Probing the fourth generation Majorana neutrino dark matter

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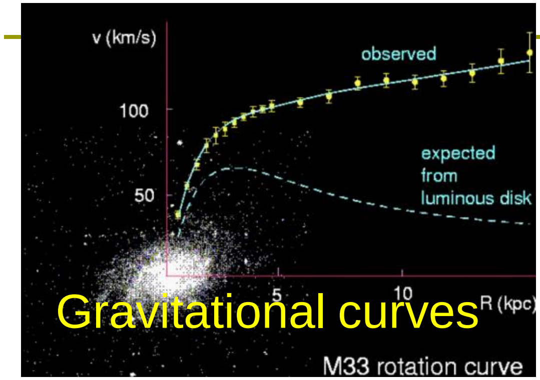
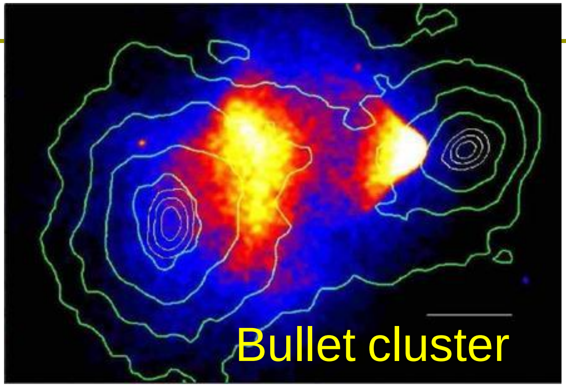
arXiv:1110.2930

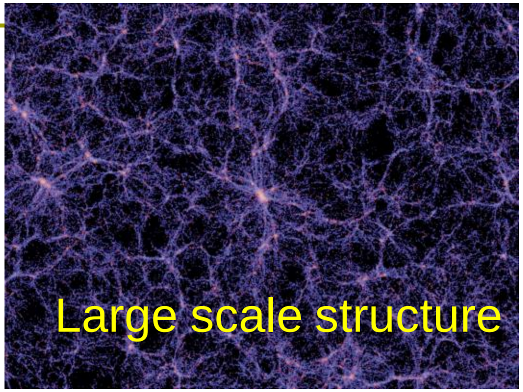
outline

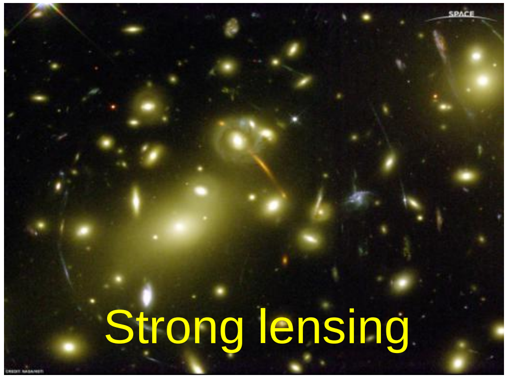
- Introduction
  - Brief overview on current DM searches
  - Neutrinos as DM candidates
  - The 4^{th} generation models
- A 4^{th} generation model with Majoran neutrino DM
  - The 4^{th} generation with U(1)'_F.
  - Correlation between relic density and event rate in direct detection searches
  - Numerical results
- Conclusions

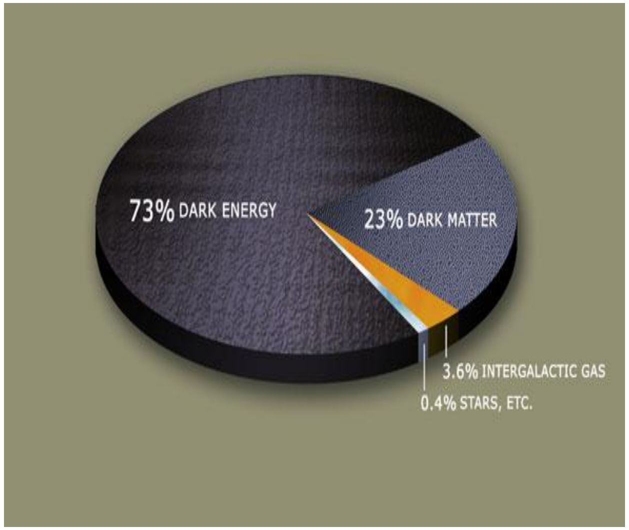
DM from gravitational effects

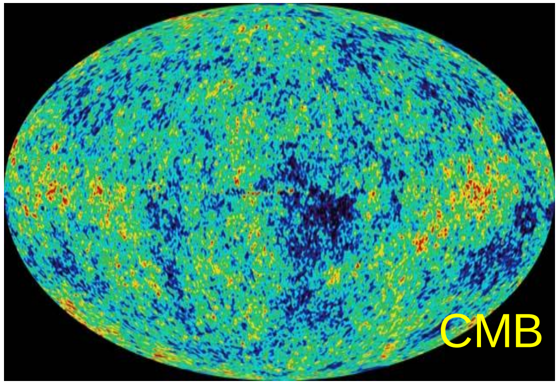


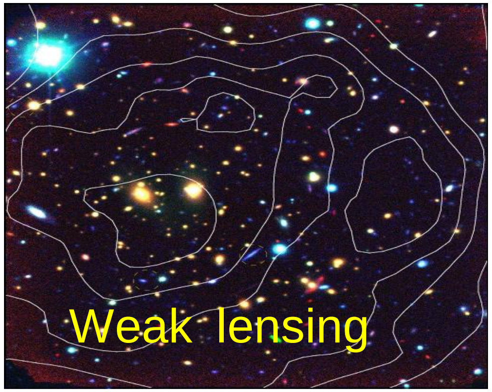




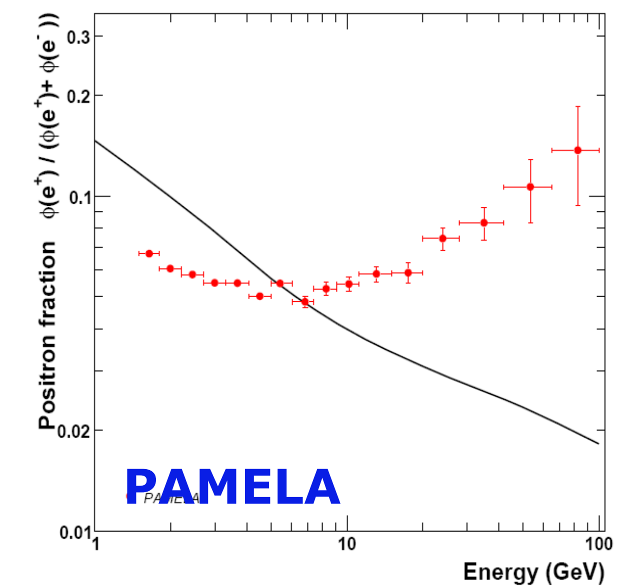




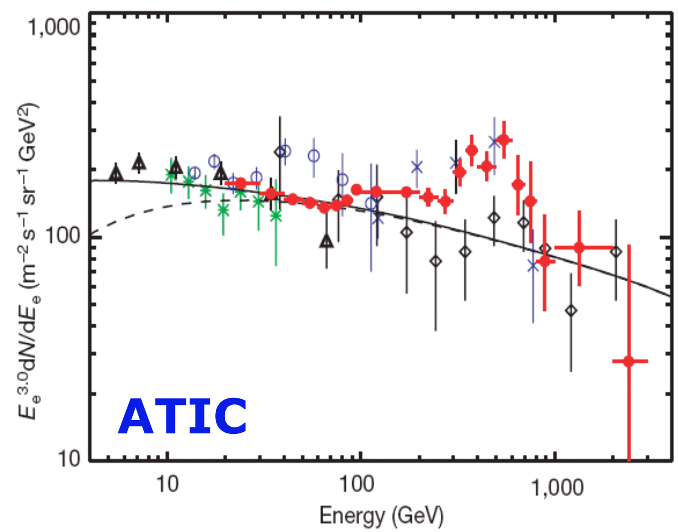




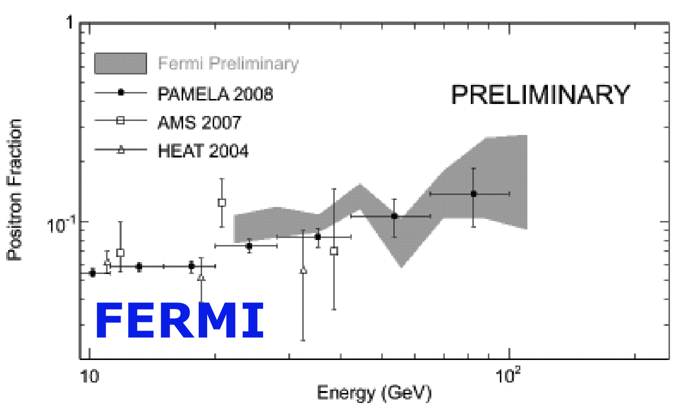
Hints of DM ?
the cosmic-ray lepton anomalies

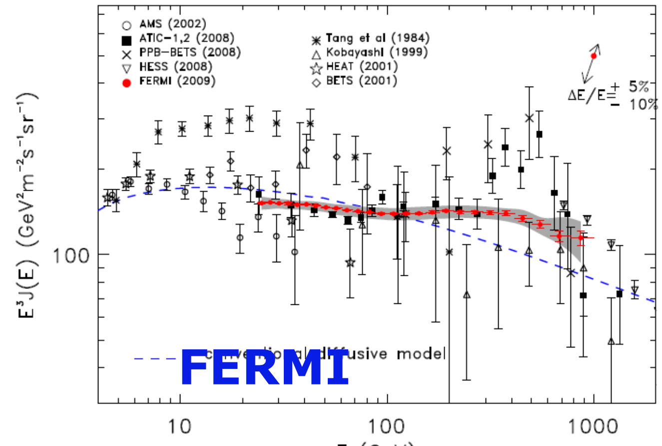


PAMELA, Nature 458, 607 (2009)



ATIC, Nature, 456, 2008,362-365

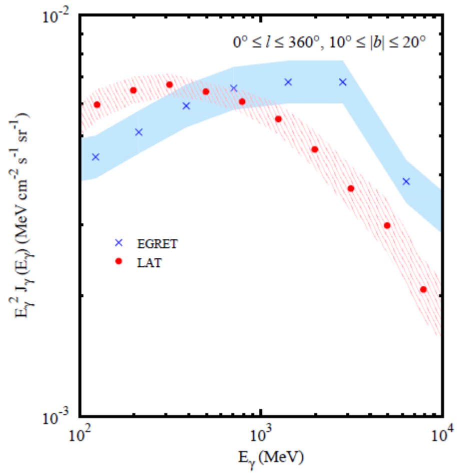


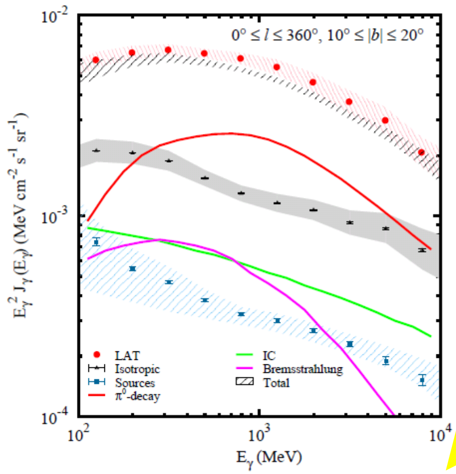


Fermi-LAT, Phys.Rev.Lett.102:181101,2009

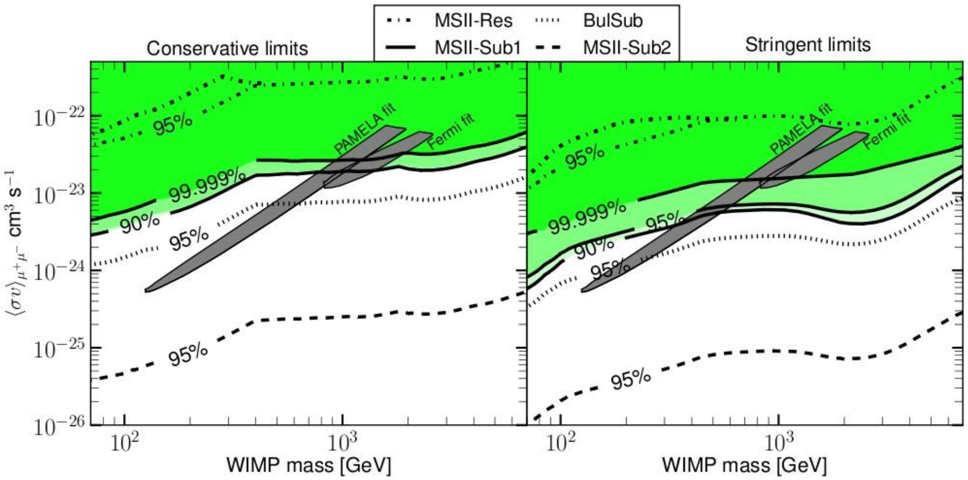
Constraints from cosmic gamma-rays

Fermi-LAT, Phys.Rev.Lett.103:251101, 2009

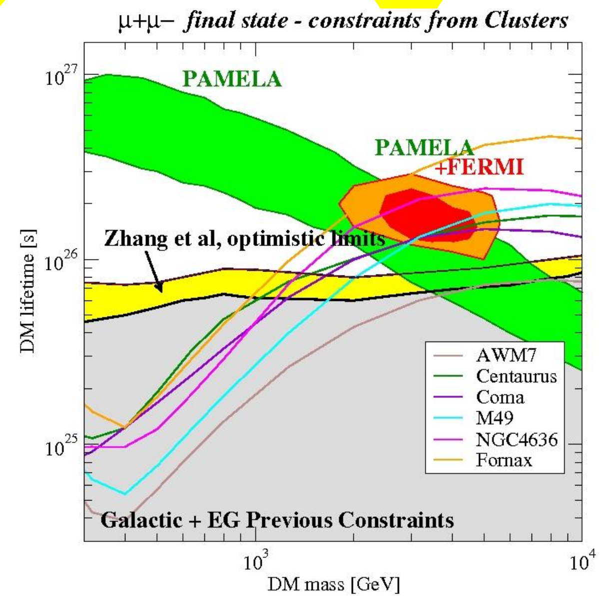




DM annihilation/decay constrained by the null results on cosmic gamma-rays



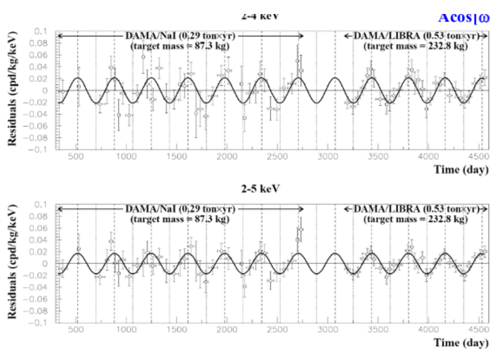
Abdo, et.al, arXiv:1002.4415



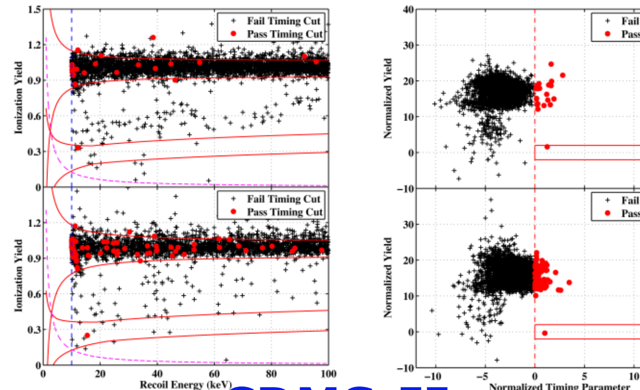
Dugger et.al, arXiv:1009.5988

Dark matter direct searches

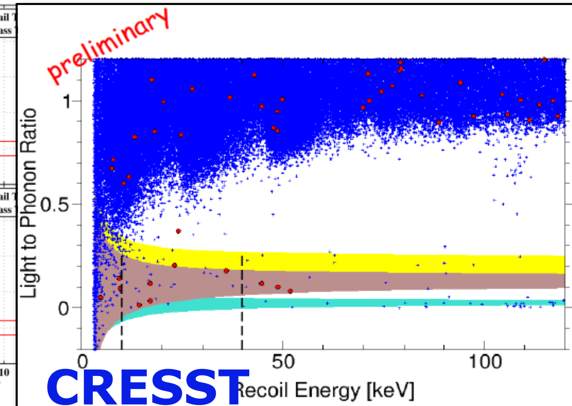
H.Kim talk



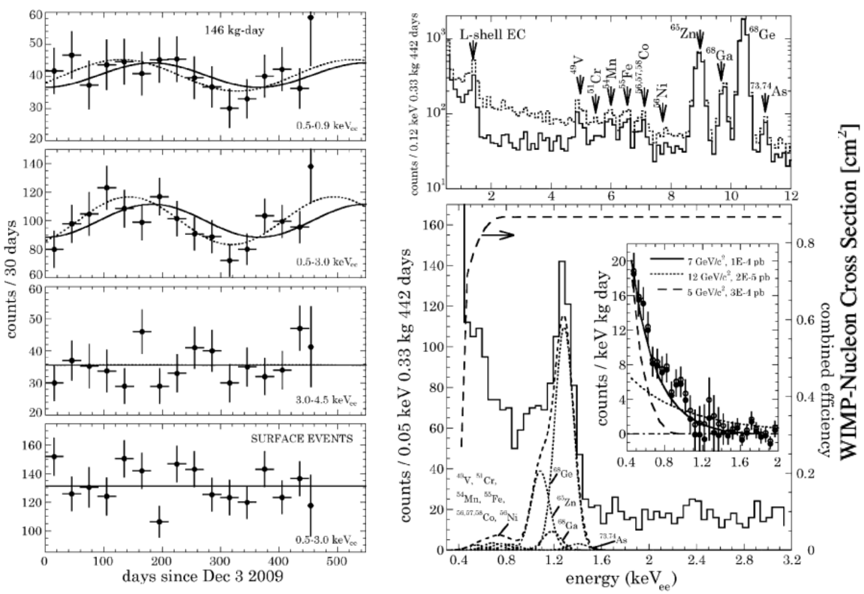
DAMA



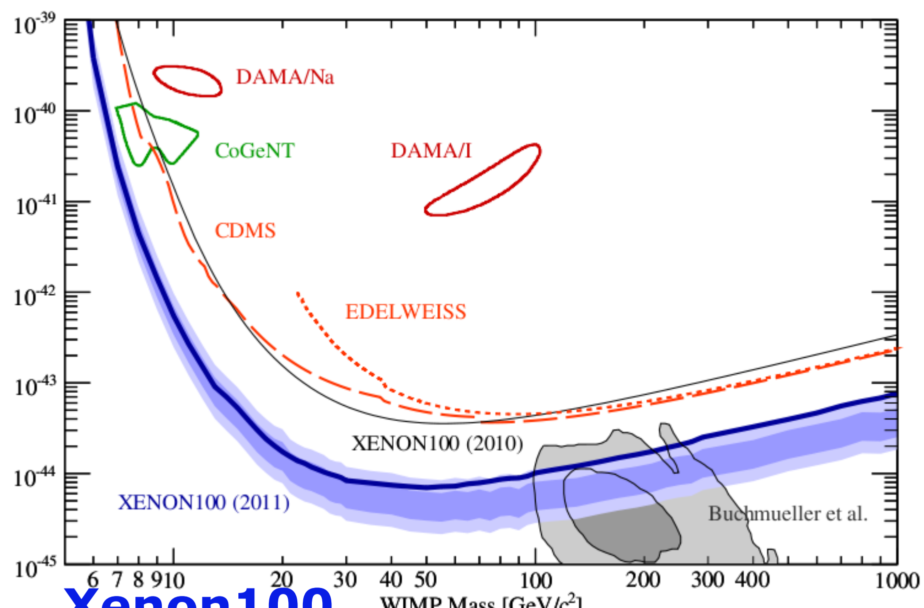
CDMS-II



CRESST

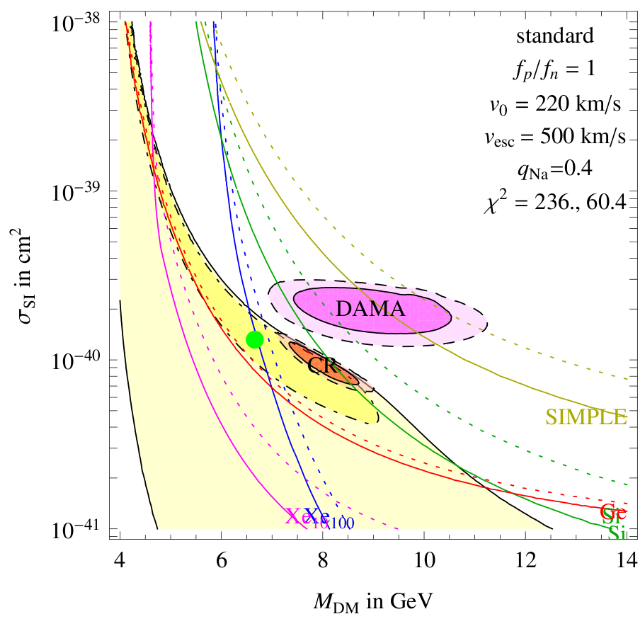


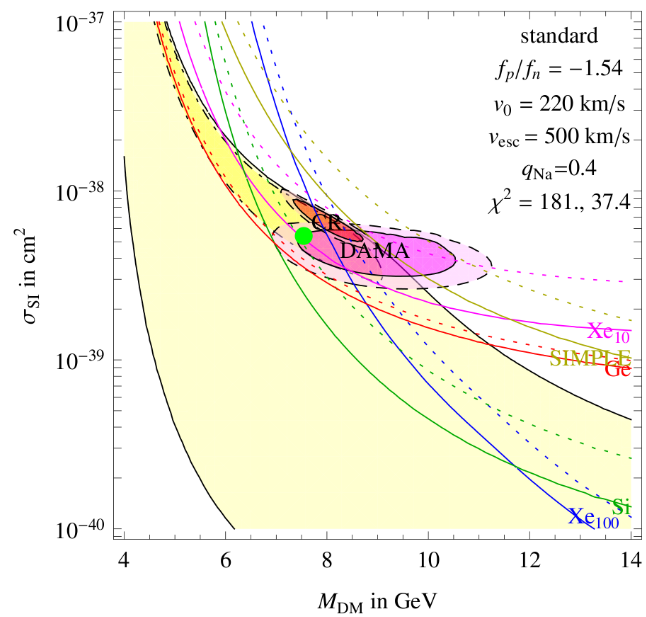
CoGeNT



Xenon100

M.Farina, etal, 1107.0715
J.Kopp, t. Schwetz, J. Zupan,1110.2721
S.Scopel talk





Explanations

- Inelastic scattering ?
- Isospin-violating DM ?
- Velocity suppressed interaction
- Momentum dependent scattering
- Resonant scattering

Uncertainties

- halo DM velocity distribution
- Quenching factors
- Channeling effects
- ……

Stability of DM

- Using extra symmetries

  motivated to evade phenomenological constraints
  - R-Parity: MSSM, LSP
  - KK-Parity: UED, LKP
  - T-Parity: Little higgs,

  motivated by DM
  - Z_2: SM+scalar DM
  - U(1)': SM+fermoin DM (**E.J.Chun, Y. Omura, C.Yu, H.S. Lee,.. talk**)
- Using the known symmetries
  - SU(2): Minimal DM model: SM + scalar/fermion with high representation, **(X.G. He talk),** SU(2) "pion" **(R.Hill talk)**
  - P, CP: LR symmetric model + scalar

Scalar DM protected by P/CP in LR models

- Adding gauge-singlet in to the LR model

W.L.Guo, Y.L.Wu, YFZ,
Phys.Rev.D79:055015(2009)
Phys.Rev.D82:095004(2010)
Phys.Rev.D81:075014(2010)

$$\phi = \begin{pmatrix} \phi_1^0 & \phi_1^+ \\ \phi_2^- & \phi_2^0 \end{pmatrix}, \chi = \begin{pmatrix} \chi_1^0 & \chi_1^+ \\ \chi_2^- & \chi_2^0 \end{pmatrix},$$

$$\Delta_{L,R} = \begin{pmatrix} \delta_{L,R}^+/\sqrt{2} & \delta_{L,R}^{++} \\ \delta_{L,R}^0 & -\delta_{L,R}^+/\sqrt{2} \end{pmatrix},$$

$$S = \frac{1}{\sqrt{2}}(S_\sigma + iS_D)$$

spontaneous CP violation assumed

Terms forbidden

$(S - S^*)^{1,3}$

$(S - S^*)\mathrm{Tr}(\phi^\dagger \phi)$

$(S - S^*)\mathrm{Tr}(\Delta_L^\dagger \Delta_L + \Delta_R^\dagger \Delta_R)$

Residual Z_2

S_D a DM candidate

P- and CP-transformations

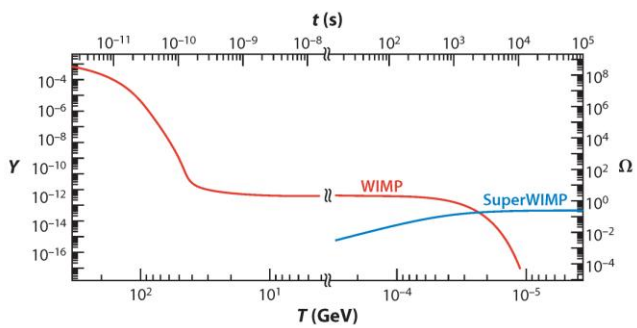
	P	CP
$\phi \rightarrow$	$\phi^\dagger \rightarrow$	ϕ^*
$\chi \rightarrow$	$\chi^\dagger \rightarrow$	χ^*
$\Delta_{L(R)} \rightarrow$	$\Delta_{R(L)} \rightarrow$	$\Delta_{L(R)}^*$
$S \rightarrow$	$S \rightarrow$	S^*

The relic density of DM

- **Thermal:** decouple from thermal equilibrium
- **Nonthermal:** never reached thermal equilibrium (super weak)

Nonthermal generation of DM

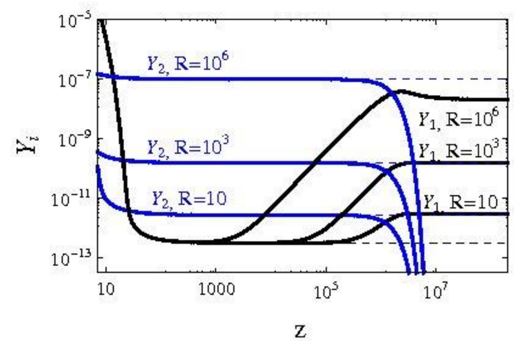
- gravitational interaction
- decay of unstable particles



J.L.Feng 2004

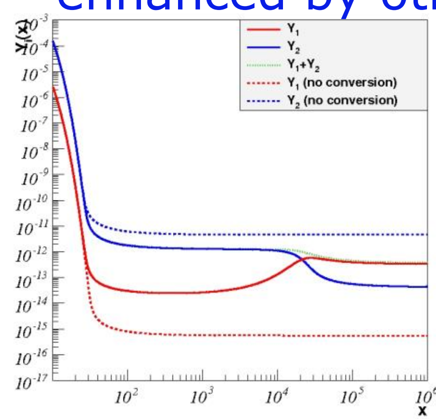
  - **Late decay may affect BBN, CMB**
  - **DM may get warm**
- by transitions from other particles

- Thermal DM density enhanced by late decay of unstable states



Zupan, etal, 2009

- Thermal DM density enhanced by other DMs



Z.P.Liu,Y.L. Wu, YFZ, Eur.Phys.J.C71:1749(2011)

Neutrinos as DM candidates

- **Very light SM neutrinos (hot DM)**

CMB bound: $\Omega_\nu h^2 < 0.0067(90\% CL)$

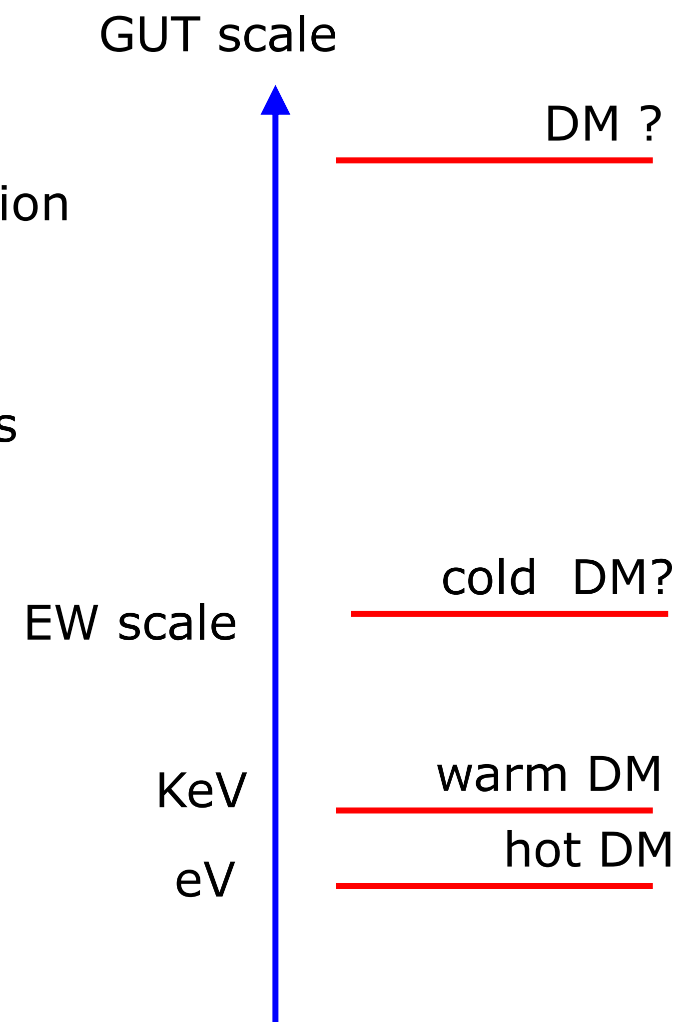
Disfavored by large scale structure formation

- **KeV sterile neutrinos (warm DM)**

Less substructure, favored by observations
Life-time longer than the Univers
Non-thermal generation
Constraints: X-ray, BBN, Ly-alpha,…
hard to detect directly ?

- **Heavy neutrinos (cold DM)**

Heavy active Dirac/Majorana neutrino cannot make up the whole DM
(not necessary in multi-DM models !)
Heavy sterile neutrino ?



A 4th generation model with neutrino DM

- SM4: Simplest extension to the SM.

$$SM + \begin{pmatrix} u_{4L} \\ d_{4L} \end{pmatrix}, \begin{pmatrix} \nu_{4L} \\ e_{4L} \end{pmatrix}, u_{4R}, d_{4R}, (\nu_{4R}), e_{4R}$$

$$V_{CKM4} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} & V_{ub'} \\ V_{cd} & V_{cs} & V_{cb} & V_{cb'} \\ V_{td} & V_{ts} & V_{tb} & V_{tb'} \\ V_{t'd} & V_{t's} & V_{t'b} & V_{t'b'} \end{pmatrix}$$

- New sources of CP violation

6 real parameters, 3 phases in CKM4

Large CP violation possible

- Effective Hamiltonian

W.S.Hou, 0803.1234

$$H_{eff} = \frac{G_F}{\sqrt{2}}\left[\lambda_u (C_1^u O_1 + C_2^u O_2 + \sum C_i^u O_i) + \lambda_c \sum C_i^c O_i - \lambda_{t'} \sum \Delta C_i^{t'} O_i\right]$$

Can help in explaning the πK CP puzzle:

A.Soni, 0807.1871

$$\Delta A_{CP} = A_{CP}(\pi^0 K^-) - A_{CP}(\pi^+ K^-) = (14.4 \pm 2.9)\%$$

Constraints on the SM4

- 4^{th} generation quarks

LHC:

R. Contino, A. Koryot

$m_{u_4} \geq 450$ GeV from searching for $u_4\overline{u_4} \to WbW\overline{b} \to b3j\ell^{\pm}E_T$,

$m_{d_4} \geq 490$ GeV from searching for $d_4\overline{d_4} \to WtW\overline{t} \to \ell^{\pm}\ell^{\pm}b3jE_T$

H.Yokoda talk

Assuming 4-3 transition and 100% Br

Tevatron:

$m_{u4} \geq 335$ GeV assuming mass spliting less than $m_W : u_4 \to Wq$

$m_{d4} \geq 385$ GeV, assuming $m_{u4} > m_{d4}$ from $d_4 \to Wt$

G. Kribs etal, 0706.3718
J.Erler,P.Langacker,1003.3211

- SM higgs with 4^{th} family

LHC ruled out:

$$120\text{GeV} \leq m_H \leq 600\text{GeV}$$

EW precision test:

Mass difference between u_4 and d_4 have to be small

Constraints on the SM4 leptons

- 4th generation leptons

$$m_{e4} \geq 100.8\mathrm{GeV}\ \text{from}\ e_4 \to \nu_4 W^{\pm}$$

- 4^{th} generation neutrinos
  - Unstable neutrinos $\nu_4 \to (e, \mu, \tau) W^{+}$

$$m_{\nu 4} \geq (101.3, 101.5, 90.3)\mathrm{GeV}\ \text{(unstable Dirac)}$$

$$m_{\nu 4} \geq (89.5, 90.7, 80.5)\mathrm{GeV}\ \text{(unstable Majorana)}$$

  - Stable neutrinos -> weaken EWPT bounds, dark matter ?

$$m_{\nu 4} \geq 45.0(39.5)\mathrm{GeV}\ \text{(stable Dirac(Majorana))}$$

The 4^{th} generation leptons must have quite different nature

A 4th generation model with stable neutrinos

- A 4th generation U(1)' model

$$q_{iL} = \begin{pmatrix} u_{iL} \\ d_{iL} \end{pmatrix}, \ell_{iL} = \begin{pmatrix} \nu_{iL} \\ e_{iL} \end{pmatrix}, u_{iR}, d_{iR}, \nu_{iR}, e_{iR} \ (i = 1, \ldots, 4), \phi_a, \phi_b$$

- Gauge interaction

$$SU(2) \otimes U(1)_Y \otimes U(1)_F$$

- Anomaly-free assignments

$U(1)_F$	charges		
u_i, d_i	Q_q	u_4, d_4	$-3Q_q$
ν_i, e_i	Q_L	ν_4, e_4	$-3Q_L$
ϕ_a	$-2Q_L$	ϕ_b	$+6Q_L$

1) vector-like interaction

$$[U(1)_F]^3, [SU(3)_C]^2, [gravity]^2 U(1)_F \to 0$$

2) due to $\sum(-Y_{qL} + Y_{qR}) = 0$ and $\sum(-Y_{\ell L} + Y_{\ell R}) = 0$

$$U(1)_Y [U(1)_F]^2 \to 0$$

3) from $\sum_{i=1}^{4} Q_{qi} = 0$ and $\sum_{i=1}^{4} Q_{Li} = 0$

$$[SU(2)_L]^2 U(1)_F \to 0$$

Anomalies canceled between generations

New interactions

- Interactions

YFZ, arXiv:110.2930

$$\mathcal{L} = \bar{f}_i i\gamma^\mu D_\mu f_i + (D_\mu\phi_a)^\dagger(D_\mu\phi_a) + (D_\mu\phi_b)^\dagger(D_\mu\phi_b)$$
$$-Y^d_{ij}\bar{q}_{iL}Hd_{iR} - Y^u_{ij}\bar{q}_{iL}\tilde{H}u_{iR} - Y^e_{ij}\bar{\ell}_{iL}He_{iR} - Y^\nu_{ij}\bar{\ell}_{iL}\tilde{H}e_{iR}$$
$$-\frac{1}{2}Y^m_{ij}\overline{\nu^c_{iR}}\phi_a\nu_{jR}\ (i,j=1,2,3) - \frac{1}{2}Y^m_4\overline{\nu^c_{4R}}\phi_b\nu_{4R} - V(\phi_a,\phi_b,H) + \text{H.c.}$$

The 4x4 CKM matrix is block diagonal
-> no mixing at tree level

- Mass of Z' from U(1)' breaking

$\langle\phi_a\rangle = v_{a,b}/\sqrt{2}$

$m^2_{Z'} = g^2_F(Q^2_a v^2_a + Q^2_b v^2_b)$,

small g_F suppresses $Z' \to \ell\bar{\ell}$,

can evade severe LHC bounds

muon $g-2$

$$\Delta a_\mu \approx \frac{g^2_F}{12\pi^2}\frac{m^2_\mu}{m^2_{Z'}} \le 3.9\times10^{-9}$$

lead to a bound

$$\sqrt{Q^2_a v^2_a + Q^2_b v^2_b} \ge 1.4\times10^2\,\text{GeV}$$

Dark matter in the model

- Possible dark matter

- Lightest active neutrino (~eV)
  $\nu_{1L}, (\nu_{2L}, \nu_{3L})$
- Light sterile neutrinos (~KeV)
  $\nu_{1R}, \nu_{2R}, \nu_{3R}$
- Lightest 4th neutrino (~100 GeV)
  ν_{4L}, ν_{4R}
- Neutral 4th bound-states ?

A multi-component DM model?

$$\sum \Omega_i = \Omega_{DM} = 0.11$$

- The 4th heavy Majorana neutrino as DM component

- allow

$$r_\Omega \equiv \frac{\Omega_{\chi_1}}{\Omega_{DM}} < 1,$$

- assumption on halo DM

$$r_\rho \equiv \frac{\rho_1}{\rho_0} \approx \frac{\Omega_{\chi_1}}{\Omega_{DM}},$$

- nontrivial correlation between relic density and the event-rate of direct detection.
- very predictive, constrained by the current exp., clear prediction for SI scattering

Neutrino masses and interaction

- 4th Neutrino mass matrix

$$m_\nu = \begin{pmatrix} 0 & m_D \\ m_D & m_M \end{pmatrix}, \quad m_1 = \left(\frac{s}{c}\right) m_D, \quad \text{and} \quad m_2 = \left(\frac{c}{s}\right) m_D. \quad \tan 2\theta = \frac{2m_D}{m_M}.$$

- Mass eigenstates (the lightest one is stable: U(1)' protected)

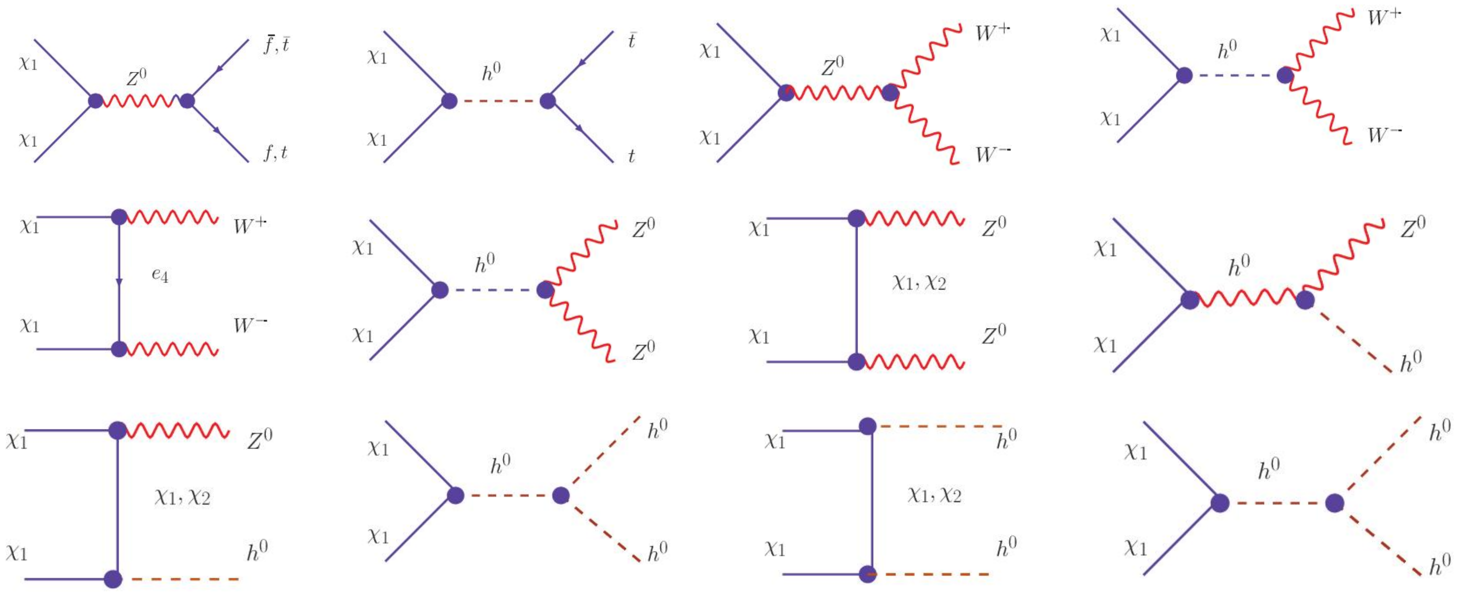
$$\nu_{1L}^{(m)} = -i(c\nu_L - s\nu_R^c), \quad \nu_{2L}^{(m)} = s\nu_L + c\nu_R^c,$$

- Interactions with Z and SM higgs

$$\mathrm{L}_{NC} = \frac{g_1}{4\cos\theta_W}\left[-c^2\bar{\chi}_1\gamma^\mu\gamma^5\chi_1 - s^2\bar{\chi}_2\gamma^\mu\gamma^5\chi_2 + 2ics\bar{\chi}_1\gamma^\mu\chi_2\right] Z_\mu,$$

$$\mathrm{L}_Y = -\frac{m_1}{v_H}\left(\frac{c}{s}\right)\left[cs\bar{\chi}_1\chi_1 + cs\bar{\chi}_2\chi_2 - i(c^2 - s^2)\bar{\chi}_1\gamma^5\chi_2\right] h^0.$$

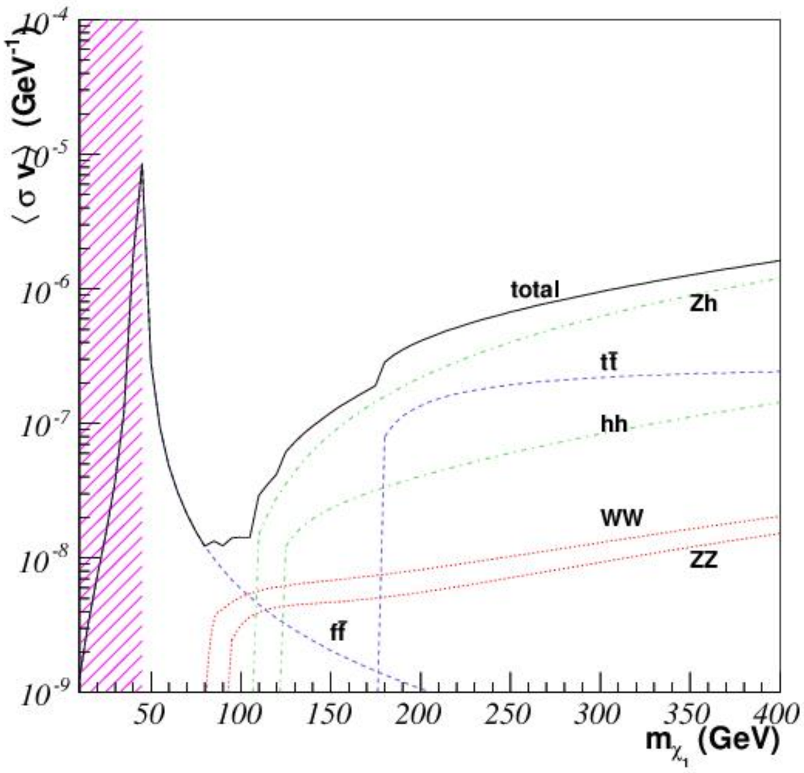
Annihilation channels



Thermally averaged cross section

$$\langle \sigma v \rangle = \frac{1}{8m_1^2 T K_2^2 (m_1 / T)} \int_{4m_1^2}^{\infty} ds \sigma (s - 4m_1^2) \sqrt{s} K_1 \left(\frac{\sqrt{s}}{T} \right),$$

Annihilation cross-sections



- Annihilation channels

1) For $m_\chi < m_Z / 2$, $f\bar{f}$ is dominant

$\langle \sigma v \rangle \approx G_F^2 m_\chi^2 \langle v^2 \rangle (C_V^2 + C_A^2) c^4$, suppressed

2) For $m_\chi > m_W, W^{\pm}W^{\mp}$ chennel opens

$\langle \sigma v \rangle \approx G_F^2 m_\chi{}^2 \langle v^2 \rangle \beta_W s^2 \, | D_Z |^2 \, c^4$, suppressed

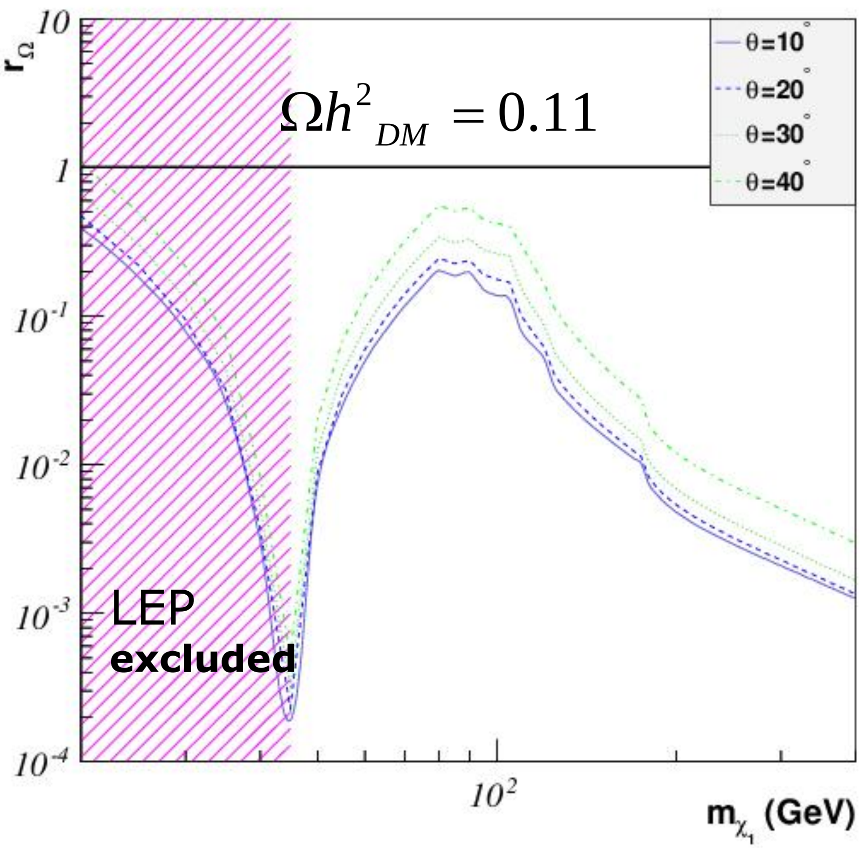
3) For $m_\chi > m_Z, Z^0 Z^0$ chennel opens

4) For $m_\chi > m_H, Z^0 h^0,\ h^0 h^0$ chennels open

5) For $m_\chi > m_t, t\bar{t}$ chennel opens

Different from Dirac neutrino DM
- ff_bar channels are helicity and velocity suppressed
- WW chanel is velocity suppressed
- Zh more important

Relic density of heavy neutrino DM



strong mass-dependence

- Relic density

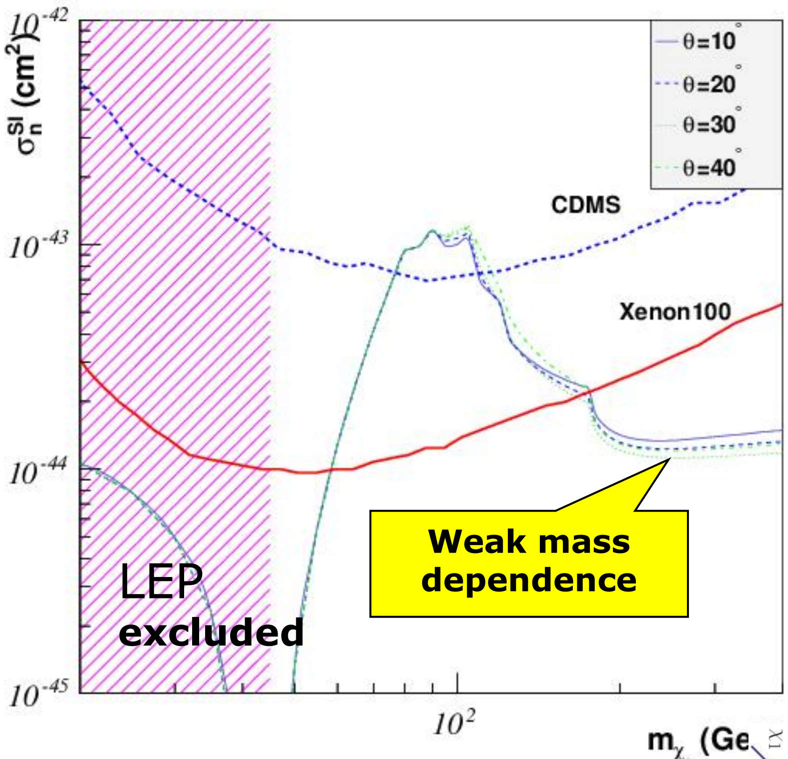
$$\Omega h^2 \simeq \frac{1.07\times 10^9\,\mathrm{GeV}^{-1}}{\sqrt{g_*}M_{pl}\int_{x_F}^{\infty}\frac{\langle\sigma v\rangle}{x^2}dx},$$

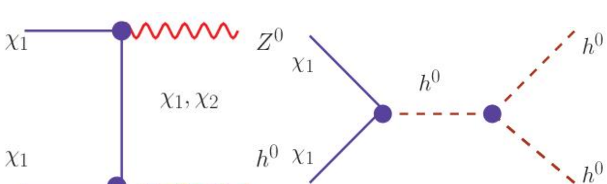
- No upper bound on neutrino mass
- Majorana neutrino can make up O(10%) of DM at 100 GeV, O(1%) at 200 GeV.

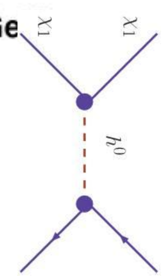
YFZ, arXiv:110.2930

SI cross section

YFZ, arXiv:110.2930







Relic density

SI scattering

- Event rate rescaled

$$r_\rho \equiv \frac{\rho_1}{\rho_0} \approx \frac{\Omega_{\chi_1}}{\Omega_{DM}}, \qquad \sigma^{SI} \to \tilde{\sigma}^{SI}$$

(mass dependent)

- Xenon ruled out mass range 55-175 GeV
- Correlation
  - Low halo density and large SI cross section all related to large Yukawa coupling

    -> cancellation

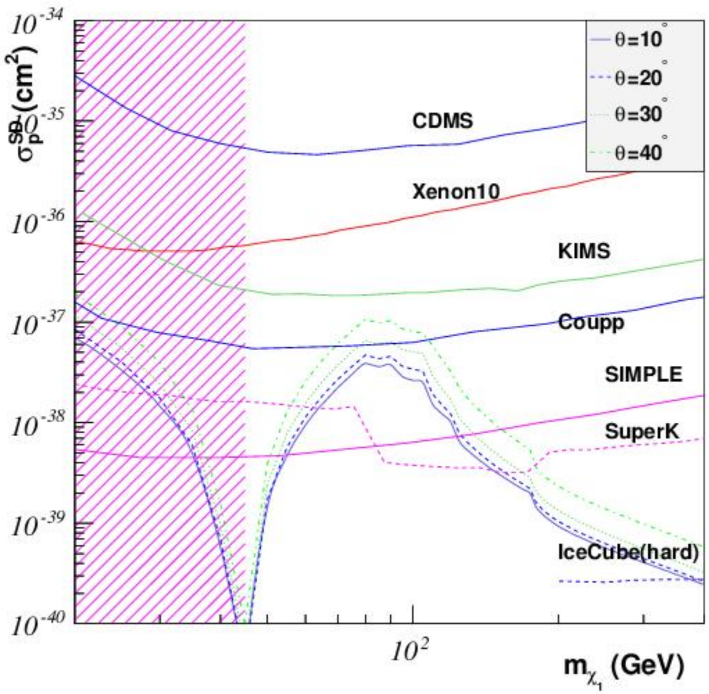
-week mixing angle/mass dependences

Prediction:

$$\tilde{\sigma}^{SI} \approx 1.5\times10^{-44}\,\text{cm}^2 \text{ for } m_\chi > 175\text{ GeV}$$

can be tested soon

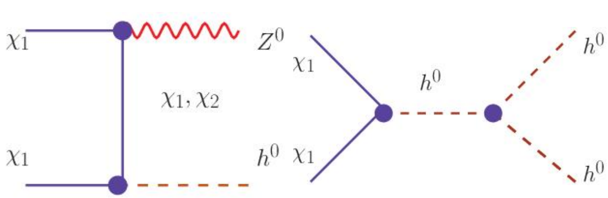
SD cross section for DM-proton

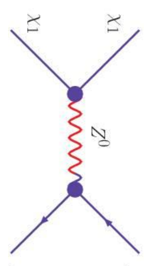


- Event rate follow the relic density
- SIMPLE ruled out mass range 50-150 GeV, compatible with Xenon100 on SI cross section
- Prediction

$$\tilde{\sigma}_p < 3\times 10^{-39}\,\mathrm{cm}^2 \text{ for } m_\chi > 175\text{ GeV}$$

- Can be reached by indirect search exp. SuperK and IceCube. The current SuperK/IceCube bounds are model dependent.





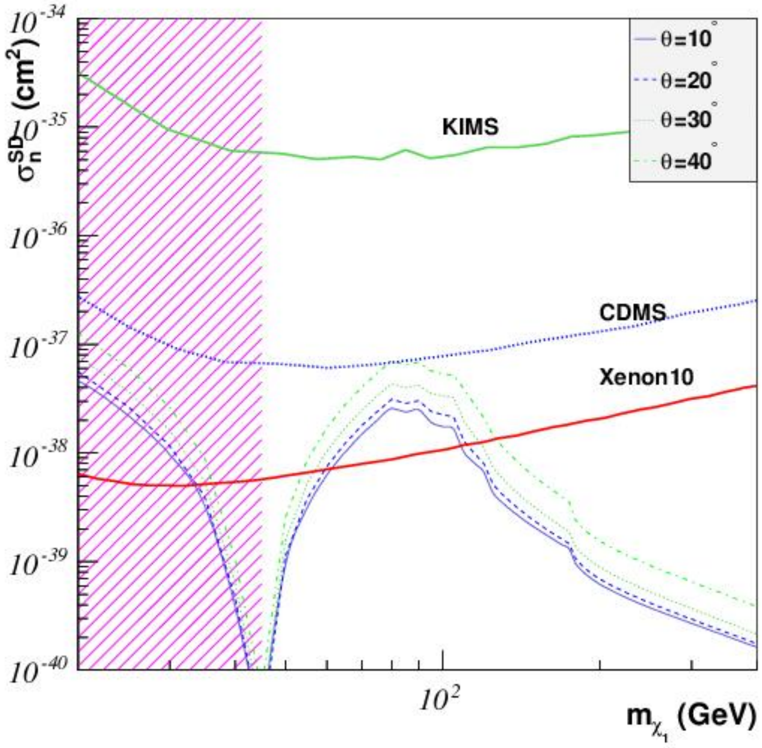
$$\sigma_N^{SD} = \frac{32}{\pi} G_F^2 \mu_n^2 \frac{J+1}{J}\left(a_p\langle S_p\rangle\rangle + a_n\langle S_n\rangle\right)^2,$$

$$d_u = -d_d = -d_s = \frac{G_F}{\sqrt{2}}.$$

Relic density

SI scattering

SD cross section for DM-neutron



- Scattering off proton and neutron are similar
- much weaker bounds compared with DM-proton case.
- The Xenon10 ruled out 60-120 GeV

YFZ, arXiv:110.2930

Conclusions

- Heavy stable neutrino as a cold DM component is highly testable in direct detection experiments even it contribute to a small fraction of the total DM relic density
- We consider a 4^{th} generation model with an anomaly-free U(1) gauge symmetry which keep the heavy 4^{th} Majorana neutrino stable. The models is less constrained by the current LHC data.
- The Xenon100 data constrain the mass of the 4^{th} neutrino to be heavier than 175 GeV. For heavier neutrino DM, the prediction for SI cross secition is 1.5x10^-44cm^2 which is insensitive to the neutrino mass due to the correlation between relic density and the SI cross section.
- The prediction for SD cross section is within the reach of SuperK and IceCube.