

LUCIEN HEURTIER

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LAPTH - WEEKLY SEMINARS

# Primordial Black Hole Archaeology



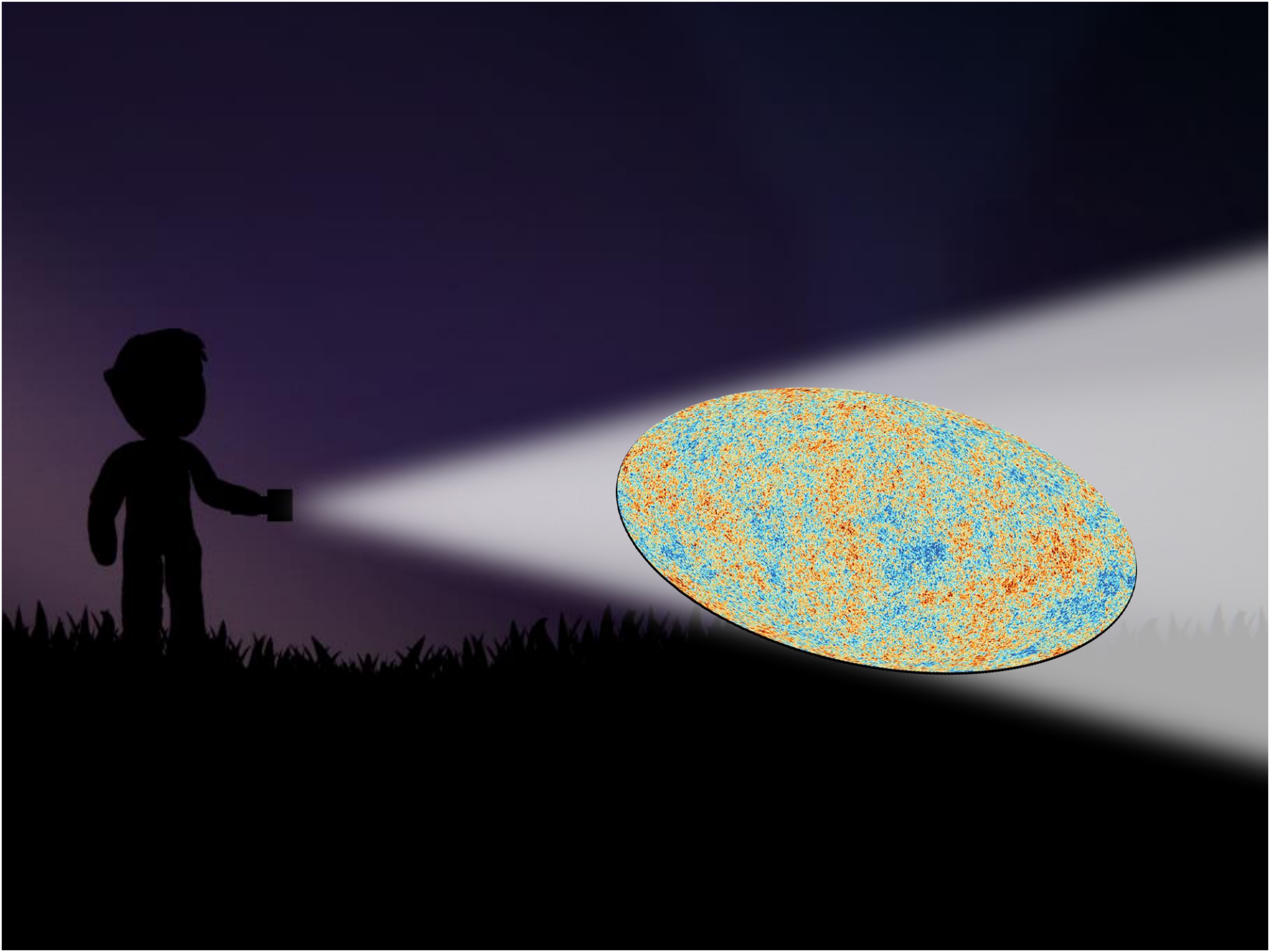
Durham  
University



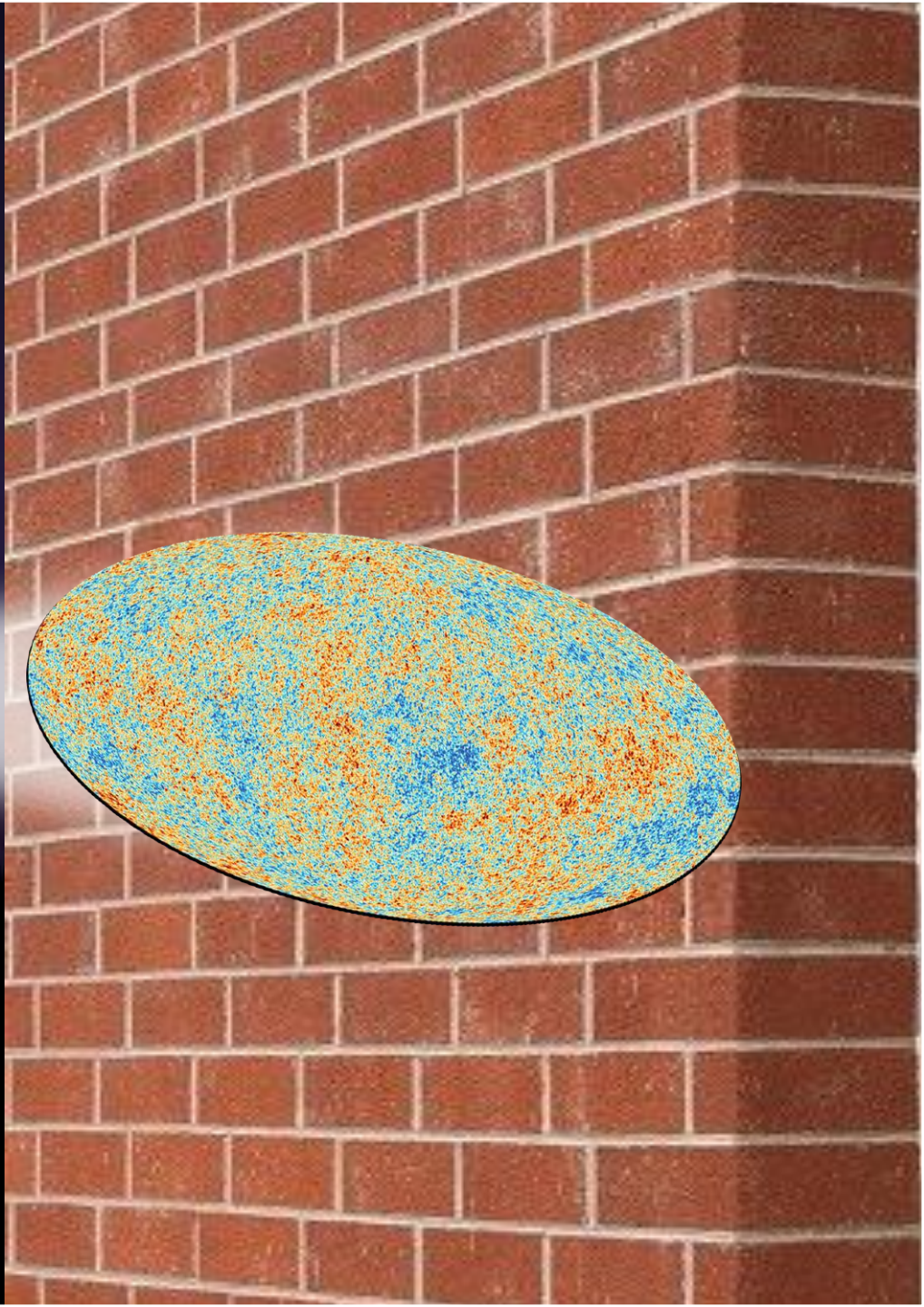
# References

- 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*

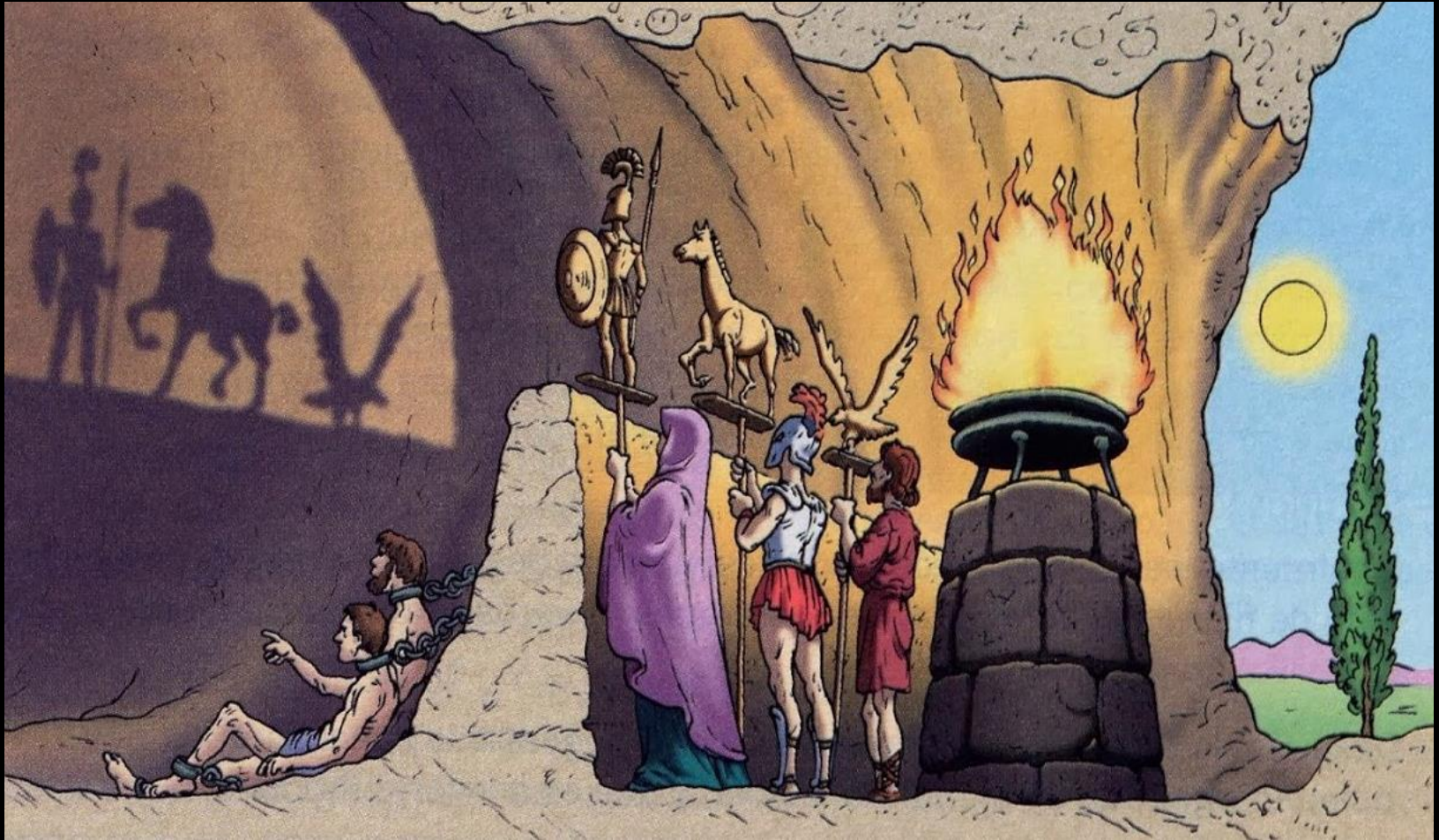
WHY  
PRIMORDIAL  
BLACK HOLES?



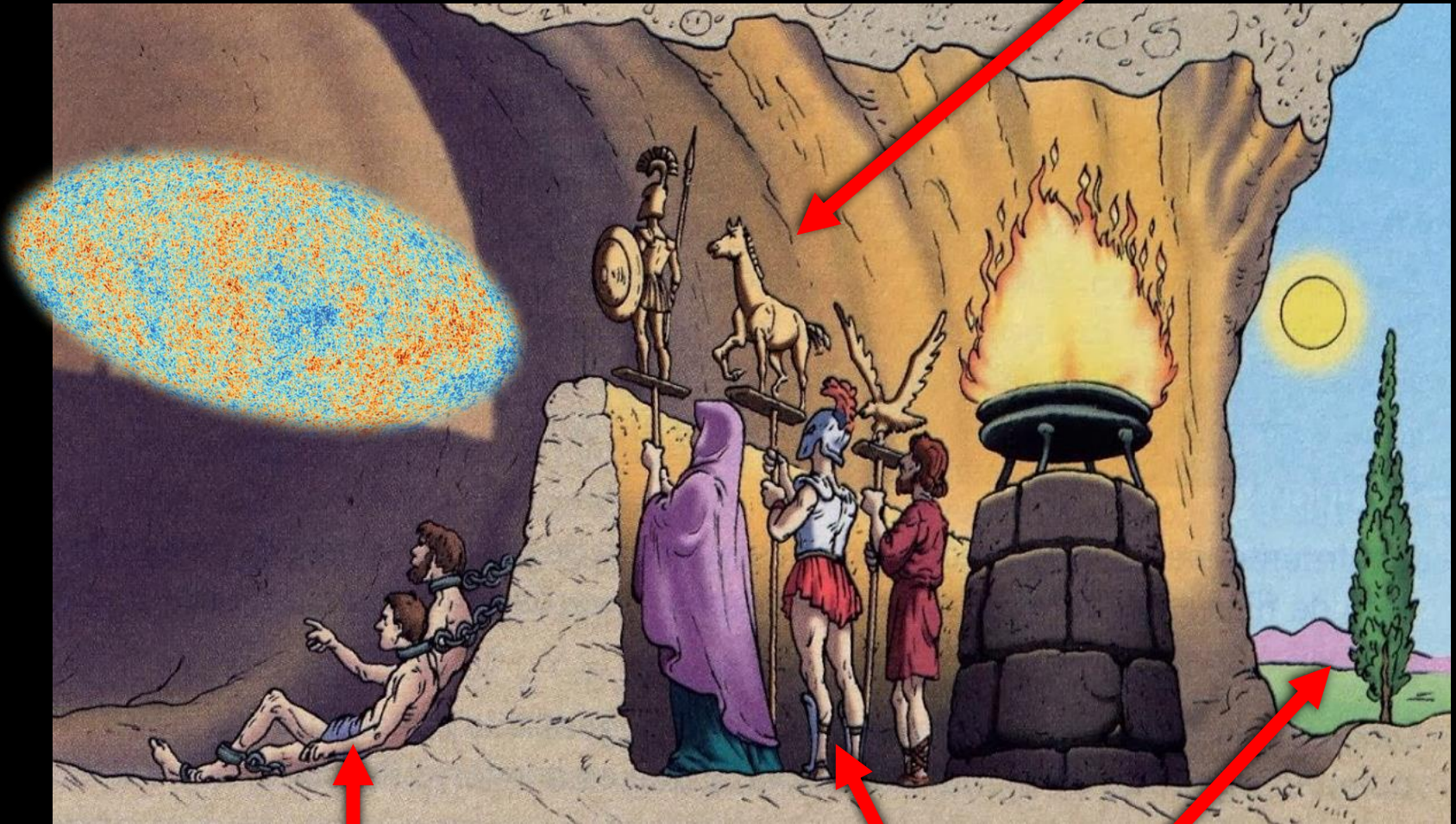
The oldest  
optical picture ever...



# Allegory of the Cave...



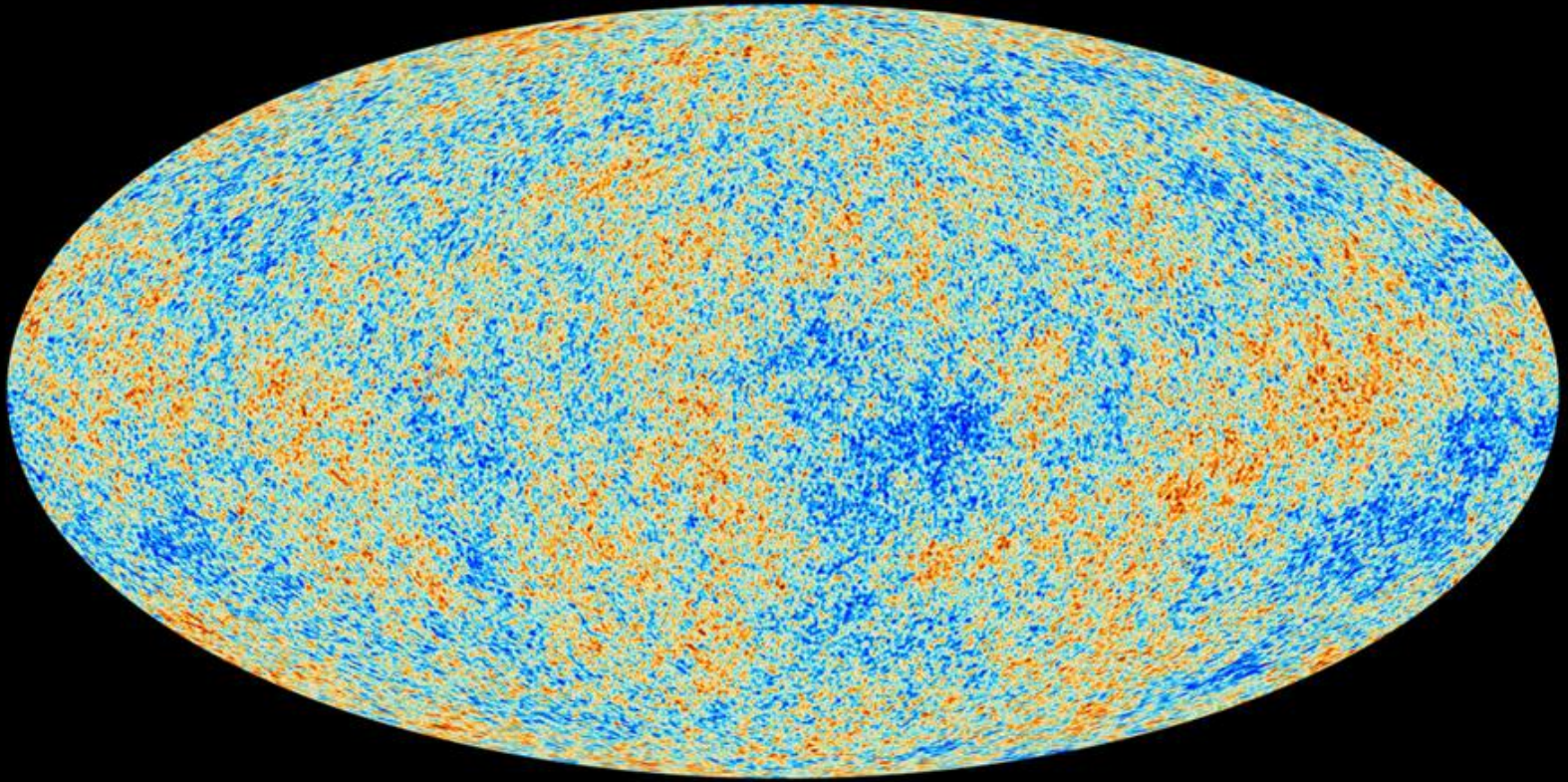
# Allegory of the Cave... $\Lambda$ CDM



Us

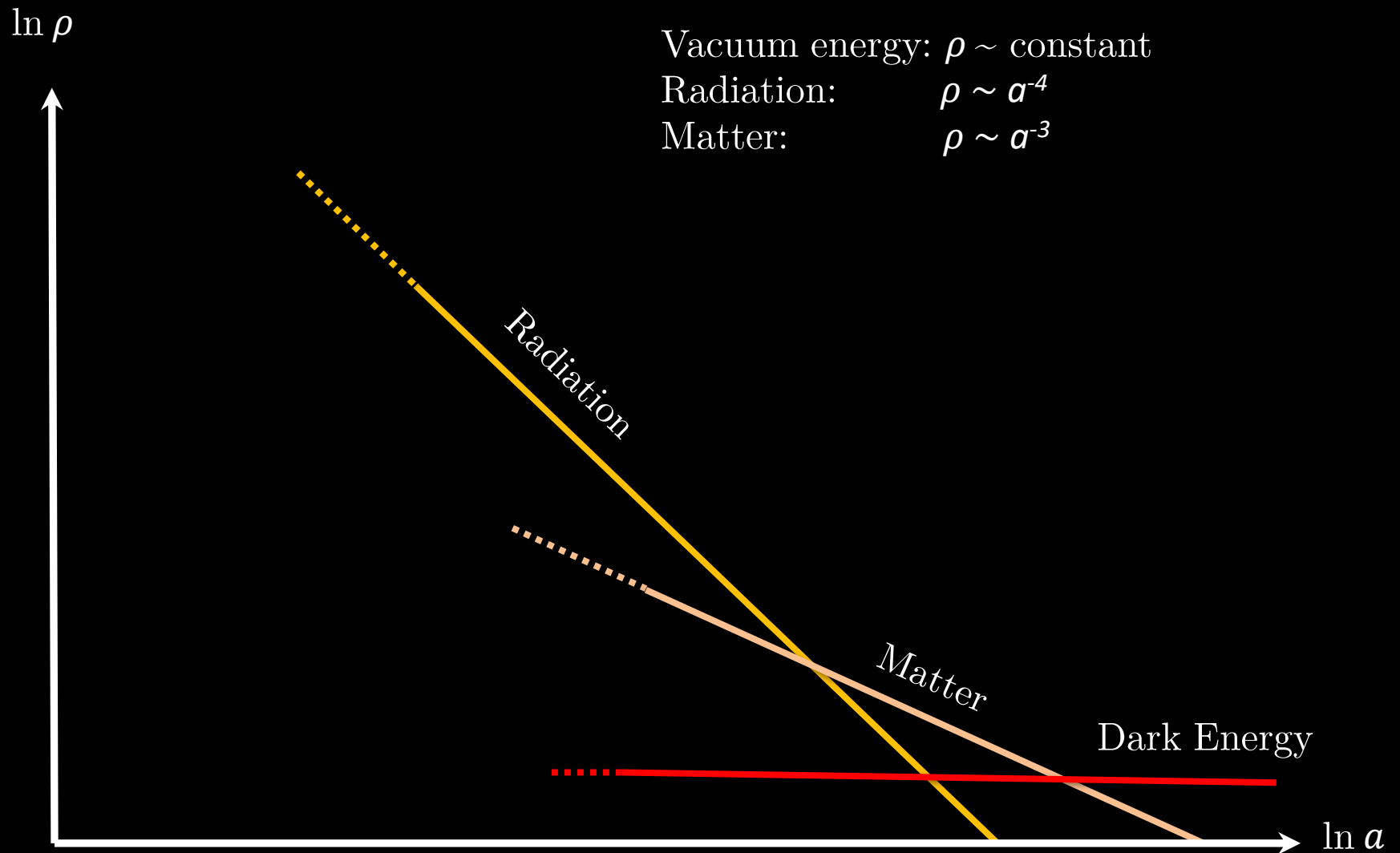
Nature

# CMB HIGHLIGHTS

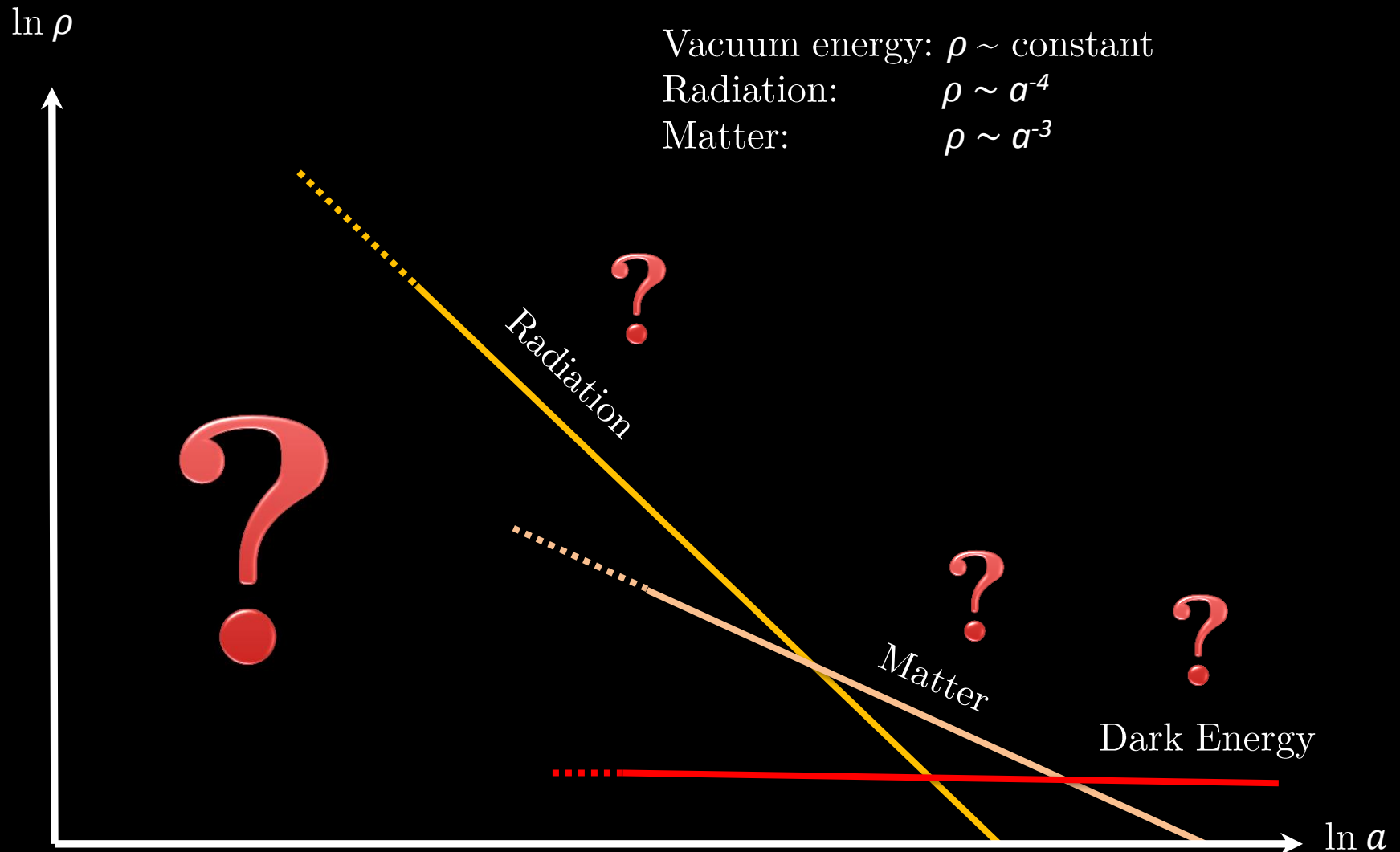


A **QUASI** — HOMOGENEIOUS, FLAT  
UNIVERSE

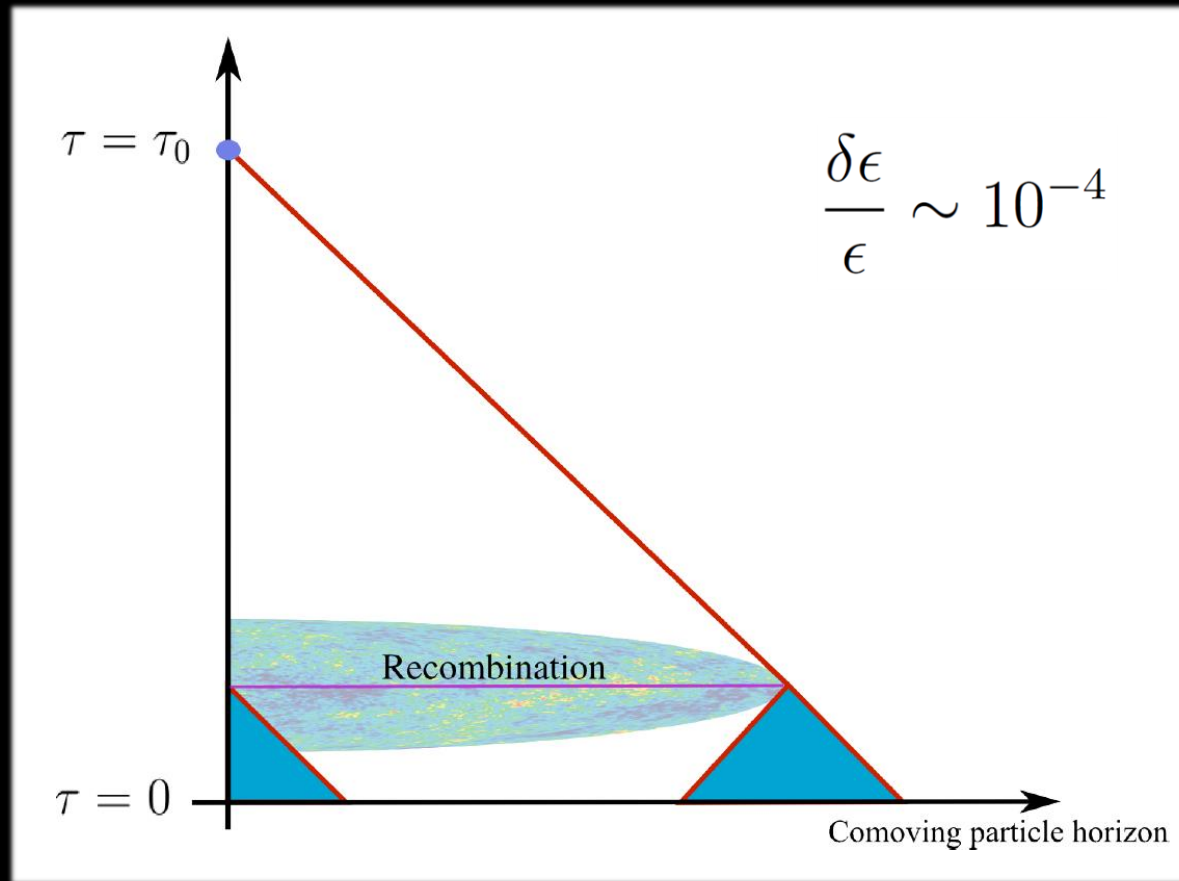
# THE $\Lambda$ CDM IDEOLOGY



# THE $\Lambda$ CDM IDEOLOGY



# THE *Horizon* PROBLEM

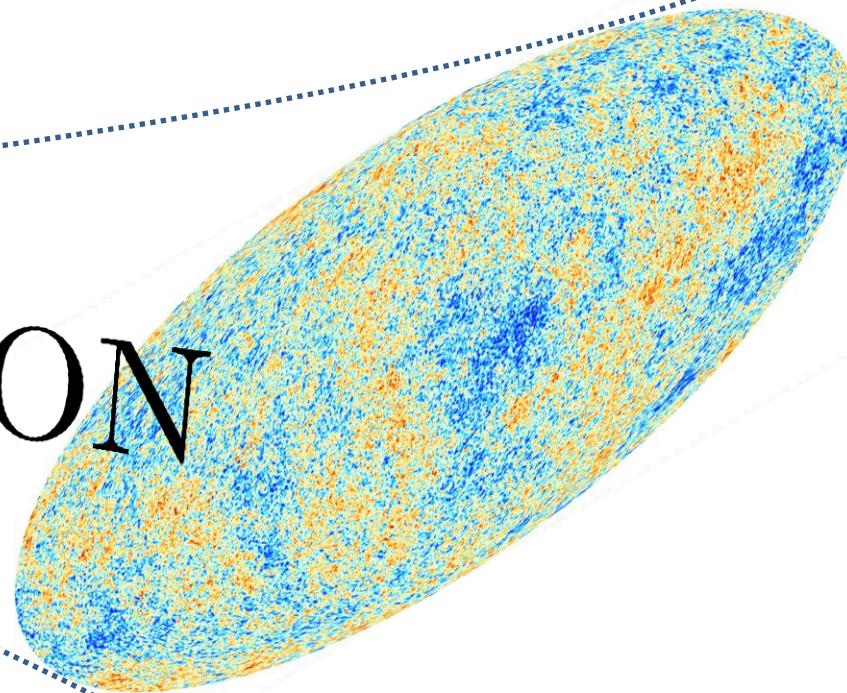


# Cosmic Inflation

Primordial  
Universe



INFLATION



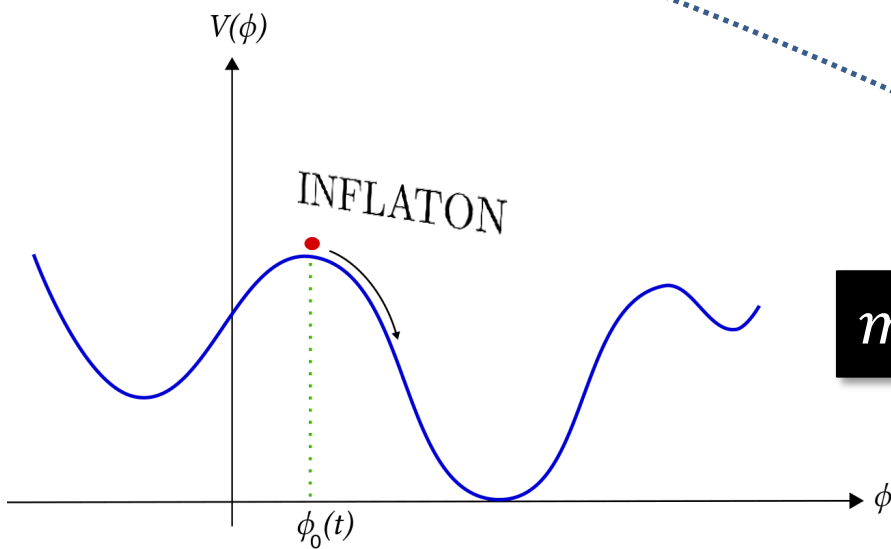
$V(\phi)$

INFLATON

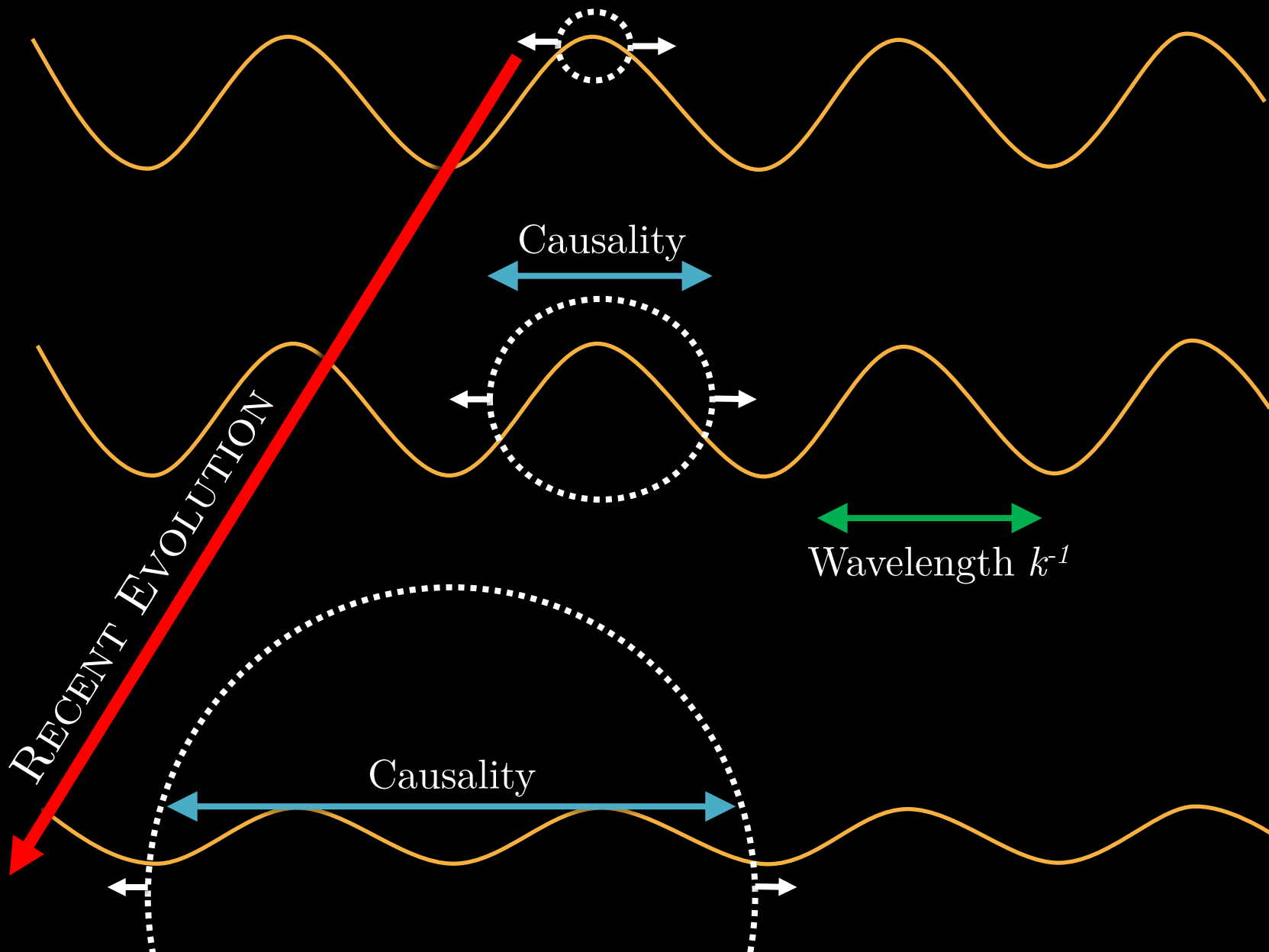
$$m_{\phi} \sim 10^{13} \text{ GeV}$$

$\phi_0(t)$

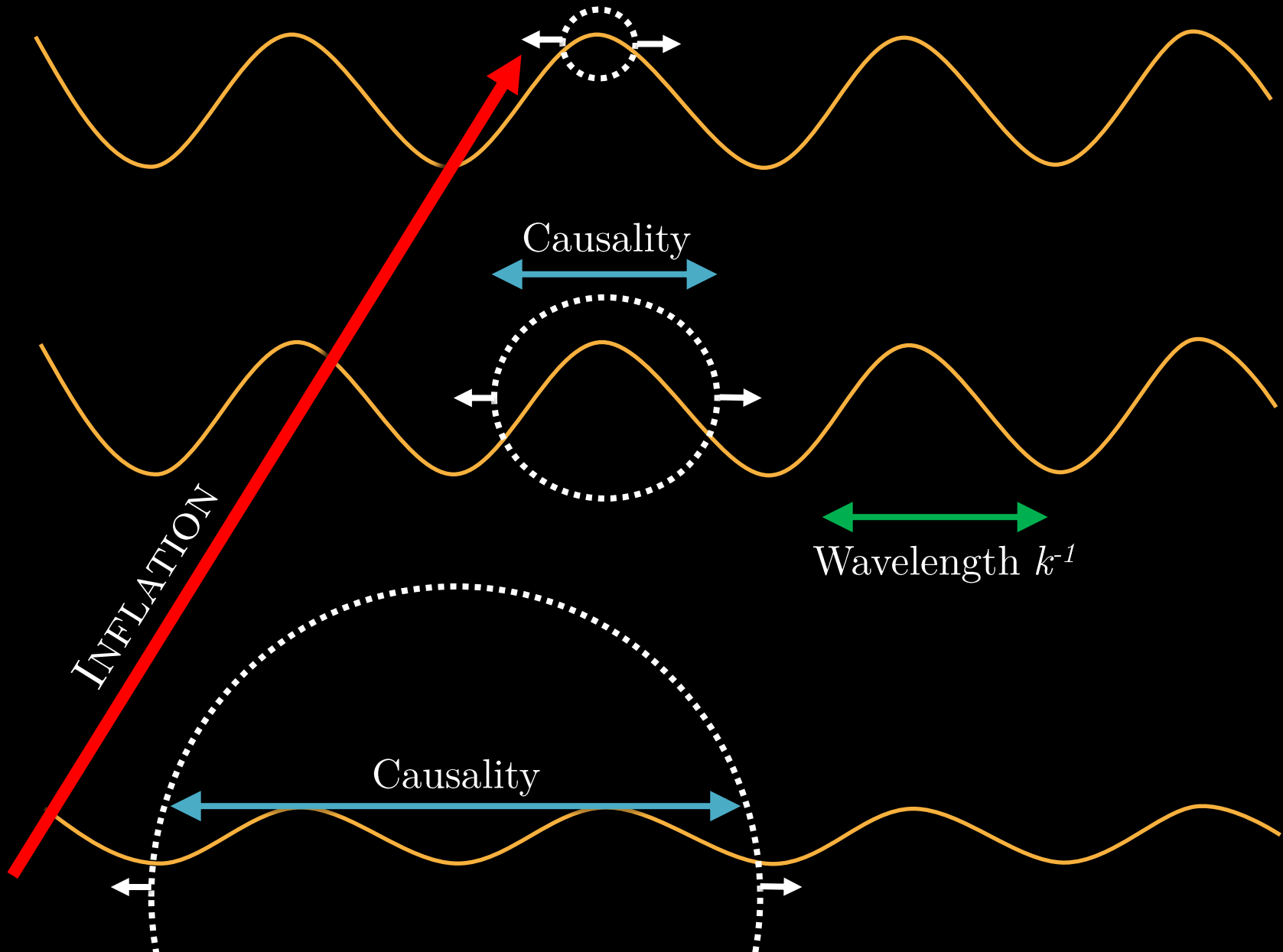
$\phi$



# PRIMORDIAL PERTURBATION EVOLUTION

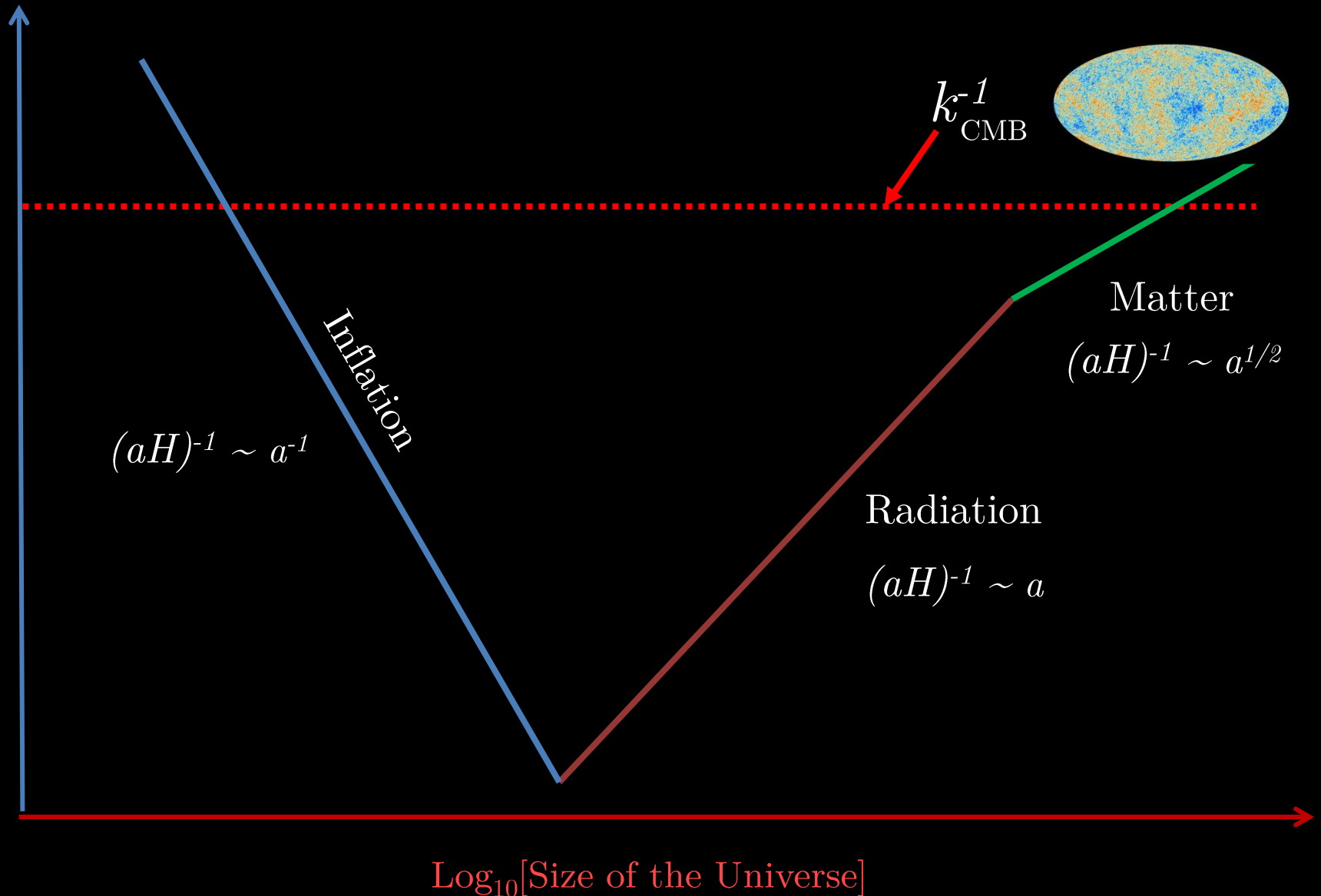


# PRIMORDIAL PERTURBATION EVOLUTION



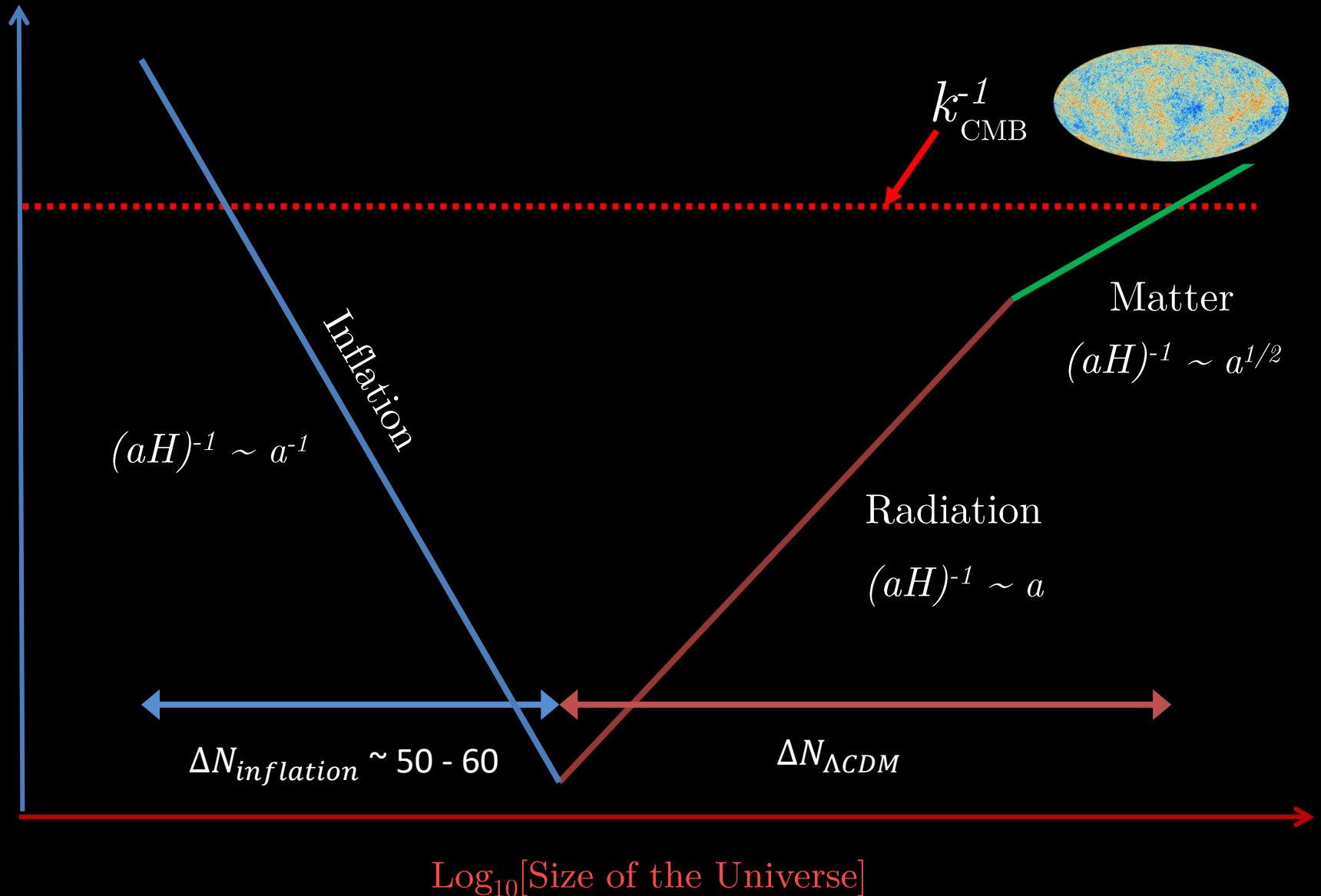
# PRIMORDIAL PERTURBATION EVOLUTION

Horizon Size

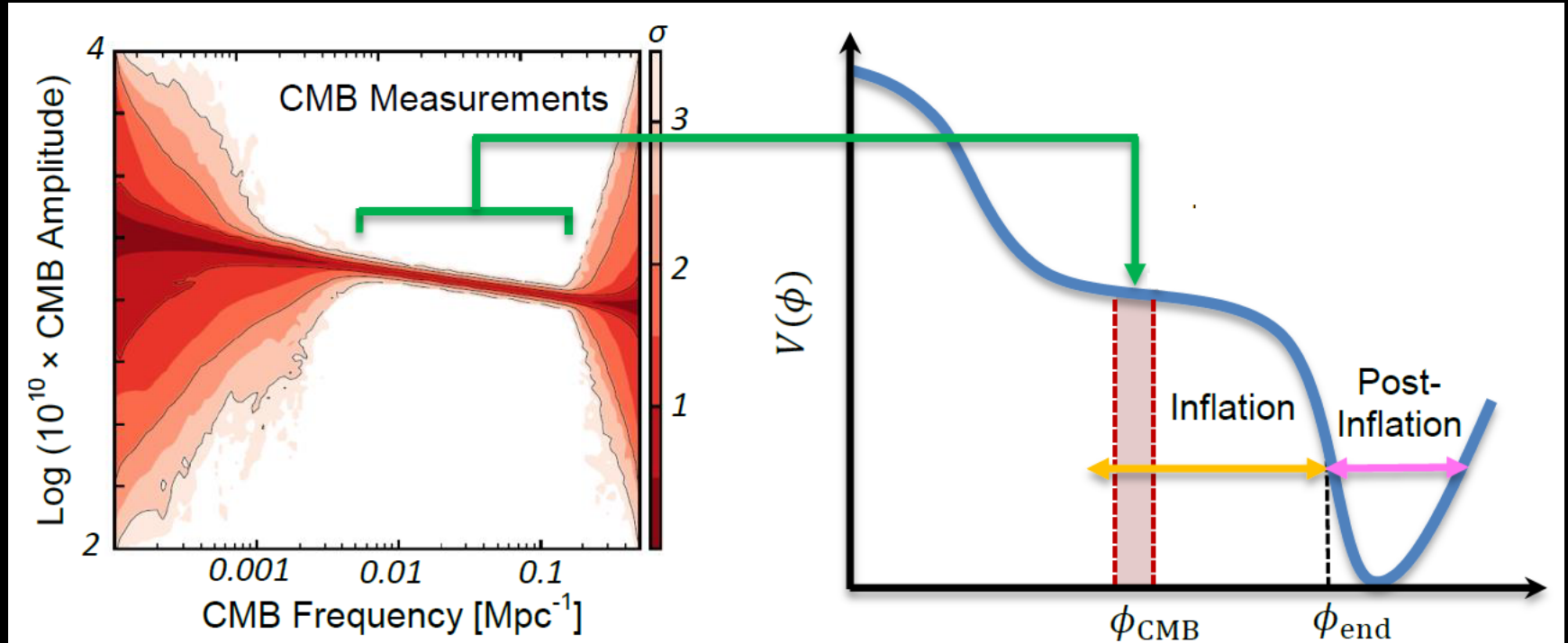


# PRIMORDIAL PERTURBATION EVOLUTION

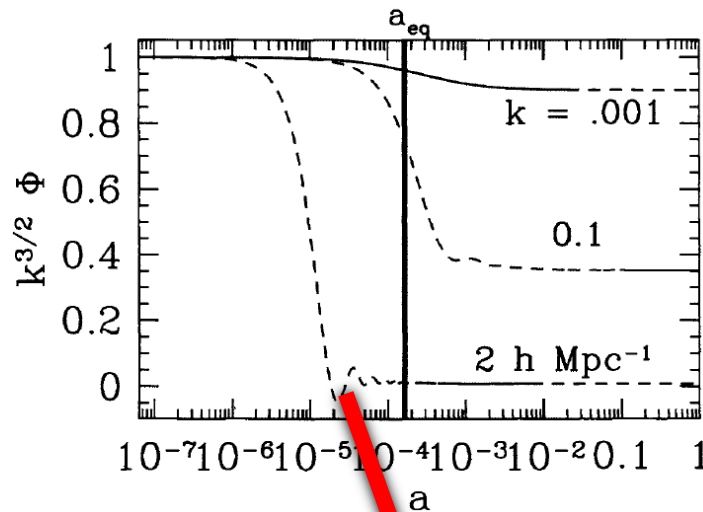
Horizon Size



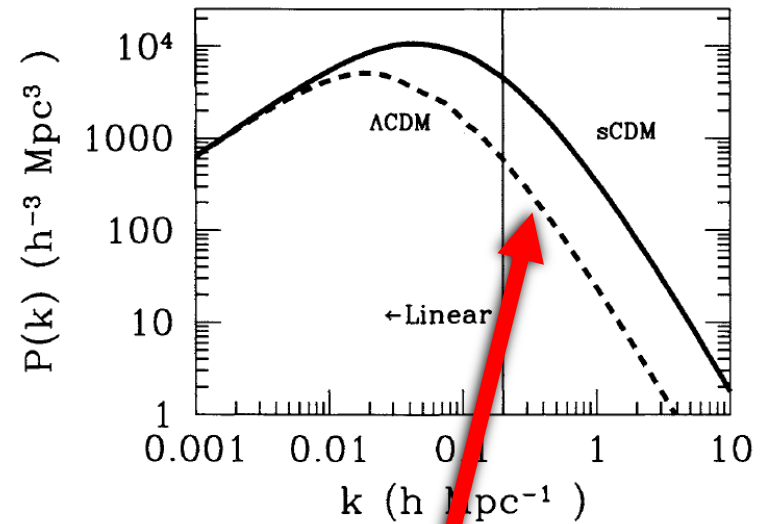
# PRIMORDIAL PERTURBATION EVOLUTION



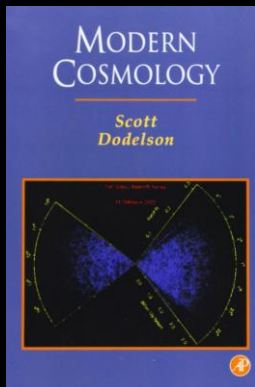
# Perturbation Horizon Crossing



**Figure 7.2.** The linear evolution of the gravitational potential  $\Phi$ . 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 ( $\Lambda$ CDM) 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.

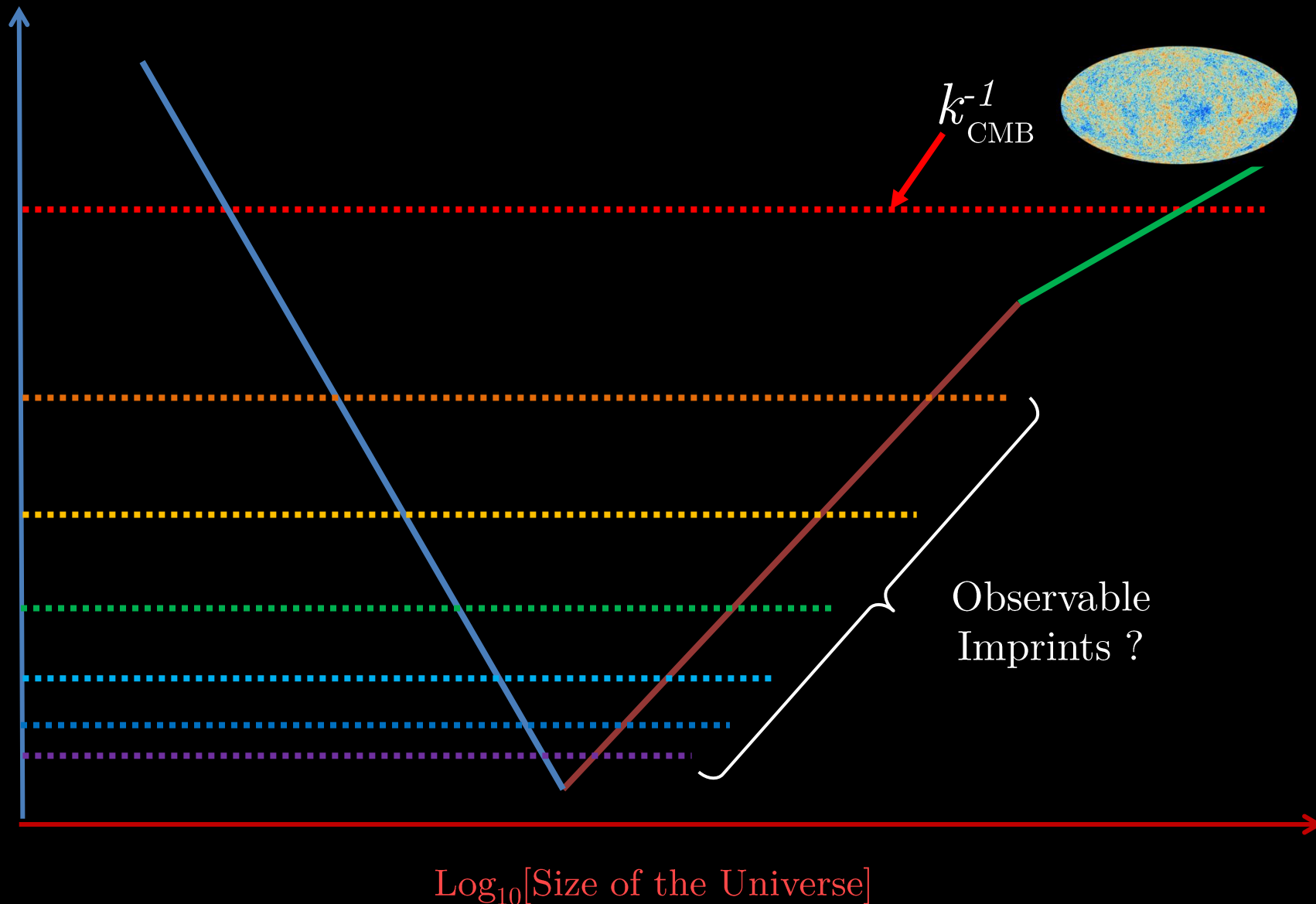


Modes entering the horizon BEFORE  
matter-radiation equality DECAY...

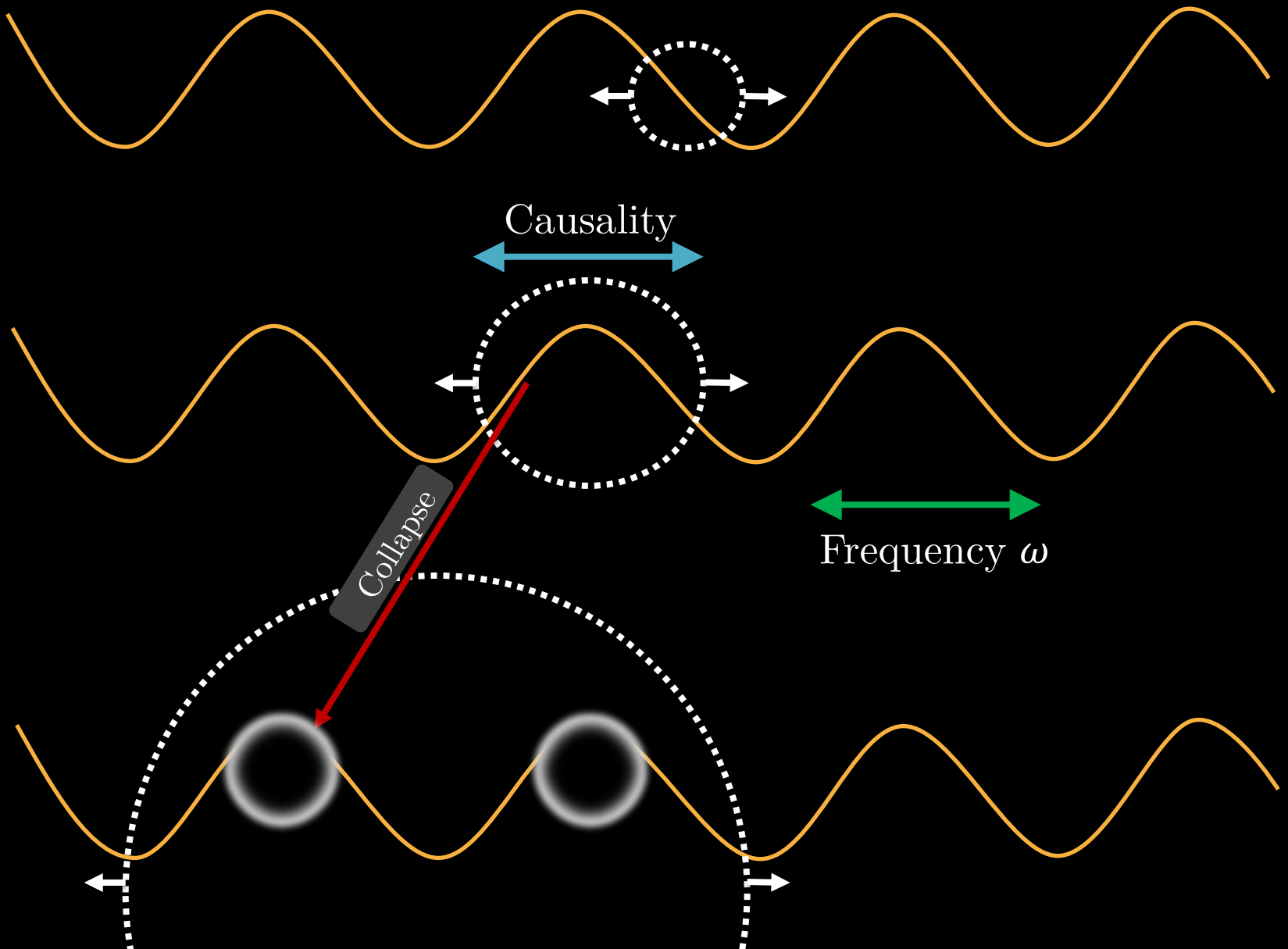
Causality erases small-scale structures

# PRIMORDIAL PERTURBATION EVOLUTION

Horizon Size

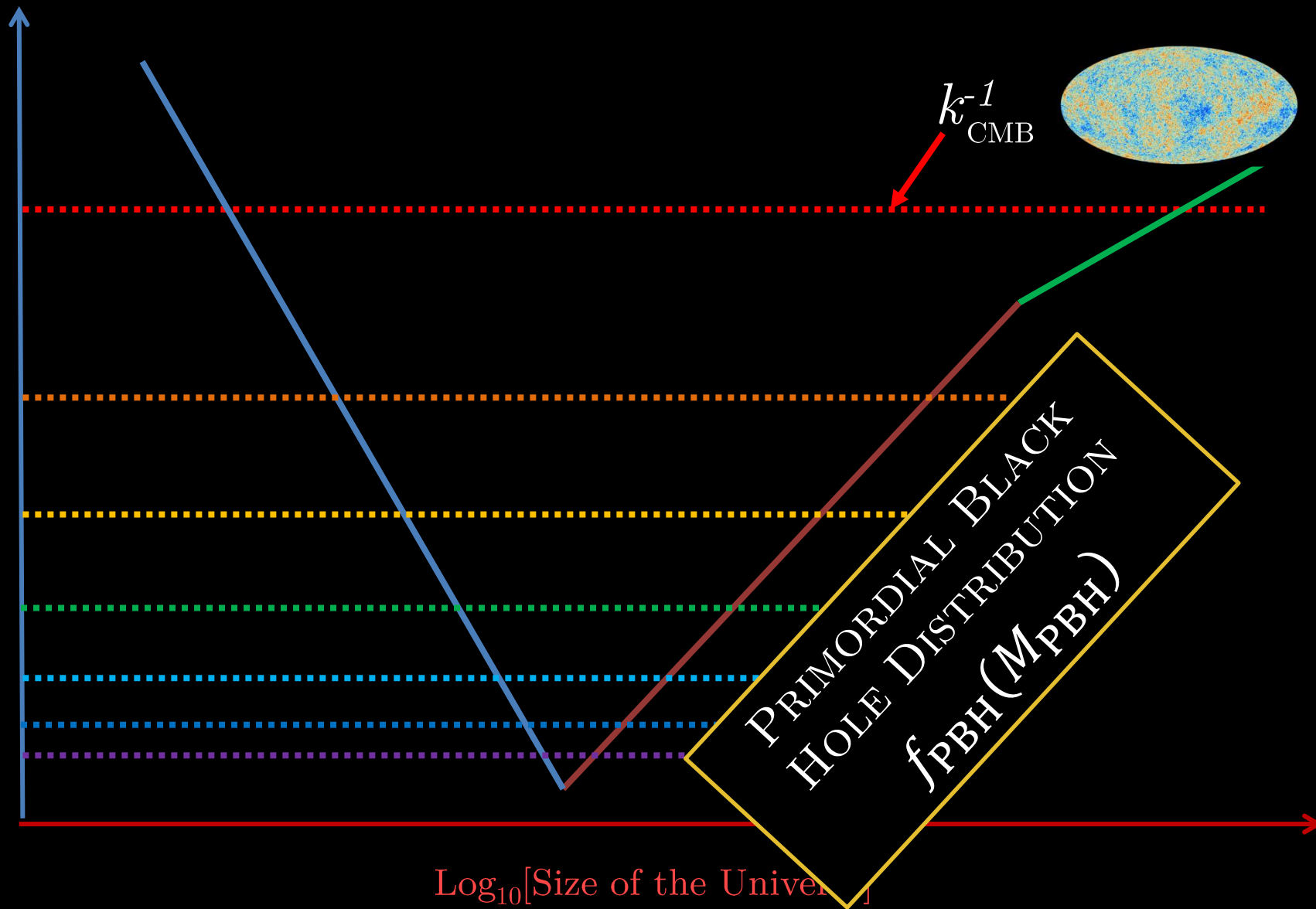


# Why Mini Primordial Black Holes?



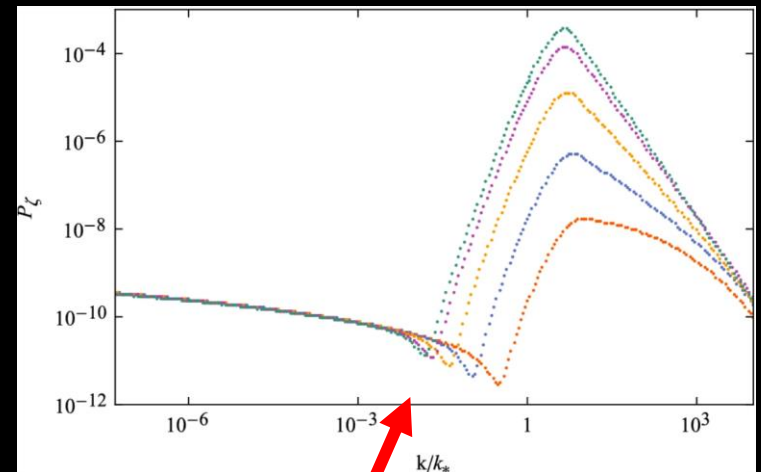
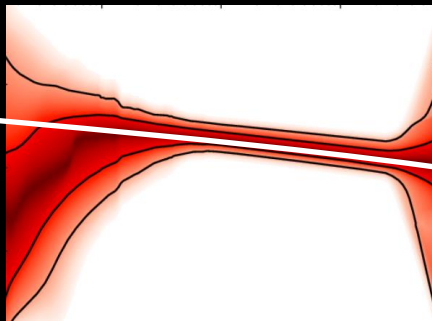
# PRIMORDIAL PERTURBATION EVOLUTION

Horizon Size



# PBHs FROM INFLATION ?

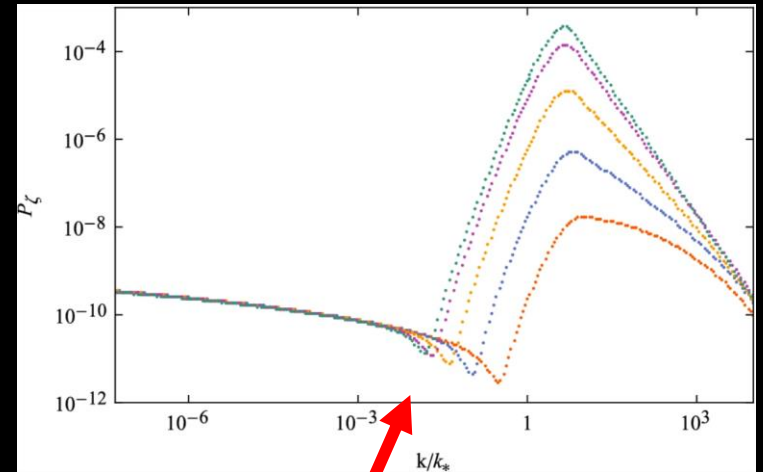
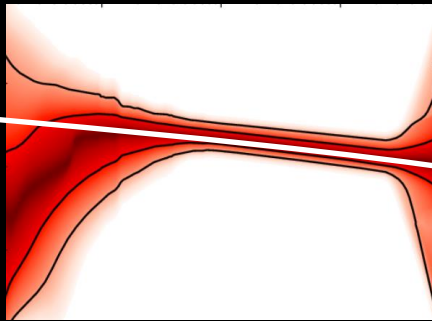
PLANCK



Ultra  
Slow-Roll

# PBHs FROM INFLATION ?

PLANCK



CAVEAT:

Very Fine-Tuned  
paradigm...

Ultra  
Slow-Roll

# PBHs LIKELY TO BE PRODUCED AFTER INFLATION

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

Karsten Jedamzik\* Martin Lemoine<sup>†</sup> and Jérôme Martin<sup>‡</sup>

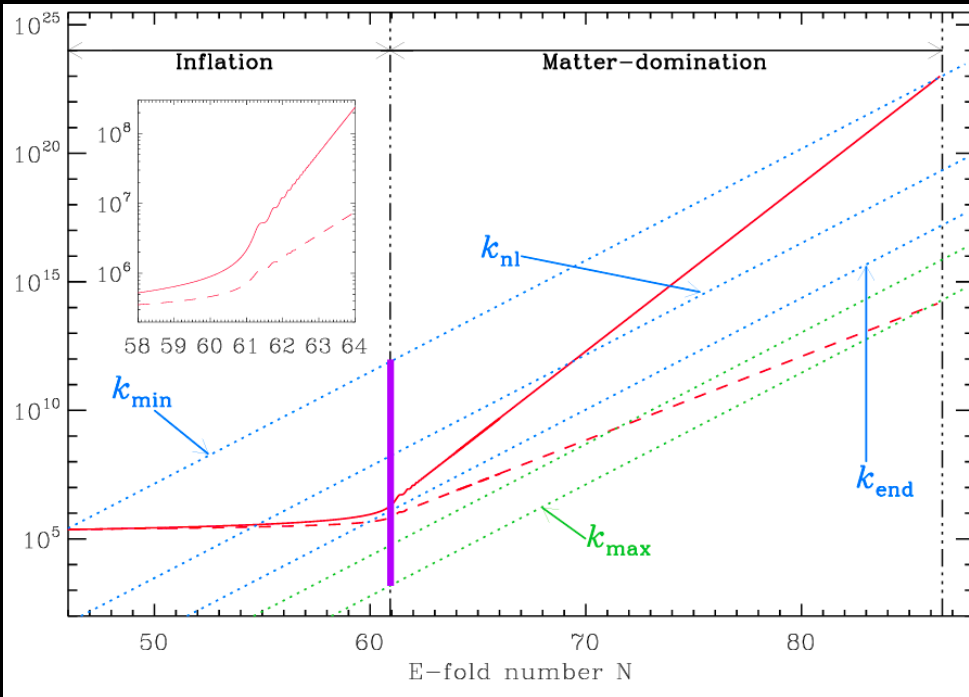
## Primordial black holes from the preheating instability in single-field inflation

Jérôme Martin,<sup>a</sup> Theodoros Papanikolaou,<sup>b</sup> Vincent Vennin<sup>b,a</sup>

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

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

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



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

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

$$\frac{d^2 \tilde{v}_{\mathbf{k}}}{dz^2} + [A_{\mathbf{k}} - 2q \cos(2z)] \tilde{v}_{\mathbf{k}} = 0 \quad (13)$$

PRIMORDIAL  
PERTURBATIONS



PRIMORDIAL BLACK  
HOLE DISTRIBUTION

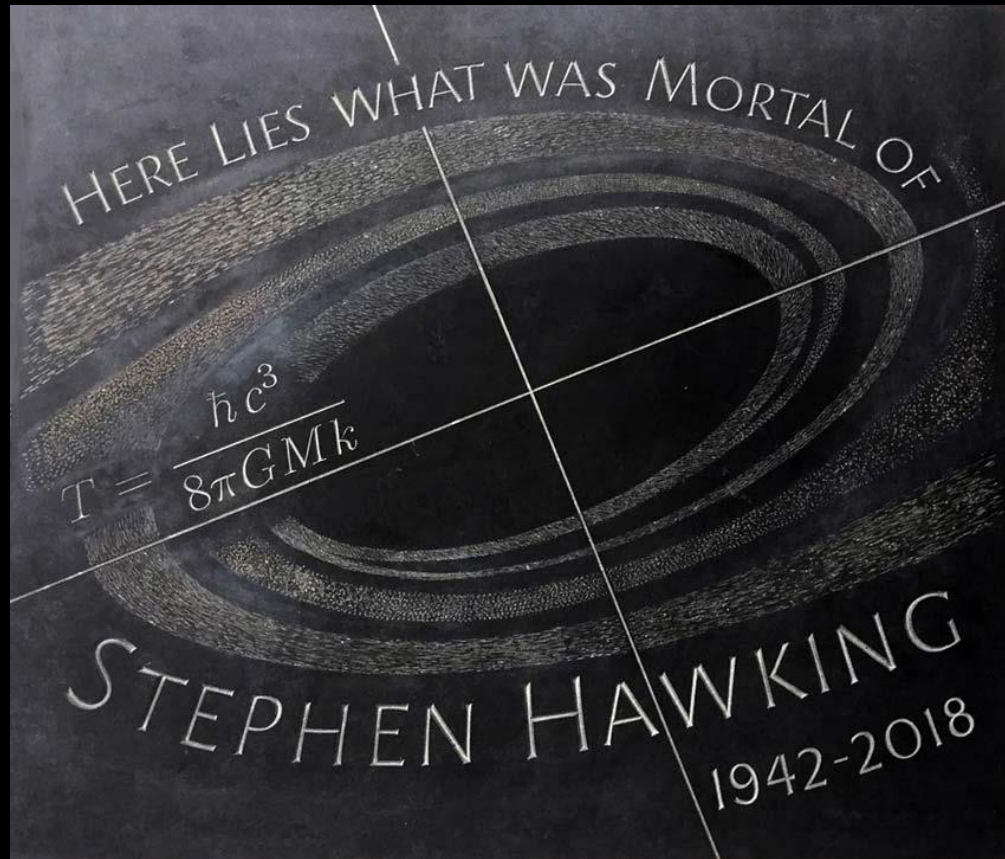
$$f_{\text{PBH}}(M_{\text{PBH}})$$



Observable Imprints ?

# BLACK HOLES EVAPORATE...

*S. HAWKING, 1974*



PRIMORDIAL BLACK  
HOLE DISTRIBUTION  
 $f_{\text{PBH}}(M_{\text{PBH}})$

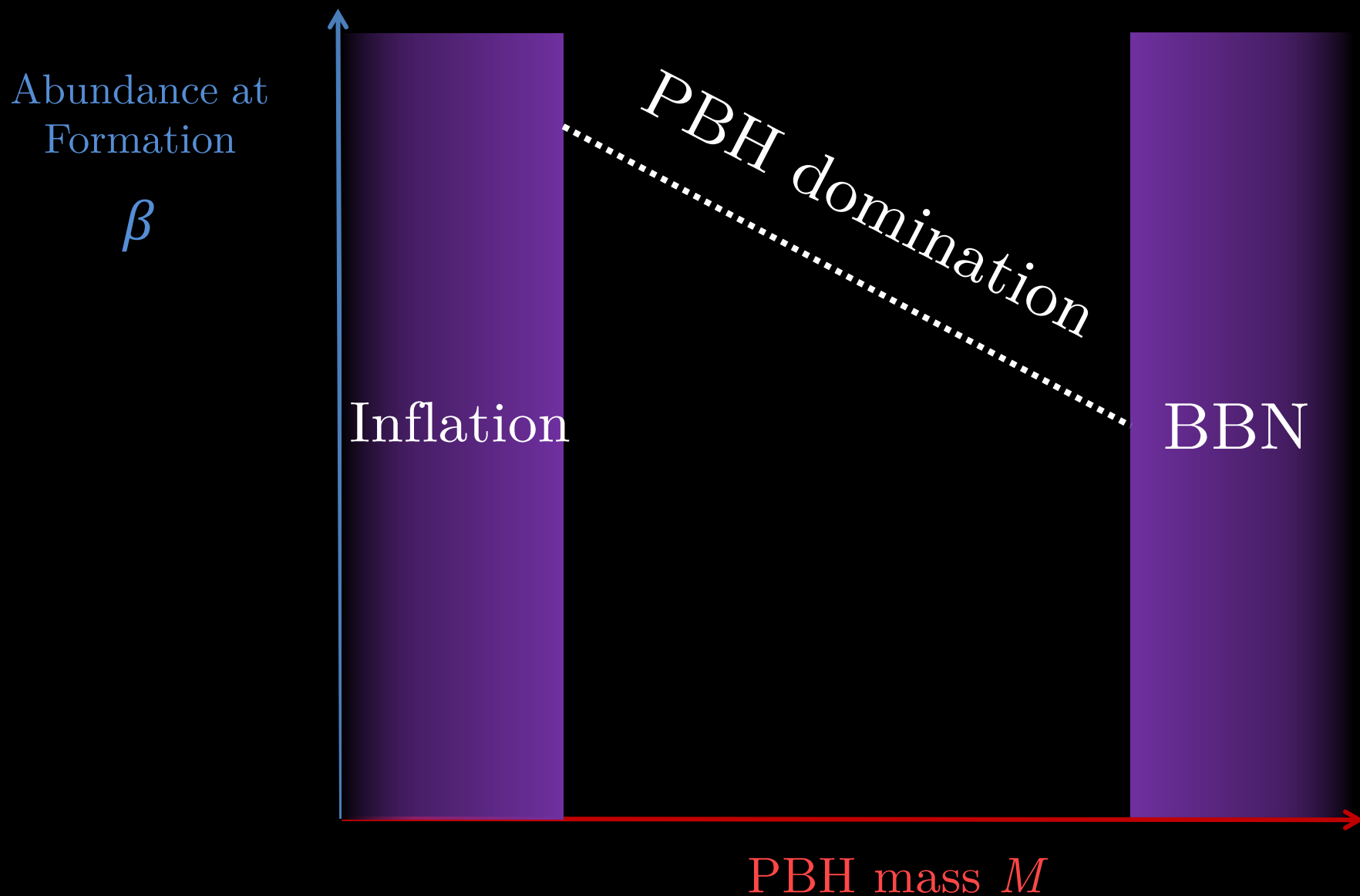
- Some may be stable and participate to the DM relic abundance ( $M_{\text{PBH}} \gtrsim 10^{15} \text{ g}$ )
- Some may be unstable and evaporate **after BBN** ( $10^9 \text{ g} \lesssim M_{\text{PBH}} \lesssim 10^{15} \text{ g}$ )
- Some may be unstable and evaporate before BBN ( $M_{\text{PBH}} \lesssim 10^9 \text{ g}$ )

PRIMORDIAL BLACK  
HOLE DISTRIBUTION  
 $f_{\text{PBH}}(M_{\text{PBH}})$

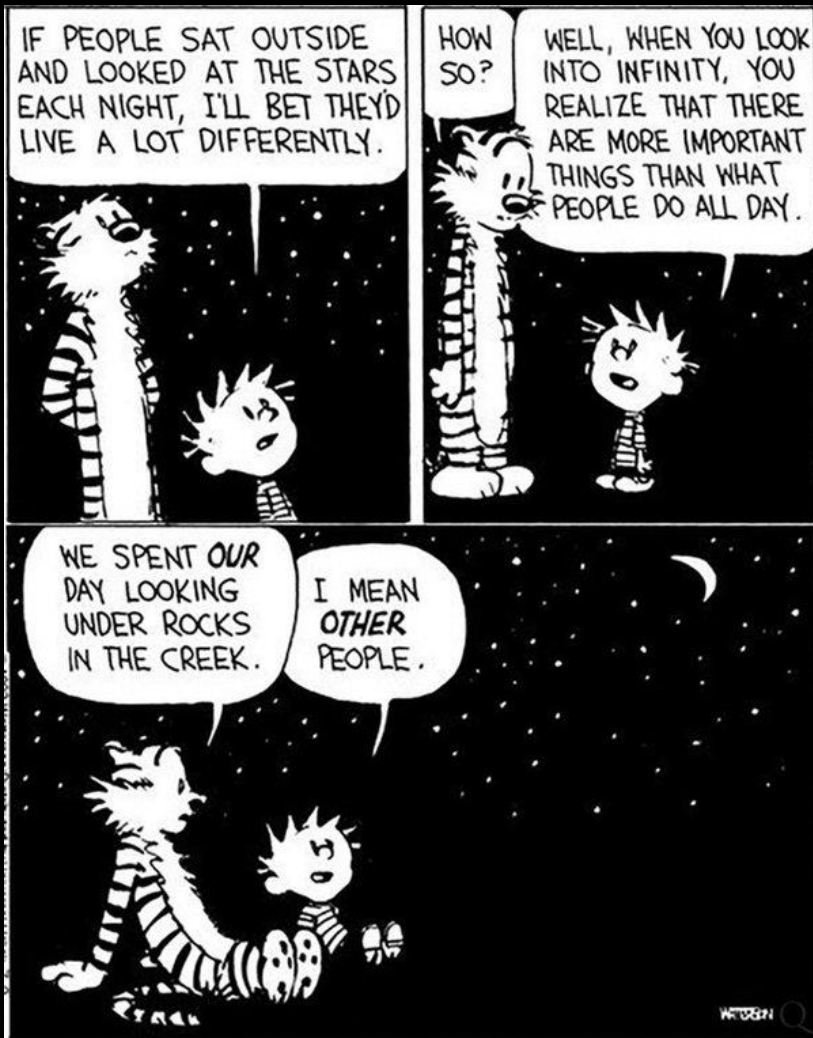
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The topic of this talk ...

# 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. Evaporation of Extended Distributions
- IV. 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

$$\frac{dM_{\text{BH}}}{dt} \equiv \sum_i \left. \frac{dM_{\text{BH}}}{dt} \right|_i = - \sum_i \int_0^\infty E_i \frac{d^2 \mathcal{N}_i}{dp dt} dp = -\varepsilon(M_{\text{BH}}) \frac{M_p^4}{M_{\text{BH}}^2}$$

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

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

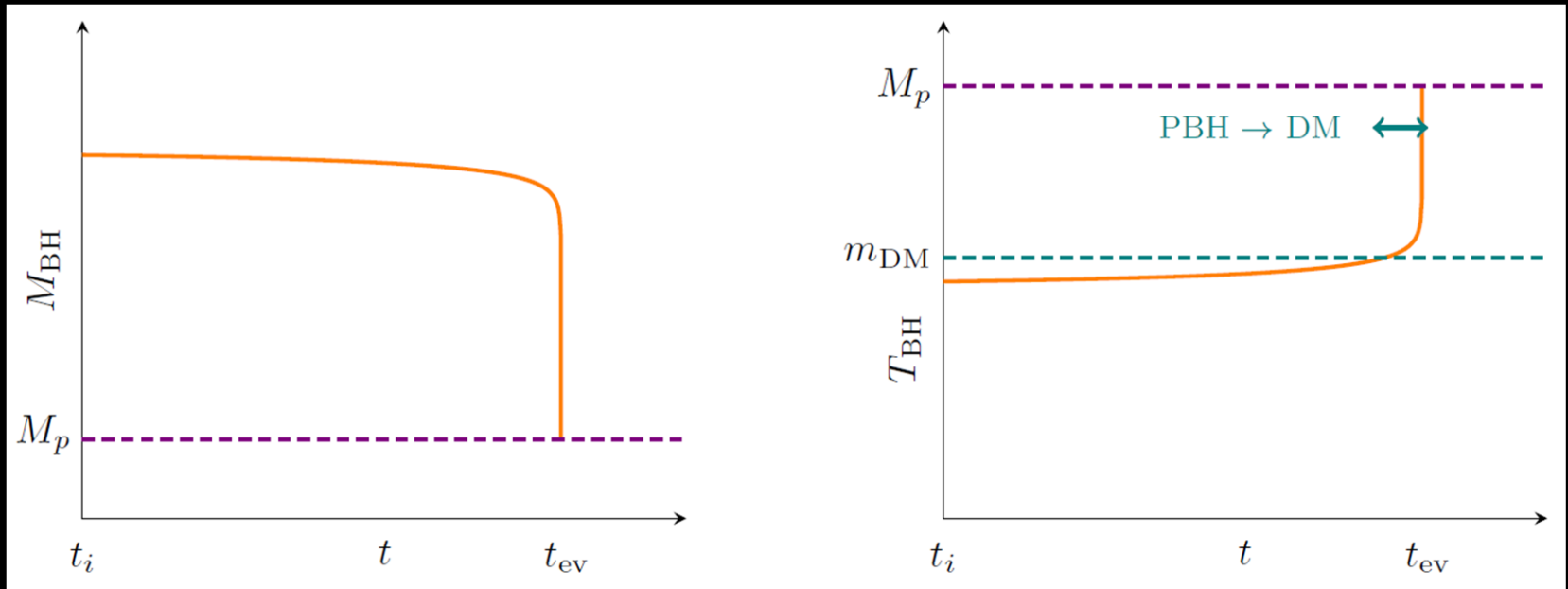
$$z_i = \mu_i/T_{\text{BH}}$$

BSM  
Contributions?

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

# PBH EVAPORATION

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



→ More and more particles contribute to the evaporation

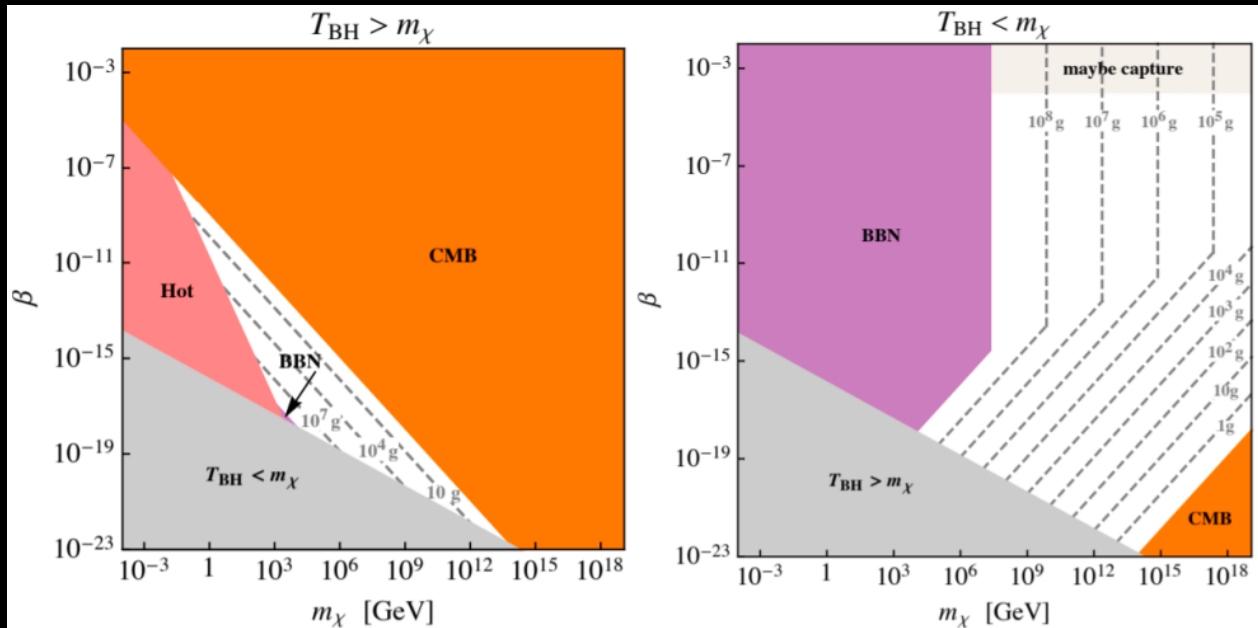
# DM FROM EVAPORATION

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

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

$$GM_{\text{BH}}p \gg 1$$

$$\sigma_{s_i}(E, \mu)|_{\text{GO}} = 27\pi G^2 M_{\text{BH}}^2$$



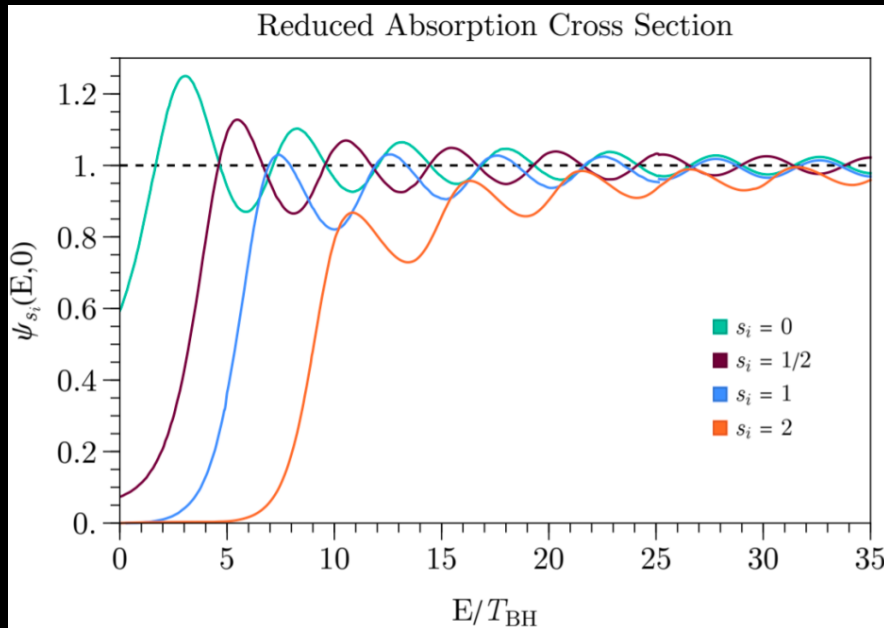
[Gondolo, Sandick and Shams Es Haghi '20]

# DM FROM EVAPORATION

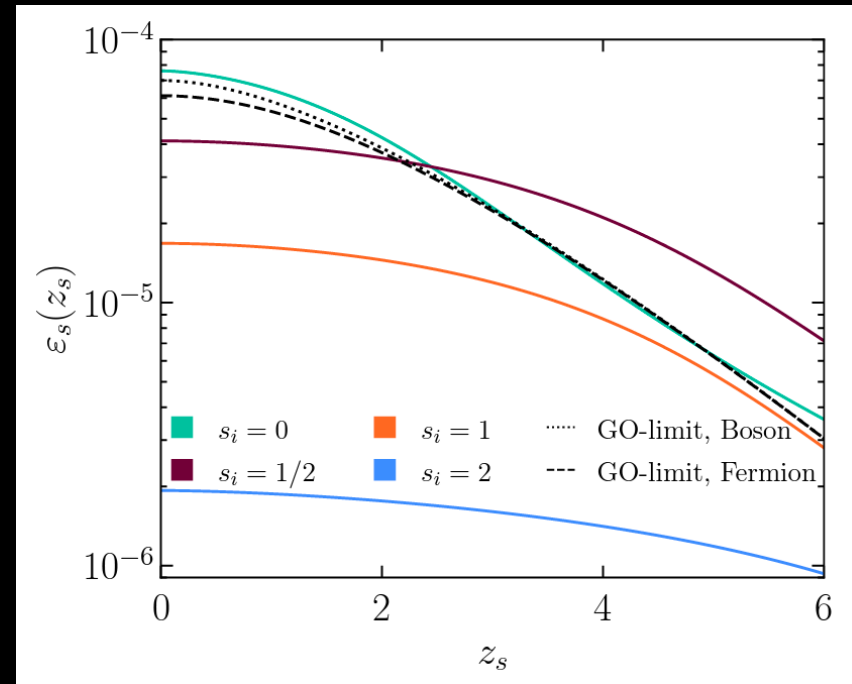
$$\frac{d^2 \mathcal{N}_i}{dp dt} = \frac{g_i}{2\pi^2} \frac{\sigma_{s_i}(M_{\text{BH}}, \mu_i, p)}{\exp[E_i(p)/T_{\text{BH}}] - (-1)^{2s_i}} \frac{p^3}{E_i(p)}$$

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

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

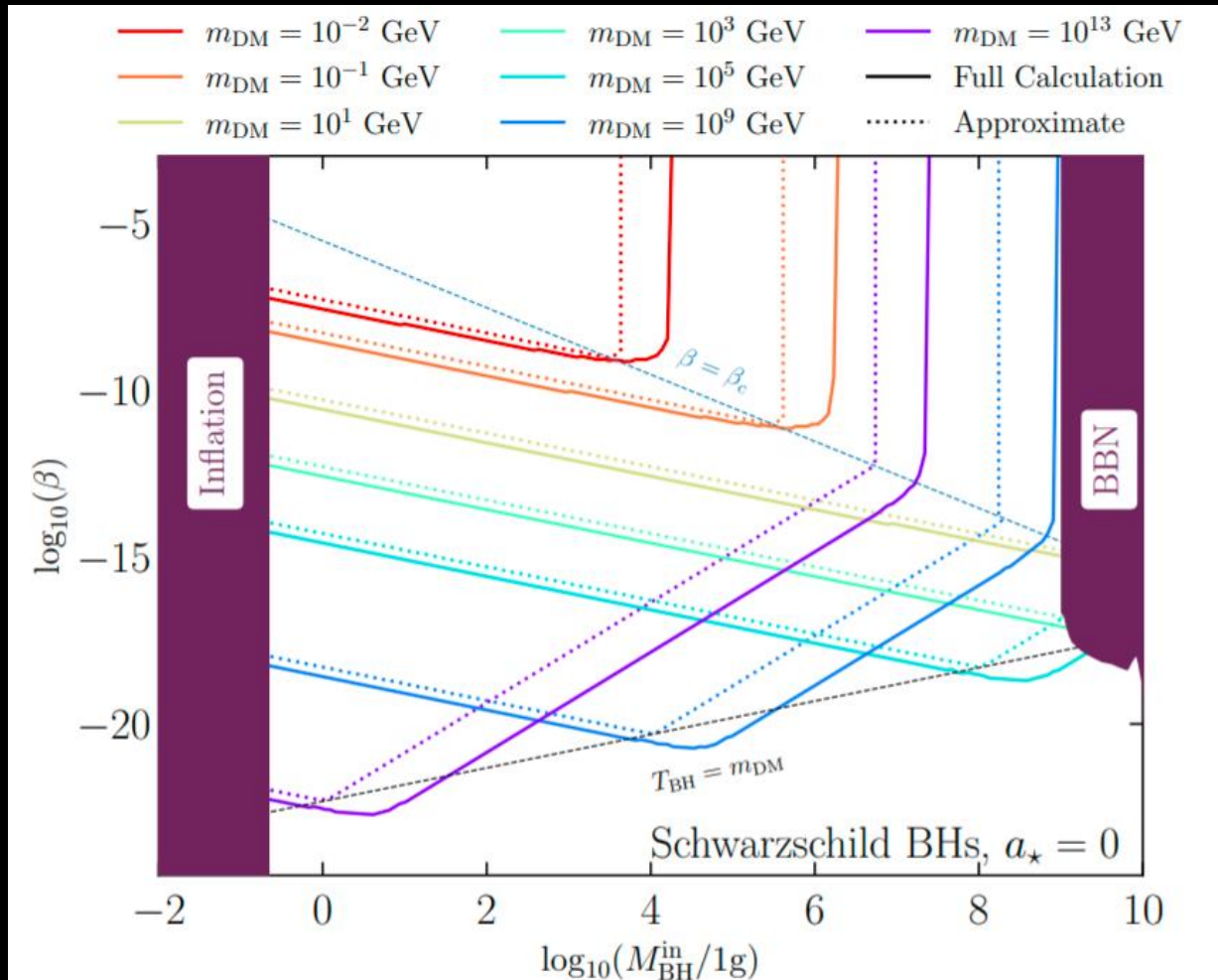


$$\varepsilon_i(z_i) = \frac{27}{8192\pi^5} \int_{z_i}^{\infty} \frac{\psi_{s_i}(x)(x^2 - z_i^2)}{\exp(x) - (-1)^{2s_i}} x dx$$



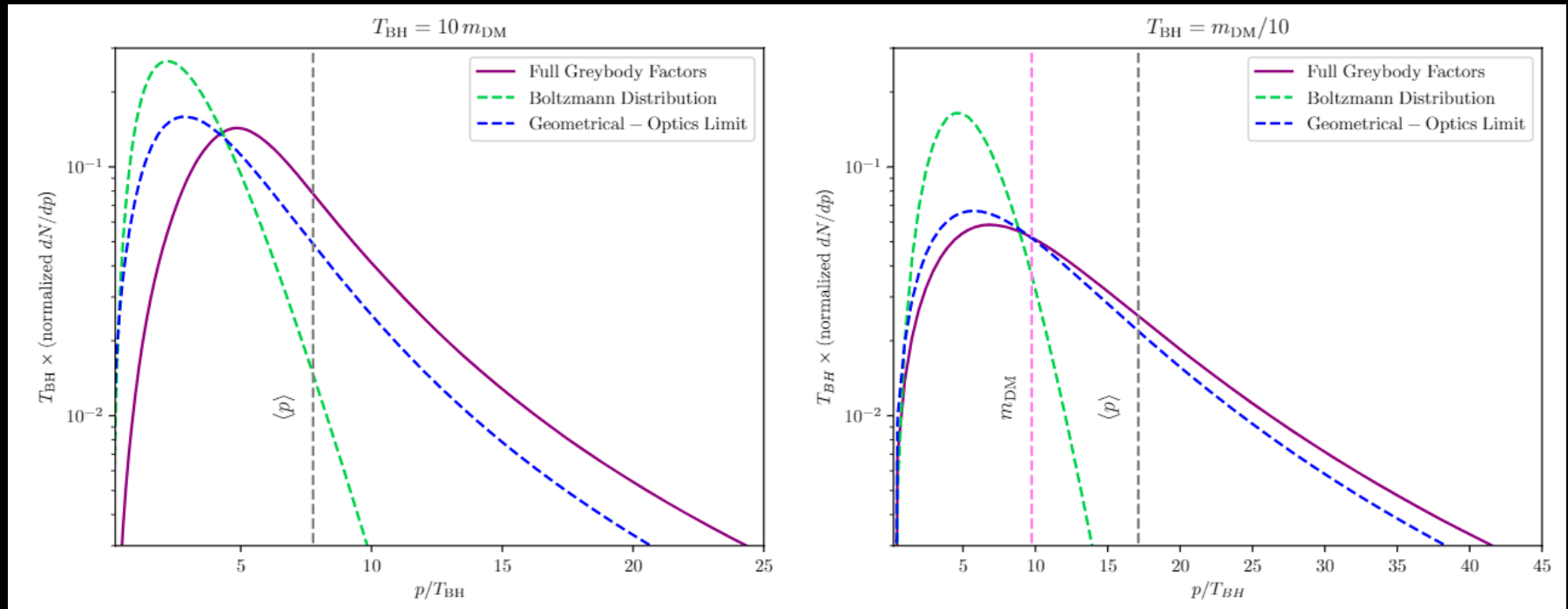
# DM FROM EVAPORATION

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



# DM FROM EVAPORATION

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



# Kerr PBHs and Warm Dark Matter

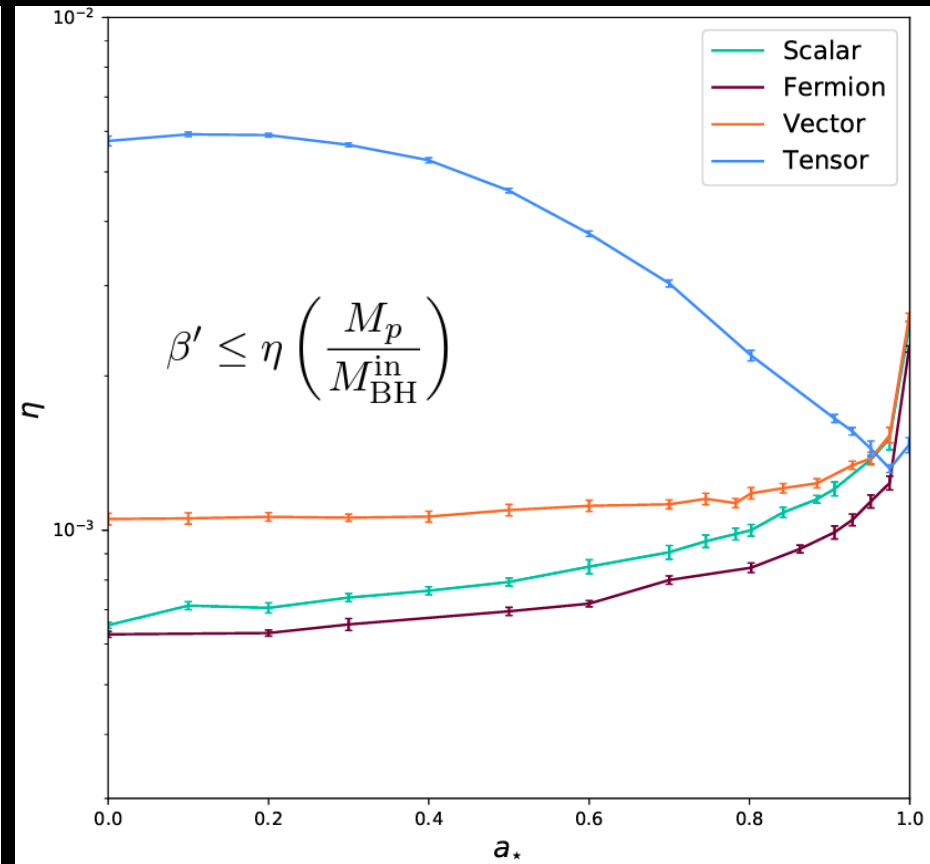
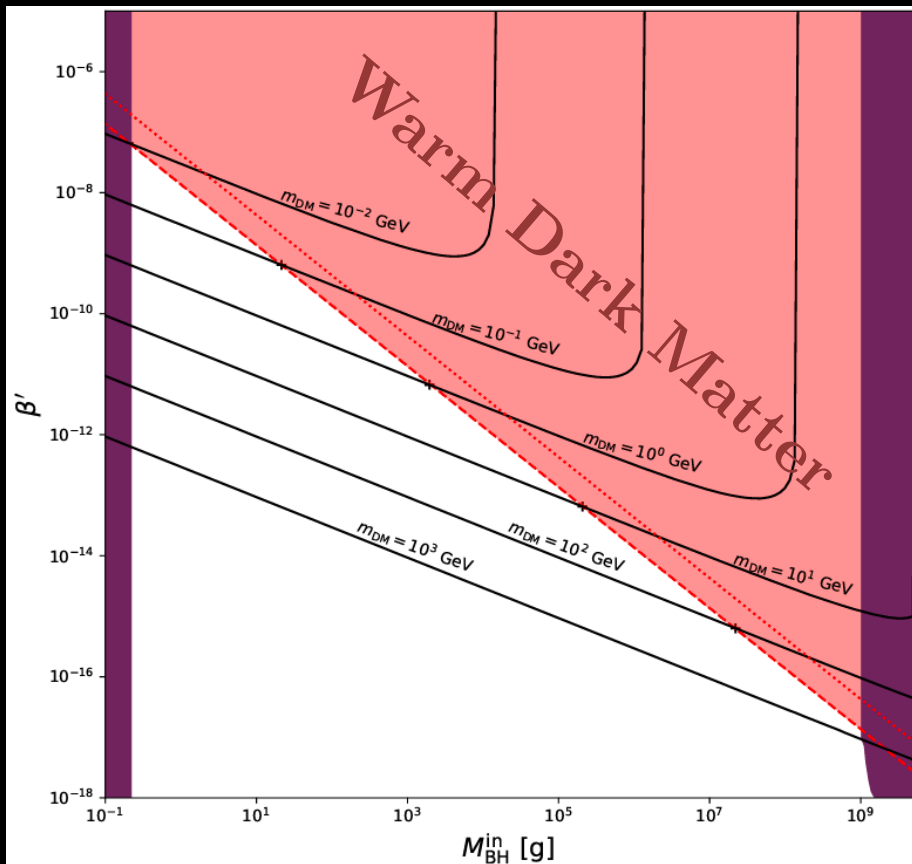
Using CLASS: expected matter power spectrum

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

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

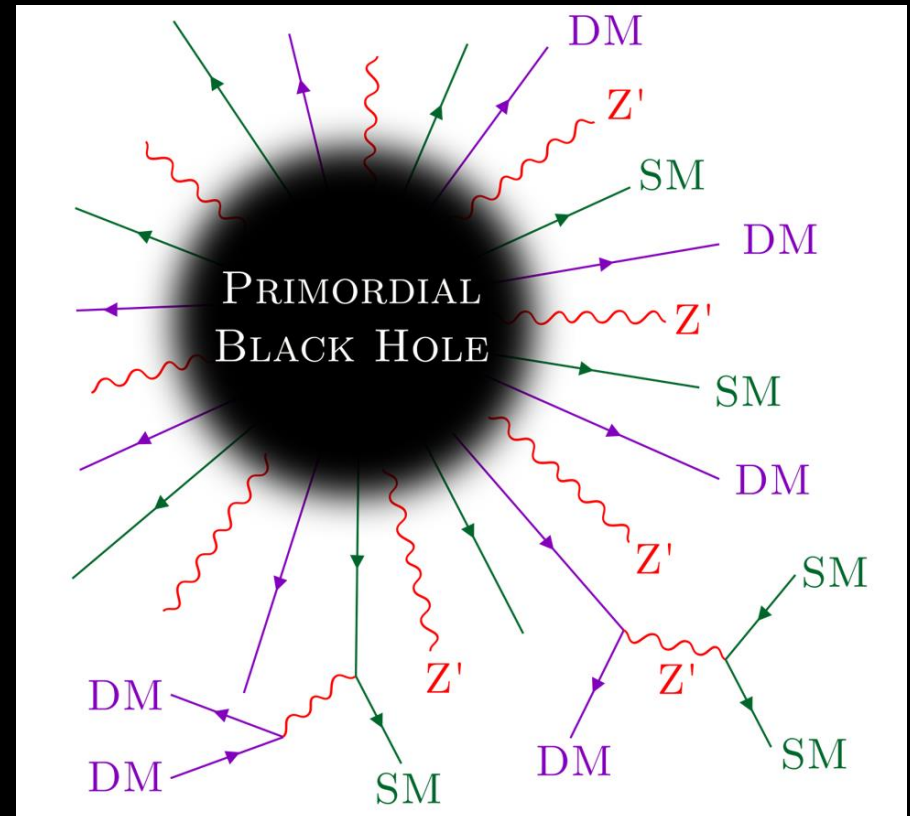
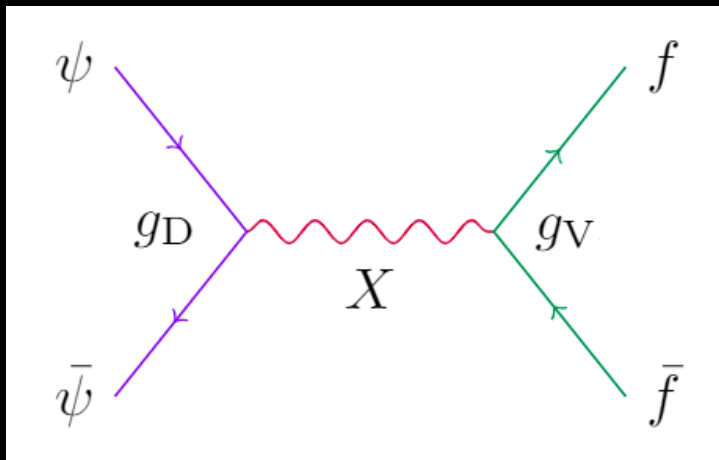
Saturated at

$$\alpha = 1.3 \times 10^{-2} \text{ Mpc } h^{-1}$$



# 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



# THERMAL PRODUCTION OF DM

$$\begin{aligned} \dot{n}_{\text{DM}} + 3Hn_{\text{DM}} &= \overbrace{g_{\text{DM}} \int C[f_{\text{DM}}] \frac{d^3p}{(2\pi)^3}}^{\text{DM Annihilation, X decay}} + \overbrace{\left. \frac{dn_{\text{DM}}}{dt} \right|_{\text{BH}}}^{\text{PBH evaporation}} \\ \dot{n}_X + 3Hn_X &= \overbrace{g_X \int C[f_X] \frac{d^3p}{(2\pi)^3}}^{\text{DM Annihilation, X decay}} + \overbrace{\left. \frac{dn_X}{dt} \right|_{\text{BH}}}^{\text{PBH evaporation}}, \end{aligned}$$

$$\dot{\rho}_{\text{SM}} + 4H\rho_{\text{SM}} = \left. \frac{dM}{dt} \right|_{\text{SM}}.$$

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



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

Simplified approach...

$$\left. \frac{dn_i}{dt} \right|_{\text{BH}} = n_{\text{BH}} g_i \int \left. \frac{\partial f_i}{\partial t} \right|_{\text{BH}} \frac{p^2 dp}{2\pi^2}$$

# THERMAL PRODUCTION OF DM

- If PBHs evaporate **before FO**:

→ Assume **INSTANTANEOUS** thermalization

- If PBHs evaporate **after FO**:

→ Assume **NO** thermalization

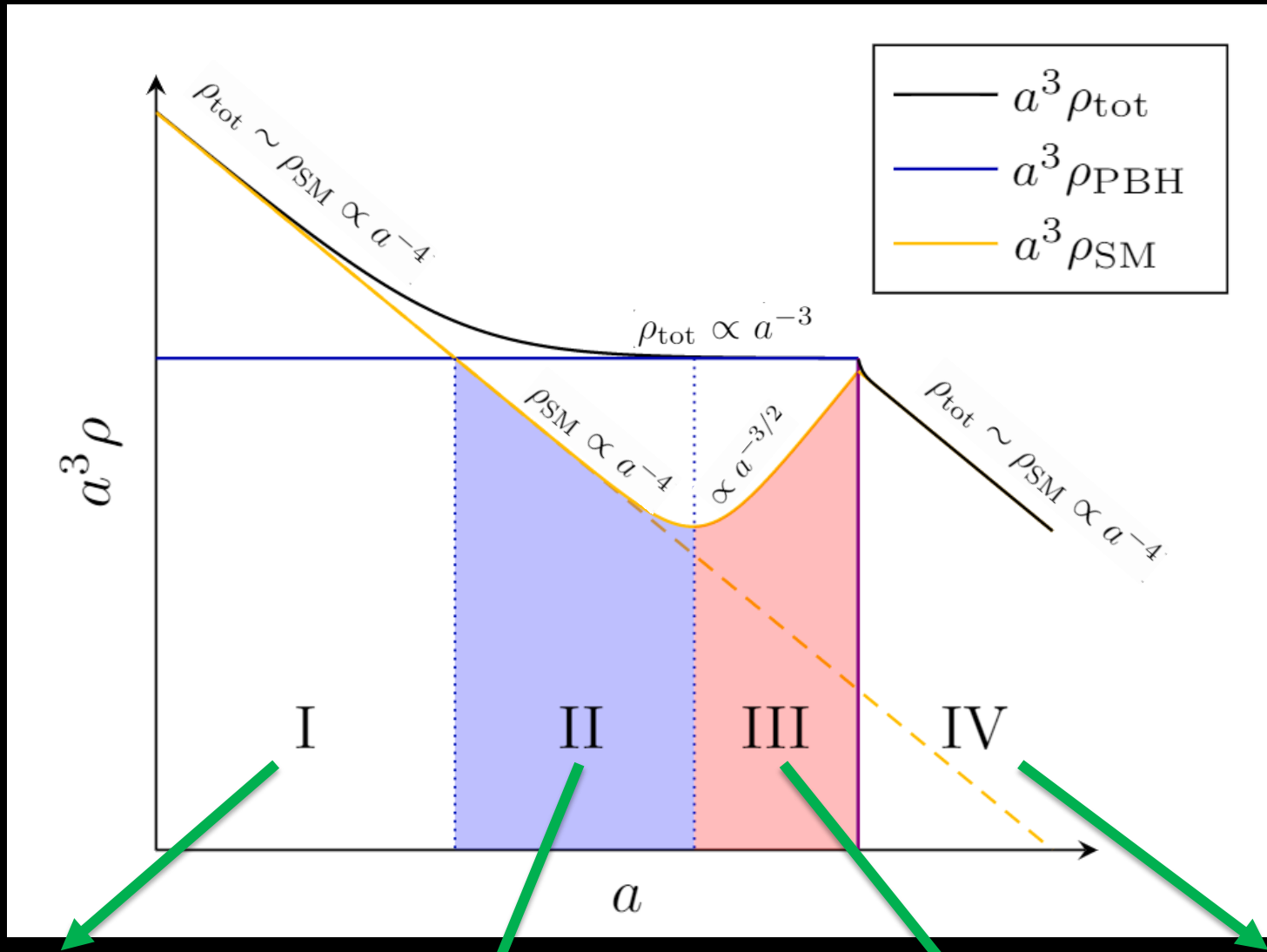
- **FI case**: assume **NO** thermalization

→ Check those assumptions by evaluating at all time

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

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

# MODIFIED COSMOLOGY



FI/FO + entropy dilution

Matter-Dominated FI/FO

FI/FO during entropy injection

Regular FI/FO

# RESULTS

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

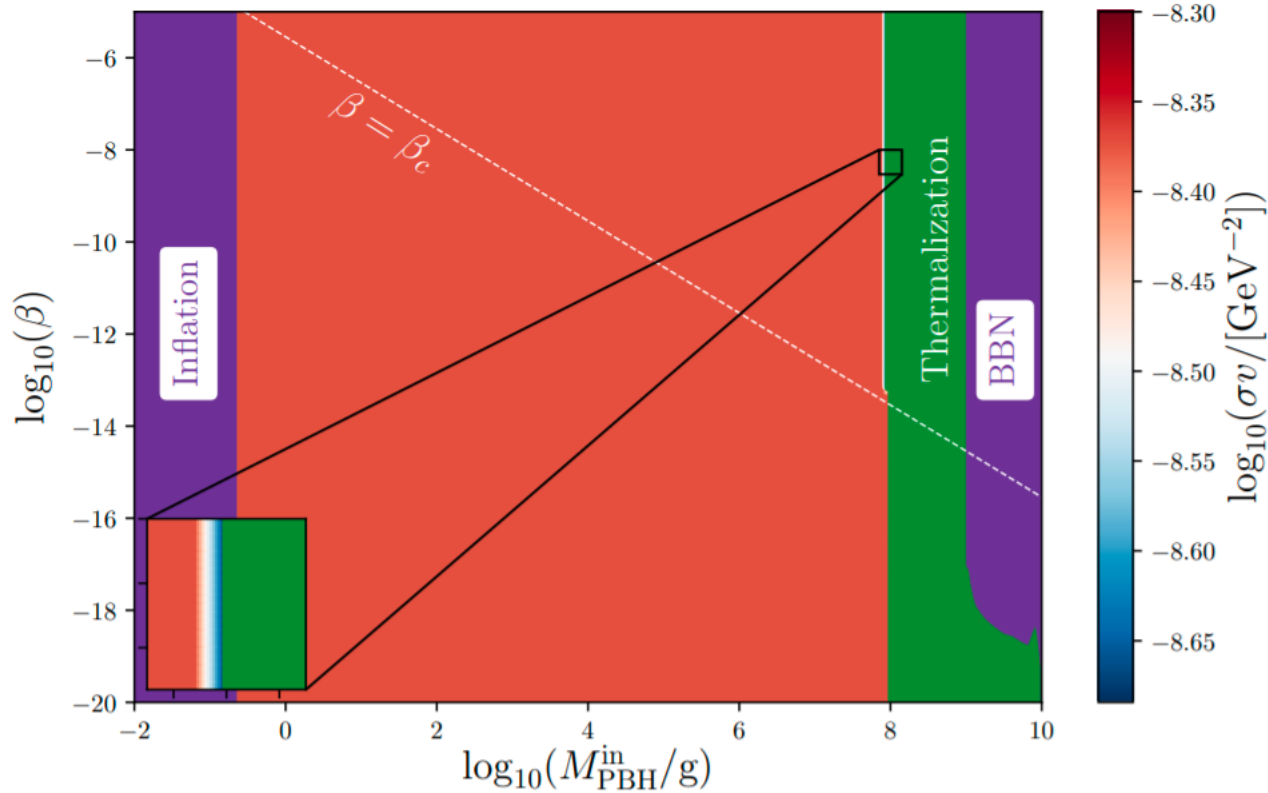


Fig. 7. Two-dimensional scan over the PBH fraction  $\beta$  and mass  $M_{\text{BH}}$  for a mediator mass  $m_X = 10 \text{ GeV}$  and a dark matter mass  $m_{\text{DM}} = 1 \text{ GeV}$ , and  $\text{Br}(X \rightarrow \text{DM}) = 0.5$ . The color map indicates the value of the non-relativistic cross-section 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]

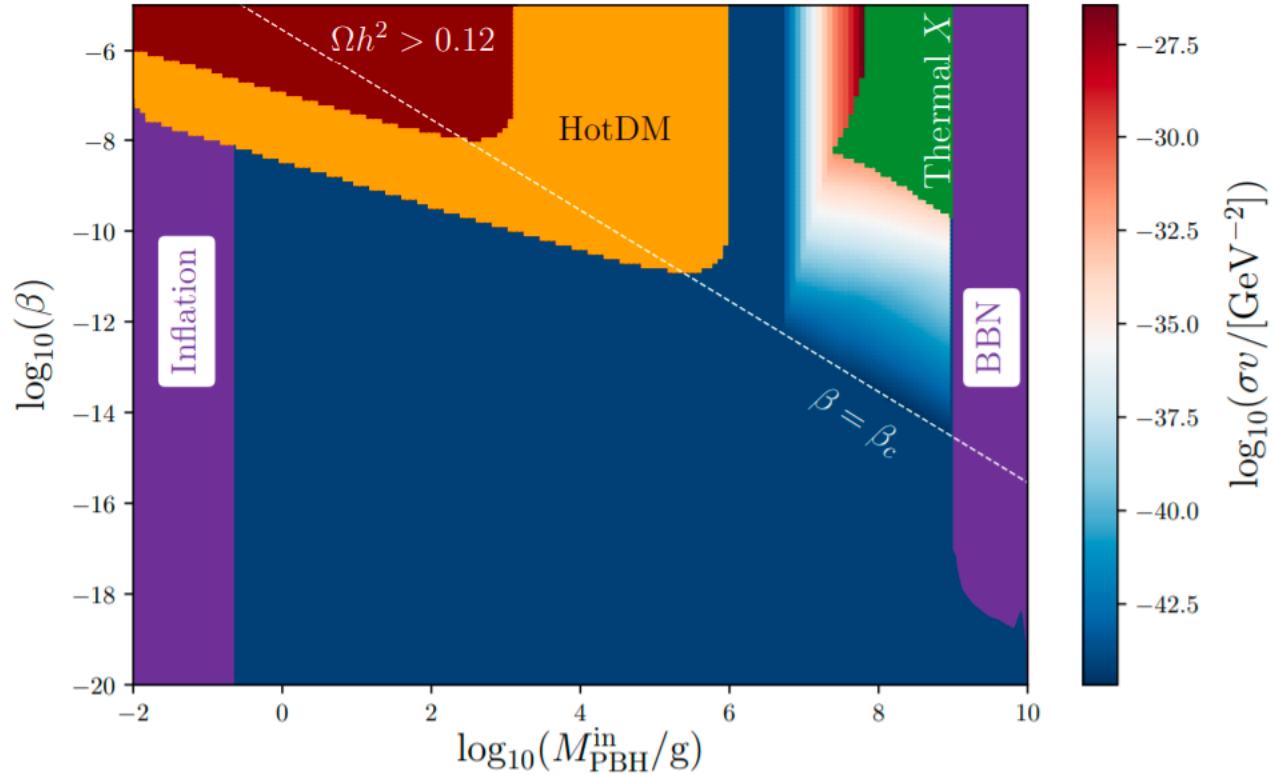


Fig. 11. Two-dimensional scan over the PBH fraction  $\beta$  and mass  $M_{\text{BH}}$  for a mediator mass  $m_X = 1 \text{ TeV}$ , a dark matter mass  $m_{\text{DM}} = 1 \text{ MeV}$ , and  $\text{Br}(X \rightarrow \text{SM}) = 10^{-7}$ . The color map indicates the value of the non-relativistic cross-section 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.

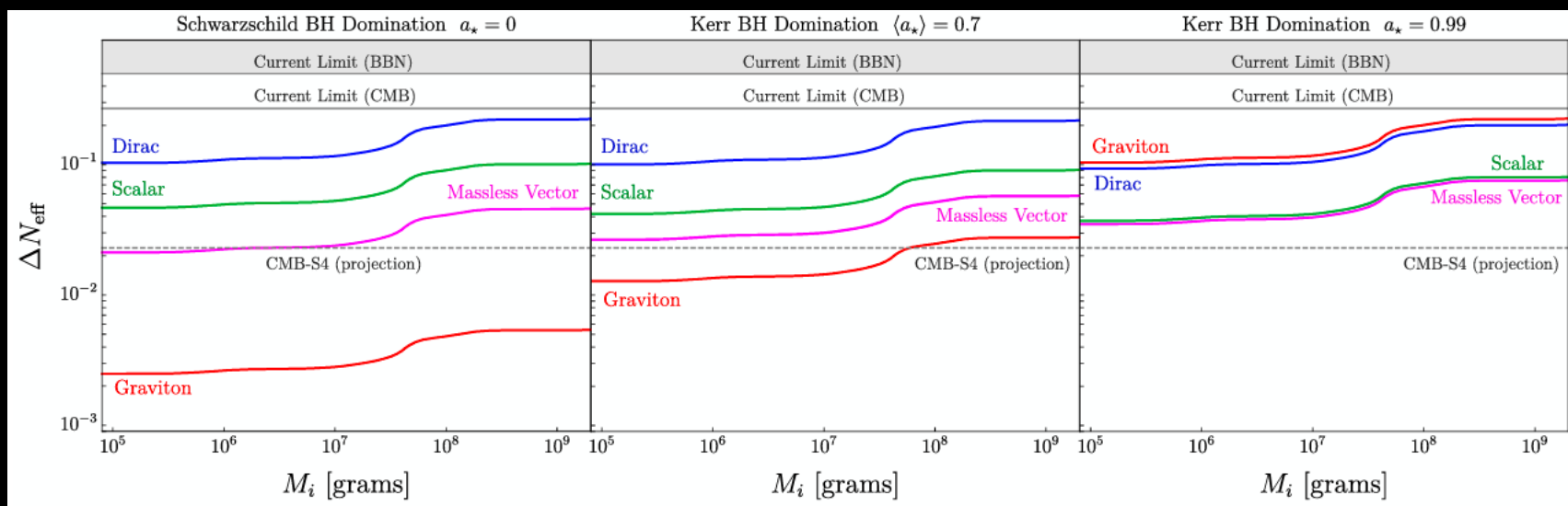
## II. Kerr PBHs and Dark Radiation

# Kerr PBHs and Dark Radiation

Dark particles with small masses can contribute to  $\Delta N_{\text{eff}}$

Schwarzschild PBH  $\longrightarrow$  Negligible

Kerr PBH  $\longrightarrow$  Argued to be critical



[Hooper et al '20]

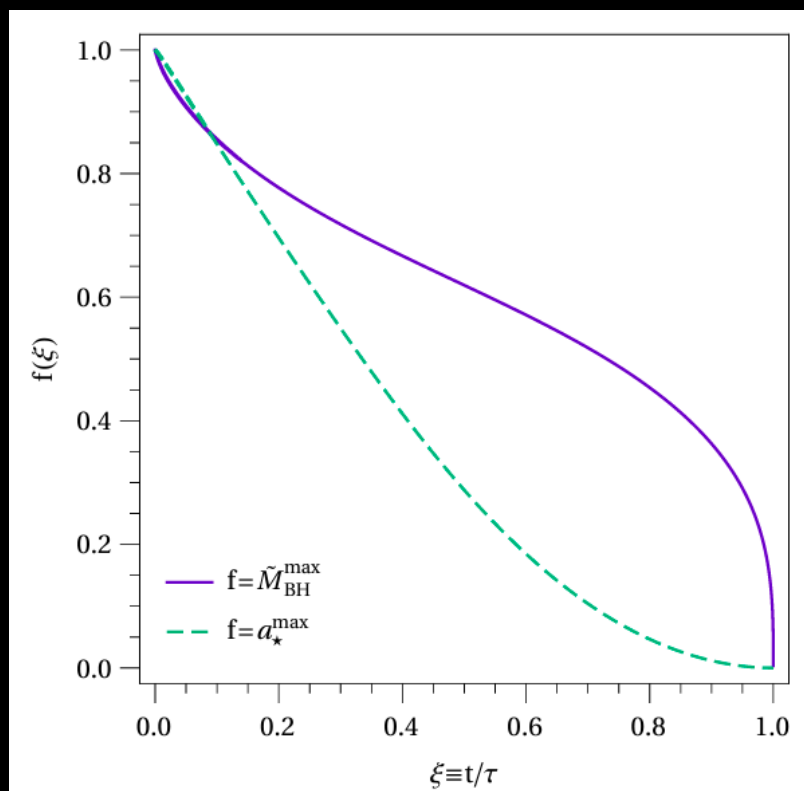
# Kerr PBHs and Dark Radiation

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

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

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

# Kerr PBHs and Dark Radiation



Major effects:

Spin loss faster than mass loss

→ Shorter lifetime

→ Different ratio Dark  
Radiation / Radiation

How to calculate  $\Delta N_{\text{eff}}$  ?

# Kerr PBHs and Dark Radiation

In the Standard Model

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

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

In the presence of Dark Radiation

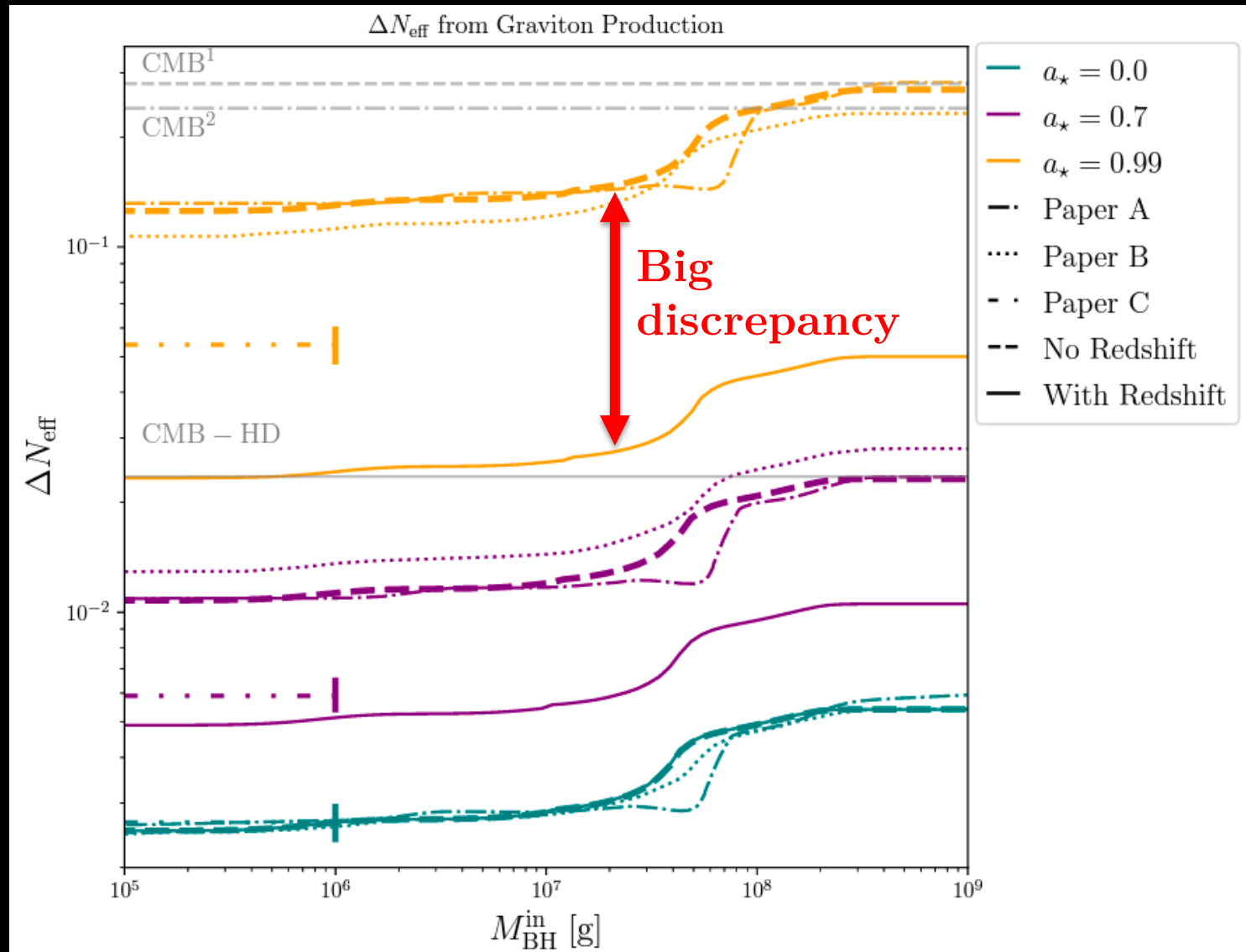
$$\rho_{\text{R}} \equiv \rho_{\gamma} \left[ 1 + \frac{7}{8} \left( \frac{T_{\nu}}{T_{\gamma}} \right) (N_{\text{eff}}^{\text{SM}} + \Delta N_{\text{eff}}) \right]$$

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



The quantity to evaluate

# Kerr PBHs and Dark Radiation



# Kerr PBHs and Dark Radiation

Why ?

# Kerr PBHs and Dark Radiation

Why ?

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

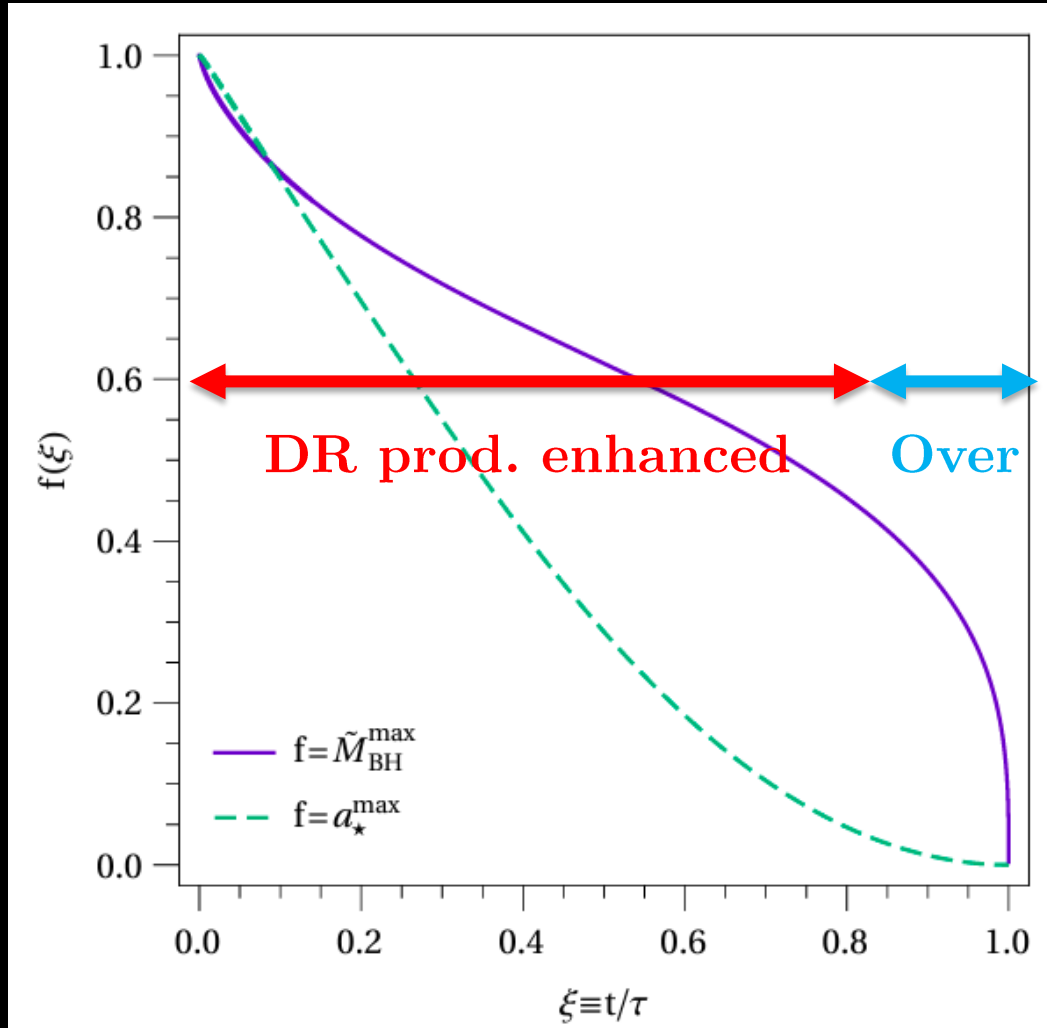


$$N_{\text{eff}} \approx 3.045 \quad (\text{not just } 3 \dots)$$

The neutrino decoupling is NOT instantaneous  
+ Temperature-dependent entropy transfer from  
electrons

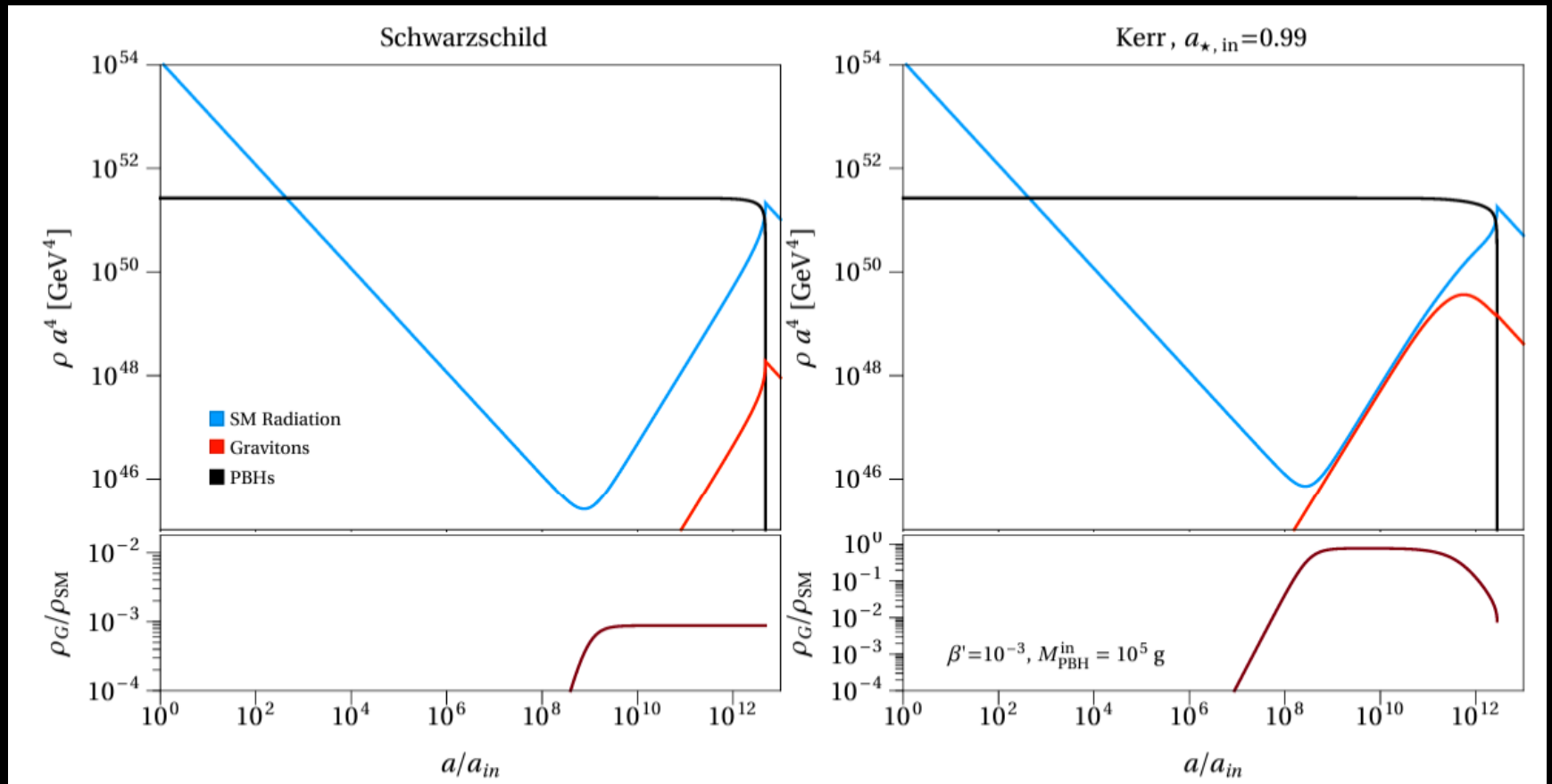
# Kerr PBHs and Dark Radiation

Why ?



# Kerr PBHs and Dark Radiation

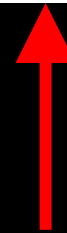
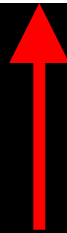
Why ?



# Kerr PBHs and Dark Radiation

Why ?

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

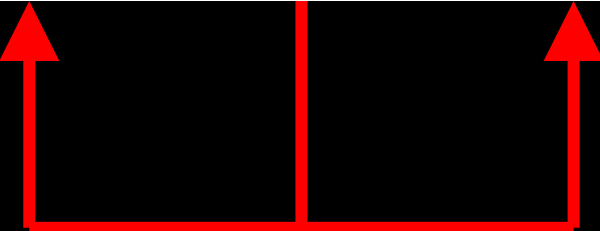


some redshift is good

# Kerr PBHs and Dark Radiation

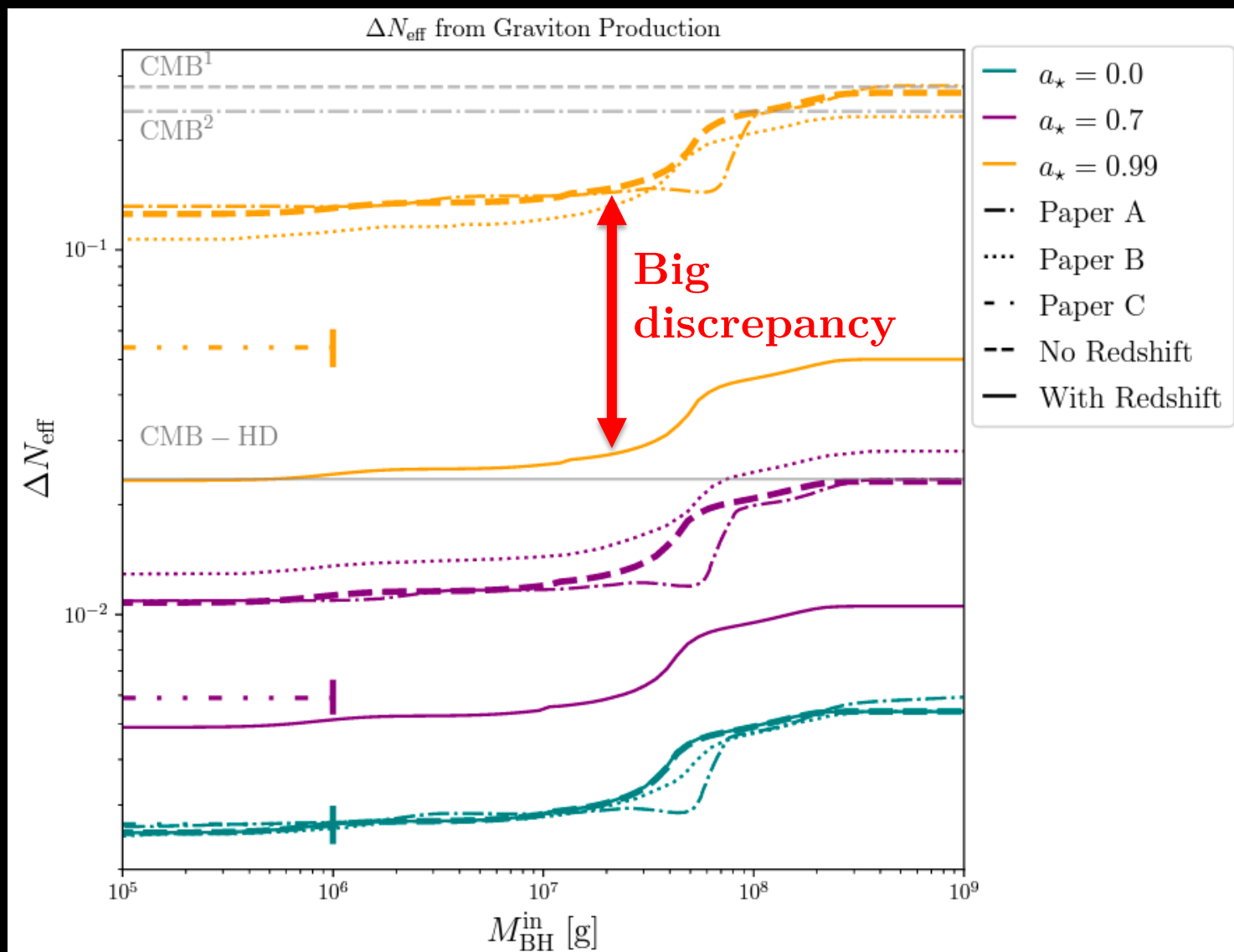
Why ?

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

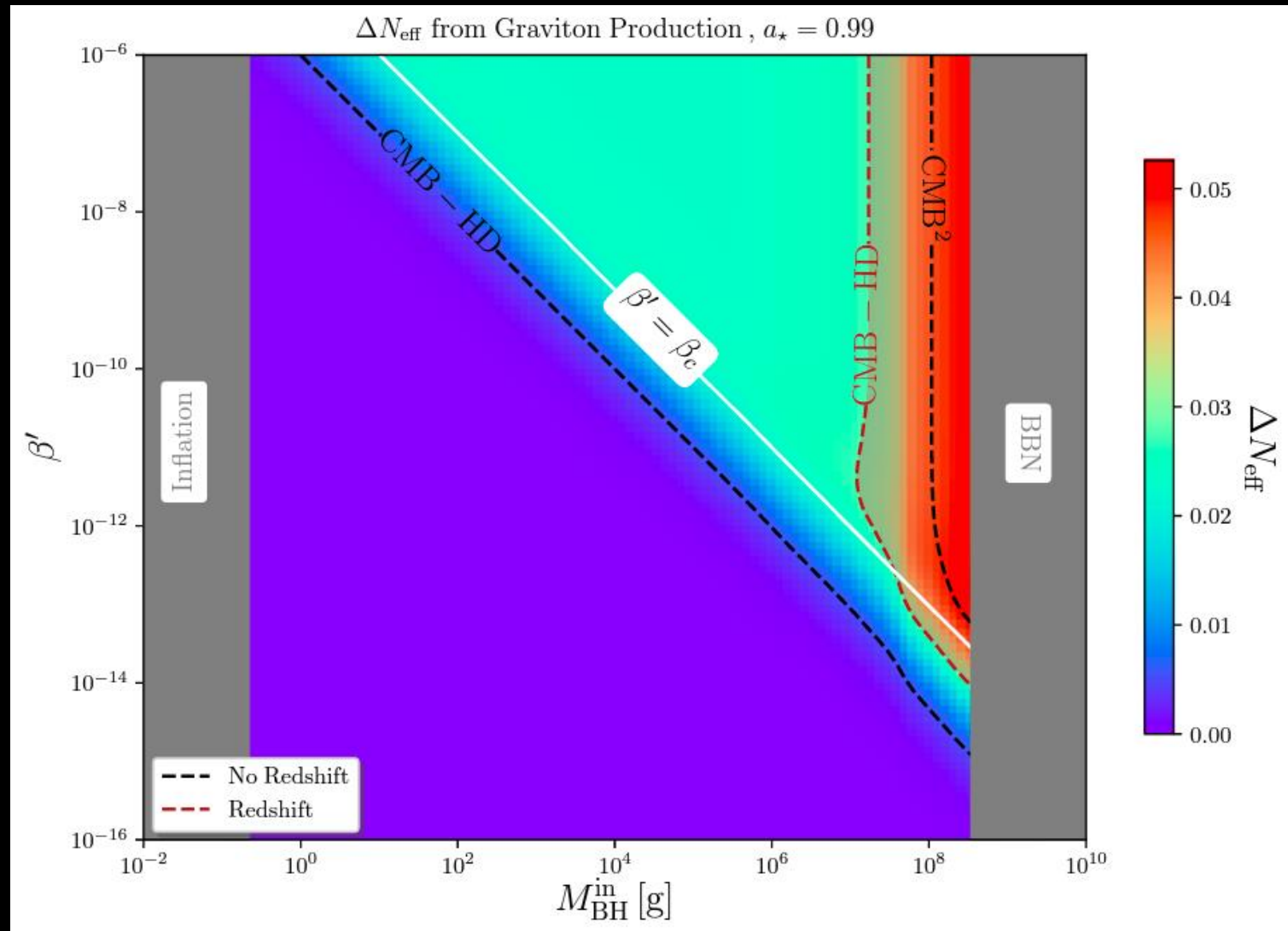


The correct one is better!

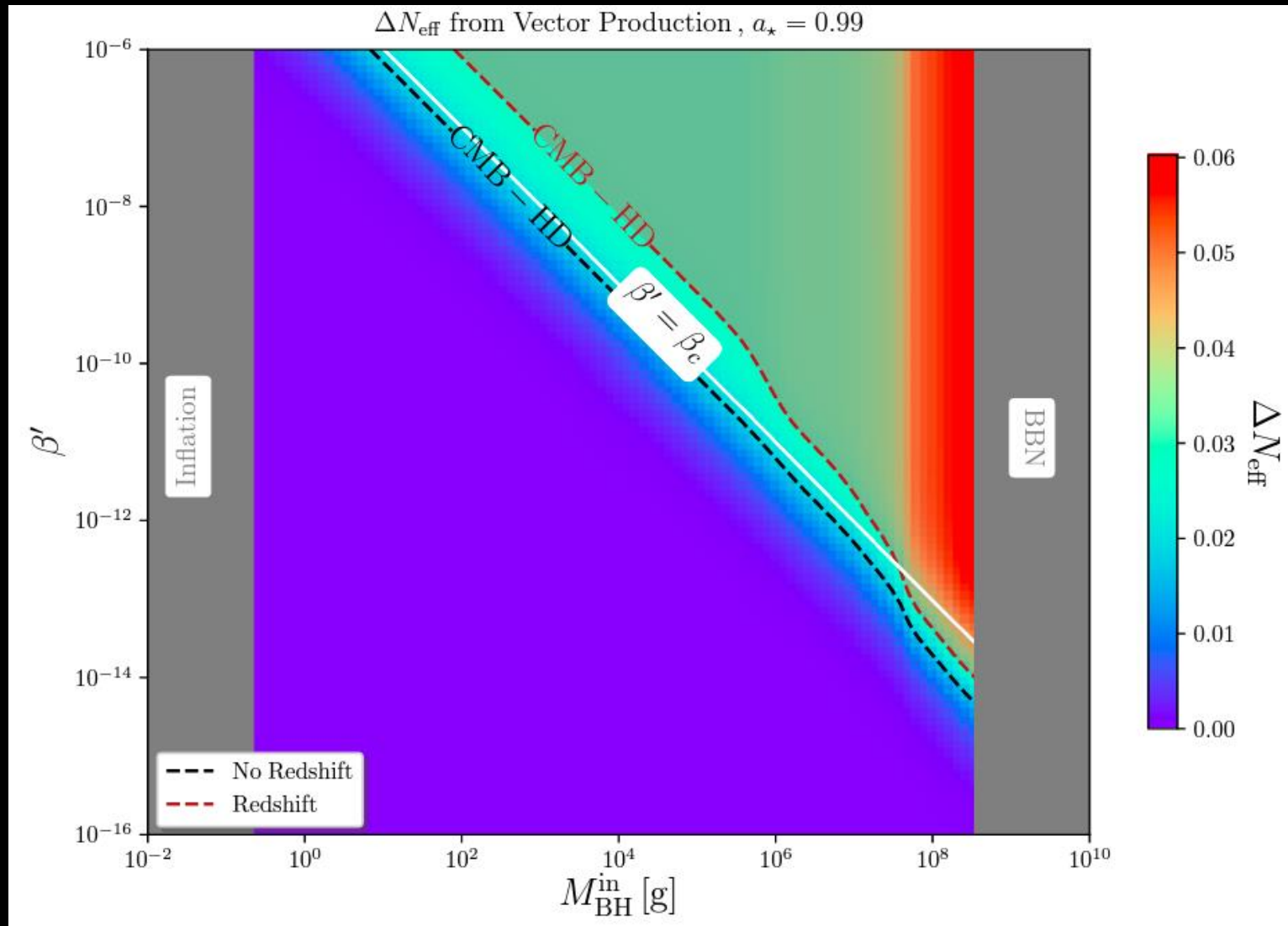
# Kerr PBHs and Dark Radiation



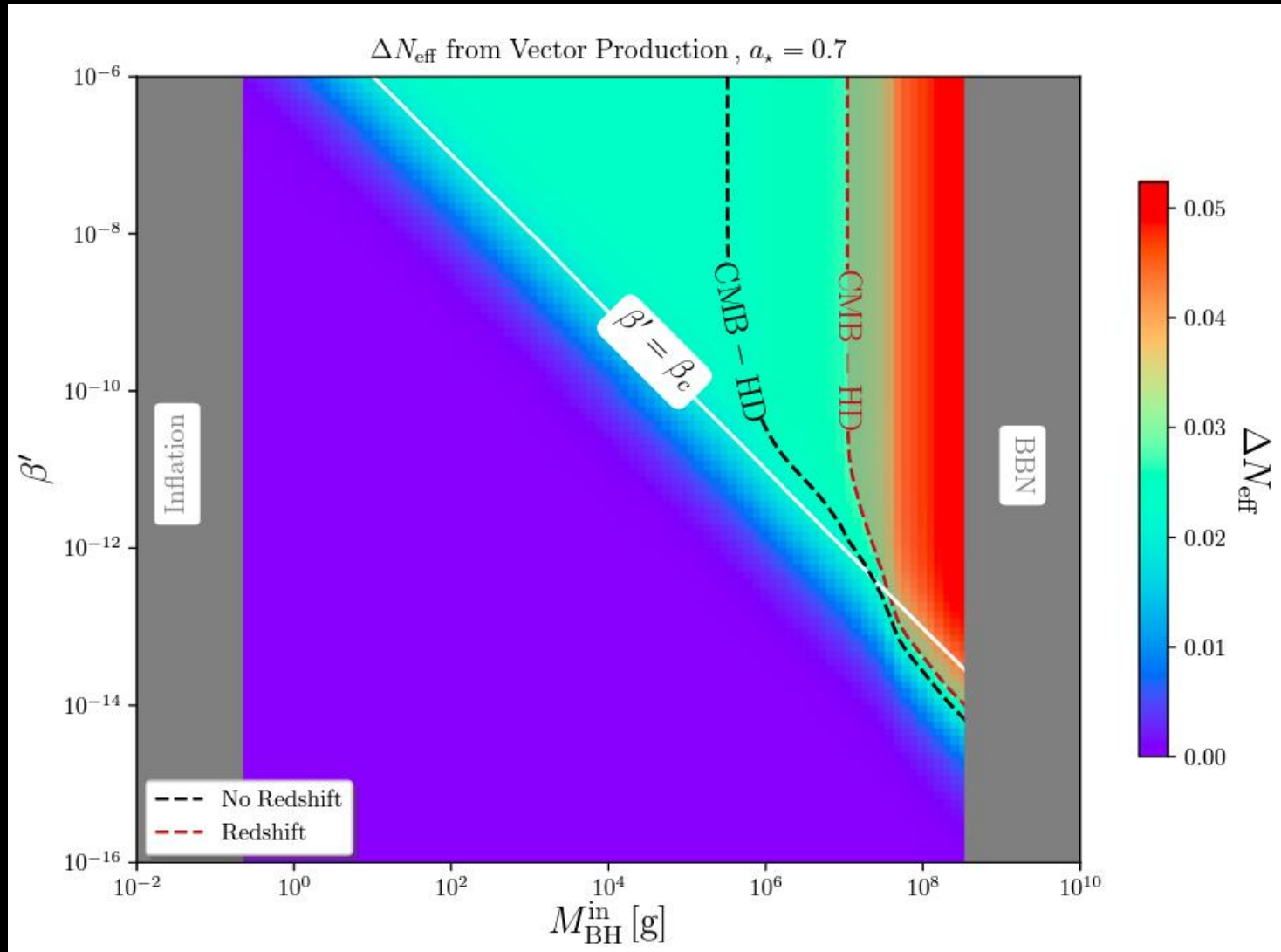
# Kerr PBHs and Dark Radiation



# Kerr PBHs and Dark Radiation



# Kerr PBHs and Dark Radiation



### III. Evaporation of Extended Distributions

### III. Evaporation of Extended Distributions

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

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



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

# III. Evaporation of Extended Distributions

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

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

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



$$\frac{da}{dt} = \frac{a}{M^3} [2f(a) - g(a)],$$

$$\frac{dM}{dt} = -\frac{f(a)}{M^2}.$$

$$\frac{dz}{dy} = \frac{f(a)}{g(a) - 2f(a)},$$

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

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

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

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

Generic  
solution( $z, \tau$ )  
for any  $M_1$

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

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

### III. Evaporation of Extended Distributions

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

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

Dynamics of the evaporation + Friedmann equations



Included in FRISBHEE

### III. Evaporation of Extended Distributions

Examples:

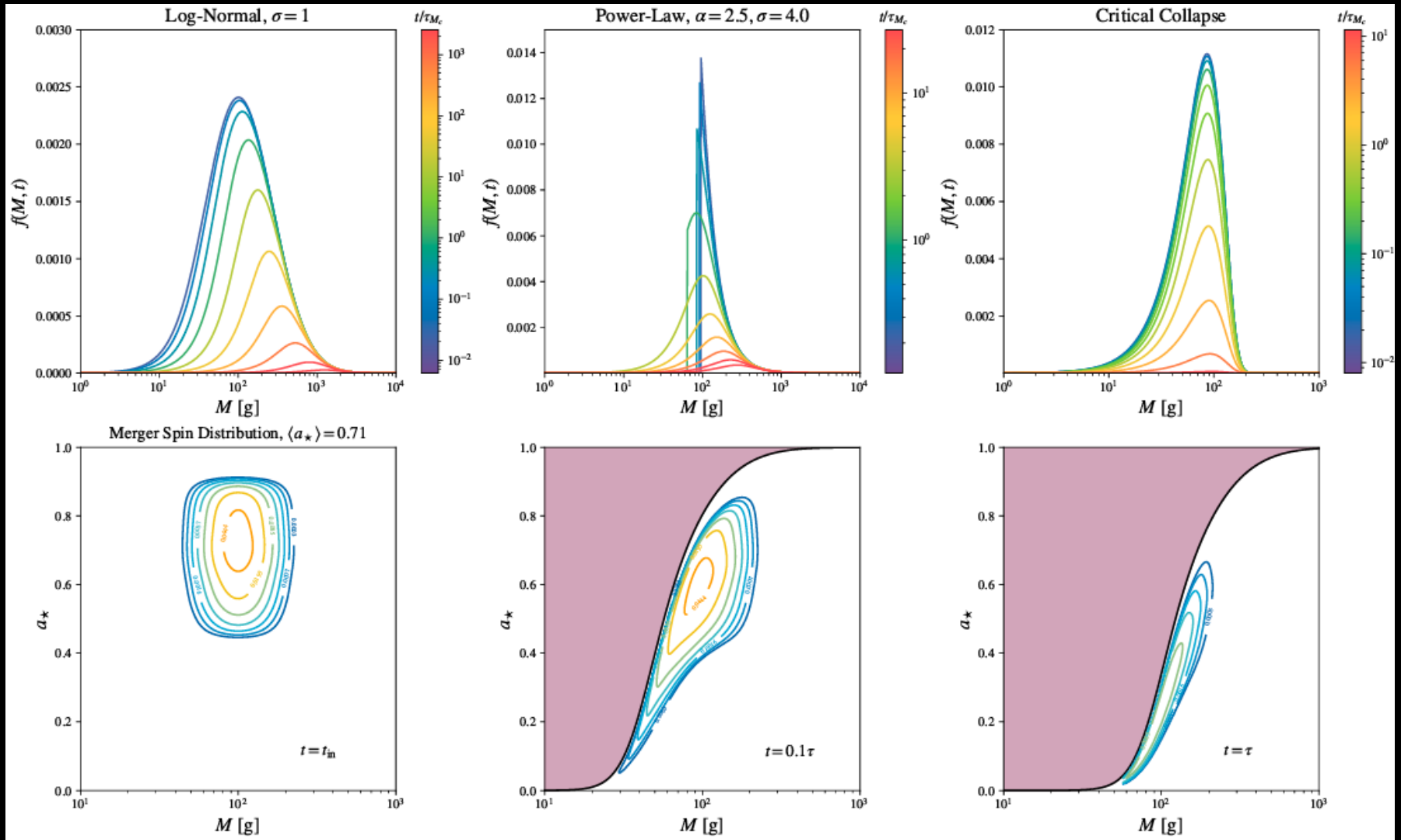
$$\frac{dn}{dM} \propto \frac{1}{M^2} \exp\left[-\frac{(\log M - \log M_c)^2}{2 \sigma^2}\right]$$

Evaporation smeared around  $\tau(M_c)$

$$\frac{dn}{dM} \propto M^{-\alpha} \quad \text{with} \quad \alpha = \frac{2(1 + 2w)}{1 + w}$$

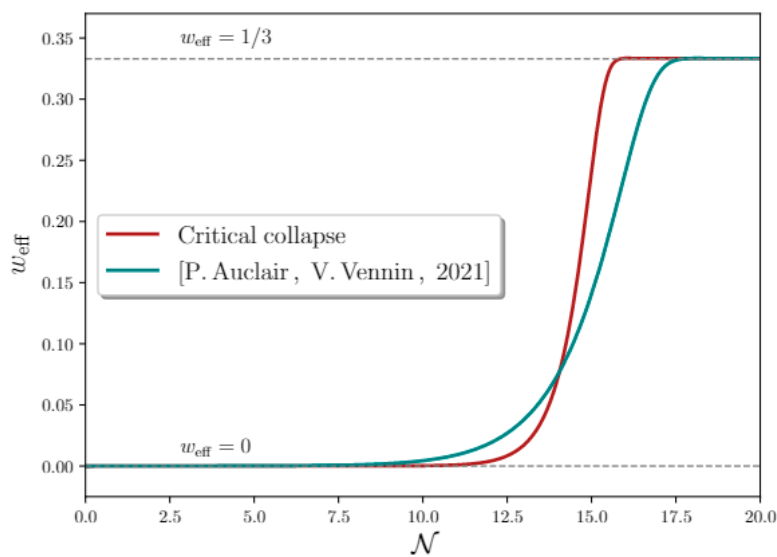
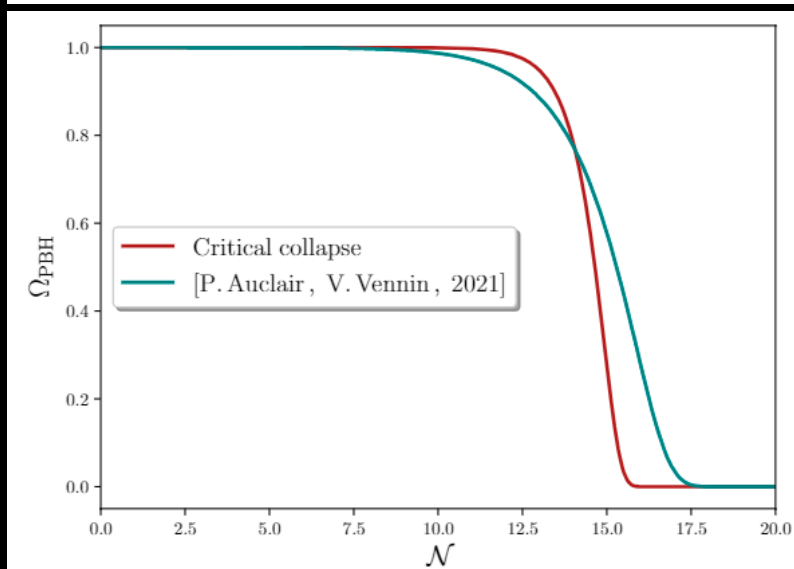
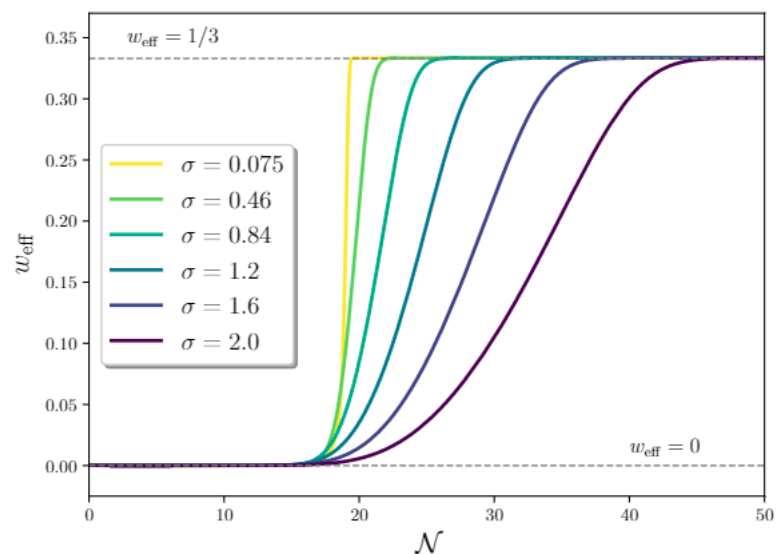
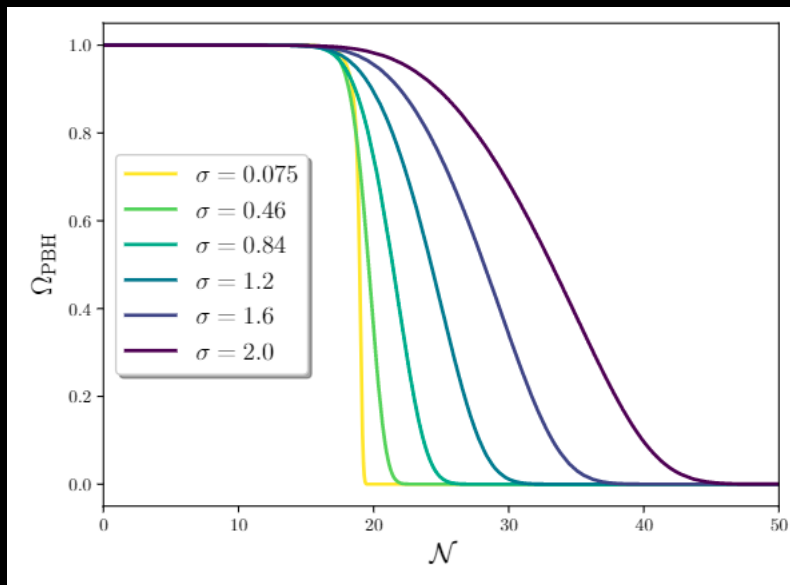
Regime of ‘Cosmological Stasis’

# III. Evaporation of Extended Distributions



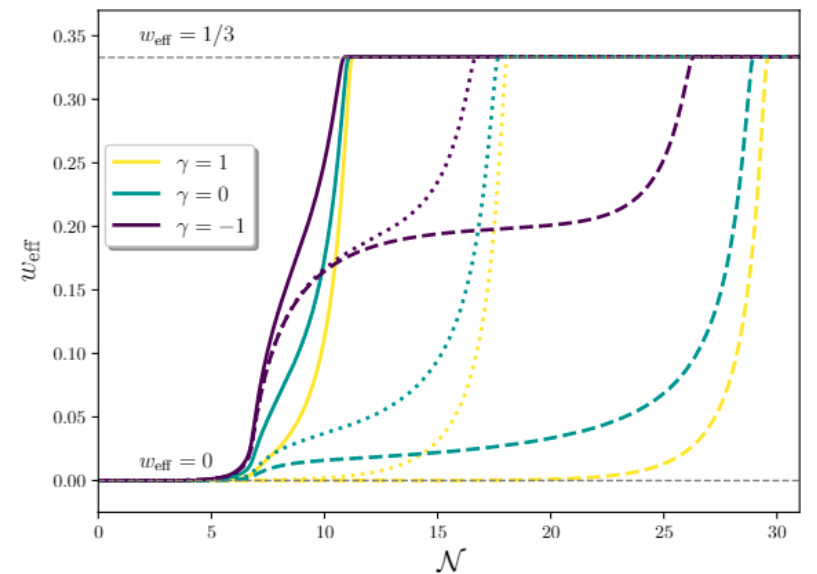
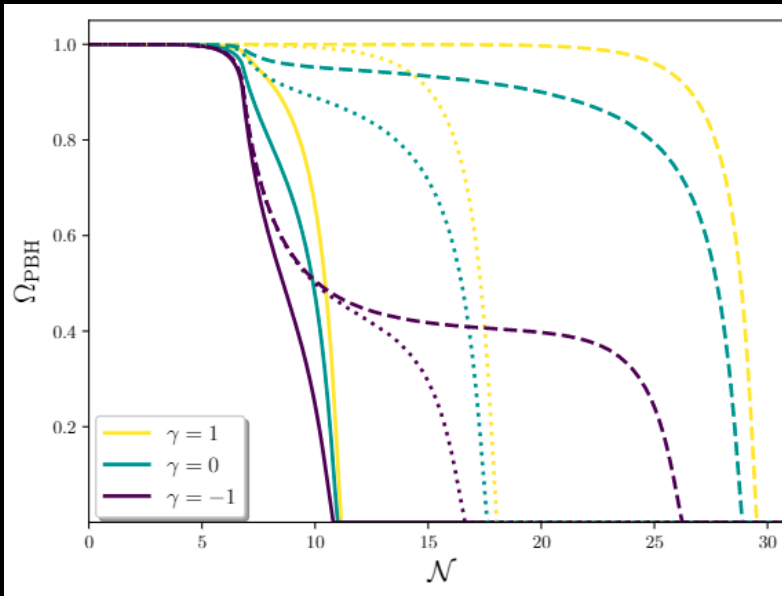
[Cheek, LH, Perez-Gonzalez, Turner '22]

# III. Evaporation of Extended Distributions



### III. Evaporation of Extended Distributions

$$\frac{dn}{dM} \propto M^{-\alpha} \quad \text{with} \quad \alpha = \frac{2(1+2w)}{1+w}$$



‘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]

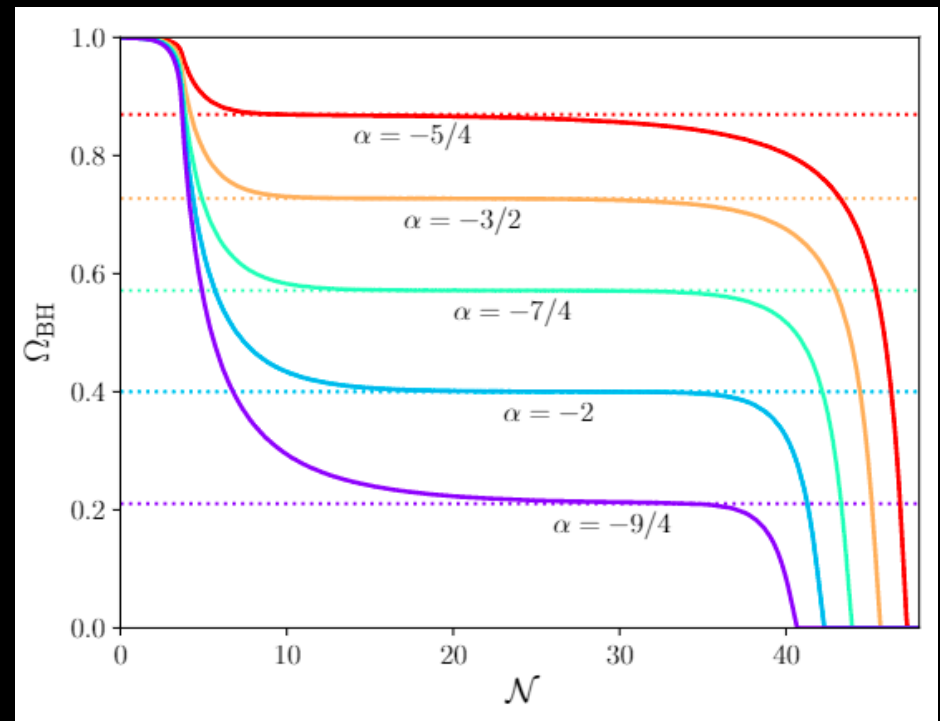
### III. Evaporation of Extended Distributions

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

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

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

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



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

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

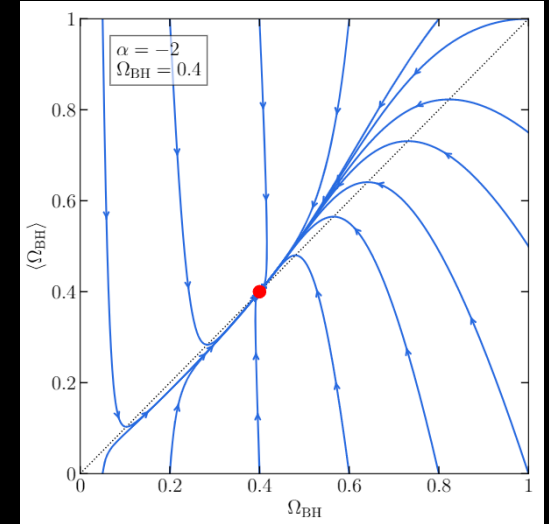
### III. Evaporation of Extended Distributions

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

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

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

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



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

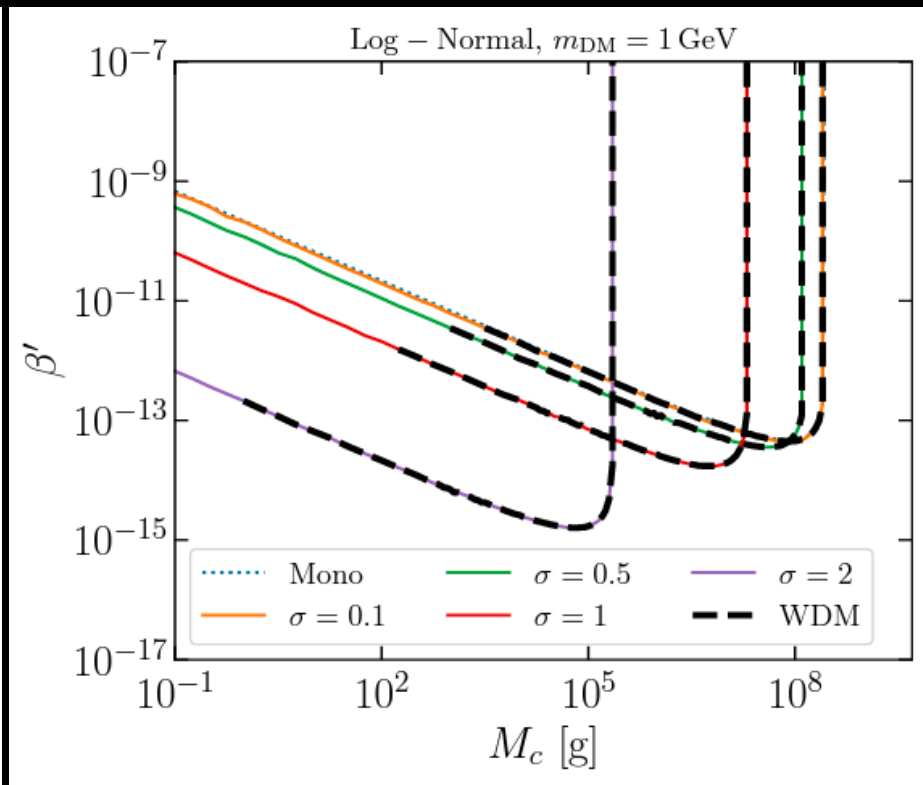
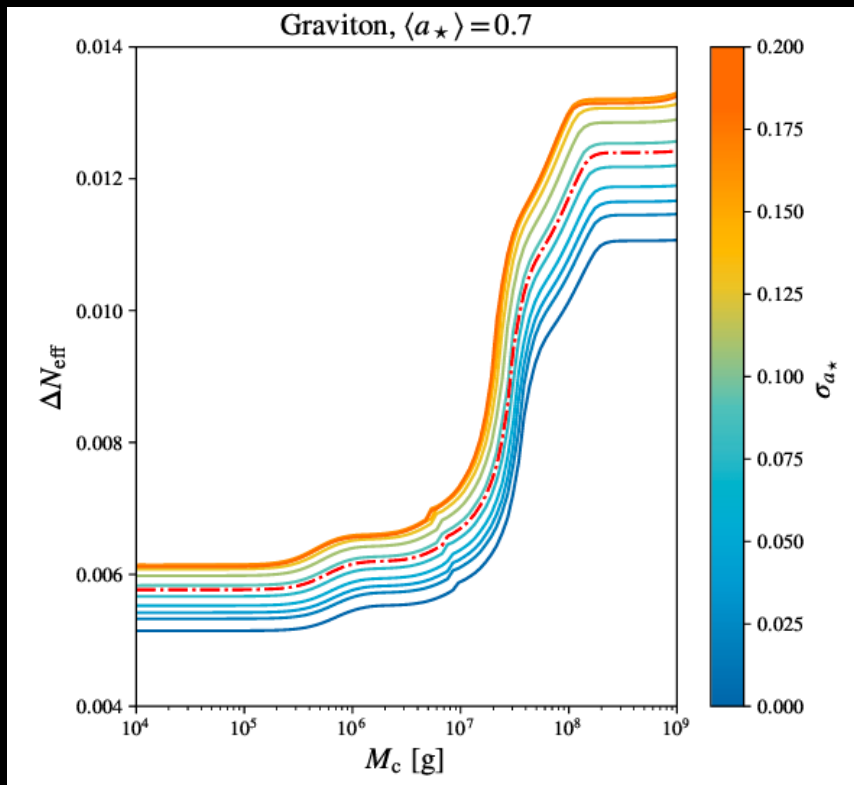
$$\Omega_{\text{BH}} = \langle \Omega_{\text{BH}} \rangle = \frac{4\alpha + 10}{\alpha + 7} \equiv \bar{\Omega}_{\text{BH}} .$$

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

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

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

### III. 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

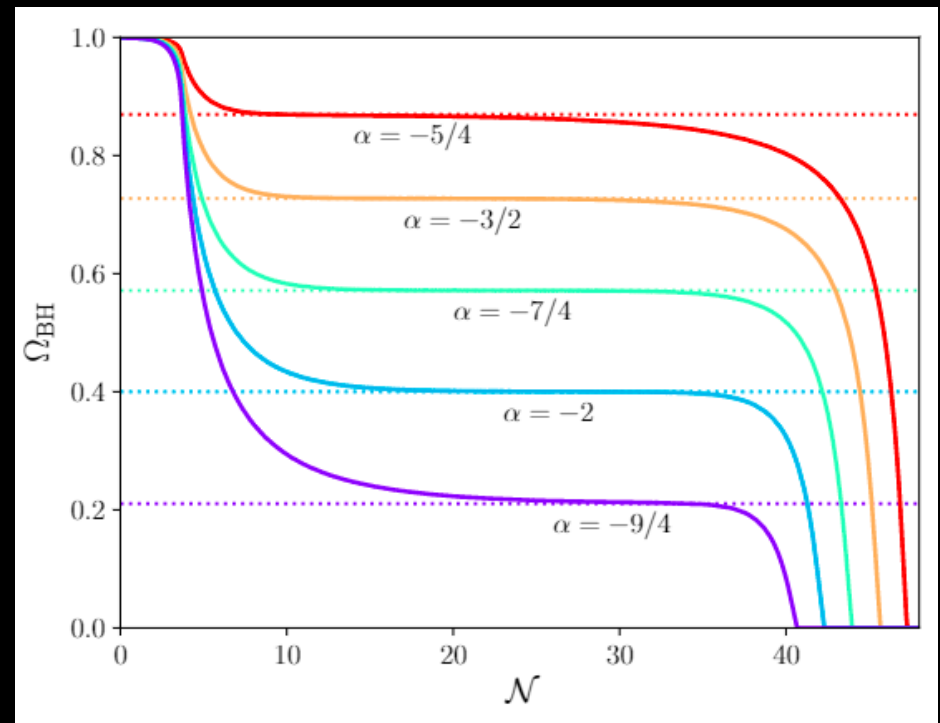
Measuring GWs can tell us a lot...

# Gravitational Waves?

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

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

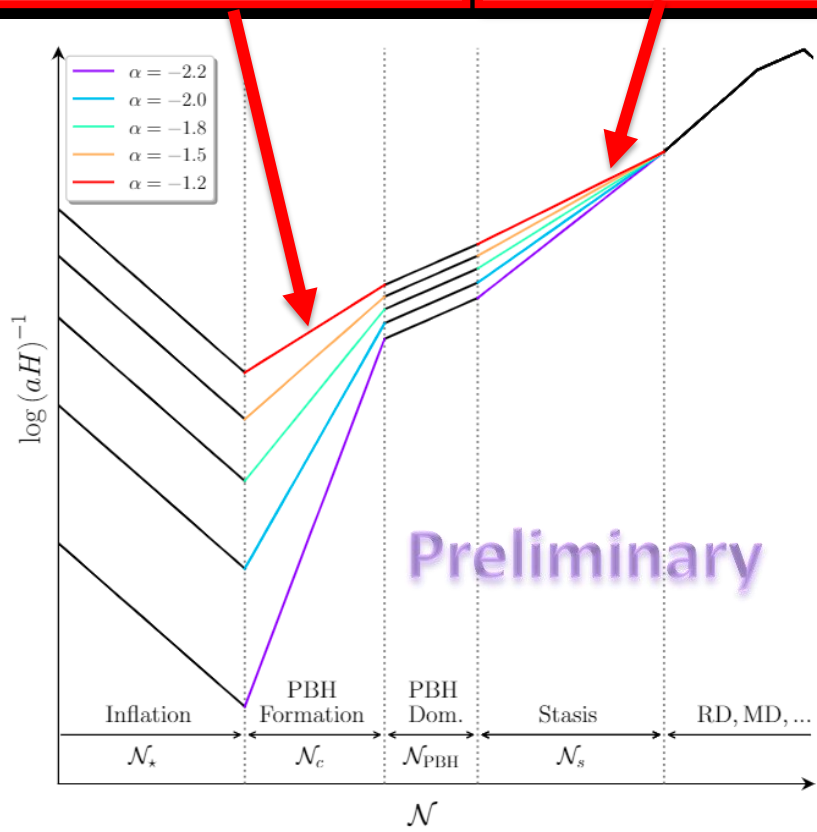
[Dienes, LH, Huang, Kim, Tait,  
Thomas '22]



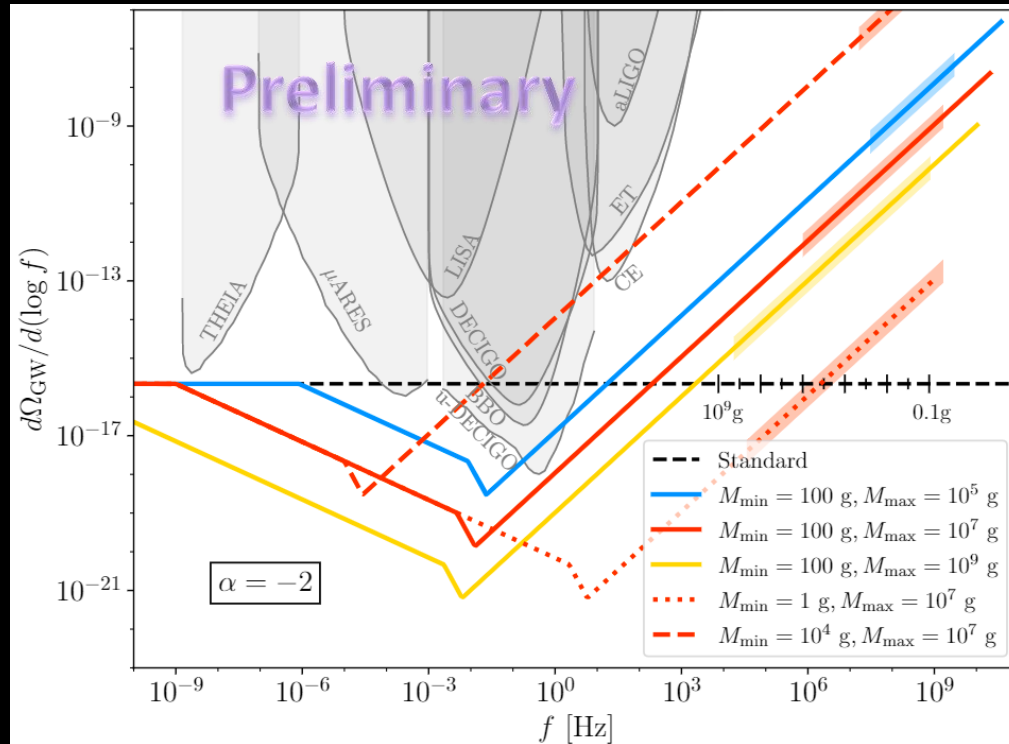
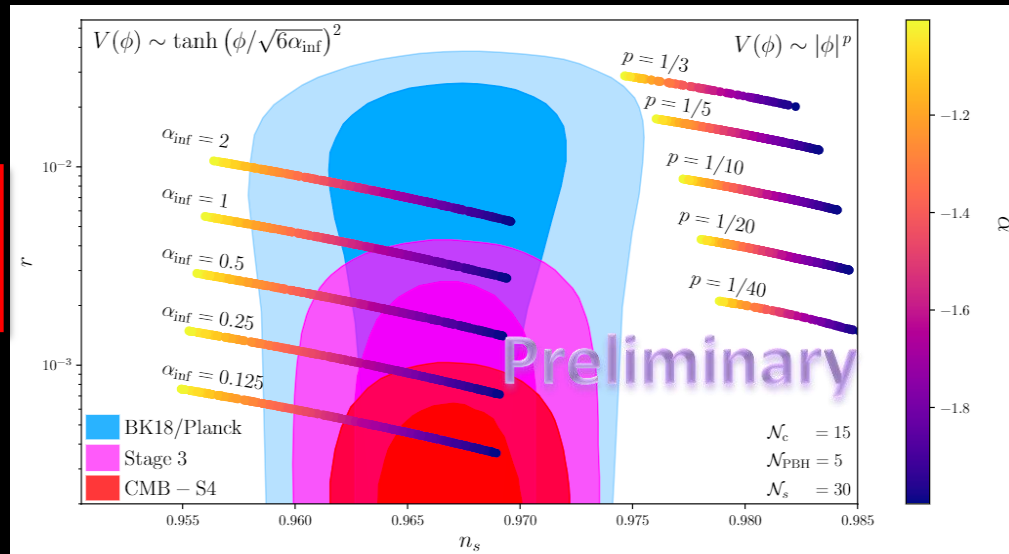
# Gravitational Waves?

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

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

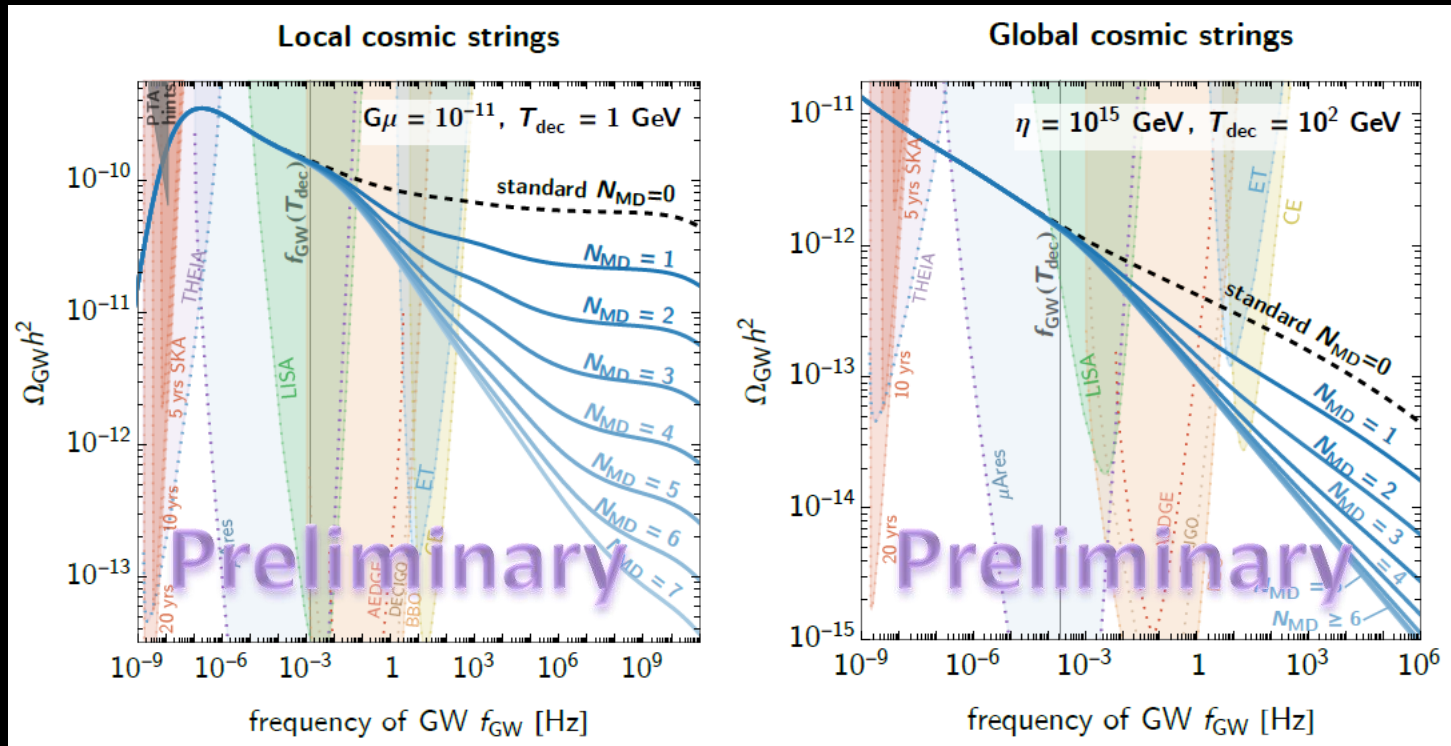


[Dienes, LH, Huang, Kim, Tait, Thomas '22]



# Gravitational Waves?

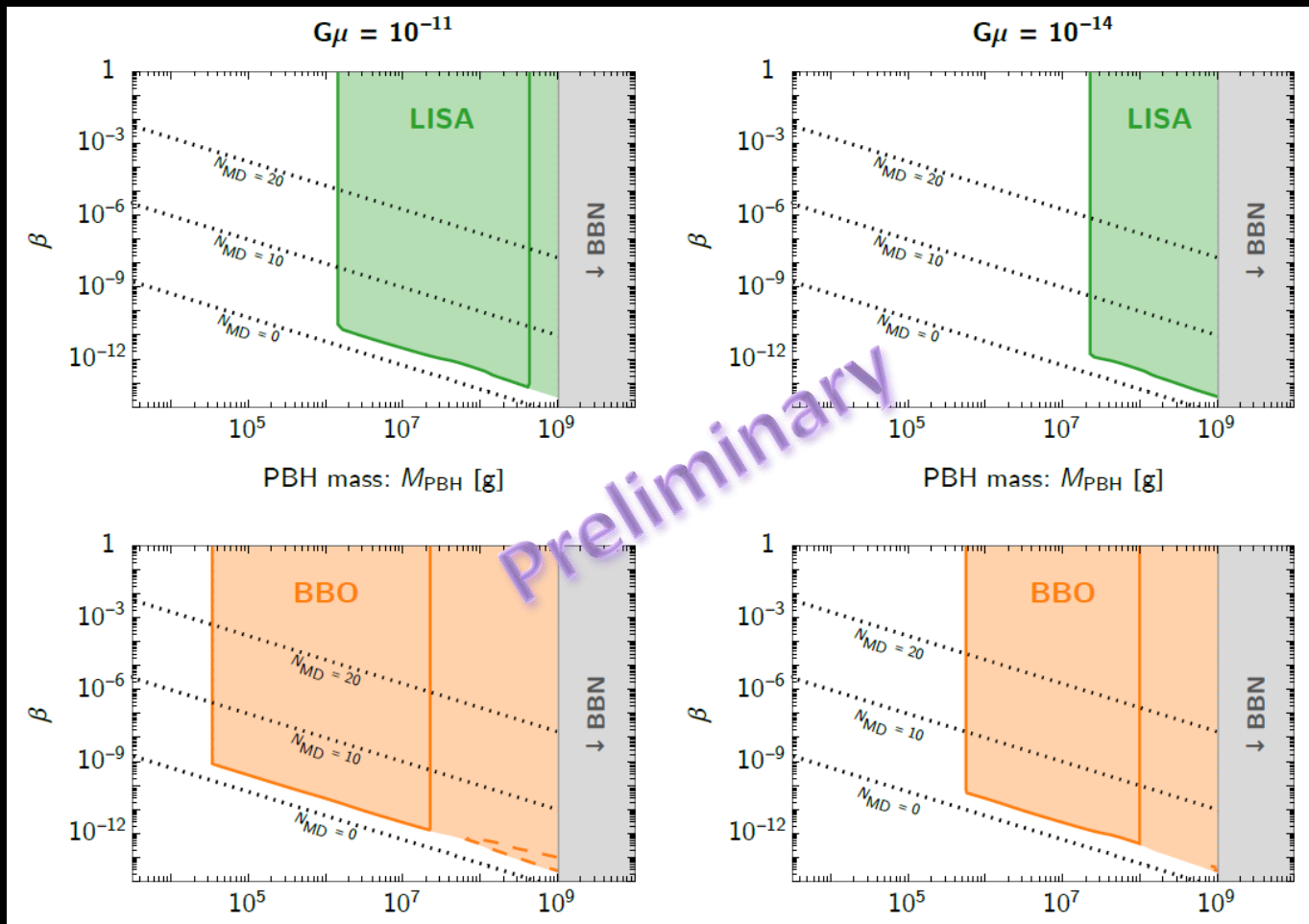
GWs from cosmic strings?



[Ghoshal, Gouttenoire, LH, Simakachorn '23]

# Gravitational Waves?

## GWs from cosmic strings?



# 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 additional 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>

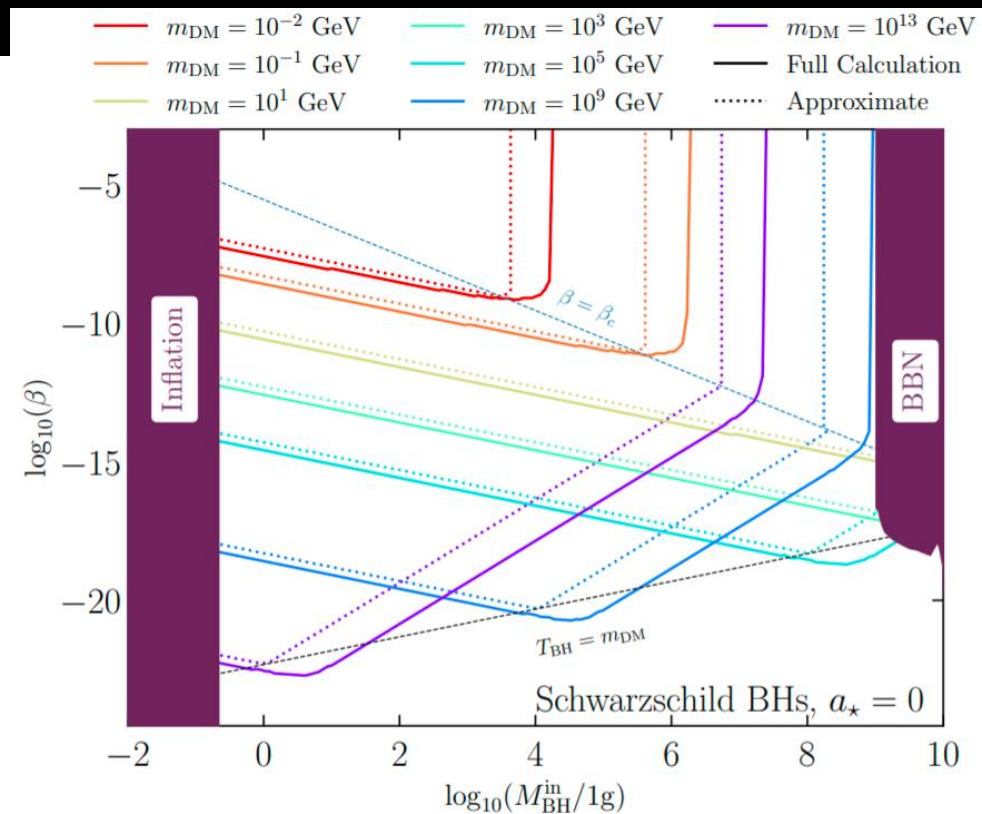
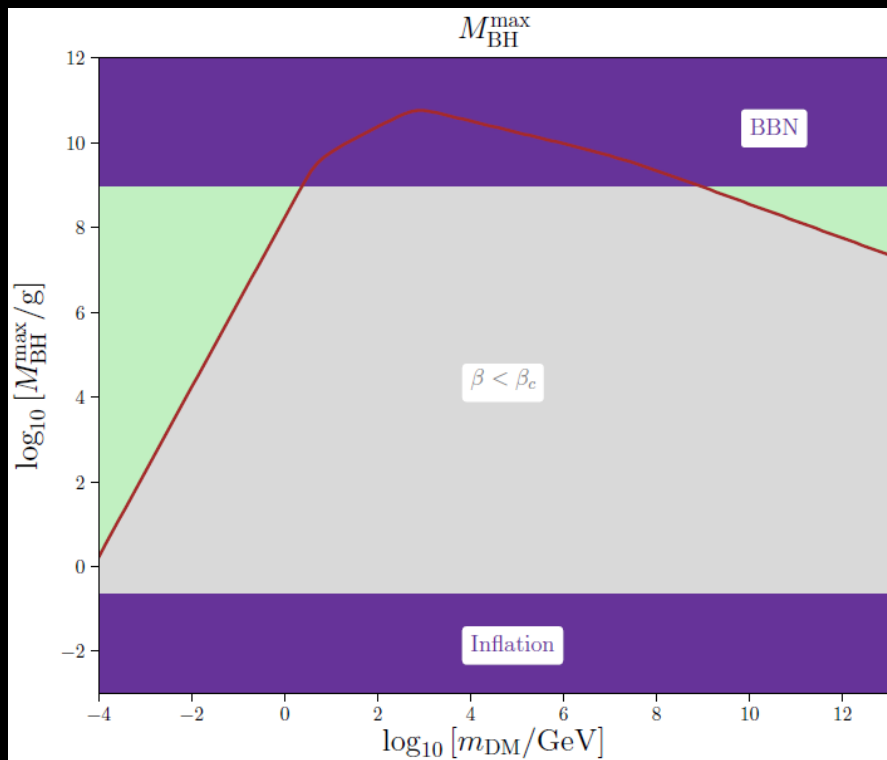
# FUTURE DIRECTIONS

- 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...

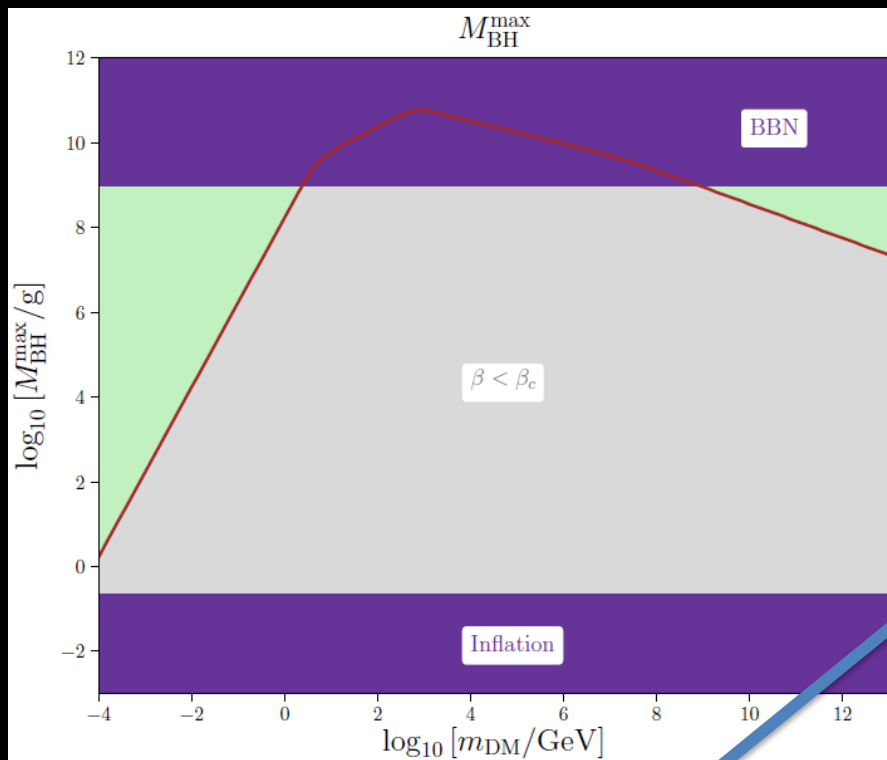
That's all folks !

Back up

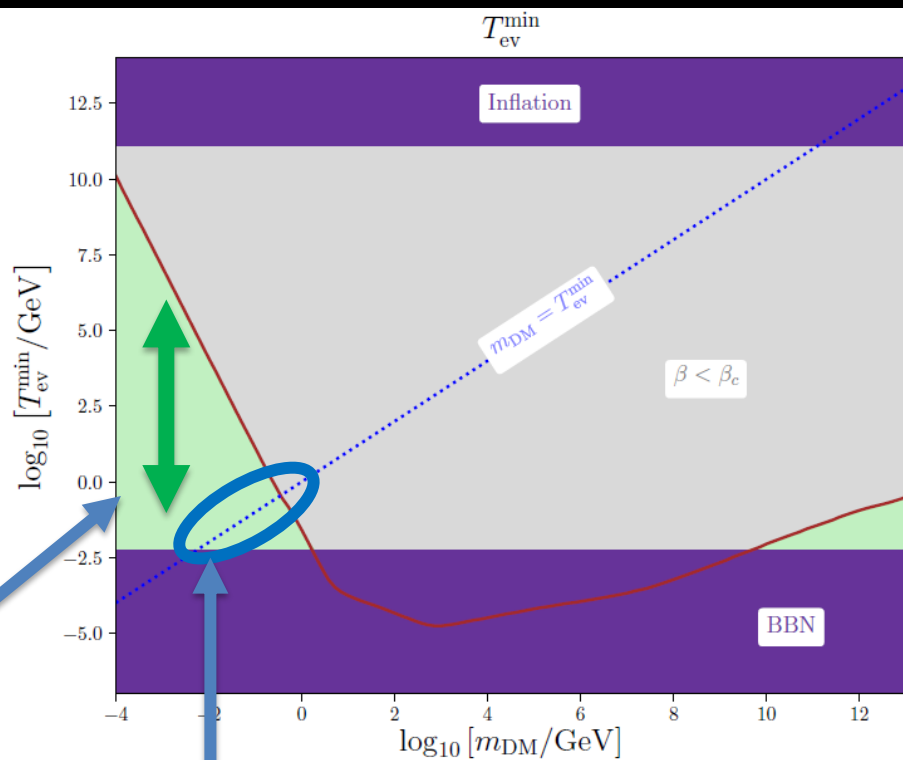
# MODIFIED COSMOLOGY



# MODIFIED COSMOLOGY

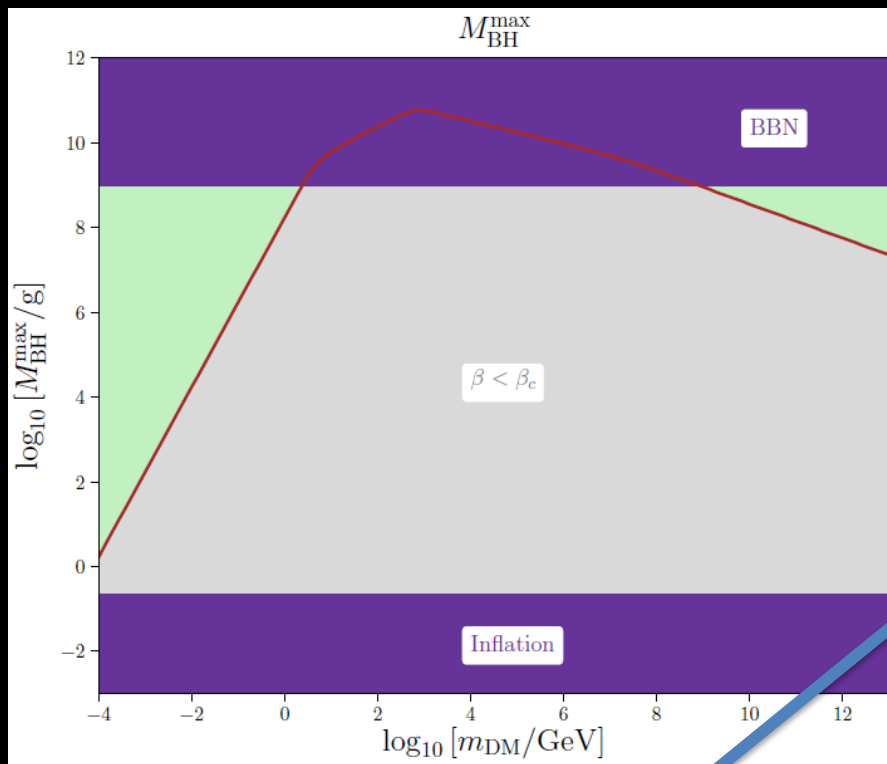


Region of interest  
for Freeze-In

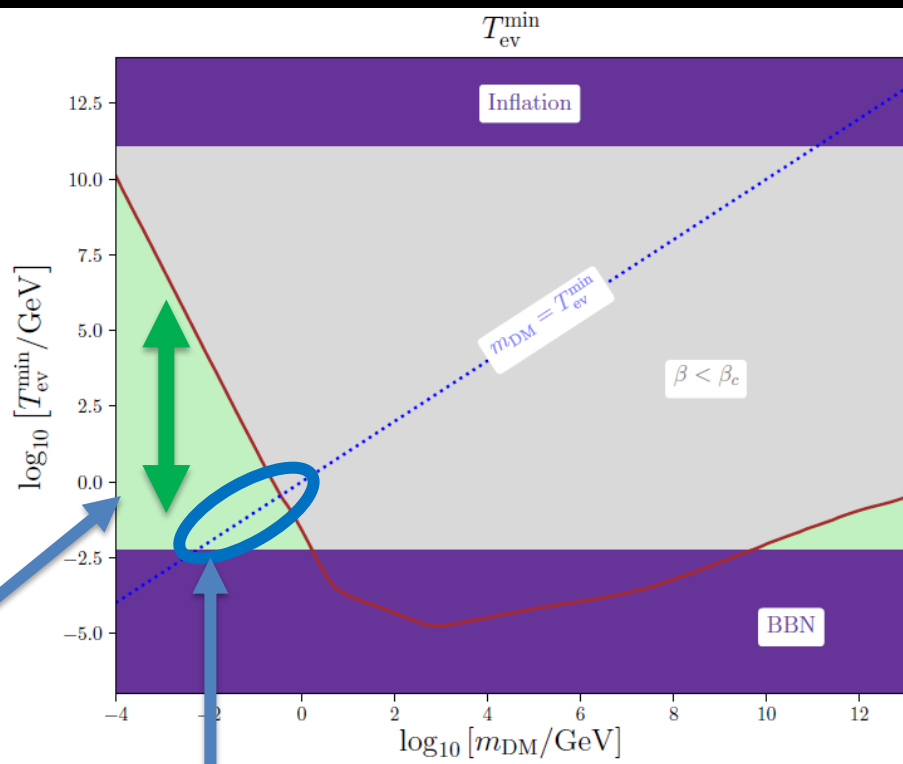


Region of interest  
for Freeze-Out

# MODIFIED COSMOLOGY



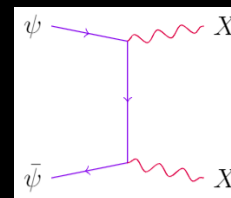
Region of interest  
for Freeze-In



~~Region of interest  
for Freeze-Out~~

**Thermalization  
Of PBHs products...**

TBH large +



# BOLTZMANN EQUATIONS

Freeze-In case:

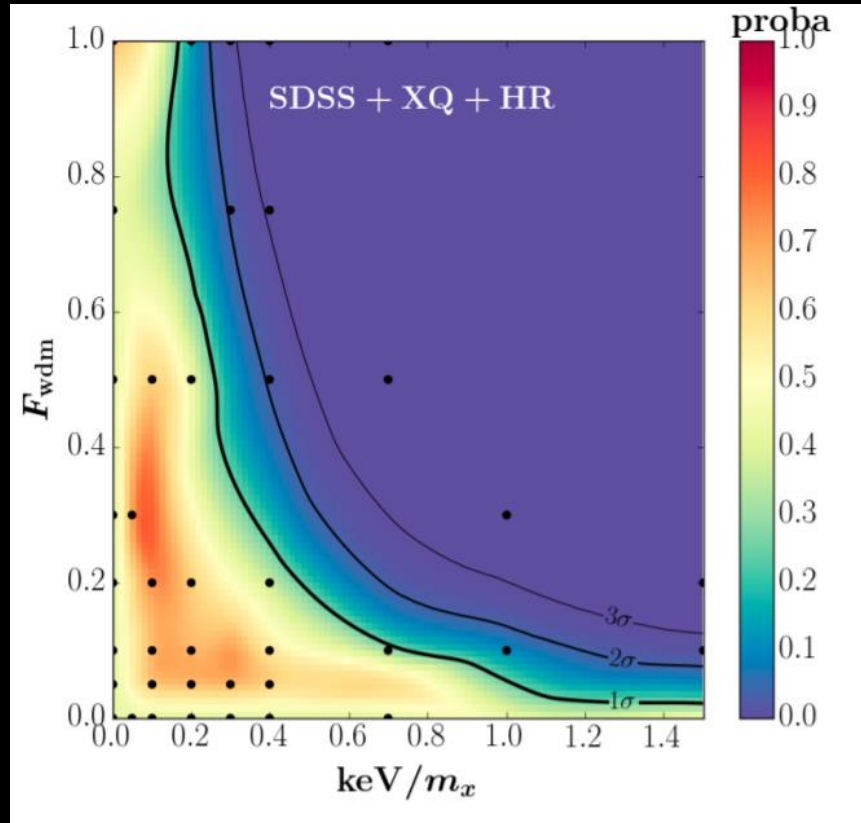
$$\dot{n}_{\text{DM}}^{\text{th}} + 3Hn_{\text{DM}}^{\text{th}} = \langle \sigma v \rangle_{\text{th}} (n_{\text{DM,eq}}^2 - n_{\text{DM}}^{\text{th}2})$$

$$\dot{n}_{\text{DM}}^{\text{ev}} + 3Hn_{\text{DM}}^{\text{ev}} = \left. \frac{dn_{\text{DM}}^{\text{ev}}}{dt} \right|_{\text{BH}} + 2\Gamma_{X \rightarrow \text{DM}} \left\langle \frac{m_X}{E_X} \right\rangle_{\text{ev}} n_X$$

$$\dot{n}_X + 3Hn_X = \left. \frac{dn_X}{dt} \right|_{\text{BH}} - \Gamma_X \left\langle \frac{m_X}{E_X} \right\rangle_{\text{ev}} n_X$$

$$\dot{\rho}_{\text{SM}} + 4H\rho_{\text{SM}} = \left. \frac{dM}{dt} \right|_{\text{SM}} + 2m_X \Gamma_{X \rightarrow \text{SM}} n_X$$

# NON-COLD DARK MATTER

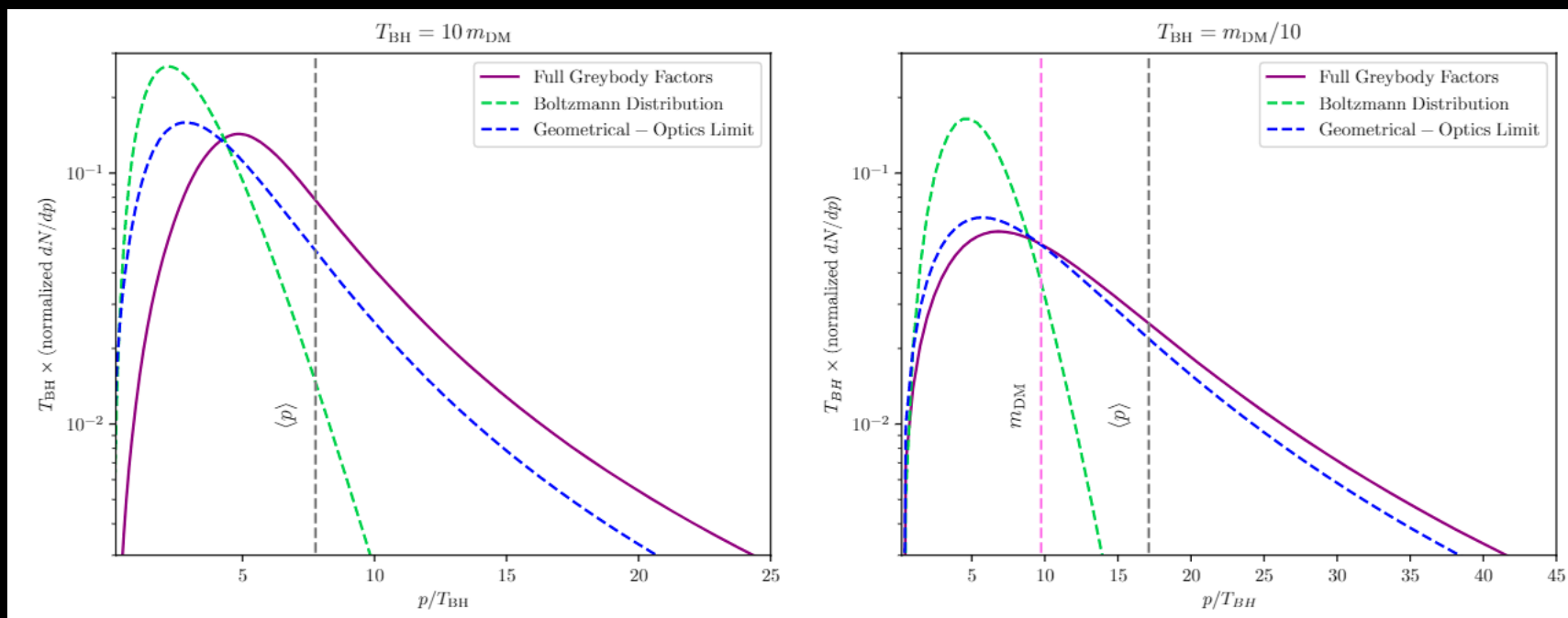


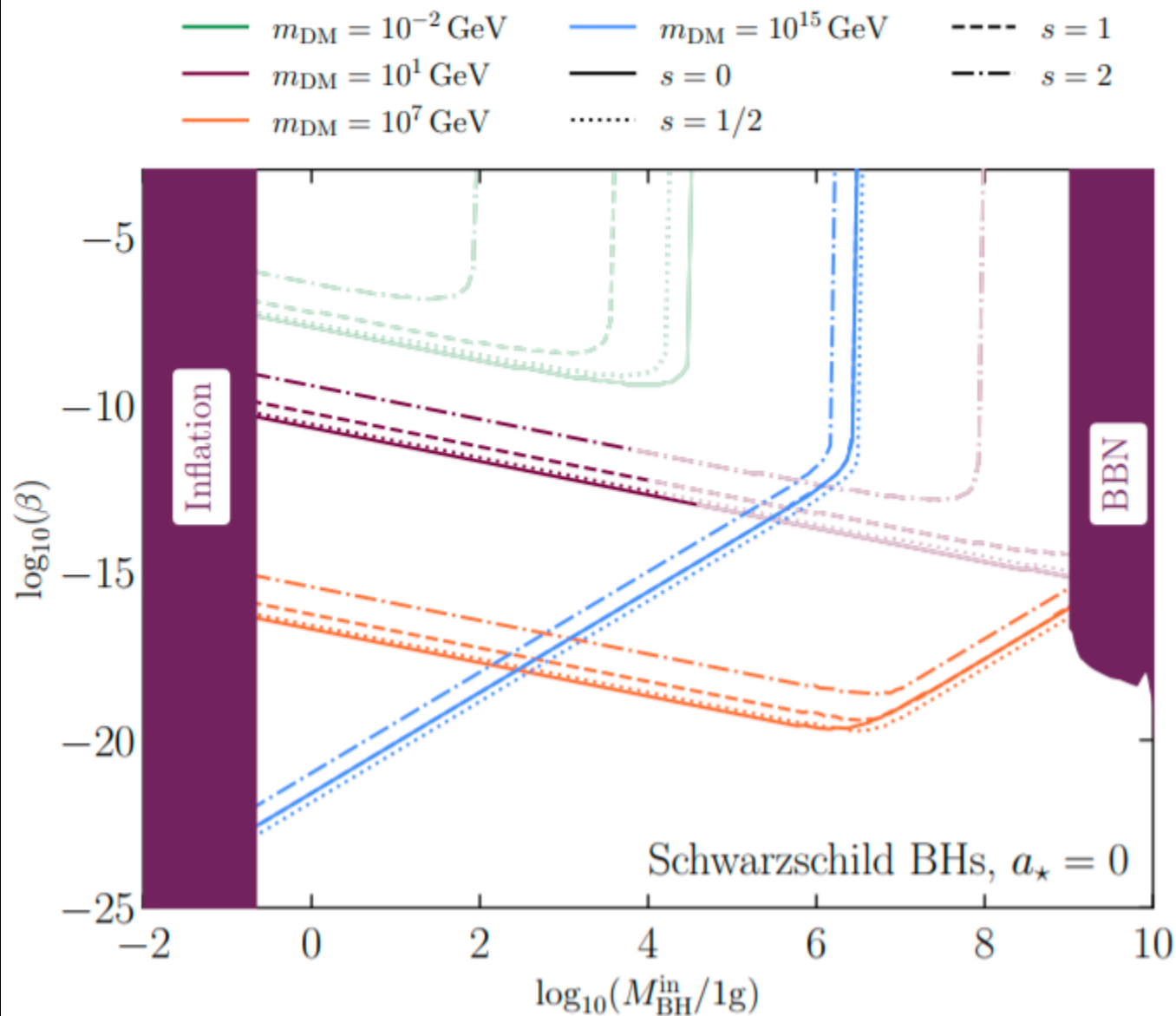
[Baur *et al.* 2017]

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

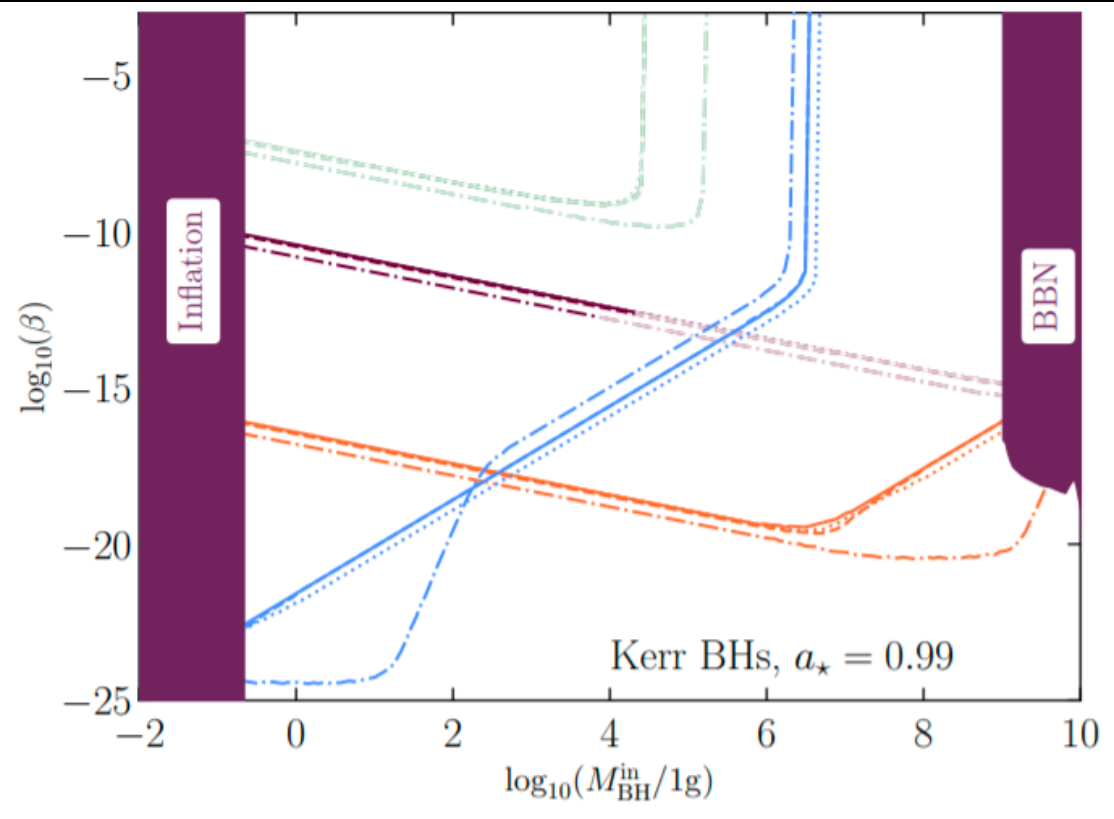
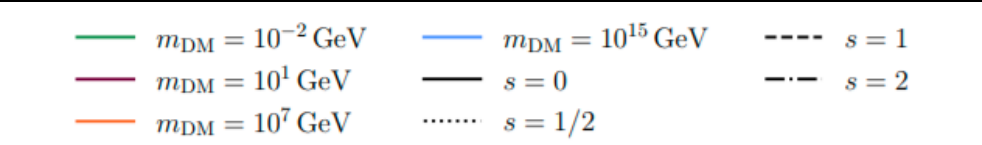
# DM FROM EVAPORATION

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





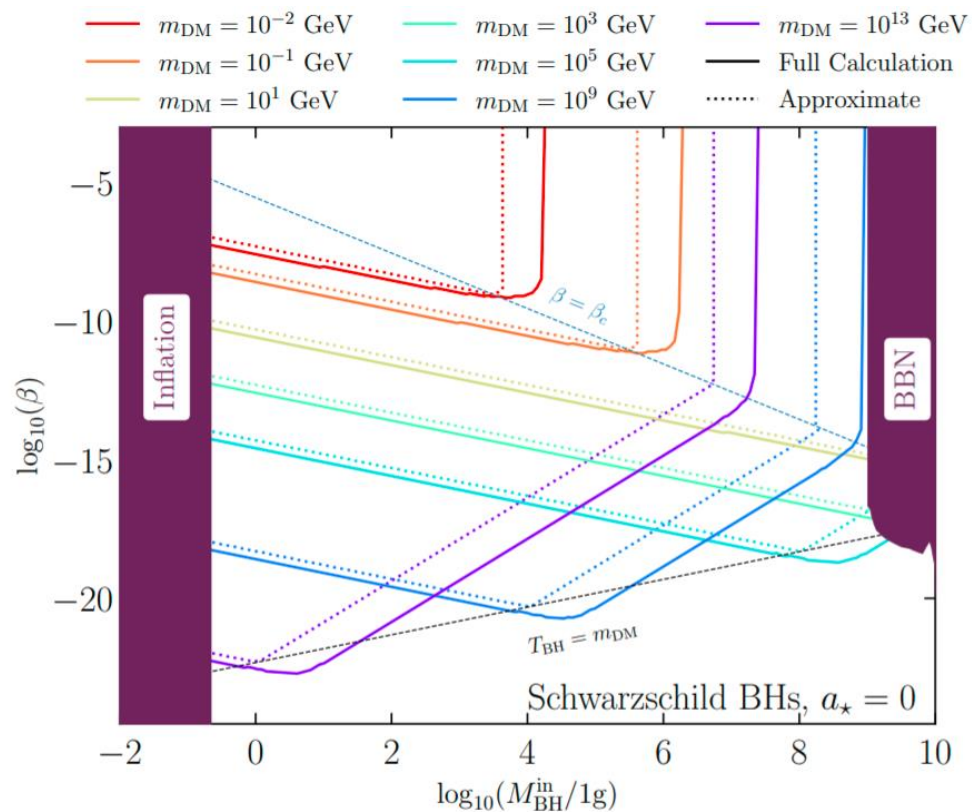
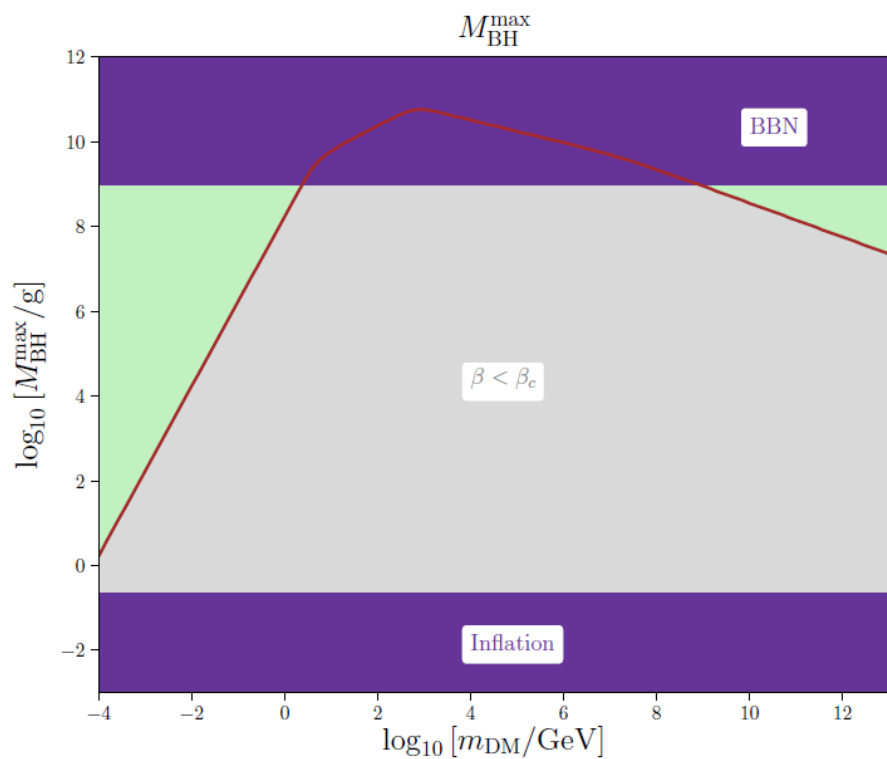
$$T_{\text{BH}} = \frac{1}{4\pi G M_{\text{BH}}} \frac{\sqrt{1 - a_\star^2}}{1 + \sqrt{1 - a_\star^2}},$$



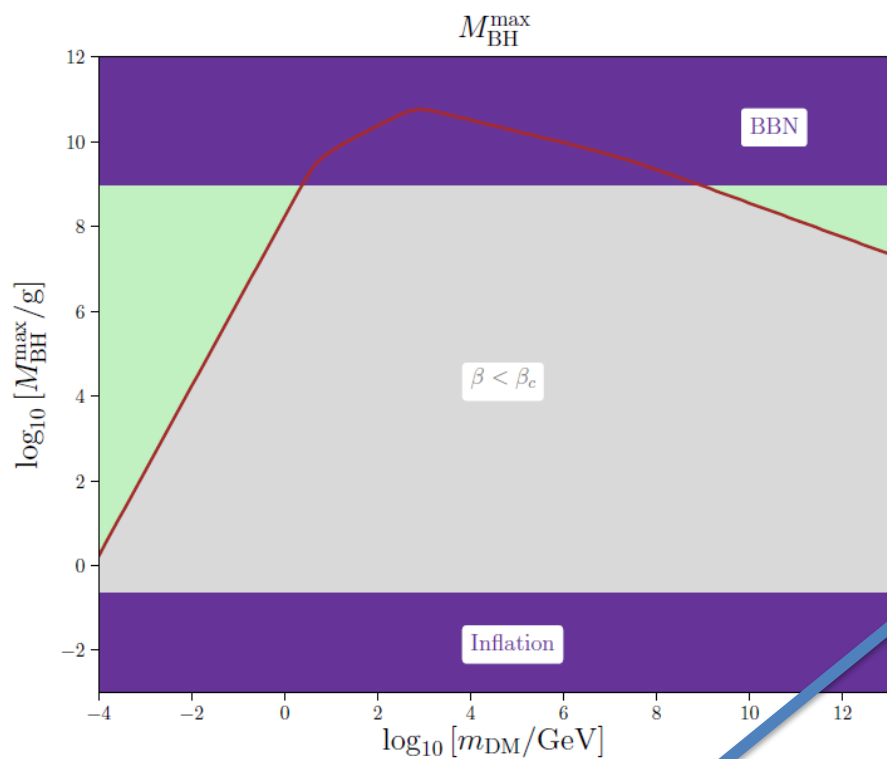
$$\frac{d^2 \mathcal{N}_{ilm}}{dp dt} = \frac{\sigma_{s_i}^{lm}(M_{\text{BH}}, p, a_\star)}{\exp[(E_i - m\Omega)/T_{\text{BH}}] - (-1)^{2s_i}} \frac{p^3}{E_i}$$

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

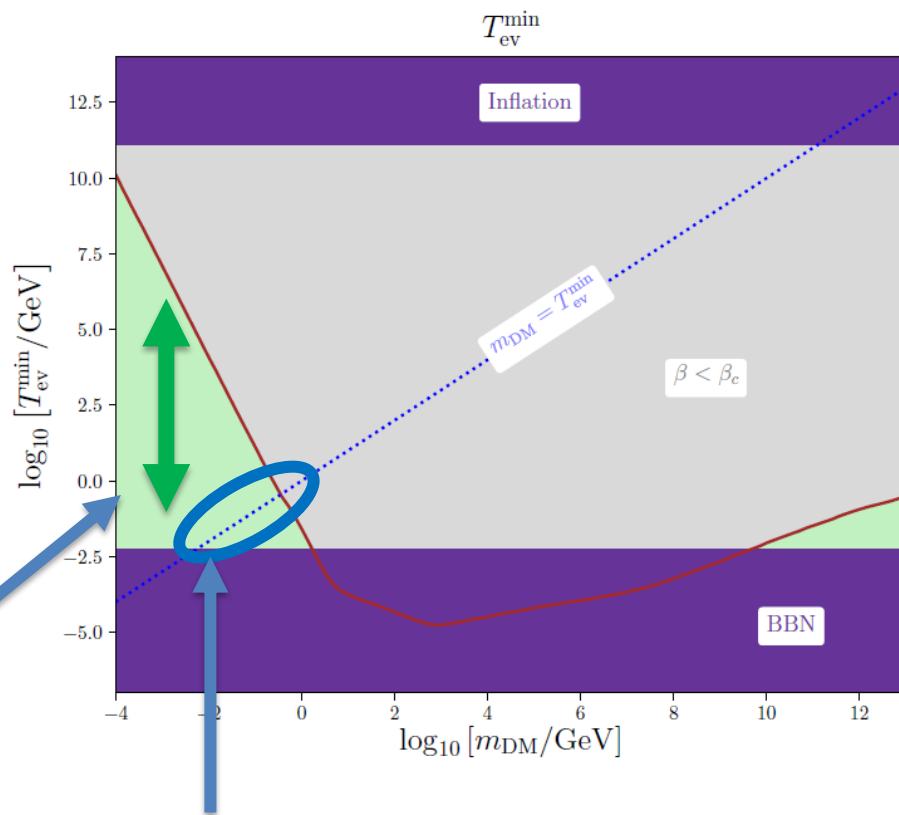
# MODIFIED COSMOLOGY



# MODIFIED COSMOLOGY

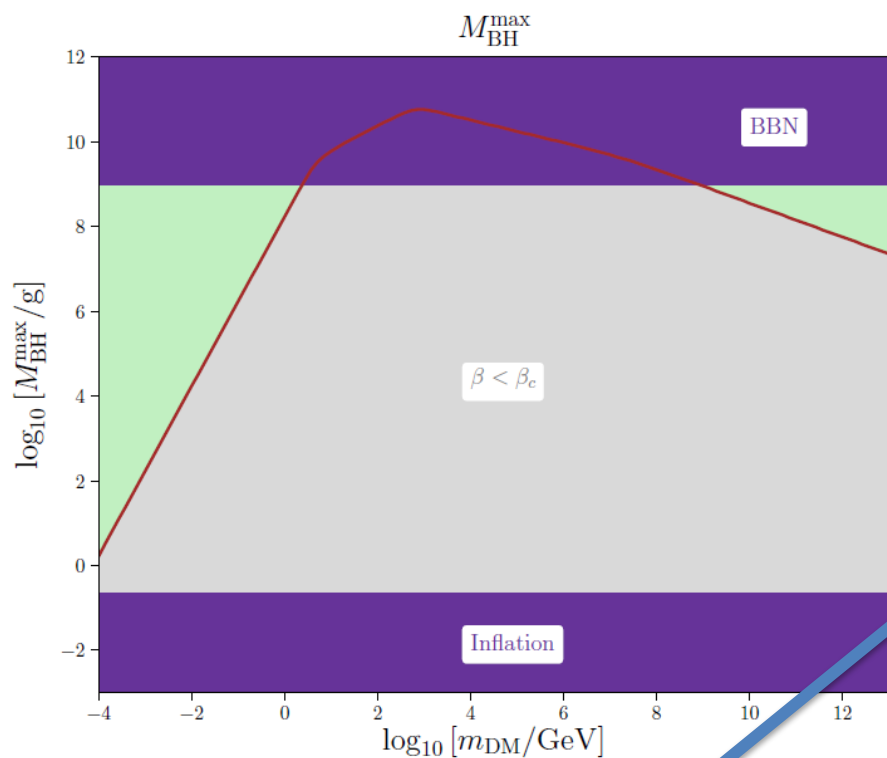


Region of interest  
for Freeze-In

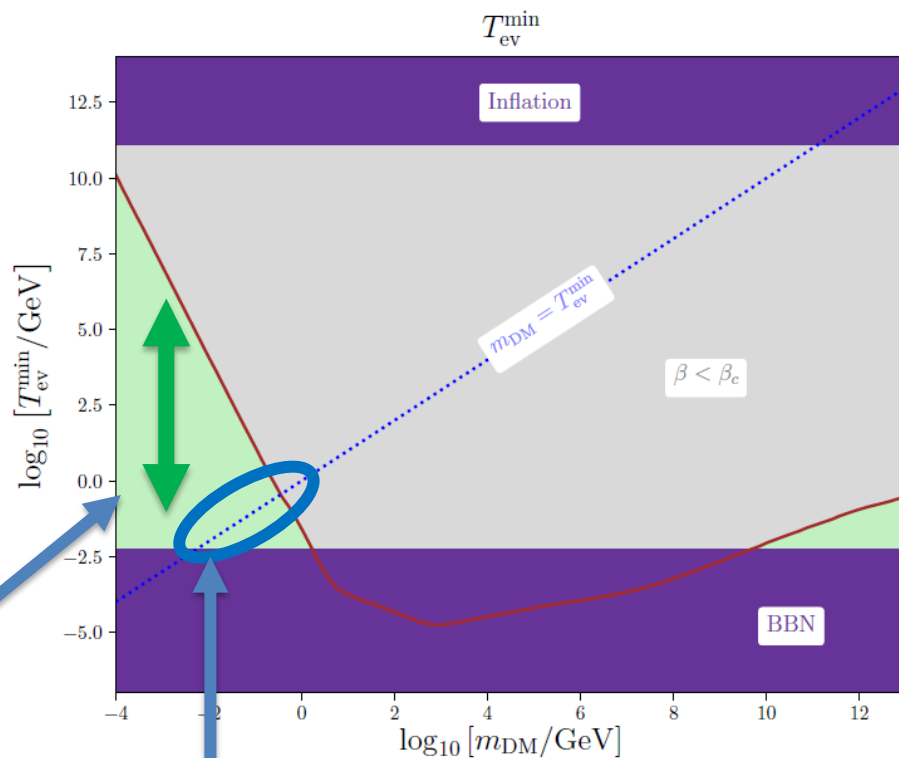


Region of interest  
for Freeze-Out

# MODIFIED COSMOLOGY



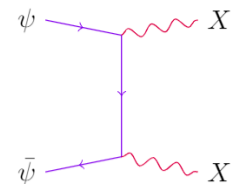
Region of interest  
for Freeze-In



~~Region of interest  
for Freeze-Out~~

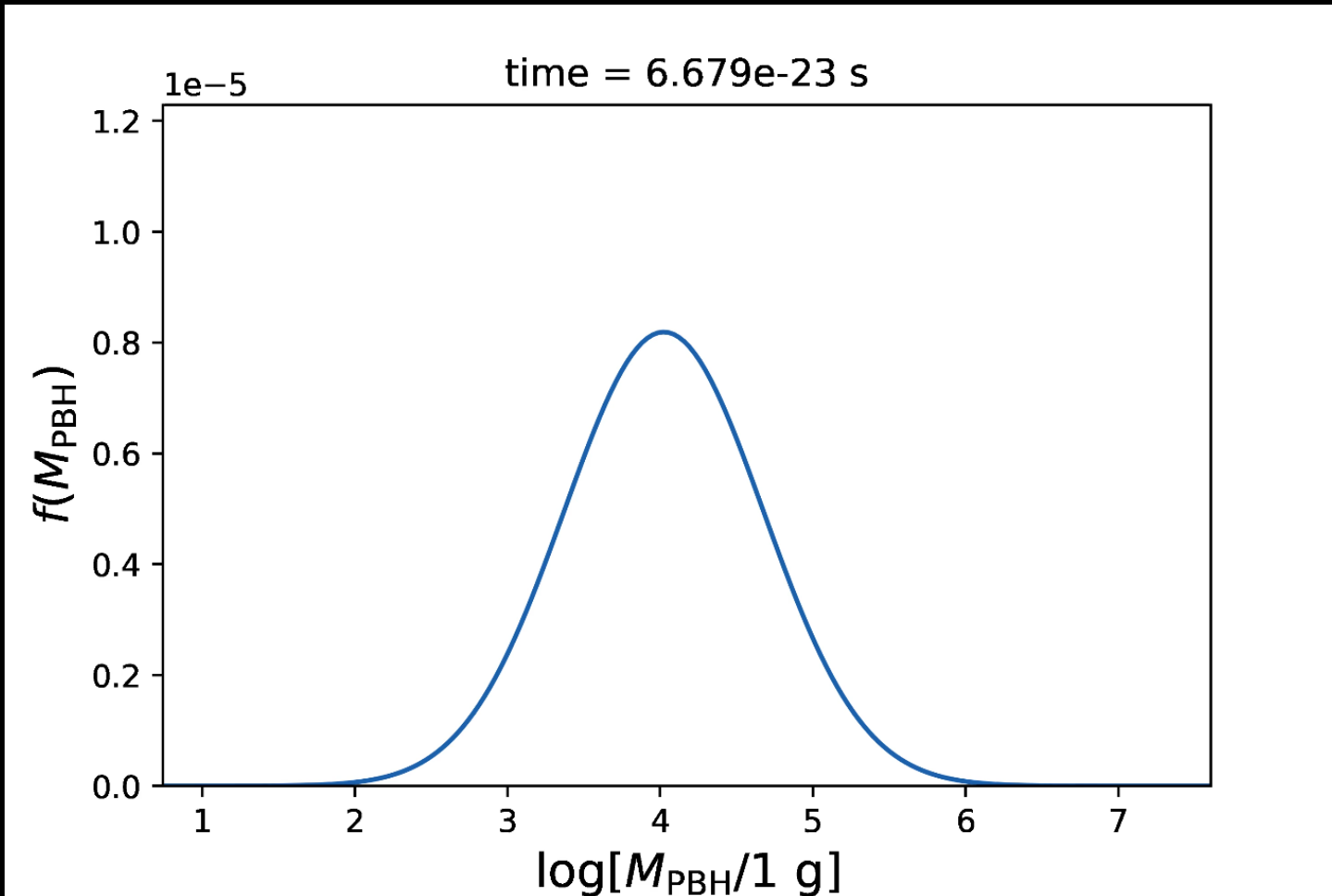
**Thermalization  
Of PBHs products...**

TBH large +



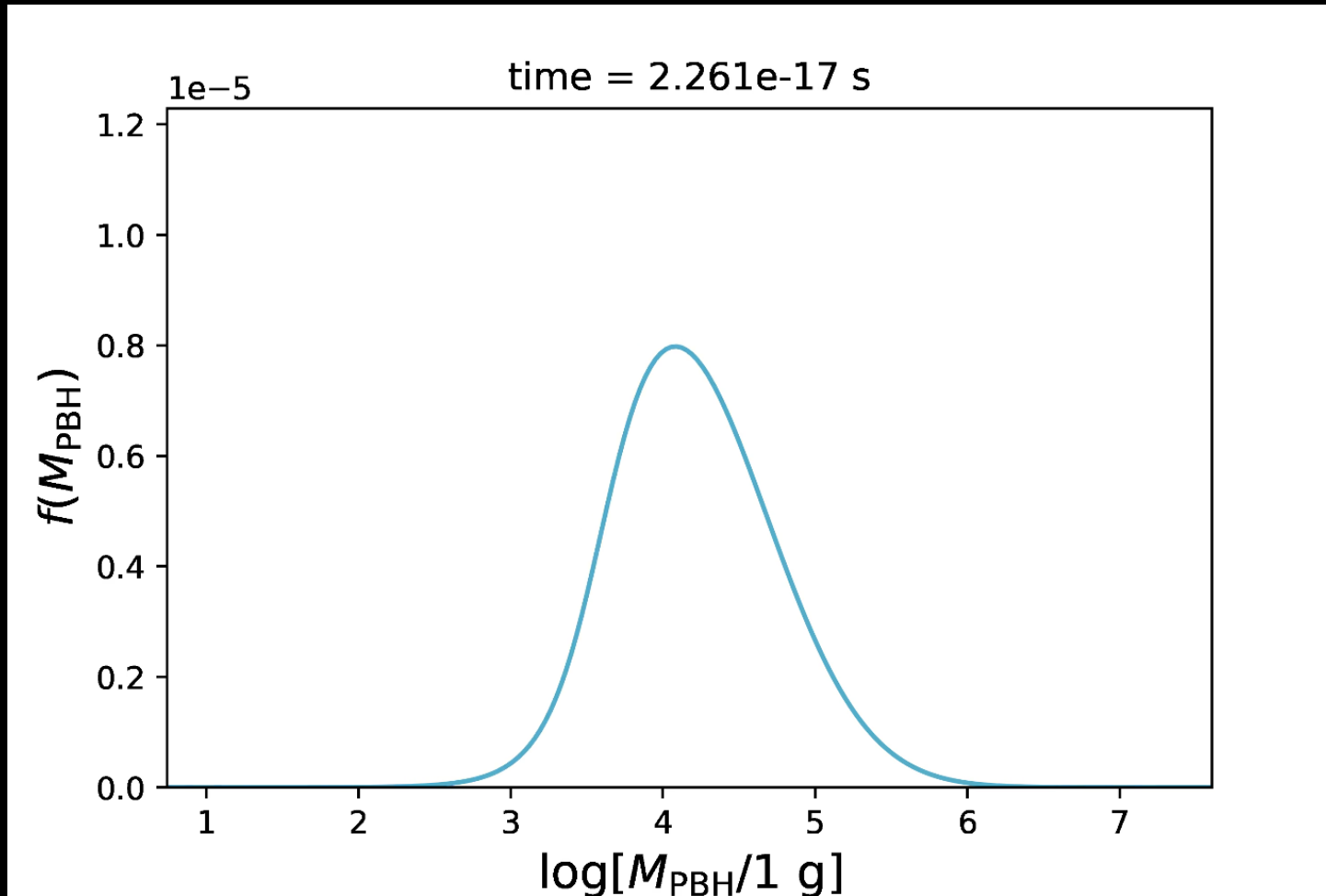
## IV. Evaporation of Extended Distributions

$$\frac{dn}{dM} \propto \frac{1}{M^2} \exp\left[-\frac{(\log M - \log M_c)^2}{2\sigma^2}\right]$$



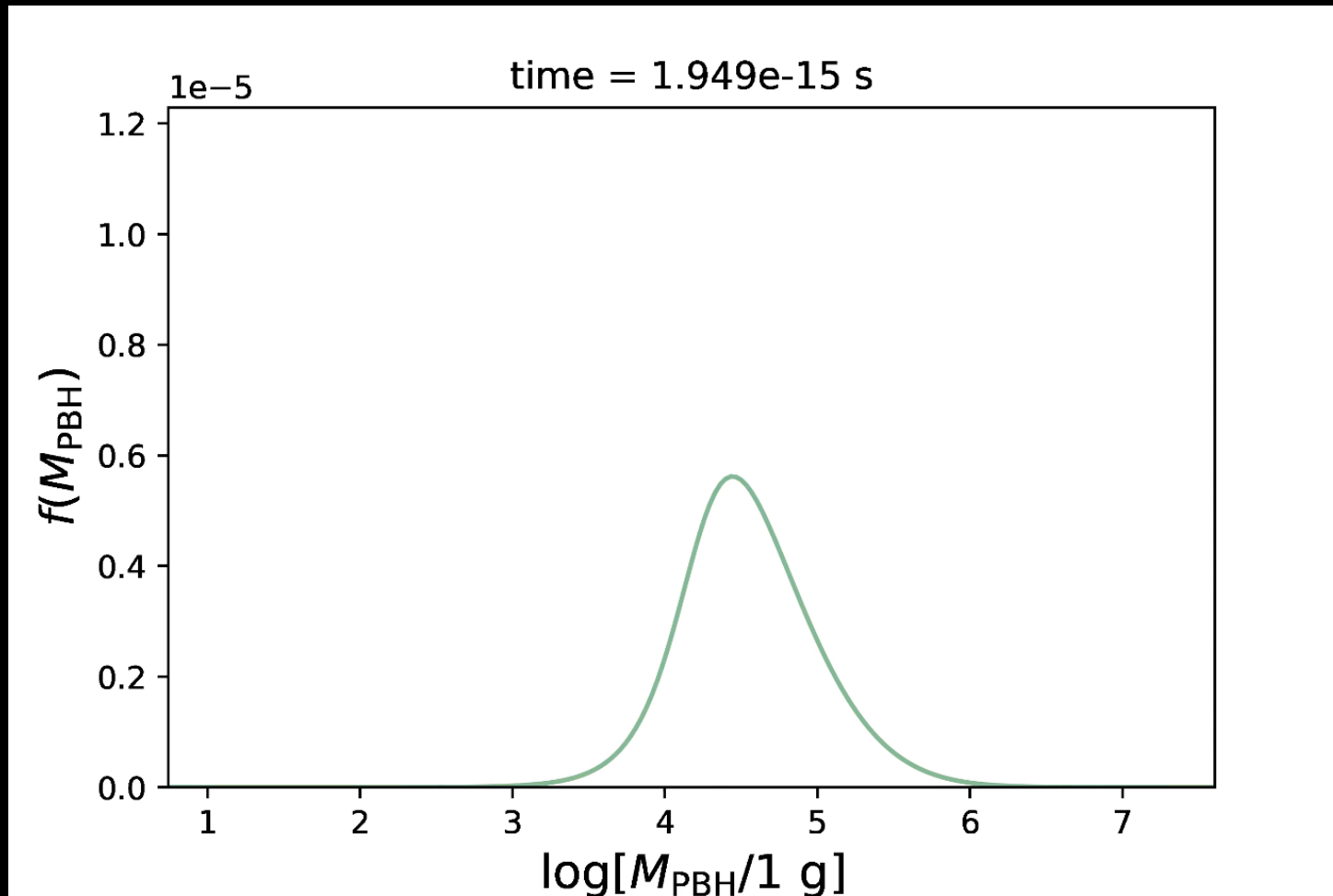
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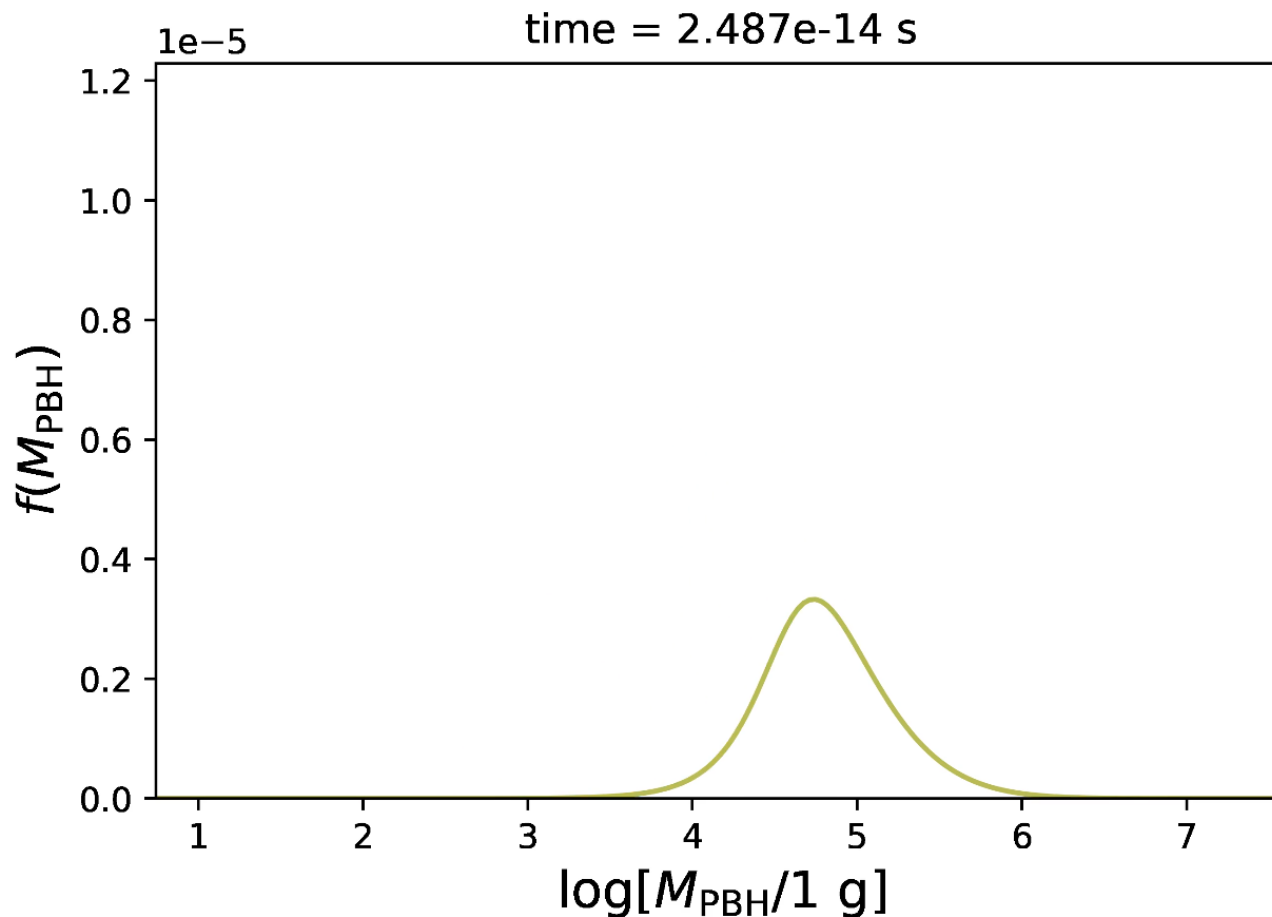
## IV. Evaporation of Extended Distributions

$$\frac{dn}{dM} \propto \frac{1}{M^2} \exp\left[-\frac{(\log M - \log M_c)^2}{2\sigma^2}\right]$$



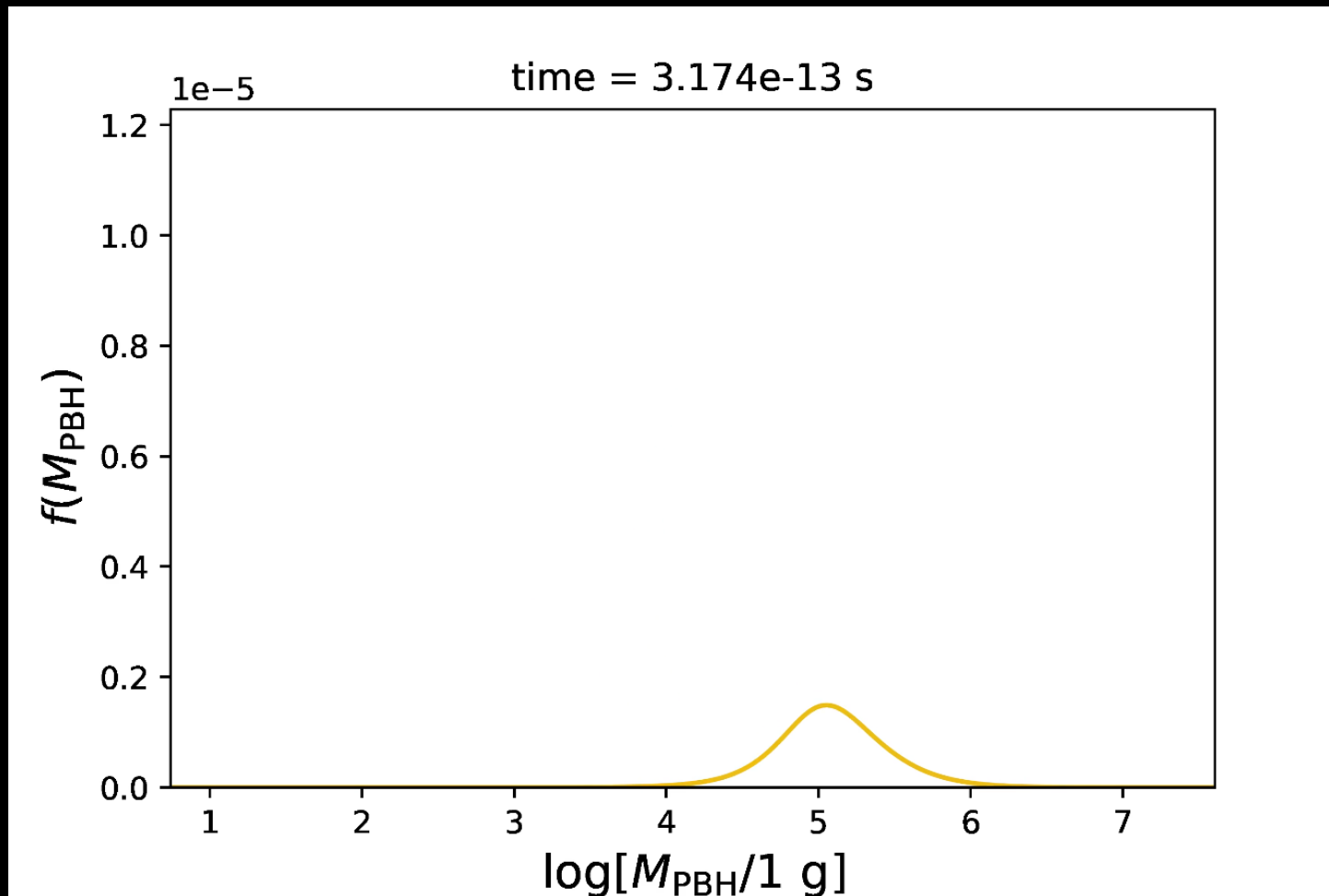
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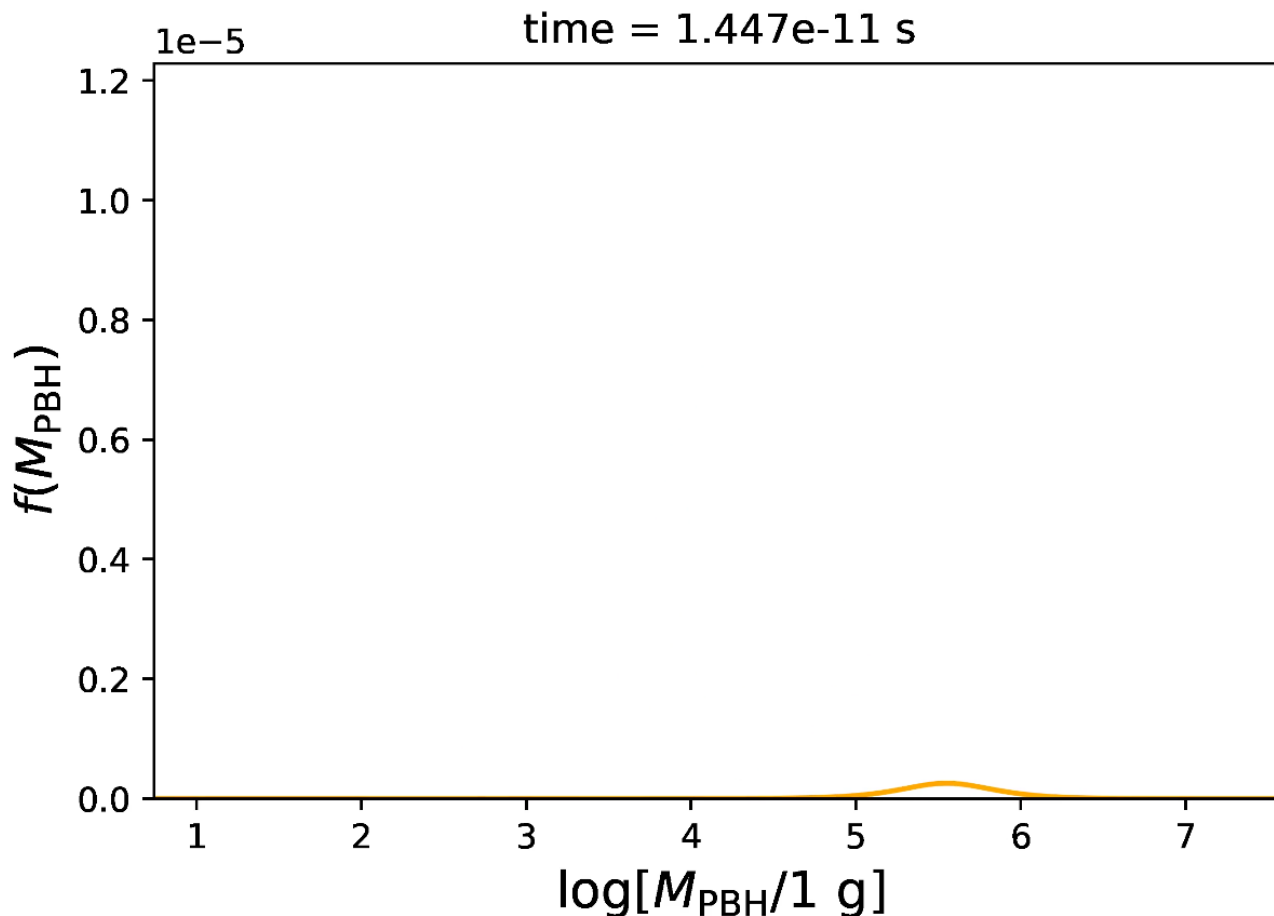
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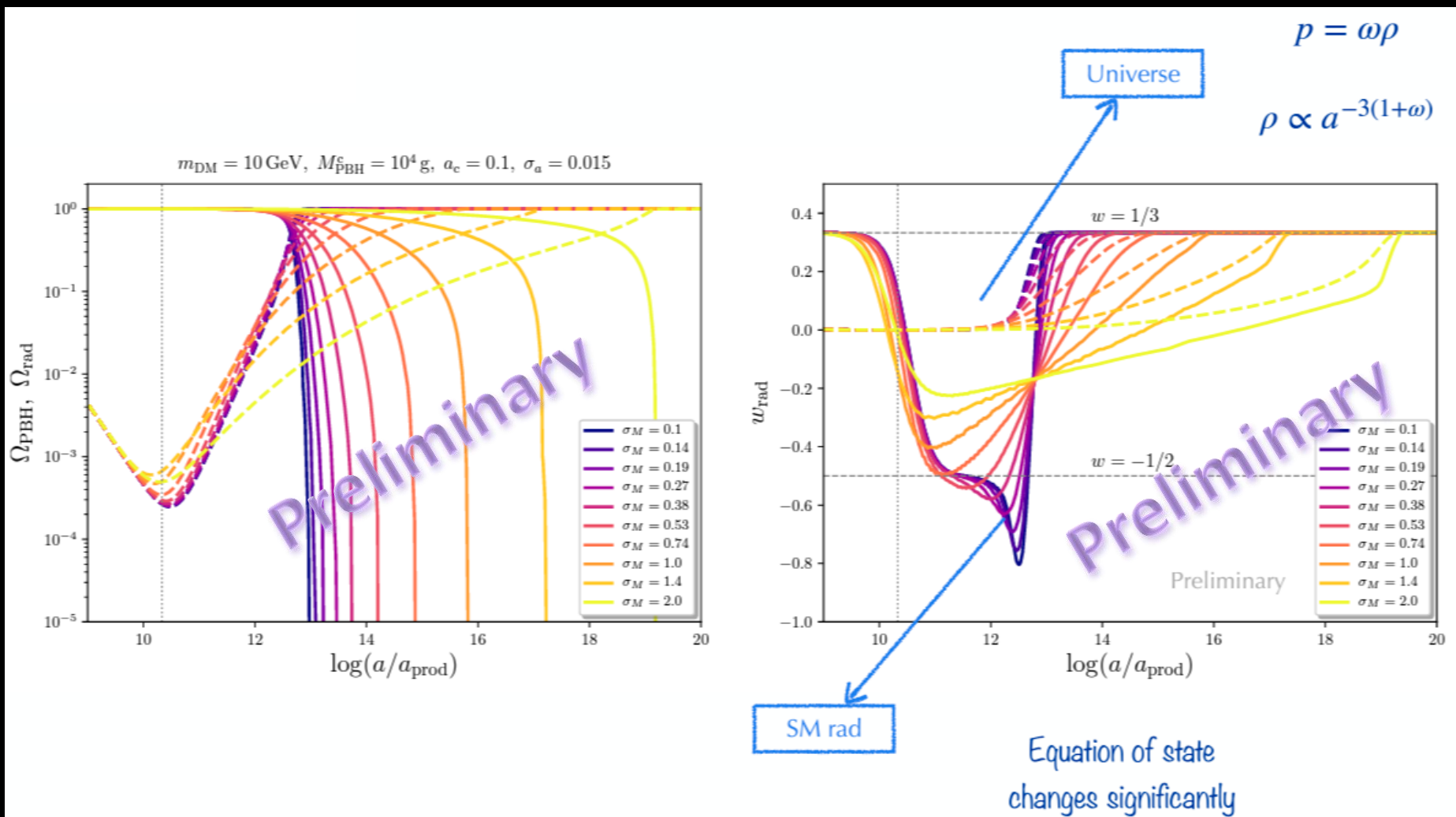


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$$f_{\text{BH}}(M) = \begin{cases} CM^{\alpha-1}, & \text{for } M_{\text{min}} \leq M \leq M_{\text{max}}; \\ 0, & \text{else.} \end{cases}$$

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

$$\begin{aligned} \frac{dH}{dt} &= -\frac{1}{2}H^2(4 - \Omega_{\text{BH}}), \\ \frac{d\Omega_{\text{BH}}}{dt} &= \Omega_{\text{BH}} \left[ \frac{\int_0^\infty f_{\text{BH}}(M, t) \frac{dM}{dt} dM}{\int_0^\infty f_{\text{BH}}(M, t) M dM} \right] \\ &\quad + H\Omega_{\text{BH}}(1 - \Omega_{\text{BH}}). \end{aligned}$$

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

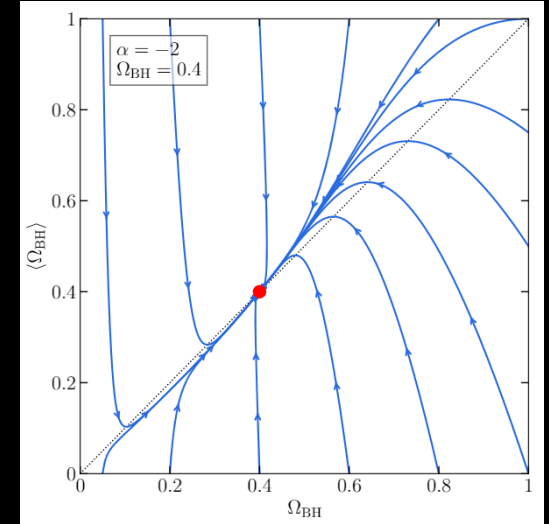
# IV. Evaporation of Extended Distributions

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

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

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

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



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

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

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

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

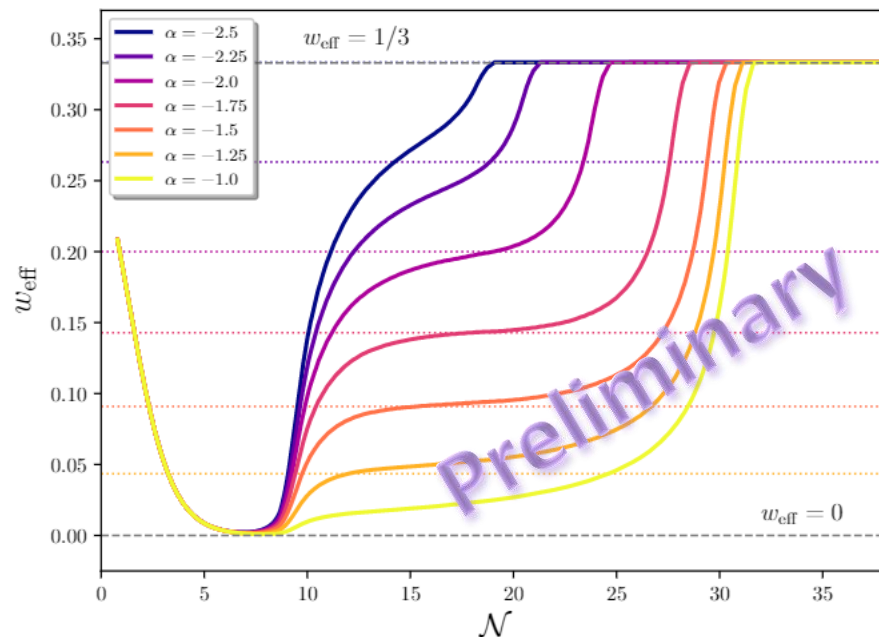
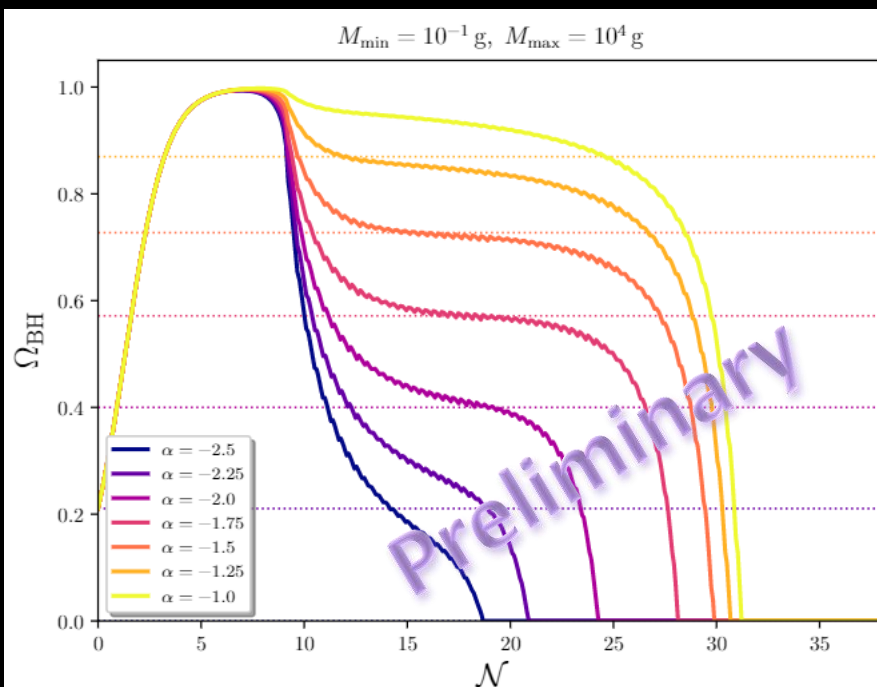
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$$w_{\text{eff}} = \frac{-\alpha - 1}{\alpha + 7}$$

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

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

$$0 < w_{\text{form.}} \leq 1 \Rightarrow 0 < \bar{\Omega}_{\text{BH}} < 1$$



‘Stasis’ regime reached for  $0 < w < 1$