STRONGLY-INTERACTING DM & THE NEUTRINO PORTAL PARADIGM

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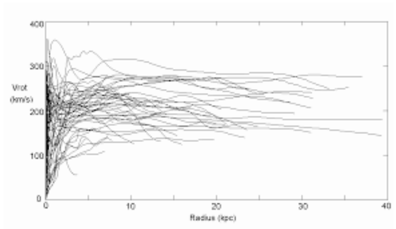
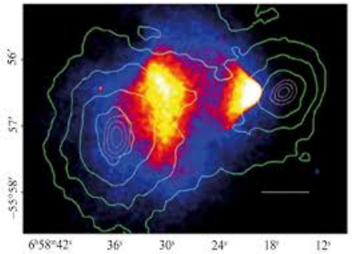
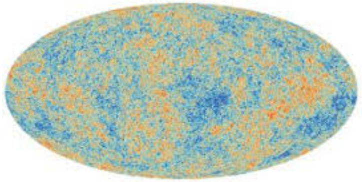
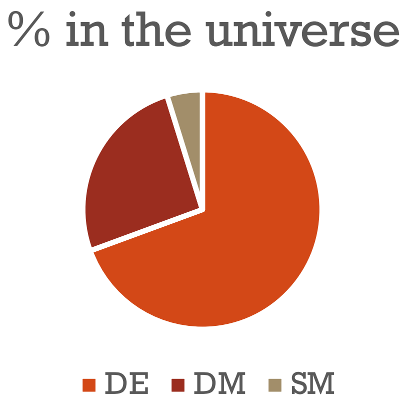
INTRODUCTION



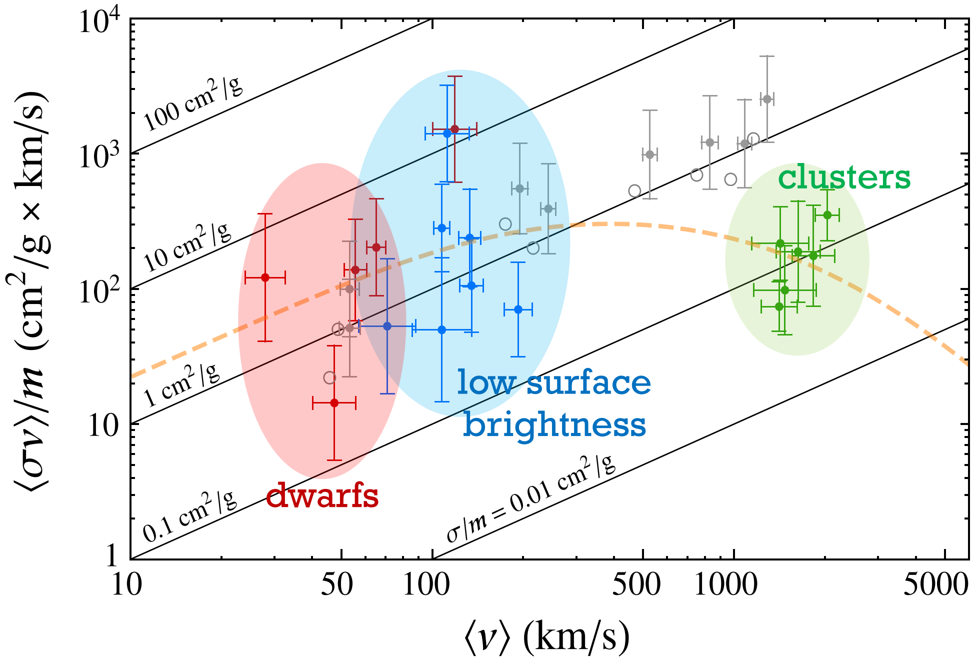



- Why DM
  - Flat rotation curves
  - Velocity profiles in galaxy clusters
  - CMBR data
  - Bullet cluster mass distribution

- What we know
  - DM evidence in astrophysical & cosmological observations
  - DM is ~6 times more abundant than SM matter
  - DM does not fit in the SM
  - DM undetected in all Earth-bound experiments (at least not yet)
  - No DM direct or indirect detection signals (at least not yet)



- Why SIDM?
  - Halo density inconsistent with non-interacting cold DM
  - Can be solved by assuming the DM has velocity- dependent self-interactions.
  - Simplest possibility: introduce a light mediator



Kaplinghat, Tulin & Yu
PRL 116, 041302 (2016)

$$\left.\frac{\sigma_{\tt eff}}{m_\Psi}\right|_{\rm galaxy} = 1.9\frac{\rm cm^2}{\rm gr} \qquad \beta_\Psi|_{\rm galaxy} = 3.3\times10^{-4}$$

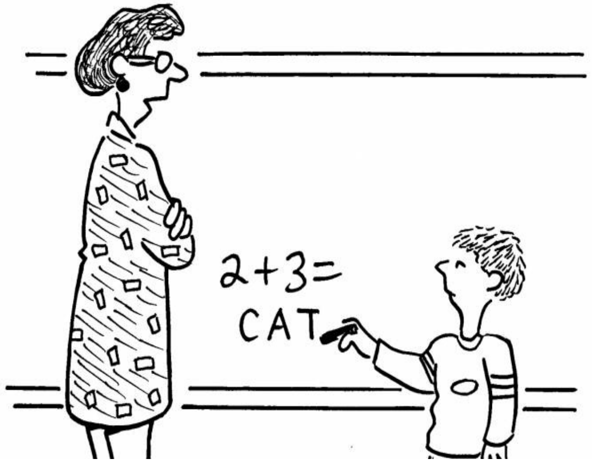
$$\left.\frac{\sigma_{\tt eff}}{m_\Psi}\right|_{\rm cluster} = 0.1\frac{\rm cm^2}{\rm gr} \qquad \beta_\Psi|_{\rm cluster} = 5.4\times10^{-3}$$

(with large errors)

There are other options (e.g. using the exclusion principle)

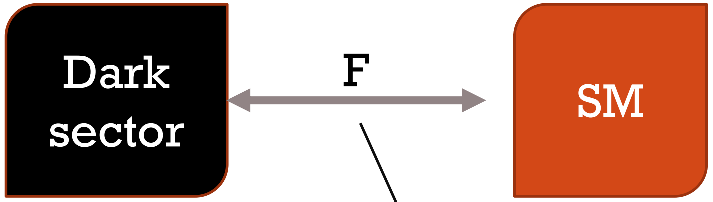
We don't know what DM is

So we make educated guesses



THE NEUTRINO PORTAL PARADIGM

The basic idea: assume a neutral fermionic mediator



F: neutral (under all dark & SM symmetries)

$$\mathcal{L} \sim F\mathcal{O}_{\mathtt{dark}} + \bar{F}\mathcal{O}_{\mathtt{SM}}$$

$\mathcal{O}_{\mathtt{dark}}$ depends on the model

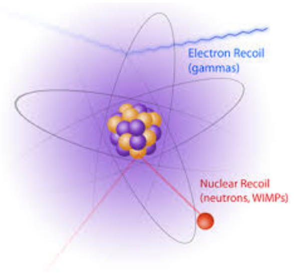
$\mathcal{O}_{\mathtt{SM}}$ can be easily listed

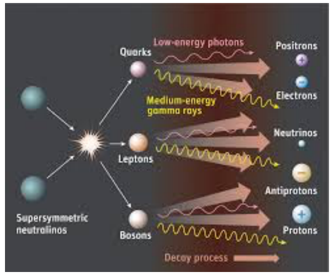
When F = fermion the leading (lowest dim.) operator

$$\mathcal{O}_{\mathtt{SM}} = \ell\tilde{\phi}$$

General features

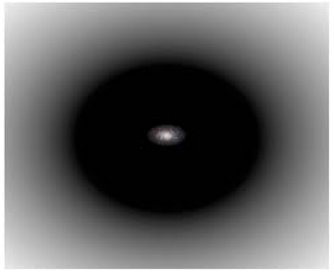
- Detection:
  - Direct detection: ≥ 1 loop $\rightarrow$ naturally suppressed ✓
  - Indirect detection: tree level annihilation into neutrinos ✓



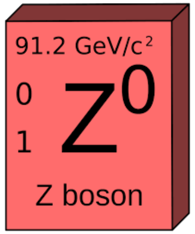


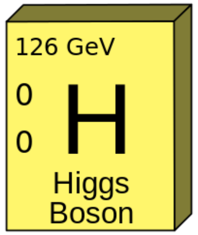
- SIDM:
  - Simple extension without B-γ_{dark} kinetic mixing ✓
  - γ_{dark} may produce DM bound states

- Relic abundance
  - DM $\rightarrow \nu, \gamma_{\text{dark}}$ annihilation channels
  - γ_{dark} may be long lived



- The F mixes with the neutrinos:
  - $\Gamma(Z\rightarrow\text{invisible})$
  - $\Gamma(H\rightarrow\text{invisible})$





DESCRIPTION OF THE MODEL

- Particle content: SM plus
  - $\Psi_\pm$ two dark fermions. Relic DM candidates
  - Φ one dark scalar. Assumed heavier than the fermions
  - V dark photon.
  - $\mathcal{F}_r$ mediator with SM family index r.

- Symmetries:
  - $\mathrm{U(1)}_{\mathrm{dark}}$:
    - Ψ_+ and Φ have the same charge
    - Ψ_+ and Ψ_- have opposite charges
  - Dark charge conjugation, $\mathrm{C}_{\mathrm{dark}}$:

$$\Psi_+ \leftrightarrow \Psi_- \,, \quad \Phi \leftrightarrow \Phi^* \,, \quad V \leftrightarrow -V$$

- Lagrangian

$$
\begin{aligned}
\mathcal{L} = & \mathcal{L}_{\mathtt{SM}} + \bar\Psi_+ (i \not{D}_+ - m_+)\Psi_+ + \bar\Psi_- (i \not{D}_- - m_-)\Psi_- + |D_+\Phi|^2 \\
& - \frac{1}{2} m_\Phi^2 |\Phi|^2 - \frac{1}{4}\lambda |\Phi|^4 - \frac{1}{4} V_{\mu\nu}V^{\mu\nu} + \frac{1}{2} m_{\mathtt{V}}^2 \boxed{\left(V_\mu - \frac{1}{m_{\mathtt{V}}} \partial_\mu \sigma \right)^2} + \bar{\mathcal{F}}(i\not\partial - m_{\mathcal{F}})\mathcal{F} \\
& - \left[\bar l Y^{(\nu)} \mathcal{F} \tilde\phi + \text{H.c.} \right] - \left[\left(\bar\Psi_+ \Phi + \bar\Psi_- \Phi^* \right) (z\mathcal{F}) + \text{H.c.} \right] - \lambda_x |\Phi|^2 |\phi|^2 ,
\end{aligned}
$$

Stuckelberg trick

H portal

ν portal

Yukawa couplings

$$D_\pm^\alpha = \partial^\alpha \pm i g V^\alpha$$

- C_{dark} softly broken: $m_\pm = m_\Psi \pm \mu$

- Mass eigenstates (will assume the N are degenerate)

Mixing angles

$$\mathcal{F} = \mathcal{C} N_L + \mathcal{S} n_L + N_R \; ;$$

$$\nu = V_{\mathtt{PMNS}}^{\dagger} \left(\mathcal{C} n_L - \mathcal{S} N_L \right) \; ,$$

light neutrinos

N mass

$$Y^{(\nu)} = \sqrt{2}\frac{m_{\rm N}}{v_{\rm H}} V_{\mathtt{PMNS}}^{\dagger} \mathcal{S}$$

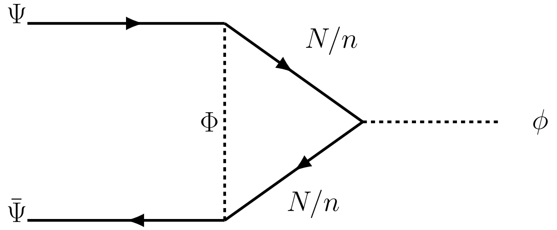
Higgs VEV

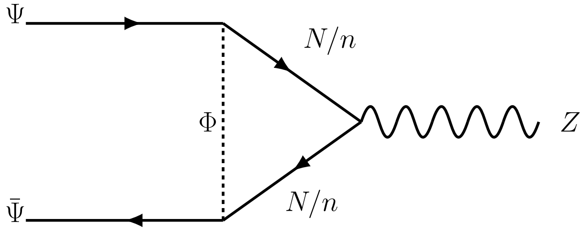
$$\mathcal{C}^2 + \mathcal{S}^2 = \mathbb{1}$$

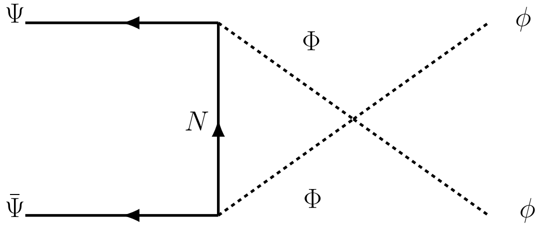
$$m_{\mathcal{F}} = m_{\rm N} \mathcal{C}$$

- Low hanging fruit:

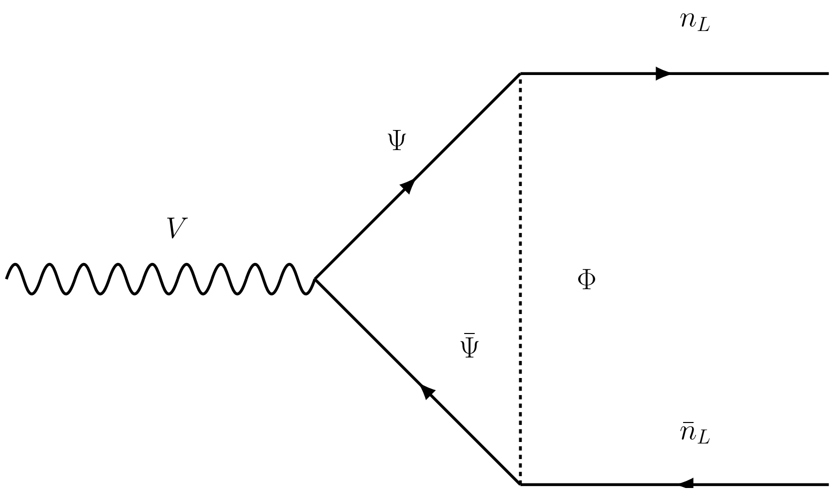
  - Indirect detection: main decays $\Psi\,\Psi \to \nu\,\nu,\ V\,V$ (no discernible $\Psi\,\Psi \to \gamma\gamma$ signal)
  - Direct detection: via Z and H exchanges -- naturally suppressed







- Self interactions
  - C_{dark}, if exact:
    - Forbids all $V^n\,\gamma^m$ (n odd) couplings ☺
    - V is stable ➤ problems with relic abundance ☹
  - $\Longrightarrow$ Break C_{dark} softly
    - Unique soft breaking term: $m_+ - m_- = \mu \neq 0$
    - Soft braking allows $V \to \nu\,\nu$ at 1 loop (($V - Z$ mixing at 2 loops; $V - \gamma$ mixing at 3 loops,)



V mass

$$\Gamma(V \to \bar n_L n_L) = \frac{m_V}{6\pi}\left\{\frac{g}{16\pi^2}\left[f\left(\frac{m_+}{m_\Phi}\right) - f\left(\frac{m_-}{m_\Phi}\right)\right]\right\}^2 \left(z\mathcal{S}^2 z^\dagger\right)^2$$

$$f(x) = \frac{1}{4}\left(\frac{x^2+1}{x^2-1}\right) - \left(\frac{x^2}{x^2-1}\right)^2 \ln x$$

- Comparison with observations
  - $\sigma(\Psi_\pm\Psi_\pm \to \Psi_\pm\Psi_\pm)$ and $\sigma(\Psi_+\Psi_- \to \Psi_+\Psi_-)$ fit the data provided,

$$m_{\rm V} = \frac{m_\Psi}{443}\,, \qquad g = \left(\frac{m_\Psi}{64\,{\rm GeV}}\right)^{3/4} .$$

… but with large errors:

$$443 \to (116,\ 1557)\,, \qquad 64\,{\rm GeV} \to (17,\ 225)\,{\rm GeV}\,.$$

  - In all cases: $m_V \ll m_\Psi$

- Bound states
  - In the NR limit V exchange generates a Yukawa potential between Ψ_+ and Ψ_-:

$$\mathcal{V}_{\mathrm{NR}} = \frac{g^2}{4\pi}\frac{e^{-m_{\mathrm{V}} r}}{r}$$

  - No bound states if: (kinetic energy) $\sim m_V^2/m_\Psi > g^2 m_V/4\pi \sim$ (potential energy)

$$0.595\frac{g^2}{4\pi} < \frac{m_{\mathrm{V}}}{m_\Psi} \xrightarrow{\mathrm{SIDM}} m_\Psi \lesssim 10\mathrm{GeV}$$

  - Of course, even if bound states are allowed they may not form.

CONSTRAINTS

- Electroweak
  - Vector bosons & Higgs: $$\begin{array}{ll} W: & \Gamma(\ell \to \nu \ell' \bar{\nu}') \\ Z: & \Gamma(Z \to NN,\, nN,\, nn) \\ H: & \Gamma(H \to NN,\, nN,\, \Phi\Phi) \end{array}$$
  - g-2 not yet competitive: $|\Delta a_\mu| \leq 10^{-11}$
- V lifetime: $\Gamma(V \to \nu\nu) > (1\ \mathrm{s})^{-1}$

- Relic abundance: $\overline{\Psi}\,\Psi \to V\,V, n_L\, n_L$

$$\sigma_0 = \frac{g^4 + \left[z\mathcal{S}^2 z^T m_\Phi^2/(m_\Psi^2 + m_\Phi^2)\right]^2}{64\pi m_\Psi^2}$$

SIDM: $g^4 \sim m_\Psi/(64\ GeV)$

EW constraints: $\mathcal{S} \lesssim 0.1$

$$\frac{dn_\Psi}{dt} + 3Hn_\Psi = -\sigma_0\left[n_\Psi^2 - \left(n_\Psi^{(\mathsf{eq})}\right)^2\right]$$

- Direct detection

proton

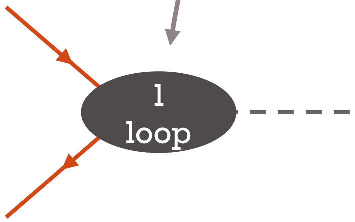
neutron

$$\mathcal{L}_{\mathtt{nucleon-DM}} = \sqrt{2}G_{\mathtt{F}}\left[\bar{\Psi}\gamma_\mu\left(\epsilon_L P_L + \epsilon_R P_R\right)\Psi\right]\left(\bar{\mathfrak{p}}\mathcal{J}^\mu_{\mathfrak{p}}\mathfrak{p} + \bar{\mathfrak{n}}\mathcal{J}^\mu_{\mathfrak{n}}\mathfrak{n}\right) + G_{\mathtt{H}}\epsilon_H\bar{\Psi}\Psi\left(\bar{\mathfrak{p}}\mathfrak{p} + \bar{\mathfrak{n}}\mathfrak{n}\right)$$

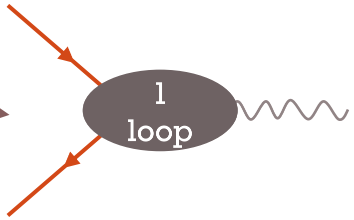
$$\mathcal{J}^\mu_{\mathfrak{p}} = \frac{1}{2}\left[\left(1 - 4s^2_{\mathtt{W}}\right)\gamma^\mu + g_A\left(\gamma^\mu - \frac{2m_{\mathcal{N}}q^\mu}{m^2_\pi + \mathbf{q}^2}\right)\gamma_5\right],$$

$$\mathcal{J}^\mu_{\mathfrak{n}} = -\frac{1}{2}\left[\gamma^\mu + g_A\left(\gamma^\mu - \frac{2m_{\mathcal{N}}q^\mu}{m^2_\pi + \mathbf{q}^2}\right)\gamma_5\right]$$

$$G_{\mathtt{H}} = -\frac{0.011}{m^2_{\mathtt{H}}}.$$



$$\to \epsilon_H\bar{\Psi}_\pm\Psi_\pm H$$



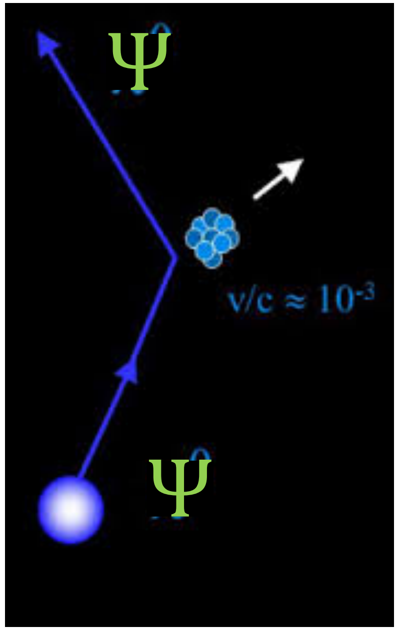
$$\to -\frac{g}{2c_{\mathtt{W}}}\bar{\Psi}_\pm \not{Z}\left(\epsilon_L P_L + \epsilon_R P_R\right)\Psi_\pm$$

Neglecting momentum transfer,

$$\sigma_{\mathcal{N}} \simeq \frac{f_1 + 2b f_2 + b^2 f_3}{16\pi^2 (m_{\mathcal{N}} + m_\Psi)^2} \kappa^2$$

$$\kappa = \sqrt{2} G_{\mathtt{F}} m_\Psi m_{\mathcal{N}} \left[2(\epsilon_L + \epsilon_R) s_{\mathtt{W}}^2 - \sqrt{8}\,\epsilon_H \frac{G_{\mathtt{H}}}{G_{\mathtt{F}}} \right]$$

$$b = \frac{(1 - 2s_{\mathtt{W}}^2)(\epsilon_L + \epsilon_R)}{\sqrt{8}\,\epsilon_H G_{\mathtt{H}}/G_{\mathtt{F}} - 2s_{\mathtt{W}}^2(\epsilon_L + \epsilon_R)} \,.$$



element	f_1	f_2	f_3
Xe	0.995256	-0.177925	0.031717
Ge	0.990137	-0.124142	0.0161359
$CaWO_4$	0.0624983	0	0

CONSTRAINT IMPLEMENTATION

- All constraints can be written in the form

Functions of the parameters ζ

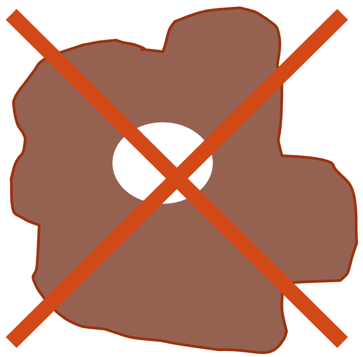
Lower bounds

$$f_i^{(low)} \leq F_i(\zeta) \leq f_i^{(up)}$$

Upper bounds

  - Define a region in parameter space
  - Assume there are no holes → need only the boundaries
  - This is a nonlinear optimization problem
  - Software packages (e.g. NLOPT) more efficient than grid scanning

    (Spot-checked w/MicrOmegas)



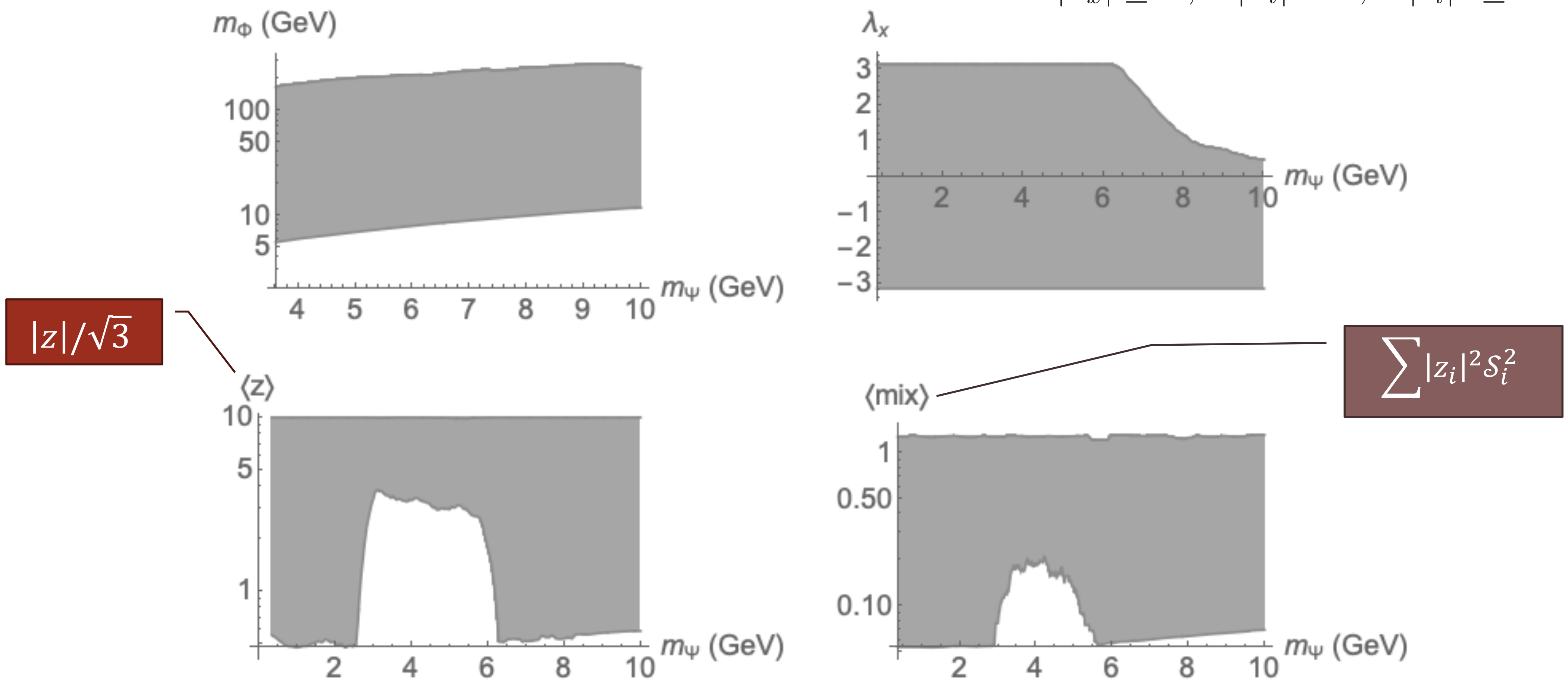
$$0.5\text{GeV} \le m_\Psi \le 10\text{GeV}\,, \qquad \mu = \frac{m_\Psi}{20}\,,$$

$$\min\{1.1 m_\Psi,\, m_\Psi + 2\text{GeV}\} \le m_\Phi < 500\text{GeV}\,,$$

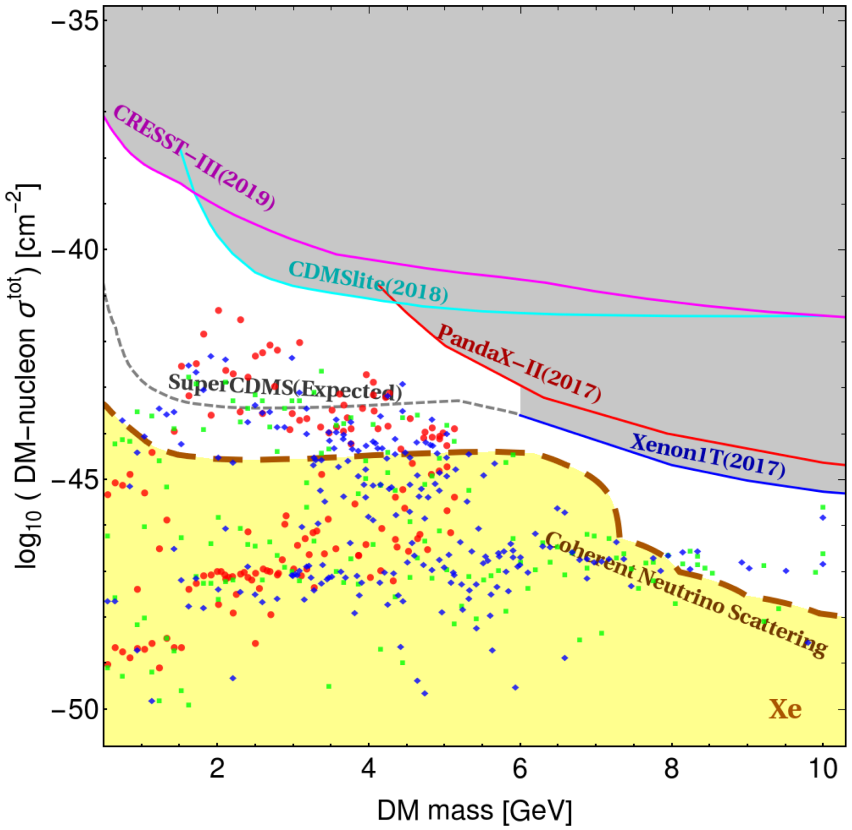
$$\min\{1.1 m_\Psi,\, m_\Psi + 2\text{GeV}\} \le m_N \le 1.5\text{TeV}\,,$$

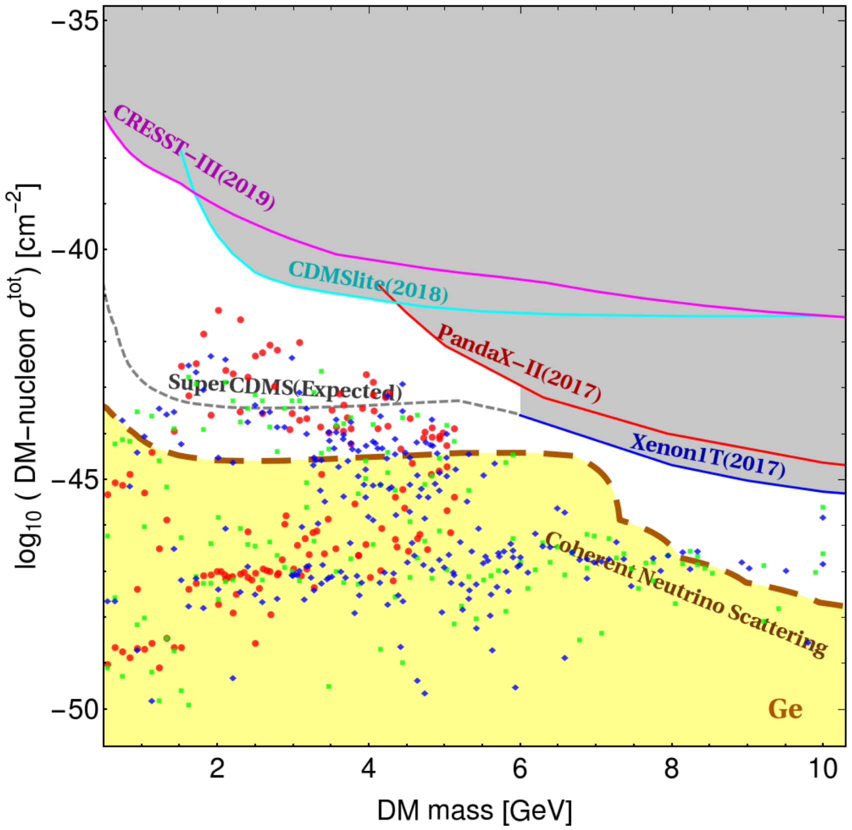
$$|\lambda_x| \le \pi\,, \quad |S_i| < 1\,, \quad |z_i|^2 \le 10 \quad (i = 1,2,3);$$

- We assumed $M_\Psi \le 10\ GeV$
- Projections to 2-d planes



- Parameter space not fully hidden by the neutrino 'floor':



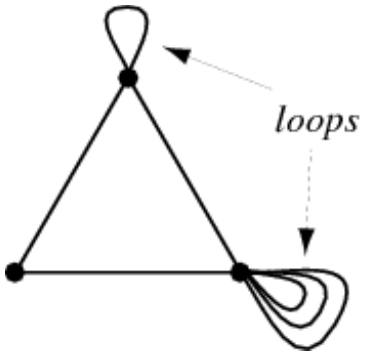


COMMENTS & FUTURE DIRECTIONS

- Model can satisfy all current constraints
  - Large g $\Longrightarrow$ DM under-production: better σ_{SIDM} data will strongly constrain the model
  - Better data on $\Gamma(H \to \text{invisible})$ will constrain λ_x
- The upper bound on m_Ψ can be relaxed: formation rate calculation
- Possible effects of $V \to \nu\nu$ decays.

EXTRA SLIDES

LOOP-INDUCED COUPLINGS



$$\mathcal{L}_{\mathtt{DM-Z}} = -\frac{g}{2c_{\mathtt{W}}}\bar{\Psi}_{\pm}\,\not{Z}\,(\epsilon_L P_L + \epsilon_R P_R)\,\Psi_{\pm}\,;$$

$$\mathcal{L}_{\mathtt{DM-H}} = \epsilon_H \bar{\Psi}_{\pm}\Psi_{\pm}H\,,$$

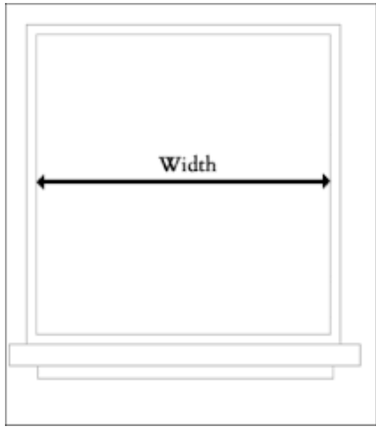
$$\epsilon_R = -\frac{(z\mathcal{S}^2\mathcal{C}^2 z^T)}{32\pi^2}\,\frac{1 - r_{\Phi\mathtt{N}} + \ln r_{\Phi\mathtt{N}}}{(1 - r_{\Phi\mathtt{N}})^2}\,;$$

$$\boxed{r_{\mathtt{ij}} = \left(\frac{m_{\mathtt{i}}}{m_{\mathtt{j}}}\right)^2},$$

$$\epsilon_L = \frac{(z\mathcal{S}^2 z^T)}{16\pi^2}\,\frac{1 - r_{\Phi\mathtt{N}} + r_{\Phi\mathtt{N}}\ln r_{\Phi\mathtt{N}}}{(1 - r_{\Phi\mathtt{N}})^2}\,;$$

$$\epsilon_H = -\frac{1}{8\pi^2}\frac{m_{\mathtt{N}}}{v_{\mathtt{H}}}\left\{(z\mathcal{S}^2\mathcal{C}z^T)\frac{1 - r_{\Phi\mathtt{N}} + r_{\Phi\mathtt{N}}\ln r_{\Phi\mathtt{N}}}{(r_{\Phi\mathtt{N}} - 1)^2} + \frac{1}{2}\lambda_x\frac{v_{\mathtt{H}}^2}{m_{\mathtt{N}}^2}(z\mathcal{C}z^T)\frac{1 - r_{\Phi\mathtt{N}} + \ln r_{\Phi\mathtt{N}}}{(r_{\Phi\mathtt{N}} - 1)^2}\right\}.$$

WIDTHS



$$\Gamma(Z \to nn) = \Gamma_0 \mathrm{tr}\left\{\mathcal{C}^4\right\} ; \qquad \Gamma_0 = \left(\frac{g}{2c_{\mathrm{W}}}\right)^2 \frac{m_{\mathrm{Z}}}{24\pi} ,$$

$$\Gamma(Z \to NN) = \Gamma_0 \mathrm{tr}\left\{\mathcal{S}^4\right\} (1 - r_{\mathrm{NZ}})\sqrt{1 - 4r_{\mathrm{NZ}}}\,\theta(1 - 4r_{\mathrm{NZ}}) ,$$

$$\Gamma(Z \to Nn) = \Gamma_0 \mathrm{tr}\left\{\mathcal{C}^2\mathcal{S}^2\right\} (2 + r_{\mathrm{NZ}})\,(1 - r_{\mathrm{NZ}})^2\,\theta(1 - r_{\mathrm{NZ}}) ,$$

$$\Gamma(H \to \Psi\bar{\Psi}) = \frac{m_{\mathrm{H}}\epsilon_H^2}{8\pi}(1 - 4r_{\Psi\mathrm{H}})^{3/2}\theta(1 - 4r_{\Psi\mathrm{H}}) ,$$

$$\Gamma(H \to n, N) = \frac{m_{\mathrm{H}}^3}{4\pi v_{\mathrm{H}}^2}\left[r_{\mathrm{NH}}(1 - r_{\mathrm{NH}})\mathrm{tr}\left\{\mathcal{S}^2\mathcal{C}^2\right\}\theta(1 - r_{\mathrm{NH}}) \; + \frac{1}{2}(1 - 4r_{\mathrm{NH}})^{3/2}\mathrm{tr}\left\{\mathcal{S}^4\right\}\theta(1 - 4r_{\mathrm{NH}})\right] ,$$

$$\Gamma(H \to \Phi\Phi) = \frac{(v_{\mathrm{H}}\,\lambda_x)^2}{16\pi m_{\mathrm{H}}}\sqrt{1 - 4r_{\Phi\mathrm{H}}}\,\theta(1 - 4r_{\Phi\mathrm{H}}) , .$$

W-MEDIATED DECAYS

$$\Gamma(\ell_r \to \ell_s \bar{\nu}\nu) \simeq (1-\Delta_r-\Delta_s)\Gamma_{\mathtt{SM}}(\ell_r \to \ell_s \bar{\nu}\nu)\,; \quad \Delta_r = \left(V^\dagger_{\mathtt{PMNS}}\mathcal{S}^2 V_{\mathtt{PMNS}}\right)_{rr} > 0\,,$$