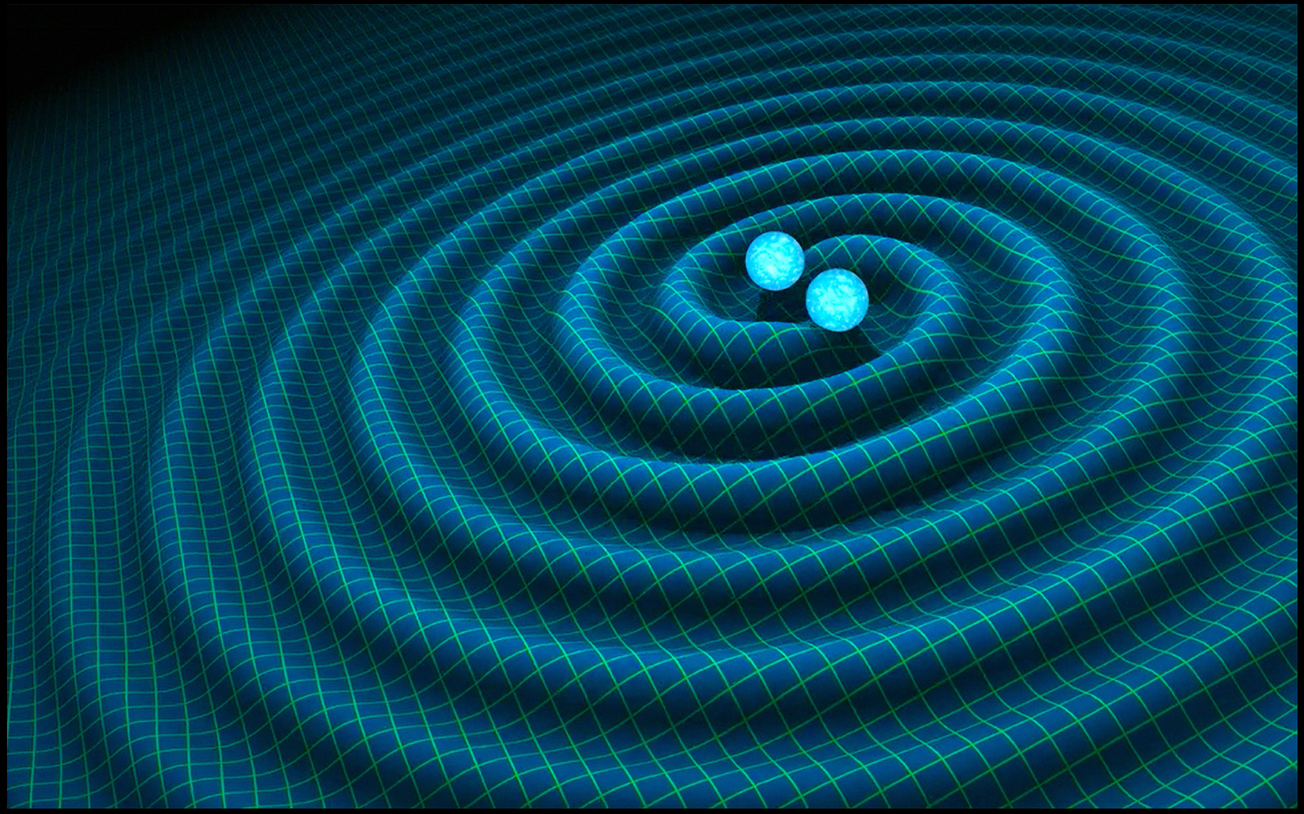


Early Matter Domination

+

additional ingredients

gravitational waves



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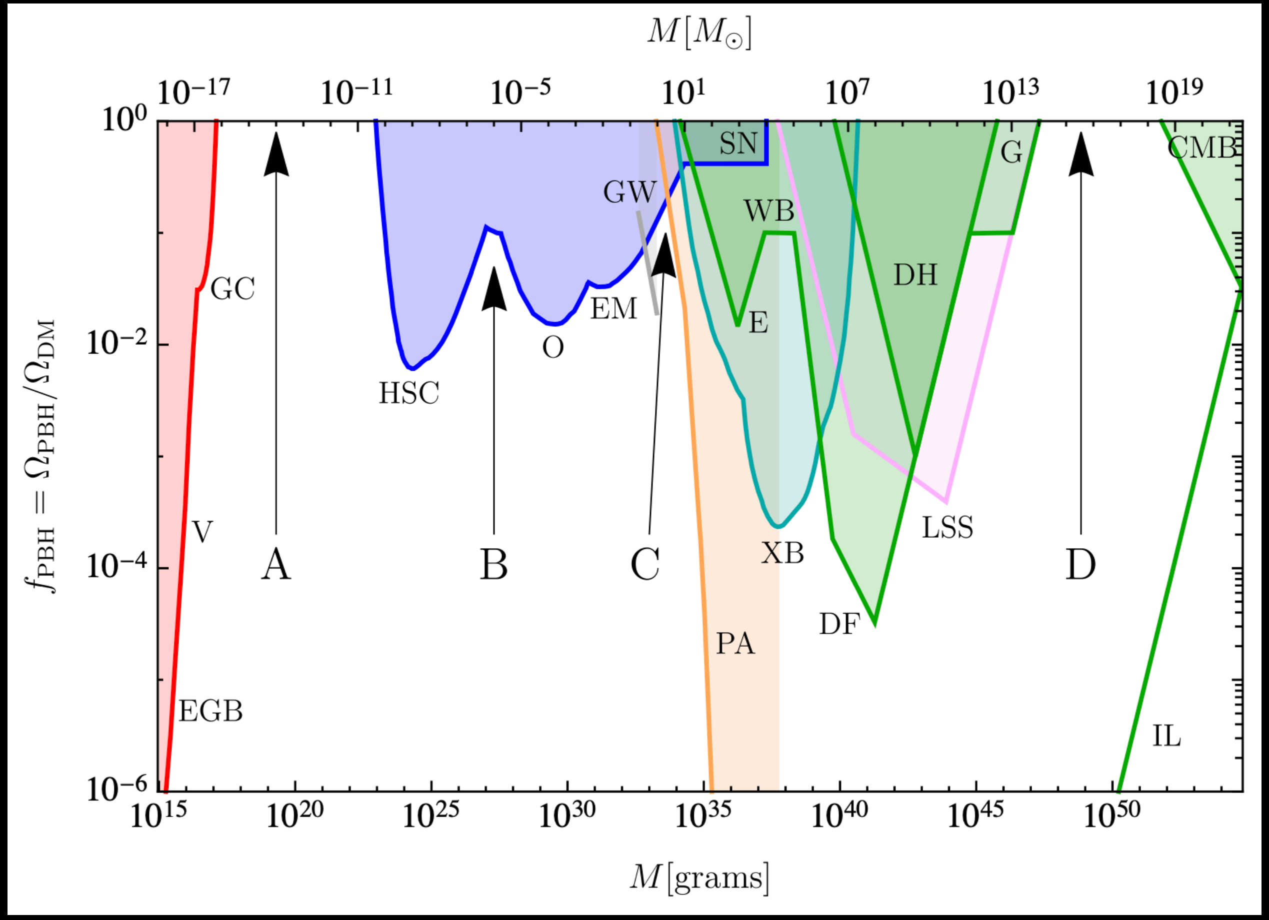

Early Matter Domination

+

additional ingredients → fifth-force

→ gravitational waves

PBH dark matter

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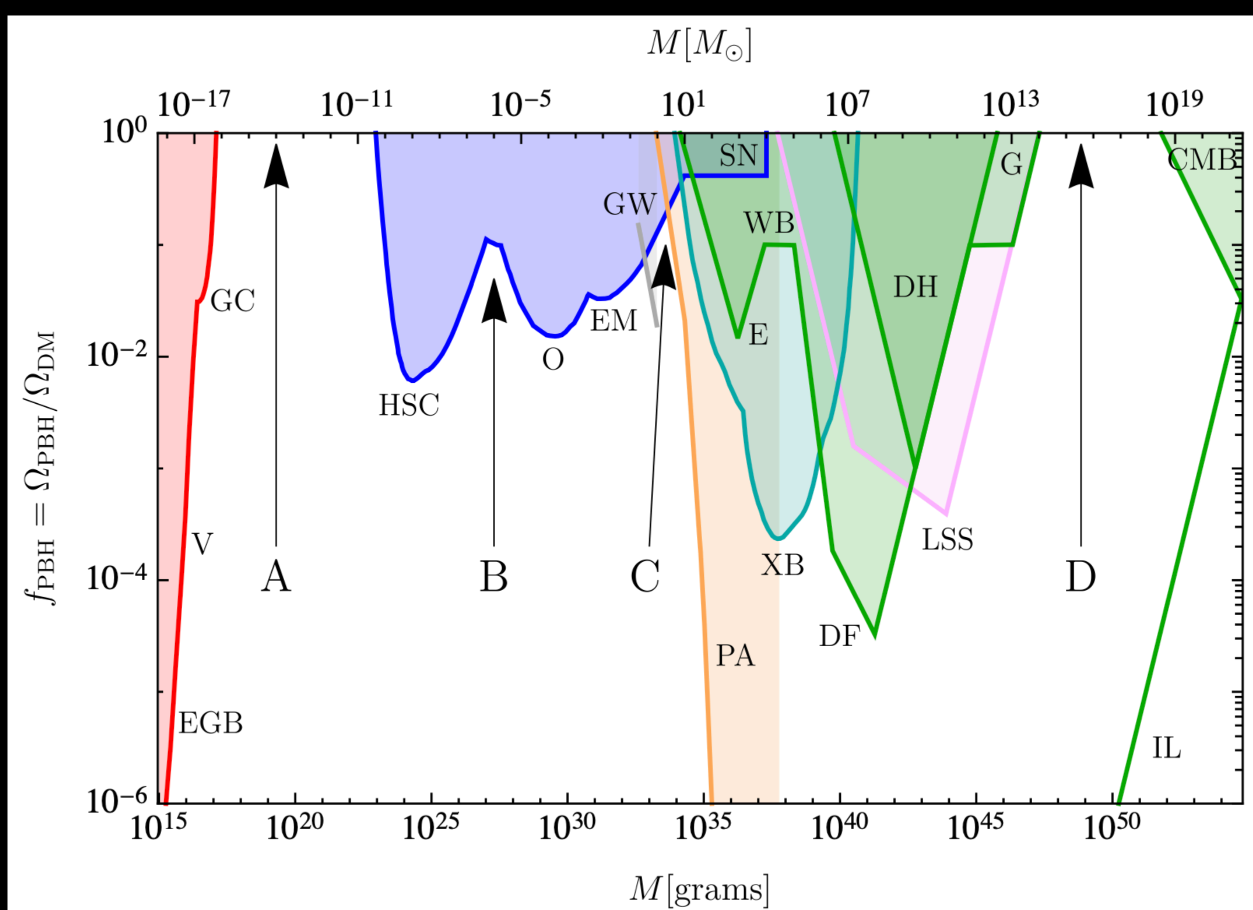

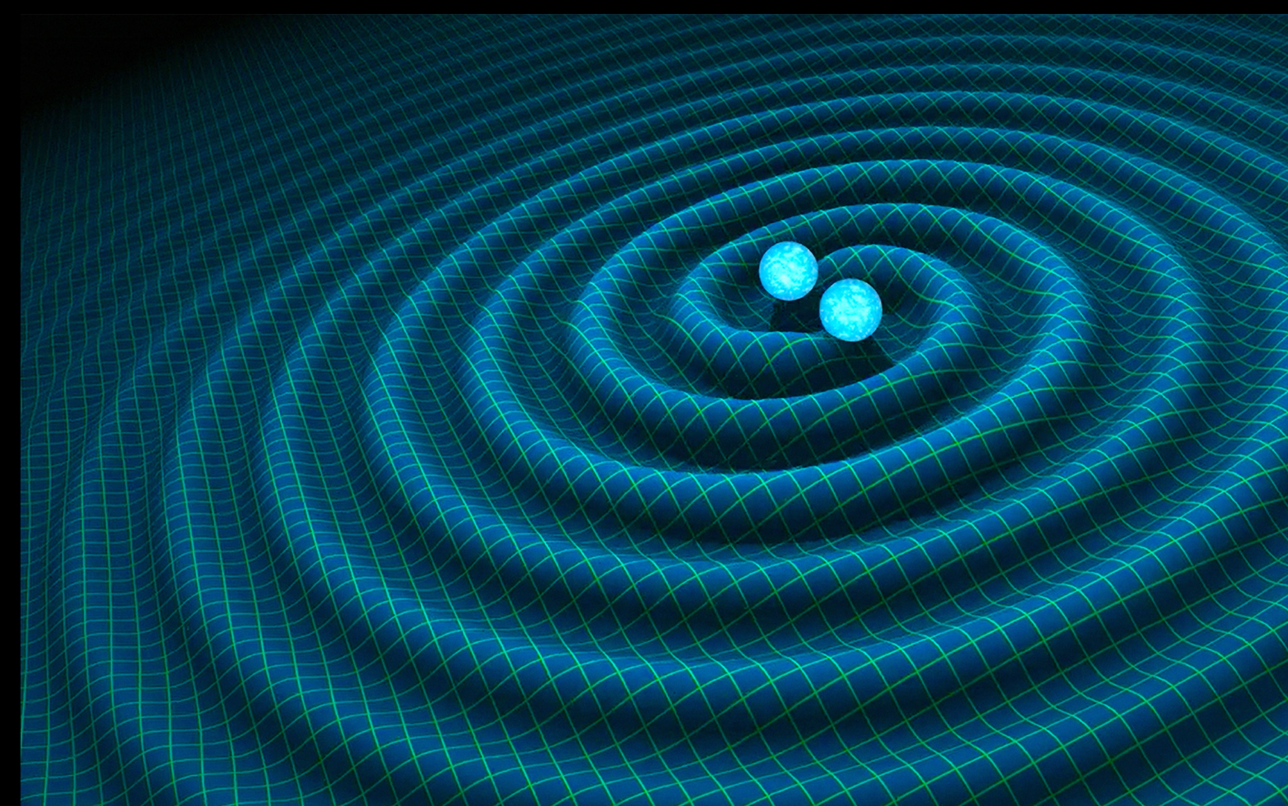

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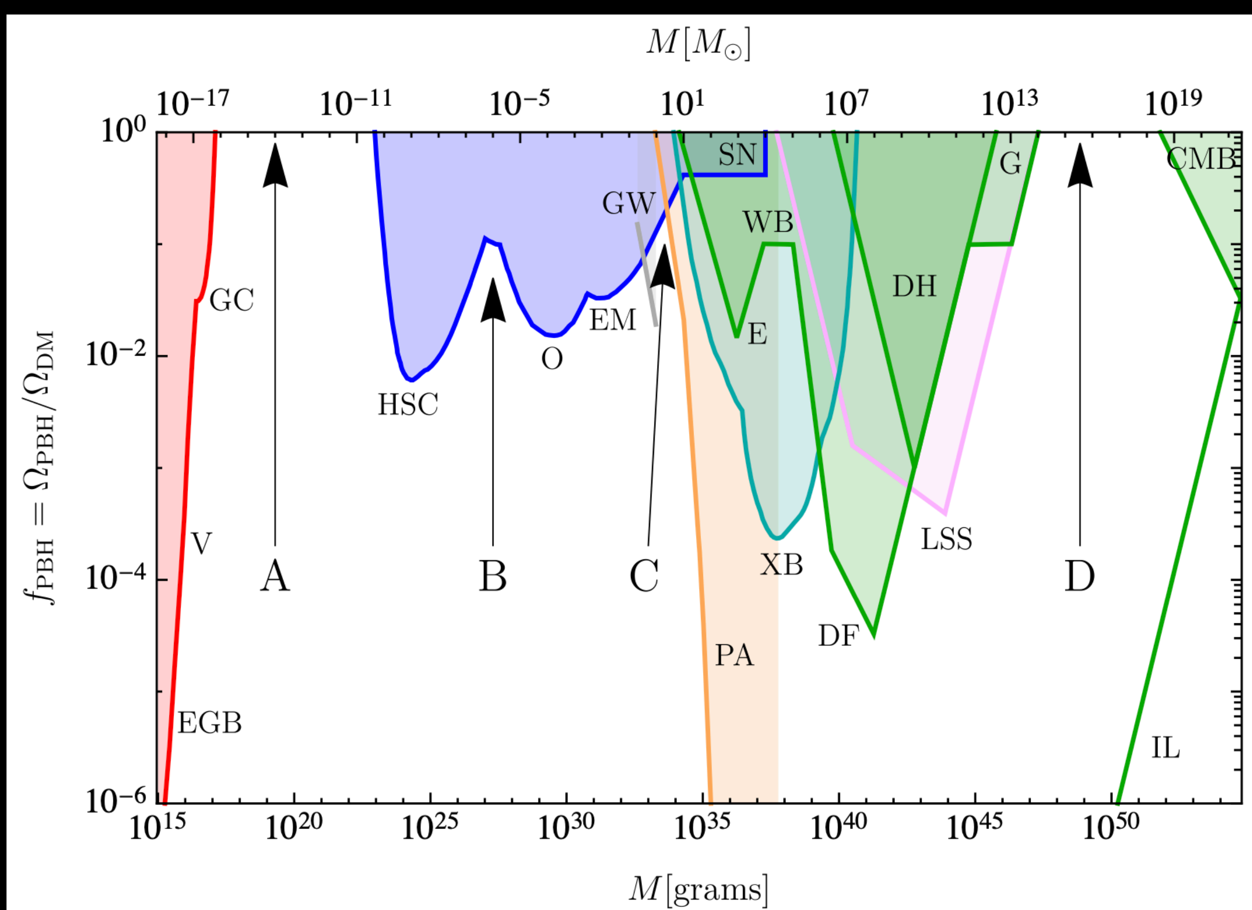

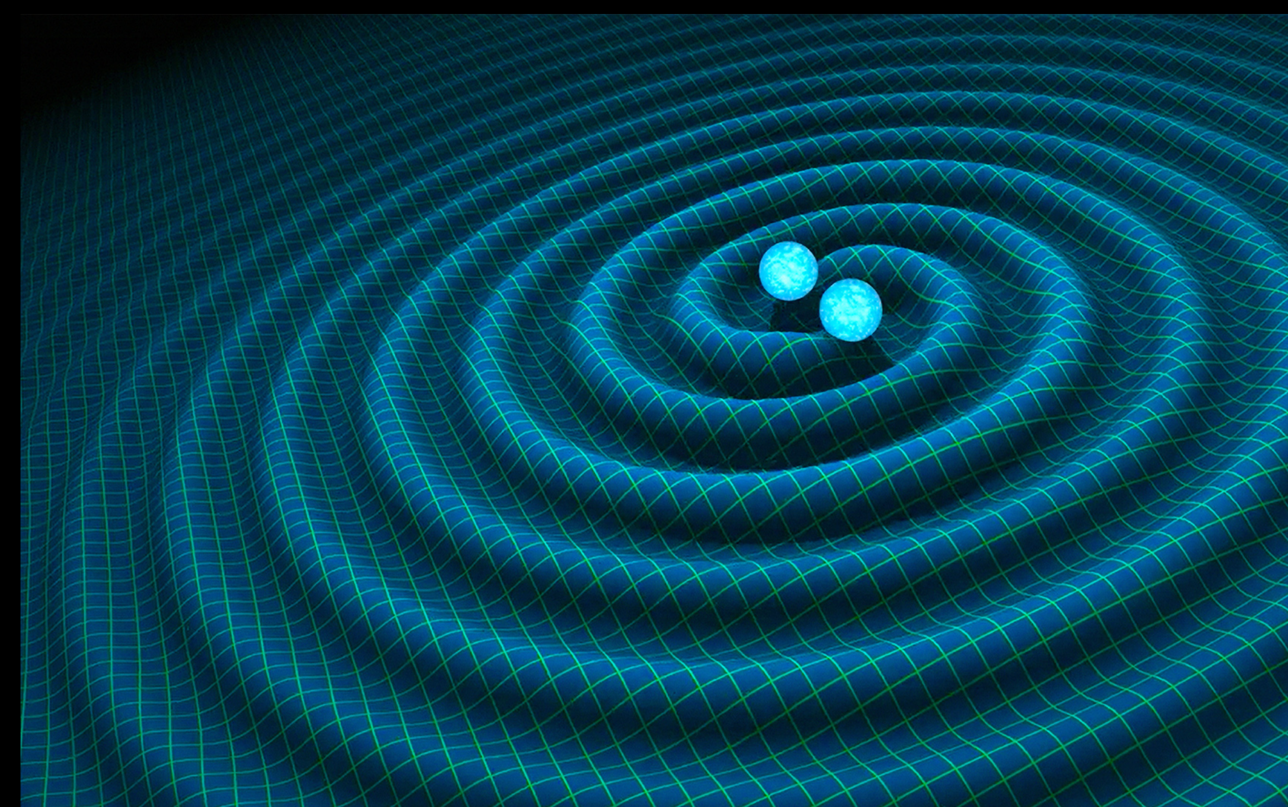

[Erickceck, Sigurdson, 2011]

[Georg, Sengor, Watson, 2016]

[Harada, Yoo, Kohri, Nakao, Jhingan, 2016]

[Georg, Watson, 2017]

[Cicoli, Diaz, Pedro, 2018]

Fifth-force interactions

[Amendola, 1999, 2003]
[Amendola, Rubio, Wetterich, 2018]
[Savastano, Amendola, Rubio, Wetterich, 2019]
[Flores, Kusenko, 2018]

$$\frac{\mathscr{L}}{\sqrt{-g}} = \frac{M_{\rm p}}{2} R + \mathscr{L}_{SM} + \mathscr{L}(\phi) + \mathscr{L}(\phi, \psi)$$

ϕ = canonically normalized scalar field

ψ = BSM fermion

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$$\mathscr{L}(\phi) = -\frac{1}{2}\partial_\mu\phi\partial_\mu\phi - V(\phi)$$

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energy-momentum transfer

$$\nabla_\nu T^{\mu\nu}_{(\phi)} = \frac{\beta(\phi)}{M_\mathrm{p}} T_{(\psi)}\partial^\mu\phi$$

$$\nabla_\nu T^{\mu\nu}_{(\psi)} = \frac{\beta(\phi)}{M_\mathrm{p}} T_{(\psi)}\partial^\mu\phi$$

$$T_{(\psi)} = T^{\mu\nu}_{(\psi)} g_{\mu\nu}$$

$$\propto 1 - 3w_\psi$$

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$\beta \gtrsim 1 \quad \Leftrightarrow$ interaction stronger than gravity

Fifth-force interactions

[Amendola, Rubio, Wetterich, 2018]

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Background equations

$$\dot{\rho}_\phi + 3H(p_\phi + \rho_\phi) = \frac{\beta}{M_{\rm p}}(\rho_\psi - 3p_\psi)\dot{\phi}$$

$$\dot{\rho}_\psi + 3H(p_\psi + \rho_\psi) = -\frac{\beta}{M_{\rm p}}(\rho_\psi - 3p_\psi)\dot{\phi}$$

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Scaling solution

$$\phi' = M_\mathrm{p}/\beta \qquad (' = d/dN)$$

$$\Omega_\psi = \frac{1}{3\beta^2} \qquad \Omega_\phi = \frac{1}{6\beta^2} \qquad \Omega_\mathrm{rad} = 1 - \frac{1}{2\beta^2}$$

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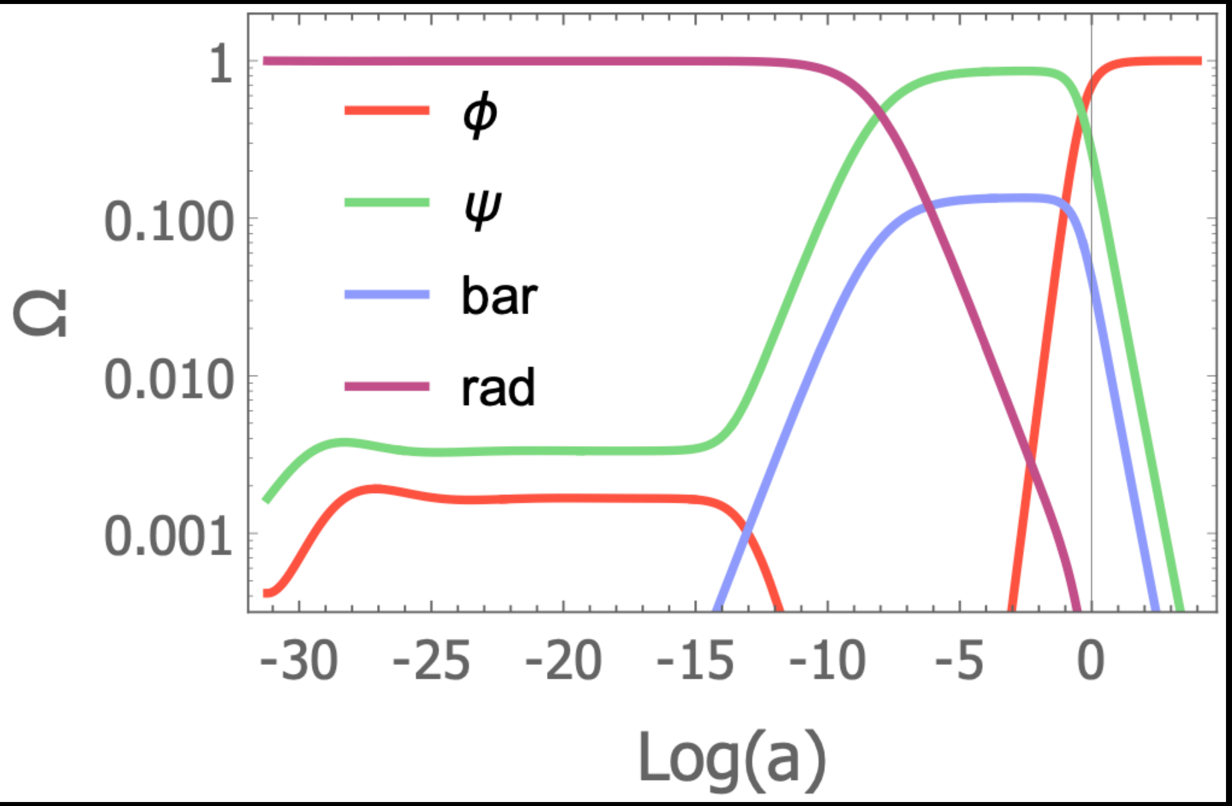

Note: radiation domination during the scaling solution

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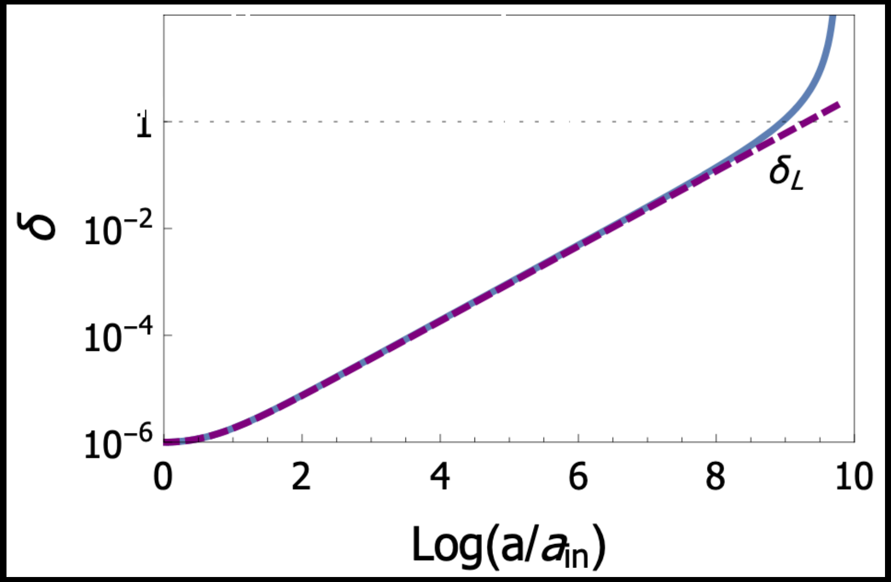
Perturbations $\delta''_\psi - \delta'_\psi - \delta_\psi = 0 \longrightarrow \delta_\psi = \delta_{\psi,\mathrm{in}}(a/a_\mathrm{in})^{1.62}$

Note: the standard behaviour during the late matter domination is

$$\delta_\psi = \delta_{\psi,\mathrm{in}}(a/a_\mathrm{in})$$

PBH and primordial DM halo production



Setup

[Das, Maharana, Muia, 2021]

Early matter domination
(due to a modulus or anything else)

Dark sector fermion ψ

Scalar force mediator ϕ

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hidden sector, sequestered from the SM

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$$\nabla_\mu T^{\mu\nu}_{(\psi)} = -\frac{\beta_{\psi}}{M_{\mathrm{p}}} g_{\rho\sigma} T^{\rho\sigma}_{(\psi)} \nabla^\nu \phi$$

$$(\Box + m^2)\phi = \frac{\beta_b}{M_{\mathrm{p}}} g_{\rho\sigma} T^{\rho\sigma}_{(\mathrm{b})} + \frac{\beta_\psi}{M_{\mathrm{p}}} g_{\rho\sigma} T^{\rho\sigma}_{(\psi)}$$

[Acharya, Maharana, Muia, 2019]

we take $\beta_{\mathrm{b}} = 0$

and $\beta_\psi = \mathrm{const.} = \mathcal{O}(10)$

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and $\beta_\psi = \mathrm{const.} = \mathcal{O}(10)$

- $T^{\mu\nu}_{(\mathrm{b})}$ and $T^{\mu\nu}_{(\psi)}$ are of perfect fluid form, with $w_b = 0$.
- ψ makes a transition from relativistic to non-relativistic: w_ψ goes from $1/3$ to 0.
- Decays of various components are governed by $\Gamma_\mathrm{b}, \Gamma_\psi, \Gamma_\phi$.

Background Dynamics

Background equations

$$\rho_b' + 3H\rho_b = 0$$

$$\rho_\psi' + 3(1 + 3w_\psi)H\rho_\psi = -\beta_\psi(1 - 3w_\psi)\,\rho_\psi\phi'$$

$$HH'\phi' + H^2\phi'' + m_\phi^2\phi + 3H^2\phi' = \beta_\psi(1 - 3w_\psi)\,\rho_\psi$$

$$H^2 = \frac{2(\rho_b + \rho_\psi + \frac{1}{2}m_\phi^2\phi^2)}{6 - \phi'^2}$$

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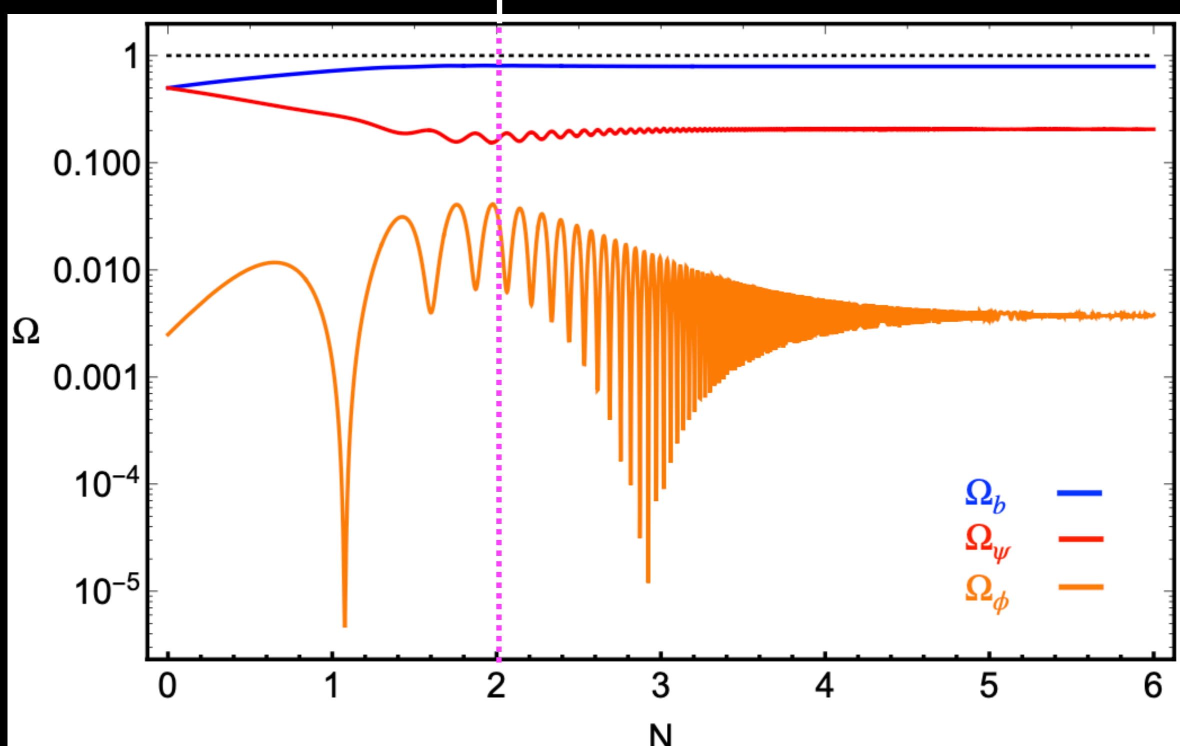
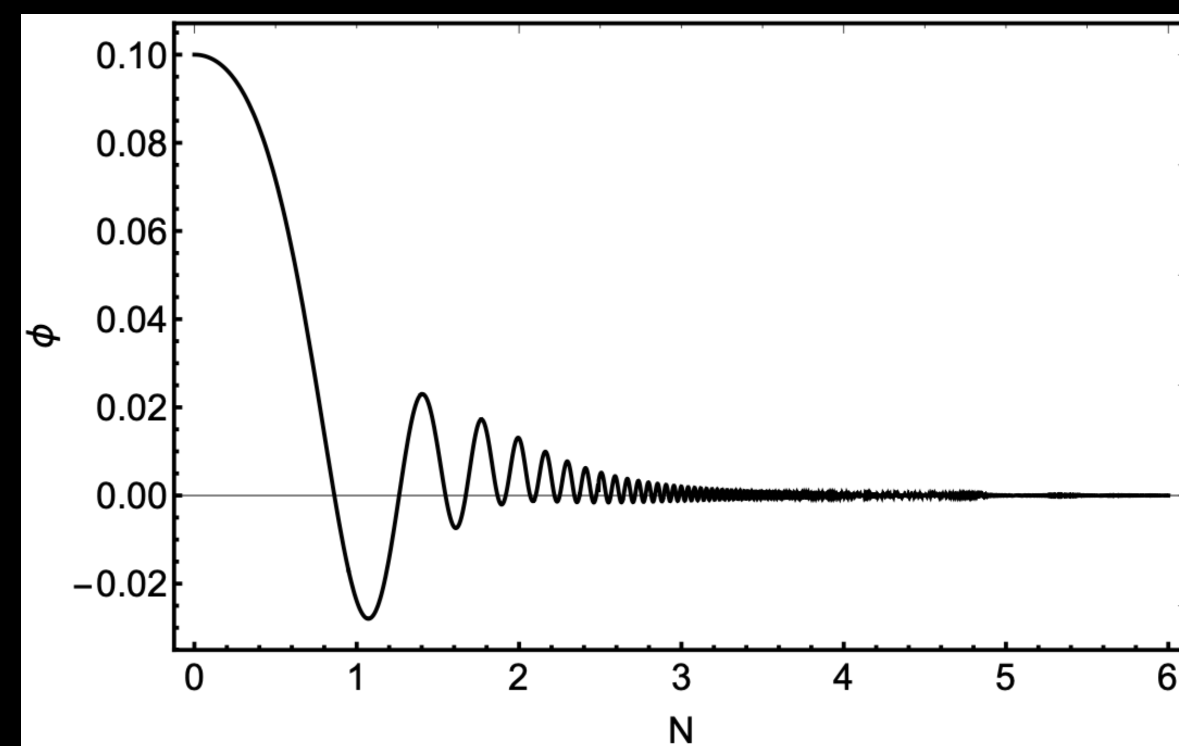
ψ becomes non-relativistic





$$\Omega_i = \frac{\rho_i}{\rho_{\rm tot}}$$

$$\beta_\psi = 30$$

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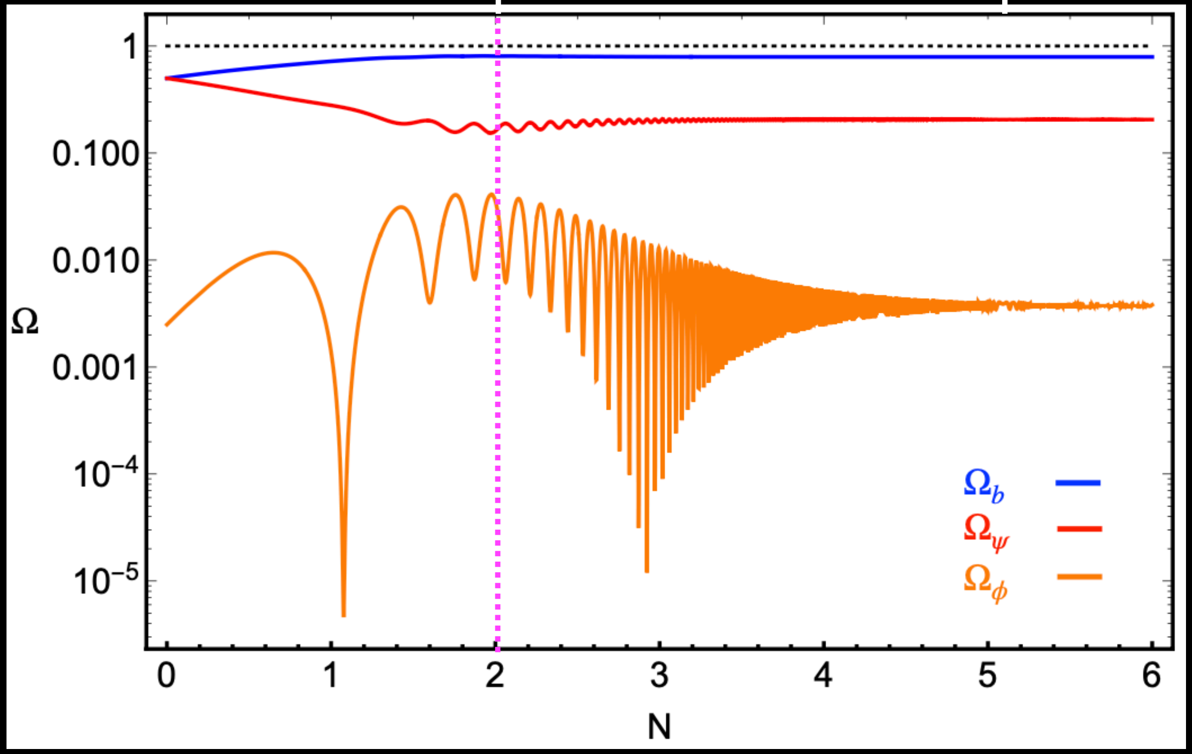
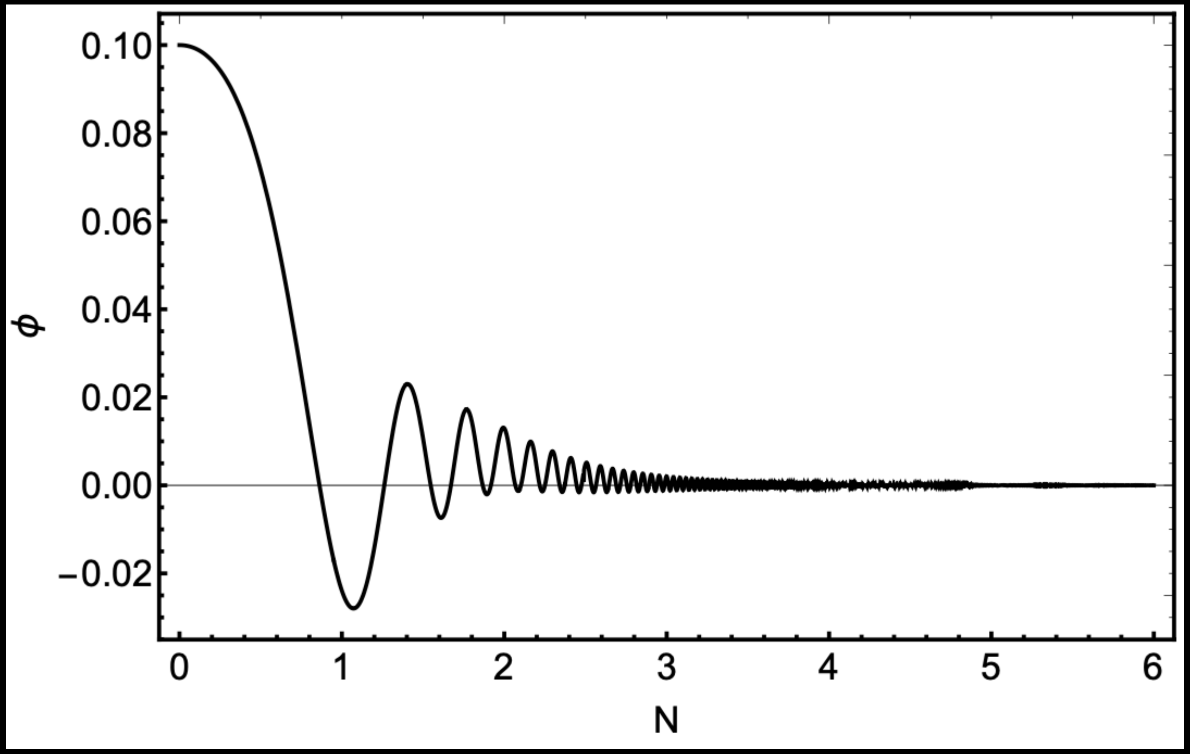
ψ becomes non-relativistic

scaling regime $\rho_i \propto a^{-3}$





$$\Omega_i = \frac{\rho_i}{\rho_{\rm tot}}$$

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Fast Growth of Perturbations

Perturbation equations

$$\delta_\psi'' + [(w_\psi + 1)\,\theta_\psi]' + 3[w_{\psi,\rho}(1 - \beta\phi')\,\delta_\psi] = 0$$

$$\delta_b'' + \left(2 + \frac{H'}{H}\right)\delta_b' - \frac{3}{2}\Omega_\psi\delta_\psi - \frac{3}{2}\Omega_b\delta_b = 0$$

$$\theta_\psi \approx -\frac{1}{w_\psi + 1}[\delta_\psi' + 3w_{\psi,\rho}(1 - \beta\phi')\,\delta_\psi]$$

$$\theta_\psi' \approx -f\theta_\psi + \frac{w_\psi + w_{\rho,\psi}}{1 + w_\psi}\left(\frac{k}{aH}\right)^2 \delta_\psi - \omega_\psi\delta_\psi - \frac{3}{2}(1 + w_\psi)\Omega_b\delta_b$$

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$$\delta_i = \frac{\delta\rho_i}{\rho_{\rm tot}}$$

$$w_{\psi,\rho} = \frac{dw_\psi}{d\ln\rho} = \frac{\rho w'_\psi}{\rho'}$$

$$\theta = \nabla_i v_i$$

$$v_i = \frac{1}{H}\frac{dx_i}{dt}$$

$$f = \left[(1 - 3w_\psi)(1 - \beta\phi') - w_{\psi,\rho}A + 1 + \frac{H'}{H}\right]\theta_\psi$$

$$A = 3 + \beta\phi'\frac{1 - 3w_\psi}{1 + w_\psi}$$

$$\omega_\psi = \frac{3}{2}(1 + w_\psi)\,\Omega_\psi\left[1 + 2\beta_\psi^2\frac{(1 - 3w_\psi)(1 - 3w_\psi - 3w_{\psi,\rho})}{(1 + w_\psi)^2}\right]$$

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valid in the
sub-Compton regime

$$k/a \gtrsim m_\phi$$

and
sub-horizon regime

$$k/a \gtrsim H$$

$$\delta_i = \frac{\delta\rho_i}{\rho_{\rm tot}}$$

$$w_{\psi,\rho} = \frac{dw_\psi}{d\ln\rho} = \frac{\rho w_\psi'}{\rho'}$$

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Analytical Result

In the limit $w_\psi, w_{\psi,\rho} \sim 0$

$\delta_\psi \gg \delta_b$

$$\delta_\psi'' + \frac{1}{2}\delta_\psi' - \tilde{\omega}_\psi \delta_\psi = 0 \longrightarrow \text{decouples}$$

$$\delta_b'' + \frac{1}{2}\delta_b' - \frac{3}{2}\Omega_\psi \delta_\psi - \frac{3}{2}\Omega_b \delta_b = 0 \longrightarrow \text{tracks } \delta_\psi$$

where $\tilde{\omega}_\psi = \frac{3}{2}\Omega_\psi(1 + 2\beta_\psi^2)$

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where $\tilde{\omega}_\psi = \frac{3}{2}\Omega_\psi(1 + 2\beta_\psi^2)$

solution $\delta_\psi \propto \exp(\gamma_\beta N)$ where $\gamma_\beta = \frac{1}{4}\left(-1 + \sqrt{1 + 16\tilde{\omega}_\psi}\right)$

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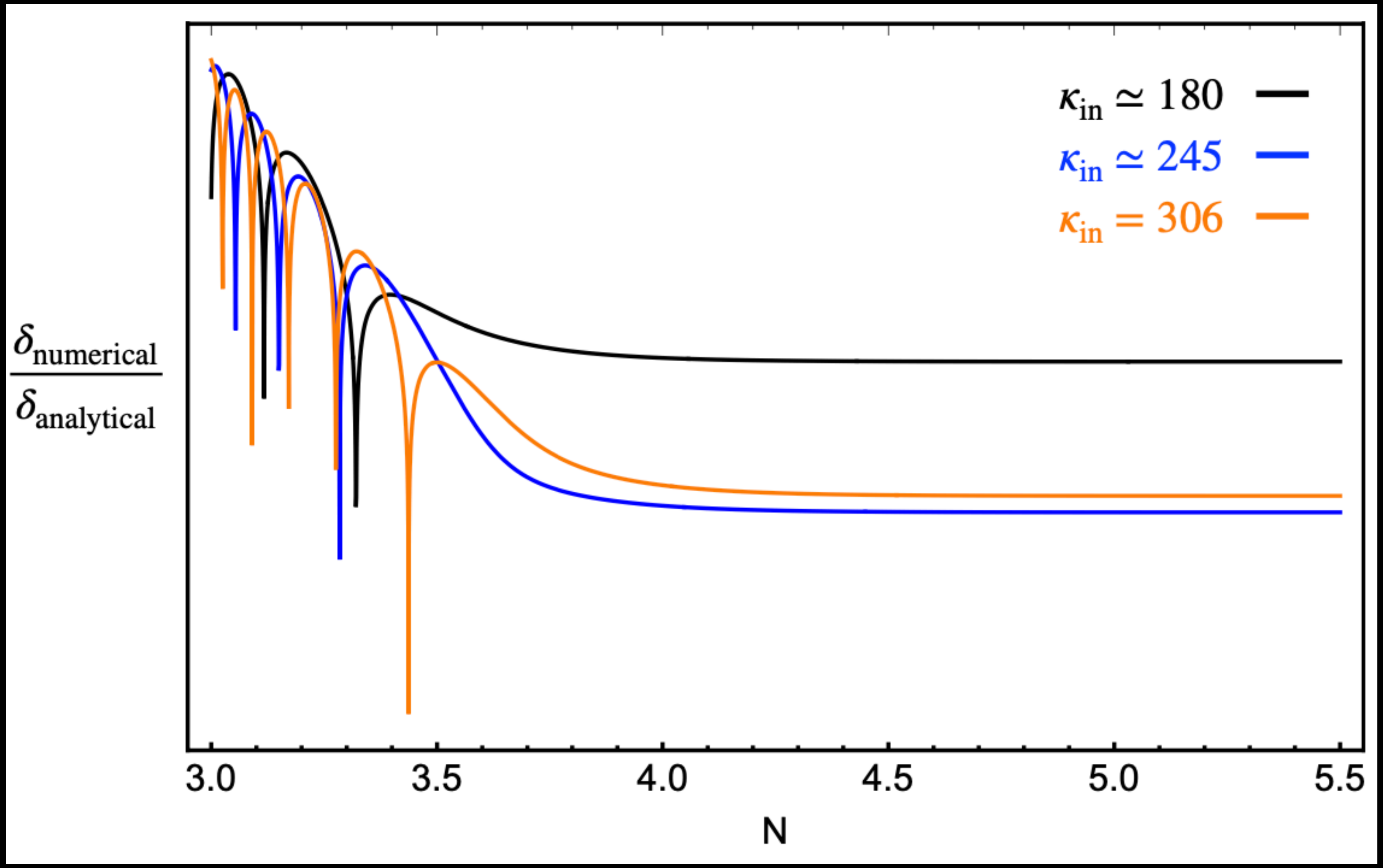


For the parameters considered in the paper

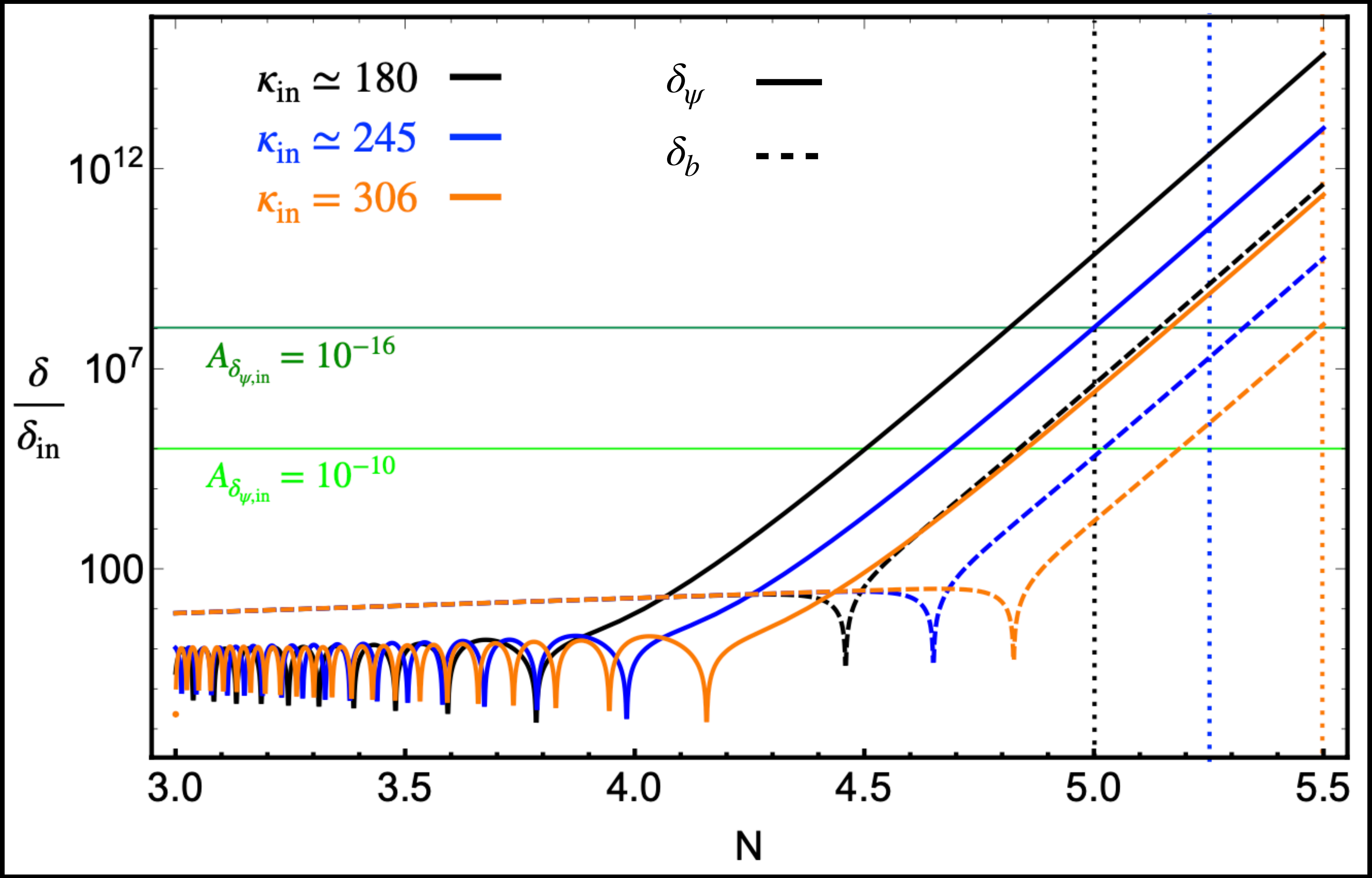
$\gamma_\beta \sim \mathcal{O}(10 - 20)$

Fast Growth of Perturbations

initial conditions

$$\delta_{\psi,\mathrm{in}} = \delta_{b,\mathrm{in}}$$

$$(\delta'_{\psi,\mathrm{in}}, \delta'_{b,\mathrm{in}}) = (0,0)$$



$$\kappa = \frac{k}{aH}$$

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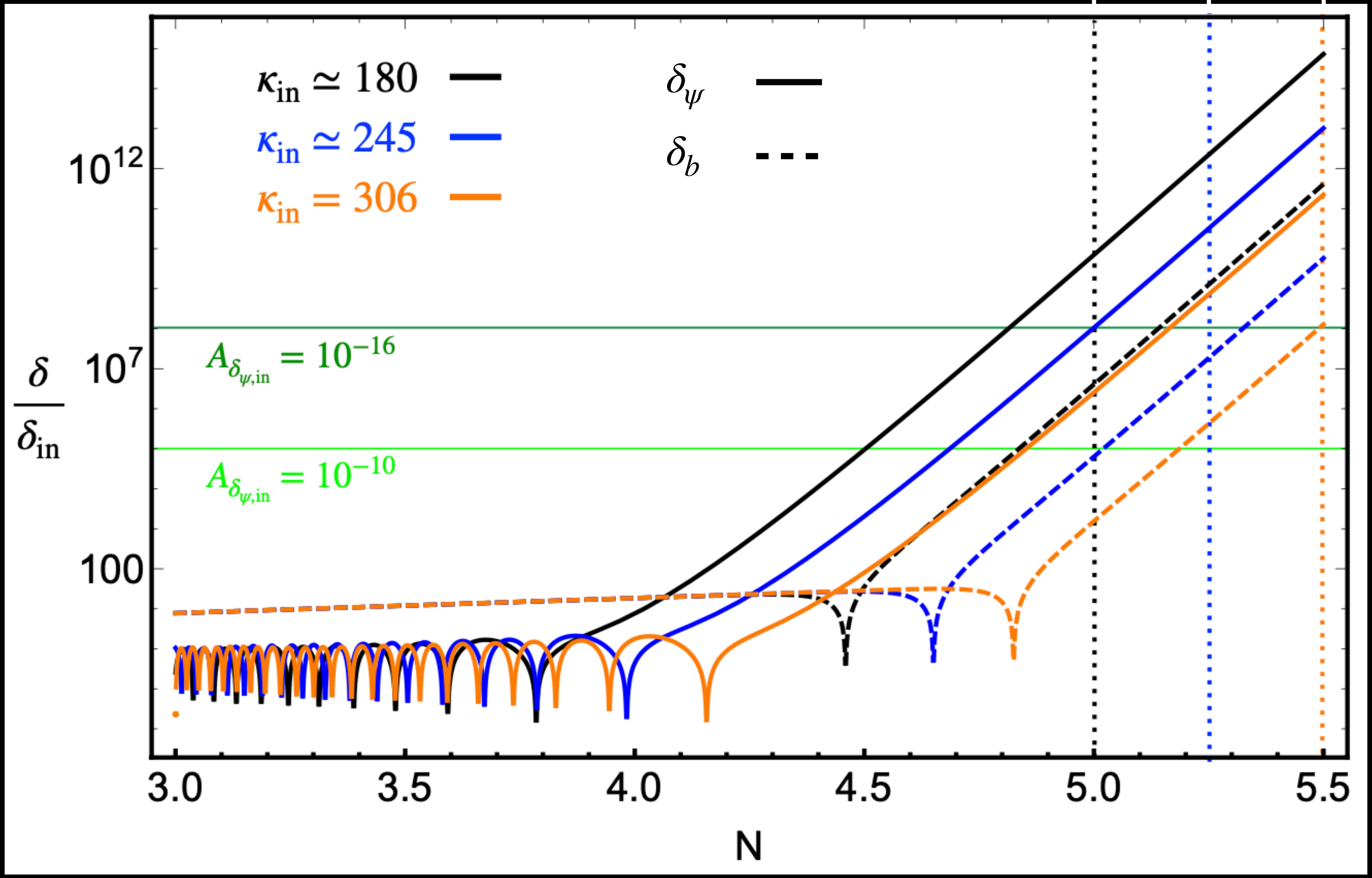
approximation breaks



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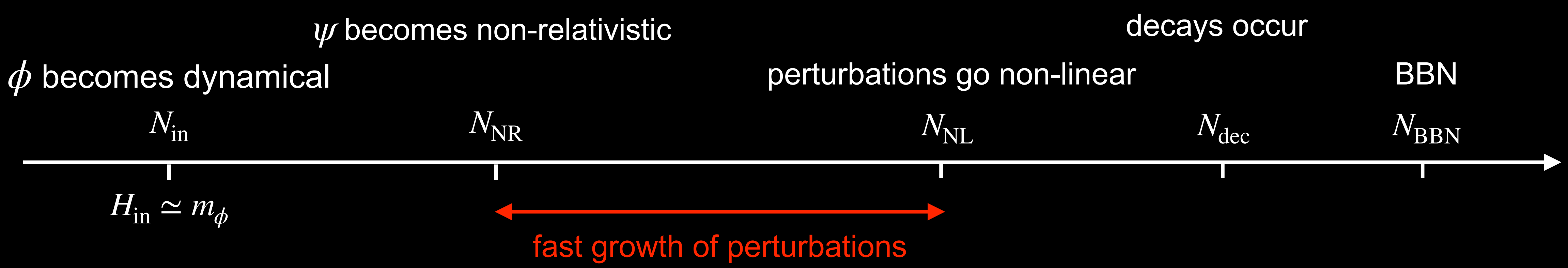
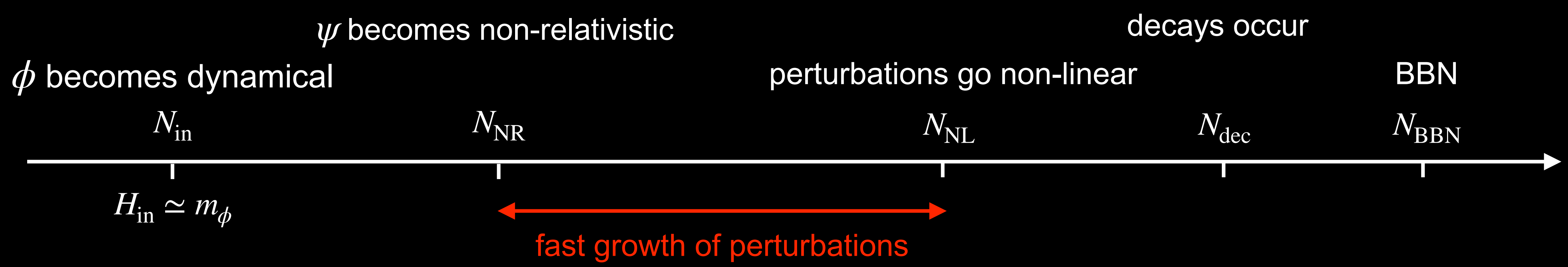
Decays


ψ becomes non-relativistic
decays occur
ϕ becomes dynamical
perturbations go non-linear
BBN
N_{in}
N_{NR}
N_{NL}
N_{dec}
N_{BBN}
$H_{\mathrm{in}} \simeq m_\phi$
fast growth of perturbations

Decays



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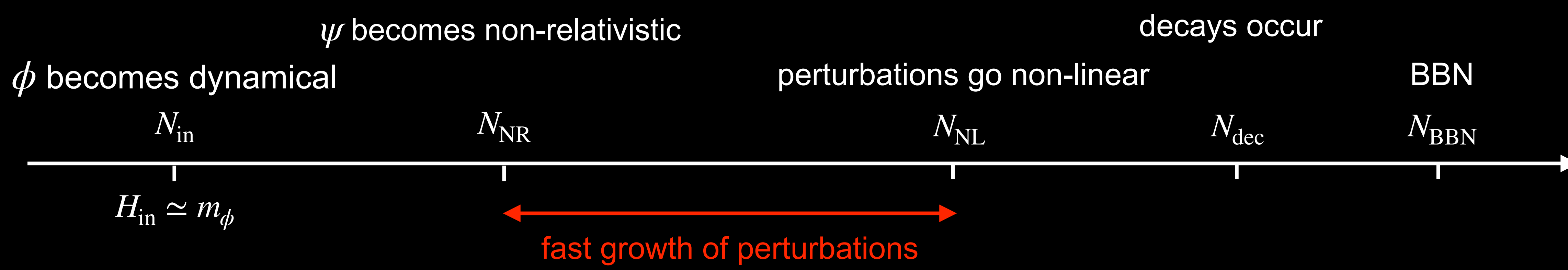

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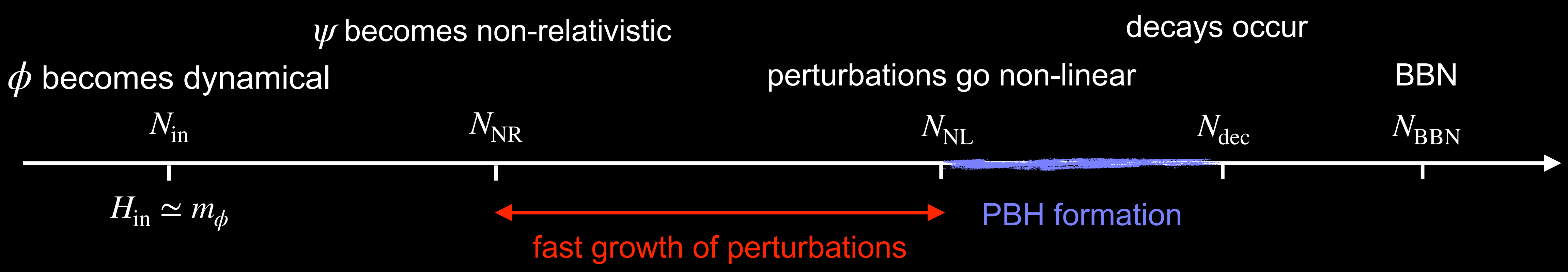
Primordial Black Holes

[Helfer, Marsh, Clough et al., 2016]
[Muia, Cicoli, Clough et al., 2019]
[Nazari, Cicoli, Clough, Muia, 2020]

when perturbations go non-linear PBH formation may occur



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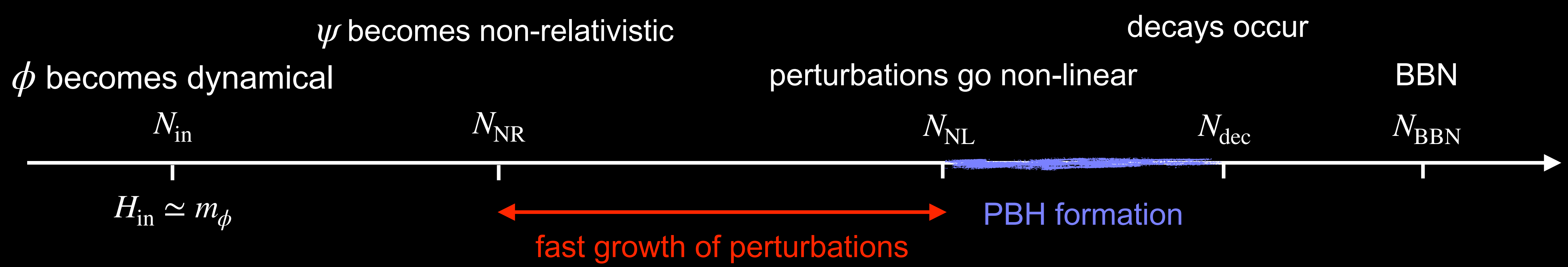

Mass of PBHs

$$M_{\rm PBH} \simeq \rho(N_{\rm NL}) \times \left(\frac{\epsilon_m}{m_\phi}\right)^3 \simeq 3 \times 10^{34}\,{\rm g} \times \exp\left(-\frac{3}{2}(2N_{\rm NL} + N_{\rm BBN})\right)$$

$\epsilon_m = 0.1$

$\epsilon_m < 1$

$$\rho(N_{\rm NL}) = 3H_{\rm NL}^2 M_{\rm p}^2 = 3\left(\frac{N_{\rm NL}}{H_{\rm in}}\right)^2 H_{\rm in}^2 M_{\rm p}^2$$

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ψ becomes non-relativistic

decays occur

ϕ becomes dynamical

perturbations go non-linear

BBN

$N_{\rm in}$ — $N_{\rm NR}$ — $N_{\rm NL}$ — $N_{\rm dec}$ — $N_{\rm BBN}$

$H_{\rm in} \simeq m_\phi$

PBH formation

fast growth of perturbations

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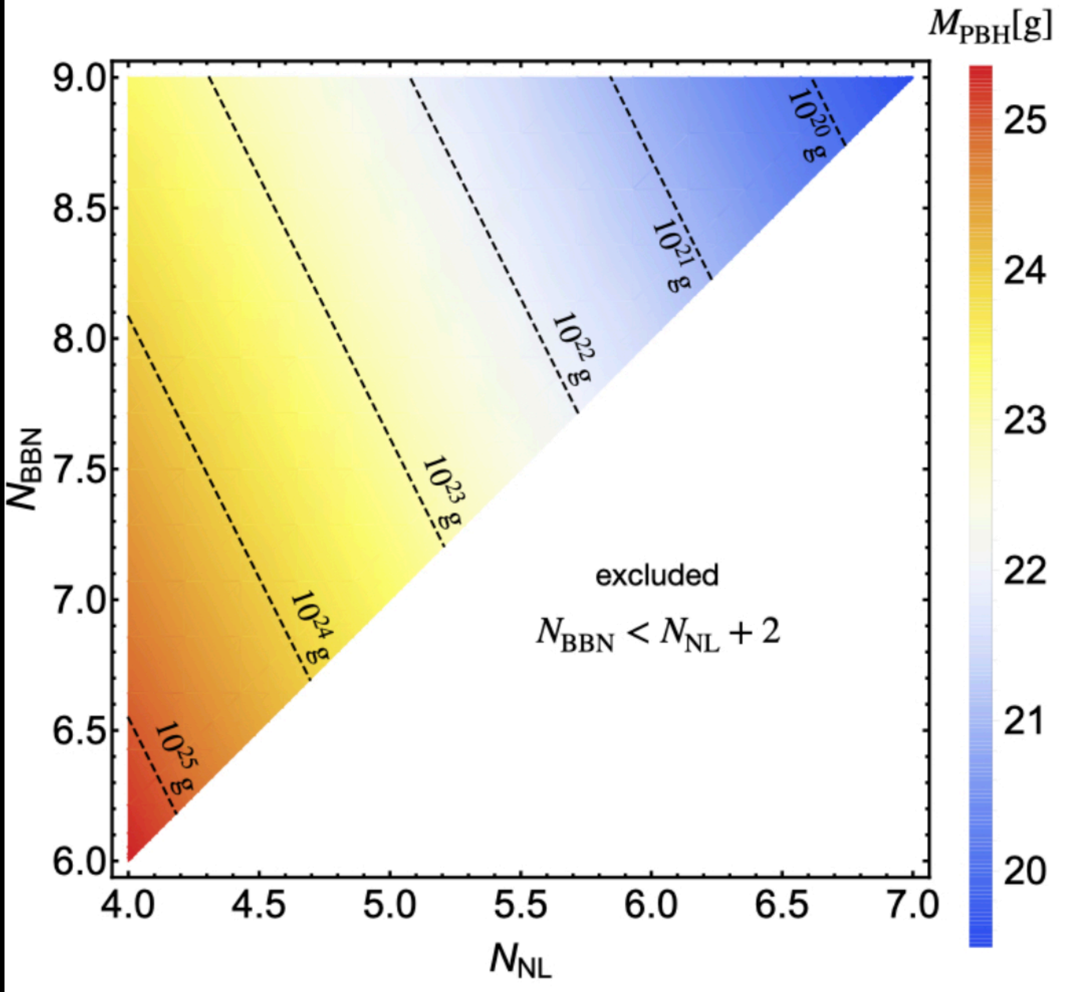
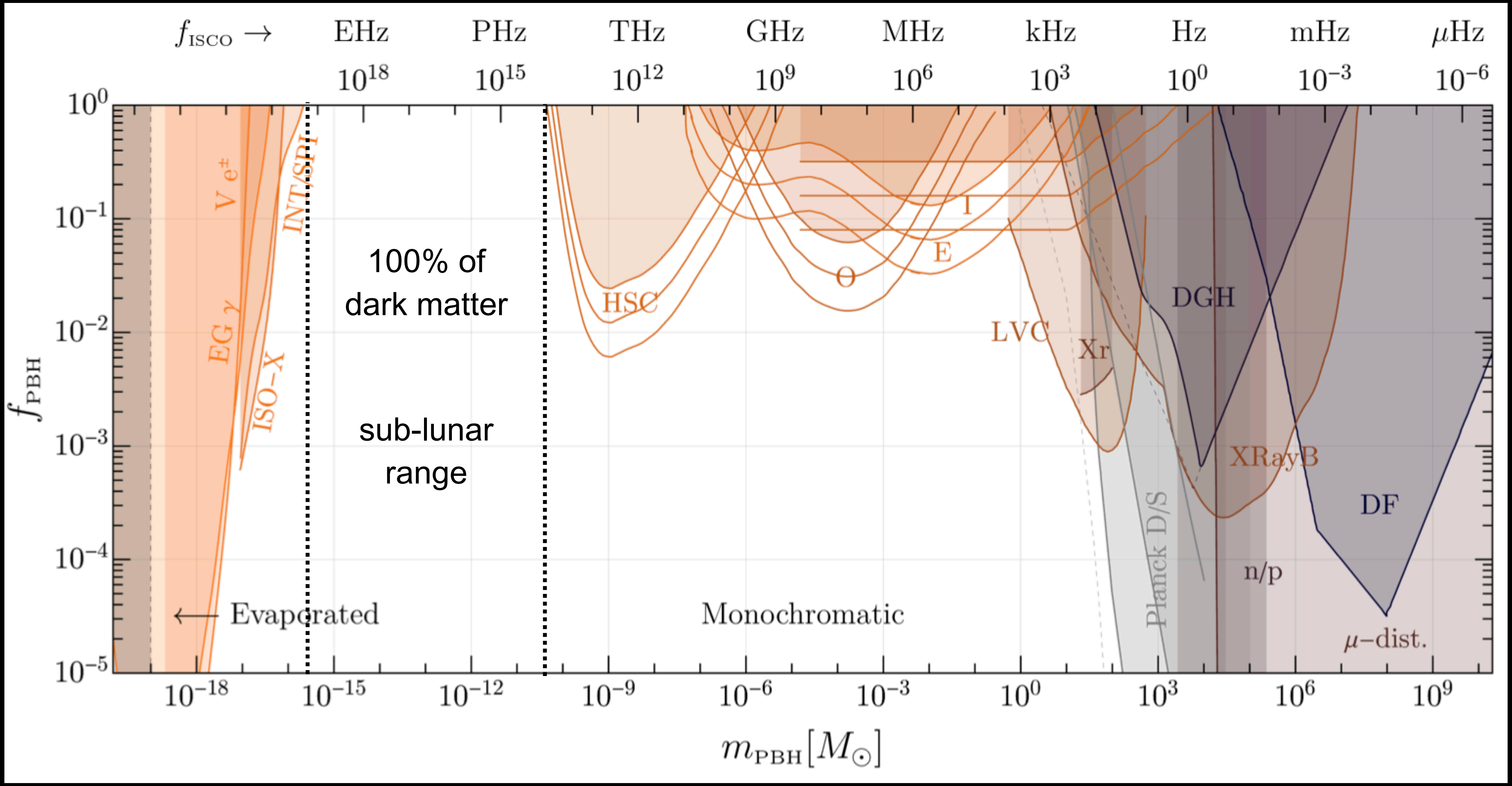


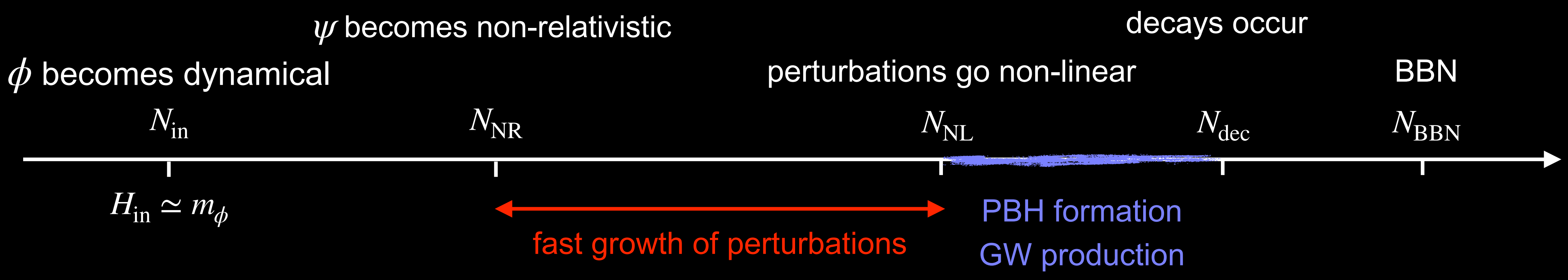
Primordial Black Holes

[Franciolini, Maharana, Muia, 2022]



Gravitational Waves

growth of perturbations induces GW production



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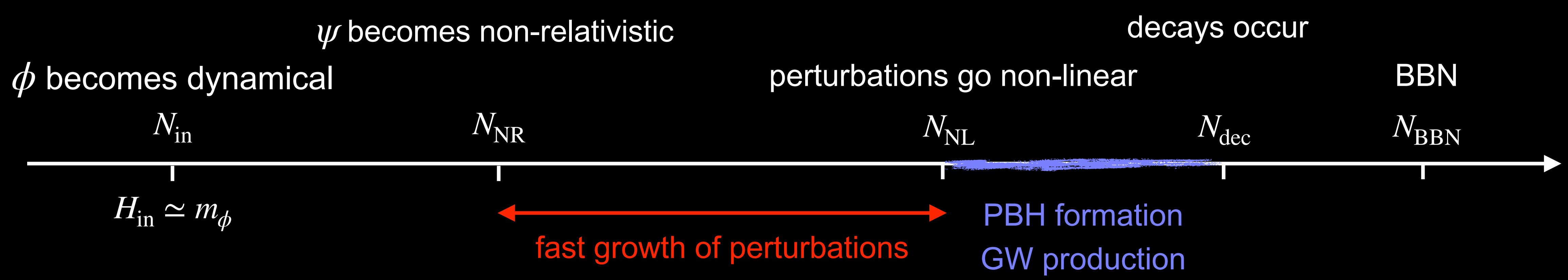


Amplitude of GW spectrum

$$\Pi_{ij}^{\rm TT} \simeq \alpha \rho_\phi \qquad \alpha \lesssim 1$$

$$\lambda = \Delta \log k$$

$$\Omega_{\rm GW,p} \simeq \frac{64\pi^2}{3M_{\rm p}^2 H_{\rm NL}^4} \frac{\rho_\phi^2(N_{\rm NL})}{(k_{\rm p}/(a_{\rm NL}H_{\rm NL}))^2} \frac{\alpha^2}{\lambda} \simeq \frac{192\pi^2 \Omega_\phi^2(N_{\rm NL})}{(k_{\rm p}/(a_{\rm NL}H_{\rm NL}))^2} \frac{\alpha^2}{\lambda} \simeq 6.5 \times 10^{-8}$$

$\rightarrow$ $\alpha, \lambda \sim 1$

$$\longrightarrow \quad \Omega_{\rm GW,0} \simeq \left(\frac{a_{\rm NL}}{a_0}\right)^4 \frac{\rho_{\rm NL}}{\rho_0} \Omega_{\rm GW,p}(k_p) \lesssim 2.4 \times 10^{-12}$$

barely detectable with LISA, BBO, CE

Peak frequency $\quad f_0 \gtrsim \left(\frac{m_\phi}{10^{-17}\,{\rm GeV}}\right) \exp\left(N_{\rm NL} - N_{\rm BBN}\right) \times 10^{-3}\,{\rm Hz}$

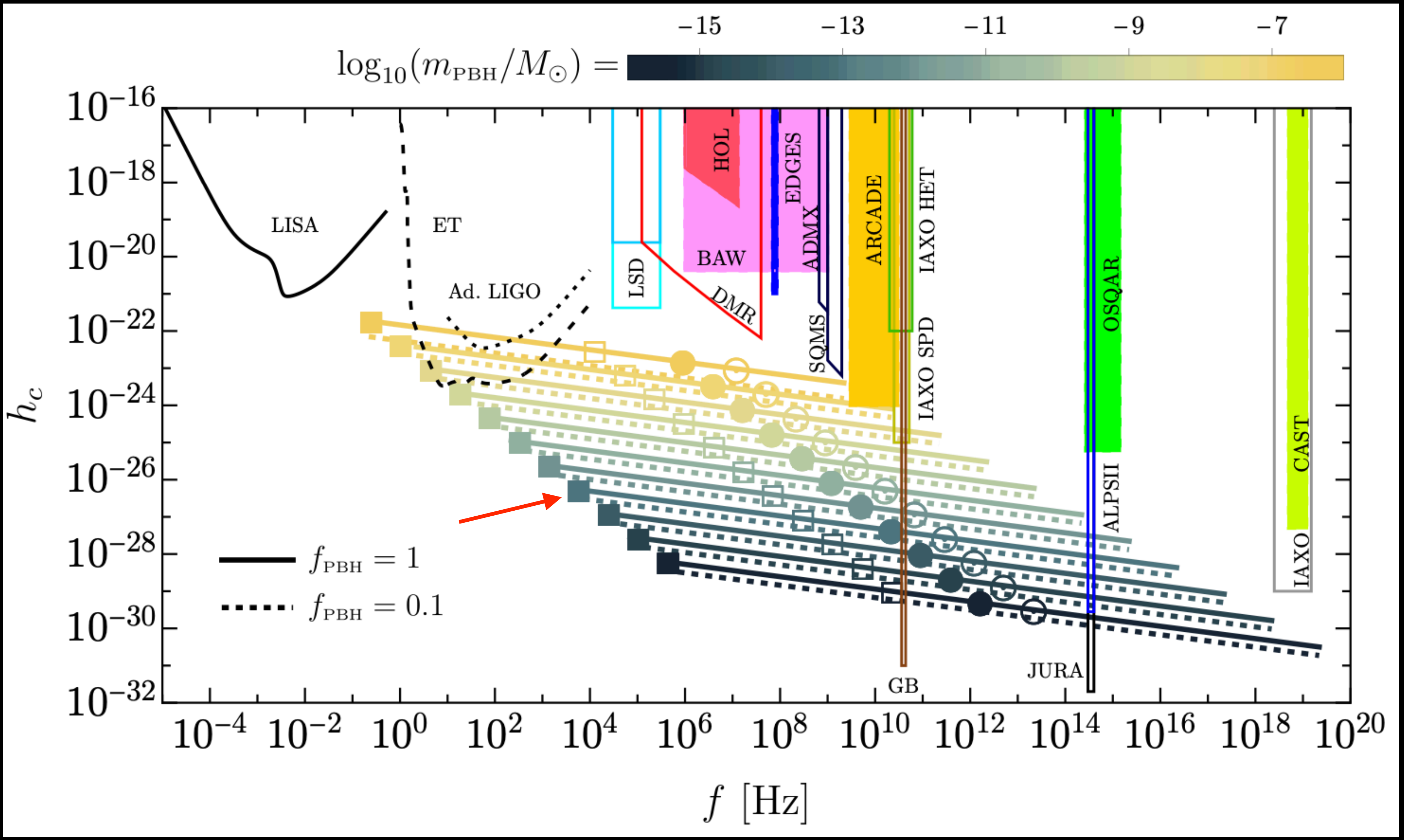
[Chatrchyan, Jaeckel, 2021]

Detectability

ISCO frequency

$$f \simeq 10^{15}\,\mathrm{Hz}\left(\frac{10^{20}\,\mathrm{g}}{M_{\mathrm{PBH}}}\right)$$

See [Muia, Quevedo et al., 2020] for a comprehensive review of Ultra-High-Frequency GWs physics



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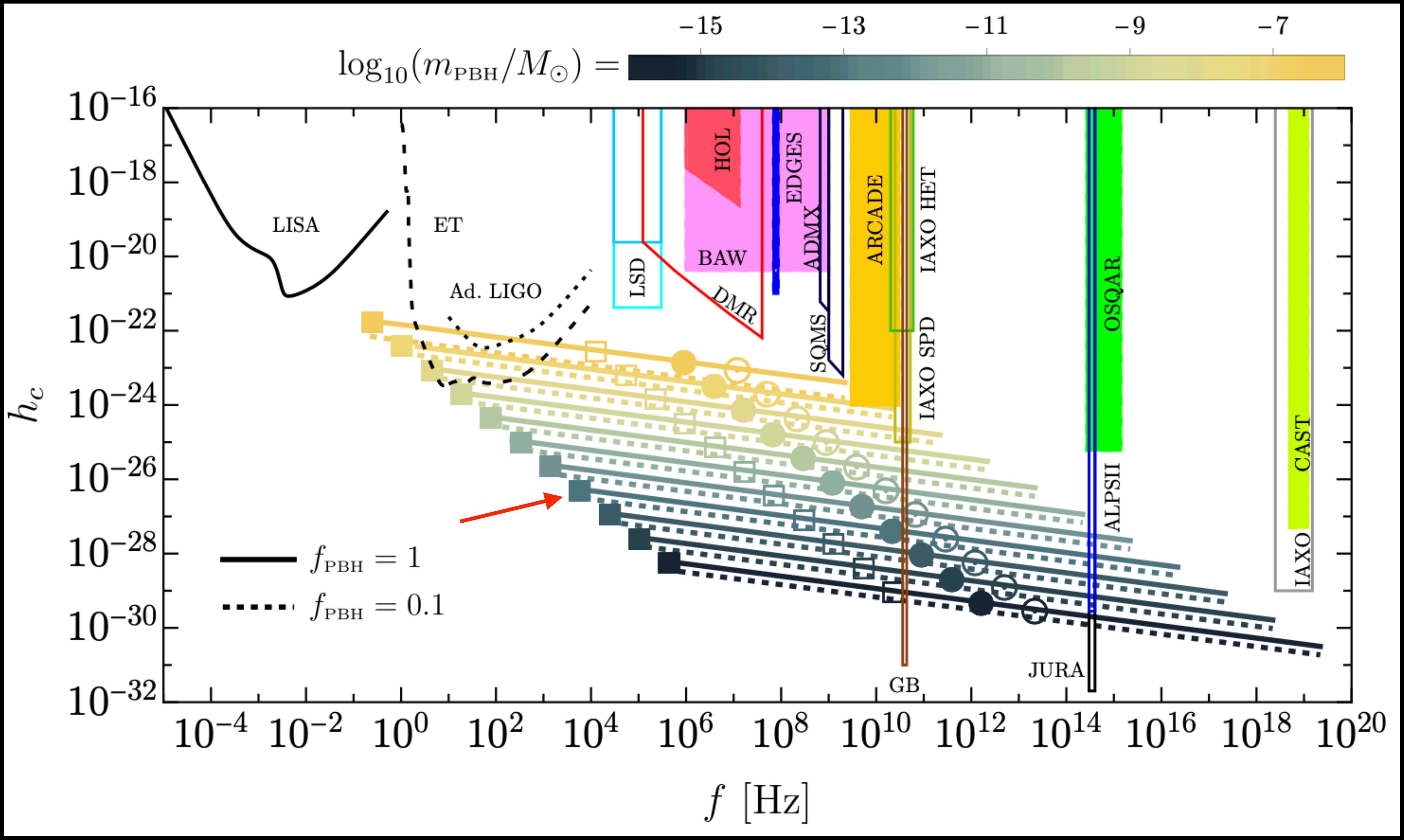
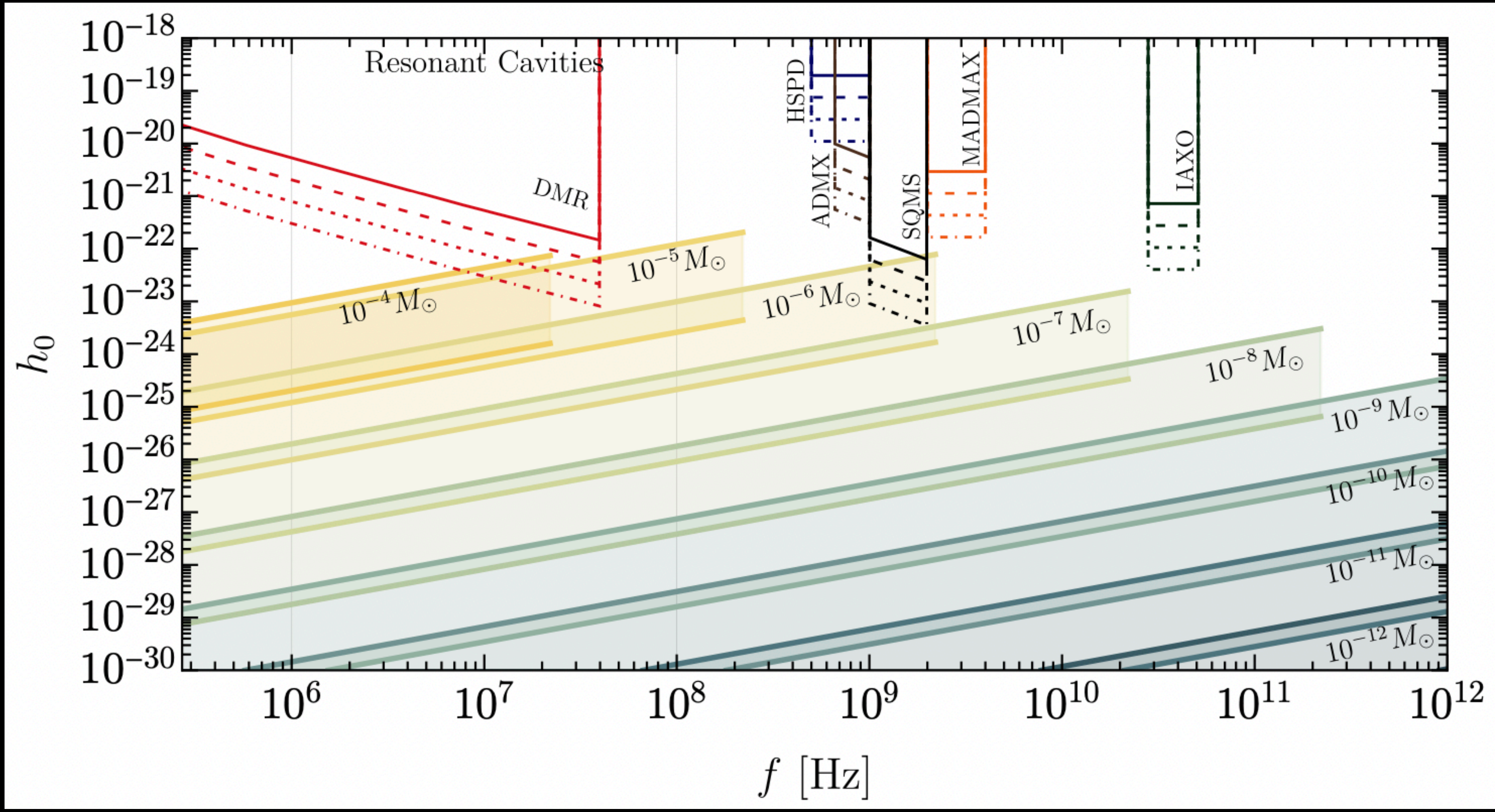


Ultra-High-Frequency range

The Hunt for Light Primordial Black Hole Dark Matter with Ultra-High-Frequency Gravitational Waves

Based on 2205.02153, with Gabriele Franciolini and Anshuman Maharana



DMR applies to $m_{\rm PBH} = (10^{-5}, 10^{-6}, 10^{-7}, 10^{-8})\,M_\odot$ at 400 MHz.

IAXO applies to $m_{\rm PBH} = (10^{-8}, 10^{-9}, 10^{-10}, 10^{-11})\,M_\odot$ at ~ 30 GHz.

Conclusions

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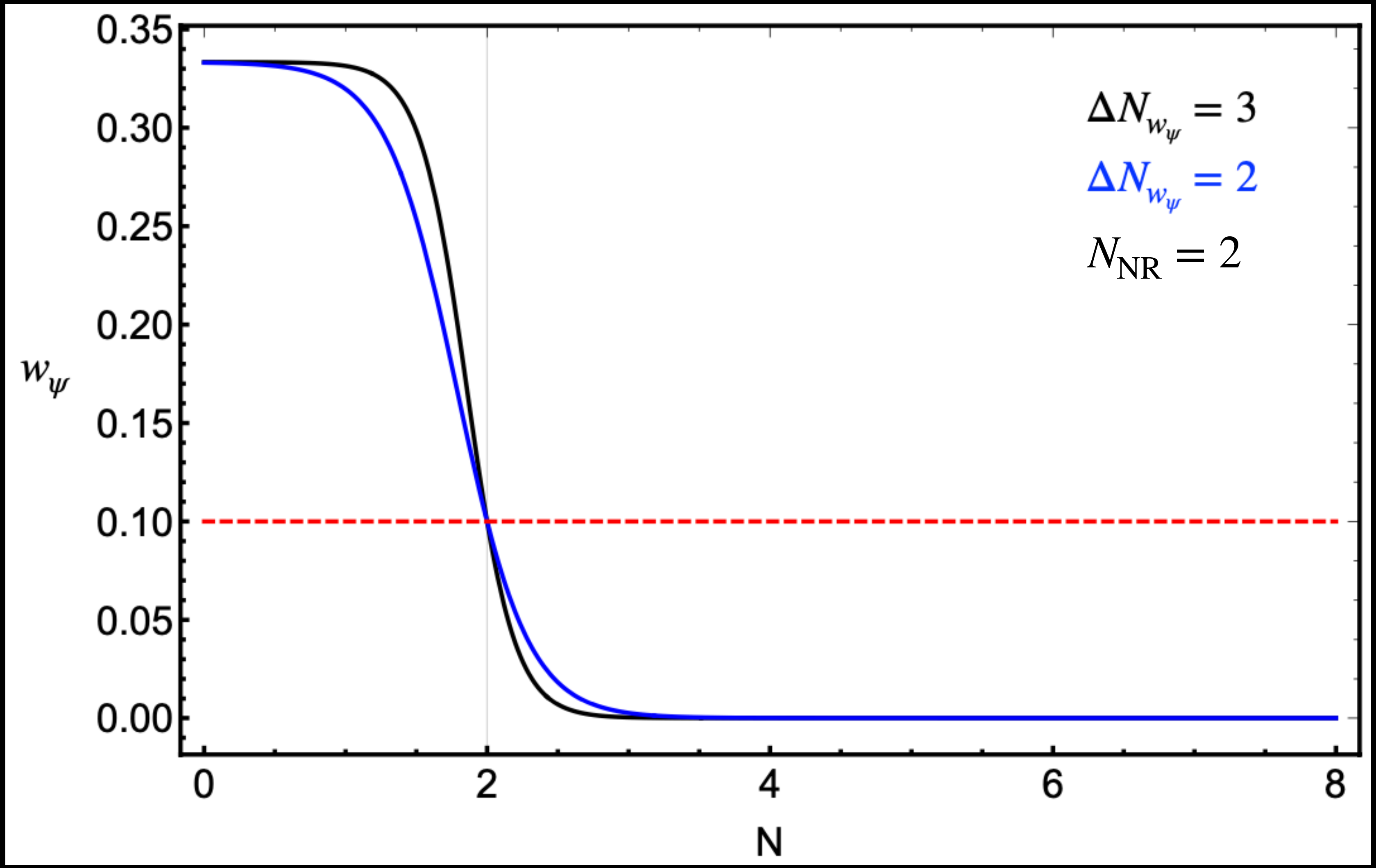
THANKS FOR THE ATTENTION

Equation of state

Parametrization: $w_\psi = \frac{1}{6}\left(-\tanh\left(\Delta N_{w_\psi}(N - (N_{\rm NR} - \delta N))\right)\right)$

$\delta N = \mathrm{arctanh}(0.6/\Delta N_{w_\psi})$



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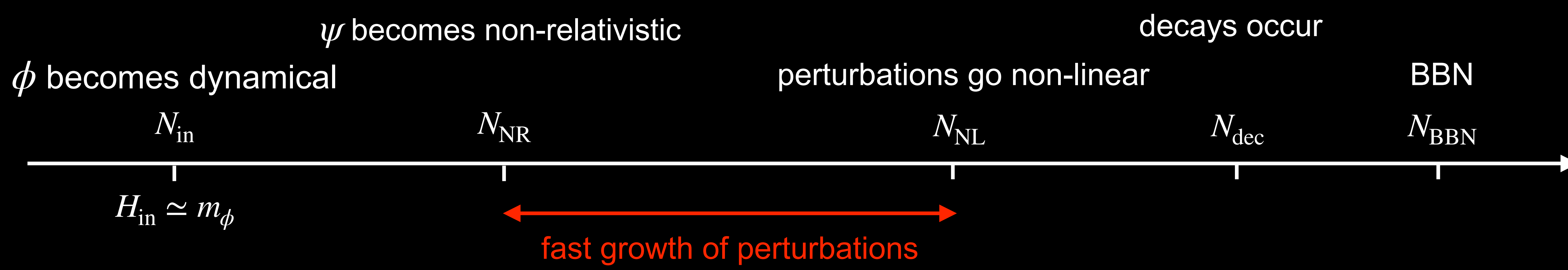

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$$\mathscr{L}_{\rm int} \supset y\phi\bar{\chi}\chi + {\rm h.c.}$$

$\Gamma_\phi \simeq \dfrac{y^2 m_\phi}{8\pi}$ $\longrightarrow$ $y_{\rm min} \lesssim m_b \lesssim y_{\rm min} \exp\left(\dfrac{3}{4}(N_{\rm BBN} - N_{\rm NL})\right)$ $\quad N_{\rm BBN} = N_{\rm NL} + 2$

$$y_{\rm min} = \sqrt{8\pi}\exp\left(-\frac{3}{4}N_{\rm BBN}\right) \qquad 0.038 \lesssim y \lesssim 0.17$$