Non-thermal WIMPy baryogenesis from early matter-dominated epoch

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Based on

arXiv: 2309.16122 (Prof. Ki-Young Choi, Erdenebulgan Lkhagvadorj)

Suite hotel, Jeju

2023. 11. 13

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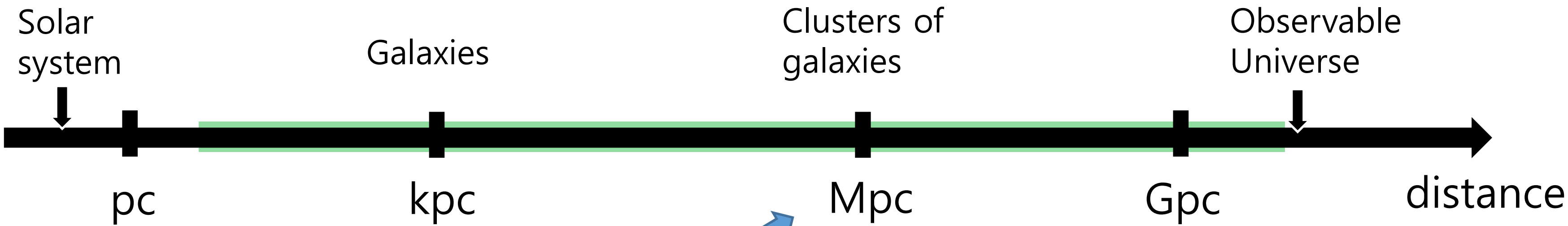
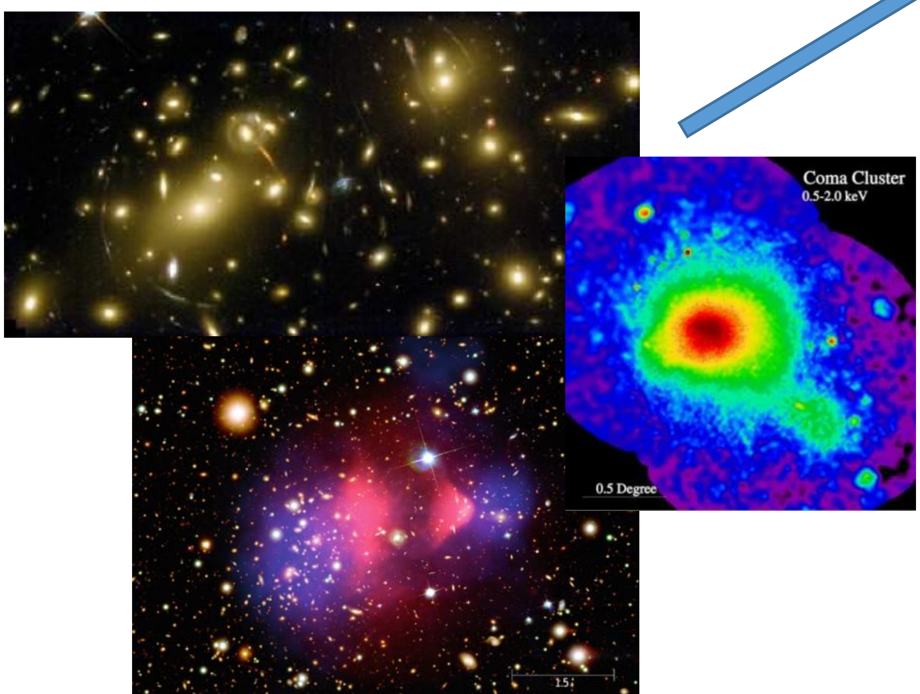
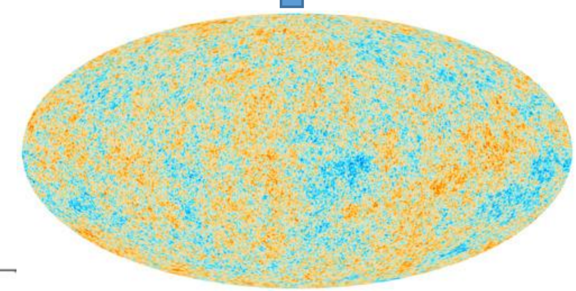
  - Dark Matter
  - Baryon Asymmetric Universe
- Thermal WIMPy baryogenesis
- Non-thermal WIMPy baryongenesis by early matter-dominated epoch
  - Primordial Black Hole
- Conclusions

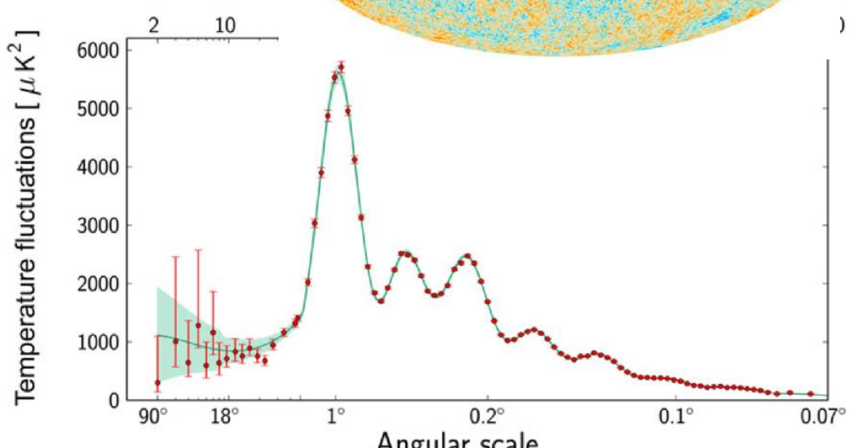
Evidences – Dark Matter

- There are undeniable evidences for dark matter in a wide range of distance scales

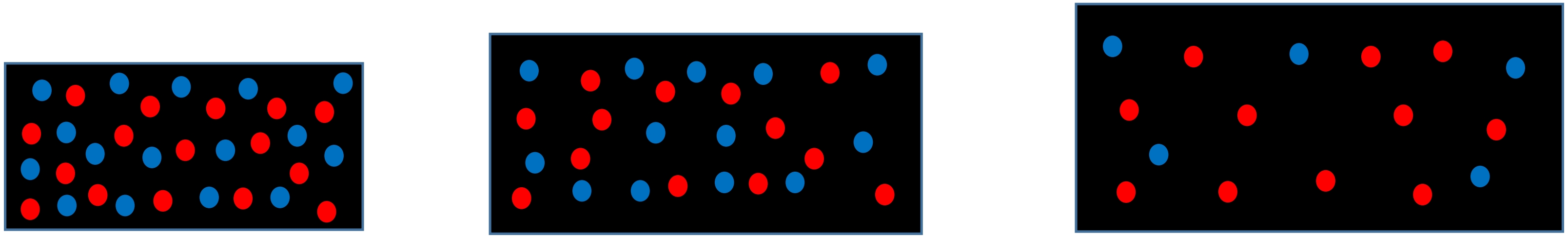






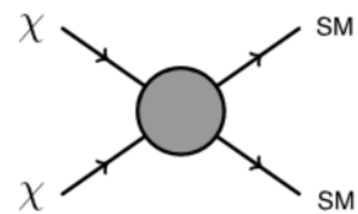


Thermal freeze-out DM production



$T \gg M_{DM}$ $T \approx M_{DM}$ $T \ll M_{DM}$

- ● : Dark Matter
- ● : Standard Model



- Dark matter population in an expanding Universe
  - **Dark matter particles can no longer annihilate**
  - **The number of dark matter particles "freeze-out"**
- Standard calculation for WIMP DM relic density
  - The Boltzmann equation $\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle \left(n_\chi^2 - n_{\rm eq}^2\right)$
- Relic density: $\Omega h^2 = 0.12 \ \rightarrow \langle\sigma v\rangle \sim 10^{-9}\text{GeV}^{-2}, x_f \equiv \frac{m_\chi}{T} \approx 25$

BBN and CMB for baryon density

- The comparison between the observed light element abundances and the theoretical calculation show that the baryon-to-photon ratio is

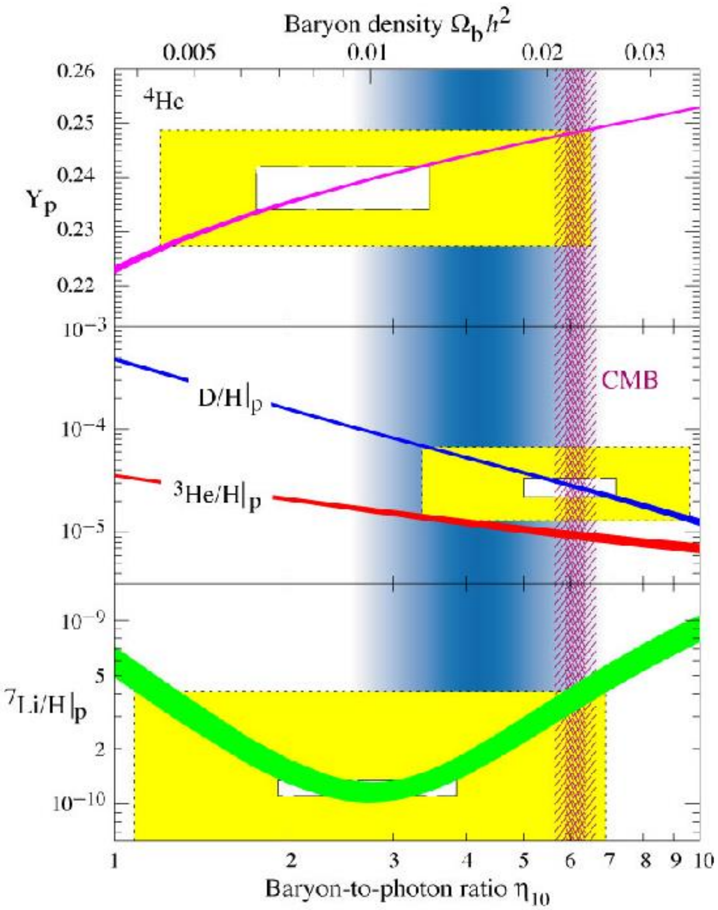
$$\eta_{10} = \frac{n_b}{n_\gamma} \times 10^{10} \sim 6$$

- Baryon energy density in the Universe

$$\rho_b = 4 \times 10^{-31}\, g/cm^3$$

- Corresponds to the baryon density

$$\Omega_b\, h^2 \simeq 0.02$$



Evolution of Baryon Density

- The Universe was extremely hot in the beginning. All particles and antiparticles enter thermal equilibrium. As the temperature cools down, most of particles and antiparticles are annihilated away

- T >> 100MeV
  - The quarks are in the state of plasma and quark and antiquark coexist in the thermal equilibrium
  - The difference between them give the Baryon asymmetry

- T << 100MeV
  - During the QCD phase transition, the anti-quarks annihilate and the difference only remains and result in the present baryons

Sakharov conditions

Sakharov, 1967

- Sakharov proposed three conditions

- Baryon number violation
  - A violation of baryon number
  - Interaction terms have B number violation

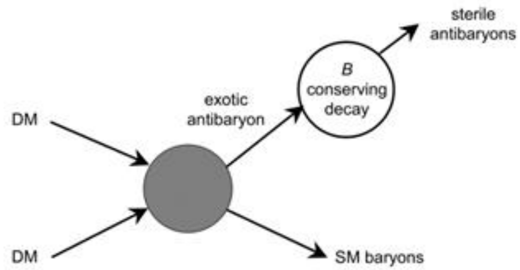
- C & CP violation
  - Bias the production of matter over antimatter
  - Interference term between tree level and one-loop level

- Departure from thermal equilibrium
  - Baryon-violating interaction goes out of thermal equilibrium

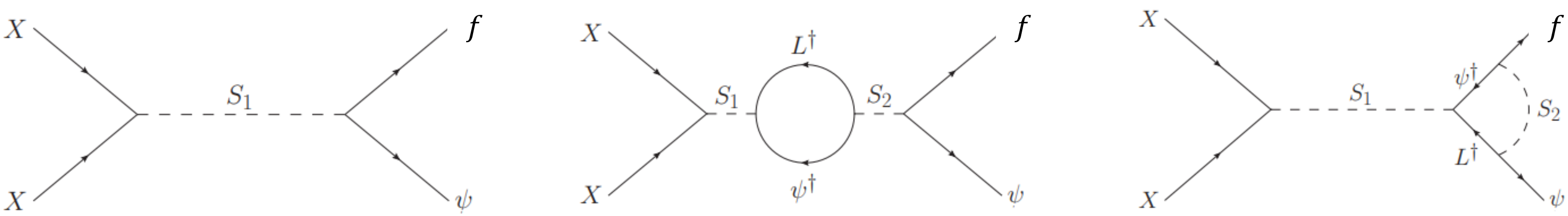
WIMPy baryogenesis

Cui et al, 2012

- DM relic density is obtained as usual in WIMP paradigm



ψ: exotic baryon



$$\frac{dY_{\Delta B}}{dx} = \frac{\epsilon\, s(x)}{x\, H(x)} \langle \sigma_{\rm ann} v \rangle \left[Y_X^2 - (Y_X^{\rm eq})^2 \right] - \frac{s(x)}{x\, H(x)} \langle \sigma_{\rm washout} v \rangle \frac{Y_{\Delta B}}{2Y_\gamma} \prod_i Y_i^{\rm eq}.$$

- DM annihilation generates more baryons during thermal freeze-out
- Simultaneously solve the observed baryon asymmetry and the Dark Matter relic abundance

$$\epsilon = \frac{\sigma_B(\chi\chi \to \cdots) - \sigma_B(\bar{\chi}\bar{\chi} \to \cdots)}{\sigma_B(\chi\chi \to \cdots) + \sigma_B(\bar{\chi}\bar{\chi} \to \cdots)}.$$

Wash-out process

Cui et al, 2012

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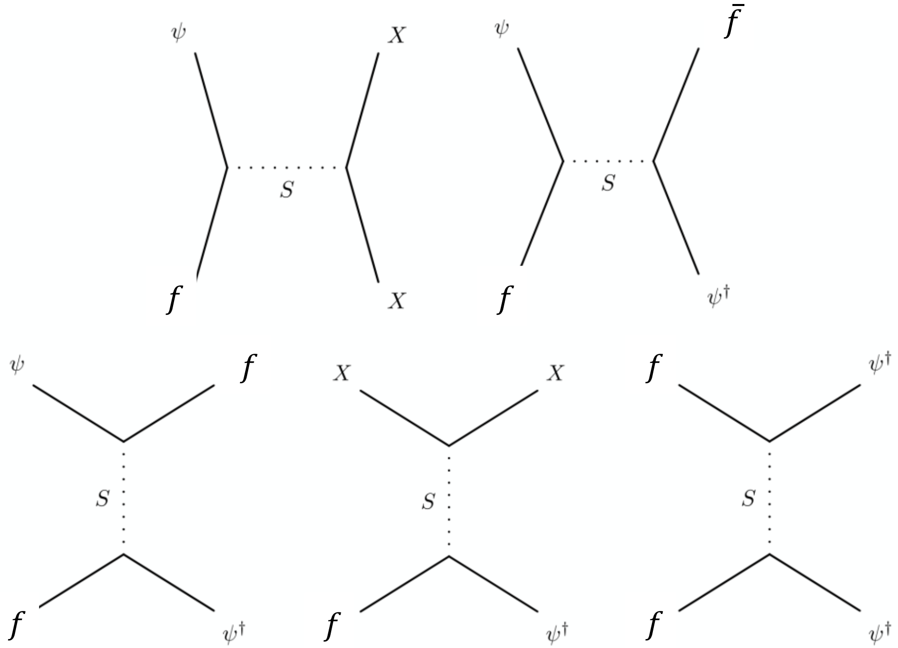

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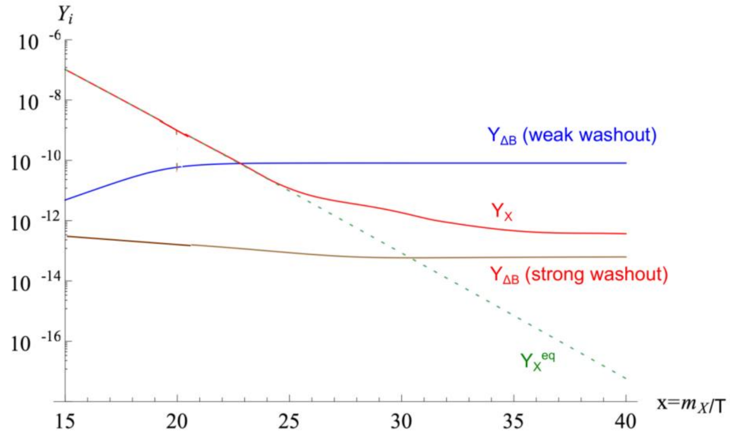
$$\frac{dY_{\Delta B}}{dx} = \frac{\epsilon\, s(x)}{x\, H(x)} \langle \sigma_{\rm ann} v\rangle \left[Y_X^2 - (Y_X^{\rm eq})^2\right] - \frac{s(x)}{x\, H(x)} \langle \sigma_{\rm washout} v\rangle \frac{Y_{\Delta B}}{2Y_\gamma} \prod_i Y_i^{\rm eq}.$$

- **If washout processes freeze out before WIMP freeze-out**, then a large baryon asymmetry may accumulate, and its final value is proportional to the WIMP abundance at the time that washout becomes inefficient

WIMPy baryogenesis

Cui et al, 2012

- Evolution of the comoving density of Dark Matter & baryon number asymmetry
  - Dark Matter freeze-out → baryon asymmetry freeze out



- **Strong washout**
  - Mass relation: $m_\psi < m_\chi$
  - washout becomes effective too small

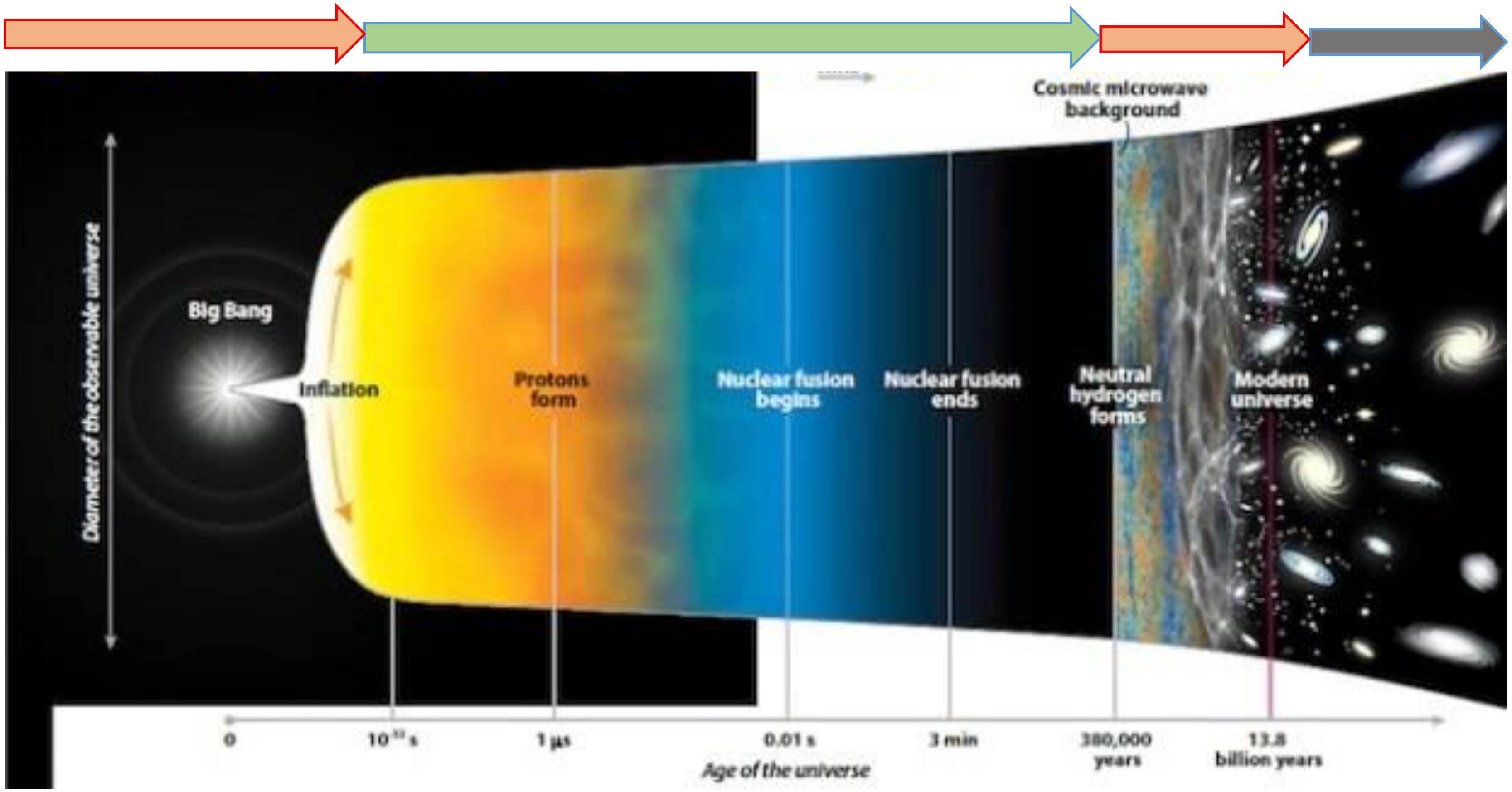
- **Weak washout**
  - Mass relation: $m_\chi < m_\psi < 2m_\chi$
  - washout freezes out well before DM freeze-out

- Baryon asymmetry accumulated

$$Y_{\Delta B}(\infty) \approx \frac{\epsilon}{2} Y_X(x_{\text{washout}}) < \frac{\epsilon}{2} Y_X^{\text{eq}}(15) \approx \epsilon \times 10^{-8}$$

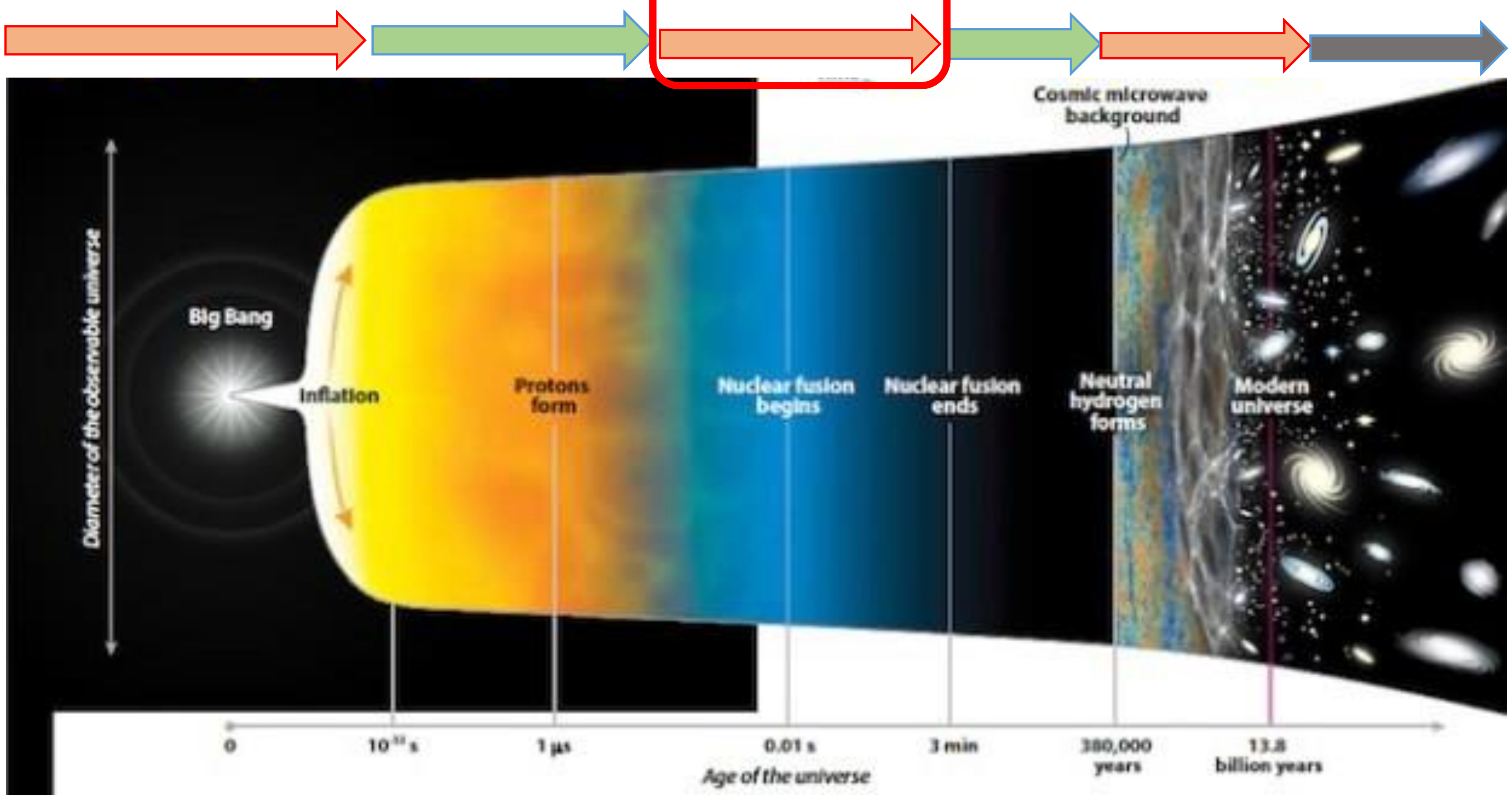
Standard cosmology

- MD RD MD Λ



Non-standard cosmology

- MD RD MD RD MD Λ



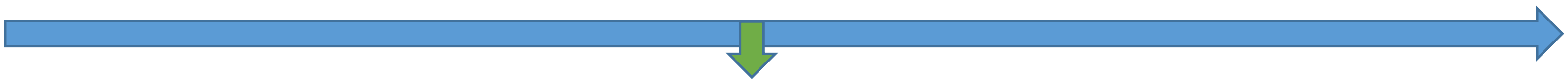
Early matter domination

- Reheating temperature
  - The energy of the decaying particle is converted to the energy of the light particles
  - The hottest temperature when RD begins

- $T > \mathrm{eV}$, the energy density was dominated by radiation
  - The most stringent constraint comes from BBN
  - CMB+BBN+LSS: $T_R > 4.7\mathrm{MeV}$ Salas et al, 2015

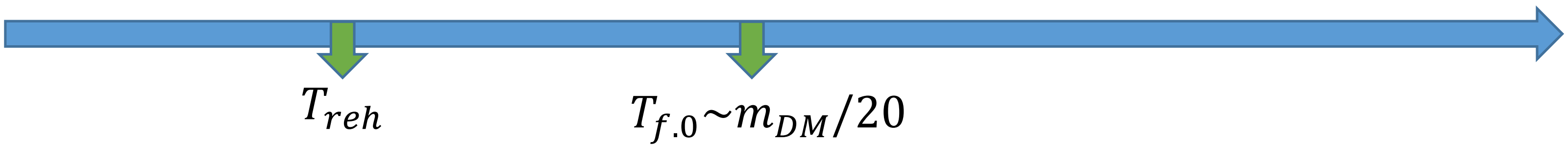
- In BSM, it often occurs that the energy density of the universe is dominated by a non-relativistic matter
  - Interact very weakly with visible sector and decay very late time in the Universe
  - Reheating temperature can be low enough
  - Primordial asymmetry is diluted during the late time reheating
  - → New generation needed

Non-thermal Dark Matter



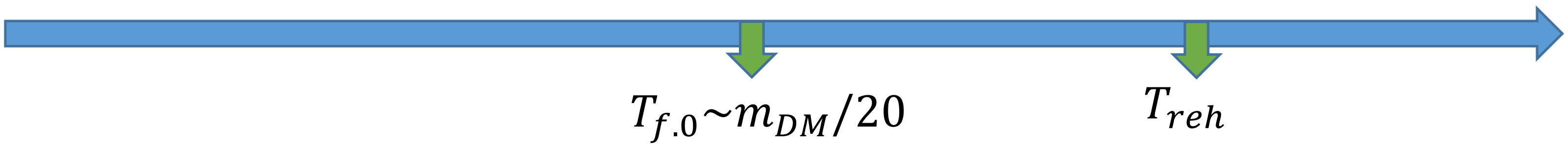
$T_{f.0} \sim m_{DM}/20$

Non-thermal Dark Matter



- $T_{reh} > T_{f.o.}$: **Decay before DM freeze-out**
  - DMs are produced before the DM freeze-out temperature
  - Thermalized → **No effect** on the DM relic abundance
  - $Y_\chi = Y_\chi^{f.o.}$

Non-thermal Dark Matter



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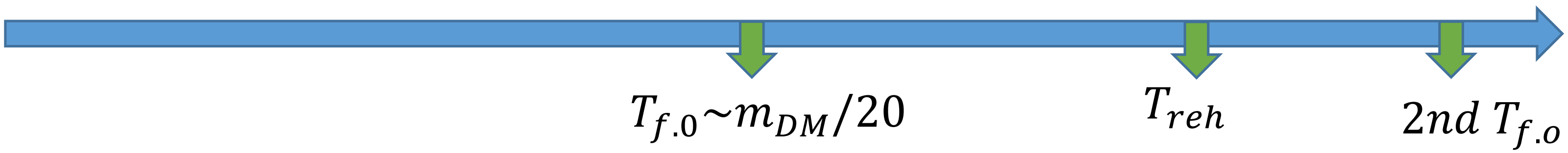
  - $Y_\chi = Y_\chi^{f.o.}$
- $T_{reh} < T_{f.o.}$ & $\Gamma_\chi < H$: **No DM re-annihilation**
  - The **simple sum** of the thermal production and non-thermal production
  - $Y_\chi = Y_\chi^{TP} + Y_\chi^{NTP}$

Non-thermal Dark Matter



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  - The simple sum of the thermal production and non-thermal production
  - $Y_\chi = Y_\chi^{TP} + Y_\chi^{NTP}$
- $T_{reh} < \; T_{f.o.}$ & $\Gamma_\chi > H$: **DM re-annihilation**
  - Heavy particle decays after DM are frozen out
  - The produced DMs are large enough → re-annihilate into SM particles

Presence of PBH

- The formation of small-mass PHB and their evaporation
  - Formed through various mechanisms
- We consider pre-existing PBHs
  - Once PBHs are formed, they behave as cold matter
- We assume that all of PBHs consist of the type of Schwarzschild BH with a single mass initially
  - Independent of the spin & angular momentum
- **We are interested in the PBH which decay after thermal freeze-out of WIMP**

DM generation from PBH evaporation

- PBH have been formed after inflation during radiation-dominated epoch

- Once formed, PBH can evaporate into particles by emitting Hawking radiation

$$T_{\rm BH} = \frac{M_p^2}{M_{\rm BH}} \simeq 10^7 {\rm GeV} \left(\frac{10^6 \text{ g}}{\rm M_{BH}} \right)$$

- PBH mass loss rate

$$\frac{dM_{\rm BH}}{dt} = \sum_i \left(\frac{dM_{\rm BH}}{dt} \right)_i = -\sum_i \int_0^\infty E_i \frac{d^2 N_i}{dp\, dt} dp$$

$$= -\frac{27 M_{\rm BH}^2}{128 \pi^3 M_p^4} T_{\rm BH}^4 \sum_i g_i \int_{z_i}^\infty \frac{\Psi_i(x)(x^2 - z_i^2)}{e^x \pm 1} x dx = -\varepsilon(M_{\rm BH}) \frac{(8\pi M_p^2)^2}{M_{\rm BH}^2},$$

  - Most energy of PBH is transferred during the final stages of the evaporation process → Mass of BH becomes small

Constraints for PBH mass

- Upper bound: Baumann et al, 2007

$$T_{\rm ev} > T_{\rm BBN} \simeq 4 \text{ MeV}$$

$$\frac{M_{\rm in}}{M_p} \lesssim 10.4 \times 10^{13} \left(\frac{g_*^2(T_{\rm BH})}{g_*(T_{\rm ev})} \right)^{1/6}$$

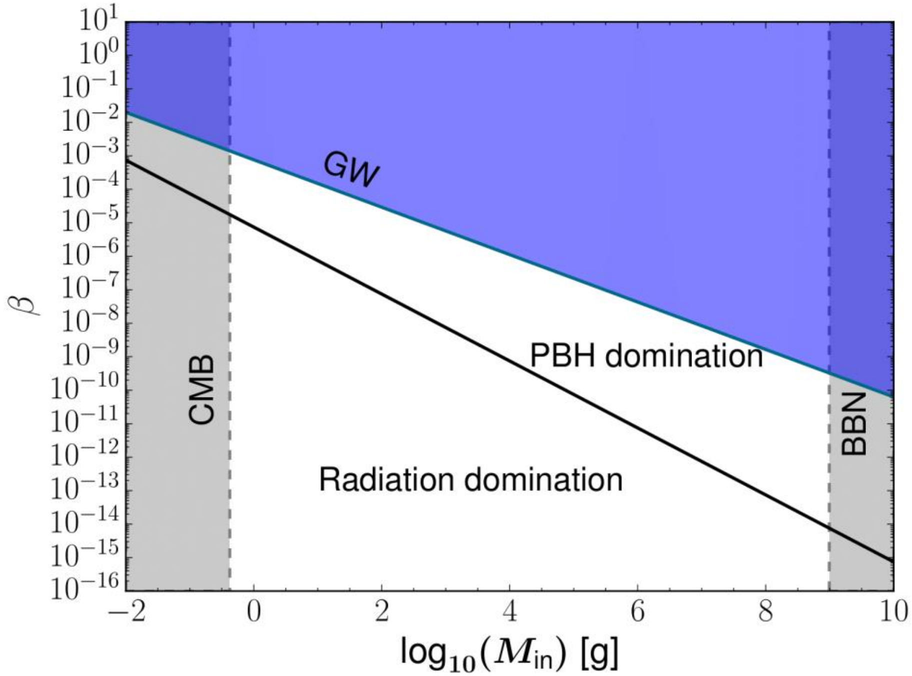
$$\Rightarrow \boxed{M_{\rm in}^{\rm max} \lesssim 9.7 \times 10^8 \text{ g.}}$$

- Lower bound: Planck 2018

$$H \leq 2.5 \times 10^{-5} M_p$$

$$M_{\rm in} > \frac{4\pi\gamma M_p}{2.5 \times 10^{-5}} \simeq \left(\frac{\gamma}{0.2} \right) 0.4 \text{ g}$$

$$\Rightarrow \boxed{M_{\rm in}^{\rm min} \gtrsim 0.4 \text{ g.}}$$



$$\beta \equiv \frac{\rho_{\rm BH}(T_{\rm in})}{\rho_{\rm rad}(T_{\rm in})}$$

- Since $\rho_{PBH} \propto a^{-3}, \rho_{rad} \propto a^{-4}$, this ratio grows with the expansion of the Universe
  - An initially RD Universe will eventually becomes MD

Non-thermal WIMPy baryogenesis

- Boltzmann equations

$$\frac{dM_{\rm BH}}{d\ln(a)} = -\frac{\varepsilon(M_{\rm BH})}{H}\frac{(8\pi M_p^2)^2}{M_{\rm BH}^2},$$

$$\frac{d\tilde{\rho}_{\rm BH}}{d\ln(a)} = \frac{\tilde{\rho}_{\rm BH}}{M_{\rm BH}}\frac{dM_{\rm BH}}{d\ln(a)},$$

$$\frac{d\tilde{\rho}_r}{d\ln(a)} = -\frac{\varepsilon_{\rm SM}(M_{\rm BH})}{\varepsilon(M_{\rm BH})}\frac{a\ \tilde{\rho}_{\rm BH}}{M_{\rm BH}}\frac{dM_{\rm BH}}{d\ln(a)},$$

$$\frac{d\tilde{n}_\chi}{d\ln(a)} = \boxed{\frac{\tilde{\rho}_{\rm BH}}{M_{\rm BH}}\frac{\Gamma_{{\rm BH}\to\chi}}{H}} - \langle\sigma_a v\rangle\frac{(\tilde{n}_\chi^2 - \tilde{n}_{\chi,\rm eq}^2)}{a^3 H},$$

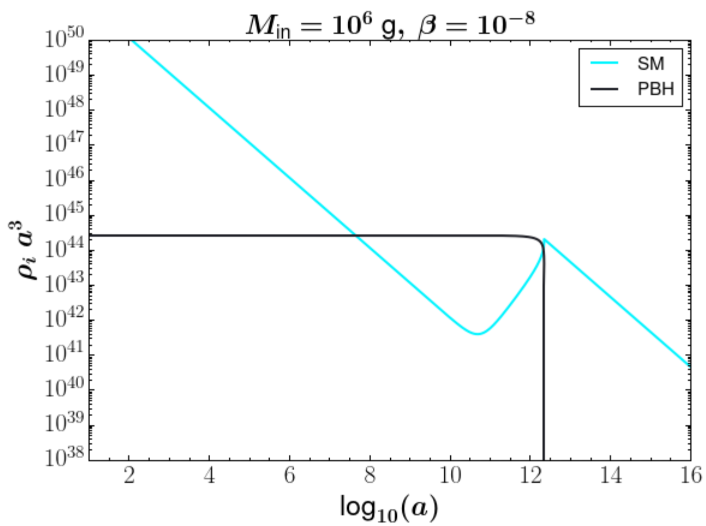
$$H^2 = \frac{1}{3M_p^2}(\rho_r + \rho_{\rm BH})$$

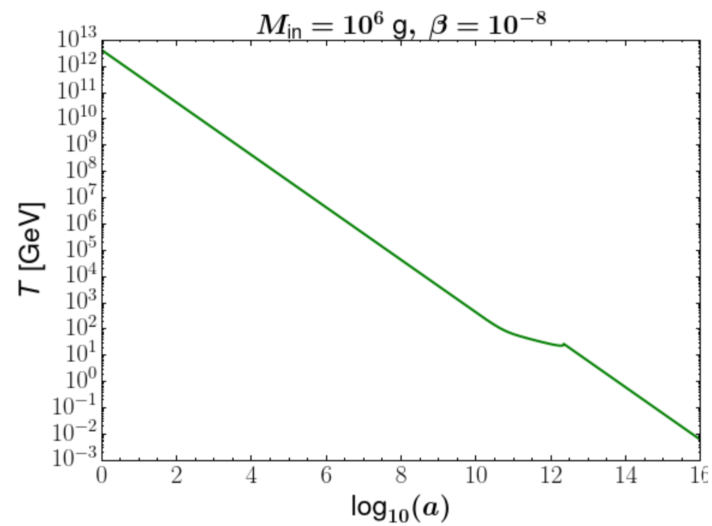
- Baryon asymmetry

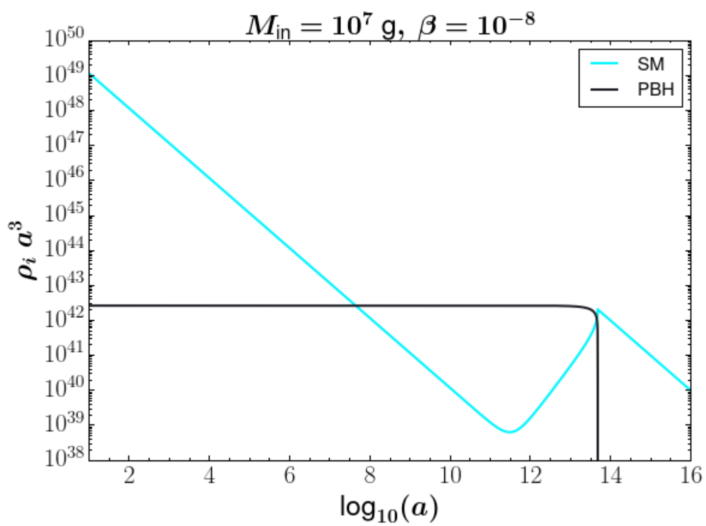
$$\frac{dn_B}{dt} + 3Hn_B = \epsilon\,\langle\sigma_B v\rangle\,(n_\chi^2 - n_{\chi,\rm eq}^2) - \langle\sigma_{\rm wo}v\rangle n_B n_{\psi,\rm eq}$$

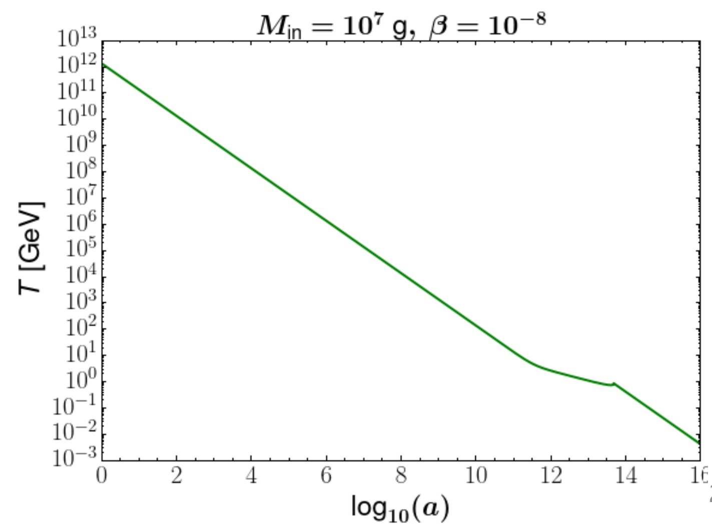
Non-thermal WIMPy baryogenesis

- Evolution of energy density







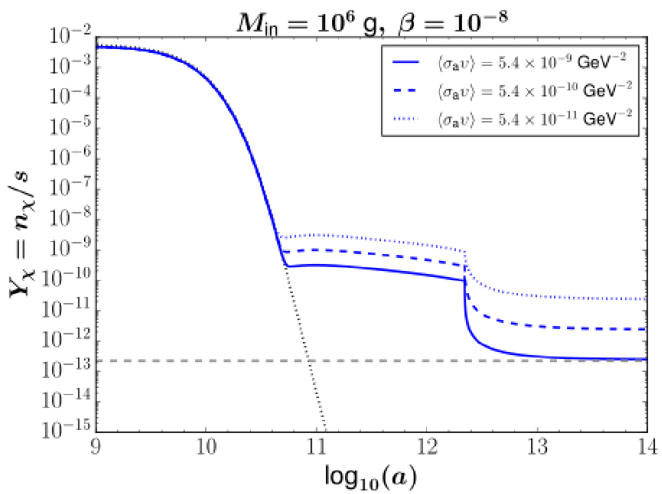


Non-thermal DM

- DM initially follow the thermal equilibrium and freeze-out

- Due to the continuous production from PBH, DMs reach a **quasi-stable state**

$$n_\chi = n_{\bar{\chi}} \simeq \left(\frac{\Gamma_{\mathrm{BH}\to\chi}}{M_{\mathrm{BH}} \langle \sigma_a v \rangle} \rho_{\mathrm{BH}} \right)^{1/2} \propto a^{-3/2}$$



- The DM yield produced by evaporation during PBH dominated era is calculated as

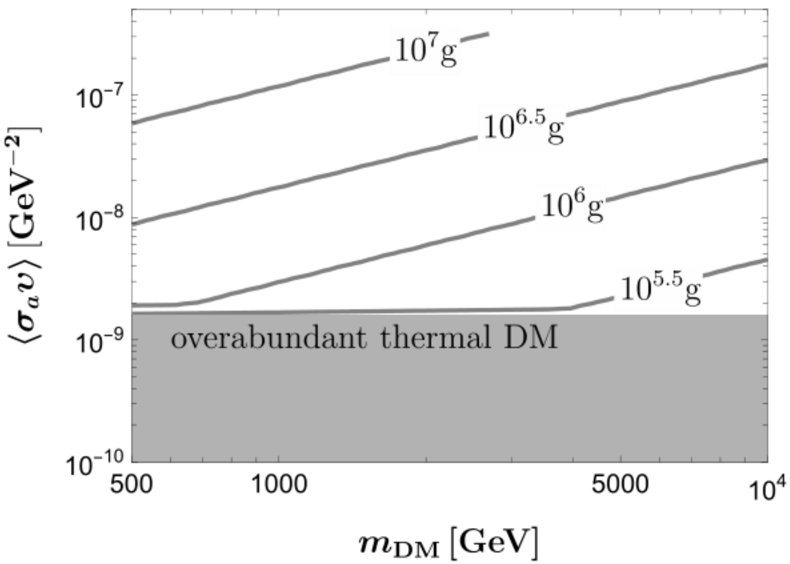
$$Y_\chi^{\rm ann}(T_{\rm ev}) \simeq \frac{2H(T_{\rm ev})}{\langle \sigma_a v \rangle\, s(T_{\rm ev})} = \sqrt{\frac{45}{2\pi^2}} \frac{g_*(T_{\rm ev})^{1/2}}{g_{*,s}(T_{\rm ev})} \frac{1}{\langle \sigma_a v \rangle\, M_p T_{\rm ev}}$$

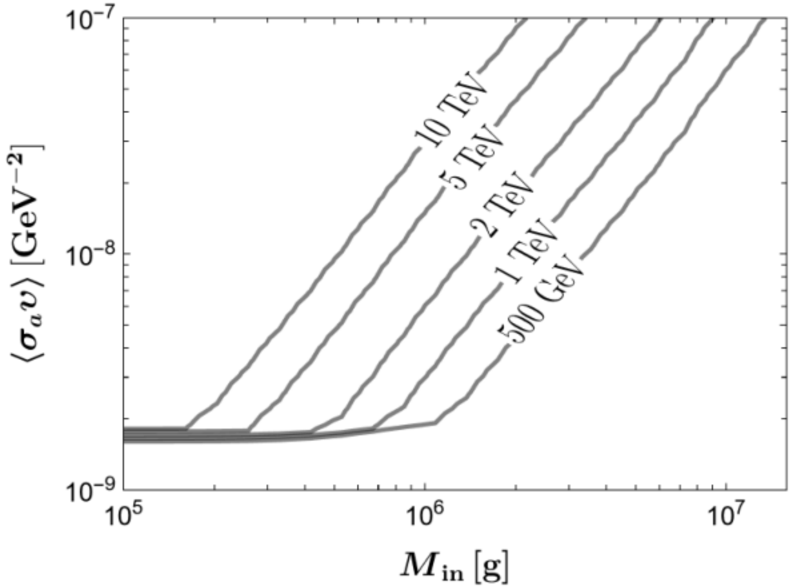
$$\Omega_\chi^{\rm ann} h^2 \simeq 4.14 \times 10^8 \, \frac{g_*(T_{\rm ev})^{1/2}}{g_{*,s}(T_{\rm ev})} \frac{1}{\langle \sigma_a v \rangle\, M_p T_{\rm ev}} \left(\frac{m_\chi}{\rm GeV} \right)$$

$$\simeq 0.115 \sqrt{\frac{100}{g_*(T_{\rm ev})}} \left(\frac{10^{-8}\ {\rm GeV}^{-2}}{\langle \sigma_a v \rangle} \right) \left(\frac{M_{\rm in}}{10^6 {\rm g}} \right)^{3/2} \left(\frac{m_\chi}{2\ {\rm TeV}} \right).$$

Non-thermal DM

- To get the correct relic abundance of DM





- The total annihilation cross section
  - Left: different PBH mass
  - Right: different DM mass

Evolution of the DM, baryon

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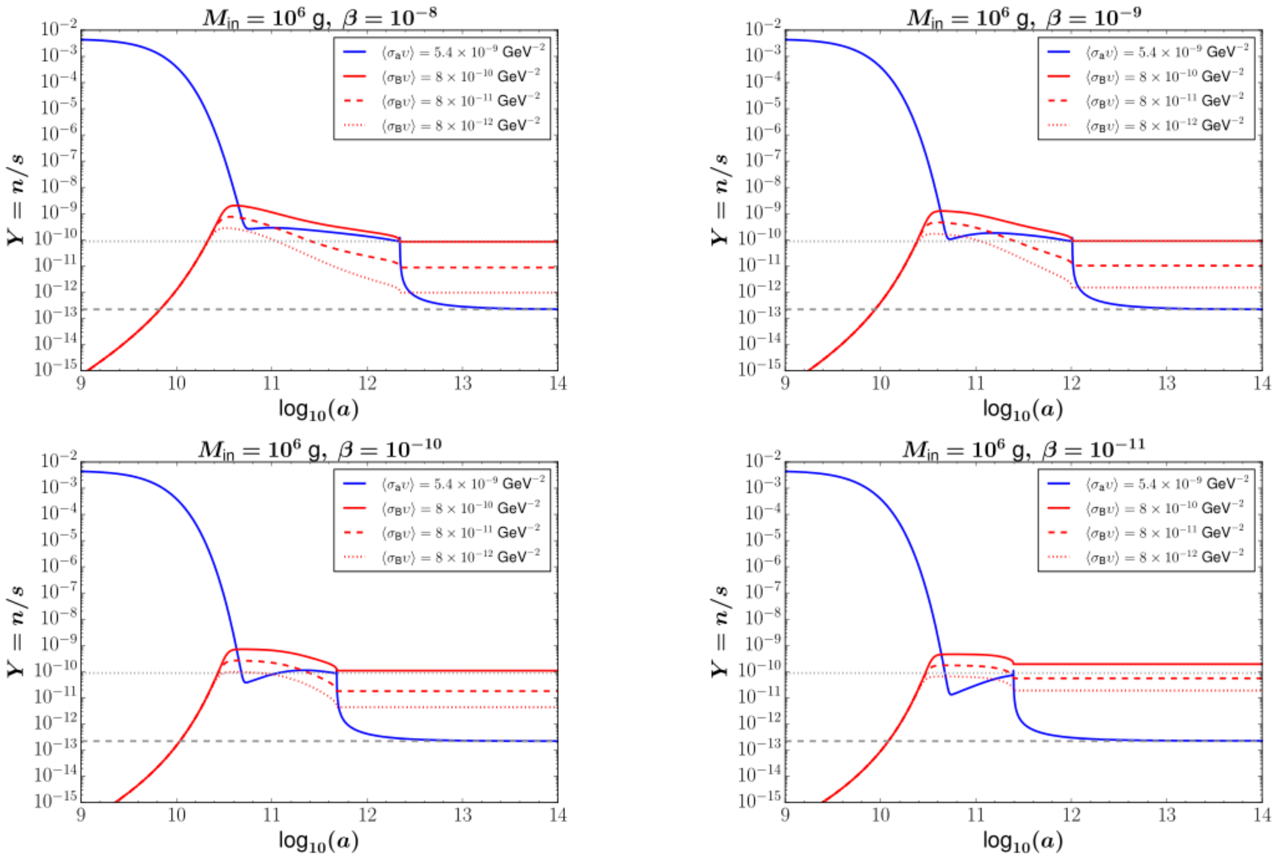

$$Y_B \equiv \frac{n_B}{s} \simeq \frac{3\sqrt{10}}{2\pi}\epsilon\Gamma_{\rm BH\to\chi}\frac{\langle\sigma_B v\rangle}{\langle\sigma_a v\rangle}\frac{M_p}{M_{\rm BH}}\left(\frac{1}{g_*(T_{\rm ev})}\right)^{1/2}\frac{1}{T_{\rm ev}}$$

$$\simeq 8.7\times10^{-11}\left(\frac{\epsilon}{0.1}\right)\left(\frac{f_\sigma}{0.15}\right)\left(\frac{100}{g_*(T_{\rm ev})}\right)^{1/2}\left(\frac{10^6{\rm g}}{M_{\rm in}}\right)^{1/2}$$

$$f_\sigma = \langle\sigma_B v\rangle / \langle\sigma_a v\rangle.$$

Relic abundance and BAU

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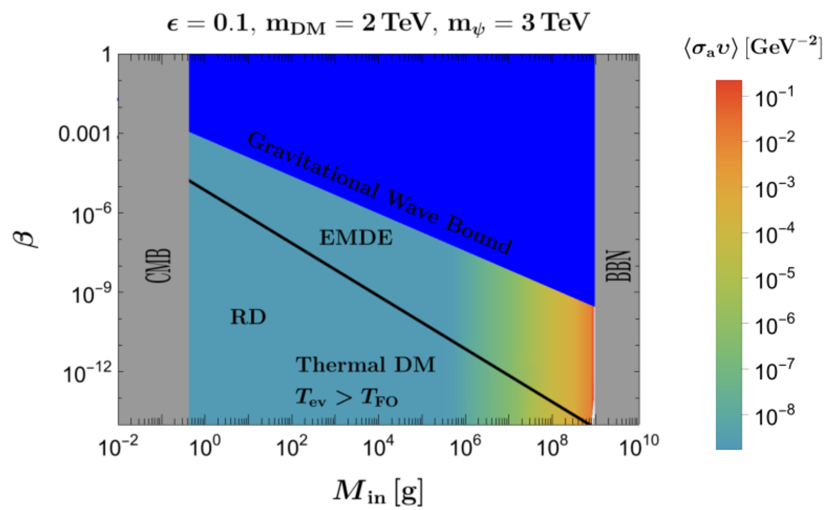

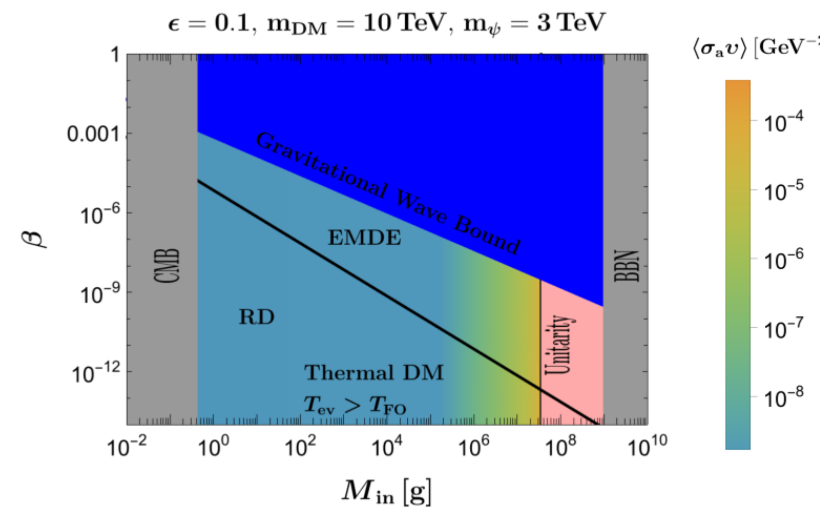

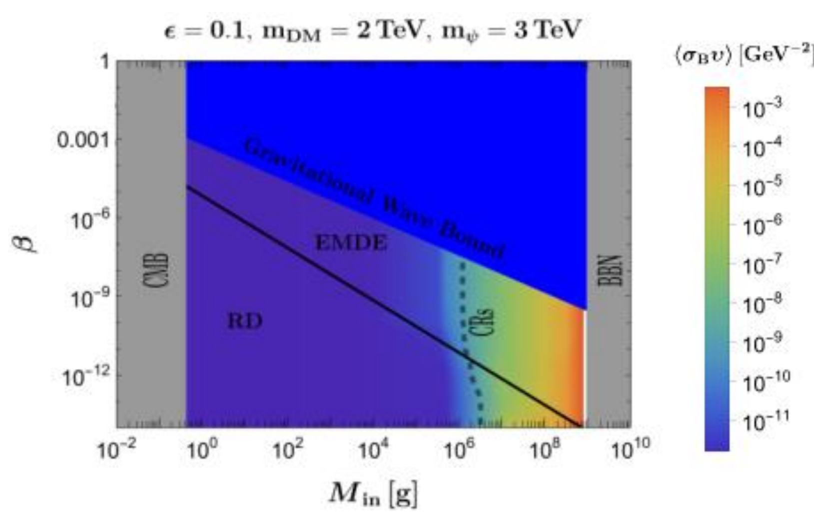

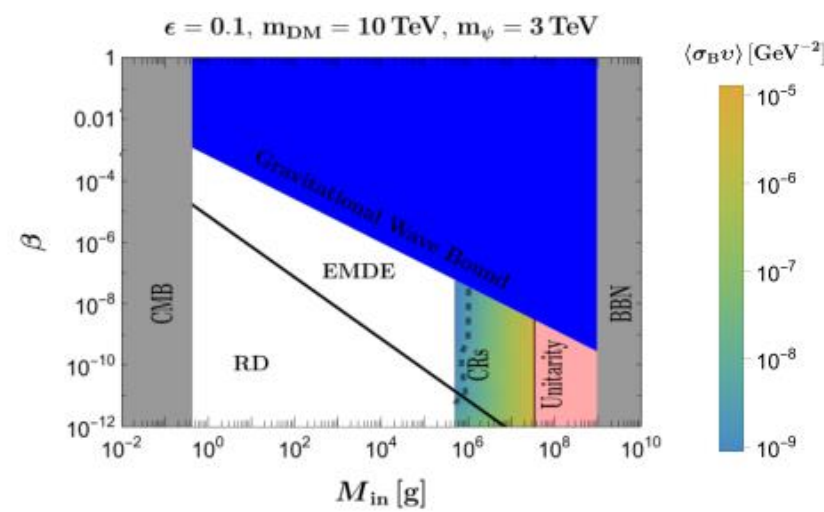

Summary

- We suggested non-thermal WIMP baryogenesis from the evaporation of primordial black hole.

- The primordial black hole with mass less than 10^7g is a good candidate as an source of TeV DM with the total annihilation cross section $\langle \sigma_a v \rangle \leq 10^{-7}\mathrm{GeV}^{-2}$ and the B-violating scattering cross section $\langle \sigma_B v \rangle \leq 2 \times 10^{-9}\mathrm{GeV}^{-2}$.

- This large annihilation cross section would make it available to search them in the indirect DM searches.

Summary

- We suggested non-thermal WIMP baryogenesis from the evaporation of primordial black hole.

- The primordial black hole with mass less than 10^7g is a good candidate as an source of TeV DM with the total annihilation

Thank you very much

- This large annihilation cross section would make it available to search them in the indirect DM searches.