Dark Matter in the time of Primordial Black Holes

Based on:
NB & Óscar Zapata – arXiv:2010.09725, 2011.02510
NB – arXiv:2005.08988

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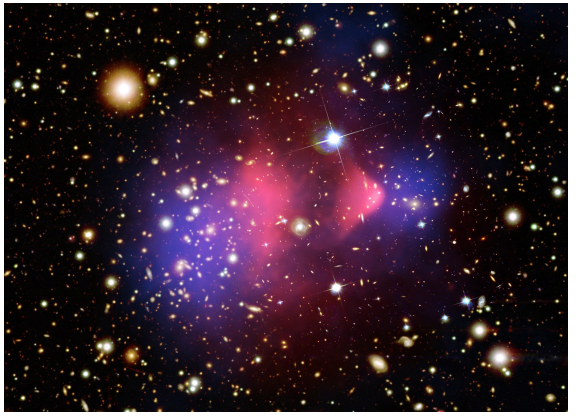
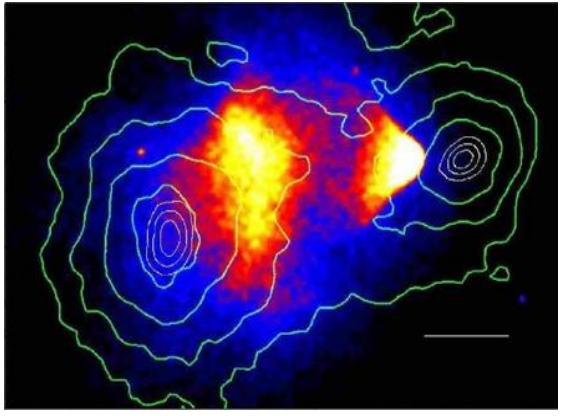
New Horizons in Primordial Black Hole Physics
June 19th-21st, 2023

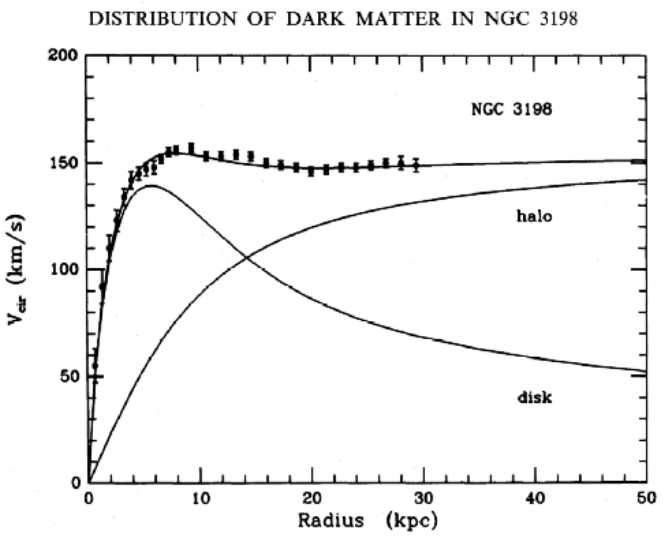
Evidences for Dark Matter

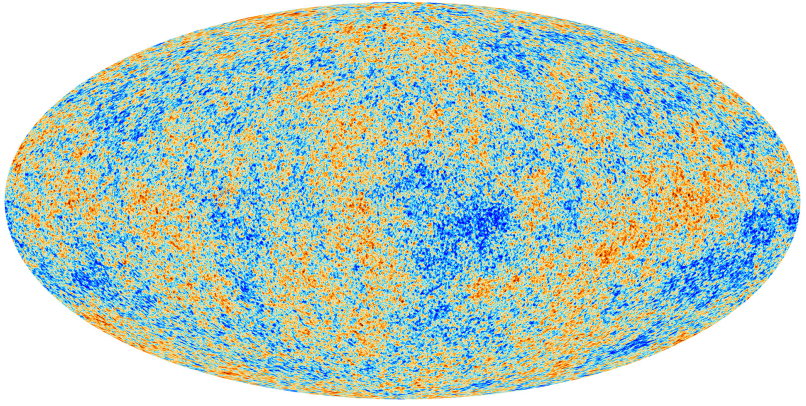
Several observations indicate the existence of non-luminous Dark Matter (missing *gravitational* force) at very different scales!

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

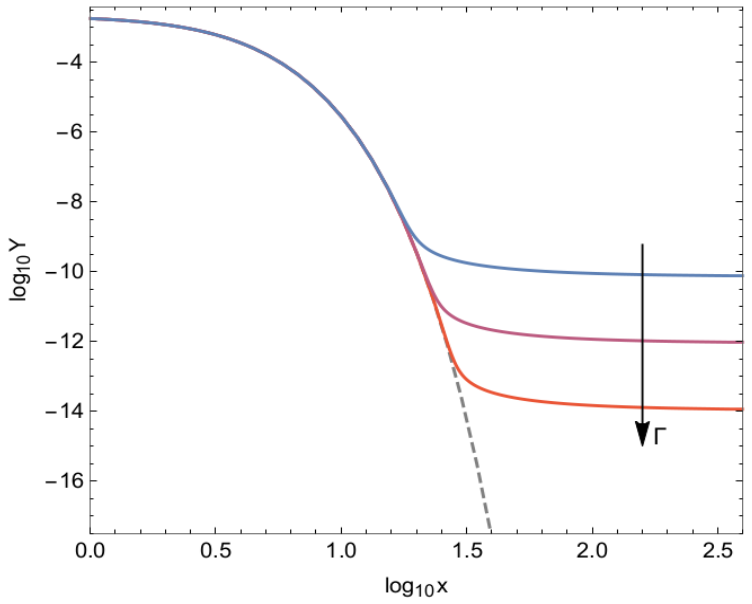








We all love WIMPs, but...



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

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

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

0. 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

Effective theory: <u>Three 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 spin $\boldsymbol{a_*}$
* Initial PBH energy density $\boldsymbol{\beta} = \rho_{BH}/\rho_{SM}$

DM from PBHs

DM density = PBH density x # DM emitted per PBH

Total number of DM particles radiated per PBH

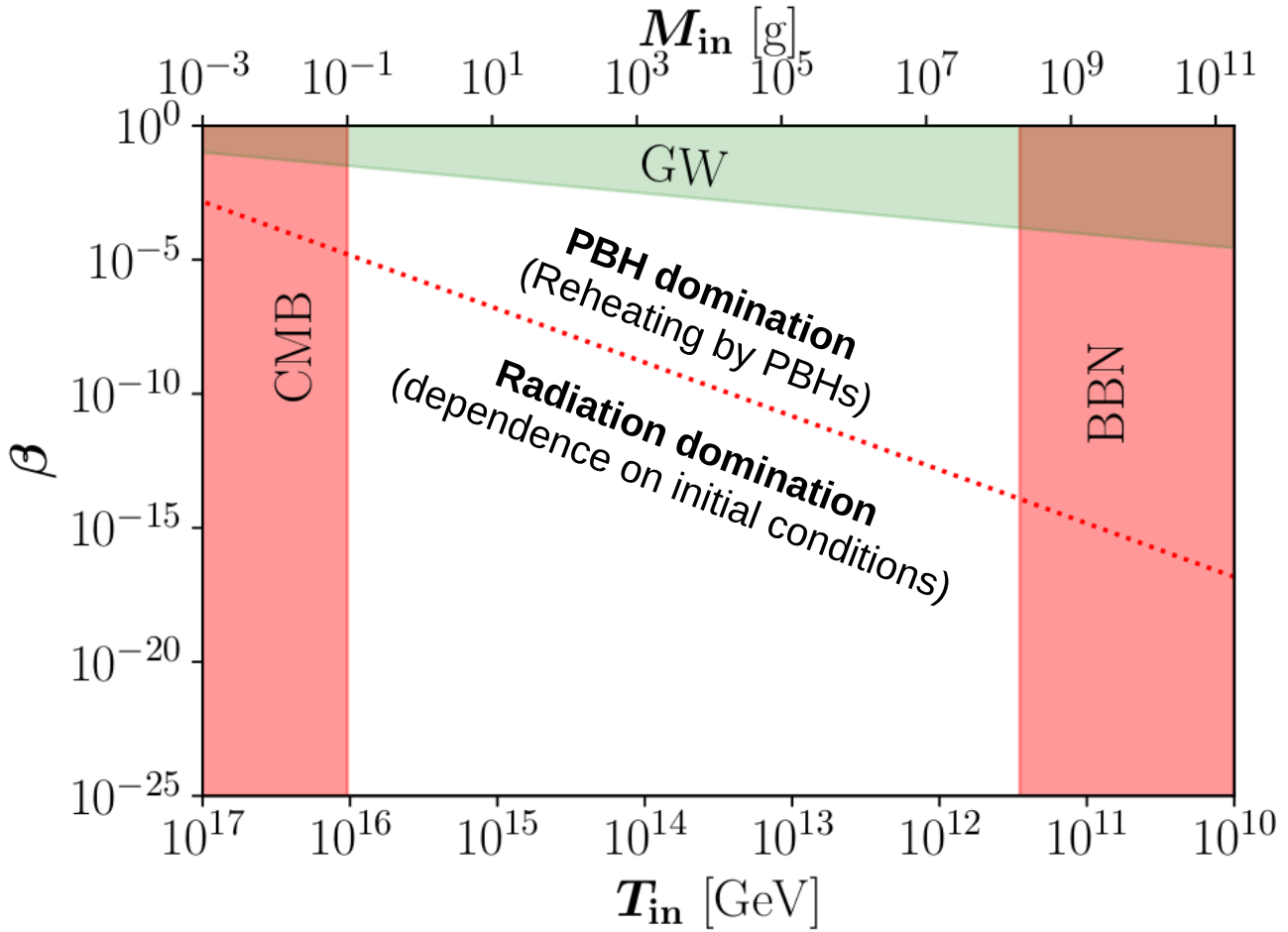
→ Depends mainly on initial PBH mass and DM mass

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

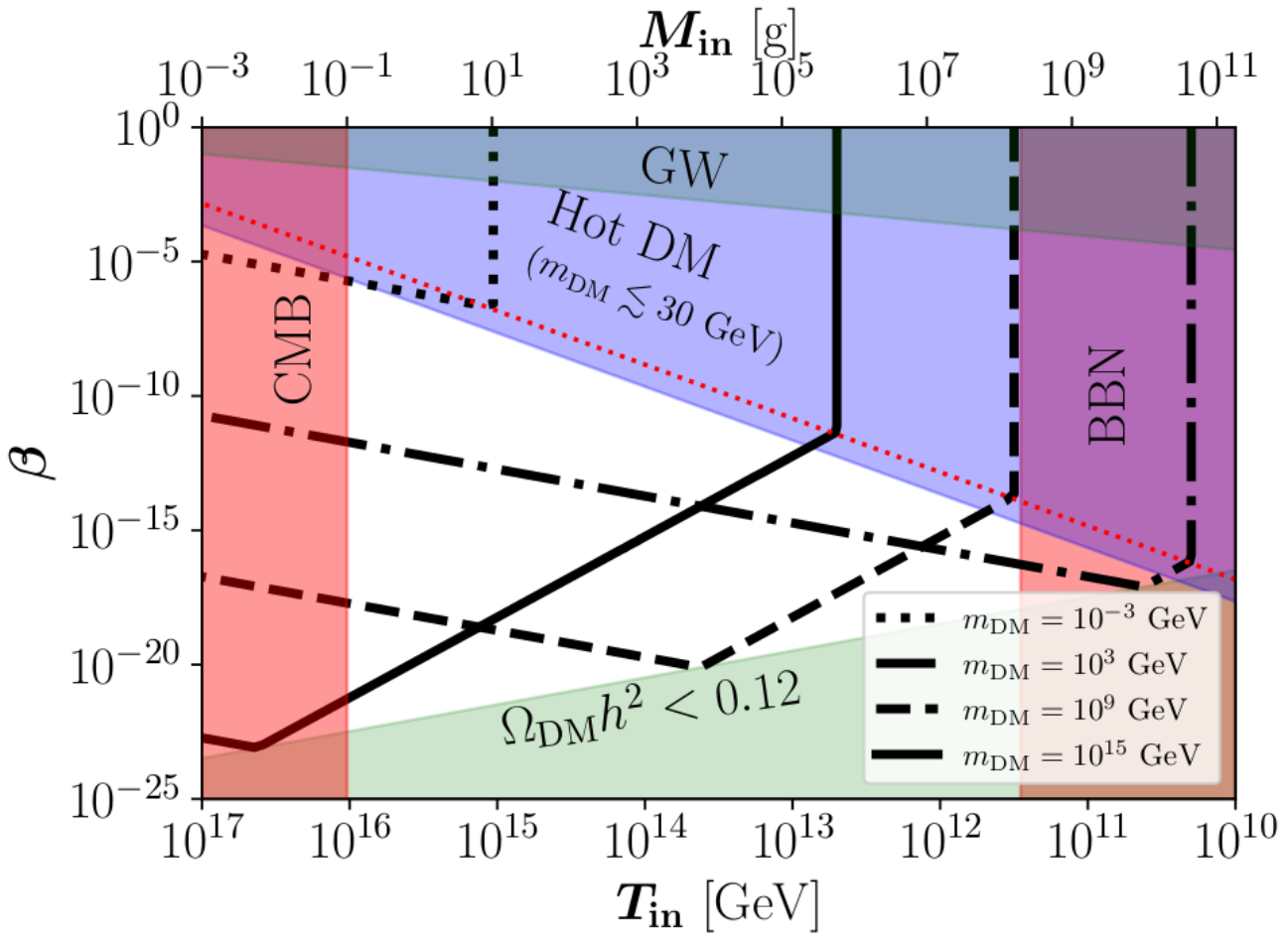
Initial DM density = 0

No interactions SM-DM besides gravity

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
PBH domination
(Reheating by PBHs)
Radiation domination
(dependence on initial conditions)
10^{17} 10^{16} 10^{15} 10^{14} 10^{13} 10^{12} 10^{11} 10^{10}
$T_{\rm in}$ [GeV]

DM from PBHs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10^{-20}
10^{-25}
β
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
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10^{17}
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$T_{\rm in}$ [GeV]

1. Self-interacting DM from PBHs

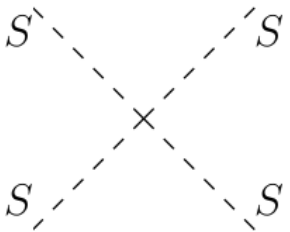
Self-interacting DM

If DM possess sizable self-interactions:

→ DM thermalizes

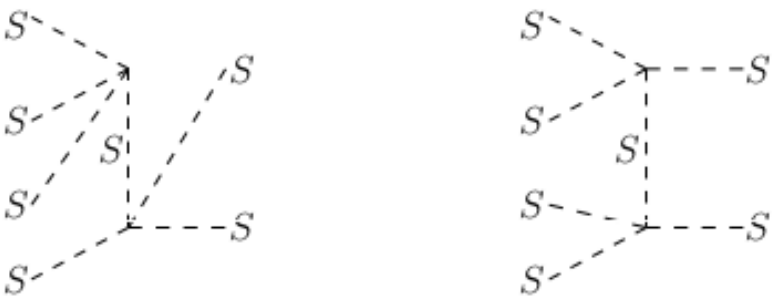
→ Number-changing interactions: $2 \leftrightarrow 3$, $2 \leftrightarrow 4$...

Elastic scattering



Kinetic equilibrium:
DM temperature

Inelastic scattering



Chemical equilibrium:
$4 \rightarrow 2$ and $2 \rightarrow 4$

Self-interacting DM

If DM possess sizable self-interactions:

→ DM thermalizes

→ Number-changing interactions: $2 \leftrightarrow 3$, $2 \leftrightarrow 4$...

* What is the energy transferred from PBHs to DM?
* What is the DM temperature? (kinetic equilibrium)
* What is DM equilibrium number density? (chemical equilibrium)
* Dark freeze-out? (self-production or cannibalization)

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* What is the DM temperature? (kinetic equilibrium)
* What is DM equilibrium number density? (chemical equilibrium)
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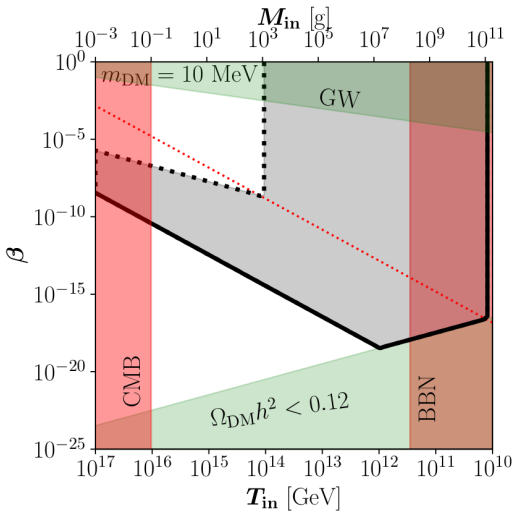
Self-interactions:

→ Increase the DM density ✅

→ Decrease the mean DM kinetic energy ✅

Self-interacting DM from PBHs

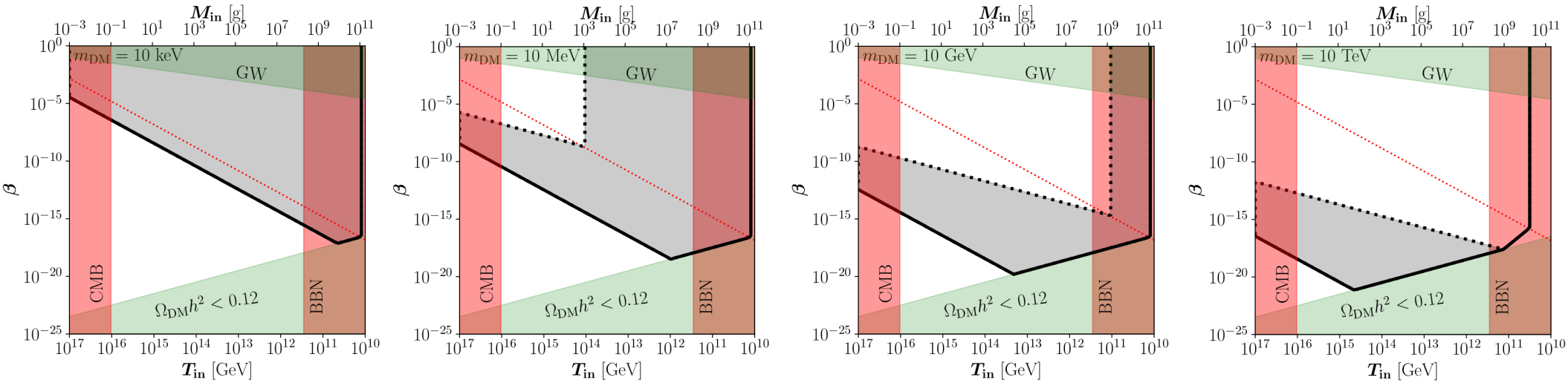


* DM production more efficient → smaller β could be explored

* DM cools down → keV DM becomes viable

* **Model independent result**

Self-interacting DM from PBHs



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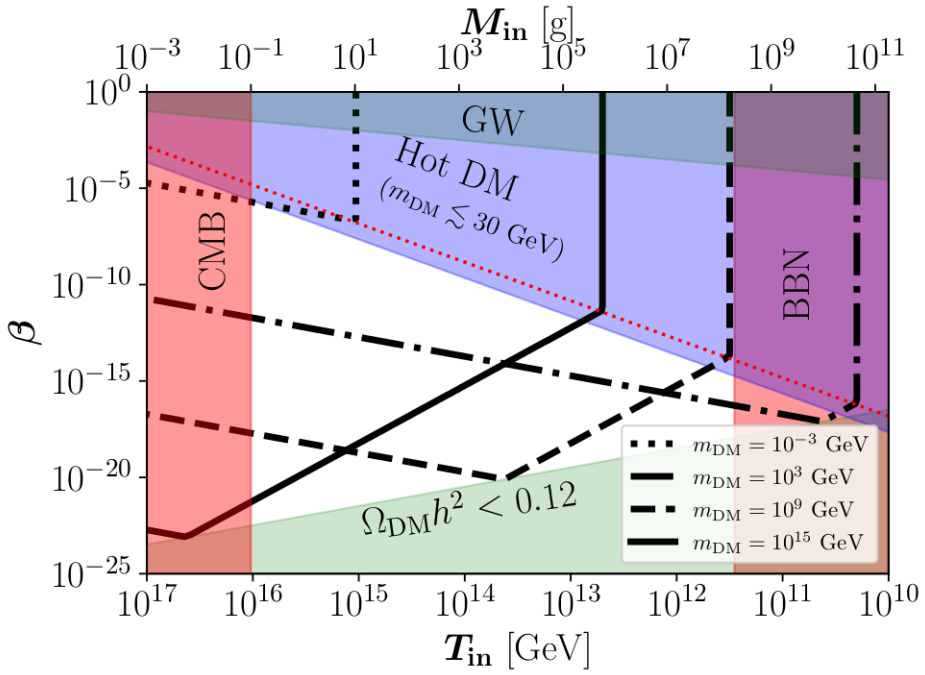
* **Model independent result**

2. Gravitational UV freeze-in

DM from PBHs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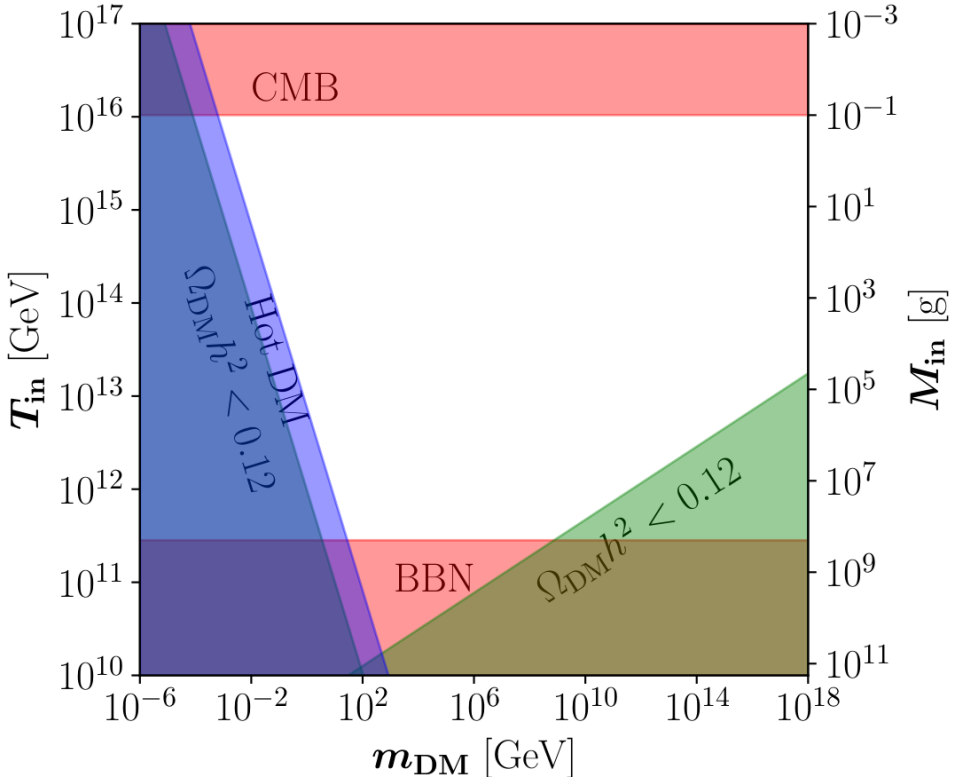
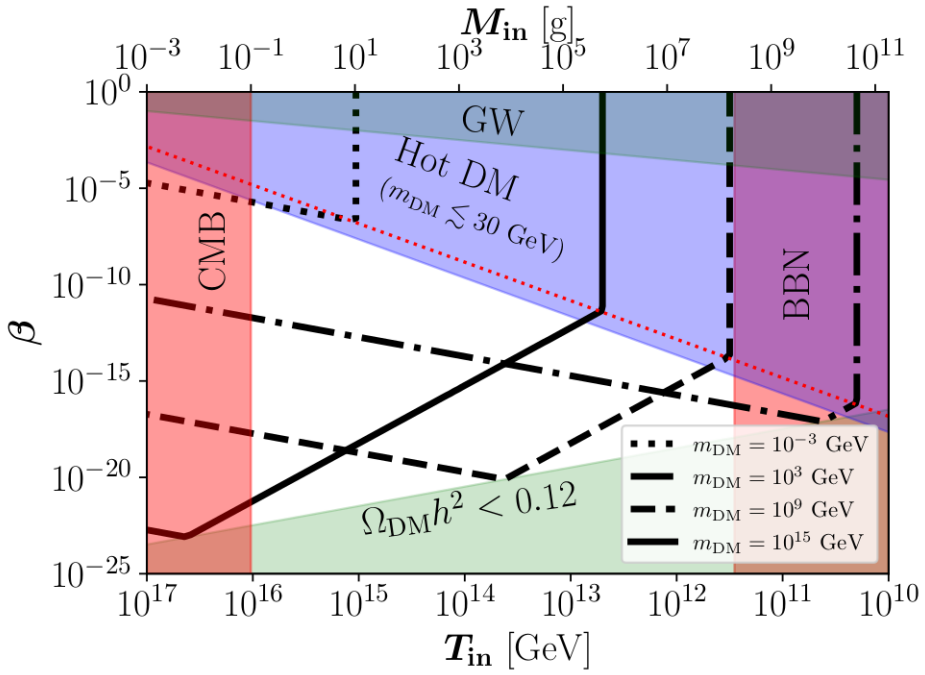
$T_{\rm in}$ [GeV]

=


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

DM from PBHs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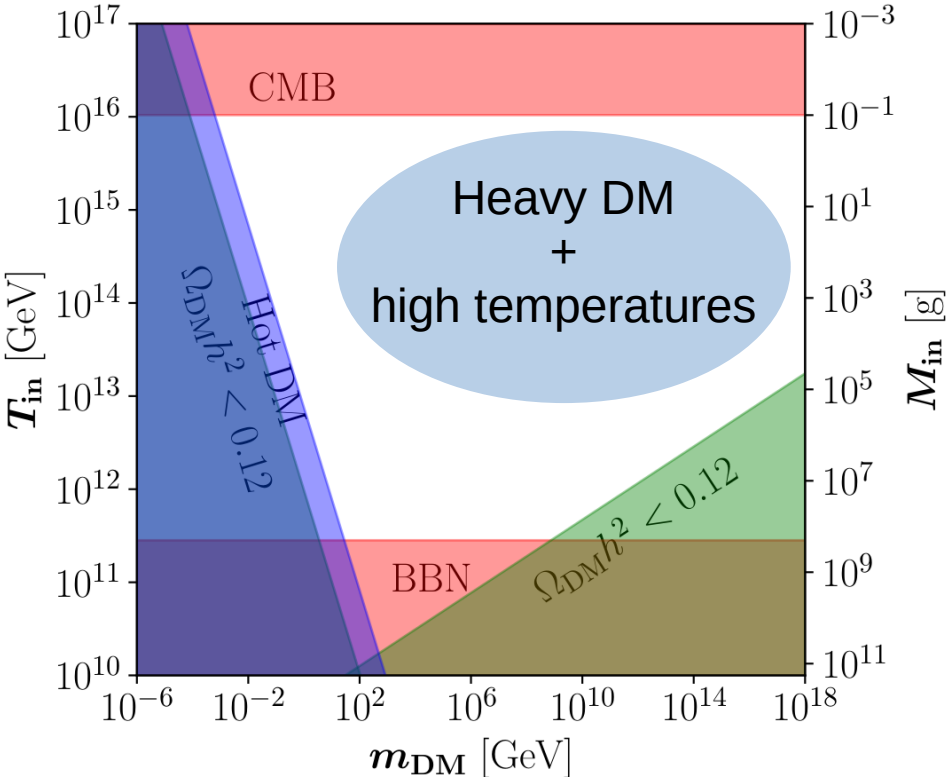
$T_{\rm in}$ [GeV]

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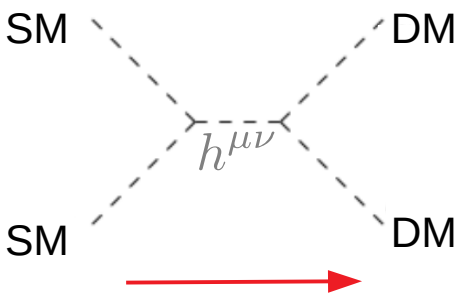
$T_{\rm in}$ [GeV]
10^{-3} 10^{-1} 10^{1} 10^{3} 10^{5} 10^{7} 10^{9} 10^{11}
$M_{\rm in}$ [g]
CMB
Heavy DM
+
high temperatures
Hot DM
$\Omega_{\rm DM}h^2 < 0.12$
BBN
$\Omega_{\rm DM}h^2 < 0.12$
10^{-6} 10^{-2} 10^{2} 10^{6} 10^{10} 10^{14} 10^{18}
$m_{\rm DM}$ [GeV]

Gravitational UV Freeze-in

An example of UV FIMP, mediated by massless SM gravitons

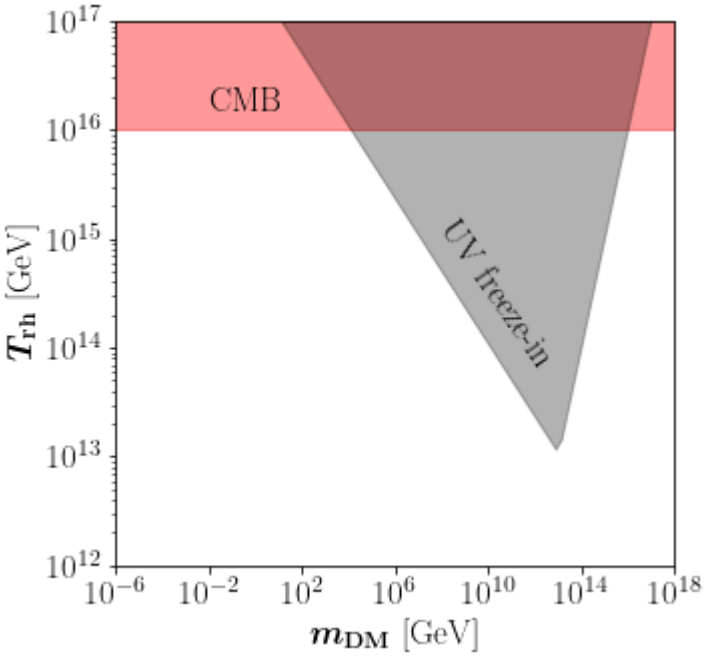


Depends on:

* 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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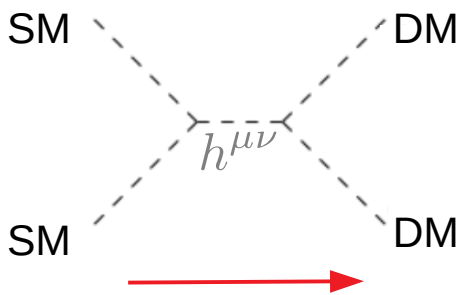

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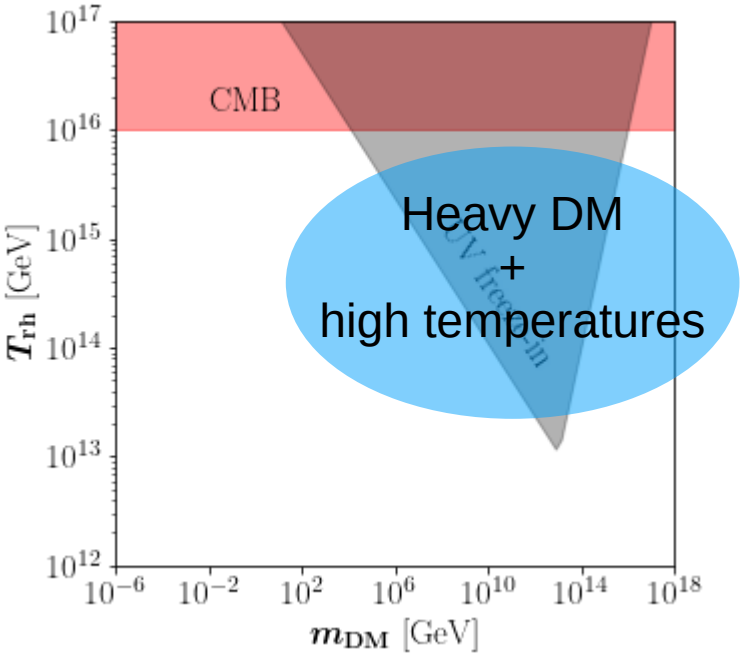
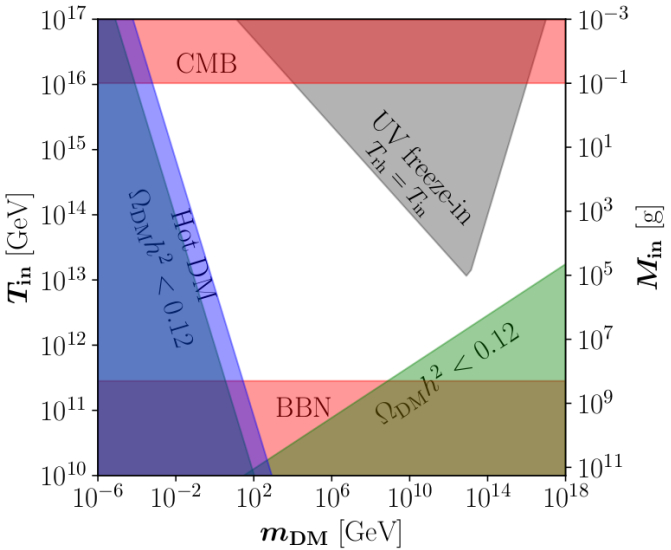
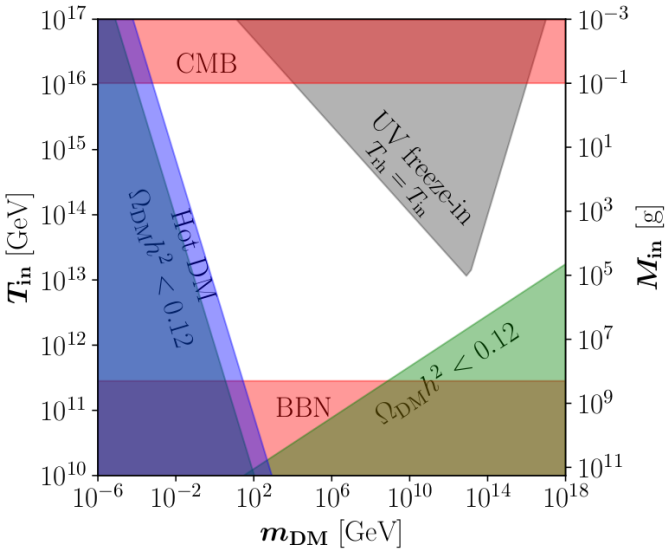


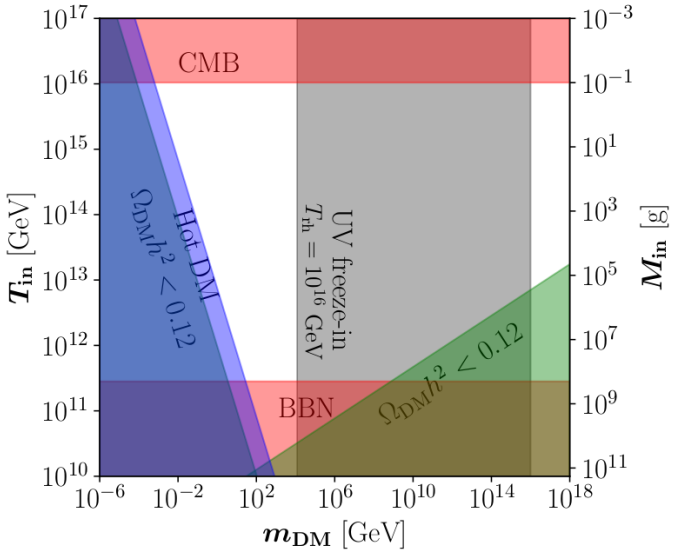
Gravitational DM: PBHs & UV Freeze-in

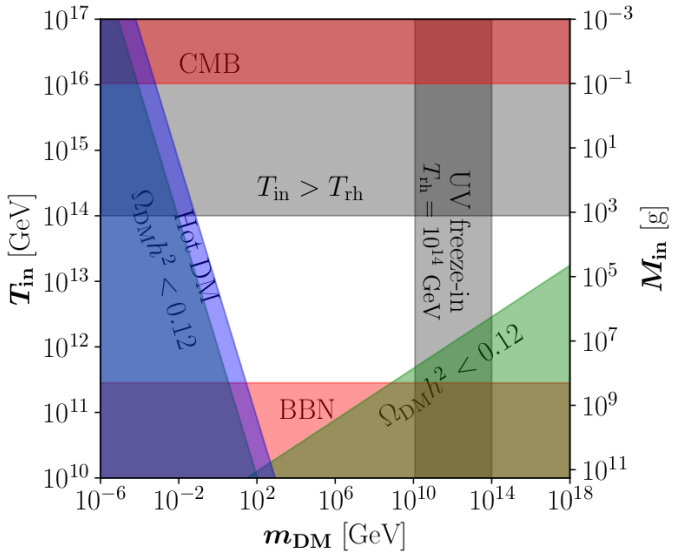


Gravitational UV freeze-in strongly constrains super heavy DM radiated by PBHs!

Gravitational DM: PBHs & UV Freeze-in







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

Conclusions

- It's possible that DM *only* features *gravitational* interactions 
- PBHs could Hawing radiate the *whole* DM density
- DM masses: 1 MeV < m_{DM} < 10^{18} GeV
- **DM self-interactions**:
  → boost DM density (self-production)
  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
- *All gravitational channels have to be taken into account!*

¡Muchas gracias!

Nicolás BERNAL @ NYUAD

DM self-interactions