Origin of Dark and Visible Matter

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School on Origin of Matter Domination in the Universe

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Some Outstanding Issues of High Energy Theory

1. Dark Matter content ($\Omega_{DM}$ is 27%)

2. Mass/model of the dark matter (DM) candidate particle

4. Ordinary Matter (baryon) Content ($\Omega_b$ is 5%)

5. Why the dark matter and baryon abundances are close
   (Mini coincidence puzzle)

6. Rapid Expansion of the Early Universe

7. Neutrino Mass and interactions
   
   Need: Theory, Experiment and Observation
Questions

Do we have a model to fit various astrophysical and particle physics observations?
Dark Matter: Cosmological History

Dark Matter content

Various Dark Matter scenarios:
• particle: No-thermal, Non-Standard cosmology, Non-particle: Primordial Black Holes
• Baryogenesis in these DM scenarios
  Why baryon and DM abundances are so close?
  Can we understand the mini-coincidence puzzle?

Concluding Insights
Particle Origin of Dark Matter

- Many ingredients: Statistical mechanics, GR, quantum field theory,…

- Distribution of DM in the thermal bath of the universe, expansion rate of the Universe (H), interaction DM with photon via weak, strong forces (or new)…

**Dark sector Mortadella?**
Dark Matter: Thermal

Production of thermal non-relativistic DM:

\[ DM + DM \Leftrightarrow SM \text{ particles} \]

Universe cools (\( T < m_{\text{DM}} \))

\[ DM + DM \Rightarrow SM \text{ particles} \]

\[ DM + DM \Leftrightarrow SM \text{ particles} \]

Boltzmann equation

\[
\frac{dn_{DM}}{dt} + 3Hn_{DM} = -\left\langle \sigma v \right\rangle_{eq} \left[ n_{DM}^2 - n_{DM,eq}^2 \right]
\]

\[
\left\langle \sigma v \right\rangle_{eq} = \frac{\int d^3 p_1 d^3 p_2 \sigma v e^{-(E_1+E_2)/T}}{(2\pi)^6}
\]

\[
= \frac{\int d^3 p_1 d^3 p_2 e^{-(E_1+E_2)/T}}{(2\pi)^6}
\]

\[
y = \frac{n}{s} = \frac{n}{g_{*s}T^3}
\]

\[
y_{eq} = \frac{\int \frac{d^3 p f(\vec{p}, t)}{(2\pi)^3}}{\rho/T} \equiv \text{nos./vol}
\]

Increasing \( <\sigma v> \)
Dark Matter: Thermal

Freeze-Out: Hubble expansion dominates over the interaction rate

Dark Matter content:

\[
\Omega_{\text{DM}} = \frac{m_{\text{DM}} n_{\text{DM}}}{\rho_c} \sim \frac{1}{\langle \sigma v \rangle} \quad \rho_c = \frac{3H_0^2}{8\pi G_N}
\]

freeze out \( \Rightarrow \quad T_f \sim \frac{m_{\text{DM}}}{20} \)

\( \Rightarrow \quad \langle \sigma v \rangle = 3 \times 10^{-26} \frac{cm^3}{s} \)

Assuming: \( \langle \sigma v \rangle_f \sim \frac{S}{\alpha^2_{\chi} \frac{m^2_{\chi}}{m^2}} \)

\( \alpha_{\chi} \sim O(10^{-2}) \) with \( m_{\chi} \sim O(100) \) GeV

leads to the correct relic abundance

\[ Y \sim 10^{-11} \] to satisfy the DM content for \( m_{\text{DM}} \sim 100 \) GeV
Thermal Dark Matter

DM particle + DM Particle $\rightarrow$ SM particles

Annihilation Cross-section Rate: $\langle \sigma_{\text{ann}} v \rangle$

DM Abundance: $\Omega_{\text{DM}} \sim \frac{1}{\langle \sigma v \rangle}$

f: SM particles; h, H, A: various Higgs; $\widetilde{f}$: New particle

We need $\langle \sigma v \rangle = 3 \times 10^{-26} \frac{cm^3}{s}$ to satisfy thermal DM requirement
Probing Particle Dark Matter

DM content (CMB) + overlapping region:

Cosmological history, particle physics models, astrophysics
**Indirect Detection: Fermi**

Experimental constraints: $<\sigma_{\text{ann}}\nu>$

**Gamma-rays constraints:**
Dwarf spheroidals

**Experimental constraints:**

- Small than the thermal value

**Excess at the Galactic center**

Due to new physics or pulsars?

- Hooper, Goodenough, PLB, 2011
- Abazajian, JCAP, 2011
- Leane, Slatyer; PRL’19
- Chang, Mishra-Sharma. Lisanti, Buschmann, Rodd, Safdi; prd’19
- Agashe, Clark, Dutta, Yuhsin, ‘20

From Planck Measurement

Annihilation affect the Cosmic Microwave Background

smaller than the thermal relic abundance value

Planck, 2018
Prior to Big Bang Nucleosynthesis (BBN): History of the Universe is not constrained

From Thermal DM picture, we found:

\[
\langle \sigma v \rangle \sim 2 \times 10^{-26} \frac{cm^3}{sec} \Rightarrow 27\%
\]

Larger/smaller \( \langle \sigma v \rangle \): (1) Non-thermal dark matter: due to heavy particle (e.g., moduli) decay prior to BBN

Prior to Big Bang Nucleosynthesis (BBN): History of the Universe is not constrained

Non thermal DM has larger region of parameter space

- \( \phi \) decays to X (DM particles)
- We may be able to answer: why dark matter and baryon abundances are so close, i.e., 27% and 5%?

(2) Non-standard cosmology: Expansion rate is different

\[
\frac{dn_{DM}}{dt} + 3Hn_{DM} = -\langle \sigma v \rangle_{eq} \left[ n_{DM}^2 - n_{DM,eq}^2 \right]
\]

H: expansion rate
1. Non-Thermal DM/Early Matter

\[ <\sigma_{\text{ann}}v> : \text{different from thermal average, } \Omega_{\text{DM}} \sim \frac{1}{\langle\sigma v\rangle} \text{ is not 27\%} \]

Non-thermal DM can be a solution

DM from the decay of heavy scalar Field \((\phi)\), e.g., Moduli decay

[Moduli : heavy scalar fields gravitationally coupled to matter]

\[ m_{\phi} < H \]

\[ H \text{ubble Friction} \]

\[ m_{\phi} > H \]

\[ \Rightarrow P=0; \text{ universe becomes moduli dominated} \]

\[ \rho_{\text{modulus}}(t) \propto \frac{1}{a^3(t)} \]

Moduli decay width

\[ \Gamma \approx \frac{m_{\phi}^3}{16\pi M_{\text{Pl}}^2} \]

Inflation \(\Rightarrow\) Reheating \(\Rightarrow\) Radiation domination \(\Rightarrow\) moduli domination \(\Rightarrow\) moduli decay \(\Rightarrow\) radiation domination \(\Rightarrow\) ....Today
Decay of moduli/heavy field occurs at:

\[ T_r(Reheat) \approx \sqrt{\Gamma M_{Pl}} \]

\[ T_r \sim c^{1/2} \left( \frac{m_\phi}{100\text{TeV}} \right)^{3/2} \quad (5\text{MeV}) \]

For \( T_r < T_f \): Non-thermal dark matter

For \( T_r > T_f \): Thermal dark matter

\[ T_r \sim \text{MeV} : \text{Not allowed by BBN} \]

Abundance of decay products (including DM)

\[ Y_\phi \equiv \frac{3T_r}{4m_\phi} \]
Non-Thermal DM

Large entropy dilutes the thermal abundance:

\[ \Omega = \Omega \left( \frac{T_r}{T_f} \right)^3 \]

Moduli decay into dark matter and the correct dark matter content can arise from the decay products:

1. \[ n_{\chi}^{eq}(T_r) \langle \sigma v \rangle = H(T_r) \quad \Omega_{\chi}^{NT}(T_r) \sim \frac{n_{\chi}(T_r)}{s(T_r)} \sim \frac{H(T_r)}{T_r^3} \sim \frac{1}{T_r}, \]

\[ \Omega_{\chi}^{NT} = \Omega_{\chi}^T \frac{T_f}{T_r} = 0.23 \times \left( \frac{3 \times 10^{-26} \, cm^3 / s}{\langle \sigma v \rangle} \right) \left( \frac{T_r}{T_f} \right) \Rightarrow \langle \sigma v \rangle = 3 \times 10^{-26} \left( \frac{T_f}{T_r} \right) cm^3 / s \]

⇒ Larger annihilation cross-section is needed since \( T_f > T_r \)

2. Abundance of Decay products (\( Y_\phi \)) is small enough, i.e., annihilation is not important anymore
DM from $\phi$: two possibilities

DM abundance

$$\frac{n_{DM}}{s} = \min \left[ \left( \frac{n_{DM}}{s} \right)_{obs}, \frac{\langle \sigma v \rangle_{f}^{th} T_f}{T_r}, Y_{\phi} Br_{\phi \rightarrow DM} \right]$$

1. First term on the RHS is the “annihilation scenario”

   Requires:

   $$\langle \sigma_{ann} v \rangle_{f} = \langle \sigma_{ann} v \rangle_{f}^{th} \frac{T_f}{T_r} = 2 \times 10^{-26} \frac{T_f}{T_r} \frac{cm^3}{sec}$$

   Since $T_r < T_f$, we need $\langle \sigma_{ann} v \rangle_{f} > \langle \sigma_{ann} v \rangle_{f}^{th}$

   $\sim 10$ MeV $\sim 1$ GeV

2. Second term on the RHS is the “branching scenario”

   Can accommodate large and small annihilation cross-sections

$Y_{\phi}$ is small to prevent the $Br_{\phi \rightarrow DM}$ from becoming too small
Generation of Baryon asymmetry:

Requirements (Sakharov Condition) ➔

B violation, C and CP violation; Out of equilibrium decay

Without violating both, B-violating processes would make just as many baryons as antibaryons

Possible scenarios:

EW Baryogenesis, GUT Baryogenesis, Leptogenesis etc

• SM is sufficient

In general baryon asymmetry physics is not correlated to that of DM

Can the baryon and the dark matter contents be correlated?
Explicit Model

\[ W_{\text{extra}} = \lambda_{i\alpha\beta} N_{\beta} u^c_i X_\alpha + \lambda'_{ij\alpha} d^c_i d^c_j X_\alpha + M_\alpha X_\alpha \bar{X}_\alpha + \frac{M_\beta}{2} N_{\beta} N_{\beta} \]

\[ N : \text{SM singlet; } X, \bar{X} : \text{Color triplet, hypercharge } \pm 4/3 \]

R= +1: \( N \) fermions and \( X \) scalars

\[ \Rightarrow \text{R parity conserved} \]

Moduli decay satisfies out of equilibrium condition

Baryogenesis: From decays of \( X, \bar{X} \) (if \( M_\alpha > M_\beta \))

Or

decays of \( N \) (if \( M_\alpha < M_\beta \))
Explicit Model

\[ \epsilon_\alpha = \frac{\sum_{i,j,\beta} \text{Im} \left( \lambda_{i\alpha} \lambda_{i\beta}^* \lambda_{j\beta}^* \lambda_{j\alpha} \right)}{24\pi \sum_i \lambda_{i\alpha}^* \lambda_{i\alpha}} \left[ 3F_S \left( \frac{M_B^2}{M_\alpha^2} \right) + F_V \left( \frac{M_B^2}{M_\alpha^2} \right) \right] . \]

\[ F_S = \frac{2\sqrt{x}}{x - 1} \quad F_V = \sqrt{x \ln(1 + \frac{1}{x})} \]

\[ \lambda \sim O(1), \quad \Rightarrow \quad \epsilon_\alpha \sim O(0.1) \]

\[ Y_\phi \equiv \frac{3T_r}{4m_\phi} \sim 10^{-7} \left( m_\phi \sim 10^3 \text{ TeV} \right) \]

\[ \text{Br}_N \sim 1 \times 10^{-2} \]

\[ \eta_B \equiv \frac{n_B - n_{\overline{B}}}{n_\gamma} = 7.04 \sum_\alpha Y_\alpha \epsilon_\alpha, \quad \text{Br}_N \sim 1 \times 10^{-10} \]

“Branching scenario” solves the coincidence problem

Baryon abundance in this model: \[
\frac{n_B}{s} = Y_\phi \varepsilon B r_{\phi \to B}
\]

\(Y_\phi\) appears in the DM abundance as well, \(Y_\phi \sim 10^{-7} - 10^{-9}\)

\(\varepsilon B r_{\phi \to B} \sim 10^{-1} - 10^{-3}\) easy to satisfy for baryogenesis,

\(\varepsilon\) (one loop factor) \(\sim 10^{-1} - 10^{-2}\)

\[
\frac{\Omega_b}{\Omega_{DM}} \frac{1}{m_{DM}} \frac{Y_\phi \varepsilon B r_{\phi \to B}}{Y_\phi B r_{\phi \to DM}} = \frac{1}{m_{DM}} \frac{\varepsilon B r_{\phi \to B}}{B r_{\phi \to DM}} = \frac{1}{5}
\]

\(\Omega = \rho / \rho_c\); \(\rho = mn\)

For \(n_B \sim n_{DM} \Rightarrow \varepsilon B r_{\phi \to B} \sim B r_{\phi \to DM} \Rightarrow m_{DM} \sim 5 m_B\)

The DM abundance and Baryon asymmetry are mostly saturated by \(Y_\phi\), \(B r_s\) contribute the remaining \(\Rightarrow\)

not much particle physics uncertainty

Allahverdi, Dutta, Sinha; Phys.Rev.D 83 (2011) 083502
2. Non-Standard Cosmology

Scalar-Tensor Theories:

\[ S = \frac{1}{2\kappa^2} \int d^4x \sqrt{-g} \, R - \int d^4x \sqrt{-g} \left[ \frac{1}{2} (\partial \phi)^2 + V(\phi) \right] \]

\[ -\int d^4x \sqrt{-\det (C(\phi)g_{\mu\nu} + D(\phi)\partial_\mu \phi \partial_\nu \phi)} \mathcal{L}_M(\tilde{g}_{\mu\nu}) . \]

In Jordan Frame:

\[ \tilde{g}_{\mu\nu} = C(\phi)g_{\mu\nu} + D(\phi)\partial_\mu \phi \partial_\nu \phi \]

A new \( H (\equiv \frac{\dot{a}}{a}) \) appears which is different compared to the standard cosmology

The Boltzmann equation is affected

Expansion rate is different compared to the standard cosmology when DM gets frozen out

\[ \Rightarrow \text{ Modify } <\sigma_{\text{ann}}v> \text{ to satisfy the DM content} \]
Conformal Case

\[ \ddot{H} = \frac{C^{1/2}(\varphi)}{C^{1/2}(\varphi_0)} \left(1 - \alpha(\varphi)\varphi'\right) \sqrt{1 - \frac{(\varphi')^2}{6(1 - \alpha(\varphi)\varphi')^2}} \sqrt{1 + \alpha^2(\varphi_0)} H_{GR} \]

Constraints:

\[ \alpha(\varphi) = \frac{d\ln C^{1/2}}{d\varphi} \]

\[ C \neq 0, \quad D = 0 \]

\[ \dot{N} = \ln \left[ \frac{\tilde{T}_0}{\tilde{T}} \left( \frac{g_s(\tilde{T})}{g_s(\tilde{T}_0)} \right)^{1/3} \right] \]

\[ \varphi' = \frac{1}{\left(1 - \alpha(\varphi) \frac{d\varphi}{d\tilde{N}}\right)} \frac{d\varphi}{d\tilde{N}} \]

\[ H_{GR}^2 = \frac{\kappa_{GR}^2}{3} \tilde{\rho} \]

Constraints:

- \[ \alpha_0^2 \lesssim 10^{-5} \]
- \[ \alpha'_0 = \frac{d\alpha}{d\varphi}|_{\varphi_0} \gtrsim -4.5 \]
- \[ \frac{\dot{H}}{H_{GR}} \text{ order 1 before the onset of BBN.} \]
Conformal Case

Expansion Rate

\[ C(\varphi) = (1 + 0.1 e^{-8 \varphi})^2 \]

\[ (\varphi_0, \varphi'_0) = (0.2, -0.99) \]

The expansion rate can be larger or smaller compared to the standard case.
Conformal Case

\[ C(\varphi) = (1 + 0.1 e^{-8 \varphi})^2 \]

\[ (\varphi_0, \varphi'_0) = (0.2, -0.99) \]
As \( H \) takes a dip, \( \Gamma > H \) and re-annihilation starts.

\[
\frac{\tilde{x}}{\tilde{Y}_{eq}} \frac{d\tilde{Y}}{d\tilde{x}} = -\frac{\tilde{\Gamma}}{\tilde{H}} \left( \left( \frac{\tilde{Y}}{\tilde{Y}_{eq}} \right)^2 - 1 \right)
\]
Conformal Case

- Factor 10 difference compared to the Standard case
- Cross-section can be smaller as well.

Dutta, Jimenez, Zavala, JCAP 06 (2017) 032
Disformal Case: $D \neq 0$

In the Radiation Dominated era ($V=0$):

\[
H' = -H \left[ \frac{3B}{2} (1 + \omega) + \frac{\varphi'^2}{2} \right],
\]

\[
\varphi'' \left[ 1 + \frac{3H^2 \varphi^2 B}{D C} \right] + 3 \varphi' \left[ 1 - \omega \frac{3H^2 \varphi^2 B}{D C} \right] + \frac{3B}{1+\chi} \alpha(\varphi)(1 - 3 \omega \gamma^2) + \frac{3H^2 \gamma^2 B}{D C} \left[ (\delta(\varphi) - \alpha(\varphi)) \varphi'^2 \right] = 0.
\]

Expansion Rate:

\[
\ddot{H} = \frac{H\gamma}{C^{1/2}} \left( 1 + \alpha(\varphi) \varphi' \right),
\]

\[
\gamma^{-2} = 1 - \frac{D}{C} H^2 \varphi'^2.
\]
Disformal Case: $D \neq 0$

$D_0 = -4.9 \times 10^{-14}$ and $(\varphi_0, \varphi'_0) = (0.2, -0.99)$

Leptogenesis: Lepton number asymmetry

\[ \Rightarrow \text{Baryon asymmetry via B+L violating sphaleron process} \]

Lepton asymmetry can arise from right-handed neutrino (N_1 decay)

\[ \epsilon_1 \equiv \frac{\Gamma(N_1 \rightarrow \phi L) - \Gamma(N_1 \rightarrow \phi^+ \bar{L})}{\Gamma(N_1 \rightarrow \phi L) + \Gamma(N_1 \rightarrow \phi^+ \bar{L})}. \]

\[ |\epsilon_1| \leq \frac{3}{16\pi} \frac{M_1}{v^2} \frac{\Delta m^2_\odot}{m_1 + m_3}, \]

\[ Y_{\Delta B} \sim \frac{1}{3} \epsilon_1 Y_{N_1}^{eq,0} \eta. \]

In the standard scenario M_1 > 10^9 \text{ GeV in order to have } \epsilon \geq 10^{-7}

v: weak scale

Davidson, Ibarra, ‘02

\[ \mathcal{L} = h_\beta^*(\bar{L}_\beta \phi^*)E_\beta - \chi_{\alpha k}^* (\bar{L}_\alpha \phi^*)N_k - \frac{1}{2} \bar{N}_j M_j N_j^c + \text{h.c.}, \]
Visible matter

However, one can lower $v$ (model dependent) $\Rightarrow$ lower the value of $M_1$

However, lower $M_1$ $\Rightarrow$ Leptogenesis happens at a lower temperature (H is smaller)

$\Rightarrow$ Washout processes ($\Delta L=2$) reach thermal equilibrium

Way out: Higher expansion rate $\Rightarrow$ Washout processes do not attain equilibrium

non-standard scenario

\[ \Gamma(YZ \leftrightarrow \tilde{Y}\tilde{Z}) \lesssim \hat{H}(T) \bigg|_{T \sim M_X} \]

X decays into Y, Z for leptogenesis

The higher expansion rate make it easier for the washout to be satisfied

In this non-standard model, The enhanced expansion rate lowers the Scale of leptogenesis to TeV or less

TeV scale physics model can give rise to Leptogenesis $\Rightarrow$ easy to probe at colliders
Baryogenesis is successful in the enclosed regions

Dutta, Fong, Jimenez, Nardi, JCAP 10 (2018) 025
3. Primordial Black holes

Primordial black holes (PBHs) have been a source of interest for nearly 50 years [Hawking’71, Carr, Hawking,’74]

Intertwines gravity, quantum mechanics, thermodynamics ---no discovery yet

PBH can be a dark matter candidate with a wide range of masses

If the PBH survives till today (without getting evaporated), the mass > $10^{15}$ gm

If they form before BBN, the mass is < $10^5 M_\odot$

Let us consider the asteroid size PBH: $10^{15-17}$ gm
Black holes emit Hawking radiation with the temperature:

\[ T_{PBH} = \frac{1}{8\pi G M_{PBH}} \sim 1 \text{ MeV} \left( \frac{10^{16} \text{ g}}{M_{PBH}} \right) \]

Evaporation rate:

\[ t_{\text{evap}} \sim 4 \times 10^{-4} \text{s} \times \left( \frac{m_{\text{BH}}}{10^8 \text{ g}} \right)^3 \]

- Asteroid-size PBH emits ~ 1-10^3 MeV gamma-ray
- AMEGO, e-ASTROGAM are sensitive
We use this region

We choose this region (asteroid size back hole) to use the allowed parameter space to obtain $O(1)$ dark matter fraction

Snowmass white paper on PBH: 2203.08967
• O(1-100) MeV region is not well constrained: MeV gap

PBH formation

PBH can be formed from the development of inhomogeneities: Overdense regions stop expanding and collapses

Density perturbation need to be larger than the Jeans length at maximum expansion in order to collapse against the pressure

Cosmological scenarios to produce PBH:

During the early stage of accelerated expansion, primordial perturbations with a vast range of wavelengths are produced from quantum fluctuations. With perturbation mode entering the horizon $\Rightarrow$ GW signals (tensor mode perturbations) can be produced.

Energy density of the gravity wave:

$$\Omega_{GW}(\eta, k) = \frac{1}{24} \left( \frac{k}{a(\eta)H(\eta)} \right)^2 P_h(\eta, k).$$

$$P_h(\eta, k) \simeq 2 \int_0^\infty dt \int_{-1}^{1} ds \left( \frac{t(t+2)(s^2-1)}{(t+s+1)(t-s+1)} \right)^2 \times I^2(s, t, k\eta) P_\zeta(uk) P_\zeta(vk),$$

$P_h$: power spectrum tensor perturbations

$$\Omega_{GW}(\eta_0, k) = 0.83 \left( \frac{g_{*,c}}{10.75} \right)^{-1/3} \Omega_r,0 \Omega_{GW}(\eta_c, k).$$

Kohri, Terada, PRD97 (2018) 12, 123532


Power spectrum

Curvature perturbation
Power Spectrum: $P_\zeta$

Limits on the power spectrum: existing and expected

\[\frac{M_{\text{PBH}}}{M_\odot} = 1.55 \times 10^{24} \left(\frac{\gamma}{0.2}\right) \left(\frac{g_*}{106.75}\right)^{1/6} (1 + z)^{-2},\]
\[\frac{M_{\text{PBH}}}{M_\odot} = 1.13 \times 10^{15} \left(\frac{\gamma}{0.2}\right) \left(\frac{g_*}{106.75}\right)^{-1/6} \left(\frac{k_{\text{PBH}}}{k_*}\right)^{-2}\]

$\kappa_*$ CMB Pivot scale: 0.05 Mpc$^{-1}$

Mishra, Sahani, JCAP04(2020)007

\[f_{GW} \sim 1 \text{ Hz} \left(\frac{10^{15} \text{Mpc}^{-1}}{k_p}\right)^{-1}\]

Larger $k$ values are not constrained

Origin of $P_\zeta$

For example:

Running mass inflation model

Enhanced symmetry point

Inflection point

etc.


Zheng, Shi, Qiu, 2106.04303

Mishra, Sahani, JCAP04(2020)007
Log-normal distribution: \[ P_\zeta(k) = \frac{A}{\sqrt{2\pi\sigma^2}} \exp\left(\frac{-(\log k - \log k_p)^2}{2\sigma^2}\right) \]

Many inflation models predict this power spectrum \cite{Pi, Sasaki, JCAP 09 (2020) 037}

\( \Omega_{GW} \) peak location does not depend on \( k_p \), frequency depends on \( k_p \) \( \Rightarrow \) different GW detectors come into play

Also, one can use \( \delta \)-function: \[ P_{\zeta,\delta}(k) = A_\delta \delta\left(\log\left(\frac{k}{k_p,\delta}\right)\right) \]
PBH: $\rho_{\text{PBH}}, \gamma$ ray and $P_\zeta$

Press-Schechter formalism: formation of PBH by gravitational collapse due to density contrast larger than $\delta_c$,

\[
\text{density contrast: } \delta \equiv \frac{(\rho - \bar{\rho})}{\rho}
\]

Probability distribution for $\delta$:
\[
p(\delta) = \frac{1}{\sqrt{2\pi}\sigma_0^2} e^{-\frac{\delta^2}{2\sigma_0^2}}.
\]

Variance:
\[
\sigma_0^2 = \int_0^\infty \frac{dk}{k} \frac{16}{81} (kR)^4 W^2(k, R) P_\zeta(k),
\]

Gaussian Window function:
\[
W(k, R) = \exp \left[ -\frac{(kR)^2}{4} \right]
\]

Power spectrum of the density fluctuation:
\[
P_\delta(k) = \frac{16}{81} \left( \frac{k}{aH} \right)^4 P_\zeta(k)
\]

Use $p(\delta)$ to calculate $\beta_R$ (abundance):
\[
\beta_R = c \int p(\delta) \, d\delta
\]

\[
\beta_R \equiv \frac{\rho_{\text{BH}, R}}{\rho_{r, R}}
\]

$\beta_R$ is the fraction of energy density in the BH formed with horizon size $R$.
Black hole mass with a given density contrast due to critical collapse

\[ m(R, \delta) = M_H(R)K(\delta - \delta_c)\gamma. \]

- The mass of a PBH depends on the amplitude of the fluctuation from which it forms.
- Constants \( \gamma \) and \( K \) depend on the shape of the perturbation and the background equation of state.

Numerical simulation: \( K, \delta_c, \gamma: 10, 0.25, 0.36 \)


S. Young, M. Musso, JCAP 11 (2020) 022,
PBH : γ ray and $P_\zeta$

PBH is formed in the deep radiation era in our case: perturbation enters at $z \sim 10^{20-21}$ for $k_p \sim 10^{14-15}$ Mpc$^{-1}$

At matter radiation equality:

$$\frac{d\beta_{eq}}{dm} = \int_0^\infty \frac{dR}{R} \frac{R_{eq}}{R} \left(2\frac{g_{*s,eq}}{g_{*s,R}} \frac{g_*,R}{g_*,eq} \right)^{1/2} \beta_R.$$ 

The mass fraction at the matter radiation equality:

$$\frac{df_{BH,eq}}{dm} = \frac{d}{dm} \left( \frac{\rho_{BH,eq}}{\rho_{CDM,eq}} \right) = \frac{\Omega_m}{\Omega_{CDM}} \frac{d\beta_{eq}}{dm},$$

The peak can be obtained as:

$$m^{\text{peak}} = \gamma_{\text{eff}} M_H(R = k_p^{-1}) \simeq 2 \times 10^{16} \text{ g} \times \gamma_{\text{eff}} \left(\frac{k_p}{10^{15} \text{ Mpc}^{-1}}\right)^{-2}$$

$$\frac{\partial N_{\gamma,tot}}{\partial E_\gamma \partial t} = \frac{\partial N_{\gamma,\text{primary}}}{\partial E_\gamma \partial t} + \sum_{i=e^\pm,\mu^\pm,\pi^\pm} \int dE_i \frac{\partial N_{i,\text{primary}}}{\partial E_i \partial t} \frac{dN_{i,\text{FSR}}}{dE_\gamma} + \sum_{i=\pi} \int dE_i 2 \frac{\partial N_{i,\text{primary}}}{\partial E_i \partial t} \frac{dN_{i,\text{decay}}}{dE_\gamma},$$

Observed γ-ray flux from all PBH:

$$\frac{\partial \Phi_\gamma}{\partial E_\gamma} = J_D \frac{\Delta \Omega}{4\pi} \int d\log m \frac{df_{BH}}{d\log m} \frac{\partial N_{\gamma,tot}}{\partial E_\gamma \partial t}.$$
$\rho_{PBH}$ and $P_\zeta$

$$\frac{df_{BH}}{dm} \quad , \quad f_{BH} \equiv \frac{\Omega_{BH}}{\Omega_{CDM}}$$

Larger $k_p \Rightarrow$ smaller black hole mass $\Rightarrow$ higher $f_{PBH}$

$$P_\zeta(k) = \frac{A}{\sqrt{2\pi}\sigma^2} \exp \left( - \frac{(\log k - \log k_p)^2}{2\sigma^2} \right)$$
PBH : $\gamma$ ray and $P_\zeta$

$\sigma$: 2.5, $\log_{10} A$: -2.0, $k_p$: $10^{15}\text{Mpc}^{-1}$

$\sigma$: 3.0, $\log_{10} A$: -2.0, $k_p$: $10^{15}\text{Mpc}^{-1}$

$\sigma$: 2.5, $\log_{10} A$: -1.9, $k_p$: $10^{15}\text{Mpc}^{-1}$

$\sigma$: 2.5, $\log_{10} A$: -2.0, $k_p$: $5\times10^{15}\text{Mpc}^{-1}$

$E_\gamma^{\text{peak}} \approx 10 T_{\text{BH}} (m^{\text{peak}}) \approx 1 \text{MeV} \left( \frac{5}{\gamma_{\text{eff}}} \right) \left( \frac{k_p}{10^{15} \text{Mpc}^{-1}} \right)^2$

$\gamma$–ray flux increases as $A$ and $k_p$ increase and $\sigma$ decreases

$\Omega_{GW}$ peak location does not depend on $k_p$, frequency depends on $k_p$
\[ P_{\zeta, \delta}(k) = A_\delta \delta \left( \log \left( \frac{k}{k_{p, \delta}} \right) \right) \]

Upper bound for \( A \): Existing bounds on \( \gamma \)-ray and \( f_{\text{BH}} \leq 1 \)

Lower bound for \( A \): Above e-Astrogam Sensitivity

Agashe, Chang, Clark, Dutta, Tsai, Xu, Phys.Rev.D 105 (2022) 12, 123009
S. Young, M. Musso, JCAP 11 (2020) 022, Snowmass, 2203.08967


Asteroid-Mass Primordial Black Hole

Small-Scale Curvature Perturbations

Gamma-ray Signals (Hawking Radiation)

Gravitational Waves Signals

Correlation
PBH with dark sector particles

For example, axions from Hawking radiation

\[ \frac{\partial N_{i,\text{primary}}}{\partial E_i \partial t} = \frac{g_i \Gamma_i(E_i, M, \mu_i)}{2\pi} e^{E_i/T_H} \pm 1 \]

\[ f = 10^{-8} \]

Agashe, Chang, Clark, Dutta, Tsai, Xu,
Phys.Rev.D 108 (2023) 2, 023014
Baryo/leptogenesis with PBH

Baryogenesis and Leptogenesis are possible with PBH

\[
\beta \equiv \frac{\rho_{BH}(T_0)}{\rho_R(T_0)} = \frac{n_0 M_{BH0}}{\rho_R(T_0)} ,
\]

\[
M_X = 10^{11} \text{ GeV}
\]

\[
\begin{align*}
Y_X &= \frac{3 \beta T_0 N_X s(T_{ev})}{4 M_{BH0} s(T_{e})} = \frac{3 \beta T_0 N_X}{4 M_{BH0}} \left( 1 + \beta \frac{T_0}{T_{ev}} \right)^{-3/4} .
\end{align*}
\]

\(T_0\): PBH formation temp,
\(N_X\): nos. of X particles,
\(T_{ev}\): evaporation temp.,
\(T_{e}\): plasma temp after evaporation

\[
Y_{B-L} = \frac{30 \epsilon Y_X}{97}
\]

Bernal, Fong, Gonzalez, Perez, 2203.08823

Similarly, we can initiate leptogenesis

- Washout is suppressed

Can we accommodate the coincidence puzzle?

Dent, Dutta, Fong, Xu, to appear
Concluding Insights

- Many dark matter Model ideas have constraints from LHC, Planck, direct and indirect detection constraints

- The constraints affect the annihilation cross-sections associated with thermal dark matter, WIMP paradigm

- Various new DM scenarios are possible. A few of them are discussed

- The scenarios include: Non-thermal, Non-standard and primordial black holes

- It is possible to understand baryogenesis/leptogenesis in these scenarios

- It is possible to understand the closeness of dark matter and baryon abundances, i.e., mini coincidence problem in some of these scenarios