Hidden Charged Dark Matter and Its Relics

Hai-Bo Yu
University of California, Irvine

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Jonathan L. Feng, Huitzu Tu and HBY JCAP 0810:043,2008. arXiv:0808.2318 [hep-ph]

Jonathan L. Feng, Huitzu Tu, Manoj Kaplinghat and HBY in the preparation.

Outline

- Review of WIMPless miracle
- Thermal relics in hidden sectors
- Cosmological bounds on hidden charged dark matter
- Summary

For experimental signals, see

Feng, Kumar and Strigari arXiv:0806.3746 [hep-ph]
Feng, Kumar, Learned and Strigari arXiv:0808.4151 [hep-ph]

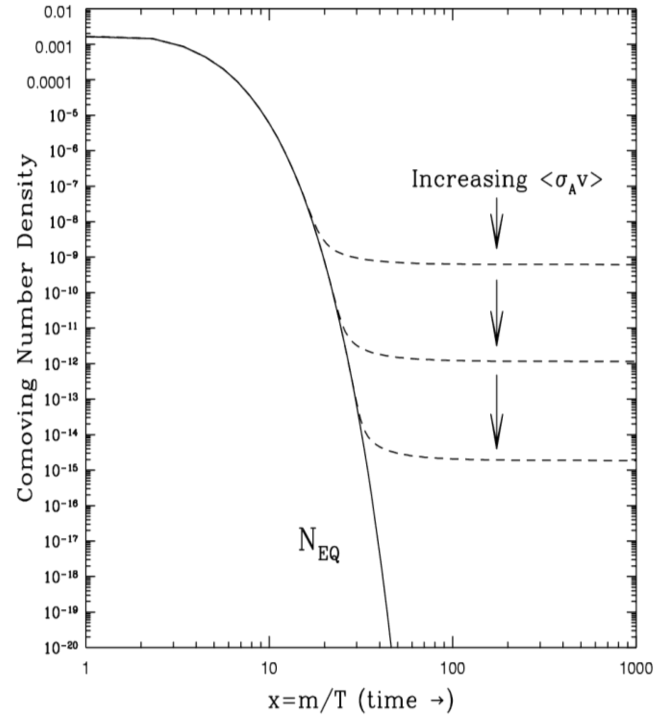
Expect new physics at TeV scale

- Gauge hierarchy problem
  weak scale vs. Planck scale

- Dark Matter
  ~20% of total mass budget of the Universe

WIMP miracle: $$\Omega h^2 \sim \frac{1}{\langle \sigma_A v \rangle} \sim \frac{m^2}{g^4}$$

g~gw, m~mw, Ωh^2~0.11



Kolb and Tuner (1990)

Supersymmetry
- Weak scale is stabilized by SUSY.
- MSSM has new particles (LSPs) for dark matter candidate.

Hidden sectors?

- But what do we really know about dark matter?
  ---Gravitational
  ---No strong, EM interactions
  ---Dark matter could be SM neutral, i.e. hidden.

- The idea of hidden sector has long history.
  Lee, Yang (1956); Gross, Harvey, Martinec, Rohm (1985), Schabinger, Wells (2005); Patt, Wilczek (2006); Strassler, Zurek (2006); Georgi (2007); Kang, Luty (2008), March-Russell, West, Cumberbatch, Hooper (2008); McDonald, Sahu (2008); Kim, Lee, Shin (2008); Krolikowski (2008); Foot (2008); …
- Hidden sector dark matter?
  ---WIMP miracle?
  ---connection to the gauge hierarchy problem?
  ---prediction?

WIMPless Miracle

- the ratio is important

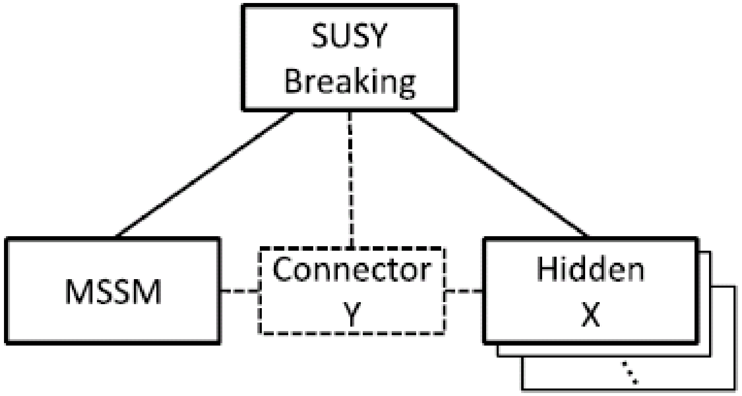
$$\Omega h^2 \sim \frac{1}{\langle \sigma_A v \rangle} \sim \frac{m^2}{g^4}$$

- SUSY partner mass of GMSB

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

- The ratio is determined solely by the SUSY breaking factor

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



Feng, Kumar (2008)

One can rescale (mx, gx) simultaneously while keep the ratio unchanged.

Thermal relics in the hidden sectors

- A GMSB-inspired concrete model for hidden sector DM.
- BBN and CMB constraints on the hidden sectors.
- Thermal dynamics with two independent thermal baths in the expanding universe.
- Lower mass limit from the thermal consideration.

A GMSB-inspired model

Feng, Tu and Yu (2008)

- SM gauge group SU(3)×SU(2)×U(1)
- One generation of matter fields, flavor-free model
- Assume gauge coupling unification $\tan\theta_W^h = \sqrt{3/5}$
- 2mx: others
  1.5mx: Z
  mx: stau (DM candidate),
  Massless: photon, (anti-)neutrino, gluon,
- Model parameters: $m_X,\ g_X,\ m_Z,\ \xi_{\rm RH} \equiv \frac{T^h_{\rm RH}}{T_{\rm RH}}$

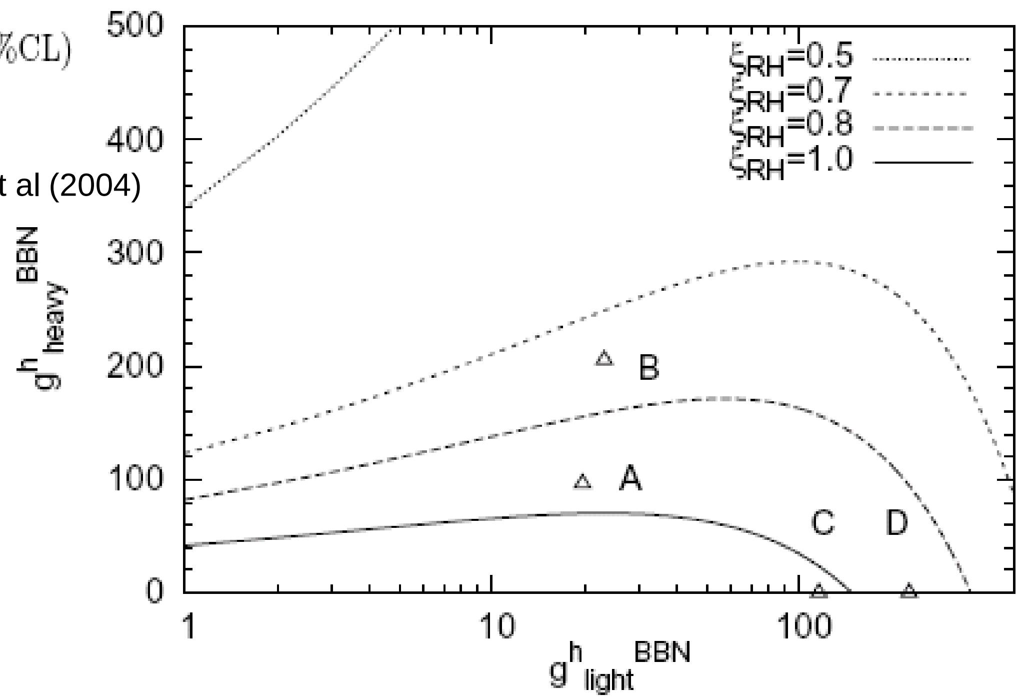
Note there is no good DM candidate in the usual MSSM with GMSB.
This scenario also works for AMSB. No good DM candidate in the MSSM with AMSB.

BBN constraints on light degree of freedom

$$g_*^h(T_{\rm BBN}^h)\left(\frac{T_{\rm BBN}^h}{T_{\rm BBN}}\right)^4 = \frac{7}{8}\cdot 2\cdot(N_{\rm eff}-3)\leq 2.52\ (95\%{\rm CL})$$

$$N_{\rm eff} = 3.24 \pm 1.2\ (95\%\ {\rm CL})$$

Cyburt et al (2004)



Feng, Tu and Yu (2008)

---Very small number of light degree of freedom if two sectors have the same T at BBN.

---Hidden sector is colder at BBN. Two ways: colder reheating temperature; more light d.o.f in the hidden sector.

$$g_*^h(T^h) = g_{*S}^h(T^h) = \begin{cases} 116.25\,(228.75)\,, & T^h \geq 2m_X \\ 19.75\,(23.25)\,, & T^h \leq m_X \end{cases}$$

A, B $\quad T^h_{BBN} < m_X < T^h_{RH}$

$$g_{*S}T^3R^3 = \text{Constant}$$

C, D $\quad m_X < T^h_{BBN}/2$

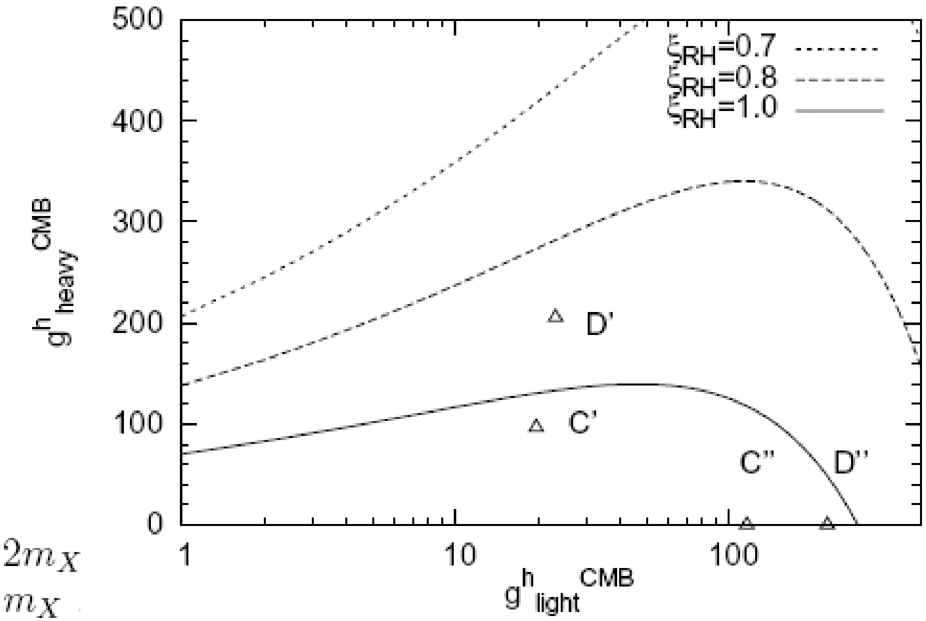
CMB constraints

$$g_*^h(T^h_{\rm CMB}) \left(\frac{T^h_{\rm CMB}}{T_{\rm CMB}}\right)^4 = \frac{7}{8} \cdot 2 \cdot (N_{\rm eff} - 3.046) \left(\frac{T_\nu}{T_\gamma}\right)^4 \le 1.30\ (68\%\ {\rm CL})$$

$$T_\nu/T_\gamma \;=\; (4/11)^{1/3}$$

$$g^{h\,{\rm CMB}}_{\rm heavy} \le \left(\frac{4.14}{\xi_{\rm RH}}\right)^3 \left(g^{h\,{\rm CMB}}_{\rm light}\right)^{\frac{1}{4}} - g^{h\,{\rm CMB}}_{\rm light}$$

$$g_*^h(T^h) = g_{*S}^h(T^h) = \begin{cases} 116.25\,(228.75)\,, & T^h \ge 2m_X \\ 19.75\,(23.25)\,, & T^h \le m_X \end{cases}$$



Feng, Tu and Yu (2008)

C', D' $\quad T^h_{\rm CMB} < m_X < T^h_{\rm RH}$

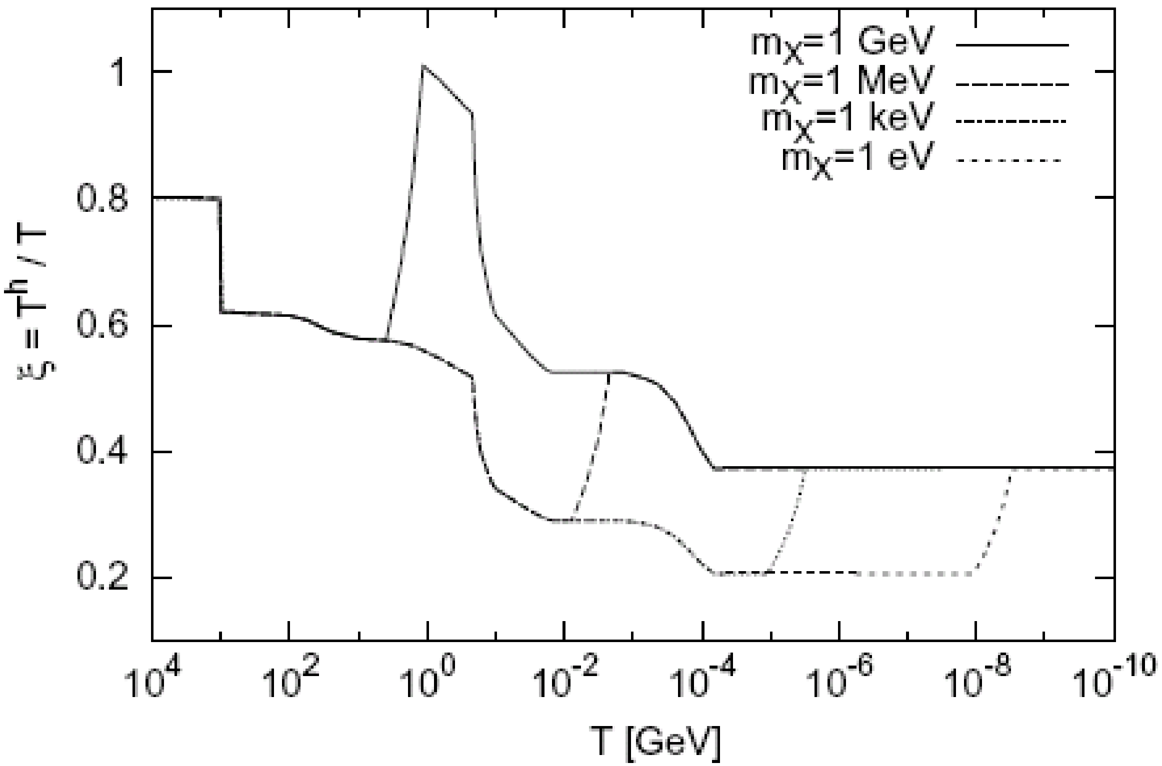
C'', D'' $\quad m_X < T^h_{\rm CMB}/2$

Temperature evolution of hidden sectors

Assume entropy is conserved in both sector independently

$$g_{*S} T^3 R^3 = \text{Constant}$$

$$\frac{g^h_{*S}(T^h_{\rm BBN}) T^{h3}_{\rm BBN}}{g^h_{*S}(T^h_{\rm RH}) T^{h3}_{\rm RH}} = \frac{g_{*S}(T_{\rm BBN}) T^3_{\rm BBN}}{g_{*S}(T_{\rm RH}) T^3_{\rm RH}}$$



Feng, Tu and Yu (2008)

$$g^h_*(T^h) = g^h_{*S}(T^h) = \begin{cases} 116.25\,(228.75)\,, & T^h \geq 2m_X \\ 19.75\,(23.25)\,, & T^h \leq m_X \end{cases}$$

Boltzman equations with two thermal baths

$$\frac{dn}{dt} = -3Hn - \langle \sigma_A v \rangle (T^h) \left[n^2 - n_{\rm eq}^2 (T^h) \right]$$

$$H(T) = \left[\frac{4\pi^3 G_N}{45} g_*^{\rm tot}(T)\, T^4 \right]^{\frac{1}{2}} \qquad g_*^{\rm tot}(T) = g_*(T) + g_*^h(T^h) \left(\frac{T^h}{T} \right)^4$$

---Both sectors have contributions to the Hubble expansion rate.

---The thermally-averaged product of cross section and Moller velocity and the number density are only determined by the hidden sector temperature.

Use visible sector T as "Clock"

$$t \to x \equiv \frac{m_X}{T} \qquad n \to Y \equiv \frac{n}{s}$$

Sit in the hidden sector

$$t \to x^h \equiv \frac{m_X}{T^h} \qquad n \to Y^h \equiv \frac{n}{s^h}$$

Annihilation Channels

$$\tilde{\tau}\tilde{\tau} \longrightarrow \nu\overline{\nu}, \gamma\gamma, \gamma Z$$

$$\langle\sigma_A v\rangle(T^h) = \frac{g_X^4}{m_X^2}\left[a_0 + a_1\left(\frac{m_X}{T^h}\right)^{-1} + a_2\left(\frac{m_X}{T^h}\right)^{-2} + \dots\right],$$

$$a_0 = \left[\frac{1}{8\pi} + \frac{1}{4\pi}\left(1 - \frac{m_{Z^h}^2}{4m_X^2}\right)\tan^2\theta_W^h\right]\sin^4\theta_W^h$$

$$a_1 = \frac{3}{2}\left[-\frac{1}{6\pi} - \frac{1}{3\pi}\tan^2\theta_W^h + \frac{1}{12\pi}\frac{1}{\cos^4\theta_W^h\left[\left(-4 + \frac{m_{Z^h}^2}{m_X^2}\right)^2 + \frac{m_{Z^h}^2\Gamma_{Z^h}^2}{m_X^4}\right]}\right]\sin^4\theta_W^h$$

---Photon channel has overall ½ smaller than photon Z channel due to the identical final states.

---Neutrino channel is P-wave suppressed. Not surprise.

---Accuracy of the dimensional analysis $\langle\sigma_A v\rangle \sim \frac{g_X^4}{m_X^2}$

Approximation formulas

$$Y_{\rm eq} = 0.145(g/g_{*S})x^{3/2}\xi^{3/2}e^{-x/\xi}$$

$$x_f \approx \xi \ln\left[0.038\, M_{\rm Pl}\, m_X\, \sigma_0 (g/\sqrt{g_*^{\rm tot}})\, \xi^{3/2}\, \delta(\delta+2)\right] - \frac{1}{2}\xi \ln\left\{\xi \ln\left[0.038\, M_{\rm Pl}\, m_X\, \sigma_0 (g/\sqrt{g_*^{\rm tot}})\, \xi^{3/2}\, \delta(\delta+2)\right]\right\}$$

$$Y_0 \approx \frac{3.79\, x_f}{\left(g_{*S}/\sqrt{g_*^{\rm tot}}\right) M_{\rm Pl}\, m_X\, \sigma_0} \qquad \sigma_0 = a_0 g_X^4/m_X^2$$

Feng, Tu and Yu (2008)

---Set xi to 1, we get formulas for one thermal bath case.
---delta takes 0.2-0.5 from the fitting.
---This approximation yields agreements typically better than 3%.

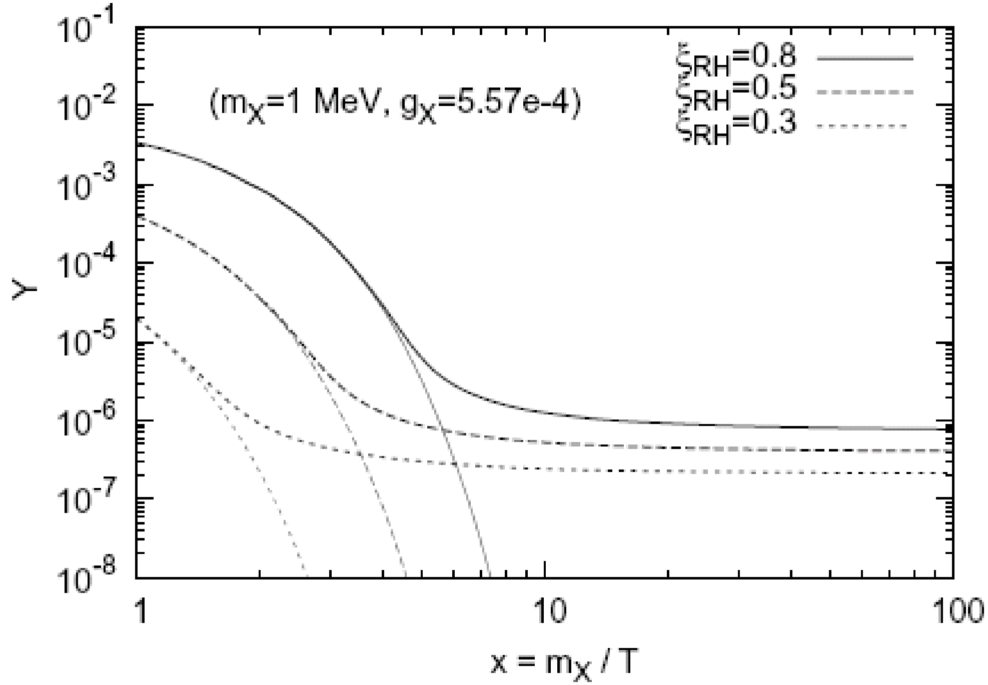
Freezeout behavior with different reheating temperature of hidden sectors

$$Y_{\rm eq} = 0.145(g/g_{*S})x^{3/2}\xi^{3/2}e^{-x/\xi}$$

$$x_f \approx \xi \ln\left[0.038\, M_{\rm Pl}\, m_X\, \sigma_0 (g/\sqrt{g_*^{\rm tot}})\, \xi^{3/2}\, \delta(\delta+2)\right] - \frac{1}{2}\xi \ln\left\{\xi \ln\left[0.038\, M_{\rm Pl}\, m_X\, \sigma_0 (g/\sqrt{g_*^{\rm tot}})\, \xi^{3/2}\, \delta(\delta+2)\right]\right\}$$

$$Y_0 \approx \frac{3.79\, x_f}{\left(g_{*S}/\sqrt{g_*^{\rm tot}}\right) M_{\rm Pl}\, m_X\, \sigma_0}$$

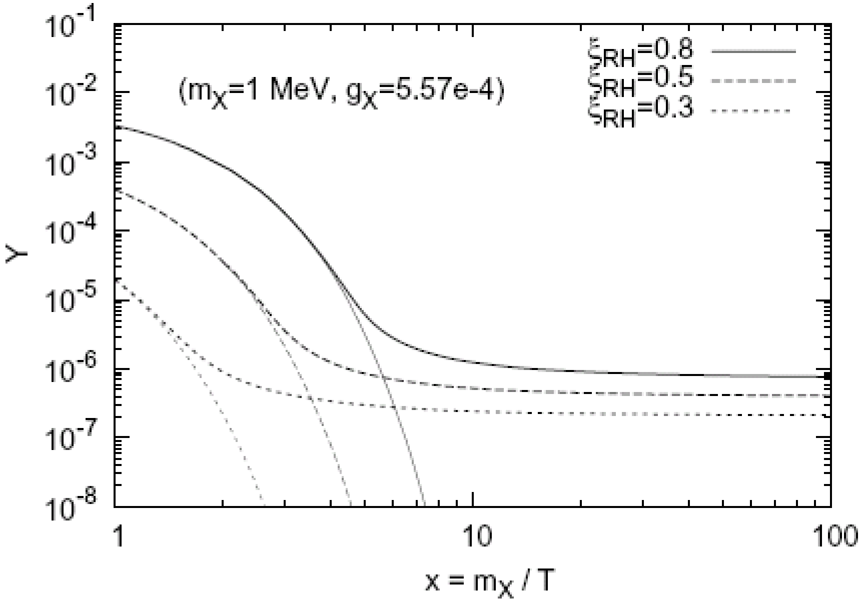
$$\Gamma = n\langle \sigma_A v\rangle$$

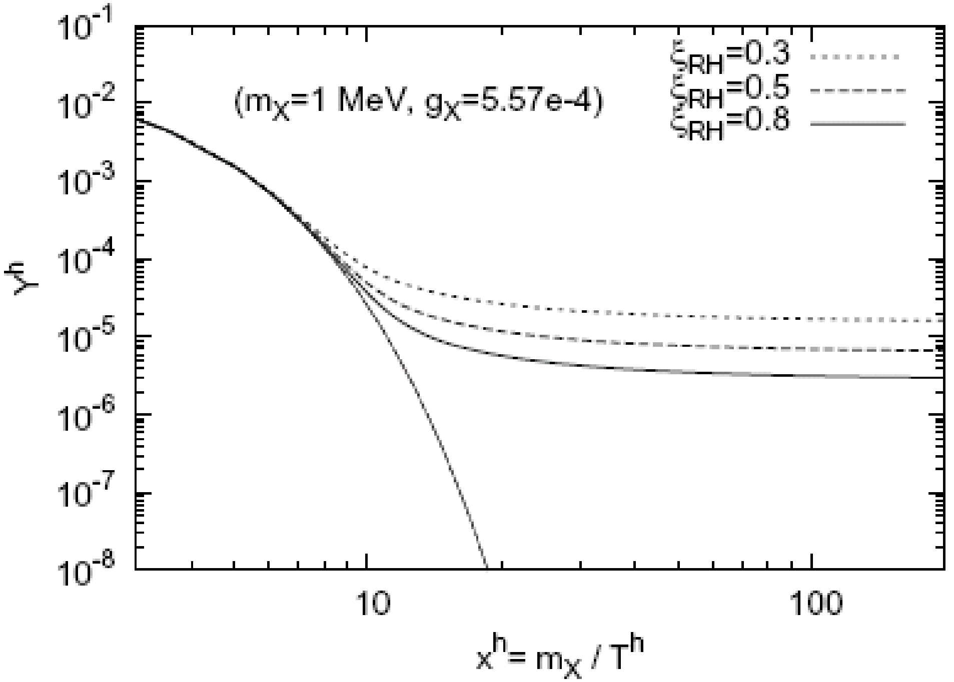


Feng, Tu and Yu (2008)

For different reheating temperature, averaged cross section is nearly the same due to S-wave dominance.

Sit in the hidden sector





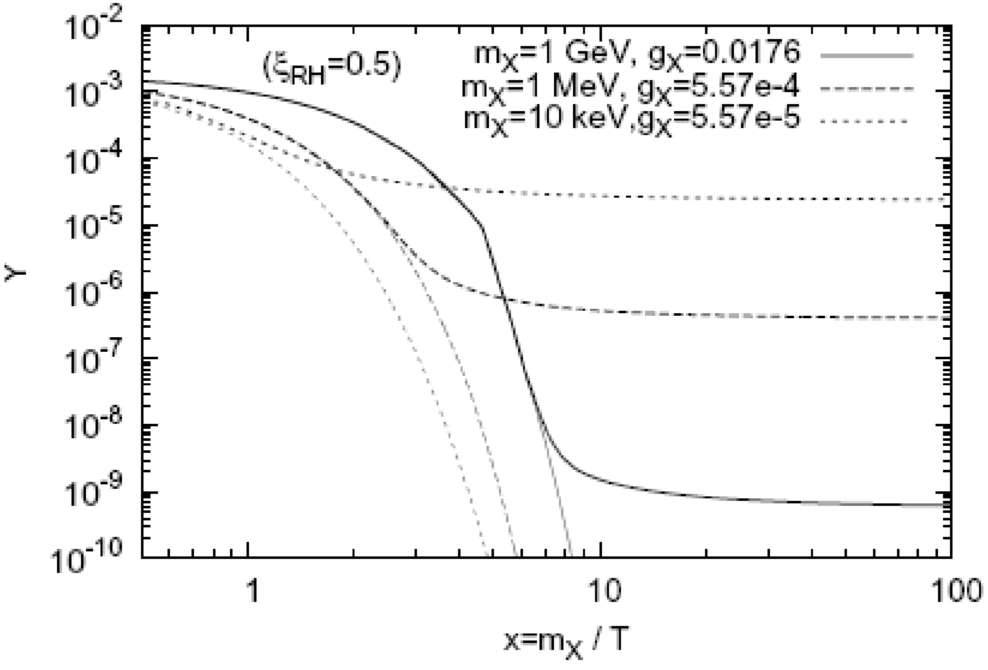
Feng, Tu and Yu (2008)

Inconsistent?

$$n_0 = Y s_0 = Y^h s_0^h$$

Freezeout with different mass

---Larger mass, smaller number density at present time, freezout occurs later, larger coupling.



Feng, Tu and Yu (2008)

Relics in the hidden sector

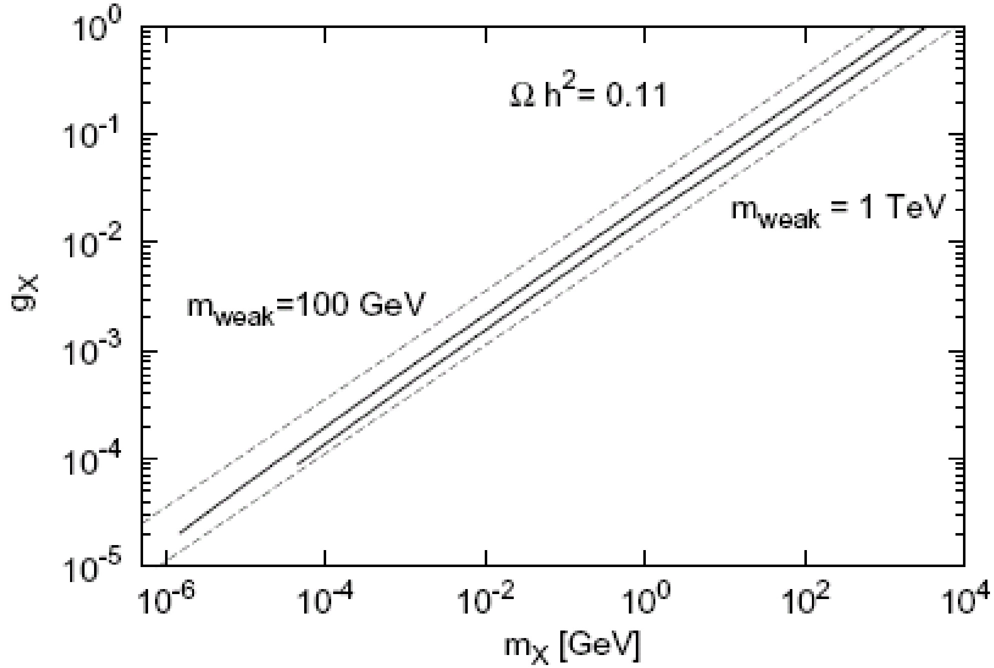
Numerically solving Boltzman equations to get (mx, gx).

---Two solid contours essentially follow the scaling relation mx~gx^2.

---The parameters that give correct relic density are those that give weak scale MSSM masses (WIMPless miracle).

---The dimensional analysis is confirmed in this concrete model.

---Colder hidden sector requires smaller coupling to get correct relic abundance for given mass.



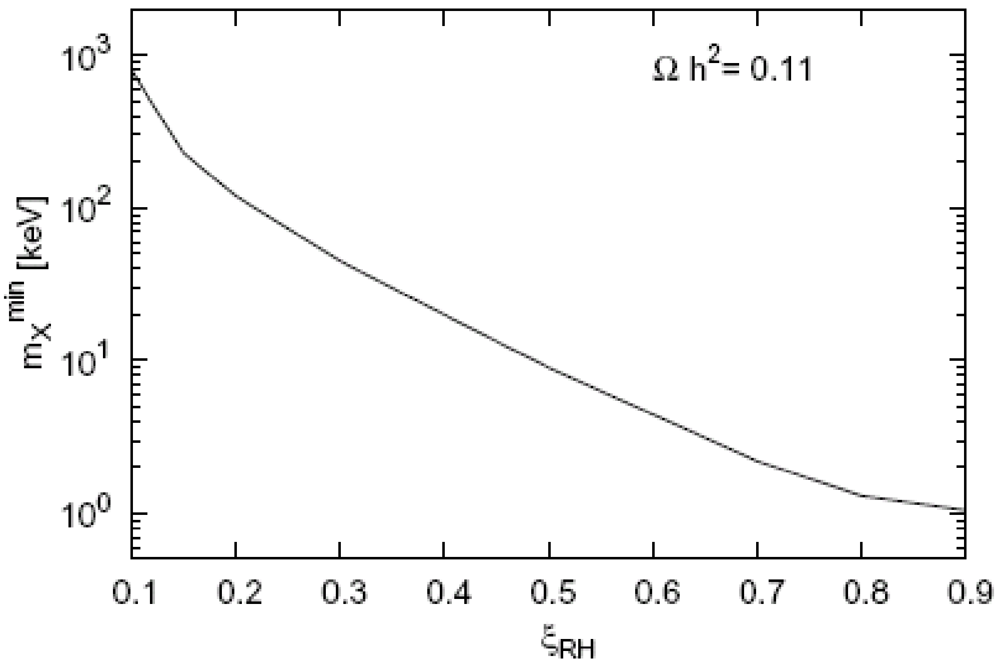
Feng, Tu and Yu (2008)

Lower mass limit

---The lower mass limit is derived by requiring freezeout xfh=mx/Th>3 and correct relic abundance.

---Lower mass limit goes up with colder hidden sector.

---The WIMPless framework may be valid at least down to dark matter masses of mx~keV.



Feng, Tu and Yu (2008)

WIMP scenario mass range (100GeV, TeV)

WIMPless scenario mass range (keV, TeV)

Some Comments

- We present a concrete example for WIMPless DM scenario.

- The choice of the hidden stau as the DM candidate is motivated by the stability of DM.

- We should check cosmological bounds on it. Hidden stau is charged under the unbroken hidden U(1)!

Effects of the long range interaction

- Long range interactions lead to the exchange of the kinetic energy between DM particles. DM has collision.

- The annihilation cross section is enhanced in small velocity regime due to the Sommerfeld effect.

- DM particles may form bound state. The rate goes ~1/v.

- Kinetic decoupling occurs later, DM has longer free-streaming length.

Scattering due to the Coulomb interaction

$$\frac{d\sigma}{d\Omega} = \frac{\alpha_X^2}{4m_X^2 v^4 \sin^4(\theta/2)}$$

- The cross section has 1/v dependence. For our Galaxy V~10^(-3) , a huge factor!
- The elastic scattering due to the Coulomb force causes the energy and momentum exchange between DM particles. DM has collision. [L. Ackerman, M. R. Buckley, S. M. Carroll and M. Kamionkowski arXiv:0810.5126 [hep-ph]]
- However observations suggest that DM is effectively collisionless. The collision of DM cause the more spherical halo. [J.~Miralda-Escude arXiv:astro-ph/0002050]
- Galactic dynamics set the bound on the parameter space (mx, alpha_x).

The rate of energy transfer

$$\dot{E}_k = \int dv d\Omega (\frac{d\sigma}{d\Omega}) v n f(v) \delta E_k$$

Feng, Tu, Kaplinghat and Yu in the preparation.

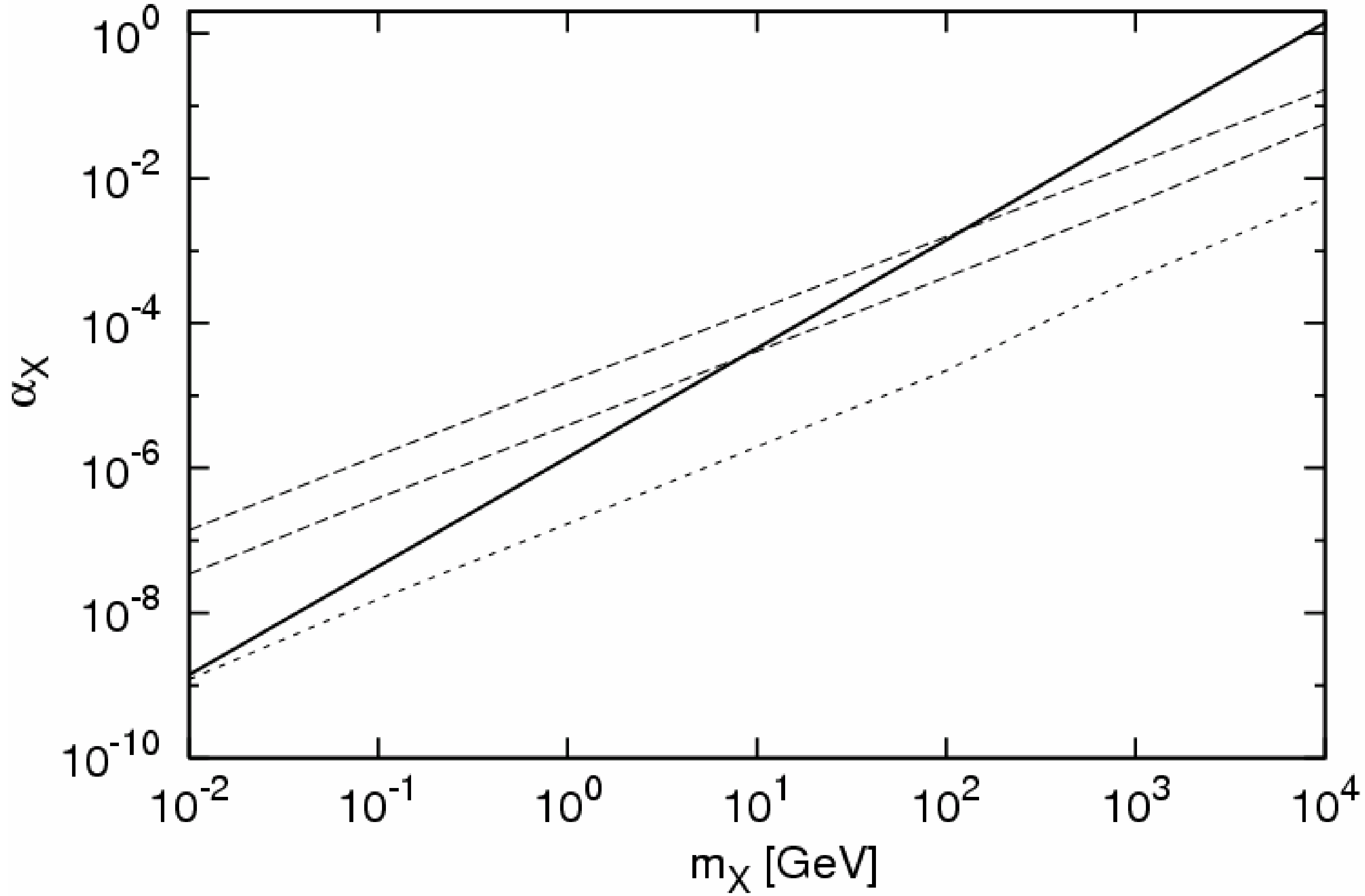
- Energy exchange in the each collision

$$\delta E_k = E_k (1 - \cos\theta)$$

- f(v) is the velocity distribution, and n is the umber density of the DM particle n=density/DM mass. We take f(v) as Maxwellian distribution.

- We demand the mean free time greater than the age of the Universe and set bounds on coupling and mass

$$\tau \equiv E_k / \dot{E}_k \sim \frac{m_X^3 v_0^3}{4\sqrt{\pi}\alpha_X^2 \rho_X} \ln^{-1}(\frac{(b_{\max} m_X v_0^2 / a_X)^2 + 1}{2}) \geq 10^{10}\text{years}$$



- Galactic dynamics in fact allows hidden charged dark matter, and the allowed parameter space is quite reasonable.
- Typically for DM particle mass 100GeV, the hidden fine structure constant should be smaller than ~0.001 to satisfy the bound.
- We find this is the strongest bound.

Feng, Tu, Kaplinghat and Yu in the preparation.

Sommerfeld effect

- If there is long range attraction force between two particles, the annihilation cross section will be enhanced.
- $$S_k \sim \frac{\alpha_X}{v} \qquad \sigma_{\rm ann} \to \sigma_{\rm ann} S_k$$
- This enhancement is not important in the early Universe.

Small velocity dispersion in Protohalos

- Protohalos have masses around

$$M_c \sim 33(T_{\rm kd}/10{\rm MeV})^{-3} M_\oplus$$

- Protohalos collapse to $\rho \sim 178\overline{\rho}(z_c)$

- The velocity dispersion is

$$v \sim G^{1/2} M_c^{1/3} \rho^{1/6} \simeq 6.0 \times 10^{-9} (M_c/M_\oplus)^{1/3} (z_c/200)^{1/2}$$

- Annihilation cross section is strongly enhanced due to the small velocity dispersion.

Bounds from CMB

$$f \simeq \Gamma_{\rm ann} t \sim \frac{178\Omega_m \rho_{\rm crit}(1+z_c)^3}{m_X} \langle \sigma_{\rm ann} S_k v \rangle \, t \leq 0.1$$

$$t \simeq 2 \times 10^{14} (z_c/200)^{-3/2} s$$

- The fraction is $f \sim 10^{-6} - 10^{-4}$ for the allowed mass range.
- The annihilation generate photon. However it will not distort the CMB spectrum because it is hidden.
- Otherwise the fraction has to be smaller than 10^(-9). [M, Kamionkowski and S. Profumo, arXiv:0810.3233 [astro-ph]]

Bound state formation

- Positive/negative charged staus can form bound states.
- Staus has to lose their kinetic energy by radiating away photon and fall to some energy level of the bound state.
- And due to the ionization process, the bound state formation issue is more important when the temperature is smaller than the binding energy.

$$\sigma_{\rm rec} = \frac{2^8\pi^2}{3}\frac{\alpha_X}{m_\chi}\frac{1}{m_\chi}\frac{B_n}{m_\chi v^2}\left(\frac{B_n}{B_n+\frac{1}{2}m_\chi v^2}\right)^2 \cdot \frac{e^{-4\sqrt{\frac{2B_n}{m_\chi v^2}}\tan^{-1}\sqrt{\frac{m_\chi v^2}{2B_n}}}}{1-e^{-2\pi\sqrt{\frac{2B_n}{m_\chi v^2}}}}$$

$$E_n = -\alpha_X^2\, m_\chi/4n^2 \equiv -B_n$$

Bounds from the Galaxy and early Universe

- For the Galactic Halo, the bound state formation rate is order magnitude 10^(-31) per second.

- For the early Universe,

$$\Gamma_{\mathrm{Bound}}(T \sim B_1) \ll H(T \sim B_1)$$

- The bound state formation rate is small if parameters satisfy the galactic dynamics bound (they also should give correct relic abundance.).

- Compare to the scattering process, bound state formation is a higher order process

$$\sigma_{\mathrm{Scattering}} \sim \frac{\alpha_X^2}{m_X^2} \qquad \sigma_{\mathrm{Bound}} \sim \frac{\alpha_X^3}{m_X^2}$$

Feng, Tu, Kaplinghat and Yu in the preparation.

Kinetic equilibrium

- After freezeout, the DM particle still keep contact with thermal bath through elastic scattering with the relativistic degree of freedom.
- Elastic scattering does not change the number density of DM particle while transfers momentum to DM and keep it in the kinetic equilibrium.
- When the Universe cools down, the kinetic decoupling occurs, DM particle begins free-streaming.
- Decoupling temperature is critical for small structure formation.

Kinetic decoupling

- Processes keep stau in the kinetic equilibrium

$\tilde{\tau}\nu \leftrightarrow \tilde{\tau}\nu \qquad \tilde{\tau}\gamma \leftrightarrow \tilde{\tau}\gamma$

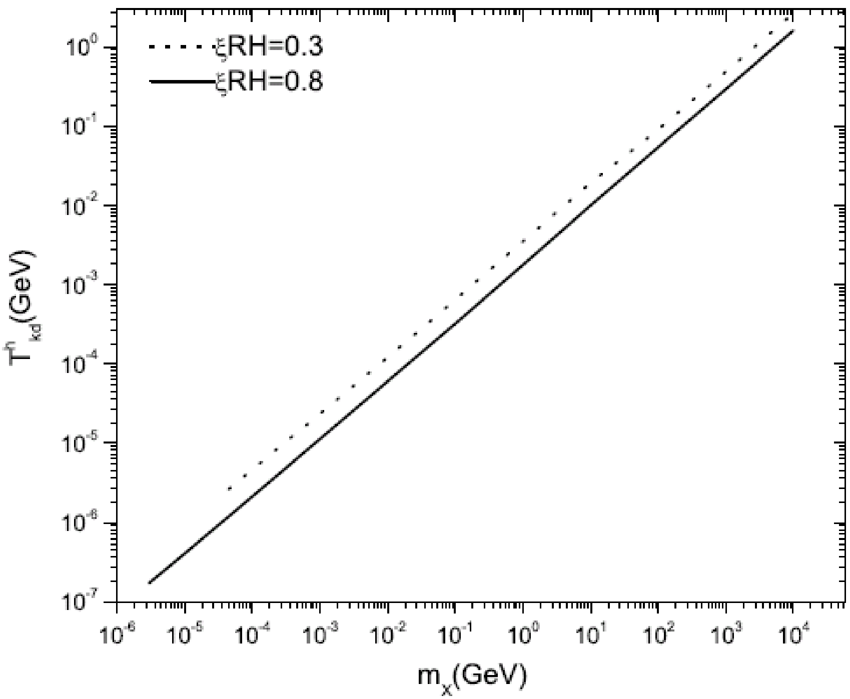
- Decoupling occurs when $\Gamma_{\rm kd} \lesssim H$

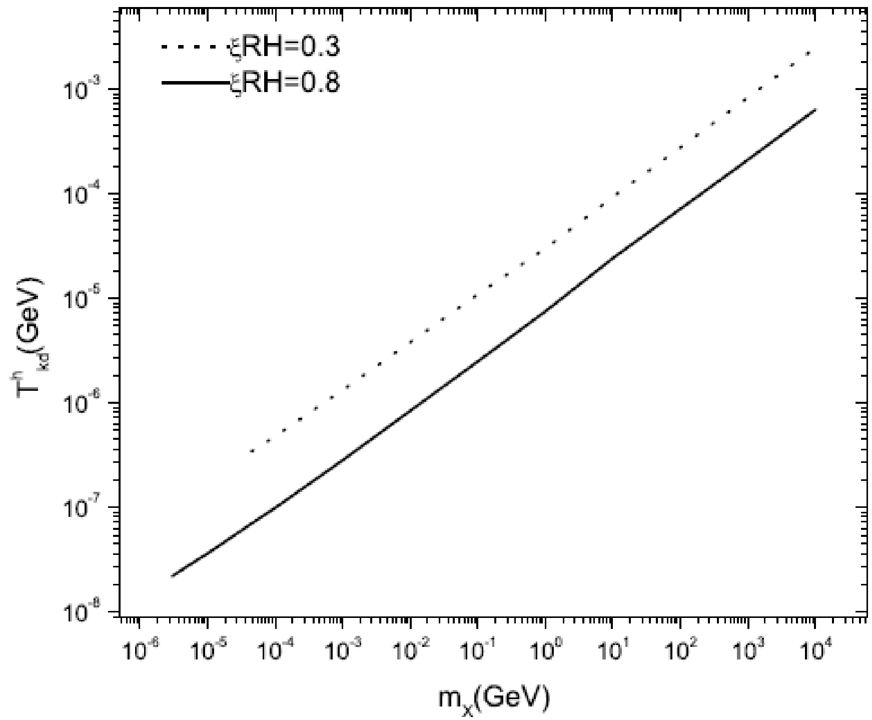
decoupling temperature $\Gamma_{\rm kd}(T_{\rm kd}) = H(T_{\rm kd})$

- Kinetic decoupling happens in two stages, neutrino process decouples first, then photon process.

$$|\mathcal{M}(\tilde{\tau}\nu \leftrightarrow \tilde{\tau}\nu)|^2_{t=0} = \frac{4g_X^4 m_X^4 \tan^4\theta_W^h}{m_Z^2(m_Z^2+\Gamma_Z^2)}\left(\frac{E}{m_X}\right)^2 \quad |\mathcal{M}(\tilde{\tau}\gamma \leftrightarrow \tilde{\tau}\gamma)|^2_{t=0} = 4g_X^4 \sin^4\theta_W^h$$

Decoupling temperature





[Feng, Tu, Kaplinghat and Yu, in the preparation]

---Larger mass, decouple earlier.

---Neutrino channel decouples earlier. (For the usual WIMP, Tkd~ order 10MeV.)

---Colder hidden sector, decoupling occurs earlier.

---Free-streaming length $\lambda_{\rm FS} \propto m_X^{-1/2} T_{\rm kd}^{-1/2}$ which sets more correct lower mass bound.

Summary

- WIMPless framework keeps WIMP miracle for hidden sector DM.
- Two thermal baths have interesting implications on thermal behaviors of the DM particle .
- We study variant bounds on the hidden charged DM. Hidden charged DM is allowed.
- Hidden charged DM has consequence on the small structure formation.