Origin of Dark and Visible Matter

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School on Origin of Matter Domination in the Universe

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Questions

Some Outstanding Issues of High Energy Theory

1. Dark Matter content (Ω_{DM} is 27%)

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

4. Ordinary Matter (baryon) Content (Ω_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

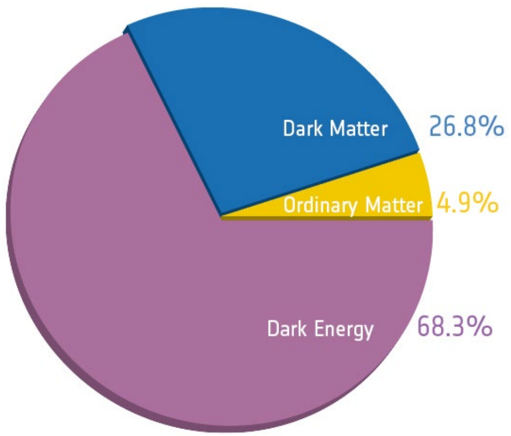
Do we have a model to fit various astrophysical and particle physics observations?

Presentation Outline

- 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?



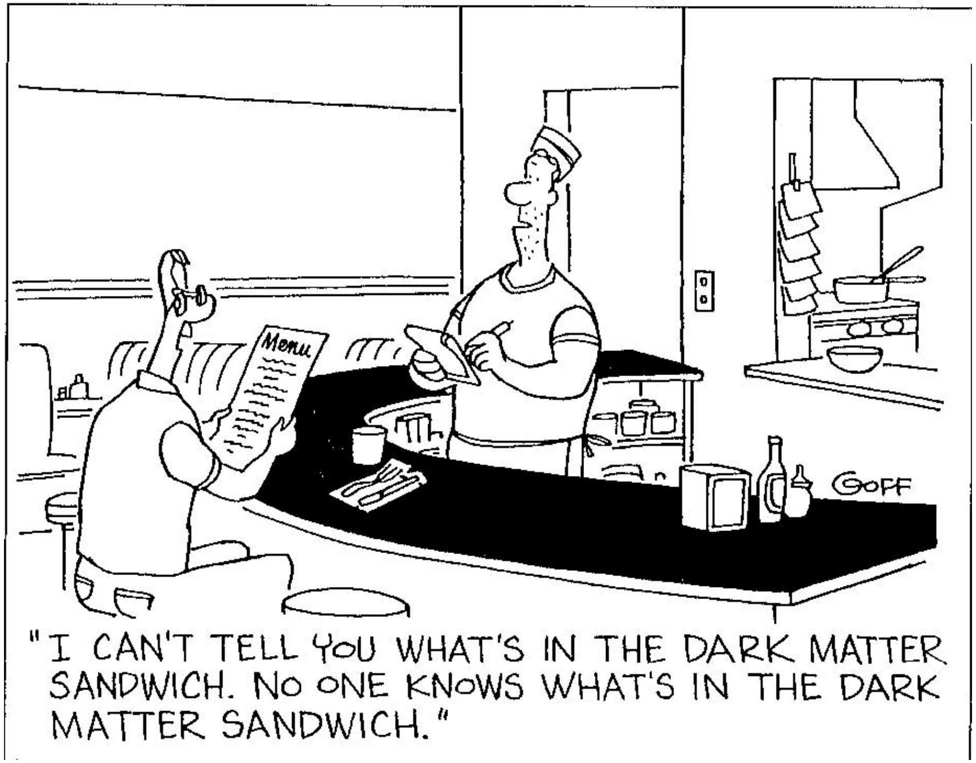
- Concluding Insights

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:

$$Y = \frac{n}{s} = \frac{n}{g_{*s} T^3}$$

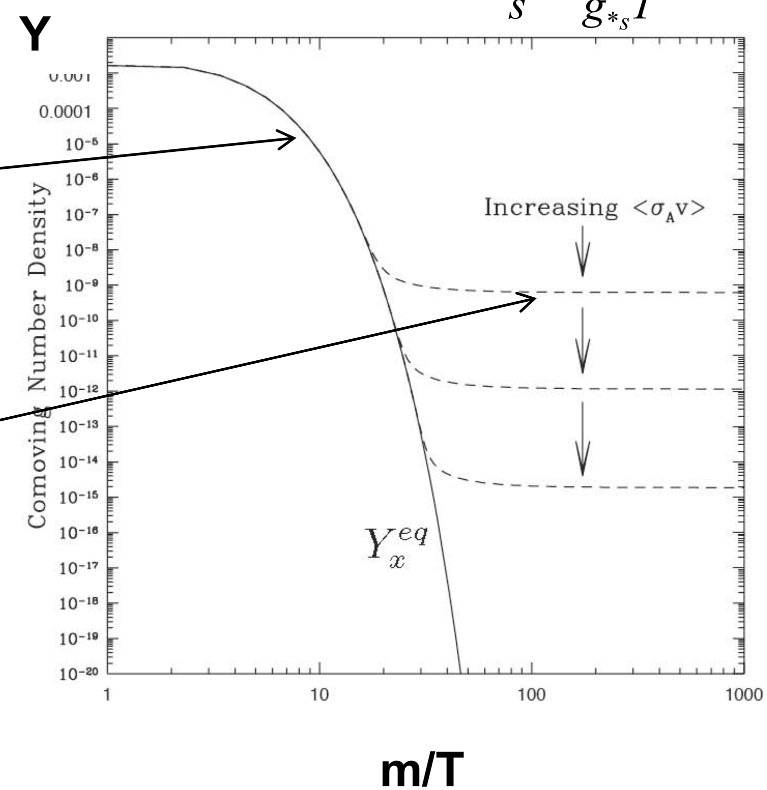
$$DM + DM \Leftrightarrow SM \quad particles$$

$$\downarrow \quad \textbf{Universe cools } (\mathbf{T<m_{DM}})$$

$$DM + DM \Rightarrow SM \quad particles$$

$$\downarrow$$

$$DM + DM \not\Leftrightarrow SM \quad particles$$



Boltzmann equation

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

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

$$n = g \int \frac{d^3 p f(\vec{p}, t)}{(2\pi)^3} \equiv nos./vol$$

Dark Matter: Thermal

Freeze-Out: Hubble expansion dominates over the interaction rate

Dark Matter content:

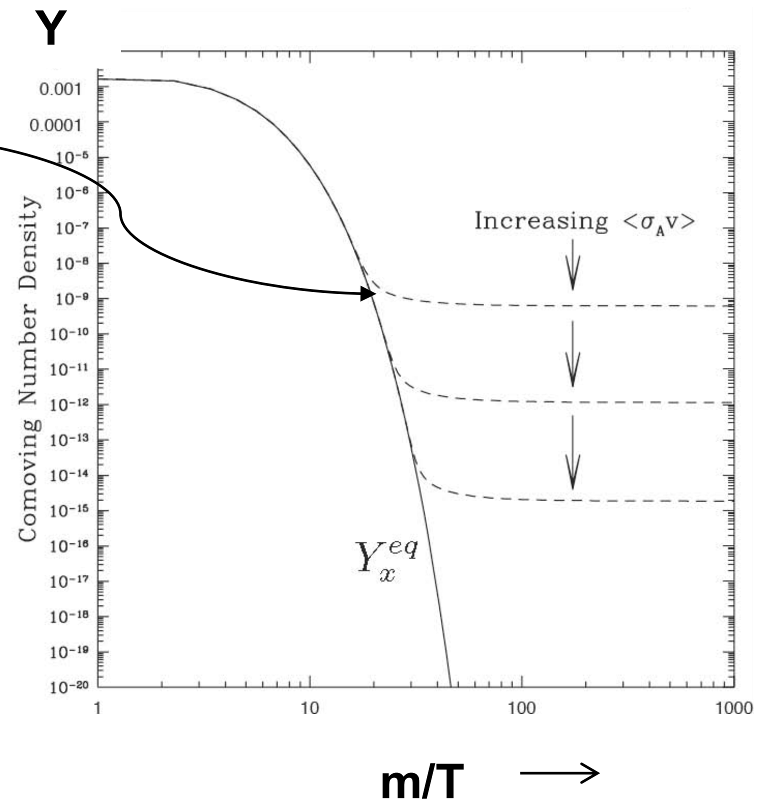
$$\Omega_{\mathrm{DM}} = \frac{m_{DM} n_{DM}}{\rho_c} \sim \frac{1}{\langle \sigma \mathrm{v} \rangle} \qquad \rho_c = \frac{3H_0^2}{8\pi G_N}$$

freeze out ➔ $T_f \sim \frac{m_{DM}}{20}$

➔ $\langle \sigma \mathrm{v} \rangle = 3 \times 10^{-26} \frac{cm^3}{s}$

Assuming : $\langle \sigma \mathrm{v} \rangle_f \sim \frac{\alpha_\chi^2}{m_\chi^2}$

α_χ~O(10^{-2}) with m_χ ~ O(100) GeV leads to the correct relic abundance



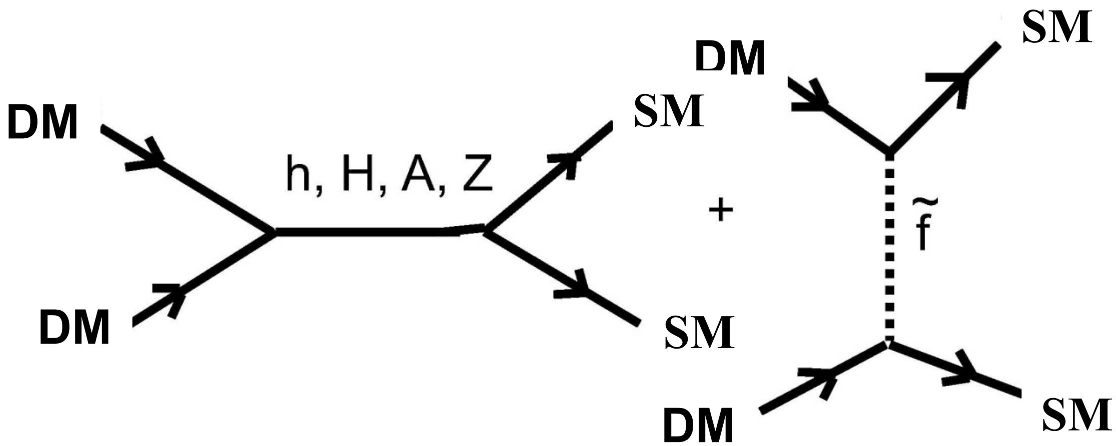
Y becomes constant for T>T_f

Y~10^{-11} to satisfy the DM content for for m_{DM}~100 GeV

Thermal Dark Matter

DM particle + DM Particle➔ SM particles

Annihilation Cross-section Rate: $< \sigma_{ann} v >$



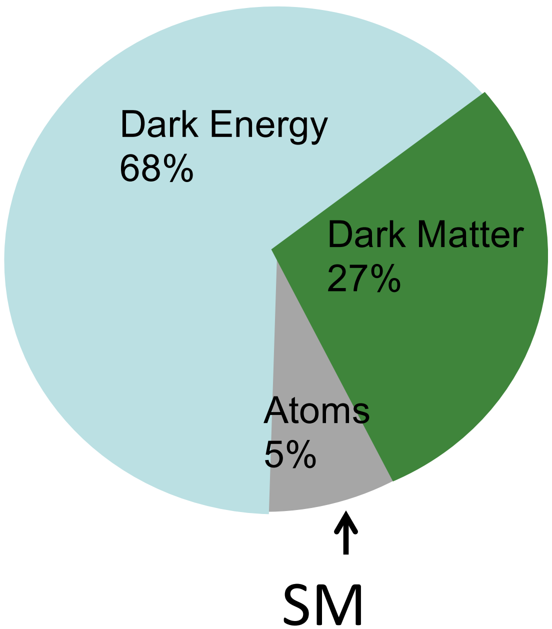
DM Abundance:

$$\Omega_{\mathrm{DM}} \sim \frac{1}{\langle \sigma \mathrm{v} \rangle}$$

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

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

Probing Particle Dark Matter



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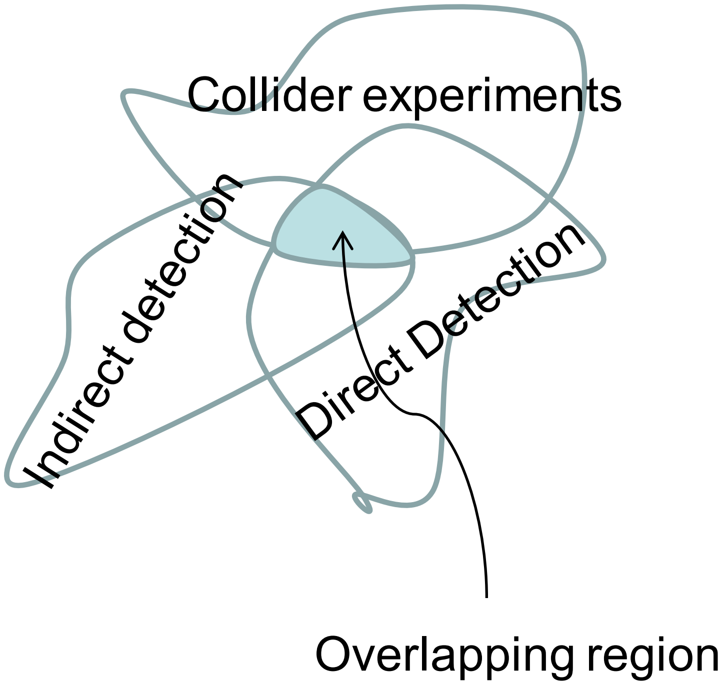
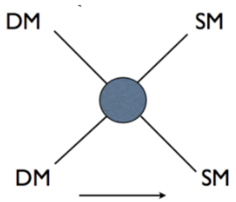


DM content (CMB) + overlapping region:

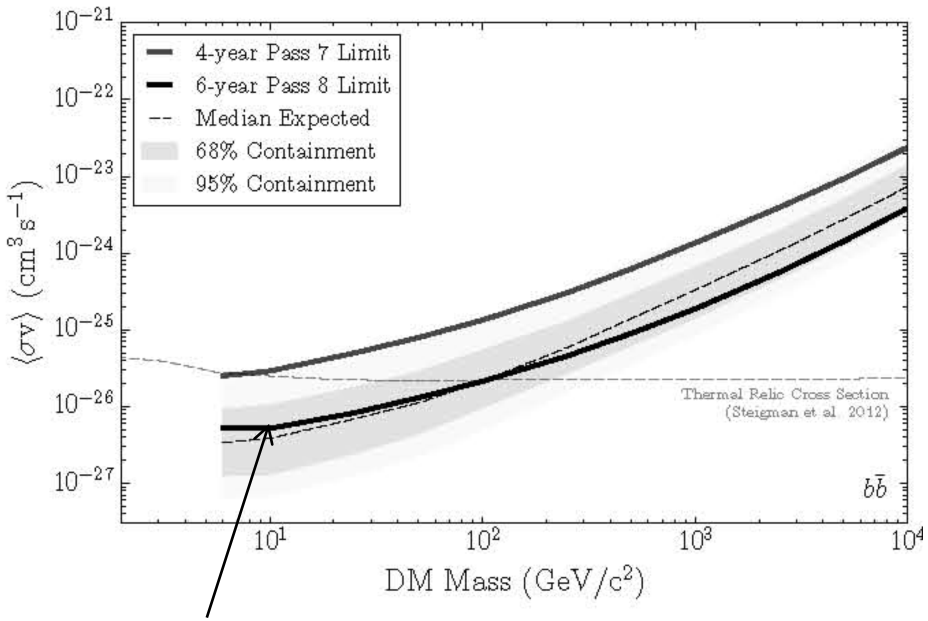
Cosmological history, particle physics models, astrophysics

Indirect Detection: Fermi



Experimental constraints: $<\sigma_{ann} v>$

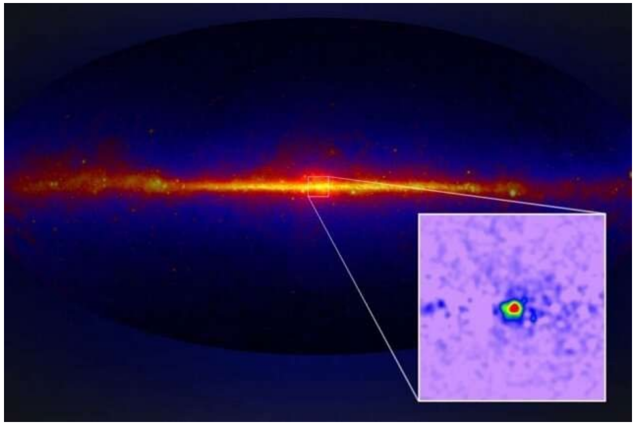
Gamma-rays constraints:
Dwarf spheroidals



smaller than the thermal value

Fermi Collaboration: arXiv:1503.02641

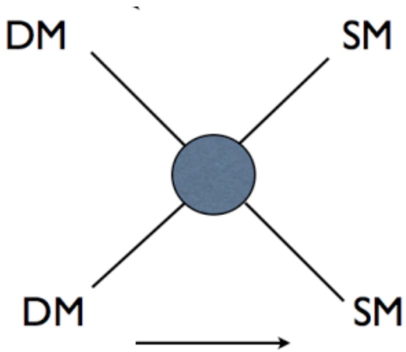
Excess at the Galactic center



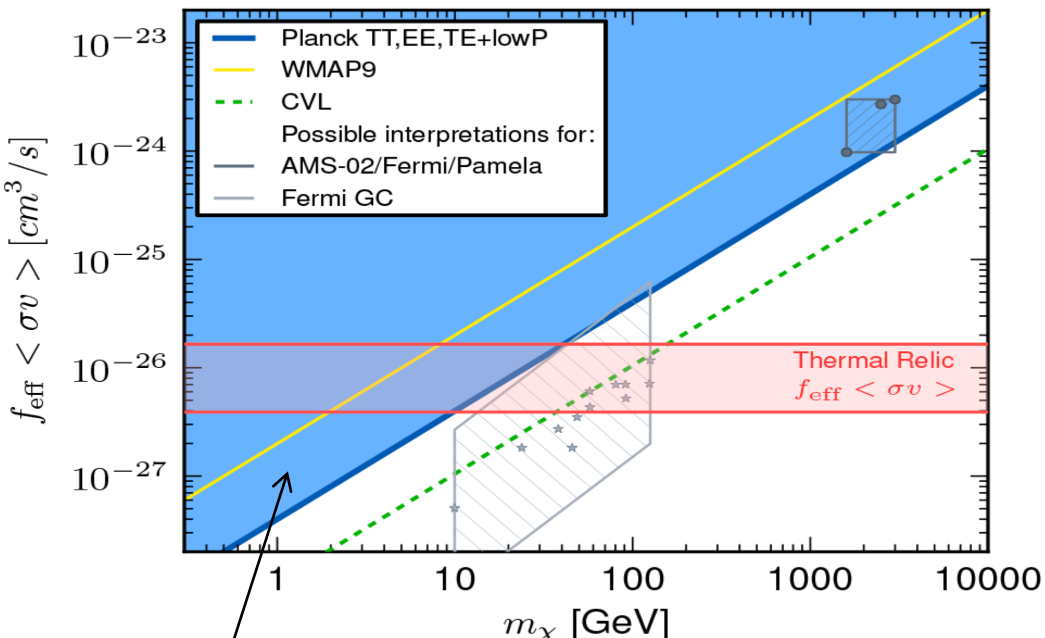
Due to new physics or pulsars?

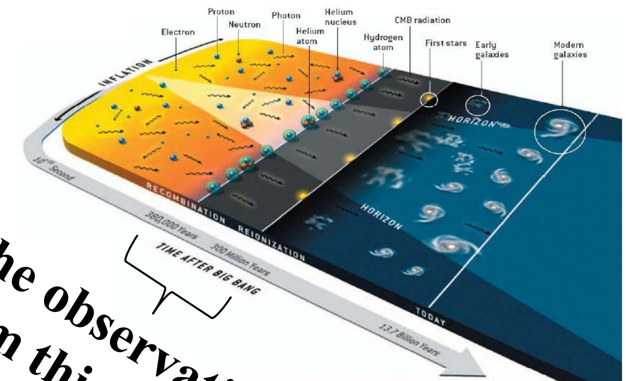
Hooper, Goodenough, PLB, 2011;
Abazajian, JCAP, 2011
Leane, Slatyer; PRL'19
Chang, Mishra-Sharma. Lisanti,
Buschmann, Rodd,Safdi; prd'19
Agashe, Clark, Dutta, Yuhsin, '20

From Planck Measurement



Annihilation affect the Cosmic Microwave Background





The observation is from this range of time

smaller than the thermal relic abundance value

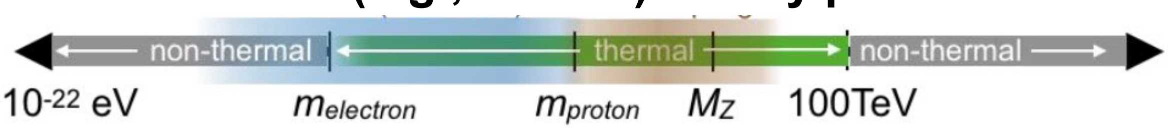
Planck, 2018

Larger or smaller <σv> for 27%

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 <σv> : (1) Non-thermal dark matter: due to heavy particle (e.g., moduli) decay prior to BBN



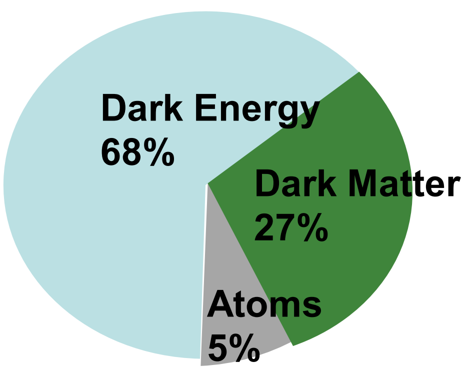
Non thermal DM has larger region of parameter space

$$\frac{d\rho_\phi}{dt} = -3H\rho_\phi - \Gamma_\phi \rho_\phi\,,$$

$$\frac{d\rho_R}{dt} = -4H\rho_R + (m_\phi - N_{LSP} m_X)\Gamma_\phi n_\phi + \langle \sigma v \rangle 2 m_X \left[n_X^2 - (n_X^{eq})^2 \right]\,,$$

$$\frac{dn_X}{dt} = -3Hn_X + N_{LSP}\Gamma_\phi n_X - \langle \sigma v \rangle \left[n_X^2 - (n_X^{eq})^2 \right]$$

- **ϕ 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 [Dark Matter is still thermal]

H: expansion rate

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

1. Non-Thermal DM/Early Matter

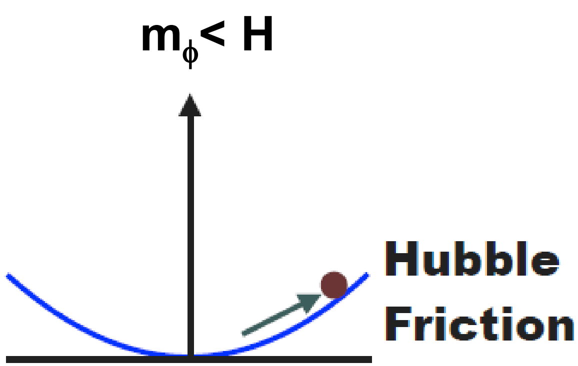
$<\sigma_{ann} v>$: **different from thermal average,** $\Omega_{\rm DM} \sim \frac{1}{\langle \sigma v \rangle}$ **is not 27%**

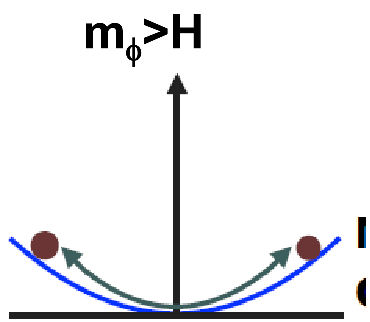
Moroi, Randall'99; Acharya, Kane, Watson'08, Randall; Kitano, Murayama, Ratz'08; Dutta, Leblond, Sinha'09; Allahverdi, Cicoli, Dutta, Sinha,'13

<u>Non-thermal DM can be a solution</u>

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

[Moduli : heavy scalar fields gravitationally coupled to matter]





Inflation→Reheating→Radiation domination→ moduli domination→moduli decay→ radiation domination→....Today

→ P=0; universe becomes moduli dominated

$$\rho_{\rm modulus}(t) \propto \frac{1}{a^3(t)}$$

Moduli decay width

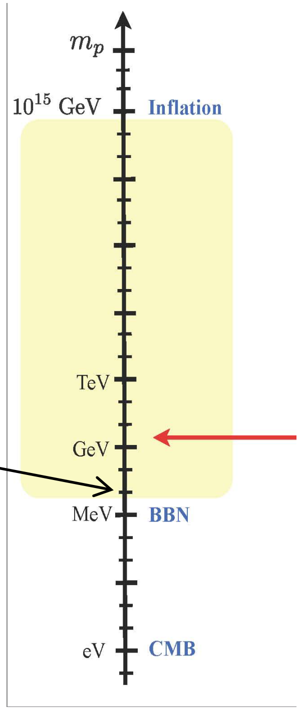
$$\Gamma \approx \frac{m_\varphi^3}{16\pi M_{\rm pl}^2}$$

Non-Thermal DM/Early Matter

Decay of moduli/heavy field occurs at:

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

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



For $T_r<T_f$: Non-thermal dark matter

For $T_r>T_f$: Thermal dark matter

$T_r\sim$ MeV : Not allowed by BBN

Abundance of decay products (including DM) $Y_\phi \equiv \dfrac{3T_r}{4m_\phi}$

Non-Thermal DM

Large entropy dilutes the thermal abundance:

$$\Omega = \Omega(\frac{T_r}{T_f})^3$$

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

1. $$n_X^{eq}(T_r)\,\langle\sigma v\rangle = H(T_r) \qquad \Omega_X^{NT}(T_r) \sim \frac{n_X(T_r)}{s(T_r)} \sim \frac{H(T_r)}{T_r^3} \sim \frac{1}{T_r},$$

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

➔ **Larger annihilation cross-section is needed since $T_f > T_r$**

2. **Abundance of Decay products (Y_ϕ) is small enough, i.e., annihilation is not important anymore**

DM from ϕ: *two possibilities*

DM abundance $$\frac{n_{DM}}{s} = \min .[\left(\frac{n_{DM}}{s}\right)_{obs} \frac{\langle \sigma v \rangle_f^{Th}}{\langle \sigma v \rangle_f} \frac{T_f}{T_r}, Y_\phi Br_{\phi \to DM}]$$

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 $\langle \sigma_{ann} v \rangle_f > \langle \sigma_{ann} v \rangle_f^{th}$

   ~10 MeV **~ 1 GeV**

2. **Second term on the RHS is the "branching scenario"**
   Can accommodate large and small annihilation cross-sections

Y_ϕ is small to prevent the Br $_{\phi \to DM}$ from becoming too small

Visible matter: Moduli scenario

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

$$W_{extra} = \lambda_{i\alpha\beta} N_\beta u_i^c X_\alpha + \lambda'_{ij\alpha} d_i^c d_j^c \overline{X}_\alpha + M_\alpha X_\alpha \overline{X}_\alpha + \frac{M_\beta}{2} N_\beta N_\beta$$

N **:** **SM singlet;** $X, \overline{X}$ **: Color triplet, hypercharge $\pm$4/3**

R= +1: *N* fermions and *X* scalars

➔ R parity conserved

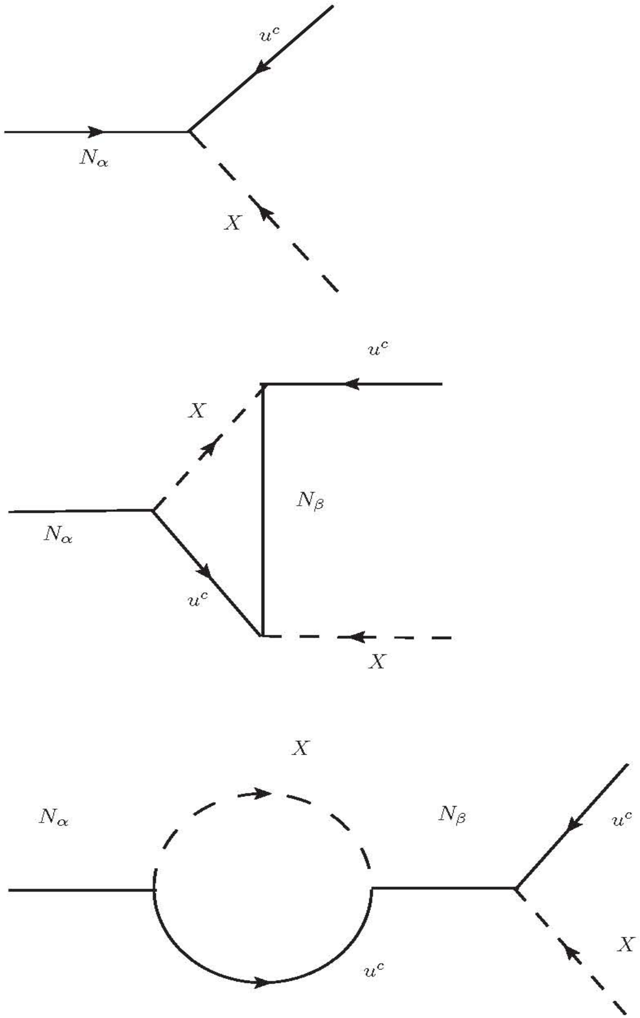
Moduli decay satisfies out of equilibrium condition

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

Or

decays of N **(if** $M_\alpha < M_\beta$ **)**

Explicit Model



$$\epsilon_\alpha = \frac{\sum_{i,j,\beta} \mathrm{Im}\left(\lambda_{i\alpha}\lambda^*_{i\beta}\lambda^*_{j\beta}\lambda_{j\alpha}\right)}{24\pi \sum_i \lambda^*_{i\alpha}\lambda_{i\alpha}} \left[3\mathcal{F}_S\left(\frac{M^2_\beta}{M^2_\alpha}\right) + \mathcal{F}_V\left(\frac{M^2_\beta}{M^2_\alpha}\right)\right]$$

$$F_s = \frac{2\sqrt{x}}{x-1} \qquad F_V = \sqrt{x}\ln(1+\frac{1}{x})$$

$\lambda \sim O(1),$ ➔ **ε_α ~O(0.1)**

$$Y_\phi \equiv \frac{3T_r}{4m_\phi}$$ **~10^{-7}** **(m_ϕ~10^3 TeV)**

Br_N ~1-10^{-2}

$$\eta_B \equiv \frac{n_B - n_{\overline{B}}}{n_\gamma} = 7.04 \sum_\alpha Y_\alpha \epsilon_\alpha , Br_N$$

~10^{-10}

Allahverdi, Dutta, Phys.Rev.D 82 (2010) 035004
Allahverdi, Dutta, Mohapatra, Sinha, Phys.Rev.Lett. 111 (2013) 051302

Dark Matter from ϕ

"Branching scenario" solves the coincidence problem

Baryon abundance in this model: $$\frac{n_B}{s} = Y_\phi \varepsilon Br_{\phi\to B}$$

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

$\varepsilon BR_{\phi\to B} \sim 10^{-1}$-$10^{-3}$ easy to satisfy for baryogenesis,
ε (one loop factor) $\sim 10^{-1}$-10^{-2}

$$\frac{\Omega_b}{\Omega_{DM}} = \frac{1}{m_{DM}} \frac{Y_\phi \varepsilon Br_{\phi\to B}}{Y_\phi Br_{\phi\to DM}} = \frac{1}{m_{DM}} \frac{\varepsilon Br_{\phi\to B}}{Br_{\phi\to DM}} = \frac{1}{5}$$

$\Omega = \rho/\rho_c$; $\rho = mn$

For $n_B \sim n_{DM}$ ➔ $\varepsilon\, BR_{\phi\to B} \sim BR_{\phi\to DM}$ ➔ $m_{DM} \sim 5\, m_B$

The DM abundance and Baryon asymmetry are mostly saturated by Y_ϕ, Brs contribute the remaining ➔ not much particle physics uncertainty

Allahverdi, Dutta, Sinha; Phys.Rev.D 83 (2011) 083502

2. Non-Standard Cosmology

Scalar-Tensor Theories:

$$S = \frac{1}{2\kappa^2}\int d^4x\sqrt{-g}\,R - \int d^4x\sqrt{-g}\left[\frac{1}{2}(\partial\phi)^2 + V(\phi)\right]$$
$$-\int d^4x\sqrt{-\det\left(C(\phi)g_{\mu\nu} + D(\phi)\partial_\mu\phi\partial_\nu\phi\right)}\,\mathcal{L}_M(\tilde{g}_{\mu\nu})\,.$$

In Jordan Frame:

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

Jordan,'49, Fierz,'56, Brans, Dicke, '61,
Bergmann, '68, Nordtvedt, '70,
Wagoner, '70, Perrotta, Baccigalupi, Matarrese,'99
Bekenstein'93, Koivisto, Wills, Zavala, '13

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

Catena Fornengo, Masiero, Pitroni, Rosati,'04
Meehan, Whittingham, '15
Gelmini, Huh, Rehagen,'13,
Wang, Imminiyaz, Mamat, '15

The Boltzmann equation is affected

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

➔ Modify <σ_{ann}v> to satisfy the DM content

Conformal Case

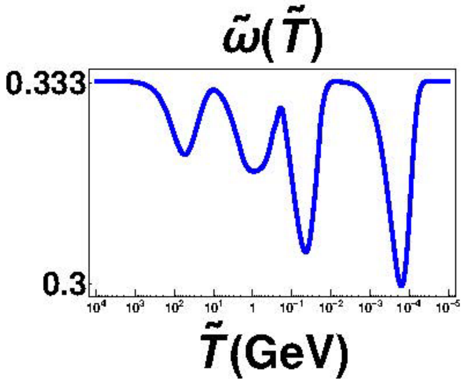
$$\tilde{H} = \frac{C^{1/2}(\varphi)}{C^{1/2}(\varphi_0)} \frac{1}{(1-\alpha(\varphi)\varphi')\sqrt{1-\frac{(\varphi')^2}{6(1-\alpha(\varphi)\varphi')^2}}} \frac{1}{\sqrt{1+\alpha^2(\varphi_0)}} H_{GR}$$

$C \neq 0, \qquad D = 0$

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

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

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



$\tilde{p} = \tilde{\omega}\tilde{\rho}$

- Radiation domination, $\tilde{\omega} \approx 1/3$.
- Matter domination, $\tilde{\omega} = 0$.
- Dark Energy domination, $\tilde{\omega} = -1$.

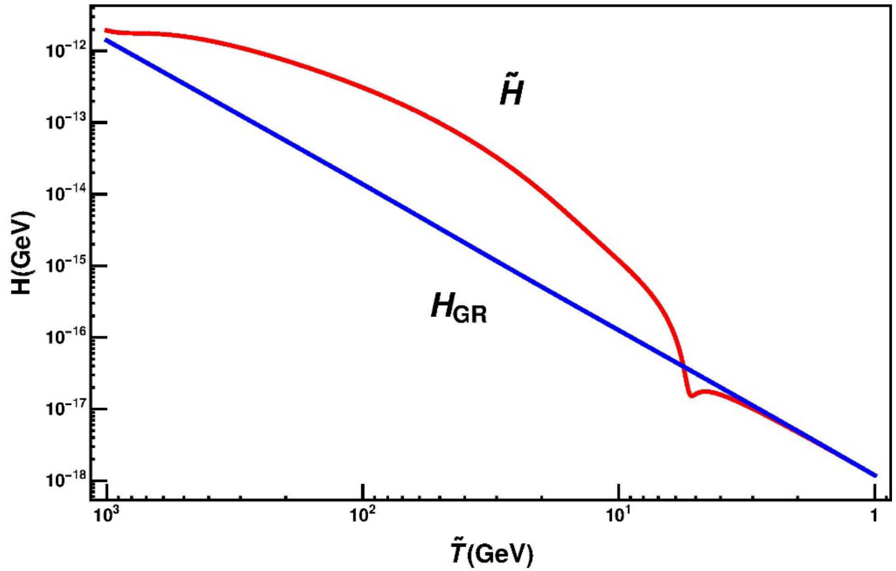
$$H_{GR}^2 = \frac{\kappa_{GR}^2}{3}\tilde{\rho}$$

Constraints:

- $\alpha_0^2 \lesssim 10^{-5}$
- $\alpha_0' = d\alpha/d\varphi|_{\varphi_0} \gtrsim -4.5$.
- $\frac{\tilde{H}}{H_{GR}}$ order 1 before the onset of BBN.

Conformal Case

Expansion Rate



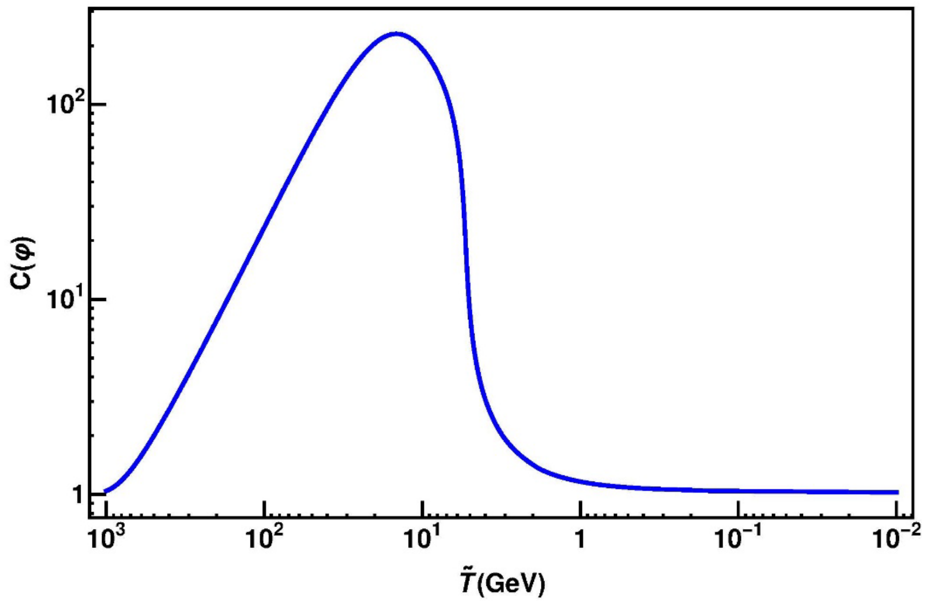
$$C(\varphi) = (1 + 0.1\, e^{-8\,\varphi})^2$$

$$(\varphi_0, \varphi_0') = (0.2, -0.99)$$

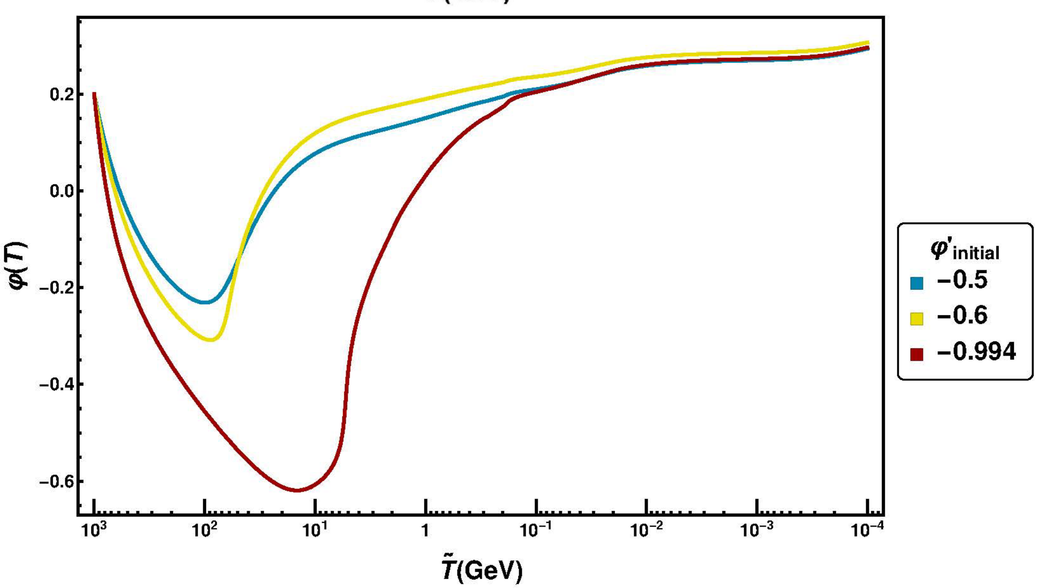
The expansion rate can be larger or smaller compared to the standard case

Conformal Case

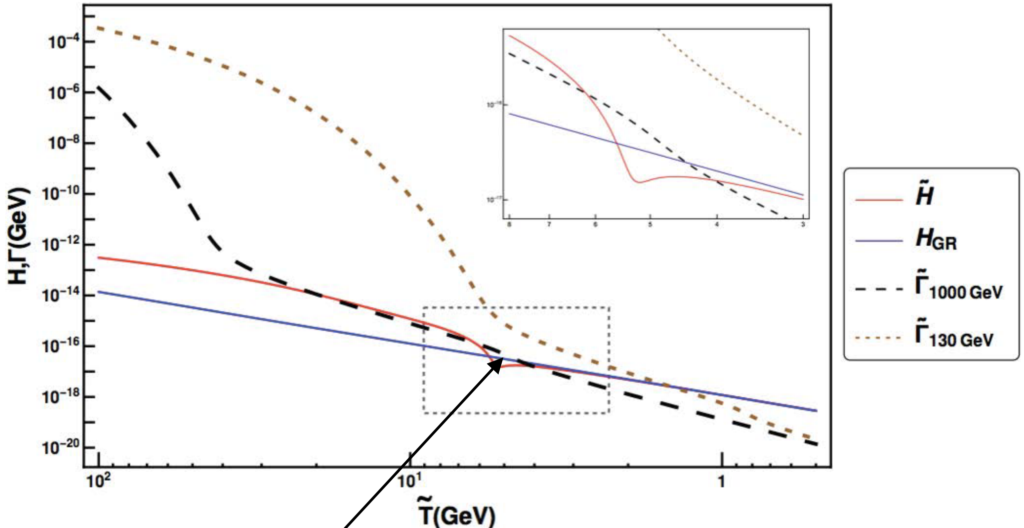
$$C(\varphi) = (1 + 0.1\, e^{-8\,\varphi})^2$$



$$(\varphi_0, \varphi_0') = (0.2, -0.99)$$

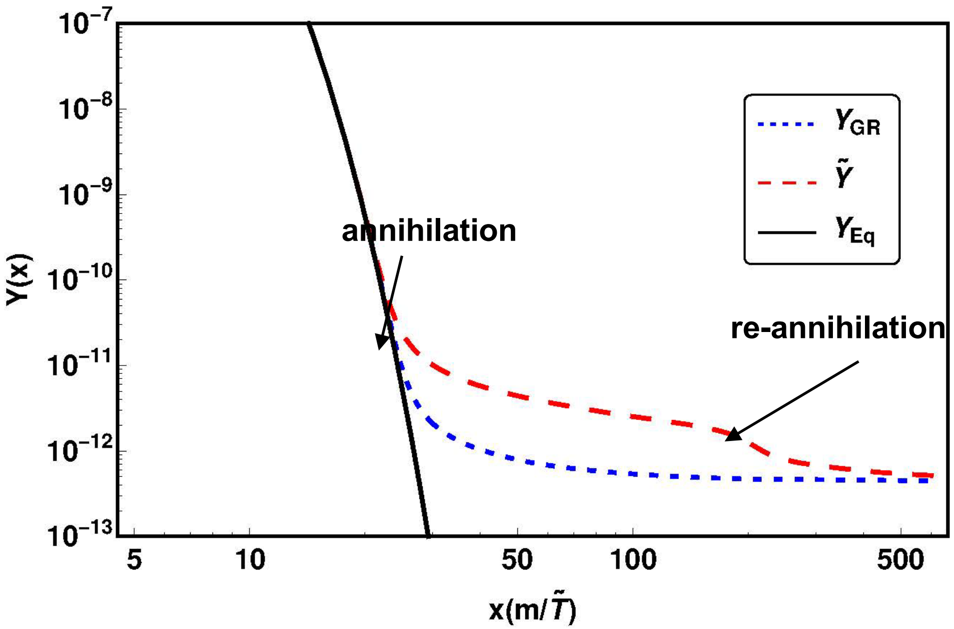


Conformal Case

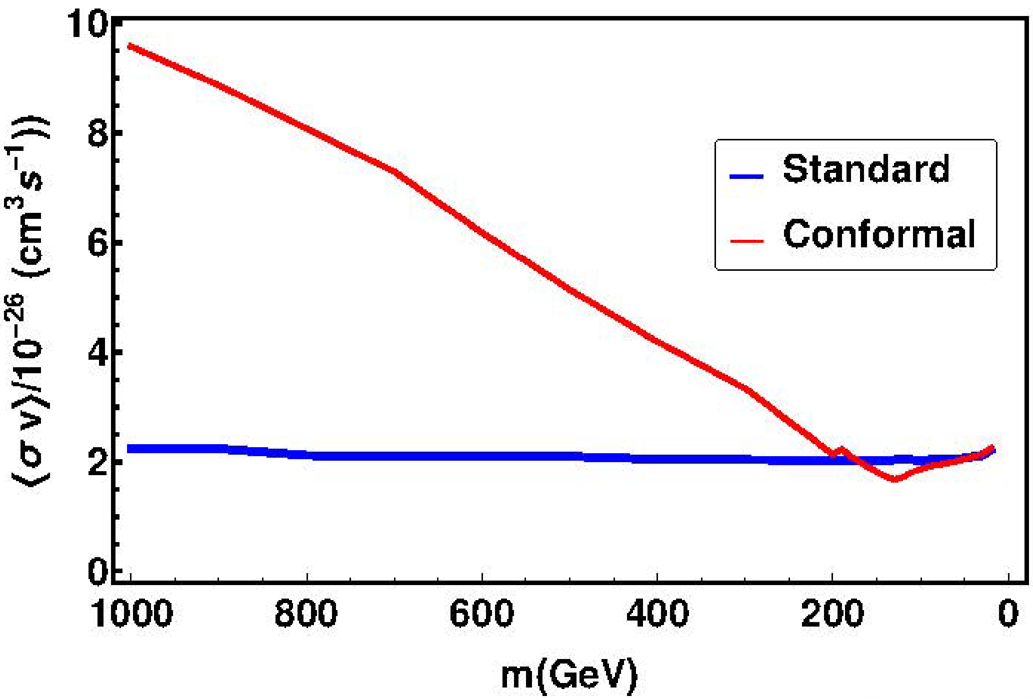


$$\frac{\tilde{x}}{\tilde{Y}_{eq}}\frac{d\tilde{Y}}{d\tilde{x}} = -\frac{\tilde{\Gamma}}{\tilde{H}}\left(\left(\frac{\tilde{Y}}{\tilde{Y}_{eq}}\right)^2 - 1\right)$$

As H takes a dip,
Γ>H and re-annihilation
starts



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):

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

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

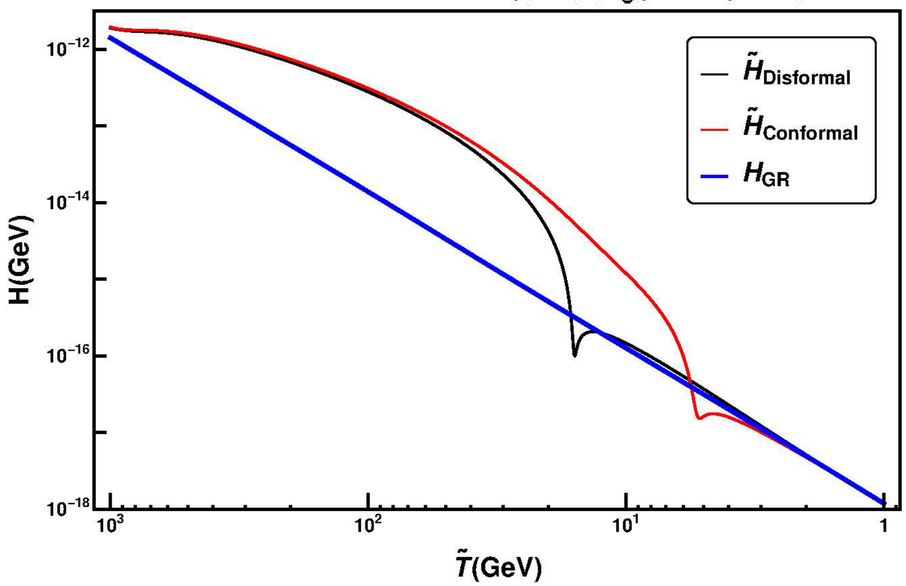
Expansion Rate:

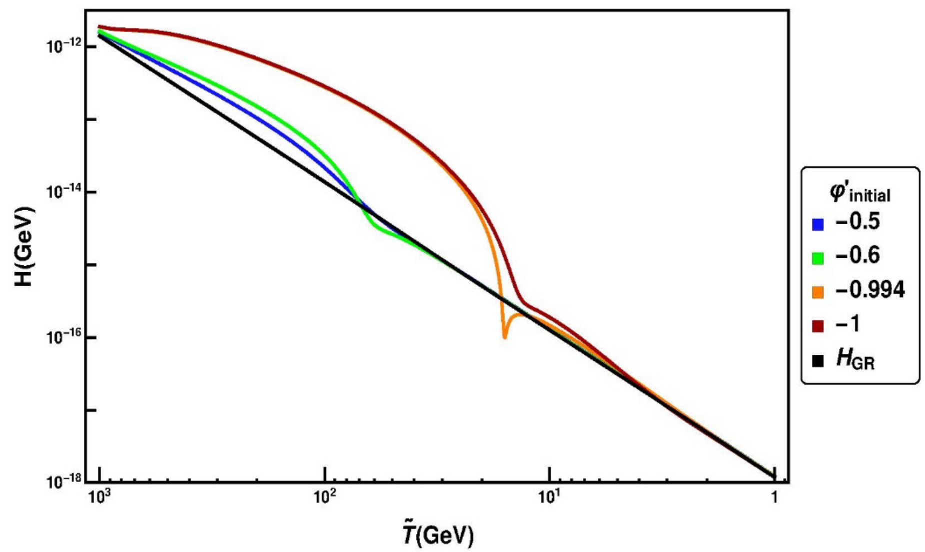
$$\tilde{H} = \frac{H\gamma}{C^{1/2}}\left(1+\alpha(\varphi)\varphi'\right),$$

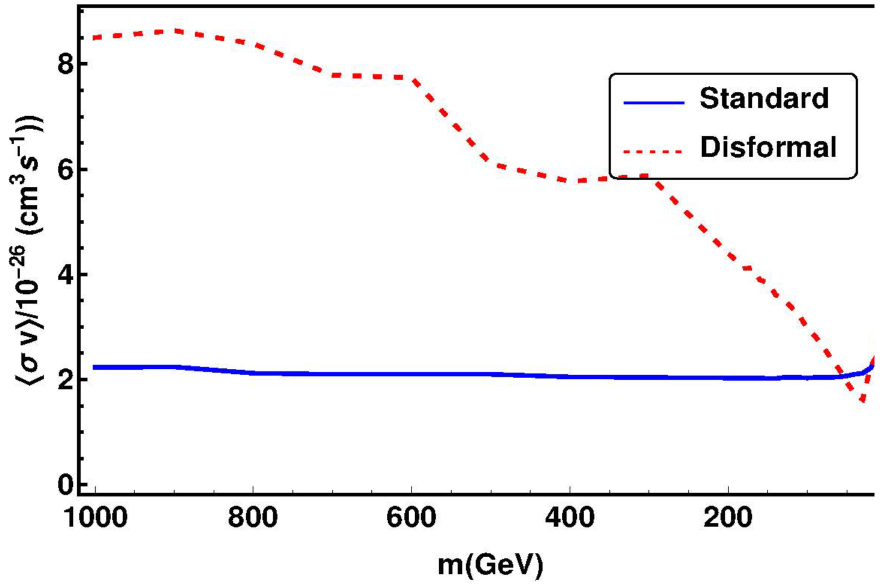
$$\gamma^{-2} = 1 - \frac{D}{C}H^2\varphi'^2.$$

Disformal Case: D≠ 0

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







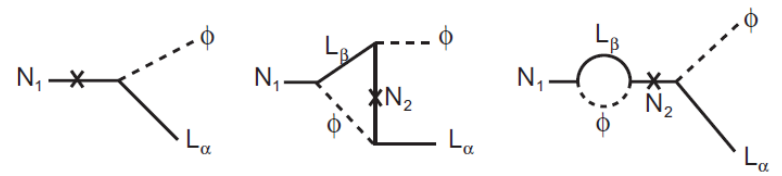
Dutta, Jimenez, Zavala, Phys.Rev.D 96 (2017) 10, 103506

Visible matter

Leptogenesis: Lepton number asymmetry
➔Baryon asymmetry via B+L violating sphaleron process

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

$$\epsilon_1 \equiv \frac{\Gamma(N_1 \to \phi L) - \Gamma(N_1 \to \phi^\dagger \bar{L})}{\Gamma(N_1 \to \phi L) + \Gamma(N_1 \to \phi^\dagger \bar{L})}.$$



N_1 mass

10^{-3} ev^2

$$\mathcal{L} = h^*_\beta(\bar{L}_\beta \phi^{c*})E_\beta - \lambda^*_{\alpha k}(\bar{L}_\alpha \phi^*)N_k - \frac{1}{2}\bar{N}_j M_j N^c_j + \text{h.c.},$$

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

Lightest and heaviest neutrino masses

v: weak scale

Davidson, Ibarra, '02

$$Y_{\Delta B} \sim \frac{1}{3}\epsilon_1 Y^{eq,0}_{N_1}\eta$$

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

Visible matter

However, one can lower v (model dependent)=➔ lower the value of M_1

However, lower M_1➔Leptogenesis happens at a lower temperature (H is smaller)
➔Washout processes ($\Delta L=2$) reach thermal equilibrium

Way out: Higher expansion rate ➔ Washout processes do not attain equilibrium

non-standard scenario

$$\Gamma(YZ \leftrightarrow \bar{Y}\bar{Z}) \lesssim \tilde{H}(T)\big|_{T\sim M_X}$$

X decays into Y, Z for leptogenesis

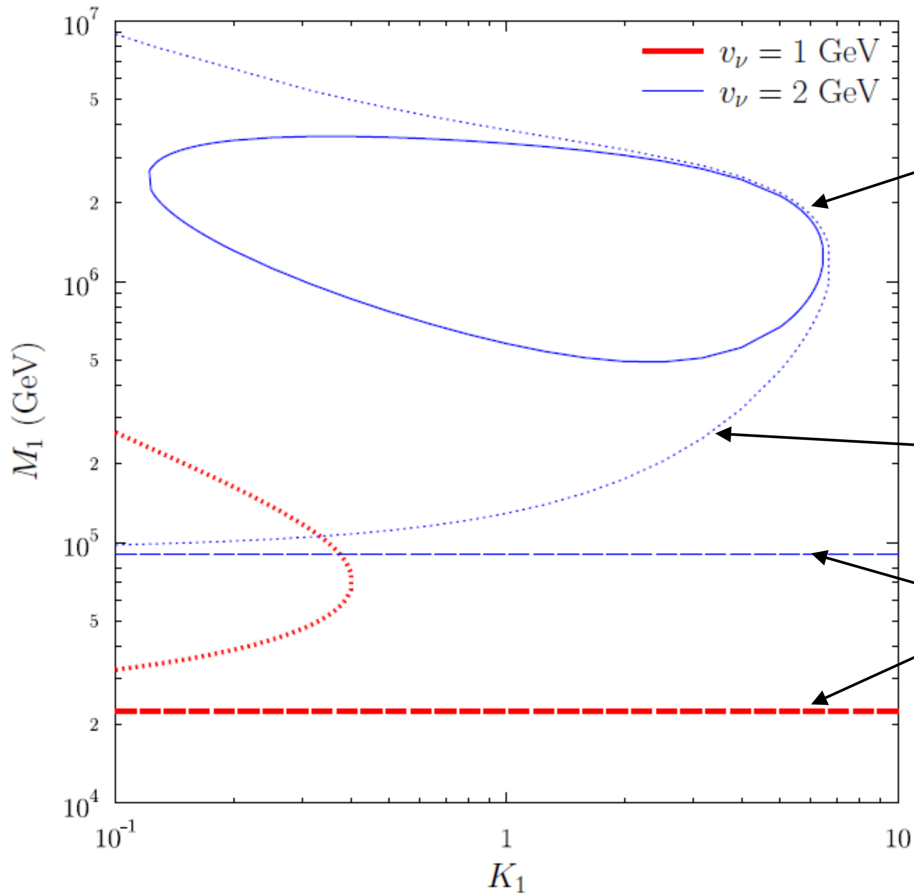
The higher expansion rate make it easier for the washout to be satisfied

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 Leptogensis➔ easy to probe at colliders

Visible matter

$$m_\nu \simeq \lambda^T \frac{v_\nu^2}{M} \lambda$$



Zero initial abundance for N_1

Thermal initial abundance for N_1

No-washout, thermal abundance

$$K_1 = \left.\frac{\Gamma_{N1}}{H}\right|_{T=M_1}$$

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: $10^{15\text{-}17}$ gm

Hawking Radiation

Black holes emit Hawking radiation with the temperature:

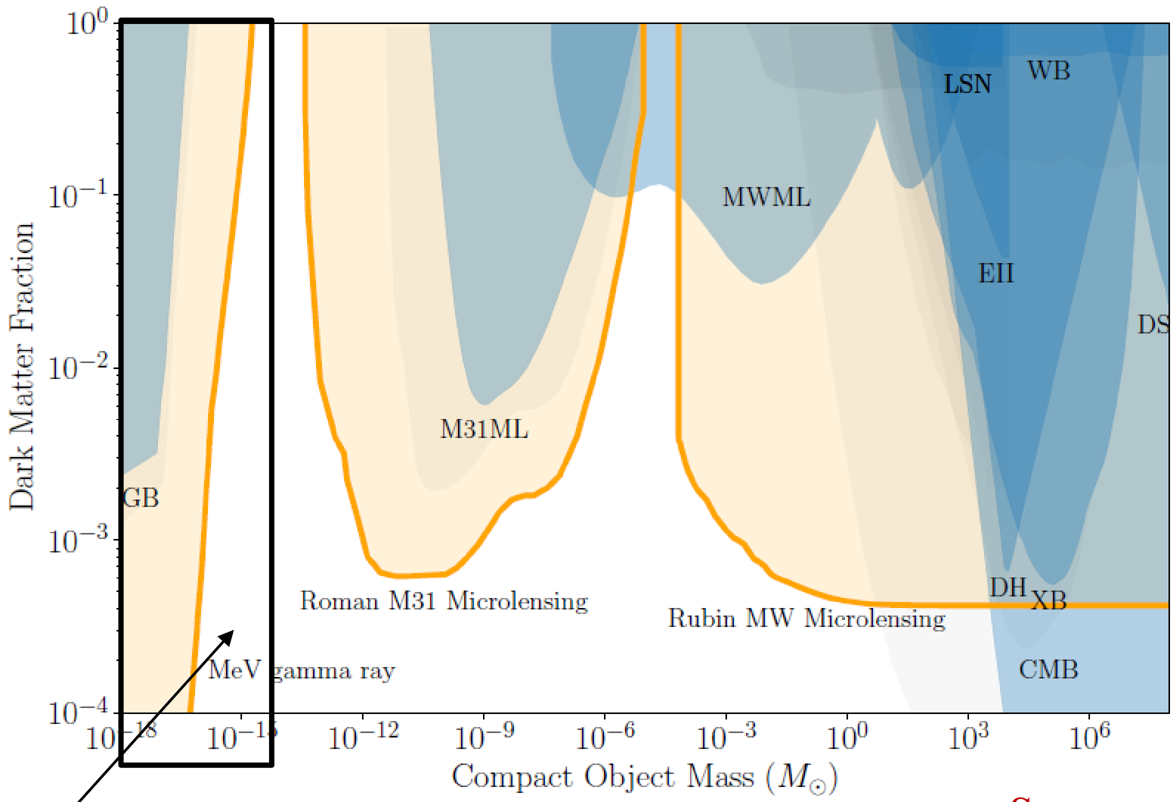
$$T_{PBH} = \frac{1}{8\pi G M_{PBH}} \sim 1\ \mathrm{MeV}\left(\frac{10^{16}\mathrm{g}}{M_{PBH}}\right)$$

Evaporation rate:

$$t_{\rm evap} \simeq 4 \times 10^{-4}\mathrm{s} \times \left(\frac{m_{\rm BH}}{10^{8}\ \mathrm{g}}\right)^{3}$$

- **Asteroid- size PBH emits ~ 1- 10^3 MeV gamma-ray**
- **AMEGO, e-ASTROGAM are sensitive**

PBH constraint

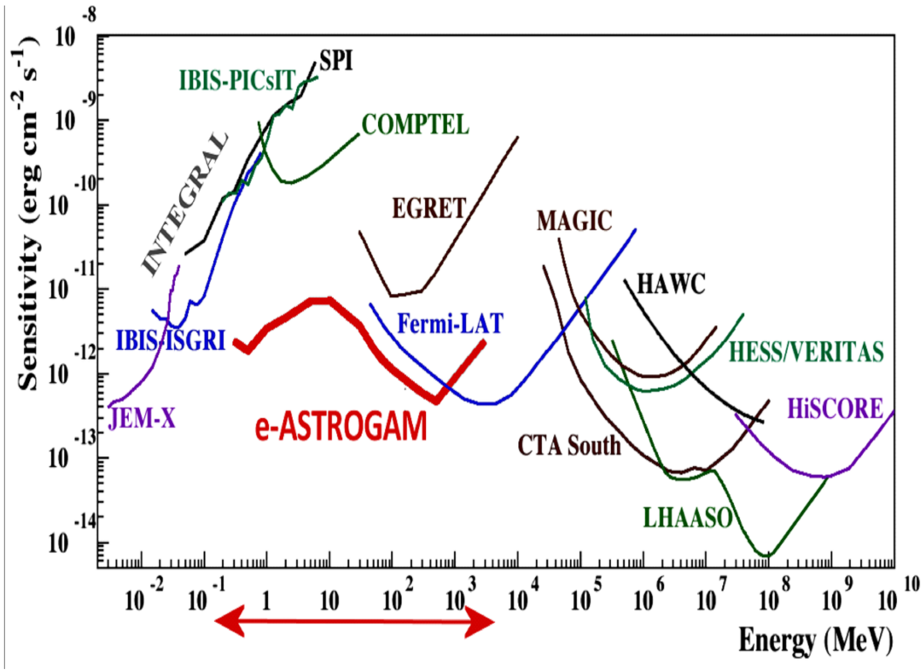


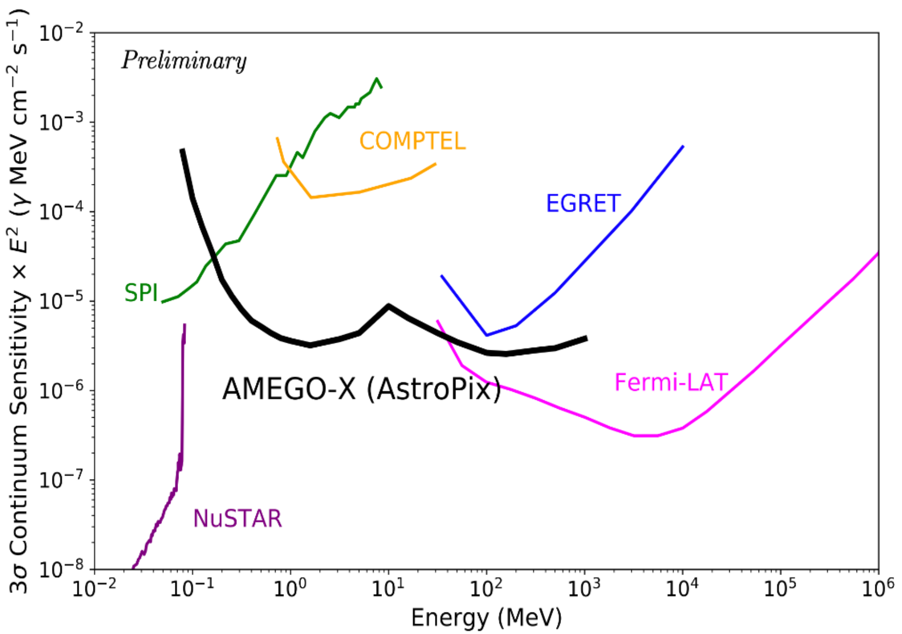
We use this region

Snowmass white paper on PBH: 2203.08967

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

Hawking Radiation





- **O(1-100) MeV region is not well constrained: MeV gap**

K. Boddy, J. Kumar, *Phys.Rev.D* 92 (2015) 2, 023533

PBH formation

PBH can be formed from the development of inhomogeneities: Overdense regions stops 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:

inflaton potentials, e.g., J. Garcia-Bellido, A. Linde, and D. Wands, Phys. Rev. D 54 (1996) 6040, J. Yokoyama,Astron. Astrophys.318 (1997) 673

bubble wall collisions during strong phase transitions, S. Hawking, I. Moss, and J. Stewart, Phys. Rev. D 26 (Nov, 1982) 2681{2693.

the dynamics of scalar condensates, E. Cotner and A. Kusenko," Phys. Rev. D 96 no. 10, (2017) 103002,

the collapse of topological defects etc S. W. Hawking, Phys. Lett. B 231 (1989) 237

Gravitational Wave

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

Energy density of the gravity wave:

Kohri, Terada, PRD97 (2018) 12, 123532
K. Inomata, T. Nakama,
Phys.Rev.D 99 (2019) 4, 043511

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

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

Power spectrum

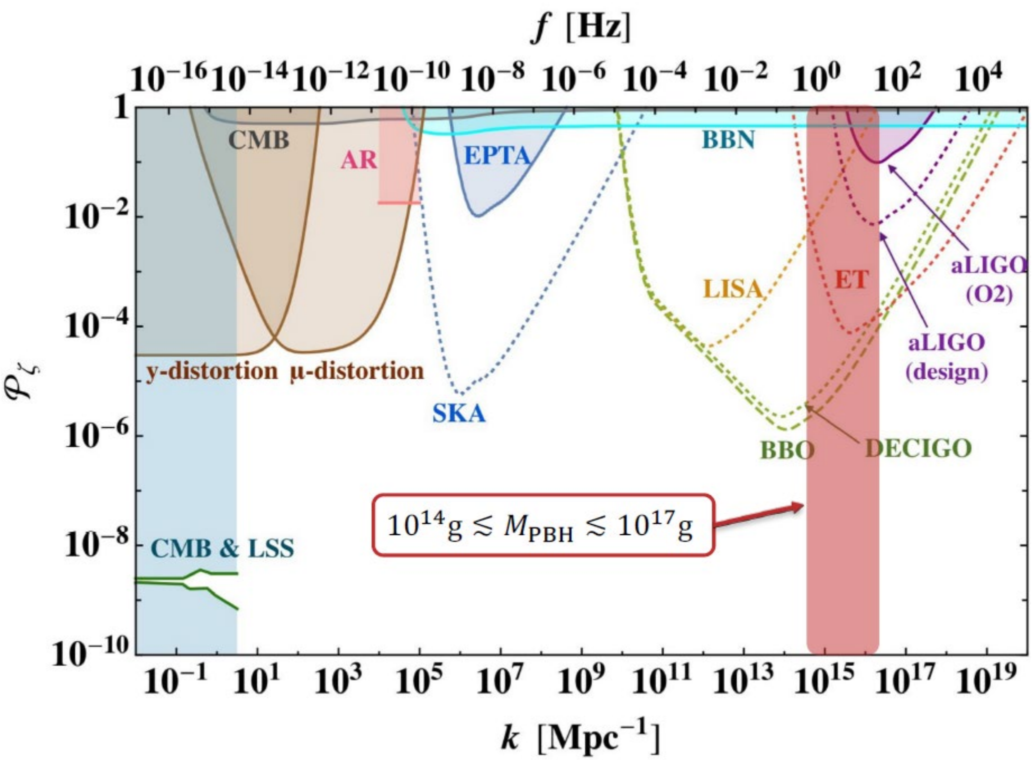
Curvature perturbation

P_h: power spectrum tensor perturbations

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

Power Spectrum: P_ζ

Limits on the power spectrum: existing and expected



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

$$\frac{M_{\text{PBH}}}{M_\odot} = 1.13 \times 10^{15} \left(\frac{\gamma}{0.2}\right)\left(\frac{g_*}{106.75}\right)^{-1/6}\left(\frac{k_{\text{PBH}}}{k_*}\right)^{-2}$$

κ_* CMB Pivot scale: 0.05 Mpc^{-1}

Mishra, Sahani, JCAP04(2020)007

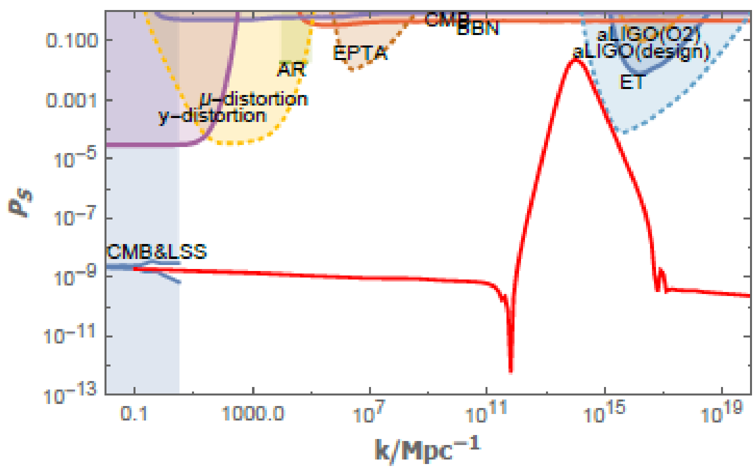
$$f_{GW} \sim 1\ \text{Hz}\left(\frac{10^{15}\text{Mpc}^{-1}}{k_p}\right)^{-1}$$

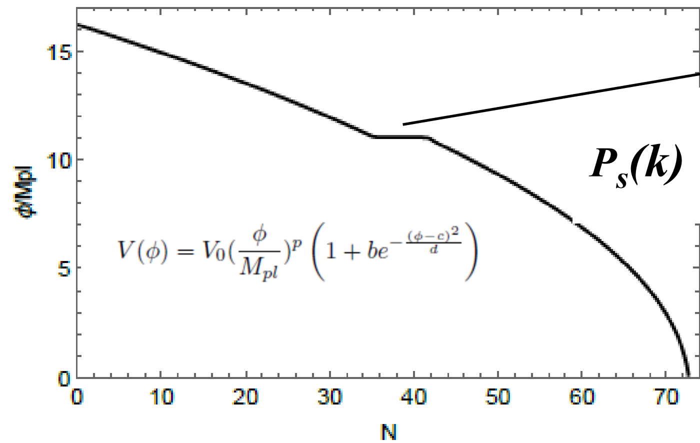
Larger k values are not constrained

K. Inomata, T. Nakama, Phys.Rev.D 99 (2019) 4, 043511

Origin of P_ζ

For example:





$\dot{\varphi} \sim 0$

$P_s(k) \sim \left(\frac{H^2}{\dot{\phi}}\right)^2_{aH=k}$

Zheng, Shi, Qiu, 2106.04303

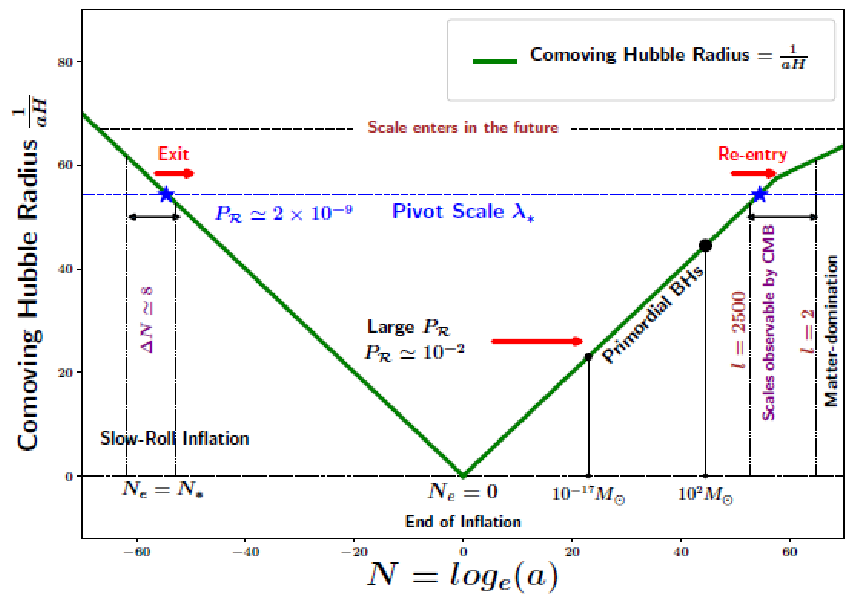
Running mass inflation model

Enhanced symmetry point

Inflection point

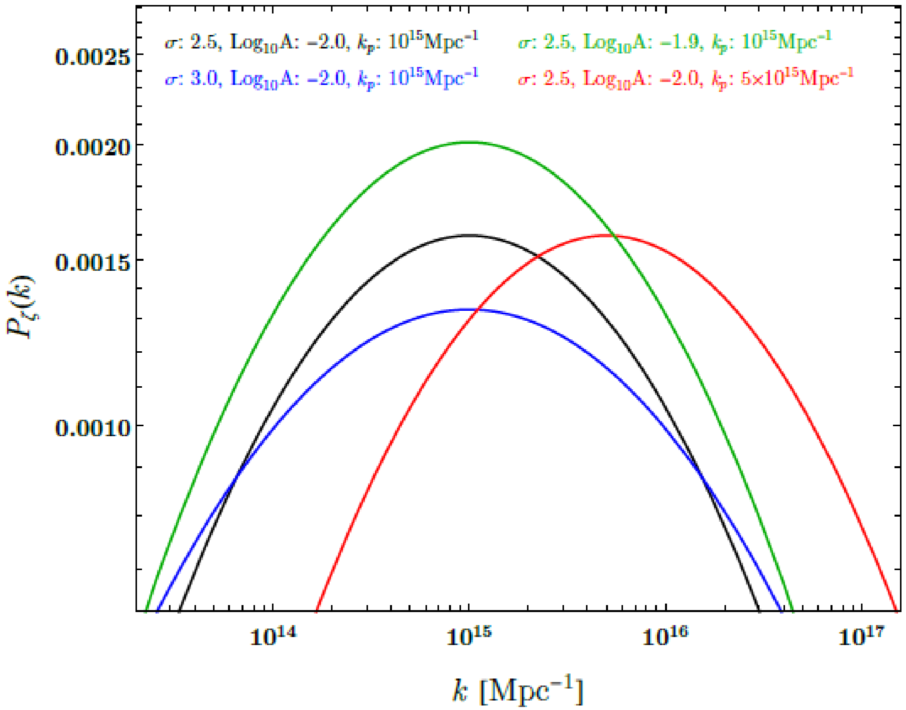
etc.

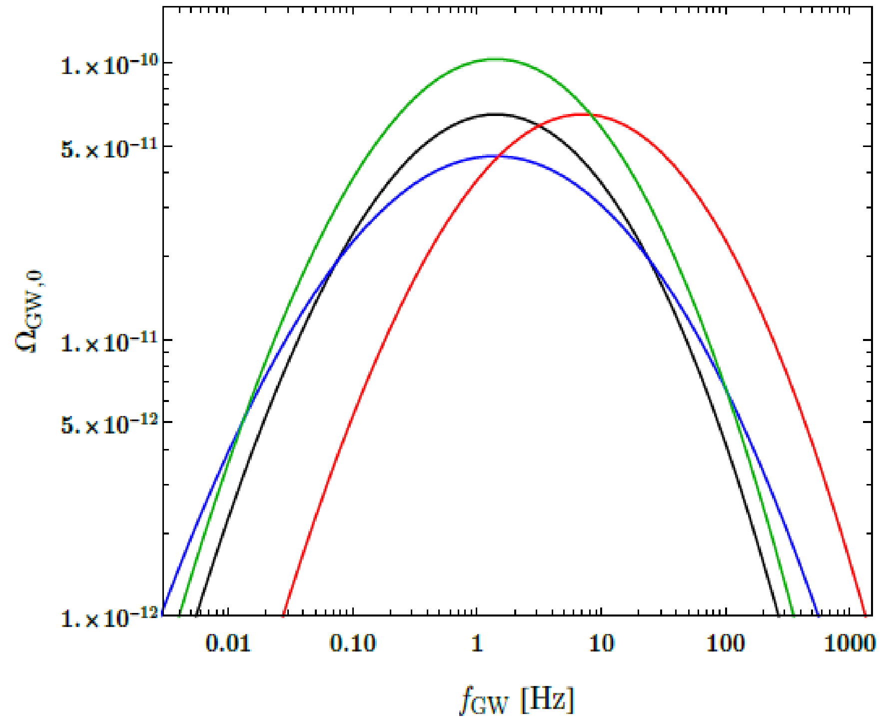
M. Sasaki, T. Suyama, T. Tanaka, S. Yokoyama, Class.Quant.Grav. 35 (2018) 6, 063001



Mishra, Sahani, JCAP04(2020)007

P_ζ and Ω_{GW}





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 **Pi, Sasaki, JCAP 09 (2020) 037**

Ω_{GW} peak location does not depend on k_p, frequency depends on k_p ➔ different GW detectors come into play

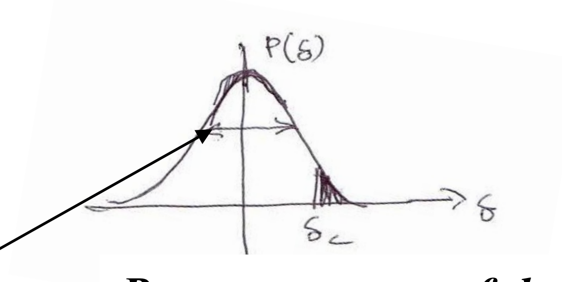
Also, one can use δ- function : $$P_{\zeta,\delta}(k) = A_\delta\,\delta\left(\log\left(\frac{k}{k_{p,\delta}}\right)\right)$$

PBH: ρ_{PBH}, γ ray and P_ζ

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

W. Press and P. Schechter, Astrophys. J. 187 (1974)
J. Kozaczuk, T. Lin, and E. Villarama, 2108.12475

density contrast: $\delta \equiv \dfrac{(\rho - \bar{\rho})}{\rho}$



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

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

Power spectrum of the density fluctuation:

$$\mathcal{P}_\delta(k) = \frac{16}{81}\left(\frac{k}{aH}\right)^4 \mathcal{P}_\zeta(k)$$

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

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

$$\beta_R \equiv \frac{\rho_{\mathrm{BH},R}}{\rho_{r,R}}$$

β_R is the fraction of energy density in the BH formed with horizon size R

PBH ρ_{PBH}, γ ray and P_ζ

Black hole mass with a given density contrast due to critical collapse

$$m(R,\delta) = M_H(R) K (\delta - \delta_c)^\gamma \,.$$

M. W. Choptuik, Phys. Rev. Lett, 70 (1993)9
J. C. Niemeyer and K. Jedamzik, Phys. Rev. Lett, 80(1998)5481

- **The mass of a PBH depends on the amplitude of the fluctuation from which it forms**
- **Constants γ and K depend on the shape of the perturbation and the background equation of state**

Numerical simulation: **K, δ_c, γ: 10, 0.25, 0.36**

S. Young, M. Musso, JCAP 11 (2020) 022,

$$\frac{\mathrm{d}\beta_R}{\mathrm{d}\delta} = \frac{2m(R,\delta)}{M_H(R)} p(\delta)\,, \quad \delta \geq \delta_c \,.$$

PBH : γ ray and P_ζ

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

At matter radiation equality:

$$\frac{\mathrm{d}\beta_{\mathrm{eq}}}{\mathrm{d}m} = \int_0^\infty \frac{\mathrm{d}R}{R}\frac{R_{\mathrm{eq}}}{R}\left(2\frac{g_{\star s,\mathrm{eq}}^{4/3}}{g_{\star s,R}^{4/3}}\frac{g_{\star,R}}{g_{\star,\mathrm{eq}}}\right)^{1/2}\beta_R \,.$$

The mass fraction at the matter radiation equality:

$$\frac{\mathrm{d}f_{\mathrm{BH,eq}}}{\mathrm{d}m} = \frac{\mathrm{d}}{\mathrm{d}m}\left(\frac{\rho_{\mathrm{BH,eq}}}{\rho_{\mathrm{CDM,eq}}}\right) = \frac{\Omega_m}{\Omega_{\mathrm{CDM}}}\frac{\mathrm{d}\beta_{\mathrm{eq}}}{\mathrm{d}m}\,,$$

The peak can be obtained as: $m^{\mathrm{peak}} = \gamma_{\mathrm{eff}} M_H(R=k_p^{-1}) \simeq 2\times10^{16}\ \mathrm{g}\times\gamma_{\mathrm{eff}}\left(\frac{k_p}{10^{15}\ \mathrm{Mpc}^{-1}}\right)^{-2}$

$$\frac{\partial N_{\gamma,\mathrm{tot}}}{\partial E_\gamma \partial t} = \frac{\partial N_{\gamma,\mathrm{primary}}}{\partial E_\gamma \partial t} + \sum_{i=e^\pm,\mu^\pm,\pi^\pm}\int dE_i \frac{\partial N_{i,\mathrm{primary}}}{\partial E_i \partial t}\frac{dN_{i,\mathrm{FSR}}}{dE_\gamma} + \sum_{i=\pi^0}\int dE_i 2\frac{\partial N_{i,\mathrm{primary}}}{\partial E_i \partial t}\frac{dN_{i,\mathrm{decay}}}{dE_\gamma}\,,$$

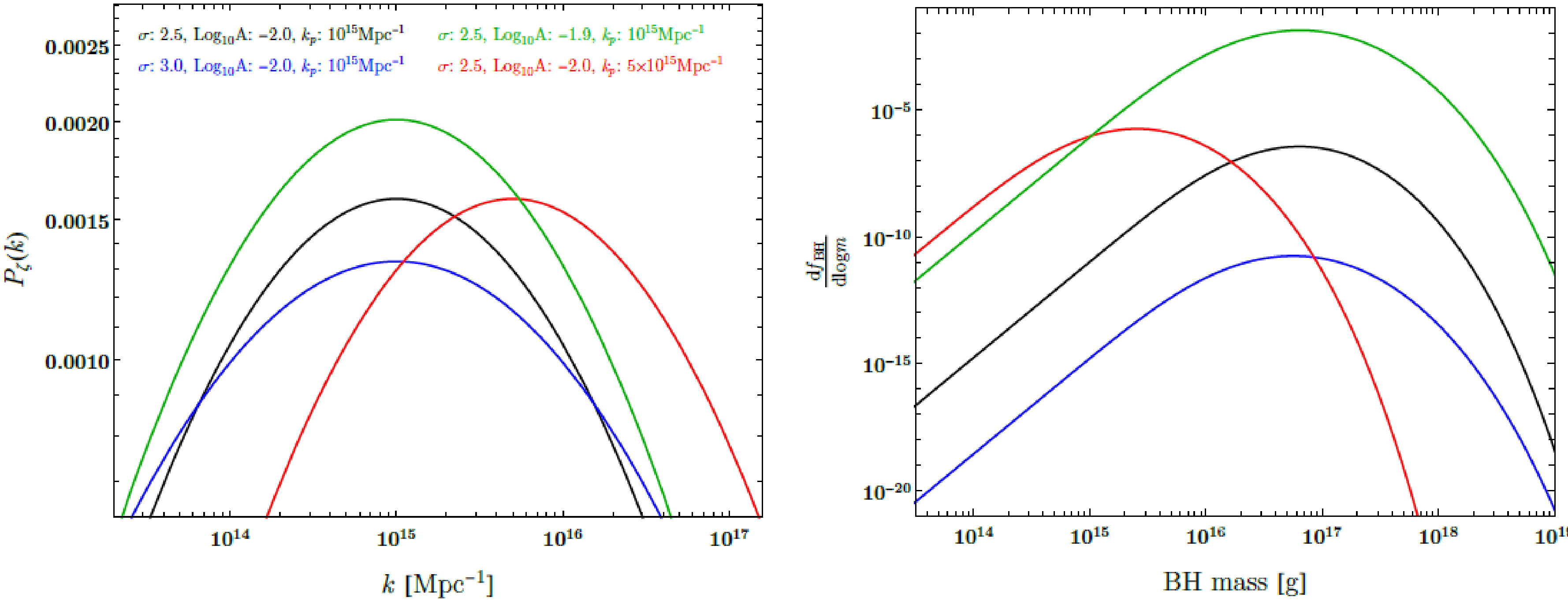
Observed γ-ray flux from all PBH

$$\frac{\partial N_{i,\mathrm{primary}}}{\partial E_i \partial t} = \frac{g_i}{2\pi}\frac{\Gamma_i(E_i,m,m_i)}{e^{E_i/T_{\mathrm{BH}}}\pm 1}\,.$$

$$\frac{\partial \Phi_\gamma}{\partial E_\gamma} = \bar{J}_D\frac{\Delta\Omega}{4\pi}\int d\log m \frac{df_{\mathrm{BH}}}{d\log m}\frac{\partial N_{\gamma,tot}}{\partial E_\gamma \partial t}\,.$$

ρ_{PBH} and P_ζ

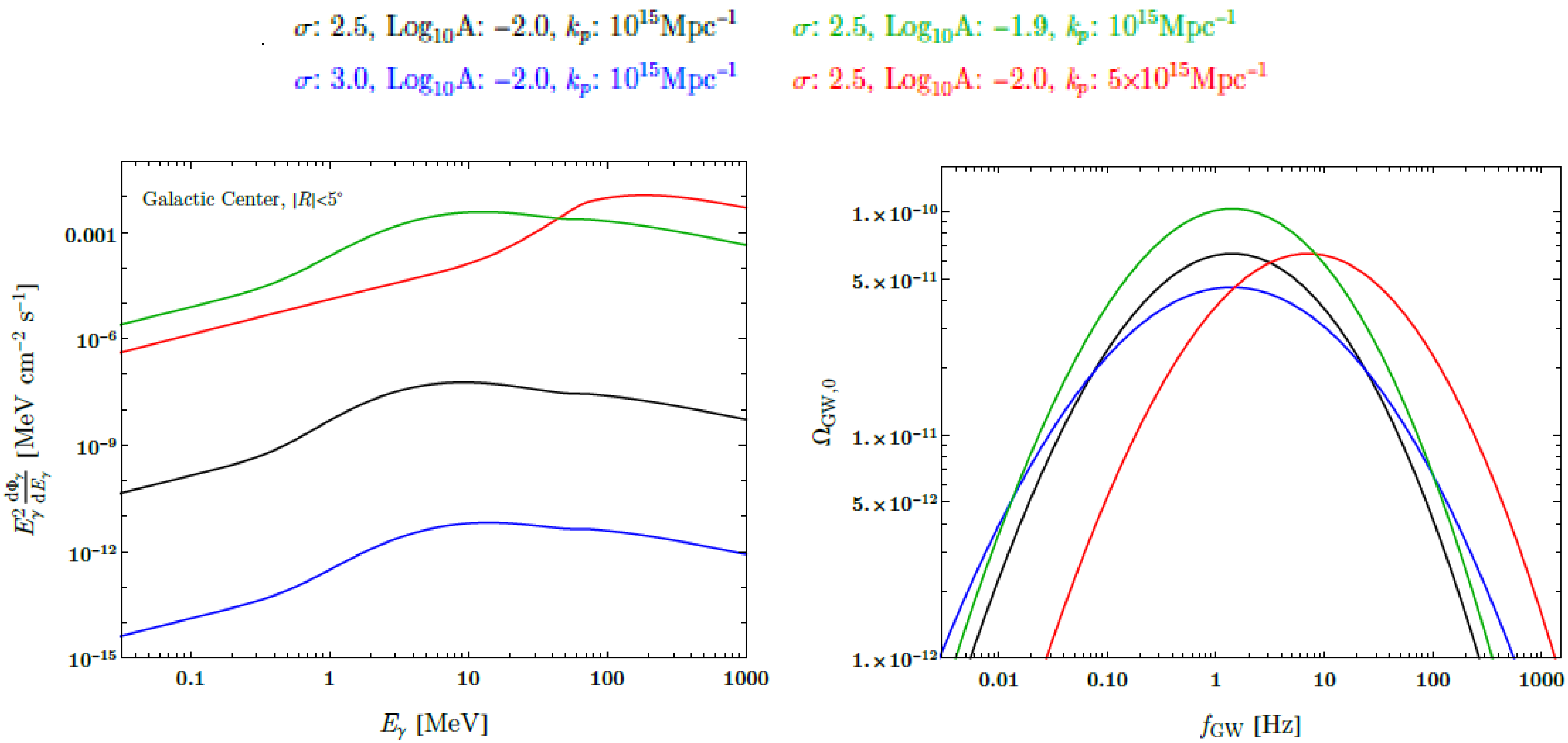
$$\frac{\mathrm{d}f_{\mathrm{BH}}}{\mathrm{d}m}, \quad f_{\mathrm{BH}} \equiv \frac{\Omega_{\mathrm{BH}}}{\Omega_{\mathrm{CDM}}}$$



Larger k_p ➔ smaller black hole mass ➔ 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 : γ ray and P_ζ



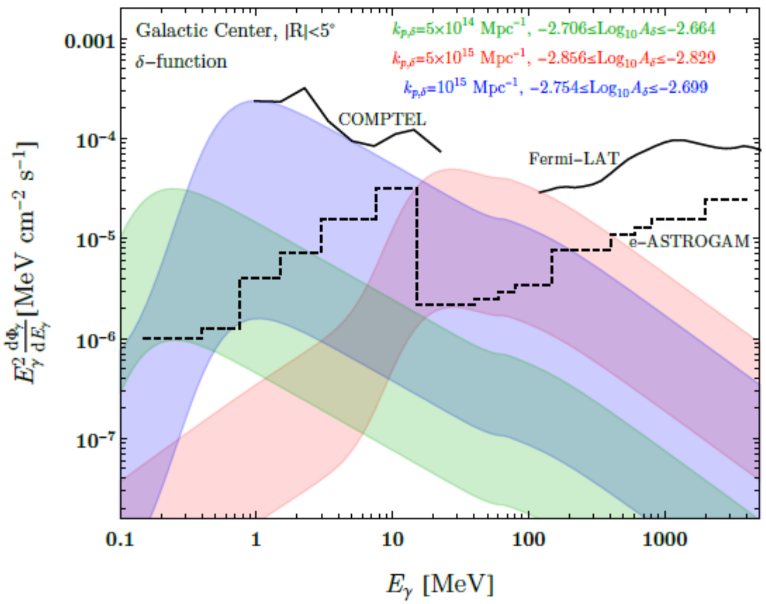
$$E_\gamma^{\rm peak} \approx 10\,T_{\rm BH}(m^{\rm peak}) \approx 1\,{\rm MeV}\left(\frac{5}{\gamma_{\rm eff}}\right)\left(\frac{k_p}{10^{15}\ {\rm Mpc}^{-1}}\right)^2$$

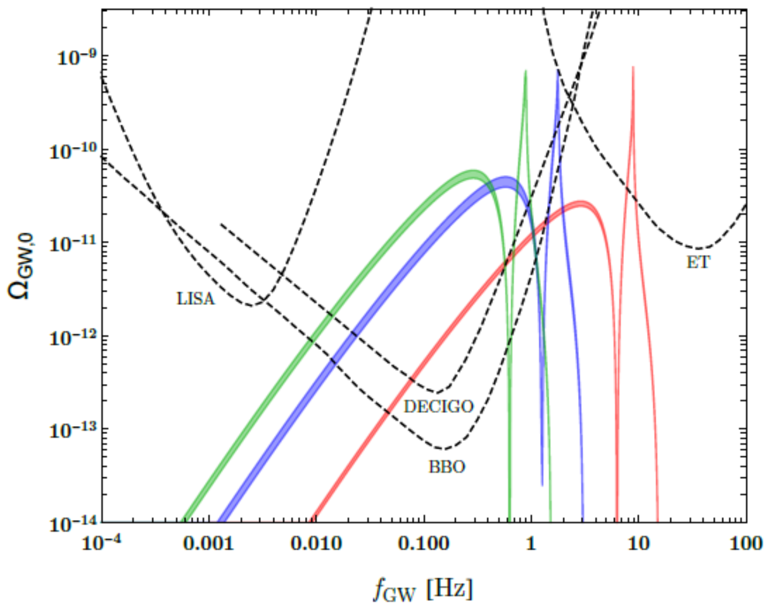
γ–ray flux increases as A and k_p increase and σ decreases

Ω_{GW} peak location does not depend on k_p, frequency depends on k_p

γ, Ω_{GW} and P_ζ

$$P_{\zeta,\delta}(k) = A_\delta\,\delta\left(\log\left(\frac{k}{k_{p,\delta}}\right)\right)$$





Upper bound for A : Existing bounds on γ-ray and $f_{BH} \leq 1$

-

Lower bound for A : Above e-Astrogam Sensitivity

Agashe, Chang, Clark, Dutta, Tsai, Xu, Phys.Rev.D 105 (2022) 12, 123009

Big Picture

S. Young, M. Musso,
JCAP 11 (2020) 022,
Snowmass, 2203.08967

, Lin, Villarama
67

Asteroid-Mass Primordial Black Hole ← **Small-Scale Curvature Perturbations**

BlackHawk: A.Arbey, J. Auffinger, Eur.Phys.J.C 81 (2021) 10

Kohri, Terada, PRD97 (2018) 12, 123532, K. Inomata, T. Nakama, Phys.Rev.D 99 (2019) 4, 043511

Gamma-ray Signals (Hawking Radiation)

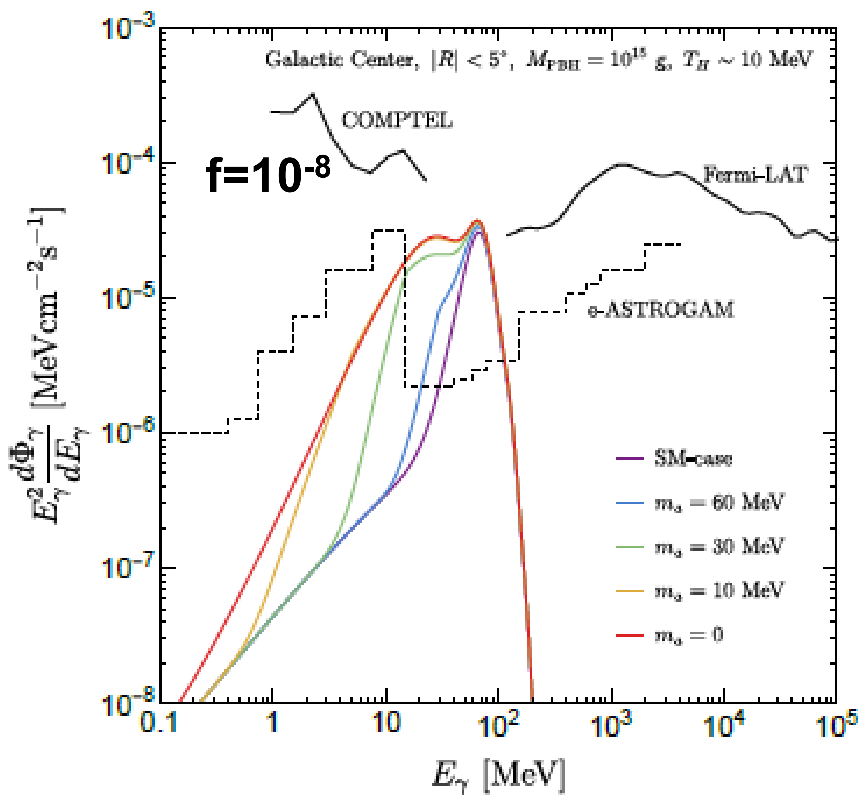
Gravitational Waves Signals

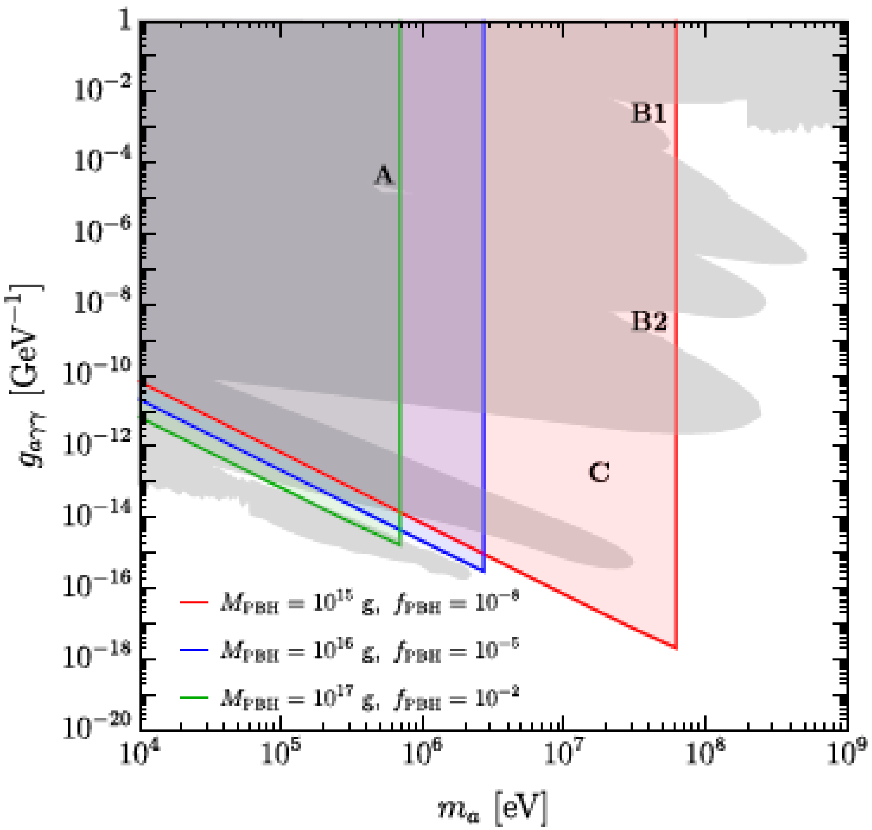
Correlation

PBH with dark sector particles

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

For example, axions from Hawking radiation



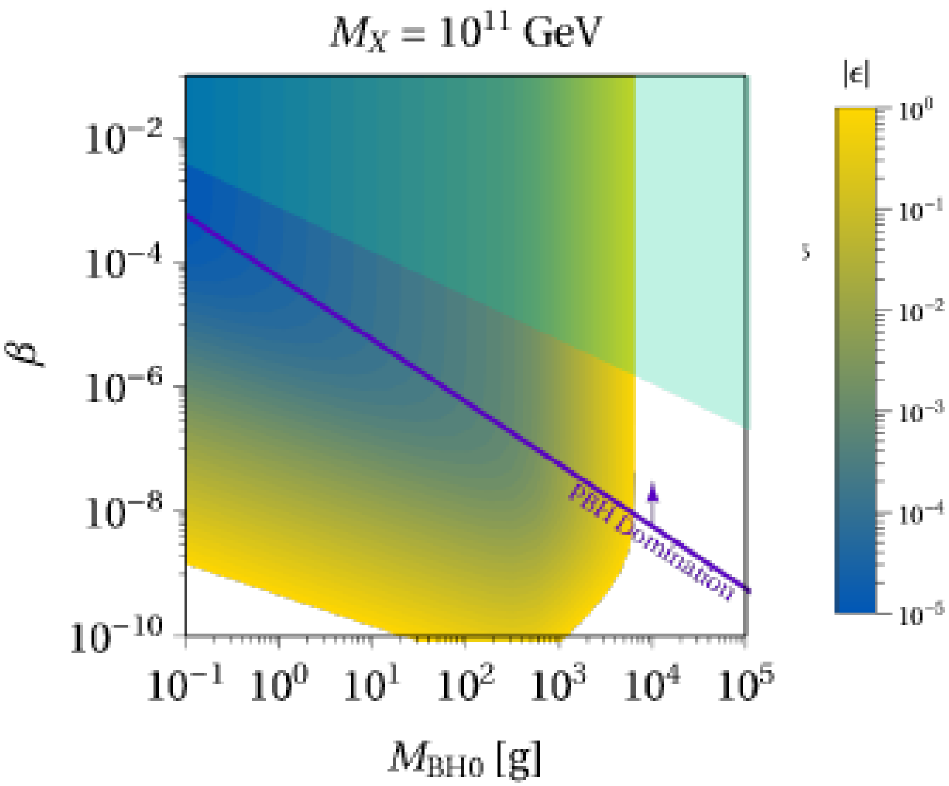


Agashe, Chang, Clark, Dutta, Tsai, Xu, Phys.Rev.D 108 (2023) 2, 023014

Baryo/leptogenesis with PBH

Baryogenesis and Leptogenesis are possible with PBH

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



Particle production

$$Y_X \equiv \frac{3\beta T_0 N_X}{4M_{\rm BH0}} \frac{s(T_{\rm ev})}{s(\tilde{T})} = \frac{3\beta T_0 N_X}{4M_{\rm BH0}} \left(1 + \beta \frac{T_0}{T_{\rm ev}}\right)^{-3/4}.$$

T_0: PBH formation temp,
Nx: nos. of X particles,
T_{ev}: evaporation temp.,
$\widetilde{T}$: plasma temp after evaporation

$$Y_B^{\rm max} = \frac{30}{97} Y_{B-L}^{\rm max} = \frac{30}{97} \epsilon Y_X,$$

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**