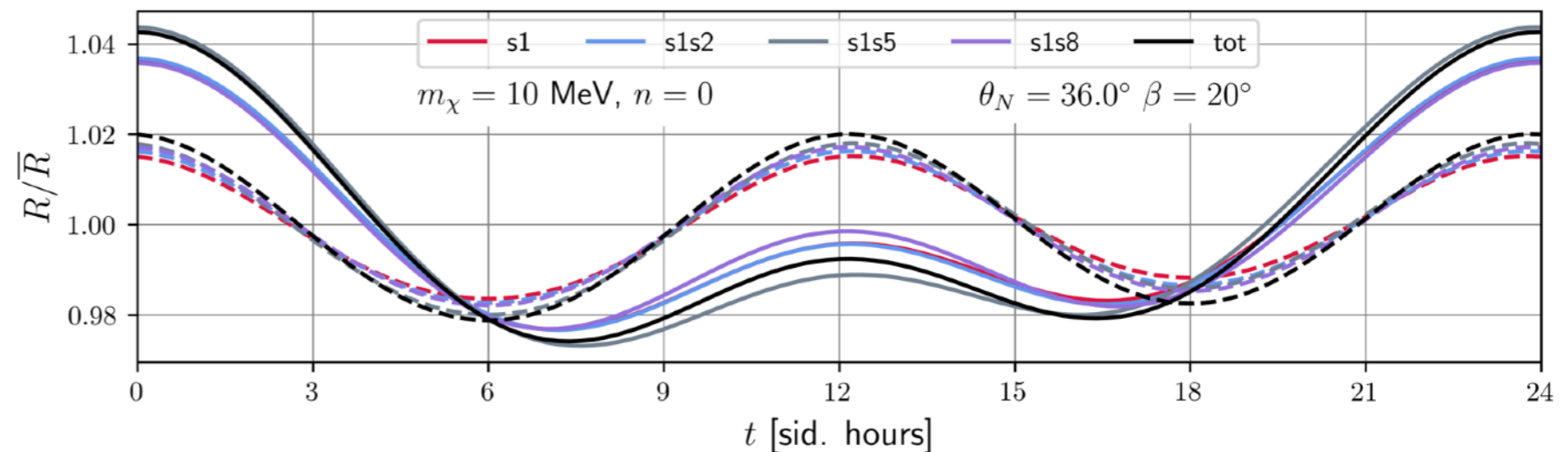


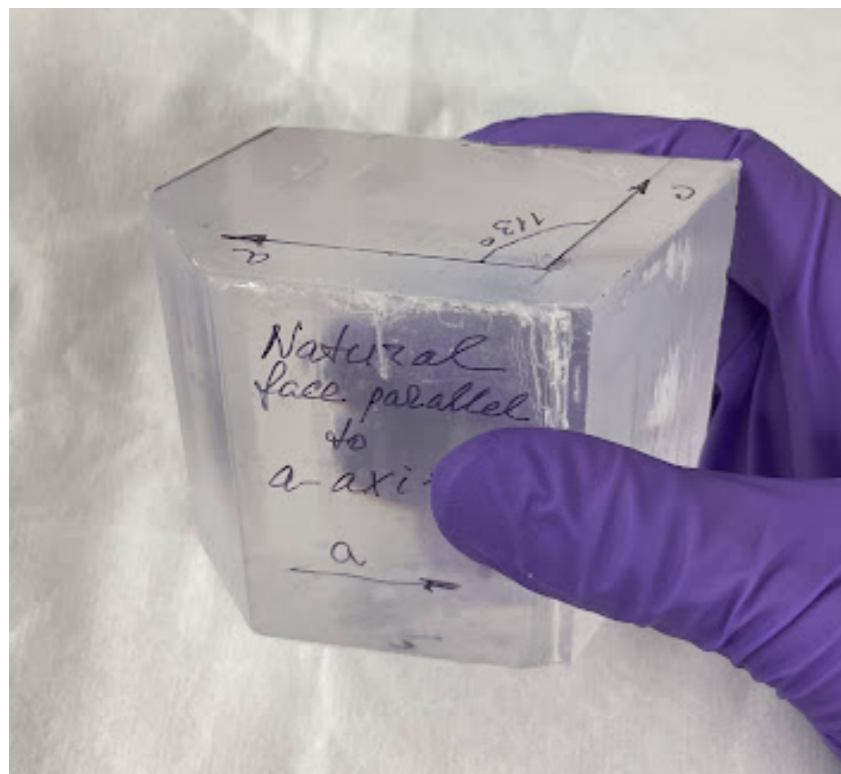
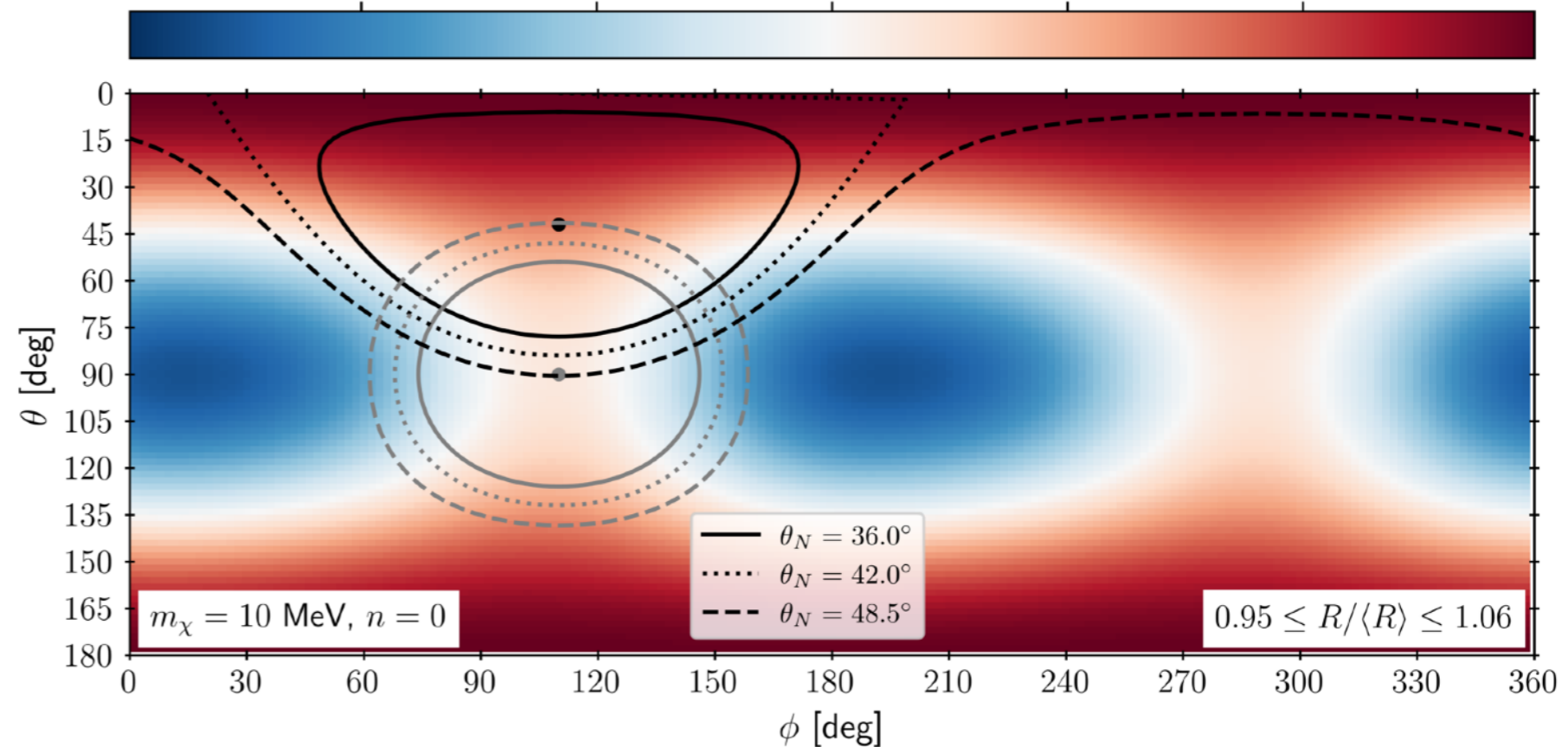
Strategies for sub-GeV Direct Detection

Design and Directionality for Next-Generation Experiments

BEN LILLARD
 PENN STATE
 PHENO 2026



$R(\theta, \phi)/\langle R \rangle$: 0.96 0.98 1.00 1.02 1.04

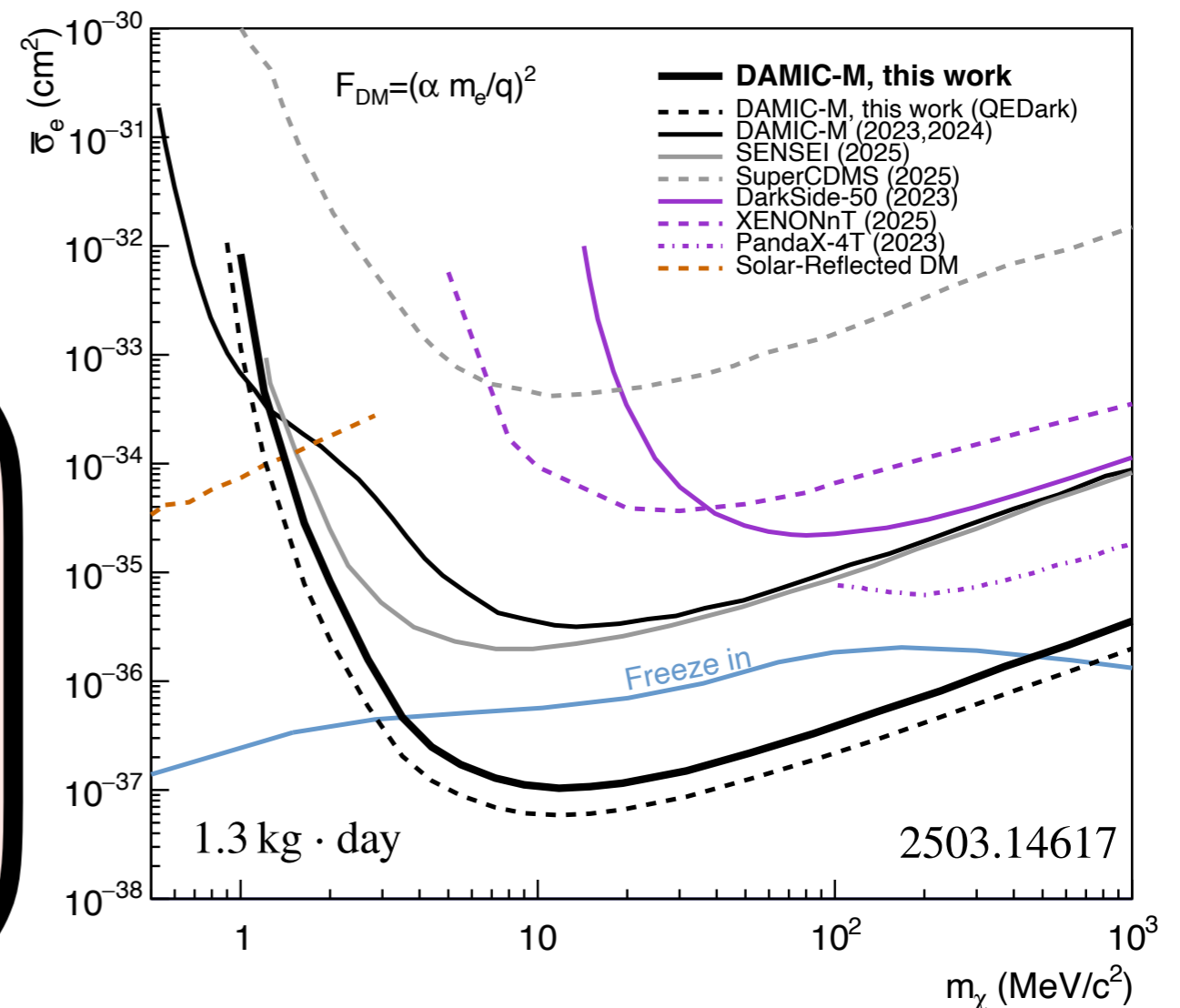


Irreducible Low-Energy Backgrounds

- **DM–nuclear scattering** experiments have discovered the irreducible background from (solar ^8B) neutrinos. → **Neutrino fog** in XENON-nT, LZ, Panda-X
- **Low Energy Excesses** in DM- e^- :
DAMIC-M, SENSEI (Si)
200–300 $1e^-$ events per kg · min
SuperCDMS, EDELWEISS (Ge)

Solution:

Use **intrinsically anisotropic** materials for the next generation of dark matter detectors, to distinguish DM scattering events from SM backgrounds



Electron Recoil *Direct Detection*

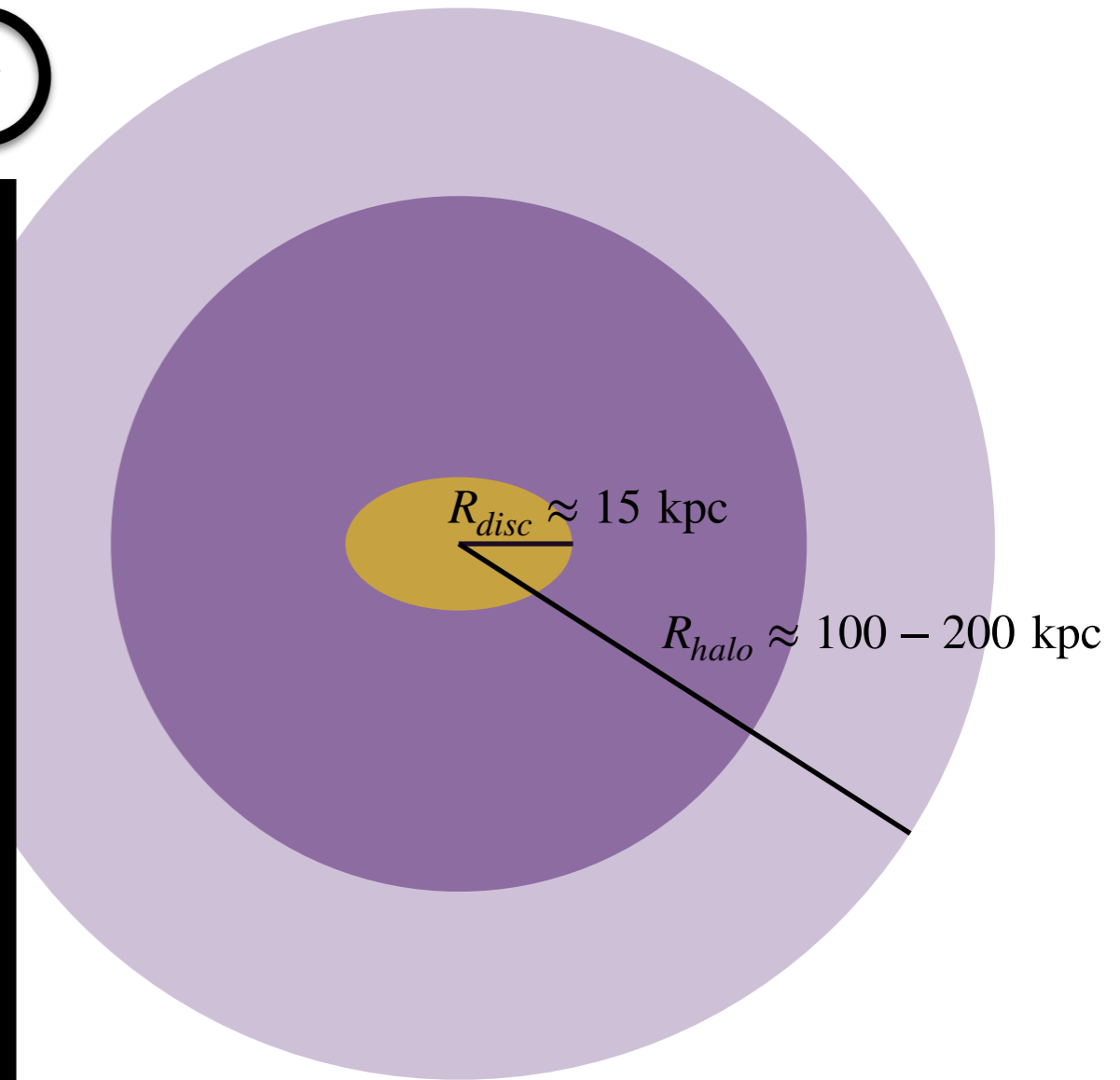
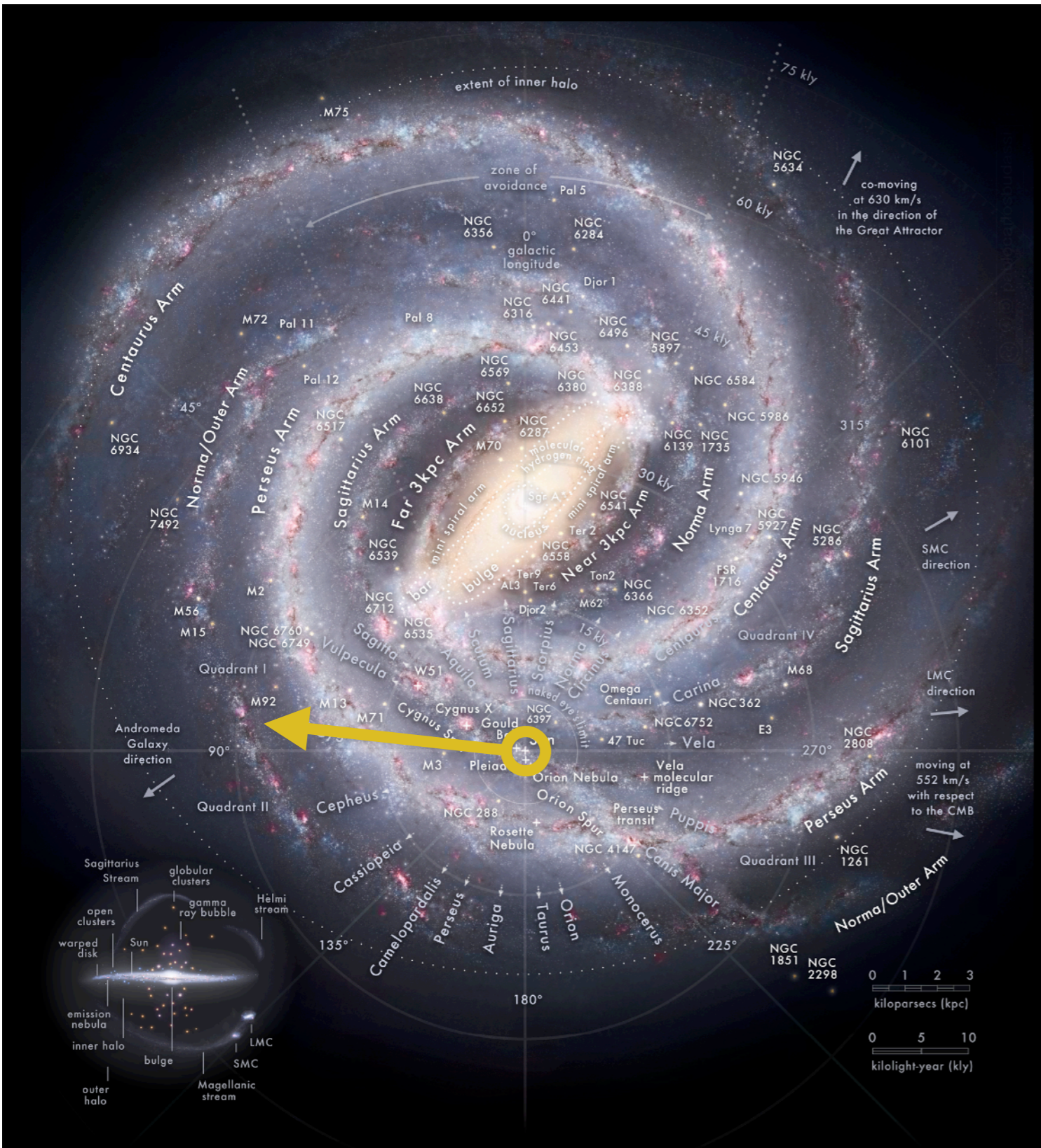
Nuclear Recoil *Direct Detection*

MeV

GeV

TeV

Directionality for Distinguishability

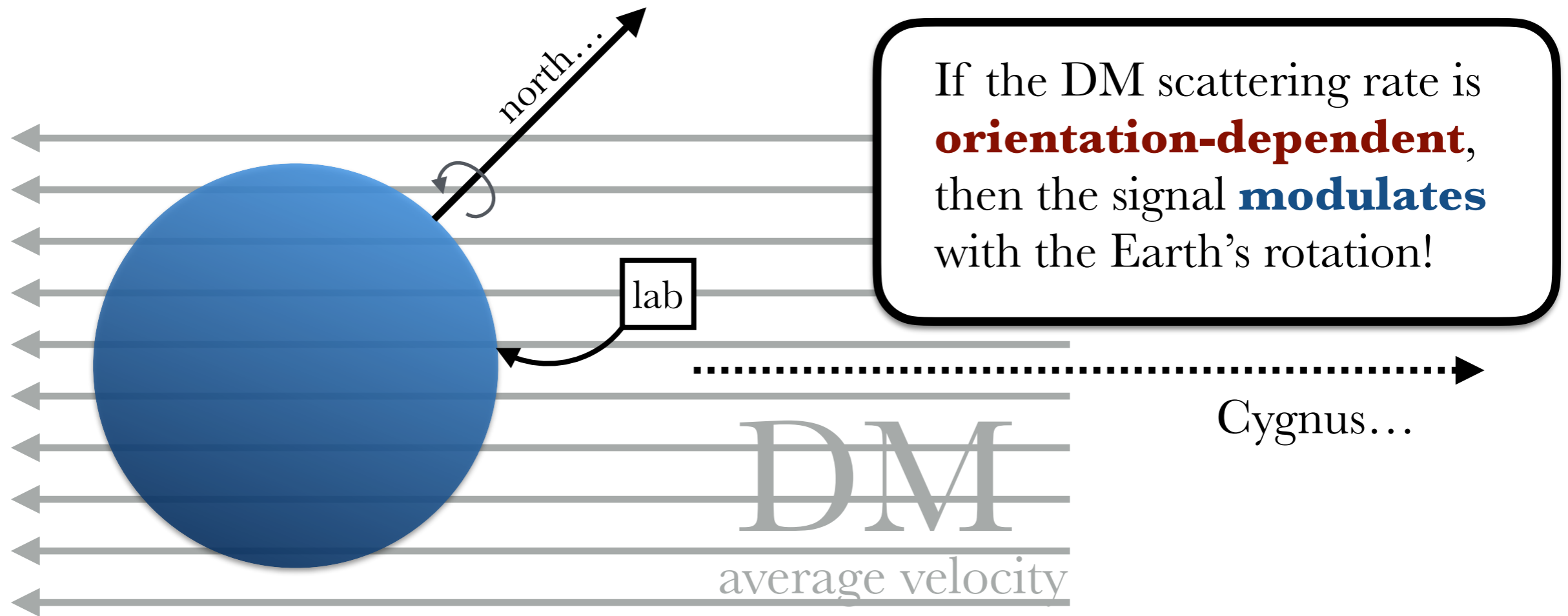


Solar system orbits the galactic center at about **250 km/s**

Earth orbits the Sun: **$\pm 15 \text{ km/s}$**

Directionality for Distinguishability

- Dark matter velocity distribution is **not isotropic** in the lab frame, thanks to the **~ 250 km/s DM “wind”**

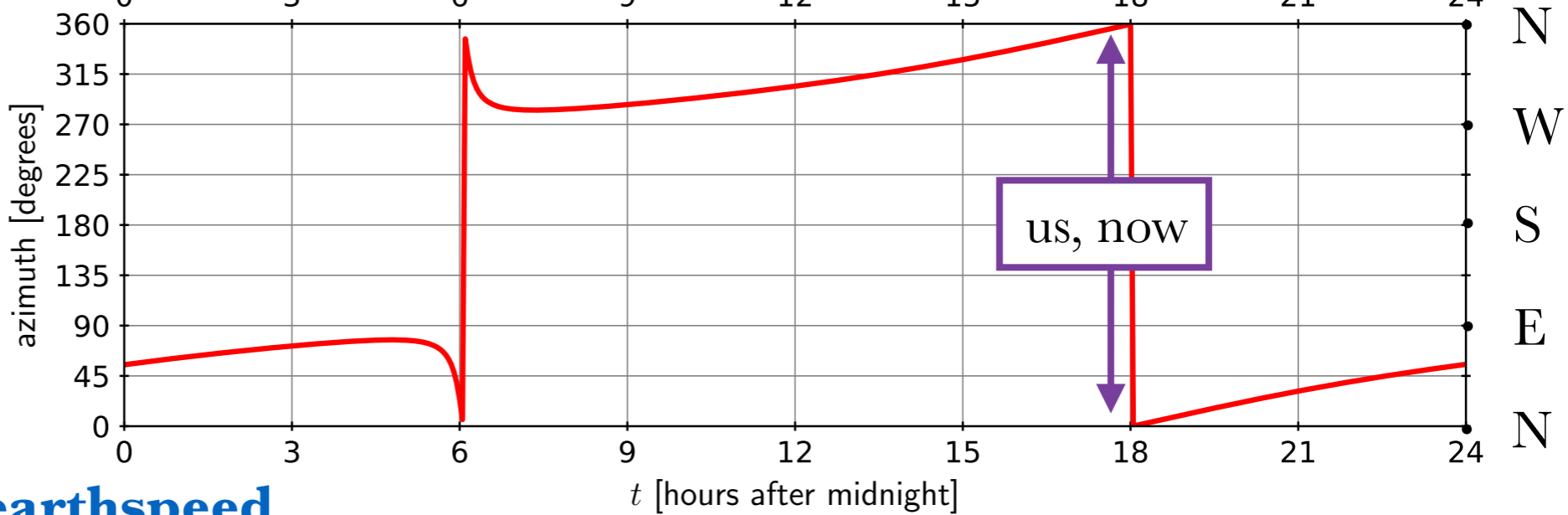
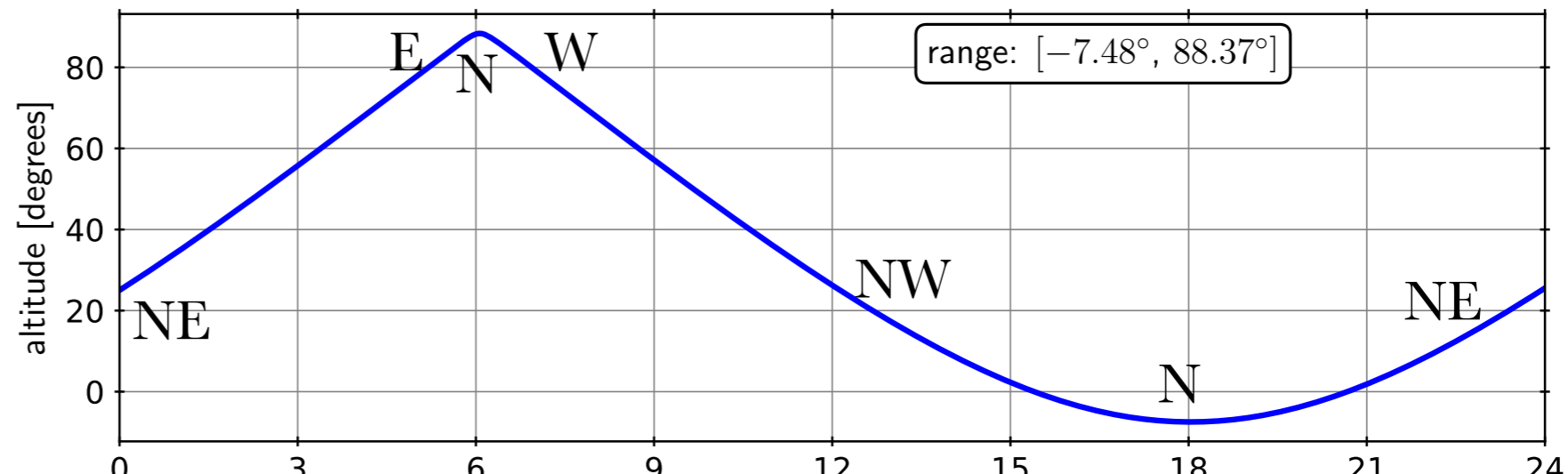
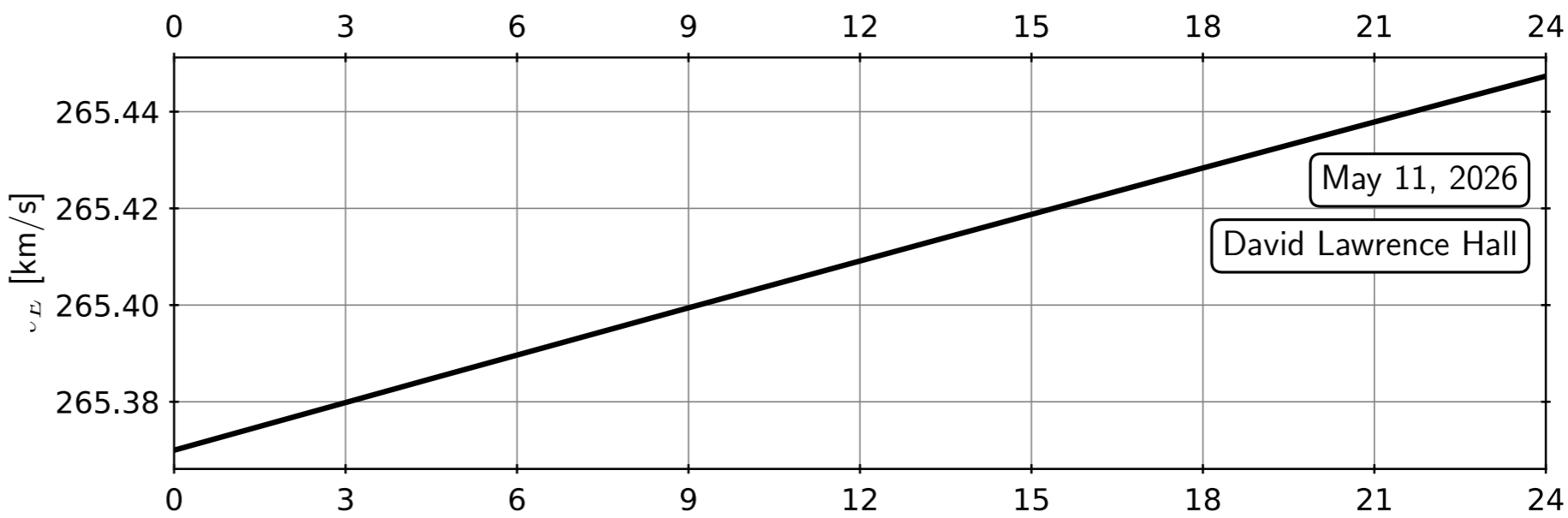
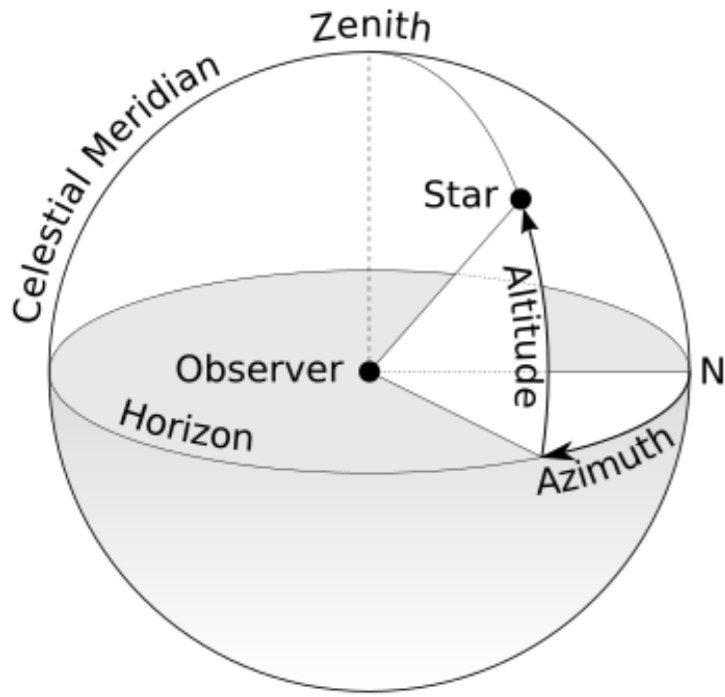


- DM velocity distribution also has $\mathcal{O}(1)$ dispersion, *not to be neglected!*

DM Wind Today:

(DLH 120, U.Pitt)

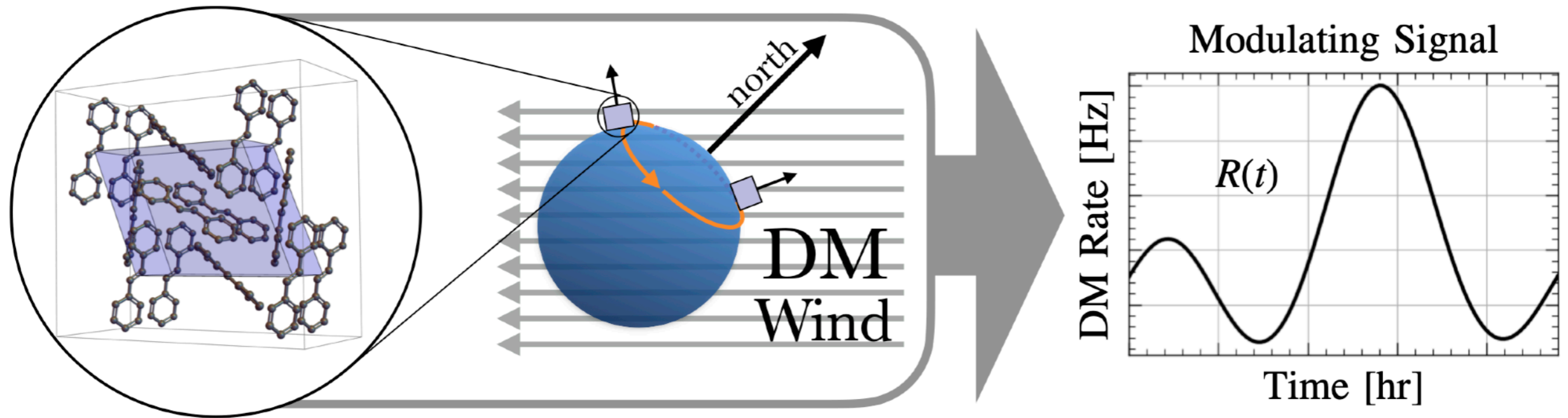
- $\theta_N = 47.9^\circ$
- $v_E \simeq 265 \text{ km/s}$



- DM wind sweeps out a cone on the sky, with opening angle:
- $\theta_N = 47.9^\circ$ (today)
 - $\theta_N \sim 42^\circ$ (average)

Anisotropy for Direct Detection

- **DM scattering rate changes with detector orientation**



Detector Material:

- anisotropic **response**

DM velocity distribution:

- anisotropic **source**

Scattering rate $R(t)$:

- varies with Earth rotation every **23.93 hours**
- $R(t)$ profile depends on DM mass, mediator type, details of NR EFT, astrophysics...

Directionality \longrightarrow Scattering Rate

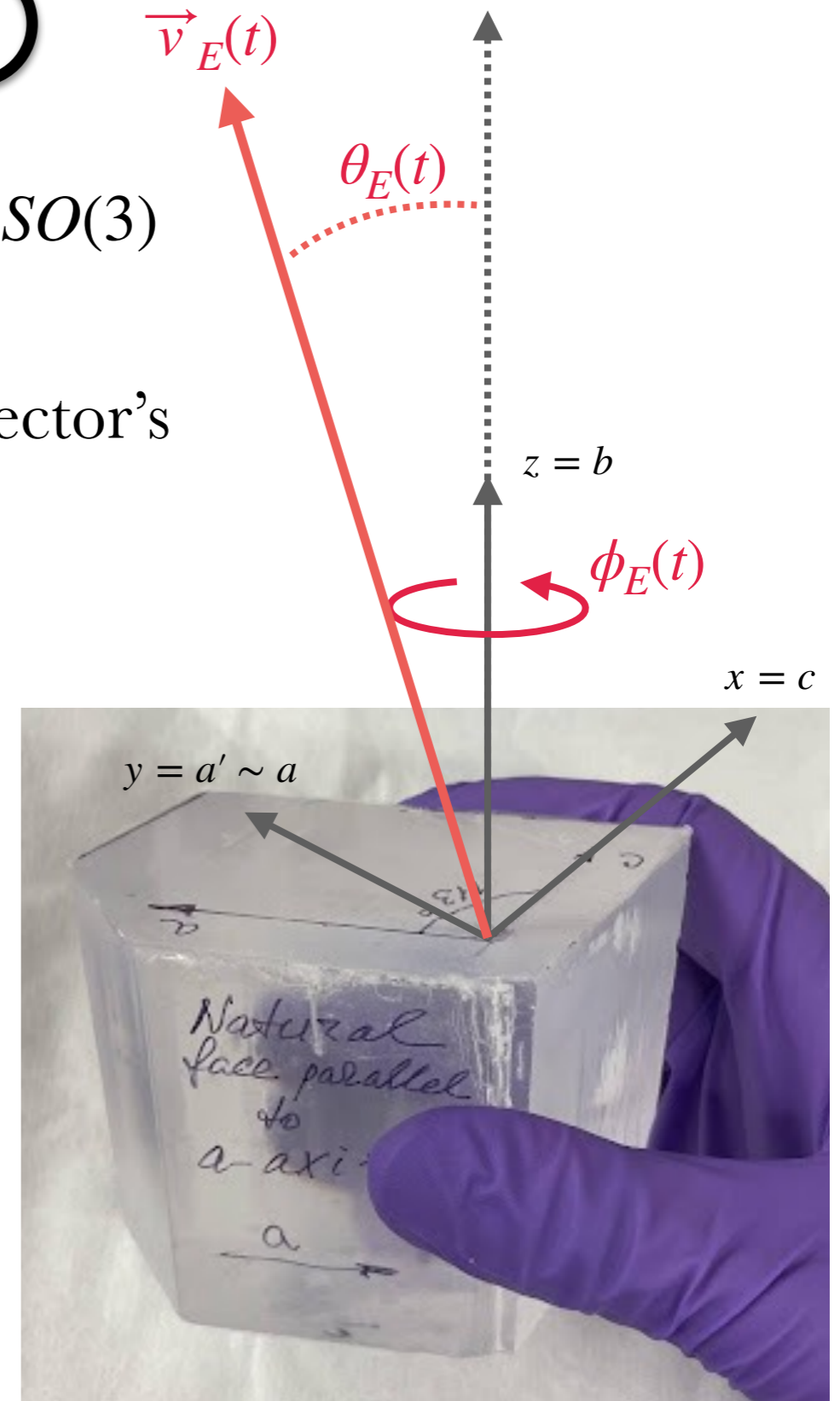
- Can rotate an anisotropic detector by $\mathcal{R} \in SO(3)$
- For Standard Halo Model (SHM), rate is a function of Earth velocity vector in the detector's reference frame ($SO(3) \longrightarrow S^2$)
- $R(\theta_E, \phi_E)$ is measurable, and has **lots of information!**
- **Unique** to each molecule or semiconductor

Use **VSDM** for fast $R(m_\chi, F_{DM}, \mathcal{R})$ calculations:

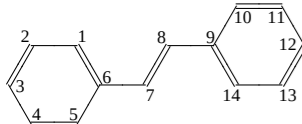
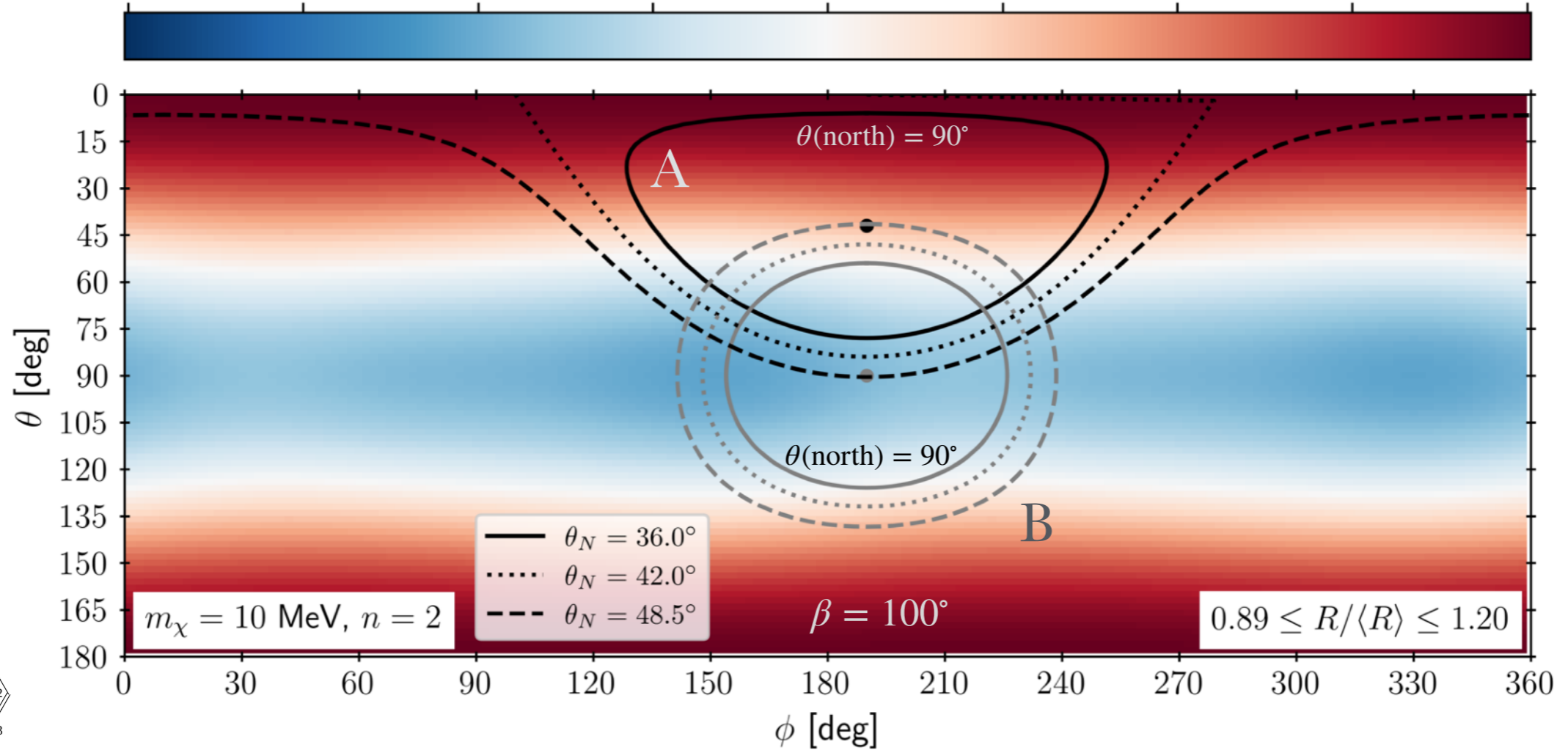
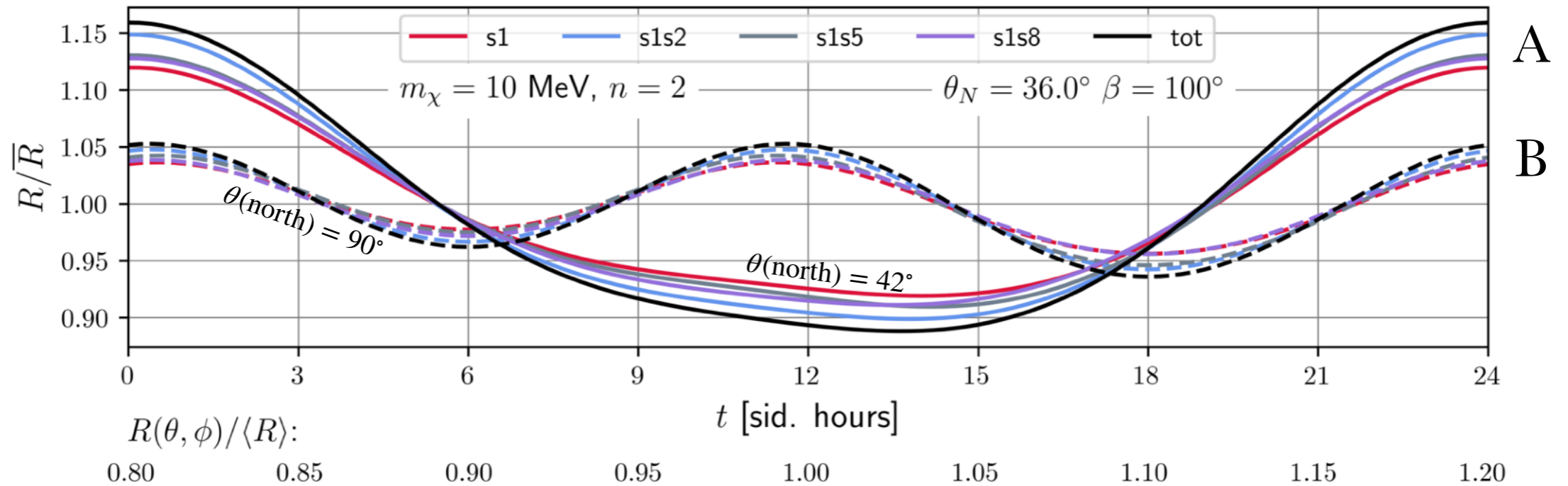
vsdm (Python): pip install vsdm

VectorSpaceDarkMatter (Julia)

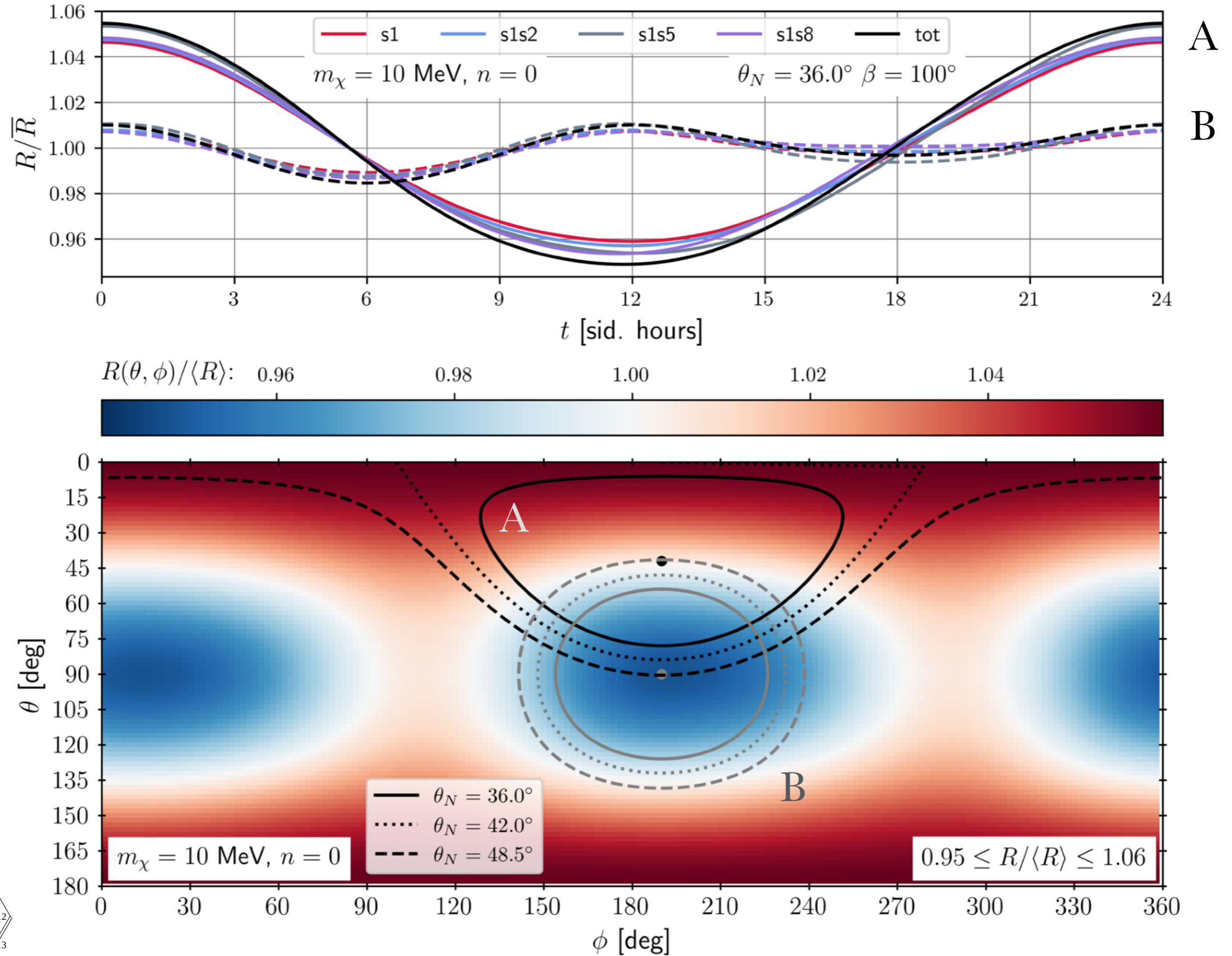
BL and Aria Radick, 2502.17547



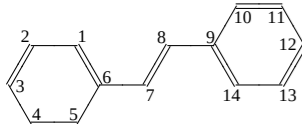
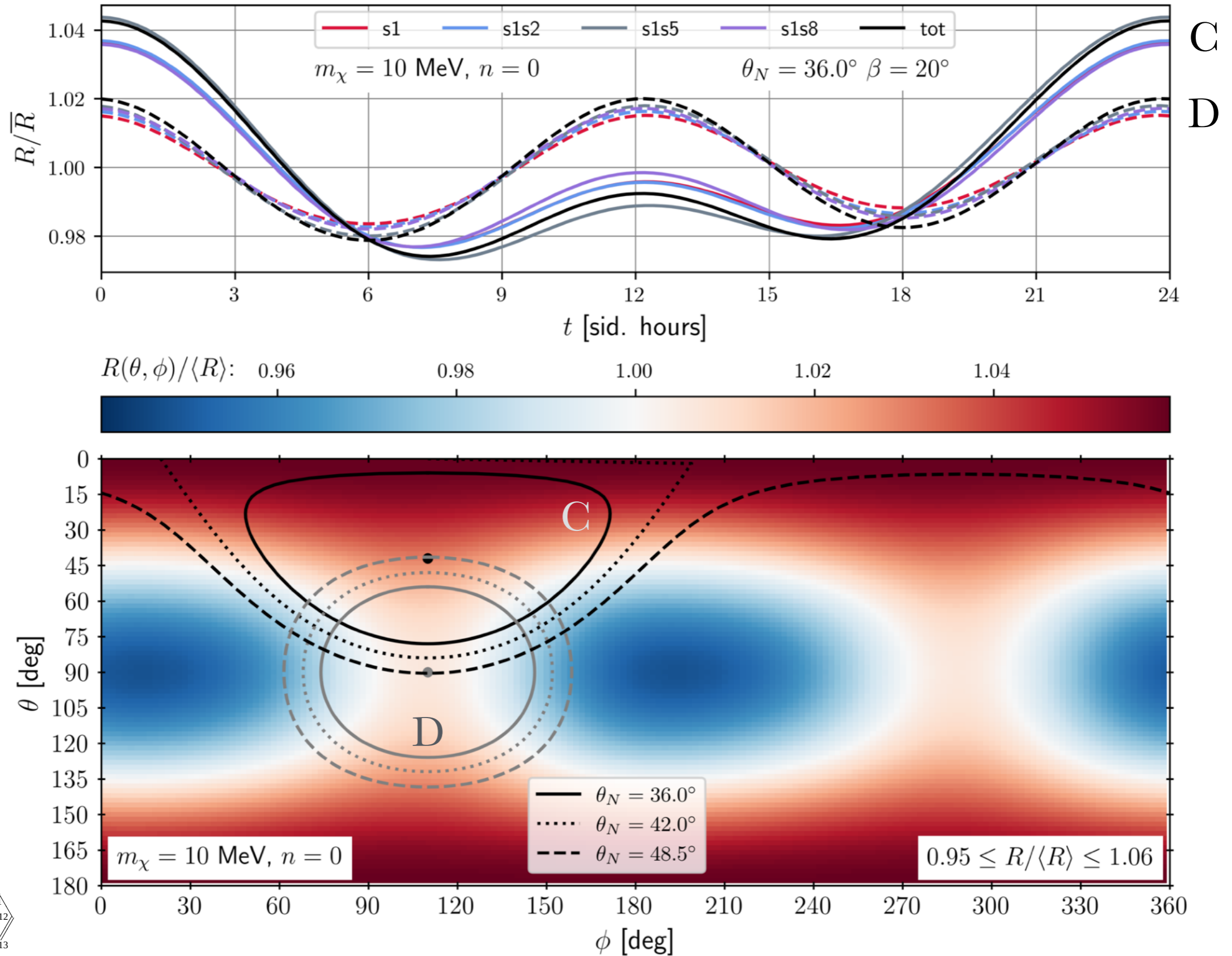
Model 1: 10 MeV DM with light mediator (Orientations A,B)



Model 2: 10 MeV DM with heavy mediator (Orientations A,B)



Model 2: 10 MeV DM with heavy mediator (Orientations C,D)



Anisotropic Detector Targets

e.g. trans-stilbene, $C_{14}H_{12}$ (arXiv:2103.08601)

- **Trans-stilbene is a great starting point:**
 - heavy mediator: $f_{\text{RMS}} \sim [3\% \text{ to } 15\%]$
 - light mediator: $f_{\text{RMS}} \sim [10\% \text{ to } 25\%]$
 - **easily scalable to kilogram size!**

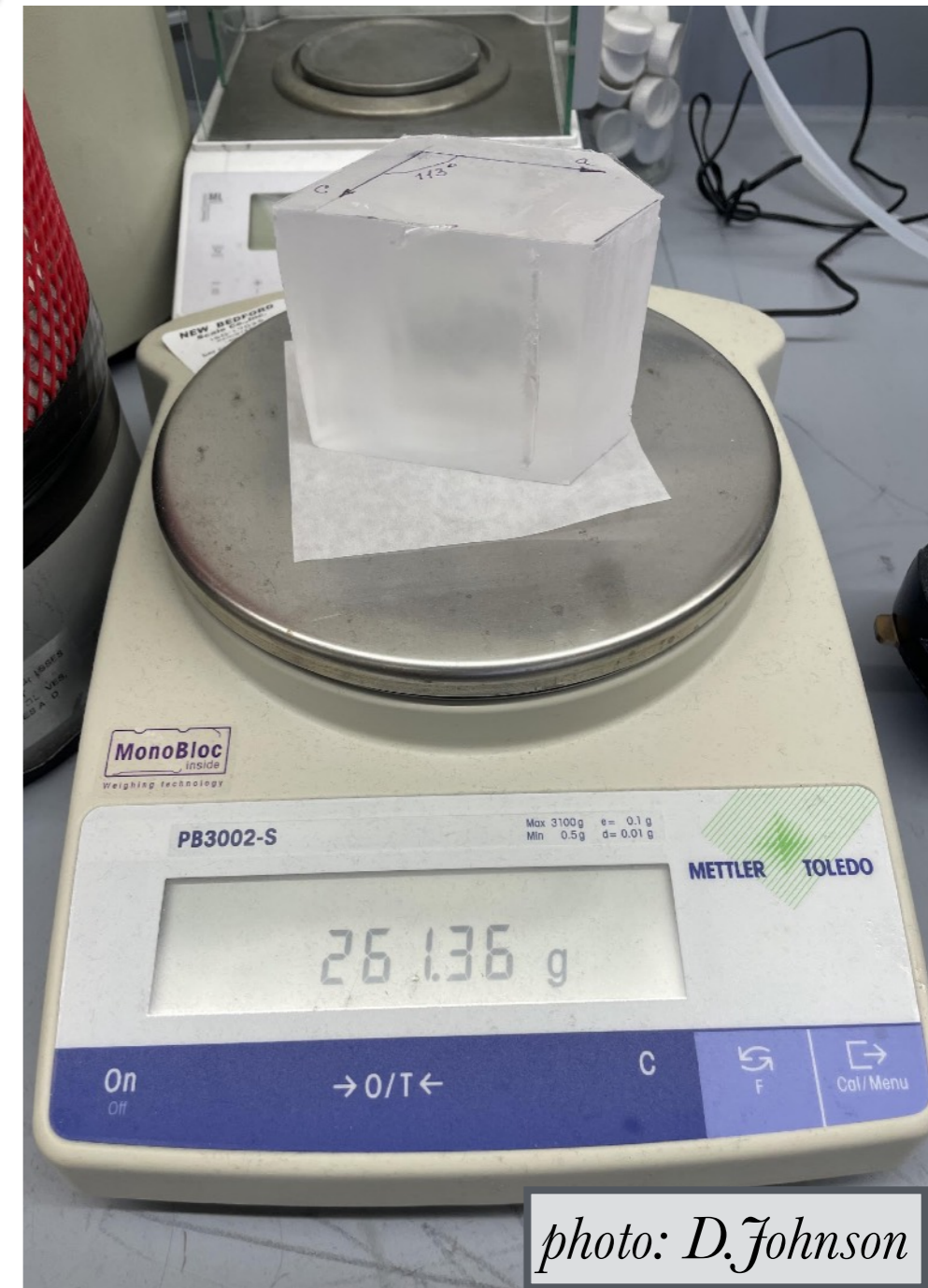
From 2602.15947 (BL, C.Blanco, J.Foster, Y.Kahn):

- Increasing the **modulation amplitude** by a factor of 2 is as good as increasing the **exposure·mass** by a factor of 4:

$$N_{\sigma} \simeq f_{\text{RMS}} \sqrt{T_{\text{exp}} \langle R \rangle}$$

$$R(t) = \frac{M_T}{m_{\text{cell}}} \cdot \frac{\rho_{\chi}}{m_{\chi}} \cdot \bar{\sigma}_0 \langle v \rangle \times [\mathcal{O}(1)](t)$$

$$f_{\text{RMS}}(R) \equiv \frac{1}{\langle R \rangle} \sqrt{\int_0^T \frac{dt}{T} \left(R(t) - \langle R \rangle \right)^2}$$



Anisotropic Detector Targets **with SCarFFF**

with Carlos Blanco and Jack Shergold (arXiv:2512.18010)

<https://github.com/jdshergold/SCarFFF>

SCarFFF: our **fast** new molecular physics code

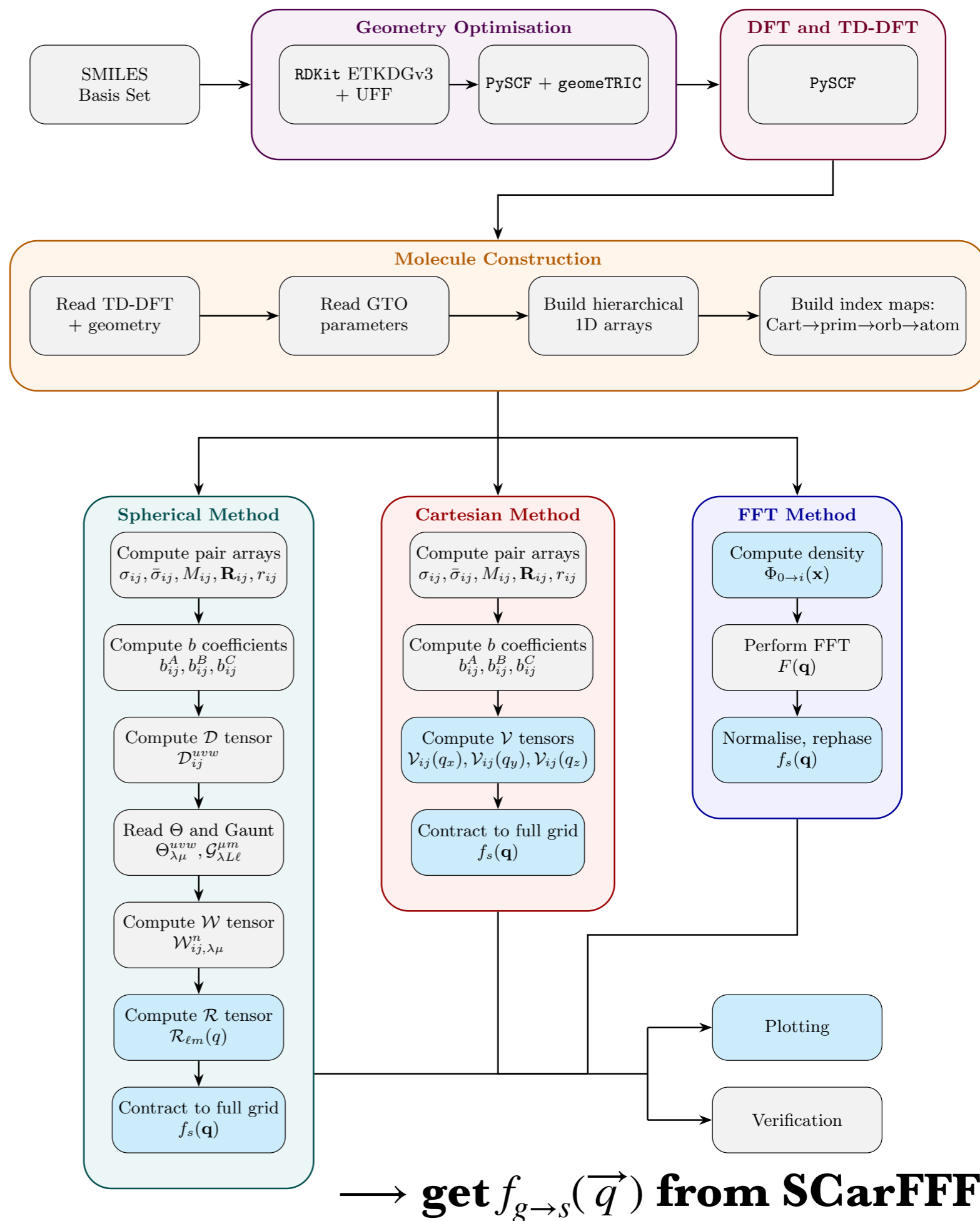
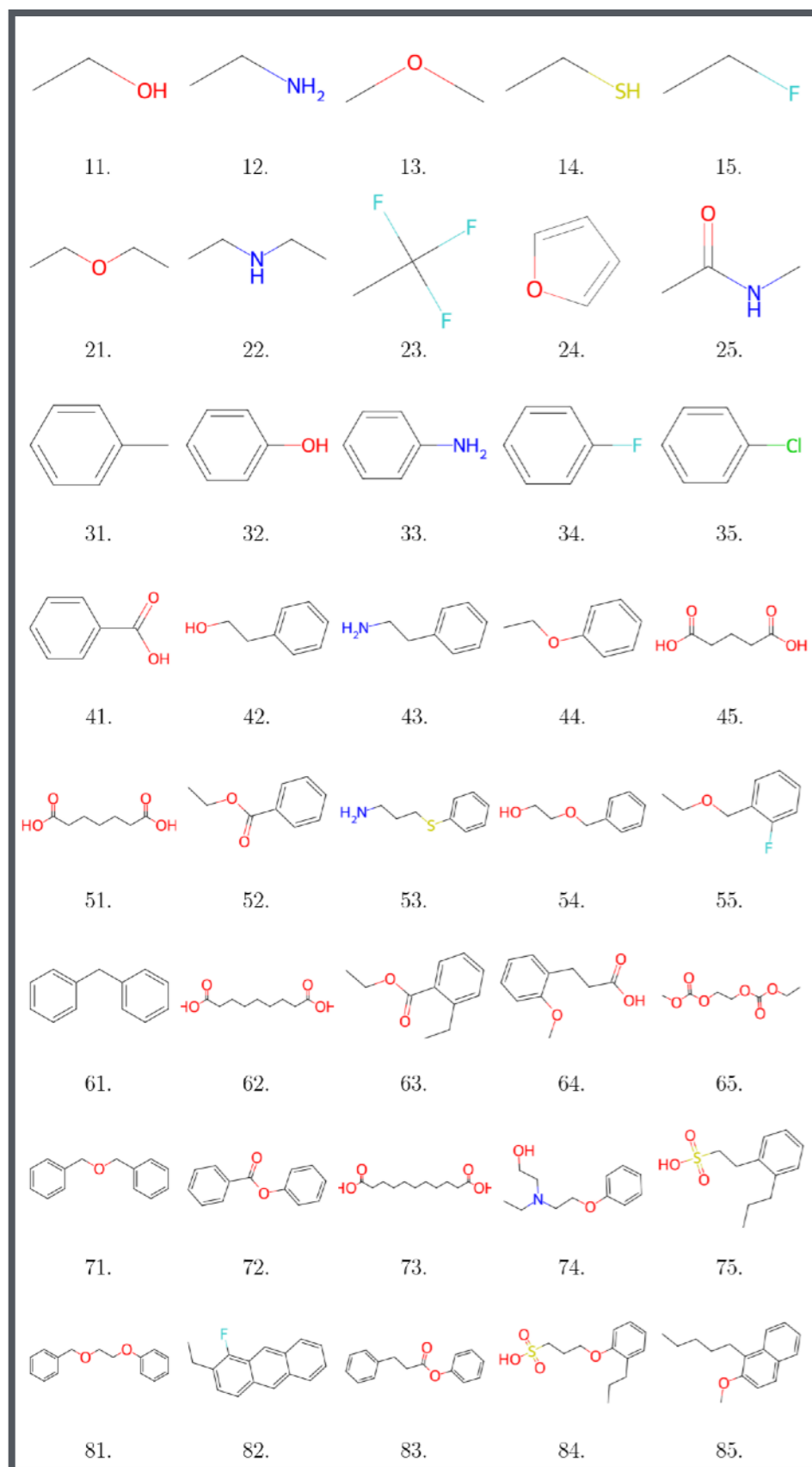
Scalar, Cartesian, and Fourier Form Factors

- calculates **electronic wavefunctions** for ground state and excited states, using time-dependent density functional theory (PySCF)
- uses analytic methods (2512.18010) to convert Gaussian basis functions into **molecular form factors**

Design Criteria:

- **low excitation energy:** < 4 eV to probe $m_\chi \sim 1$ MeV
- **large anisotropy:** $N_\sigma \propto f_{RMS} \sqrt{M_T}$
- **scalable to kilogram size**

• **pick a molecule...** →



Design Criteria for **Spin Dependence**

Simplified Spin Dependence

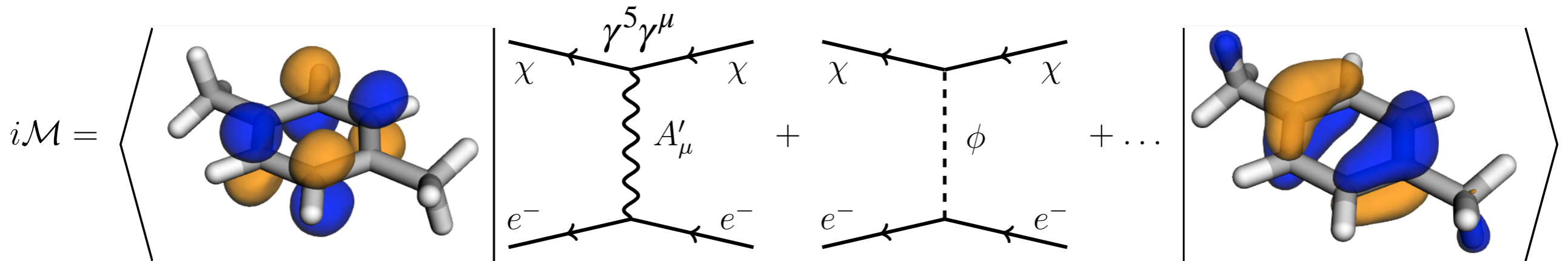
2511.10764 with Pierce Giffin,
Pankaj Munbodh, Tien-Tien Yu

Spin-Independent DM- e^- :
e.g. scalar mediator

- a_0, a_1, \dots, a_4 : **DM particle physics**, nonrelativistic EFT
- $B_1, \dots, B_5, \vec{B}_6, \vec{B}_7$: material-specific response functions (**molecular form factors**)

$$\begin{aligned}
 |\overline{\mathcal{M}}_{1 \rightarrow 2}|^2 = & \underbrace{a_0 B_1}_{\text{Spin-Independent}} + a_1 \left[|\vec{v}_0^\perp|^2 B_1 + \frac{m_e}{\mu_{\chi e}} \text{Re } B_2 + B_3 - 2 \text{Re} \left(\vec{v} \cdot \vec{B}_6 \right) \right] \\
 & + a_2 \frac{m_e^2}{q^2} \left[\left(\frac{\vec{q} \cdot \vec{v}_0^\perp}{m_e} \right)^2 B_1 - 2 \left(\frac{\vec{q} \cdot \vec{v}_0^\perp}{m_e} \right) \text{Re } B_2 + B_4 \right] \\
 \text{Exclusively Parity-Odd: } & + a_3 \left[B_5 - 2 \text{Im} \left(\vec{v} \cdot \vec{B}_7 \right) \right] - 2 \text{Re} (a_4) \text{Im } B_2 \\
 & + 2 \text{Im}(a_4) \left[\left(\frac{\vec{q} \cdot \vec{v}_0^\perp}{m_e} \right) B_1 - \text{Re } B_2 \right].
 \end{aligned}$$

Design Criteria: Parity-Breaking Materials

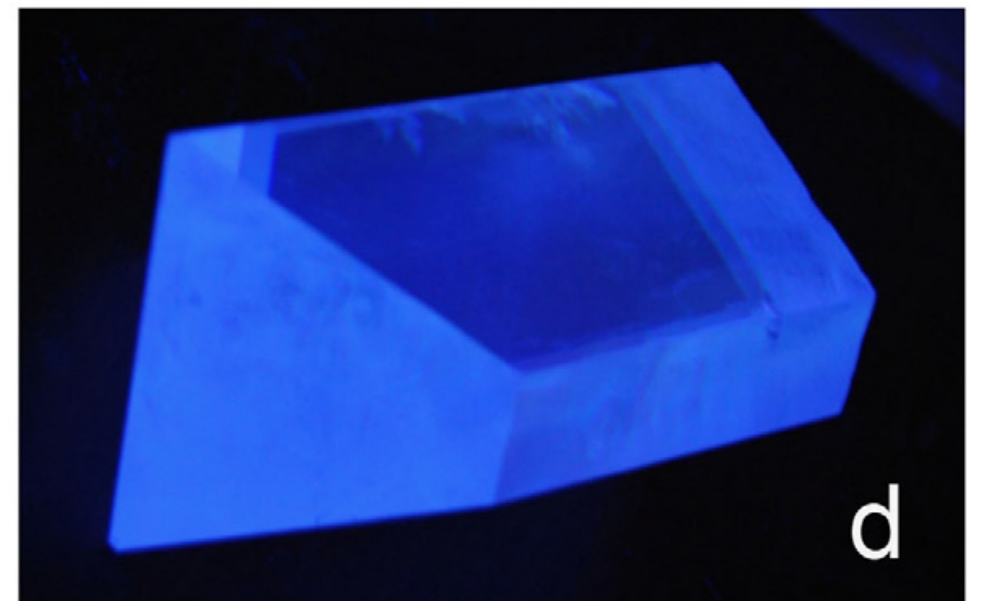
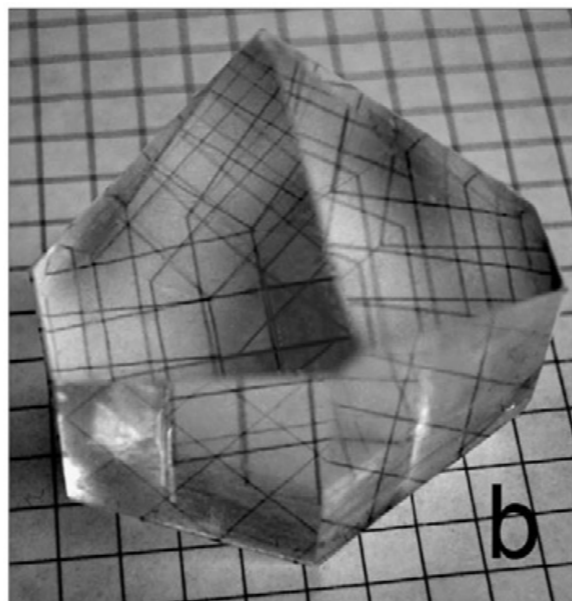


Parity-Odd, Spin-Dependent DM-SM interactions

a_3 $B_5 - 2 \text{Im} (\vec{v} \cdot \vec{B}_7)$

Parity-Odd Material Response Functions

New criterion:
need parity-violating materials to discover parity-violating DM-SM interactions



N. Zaitseva et al. / Journal of Crystal Growth 314 (2011) 163–170

Pipeline for Discovery

1. Make a list of molecules: **databases or ML**

2. Quantum Chemistry Calculation: **SCarFFF**

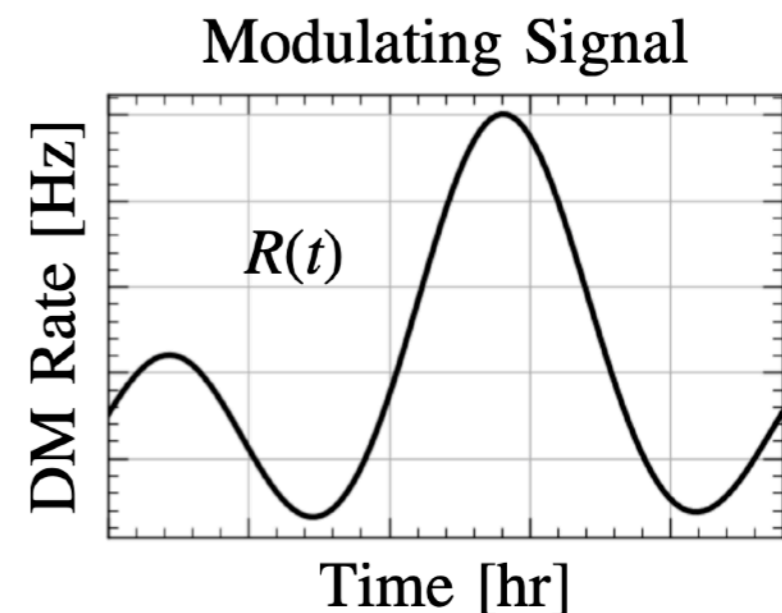
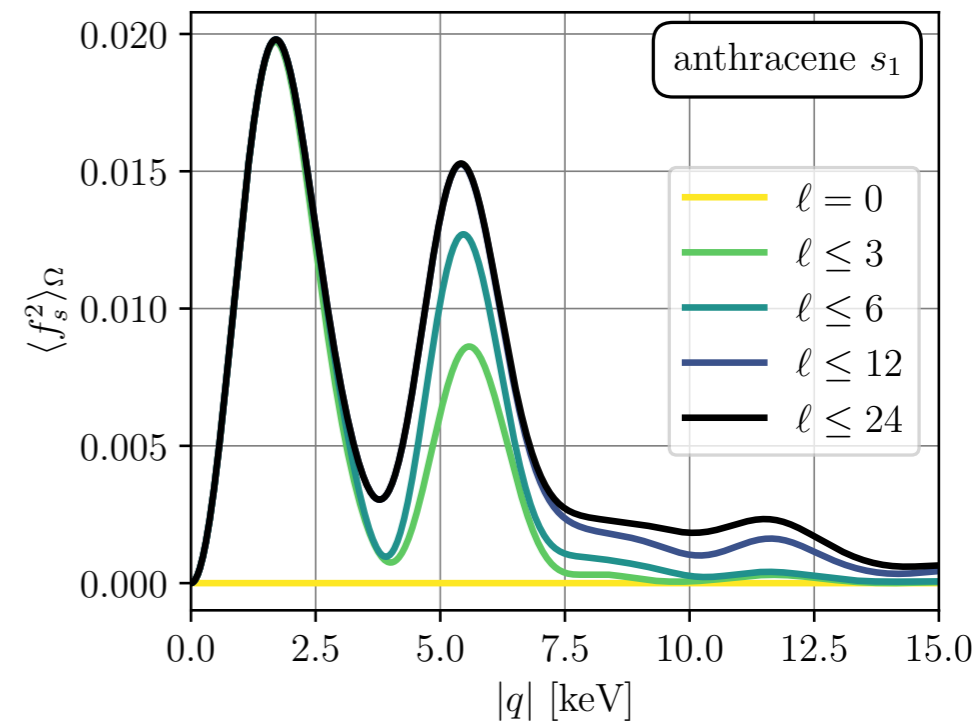
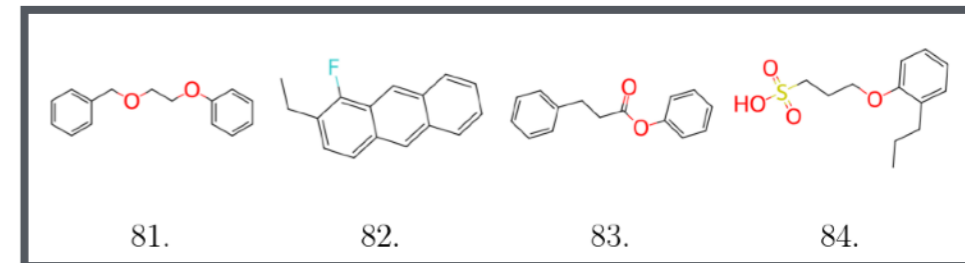
3. Determine the crystal geometry

4. Let **VSDM** do the rate calculation

5. Find the optimal orientations and daily modulation amplitudes

- Figure of merit: optimize $N_\sigma \sim f_{\text{RMS}} \sqrt{N_{\text{events}}}$
- Look for **parity-violating** *and* **parity-symmetric** materials; multiple **point group** symmetries; a range of **excitation energies**, 0.5–10 eV

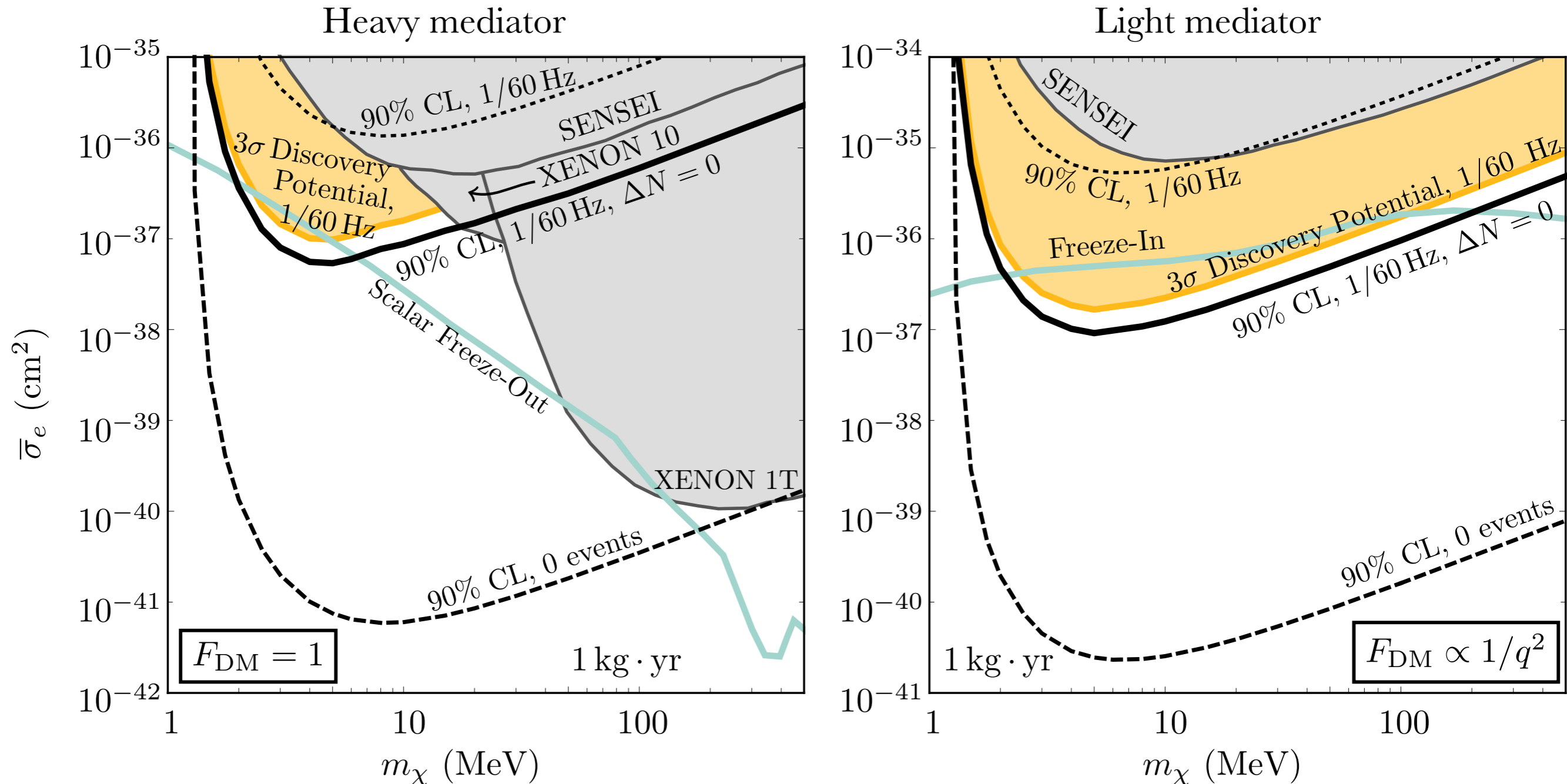
6. Design a **full-size experiment** with an **ensemble** of the best anisotropic materials



Results

arXiv:2103.08601

Discovery potential (gold region): DM models that could be discovered even with a $1 \text{ kg}^{-1} \cdot \text{min}^{-1}$ background rate

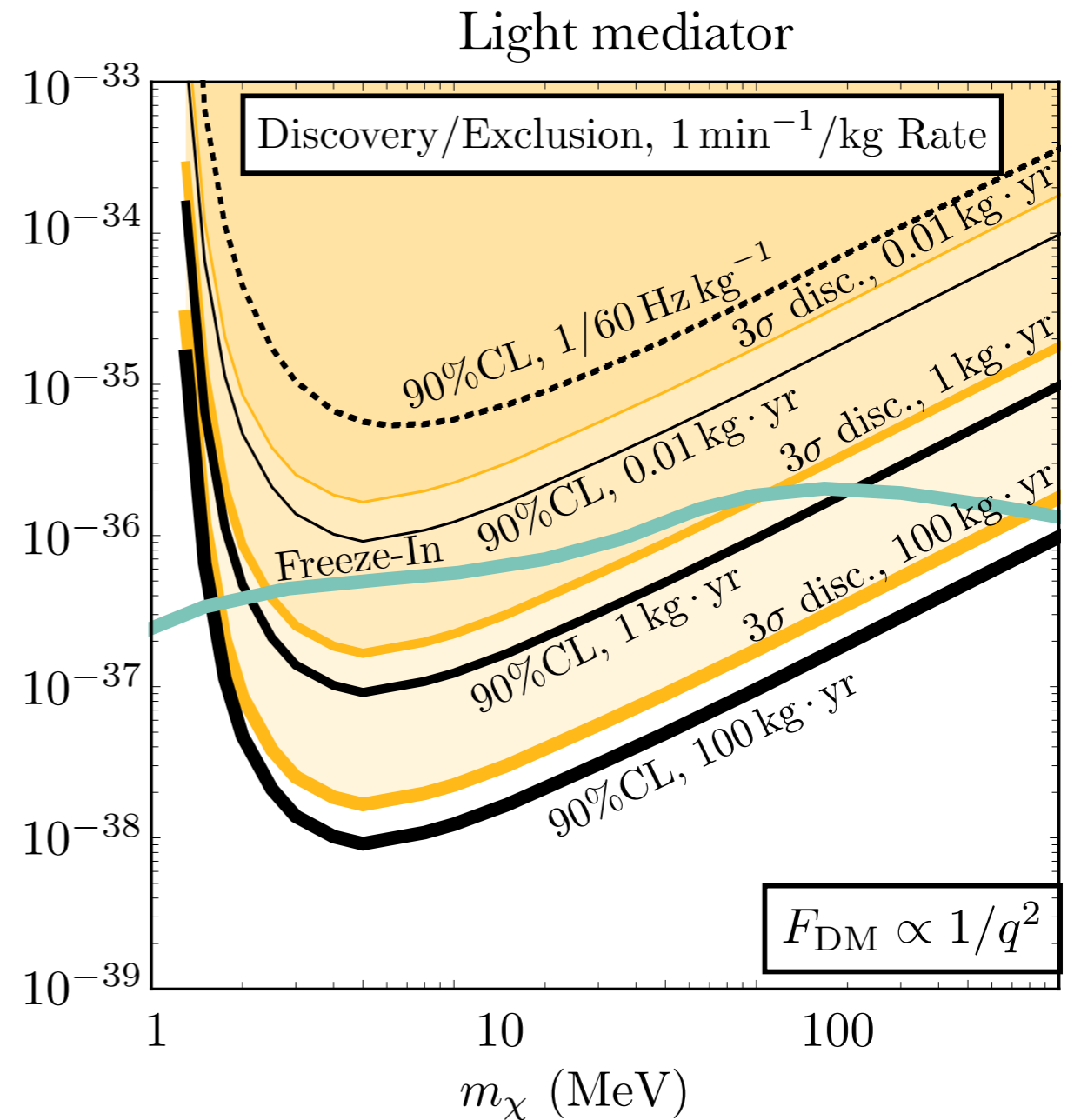
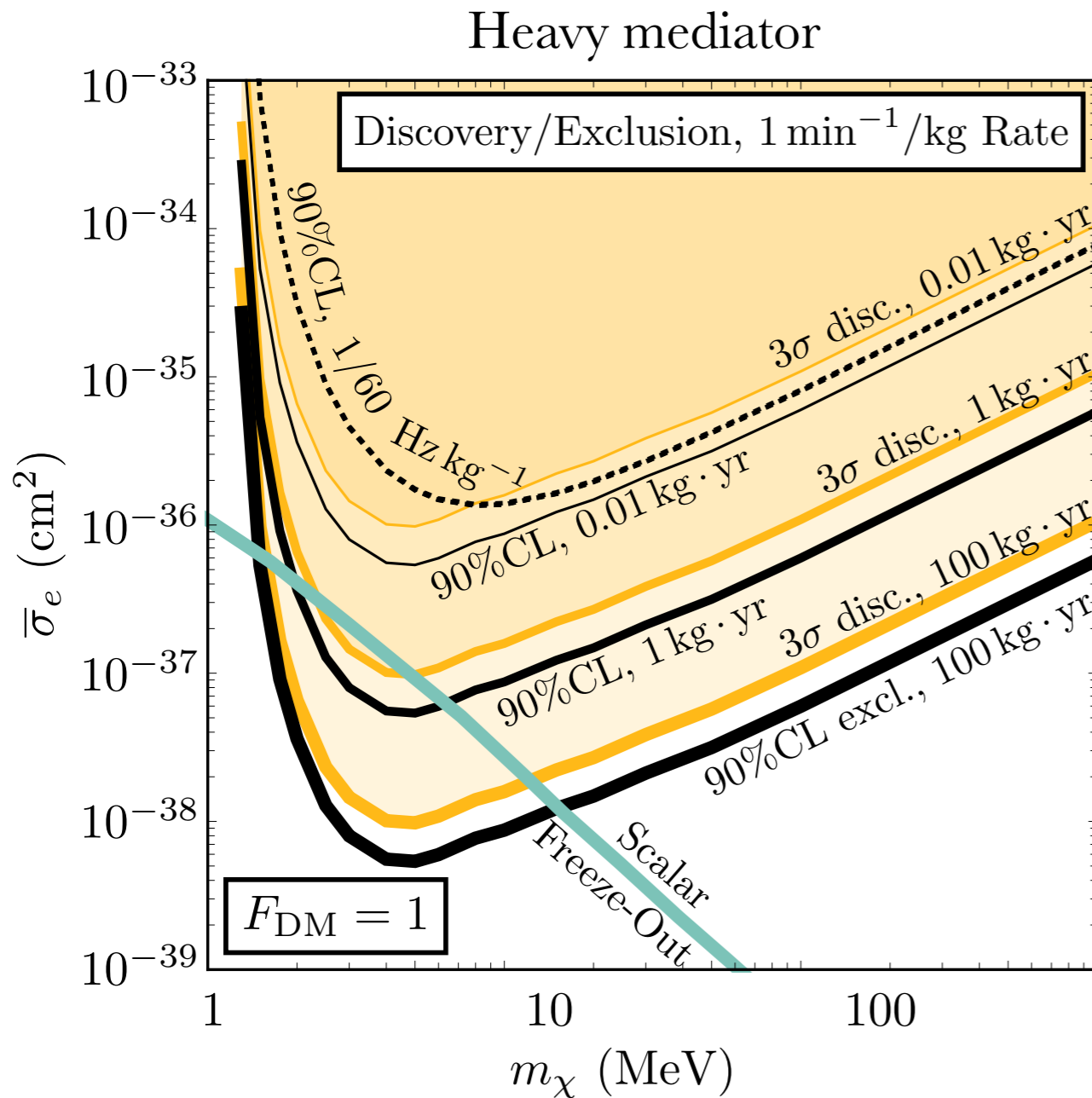
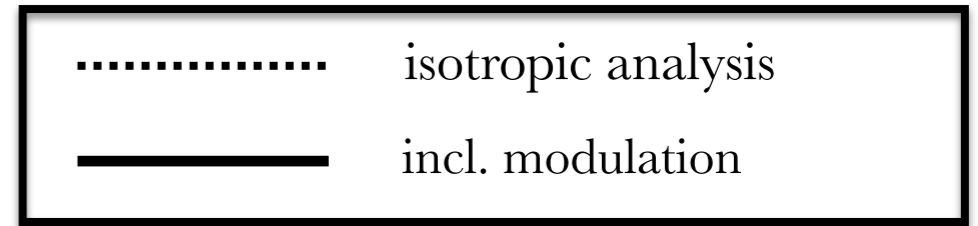


Dark Matter Daily Modulation With Anisotropic Organic Crystals. Carlos Blanco, Yonatan Kahn, BL, Samuel D. McDermott
arXiv:2103.08601

Results

arXiv:2103.08601

***assuming 1 event/min/kg background**



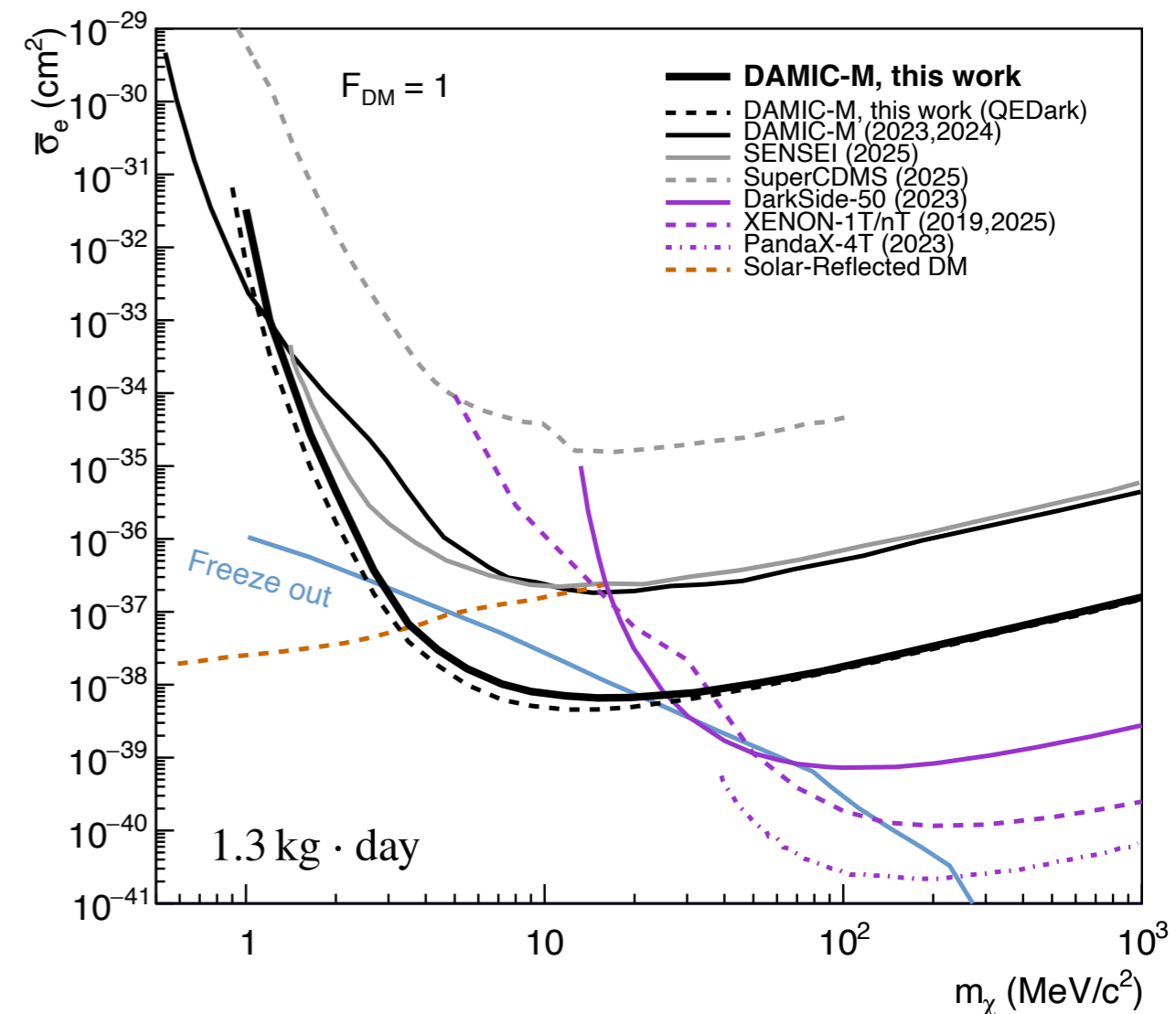
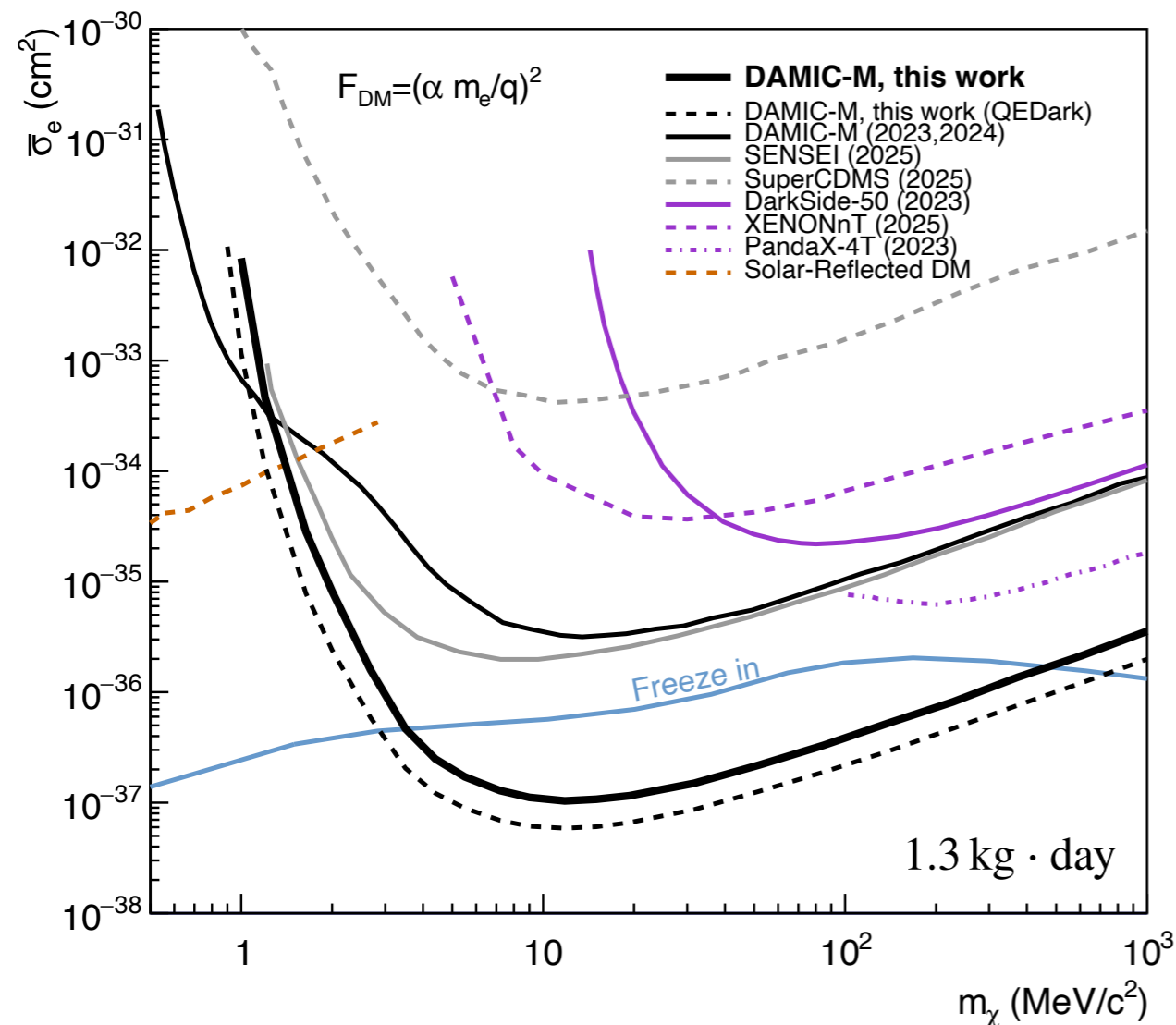
Dark Matter Daily Modulation With Anisotropic Organic Crystals. Carlos Blanco, Yonatan Kahn, BL, Samuel D. McDermott
arXiv:2103.08601

Low Backgrounds in Semiconductors: DAMIC-M

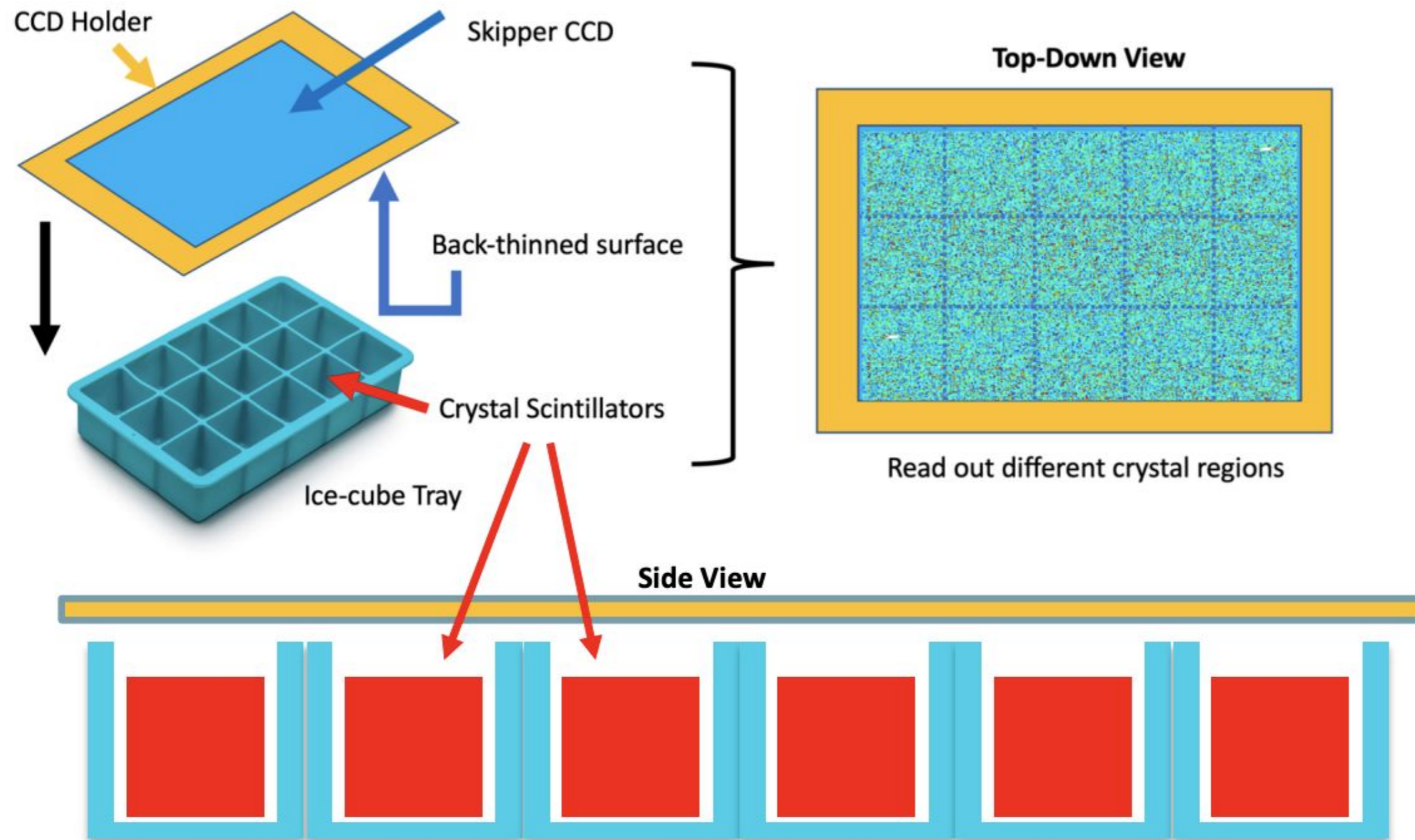
DAMIC-M: thick Skipper CCDs (Si, 3.3g each)

- 1.3 kg · day exposure, measured just 144 events in $2e^-$ bin (a.k.a 4.6 per kg · hour, or **0.077** per kg · min)
- Still seeing $\sim 4 \cdot 10^5$ events at $1e^-$ (**200–300** per kg · min)

DAMIC-M: 2503.14617

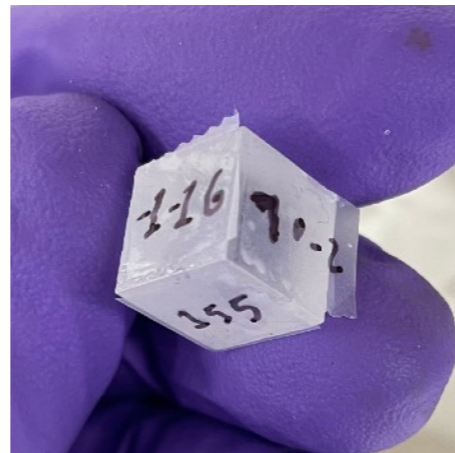
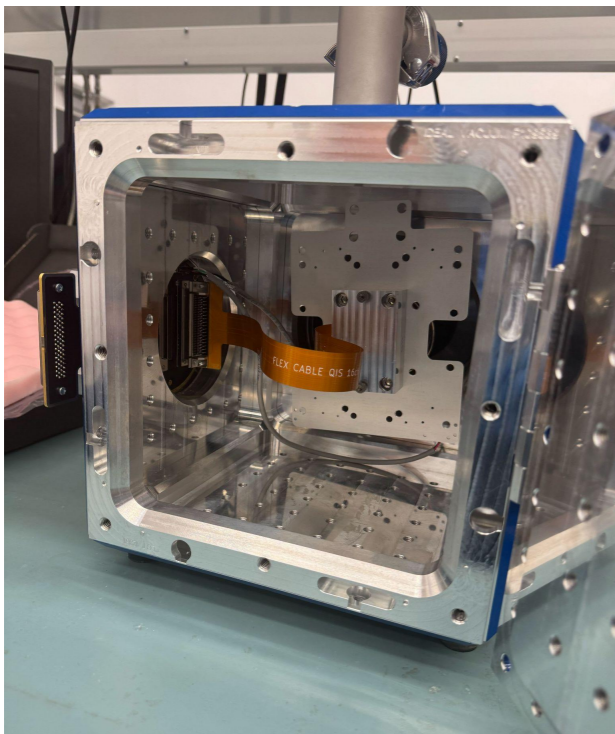


Design: t-stilbene with Skipper CCDs



Prototype Experiment at Fermilab!

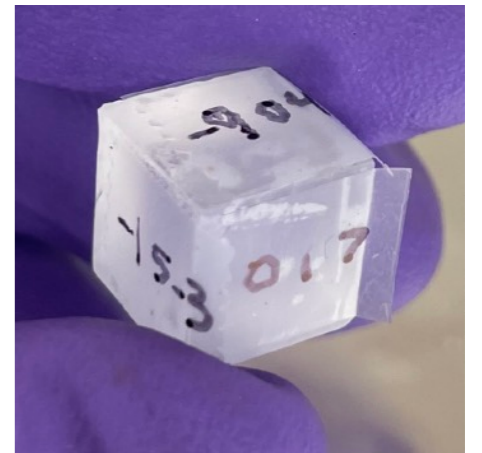
- Eight (8) gram-sized trans-stilbene crystals
- Skipper CCD for single-photon readout
- Calibrating detector response now, then on to MINOS!



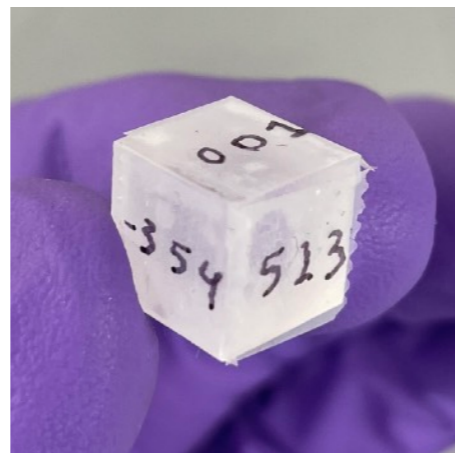
$(-1,-1,6), (7,0,-2), (1,5,5)$



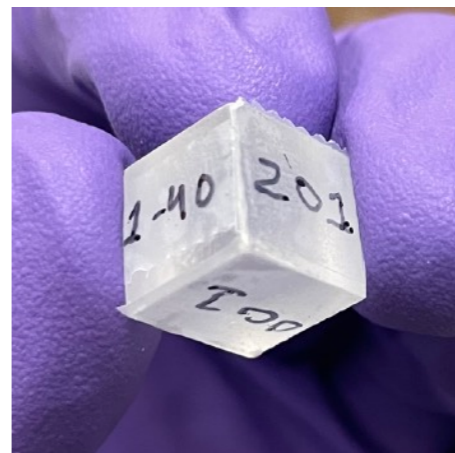
$(0,0,1), (8,-1,3), (3,6,2)$



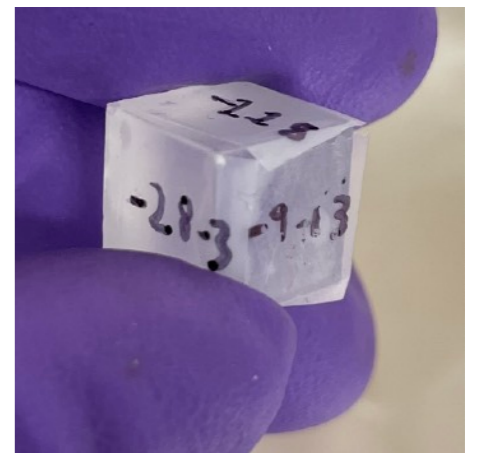
$(-9,0,4), (0,1,7), (-1,5,-3)$



$(0,0,1), (5,1,3), (-3,5,4)$



$(0,0,1), (2,0,1), (1,-4,0)$



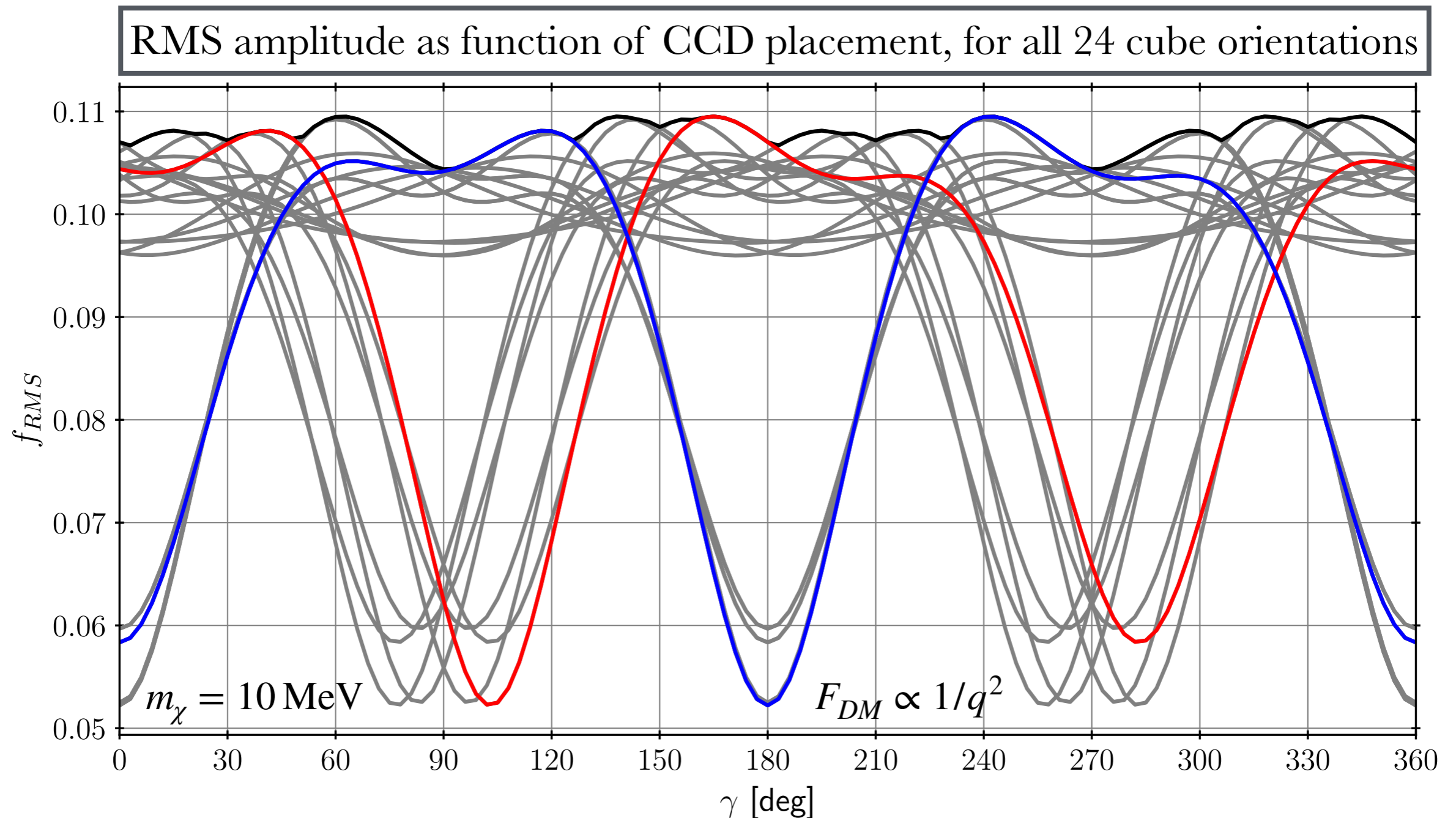
$(-1,1,8), (-9,-1,-3), (-2,8,-3)$

T-stilbene photos and normal vectors from Dane Johnson (MIT)

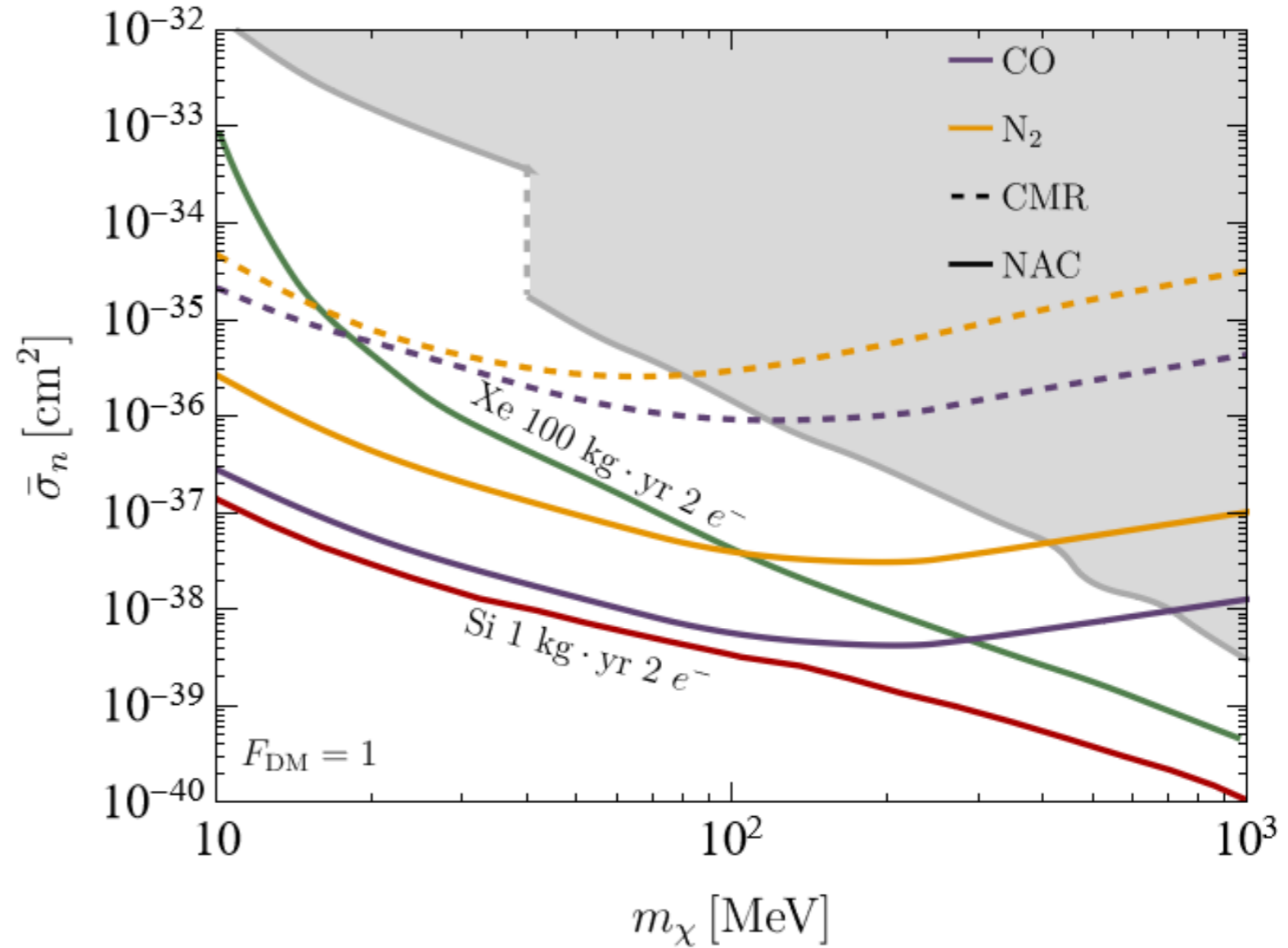
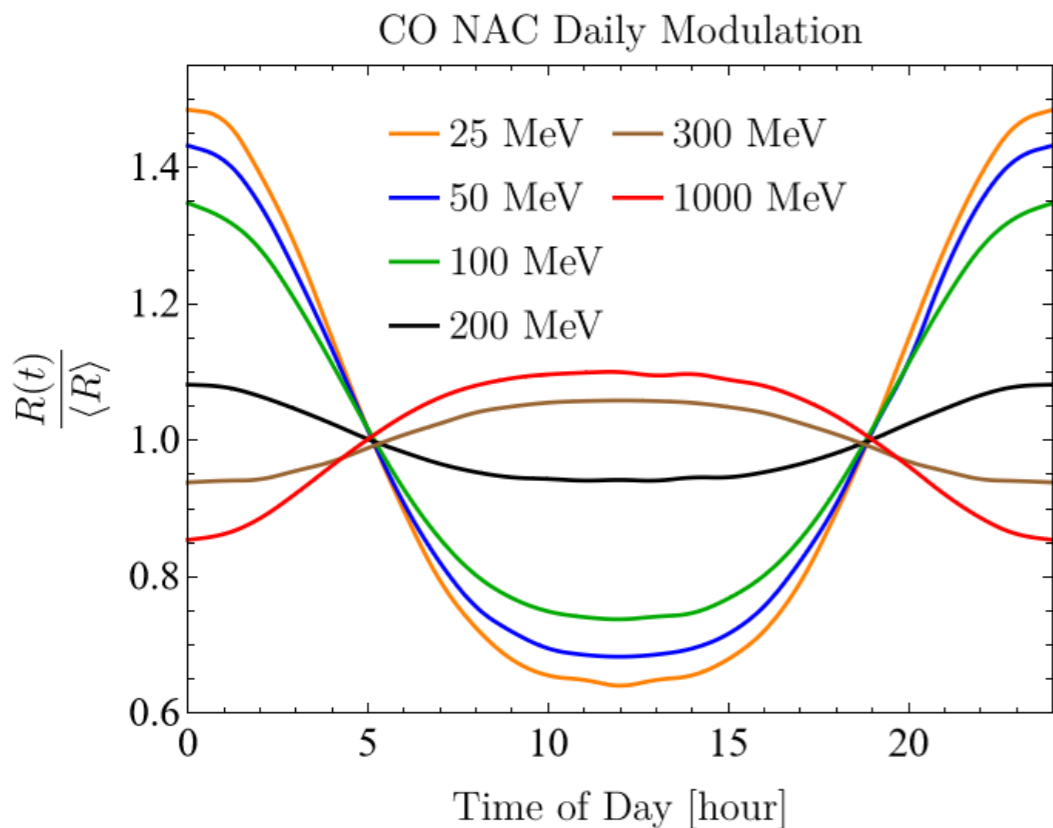
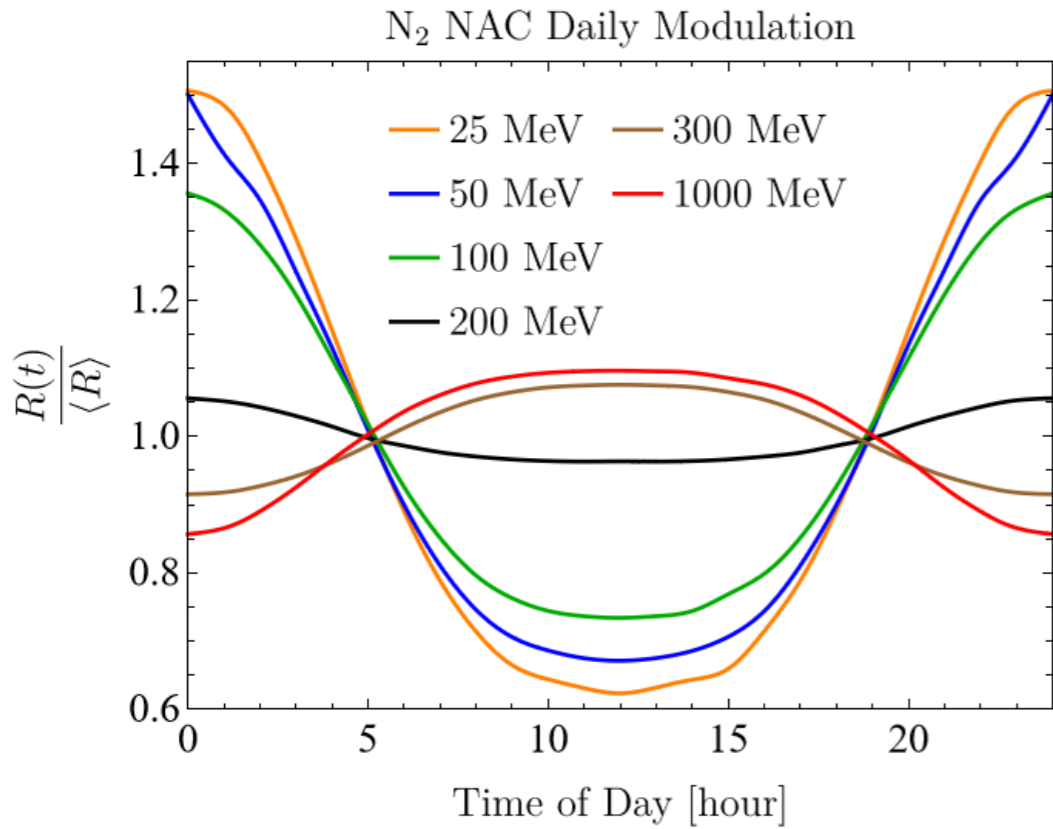
Nora Hoch, “Developing Novel Light Detectors for MeV Dark Matter Experiments”, CPAD 2024, Nov 22 2024

Prototype Experiment at Fermilab!

- Cool feature: can change the strength of the DM modulation signal just by rotating the whole apparatus



Directionality in Molecular Migdal Effect: (2208.09002)



• Repeat calculation for crystal-forming molecules...

→ *trans-stilbene...* ←