Direct detection of freeze-in dark matter

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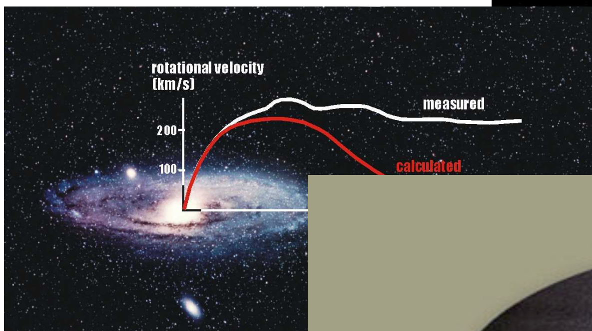
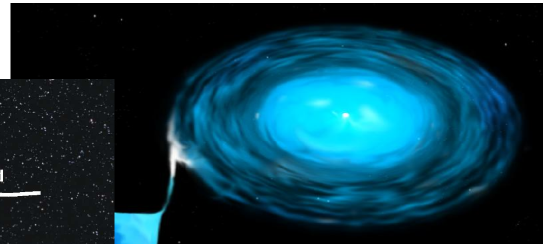
Low Energy Recoils from Deep Underground

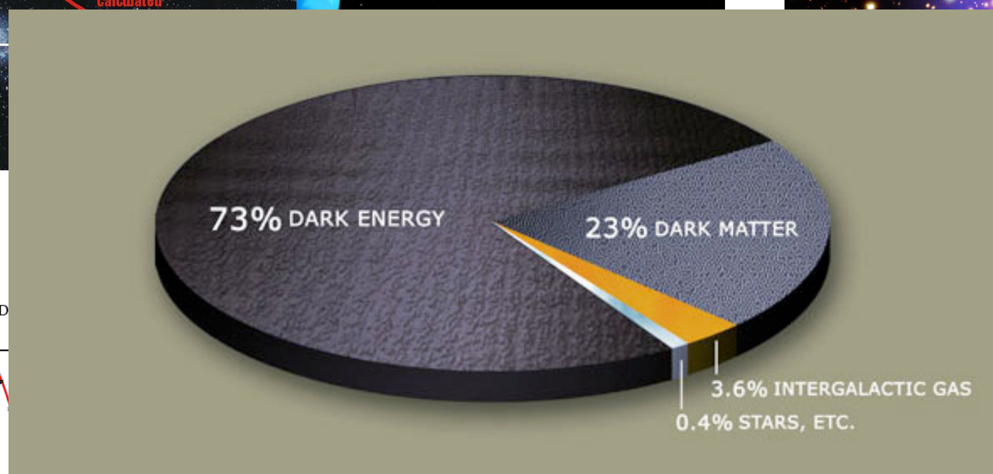
@PKU, Sep 26, 2020

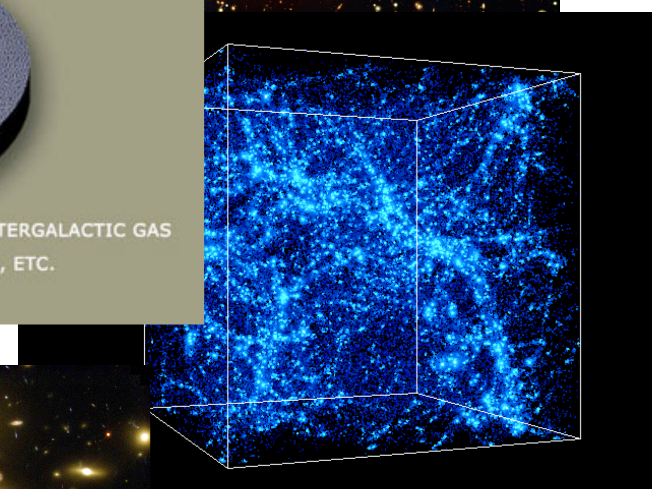
In collaboration with Daneng Yang
arXiv: 2006.15672

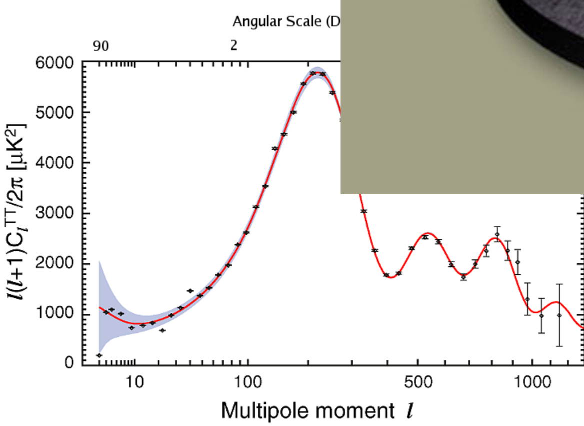
Concordant universe

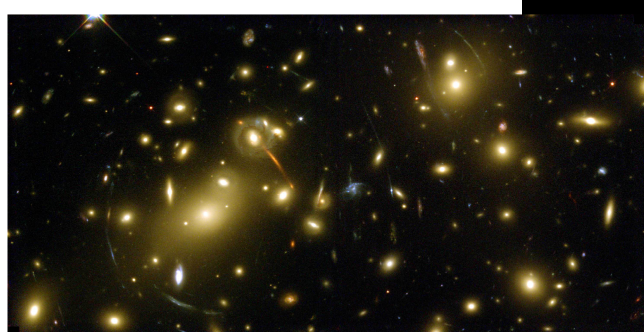




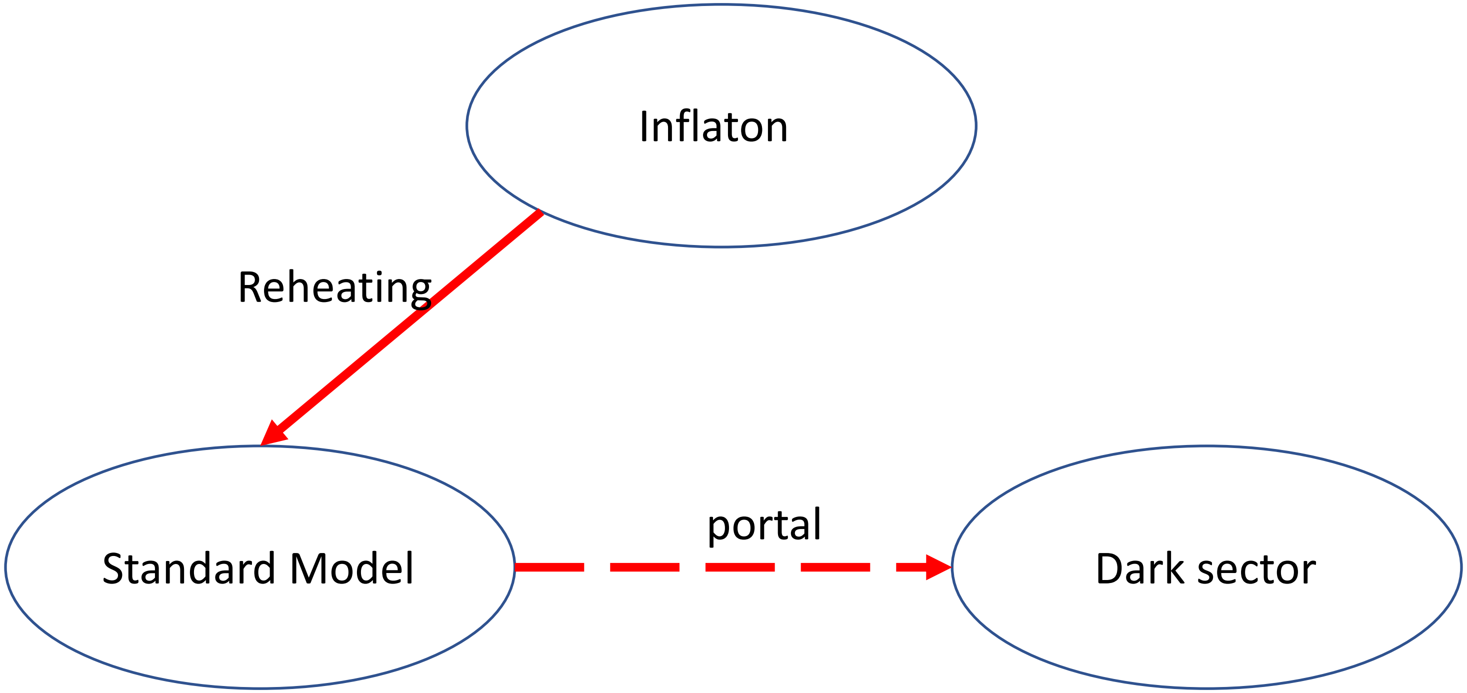






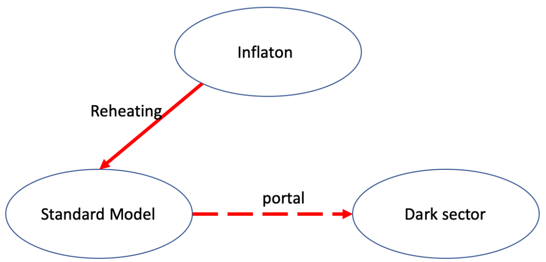


Freeze-in model



Hall, Jedamzik, March-Russell, West, 0911.1120

Estimation of production rate and relic abundance



Boltzmann equations:

$$\frac{dn_D}{dt} + 3Hn_D = \Gamma \; n_{\rm SM}$$

$$\frac{1}{T}\frac{dT}{dt} \approx -H$$

convertion rate

Number density of certain SM particles

$$\frac{d}{dt}\left(\frac{n_D}{T^3}\right) = \frac{n_{\rm SM}\Gamma}{T^3} \sim \Gamma$$

Where to start with?

- The relic abundance is the only number we know about dark matter

$$5 \approx \frac{\Omega_D}{\Omega_B} = \frac{n_D m_D}{n_B m_B} = \frac{n_D m_D}{\eta_\gamma n_\gamma m_B} \sim \left(\frac{m_D}{\eta_\gamma m_B}\right)\left(\frac{n_D}{T^3}\right)$$

$$\left.\frac{n_D}{T^3}\right|_{t_0} \sim \int_{t_{\mathrm{initial}}}^{t_0} \Gamma(t) dt \sim \int_{T_0}^{T_{\mathrm{initial}}} \Gamma(T) \frac{dT}{HT}$$

IR freeze-in

$$\frac{n_D}{T^3}\Big|_{t_0} \sim \int_{t_{\text{initial}}}^{t_0} \Gamma(t)dt \sim \int_{T_0}^{T_{\text{initial}}} \Gamma(T)\frac{dT}{HT}$$

$$[\Gamma] = 1 \qquad\qquad H \sim \frac{T^2}{m_{\text{pl}}}$$

Assuming marginal interactions: $\Gamma(T) \sim \alpha^n T$

$$\frac{n_D}{T^3}\Big|_{t_0} \sim \alpha^n \int_{T_0} \frac{m_{\text{pl}}dT}{T^2}$$

IR divergence

Whichever regularizes the IR determines the size of freeze-in.

IR freeze-in

$$\left.\frac{n_D}{T^3}\right|_{t_0} \sim \alpha^n \int_{T_0} \frac{dT}{T^2}$$

Possible cut-offs: $\left\{ \begin{array}{l} m_D \\ m_e \\ m_V \end{array} \right.$

In the case $m_D \gg m_V, m_e$

$$\left.\frac{n_D}{T^3}\right|_{t_0} \sim \alpha^n \int_{T_0} \frac{m_{\rm pl} dT}{T^2} \sim \frac{\alpha^n m_{\rm pl}}{m_D}$$

$$5 \approx \frac{\Omega_D}{\Omega_B} = \frac{n_D m_D}{n_B m_B} = \frac{n_D m_D}{\eta_\gamma n_\gamma m_B} \sim \left(\frac{m_D}{\eta_\gamma m_B}\right)\left(\frac{n_D}{T^3}\right)$$

$$\alpha^n \sim \frac{\eta_\gamma m_B}{m_{\rm pl}} \sim 10^{-28}$$

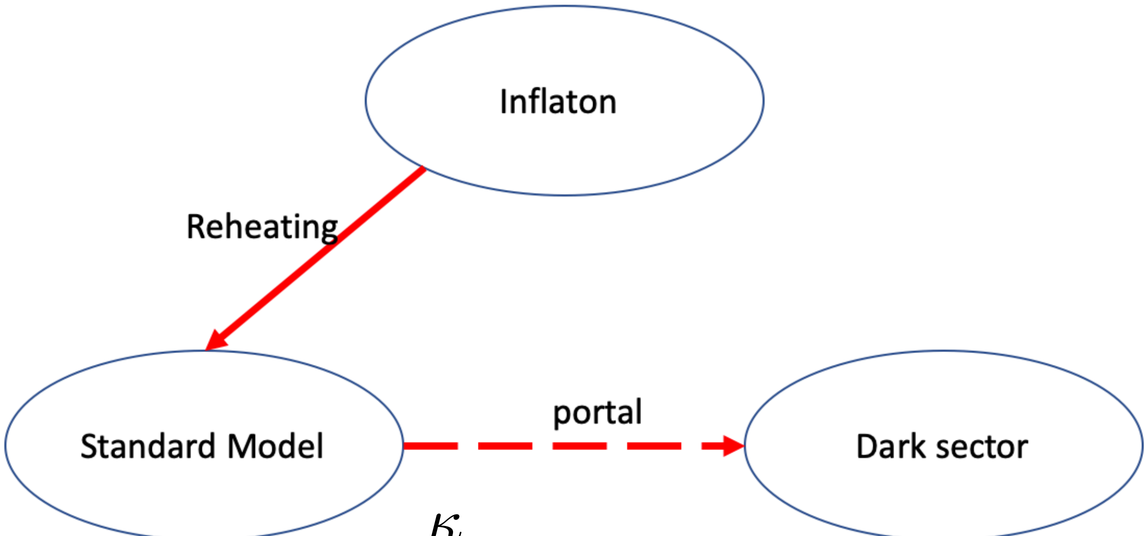
Motivation

- Can we test this kind of models with direct detection experiment?

$$\alpha^n \sim \frac{\eta_\gamma m_B}{m_{\rm pl}} \sim 10^{-28}$$

- The direct detetion cross section is also proportional to this number.

Vector portal models as examples



$$-\frac{\kappa}{2}F_{\mu\nu}V^{\mu\nu}$$

$$e_D V_\mu J_D^\mu$$

Production rate

Focus on the regime $2m_e < m_V < 2m_D$

V decays back to the SM sector, or the rate of dark matter production can go through on-shell V, and κ will become even smaller.

In this specific regime: $\kappa e_D \sim 10^{-11} - 10^{-12}$

Rate for direct detection

$$2m_e < m_V < 2m_D$$

$$\sigma \sim \frac{4\sqrt{2}\kappa^2 e_D^2 \alpha_{\rm em} \mu^2}{m_V^4}$$

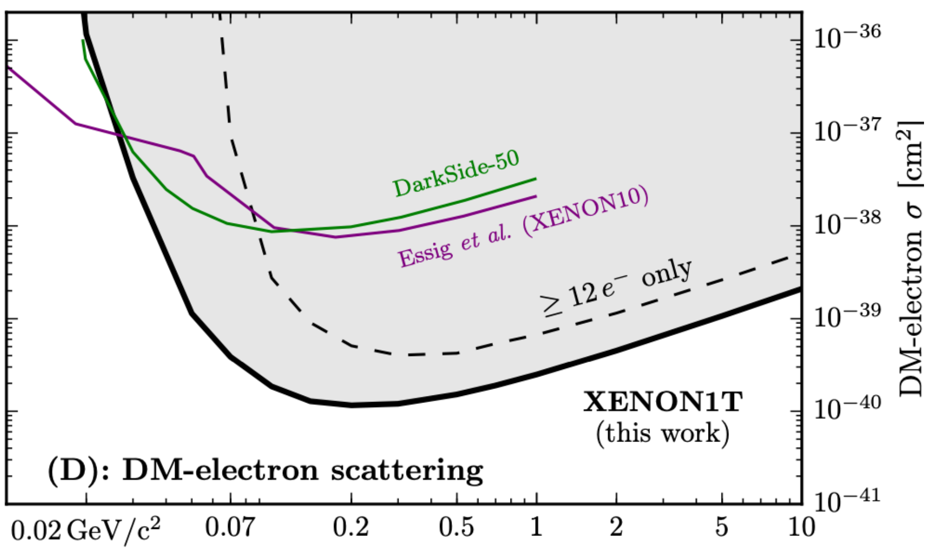
$$N_{\rm obs} \sim \sigma \langle v \rangle n_D \times N_e^{\rm tot} \times T_{\rm live} \sim 10$$

$$T_{\rm live} = 1 \text{ year}, N_e^{\rm tot} = 1 \text{ tot}/m_p,\ m_D = 1 \text{ MeV}$$

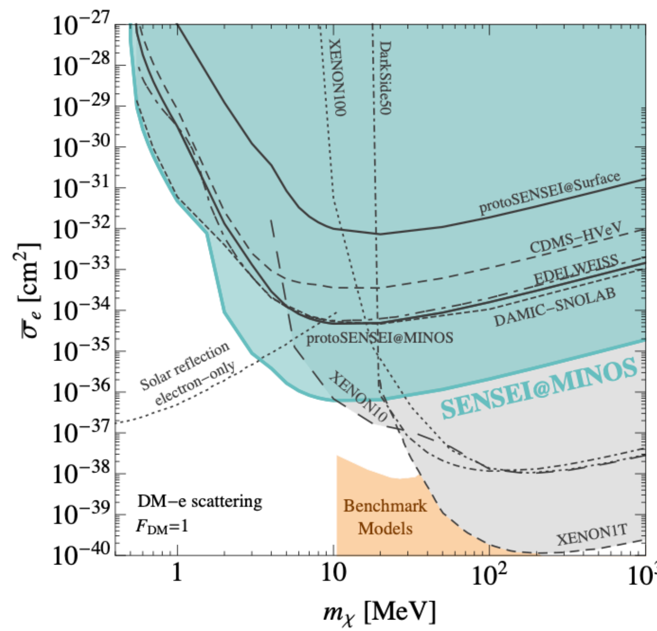
This is the best we can have, incease mD will only make signal smaller.

Direct detection

- The rate is ok. $N_{\rm obs} \sim \sigma \langle v \rangle n_D \times N_e^{\rm tot} \times T_{\rm live} \sim 10$
- What about the recoild energy?



XENON1T:1907.11485



SENSEI: 2004.11378

Direct detection

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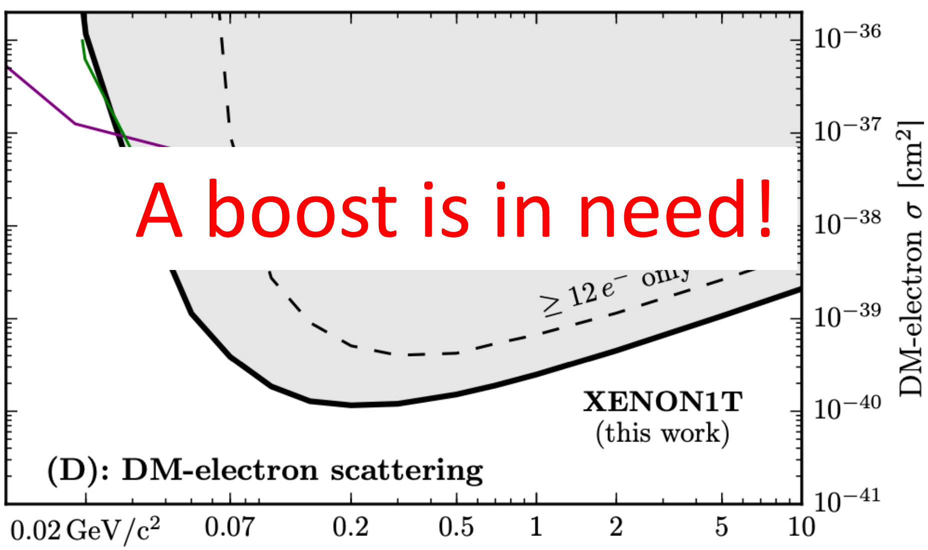
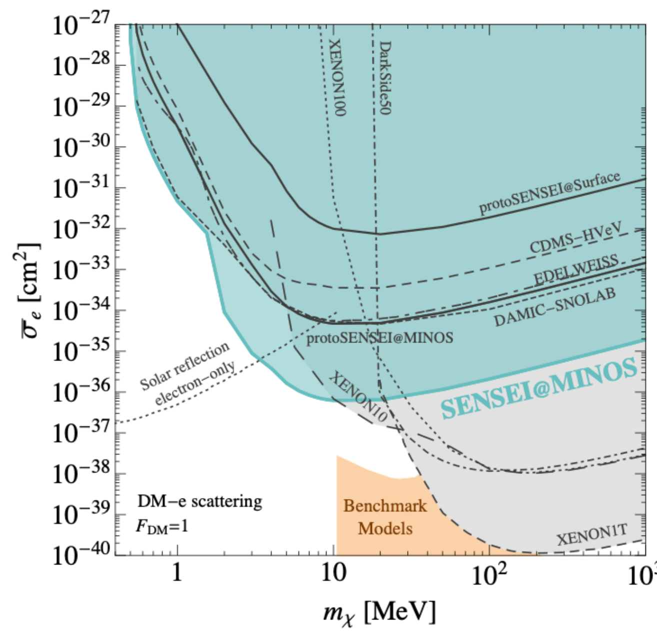


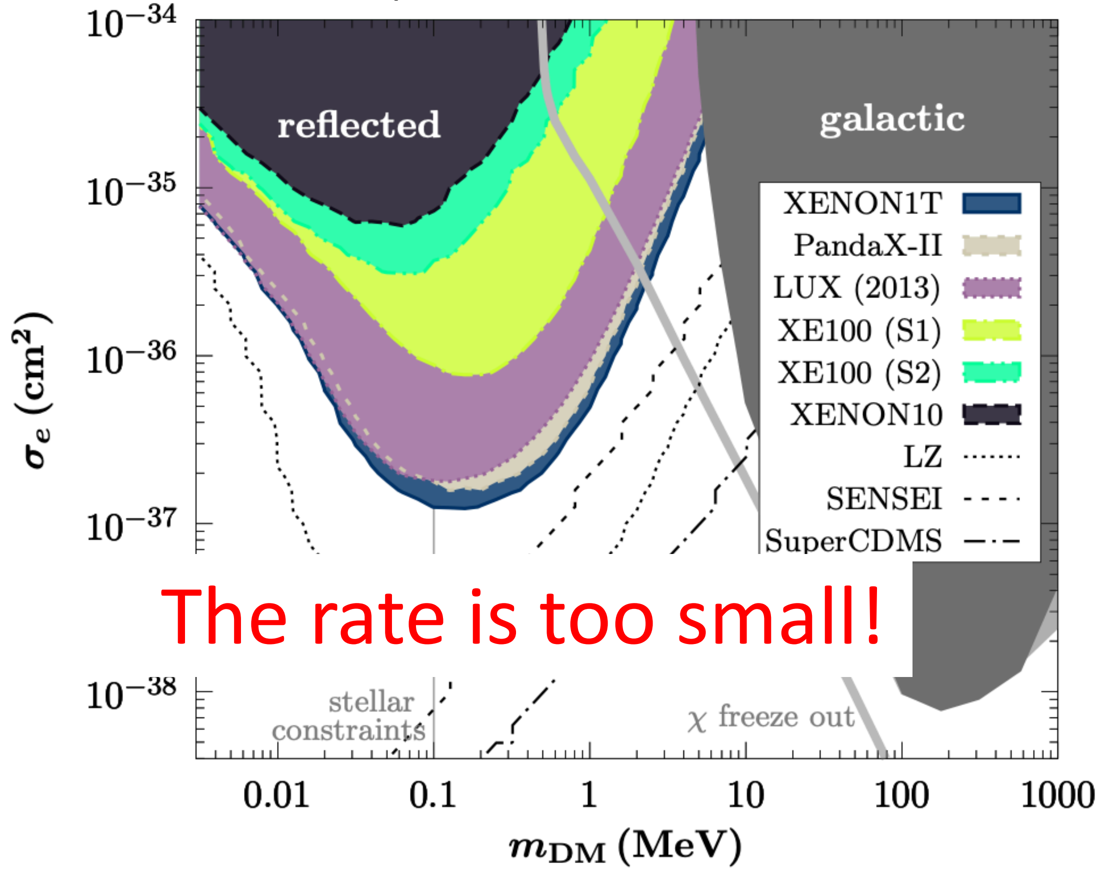


XENON1T:1907.11485

SENSEI: 2004.11378

Can the Sun help us this time?

HA, Pospelov, Pradler, Ritz, 1708.03642



The rate is too small!

Boost with down-scattering

- Introduce the a small splitting of DM $\chi \to \chi_1, \chi_2$

- In scalar model:

$$\begin{aligned}\mathcal{L}^{sc} &= \frac{1}{2}\partial_\mu\chi_1\partial^\mu\chi_1 + \frac{1}{2}\partial_\mu\chi_2\partial^\mu\chi_2 - \frac{1}{2}m_1^2\chi_1^2 - \frac{1}{2}m_2^2\chi_2^2 \\ &\quad -e_D V^\mu(\chi_1\partial_\mu\chi_2 - \chi_2\partial_\mu\chi_1) + \frac{1}{2}e_D^2 V_\mu V^\mu(\chi_1^2 + \chi_2^2)\end{aligned}$$

- In spinor model:

$$\begin{aligned}\mathcal{L}^{sp} &= \chi_1^\dagger i\sigma^\mu\partial_\mu\chi_1 + \chi_2^\dagger i\sigma^\mu\partial_\mu\chi_2 - \frac{1}{2}(m_1\chi_1\chi_1 + m_2\chi_2\chi_2 \\ &\quad +h.c.) + e_D V^\mu(\chi_1^\dagger\sigma_\mu\chi_2 - \chi_2^\dagger\sigma_\mu\chi_1)\ .\end{aligned}$$

Determine $f_2 = n_{\chi 2}/n_D$

- It must be cosmologically stable.

$$2m_e > \Delta m \equiv (m_{\chi_2} - m_{\chi_1})$$

- The self-annihilation process must be small enough.

$\chi_2\chi_2 \to \chi_1\chi_1$ e_D must be small.

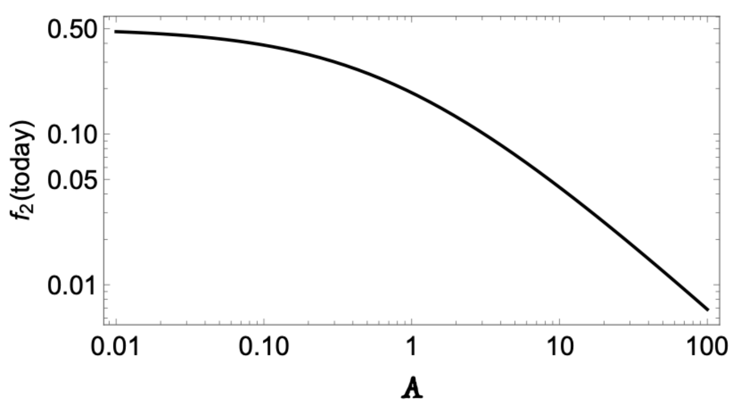
Determine $f_2 = n_{\chi 2}/n_D$

- Solving the Boltzmann equation

$$\frac{df_2}{dx} = -\mathcal{A}x^{-1}K_1(x)\left[f_2^2(x)e^{x} - (1-f_2)^2 e^{-x}\right]$$

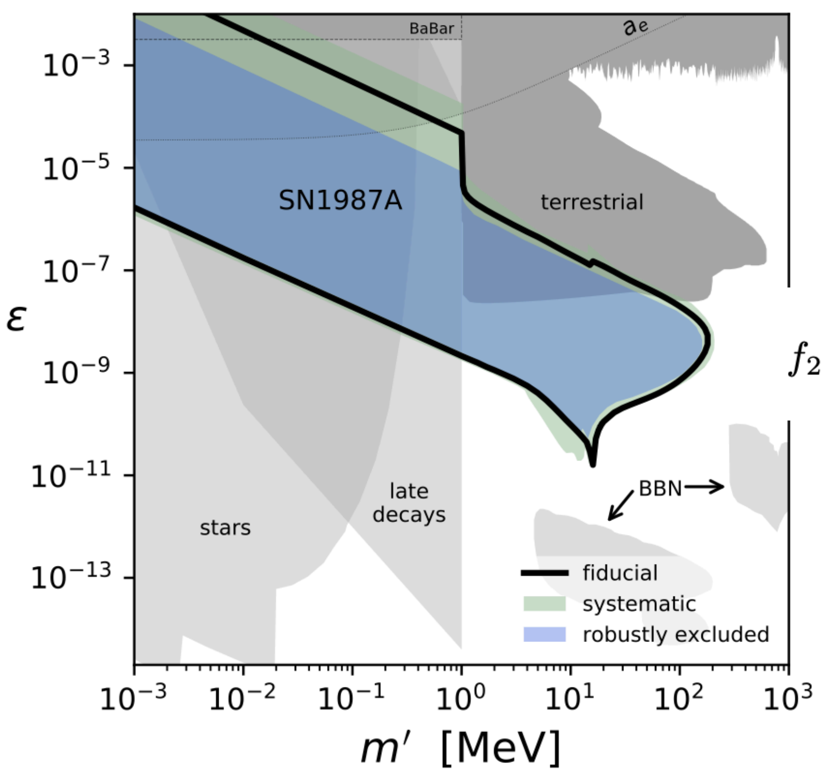
$$T_D = \eta T^2/m_D$$

$$\mathcal{A} = \left(\frac{9\sqrt{5}}{16\pi^4}\frac{m_{\rm pl}^3 H_0^2 \Omega_D}{g_\star^{1/2} T_{\rm CMB}^3}\right)\left(\frac{e_D^4 m_D \Delta}{m_V^4 \eta^{1/2}}\right)$$
$$\approx \frac{0.37}{\eta^{1/2}}\left(\frac{e_D}{10^{-3}}\right)^4\left(\frac{m_V}{1.5\text{MeV}}\right)^{-4}\frac{m_D}{0.9\text{MeV}}\frac{\Delta}{4\text{keV}}$$



Stellar constraint

- But $\kappa \cdot e_D$ is fixed. Small e_D means a relatively large κ. The stellar constraint becomes important.



Chang, Essig, McDermott, 1611.03864

$$\kappa < 2.5 \times 10^{-9} (1\ \mathrm{MeV}/m_V)^2$$

$$f_2 \lesssim 2.8 \times 10^{-3} \left(\frac{m_V}{1.1\mathrm{MeV}}\right)^4 \left(\frac{m_D}{0.6\mathrm{MeV}}\right)^{-1} \left(\frac{\Delta}{0.5\mathrm{keV}}\right)^{-1}$$

The XENON anomaly

- Excess about 50 events/ton/year at 2-3 keVee.

- We'd better be able to fit it.

$$\frac{d\langle\sigma_{\rm ion}^{nl}v\rangle}{d\ln E_r} = \frac{\kappa^2 e_D^2 \alpha_{\rm em}}{2m_V^4}\int q dq \left\langle \frac{1}{v}\theta(v-v_{\rm min})\right\rangle \times \frac{k^3}{(2\pi)^3}\int d\Omega_k \left|\int d^3x e^{-i\vec{k}\cdot\vec{x}-i\vec{q}\cdot\vec{x}}\psi_{nlm}\right|$$

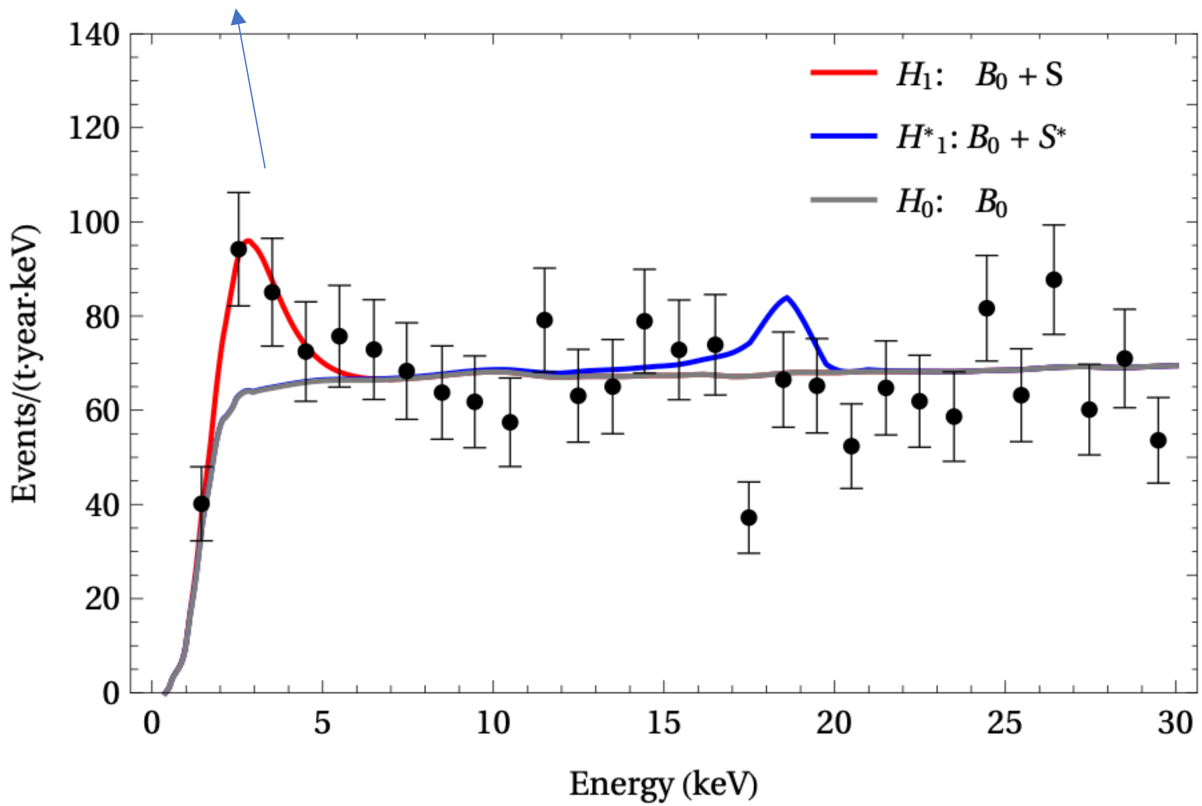
$$e^{i\vec{k}\cdot\vec{x}} \to e^{i\vec{k}\cdot\vec{x}} - \int d^3y e^{i\vec{k}\cdot\vec{y}}\psi^*_{nlm}(y)\psi_{nlm}(x)$$

$$v_{\rm min} = \left|\frac{E_k}{q} + \frac{q}{2m_D} + \frac{E_B - \Delta}{q}\right|$$

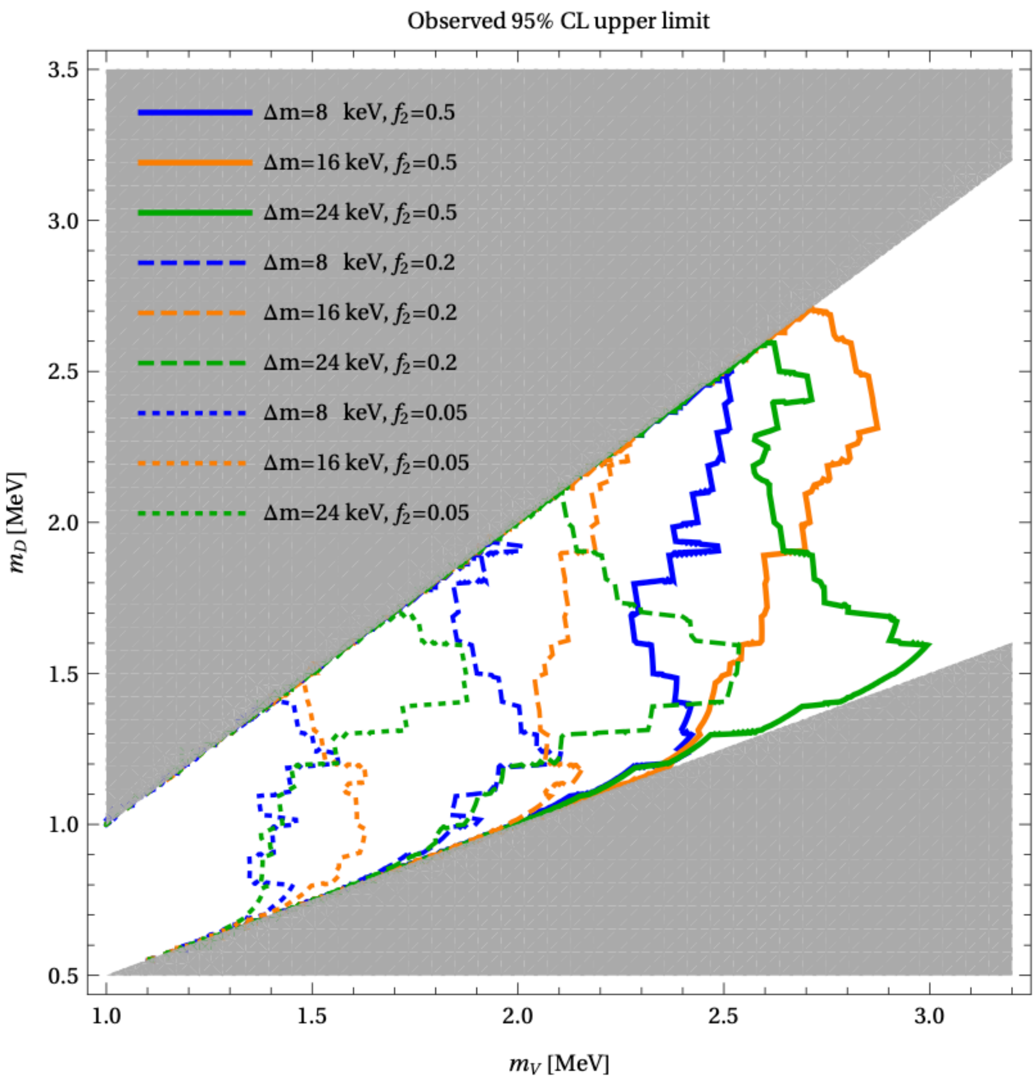
Fitting the XENON1T anomaly

$\Delta = 5\ \mathrm{keV}, m_D = 0.8\ \mathrm{MeV}$

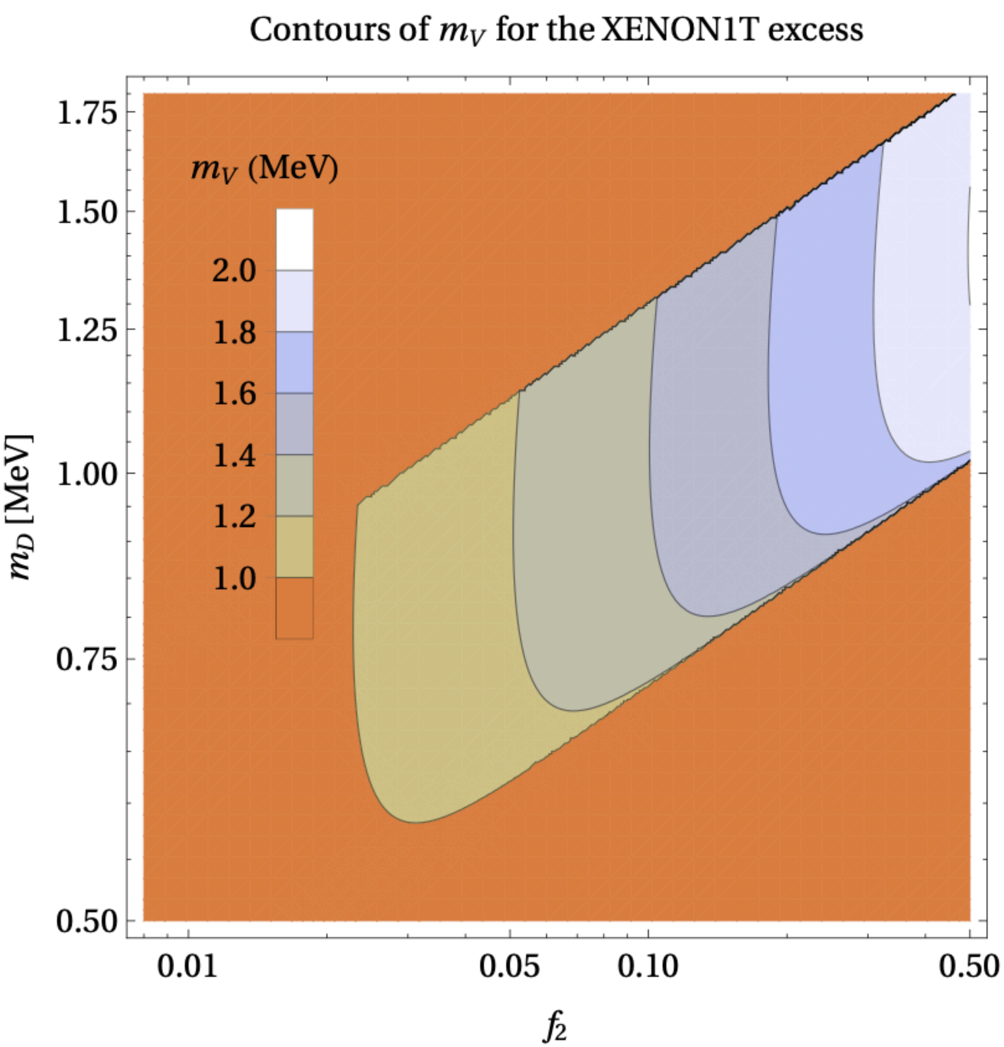
$\kappa e_D = 1.29 \times 10^{-11}, f_2 = 0.063$



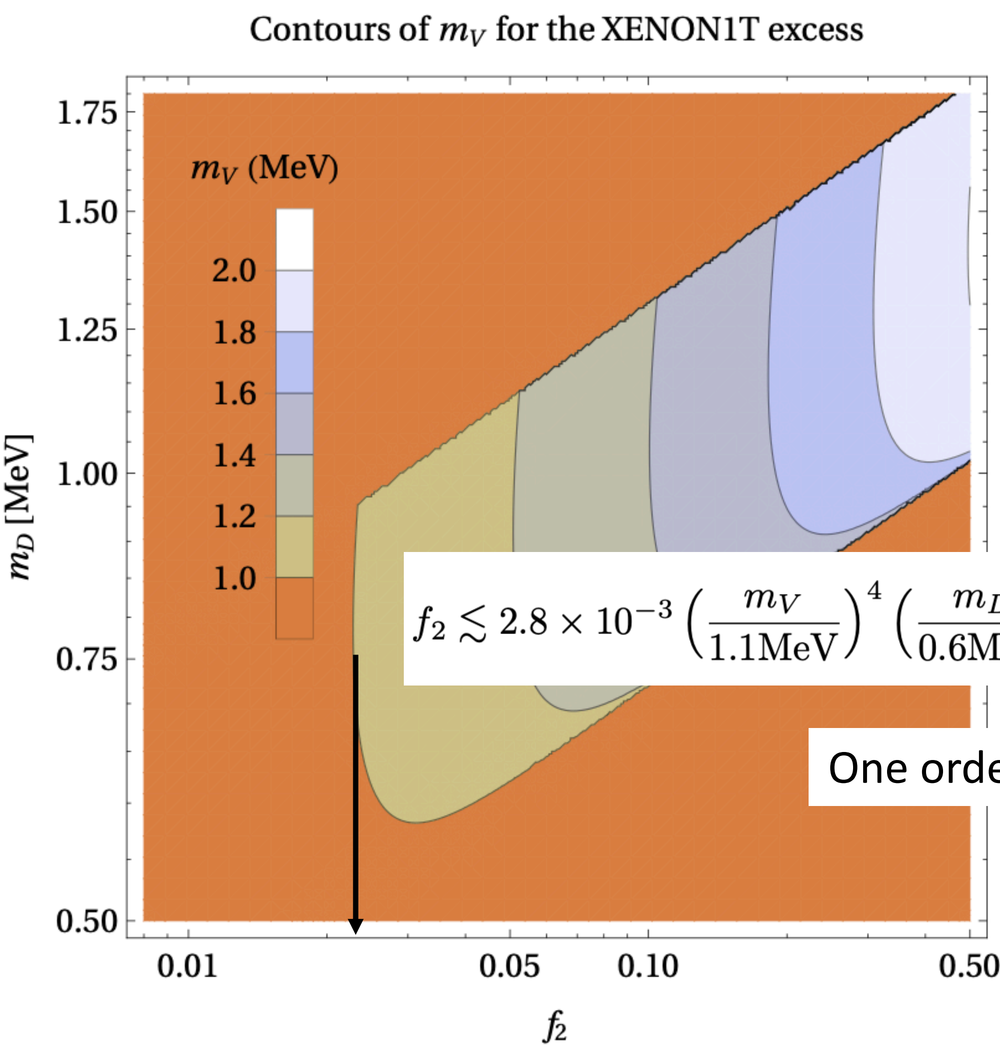
Constraint on parameter space



Fitting the XENON anomaly



Tension with the stellar constraint



$$f_2 \lesssim 2.8 \times 10^{-3} \left(\frac{m_V}{1.1\mathrm{MeV}}\right)^4 \left(\frac{m_D}{0.6\mathrm{MeV}}\right)^{-1} \left(\frac{\Delta}{0.5\mathrm{keV}}\right)^{-1} \quad (17)$$

One order of magnitude smaller

Re-examine the model (scalar case)

$$\mathcal{L}^{sc} = \frac{1}{2}\partial_\mu\chi_1\partial^\mu\chi_1 + \frac{1}{2}\partial_\mu\chi_2\partial^\mu\chi_2 - \frac{1}{2}m_1^2\chi_1^2 - \frac{1}{2}m_2^2\chi_2^2$$
$$-e_D V^\mu(\chi_1\partial_\mu\chi_2 - \chi_2\partial_\mu\chi_1) + \frac{1}{2}e_D^2 V_\mu V^\mu(\chi_1^2+\chi_2^2)$$

Additional term is always there!

Should be positive!

$$-\frac{\lambda}{2}(|\chi|^2)^2 \rightarrow -\lambda\chi_1^2\chi_2^2$$

$$|\mathcal{M}|^2_{\chi_2\chi_2\to\chi_1\chi_1} = \left|\frac{8e_D^2 m_D^2}{m_V^2} - \lambda\right|^2$$

Fitting the XENON1T anomaly needs about 60% of cancelation.

Re-examine the model (spinor case)

$$\mathcal{L}^{sc} = \frac{1}{2}\partial_\mu\chi_1\partial^\mu\chi_1 + \frac{1}{2}\partial_\mu\chi_2\partial^\mu\chi_2 - \frac{1}{2}m_1^2\chi_1^2 - \frac{1}{2}m_2^2\chi_2^2$$
$$-e_D V^\mu(\chi_1\partial_\mu\chi_2 - \chi_2\partial_\mu\chi_1) + \frac{1}{2}e_D^2 V_\mu V^\mu(\chi_1^2 + \chi_2^2)$$

Additional term is always there!

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$$|\mathcal{M}|^2_{\chi_2\chi_2\to\chi_1\chi_1} = \left|\frac{8e_D^2 m_D^2}{m_V^2} - \lambda\right|^2$$

Fitting the XENON1T anomaly needs about 60% of cancelation.

Future work

$$\mathcal{L}^{sp} = \chi_1^\dagger i\sigma^\mu \partial_\mu \chi_1 + \chi_2^\dagger i\sigma^\mu \partial_\mu \chi_2 - \frac{1}{2}(m_1 \chi_1 \chi_1 + m_2 \chi_2 \chi_2$$
$$+h.c.) + e_D V^\mu (\chi_1^\dagger \sigma_\mu \chi_2 - \chi_2^\dagger \sigma_\mu \chi_1) \ .$$

- We need to introduce new particles in the dark sector to have the cancelation effect.

Summary and outlook

- Direct detection experiments start to be sensitive to inelastic scenarios of freeze-in models.
- We can even find parameter space to fit the XENON1T anomaly.

- To have the cancelation in the scalar model $\lambda \sim e_D^2$

  Isn't this a hint for SUSY?