New Techniques in Dark Matter Direct Detection

- **New Signals**
- **New Materials**
- **New Rate Calculation**
- **New VSDM Code**

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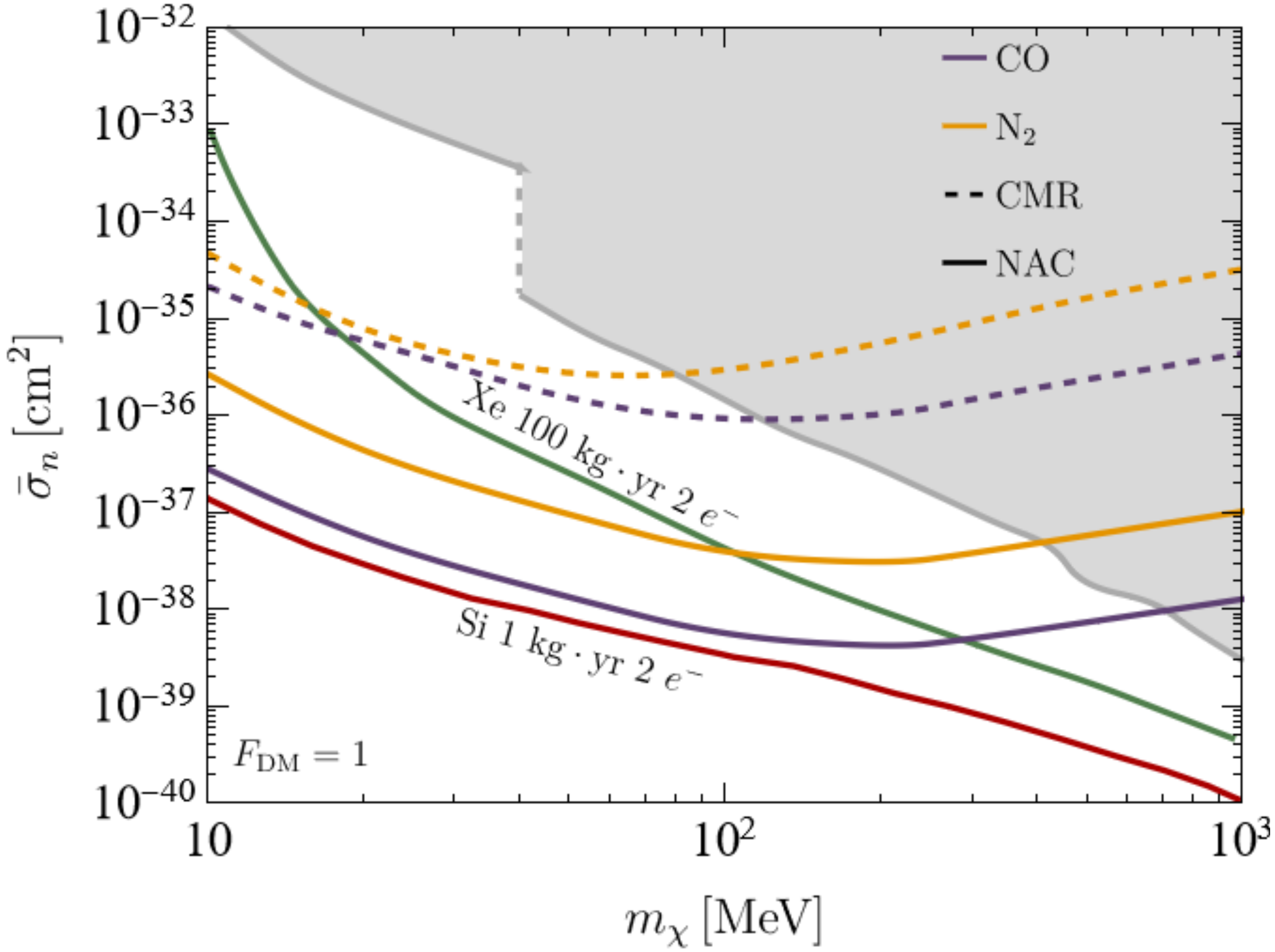
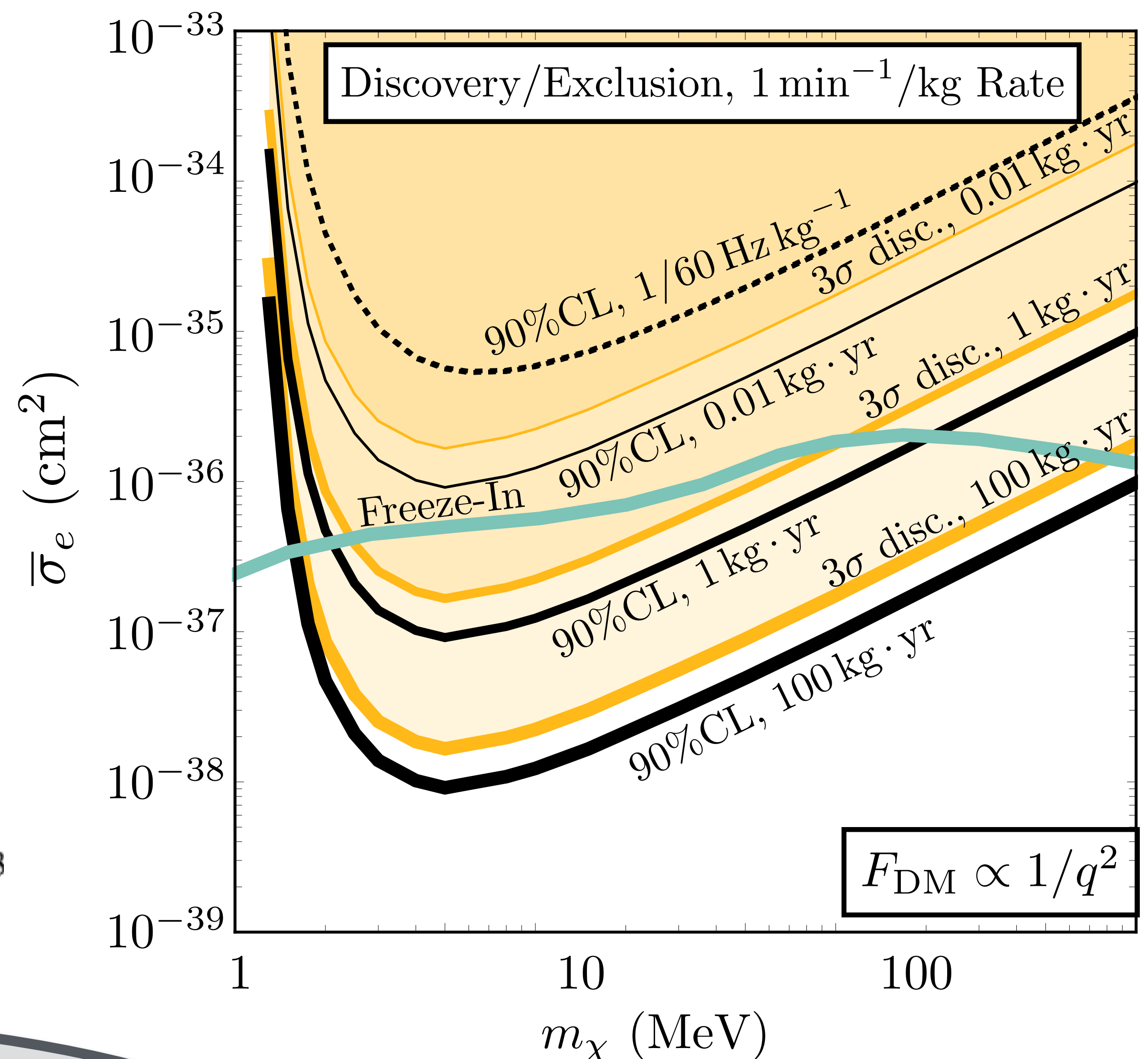
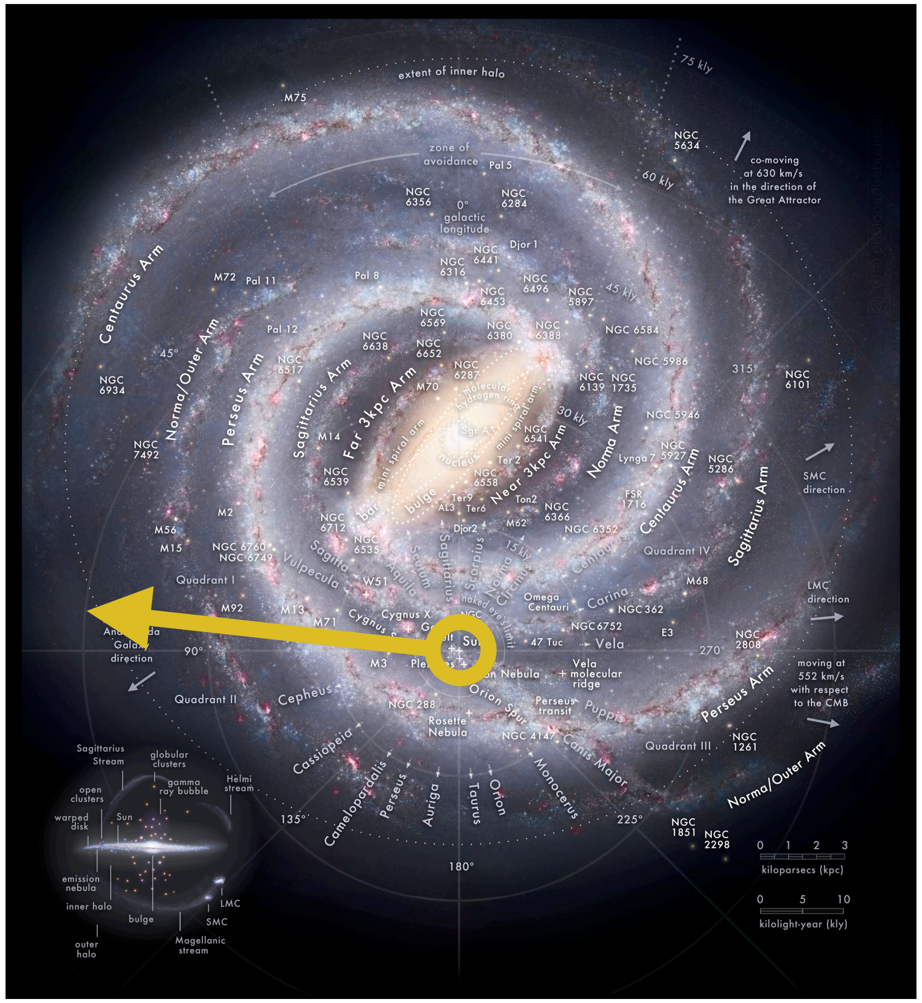
PHENO 2024





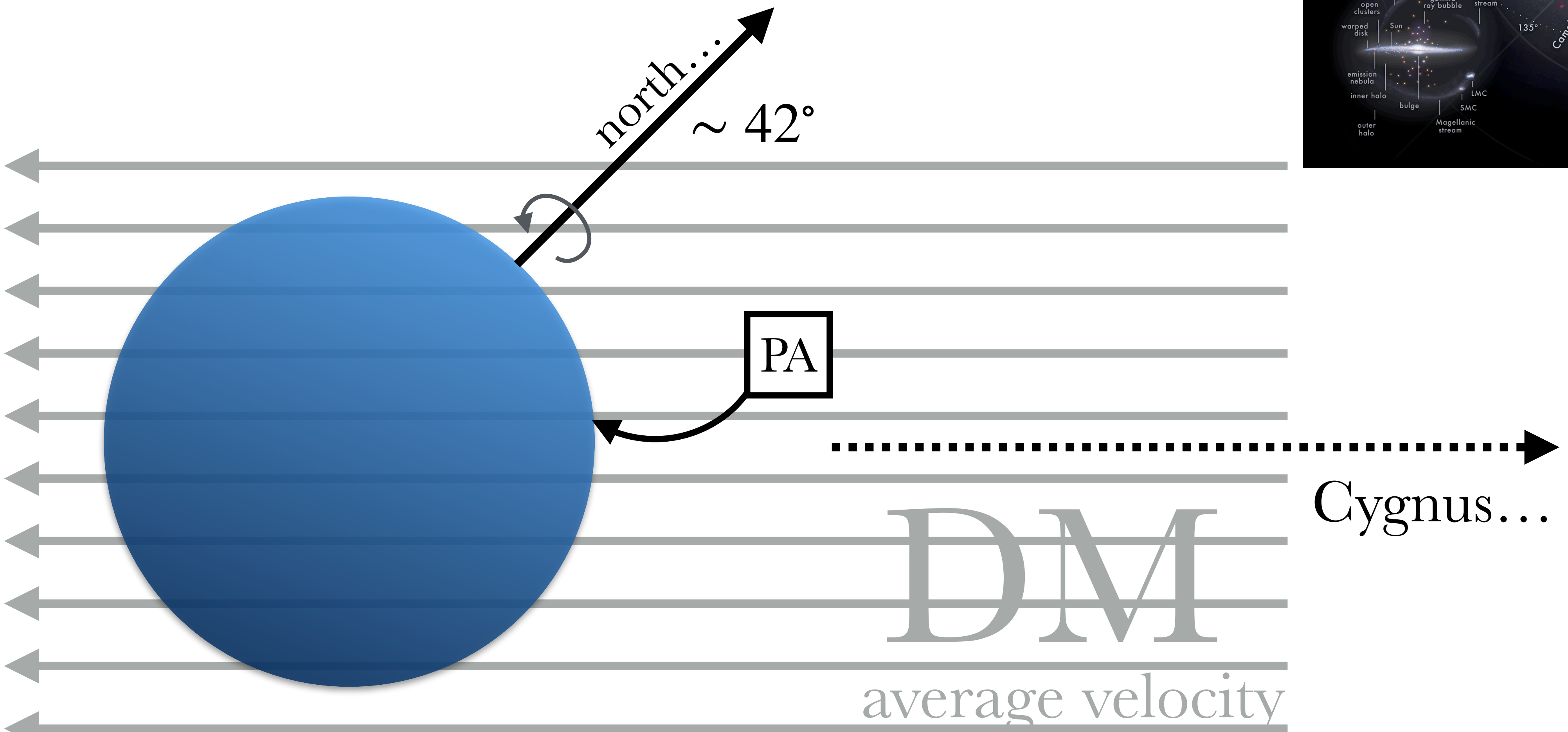
Directionality for DM Direct Detection



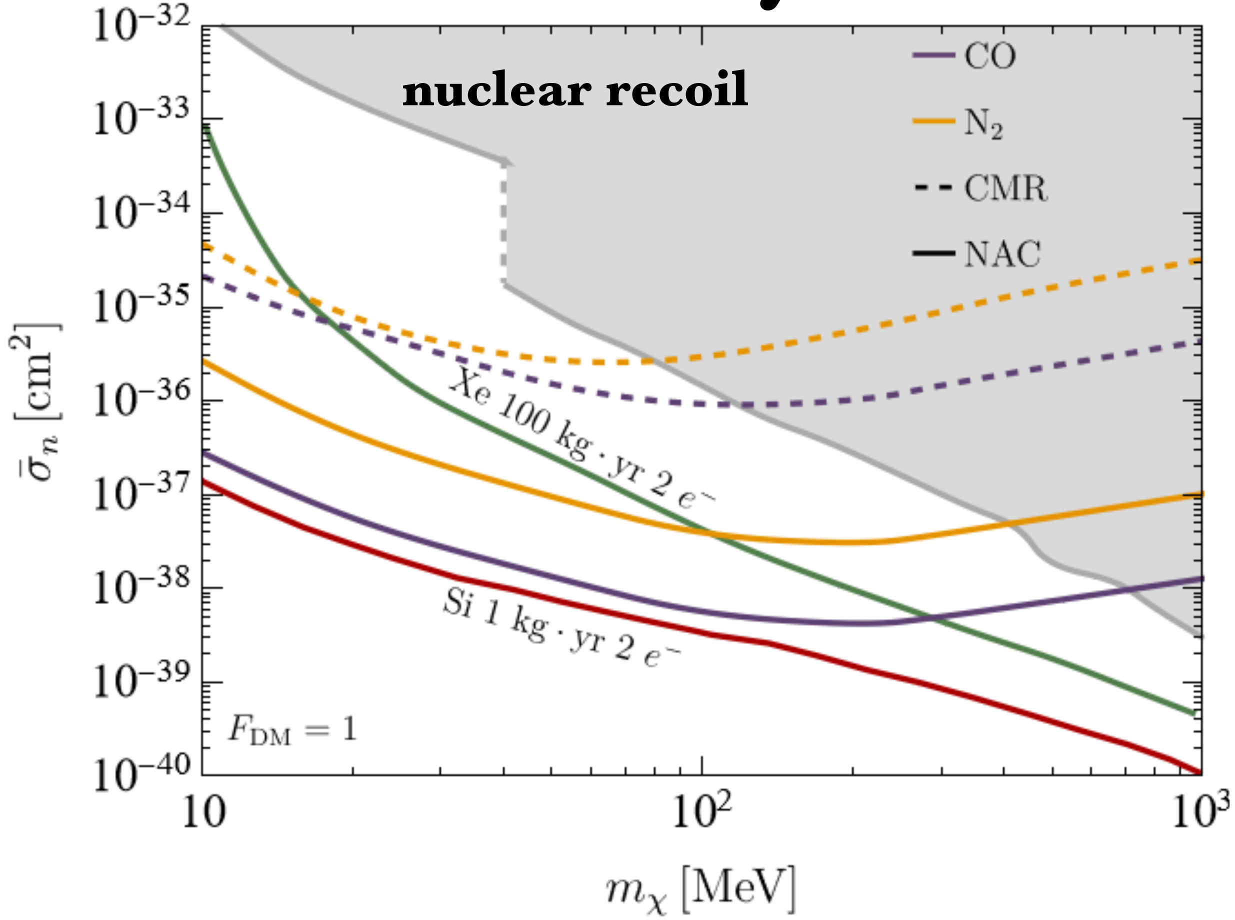
At low energy, how to distinguish (*DM*) **signal** from (*SM*) **background?**

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

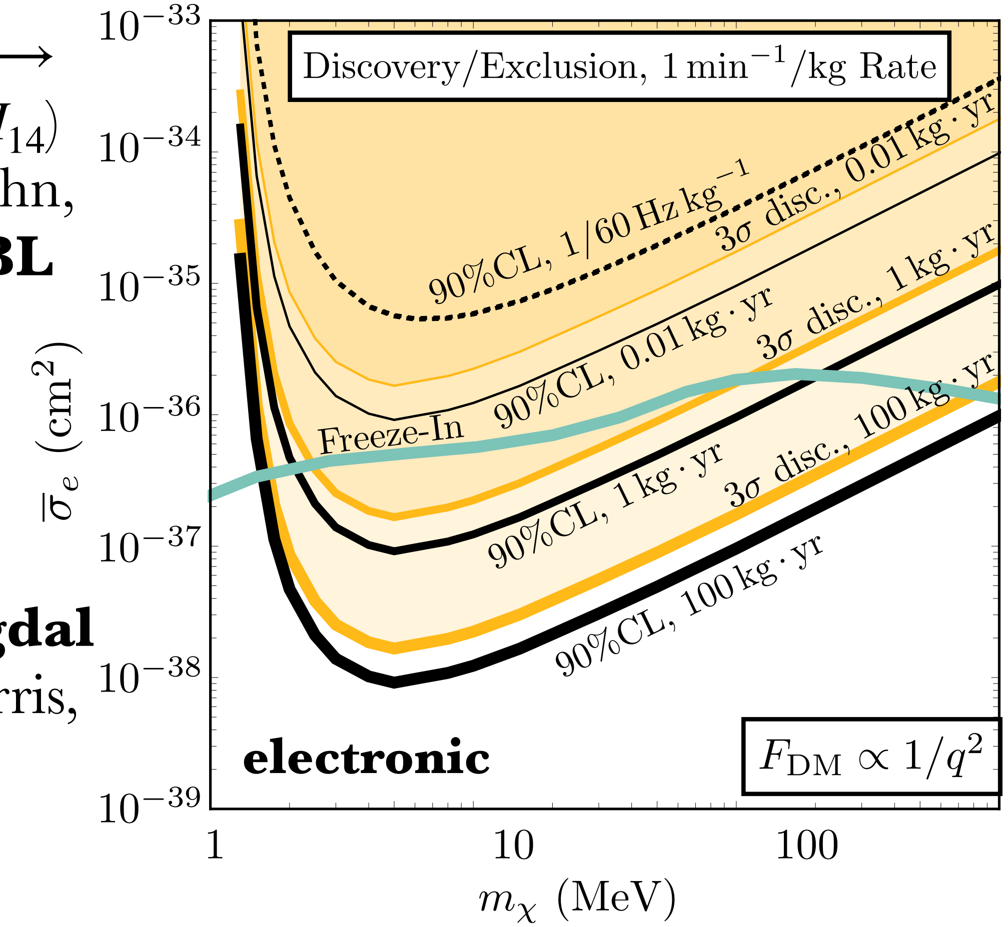
then the scattering rate **modulates** every 23 hours 56 minutes



Directionality for DM Direct Detection

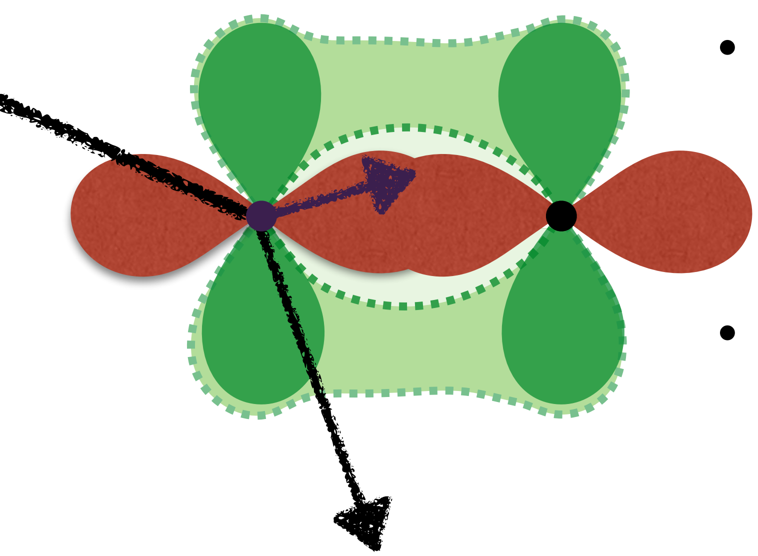


2103.08601 ⟶
t-stilbene ($C_{14}H_{14}$)
C. Blanco, Y. Kahn, S. McDermott, **BL**

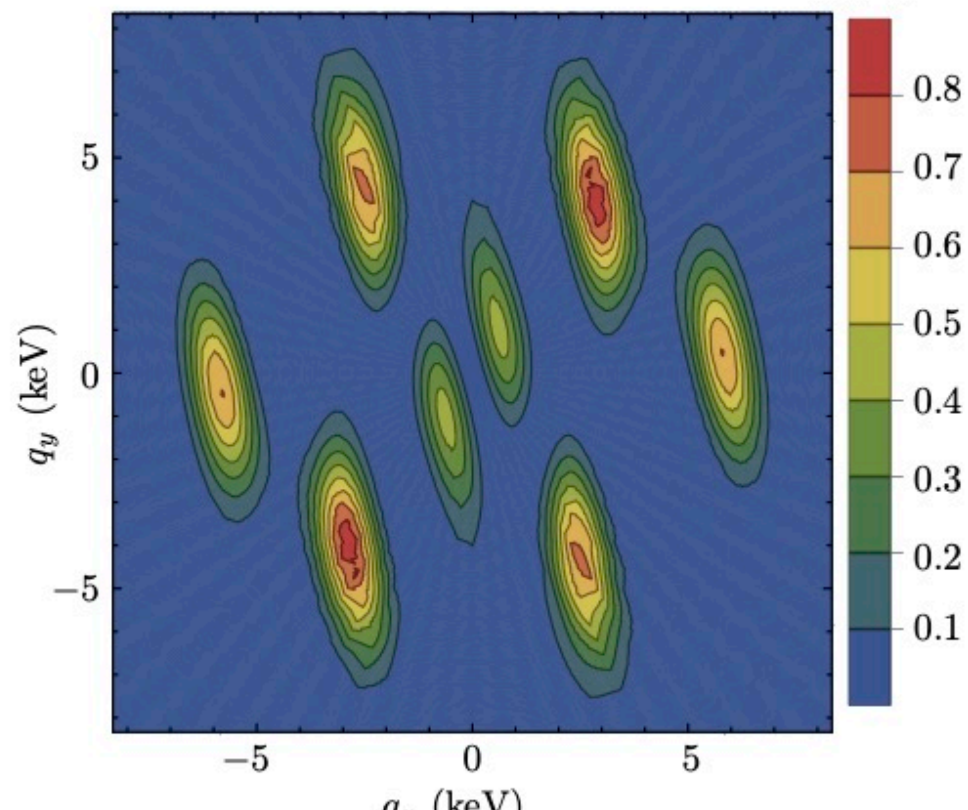


⟵ 2208.09002
molecular Migdal
C. Blanco, I. Harris, Y. Kahn, **BL**, J. Pérez-Ríos

Some DM detector targets have **intrinsically anisotropic** scattering rates:



- **DM–electron:** via asymmetric electronic wavefunctions
- **DM-nucleon (Migdal):** from asymmetric potential on nuclei



Newly Challenging Rate Calculation:

Astrophysics | **Particle Physics (DM-SM)**

$$R_s = N_{\rm SM} n_\chi \bar{\sigma}_0 \int \frac{d^3q}{4\pi\mu^2_{\chi{\rm SM}}} \int d^3v\, g_\chi(\mathbf{v}) \times \delta\left(\omega_s + \frac{q^2}{2m_\chi} - \mathbf{q}\cdot\mathbf{v}\right) F^2_{\rm DM}(q) \times f_s^2(\mathbf{q})$$

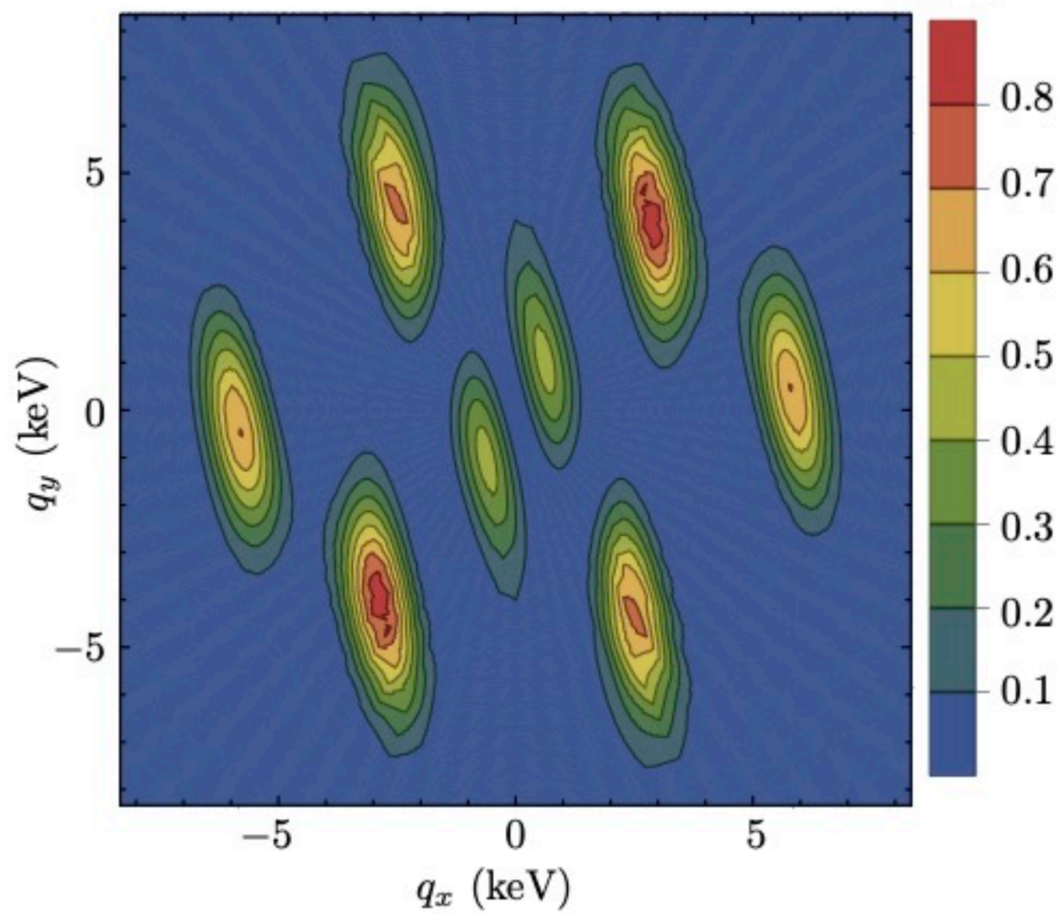
SM Detector Physics

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

Repeat for every…

- **DM mass and F_{DM}** • $50 - 10^2$
- **velocity distribution** • $1 - 10^3$
- **detector form factor** • $1 - 10^2$
- **detector orientation** • $1 - 10^4$

- **TOTAL:** • $50 - 10^{11}$



Vector **S**paces for **D**ark **M**atter **(VSDM)**

github: https://github.com/blillard/vsdm
arXiv: 2310.01480 and 2310.01483

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

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

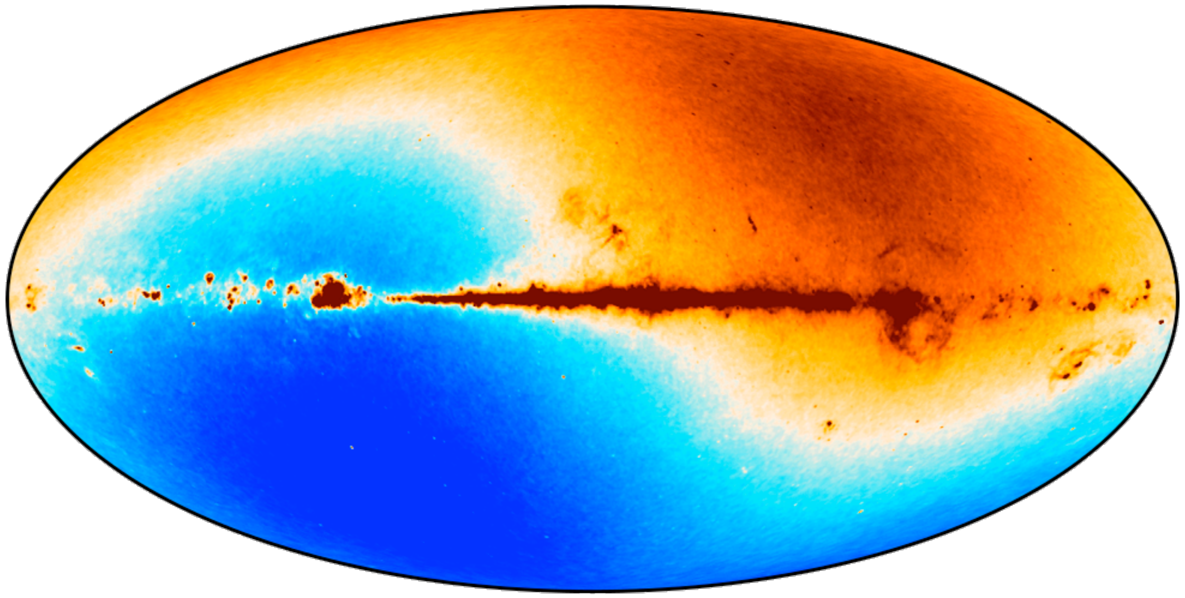
1. Define **basis functions**, $|nlm\rangle = r_n(q)\, Y_{lm}(\hat{q})$, with spherical harmonics Y_{lm}
2. Projections of g_χ and f_s^2 onto each basis $\longrightarrow$ **vectors**
3. Kinematic operator (incl. m_χ) $\longrightarrow$ **matrix** connecting ***(v, q)*** spaces
4. Detector rotations $\longrightarrow$ **matrix multiplication**

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

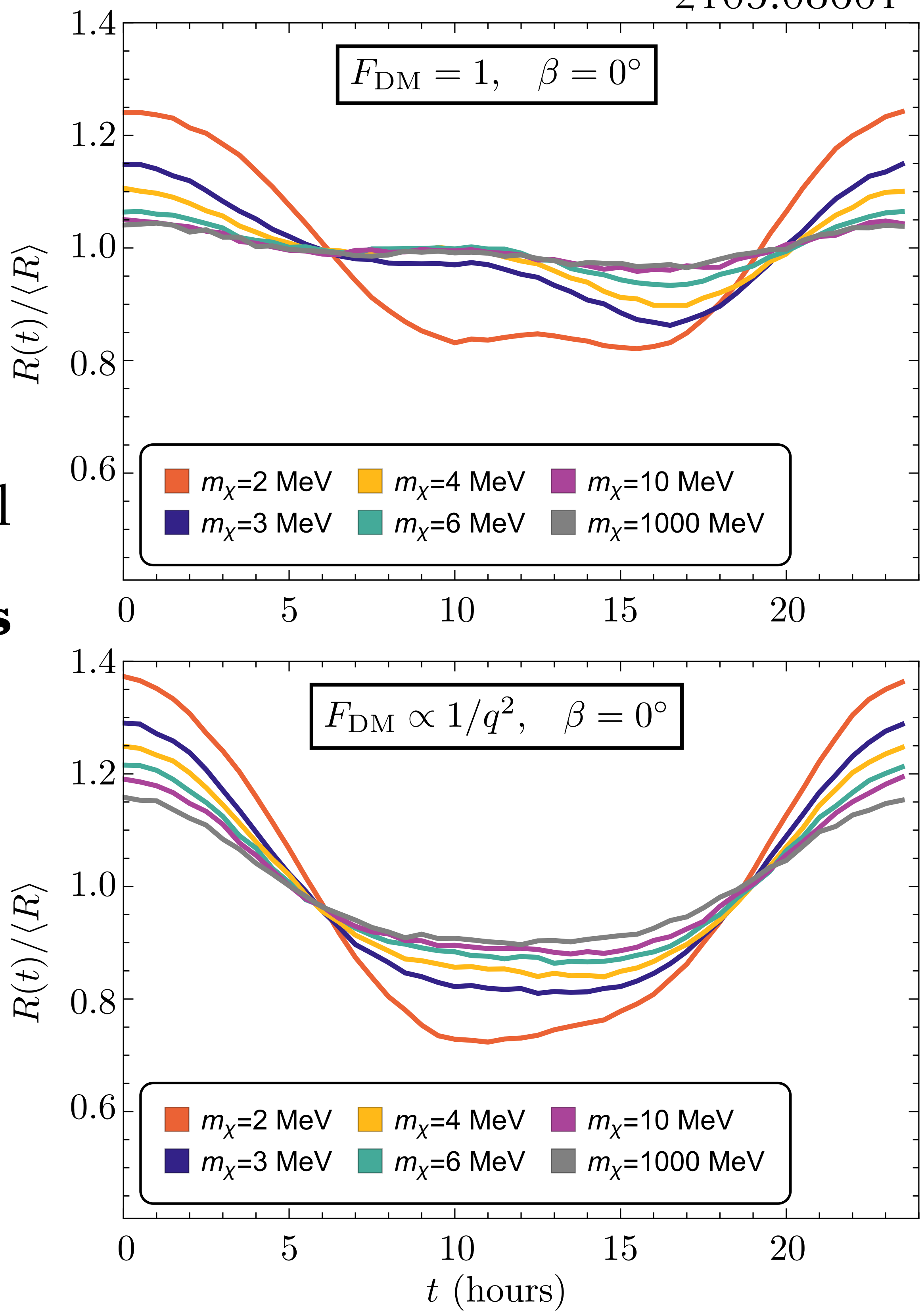
Difficult integrals $\langle g_\chi | \phi_v \rangle$ and $\langle \varphi_q | f_s^2 \rangle$ only need to be done **once** (per model)
Easily saved and shared among researchers.

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…



2103.08601



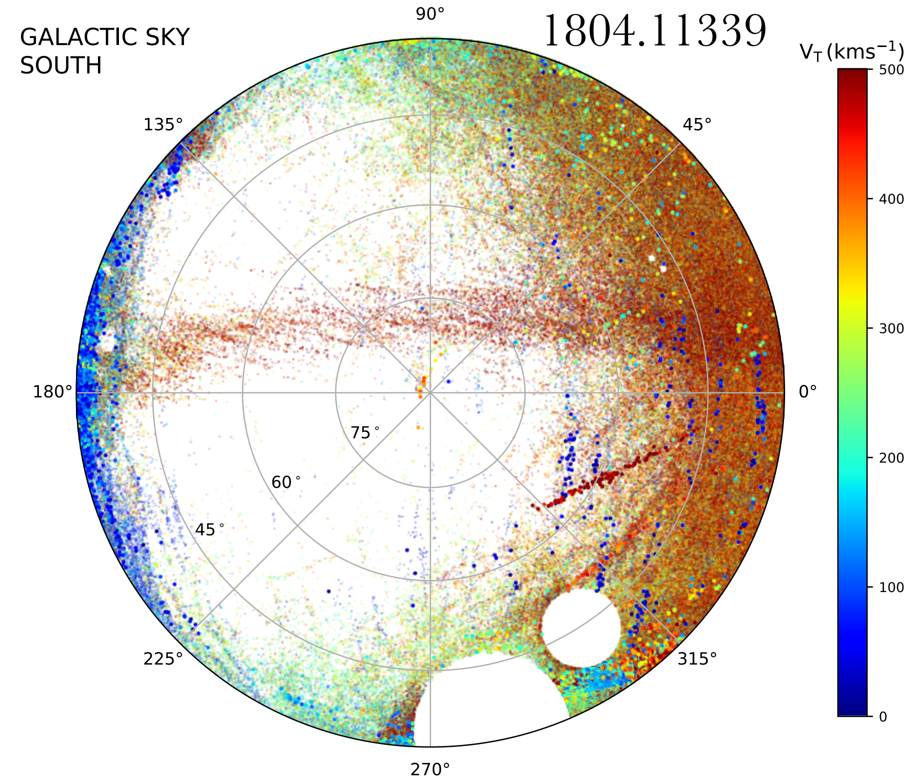
Looking To The Future: A Library of DM Systems

Difficult integrals $\langle g_\chi | \phi_v \rangle$ and $\langle \varphi_q | f_s^2 \rangle$ only need to be done **once** (per model)

Easily saved and shared among researchers.

Are ***you*** studying a DM velocity distribution or a detector form factor?

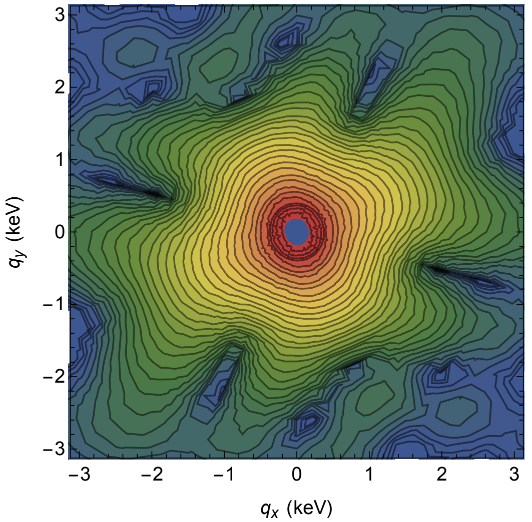
- Want to share??

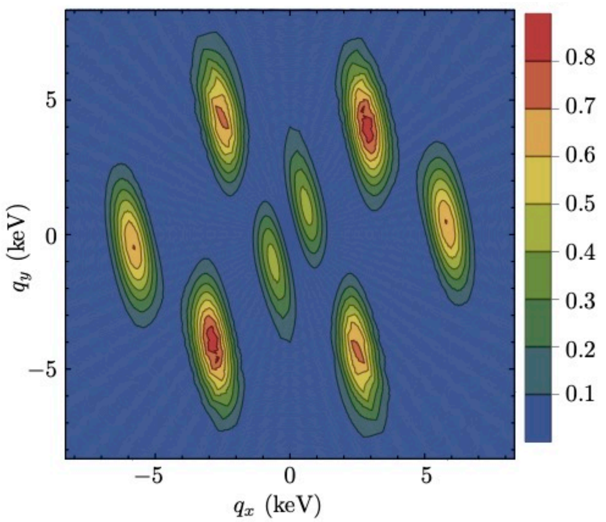


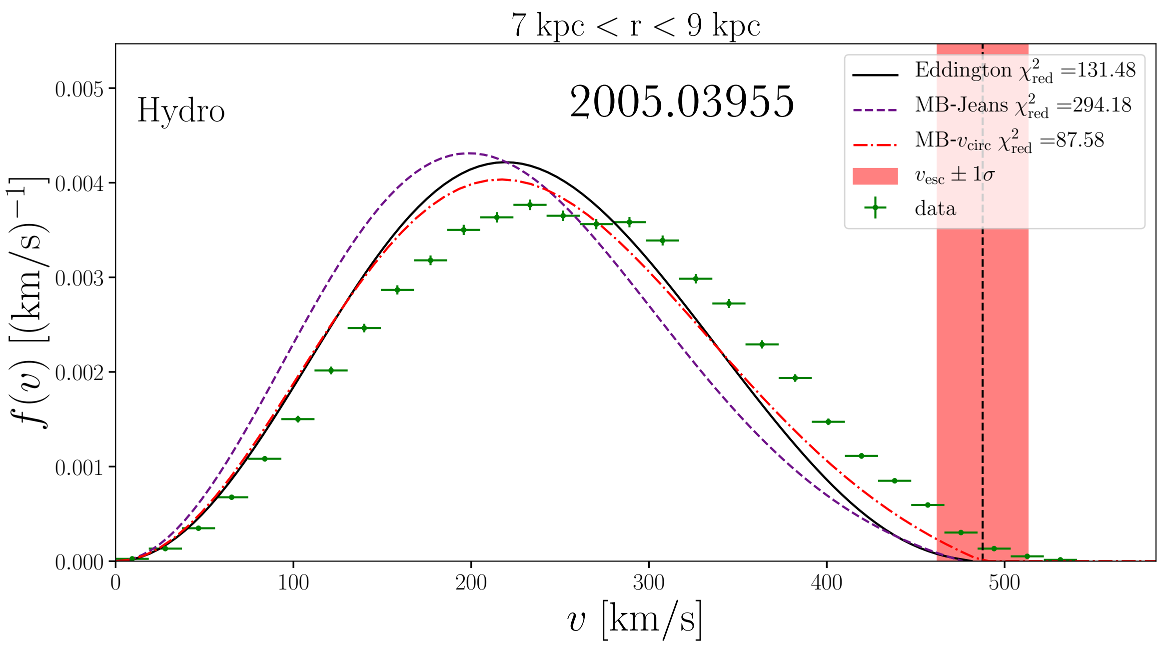
VSDM: at github.com/billard/vsdm

or: **pip install vsdm**

Coming this summer: implementation in **Julia**, by **Aria Radick** (U. Oregon)







Molecules for Nuclear Scattering

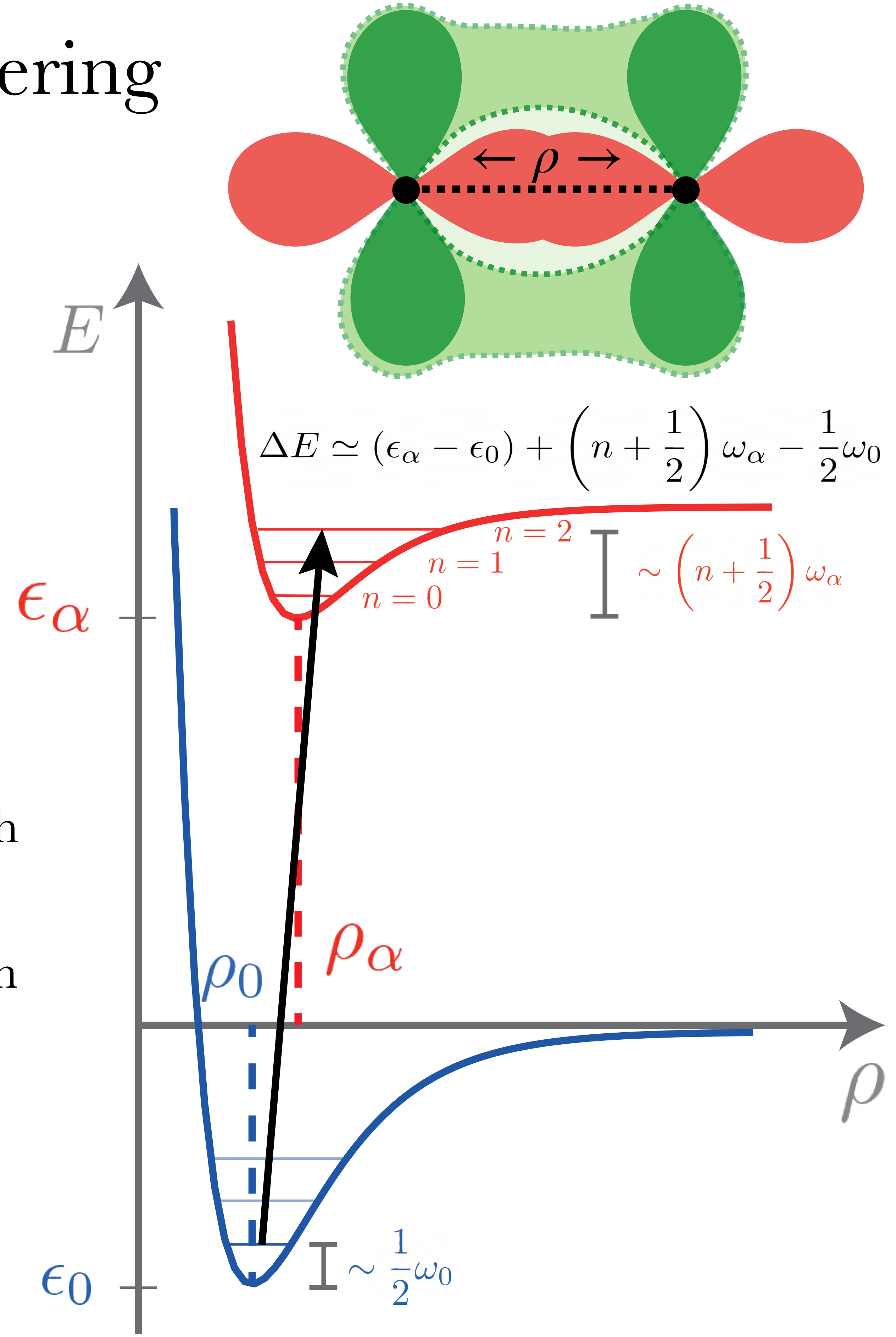
Detectable?

- **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**.

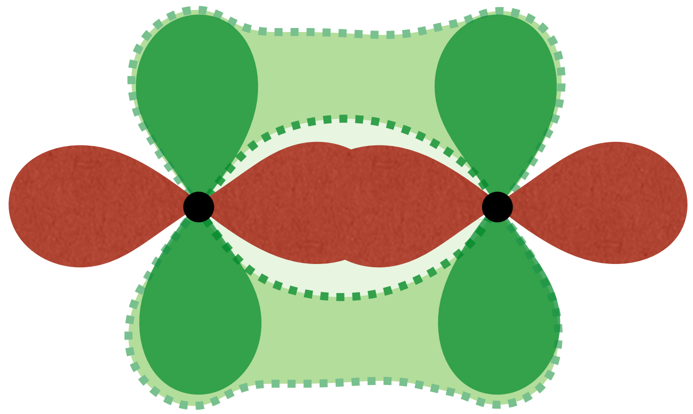
For directionality, use **bound final states**
→ **Bonus**: lower energy threshold

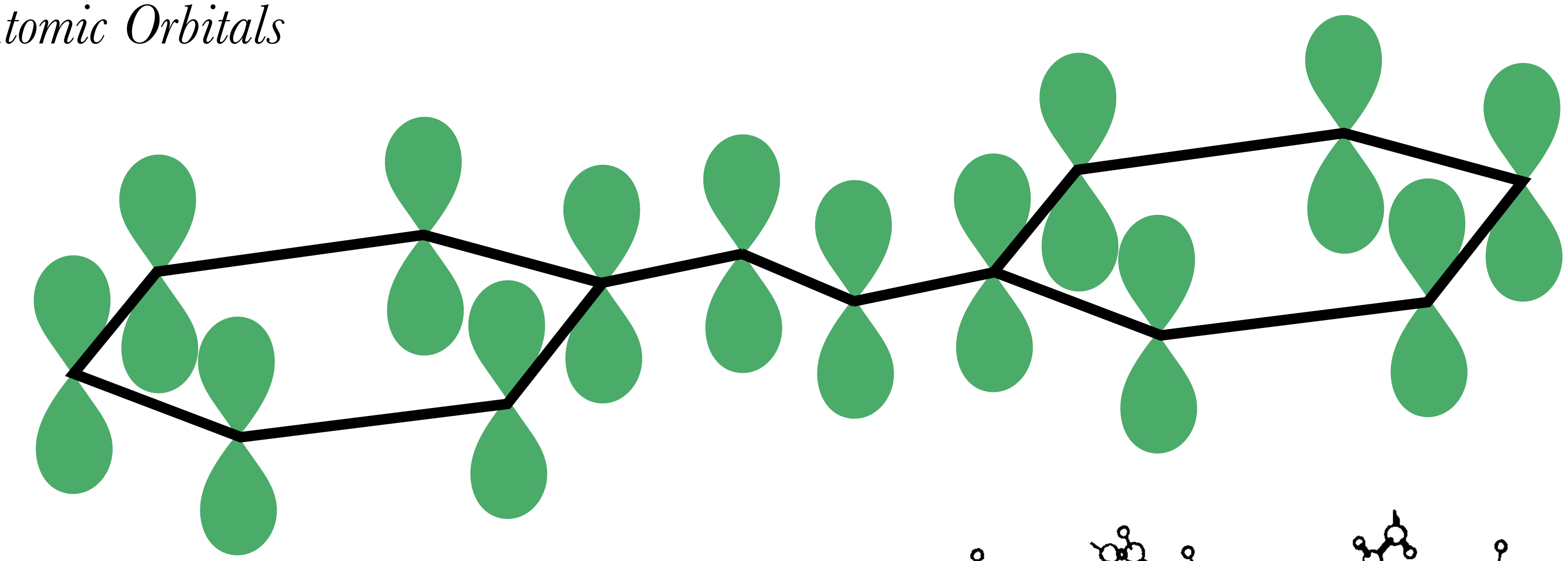


How to calculate DM–molecule scattering:

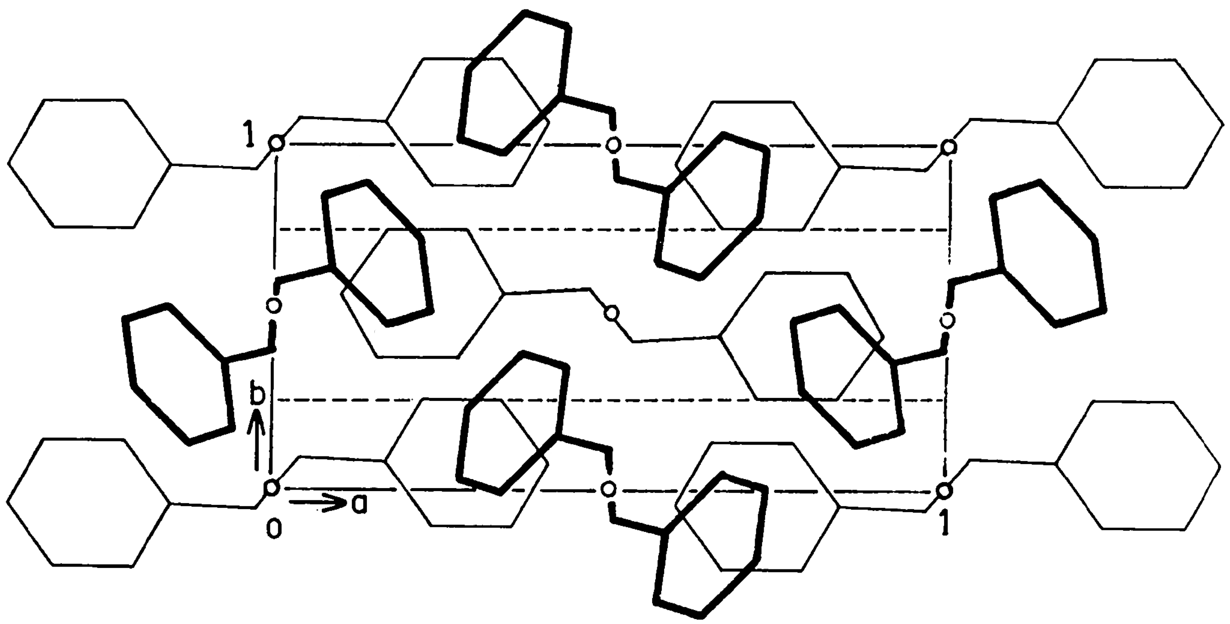
see arXiv:2103.08601

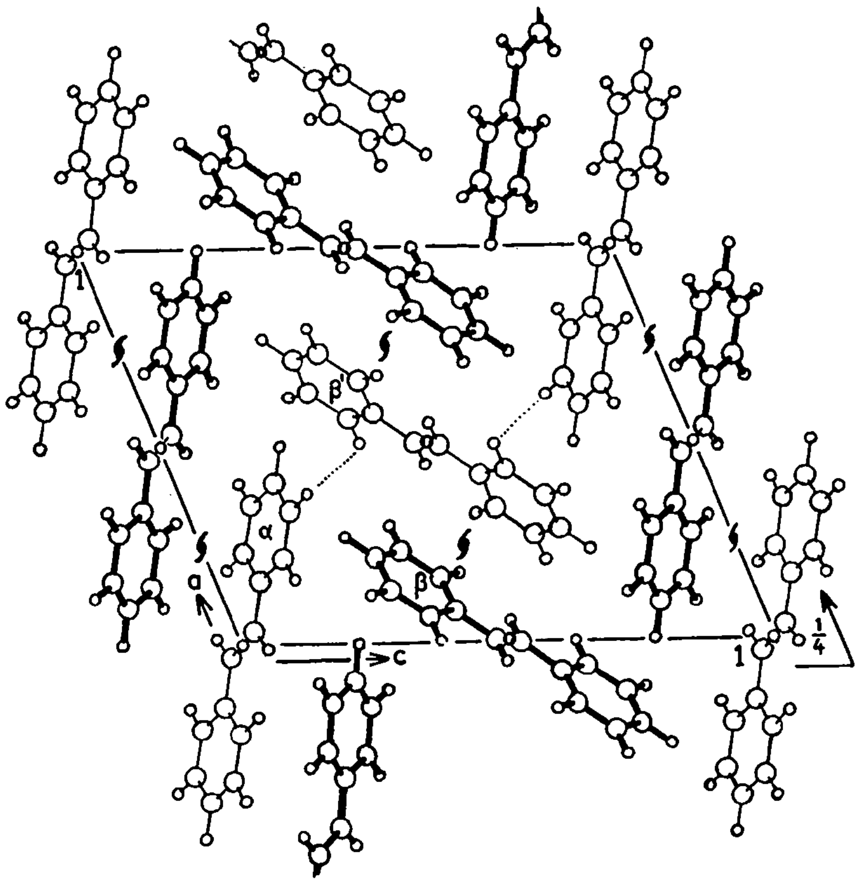
LCAO: Linear Combinations of Atomic Orbitals





A Complication: trans-stilbene crystals form unit cell with 4 components

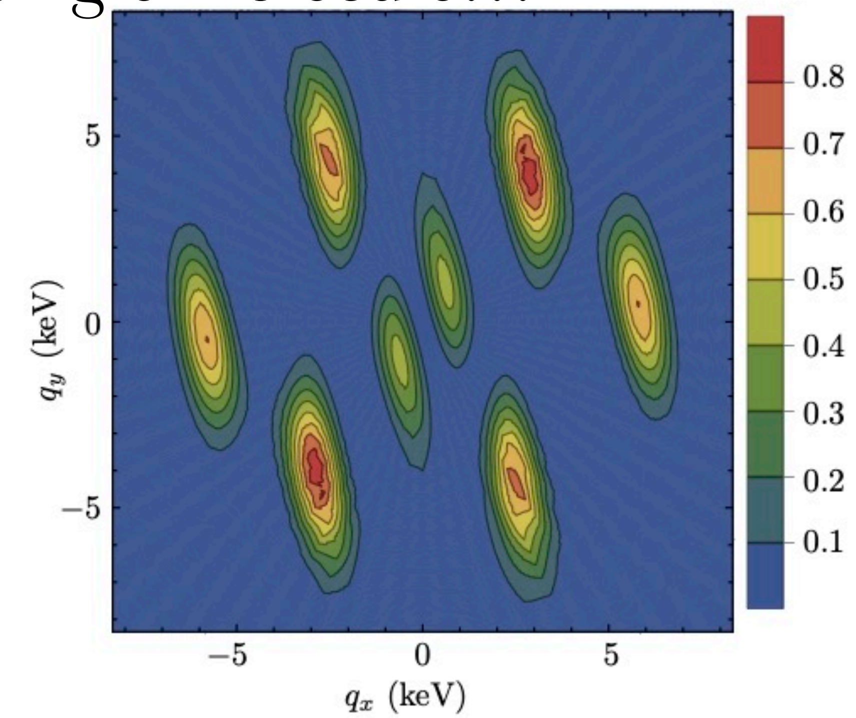




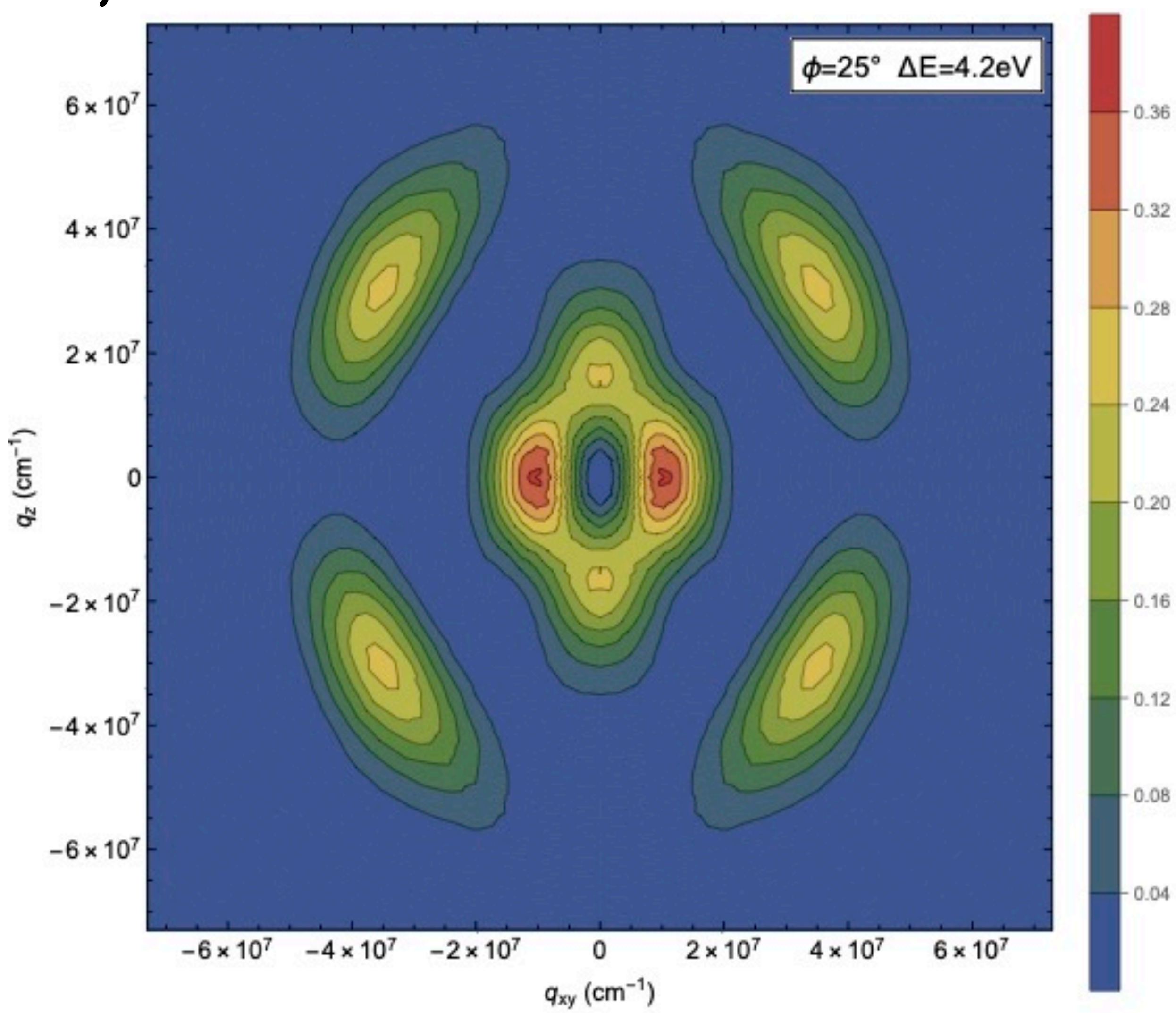
III. Results

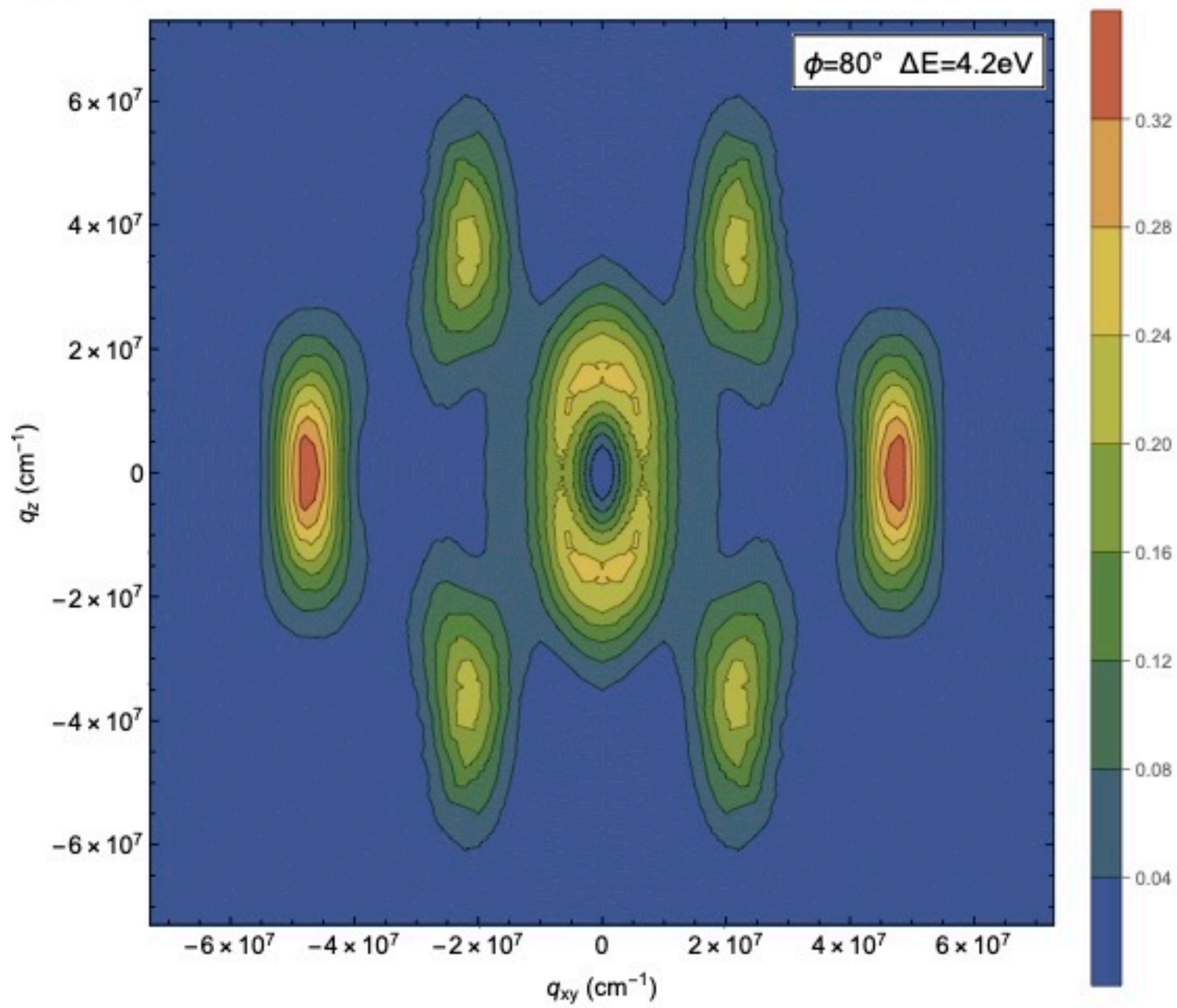
arXiv:2103.08601

single molecule…

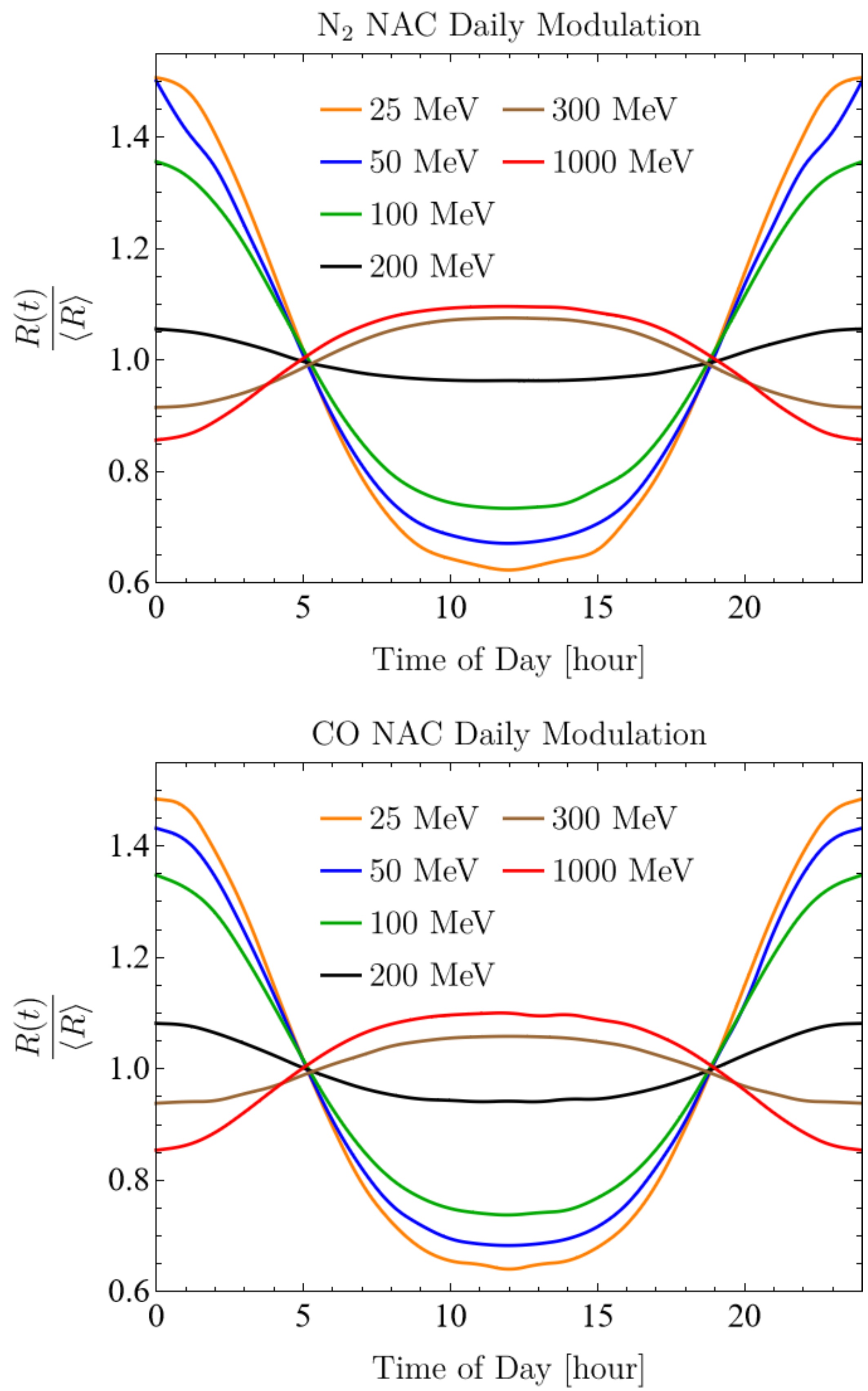


Crystal Form Factor

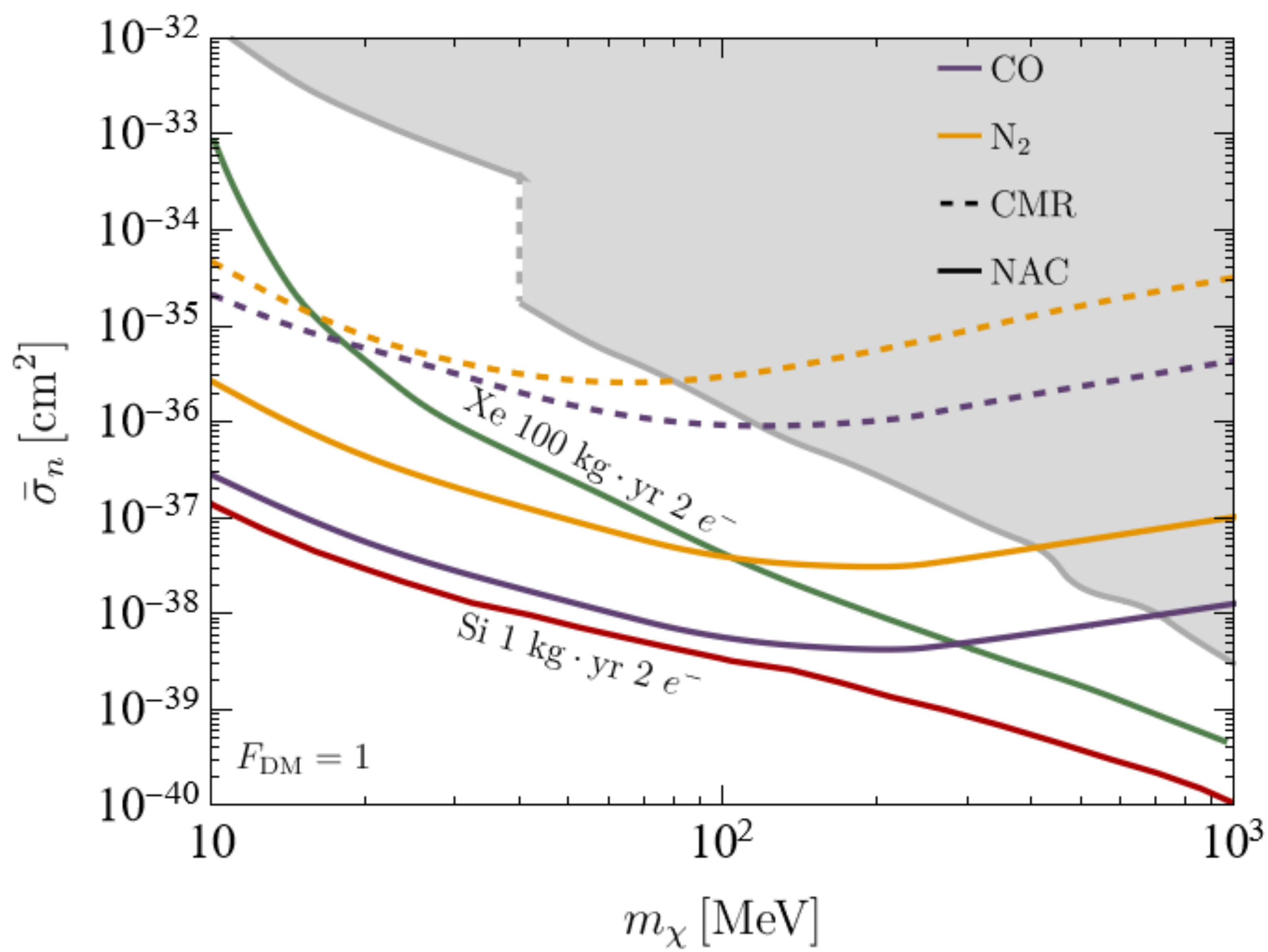


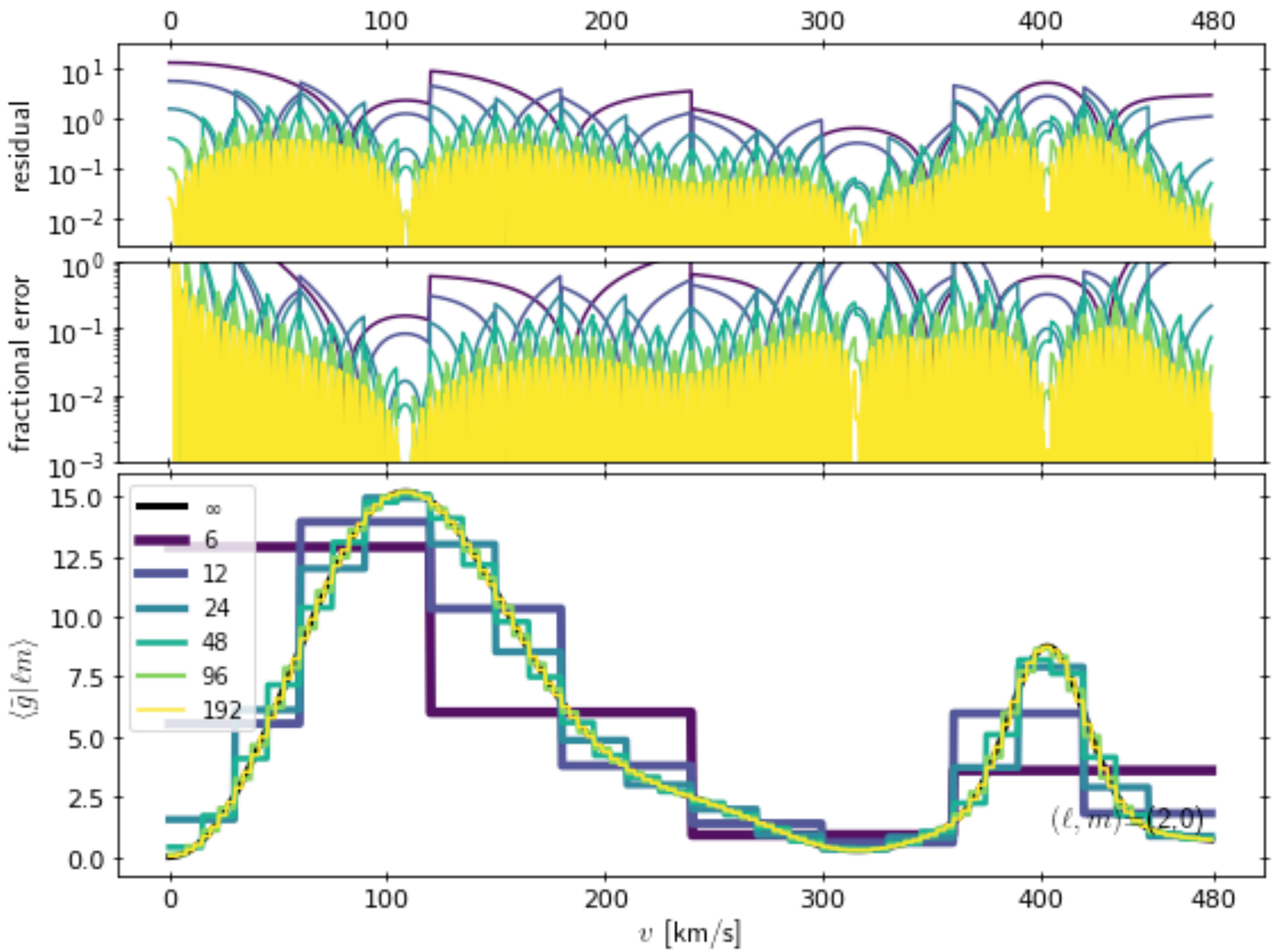


Results: Diatomic Molecules CO and N_2 (2208.09002)



- **NAC Migdal Effect** is the important one





residual
fractional error
$\langle \bar{g} | \ell m \rangle$
v [km/s]
∞
6
12
24
48
96
192
$(\ell, m) = (2, 0)$