Dark Matter Relic Density from Asymmetric Partcile Late Decay

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4/3/2011

Ⅰ。 Some Background

Ⅱ。 New Scenario： DM relic density from asymmetric particle late decay

Ⅲ。 Applications

Ⅳ。 Conclusion

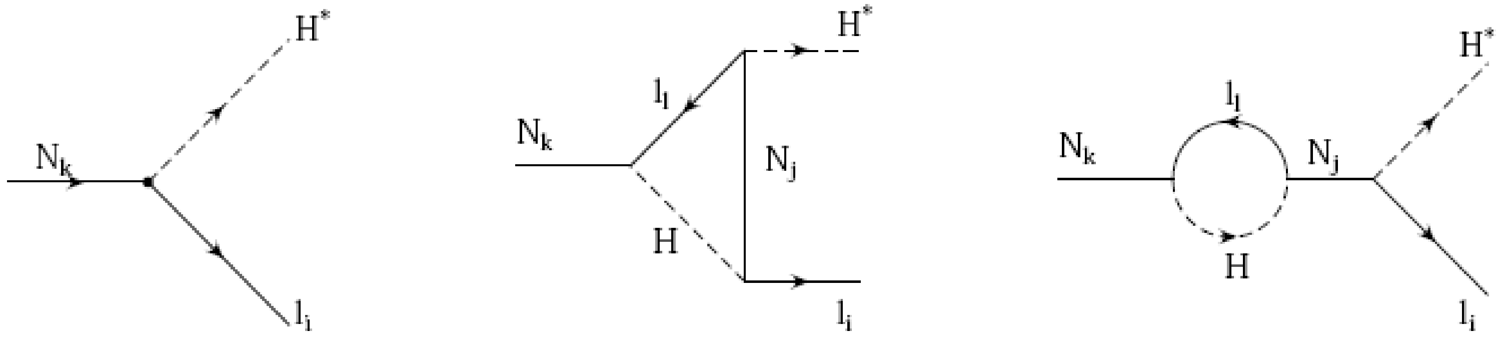
I。 Some Background

1。 Baryon asymmetry

A) Obserbvation：

B) Theoretical：

C) Baryon asymmetry from Leptogensis：
RHN CP-violation decay

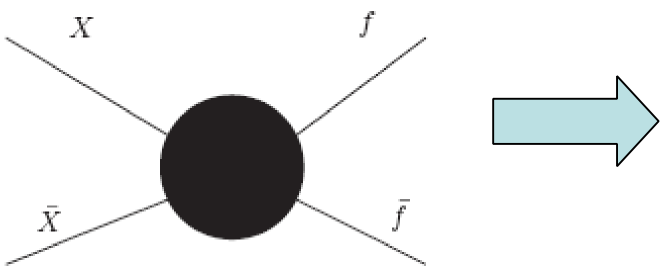


(a) (b) (c)

2。On the dark matter relic density

A) weakly interactive massive particle (WIMP)

freeze-out via annihilating into ***lighter*** states



$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

- **WIMP miracle**： if particle mass/interaction are typically at the weak scale/strength $\Omega h^2 \approx 0.1$
- **Fine tuning**： however， in fact this miracle involves ***high power*** of mass or coupling parameters, that implies rather high fine-tuning to satisfy numerical coincidence.
- **Superficial**： matter and dark matter with surprisingly close energy fraction $\Omega_{DM} h^2 : \Omega_B h^2 \approx 5:1$! Does it hint some more profound physics? Freeze-out scenario alone is lack of the power to explore that.

J. L. Feng *et/* Phys. Rev. Lett. 101 (2008) 231301

B) No weak scale mass and interaction (WIMPless)

$$\frac{m_X}{g_X^2} \sim \frac{m}{g^2} \sim \frac{F}{16\pi^2 M}$$

- **WIMPless miracle**： in the gauge mediation model, dark matter (***interacts with messgners***) mass origin and annihilation in the dark sector are controlled by ***the same coupling***, as a result they cancels in the $\langle \sigma v \rangle$。 The miracle is the cross section controlled by a single parameter F/M just gives the right order.!

- **Artifiical**： although avoids fine tuning, it requires a whole new sector introudced by hand。 And it can not explain the coincidence neither.

C) Feebly interactive massive particle (FIMP)

D) Asymmetric dark matter (ADM)

$$n_+^{eq} - n_-^{eq} = f_{b,f}(m/T) \times \frac{gT^2}{6}\mu_\phi,$$

$$\theta_{b,f} = \mp 1 \qquad f_{b,f}(m/T) = \frac{6}{\pi^2}\int_0^\infty dx \frac{x^2 \exp[-\sqrt{x^2+(m/T)^2}]}{\left(\theta_{b,f} + \exp[-\sqrt{x^2+(m/T)^2}]\right)^2},$$

$$m \ll T, \; f_{b,f} \to 2, \; 1$$

- **Prediction**： although avoids fine tuning, it requires a whole new sector introudced by hand。 And it can not explain the coincidence neither.
- **Expeiment favored?**： If the so called signals from DAMA/CoGeNT FGST can be confirmed, then dark matter should be light about 8 GeV, moreover with somewhat larger interactions with quarks.
- **Hot**： so many guys are interesting in it.....

- **Novel dynamics**：although avoids fine tuning, it requires a whole new sector introudced by hand。And it can not explain the coincidence neither.

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II New scenario： DM relic density from asymmetric particle late decay

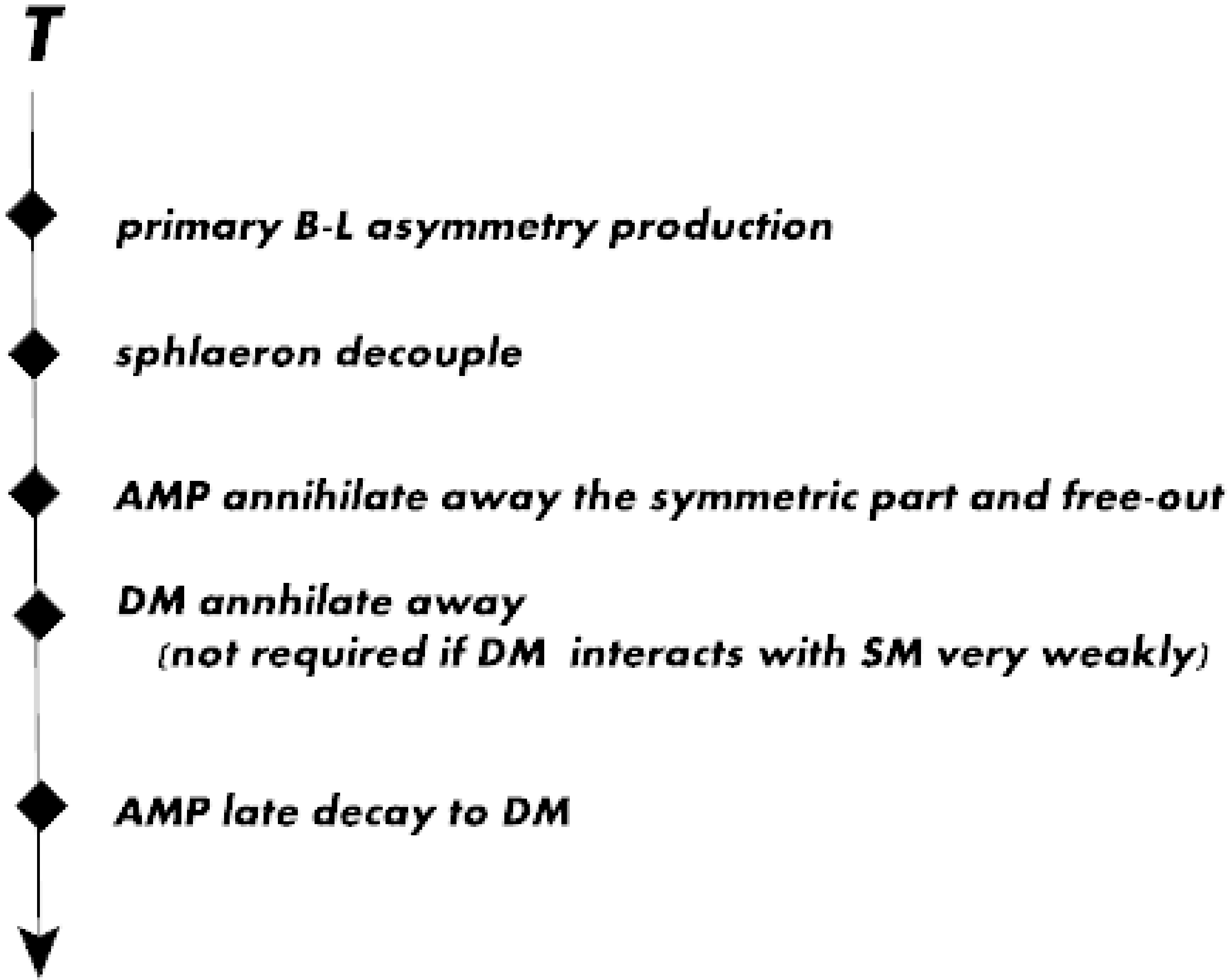
- There exists a stable DM candidate χ with mass m_χ. If it enters the thermal plasma and decouples at some temperature $x_f = m_\chi/T_f$, leaving inappreciable relic density. If it never undergoes thermal equilibrium, such as the WIMPless candidate gravitino $\widetilde{G}$, its production after inflation is also should be small.

- At least one asymmetric metastable particle (AMP) exists in the theory, denoted as X. Its late decay at proper time scale is the center element to produce proper number density for the DM. The dynamics of AMP is the same with the ADM, except that its mass is not directly constrained by the energy density since only its asymmetric number density is required in this mechanism.

- A link between those two particle renders X decay to DM. The decay lifetime τ_X is a crucial parameter, and the mechanism works for different cases: for a WIMPless, τ_X is not constrained; While for the weak/strong interactive DM, τ_X should be arranged to longer than the decoupling time of dark matter. In other word, the AMP lifetime is required to satisfy $\tau_{AMP} \gg H^{-1} \simeq 0.3 g_*^{-1/2} M_{Pl}/T_{DM}^2$, equivalently

$$\Gamma_{AMP} \ll 3.8 \times 10^{-18} \times \left(\frac{m_{AMP}}{100\text{GeV}} \right)^2 \text{GeV}.$$

where T_{DM} is the DM decoupling temperature, typically at $T_{DM} \sim m_{DM}/x_{DM}$ for WIMP $x_{DM} \simeq 20$.


T
primary B-L asymmetry production
sphlaeron decouple
AMP annihilate away the symmetric part and free-out
DM annhilate away
(not required if DM interacts with SM very weakly)
AMP late decay to DM

- **More benefit from asymmtric**： although avoids fine tuning, it requires a whole new sector introudced by hand。And it can not explain the coincidence neither.
- **Predictive scenario in MSSM**： If the so called signals from DAMA/CoGeNT FGST can be confirmed, then dark matter should be light about 8 GeV, moreover with somewhat larger interactions with quarks.
- **Econic**： no new interaction， no new artficial degree of freedoms

III。Applications

1。Gravitino Dark Matter

- **Troublesome**: gravitino is a trouble in cosmology，due to its exteremely suppressed coupling to matters：

$m_{\tilde{G}} = F/\sqrt{3}M_{PL}$

⇩

SUSY-breaking scale

$$\mathcal{L}_{\text{goldstino}} = -i\tilde{G}^{\dagger}\overline{\sigma}^{\mu}\partial_{\mu}\tilde{G} - \frac{1}{\langle F \rangle}(\tilde{G}\partial_{\mu}j^{\mu} + \text{c.c.})$$

$$j^{\mu}_{\alpha} = (\sigma^{\nu}\overline{\sigma}^{\mu}\psi_i)_{\alpha}\partial_{\nu}\phi^{*i} + \sigma^{\nu}\overline{\sigma}^{\rho}\sigma^{\mu}\lambda^{\dagger a}F^{a}_{\nu\rho}/2\sqrt{2} + \ldots$$

  - Unstable：rather late time decay affect BBN
  - Stable：be the DM, but may overclose the universe

- **Production**: gravitino can be produced with proper relic density via several ways，but each is problematic

  - Thermally freeze-out and $m_{\tilde{G}} \sim \text{keV}$

    But this warm DM is bounded by WMAP $m_{\tilde{G}} < 16$ eV

- Produced during reheating by scattering and $T_R \sim 10^{10}$

  But who make sure the reheating termperature?

- Produced from NLSP such as charged right-handed slepton late decay (far behind BBN)。 It is ***testable***, but there is a stubborn cosmological constrain： namely $\widetilde{\tau}^-$ forms ***bound states*** with $^4\mathrm{He}$， which leads to ***overproduction*** $^6\mathrm{Li}$， $^4\mathrm{He}\,\widetilde{\tau}^- \to {}^6\mathrm{Li}+\widetilde{\tau}^-$

Perfect in our scenario: assume reheating termerature suffciently low so that the production of gravitino is negligible. The charged slepton is the AMP——

- If AMP is the ***positive*** slepton, then bound effect disappear automatically!

- Predicates a ***gauge-gravity hypbrid mediation*** sceanrio

$$x_{sq} \equiv m_{\widetilde{q}}/T_{sp}$$

$$n_B = 2\left(1+2f_{\widetilde{q}}\right)T_{sp}^2 u_L,$$

$$n_{\widetilde{e}_R} = -\frac{3}{2}f_{\widetilde{e}_R}\frac{10(1+f_{\widetilde{q}})+3(f_{\widetilde{e}_R}-f_{\widetilde{\ell}})+4(f_h+f_{\widetilde{h}})}{9+6f_{\widetilde{q}}+3f_{\widetilde{e}_R}+2(f_h+f_{\widetilde{h}})}T_{sp}^2 u_L.$$

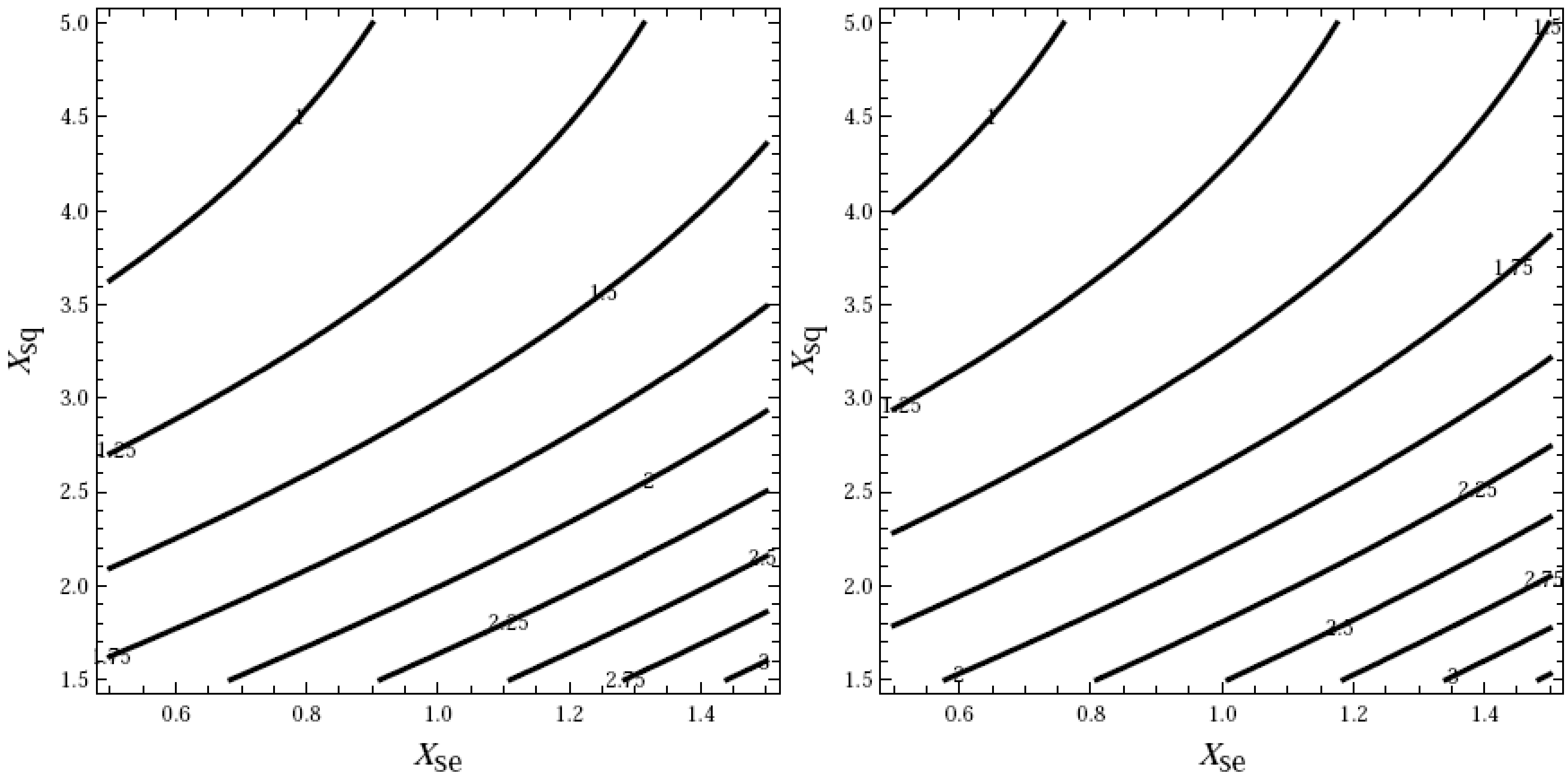


FIG. 1: The contour of the number density ratio $n_B/n_{\tilde{e}_R}$ on the $x_{se} - x_{sq}$ plan. The left figure is plotted with a lighter $\tilde{\ell}$, $x_{\tilde{\ell}} = 1$, while for the right $x_{\tilde{\ell}} = 2$.

$$m_{\tilde{G}} = \frac{\Omega_{DM} h^2}{\Omega_B h^2} \frac{n_B}{n_{\tilde{e}_R}} m_p.$$

$$m_{\tilde{G}} \sim 5\,\mathrm{GeV} - 15\,\mathrm{GeV}.$$

A gravitino with mass about several GeVs is interesting itself, since it implies gravity mediation fails in acconting for all soft terms, and their origin should be dominated by the gauge mediation, in particular, the ***messenger scale must be sub-GUT.***

$$m_{\tilde{G}} = \frac{1}{\sqrt{3}} \frac{\Lambda M_{mess}}{M_{PL}}.$$

- **More test** (at LHCb) from flavor changing due to the ***familiy universal*** contribution from gravity mediation。

2。Right-handed sneutrino DM

- **Dirac neutrino mass**: as a minimal extension of the MSSM to account for the neutrino mass scale, including a right-handed neutrino forming tiny Dirac mass with the left-handed neutrino. Consequently the Yukawa is very small, and the sneutrino never enters equilibrium. But it inherits the AMP density.

3。Light U(1)_X dark sector with Light DM

- **Original motiviation：** inspired by the cosmic ray anomaly, a sub-GeV hidden gauge boson to provide Sommerfield enhancement and kinetic suppressing the anti-proton products。

N. Arkani-Hamed etl, Phys. Rev. D 79, 015014 (2009)

- **Scale close to light DM：** CoGeNT/DAMA/FGST hints for a several GeV DM, and a light DM may origin from such a U(1)_X secctor, providing a ***unified picture*** to understand the heavy DM inspired by cosmic ray anomaly and the light DM by direct detection。

A natrual realization in

Zhaofeng Kang etl, JCAP 1101, 028 (2011)

- Effective DM model $W_{hid} \supset M_h \bar{h} h.$

- Suffers from the relic density problem for light DM that has ***large annihilation cross section***。 But in our new proposal, it is just a required property。

Very weakly couples to SM： the coupling is due to Abelian gauge group kinetic mixing

$$\mathcal{L}_{int} \supset \theta g_X \widetilde{B} \sum_i Q_{X,i} \widetilde{H}_i^\dagger H_i + \theta \mathcal{O}(m_{\widetilde{X}/\widetilde{B}}) g_Y \widetilde{X} \sum_i Q_{Y,i} \widetilde{f}_i^\dagger f_i + h.c.$$

$$c_1 \widetilde{f}^\dagger \widetilde{X} f, \qquad \frac{c_2}{\Lambda} \widetilde{f}^\dagger X \widetilde{X}^\dagger f, \qquad \frac{c_3}{\Lambda} C^{\pm} \gamma^\mu X \widetilde{X}^\dagger W_\mu^{\mp}$$

$$\Gamma_{OLSP}(\widetilde{H}^\pm \to W^\pm \widetilde{h}^* h) \sim \frac{1}{(32\pi)^3} \epsilon_0^2 \epsilon_c^2 (Q_h g_X)^2 g_2^2 \theta^2 \left(\frac{\Delta m^2}{m_{\rm AMP}^2} \right)^3 \frac{m_{\rm AMP}^3}{\Lambda^2}$$
$$\sim 10^{-21} \rm GeV$$