Cogenesis of baryon asymmetry and gravitational dark matter from primordial black holes

based on JCAP 08 (2022) 068

with Basabendu Barman, Debasish Borah, Rishav Roshan

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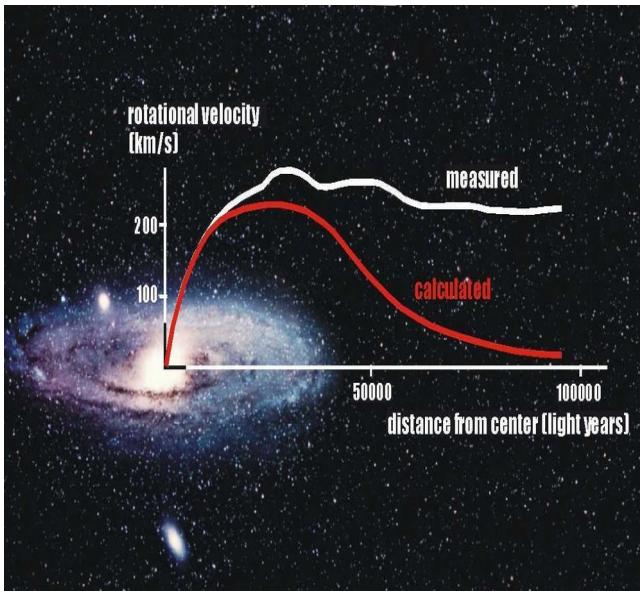
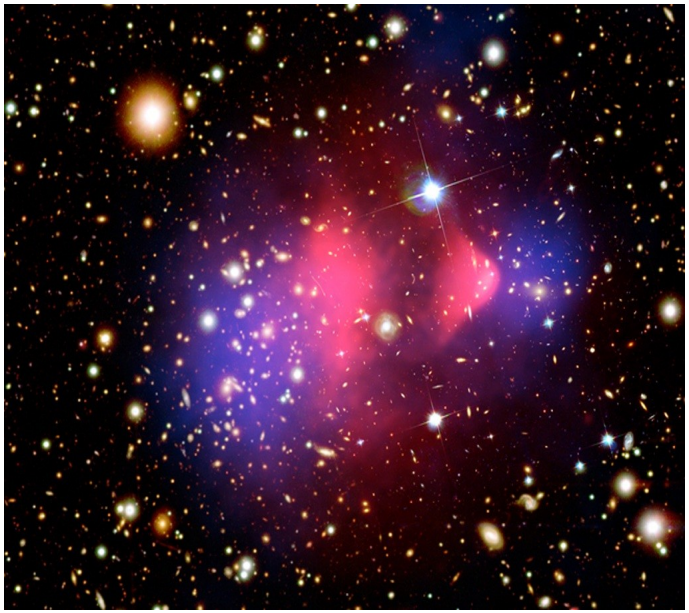
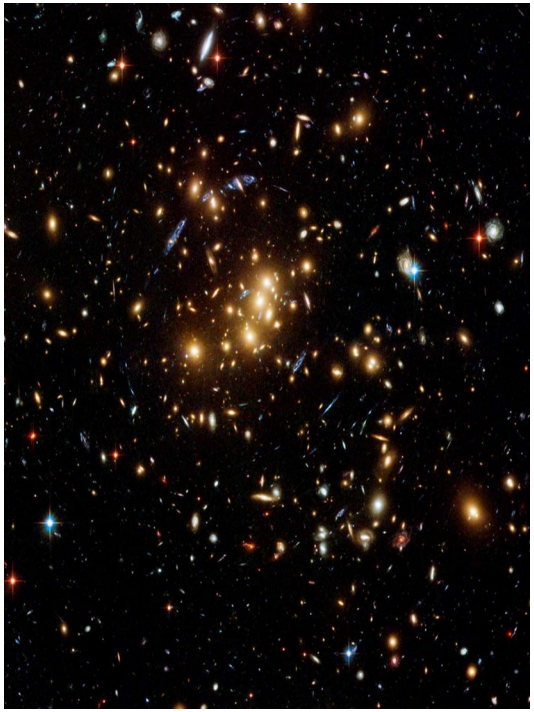
Motivation



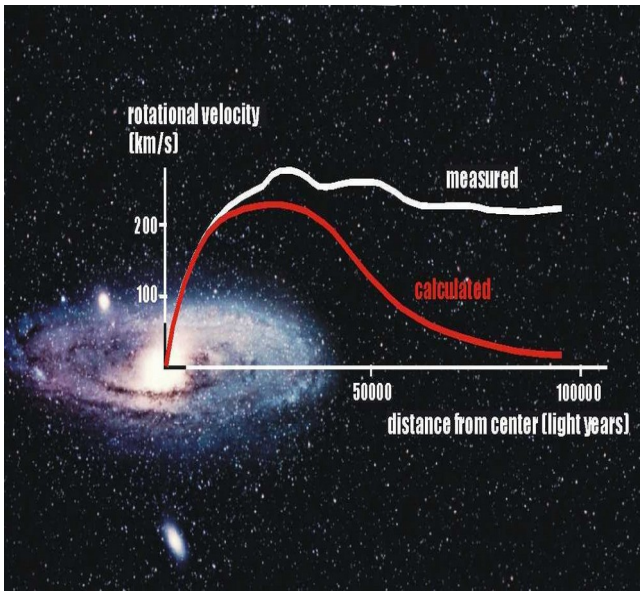


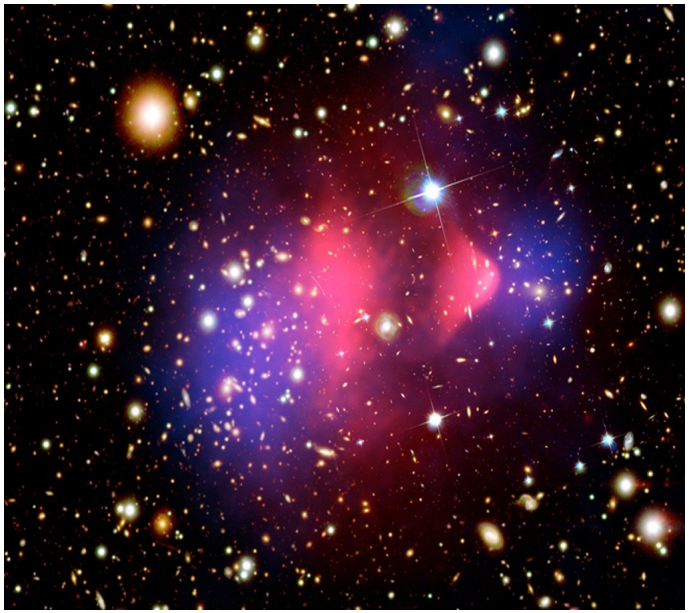


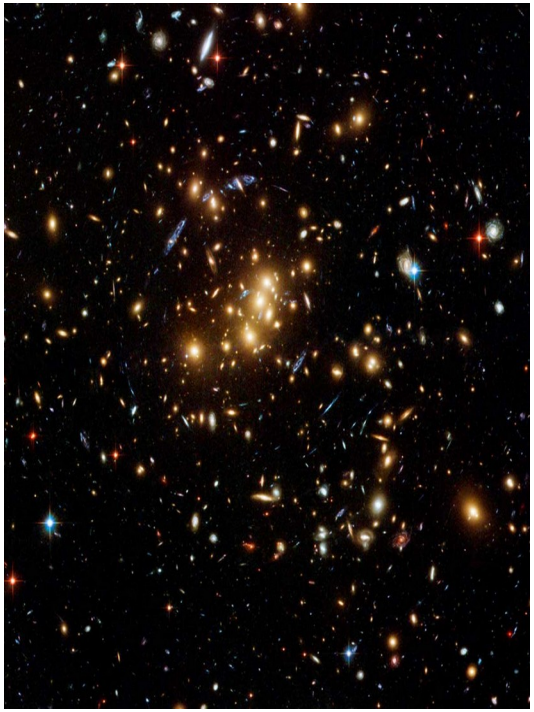
No evidence of WIMP so far...

Dark Matter interacts only gravitationally ?

Motivation







No evidence of WIMP so far...

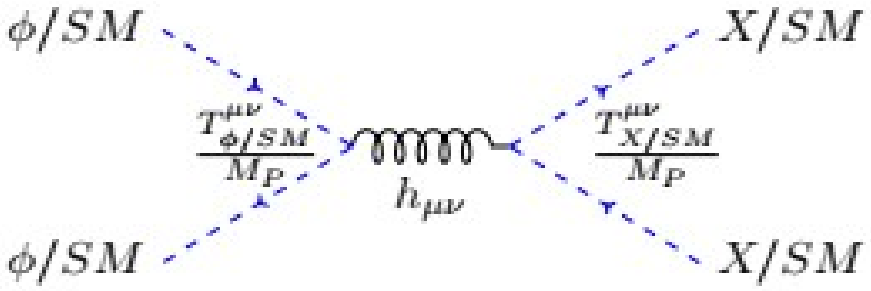
Dark Matter interacts only gravitationally ?

- How to produce gravitational DM?
- How to detect?

Gravitational DM production routes

- Gravity mediated scatterings:

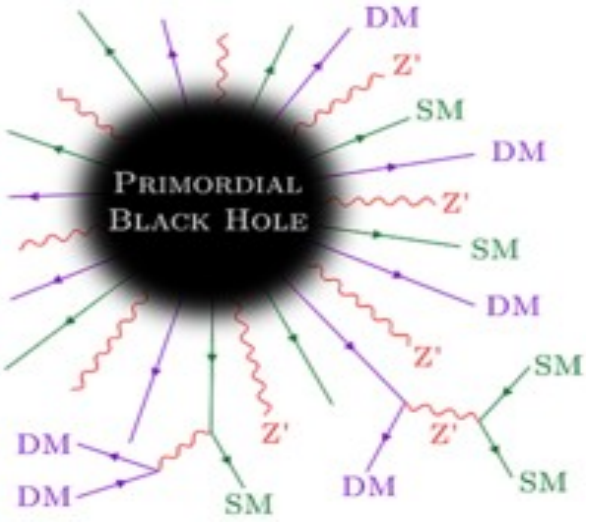
2112.15214 (Y. Mambrini et al.)



- Gravitational particle production due to departure from adiabaticity. → Talk by Siyang Ling.

- PBH as DM. → Talk by Sarah Geller.

- **Hawking evaporation of PBH.**



PRD. 105, 015022

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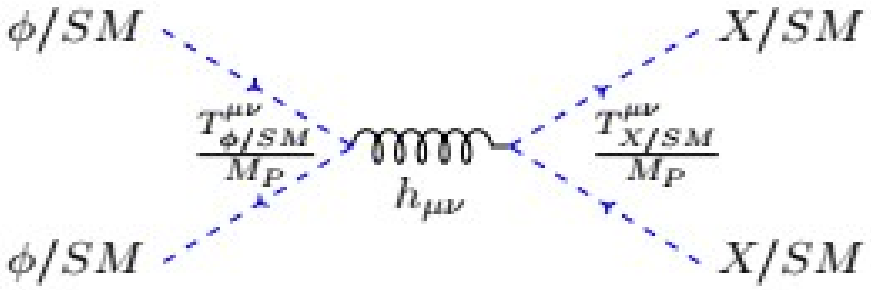

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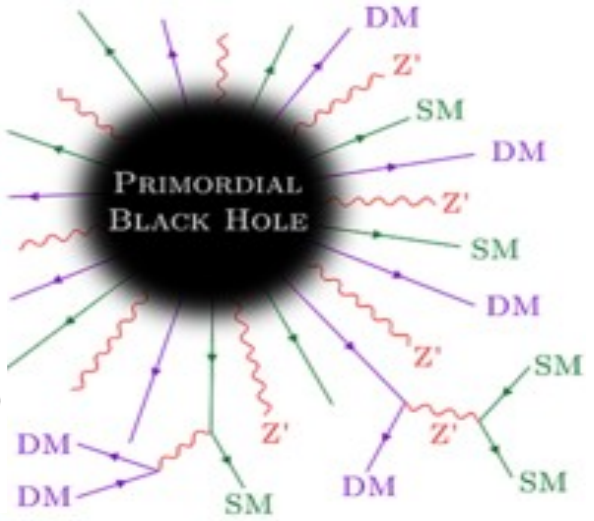
Baryon Asymmetry from PBH:

$$(\text{PBH}) \xrightarrow[\times N_\nu]{\text{evaporation}} \begin{pmatrix}\text{right handed}\\ \text{neutrino}\end{pmatrix} \xrightarrow[\times \epsilon]{\text{decay}} \begin{pmatrix}\text{lepton}\\ \text{number}\end{pmatrix} \xrightarrow[\times \kappa]{\text{sphaleron}} \begin{pmatrix}\text{baryon}\\ \text{number}\end{pmatrix}.$$



PRD. 105, 015022

Rate of Hawking emission (Hawking 1974) :

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

$$\mathcal{N}_X = \frac{g_{X,H}}{g_{\star,H}(T_{\rm BH})}\begin{cases}\frac{4\pi}{3}\left(\frac{m_{\rm in}}{M_{\rm pl}}\right)^2 & \text{for } m_X < T_{\rm BH}^{\rm in}\,,\\ \frac{1}{48\pi}\left(\frac{M_{\rm pl}}{m_X}\right)^2 & \text{for } m_X > T_{\rm BH}^{\rm in}\,.\end{cases}$$

DM relic from PBH:

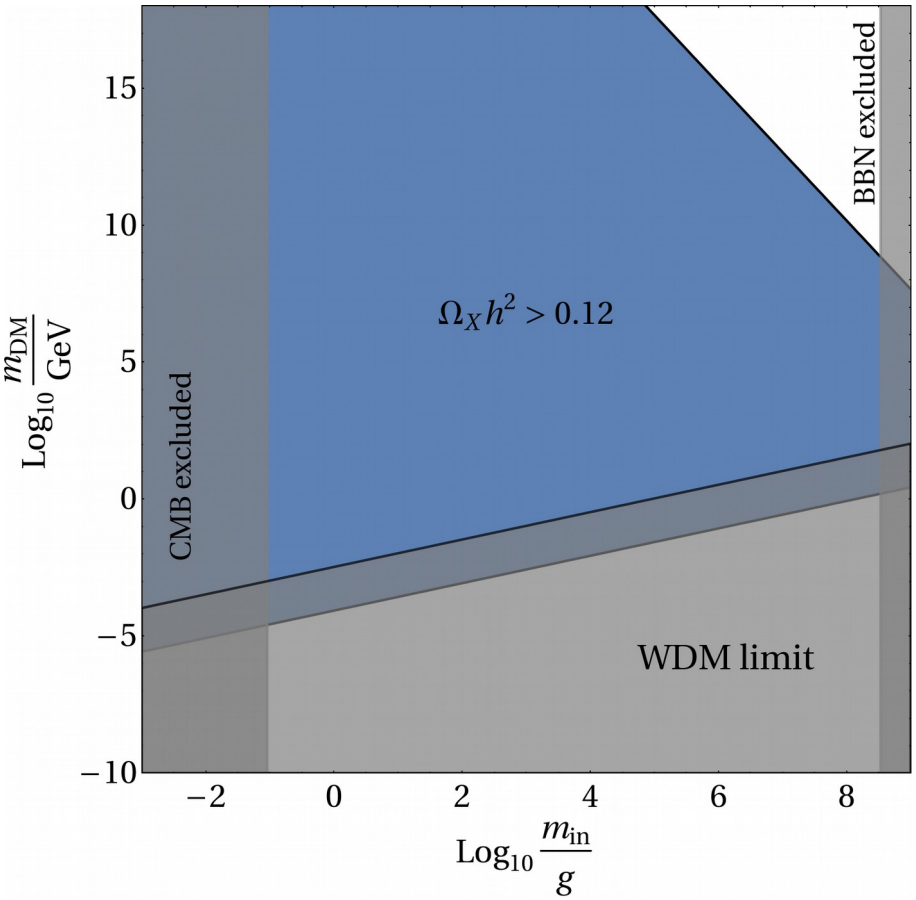
$$\Omega_{\rm DM}\,h^2 = \mathbb{C}(T_{\rm ev})\begin{cases}\frac{1}{\pi^2}\sqrt{\frac{M_P}{m_{\rm BH}}}\,m_{\rm DM} & \text{for } m_{DM} < T_{BH}^{in}\,,\\ \frac{1}{64\,\pi^4}\left(\frac{M_P}{m_{\rm BH}}\right)^{5/2}\frac{M_P^2}{m_{\rm DM}} & \text{for for } m_{DM} > T_{BH}^{in}\,.\end{cases}$$

Baryon yield from PBH:

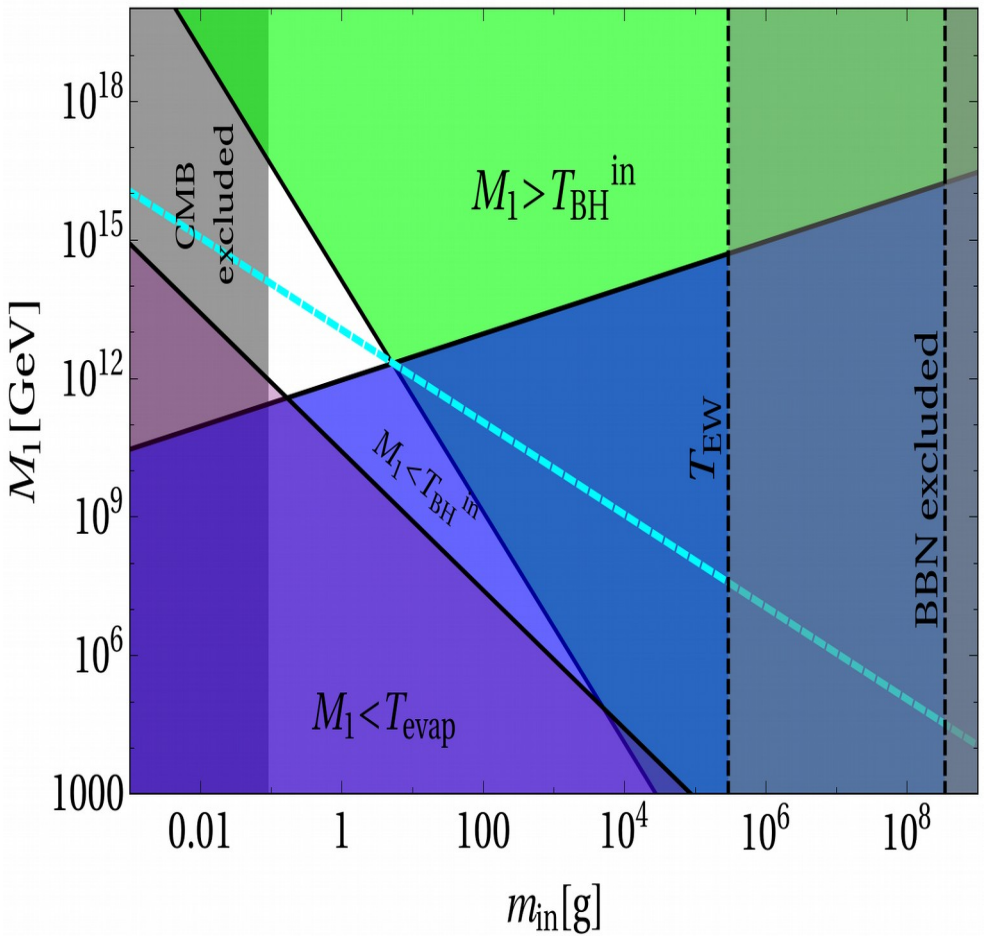
$$\frac{n_B}{s}(T_0) = \mathcal{N}\,\epsilon_{\Delta L}\,a_{\rm sph}\,\frac{n_{\rm PBH}}{s}\bigg|_{T_{\rm evap}}.$$

DI bound: $\epsilon_{\Delta L} \lesssim \frac{3}{16\,\pi}\frac{M_1\,m_{\nu,\max}}{v^2}$

PBH and cogenesis

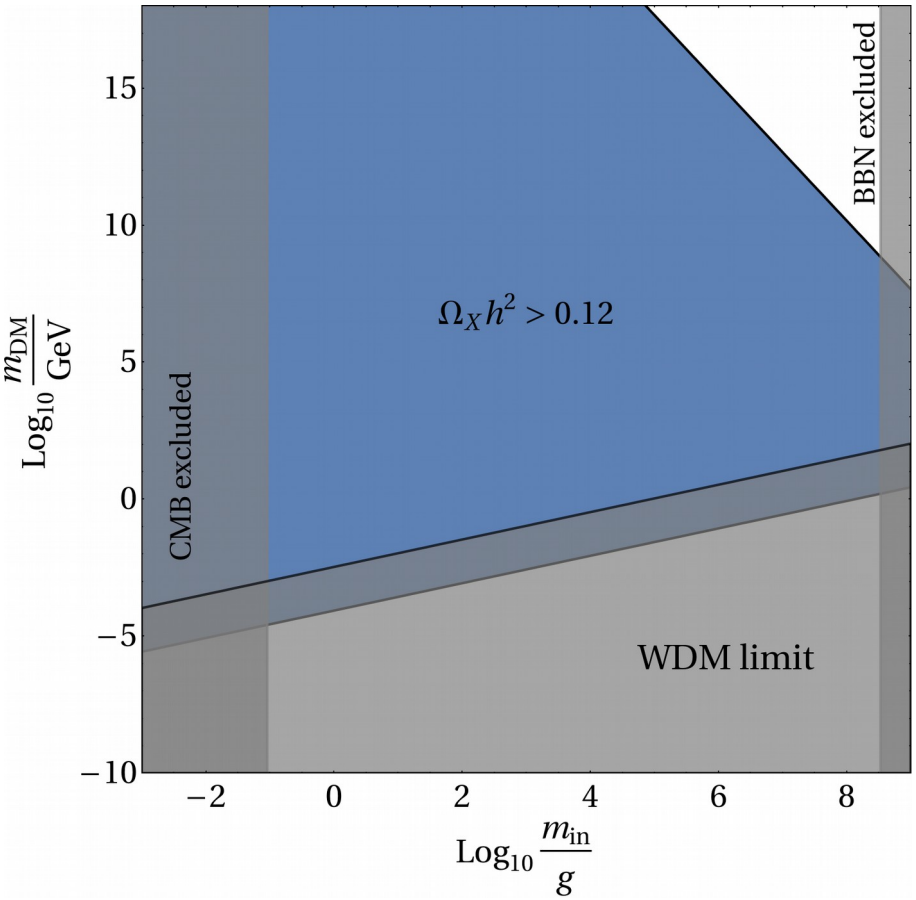


- DM overproduced unless superheavy.
- Free-streaming length constrained from structure formation.



- Correct asymmetry for heavy RHN and ultralight PBH: 0.1-10 g.

PBH and cogenesis



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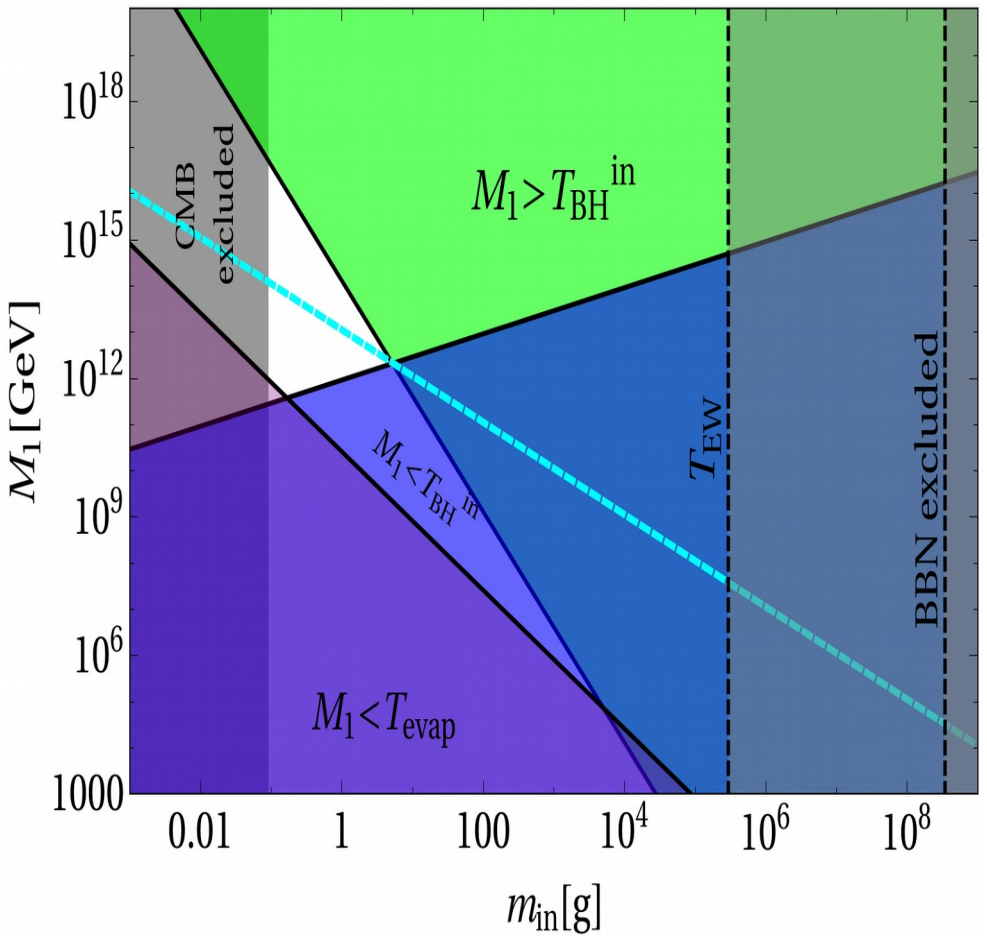
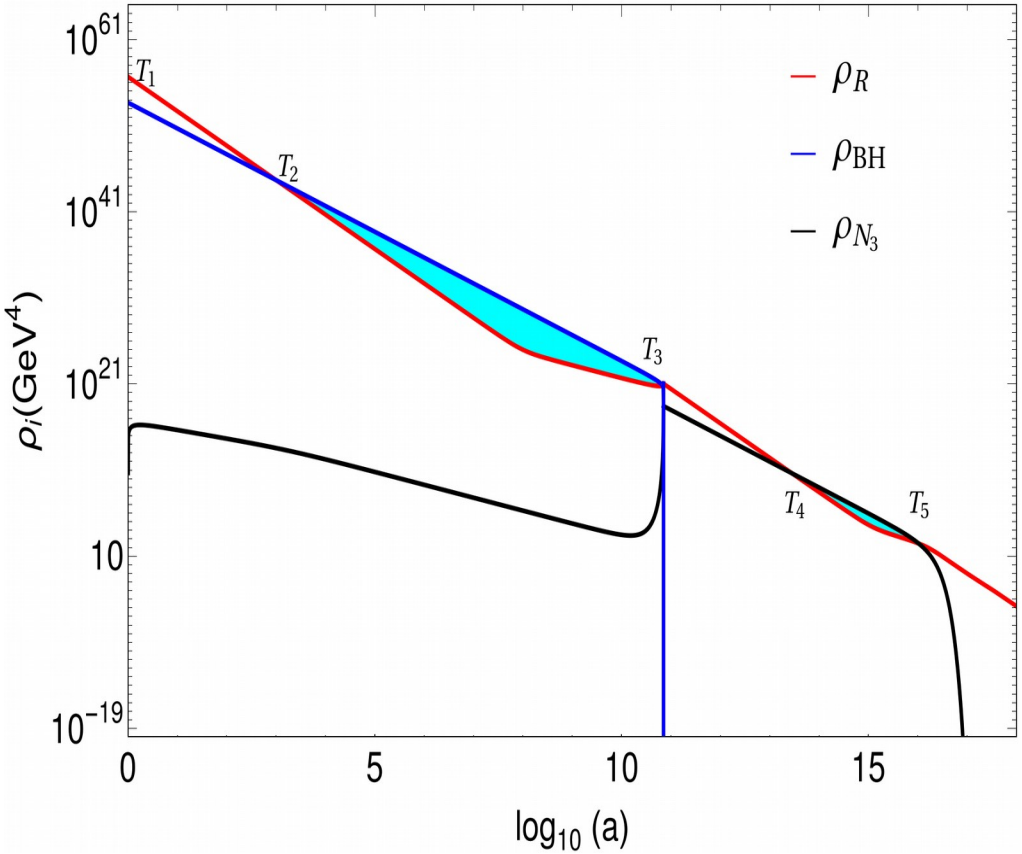


- Correct asymmetry for heavy RHN and ultralight PBH: 0.1-10 g.

Need some mechanism to bring down the DM abundance !

Late decay of a long-lived field



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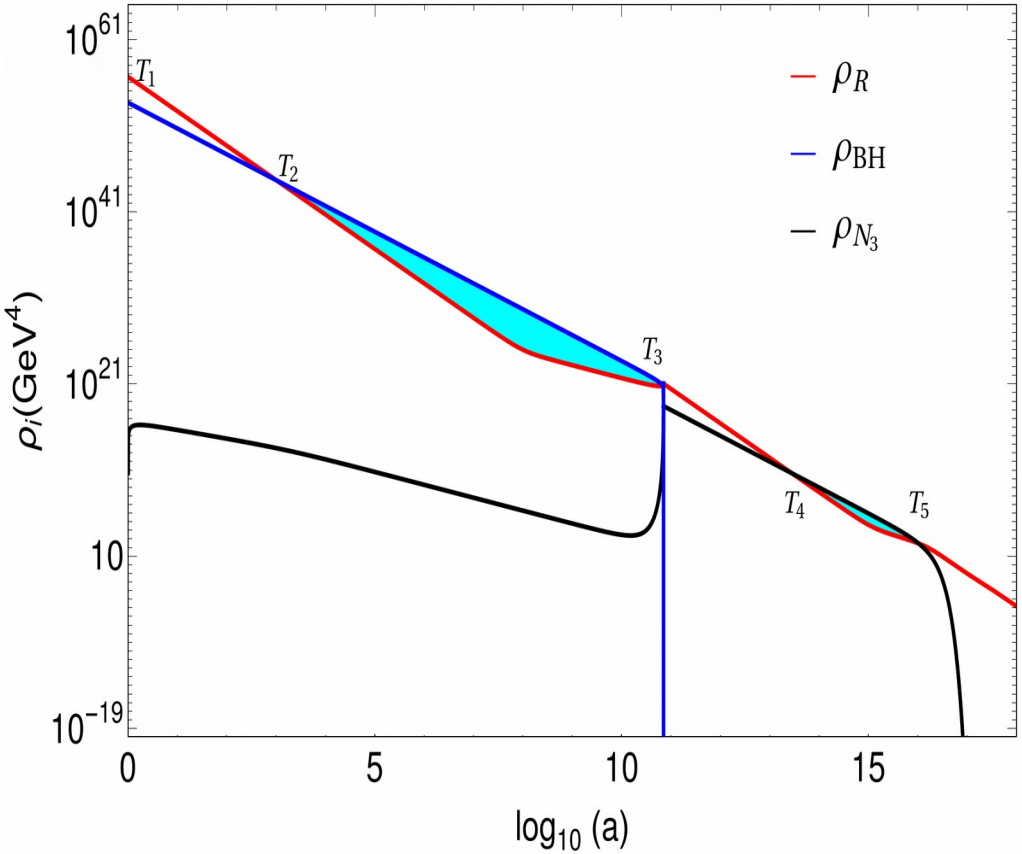

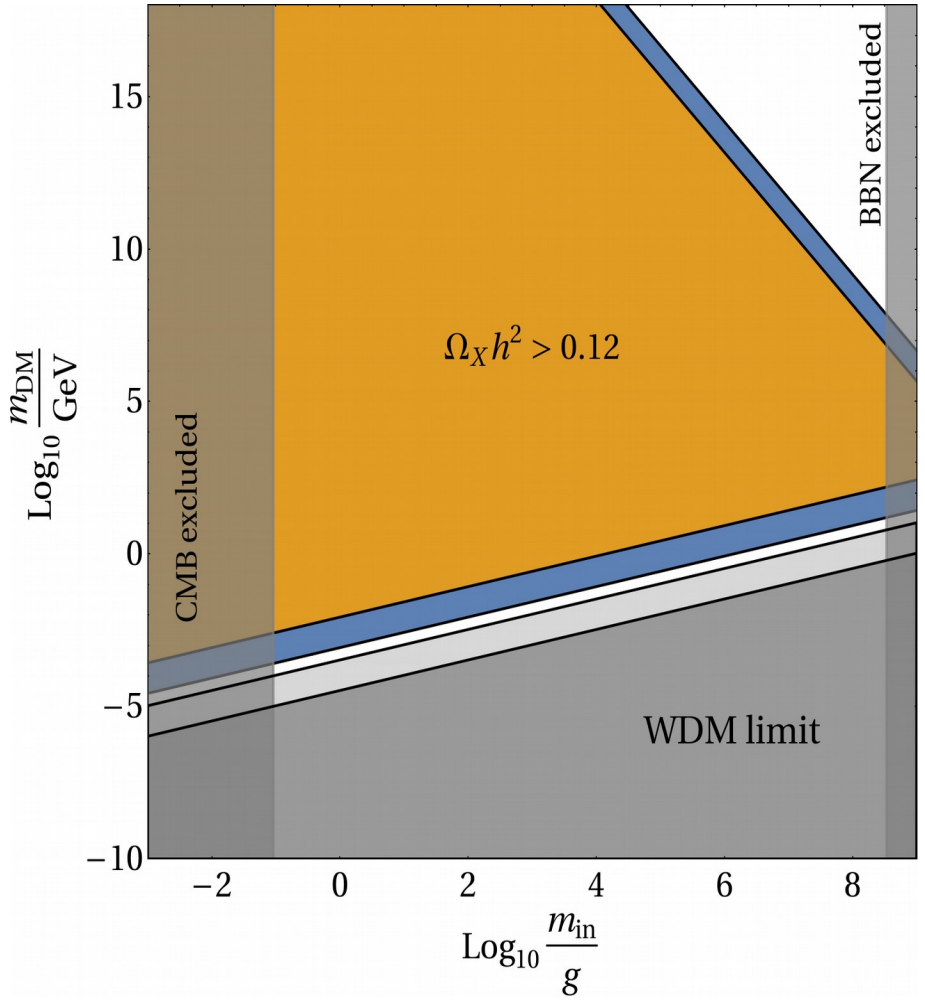

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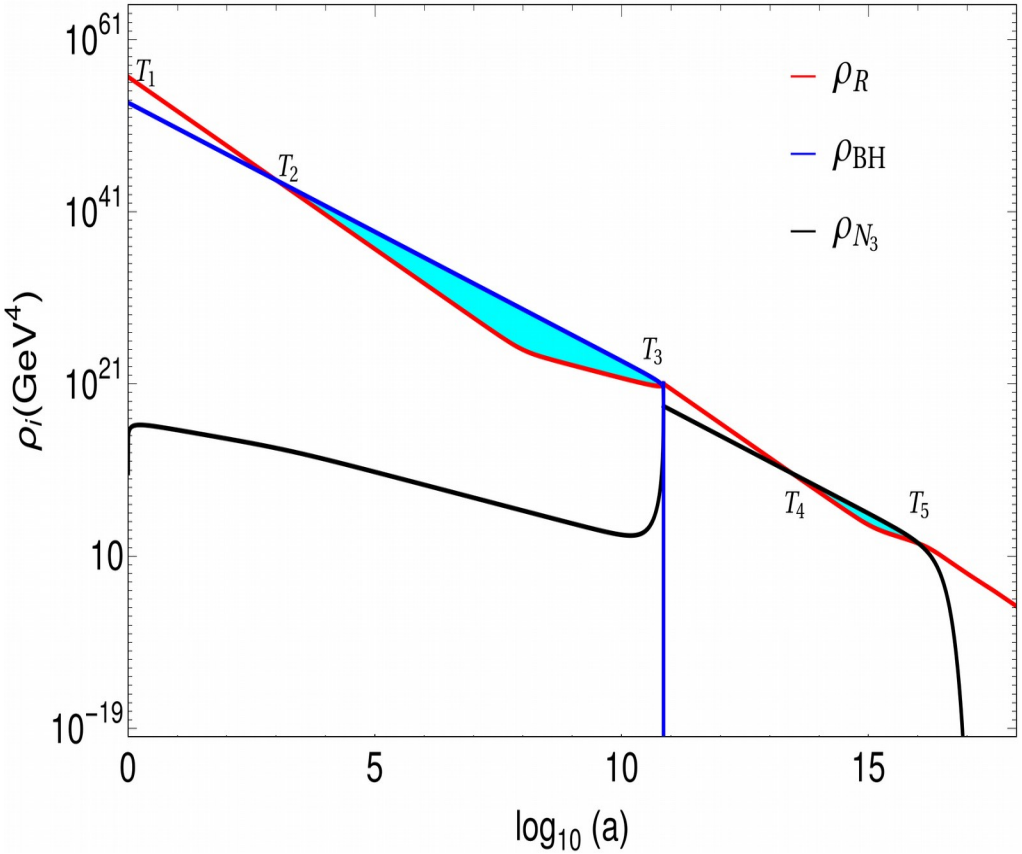
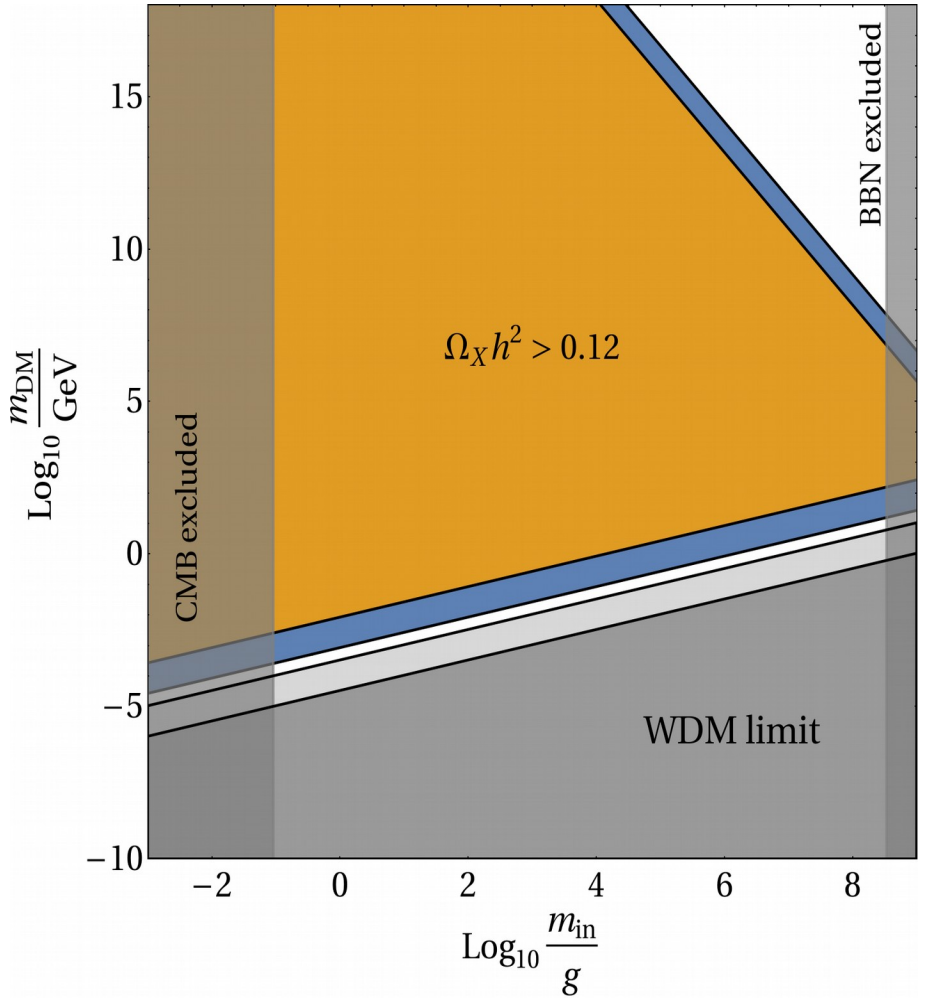
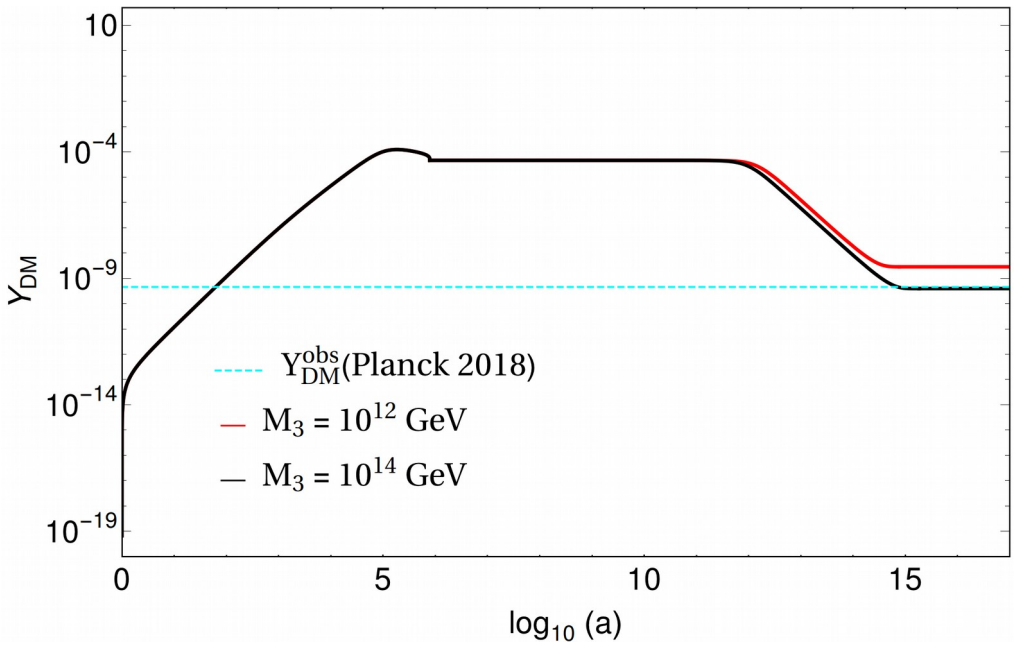


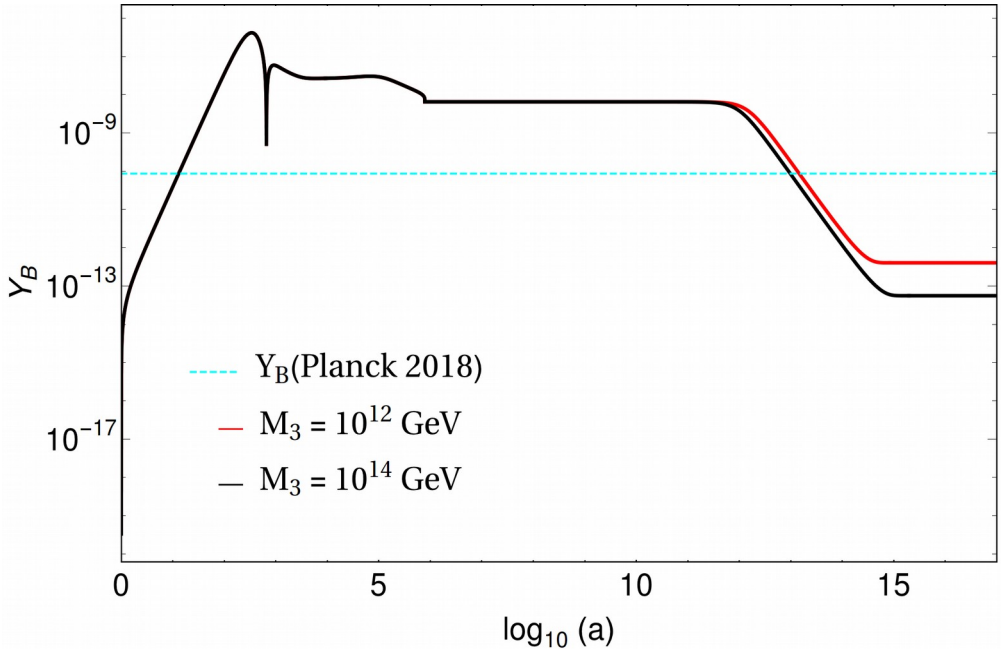


- Extra matter-dominated era after PBH evaporation, before BBN.
- The framework :

$$-\mathcal{L} \supset \frac{1}{2} M_N \overline{N^c} N + y_N \overline{N}\, \tilde{H}^\dagger\, \ell + \mathrm{h.c.}\,.$$

Evolution of baryon and DM yields





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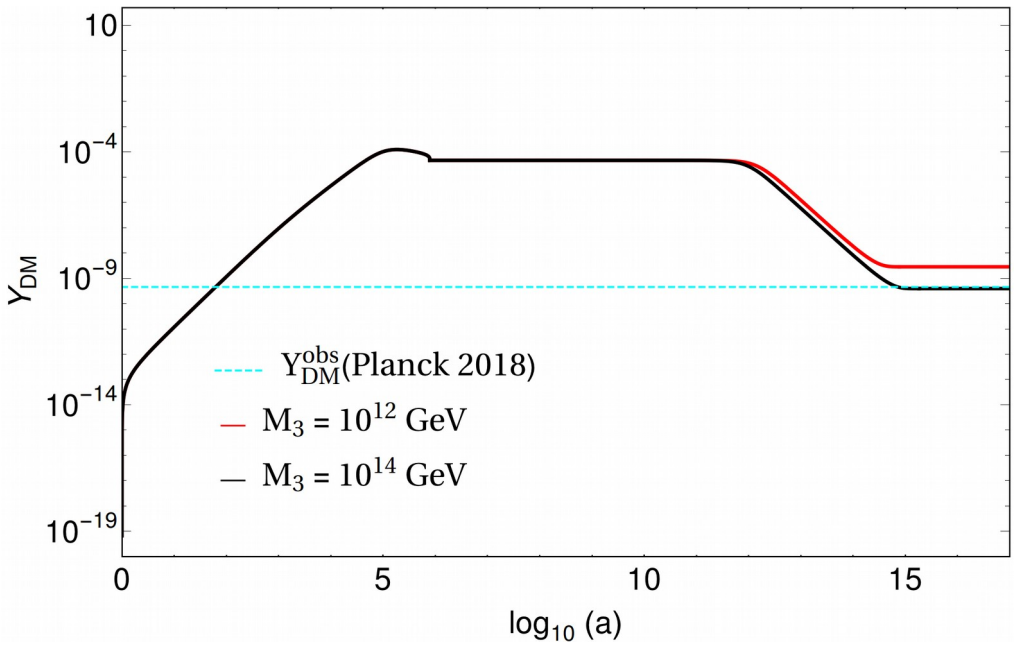
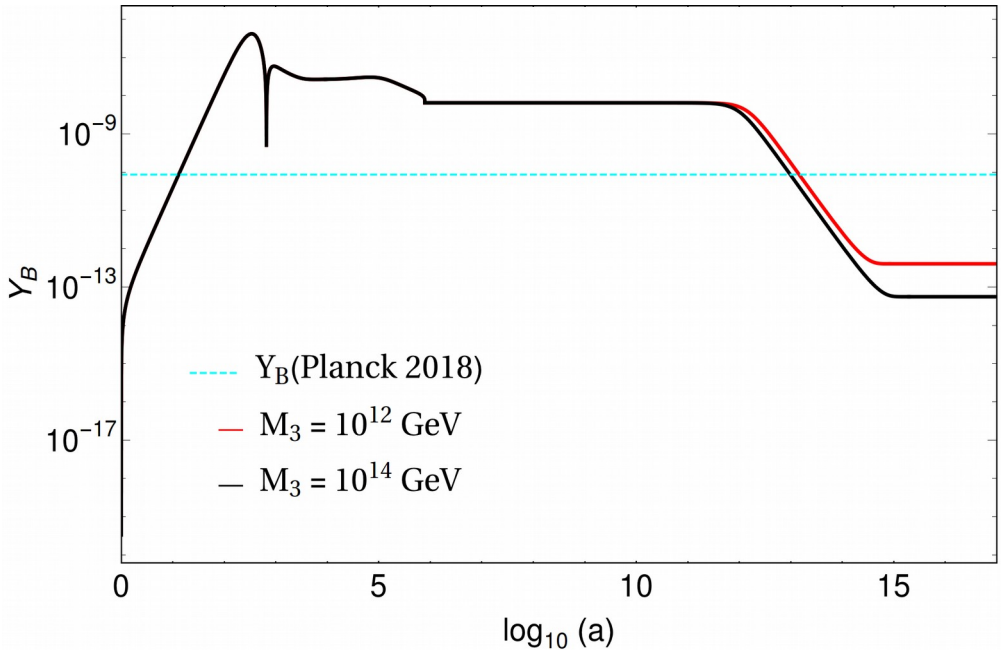
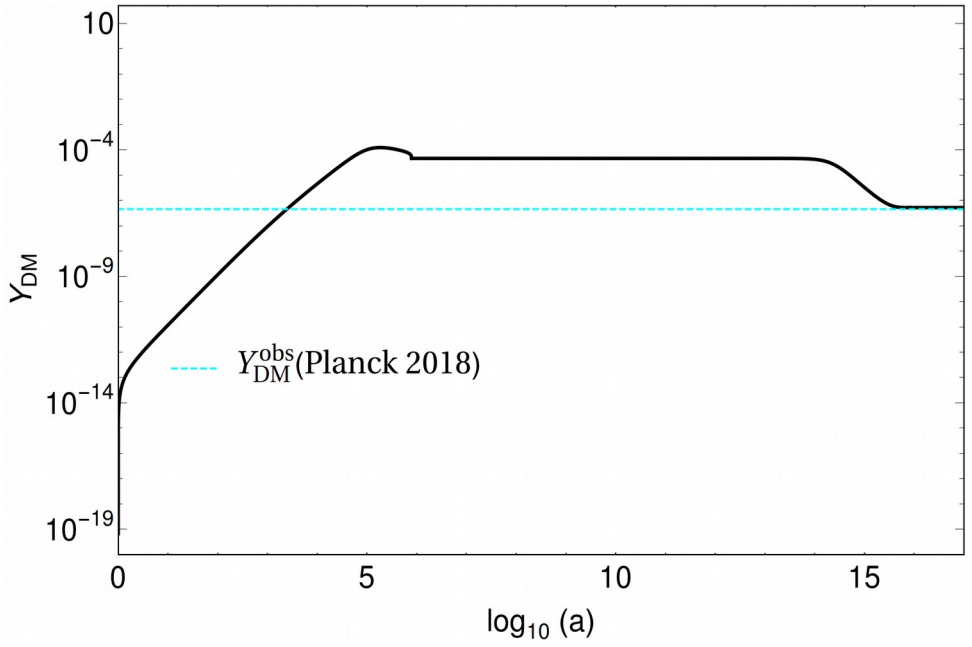
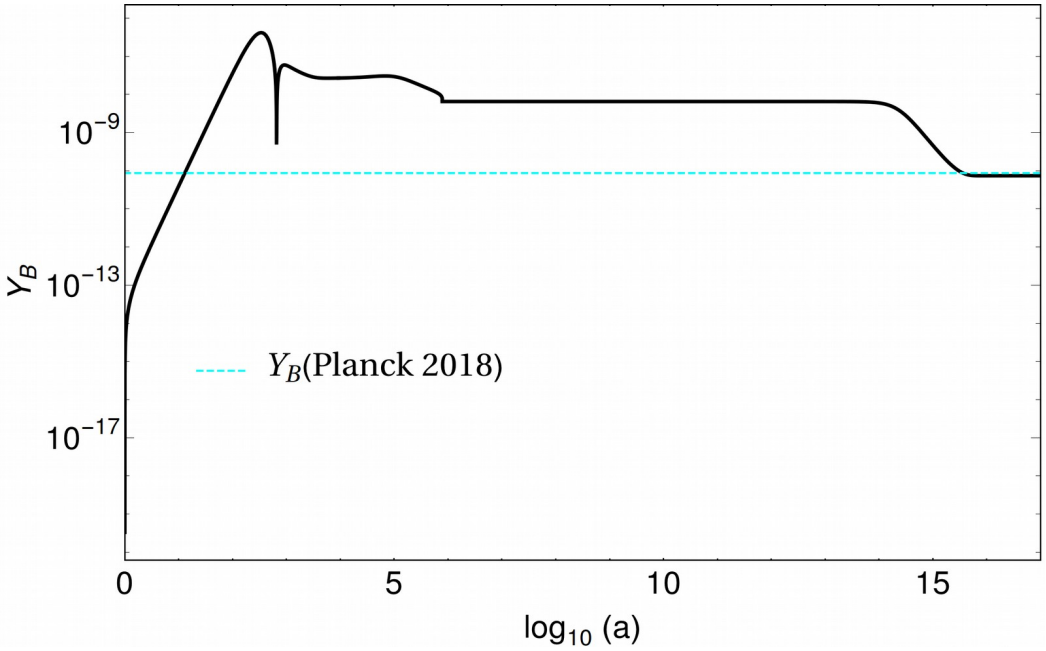




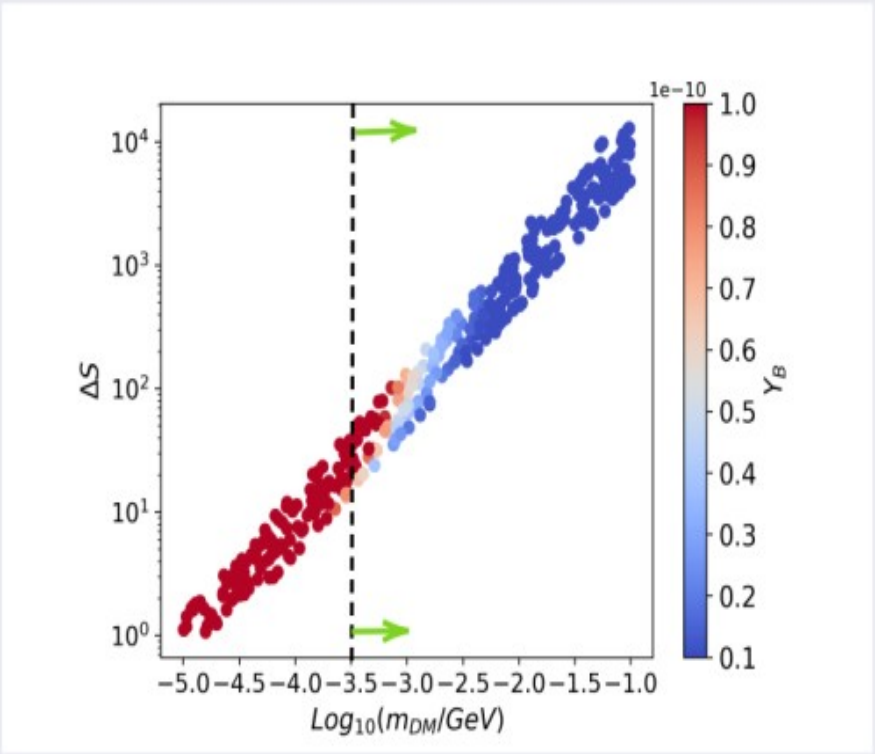




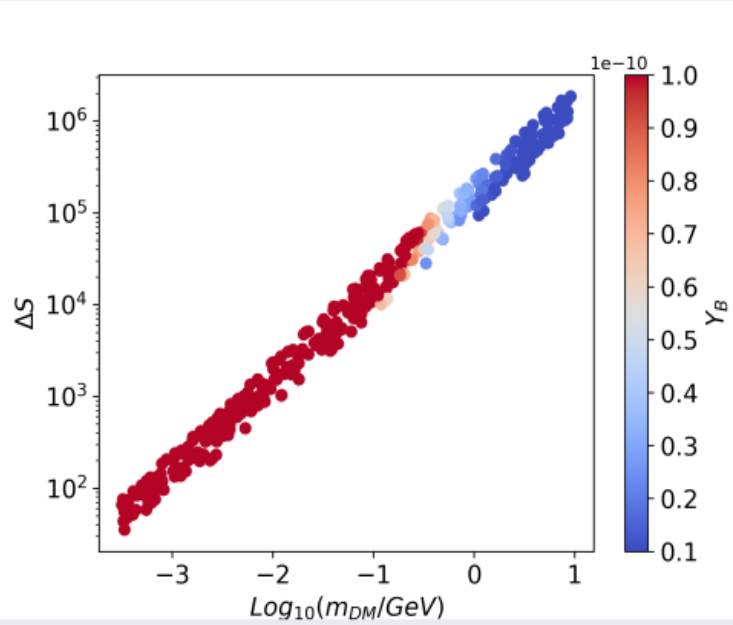
Parameter space for cogenesis

m_{DM} : keV-GeV; $m_{\rm BH}$: $\{0.5 - 5\}$ g;

Parameter space of observed DM abundance:



Parameter space of observed DM abundance, with Resonant Leptogenesis:



Detection through Gravitational Waves

- Spontaneous symmetry breaking of gauge group leads to:

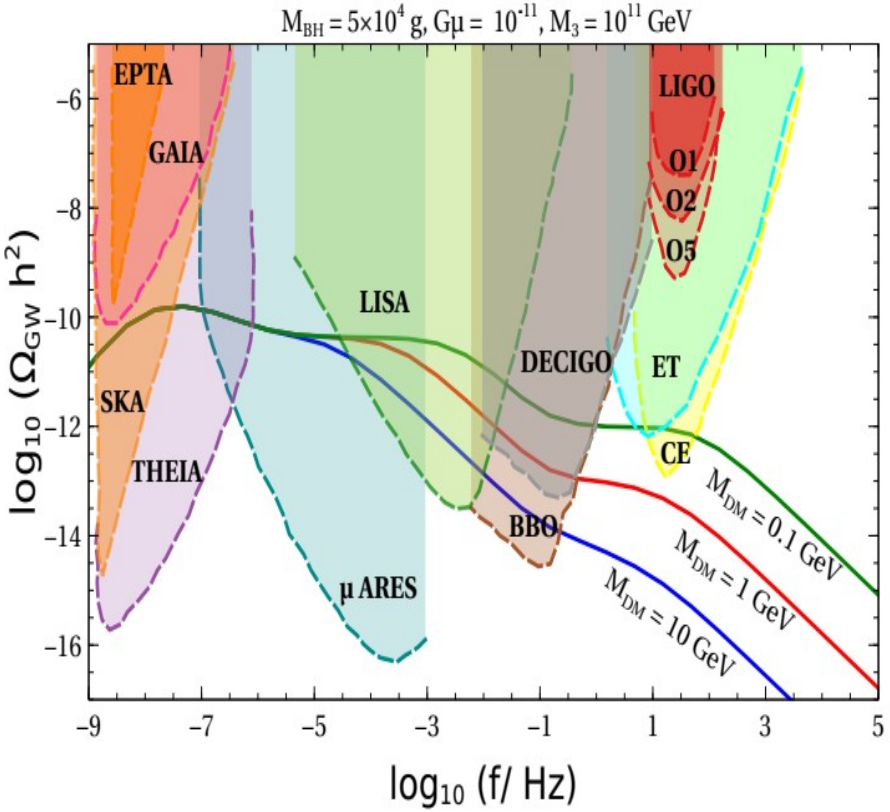
  a) Dynamical origin of seesaw scale, b) Cosmic Strings (Kibble 1976).
- Strings loose energy in the form of GW.
- Spectral Shape: Flat plateau with

$$\Omega_{GW} \sim \Lambda_{CS}$$ (Symmetry breaking scale)

- In case of early-matter domination, plateau breaks

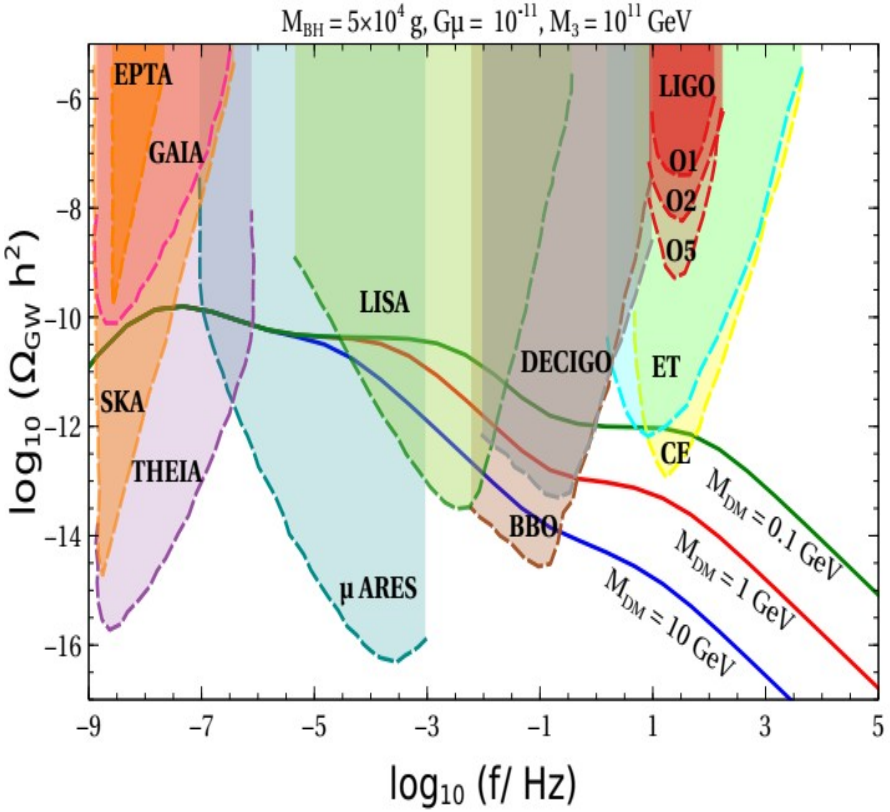
$$f_\Delta \propto T_\Delta$$

T_Δ : End of matter-domination / beginning of radiation-domination.


$M_{BH} = 5\times10^4$ g, $G\mu = 10^{-11}$, $M_3 = 10^{11}$ GeV
EPTA
GAIA
SKA
THEIA
LISA
μ ARES
DECIGO
BBO
LIGO
O1
O2
O5
ET
CE
$M_{DM} = 0.1$ GeV
$M_{DM} = 1$ GeV
$M_{DM} = 10$ GeV
$\log_{10}(\Omega_{GW}\, h^2)$
$\log_{10}$ (f/ Hz)

2208.0495

GW from PBH density fluctuations



2208.0495

- GW from inhomogeneity in PBH distribution.
- GW induced at second-order (Domenech et al. 2021).

$$\Omega_{GW}(t_0, f) \simeq \Omega_{GW}^{\rm peak} \left(\frac{f}{f^{\rm peak}}\right)^{11/3} \Theta\left(f^{\rm peak} - f\right)$$

$$\mathrm{f_{peak}} \simeq 1.7 \times 10^3\,\mathrm{Hz} \left(\frac{m_{\rm in}}{10^4 \mathrm{g}}\right)^{-5/6}$$

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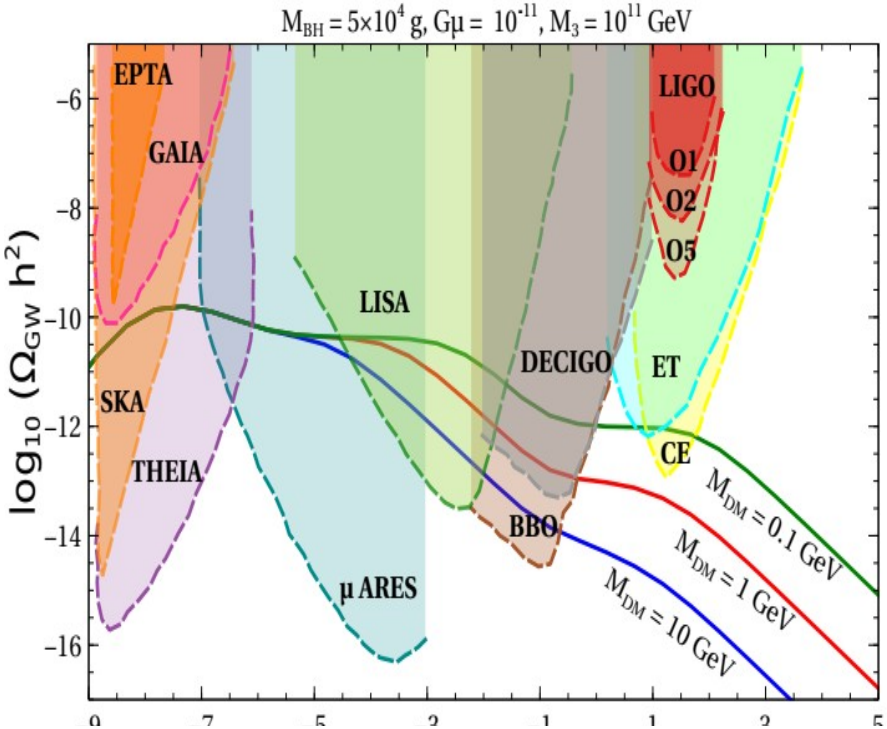

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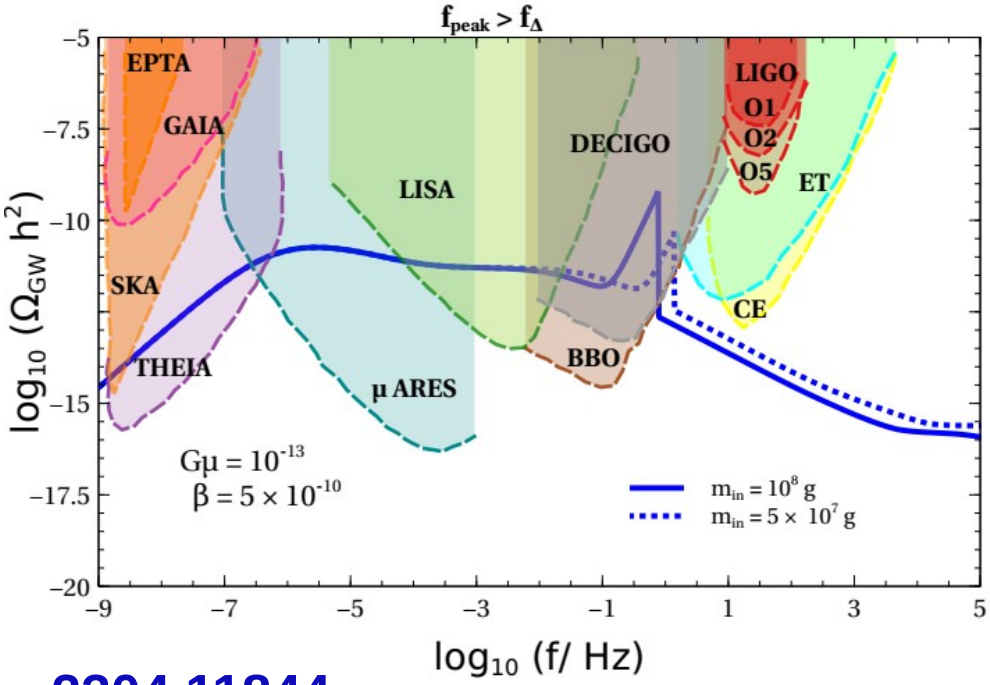

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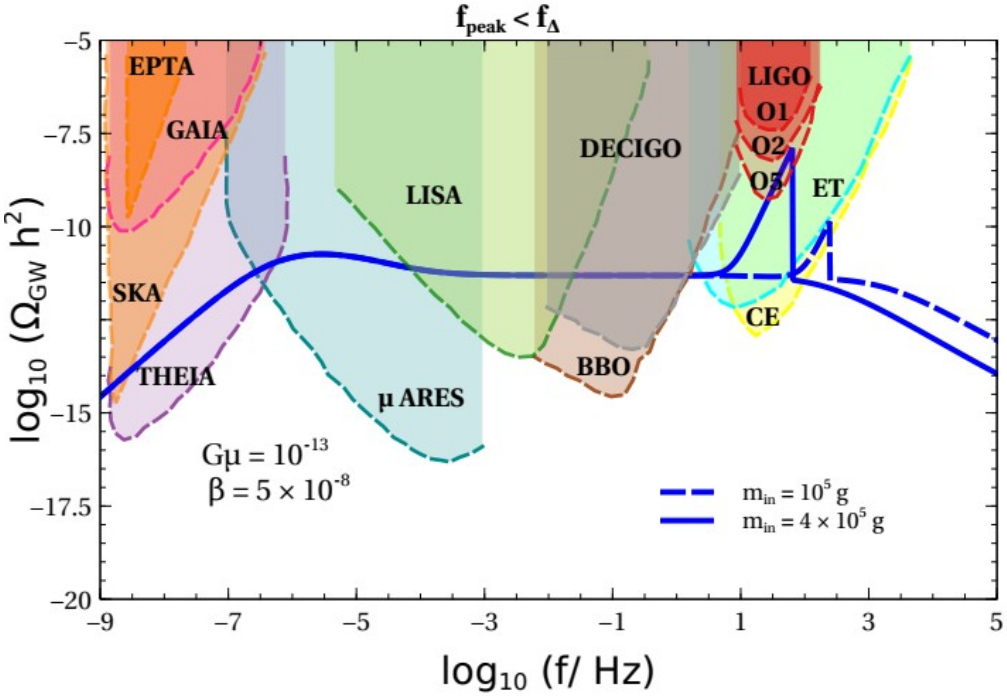

Direct baryon asymmetry from decay of colored scalar

1712.02713 (R. Allhaverdi et al.)

$$-\mathrm{L} \supset \lambda\, S\, \psi\, u^c + \lambda'\, S^\star\, d^c\, d^c + \tfrac{1}{2}\, m_\psi\, \overline{\psi^c}\, \psi + \mathrm{h.c.}$$

Baryogenesis and DM from PBH

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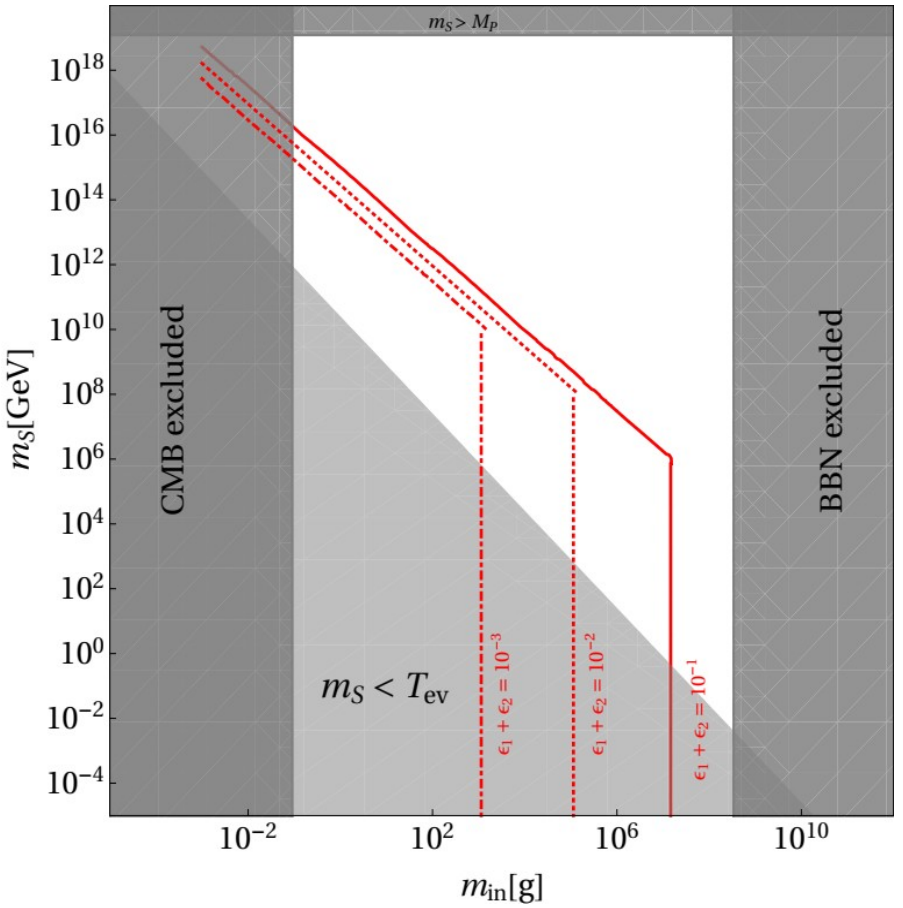
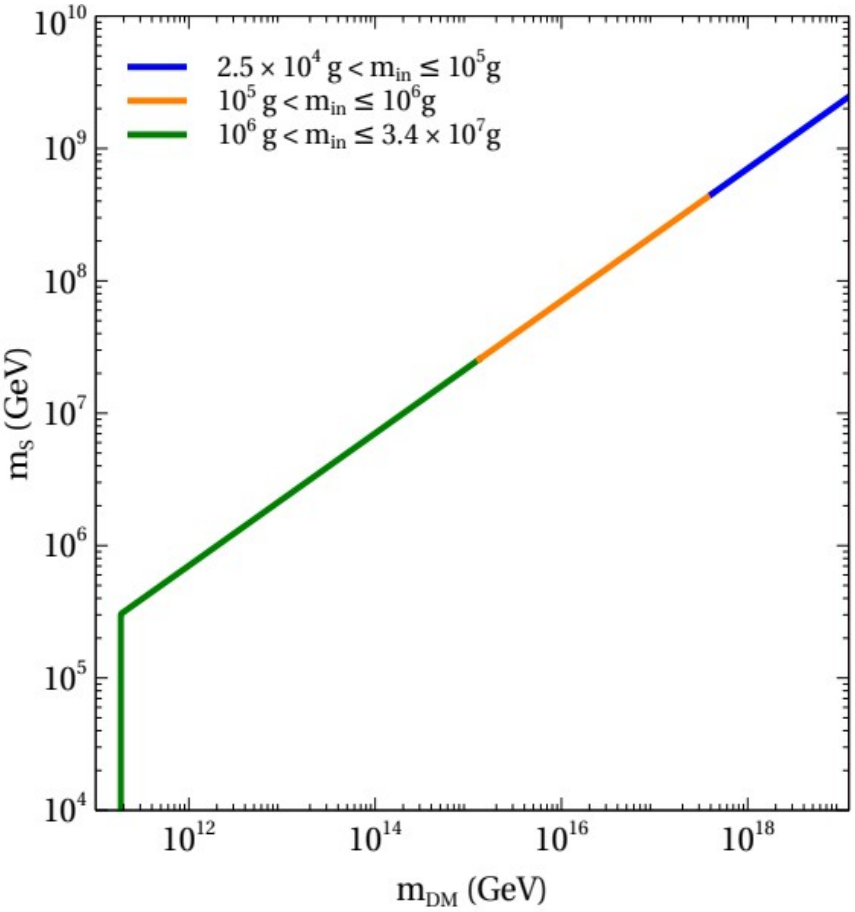


Superheavy DM from PBH



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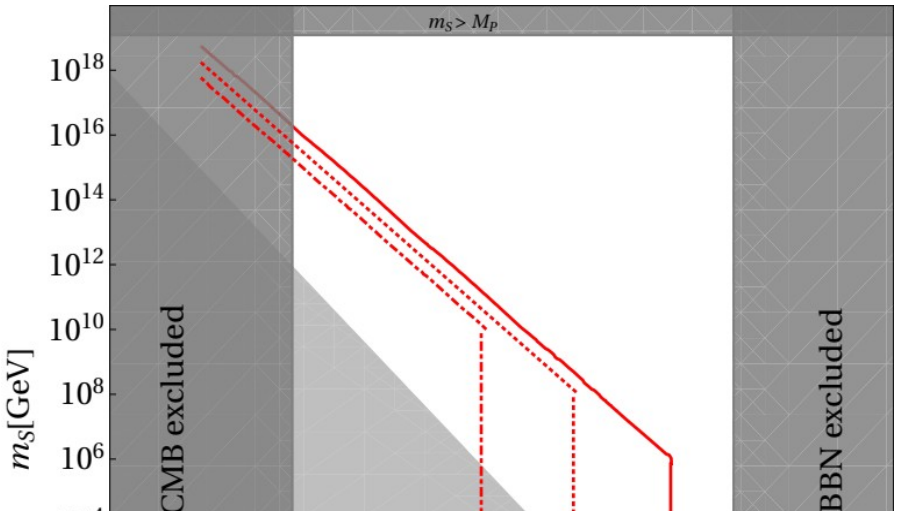

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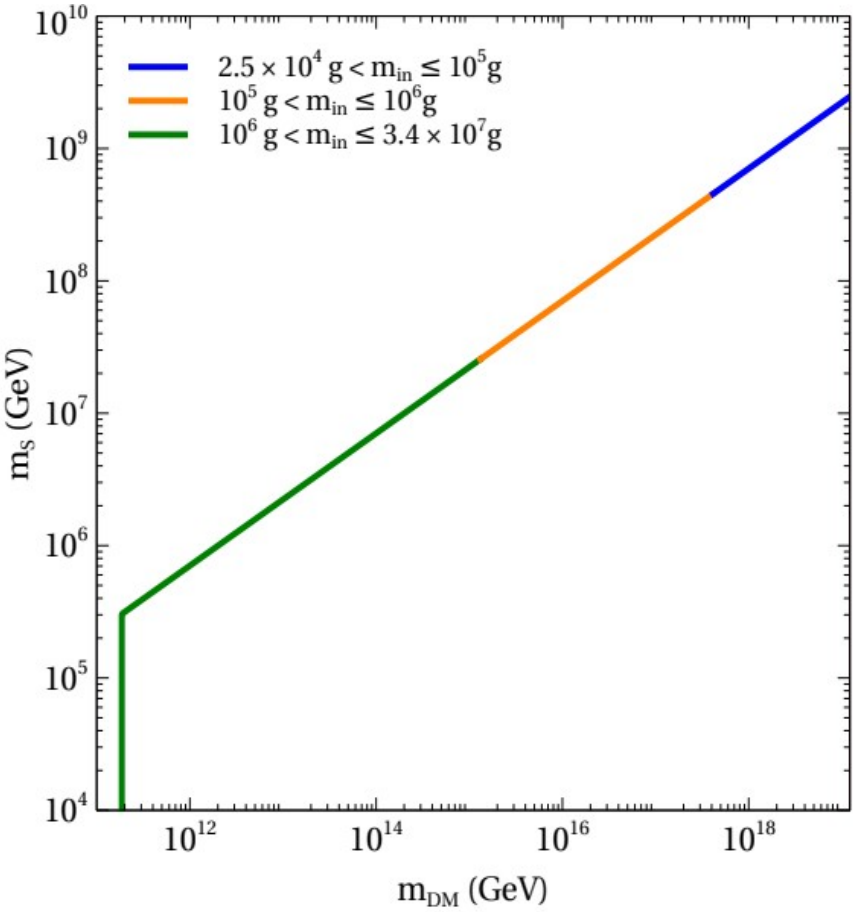

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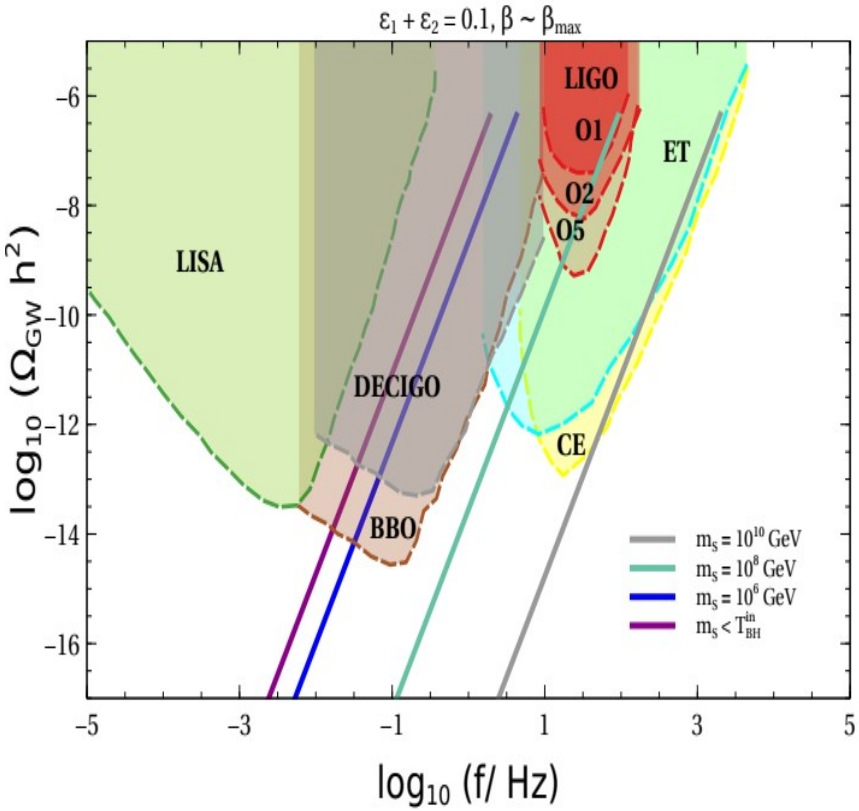

Summary

- Explored a scenario where DM with **only gravitational interactions** is produced solely from PBH evaporation.
- Leads to **overabundance**, unless DM is superheavy.
- Light DM window (upto PeV scale) can be opened with **entropy dilution** by decay of a matter field.
- **Cogenesis** of DM and baryons highly constrains parameter space, squeezing M_{DM} upto GeV.
- Observational consequences in the form of **gravitational waves** (from cosmic strings, PBH density fluctuations) in future experiments.
- Predicts vanishingly small neutrino mass, complementary aspects in experiments like KATRIN.

THANK YOU

Questions / Comments?

BACK-UP SLIDES

PBH:

$$M_{\rm BH}(T_{\rm in}) \approx \frac{4\pi}{3}\frac{\rho_{\rm Rad}(T_{\rm in})}{H^3(T_{\rm in})}.$$

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

$$\frac{dM_{BH}}{dt} = -\sum_a \frac{g_a}{2\pi^2}\int_0^\infty \frac{\sigma^{s_a}_{\rm abs}(M_{BH},p)\,p^3\,dp}{\exp[E_a(p)/T_{\rm BH}] - (-1)^{2s_a}}$$

$$\approx -5.34\times 10^{25}\,\boxed{\varepsilon(M_{BH})}\left(\frac{1\ {\rm g}}{M_{BH}}\right)^2 gs^{-1}.$$

$$T_{\rm ev} \approx \left(\frac{9g_*(T_{\rm BH})}{10240}\right)^{\frac{1}{4}}\left(\frac{M_{\rm Pl}^5}{M_{\rm in}^3}\right)^{\frac{1}{2}}.$$

$$\mathcal{N}_X = \frac{g_{X,H}}{g_{\star,H}(T_{\rm BH})} \begin{cases} \frac{4\,\pi}{3}\left(\frac{m_{\rm in}}{M_{\rm pl}}\right)^2 & \text{for } m_X < T_{\rm BH}^{\rm in}\,, \\ \frac{1}{48\,\pi}\left(\frac{M_{\rm pl}}{m}\right)^2 & \text{for } m_X > T_{\rm BH}^{\rm in}\,. \end{cases}$$

$$\Omega_{\rm DM}\,h^2 = \mathbb{C}(T_{\rm ev}) \begin{cases} \frac{1}{\pi^2}\sqrt{\frac{M_P}{m_{\rm BH}}}\,m_{\rm DM} & \text{for } m_{DM} < T_{BH}^{in}\ , \\ \frac{1}{64\,\pi^4}\left(\frac{M_P}{m_{\rm BH}}\right)^{5/2}\ \frac{M_P^2}{m_{\rm DM}} & \text{for } m_{DM} > T_{BH}^{in}\ . \end{cases}$$

$$m_{\rm DM} \gtrsim 10^4\,\frac{T_{\rm eq}}{\xi}\sqrt{\frac{m_{\rm BH}^{\rm in}}{M_{\rm pl}}}\,\left[\frac{g_{\star,s}(T_{\rm eq})}{g_{\star,s}(T_{\rm ev})}\right]^{\frac{1}{3}}\ .$$

Cosmic Strings:

$$\frac{dE}{dt} = -\Gamma G\mu^2,\ l(t) = \alpha t_i - \Gamma G\mu(t - t_i).$$

$$f_k = 2k/l(k = 1, 2, 3, ...\infty)$$

$$f \simeq \sqrt{\frac{8}{\alpha\Gamma G\mu}} t_i^{-1/2} t_0^{-2/3} t_{\rm eq}^{1/6} = \sqrt{\frac{8}{z_{\rm eq}\alpha\Gamma G\mu}} \left(\frac{g_*(T_i)}{g_*(T_0)}\right)^{1/4} \frac{T_i}{T_0} t_0^{-1}$$

$$\Omega_{\rm GW}^{(k)}(t_0, f) = \frac{2kG\mu^2\Gamma_k}{f\rho_c} \int_{t_i}^{t_0} dt \left[\frac{a(t)}{a(t_0)}\right]^5 n\left(t, l_k\right) \Theta(t_i - t_{\rm osc})\Theta(t_i - l_c/\alpha).$$

$$\Omega_{\rm GW}^{(k=1)}(f) = \frac{128\pi G\mu}{9\zeta(\delta)} \frac{A_r}{\epsilon_r} \Omega_r \left[(1 + \epsilon_r)^{3/2} - 1\right] \sim v_{BL}. \quad \epsilon_r = \frac{\alpha}{\Gamma G\mu}$$

$$n\left(\tilde{t}, l_k(\tilde{t})\right) = \frac{A_\beta}{\alpha} \frac{\left(\alpha + \Gamma G \mu\right)^{3(1-\beta)}}{\left[l_k(\tilde{t}) + \Gamma G \mu \tilde{t}\right]^{4-3\beta} \tilde{t}^{3\beta}}.$$

BP	$m_{\rm in}$(g)	$M_{\rm DM}$(GeV)	1st TPF	2nd TPF	3rd TPF
BP1	3×10^3	0.01	ET	NONE	NONE
BP2	1.2×10^4	5	LISA, DECIGO, BBO	CE	NONE
BP3	5×10^4	0.1	LISA	DECIGO, BBO	CE
BP4	10^5	0.3	LISA, μARES	DECIGO, BBO	NONE
BP5	5×10^5	0.15	μARES	LISA	DECIGO, BBO

$$\frac{dm_{\rm BH}}{da} = -\frac{\kappa}{a\,\mathcal{H}}\,\epsilon(m_{\rm BH})\,\left(\frac{1{\rm g}}{m_{\rm BH}}\right)^2\,,$$

$$\frac{d\widetilde{\rho}_R}{da} = -\frac{\epsilon_{\rm SM}(m_{\rm BH})}{\epsilon(m_{\rm BH})}\,\frac{a}{m_{\rm BH}}\,\frac{dm_{\rm BH}}{da}\,\widetilde{\rho}_{\rm BH} + \frac{a}{\mathcal{H}}\Gamma_3 M_3 \widetilde{n}^{\rm BH}_{N_3}\,,$$

$$\frac{d\widetilde{\rho}_{\rm BH}}{da} = \frac{1}{m_{\rm BH}}\,\frac{dm_{\rm BH}}{da}\,\widetilde{\rho}_{\rm BH}\,,$$

$$a\mathcal{H}\frac{d\widetilde{n}^{\rm BH}_{N_3}}{da} = \Gamma_{{\rm BH}\to N_3}\,\frac{\widetilde{\rho}_{BH}}{m_{BH}} - \Gamma_3\widetilde{n}^{\rm BH}_{N_3}$$

$$a\mathcal{H}\frac{d\widetilde{n}^{\rm BH}_{DM}}{da} = \Gamma_{{\rm BH}\to DM}\,\frac{\widetilde{\rho}_{BH}}{m_{BH}}$$

$$\frac{dT}{da} = -\frac{T}{\Delta}\left[\frac{1}{a} + \frac{\epsilon_{\rm SM}(m_{\rm BH})}{\epsilon(m_{\rm BH})}\,\frac{1}{m_{\rm BH}}\,\frac{dm_{\rm BH}}{da}\,\frac{g_\star(T)}{g_{\star s}(T)}\,a\,\frac{\widetilde{\rho}_{BH}}{4\,\widetilde{\rho}_R} + \frac{\Gamma_3 M_3}{3\mathcal{H}\;s\;a^4}\widetilde{n}^{\rm BH}_{N_3}\right]\,.$$