NEUTRINO PORTAL DARK MATER

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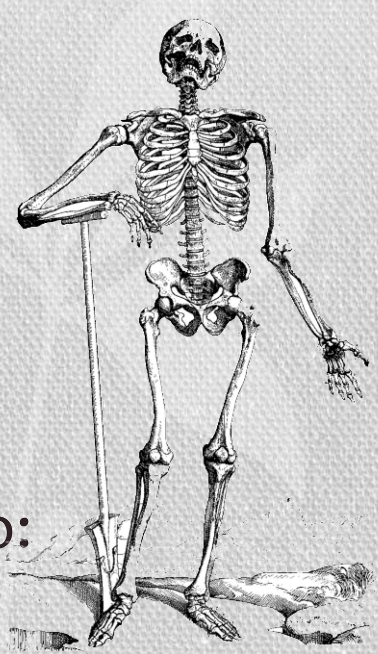
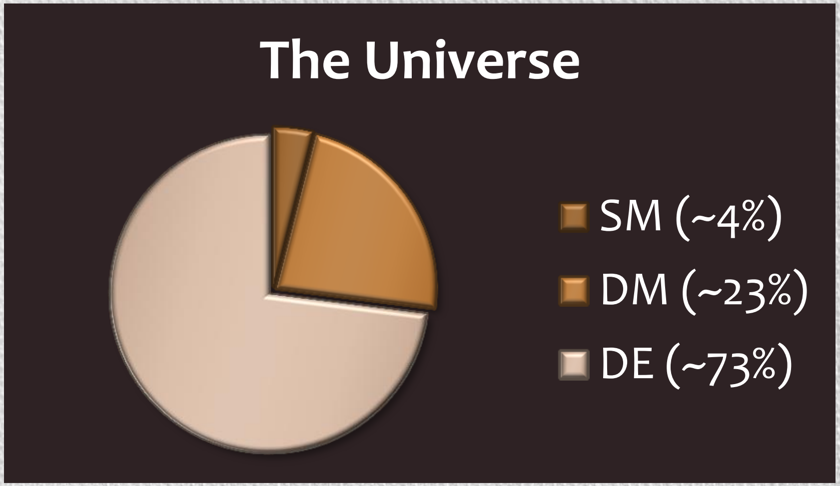
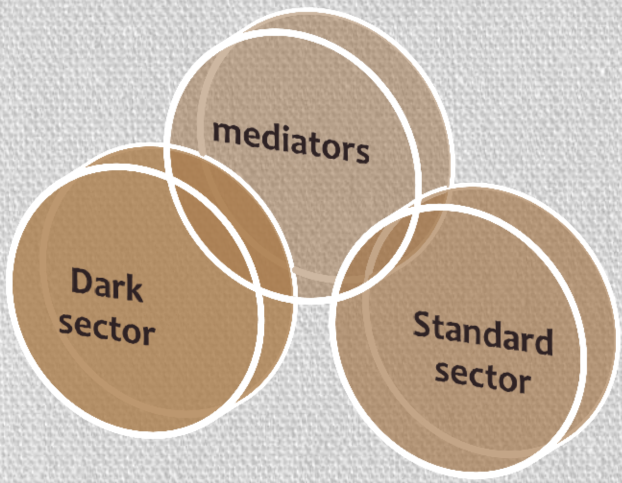
Talk skeleton



- DM paradigm
- Effective theory & hierarchy
- Fermion mediators & the neutrino portal scenario:
  - Relic abundance
  - Direct detection
  - Simple UV completion
- UV completion
- End matters

DM paradigm





Assumptions:

- standard & dark sectors interact via the exchange of heavy mediators
- DM stabilized against decay by some symmetry G_{DM}
- SM particles: G_{DM} singlets
- Dark particles: G_{SM} singlets
- Weak coupling

Effective theory of DM-SM interactions

Within the paradigm:

$$\mathcal{L}_{\rm eff} \sim \frac{1}{M^k}\mathcal{O}_{SM} \times \mathcal{O}_{DM}$$

Mediator mass

Leading interactions:

Lowest dimension (smallest M suppression)

Tree generated (no loop suppression factor)

Depends on the mediator type

Leading interactions (dim ≤ 6)

dim.	category	
4	I	$\lvert\phi\rvert^2(\Phi^\dagger\Phi)$
5	II	$\lvert\phi\rvert^2\bar{\Psi}\Psi$ $\quad$ $\lvert\phi\rvert^2\Phi^3$
	III	$(\bar{\Psi}\Phi)(\phi^T\epsilon\ell)$
	IV	$B_{\mu\nu}X^{\mu\nu}\Phi$ $\quad$ $B_{\mu\nu}\bar{\Psi}\sigma^{\mu\nu}\Psi$
6	V	$\lvert\phi\rvert^2\mathcal{O}^{(4)}_{\rm dark}$ $\quad$ $\Phi^2\mathcal{O}^{(4)}_{\rm SM}$
	VI	$(\bar{\Psi}\Phi^2)(\phi^T\epsilon\ell)$ $\quad$ $(\bar{\Psi}\Phi)\not{\partial}(\phi^T\epsilon\ell)$
	VII	$J_{\rm SM}.J_{\rm dark}$
	VIII	$B_{\mu\nu}\mathcal{O}^{(4)\,\mu\nu}_{\rm dark}$

Higgs portal

ν portal

Φ : dark scalar
Ψ : dark fermion
ϕ : SM scalar doublet
ℓ : SM lepton doublet

Where:

$J^{(\phi)}_{\mu} \supset v^2 Z_{\mu}$

$$J_{\rm SM}^{(\psi)\,\mu} = \bar{\psi}\gamma^{\mu}\psi\,, \qquad J_{\rm SM}^{(\phi)\,\mu} = \frac{1}{2i}\phi^{\dagger}\overleftrightarrow{D}^{\mu}\phi\,,$$

$$J_{\rm dark}^{(L,R)\,\mu} = \bar{\Psi}\gamma^{\mu}P_{L,R}\Psi \qquad J_{\rm dark}^{(\Phi)\,\mu} = \frac{1}{2i}\Phi^{\dagger}\overleftrightarrow{\mathcal{D}}^{\mu}\Phi$$

and

$\mathcal{O}_{\rm DM,\,SM}$ = operators of dimension 4

Simplifications:

- Scalar or fermions mediators
- Leading observable effects (≤ 1 loops)

dim.	category	
5	II	$\lvert\phi\rvert^2\bar{\Psi}\Psi$
	III	$(\bar{\Psi}\Phi)(\phi^T\epsilon\ell)$
6	V	$\mathcal{O}_r^{(6)} \in \{\lvert\phi\rvert^2\bar{\Psi}\Phi\Psi',\ \lvert\phi\rvert^2 X_{\mu\nu}^2,\ \Phi^2\bar{\psi}\varphi\psi',\ \Phi^2 B_{\mu\nu}^2,\ \Phi^2(W_{\mu\nu}^I)^2\}$
	VII	$J_{\rm SM}^{(i)} \cdot J_{\rm dark}^{(a)}\ (i = \ell, \phi;\ a = \Phi, L, R)$

Effective Lagrangian

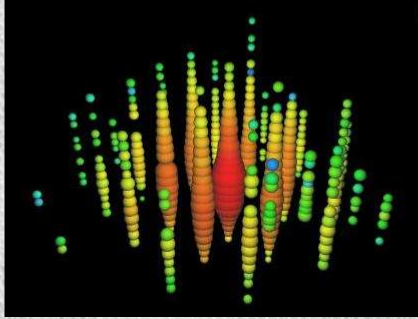
Integrate all modes with energies > Λ =ω (mediator) mass

$$\mathcal{L}_{\rm eff}^{(\omega)} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm dark} + c_{\rm I}|\phi|^2|\Phi|^2 + \mathcal{L}^{(\omega-{\rm tree})} + \mathcal{L}^{(\omega-{\rm loop})}$$

Tree generated: from integrating the ω

Loop-generated from integrating out

- Dark modes with energies > Λ
- SM modes with energies > Λ
- The mediators



Neutrino portal scenario

- **Dark sector: at least Φ & Ψ**
- G_{DM}: **just about anything; Φ & Ψ transform in the same way**
- **Fermion mediators (Dirac): $\mathcal{F}$**

Relic abundance
Indirect detection

$$\mathcal{L}^{(\mathcal{F}-\text{tree})} = \frac{c_{\text{III}}}{\Lambda}(\bar\Psi\Phi)(\tilde\phi^\dagger\ell) + \cdots$$

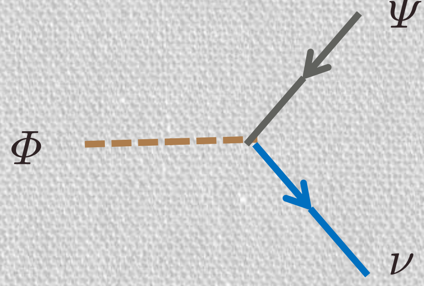
$$\mathcal{L}^{(\mathcal{F}-\text{loop})} = \frac{c_{\text{II}}}{16\pi^2\Lambda}|\phi|^2\bar\Psi\Psi + \sum_{a=\ell\,\phi;\,i=L,R,\Phi} \frac{c_{\text{VII}}^{(a|i)}}{(4\pi\Lambda)^2}\left(J_{\text{SM}}^{(a)}\cdot J_{\text{dark}}^{(i)}\right) + {\sum_r}' \frac{c_{\text{V}}^r}{(4\pi\Lambda)^2}\mathcal{O}_r^{(6)} + \cdots$$

Relic ab. (if $m_\Psi \sim m_H/2$)
Dir. detection (H exch)

Relic ab. (if $m_\Psi \sim m_Z/2$)
Dir. detection (Z exch)

Assume: $\mathbf{m}_{\Phi} > \mathbf{m}_{\Psi}$ $\Rightarrow$ all Φ's have decayed: fermionic DM.

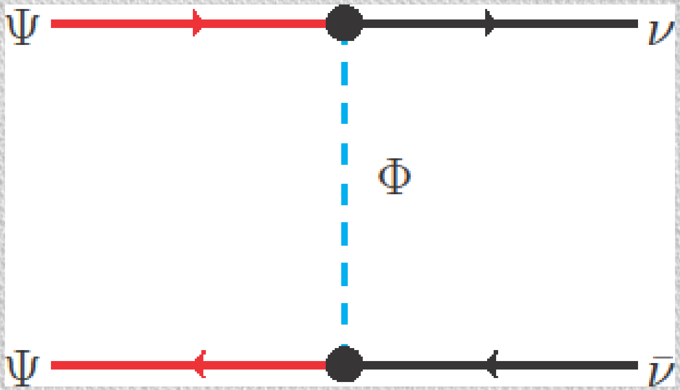
$$(\bar{\ell}\tilde{\phi})(\Phi^\dagger\Psi) \to \frac{v}{\sqrt{2}}\bar{\nu}_L\Phi^\dagger\Psi$$

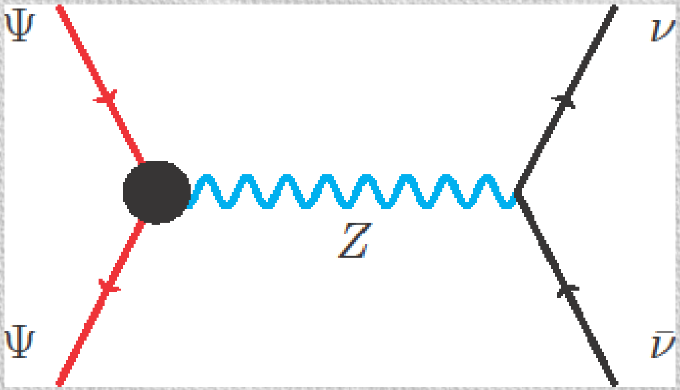


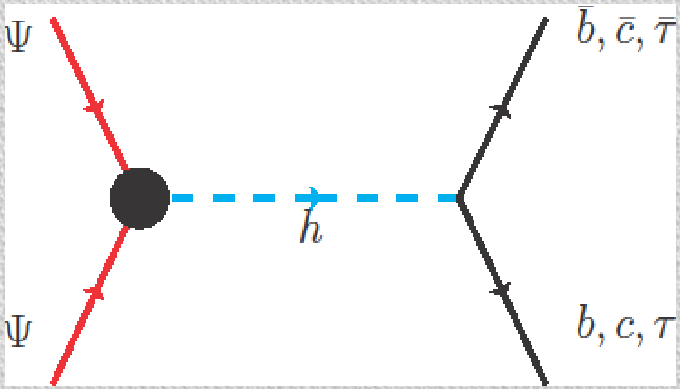
[If $\mathbf{m}_{\Phi} < \mathbf{m}_{\Psi}$ Φ = DM … like the Higgs portal scenario]

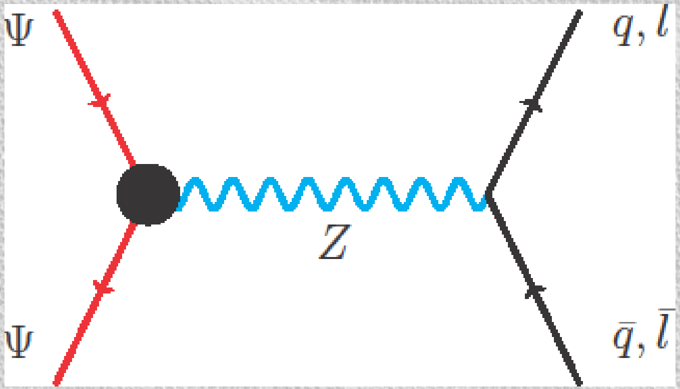
Relic abundance

Main processes (Z and H exchanges: 1 loop $\Rightarrow$ important on resonance)

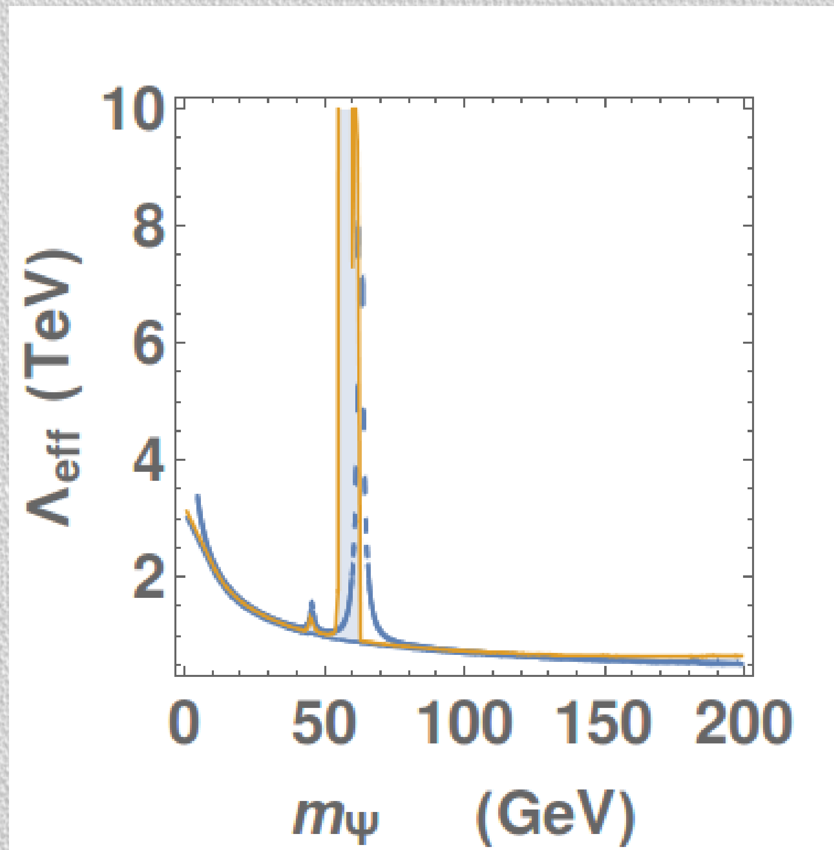




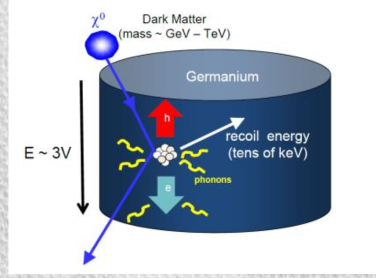




Constraint: - $_{\text{Planck}}h^2 = 0.1198 \pm 0.0026 \quad (3\,\sigma)$



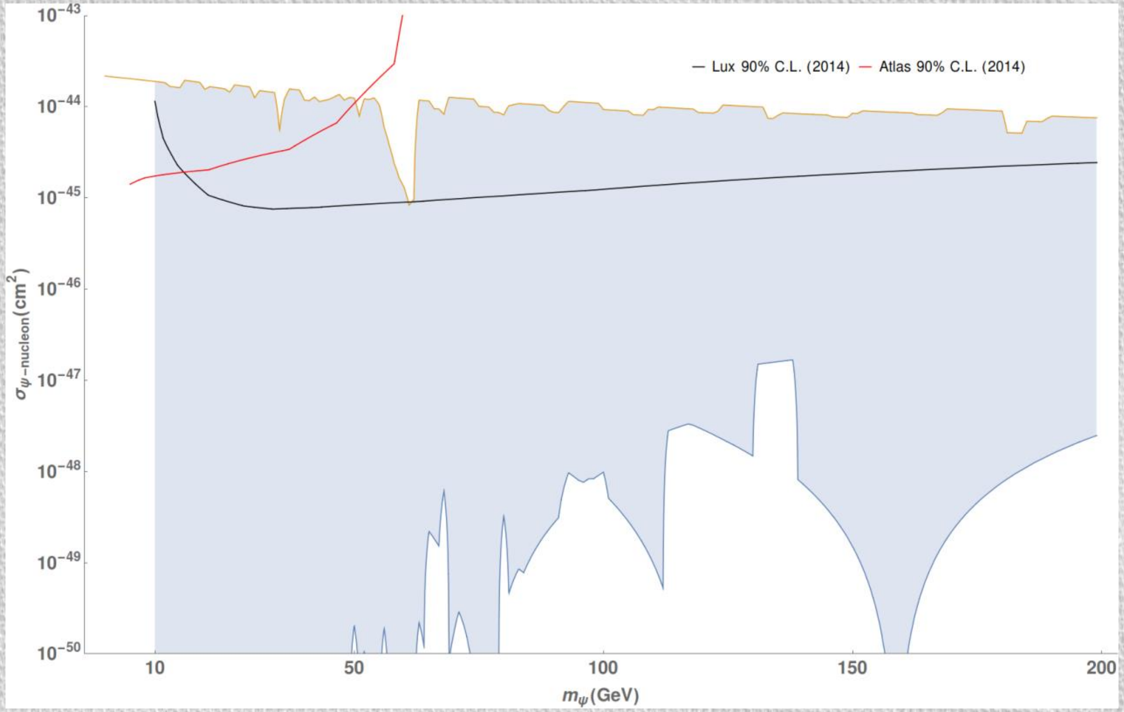
$$\Lambda_{\text{eff}} = \sqrt{1 + \frac{m_\Phi^2}{m_\Psi^2}\frac{\Lambda}{c_{\text{III}}}} \simeq \sqrt{\frac{m}{m_\Psi}}\,\text{TeV}; \quad m \quad \simeq 74\text{GeV} \quad (\text{non-resonant region})$$



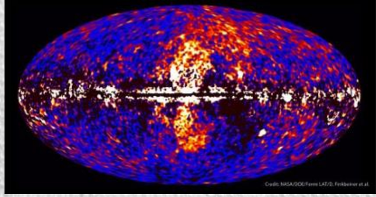
Direct detection

Main processes Z and H exchanges: 1 loop $\Rightarrow$ naturally suppressed

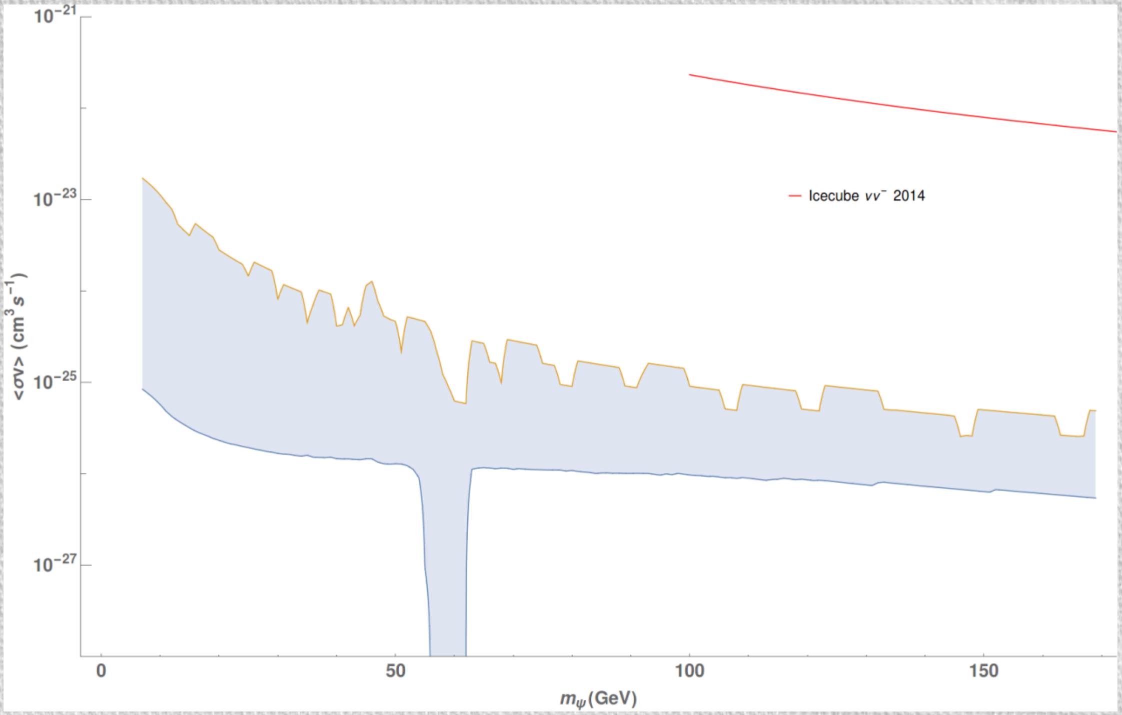
$$\mathcal{L}^{(\mathcal{F}-\mathrm{loop})} \supset \frac{v c_{\mathrm{II}}}{16\pi^2\Lambda} H\bar{\Psi}\Psi - \frac{g}{2c_{\mathrm{w}}} \frac{v^2}{16\pi^2\Lambda^2} \bar{\Psi} \not{Z} \left(c_{\mathrm{VII}}^{(\phi|L)} P_L + c_{\mathrm{VII}}^{(\phi|R)} P_R \right) \Psi$$



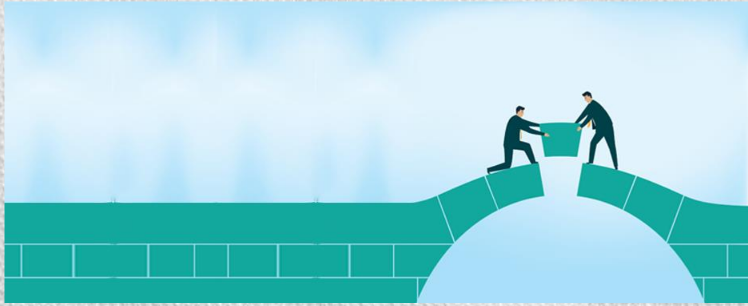
Indirect detection



- No significant $\gamma\gamma$ signal
- Interesting $\nu\nu$ monochromatic signal @ E = m_Ψ
- Not enough experimental sensitivity



UV completion



Add neutral *Dirac* fermions $\mathcal{F}$ to the SM:

L is conserved

$$\mathcal{L} = \bar{\ell} i \not{D} \ell + \bar{\Psi}(i\not{\partial} - m_\Psi)\Psi + \bar{\mathcal{F}}(i\not{\partial} - \tilde{M})\mathcal{F} + |\partial\Phi|^2 - m_\Phi^2|\Phi|^2 + \left(\bar{\ell}Y^{(e)}e\phi + \bar{\ell}Y^{(\nu)}\mathcal{F}\tilde{\phi} + \bar{\Psi}\tilde{z}\mathcal{F}\Phi + \mathrm{H.c}\right)$$

ν masses are NOT $\propto$ Y$^{(\nu)}$

Mass eigentsates: $\boldsymbol{n_L}$ (mass = 0), and **N** (mass = $\boldsymbol{M}$)

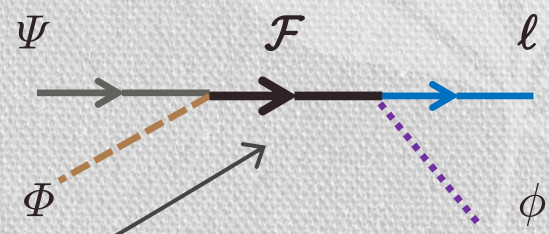
~ inverse see-saw

$$N = C_{N_L}\frac{1}{\sqrt{1+\epsilon\epsilon^\dagger}}(\mathcal{F}_L + \epsilon\nu_L) + C_{N_R}\mathcal{F}_R]$$

$$n_L = C_n\frac{1}{\sqrt{1+\epsilon^\dagger\epsilon}}\left(\nu_L - \epsilon^\dagger\mathcal{F}_L\right)$$

$$\epsilon = -\frac{1}{M}\mathcal{V}_\nu\boldsymbol{\mu} \qquad \frac{v}{\sqrt{2}}Y^{(\nu)} = \mathcal{U}_\nu\mathcal{V}_\nu\boldsymbol{\mu}\mathcal{V}_\nu^\dagger \qquad C_i,\, \mathcal{U}_\nu,\, \mathcal{V}_\nu = \text{unitary}$$

Effective couplings (one mediator):



$$\mathcal{L}^{(\mathcal{F}-\text{tree})} \supset \frac{c_{\rm III}}{\Lambda}(\bar{\Psi}\Phi)(\tilde{\phi}^{\dagger}\ell)$$

$$\mathcal{L}^{(\mathcal{F}-\text{loop})} \supset \frac{v c_{\rm II}}{16\pi^2\Lambda} H\bar{\Psi}\Psi - \frac{g}{2c_{\rm w}}\frac{v^2}{16\pi^2\Lambda^2}\bar{\Psi}\not{Z}\left(c_{\rm VII}^{(\phi|L)}P_L + c_{\rm VII}^{(\phi|R)}P_R\right)\Psi$$

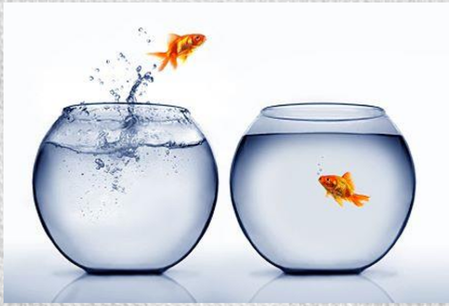
Where Λ = ***M***

$$c_{\rm III} = \frac{\sqrt{2}\,\mu z}{v}$$

$$c_{\rm II} = -\left[c_{\rm III}^2 + 2z^2 c_{\rm I}\ln\left(\frac{\Lambda}{m_\Phi}\right)\right]$$

$$c_{\rm VII}^{(\phi|L)} = \frac{1}{2}c_{\rm III}^2$$

$$c_{\rm VII}^{(\phi|R)} = \frac{1}{2}c_{\rm III}^2 \ln\left(\frac{\Lambda}{m_\Phi}\right)$$



Modification to SM couplings

$$
\begin{aligned}
W: &\quad -\frac{g}{\sqrt{2}}\bar{n}_L \zeta_n \mathbf{U}_{\mathrm{PMNS}} \not{W} e_L \qquad \zeta_n^2 = 1-\delta_n^2 = C_n^\dagger \frac{1}{1+\epsilon^\dagger\epsilon} C_n = \text{diagonal} \\
Z: &\quad -\frac{g}{2c_{\mathrm{w}}}\bar{n}_L \zeta_n^2 \not{Z} n_L \\
H: &\quad -\frac{H}{v}\left[\bar{N}_R \left(C_{N_R}^\dagger M \frac{\epsilon\epsilon^\dagger}{\sqrt{1+\epsilon\epsilon^\dagger}} C_{N_L}\right) N_L + \bar{N}_R \left(C_{N_R}^\dagger M \epsilon C_n \zeta_n\right) n_L + \text{H.c.}\right]
\end{aligned}
$$

Best limits

$$\frac{\Delta\Gamma(Z \to \text{inv})}{\Gamma(Z \to \text{inv})} = \frac{2}{3}(\delta_e^2 + \delta_\mu^2 + \delta_\tau^2) < 0.009 \quad (3\sigma) \quad \Rightarrow \quad \delta_{e,\,\mu,\,\tau} < 0.014 \quad (3\sigma)$$

($\tau \to \mu\nu\nu$, e$\nu\nu$; π $\to \mu\nu$: weaker limits)

$$M > 10 Y^{(\nu)}\,\text{TeV} \quad (\text{roughly})$$

Tension with relic abundance:

$$\sigma \propto |z|^2 \sum \delta^2$$

work in progress ...

Neutrino masses: add a <u>*small*</u> Majorana mass for the $\mathcal{F}$:

$$
\begin{aligned}
\mathcal{L}_{\mathrm{Maj.}} &= -\left(\mathcal{F}^T C \tilde{\mathcal{M}} \mathcal{F}\right) + \mathrm{H.c} \\
&= -n_L^T C \mathcal{M}_{\mathrm{Maj}} n_L + \cdots ; \qquad \mathcal{M}_{\mathrm{Maj}} = \left(\frac{1}{\sqrt{1+\epsilon\epsilon^\dagger}}\epsilon\right)^T \tilde{\mathcal{M}} \left(\frac{1}{\sqrt{1+\epsilon\epsilon^\dagger}}\epsilon\right)
\end{aligned}
$$

$$
\mathcal{M}_{\mathrm{Maj}} \sim 3 \times 10^{-4} \tilde{\mathcal{M}} \quad \text{(roughly)}
$$

End matters

- Neutrino portal scenario works quite well, but difficult to confirm.
- The clearest signature: monochromatic neutrino line

- Collider constraints mainly from H and Z invisible widths
- DM-assisted LNV

- Other possible dark-standard interactions besides Higgs and neutrino portals might also be of interest