Durham University

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IP3

Interplay Between
Dark Matter Freeze-In/Out Production
and
Primordial Black Hole Evaporation

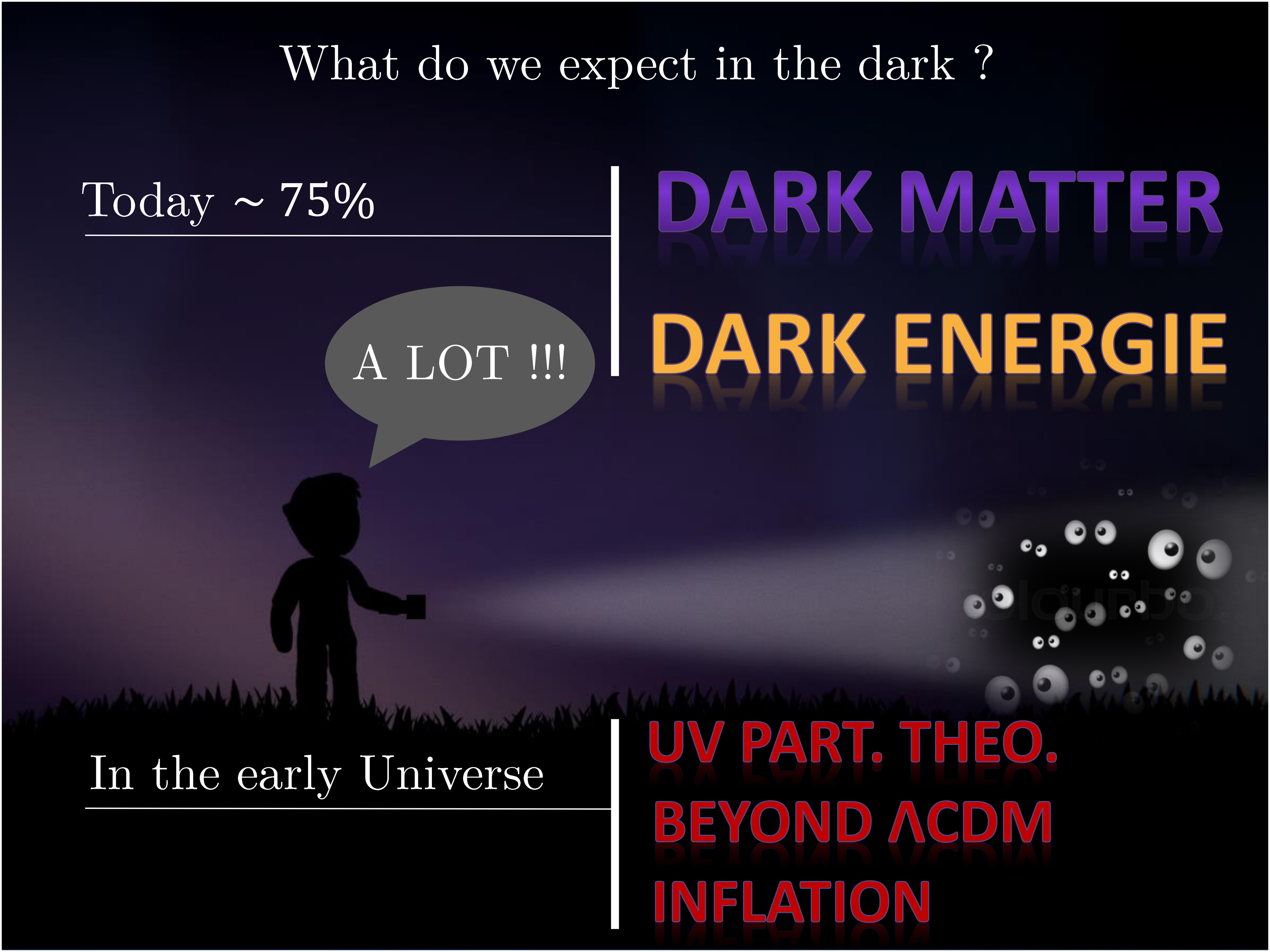
Based on:

Andrew Cheek, LH, Yuber F. Perez-Gonzalez and Jessica Turner

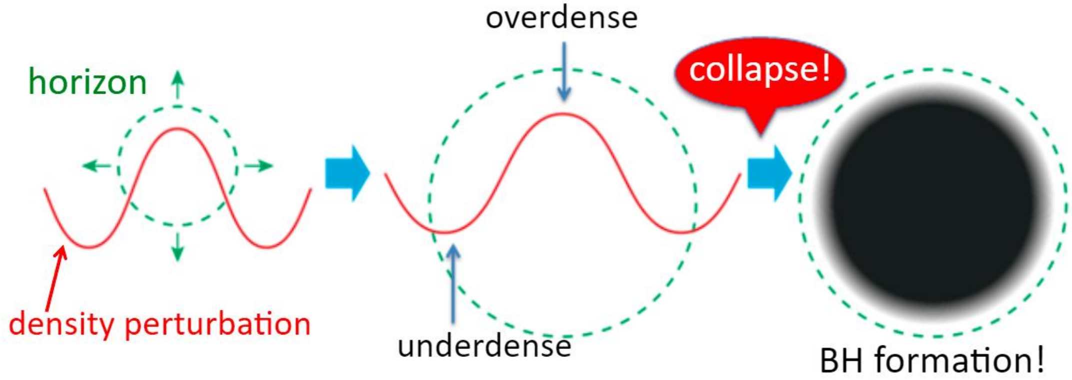
[arXiv:2107.00013], [arXiv:2107.00016]

IRN terascale, July 2021

What do we expect in the dark ?


What do we expect in the dark ?
Today ~ 75%
DARK MATTER
DARK ENERGIE
A LOT !!!
In the early Universe
UV PART. THEO.
BEYOND ΛCDM
INFLATION

Primordial Black Holes



[picture borrowed from N. Kitajima]

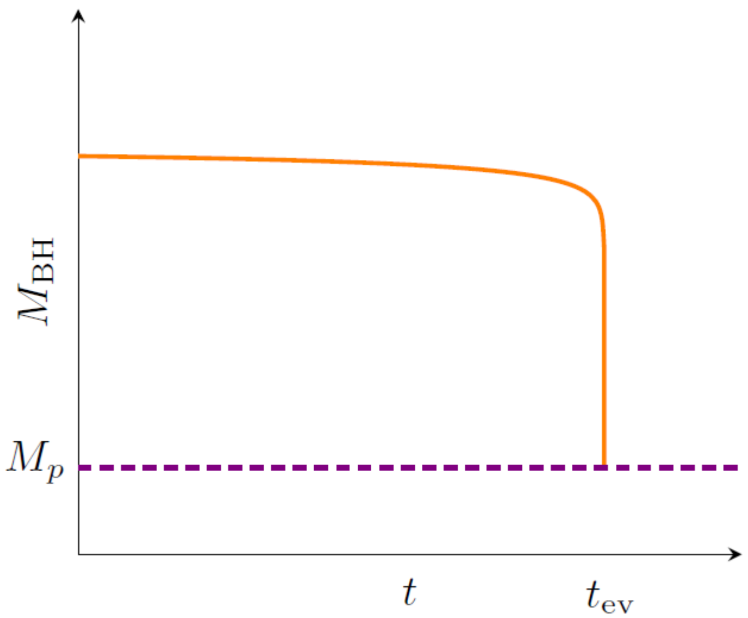
- May be stable and participate to the DM relic abundance ($M \gtrsim 10^{15}$ g)

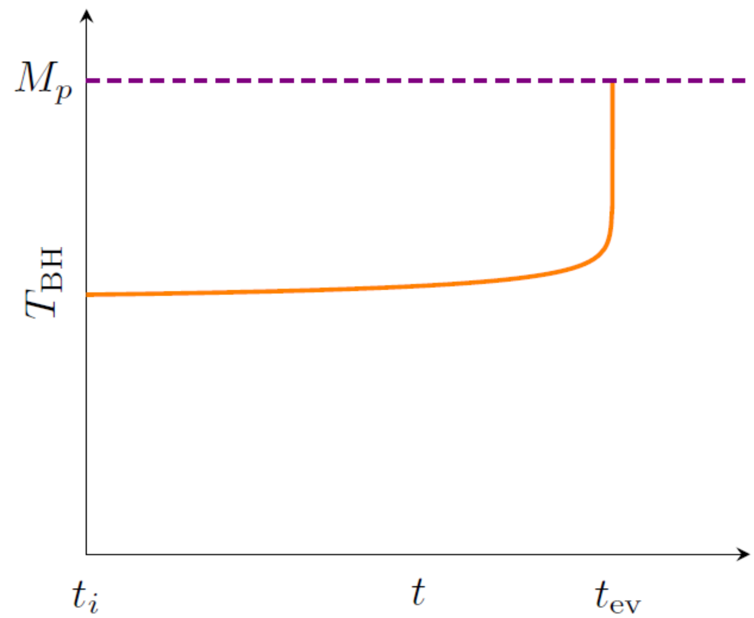
- May be unstable and evaporate before BBN ($M \lesssim 10^{9}$ g)

Primordial Black Holes

- Hawking Temperature:

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





Primordial Black Holes

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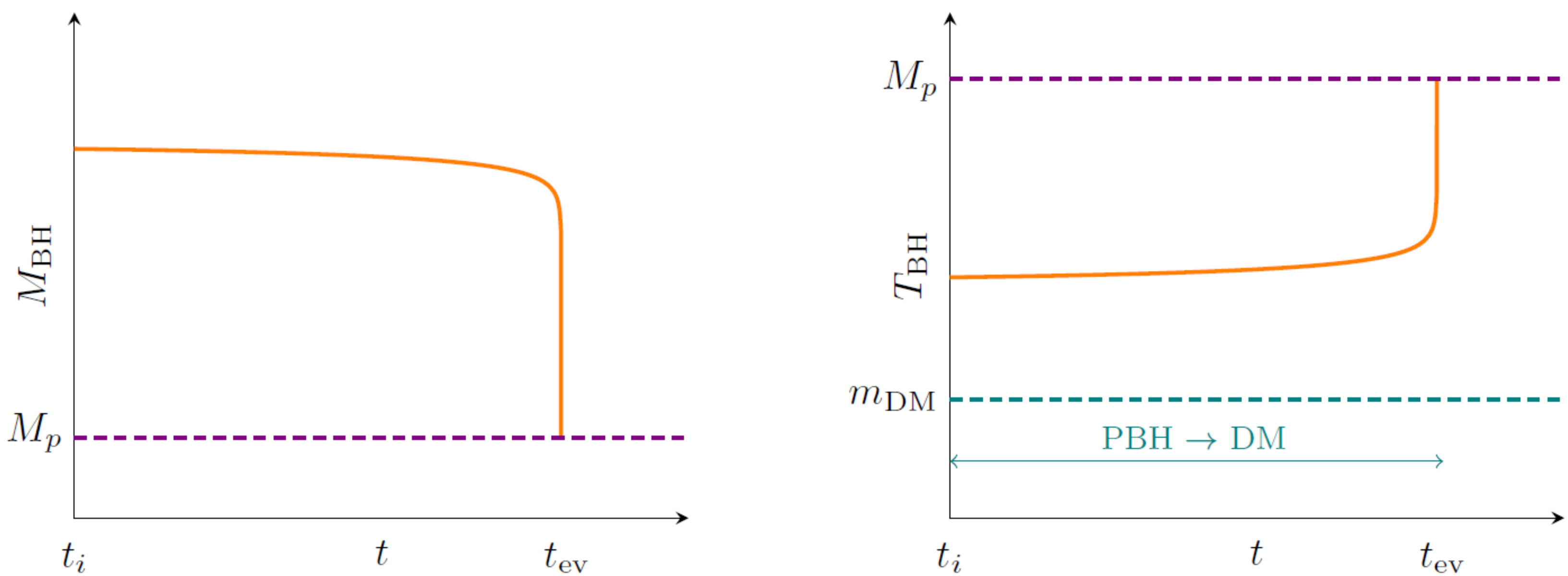

Primordial Black Holes

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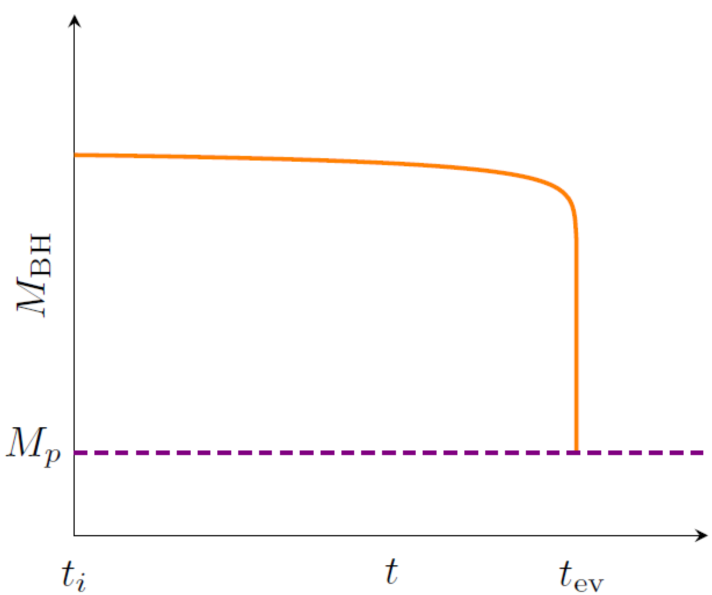
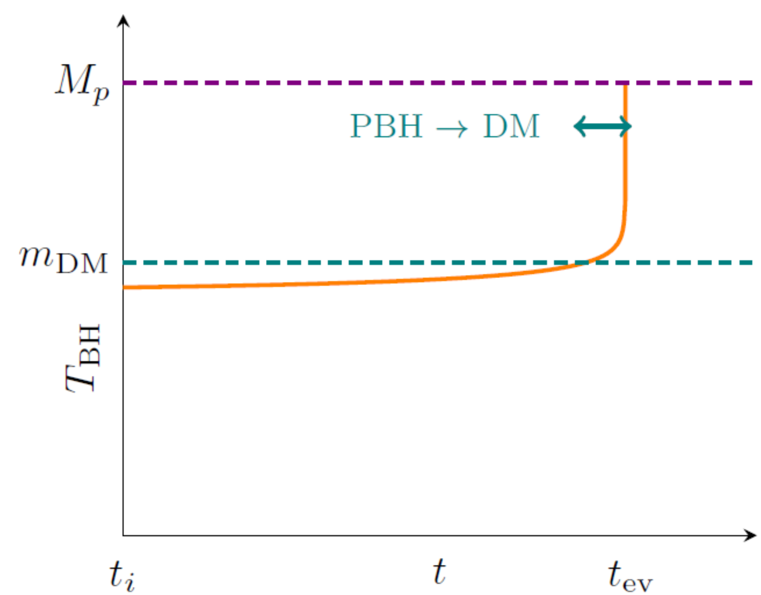
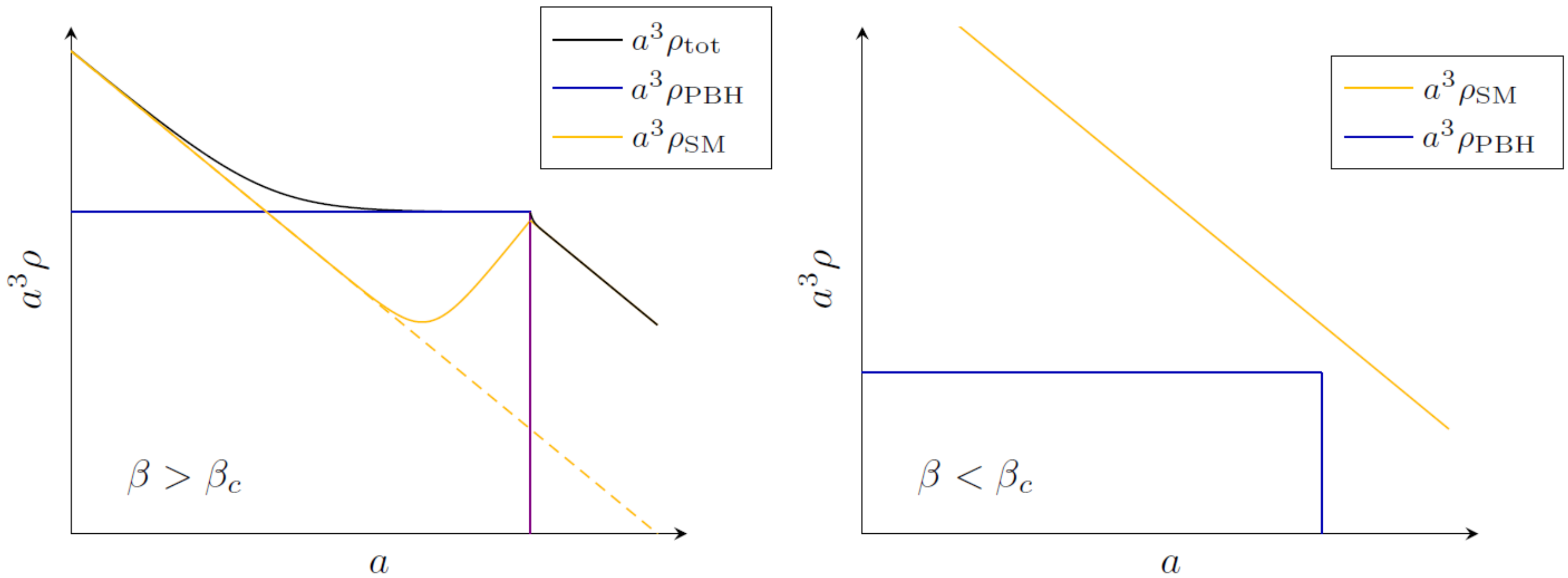




Primordial Black Holes

- PBH energy density fraction: $\beta \equiv \frac{\rho^{\mathrm{i}}_{\mathrm{PBH}}}{\rho^{\mathrm{i}}}$



DM from Evaporation

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

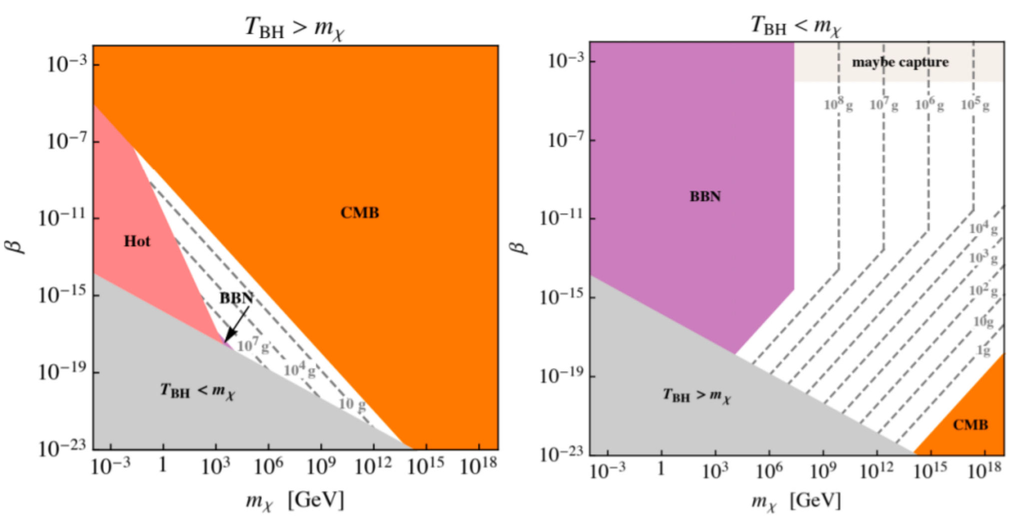
Very much used in the literature: the **geometrical-optics limit**

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

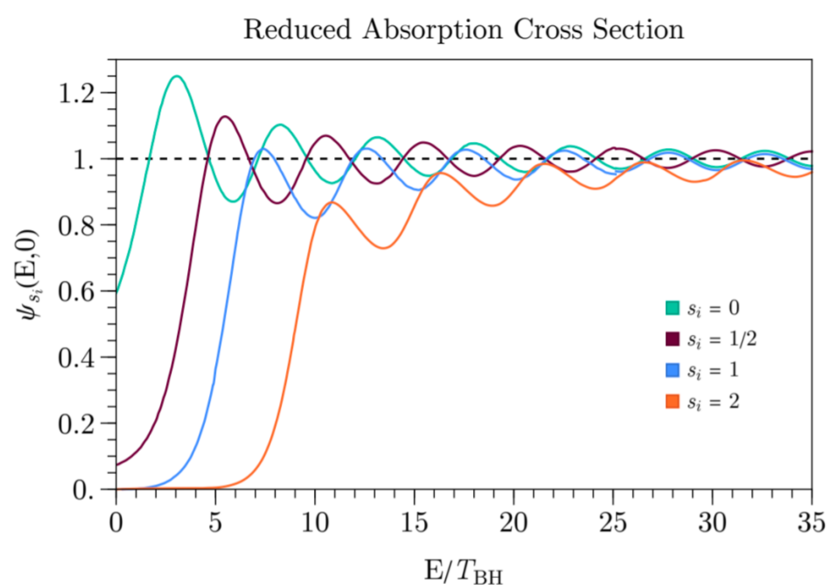
$$\sigma_{s_i}(E,\mu)|_{\rm GO} = 27\pi G^2 M_{\rm BH}^2$$

Very bad approximation at low momentum...

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



[Gondolo, Sandick and Shams Es Haghi 2020]



[Cheek, LH, Perez-Gonzalez and Turner 2021]

DM from Evaporation

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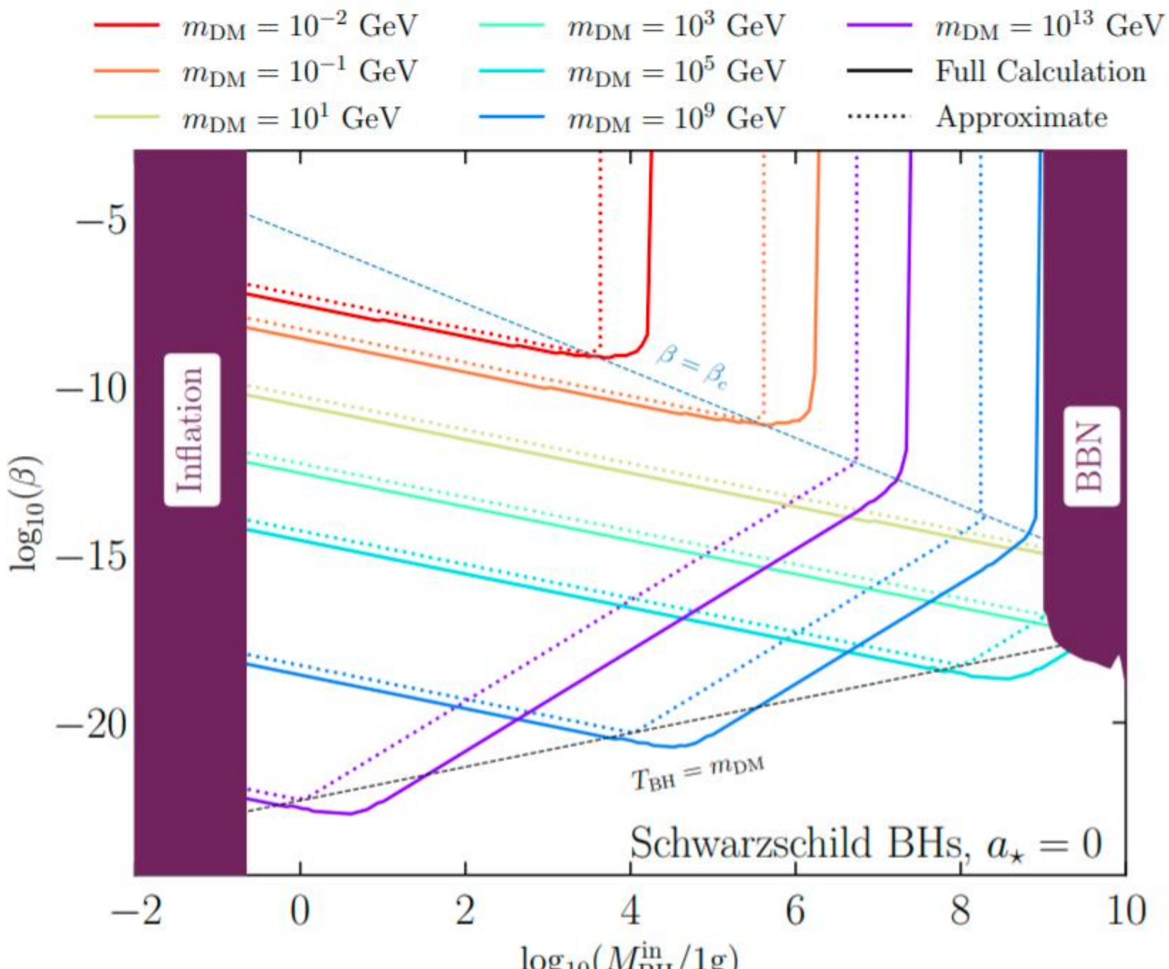


[Cheek, LH, Perez-Gonzalez and Turner 2021]

Thermal Production of DM

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

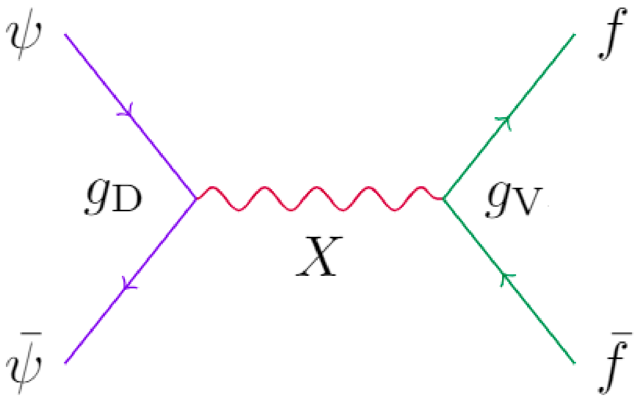
- Freeze-In or Freeze-Out

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

Regime $T_{\rm RH} > m_{\rm X} > m_{\rm DM}$

Freeze - In at $T \sim m_{\rm X}$
Freeze - Out at $T \sim m_{\rm DM}$

Localized in Temperature space ...



Effects of PBH Evaporation

1. PBHs produce additional DM particles $n_{\rm DM}^{\rm ev}$

When PBH do not dominate the energy density...

$$\Omega_\chi^{\text{fr-out}}(\langle\sigma v\rangle)h^2 \le \Omega_{\rm c}h^2, \qquad (t_{\rm eva} < t_{\text{fr-out}}),$$

$$\Omega_\chi^{\text{fr-out}}(\langle\sigma v\rangle)h^2 + \Omega_\chi^{\rm BH}(m_\chi, M_{\rm BH}, \beta)h^2 \le \Omega_{\rm c}h^2, \qquad (t_{\rm eva} > t_{\text{fr-out}}).$$

$$\Omega_\chi^{\text{fr-in}}(\lambda)h^2 + \Omega_\chi^{\rm BH}(m_\chi, M_{\rm BH}, \beta)h^2 \le \Omega_{\rm c}h^2.$$

[Gondolo *et al* 2020]

Effects of PBH Evaporation

1. PBHs produce additional DM particles $n_{\rm DM}^{\rm ev}$

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

2. PBHs produce mediator particles X

Effects of PBH Evaporation

1. PBHs produce additional DM particles $n_{\rm DM}^{\rm ev}$
   [Gondolo *et al* 2020, Bernal *et al* 2020]

2. PBHs produce mediator particles X

3. The evaporation of PBHs can modify the cosmological background *after* the thermal production of DM [Bernal *et al* 2020]

Case of a UV freeze-In

The dilution factor D is defined

$$D = \frac{Y_{\rm DM}^{\rm RD}}{Y_{\rm DM}^{\rm MD}} \simeq \beta \, \frac{T_{\rm in}}{\bar{T}_{\rm ev}} \geq 1\,. \tag{4.2}$$

[Bernal *et al* 2020]

Effects of PBH Evaporation

1. PBHs produce additional DM particles $n_{\rm DM}^{\rm ev}$

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

2. PBHs produce mediator particles X

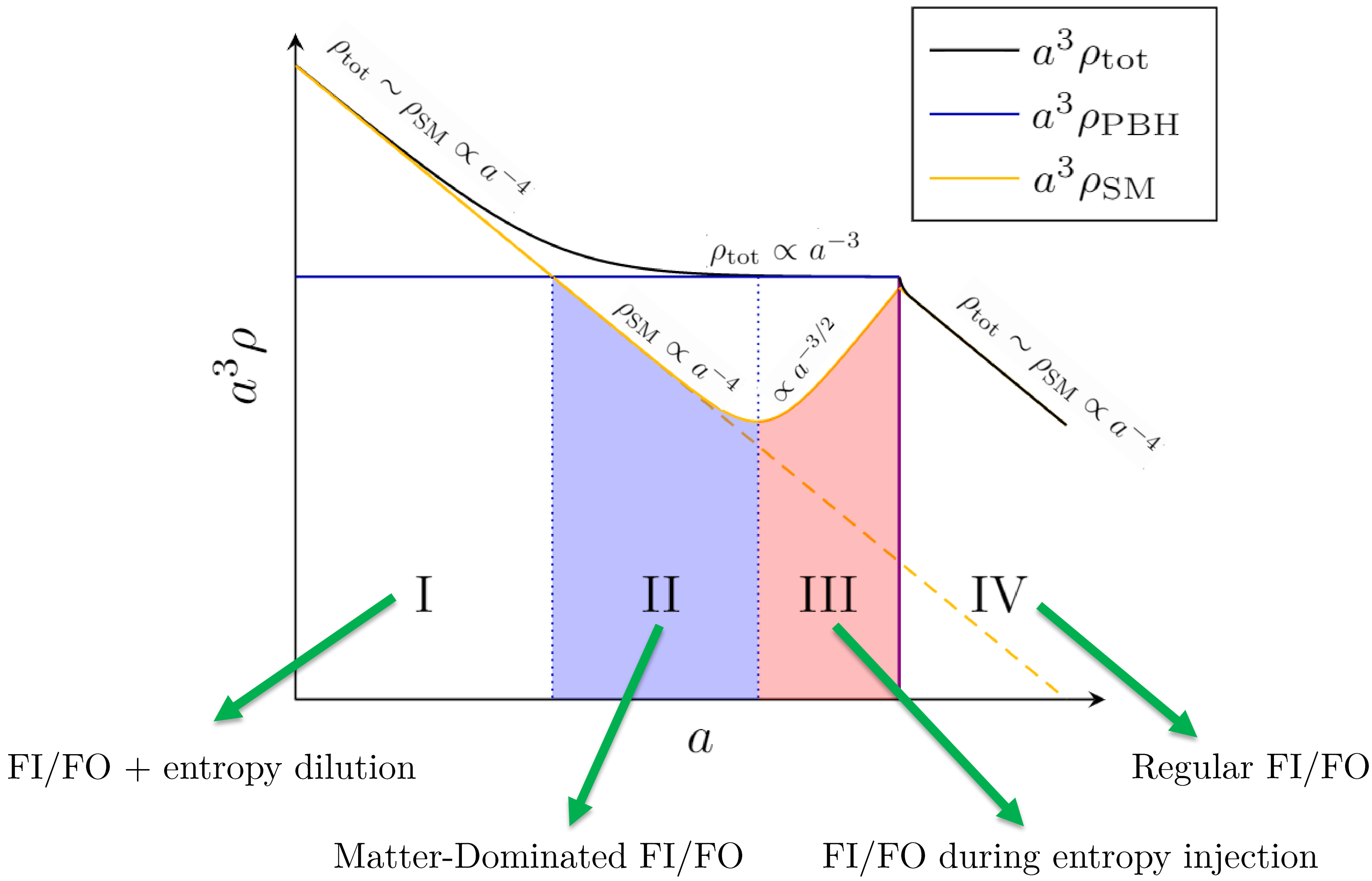
3. The evaporation of PBHs can modify the cosmological background *after* the thermal production of DM

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

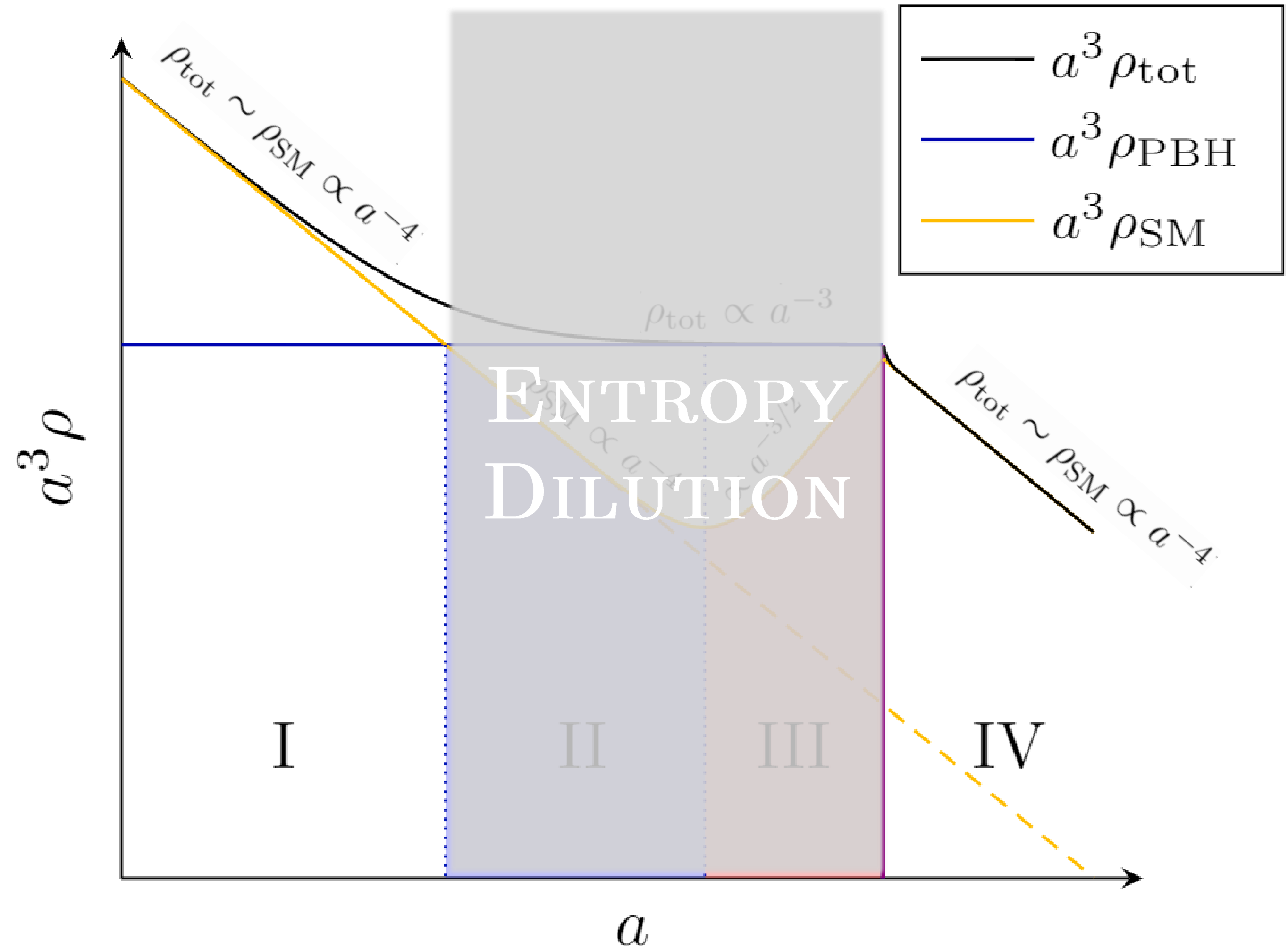
5. Light particles produced with energy $E \sim T_{\rm BH}$

   [Baldes *et al* 2020]

Modified Cosmology



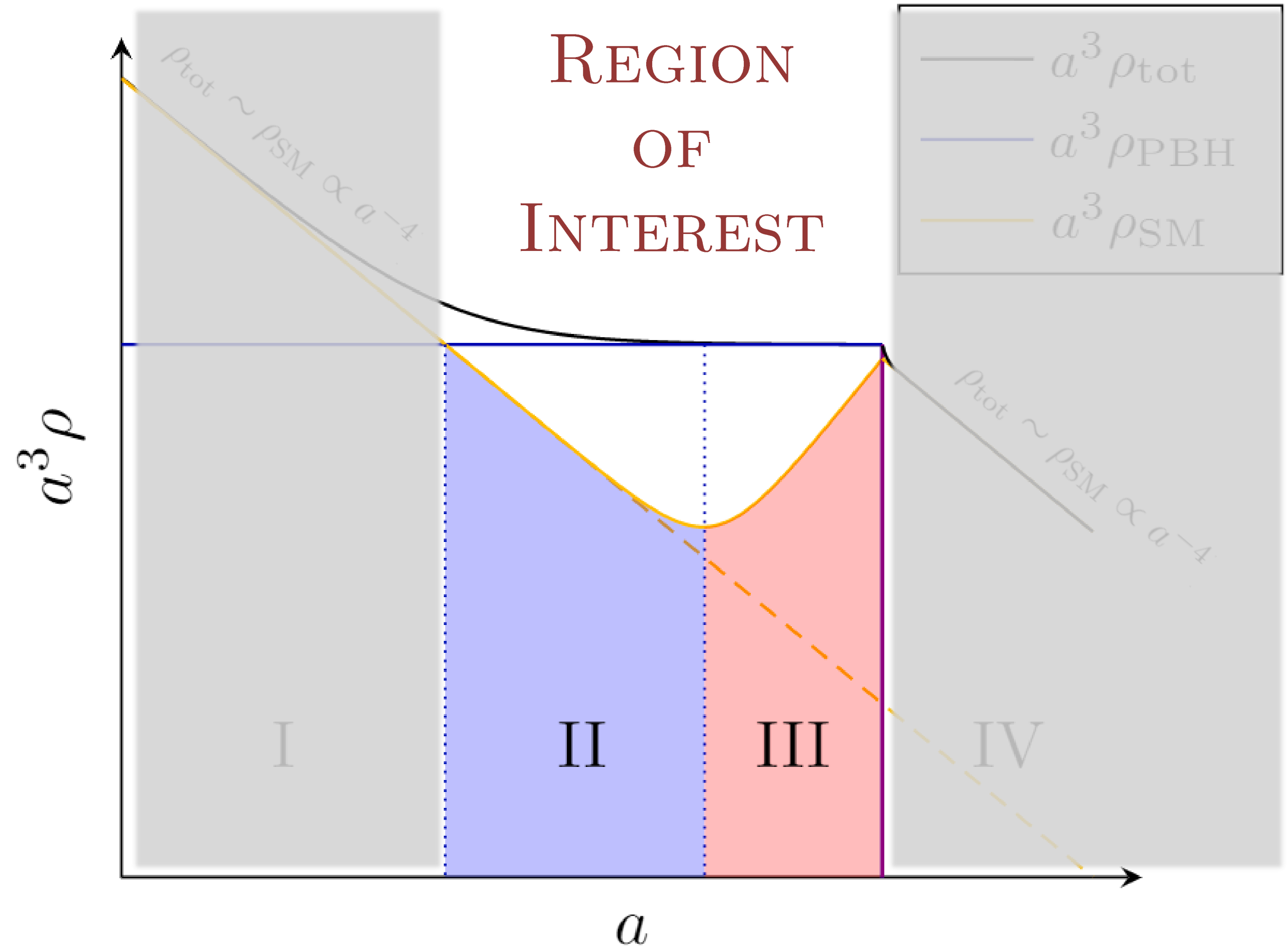
Modified Cosmology



Simple cases already discussed in the literature

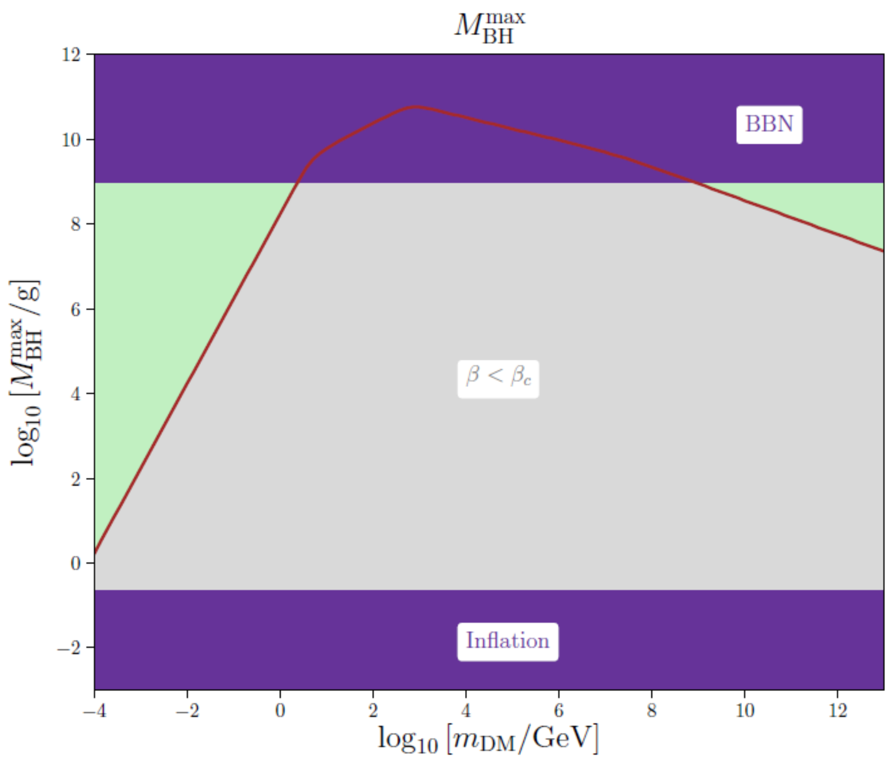
[Gondolo, Sandick and Shams Es Haghi 2020, Bernal and Zapata 2020]

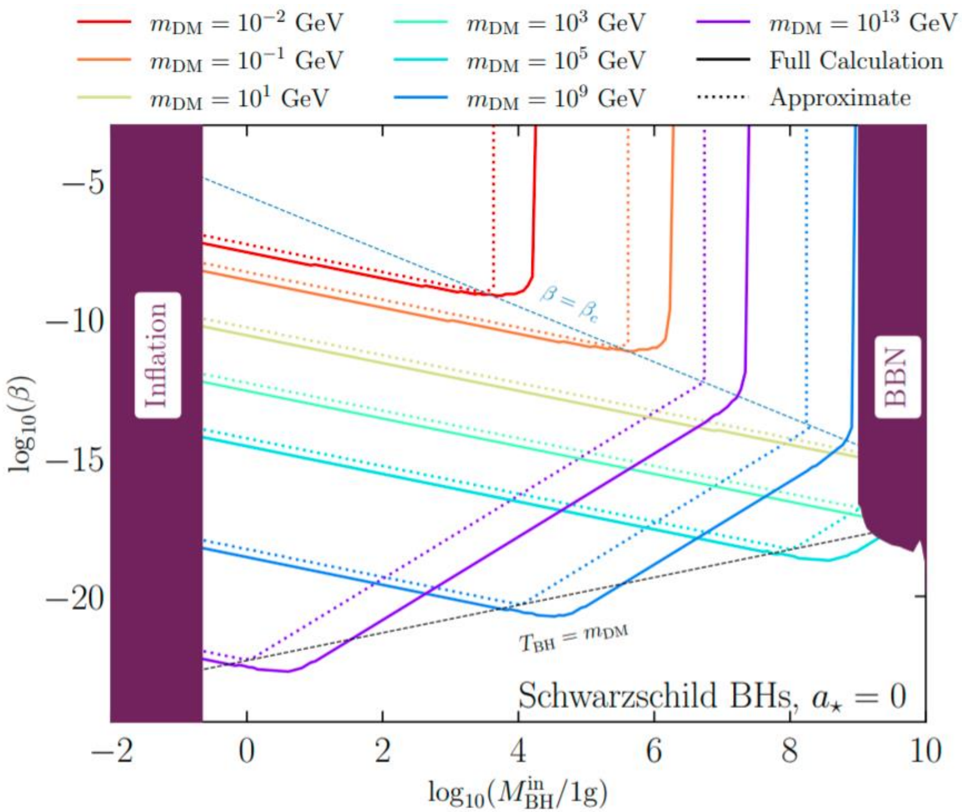
Modified Cosmology



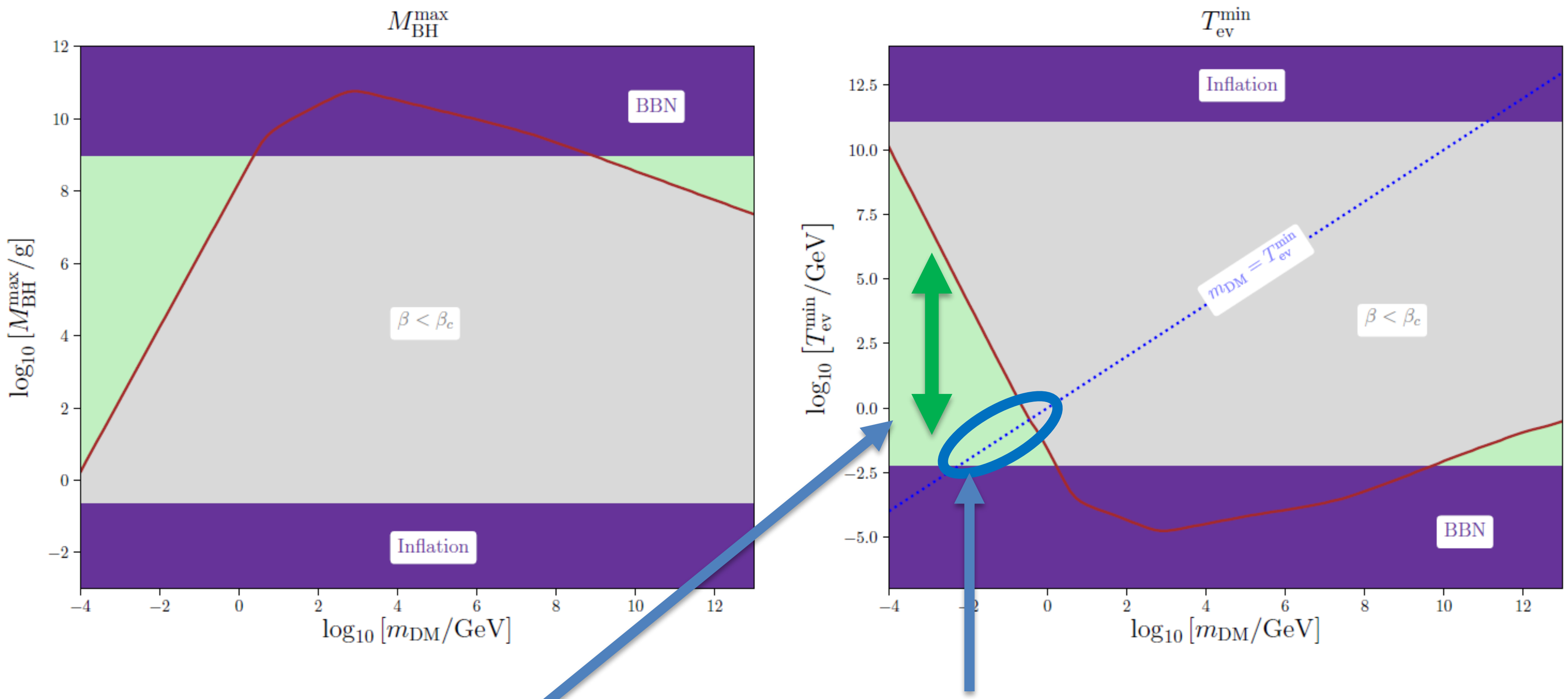
Need PBHs to dominate without overclosing the universe...

Modified Cosmology





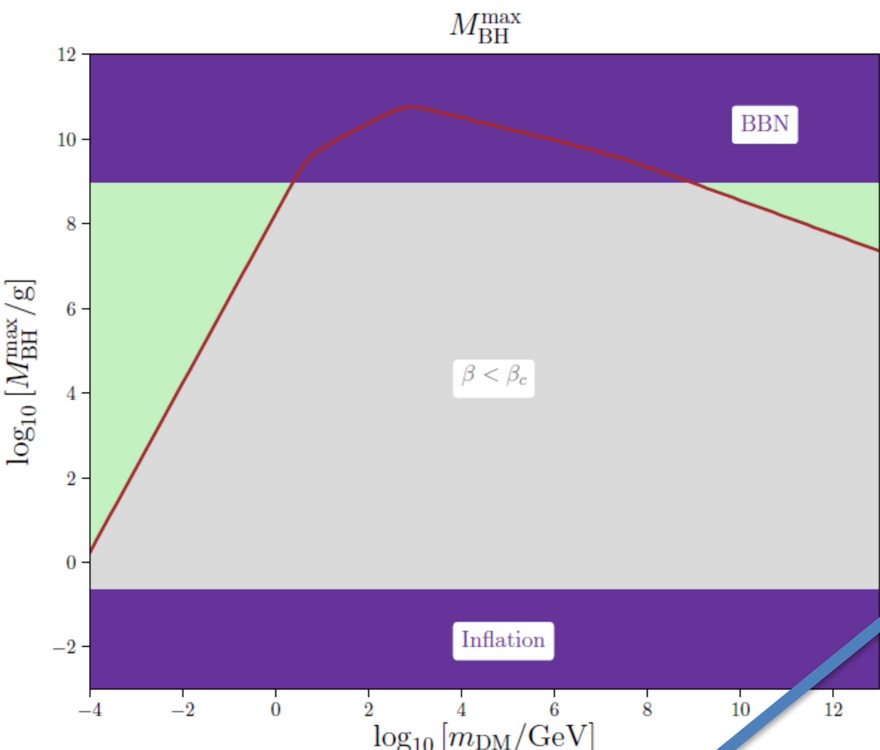
Modified Cosmology

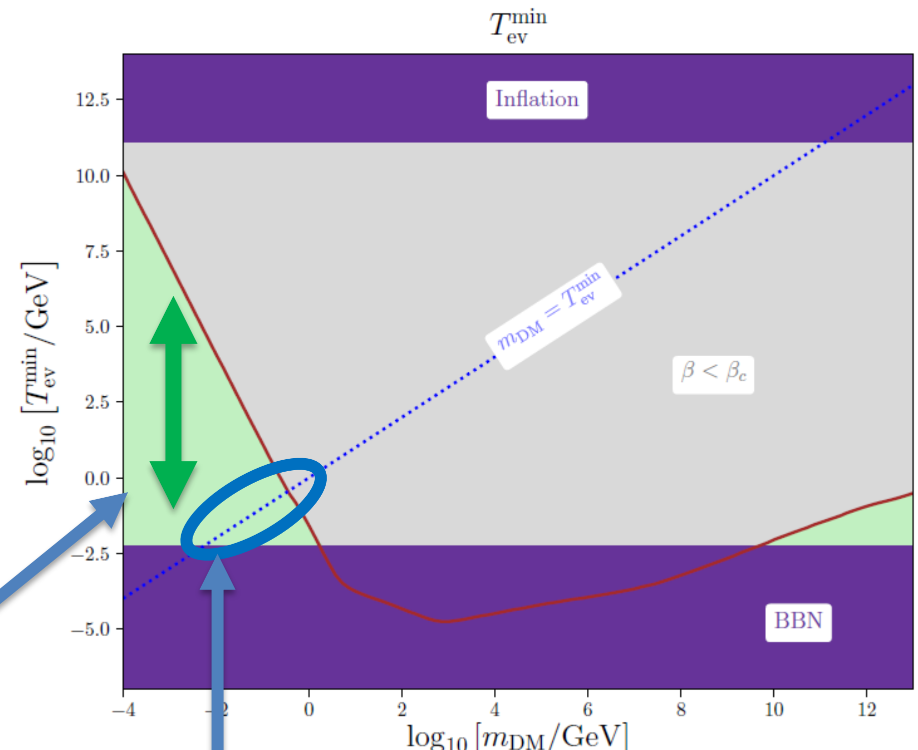


Region of interest
for Freeze-In

Region of interest
for Freeze-Out

Modified Cosmology



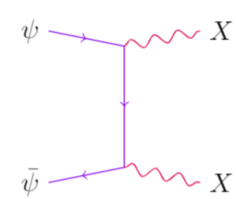


Region of interest
for Freeze-In

~~Region of interest
for Freeze-Out~~

**Thermalization
Of PBHs products…**

TBH large +



Boltzmann Equations

DM Annihilation, X decay — PBH evaporation

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

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

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

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

↓

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

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

Simplified approch...

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

$$\Gamma_{\mathrm{th+ev}} \equiv \frac{\langle \sigma \cdot v \rangle_{\mathrm{th+ev}} \times n^{\mathrm{th}}}{H} \qquad \langle \sigma \cdot v \rangle_{\mathrm{th+ev}} \equiv \frac{\displaystyle\int \sigma \cdot v_{\mathrm{moll}} f_{\mathrm{ev}} f_{\mathrm{th}} d^3\vec{p}_1 d^3\vec{p}_2}{\left[\displaystyle\int d^3\vec{p}_1 f_{\mathrm{ev}}\right]\left[\displaystyle\int d^3\vec{p}_2 f_{\mathrm{th}}\right]}.$$

Analytical Results

Freeze-In contribution

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

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

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

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

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:

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

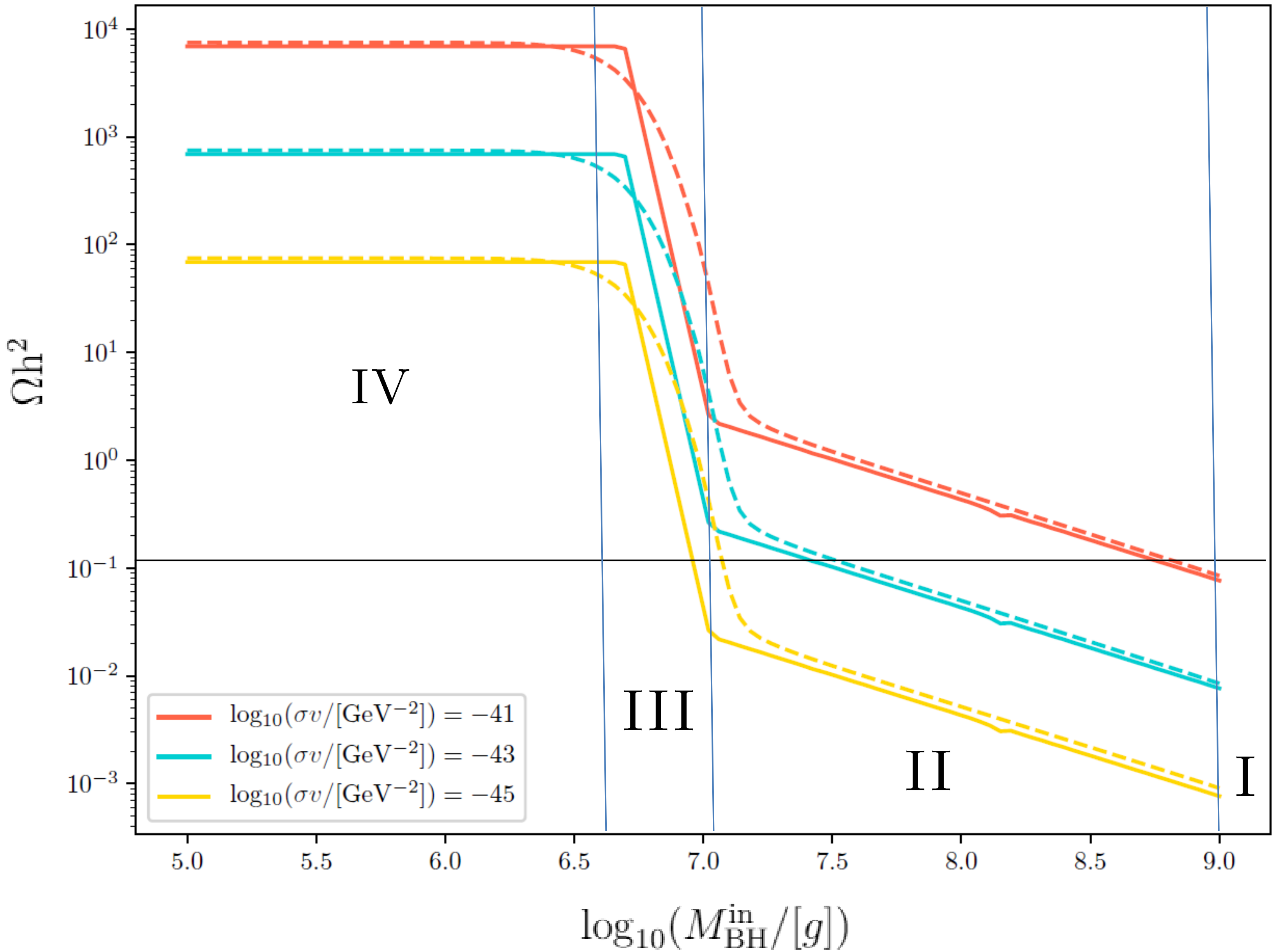
$$\Omega_{\rm I} = \frac{15}{2\pi} \frac{x_{\rm FO}}{\sqrt{10 g_\star(T_{\rm FO})}} \frac{s_{\rm eq}}{m_p \langle\sigma v\rangle \rho_c} \left(\frac{a_{\rm eq}}{a_0}\right)^3,$$

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

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

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

Results



10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
Ωh^2
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 2021, arXiv:2107.00016]

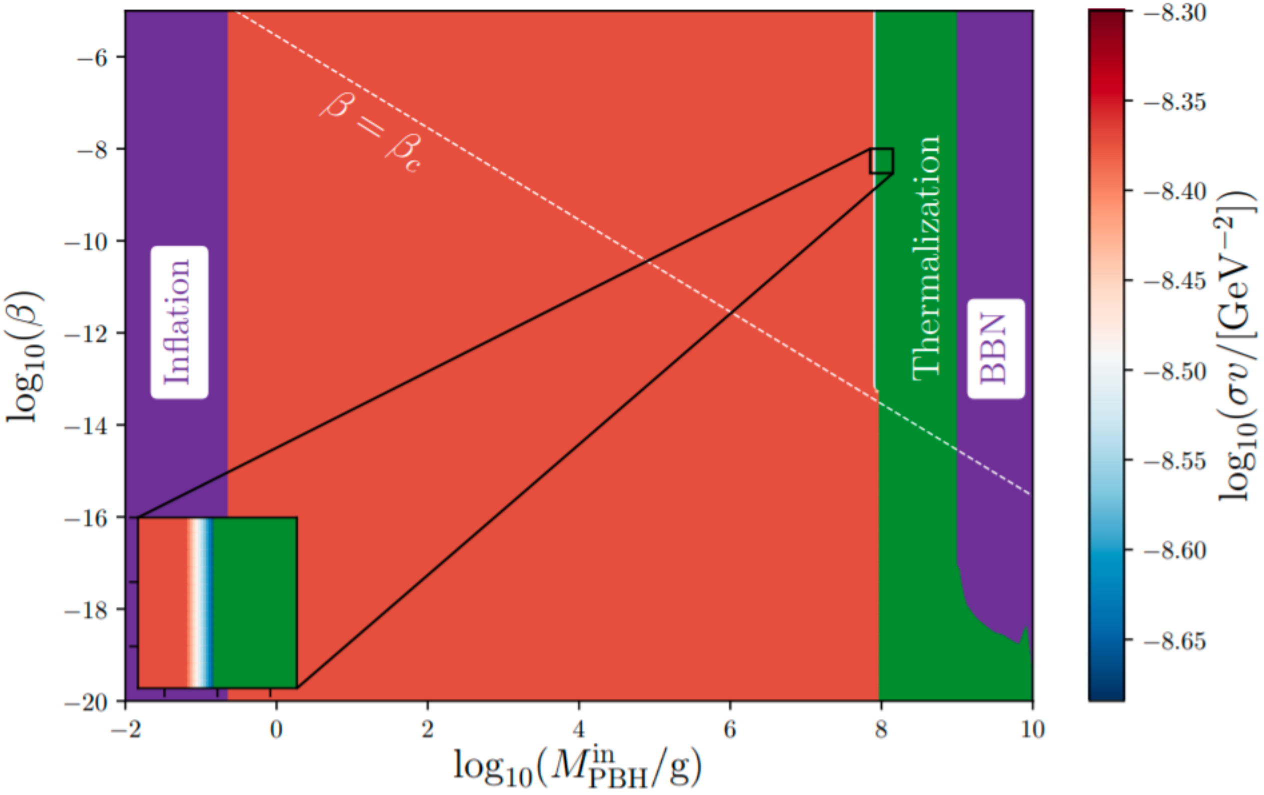


Fig. 7. Two-dimensional scan over the PBH fraction β and mass $M_{\rm BH}$ for a mediator mass $m_X = 10\,{\rm GeV}$ and a dark matter mass $m_{\rm DM} = 1\,{\rm GeV}$, and ${\rm Br}(X \to {\rm DM}) = 0.5$. The color map indicates the value of the non-relativistic cross-section of DM annihilation leading 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 2021, arXiv:2107.00016]

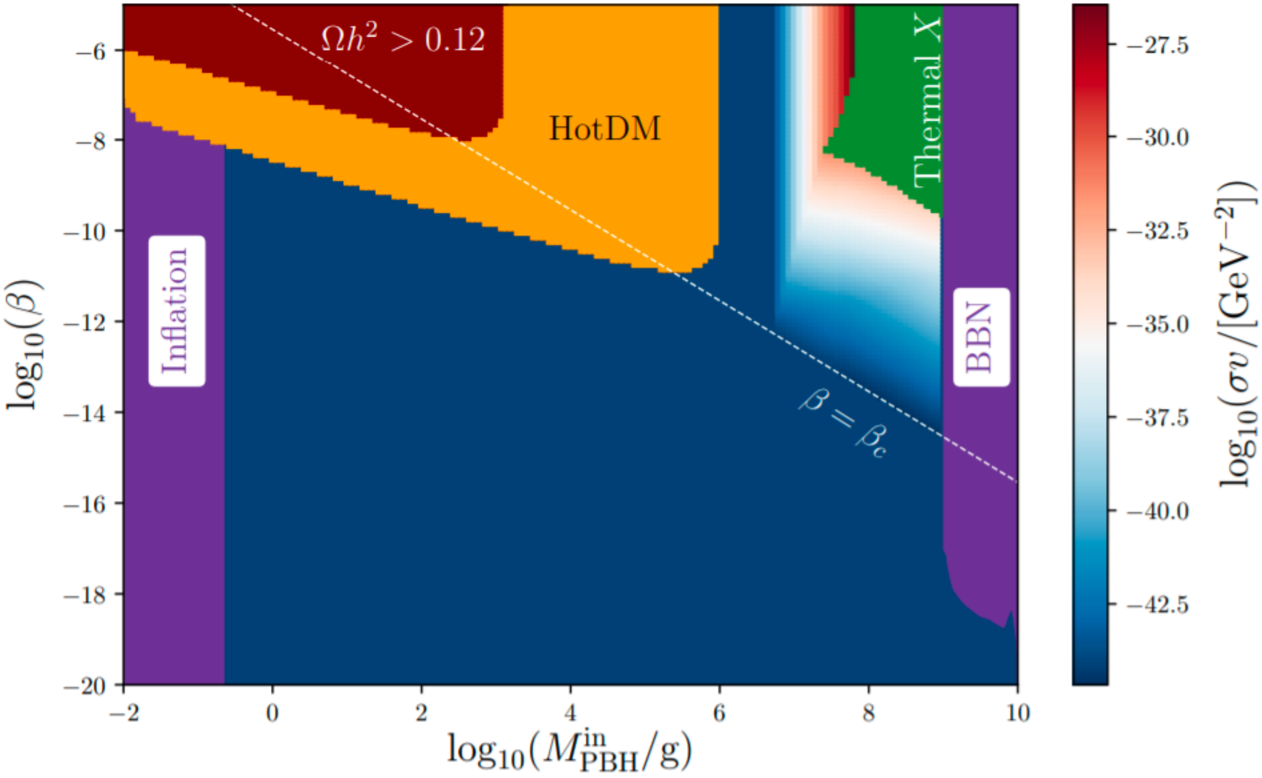


Fig. 11. Two-dimensional scan over the PBH fraction β and mass $M_{\rm BH}$ for a mediator mass $m_X = 1\,{\rm TeV}$, a dark matter mass $m_{\rm DM} = 1\,{\rm MeV}$, and ${\rm Br}(X \to {\rm SM}) = 10^{-7}$. The color map indicates the value of the non-relativistic cross-section of DM annihilation leading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

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 thermalization rates on the resonance
  - Enhance the secondary production of DM particles
- The annihilation cross-section can vary over orders of magnitude
- Our code is accessible online: https://github.com/earlyuniverse/ulysses

Back up

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:

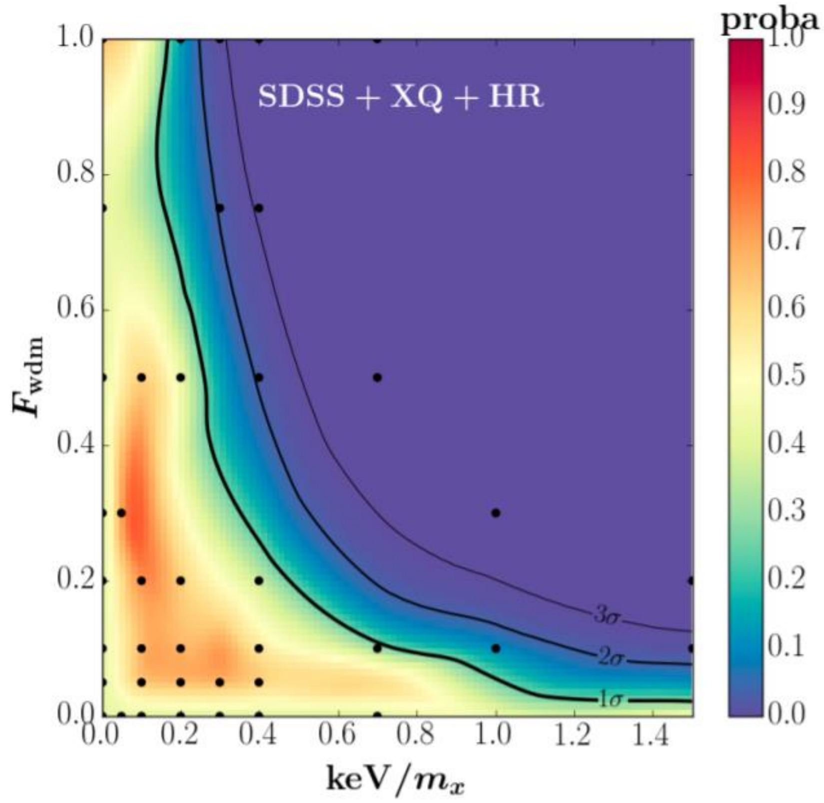
$$\dot{n}_{\rm DM}^{\rm th} + 3Hn_{\rm DM}^{\rm th} = \langle\sigma v\rangle_{\rm th}\left(n_{\rm DM,eq}^{2} - n_{\rm DM}^{\rm th\,2}\right)$$

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

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

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

Non-cold Dark Matter

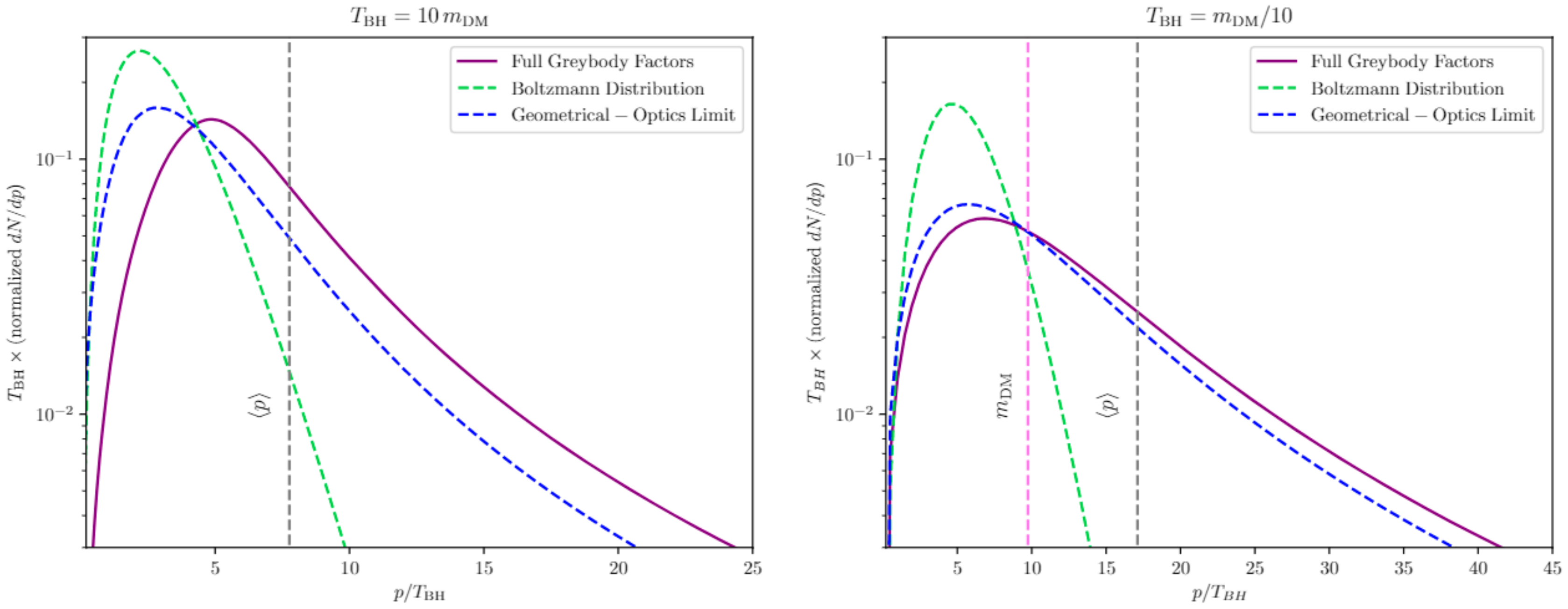


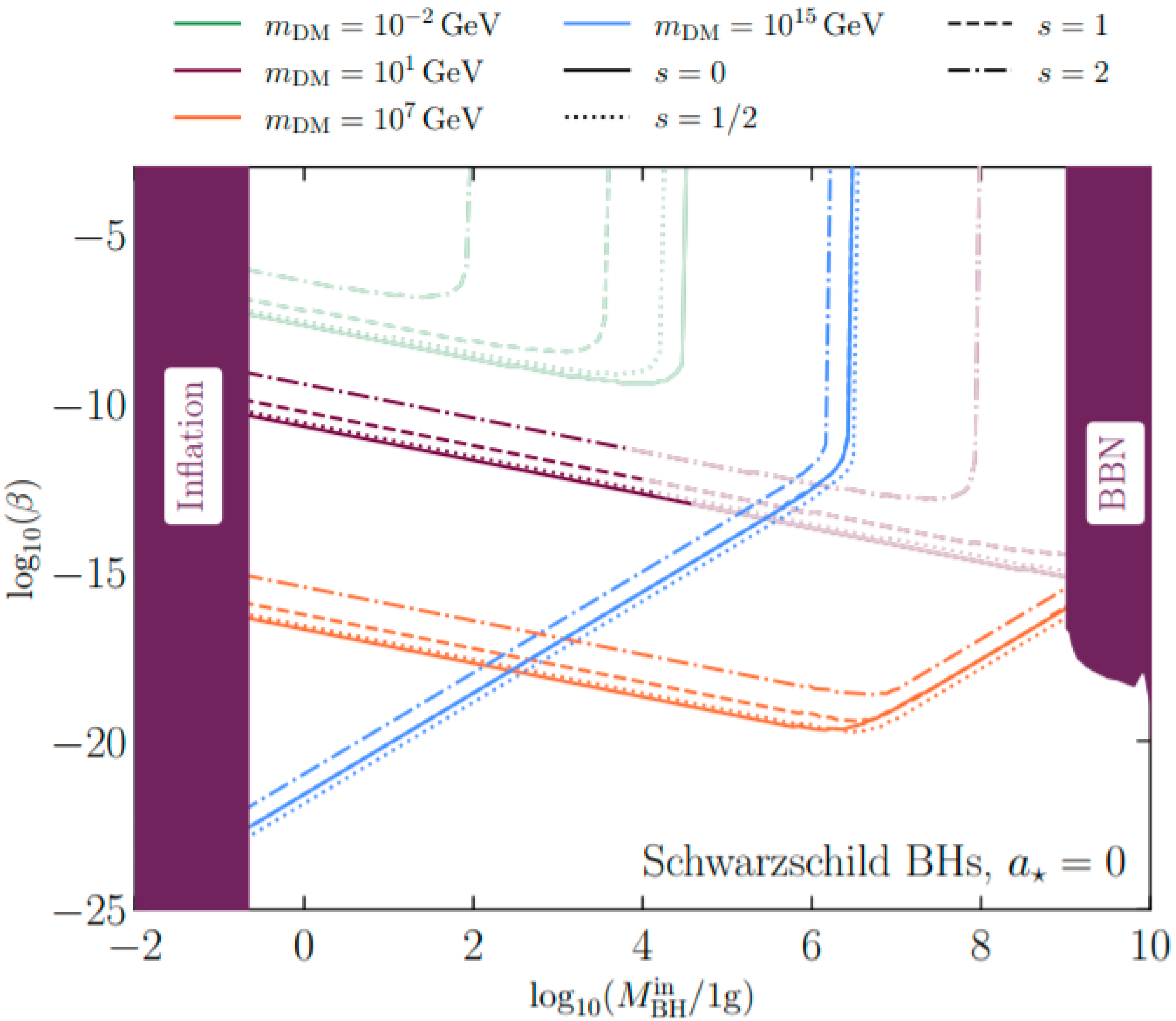
[Baur *et al.* 2017]

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

DM from Evaporation

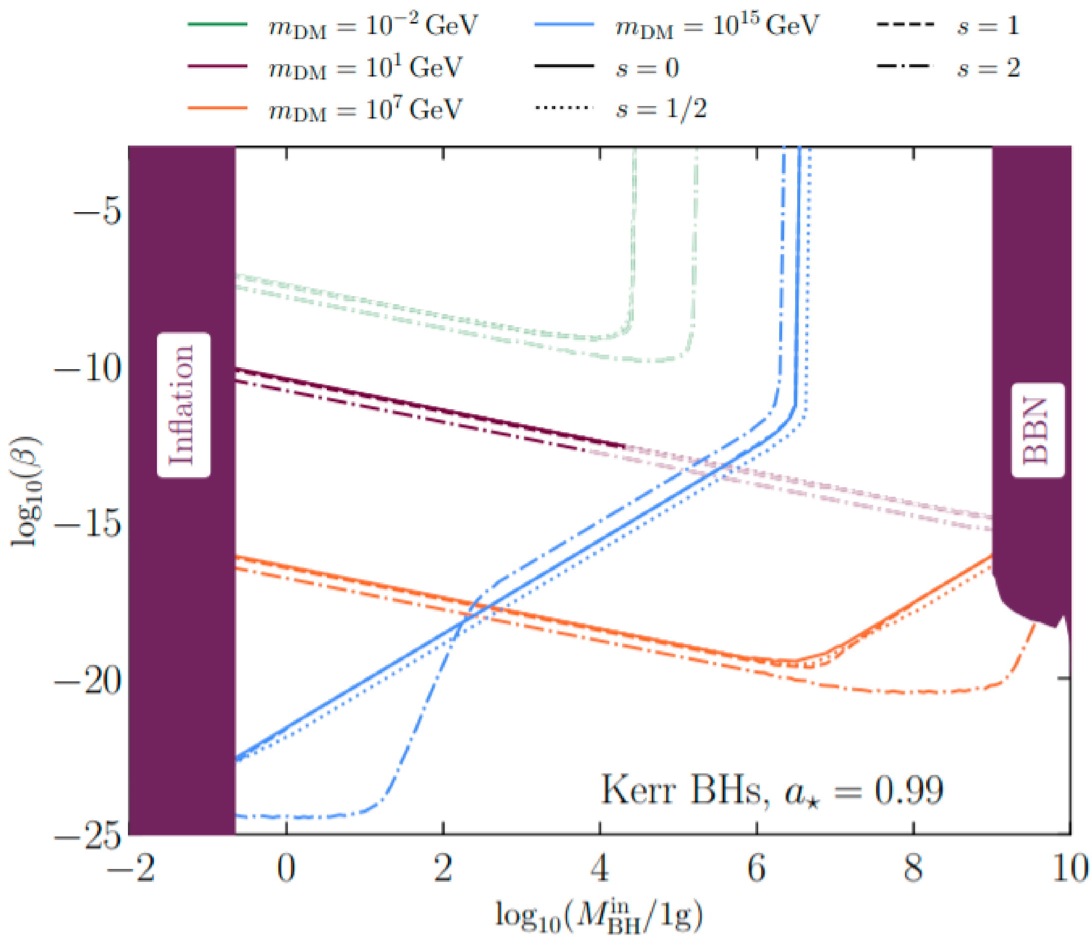
- Peculiar spectrum of evaporated DM particles
- Non-negligible difference between geometrical-optics limit and full distributions





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