
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](https://arxiv.org/abs/2107.00013)], [arXiv:[2107.00016](https://arxiv.org/abs/2107.00016)]

What do we expect in the dark ?



What do we expect in the dark ?

Today ~ 75%

A LOT !!!



In the early Universe

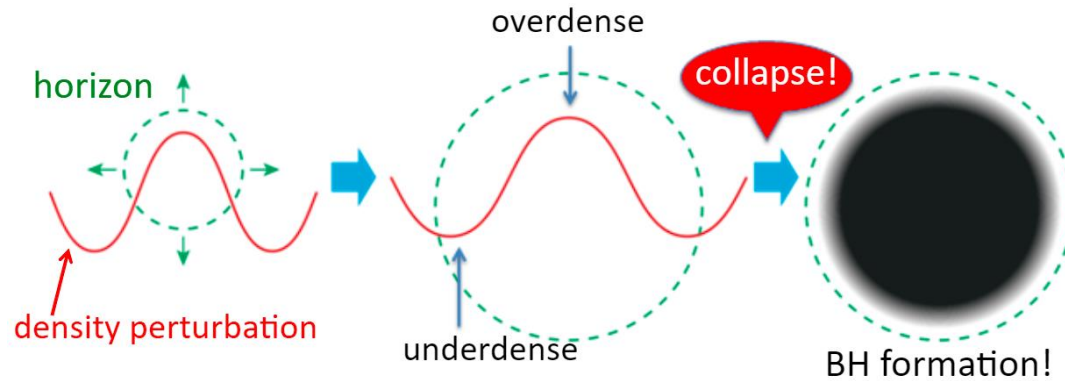
DARK MATTER

DARK ENERGIE

**UV PART. THEO.
BEYOND Λ CDM
INFLATION**



PRIMORDIAL BLACK HOLES



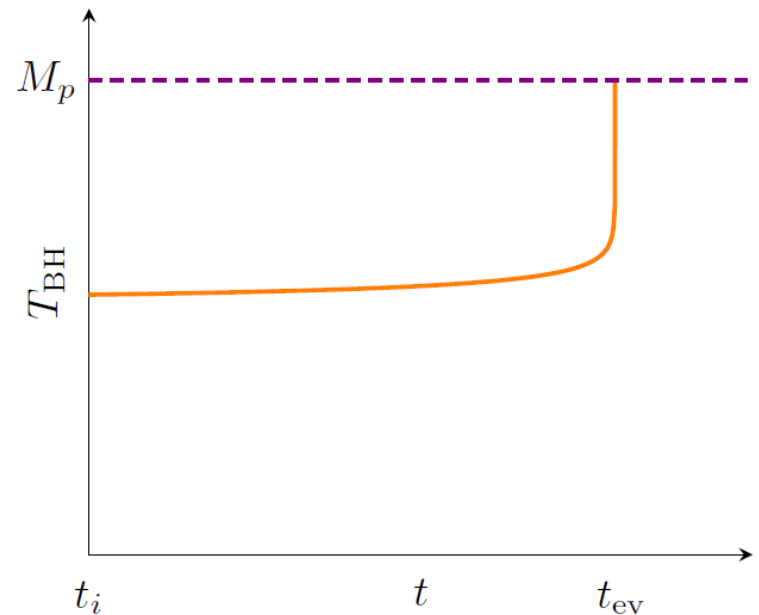
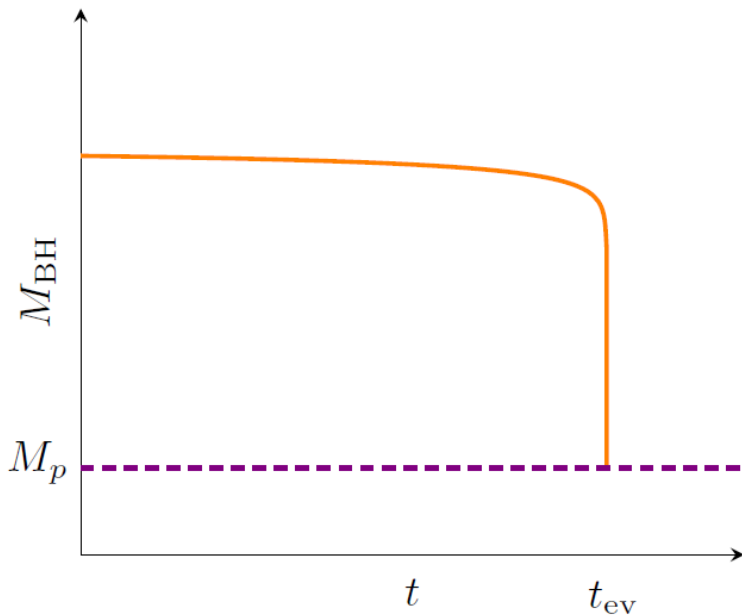
[picture borrowed from N. Kitajima]

- 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:

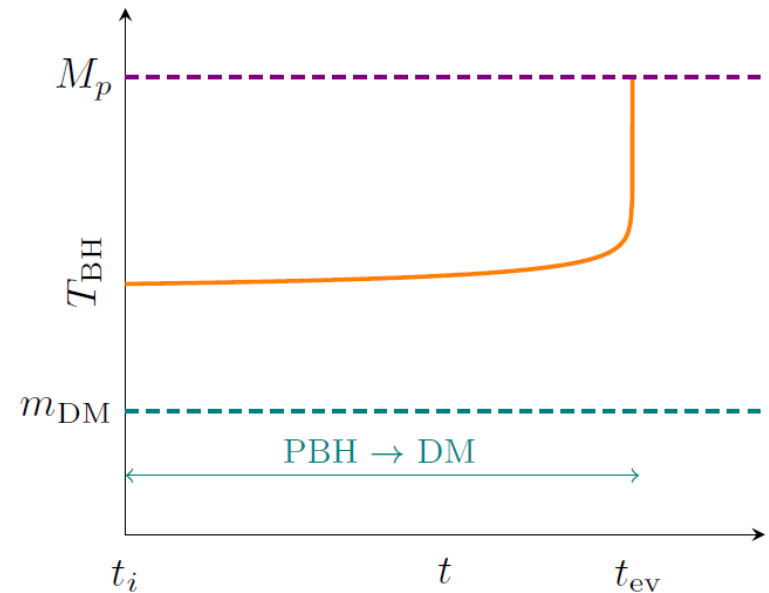
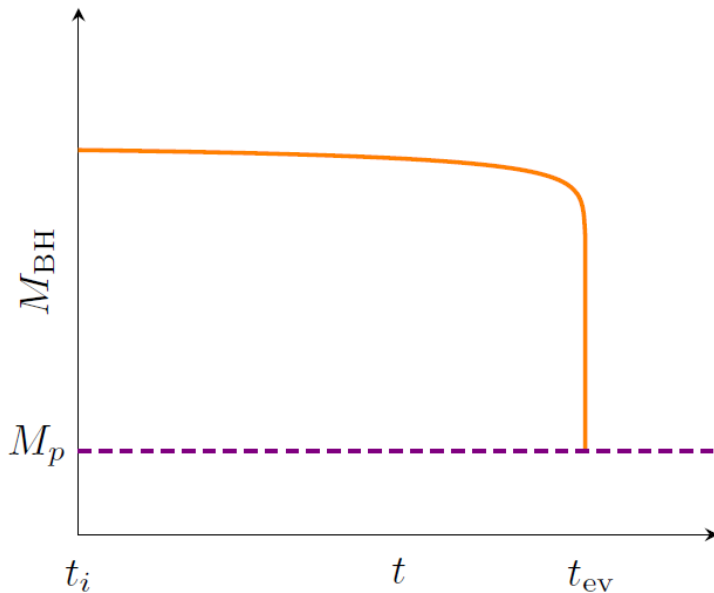
$$T_{\text{BH}} = \frac{1}{8\pi G M_{\text{BH}}} \sim 1.06 \text{ GeV} \left(\frac{10^{13} \text{ g}}{M_{\text{BH}}} \right)$$



PRIMORDIAL BLACK HOLES

- Hawking Temperature:

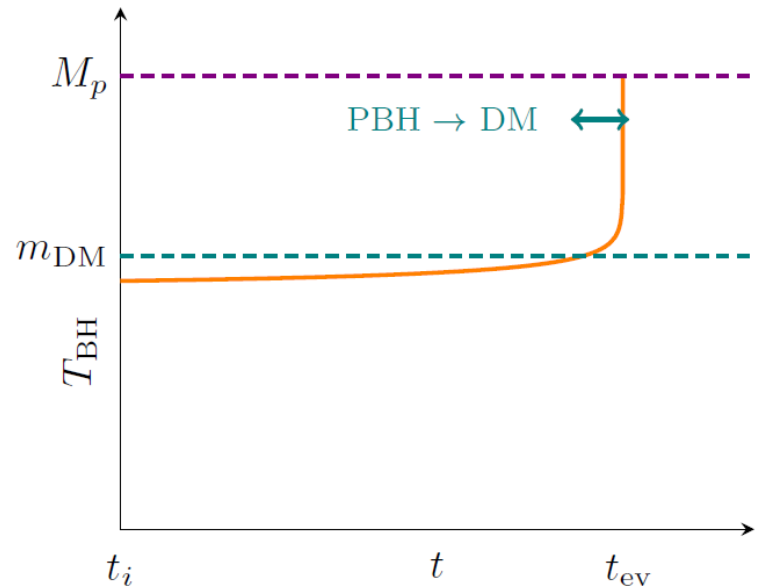
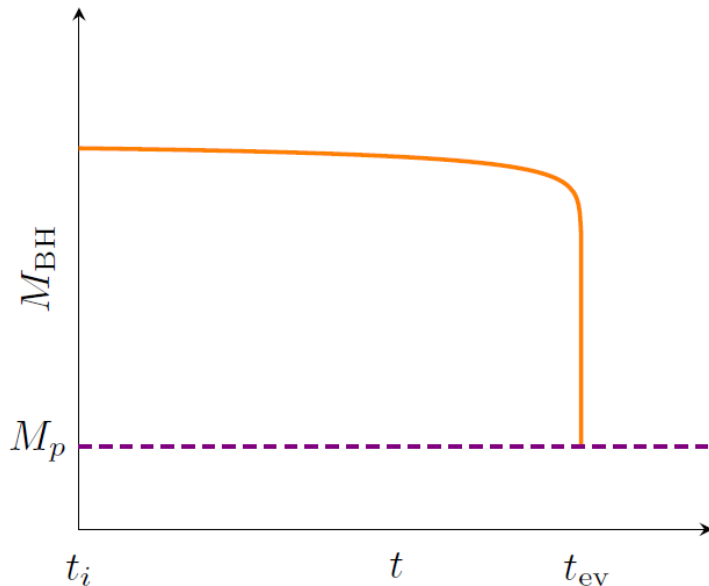
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PRIMORDIAL BLACK HOLES

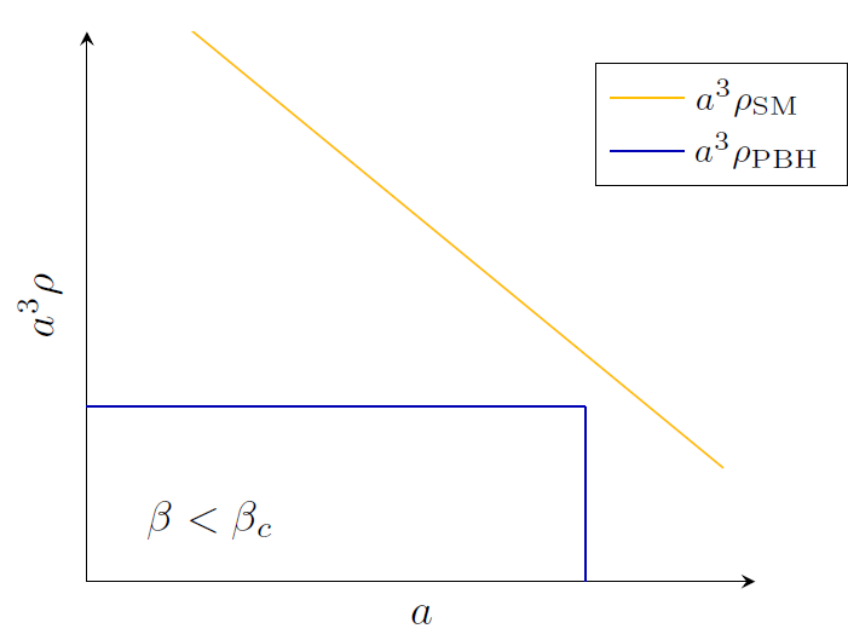
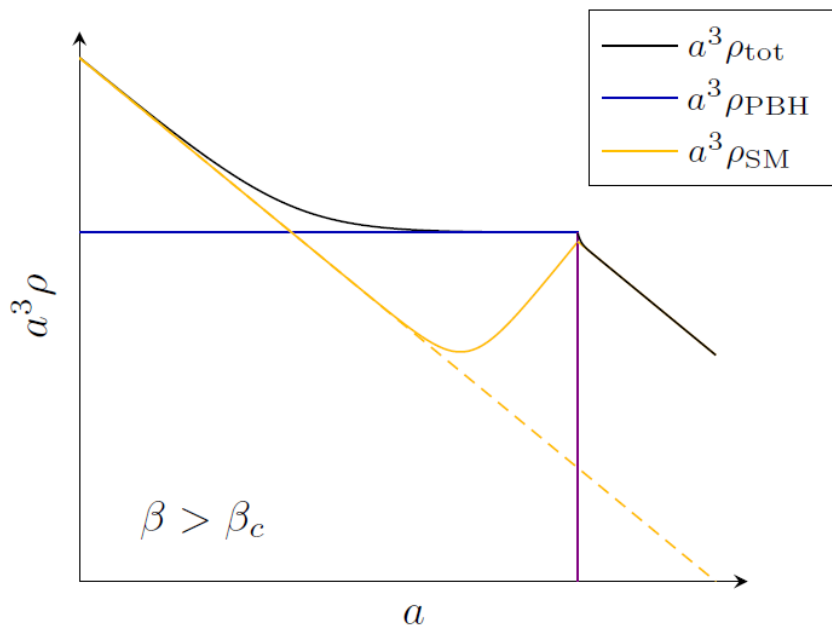
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PRIMORDIAL BLACK HOLES

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



DM FROM EVAPORATION

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

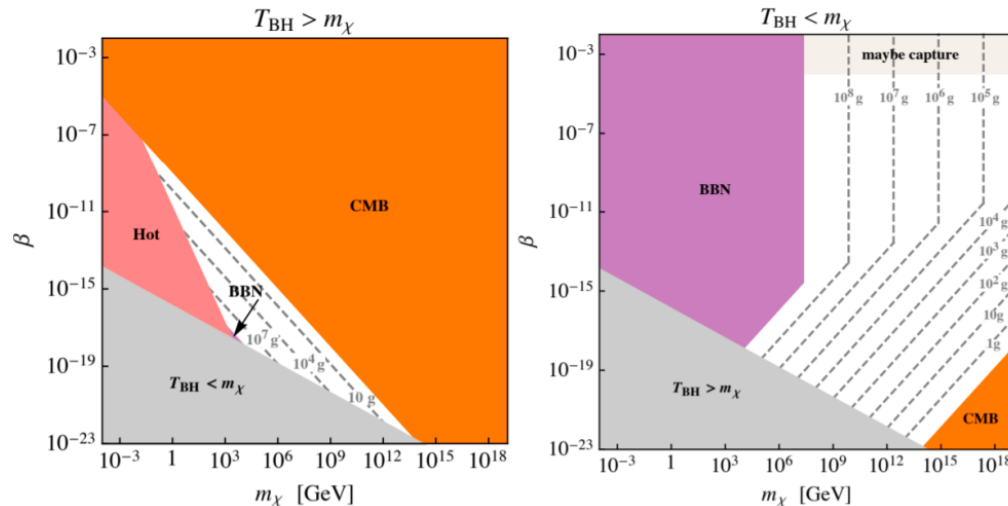
Very much used in the literature:
the **geometrical-optics limit**

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

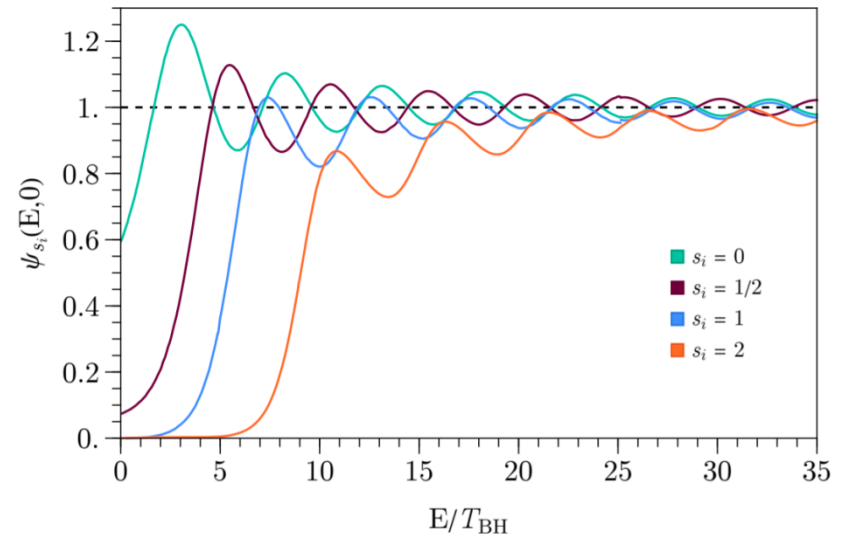
$$\sigma_{s_i}(E, \mu)|_{\text{GO}} = 27\pi G^2 M_{\text{BH}}^2$$

Very bad approximation at low
momentum...

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



Reduced Absorption Cross Section

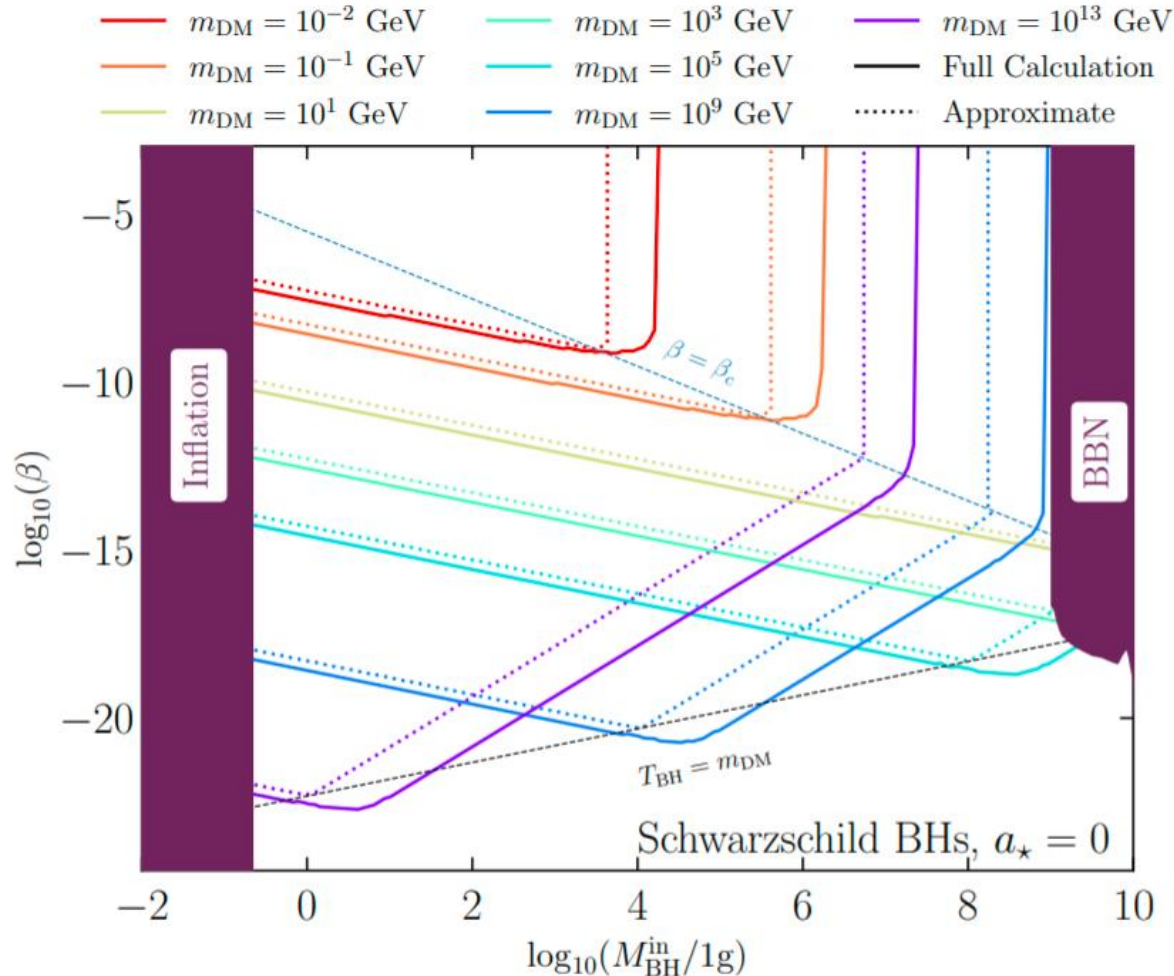


[Gondolo, Sandick and Shams Es Haghi 2020]

[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

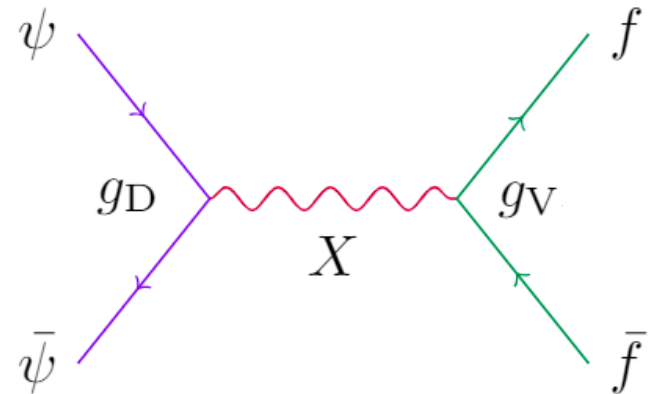
$$\dot{n}_{\text{DM}}^{\text{th}} + 3Hn_{\text{DM}}^{\text{th}} = \langle \sigma v \rangle_{\text{th}} (n_{\text{DM,eq}}^2 - n_{\text{DM}}^{\text{th}2})$$

Regime $T_{\text{RH}} > m_X > m_{\text{DM}}$

Freeze - In at $T \sim m_X$

Freeze - Out at $T \sim m_{\text{DM}}$

Localized in Temperature space ...



EFFECTS OF PBH EVAPORATION

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

When PBHs do not dominate the energy density...

$$\begin{aligned}\Omega_{\chi}^{\text{fr-out}}(\langle\sigma v\rangle)h^2 &\leq \Omega_{\text{c}}h^2, & (t_{\text{eva}} < t_{\text{fr-out}}), \\ \Omega_{\chi}^{\text{fr-out}}(\langle\sigma v\rangle)h^2 + \Omega_{\chi}^{\text{BH}}(m_{\chi}, M_{\text{BH}}, \beta)h^2 &\leq \Omega_{\text{c}}h^2, & (t_{\text{eva}} > t_{\text{fr-out}}). \\ \Omega_{\chi}^{\text{fr-in}}(\lambda)h^2 + \Omega_{\chi}^{\text{BH}}(m_{\chi}, M_{\text{BH}}, \beta)h^2 &\leq \Omega_{\text{c}}h^2.\end{aligned}$$

[Gondolo *et al* 2020]

EFFECTS OF PBH EVAPORATION

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

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

2. PBHs produce mediator particles X

EFFECTS OF PBH EVAPORATION

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

$$D = \frac{Y_{\text{DM}}^{\text{RD}}}{Y_{\text{DM}}^{\text{MD}}} \simeq \beta \frac{T_{\text{in}}}{T_{\text{ev}}} \geq 1. \quad (4.2)$$

[Bernal *et al* 2020]

EFFECTS OF PBH EVAPORATION

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

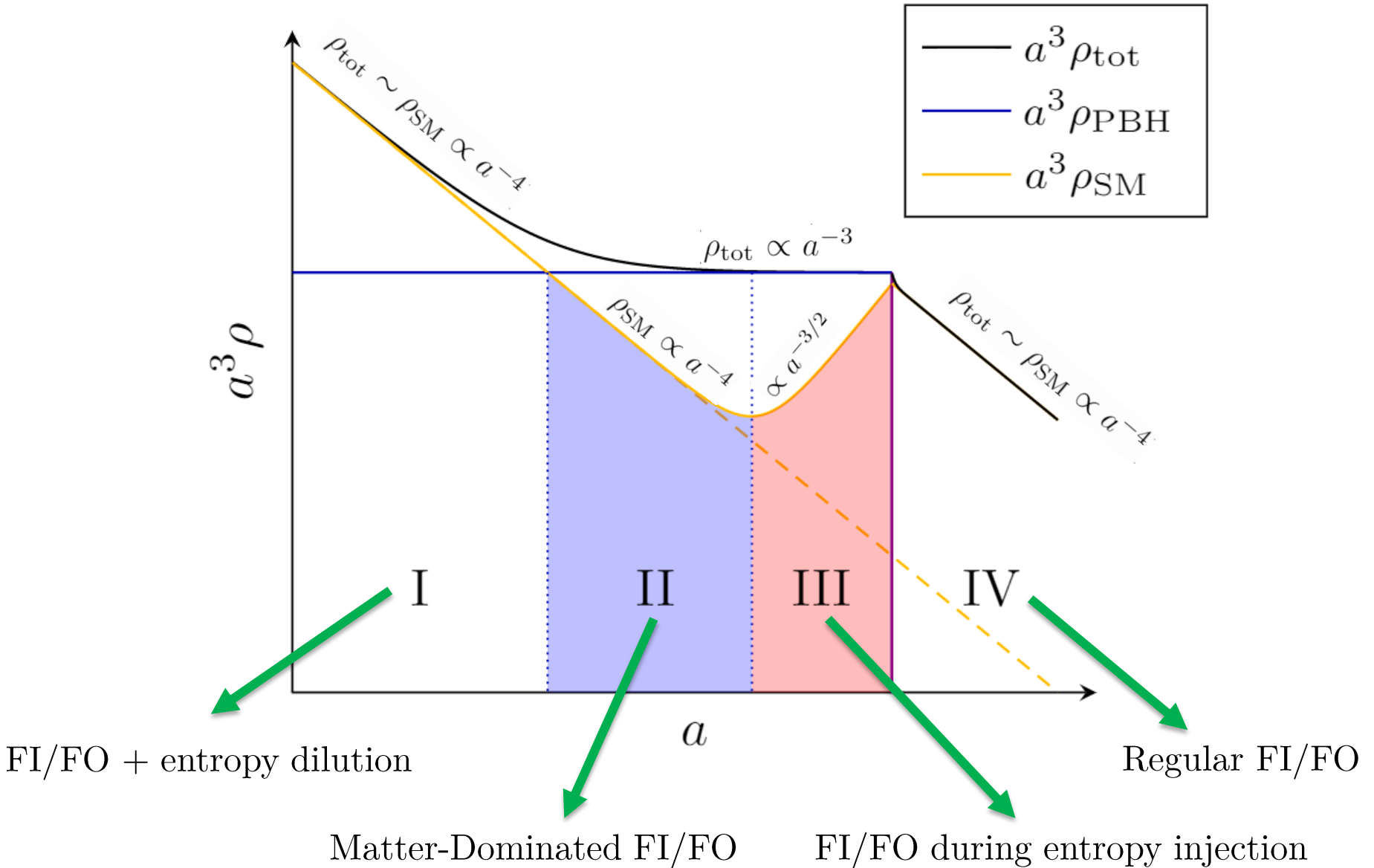
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3. The evaporation of PBHs can modify the cosmological background *after* the thermal production of DM

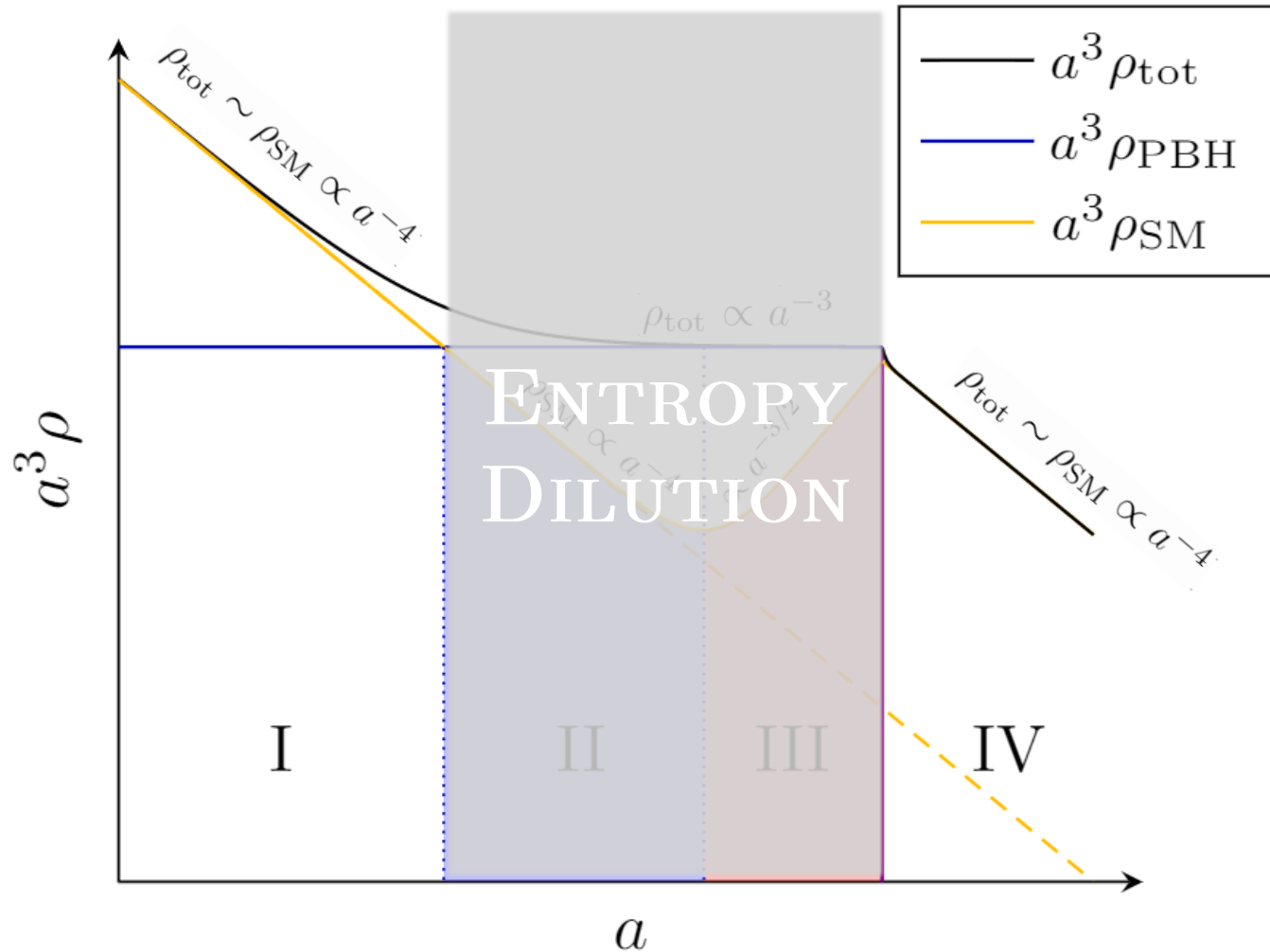
4. The evaporation of PBHs can modify the cosmological background *during* the thermal production of DM

5. Light particles produced with energy $E \sim T_{\text{BH}}$
[Baldes *et al* 2020]

MODIFIED COSMOLOGY



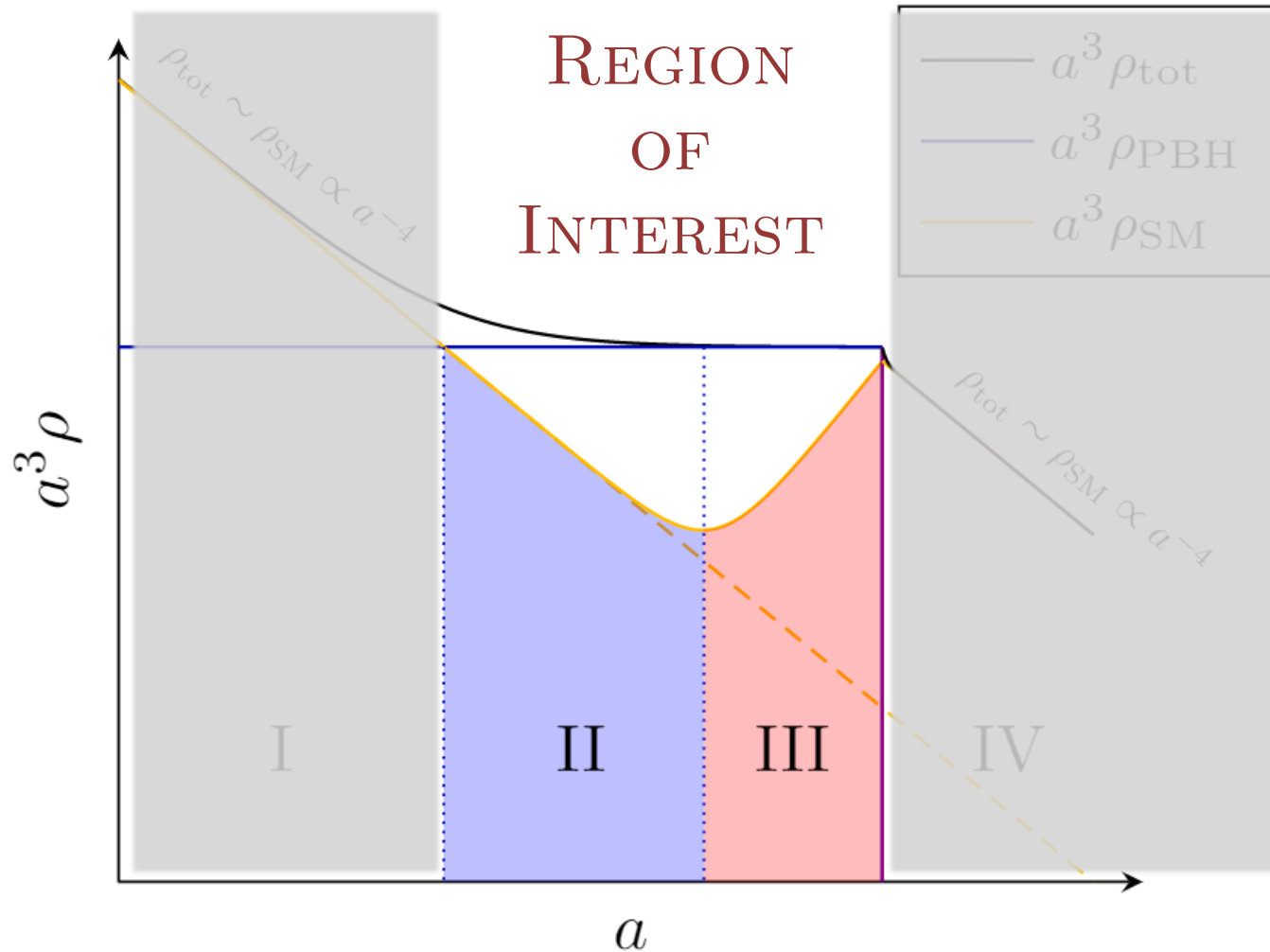
MODIFIED COSMOLOGY



Simple cases already discussed in the literature

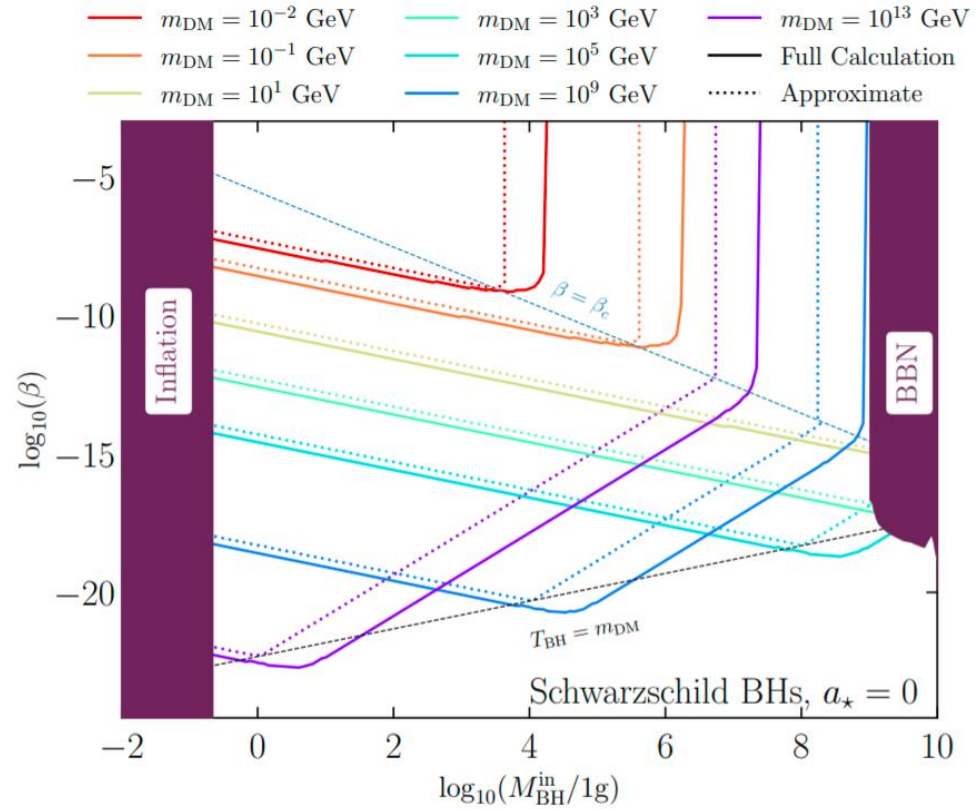
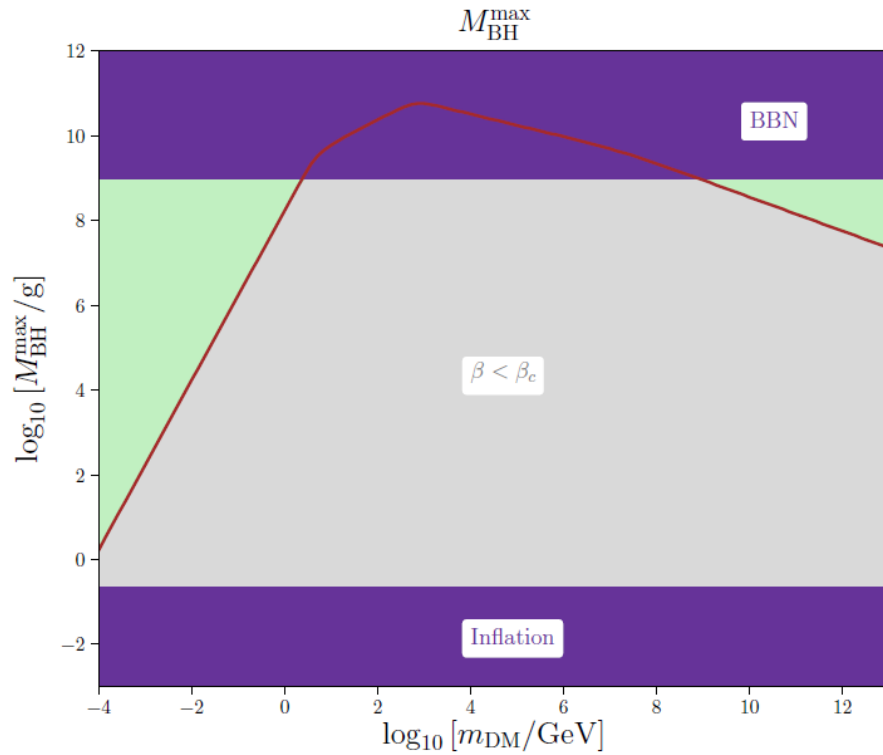
[Gondolo, Sandick and Shams Es Haghi 2020, Bernal and Zapata 2020]

MODIFIED COSMOLOGY

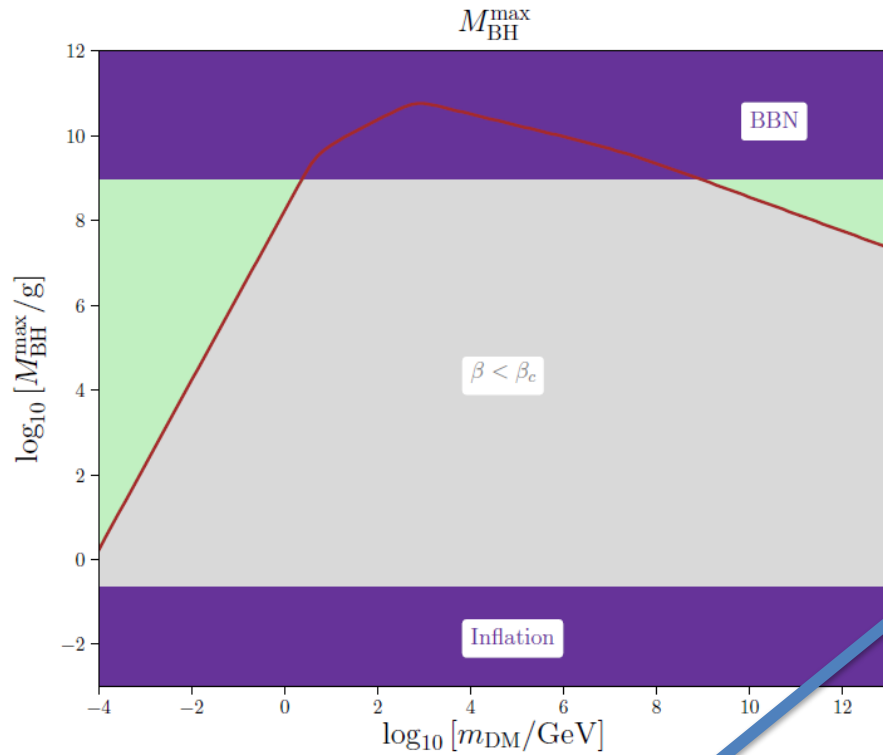


Need PBHs to dominate without overclosing the universe...

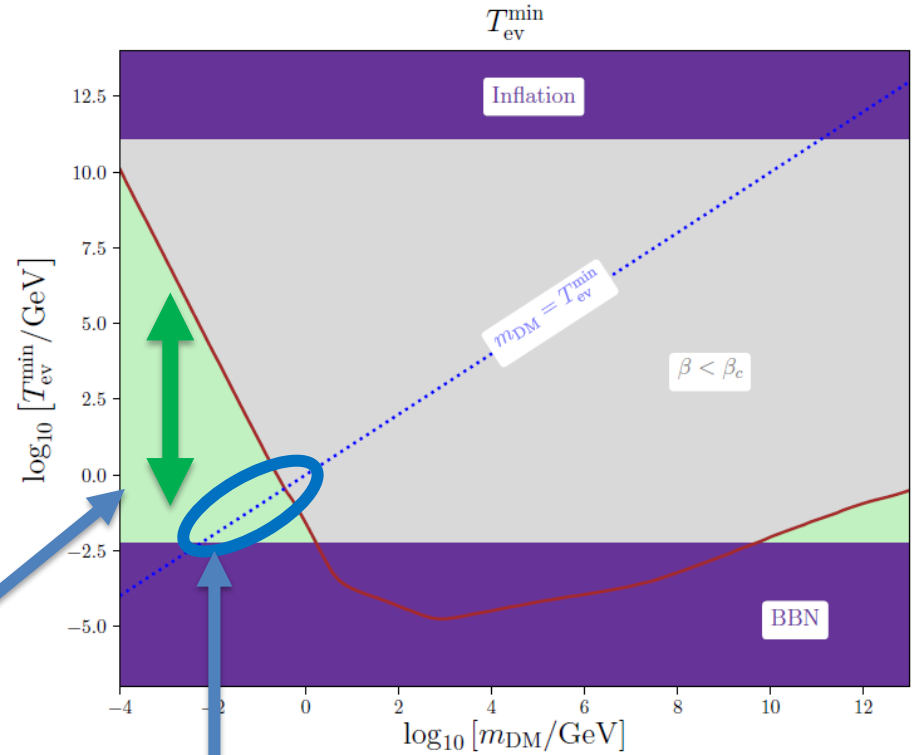
MODIFIED COSMOLOGY



MODIFIED COSMOLOGY

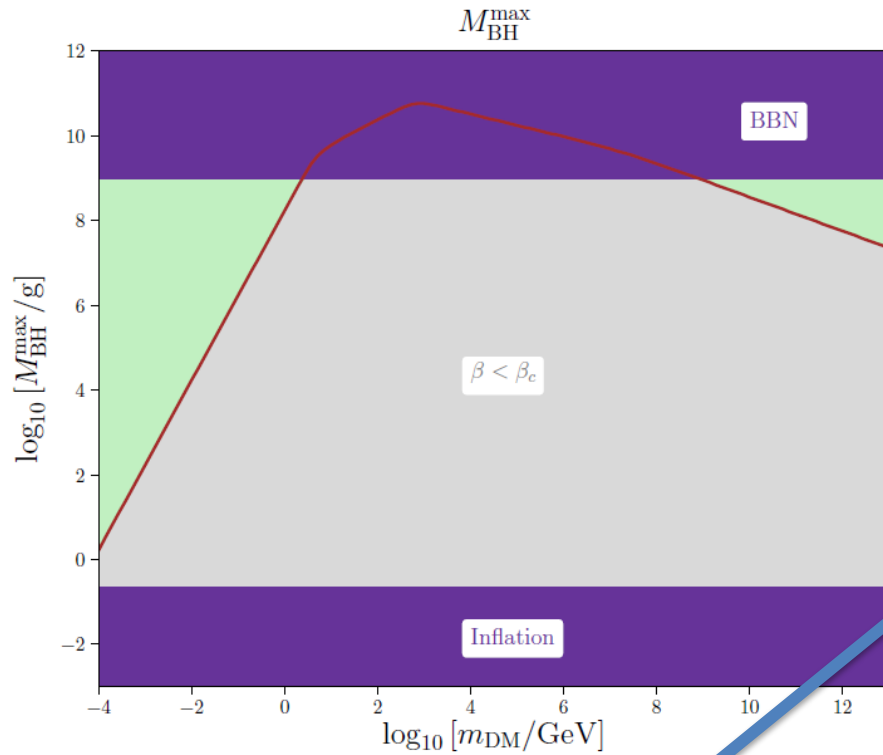


Region of interest
for Freeze-In

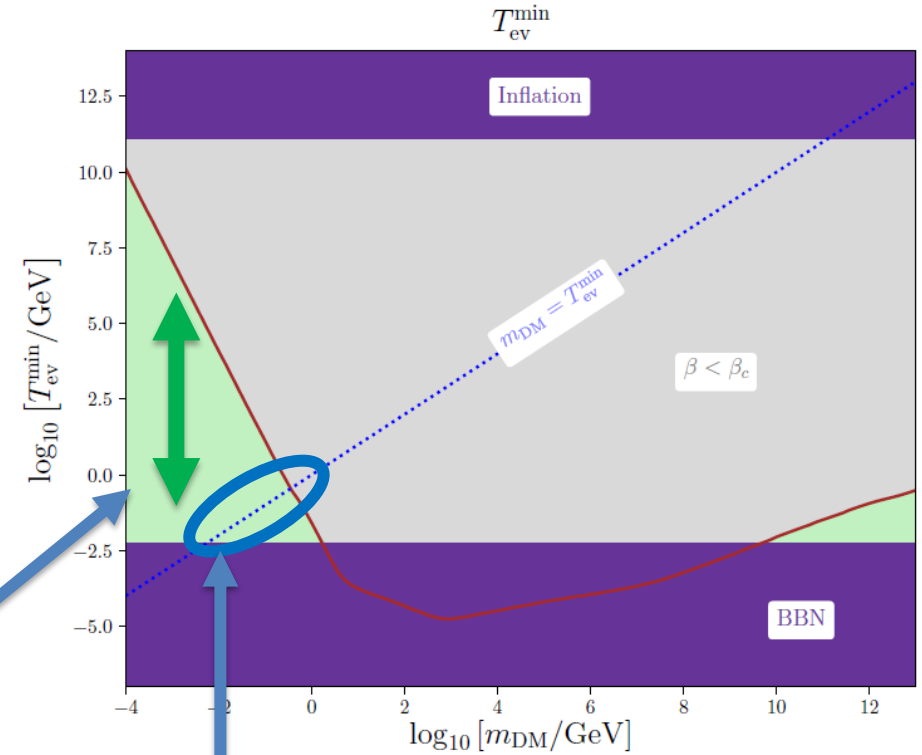


Region of interest
for Freeze-Out

MODIFIED COSMOLOGY



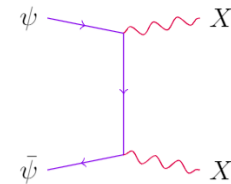
Region of interest
for Freeze-In



~~Region of interest
for Freeze-Out~~

**Thermalization
Of PBHs products...**

TBH large +



BOLTZMANN EQUATIONS

$$\begin{aligned}
 \dot{n}_{\text{DM}} + 3Hn_{\text{DM}} &= \overbrace{g_{\text{DM}} \int C[f_{\text{DM}}] \frac{d^3 p}{(2\pi)^3}}^{\text{DM Annihilation, X decay}} + \overbrace{\left. \frac{dn_{\text{DM}}}{dt} \right|_{\text{BH}}}^{\text{PBH evaporation}} \\
 \dot{n}_X + 3Hn_X &= \overbrace{g_X \int C[f_X] \frac{d^3 p}{(2\pi)^3}}^{\text{DM Annihilation, X decay}} + \overbrace{\left. \frac{dn_X}{dt} \right|_{\text{BH}}}^{\text{PBH evaporation}}, \\
 \dot{\rho}_{\text{SM}} + 4H\rho_{\text{SM}} &= \left. \frac{dM}{dt} \right|_{\text{SM}}.
 \end{aligned}$$

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



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

Simplified approach...

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

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

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

ANALYTICAL RESULTS

Freeze-In contribution

$$\begin{aligned}\Omega_{\text{I}} &= \alpha m_X^3 \frac{m_{\text{DM}}}{\rho_c} \frac{36\sqrt{10}}{\pi \sqrt{g_{\star,\rho}(m_X)}} \frac{g_{\star,s}(T_{\text{eq}})}{g_{\star,s}(m_X)} \frac{T_{\text{eq}}^3 m_p}{m_X^4} \frac{a_{\text{eq}}^3}{a_0^3} G_{1,3}^{2,1} \left(\frac{3}{2}, \frac{1}{2}, 0 \left| \frac{m_X}{T_{\text{eq}}}, \frac{1}{2} \right. \right), \\ \Omega_{\text{II}} &= \frac{\alpha m_X^3}{4} \frac{m_{\text{DM}}}{\rho_c} \sqrt{\frac{3m_p^2}{\rho_{\text{PBH}}^c}} \left(\frac{a_c}{a_0} \right)^3 T_c \left(\frac{g_{\star,s}(T_c)}{g_{\star,s}(m_X)} \right)^{\frac{1}{3}} G_{1,3}^{2,1} \left(-\frac{3}{2}, \frac{1}{2}, -\frac{7}{4} \left| \frac{m_X}{2T_c} \left(\frac{g_{\star,s}(m_X)}{g_{\star,s}(T_c)} \right)^{\frac{1}{3}}, \frac{1}{2} \right. \right), \\ \Omega_{\text{III}} &= 2\alpha m_X^3 \frac{m_{\text{DM}}}{\rho_c} \sqrt{\frac{3m_p^2}{\rho_{\text{PBH}}^{\text{ev}}}} \left(\frac{a_{\text{ev}}}{a_0} \right)^3 T_{\text{ev}} G_{1,3}^{2,1} \left(-\frac{9}{2}, \frac{1}{2}, -\frac{11}{2} \left| \frac{m_X}{2T_{\text{ev}}}, \frac{1}{2} \right. \right), \\ \Omega_{\text{IV}} &= \alpha m_X^3 \frac{m_{\text{DM}}}{\rho_c} \frac{36\sqrt{10}}{\pi \sqrt{g_{\star,\rho}(m_X)}} \frac{g_{\star,s}(T_0)}{g_{\star,s}(m_X)} \frac{T_0^3 m_p}{m_X^4} G_{1,3}^{2,1} \left(\frac{3}{2}, \frac{1}{2}, 0 \left| \frac{m_X}{T_0}, \frac{1}{2} \right. \right),\end{aligned}$$

Freeze-Out contribution

- Regime I and IV:

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

- Regime II:

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

- Regime III:

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

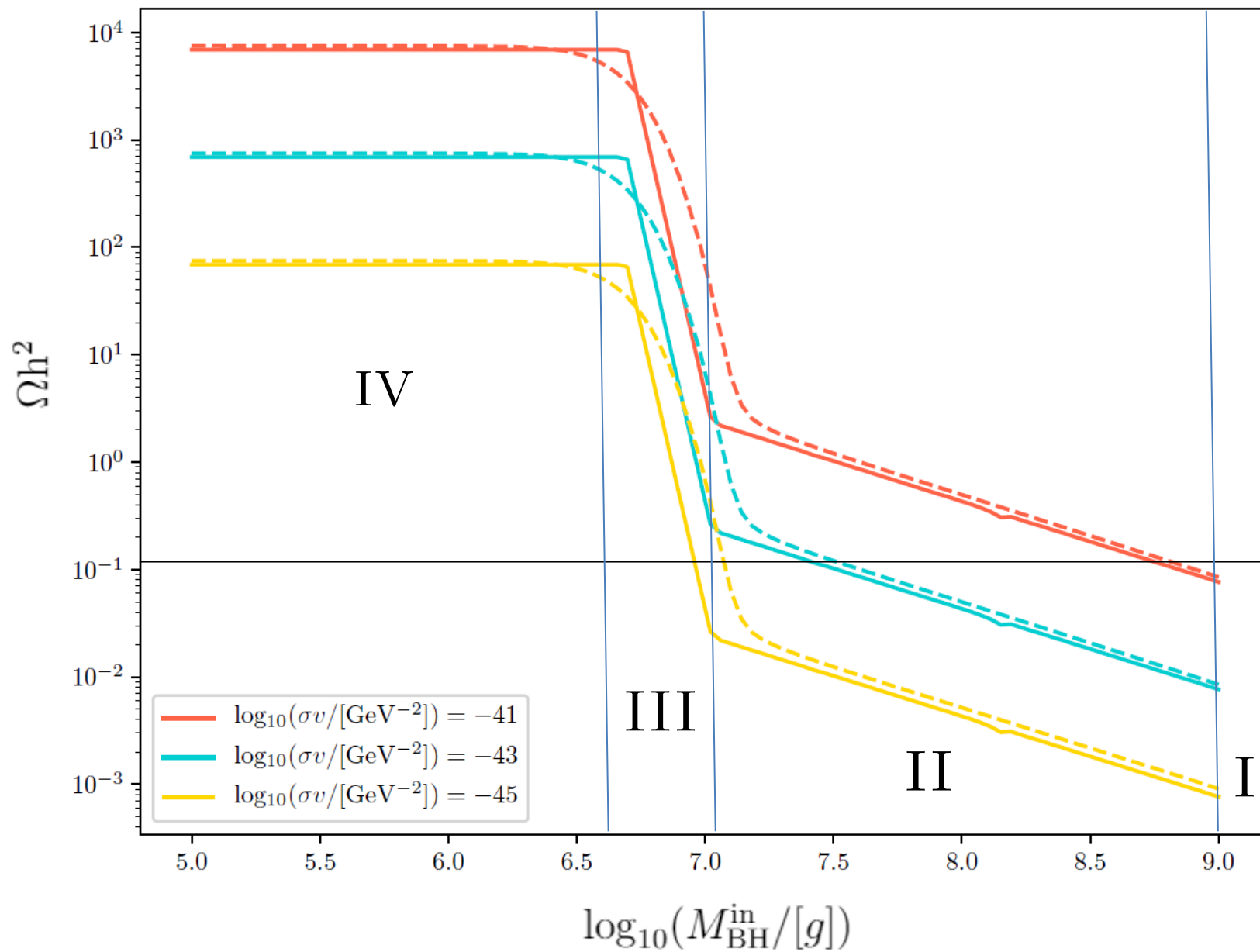
$$\Omega_{\text{I}} = \frac{15}{2\pi} \frac{x_{\text{FO}}}{\sqrt{10 g_{\star}(T_{\text{FO}})}} \frac{s_{\text{eq}}}{m_p \langle \sigma v \rangle \rho_c} \left(\frac{a_{\text{eq}}}{a_0} \right)^3,$$

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

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

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

RESULTS



RESULTS

Freeze-Out [Cheek, LH, Perez-Gonzalez and Turner 2021, arXiv:2107.00016]

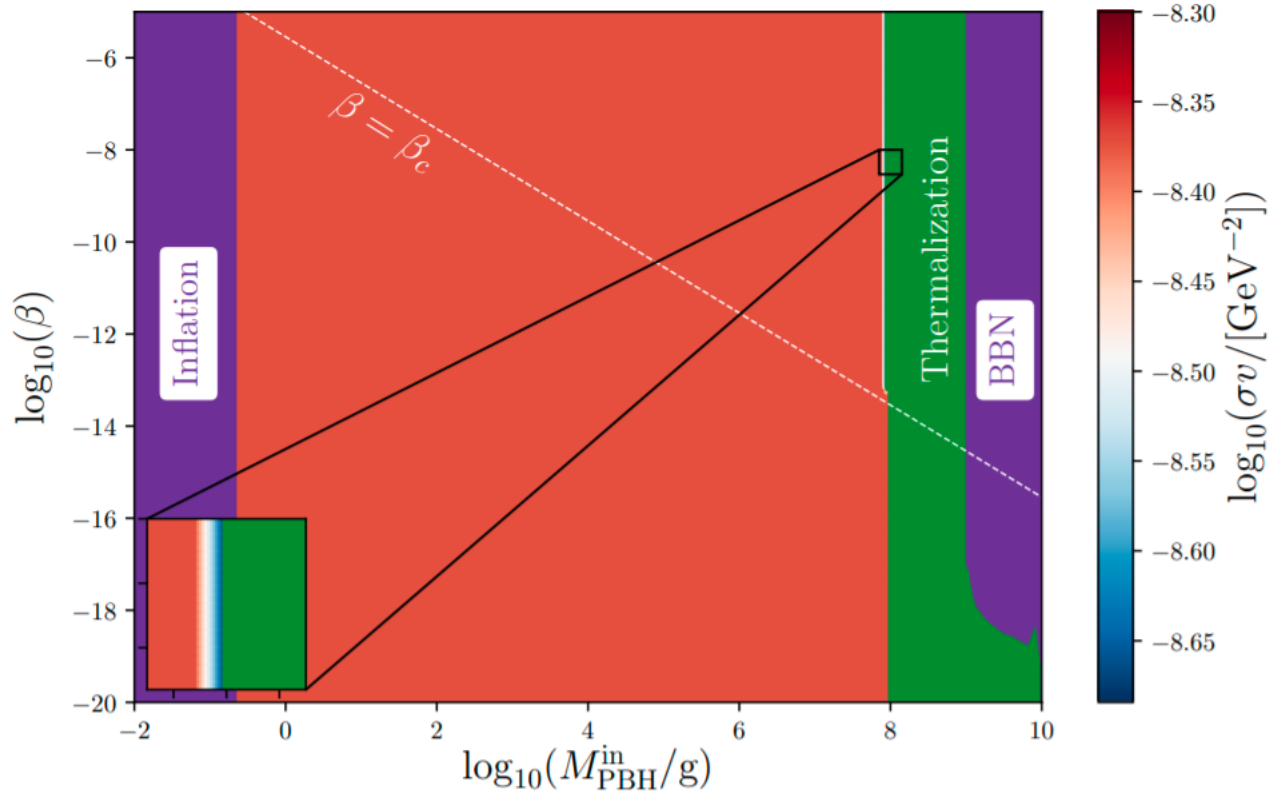


Fig. 7. Two-dimensional scan over the PBH fraction β and mass M_{BH} for a mediator mass $m_{\mathcal{X}} = 10 \text{ GeV}$ and a dark matter mass $m_{\text{DM}} = 1 \text{ GeV}$, and $\text{Br}(\mathcal{X} \rightarrow \text{DM}) = 0.5$. The color map indicates the value of the non-relativistic cross-section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

RESULTS

Freeze-In

[Cheek, LH, Perez-Gonzalez and Turner 2021, arXiv:2107.00016]

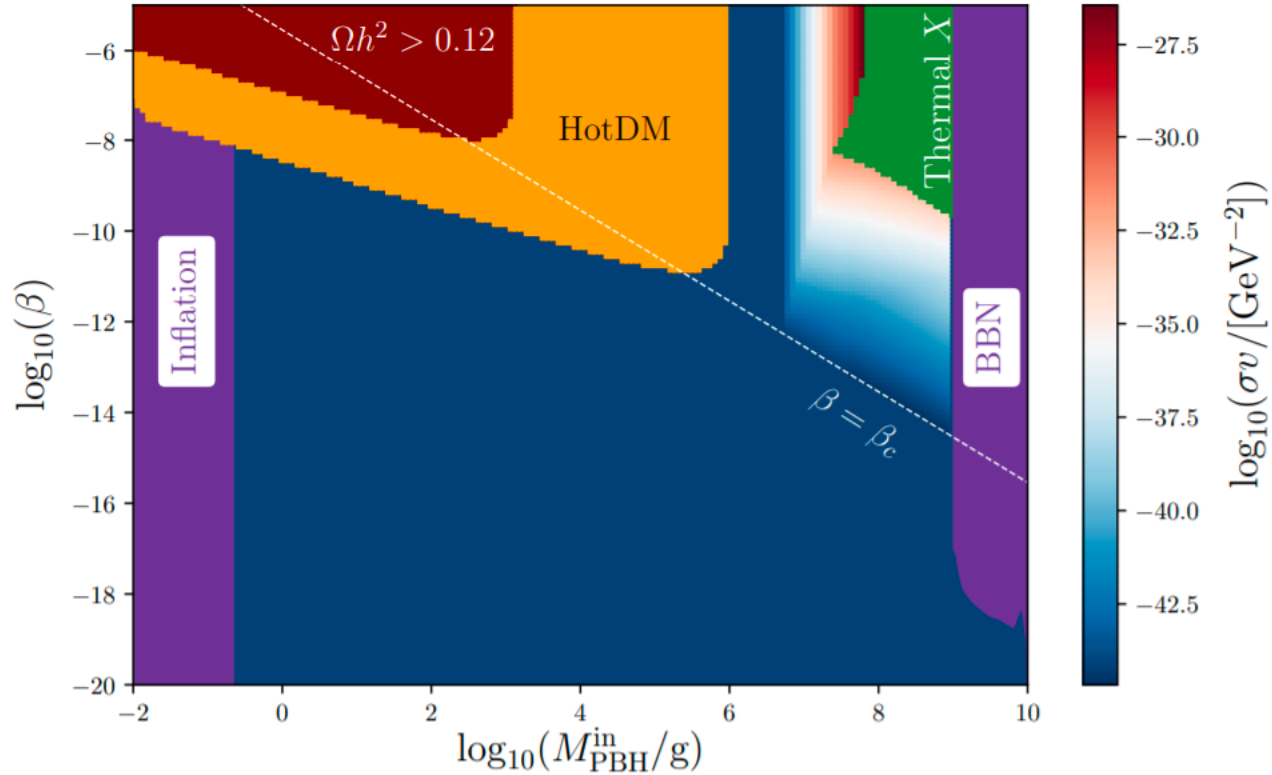


Fig. 11. Two-dimensional scan over the PBH fraction β and mass M_{BH} for a mediator mass $m_X = 1 \text{ TeV}$, a dark matter mass $m_{\text{DM}} = 1 \text{ MeV}$, and $\text{Br}(X \rightarrow \text{SM}) = 10^{-7}$. The color map indicates the value of the non-relativistic cross-section of DM annihilation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

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:

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

$$\dot{n}_{\text{DM}}^{\text{ev}} + 3Hn_{\text{DM}}^{\text{ev}} = \left. \frac{dn_{\text{DM}}^{\text{ev}}}{dt} \right|_{\text{BH}}$$
$$\dot{n}_X + 3Hn_X = \left. \frac{dn_X}{dt} \right|_{\text{BH}}$$
$$\dot{\rho}_{\text{SM}} + 4H\rho_{\text{SM}} = \left. \frac{dM}{dt} \right|_{\text{SM}}$$

BOLTZMANN EQUATIONS

Freeze-In case:

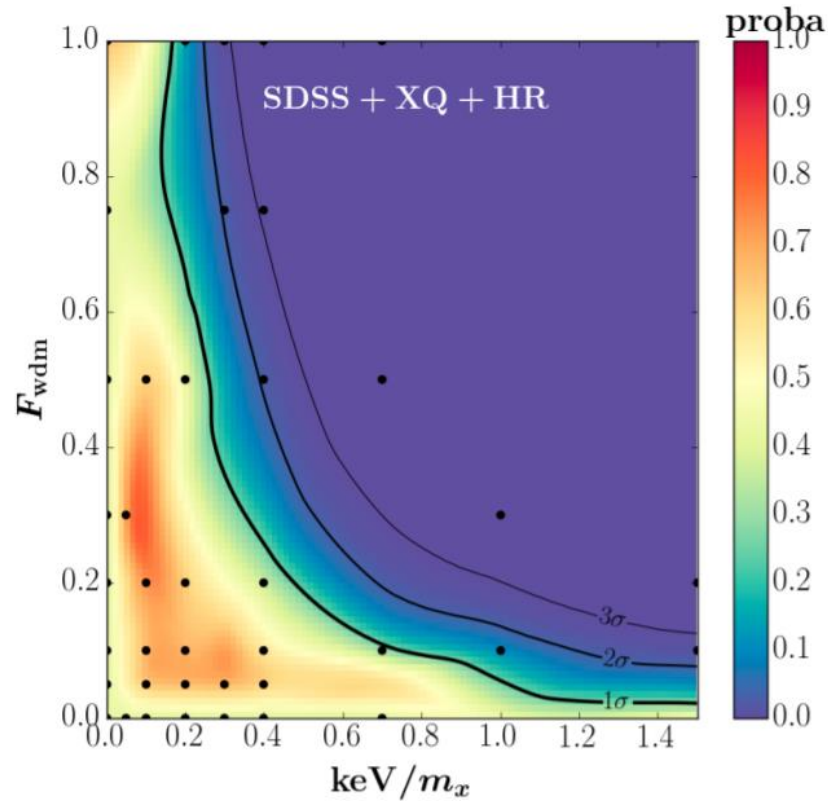
$$\dot{n}_{\text{DM}}^{\text{th}} + 3Hn_{\text{DM}}^{\text{th}} = \langle \sigma v \rangle_{\text{th}} (n_{\text{DM,eq}}^2 - n_{\text{DM}}^{\text{th}2})$$

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

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

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

NON-COLD DARK MATTER

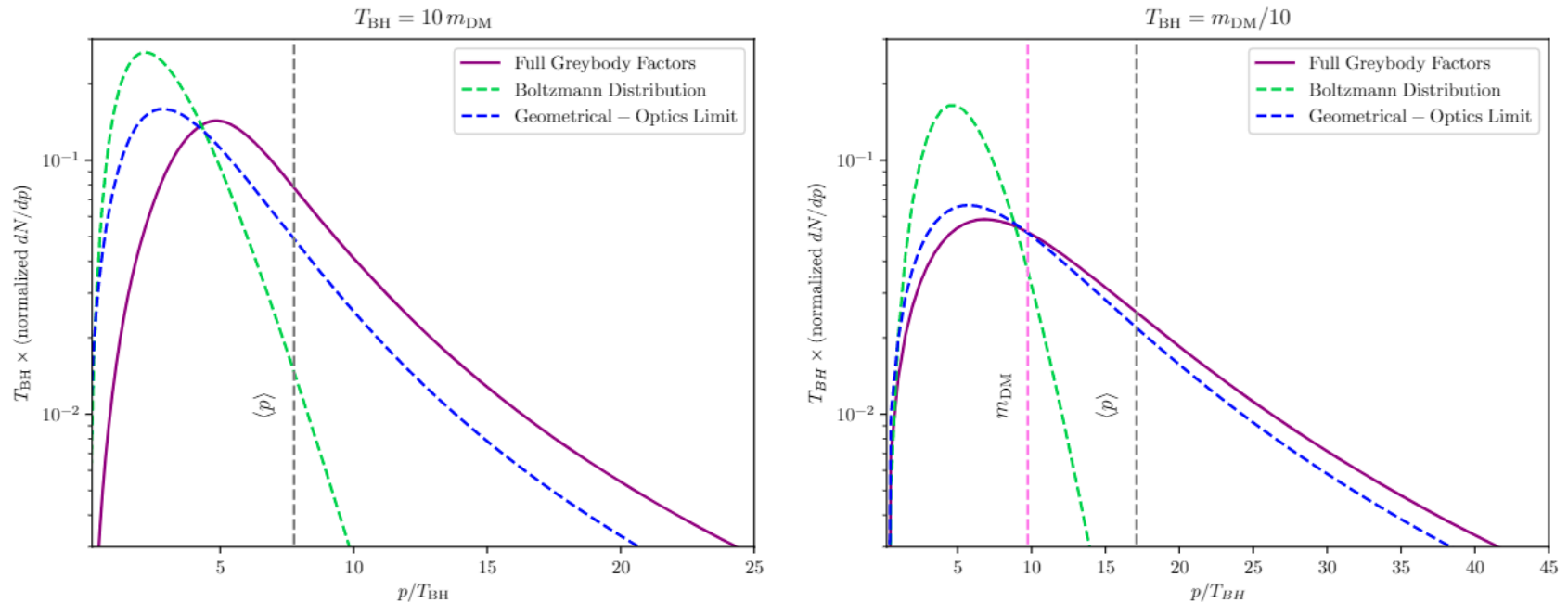


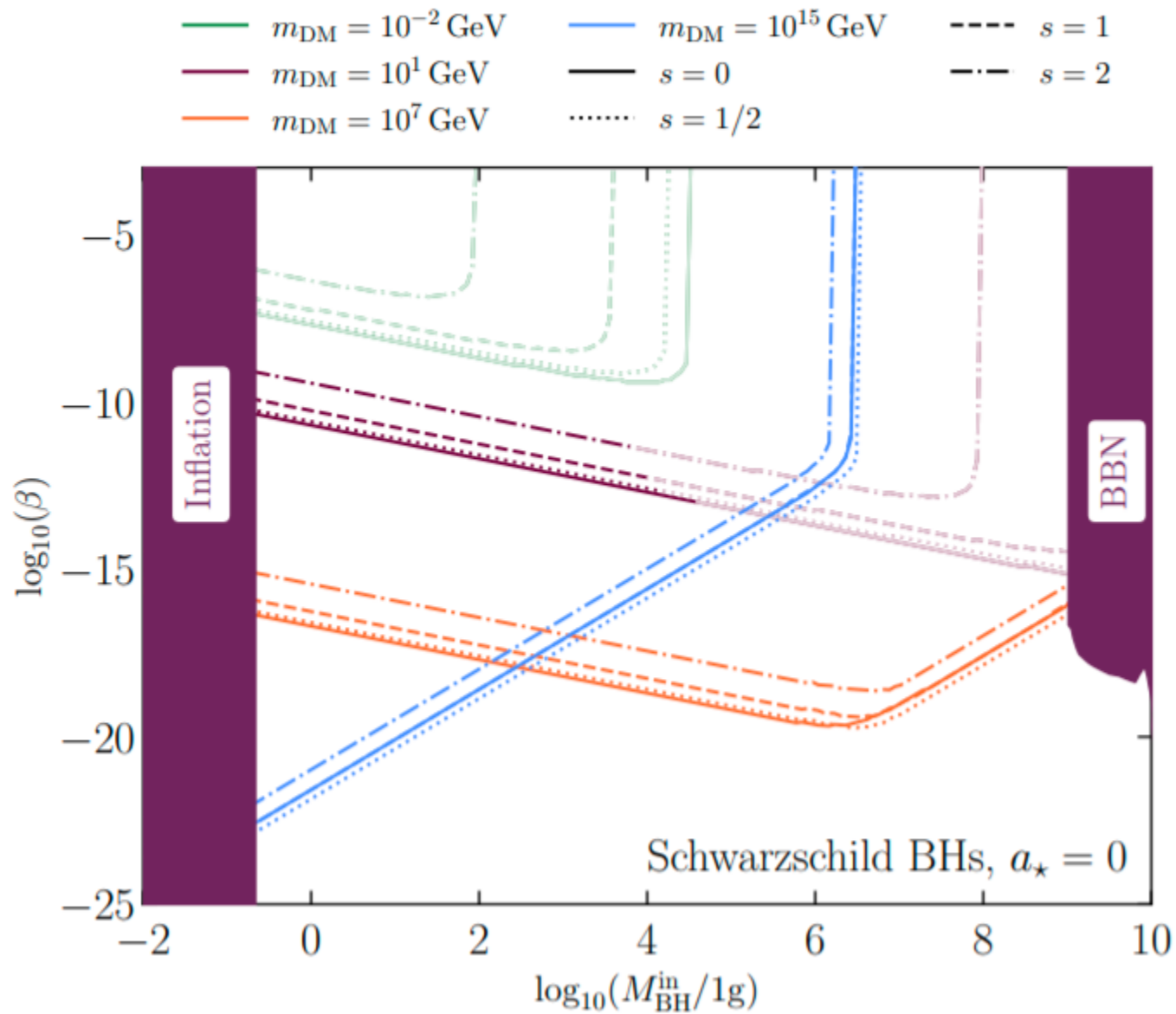
[Baur *et al.* 2017]

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

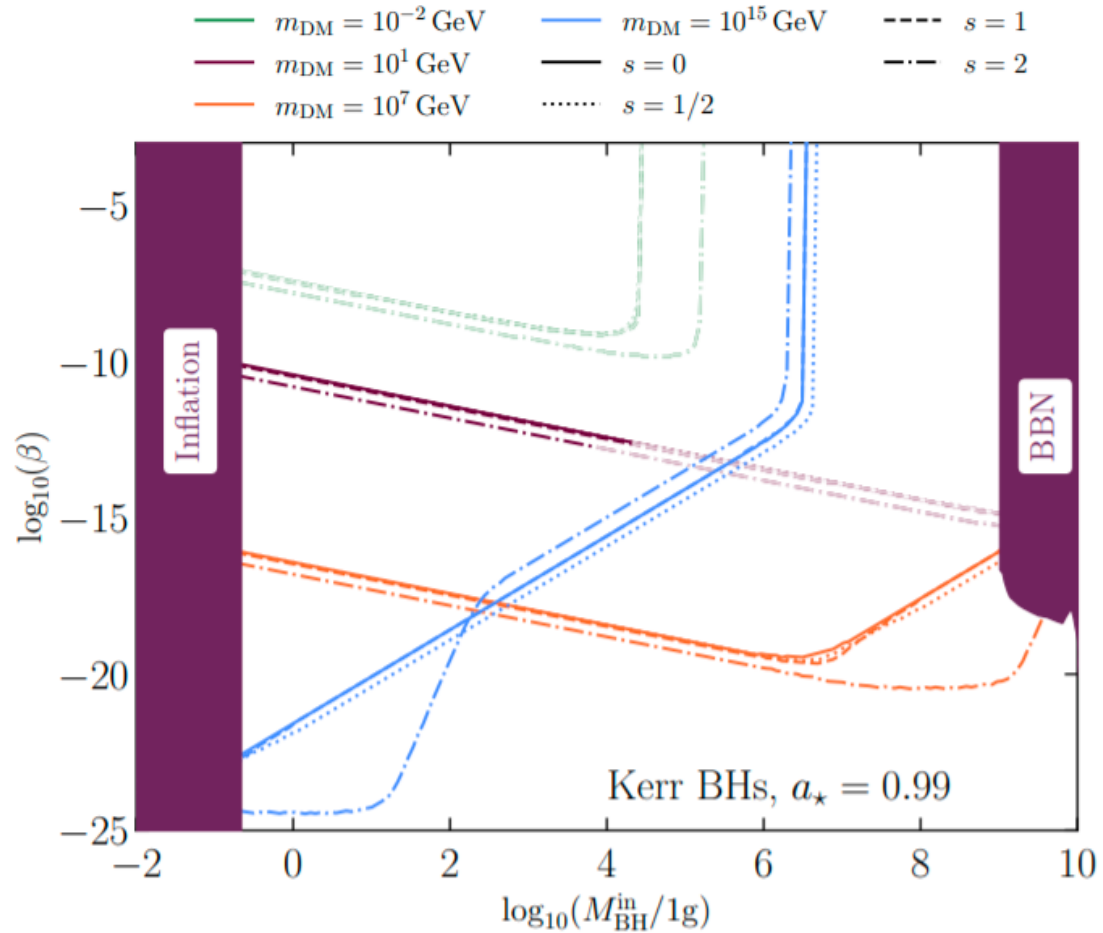
DM FROM EVAPORATION

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





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



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

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