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First KIAS-NCTS Joint Workshop on Particle Physics, String Theory and Cosmology @ High1

Dark Matter in Models with Discrete Gauge Symmetry

Cheng-Wei Chiang (蔣正偉)

National Central University
Academia Sinica
National Center for Theoretical Sciences

In collaboration with T. Nomura, J. Tandean
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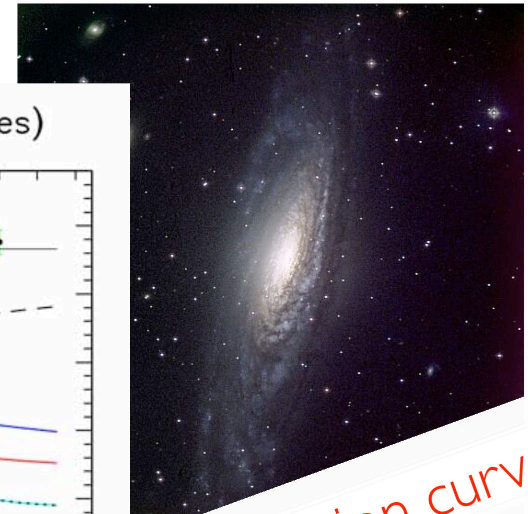
Evidence of BSM

- Celestial evidence of DM (familiar ones):



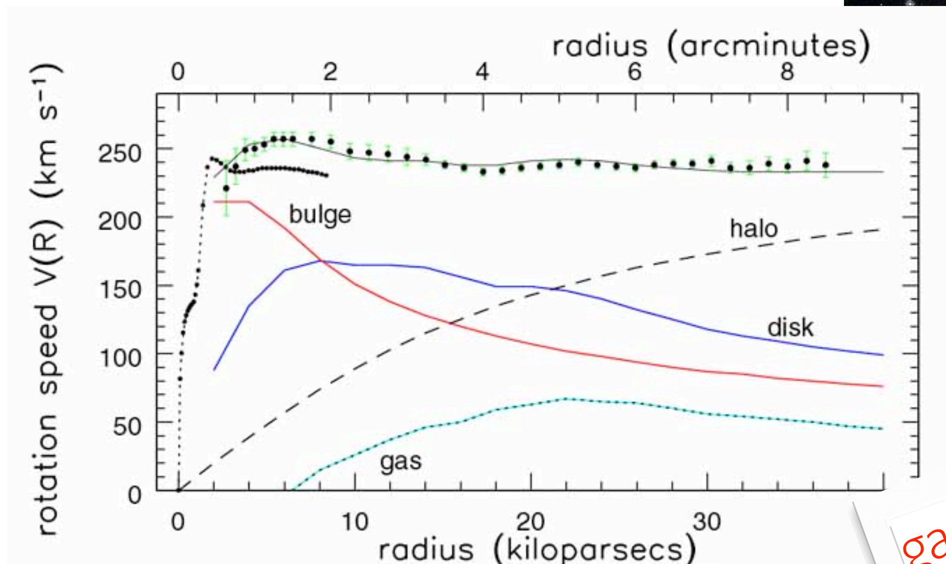
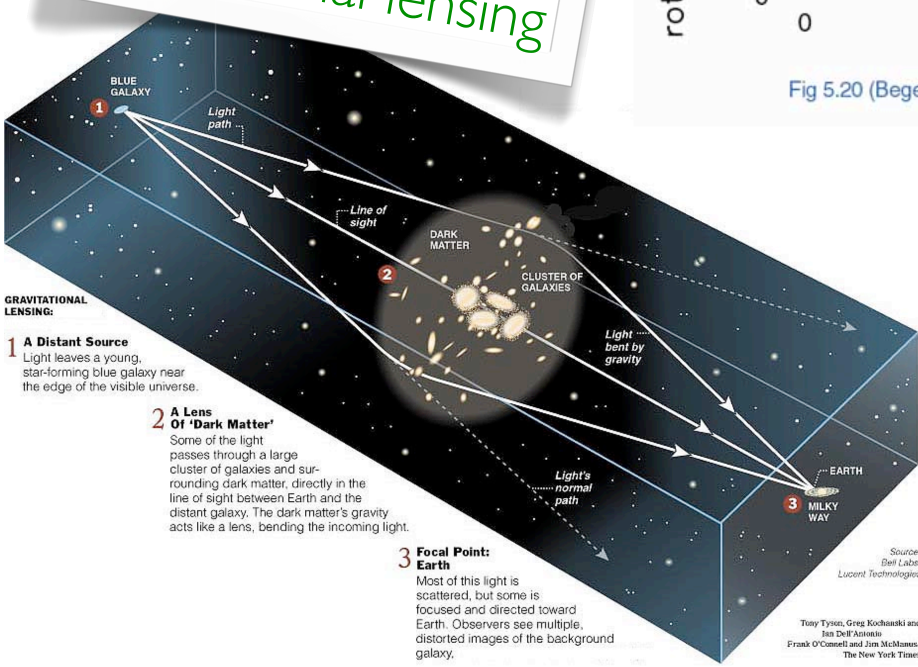
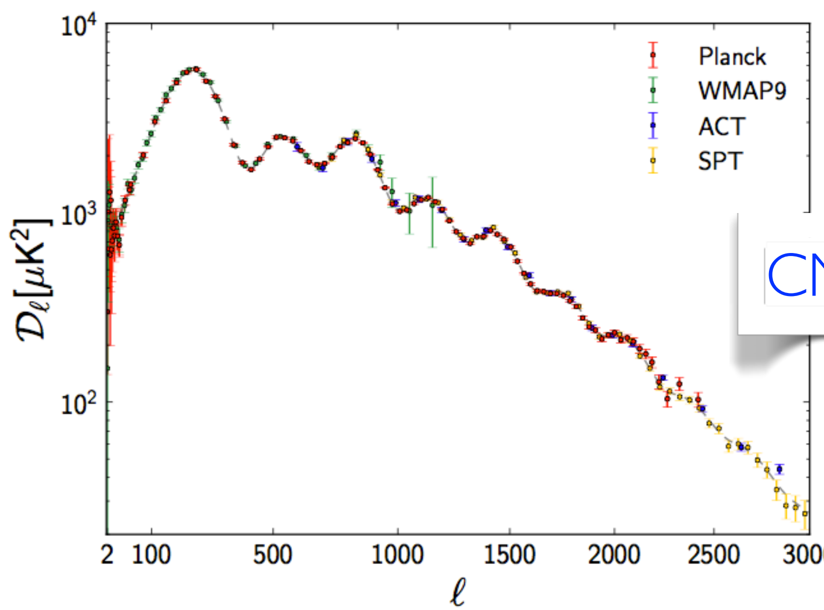


Fig 5.20 (Begeman, Sofue) 'Galaxies in the Universe' Sparke/Gallagher CUP 20

galaxy rotation curve

galaxy clusters and gravitational lensing

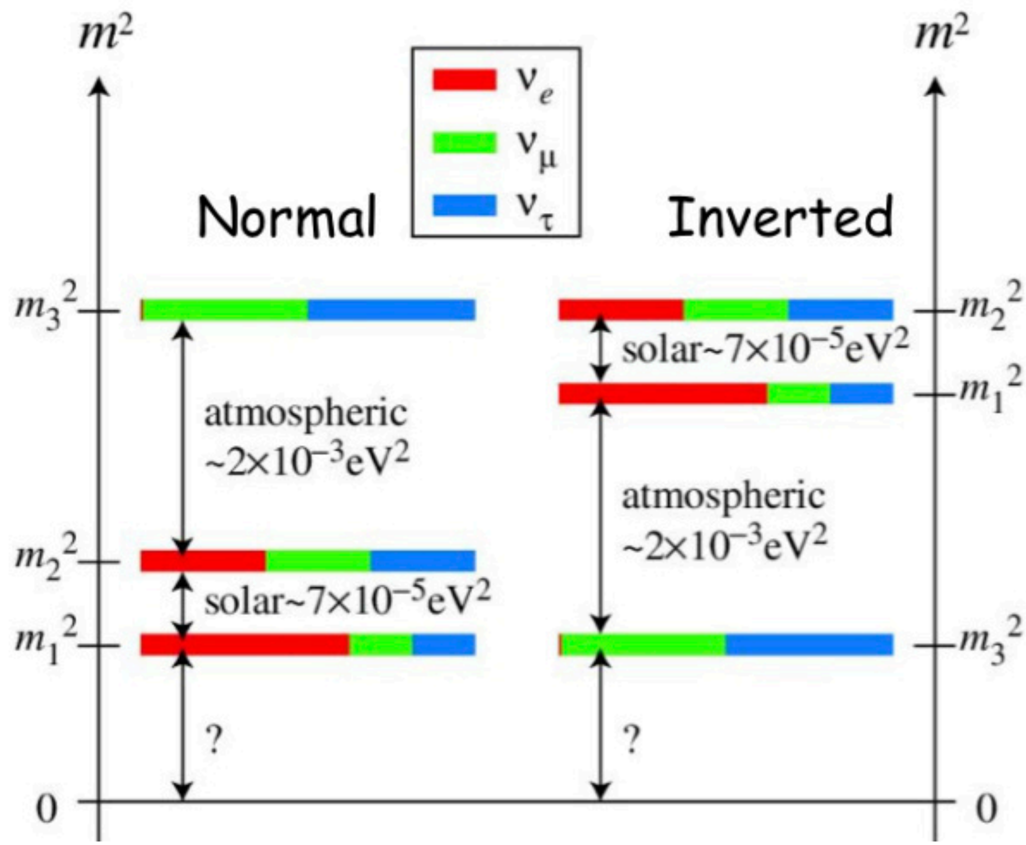




CMB

Evidence of BSM

- Celestial / terrestrial evidence: neutrino mass

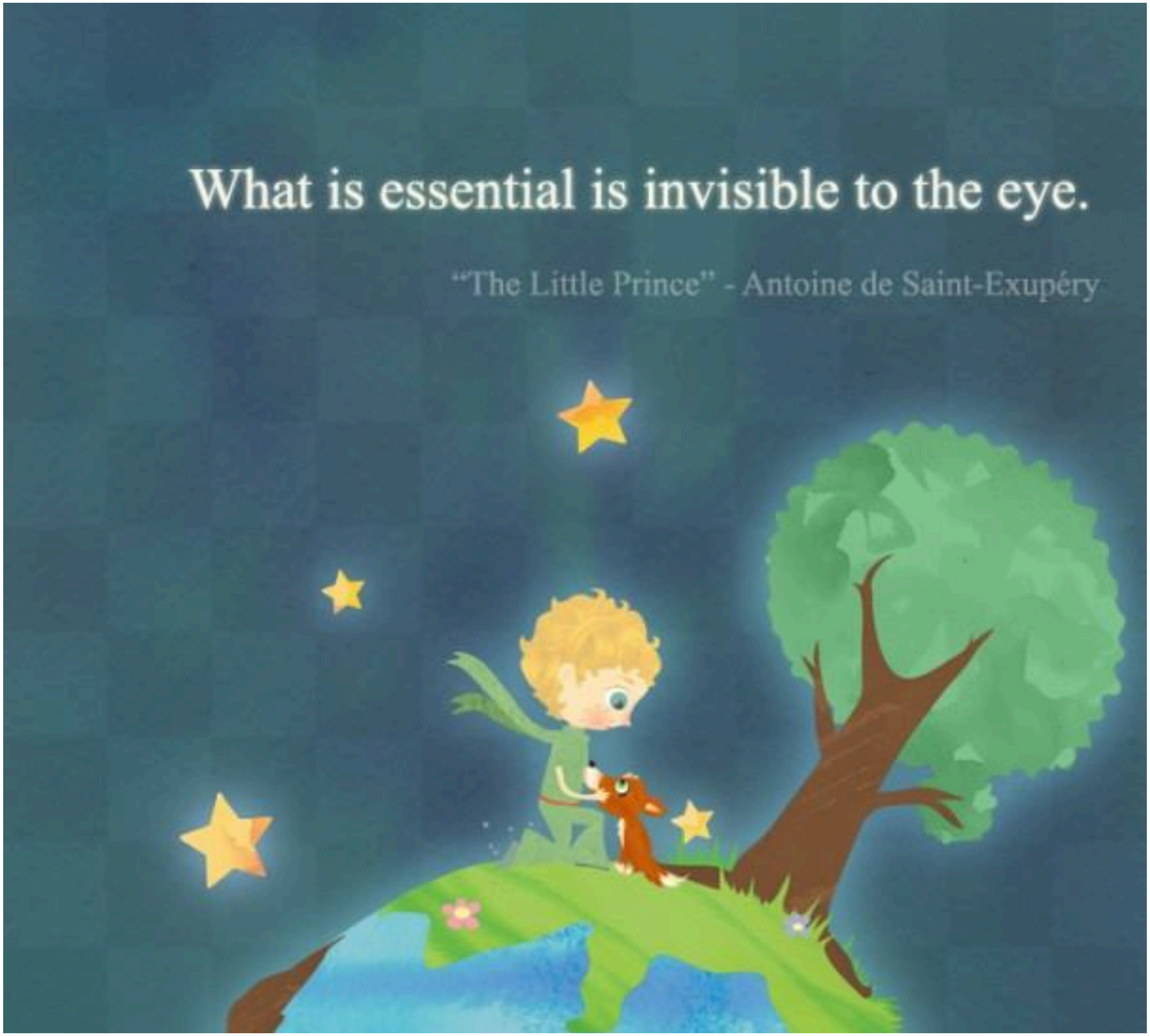


by Steve King 2011

One Property in Common

- Both DM and neutrinos are difficult to see (catch in detectors)

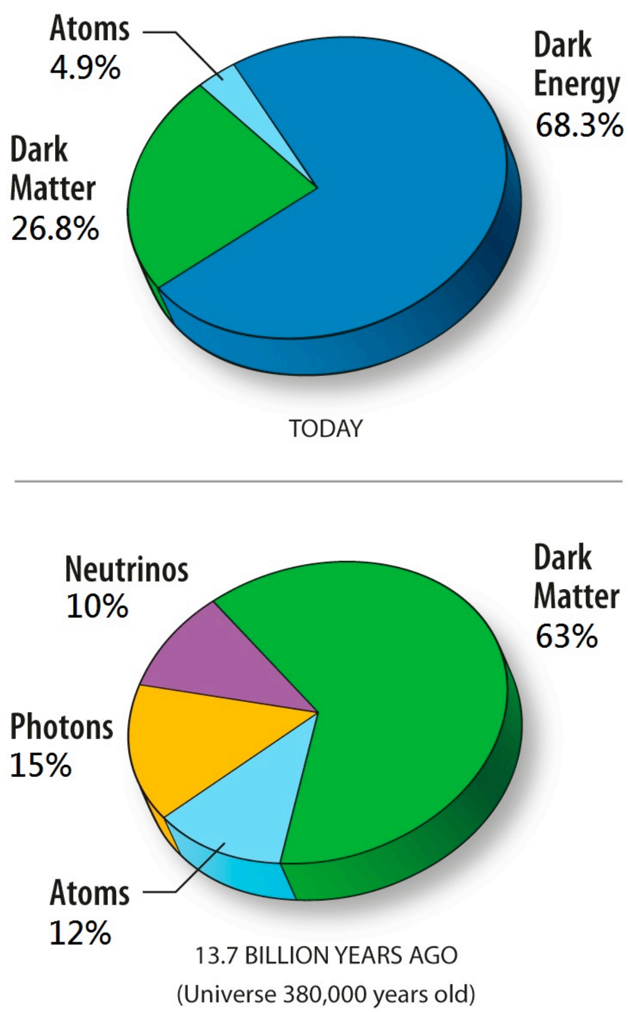
What is Essential?



Introducing the Elephant

- When there's an elephant in the room, introduce them.

--- Randy Pausch, *The Last Lecture*



Examining Elephant by the Blind

Everyone Has His Own Story

- Dark matter is scalar / fermionic / vectorial or a combination of them.

Our Story

- Model with Z_2 symmetry emerged from U(1)
  ➠ scalar DM

- Model with Z_2 symmetry emerged from SU(2)
  ➠ non-Abelian vector DM

- Summary

MODEL I

Humble Criteria of Model

- Stabilized DM candidate
- Simplest gauge group extension
- Minimal new particle contents
- Generating neutrino mass

The Model

- Extend SM gauge group by extra $U(1)_\zeta$
- Add 3 RH neutrinos and 2 complex scalar fields, S and D
- Anomaly cancellation demands $U(1)_\zeta$ nothing but $U(1)_{B-L}$
  ➠ $G_{SM} \times U(1)_{B-L}$

- Quantum number assignment:

	$f_{\rm SM}$	ν_{kR}	H	S	D
SU(2), $U(1)_Y$	$g^f_{\rm SM}$	1, 0	2, 1/2	1, 0	1, 0
$U(1)_\zeta$ $[Z_2]$	ζ_f [−]	−1 [−]	0 [+]	2 [+]	1 [−]

Table 1: Charge assignments of the fermions and scalars in the model. $f_{\rm SM}$ ($g^f_{\rm SM}$) denotes SM fermions (their assignments) and H the usual complex doublet. For quarks and leptons, $\zeta_f = 1/3$ and -1, respectively.

Discrete Gauge Symmetry

Krauss, Wilczek 1989
Nakayama, Takahashi, Yanagida 2011

- New scalar Lagrangian:

$$\mathcal{L} = (\mathcal{D}^\mu D)^\dagger \mathcal{D}_\mu D + (\mathcal{D}^\mu S)^\dagger \mathcal{D}_\mu S - \mathcal{V}$$

$$\mathcal{D}_\mu = \partial_\mu + i g_\zeta \zeta Z'_\mu$$

zero VEV to maintain Z_2 and DM longevity

induces nonzero $\langle S \rangle$ and breaks $U(1)_{B-L}$

$$\begin{aligned}\mathcal{V} =& \mu_D^2 |D|^2 - \mu_S^2 |S|^2 + \mu_{DS} \left(D^2 S^\dagger + \text{h.c.}\right) \\ &+ 2\lambda_{DS}|D|^2|S|^2 + 2\left(\lambda_{DH}|D|^2 + \lambda_{HS}|S|^2\right) H^\dagger H \\ &+ \lambda_D |D|^4 + \lambda_S |S|^4 + \left(\lambda_H H^\dagger H - \mu_H^2\right) H^\dagger H\end{aligned}$$

all λ's > 0 for vacuum stabililty

essential to the breaking $U(1)_{B-L} \to Z_2$

S-H mixing, assumed to be negligible

Scalar DM

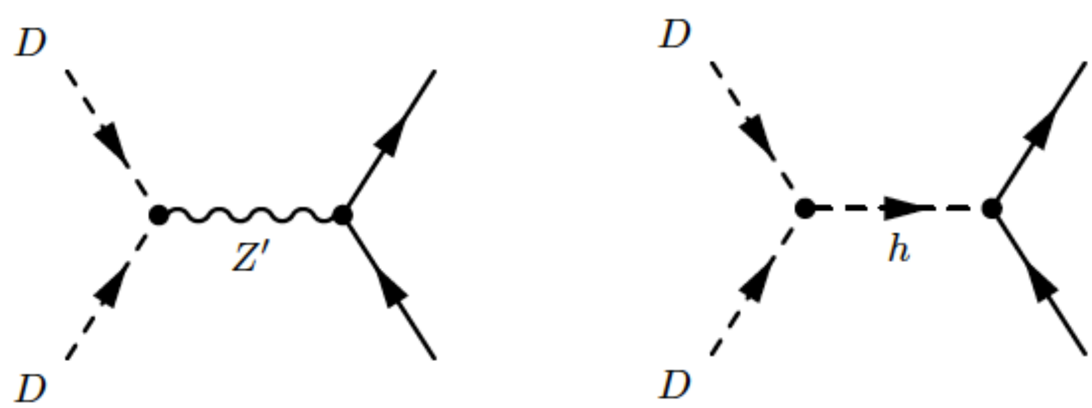
- Scalar VEV's:

$$\langle H \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_H \end{pmatrix} \quad , \quad \langle S \rangle = \frac{v_S}{\sqrt{2}}$$

- Mass eigenstates of $D = (D_R + i\, D_I)/\sqrt{2}$ (both dubbed darkons):

$$m^2_{D_R, D_I} = \mu^2_D + \lambda_{DH}\, v^2_H + \lambda_{DS}\, v^2_S \pm \sqrt{2}\, \mu_{DS}\, v_S > 0$$

- Consider nearly-degenerate case (μ_{DS} > 0 and ~ 0)
  - ➠ D_I as WIMP DM (~ simplest darkon) — Silveria, Zee 1985
  - ➠ coannihilation with D_R possible



Neutrino Mass

- Neutrino sector contains both Dirac and Majorana terms:

$$i\lambda_{kl}\,\bar{\nu}_{kR}\,H^{\mathrm{T}}\tau_2 L_{lL} - \tfrac{1}{2}\lambda'_{kl}\,\bar{\nu}_{kR}\,(\nu_{lR})^{\mathrm{c}}S^{\dagger} + \mathrm{h.c.}$$

$$\mathcal{M}_D = \frac{1}{\sqrt{2}}\,\lambda\,v_H\ , \quad \mathcal{M}_{\nu_R} = \frac{1}{\sqrt{2}}\,\lambda' v_S$$

~ multi-TeV

- Majorana neutrino mass is generated through usual Type-I seesaw.

A Word About Higgses

- Physical h and s are almost purely from H and S, respectively, under our assumption of negligible mixing
- Mass eigenvalues

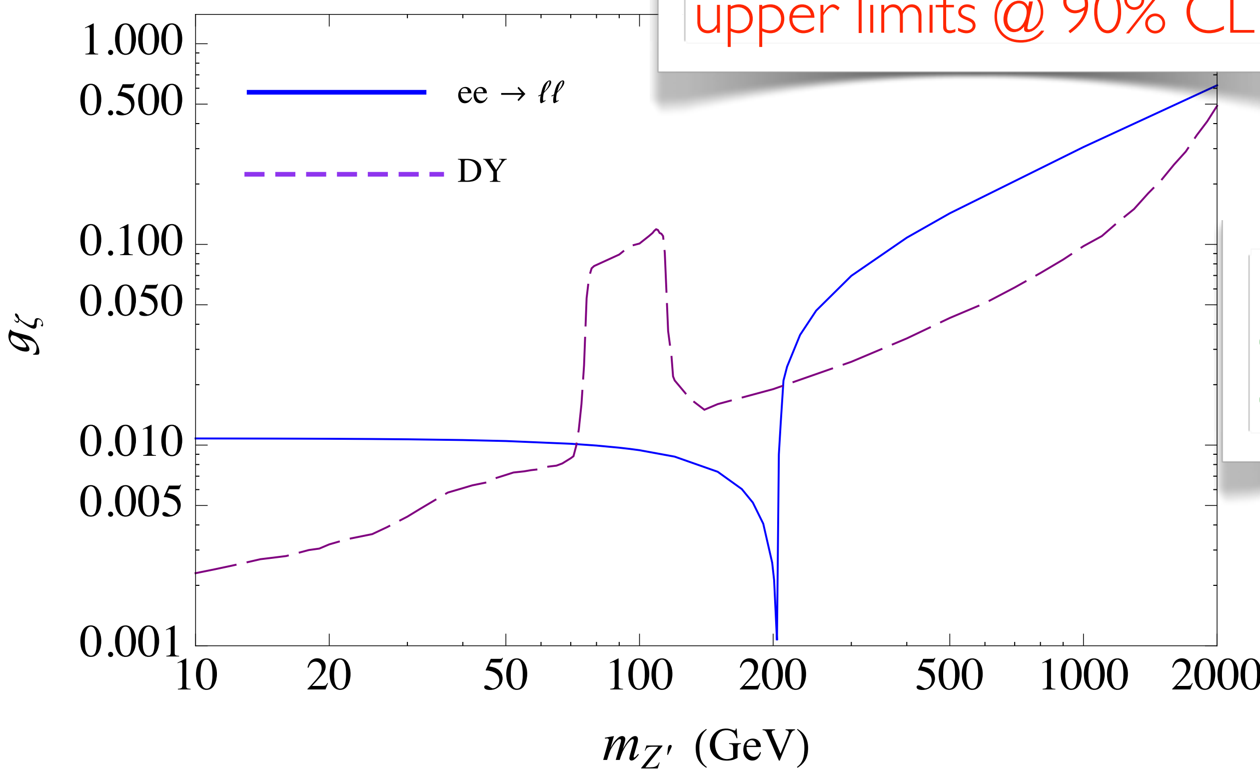
$$M_{h,s}^2 \simeq 2\lambda_{H,S}\, v_{H,S}^2$$

- M_h fixed at 125 GeV
- M_s is multi-TeV in view of RH neutrino's Majorana mass, provided all λ's are of O(1)

Constraints on Gauge Coupling

- Z' mass induced purely by S: $m_{Z'} = 2g_\zeta v_S$
  ➠ no Z-Z' mixing at tree level
- $e^+e^- \to Z' \to \ell^+\ell^-$ @ LEP-II: σ + A_{FB}
- $pp \to Z' \to \ell^+\ell^- X$ @ LHC 7 TeV (4.5/fb): σ

upper limits @ 90% CL



using method adapted from
CWC, Christensen, Ding, Han 2012
CWC, Lin, Tandean 2012

Relic Density of DM

- Assume mass degeneracy between darkons
- Employ approximate Boltzmann equation solution

$$\Omega_D h_0^2 = \frac{1.07 \times 10^9}{\sqrt{g_*}\, m_{\rm Pl}\, J \ {\rm GeV}} \qquad J = \int_{x_f}^{\infty} dx\, \frac{\langle \sigma_{\rm eff}\, v_{\rm rel} \rangle}{x^2} = J_{Z'} + J_h$$

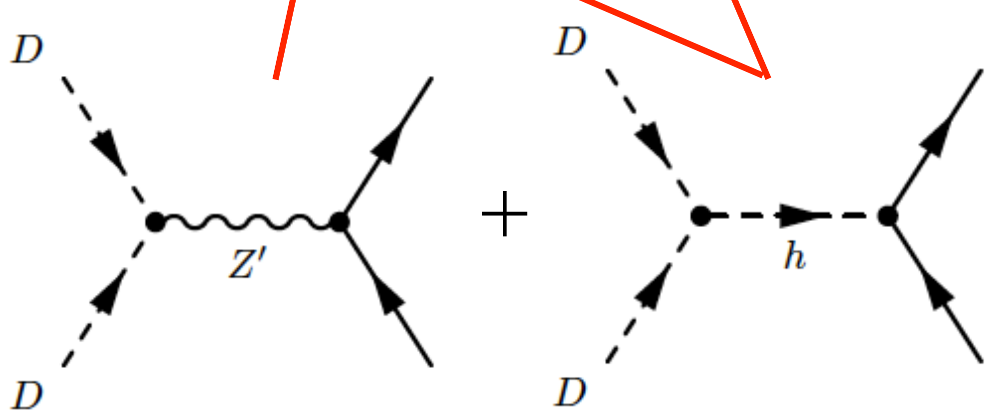
Hubble constant in units of 100/km/s/Mpc

$$x_f = \ln\left[0.038\, g_{\rm eff}\, m_D\, m_{\rm Pl}\, \langle \sigma_{\rm eff} v_{\rm rel} \rangle (g_* x_f)^{-1/2}\right]$$

darkon's effective # of dof's in coannihilation

# of relativistic dof's below freeze-out temp T_f

$$\sigma_{\rm eff} \simeq \frac{1}{4}\left(2\sigma_{IR} + \sigma_{II} + \sigma_{RR}\right)$$



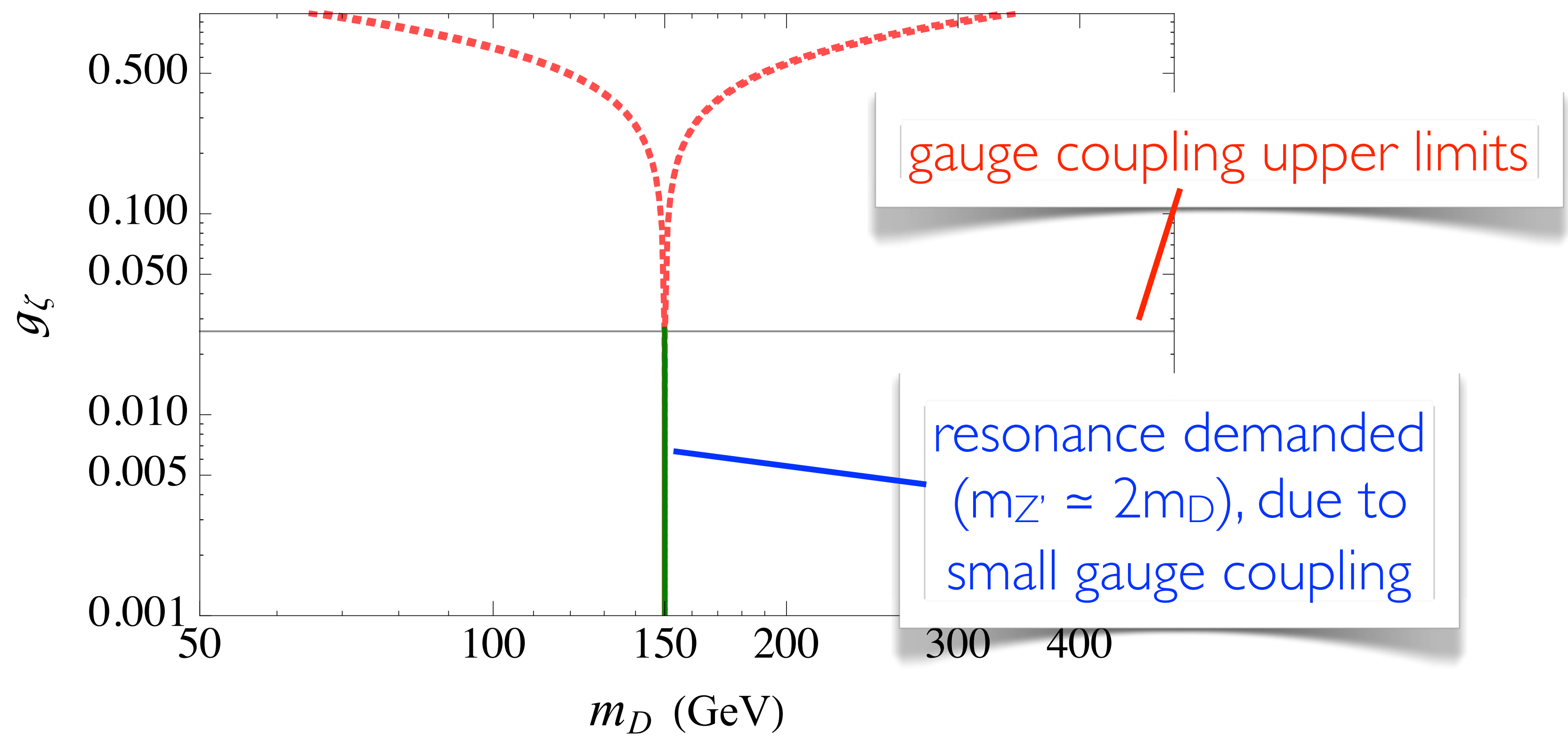
Relic Density Constraint

- Employ 90%-CL range:

$$0.092 \leq \Omega_D h_0^2 \leq 0.118$$

WMAP 2011

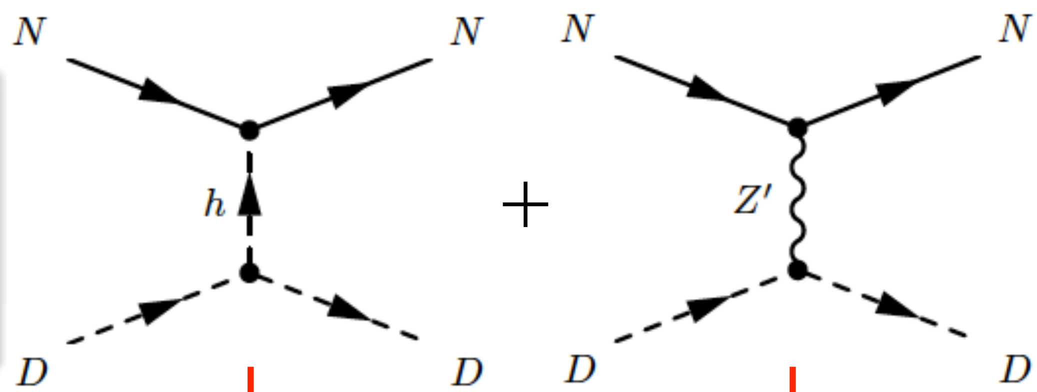
- Reference value $m_{Z'}$ = 300 GeV as an example:



DM-Nucleon Scattering

- Scattering cross section for direct detection

resonance relation, $m_{Z'} \simeq 2m_D$, is assumed
(rather strong assumption)



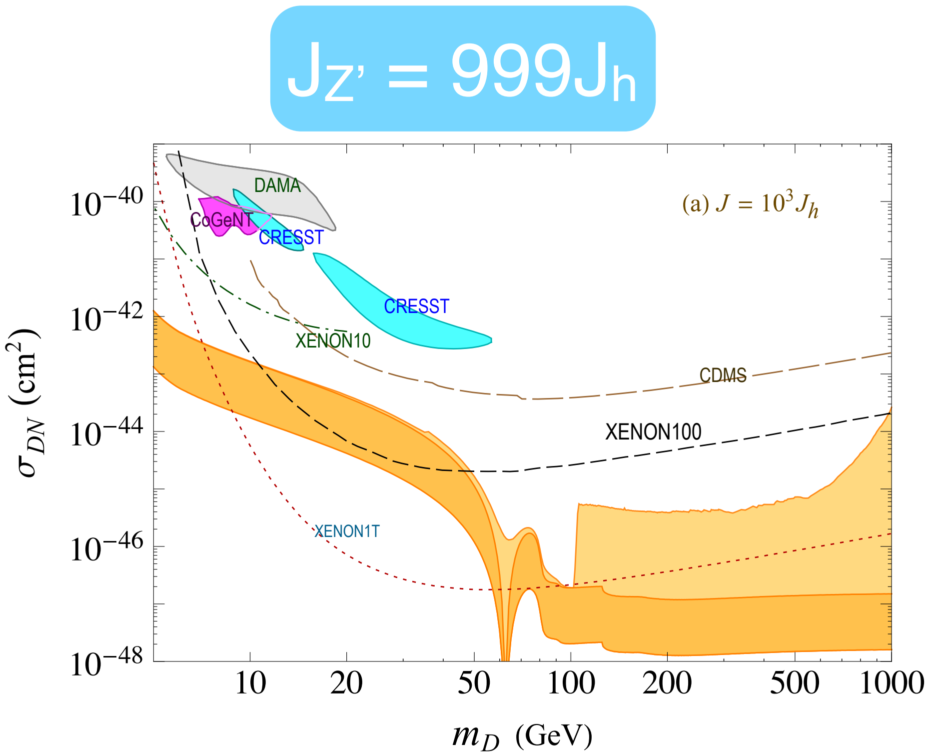
$$\sigma_{DN} \simeq \frac{\lambda_{DH}^2\, g_{NNh}^2\, \mu_{DN}^2\, v_H^2}{\pi\, m_D^2\, m_h^4} + \frac{g_\zeta^4\, \mu_{DN}^2}{\pi\, m_{Z'}^4}$$

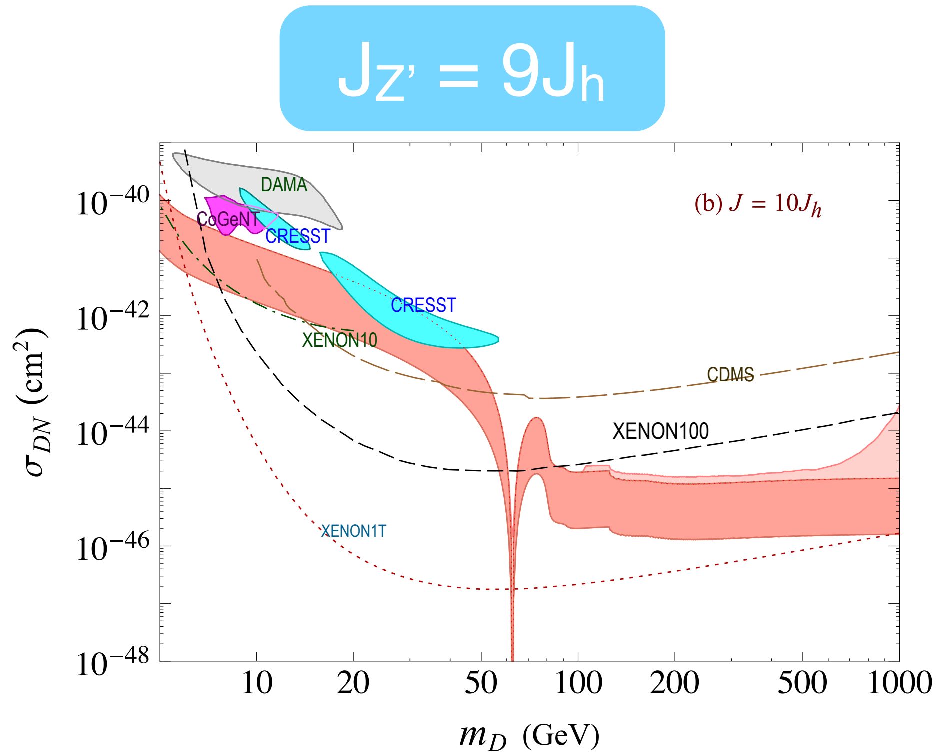
Higgs-nucleon effective coupling
$0.0011 \lesssim g_{NNh} \lesssim 0.0032$

$$\mu_{DN} = \frac{m_D m_N}{m_D + m_N}$$

Cheng, CWC 2012

Direct Search Constraint

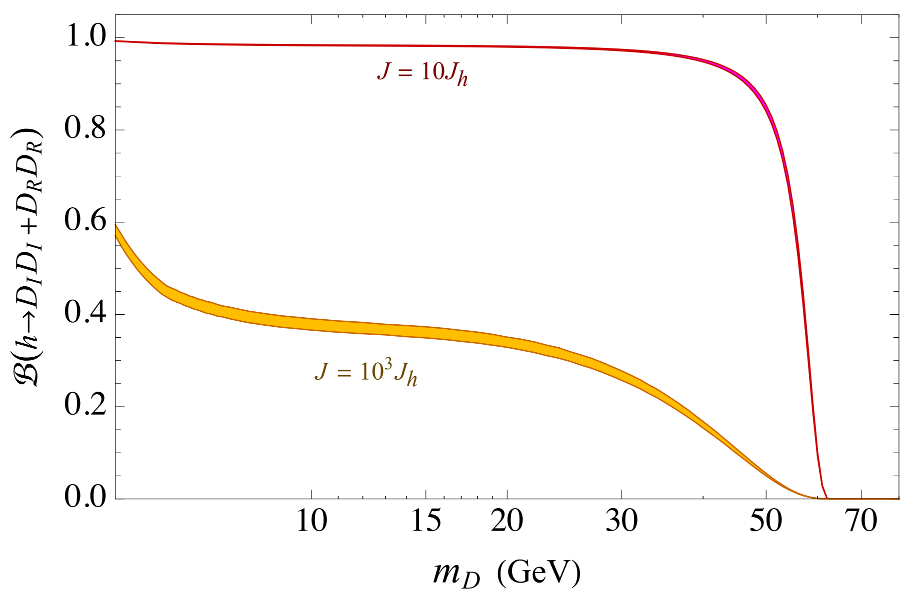




- darker region: purely Higgs; lighter region: Higgs + Z'
- Only some space below 50 GeV ruled out by data
- Higgs dominant in small m_D region
- Z' dominant for $m_D \gtrsim m_h$, also allowed by data
- Wait for XENON1T to probe

Invisible Higgs Decays

- Invisible $h \to DD$ decays possible if $m_D < m_h/2$
- hDD coupling $\propto \lambda_{DH}\, v_H$
- BR($h \to$ inv) $\lesssim$ 0.2 from LHC data Giardino, Kannike, Raidal, Strumia 2012



cf. simplest darkon model is ruled out in this region

- BR($h \to DD$) large even if h subdominant in DD annihilation
  ➠ hDD coupling more constrained for $m_D < m_h/2$

MODEL II

Resonance Relation

- Both direct DM search and Higgs data favor Z'-dominated DM annihilation.
- All assumptions in previous model are acceptable except for one, namely, resonance mass relation between darkons and Z'.

- Is it possible to obtain resonance mass relation more naturally, while keeping gauge structure and representations as simple as possible?

Improved Model

- Extend SM gauge group by $SU(2)_X \times U(1)_{B-L}$
- Add 3 RH neutrinos, 1 5-plet scalar fields (Φ_5), 1 singlet scalar (S), 3 SU(2) gauge bosons (X_μ, X^*_μ, C_μ), and 1 U(1) gauge boson (E_μ)
- Anomaly cancellation satisfied

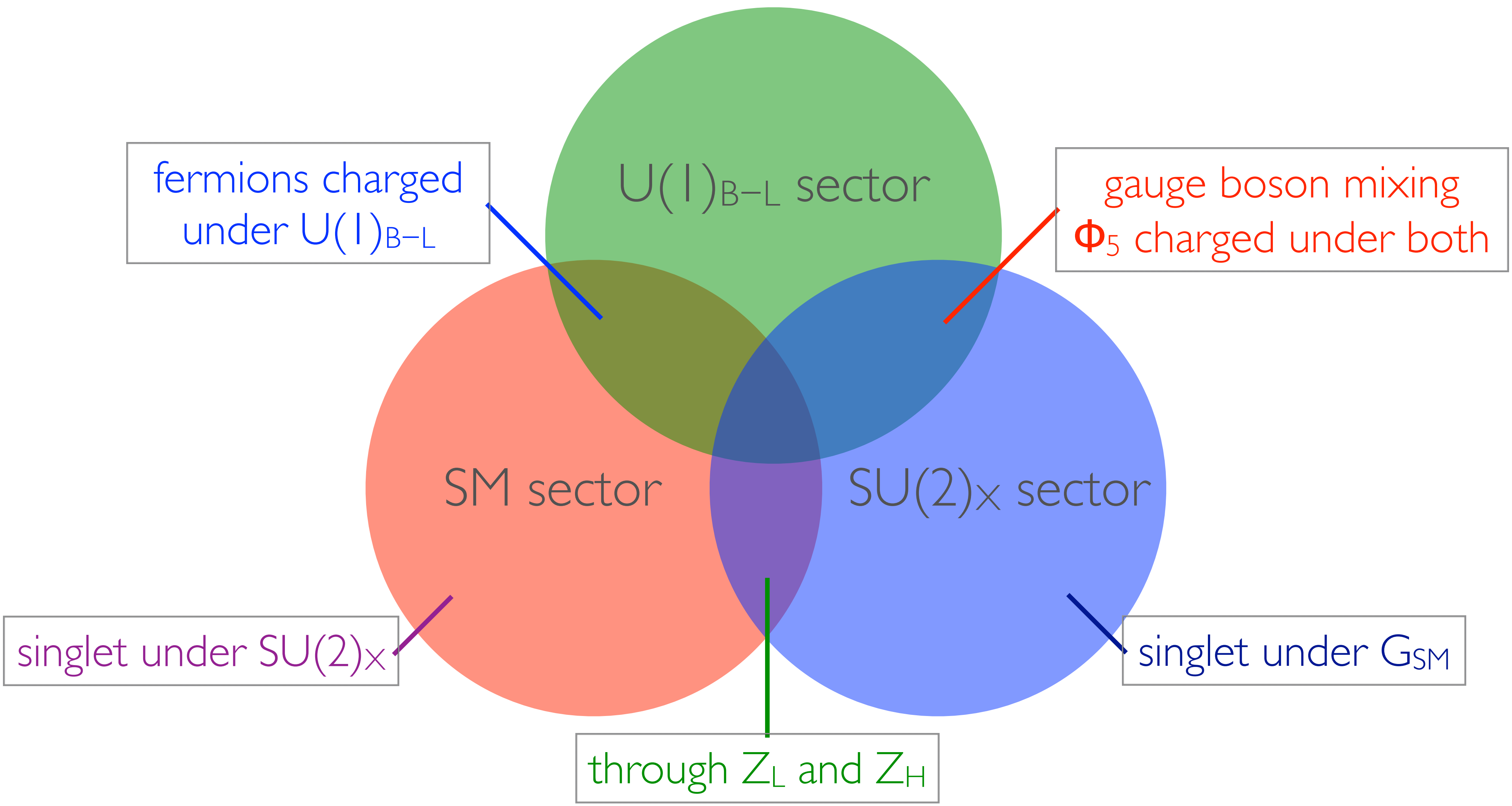
  ➠ $G_{SM} \times SU(2)_X \times U(1)_{B-L}$

  └→ Z_2^X: even/odd T_{3X} component
- Quantum number assignment:

	$f_{\rm SM}$	ν_R	H	S	ϕ_2	ϕ_1	ϕ_0	ϕ_{-1}	ϕ_{-2}	X	$X^\dagger$	C_3	E
$SU(2)_X$ $[U(1)_{B-L}]$	$1\,[B-L]$	$1\,[-1]$	$1\,[0]$	$1\,[2]$	$5\,[2]$	$5\,[2]$	$5\,[2]$	$5\,[2]$	$5\,[2]$	$3\,[0]$	$3\,[0]$	$3\,[0]$	$1\,[0]$
T_{3X}	0	0	0	0	2	1	0	-1	-2	1	-1	0	0
Z_2^X	+	+	+	+	+	$-$	+	$-$	+	$-$	$-$	+	+

TABLE I: The charge assignments under $SU(2)_X \times U(1)_{B-L}$ and Z_2^X parity of the fermions, scalars and new gauge bosons in the model, with $f_{\rm SM}$ referring to SM fermions, $X = (C_1 - iC_2)/\sqrt{2}$, and T_{3X} denoting the eigenvalue of the third generator of $SU(2)_X$.

Structure of Model



Symmetry Breaking

- VEV's

$$v_S \gg v_\Phi > 0$$

$$\langle H \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_H \end{pmatrix} \,, \quad \langle S \rangle = \frac{v_S}{\sqrt{2}} \,, \quad \langle \Phi_5 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} v_\Phi \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

$$U(1)_{B-L} \longrightarrow Z_2^{B-L}$$

$$SU(2)_X \longrightarrow Z_2^X$$

- Since $\langle \Phi_5 \rangle \neq 0$ occurs via its $T_{3X} = 2$ component, Z_2^X symmetry emerges naturally as subgroup of $SU(2)_X$
  ➠ stabilizing X and $X^\dagger$ as DM candidates
  ➠ take Z_2^X-odd scalars to be more massive
- Z_2^{B-L} is remnant of $U(1)_{B-L}$ after $\langle S \rangle \neq 0$ as before, but does not play any role in stabilizing X

New Gauge Bosons

- X and X†:

$$X = \frac{1}{\sqrt{2}}(C_1 - iC_2) \ , \quad X^\dagger = \frac{1}{\sqrt{2}}(C_1 + iC_2)$$

  - W boson-like, but electrically neutral
  - sub-TeV mass $m_X^2 = g_X^2 v_\Phi^2$

- Z_L and Z_H:

$$\begin{pmatrix} Z_L \\ Z_H \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} C_3 \\ E \end{pmatrix}$$

$$R_v = \frac{v_\Phi^2}{v_S^2} \ll 1$$

$$v_S \gg v_\Phi > 0$$
$$g_X \simeq g_{B-L}$$

$$|\theta| \simeq \frac{g_X}{g_{B-L}} R_v \simeq R_v$$

$$m_{Z_L}^2 \simeq 4m_X^2(1 - R_v)$$

resonance relation
cf. ρ parameter in SM

$$m_{Z_H}^2 \simeq 4m_X^2 \frac{g_{B-L}^2}{g_X^2 R_v}(1 + R_v)$$

Neutrino Mass

- The story of neutrino mass generation is same as before

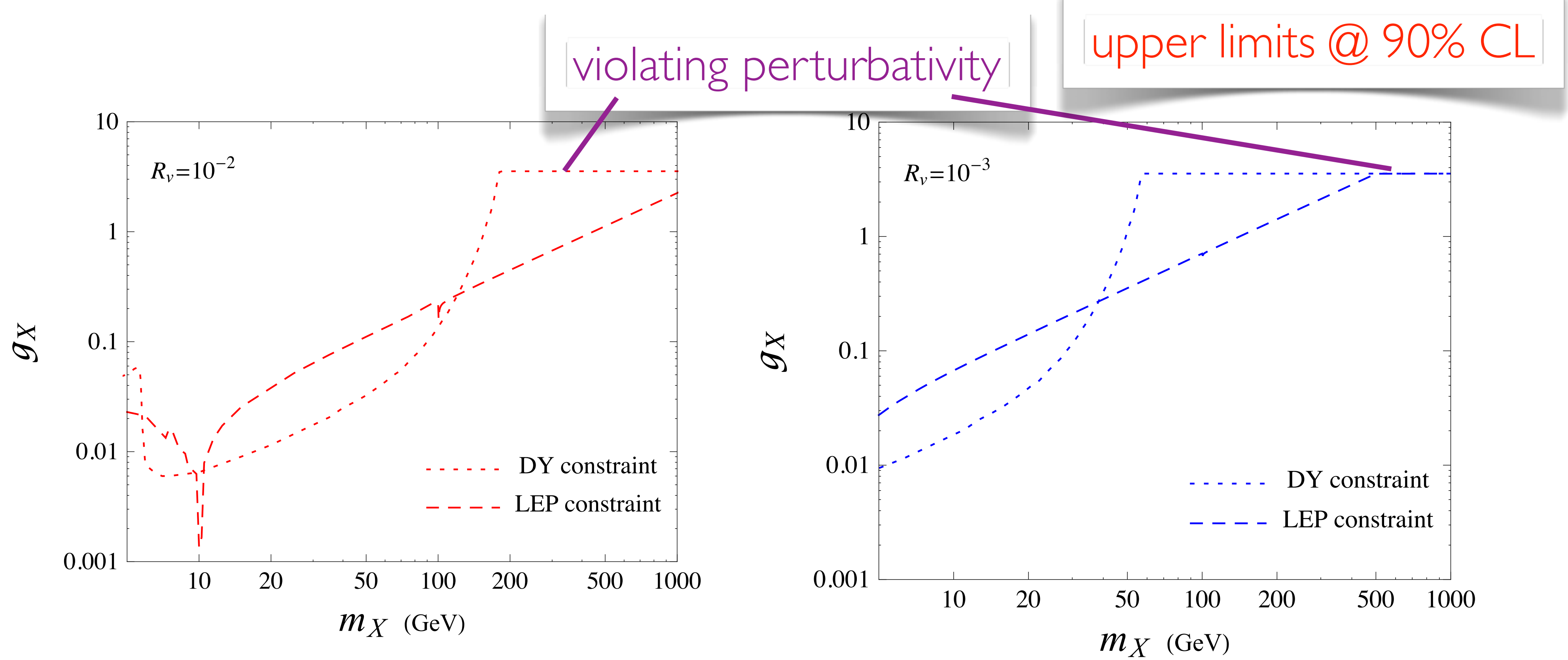
$Z_{L,H}$ Coupling to Fermions

- At tree level:
  - Z_L-f-fbar coupling $\propto g_{B-L} \sin\theta \sim g_{B-L}\,\theta$
  - Z_H-f-fbar coupling $\propto g_{B-L} \cos\theta \sim g_{B-L}$
- Although Z_H is much heavier than Z_L, it turns out that the coupling between the former and SM fermions makes its contributions to the $e^+e^- \to Z_{L,H} \to \ell^+\ell^-$ and $pp \to Z_{L,H} \to \ell^+\ell^- X$ more dominant.

Constraints on Gauge Coupling

- Take $g_X = g_{B-L}$ for definiteness and simplicity

- $e^+e^- \to Z_{L,H} \to \ell^+\ell^-$ @ LEP-II: $\sigma + A_{FB}$
- $pp \to Z_{L,H} \to \ell^+\ell^- X$ @ LHC 7 TeV (4.5/fb): σ



Relic Density of DM

- Pair annihilation is dominated by Z_L due to **resonance** and **lighter mass** than Z_H
- Employ approximate Boltzmann equation solution

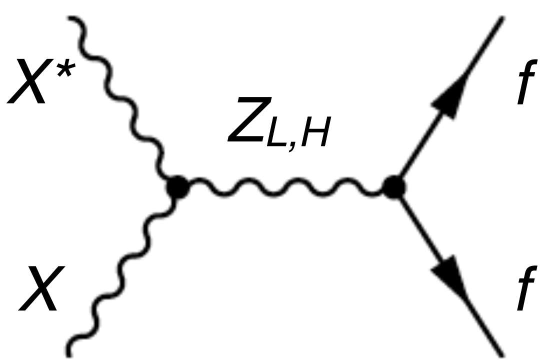
$$\Omega_D h_0^2 = \frac{1.07 \times 10^9}{\sqrt{g_*}\, m_{\rm Pl}\, J \text{ GeV}} \qquad J = \int_{x_f}^{\infty} dx \, \frac{\langle \sigma_{\rm eff}\, v_{\rm rel} \rangle}{x^2}$$

Hubble constant in units of 100/km/s/Mpc

$$x_f = \ln\left[0.038\, g_{\rm eff}\, m_X\, m_{\rm Pl} \langle \sigma_{\rm eff} v_{\rm rel} \rangle (g_* x_f)^{-1/2}\right]$$

g=3 for spin-1 X

# of relativistic dof's below freeze-out temp T_f



$$\sigma \propto g_X^2 g_{B-L}^2 \cos^2\theta \sin^2\theta \sim g_X^2 g_{B-L}^2 \theta^2$$

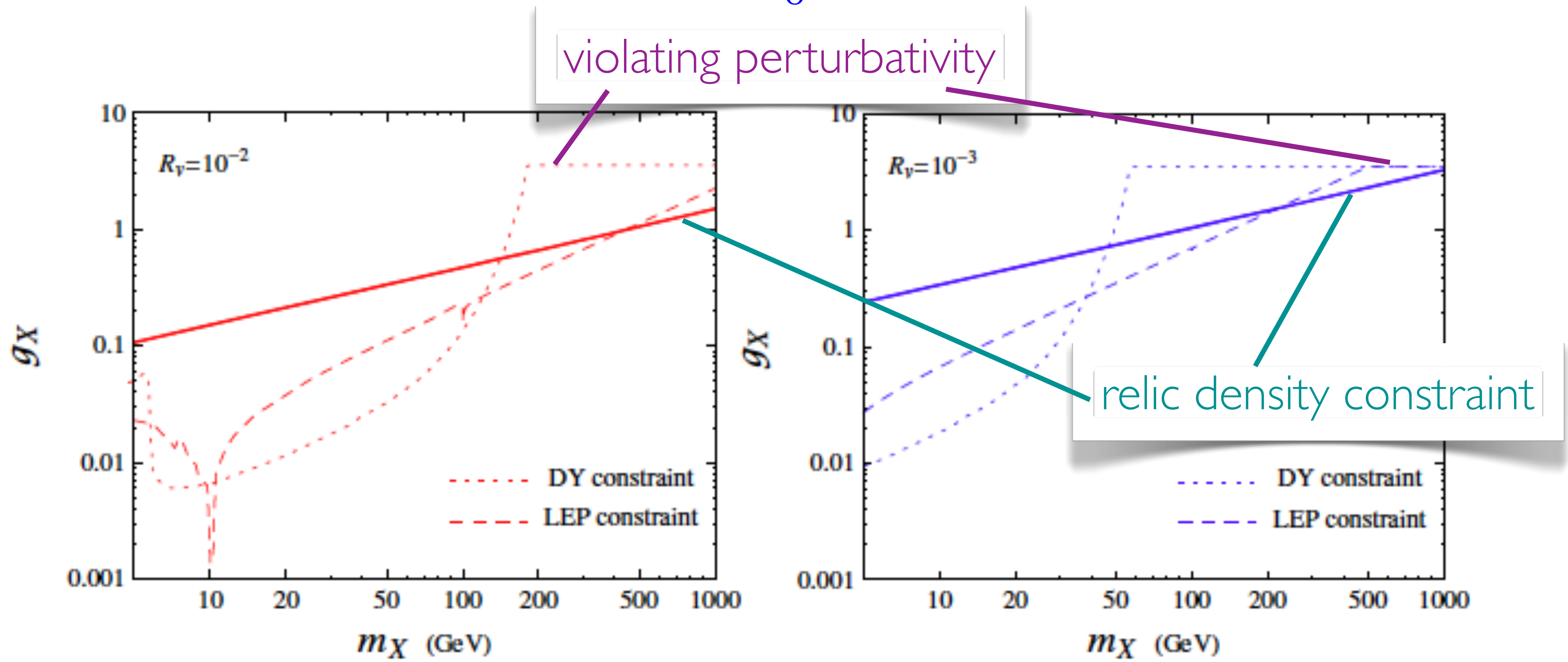
larger gauge couplings demanded

Relic Density Constraint

- Employ 90%-CL range:

$$0.1159 \le \Omega_D h_0^2 \le 0.1215$$

Planck 2013

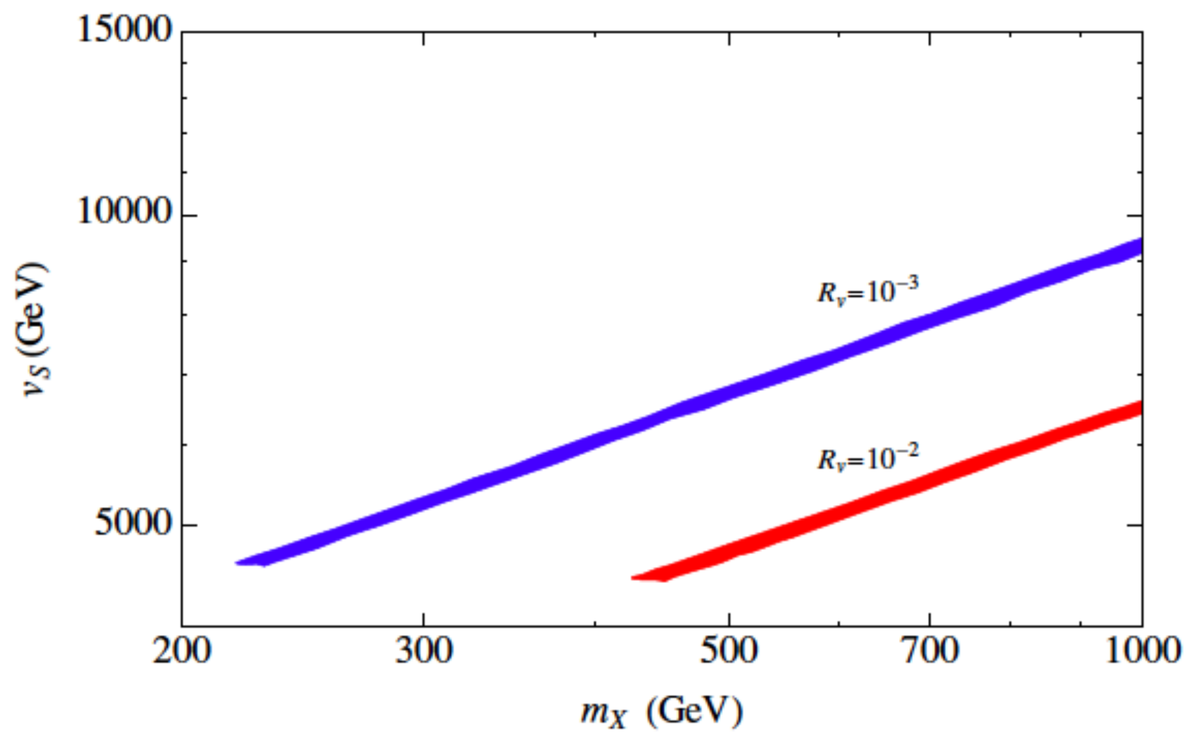


- m_X > 420 (220) GeV is allowed for R_v=10^{-2} (10^{-3})
- O(1) gauge coupling constant is required

A Word About v_S

- A linear relation between DM mass and the S VEV:

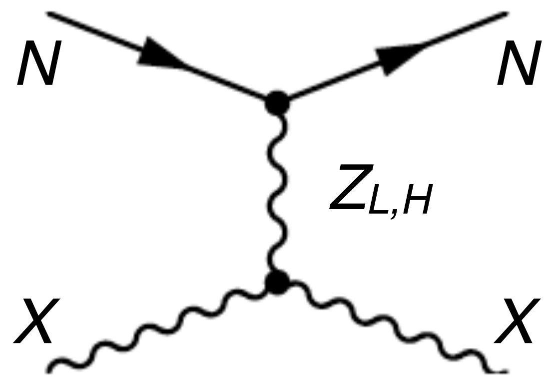
$$m_X = g_X v_\Phi = g_X \sqrt{R_v} v_S$$



- v_S should be above ~5–10 TeV, preferring TeV-scale type-I seesaw

DM-Nucleon Scattering

- Scattering cross section for direct detection in non-relativistic limit

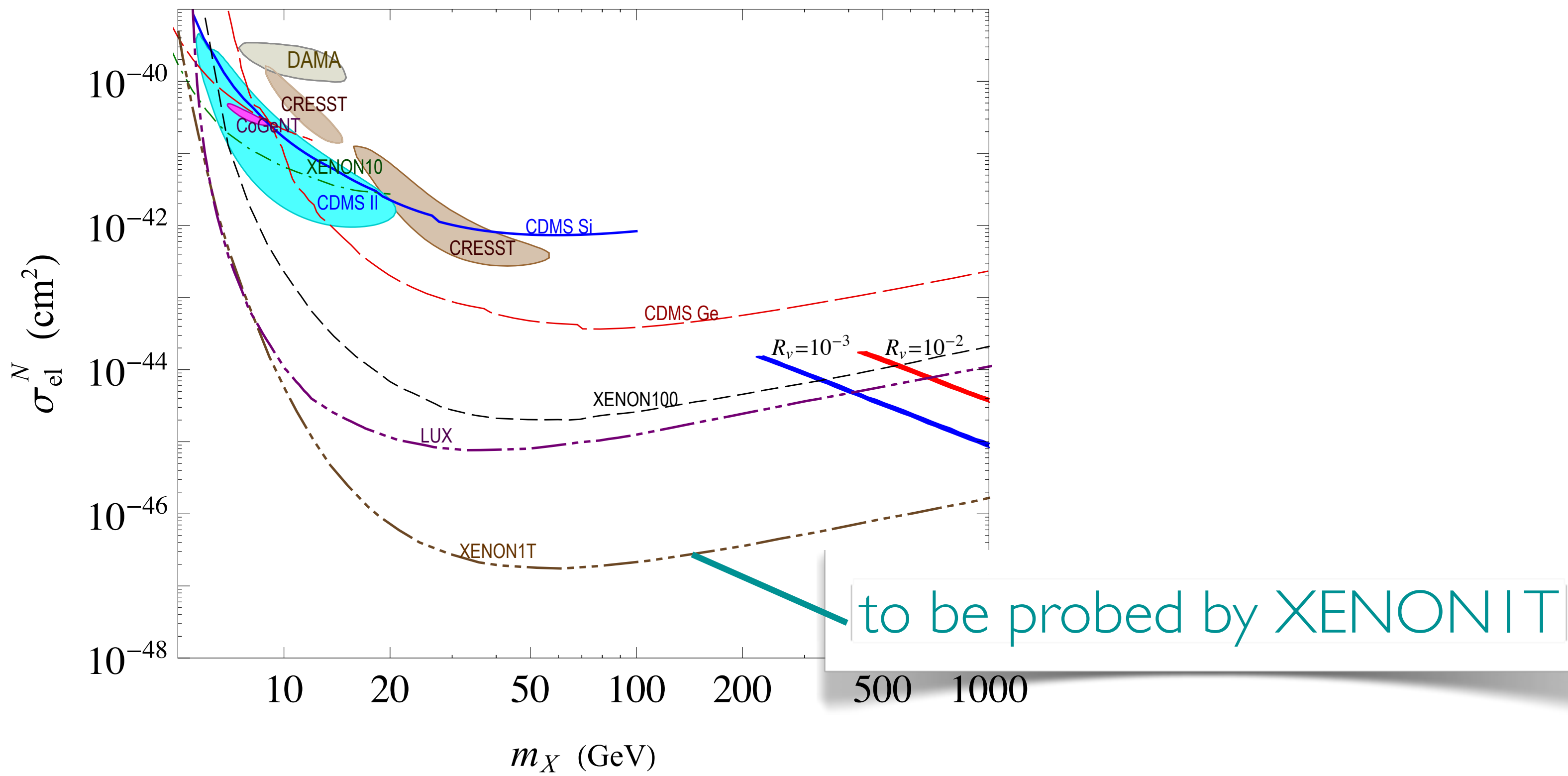


$$\mu_{XN} = \frac{m_X m_N}{m_X + m_N}$$

$$\sigma^{\rm el}_{XN} = \frac{g_X^2\, g_{B-L}^2 \cos^2\theta \sin^2\theta\, \mu_{XN}^2}{\pi m_{Z_L}^4} \simeq \frac{g_X^4\, R_v^2\, \mu_{XN}^2}{16\pi\, m_X^4}$$

- Still dominated by Z_L due to lighter mass

Direct Search Constraint



- A significant portion of parameter space at high m_X is allowed by direct search
- Smaller R_v is not helpful as it is ruled out by gauge coupling constraints

Summary

- Z_2 symmetry for stabilizing DM candidates (darkons) emerges naturally as remnant of extra gauge groups, rather than *ad hoc*.
- Models easily accommodate SM-like Higgs, but also leave ample room for non-SM-like Higgs (including invisible Higgs decays).
- Incorporated minimal mechanism for (1) stabilizing DM using DGS and (2) generating neutrino mass through breaking of same group.
- Z' as well as Higgs contribute to DM interactions with SM particles.
  ➠ consider Z' dominant in DM relic density determination
  ➠ coannihilation is taken into account in U(1) model
  ➠ natural resonance effect in non-Abelian extensions
- Checked constraints of new gauge coupling, DM relic density, and DM direct detection. WIMP of O(100) GeV is favored.
- Computed invisible Higgs decays.
- Comments on collider pheno are given in paper.

Summary

- We had a very successful workshop.
- I learned physics and ski.
- Many thanks to Eung Jin and organizing staff!

THANK YOU AND
LOOK FORWARD TO
SEEING YOU ALL IN "T-HIGH I"