Lucien HEURTIER

King's College – TPPC Seminar

Primordial Black Hole Archaeology

Durham University

UKRI Science and Technology Facilities Council

References

- A. Cheek (Warsaw), L.H., Y.F. Perez-Gonzalez (Durham), J. Turner (Durham)

- *Phys.Rev.D 105 (2022) 1, 015022* [PRD Highlights]

- *Phys.Rev.D 105 (2022) 1, 015023* [PRD Highlights]

- Phys.Rev.D *106 (2022) 10, 103012*

- ArXiv: 2212.03878 Dec 2022, Submitted to PRD

- K.R. Dienes (Arizona), L.H., F. Huang (Israel), D. Kim (Texas), B. Thomas, and T.M.P. Tait (California)

- ArXiv: 2212.01369 Dec 2022, Submitted to PRD

- A. Ghoshal (Warsaw), Y. Gouttenoire (Israel), L.H., P. Simakachorn (Spain)

- ArXiv: 2302.XXXX Feb 2023, *to appear*

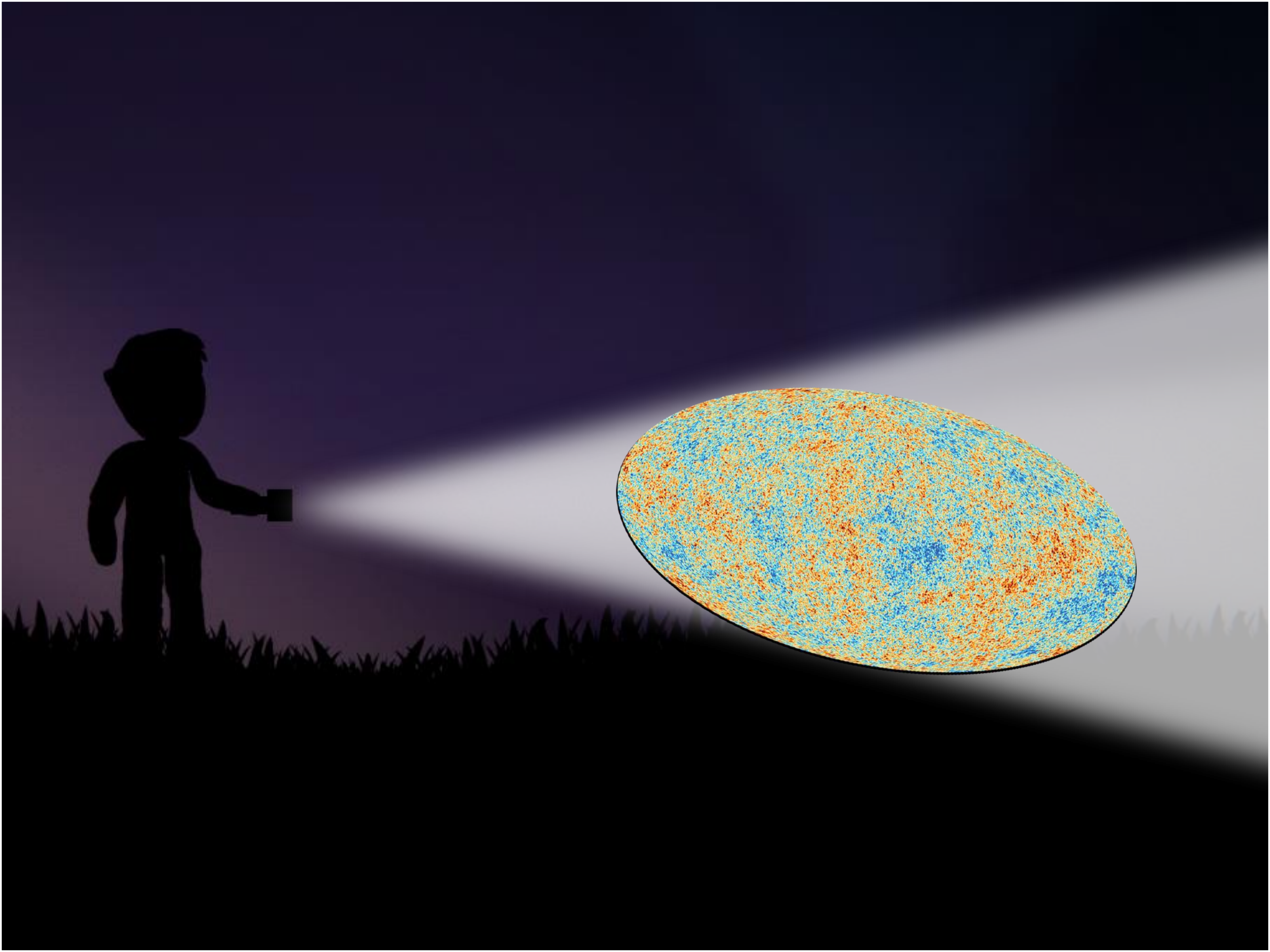
- S. Mishra (Nottingham), L.H., and V. Vennin (Paris)

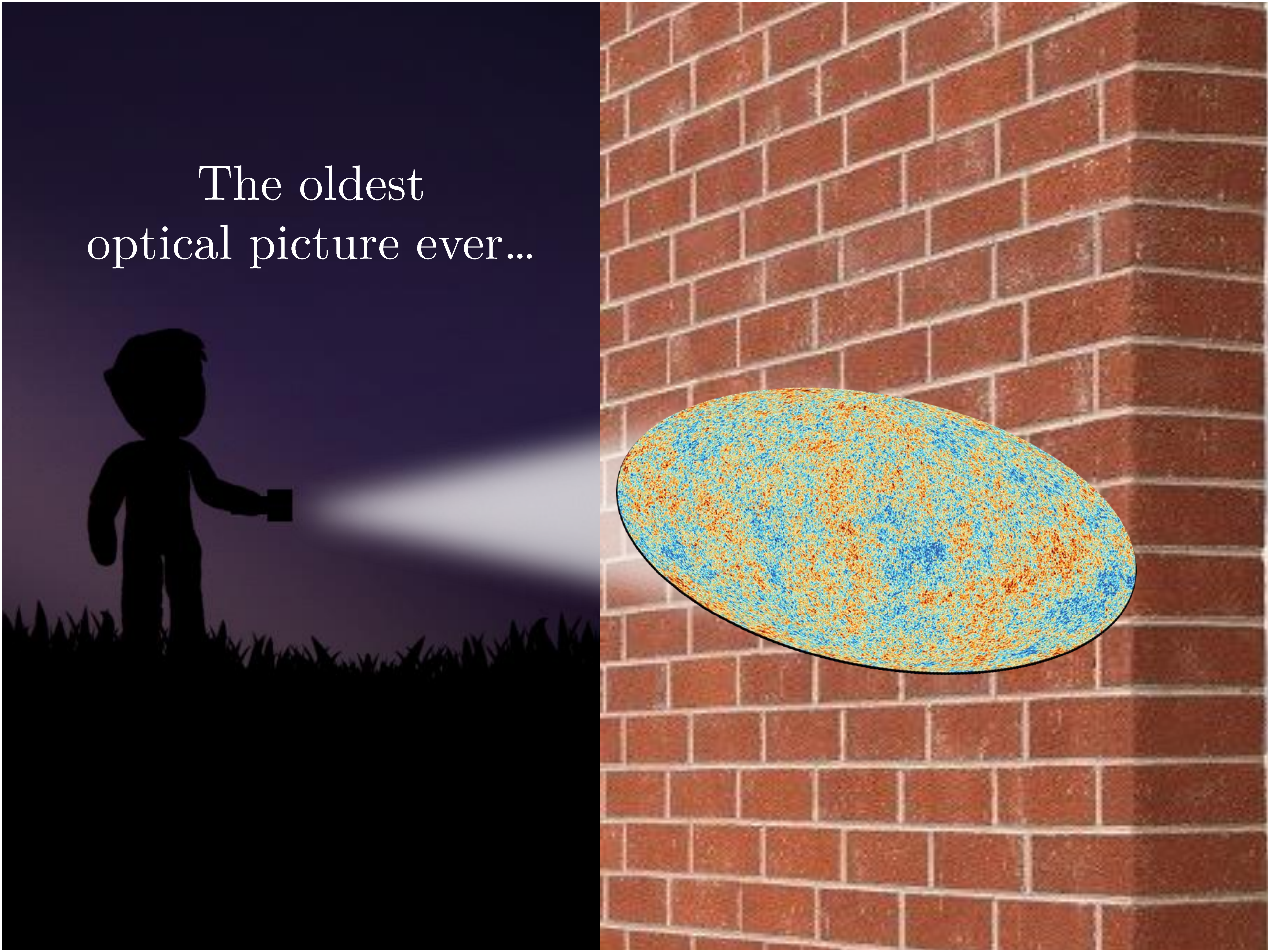
- ArXiv: 23XX.XXXX 2023, *on-going project*

WHY

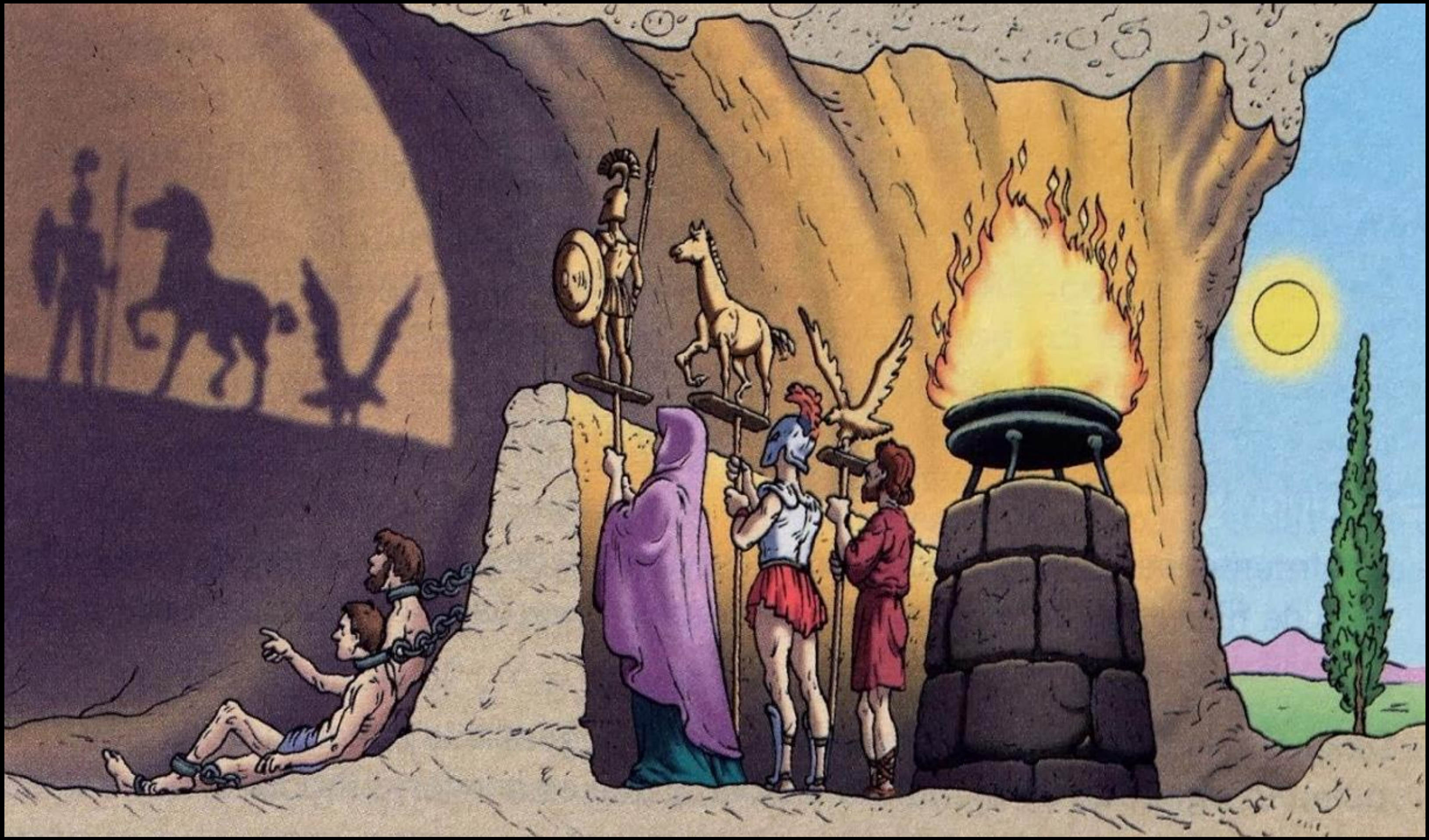
Primordial

Black Holes?




The oldest
optical picture ever...

Allegory of the Cave...



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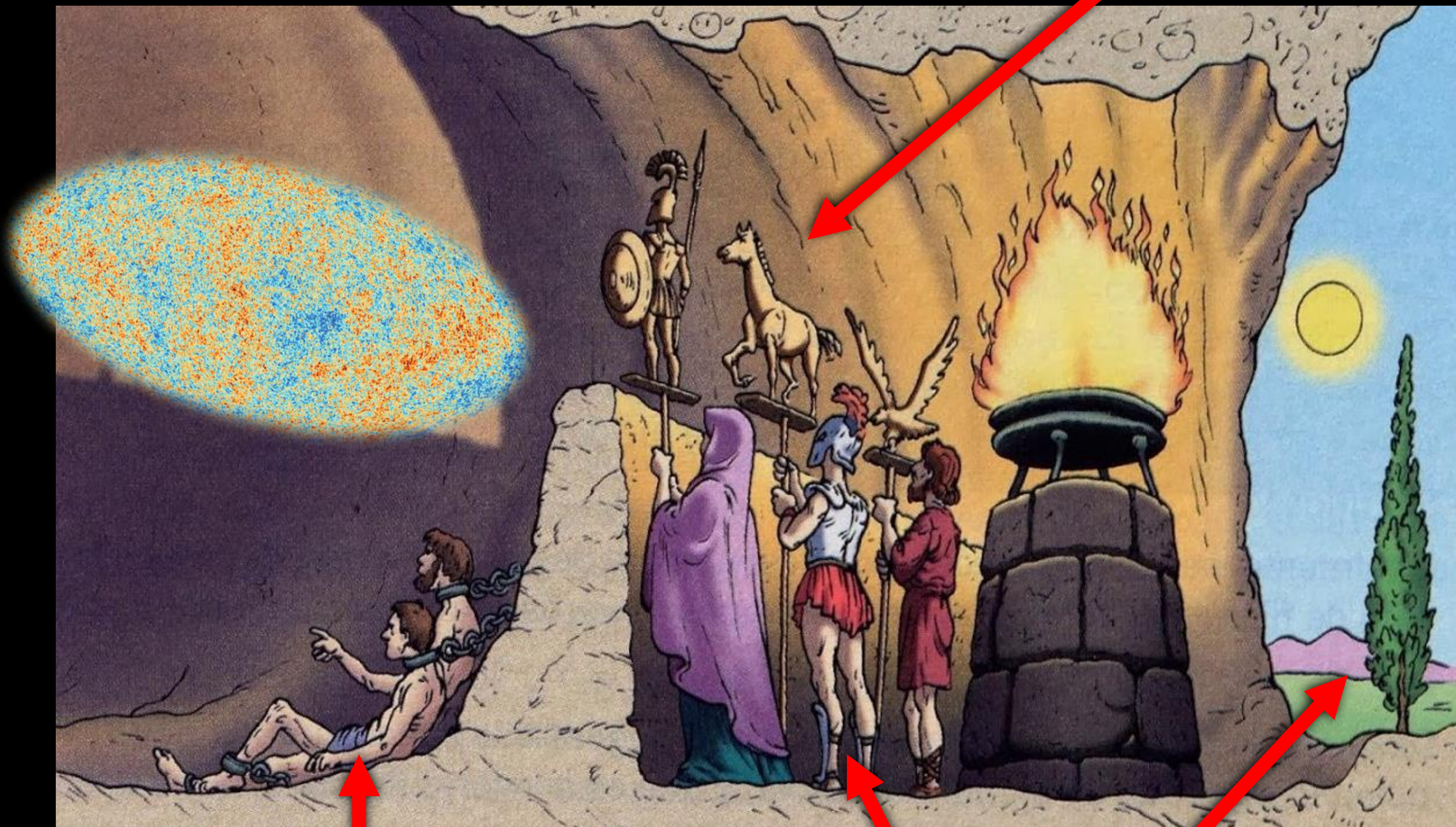
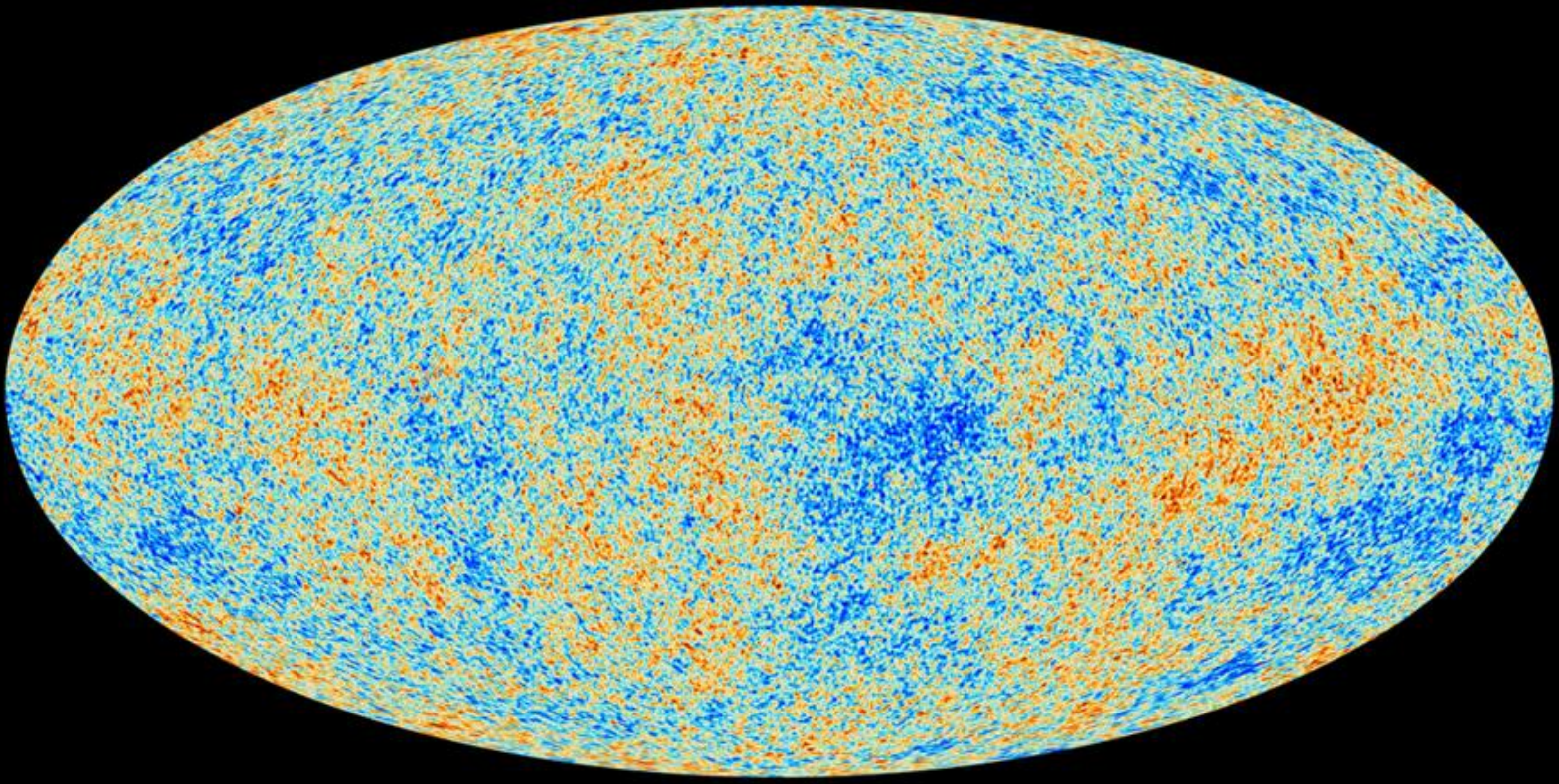
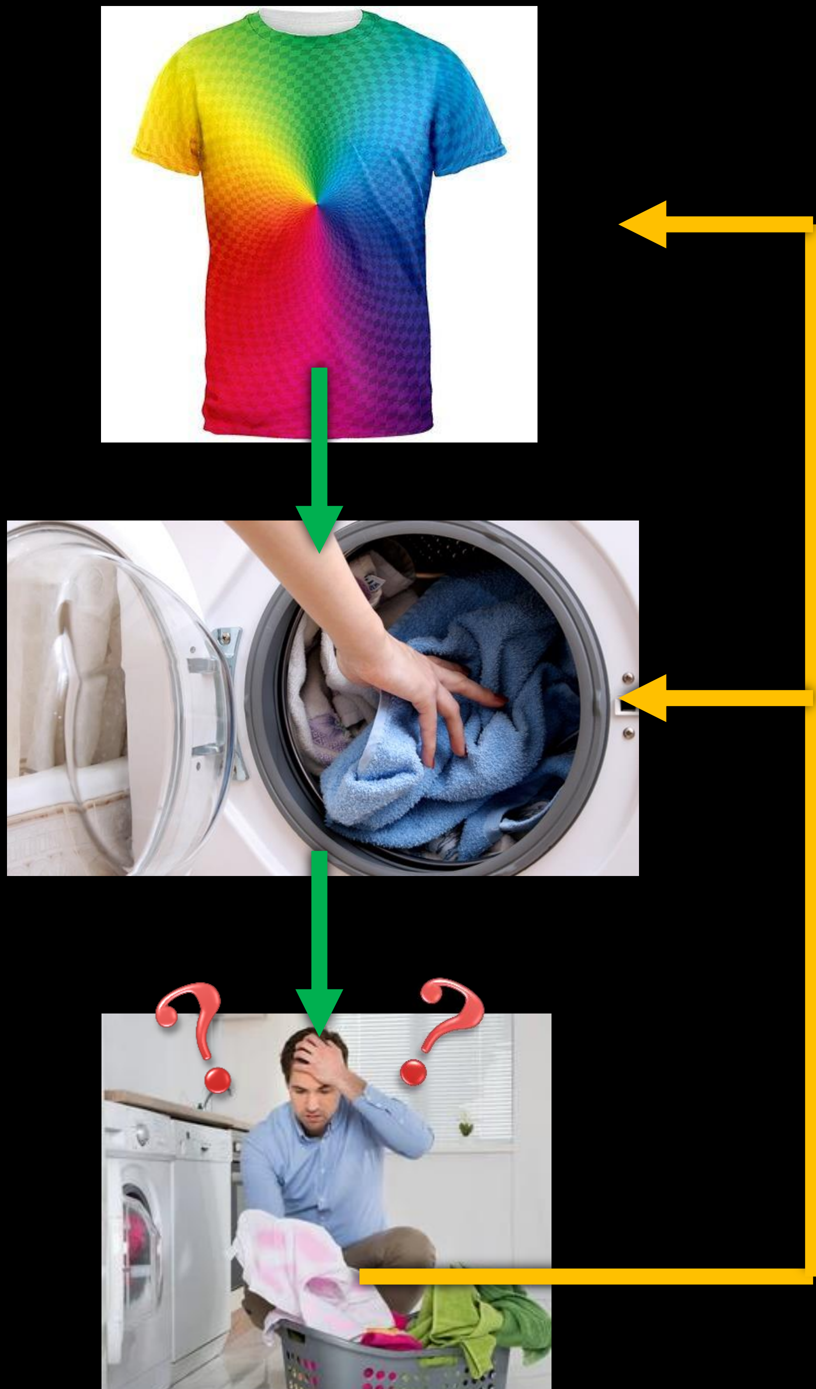


CMB HIGHLIGHTS

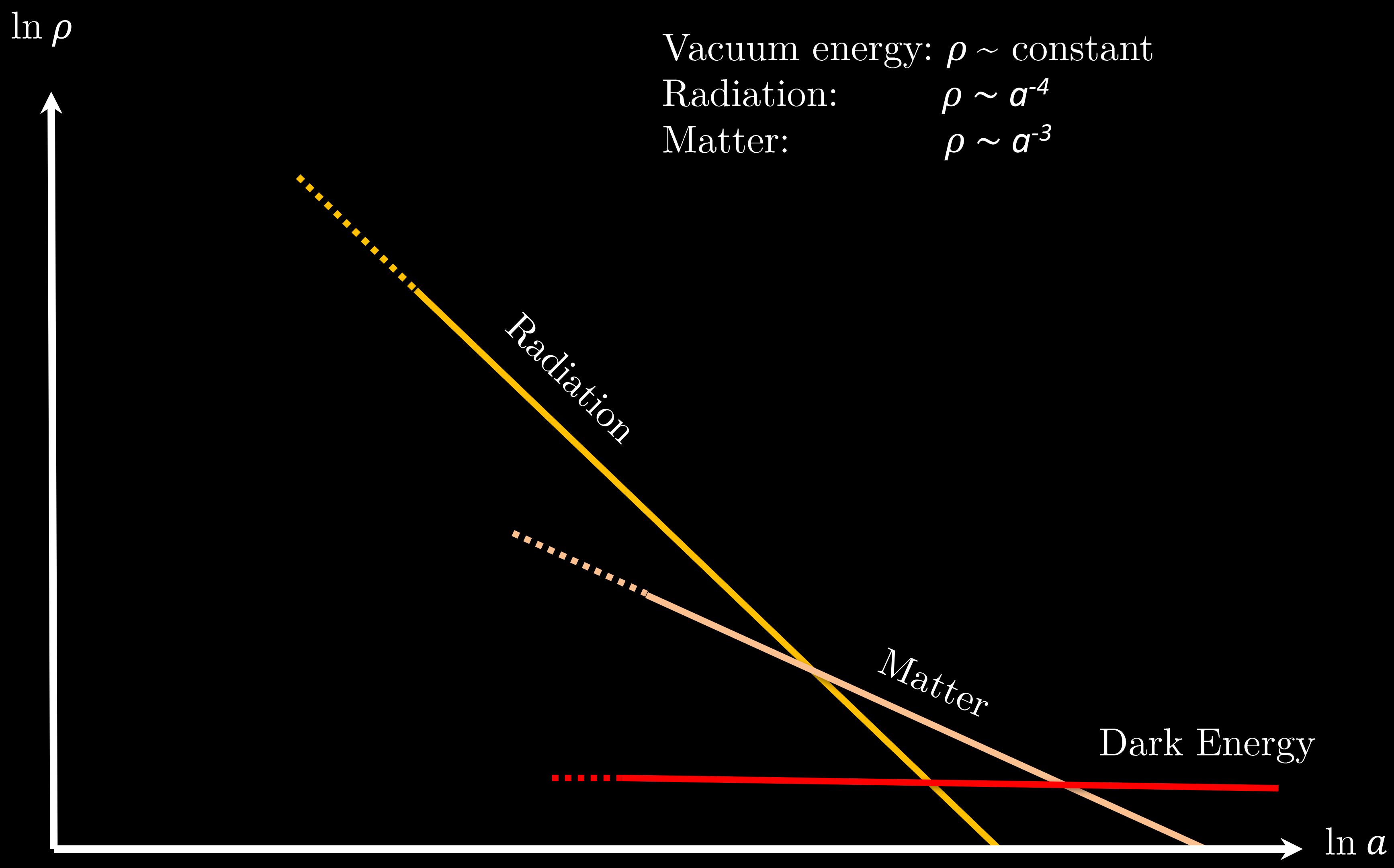


A QUASI – HOMOGENEOUS, FLAT UNIVERSE



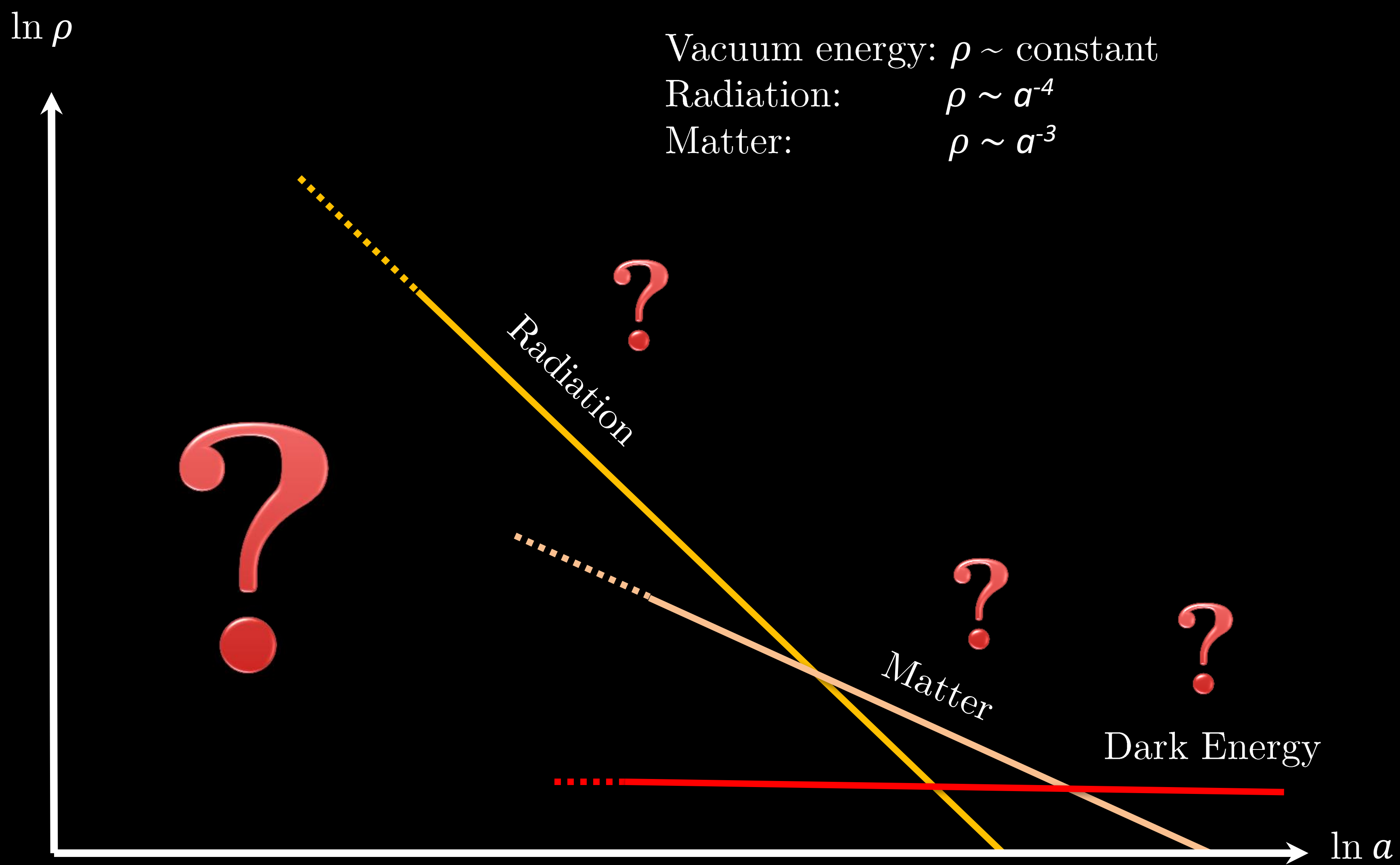
What kind of model can explain the data?

The ΛCDM Ideology

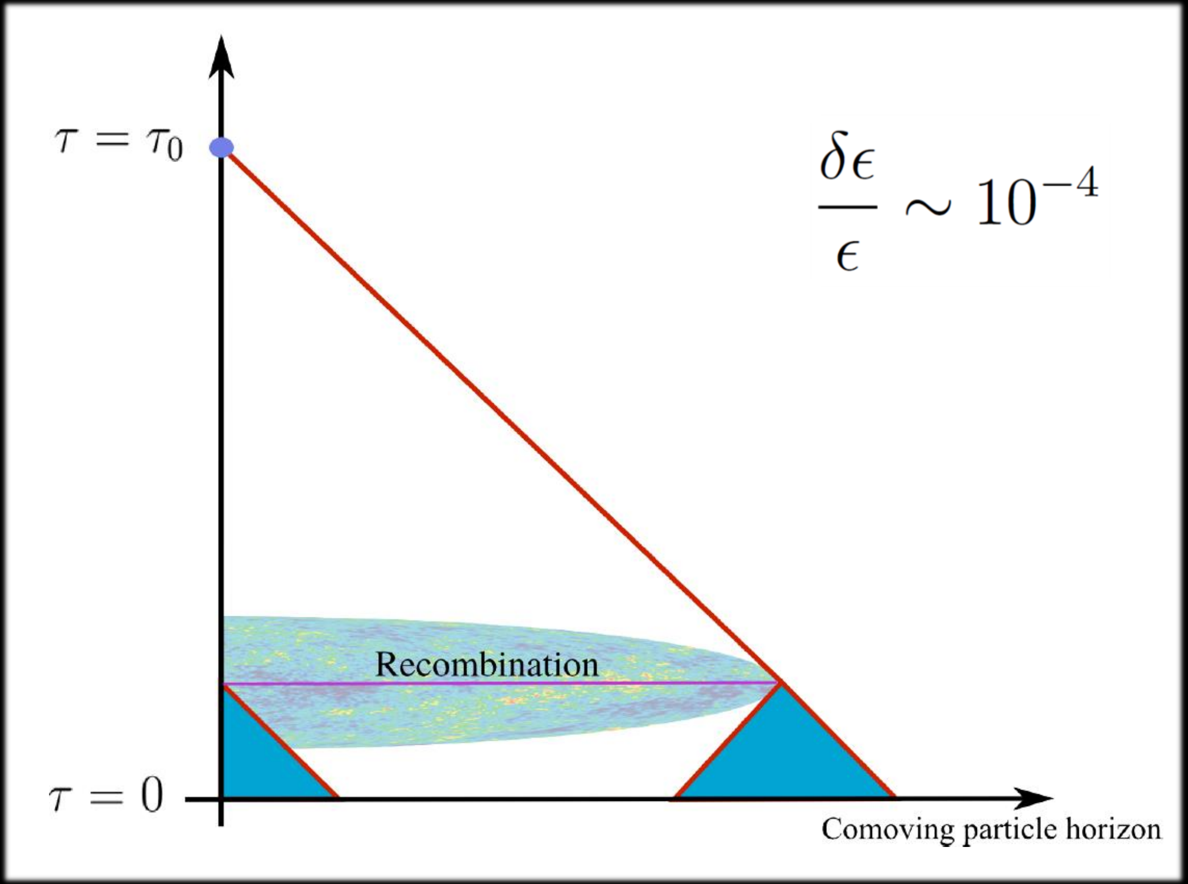


The ΛCDM Ideology

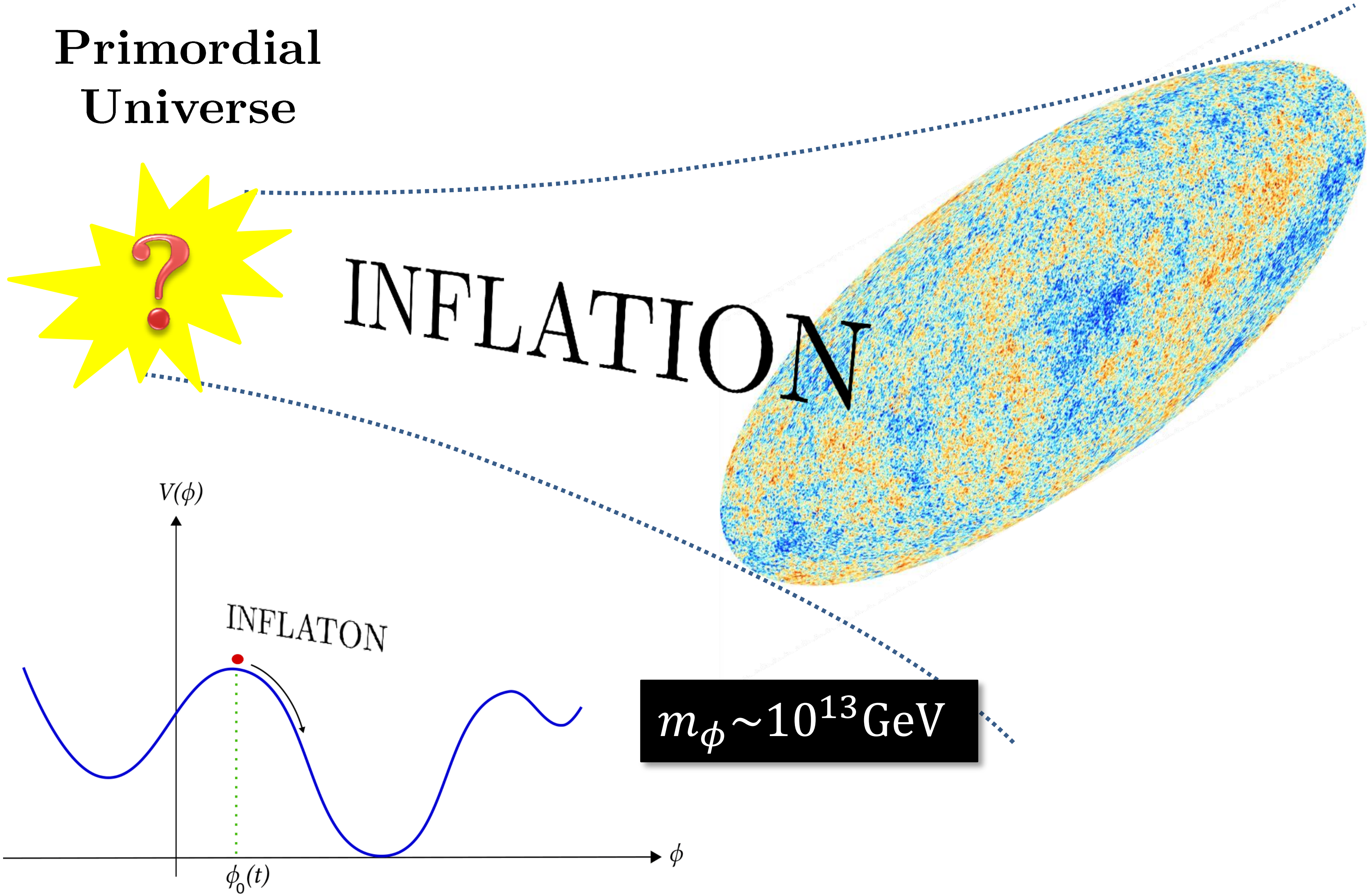
Vacuum energy: $\rho \sim$ constant
Radiation: $\rho \sim a^{-4}$
Matter: $\rho \sim a^{-3}$



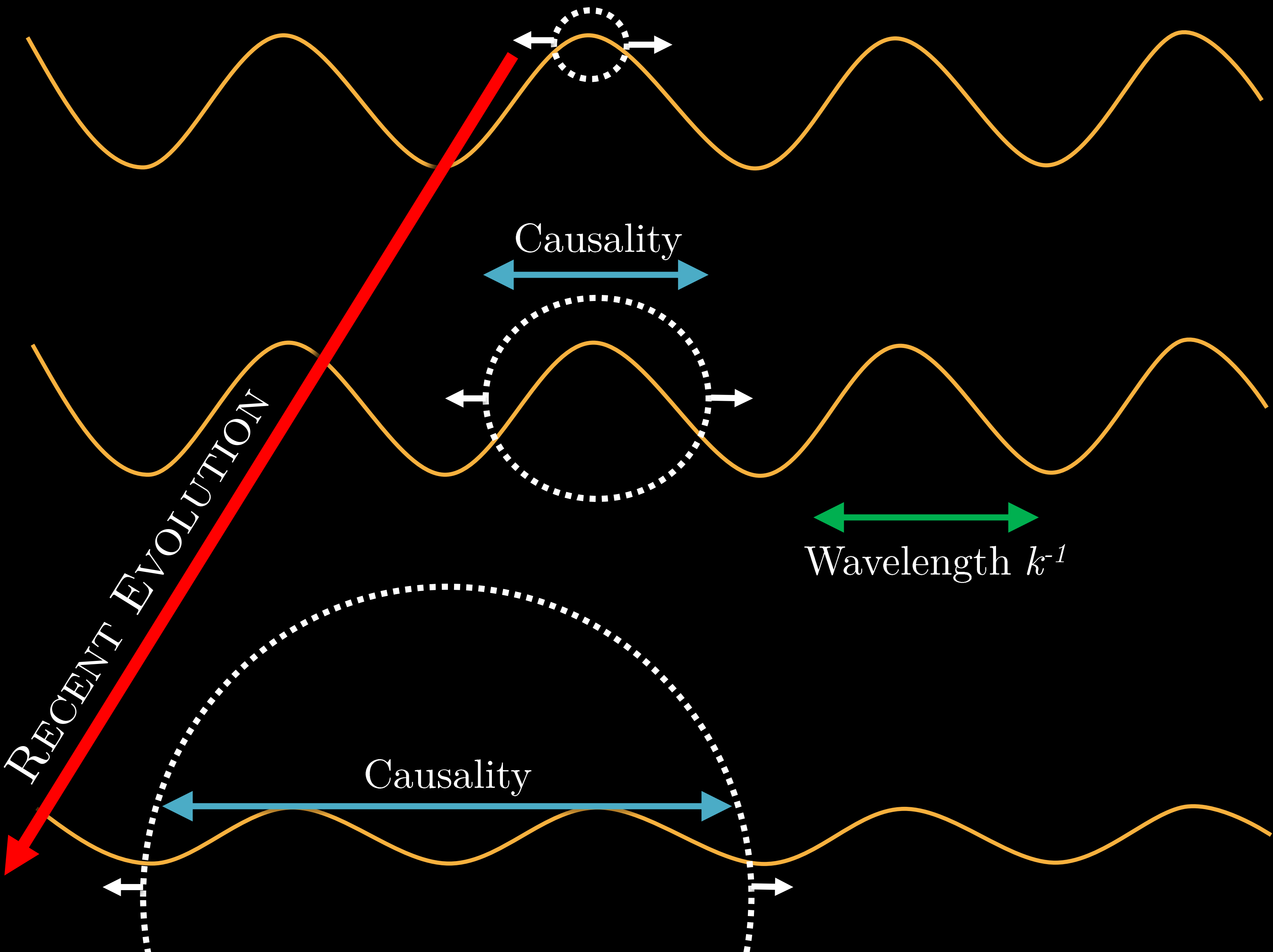
The *Horizon* Problem



Cosmic Inflation



Primordial Perturbation Evolution



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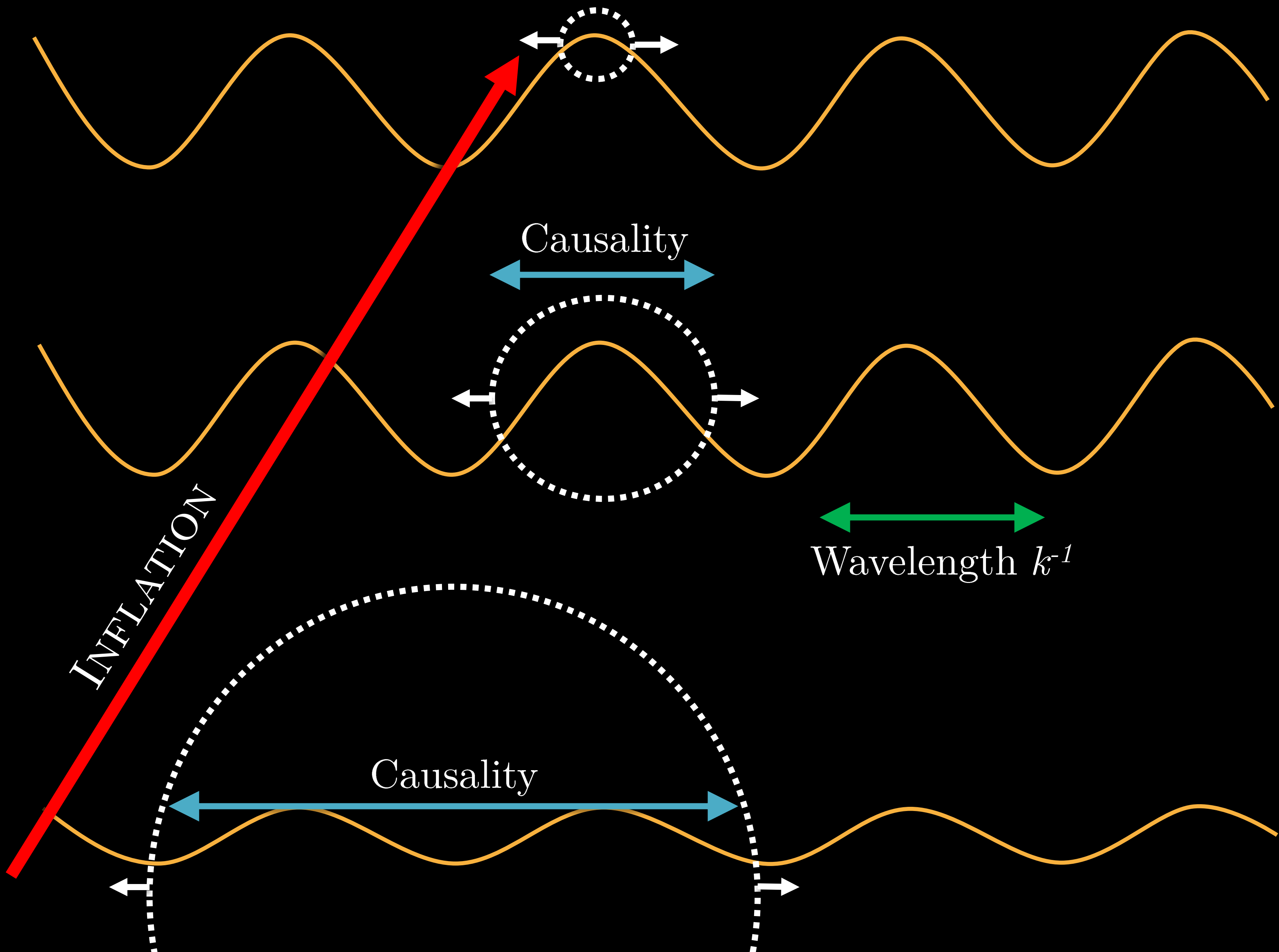

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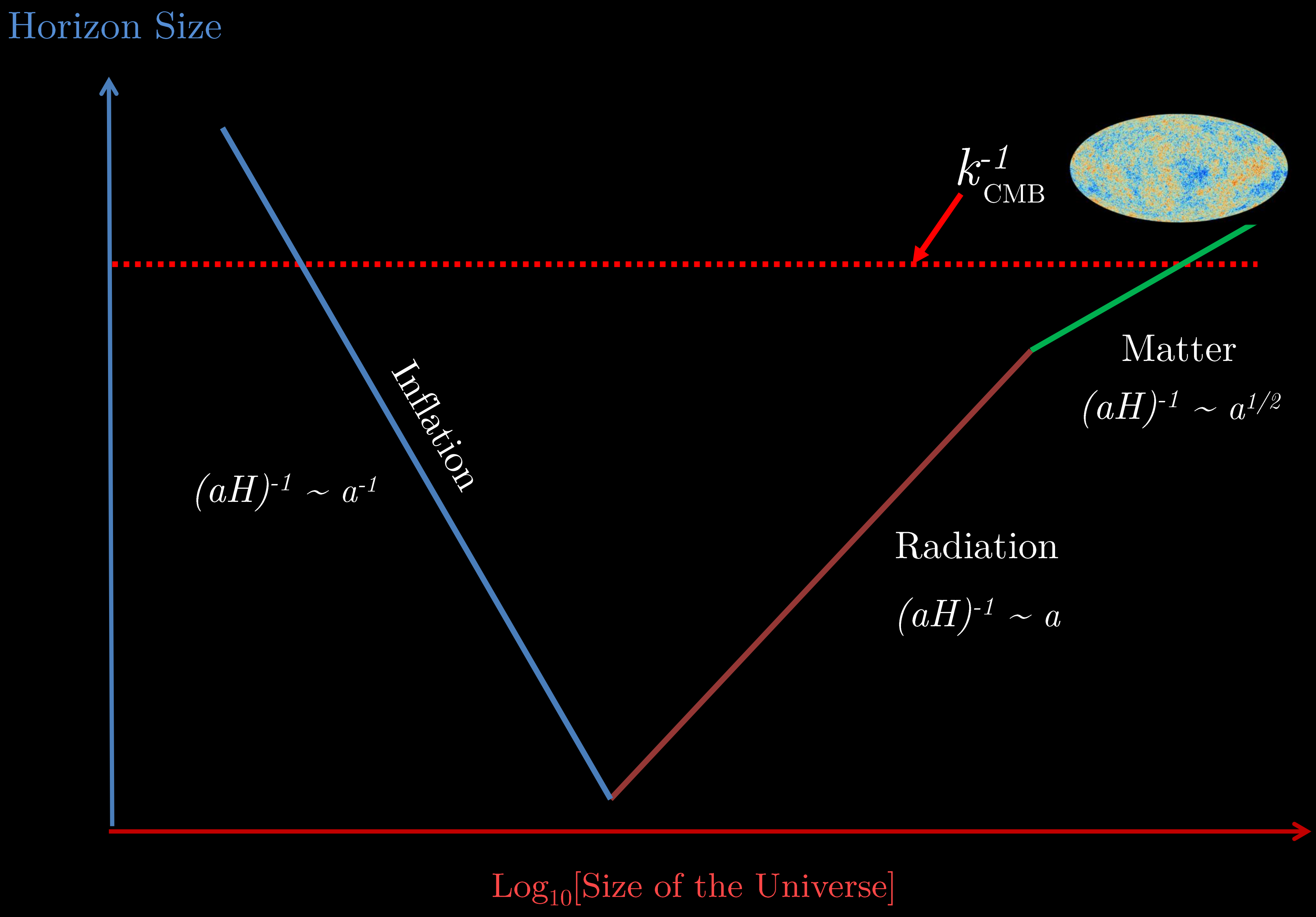

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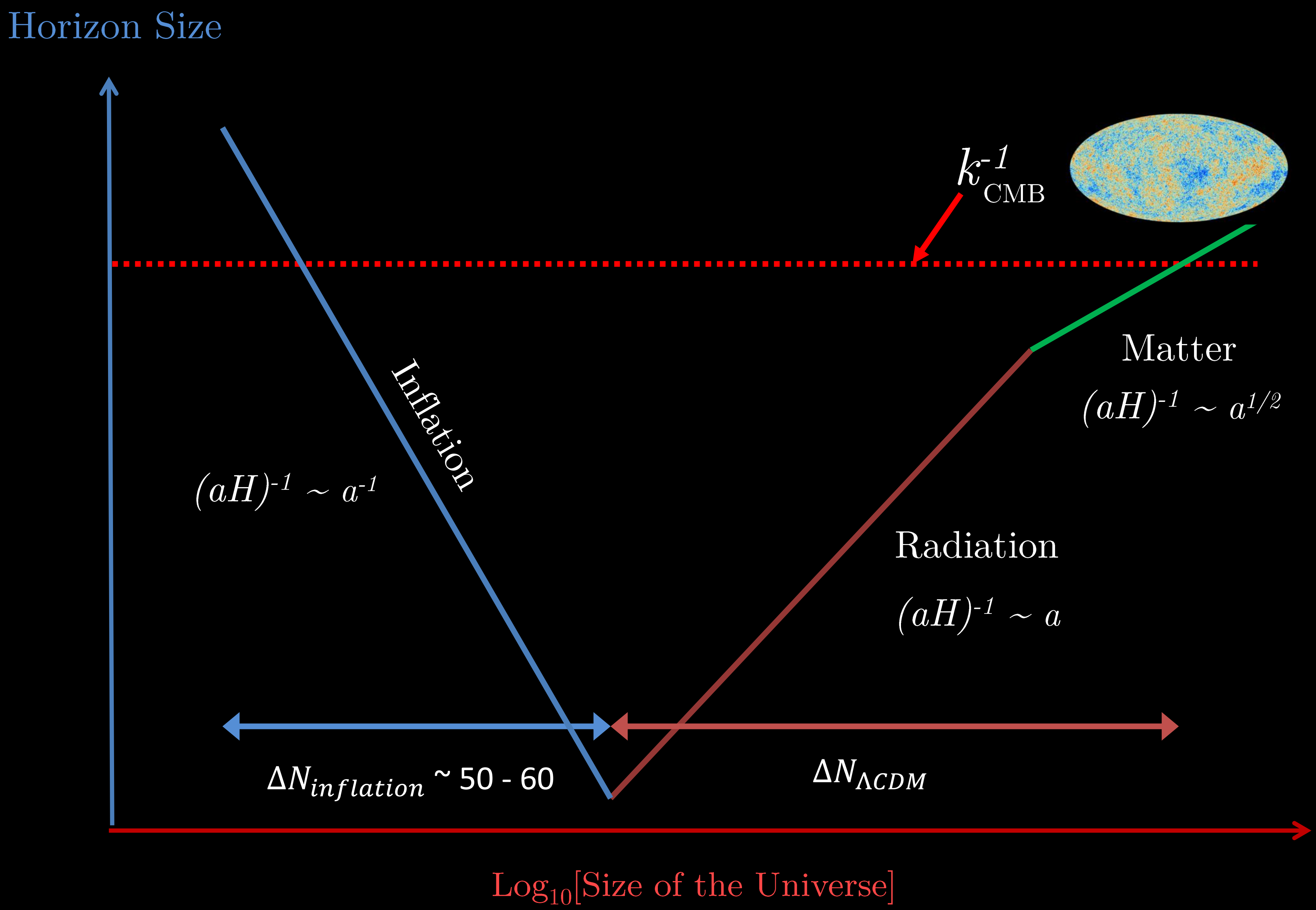

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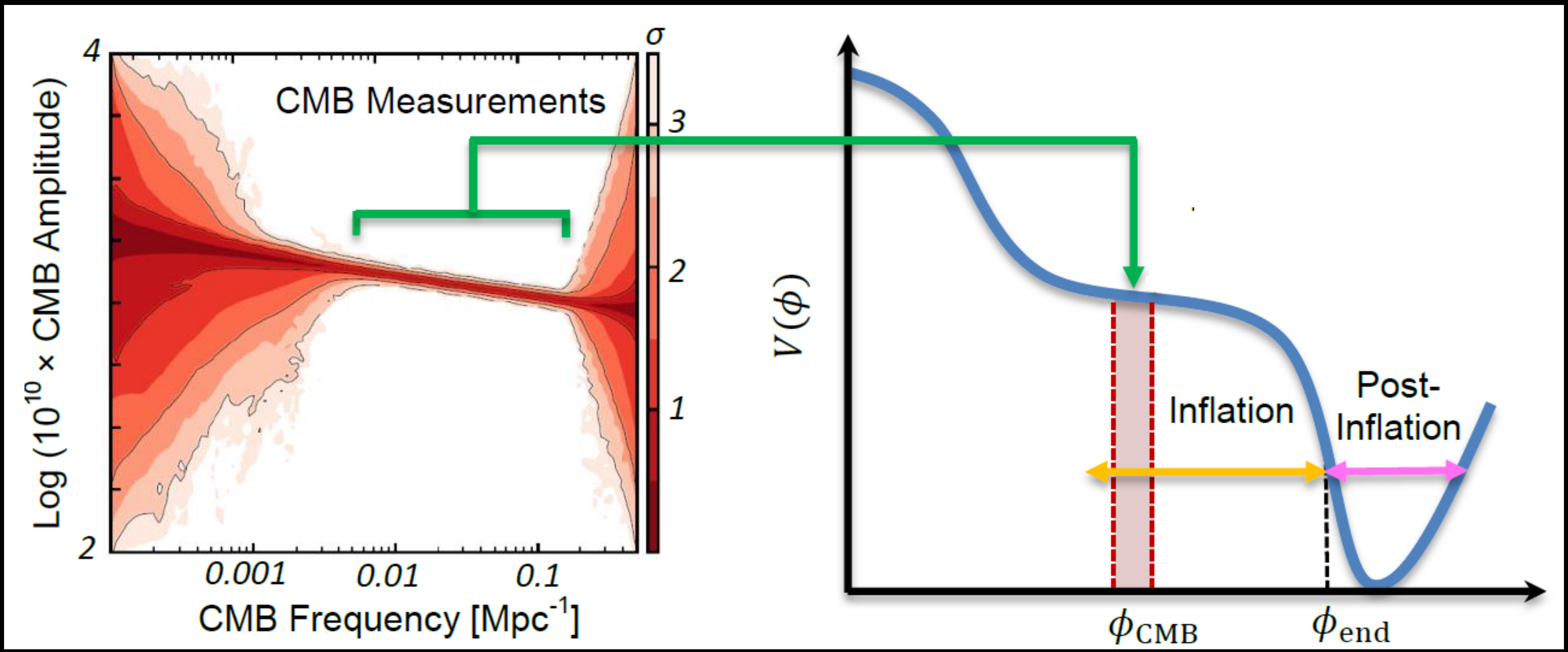


Perturbation Horizon Crossing

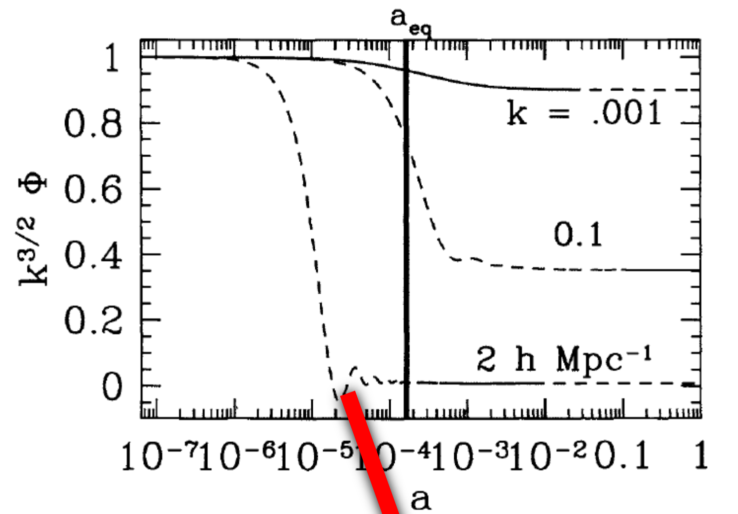


Figure 7.2. The linear evolution of the gravitational potential Φ. Dashed line denotes that the mode has entered the horizon. Evolution through the shaded region is described by the transfer function. The potential is unnormalized, but the relative normalization of the three modes is as it would be for scale-invariant perturbations. Here baryons have been neglected, $\Omega_m = 1$, and $h = 0.5$.

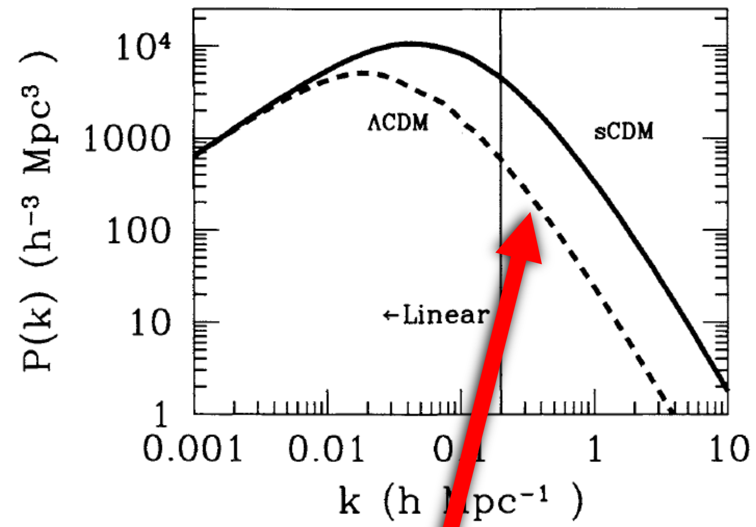
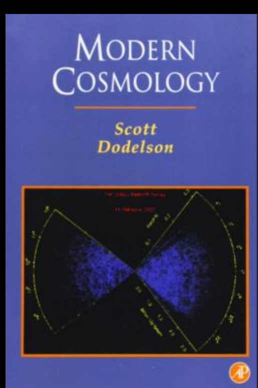


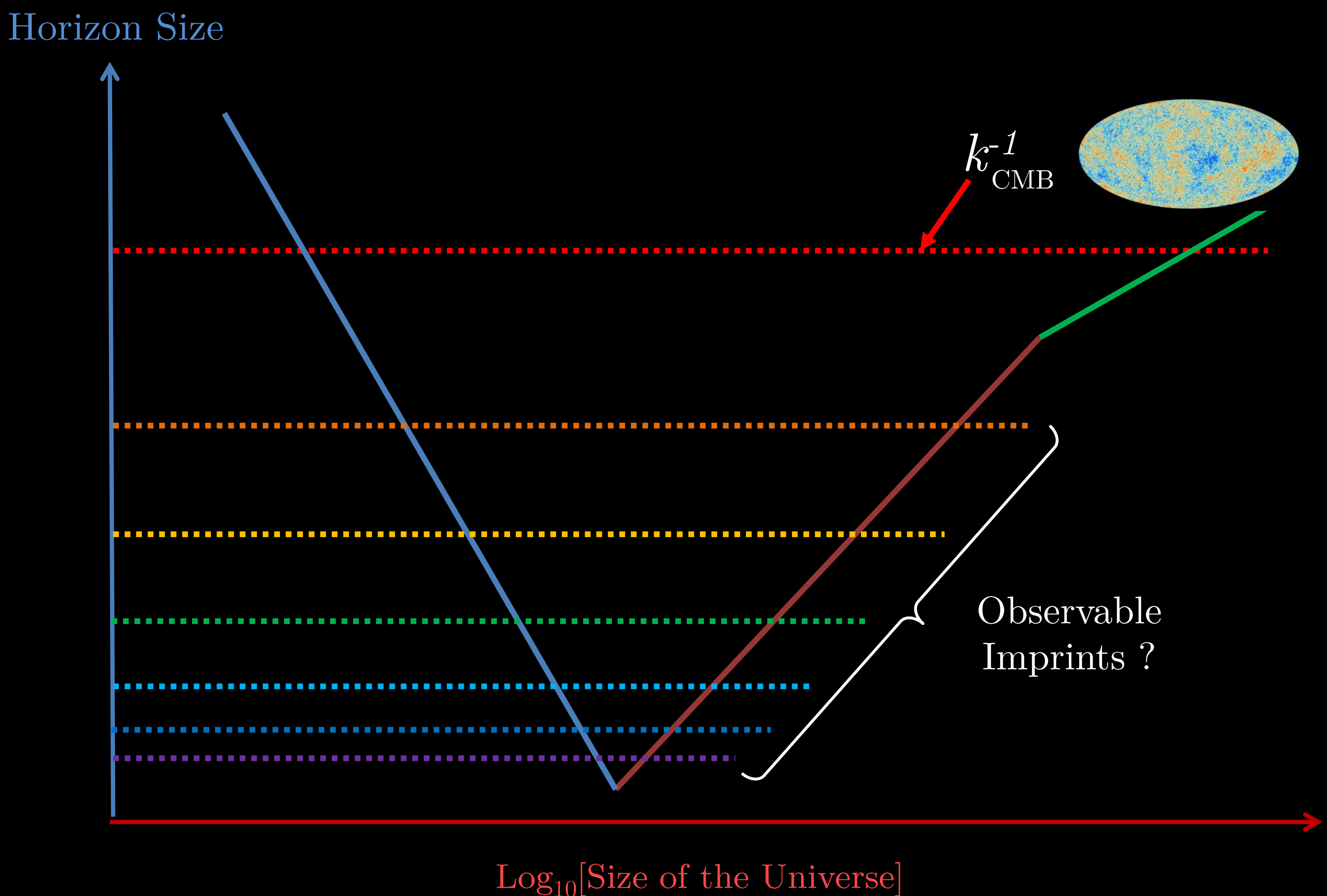
Figure 7.4. The power spectrum in two Cold Dark Matter models, with (ΛCDM) and without (sCDM) a cosmological constant. The spectra have been normalized to agree on large scales. The spectrum in the cosmological constant model turns over on larger scales because of a later a_{eq}. Scales to the left of the vertical line are still evolving linearly.



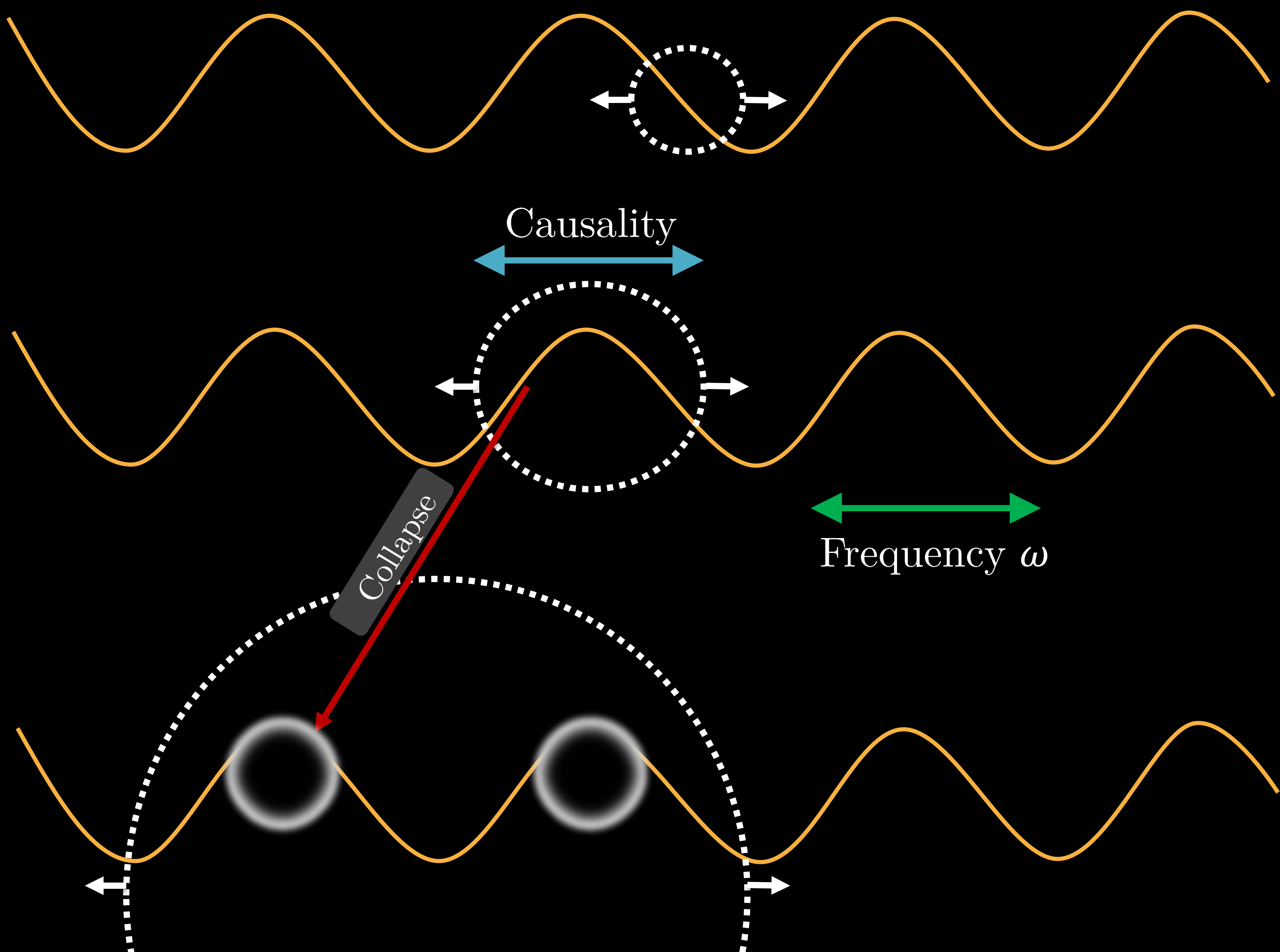
Modes entering the horizon BEFORE matter-radiation equality DECAY…

Causality erases small-scale structures

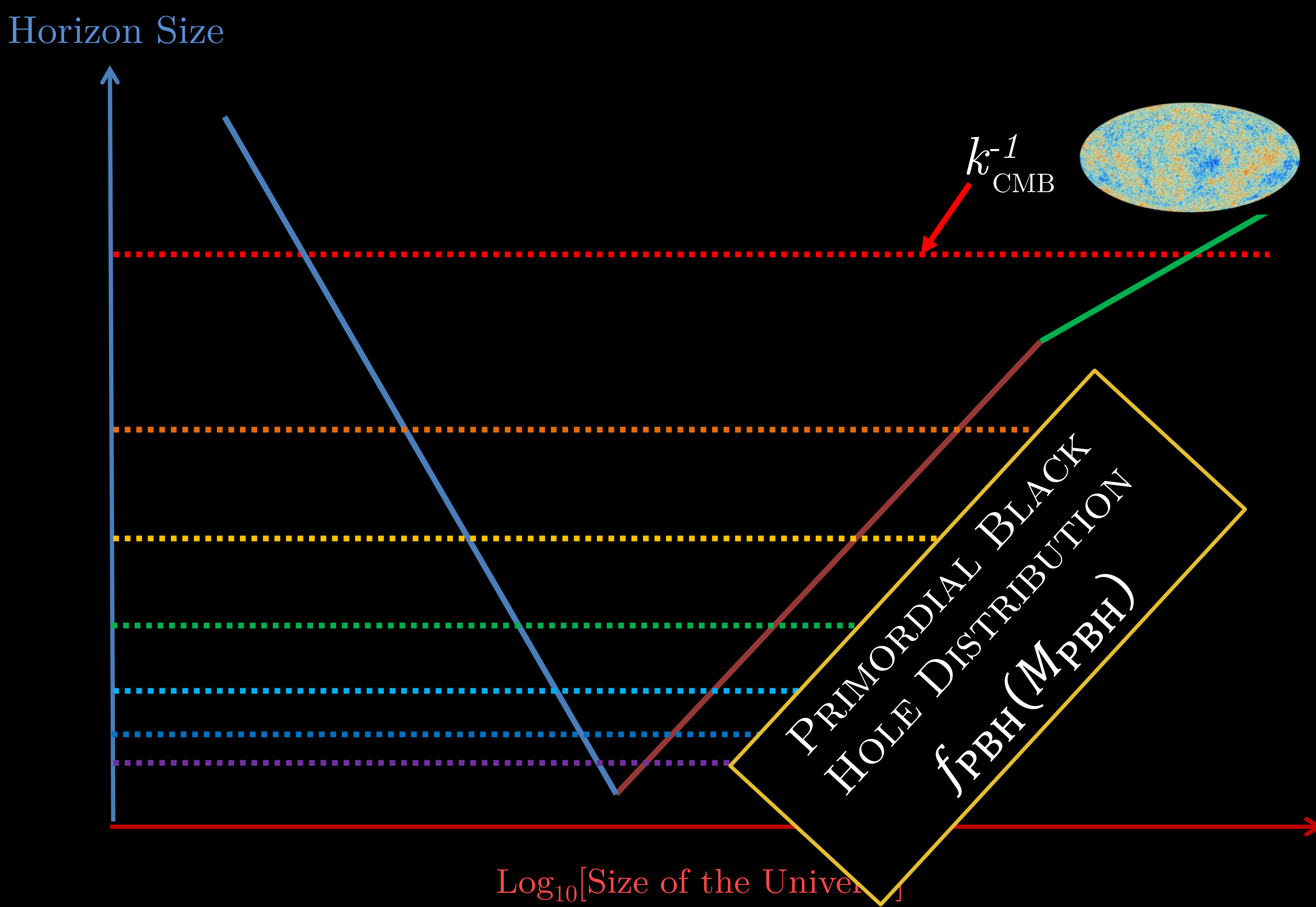
Primordial Perturbation Evolution



Why Mini Primordial Black Holes?



Primordial Perturbation Evolution



PBHs are likely to be produced

Collapse of Small-Scale Density Perturbations during Preheating in Single Field Inflation

Karsten Jedamzik* Martin Lemoine† and Jérôme Martin‡

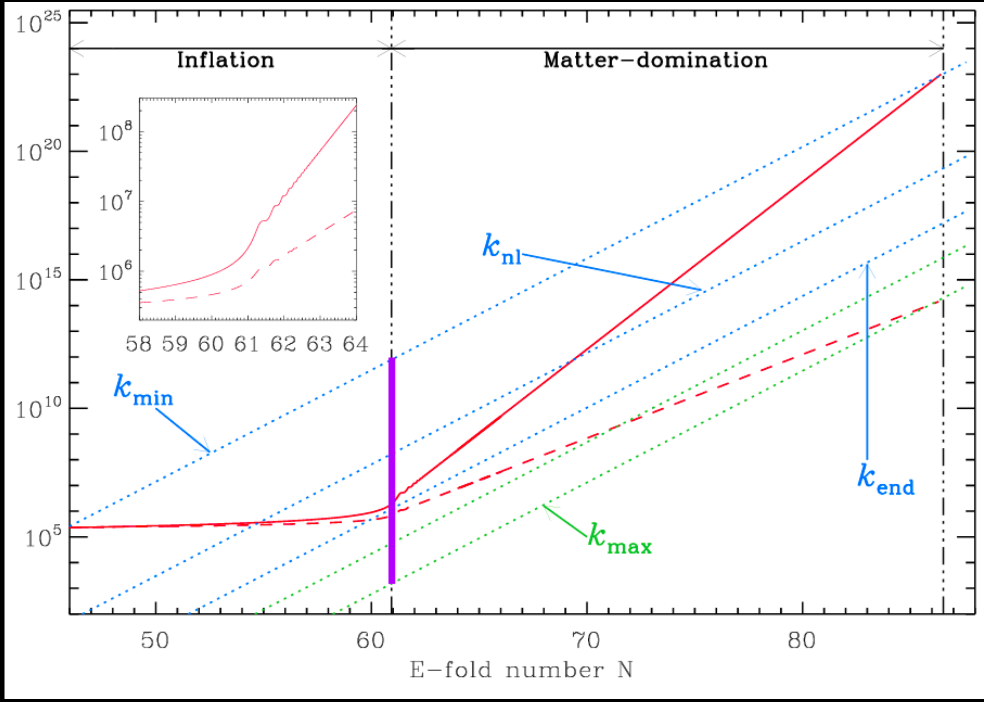
Primordial black holes from the preheating instability in single-field inflation

Jérôme Martin,[a] Theodoros Papanikolaou,[b] Vincent Vennin[b,a]

$$V\left(\phi\right)=\frac{m^2}{2}\phi^2.$$

$$m=2H_{\mathrm{end}}\frac{M_{\mathrm{Pl}}}{\phi_{\mathrm{end}}}\,.$$

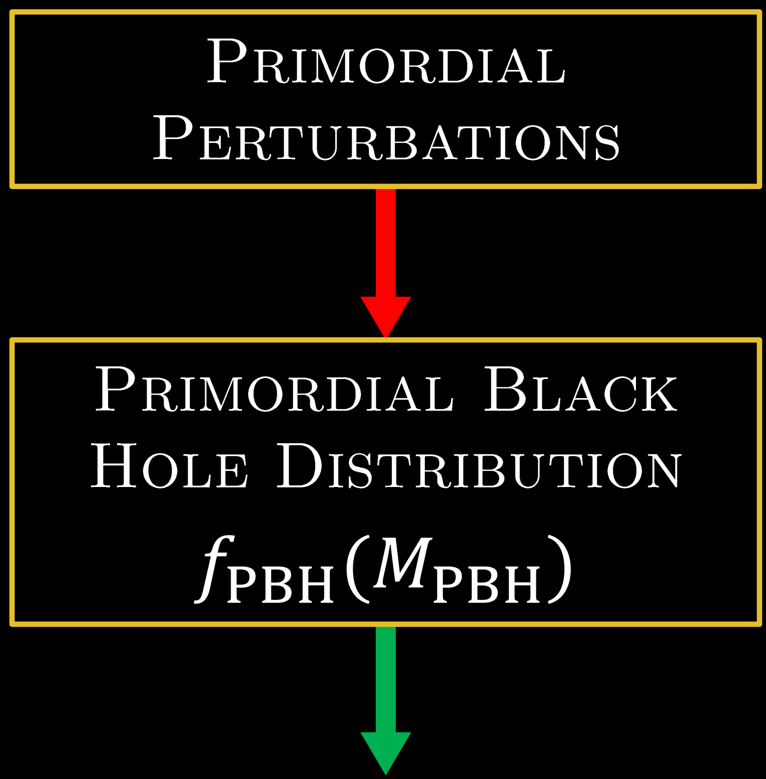
$$\phi(t)\simeq\phi_{\mathrm{end}}\left(\frac{a_{\mathrm{end}}}{a}\right)^{3/2}\sin\left(mt\right)$$



$$\frac{\mathrm{d}^2\tilde{v}_{\boldsymbol{k}}}{\mathrm{d}z^2}+\left[1+\frac{k^2}{m^2a^2}-\sqrt{6}\kappa\phi_{\mathrm{end}}\left(\frac{a_{\mathrm{end}}}{a}\right)^{3/2}\cos\left(2z\right)\right]\tilde{v}_{\boldsymbol{k}}=0\,,$$

where we have defined $z\equiv mt+\pi/4$. This equation is similar to a Mathieu equation

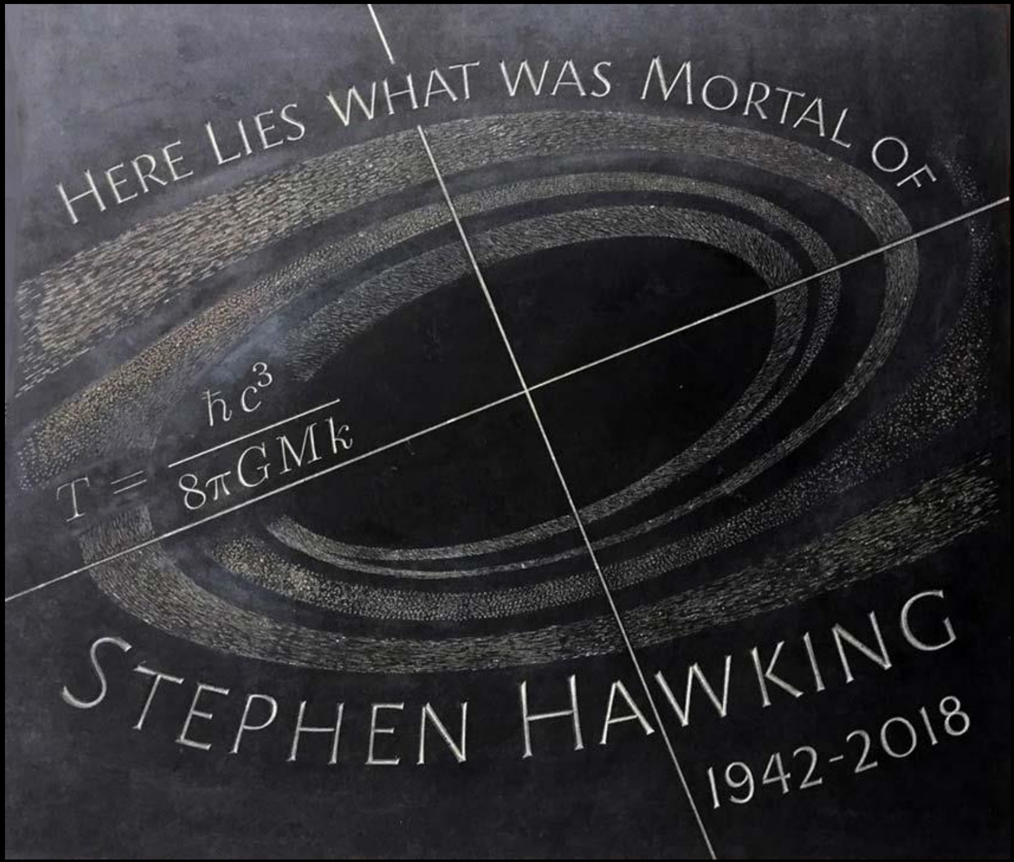
$$\frac{\mathrm{d}^2\tilde{v}_{\boldsymbol{k}}}{\mathrm{d}z^2}+\left[A_{\boldsymbol{k}}-2q\cos(2z)\right]\tilde{v}_{\boldsymbol{k}}=0 \qquad (13)$$



Observable Imprints ?

Black Holes Evaporate...

S. Hawking, 1974



Primordial Black Hole Distribution

$f_{\mathrm{PBH}}(M_{\mathrm{PBH}})$

- Some may be stable and participate to the DM relic abundance ($M_{\mathrm{PBH}} \gtrsim 10^{15}\,\mathrm{g}$)
- Some may be unstable and evaporate after BBN ($10^{9}\,\mathrm{g} \lesssim M_{\mathrm{PBH}} \lesssim 10^{15}\,\mathrm{g}$)
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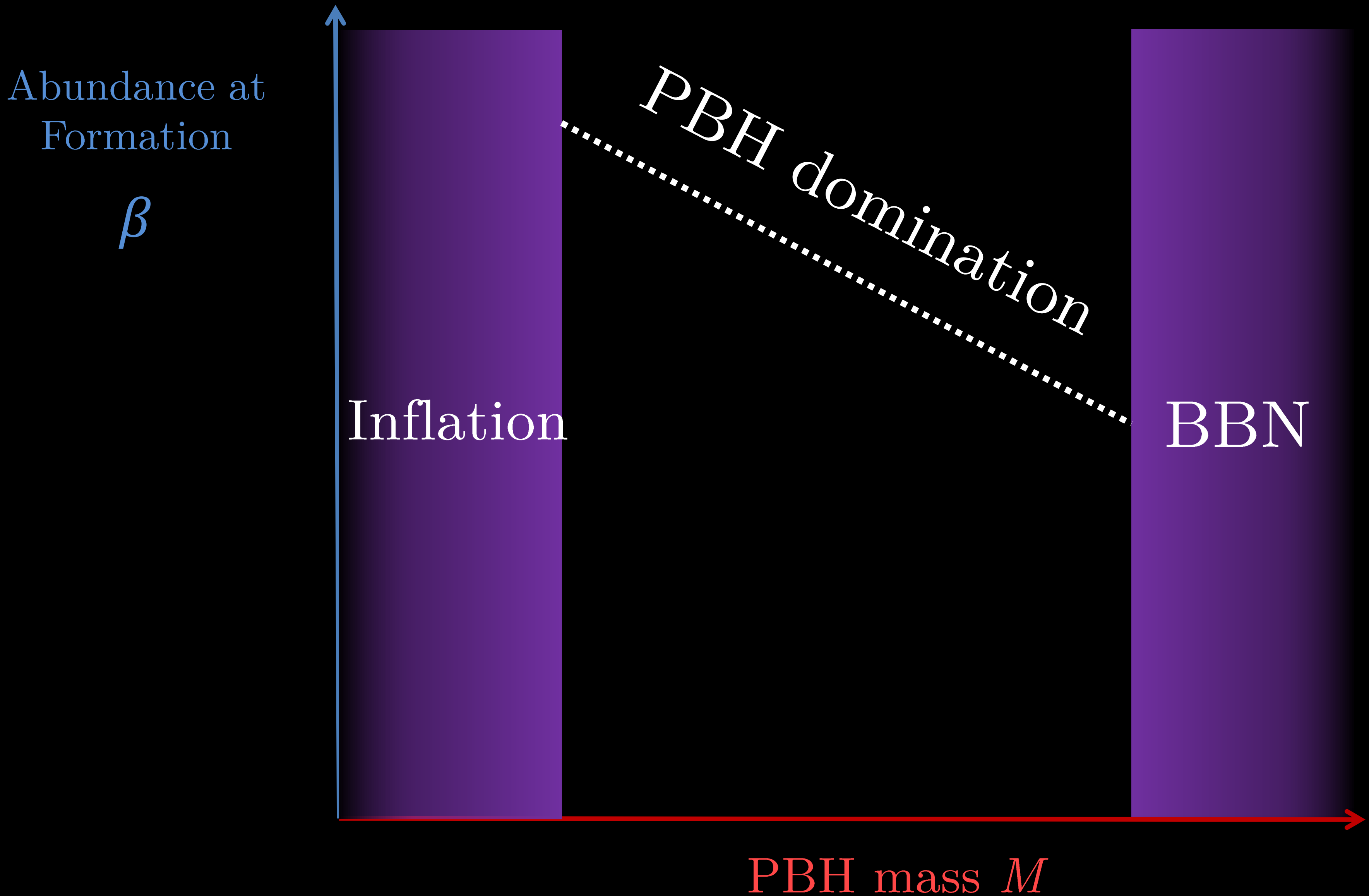
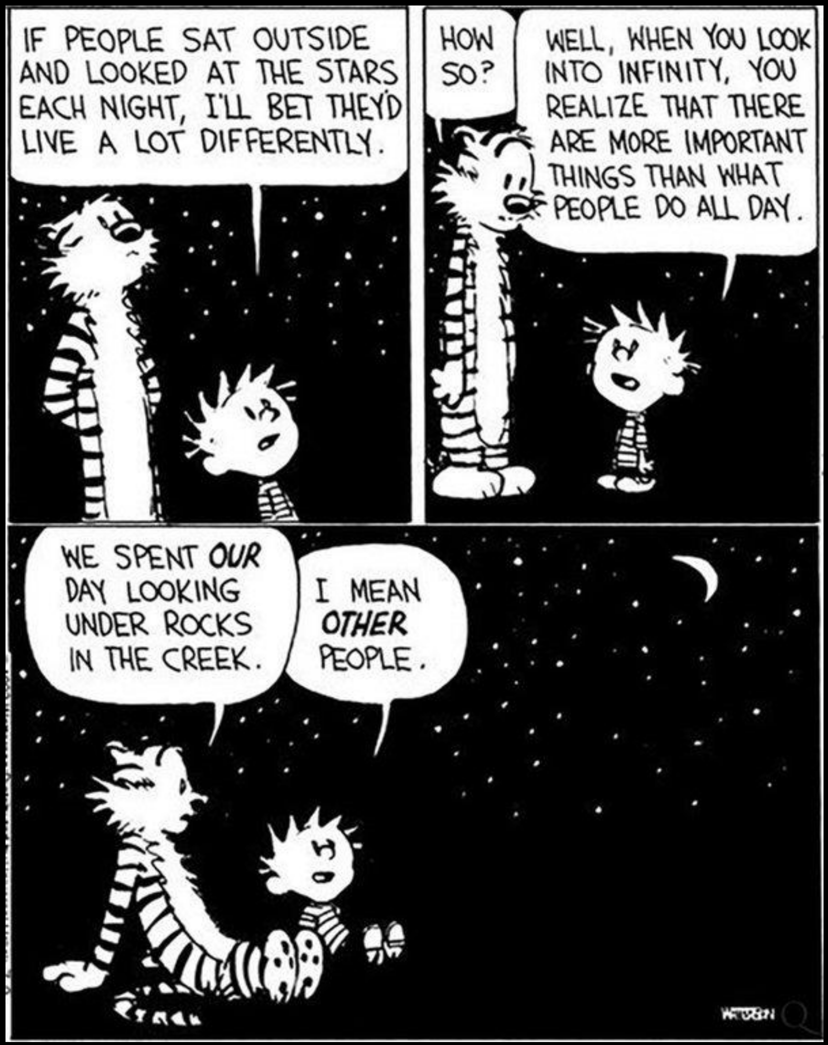
The topic of this talk ...

The Parameter Space



Is the SM still alone at the Planck scale?



Any BSM particle can be produced through PBH evaporation...

Outline

I. Effect of PBH evaporation on Dark-Matter Phenomenology

II. Kerr PBHs and Dark Radiation

III. Kerr PBHs and Warm Dark Matter

IV. Evaporation of Extended Distributions

V. Gravitational Waves ?

I. Effect of PBH evaporation on Dark-Matter Phenomenology

If the DM relic density is made, at least partially, of particles, PBHs would contribute to its production.

PBH EVAPORATION

$$\frac{\mathrm{d}M_{\mathrm{BH}}}{\mathrm{d}t} \equiv \sum_i \left.\frac{\mathrm{d}M_{\mathrm{BH}}}{\mathrm{d}t}\right|_i = -\sum_i \int_0^\infty E_i \frac{\mathrm{d}^2\mathcal{N}_i}{\mathrm{d}p\mathrm{d}t}\mathrm{d}p \;= -\varepsilon(M_{\mathrm{BH}})\frac{M_p^4}{M_{\mathrm{BH}}^2}$$

$$\frac{\mathrm{d}^2\mathcal{N}_i}{\mathrm{d}p\,\mathrm{d}t} = \frac{g_i}{2\pi^2}\frac{\sigma_{s_i}(M_{\mathrm{BH}},\mu_i,p)}{\exp\left[E_i(p)/T_{\mathrm{BH}}\right]-(-1)^{2s_i}}\frac{p^3}{E_i(p)}$$

$$\varepsilon(M_{\mathrm{BH}}) \equiv \sum_i g_i\varepsilon_i(z_i)$$

$$z_i \;=\; \mu_i/T_{\mathrm{BH}}$$

BSM Contributions?

$$T_{\mathrm{BH}} = \frac{1}{8\pi G M_{\mathrm{BH}}} \sim 1.06\ \mathrm{GeV}\left(\frac{10^{13}\ \mathrm{g}}{M_{\mathrm{BH}}}\right)$$

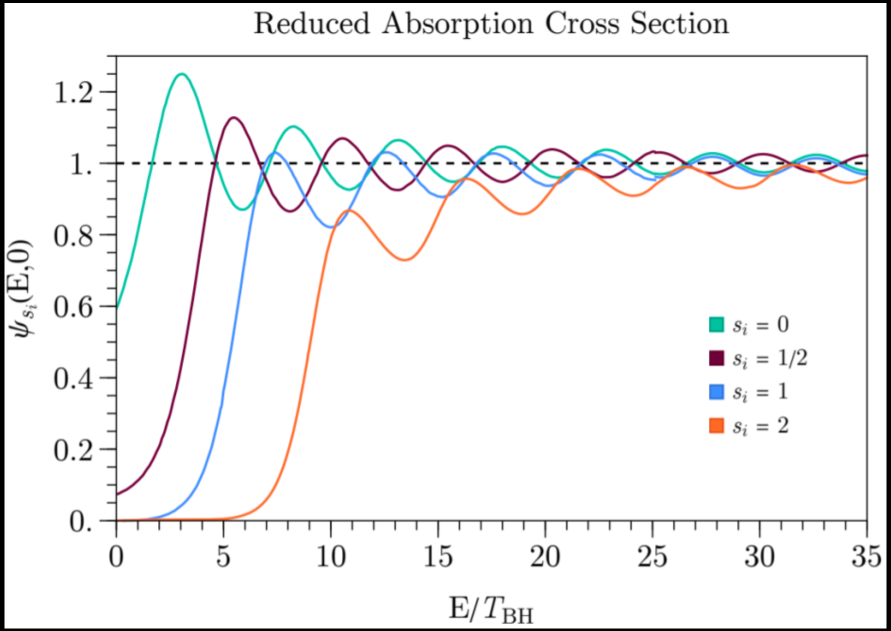
DM from Evaporation

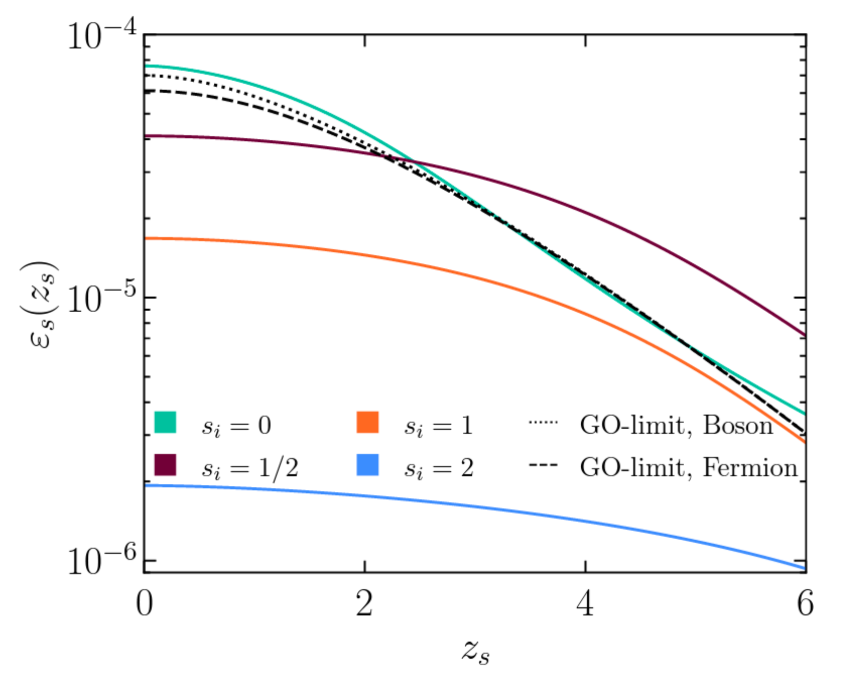
$$\frac{d^2\mathcal{N}_i}{dp\,dt} = \frac{g_i}{2\pi^2}\frac{\sigma_{s_i}(M_{\rm BH},\mu_i,p)}{\exp\left[E_i(p)/T_{\rm BH}\right]-(-1)^{2s_i}}\frac{p^3}{E_i(p)}$$

Very bad approximation at (not too) low momentum...

$$\psi_{s_i}(E,\mu) \equiv \frac{\sigma_{s_i}(E,\mu)}{27\pi G^2 M_{\rm BH}^2}$$

$$\varepsilon_i(z_i) = \frac{27}{8192\pi^5}\int_{z_i}^{\infty}\frac{\psi_{s_i}(x)(x^2-z_i^2)}{\exp(x)-(-1)^{2s_i}}\,x\,dx$$



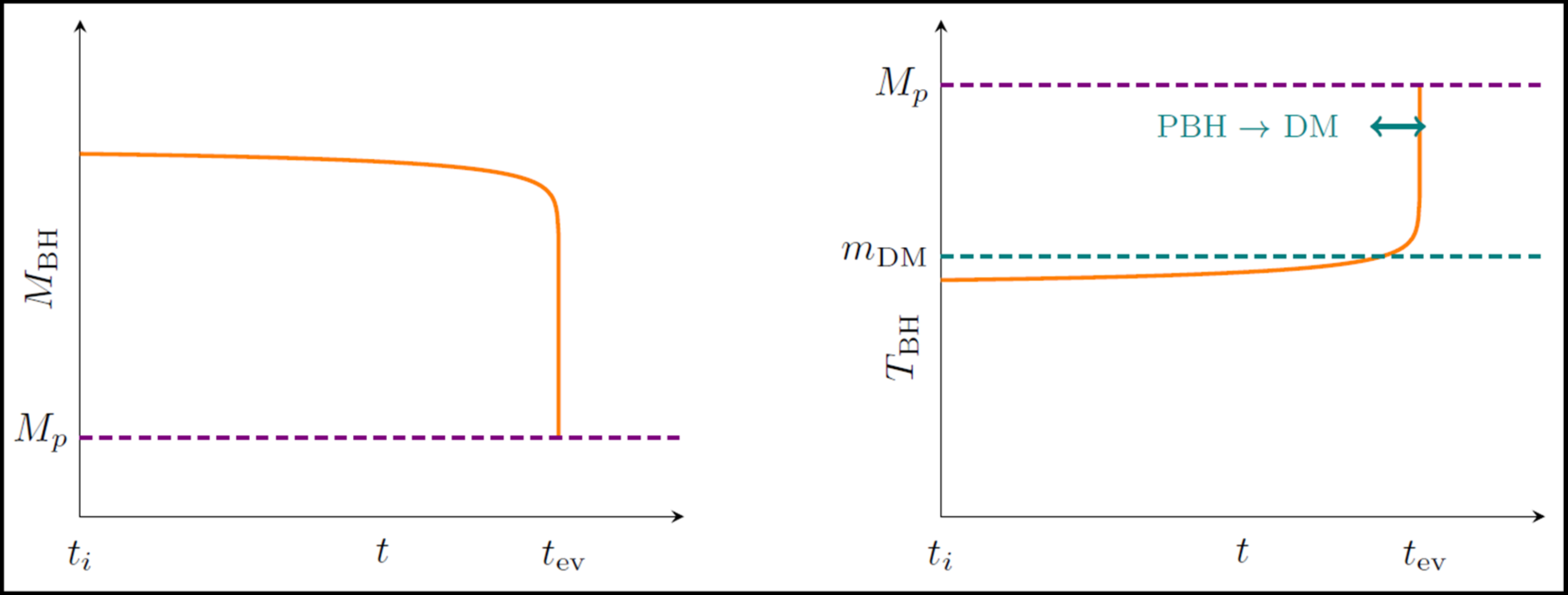


[Cheek, LH, Perez-Gonzalez and Turner '22]

Code Publicly available: FRISBHEE

PBH evaporation

$$T_{\rm BH} = \frac{1}{8\pi G M_{\rm BH}} \sim 1.06 \text{ GeV} \left(\frac{10^{13}\text{ g}}{M_{\rm BH}}\right)$$



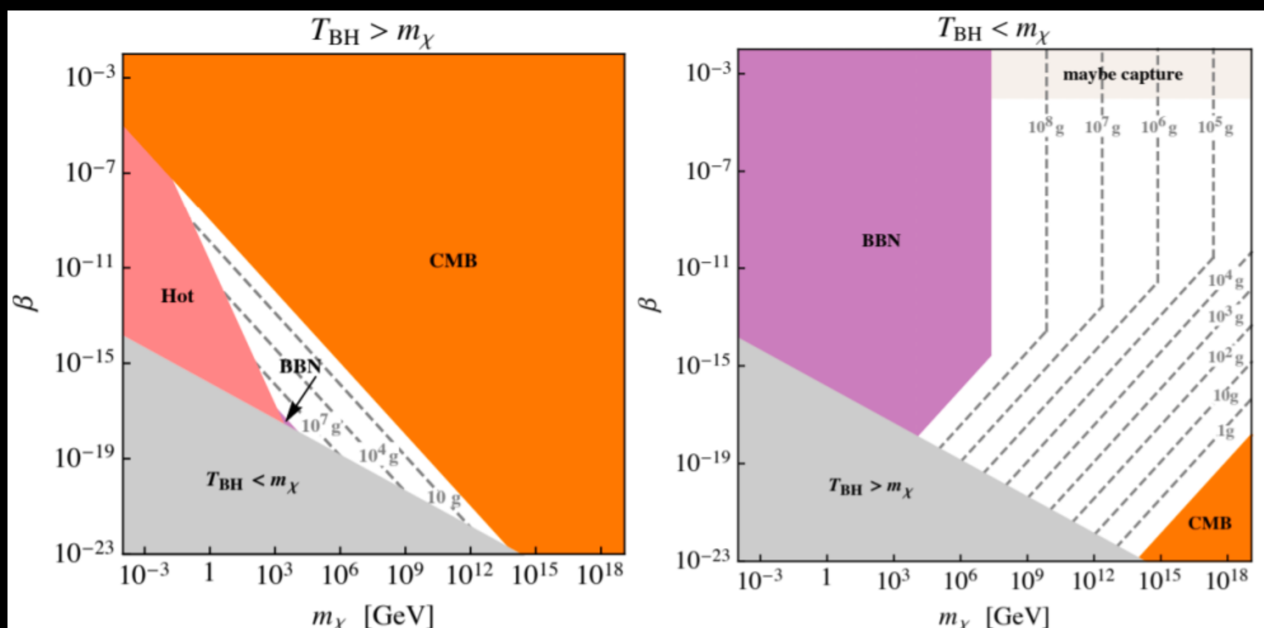
→ More and more particles contribute to the evaporation

DM from Evaporation

$$\frac{\mathrm{d}^2\mathcal{N}_i}{\mathrm{d}p\,\mathrm{d}t} = \frac{g_i}{2\pi^2}\frac{\sigma_{s_i}(M_{\rm BH},\mu_i,p)}{\exp\left[E_i(p)/T_{\rm BH}\right]-(-1)^{2s_i}}\frac{p^3}{E_i(p)}$$

Very much used in the literature: the **geometrical-optics limit**

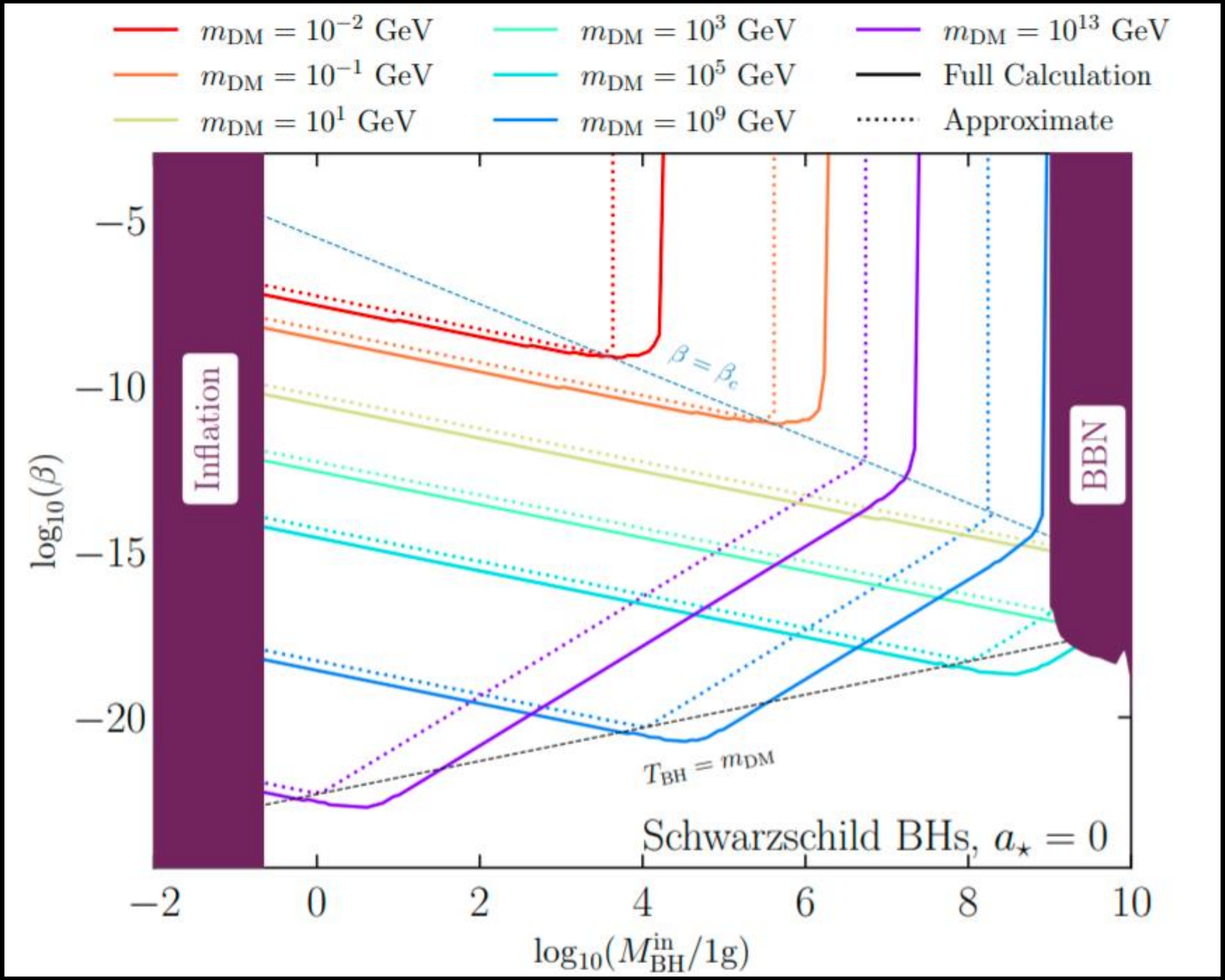
$$GM_{\rm BH}p \gg 1$$
$$\sigma_{s_i}(E,\mu)|_{\rm GO} = 27\pi G^2 M_{\rm BH}^2$$



[Gondolo, Sandick and Shams Es Haghi ‘20]

DM from Evaporation

$$f_{\text{PBH}}(M) = \delta(M - M_{\text{PBH}})$$



[Cheek, LH, Perez-Gonzalez and Turner '22]   **Code Publicly available: FRISBHEE**

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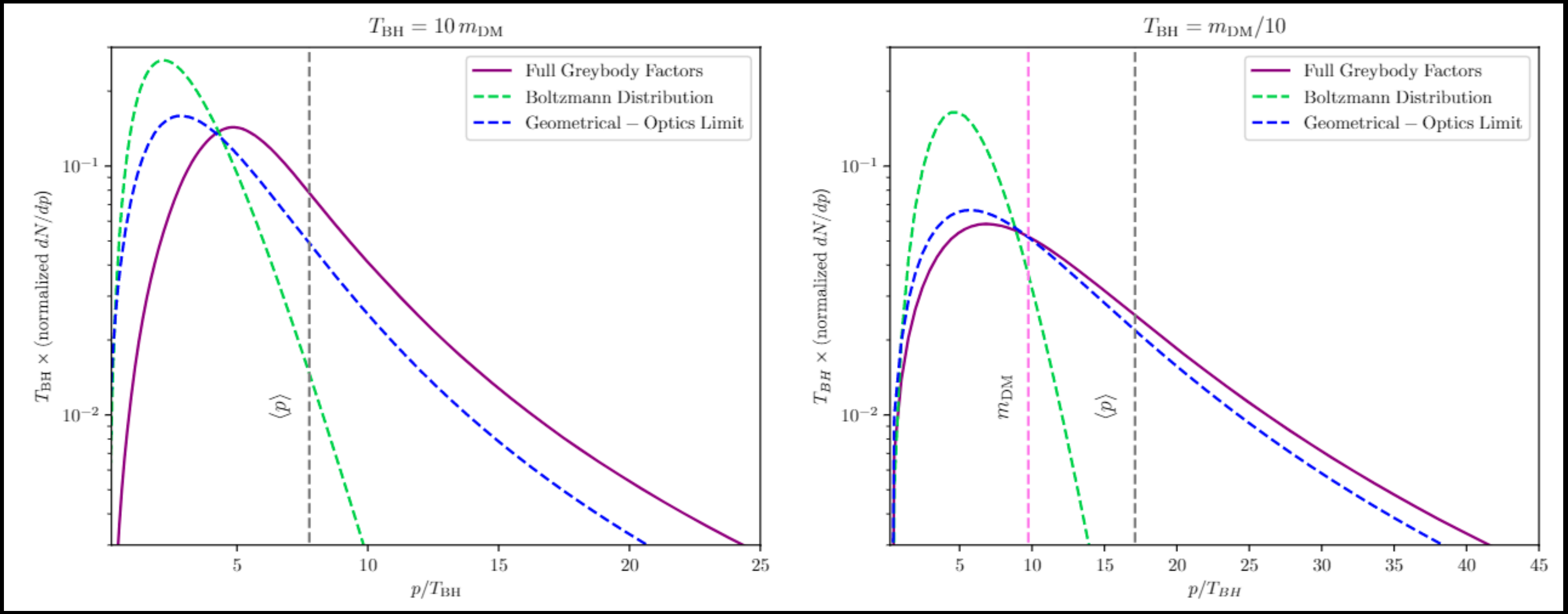

[Cheek, LH, Perez-Gonzalez and Turner '22] Code Publicly available: FRISBHEE

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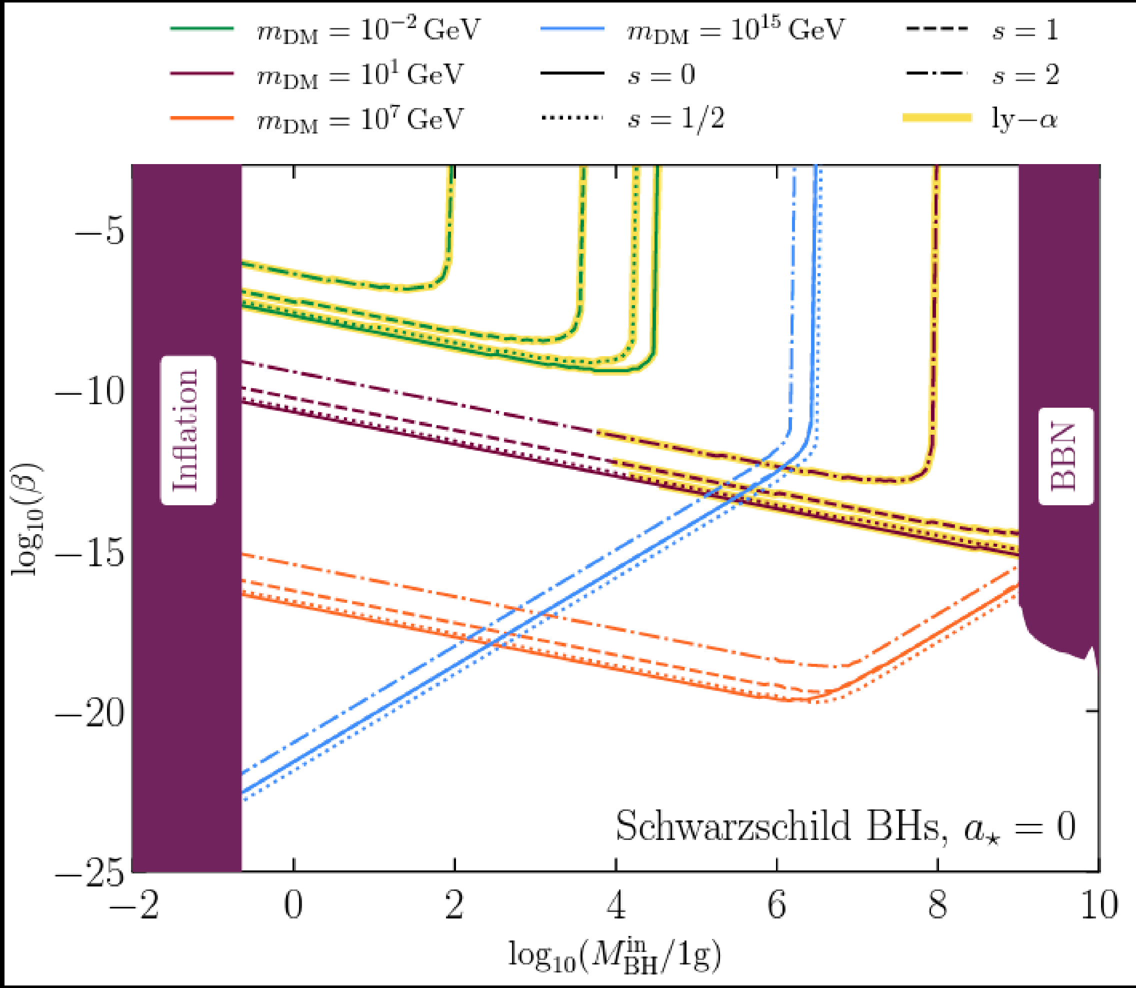
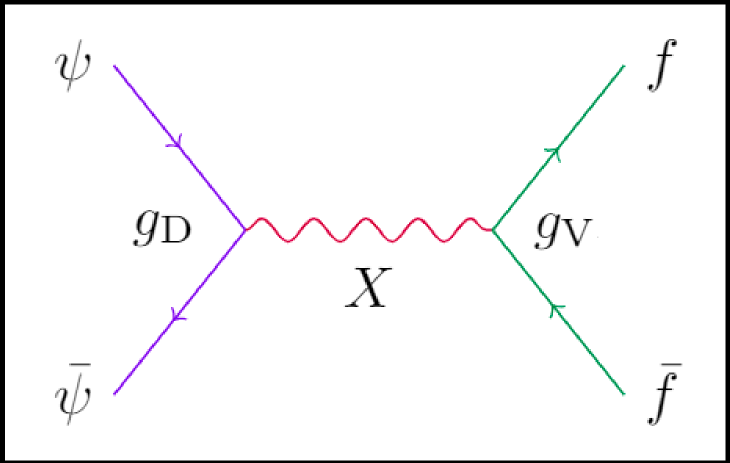


[Cheek, LH, Perez-Gonzalez and Turner '22] **Code Publicly available: FRISBHEE**

Thermal Production of DM

- DM may interact with SM particles and be produced in the early universe through thermal processes...
- Freeze-In or Freeze-Out

$$\dot{n}^{\mathrm{th}}_{\mathrm{DM}} + 3Hn^{\mathrm{th}}_{\mathrm{DM}} = \langle \sigma v \rangle_{\mathrm{th}} \left(n^2_{\mathrm{DM,eq}} - n^{\mathrm{th}\,2}_{\mathrm{DM}} \right)$$



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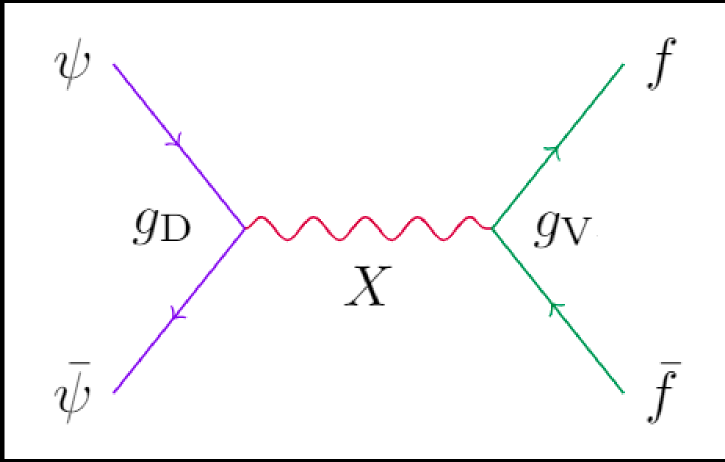

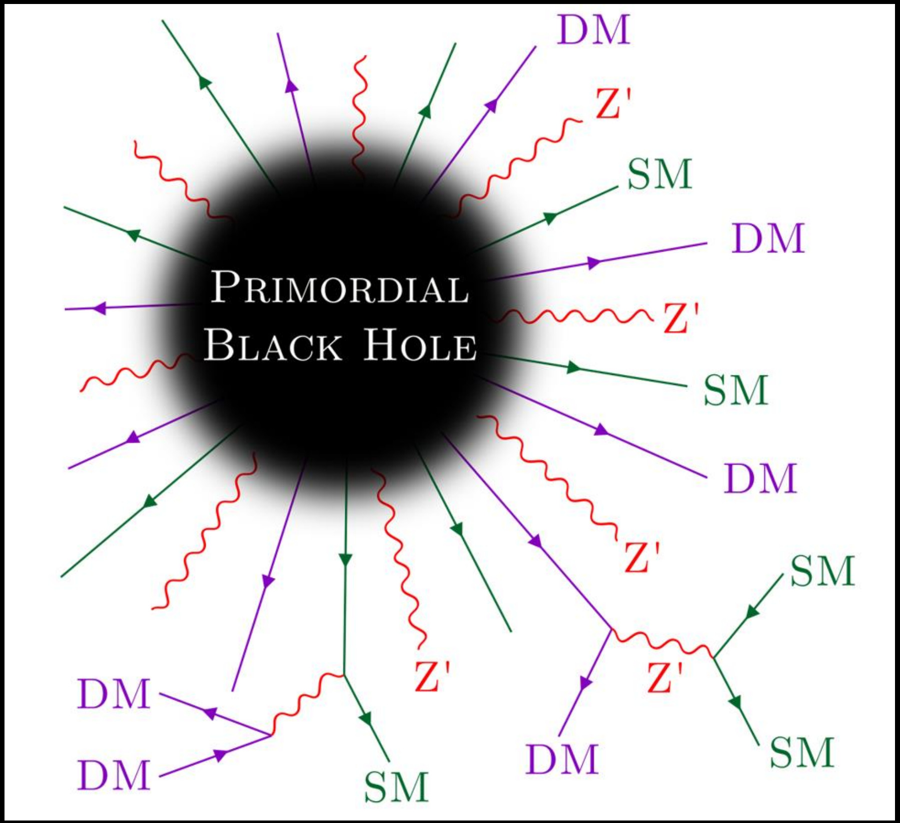

Thermal Production of DM

DM Annihilation, X decay — PBH evaporation

$$\dot{n}_{\rm DM} + 3H n_{\rm DM} = g_{\rm DM}\int C[f_{\rm DM}]\frac{\mathrm{d}^3p}{(2\pi)^3} + \left.\frac{\mathrm{d}n_{\rm DM}}{\mathrm{d}t}\right|_{\rm BH},$$

$$\dot{n}_X + 3H n_X = g_X\int C[f_X]\frac{\mathrm{d}^3p}{(2\pi)^3} + \left.\frac{\mathrm{d}n_X}{\mathrm{d}t}\right|_{\rm BH},$$

$$\dot{\rho}_{\rm SM} + 4H\rho_{\rm SM} = \left.\frac{\mathrm{d}M}{\mathrm{d}t}\right|_{\rm SM}.$$

PBHs evaporate **non-trivial distributions** of DM and X particles

↓

Non-trivial evolution of the full distributions $f_X(p)$ and $f_{\rm DM}(p)$

Simplified approch...

$$\left.\frac{\mathrm{d}n_i}{\mathrm{d}t}\right|_{\rm BH} = n_{\rm BH} g_i \int \left.\frac{\partial f_i}{\partial t}\right|_{\rm BH}\frac{p^2\mathrm{d}p}{2\pi^2}$$

Thermal Production of DM

- If PBHs evaporate **before FO**:

  → Assume Instantaneous thermalization

- If PBHs evaporate **after FO**:

  → Assume No thermalization

- **FI case**: assume No thermalization

→ Check those assumptions by evaluating at all time

$$\Gamma_{\rm th+ev} \equiv \frac{\langle \sigma \cdot v \rangle_{\rm th+ev} \times n^{\rm th}}{H}$$

$$\langle \sigma \cdot v \rangle_{\rm th+ev} \equiv \frac{\displaystyle\int \sigma \cdot v_{\rm moll} f_{\rm ev} f_{\rm th} d^3\vec{p}_1 d^3\vec{p}_2}{\left[\displaystyle\int d^3\vec{p}_1 f_{\rm ev}\right]\left[\displaystyle\int d^3\vec{p}_2 f_{\rm th}\right]}\,.$$

Effects of PBH Evaporation

1. PBHs produce additional DM particles

[Gondolo *et al* 2020, Bernal *et al* 2020]

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4. The evaporation of PBHs can modify the cosmological evolution *during* the thermal production of DM

Effects of PBH Evaporation

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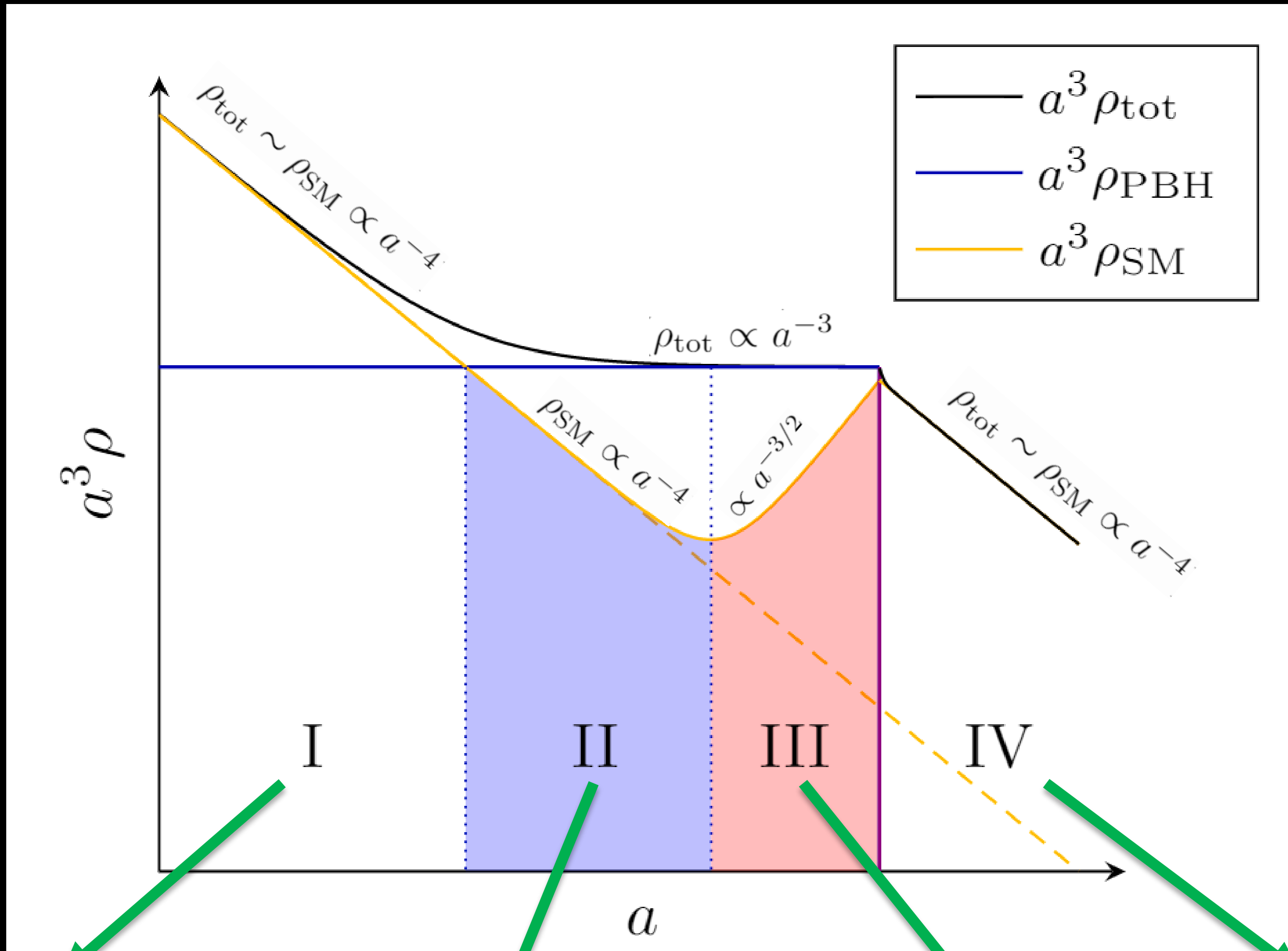
2. PBHs produce mediator particles X

3. The evaporation of PBHs can inject entropy in the SM bath *after* the thermal production of DM

4. The evaporation of PBHs can modify the cosmological evolution *during* the thermal production of DM

5. Particles with energy $E \sim T_{\rm BH}$ may be warm...

Modified Cosmology



FI/FO + entropy dilution

Regular FI/FO

Matter-Dominated FI/FO

FI/FO during entropy injection

Analytical Results

Freeze-In contribution

$$\Omega_{\rm I} = \alpha\, m_X^3 \frac{m_{\rm DM}}{\rho_c} \frac{36\sqrt{10}}{\pi\sqrt{g_{\star,\rho}(m_X)}} \frac{g_{\star,s}(T_{\rm eq})}{g_{\star,s}(m_X)} \frac{T_{\rm eq}^3 m_p}{m_X^4} \frac{a_{\rm eq}^3}{a_0^3} G^{2,1}_{1,3}\left(\begin{matrix} 1 \\ \frac{3}{2},\frac{5}{2},0 \end{matrix} \middle| \frac{m_X}{T_{\rm eq}}, \frac{1}{2} \right),$$

$$\Omega_{\rm II} = \frac{\alpha\, m_X^3}{4} \frac{m_{\rm DM}}{\rho_c} \sqrt{\frac{3m_p^2}{\rho_{\rm PBH}^c}} \left(\frac{a_c}{a_0}\right)^3 T_c \left(\frac{g_{\star,s}(T_c)}{g_{\star,s}(m_X)}\right)^{\frac{1}{3}} G^{2,1}_{1,3}\left(\begin{matrix} -\frac{3}{4} \\ -\frac{1}{2},\frac{1}{2},-\frac{7}{4} \end{matrix} \middle| \frac{m_X}{2T_c} \left(\frac{g_{\star,s}(m_X)}{g_{\star,s}(T_c)}\right)^{\frac{1}{3}}, \frac{1}{2} \right),$$

$$\Omega_{\rm III} = 2\alpha\, m_X^3 \frac{m_{\rm DM}}{\rho_c} \sqrt{\frac{3m_p^2}{\rho_{\rm PBH}^{\rm ev}}} \left(\frac{a_{\rm ev}}{a_0}\right)^3 T_{\rm ev} G^{2,1}_{1,3}\left(\begin{matrix} -\frac{9}{2} \\ -\frac{1}{2},\frac{1}{2},-\frac{11}{2} \end{matrix} \middle| \frac{m_X}{2T_{\rm ev}}, \frac{1}{2} \right),$$

$$\Omega_{\rm IV} = \alpha\, m_X^3 \frac{m_{\rm DM}}{\rho_c} \frac{36\sqrt{10}}{\pi\sqrt{g_{\star,\rho}(m_X)}} \frac{g_{\star,s}(T_0)}{g_{\star,s}(m_X)} \frac{T_0^3 m_p}{m_X^4} G^{2,1}_{1,3}\left(\begin{matrix} 1 \\ \frac{3}{2},\frac{5}{2},0 \end{matrix} \middle| \frac{m_X}{T_0}, \frac{1}{2} \right),$$

Freeze-Out contribution

- Regime I and IV:

$$x_{\rm FO} = \ln\left[\frac{3}{2}\sqrt{\frac{5}{\pi^5 g_\star(T_{\rm FO})}} g_{\rm DM} m_{\rm DM} m_p \langle\sigma v\rangle \sqrt{x_{\rm FO}}\right]$$

- Regime II:

$$x_{\rm FO} = \ln\left[\frac{3}{2}\sqrt{\frac{5}{\pi^5 g_\star(T_{\rm FO})}} \frac{g_{\rm DM} m_{\rm DM} m_p \langle\sigma v\rangle}{\sqrt{\kappa}}\right],$$

- Regime III:

$$x_{\rm FO} = \ln\left[\frac{3}{2}\sqrt{\frac{5}{\pi^5 g_\star(T_{\rm FO})}} \frac{g_{\rm DM} m_p \langle\sigma v\rangle}{m_{\rm DM}} T_{\rm ev}^2 x_{\rm FO}^{5/2}\right].$$

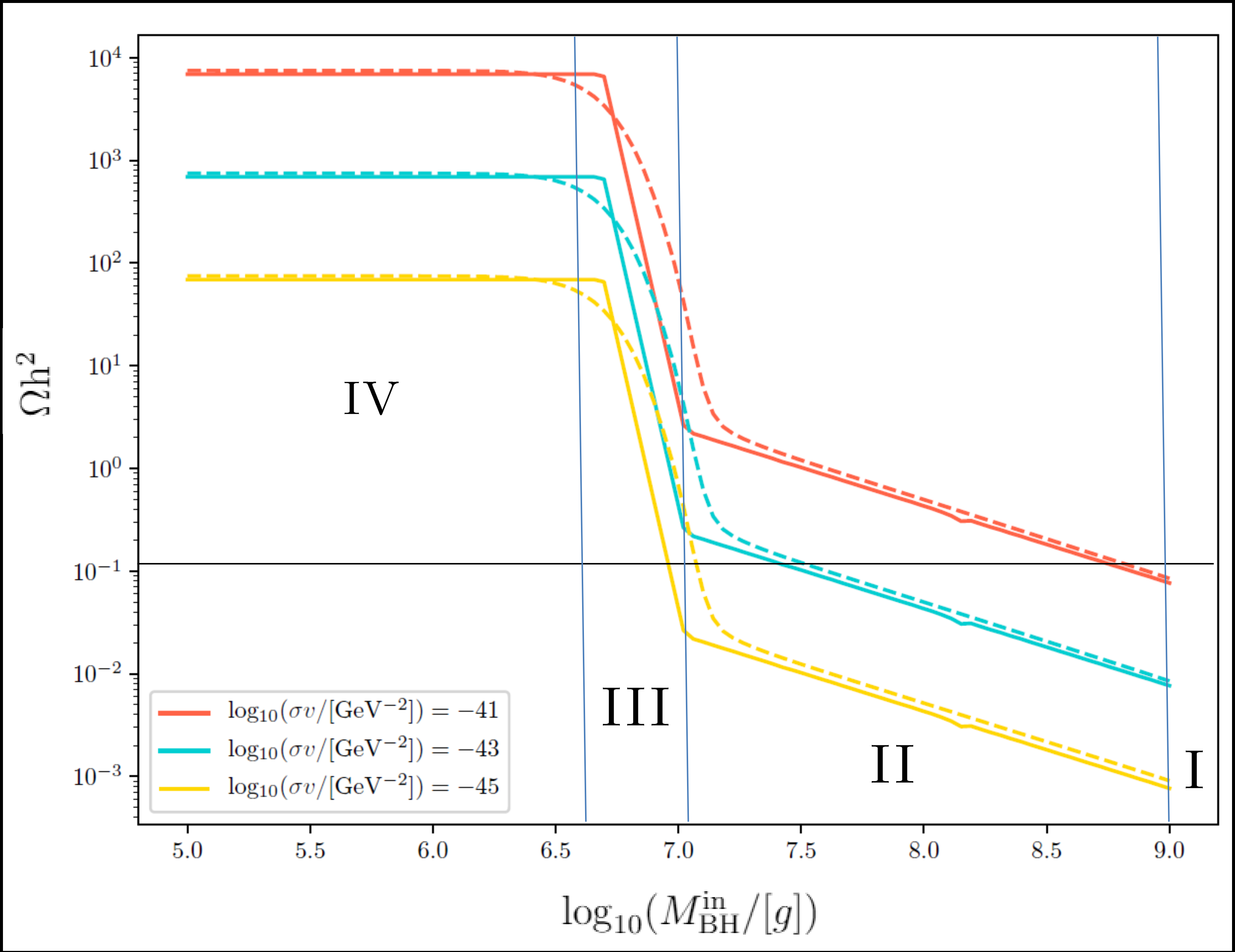
$$\Omega_{\rm I} = \frac{15}{2\pi} \frac{x_{\rm FO}}{\sqrt{10 g_\star(T_{\rm FO})}} \frac{s_{\rm eq}}{m_p\langle\sigma v\rangle\rho_c} \left(\frac{a_{\rm eq}}{a_0}\right)^3,$$

$$\Omega_{\rm II} = \frac{45}{4\pi} \frac{1}{m_{\rm DM} m_p \langle\sigma v\rangle} \sqrt{\frac{\kappa}{10 g_\star(T_{\rm FO}}} x_{\rm FO}^{3/2},$$

$$\Omega_{\rm III} = \frac{\pi}{2}\sqrt{\frac{g_\star(T_{\rm FO})}{10}} \frac{m_{\rm DM}^2}{m_p\langle\sigma v\rangle} \kappa \left(\frac{m_{\rm DM} T_{\rm ev}}{T_{\rm FO}^2}\right)^2,$$

$$\Omega_{\rm IV} = \frac{15}{2\pi} \frac{x_{\rm FO}}{\sqrt{10 g_\star(T_{\rm FO})}} \frac{s_0}{m_p\langle\sigma v\rangle\rho_c},$$

Comparison with Numerics



Results

Freeze-Out [Cheek, LH, Perez-Gonzalez and Turner '22]

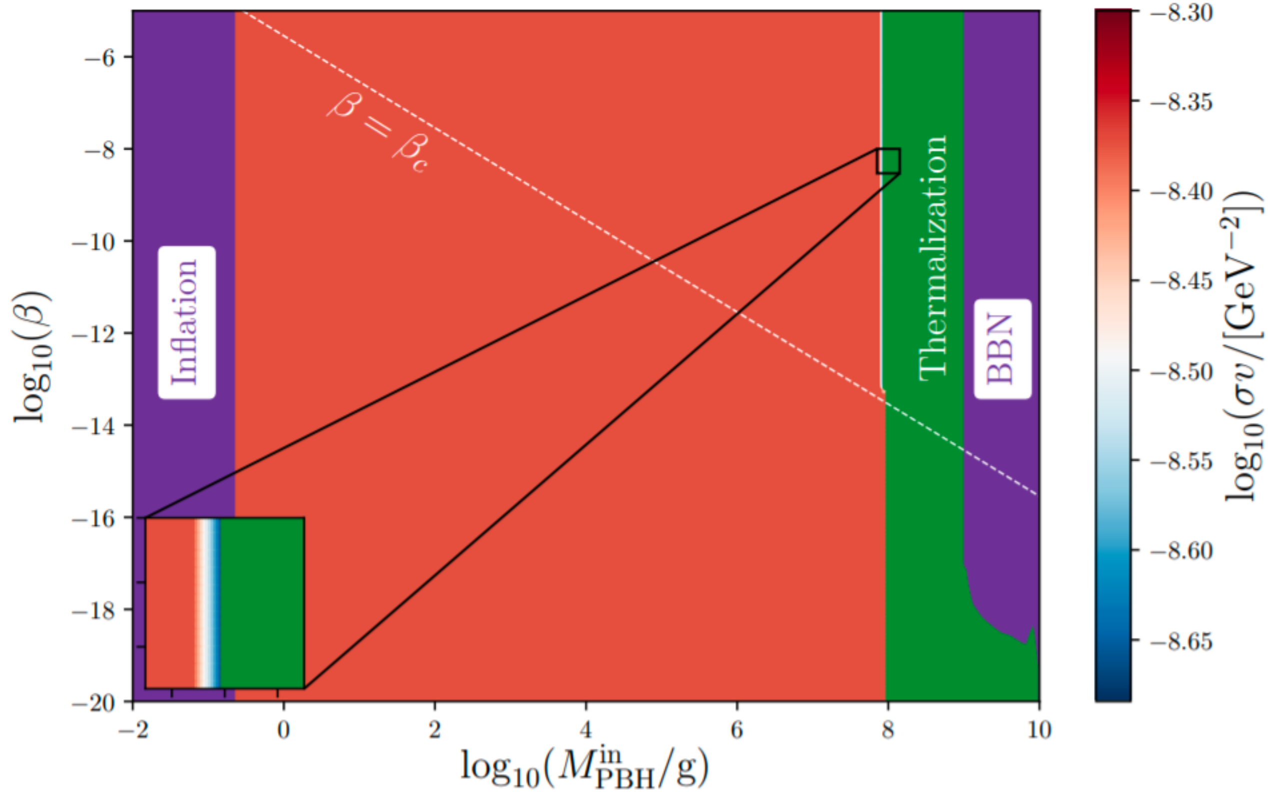


Fig. 7. Two-dimensional scan over the PBH fraction β and mass $M_{\rm BH}$ for a mediator mass $m_X = 10\,{\rm GeV}$ and a dark matter mass $m_{\rm DM} = 1\,{\rm GeV}$, and ${\rm Br}(X \to {\rm DM}) = 0.5$. The color map indicates the value of the non-relativistic cross-section of DM annihilation leading to the correct relic abundance in the Freeze-Out case. See the main text for a description of the different constraints.

Results

Freeze-In [Cheek, LH, Perez-Gonzalez and Turner '22]

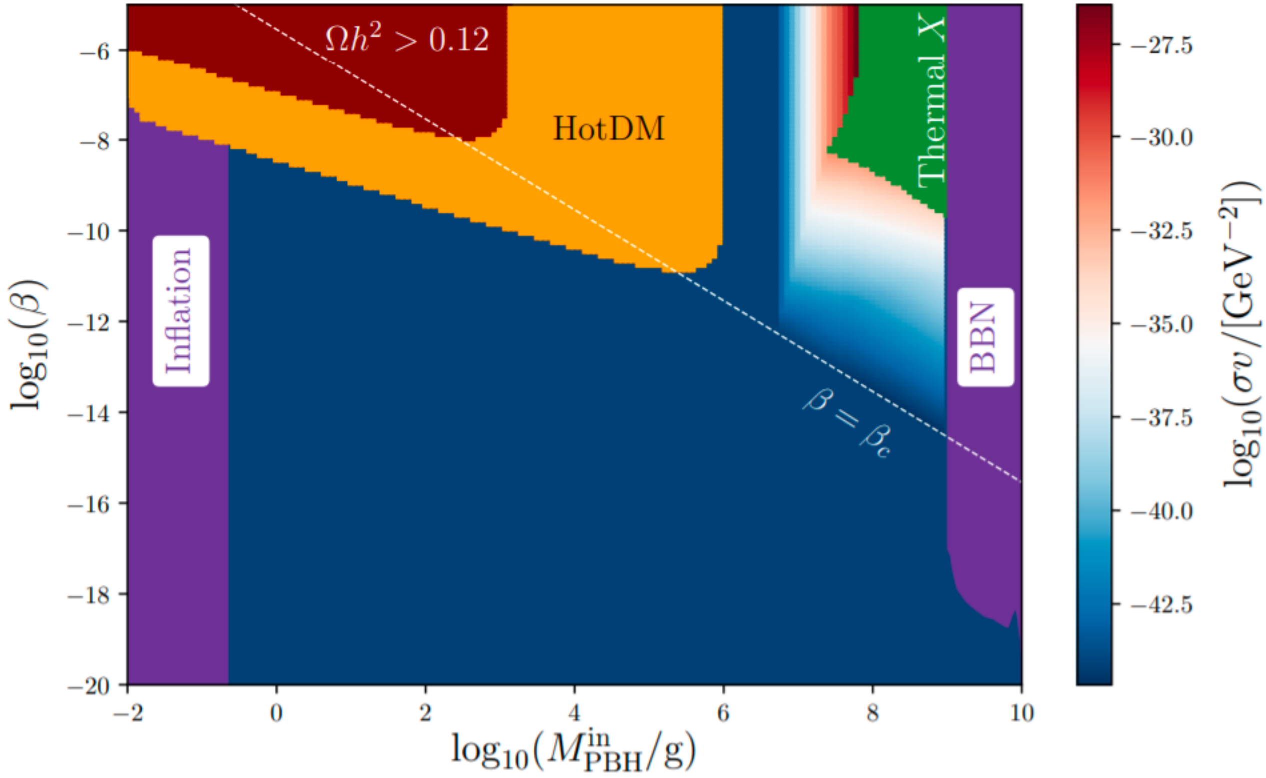


Fig. 11. Two-dimensional scan over the PBH fraction β and mass $M_{\rm BH}$ for a mediator mass $m_X = 1\,{\rm TeV}$, a dark matter mass $m_{\rm DM} = 1\,{\rm MeV}$, and ${\rm Br}(X \to {\rm SM}) = 10^{-7}$. The color map indicates the value of the non-relativistic cross-section of DM annihilation leading to the correct relic abundance in the Freeze-In case. See the main text for a description of the different constraints.

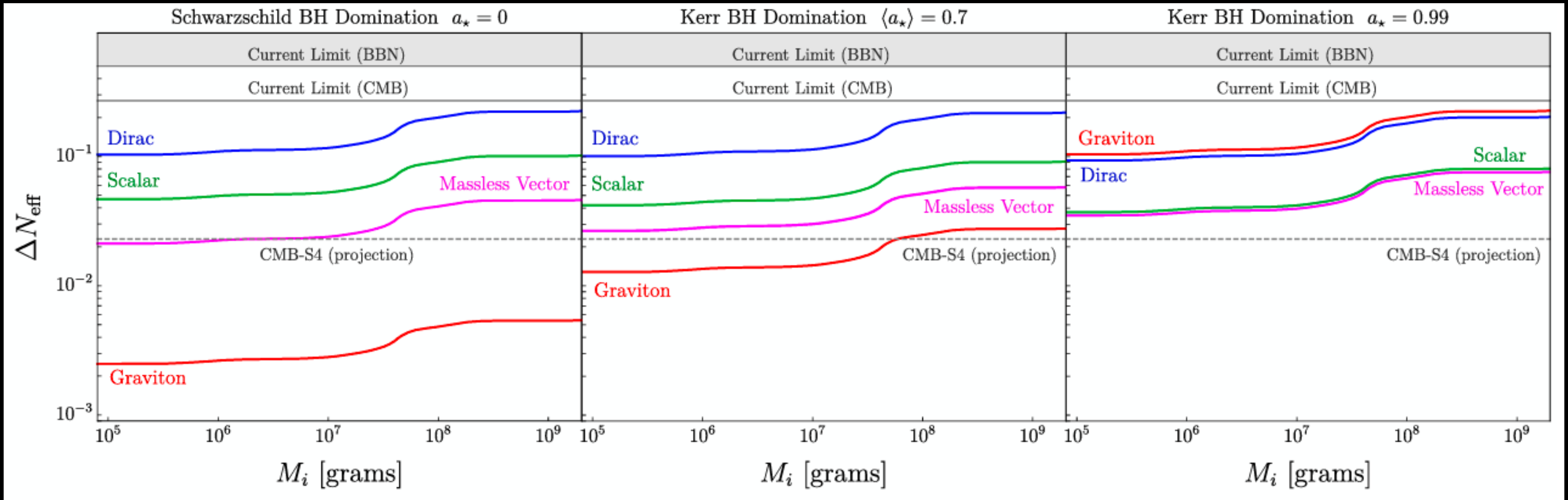
II. Kerr PBHs and Dark Radiation

Kerr PBHs and Dark Radiation

Dark particles with small masses can contribute to ΔNeff

Schwarzschild PBH → Negligible

Kerr PBH → Argued to be critical



[Hooper et al '20]

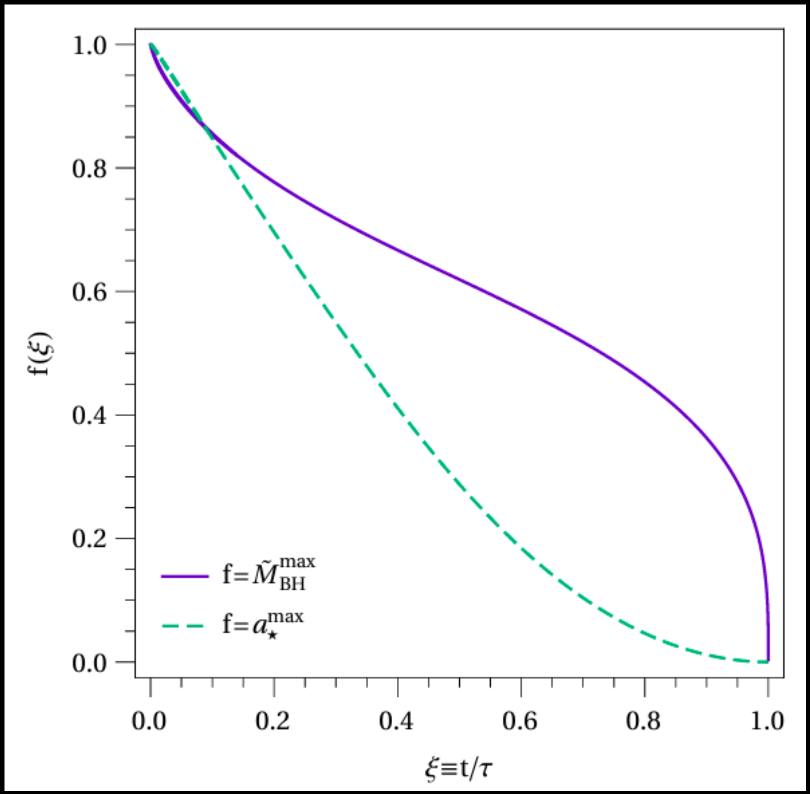
Kerr PBHs and Dark Radiation

$$\frac{\mathrm{d}^2\mathcal{N}_{ilm}}{\mathrm{d}p\mathrm{d}t} = \frac{\sigma_{s_i}^{lm}(M_{\mathrm{BH}}, p, a_\star)}{\exp\left[(E_i - m\Omega)/T_{\mathrm{BH}}\right] - (-1)^{2s_i}} \frac{p^3}{E_i}$$

$$\frac{dM_{\mathrm{BH}}}{dt} = -\epsilon(M_{\mathrm{BH}}, a_\star)\frac{M_p^4}{M_{\mathrm{BH}}^2}\,,$$

$$\frac{da_\star}{dt} = -a_\star[\gamma(M_{\mathrm{BH}}, a_\star) - 2\epsilon(M_{\mathrm{BH}}, a_\star)]\frac{M_p^4}{M_{\mathrm{BH}}^3}\,,$$

Kerr PBHs and Dark Radiation



Major effects:

Spin loss faster than mass loss

→ Shorter lifetime

→ Different ratio Dark Radiation / Radiation

How to calculate ΔNeff ?

Kerr PBHs and Dark Radiation

In the Standard Model

$$\rho_{\rm R}^{\rm SM} = \rho_\gamma \left[1 + \frac{7}{8}\left(\frac{T_\nu}{T_\gamma}\right) N_{\rm eff}^{\rm SM}\right] ,$$

$$T_\nu = (4/11)^{1/3} T_\gamma$$

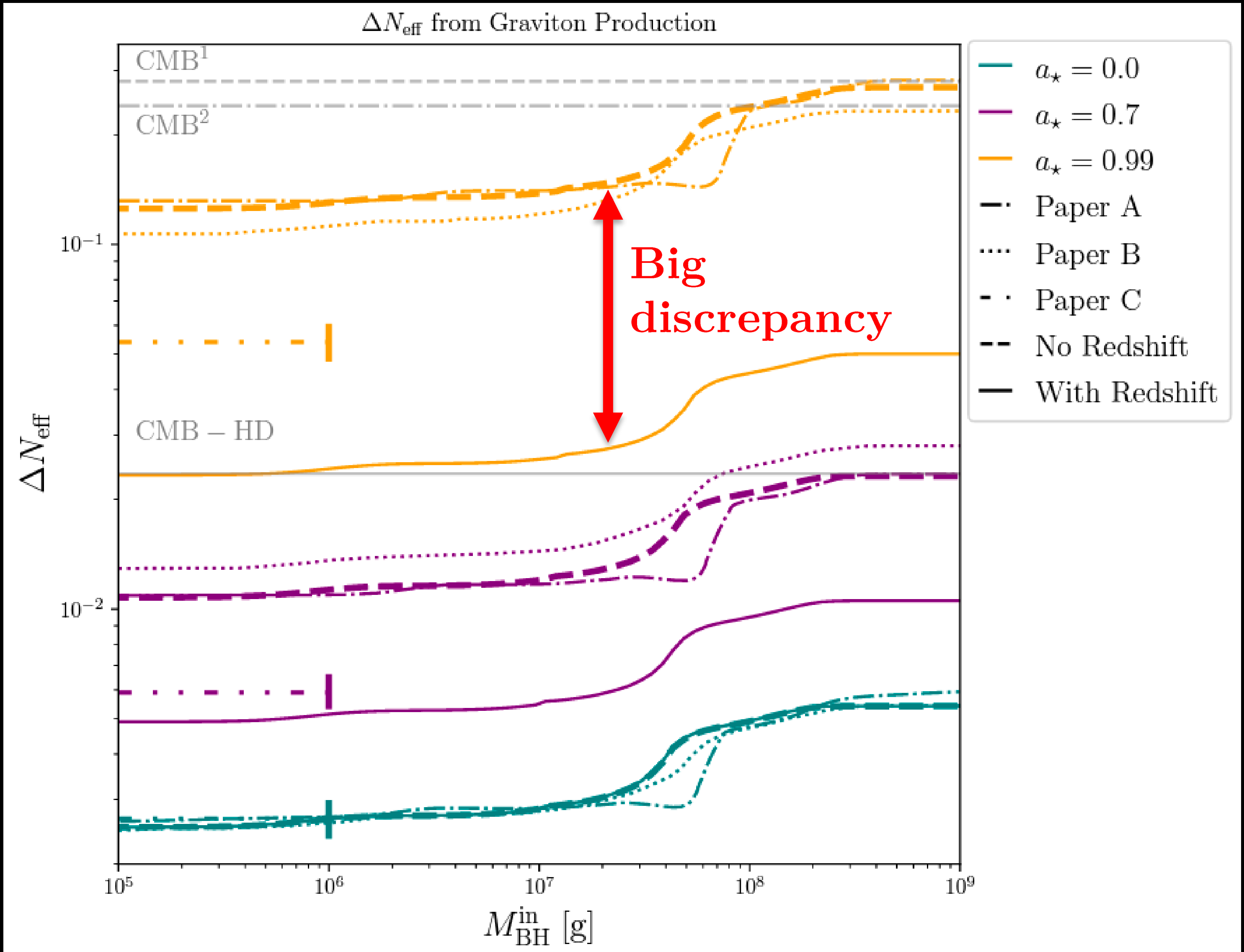
In the presence of Dark Radiation

$$\rho_{\rm R} \equiv \rho_\gamma \left[1 + \frac{7}{8}\left(\frac{T_\nu}{T_\gamma}\right) (N_{\rm eff}^{\rm SM} + \Delta N_{\rm eff})\right]$$

$$\Delta N_{\rm eff} = \left\{\frac{8}{7}\left(\frac{4}{11}\right)^{-\frac{4}{3}} + N_{\rm eff}^{\rm SM}\right\} \frac{\rho_{\rm DR}(T_{\rm ev})}{\rho_{\rm R}^{\rm SM}(T_{\rm ev})} \left(\frac{g_*(T_{\rm ev})}{g_*(T_{\rm eq})}\right) \left(\frac{g_{*S}(T_{\rm eq})}{g_{*S}(T_{\rm ev})}\right)^{\frac{4}{3}}$$

The quantity to evaluate

Kerr PBHs and Dark Radiation



Kerr PBHs and Dark Radiation

Why ?

Kerr PBHs and Dark Radiation

Why ?

$$\rho_{\rm R}^{\rm SM} = \rho_\gamma \left[1 + \frac{7}{8}\left(\frac{T_\nu}{T_\gamma}\right) N_{\rm eff}^{\rm SM}\right] \,,$$

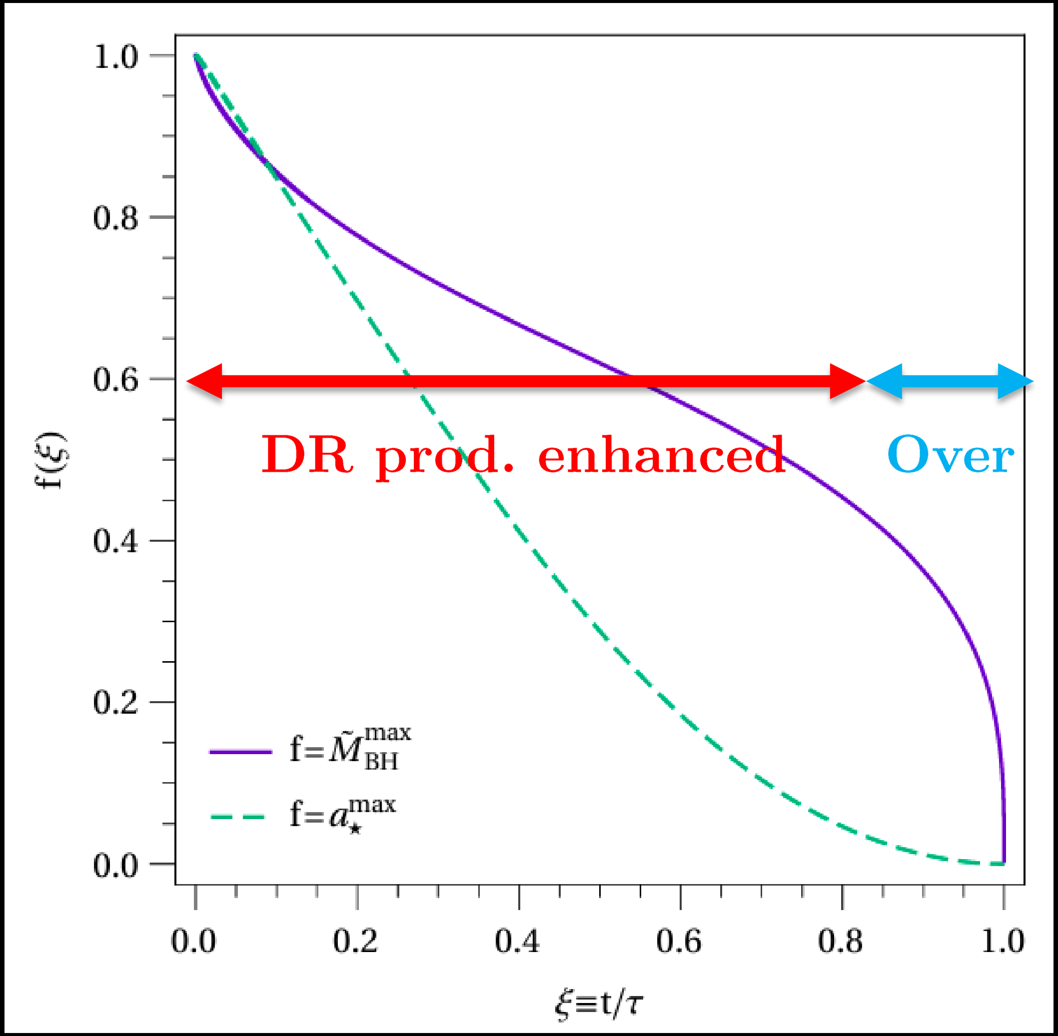
$$N_{\rm eff} \approx 3.045$$ (not just 3 ...)

The neutrino decoupling is NOT instantaneous

+ Temperature-dependent entropy transfer from electrons

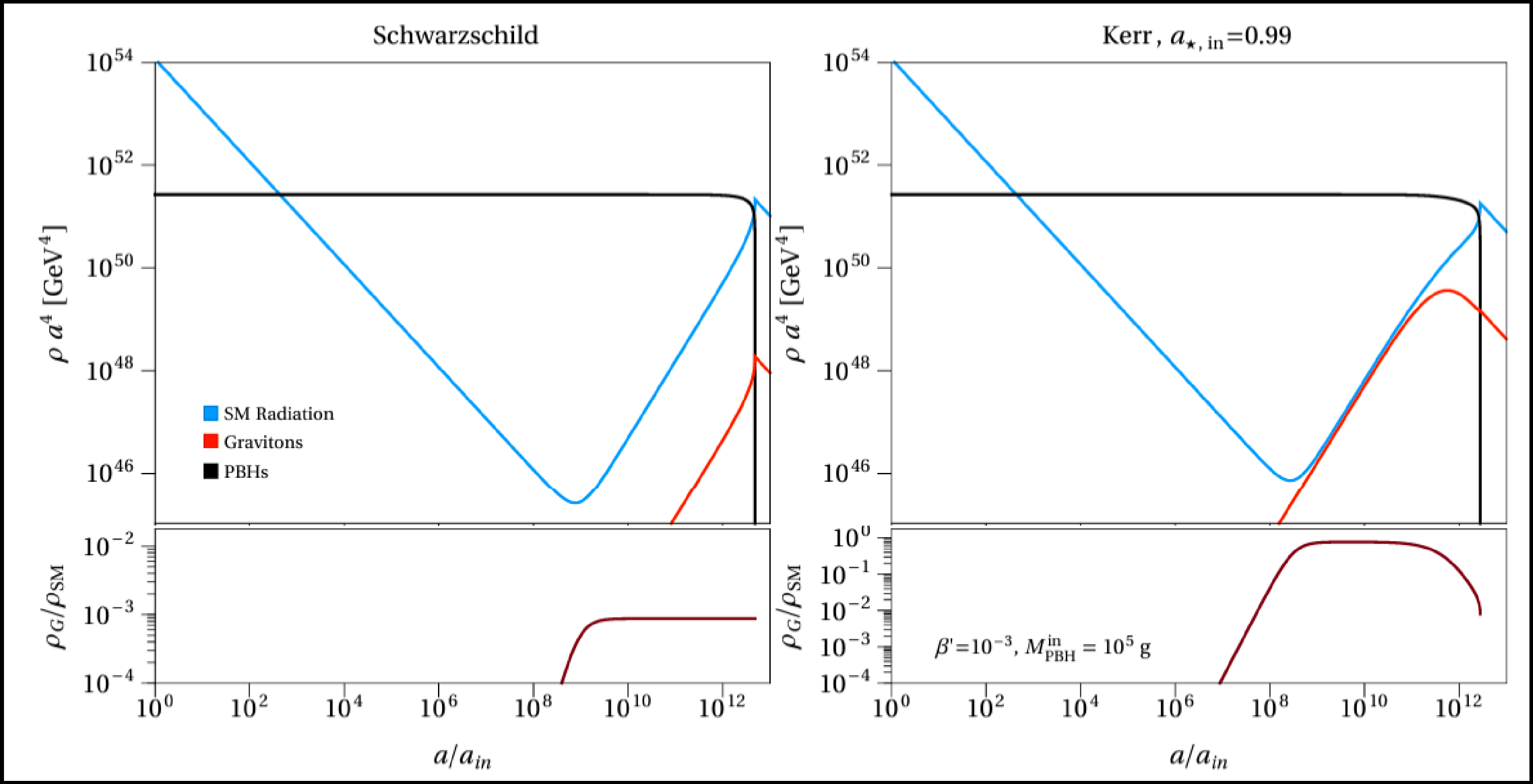
Kerr PBHs and Dark Radiation

Why ?



Kerr PBHs and Dark Radiation

Why ?



[Cheek, LH, Perez-Gonzalez and Turner '22] Code Publicly available: FRISBHEE

Kerr PBHs and Dark Radiation

Why ?

$$\frac{\mathrm{d}\mathcal{N}_{\rm DM}}{\mathrm{d}p} = \int_0^{\tau} \mathrm{d}t' \, \frac{a(\tau)}{a(t')} \times \frac{\mathrm{d}^2\mathcal{N}_{\rm DM}}{\mathrm{d}p'\mathrm{d}t'} \left(p \frac{a(\tau)}{a(t')}, t' \right)$$

some redshift is good

[Cheek, LH, Perez-Gonzalez and Turner '22] **Code Publicly available: FRISBHEE**

Kerr PBHs and Dark Radiation

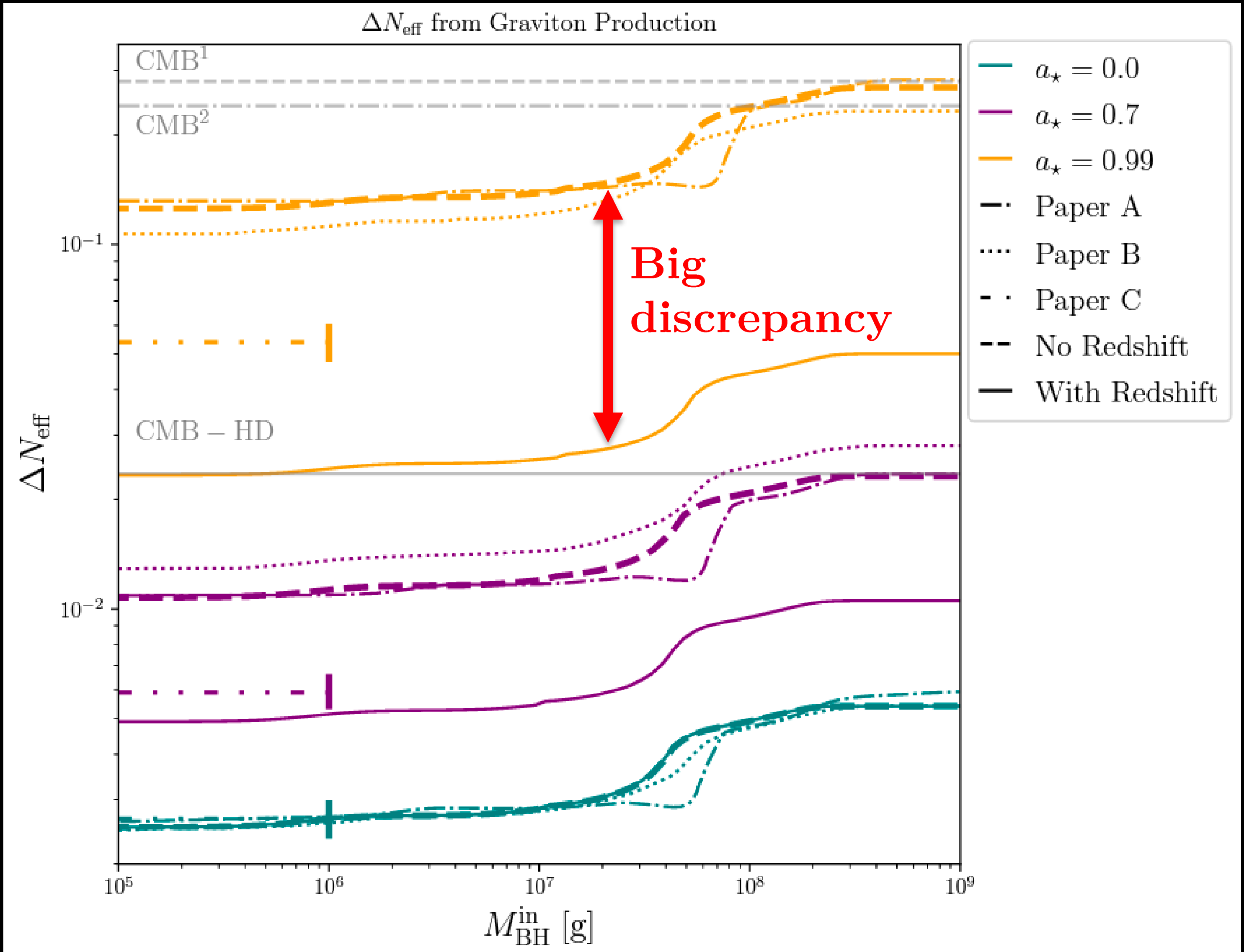
Why ?

$$\frac{\mathrm{d}\mathcal{N}_{\mathrm{DM}}}{\mathrm{d}p} = \int_0^\tau \mathrm{d}t' \frac{a(\tau)}{a(t')} \times \frac{\mathrm{d}^2\mathcal{N}_{\mathrm{DM}}}{\mathrm{d}p'\mathrm{d}t'} \left(p\frac{a(\tau)}{a(t')}, t' \right)$$

The correct one is better!

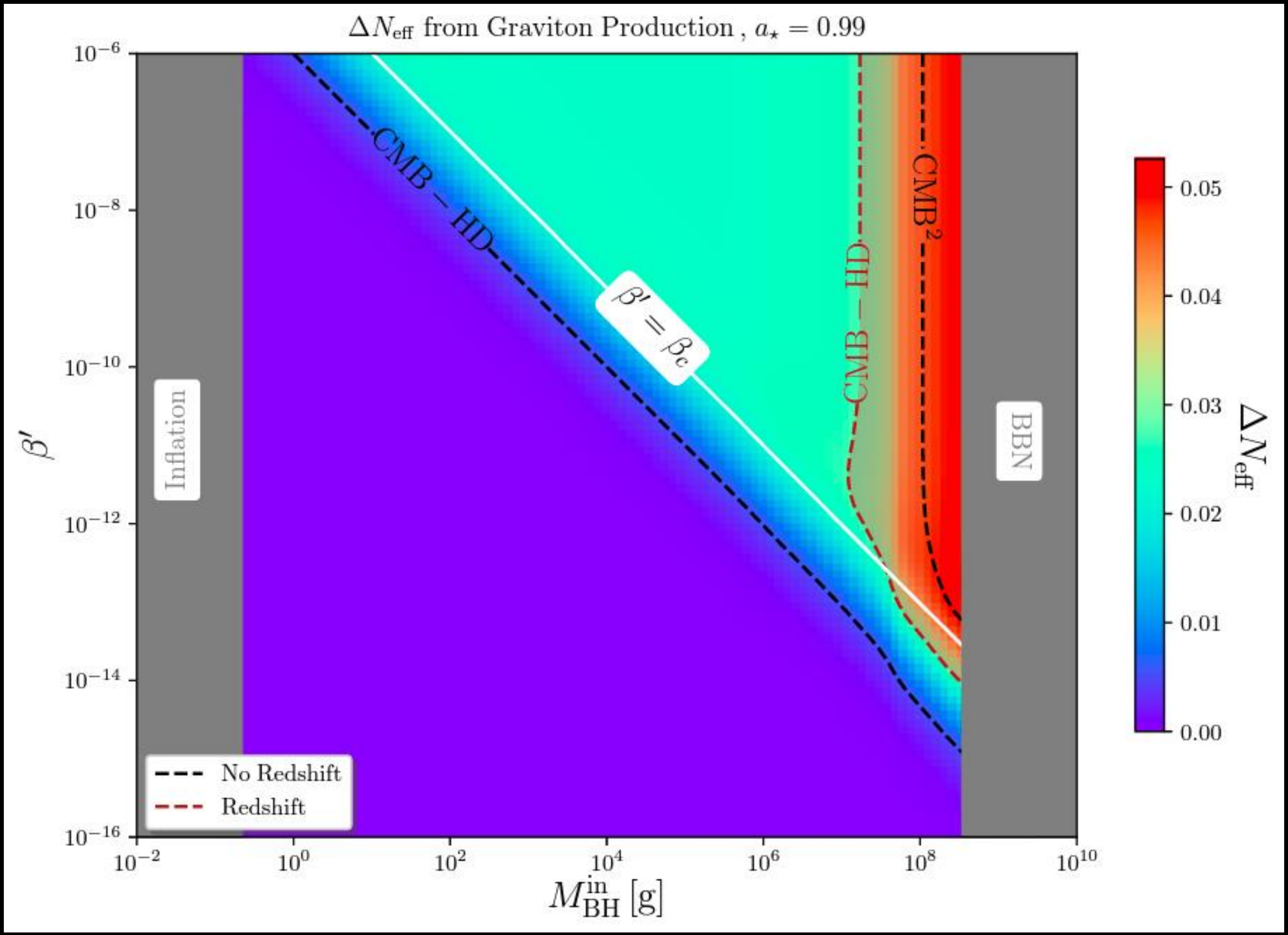
[Cheek, LH, Perez-Gonzalez and Turner '22] **Code Publicly available: FRISBHEE**

Kerr PBHs and Dark Radiation



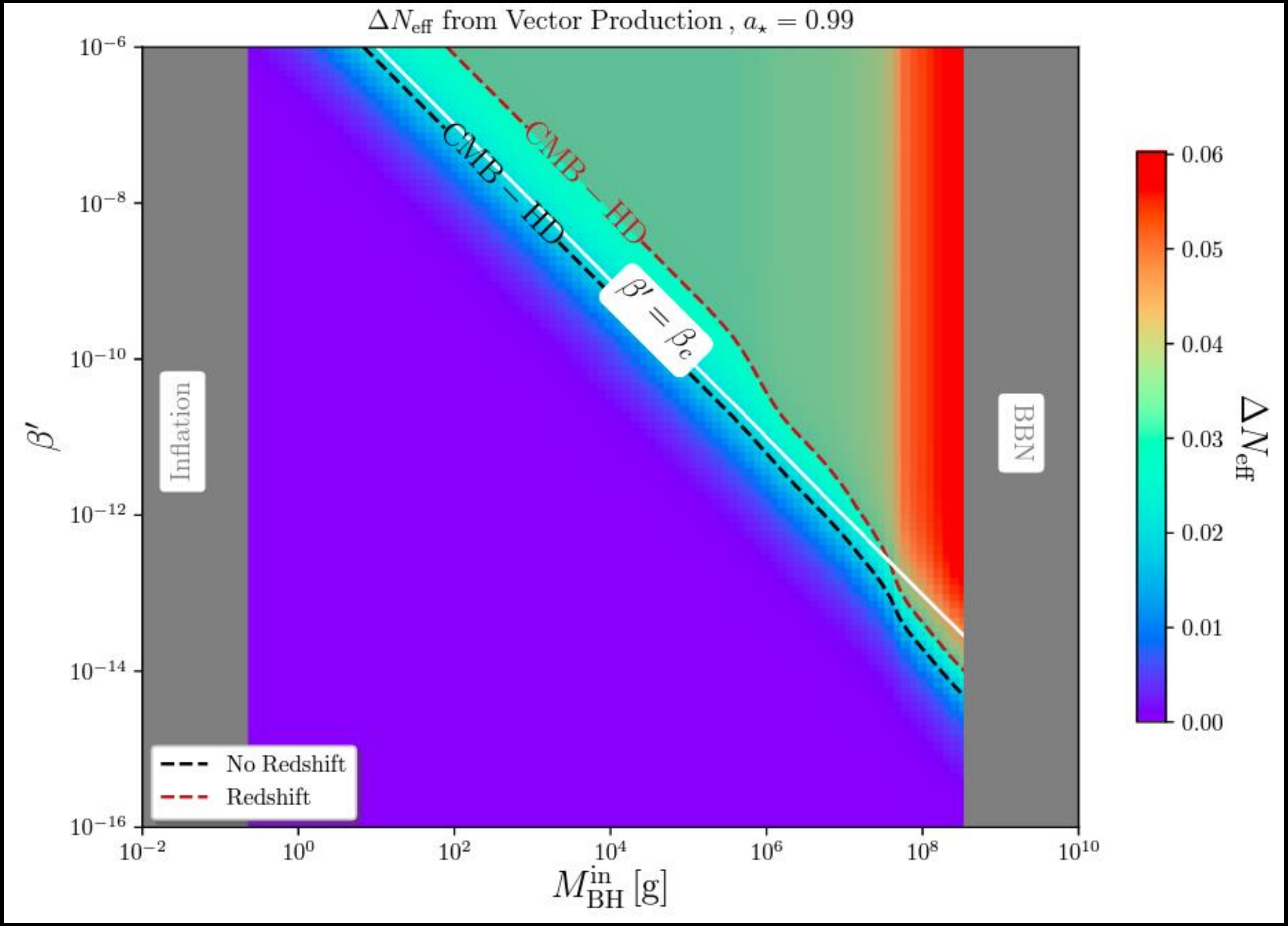
[Cheek, LH, Perez-Gonzalez and Turner '22] Code Publicly available: **FRISBHEE**

Kerr PBHs and Dark Radiation



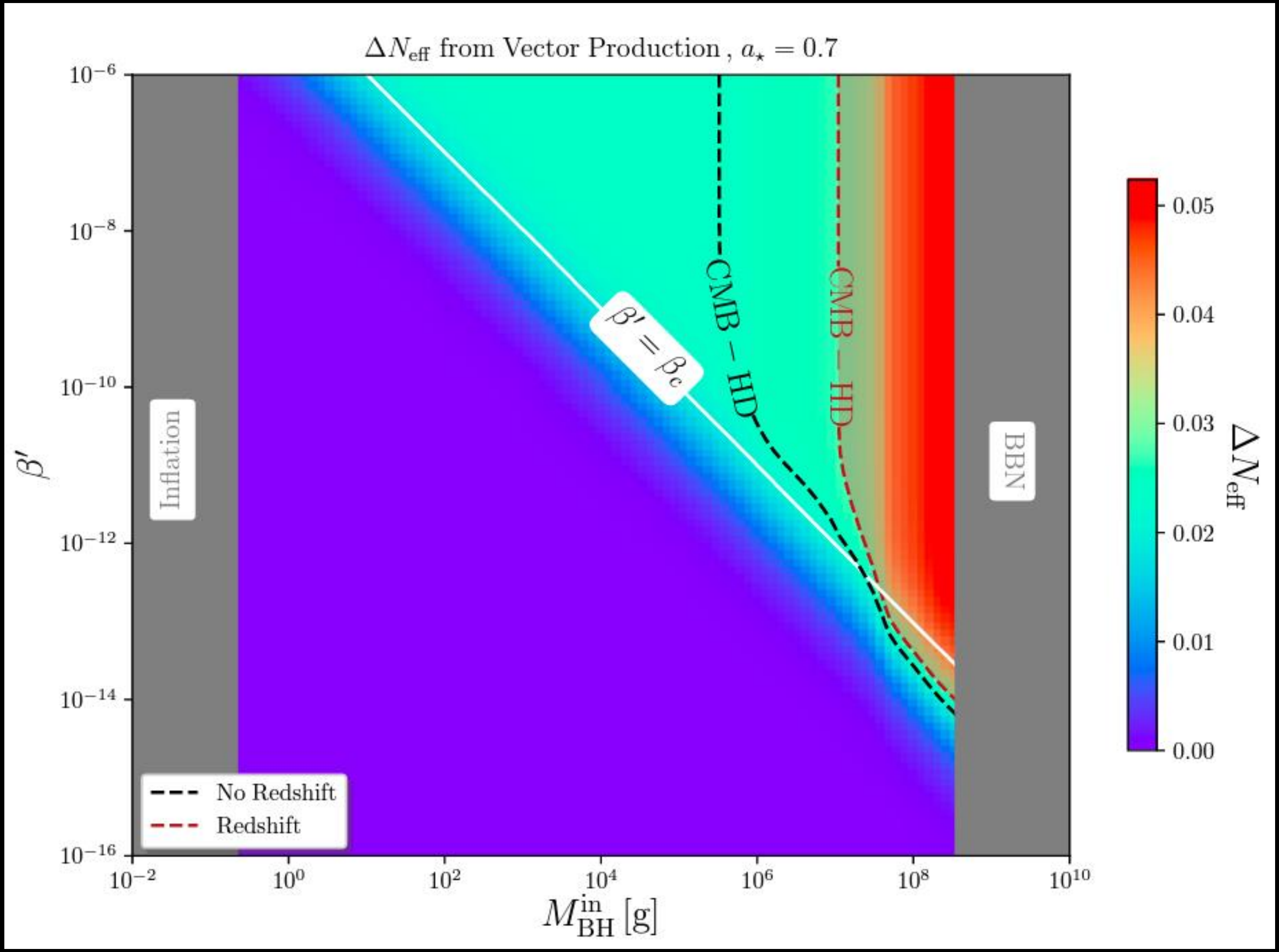
[Cheek, LH, Perez-Gonzalez and Turner '22] **Code Publicly available: FRISBHEE**

Kerr PBHs and Dark Radiation



[Cheek, LH, Perez-Gonzalez and Turner '22] **Code Publicly available: FRISBHEE**

Kerr PBHs and Dark Radiation



[Cheek, LH, Perez-Gonzalez and Turner '22] **Code Publicly available: FRISBHEE**

III. Kerr PBHs and Warm Dark Matter

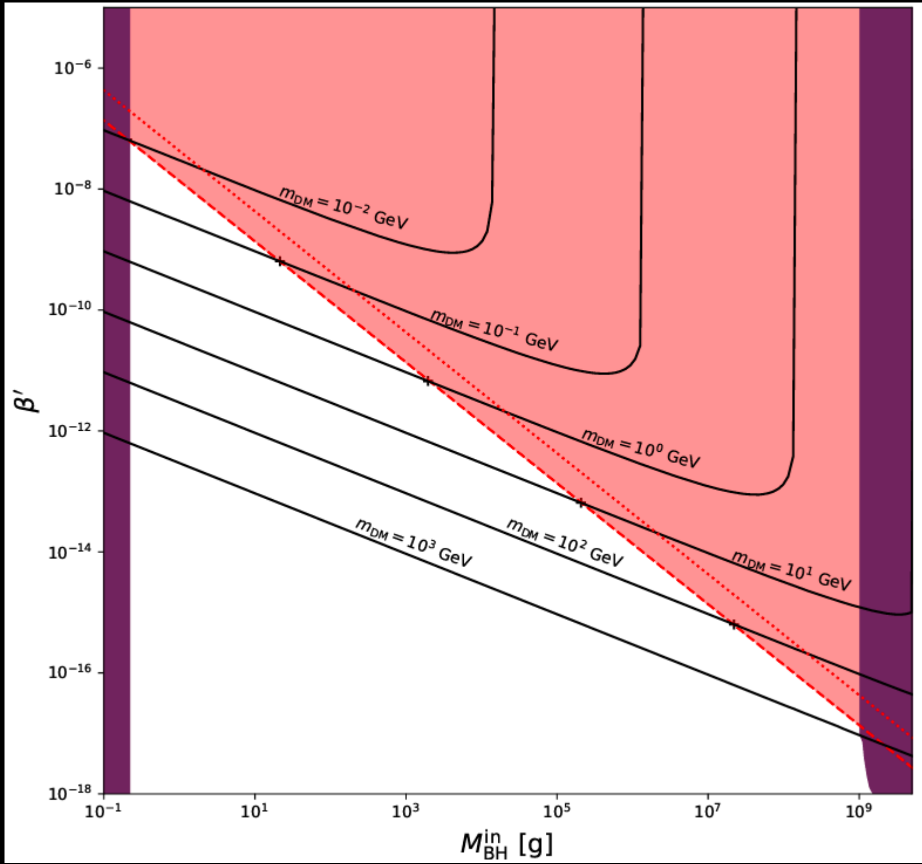
Kerr PBHs and Warm Dark Matter

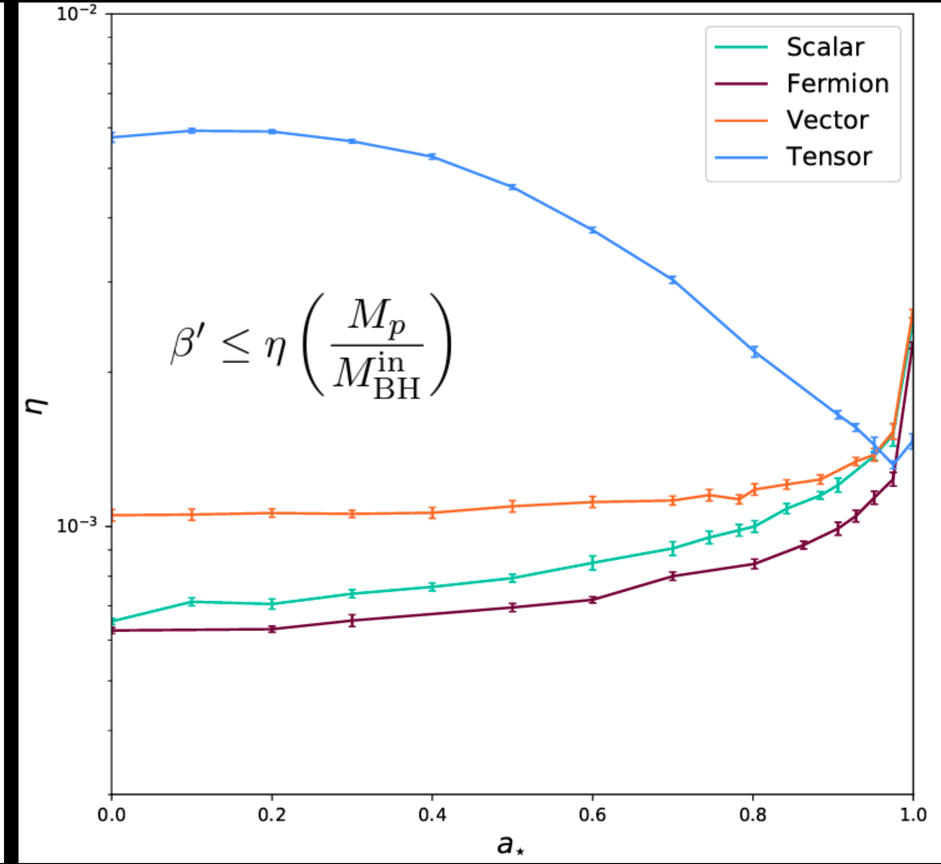
Using CLASS: expected matter power spectrum

$$P(k) = P_{\rm CDM}(k) T^2(k)$$

$$T(k) = (1 + (\alpha k)^{2\mu})^{-5/\mu}$$

Saturated at $\alpha = 1.3 \times 10^{-2}\,{\rm Mpc}\,h^{-1}$





IV. Evaporation of Extended Distributions

IV. Evaporation of Extended Distributions

In reality, PBHs don't all have the same mass...

$$f_{\mathrm{PBH}}(M, a) = \delta(M - M_{\mathrm{PBH}}) \times \delta(a - a_*)$$

↓

$$f_{\mathrm{PBH}}(M, a) = F(M - M_{\mathrm{PBH}}) \times A(a - a_*)$$

IV. Evaporation of Extended Distributions

[D. N. Page, Phys. Rev. D 14, 3260 (1976)]

$$\frac{dM_{\rm BH}}{dt} = -\epsilon(M_{\rm BH}, a_\star)\frac{M_p^4}{M_{\rm BH}^2} ,$$

$$\frac{da_\star}{dt} = -a_\star[\gamma(M_{\rm BH}, a_\star) - 2\epsilon(M_{\rm BH}, a_\star)]\frac{M_p^4}{M_{\rm BH}^3} ,$$

$$\frac{\mathrm{d}a}{\mathrm{d}t} = \frac{a}{M^3}\left[2f(a) - g(a)\right] ,$$

$$\frac{\mathrm{d}M}{\mathrm{d}t} = -\frac{f(a)}{M^2} .$$

$$y \equiv -\ln(a)$$

$$z \equiv -\ln\left(\frac{M}{M_1}\right)$$

$$\tau \equiv M_1^{-3}t$$

$$\frac{\mathrm{d}z}{\mathrm{d}y} = \frac{f(a)}{g(a) - 2f(a)} ,$$

$$\frac{\mathrm{d}\tau}{\mathrm{d}y} = \left(\frac{M}{M_1}\right)^3\frac{1}{g(a) - 2f(a)} ,$$

Generic solution (z, τ) for any M_1

$$M = M_i e^{z_i - z} ,$$

$$(t - t_i) = M_i^3 e^{3z_i}(\tau - \tau_i) ,$$

IV. Evaporation of Extended Distributions

$$\begin{aligned} \mathrm{d}n_{\rm BH} &= f_{\rm BH}(M, a, t)\mathrm{d}M\mathrm{d}a \\ &= f_{\rm BH}(M_i, a_i, t_i)\mathrm{d}M_i\mathrm{d}a_i \,. \end{aligned}$$

$$\frac{\mathrm{d}\varrho_{\rm BH}}{\mathrm{d}t} = \int_0^\infty \frac{\mathrm{d}M}{\mathrm{d}t}\Theta(M) f_{\rm BH}(M_i, a_i, t_i)\mathrm{d}M_i\mathrm{d}a_i$$

Dynamics of the evaporation + Friedmann equations

→ Included in FRISBHEE

IV. Evaporation of Extended Distributions

Examples:

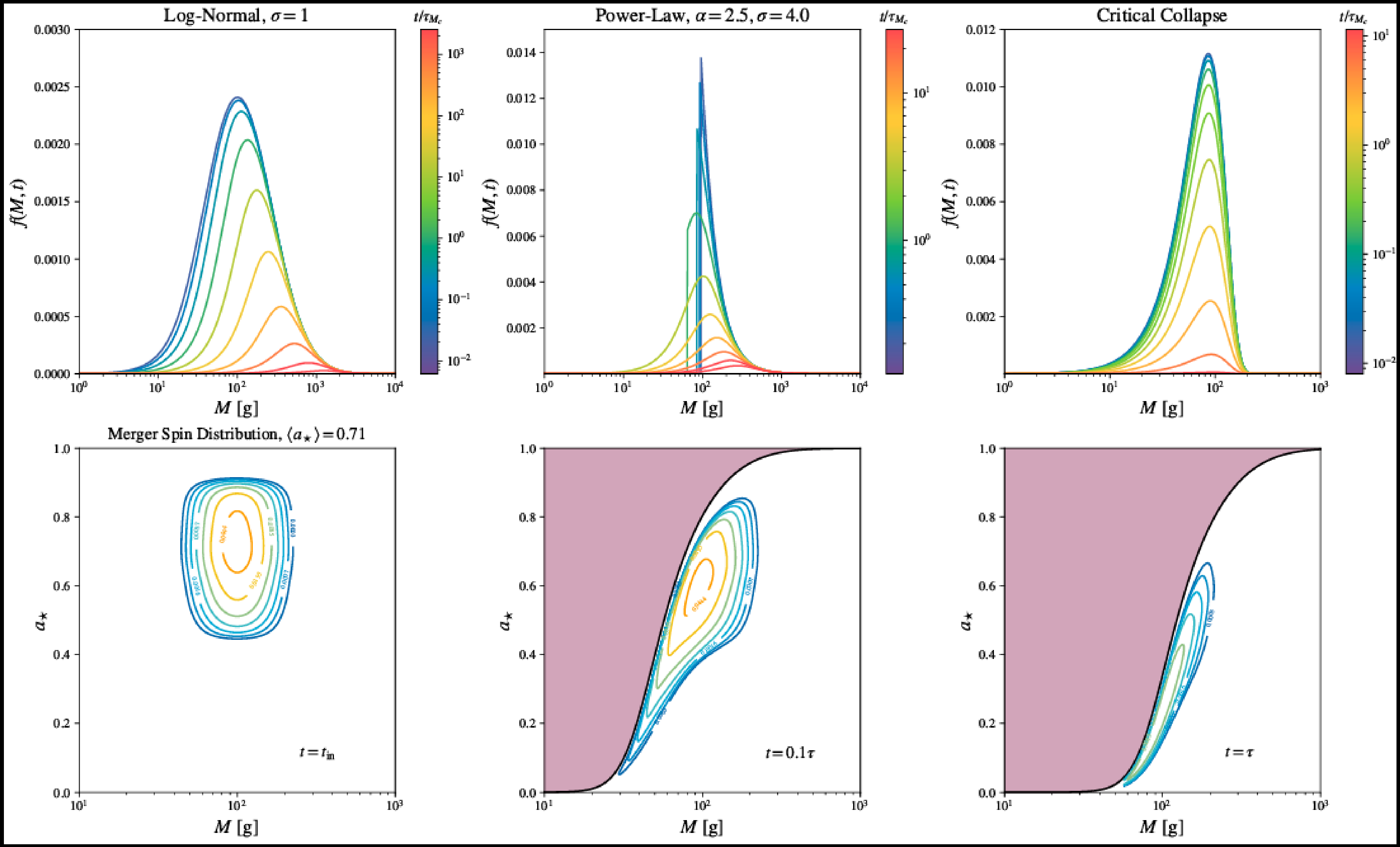
$$\frac{\mathrm{d}n}{\mathrm{d}M} \propto \frac{1}{M^2} \exp\left[-\frac{(\log M - \log M_\mathrm{c})^2}{2\,\sigma^2}\right]$$

Evaporation smeared around $\tau(M_c)$

$$\frac{\mathrm{d}n}{\mathrm{d}M} \propto M^{-\alpha} \quad \text{with} \quad \alpha = \frac{2\,(1+2\,w)}{1+w}$$

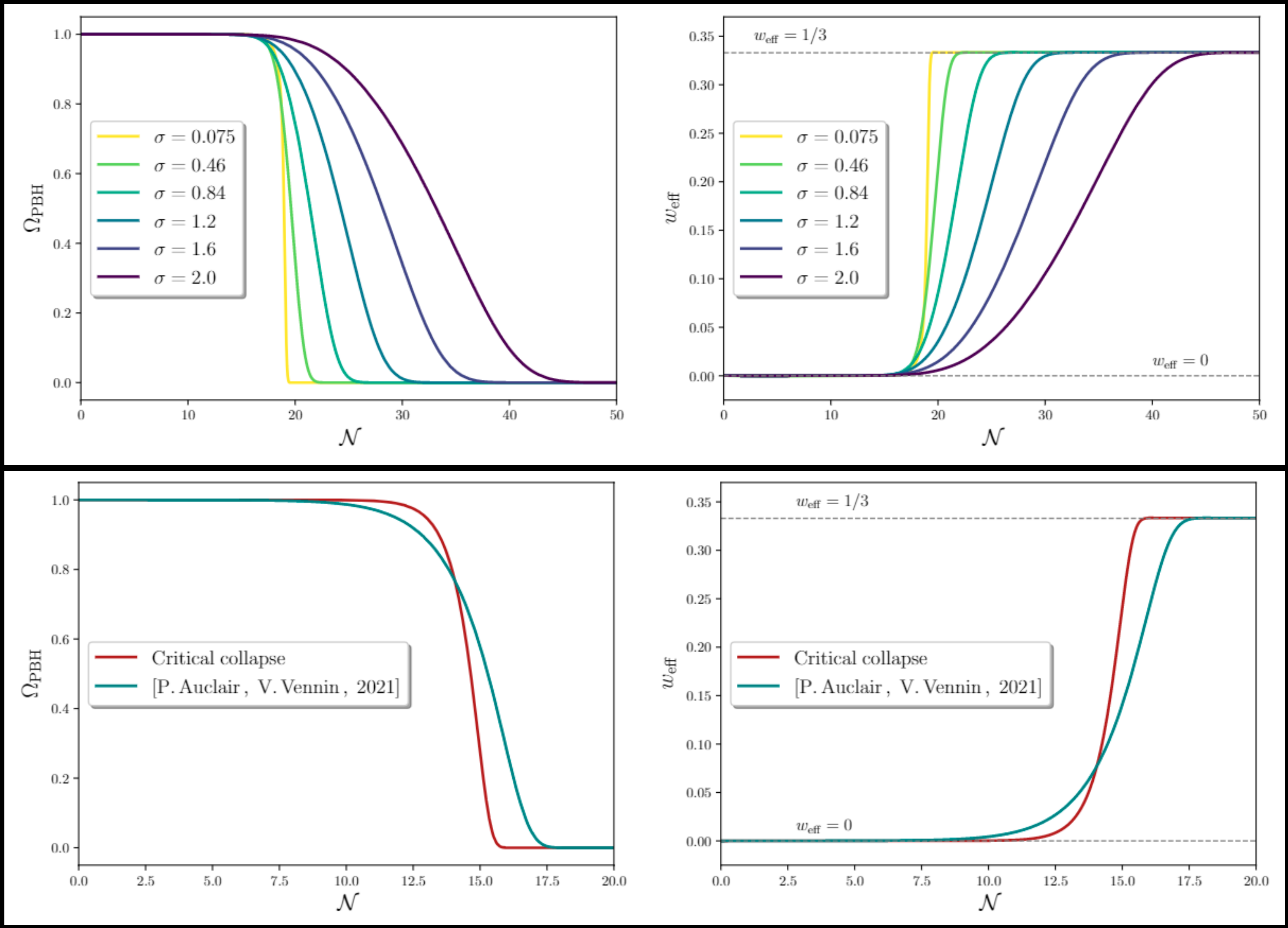
Regime of ‘Cosmological Stasis’

Evaporation of Extended Distributions



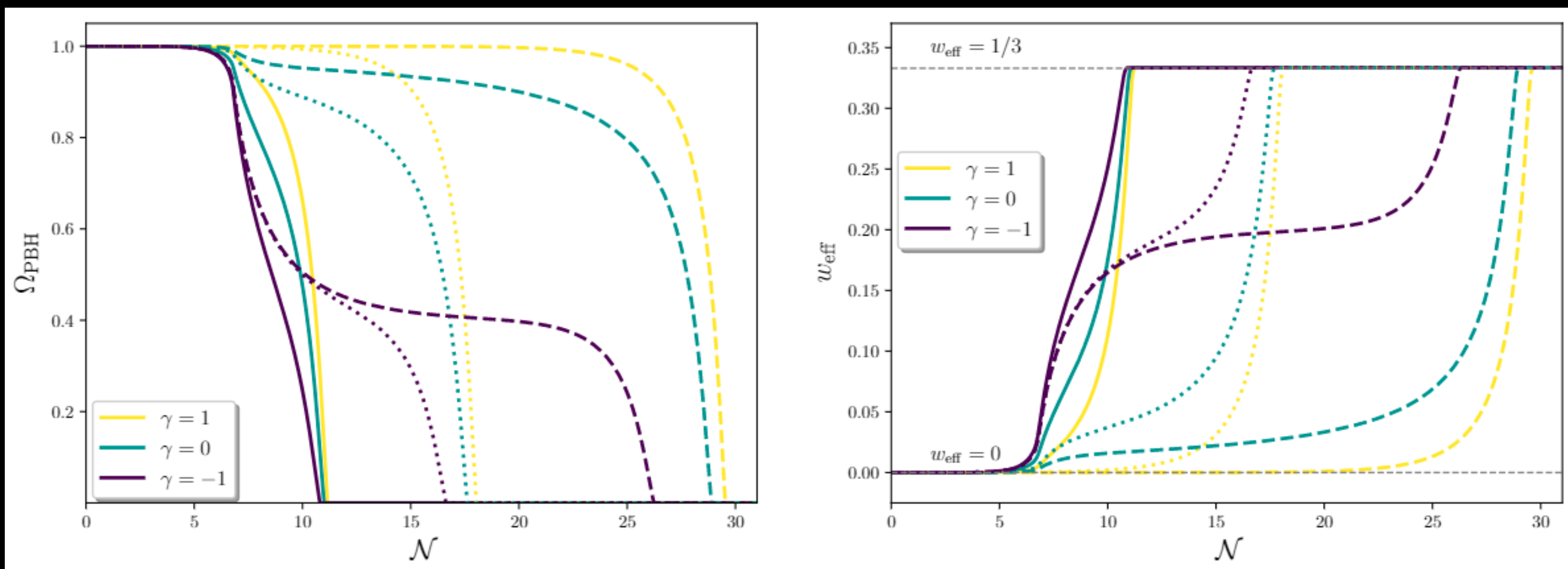
[Cheek, LH, Perez-Gonzalez, Turner '22]

Evaporation of Extended Distributions



Evaporation of Extended Distributions

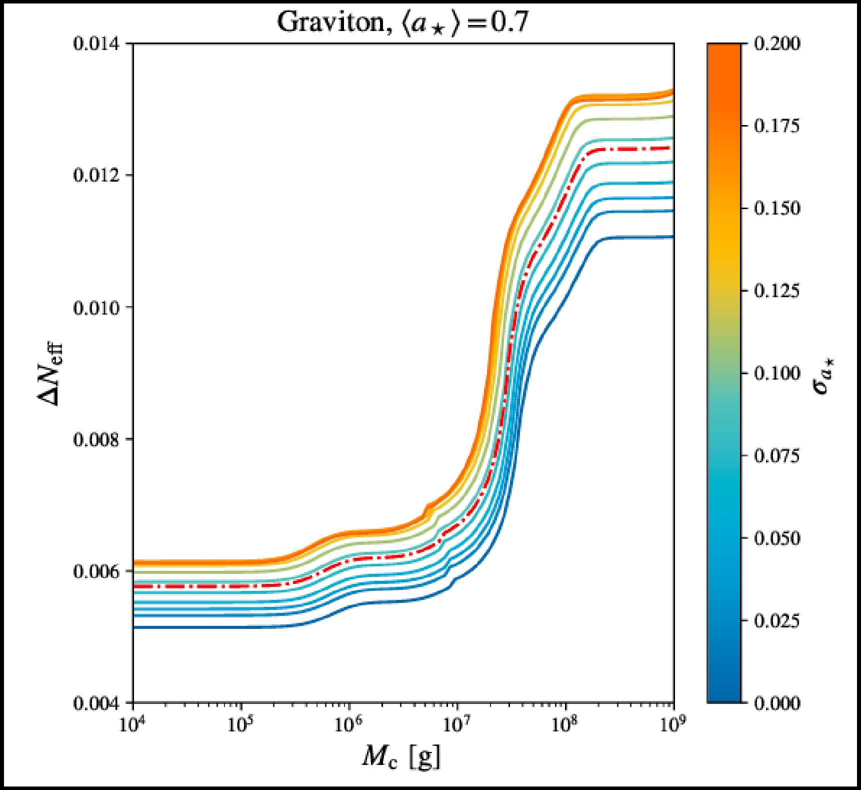
$$\frac{\mathrm{d}n}{\mathrm{d}M} \propto M^{-\alpha} \quad \text{with} \quad \alpha = \frac{2\,(1+2\,w)}{1+w}$$

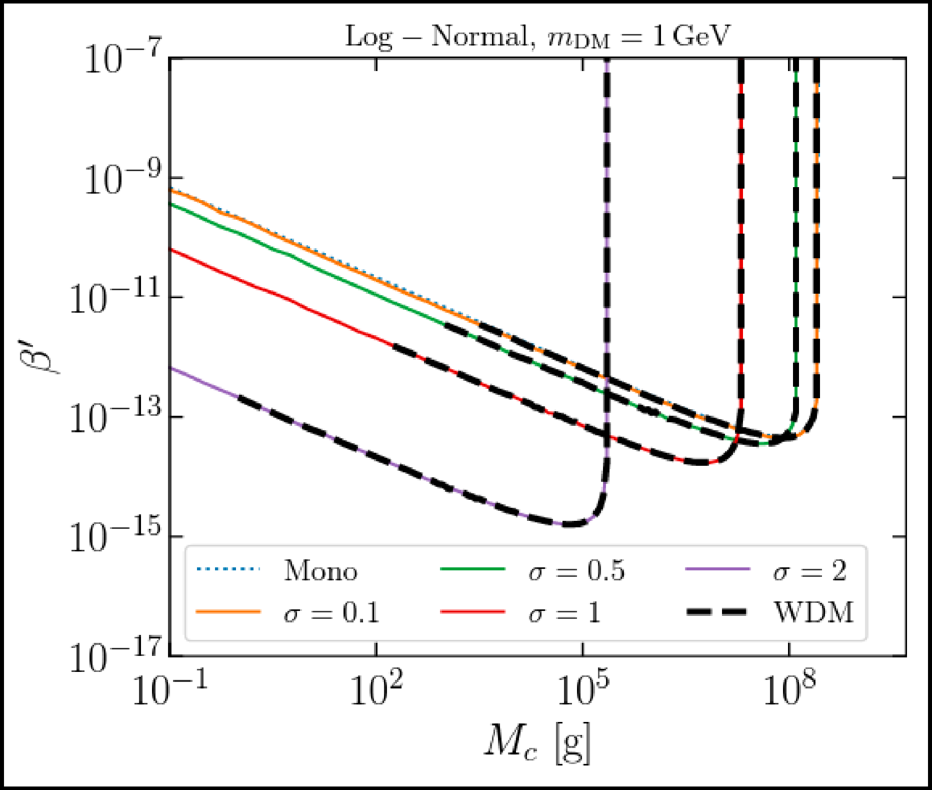


'Stasis' regime reached for $0 < w \leq 1$

[Copeland, Liddle, Barrow '91]
[Dienes, LH, Huang, Kim, Tait, Thomas '22]
[Cheek, LH, Perez-Gonzalez, Turner '22]

Evaporation of Extended Distributions





[Cheek, LH, Perez-Gonzalez, Turner ‘22]

Gravitational Waves?

PBHs are known to source GWs in many different ways

Any GW spectrum gets affected by post-inflationary cosmology

Measuring GWs can tell us a lot...

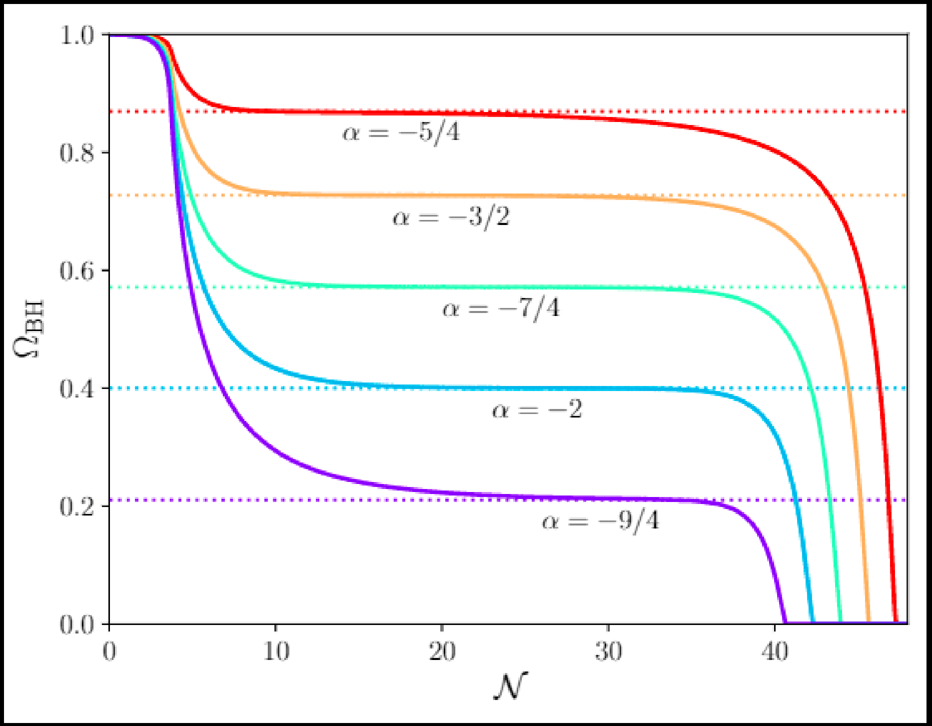
Gravitational Waves?

$$f_{\rm BH}(M) = \begin{cases} C M^{\alpha-1}, & \text{for } M_{\rm min} \le M \le M_{\rm max}; \\ 0, & \text{else.} \end{cases}$$

$$\alpha \equiv \frac{(-3w_{\rm form.} - 1)}{(w_{\rm form.} + 1)}$$

$$\frac{dH}{dt} = -\frac{1}{2}H^2(4 - \Omega_{\rm BH}),$$

$$\frac{d\Omega_{\rm BH}}{dt} = \Omega_{\rm BH}\left[\frac{\int_0^\infty f_{\rm BH}(M,t)\frac{dM}{dt}dM}{\int_0^\infty f_{\rm BH}(M,t)M\,dM}\right] + H\Omega_{\rm BH}(1 - \Omega_{\rm BH}).$$



$$= \frac{1+\alpha}{3(t - t_i)}$$

[Dienes, LH, Huang, Kim, Tait, Thomas ‘22]

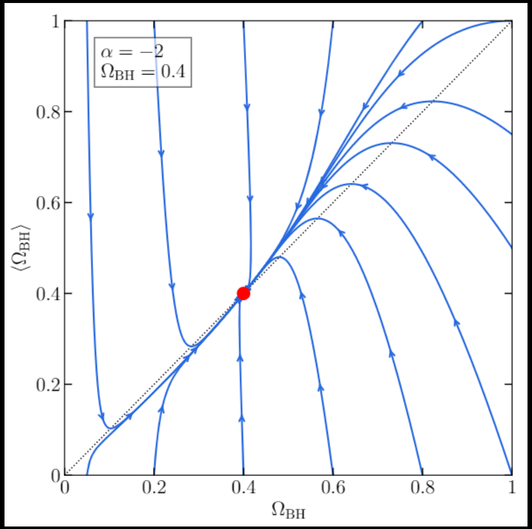
Gravitational Waves?

$$\begin{cases} \dfrac{d\Omega_{BH}}{dt} = \dfrac{1}{t-t_i} f(\Omega_{BH}, \langle\Omega_{BH}\rangle) \\ \dfrac{d\langle\Omega_{BH}\rangle}{dt} = \dfrac{1}{t-t_i} g(\Omega_{BH}, \langle\Omega_{BH}\rangle)\ , \end{cases}$$

$$f(\Omega_{BH}, \langle\Omega_{BH}\rangle) \equiv \Omega_{BH}\left[\frac{1+\alpha}{3} + \frac{2(1-\Omega_{BH})}{4-\langle\Omega_{BH}\rangle}\right]$$

$$g(\Omega_{BH}, \langle\Omega_{BH}\rangle) \equiv \Omega_{BH} - \langle\Omega_{BH}\rangle\,,$$

$$\langle\Omega_{BH}\rangle \equiv \frac{1}{t-t_i}\int_{t_i}^{t} dt'\,\Omega_{BH}(t')\ .$$



$$w_{eff} = \frac{-\alpha-1}{\alpha+7}$$

$$\Omega_{BH} = \langle\Omega_{BH}\rangle = \frac{4\alpha+10}{\alpha+7} \equiv \bar{\Omega}_{BH}\,.$$

$$\mathcal{J} \equiv \frac{1}{t-t_i}\begin{pmatrix} \partial_{\Omega_{BH}} f & \partial_{\langle\Omega_{BH}\rangle} f \\ \partial_{\Omega_{BH}} g & \partial_{\langle\Omega_{BH}\rangle} g \end{pmatrix}$$

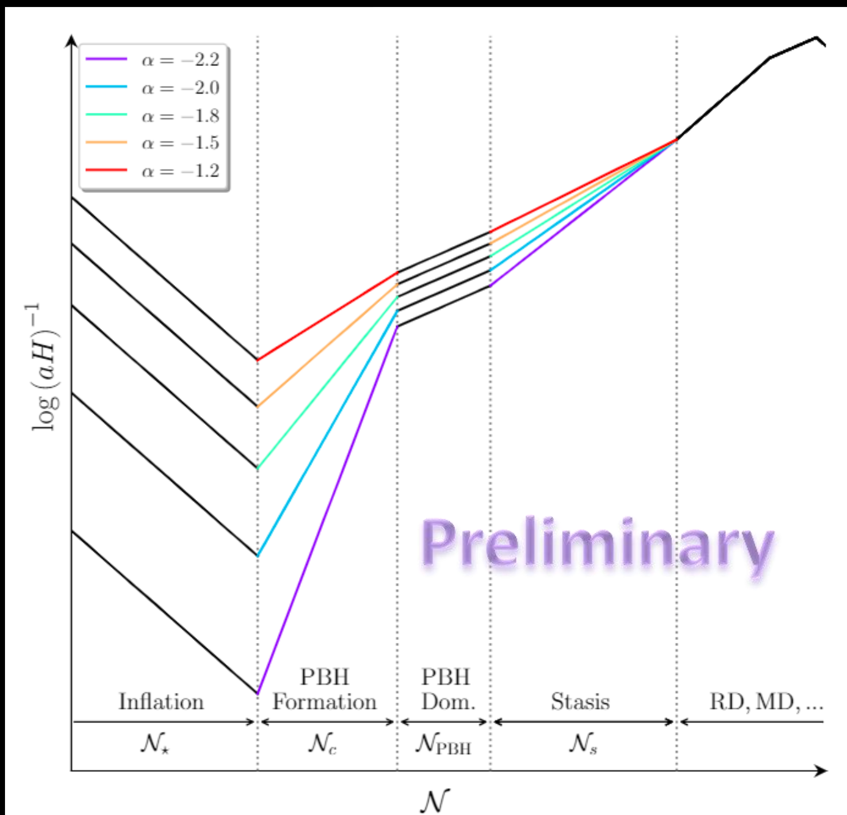
$$\lambda_\pm = \frac{1}{18}\left(-4\alpha \pm \sqrt{-19-4\alpha(2\alpha+19)-59}\right)$$

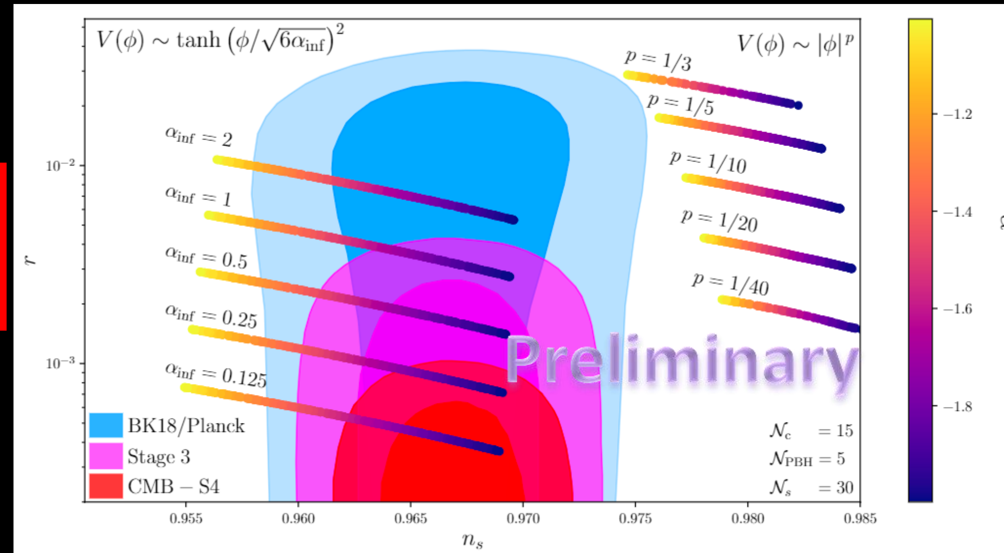
[Dienes, LH, Huang, Kim, Tait, Thomas ‘22] [Copeland, Liddle, Barrow ‘91]

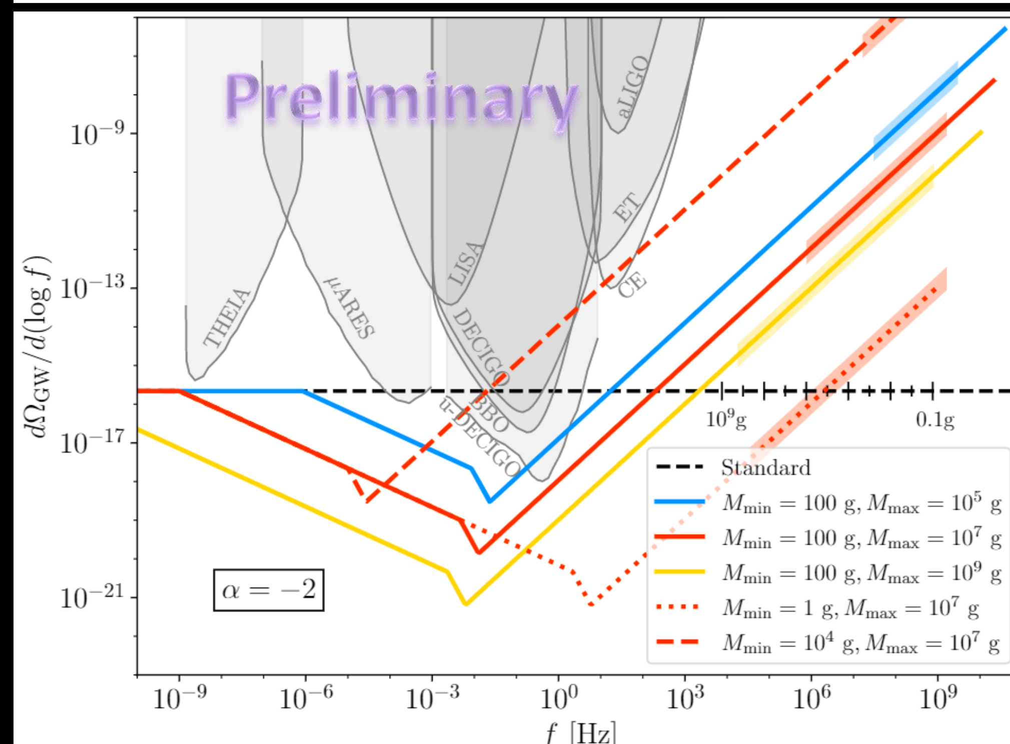
Gravitational Waves?

$$w_{\text{eff}} = \frac{-\alpha - 1}{\alpha + 7}$$

$$\alpha \equiv \frac{(-3w_{\text{form.}} - 1)}{(w_{\text{form.}} + 1)}$$



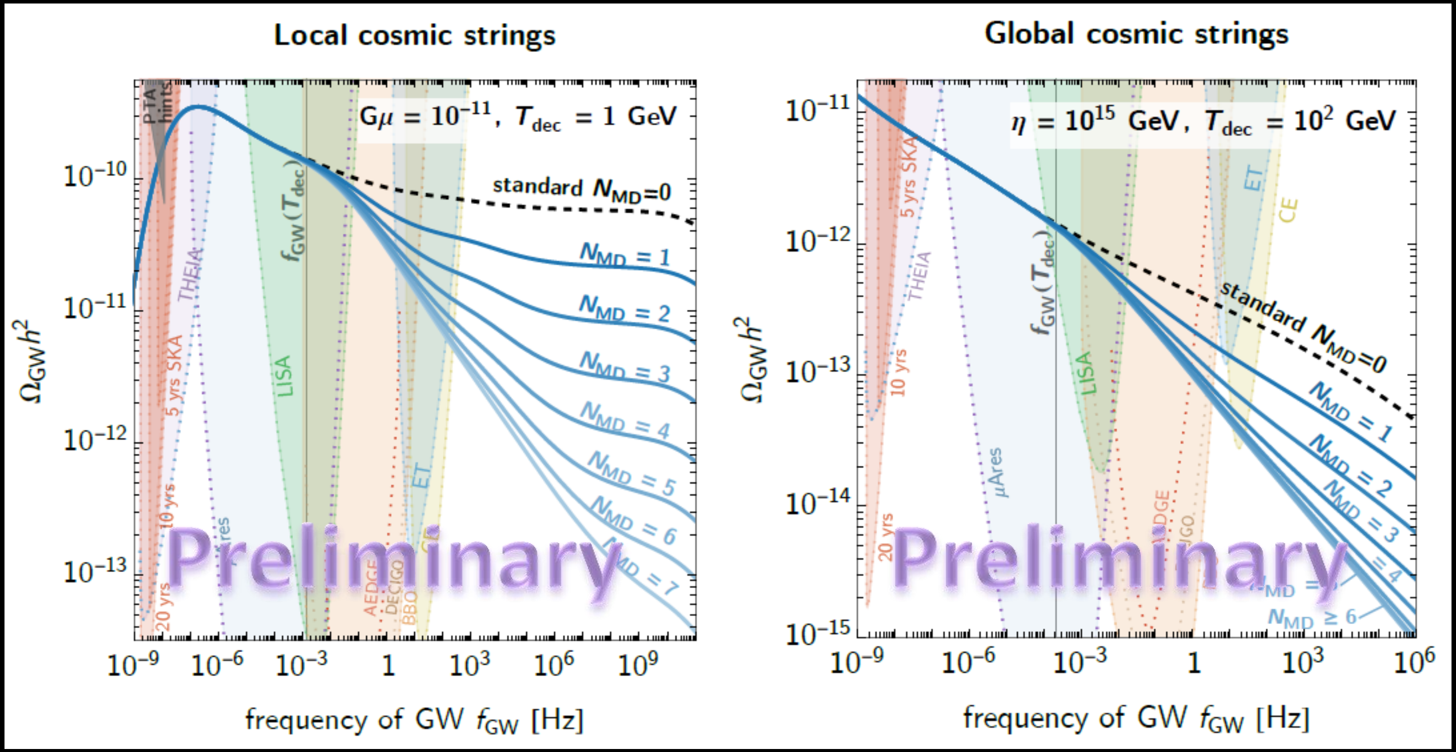




[Dienes, LH, Huang, Kim, Tait, Thomas '22]

Gravitational Waves?

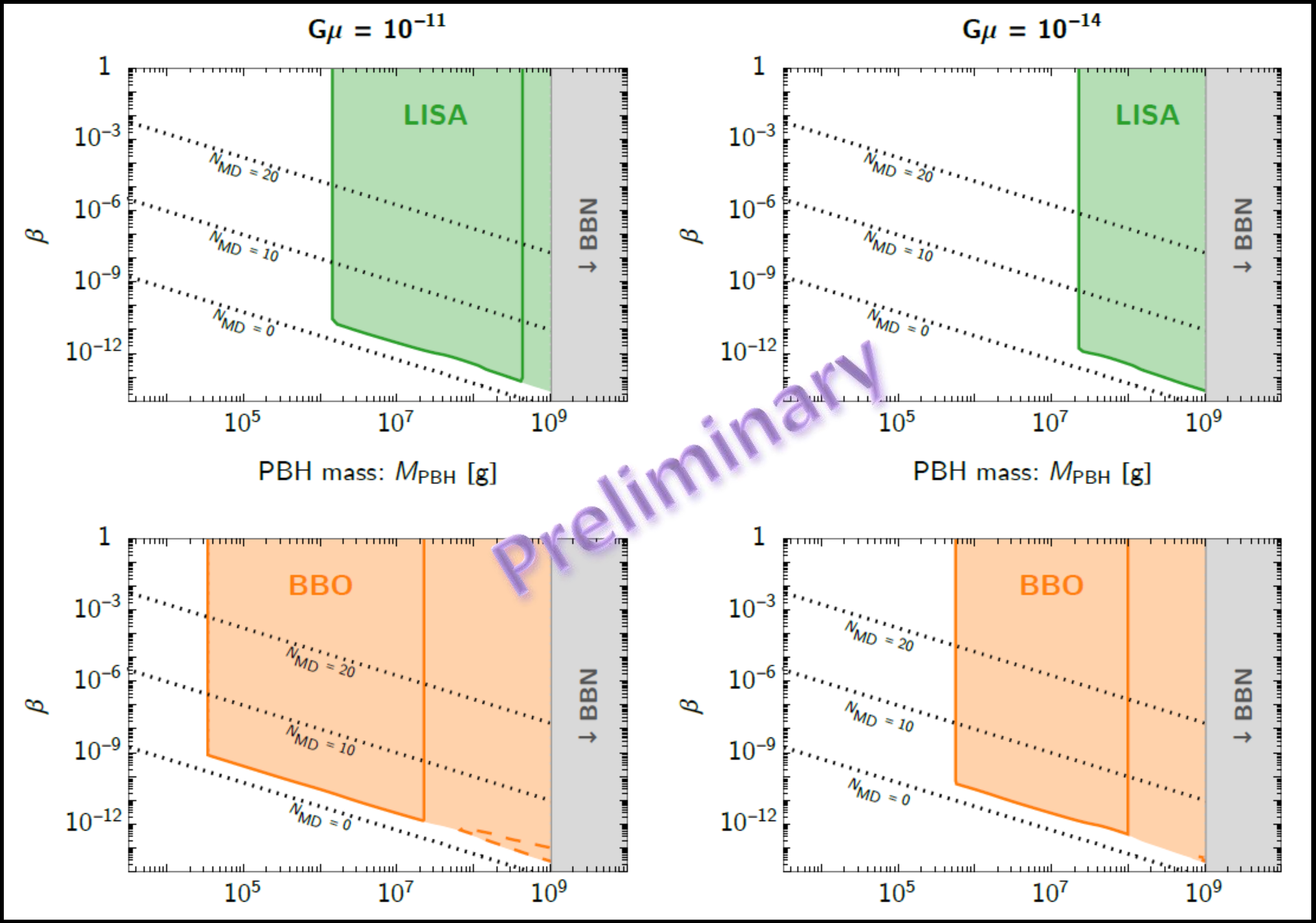
GWs from cosmic strings?



[Ghoshal, Gouttenoire, LH, Simakachorn '23]

Gravitational Waves?

GWs from cosmic strings?



[Ghoshal, Gouttenoire, LH, Simakachorn '23]

Conclusion

PBHs can leave several imprints in the early Universe

- Modify cosmology (EMD+ entropy inj.)
- Produce dark matter, leading to modified predictions for particle searches
- Particles produced from evaporation can be extremely boosted, which can lead to additionnal constraints from structure formation
- Kerr PBHs can lead to a large production of gravitons – existing results were refined
- Our code is accessible online: ⍰

`https://github.com/yfperezg/frisbhee`

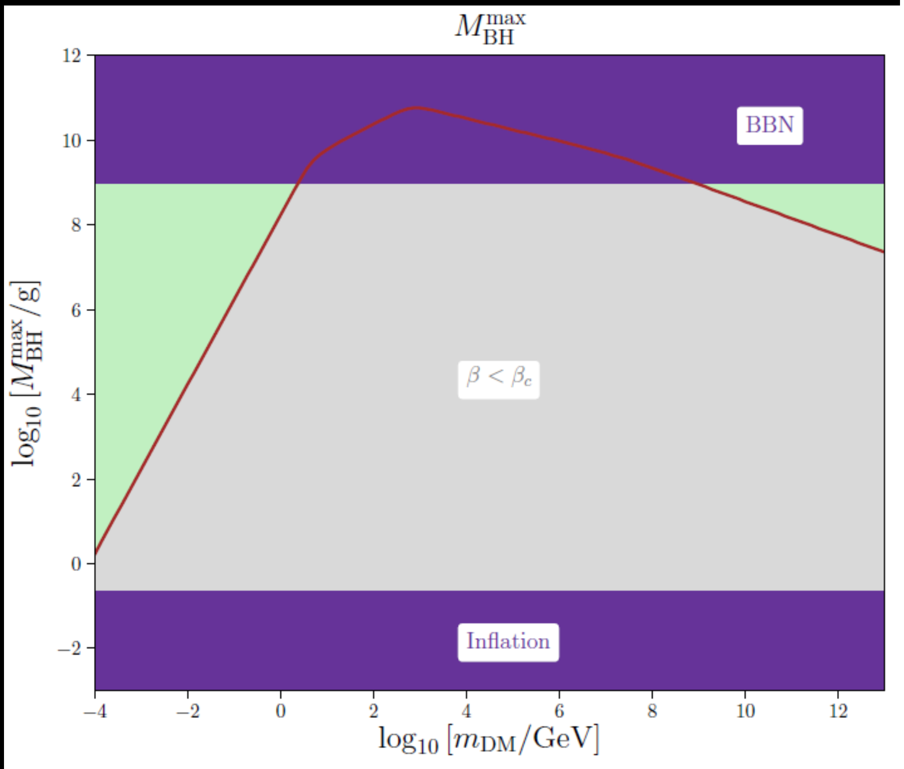
Future Directions

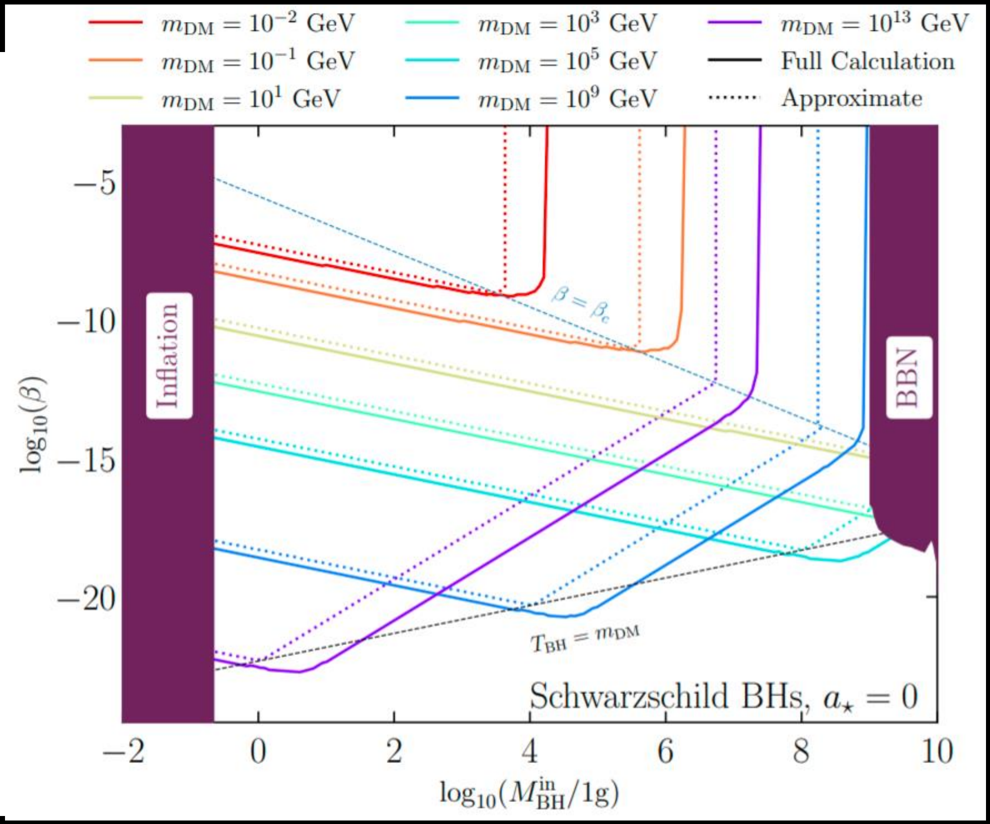
- What distribution of PBHs is produced from different classes of inflation theories?
- Limits on PBHs using the EW vacuum metastability?
- Correlations between PBH mass distribution and GW spectrum?
- Boosted evaporation products: Energy deposition, thermalization dynamics...

That's all folks !

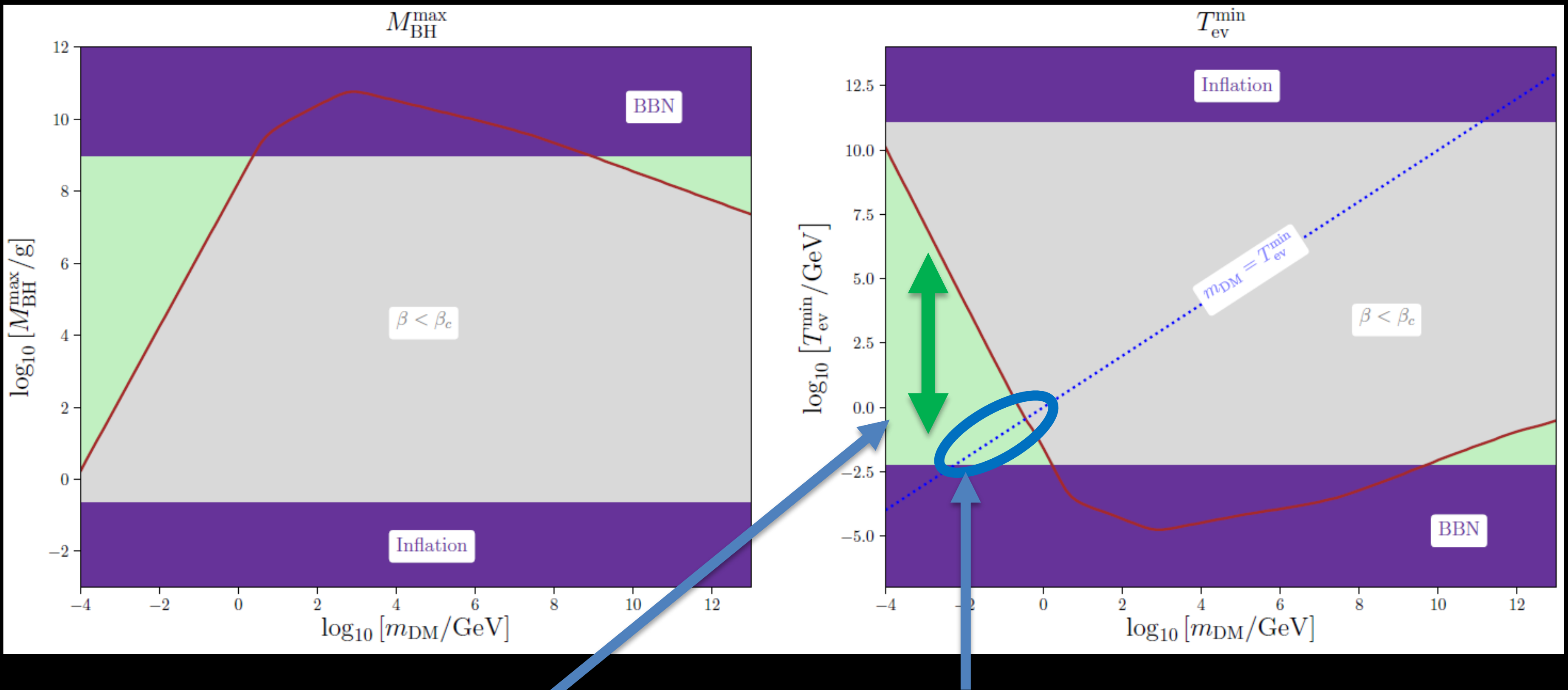
Back up

Modified Cosmology





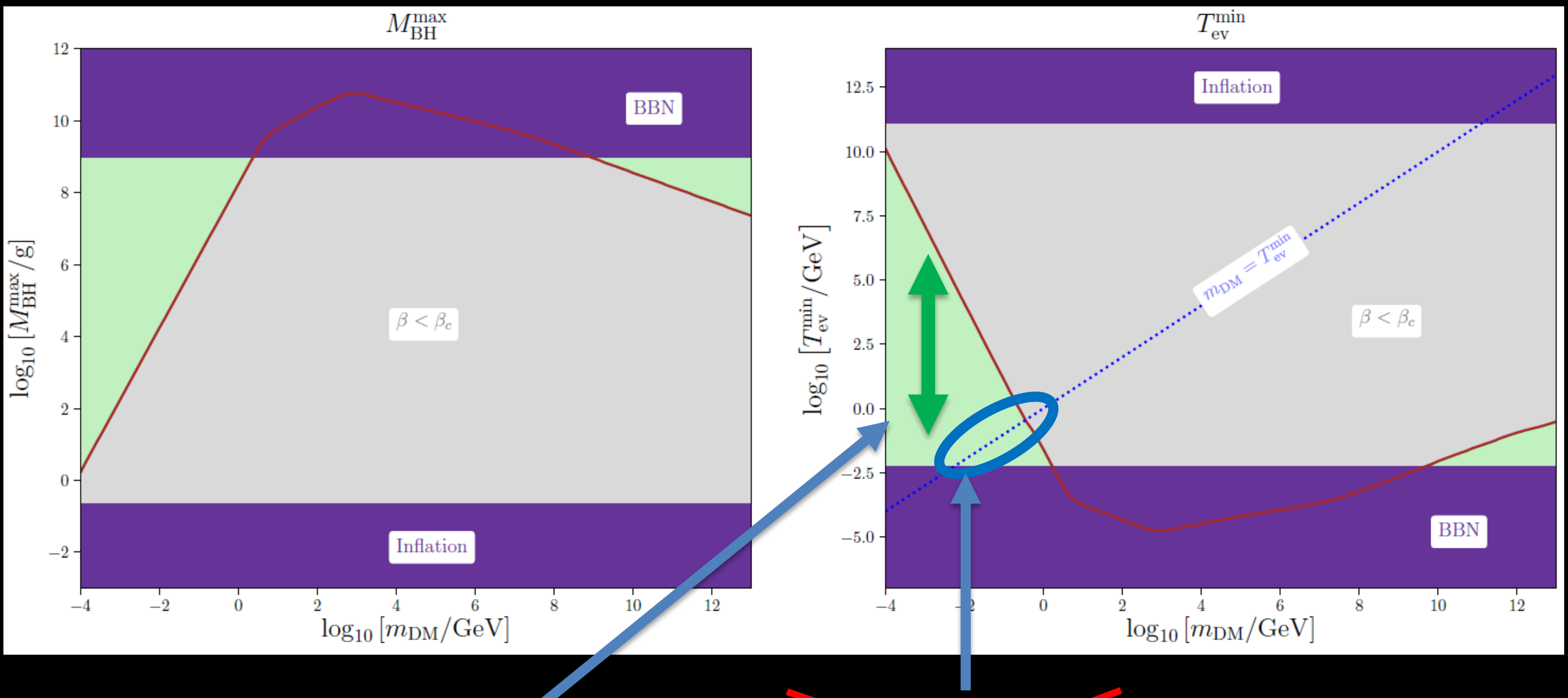
Modified Cosmology



Region of interest for Freeze-In

Region of interest for Freeze-Out

Modified Cosmology

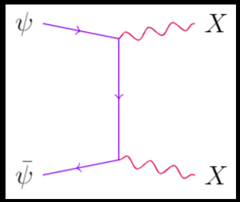


Region of interest
for Freeze-In

~~Region of interest
for Freeze-Out~~

**Thermalization
Of PBHs products…**

TBH large +



Boltzmann Equations

Freeze–In case:

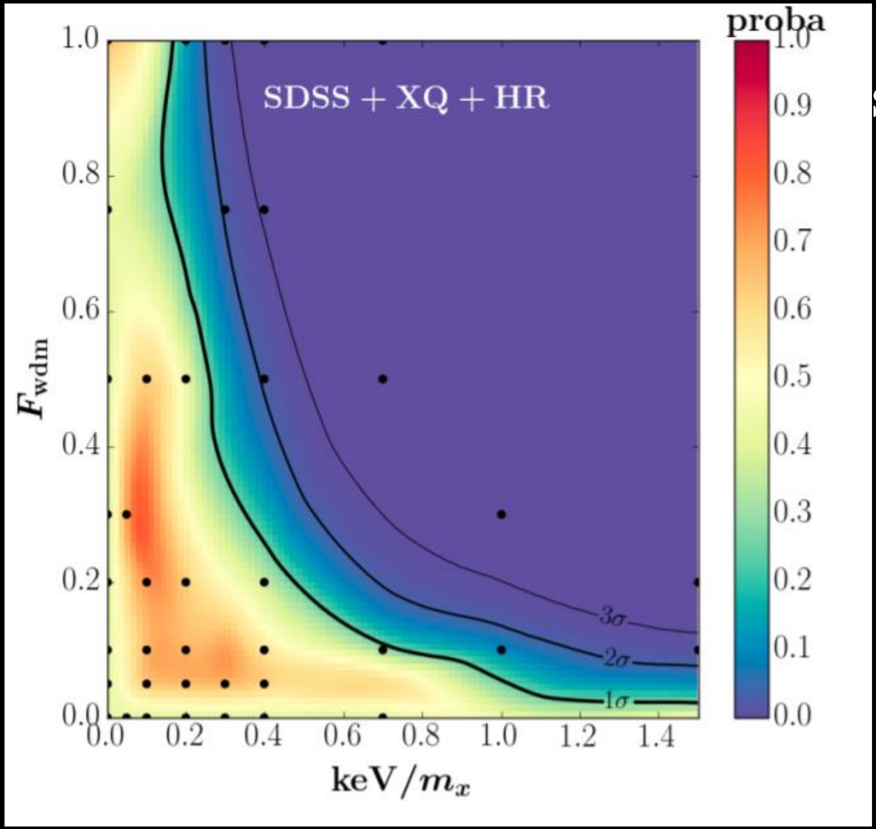
$$\dot{n}^{\rm th}_{\rm DM} + 3H n^{\rm th}_{\rm DM} = \langle \sigma v \rangle_{\rm th} \left(n^2_{\rm DM,eq} - n^{\rm th\,2}_{\rm DM} \right)$$

$$\dot{n}^{\rm ev}_{\rm DM} + 3H n^{\rm ev}_{\rm DM} = \left.\frac{{\rm d}n^{\rm ev}_{\rm DM}}{{\rm d}t}\right|_{\rm BH} + 2\,\Gamma_{X\to{\rm DM}} \left\langle \frac{m_X}{E_X} \right\rangle_{\rm ev} n_X$$

$$\dot{n}_X + 3H n_X = \left.\frac{{\rm d}n_X}{{\rm d}t}\right|_{\rm BH} - \Gamma_X \left\langle \frac{m_X}{E_X} \right\rangle_{\rm ev} n_X$$

$$\dot{\rho}_{\rm SM} + 4H \rho_{\rm SM} = \left.\frac{{\rm d}M}{{\rm d}t}\right|_{\rm SM} + 2 m_X \Gamma_{X\to{\rm SM}} n_X$$

Non-cold Dark Matter

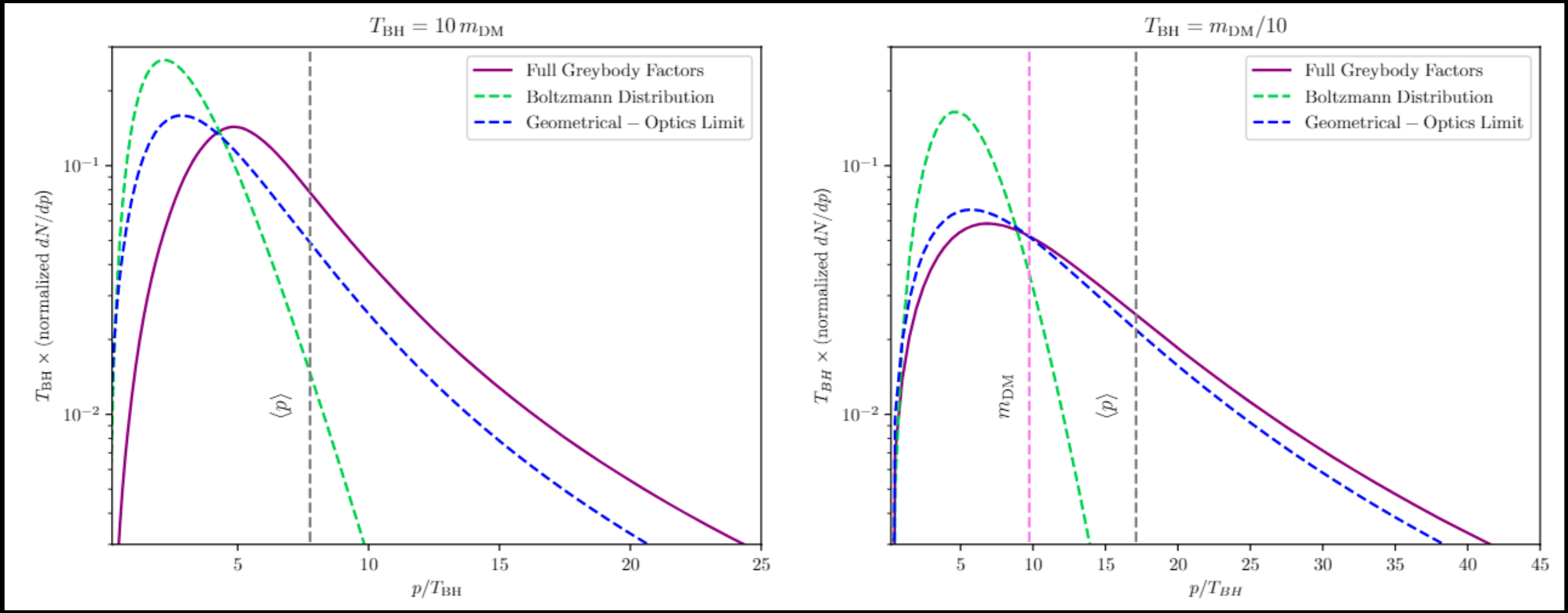


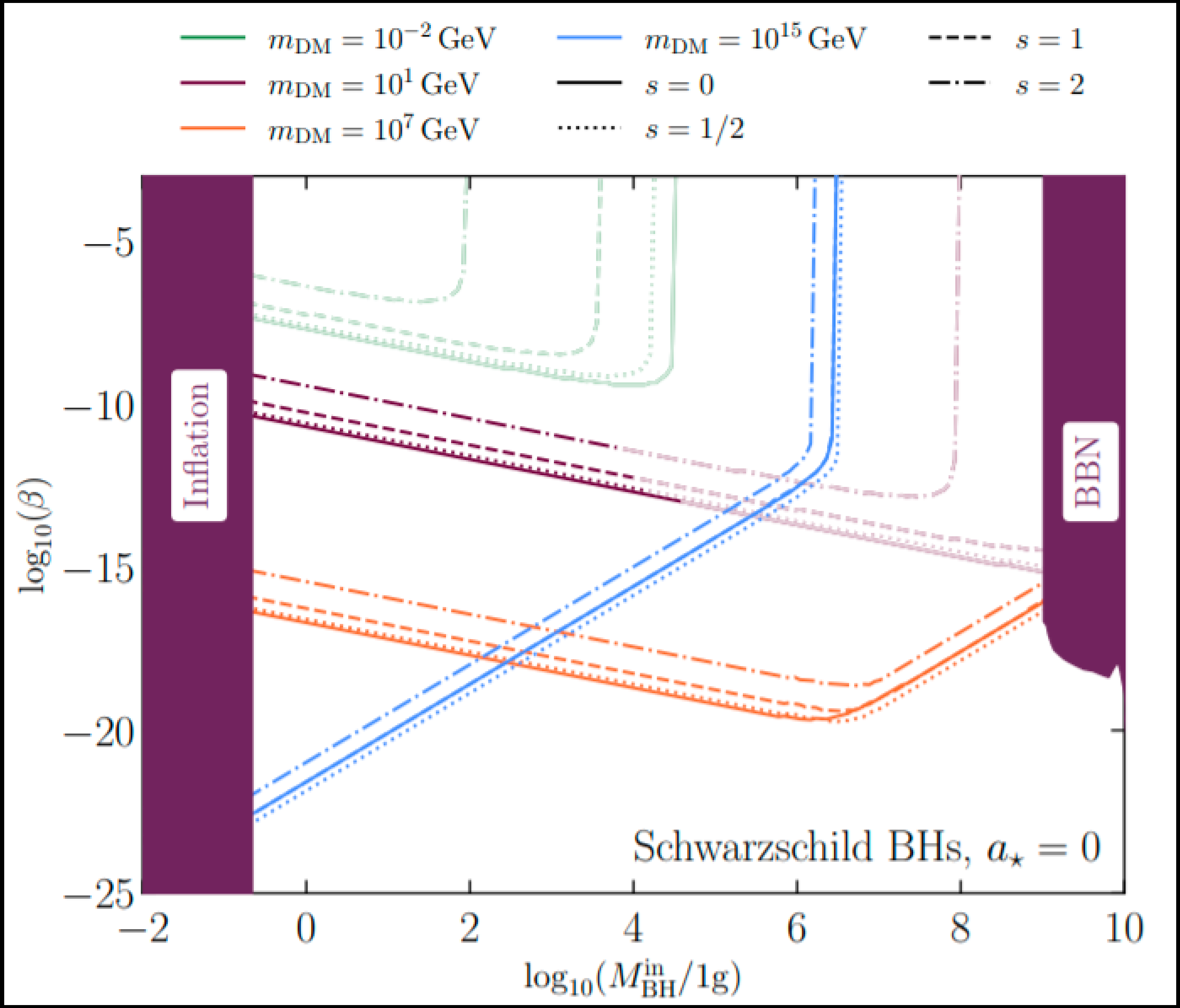
[Baur *et al.* 2017]

$$\langle v \rangle|_{t=t_0} = a_{\mathrm{ev}} \times \frac{\langle p \rangle|_{t=t_{\mathrm{ev}}}}{m_{\mathrm{DM}}}$$

DM from Evaporation

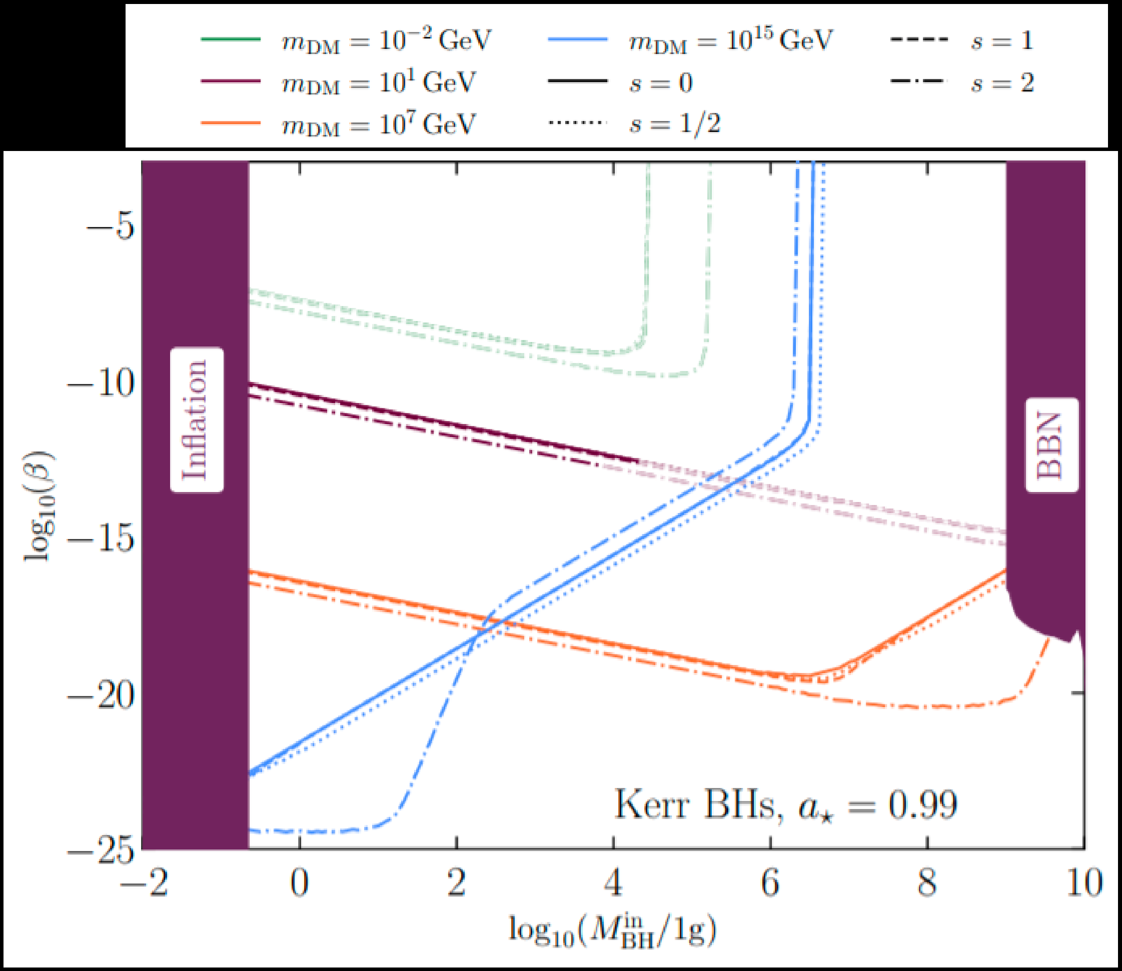
- Peculiar spectrum of evaporated DM particles
- Non-negligible difference between geometrical-optics limit and full distributions





$m_{\rm DM} = 10^{-2}$ GeV
$m_{\rm DM} = 10^{1}$ GeV
$m_{\rm DM} = 10^{7}$ GeV
$m_{\rm DM} = 10^{15}$ GeV
$s = 0$
$s = 1/2$
$s = 1$
$s = 2$
Inflation
BBN
Schwarzschild BHs, $a_\star = 0$
$\log_{10}(\beta)$
$\log_{10}(M_{\rm BH}^{\rm in}/1{\rm g})$
−5
−10
−15
−20
−25
−2
0
2
4
6
8
10

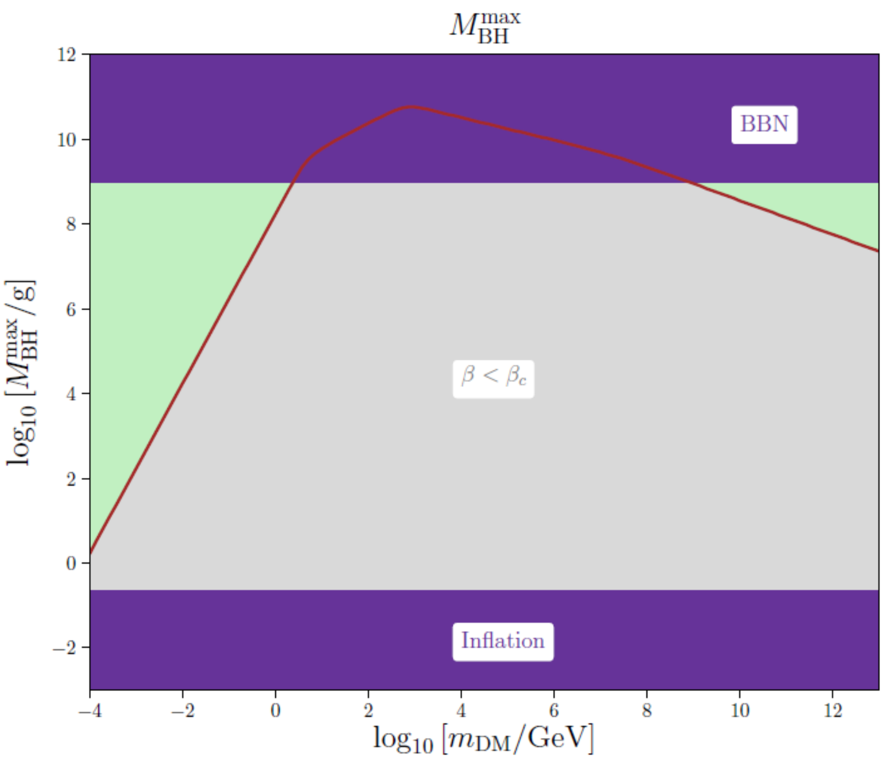
$$T_{\rm BH} = \frac{1}{4\pi G M_{\rm BH}} \frac{\sqrt{1-a_\star^2}}{1+\sqrt{1-a_\star^2}}\,,$$

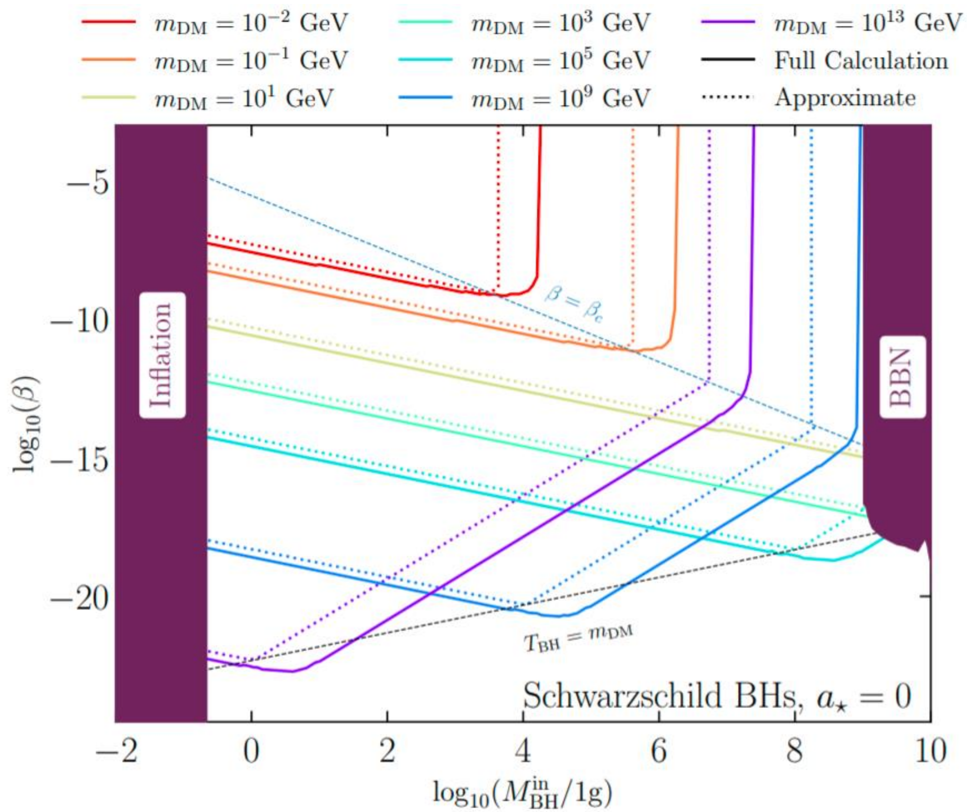


$$\frac{{\rm d}^2\mathcal{N}_{ilm}}{{\rm d}p{\rm d}t} = \frac{\sigma_{s_i}^{lm}(M_{\rm BH}, p, a_\star)}{\exp\left[(E_i - m\Omega)/T_{\rm BH}\right] - (-1)^{2s_i}} \frac{p^3}{E_i}$$

where $\Omega = (a_\star/2GM_{\rm BH})(1/(1+\sqrt{1-a_\star^2}))$

Modified Cosmology





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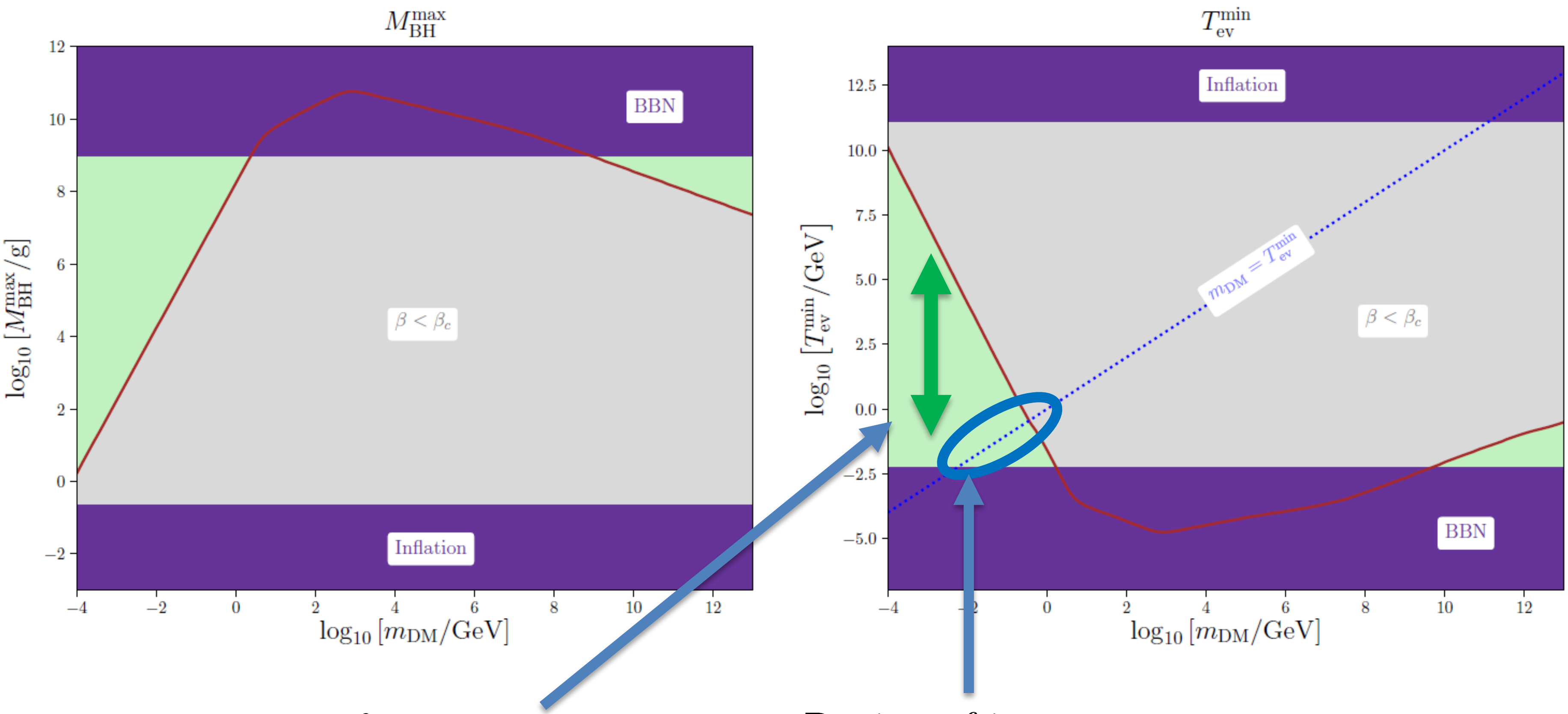
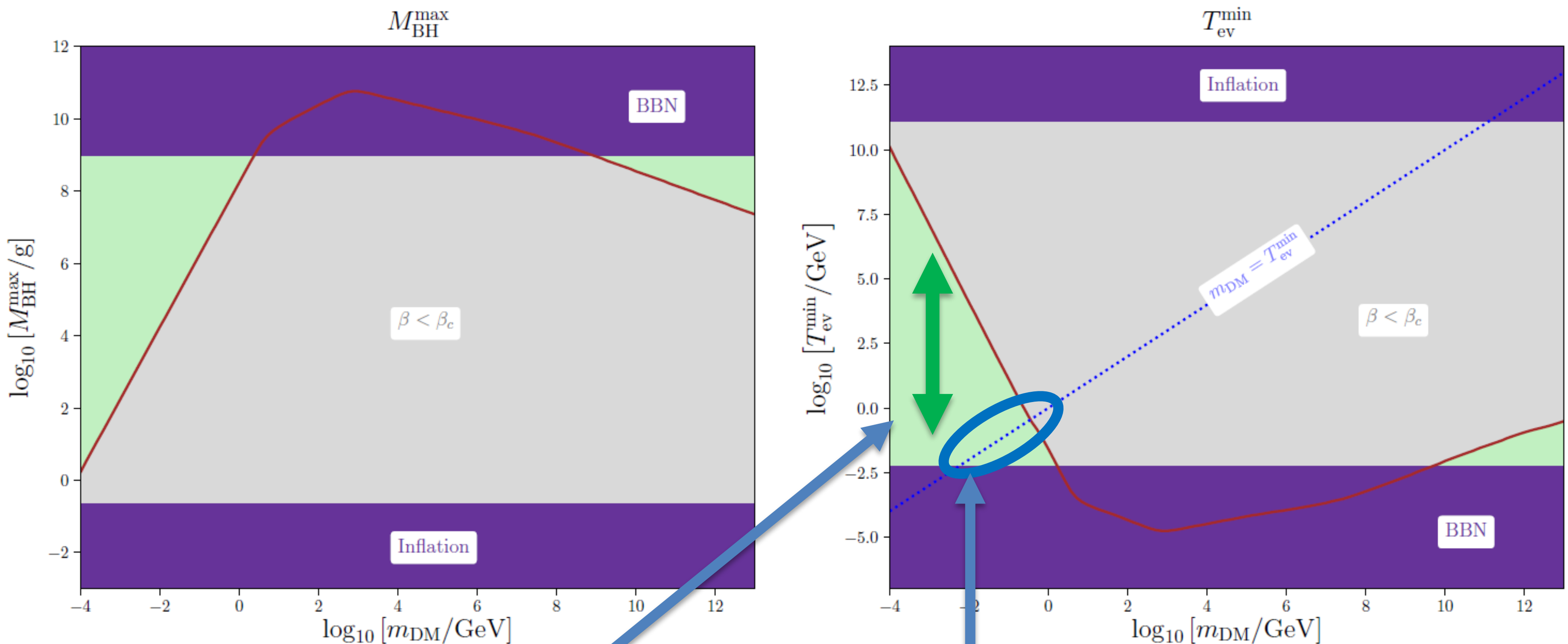


Region of interest
for Freeze-In

Region of interest
for Freeze-Out

Modified Cosmology

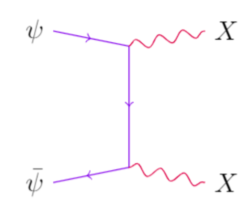


Region of interest
for Freeze-In

~~Region of interest
for Freeze-Out~~

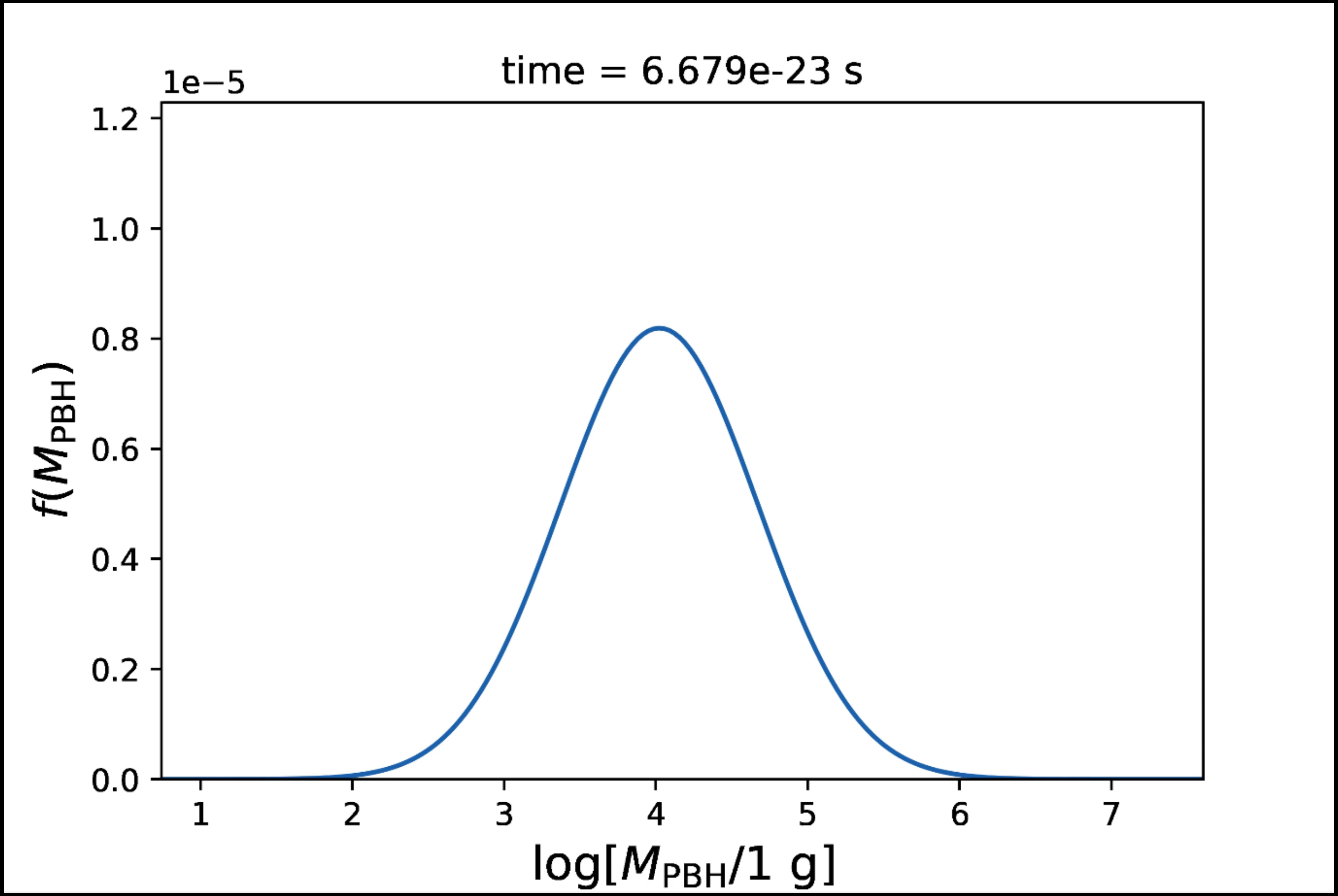
**Thermalization
Of PBHs products…**

TBH large +



IV. Evaporation of Extended Distributions

$$\frac{\mathrm{d}n}{\mathrm{d}M} \propto \frac{1}{M^2}\,\exp\left[-\frac{(\log M - \log M_\mathrm{c})^2}{2\,\sigma^2}\right]$$



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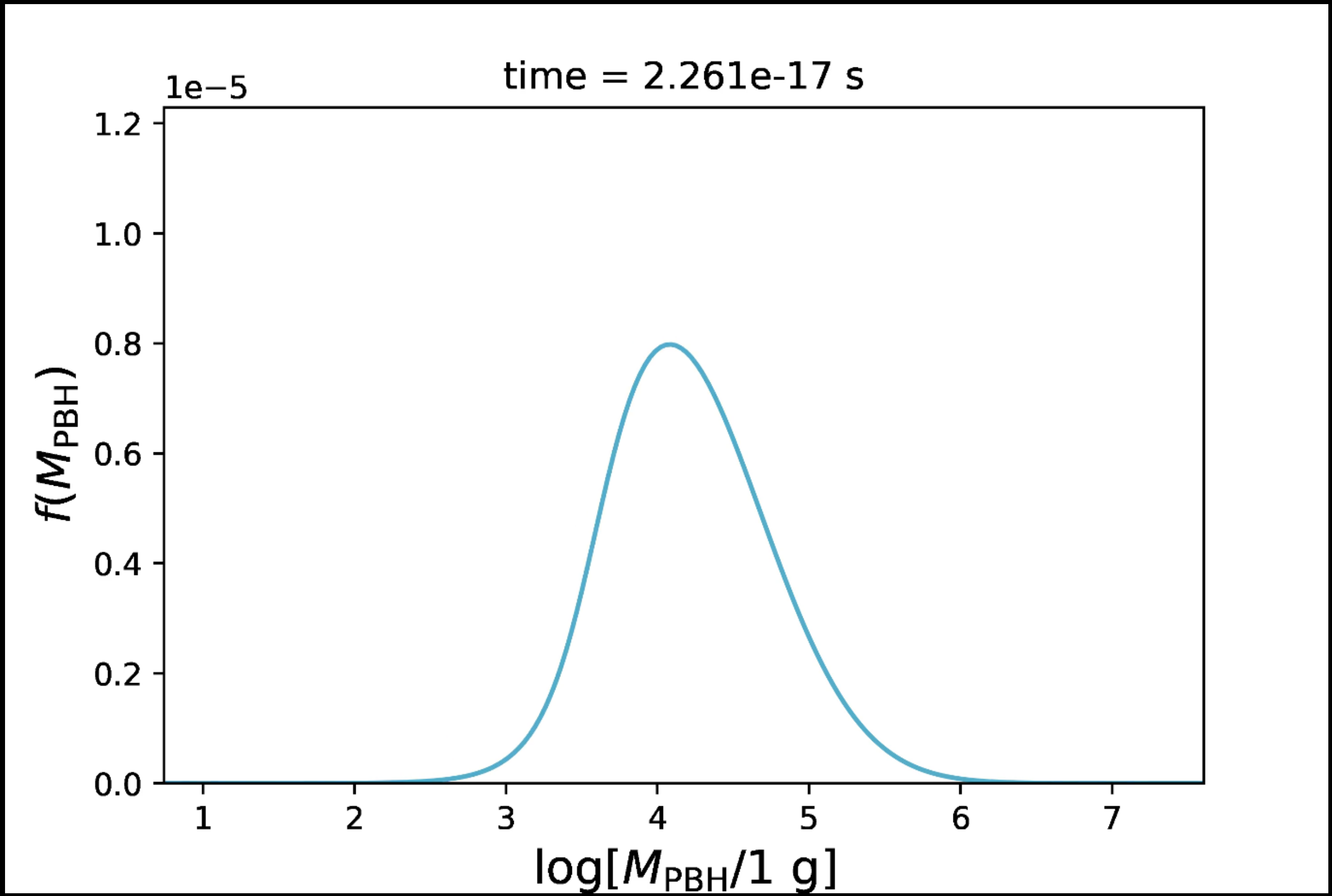

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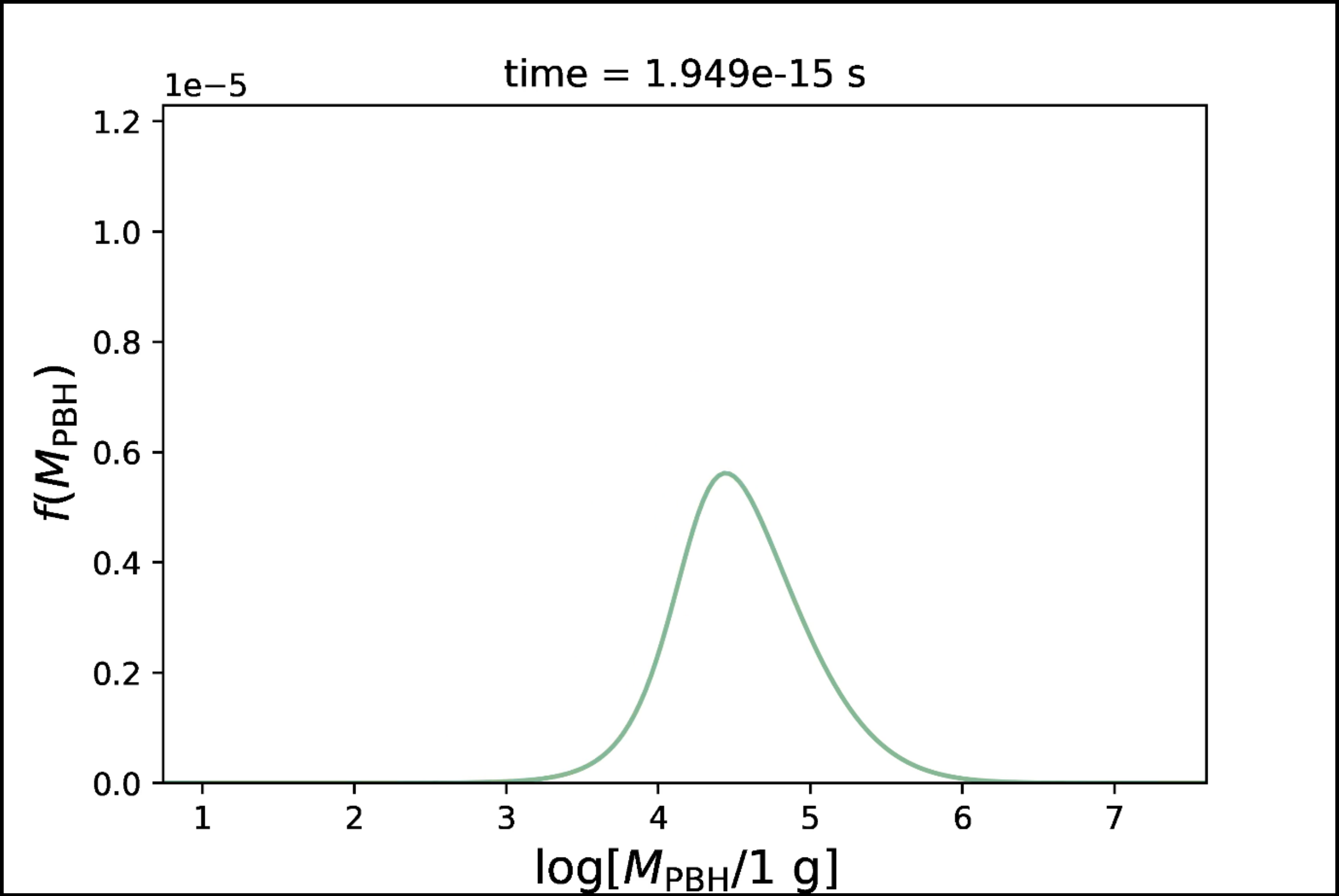

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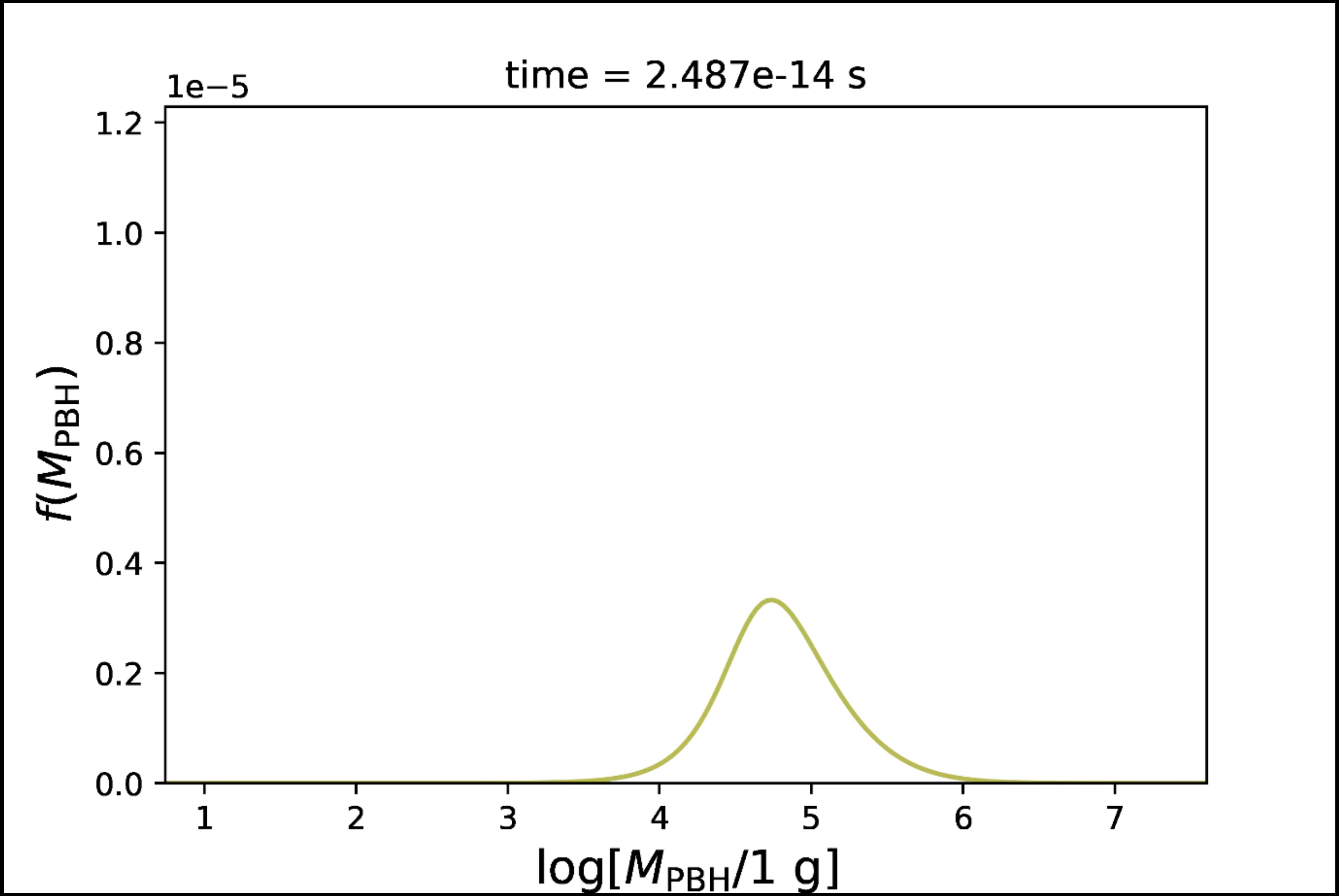

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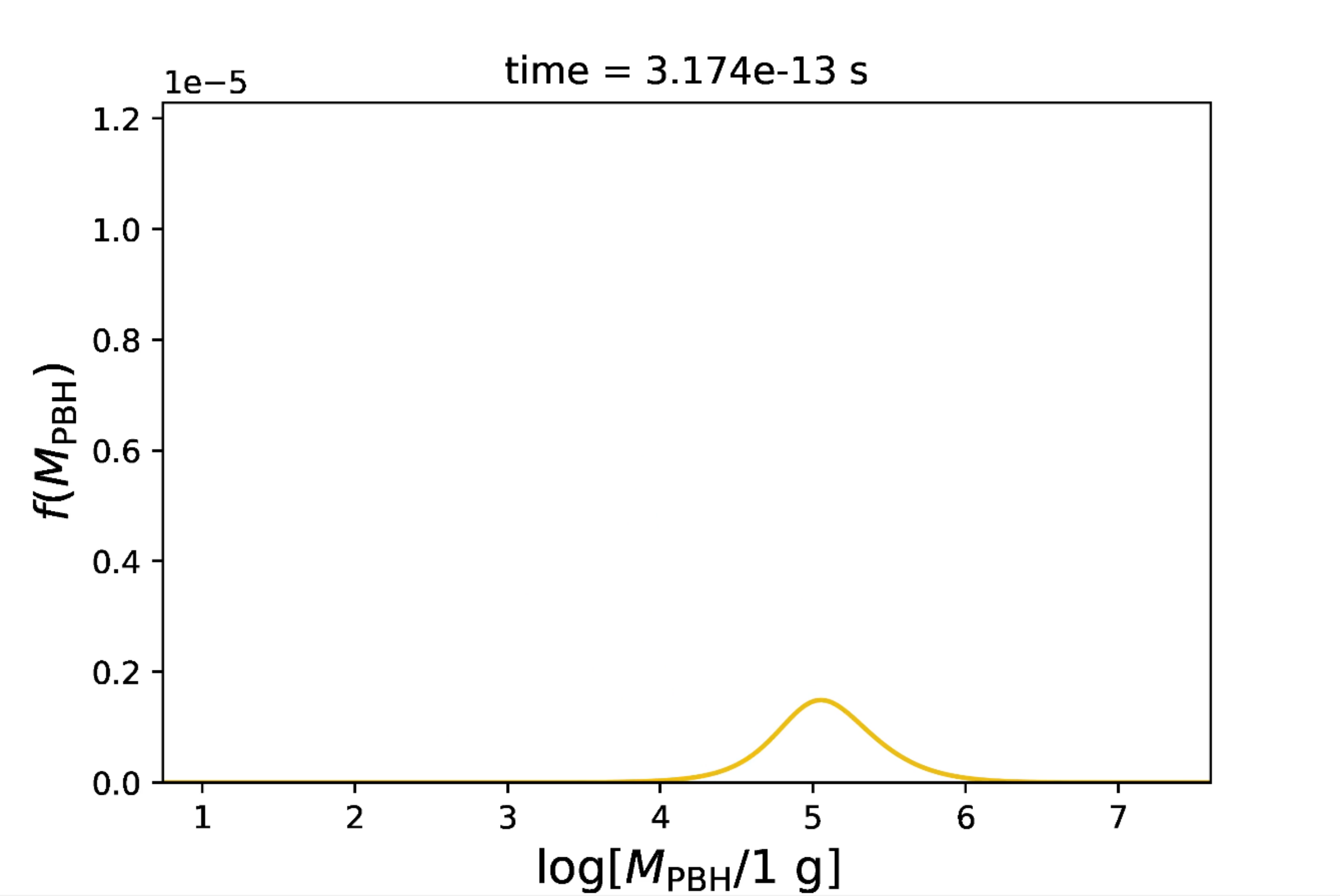

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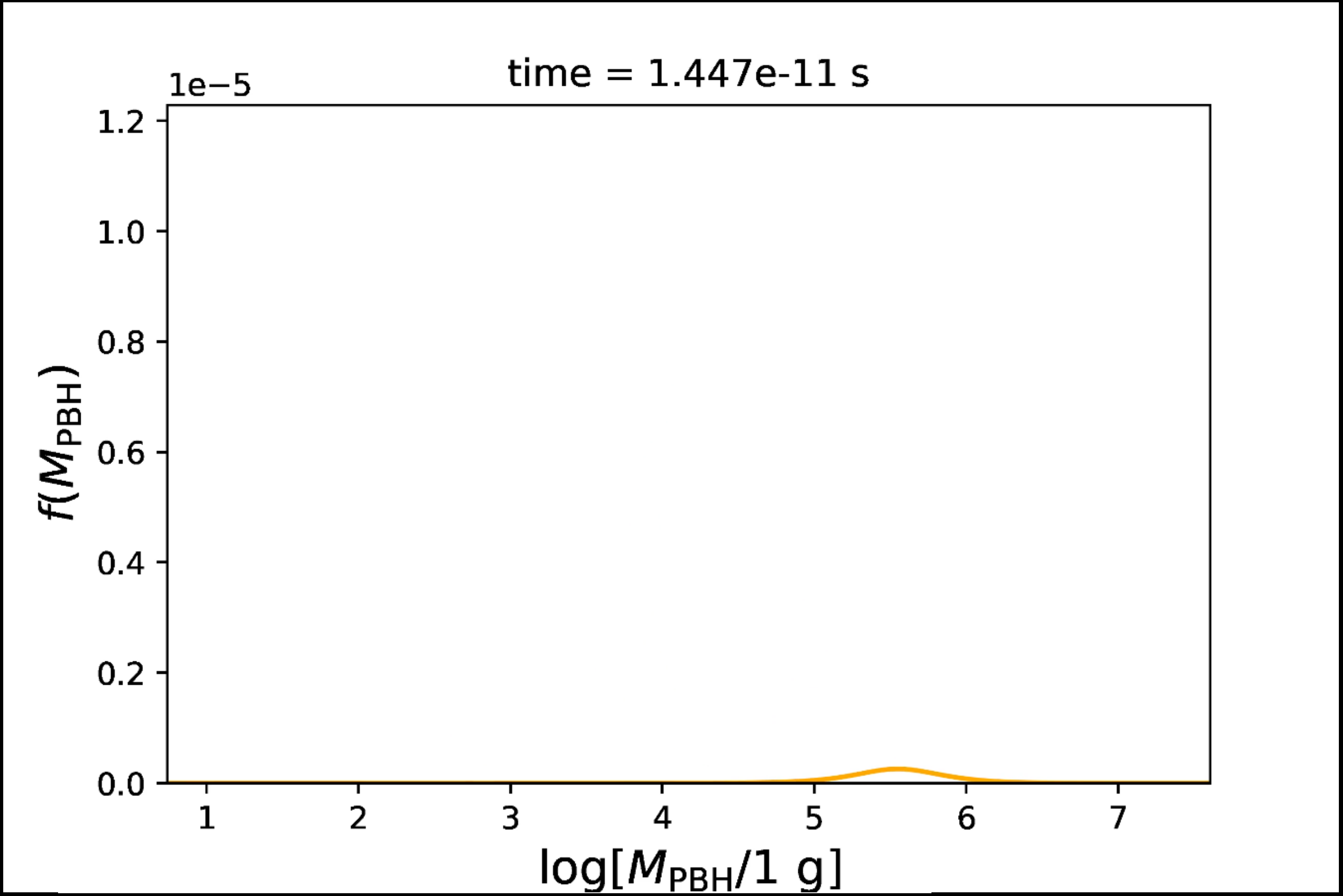
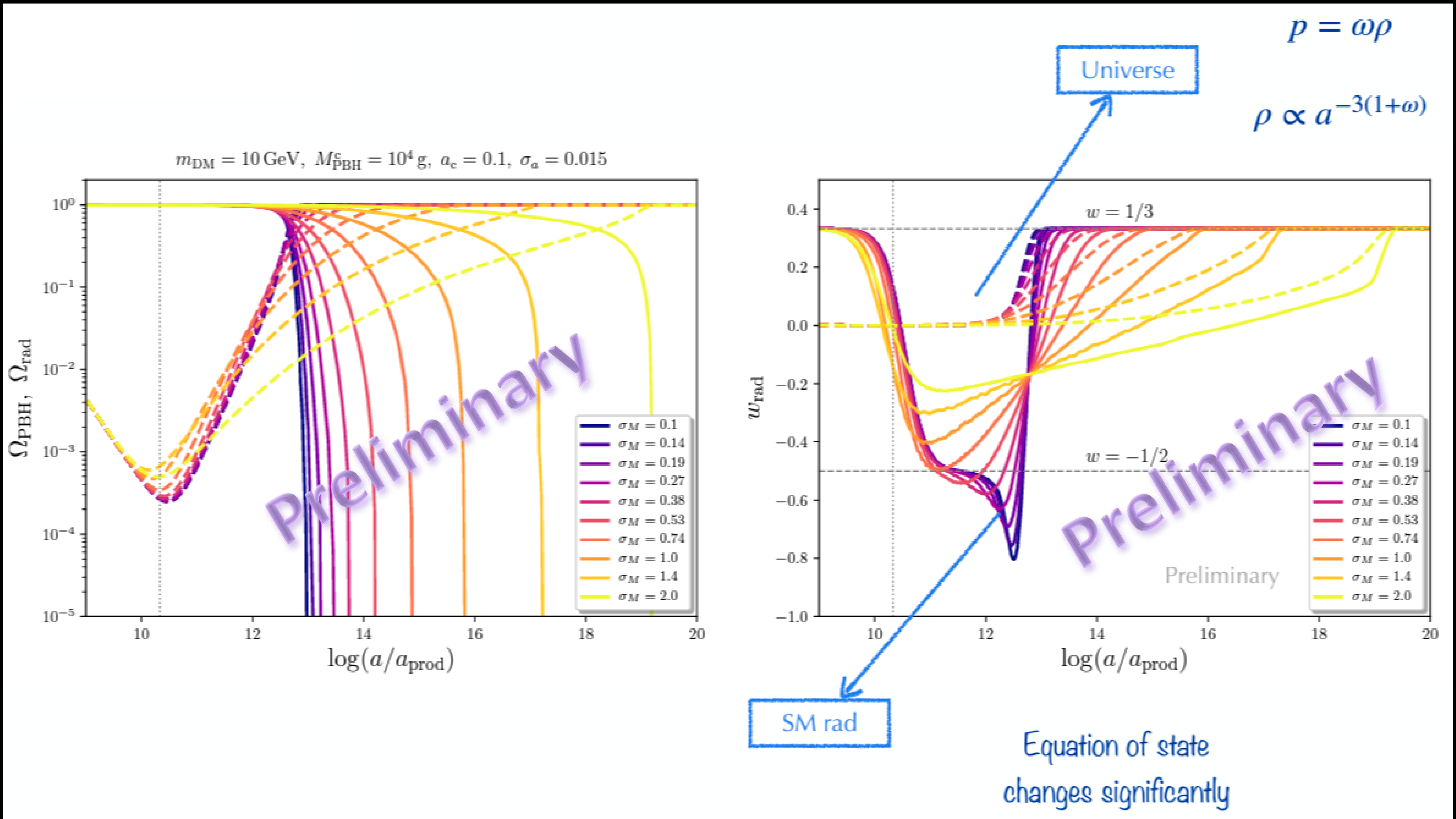


IV. Evaporation of Extended Distributions



IV. Evaporation of Extended Distributions

$$f_{\rm BH}(M) = \begin{cases} CM^{\alpha-1}, & \text{for } M_{\rm min} \le M \le M_{\rm max}; \\ 0, & \text{else.} \end{cases}$$

$$\alpha \equiv \frac{(-3w_{\rm form.} - 1)}{(w_{\rm form.} + 1)}$$

$$\frac{\mathrm{d}H}{\mathrm{d}t} = -\frac{1}{2}H^2(4 - \Omega_{\rm BH}),$$

$$\frac{\mathrm{d}\Omega_{\rm BH}}{\mathrm{d}t} = \Omega_{\rm BH}\left[\frac{\int_0^\infty f_{\rm BH}(M,t)\frac{\mathrm{d}M}{\mathrm{d}t}\mathrm{d}M}{\int_0^\infty f_{\rm BH}(M,t)M\mathrm{d}M}\right] + H\Omega_{\rm BH}(1 - \Omega_{\rm BH}).$$

$$= \frac{1+\alpha}{3(t-t_i)}$$

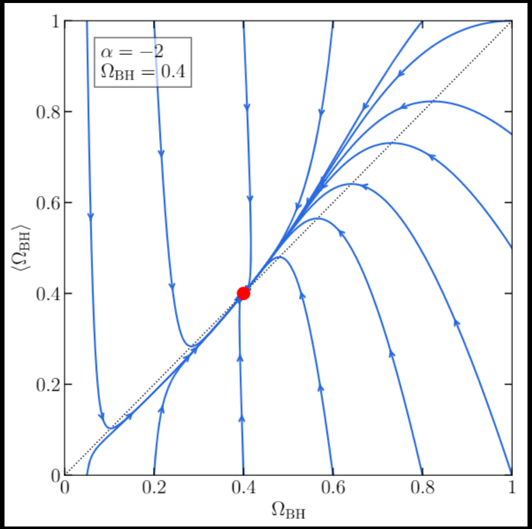
IV. Evaporation of Extended Distributions

$$\begin{cases} \dfrac{\mathrm{d}\Omega_{\mathrm{BH}}}{\mathrm{d}t} = \dfrac{1}{t-t_i}\, f(\Omega_{\mathrm{BH}}, \langle\Omega_{\mathrm{BH}}\rangle) \\ \dfrac{\mathrm{d}\langle\Omega_{\mathrm{BH}}\rangle}{\mathrm{d}t} = \dfrac{1}{t-t_i}\, g(\Omega_{\mathrm{BH}}, \langle\Omega_{\mathrm{BH}}\rangle) \end{cases},$$

$$f(\Omega_{\mathrm{BH}}, \langle\Omega_{\mathrm{BH}}\rangle) \equiv \Omega_{\mathrm{BH}}\left[\frac{1+\alpha}{3} + \frac{2(1-\Omega_{\mathrm{BH}})}{4-\langle\Omega_{\mathrm{BH}}\rangle}\right]$$

$$g(\Omega_{\mathrm{BH}}, \langle\Omega_{\mathrm{BH}}\rangle) \equiv \Omega_{\mathrm{BH}} - \langle\Omega_{\mathrm{BH}}\rangle\,,$$

$$\langle\Omega_{\mathrm{BH}}\rangle \equiv \frac{1}{t-t_i}\int_{t_i}^{t} dt'\,\Omega_{\mathrm{BH}}(t')\,.$$



$$w_{\mathrm{eff}} = \frac{-\alpha-1}{\alpha+7}$$

$$\Omega_{\mathrm{BH}} = \langle\Omega_{\mathrm{BH}}\rangle = \frac{4\alpha+10}{\alpha+7} \equiv \overline{\Omega}_{\mathrm{BH}}\,.$$

$$\mathcal{J} \equiv \frac{1}{t-t_i}\begin{pmatrix} \partial_{\Omega_{\mathrm{BH}}} f & \partial_{\langle\Omega_{\mathrm{BH}}\rangle} f \\ \partial_{\Omega_{\mathrm{BH}}} g & \partial_{\langle\Omega_{\mathrm{BH}}\rangle} g \end{pmatrix}$$

$$\lambda_\pm = \frac{1}{18}\left(-4\alpha \pm \sqrt{-19 - 4\alpha(2\alpha+19) - 59}\right)$$

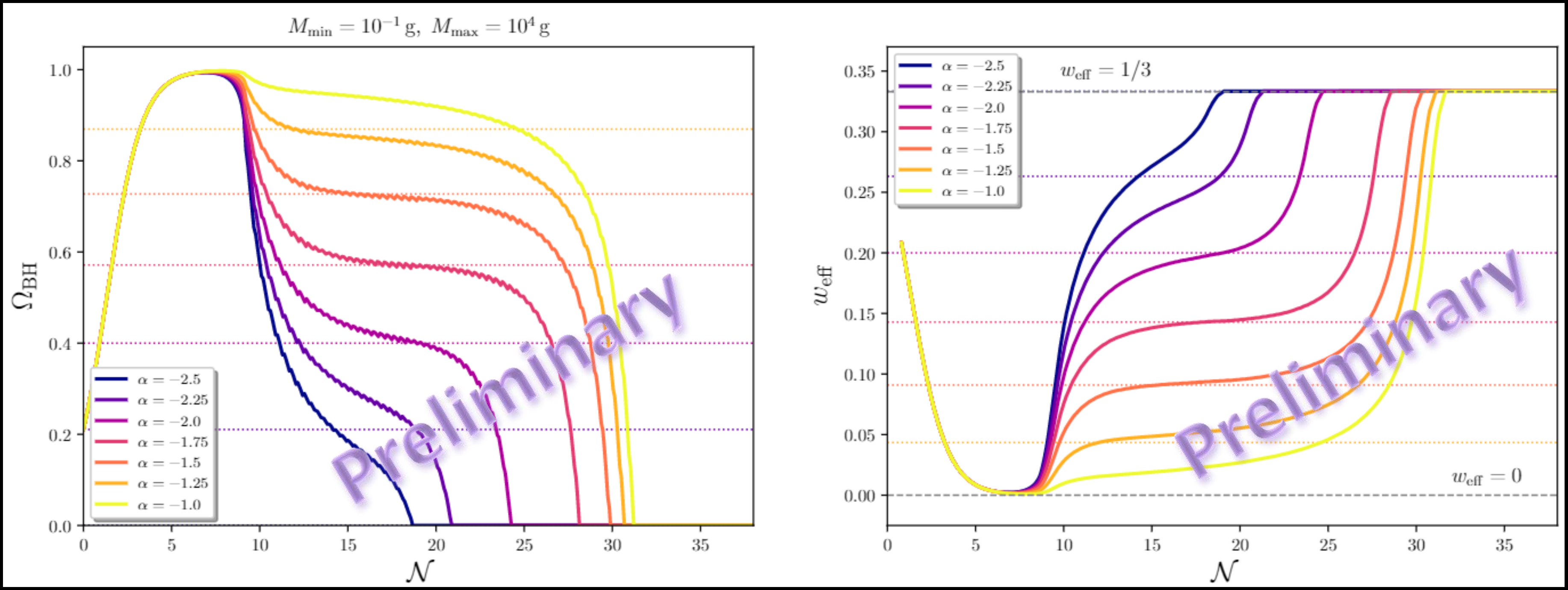
IV. Evaporation of Extended Distributions

$$w_{\rm eff} = \frac{-\alpha - 1}{\alpha + 7}$$

$$\alpha \equiv \frac{(-3w_{\rm form.} - 1)}{(w_{\rm form.} + 1)}$$

$$\Omega_{\rm BH} = \langle \Omega_{\rm BH} \rangle = \frac{4\alpha + 10}{\alpha + 7} \equiv \overline{\Omega}_{\rm BH}\,.$$

$$0 < w_{\rm form.} \leq 1 \quad \Rightarrow \quad 0 < \overline{\Omega}_{\rm BH} < 1$$



'Stasis' regime reached for $0 < w < 1$