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
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Nicolás BERNAL

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SILAFAE XII ¾
November 8-12, 2021

SILAFAE EXPRESS

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El conocimiento es de todos

Minciencias

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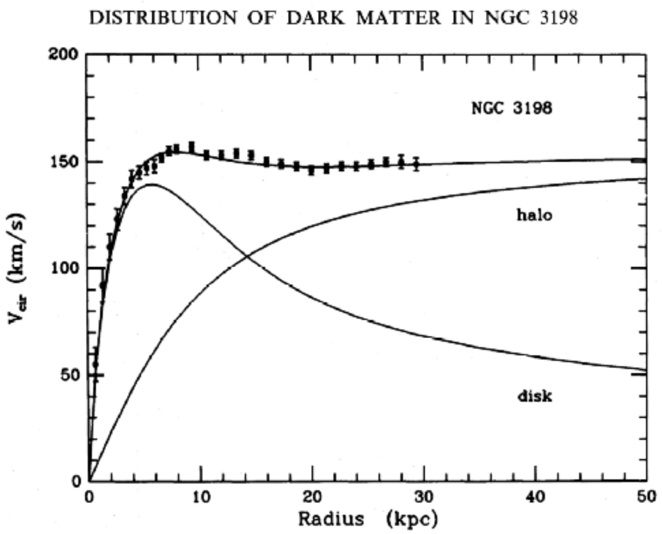
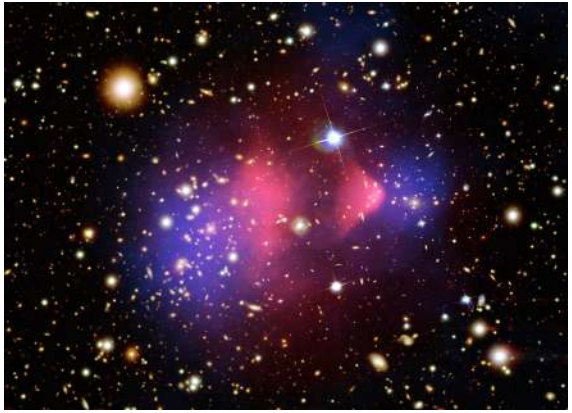
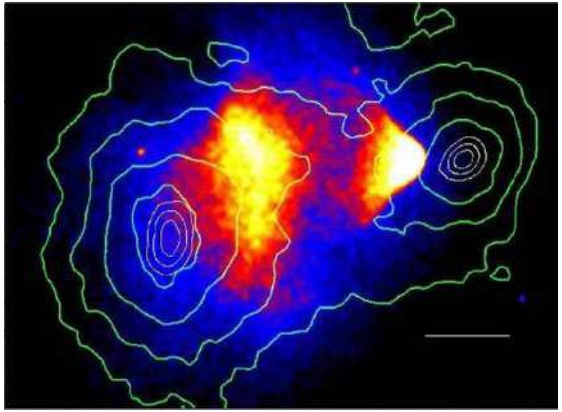
Evidences for Dark Matter

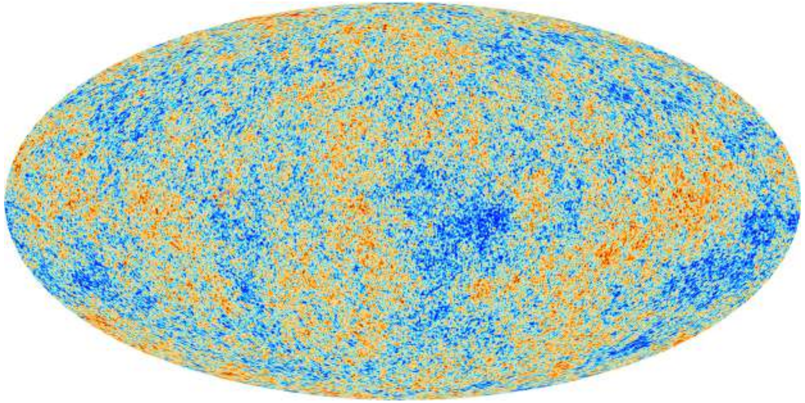
Several observations indicate the existence of non-luminous Dark Matter (missing *gravitational* force) at very different scales!

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



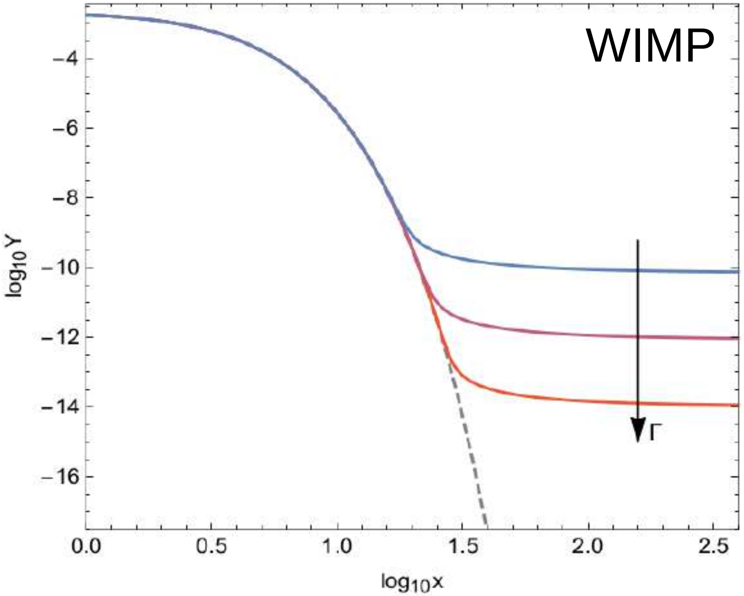


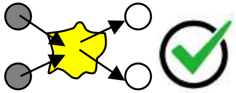


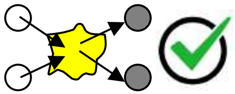


Dark Matter: WIMP

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

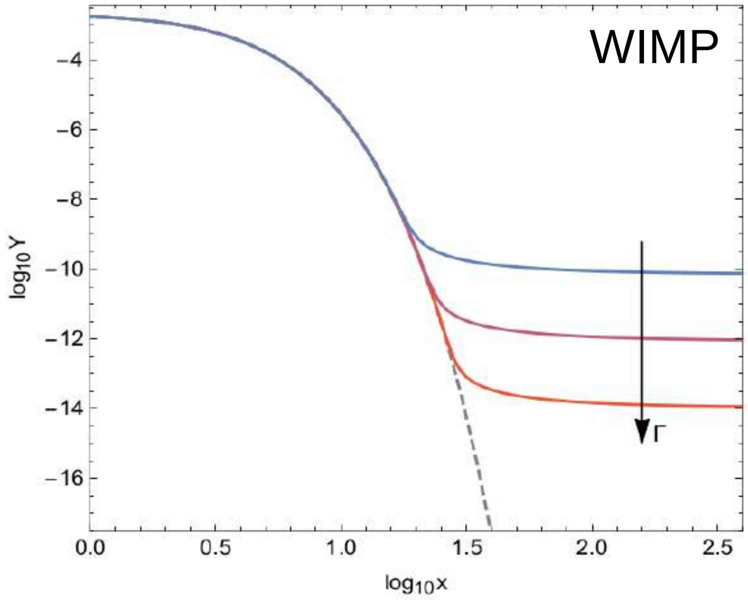


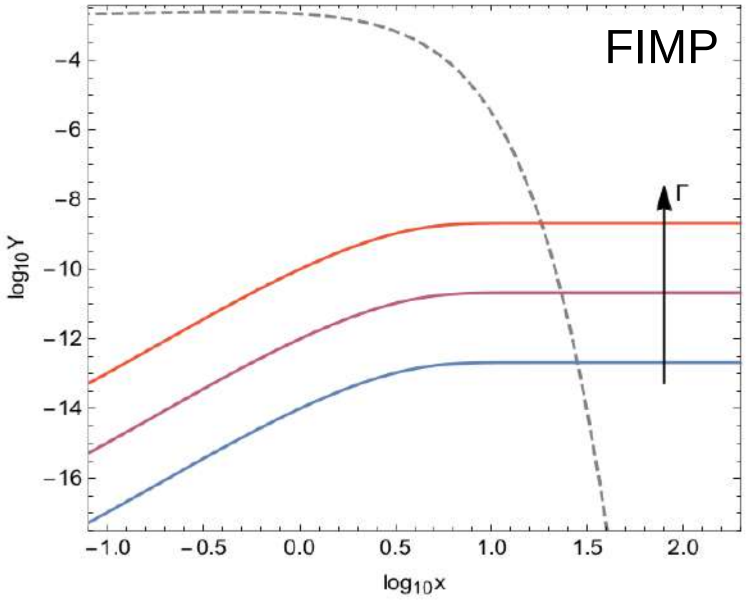


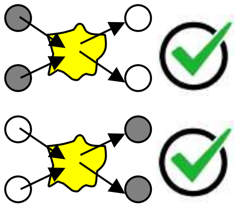


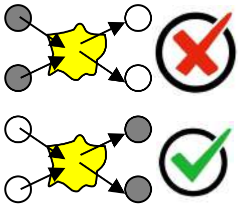
Dark Matter: WIMP vs FIMP

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









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

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DM is *unavoidably* produced by PBH Hawking evaporation!

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: <u>Two free parameters</u>
* A single PBH characterized by its mass at formation $\boldsymbol{M_{in}}$
  (or equivalently, by the SM temperature T_{in} at formation)

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

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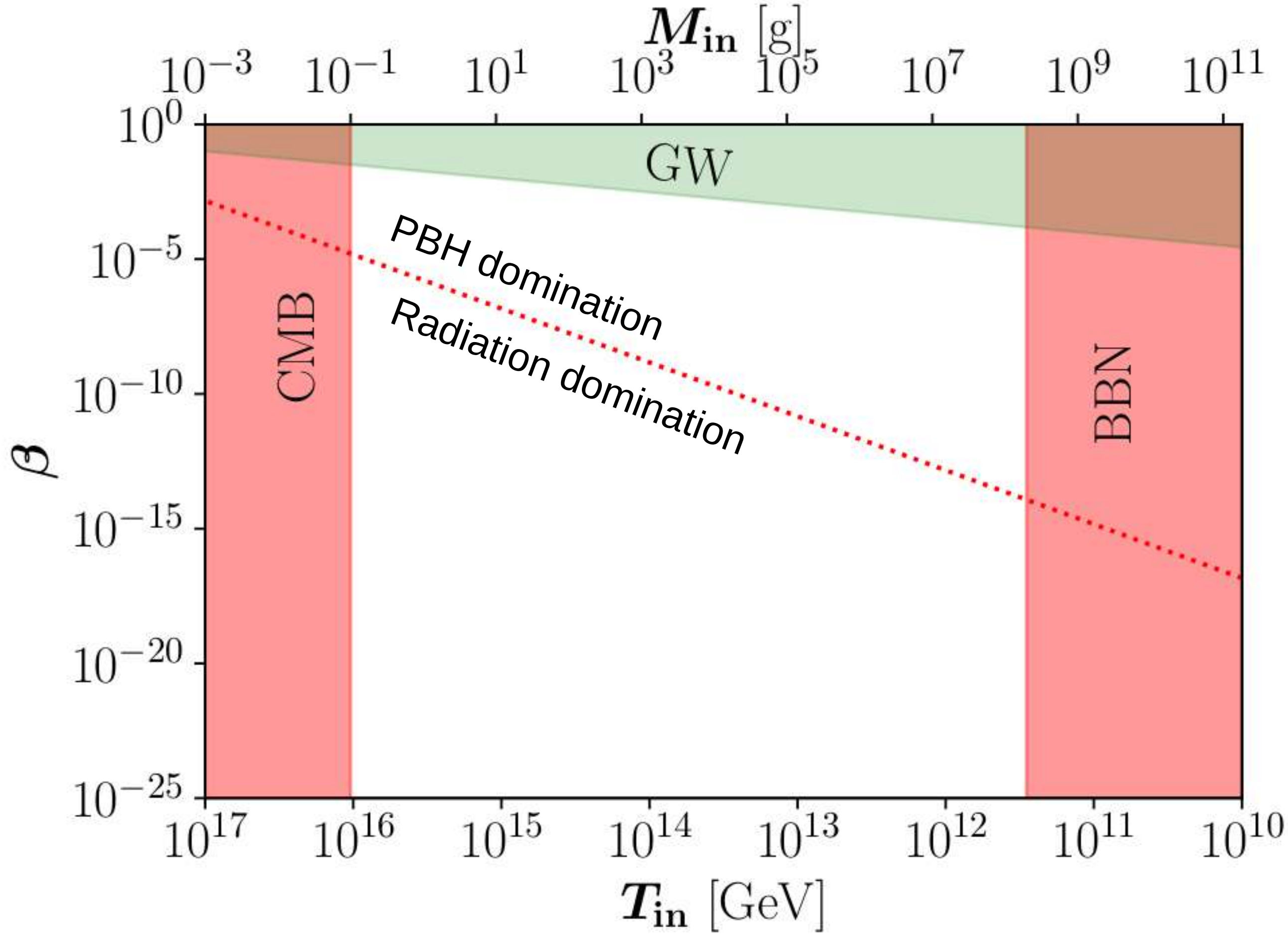
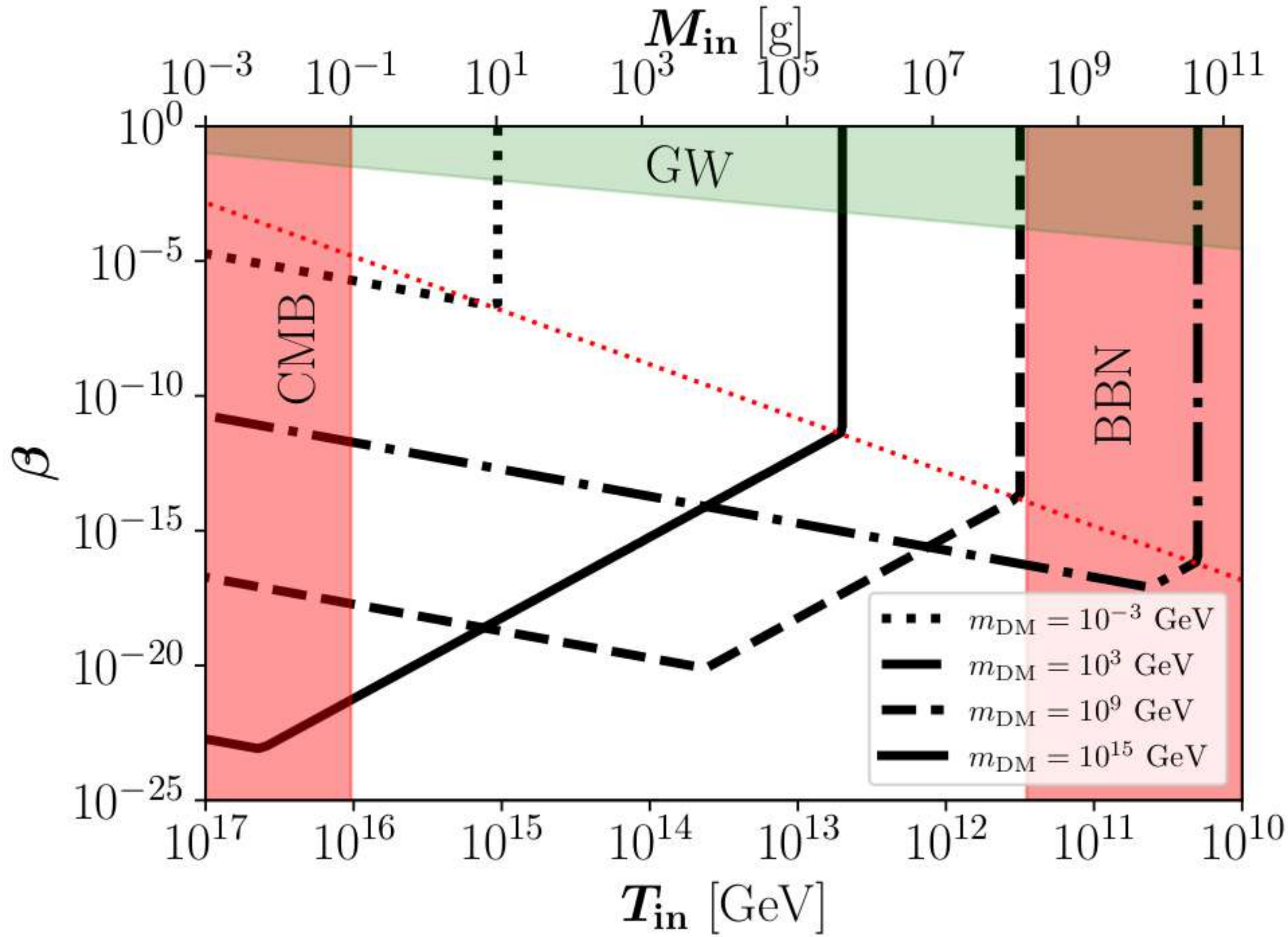
As PBH scale like non-relativistic matter,
they can dominate the total energy density of the universe
→ Nonstandard expansion!

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



$M_{\rm in}$ [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
$m_{\rm DM} = 10^{-3}$ GeV
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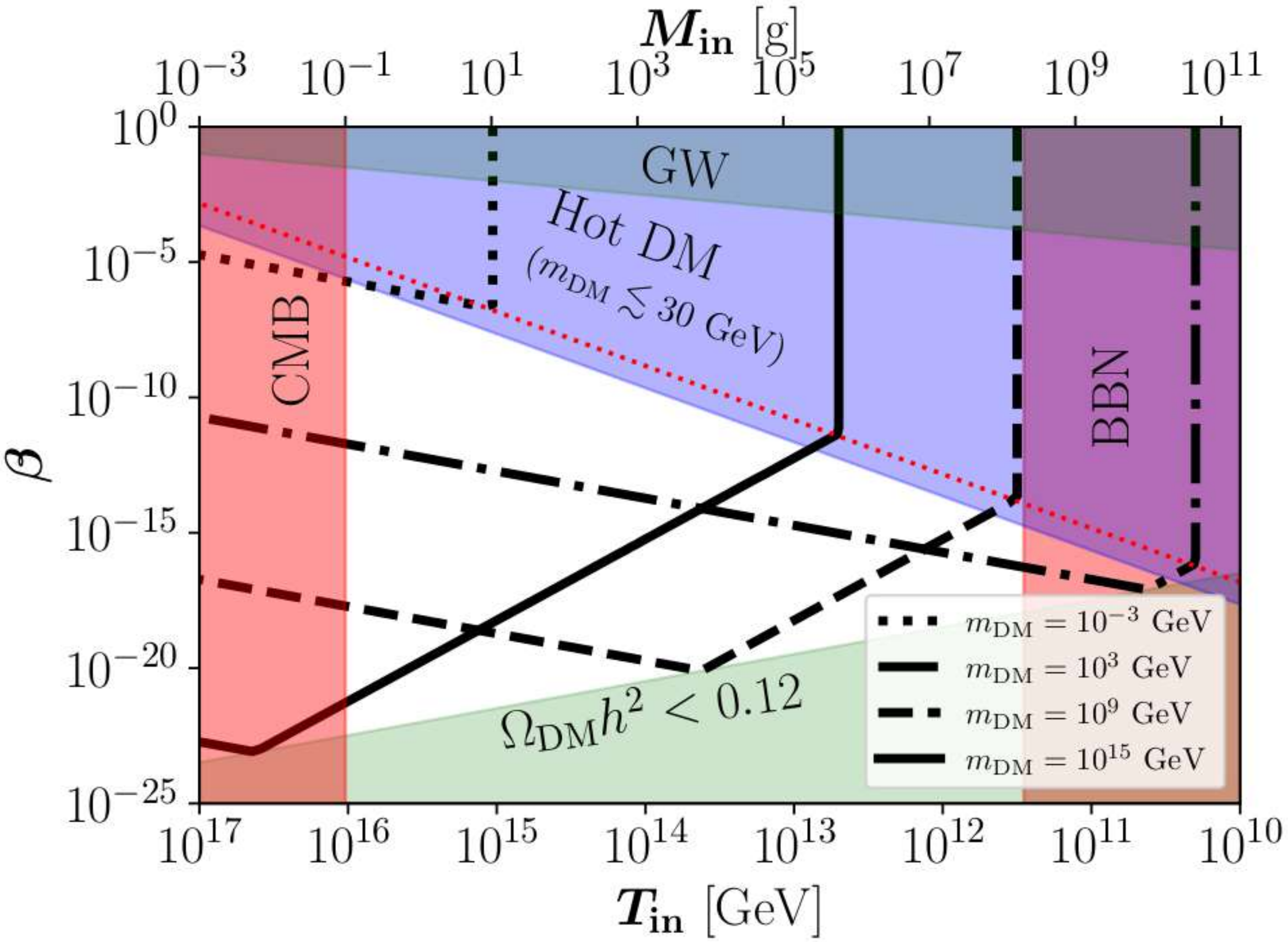
$T_{\rm in}$ [GeV]

DM from PBHs



M_{in} [g]
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Hot DM
($m_{DM} \lesssim 30$ GeV)
CMB
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$\Omega_{DM} h^2 < 0.12$
$m_{DM} = 10^{-3}$ GeV
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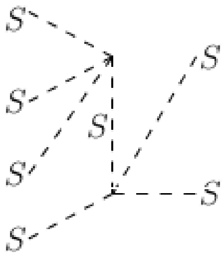
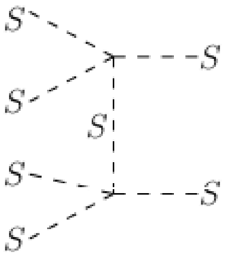
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
T_{in} [GeV]

1. **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)

Self-interacting DM from PBHs

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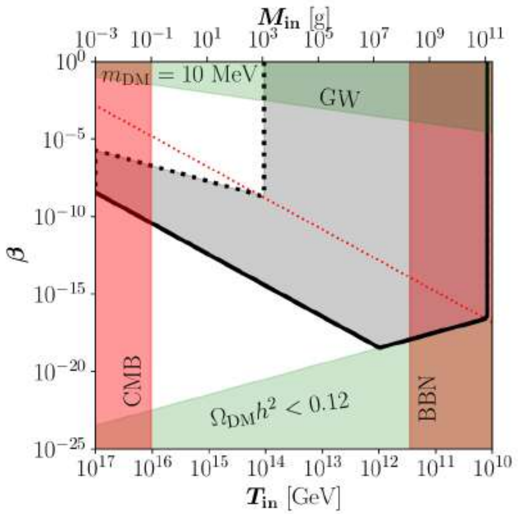
* What is the energy transferred from PBHs to DM?
* What is the DM temperature? (kinetic equilibrium)
* What is DM equilibrium number density? (chemical equilibrium)

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

Self-interacting DM from PBHs

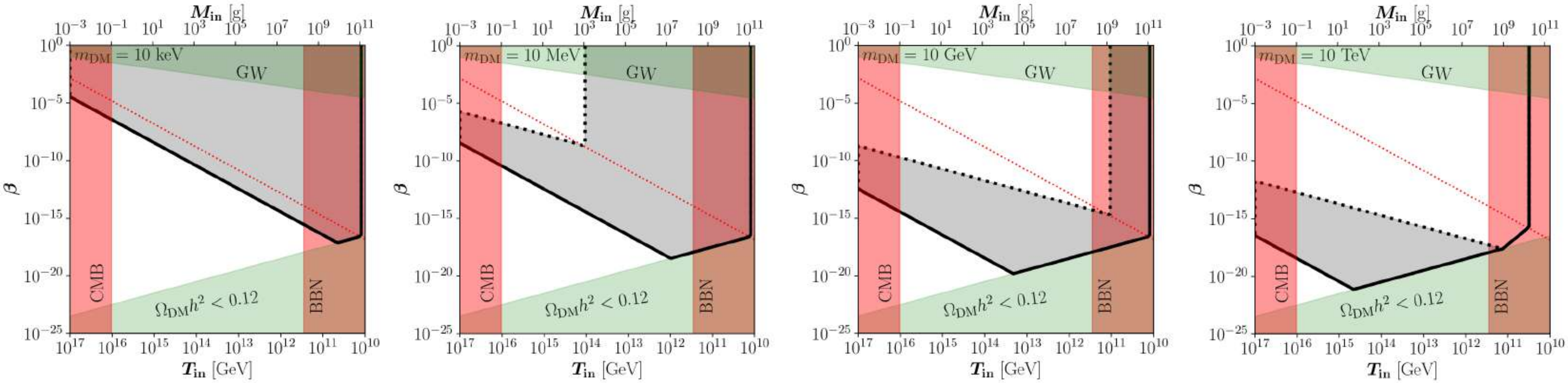


* DM production more efficient → smaller β could be explored

* DM cools down → keV DM becomes viable

* **Model independent result**

Self-interacting DM from PBHs



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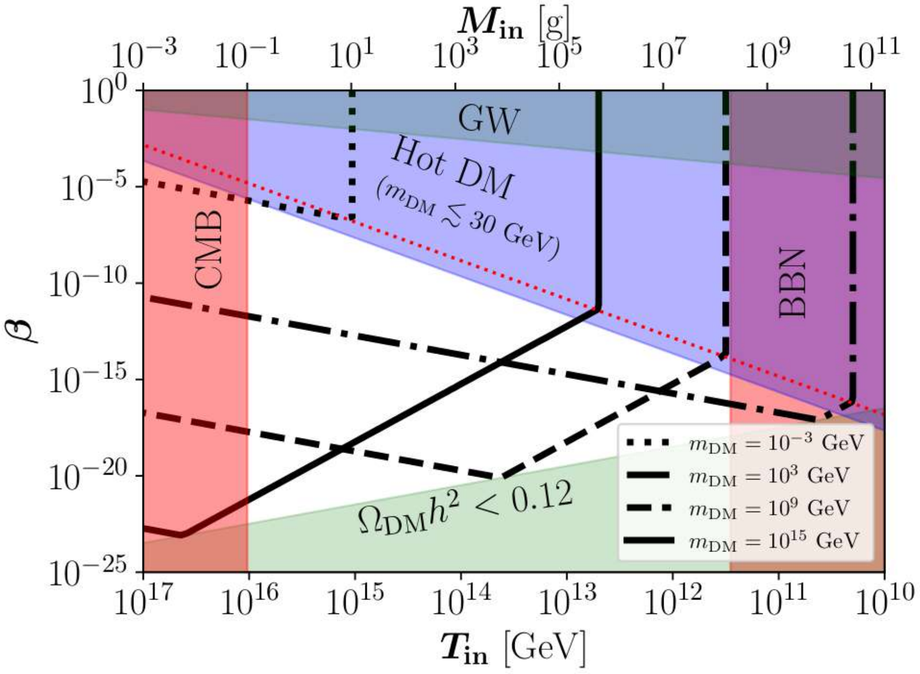
2. **Gravitational UV freeze-in**

DM from PBHs



M_{in} [g]
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β
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GW
Hot DM
($m_{DM} \lesssim 30$ GeV)
CMB
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$\Omega_{DM}h^2 < 0.12$
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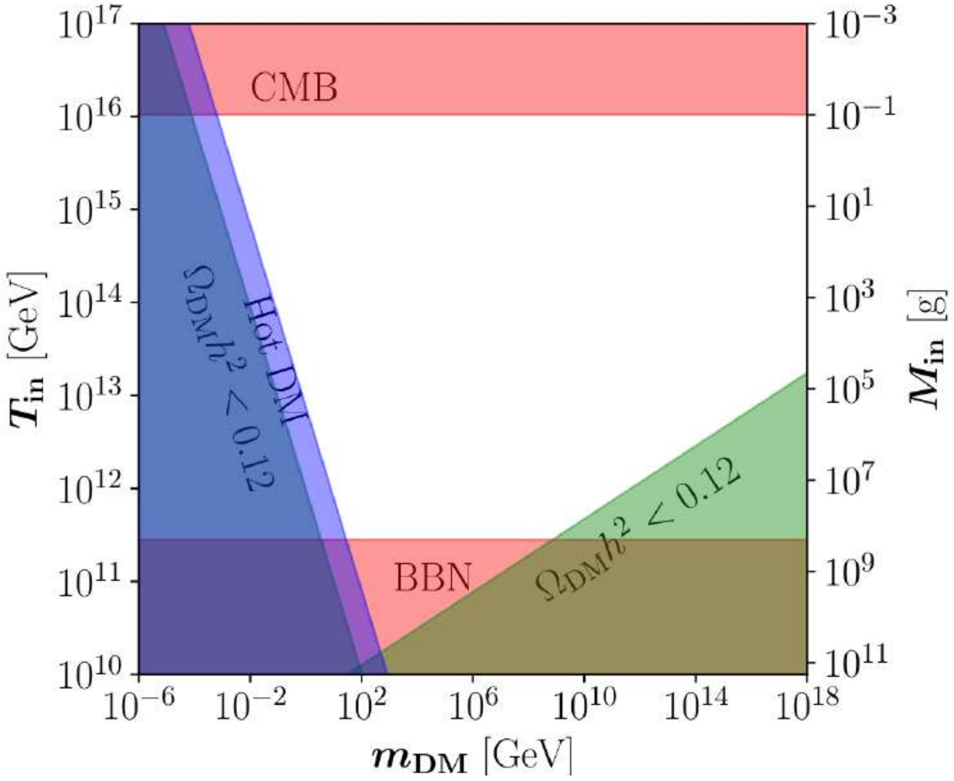
$m_{DM} = 10^{15}$ GeV
10^{17} 10^{16} 10^{15} 10^{14} 10^{13} 10^{12} 10^{11} 10^{10}
T_{in} [GeV]

=



T_{in} [GeV]
10^{17} 10^{16} 10^{15} 10^{14} 10^{13} 10^{12} 10^{11} 10^{10}
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Hot DM
BBN
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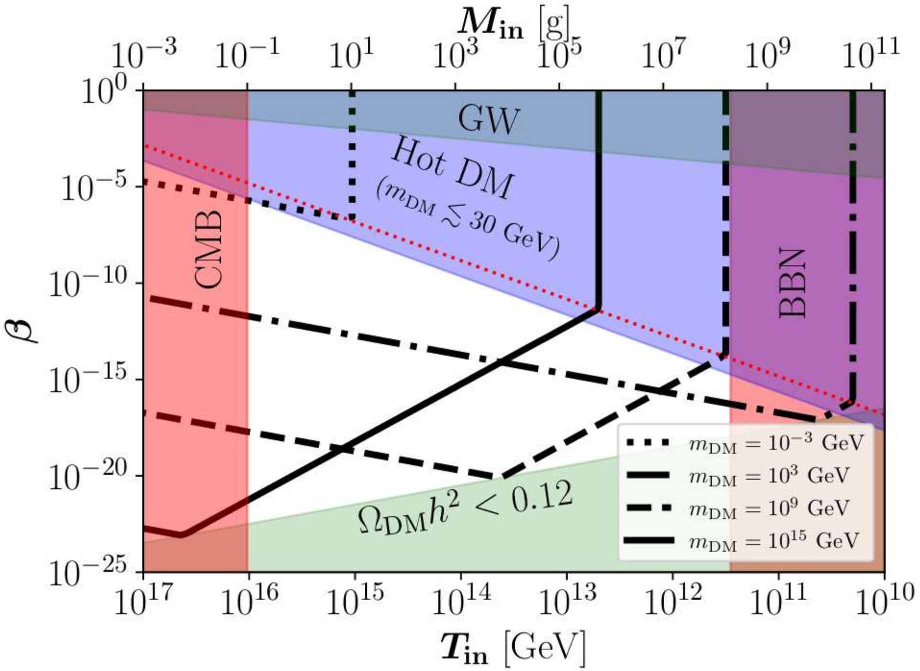
10^{-3} 10^{-1} 10^{1} 10^{3} 10^{5} 10^{7} 10^{9} 10^{11}
M_{in} [g]
10^{-6} 10^{-2} 10^{2} 10^{6} 10^{10} 10^{14} 10^{18}
m_{DM} [GeV]

DM from PBHs



M_{in} [g]
GW
Hot DM
($m_{\text{DM}} \lesssim 30$ GeV)
CMB
BBN
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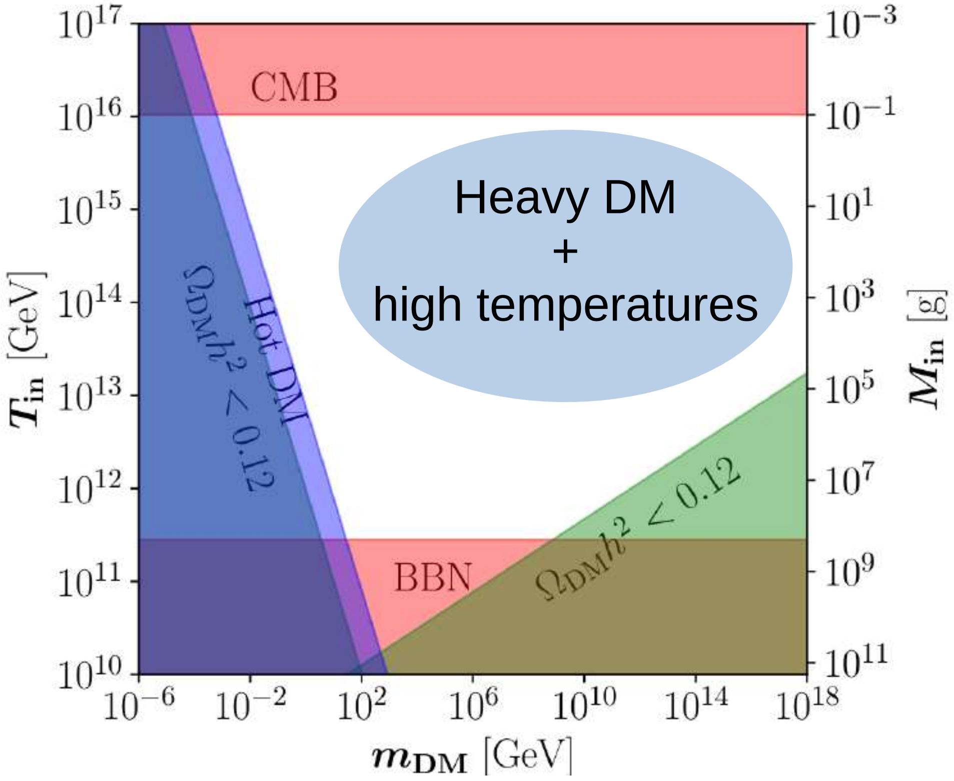
$m_{\text{DM}} = 10^{15}$ GeV
β
T_{in} [GeV]

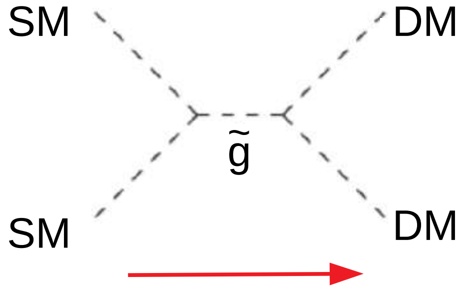
=



CMB
Heavy DM
+
high temperatures
Hot DM
$\Omega_{\text{DM}} h^2 < 0.12$
BBN
$\Omega_{\text{DM}} h^2 < 0.12$
T_{in} [GeV]
M_{in} [g]
m_{DM} [GeV]

Gravitational UV Freeze-in

An example of UV FIMP, mediated by massless SM gravitons

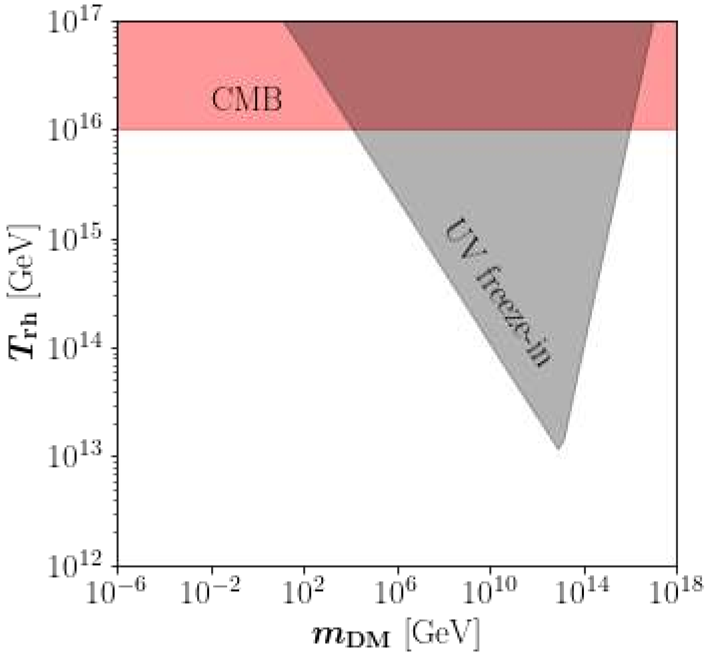


Depends on:

* 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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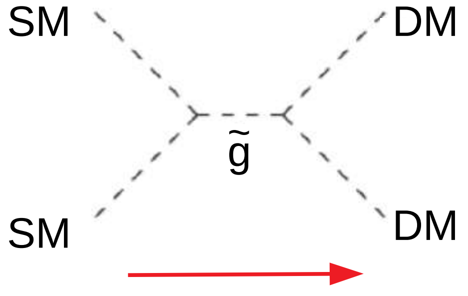

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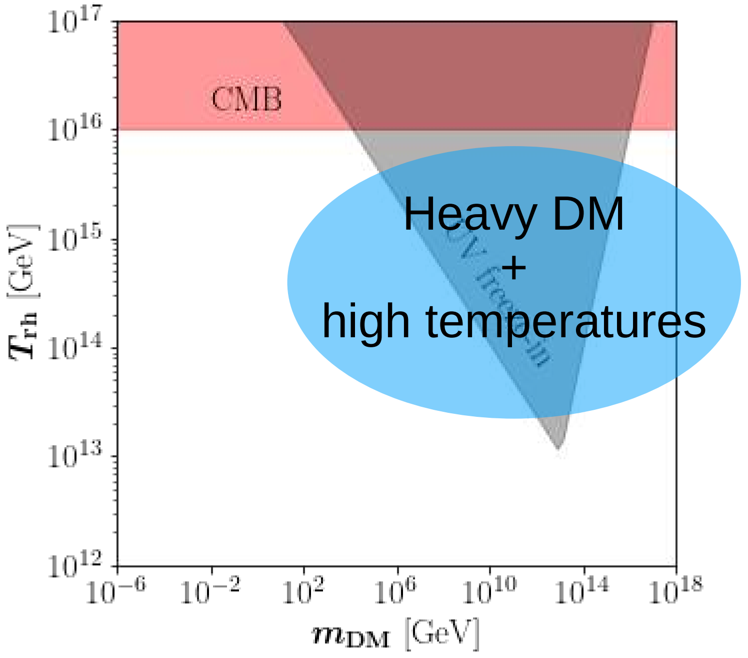
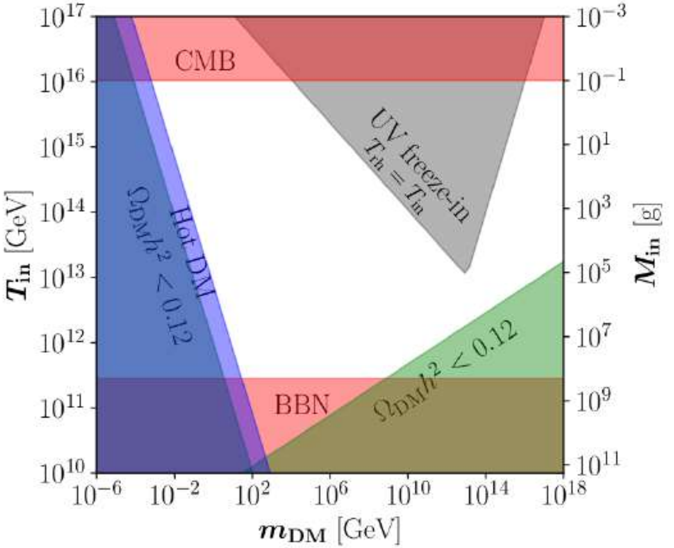


Gravitational DM: PBHs & UV Freeze-in



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

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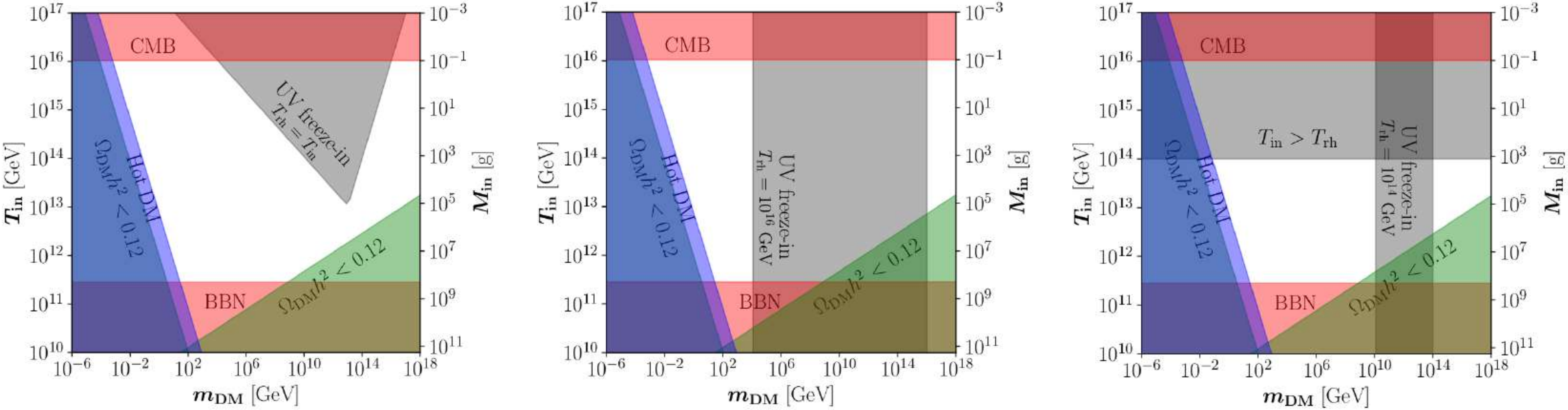

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3. **QCD Axion and PBHs**

Strong CP Problem

Talk by E. Nardi

$$\mathcal{L}_{\rm QCD} = \underbrace{-\frac{1}{4} G_{\mu\nu a} G_a^{\mu\nu} + \sum_q i\,\bar{q}\gamma^\mu D_\mu q - m_q\,\bar{q}q}_{\text{CP conserving}}$$

Strong CP Problem

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usually forgotten!

Strong CP Problem

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usually forgotten!

Electric dipole moment of the neutron…

$$d_n = (2.4 \pm 1.0)\,\theta \times 10^{-3}\ e\ \text{fm}$$

Strong CP Problem

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$$\mathcal{L}_{\text{QCD}} = \underbrace{-\frac{1}{4} G_{\mu\nu a} G_a^{\mu\nu} + \sum_q i\,\bar{q}\gamma^\mu D_\mu q - m_q\,\bar{q}q}_{\text{CP conserving}} + \underbrace{\frac{\alpha_a}{8\pi}\,\theta\,G_{\mu\nu a}\tilde{G}_a^{\mu\nu}}_{\text{CP violating}}$$

usually forgotten!

Electric dipole moment of the neutron… *not observed!*

$$d_n = (2.4 \pm 1.0)\,\theta \times 10^{-3}\ e\ \text{fm}$$

$$|\theta| < 1.3 \times 10^{-10}$$

← **Strong CP problem!**

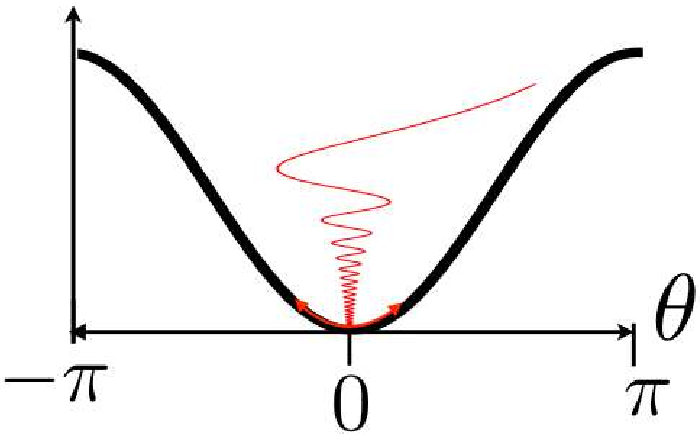
Axion

Talk by E. Nardi

If θ is a *dynamical field*, QCD will relax it to its minimum…

→ Strong QCD problem explained!

Peccei & Quinn '77



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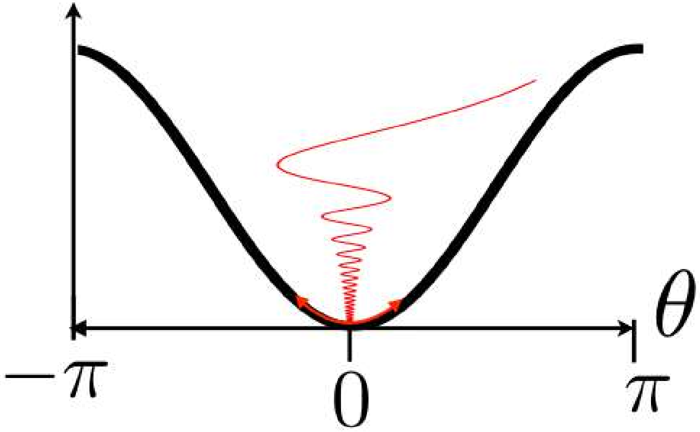
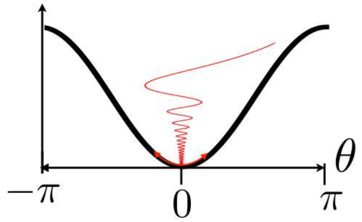


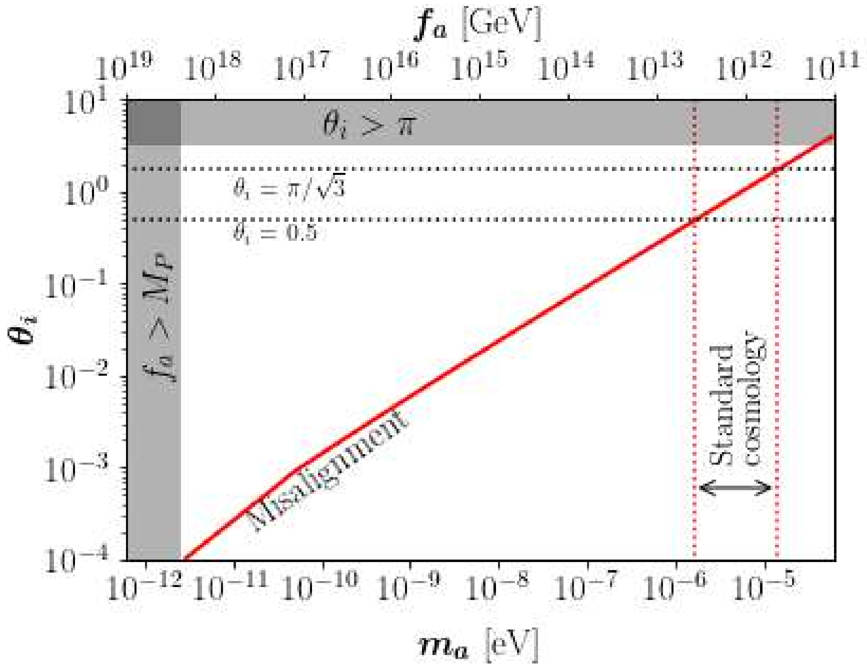
Axion oscillates in a ~ quadratic potential
→natural *cold dark matter* candidate

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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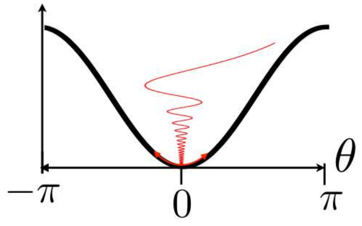

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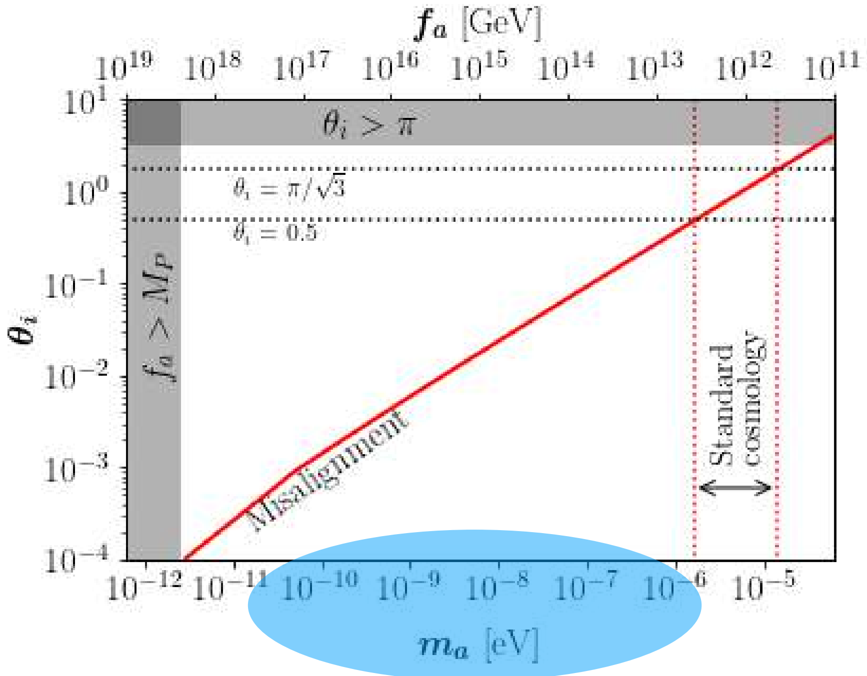
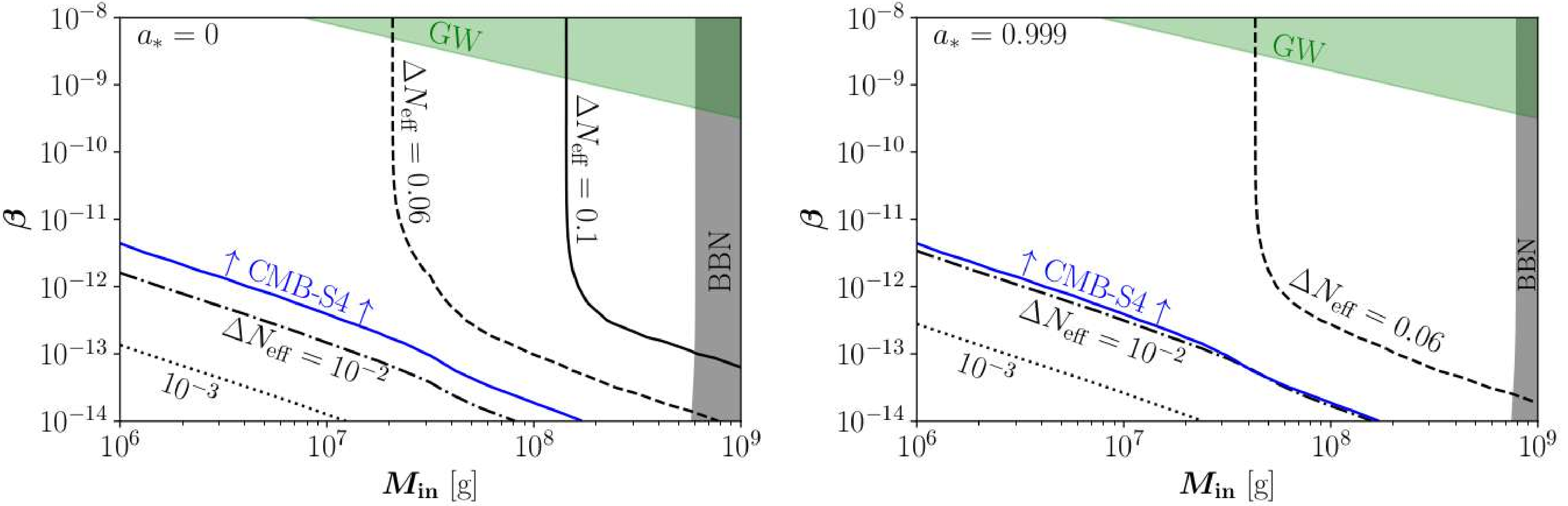


Axions from PBHs: Dark Radiation



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 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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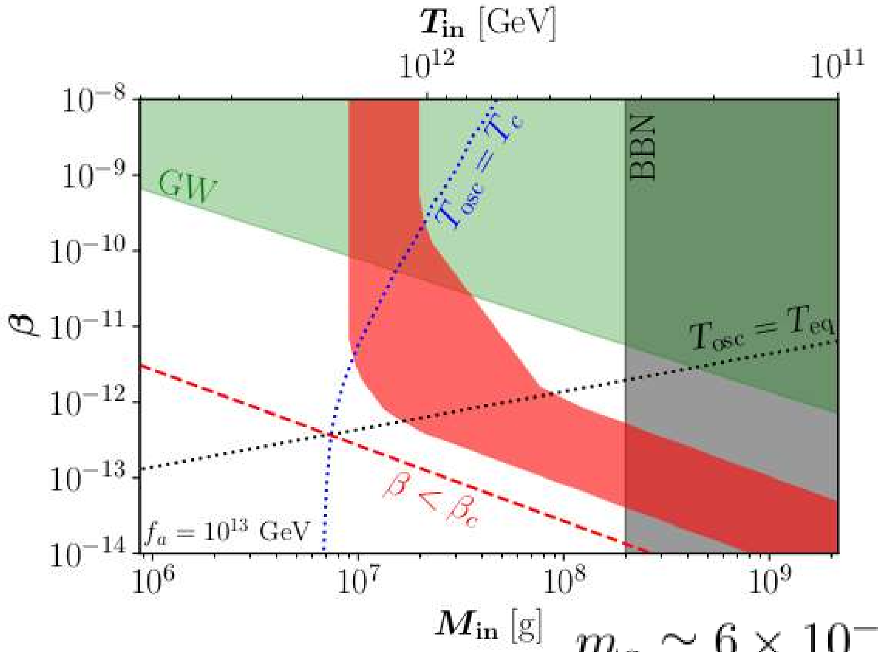

$m_a \simeq 6 \times 10^{-7}$ eV

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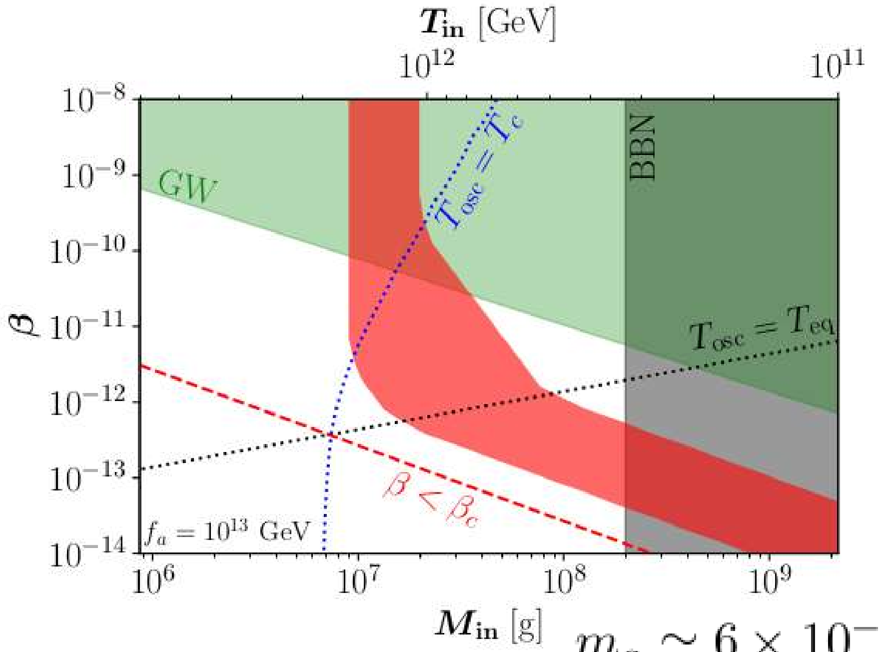
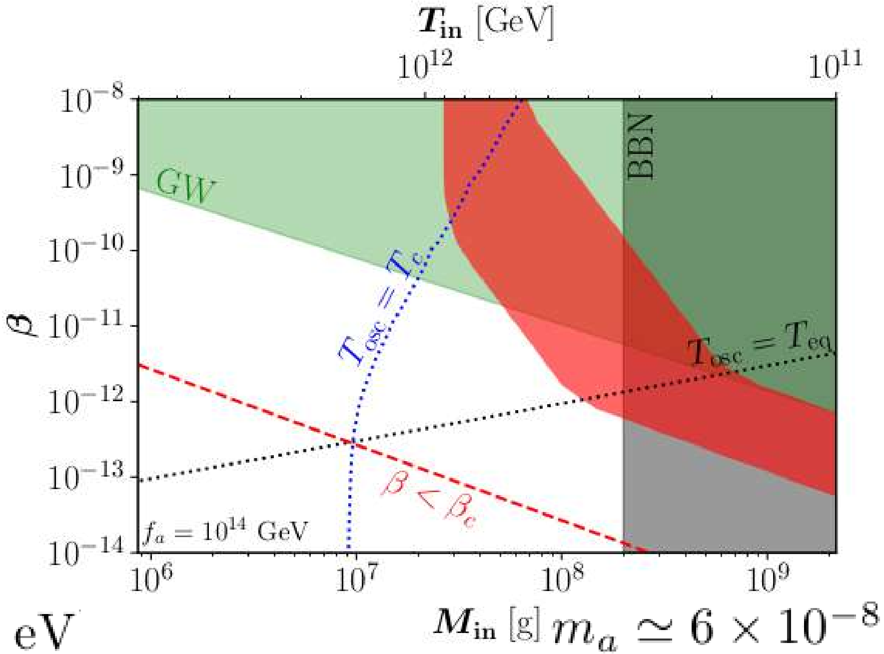
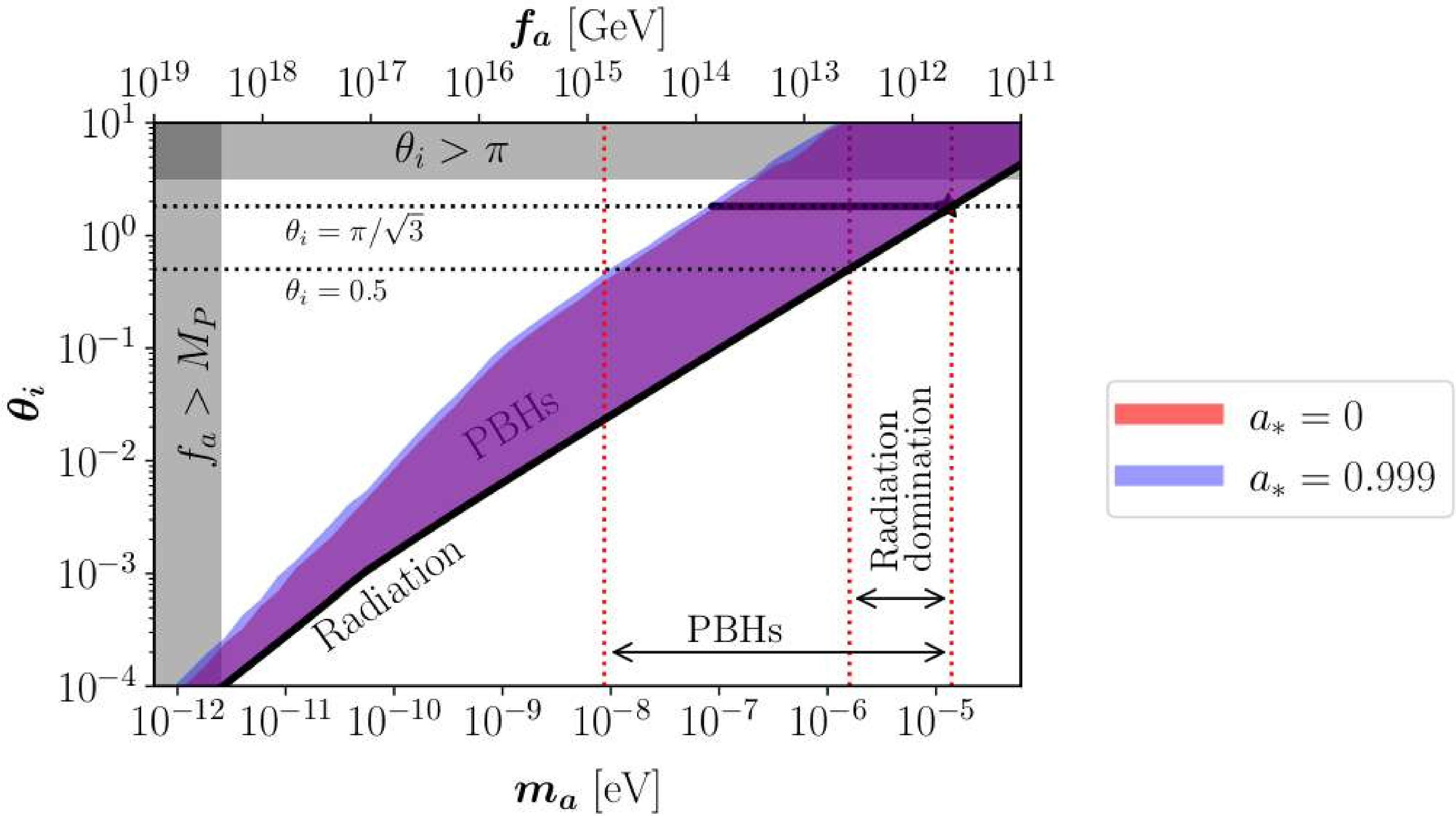


$m_a \simeq 6 \times 10^{-7}$ eV



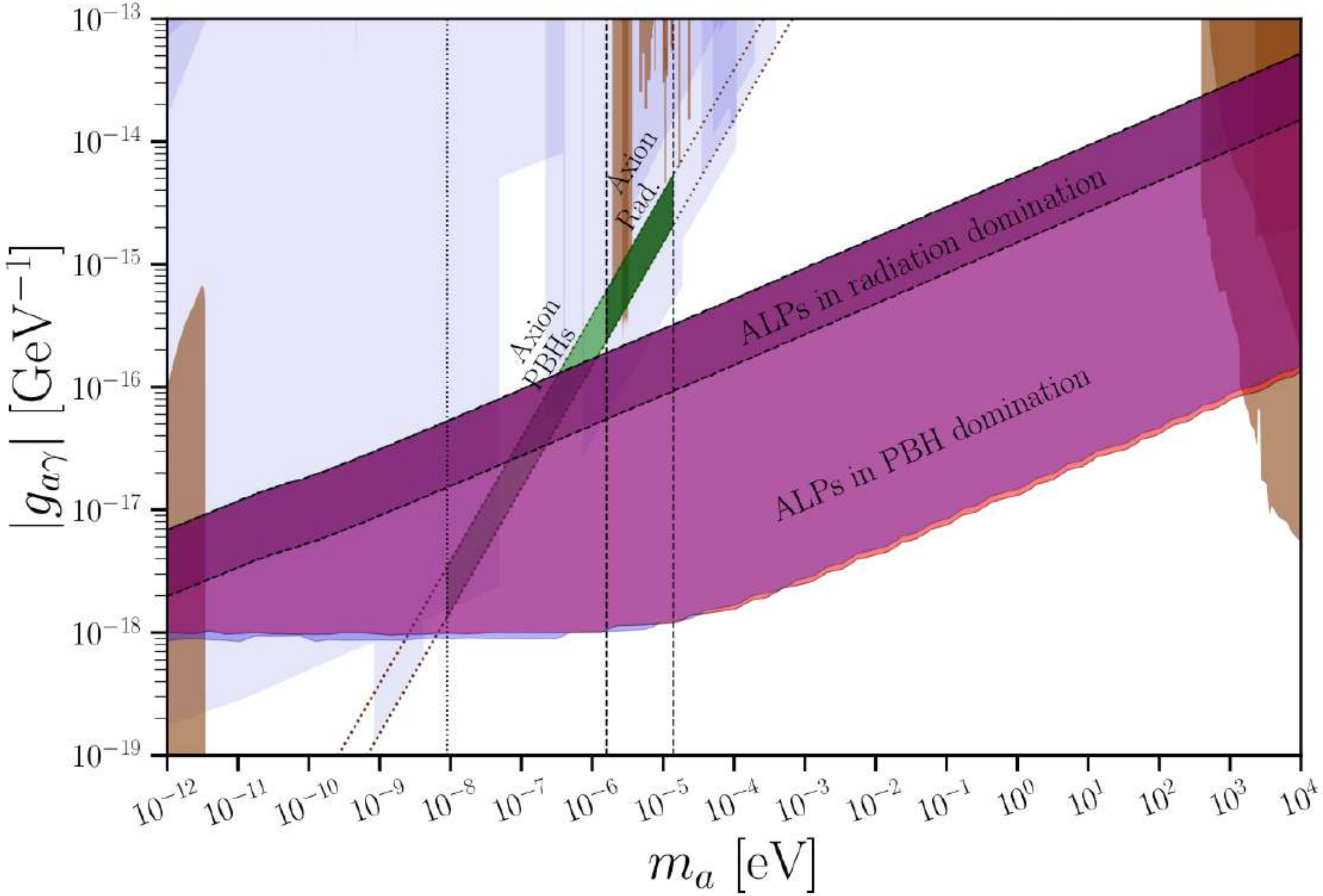
$m_a \simeq 6 \times 10^{-8}$ eV

Misalignment with PBHs



4. **ALPs and PBHs**

QCD Axion and ALPs with PBHs



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!
- PBHs radiates axions → Dark radiation within the reach of CMB-S4
- Nonstandard cosmology due to PBHs have a strong impact on misalignment
  → preferred axion mass wider: lighter axions allowed
  → ALPs within the read of future ABRACADABRA, KLASH, ADMX, and DM-Radio

¡Muchas gracias!

Muito Obrigado!