Oscillating Asymmetric Sneutrino DM
from
Maximally $U(1)_L$ Inverse Seesaw

CosPA 2015, 12-16 October 2015, KAIST Munji Campus, Daejeon, Korea

Zhaofeng Kang, KIAS,13/10/2015

outline

- Asymmetric dark matter (ADM)
- Oscillating ADM
- Oscillating sneutrino ADM from M$\not{L}$SIS
- conclusions

Asymmetric dark matter (ADM)

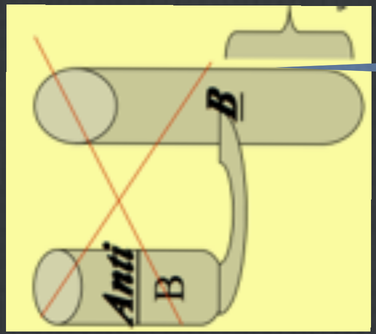
K. Petraki and R. R. Volkas, Int. J. Mod. Phys. A 28, 1330028 (2013)
K. M. Zurek, Phys. Rept. 537, 91 (2014)

- **ADM as a solution to the coincidence puzzle**

Cosmic coincidence puzzle in the energy cake: why dark matter: visible matter~5:1?

Hints from the baryonic matter: our maximally asymmetric universe today originates in the early universe with tiny asymmetry

$$\eta_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} = 6\times 10^{-10}$$



without this asymmetry, the baryon energy fraction would be only ~10^{-8}×5% after the normal freeze-out of $B-\bar{B}$ annihilating, very fast

M. Barr, R. S. Chivukula and E. Farhi, Phys. Lett. B 241, 387 (1990);
D. B. Kaplan, Phys. Rev. Lett. 68, 741 (1992) .

Similar phenomena in DM?—the ADM scenario—
DM obtains *comparable asymmetry* dynamically connected with the baryon asymmetry; only the asymmetric parts left for both. Then the puzzle is solved for ADM~5 GeV – predication of light DM! 👍

light DM anomaly? D. E. Kaplan, M. A. Luty and K. M. Zurek, Phys. Rev. D 79, 115016 (2009).

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K. Petraki and R. R. Volkas, Int. J. Mod. Phys. A 28, 1330028 (2013)
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- **A closer look on ADM**

The master formula: particle asymmetry & chemical potential μ

$$n_+ - n_- = \begin{cases} f_b(m_\phi/T) \times \frac{gT^3}{3}\left(\frac{\mu_\phi}{T}\right), & \text{(for bosons)} \\ f_f(m_\phi/T) \times \frac{gT^3}{6}\left(\frac{\mu_\phi}{T}\right), & \text{(for fermions)} \end{cases}$$

the Boltzman factor $f_{b/f}$ are 1 for a relativistic particle; otherwise they are greatly suppressed

- **How to be an ADM?**

1) carry a charge ➠ complex scalar or Dirac fermion, charged $U(1)_L$?

2) gain asymmetry ➠ common genesis
& transfer via establishing chemical equilibrium between sectors

3) annihilate away ➠ available final states & a large cross section

of concern for the GeV scale ADM

👍 the concrete value is not important, as long as it is sufficiently large > a few pb. Maybe this is the core of ADM.

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- **Nonstandard ADM**

Heavy ADM far above GeV scale: long last equilibrium such that it decouples when DM becomes nonrelativistic and $f_{b/f}(x_d) \ll 1$, so ADM asymmetry is suppressed and an accordingly heavy ADM is required, says ~ TeV

M. R. Buckley and L. Randall, JHEP 1109, 009 (2011).

AMP, metastable asymmetric particle: DM (with negligible relic density via conventional ways) inherits density from AMP late decay

Z. Kang and T. Li, JHEP 1210, 150 (2012);
J. Unwin, JHEP 1306, 090 (2013) ;
S. M. Barr and R. J. Scherrer, arXiv:1508.07469

equally good or even better in some sense; DM itself is not required to be ADM and AMP is freer, widening model building; with gravitino as a good example

ADM without asymmetry: oscillating ADM, played in this talk ☞

with distinguishable feature to ADM which does not annihilate today; while oscillating ADM may have annihilation rate > pb!

T. Cohen and K. M. Zurek, Phys. Rev. Lett. 104 (2010) 101301;
Z. Kang, J. Li, T. Li, T. Liu and J. Yang, arXiv:1102.5644
E. J. Chun, Phys. Rev. D 83 (2011) 053004;
A. Falkowski, J. T. Ruderman, T. Volansky, JHEP 1105 (2011) 106.

Oscillating ADM

- **Arise when the DM charge is not exact**

  For example, pseudo-complex/Dirac particles

  $$\mathscr{L}_{\text{fermion}} = \bar{X}(i\partial\!\!\!/ - m_X)X - \frac{1}{2} m_M(\bar{X}^C X + \bar{X} X^C) + \mathscr{L}_{\text{int}} \,, \qquad \mathscr{L}_{\text{scalar}} = |\partial_\mu X|^2 - m_X^2 |X|^2 - \frac{1}{2} m_M^2 (X^{C\dagger} X + X^\dagger X^C) + \mathscr{L}_{\text{int}} \,,$$

  The consequence of such a slight breaking term is the mixing between DM and antiDM and a tiny mass splitting

  In analogy with neutrino physics, flavor mixing between stable particles leads to oscillation

  Therefore, fast oscillation would lead to asymmetry washing. If it is effective before freeze-out, we would recover the ordinary DM scenario; otherwise, it only regenerates the symmetric parts.

  an interesting application is explaining the cosmic ray anomaly which requires an anomalously large cross section ~1000 pb

- **So, when does oscillation begin?** ☟

Oscillating ADM

- **BE for oscillating ADM**

Derived using the density matrix approach, treating DM and antiDM as two coherent flavors 1 & 2. The comoving number density matrix

$$Y(x) = \begin{pmatrix} Y_{11}(x) & Y_{12}(x) \\ Y_{21}(x) & Y_{22}(x) \end{pmatrix}$$

S. Tulin, H. B. Yu and K. M. Zurek, JCAP 1205, 013 (2012).
M. Cirelli, P. Panci, G. Servant and G. Zaharijas, JCAP 1203, 015 (2012).

Consider the evaluations of the sum and minus of two flavors

$$Y_{\pm} = Y_{11} \pm Y_{22}$$

$$Y_{c\pm} = Y_{12} \pm Y_{21}$$

the initial conditions are: $Y_{-}(x_0)=\eta_0 \sim \eta_b$, $Y_{c-\pm}(x_0)=0$

$$\begin{aligned} Y'_{+}(x) &= -2\frac{\langle\sigma v\rangle s(x)}{xH(x)}\left[\frac{1}{4}\left(Y_{+}^2(x) - Y_{-}^2(x) + Y_{c-}^2(x)\right) - Y_{eq}^2(x)\right], \\ Y'_{-}(x) &= 2\frac{\delta m}{xH(x)}Y_{c-}(x), \\ Y'_{c-}(x) &= -2\frac{\delta m}{xH(x)}Y_{-}(x) - \frac{\langle\sigma v\rangle s(x)}{xH(x)}Y_{c-}(x)Y_{+}(x), \end{aligned}$$

the first two terms are those of the BE in ADM

the second BE is crucial because it affects $Y_{-}(x)$; in the limit of $\delta m \to 0$ one recovers a constant $Y_{-}(x)$

An estimation of the oscillating time scale

$$x_{osc} \approx \left(\frac{H_m \sigma_0 s_m \eta_0/2}{\delta m^2}\right)^{1/5} \sim 7.6\left(\frac{m_{\rm DM}}{400{\rm GeV}}\right)\left(\frac{10^{-5}{\rm eV}}{\delta m}\right)^{2/5}\left(\frac{g_{*S}}{10}\sqrt{\frac{g_*}{10}}\frac{\sigma_0}{10{\rm pb}}\frac{\eta_0}{0.1\eta_B}\right)^{1/5}.$$

Oscillating ADM

- **Numerical solution for BEs**

The heavier snuetrino LSP can tolerate larger mass splitting

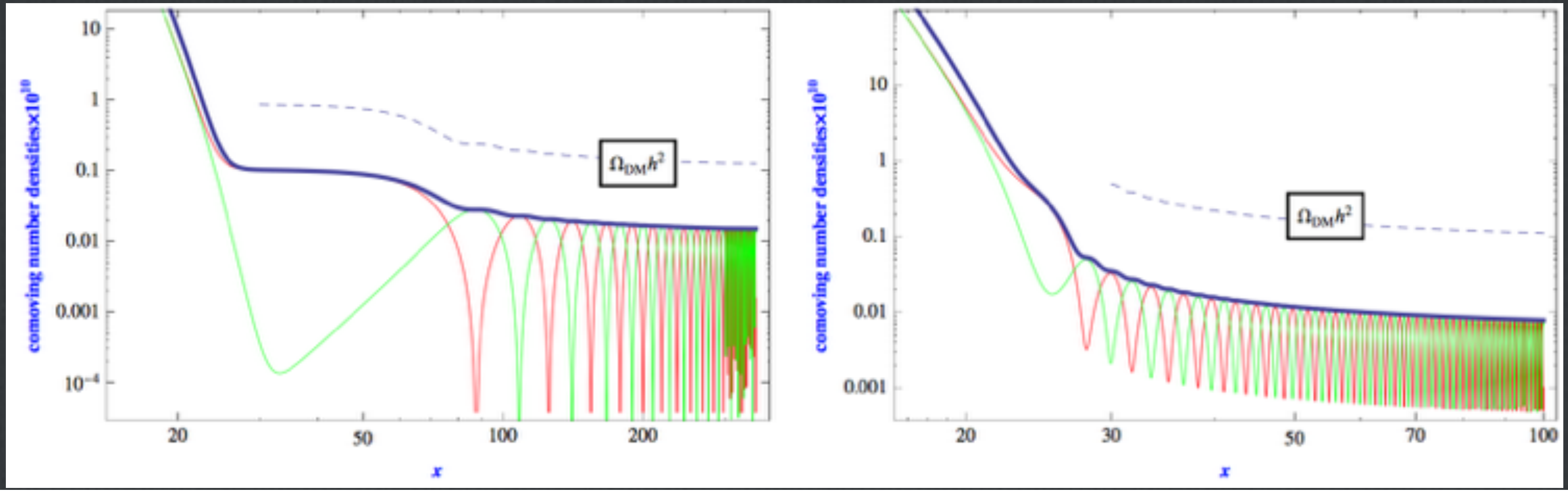


FIG. 2: Evolutions of the comoving densities of the quantities Y_+ (thick black line), Y_{11} (red line) and Y_{22} (green line). Parameter set are Left: $\delta m = 10^{-7}$ eV, $m_{\tilde{\nu}_1} = 300$ GeV, $\sigma_0 = 3$ pb, $\eta_0 = 0.1\eta_B$; Right: $\delta m = 10^{-5}$ eV, $m_{\tilde{\nu}_1} = 500$ GeV, $\sigma_0 = 2$ pb, $\eta_0 = 0.5\eta_B$.

Oscillating sneutrino ADM from M*L*SIS

- **Maximally $U(1)_L$ supersymmetric inverse seesaw (M*L*SIS)**

Inverse seesaw explains the tiny neutrino mass origin following the symmetry principle:

$$W_{\rm IS} = y_N H_u L N^c + m_N N N^c + \frac{M_N}{2} N^2. \quad \Rightarrow \quad m_\nu^{eff} = -\frac{m_D^2}{m_N^2 + m_D^2} M_N,$$

M_N is the source of lepton number violation

Let M_N as small as possible, then $U(1)_L$ is maximally retained; thus, in the supersymmetric version, sneutrino LSP is an oscillating ADM

Direct detection requires a singlet-like (complex) sneutrino LSP $\tilde{\nu}_1$

$$N^c = (\widetilde{\nu}_R^*, \nu_R^\dagger) \text{ and } N = (\widetilde{\nu}'_L, \nu'_L). \qquad \widetilde{\nu'_L} \approx -\sin\widetilde{\theta}\,\widetilde{\nu}_1 + \cos\widetilde{\theta}\,\widetilde{\nu}_2, \quad \widetilde{\nu_R} \approx \cos\widetilde{\theta}\,\widetilde{\nu}_1 + \sin\widetilde{\theta}\,\widetilde{\nu}_2,$$

Mass splitting between the CP-even and -odd components of $\tilde{\nu}_1$ is

$$\delta m \approx \frac{\delta m_{11}^2}{m_{\widetilde{\nu}_1}} = \frac{m_N M_N \sin 2\widetilde{\theta} - B_M M_N \sin^2\widetilde{\theta}}{m_{\widetilde{\nu}_1}}.$$

B_M~ soft SUSY-breaking scale, so typically $\boldsymbol{\delta}m$ is not far from M_N, so we need a very light neutrino to get a naturally small $\boldsymbol{\delta}m$ ⚡ ⚡ ⚡

valid in the decoupling limit; as expected, $\tilde{\theta} \to 0$ is good for decreasing the splitting

Oscillating sneutrino ADM from M*L*SIS

- **Initial asymmetry transferred from baryons**

Primal asymmetry is assumed to be generated in the visible sector by the well-known mechanisms such as baryogensis, etc.

In the M*L*SIS, sneutrino establishes chemical equilibrium with the leptonic sector of SM.

Via the Yukawa interactions from the superpotential one arrives

$$\mu_{u_L} = \mu_{u_R}, \quad \mu_{d_L} = \mu_{d_R}$$
$$\mu_{e_L} = \mu_{e_R}, \quad \mu_{\nu_L} = \mu_{\nu_R} = \mu_{\nu'_L}.$$

$$\mu_{\tilde{\nu}_R} = \mu_{\tilde{\nu}'_L} = \mu_{\nu_L}.$$

Other equations follow those in MSSM, and eventually we have

$$B(T_{sph}) = \frac{T_{sph}^2}{6}\left[2 \times 3(2\mu_{u_L} + \mu_W)\right] = 6T_{sph}^2\mu_{u_L},$$
$$S_{\rm ADM}(T_{sph}) = \frac{T_{sph}^2}{3}k\mu_{\nu_L} = -\frac{11k}{3}T_{sph}^2\mu_{u_L}.$$

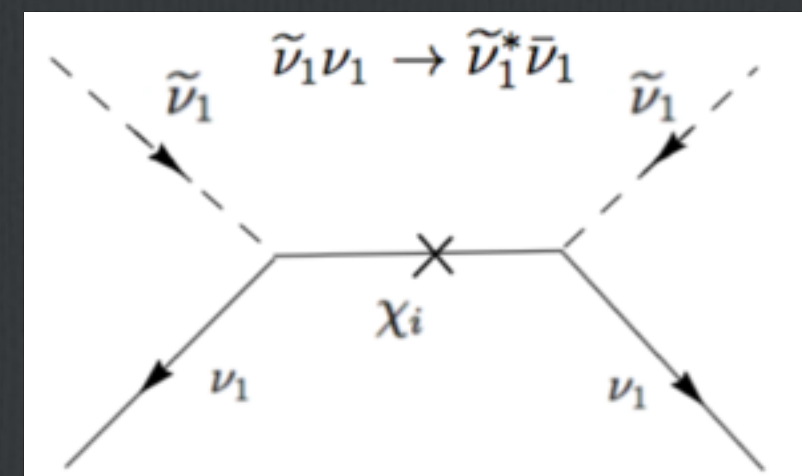
symmetry transfer from baryon to lepton thus sneutrino ceases at the electroweak sphaleron process out-of-equilibrium temperature T_{sp} ~100 GeV, thus using it here.

Oscillating sneutrino ADM from M*L*SIS

- **Charge-violating-scattering washing-out**

Snuetrino LSP is not the lightest particle under $U(1)_L$, so neutralinos can mediate the DM charge washing-out scattering processes

$$-\mathcal{L}_{wash} = \frac{1}{2} M_i^2 \bar{\chi}_i \chi_i + (y_{i1} \widetilde{\nu}_1^* \bar{\chi}_i P_L \nu_1 + h.c.)\,.$$



Since neutrinos are relativistic, the scattering may be much faster than the nonrelativistic DM annihilating during freeze-out

The condition for decoupling scattering *before* freeze-out

$$\Gamma_{CVS} = \frac{19845\,\mathrm{Zeta}[7]}{4} \frac{|y_{i1}^2|^2}{12\pi^3} \left(\frac{T}{M_i}\right)^4 \left(\frac{T}{m_{\tilde{\nu}_1}}\right)^2 T.$$

$$|y_{i1}^2|^2 \lesssim 0.41 x_d \left(\frac{M_i}{T_d}\right)^4 \frac{m_{\tilde{\nu}_1}}{M_{Pl}} = 0.33 \times 10^{-8} \left(\frac{M_i/m_{\tilde{\nu}_1}}{10}\right)^4 \left(\frac{x_d}{10}\right)^5 \left(\frac{m_{\tilde{\nu}_1}}{100\mathrm{GeV}}\right)$$

as long as neutralino can be at TeV scale, effective couplings below 10-2 are safe

Oscillating sneutrino ADM from M*L*SIS

- **How to annihilate away?**

  Since $\tilde{\nu}_1$ is dominated by the singlets and moreover M_N & y_N are disfavored to be large, large annihilation for $\tilde{\nu}_1$ requires extension; we introduce a light singlet S with sizable coupling $\lambda_n SNN^c$

- **Can it be embedded into NMSSM?**

  It is of interest to identify S with the one in the Z3-NMSSM

$$W = W_{\rm NMSSM} + (y_{N,i\alpha} L_i H_u N^c_\alpha + \lambda_{1,\alpha} S N_\alpha N^c_\alpha) + \frac{\lambda_{2,\alpha\beta}}{4M_*} S^2 N_\alpha N_\beta,$$

  Dynamically generations of all the mass scales, including the tiny lepton number violating term, from the dimension-five operator

👍 for TeV scale singlet VEV, it is naturally to obtain $M_N \ll$ eV even if the cut off scale M_*=Planck scale

Conclusions

- Oscillating asymmetric dark matter is not standard, but interesting & distinguishable (in indirect detection)

- It (~weak scale) naturally arises in the supsymmetric inverse seesaw models with maximally $U(1)_L$

thank you!