Durham University
LUCIEN HEURTIER
IP3

WHEN PRIMORDIAL BLACK HOLES MESS UP WITH DARK MATTER

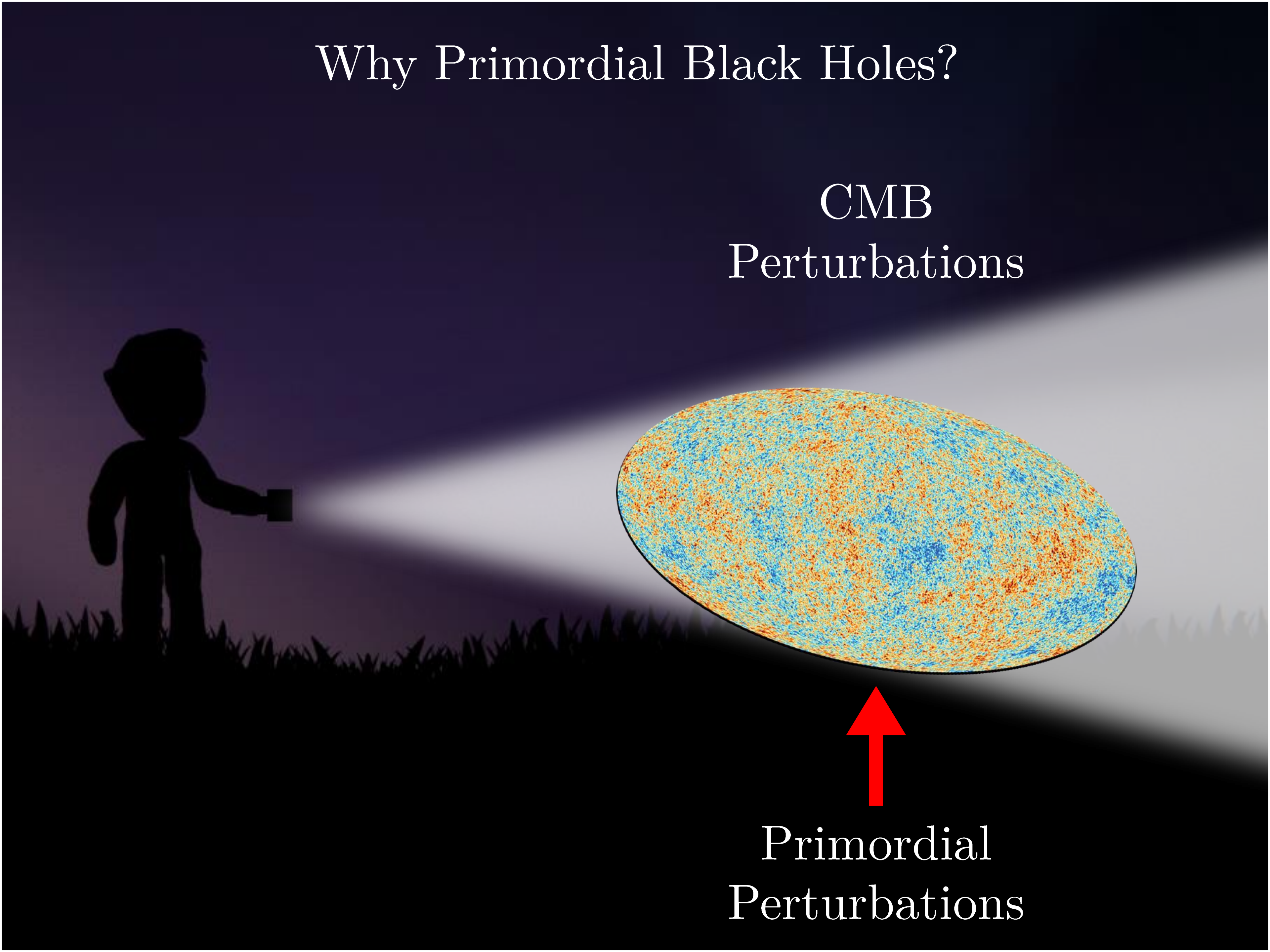
Based on:

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

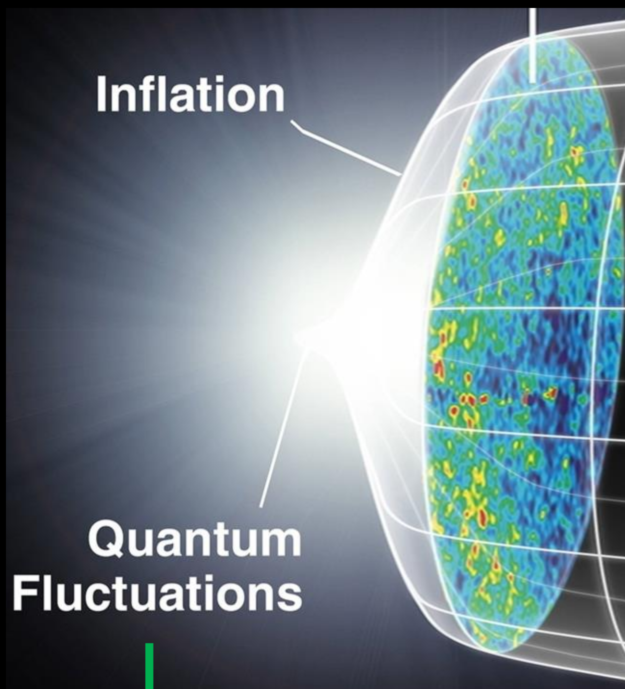
[January 2022 PRD Editors' Suggestion]

A. Cheek, L.H., Y. F. Perez-Gonzalez, and J. Turner, [2206.XXXX]

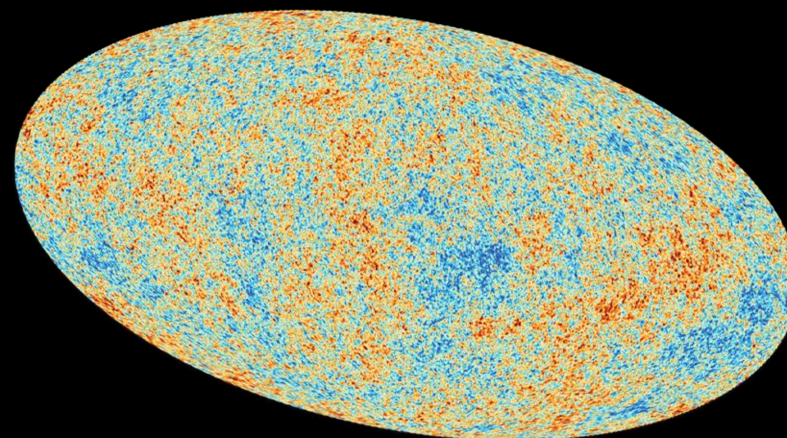
DMUK, Birmingham, May 2022


Why Primordial Black Holes?
CMB
Perturbations
Primordial
Perturbations

Why Primordial Black Holes?

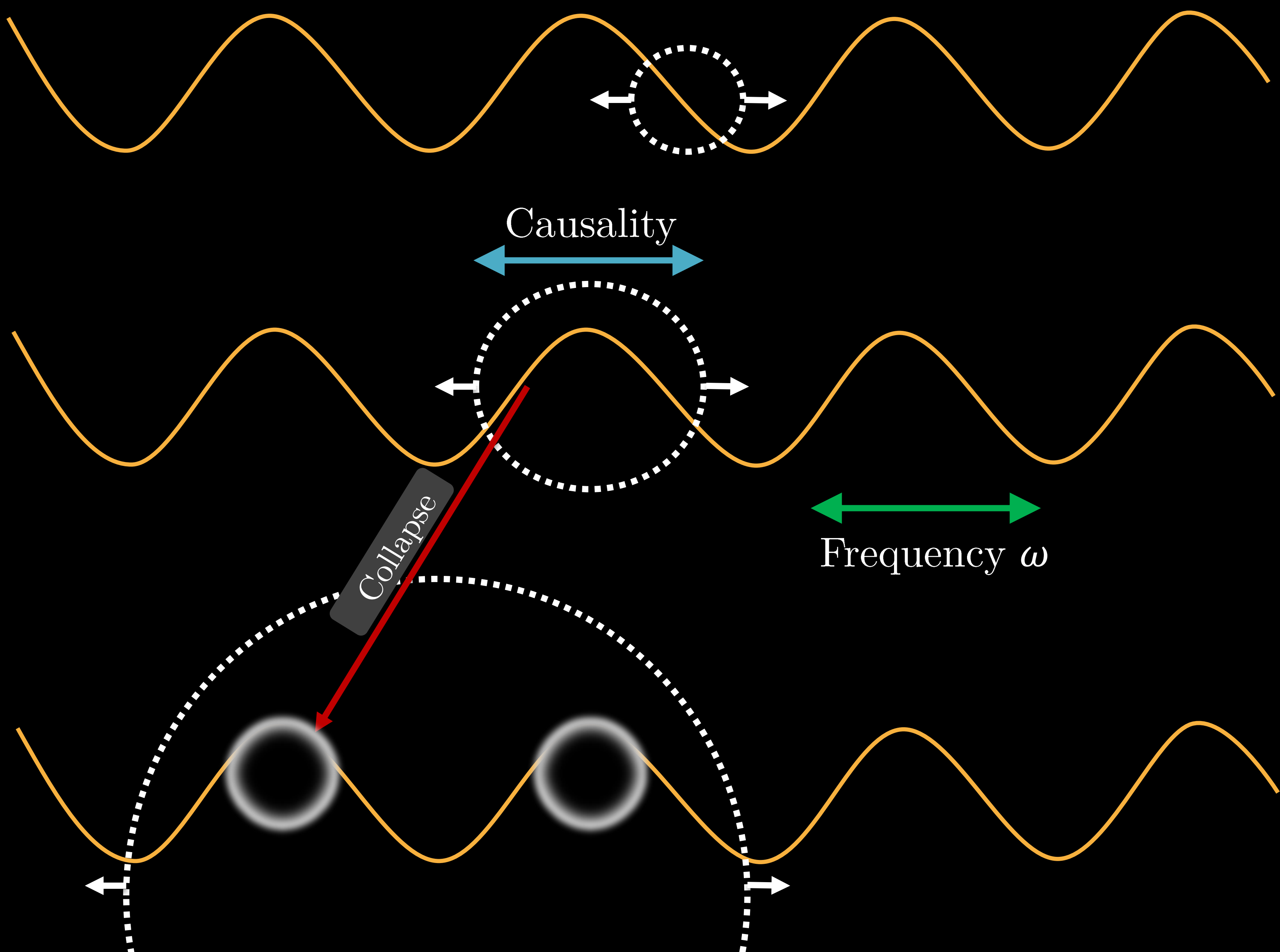


CMB
Perturbations



Primordial
Perturbations

Why Primordial Black Holes?



Why Primordial Black Holes?

PRODUCTION MECHANISM

Inflation, Bubble collapse, ...

↓

POWER SPECTRUM

$P(\omega)$

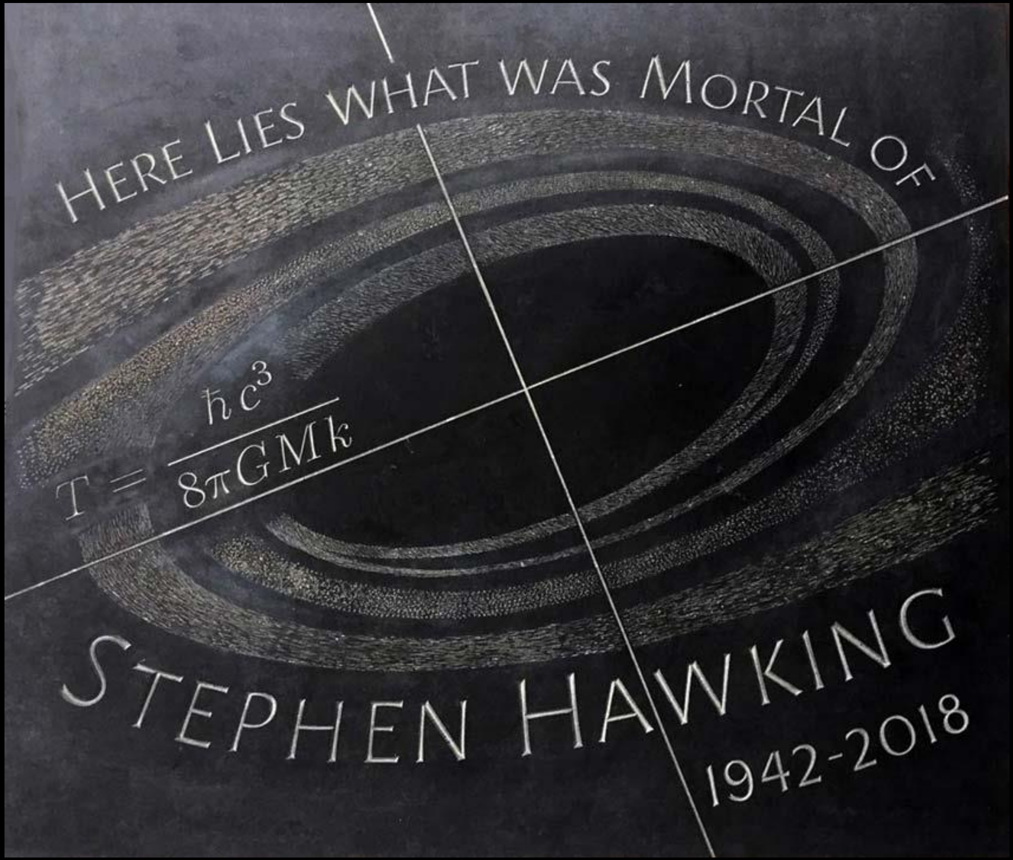
↓

PRIMORDIAL BLACK HOLE DISTRIBUTION

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

Black Holes Evaporate...

S. Hawking, 1975



Why Primordial Black Holes?

Primordial Black Hole Distribution

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

- Some may be stable and participate to the DM relic abundance ($M_{\rm PBH} \gtrsim 10^{15}\,{\rm g}$)
- Some may be unstable and evaporate after BBN ($10^{15}\,{\rm g} \lesssim M_{\rm PBH} \lesssim 10^{9}\,{\rm g}$)
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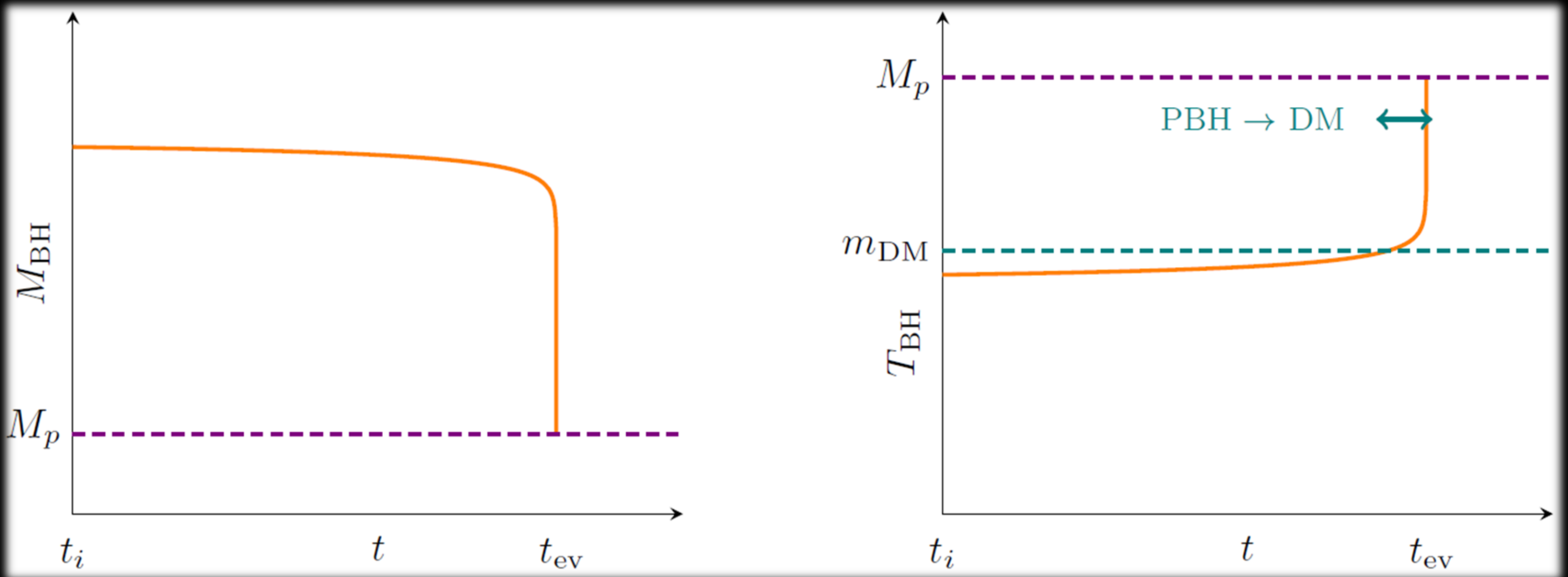
Can (Seriously) affect the production of DM...

PBH evaporation

- PBH can produce DM particles

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



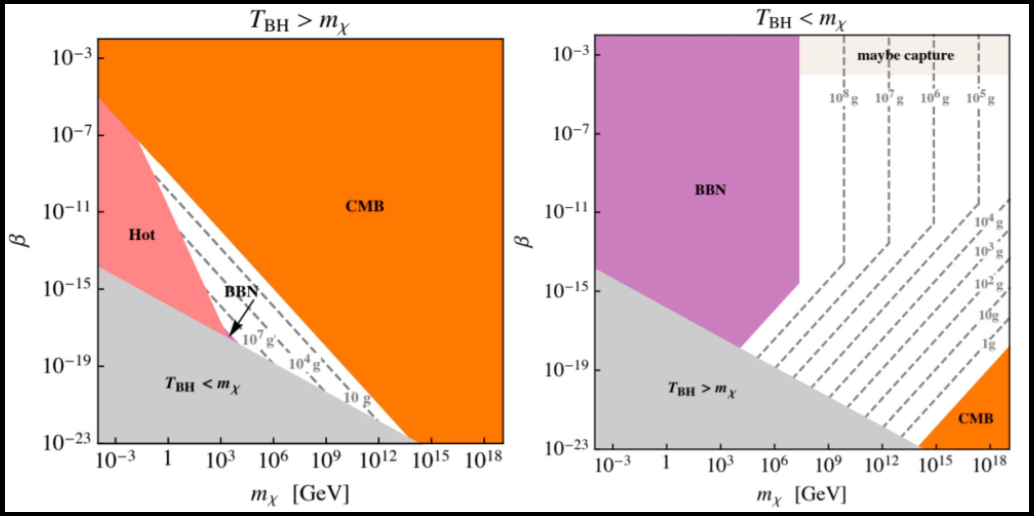
→ Contribution to the relic density…

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

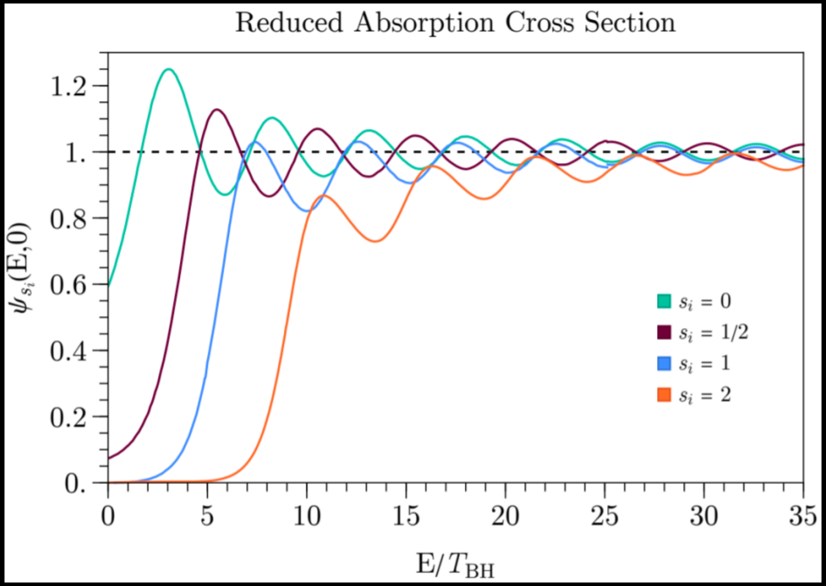
$$G M_{\rm BH} p \gg 1$$
$$\sigma_{s_i}(E,\mu)|_{\rm GO} = 27\pi G^2 M_{\rm BH}^2$$



[Gondolo, Sandick and Shams Es Haghi ‘20]

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

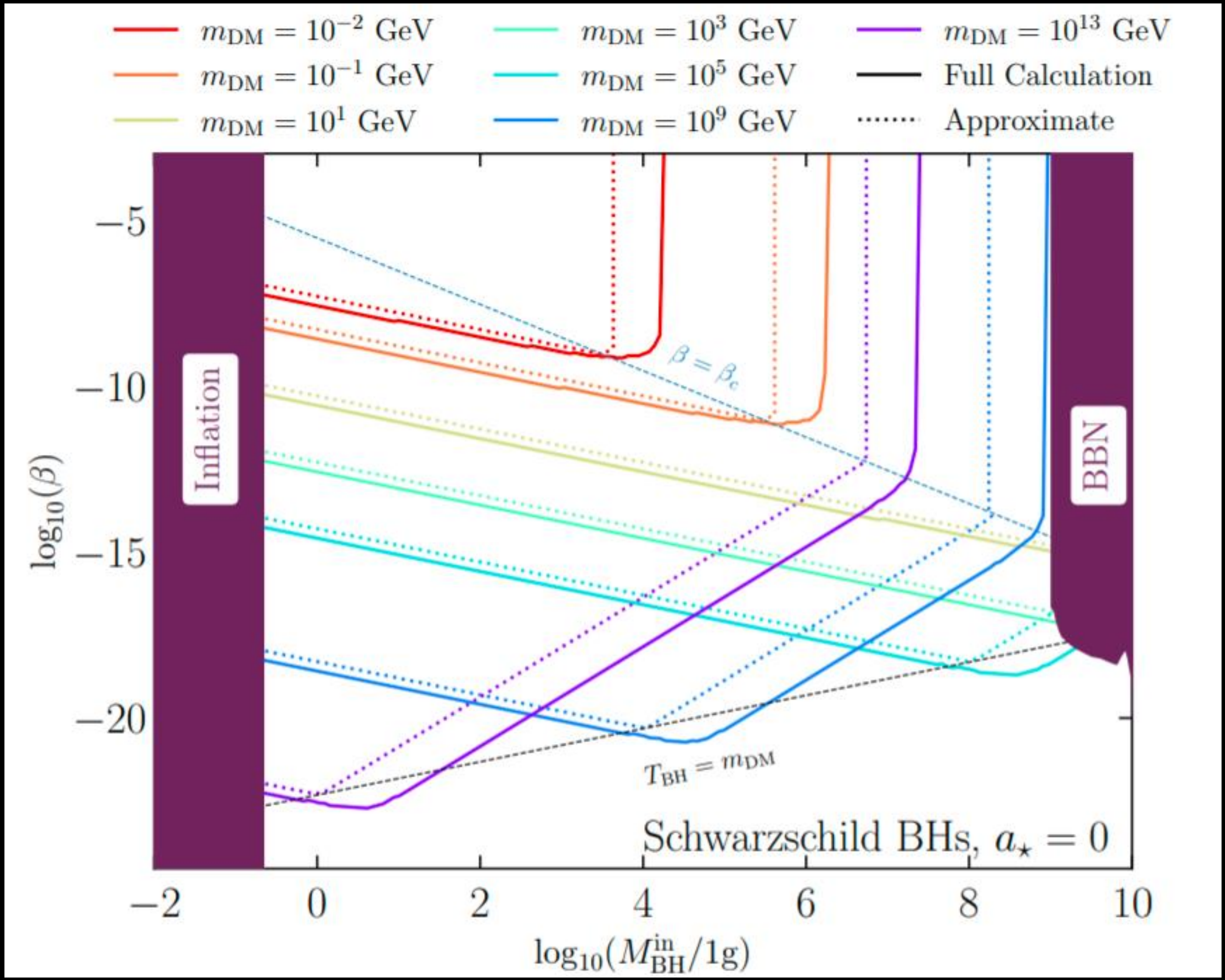
$$\psi_{s_i}(E,\mu) \equiv \frac{\sigma_{s_i}(E,\mu)}{27\pi G^2 M_{\rm BH}^2}$$



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

DM from Evaporation

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



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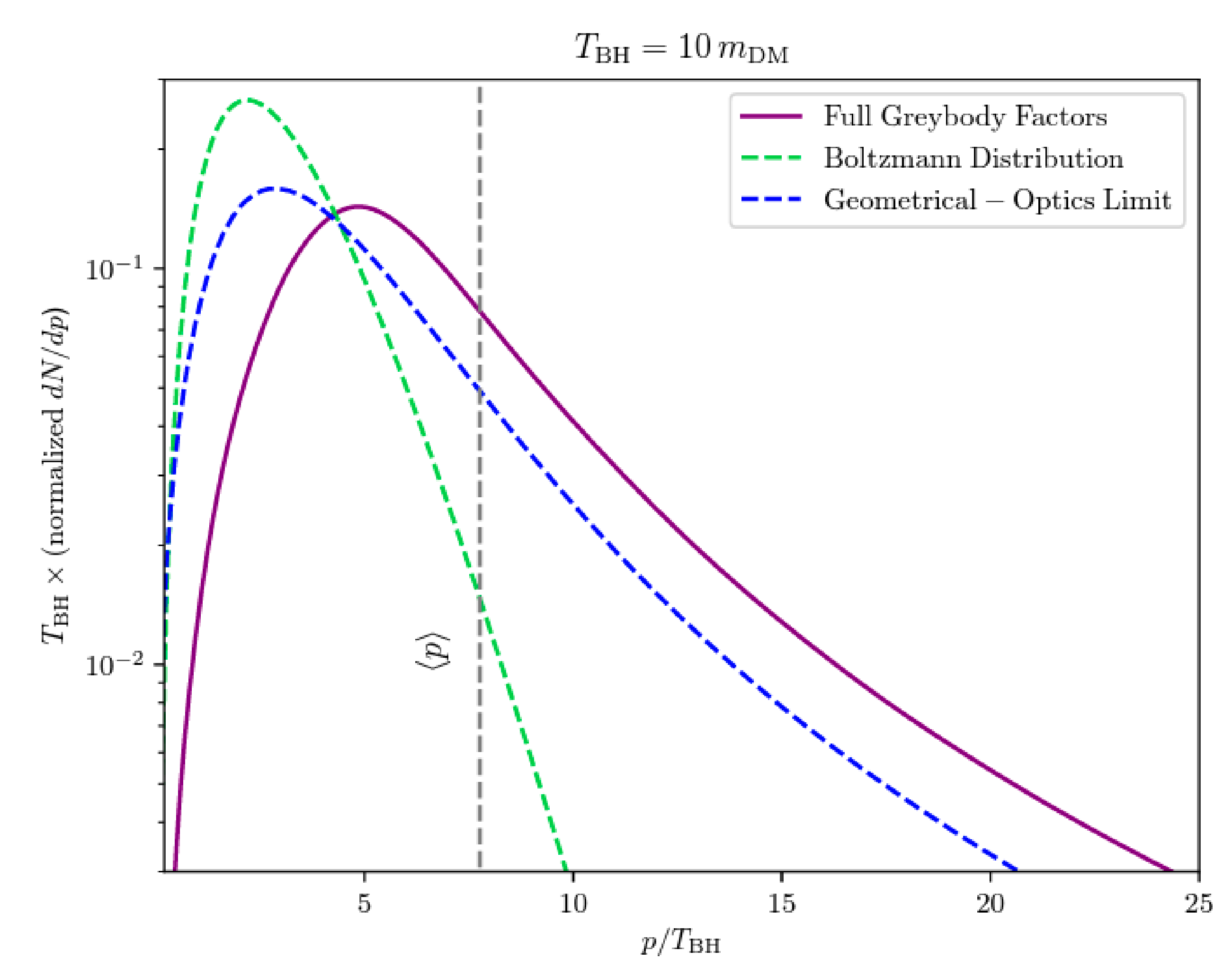

[Cheek, LH, Perez-Gonzalez and Turner '22]

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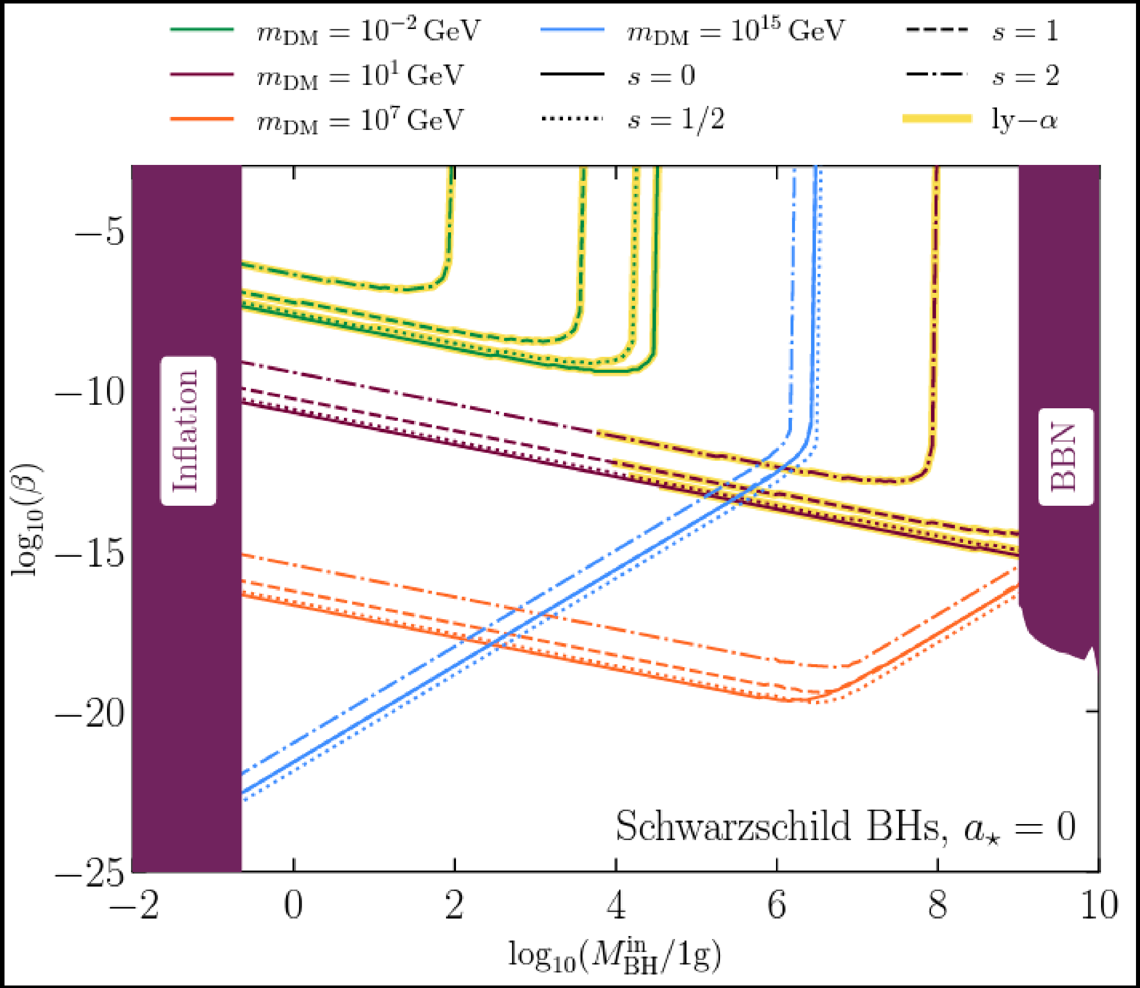
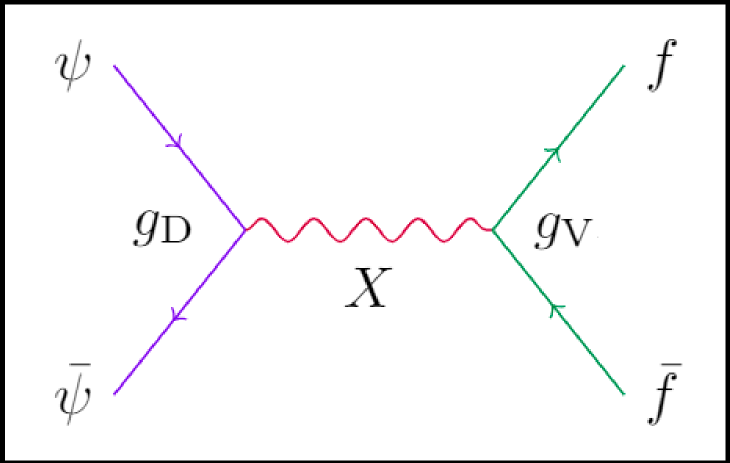


[Cheek, LH, Perez-Gonzalez and Turner '22]

Thermal Production of DM

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

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



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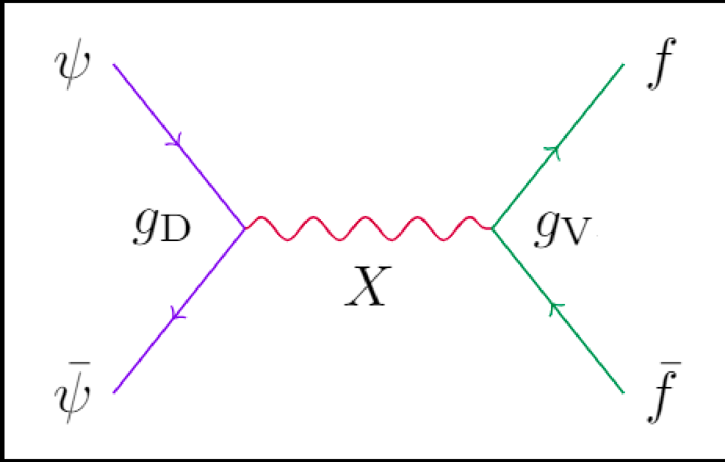

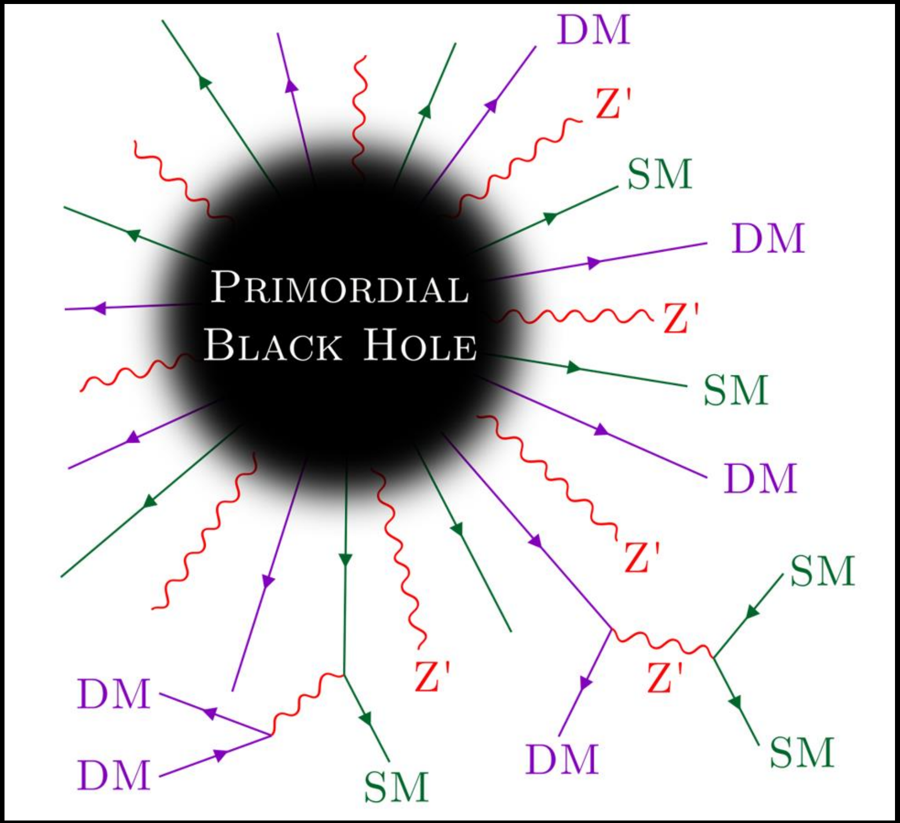

Effects of PBH Evaporation

1. PBHs produce additional DM particles

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

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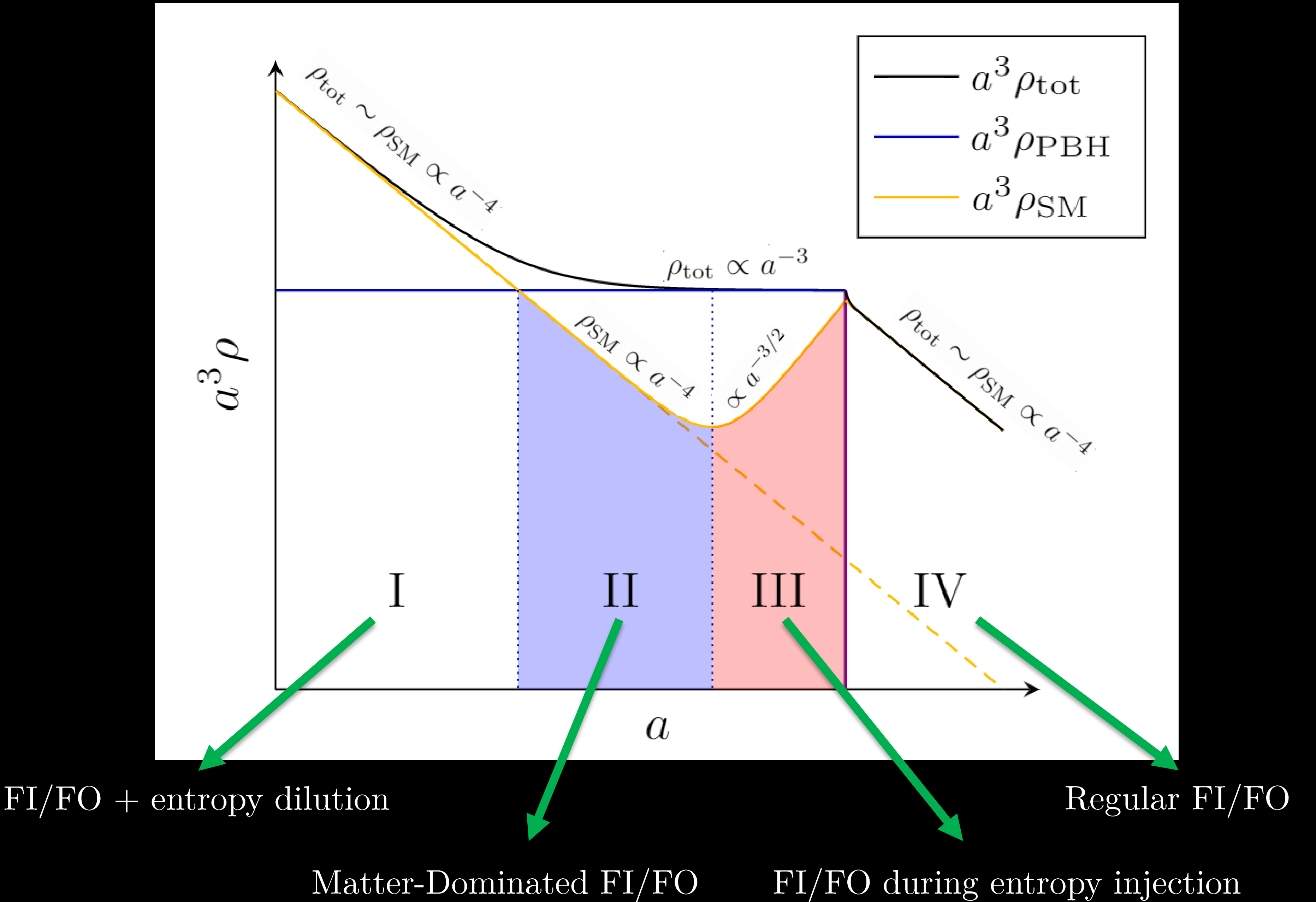
2. PBHs produce mediator particles X

3. The evaporation of PBHs can modify the cosmological background *after* the thermal production of DM

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

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

Modified Cosmology



Analytical Results

Freeze-In contribution

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

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

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

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

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:

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

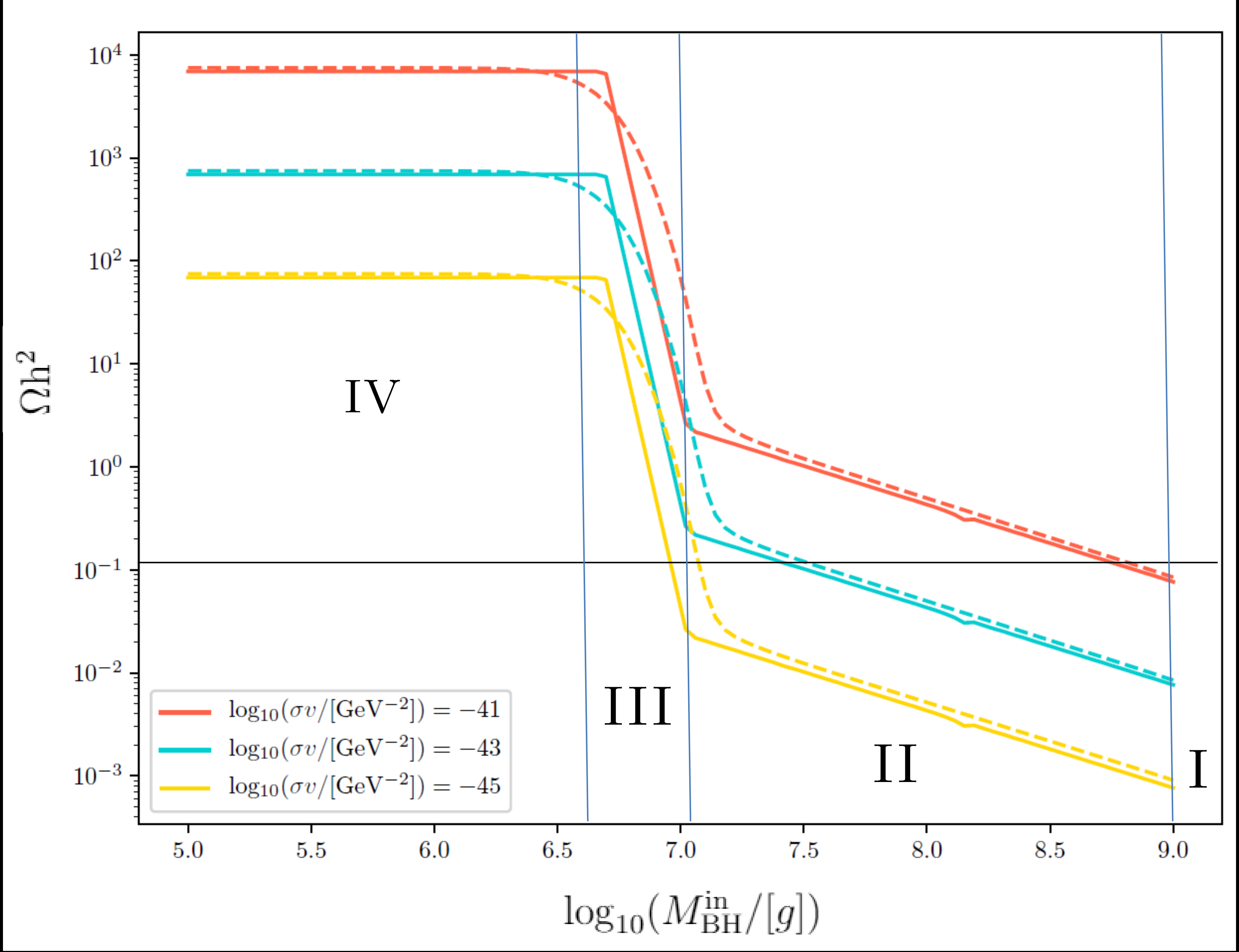
$$\Omega_{\rm I} = \frac{15}{2\pi} \frac{x_{\rm FO}}{\sqrt{10 g_\star(T_{\rm FO})}} \frac{s_{\rm eq}}{m_p \langle\sigma v\rangle \rho_c} \left(\frac{a_{\rm eq}}{a_0}\right)^3,$$

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

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

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

Results



Ωh^2
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
IV
III
II
I
$\log_{10}(\sigma v/[\mathrm{GeV}^{-2}]) = -41$
$\log_{10}(\sigma v/[\mathrm{GeV}^{-2}]) = -43$
$\log_{10}(\sigma v/[\mathrm{GeV}^{-2}]) = -45$
5.0
5.5
6.0
6.5
7.0
7.5
8.0
8.5
9.0
$\log_{10}(M_{\mathrm{BH}}^{\mathrm{in}}/[g])$

Results

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

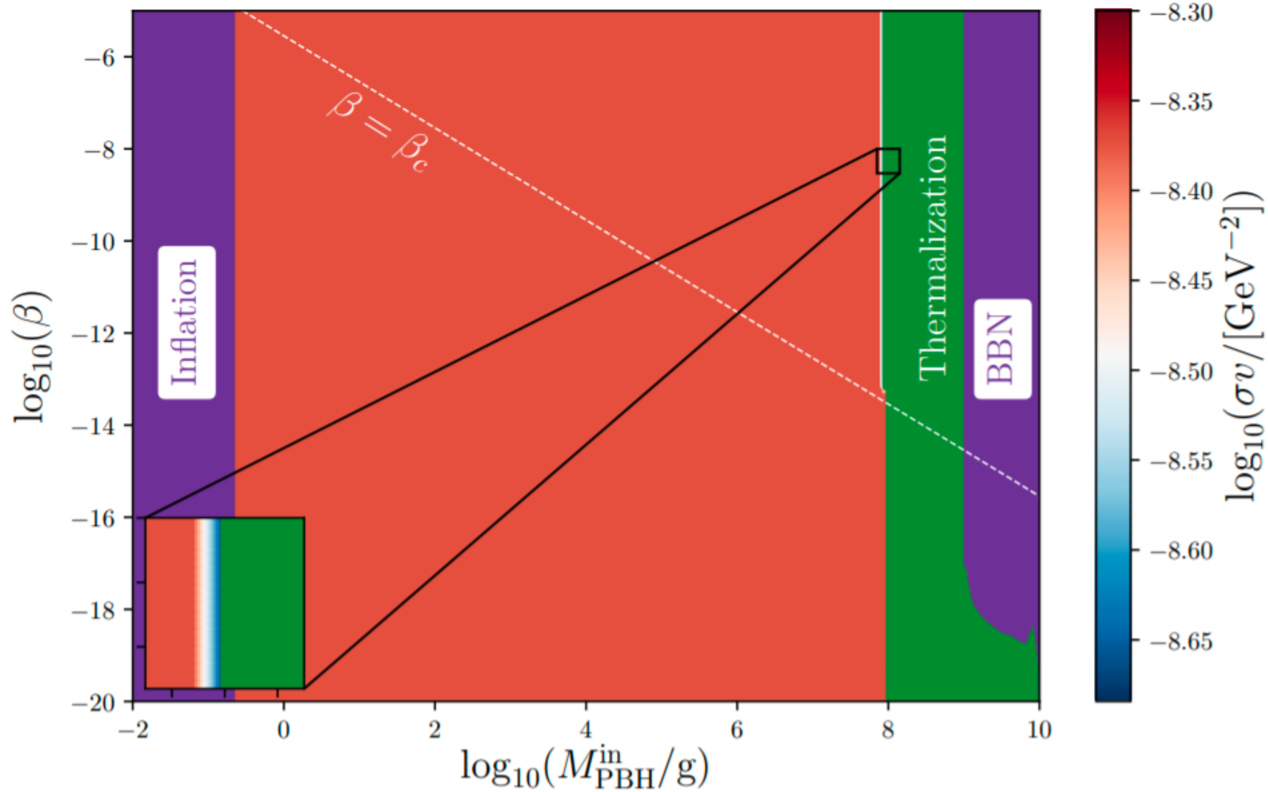


Fig. 7. Two-dimensional scan over the PBH fraction β and mass $M_{\rm BH}$ for a mediator mass $m_X = 10\,{\rm GeV}$ and a dark matter mass $m_{\rm DM} = 1\,{\rm GeV}$, and ${\rm Br}(X \to {\rm DM}) = 0.5$. The color map indicates the value of the non-relativistic cross-section of DM annihilation leading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

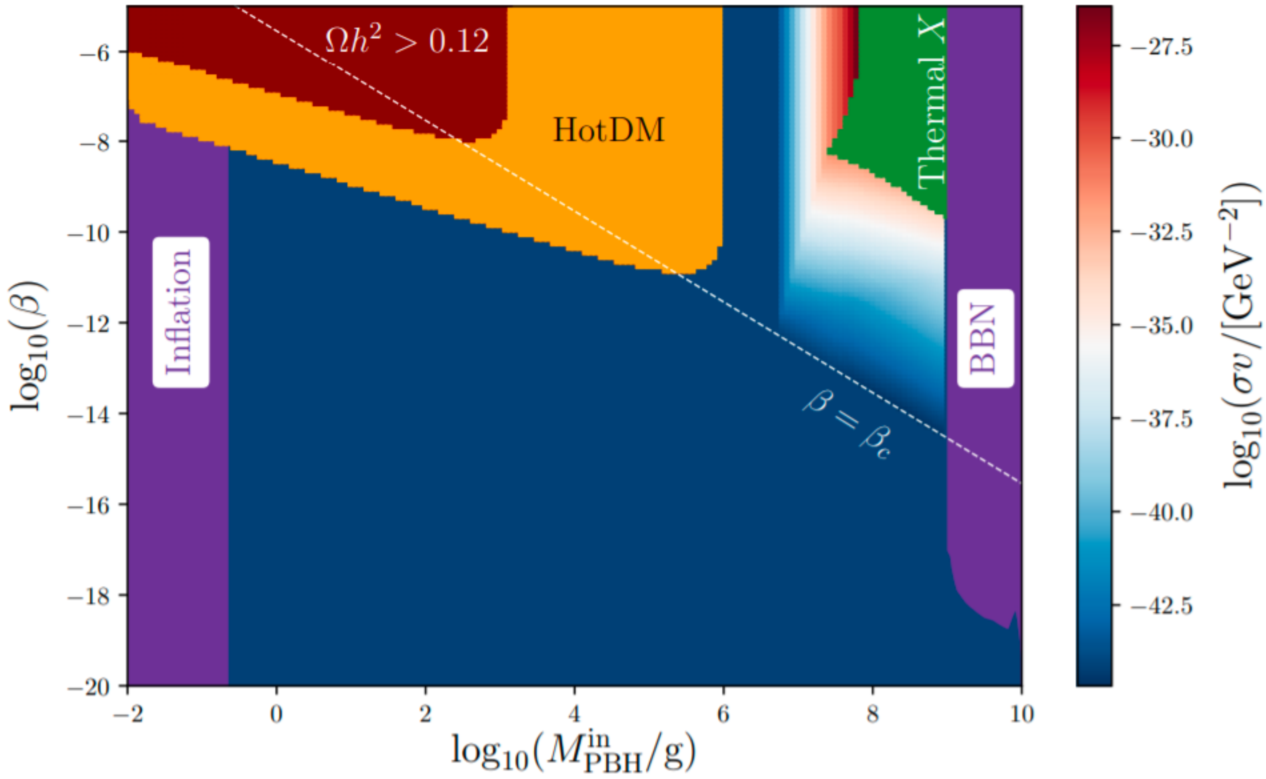


Fig. 11. Two-dimensional scan over the PBH fraction β and mass $M_{\rm BH}$ for a mediator mass $m_X = 1\,{\rm TeV}$, a dark matter mass $m_{\rm DM} = 1\,{\rm MeV}$, and ${\rm Br}(X \to {\rm SM}) = 10^{-7}$. The color map indicates the value of the non-relativistic cross-section of DM annihilation leading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

Beyond the Monochromatic Approximation

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

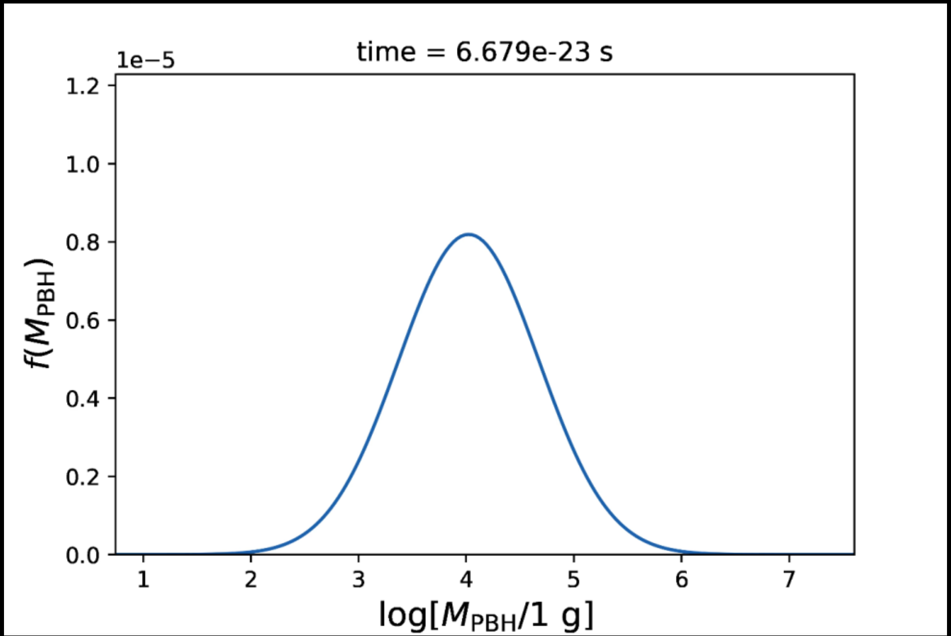
$$f_{\mathrm{PBH}}(M) = \delta(M - M_{\mathrm{PBH}})$$

$\downarrow$

Arbitrary $f_{\mathrm{PBH}}(M)$

Beyond the Monochromatic Approximation

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



Log-normal distribution

Dolgov, 93
Green, 2016
Kannike, 2017

Beyond the Monochromatic Approximation

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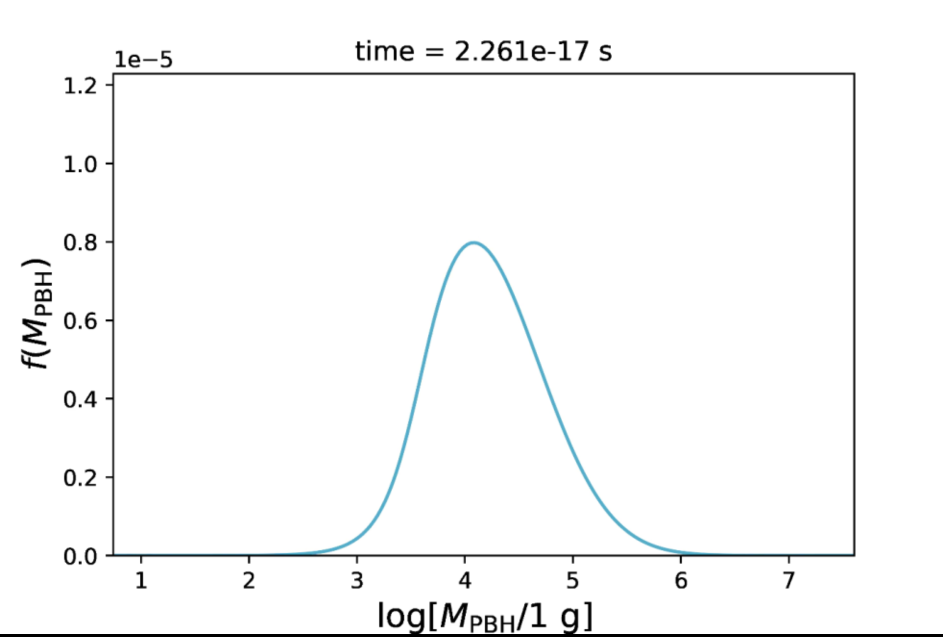

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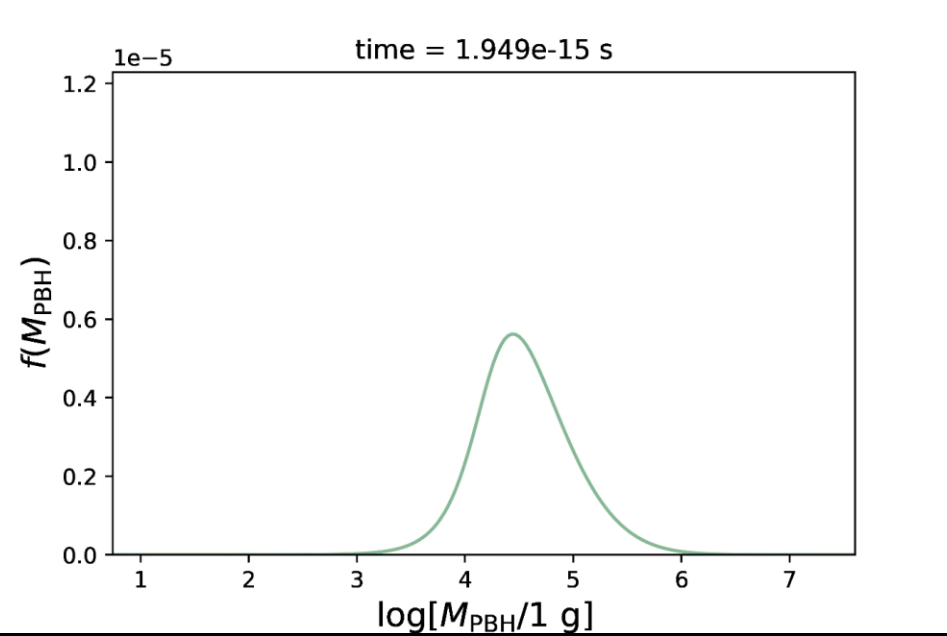

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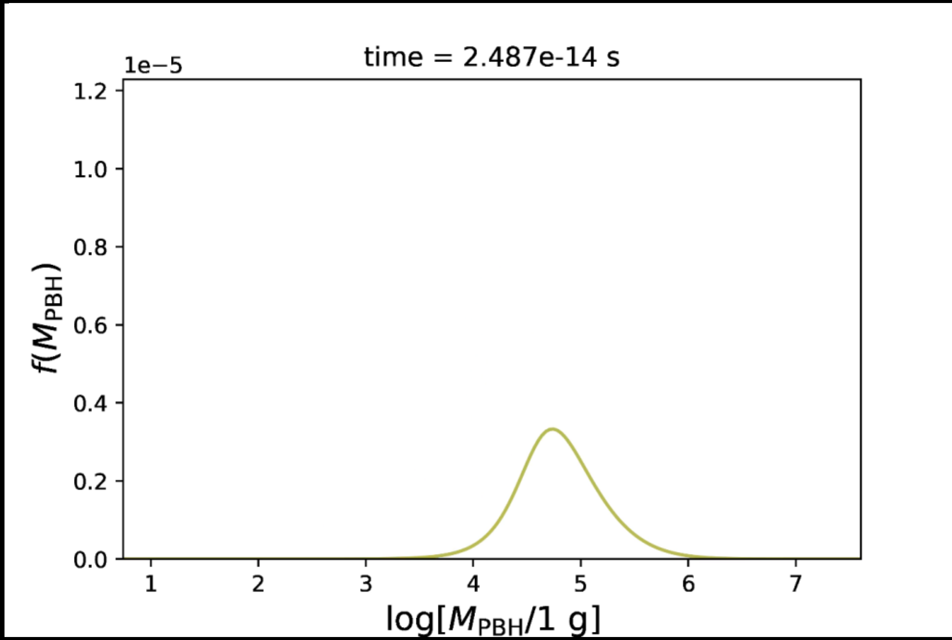

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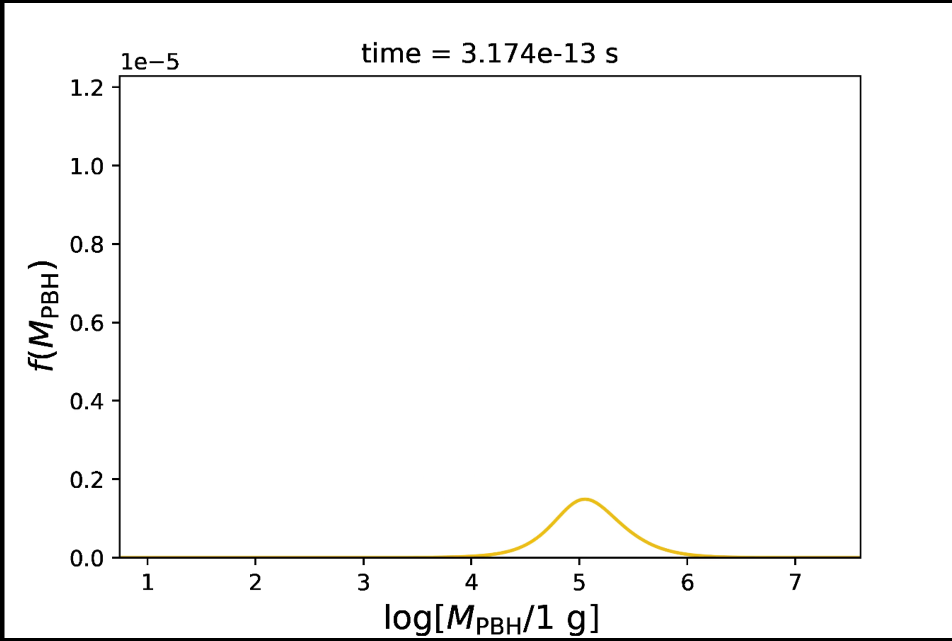

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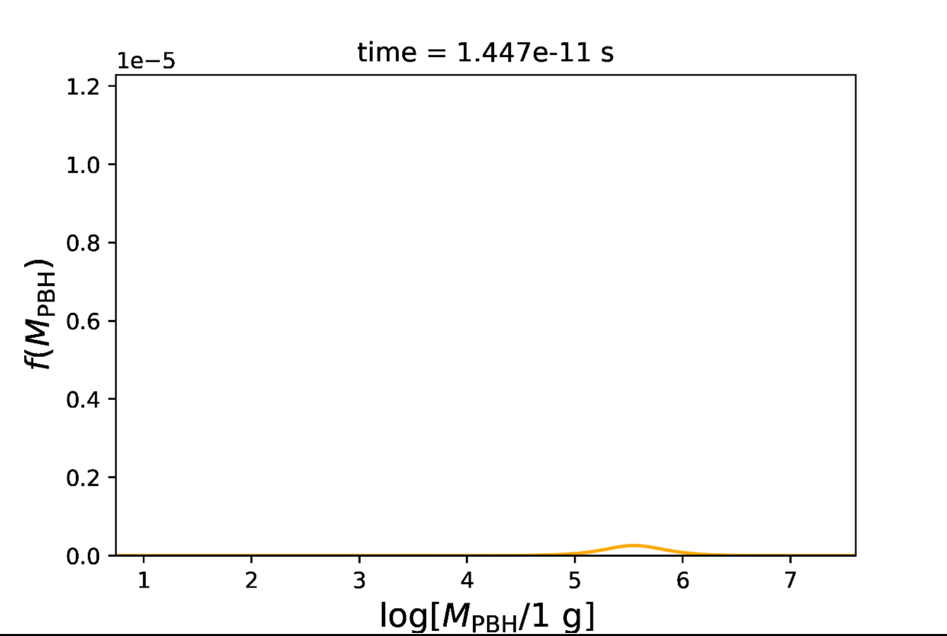

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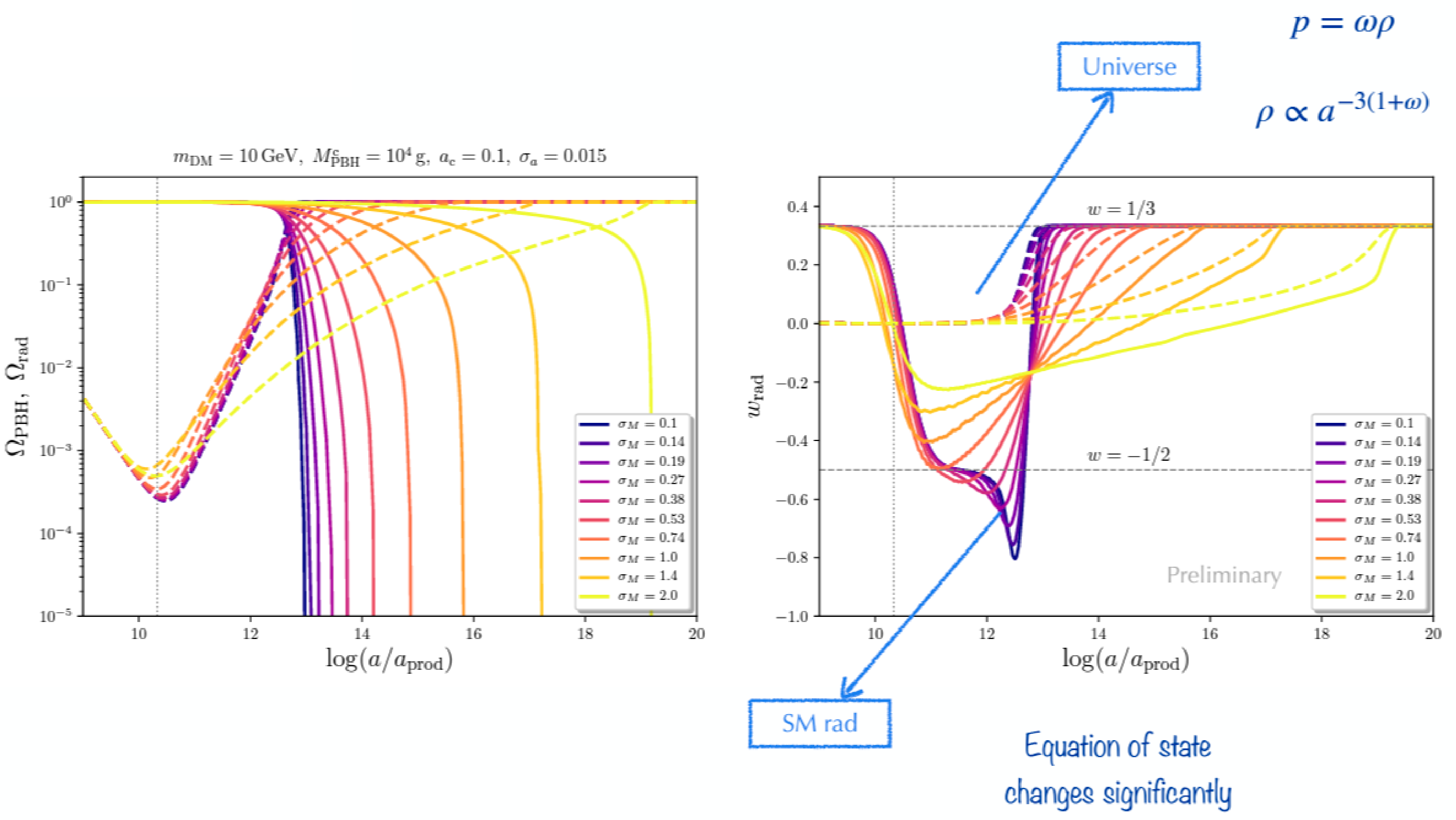


Conclusion

PBHs not only produce DM particles but also...

- Modify cosmology (EMD+ entropy inj.)
- Produce very boosted particles that can thermalize after evaporation
- The presence of a mediator can enhance the production of DM particles from evaporation
- The annihilation cross-section necessary to have the correct relic abundance can vary over orders of magnitude
- Our code is accessible online: https://github.com/earlyuniverse/ulysses

Back up

Boltzmann Equations

DM Annihilation, X decay — PBH evaporation

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

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

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

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

↓

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

Simplified approch...

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

Boltzmann Equations

- If PBHs evaporate **before FO**:
  → Assume Instantaneous thermalization

- If PBHs evaporate **after FO**:
  → Assume No thermalization

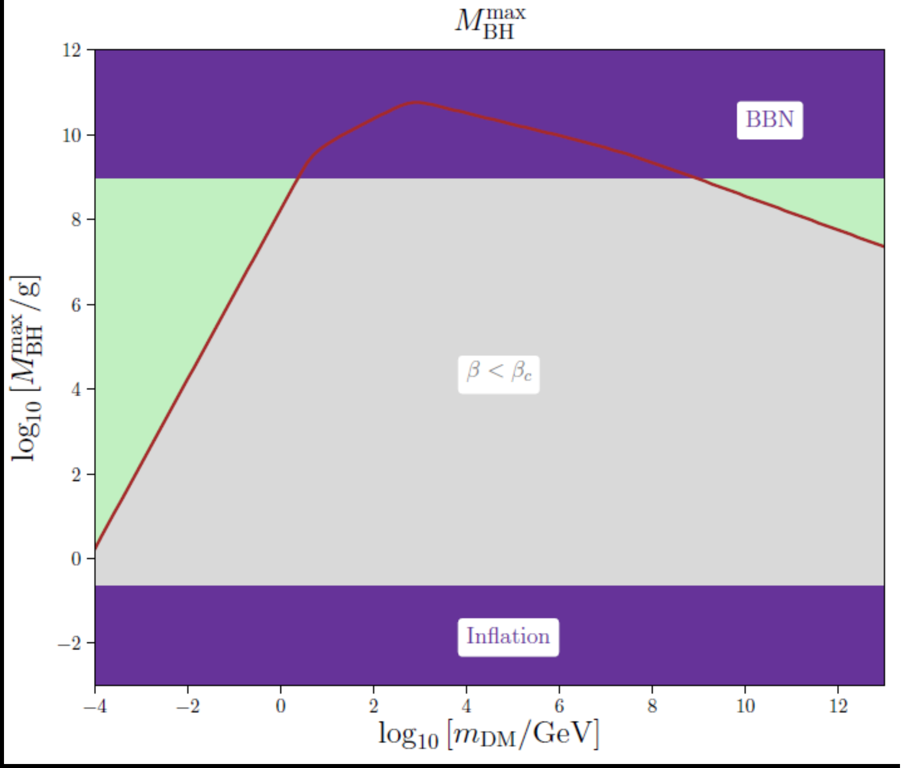
- **FI case**: assume No thermalization

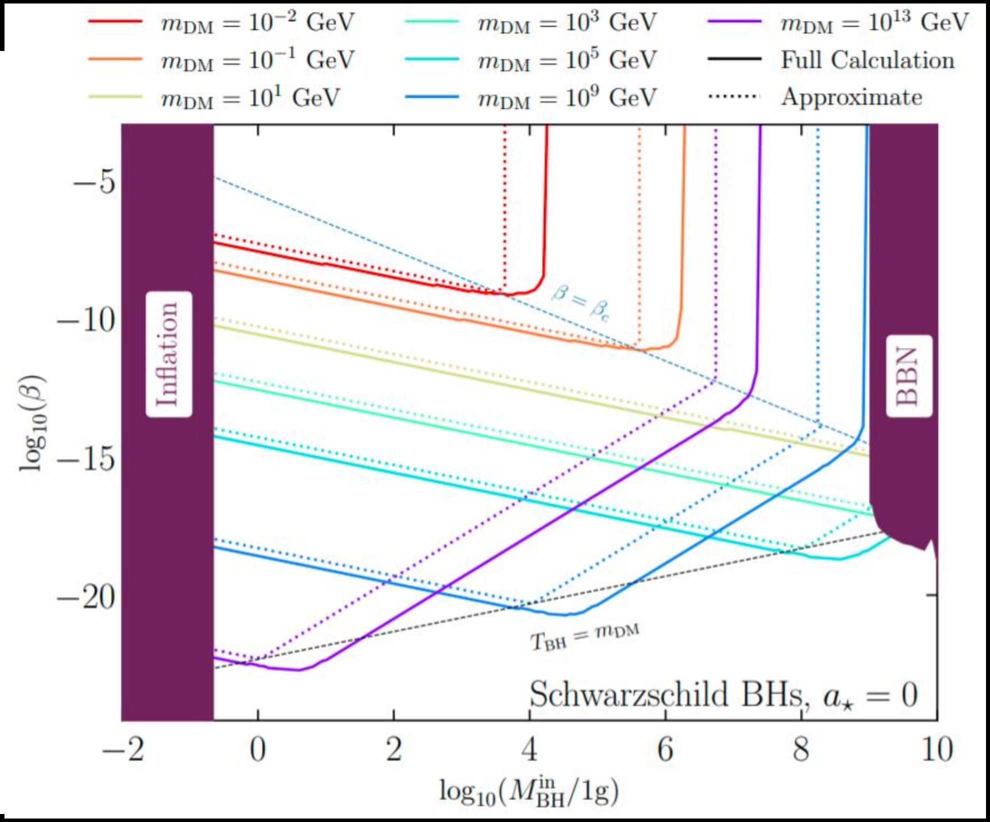
→ Check those assumptions by evaluating at all time

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

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

Modified Cosmology





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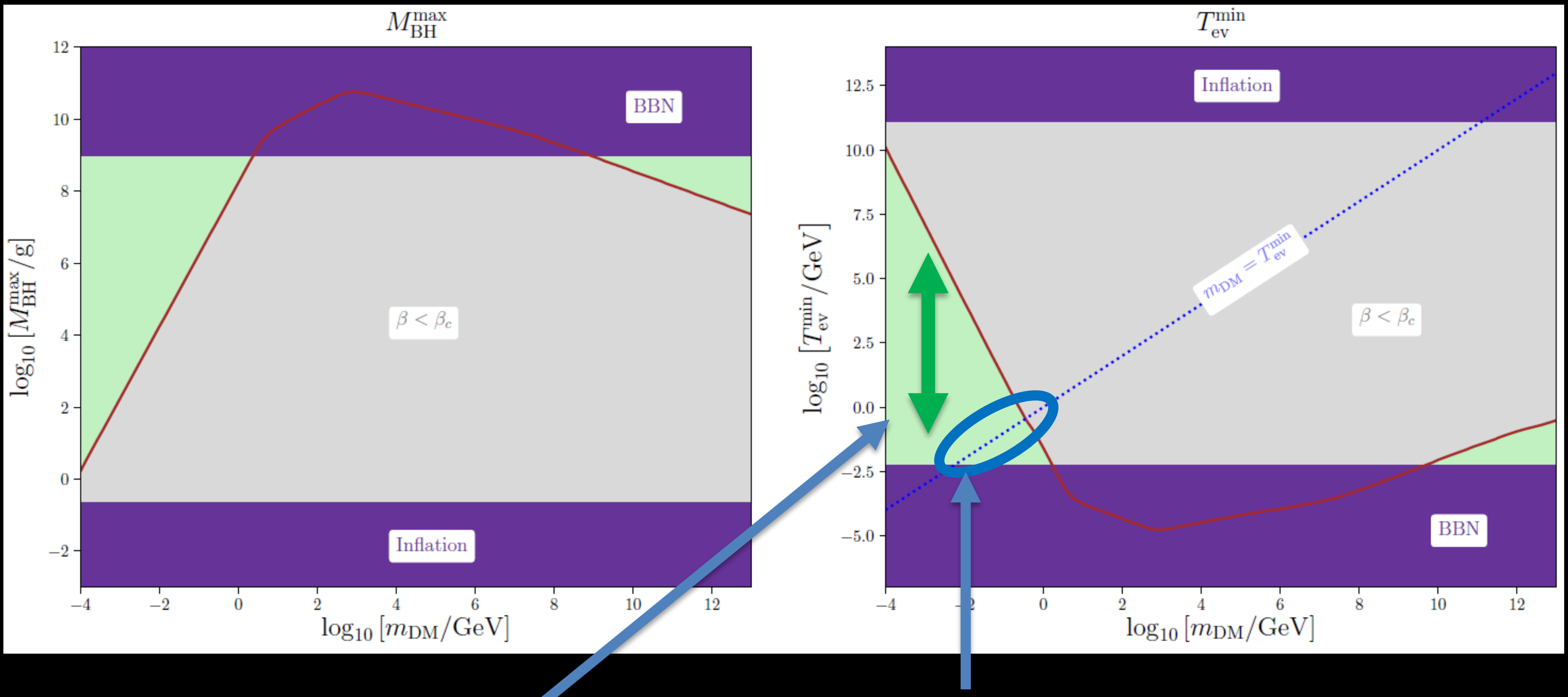
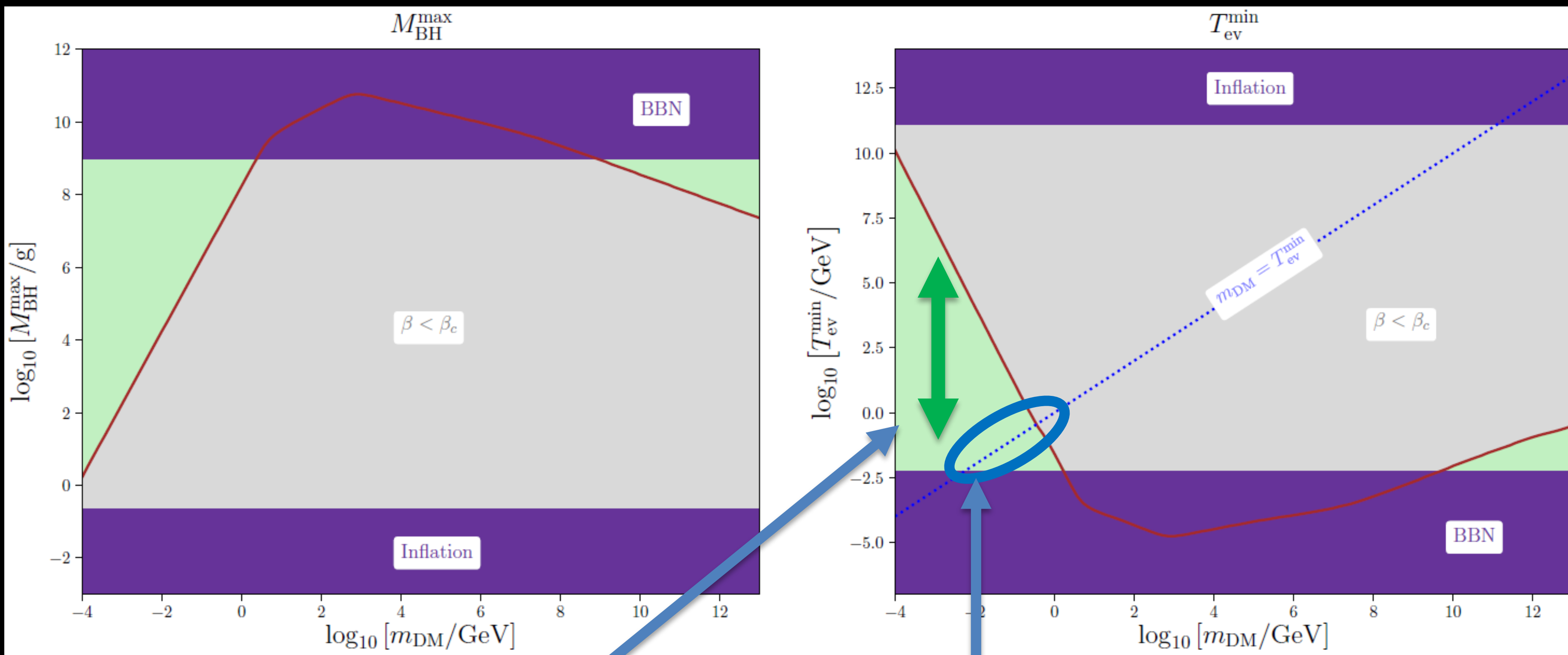


Region of interest
for Freeze-In

Region of interest
for Freeze-Out

Modified Cosmology

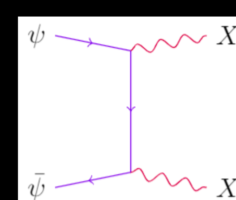


Region of interest
for Freeze-In

~~Region of interest
for Freeze-Out~~

**Thermalization
Of PBHs products…**

TBH large +



Boltzmann Equations

Freeze–In case:

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

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

$$\dot{n}_X + 3Hn_X = \left.\frac{{\rm d}n_X}{{\rm d}t}\right|_{\rm BH}$$

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

Boltzmann Equations

Freeze–In case:

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

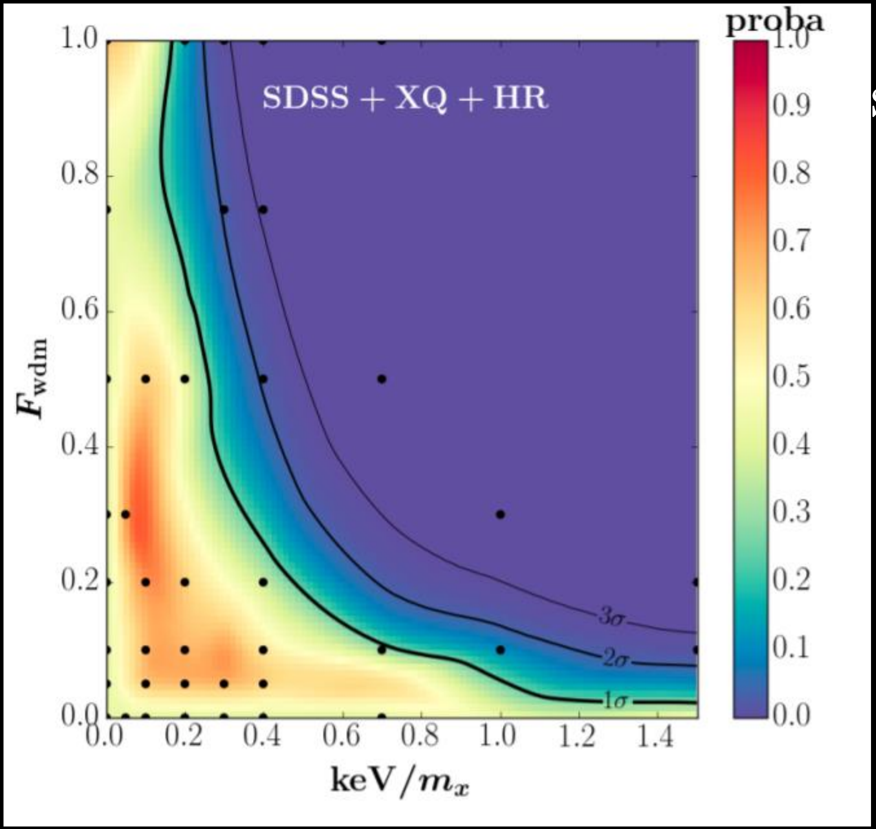
$$\dot{n}_{\rm DM}^{\rm ev} + 3Hn_{\rm DM}^{\rm ev} = \left.\frac{{\rm d}n_{\rm DM}^{\rm ev}}{{\rm d}t}\right|_{\rm BH} + 2\,\Gamma_{X\to{\rm DM}} \left\langle \frac{m_X}{E_X} \right\rangle_{\rm ev} n_X$$

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

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

Non-cold Dark Matter

s

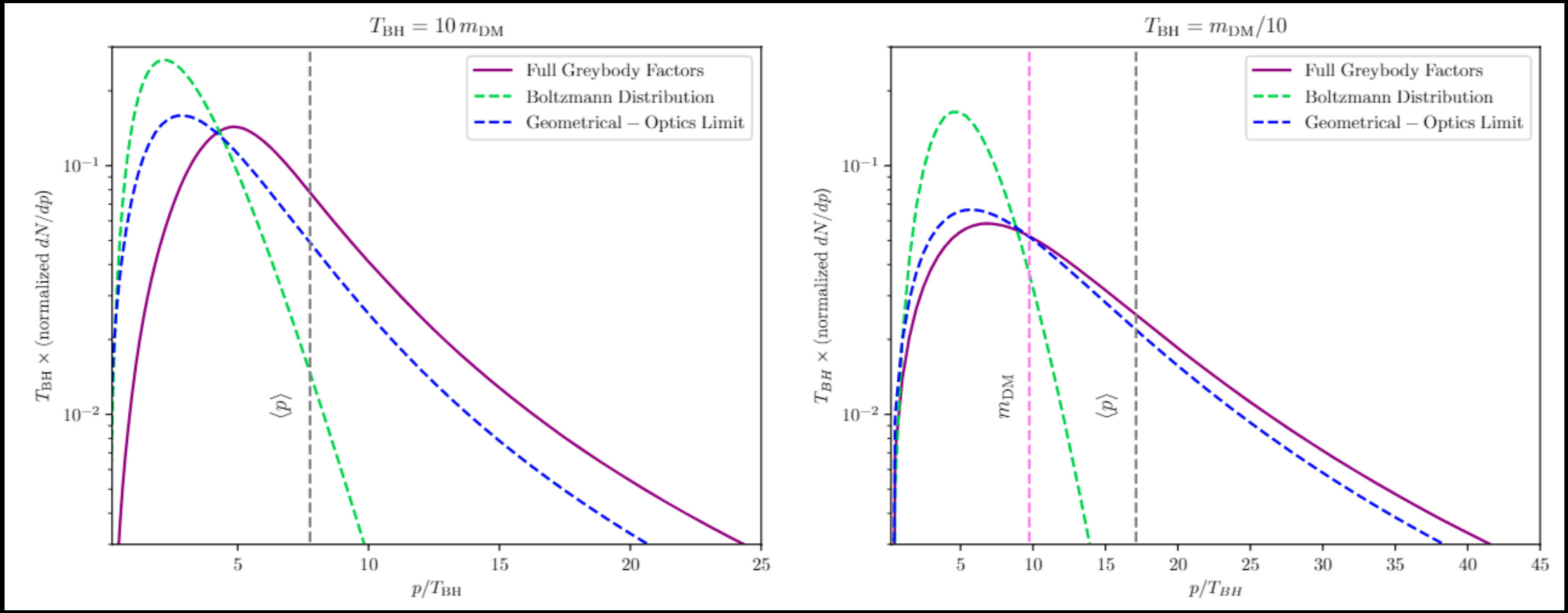


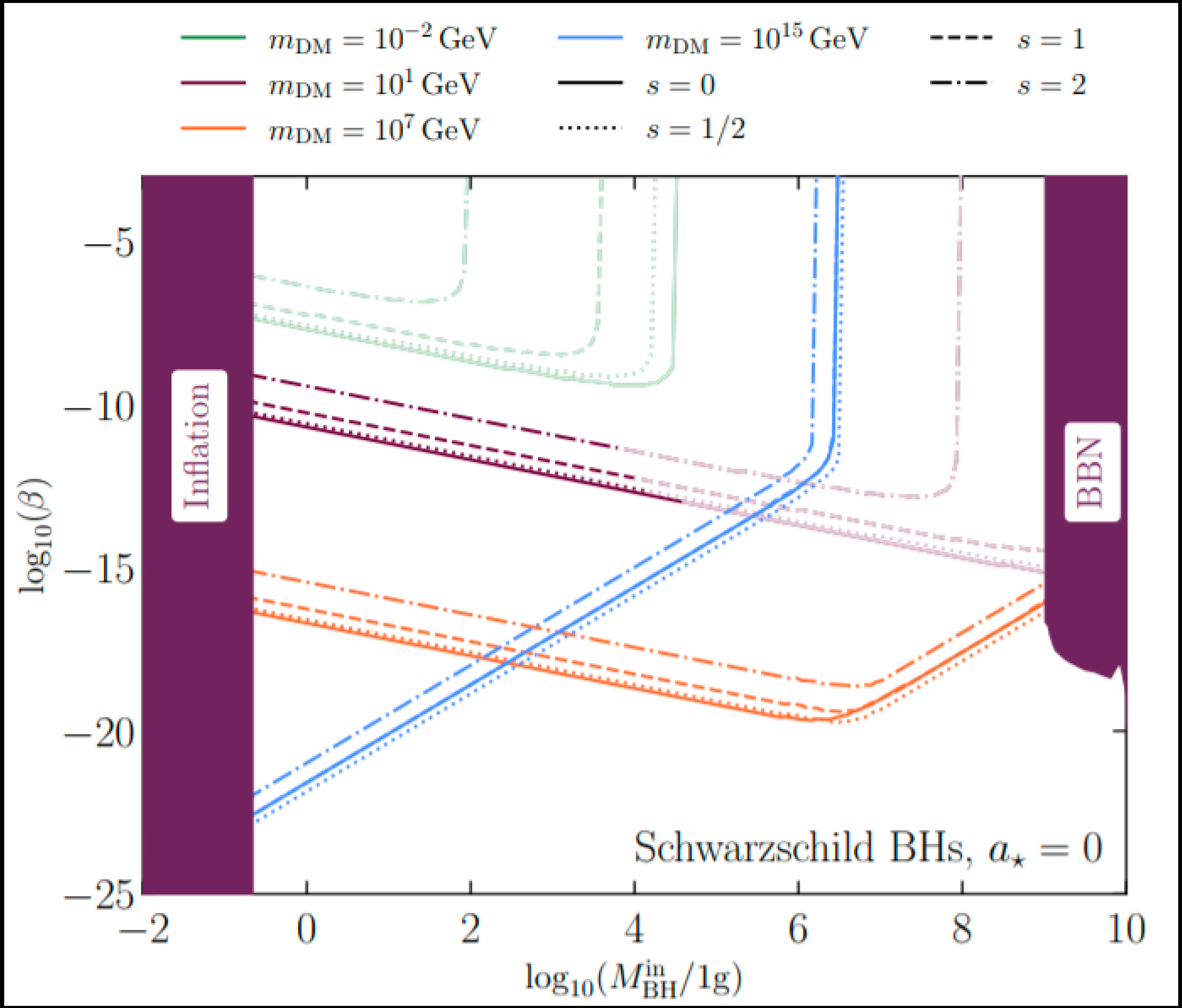
[Baur *et al.* 2017]

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

DM from Evaporation

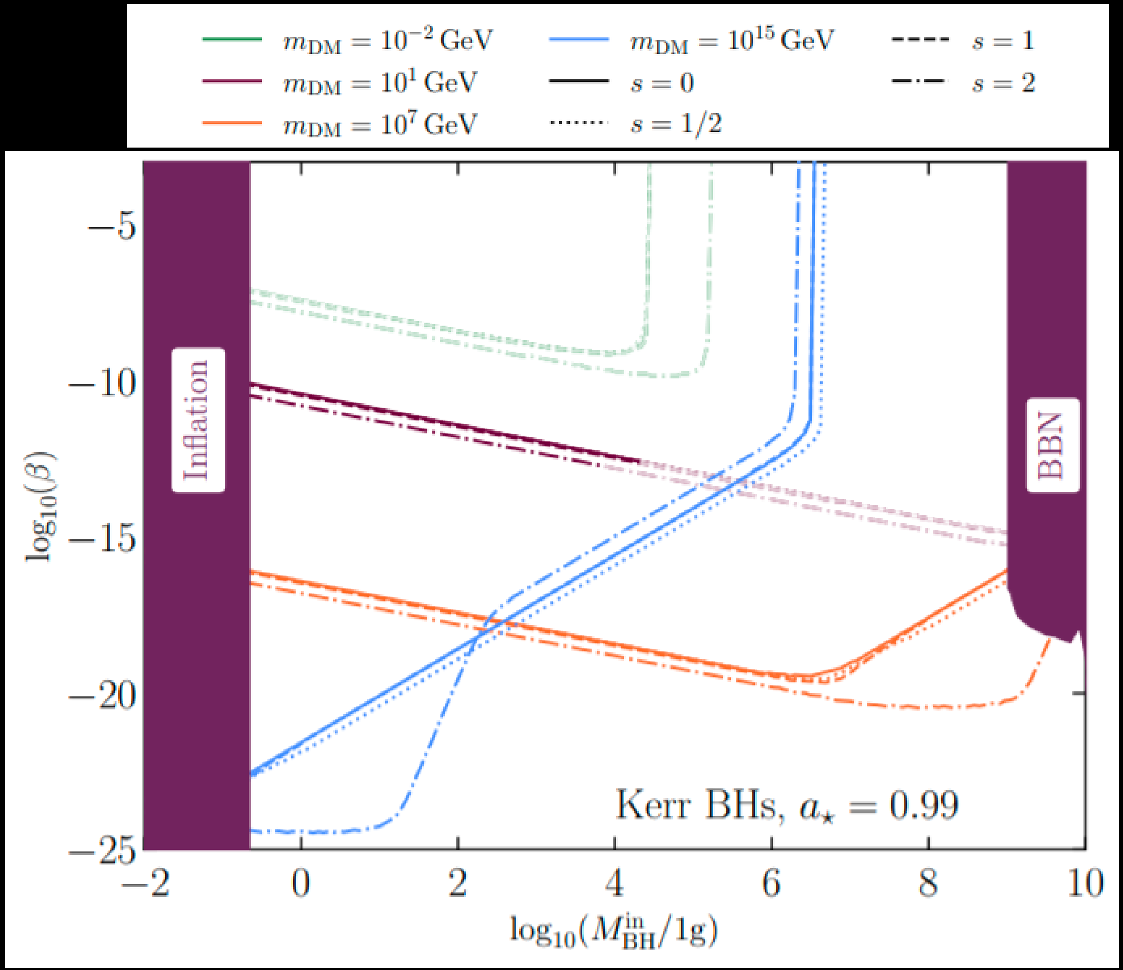
- Peculiar spectrum of evaporated DM particles
- Non-negligible difference between geometrical-optics limit and full distributions





$m_{\rm DM} = 10^{-2}$ 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 $\Omega = (a_\star/2GM_{\rm BH})(1/(1+\sqrt{1-a_\star^2}))$