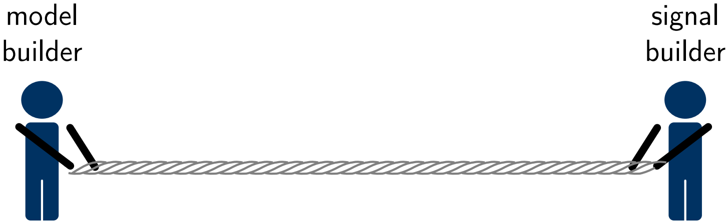
Fermionic DM absorption

1905.12635: with Gilly Elor, Robert McGehee
1908.10861: with Gilly Elor, Robert McGehee
191x.xxxxx: with Gilly Elor, Robert McGehee, Tien-Tien Yu

○ Time for a debate...



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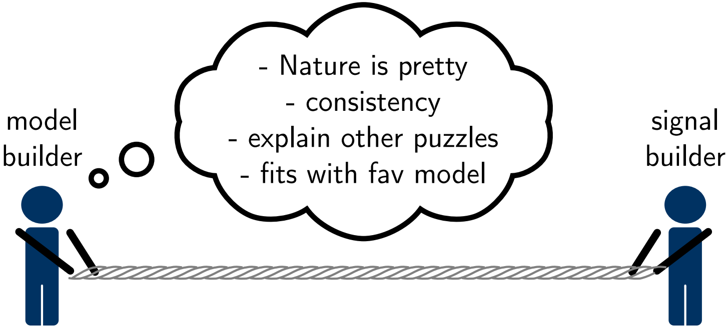

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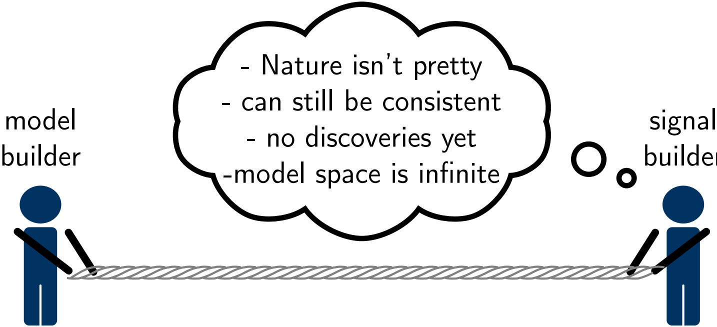


This talk: signal approach

- Types of searches

Elastic scattering

WIMPs
χ freeze-in
...

Bosonic absorption

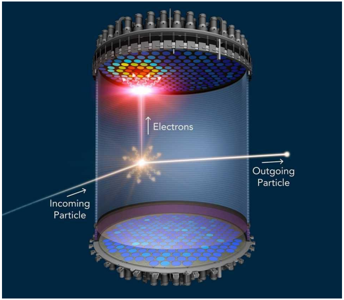
dark photon
axion-like particle
...

- Progress getting expensive

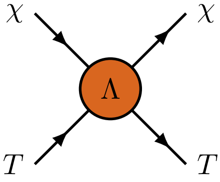
  Xenon1T $\sim \$\,10^7$
  DARWIN $\sim \$\,10^8$

- About to hit ν floor
- Different signals?

  $\Rightarrow$ big gain/small cost



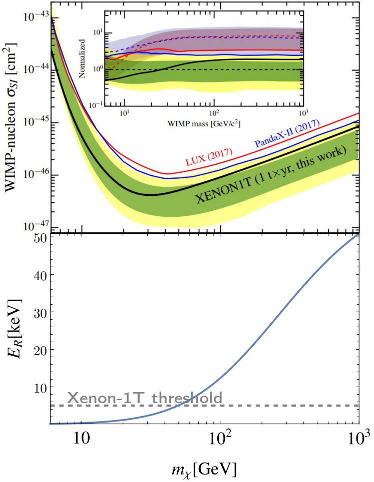
- Elastic scattering ($T = n, e$);



- Conserves DM-number (stable)
- Target recoil energy:

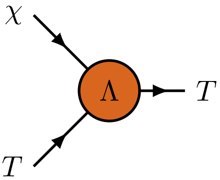
$$E_R = \frac{\mu^2}{2m_T} v^2$$

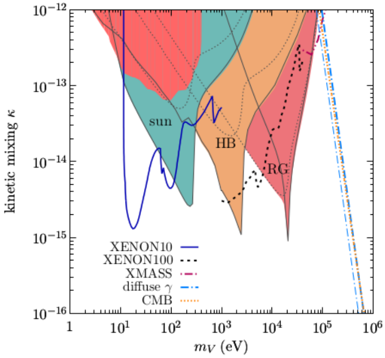
- $f(v) \sim e^{-v^2/v_0^2}$



Bosonic absorption

- Absorption of bosonic dark matter



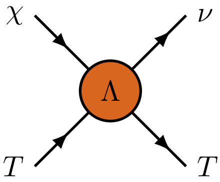


- Recoil energy: $E_R \simeq m_\chi$
- Lighter DM (by $\sim v^2$)
- DM is inherently unstable

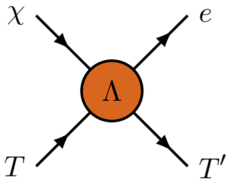
$$A' \to \gamma\gamma\gamma$$
$$a \to \gamma\gamma$$

- Metastable for $m_\chi \lesssim \text{ MeV}$

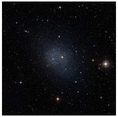
"Neutral current"

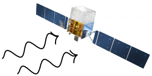


"Charged current"



- Mass range:

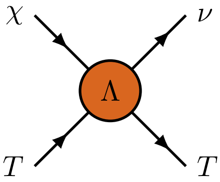




Neutral current processes

- Operators of the form,

$$\frac{1}{\Lambda^2}\left[\bar{\chi}\Gamma_i\nu\right]\,\left[\bar{T}\Gamma_j T\right]$$



- Neutrino carries away most of energy:

$$E_\nu \sim m_\chi \qquad E'_T \sim m_\chi^2/2m_T$$

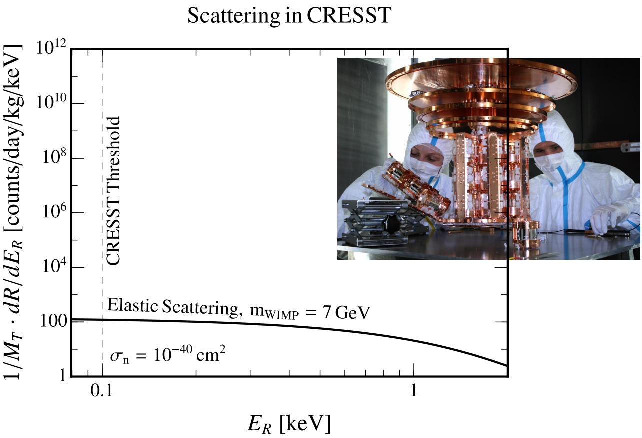
- Look for (smaller) nuclear recoil:

$$m_\chi \sim \text{ MeV}, m_T \sim 10 \text{ GeV} \Rightarrow E'_T \sim 0.1 \text{ keV}$$

- Related ideas: [Kile, Soni - 0908.3892]
[Graham, Harnik, Rajendran, Saraswat - 1004.0937]

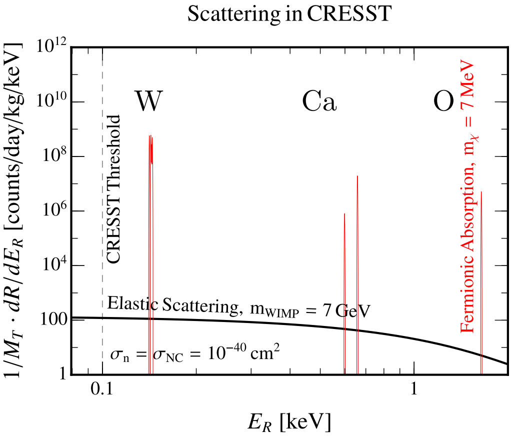
Features

- Elastic scattering ($CaWO_4$):



Features

- Peak at $E_R \sim m_\chi^2/2m_T$, width $\Delta E_R/E_R \sim 10^{-3}$



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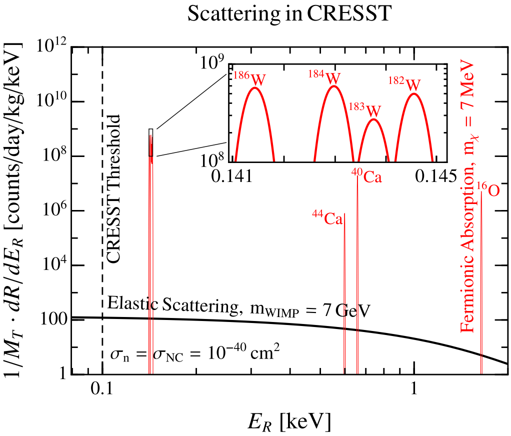
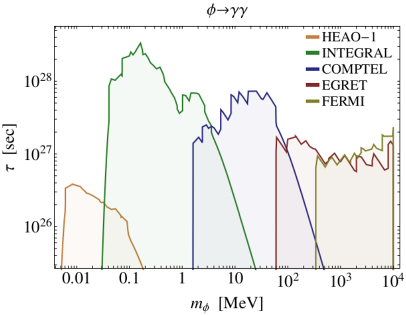


- No neutrino floor

- Complete models will have decays:

$\chi \to \nu\gamma$ $\qquad\qquad$ $\bar{\chi} F_{\mu\nu} \sigma^{\mu\nu} \nu$ $\qquad\qquad$ $\leftarrow$ often zero



[Essig, Kuflik, McDermott, Volansky, Zurek - 1309.4091]

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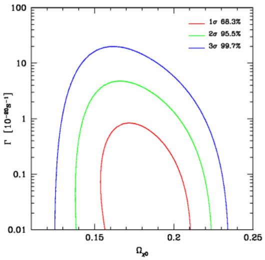
$\chi \to \nu\gamma$ $\qquad \bar{\chi} F_{\mu\nu} \sigma^{\mu\nu} \nu$ $\qquad \leftarrow$ often zero

$\chi \to \nu\nu\nu$ $\qquad [\bar{\chi}\Gamma_i \nu]\,[\bar{\nu}\Gamma_j \nu]$ $\qquad \leftarrow$ can vanish to $\mathcal{O}(\Lambda^{-4})$

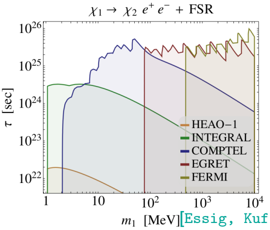


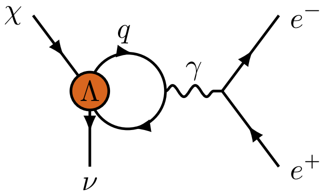
[Gong,Chen - 0802.2296]

χ decays

- Complete models will have decays:

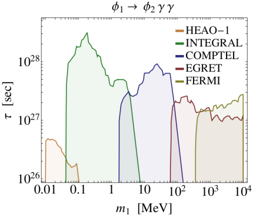
$\chi \to \nu\gamma$	$\bar{\chi} F_{\mu\nu} \sigma^{\mu\nu} \nu$	$\leftarrow$ often zero
$\chi \to \nu\nu\nu$	$[\bar{\chi}\Gamma_i \nu]\,[\bar{\nu}\Gamma_j \nu]$	$\leftarrow$ can vanish to $\mathcal{O}(\Lambda^{-4})$
$\chi \to e^+ e^- \nu$	$[\bar{\chi}\Gamma_i \nu]\,[\bar{e}\Gamma_j e]$	$\leftarrow$ loop induced

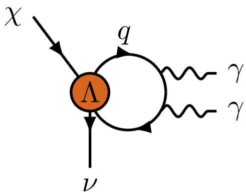




[Essig, Kuflik, McDermott, Volansky, Zurek - 1309.4091]

- Complete models will have decays:





(Λ^{-4})

d

[Essig, Kuflik, McDermott, Volansky, Zurek - 1309.4091]

$\chi \to \nu\gamma\gamma$ $\quad [\bar{\chi}\Gamma\nu]\, F_{\mu\nu}F^{\mu\nu}$ $\quad \leftarrow$ loop induced

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$\chi \to \nu\gamma$	$\bar{\chi} F_{\mu\nu} \sigma^{\mu\nu} \nu$	$\leftarrow$ often zero
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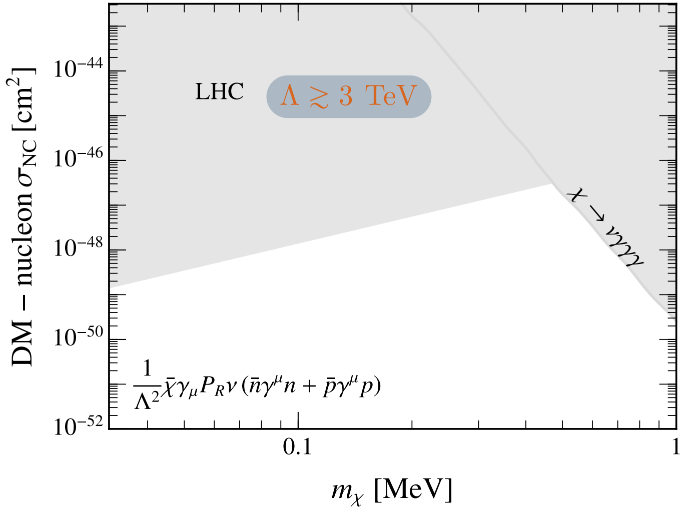
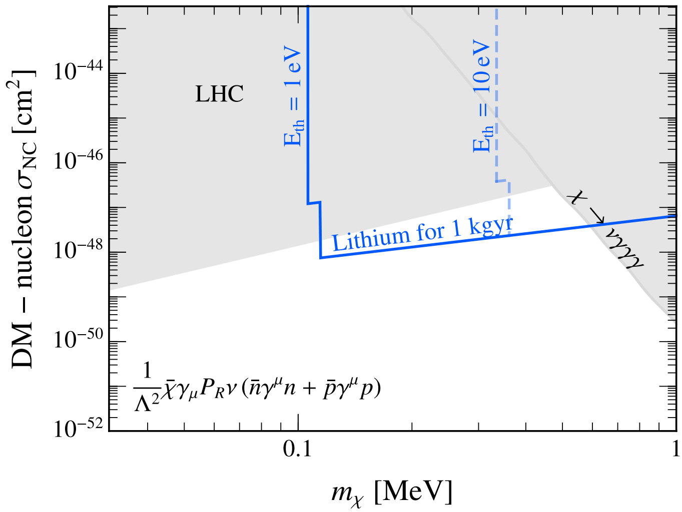
$\chi \to \nu\gamma\gamma$	$[\bar{\chi}\Gamma \nu]\, F_{\mu\nu} F^{\mu\nu}$	$\leftarrow$ loop induced
$\chi \to \nu\gamma\gamma\gamma$	$[\bar{\chi}\Gamma \nu]\, F_{\mu\nu} F^{\nu\alpha} F^{\mu}_{\alpha} + \ldots$	$\leftarrow$ small

Projected sensitivity

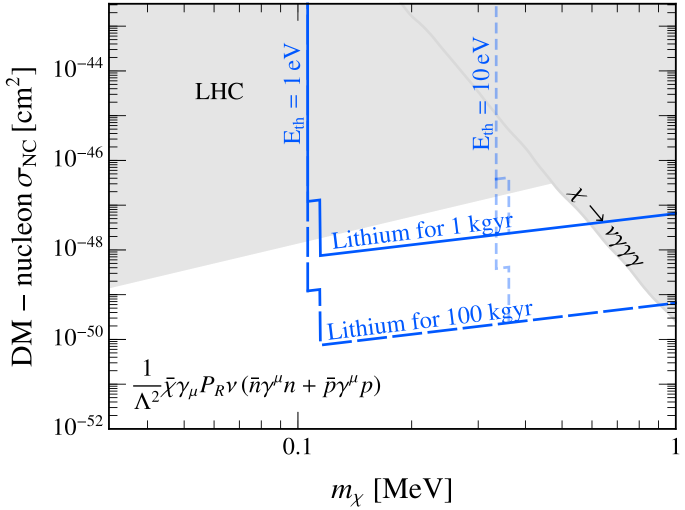
- Projected sensitivity ($\sigma_{NC} \equiv m_\chi^2/4\pi\Lambda^4$)



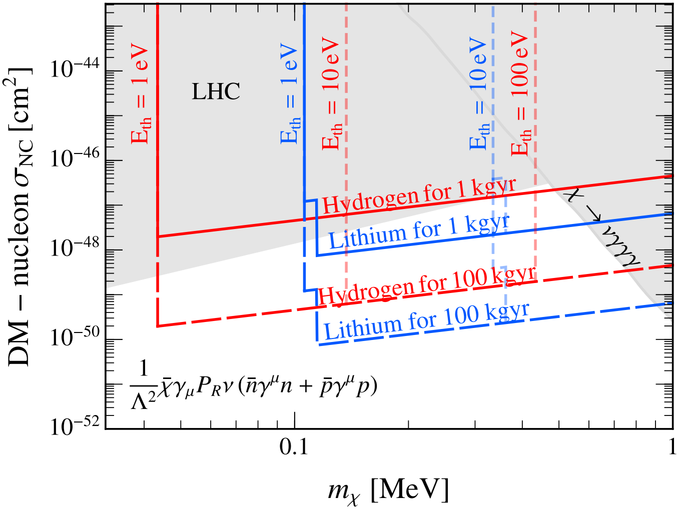
- Lithium target (^{6}Li and ^{7}Li)



- Larger experiments

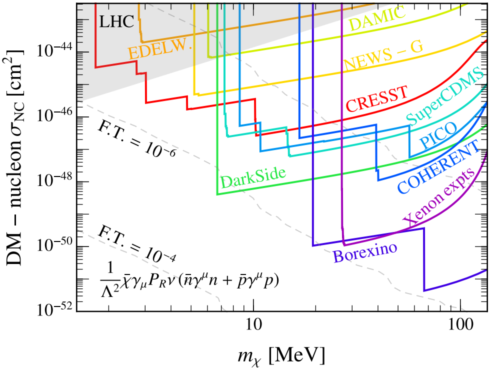


- Hydrogen target



Projected sensitivity

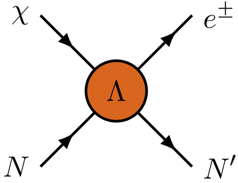
- Current experiments-larger thresholds
- Need $m_\chi \gtrsim$ MeV
- Tune away decays?



Charged current processes

- Operators of the form,

$$\frac{1}{\Lambda^2}\left[\bar{\chi}\Gamma_i e\right]\left[\bar{n}\Gamma_j p\right]$$



- Induce a β^- or β^+ decay in a nucleus:

$$\chi + n \to p + e^- \;\Rightarrow\; \chi + {}^A_Z\mathrm{N} \to {}_{Z+1}^{\;\;A}\mathrm{N} + e^-$$
$$\bar{\chi} + p \to n + e^+ \;\Rightarrow\; \chi + {}^A_Z\mathrm{N} \to {}_{Z-1}^{\;\;A}\mathrm{N} + e^+$$

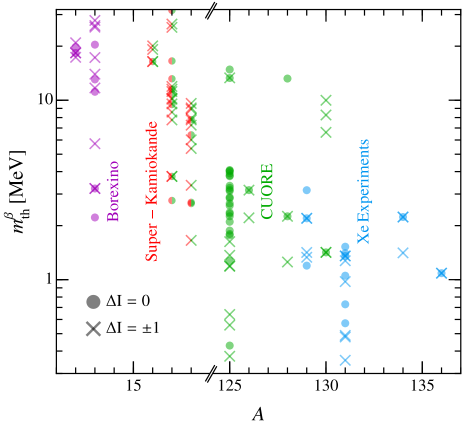
- $e^\pm$ gets most of χ energy
- β^- transition allowed if,

β^+ on Hydrogen: [Kile, Soni - 0908.3892]
Sterile ν: [Lasserre et al - 1609.04671]

$$m_\chi > m_{\rm th} \equiv M_{A,Z+1} + m_e - M_{A,Z}$$

Kinematics

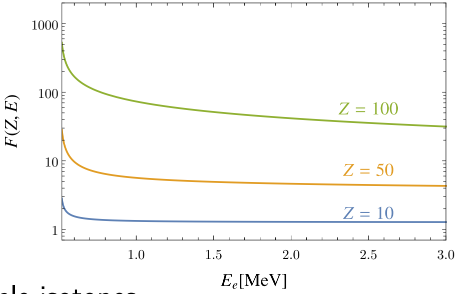
- Best transition in SM: ${}^{163}_{66}\mathrm{Dy} \to {}^{163}_{67}\mathrm{Ho}$ (2.6keV)
- Thresholds in known experiments:



- Rate analogous to neutrino scattering:

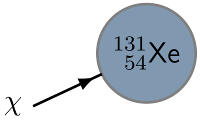
$$R \sim N_T \frac{\rho_\chi}{m_\chi} F(Z,E) \sigma_{\chi n \to p \nu}$$

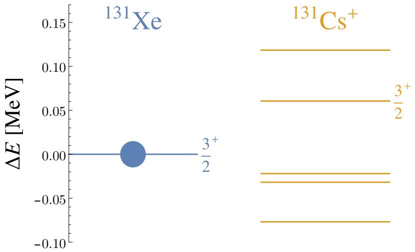
- Coulomb enhancement



- Focus on stable isotopes

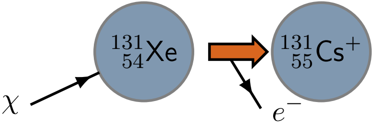
- Multiple detection opportunities:

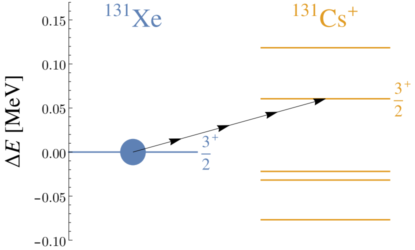




- Multiple detection opportunities:

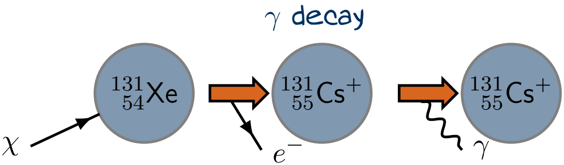
Shoot off electron + nuclear recoil

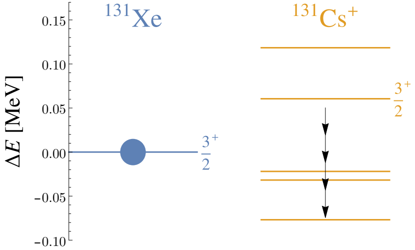




Signal

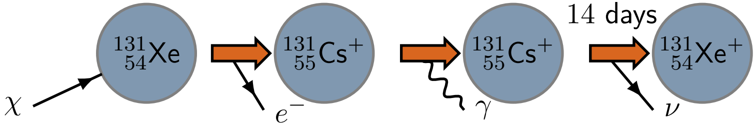
- Multiple detection opportunities:

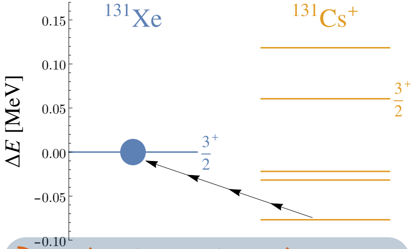




- Multiple detection opportunities:

Swallow an electron + nuclear recoil

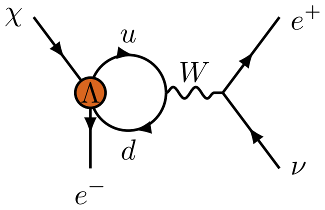




Details depend on isotope

Decays

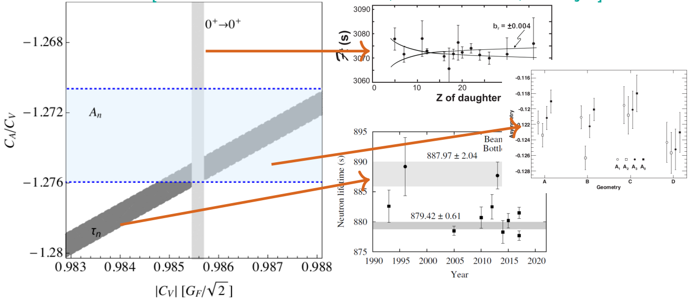
- Same decays as neutral current
  - $\chi \to \nu\gamma$
  - $\chi \to \nu\nu\nu$
  - $\chi \to \nu e^+ e^-$
  - $\chi \to \nu\gamma\gamma$
  - $\chi \to \nu\gamma\gamma\gamma...$
- Can all be suppressed by additional m_W^2 or Λ^2



- Current experiments probe un-tuned parameter space!

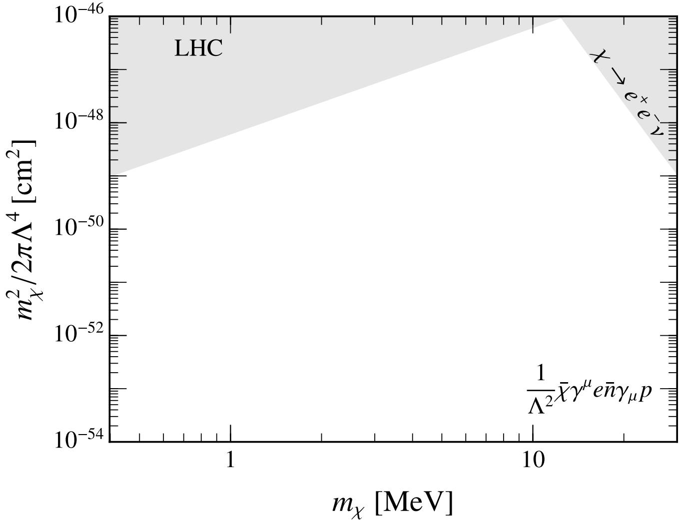
- LHC: $\Lambda \gtrsim 3\ \text{TeV}$
- β decay test of $V-A$ structure: $(\bar{\nu}\Gamma e)(\bar{n}\Gamma p)$

[1803.08732 - Gonzalez-Alonso, Naviliat-Cuncic, Severijns]

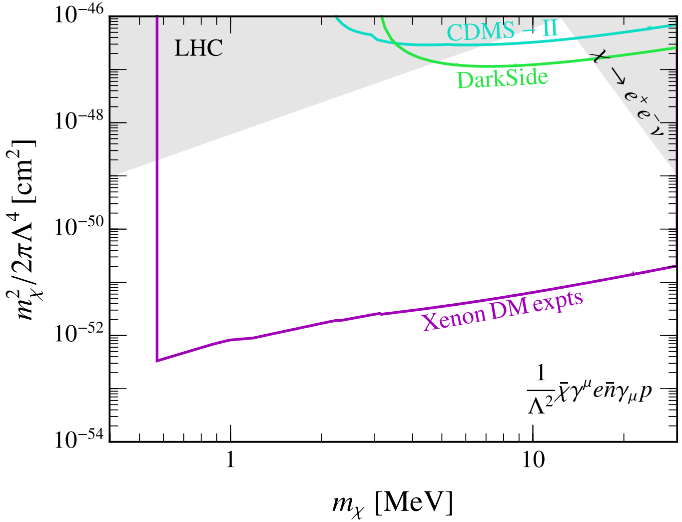


- Fermion absorption: no interference ($\mathcal{O}(G_F^{-2}\Lambda^{-4})$ vs $\mathcal{O}(G_F^{-1}\Lambda^{-2})$)
- Constraints satisfied if $\Lambda \gtrsim\ \ \text{TeV}$

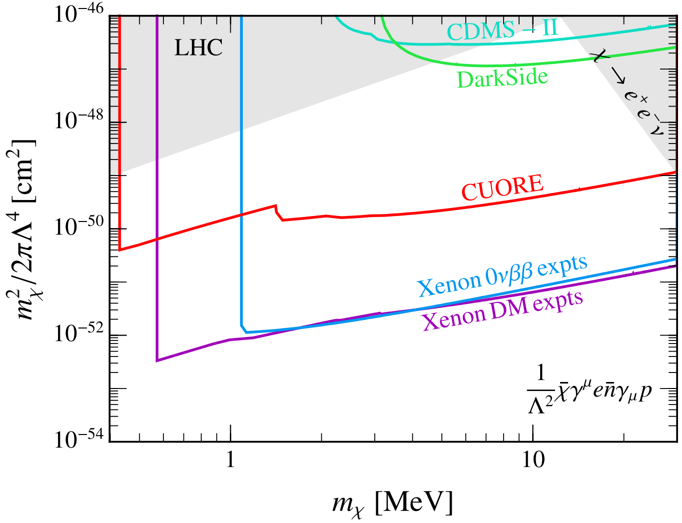
- Projected sensitivity



- Direct detection

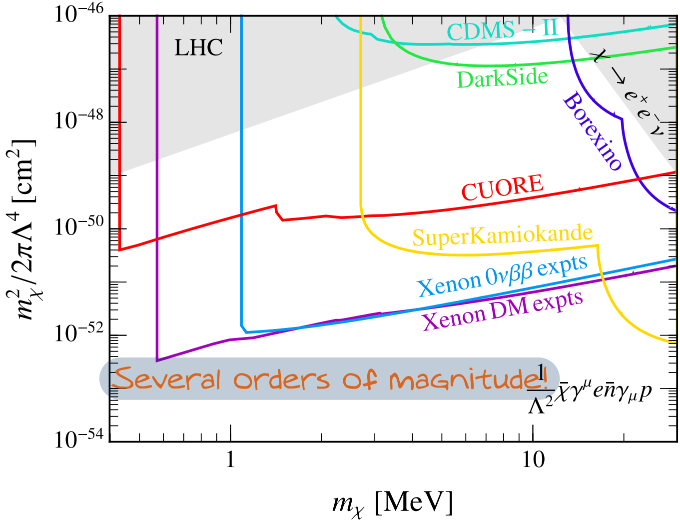


- $0\nu2\beta$



LHC
CDMS − II
DarkSide
$\chi \to e^+e^-\nu$
CUORE
Xenon $0\nu\beta\beta$ expts
Xenon DM expts
$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu e\bar{n}\gamma_\mu p$
10^{-46}
10^{-48}
10^{-50}
10^{-52}
10^{-54}
1
10
$m_\chi^2/2\pi\Lambda^4$ [cm^2]
m_χ [MeV]

- Neutrino monsters

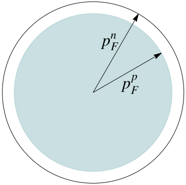


- Alternative: β^+ decay

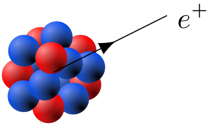
$$\bar{\chi} + p \rightarrow n + e^+$$

- May be only signal (asymmetric DM)
- Rate suppressed in heavy elements

1) Pauli blocking

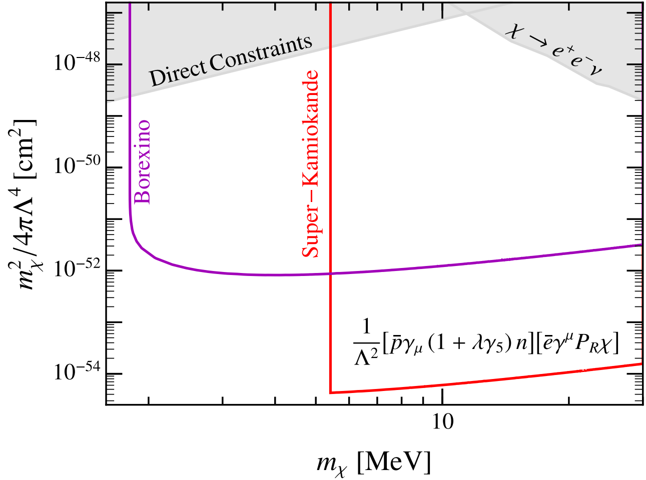


2) Columb repulsion

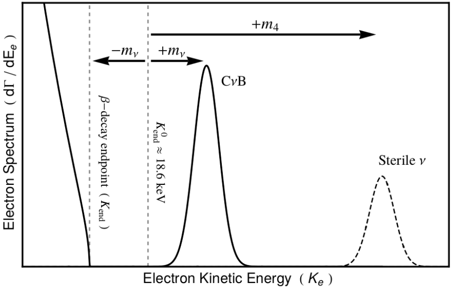


- Focus on Hydrogen targets (Borexino,SuperK)

- Projections from neutrino experiments:



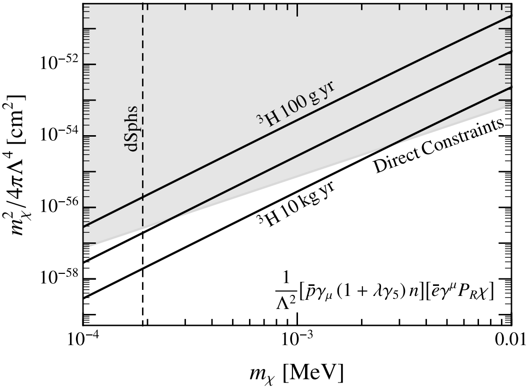
- Can also have DM altered $\beta^{\pm}$ spectra
- Tritium - popular transition $\quad {}^3_1\text{H} \rightarrow {}^3_2\text{He} + e^- + \nu$



[Long, Lunardini, Sabancilar - 1405.7654]

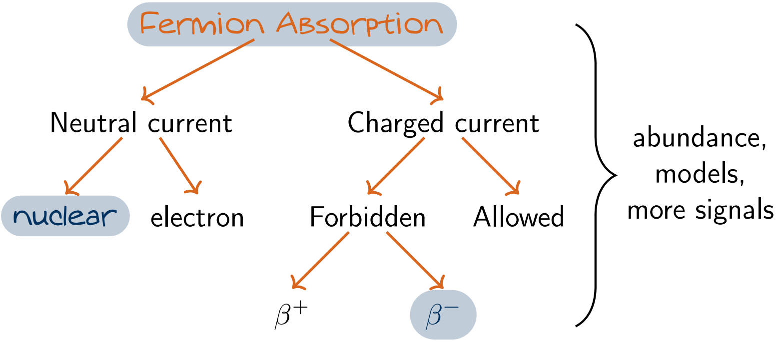
- Small experiments (typically $\sim$ gram)
- PTOLEMY (100 gram)

- Projections... need some optimism



- Simple question...

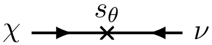
Can fermions be absorbed in DM experiments?



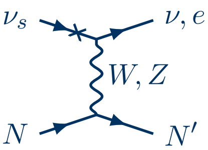
Thanks!

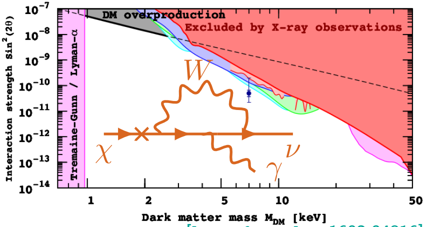
Relation to sterile neutrinos

- Fermion absorption can occur for “classic” sterile neutrinos
- Only interaction through mixing: $(\mathcal{L} \supset (s_\theta m_s)\nu_s\nu)$



- Direct detection is related to Decay





[lots of people - 1602.04816]

$$\Lambda^2 \simeq m_W^2 / s_\theta \gtrsim (100\ \text{TeV})^2 \qquad \text{(hard)}$$

- UV completion: U(1) broken at a TeV ($m_{Z'} = \text{ TeV}$)

$$\mathcal{L} \supset g_X \Big(\frac{1}{3} \sum_{q \in u,d} Q_q \bar{q} \gamma_\mu q + Q_\chi \bar{\chi} \gamma_\mu \chi \Big) Z'^\mu$$

- "Protophobic" $Q_u = -1/3$, $Q_d = 2/3$
- Integrating out Z':

$$\mathcal{L} \supset \frac{g_X^2 Q_q Q_\chi}{m_{Z'}^2} \bar{n} \gamma^\mu n \bar{\chi} \gamma_\mu \chi$$

- So far model only has elastic scattering

- Now suppose we have some mixing between χ and ν:

$$\mathcal{L} \supset H \left(y\bar{\nu} + y'\bar{\chi} \right) P_L \ell + m\bar{\chi} P_R \nu + m' \bar{\chi}\chi$$

- Mixing between states:

$$\theta_R \simeq -\frac{m}{m'}\,, \quad \text{and} \quad \theta_L \simeq -\frac{y'v}{m'}$$

- Set mixing between left handed states to be small ($y' \to 0$):

$$\mathcal{L} \supset \frac{g_X^2 Q_q Q_\chi s_{\theta_R}}{m_{Z'}^2} \bar{n}\gamma_\mu n \, \bar{\chi}\gamma_\mu P_R \nu + \text{h.c.}$$

- Additional interactions induce $\chi \to 3\nu$
- $\Gamma_{\chi \to 3\nu} \propto s_{\theta_R}^6 \Rightarrow$ easy to suppress

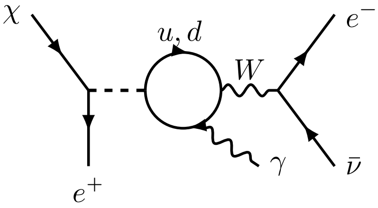
- Consider hypercharged, SU(2)-singlet, scalar, $\phi^{\pm}$ $(Y = 1)$
- It can have interactions:

$$\mathcal{L} \supset g_X \left(Q_e \phi^- \bar{\chi} P_R e + \phi^- Q_q \bar{u} P_R d \right)$$

- Integrating out scalar:

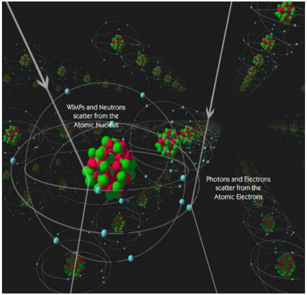
$$\mathcal{L} \supset \frac{g_X^2 Q_e Q_q}{m_\phi^2} \bar{\chi} P_R e \bar{u} P_R d$$

- Leading decay:



Electron scattering

- $\chi e \to \nu e$: natural place to look for fermion absorption
- $E_e \sim m_\chi^2/m_e$
- keV DM $\Rightarrow E_e \sim \text{eV}$
- Reach Tremaine-Gunn!
- Decays are suppressed (no $\chi \to e^+e^-\nu$, small m)
- Only have $\chi \to \nu\gamma, \nu\gamma\gamma, 3\nu, \ldots$



- Direct detection: Hard to compute
- Future work...

- Rich indirect detection signatures
- Decays always present
- Excess of events in baryon rich regions
- CMB constraints:

$$
\begin{aligned}
n_\chi n_b \langle \sigma v \rangle_{\chi n \to e p} &\simeq n_\chi^2 \langle \sigma v \rangle_{\chi\chi \to e^+ e^-} \\
\Rightarrow \langle \sigma v \rangle_{\chi n \to e p} &= \frac{\Omega_b}{\Omega_\chi} \frac{m_p}{m_\chi} \langle \sigma v \rangle_{\chi\chi \to e^+ e^-} \\
&= 2 \times 10^{-38} \mathrm{cm}^2
\end{aligned}
$$

- (much larger than our parameter space)
- Can you do better with specialized indirect detection?