Inelastic Dark Matter @ Large Volume Detectors

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2312.08478 and 1904.09994 (JHEP)

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MITP "DM Landscape: From Feeble to Strong Interactions"
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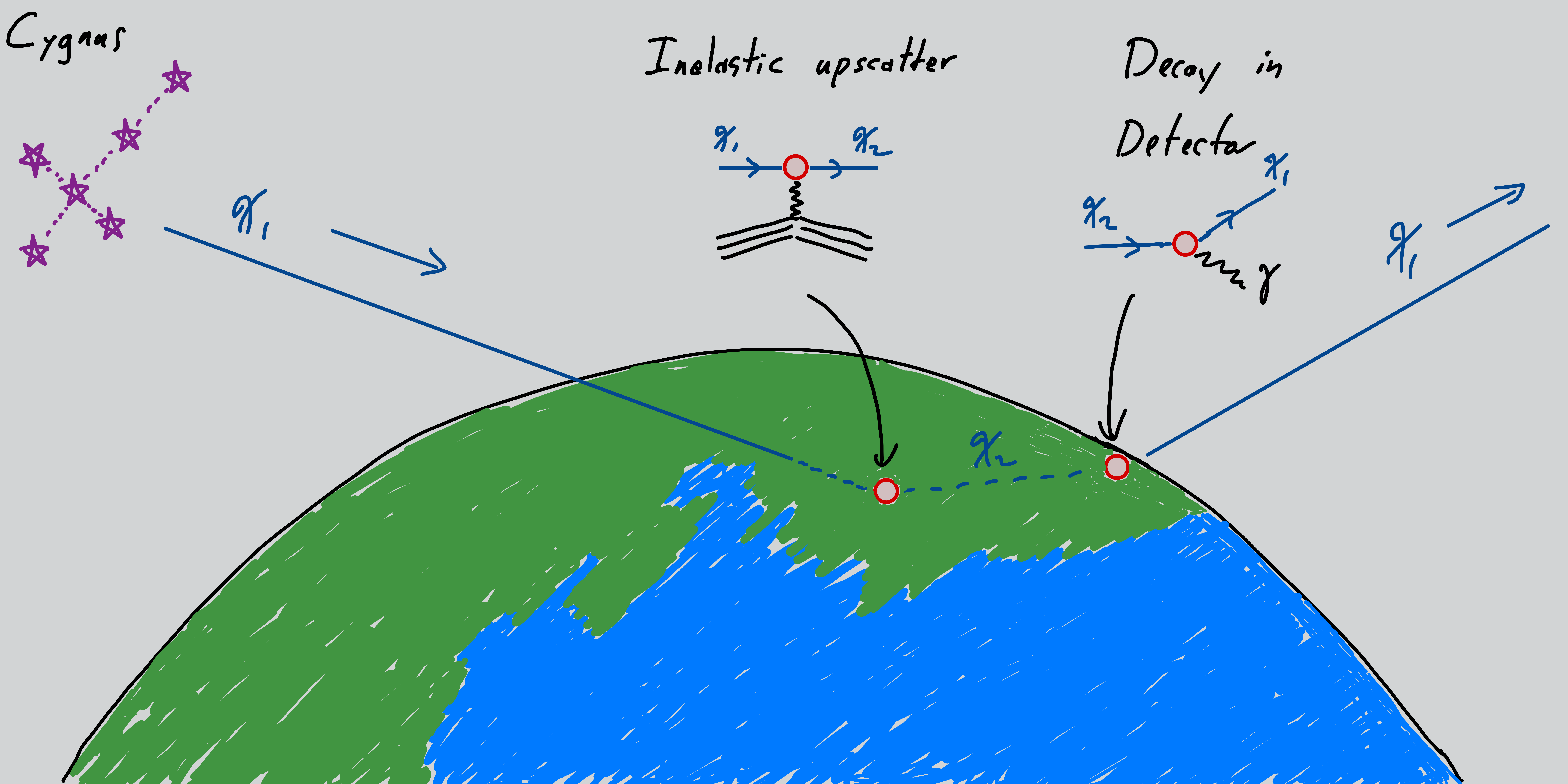
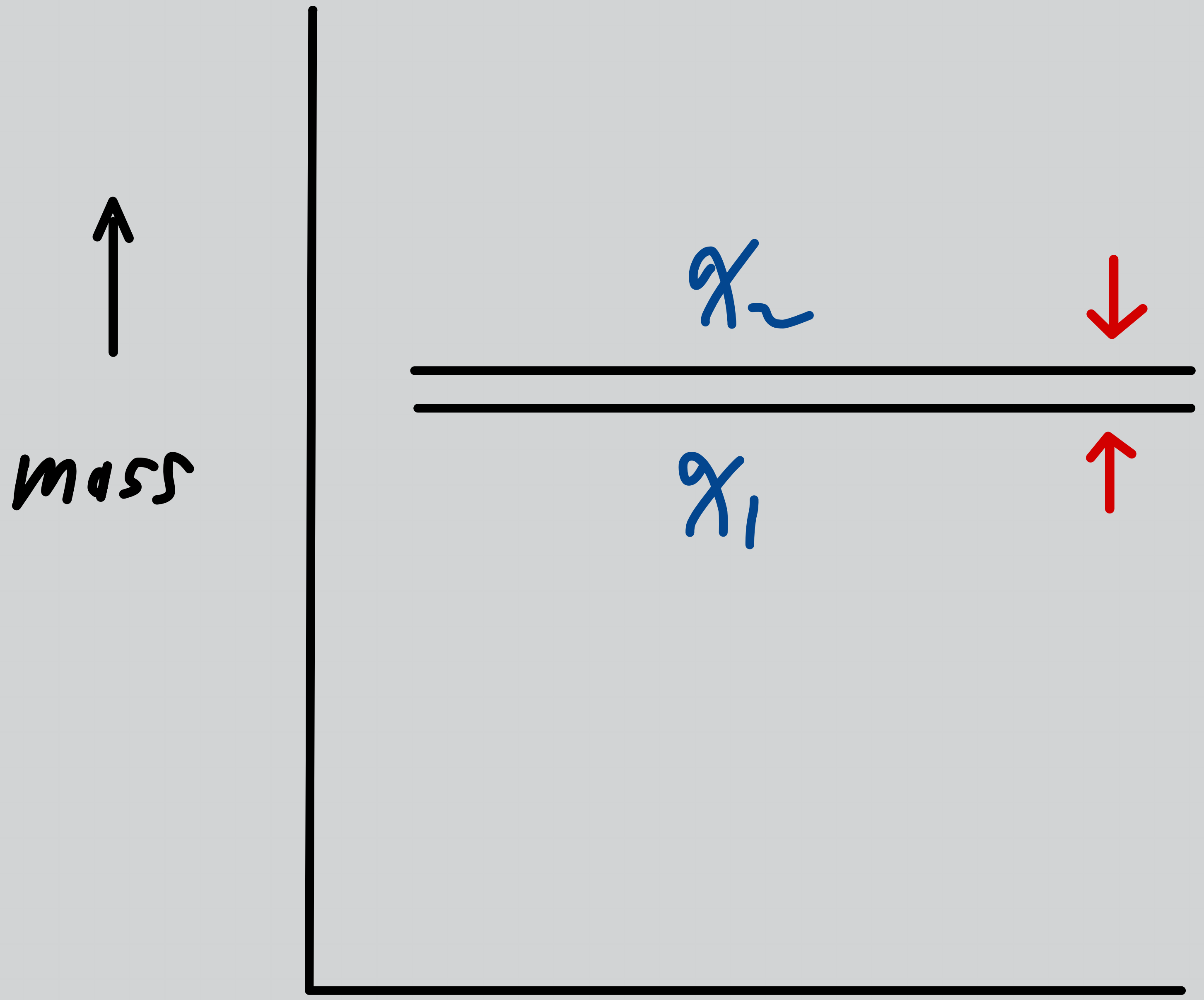
Monoenergetic Photon Signal



Inelastic Dark Matter

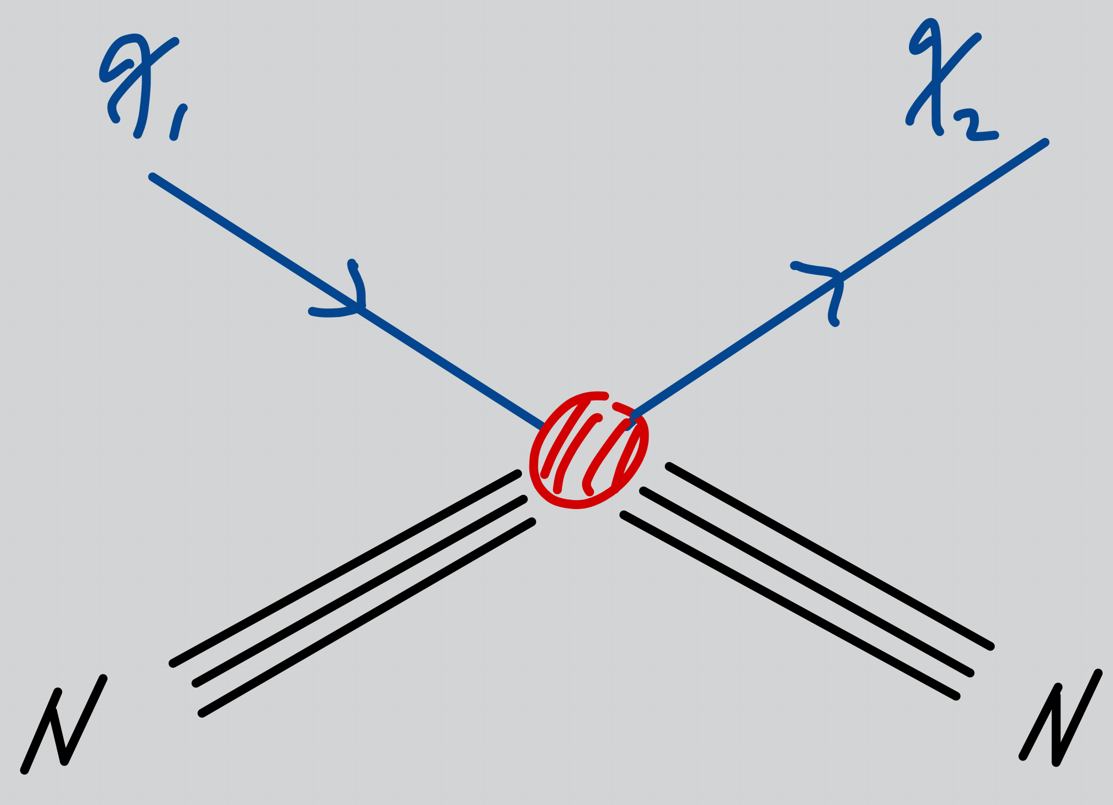
[Han, Hempfling; Hall, Moroi, Murayama; Tucker-Smith, Weiner ...]

Model with dark matter (χ_1) and excited state (χ_2):



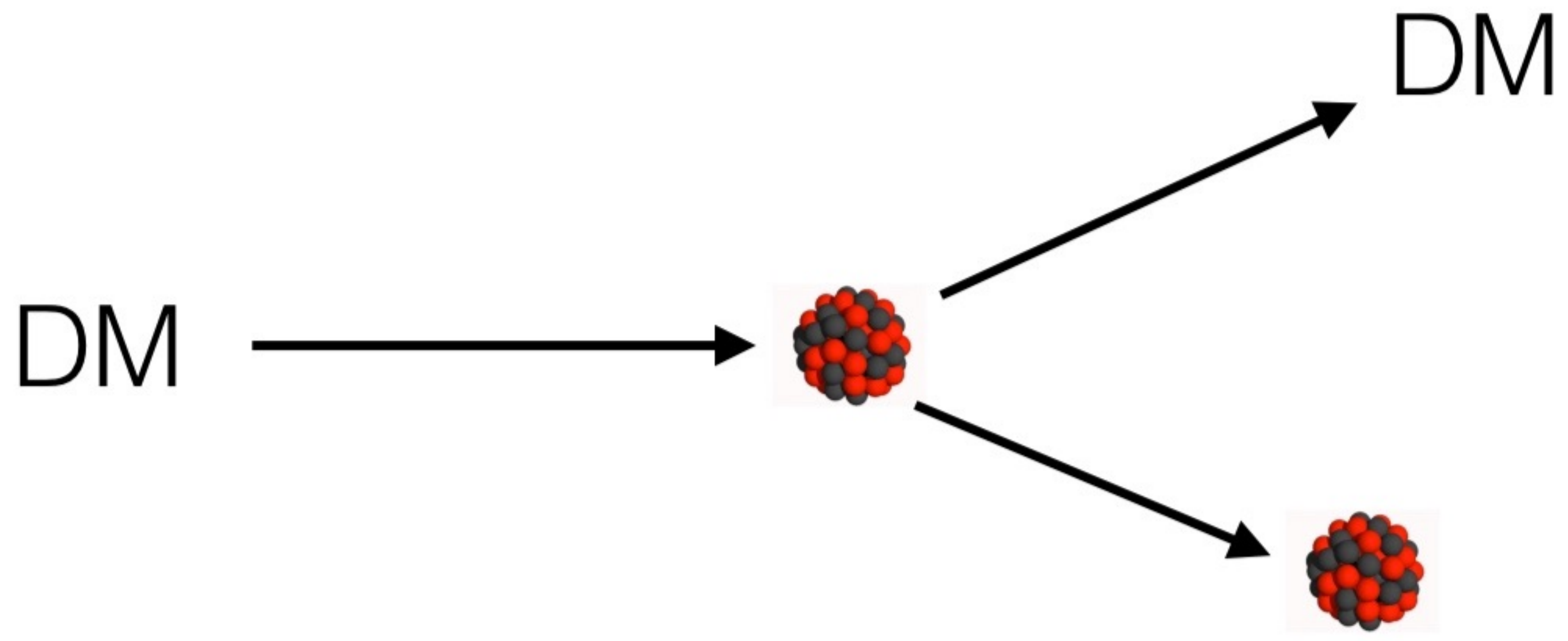
$$\delta \equiv m_{\chi_2} - m_{\chi_1}$$

Scattering proceeds dominantly through inelastic upscatter:



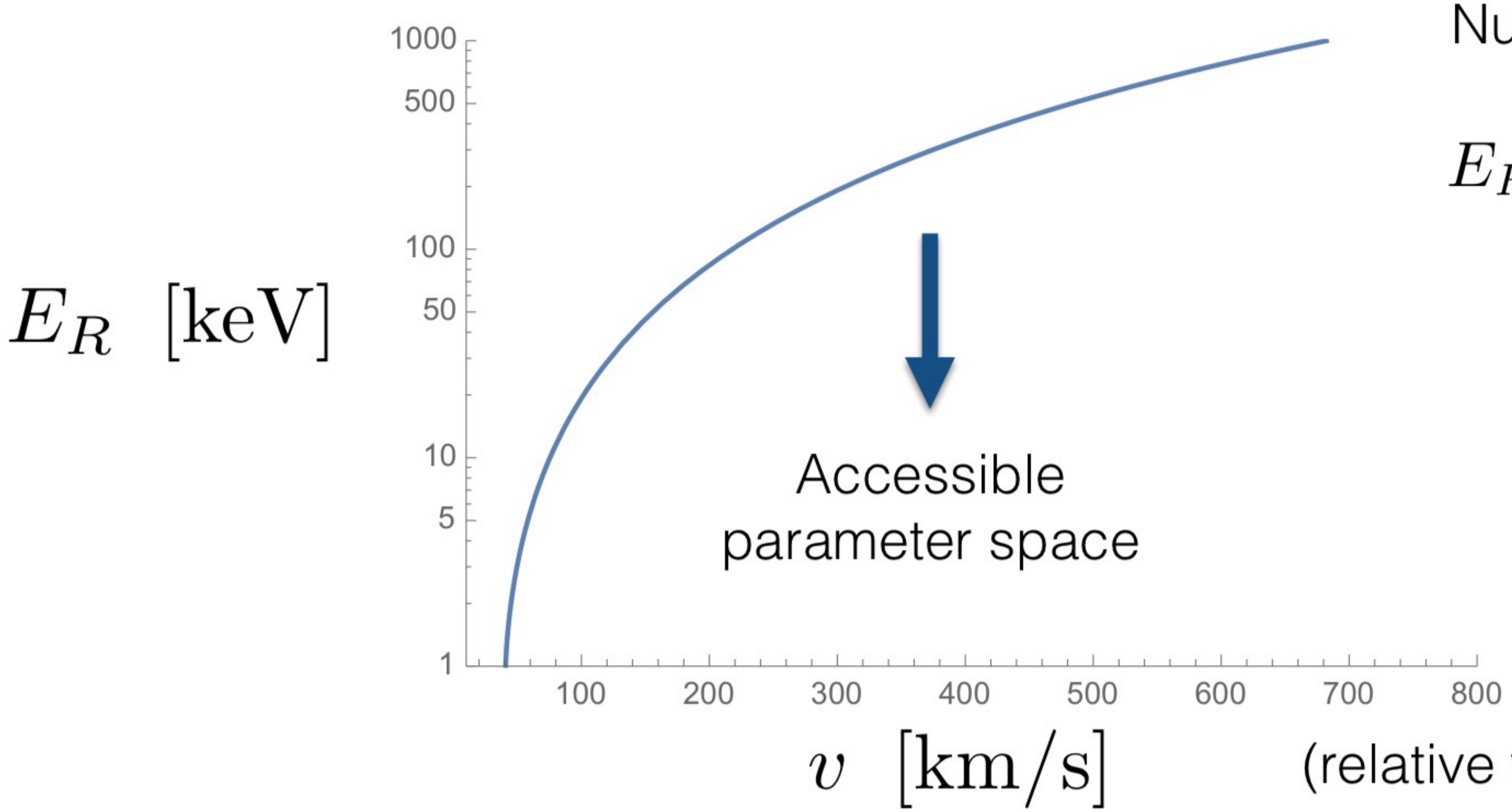
whose cross section is suppressed relative to elastic by smaller flux of DM capable of upscattering.

Elastic Kinematics



Nucleus recoil energy:

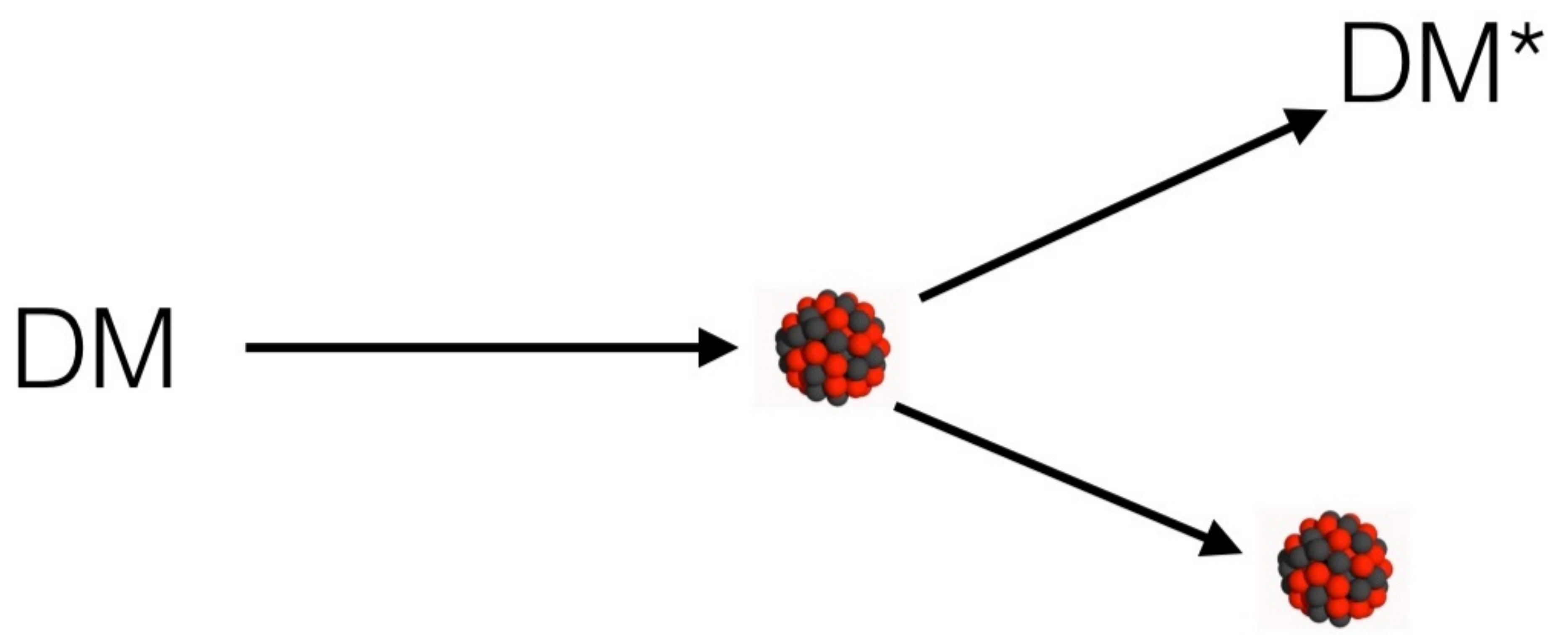
$$E_R = \frac{2\mu^2 v^2 \cos^2 \theta_{\rm lab}}{m_N}$$



(relative velocity)

Inelastic Kinematics

Now, some energy absorbed into the upscatter DM* mass

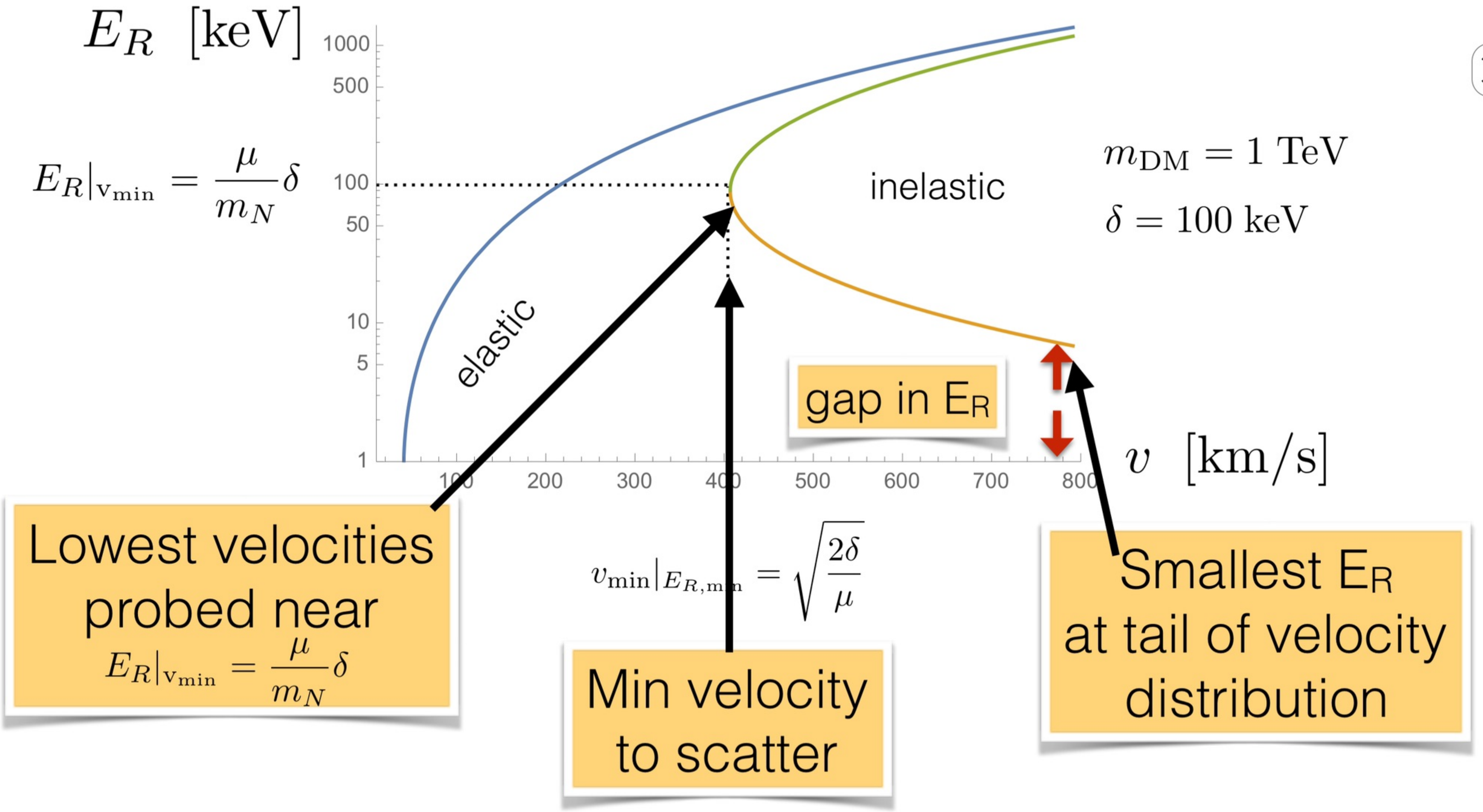


Recoil energy has a more complicated form

$$E_R = \frac{\mu}{m_N}\left[(\mu v^2 \cos^2\theta_{\rm lab} - \delta) \pm (\mu v^2 \cos^2\theta_{\rm lab})^{1/2}(\mu v^2 \cos^2\theta_{\rm lab} - 2\delta)^{1/2}\right]$$

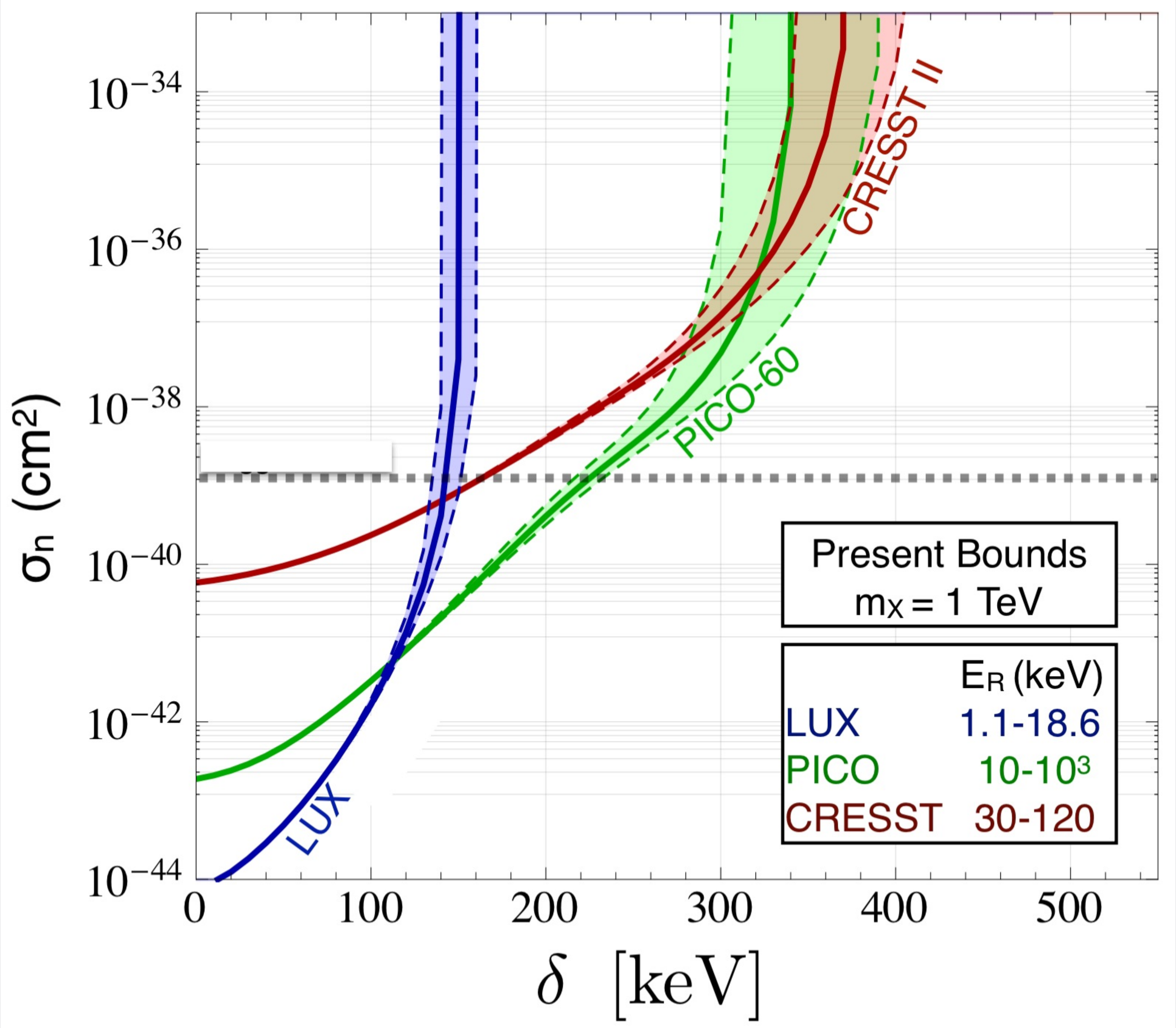
Fox, GK, Tait 1011.1910

Inelastic Kinematics

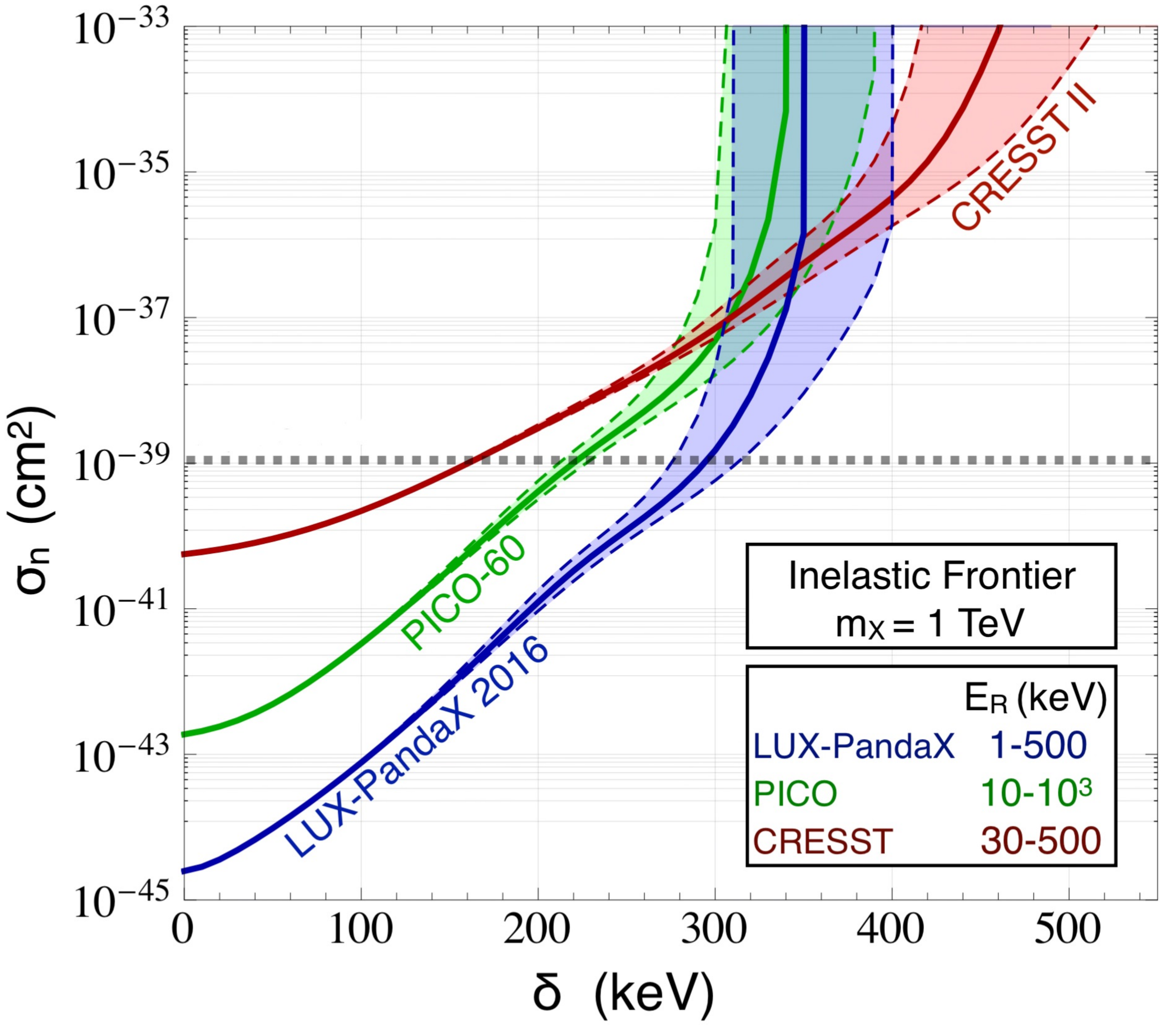


Inelastic DM Direct Detection

Then ...



... projected



[Bramante
Fox
GK
Martin
1608.02662]

Magnetic Inelastic Dark Matter

[Kopp, Schwetz, Zupan; Chang, Weiner, Yavin; Feldstein, Graham, Rajendran]

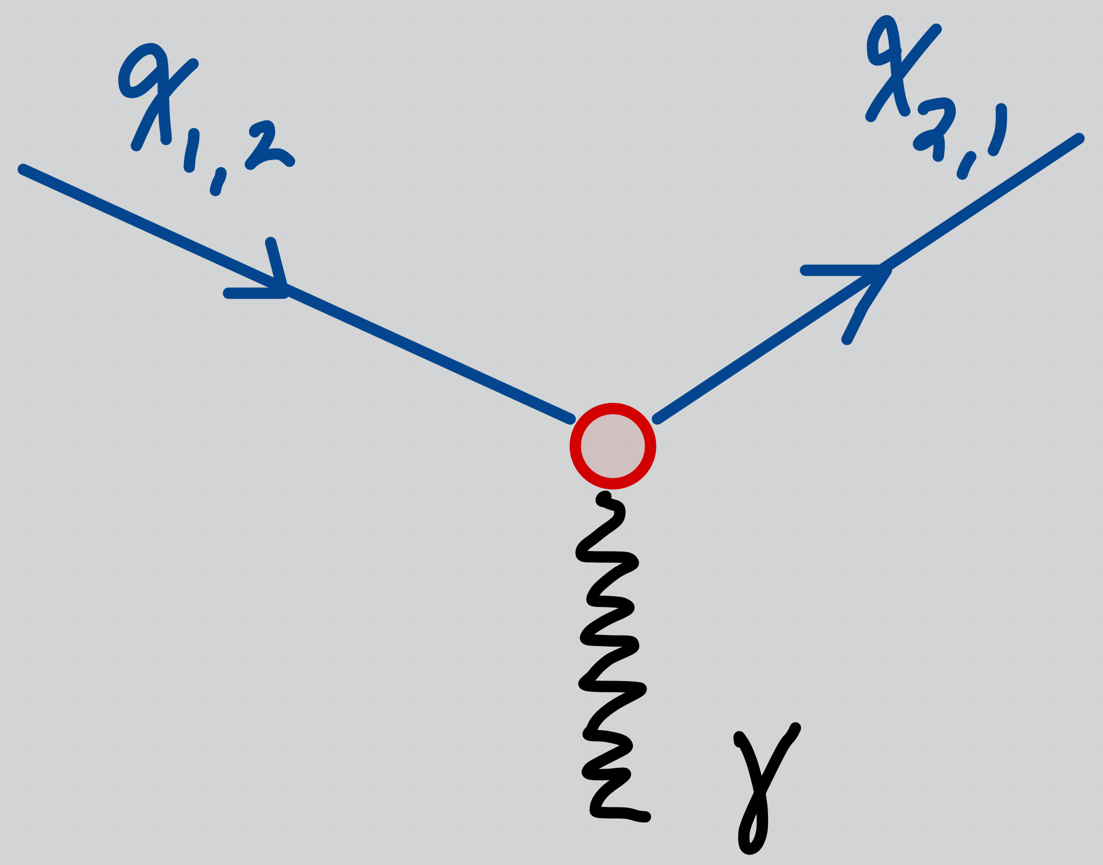
EFT of DM with SM has dimension-5 interaction:

$$\Delta \mathcal{L} = \frac{1}{2} \tilde{\mu} \, \bar{\chi}_2 \Sigma^{\mu\nu} \chi_1 F_{\mu\nu}$$

$\bar{\chi}_2$: excited state

$\Sigma^{\mu\nu}$: $\frac{i}{2}[\gamma^\mu, \gamma^\nu]$

χ_1: DM



$$\tilde{\mu} \equiv g_M \frac{e}{4 m_{\chi_1}}$$

g_M: dimensionless coefficient

$$g_M \sim \frac{1}{16\pi^2} \frac{m_{\chi_1}}{m_\pm} \quad \text{perturbative UV completion}$$

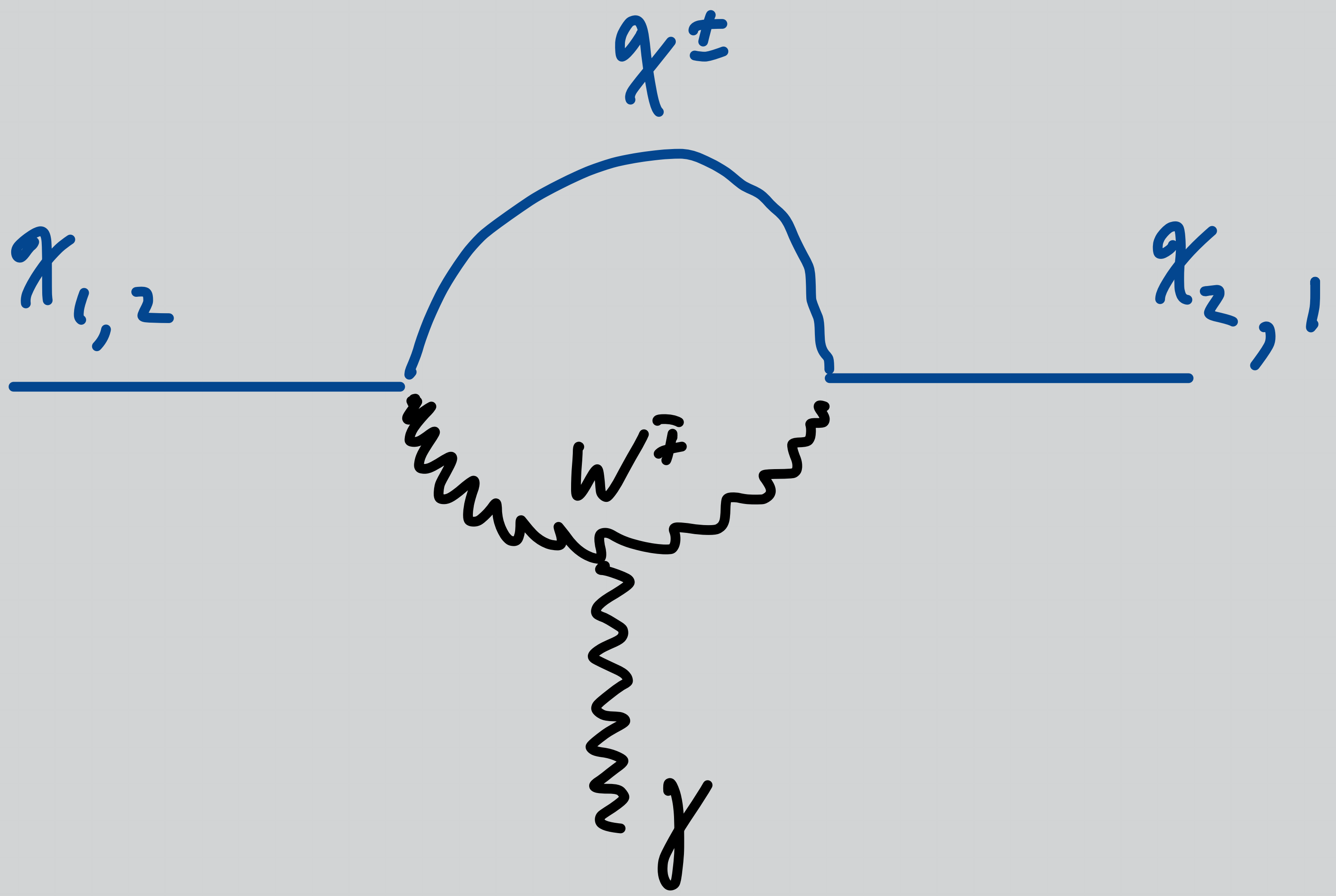
$$g_M \sim 1 \quad \text{strongly coupled}$$

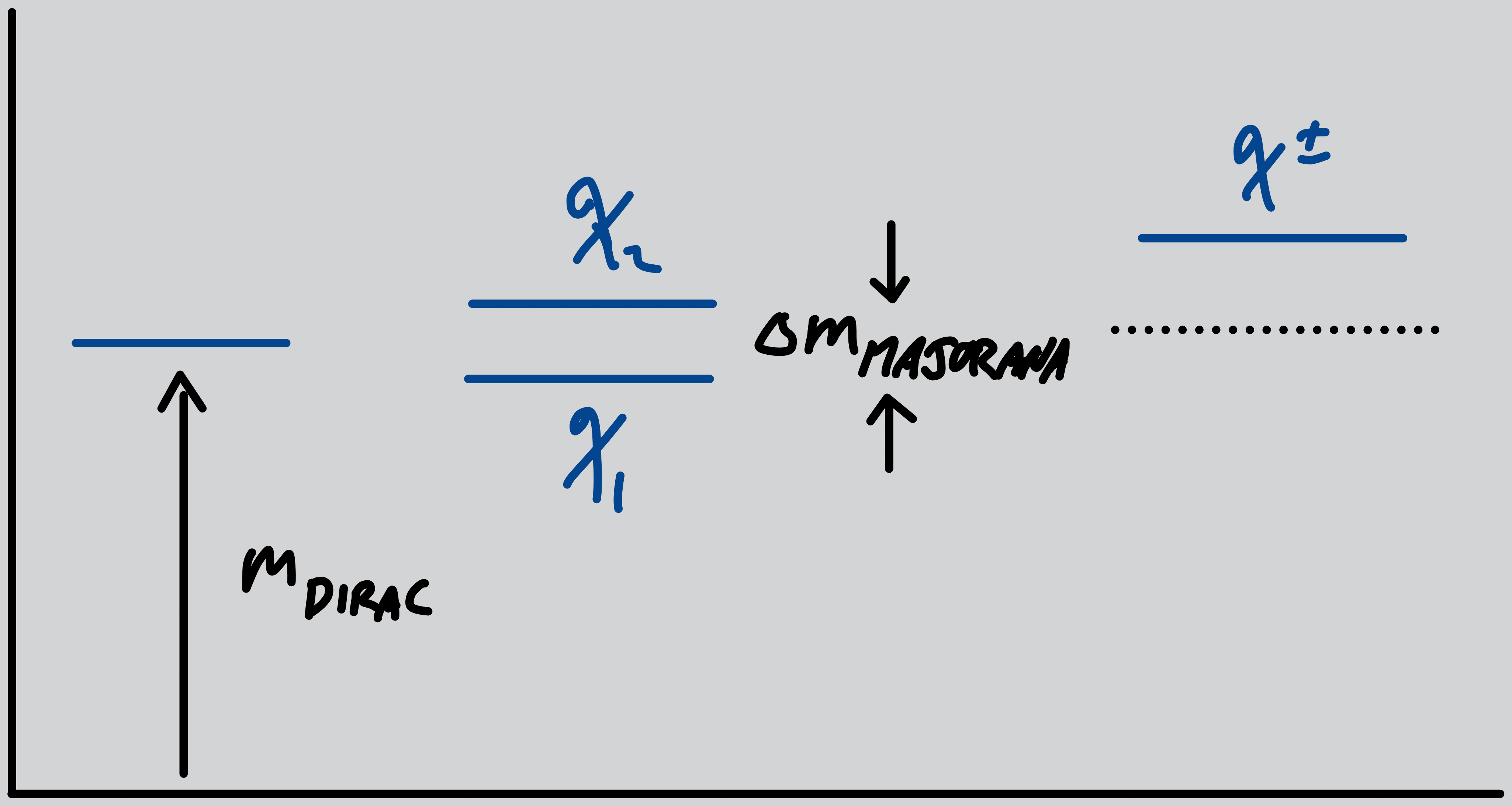
Perturbative

[Kopp, Schwetz, Zupan; Chang, Weiner, Yavin]

Pair of neutral Weyl fermions (and heavier charged states) with

- large Dirac mass
- small Majorana masses
- magnetic dipole transition





In this UV completion, there is no magnetic dipole moment for $\chi_{1,2}$ since these are Majorana fermions.

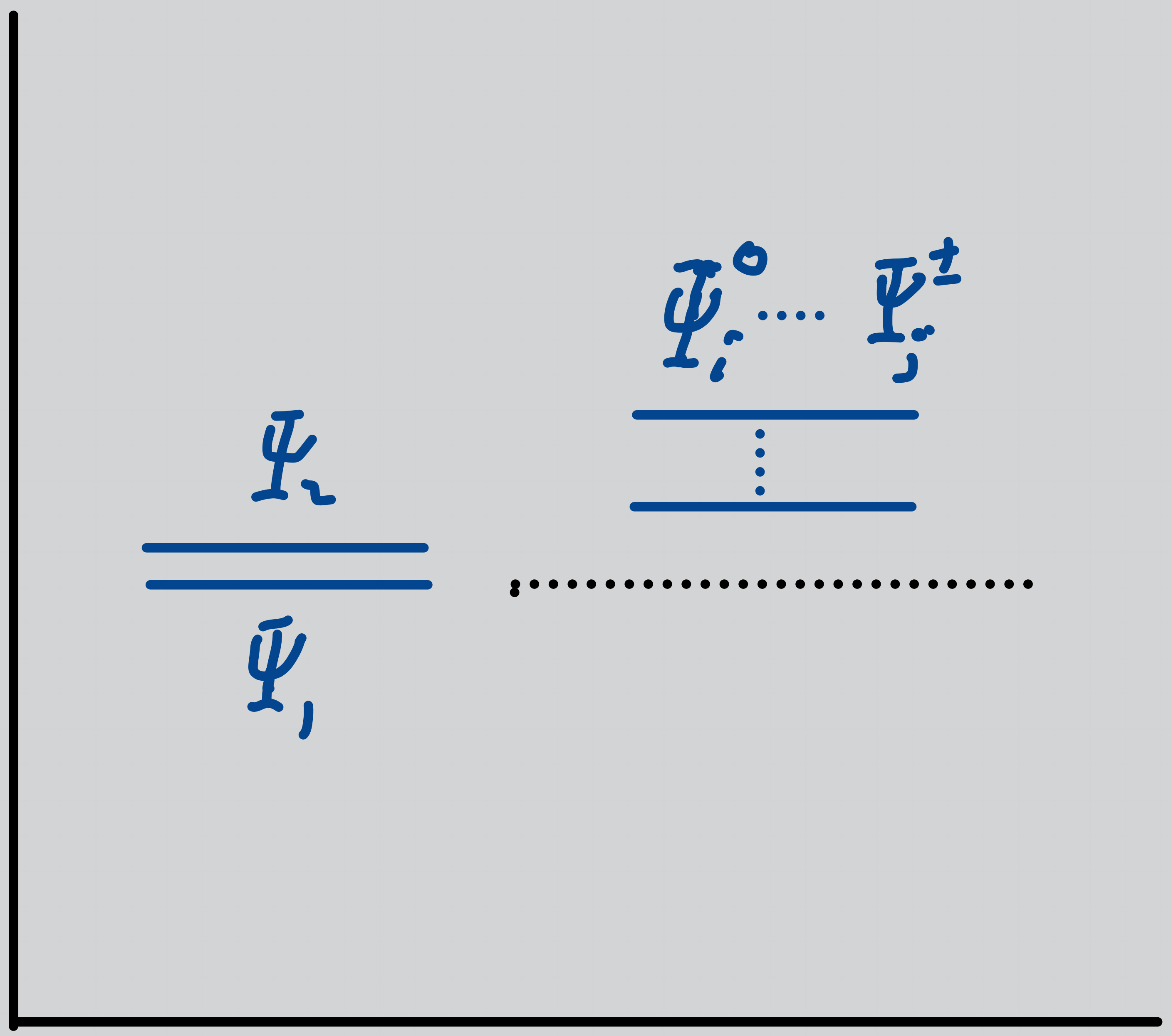
Nonperturbative

Pair of neutral Dirac fermions with

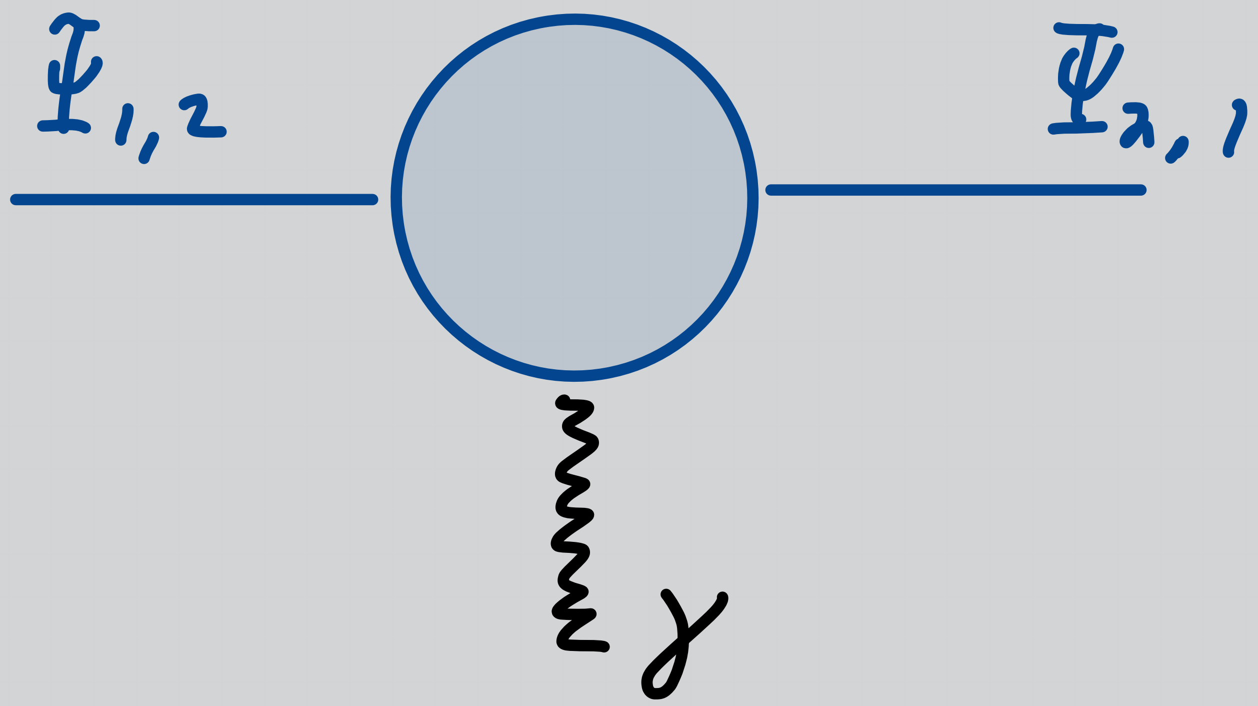
$$\frac{1}{2}\left(\bar{\Psi}_1\ \ \bar{\Psi}_2\right)\begin{pmatrix}\tilde{\mu}_{11} & \tilde{\mu}_{12}\\ \tilde{\mu}_{21} & \tilde{\mu}_{22}\end{pmatrix}\Sigma^{\mu\nu}\begin{pmatrix}\Psi_1\\ \Psi_2\end{pmatrix}F_{\mu\nu}$$

magnetic dipole transitions ($\tilde{\mu}_{12}$, $\tilde{\mu}_{21}$)

magnetic dipole moments* ($\tilde{\mu}_{11}$, $\tilde{\mu}_{22}$)



Example: Λ_s^0, Σ^0 baryons of QCD.

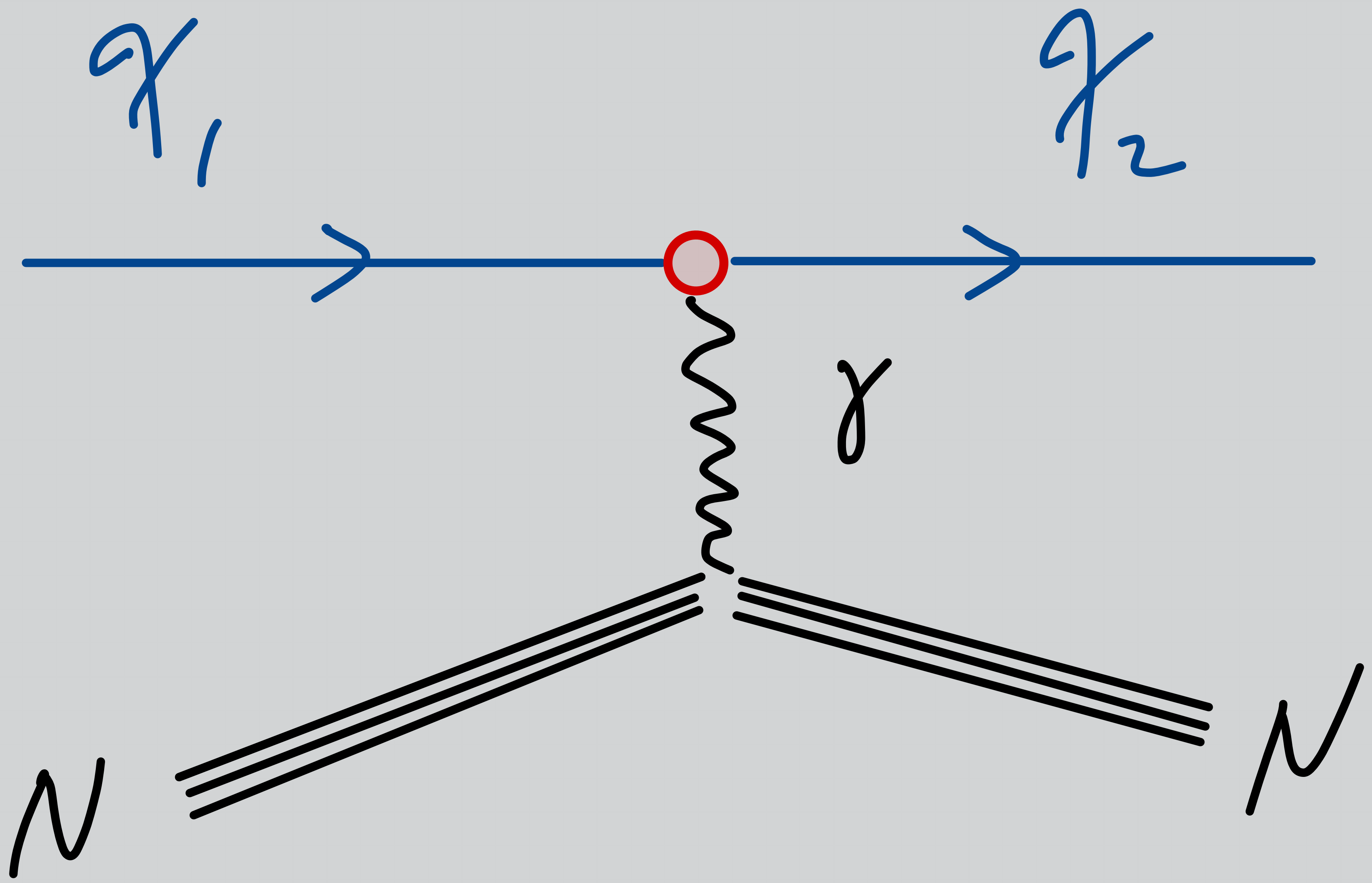


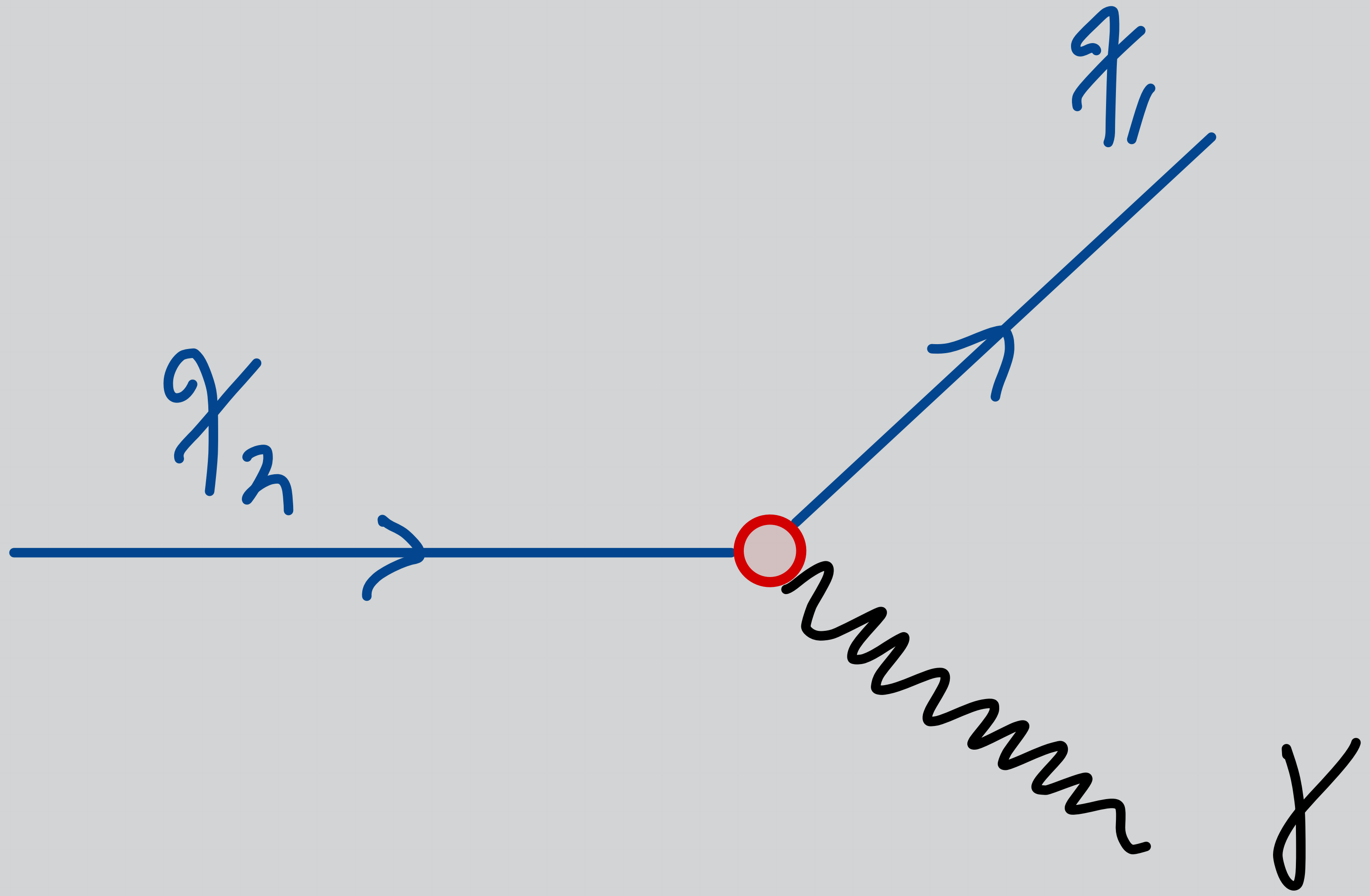
*In a nontrivial class of composite DM theories,

$\tilde{\mu}_{11} = \tilde{\mu}_{22} = 0$ (to appear with Asadi, GK, Mantel)

In EFT, Two Critical Processes

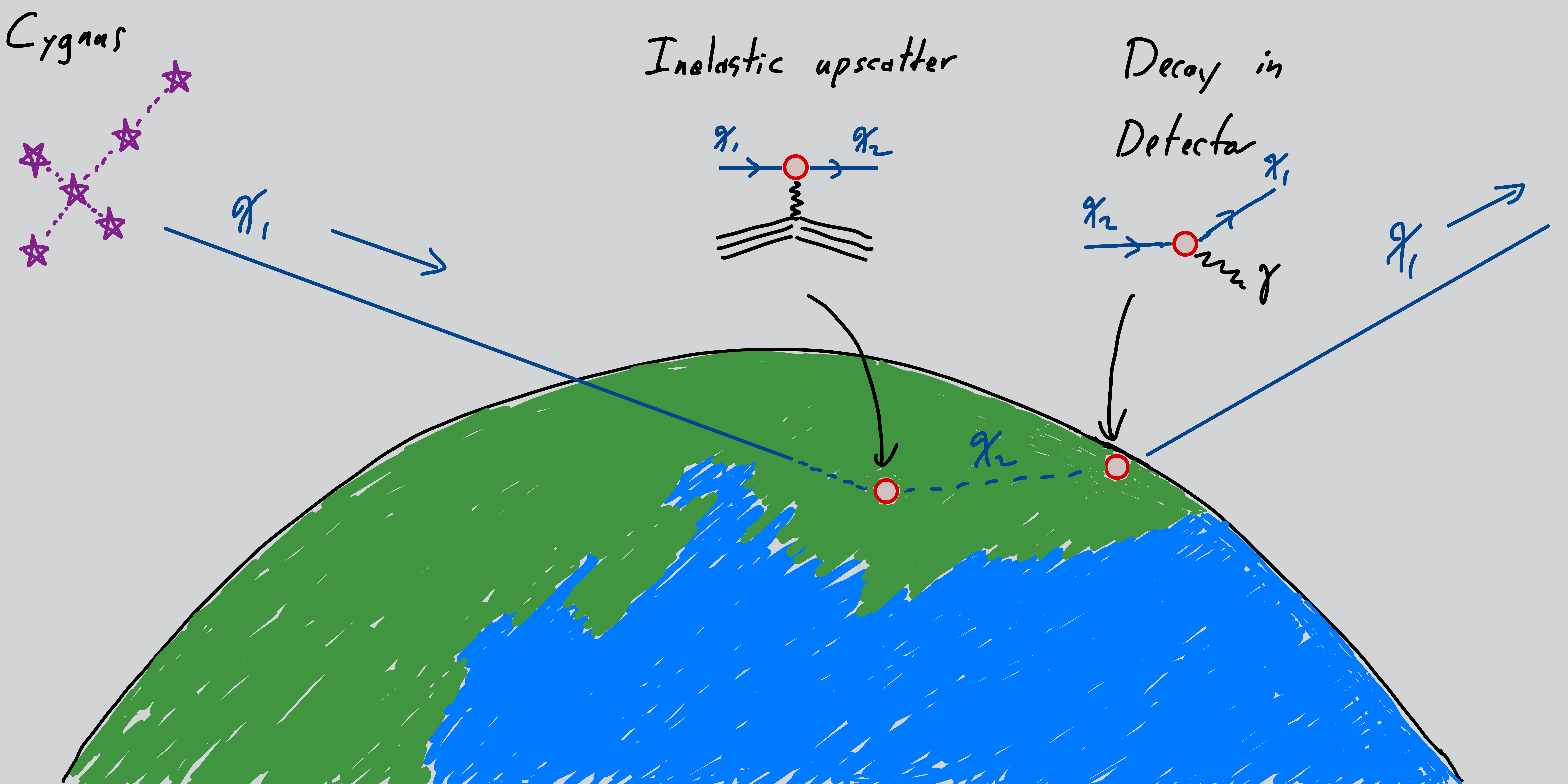
Upscatter off nuclei and χ_2 decay



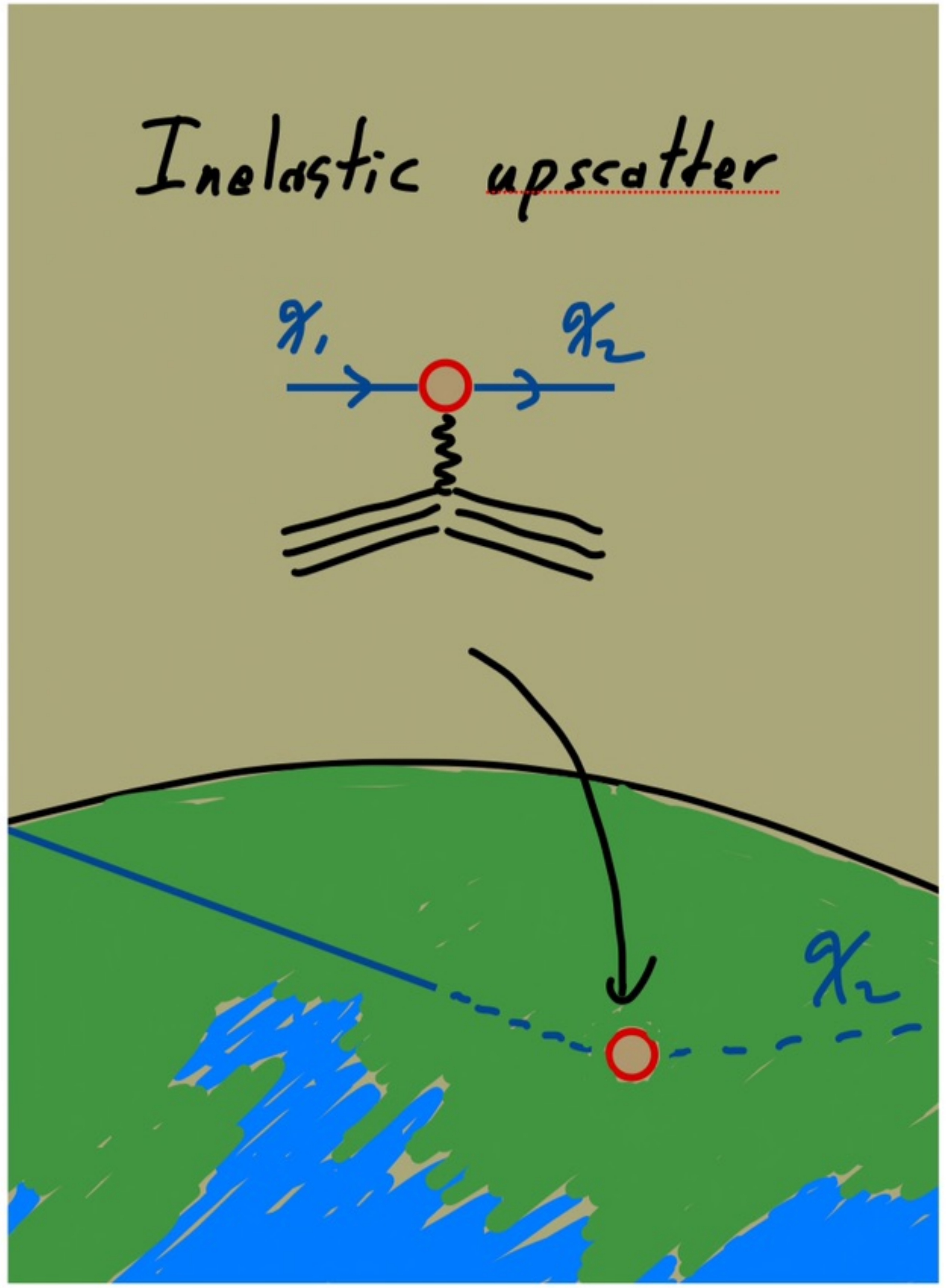


through the same magnetic dipole transition interaction.

Monoenergetic Photon Signal



Step 1:

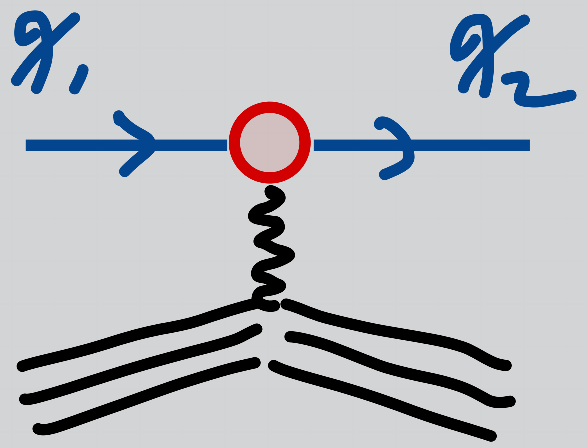


Inelastic Upscatter through Magnetic Dipole Transition

$$\langle N'|eJ^{\mu}_{em}|N\rangle \frac{g_{\mu\nu}}{Q^2} \langle \chi_2|J^{\nu}_{\mathrm{MDT}}|\chi_1\rangle$$

nucleon interaction

magnetic dipole transition



NR limit

Fitzpatrick / Haxton et al basis

$$\begin{aligned}
\mathcal{O}_1 &= \mathbb{1} \\
\mathcal{O}_4 &= \vec{S}_\chi \cdot \vec{S}_N \\
\mathcal{O}_5 &= i\vec{S}_\chi \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right) \\
\mathcal{O}_6 &= \left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left(\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right)
\end{aligned}$$

nonzero coefficients

$$\begin{aligned}
c_1^N &= \frac{Q_N e \tilde{\mu}_\chi}{2m_\chi}\,, \\
c_4^N &= \frac{g_N e \tilde{\mu}_\chi}{m_N}\,, \\
c_5^N &= -\frac{2Q_N e \tilde{\mu}_\chi m_N}{q^2}\,, \\
c_6^N &= -\frac{g_N e \tilde{\mu}_\chi m_N}{q^2}\,.
\end{aligned}$$

$\frac{1}{|q|^2}$

$$\mathcal{M}_{\chi,N} = c_1^N \mathcal{O}_1 + c_4^N \mathcal{O}_4 + c_5^N \mathcal{O}_5 + c_6^N \mathcal{O}_6$$

Nucleons → Nucleus

$$\frac{1}{(2j_\chi+1)(2j_\mathcal{N}+1)}\sum_{\text{spins}}|\mathcal{M}_{\text{NR}}|^2 = \frac{4\pi}{2j_\mathcal{N}+1}\sum_k\sum_{\substack{\tau=0,1\\ \tau'=0,1}} R_k^{\tau\tau'}\left(v_\mathcal{N}^{\perp\,2},\frac{q^2}{m_N^2},\delta,c_i\right)W_k^{\tau\tau'}(y)$$

Model dependence

$$R_M^{\tau\tau'} = c_1^\tau c_1^{\tau'} + \frac{|\vec{q}|^2}{4m_n^2}c_5^\tau c_5^{\tau'}\left(v_\mathcal{N}^2 - v_{\min\,\mathcal{N}}^2\right)$$

$$R_{\Sigma'}^{\tau\tau'} = \frac{c_4^\tau c_4^{\tau'}}{16},$$

$$R_\Delta^{\tau\tau'} = \frac{c_5^\tau c_5^{\tau'}|\vec{q}|^2}{4m_N^2},$$

$$R_{\Delta\Sigma'}^{\tau\tau'} = \frac{c_5^\tau c_4^{\tau'}}{4}.$$

(no dependance on c_6)

$$v_\mathcal{N}^{\perp\,2} = v_\chi^2 - v_{\min\,T}^2 \text{ with } v_{\min\,T}^2 = \left(\frac{q^2}{2\mu}+\delta\right)^2$$

Nuclear responses (isotope - dependent)

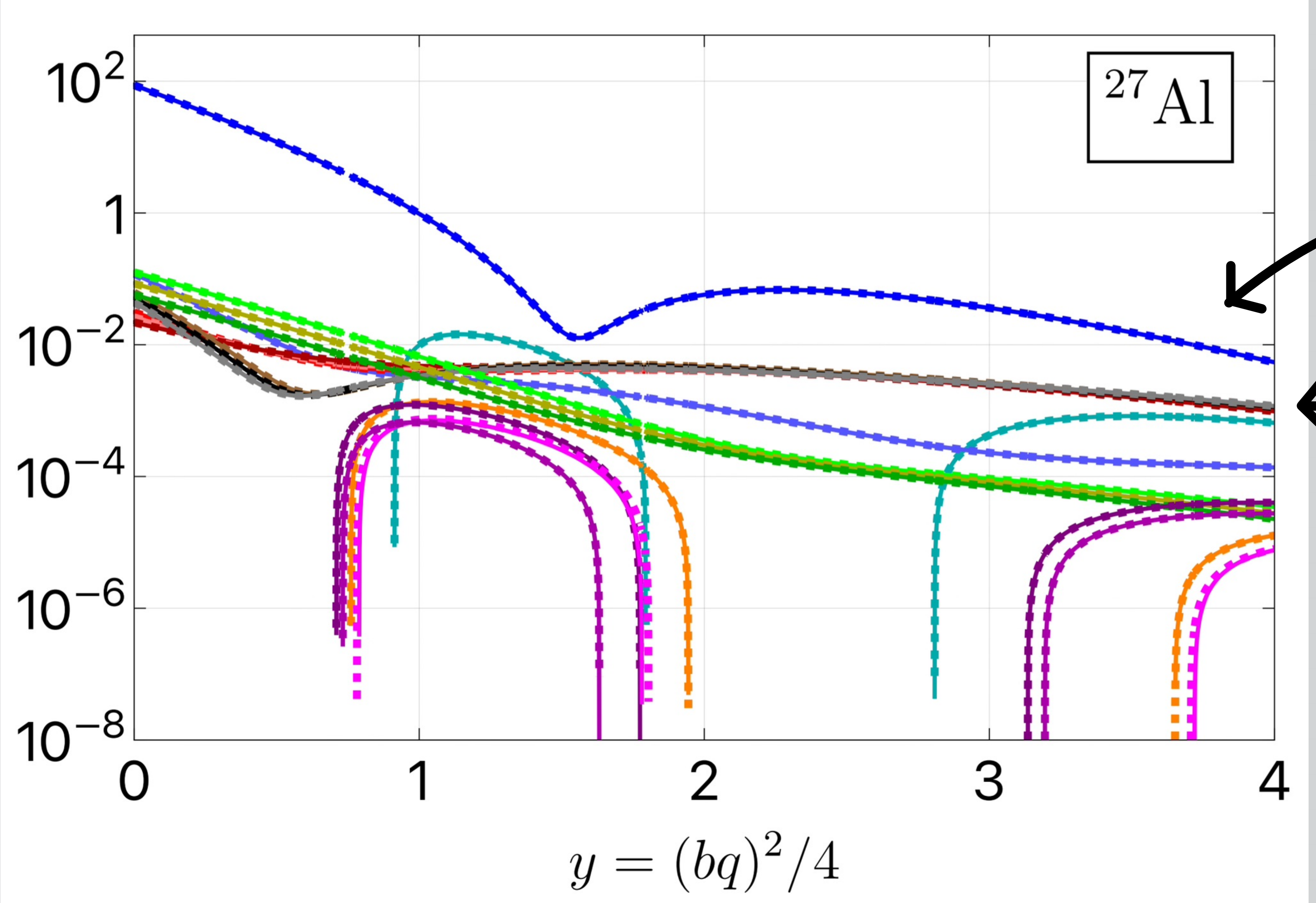
Minimum DM speed necessary to scatter with $E_R = \frac{q^2}{2\mu}$; δ

[Barello, Chang, Newby]

Nuclear Responses

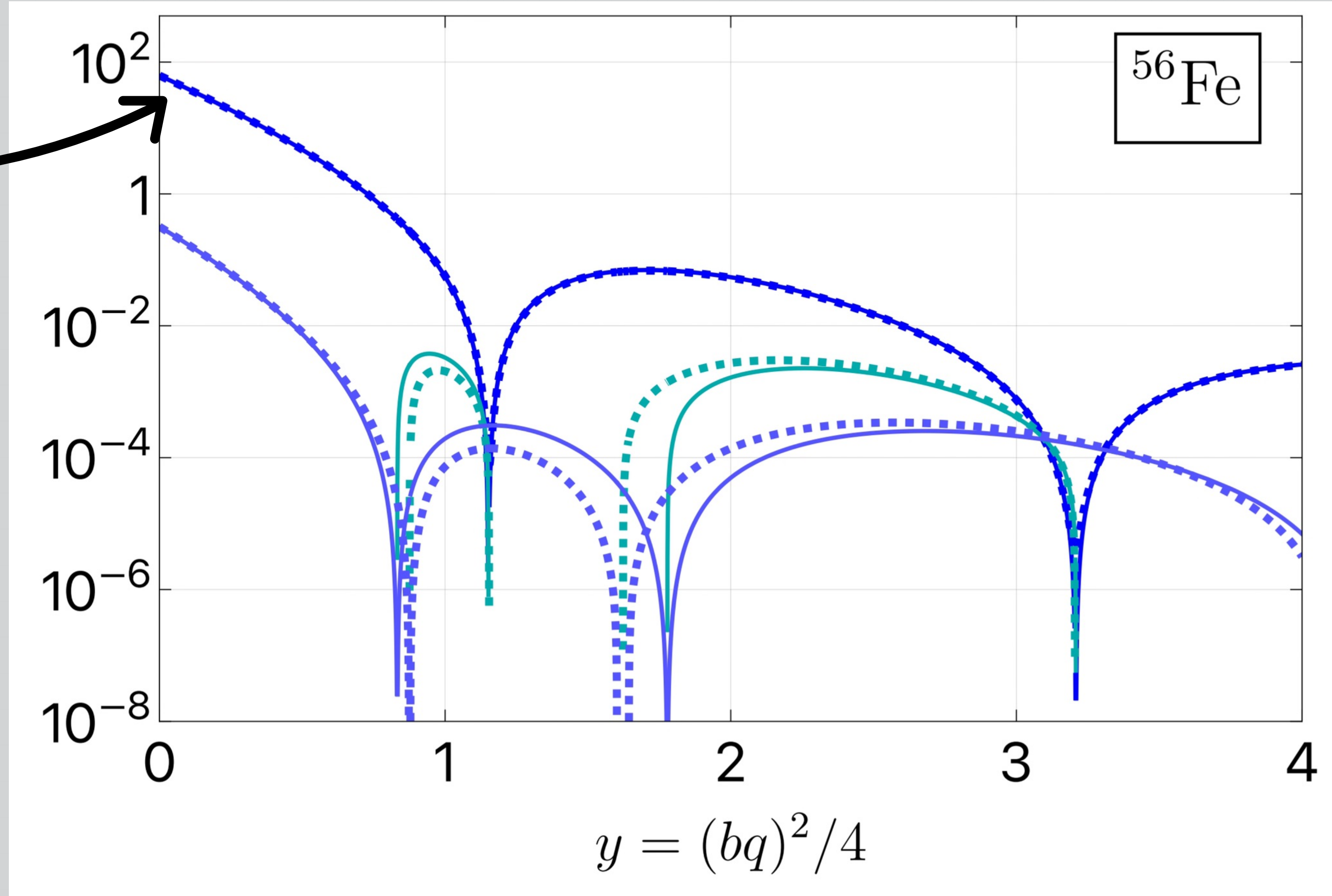
Fitzpatrick / Haxton ; Catena-Schwab ; Eby, Fox, GK :

$$W^{\tau\tau'}_{\mathcal{O}^A\mathcal{O}^B} = \sum_{J=0}^{\infty} \langle j_\mathcal{N} || \mathcal{O}^A_{J;\tau} || j_\mathcal{N} \rangle \langle j_\mathcal{N} || \mathcal{O}^B_{J;\tau'} || j_\mathcal{N} \rangle$$



W^{00}_{M}

$W^{00}_{\Sigma'}$



Our results, using BIGSTICK (nuclear shell model) [Johnson et al]

https://github.com/joshaeby/IsotopeResponses

Example : $\frac{dR}{dE_R}$ for ^{27}Al

$$\frac{1}{(2j_\chi+1)(2j_\mathcal{N}+1)}\sum_{\text{spins}}|\mathcal{M}_{\rm NR}|^2 = \frac{4\pi}{2j_\mathcal{N}+1}\sum_k\sum_{\substack{\tau=0,1\\ \tau'=0,1}} R_k^{\tau\tau'}\left(v_\mathcal{N}^{\perp 2}, \frac{q^2}{m_N^2}, \delta, c_i\right) W_k^{\tau\tau'}(y)$$

$$\frac{d\sigma^{Z,A}_{\rm MDT}}{d\cos\theta^{\rm cm}}(v^2,q^2) = \frac{\mu^2}{4\pi}\sqrt{1-\frac{2\delta}{\mu v^2}}\,\frac{1}{(2j_\chi+1)(2j_\mathcal{N}+1)}\sum_{\text{spins}}|\mathcal{M}_{\rm NR}|^2$$

$$\frac{dR^{Z,A}}{dE_R} = \frac{\rho_\chi N_T}{m_\chi}\int_{v_{\rm min}}^{v_{\rm max}} d^3v_{\rm MB}\, v\, f_{\rm gal}(v_{\rm MB})\frac{d\sigma^{Z,A}_{\rm MDT}}{dE_R}(v^2,q^2)$$

$$R_M^{\tau\tau'} = c_1^\tau c_1^{\tau'} + \frac{|\vec{q}|^2}{4m_n^2}c_5^\tau c_5^{\tau'}\left(v_\mathcal{N}^2 - v_{\min\mathcal{N}}^2\right)$$

$$R_{\Sigma'}^{\tau\tau'} = \frac{c_4^\tau c_4^{\tau'}}{16},$$

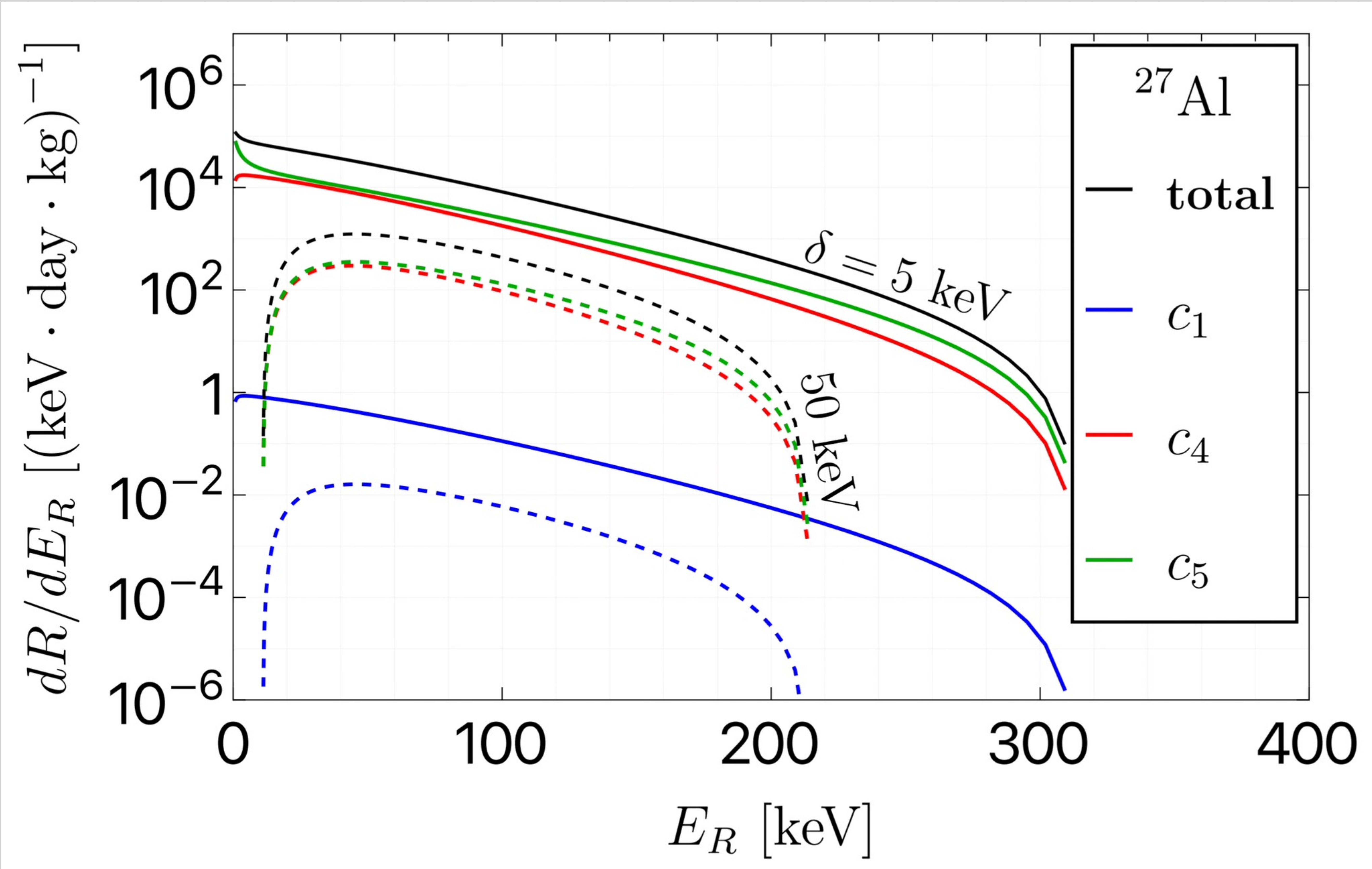
$$R_\Delta^{\tau\tau'} = \frac{c_5^\tau c_5^{\tau'}|\vec{q}|^2}{4m_N^2},$$

$$R_{\Delta\Sigma'}^{\tau\tau'} = \frac{c_5^\tau c_4^{\tau'}}{4}.$$

$\mathcal{O}_5$ DM spin / nuclear angular momentum

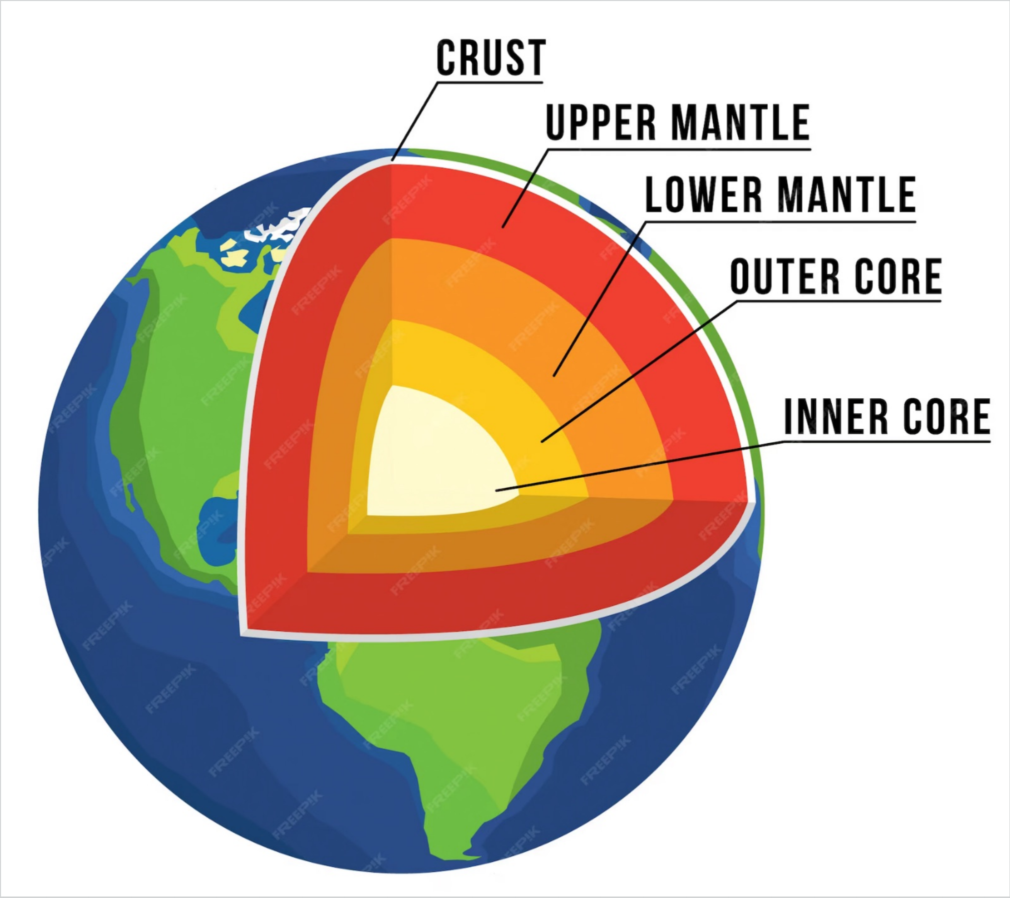
$\mathcal{O}_4$ DM spin / nuclear spin

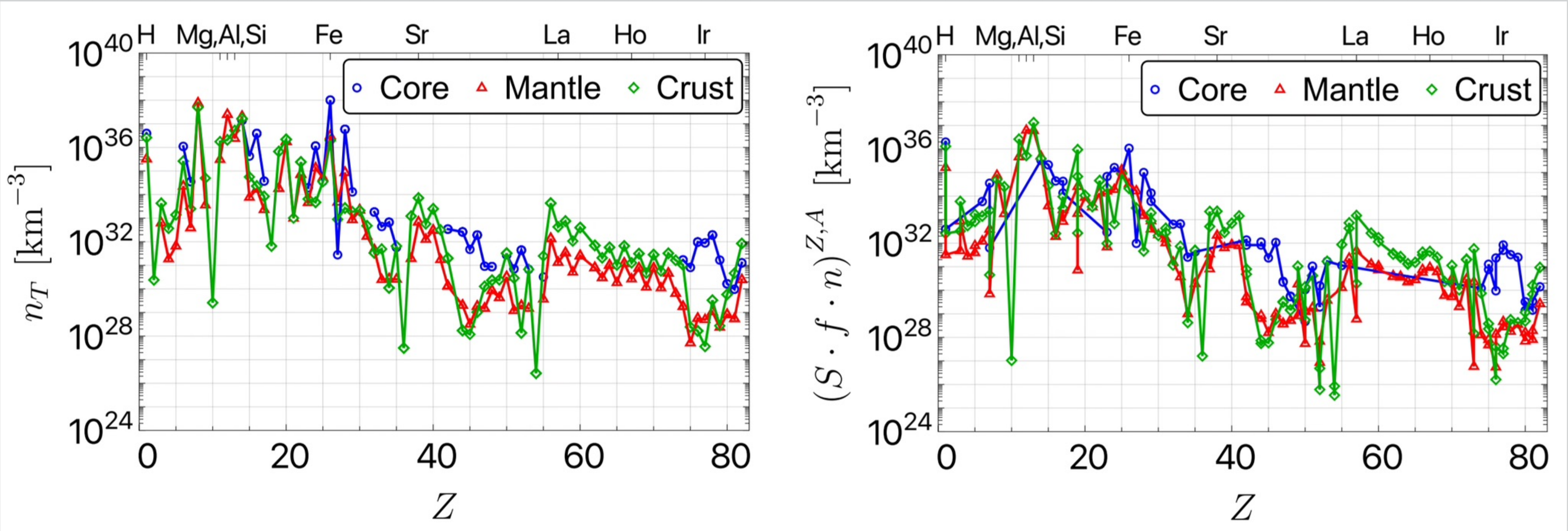
dominate the nuclear responses.



Which Elements Dominate Scattering?

number density — spin-weighted number density





The answer depends on many critical details:

- Inelasticity: larger δ requires larger A
- Spin dependence: isotopes with higher spin have $\mathcal{O}_4$ contributions
- Scattering location: abundances vary within the Earth

Major Importance

^{27}Al

- Large abundance
- High spin ($\mathcal{O}_4$) & $\mathcal{O}_5$
- Scattering $\delta \lesssim 75$ keV

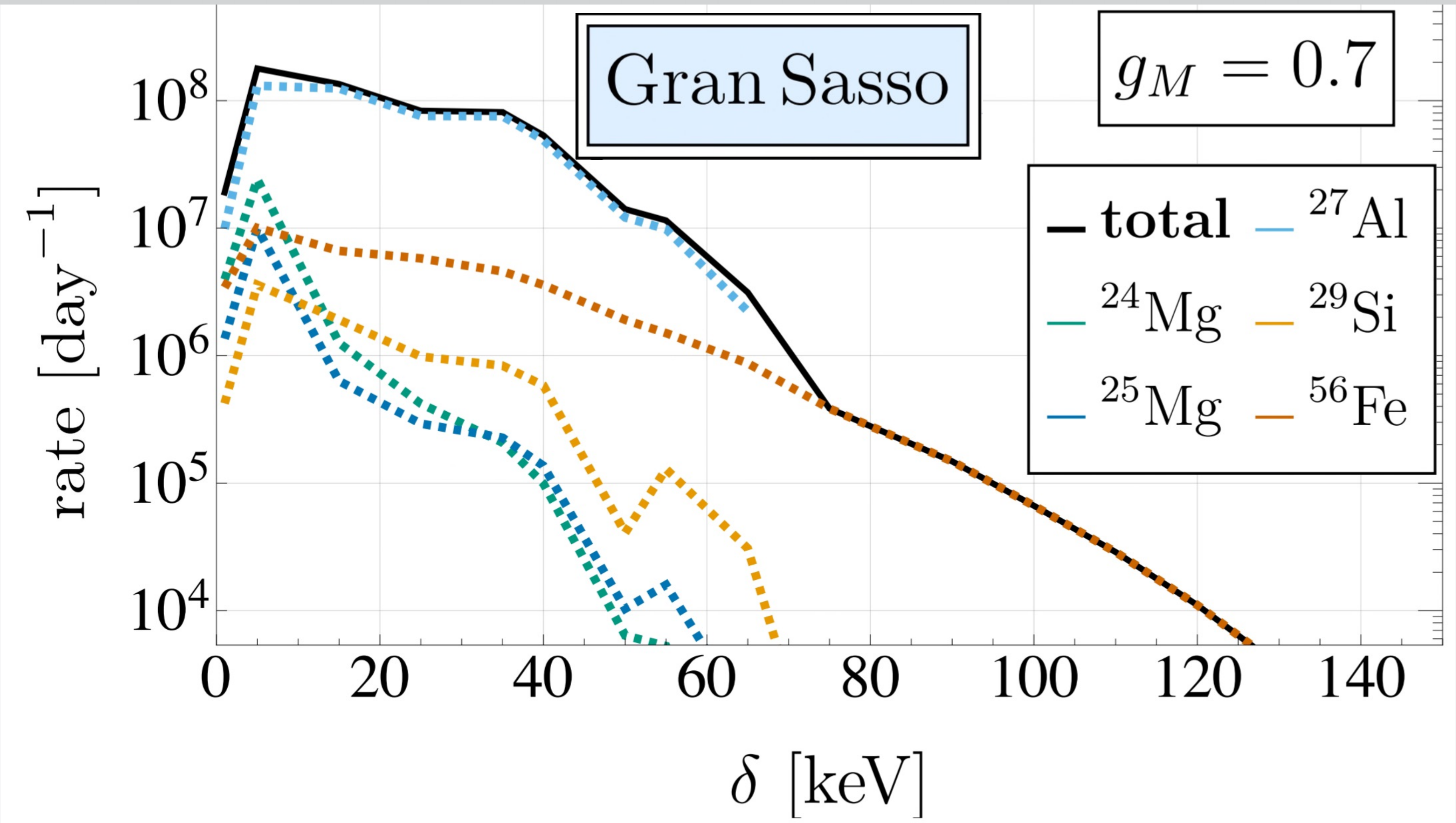
^{56}Fe

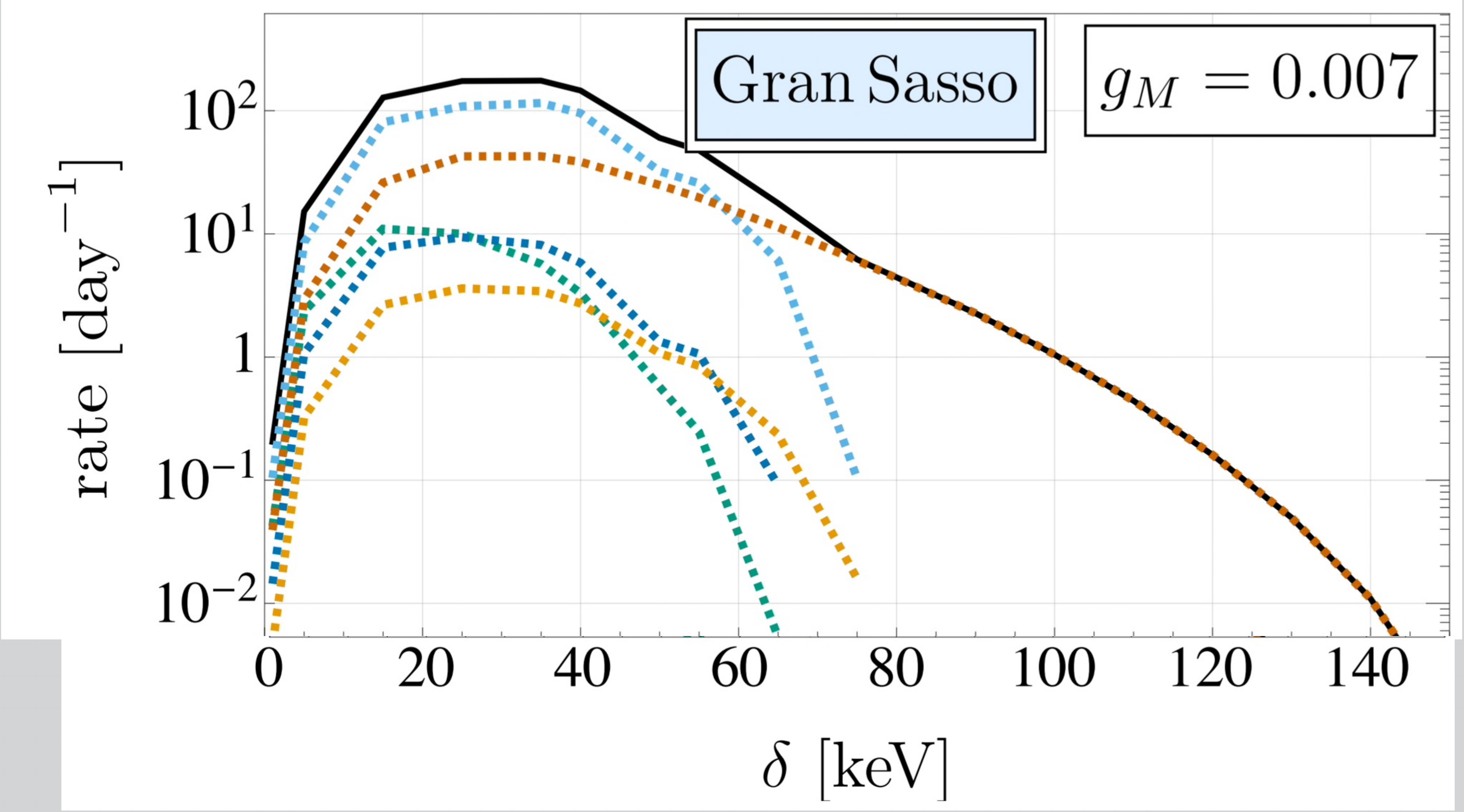
- Large abundance
- No spin ($\mathcal{O}_5$)
- Scattering $\delta \lesssim 150$ keV

^{2xx}Pb

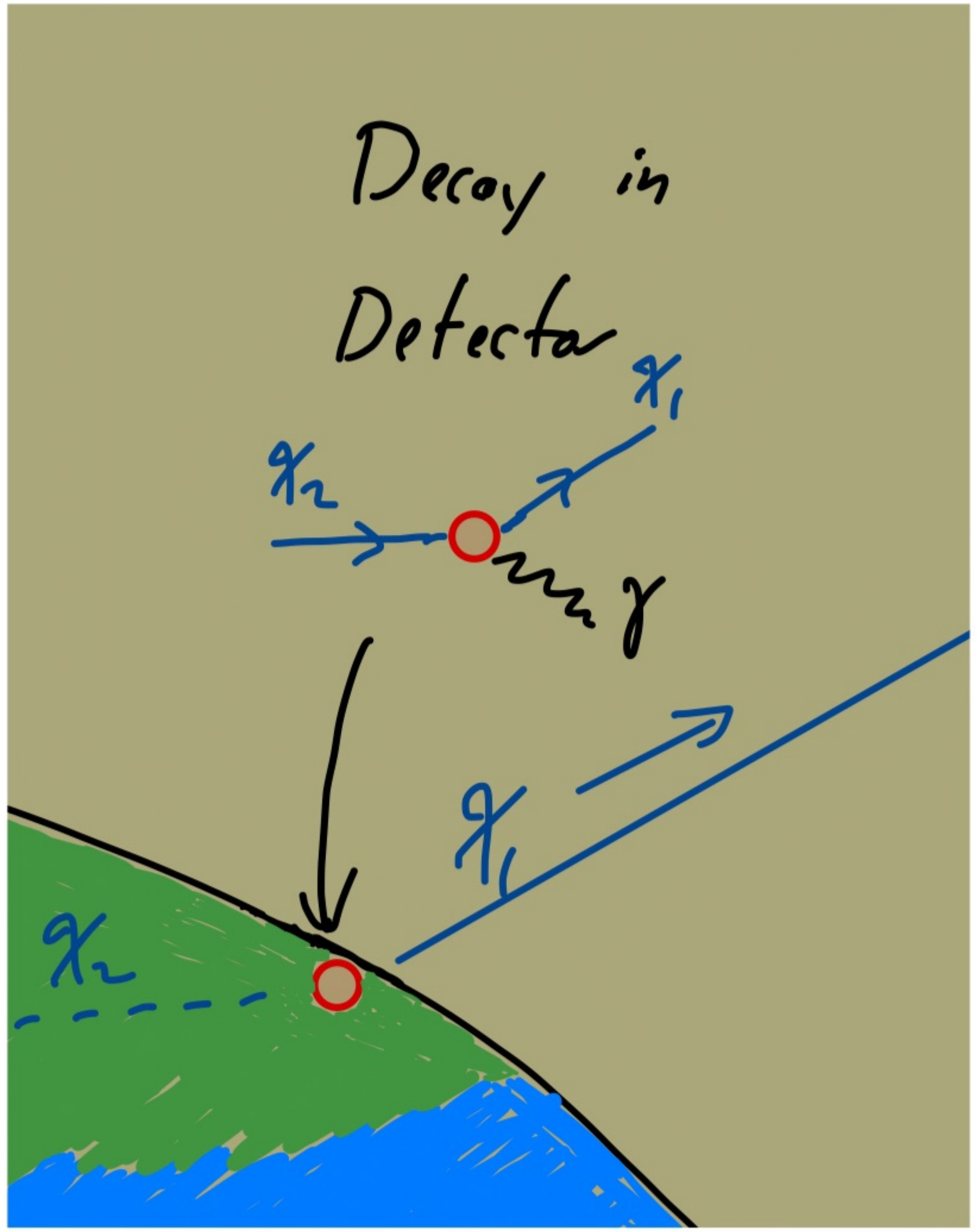
$150 \lesssim \delta \lesssim 400$ keV

[1904.09994]





Step 2:

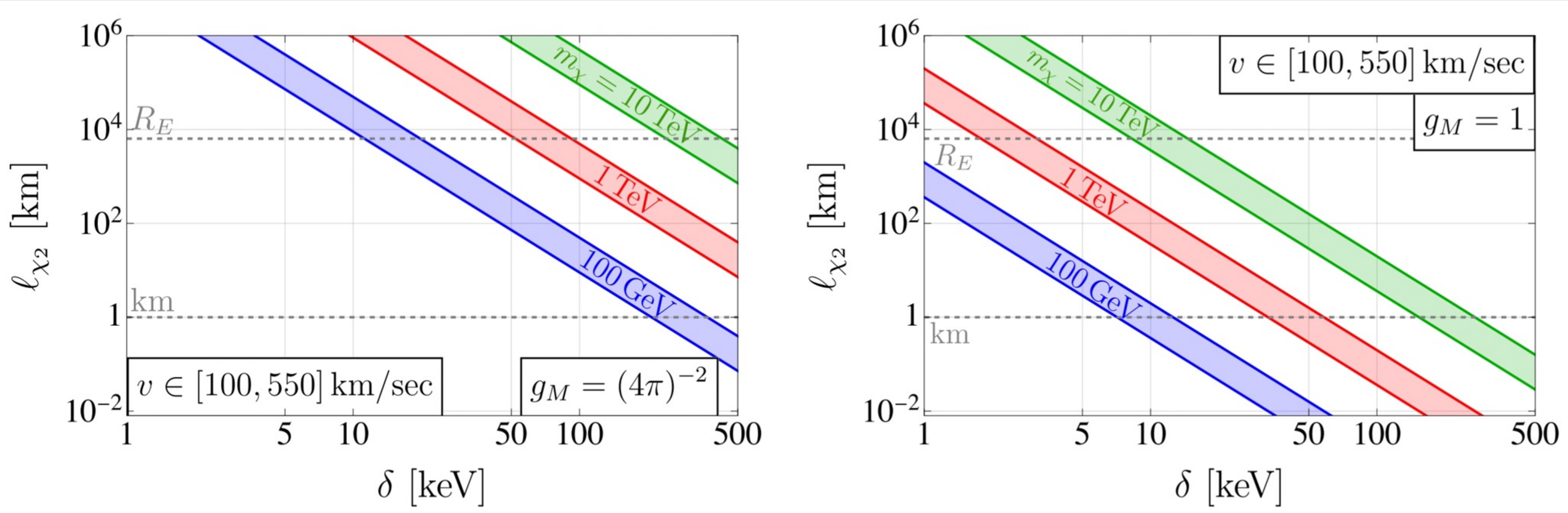


Excited State Decay

$\chi_2 \to \chi_1 + \gamma$ characteristic decay length

$$\ell_{\chi_2} = v\,\tau_2 \simeq (1\text{ km}) \times \left(\frac{0.1}{g_M}\right)^2 \left(\frac{m_\chi}{\text{TeV}}\right)^2 \left(\frac{250\,\text{keV}}{\delta}\right)^3 \left(\frac{v}{450\,\text{km/sec}}\right)$$

$g_M = \frac{1}{16\pi^2}$ $g_M = 1$



← Earth radius

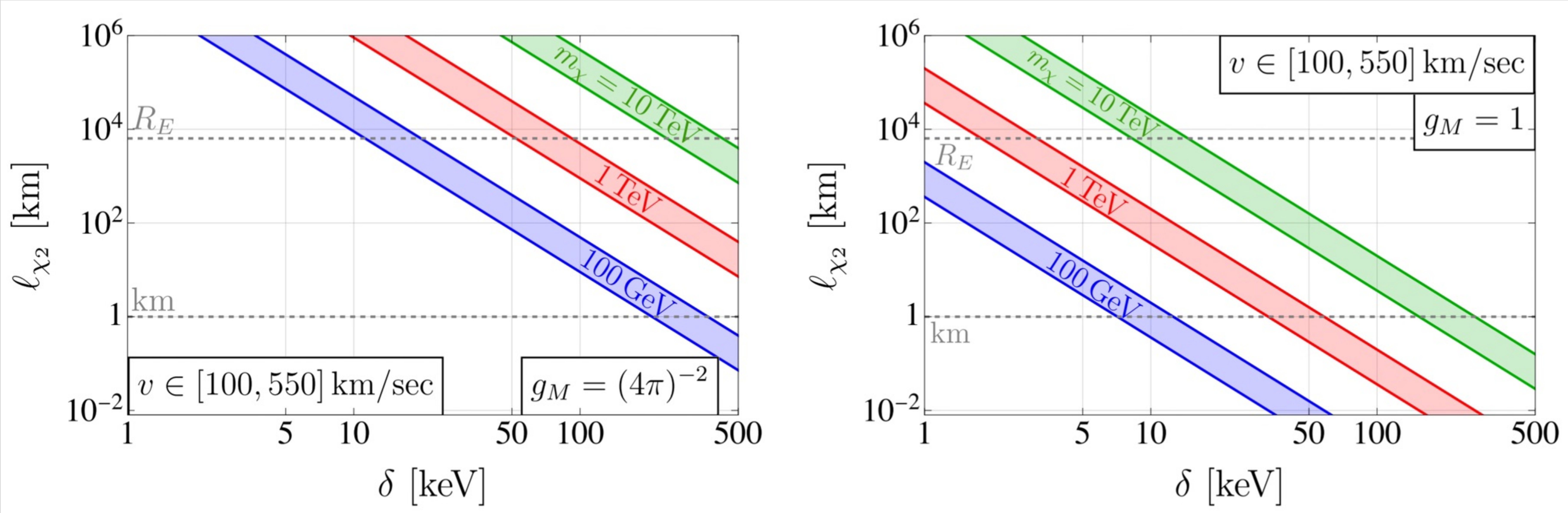
← detector depth

Upshot

Broad parameter space (m_χ, g_M, δ) where

size of detector $\ll \ell_{\chi_2} \lesssim$ radius of Earth

$g_M = \frac{1}{16\pi^2}$ $\qquad$ $g_M = 1$

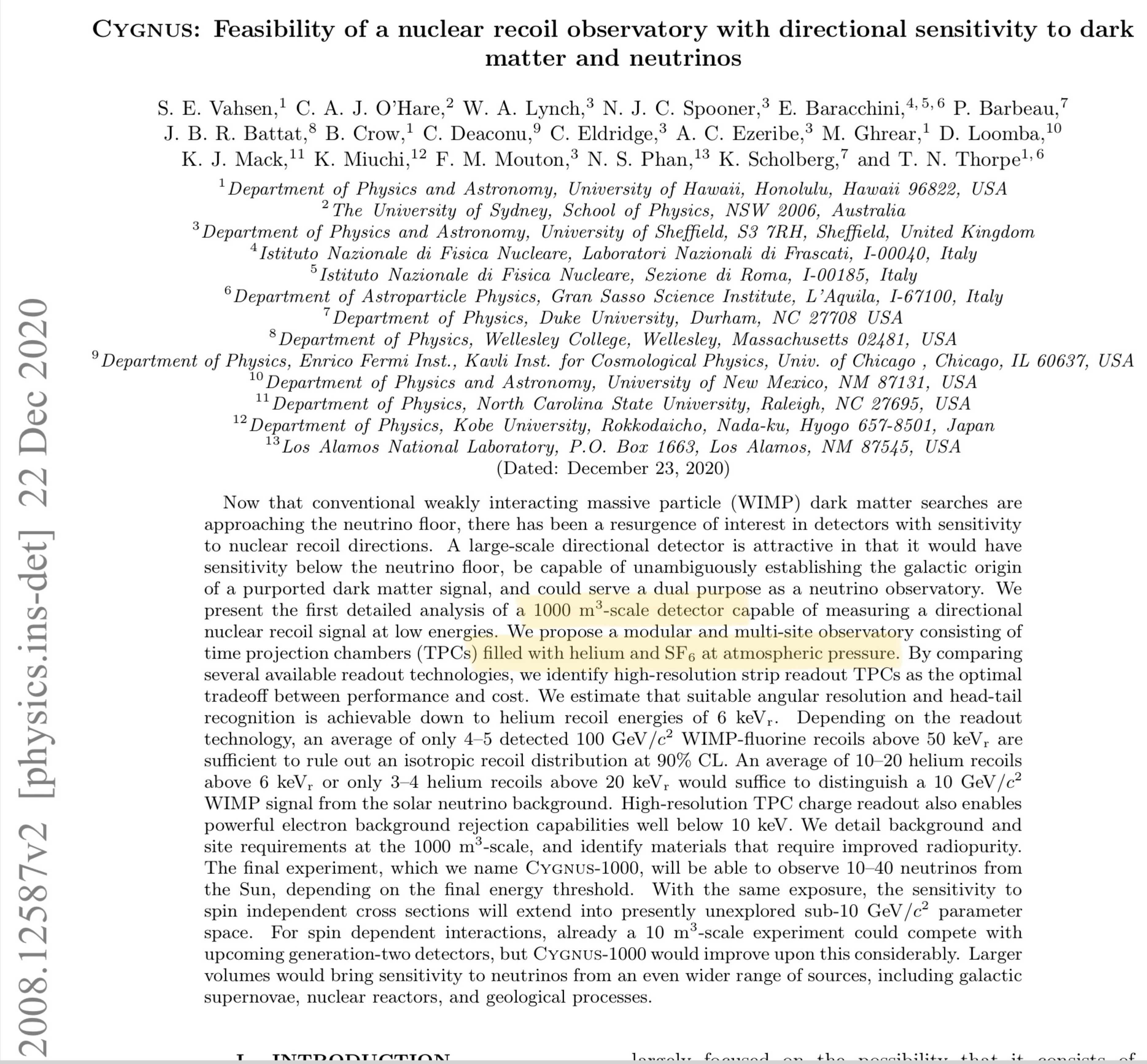


← Earth radius

← detector depth

Detection

Large volume (not mass) gaseous detector is ideal:



CYGNUS: Feasibility of a nuclear recoil observatory with directional sensitivity to dark matter and neutrinos

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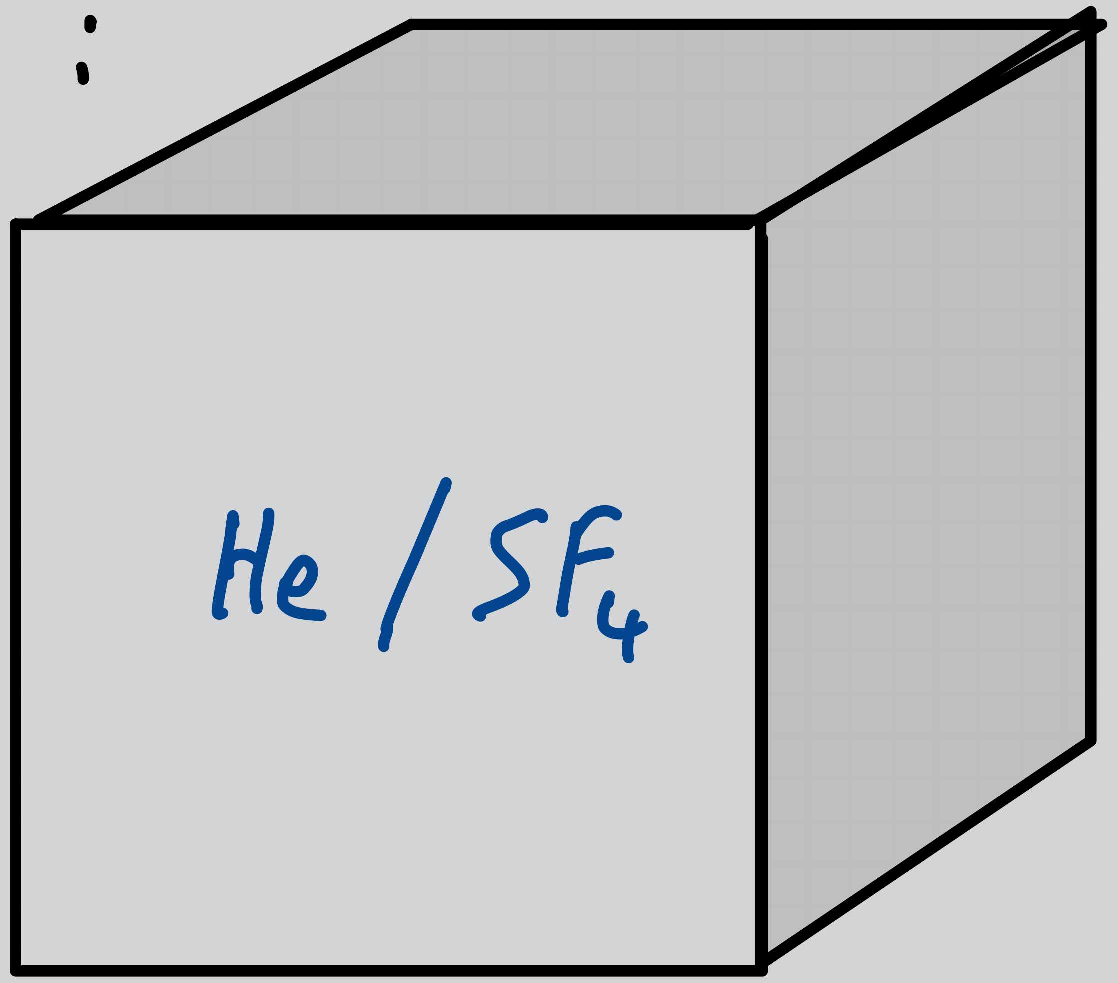
(Dated: December 23, 2020)

Now that conventional weakly interacting massive particle (WIMP) dark matter searches are approaching the neutrino floor, there has been a resurgence of interest in detectors with sensitivity to nuclear recoil directions. A large-scale directional detector is attractive in that it would have sensitivity below the neutrino floor, be capable of unambiguously establishing the galactic origin of a purported dark matter signal, and could serve a dual purpose as a neutrino observatory. We present the first detailed analysis of a 1000 m^3-scale detector capable of measuring a directional nuclear recoil signal at low energies. We propose a modular and multi-site observatory consisting of time projection chambers (TPCs) filled with helium and SF_6 at atmospheric pressure. By comparing several available readout technologies, we identify high-resolution strip readout TPCs as the optimal tradeoff between performance and cost. We estimate that suitable angular resolution and head-tail recognition is achievable down to helium recoil energies of 6 keV_r. Depending on the readout technology, an average of only 4–5 detected 100 GeV/c^2 WIMP-fluorine recoils above 50 keV_r are sufficient to rule out an isotropic recoil distribution at 90% CL. An average of 10–20 helium recoils above 6 keV_r or only 3–4 helium recoils above 20 keV_r would suffice to distinguish a 10 GeV/c^2 WIMP signal from the solar neutrino background. High-resolution TPC charge readout also enables powerful electron background rejection capabilities well below 10 keV. We detail background and site requirements at the 1000 m^3-scale, and identify materials that require improved radiopurity. The final experiment, which we name CYGNUS-1000, will be able to observe 10–40 neutrinos from the Sun, depending on the final energy threshold. With the same exposure, the sensitivity to spin independent cross sections will extend into presently unexplored sub-10 GeV/c^2 parameter space. For spin dependent interactions, already a 10 m^3-scale experiment could compete with upcoming generation-two detectors, but CYGNUS-1000 would improve upon this considerably. Larger volumes would bring sensitivity to neutrinos from an even wider range of sources, including galactic supernovae, nuclear reactors, and geological processes.

2008.12587v2 [physics.ins-det] 22 Dec 2020

CYGNUS proposal:

$1000\ m^3$



Threshold: few keV_{ee}

E-resolution: $\frac{\sigma_E}{E} \simeq 10\% \sqrt{\frac{5.9\,keV_{ee}}{E}}$

Backgrounds: 10^4 electron events/keV/year

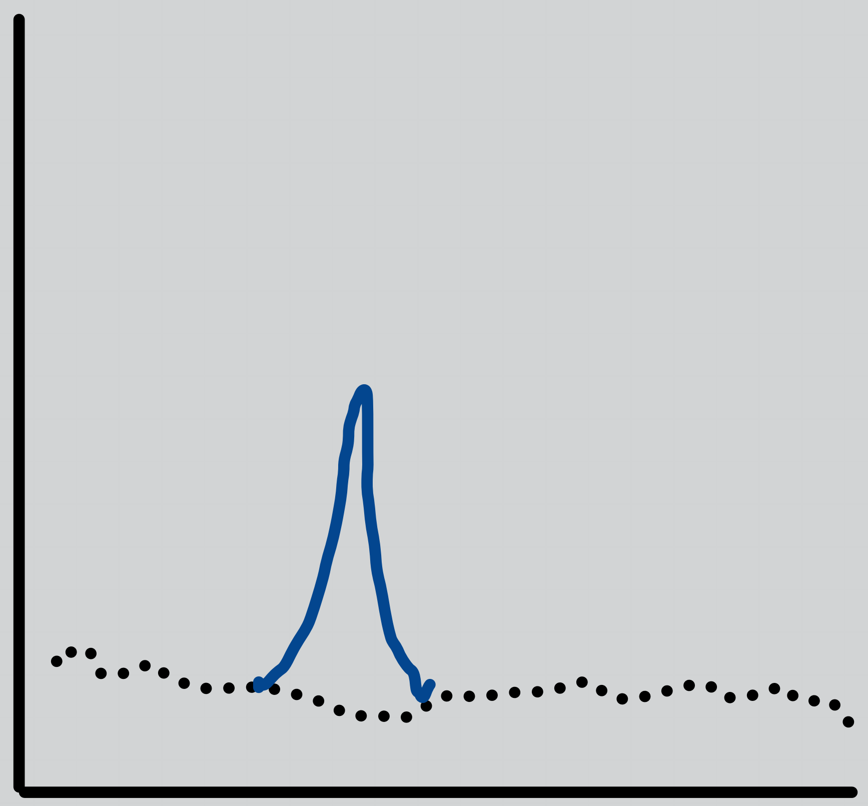
We utilize the volume, not the directionality!

Monoenergetic Photon Signal

Rate:

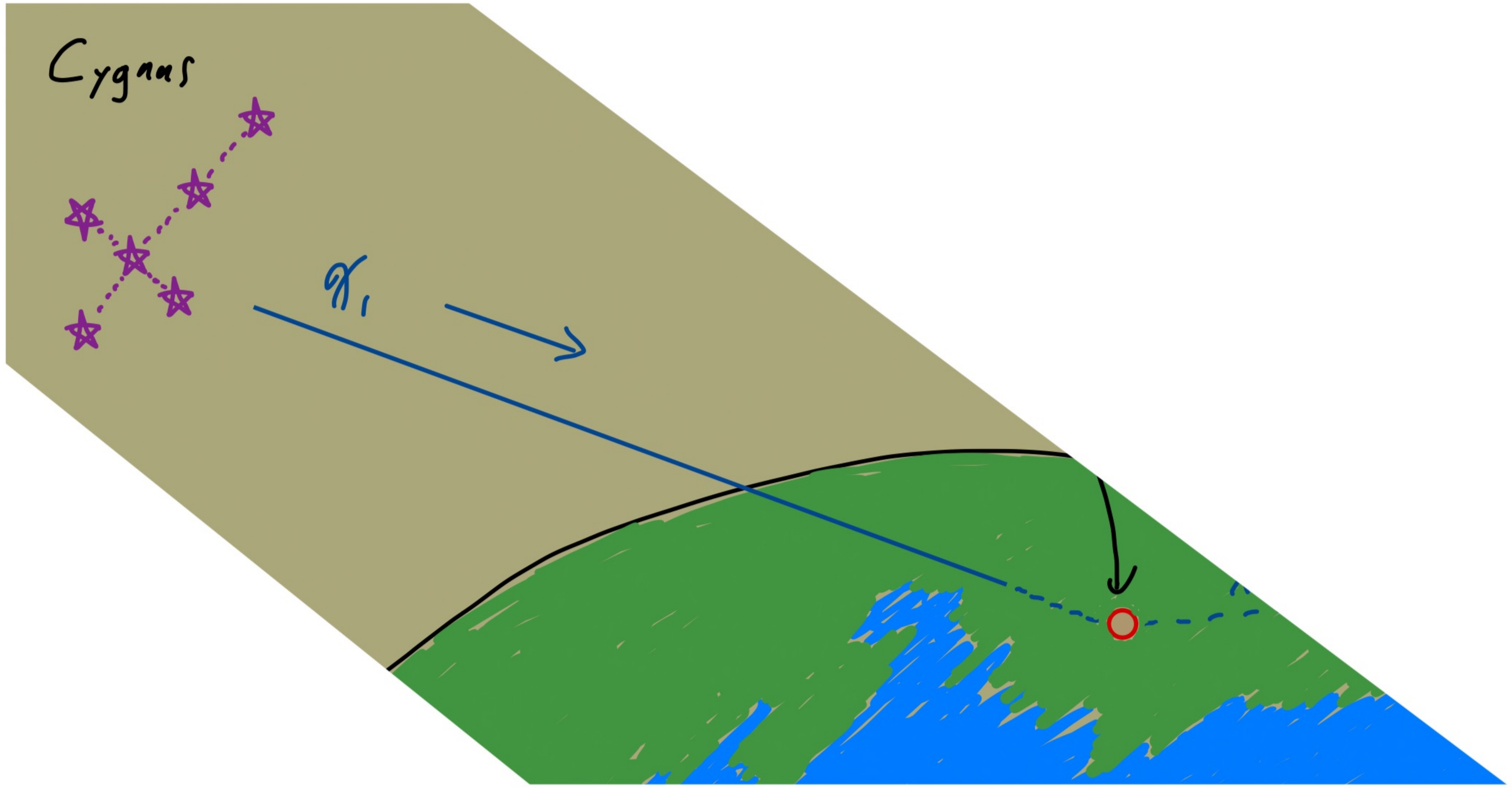
$$\Gamma^{Z,A} = \sum_{\pm} \int d^3 r_s\, d^3 v_{\rm MB} \left\{ n^{Z,A}(r_s)\, \frac{\rho_\chi}{m_\chi} \left[\frac{R_D}{|\vec{r}_s - \vec{r}_D|\ \theta^{\rm lab}_{\rm max}} \right]^2 P(v^{\rm lab}_{{\rm out},\pm}, L, \tau_2) \right.$$
$$\left. \times v\, f_{\rm gal}(v_{\rm MB})\, \frac{d\sigma^{Z,A}_{\rm MDT}(v^2, q^2_\pm)}{d\cos\theta^{\rm cm}}\, |J_\pm(v)| \right\}.$$

The key is finding the monoenergetic photon signal above backgrounds.



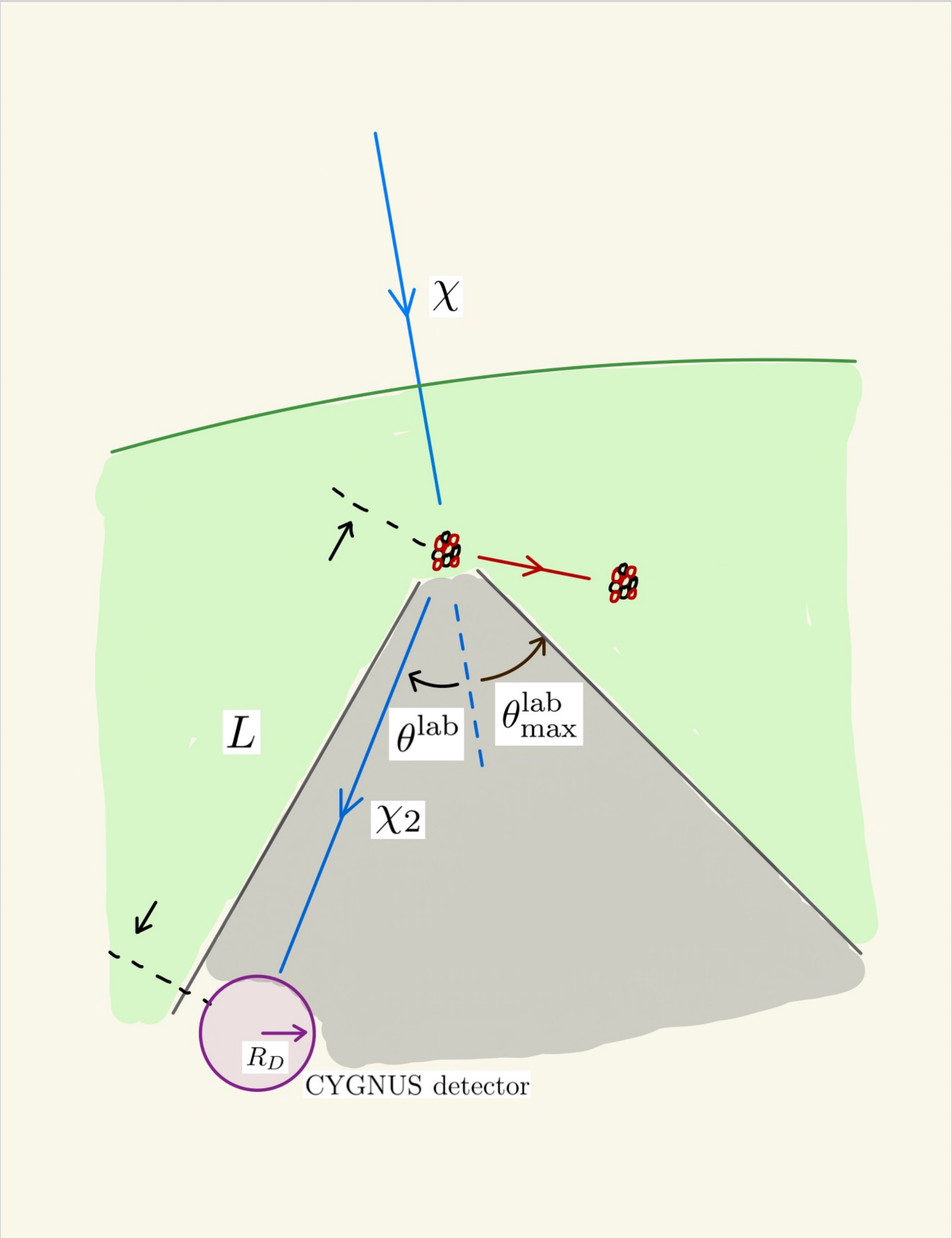
We utilized the fact that our signal rate depends strongly on the amount of rock overburden (allowing DM to upscatter)

Step 3

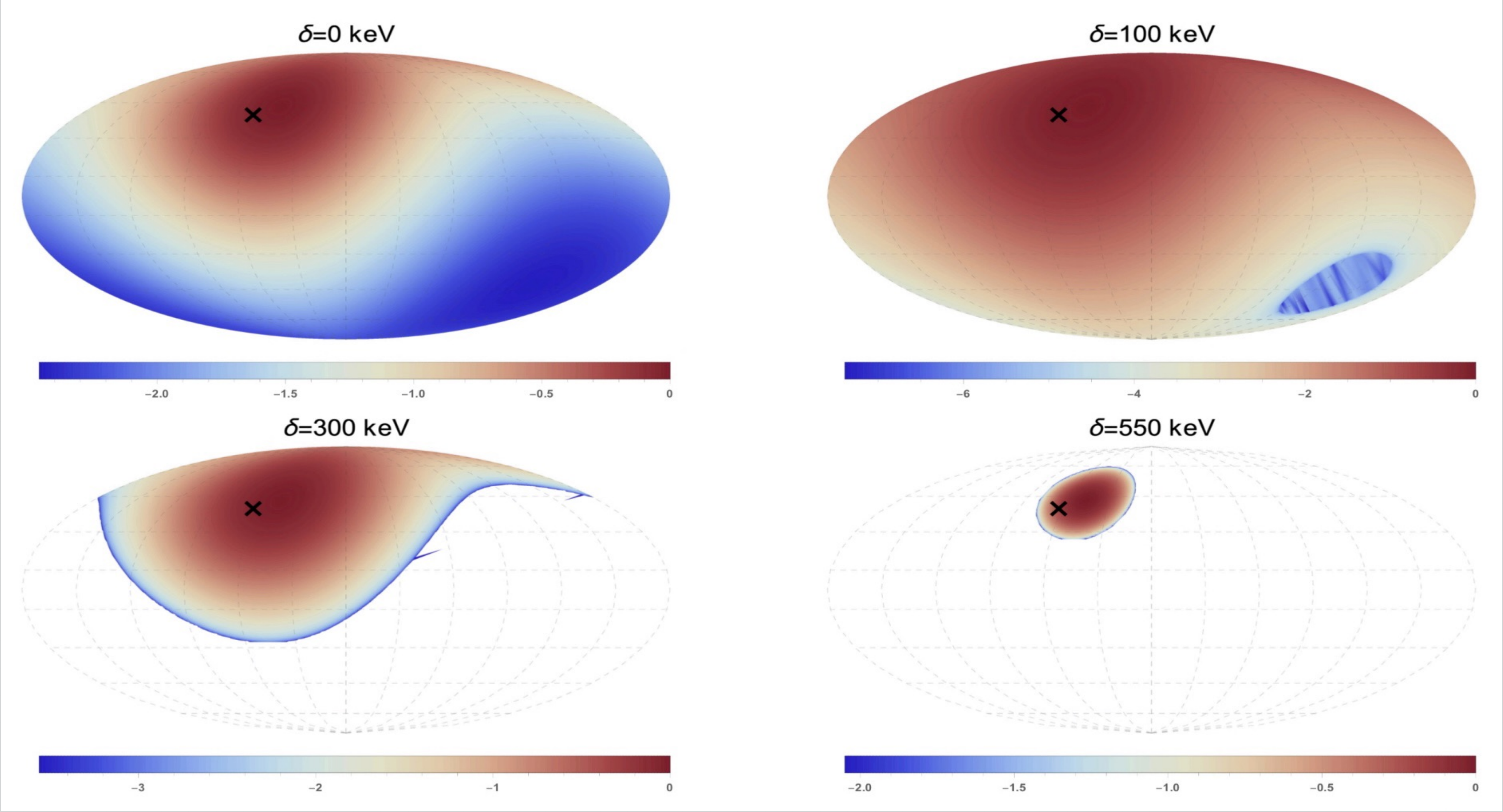


Directionality of (Inelastic) Dark Matter

Heavy DM ($m_{\chi_1} \gtrsim m_{nucleus}$) will upscatter with χ_2 heading largely in direction of initial χ_1.

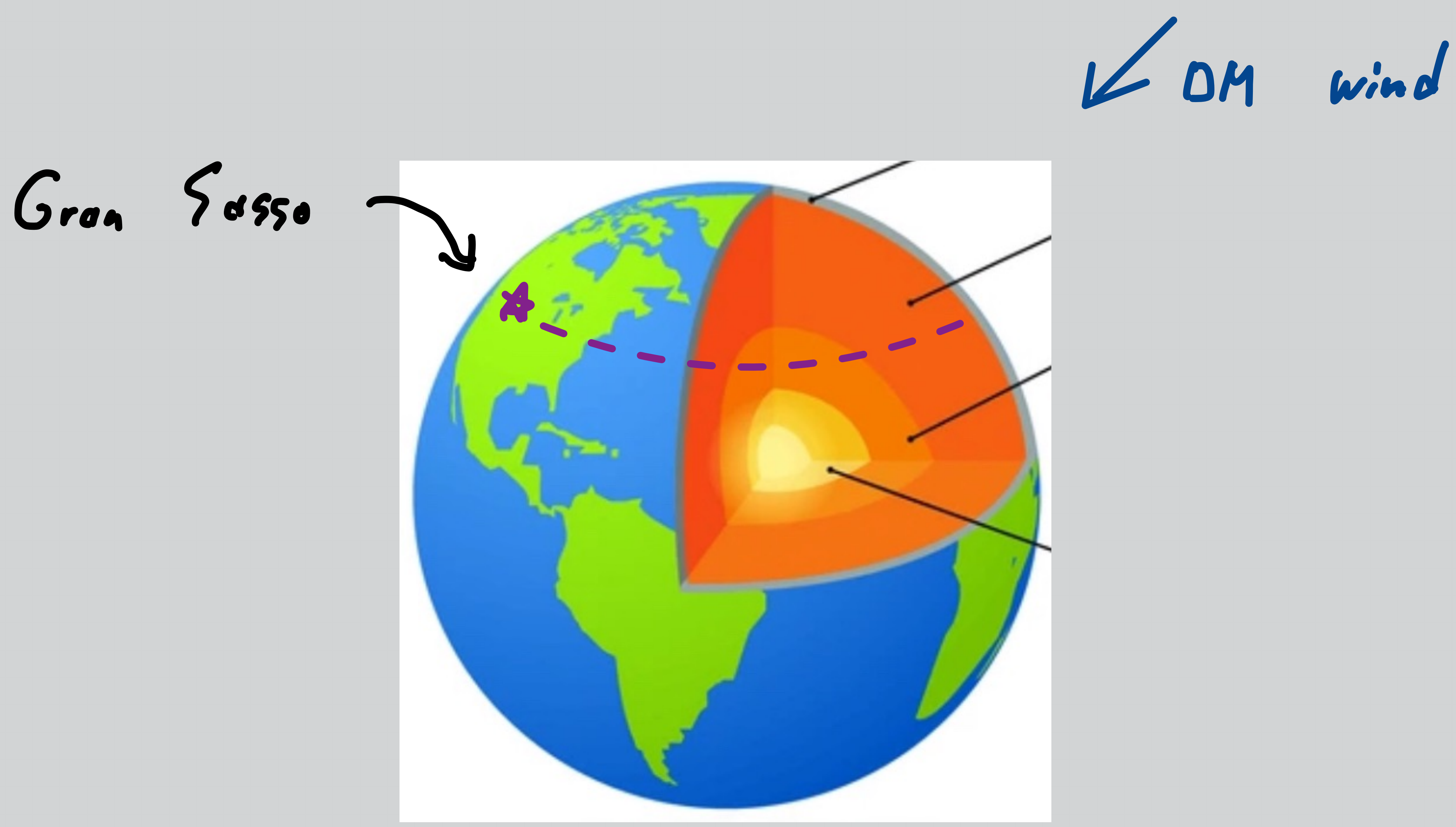


DM dominantly coming toward us from Cygnus constellation, enhanced by the inelasticity.



[Bramante, Fox, GK, Martin, 1608.02662]

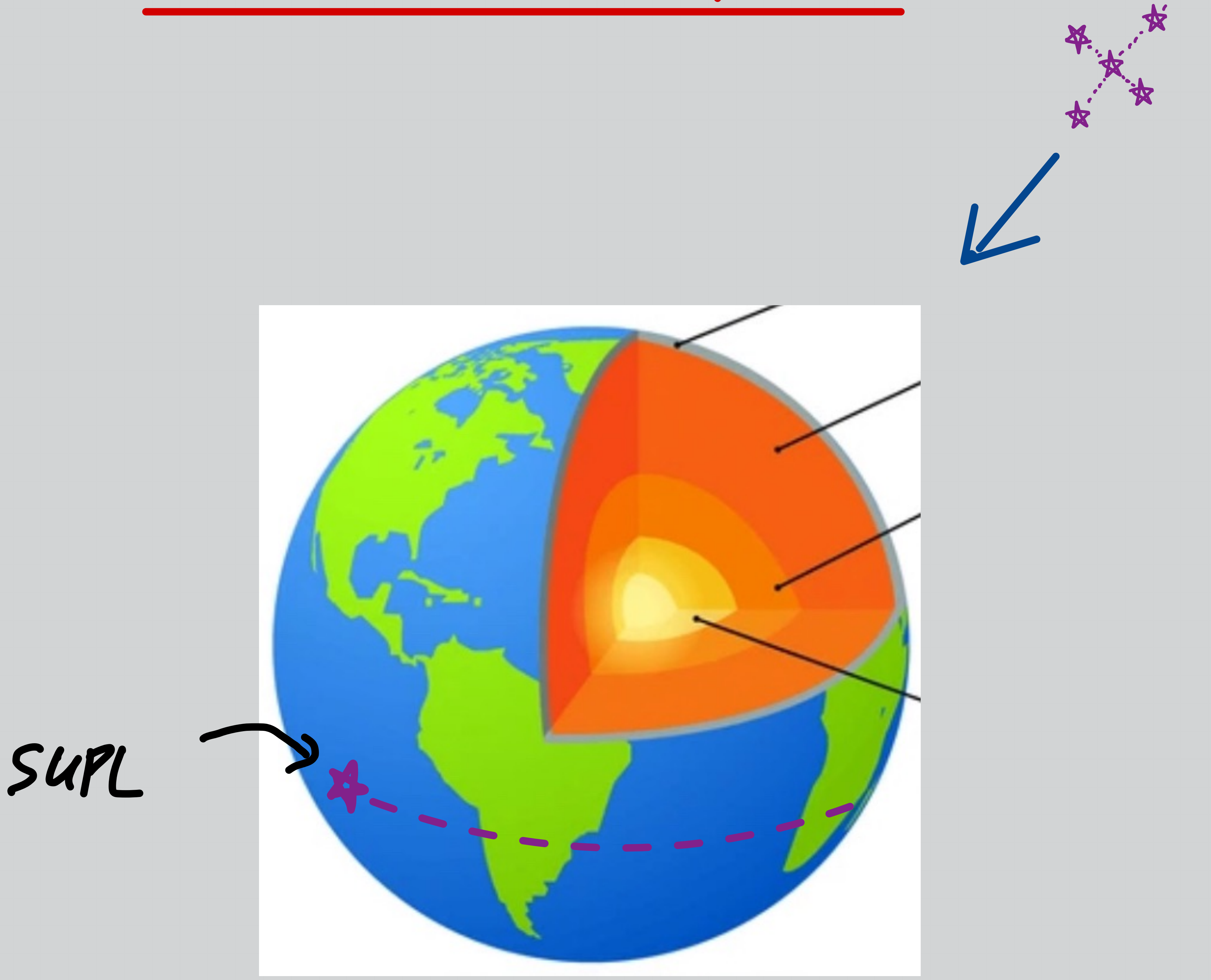
Northern Hemisphere



DM can scatter in the crust

(Cygnus above horizon most of the day)

Southern Hemisphere

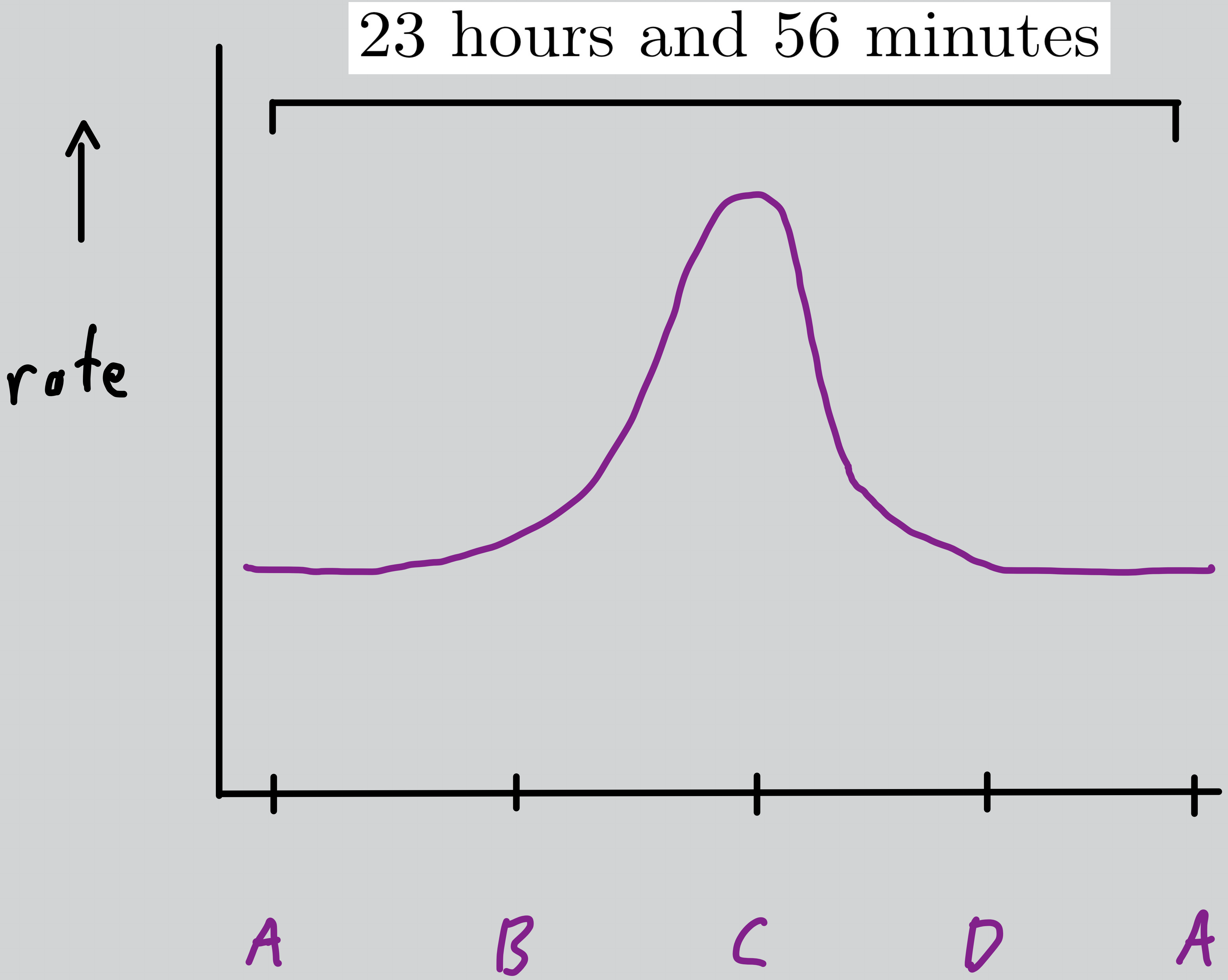


DM can scatter in the entire Earth

(Cygnus below horizon most of the day)

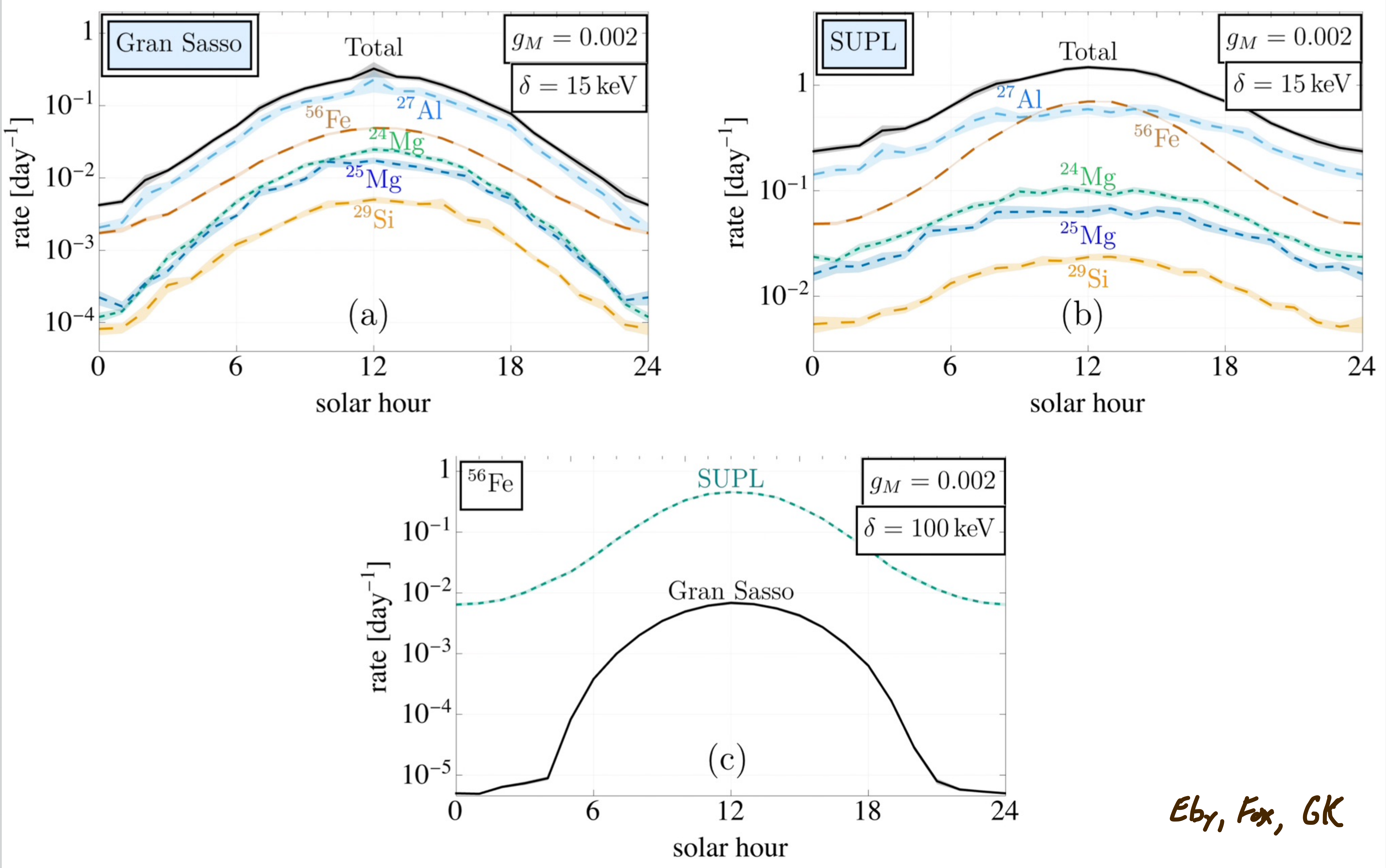
Signal rates larger for detector @ SUPL

Sidereal Daily Modulation



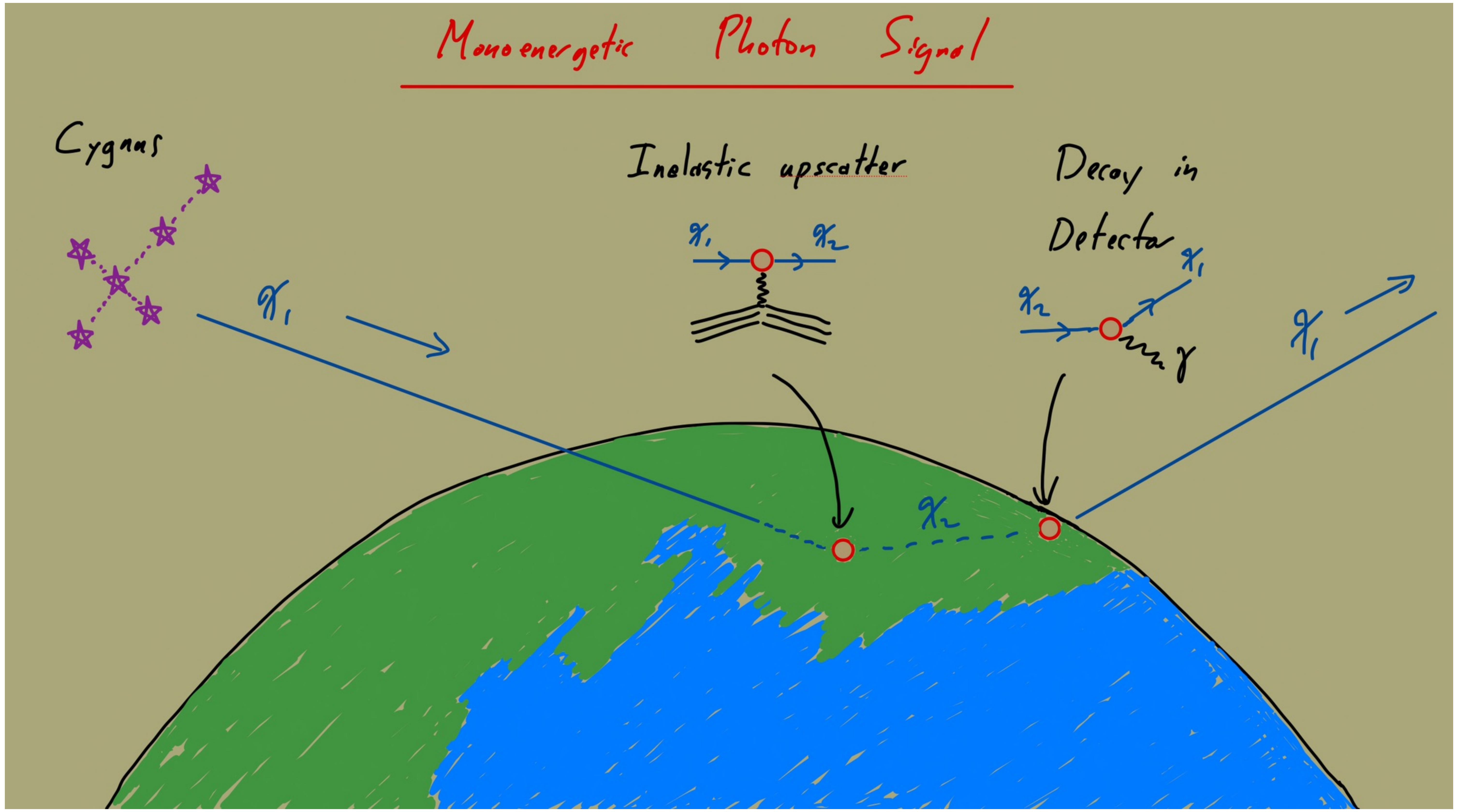
Outstanding method to separate signal from backgrounds.

Sidereal Daily Modulation Rates



Eby, Fox, GK

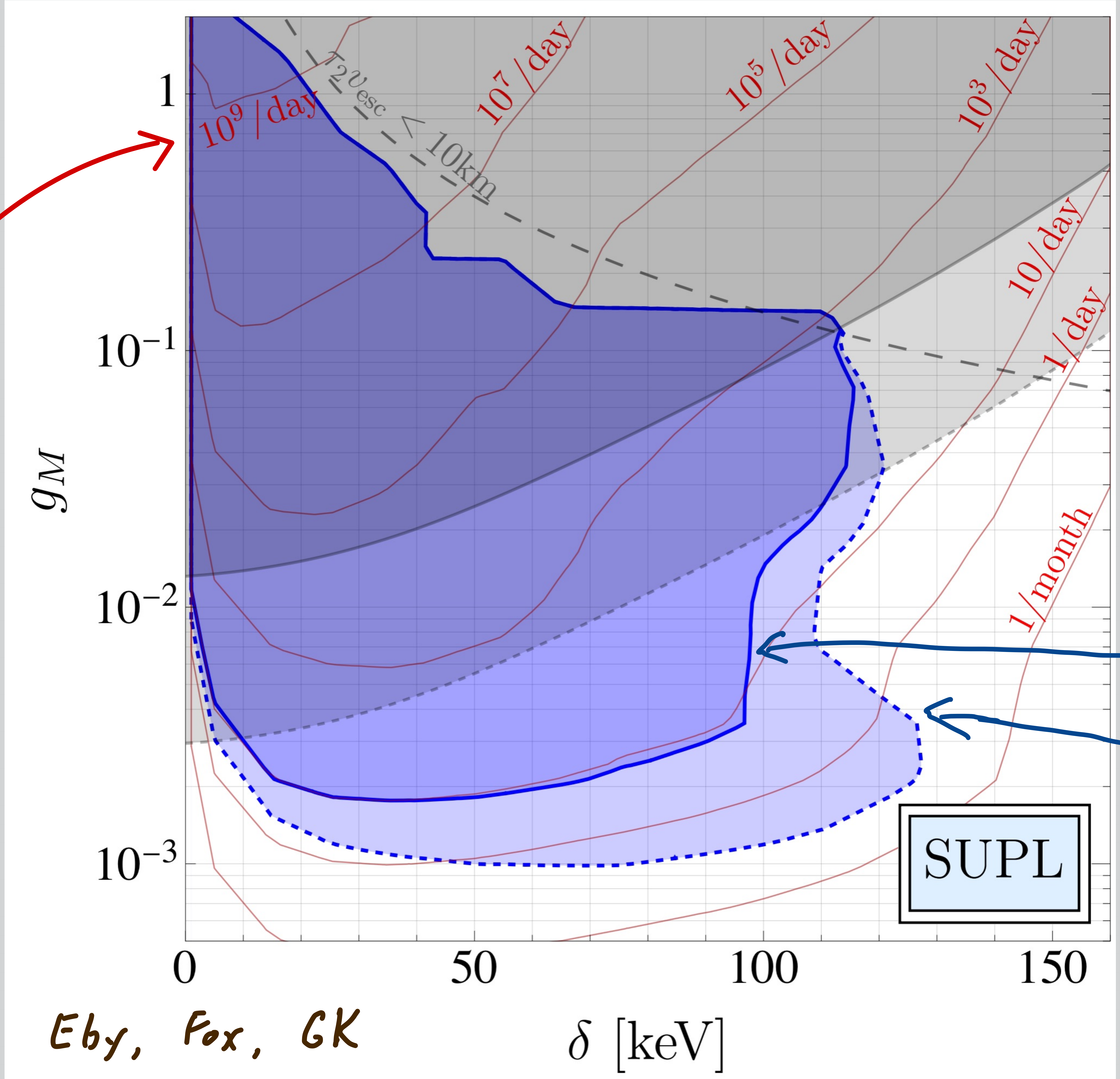
Put all the parts together



Projected Sensitivity

m_{χ_1} = 1 TeV

Cygnus signal rate contours



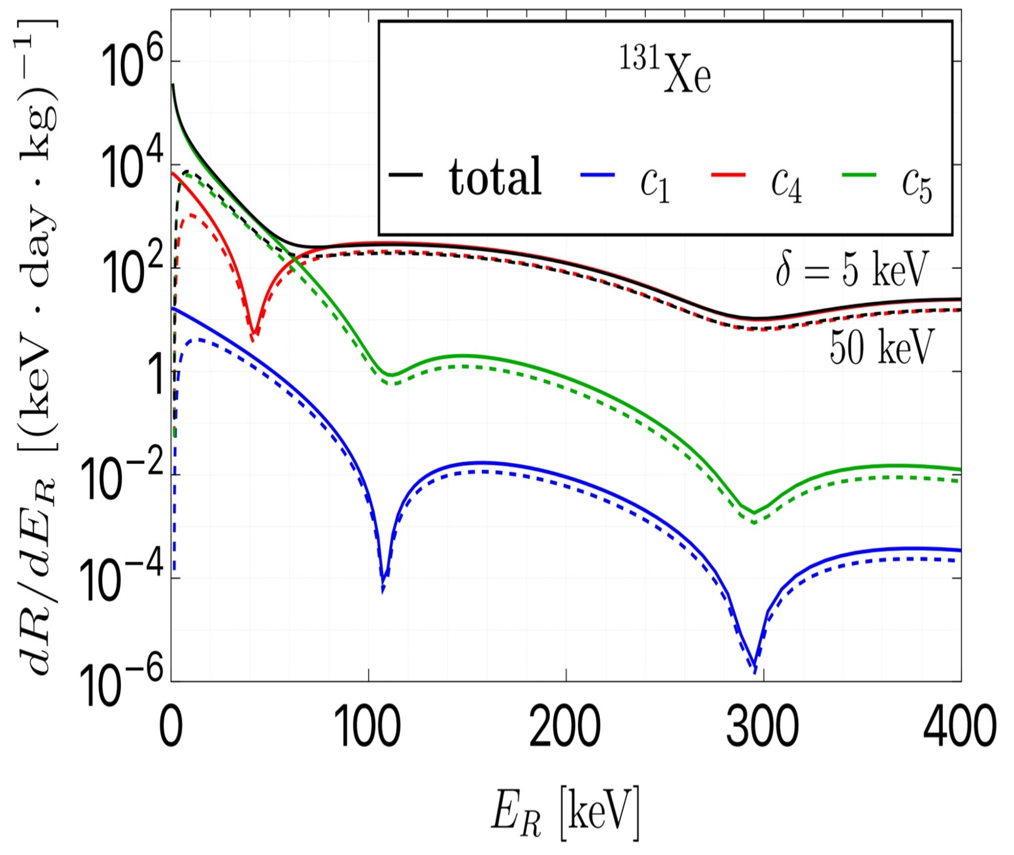
Cygnus daily modulation sensitivity 1000 m^3

a) as proposed (6 years)

b) optimized for negligible backgrounds (1 year)

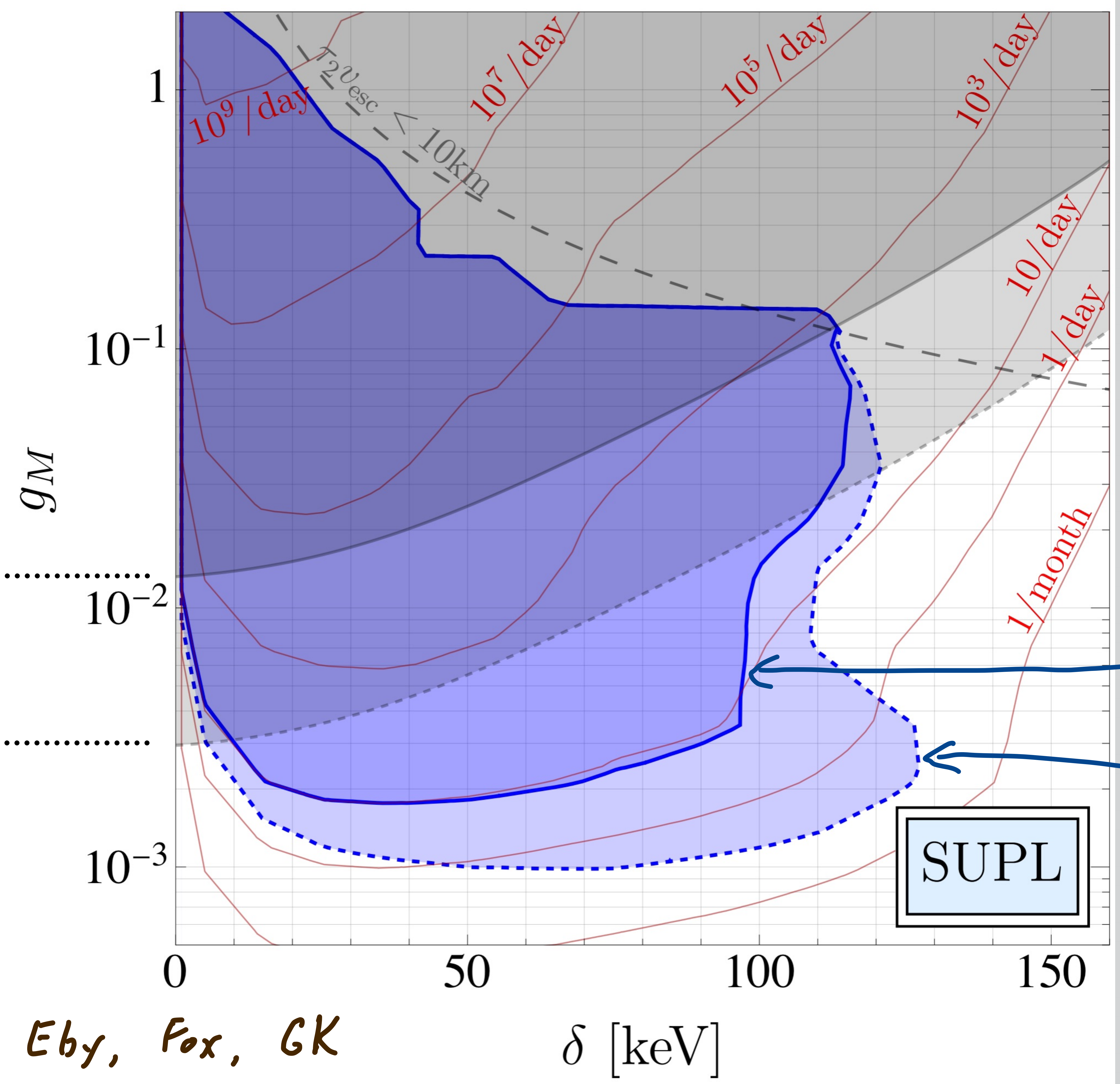
Projected Sensitivity

LZ nuclear recoil bounds!



LZ calibration-indep. limit

LZ nuclear recoil limit



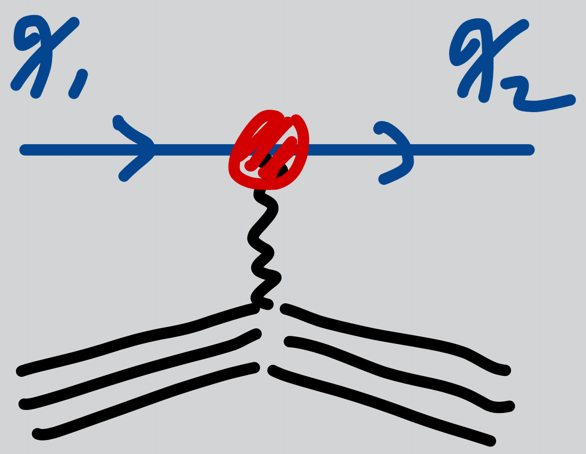
Eby, Fox, GK

CYGNUS daily modulation sensitivity 1000 m^3

a) as proposed (6 years)

b) optimized for negligible backgrounds (1 year)

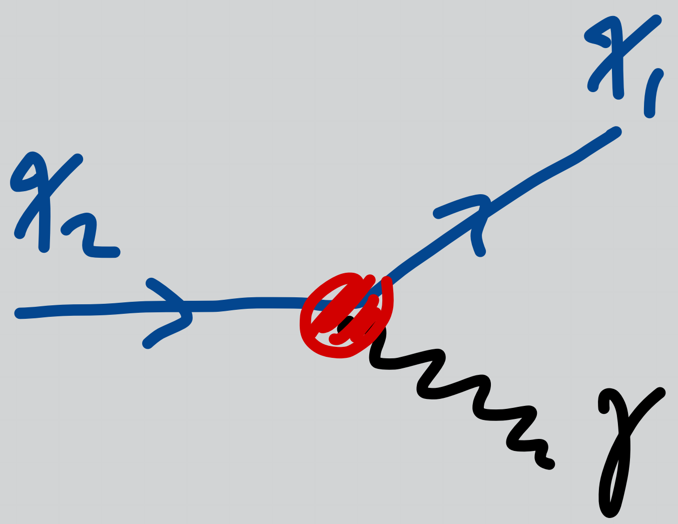
Conclusions

- 

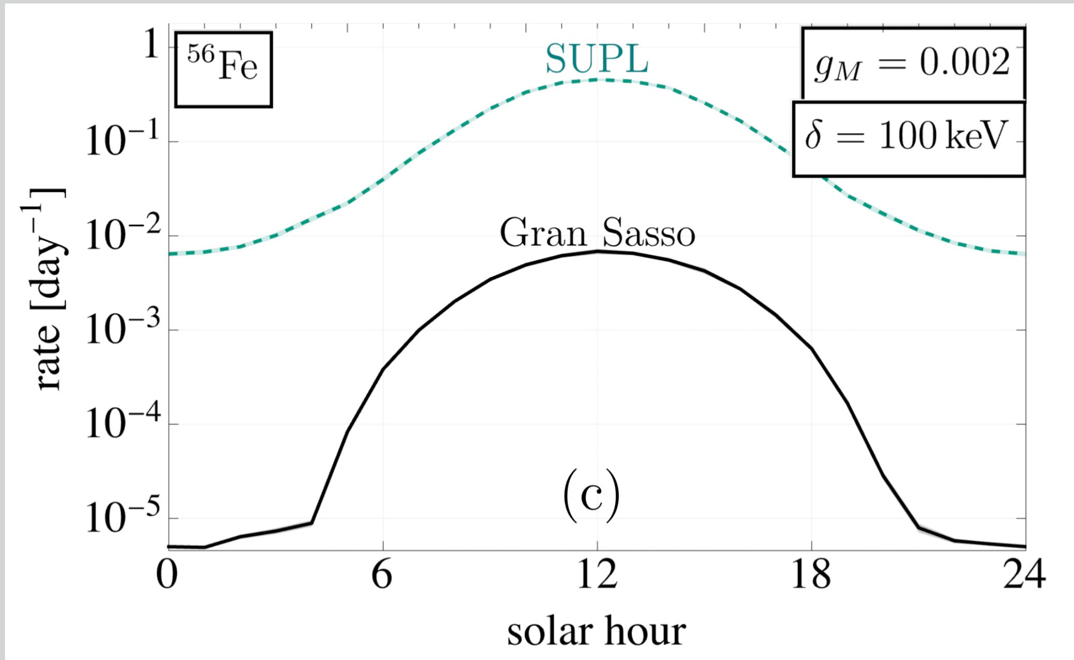
leads to qualitatively new signals of DM

- Entire  can be utilized as an upscatter target

  Optimal isotopes ^{27}Al, ^{56}Fe w/ $\mathcal{O}_4$, $\mathcal{O}_5$ operators

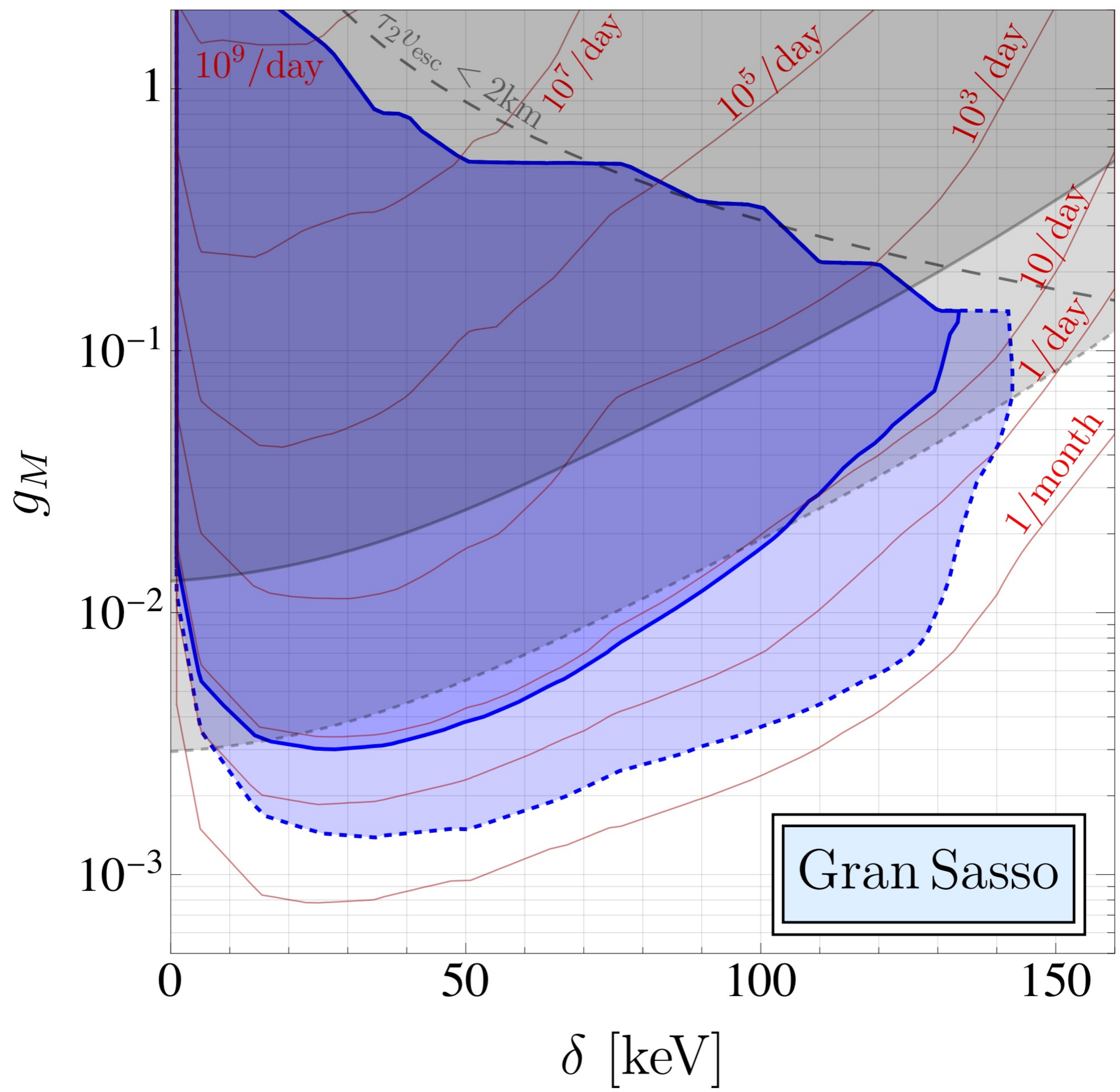
- Observe 

sidereal daily modulation

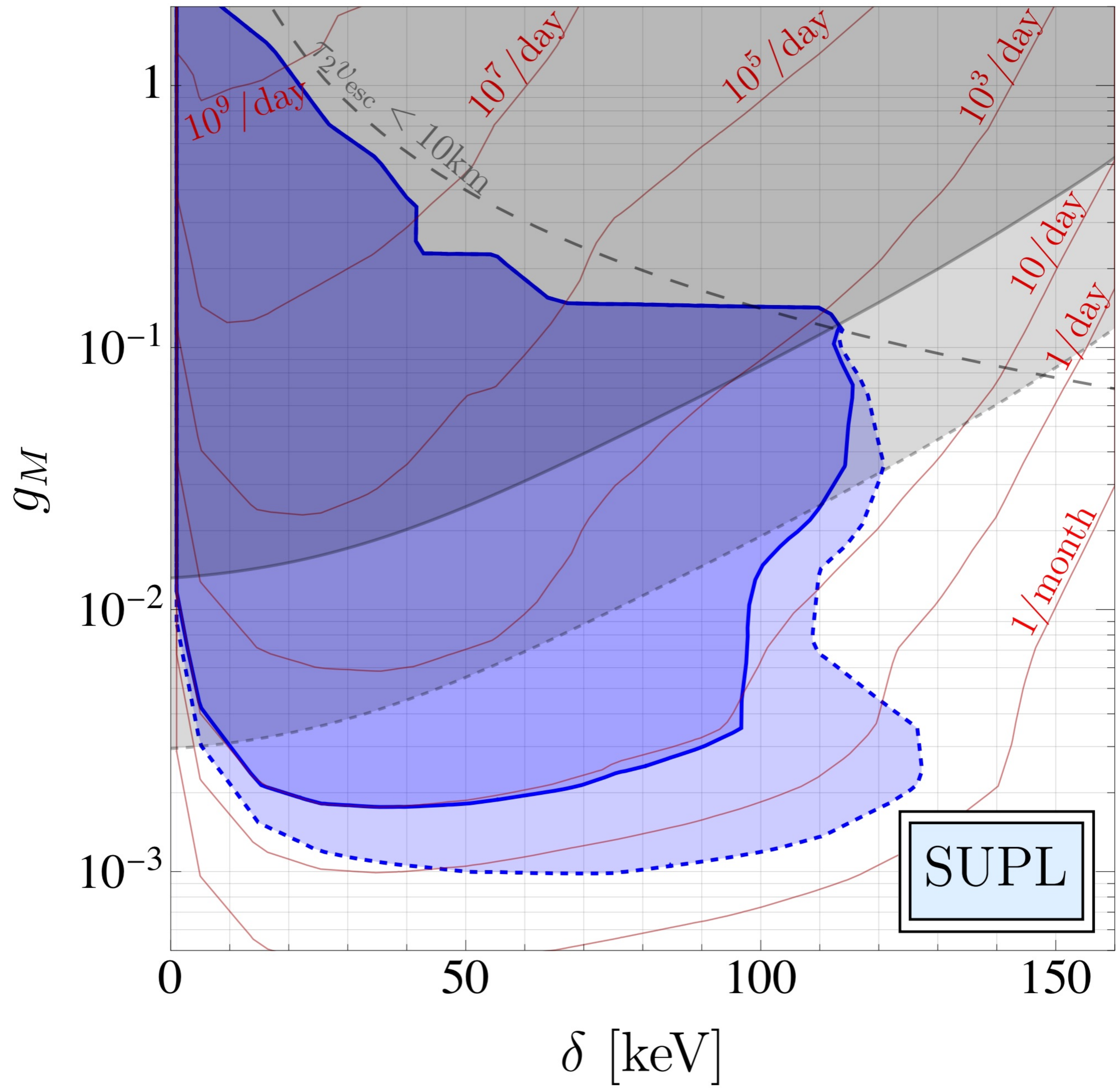


- CYGNUS - 1000 m^3 complementary to LZ nuclear upscatter, (could easily exceed in sensitivity with reduction of backgrounds)

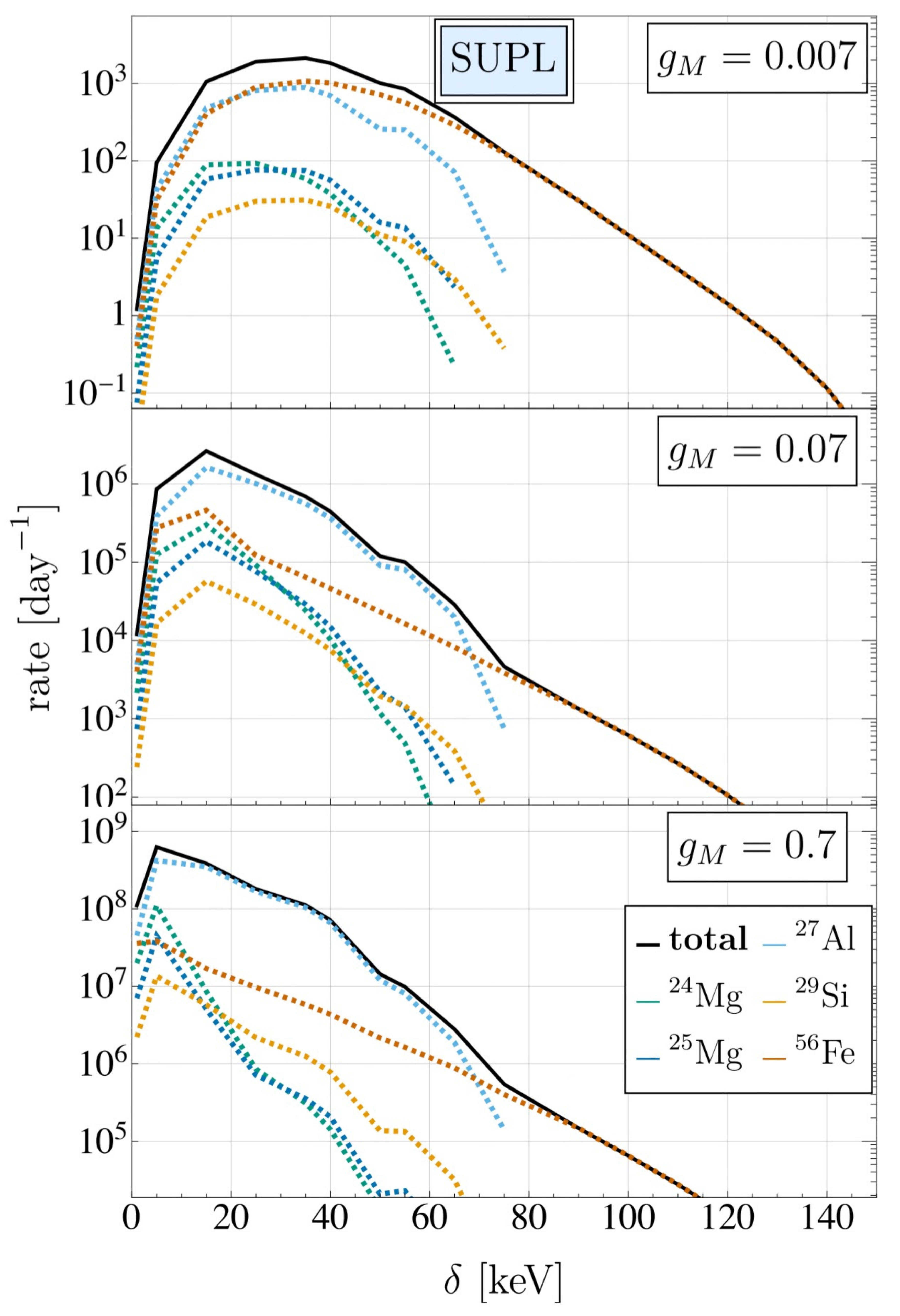
Extra



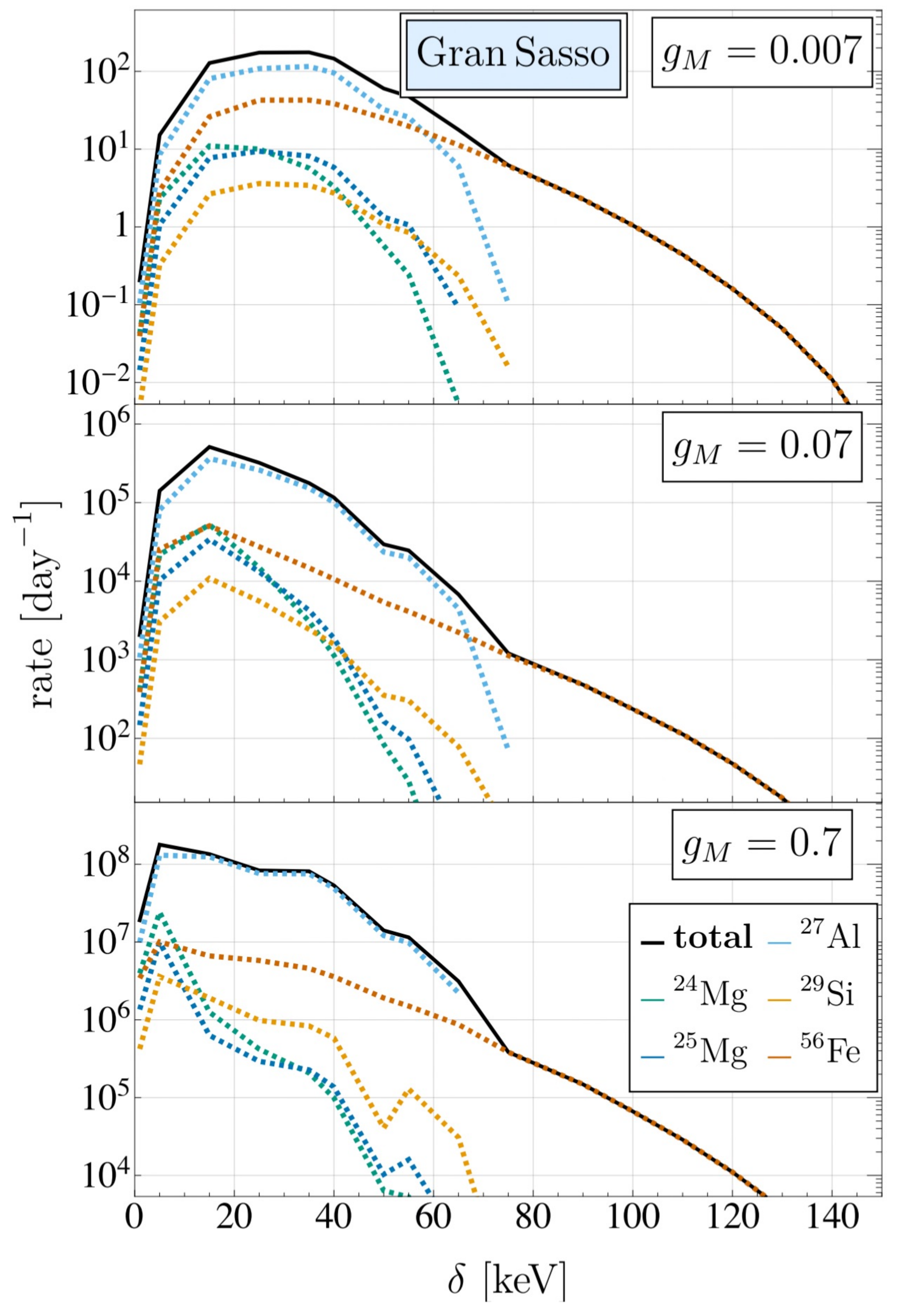
10^9/day
$\tau_2 v_{esc} < 2$km
10^7/day
10^5/day
10^3/day
10/day
1/day
1/month
Gran Sasso
1
10^{-1}
10^{-2}
10^{-3}
g_M
0
50
100
150
δ [keV]



10^9/day
10^7/day
10^5/day
10^3/day
10/day
1/day
1/month
$\tau_2 v_{esc} < 10$km
SUPL
g_M
δ [keV]



SUPL
$g_M = 0.007$
$g_M = 0.07$
$g_M = 0.7$
rate [day^{-1}]
10^{-1}
1
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
0
20
40
60
80
100
120
140
δ [keV]
total
^{27}Al
^{24}Mg
^{29}Si
^{25}Mg
^{56}Fe



Gran Sasso
$g_M = 0.007$
$g_M = 0.07$
$g_M = 0.7$
rate [day^{-1}]
10^{-2}
10^{-1}
1
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^8
0
20
40
60
80
100
120
140
δ [keV]
total
^{27}Al
^{24}Mg
^{29}Si
^{25}Mg
^{56}Fe