iDM@IDM: The ups and downs of inelastic Dark Matter

Electron recoils from terrestrial upscattering

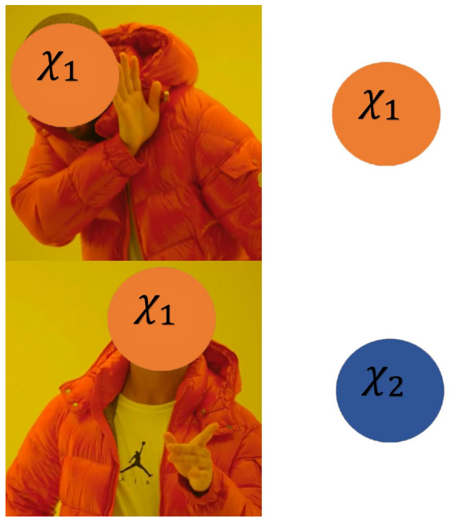
2112.06930 – Timon Emken, JF, Saniya Heeba, Felix Kahlhoefer

Jonas Frerick (jonas.frerick@desy.de)
19.07.22, Vienna

HELMHOLTZ

DESY.

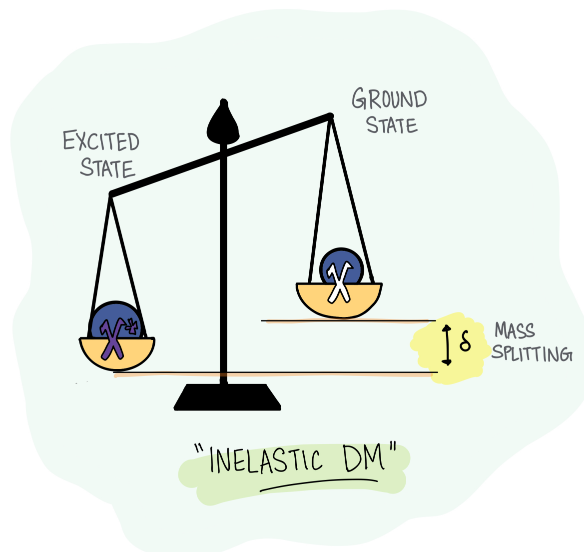
What is inelastic DM?



Off-diagonal interactions

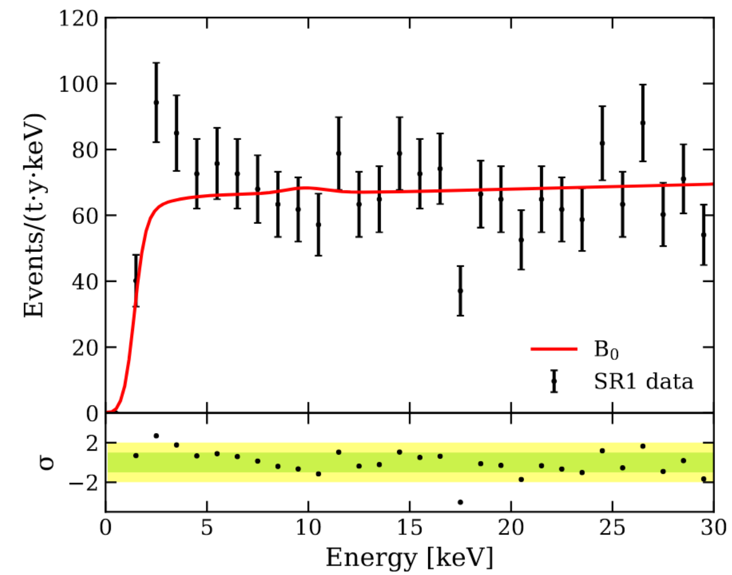
+

Doodles by @saniaheba



(Small) mass splitting δ

(?) =



How (not) to explain the XENON1T excess

Essig et al. showed that standard (elastic) DM-electron scattering fails to reproduce the XENON1T excess [2006.14521]

Why is that?

$$\frac{\mathrm{d}R_{\mathrm{ion}}}{\mathrm{d}E_{\mathrm{er}}} = \frac{\rho}{m_\chi} \frac{\sigma_e}{8E_{\mathrm{er}}\mu_e^2} \boxed{\sum_{n,l} \int_{q_{\min}}^{q_{\max}} q\mathrm{d}q \, |f_{n,l\to E_r}(q)|^2} \boxed{\int_{v>v_{\min}} \mathrm{d}^3 v \frac{f^*(\mathbf{v})}{v}}$$

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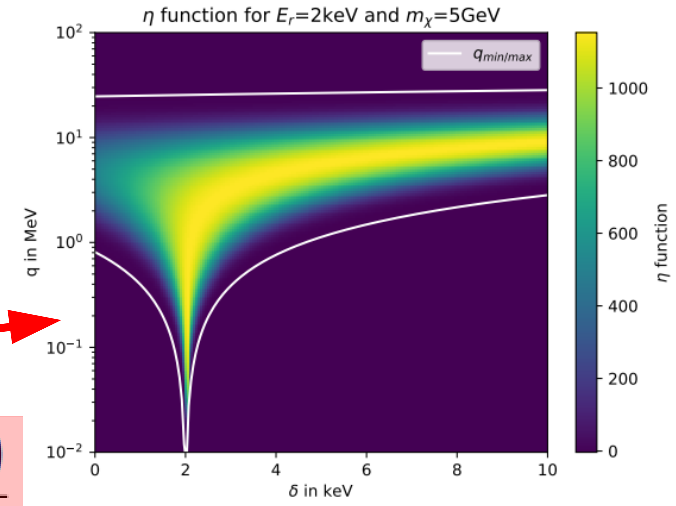

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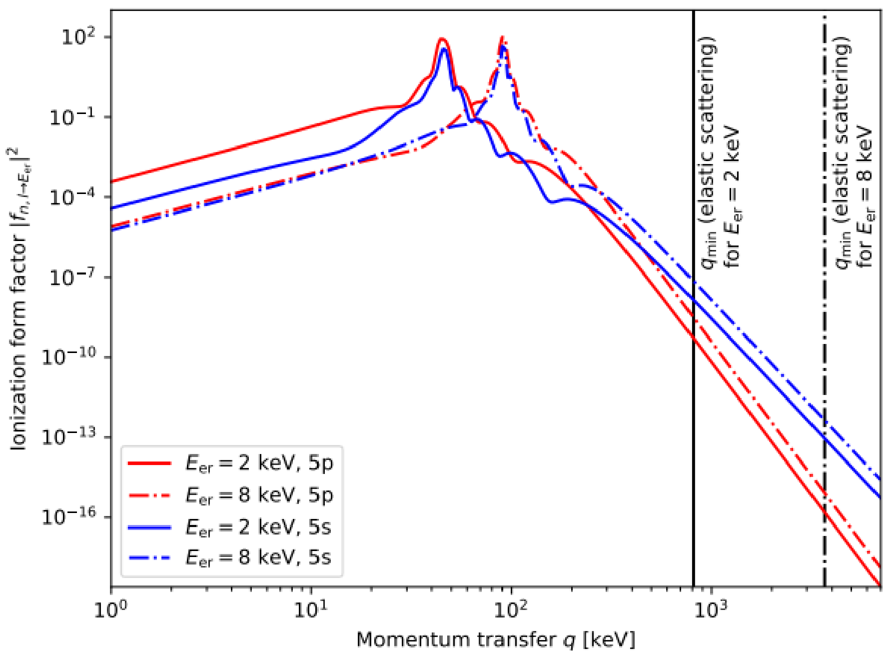

DarkARC [1912.08204]

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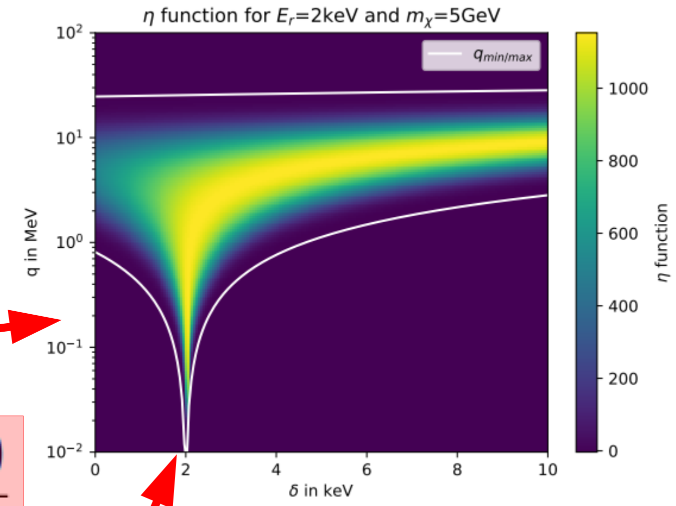

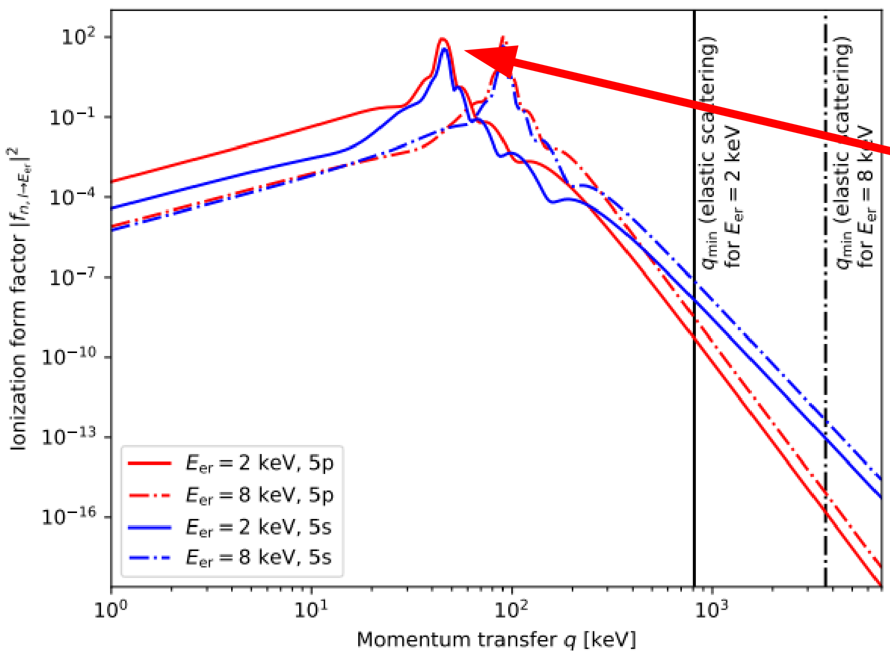

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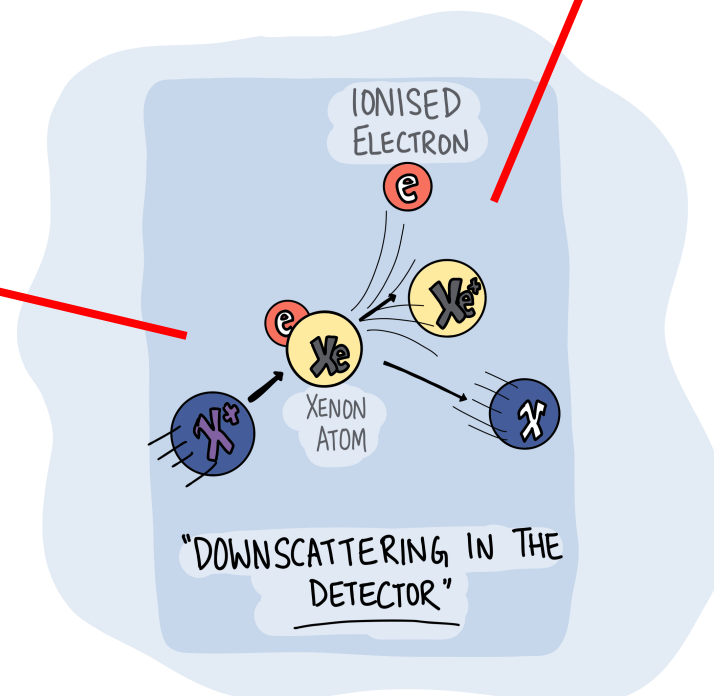
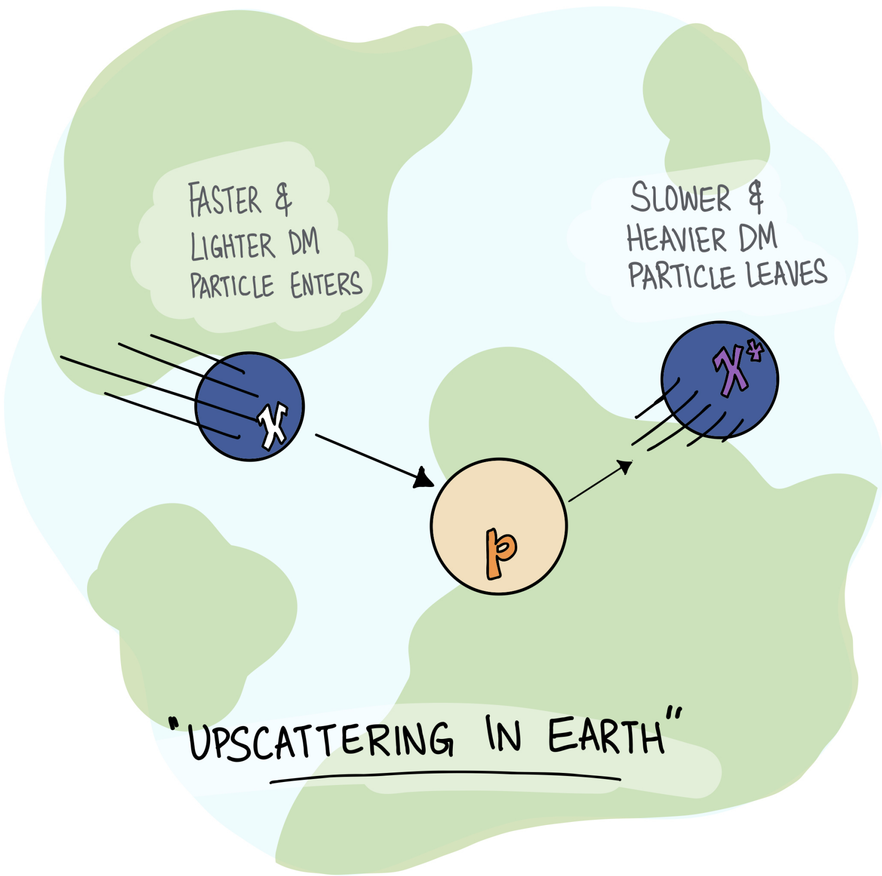


Production mechanism: Terrestrial upscattering



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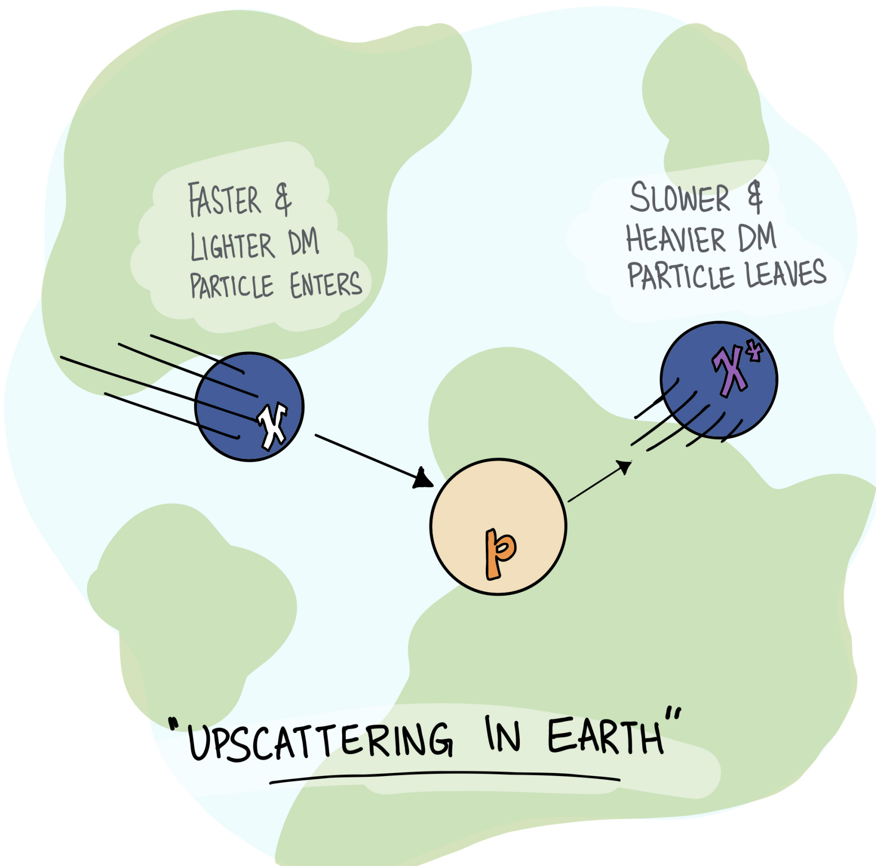
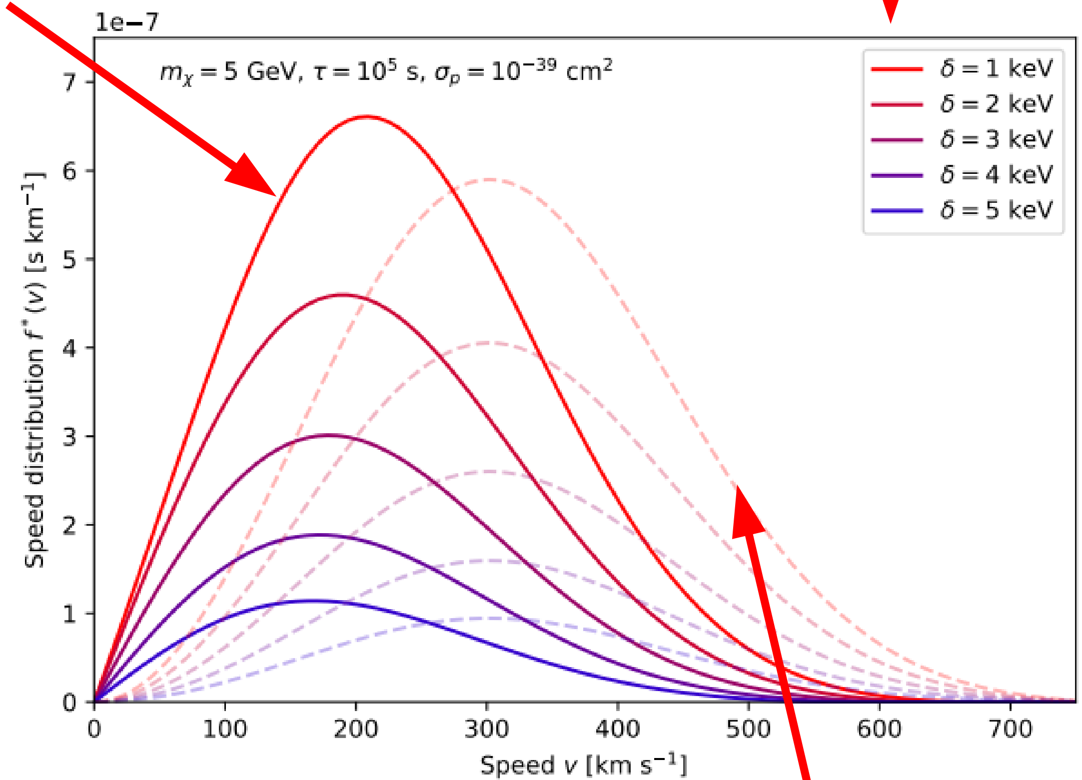


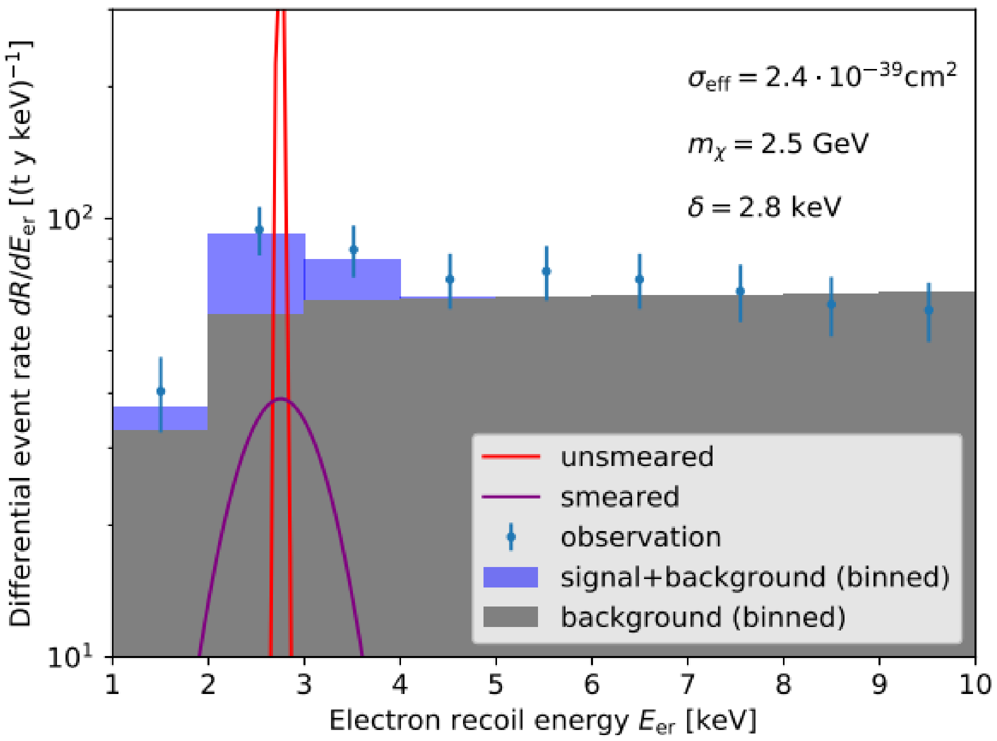
Varying the mass splitting

Excited speed distributions



Original speed distributions (rescaled)

Fitting XENON1T with exothermic DM



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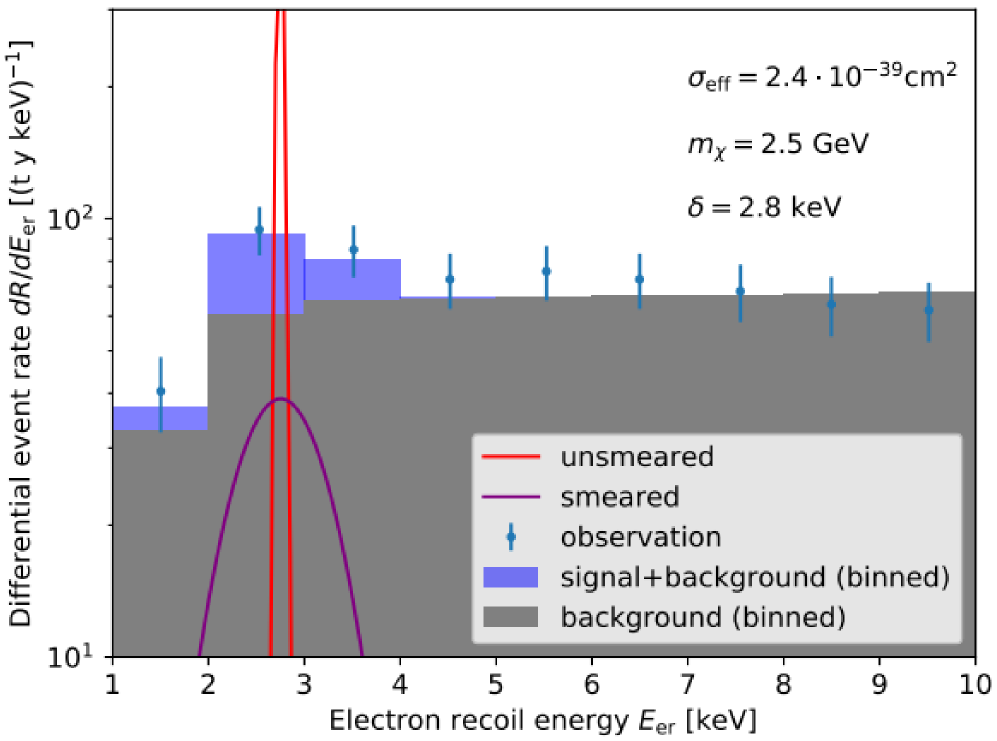

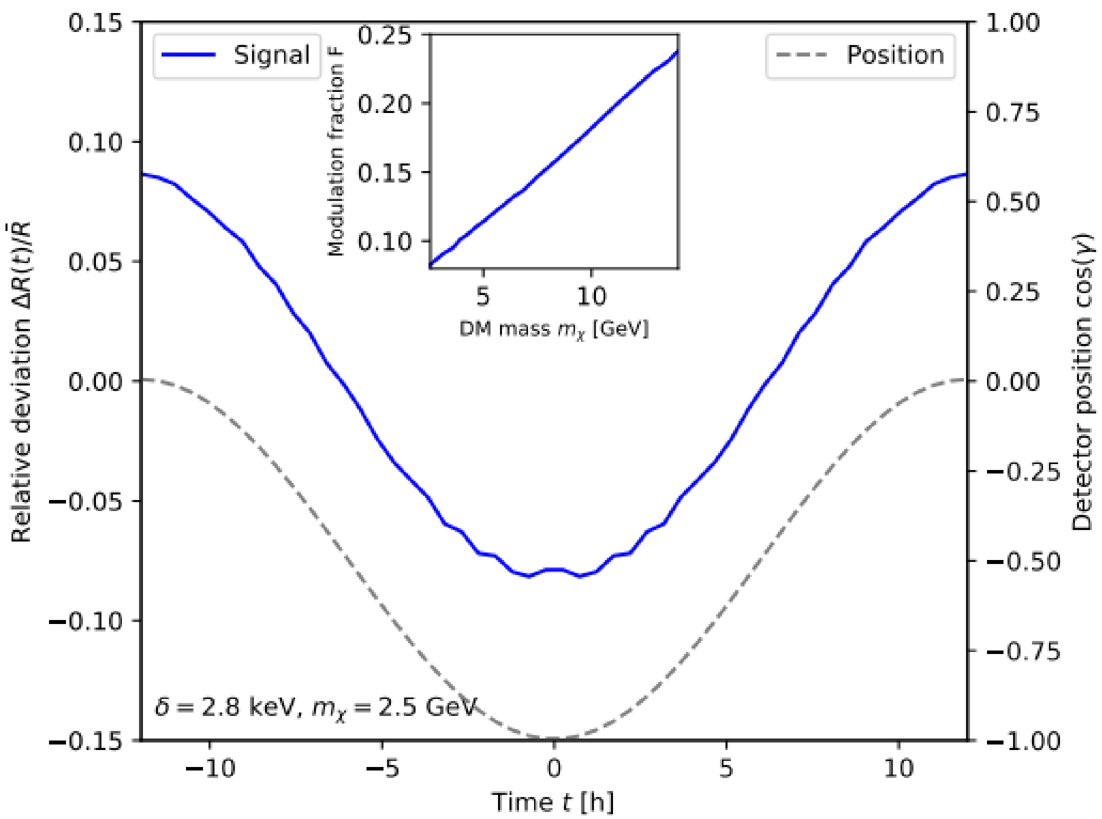

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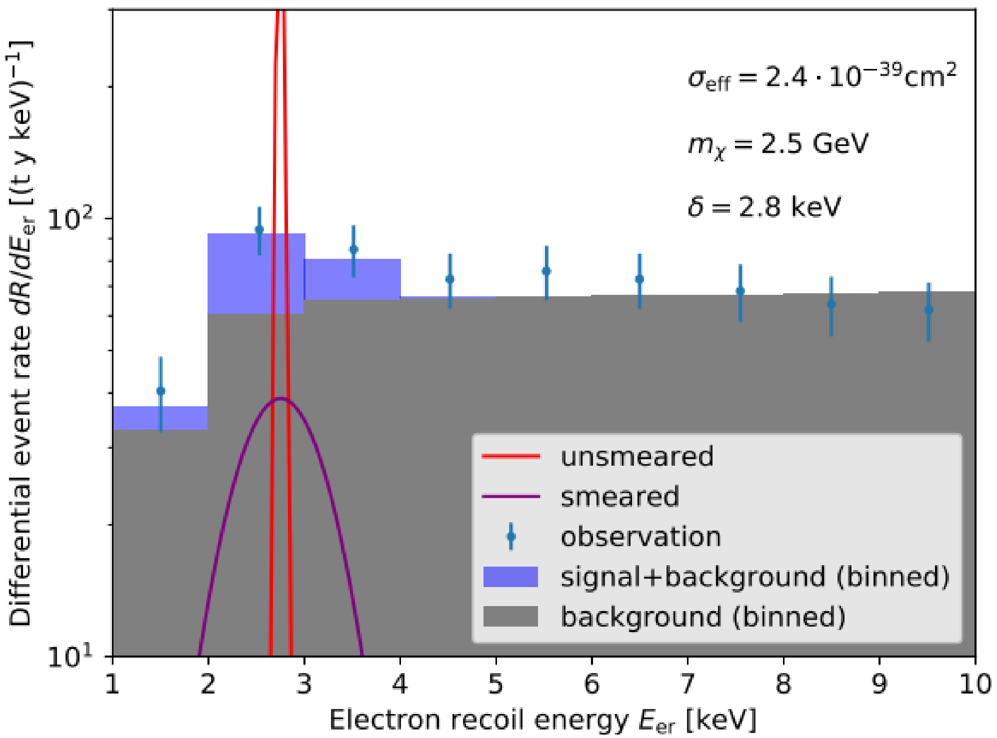
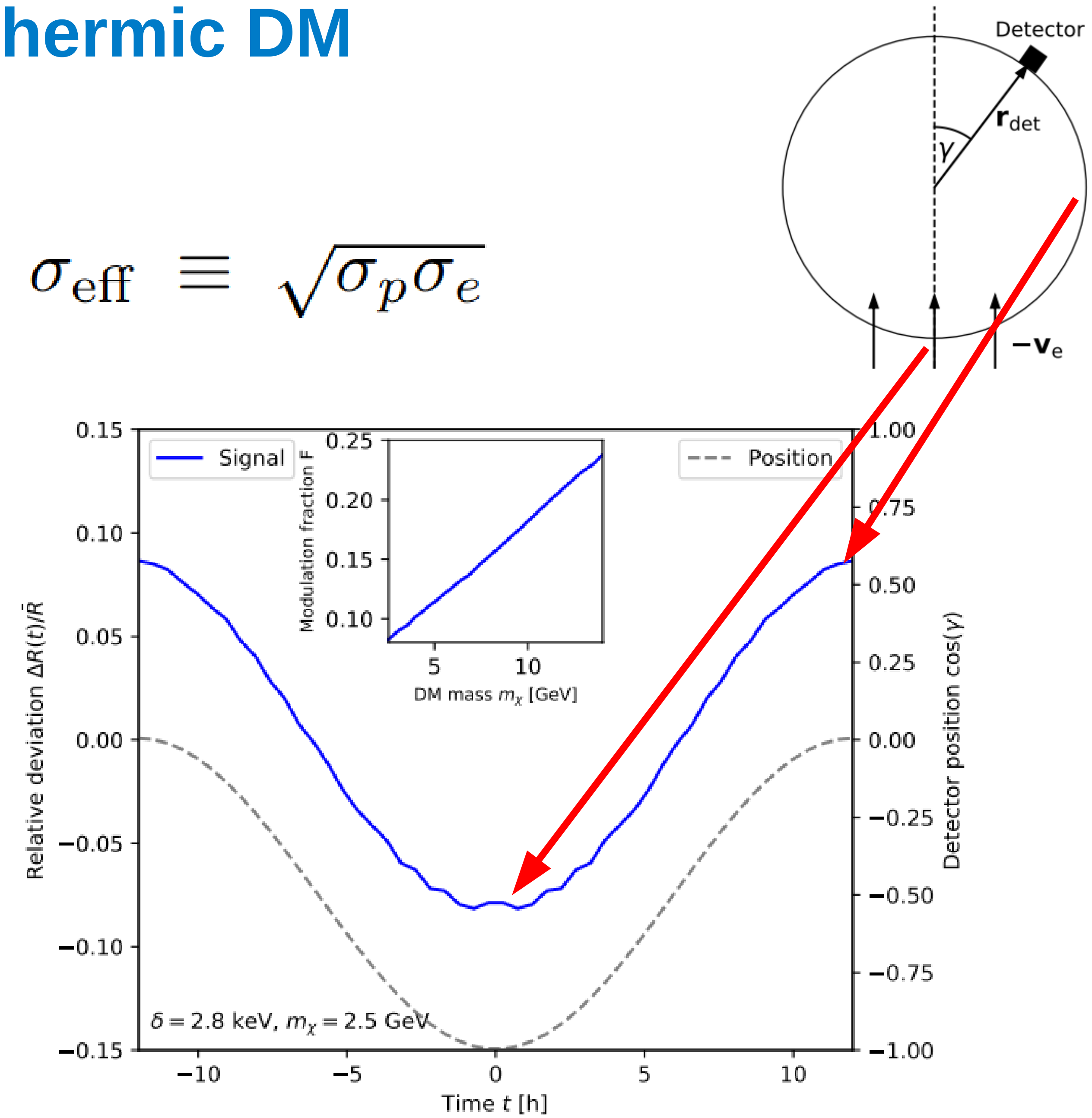
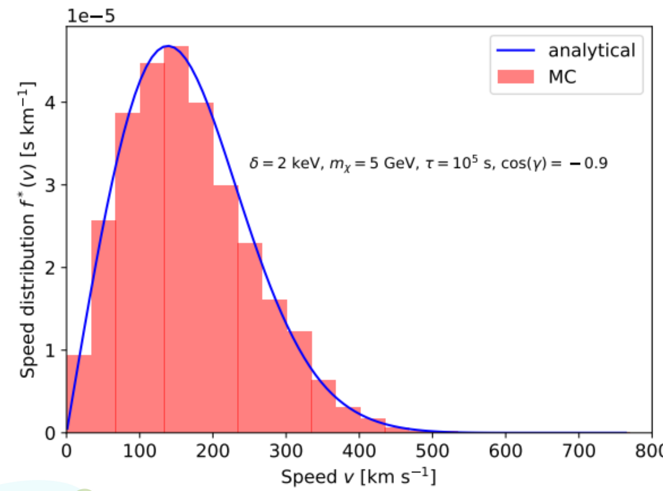
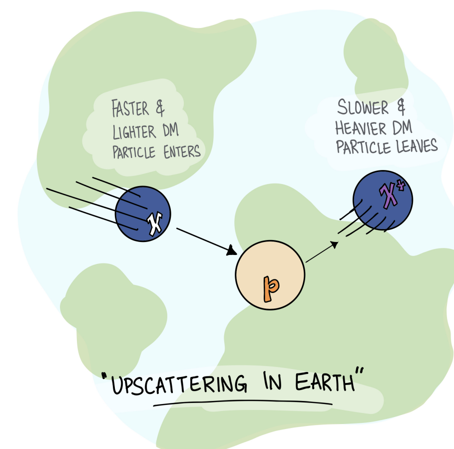


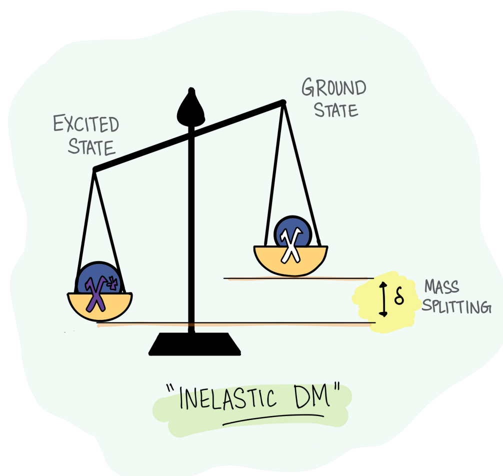


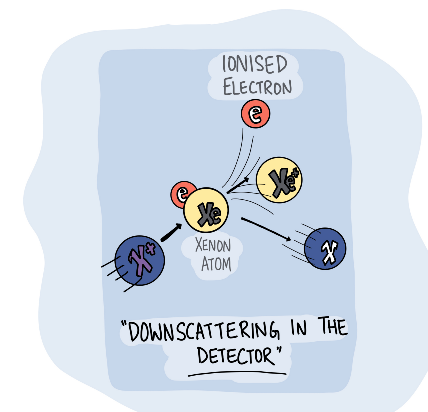
Conclusions



- Calculate density and speed distribution of excited state (MC confirmed)
- Formalism fits XENON1T in allowed parameter region
- Interesting modulation signature







Thank you!

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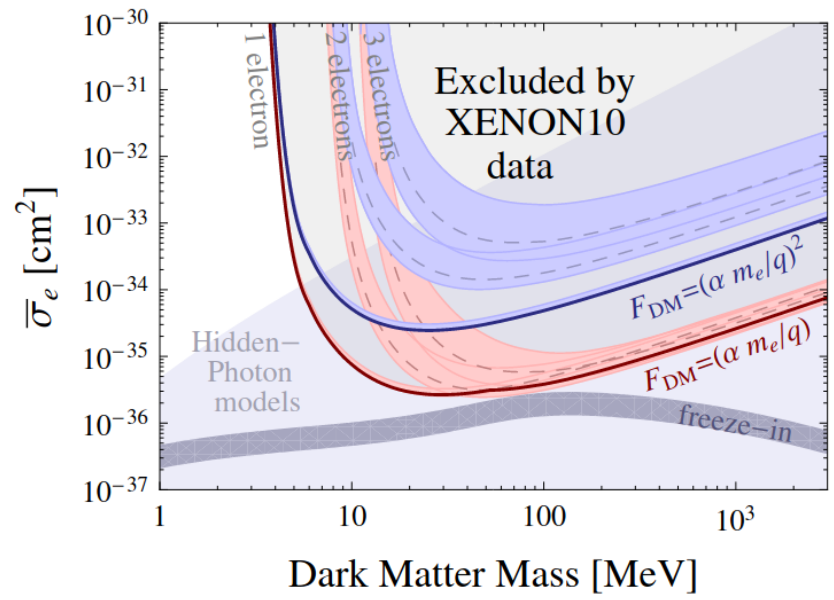
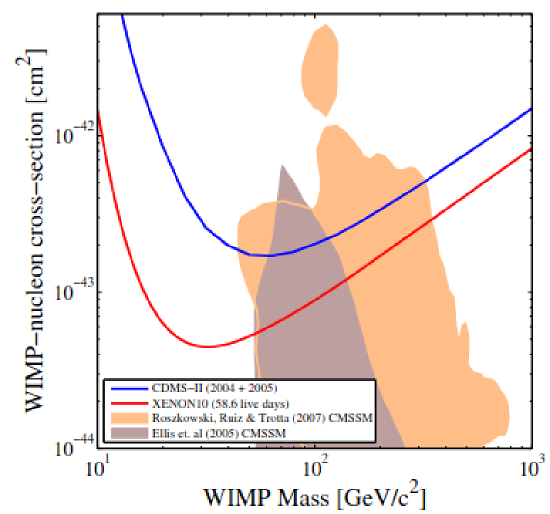
Electron scattering in nuclear recoil searches

- Essig et al. realized that classical searches for nuclear recoils can also be sensitive to DM-electron scattering [1108.5383,1206.2644,1509.01598]
- Advantage: Sensitivity to much lighter DM candidates (sub-GeV)
- Disadvantage: Requires input from atomic physics to account for the bound electrons

$$|f_{n,l\to E_{\mathrm{er}}}(q)|^2 = \frac{4k'^3}{(2\pi)^3}\sum_{l'=0}^{\infty}\sum_{m=-l}^{l}\sum_{m'=-l'}^{l'}|f_{1\to 2}(q)|^2$$

$$f_{1\to 2}(\mathbf{q}) = \int \mathrm{d}^3x\, \psi^*_{k'\ell'm'}(\mathbf{x})e^{i\mathbf{x}\cdot\mathbf{q}}\psi_{n\ell m}(\mathbf{x})$$





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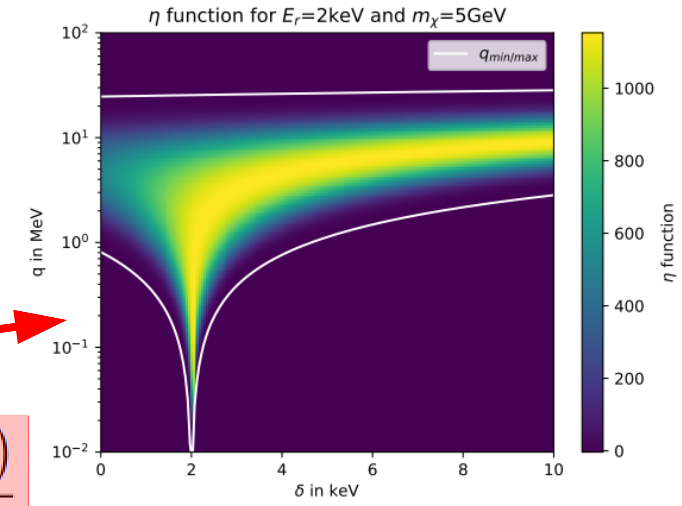

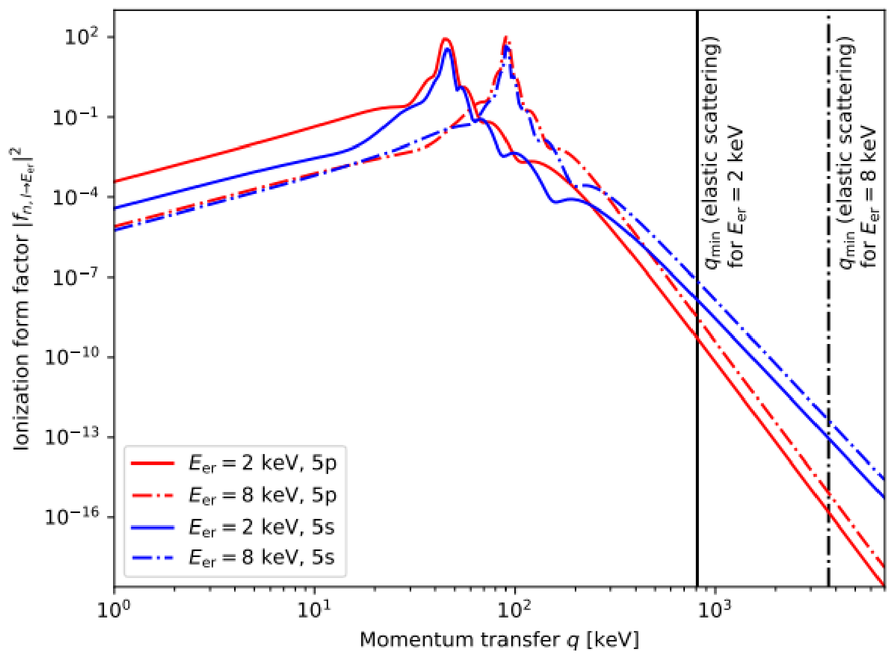

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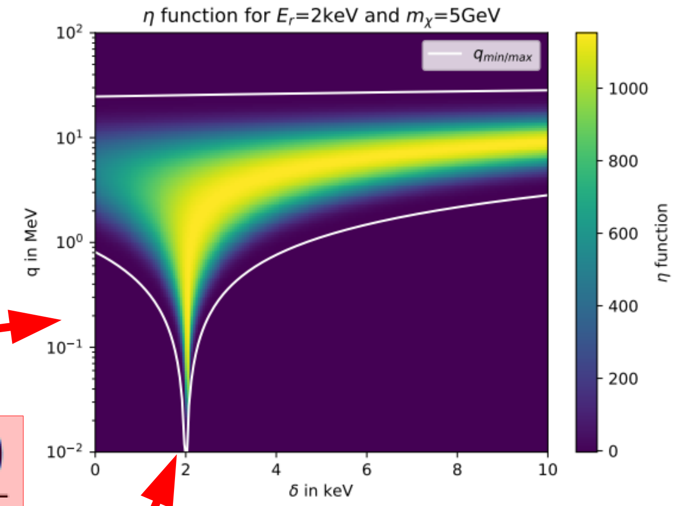

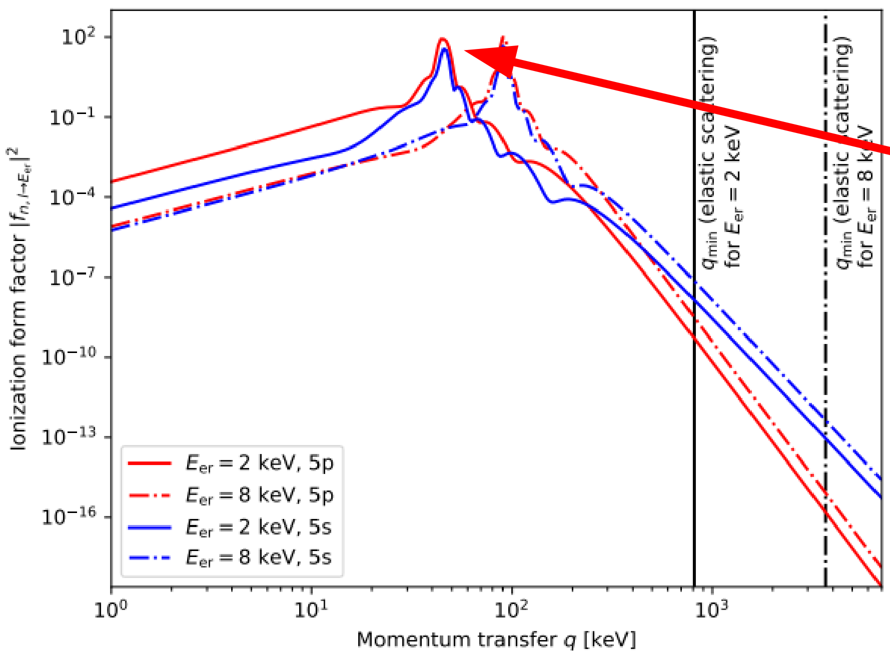

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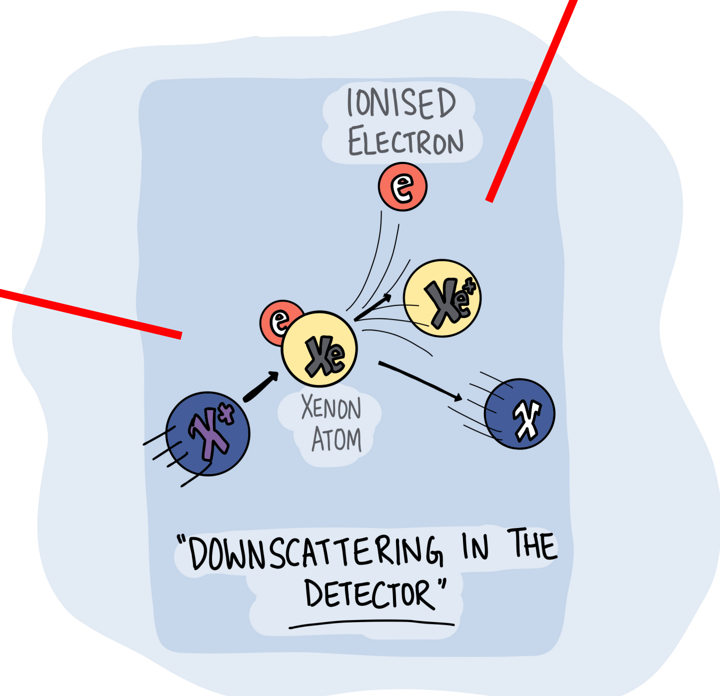
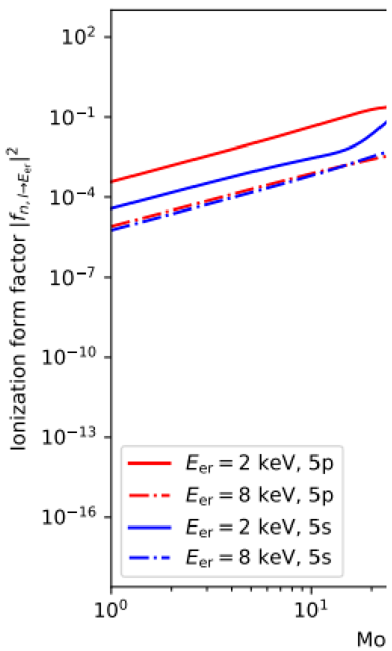


How (not)

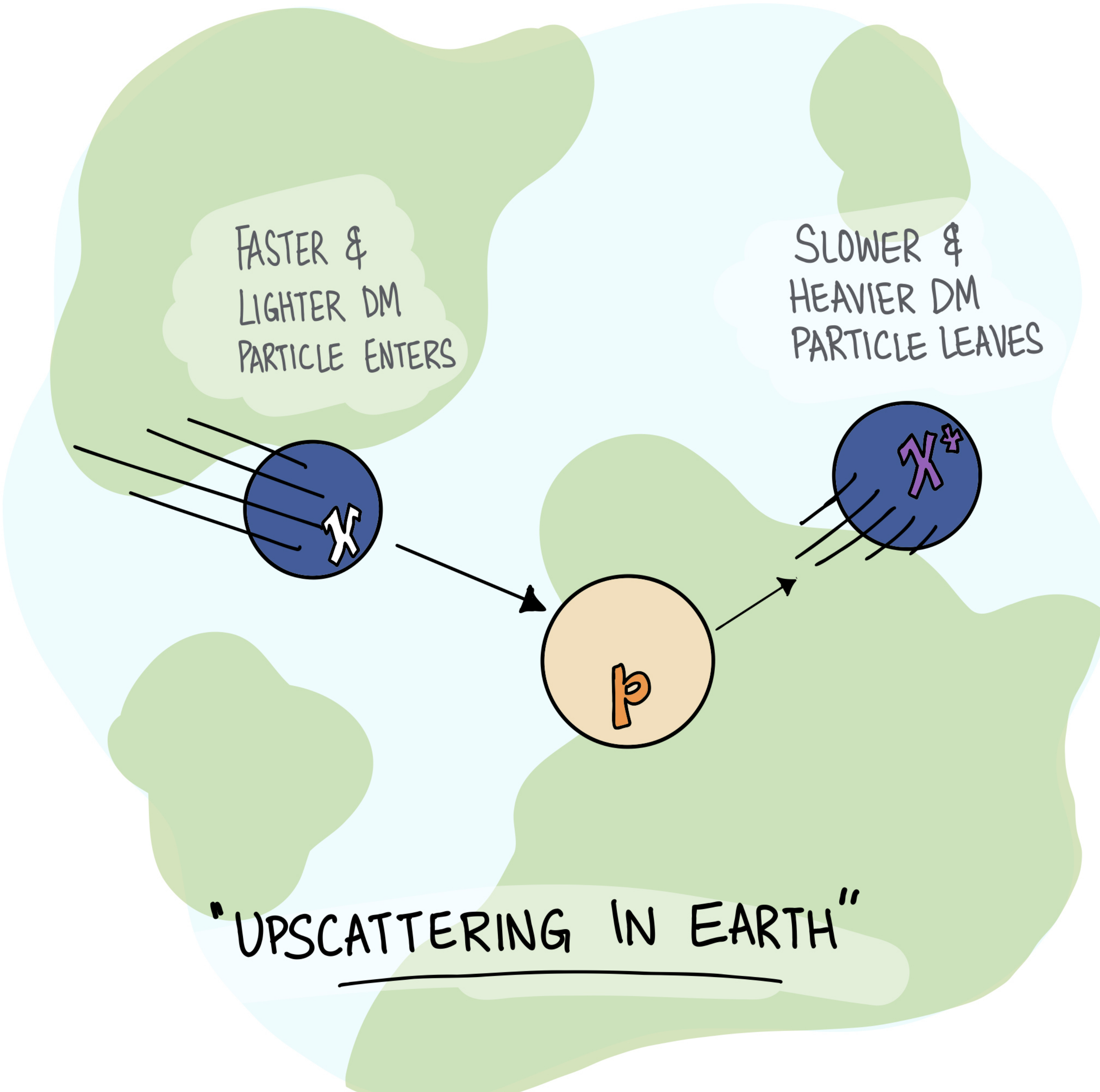
Essig et al. showe
reproduce the XEI

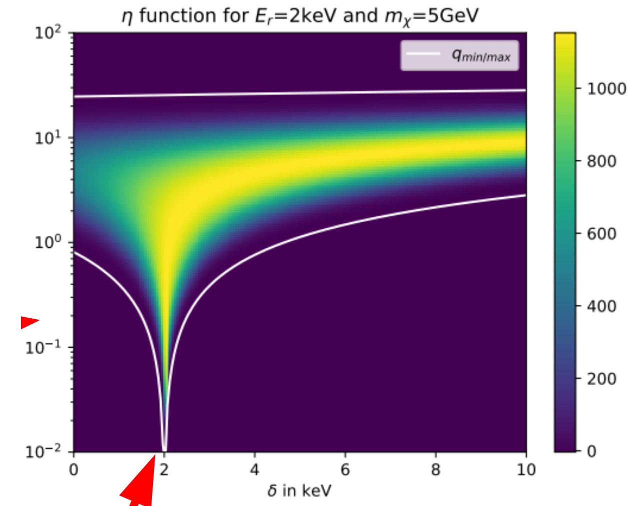
Why is that?

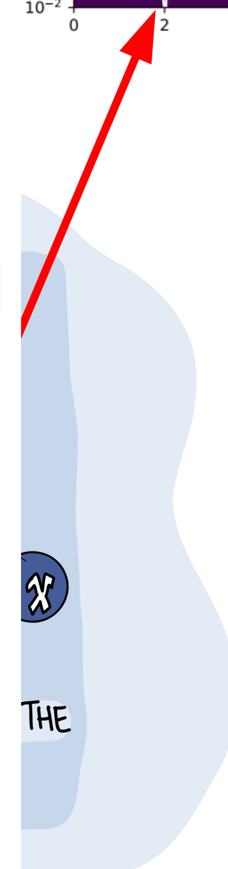
$$\frac{\mathrm{d}R_{\mathrm{ion}}}{\mathrm{d}E_{\mathrm{er}}} = \frac{\rho}{m_\chi}$$



Darl

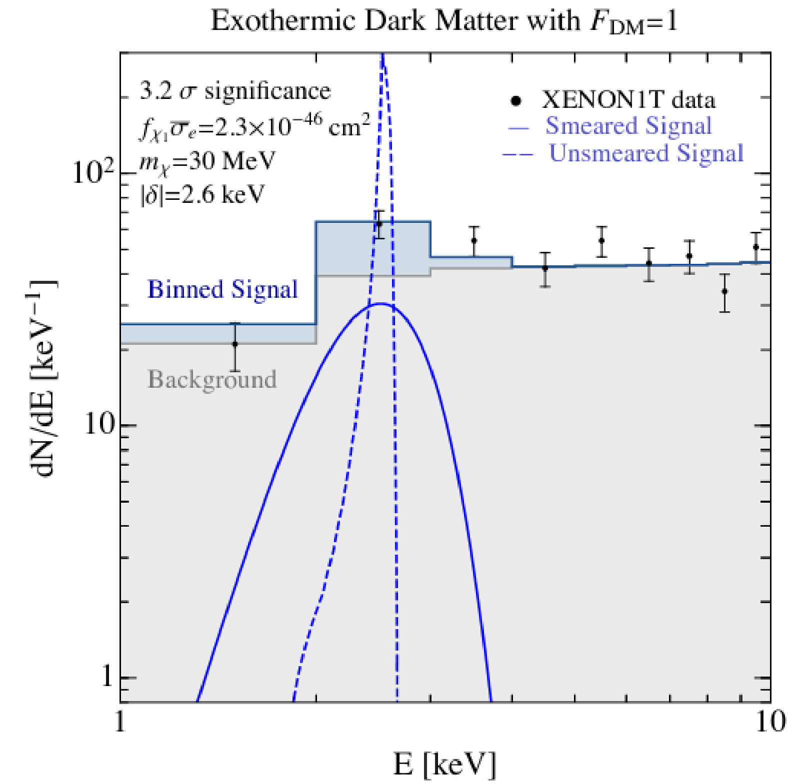






Inelastic DM works… So what next?

But where does the excited state come from?



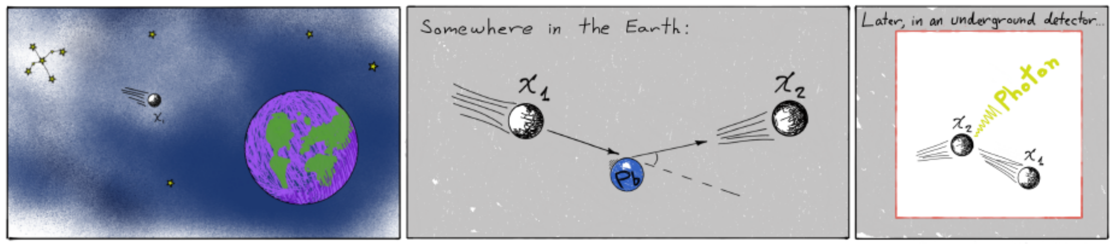
Decay time τ

Cosmological origins [2006.13918,2108.13422]

Cosmic ray upscattering [2008.12137]

Solar upscattering [2006.13918(?),2202.13339(?)]

Terrestrial upscattering [1904.09994 (luminous DM only)]

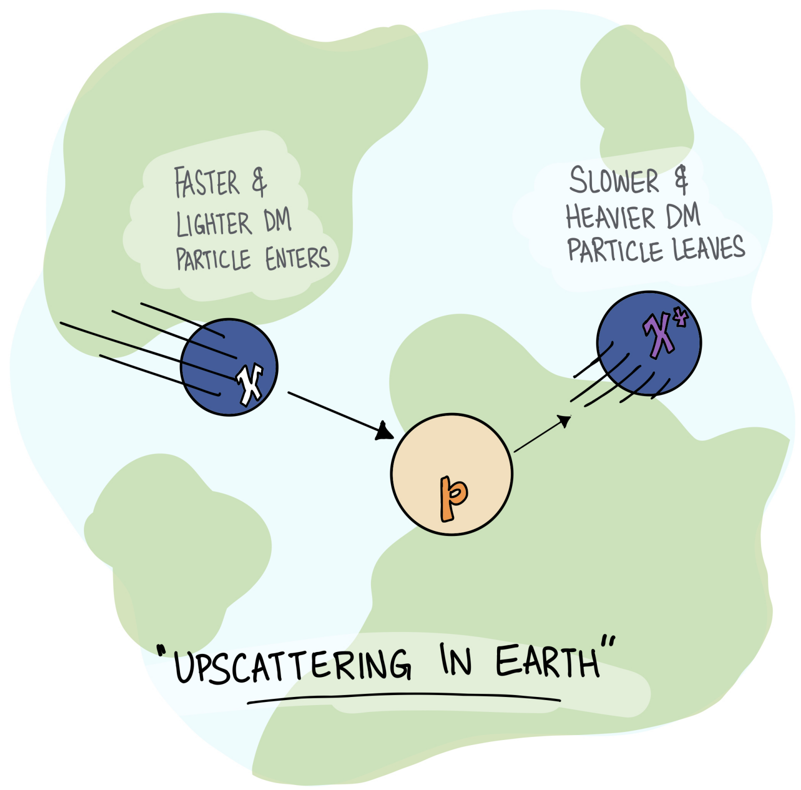


Our work:

Generalise to luminous AND exothermic DM

What's the plan?

Kavanagh et al. implemented a formalism to calculate the perturbation of the speed distribution of elastic DM [1611.05453]



We will now generalize their mechanism. What do we need?

- Initial velocity distribution: Standard Halo Model ✓
- Model of the atomic density of Earth ✓ (improved)
- Detailed analysis of the kinematics × (start from scratch)
- Take into account the detector position (daily modulations) ✓
- Use our previous results for electron scattering

- AND: confirm analytical approach with Monte Carlo simulation

The master formula

Conceptually easy approach [1611.05453]:

Equate the outgoing and incoming fluxes for a scattering point and integrate over the whole volume of Earth.

$$f^*(v) = \sum_{\pm,i} \int_0^1 \mathrm{d}\cos\theta \int_0^{2\pi} \mathrm{d}\phi \int_{-1}^1 \mathrm{d}\cos\theta' \times \frac{\sigma_i \bar{n}_i d_{\mathrm{eff},i}(\cos\theta)}{2\pi} \left| \frac{\mathrm{d}\kappa_{\pm,i}^{-1}(v',\alpha)}{\mathrm{d}v'} \right|^{-1} \times \frac{v'^3}{v} f_0(v',\cos\theta') P_{\pm,i}(\cos\alpha) \Big|_{v'=\kappa_i(v,\alpha)}$$

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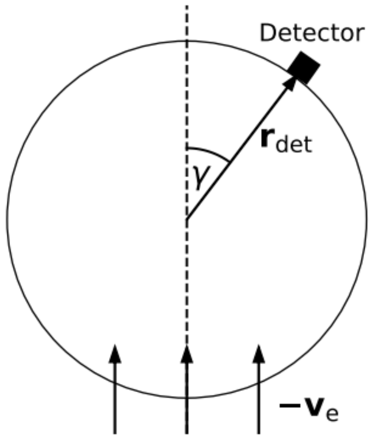

Speed distribution of the excited state

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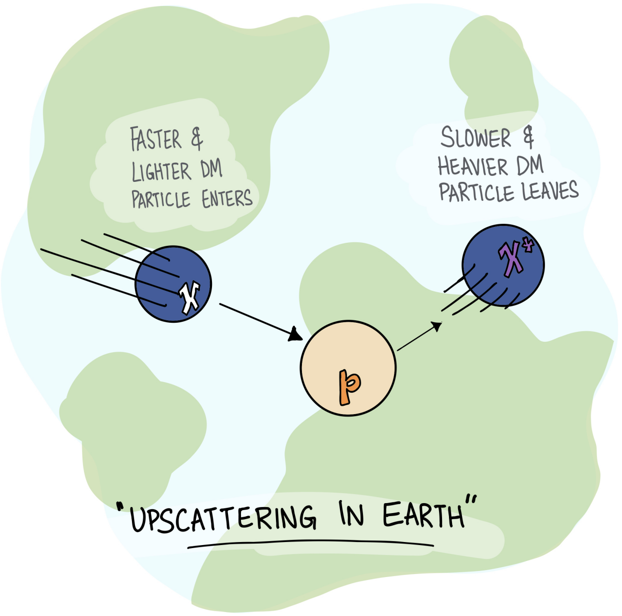

Sum over all (relevant) elements

Element	O	Si	Mg	Fe	Ca	Na	S	Al	Ni	total
Mass in GeV	14.9	26.1	22.3	52.1	37.2	21.4	29.8	25.1	58.7	
Relative abundance mantle	0.4400	0.2100	0.2280	0.0626	0.0253	0.0027	0.0003	0.0235	0	0.9924
Relative abundance core	0	0.060	0	0.855	0	0	0.019	0	0.052	0.986

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Scattering on terrestrial nuclei and decays

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Standard Halo Model

The master formula

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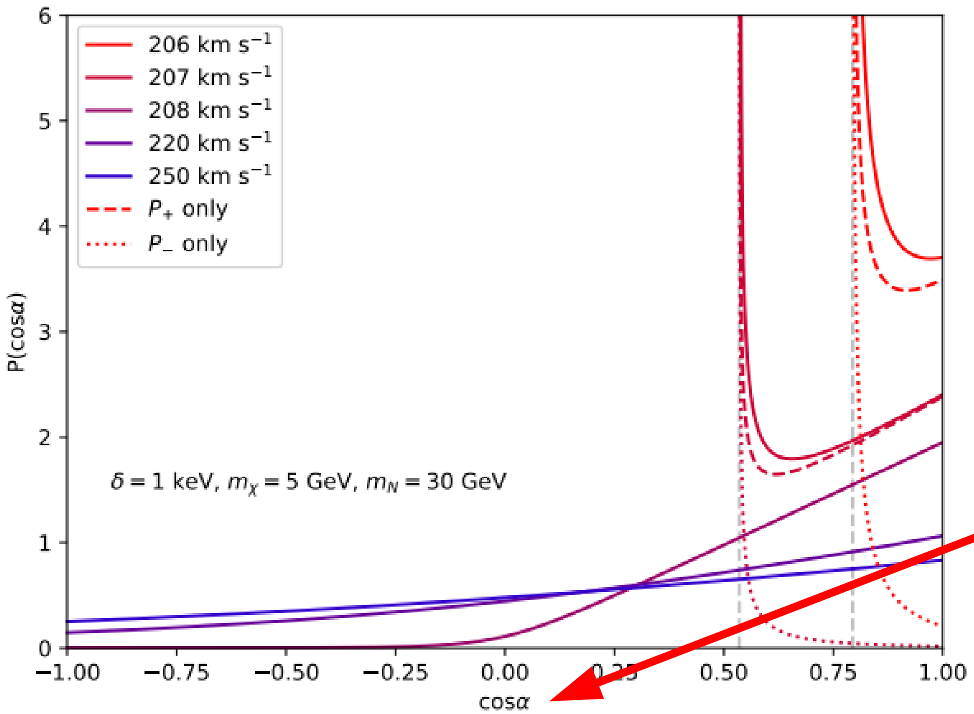
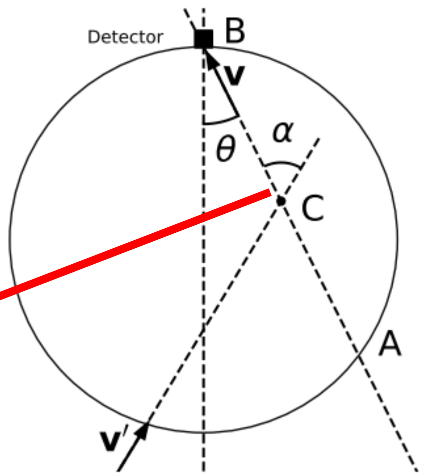
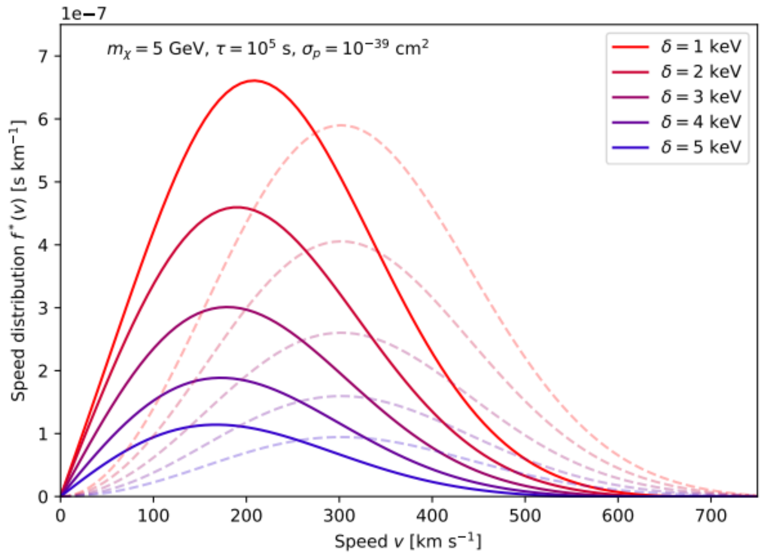




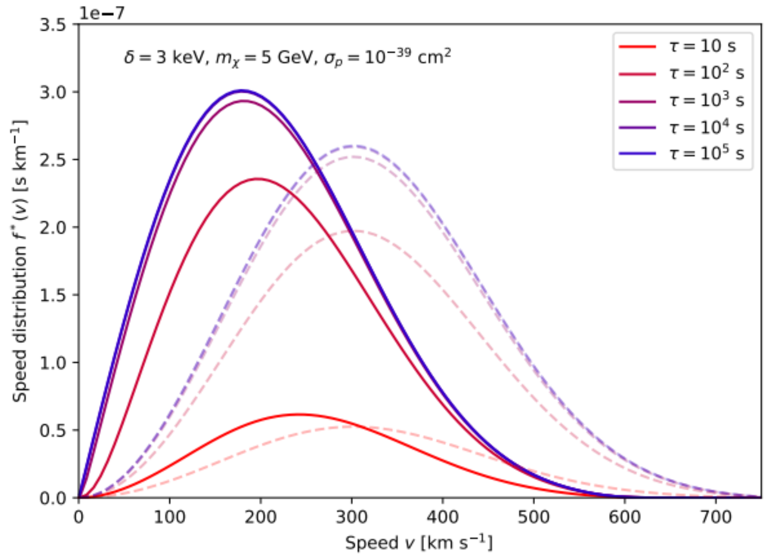
Kinematics

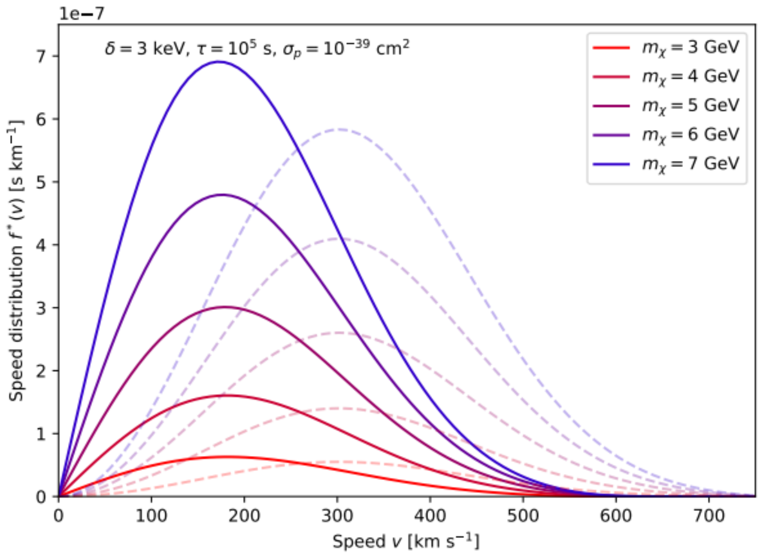
The excited speed distribution



Varying the mass splitting

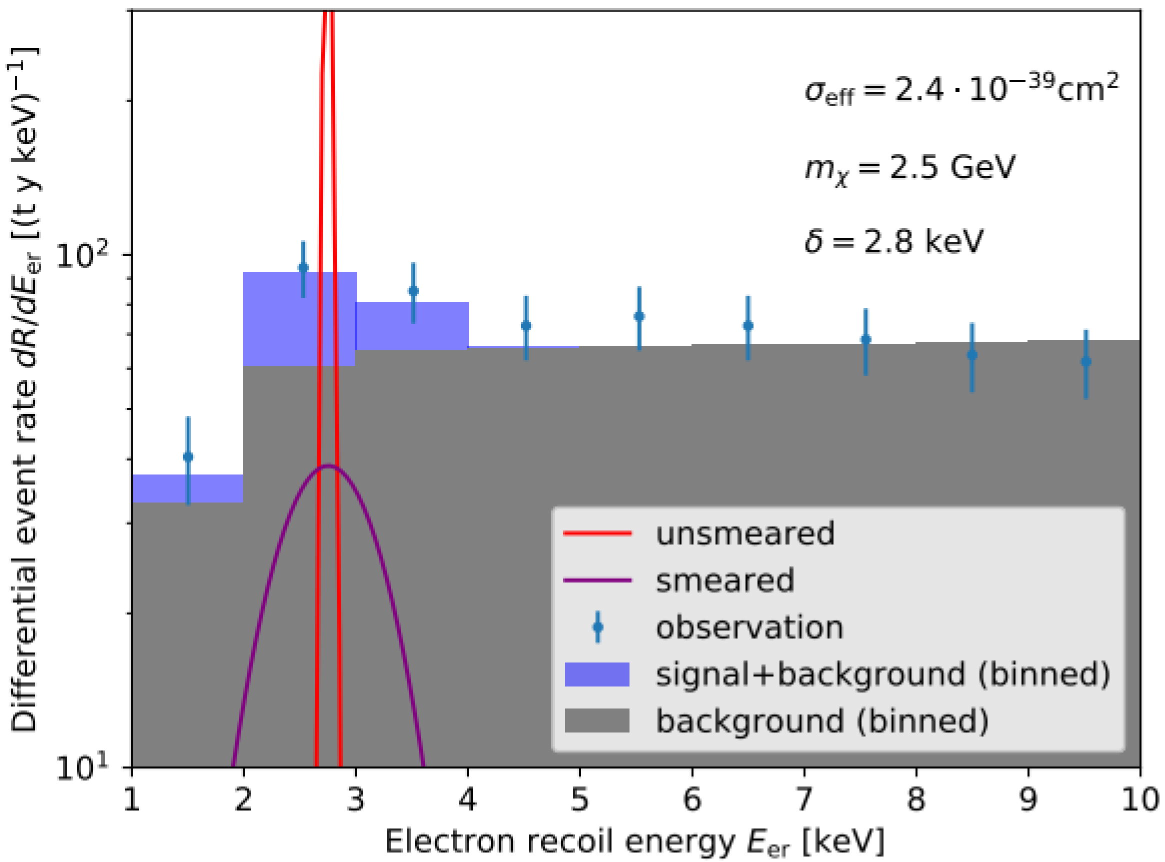
Varying the decay time





Varying the DM mass

Fitting XENON1T with exothermic DM



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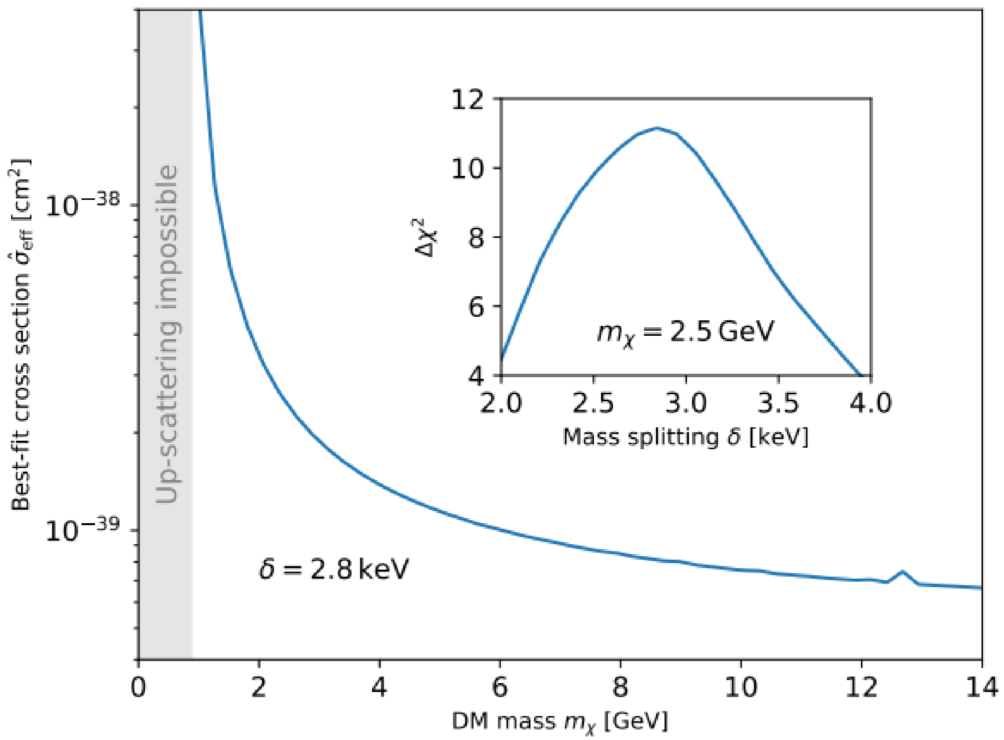
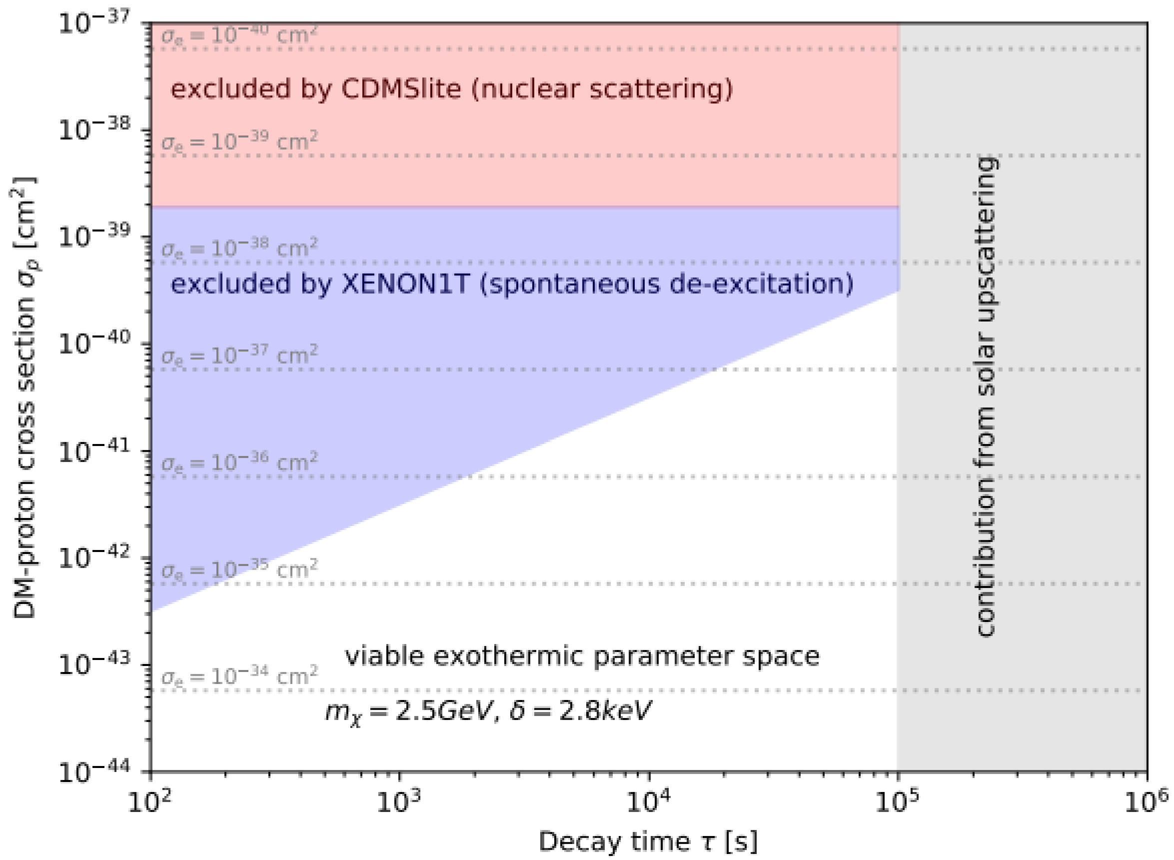


What do we know about the effective cross section?



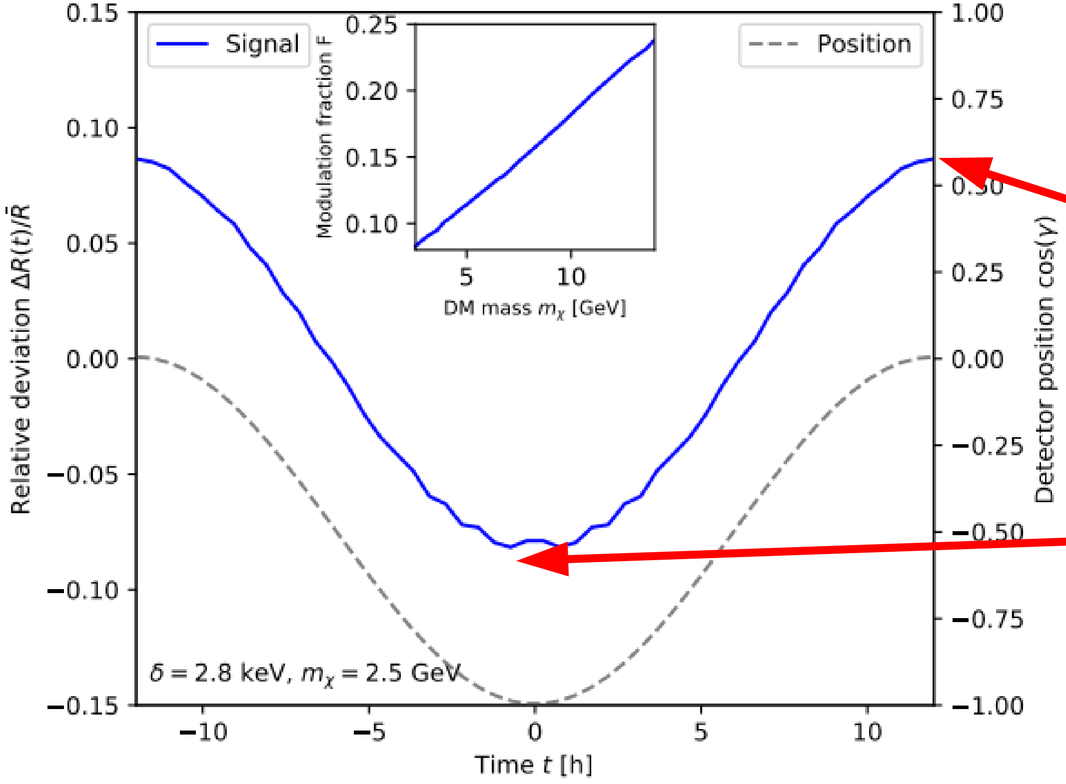
Idea for luminous DM: monochromatic line with total rate

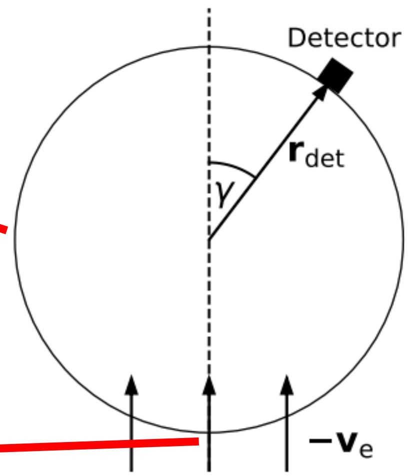
$$R = \frac{\rho^* V_{\mathrm{det}}}{\tau m_\chi}$$

Preference for small DM mass and large life times

Time modulation: The special signature of our mechanism

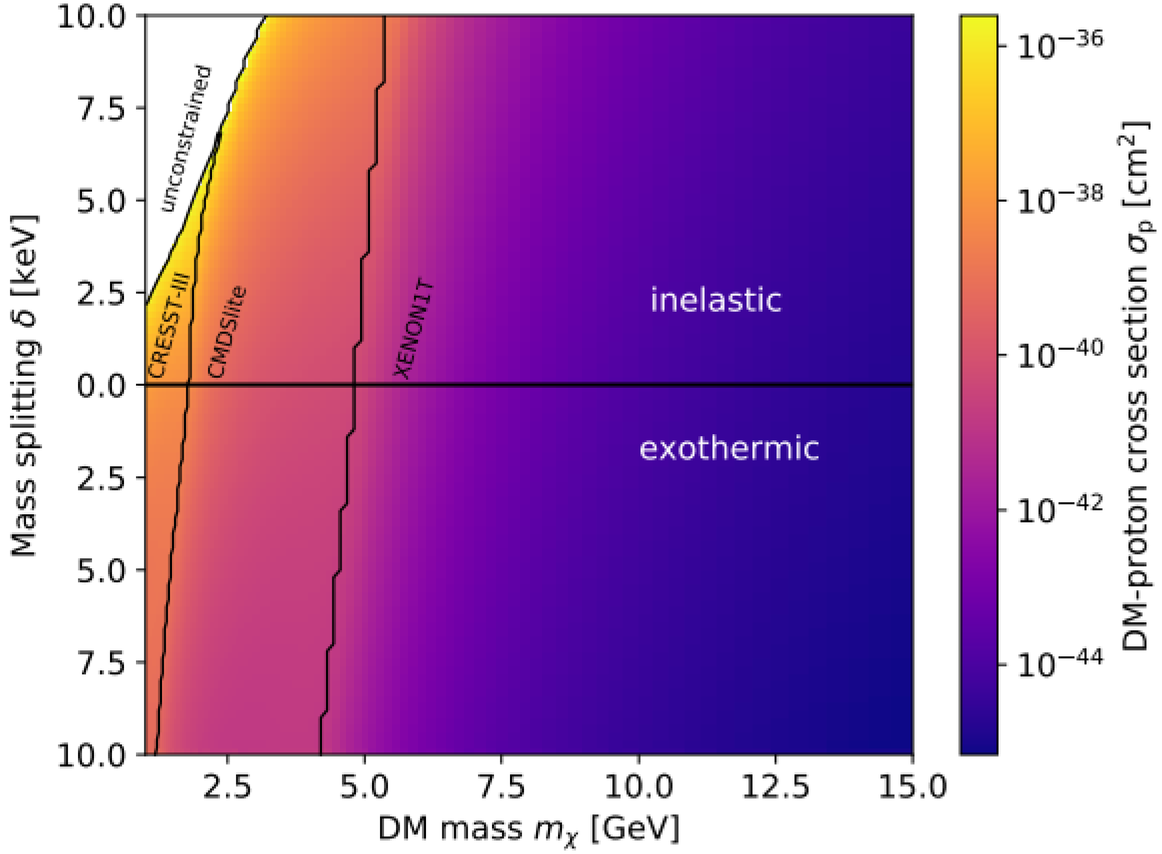
Remember: speed distribution depends on orientation between DM wind and the detector’s position on Earth





Specific to location of XENON1T

Direct detection constraints



Additional constraints and problems

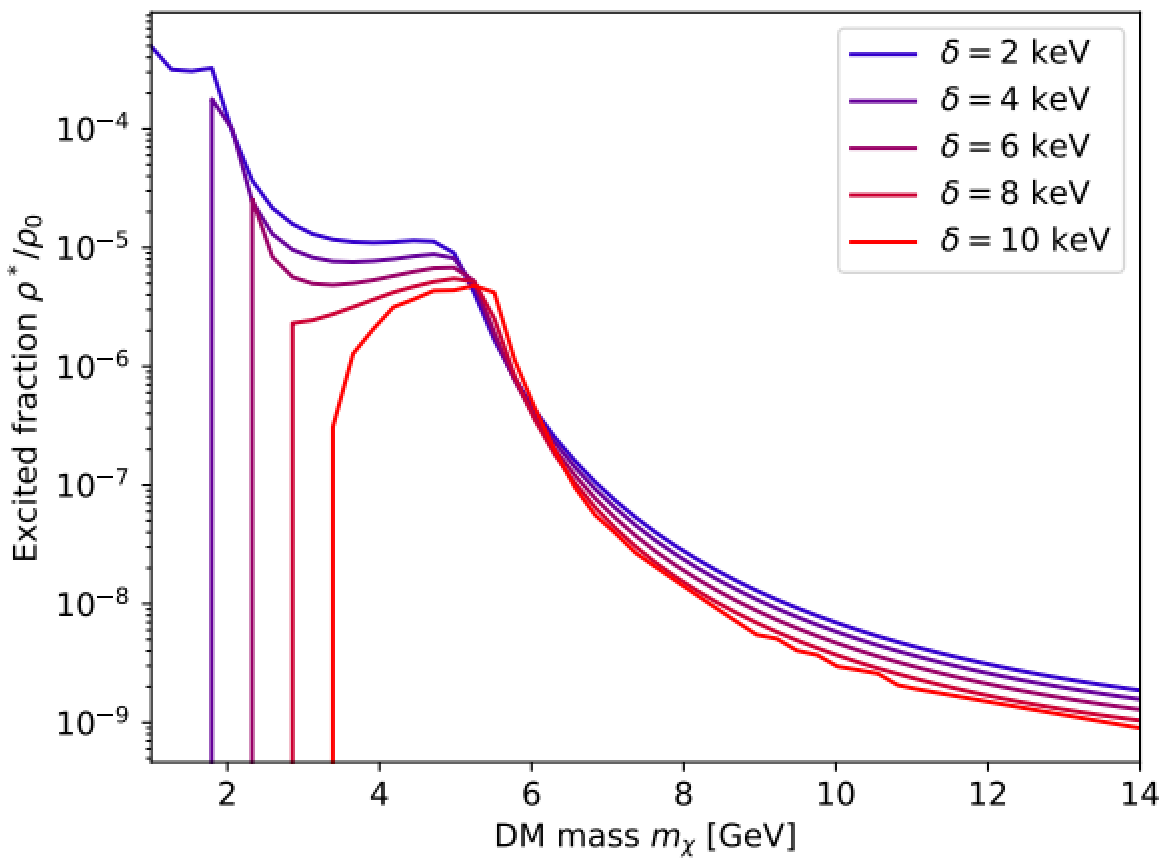
- Observable x-ray line from DM-DM (model-dependent!) and DM-SM upscattering in DM halos
- Solar upscattering (electrons non-negligible?)
- Cross section hierarchy due to the strong constraints from classical WIMP searches

$$\frac{\sigma_e}{\sigma_p} = \frac{\mu_e^2}{\mu_p^2} \approx \frac{m_e^2}{m_p^2} < 10^{-6}$$

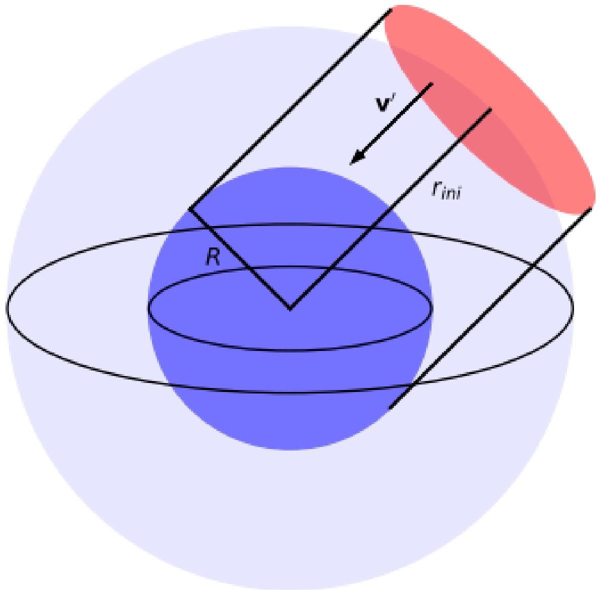
$\Longrightarrow$ model building challenge & strong preference for smaller DM masses

- Modulation for small masses (~10%) is rather weak (20 times the XENON1T statistics required for 3σ)
- Single scattering approximation and local nuclear densities

The excited fraction



Details on the MC

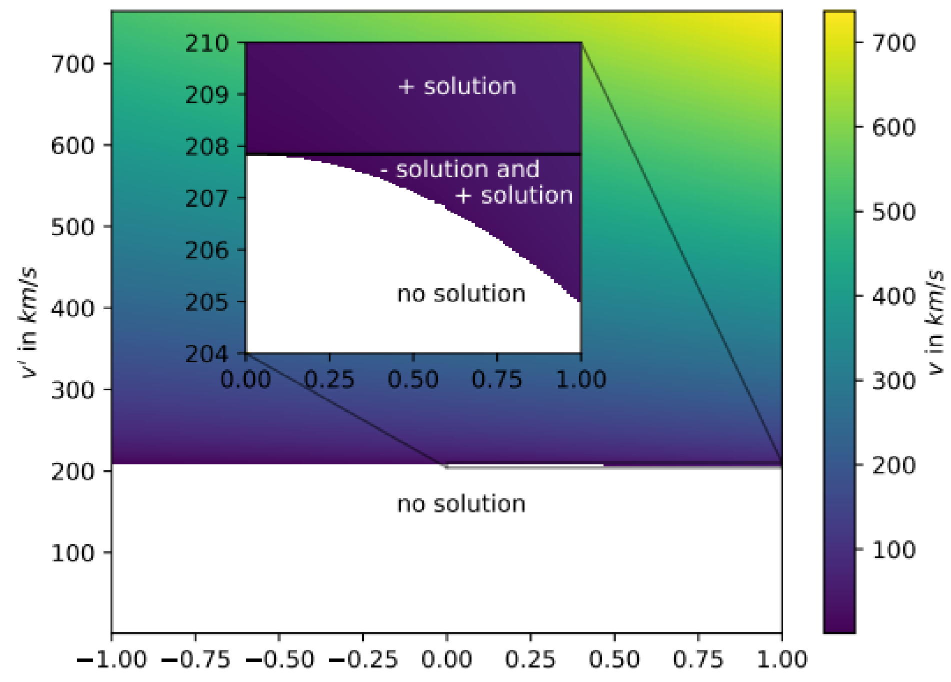


$$\mathbf{v} = \frac{\sqrt{m_a^2 v'^2 - \frac{2\delta}{m_\chi} m_a (m_a + m_\chi)}\,\mathbf{n} + m_\chi \mathbf{v}'}{m_a + m_\chi}$$

More on the kinematics

$$\kappa_{\pm}^{-1}(v',\alpha) = v' \frac{\cos\alpha \pm \sqrt{\frac{m_N^2}{m_\chi^2} - \sin^2\alpha - \frac{2\delta m_N(m_N+m_\chi)}{m_\chi^3 v'^2}}}{1 + m_N/m_\chi}$$

$$\kappa_{\pm}(v,\alpha) = v \frac{\cos\alpha \mp \sqrt{\frac{m_N^2}{m_\chi^2} - \sin^2\alpha + \frac{2\delta m_N(m_N-m_\chi)}{m_\chi^3 v^2}}}{1 - m_N/m_\chi}$$



$\cos\alpha$	κ'	κ	condition	explanation
>0	-	-	no solution as $\kappa < 0$	1
<0	-	-	no solution as $\kappa' < 0$	2
>0	+	-	no solution as $\kappa < 0$	3
<0	+	-	no solution as $m_\chi^2 \not> m_A^2 + \frac{2\delta m_A(m_A-m_\chi)}{m_\chi}$	4
>0	-	+	solution if $v' \leq \sqrt{\frac{2\delta m_A}{m_\chi(m_A-m_\chi)}}$	5
<0	-	+	no solution as $\kappa' < 0$	6
>0	+	+	unconditional existence of solution	7
<0	+	+	solution if $v' \geq \sqrt{\frac{2\delta m_A}{m_\chi(m_A-m_\chi)}}$	8