Lucien HEURTIER

LPTHE – Particle & Cosmology Series

Unveiling Cosmic History with Primordial Black Holes Archaeology

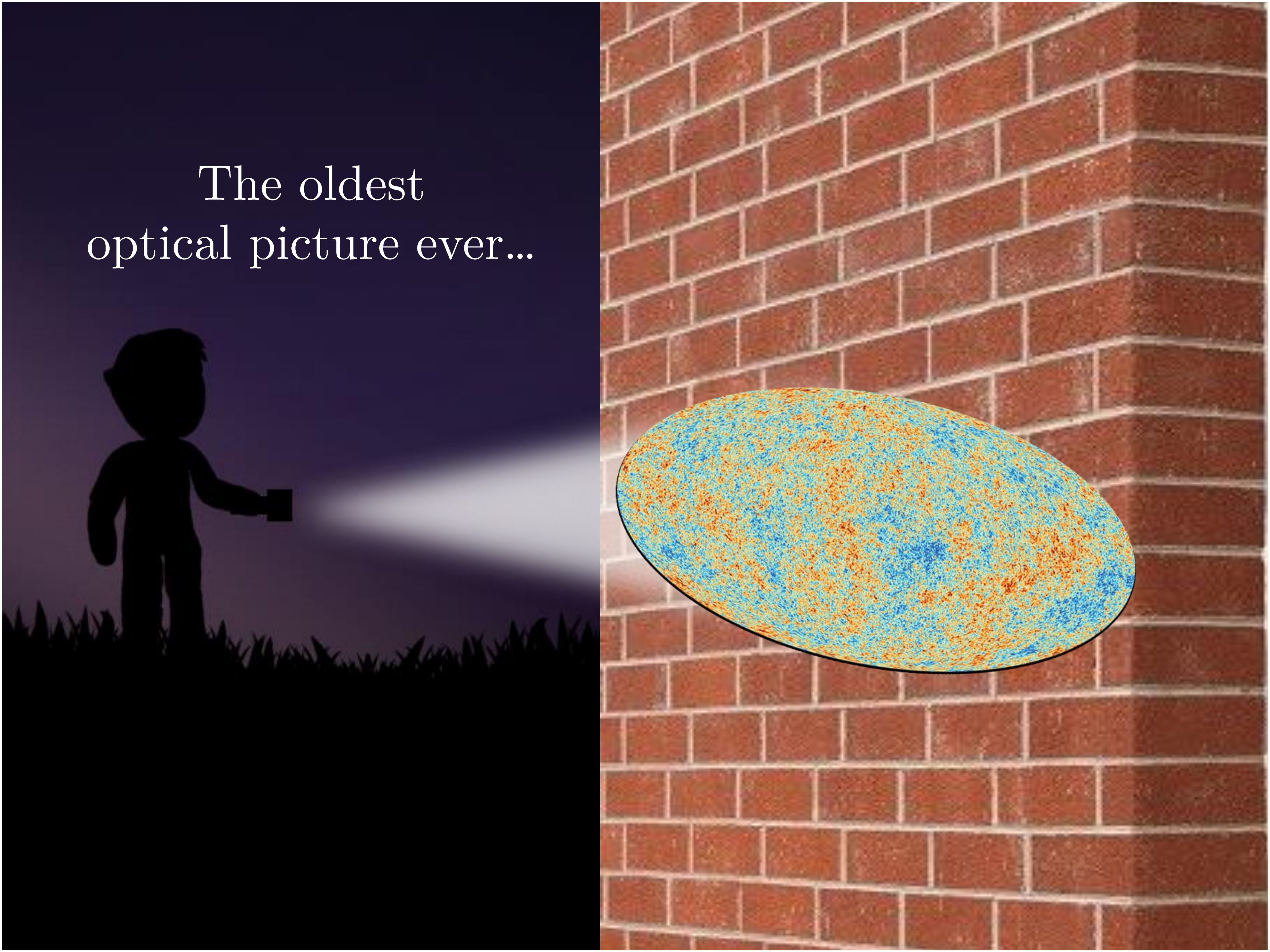
King's College London

UKRI Science and Technology Facilities Council

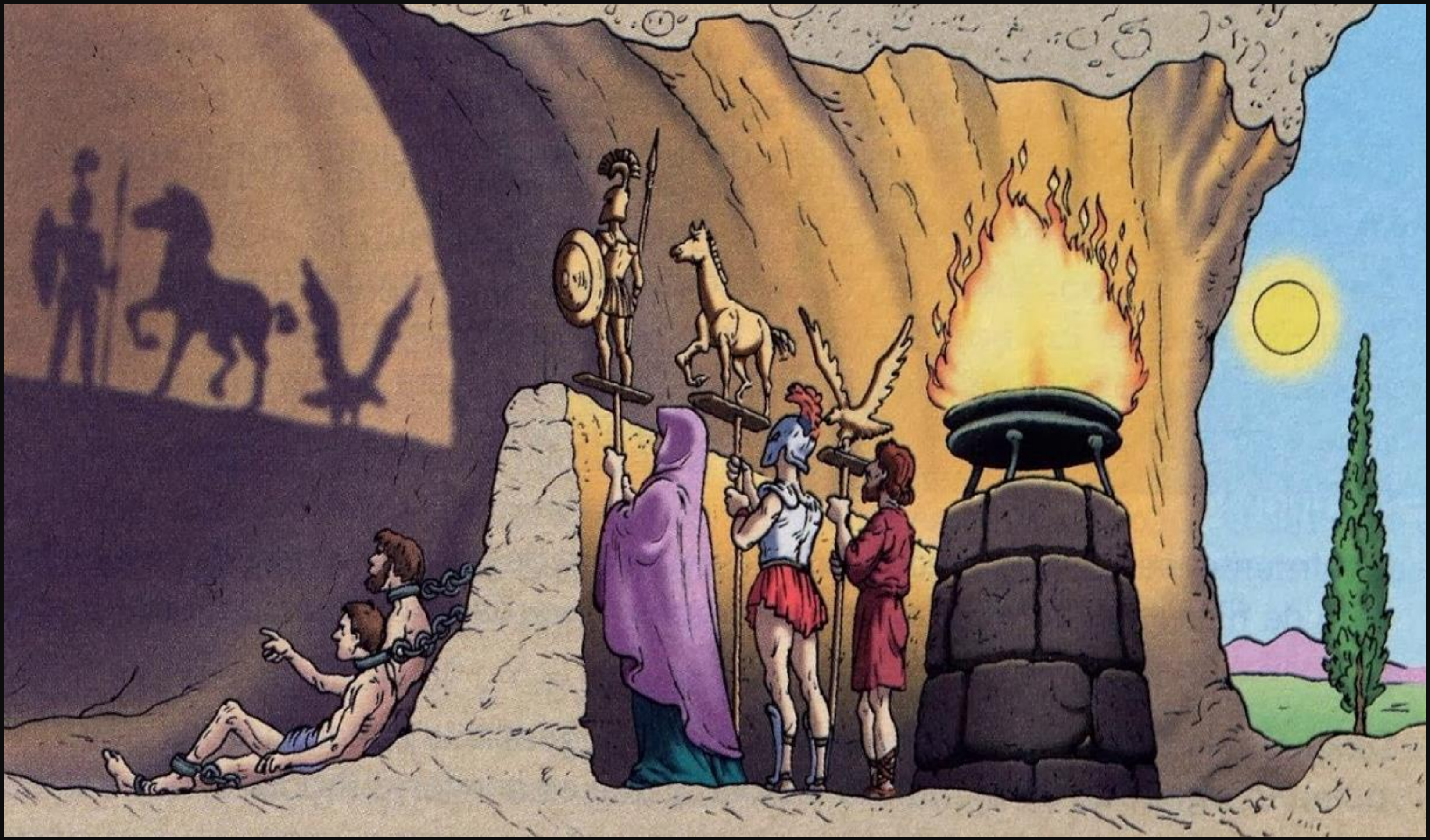
WHY

Primordial

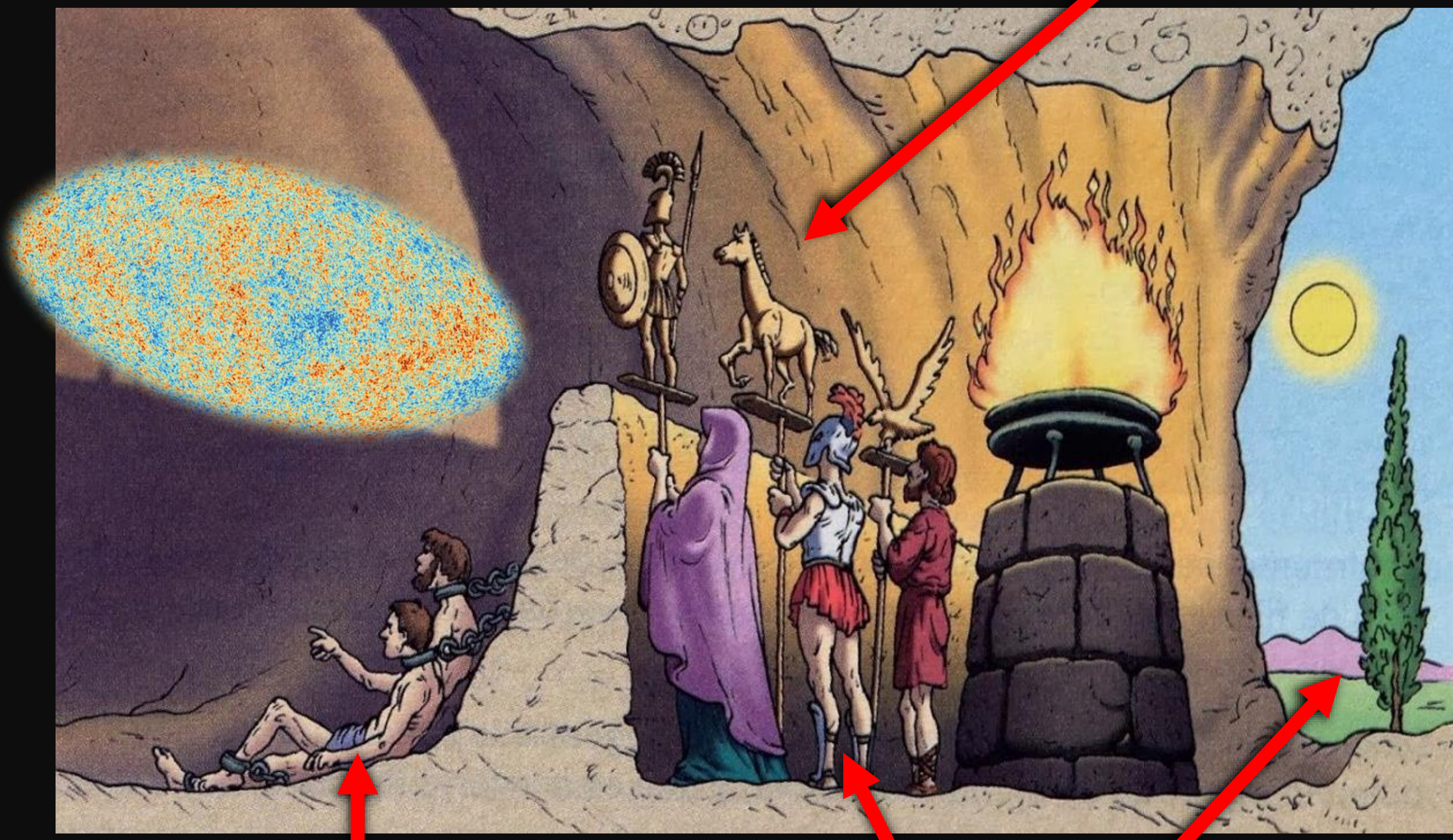
Black Holes?


The oldest
optical picture ever...

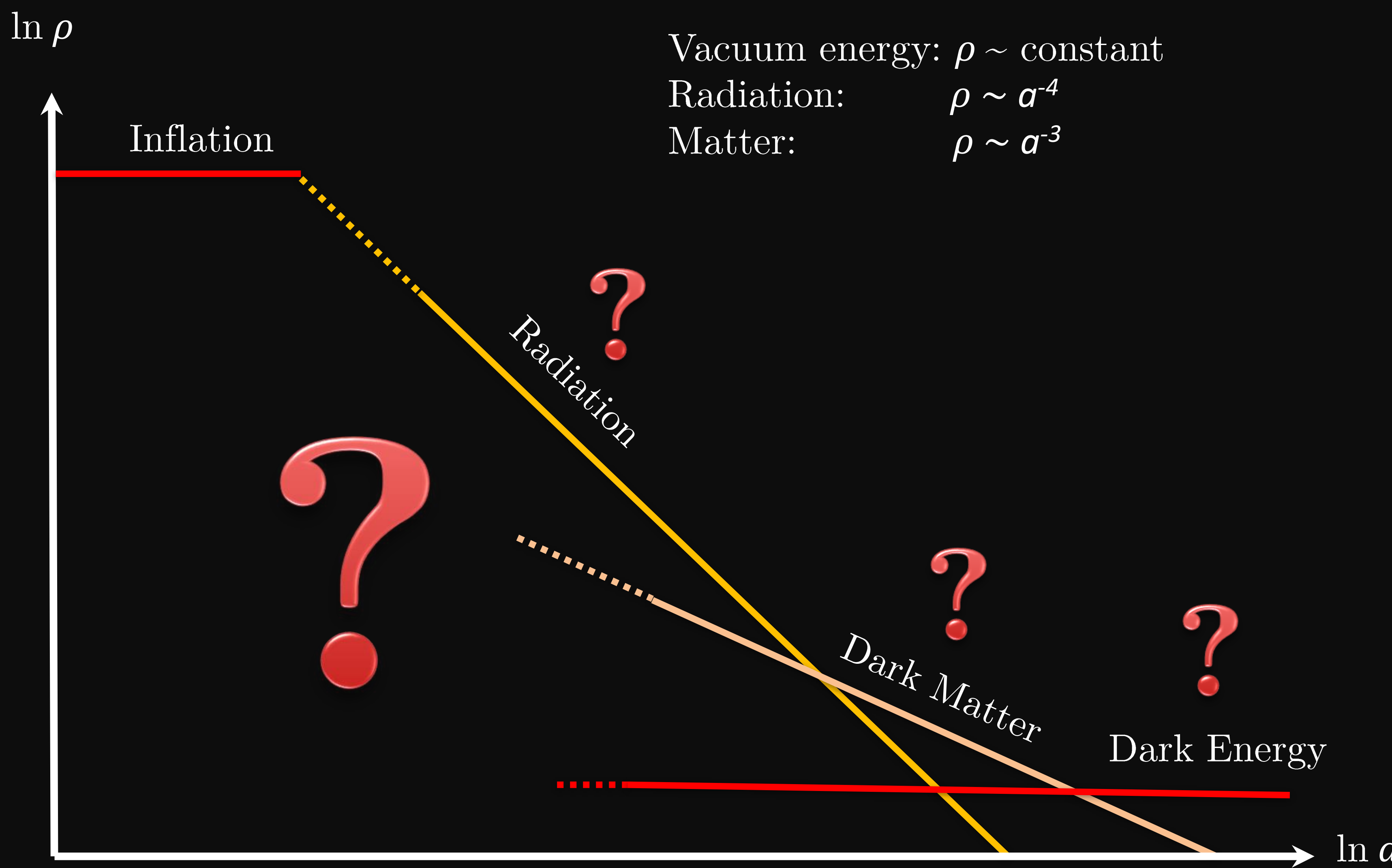
Allegory of the Cave...

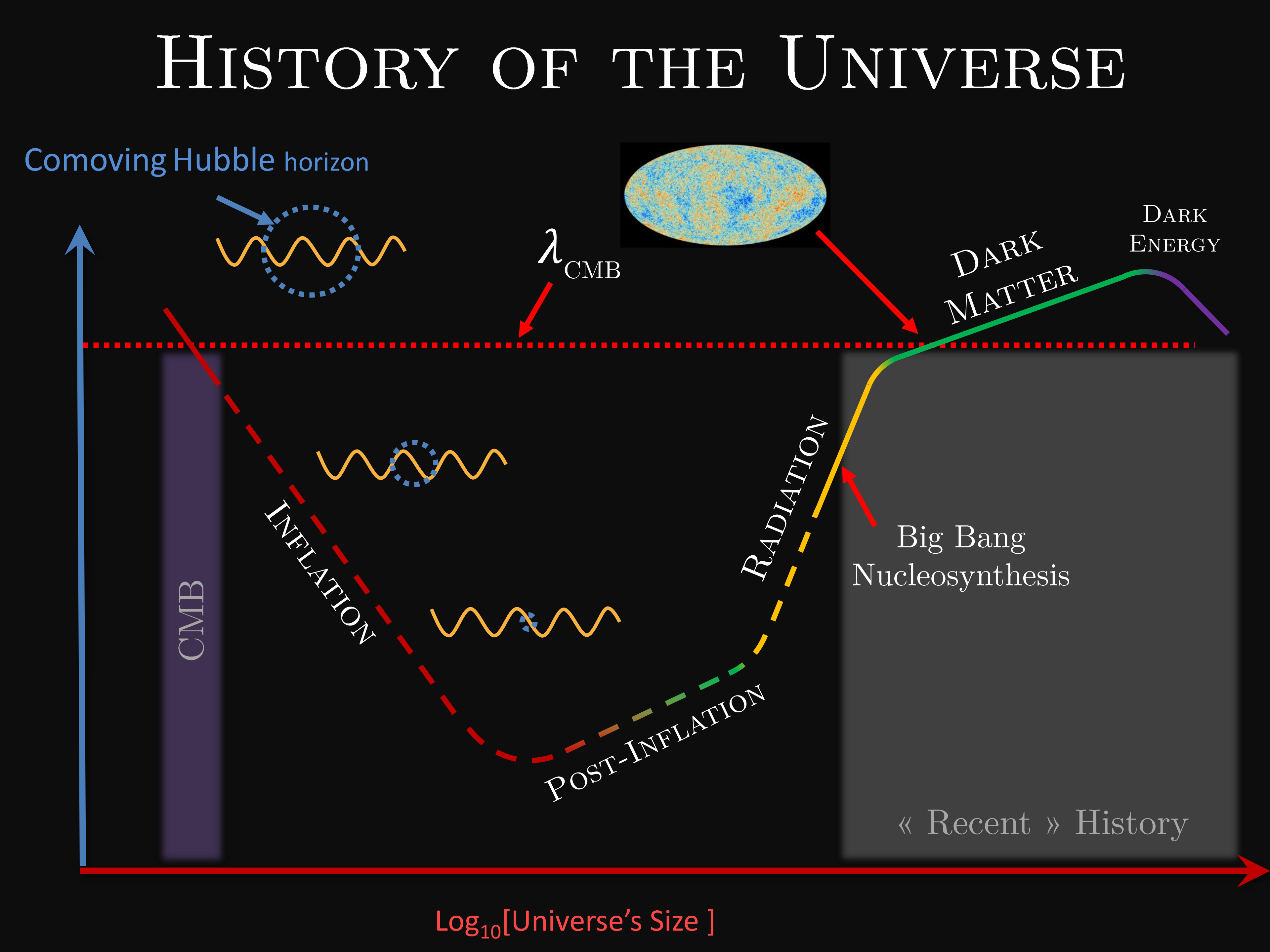


Allegory of the Cave...

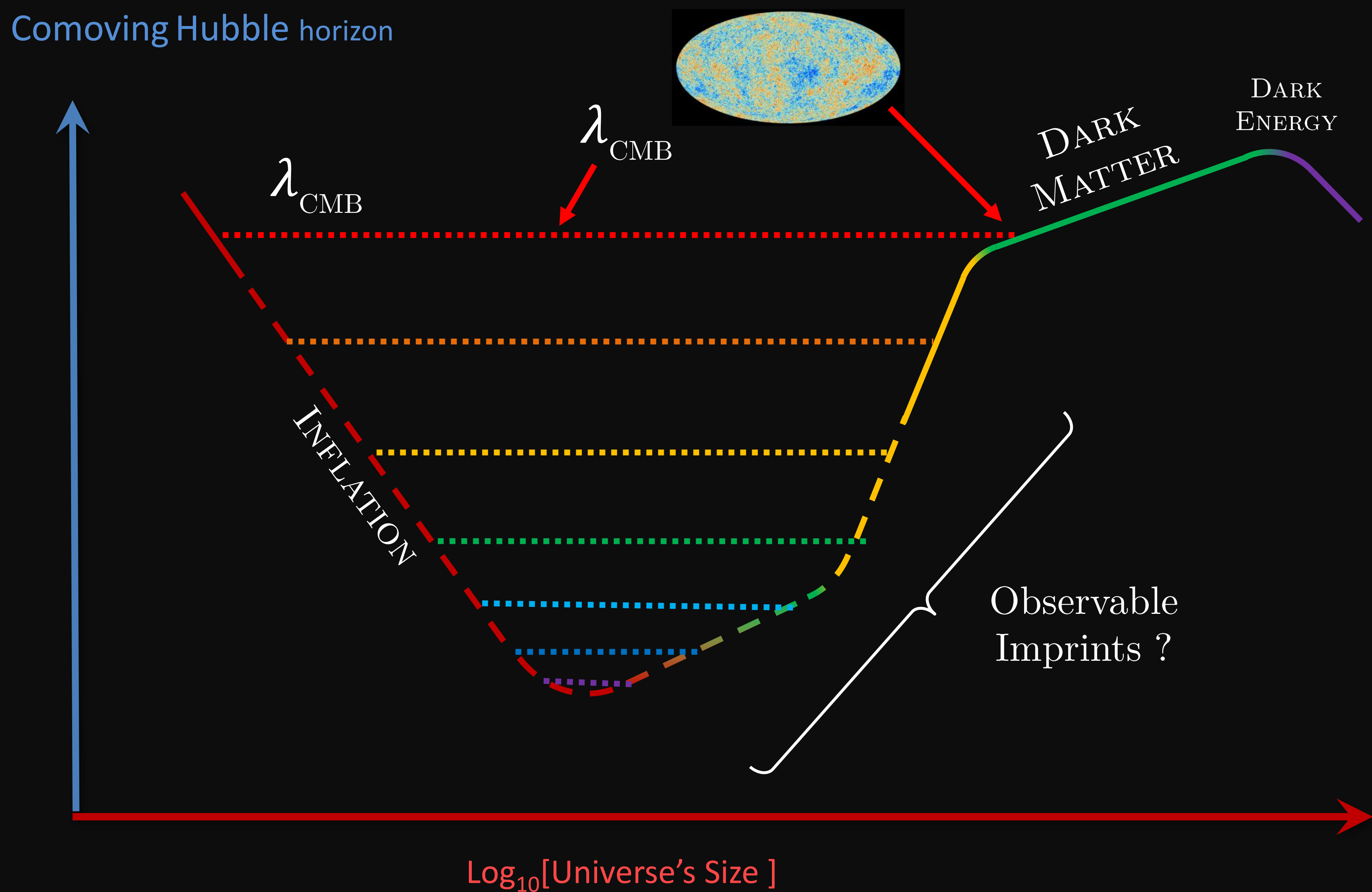


The ΛCDM Ideology

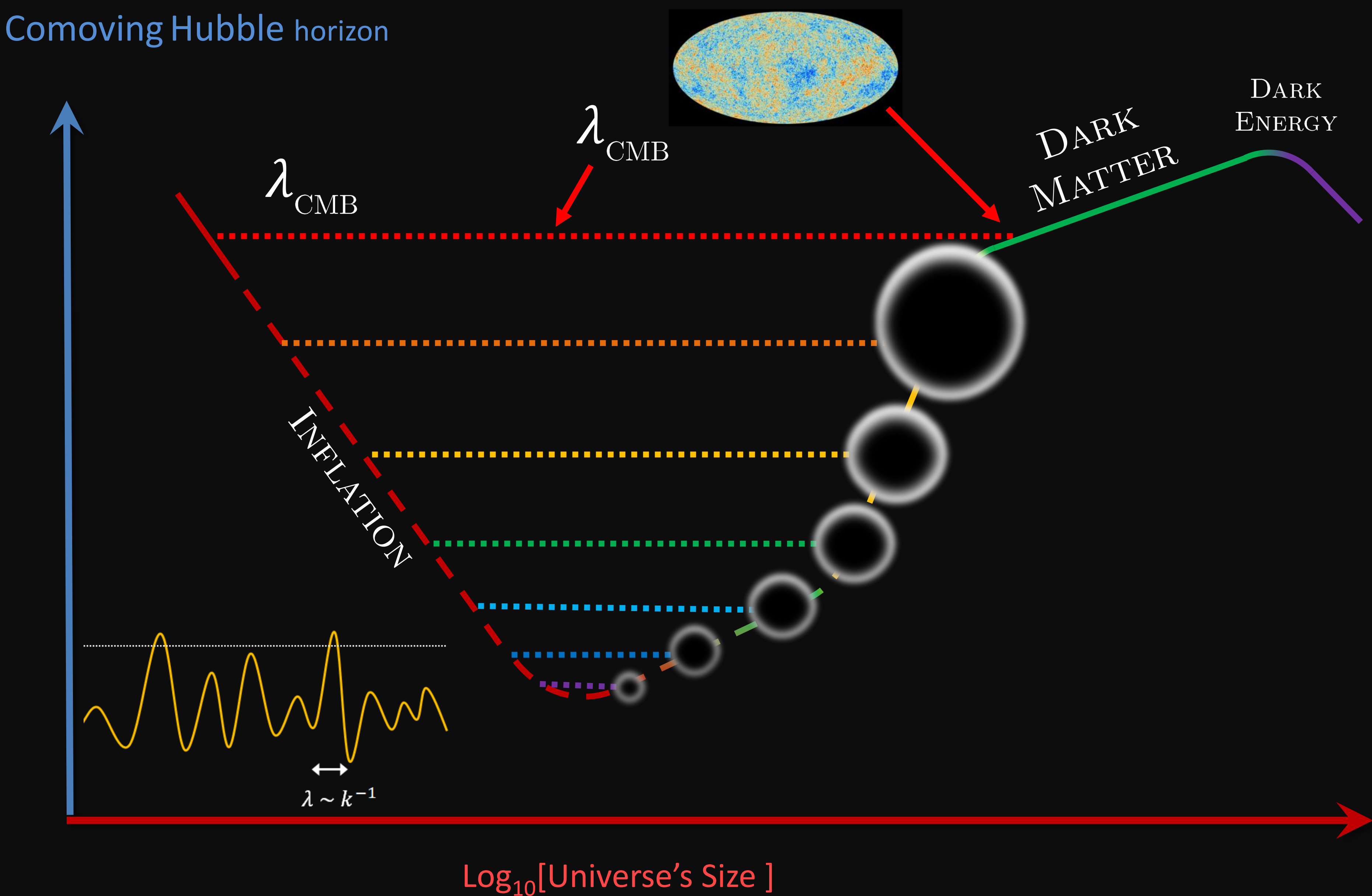



History of the Universe
Comoving Hubble horizon
λ_{CMB}
Dark Energy
Dark Matter
Radiation
Inflation
Post-Inflation
CMB
Big Bang Nucleosynthesis
« Recent » History
Log_{10}[Universe's Size]

History of the Universe

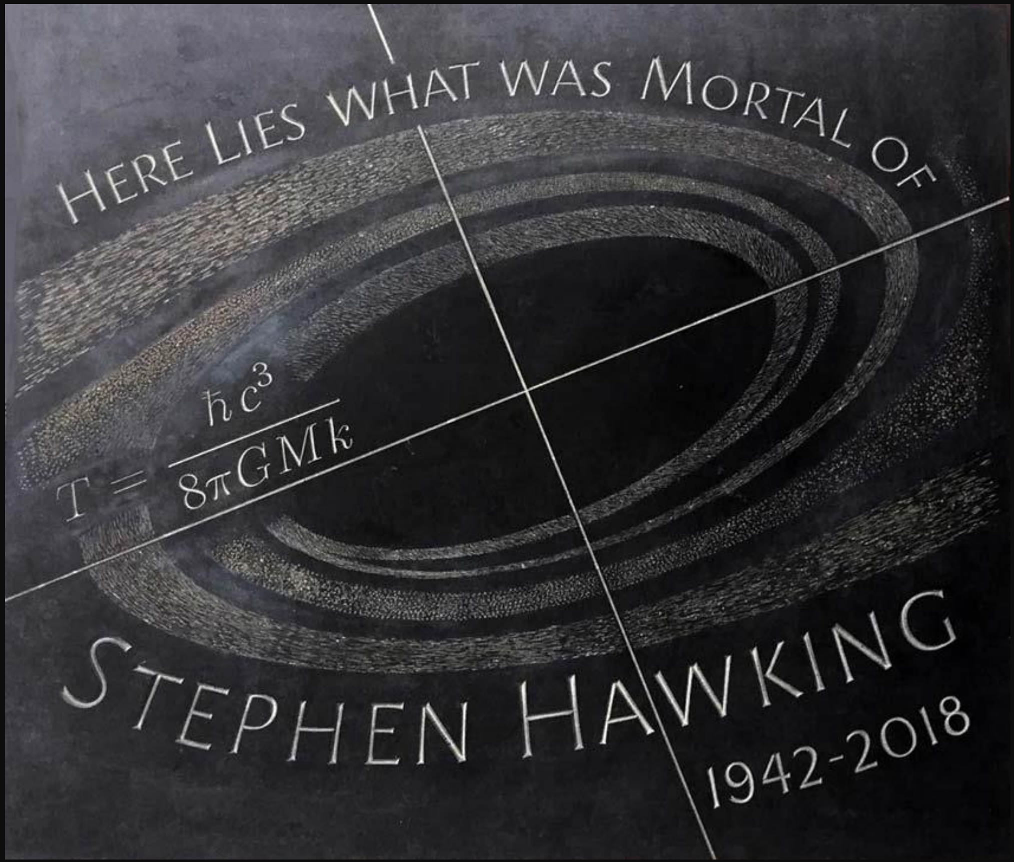


History of the Universe

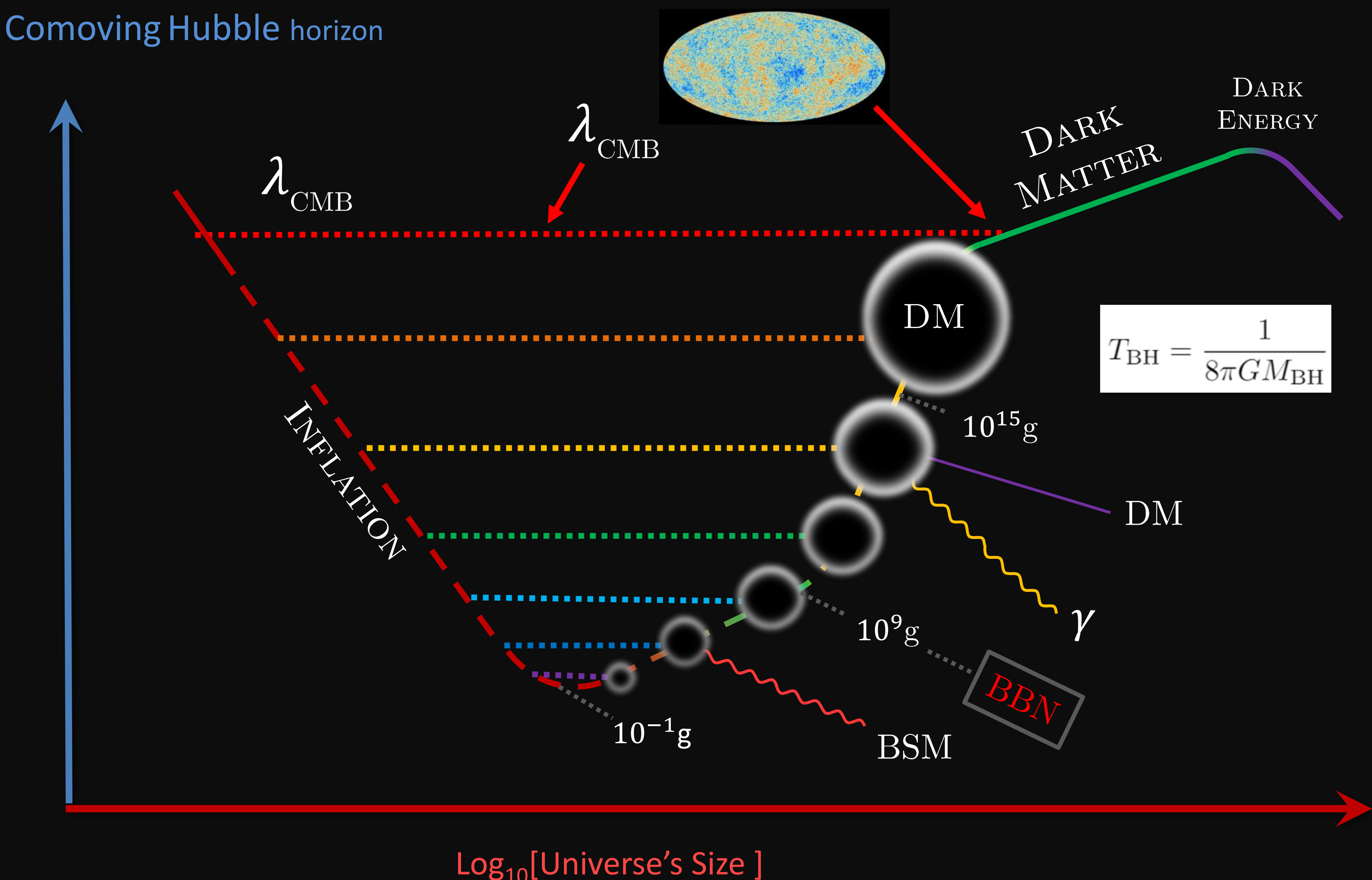


Black Holes Evaporate...

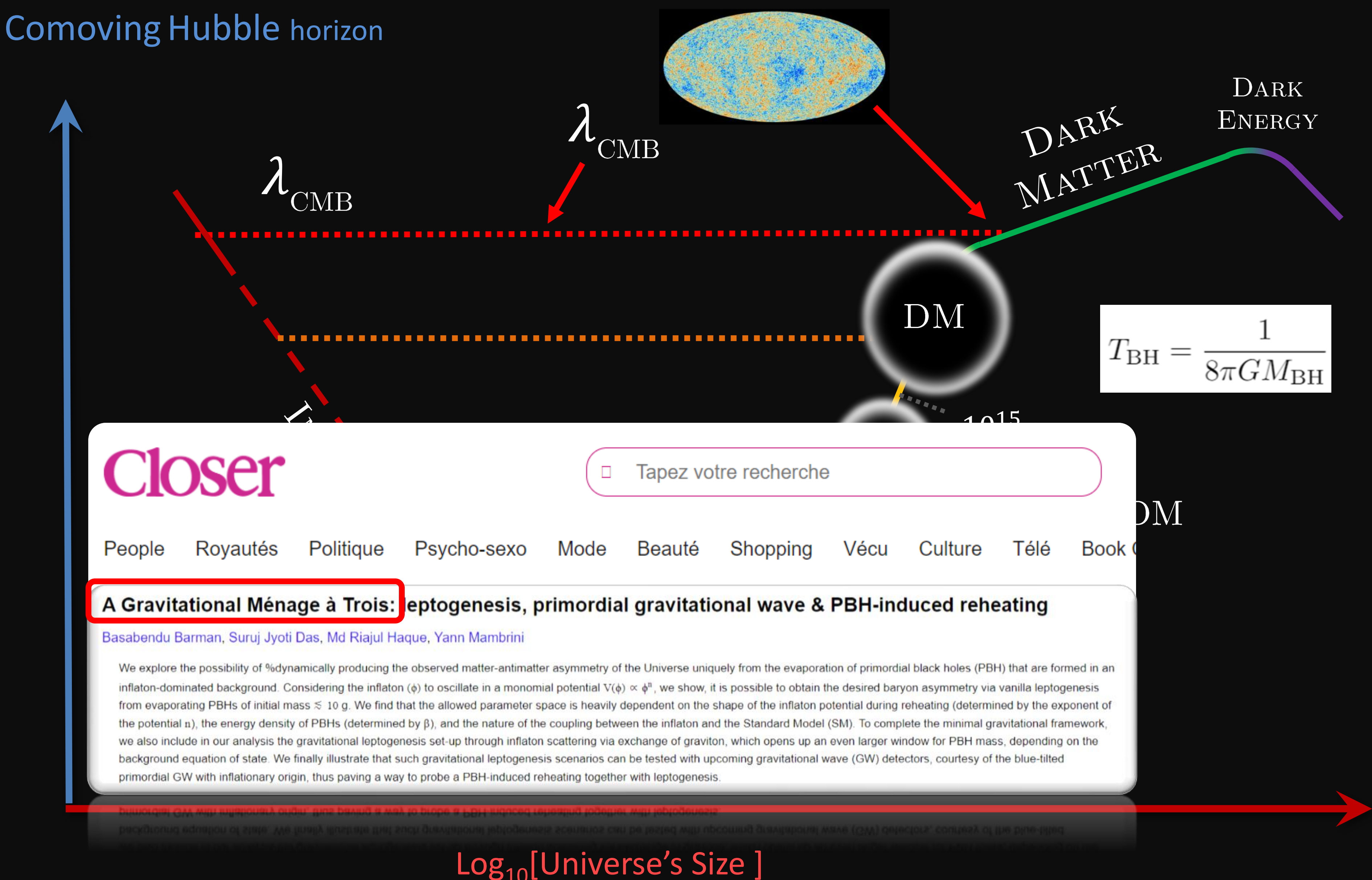
S. Hawking, 1974



History of the Universe



History of the Universe



A Gravitational Ménage à Trois: leptogenesis, primordial gravitational wave & PBH-induced reheating

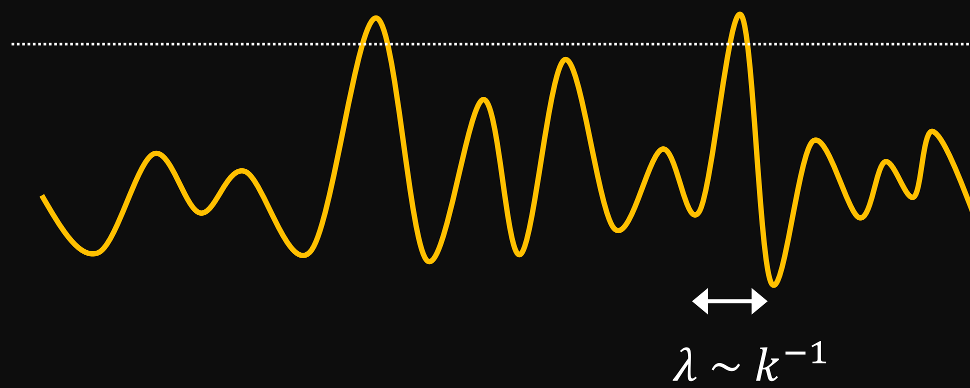
Basabendu Barman, Suruj Jyoti Das, Md Riajul Haque, Yann Mambrini

We explore the possibility of %dynamically producing the observed matter-antimatter asymmetry of the Universe uniquely from the evaporation of primordial black holes (PBH) that are formed in an inflaton-dominated background. Considering the inflaton (ϕ) to oscillate in a monomial potential $V(\phi) \propto \phi^n$, we show, it is possible to obtain the desired baryon asymmetry via vanilla leptogenesis from evaporating PBHs of initial mass $\lesssim 10$ g. We find that the allowed parameter space is heavily dependent on the shape of the inflaton potential during reheating (determined by the exponent of the potential n), the energy density of PBHs (determined by β), and the nature of the coupling between the inflaton and the Standard Model (SM). To complete the minimal gravitational framework, we also include in our analysis the gravitational leptogenesis set-up through inflaton scattering via exchange of graviton, which opens up an even larger window for PBH mass, depending on the background equation of state. We finally illustrate that such gravitational leptogenesis scenarios can be tested with upcoming gravitational wave (GW) detectors, courtesy of the blue-tilted primordial GW with inflationary origin, thus paving a way to probe a PBH-induced reheating together with leptogenesis.

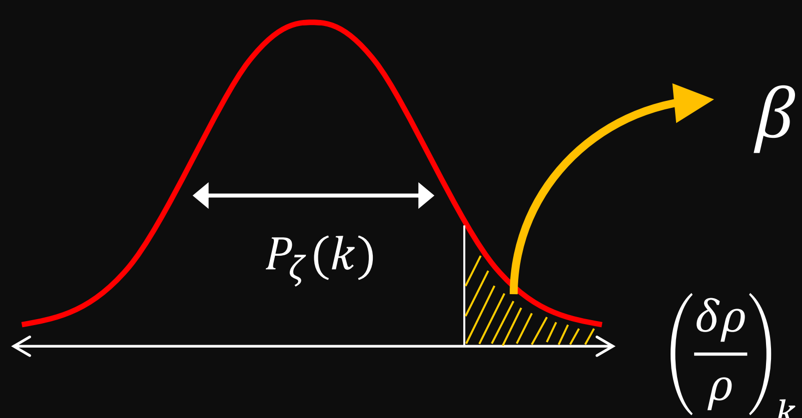
PBH Formation

Collapse of Overdensities

$$\left|\frac{\delta\rho}{\rho}\right| > \rho_c$$



Key Ingredients : 1) Scalar curvature *Power Spectrum* $P_\zeta(k)$



$$\beta(M_k) \sim \exp\left(-\frac{1}{P_\zeta(k)}\right)$$

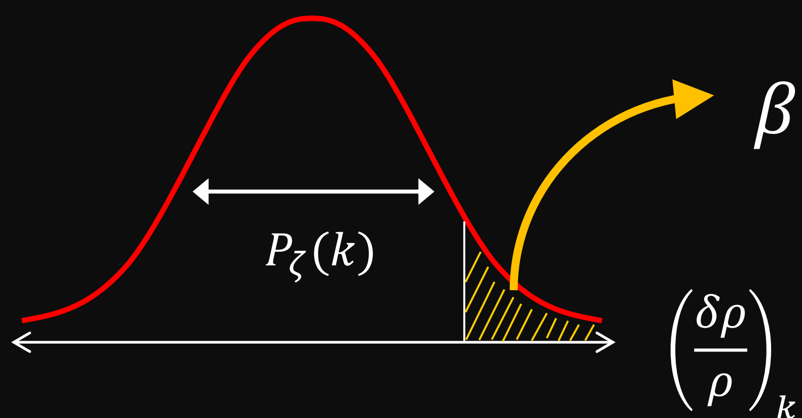
Small Power Spectrum → Small density of PBHs formed

PBH Formation

Key Ingredients : 1) Scalar curvature *Power Spectrum* $P_\zeta(k)$

2) Equation of State in the Universe $\boldsymbol{w}$

$$\delta_c(k) = \frac{3(1+w)}{5+3w}\sin^2\left(\frac{\pi\sqrt{w}}{1+3w}\right)$$



$$\beta(M_k) \sim \exp\left(-\frac{1}{P_\zeta(k)}\right)$$

Small Power Spectrum → Small density of PBHs formed

PBH Formation

Key Ingredients : 1) Scalar curvature *Power Spectrum* $P_\zeta(k)$

During inflation, small perturbations may be generated at scales $k \sim k_{\mathrm{CMB}}$

After inflation, larger perturbations may be sourced at scales $k \gg k_{\mathrm{CMB}}$

- Bumpy potentials (Ultra-Slow-Roll period)
- Colliding scalar-field bubbles
- Enhancement due to early matter domination
- ...

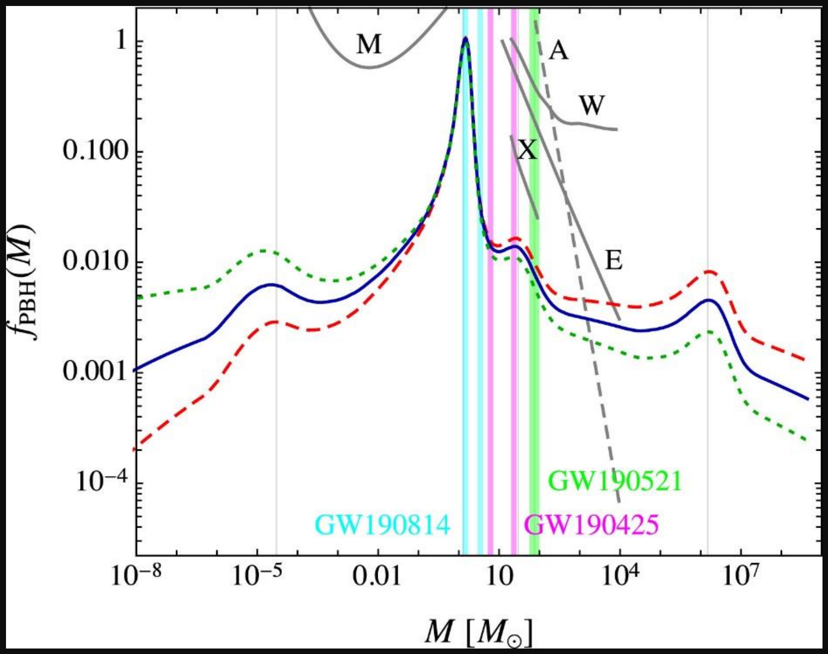
PBH Formation

Key Ingredients : 2) Equation of State in the Universe $\boldsymbol{w}$

Fluctuation of w : During phase transitions (QCD) may fluctuate → variations of $\beta(M)$

Dynamics of w leaves an imprint in the PBH spectrum

Probing its shape → Reading the spectrum pattern



[Byrnes, Hindmarsh, Young, Hawkins ‘18]
[Carr, Clesse, García-Bellido, Kühnel ’20]
[Juan, Serpico, Abellán ‘22]
[Musco, Jedamzik, Young ‘23]

PBH Formation

Key Ingredients : 2) Equation of State in the Universe $\boldsymbol{w}$

Cosmological moduli may start to oscillate

→ Early Matter Domination ($\boldsymbol{w} = 0$)

String Theory compactification

Transverse directions in SUGRA

Axion-like particle models

...

PBH Formation

Key Ingredients : 2) Equation of State in the Universe w

Compact Extra Dimensions may place the Universe in *Stasis*

→ Mixed Matter/Radiation state ($w \in [0\,,1/3]$)

A tower of states with regular spectrum

Energy densities with similar pattern

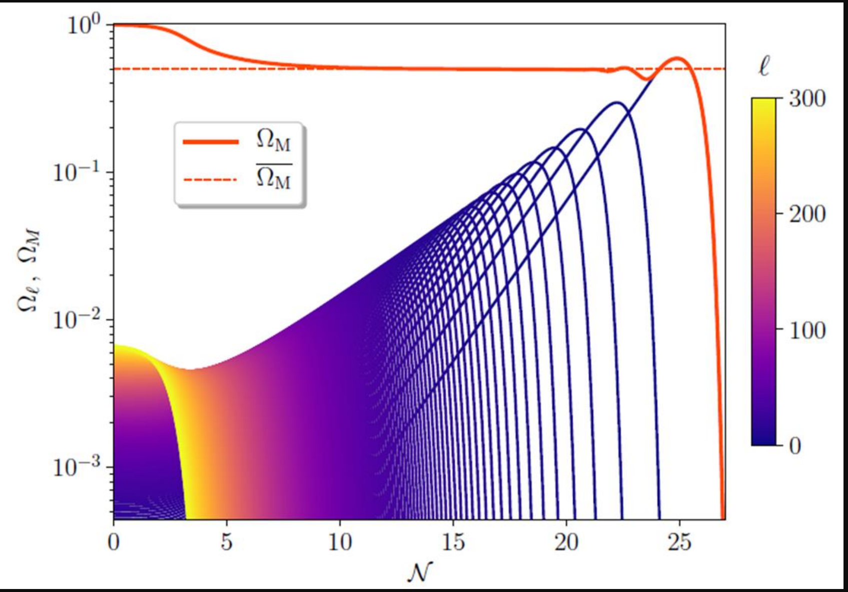
→ The ensemble is attracted to a mixed-state system...

$$m_\ell = m_0 + (\Delta m)\ell^\delta$$

$$\Gamma_\ell = \Gamma_0 \left(\frac{m_\ell}{m_0}\right)^\gamma \qquad \Omega_\ell^{(0)} = \Omega_0^{(0)} \left(\frac{m_\ell}{m_0}\right)^\alpha$$

$$\overline{\Omega}_M = \frac{2\gamma\delta - 4(1+\alpha\delta)}{2\gamma\delta - (1+\alpha\delta)} .$$

[Dienes, LH, Huang, Kim, Tait, Thomas '21]

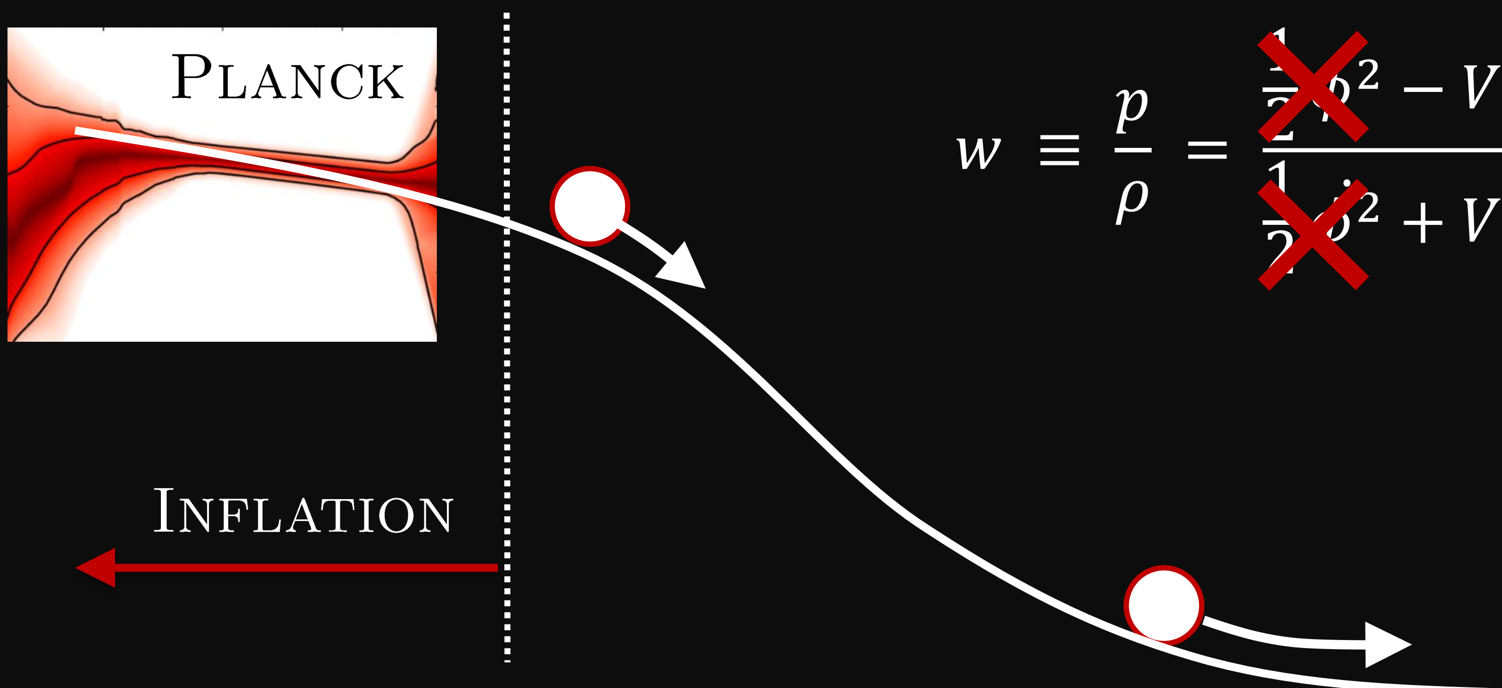


PBH Formation

Key Ingredients : 2) Equation of state in the Universe $\boldsymbol{w}$

Runaway directions : Quintessential (non-oscillatory) inflation

→ Kination ($\boldsymbol{w} = 1$)



$$w \equiv \frac{p}{\rho} = \frac{\cancel{\frac{1}{2}\dot{\phi}^2} - V(\phi)}{\cancel{\frac{1}{2}\dot{\phi}^2} + V(\phi)} \approx -1$$

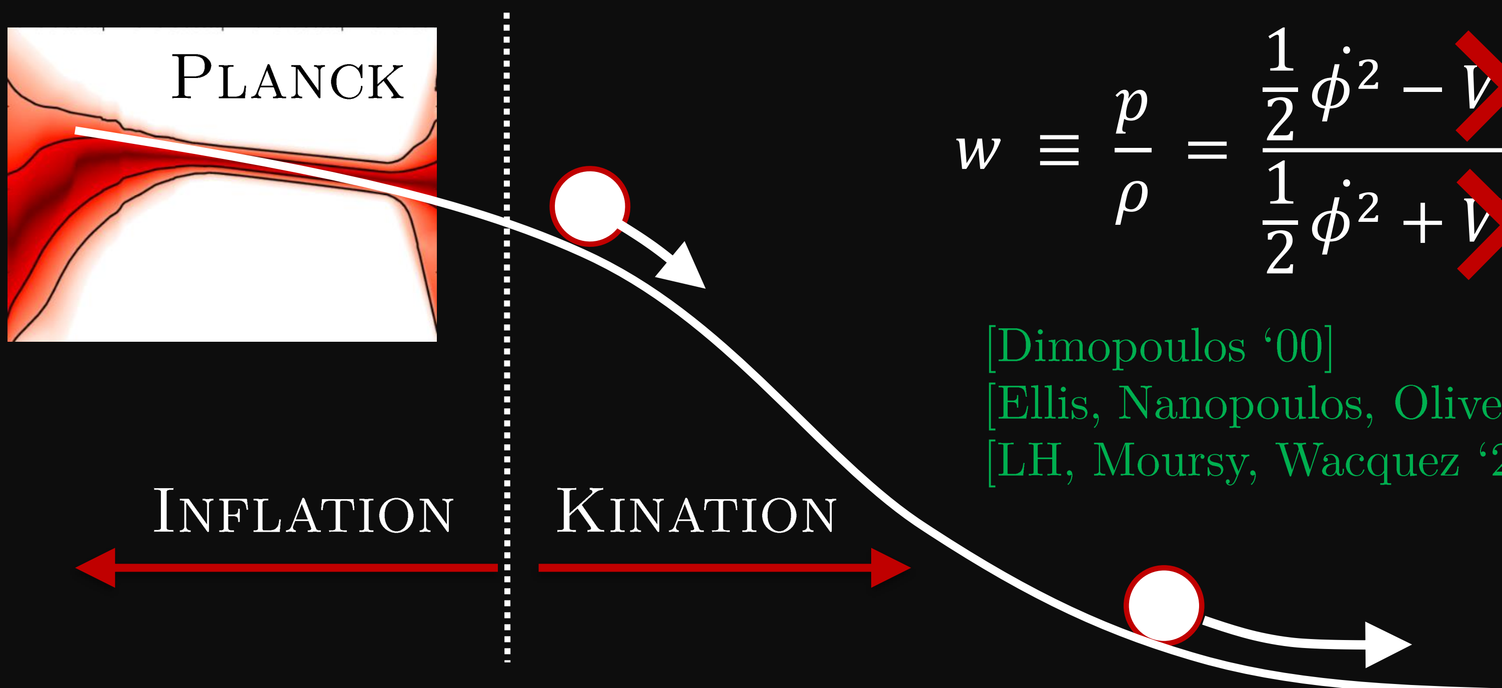
PBH Formation

Key Ingredients : 2) Equation of state in the Universe $\boldsymbol{w}$

The post-inflationary Universe, quèsaco ?

Runaway directions : Quintessential (non-oscillatory) inflation

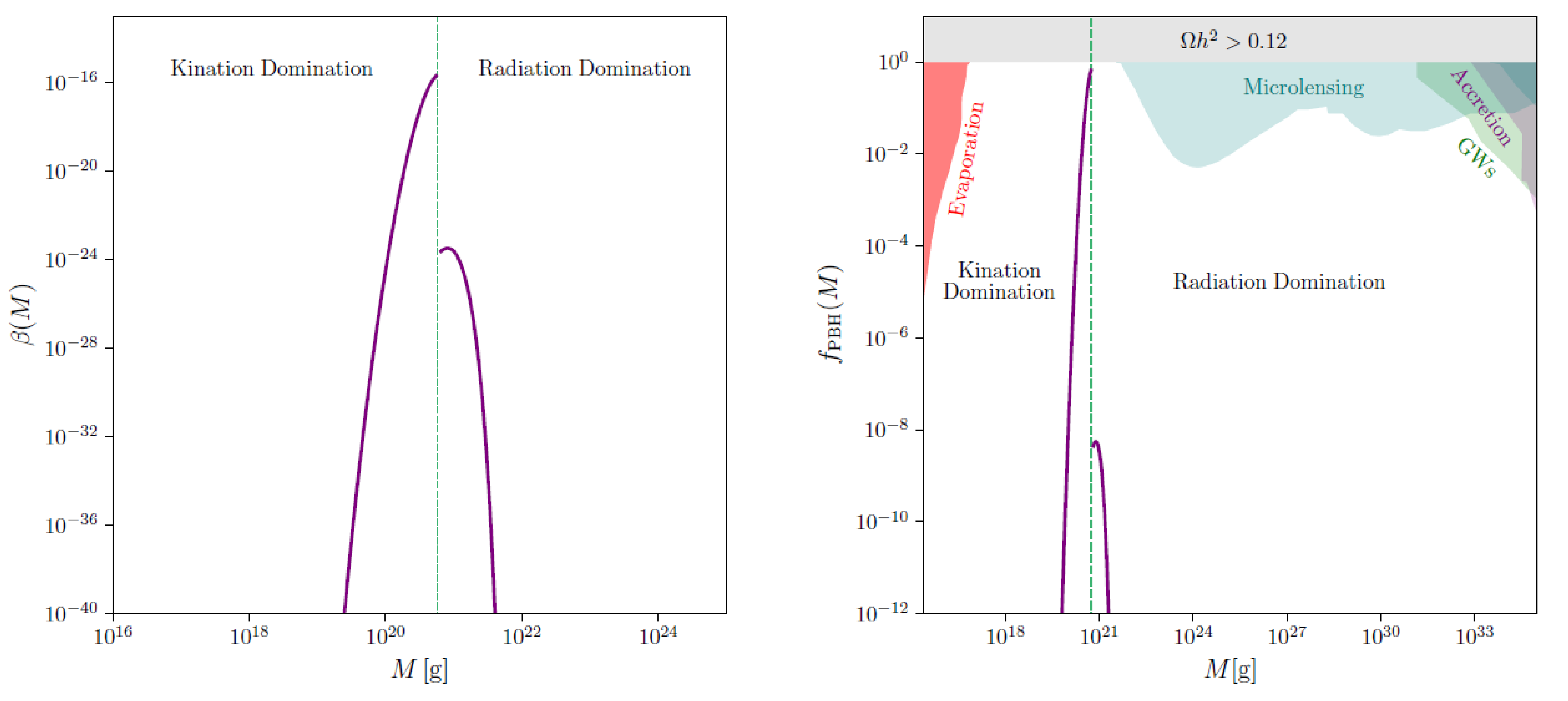
→ Kination ($\boldsymbol{w} = 1$)



$$w \equiv \frac{p}{\rho} = \frac{\frac{1}{2}\dot{\phi}^2 - V(\phi)}{\frac{1}{2}\dot{\phi}^2 + V(\phi)} \approx 1$$

[Dimopoulos '00]
[Ellis, Nanopoulos, Olive, Verner '20]
[LH, Moursy, Wacquez '22] ...

PBH Formation



[LH, Moursy, Wacquez '22]

PBH Formation

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

Karsten Jedamzik[*] Martin Lemoine[†] and Jérôme Martin[‡]

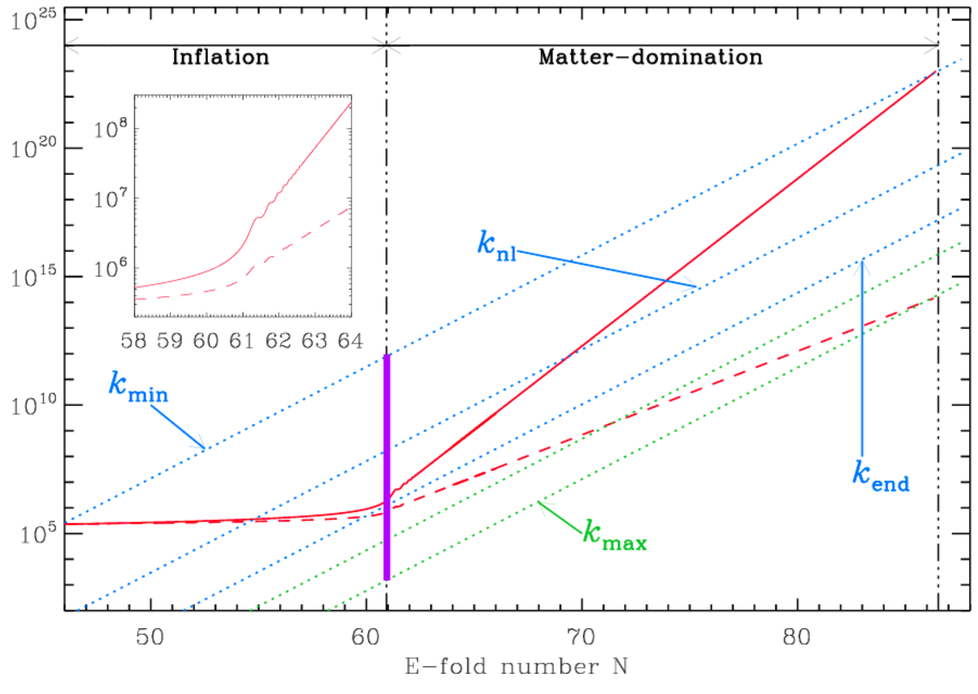
Primordial black holes from the preheating instability in single-field inflation

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

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

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

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



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

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

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

WHAT ABOUT

LIGHT, EVAPORATING, PRIMORDIAL BLACK HOLES ?

PBH EVAPORATION

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

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

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

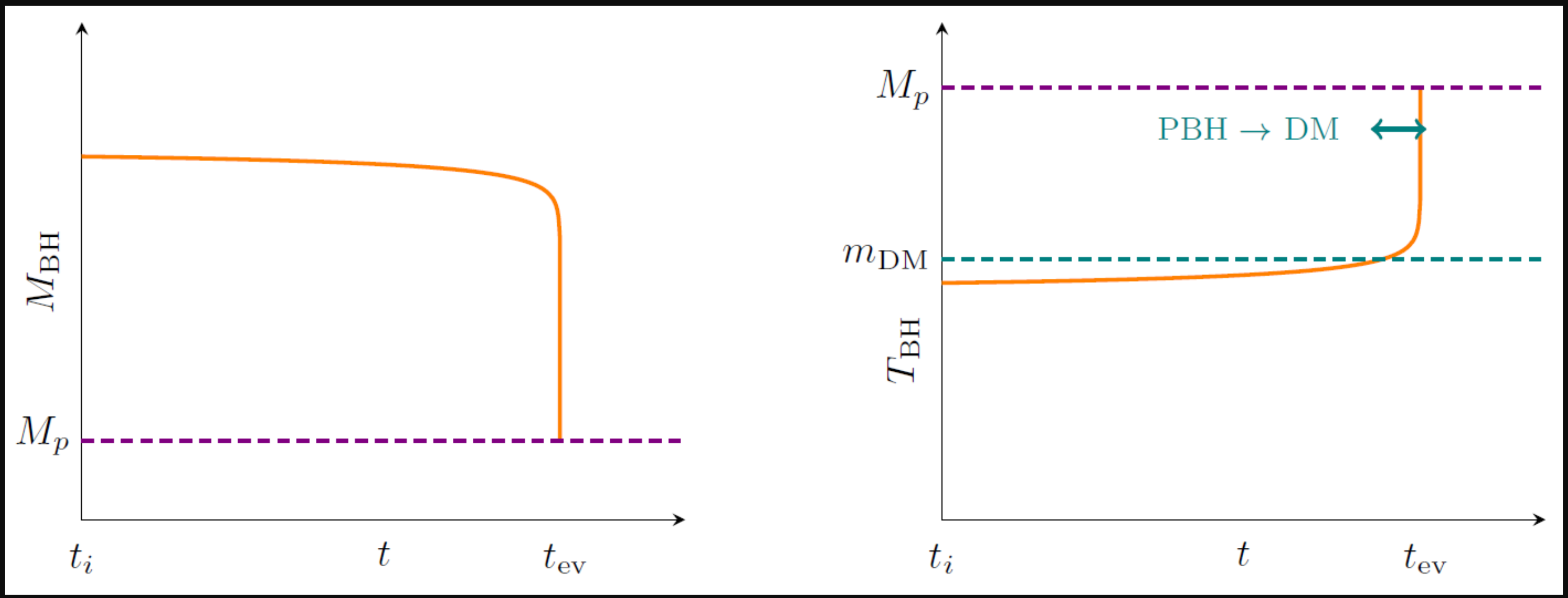
$$z_i \;=\; \mu_i/T_{\mathrm{BH}}$$

BSM Contributions?

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

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

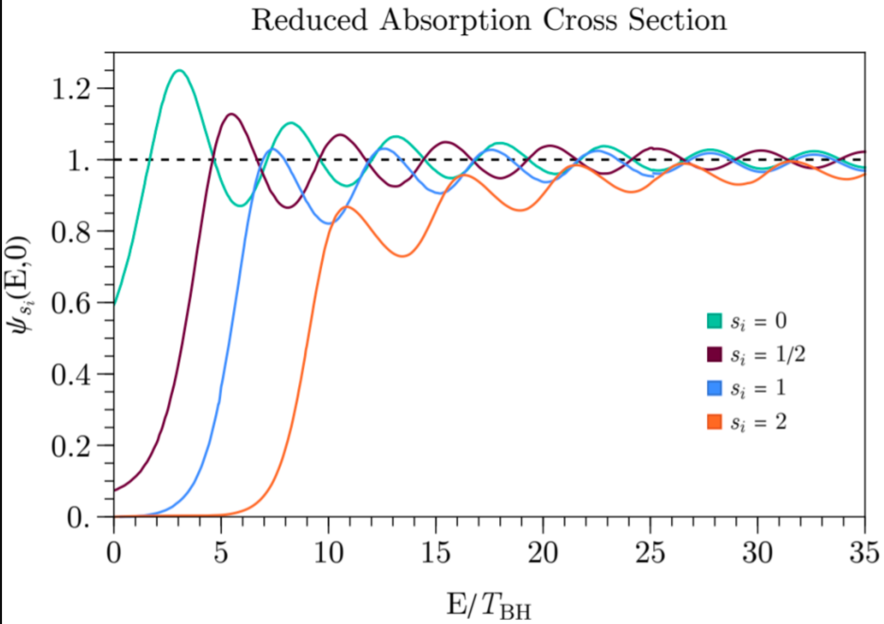
$$\frac{d^2\mathcal{N}_i}{dp\,dt} = \frac{g_i}{2\pi^2}\frac{\sigma_{s_i}(M_{\rm BH},\mu_i,p)}{\exp\left[E_i(p)/T_{\rm BH}\right]-(-1)^{2s_i}}\frac{p^3}{E_i(p)}$$

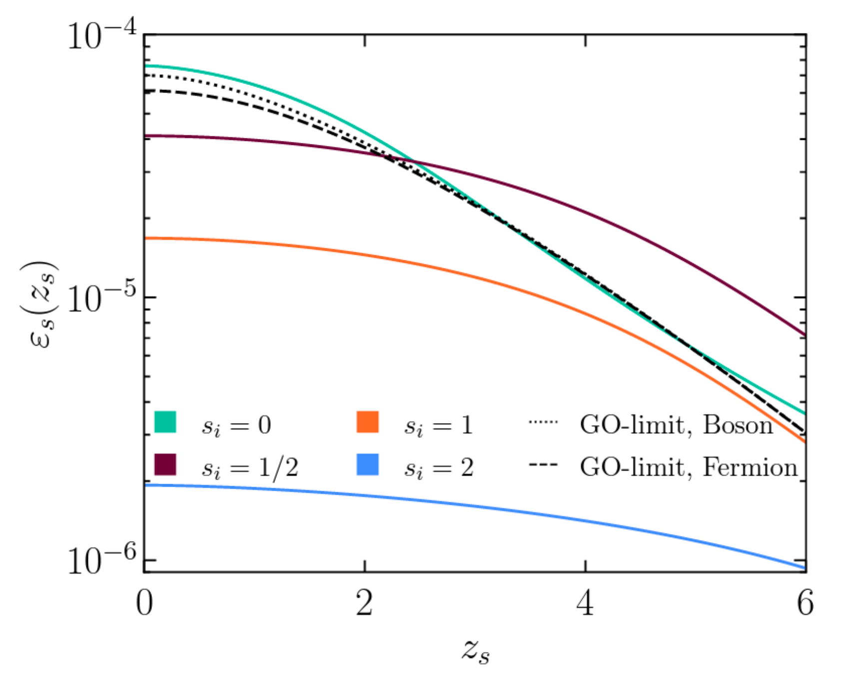
Very bad approximation at (not too)

low momentum…

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

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



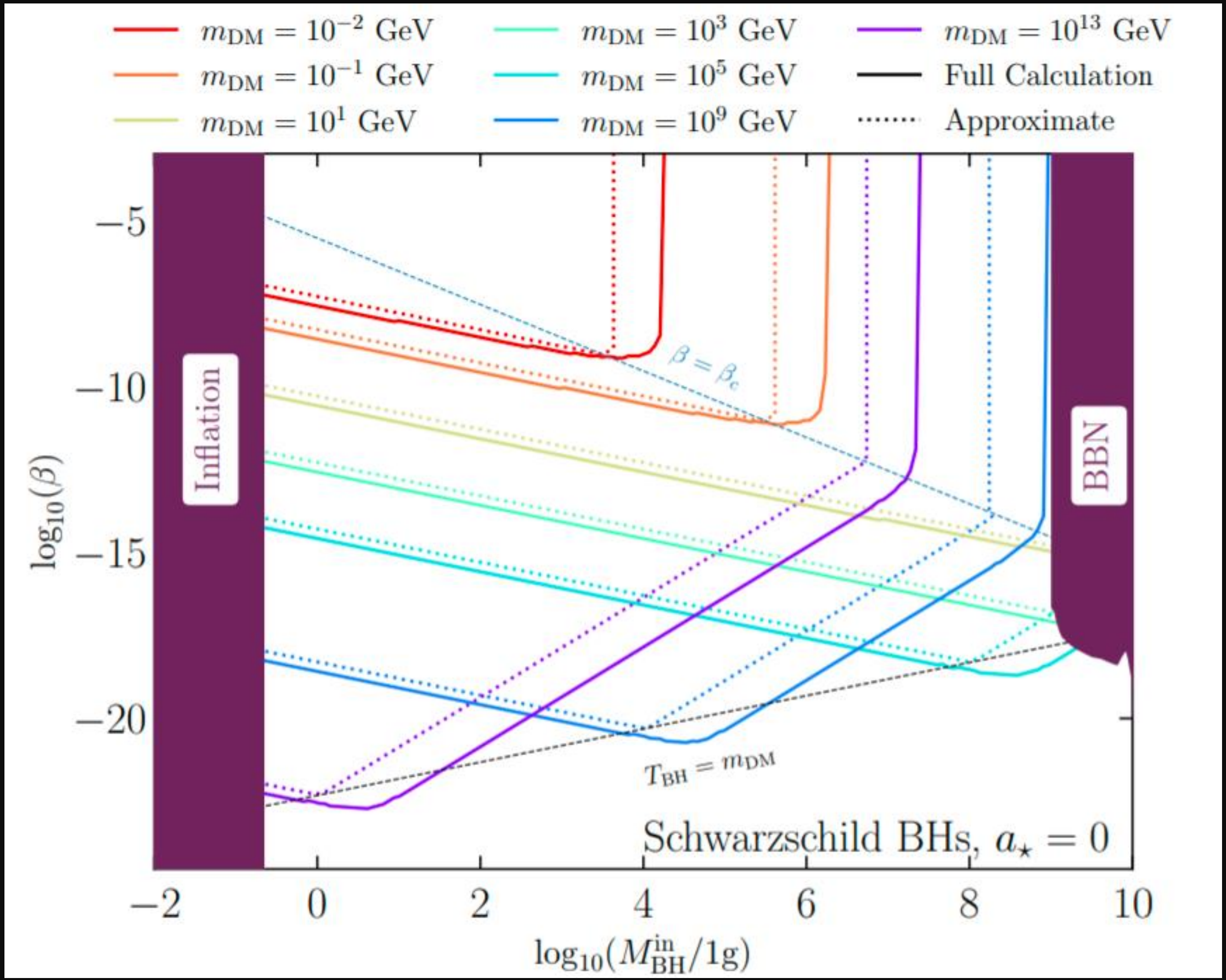


[Cheek, LH, Perez-Gonzalez and Turner '22]

Code Publicly available: FRISBHEE

DM from Evaporation

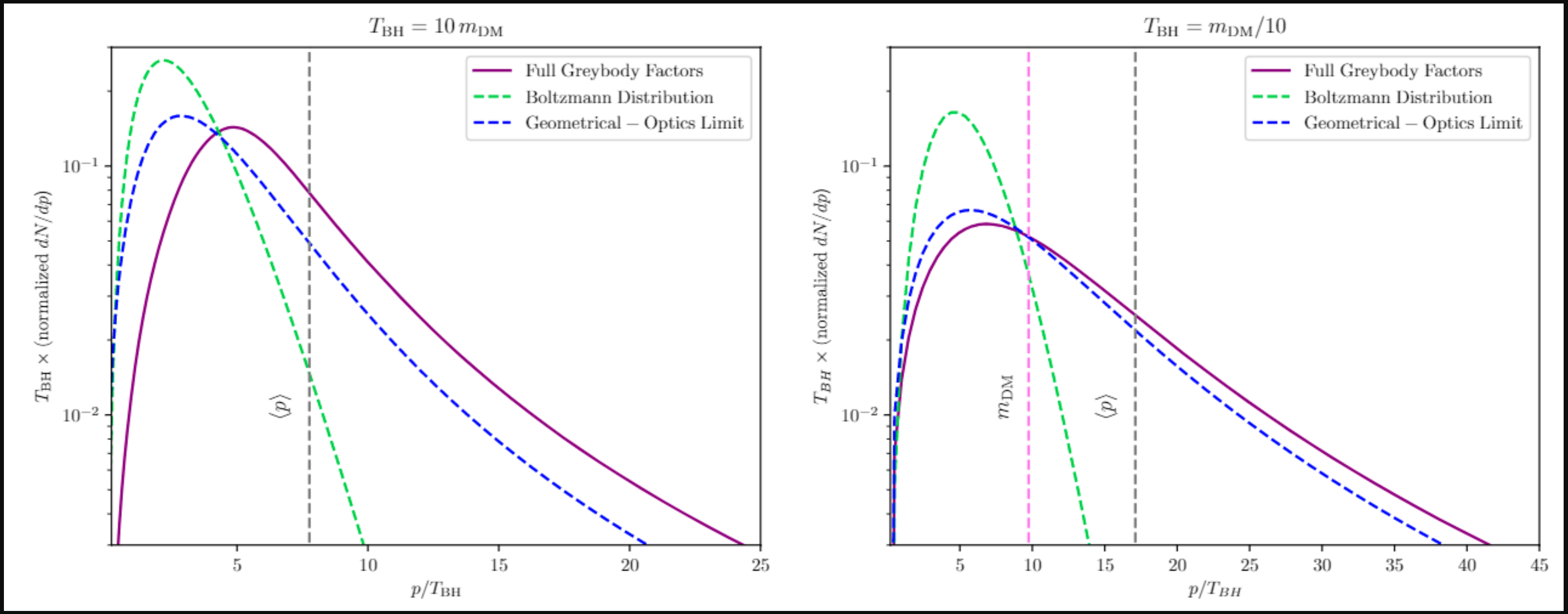
$$f_{\rm PBH}(M) = \delta(M - M_{\rm PBH})$$



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

DM from Evaporation

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

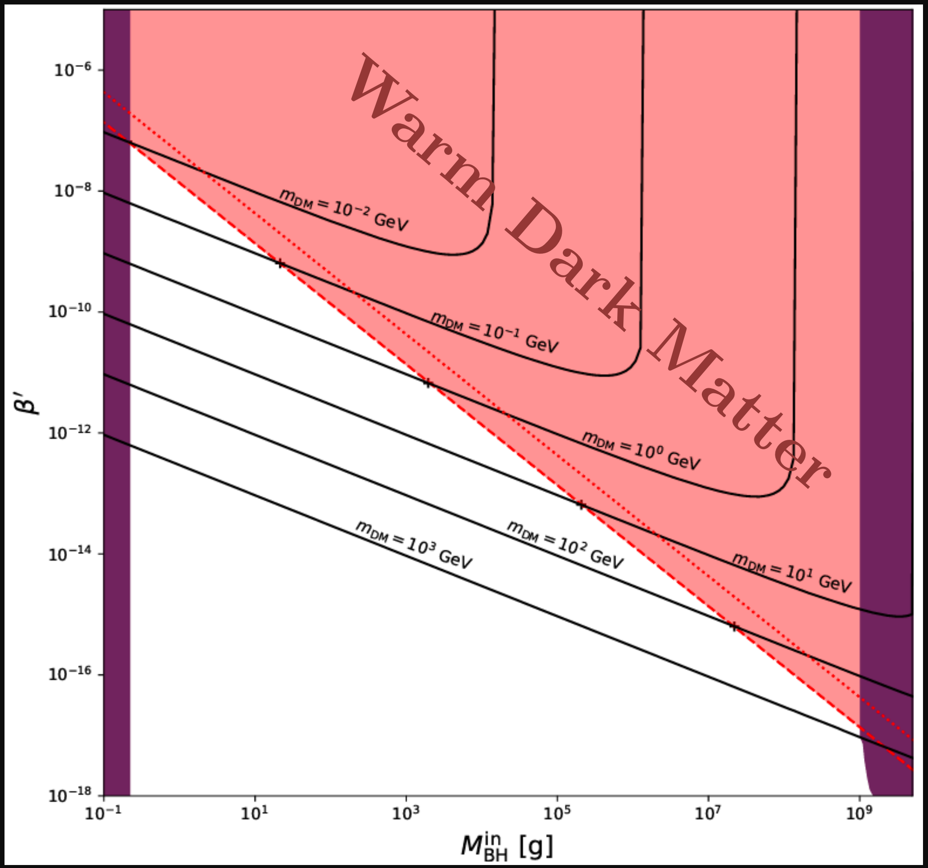


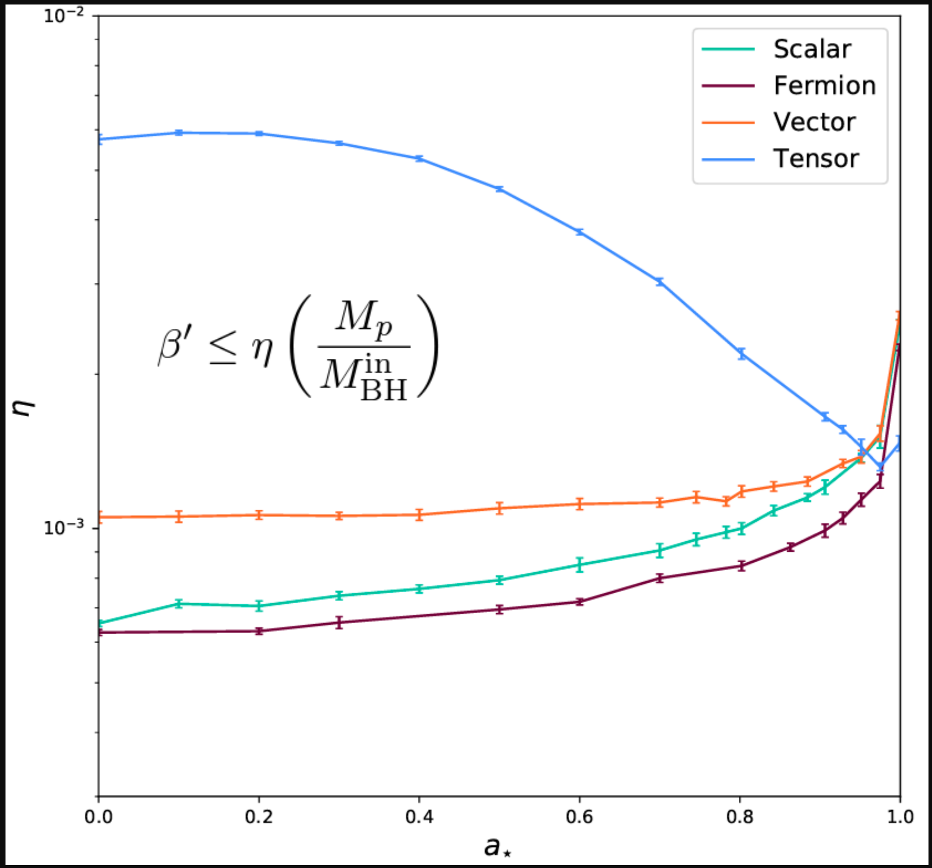
[Cheek, LH, Perez-Gonzalez and Turner '22] **Code Publicly available: FRISBHEE**

Kerr PBHs and Warm Dark Matter

Using CLASS: expected matter power spectrum

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

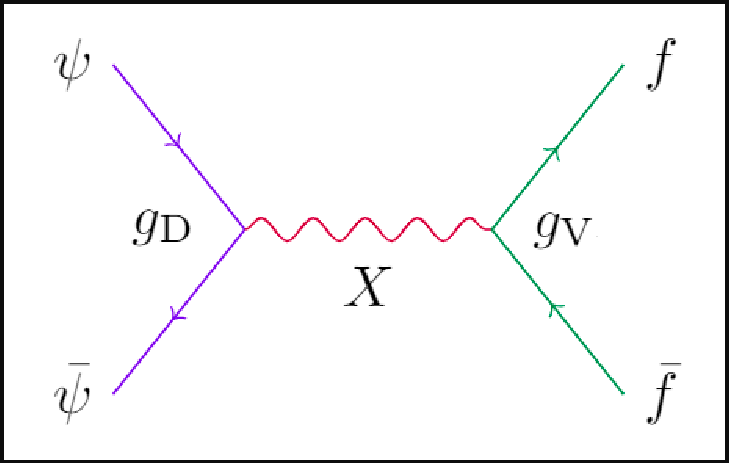


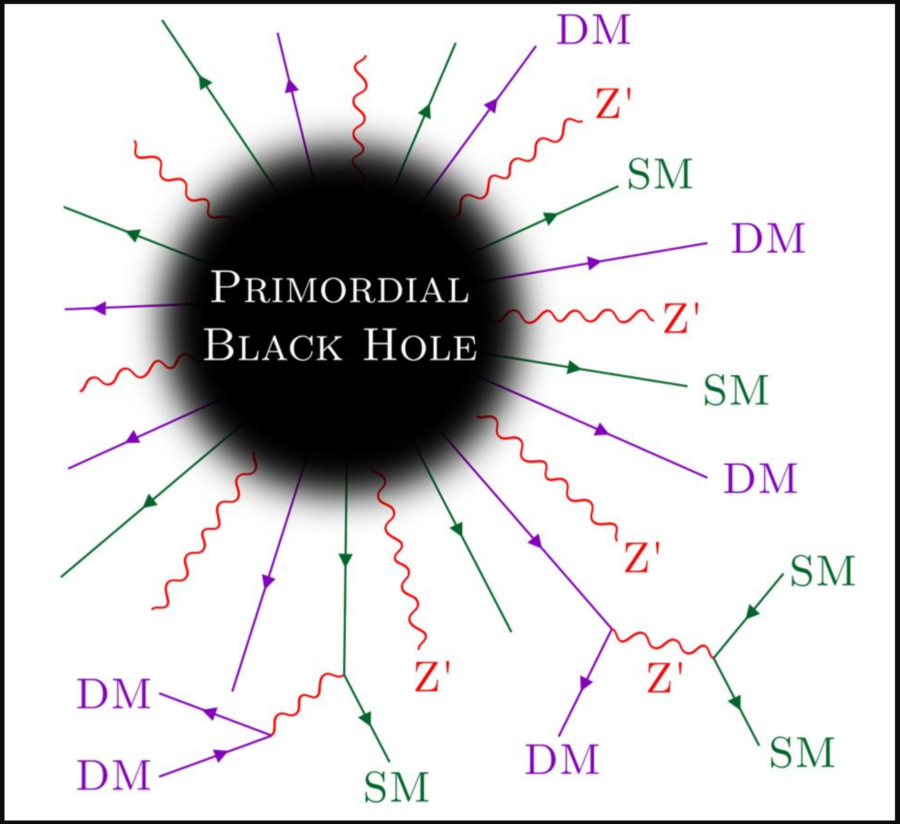


Thermal Production of DM

- 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

DM Annihilation, X decay — PBH evaporation

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

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

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

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

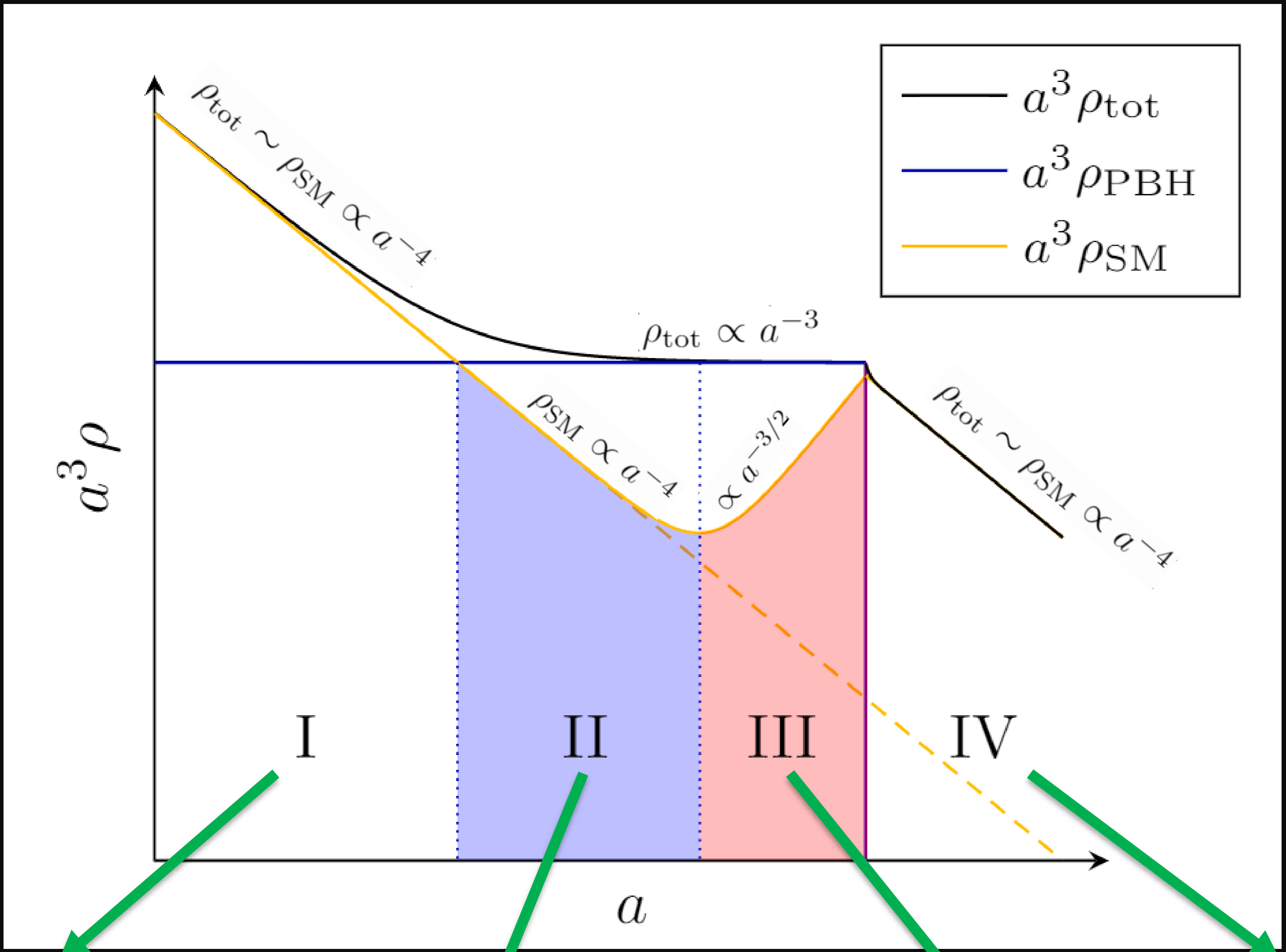
↓

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

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

Simplified approch...

Modified Cosmology



FI/FO + entropy dilution

Regular FI/FO

Matter-Dominated FI/FO

FI/FO during entropy injection

Analytical Results

Freeze-In contribution

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

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

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

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

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:

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

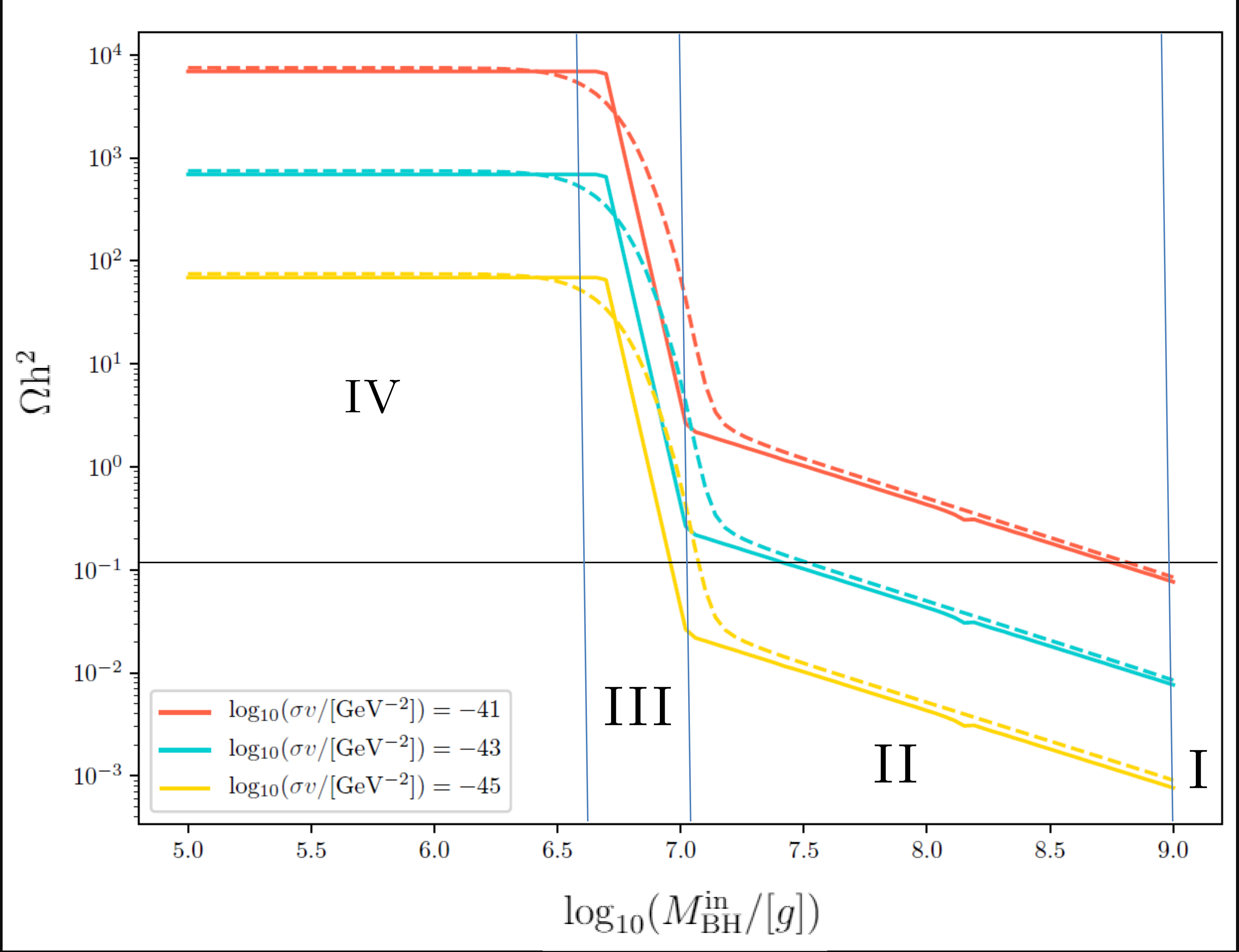
$$\Omega_{\rm I} = \frac{15}{2\pi} \frac{x_{\rm FO}}{\sqrt{10 g_\star(T_{\rm FO})}} \frac{s_{\rm eq}}{m_p \langle\sigma v\rangle \rho_c} \left(\frac{a_{\rm eq}}{a_0}\right)^3,$$

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

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

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

Comparison with Numerics



Results

Freeze-In

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

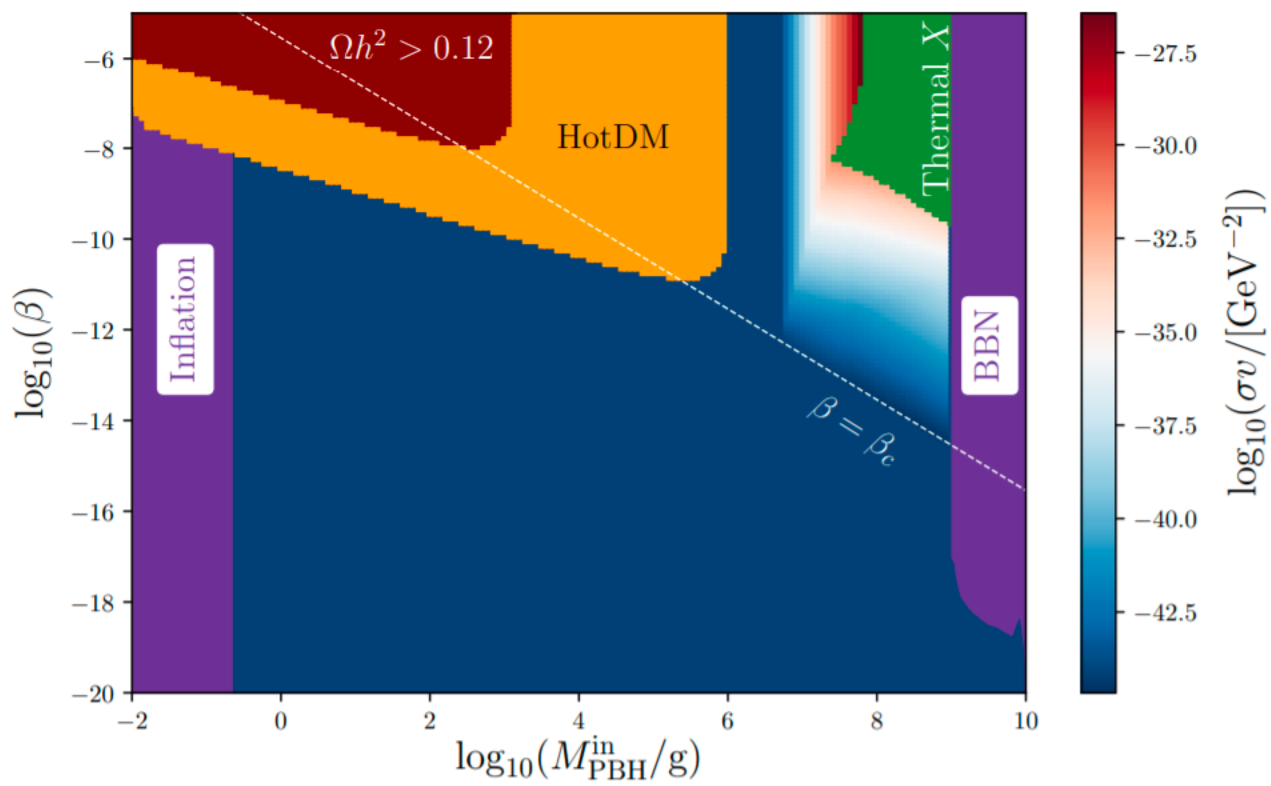


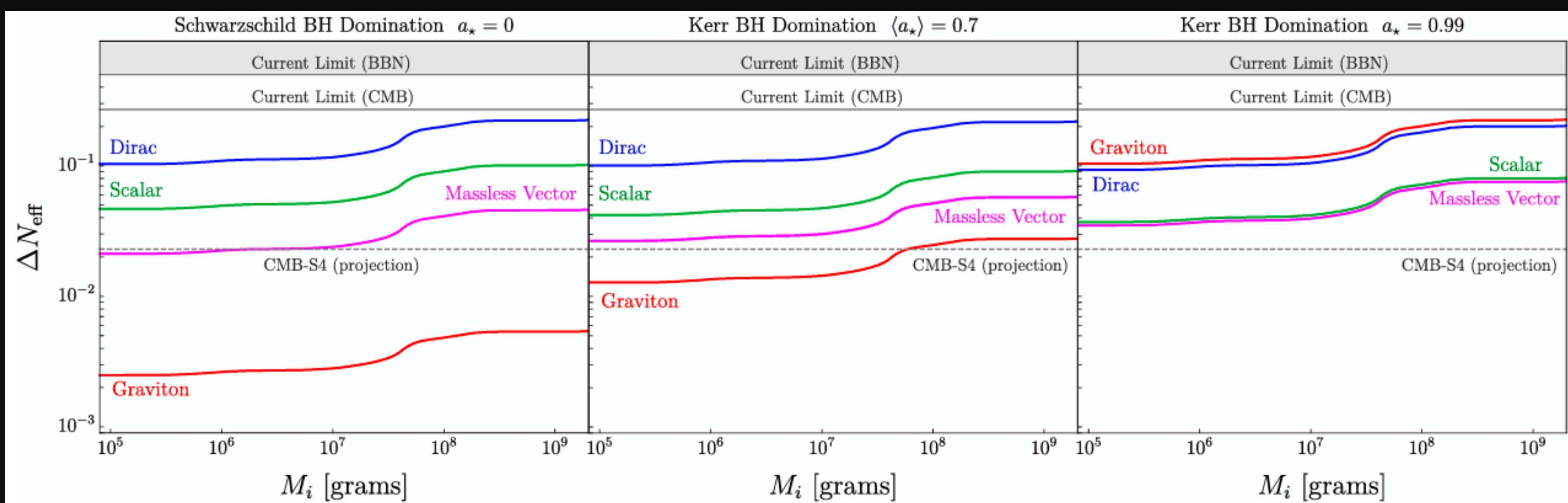
Fig. 11. Two-dimensional scan over the PBH fraction β and mass $M_{\rm BH}$ for a mediator mass $m_X = 1\,{\rm TeV}$, a dark matter mass $m_{\rm DM} = 1\,{\rm MeV}$, and ${\rm Br}(X \to {\rm SM}) = 10^{-7}$. The color map indicates the value of the non-relativistic cross-section of DM annihilation leading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

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]

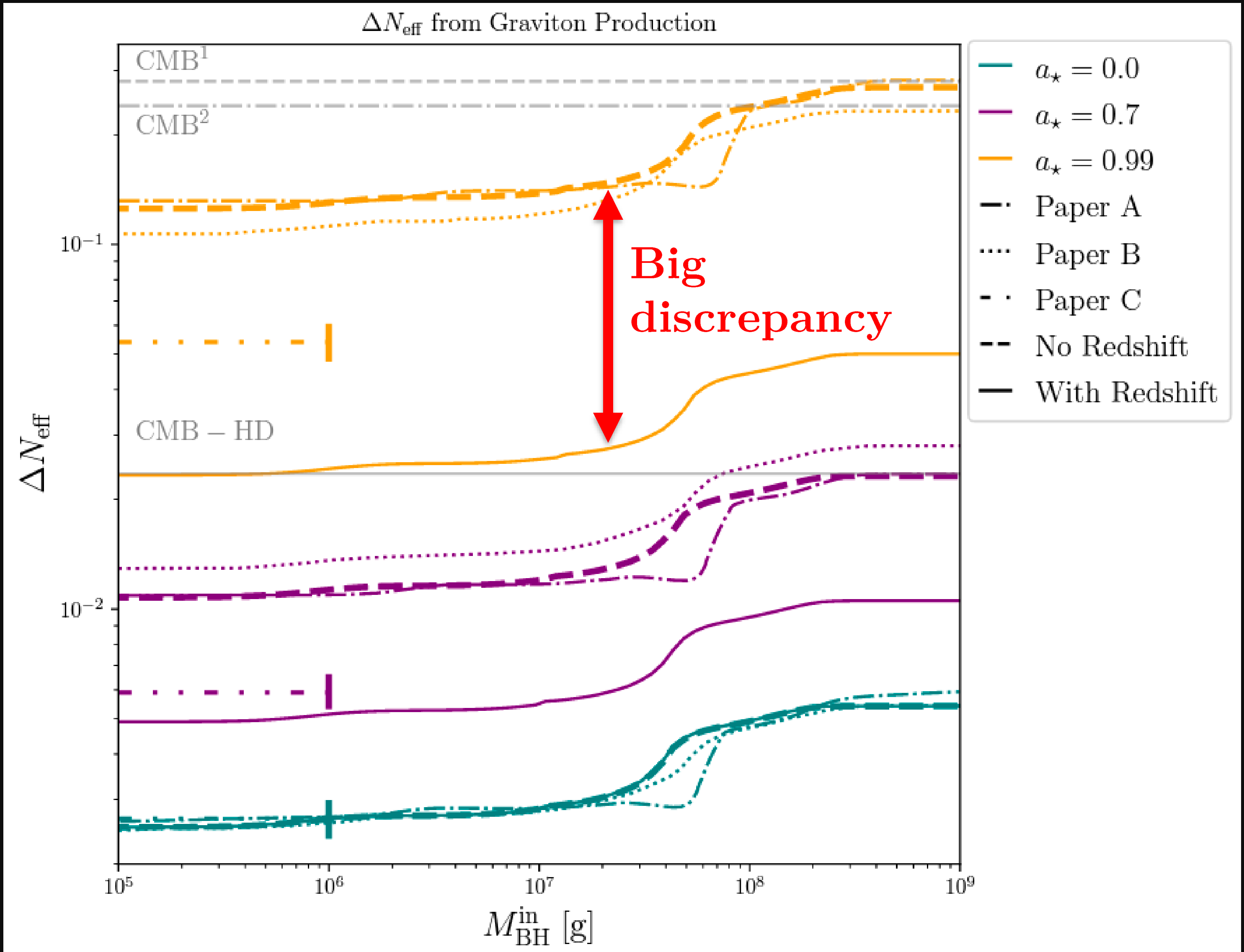
Kerr PBHs and Dark Radiation

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

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

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

Kerr PBHs and Dark Radiation



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

Code Publicly available: FRISBHEE

Kerr PBHs and Dark Radiation

Why ?

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

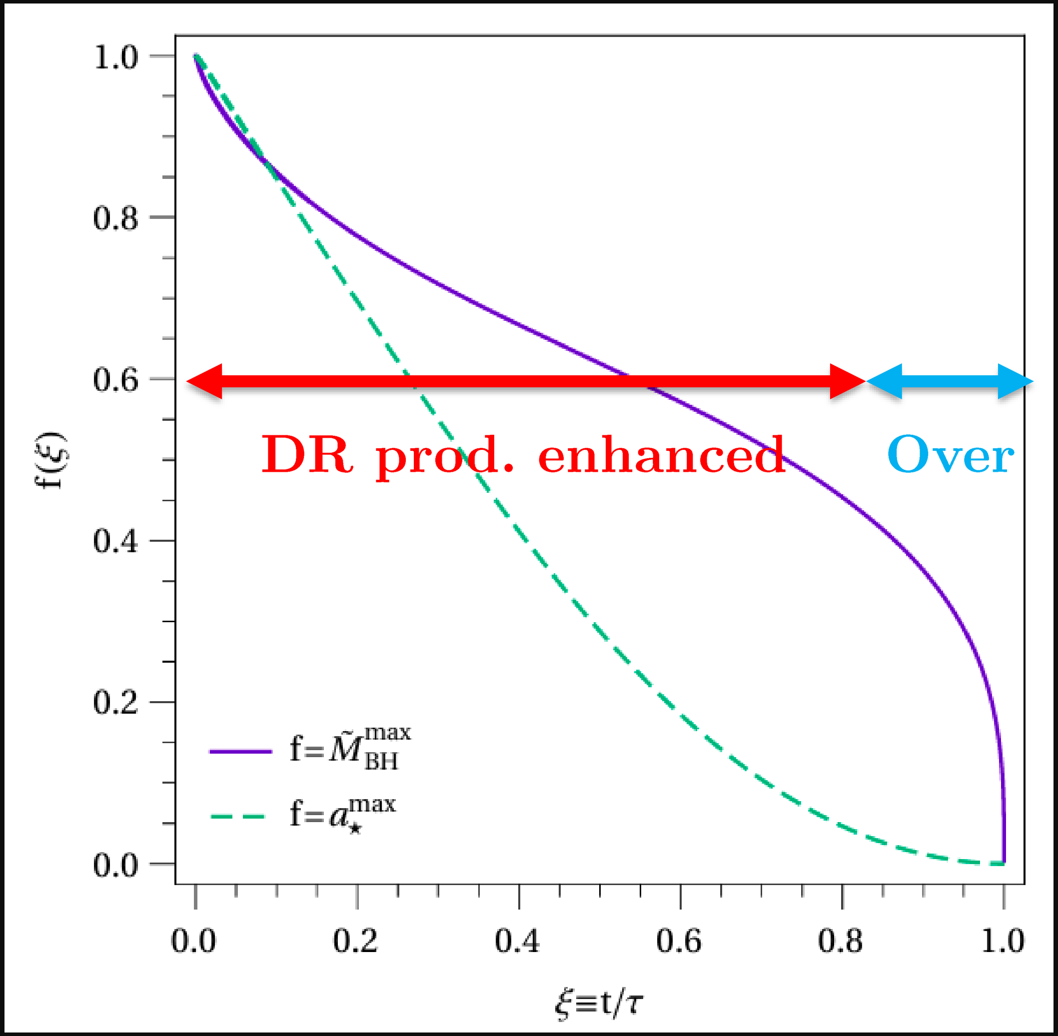
$$N_{\rm eff} \approx 3.045$$ (not just 3 ...)

The neutrino decoupling is NOT instantaneous

+ Temperature-dependent entropy transfer from electrons

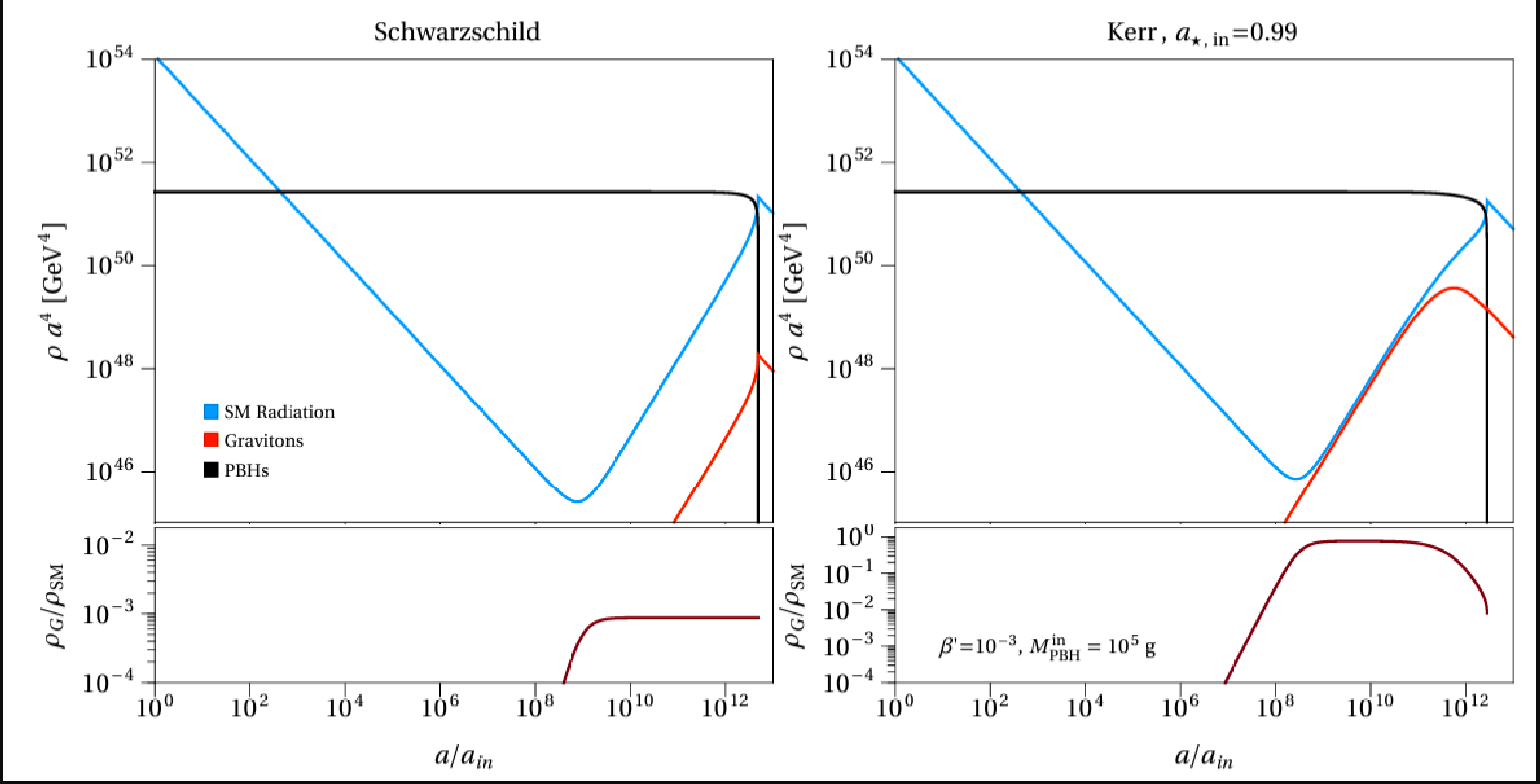
Kerr PBHs and Dark Radiation

Why ?



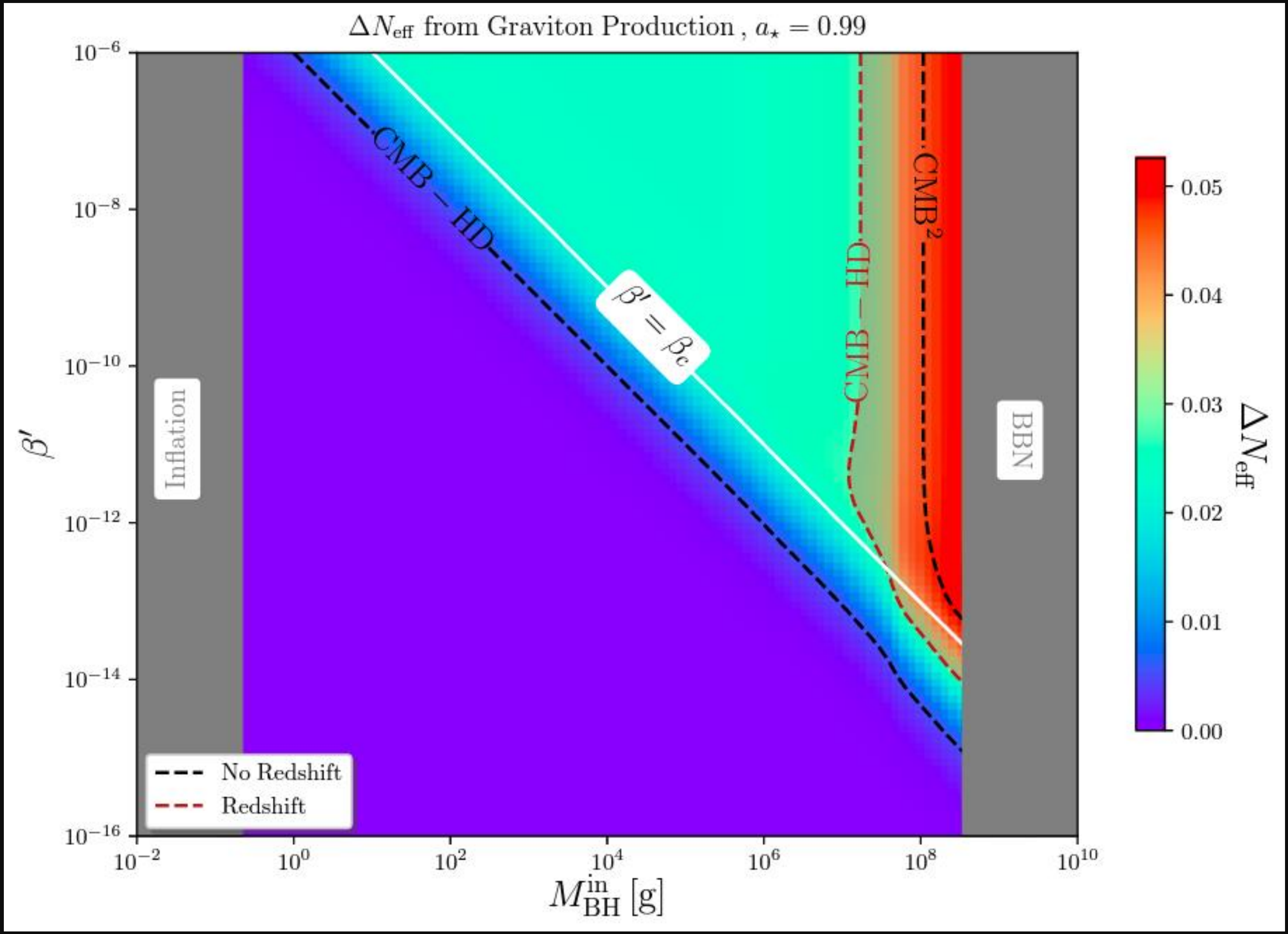
Kerr PBHs and Dark Radiation

Why ?



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

Kerr PBHs and Dark Radiation



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

Evaporation of Extended Distributions

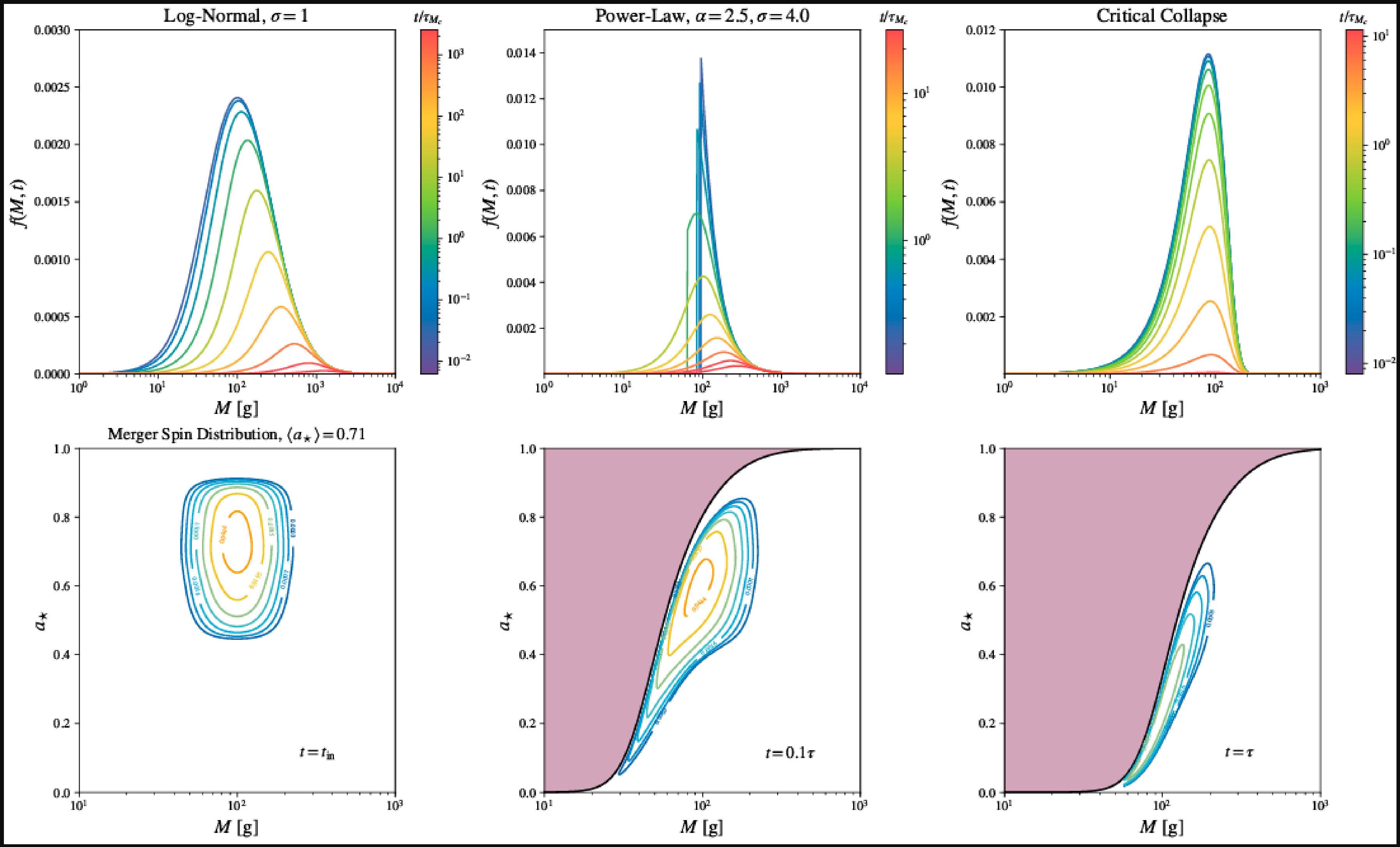
In reality, PBHs don't all have the same mass...

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

$$\downarrow$$

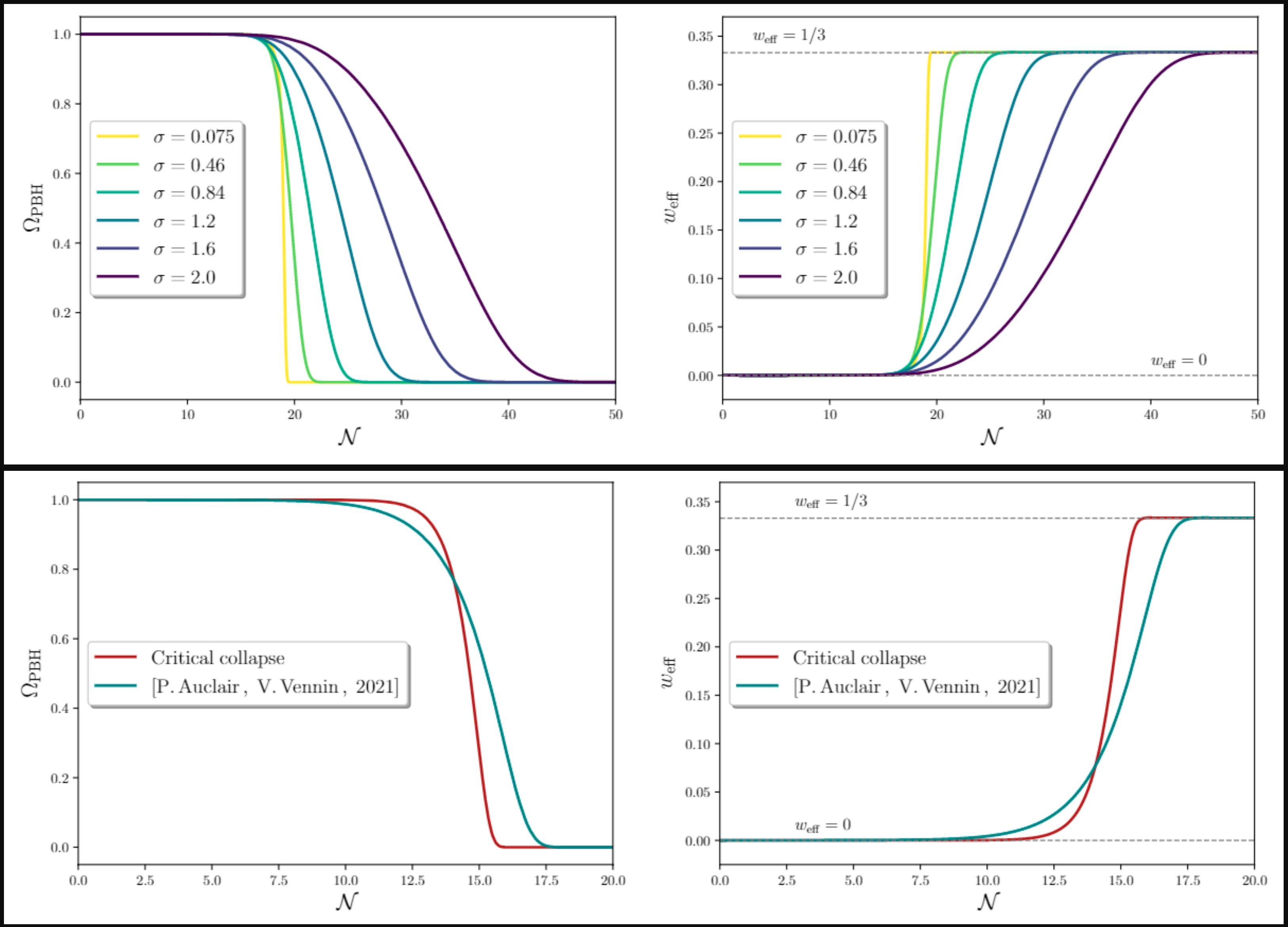
$$f_{\mathrm{PBH}}(M,a) = F(M - M_{\mathrm{PBH}}) \times A(a - a_*)$$

Evaporation of Extended Distributions



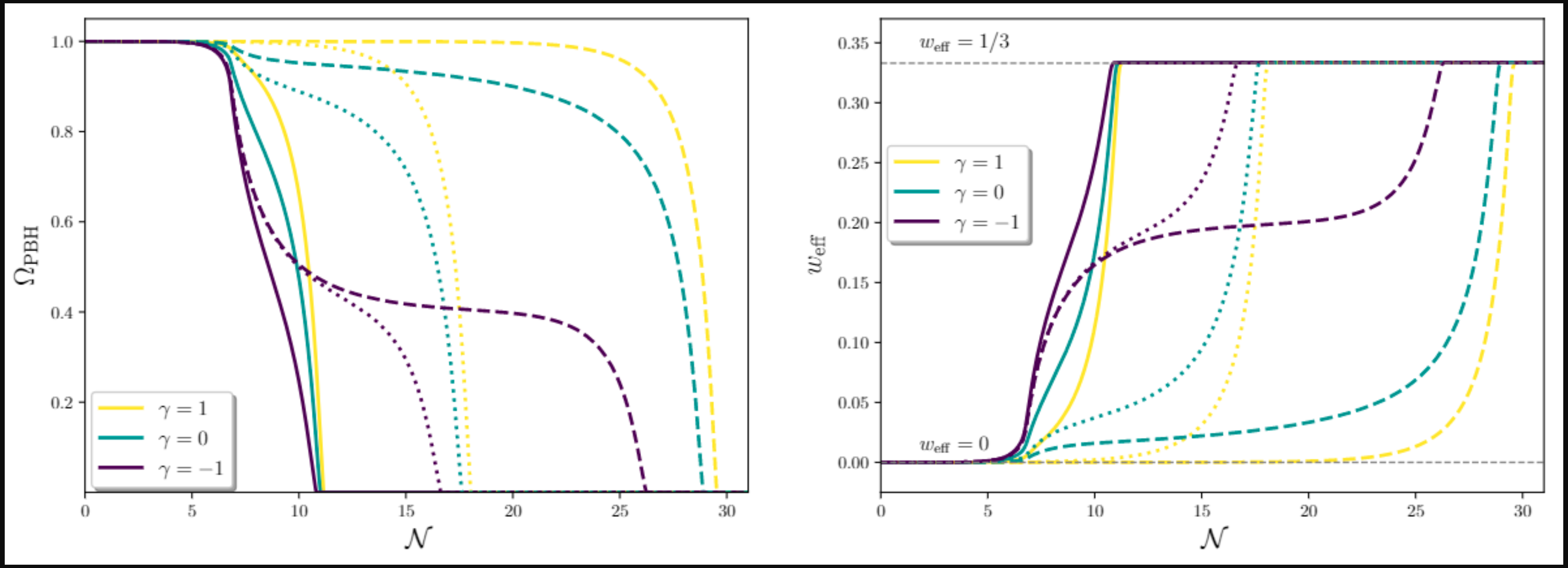
[Cheek, LH, Perez-Gonzalez, Turner '22]

Evaporation of Extended Distributions



Evaporation of Extended Distributions

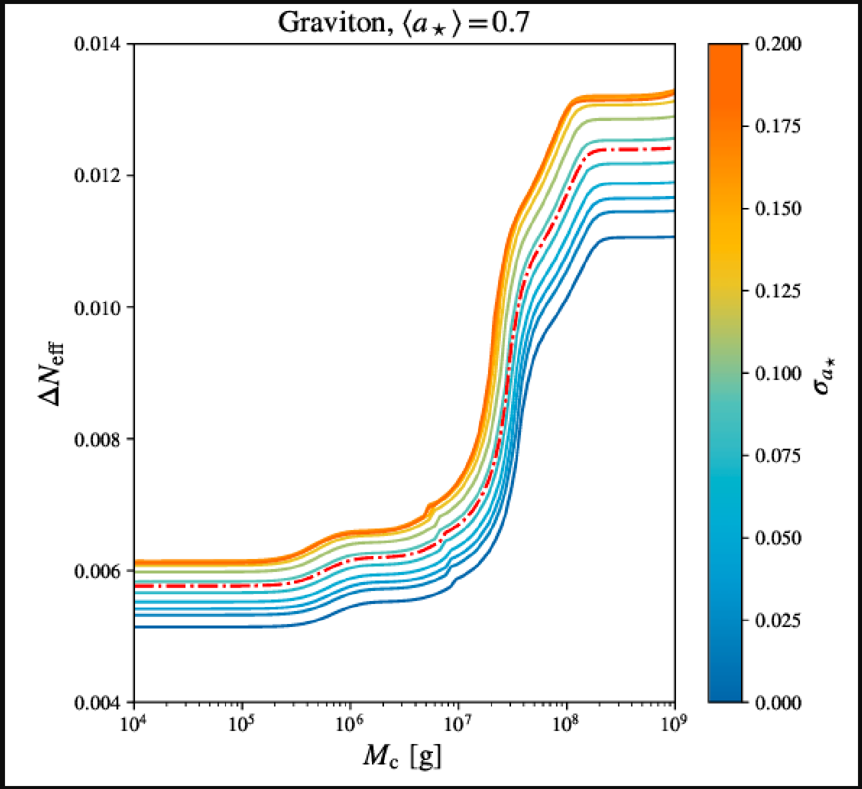
$$\frac{\mathrm{d}n}{\mathrm{d}M} \propto M^{-\alpha} \quad \text{with} \quad \alpha = \frac{2\,(1+2\,w)}{1+w}$$

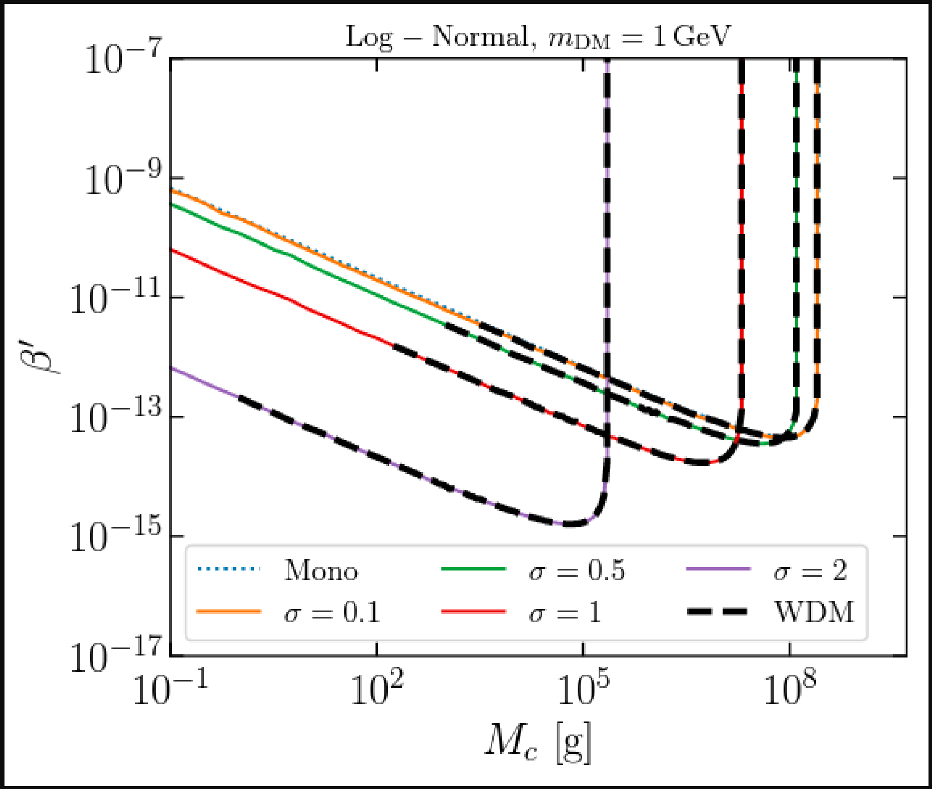


'Stasis' regime reached for $0 < w \leq 1$

[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]

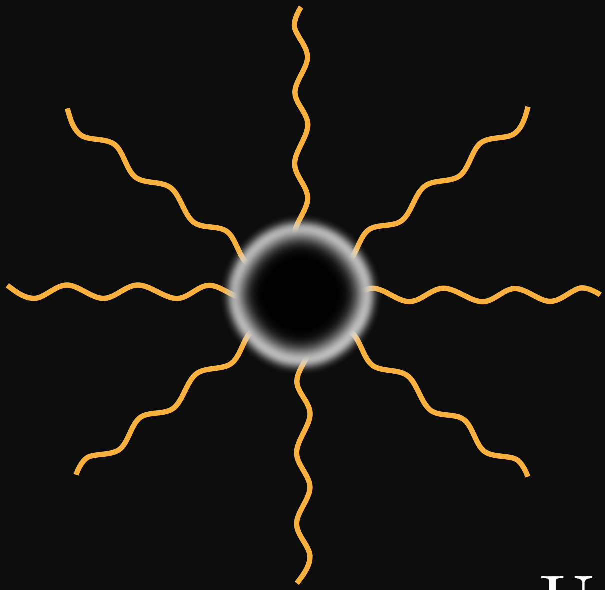
Primordial Black Holes

are

Powerful & Local radiators

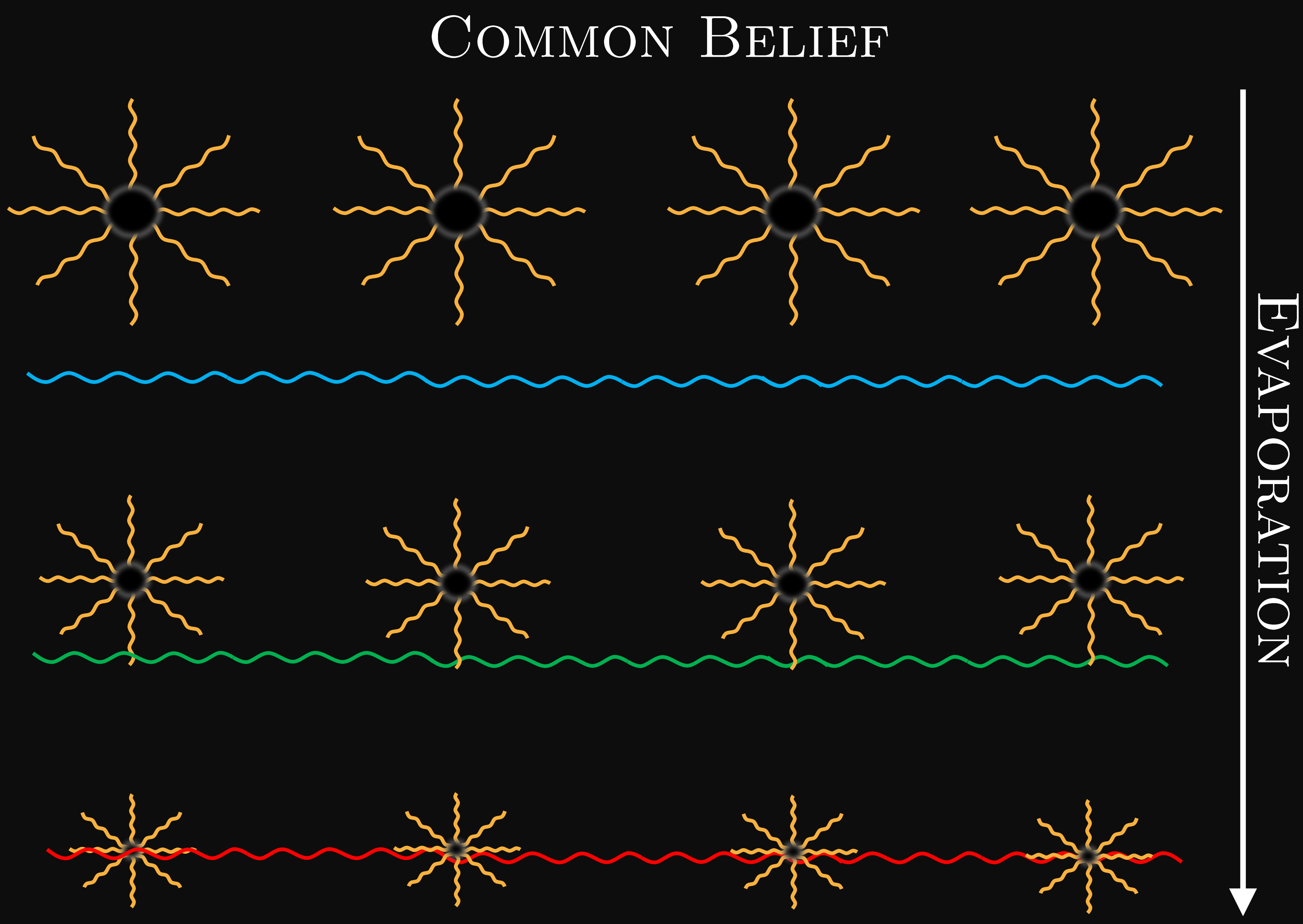
in

Cosmology

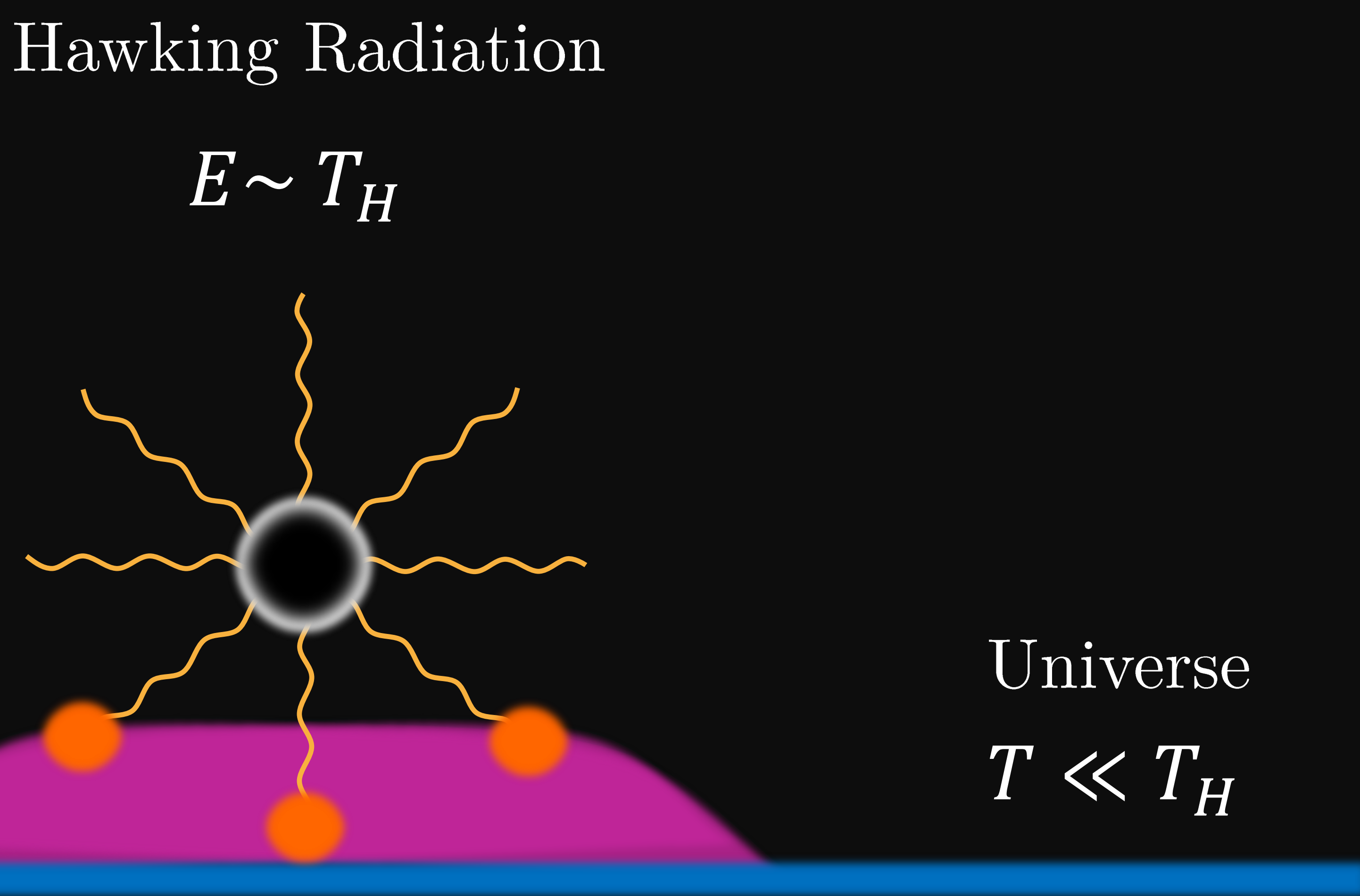


Hawking Radiation $E \sim T_H$

Universe Temperature $T \ll T_H$


Common Belief
Evaporation

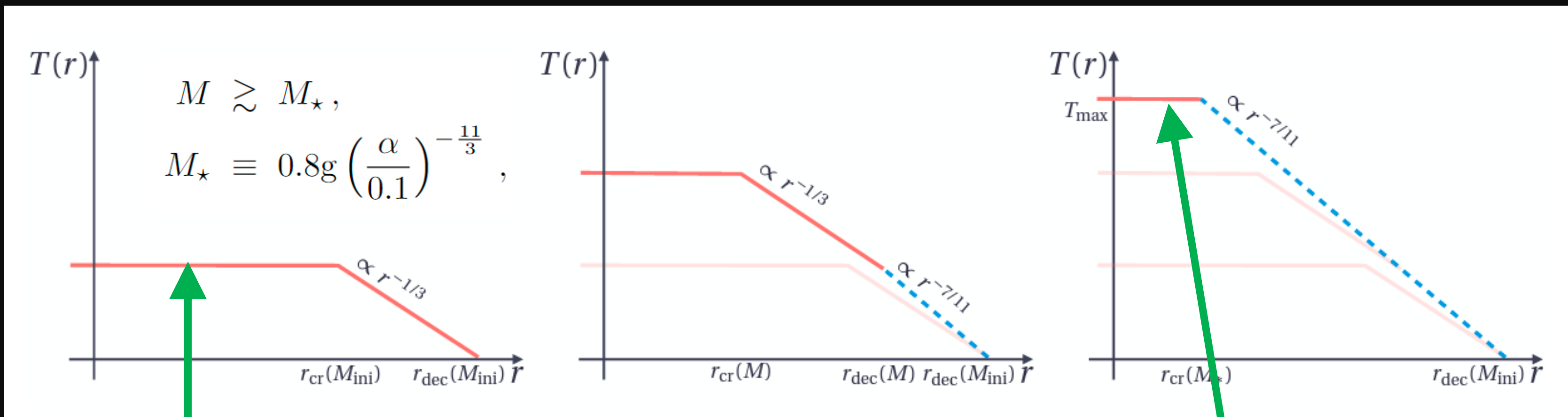
In Reality



In Reality

Hawking Radiation heats the ambient plasma locally

He et al. *JCAP* 01 (2023) 027



$$T_{\rm plateau} \approx 2\times 10^{-4}\left(\frac{\alpha}{0.1}\right)^{\frac{8}{3}} T_H$$

$$r_{\rm plateau} \approx 7\times 10^{8}\left(\frac{\alpha}{0.1}\right)^{-6} r_H$$

$$T_{\rm max} \approx 2\times 10^{9}\mathrm{GeV}\left(\frac{\alpha}{0.1}\right)^{\frac{19}{3}}$$

$$r_{\rm max} = r_{\rm plateau}\Big|_{T_H = T_{\rm max}}$$

In Reality

Hawking Radiation heats the ambient plasma locally

Hot Spot cooling is slow.

Hot Spots can shield Hawking evaporation.

Implications Expected for Warm Dark Matter, leptogenesis, BBN, CMB, and possibly more...

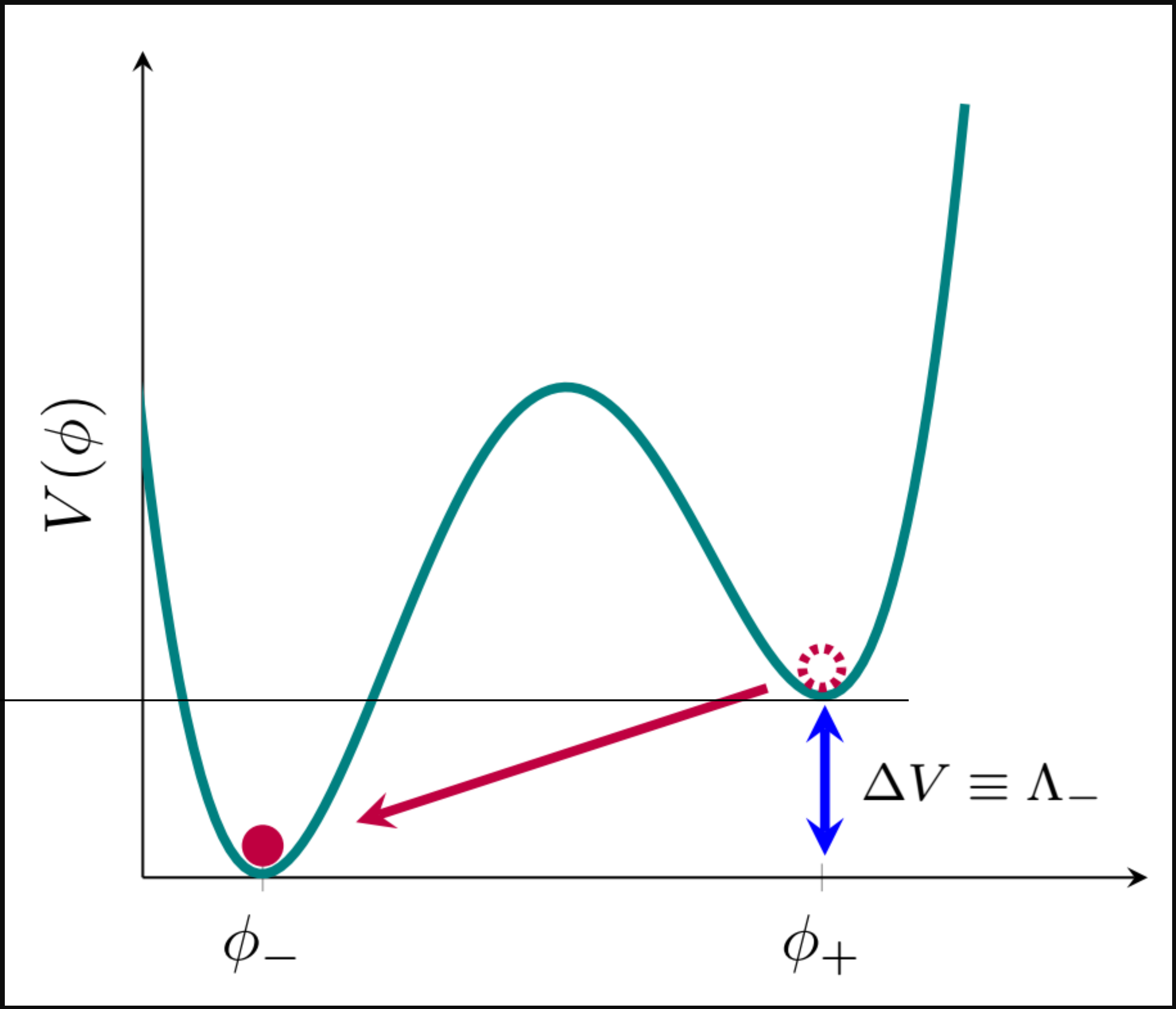
Papers to come. Stay tuned.

In Reality

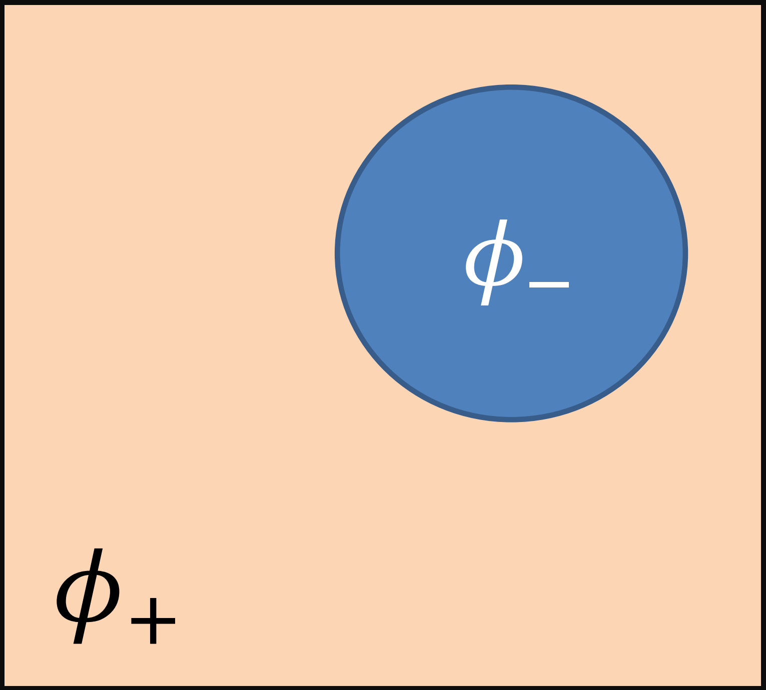
Hawking Radiation heats the ambient plasma locally

[L. Heurtier and S. Pan, September 2023]

1^{st}-Order Phase Transitions for Dummies



1^{st}-Order Phase Transitions for Dummies



Transition ⟷ Energy Loss

In the vacuum: S. R. Coleman, Phys. Rev. D 15, 2929 (1977)

→ The bubble expands ($O(4)$ symmetric bubble)

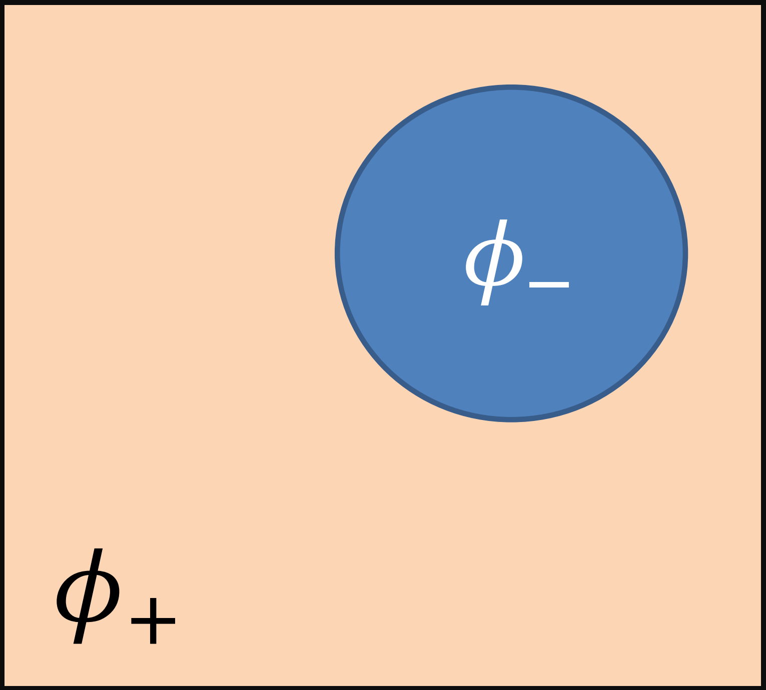
Energy = Kinetic

In a Thermal Bath: A. D. Linde, Phys. Lett. B 100, 37 (1981).

→ The bubble is static ($O(3)$ symmetric bubble)

Energy from Thermostat

1$^{\text{st}}$-Order Phase Transitions for Dummies



Transition ⟷ Energy Loss

In (COLD) GR: Coleman & De Luccia, Phys. Rev. D 21, 3305 (1980).

→ The metric and bubble adjust to conserve energy

Energy = Metric Deformation

Question: What happens around a radiating Black Hole?

1st-Order Phase Transitions for Dummies

Question: What happens around a radiating Black Hole?

So Far: Only considered in very extreme situations...

BH radiating in the vacuum (Unruh vacuum)

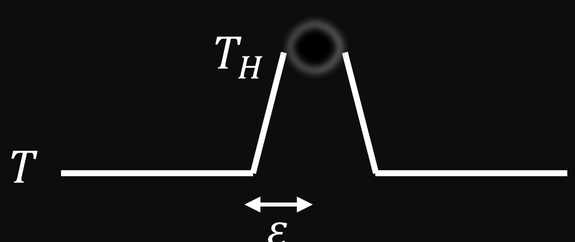
→ No definite answer. Partial results only obtained in 2D.

BH in thermal equilibrium with the plasma (Hartle-Hawking vacuum)

→ The BH and the plasma both behave as thermostats.

$$I_{\mathrm{b}}[T] = \beta \int dx^3 \sqrt{-h} \left(-\frac{R}{16\pi G} + \frac{1}{2} h^{\mu\nu} \partial_\mu \phi \partial_\nu \phi + V(\phi) \right)$$

+ Bckgd terms
+ Conical deficit
if $\beta \neq \beta_H$



$$I_{\mathrm{b}}[T] = \frac{\mathcal{A}_+}{4G} - \frac{\mathcal{A}_-}{4G} = I_{\mathrm{b}}[T_H]$$

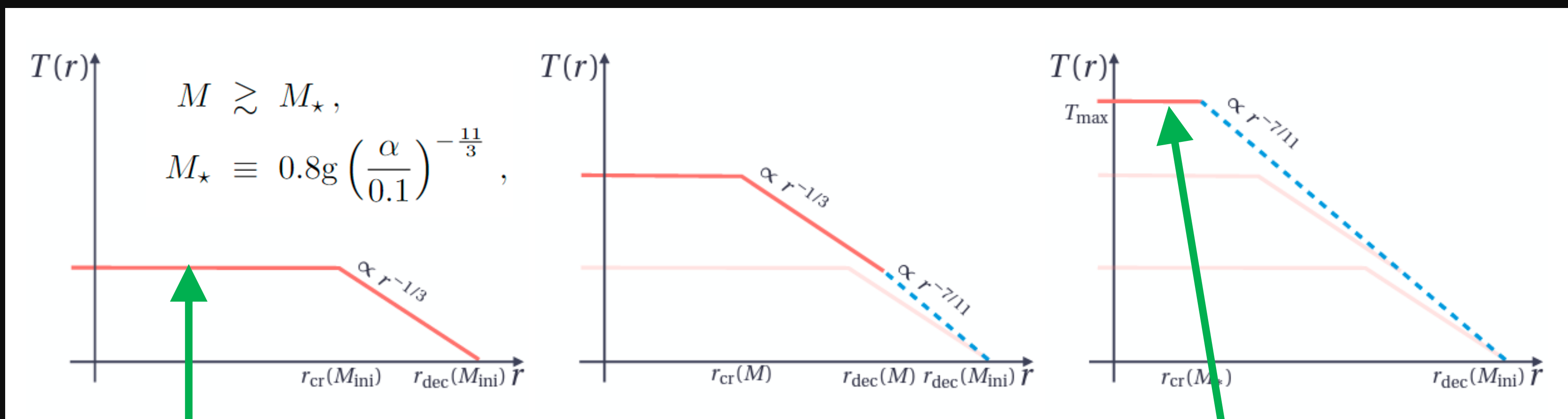
Gregory, Moss, and Withers, JHEP 03, 081(2014)

Only used with Hartle-Hawking so far...

In Reality

Hawking Radiation heats the ambient plasma locally

He et al. *JCAP* 01 (2023) 027



$$T_{\rm plateau} \approx 2\times 10^{-4}\left(\frac{\alpha}{0.1}\right)^{\frac{8}{3}} T_H$$

$$r_{\rm plateau} \approx 7\times 10^{8}\left(\frac{\alpha}{0.1}\right)^{-6} r_H$$

$$T_{\rm max} \approx 2\times 10^{9}\,{\rm GeV}\left(\frac{\alpha}{0.1}\right)^{\frac{19}{3}}$$

$$r_{\rm max} = r_{\rm plateau}\Big|_{T_H = T_{\rm max}}$$

In Reality

Hawking Radiation heats the ambient plasma locally

→ In the $\varepsilon \to 0$ limit, can use the result

$$I_{\rm b}[T] = \frac{\mathcal{A}_+}{4G} - \frac{\mathcal{A}_-}{4G} = I_{\rm b}[T_H] \quad (*)$$

→ To calculate the rate:

$$\Gamma^{\rm HH}_{\rm FVD} \equiv (GM_+)^{-1} \left(\frac{I_{\rm b}[T_H]}{2\pi}\right)^{1/2} \exp\left(-I_{\rm b}[T_H]\right) .$$

T_H

Linde's result

$$\frac{\Gamma}{V} = T\left(\frac{S_3(\varphi)}{2\pi T}\right)^{3/2} \exp\left[-S_3(\varphi)/T\right]$$

Generalisation to arbitrary T

$$\Gamma_{\rm FVD}(T) \approx T\left(\frac{I_{\rm b}[T]}{2\pi}\right)^{1/2} \exp\left(-I_{\rm b}[T]\right) ,$$

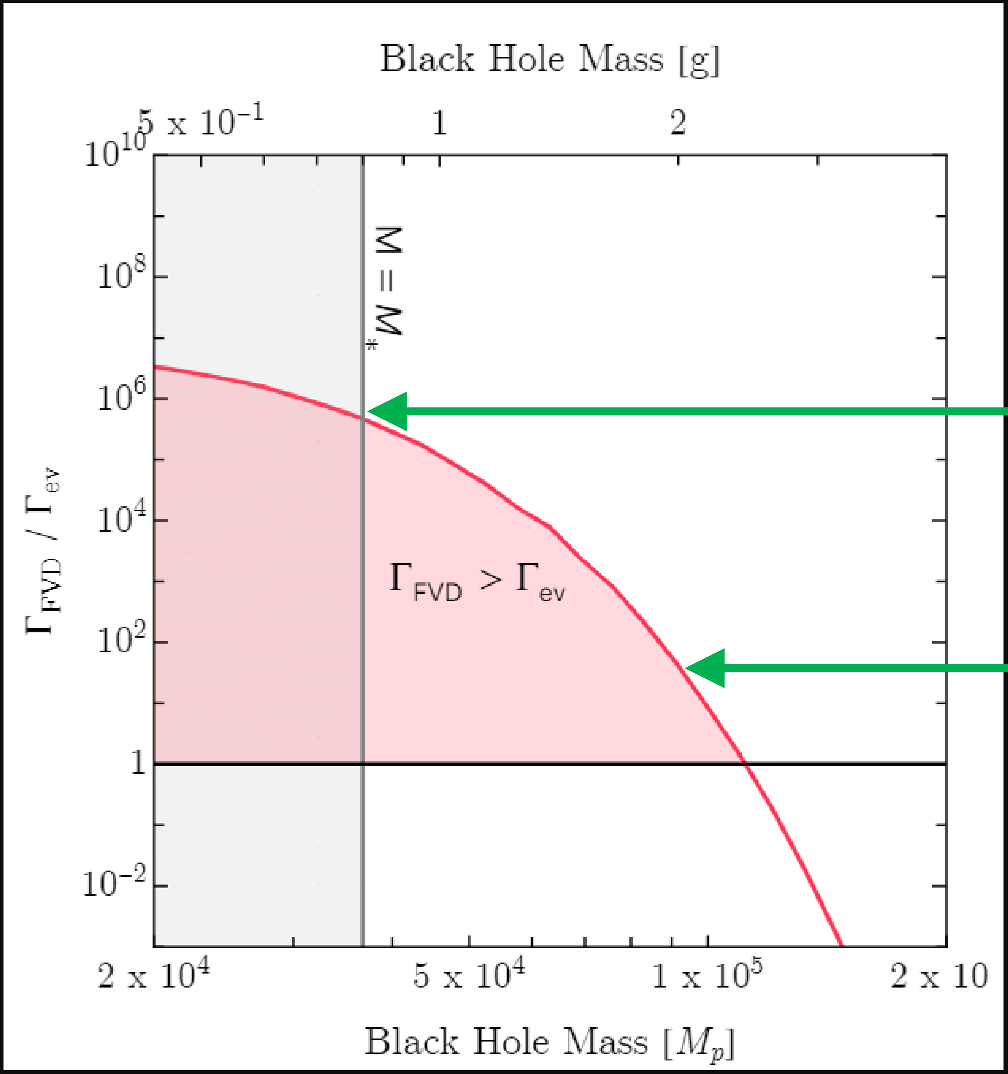
$$\approx T\left(\frac{I_{\rm b}[T_H]}{2\pi}\right)^{1/2} \exp\left(-I_{\rm b}[T_H]\right)$$

$(*)$

Rate to be compared to the evaporation rate...

An example: The EW vacuum

Our Universe may be metastable (at ~2σ)



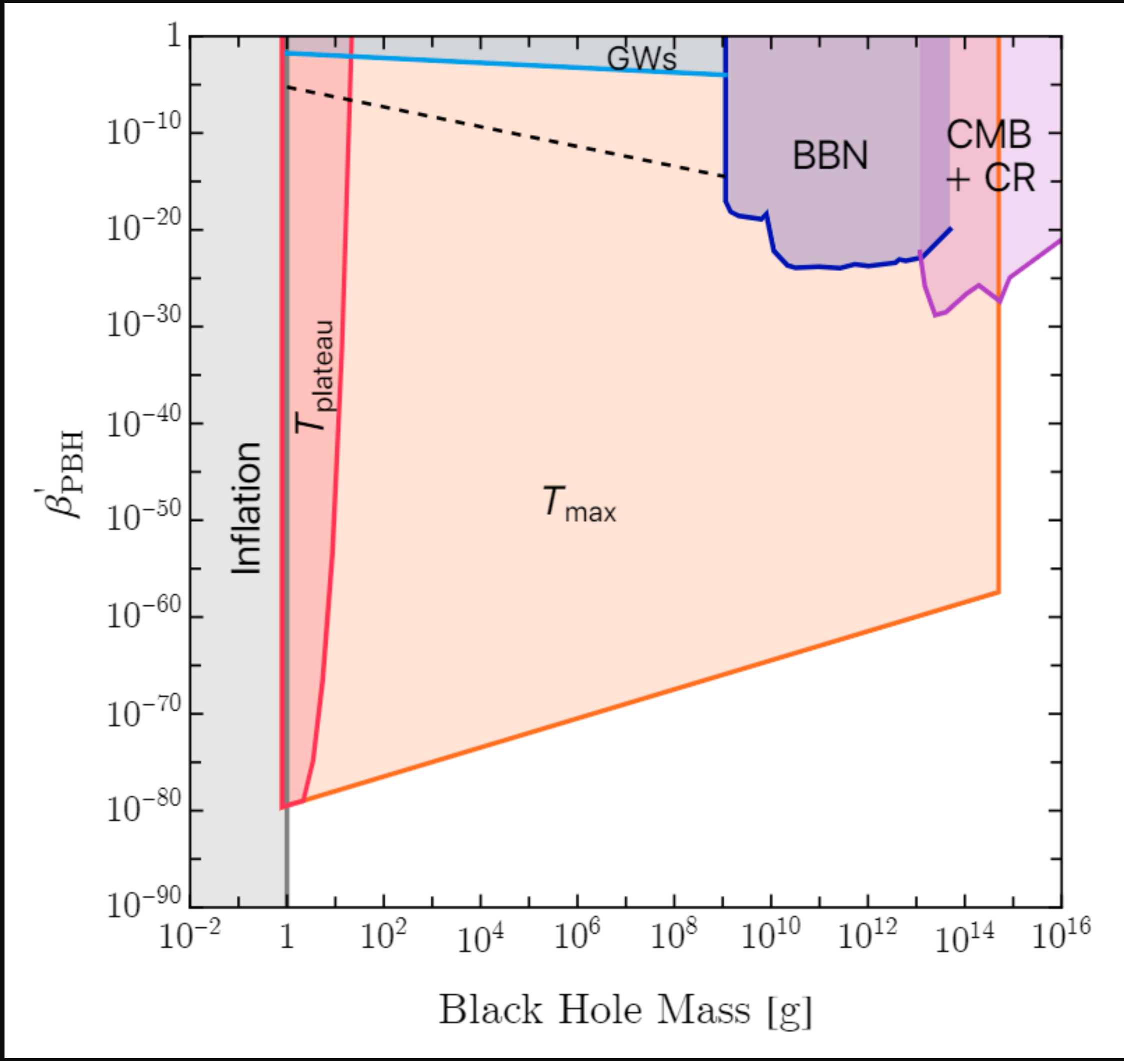
At $M = M_*$, $T = T_{max}$

Using $T_{plateau}(M)$

[Hamaide, LH, Hu, Cheek, ArXiv:2311.01869]

An example: The EW vacuum

Our Universe may be metastable (at ~2σ)



[Hamaide, LH, Hu, Cheek, ArXiv:2311.01869]

Conclusion

PBHs can leave several imprints in the early Universe

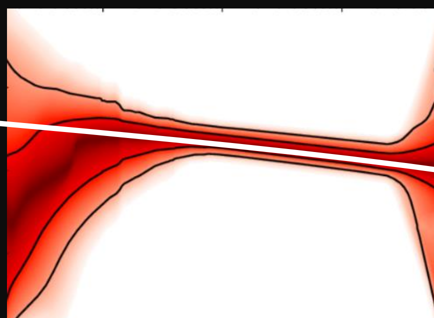
- Modify cosmology (EMD+ entropy inj.)
- Produce dark matter, leading to modified predictions for particle searches
- Affect Cosmic expansion, reheat the universe
- PBHs can act as local radiators, leading to hot spots that can survive for a long time in the early Universe...
- FRISBHEE is accessible online:

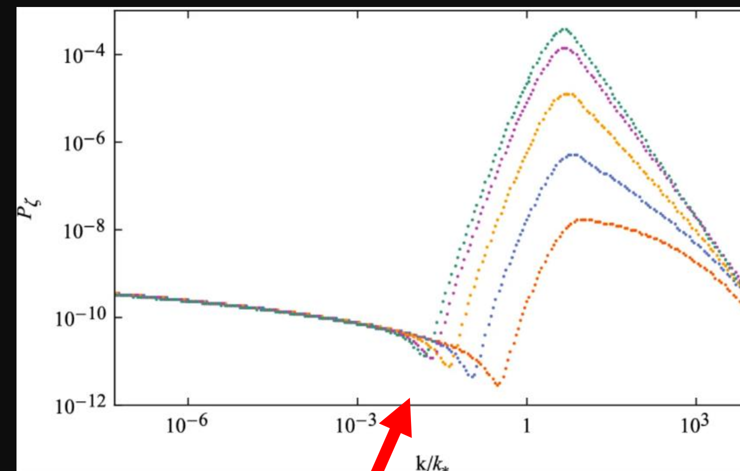
https://github.com/yfperezg/frisbhee

Thank you very much !

PBH Formation

Planck



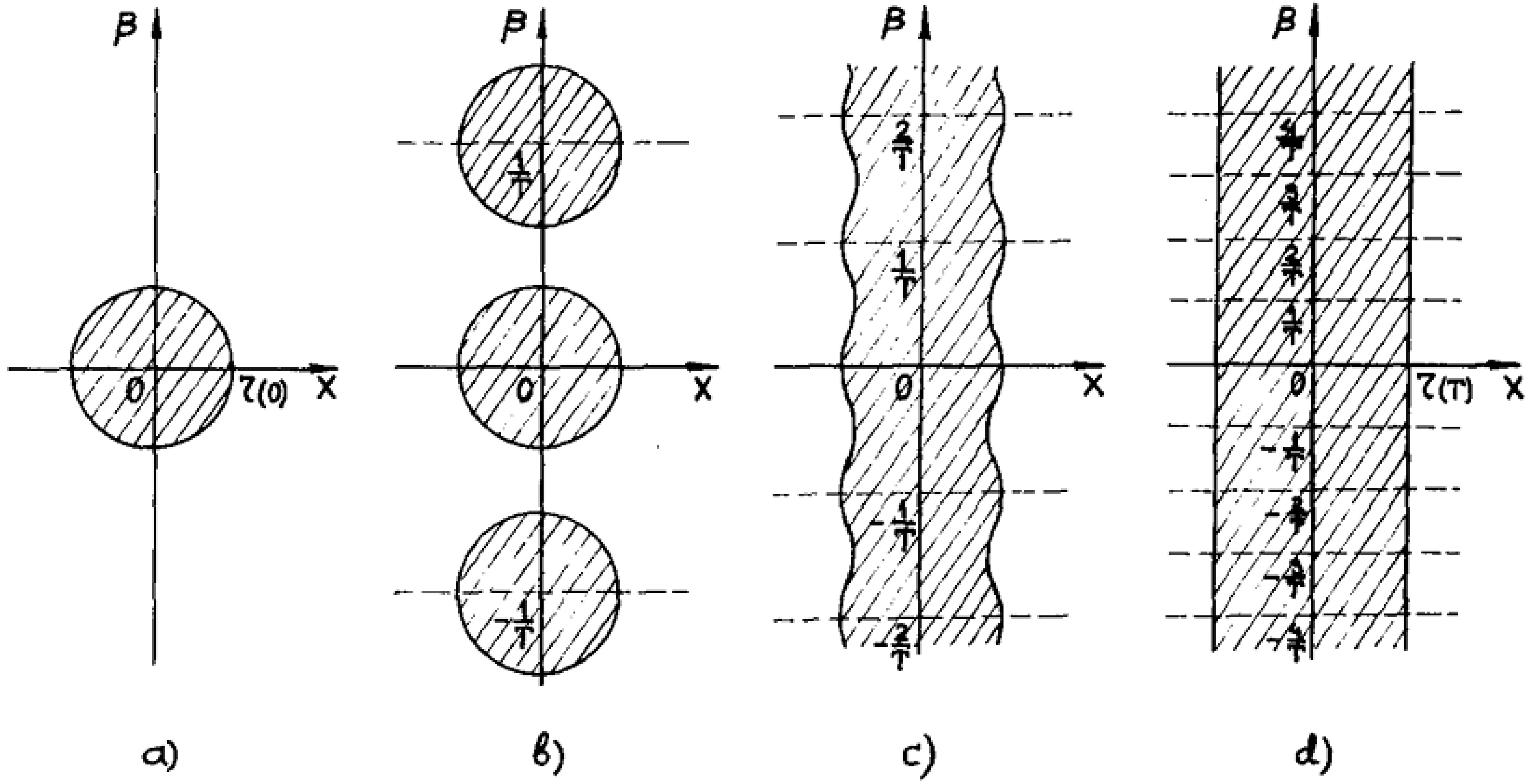


Ultra
Slow-Roll

[LH, Moursy, Wacquez ‘22]

$$W = \left(1 - \frac{S}{\sqrt{3}}\right)^3 f(Z)$$

$$K = K_1\left(Z, \overline{Z}\right) - 3\log\left[1 - \frac{|S|^2}{3} + \frac{|S|^4}{\Lambda^2}\right]$$



β
0
τ(0)
X
a)
β
1/T
0
X
-1/T
b)
β
2/T
1/T
0
X
-1/T
-2/T
c)
β
0
τ(T)
X
d)

Kerr PBHs and Dark Radiation

In the Standard Model

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

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

In the presence of Dark Radiation

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

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

The quantity to evaluate

Kerr PBHs and Dark Radiation

Why ?

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

some redshift is good

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

Kerr PBHs and Dark Radiation

Why ?

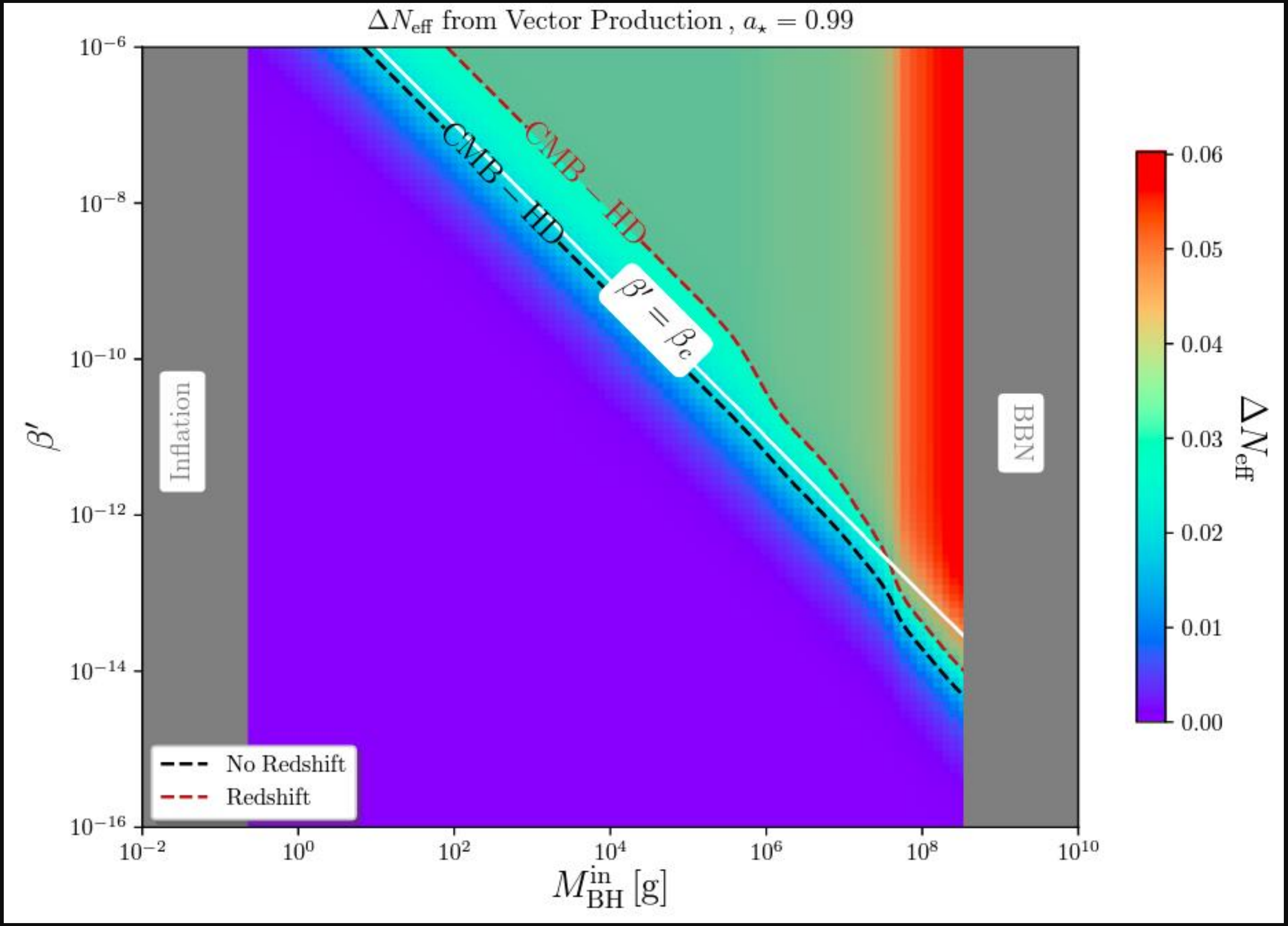
$$\frac{\mathrm{d}\mathcal{N}_{\mathrm{DM}}}{\mathrm{d}p} = \int_0^\tau \mathrm{d}t' \, \frac{a(\tau)}{a(t')} \times \frac{\mathrm{d}^2\mathcal{N}_{\mathrm{DM}}}{\mathrm{d}p'\mathrm{d}t'} \left(p\frac{a(\tau)}{a(t')}, t' \right)$$

The correct one is better!

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

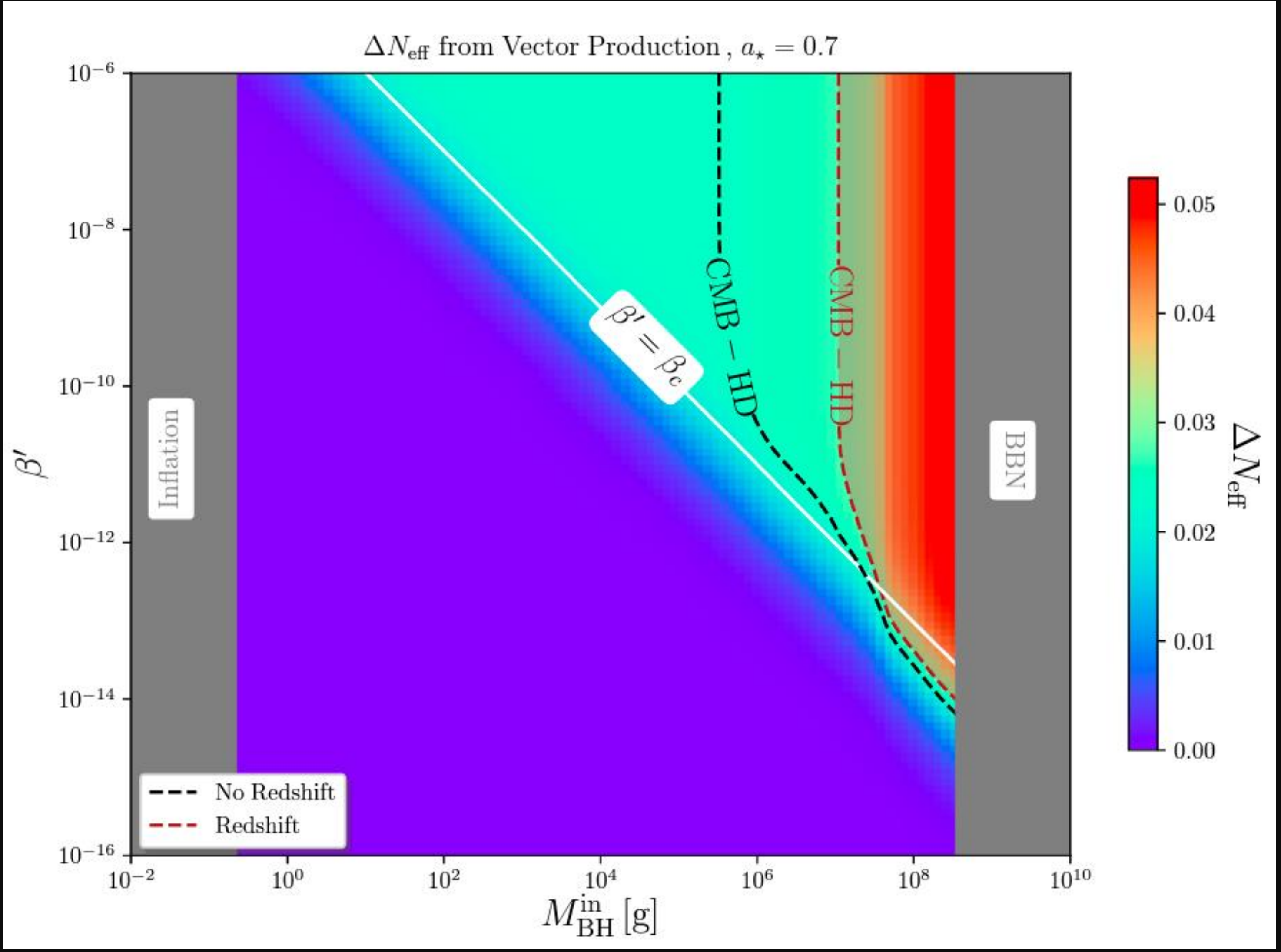
Code Publicly available: FRISBHEE

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

III. 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

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

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

III. 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’

Results

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

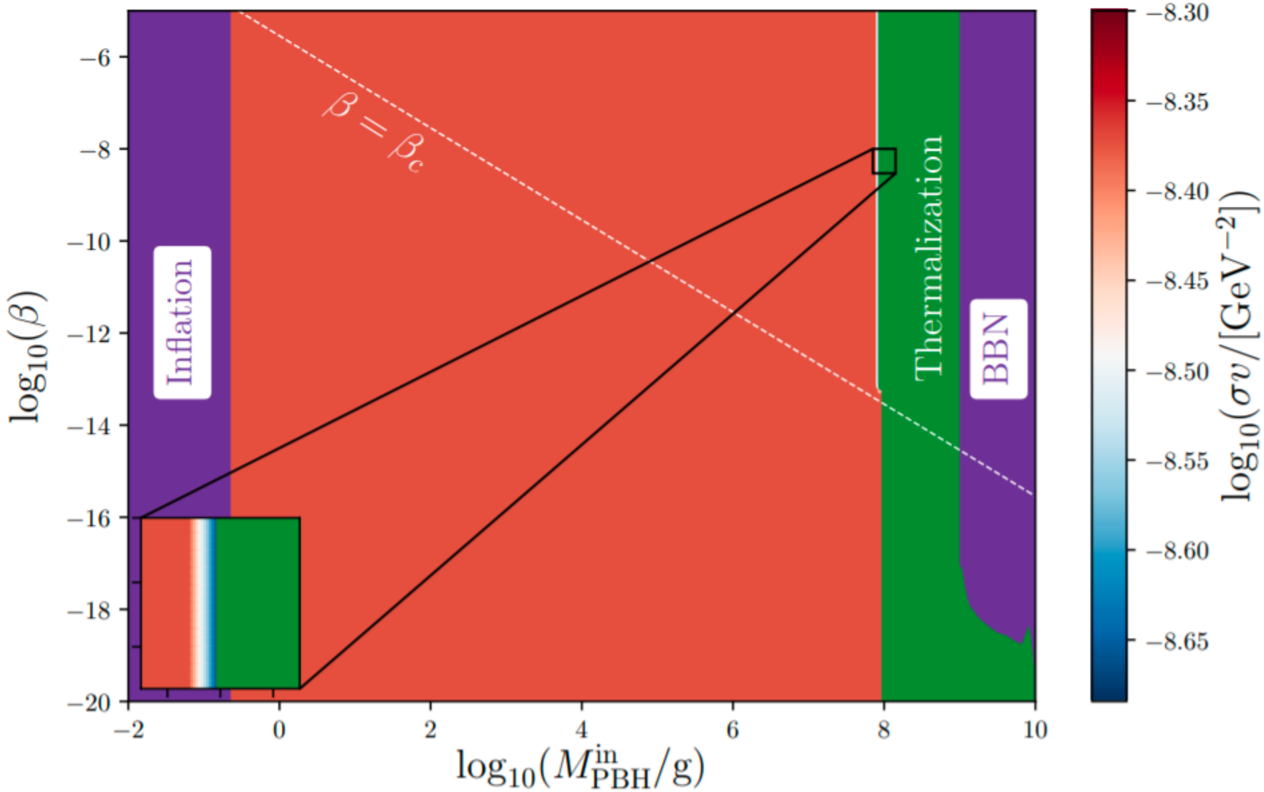


Fig. 7. Two-dimensional scan over the PBH fraction β and mass $M_{\rm BH}$ for a mediator mass $m_X = 10\,{\rm GeV}$ and a dark matter mass $m_{\rm DM} = 1\,{\rm GeV}$, and ${\rm Br}(X \to {\rm DM}) = 0.5$. The color map indicates the value of the non-relativistic cross-section of DM annihilation leading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

III. Evaporation of Extended Distributions

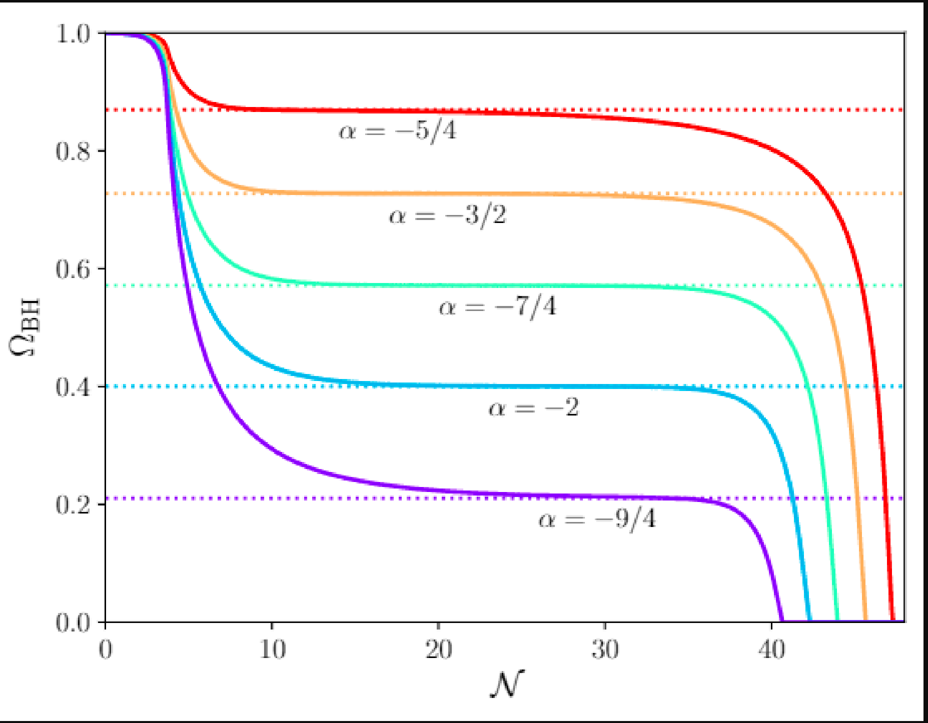
$$f_{\rm BH}(M) = \begin{cases} CM^{\alpha-1}, & \text{for } M_{\rm min} \leq M \leq M_{\rm max}; \\ 0, & \text{else.} \end{cases}$$

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

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

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

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



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

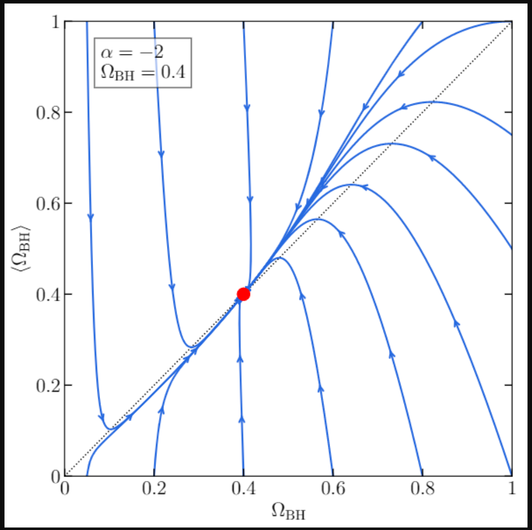
III. Evaporation of Extended Distributions

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

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

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

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



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

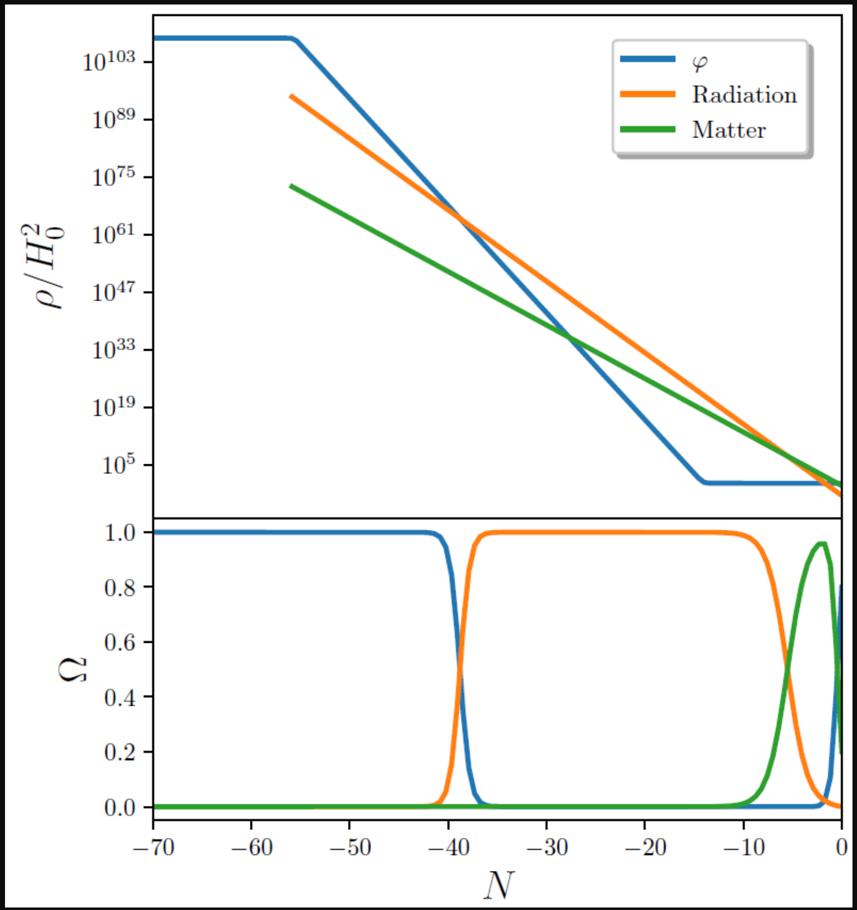
$$\Omega_{\rm BH} = \langle\Omega_{\rm BH}\rangle = \frac{4\alpha+10}{\alpha+7} \equiv \overline{\Omega}_{\rm BH} \, .$$

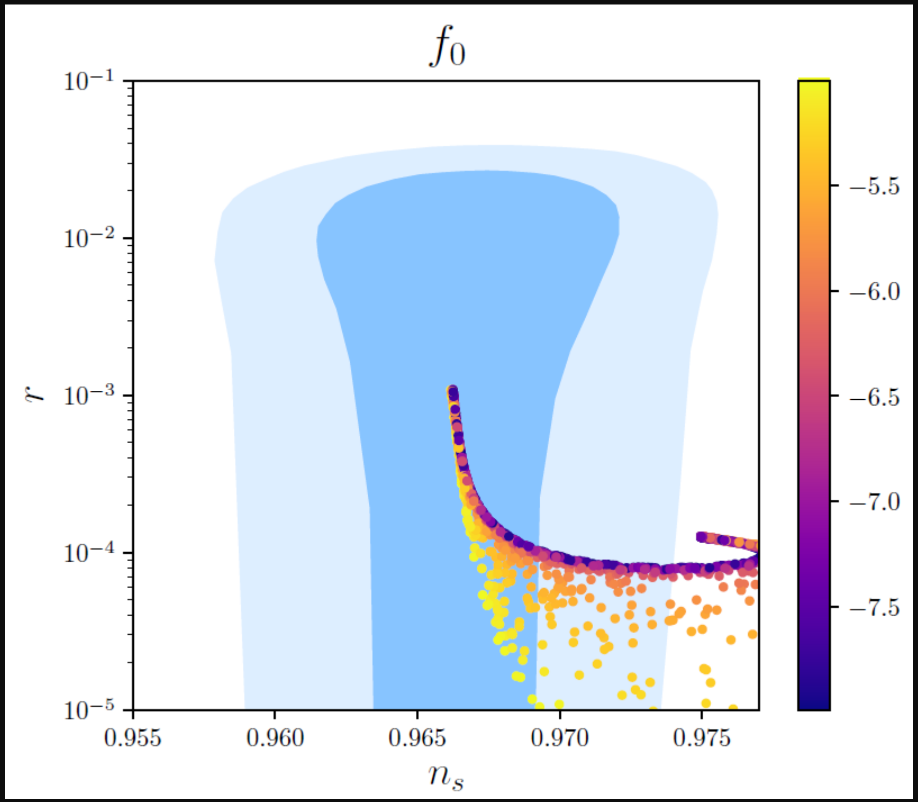
$$\mathcal{J} \equiv \frac{1}{t-t_i}\begin{pmatrix} \partial_{\Omega_{\rm BH}} f & \partial_{\langle\Omega_{\rm BH}\rangle} f \\ \partial_{\Omega_{\rm BH}} g & \partial_{\langle\Omega_{\rm BH}\rangle} g \end{pmatrix}$$

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

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

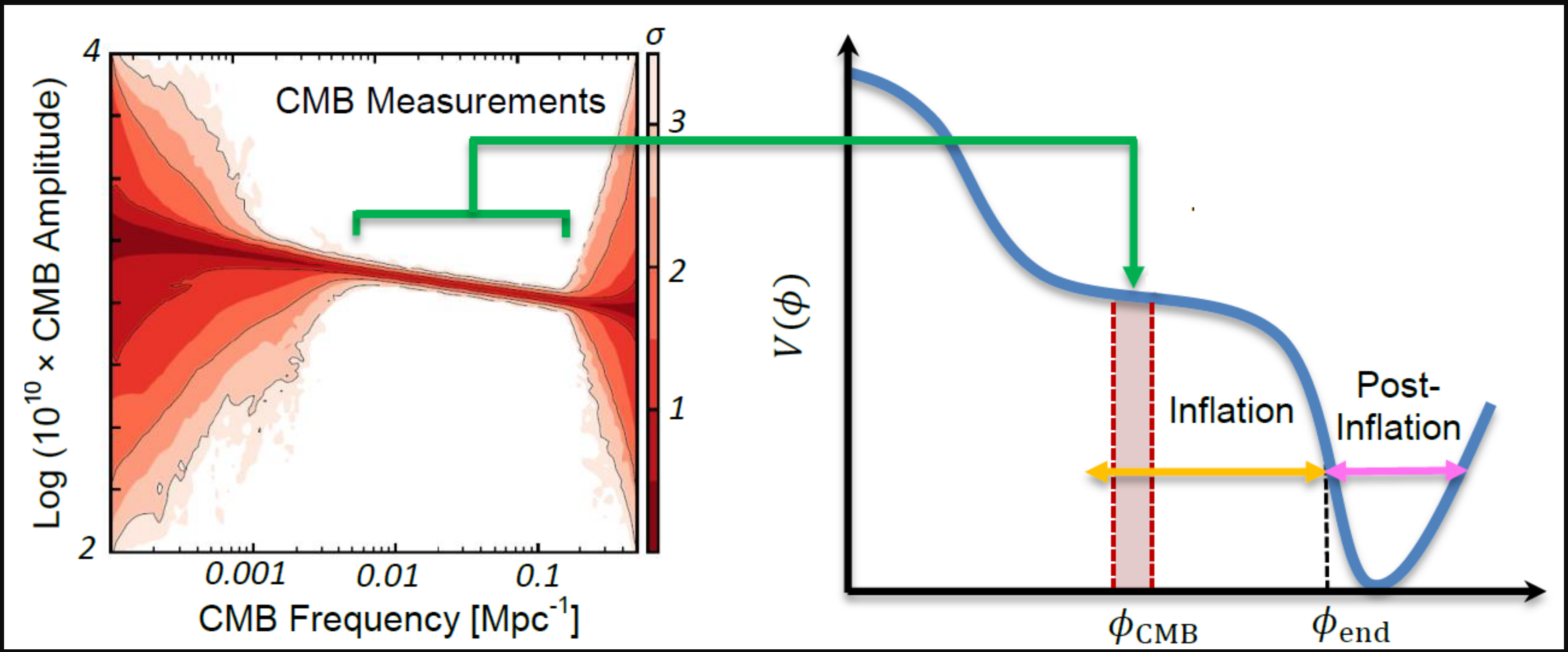
PBH Formation





[LH, Moursy, Wacquez '22]

Primordial Perturbation Evolution



Perturbation Horizon Crossing

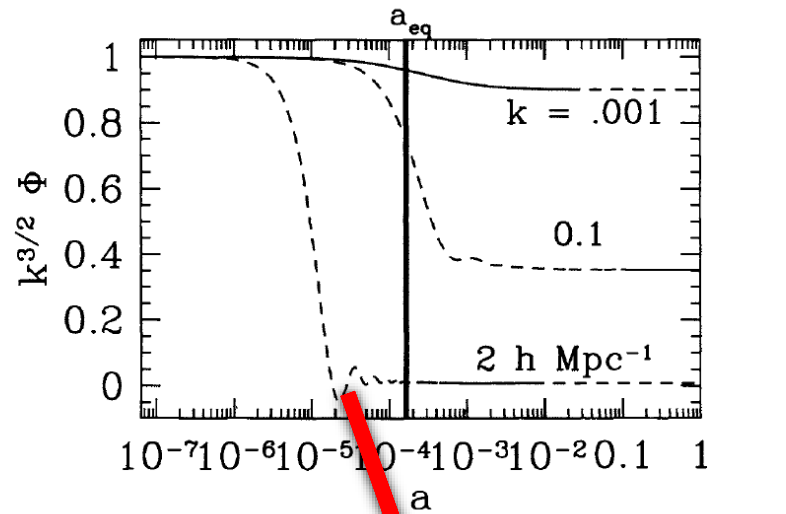


Figure 7.2. The linear evolution of the gravitational potential Φ. Dashed line denotes that the mode has entered the horizon. Evolution through the shaded region is described by the transfer function. The potential is unnormalized, but the relative normalization of the three modes is as it would be for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

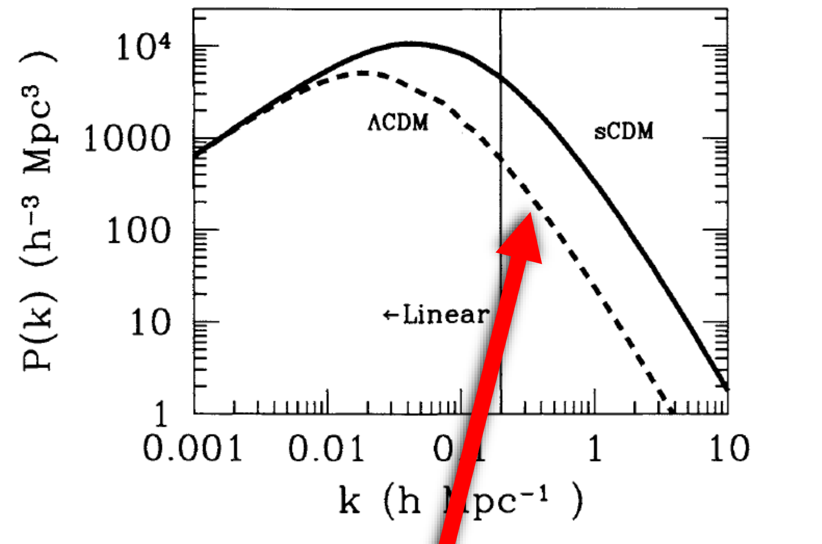
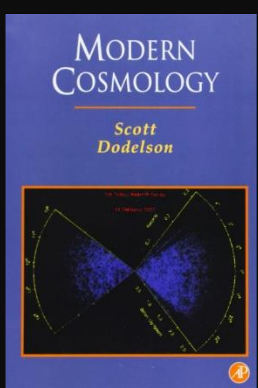


Figure 7.4. The power spectrum in two Cold Dark Matter models, with (ΛCDM) and without (sCDM) a cosmological constant. The spectra have been normalized to agree on large scales. The spectrum in the cosmological constant model turns over on larger scales because of a later a_{eq}. Scales to the left of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



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

Causality erases small-scale structures

An example: The EW vacuum

Our Universe may be metastable (at ~2σ)

$$P_{\rm FVD} \equiv 1 - e^{-\Gamma_{\rm FVD}\Delta t}$$

Using $T_{plateau}(M)$

$$\Delta t \sim \Gamma_{\rm ev}^{-1}$$

$$P_{\rm FVD}(M) = 1 - e^{-\Gamma_{\rm FVD}(T_{\rm plateau})/\Gamma_{\rm ev}}$$

Using T_{max}

$$P_{\rm FVD} \approx 1 \text{ as long as } \Delta t \lesssim 10^{-6} \times \Gamma_{\rm ev}^{-1}$$

Constraint:

$$\beta_{\rm PBH} = \frac{4}{3}\frac{M N_{\rm PBH} H_0^3}{s_0 T_f} \approx 2\times 10^{-80} N_{\rm PBH}\left(\frac{M}{M_\star}\right)^{3/2}$$

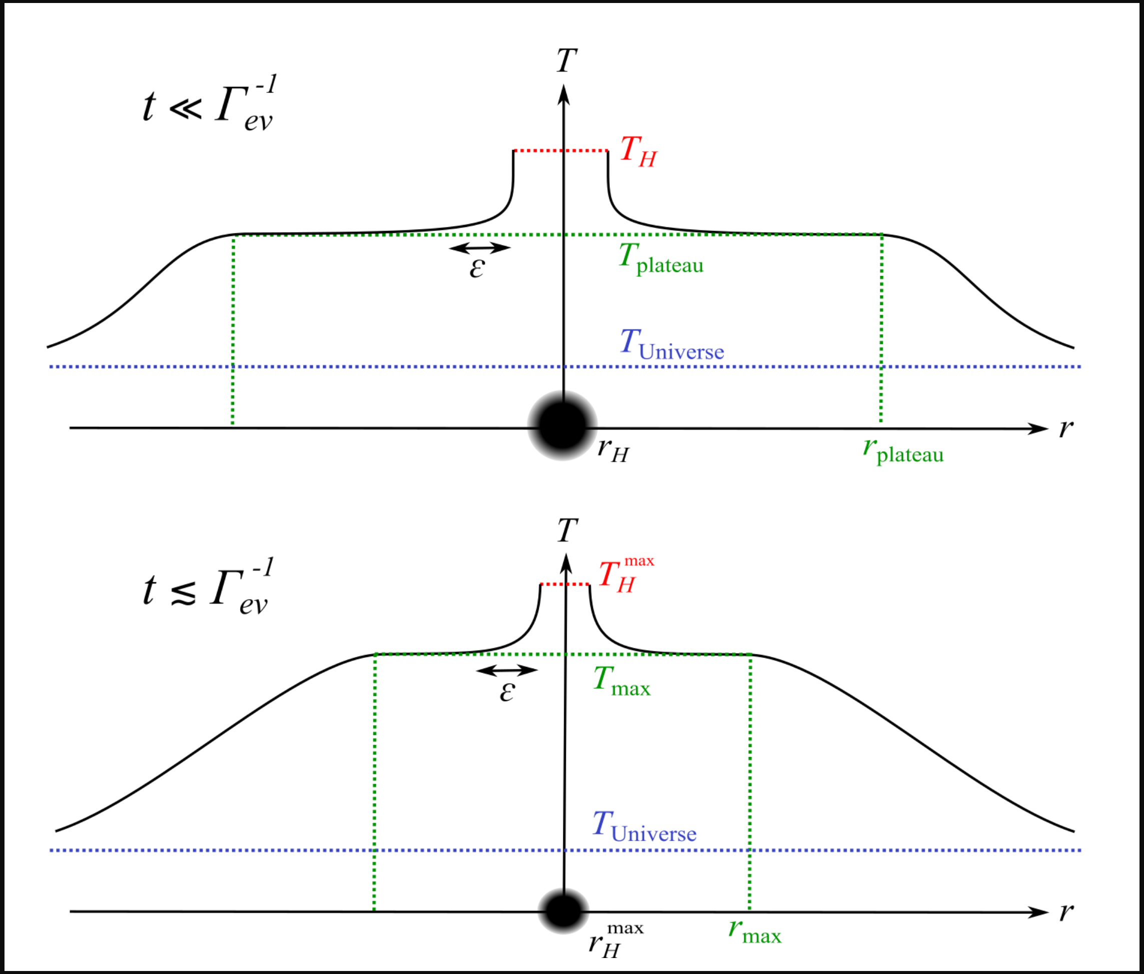
$$N_{\rm PBH}\, P_d < 2.7$$

[Hamaide, Heurtier, Hu, Cheek, to appear]

In Reality

Hawking Radiation heats the ambient plasma locally

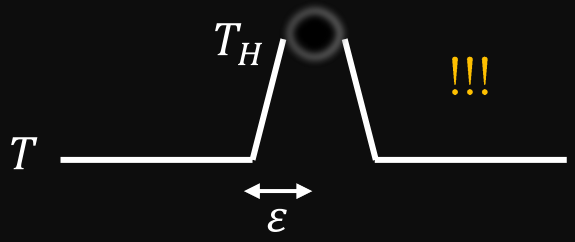
Our best guess:



$$\Gamma(T) \sim \alpha^2 T \sqrt{\frac{T}{T_H}} \,.$$

$$dP \sim \Gamma(T) e^{-(r-r_H)\Gamma(T)} dr$$

Physical realisation of



[Hamaide, Heurtier, Hu, Cheek, to appear]