Collider–DD Dark Matter Search Complimentarity

DM Lunch
Joe McLaughlin
07/July/2026

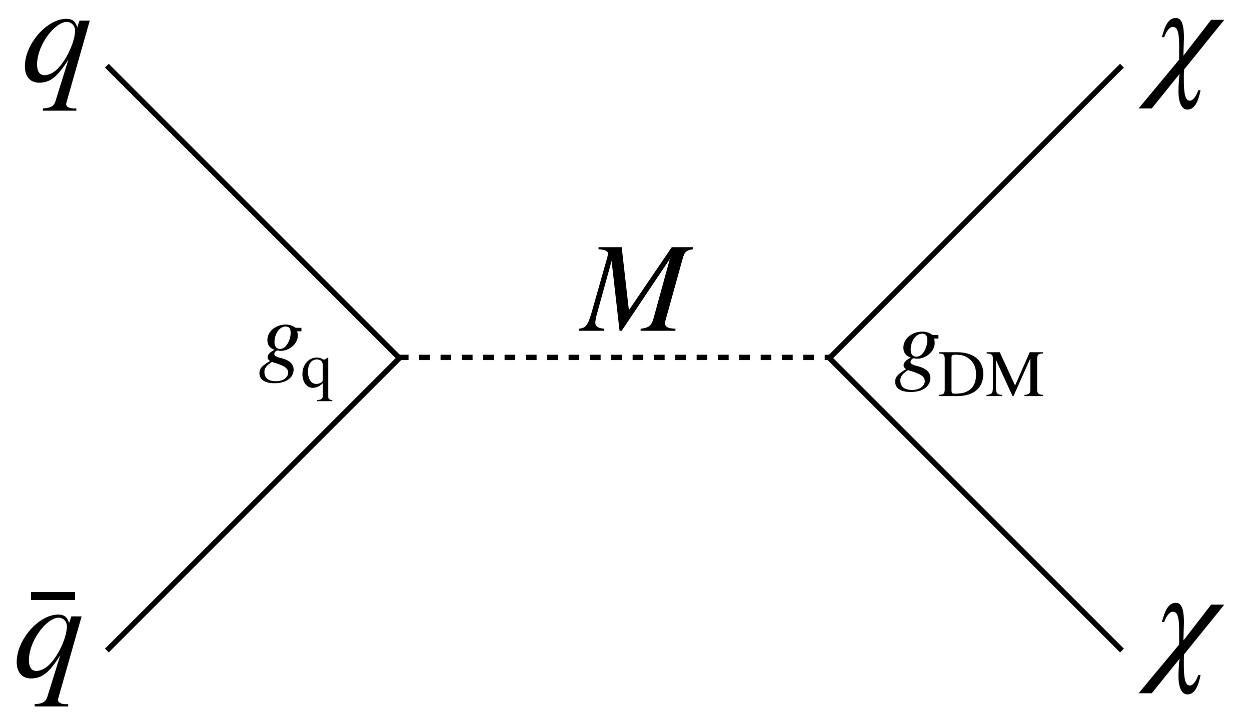
From Data to Limits

Collider Production

Direct Detection

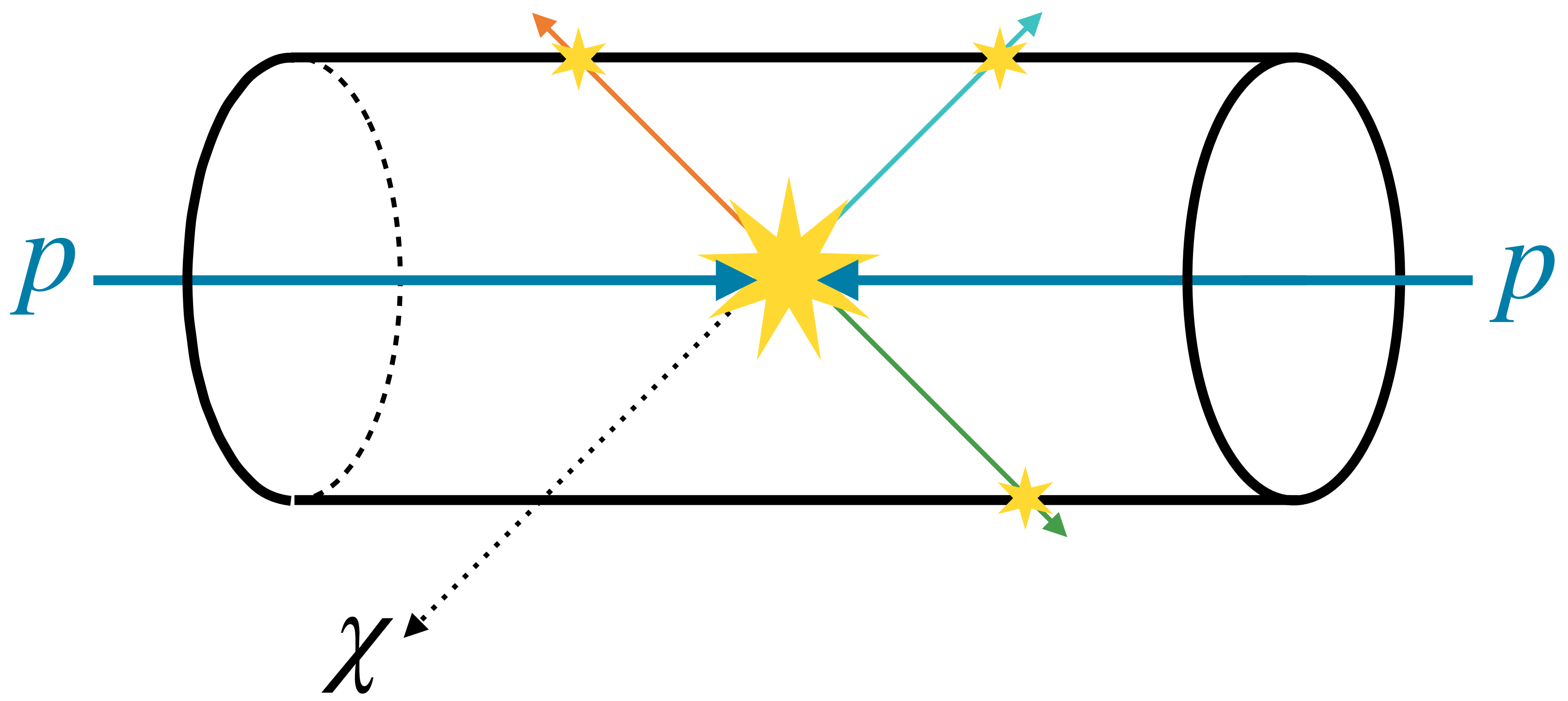
From Data to Limits

Collider Production



- Looking at s-channel production from $q\bar{q}$
- Sensitive to DM mass, mediator mass, and particle couplings

- Sum up all the traverse momentum vectors from pp vertex
- DM won't interact with detector like other products leaving a ***missing transverse energy*** (MET) signature



Direct Detection

From Data to Limits

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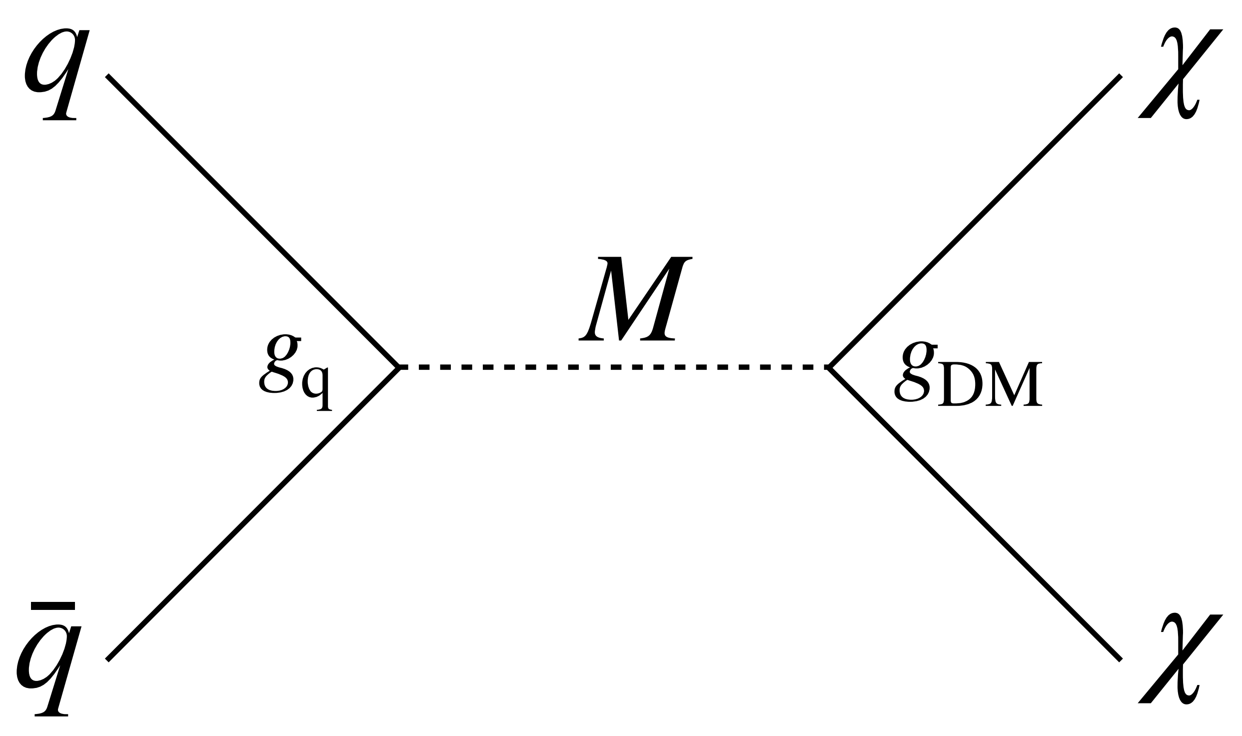

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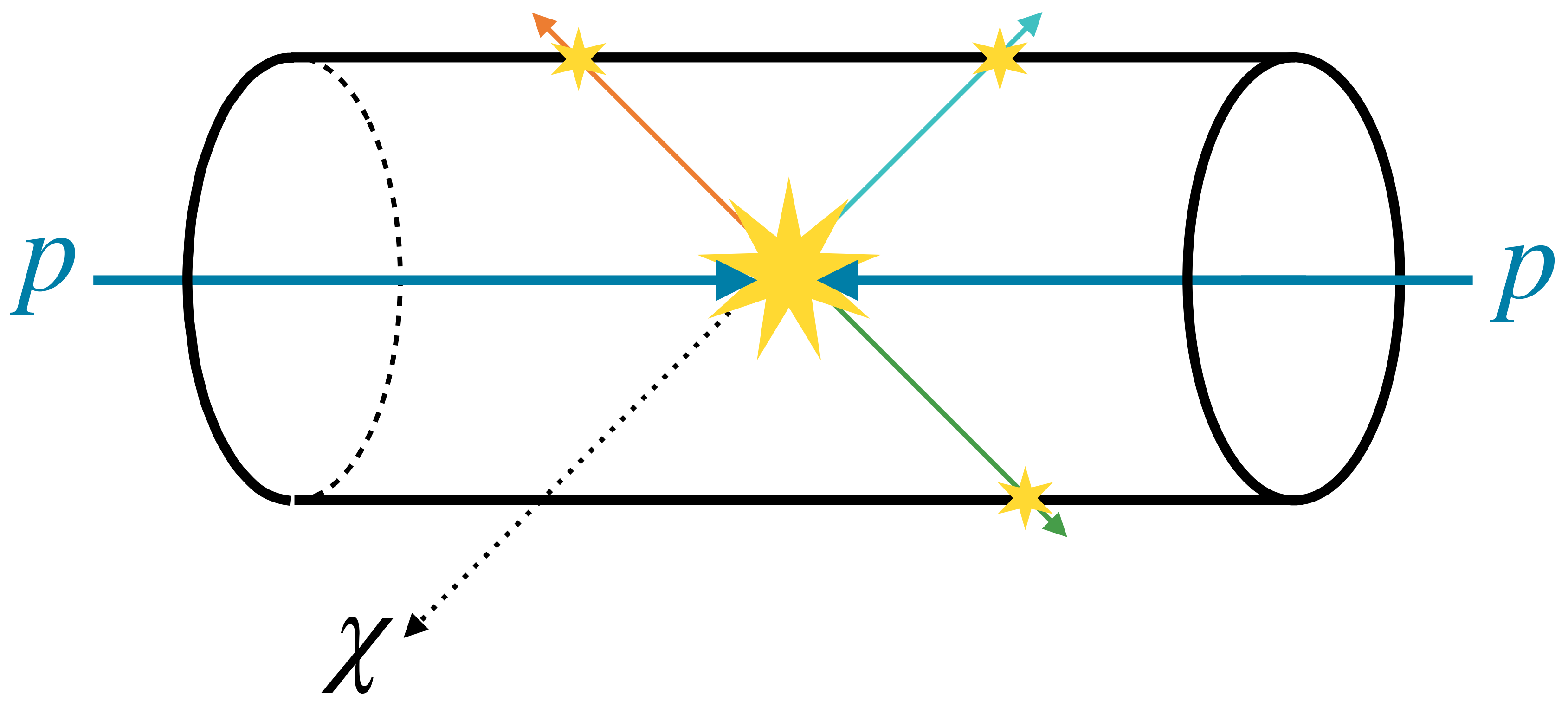

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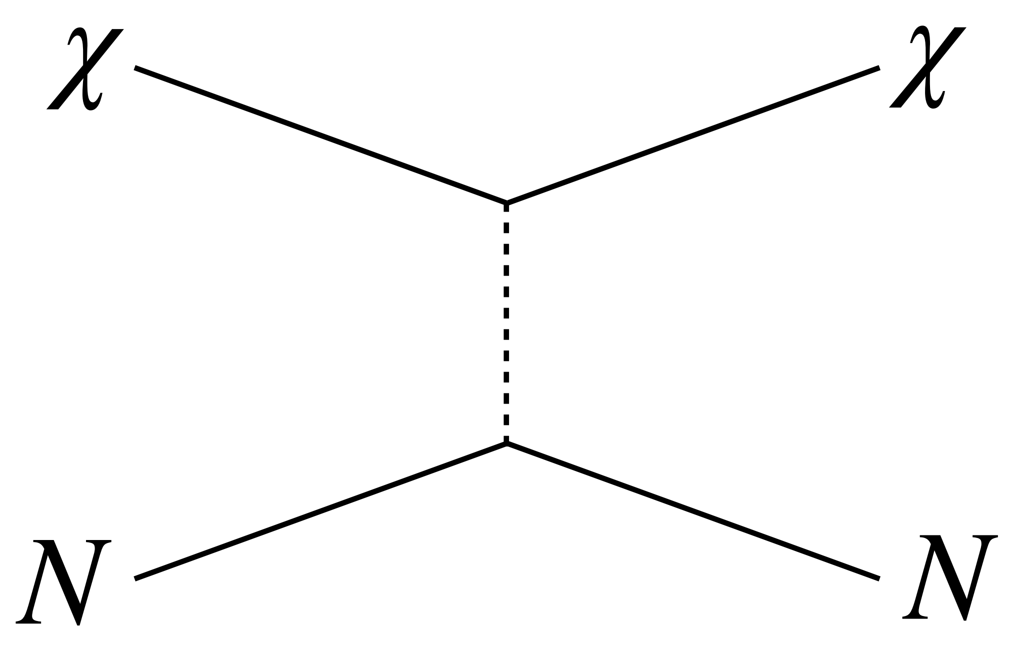
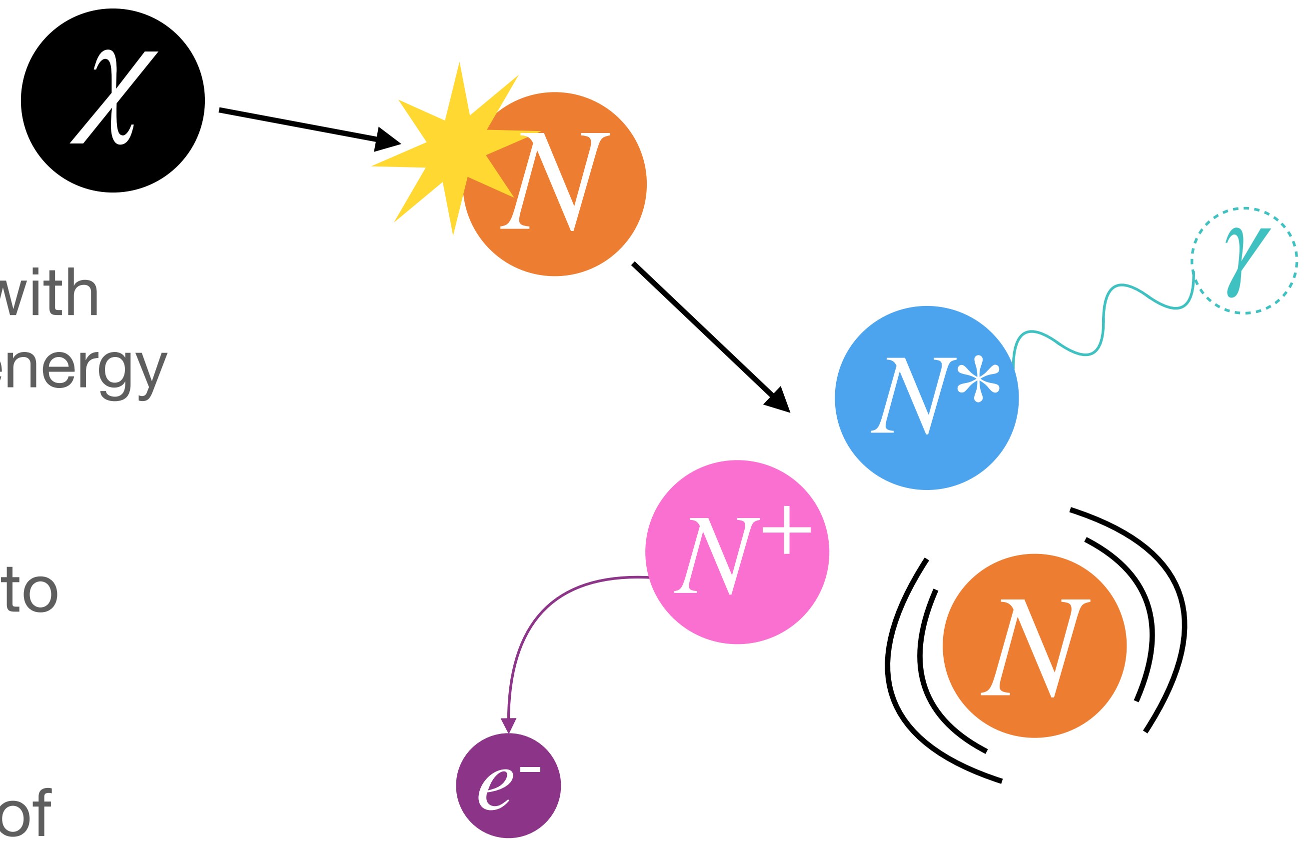


- Looking at coherent t-channel scattering with entire target nucleus N
- Parameterise individual couplings and mediator mass in coherent scattering cross-section

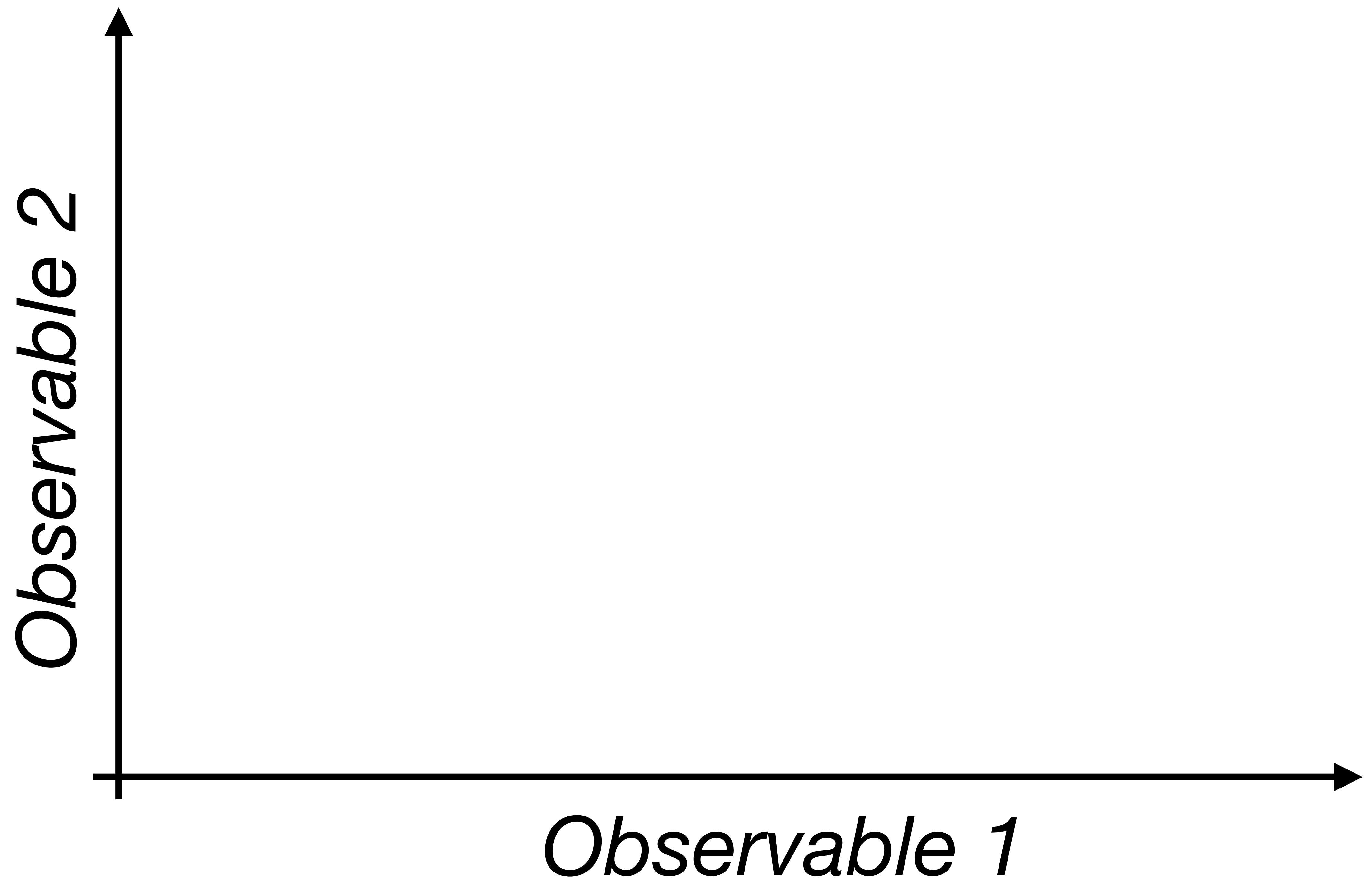


- Assume DM elastically scatter with target; target then recoils with energy ~keV
- Recoiling nucleus loses energy to ionisation, excitation, and heat
- Measure various combinations of charge, light, and thermal excitations

From Data to Limits

Typical Analysis Pipeline in DD

- Pick an observable space where you can cleanly find potential DM interactions
- Ideally a multidimensional space containing energy information and particle ID



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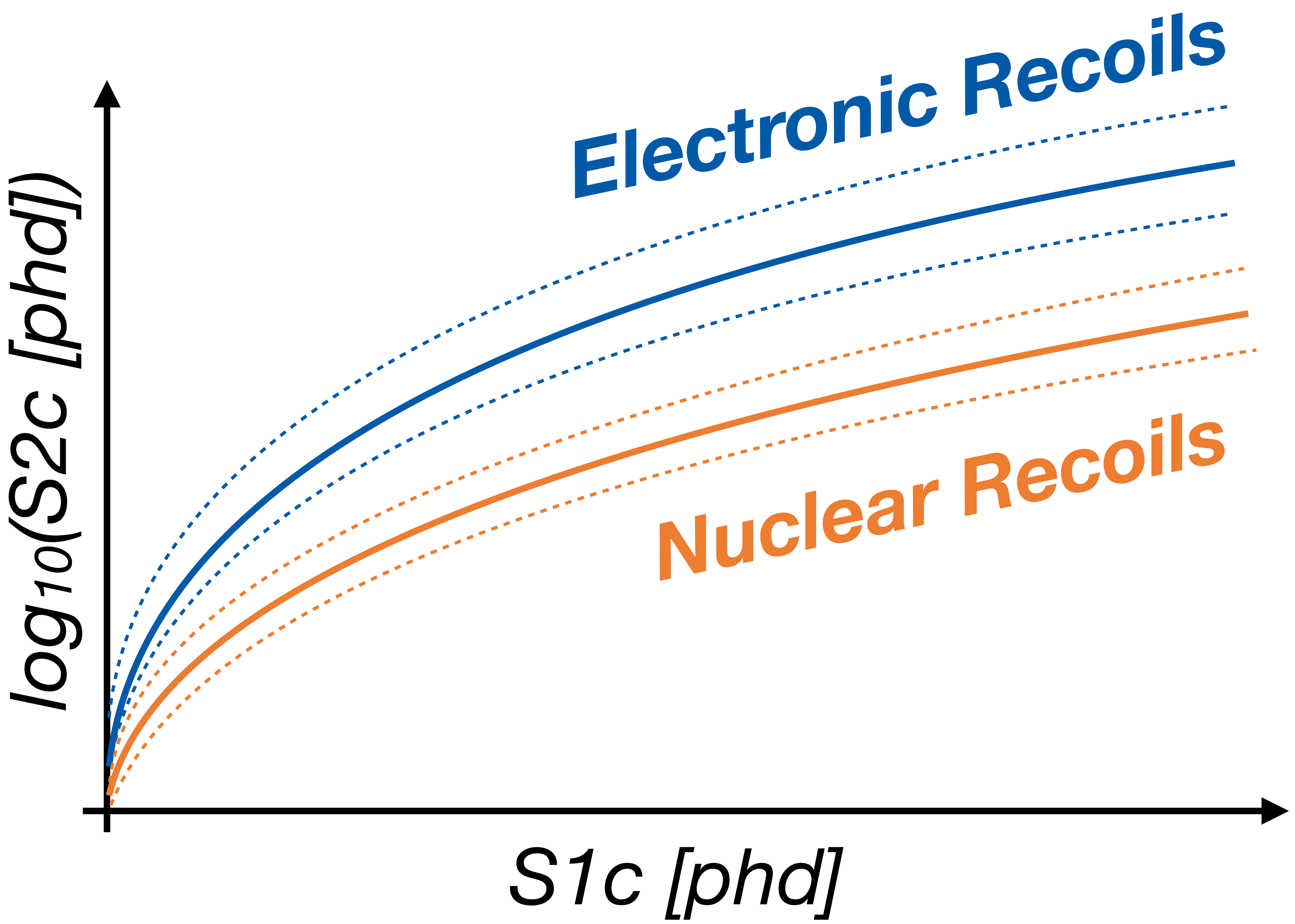

phd = photons detected

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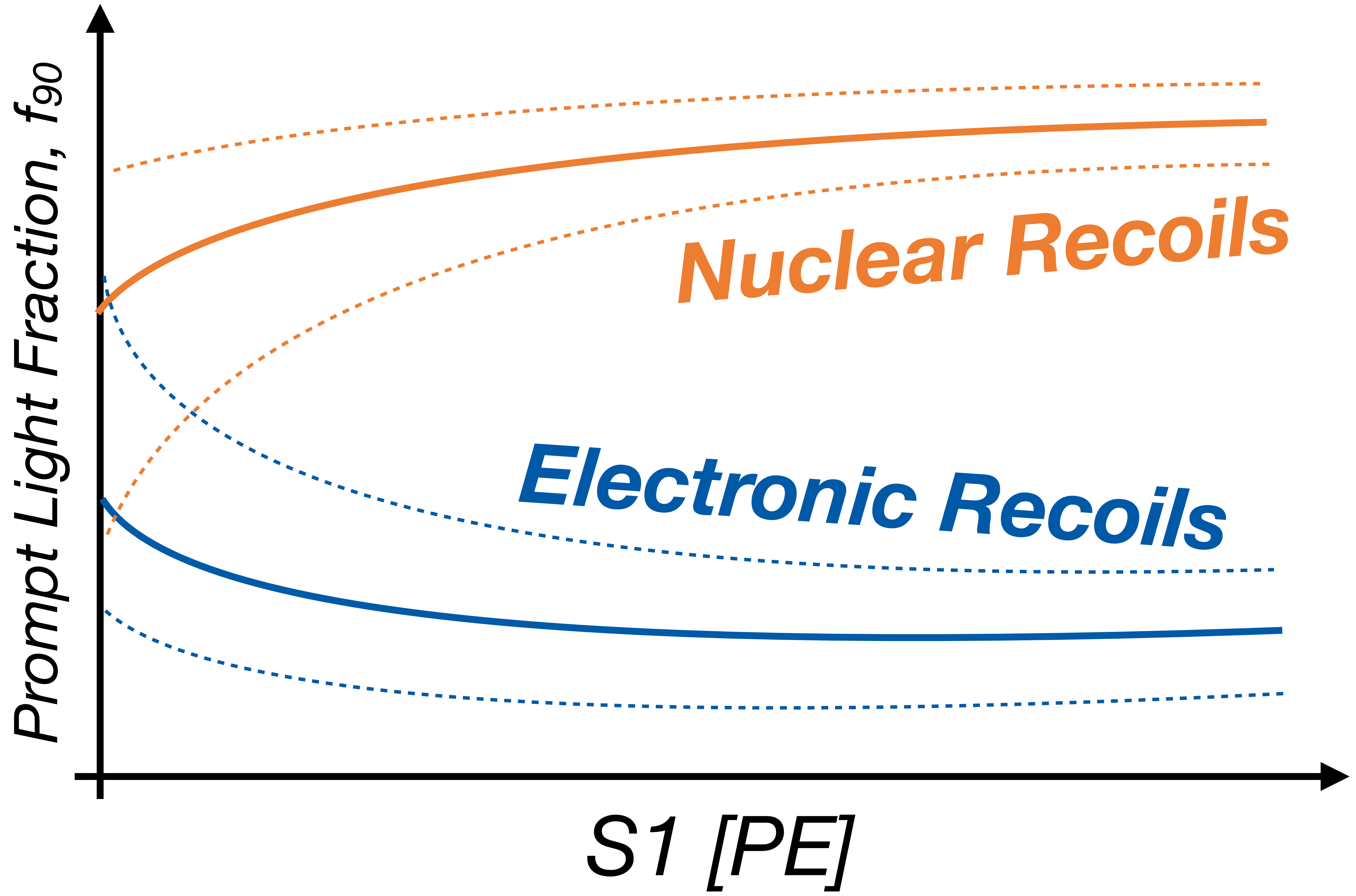

PE = photoelectrons

$$\textbf{\textit{f90}} = \frac{\sum_{t=0}^{90\,\mathrm{ns}} \mathrm{S1}(t)}{\sum_{t=0}^{\infty} \mathrm{S1}(t)}$$

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- Examples include:
  - ***LUX-ZEPLIN*** (light, charge)
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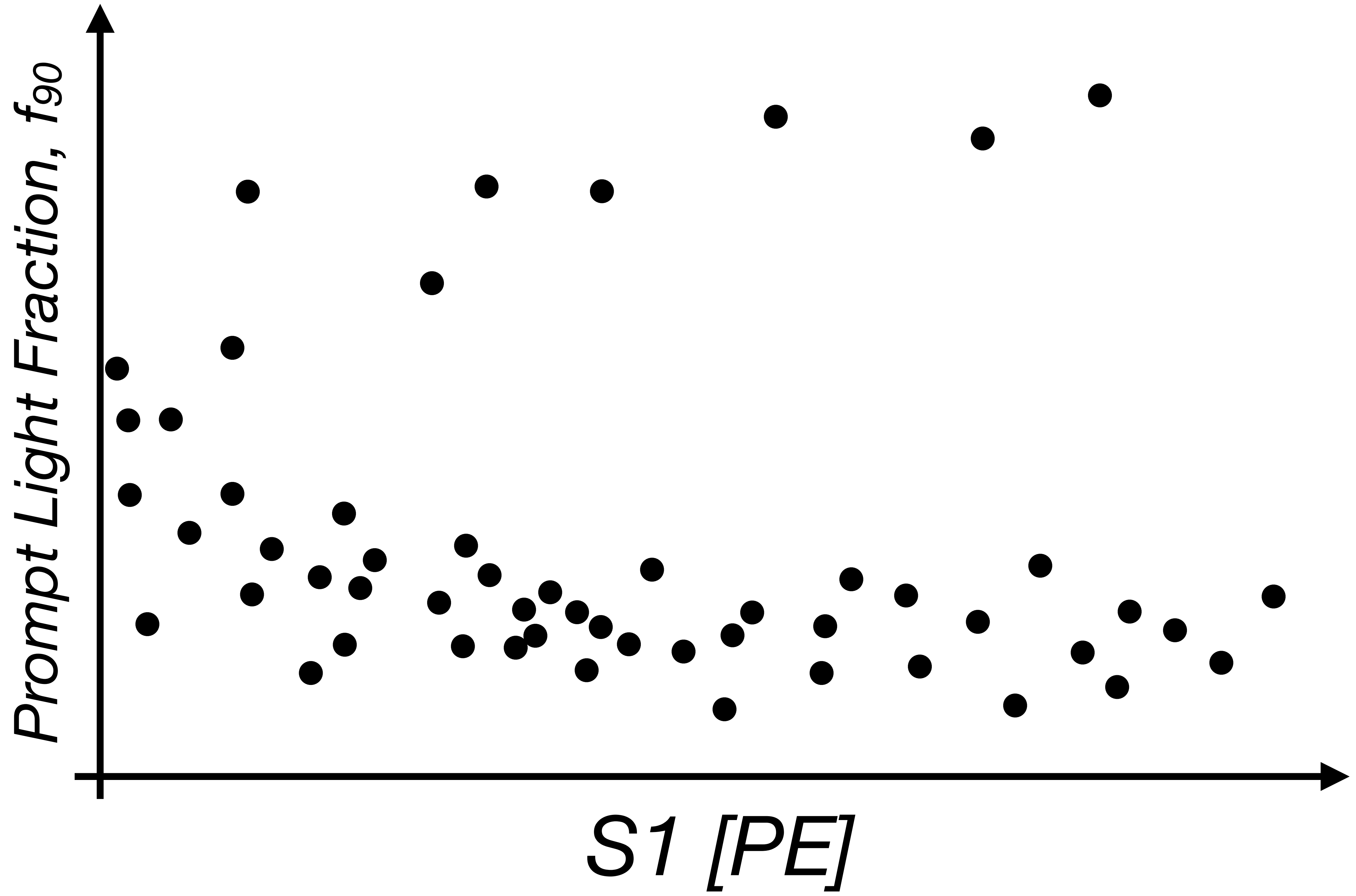
- Data after cleaning and fiducial cuts tends to include:
  - Densely populated ER band (low energy gammas and betas)
  - Sparsely populated NR band (neutrons and degraded alphas)



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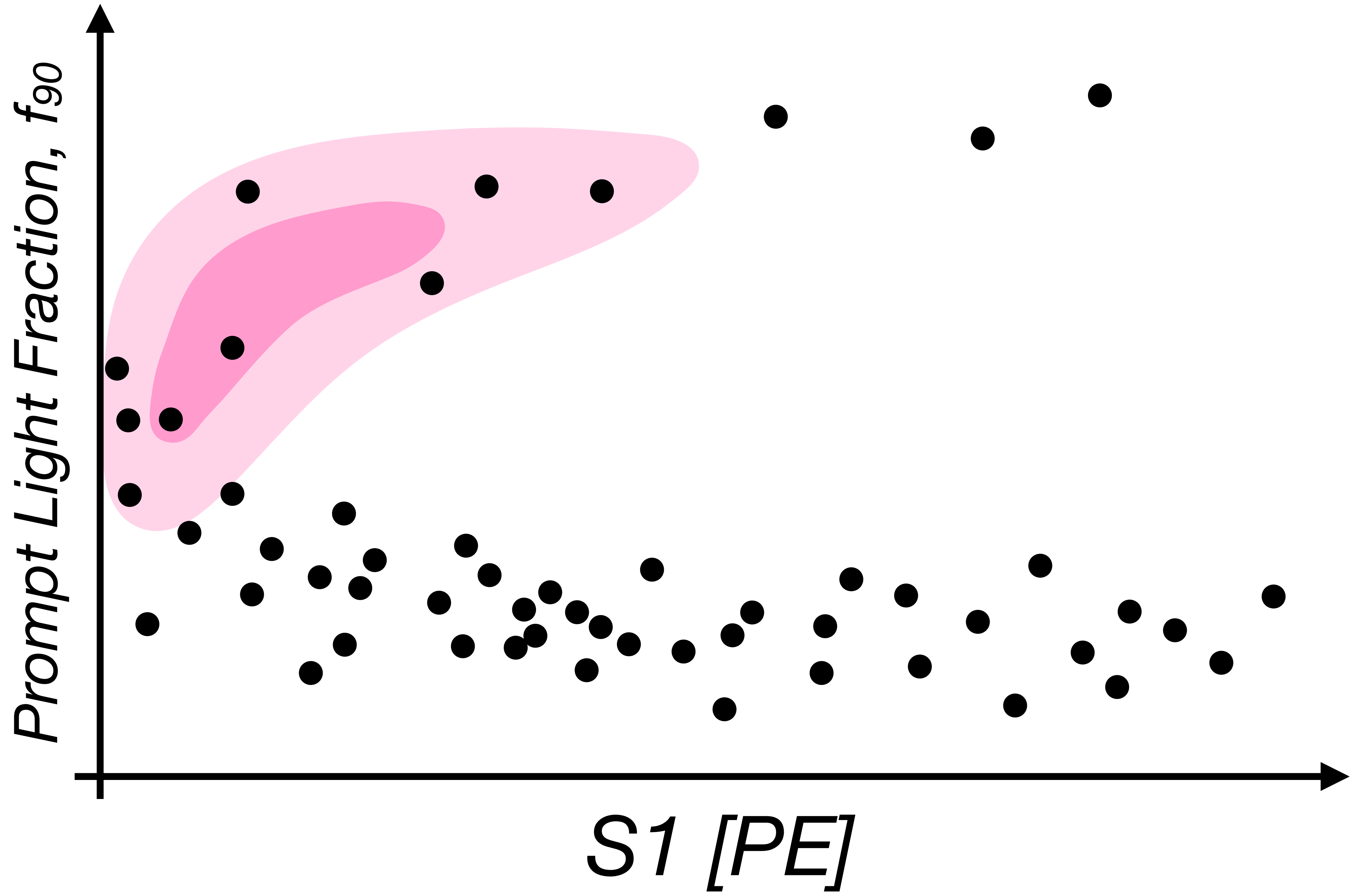

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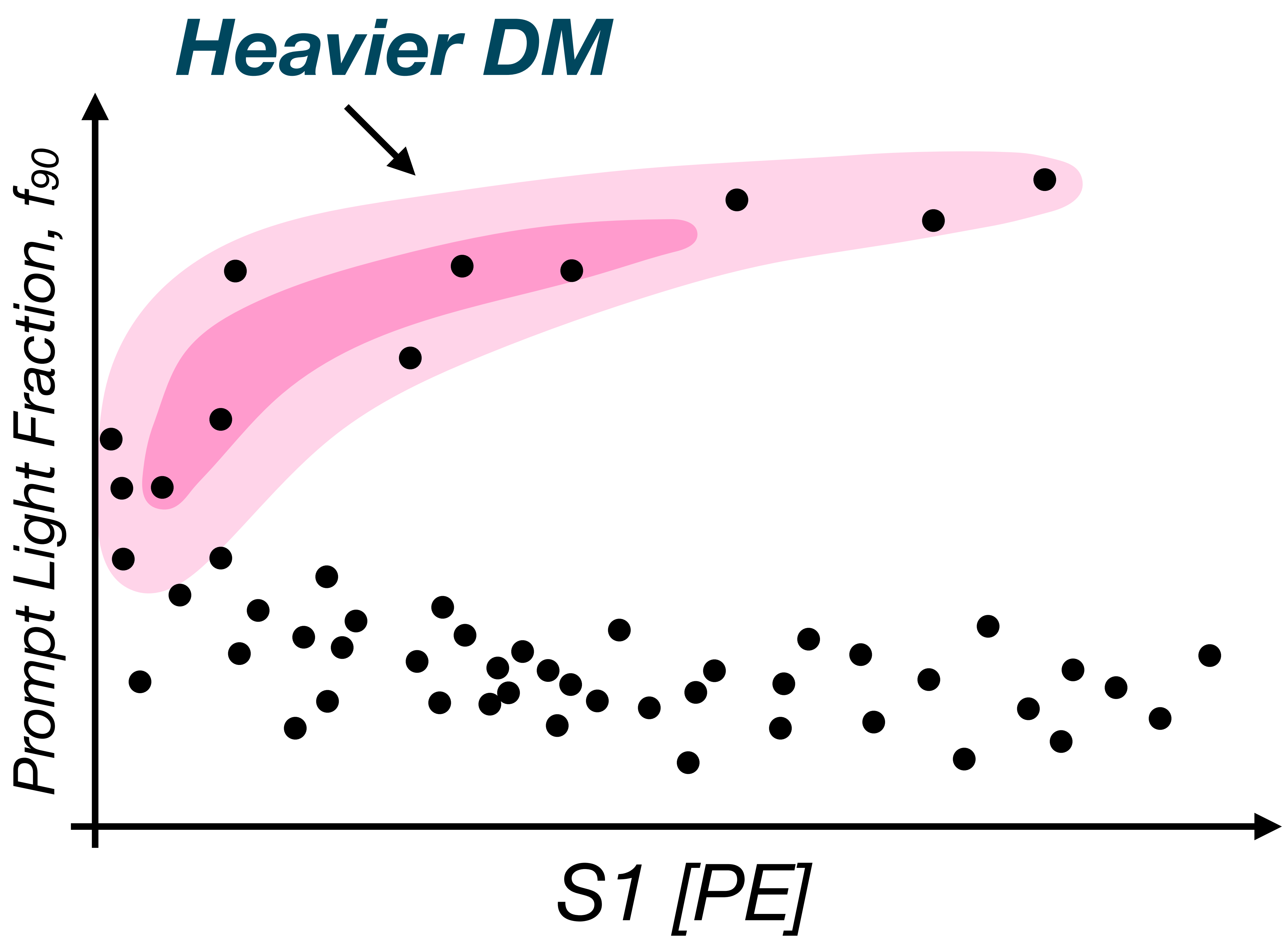

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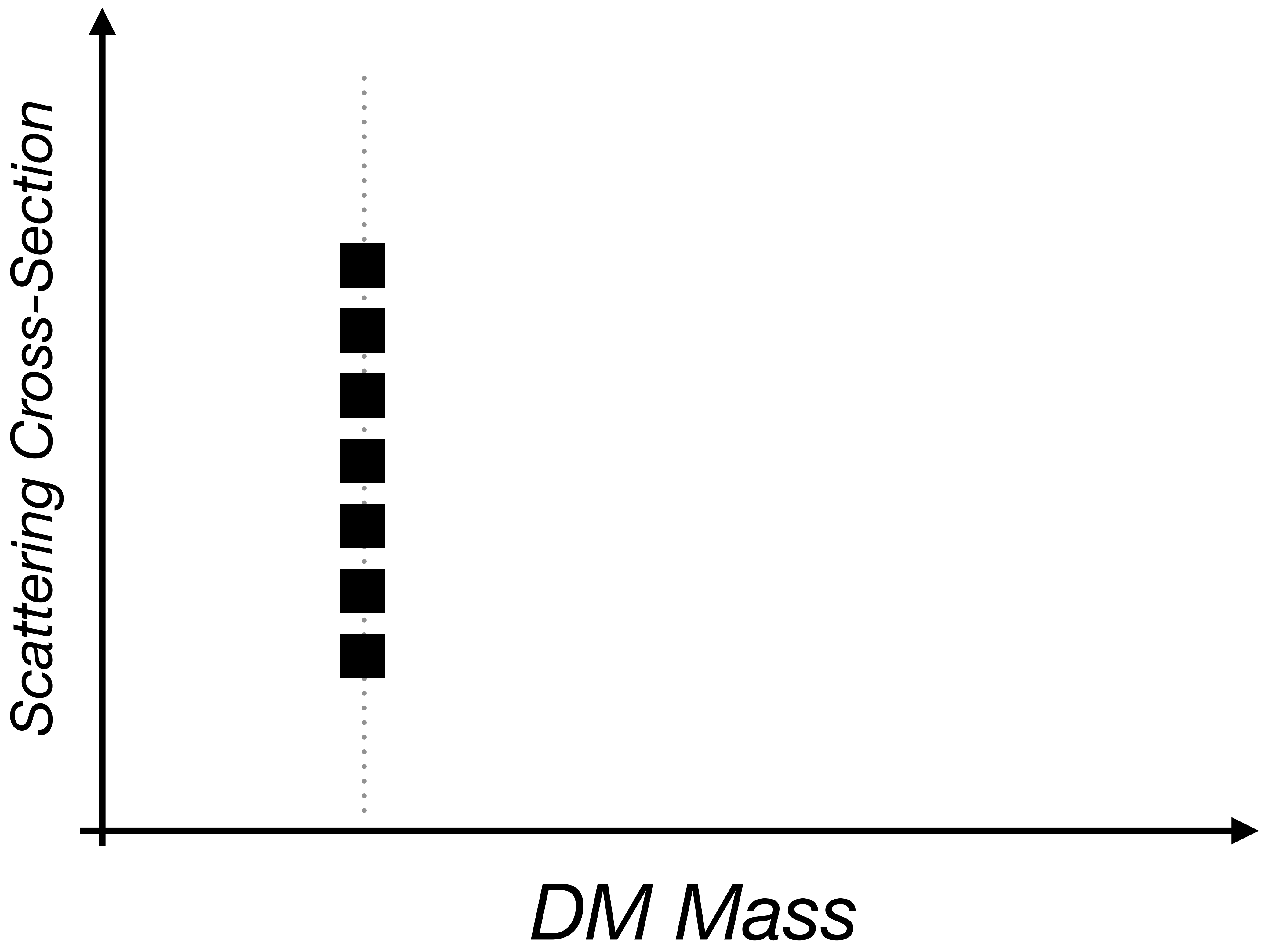

⁕ ***ASSUMING NO SIGNAL EXCESS IS DISCOVERED***

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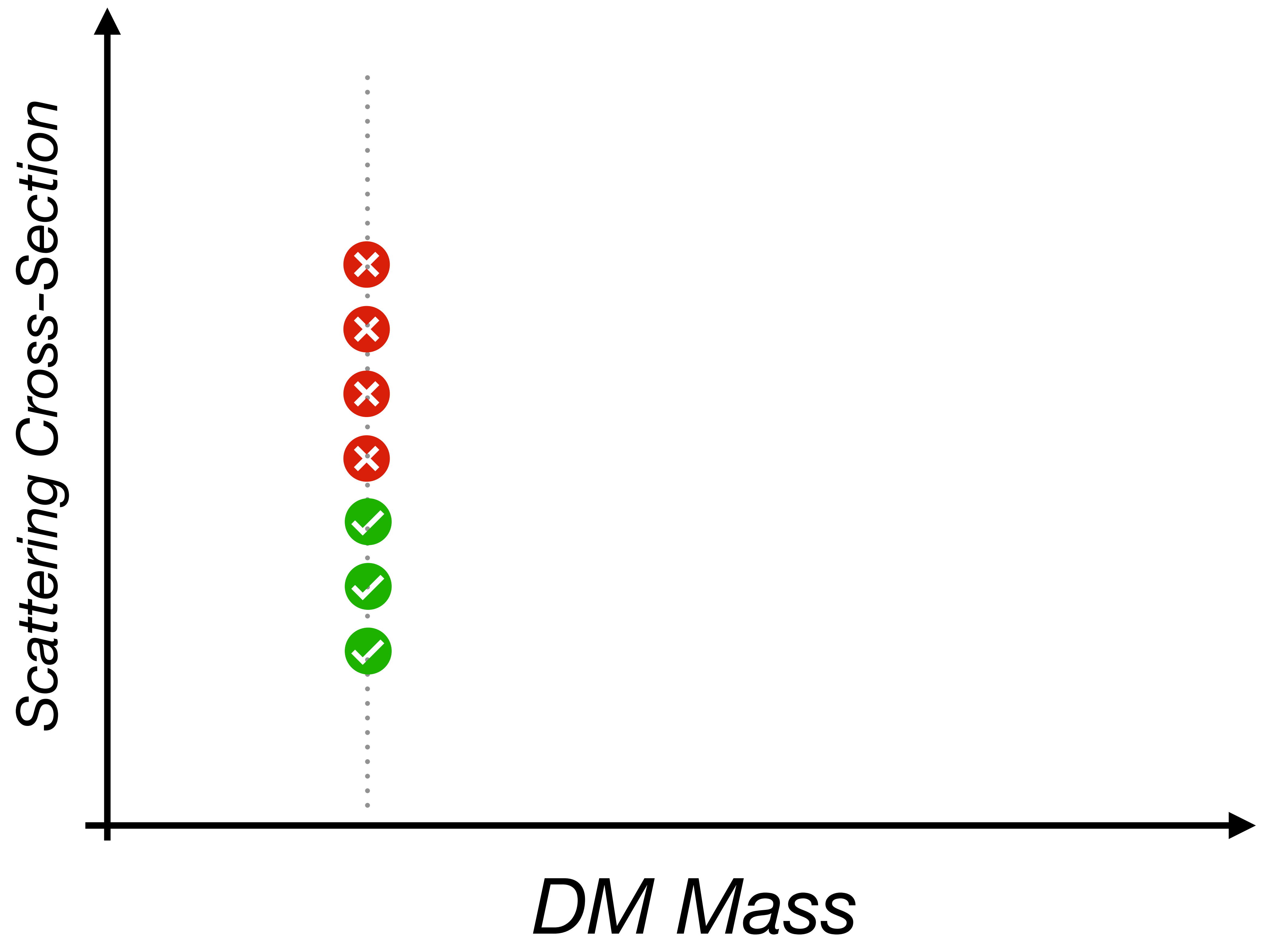

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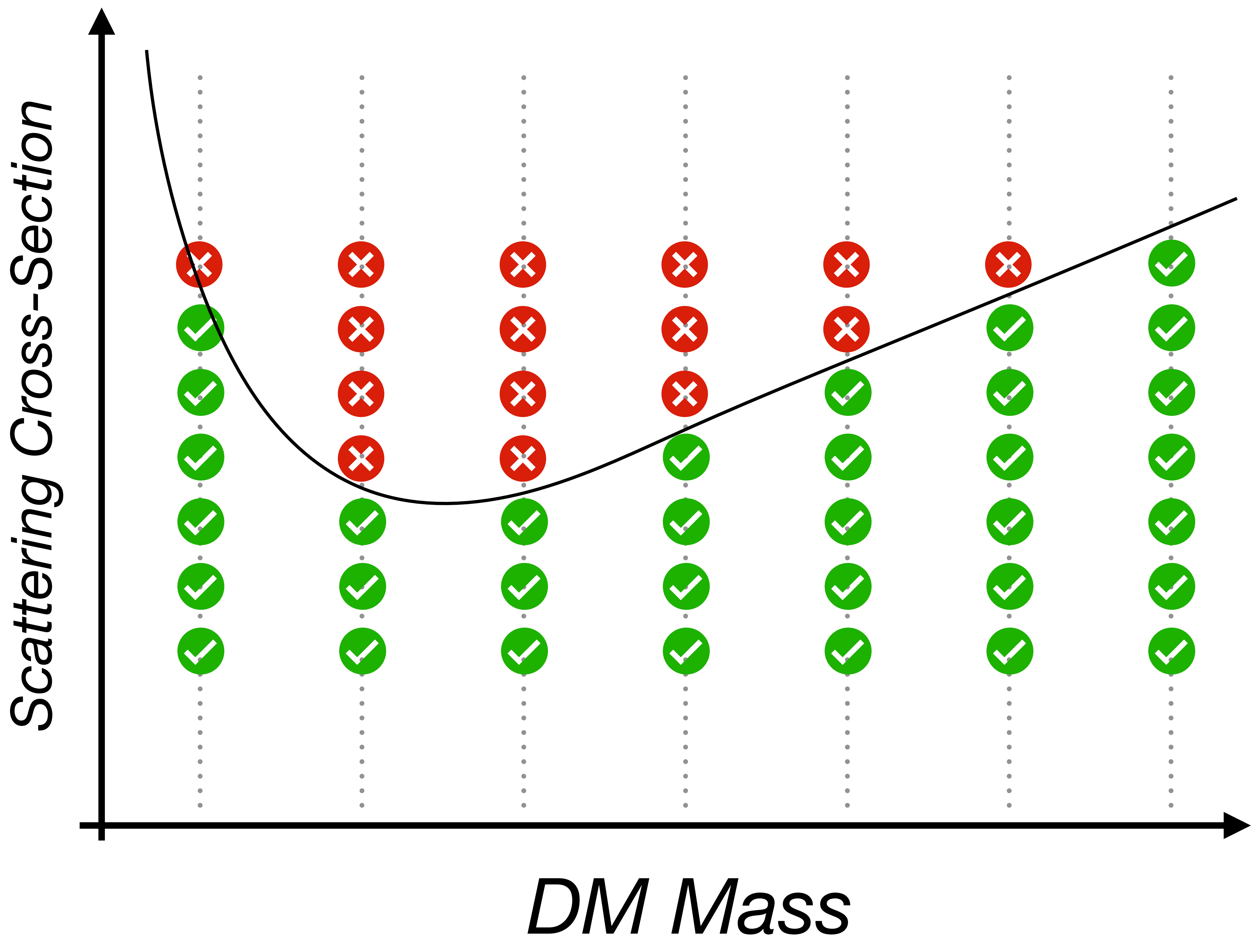

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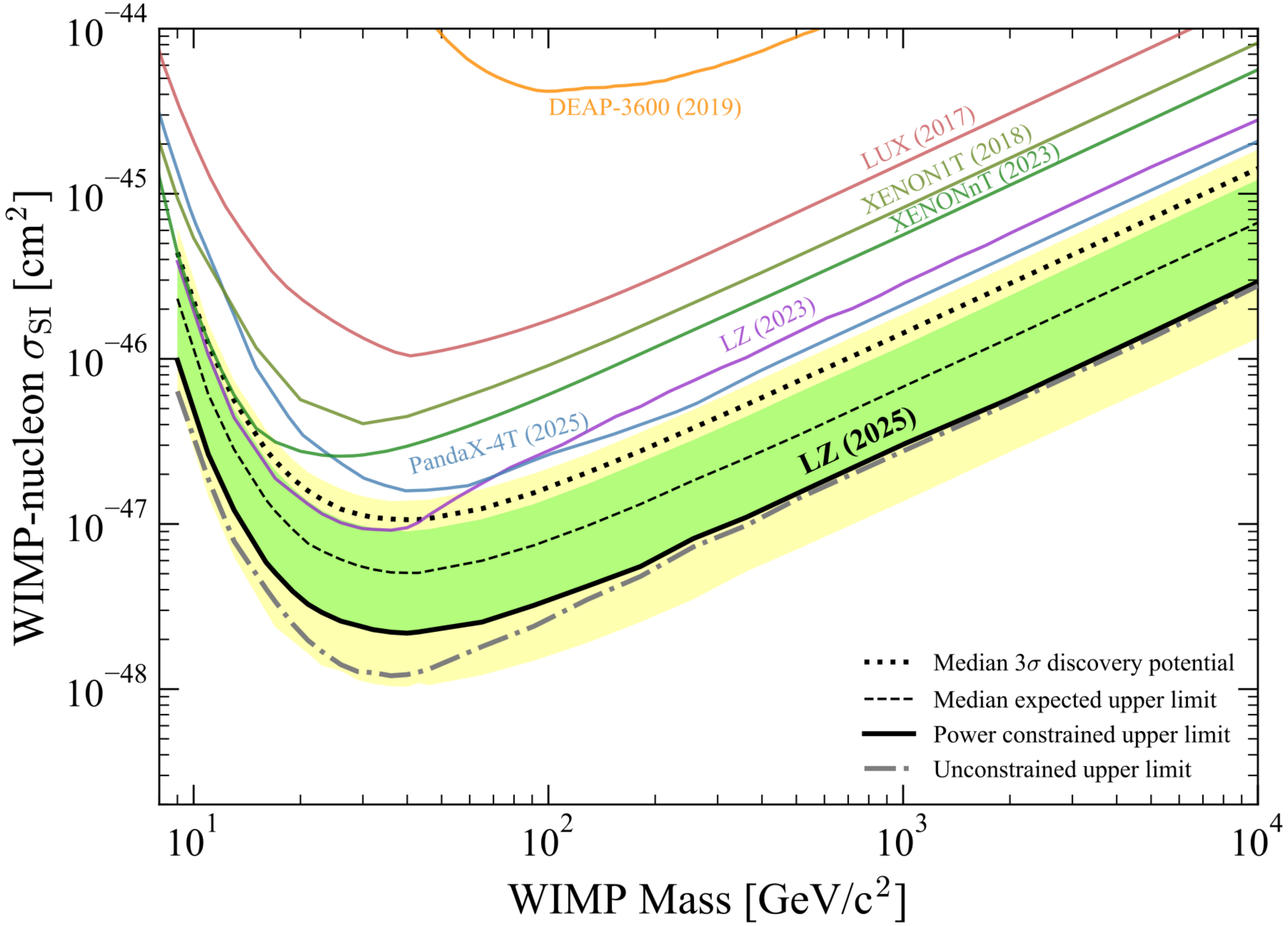

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PLR in DD experiments

Subtle differences in our Profile Likelihood analysis:

1. ***Unbinned analysis***

   Our data generally has much lower statistics than in collider DM searches, and we therefore use unbinned likelihoods to maximise resolution

2. ***Non-asymptotic confidence intervals***

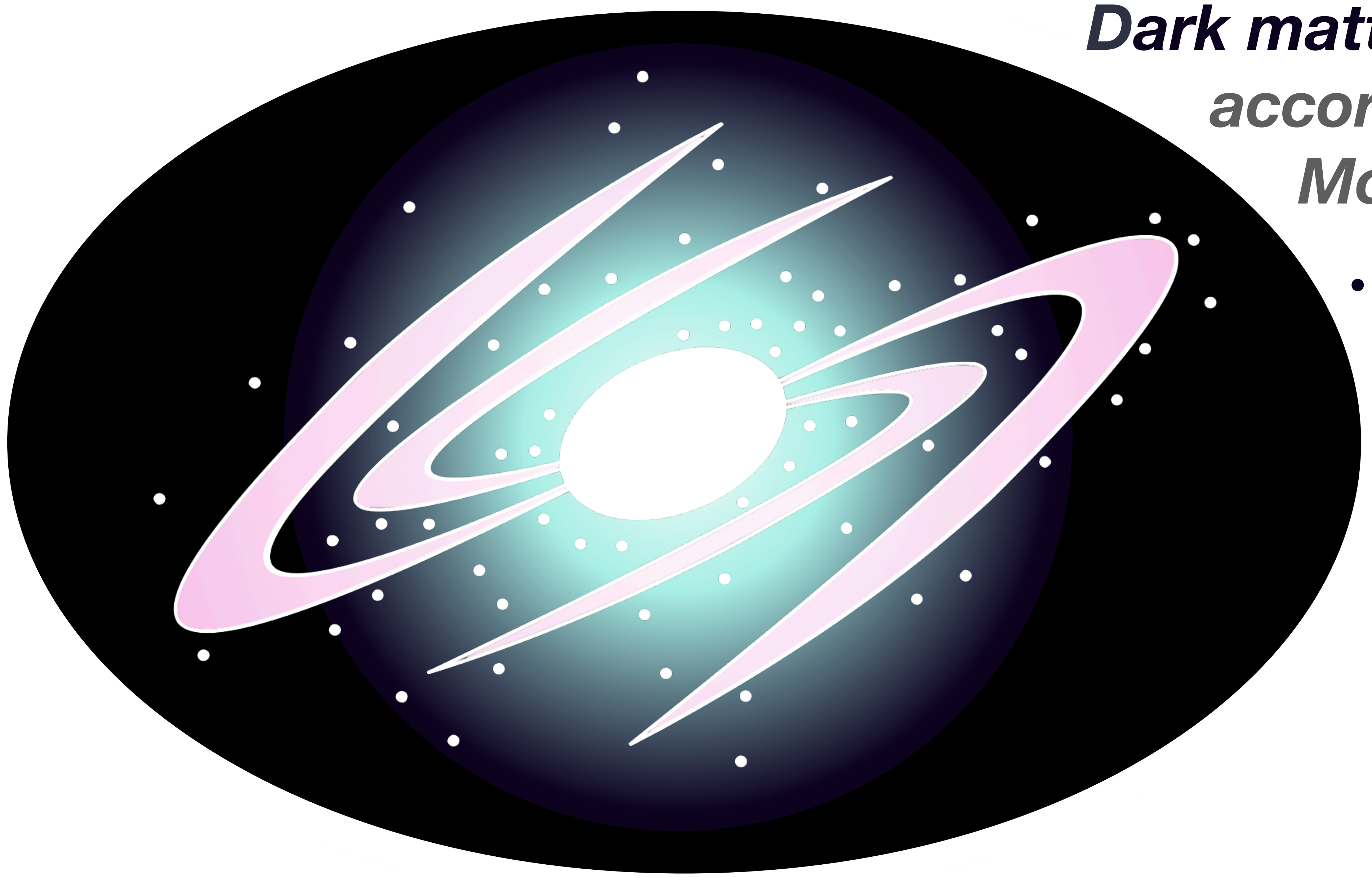
   Also because we have lower statistics, our PLR test statistic distributions rarely reach a limit where asymptotic approximations hold.

3. ***Bias mitigation***

   Our signal model systematics are often dwarfed by detector systematics. A sufficiently robust DD likelihood can be over tuned to suppress a signal excess without careful treatment, e.g. blinding or salting of the signal region

Signals in DD

We assume that…



***Dark matter** is distributed according to the Standard Halo Model*

- Isothermal sphere of DM, $\rho \propto r^{-2}$
  - Local density ρ_0 ~ 0.3 GeV/cm³
    - Earth constantly seeing a dark matter 'wind' with Characteristic velocity $v_0 = 220$ km/s

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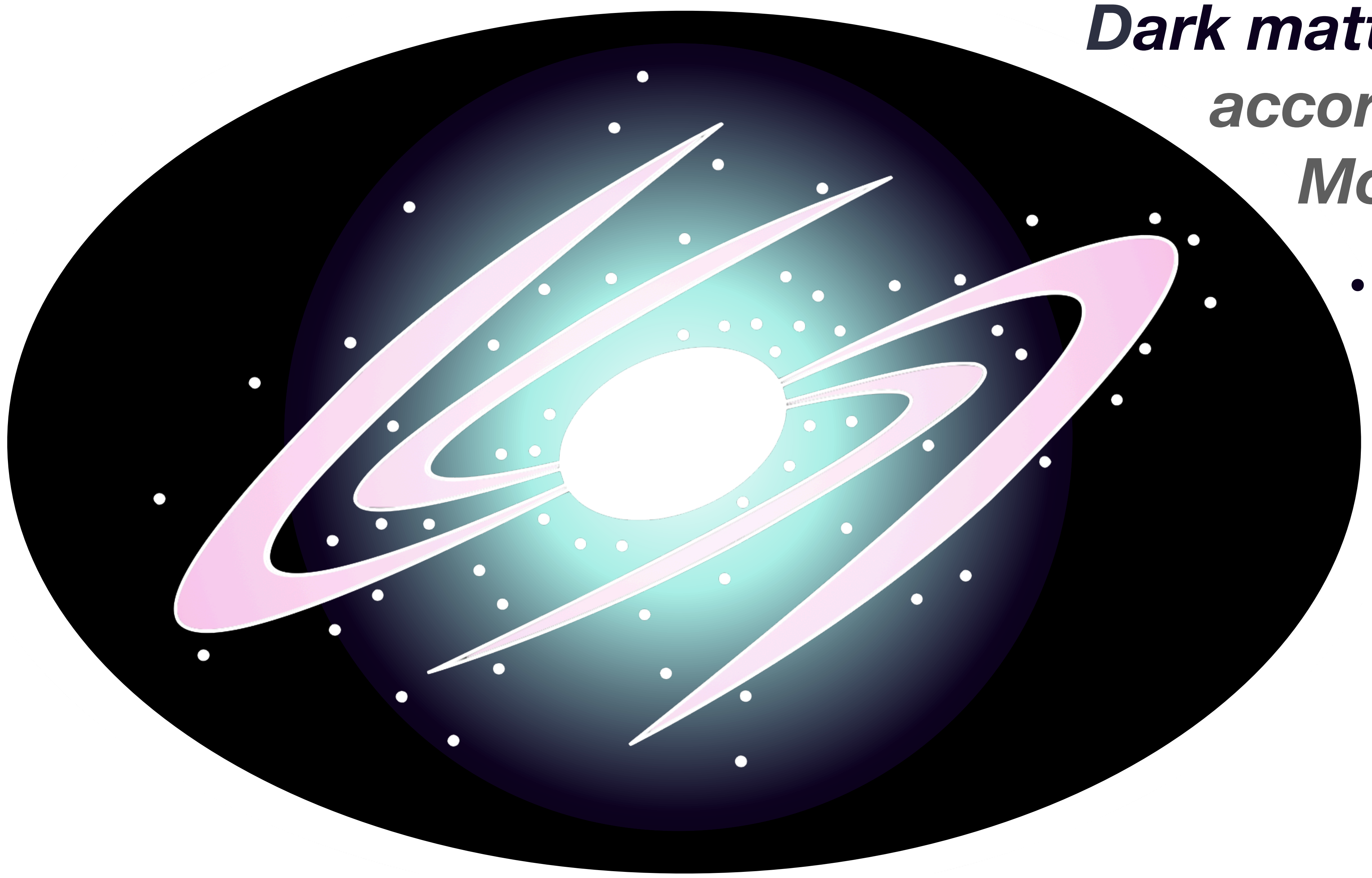

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***Dark matter** consists of particles with:*

- Non relativistic velocity distribution
- Extremely weak coupling to baryonic matter
- Half-integer spin (mostly)
- Masses ranging from MeV-TeV scales (mostly)

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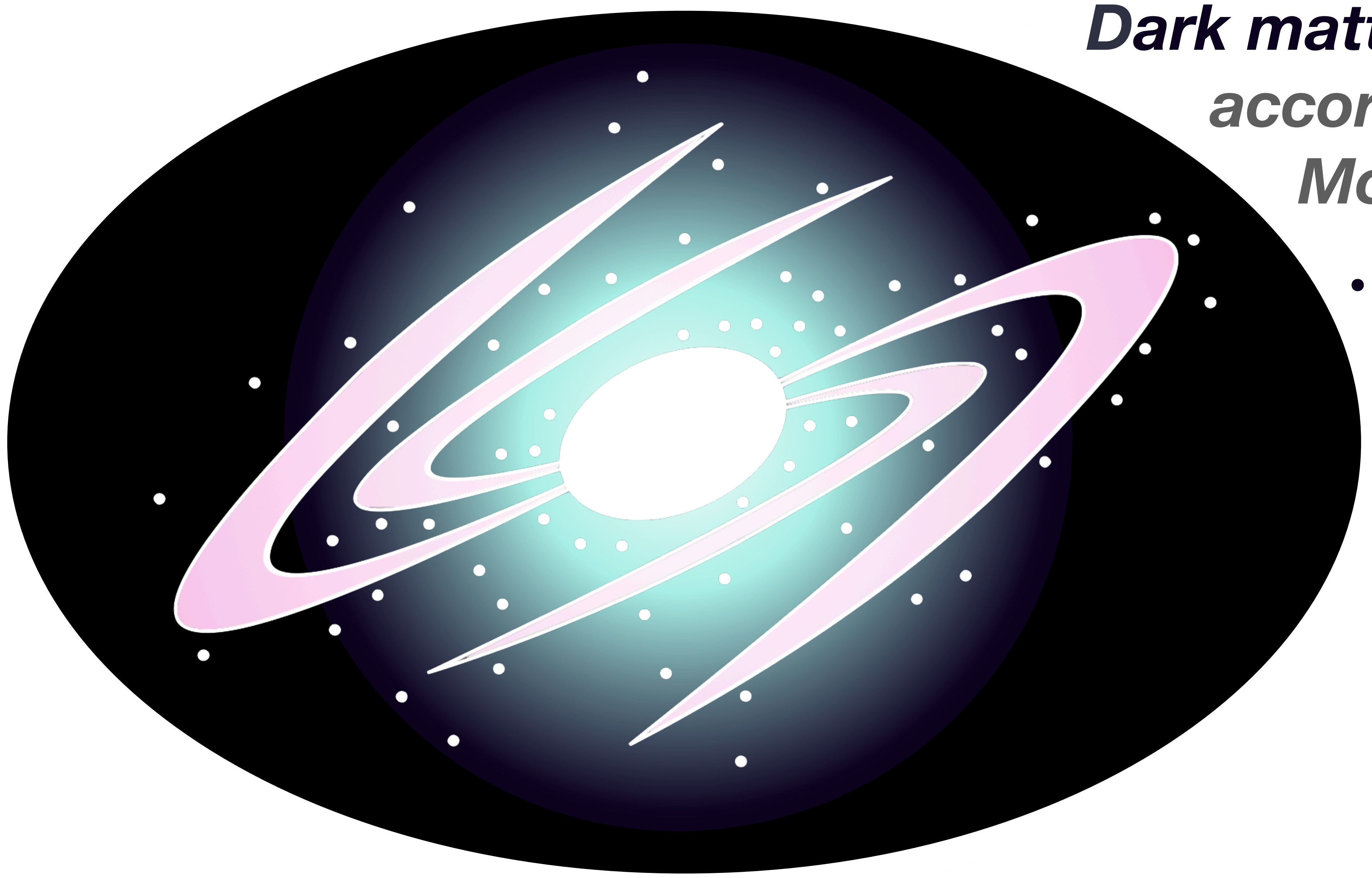

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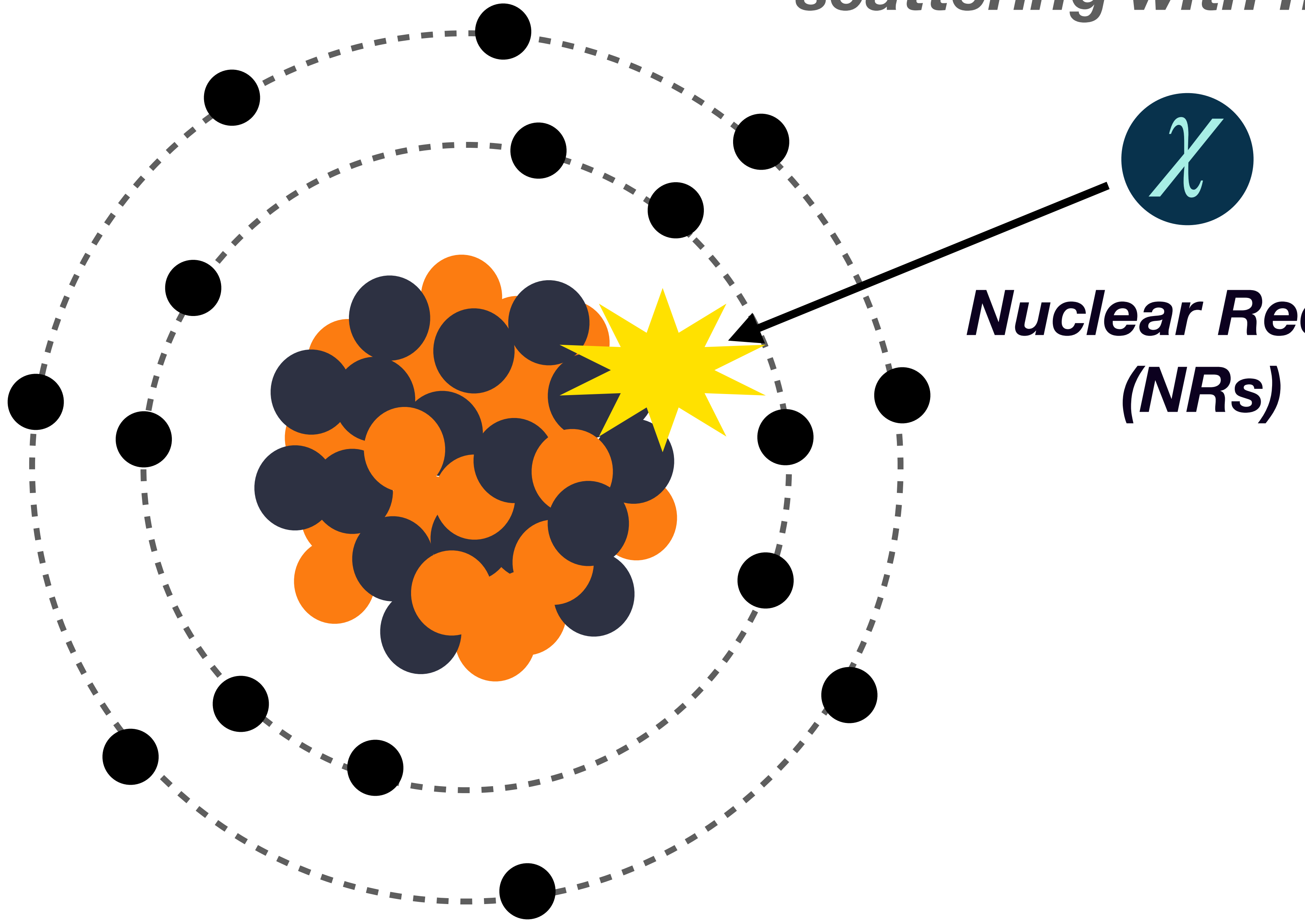

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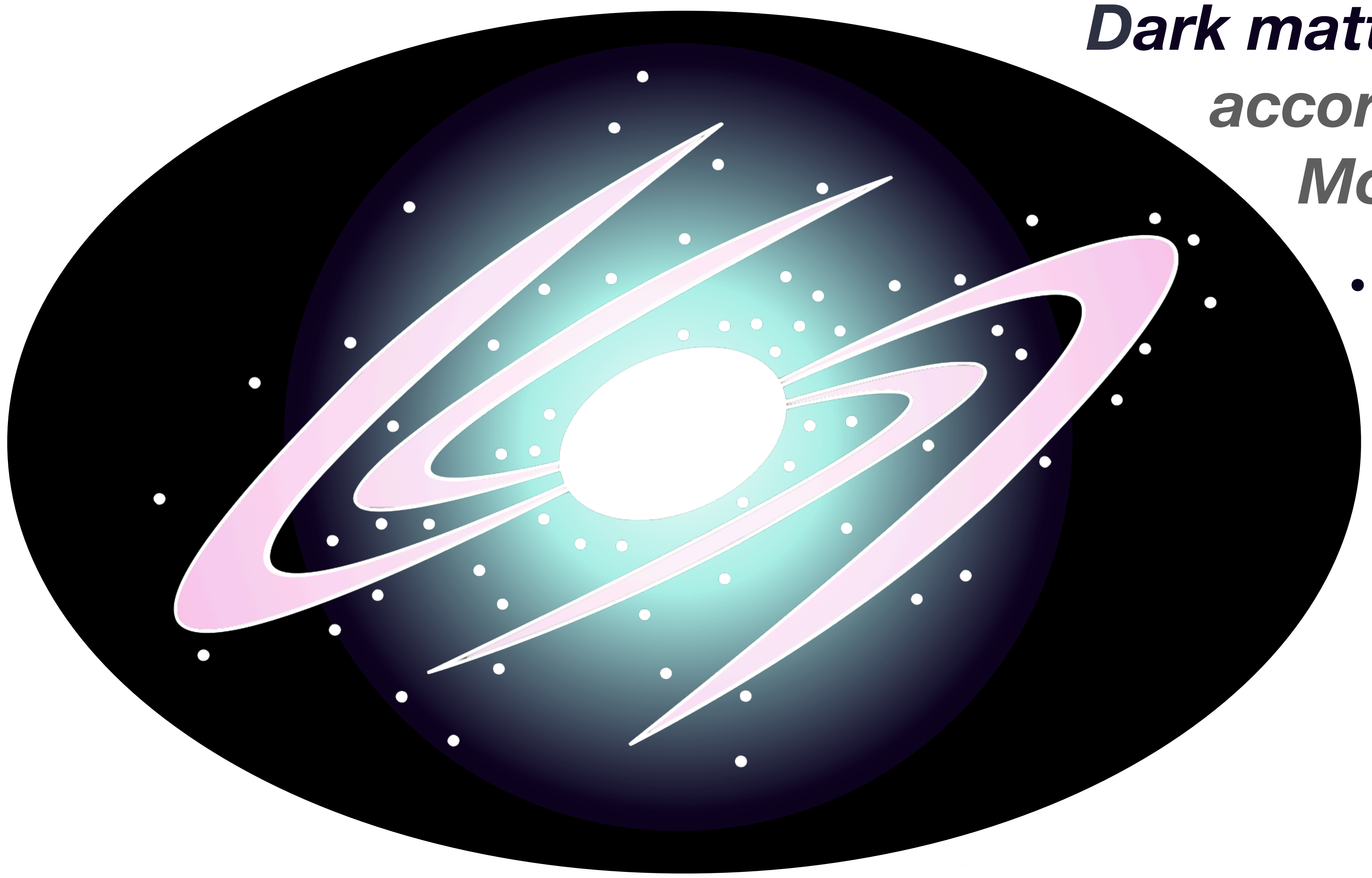

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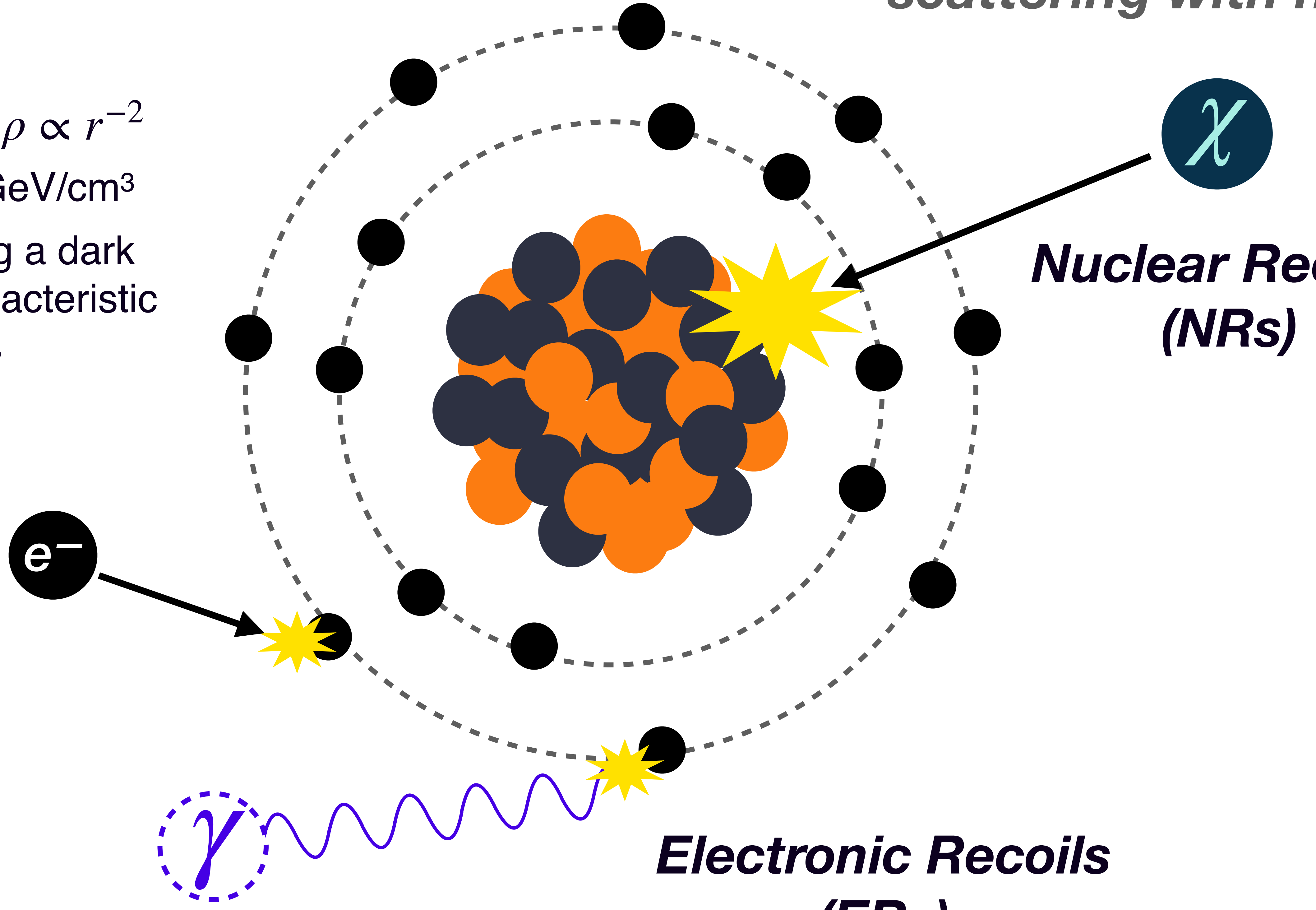

Nuclear Recoils (NRs)

Electronic Recoils (ERs)

***Dominant backgrounds** are low energy electrons and gammas, kinematically limited to scatter with atomic electrons*

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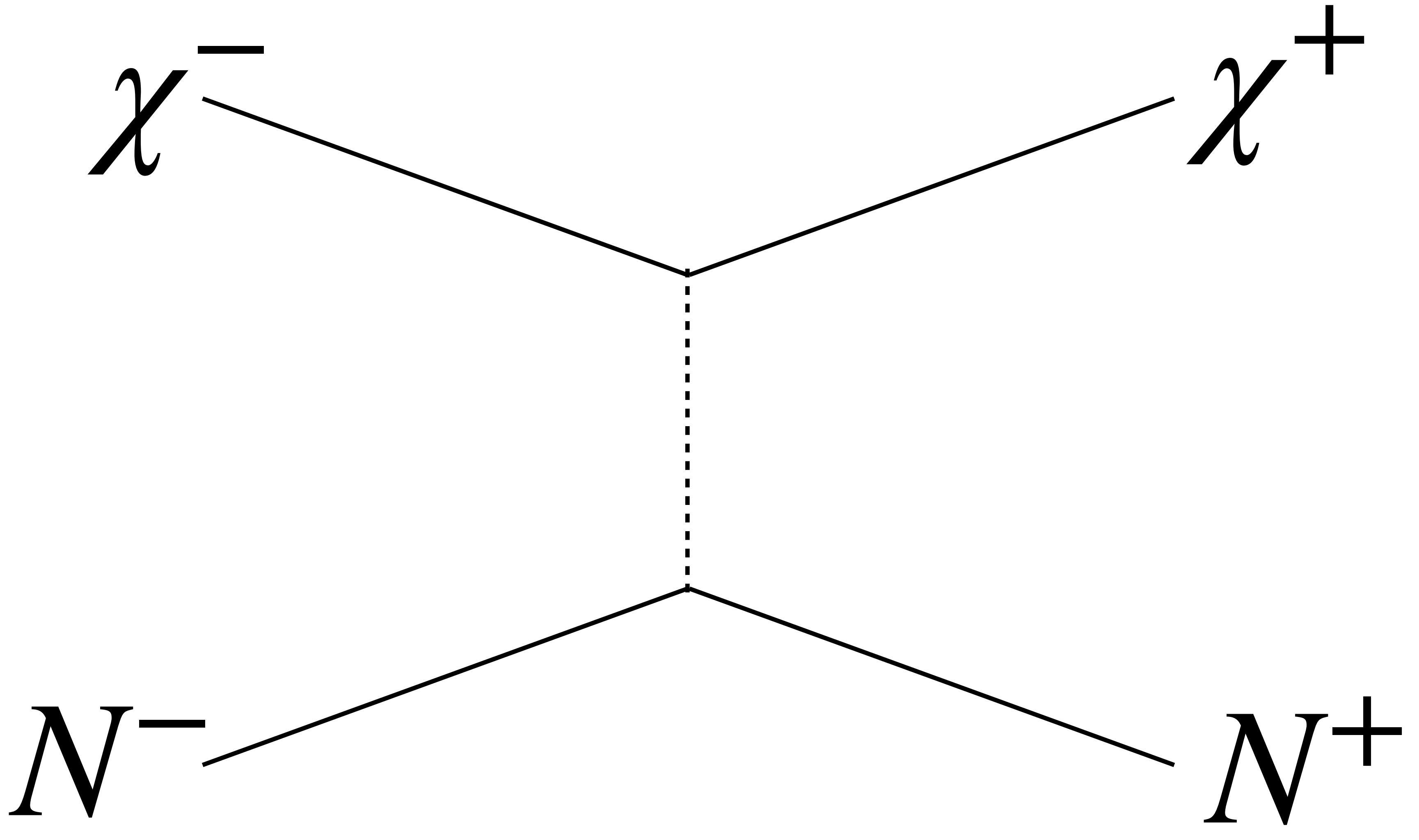
NR-EFT

Non-Relativistic Effective Field Theory

DOI: 10.1088/1475-7516/2013/02/004



- Since we're interested in low-q elastic scattering, all possible DM-N interactions described by a four-fermion Lagrangian term of the form

$$\mathscr{L}_{\text{int}} = \mathcal{O}\chi^+\chi^-N^+N^-$$

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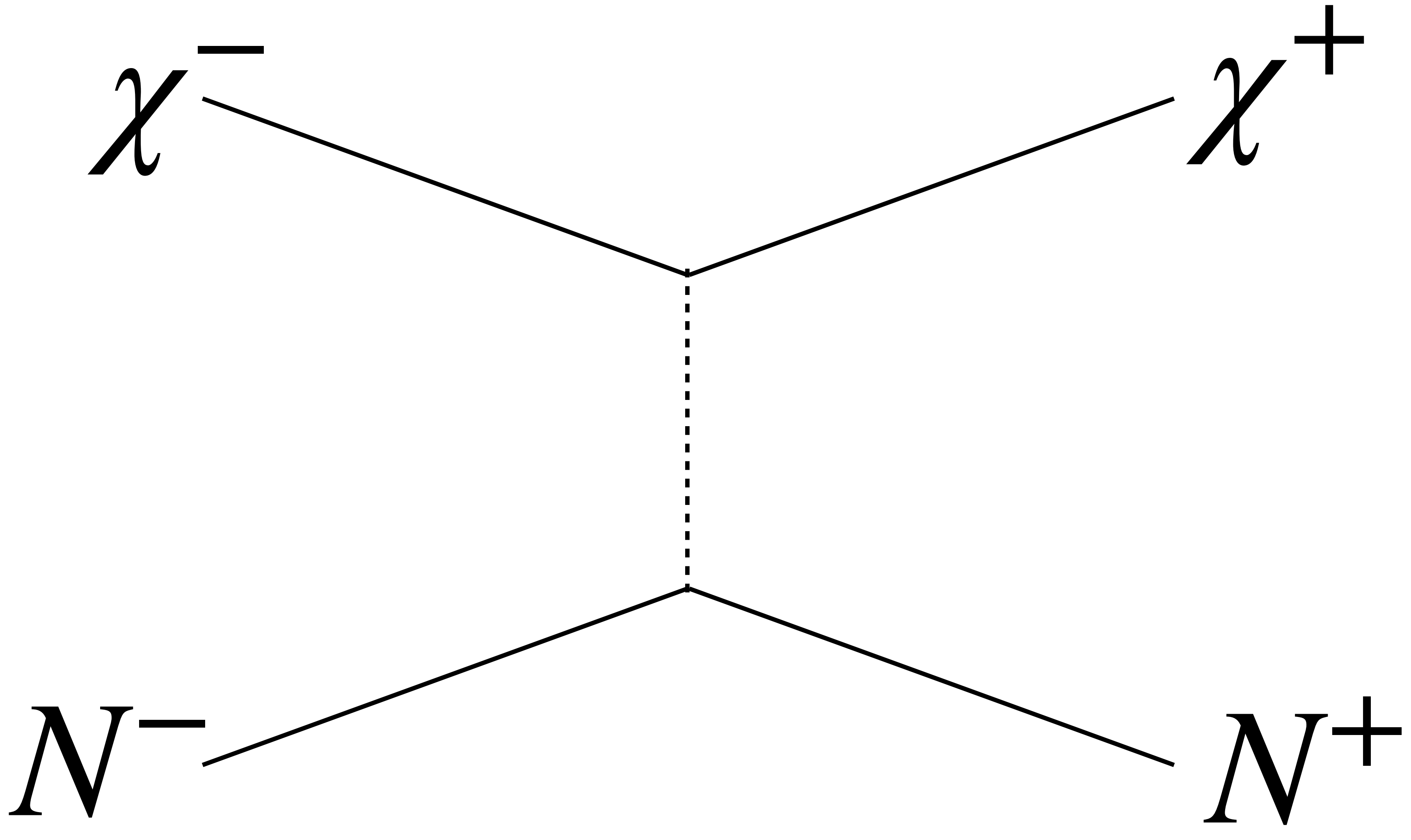

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  1. Galilean invariance
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  3. Hermiticity

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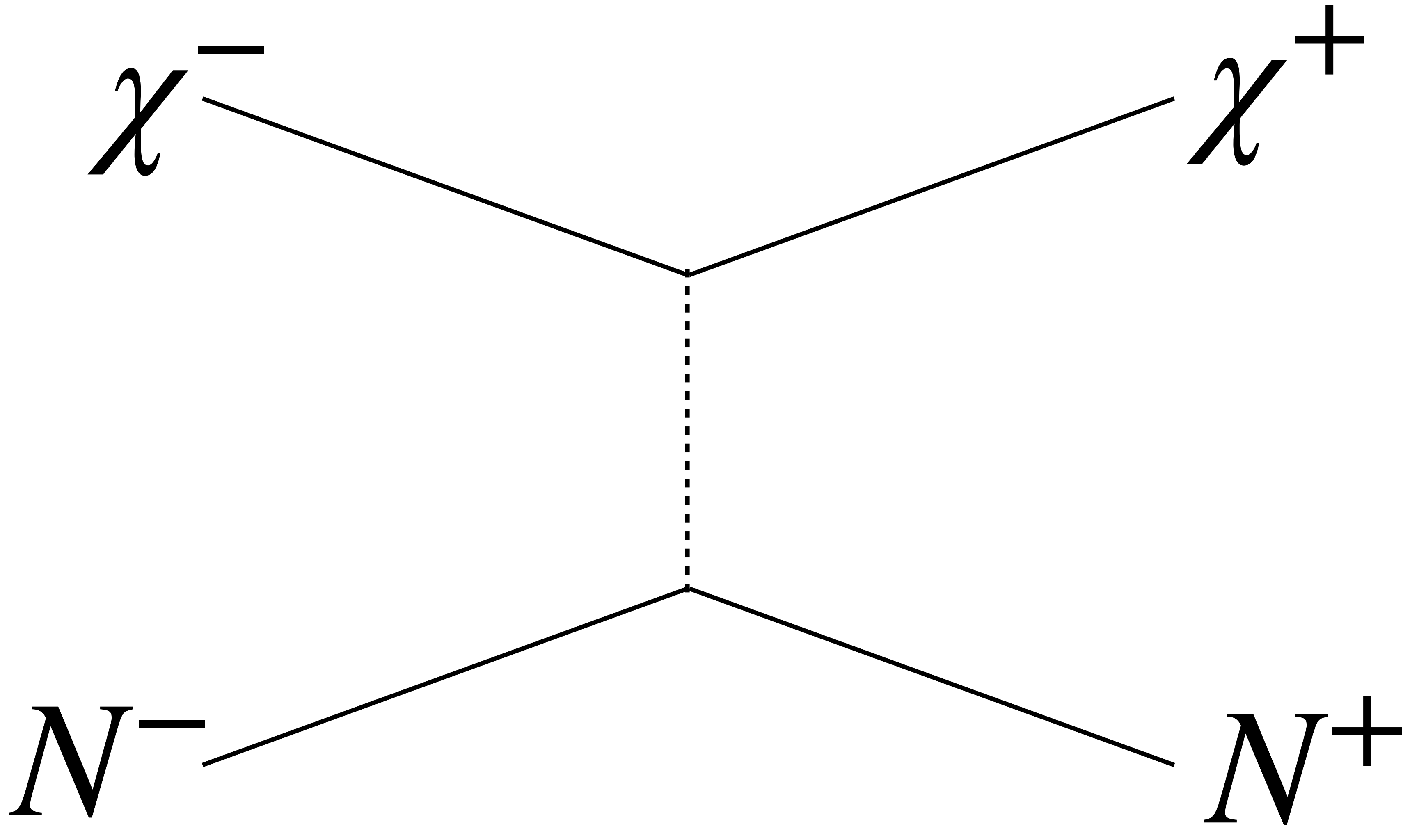

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All relevant quantities that obey these symmetries:

$$i\vec{q} \qquad \vec{v} + \frac{\vec{q}}{2\mu_N} \equiv \vec{v}^{\perp} \qquad \vec{S}_\chi \qquad \vec{S}_N$$

** $\vec{v} \equiv$ DM velocity in target rest frame, $\vec{q} \equiv$ Momentum transfer, $\vec{S}_{\chi,N} \equiv$ DM and nucleon spins respectively

NR-EFT

Non-Relativistic Effective Field Theory

DOI: [10.1088/1475-7516/2013/02/004](10.1088/1475-7516/2013/02/004)

- Construct operators out of combinations of these building blocks
- In low-q limit, we exclude all orders of q higher than 2, which leaves us with the following:

$$\mathcal{O}_1 = \mathbf{1}, \qquad \mathcal{O}_2 = (\vec{v}^\perp)^2, \qquad \mathcal{O}_3 = \vec{S}_N \cdot (i\vec{q} \times \vec{v}^\perp), \qquad \mathcal{O}_4 = \vec{S}_N \cdot \vec{S}_\chi,$$

$$\mathcal{O}_5 = \vec{S}_\chi \cdot (i\vec{q} \times \vec{v}^\perp), \qquad \mathcal{O}_6 = (\vec{S}_\chi \cdot \vec{q})(\vec{S}_N \cdot \vec{q}), \qquad \mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp,$$

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Standard SI and SD operators

NR-EFT

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Kinematically most suppressed

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Suppressed by velocity $|\vec{v}| \sim 10^{-3}c$

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- The full NREFT at the interaction level (excluding nuclear effects) is a linear combination of all these operators

$$\mathcal{L}_{\text{int}} = \sum_{N=p,n} \sum_{i} c_i^{(N)} \mathcal{O}_i \chi^+ \chi^- N^+ N^-$$

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Wilson coefficients

encoding all the high energy physics we integrate out, e.g.:

- Mediator mass and individual DM/nucleon couplings
- Lorentz structure of the interaction
- quark-to-nucleon physics

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Non-Relativistic Matching

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$\bar\chi\chi\bar N N$	$4m_\chi m_N 1_\chi 1_N$	$4m_\chi m_N \mathcal{O}_1$
$i\bar\chi\chi\bar N\gamma^5 N$	$-4m_\chi i\vec q\cdot\vec S_N$	$-4m_\chi\mathcal{O}_{10}$
$i\bar\chi\gamma^5\chi\bar N N$	$4m_N i\vec q\cdot\vec S_\chi$	$4m_N\mathcal{O}_{11}$
$\bar\chi\gamma^5\chi\bar N\gamma^5 N$	$-4\vec q\cdot\vec S_\chi\vec q\cdot\vec S_N$	$-4\mathcal{O}_6$
$P^\mu\bar\chi\chi K_\mu\bar N N$	$(4m_\chi m_N)^2 1_\chi 1_N$	$(4m_\chi m_N)^2\mathcal{O}_1$
$P^\mu\bar\chi\chi\bar N i\sigma_{\mu\alpha}q^\alpha N$	$-(4m_\chi^2)q^2+16m_N m_\chi^2 i\vec v^\perp\cdot(\vec q\times\vec S_N)$	$-4m_\chi^2 q^2\mathcal{O}_1-16m_N m_\chi^2\mathcal{O}_3$
$P^\mu\bar\chi\chi\bar N\gamma_\mu\gamma^5 N$	$-16m_N m_\chi^2\vec v^\perp\cdot\vec S_N$	$-16m_N m_\chi^2\mathcal{O}_7$
$iP^\mu\bar\chi\chi K_\mu\bar N\gamma^5 N$	$-16m_\chi^2 m_N i\vec q\cdot\vec S_N$	$-16m_\chi^2 m_N\mathcal{O}_{10}$
$\bar\chi i\sigma^{\mu\nu}q_\nu\chi K_\mu\bar N N$	$(2m_N)^2q^2-16m_N^2 m_\chi i\vec v^\perp\cdot(\vec q\times\vec S_\chi)$	$4m_N^2q^2\mathcal{O}_1+16m_N^2 m_\chi\mathcal{O}_5$
$\bar\chi i\sigma^{\mu\nu}q_\nu\chi\bar N i\sigma_{\mu\alpha}q^\alpha N$	$16m_\chi m_N(\vec q\times\vec S_\chi)\cdot(\vec q\times\vec S_N)$	$16m_N m_\chi(q^2\mathcal{O}_4-\mathcal{O}_6)$
$\bar\chi i\sigma^{\mu\nu}q_\nu\chi\bar N\gamma^\mu\gamma^5 N$	$16m_N m_\chi i\vec S_N\cdot(\vec q\times\vec S_\chi)$	$16m_N m_\chi\mathcal{O}_9$
$i\bar\chi i\sigma^{\mu\nu}q_\nu\chi K_\mu\bar N\gamma^5 N$	$4m_N(-q^2+4m_\chi i\vec v^\perp\cdot(\vec q\times\vec S_\chi))i\vec q\cdot\vec S_N$	$4m_N\mathcal{O}_{10}(-q^2-4m_\chi\mathcal{O}_5)$
$\bar\chi\gamma^\mu\gamma^5\chi K_\mu\bar N N$	$16m_N^2 m_\chi\vec v^\perp\cdot\vec S_\chi$	$16m_N^2 m_\chi\mathcal{O}_8$
$\bar\chi\gamma^\mu\gamma^5\chi\bar N i\sigma_{\mu\alpha}q^\alpha N$	$16m_\chi m_N i\vec S_\chi\cdot(\vec q\times\vec S_N)$	$-16m_\chi m_N\mathcal{O}_9$
$\bar\chi\gamma^\mu\gamma^5\chi\bar N\gamma^\mu\gamma^5 N$	$-16m_N m_\chi\vec S_\chi\cdot\vec S_N$	$-16m_N m_\chi\mathcal{O}_4$
$i\bar\chi\gamma^\mu\gamma^5\chi K^\mu\bar N\gamma^5 N$	$-16m_\chi m_N\vec v^\perp\cdot\vec S_\chi i\vec q\cdot\vec S_N$	$-16m_\chi m_N\mathcal{O}_{10}\mathcal{O}_8$
$iP^\mu\bar\chi\gamma^5\chi K_\mu\bar N N$	$16m_N^2 m_\chi i\vec q\cdot\vec S_\chi$	$16m_N^2 m_\chi\mathcal{O}_{11}$
$iP^\mu\bar\chi\gamma^5\chi\bar N i\sigma_{\mu\alpha}q^\alpha N$	$(4m_\chi)(i\vec q\cdot\vec S_\chi)(-q^2+4m_N i\vec v^\perp\cdot(\vec q\times\vec S_N))$	$4m_\chi\mathcal{O}_{11}(-q^2-4m_N\mathcal{O}_3)$
$iP^\mu\bar\chi\gamma^5\chi\bar N\gamma_\mu\gamma^5 N$	$-16m_\chi m_N(i\vec q\cdot\vec S_\chi)\vec v^\perp\cdot\vec S_N$	$-16m_\chi m_N\mathcal{O}_{11}\mathcal{O}_7$
$P^\mu\bar\chi\gamma^5\chi K_\mu\bar N\gamma^5 N$	$-16m_N m_\chi\vec q\cdot\vec S_\chi\vec q\cdot\vec S_N$	$-16m_N m_\chi\mathcal{O}_6$

- A good starting point for discussion
- LHCDMWG has conversions for scalar and axial vector couplings (i.e. SI and SD operators)
- This table can maybe help us figure out where to go with the other operators where DD is more kinematically suppressed

$p^\mu(p^{\mu'}) \equiv$ Incoming (outgoing) DM 4-momentum

$k^\mu(k^{\mu'}) \equiv$ Incoming (outgoing) N 4-momentum

$$P^\mu = p^\mu + p^{\mu'}, \quad K^\mu = k^\mu + k^{\mu'}$$