DIRECT DETECTION OF DARK MATTER IN A MODEL WITH RADIATIVE NEUTRINO MASSES

Daniel Schmidt, Thomas Schwetz, Takashi Toma

[*Physical Review D85 (2012) 073009*]

FLASY12

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INTERNATIONAL MAX PLANCK RESEARCH SCHOOL PT FS FOR PRECISION TESTS OF FUNDAMENTAL SYMMETRIES

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

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OUTLINE

- The Model
- Dark Matter
- Direct Detection

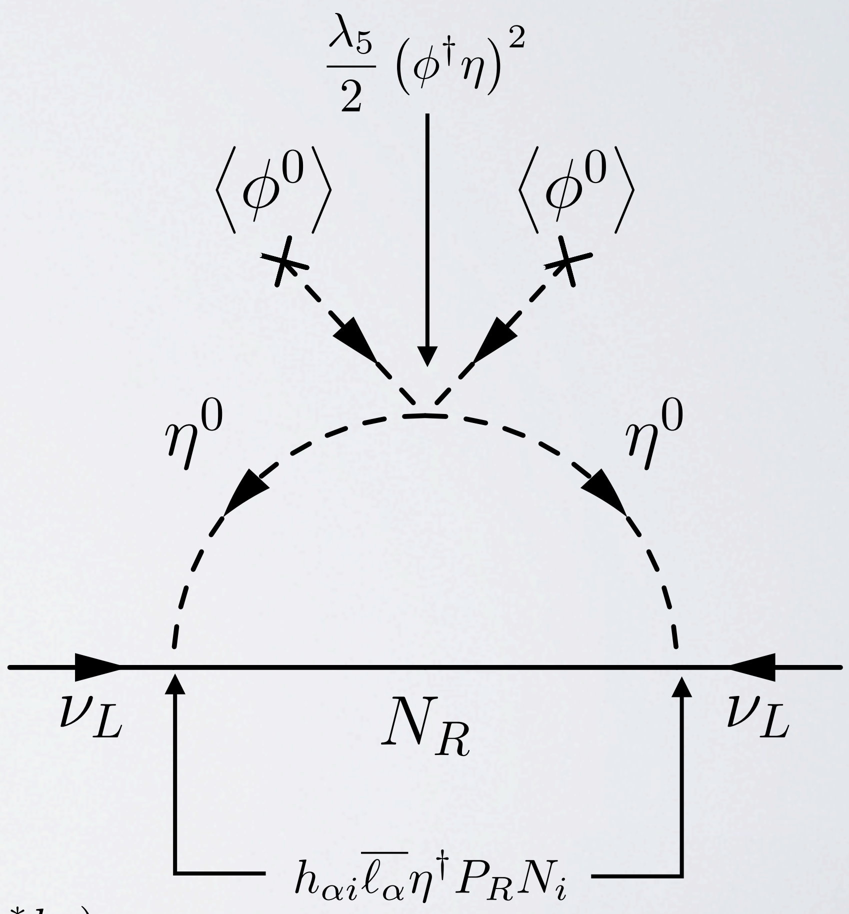
THE MODEL

Ma, Phys. Rev. D73 (2006) 077301

neutrino masses at 1 loop

flavor structure:

$$h_{\alpha i} = \begin{pmatrix} 0 & 0 & h_3' \\ h_1 & h_2 & h_3 \\ h_1 & h_2 & -h_3 \end{pmatrix}$$



lepton-flavor violation (LFV):

$$\mathrm{Br}(\ell_\alpha \to \ell_\beta\gamma) = \frac{3\alpha_{\mathrm{em}}}{64\pi G_F^2 M_\eta^4}\left|\sum_{i=1}^{3} h_{\alpha i}^* h_{\beta i} F_2\left(\frac{M_i^2}{M_\eta^2}\right)\right|^2 \mathrm{Br}\left(\ell_\alpha \to \ell_\beta \nu_\alpha \overline{\nu_\beta}\right)$$

$$\mathrm{Br}(\mu \to e\gamma) < 2.4\times 10^{-12} :\ M_3 = 6000\,\mathrm{GeV},\ \mathrm{h}_3 = 0.3\,(\mathrm{benchmark\,point})$$

independent parameters: $M_\eta,\ M_1,\ \delta \equiv M_2 - M_1,\ \xi \equiv \mathrm{Im}(h_2^* h_1)$

THE MODEL

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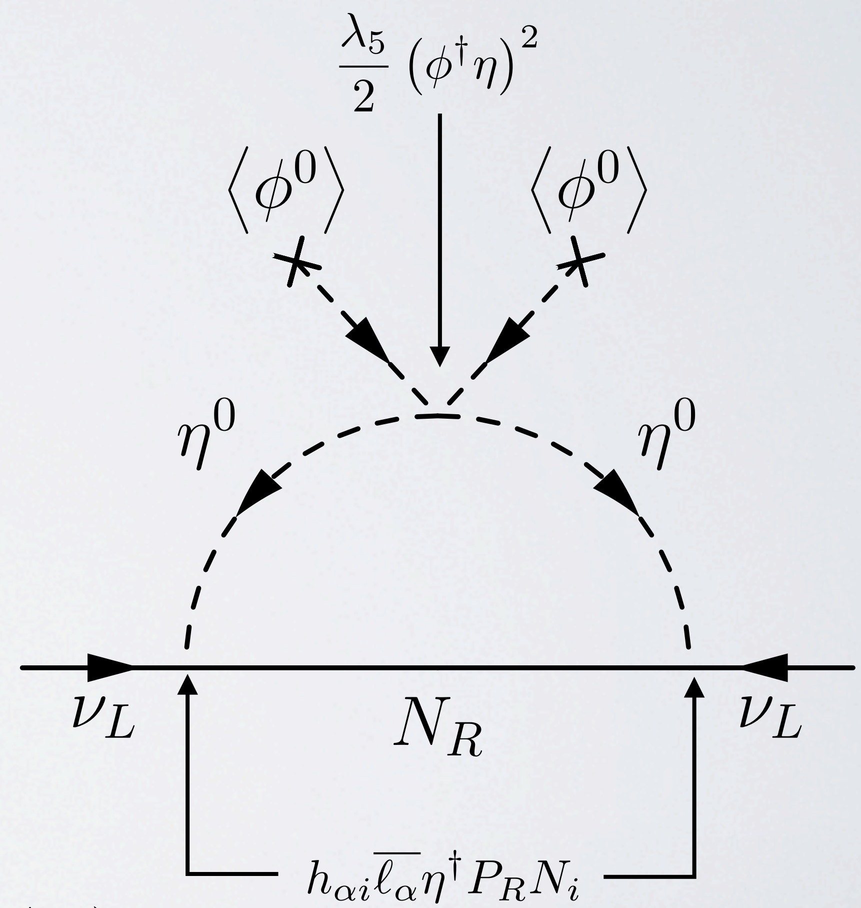
neutrino masses at 1 loop

flavor structure:

$$h_{\alpha i} = \begin{pmatrix} \epsilon_1 & \epsilon_2 & h_3' \\ h_1 & h_2 & h_3 \\ h_1 & h_2 & -h_3 \end{pmatrix} + \mathcal{O}(\epsilon^2)$$

allowing $\sin\Theta_{13} \equiv \epsilon_3 \neq 0°$

$\epsilon_1 h_1 + \epsilon_1 h_1 \equiv P\epsilon_3$



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$$\mathrm{Br}(\ell_\alpha \to \ell_\beta\gamma) = \frac{3\alpha_{\rm em}}{64\pi G_F^2 M_\eta^4}\left|\sum_{i=1}^{3} h_{\alpha i}^* h_{\beta i} F_2\left(\frac{M_i^2}{M_\eta^2}\right)\right|^2 \mathrm{Br}\left(\ell_\alpha \to \ell_\beta \nu_\alpha \overline{\nu_\beta}\right)$$

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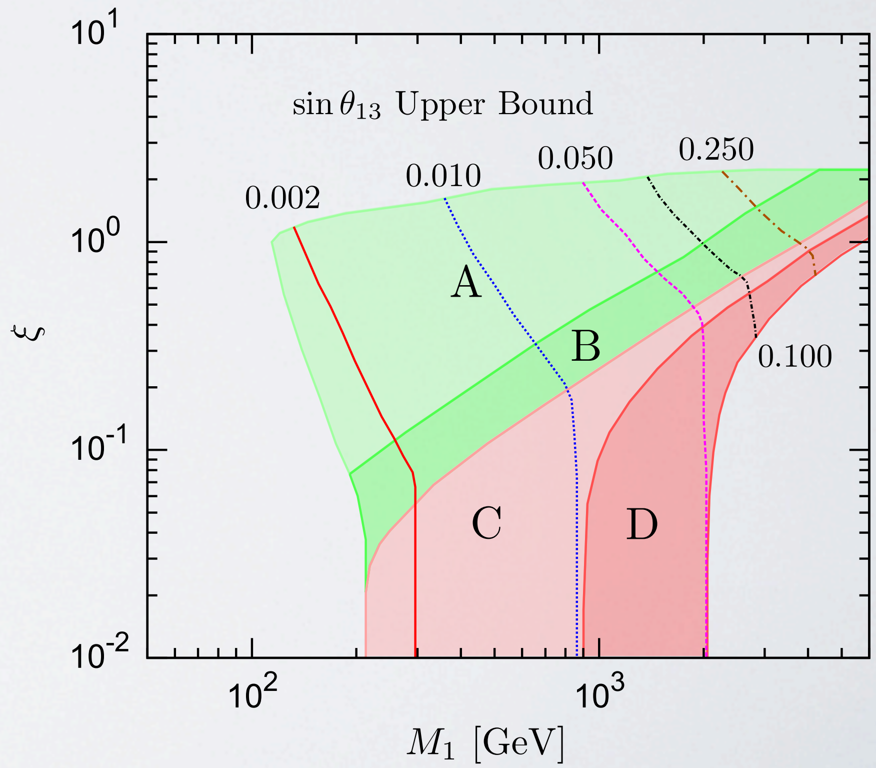
DARK MATTER

Dark Matter (DM) candidate (lightest odd particle):

N_1 with $\mathrm{m_{N_1}} \lesssim \mathrm{m_{N_2}} < \mathrm{m_{N_3}}$

freeze-out: $$\sigma_{\rm eff} v = \left[\frac{\xi^2}{2\pi}\frac{M_1^2}{\left(M_\eta^2+M_1^2\right)^2}\right] + \left[\frac{|h_1^2+h_2^2|^2}{24\pi}\frac{M_1^2\left(M_\eta^4+M_1^4\right)}{\left(M_\eta^2+M_1^2\right)^4} + \frac{\xi^2}{2\pi}\frac{M_1^2\left(M_\eta^4-3M_\eta^2M_1^2-M_1^4\right)}{\left(M_\eta^2+M_1^2\right)^4}\right]v^2 + \mathcal{O}(v^4)$$

parameter regions:
$$A: 2.0 < M_\eta/M_1 < 9.8$$
$$B: 1.2 < M_\eta/M_1 < 2.0$$
$$C: 1.05 < M_\eta/M_1 < 1.20$$
$$D: 1.0 < M_\eta/M_1 < 1.05$$

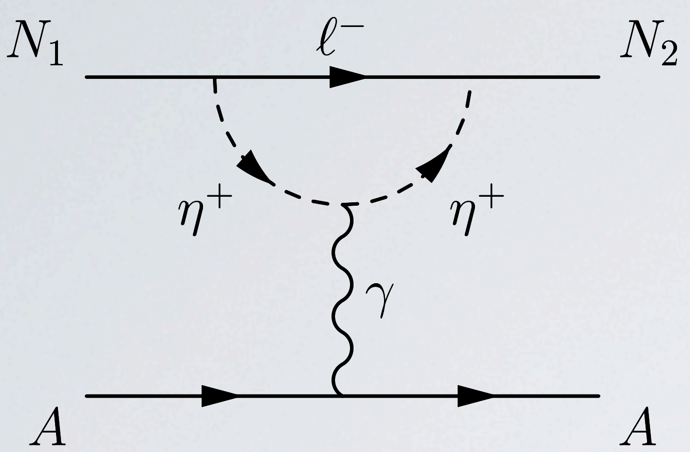


A,B,C, and D consistent with neutrino data, LFV, perturbativity and DM relic density

$\sin^2 2\theta_{13} = 0.092 \pm 0.016 \pm 0.005$: additional contributions to $\mu \to e\gamma$

DAYA-BAY, Phys.Rev.Lett. 108(2012) 171803

DIRECT DETECTION: CROSS SECTIONS



$$\mathcal{L}_{\rm eff} = i a_{12}\overline{N_2}\gamma^\mu N_1 \partial^\nu F_{\mu\nu} + i\left(\frac{\mu_{12}}{2}\right)\overline{N_2}\sigma^{\mu\nu}N_1 F_{\mu\nu} + i c_{12}\overline{N_2}\gamma^\mu N_1 A_\mu$$

charge-charge (CC)

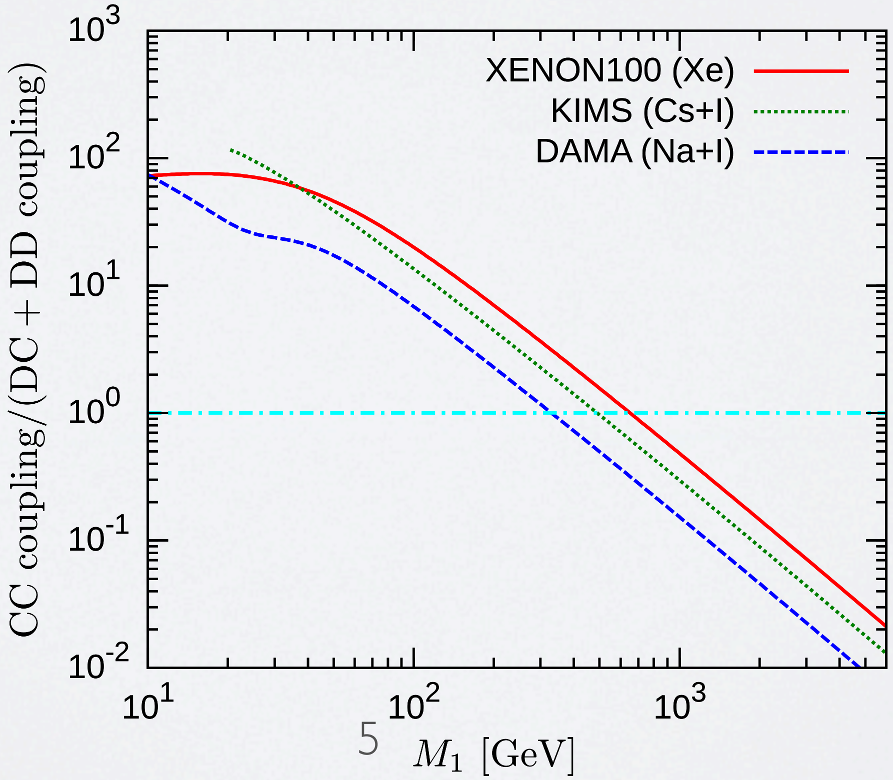
$$\frac{d\sigma_{\rm CC}}{dE_R} = \frac{Z^2 b_{12}^2 m_A}{2\pi v^2}F^2(E_R) \quad ; \quad b_{12} = (a_{12} + c_{12}/q^2)e$$

dipole-charge (DC)

$$\frac{d\sigma_{\rm DC}}{dE_R} = \frac{Z^2\alpha_{\rm em}\mu_{12}^2}{E_R}\left[1 - \frac{E_R}{v^2}\left(\frac{1}{2m_A} + \frac{1}{M_1}\right) - \frac{\delta}{v^2}\frac{1}{\mu_{\rm DM}} - \frac{\delta^2}{v^2}\frac{1}{2m_A E_R}\right]F^2(E_R)$$

dipole-dipole (DD)

$$\frac{d\sigma_{\rm DD}}{dE_R} = \frac{\mu_A^2\mu_{12}^2 m_A}{\pi v^2}\left(\frac{J_A+1}{3J_A}\right)F_D^2(E_R)$$



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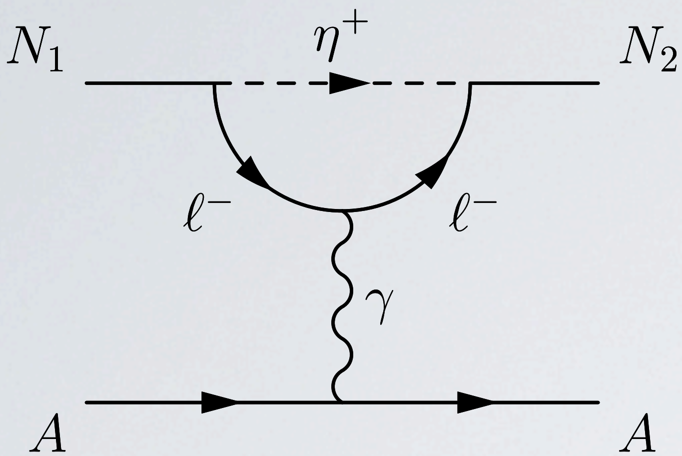

$$\mathcal{L}_{\rm eff} = i a_{12} \overline{N_2} \gamma^\mu N_1 \partial^\nu F_{\mu\nu} + i \left(\frac{\mu_{12}}{2}\right) \overline{N_2} \sigma^{\mu\nu} N_1 F_{\mu\nu} + i c_{12} \overline{N_2} \gamma^\mu N_1 A_\mu$$

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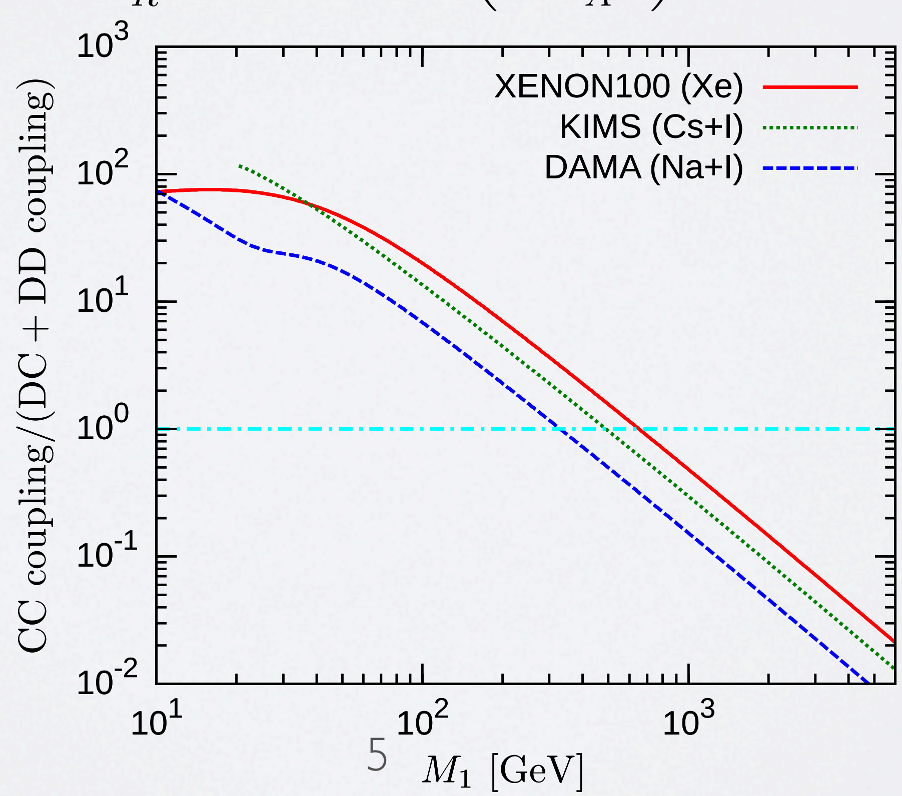

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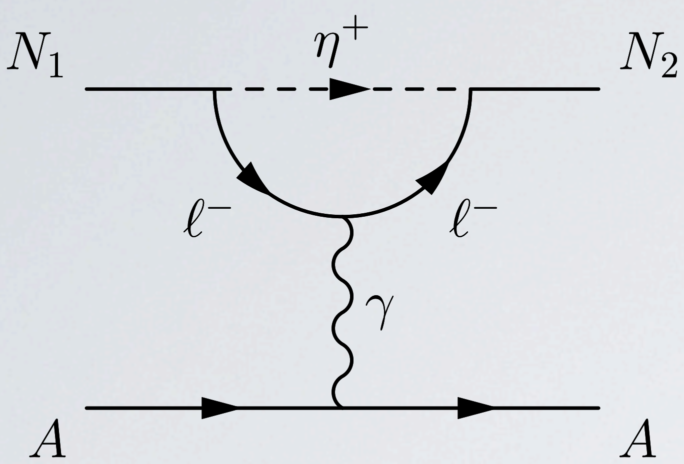

$$\mathcal{L}_{\rm eff} = i a_{12} \overline{N_2} \gamma^\mu N_1 \partial^\nu F_{\mu\nu} + i \left(\frac{\mu_{12}}{2}\right) \overline{N_2} \sigma^{\mu\nu} N_1 F_{\mu\nu} + i c_{12} \overline{N_2} \gamma^\mu N_1 A_\mu$$

charge-charge (CC)

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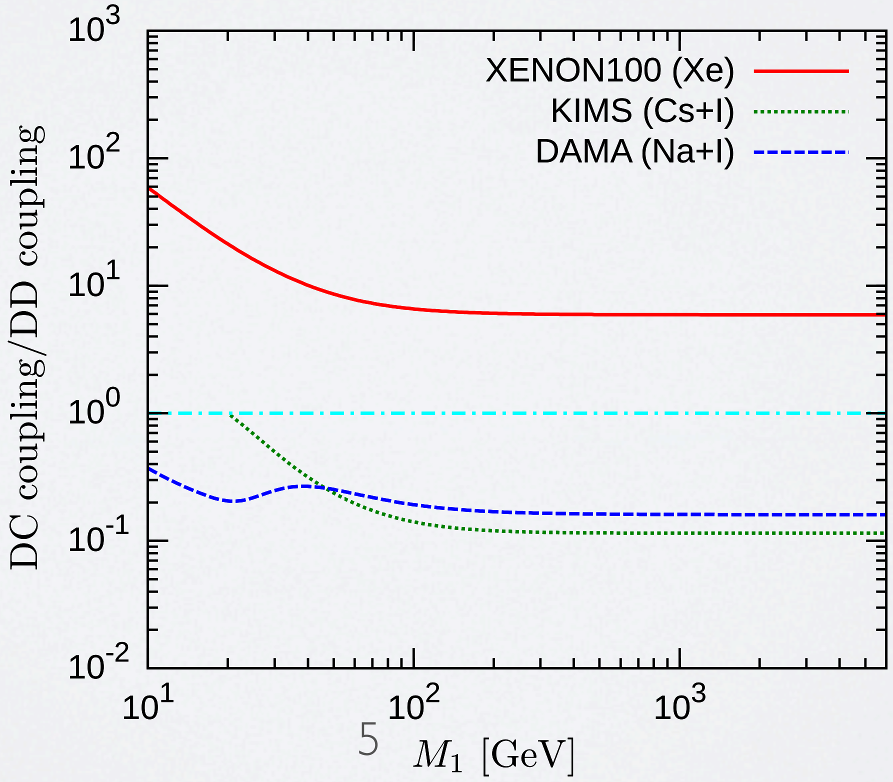
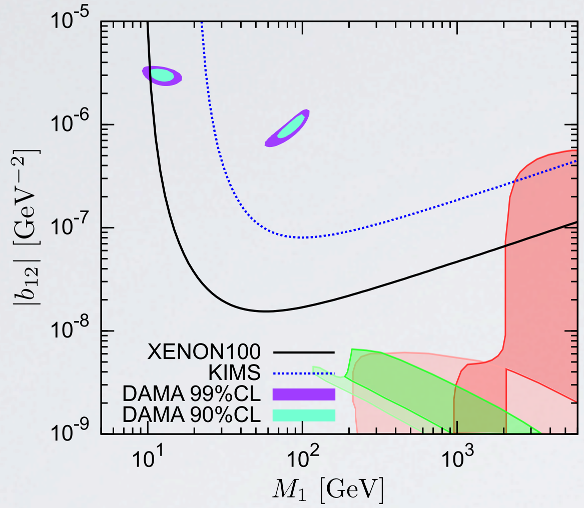
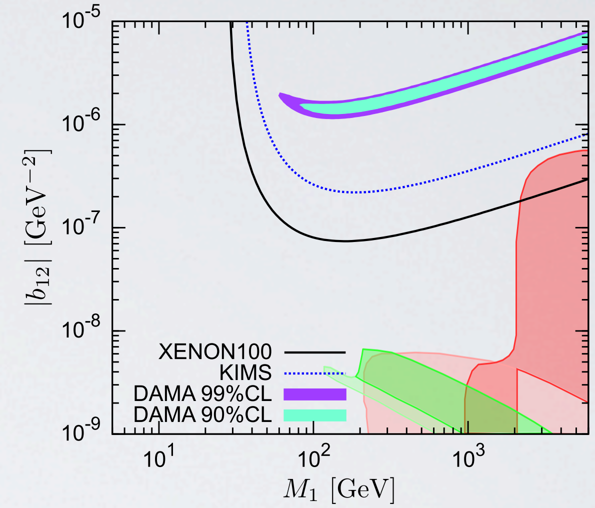


DIRECT DETECTION: COMPARISION WITH EXPERIMENTS

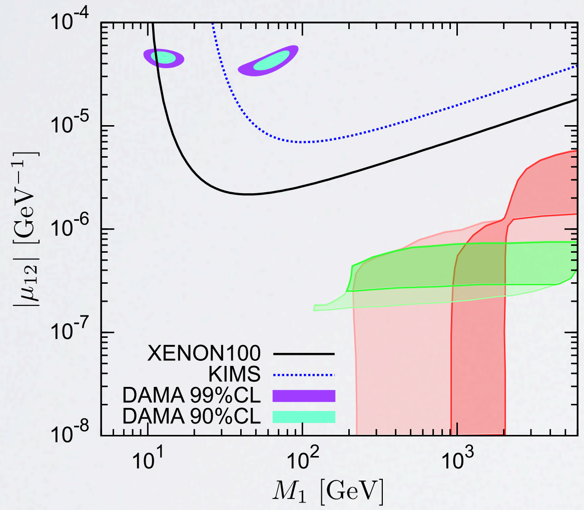
$\delta = 0\,\mathrm{KeV}$ | $\delta = 80\,\mathrm{KeV}$

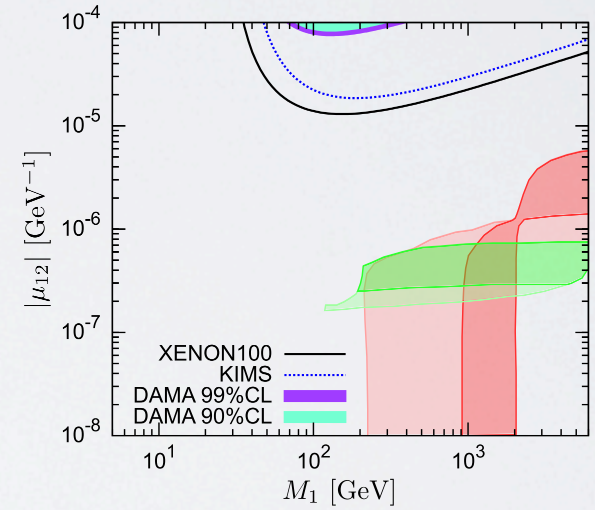
CC



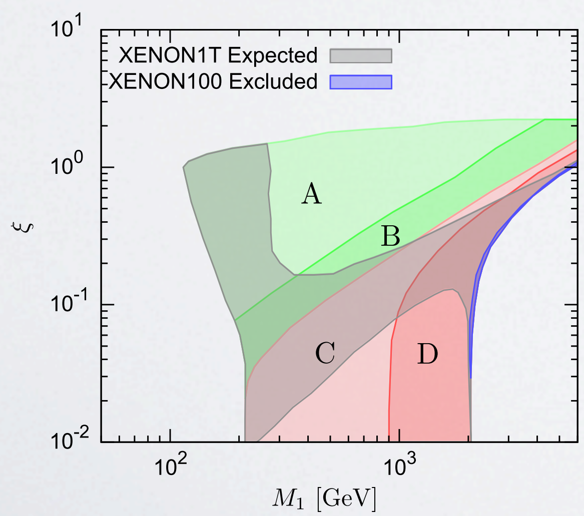


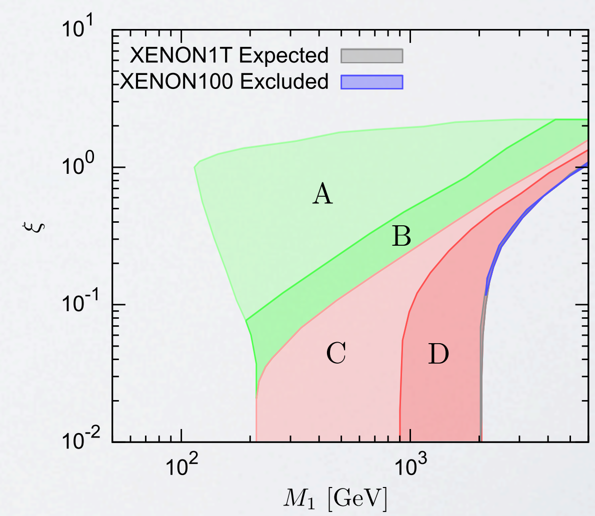
DC+ DD



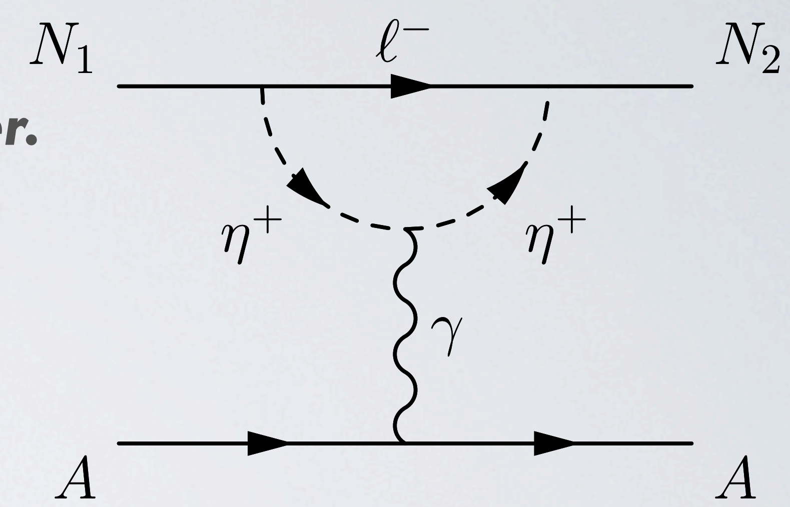


Yukawa





CONCLUSION



Ma model: ***Neutrinos have mass and the Universe has Dark Matter.***

constrains from LFV processes

coannihilations important for DM relic density

direct detection of leptophilic DM possible by photon exchange

calculation of relevant loop processes for the first time

charge-charge interactions dominate XENON100 event rate

stringent test by XENON1T

CONCLUSION

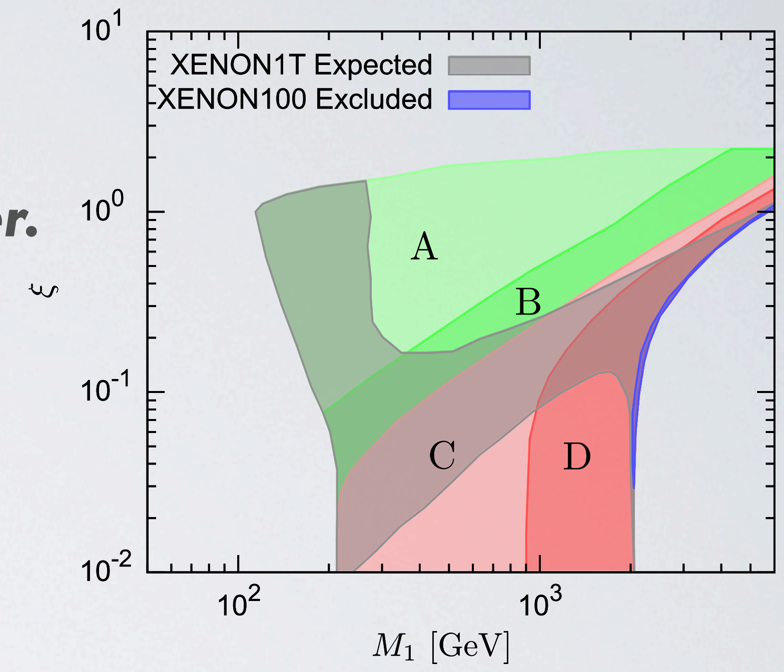


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photo by M. Ansorg
THANKS

APPENDIX A: THE MODEL

$$\mathcal{L}_N = \overline{N_i} i \partial\!\!\!/ P_R N_i + (D_\mu \eta)^\dagger (D^\mu \eta) - \frac{M_i}{2} \overline{N_i{}^c} P_R N_i + h_{\alpha i} \overline{\ell_\alpha} \eta^\dagger P_R N_i + \text{h.c.}$$

$$\mathcal{V}(\phi, \eta) = m_\phi^2 \phi^\dagger \phi + m_\eta^2 \eta^\dagger \eta + \frac{\lambda_1}{2} \left(\phi^\dagger \phi\right)^2 + \frac{\lambda_2}{2} \left(\eta^\dagger \eta\right)^2$$
$$+ \lambda_3 \left(\phi^\dagger \phi\right) \left(\eta^\dagger \eta\right) + \lambda_4 \left(\phi^\dagger \eta\right) \left(\eta^\dagger \phi\right) + \frac{\lambda_5}{2} \left(\phi^\dagger \eta\right)^2 + \text{h.c.}$$

$$(m_\nu)_{\alpha\beta} \simeq \sum_{i=1}^{3} \frac{2 \lambda_5 h_{\alpha i} h_{\beta i} \left\langle \phi^0 \right\rangle^2}{(4\pi)^2 M_i} I\left(\frac{M_i^2}{M_\eta^2}\right)$$

$$M_\eta^2 \simeq m_\eta^2 + (\lambda_3 + \lambda_4) \left\langle \phi^0 \right\rangle^2$$

$$I(x) = \frac{x}{1-x} \left(1 + \frac{x \log x}{1-x}\right)$$

APPENDIX B: FLAVOR STRUCTURE

perturbation:

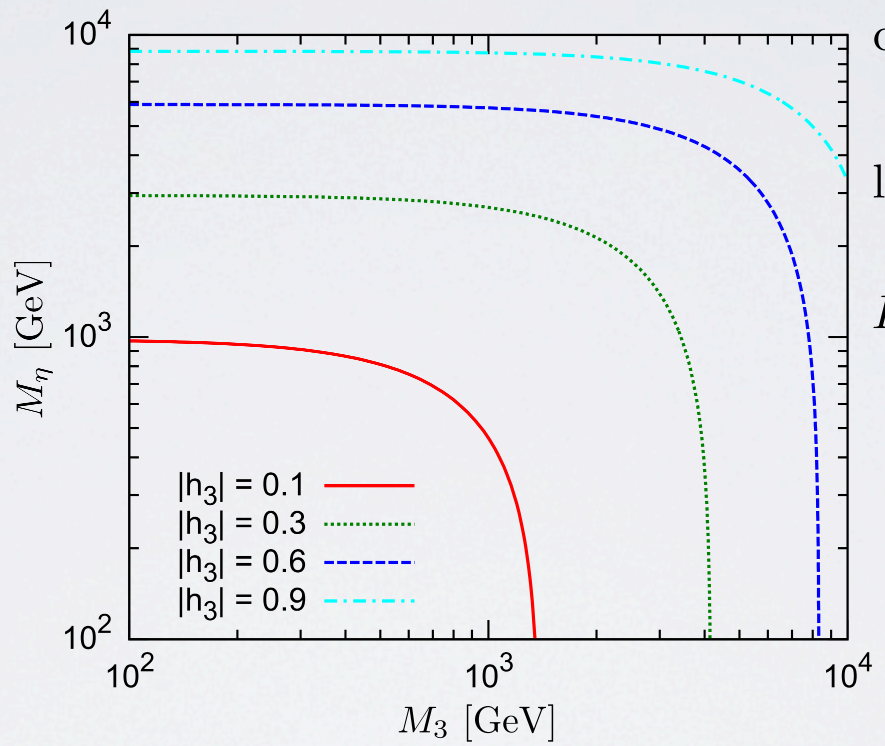
$$\sin\Theta_{13} = \epsilon_3$$

$$\cos\Theta_{13} = 1 + \mathcal{O}(\epsilon_3^2)$$

$$\sin\Theta_{23} = \frac{1}{\sqrt{2}} + \epsilon_4$$

$$\cos\Theta_{23} = \frac{1}{\sqrt{2}} - \epsilon_4$$

$$h_{\alpha i} = \begin{pmatrix} \epsilon_1 & \epsilon_2 & h_3' \\ h_1 & h_2 & h_3 \\ h_1 & h_2 & -h_3 \end{pmatrix} + \mathcal{O}(\epsilon^2)$$



contours of $\mathrm{Br}(\mu \to \mathrm{e}\gamma) = 2.4 \times 10^{-12}$

loop function:

$$F_2(x) = \frac{1 - 6x + 3x^2 + 2x^3 - 6x^2 \log x}{6(1-x)^4}$$

$$\epsilon_4 = \frac{1}{\sqrt{2}} \frac{\tan\theta_{12} h_3^2 \Lambda_3}{(h_1^2 + h_2^2)\,\Lambda_1 - h_3^2 \Lambda_3} \epsilon_3$$

diagonalization of mass matrix: $\epsilon_1 h_1 + \epsilon_2 h_2 \approx \sqrt{2}\,(h_1^2 + h_2^2) \equiv P\epsilon_3.$

LFV: $\mathrm{Br}\,(\mu \to e\gamma) = \frac{3\alpha_{\mathrm{em}}}{64\pi G_F^2 M_\eta^4} \left| P\epsilon_3 F_2\left(\frac{M_1^2}{M_\eta^2}\right) + \sqrt{2}\tan\theta_{12} |h_3|^2 F_2\left(\frac{M_3^2}{M_\eta^2}\right) \right|^2$

APPENDIX C: DARK MATTER

$$\sigma_{\rm eff} v = a_{\rm eff} + b_{\rm eff} v^2 + \mathcal{O}(v^4)$$

$$a_{\rm eff} = \frac{\xi^2}{2\pi} \frac{M_1^2}{\left(M_\eta^2 + M_1^2\right)^2}$$

$$b_{\rm eff} = \frac{|h_1^2 + h_2^2|^2}{24\pi} \frac{M_1^2 \left(M_\eta^4 + M_1^4\right)}{\left(M_\eta^2 + M_1^2\right)^4} + \frac{\xi^2}{2\pi} \frac{M_1^2 \left(M_\eta^4 - 3M_\eta^2 M_1^2 - M_1^4\right)}{\left(M_\eta^2 + M_1^2\right)^4}$$

$$\Omega h^2 \simeq \frac{1.07 \times 10^9 x_f \ [{\rm GeV}^{-1}]}{\sqrt{g_*} m_{\rm pl} \left(a_{\rm eff} + 3b_{\rm eff}/x_f\right)}$$

$$x_f = \frac{M_1}{T}$$

APPENDIX D: EFFECTIVE INTERACTIONS

$$a_{12} = -\sum_\alpha \frac{\mathrm{Im}\,(h^*_{\alpha 2} h_{\alpha 1})\, e}{2(4\pi)^2 M_\eta^2} I_\mathrm{a}\left(\frac{M_1^2}{M_\eta^2}, \frac{m_\alpha^2}{M_\eta^2}\right)$$

$$I_\mathrm{a}(x,y) = \frac{1}{3}\int_0^1 \frac{3u^2 - 6u + 1}{xu^2 - (1+x-y)u + 1}$$

$$\mu_{12} = -\sum_\alpha \frac{\mathrm{Im}\,(h^*_{\alpha 2} h_{\alpha 1})\, e}{2(4\pi)^2 M_\eta^2} 2M_1 I_\mathrm{m}\left(\frac{M_1^2}{M_\eta^2}, \frac{m_\alpha^2}{M_\eta^2}\right)$$

$$I_\mathrm{m}(x,y) = -\int_0^1 \frac{u(1-u)}{xu^2 - (1+x-y)u + 1}$$

$$c_{12} = \sum_\alpha \frac{\mathrm{Im}\,(h^*_{\alpha 2} h_{\alpha 1})\, e}{2(4\pi)^2 M_\eta^2} q^2 I_\mathrm{c}\left(\frac{M_1^2}{M_\eta^2}, \frac{m_\alpha^2}{M_\eta^2}\right)$$

$$I_\mathrm{c}(x,y) = I_\mathrm{m}(x,y)$$

APPENDIX E: DIRECT DETECTION

magnetic moments in units of nuclear magneton

	$^{19}_{9}\mathrm{F}$	$^{23}_{11}\mathrm{Na}$	$^{73}_{32}\mathrm{Ge}$	$^{127}_{53}\mathrm{I}$	$^{131}_{54}\mathrm{Xe}$	$^{133}_{55}\mathrm{Cs}$	$^{183}_{74}\mathrm{W}$
J_A	1/2	3/2	9/2	5/2	3/2	7/2	1/2
μ_A/μ_N	2.629	2.218	−0.879	2.813	0.692	2.582	0.118

energy range and the quenching factor forXENON100, KIMS,DAMA

	Energy range	Quenching factor
XENON100	8.4 – 44.6 keV	–
KIMS	3.6 – 5.8 keVee	0.1 (Cs), 0.1 (I)
DAMA	2 – 8 keVee	0.3 (Na), 0.09 (I)