# Primordial black holes and mattergenesis

*Chee Sheng Fong*
*Federal University of ABC, Brazil*

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In collaboration with James Dent, Bhaskar Dutta & Tao Xu

CCNH CENTRO DE CIÊNCIAS NATURAIS E HUMANAS Universidade Federal do ABC

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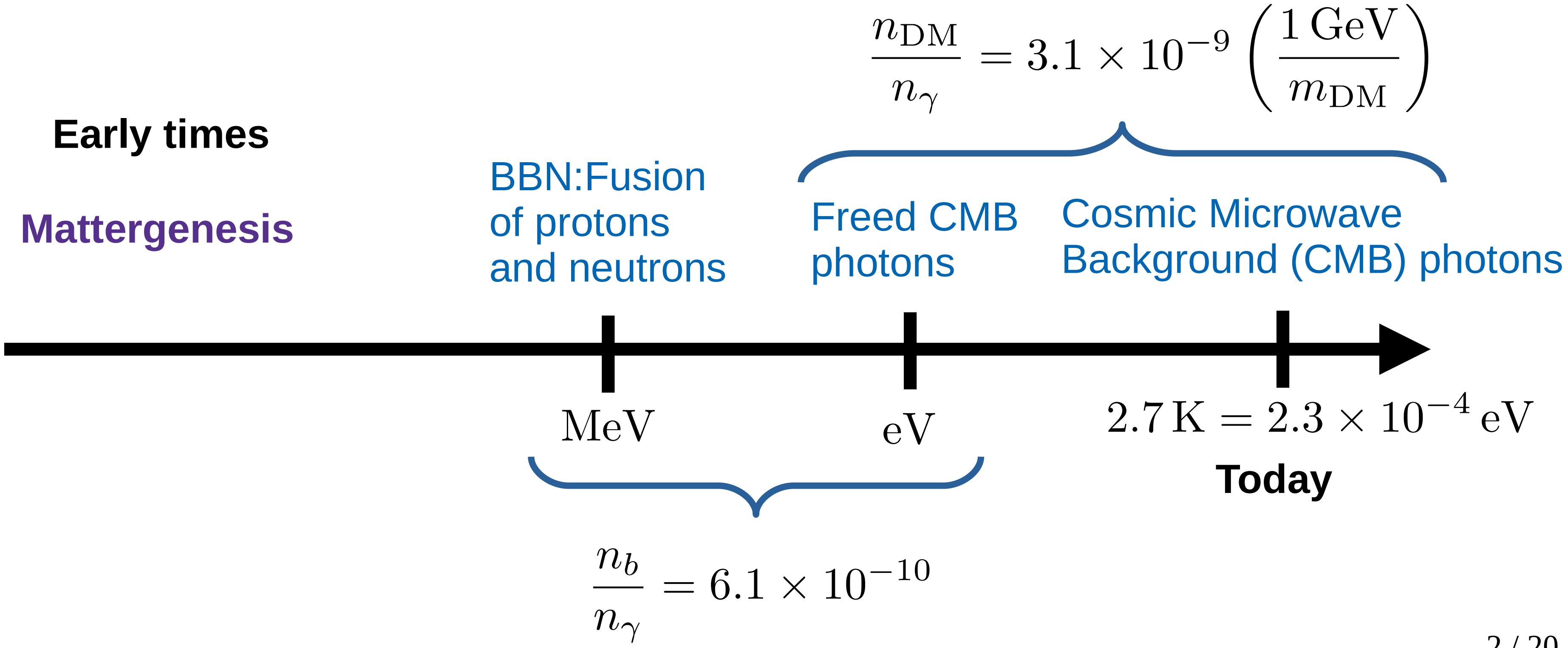
# History of the Universe

A baryon asymmetry and dark matter should be produced at early times



# History of the Universe

A baryon asymmetry and dark matter should be produced at early times

$$\frac{n_{\rm DM}}{n_\gamma} = 3.1 \times 10^{-9}\left(\frac{1\,{\rm GeV}}{m_{\rm DM}}\right)$$

**Early times**

**Mattergenesis**

BBN:Fusion of protons and neutrons

Freed CMB photons

Cosmic Microwave Background (CMB) photons

$$\frac{n_B}{n_\gamma} \equiv \frac{n_b - n_{\bar{b}}}{n_\gamma} = 6.1 \times 10^{-10}$$

$\rm MeV$ $\qquad$ $\rm eV$ $\qquad$ $2.7\,{\rm K} = 2.3 \times 10^{-4}\,{\rm eV}$

**Today**

$$\frac{n_{\rm DM}}{n_\gamma} =?$$

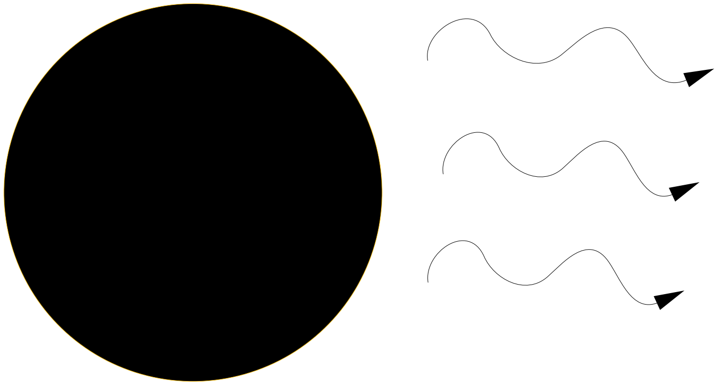
$$\frac{n_b}{n_\gamma} = 6.1 \times 10^{-10}$$

# History of the Universe

With primordial black holes (PBHs) at early times: not from stellar collapse

$$T_{\rm BH} \sim \frac{1}{8\pi r_g} = 10^3\,{\rm GeV}\left(\frac{10^{10}\,{\rm g}}{M_{\rm BH}}\right)$$

$$t_{\rm BH} \sim \frac{M_{\rm BH}^3}{M_{\rm Pl}^4} = 0.005\,{\rm s}\left(\frac{M_{\rm BH}}{10^9\,{\rm g}}\right)^3$$



Hawking radiation

$$X \to \ldots \to n_b > n_{\bar{b}}$$ Baryogenesis

DM — Dark matter production

$$r_g \equiv M_{\rm BH}/M_{Pl}^2$$

# Outline

- Properties of PBH
- PBH particle production and constraints
- Parameter space of mattergenesis
- Discussions

# Properties of PBH

- Large density perturbation $p/\rho \gtrsim 1/3$ reenters the horizon of size *R* and collapses

$$M_{\rm BH0} = \gamma 4\pi R^3 \rho/3$$

[Carr & Hawking (1974)]

- In a radiation dominated Universe $H = (2t_f)^{-1} = R^{-1} = \sqrt{8\pi\rho/(3M_{\rm Pl}^2)}$

$$M_{\rm BH0} = \gamma t_f M_{\rm Pl}^2 = 8\times 10^{37}\,{\rm g}\left(\frac{\gamma}{0.2}\right)\left(\frac{t_f}{1\,{\rm s}}\right) = 4\times 10^4 M_\odot\,{\rm g}\left(\frac{\gamma}{0.2}\right)\left(\frac{t_f}{1\,{\rm s}}\right)$$

$$= 3\times 10^4 M_\odot \left(\frac{\gamma}{0.2}\right)\left(\frac{10.75}{g_\star}\right)^{1/2}\left(\frac{1\,{\rm MeV}}{T_f}\right)^2$$

- Nonobservation of inflationary tensor perturbation by Planck $H_I < 2.5\times 10^{-5}\,M_{\rm Pl}$

[Planck collaboration, 1807.06211]

$$M_{\rm BH0} > 0.09\,{\rm g}\left(\frac{\gamma}{0.2}\right)\left(\frac{106.75}{g_\star}\right)^{1/2}\left(\frac{1.5\times 10^{16}\,{\rm GeV}}{T_{f,\rm max}}\right)^2$$

# Properties of PBH

- The emission rate through Hawking radiations [Hawking (1974, 1975)]

$$\frac{d^2 N_i}{dt d\omega} = \frac{g_i}{2\pi^2} \sum_{\ell \geq s_i} \sum_{m=-\ell}^{\ell} \frac{\sigma_{s_i \ell m} \omega^2}{e^{(\omega - m\Omega)/T_{\rm BH}} - \eta_i}$$

$$\eta_i \equiv (-1)^{2s_i}$$

$$\omega r_g \gg 1 \quad \sigma_{s_i \ell m} \to 27\pi r_g^2 \equiv \sigma_{\rm go}$$

Spin

$$\Omega \equiv \frac{a_\star}{1+\sqrt{1-a_\star^2}} \frac{1}{2r_g} \qquad a_\star \equiv \frac{J}{r_g M_{\rm BH}}$$

Temperature

$$T_{\rm BH} \equiv \frac{1}{8\pi r_g} \frac{2\sqrt{1-a_\star^2}}{1+\sqrt{1-a_\star^2}} = 10^3\,{\rm GeV} \left(\frac{10^{10}\,{\rm g}}{M_{\rm BH}}\right) \frac{2\sqrt{1-a_\star^2}}{1+\sqrt{1-a_\star^2}}$$

(Could emit efficiently all the SM particles)

BH loses its charges quickly unless $M_{\rm BH0} > 10^5 M_\odot$

[Carter (1974); Zaumen (1974); Gibbons (1975); Page (1976)]

# Properties of PBH

- The evolutions of mass and spin are described by [Page (1976)]

$$\frac{dM_{\rm BH}}{dt} = -\sum_i \int_{m_i}^{\infty} \frac{d^2N_i}{dtd\omega}\omega d\omega \equiv -T_{\rm BH}^4 r_g^2 \sum_i \sum_{\ell \geq s_i} \sum_{m=-\ell}^{\ell} \mathcal{L}^{(3)}_{s_i \ell m}(x_i, a_\star),$$

$$\frac{dJ}{dt} = -\sum_i \int_{m_i}^{\infty} \frac{d^2N_i}{dtd\omega} m d\omega \equiv -T_{\rm BH}^3 r_g^2 \sum_i \sum_{\ell \geq s_i} \sum_{m=-\ell}^{\ell} m\mathcal{L}^{(2)}_{s_i \ell m}(x_i, a_\star).$$

$$t_{\rm BH,go} = 0.24\,{\rm s}\left(\frac{M_{\rm BH0}}{10^9\,{\rm g}}\right)^3 \left(\frac{106.75}{g_\star}\right)\left(\frac{27\pi}{\overline{\sigma}_{\rm go}}\right)$$

Still be here today $\quad t_{\rm BH} \gtrsim t_U = 4.3 \times 10^{17}\,{\rm s} \qquad M_{\rm BH0} \gtrsim 10^{15}\,{\rm g}$

# PBH particle production and constraints

- Number of particle *i* with mass $m_i$ emitted from a BH

$$N_i = \int_0^{t_{\rm BH}} dt \int_{m_i}^{\infty} d\omega \frac{d^2 N_i}{dt d\omega}$$

In geometrical optic limit, we have for scalar {fermion}

$$N_i = \begin{cases} \{3/4\} \dfrac{120 g_i M_{\rm BH0}^2}{\pi^3 g_\star M_{\rm Pl}^2} \zeta(3) & m_i \ll T_{\rm BH0} \\ \{15/16\} \dfrac{45 g_i M_{\rm Pl}^2}{2\pi^5 g_\star m_i^2} \zeta(5) & m_i \gg T_{\rm BH0} \end{cases}$$

Becomes independent of mass for $m_i \lesssim 10^5\,{\rm GeV} \left(\dfrac{10^8\,{\rm g}}{M_{\rm BH}}\right)$

# PBH particle production and constraints

- Let us consider a bunch of PBHs at formation radiation temperature $T_f$

$$\beta \equiv \frac{\rho_{\rm BH}(T_f)}{\rho_R(T_f)} = \frac{n_0 M_{\rm BH0}}{\rho_R(T_f)}$$

- The abundance of particle *i* generated

$$Y_i^0 \equiv \frac{N_i n(T_{\rm ev})}{s(T_{\rm ev})} = \frac{N_i n_0}{s(T_f)} = \frac{3\beta T_f N_i}{4 M_{\rm BH0}}$$

PBH domination

$$H(T_{\rm ev}) = \frac{2}{3 t_{\rm BH}}$$

- Using the “sudden evaporation approximation”, we have the entropy dilution

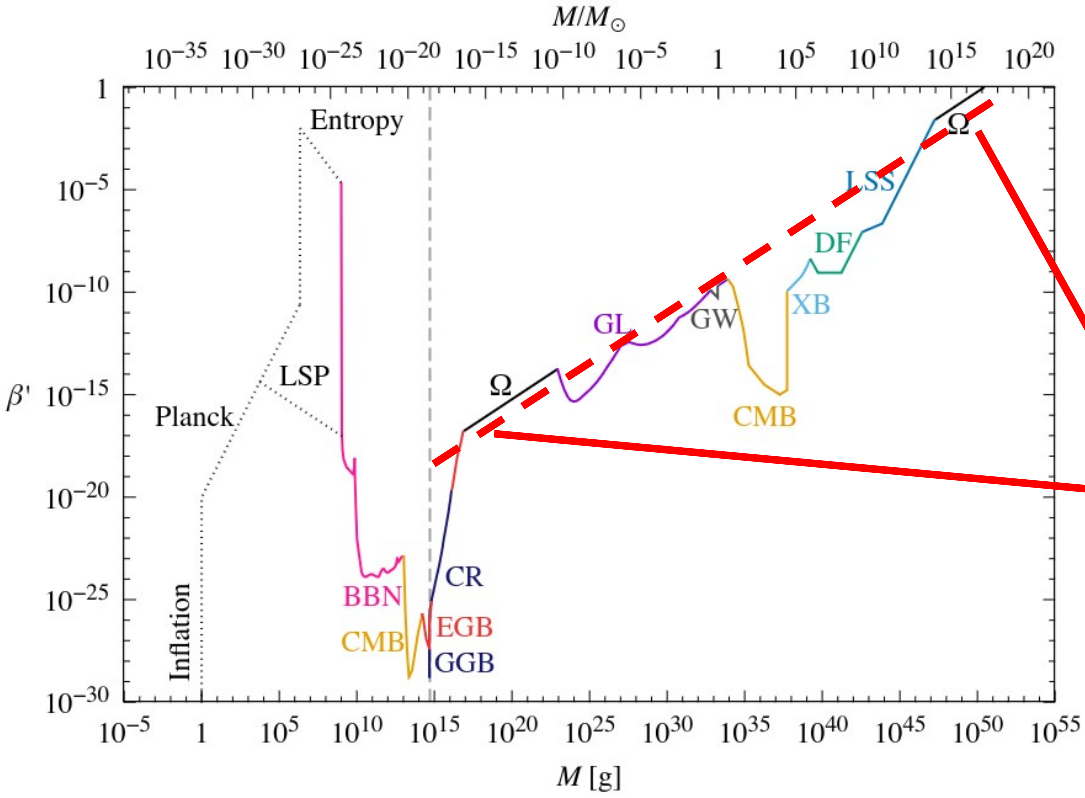
$$\frac{\pi^2}{30} g_\star T_{\rm ev}^4 + M_{\rm BH0} \frac{n_0}{s(T_0)} s(T_{\rm ev}) = \frac{\pi^2}{30} g_\star \tilde{T}^4 \implies d \equiv \left(\frac{\tilde{T}}{T_{\rm ev}}\right)^3 = \left(1 + \frac{\beta T_f}{T_{\rm ev}}\right)^{3/4}$$

Dilution is relevant $\beta > 6.4 \times 10^{-8} \left(\frac{0.2}{\gamma}\right)^{1/2} \left(\frac{100\,{\rm g}}{M_{\rm BH0}}\right)$

# PBH particle production and constraints

- The current constraints on PBHs $\Omega_{\rm PBH} = 0.19\left(\frac{\beta}{10^{-15}}\right)\left(\frac{10^{20}\,{\rm g}}{M_{\rm BH0}}\right)^{1/2}\left(\frac{\gamma}{0.2}\right)^{1/2}\left(\frac{106.75}{g_\star}\right)^{1/4}$

$$\beta' \equiv \beta\sqrt{\gamma}g_\star^{-1/4} = 0.14\beta\left(\frac{\gamma}{0.2}\right)^{1/2}\left(\frac{106.75}{g_\star}\right)^{1/4}$$




PBHs are all the dark matter!

[Carr et al., 2002.12778]

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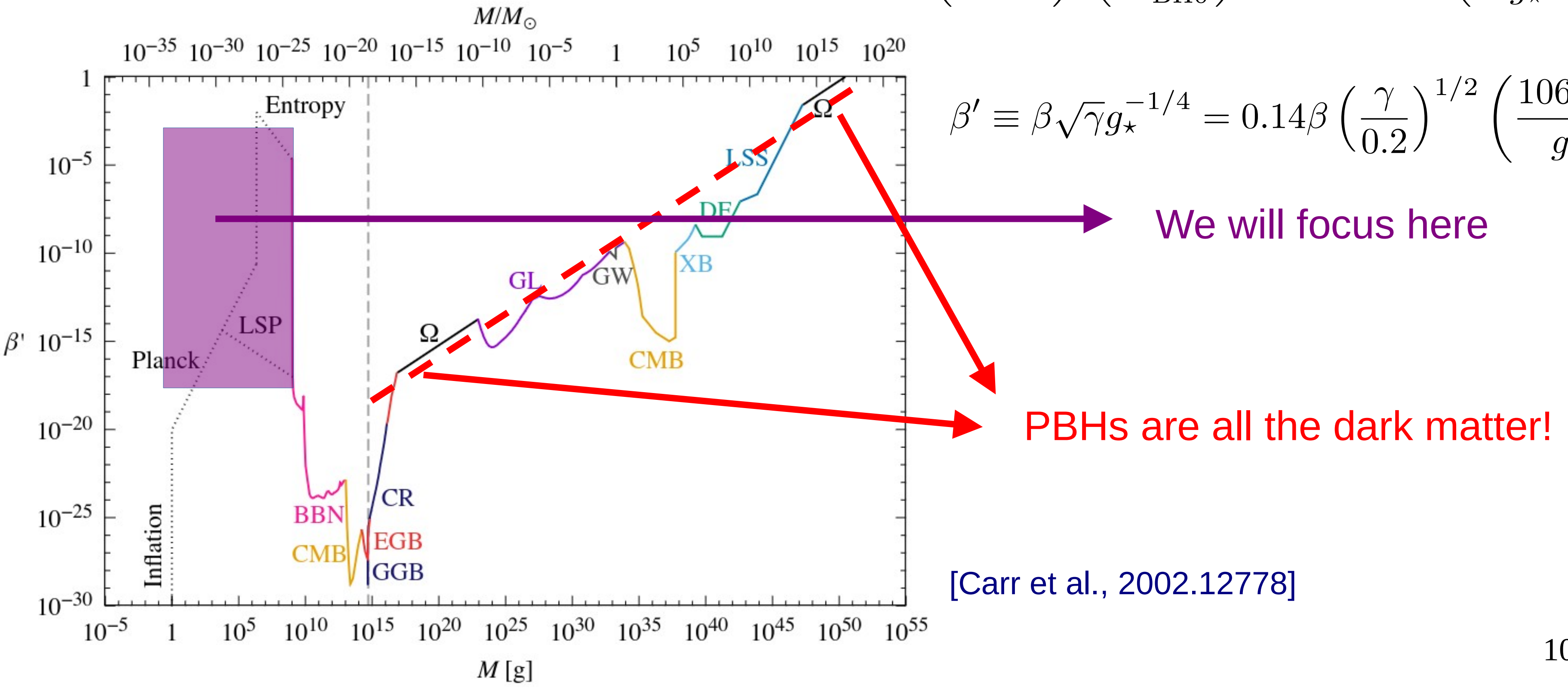



[Carr et al., 2002.12778]

# PBH particle production and constraints

- PBH domination → Hawking radiation → Gravitational wave (GW)→ Big Bang Nucleosynthesis (BBN)

$$\beta \lesssim 1.1 \times 10^{-6} \left(\frac{\gamma}{0.2}\right)^{-1/2} \left(\frac{M_{\rm BH0}}{10^4\,{\rm g}}\right)^{-\frac{17}{24}}$$

[Domènech, Lin & Sasaki, 2012.08151]

- Warm/hot dark matter (emitted from PBHs) bound

$$m_{\rm DM} \geq 5.2\,(4.4)\ {\rm keV} \left(\frac{m_{\rm WDM}^{\rm Ly-\alpha}}{\rm keV}\right)^{4/3} \left(\frac{M_{\rm BH0}}{M_{\rm Pl}}\right)^{1/2}$$

[Baldes, Decant, Hooper & Lopez-Honorez, 2004.14773]

# Parameter space for mattergenesis

- From Planck measurements [Planck collaboration, 1807.06211]

$$Y_{\rm DM}^{\rm obs} = 4.4 \times 10^{-10} \left(\frac{1\,{\rm GeV}}{m_{\rm DM}}\right), \quad Y_B^{\rm obs} = 8.8 \times 10^{-11}$$

- It is a number game

Dark matter: Planck Scale Remnant or fundamental particle

$$Y_{\rm PSR} = \frac{3\beta T_f}{4M_{\rm BH0}} d \qquad Y_{\rm DM} = \frac{3\beta T_f}{4M_{\rm BH0}} d \times N_{\rm DM}$$

Baryogenesis (from decays): Lower limit on number of X particle

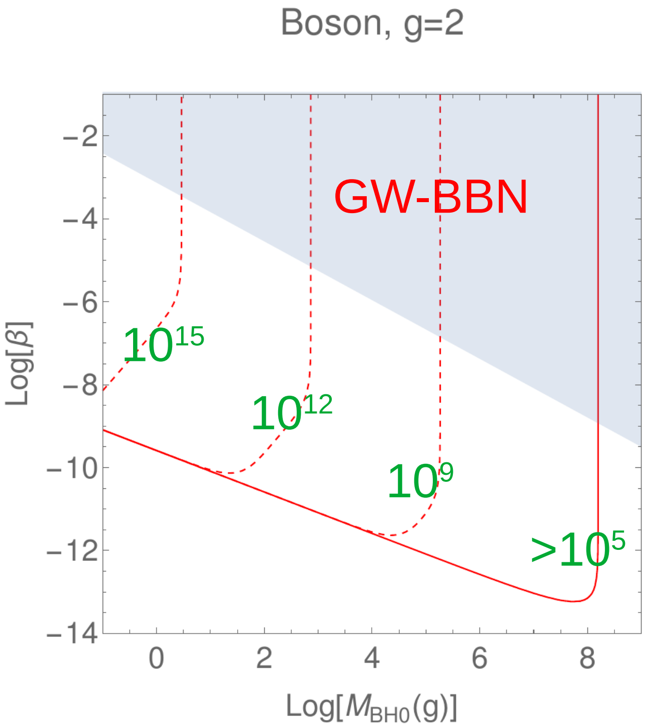
$$Y_B = \underbrace{r\eta}_{\text{Particle physics}} \times \epsilon Y_X = r\eta\epsilon \times \frac{3\beta T_f}{4M_{\rm BH0}} d \times N_X \implies \boxed{Y_X \geq Y_B^{\rm obs}}$$

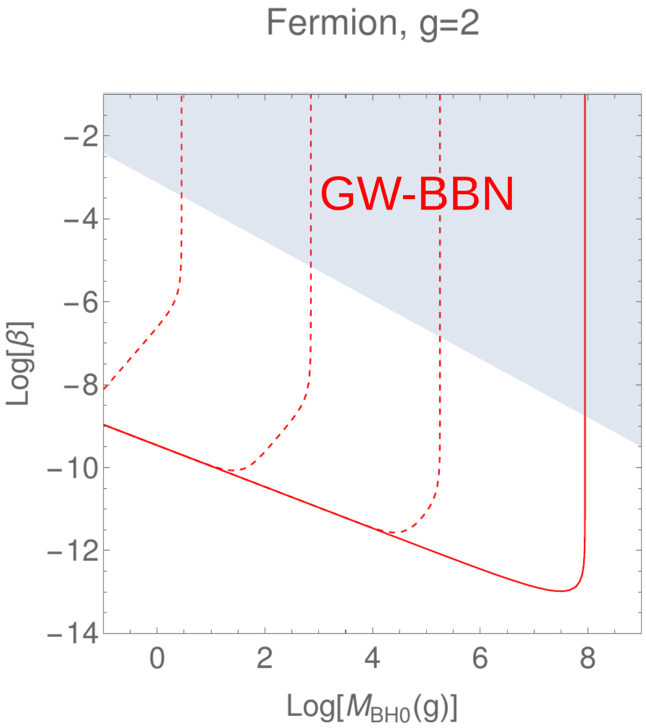
Particle physics

Absolute bound

# Parameter space for mattergenesis

- Parameter space for baryogenesis for all mass scale of $m_X$ (GeV)

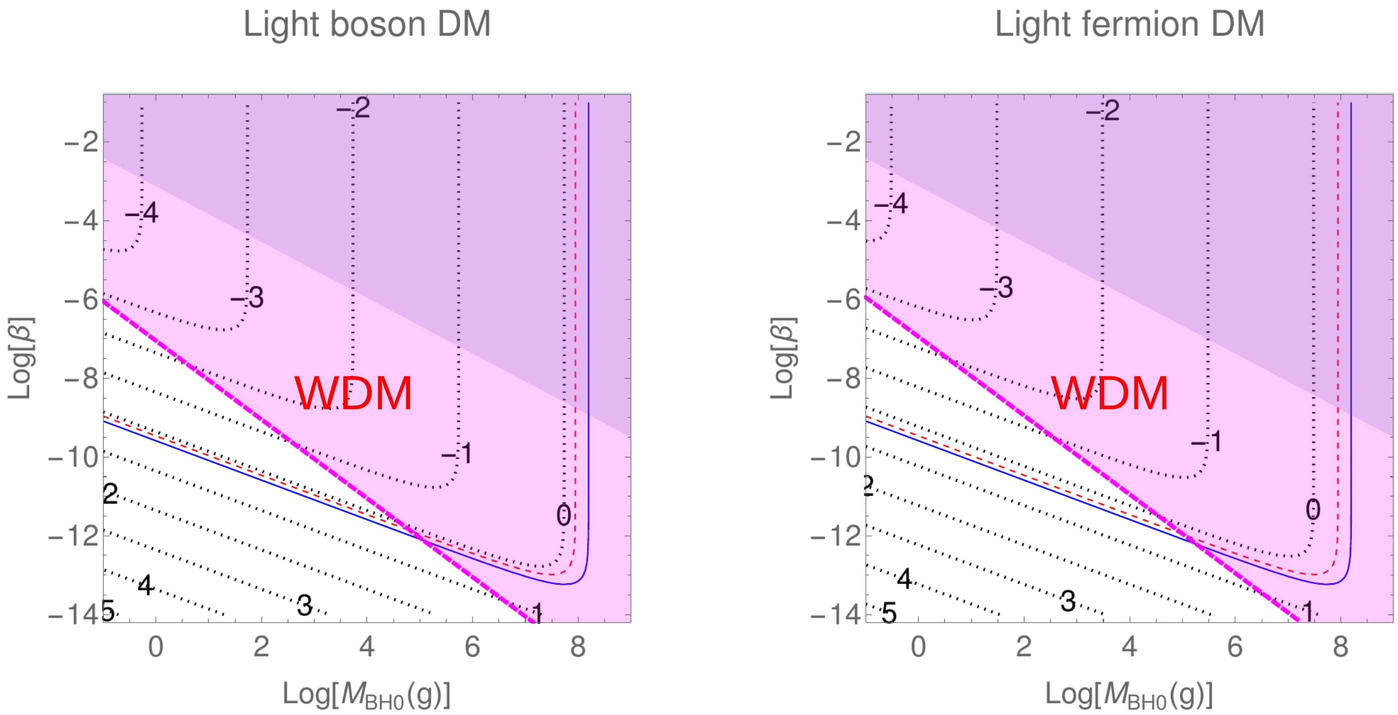



See also [Bernal, CSF, Perez-Gonzalez & Turner, 2203.08823]
[Hooper & Krnjaic, 2010.01134]

# Parameter space for mattergenesis

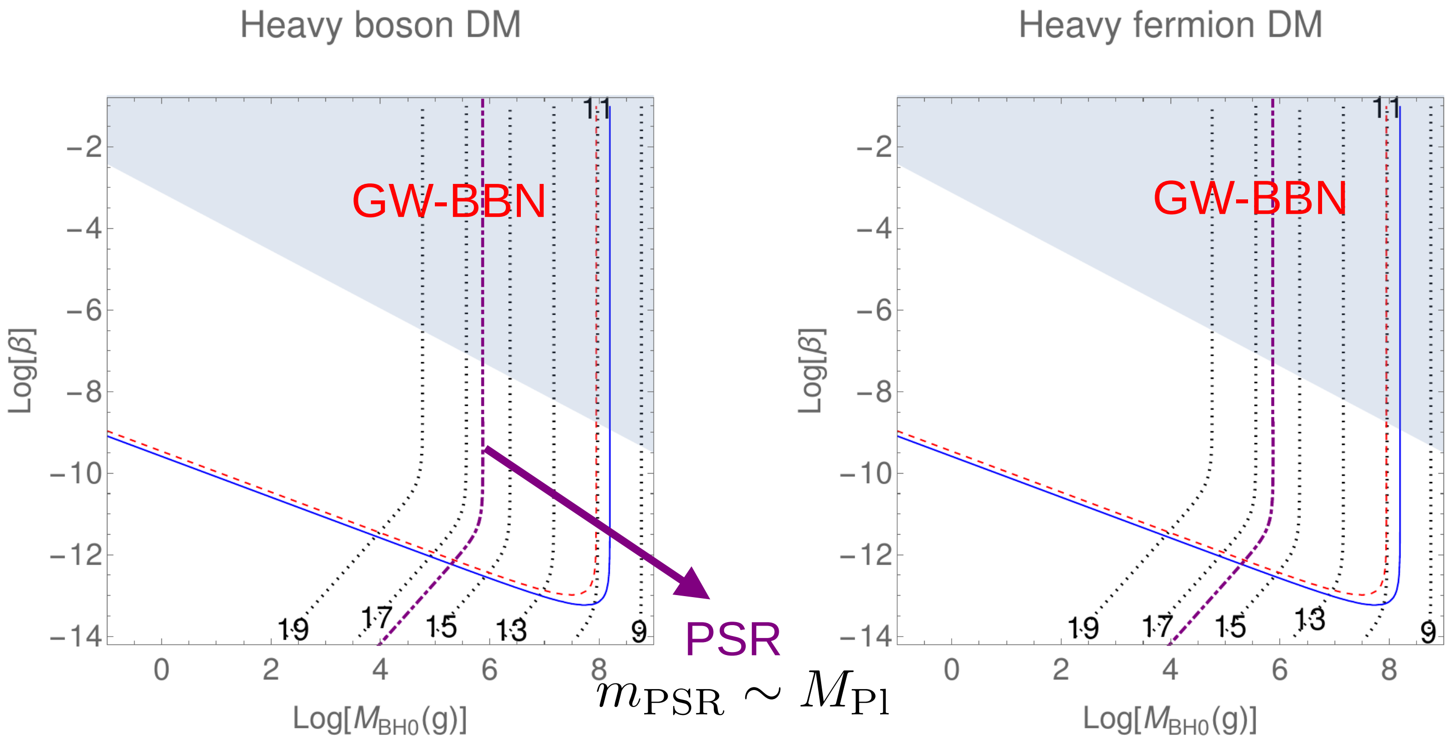
- Parameter space for light DM of $\log(m_{DM})$ (GeV)




See also [Cheek, Heurtier, Perez-Gonzalez & Turner, 2207.09462]

# Parameter space for mattergenesis

- Parameter space for heavy DM of log($m_{DM}$) (GeV)




Earlier work [Baumann, Steinhardt & Turok, hep-th/0703250]

# Discussions

- Baryogenesis from PBHs requires $\beta \gtrsim 10^{-13}$ $M_{\rm BH} \lesssim 10^8\,{\rm g}$ $m_X \lesssim 10^{15}{\rm GeV}$
- In the regime, PBHs can produce correct DM abundance for

$$\text{MeV} \lesssim m_{\rm DM} \lesssim \text{GeV} \qquad 10^{11}\,\text{GeV} \lesssim m_{\rm DM} \lesssim M_{\rm Pl}\,(\text{PSR})$$

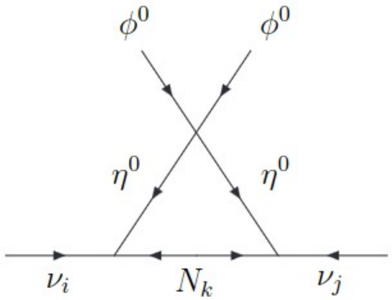
- Model(s)? E.g. Scotogenic [Ma, hep-ph/0601225]

$$m_{N_2}, m_{N_3} \sim 10^4\,\text{GeV}$$

$$m_\eta \sim 10^2\,\text{GeV}$$

$m_{N_1} \sim \text{GeV}$ DM

Neutrino mass




Leptogenesis

$$N_{2,3} \to \ell + \phi$$

$N_1$ leptogenesis
[Hugle, Platscher & Schmitz, 1804.09660]

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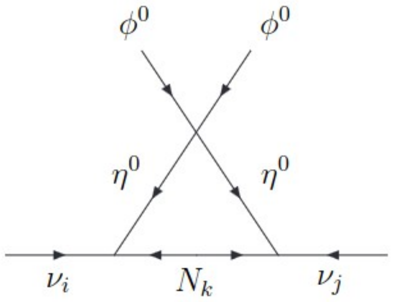


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Type-I seesaw at natural scale $m_N \gtrsim 10^9\,\text{GeV}$ with sub-GeV DM also fit

Thanks for your attention!

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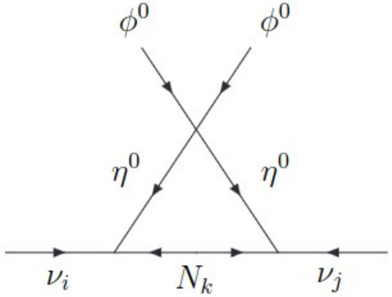


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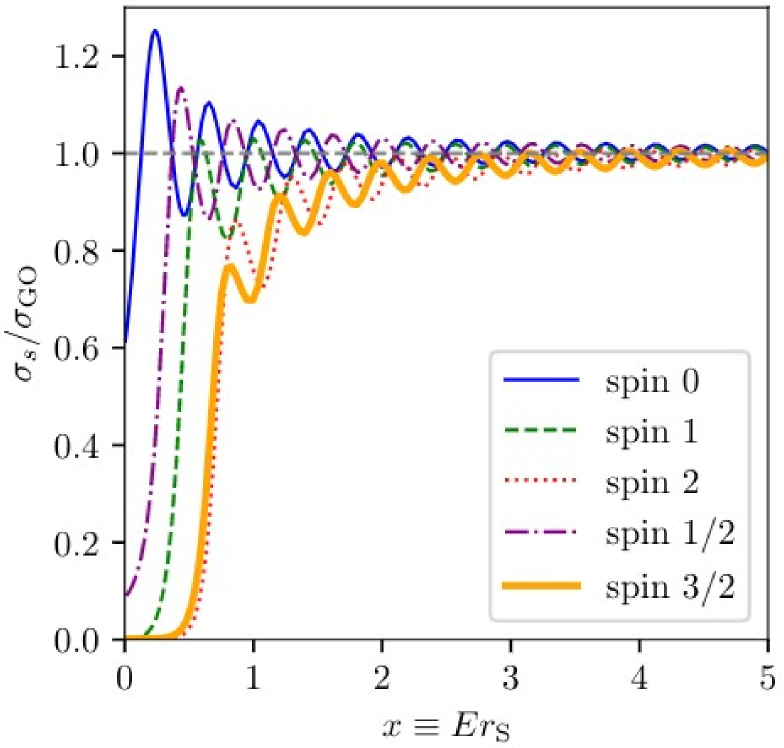
# Properties of PBH

- Greybody factors




$$\omega r_g \gg 1 \qquad \sigma_s \to 27\pi r_g^2 \equiv \sigma_{\rm go}$$

[BlackHawk, 1905.04268, 2108.02737]

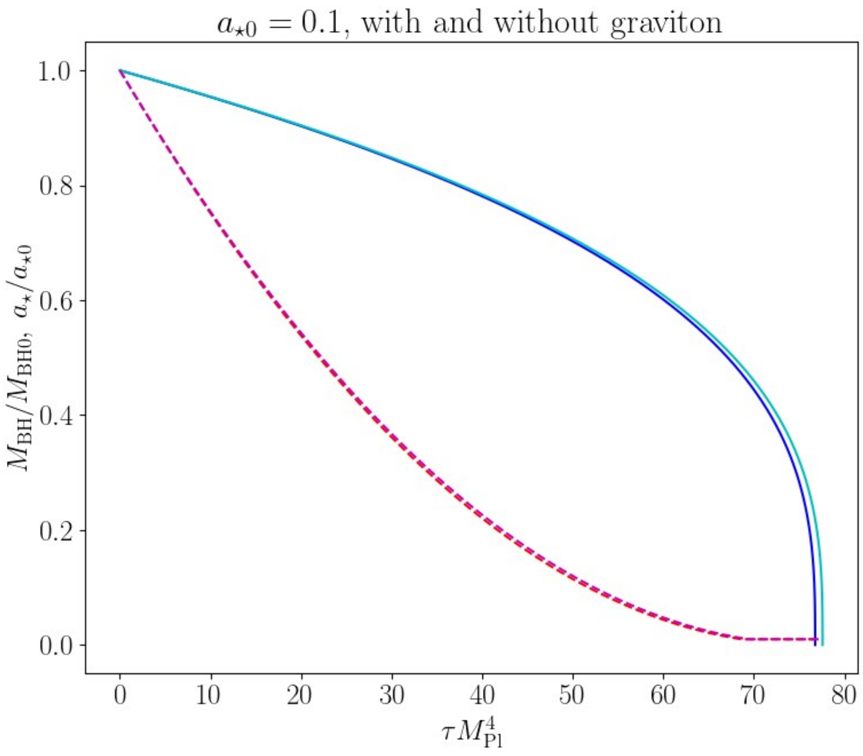
Backup

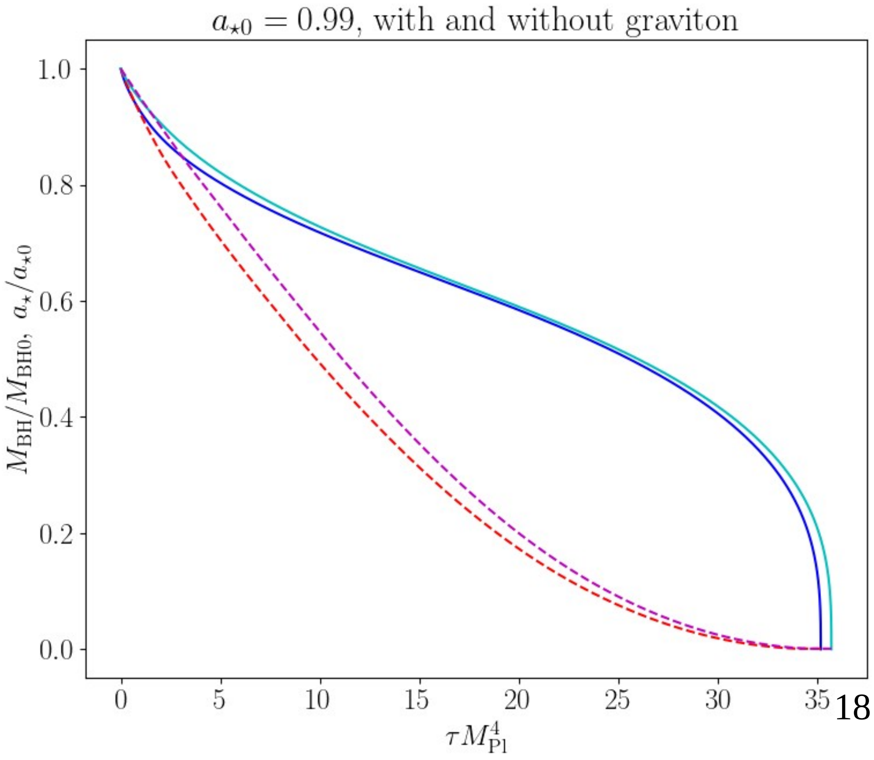
# Properties of PBH

- Notice that $\frac{dM_{\rm BH}}{dt} \propto T_{\rm BH}^4 r_g^2 \propto M_{\rm BH}^{-2} \implies t \propto M_{\rm BH}^3$

"Scale invariant"

$$\tau \equiv M_{\rm BH0}^{-3} t$$



Backup

# Properties of PBH

- A Schwarzschild PBH lifetime in geometrical optic limit

$$t_{\rm BH,go} = \frac{45}{M_{\rm Pl}^4}\left(\frac{106.75}{g_\star}\right)\left(\frac{27\pi}{\bar{\sigma}_{\rm go}}\right) M_{\rm BH}^3 = 0.24\,{\rm s}\left(\frac{M_{\rm BH0}}{10^9\,{\rm g}}\right)^3\left(\frac{106.75}{g_\star}\right)\left(\frac{27\pi}{\bar{\sigma}_{\rm go}}\right)$$

Including greybody factors

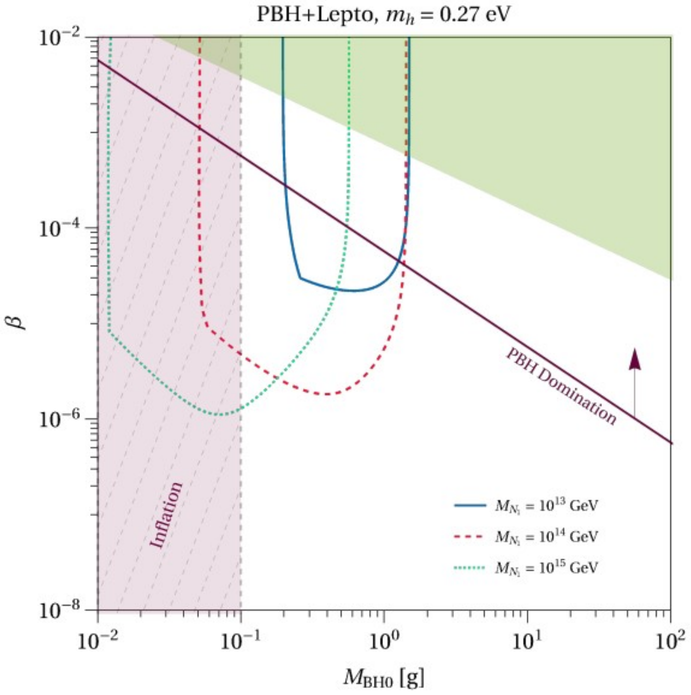
$$\tau_{\rm BH}(a_{\star 0}=0) = \frac{78}{M_{\rm Pl}^4} \qquad \tau_{\rm BH}(a_{\star 0}=0.99) = \frac{36}{M_{\rm Pl}^4}$$

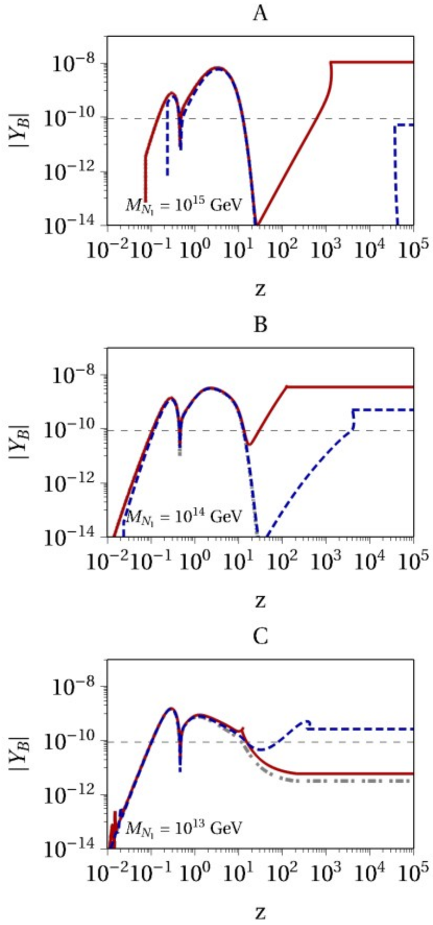
Still be here today $\quad t_{\rm BH} \gtrsim t_U = 4.3\times 10^{17}\,{\rm s} \qquad M_{\rm BH0} \gtrsim 10^{15}\,{\rm g}$

Backup

# PBH on type-I leptogenesis

- Can be successful despite large washout at earlier times




[Bernal, CSF, Perez-Gonzalez & Turner, 2203.08823]