Dark Matter in the time of Primordial Black Holes

Based on:
NB & Óscar Zapata – arXiv:2010.09725, 2011.02510, 2011.12306
NB, Fazlollah Hajkarim & Yong Xu – arXiv:2107.13575
NB, Yuber Pérez-González, Yong Xu & Óscar Zapata – arXiv:2110.04312
NB, Yuber Pérez-González & Yong Xu – arXiv:2205.11522

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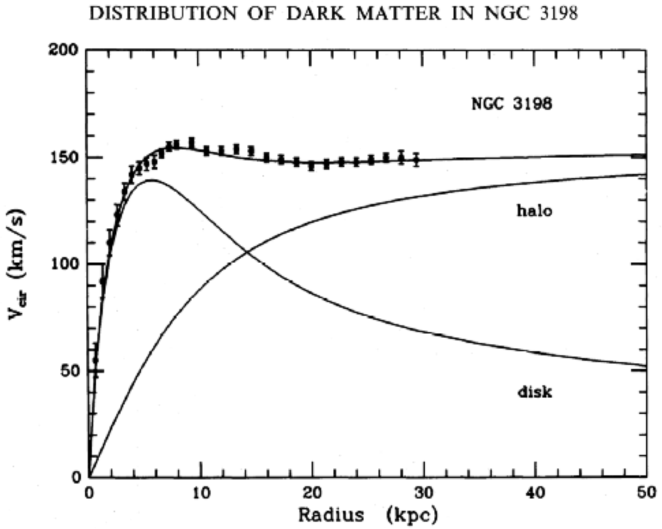
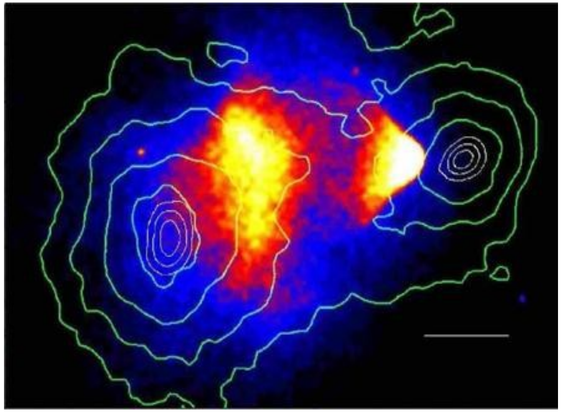
El conocimiento es de todos
Minciencias

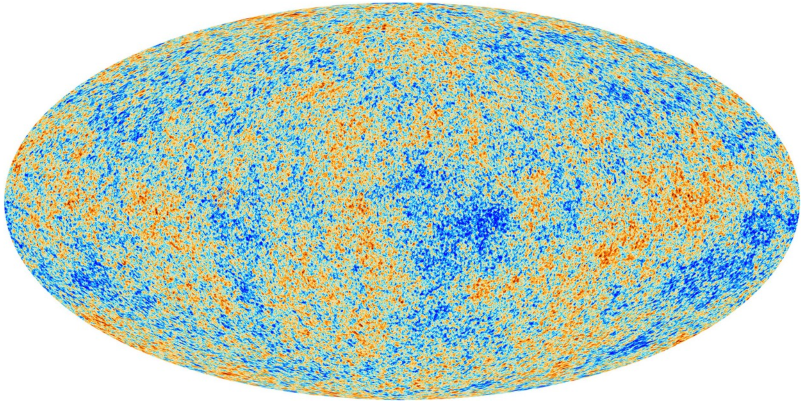
Evidences for Dark Matter

Several observations indicate the existence of non-luminous Dark Matter (missing *gravitational* force) at very different scales!

* Galactic rotation curves
* RC in Clusters of galaxies
* Clusters of galaxies
* CMB anisotropies

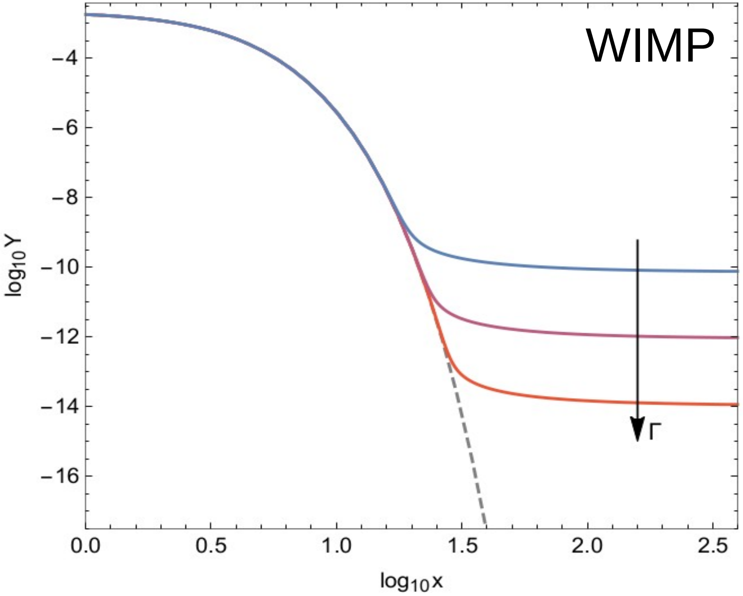


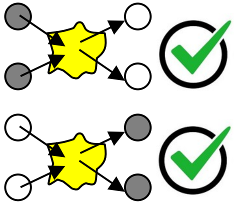




Dark Matter: WIMP

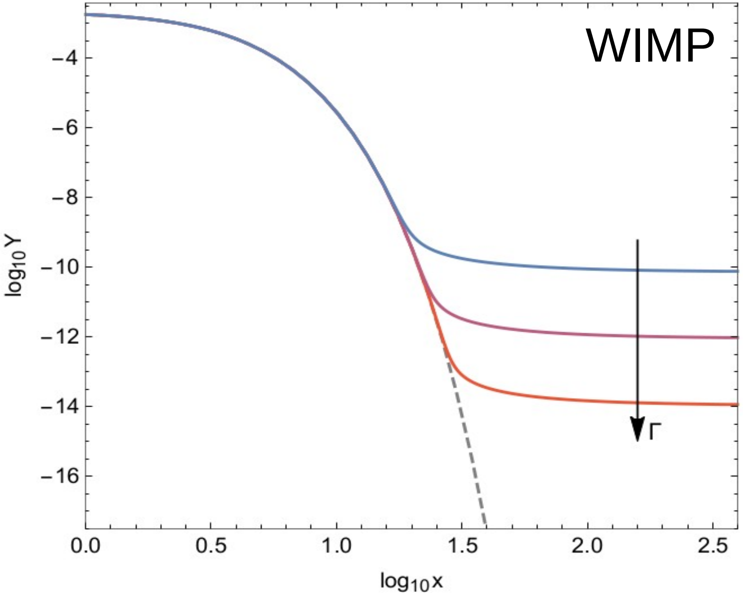
$$\frac{dn_\chi}{dt} + 3\,H\,n_\chi = -\langle v\sigma_\chi\rangle\left[n_\chi^2 - (n_\chi^{\rm eq})^2\right]$$

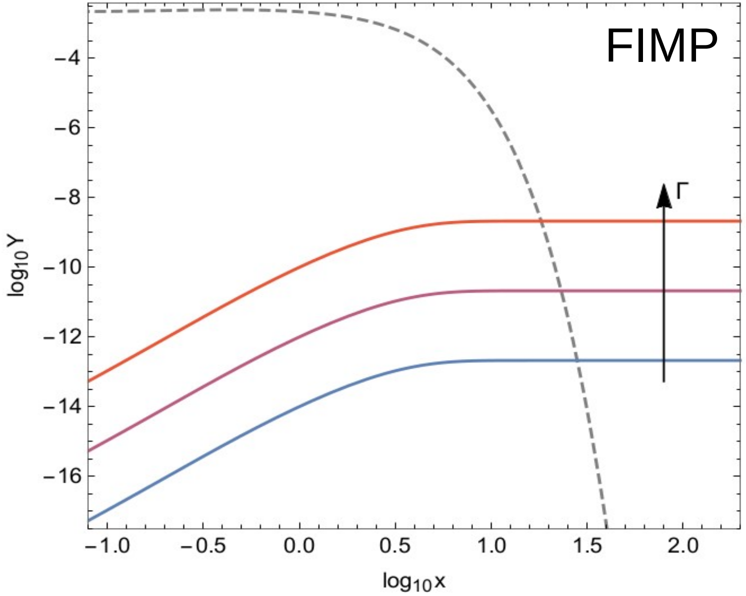


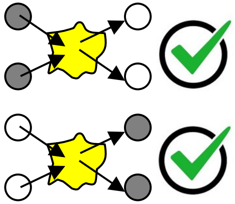


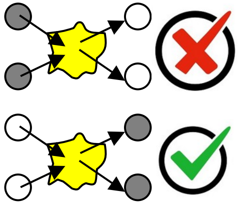
Dark Matter: WIMP vs FIMP

$$\frac{dn_\chi}{dt} + 3\,H\,n_\chi = -\langle v\sigma_\chi\rangle\left[n_\chi^2 - (n_\chi^{\rm eq})^2\right]$$









What if DM *only* couples to the SM via *gravitational interactions*?

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DM is *unavoidably* produced by a number of *gravitational processes*!

1. **DM from PBHs**

Primordial Black Holes

* Density fluctuations can collapse into a PBH in the early universe

* Lose mass by emitting *all* particles via Hawking evaporation
  → PBH have a ~black body spectrum, with temperature $T_{BH} \sim 1/M_{BH}$
  → PBHs unavoidable radiate DM!

* If $M_{in} < 10^9$ g, PBH completely evaporate before BBN
  → poorly constrained

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Effective theory: Three free parameters

* A single PBH characterized by its mass at formation $\boldsymbol{M}_{\bf in}$
    (or equivalently, by the SM temperature $T_{\rm in}$ at formation)

* Initial spin $\boldsymbol{a}_*$
* Initial PBH energy density $\boldsymbol{\beta} = \rho_{\rm BH}/\rho_{\rm SM}$

DM from PBHs

DM density = PBH density x # DM emitted per PBH

Number of DM particles radiated per PBH

→ Only depends on initial PBH mass!

$$N_j = \frac{15\,\zeta(3)}{\pi^4} \frac{g_j\,\mathcal{C}_n}{g_\star(T_{\rm BH})} \begin{cases} \left(\frac{M_{\rm in}}{M_P}\right)^2 & \text{for} \quad m_j \leq T_{\rm BH}^{\rm in} \\ \left(\frac{M_P}{m_j}\right)^2 & \text{for} \quad m_j \geq T_{\rm BH}^{\rm in} \end{cases}$$

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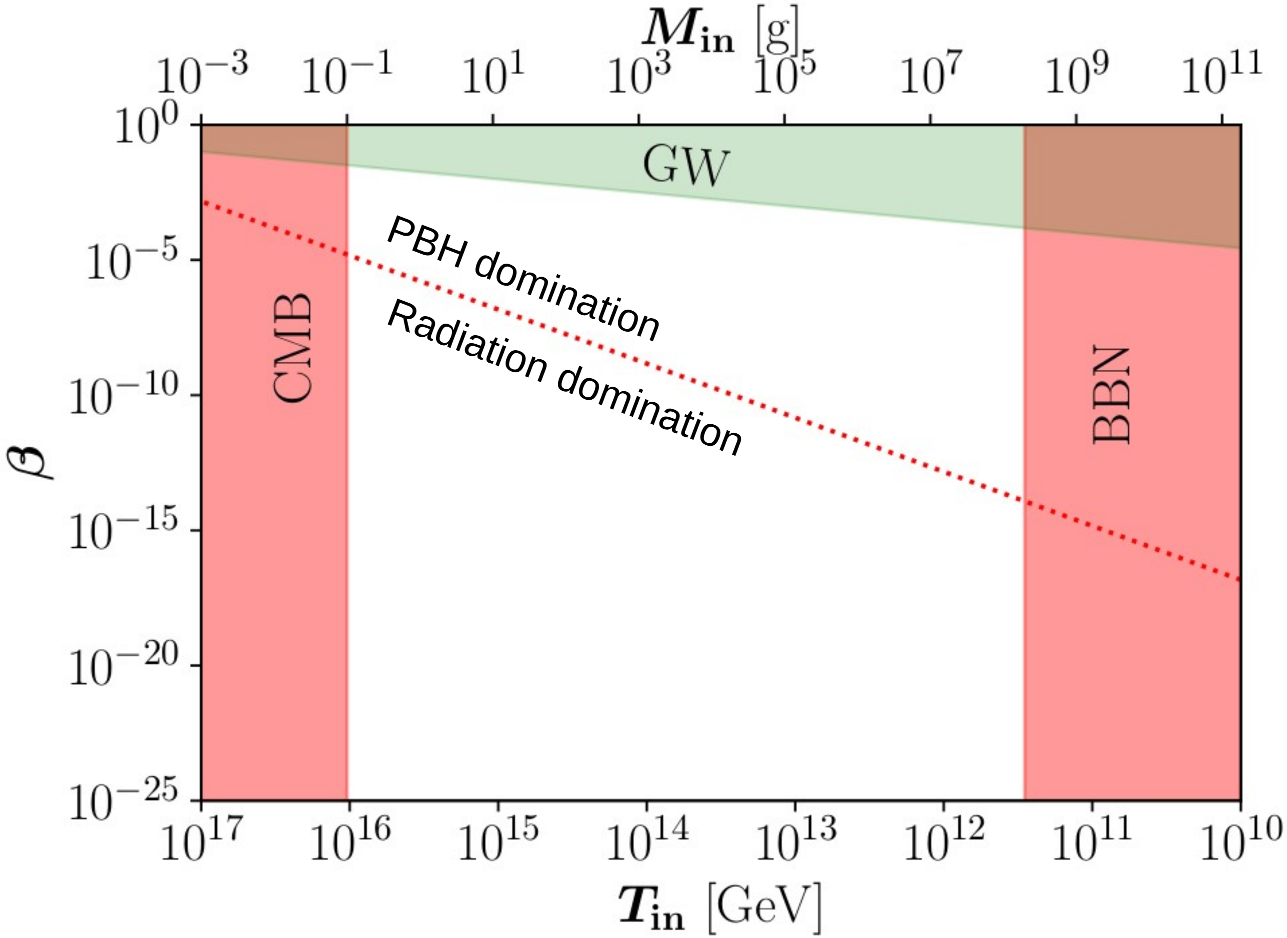
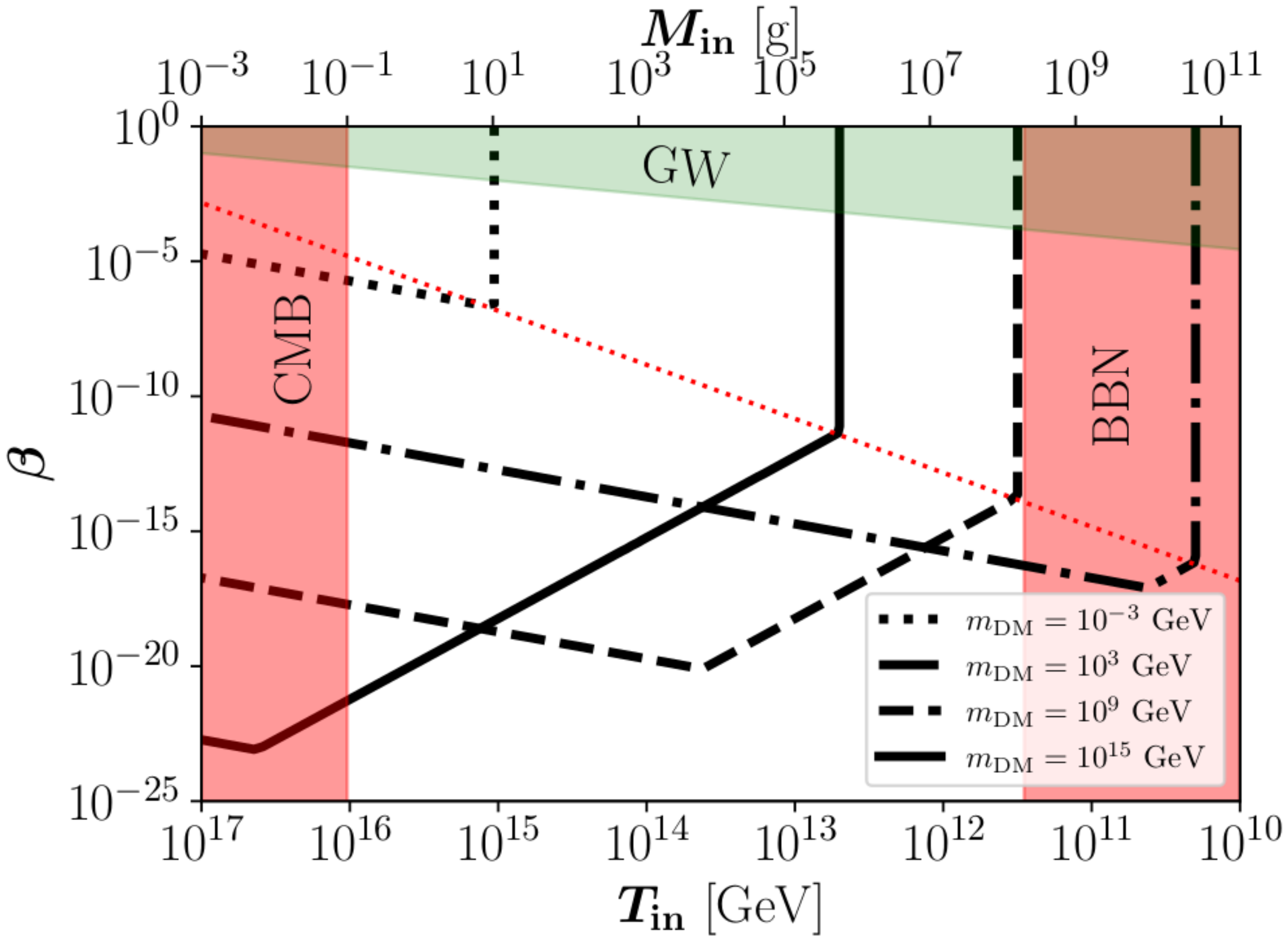
As PBH scale like non-relativistic matter,
they can dominate the total energy density of the universe
→ *Nonstandard* expansion!

DM from PBHs


M_{in} [g]
10^{-3} 10^{-1} 10^{1} 10^{3} 10^{5} 10^{7} 10^{9} 10^{11}
10^{0} 10^{-5} 10^{-10} 10^{-15} 10^{-20} 10^{-25}
β
GW
CMB
BBN
PBH domination
Radiation domination
10^{17} 10^{16} 10^{15} 10^{14} 10^{13} 10^{12} 10^{11} 10^{10}
T_{in} [GeV]

DM from PBHs



M_{in} [g]
10^{-3} 10^{-1} 10^{1} 10^{3} 10^{5} 10^{7} 10^{9} 10^{11}
10^{0}
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10^{-10}
10^{-15}
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β
GW
CMB
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$m_{DM} = 10^{-3}$ GeV
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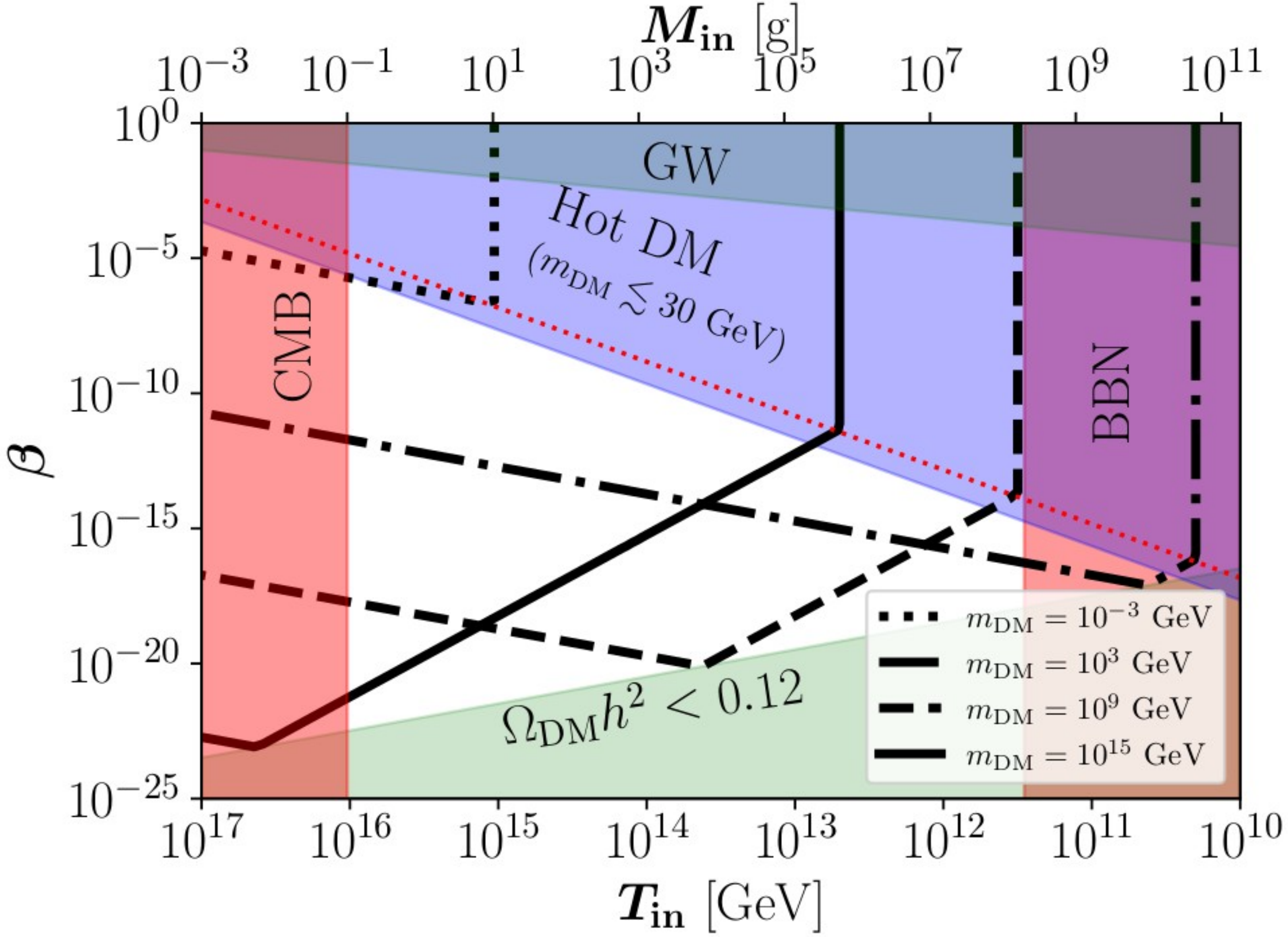
T_{in} [GeV]

DM from PBHs



M_{in} [g]
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β
10^{0} 10^{-5} 10^{-10} 10^{-15} 10^{-20} 10^{-25}
GW
Hot DM
($m_{DM} \lesssim 30$ GeV)
CMB
BBN
$\Omega_{DM}h^2 < 0.12$
$m_{DM} = 10^{-3}$ GeV
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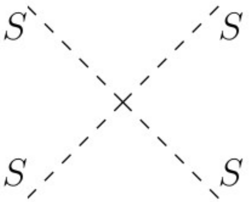
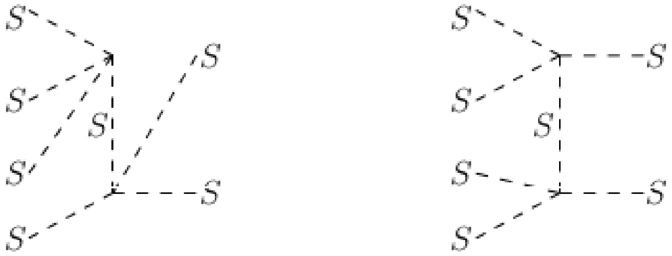
T_{in} [GeV]

2. **Self-interacting DM from PBHs**

Self-interacting DM from PBHs

- If DM possess sizable self-interactions:
  → DM thermalizes
  → Number-changing interactions: **2**↔**3**, **2**↔**4**...





Self-interacting DM from PBHs

- If DM possess sizable self-interactions:
  - → DM thermalizes
  - → Number-changing interactions: **2**↔**3**, **2**↔**4**...

  * What is the energy transferred from PBHs to DM?
  * What is the DM temperature? (kinetic equilibrium)
  * What is DM equilibrium number density? (chemical equilibrium)

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  → DM thermalizes
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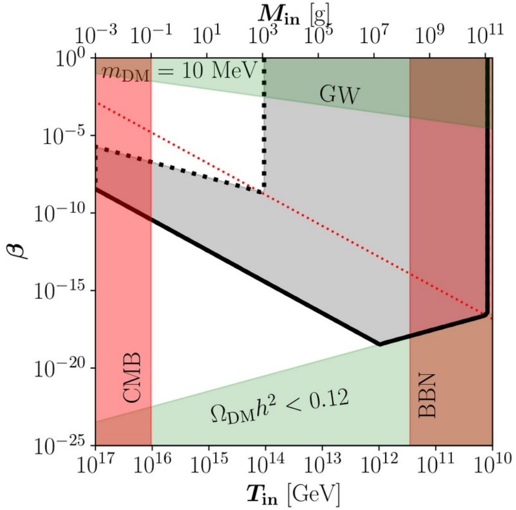
  * What is the energy transferred from PBHs to DM?
  * What is the DM temperature? (kinetic equilibrium)
  * What is DM equilibrium number density? (chemical equilibrium)

  Self-interactions:
  → Increase the DM density
  → Decrease the mean DM kinetic energy

Self-interacting DM from PBHs

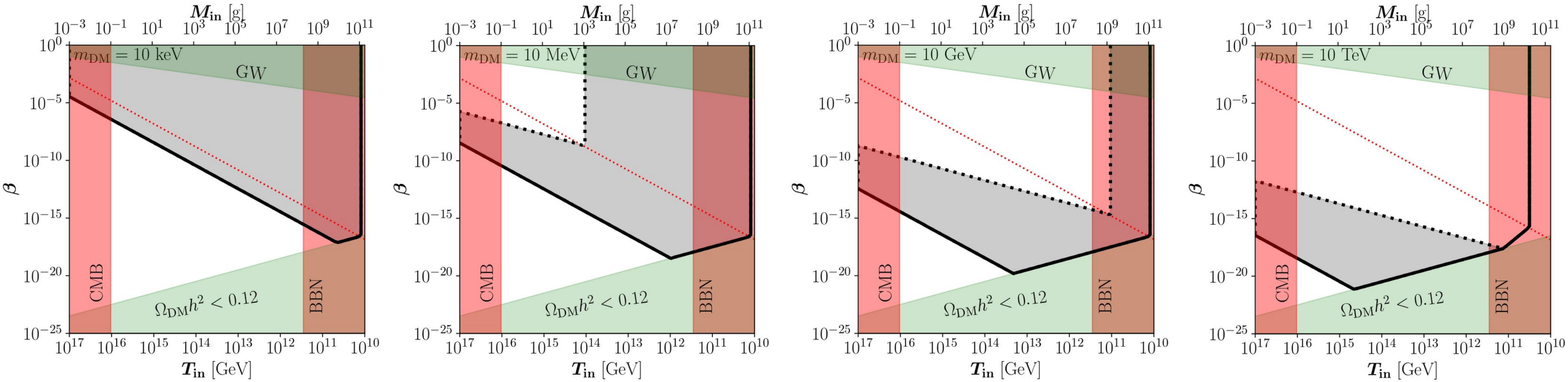


* DM production more efficient → smaller β could be explored

* DM cools down → keV DM becomes viable

* **Model independent result**

Self-interacting DM from PBHs



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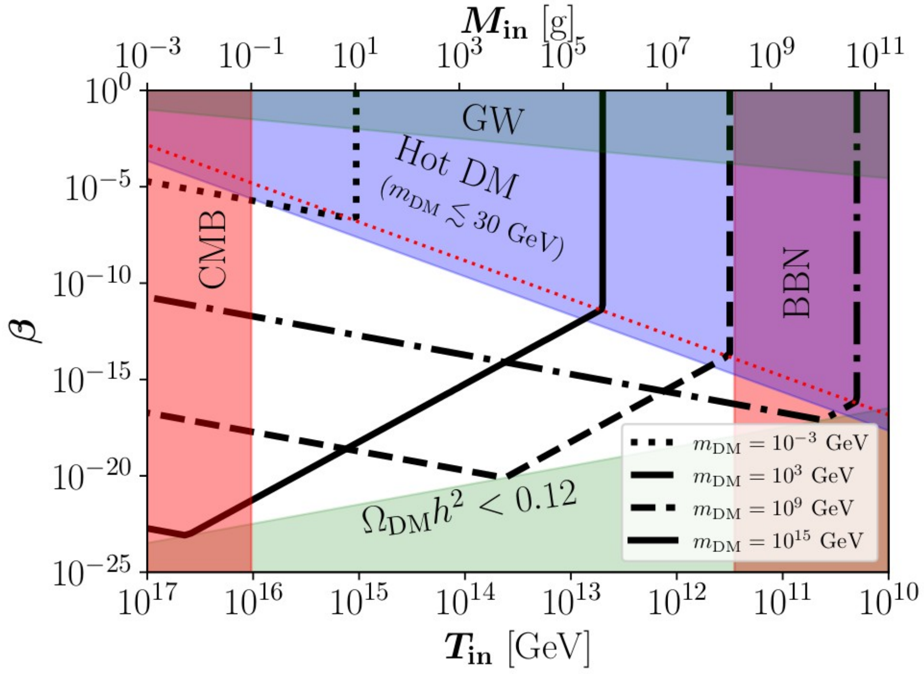
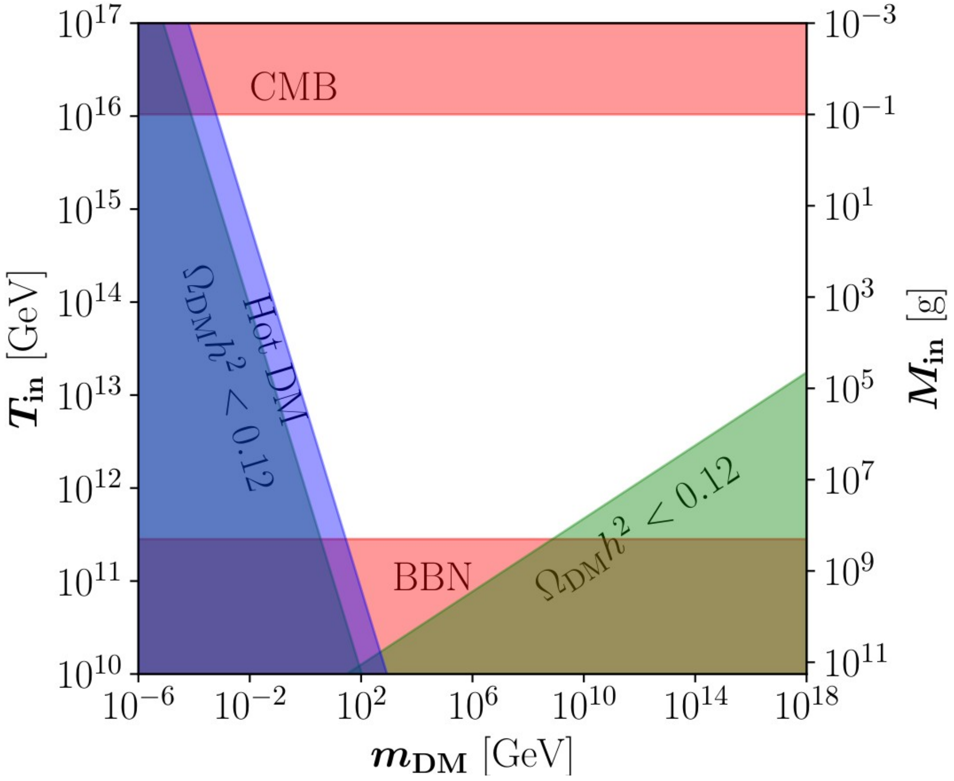
3. **Gravitational UV freeze-in**

DM from PBHs



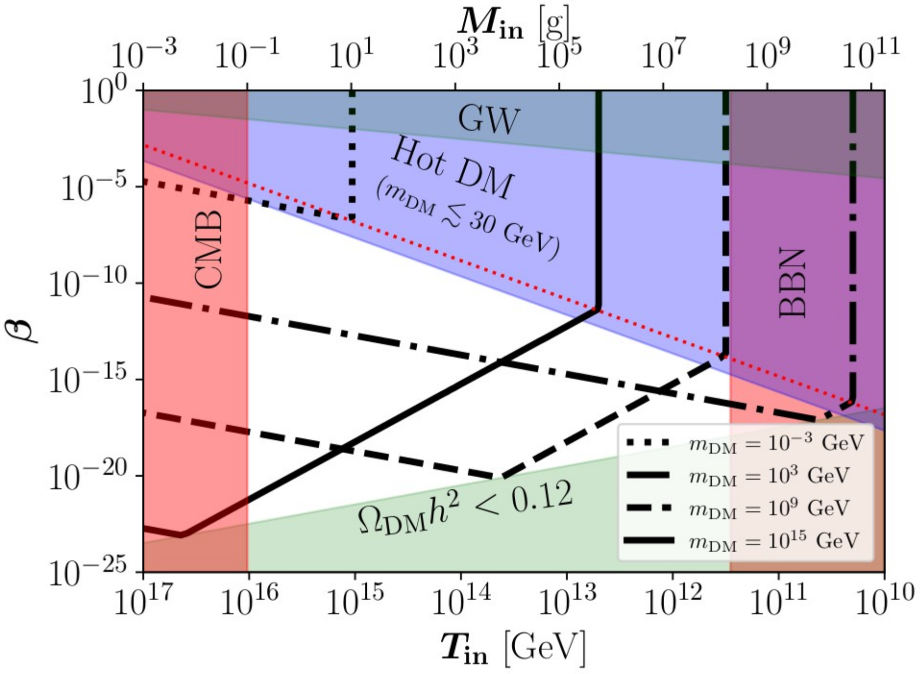
$M_{\rm in}$ [g]
GW
Hot DM
($m_{\rm DM} \lesssim 30$ GeV)
CMB
BBN
$\Omega_{\rm DM}h^2 < 0.12$
$m_{\rm DM} = 10^{-3}$ GeV
$m_{\rm DM} = 10^{3}$ GeV
$m_{\rm DM} = 10^{9}$ GeV
$m_{\rm DM} = 10^{15}$ GeV
β
$T_{\rm in}$ [GeV]

=



CMB
$\Omega_{\rm DM}h^2 < 0.12$
Hot DM
BBN
$\Omega_{\rm DM}h^2 < 0.12$
$T_{\rm in}$ [GeV]
$M_{\rm in}$ [g]
$m_{\rm DM}$ [GeV]

DM from PBHs



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β
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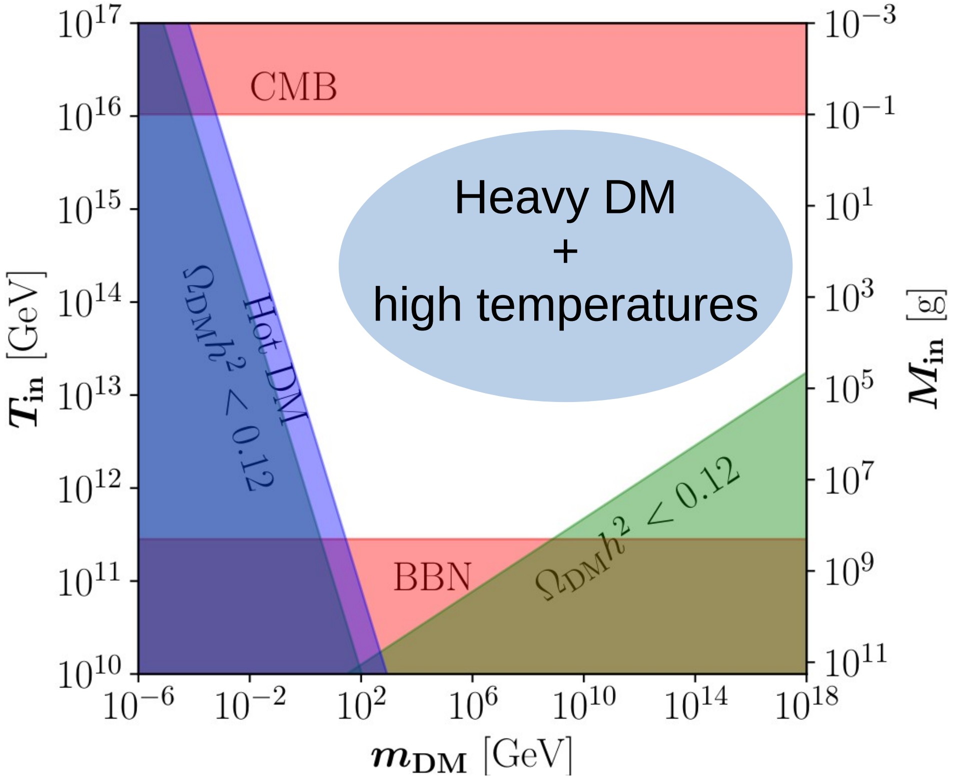
$T_{\rm in}$ [GeV]

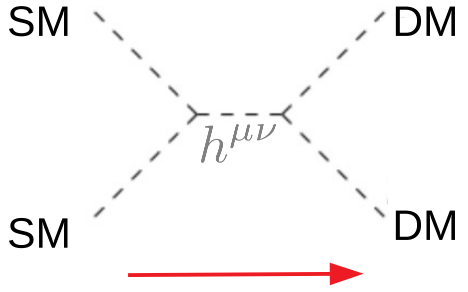
=

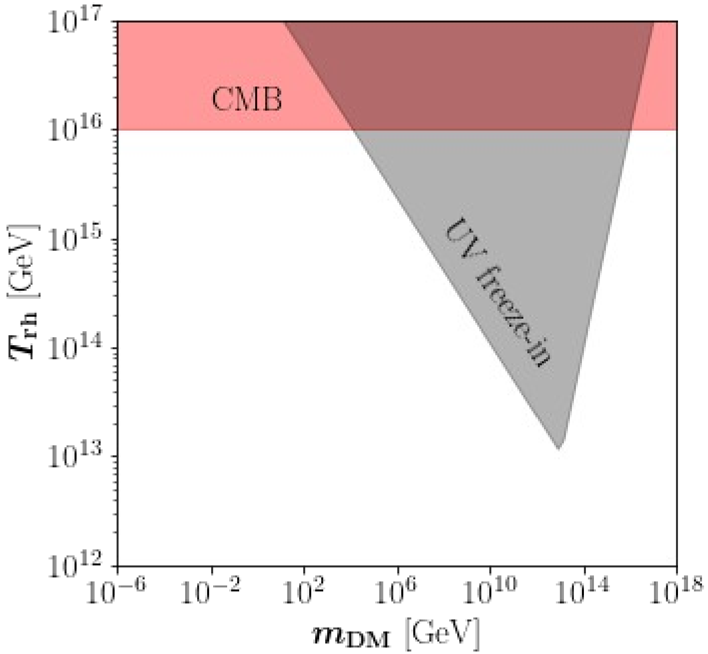


$T_{\rm in}$ [GeV]
10^{17} 10^{16} 10^{15} 10^{14} 10^{13} 10^{12} 10^{11} 10^{10}
CMB
Heavy DM
+
high temperatures
$\Omega_{\rm DM}h^2 < 0.12$
Hot DM
BBN
$\Omega_{\rm DM}h^2 < 0.12$
10^{-3} 10^{-1} 10^{1} 10^{3} 10^{5} 10^{7} 10^{9} 10^{11}
$M_{\rm in}$ [g]
10^{-6} 10^{-2} 10^{2} 10^{6} 10^{10} 10^{14} 10^{18}
$m_{\rm DM}$ [GeV]

Gravitational UV Freeze-in

An example of UV FIMP, mediated by massless SM gravitons





Depends on:

* DM mass and spin
* Reheating temperature T_{rh}

→ No free couplings: M_P

$\Omega h^2 \sim m * (T_{rh}/M_P)^3$

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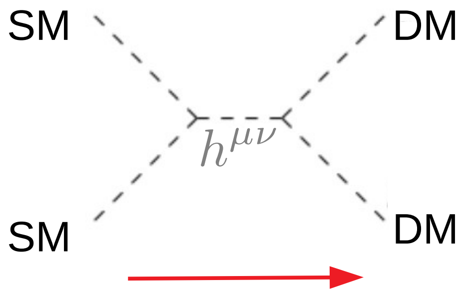

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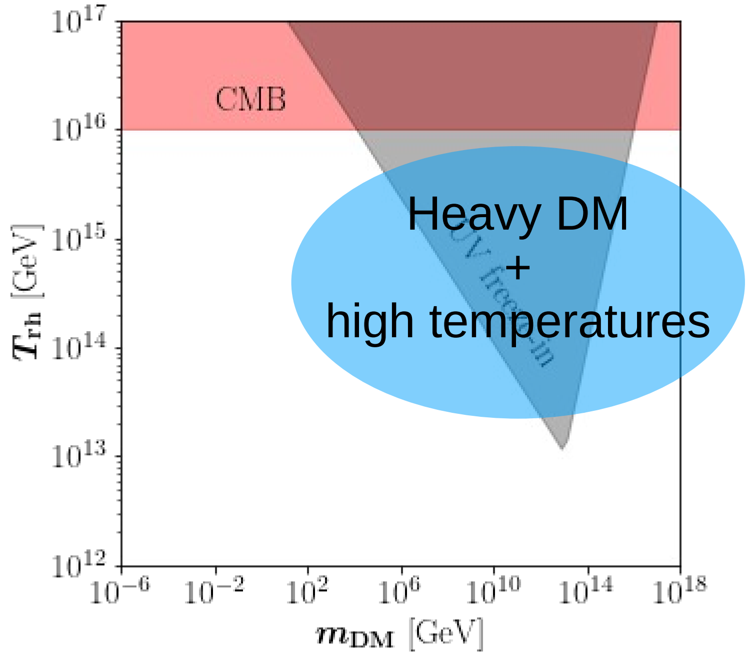
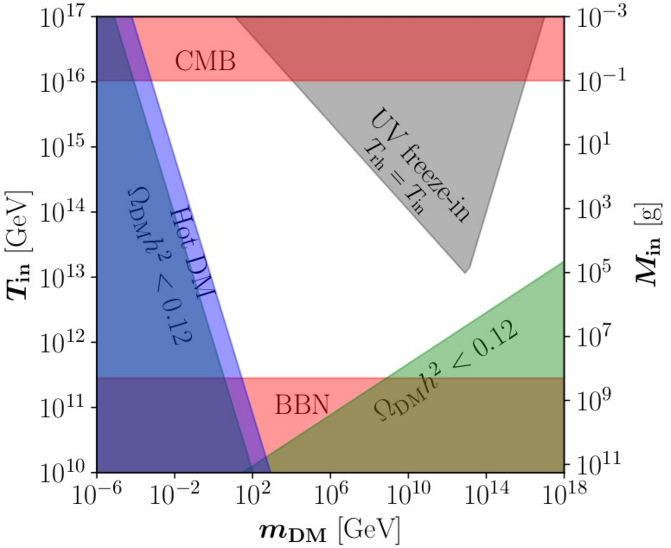


Gravitational DM: PBHs & UV Freeze-in



Gravitational UV freeze-in strongly constrains super heavy DM radiated by PBHs!

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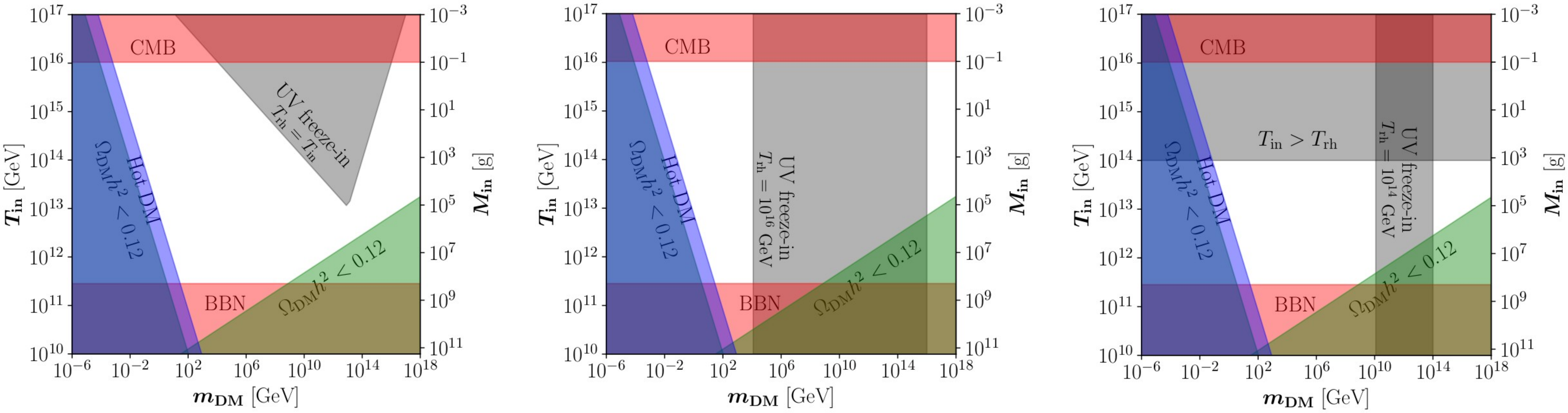
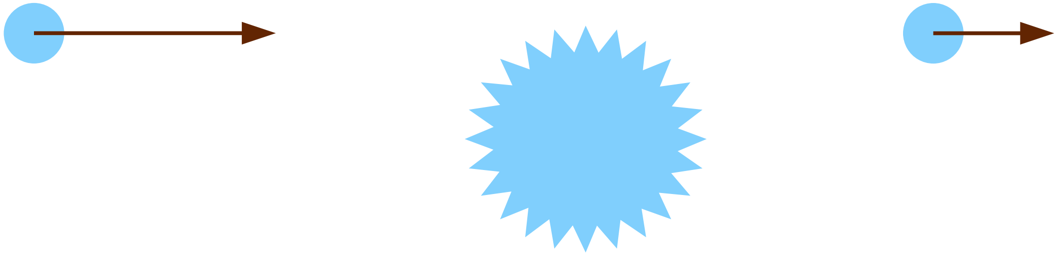


Gravitational UV freeze-in strongly constrains super heavy DM radiated by PBHs!

4. **Superradiance**

Superradiance in a Nutshell

* Ball scattering off a cylinder with lossy surface *slows down*



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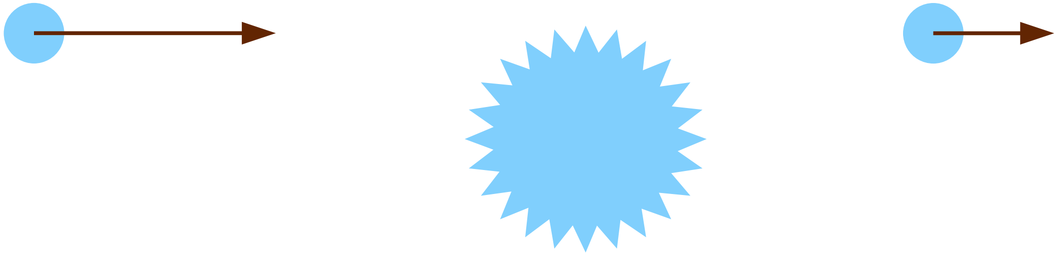
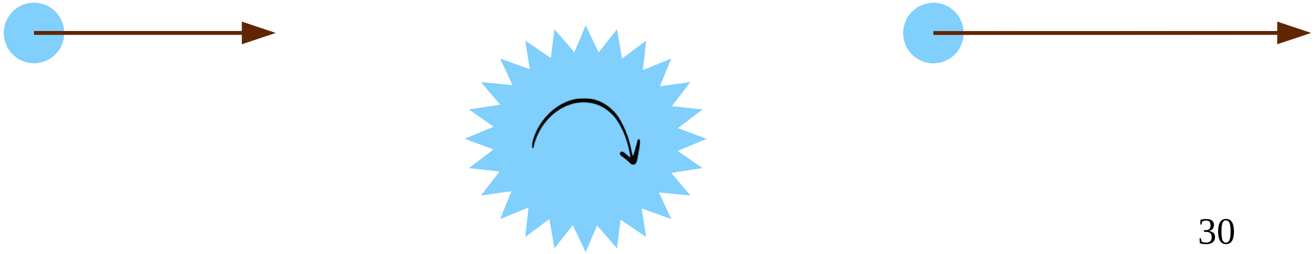


* Ball scattering off a **rotating** cylinder can *increase angular momentum and energy*

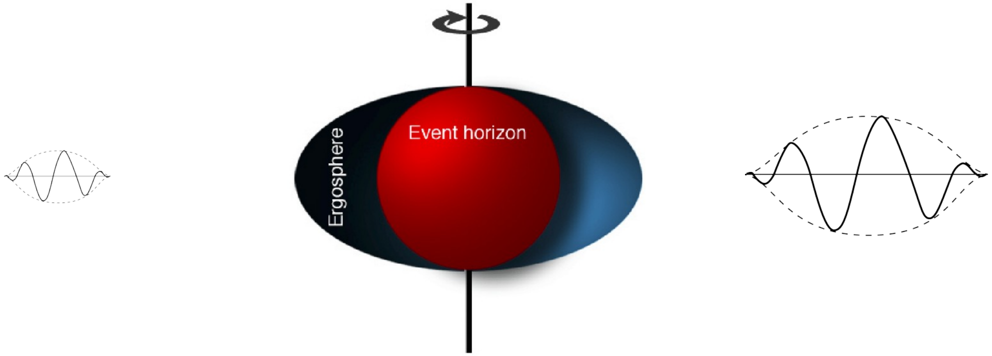
* Effect depends on **dissipation**, necessary to change velocity



Superradiance in a Nutshell

* A wave scattering off a *rotating BH* can increase in amplitude by extracting angular momentum and energy

* Dissipation necessary to increase wave amplitude

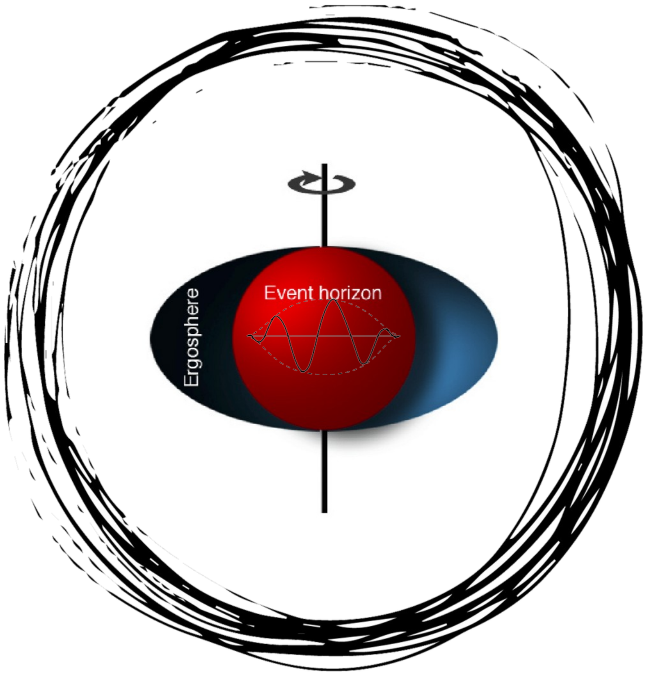


→ Angular velocity of BH horizon bigger that angular velocity of the wave

Superradiance in a Nutshell

* Particles/waves *trapped* near a BH repeat this process continuously

* “BH bomb”
→ exponential instability when surround BH by a mirror



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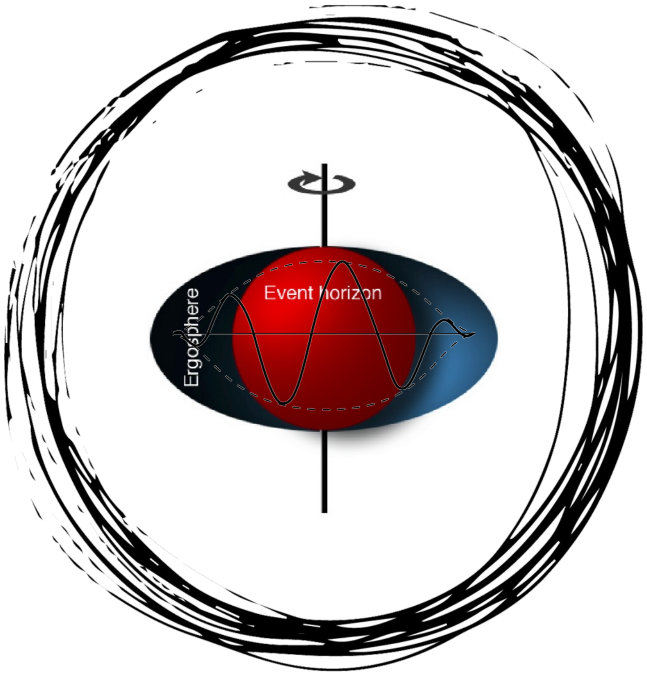

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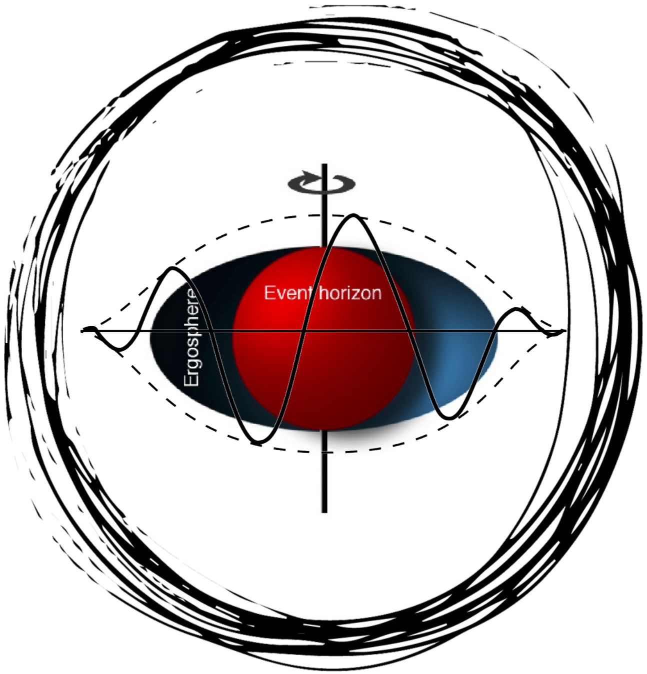

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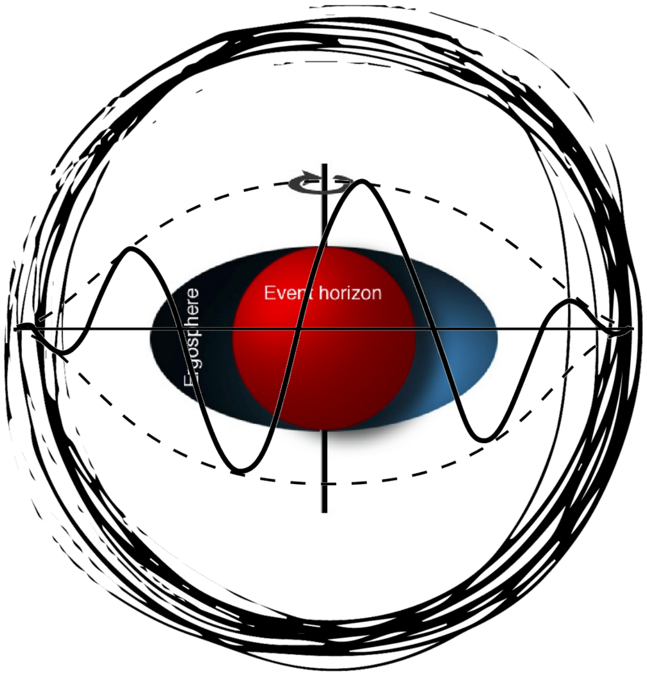

Superradiance in a Nutshell

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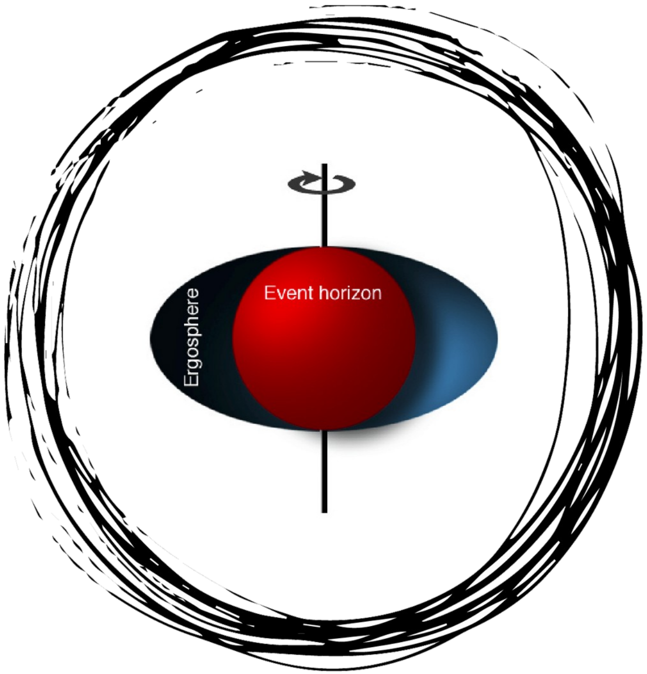
* For massive particles,
gravitational potential barrier provides trapping

* High superradiance rate:
Compton wavelength comparable to BH radius



Superradiance in a Nutshell

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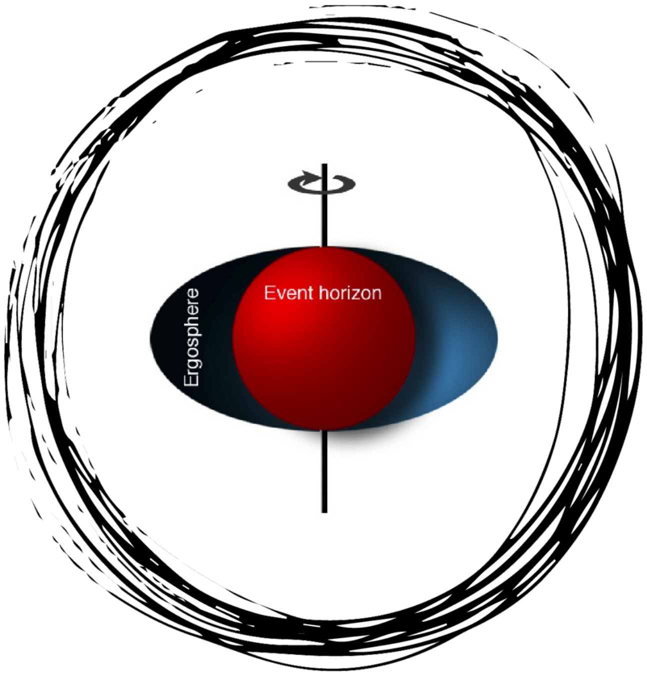
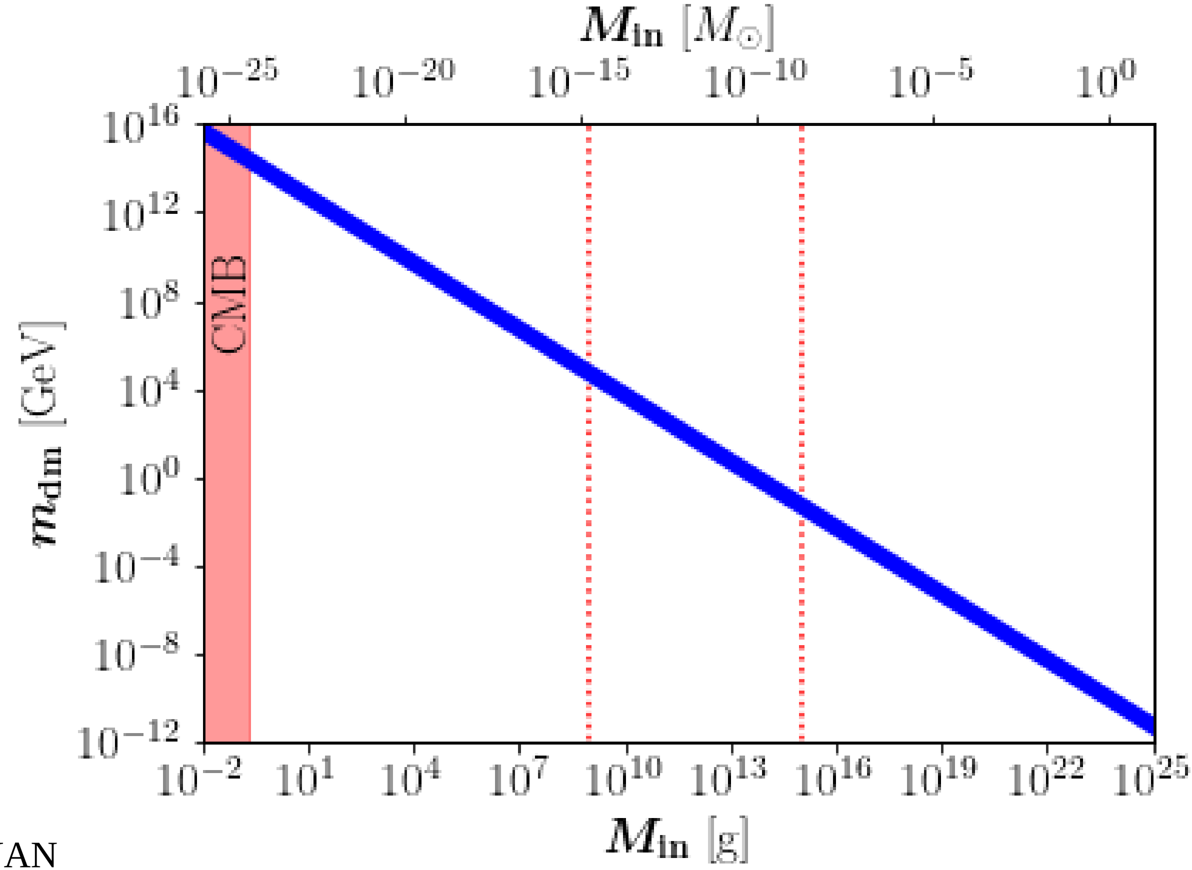
* High superradiance rate:
Compton wavelength comparable to BH radius

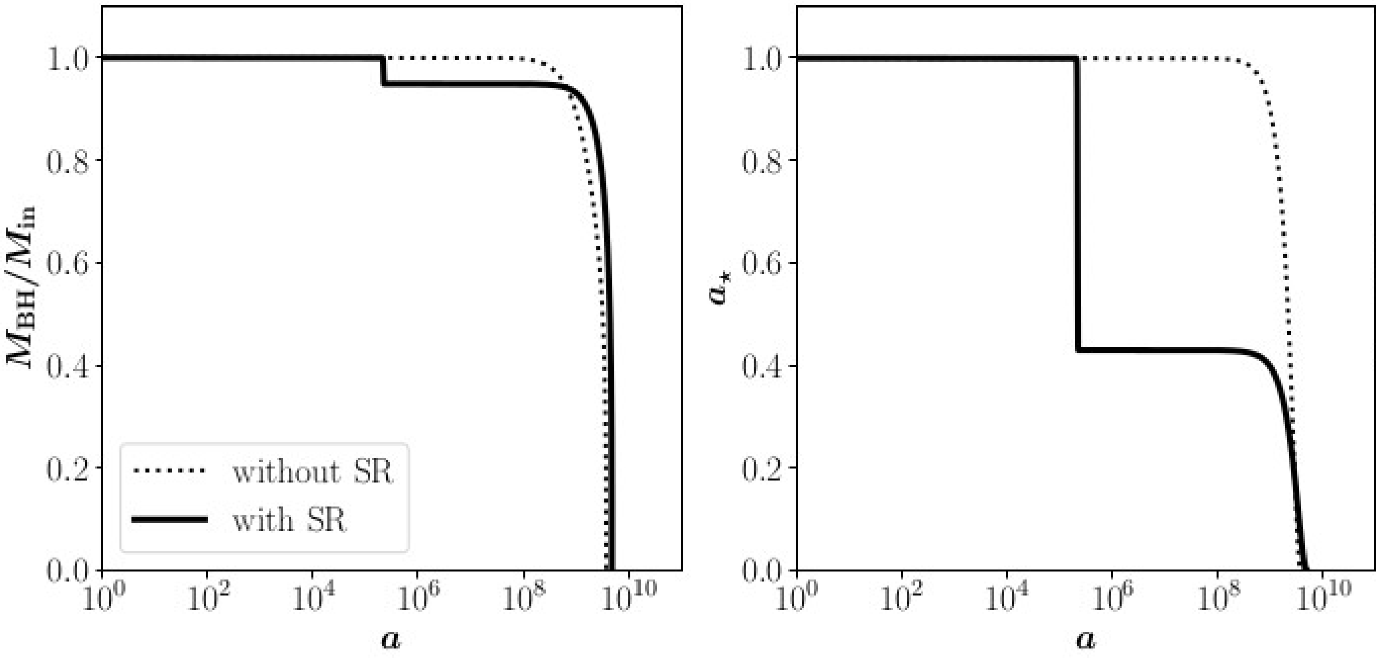
* Formation of bound states:
→ "Gravitational atoms"



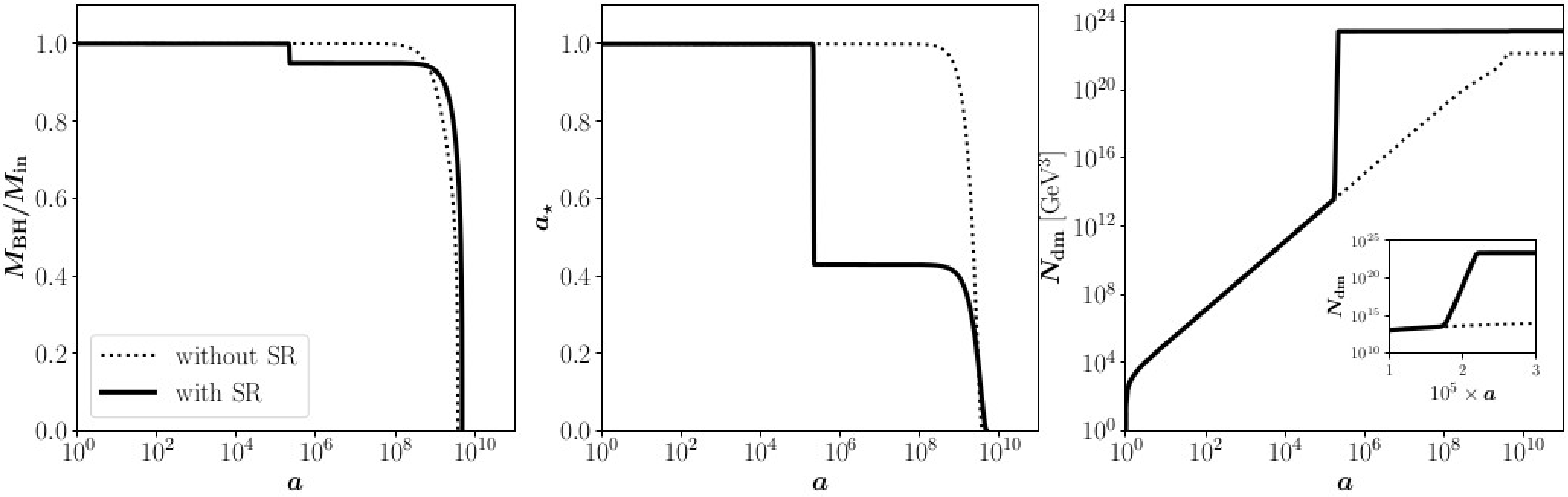
PBHs with Superradiance



PBHs with Superradiance



PBHs with Superradiance



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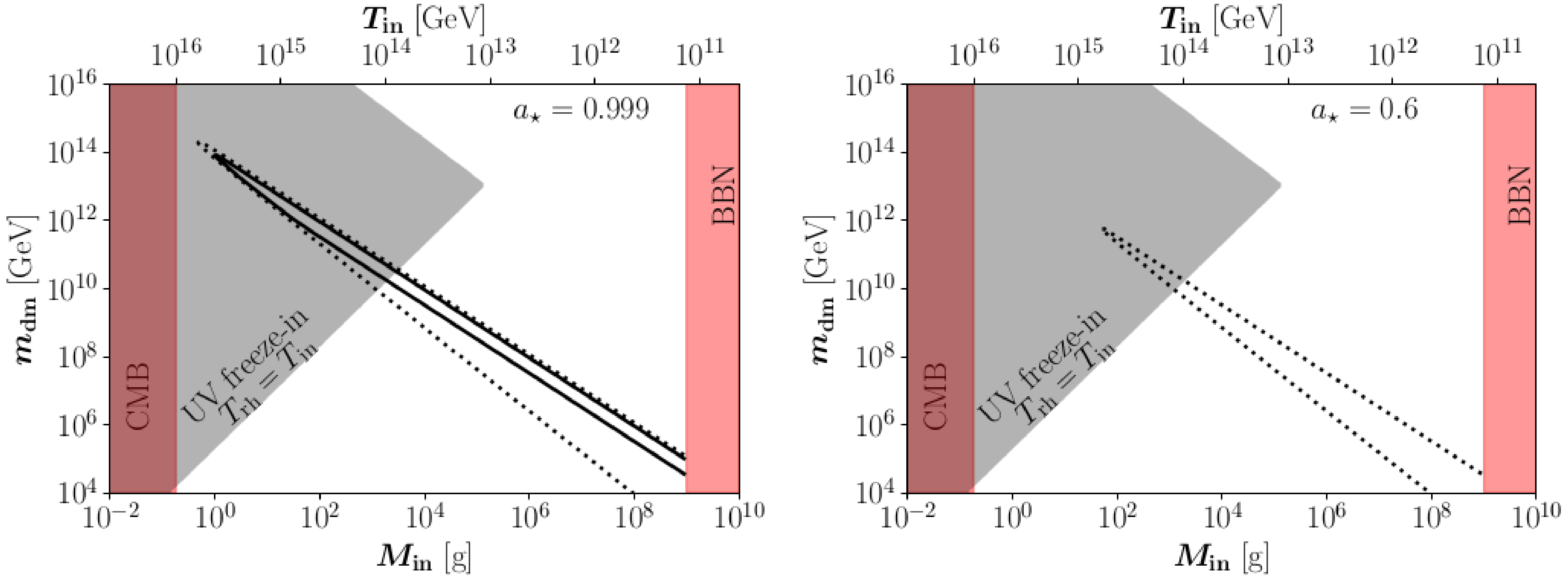
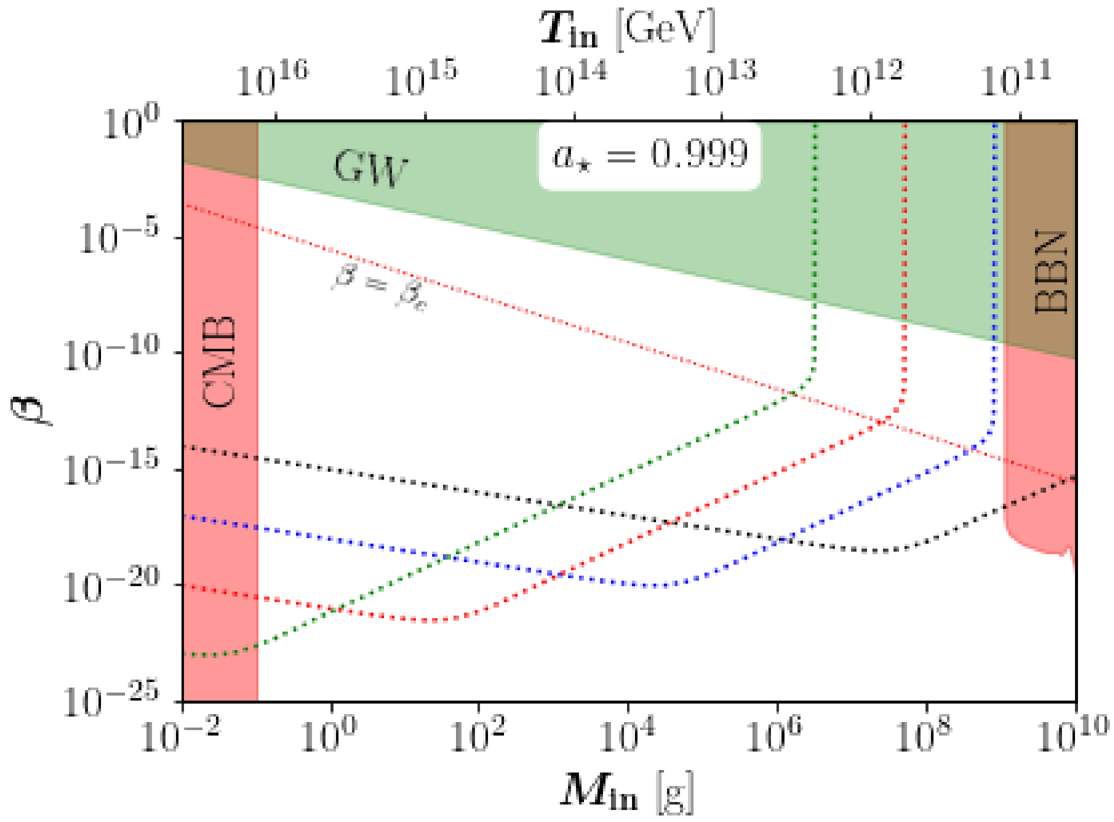


Hawking

m_{dm} = 10^{15} GeV
m_{dm} = 10^{12} GeV
m_{dm} = 10^{9} GeV
m_{dm} = 10^{6} GeV



* Hawking radiation

Hawking, Superradiance

m_{dm} = 10^{15} GeV
m_{dm} = 10^{12} GeV
m_{dm} = 10^{9} GeV
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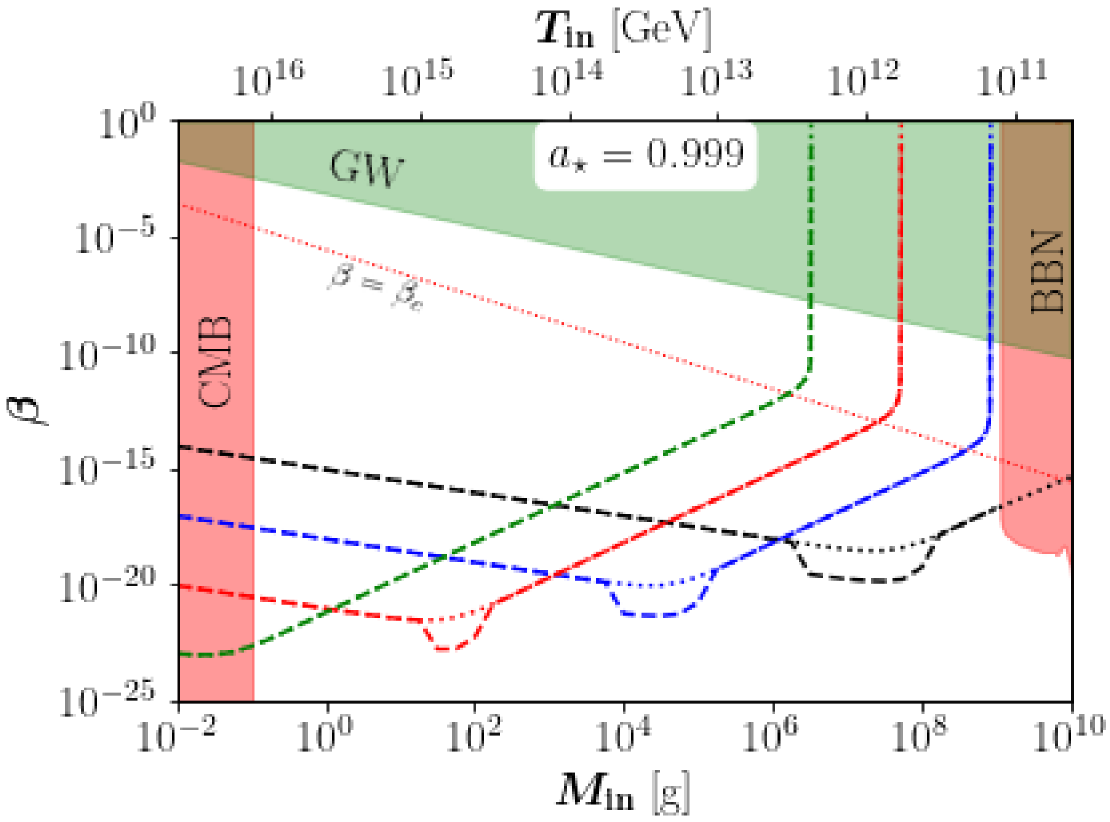

* Hawking radiation
* Superradiance

Hawking, Superradiance & UV Freeze-in

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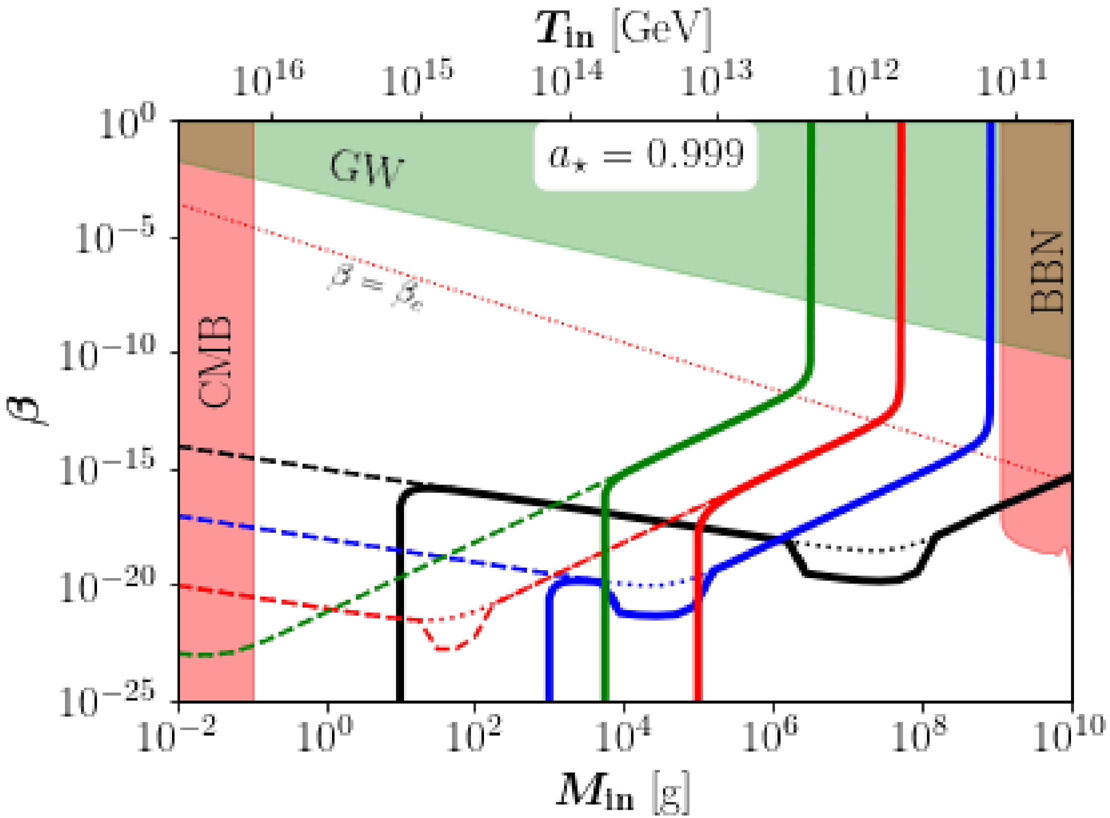
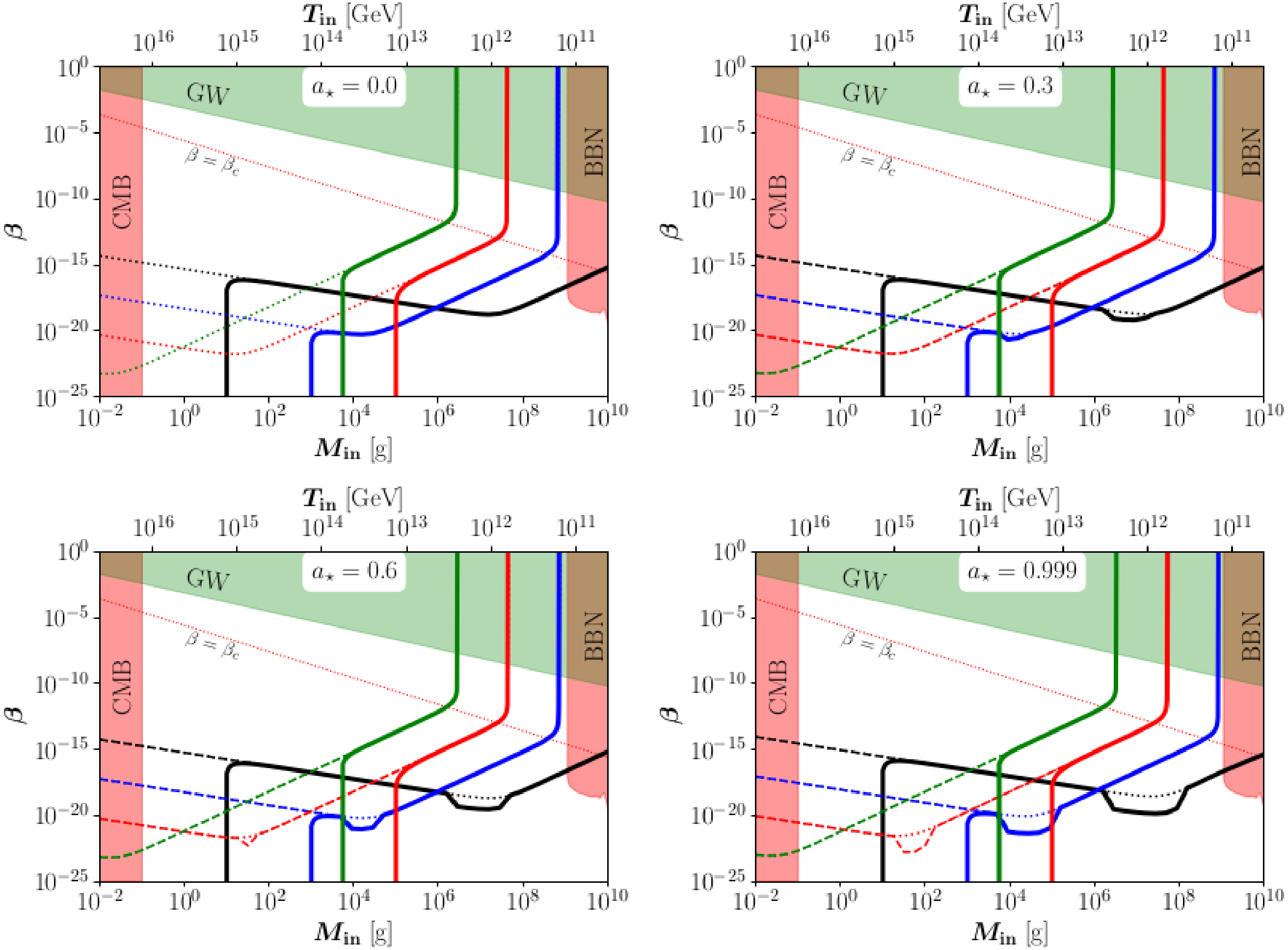
m_{dm} = 10^{9} GeV
m_{dm} = 10^{6} GeV



* Hawking radiation
* Superradiance
* UV freeze-in

PBHs and Gravitational DM



Conclusions

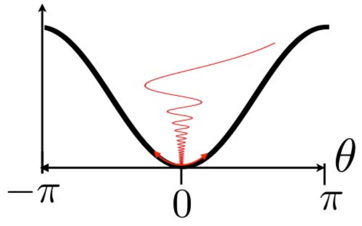
- It's possible that DM *only* features *gravitational* interactions 
- PBHs formed in the early universe
- 0.1 g < M_{in} < 10^9 g evaporate before BBN
- PBHs could Hawing radiate the *whole* DM density
- DM masses: 1 MeV < m_{DM} < 10^{18} GeV
- DM self-interactions:
  → boost DM density
  Boost factors of several order of magnitude can be computed in a *model independent* way!
  → cools down DM: keV DM becomes viable
- Gravitational DM production is unavoidable!
- Gravitational UV freeze-in effective for heavy DM and high reheating temperatures
- PBH superradiance effective for Kerr BHs, when Compton length = PBH radius
- *All gravitational channels have to be taken into account!*

Muchas gracias!

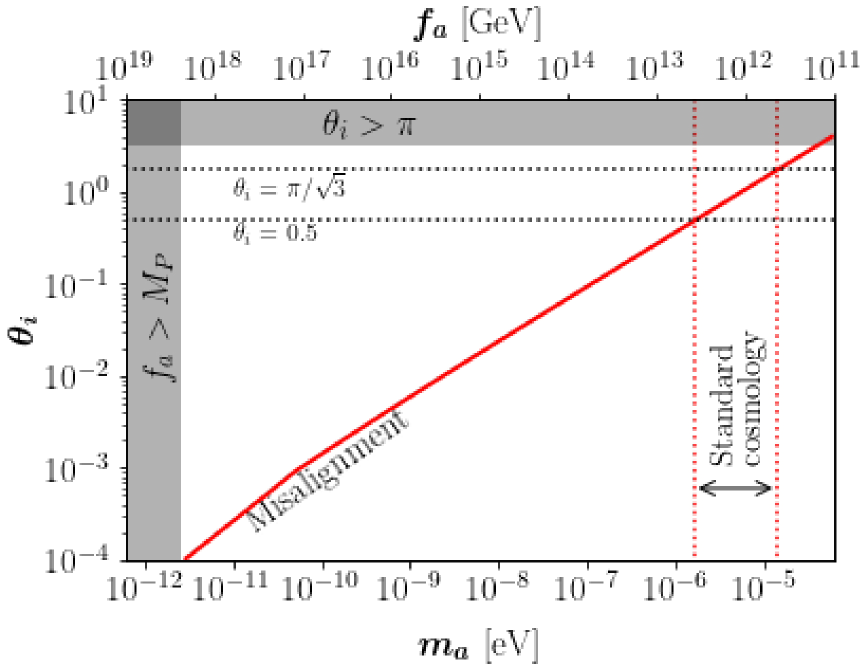
5. **QCD Axion and PBHs**

Producing Axion DM: Misalignment

Effective axion potential $V(\theta) = \chi(T)\,(1 - \cos\theta)$



Evolution of the axion field $\ddot{\theta} + 3\,H(T)\,\dot{\theta} + m_a^2(T)\,\sin\theta = 0$



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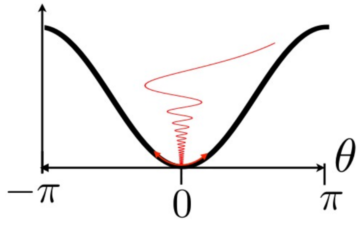

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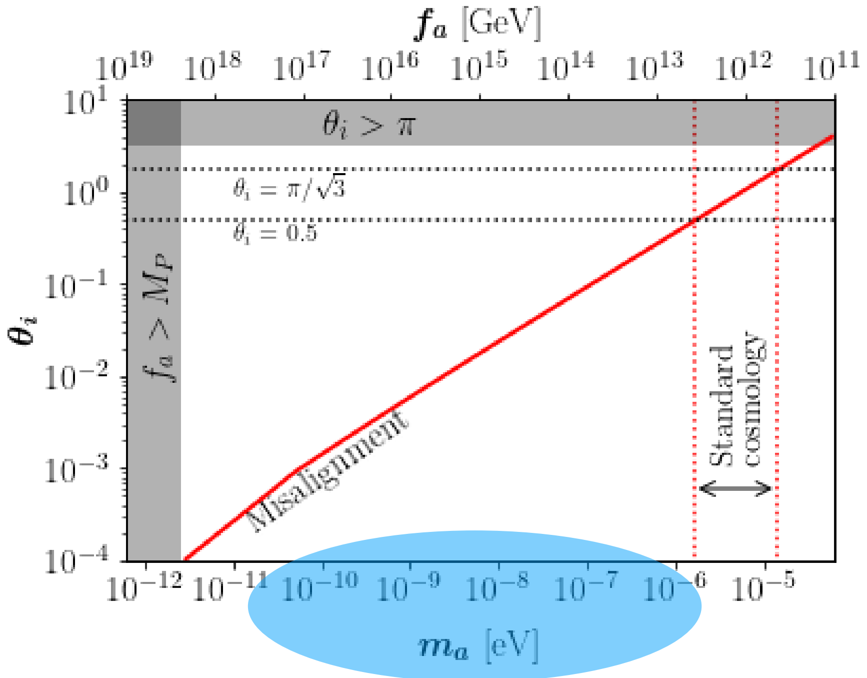
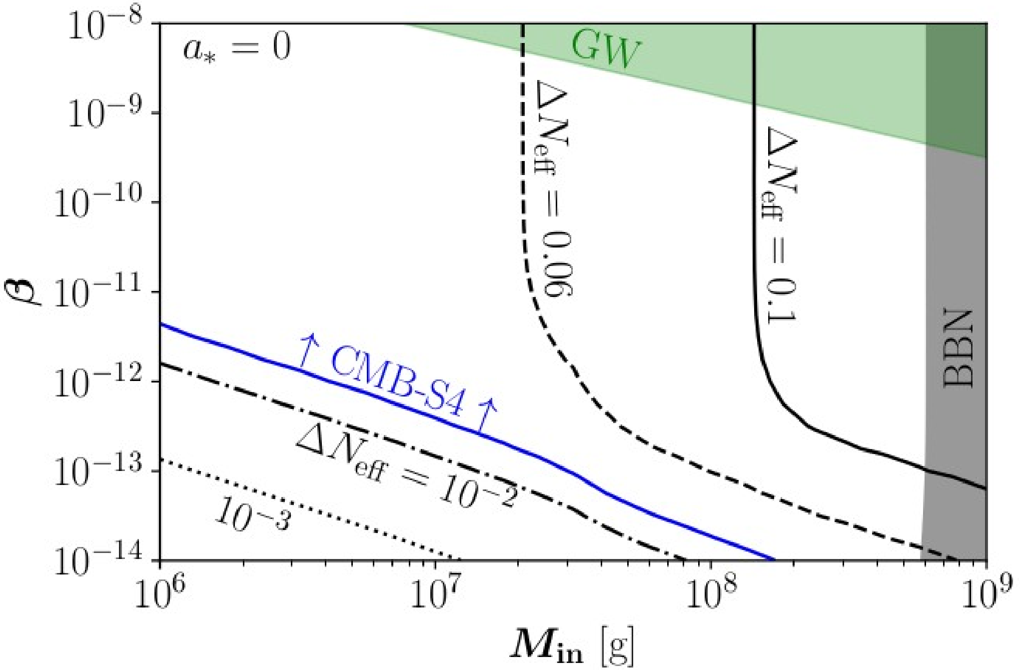
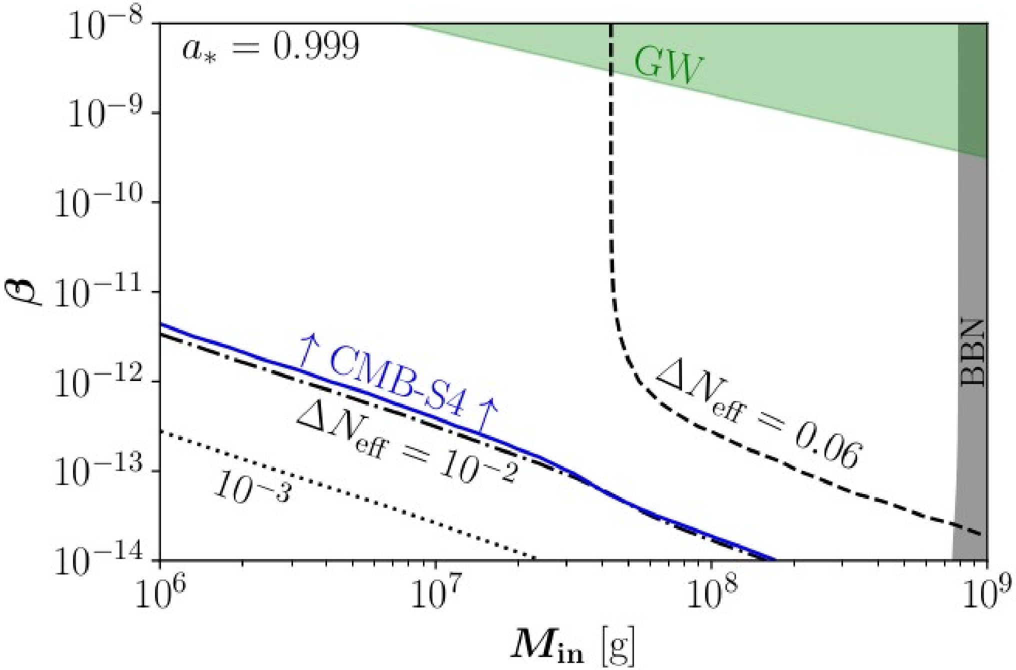


Axions from PBHs: Dark Radiation





As these axions are ultra-relativistic:

→ can't be the cold DM

→ contribute to dark radiation $\Delta N_{\rm eff} \simeq 0.04$

within the reach of future CMB-S4 experiment!

Misalignment with PBHs

Even if axions radiated by PBHs can’t be the DM, PBHs can have a strong impact on the DM genesis via the misalignment mechanism

Non-standard cosmological evolution:

→ enhanced Hubble expansion rate

→ entropy injection by PBH evaporation

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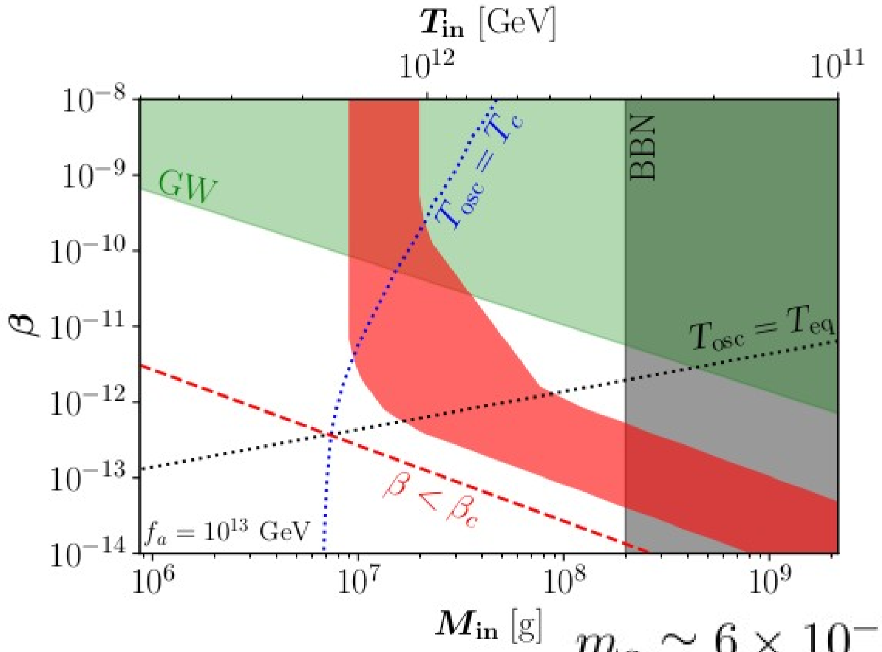

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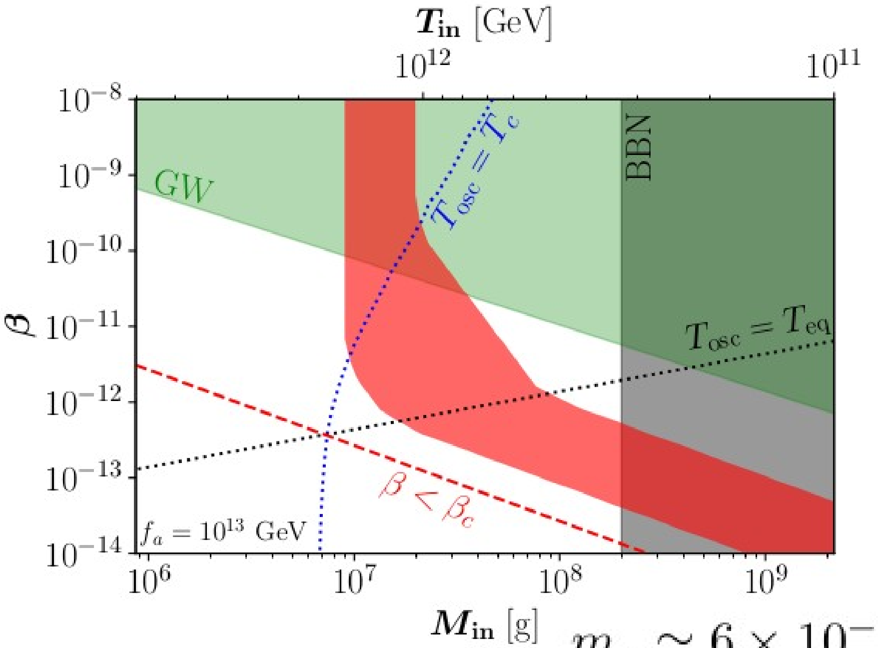

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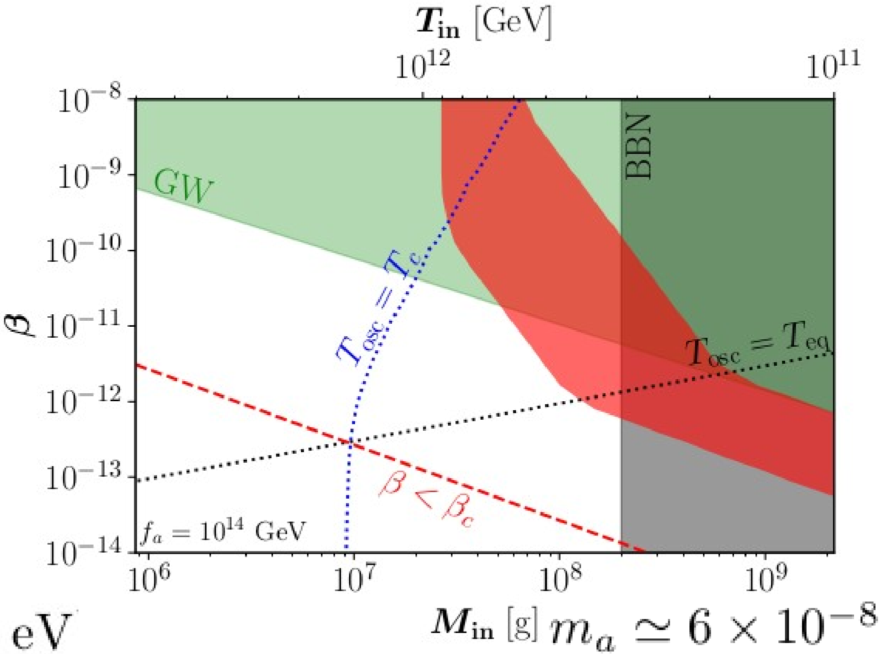
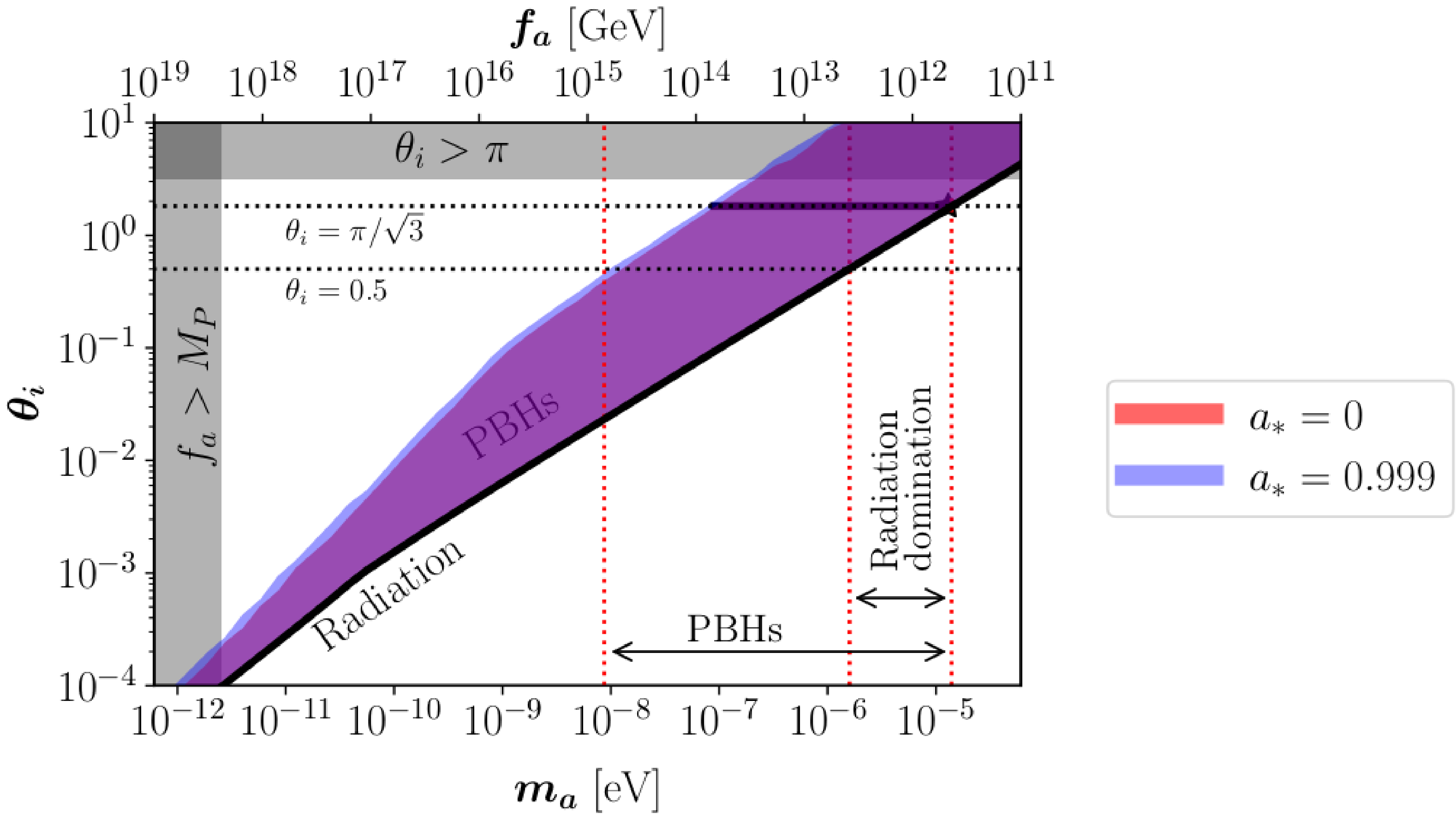


$m_a \simeq 6 \times 10^{-8}$ eV

Misalignment with PBHs



6. ALPs and PBHs

QCD Axion and ALPs with PBHs