CSIC
Consejo Superior de Investigaciones Científicas

Vniversitat de València

IFIC Institut de Física Corpuscular

Excelencia Severo Ochoa

Direct Detection of CP-violation in QCD-like Dark Matter

Based on (*soon*): arXiv 26XX.XXXXX

Flavour and Origin of Matter
Sabor y Origen de la Materia

IDM2026 ZARAGOZA

Pablo Figueroa

In collaboration with: **Camilo García Cely (IFIC)** and **Giacomo Landini (INFN)**

ChatGPT

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Hey! I am a poor first year PhD student, and I am going to my first IDM, IDM 2026 in Zaragoza :). I will be presenting our current work "Direct Detection of CP violation in QCD-like Dark Matter", in front of an audience full of experts. Please give me a couple of very precise advices (short and specific bullet points) so my IDM debut is not a disaster hahaha

Pensó durante 20s ›

You'll be fine hahaha. For an expert audience, optimize for **clarity and control**, not for showing every detail.

- **State the "one-line physics message" in the first minute.**
  Example: *"We show that CP violation in a QCD-like dark sector can leave directly detectable electromagnetic/nuclear signatures, complementary to standard CP-conserving SIDM/direct-detection probes."*
- **Do not over-explain the model.**
  Experts can follow Lagrangians. Spend time on: *what is new, what observable is CP-violating, what controls the size, and what experiments constrain it.*
- **Label every plot with the physical takeaway.**
  Not just "limits on $g\bar{g}$" but: *"nEDM kills this region," "direct detection dominates here," "radiative splitting matters here," "SIDM target region."*

Overview

1. Strongly coupled dark sectors
2. Direct Detection of dark neutron EDM
3. CP-violation and Self Interacting DM
4. Conclusions

Strongly coupled dark sectors

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General Setup

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A (dark) sector with a gauge symmetry $SU(N_c)$ and N_f light Dirac fermions q

$$\mathcal{L}_{\mathrm{QCD}}(q,G) = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{q}i\not{D}q - (\bar{q}_L M q_R + \text{h.c.}) + \underbrace{\theta\frac{g^2}{32\pi^2}F_{\mu\nu}\widetilde{F}_{\mu\nu}}_{\text{CP-violation}},$$

But,... **as we all know QCD is complicated** ... It's low energy description

$$\mathcal{L}_{\mathrm{QCD}}(q,G) \implies \mathcal{L}^{\theta\neq 0}_{\mathrm{B}\chi\mathrm{PT}}(N,\pi)$$

However,... **this is still complicated**...

$$\mathcal{L}_{\mathrm{QCD}}(q,G) \implies \mathcal{L}^{\theta\neq 0}_{\mathrm{B}\chi\mathrm{PT}}(N,\pi) \implies \mathcal{L}^{(\pi NN)}_{\mathrm{eff}}$$

Dark Matter as Baryons

- QCD-like dynamics: (Dark) **Baryons and Pions**

$$\underbrace{N = \begin{pmatrix} p \\ n \end{pmatrix}}_{\text{Nucleon Isospin doublet}} \quad , \quad \underbrace{\boldsymbol{\pi} = \begin{pmatrix} \pi^1 \\ \pi^2 \\ \pi^3 \end{pmatrix}}_{\text{Isospin triplet of light } \pi\text{'s}}$$

- **The interactions between N's and π's can be generically described by** [Crewther et al. (1979)]

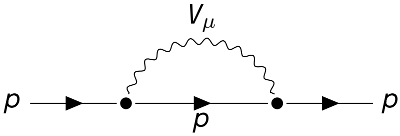
$$\mathcal{L}_{\text{eff}}^{(\pi NN)} = \underbrace{g_{\pi NN}\,\bar{N} i\gamma_5 \boldsymbol{\sigma}\cdot\boldsymbol{\pi}\,N}_{\text{CP - even}} + \underbrace{\bar{g}_{\pi NN}\,\bar{N}\boldsymbol{\sigma}\cdot\boldsymbol{\pi}\,N}_{\text{CP - odd}}$$

A dark photon portal

We extend the model by introducing a $U(1)_d$ gauge symmetry [García-Cely et al. (2025)]:

$$\mathcal{L}_{\rm DP} = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + \frac{1}{2} m_V^2 V_\mu V^\mu + \frac{\varepsilon}{2} V_{\mu\nu} B^{\mu\nu} ,$$

Mass Splitting



$\longrightarrow$

$$m_p > m_n$$
$$\Downarrow$$
Neutron DM

Dark dipole moments

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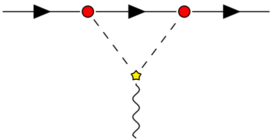
The **(dark) electromagnetic nucleon matrix element** in a CP violating vacuum [Kubis and Meissner (2001); Scherer and Schindler (2005); Abramczyk et al. (2017)]:

$$\Gamma^\mu(q) = \gamma^\mu F_E(q^2) + \underbrace{\frac{i\sigma^{\mu\nu}q_\nu}{2m_n}F_M(q^2)}_{\text{Magnetic Dipole}} + \underbrace{\frac{\sigma^{\mu\nu}q_\nu\gamma^5}{2m_n}F_D(q^2)}_{\text{Electric Dipole}} + \frac{(\gamma^\mu q^2 - 2M_N q^\mu)\gamma^5}{m_n^2}F_A(q^2)$$

- F_E, F_M, F_D and F_A are the charge, magnetic dipole, electric dipole, and anapole.
- The electric dipole is $d_n = -F_D(0)/(2m_n)$.



Dark dipole moments

The electromagnetic properties within BχPT are given by
[Pich and de Rafael (1991); Jenkins et al. (1993); Durand and Ha (1998)]

$$d_n = \frac{e_\mathrm{d}}{2m_n} \frac{g_{\pi NN}\bar{g}_{\pi NN}}{2\pi^2} \log\left(\frac{m_n}{m_{\pi^\pm}}\right) \;, \quad \mu_n = \mathcal{O}(1) \times \frac{e_\mathrm{d}}{2m_n}$$

while for the charge radius we adopt $b_n \sim e_\mathrm{d}/\Lambda^2 \sim e_\mathrm{d}/m_n^2$.

Direct Detection of dark neutron EDM

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A well known diagram

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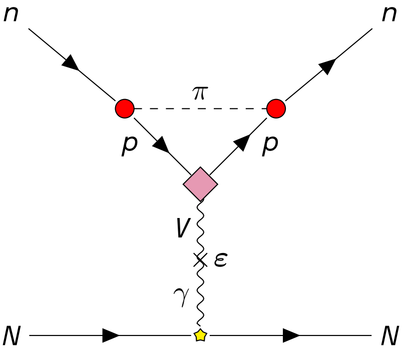
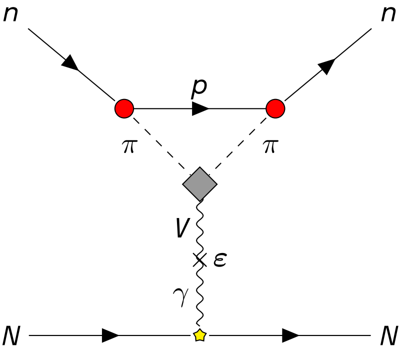




$$\mathcal{M}_{\text{NR}} \sim \underbrace{c_i^N(q^2, \boldsymbol{v}_\perp^2)}_{\text{Wilson coefficients}} \cdot \underbrace{\mathcal{O}_i^N}_{\text{NR Operators}}$$

The Matching Procedure

Operator: $\mathcal{O}_i$			Coefficient: $c_i^N(q^2, \boldsymbol{v}_\perp^2)$
O_1	$1_\chi 1_N$	CP-even	$\frac{ec_W\epsilon Q_N}{2m_\chi}\frac{q^2}{q^2+m_V^2}\mu_n + ec_W\epsilon Q_N\frac{q^2}{q^2+m_V^2}b_n$
O_4	$\boldsymbol{S}_\chi \cdot \boldsymbol{S}_N$	CP-even	$\frac{ec_W\epsilon g_N}{m_N}\frac{q^2}{q^2+m_V^2}\mu_n$
O_5	$i\boldsymbol{S}_\chi \cdot \left(\frac{\boldsymbol{q}}{m_N} \times \boldsymbol{v}^\perp\right)$	CP-even	$\frac{2ec_W\epsilon Q_N m_N}{q^2+m_V^2}\mu_n$
O_6	$\left(\boldsymbol{S}_\chi \cdot \frac{\boldsymbol{q}}{m_N}\right)\left(\boldsymbol{S}_N \cdot \frac{\boldsymbol{q}}{m_N}\right)$	CP-even	$-\frac{ec_W\epsilon g_N m_N}{q^2+m_V^2}\mu_n$
O_{11}	$i\boldsymbol{S}_\chi \cdot \frac{\boldsymbol{q}}{m_N}$	CP-odd	$\frac{2ec_W\epsilon Q_N m_N}{q^2+m_V^2}d_n$

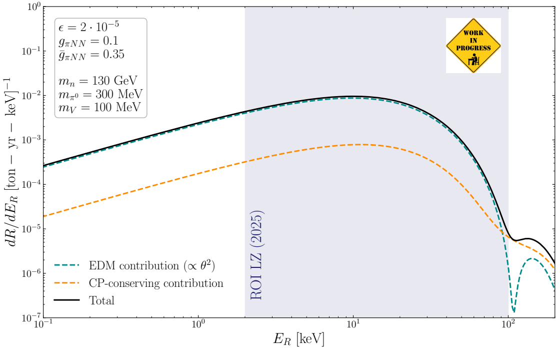
Our Dipole Signal

The **differential event rate** of DM-nucleus scattering with recoil E_R is [Jeong et al. (2022); Ibarra et al. (2025)]:

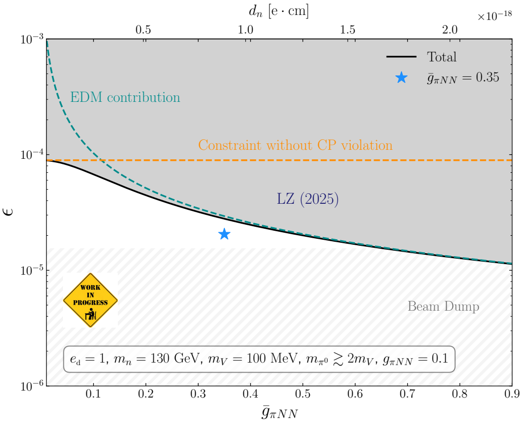
$$\frac{dR}{dE_R} = N_T \frac{\rho_\chi}{m_n} \int_{v_{\min}} \frac{d\sigma}{dE_R} v\, f_\oplus(\boldsymbol{v}, \boldsymbol{v}_E(t))\, d^3\boldsymbol{v}$$

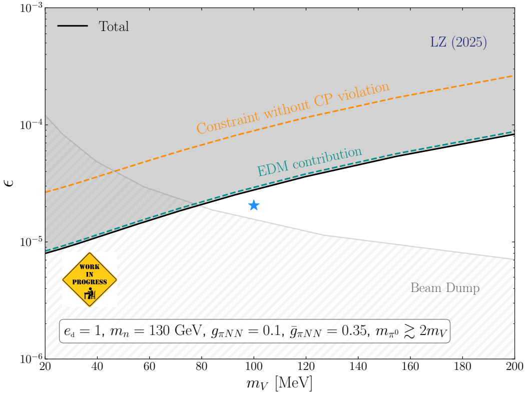
- $d\sigma/dE_R$: The differential DM-nucleus scattering.
- $f_\oplus(\boldsymbol{v}, \boldsymbol{v}_E(t))$: DM velocity distribution in the Earth frame.

Thanks WimPyDD!!

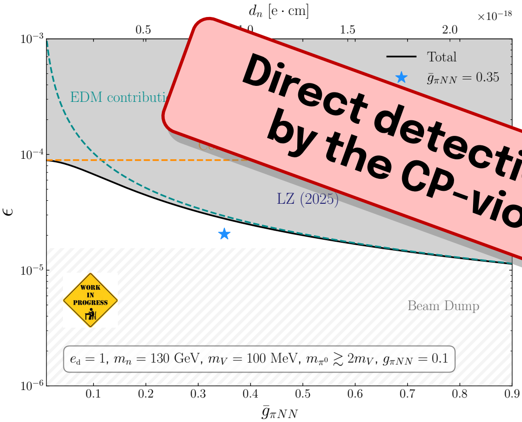


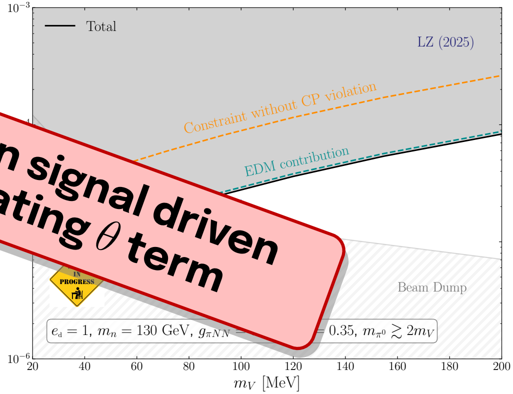
So, where are we?





So, where are we?



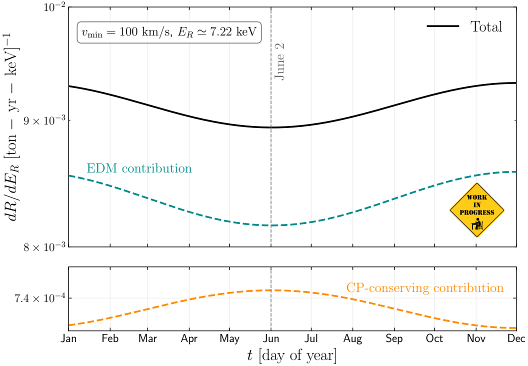


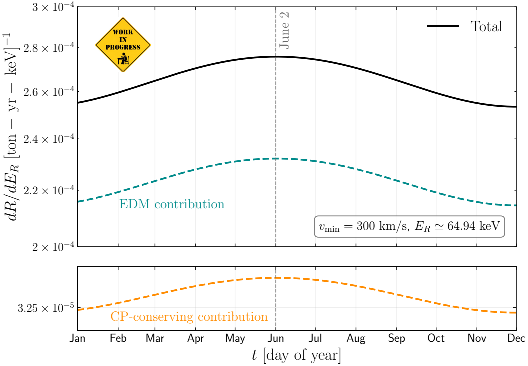
Direct detection signal driven by the CP-violating θ term

CP-odd or CP-even?

CP-odd $\sim d_n \mathcal{O}_{11}$

CP-even $\sim \mu_n \mathcal{O}_5$





CP-violation and Self Interacting DM

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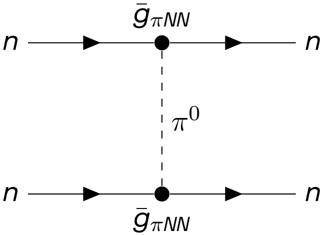
One Pion Exchange

For our neutron DM, there is only one scattering channel to be taken into account, *nn* with π^0 as mediator:



θ-Induced Yukawa potential

$$V(r) = -\frac{\bar{g}^2_{\pi NN}}{4\pi}\frac{e^{-m_\pi r}}{r}$$

Matching the effective low-energy baryon-meson interaction Lagrangian,

$$\bar{g}^2_{\pi NN} = \theta^2 \left(\frac{m_\pi}{f_\pi}\right)^2 m_\pi^2\, b_1^2$$

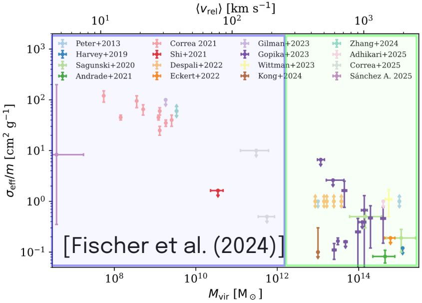
Self-Scattering Cross Sections

Small scales = Small- velocities **Large scales = Large velocities**

$$\sigma/m_n \sim 1 - 10\ [\mathrm{cm}^2\ \mathrm{g}^{-1}]$$

$$\sigma/m_n \lesssim 0.5\ [\mathrm{cm}^2\ \mathrm{g}^{-1}]$$

Small-scales

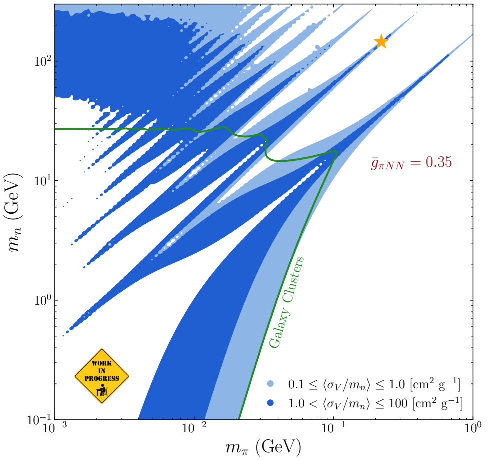


Galaxy Clusters

Data *suggests* **velocity-dependent** cross-sections

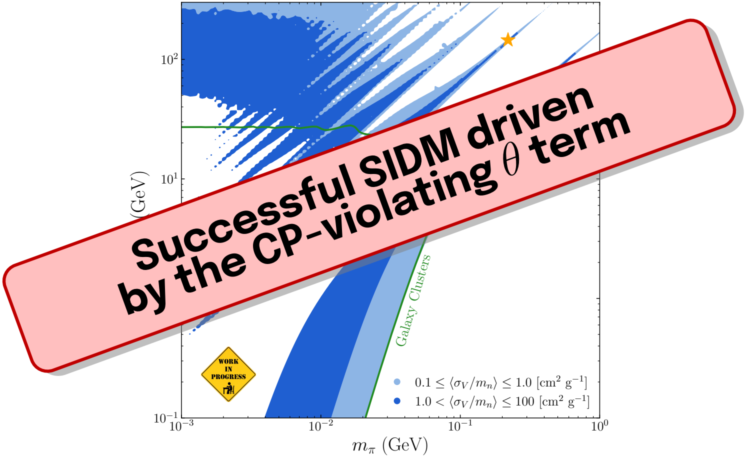
Self-Scattering Cross Sections

At small scales
$v_0 \sim 10\ \mathrm{km/s}$



At Galaxy Clusters
$v_0 \sim 10^3\ \mathrm{km/s}$

Self-Scattering Cross Sections



Conclusions

Conclusions

CP-violating π mediators are GREAT!

$$\downarrow$$

Naturally light pseudo-scalars (Goldstones)

- Potential signatures from direct detection of dark EDM.
- Sucessful SIDM with velocity dependence.

The dark θ angle changes the game!

Outlook

New and successful collaborations with you :)

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Thank you for your attention

Pablo Figueroa

In collaboration with: **Camilo García Cely (IFIC)** and **Giacomo Landini (INFN)**

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Back Up

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Baryon-Meson Effective Lagrangian

For the two-flavour sector (u,d): $\bar{B} \equiv \bar{N} = (\bar{p}, \bar{n})$, $\Phi = \frac{\tau\cdot\pi}{\sqrt{2}}$, the lowest-order baryon-meson effective Lagrangian with at most two baryons [Pich (1995)]:

$$\mathcal{L}_1^{(N)} = \mathrm{tr}[\bar{N} i\gamma^\mu \nabla_\mu N] + (D+F)\,\mathrm{tr}\left[\bar{N}\gamma^\mu\gamma_5\left(a_\mu - \frac{1}{\sqrt{2}f_\pi}(\partial_\mu\Phi) + \frac{i}{\sqrt{2}f_\pi}[v_\mu,\Phi]\right)N\right]$$

where ∇_μ, is the covariant derivative:

$$\nabla_\mu N \equiv \partial_\mu N + [\Gamma_\mu, N]$$

Our dark photon field v_μ: $v_\mu = e_D Q_D V_\mu$, with $Q_D = \mathrm{diag}(2/3, -1/3)$ SM-like.

Baryon-Meson Effective Lagrangian

Following the convention $(D+F) \equiv g_A$, and isolating the $\bar{N}N\Phi$ interaction term:

$$\mathcal{L}_1^{(\pi NN)} = -\frac{g_A}{2f_\pi} \operatorname{tr}\left[\bar{N}\gamma^\mu\gamma_5\tau^a N(\partial_\mu\pi^a)\right]$$

By IBP's $\partial_\mu(\bar{N}\gamma^\mu\gamma_5\tau^a N\pi^a) = \partial_\mu(\bar{N}\gamma^\mu\gamma_5\tau^a N)\pi^a + \bar{N}\gamma^\mu\gamma_5\tau^a N(\partial_\mu\pi^a) = 0$:

$$\mathcal{L}_1^{(\pi NN)} = \frac{g_A}{f_\pi} M_N \operatorname{tr}\left[\bar{N}i\gamma_5\tau^a\pi^a N\right] = \underbrace{\frac{g_A}{f_\pi} M_N}_{\equiv g_{\pi NN}} \bar{N}_j i\gamma_5(\tau^a)_{jk}\pi^a N_k$$

where we have defined $g_{\pi NN} \equiv g_A M_N/f_\pi$ (**Goldberger-Treiman relation**).

CP-violating terms

The CP non-conserving meson-baryon interaction terms are given by [Pich (1995)]:

$$\mathcal{L}_{\bar{\theta}}^{(\pi NN)} = \theta \left(\frac{m_\pi^2}{f_\pi} \right) b_1 \left[\bar{p}\pi^0 p + \sqrt{2}\bar{p}\pi^+ n + \sqrt{2}\bar{n}\pi^- p - \bar{n}\pi^0 n \right]$$

where b_1 is obtained via the mass splittings.

For this, $\chi = 2B_0\mathcal{M}$ with $\mathcal{M} = \mathrm{diag}(m_u, m_d, m_s)$, in the lowest $\mathcal{O}(\mathcal{M})$ interactions:

$$\mathcal{L}_{\bar{\mathcal{M}}}^{(B)} \subset -b_0(4B_0)\,\mathrm{tr}[\mathcal{M}]\mathrm{tr}[\bar{B}B] - b_1(4B_0)\mathrm{tr}[\bar{B}\mathcal{M}B] - b_2(4B_0)\mathrm{tr}[\bar{B}B\mathcal{M}]$$

After single out the mass terms for Ξ , Σ and $N \rightarrow b_1 = \frac{M_\Xi - M_\Sigma}{4B_0(m_s - \hat{m})}$

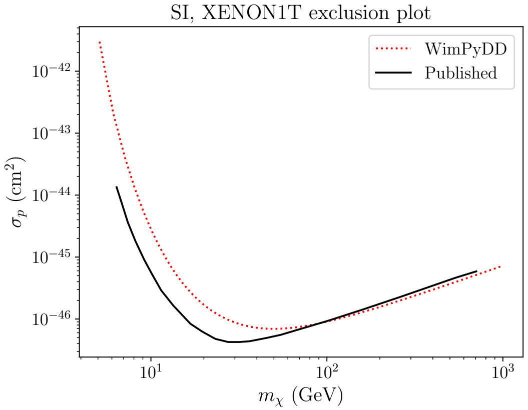
Limits setting

We follow a standard likelihood approach

$$\mathcal{L} = \frac{1}{n_{\text{obs}}!}(n_{\text{sig}} + n_{\text{bck}})^{n_{\text{obs}}} \exp\{(-(n_{\text{sig}} + n_{\text{bck}}))\}$$

$$\chi^2 = -2\log\mathcal{L} = 2\left(n_{\text{sig}} + n_{\text{bck}} - n_{\text{obs}}\log\left(n_{\text{sig}} + n_{\text{bck}}\right) + \log(n_{\text{obs!}})\right)$$

WimPyDD



SI, XENON1T exclusion plot
WimPyDD
Published
σ_p (cm^2)
m_χ (GeV)
10^{-42}
10^{-43}
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10^{-45}
10^{-46}
10^1
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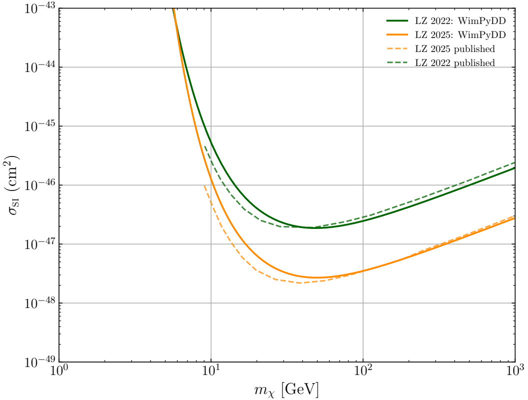

LZ 2022: WimPyDD
LZ 2025: WimPyDD
LZ 2025 published
LZ 2022 published
$\sigma_{\rm SI}$ (cm^2)
m_χ [GeV]
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10^{-49}
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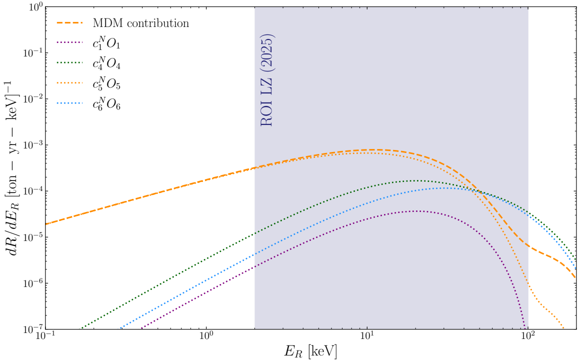
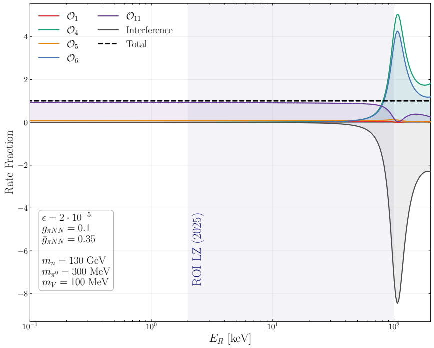
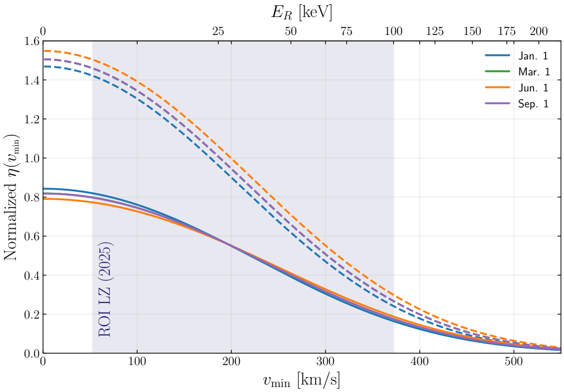
10^2
10^3

Operators Contribution





Velocity Integrals



The different time dependences might be understood already at the level of halo integrals $\eta(v_{\min}, t)$ [Nobile et al. (2016)]

$$\eta_n(v_{\min}, t) = \int_{v>v_{\min}} v^{2n} \frac{f(\mathbf{v}, \mathbf{v}_E(t))}{v} d^3 v$$

Are we cheating?

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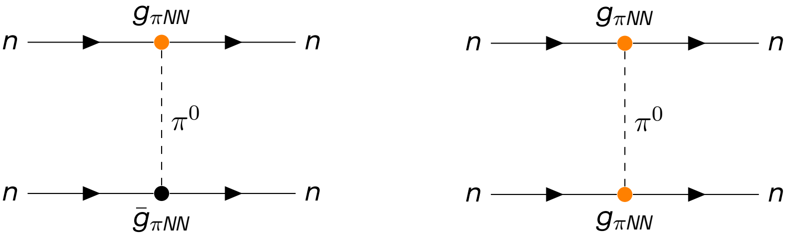

From the pseudoscalar part [Kahlhoefer et al. (2017); Agrawal et al. (2020)],

$$\frac{d\sigma}{d\Omega} = \frac{\bar{g}_{\pi NN}^2 m_n^2}{32\,\pi^2\, m_\pi^4}\left[\bar{g}_{\pi NN}^2\left(1 - \frac{m_n^2}{m_\pi^2} v^2\right) + \frac{1}{4} g_{\pi NN}^2 v^2\right] + \mathcal{O}(v^4)$$

Self-Interacting Cross Sections

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The *viscosity cross-section* σ_V:

$$\sigma_V = \frac{1}{(2s+1)^2}\frac{4\pi}{k^2}\sum_{l=0}^{\infty}\frac{(l+1)(l+2)}{(2l+3)}\sin^2(\delta_{l+2}-\delta_l)$$

To compute the phase shifts [Chu et al. (2020)]:

$$\frac{d\delta_{l,k}(r)}{dr} = -k\, m_n\, r^2\, V(r)\Big(\cos[\delta_{l,k}(r)]j_l(kr) - \sin[\delta_{l,k}(r)]n_l(kr)\Big)^2$$

The boundary conditions are:

$$\delta_{l,k}(0) = 0 \quad \text{and} \quad \delta_{l,k}(r) \to \delta_l$$

Here, $k = m_n v/2$ is the momentum of the DM, and v is the relative velocity.