Leptogenesis and dark matter in the presence of primordial black holes

based on JCAP 11 (2021) 019 (arXiv 2104.14496), with D. Borah, D. Mahanta,

and arXiv 2111.08034, with B. Barman, D. Borah, R. Roshan.

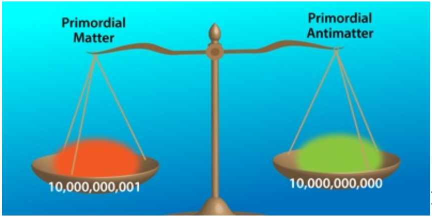
Weekly meeting on Cosmology, IIT Madras.

Suruj Jyoti Das, Department of Physics,
Indian Institute of Technology, Guwahati.

Outline

- Introduction and Motivation.
- Primordial Black Holes.
- The Scotogenic model.
- Leptogenesis and DM from PBH.
- Asymmetric DM from PBH.
- Conclusion.

Matter - Antimatter Asymmetry.

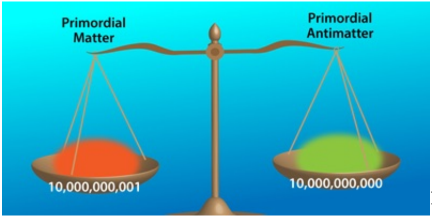


[1]

Baryon Asymmetry (from BBN and CMB) : $\eta_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 6.1 \times 10^{-10}$.

[1] Credit : Alan Stonebraker

Matter - Antimatter Asymmetry.



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- Conditions for Baryogenesis (Sakharov 1967) :

  a) Baryon No. Violation ($X \to Y + B$).

  b) C and CP violation : $\Gamma(X \to Y + B) \neq \Gamma(\bar{X} \to \bar{Y} + \bar{B})$ and

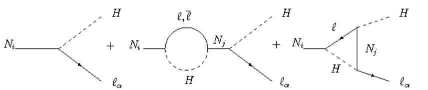
  $\Gamma(X \to q_L q_L) + \Gamma(X \to q_R q_R) \neq \Gamma(\bar{X} \to \bar{q}_L \bar{q}_L) + \Gamma(\bar{X} \to \bar{q}_R \bar{q}_R)$.

  c) Departure from thermal equilibrium : $\Gamma(X \to Y + B) \neq \Gamma(Y + B \to X)$.

The SM of Particle Physics fails to provide these.

[1]Credit : Alan Stonebraker

Baryogenesis through Leptogenesis : $Y_{ij}\bar{L}_i\widetilde{H}N_j + M_{ij}N_iN_j$



[a] $\epsilon_i = \frac{\sum_\alpha \Gamma(N_i \to l_\alpha H) - \Gamma(N_i \to \bar{l}_\alpha \bar{H})}{\sum_\alpha \Gamma(N_i \to l_\alpha H) + \Gamma(N_i \to \bar{l}_\alpha \bar{H})}$

Asymmetry ($n_{\Delta L}$) created in lepton sector (around $T \sim M_N$).

$\downarrow$

$B + L$ violating sphaleron processes (Khlebnikov & Shaposhnikov'88)

$\downarrow$

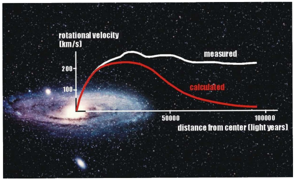
Baryon Asymmetry ($\frac{n_{\Delta B}}{s} \approx -\frac{28}{79}\frac{n_{\Delta L}}{s}$).

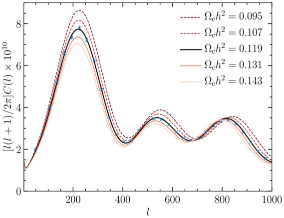
[a] Credit : 1301.3062[hep-ph]

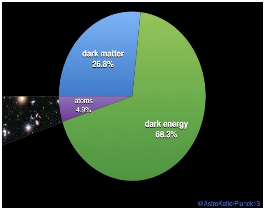
Bonus : Closely connected to neutrino mass through seesaw mechanisms [R.N. Mohapatra et al. 1980].

Dark Matter.

A plethora of evidences...







Credits : Queens Uni., Planck, NASA.

$$\Omega_{DM} h^2 = 0.12 \pm 0.01$$ (Planck 2018)

Dark Matter.

The SM of Particle Physics fails to explain... Some BSM particle ?

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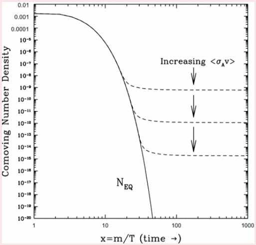
WIMPs : coupling strength with SM of the order of weak interactions.

- Decouple from the thermal bath when $\Gamma \lesssim H$.



0901.4090

- $\Omega_{DM} h^2 \approx \frac{3\times 10^{-27} cm^3 s^{-1}}{<\sigma v>}$

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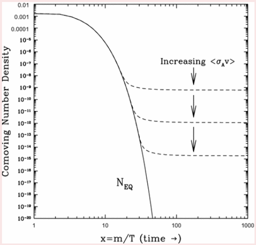

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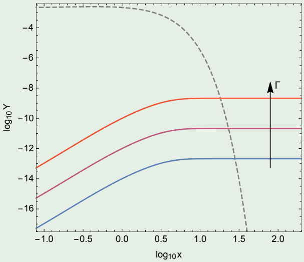
FIMPs [0911.1120[hep-ph]] : Feeble interaction with the SM particles.

- Initial abundance zero, produced later from other particles.



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Cosmic History prior to BBN ?

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A Universe dominated by Primordial Black Holes (PBH)....(Hawking 1975)

(from a few grams to some solar masses).

Formation (B. Carr et al. 2002.12778) :

- Collapse of large inhomogeneities.
- Bubble collisions.
- Collapse of cosmic string loops.

Primordial Black Holes .

- PBH formed in the very early universe,

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

$$\boxed{\text{Lower bound : } H_I \leq 2.5\times 10^{-5} M_{\rm Pl} \implies M_{\rm in} \gtrsim 0.1\ g}$$

- Black hole temperature :

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

- Initial PBH fraction :

$$\beta = \frac{\rho_{\rm BH}(T_{\rm in})}{\rho_{\rm Rad}(T_{\rm in})}.$$

- Hawking evaporation :

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

$$\approx -5.34\times 10^{25}\,\boxed{\varepsilon(M_{BH})}\left(\frac{1\ {\rm g}}{M_{BH}}\right)^2 gs^{-1}. \qquad J.MacGibbon, 1991.$$

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

- $M_{in} \gtrsim 10^{15} g$ can be a DM candidate.
- $M_{in} \lesssim 10^{15} g$ can lead to DM-genesis, matter-antimatter asymmetry.

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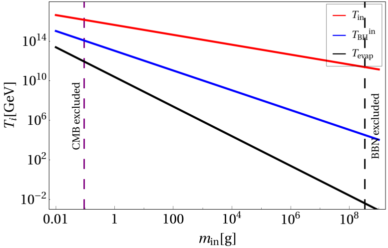

Upper bound : $M_{\rm in} \lesssim 2 \times 10^8$ g (BBN) $M_{\rm in} \lesssim 2 \times 10^5$ g (Sphaleron).

- PBH evaporate to RHNs which are heavy enough (Fujita et al. 1401.1909) :

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

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- We consider a low scale leptogenesis setup.
- Both thermal and non-thermal contribution important.
- PBH may evaporate before, during or after the scale of leptogenesis (Y.F. Perez et al. 2010.03565).
- Initial PBH abundance (β) high enough, giving maximal contribution to leptogenesis and DM.

BSM Particles	$SU(2)_L$	Z_2
$N_i(i=1,2,3)$	0	$-$
$\eta = (\eta^{\pm} \;\; H^0 + i\,A^0/\sqrt{2})$	1	$-$

$$\mathcal{L} \supset \frac{1}{2}(M_N)_{ij} N_i N_j + \left(Y_{ij}\,\bar{L}_i \tilde{\eta} N_j + \text{h.c.}\right)$$

$$V(\Phi_1,\eta) = \mu_1^2|\Phi_1|^2 + \mu_2^2|\eta|^2 + \frac{\lambda_1}{2}|\Phi_1|^4 + \frac{\lambda_2}{2}|\eta|^4 + \lambda_3|\Phi_1|^2|\eta|^2 + \lambda_4|\Phi_1^\dagger\eta|^2 + \left[\frac{\lambda_5}{2}(\Phi_1^\dagger\eta)^2 + \text{h.c.}\right].$$

- Light neutrino mass at loop-level :

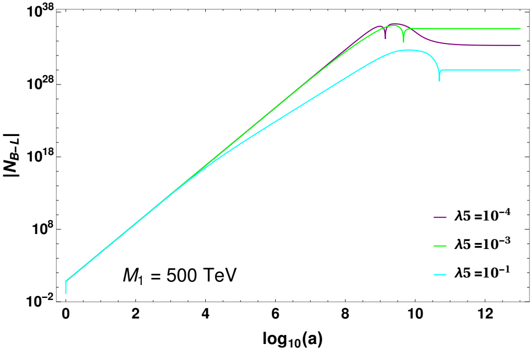
$$(m_\nu)_{ij} = \sum_k \frac{Y_{ik}Y_{jk}M_k}{32\pi^2}\left[L_k(m^2_{H^0}) - L_k(m^2_{A^0})\right]$$

$$L_k(m^2) = \frac{m^2}{m^2 - M_k^2}\ln\frac{m^2}{M_k^2}.$$

The Scotogenic model

- CP asymmetry :

$$\epsilon_i = \frac{\sum_\alpha \Gamma(N_i \to l_\alpha \eta) - \Gamma(N_i \to \bar{l}_\alpha \bar{\eta})}{\sum_\alpha \Gamma(N_i \to l_\alpha \eta) + \Gamma(N_i \to \bar{l}_\alpha \bar{\eta})}$$
$$= \frac{1}{8\pi (Y^\dagger Y)_{ii}} \sum_{j \neq i} \mathrm{Im}[((Y^\dagger Y)_{ij})^2] \frac{1}{\sqrt{r_{ji}}} F(r_{ji}, \eta_i).$$



Scotogenic leptogenesis in the presence of PBH

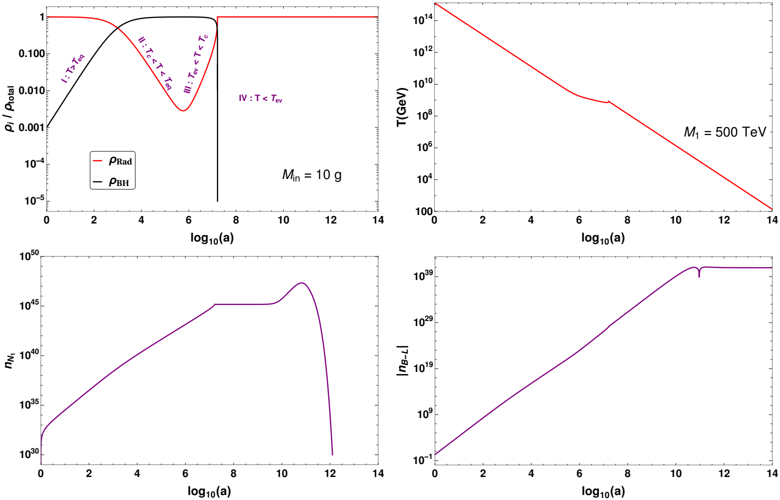
Boltzmann equations :

$$
\begin{aligned}
\frac{d\varrho_{\rm BH}}{da} &= \frac{1}{M_{\rm BH}}\frac{dM_{\rm BH}}{da}\varrho_{\rm BH}\,,\\
\frac{d\varrho_{\rm Rad}}{da} &= -\frac{\epsilon_{\rm SM}(M_{\rm BH})}{\epsilon(M_{\rm BH})}\frac{1}{M_{\rm BH}}\frac{dM_{\rm BH}}{da}a\varrho_{\rm BH}\,,\\
aH\frac{dn^T_{N_1}}{da} &= -\left(n^T_{N_1}-n^{\rm eq}_{N_1}\right)\Gamma^T_1\,,\\
aH\frac{dn^{\rm BH}_{N_1}}{da} &= -\left(n^{\rm BH}_{N_1}\right)\Gamma^{\rm BH}_1 + n_{\rm BH}\Gamma_{{\rm BH}\to N_1}\,,\\
aH\frac{dn_{B-L}}{da} &= \epsilon_1\left[\left(n^T_{N_1}-n^{\rm eq}_{N_1}\right)\Gamma^T_1 + n^{\rm BH}_{N_1}\Gamma^{\rm BH}_1\right] - (W_{ID}+\Delta W_{scattering})n_{B-L}\,,\\
\frac{dT}{da} &= -T\left(\frac{1}{a}+\frac{\epsilon_{SM}(M_{\rm BH})}{\epsilon(M_{\rm BH})}\frac{1}{M}\frac{dM_{BH}}{da}\frac{a\varrho_{\rm BH}}{4\varrho_{\rm Rad}}\right).
\end{aligned}
$$

N_1 produced from PBH :

$$
\Gamma_{{\rm BH}\to N_1} = \int_0^\infty \frac{d^2\mathcal{N}}{dp\,dt}\,dp \simeq \frac{27\,T_{\rm BH}}{32\pi^2}\left(-z_{\rm BH}{\rm Li}_2(-e^{-z_{\rm BH}}) - {\rm Li}_3(-e^{-z_{\rm BH}})\right).
$$

PBH evaporate before leptogenesis scale :



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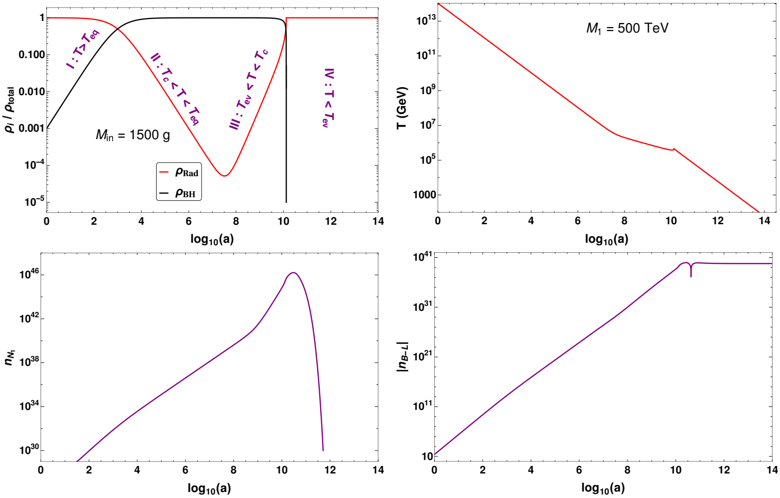

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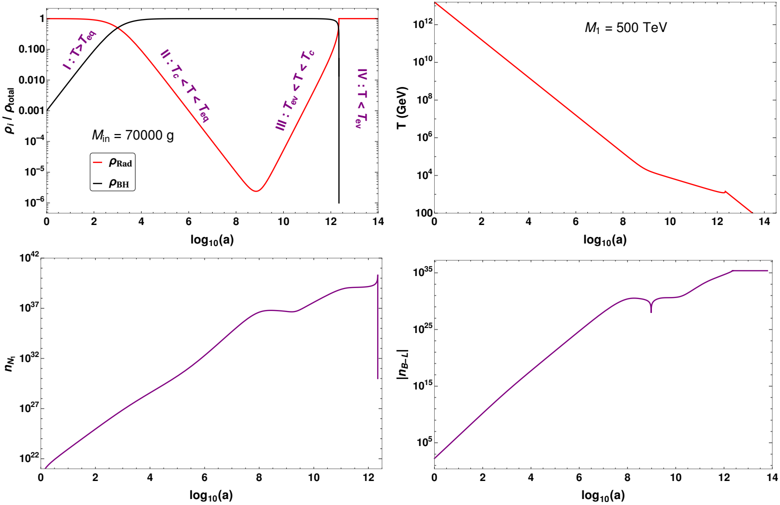
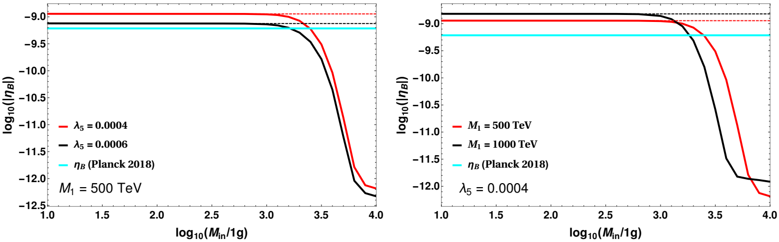
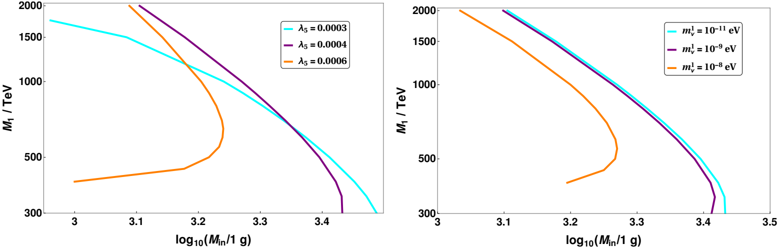


Scotogenic leptogenesis in the presence of PBH

PBH mass vs BAU :



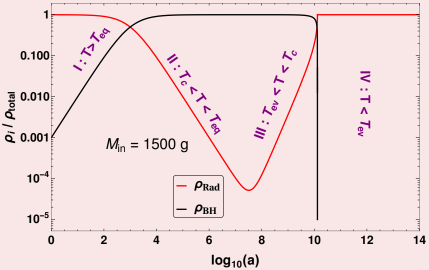
PBH mass vs Leptogenesis Scale :



- Case I : DM candidate $\rightarrow$ Lightest scalar of inert doublet.

In the presence of PBH (N. Bernal et al. 2011.12306) :

1. $T_{fo} > T_{eq}$: Usual WIMP DM in a RD universe, with PBH dilution.
2. $T_c < T_{fo} < T_{eq}$: PBH dominate (for $\beta > \beta_c$), $\rho_{Rad} \propto a^{-4}$.
3. $T_{ev} < T_{fo} < T_c$: $\rho_{Rad} \propto a^{-3/2}$.
4. $T_{fo} < T_{ev}$: RD universe again, no PBH dilution.



Dark Matter in the presence of PBH

$$\Omega_{\rm DM}^{\rm total} h^2 = \Omega_{\rm DM}^{\rm BH} h^2 + \Omega_{\rm DM}^{\rm fo} h^2$$ (P. Gondolo et al. 2009.02424).

$$T_{fo} > T_{ev} \implies M_{DM} > 3\, MeV\, (trivially\ satisfied).$$

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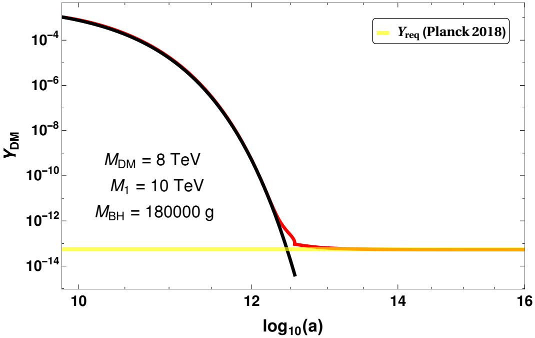

Dark Matter in the presence of PBH

DM from PBH (P. Gondolo et al. 2009.02424) :

$$N_{\rm DM} = \frac{15\zeta(3)}{\pi^4}\frac{1}{g_*(T_{\rm BH})} \times \begin{cases} \left(\frac{M_{\rm in}}{M_{\rm Pl}}\right)^2 & \text{for} \quad M_{\rm DM} \leq T_{\rm BH}^{\rm in}, \\ \left(\frac{M_{\rm Pl}}{M_{\rm DM}}\right)^2 & \text{for} \quad M_{\rm DM} \geq T_{\rm BH}^{\rm in}. \end{cases}$$

$$Y_{\rm DM} = \frac{n_{\rm DM}(T_0)}{s(T_0)} \simeq \frac{3}{4} N_{\rm DM} \times \begin{cases} \beta \frac{T_{\rm in}}{M_{\rm in}} & \text{for RD, } \beta \leq \beta_c, \\ \frac{\bar{T}_{\rm ev}}{M_{\rm in}} & \text{for MD, } \beta \geq \beta_c. \end{cases}$$

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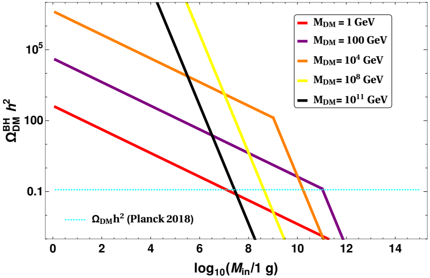
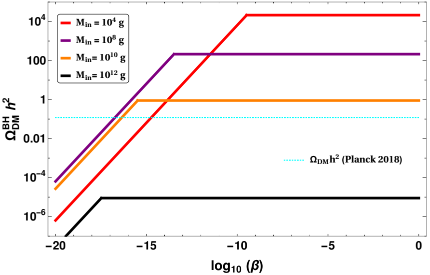
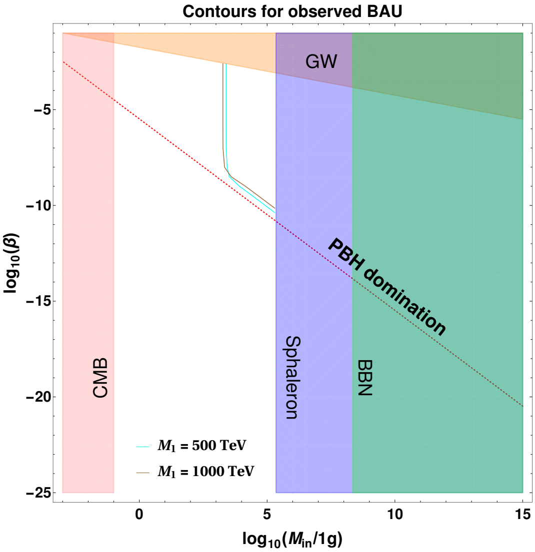
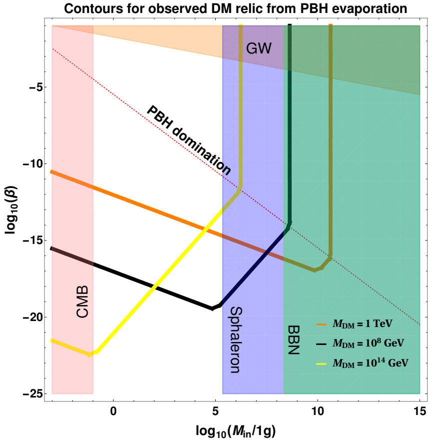






Contours for observed BAU
GW
PBH domination
CMB
Sphaleron
BBN
M_1 = 500 TeV
M_1 = 1000 TeV
−5
−10
−15
−20
−25
0
5
10
15
$\log_{10}(\beta)$
$\log_{10}(M_{in}/1g)$



- $M_{DM} \gtrsim 4\ GeV$ gets overproduced from PBH with large β.
- Light scalar DM ruled out from direct search constraints.

- N_1 : Light, singlet DM candidate.
- Thermal DM difficult to realize (Lee and Weinberg 1977), FIMP : $lW^{\pm}(Z) \longrightarrow N_1\eta$, $l\eta \longrightarrow W^{\pm}(Z)N_1$, $\eta \to N_1 l$.
- Leptogenesis from N_2 decay.

Case II : N_2 Leptogenesis and fermion DM.

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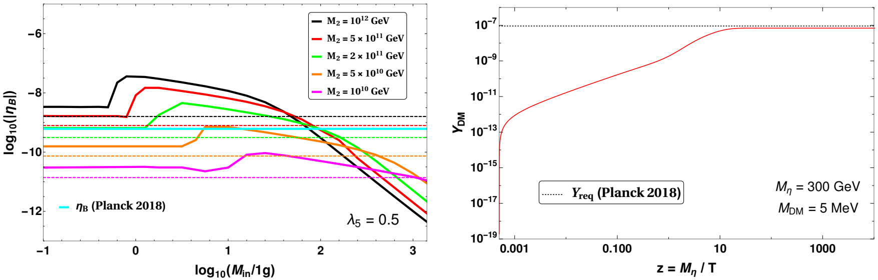
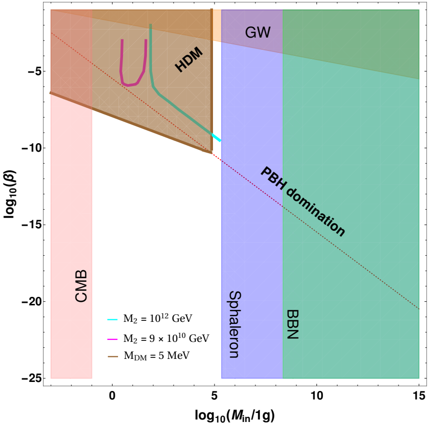


Contours for observed BAU and DM abundance :



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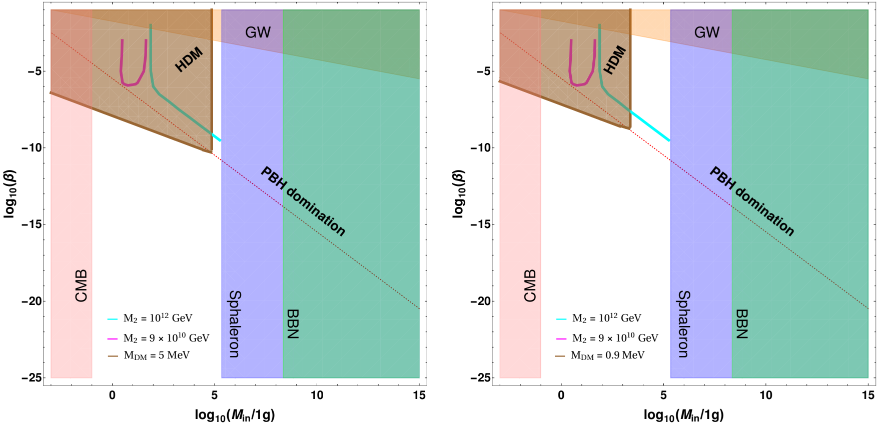
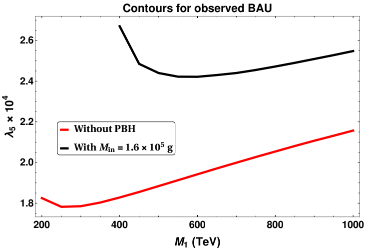
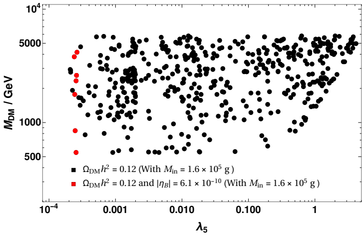
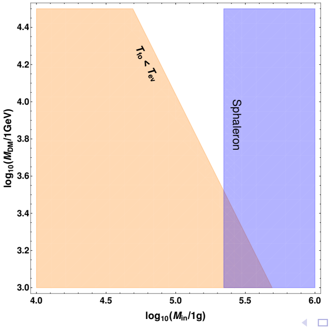


Parameter space with and without PBH :





PBH evaporate before DM freezeout :



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- A common origin of dark and visible sector ?

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Baryonic matter Abundance.

- Matter-antimatter pair annihilates, asymmetric part $(n_B - n_{\overline{B}})$ remains.
- Not thermal (freezeout) production.

Asymmetric Dark Matter (Nussinov 1985, Kaplan 1992).

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Dark matter Abundance.

- An asymmetry $(n_{\Delta DM} = n_{DM} - n_{\overline{DM}})$ generated in the early universe.
- Symmetric component annihilated away.
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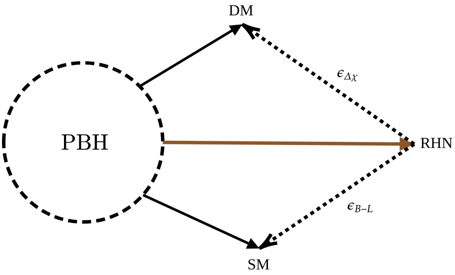
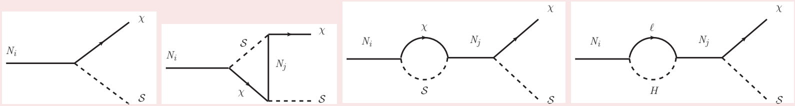
Same out-of-equilibrium decay of a heavier particle generates $n_B - n_{\overline{B}} \sim n_{DM} - n_{\overline{DM}}$.



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

Dark Sector Asymmetry



$$\epsilon_{\Delta L} = \frac{\sum_\alpha [\Gamma(N_1 \to l_\alpha + H) - \Gamma(N_1 \to \overline{l_\alpha} + H^*)]}{\Gamma_1}$$

$$\simeq \frac{M_1}{8\,\pi} \frac{\mathrm{Im}[(3\, y_N^*\, y_N^T + y_\chi^*\, y_\chi^T)\, M^{-1} y_N\, y_N^\dagger]_{11}}{[2\, y_N\, y_N^\dagger + y_\chi\, y_\chi^\dagger]_{11}}\,,$$

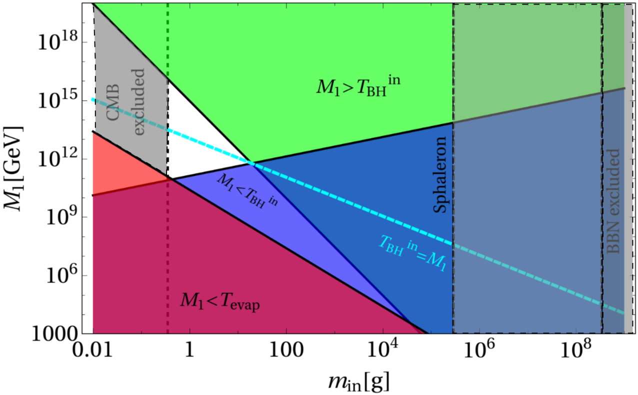
$$\epsilon_{\Delta\chi} = \frac{\Gamma(N_1 \to \chi + S) - \Gamma(N_1 \to \bar{\chi} + S^*)}{\Gamma_1}$$

$$\simeq \frac{M_1}{8\,\pi} \frac{\mathrm{Im}[(y_N^*\, y_N^T + y_\chi^*\, y_\chi^T) M^{-1} y_\chi\, y_\chi^\dagger]_{11}}{[2\, y_N\, y_N^\dagger + y_\chi\, y_\chi^\dagger]_{11}}\,.$$

$$\boxed{\epsilon_{\Delta L} \lesssim \frac{3}{16\,\pi} \frac{M_1\, m_{\nu,\mathrm{max}}}{v^2}} (Davidson - Ibbara\ bound).$$

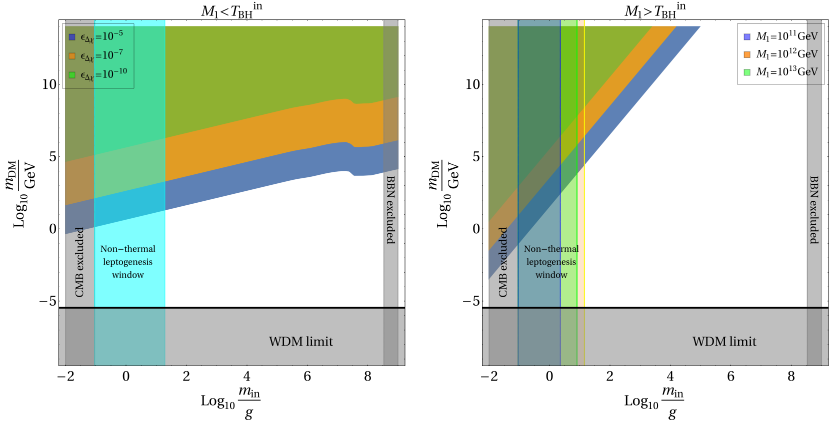
- Baryon Number Yield : $\frac{n_B}{s}\,(T_0) = \mathcal{N}\, \epsilon_{\Delta L}\, a_{\mathrm{sph}}\, \frac{n_{\mathrm{PBH}}}{s}\Big|_{T_{\mathrm{evap}}}$.

$$M_1 \begin{cases} > \dfrac{2\, g_\star(T_{\mathbf{BH}})}{a_{\mathbf{sph}}\, g_N} \dfrac{M_{\mathbf{pl}}^2\, v^2}{m_{\nu,\mathbf{max}}\, m_{\mathbf{in}}^2}\, Y_B(T_0)\, \dfrac{n_{\mathbf{PBH}}}{s}\Big|_{T_{\mathbf{evap}}} & \text{for } M_1 < T_{\mathrm{BH}}^{\mathrm{in}}\,; \\ < \dfrac{a_{\mathbf{sph}}\, g_N}{128\,\pi\, g_\star(T_{\mathbf{BH}})} \dfrac{M_{\mathbf{pl}}^2\, m_{\nu,\mathbf{max}}}{v^2} \dfrac{1}{Y_B(T_{\mathbf{0}})} \dfrac{n_{\mathbf{PBH}}}{s}\Big|_{T_{\mathbf{evap}}} & \text{for } M_1 > T_{\mathrm{BH}}^{\mathrm{in}}\,, \end{cases}$$



- Asymmetric DM Yield : $Y_{\rm DM}(T_0) = \epsilon_{\Delta\chi}\,\mathcal{N}\,\frac{n_{\rm PBH}}{s}(T_{\rm evap})$.

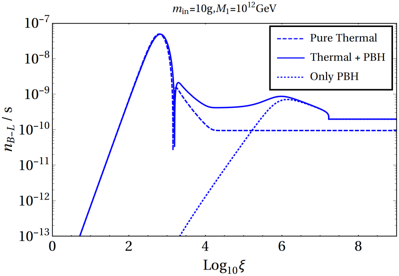
$$\Omega_{\rm DM}\,h^2 = \frac{g_{\rm DM}}{g_\star(T_{\rm evap})}\,\frac{m_{\rm DM}\,s_0}{\rho_c}\,\epsilon_{\Delta\chi}\,\frac{n_{\rm PBH}}{s}\Big|_{T_{\rm evap}} \begin{cases} \frac{4\pi}{3}\,(m_{\rm in}/M_{\rm pl})^2 & \text{for } T_{\rm BH}^{\rm in} > M_1\,; \\ \frac{1}{48\pi}\,(M_{\rm pl}/M_1)^2 & \text{for } T_{\rm BH}^{\rm in} < M_1\,. \end{cases}$$

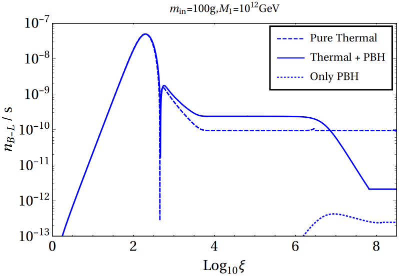


Boltzmann equations for asymmetry :

$$a\mathcal{H}\frac{d\widetilde{N}_{B-L}}{d\xi} = \epsilon_{\Delta L}\left[\left(\widetilde{n}^{T}_{N_1} - \widetilde{n}^{eq}_{N_1}\right)\Gamma^{T}_{N_1} + \widetilde{n}^{BH}_{N_1}\Gamma^{BH}_{N_1}\right] - \mathrm{Br}_{SM}\,\mathcal{W}\,\widetilde{N}_{B-L}\,,$$

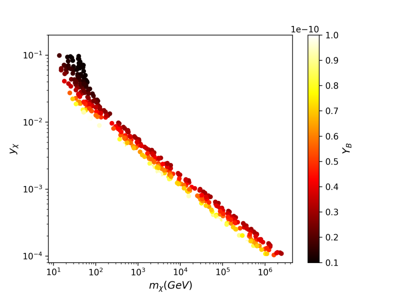
$$a\mathcal{H}\frac{dX}{d\xi} = \epsilon_{\Delta\chi}\left[\left(\widetilde{n}^{T}_{N_1} - \widetilde{n}^{eq}_{N_1}\right)\Gamma^{T}_{N_1} + \widetilde{n}^{BH}_{N_1}\Gamma^{BH}_{N_1}\right] - \mathrm{Br}_{DM}\,\mathcal{W}\,X\,.$$



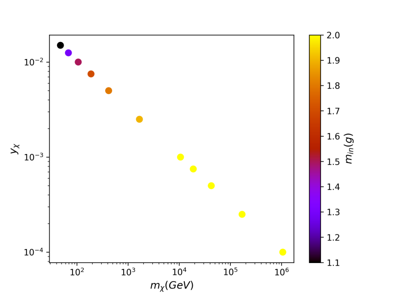


$$m_\chi : \{1 - 10^5\}\ \text{GeV};\ m_{\rm BH} : \{1 - 12\}\ \text{g};\ y_\chi : \{10^{-4} - 10^{-1}\}.$$

Parameter space of observed DM abundance:



Observed DM abundance and BAU:



Conclusion

- We have studied leptogenesis and DM in a common setup (Scotogenic Model), in the presence of PBH.
- PBH lead to non-thermal source of leptogenesis as well as dilution of asymmetry.
- For N_1 leptogenesis and scalar DM, no region of PBH parameters can simultaneously affect both.
- N_2 leptogenesis and fermion DM : cogenesis possible with PBH dependency.
- Light DM constrained from mixed DM astrophysical bounds.
- Observational consequences like gravitational waves in future experiments.

Conclusion

- Studied Asymmetric Dark matter, motivated from baryon-DM coincidence problem.
- Considered a non-thermal origin of these asymmetries from PBH.
- We stick to ultralight PBH ($\sim$1 g - 10 g) and high M_1 mass.
- Non-thermal RHNs dominate over thermal in generating the asymmetry.
- Asymmetry generated simultaneously in visible and dark sector with different DM masses.
- Origin, mass distribution, spin of PBH.... ?

Questions/ Comments ?

- CP asymmetry functions :

$$F(r_{ji},\eta_i) = \sqrt{r_{ji}}\left[f(r_{ji},\eta_i) - \frac{\sqrt{r_{ji}}}{r_{ji}-1}(1-\eta_i)^2\right],$$
$$f(r_{ji},\eta_i) = \sqrt{r_{ji}}\left[1 + \frac{(1-2\eta_i+r_{ji})}{(1-\eta_i^2)^2}\ln\left(\frac{r_{ji}-\eta_i^2}{1-2\eta_i+r_{ji}}\right)\right].$$

- CP asymmetry functions :

$$F(r_{ji}, \eta_i) = \sqrt{r_{ji}} \left[f(r_{ji}, \eta_i) - \frac{\sqrt{r_{ji}}}{r_{ji} - 1}(1 - \eta_i)^2 \right],$$

$$f(r_{ji}, \eta_i) = \sqrt{r_{ji}} \left[1 + \frac{(1 - 2\eta_i + r_{ji})}{(1 - \eta_i^2)^2} \ln\left(\frac{r_{ji} - \eta_i^2}{1 - 2\eta_i + r_{ji}}\right) \right].$$

- Washout parameters :

$$W_{\rm ID} = \frac{1}{4} \Gamma_{N_1}^T K_2(z) z^2,$$

$$\Delta W = \frac{36\sqrt{5} M_P M_1 m_{\xi}^{\bar{2}} H}{2\sqrt{\pi}\sqrt{g_*} v^4 z \lambda_5^2}.$$

- Boltzmann equations (WIMP) :

$$k\frac{d\ Y_{\rm DM}}{dz} = -\frac{<\sigma v> s}{Hz}\left(Y_{\rm DM}^2 - Y_{\rm eq}^2\right).$$

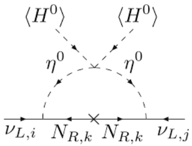
- Boltzmann equations (FIMP) :

$$\frac{dY_\eta}{dz} = -\frac{4\pi^2}{45}\frac{M_{\rm Pl} m_\eta}{1.66}\frac{\sqrt{g_*(z)}}{z^2}\left[\sum_{p\equiv{\rm SM\ particles}}\langle\sigma v\rangle_{\eta\eta\to pp}\left(Y_\eta^2 - (Y_\eta^{\rm eq})^2\right)\right]$$

$$-\frac{M_{\rm Pl}}{1.66}\frac{z}{m_\eta^2}\frac{\sqrt{g_*(z)}}{g_s(z)}\Gamma_{\eta\to N_1 l}Y_\eta$$

$$\frac{dY_{N_1}}{dz} = \frac{M_{\rm Pl}}{1.66}\frac{z}{m_\eta^2}\frac{\sqrt{g_*(z)}}{g_s(z)}\Gamma_{\eta\to N_1 l}Y_\eta$$

$$+\frac{4\pi^2}{45}\frac{M_{\rm Pl} M_\eta}{1.66}\frac{\sqrt{g_\star(z)}}{z^2}\times\left(\sum_{x=W^\pm,Z,\eta}\langle\sigma {\rm v}_{lx\to N_1 x}\rangle\left(Y_x^{eq}Y_l^{eq} - Y_{N_1}Y_x\right)\right)$$



(Credit :2010.01437)