Durham University

Lucien HEURTIER

IP3

Imprints of Mini Primordial Black Holes In Cosmological Data

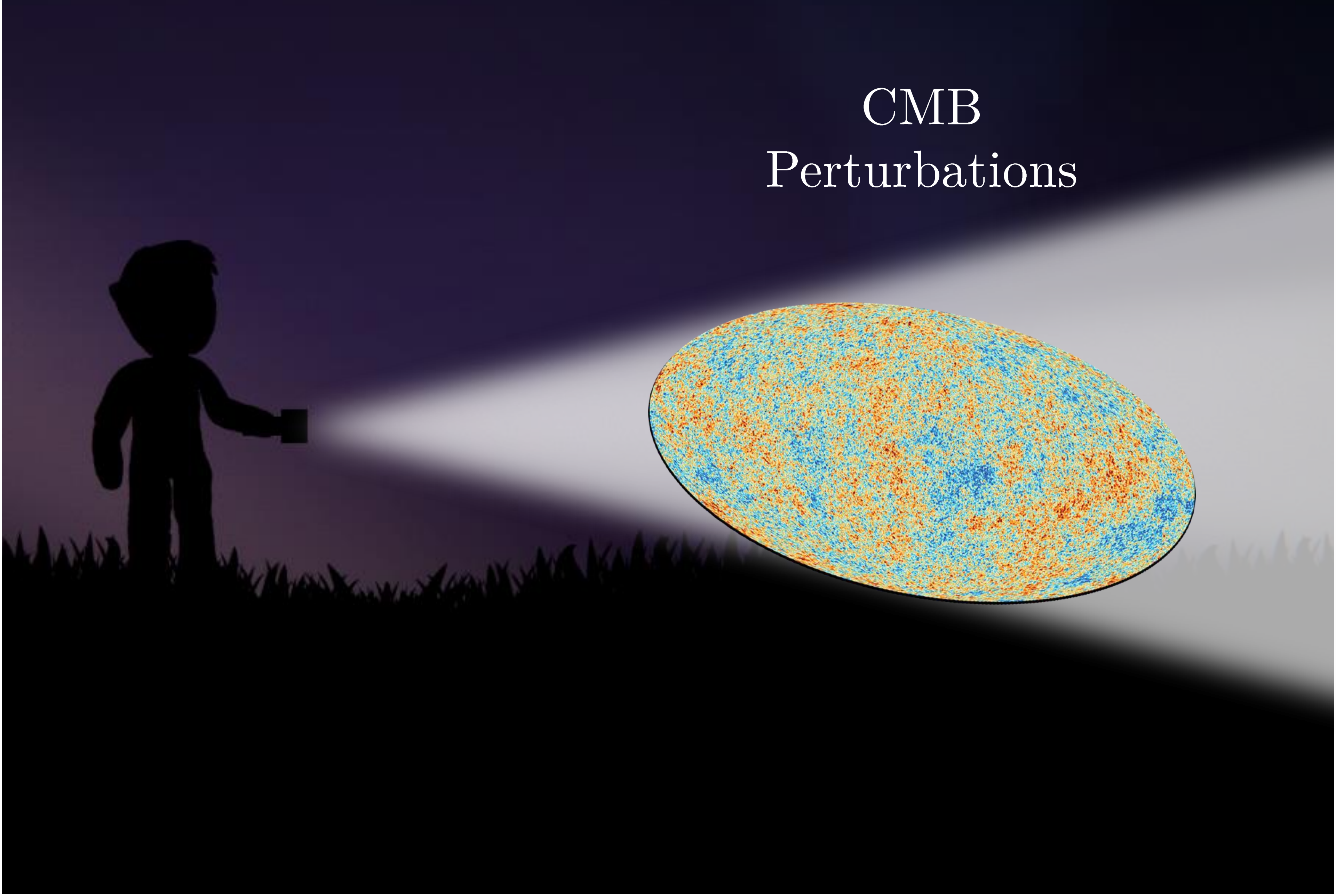
A. Cheek, L.H., Y. F. Perez-Gonzalez, and J. Turner
Phys.Rev.D 105 (2022) 1, 015022. and *Phys.Rev.D 105 (2022) 1, 015023* [PRD Highlights]

A. Cheek, L.H., Y. F. Perez-Gonzalez, and J. Turner
To appear [ArXiv: 2211.XXXX]

K.R. Dienes, L.H., F. Huang, D.Kim, B. Thomas, and T.M.P. Tait
To appear [ArXiv: 2211.XXXX]

Astroparticle Symposium, Université Paris Saclay, 2nd November 2022

Why Mini Primordial Black Holes?



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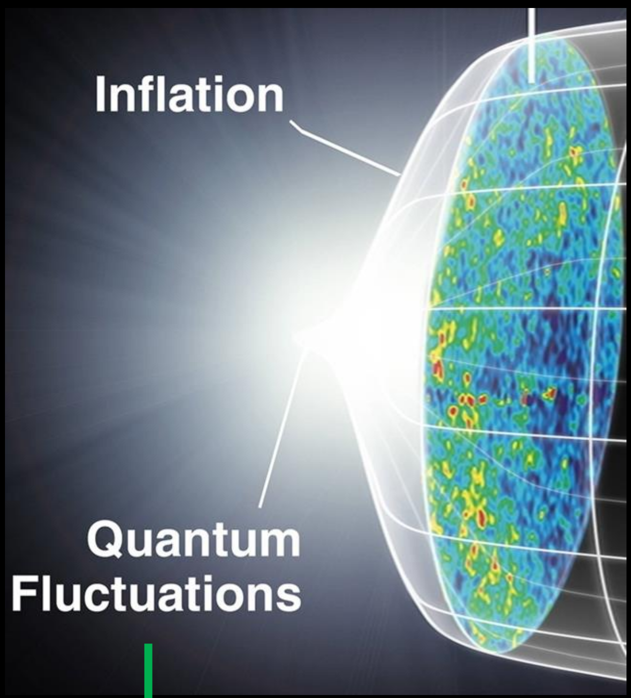
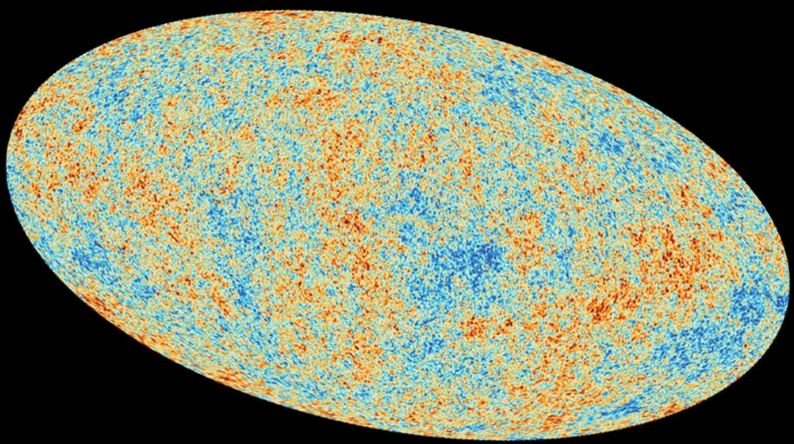
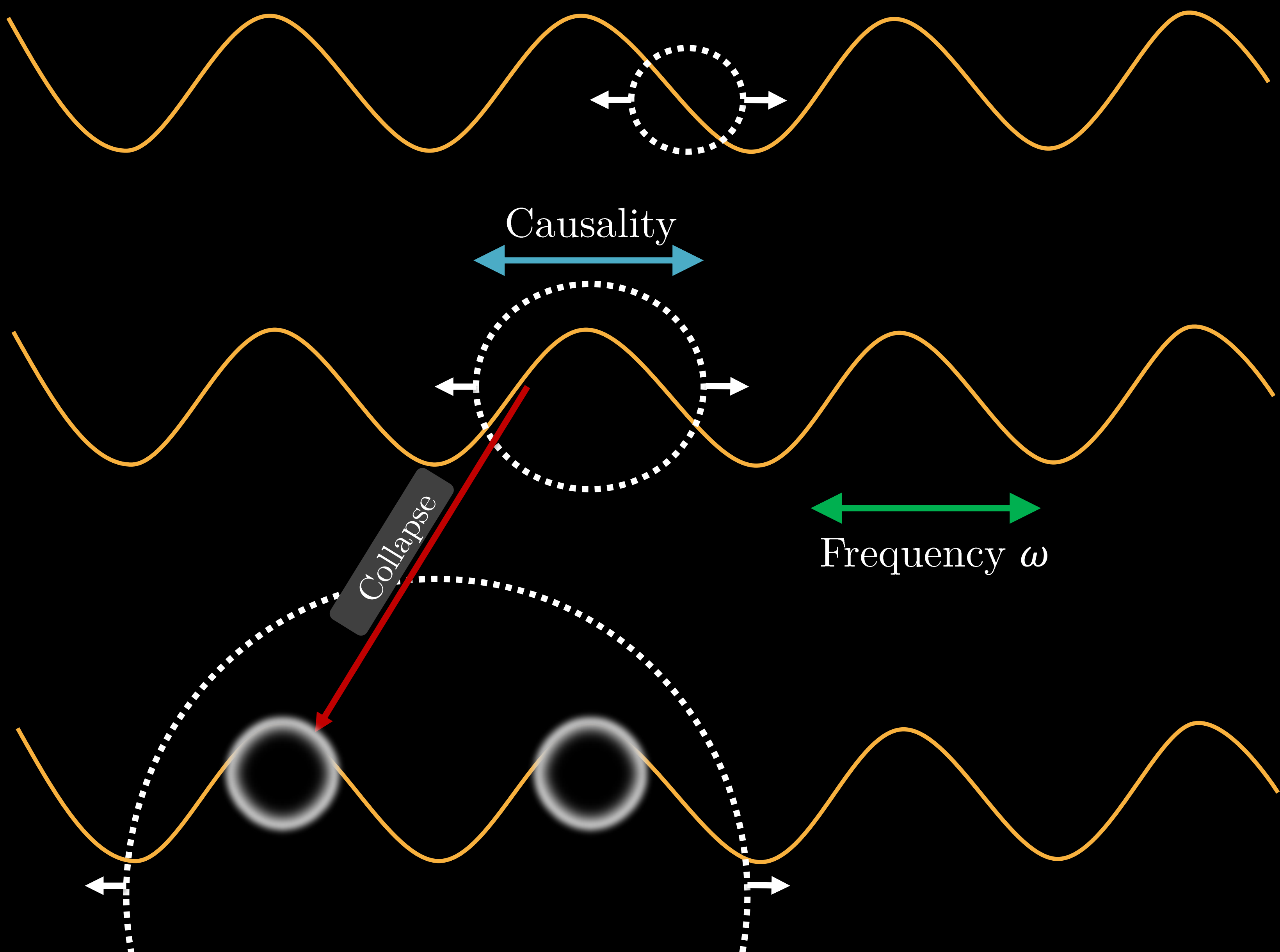


CMB
Perturbations



Primordial
Perturbations

Why Mini Primordial Black Holes?



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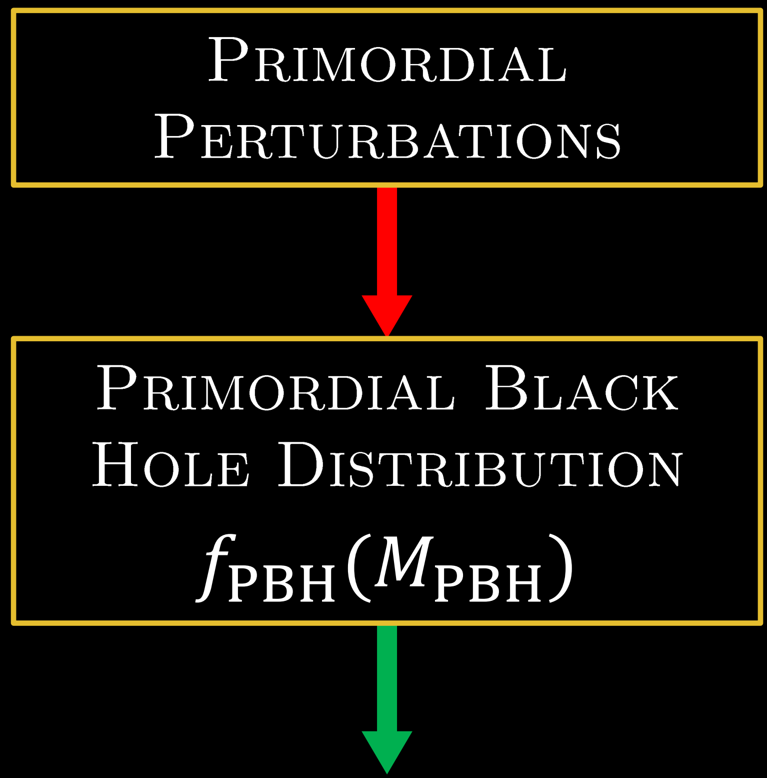
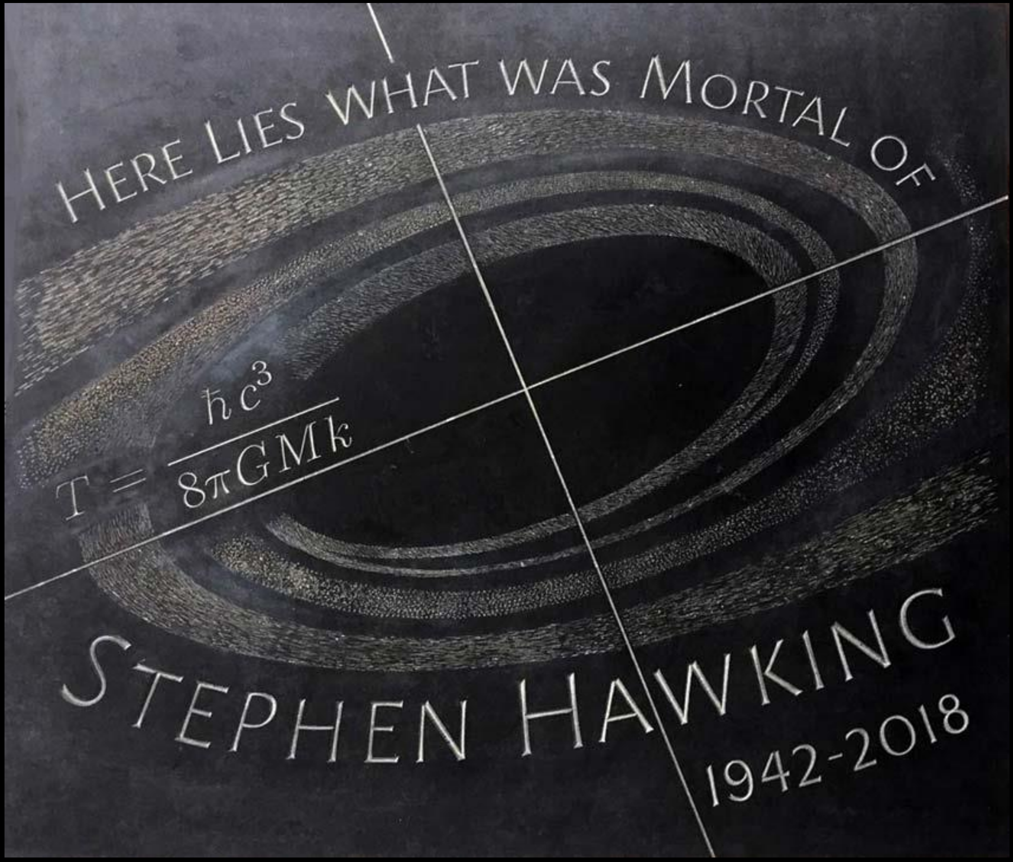


Observable Imprints ?

Black Holes Evaporate...

S. Hawking, 1974



Why Mini Primordial Black Holes?

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 ($10^{15}\,\mathrm{g} \lesssim M_{\mathrm{PBH}} \lesssim 10^{9}\,\mathrm{g}$)
- Some may be unstable and evaporate before BBN ($M_{\mathrm{PBH}} \lesssim 10^{9}\,\mathrm{g}$)

The topic of this talk ...

Outline

I. Effect of PBH evaporation on Dark-Matter Phenomenology

II. Kerr PBHs and Dark Radiation

III. Kerr PBHs and Warm Dark Matter

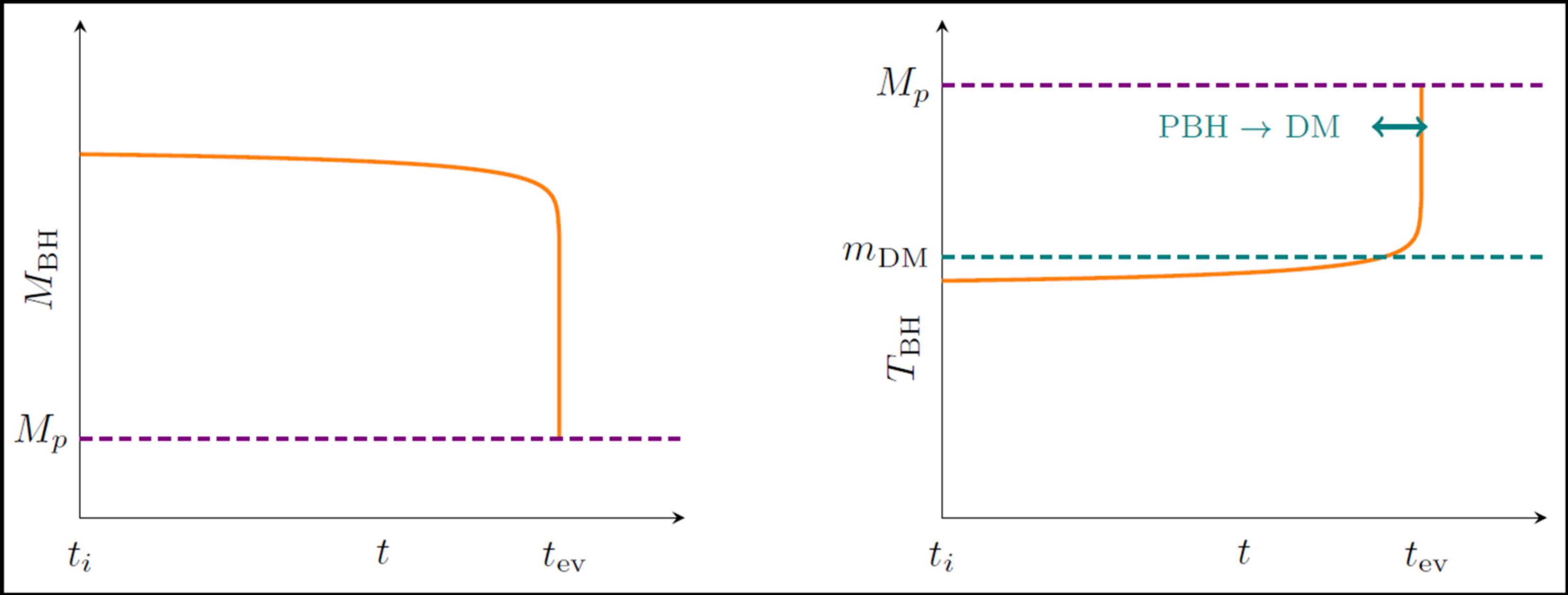
IV. Evaporation of Extended Distributions

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

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



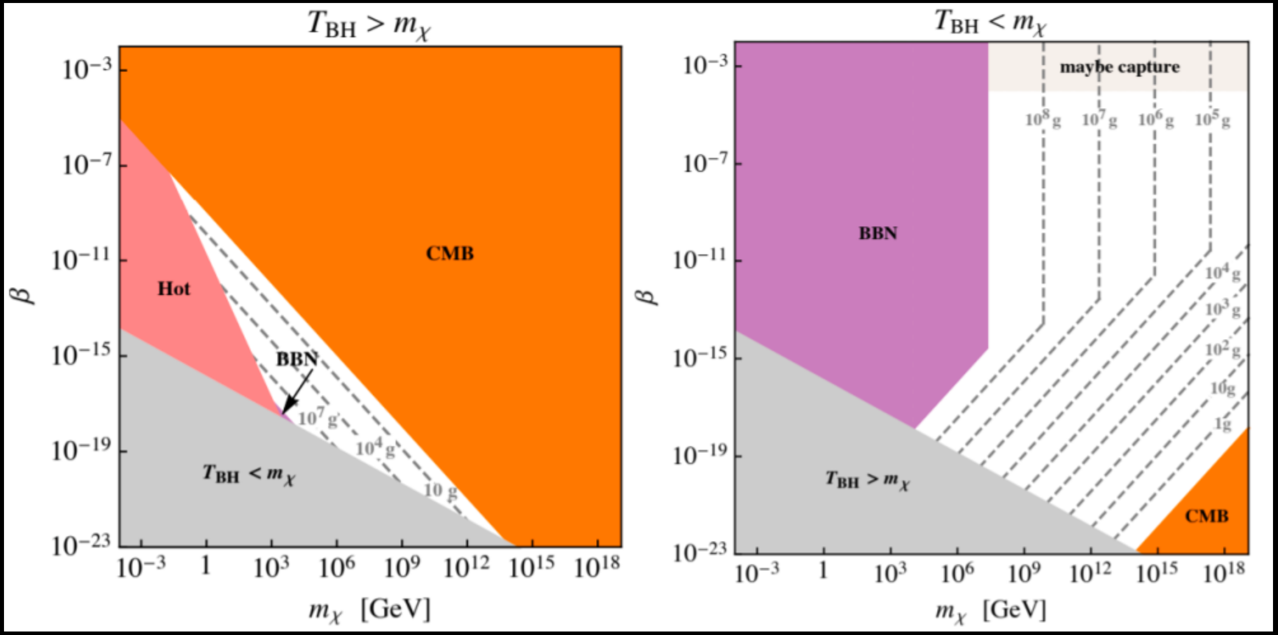
→ More and more particles contribute to the evaporation

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]

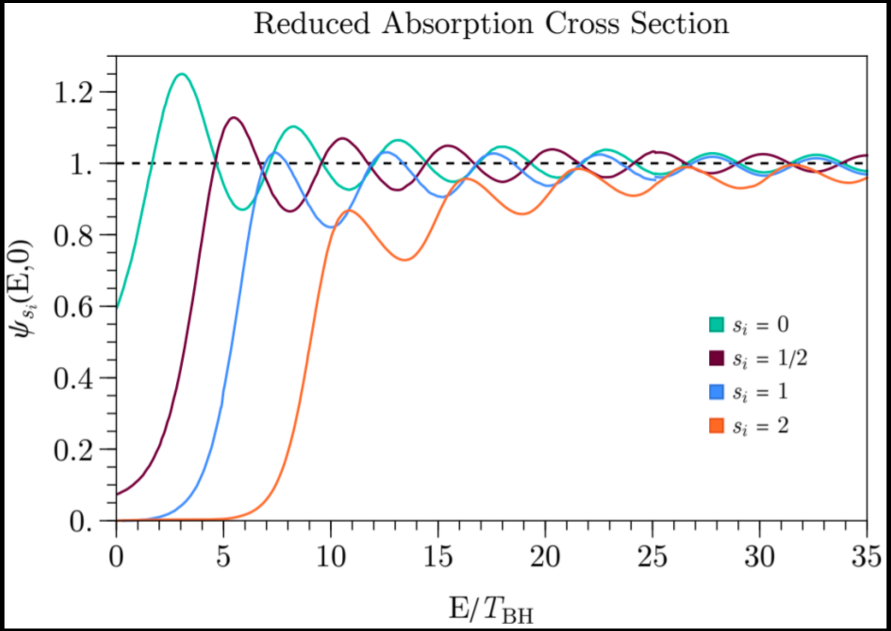
DM from Evaporation

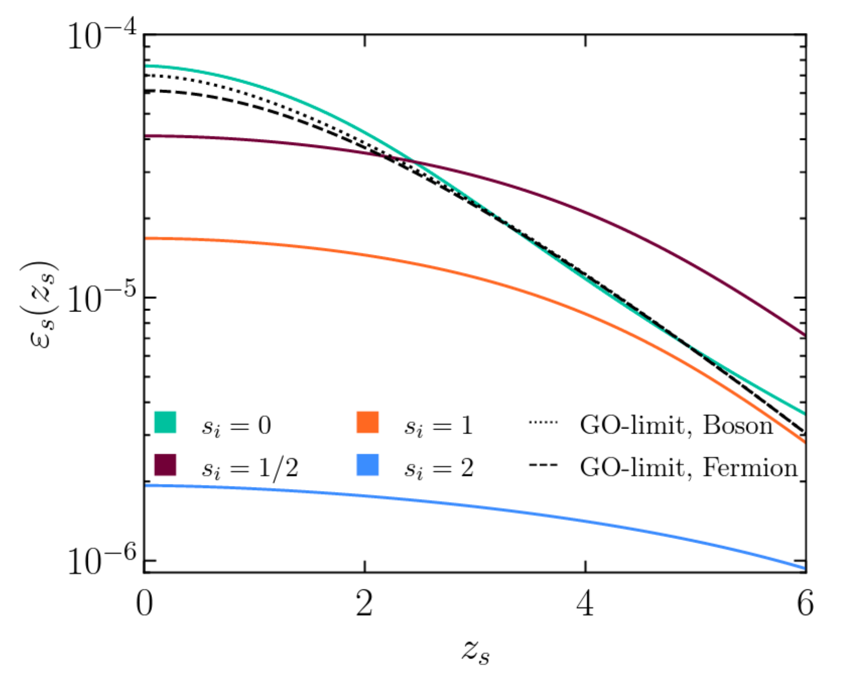
$$\frac{\mathrm{d}^2\mathcal{N}_i}{\mathrm{d}p\,\mathrm{d}t} = \frac{g_i}{2\pi^2}\frac{\sigma_{s_i}(M_{\rm BH},\mu_i,p)}{\exp\left[E_i(p)/T_{\rm BH}\right]-(-1)^{2s_i}}\frac{p^3}{E_i(p)}$$

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

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

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



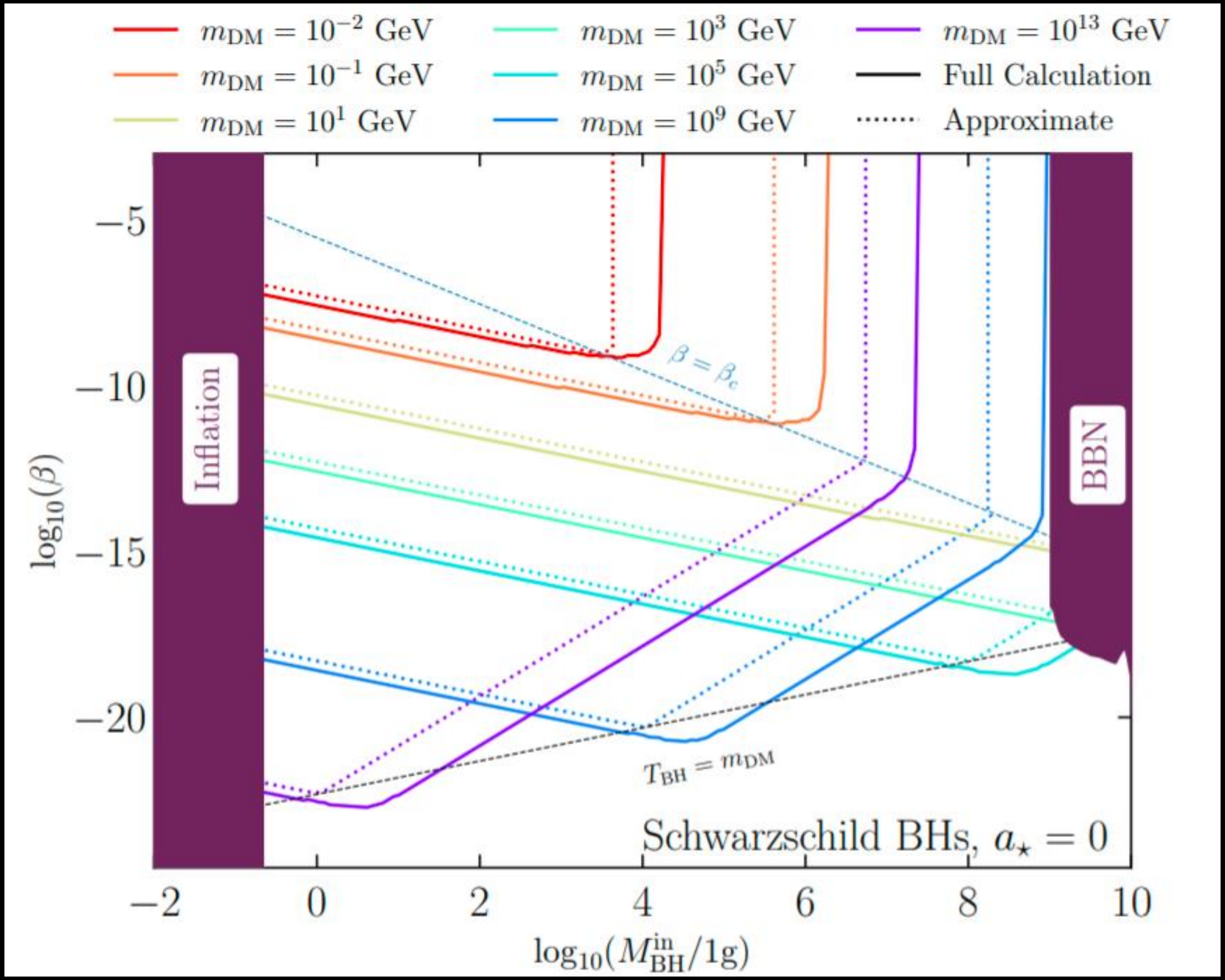


[Cheek, LH, Perez-Gonzalez and Turner '22]

Code Publicly available: FRISBHEE

DM from Evaporation

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



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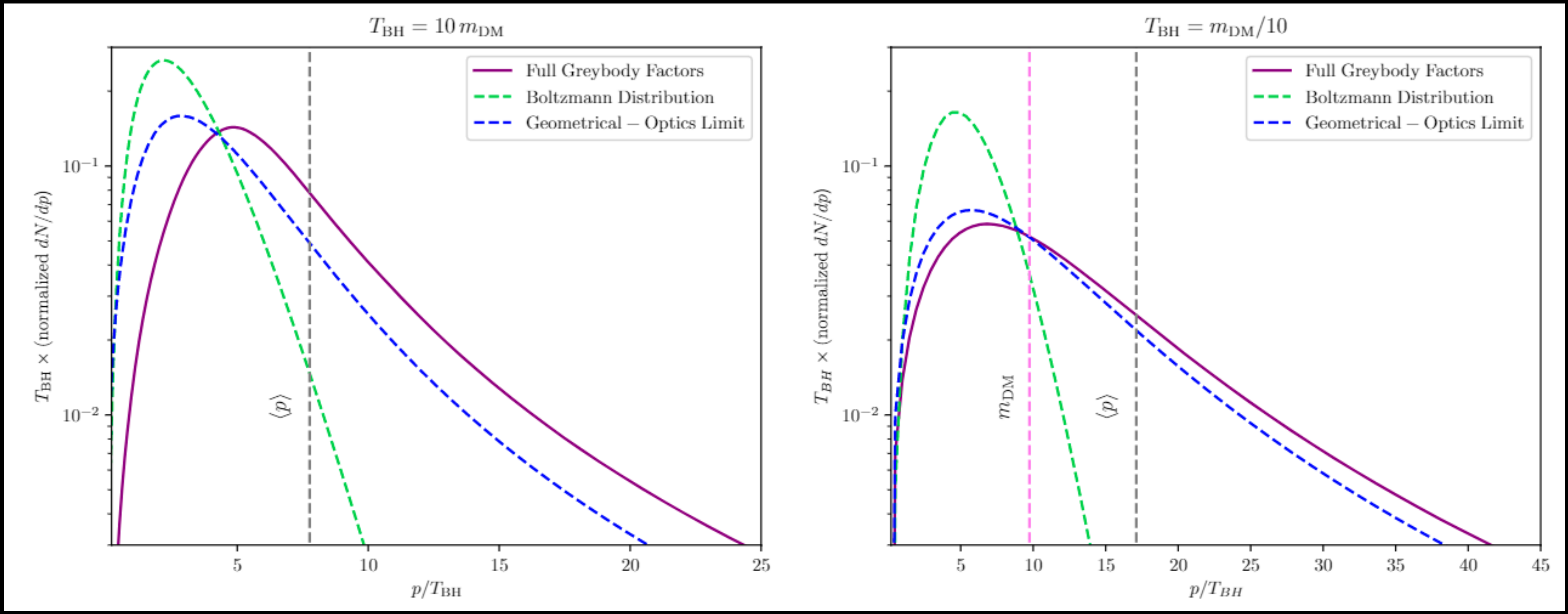

[Cheek, LH, Perez-Gonzalez and Turner '22] **Code Publicly available: FRISBHEE**

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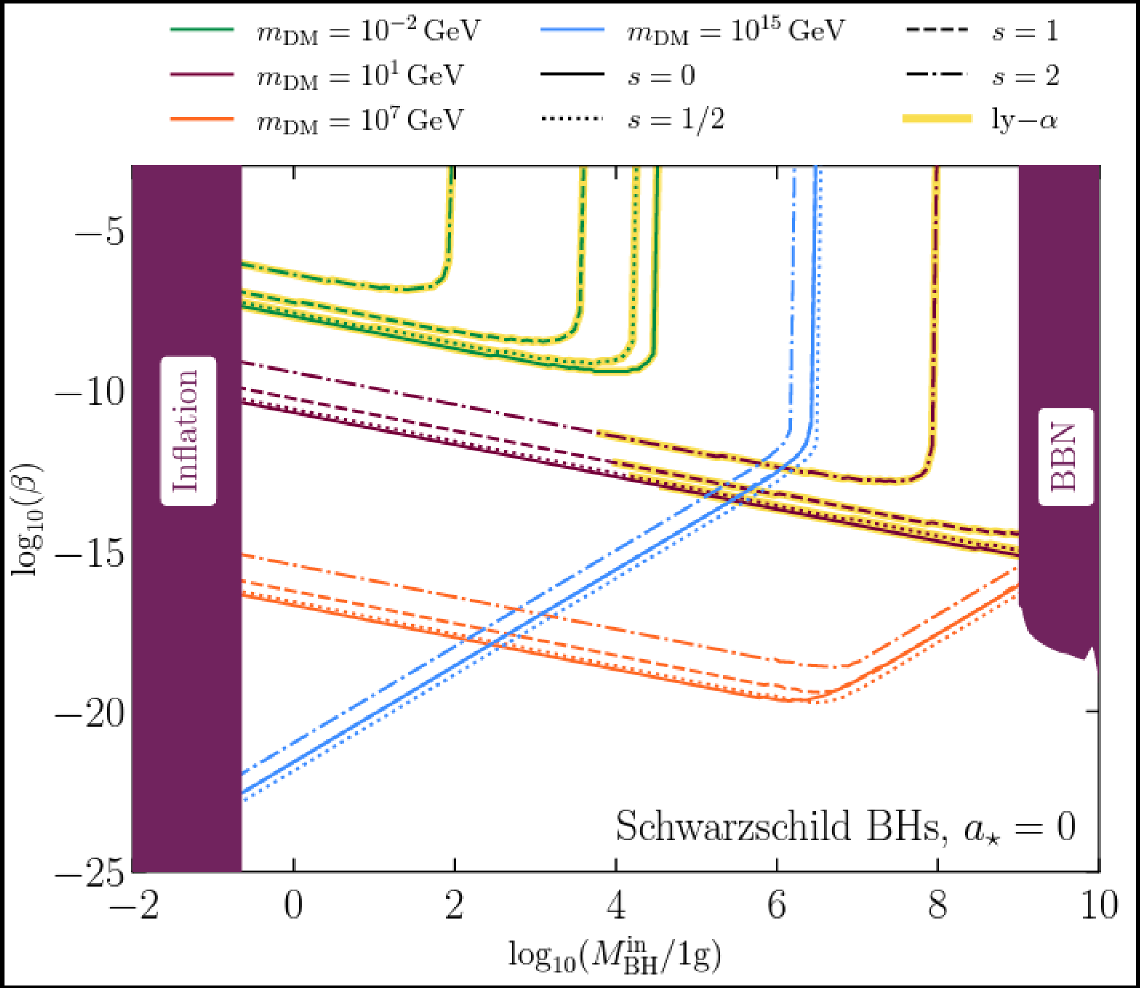
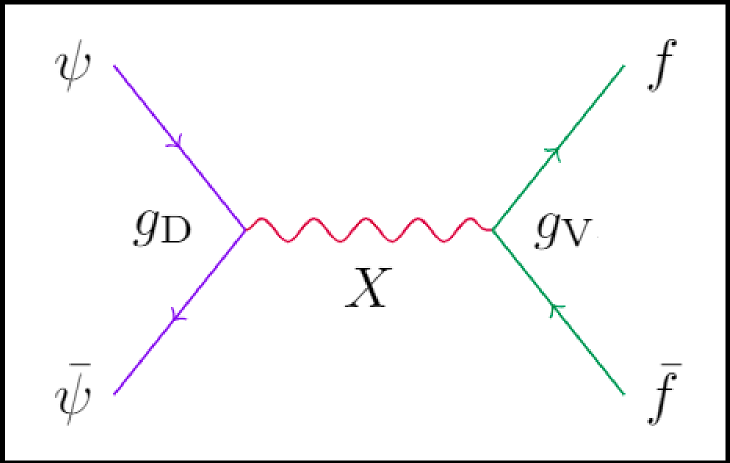


[Cheek, LH, Perez-Gonzalez and Turner '22] **Code Publicly available: FRISBHEE**

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

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



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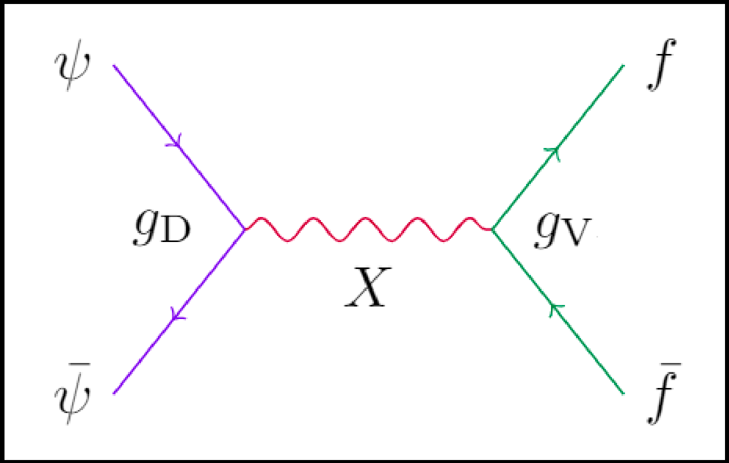
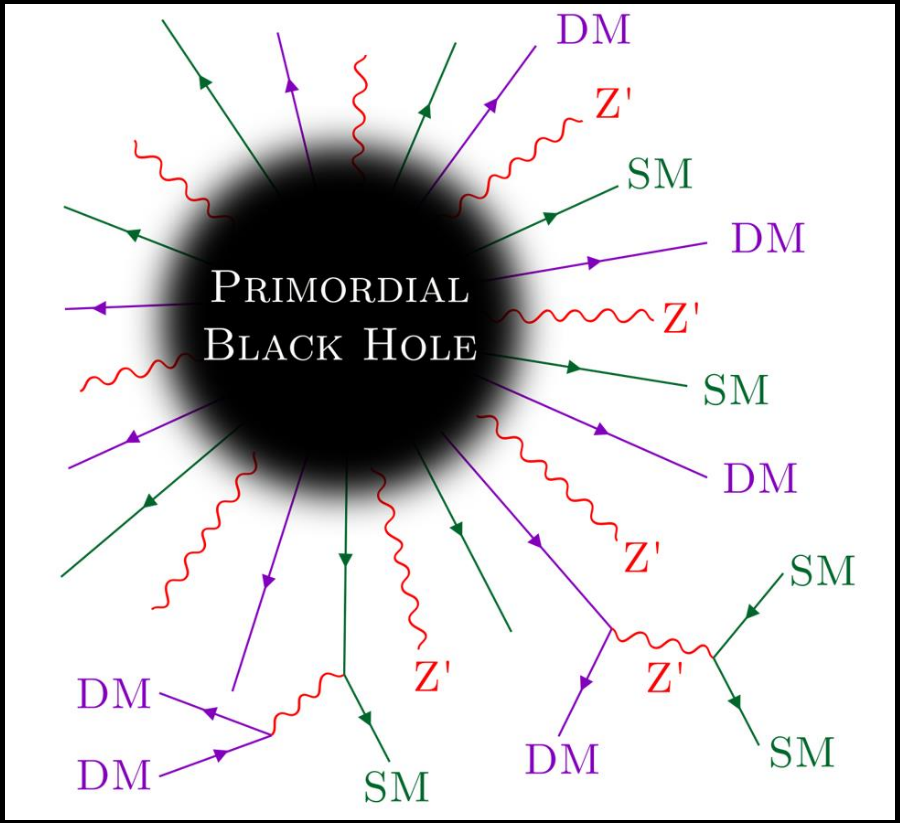
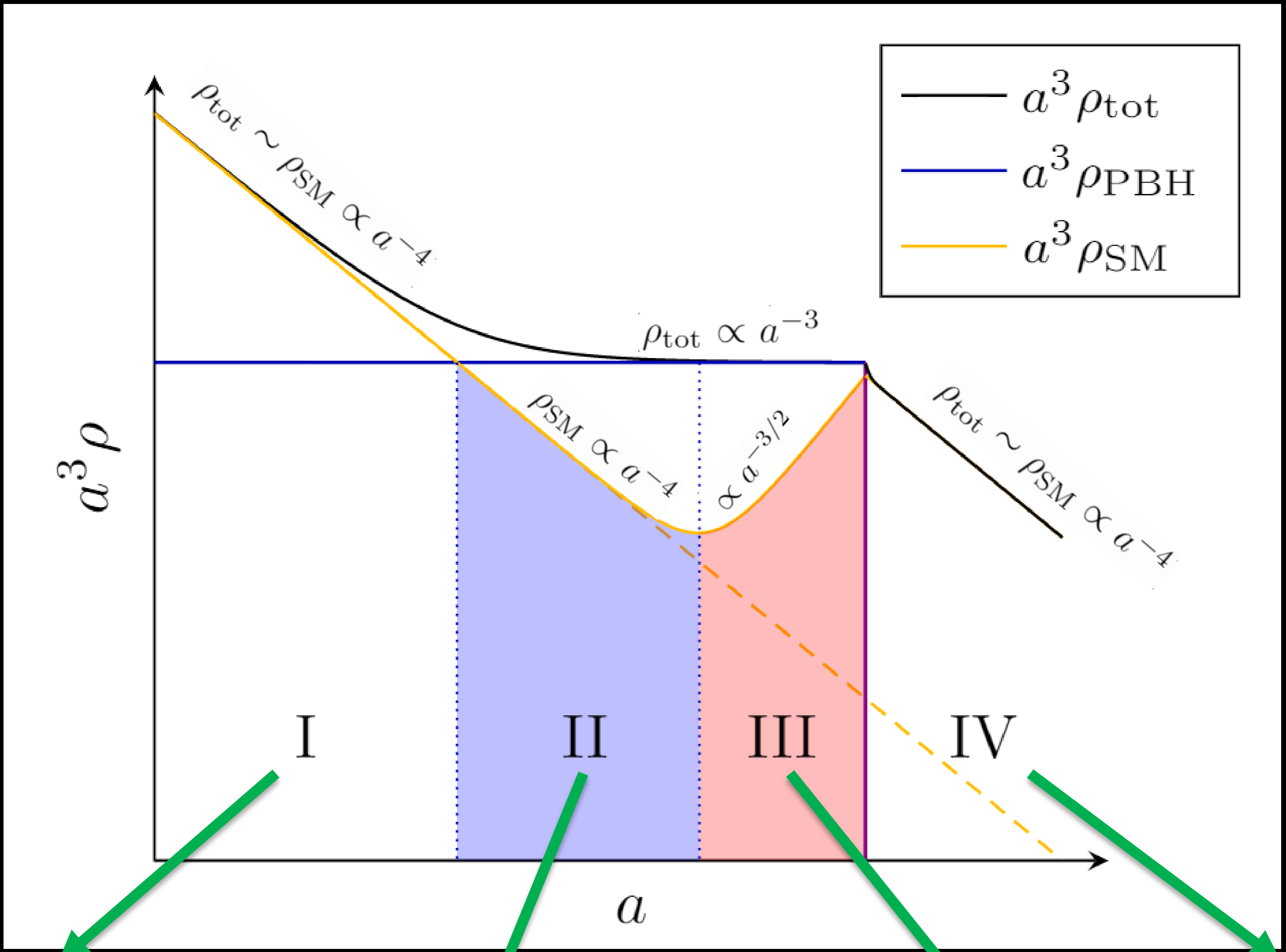




Modified Cosmology



FI/FO + entropy dilution

Regular FI/FO

Matter-Dominated FI/FO

FI/FO during entropy injection

Analytical Results

Freeze-In contribution

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

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

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

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

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:

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

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

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

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

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

Results

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

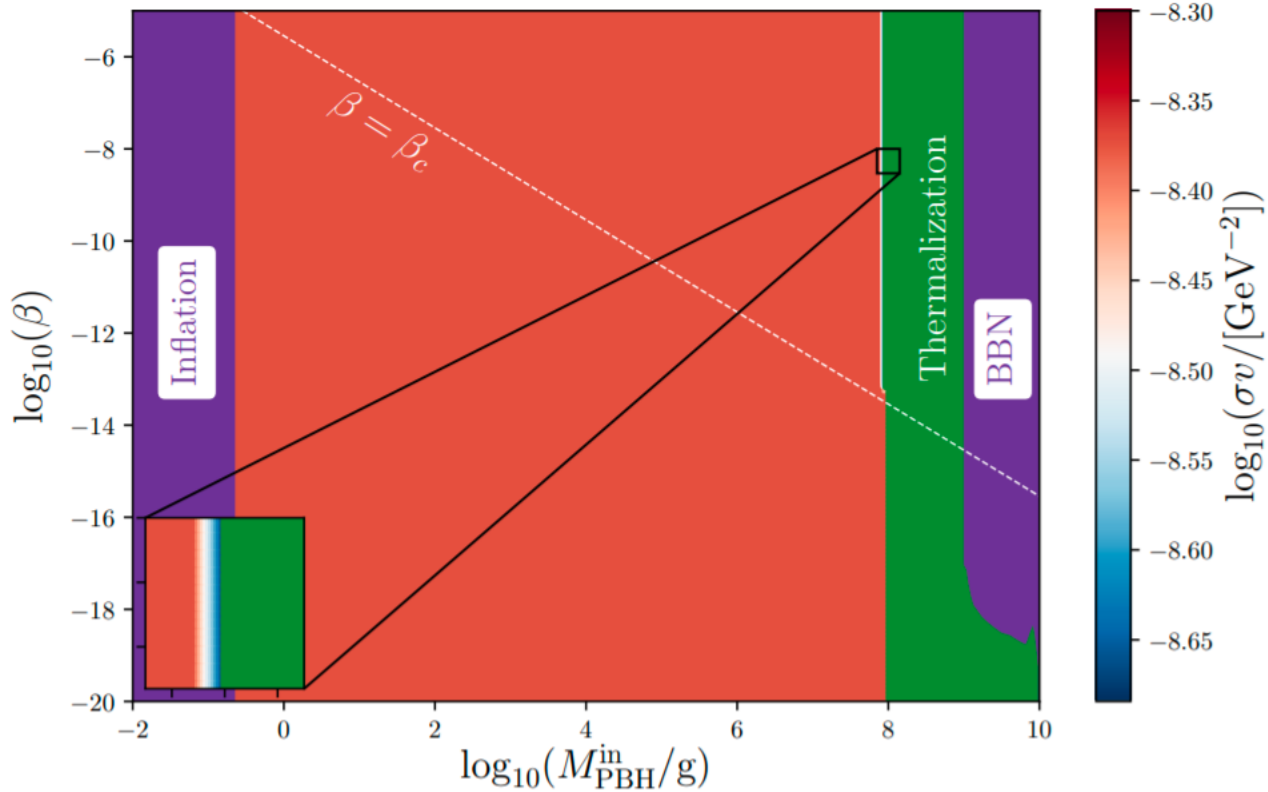


Fig. 7. Two-dimensional scan over the PBH fraction β and mass $M_{\rm BH}$ for a mediator mass $m_X = 10\,{\rm GeV}$ and a dark matter mass $m_{\rm DM} = 1\,{\rm GeV}$, and ${\rm Br}(X \to {\rm DM}) = 0.5$. The color map indicates the value of the non-relativistic cross-section of DM annihilation leading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

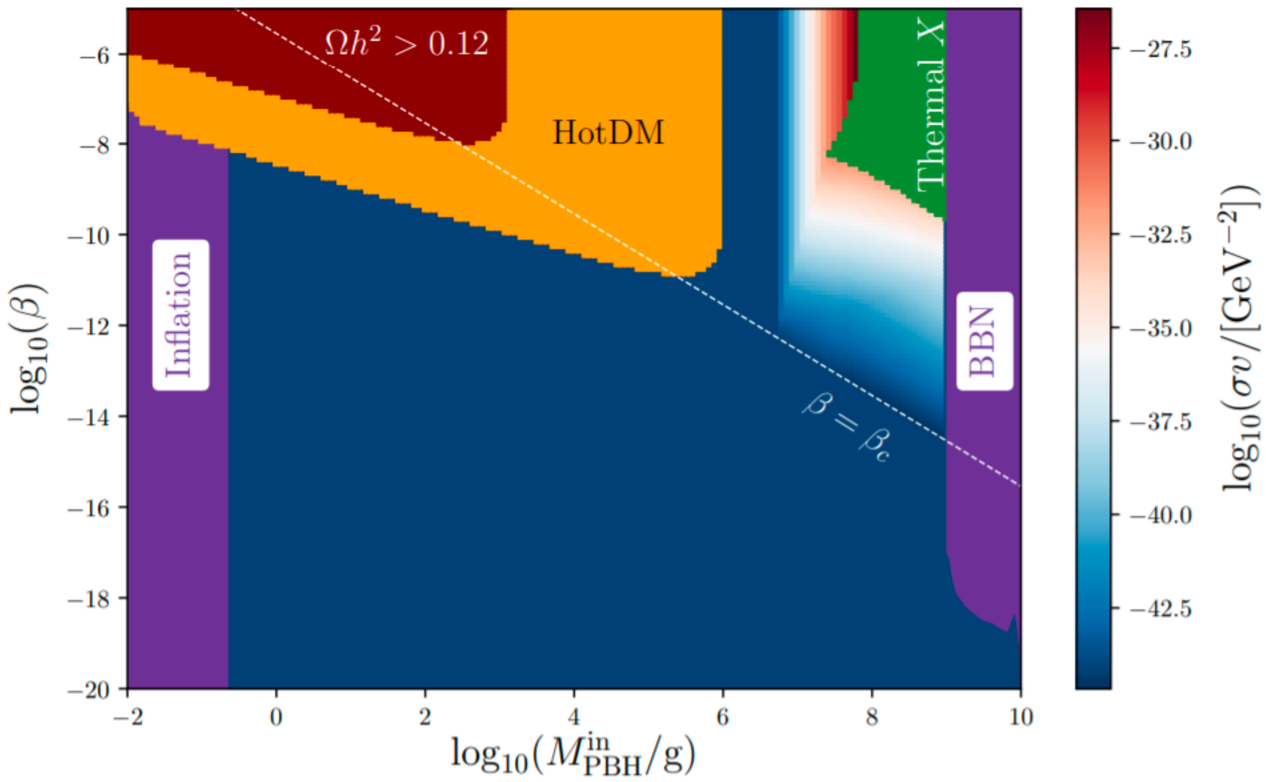


Fig. 11. Two-dimensional scan over the PBH fraction β and mass $M_{\rm BH}$ for a mediator mass $m_X = 1\,{\rm TeV}$, a dark matter mass $m_{\rm DM} = 1\,{\rm MeV}$, and ${\rm Br}(X \to {\rm SM}) = 10^{-7}$. The color map indicates the value of the non-relativistic cross-section of DM annihilation leading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

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

$$\varepsilon_i(M_{\rm BH}, a_\star) = \frac{g_i}{2\pi^2}\int_0^\infty \sum_{l=s_i}\sum_{m=-l}^{l} \frac{\mathrm{d}^2\mathcal{N}_{ilm}}{\mathrm{d}p\mathrm{d}t} E dE\,,$$

$$\gamma_i(M_{\rm BH}, a_\star) = \frac{g_i}{2\pi^2}\int_0^\infty \sum_{l=s_i}\sum_{m=-l}^{l} m\frac{\mathrm{d}^2\mathcal{N}_{ilm}}{\mathrm{d}p\mathrm{d}t} dE\,,$$

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

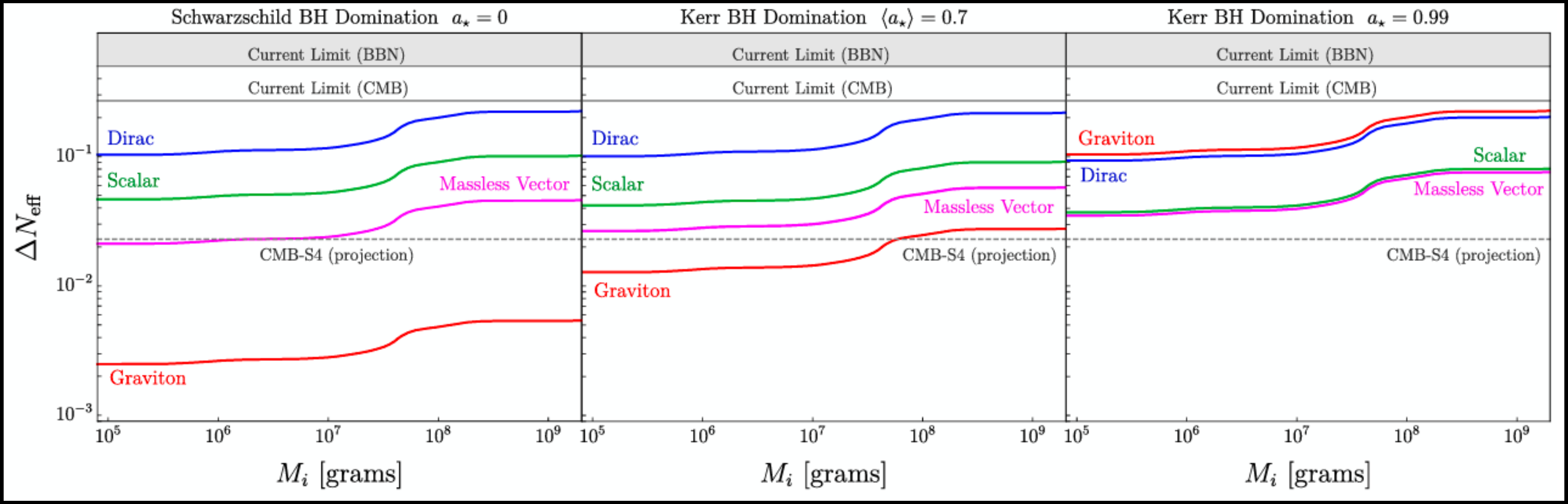
$$\frac{da_\star}{dt} = -a_\star[\gamma(M_{\rm BH}, a_\star) - 2\epsilon(M_{\rm BH}, a_\star)]\frac{M_p^4}{M_{\rm BH}^3}\,.$$

Kerr PBHs and Dark Radiation

Dark particles with small masses can contribute to ΔNeff

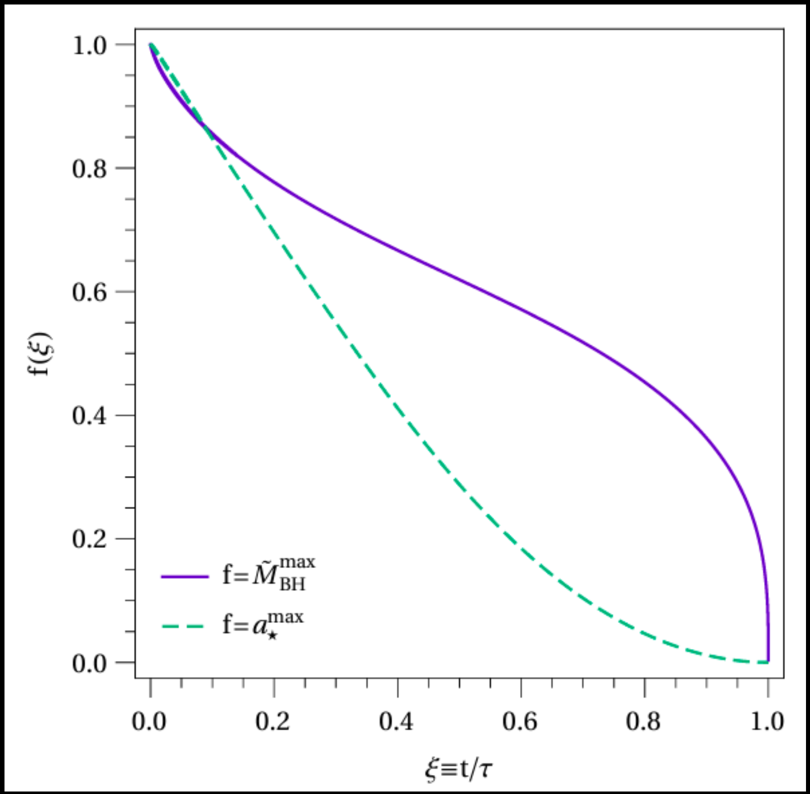
Schwarzschild PBH → Negligible

Kerr PBH → Argued to be critical



[Hooper et al ‘20]

Kerr PBHs and Dark Radiation



Major effects:

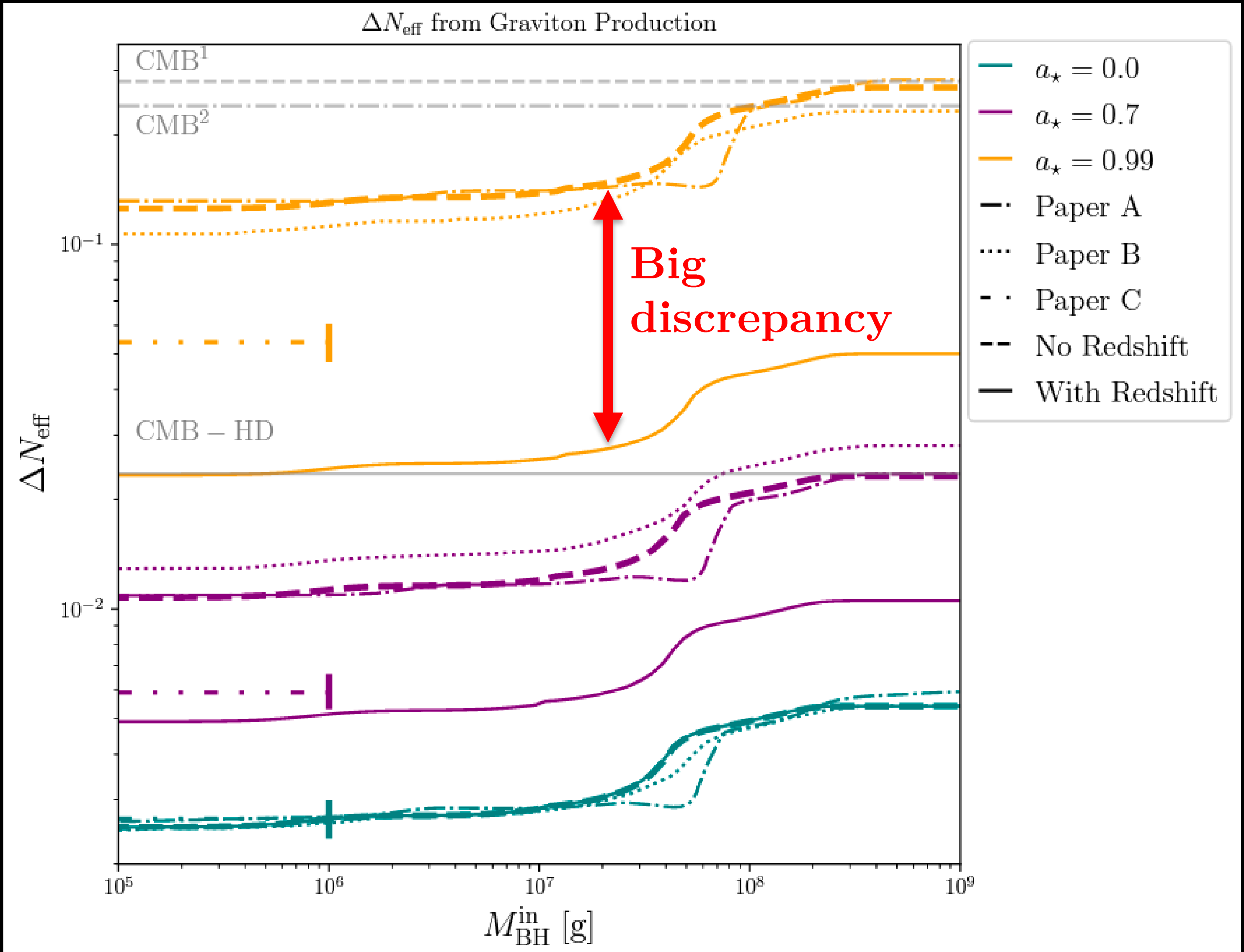
Spin loss faster than mass loss

→ Shorter lifetime

→ Different ratio Dark Radiation / Radiation

How to calculate ΔNeff ?

Kerr PBHs and Dark Radiation



Kerr PBHs and Dark Radiation

Why ?

Kerr PBHs and Dark Radiation

Why ?

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

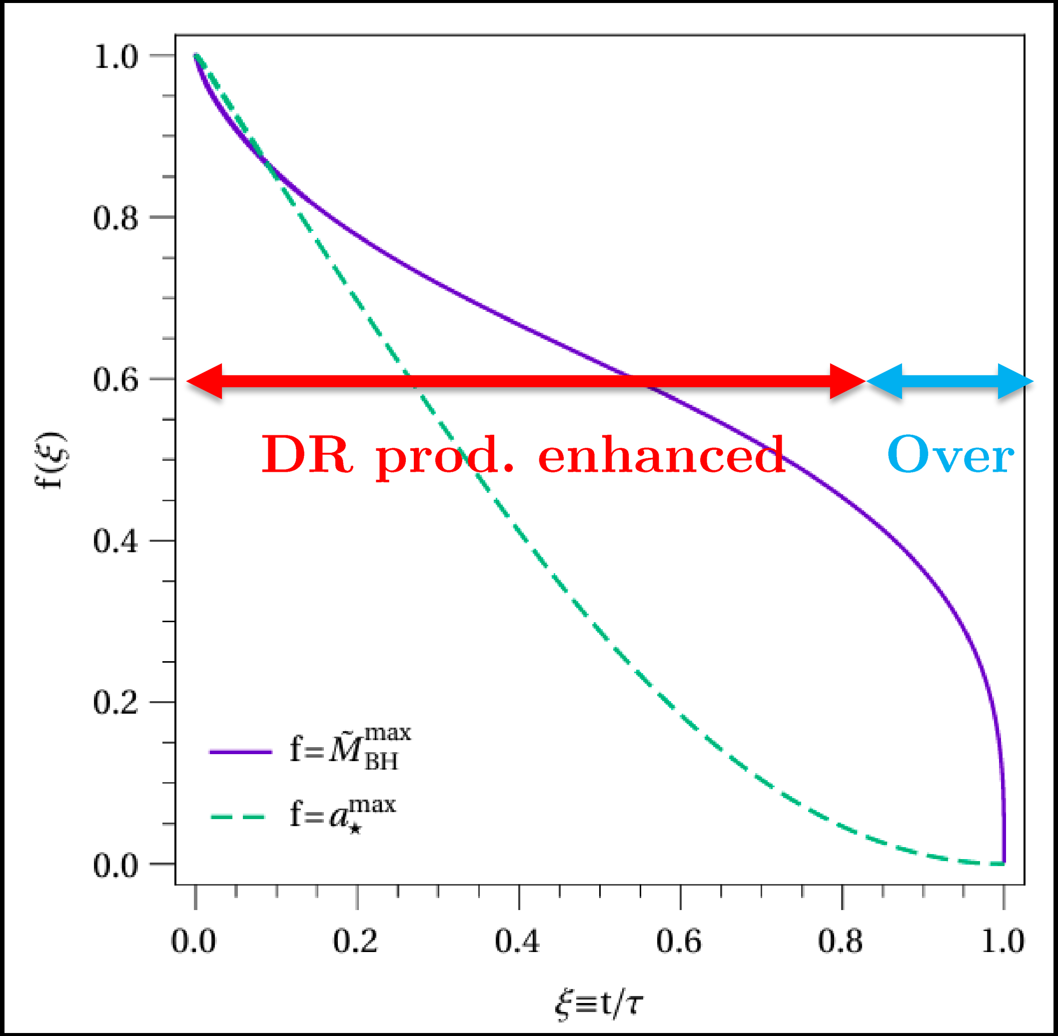
$$N_{\rm eff} \approx 3.045$$ (not just 3 ...)

The neutrino decoupling is NOT instantaneous

+ Temperature-dependent entropy transfer from electrons

Kerr PBHs and Dark Radiation

Why ?



Kerr PBHs and Dark Radiation

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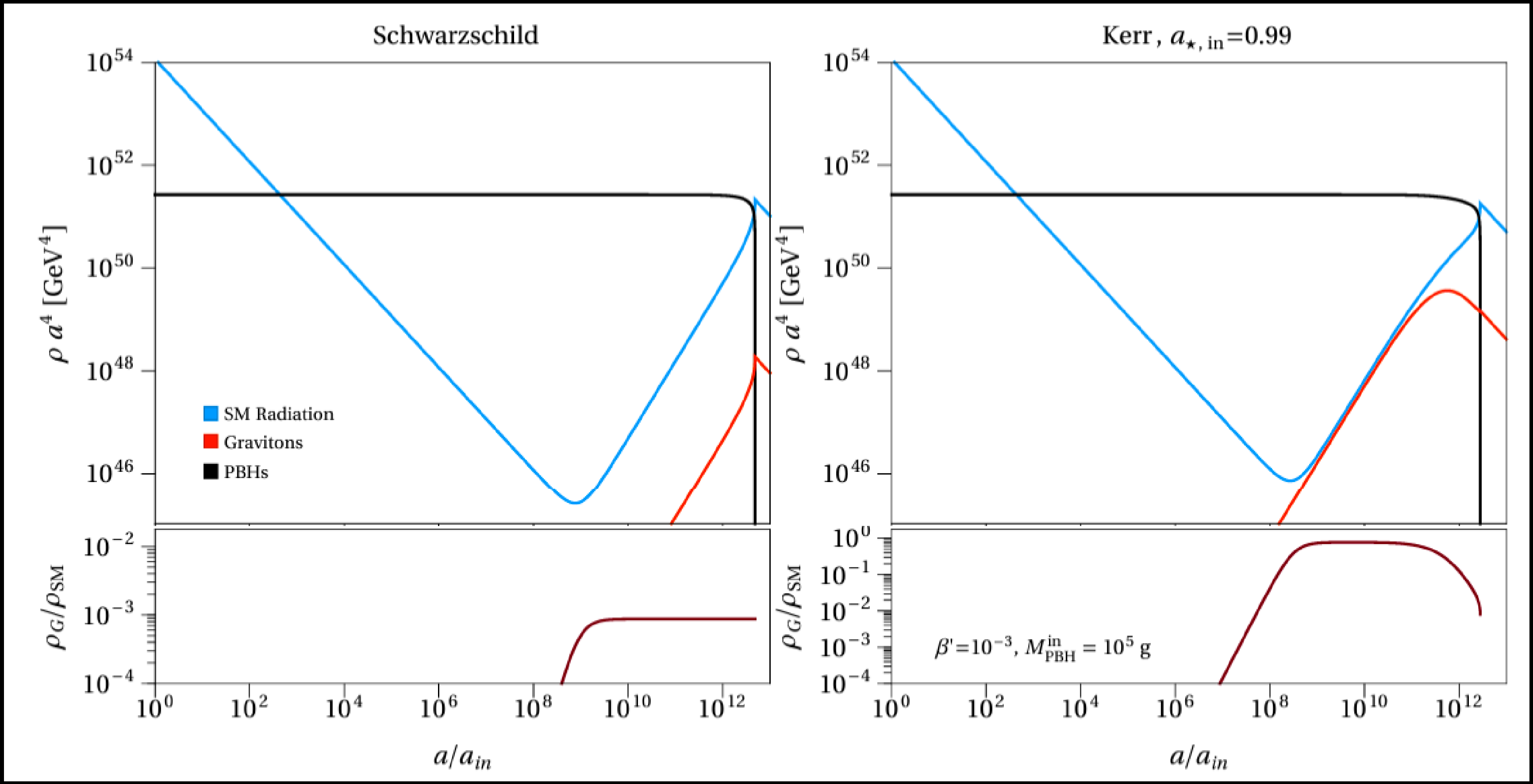


[Cheek, LH, Perez-Gonzalez and Turner '22] Code Publicly available: FRISBHEE

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

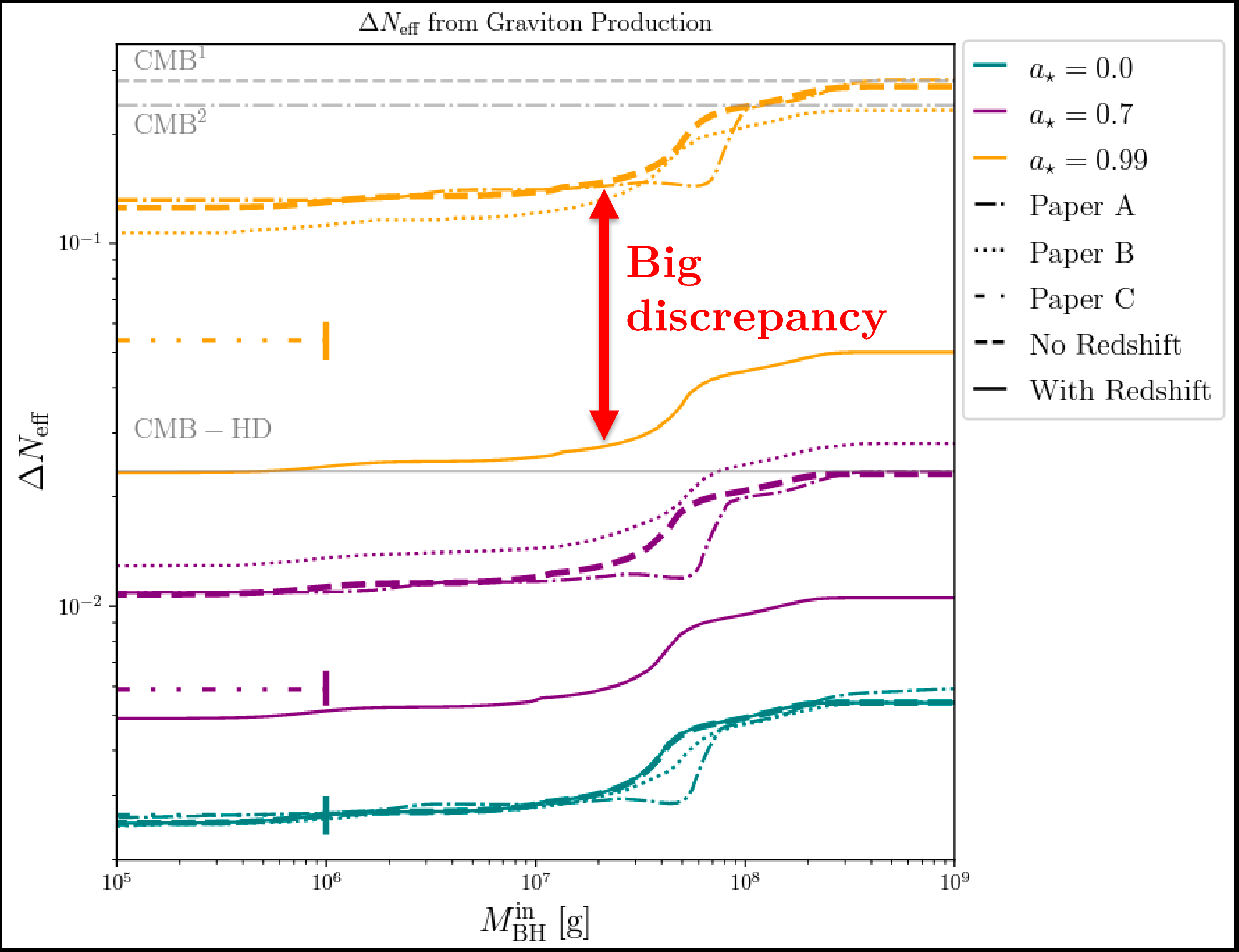
Why ?

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

The correct one is better!

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

Kerr PBHs and Dark Radiation



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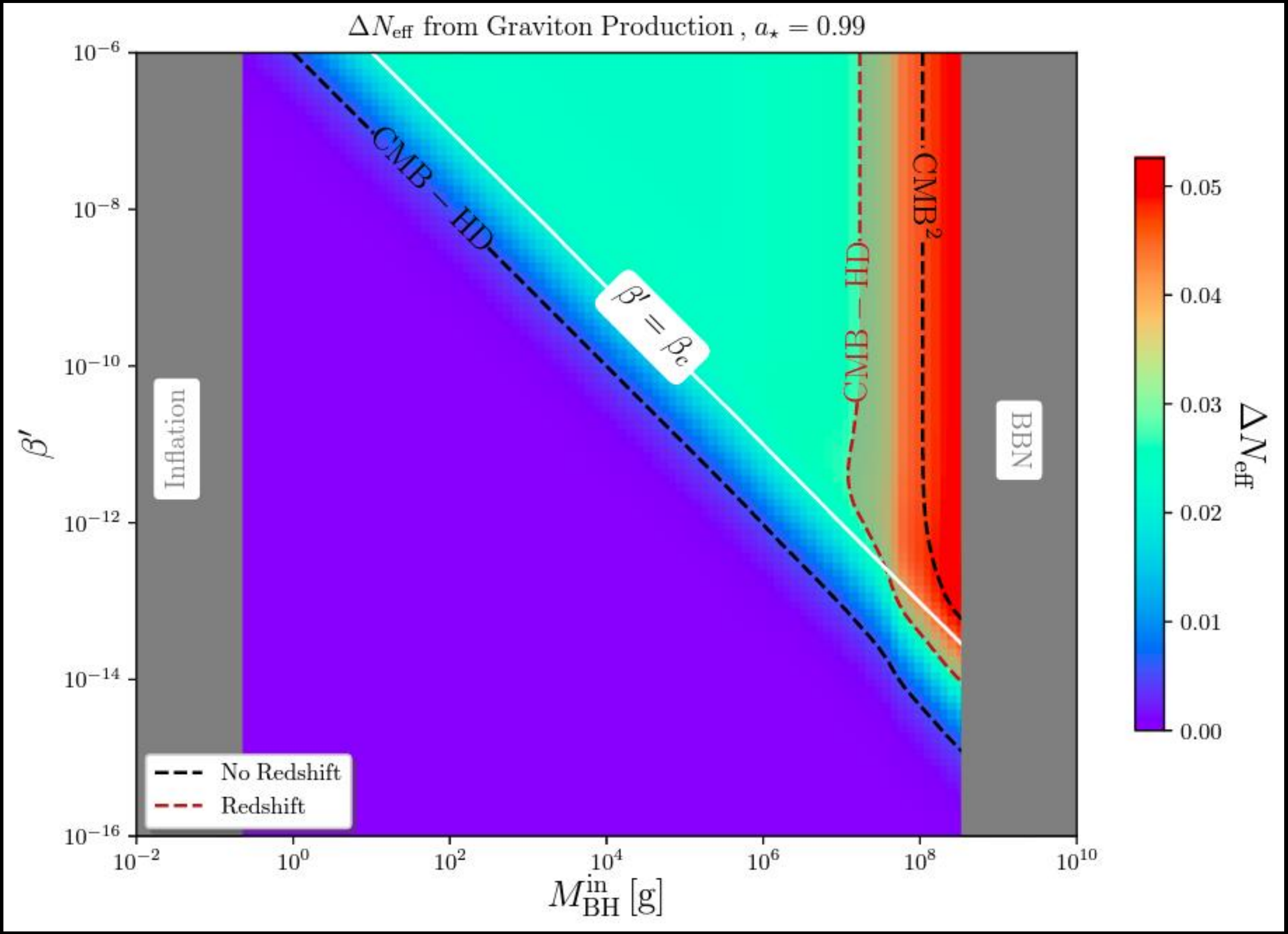

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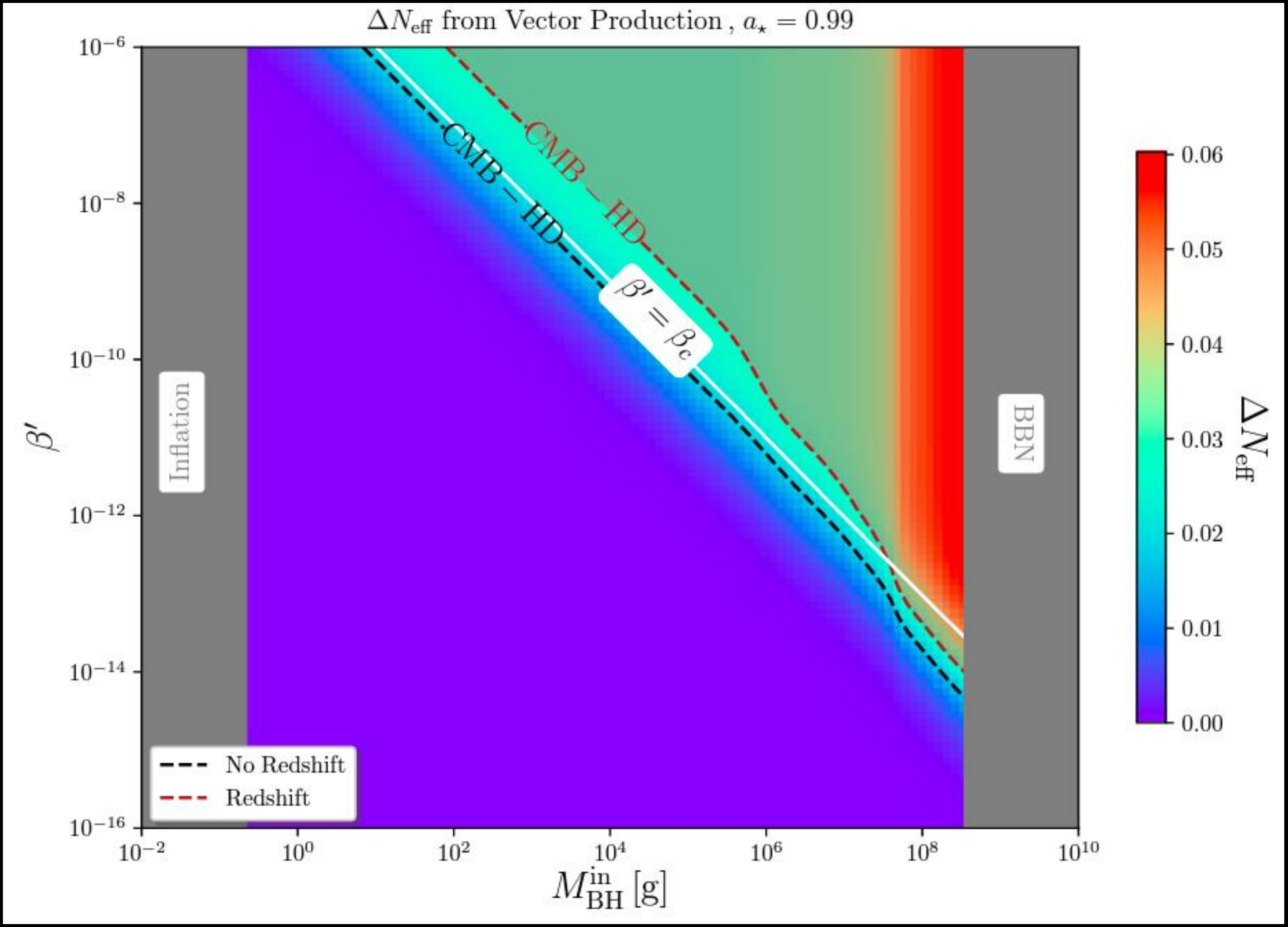

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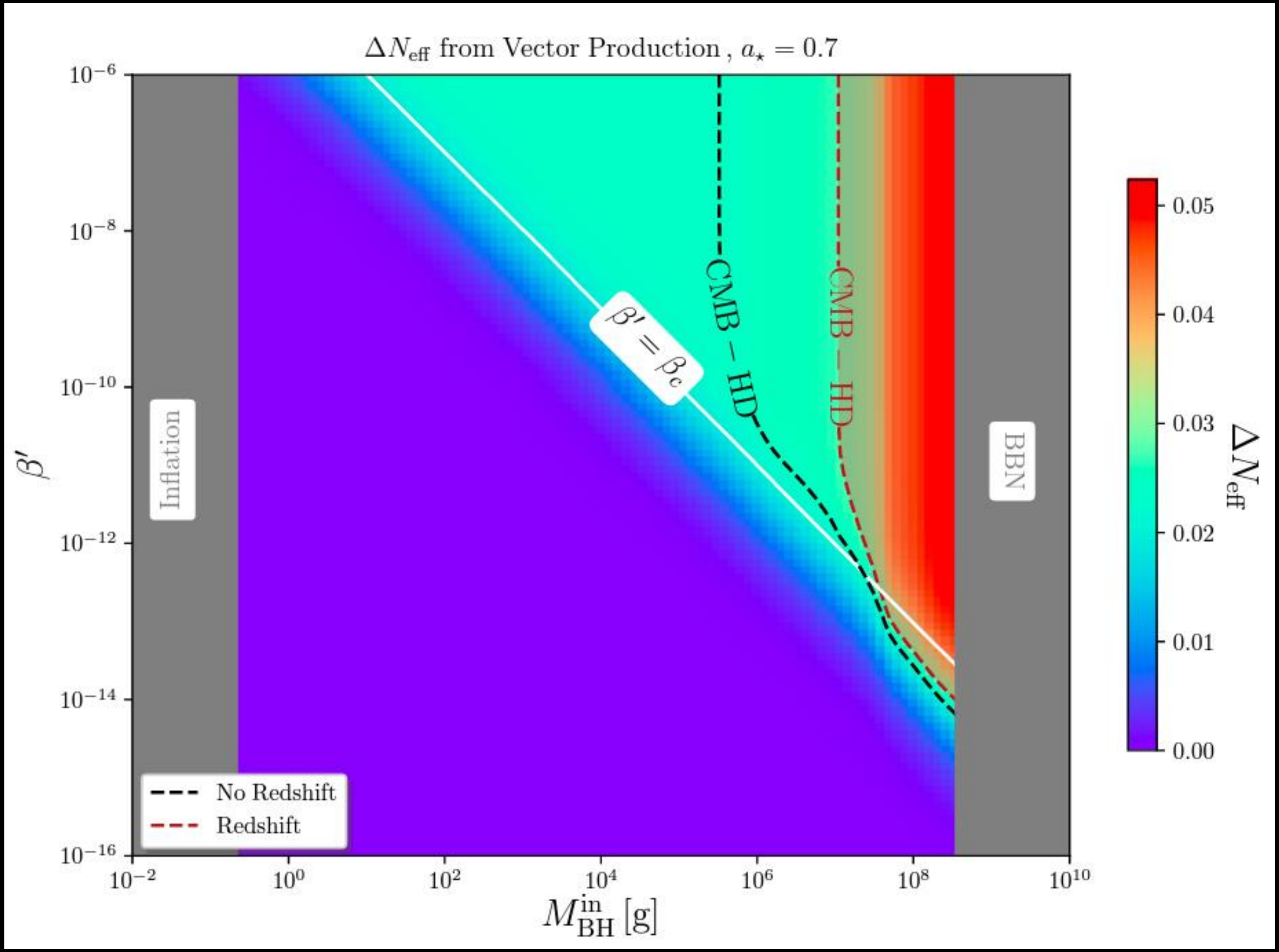


[Cheek, LH, Perez-Gonzalez and Turner '22] **Code Publicly available: FRISBHEE**

III. Kerr PBHs and Warm Dark Matter

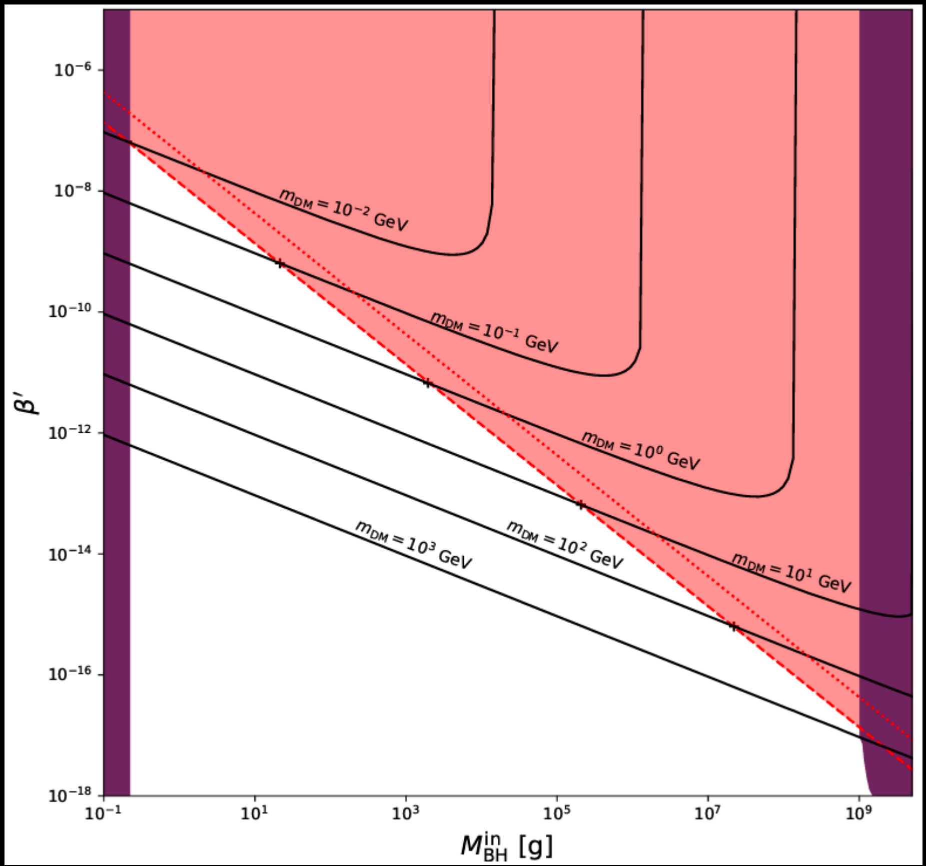
Kerr PBHs and Warm Dark Matter

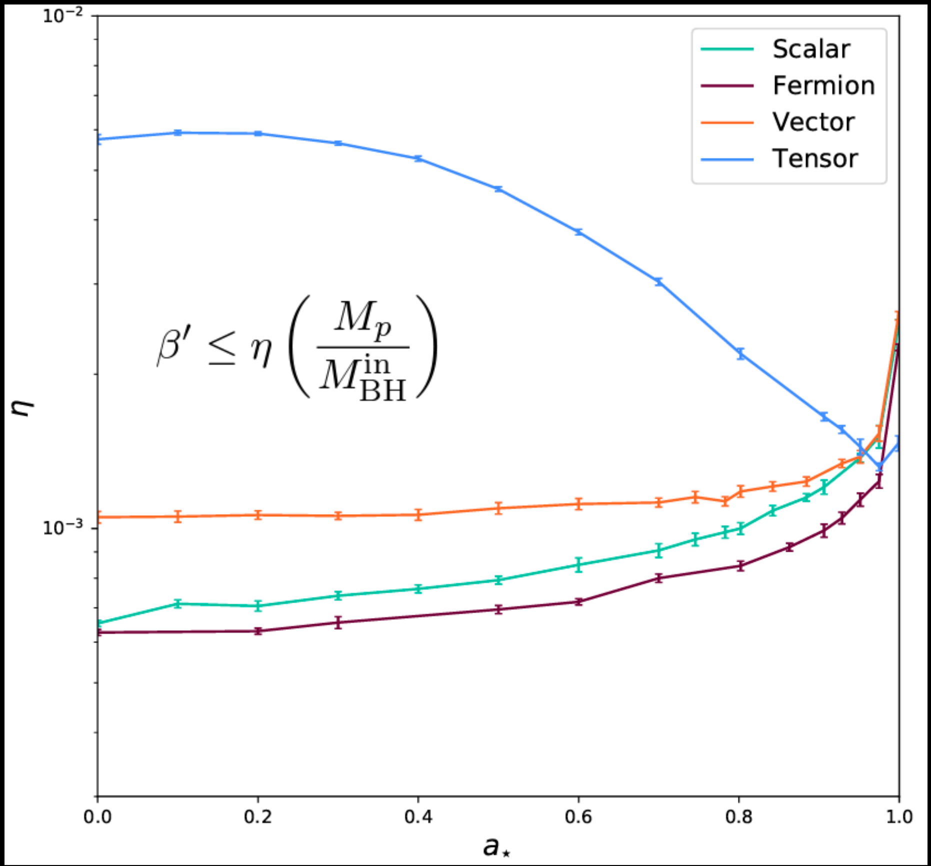
Using CLASS: expected matter power spectrum

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

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

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





IV. Evaporation of Extended Distributions

III. Evaporation of Extended Distributions

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

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

$$\downarrow$$

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

III. Evaporation of Extended Distributions

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

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

Dynamics of the evaporation + Friedmann equations

→ Included in `FRISBHEE`

https://github.com/yfperezg/frisbhee

III. Evaporation of Extended Distributions

Examples:

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

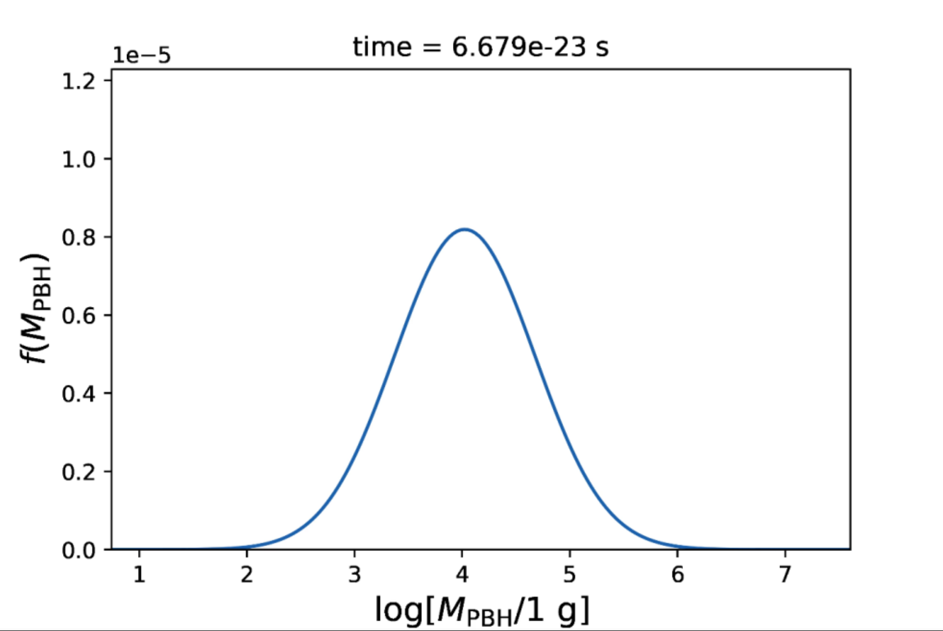
Evaporation smeared around $\tau(M_c)$

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

Regime of 'Cosmological Stasis'

III. Evaporation of Extended Distributions

$$n_{\rm PBH} = \int dM\, f(M) \qquad f(M) = \frac{n_{\rm BH}}{\sqrt{2\pi}\sigma M} \exp\left(-\frac{\log^2(M/M_c)}{2\sigma^2}\right)$$



Log-normal distribution

Dolgov, 93
Green, 2016
Kannike, 2017

III. Evaporation of Extended Distributions

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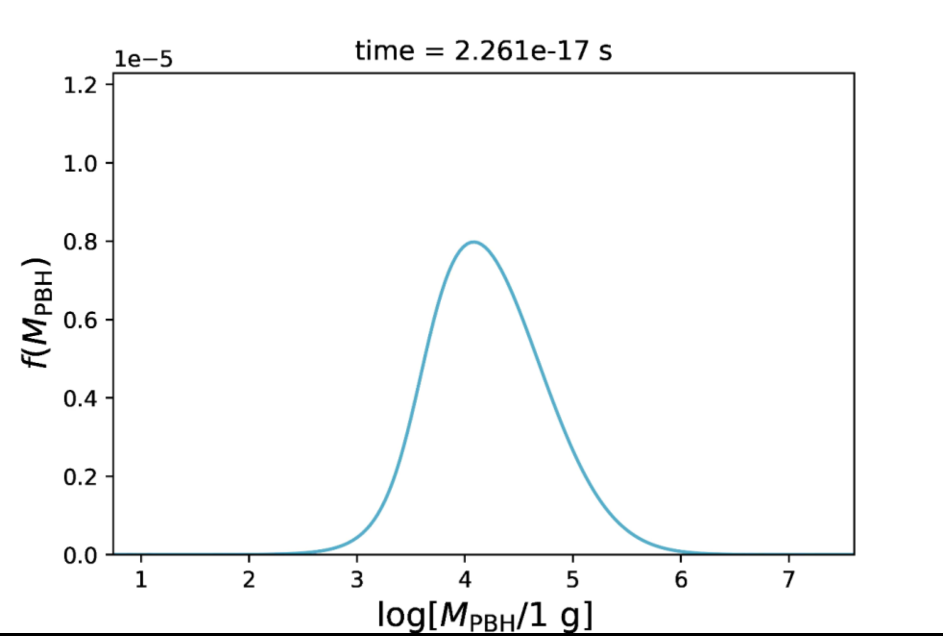

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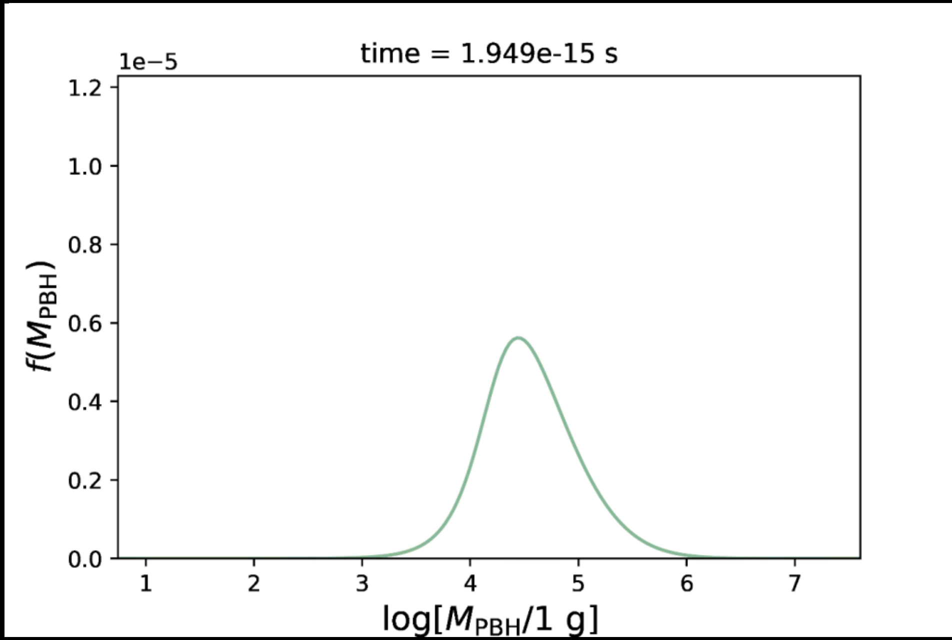
Kannike, 2017

III. Evaporation of Extended Distributions

$$n_{\rm PBH} = \int dM\, f(M) \qquad f(M) = \frac{n_{\rm BH}}{\sqrt{2\pi}\sigma M} \exp\left(-\frac{\log^2(M/M_c)}{2\sigma^2}\right)$$



Log-normal distribution

Dolgov, 93
Green, 2016
Kannike, 2017

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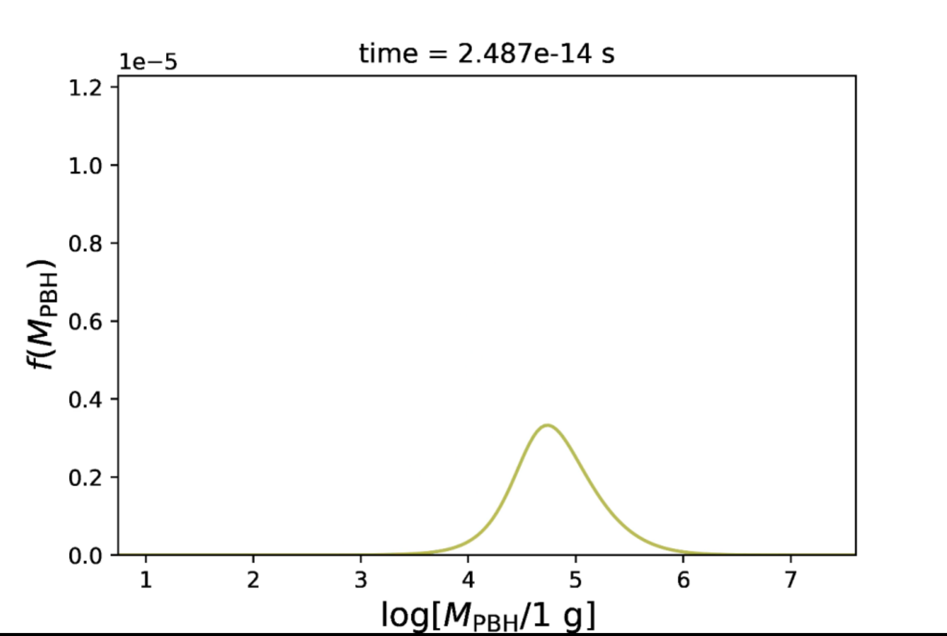

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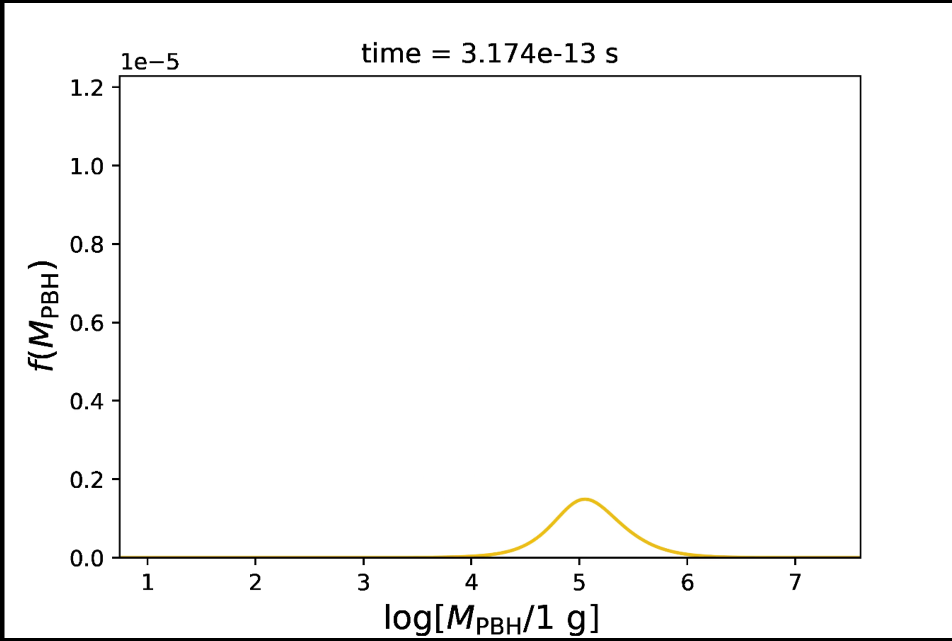

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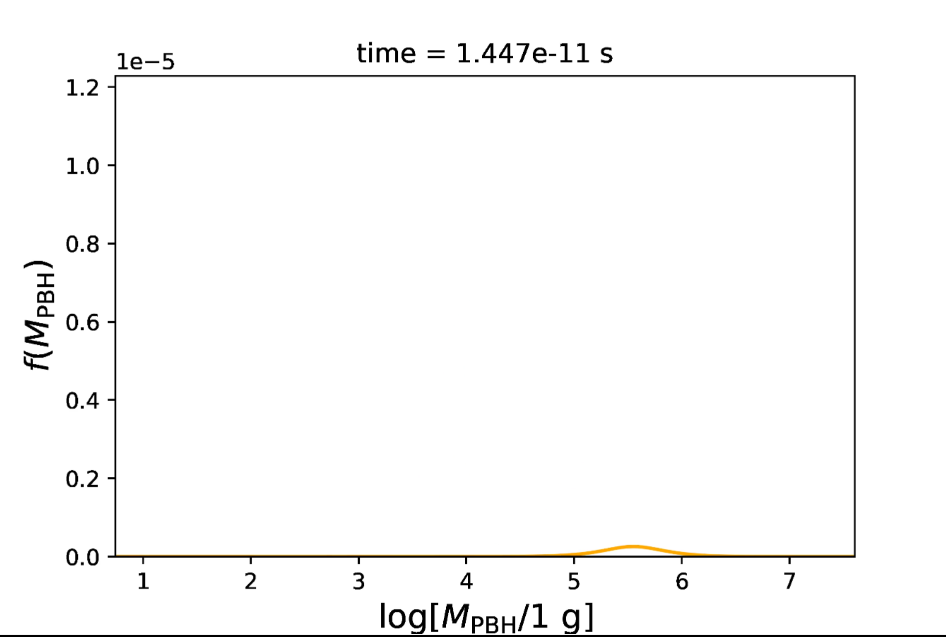

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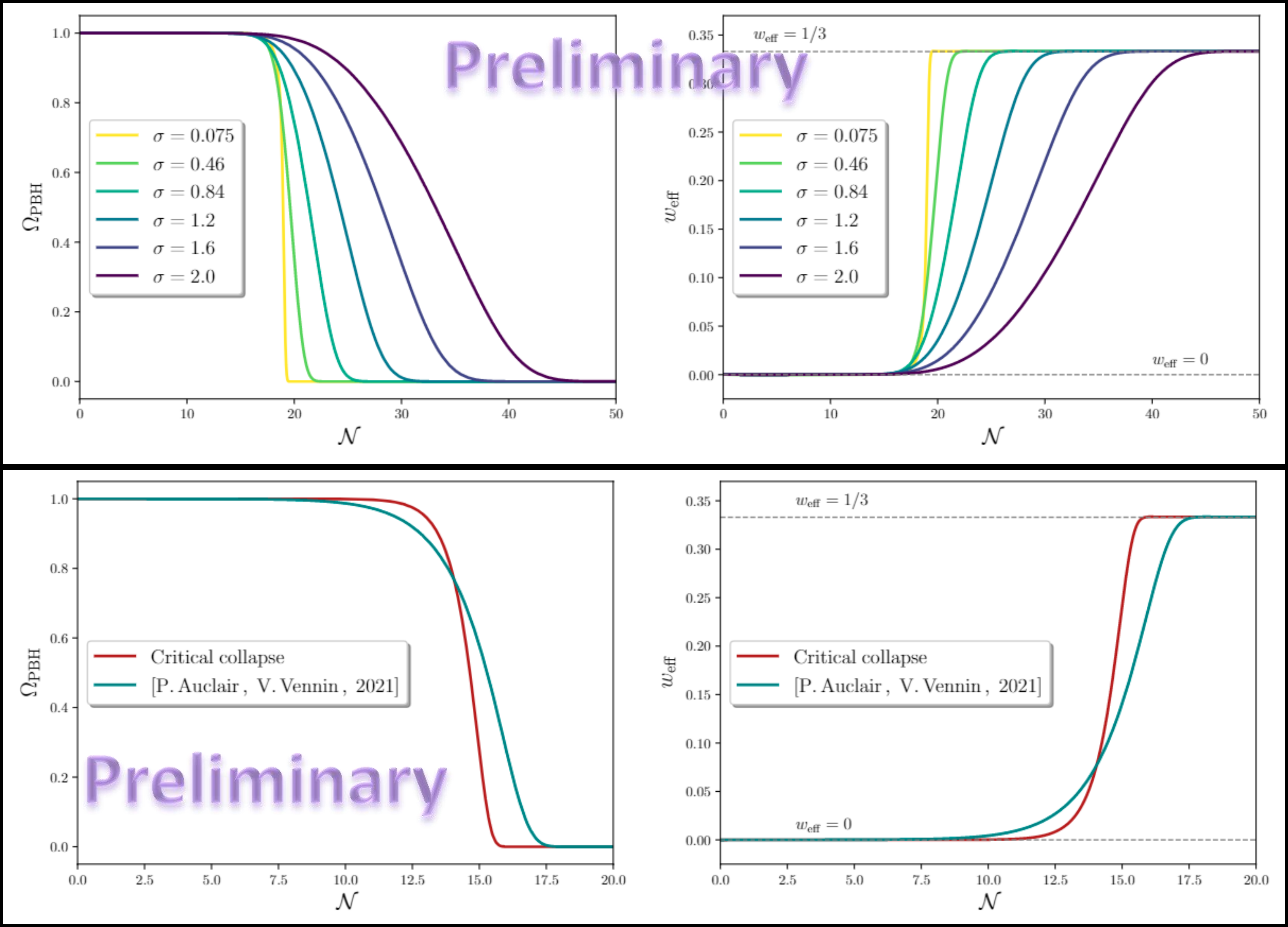
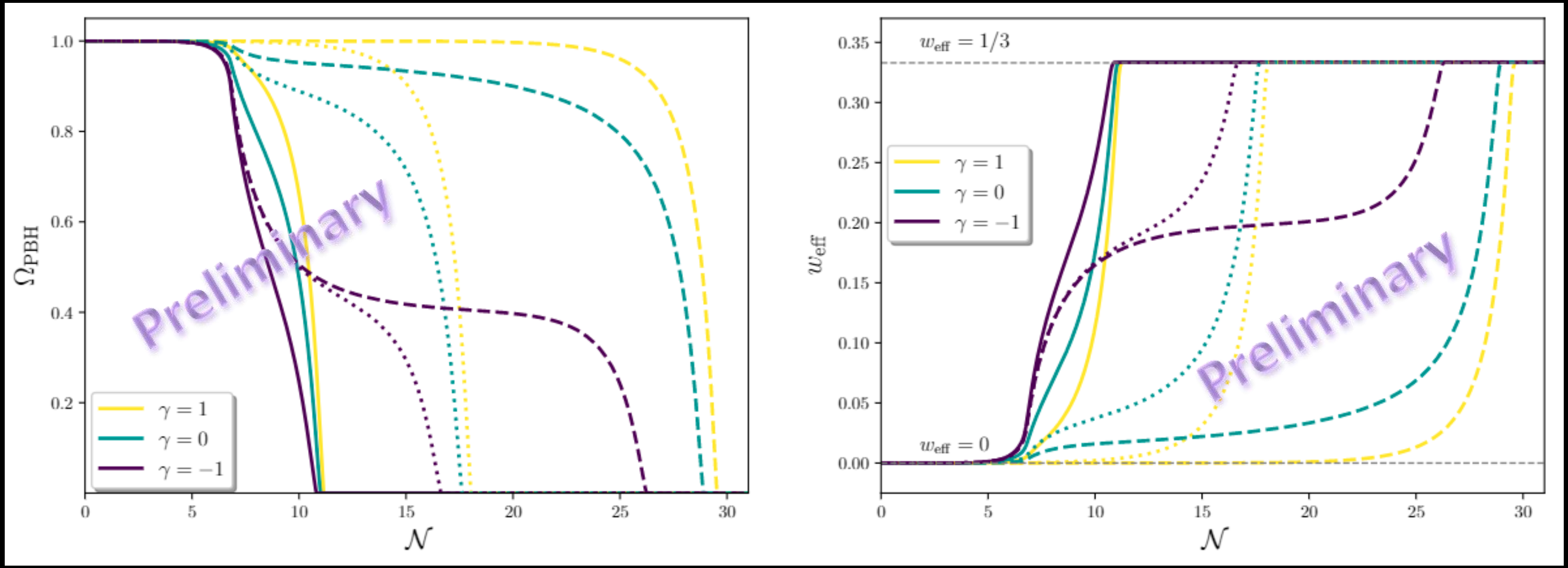
III. Evaporation of Extended Distributions



III. Evaporation of Extended Distributions

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



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

Conclusion

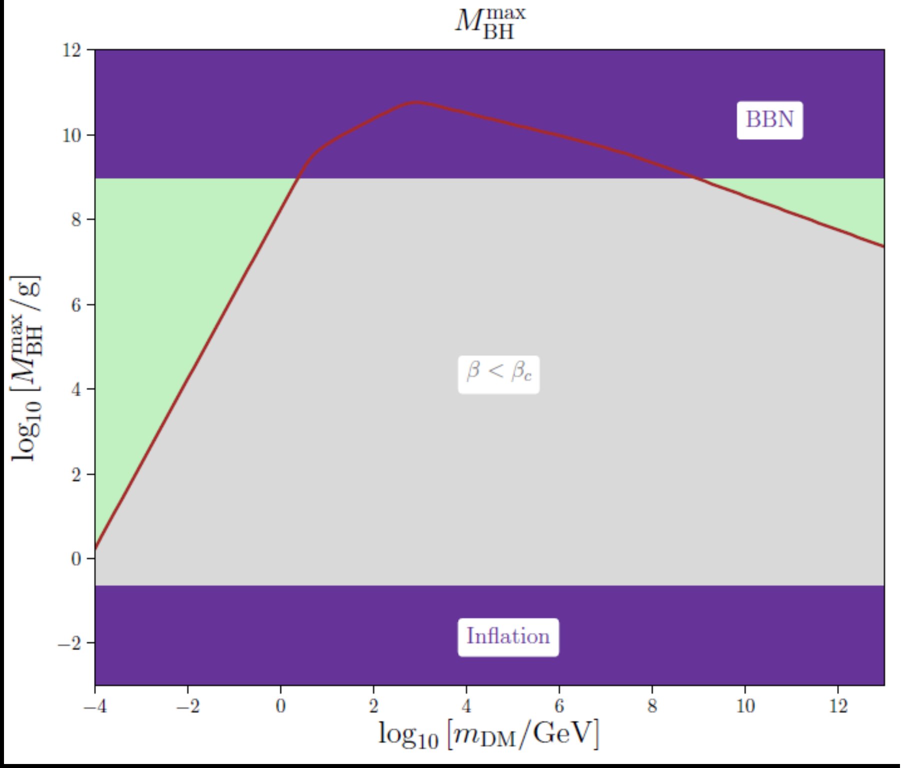
Mini PBHs can leave several imprints in the early Universe

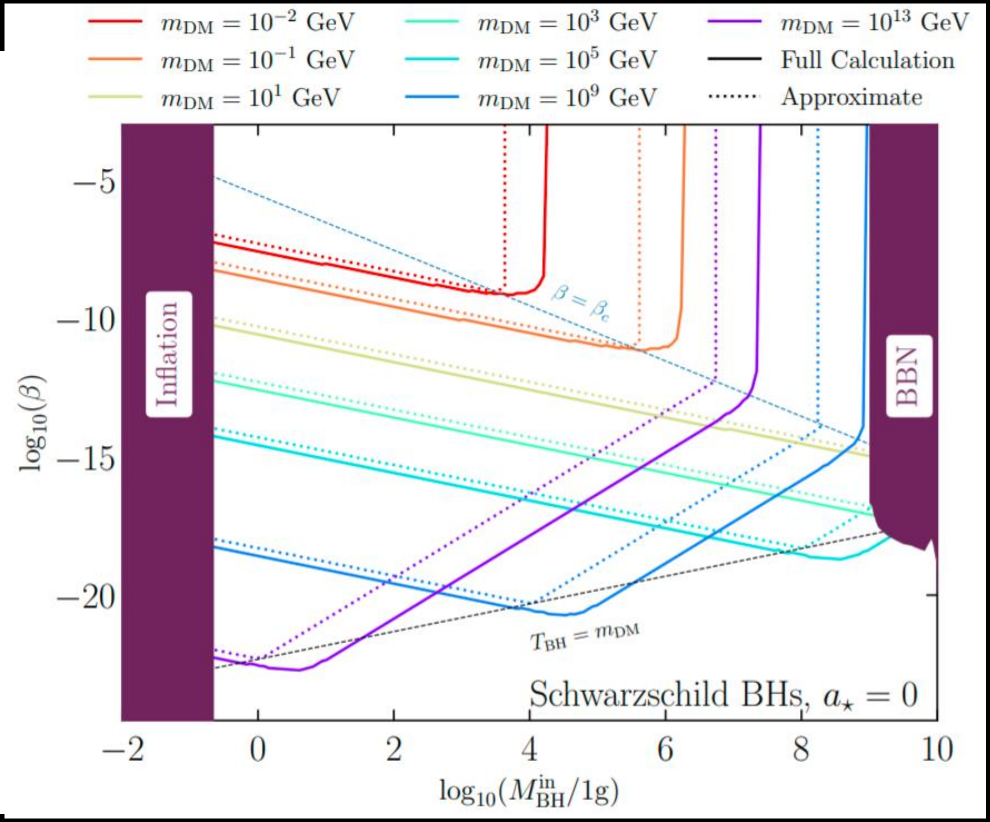
- Modify cosmology (EMD+ entropy inj.)
- Produce dark matter, leading to modified predictions for particle searches
- Particles produced from evaporation can be extremely boosted, which can lead to additionnal constraints from structure formation
- Kerr PBHs can lead to a large production of gravitons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

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

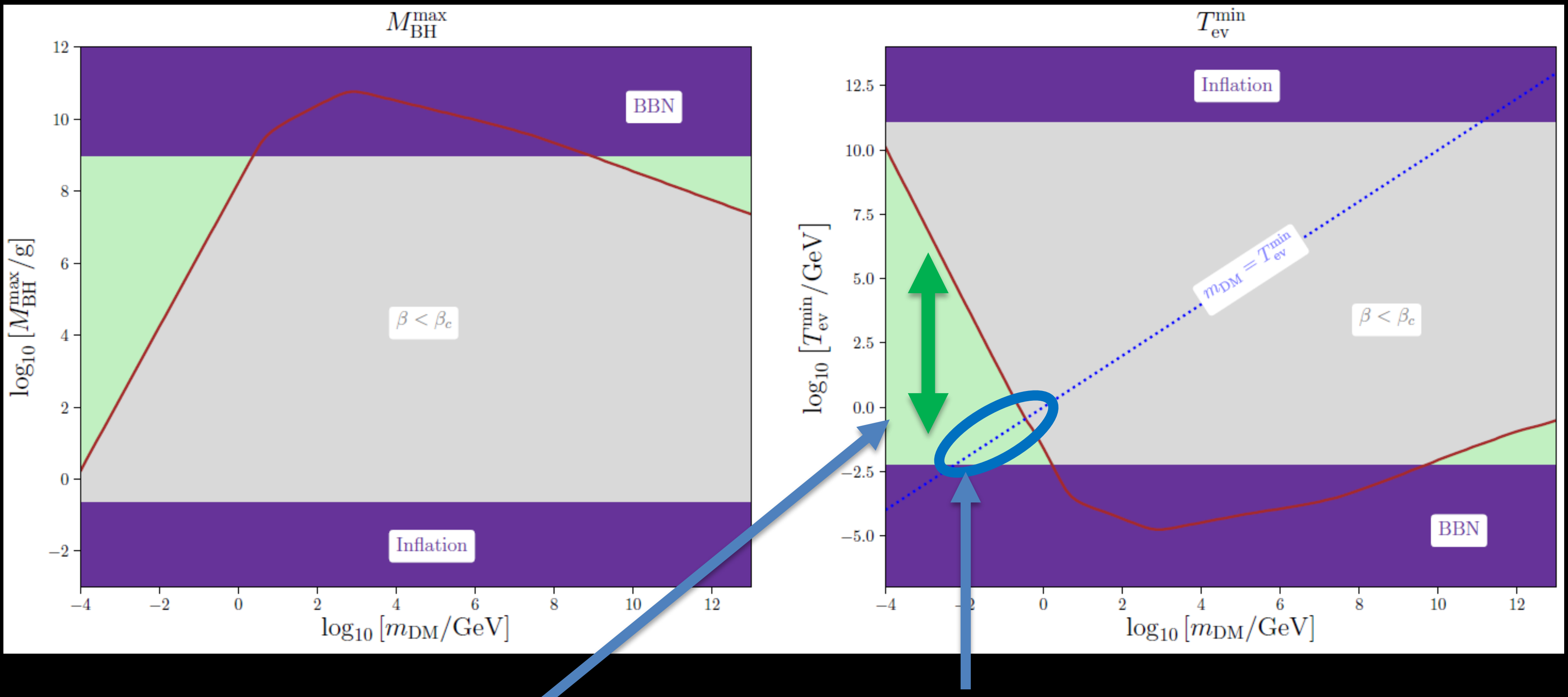
Back up

Modified Cosmology





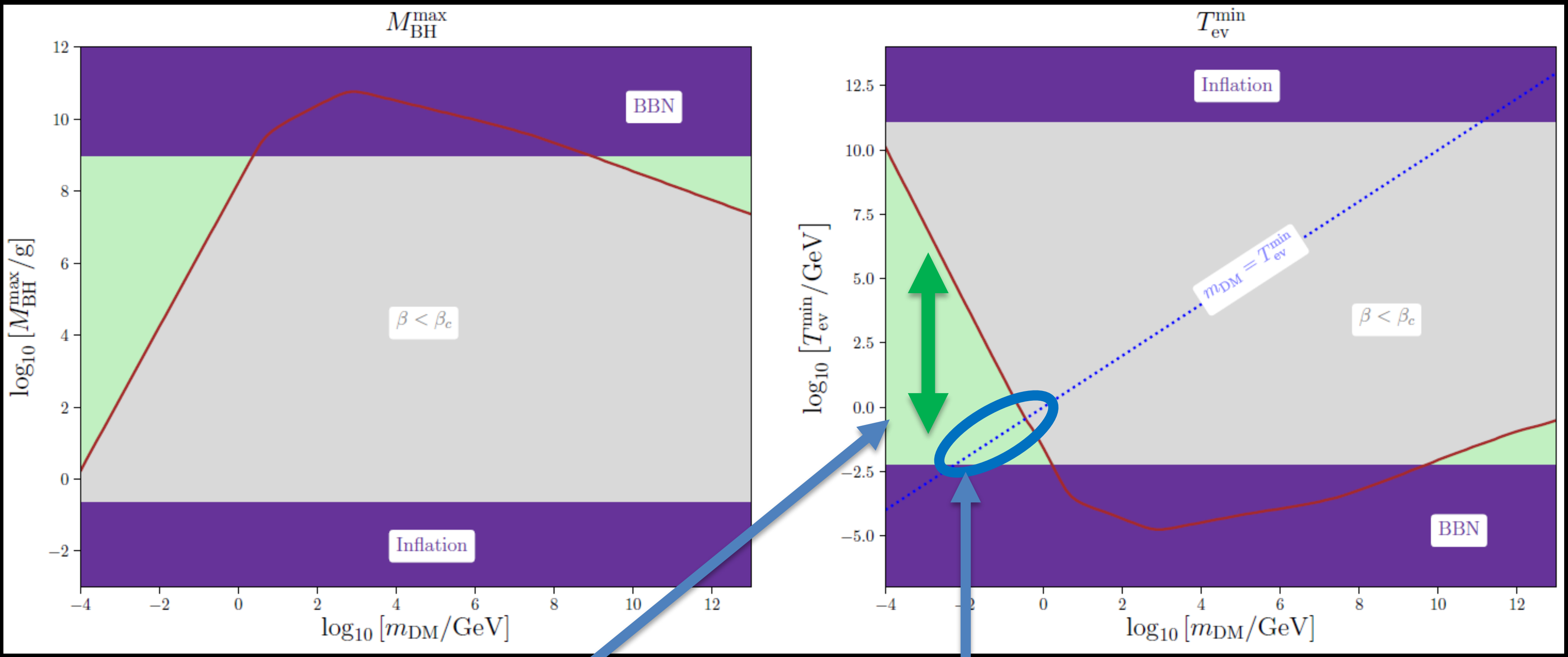
Modified Cosmology



Region of interest
for Freeze-In

Region of interest
for Freeze-Out

Modified Cosmology

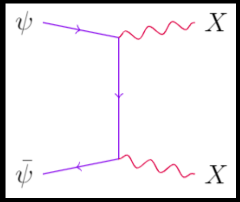


Region of interest for Freeze-In

~~Region of interest for Freeze-Out~~

Thermalization Of PBHs products…

TBH large +



Boltzmann Equations

Freeze–In case:

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

$$\dot{n}^{\rm ev}_{\rm DM} + 3Hn^{\rm ev}_{\rm DM} = \left. \frac{{\rm d}n^{\rm ev}_{\rm DM}}{{\rm d}t} \right|_{\rm BH}$$

$$\dot{n}_{X} + 3Hn_{X} = \left. \frac{{\rm d}n_{X}}{{\rm d}t} \right|_{\rm BH}$$

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

Boltzmann Equations

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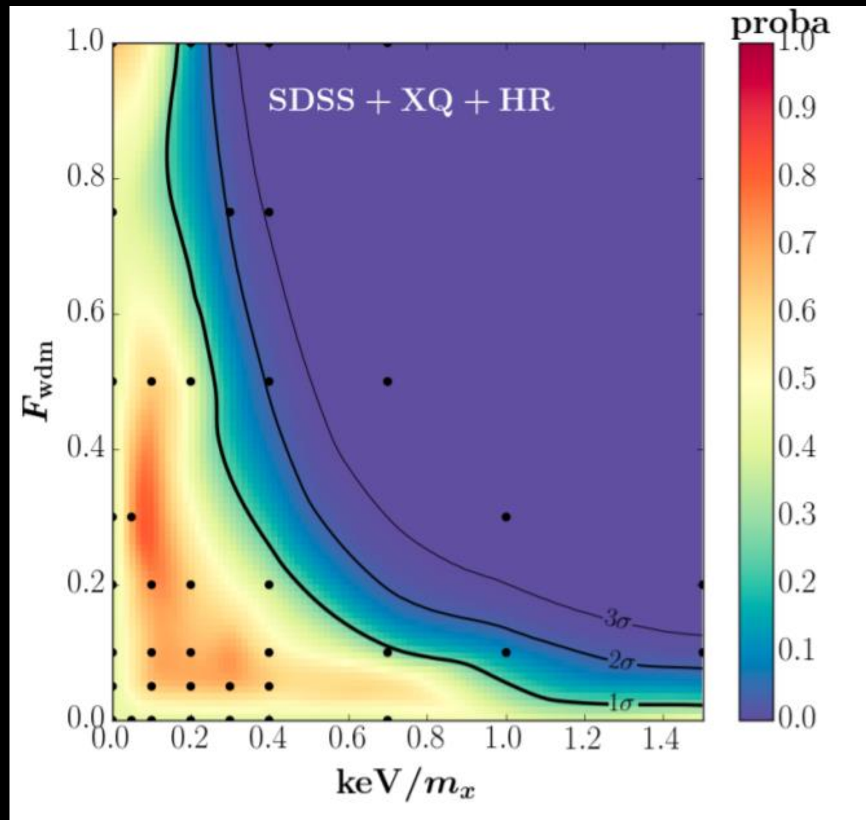
$$\dot{n}^{\rm th}_{\rm DM} + 3H n^{\rm th}_{\rm DM} = \langle \sigma v \rangle_{\rm th} \left(n^2_{\rm DM,eq} - n^{\rm th\,2}_{\rm DM} \right)$$

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

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

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

Non-cold Dark Matter

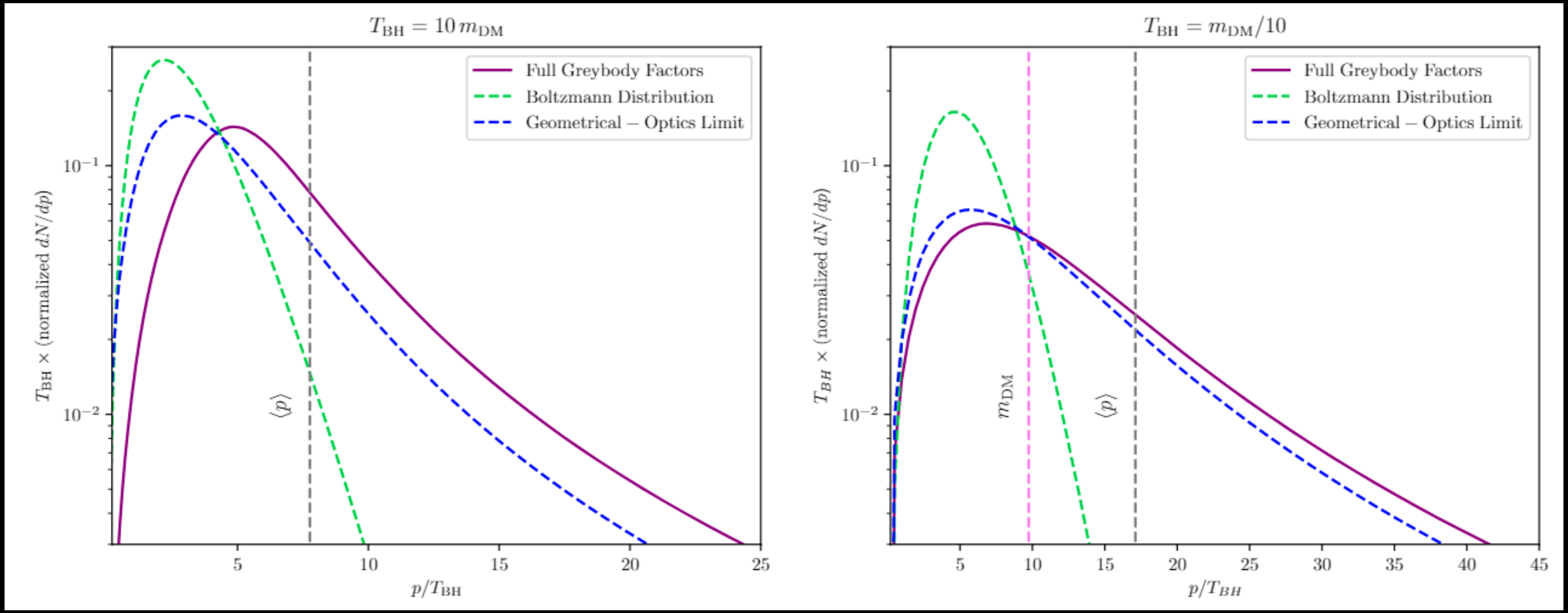


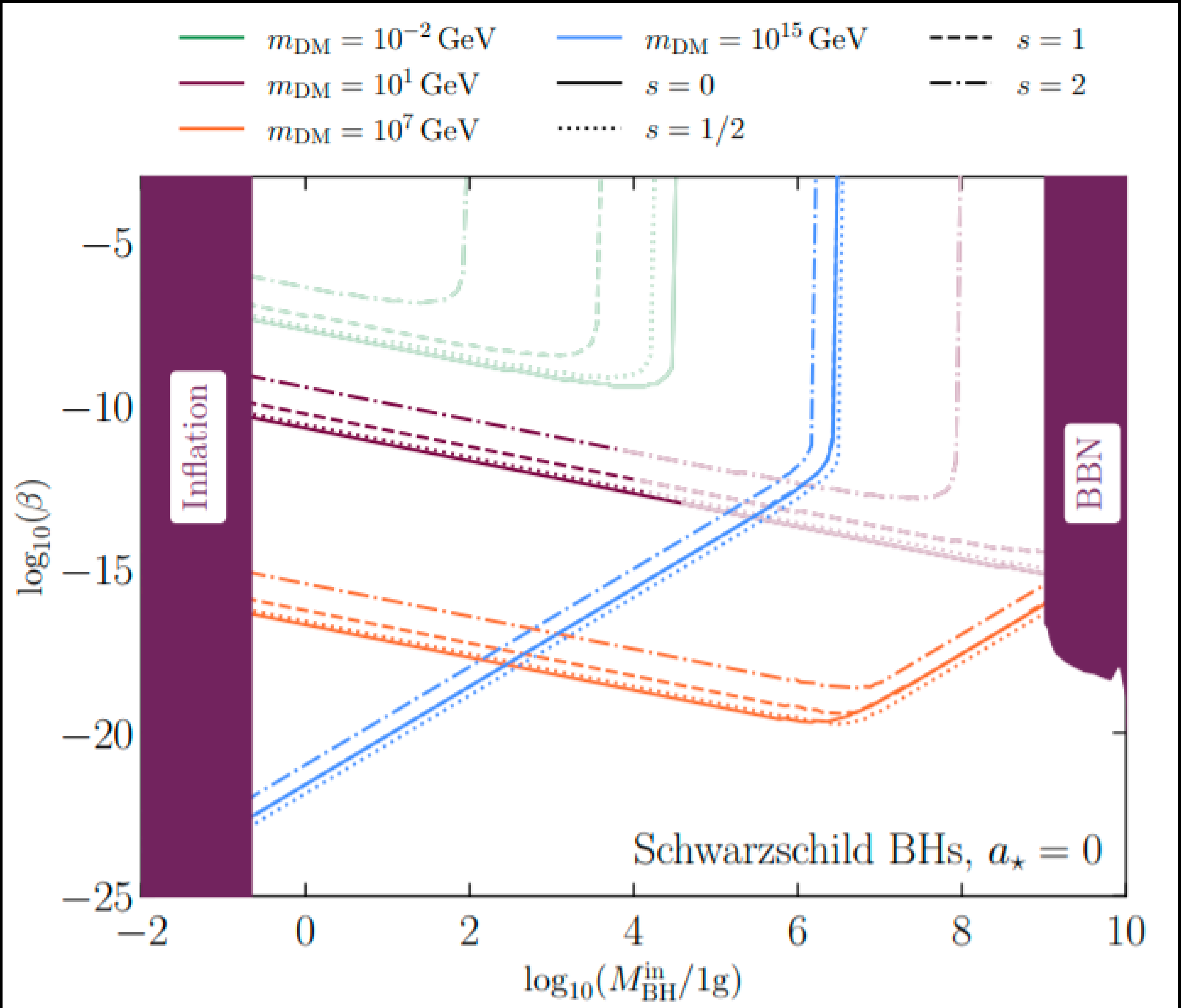
[Baur *et al.* 2017]

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

DM from Evaporation

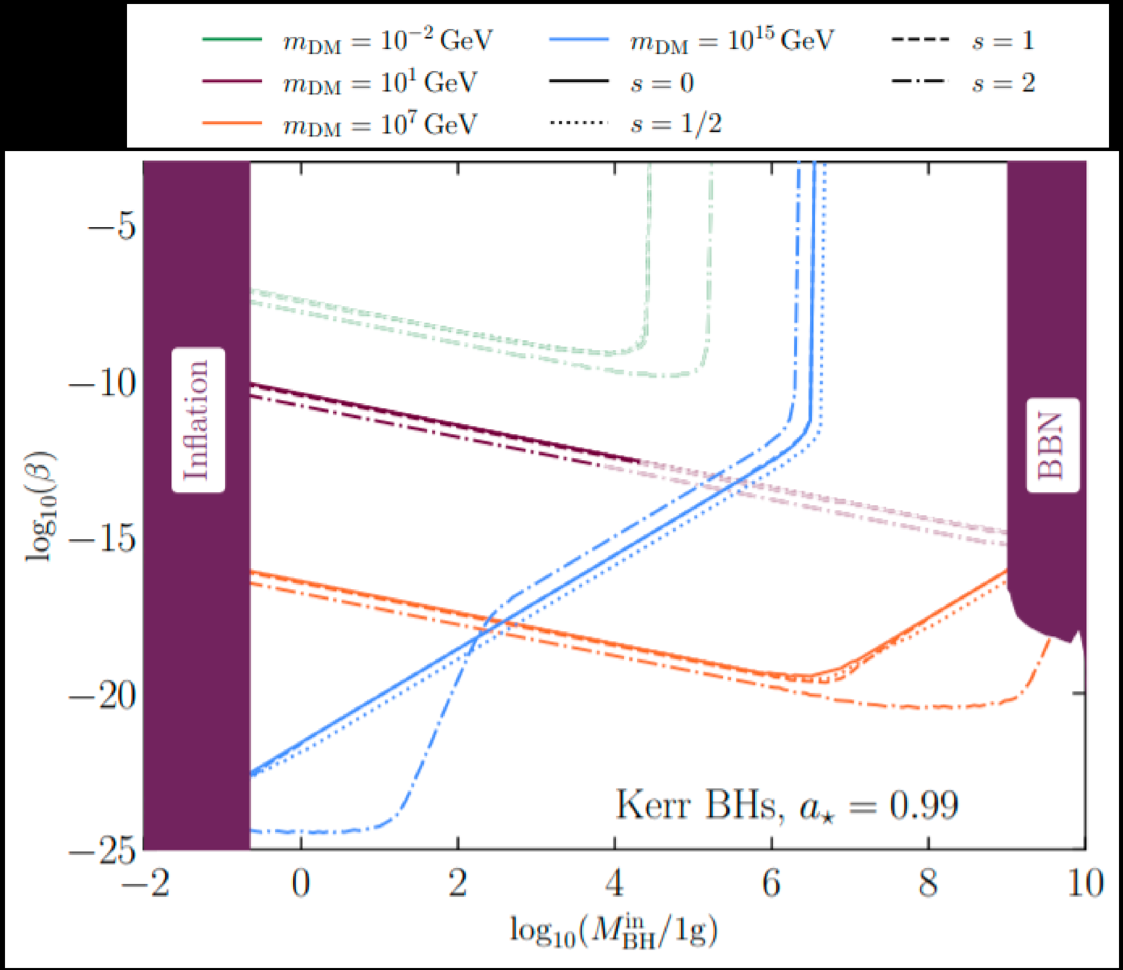
- Peculiar spectrum of evaporated DM particles
- Non-negligible difference between geometrical-optics limit and full distributions





$m_{\rm DM} = 10^{-2}$ 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

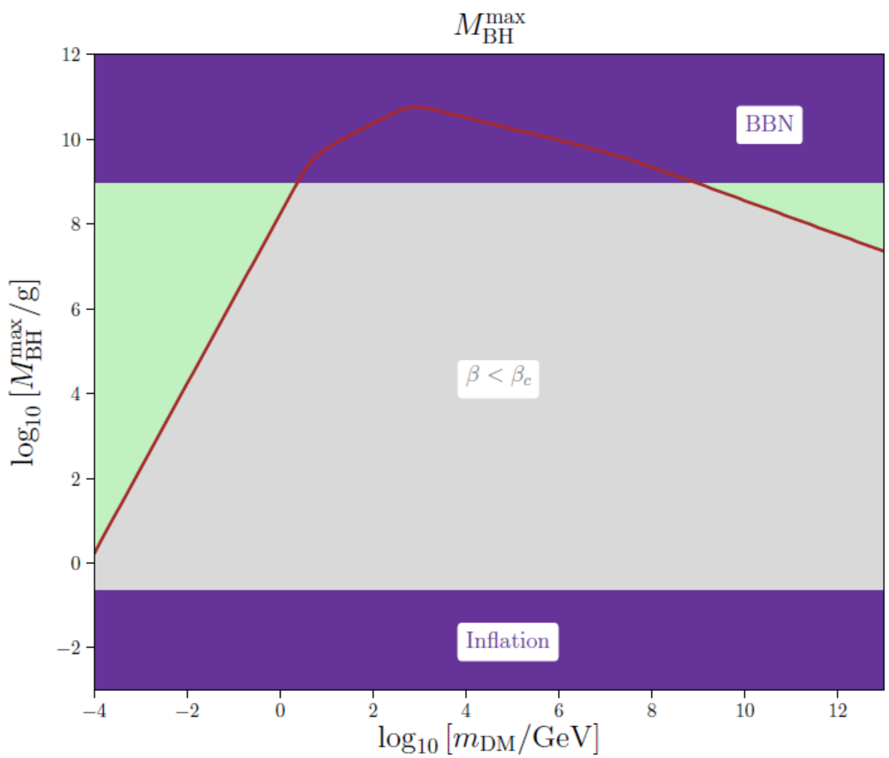
$$T_{\rm BH} = \frac{1}{4\pi G M_{\rm BH}} \frac{\sqrt{1-a_\star^2}}{1+\sqrt{1-a_\star^2}} \,,$$

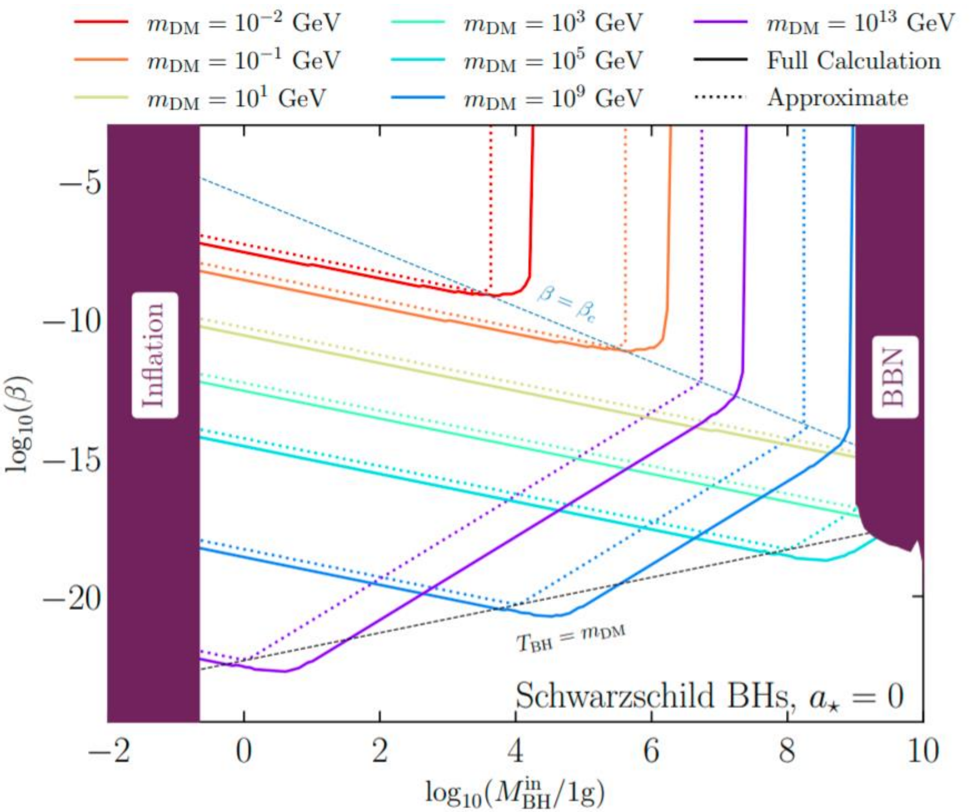


$$\frac{{\rm d}^2\mathcal{N}_{ilm}}{{\rm d}p{\rm d}t} = \frac{\sigma_{s_i}^{lm}(M_{\rm BH}, p, a_\star)}{\exp\left[(E_i - m\Omega)/T_{\rm BH}\right] - (-1)^{2s_i}} \frac{p^3}{E_i}$$

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

Modified Cosmology





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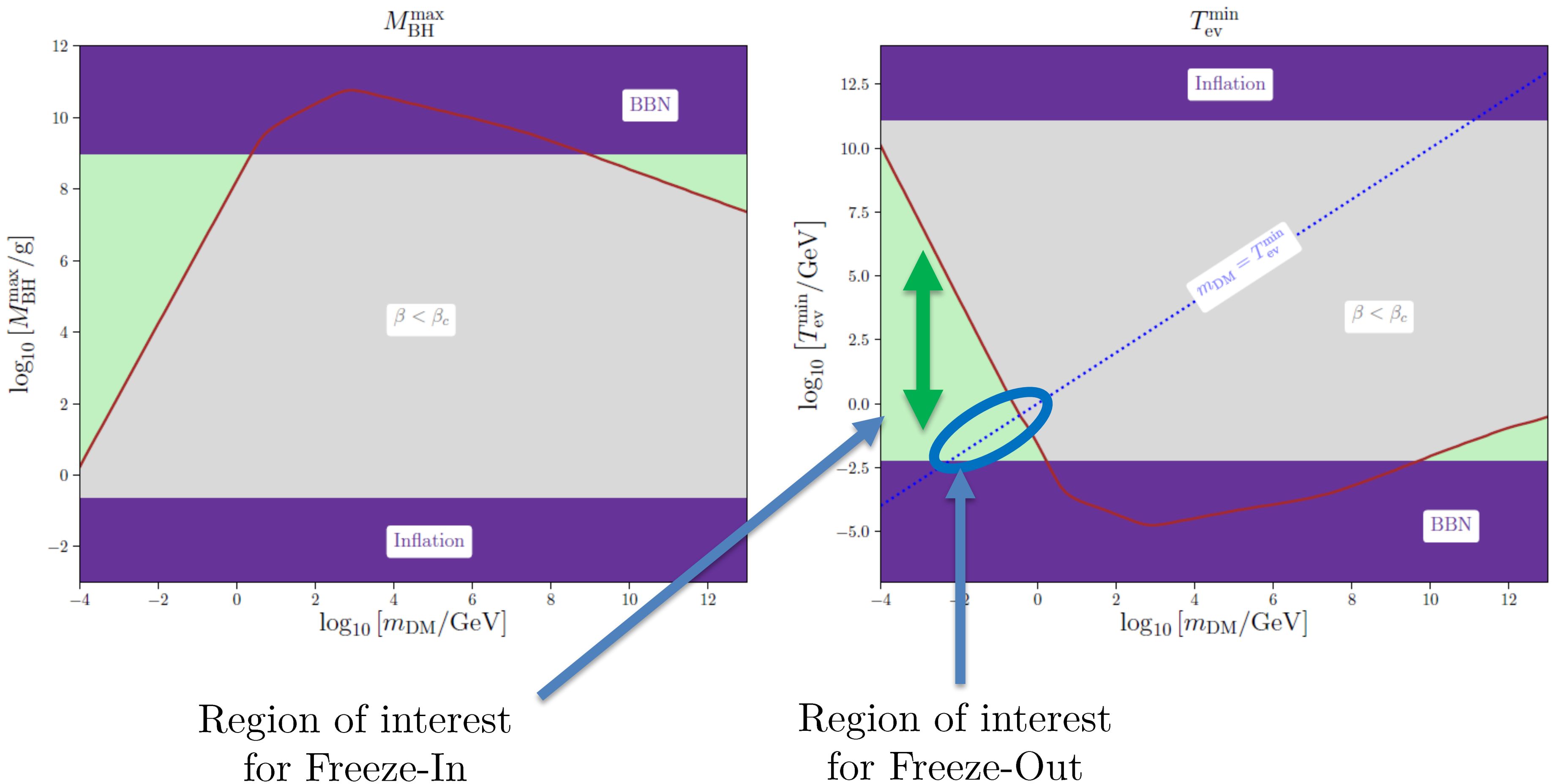

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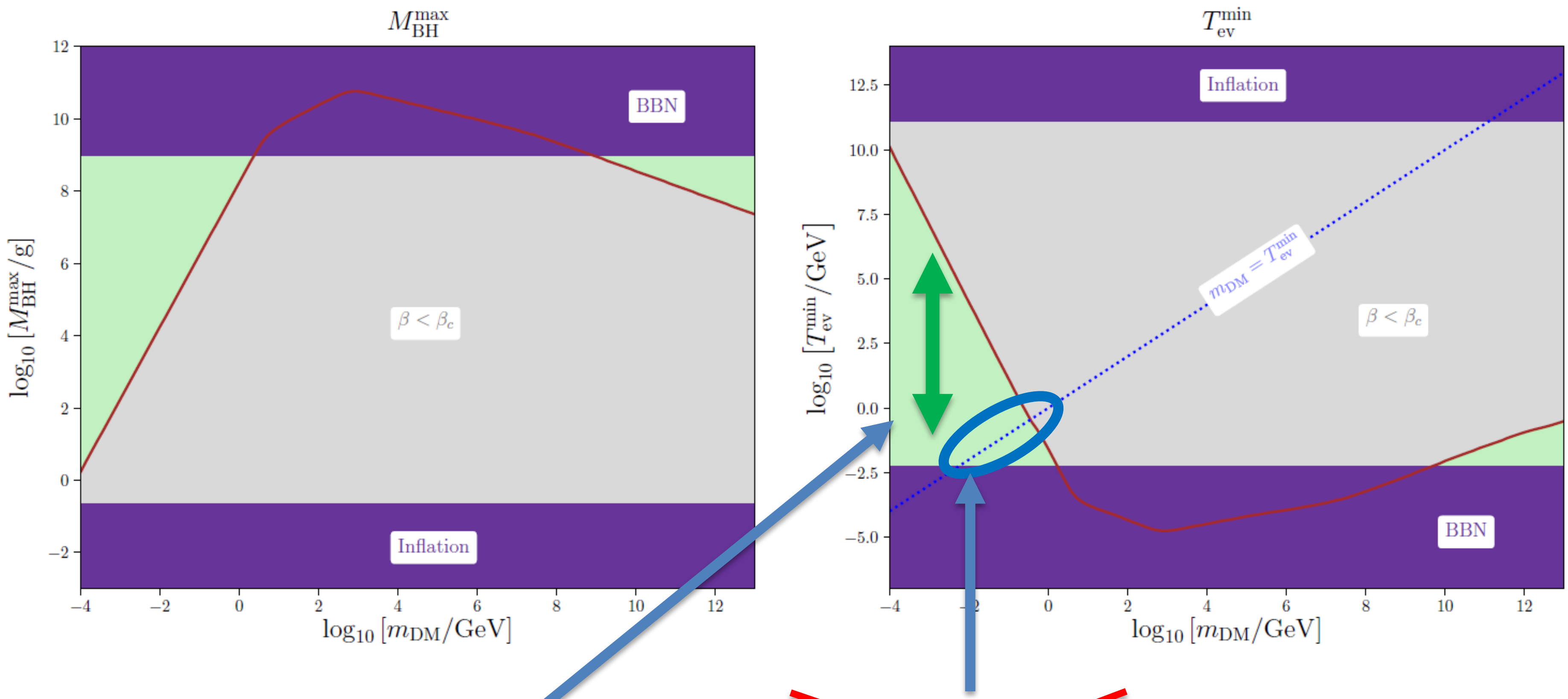

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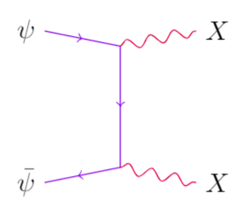
**Thermalization
Of PBHs products…**

TBH large +



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?

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

Kerr PBHs and Dark Radiation

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

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

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

$$\varepsilon_i(M_{\rm BH}, a_\star) = \frac{g_i}{2\pi^2}\int_0^\infty \sum_l \sum_{m=-l}^{l} \frac{\mathrm{d}^2\mathcal{N}_{ilm}}{\mathrm{d}p\mathrm{d}t} E dE\,,$$

$$\gamma_i(M_{\rm BH}, a_\star) = \frac{g_i}{2\pi^2}\int_0^\infty \sum_l \sum_{m=-l}^{l} m\frac{\mathrm{d}^2\mathcal{N}_{ilm}}{\mathrm{d}p\mathrm{d}t} dE\,,$$

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 $f_X(p)$ and $f_{\rm DM}(p)$

Simplified approch...

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

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

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

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

Effects of PBH Evaporation

1. PBHs produce additional DM particles

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

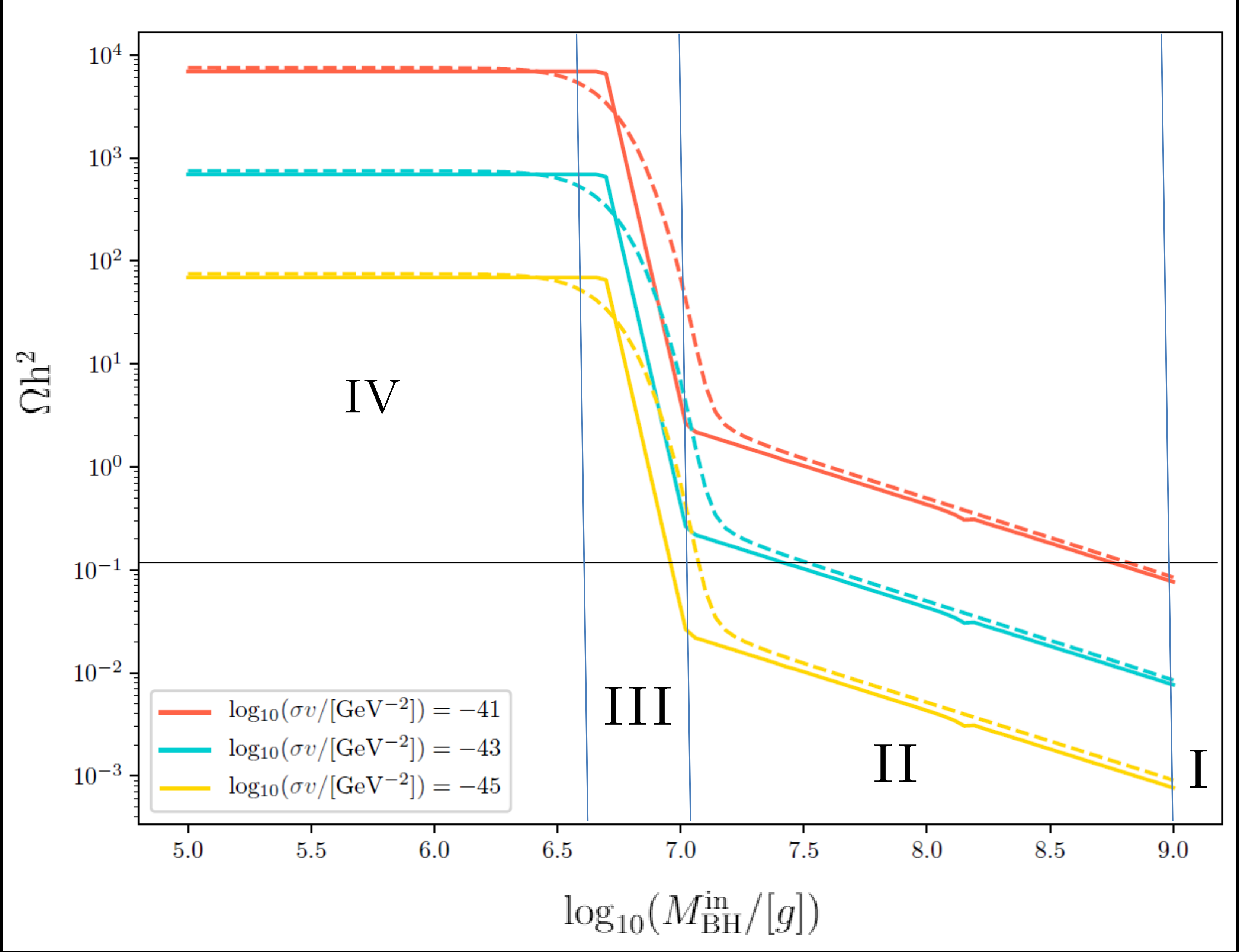
2. PBHs produce mediator particles X

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...

Comparison with Numerics



Kerr PBHs and Dark Radiation

In the Standard Model

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

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

In the presence of Dark Radiation

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

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

The quantity to evaluate