

Directionality for DM Direct Detection

At low energy, how to distinguish (*DM*) **signal** from (*SM*) **background?**

Directionality: if the scattering rate depends on the detector orientation,

 then the scattering rate **modulates** every 23 hours 56 minutes

 $2/7$

101 **Directionality** for DM Direct Detection

Some DM detector targets have int some Divi accector targets mave in **anisotropic** scattering rates: eciency. Current exclusion limits from direct nuclear scattering fr Some DM detector targets have **intrinsically** *a a a <i>s l s* $\frac{1}{2}$ *l* $\frac{1}{2}$ anisotropic scattering rates:

- **DM–electron:** via asymmetric electronic wavefunctions \mathbb{E} of 1037 cm2. This cross section is \blacksquare
- **DM-nucleon (Migdal):** from -5 **to be the mediate of the mediate of** asymmetric potential on nuclei ω *The observation* pot asymmetric potential on nuclei and **reach for a total DM-nucleon (Miodal)** from t_{max} medicum $\left(\frac{1}{2}, \frac{1}{2}\right)$. Then \mathbf{b}

the de-excitation of the de-excitation of the CMR or \mathcal{A}

Eqs. (34)–(35) has energy *O*(10 eV), and we assume 100%

Newly Challenging Rate Calculation:

$$
R_s = N_{\text{SM}} n_{\chi} \bar{\sigma}_0 \int \frac{d^3q}{4 \pi \mu_{\chi \text{SM}}^2} \underbrace{\int d^3v \, g_{\chi}(\mathbf{v})}_{\text{W}} \times \underbrace{\int d^2v \, g_{\chi}(\mathbf{v})
$$

With **directionality**, what was a 2d integral is now a 6d integral:

Repeat for every…

- \bullet **DM mass and** F_{DM} **•** $50 - 10^2$
- **• velocity distribution** 1 − 103
- **• detector form factor** • $1 - 10^2$
- **• detector orientation** • $1 - 10^4$
- **• TOTAL: •** $50 - 10^{11}$

SM Detector Physics

BEN LILLARD – UOREGON MAY 13, PHENO 2024

Vector Spaces for Dark Matter (VSDM)

| github:<https://github.com/blillard/vsdm> <u>.²*d*₄</u> ⇣ arXiv: [2310.01480](https://arxiv.org/abs/2310.01480) and [2310.01483](https://arxiv.org/abs/2310.01483)

$$
R_s = N_{\text{SM}} n_{\chi} \bar{\sigma}_0 \int \frac{d^3 q}{4\pi \mu_{\chi \text{SM}}^2} \int d^3 v \, g_{\chi}(\mathbf{v}) \times \delta \left(\Delta E + \frac{q^2}{2m_{\chi}} - \mathbf{q} \cdot \mathbf{v}\right) F_{\text{DM}}^2(q) \times f_s^2(\mathbf{q})
$$

$$
R_s = \frac{N_{\text{SM}} n_{\chi} \bar{\sigma}_0}{4\pi \mu_{\chi \text{SM}}^2} \langle g_{\chi} | \phi_v \rangle \cdot \left\langle \phi_v \left| \delta \left(\Delta E + \frac{q^2}{2m_{\chi}} - \mathbf{q} \cdot \mathbf{v}\right) F_{\text{DM}}^2(q) \right| \varphi_q \right\rangle \cdot \left\langle \varphi_q \left| f_s^2 \right\rangle \right.
$$

- 1. Define **basis functions**, $|nlm\rangle = r_n(q) Y_{lm}(\hat{q})$, with spherical harmonics Y_{lm} 4⇡*µ*² SM 2*m* $\frac{1}{2}$
- 2. Projections of g_χ and f_s^2 onto each basis \longrightarrow **vectors** $oj\epsilon$ \therefore $f(x) = \frac{f(x)}{f(x)}$ and $f(x) = \frac{f(x)}{f(x)}$ and $f(x) = \frac{f(x)}{f(x)}$ (basis \Rightarrow **vectors**
- 3. Kinematic operator (incl. m_{χ}) \longrightarrow **matrix** connecting (*v*, *q*) spaces α ^vs
matic operator (incl. *m*) \longrightarrow matrix connecting (*v*, *q*) spaces
- 4. Detector rotations \longrightarrow **matrix multiplication**

Outcome: can calculate **thousands** of $R(g_\chi, f_s^2, m_\chi, F_{DM})$ per second.

Difficult integrals $\langle g_\chi | \phi_\nu \rangle$ and $\langle \phi_q | f_s^2 \rangle$ only need to be done $\bf once$ (per model) *Easily saved and shared among researchers.*

Applications

- Which detector orientations maximize or minimize a **modulation signal?**
- Propagate astro/materials **uncertainties** through the rate calculation
- Infer **particle physics properties** (e.g. m_χ) from shape of the modulation signal
- Compare many different **target materials**
- Search for **substructures** in DM velocity distribution…

orientations. Above 10 MeV, the rate relaxes into a function of the relaxes and additions of the DM mass and with the

Looking To The Future: A Library of DM Systems

Difficult integrals $\langle g_\chi | \phi_\nu \rangle$ and $\langle \phi_q | f_s^2 \rangle$ only need to be done $\bf once$ (per model) *Easily saved and shared among researchers.*

.
DMO ALAMAN

BEN LILLARD – UOREGON MAY 13, PHENO 2024 7/7 red =62*.*14 $0<\pm$.
7

MB-*v*circ ²

red =136*.*72

Molecules for Nuclear Scattering

Detectable?

- **Yes**: if electrons get involved
	- 1. DM transfers \vec{q} to nucleus
	- 2. nuclear motion excites an electron
	- 3. electron emits photon to return to ground state
	- 4. Detect the photon

Simple example: strike a nucleus with enough energy to break or ionize the molecule.

• But: **high energy** processes like ionization are approximately **isotropic**.

For directionality, use **bound final states** → **Bonus**: lower energy threshold

How to calculate DM-molecule scattering: molecules (Brown, 1966). The N-N bonds are also mately perpendicular to each other. \blacksquare 11 VI $-$ malecule s **D**IN HIDICURL 5

and $\mathcal{O}(\mathcal{A})$ for the fl molecules.

gaseous state

is 1 \sim 1 \sim [½,y,0] and [0,y,½]. Within a column successive mole-

obtained from the variance-covariance matrix of the coordinates (Darlow, 1960) are 0.0015 A_ for C-C and 0.11 ° for C-C-C. Owing to the disorder described above we have multiplied these values by a factor of $t \sim$ molecules. Corresponding bond lengths \sim and C-C-C valence angles in the two molecules do not show significant differences. The disorder of the molecules is so small that it does not affect the thermal parameters to a large extent. The value of $(1-p)^2$ cipal axis)) $x \rightarrow 0$ for the C atoms is 0.0217 α

see arXiv:2103.08601

LCAO: Linear Combinations of Atomic Orbitals molecules is not the same for the two columns.

A Complication: trans-stilbene crystals form unit cell with 4 components Λ Ω and \mathbf{I} and \mathbf{I} and \mathbf{I} **a complication:** trans **is** H(ct, y=0)'- .H(fl', y= 1)=2.222/~. \mathbf{p} -ctilhene crystals torm m_{SUS} checks shown for m_{SUS}

Fig. 4. Projection along [001] onto the plane (001). The 0~ molecules having their centres at z=0 are drawn with thin lines, **the**

.
The male of this in the internal and thick along a this internal and an antification of this internal and the internal experience exact

by Brown (1966; Fig. 2). In contrast to the strong disorder in the p-azotoluene crystals studied by Brown and in the TSB crystals studied by Finder *et al.* (1974),

Fig. 2. Superposition of two centrosymmetric p-azotoluene molecules (Brown, 1966). The N-N bonds are approxi-

mately perpendicular to each other.

single molecule…

 q_x (keV)

Crystal Form Factor

BEN LILLARD – UOREGON MAY 8, PHENO 2023 11/7

Results: Diatomic Molecules CO and *N*₂ (2208.09002)

BEN LILLARD - UOREGON

