Minimal Dark Matter and Direct Detection as a Probe of Reheating

Masahiro Ibe [*ICRR & IPMU*]
10/22/2013 @ Tohoku Forum for Creativity

Based on arXiv:1310.xxxx (B.Feldstein, MI, T.T.Yanagida)

Introduction

✔ What do we learn from the discovery?

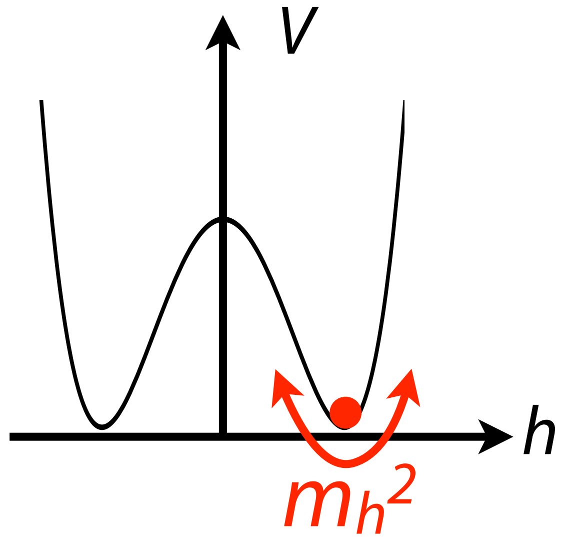
1. Higgsless models are almost excluded !
2. Higgs is more like an elementary scalar !

In the simplest implementation...

$$V = -m_{higgs}^2/2\, h^\dagger h + \lambda/4\, (h^\dagger h)^2$$

$$m_{higgs} = \lambda^{1/2} v \quad [v=174.1\text{GeV}]$$

$$m_{higgs} \sim 125\text{GeV} \longrightarrow \lambda \sim 0.5$$



✔ The quartic coupling λ is small and this simple elementary scalar Higgs description works consistently !

The Minimal Standard Model works !

Introduction

✓ Naturalness ?

The mass of the elementary Higgs boson is not protected by any symmetries...

Why $m_{higgs}^2 \ll M_{GUT}^2, M_{PLANCK}^2$?

- It is quite reasonable to expect new physics behind the Standard Model at around *O(100)GeV - O(1)TeV* !
  - Supersymmetric Standard Models ?
  - Extra Dimensional Models ?
  - Composite Higgs Models ?

These are very exciting possibilities to be tested at the *14TeV* run of the LHC, at the ILC, at the *100TeV* collider experiments !

Introduction

✔ So far, we have no direct observational data which support these possibilities from collider experiments...

cf.) No supersymmetric particles have been discovered at the LHC ;

squark/gluino mass > *1.8 TeV*
gluino mass >*1.4 TeV* for squark >> *TeV*

Negative pressure on Supersymmetry as a solution to the *Naturalness problem*...

⚠ We have no imminent need to give up the *Naturalness problem* as a guiding ~~principle~~ strategy at all.

As Andrew emphasized in his talk, we might need to start thinking differently.

The success of the simplest Higgs mechanism might suggest that *Simplicity* is a more important guiding strategy in constructing models of new physics...

What can we think of if we impose *Simplicity* on dark matter ?

Introduction

✓ We take $SU(2)_L$ charged dark matter, so-called minimal dark matter, as an example of *Simple* dark matter model.

$Y \neq 0$: hypercharged minimal dark matter
→ a viable *WIMPZILLA* candidate for $M_{DM} > 10^7\ GeV$.

✓ Next generation direct detection experiments reach to $M_{DM} = 10^{10\text{-}11} GeV$.

✓ Through the direct detection experiments we can determine the reheating temperature to $T_R \sim 10^{7\text{-}9} GeV\ (M_{DM}/2\text{x}10^{10} GeV)$.

[*cf.* $Y = 0$: minimal dark matter ['05 Cirelli, Fornengo, Strumia]
→ a viable WIMP candidate but difficult
to be detected at direct detection experiments]

Putting *Simplicity* on Dark Matter

- How to impose Simplicity on the dark matter sector ?

  No unique definition of simplicity...
  There are tons of ways...,

- Let us explore the extreme cases :

  The dark sector sector consists of just a single new particle with the charges under the Standard Model gauge group.

  [cf. neutral single dark matter with new higgs interactions
  ('04 Davoudiasl, Kitano, Li, Murayama; Joseph's talk)]

  - (Integer) Charged dark matter
    Neutron star lifetime ['90 Gloud et.al.],
    $\rightarrow M_{DM} > O(10^{17})\ GeV$ [e.g. `01 Perl et.al.]

  - Colored dark matter (SIMP)
    constrained by direct detection experiments, Earth heating
    $\rightarrow M_{DM} > O(10^{16})\ GeV$ [e.g. `07 Mack et.al.]

Putting *Simplicity* on Dark Matter

✔ How about $SU(2)_L$ charged dark matter ?

The dark matter particle is the neutral component in k-tuplet of $SU(2)_L$ with $U(1)_Y$ hypercharge Y.

$$Q = T_3 + Y = 0$$

ex) doublet $(k=2) : |Y| = 1/2$ triplet $(k=3) : |Y| = 0, 1$

quartet $(k=4) : |Y| = 1/2, 3/2$ quintet $(k=5) : |Y| = 0, 1, 2$

$SU(2)_L$ charged dark matter

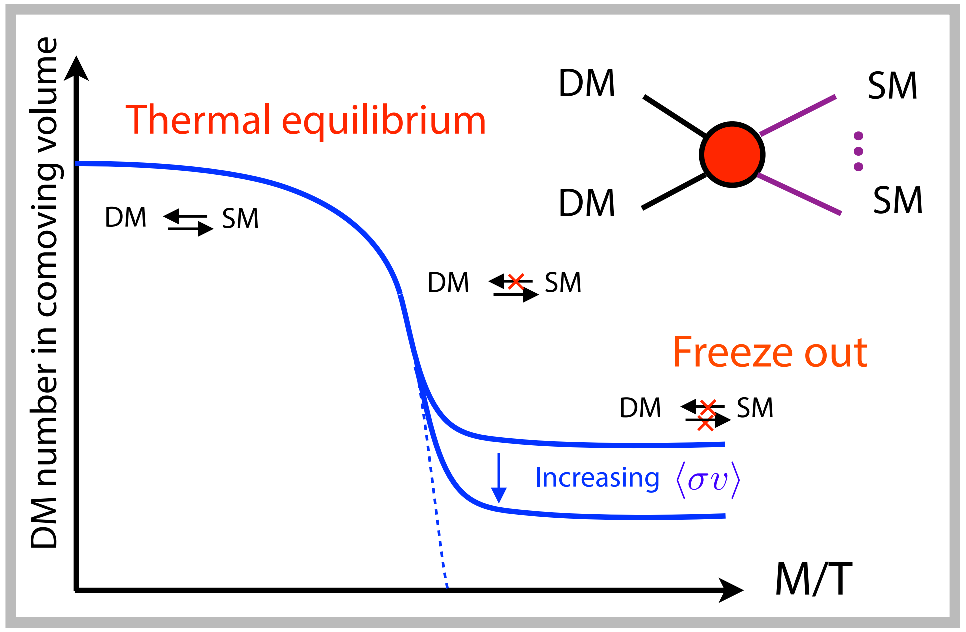
- $Y = 0$: minimal dark matter ['05 Cirelli, Fornengo, Strumia]
- $Y \neq 0$: hypercharged minimal dark matter

Stability? We simply assume there is a Z_2 symmetry.

For k > 5 (7), fermionic (scalar) dark matter is automatically stable due to an accidental symmetry ['05 Cirelli, Fornengo, Strumia]...

Putting *Simplicity* on Dark Matter

✔ *SU(2)$_L$* charged dark matter can be a good candidate of weakly interacting massive particle (WIMP) !



- DM is in thermal equilibrium for $T > M_{DM}$.
- For $M_{DM} < T$, DM is no more created
- DM is still annihilating for $M_{DM} < T$ for a while...
- DM is also diluted by the cosmic expansion
- DM cannot find each other and stop annihilating at some point
- DM number in comoving volume is frozen

The WIMPs works for the annihilation cross section : $\langle \sigma v \rangle \sim 10^{-9} \mathrm{GeV}^{-2}$

$$\Omega_{DM} h^2 \simeq 0.1 \times \left(\frac{10^{-9}\ \mathrm{GeV}^{-2}}{\langle \sigma v \rangle} \right)$$

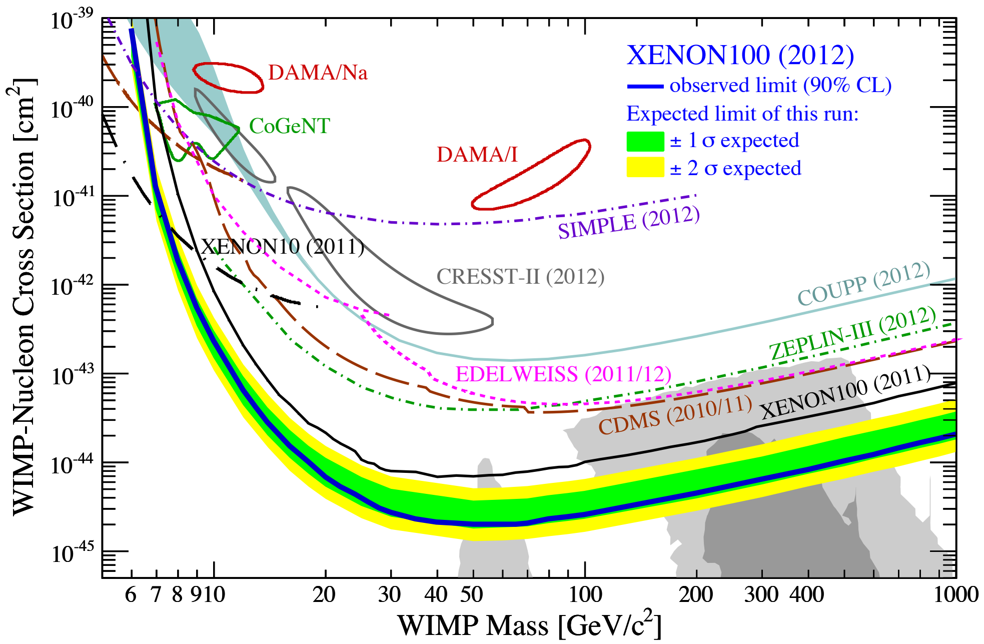
✔ Minimal dark matter annihilate into the vector bosons and the fermions!

$$\langle \sigma v \rangle \simeq \frac{(g_2^4 (2 + 17k^2 - 19) + 4Y^4 g_Y^4 (41 + 8Y^2) + 16 g_2^2 g_Y^2 (k^2 - 1))}{256 k \pi k M_{\mathrm{DM}}^2}$$

→ good candidate for the WIMP for $M_{DM} = O(1)$*TeV* !

Hypercharged Minimal Dark Matter

- Direct dark matter detection experiments have put severe constraints on hypercharged minimal dark matter!



Nucleus scattering rate via Z-boson exchange

$$\sigma_{\chi N} = \frac{G_F^2 \mu_N^2}{2\pi} Y^2 (N - (1 - 4\sin\theta_W) Z)^2$$

(*x4* for scalar DM)

G_F : Fermi constant, (N,Z) # of (n,p)

The strongest limit from the XENON100 experiment :

$$\sigma_{\chi \mathrm{Xe}} \gtrsim 6 \times 10^{-36} \mathrm{cm}^2 \times \left(\frac{M_{\mathrm{DM}}}{1\,\mathrm{TeV}} \right)$$

→ $M_{DM} > 30$ PeV x $(2Y)^2$

Hypercharged minimal dark matter cannot be a WIMP candidate...

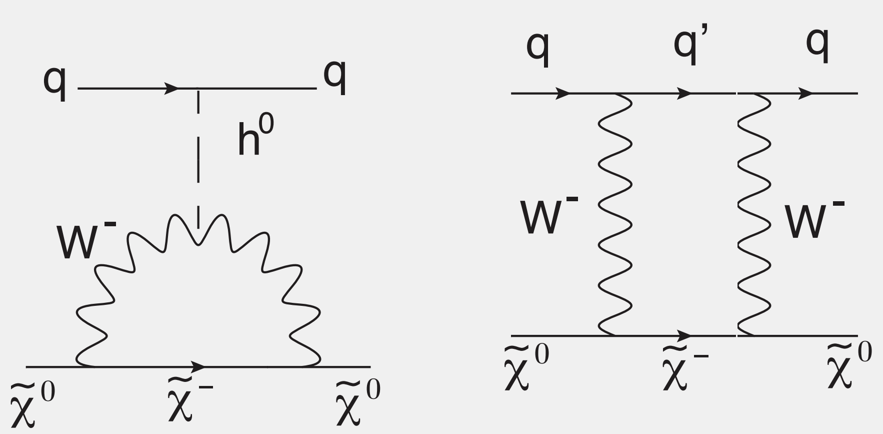
Hypercharged Minimal Dark Matter

For comparison...

- ✔ Direct dark matter detection experiments of minimal dark matter ($Y=0$)

  - ✔ The scattering is highly suppressed at the tree-level, due to the absence of tree-level interactions with Z nor Higgs.

  - ✔ At the higher loop level, the cross section on a nucleon is estimated to be $O(10^{-47})\mathrm{cm}^2$, which is two-orders of magnitude smaller than the current limit...



One-loop diagrams which contribute to the triplet DM-nucleon scatterings.

['10 Hisano, Ishiwata, Nagata]

Minimal dark matter ($Y=0$) is a viable candidate of the WIMP !

Hypercharged Minimal Dark Matter

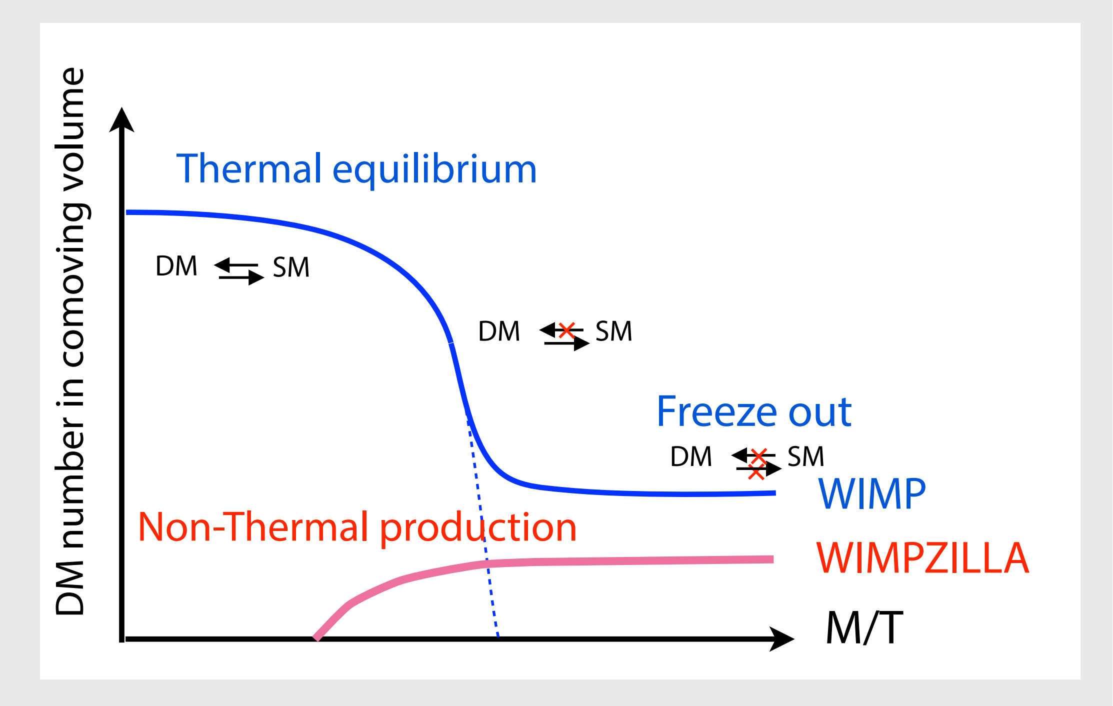
$SU(2)_L$ charged dark matter

- $Y = 0$: minimal dark matter
  → a viable WIMP candidate !
- $Y \neq 0$: hypercharged minimal dark matter
  → excluded as a WIMP candidate !

Are hypercharged minimal dark matter scenarios excluded ?

- ✓ Let us simply discard the assumption that dark matter has attained thermal equilibrium after inflation...

- ✓ Instead, let us assume that the dark matter density is determined by a delicate choice of the dark matter mass and the temperature after inflation assuming $M_{DM} > T_R$.



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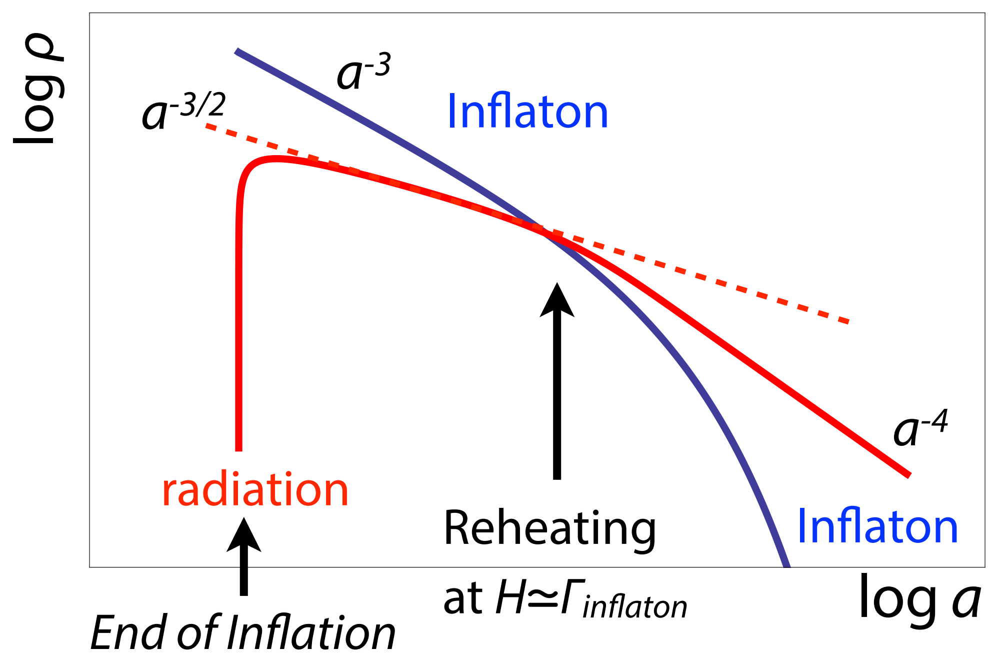
Hypercharged minimal dark matter is revived as the so-called *WIMPZILLA* without extending the dark matter sector at all!

[WIMPZILLA ['98 Kolb,Chung, Riotto]: weakly interacting *very heavy* dark matter]

Hyercharged minimal dark matter can be also revived by introducing mass splitting between Dirac neutral components to avoid the constraint from direct detection experiments... no more Simple though.

Hypercharged Minimal Dark Matter

✔ Dark Matter production during reheating between T_{MAX} and T_R



During reheating

- ✔ $H = H_R (a/a_R)^{-3/2}$
- ✔ $T = T_R (a/a_R)^{-3/8}$

After reheating

- ✔ $H = H_R (a/a_R)^{-2}$
- ✔ $T = T_R (a/a_R)^{-1}$

$$T_{MAX} = T_R (H_{inf}/H_R)^{1/4}$$

[When the inflaton feels significant back-reaction from the thermal bath, the evolutions of $\rho_{inflaton}$ and ρ_R get more complicated...
(e.g. '12 Mukaida & Nakayama)]

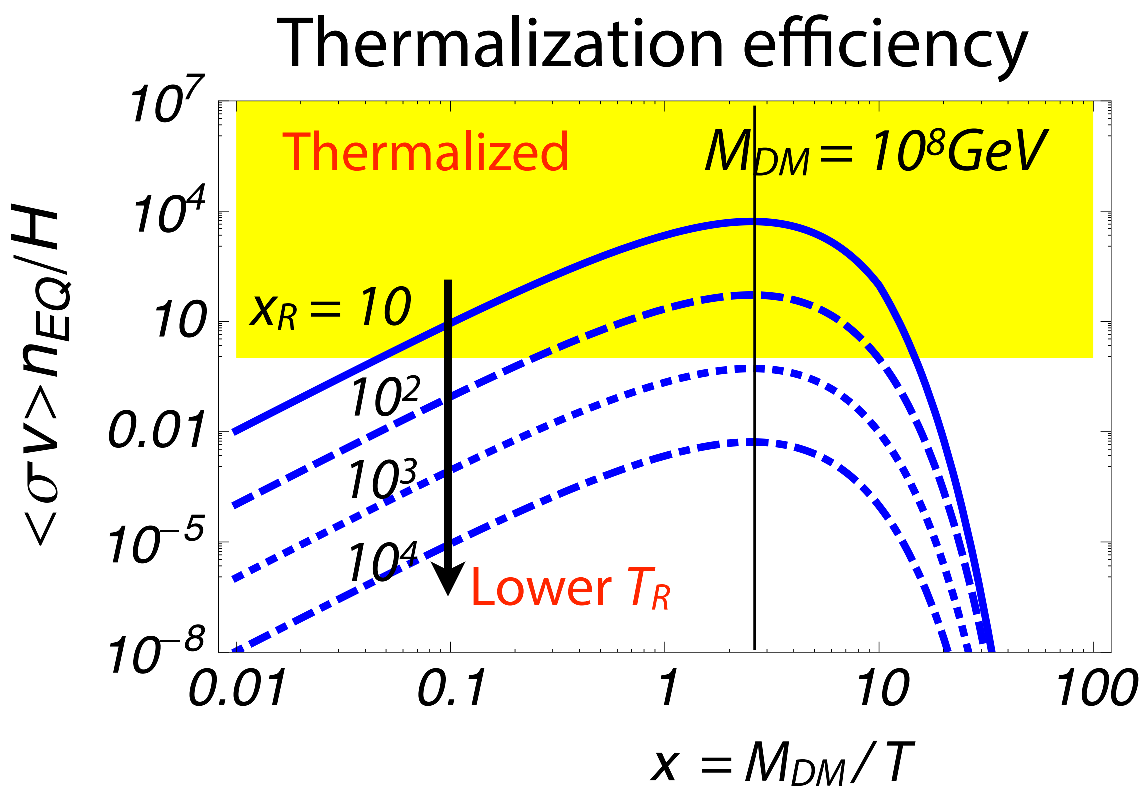
Boltzmann Equation :

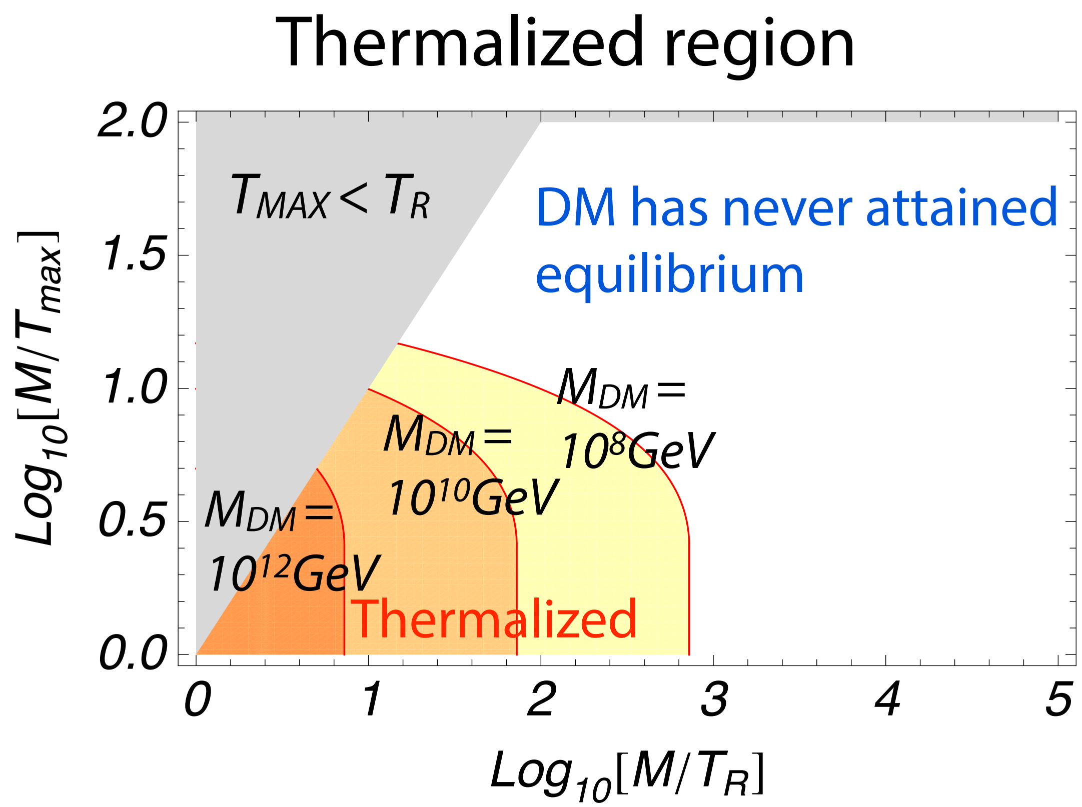
$$\frac{d}{dt}n + 3Hn = -\langle\sigma v\rangle\left(n^2 - n_{\rm EQ}^2\right) \quad (n_{EQ} = 2\,(M_{DM}T/2\pi)^{3/2} Exp[-M_{DM}/T])$$

with boundary condition : $n = 0$ at the end of inflation.

Hypercharged Minimal Dark Matter

✔ Dark Matter has attained thermal equilibrium?





The efficiency has a peak at around $x_{med} \simeq 3$ - 4.
[Even if we take $T_{MAX} \gg M_{DM}$, DM has not necessarily attained equilibrium!]

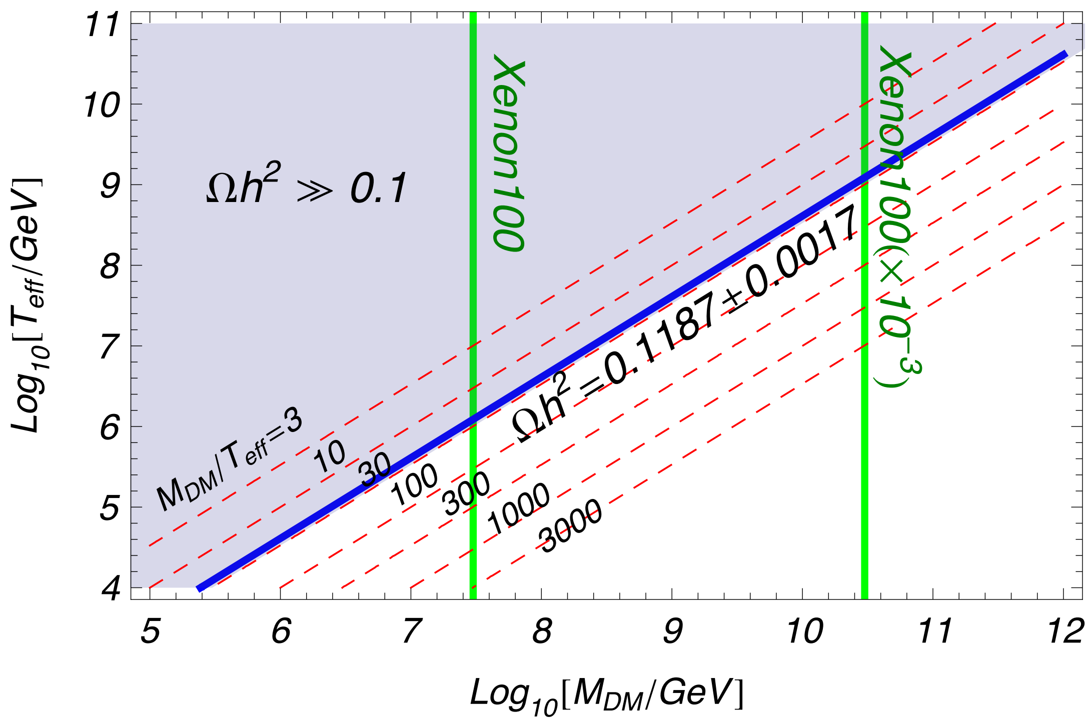
The efficiency decreases for a lower T_R for a given x (efficiency $\propto T_R^2$)

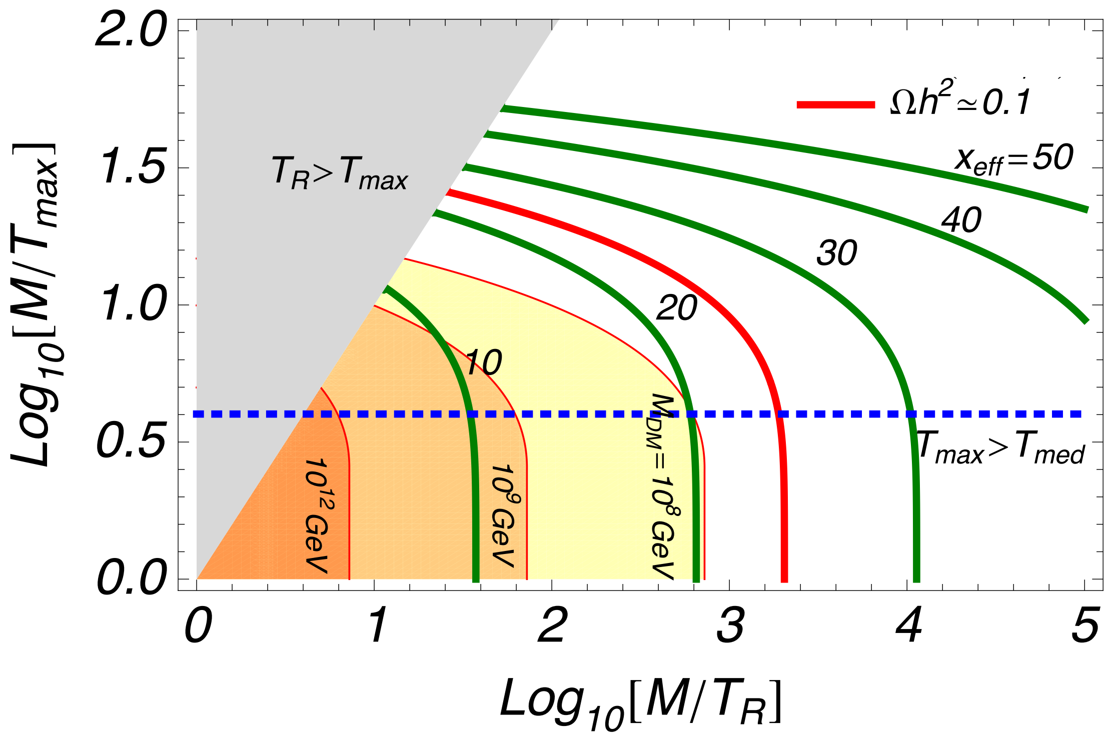
The efficiency decreases for a larger M_{DM} for a given x (efficiency $\propto M_{DM}^{-1}$)

In most parameter space, DM has never attained thermal equilibrium after inflation ! → Non-thermal Minimal Dark Matter !

Hypercharged Minimal Dark Matter

✔ The relic abundance of non-thermal minimal dark matter :





$$\Omega_{\rm DM} h^2 \simeq \frac{4}{\pi^6}\left(\frac{45}{8 g_*}\right)^{3/2} \frac{s_0 \langle \sigma v \rangle M^2}{H_0^2 M_{\rm pl}} e^{-2 x_{\rm eff}}$$

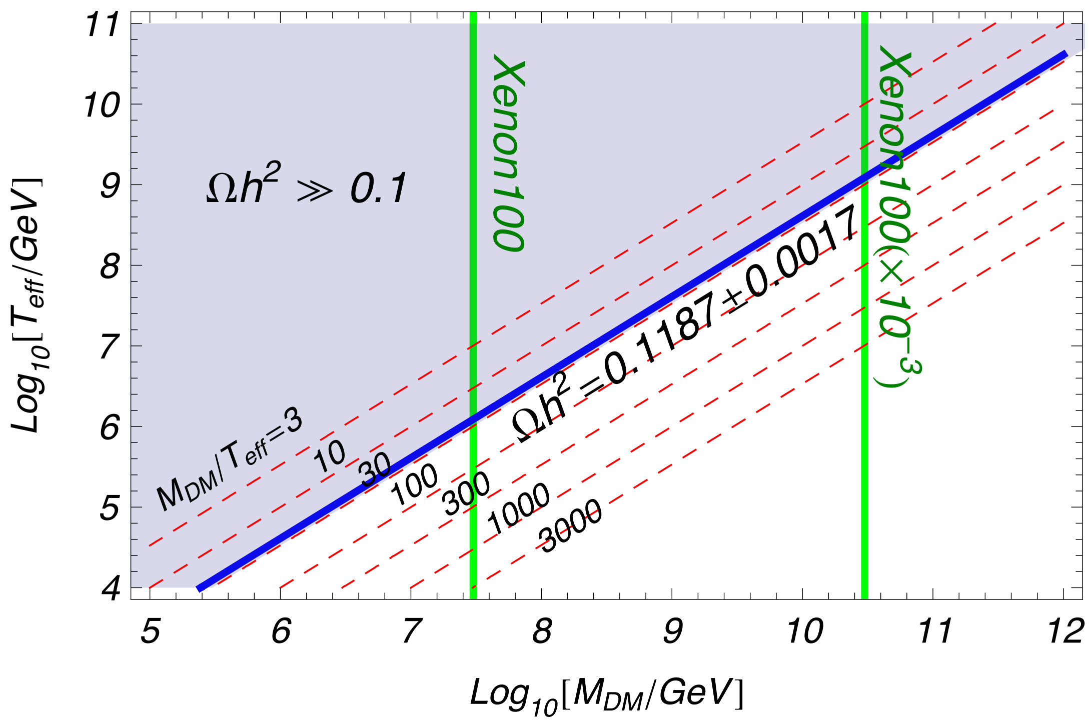
($x_{eff} = M_{DM}/T_{eff}$, s_0 entropy density at present, $H_0 = 100 km/s/Mpc$)

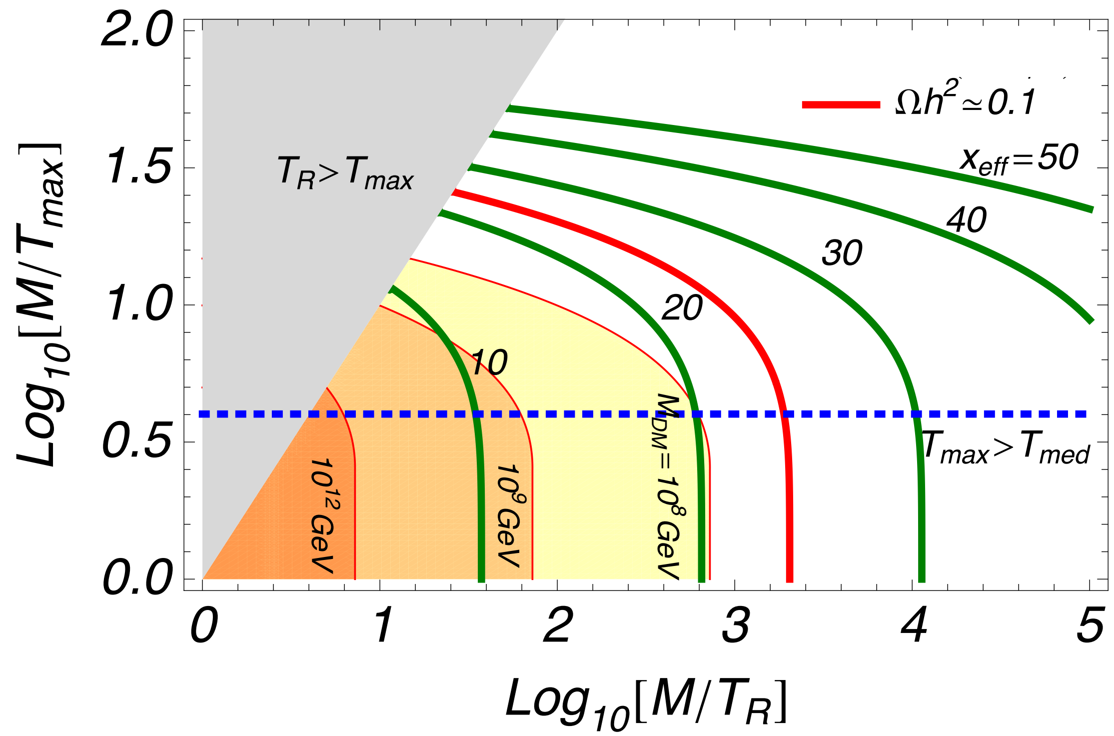
✔ The relic abundance depends on M_{DM} only through x_{eff} ($\langle \sigma v \rangle \propto M_{DM}^{-2}$)

✔ The observed dark matter abundance is realized for $x_{eff} \simeq 26$.

Hypercharged Minimal Dark Matter

✔ The relic abundance of non-thermal minimal dark matter :





✔ The relation between T_{eff} and T_{MAX} , T_R :

$$x_{\rm eff} = (x'_{\rm med} - 1)\log x_R - \frac{1}{2}\log\left[\epsilon^{-1} 2^{-2x'_{\rm med}}\Gamma[2x'_{\rm med}, 2x_{\rm max}]\right] \qquad (x_{med}' = 4.5)$$

✔ T_{eff} becomes independent of T_{max} (thermalization peaks at T_{med})

Once M_{DM} is determined by the direct detection experiments :

$T_R \sim 10^{7\text{-}9}$GeV $(M_{DM}/2\text{x}10^{10}\text{GeV})$

Hypercharged Minimal Dark Matter

✔ Can we test Hypercharged Minimal Dark Matter Further ?
Can we distinguish from the Higgs portal dark matter ?

✔ The direct detection cross section shows the isospin violating nature due to the *Z*-boson exchange !

$$\sigma_{\chi N} = \frac{G_F^2 \mu_N^2}{2\pi} Y^2 (N - (1 - 4\sin^2\theta_W)Z)^2$$

Isospin preserving

$$\frac{\sigma_{\chi N_1}}{\sigma_{\chi N_2}} = \frac{A_1^2}{A_2^2}$$

Xe/Ge : *3.27*
Xe/Ar : *10.8*

Isospin violating

$(1-4\sin^2\theta_W) \simeq 0.04$

$$\frac{\sigma_{\chi N_1}}{\sigma_{\chi N_2}} \simeq \frac{N_1^2}{N_2^2}$$

Xe/Ge : *3.62*
Xe/Ar : *12.4*

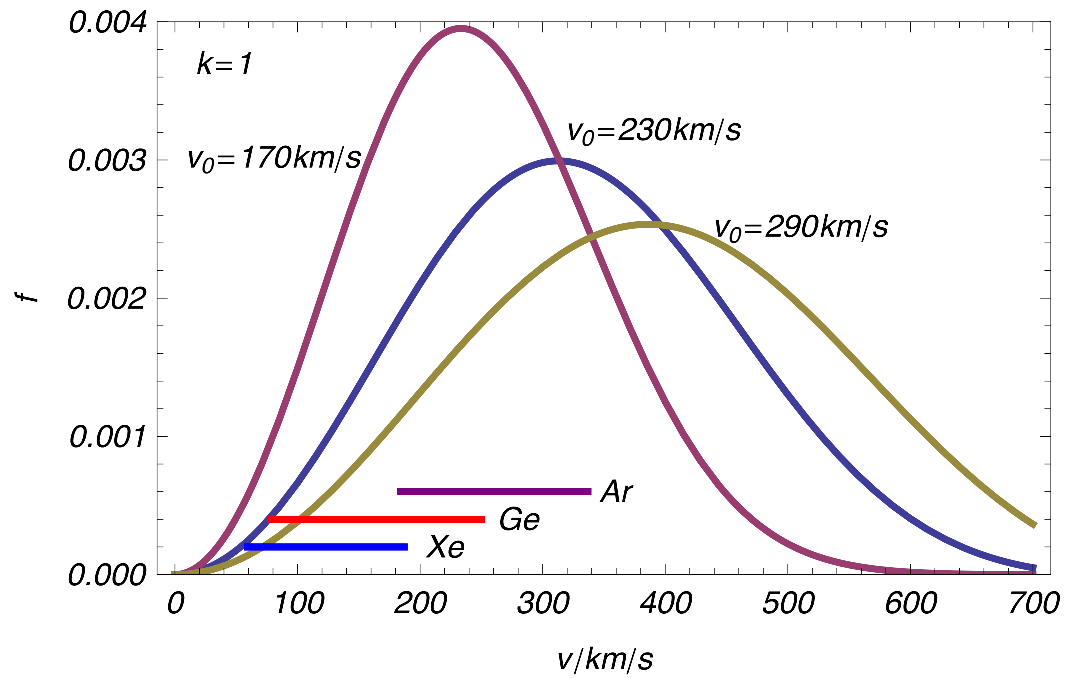
About a 10% difference !

By comparing signals at different target materials, we can test the isospin violation !

Hypercharged Minimal Dark Matter

✓ Can we test Hypercharged Minimal Dark Matter Further ?
Can we distinguish from the Higgs portal dark matter ?

✓ One caveat : We do not know the DM velocity distribution very precisely...



Minimal velocity for E_{recoil}.

$$v_{\rm min} = \sqrt{\frac{E_{\rm recoil}}{2M_N}}$$

Velocities for a given E_{recoil} are different for different target...

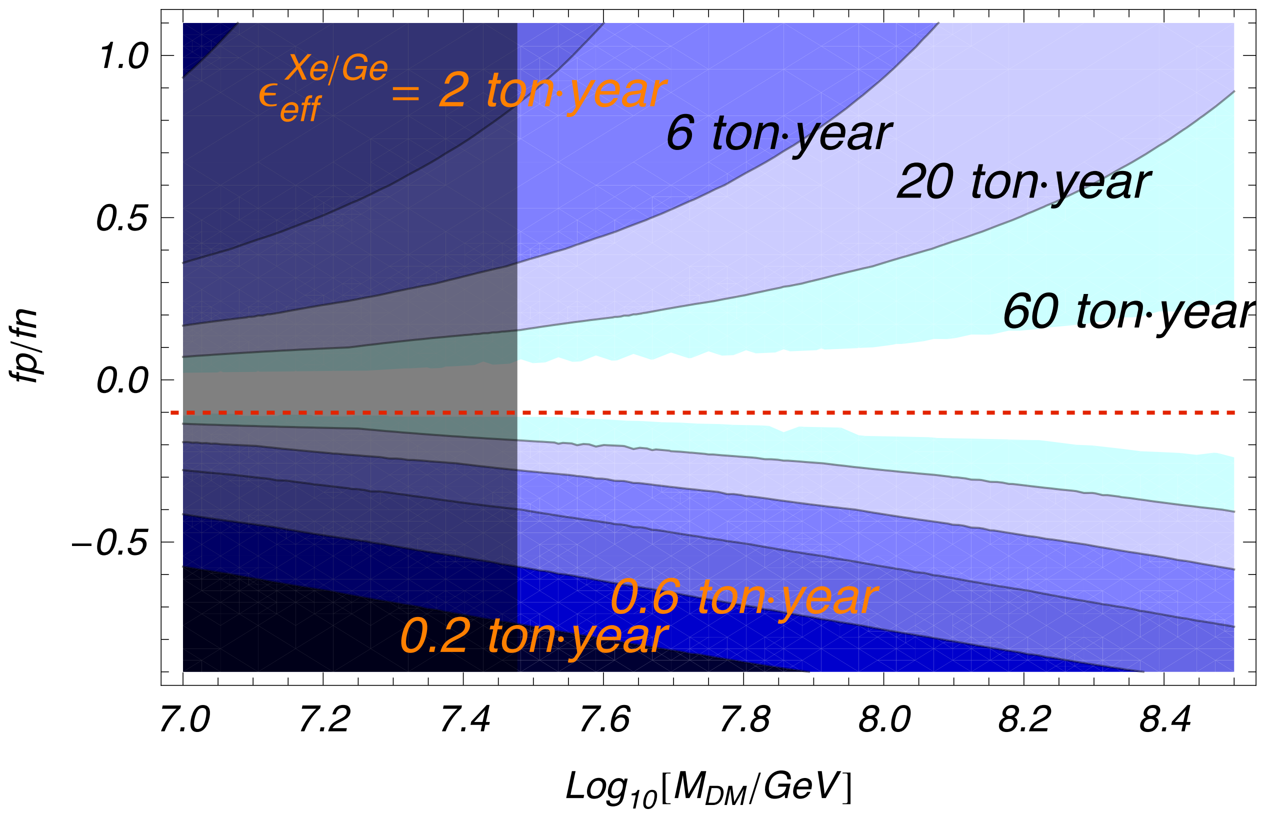
The effects of the isospin violation can be mimicked by the small change of the velocity distributions in the *Xe/Ar* comparison.

→ We only use *Xe/Ge* comparison.

Hypercharged Minimal Dark Matter

✔ Can we test Hypercharged Minimal Dark Matter Further ?
Can we distinguish from the Higgs portal dark matter ?

90% exclusion of f_p/f_n



The effective exposure after background rejection to exclude f_p/f_n

$$\sigma_{\chi N} = \frac{G_F^2 \mu_N^2}{2\pi} Y^2 (N^2 + f_p/f_n Z)^2$$

Irreducible background from nuclear scattering by the atmospheric neutrino becomes non-negligible for *O(10-100) ton.year...*

With a multi-ton effective exposure (~*O(100)* events), we can exclude the isospin preserving model, i.e. *fp/fn = 1*, for hypercharged minimal dark matter of $M_{DM} < 10^{8\text{-}9}$ GeV !

Multi-ton scale detectors :

- ✔ Ge : superCDMS/GEODM, EURECA... ✔ Xe : Xenon1T, DARWIN...

Summary

SU(2)$_L$ charged dark matter:

- $Y = 0$: minimal dark matter
  → a viable WIMP candidate !
- $Y \neq 0$: hypercharged minimal dark matter
  → a viable *WIMPZILLA* candidate !

✓ Which scenario is more favorable ?

- ✓ The WIMP scenario fits together well with the *Naturalness* arguments.
- ✓ From the view point of *Simplicity* of the dark matter sector, however, both scenarios are equally acceptable !

✓ Features of hypercharged minimal dark matter.

- ✓ Next generation direct detection experiments reach to $M_{DM} = 10^{10\text{-}11} GeV$.
- ✓ Through the direct detection experiments we can determine the reheating temperature to $T_R \sim 10^{7\text{-}9} GeV\ (M_{DM}/2\mathrm{x}10^{10} GeV)$.
- ✓ By collecting *O(100)* DM signal events on different target materials, we will get strong hints on the hypercharged DM through the test of the isospin violation !

Z-boson exchange

$$\mathcal{L} = \bar{q} i \gamma^\mu (\partial_\mu - i Q_{\mathrm{EM}} A_\mu) q$$

$$+ \frac{g}{\sqrt{2}} W_\mu^+ \bar{q}_L \gamma^\mu \tau_+ q_L + h.c.$$

$$+ \frac{g}{2 \cos\theta_W} Z_\mu \left(\bar{q}_L \gamma^\mu \tau_3 q_L - Q_{\mathrm{EM}} \sin^2\theta_W \bar{q} \gamma^\mu q \right)$$

$$g_V = \tau_3 - 2 Q_{\mathrm{EM}} \sin^2\theta_W \qquad g_A = -\tau_3$$

q	g_V	g_A
u	$\frac{1}{2} - \frac{4}{3}\sin^2\theta_W$	$\frac{1}{2}$
d	$-\frac{1}{2} + \frac{2}{3}\sin^2\theta_W$	$-\frac{1}{2}$

P(uud) : $g_V = (1 - 4\sin^2\theta_W)/2$

n(udd) : $g_V = -1/2$

Putting *Simplicity* on Dark Matter

✓ The neutral component is the lightest !

The Coulomb generated by γ, Z, W potentials pushes up each masses:

$$\delta M = \int d^3x \left[\frac{1}{2}(\nabla\varphi)^2 + \frac{M_V}{2}\varphi^2\right] = \frac{g^2 e^{-M_V r}}{8\pi r}(1 + M_V r)\Big|_{r=0}^{r=\infty}$$

$$\varphi = \frac{g}{4\pi r} e^{-M_V r}$$

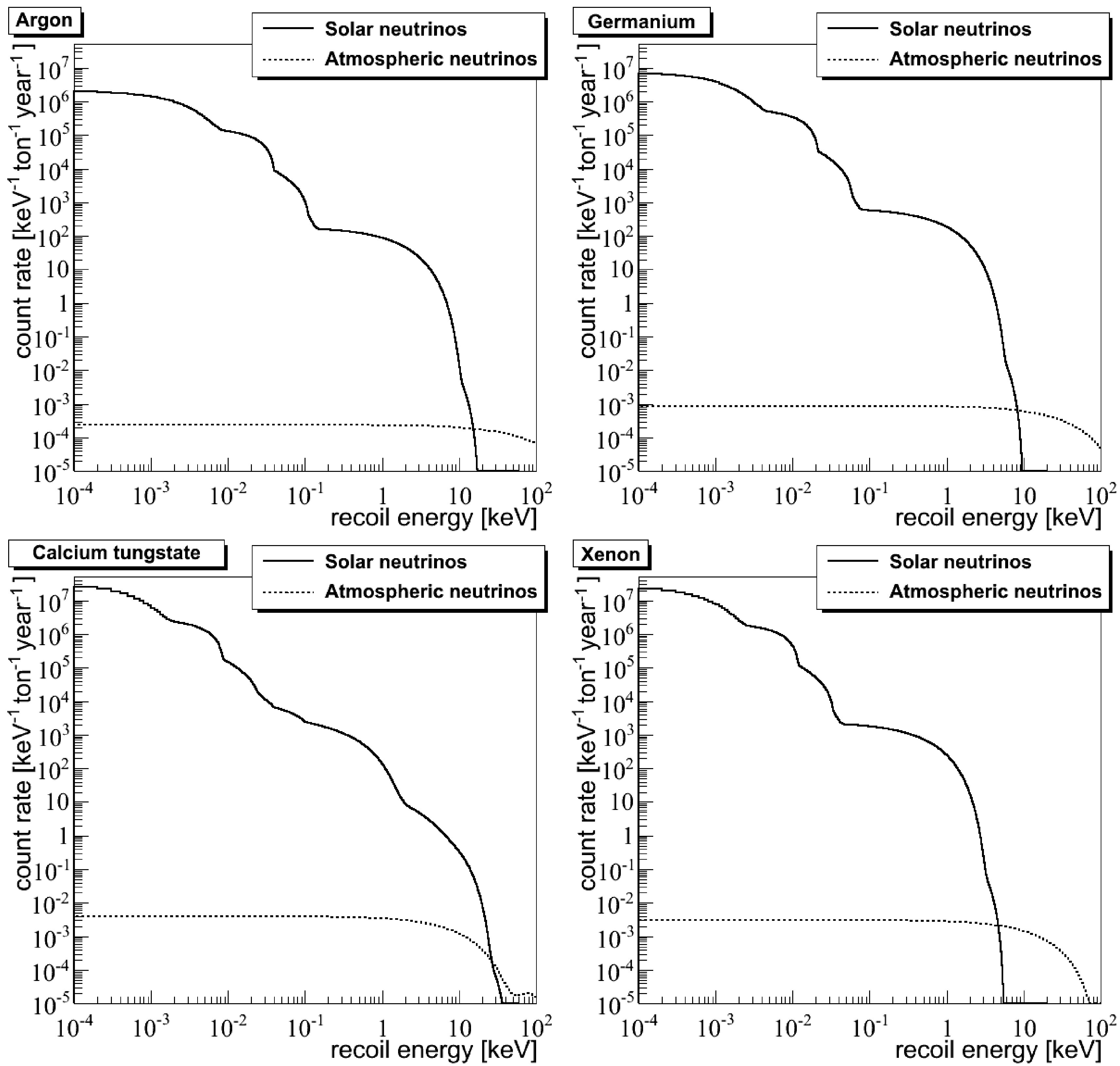
Ex) doublet $Y=1/2$

	γ	Z	W
χ^0	0	$g_2/2c_W$	g_2
$\chi^\pm$	1	$g_2/2c_W\,(1-s_W^2)$	g_2

Mass difference : $M_{charged} - M_{neutral} = \alpha_2\, s_W^2\, M_Z / 2 = 350\ MeV.$

Direct Detection @ Tree-level

Recoil nuclear spectrum by neutrinos [arxiv:1003.5530]



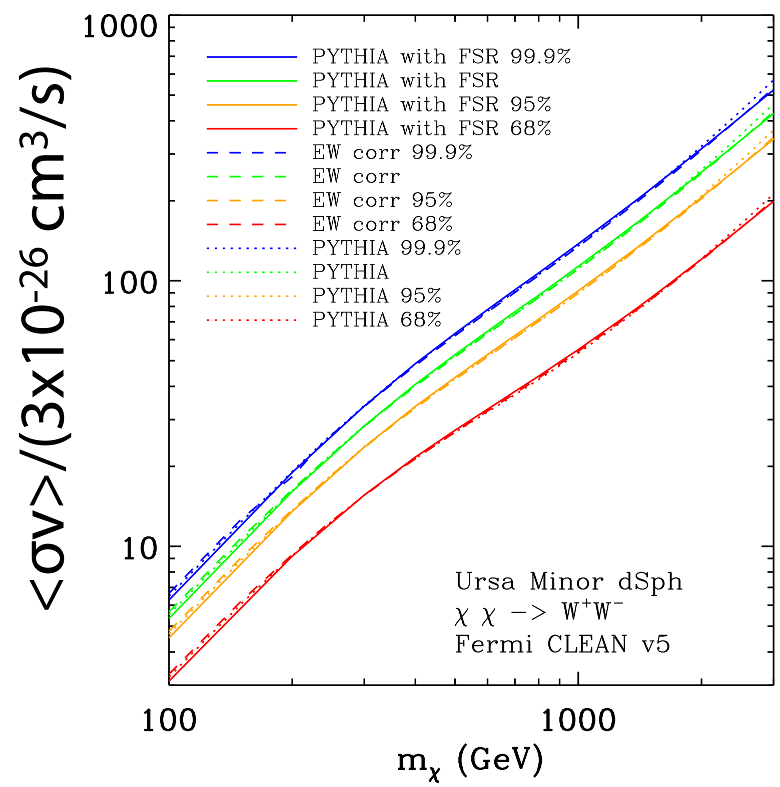
Constraints on the minimal triplet DM

Triplet Dark Matter Search (indirect detections, $\chi\chi \to WW$)

✓ Continuum gamma ray from dSph

Robust constraint on the DM annihilation cross section from the Fermi-LAT 2year data of Ursa Minor dSph ['12 Cholis and Salucci]

['12 Cholis and Salucci]

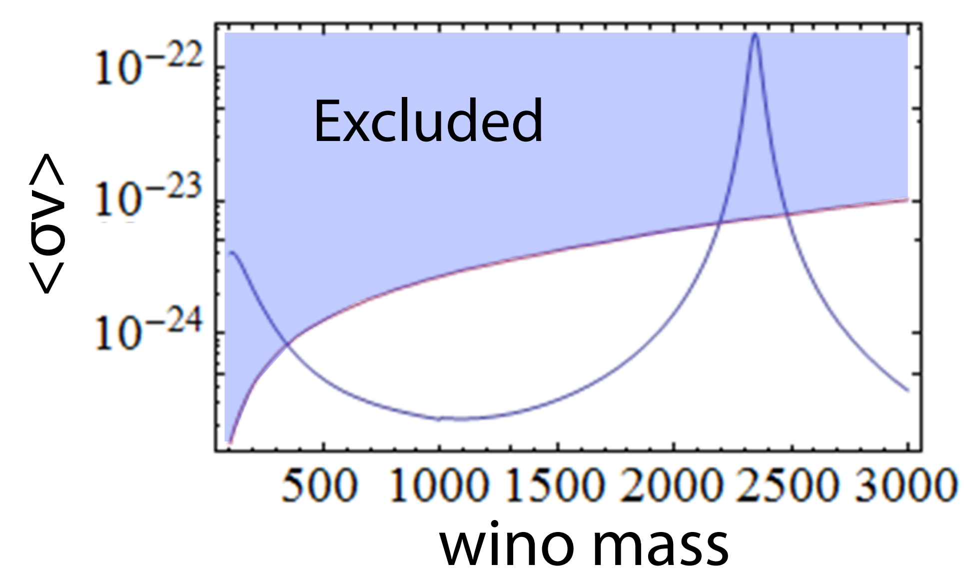


More stringent constraint is obtained with 6 classical and 4 ultra-faint dSphs ['11 Fermi-LAT]
J-factors of the ultra-faint dSphs are not well known.
BG from some classical dSphs are not well understood.

The dSph continuum gamma ray search by Fermi-LAT has excluded the wino mass in

$$m_{wino} < 340GeV$$

$$2200GeV < m_{wino} < 2500GeV$$



→ the whole range (m_{wino}<3TeV) will be covered if the ultra-faint dSphs are well understood!

[Figure by Matsumoto san]

Constraints on the minimal triplet DM

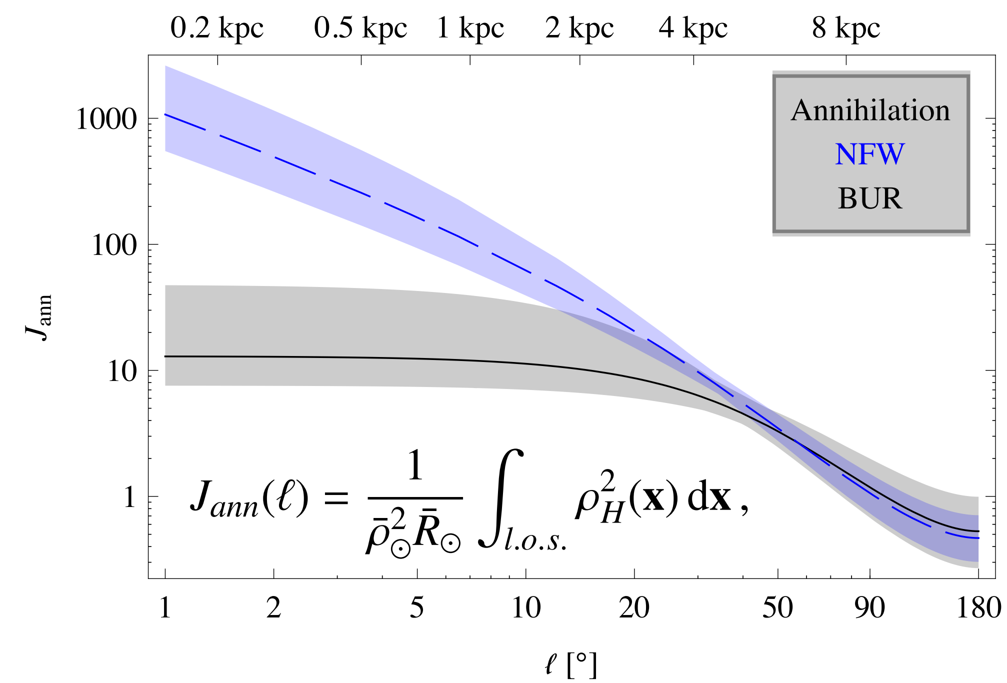
Triplet Dark Matter Search (indirect detections, $\chi\chi \rightarrow WW$)

✔ Line gamma ray from GC

The constraints depend on the DM density profile (i.e. the J-factor) ...

A stringent constraint is obtained by assuming the NFW (cuspy) DM profle ['13 Fan, Reece].
The Burket (cored) profile is getting favored now...
['13 Nesti, Salucci]

['13 Nesti, Salucci]

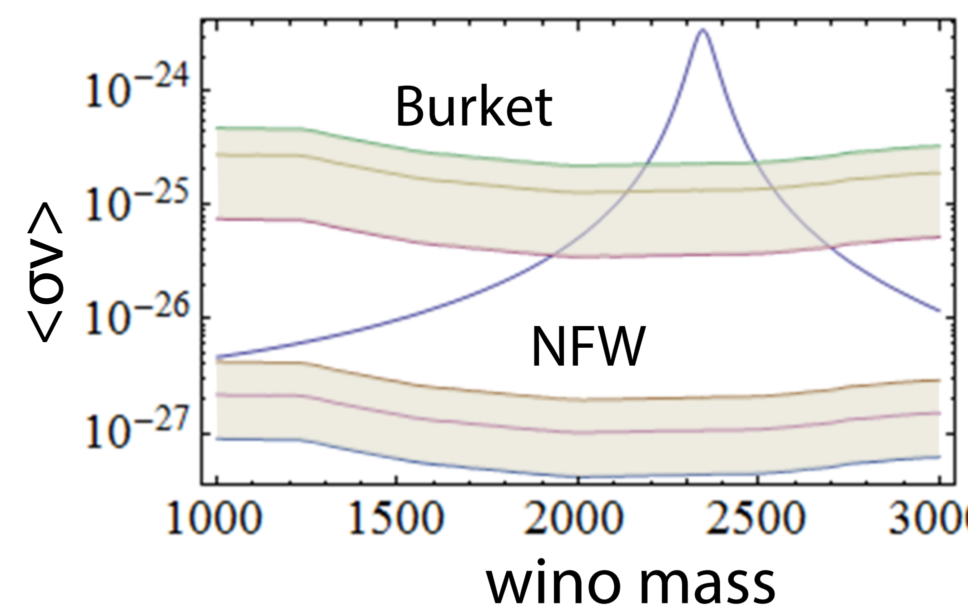


The line gamma ray search from GC by H.E.S.S. has excluded the wino mass in

$$2200GeV < m_{wino} < 2500GeV$$

assuming the Burket profile.

→ CTA has a lot of chance to find the wino DM!



The constraint on the wino mass from the continuum gamma ray from GC has been obtained by assuming NFW ['12 Hooper et.al.].

BG from the GC is not well understood.

Hypercharged Minimal Dark Matter

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✓ Which scenario is more favorable ?

- ✓ The WIMP scenario fits together well with the *Naturalness* arguments (cf. the neutralino in Supersymmetry)
- ✓ From the view point of *Simplicity* of the dark matter sector, however, both scenarios are equally acceptable !

How hypercharged dark matter works as *WIMPZILLA* ?

What can we learn if dark matter is hypercharged?