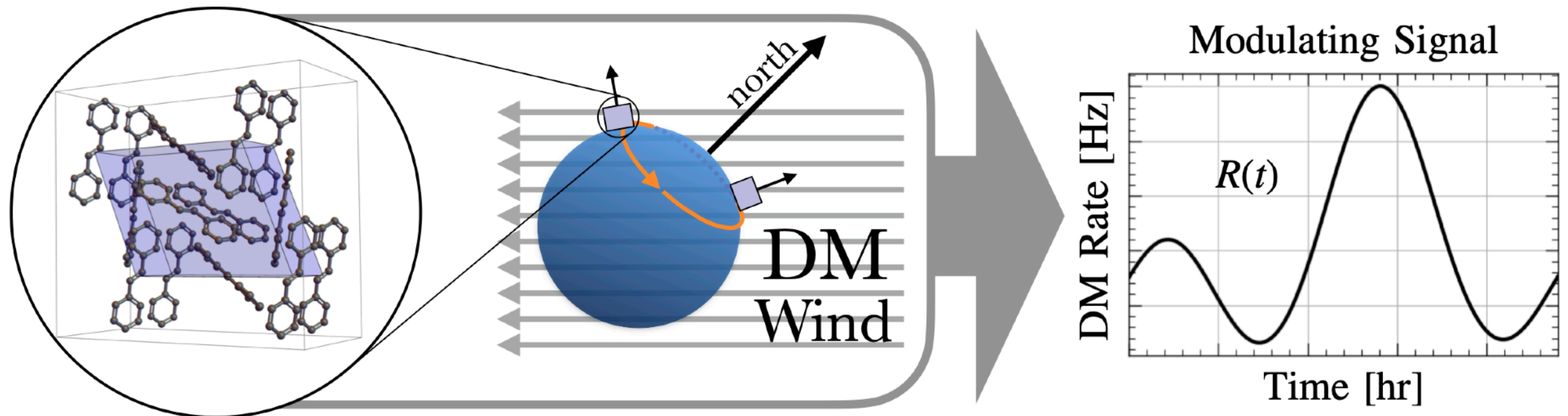
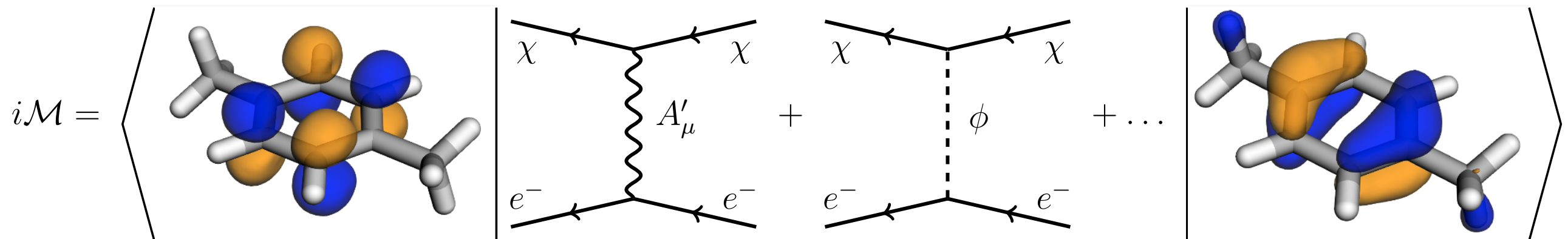
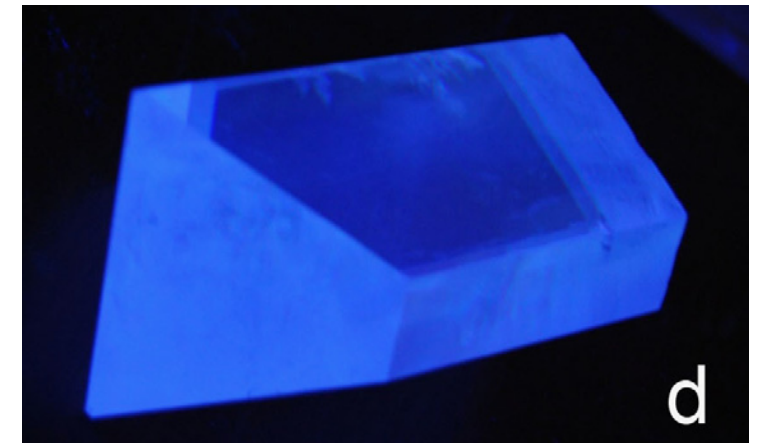


Design Strategies for sub-GeV DM Detection

Directionality for **Next-Generation Experiments**

BEN LILLARD
PENN STATE

LIGHT DARK WORLD
CARLETON, JULY 2026



Searching for Lighter (MeV-scale) Dark Matter

Sub-GeV experiments need **lower energy thresholds** compared to WIMP searches:

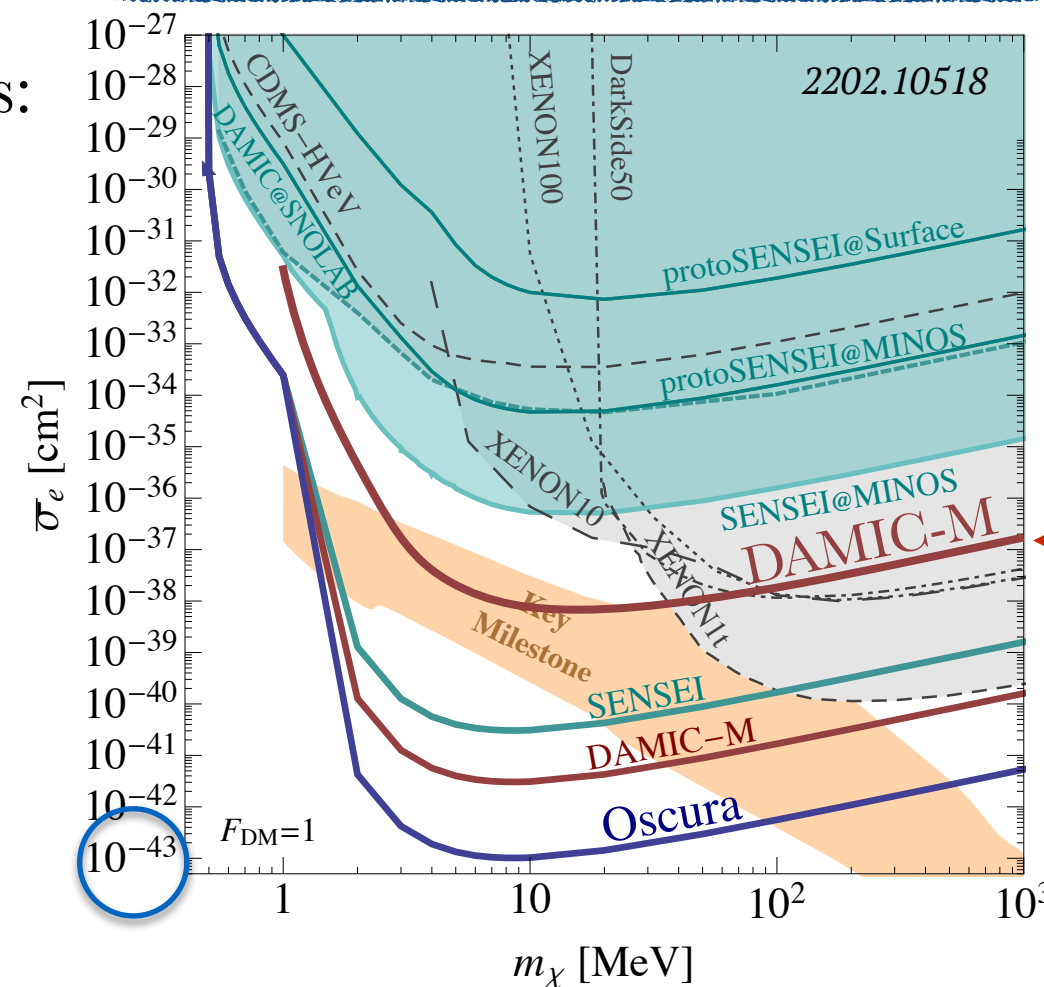
$$\frac{\Delta E}{q} + \frac{q}{2m_0} \geq v_{\text{esc}} + v_E$$

For $v_{\text{esc}} \approx 540 \text{ km/s}$, DM scattering becomes undetectable for $m_\chi \leq m_0$:

$$m_0 = 300 \text{ MeV} \times \left(\frac{\Delta E}{1 \text{ keV}} \right)$$

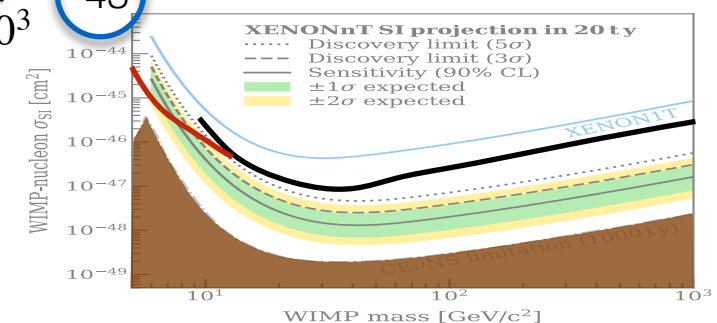
- **MeV-scale DM** has **eV-scale kinetic energy**

Electron Recoil *Direct Detection*



2025

Nuclear Recoil *Direct Detection*



Electron Recoil *Direct Detection*

Nuclear Recoil *Direct Detection*

MeV

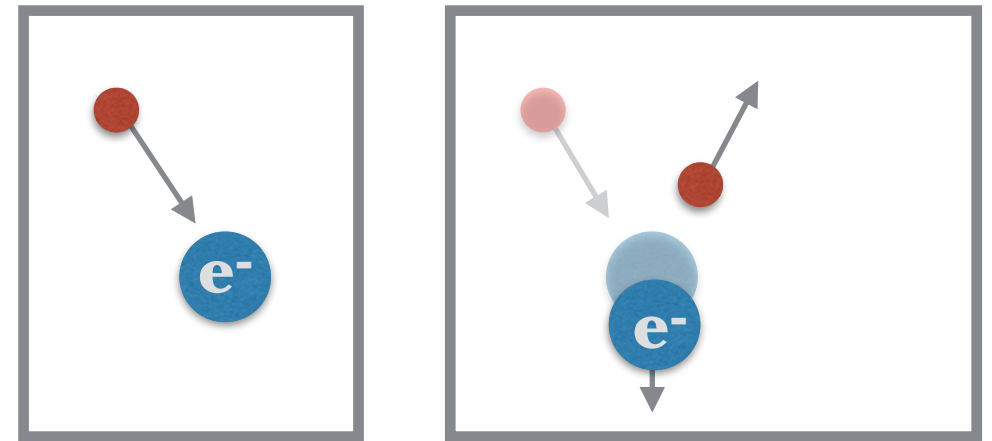
GeV

TeV

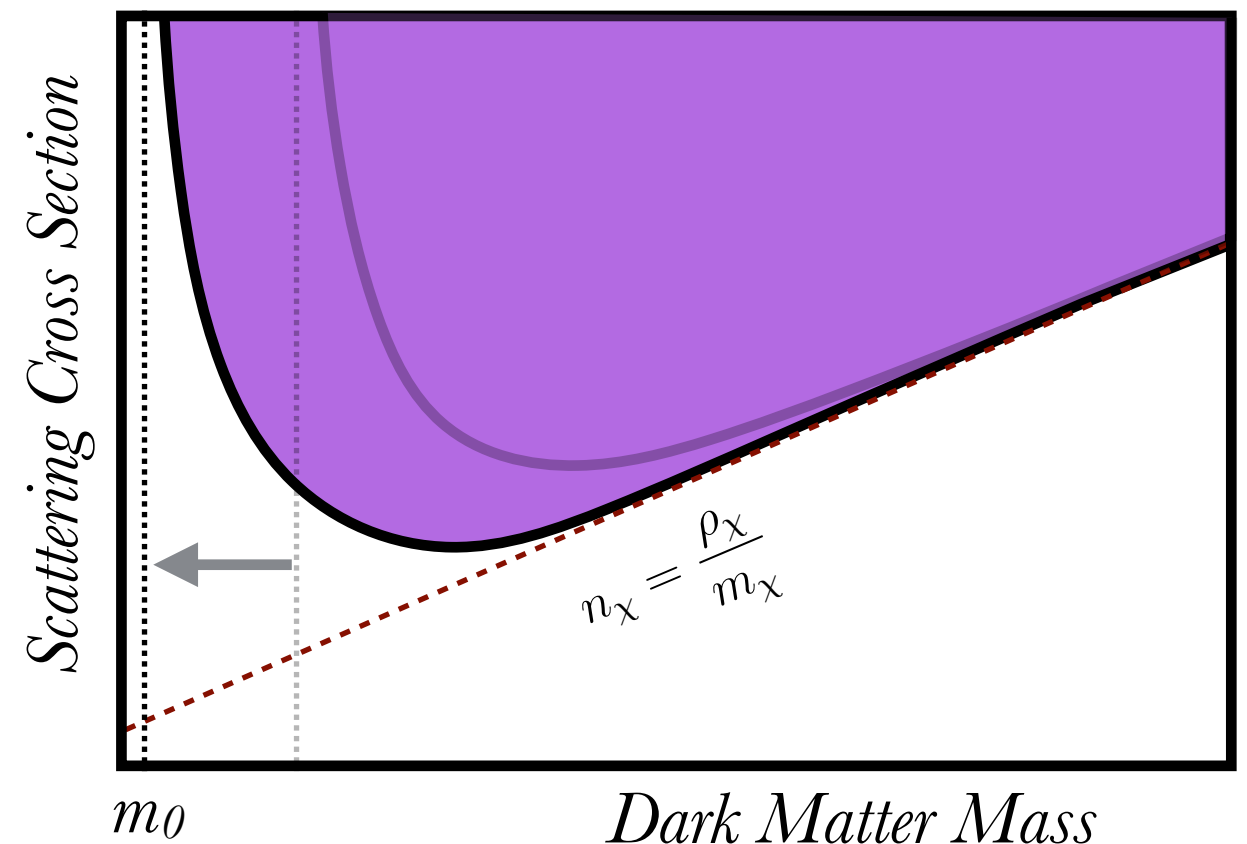
Kinematics: DM–electron scattering

- Typical ΔE for electrons is much lower:
 $\sim 10 \text{ eV}$ for ionization, etc.

$$m_0 = 3 \text{ MeV} \times \left(\frac{\Delta E}{10 \text{ eV}} \right)$$



Generic DM Exclusion Plot



- Note:** Low-threshold experiments
typically detect more noise

$$m_0 = 300 \text{ MeV} \times \left(\frac{\Delta E}{1 \text{ keV}} \right)$$

What makes a good (light DM) detector?

An ideal detector target has...

- **Low Energy Threshold (ΔE):** easily activated by DM
- **High e^- Density:** less instrumentation per mole of electrons
- **Good Transparency:** whenever DM interacts with the target, we want to be able to see the result

Target	ΔE	<i>Density</i>	<i>Transparent</i>
rocks	10 eV	3 kg/L	NO*

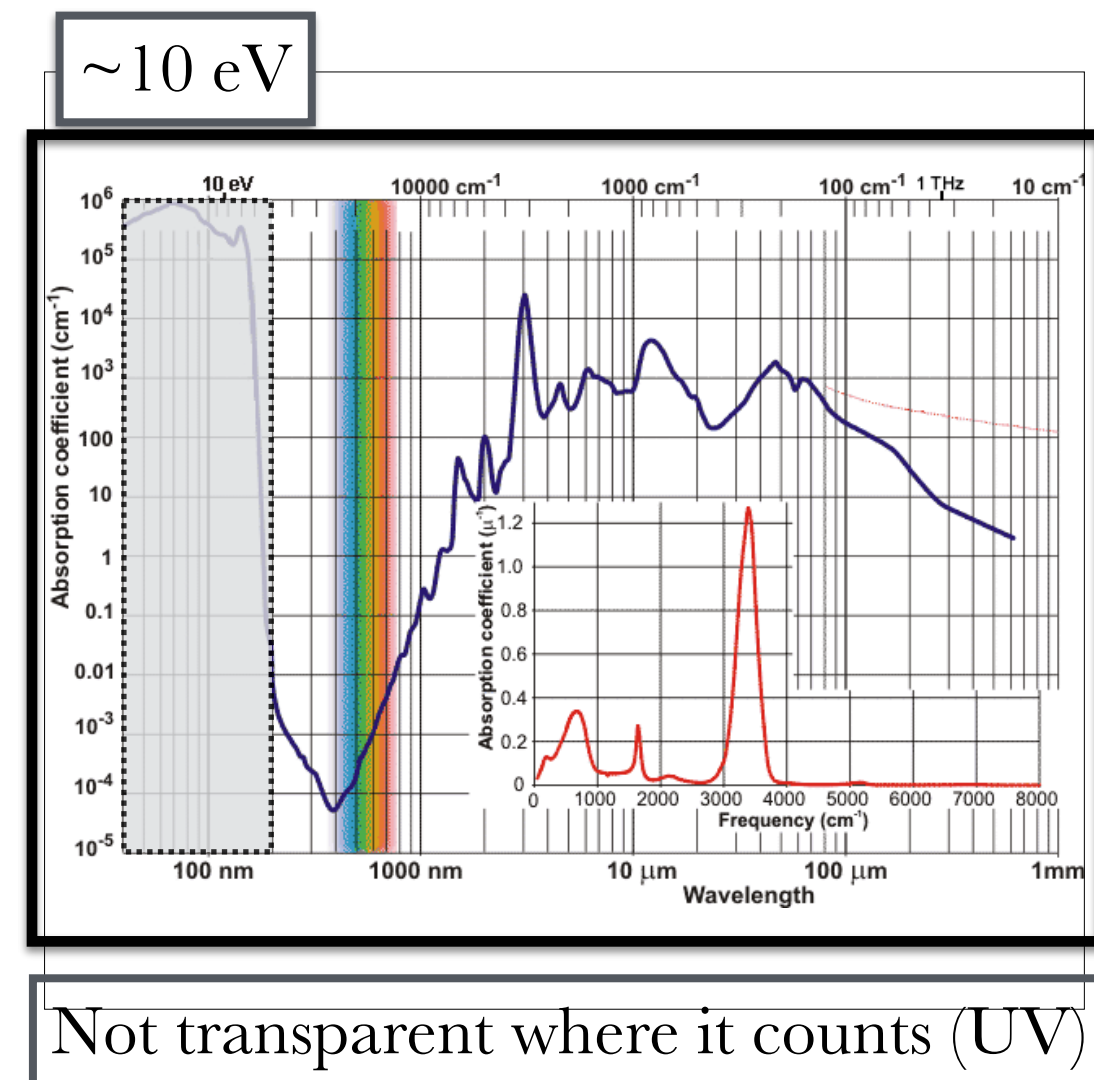


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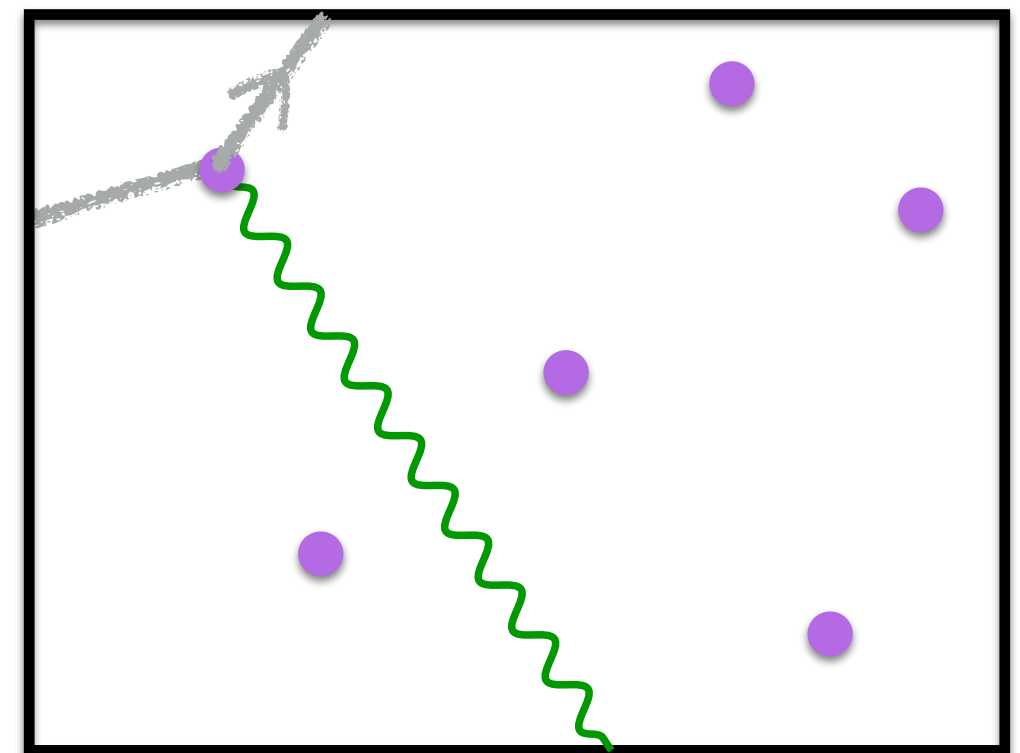
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“water”	10 eV	1 kg/L	NO
gas	10 eV	10^{-3} kg/L	Yes

e.g. CYGNUS: 2008.12587



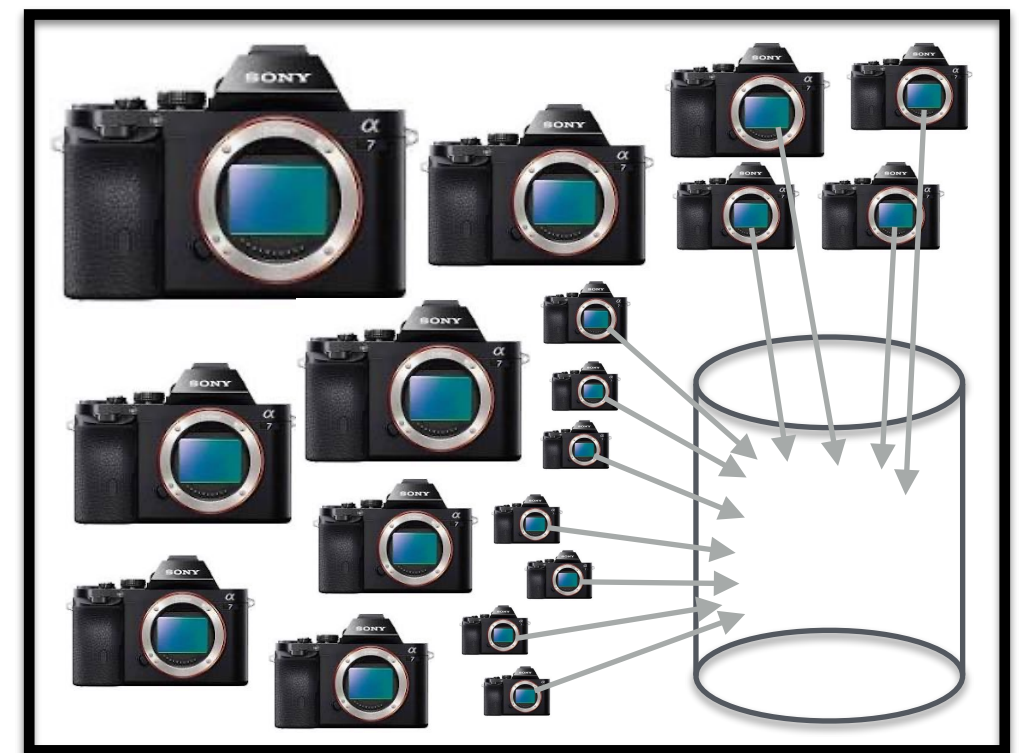
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rocks	10 eV	3 kg/L	NO*
“water”	10 eV	1 kg/L	NO
gas	10 eV	10^{-3} kg/L	Yes
Si, Ge, ...	1 eV	3 kg/L	Yes

e.g. SENSEI, DAMIC



What makes a good (light DM) detector?

An ideal detector target has...

- **Low Energy Threshold (ΔE):** easily activated by DM
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Target	ΔE	<i>Density</i>	<i>Transparent</i>
rocks	10 eV	3 kg/L	NO*
“water”	10 eV	1 kg/L	NO
gas	10 eV	10^{-3} kg/L	Yes
Si, Ge, ...	1 eV	3 kg/L	Yes
scintillator	3 eV	1 kg/L	Yes



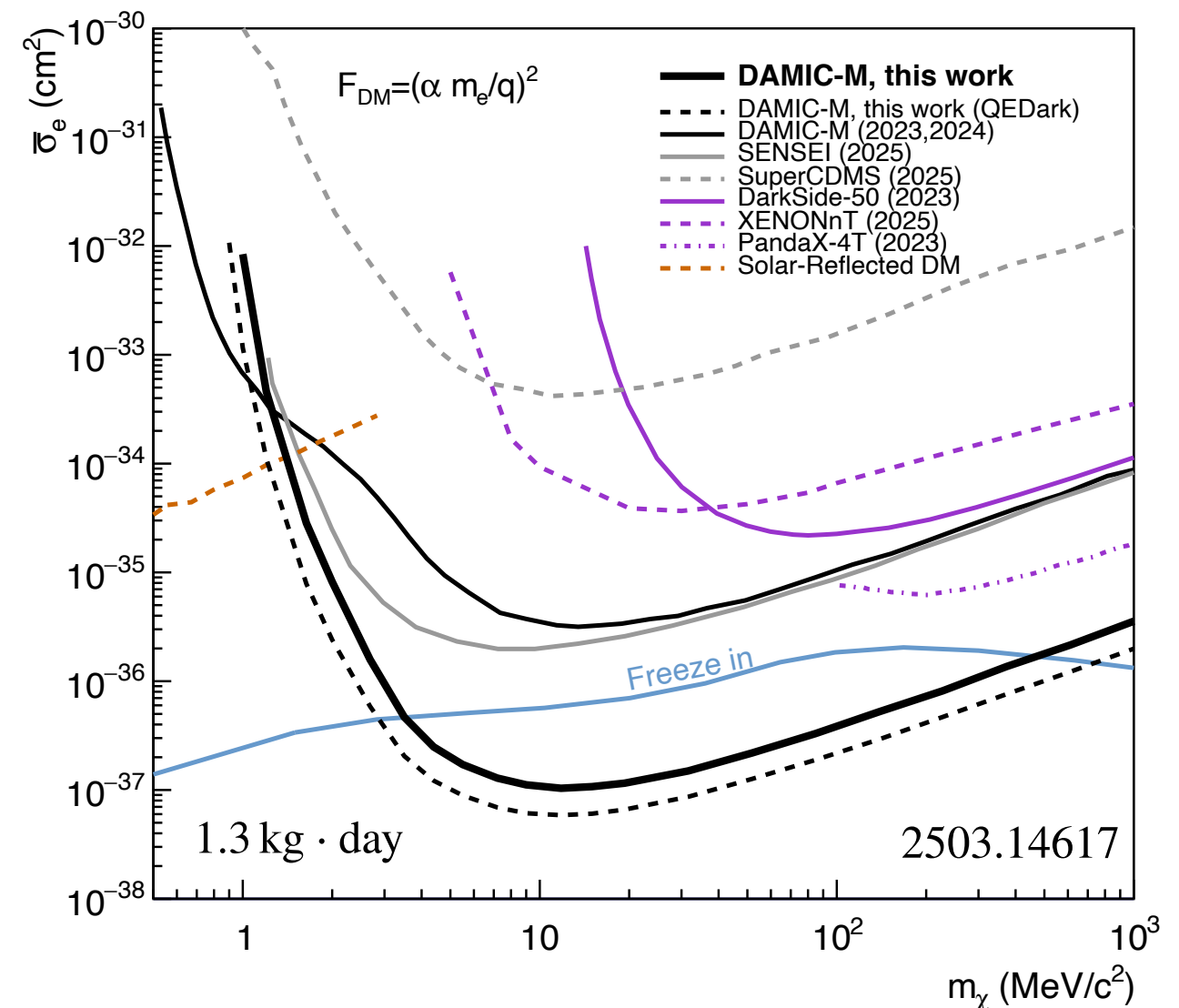
- **Background Rejection:** to distinguish the DM signal from the noise

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, to distinguish between DM scattering and SM backgrounds



Electron Recoil *Direct Detection*

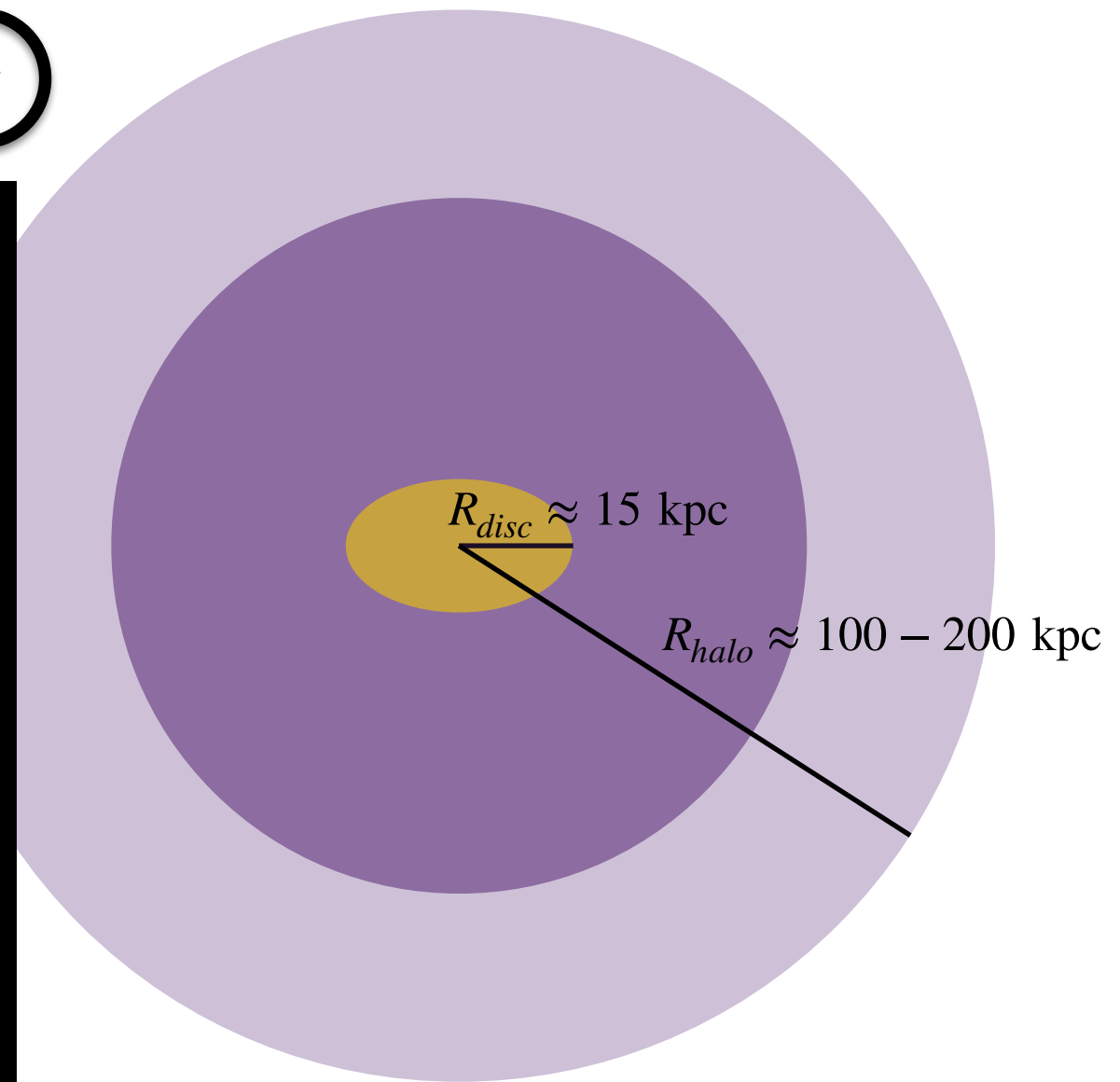
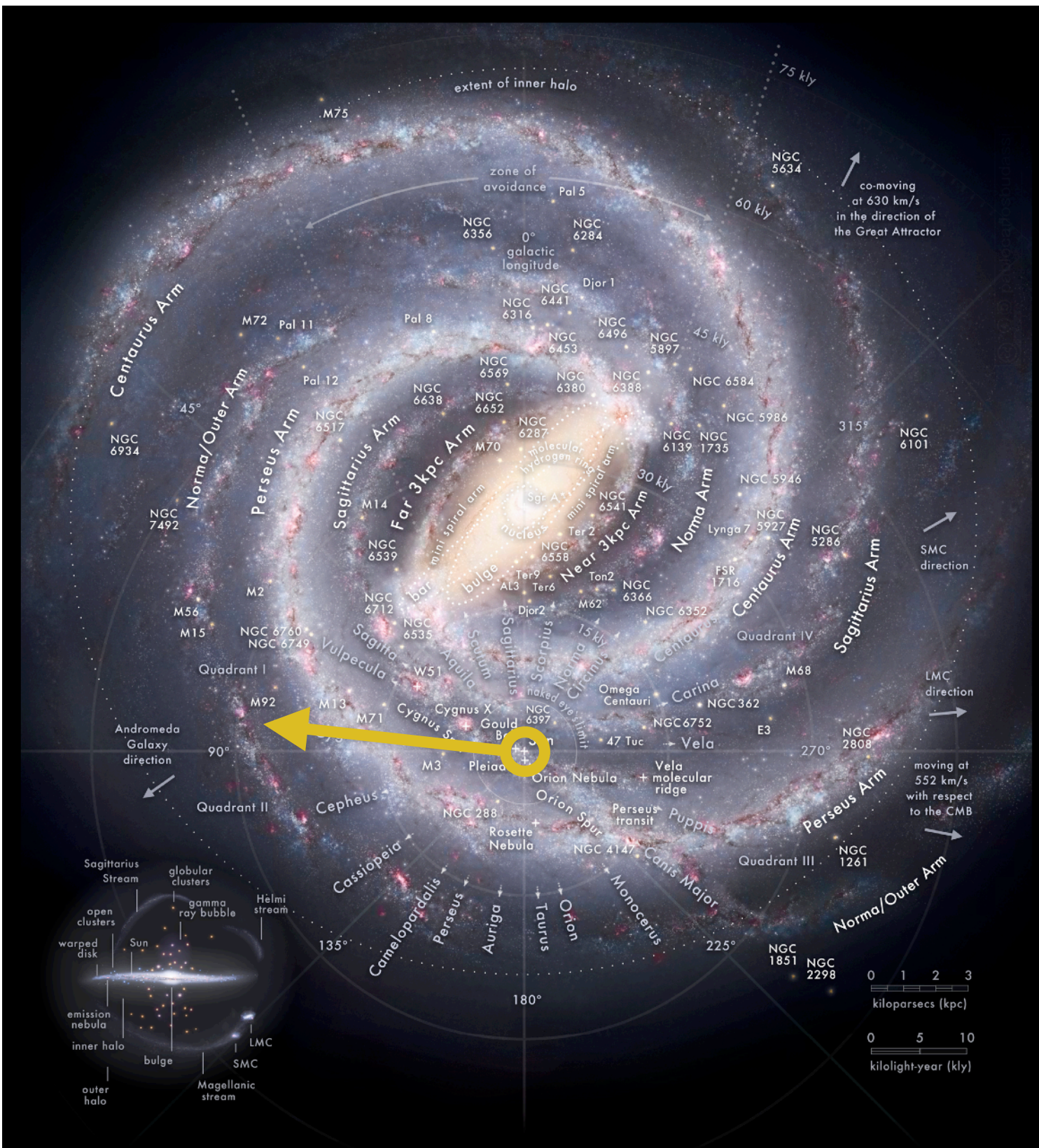
Nuclear Recoil *Direct Detection*

MeV

GeV

TeV

Directionality for Distinguishability

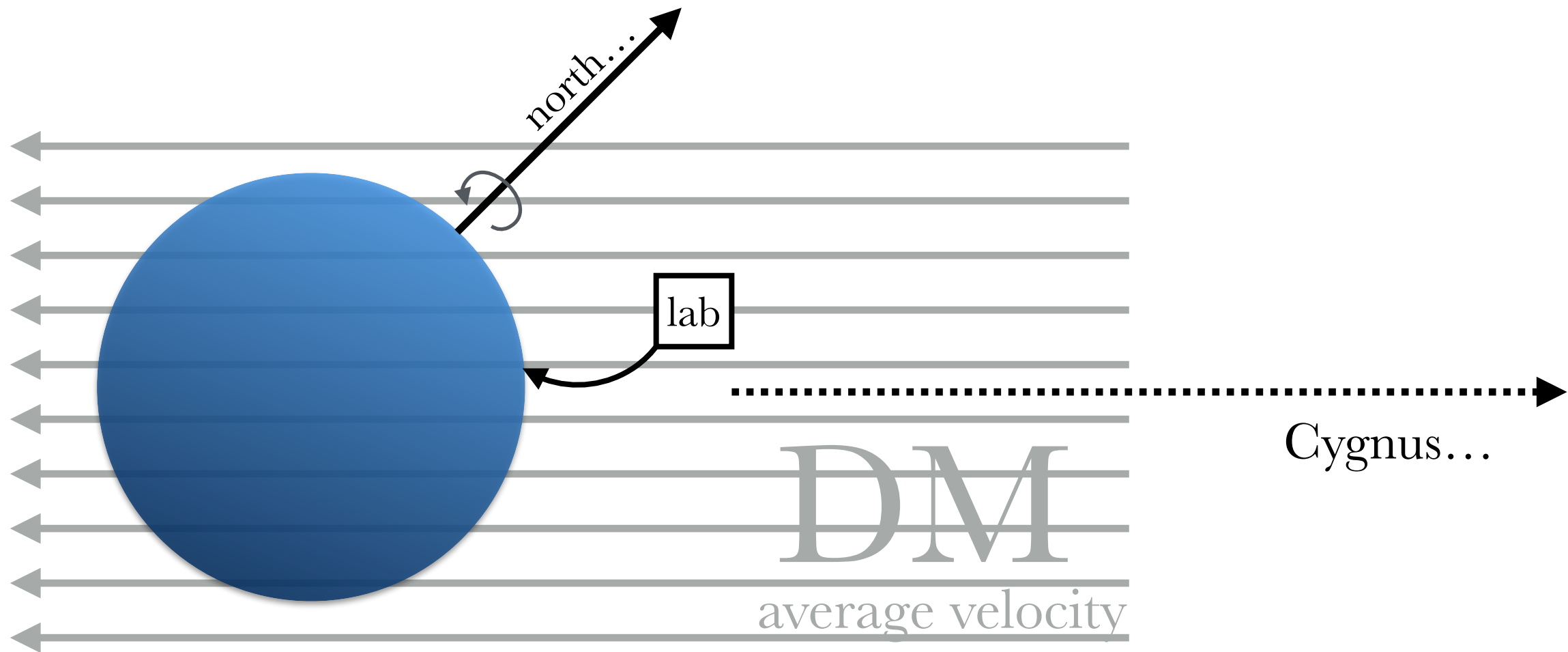


Solar system orbits the galactic center at about **250 km/s**

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”**



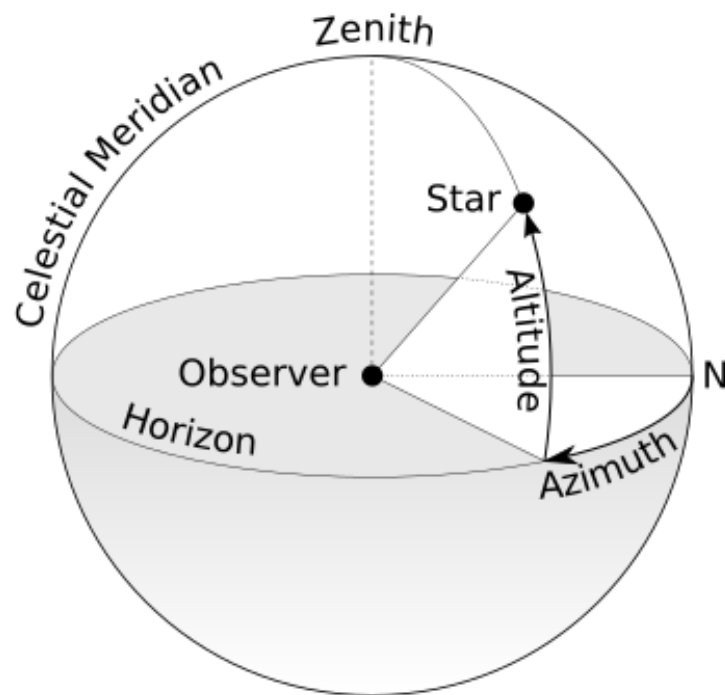
- DM velocity distribution also has $\mathcal{O}(1)$ dispersion, *not to be neglected!*

DM Wind Today:

(Carleton University, Wednesday)

DM wind sweeps out a cone on the sky, with opening angle:

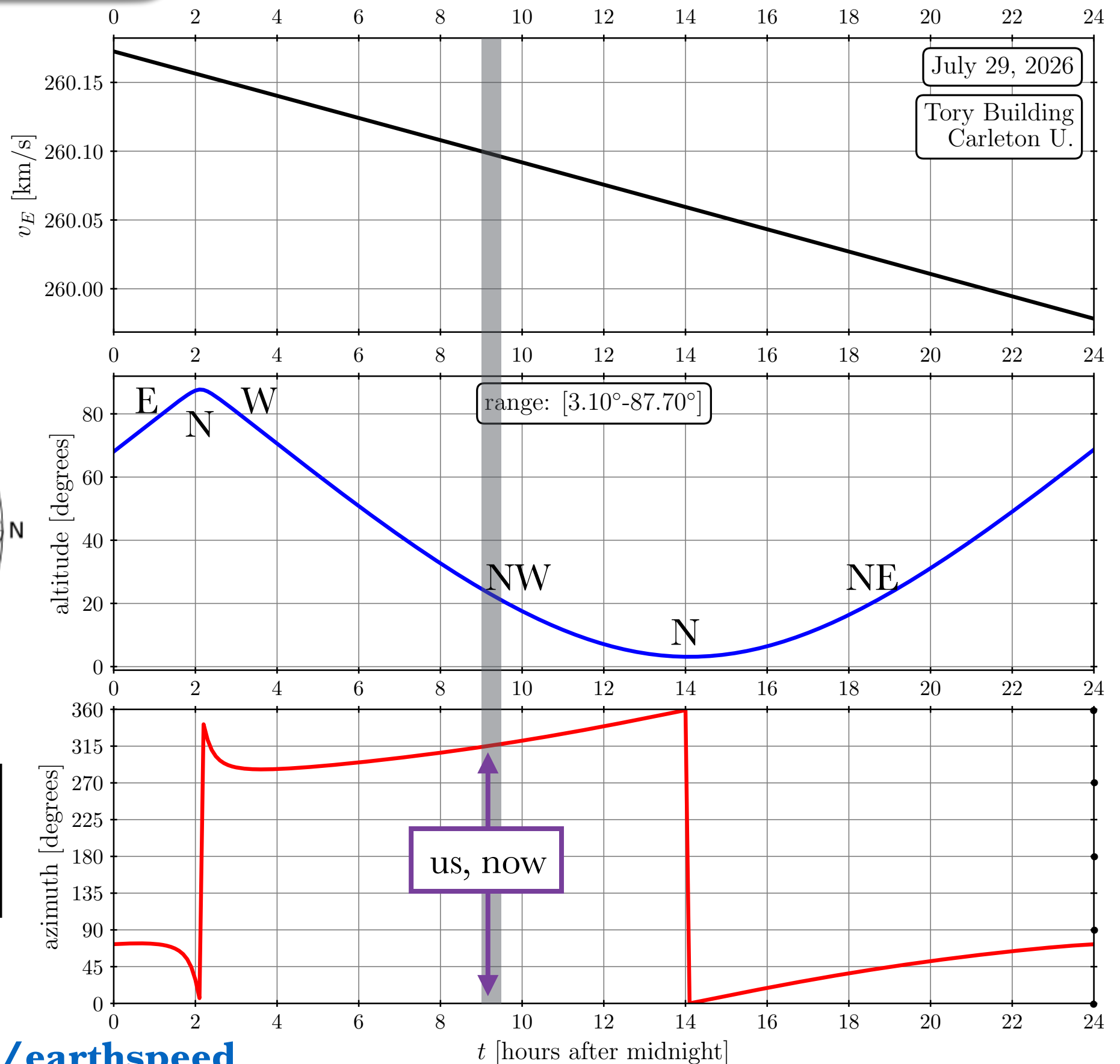
- $\theta_N = 42.5^\circ$ (today)
- $v_E \simeq 260 \text{ km s}^{-1}$



Annual variation:

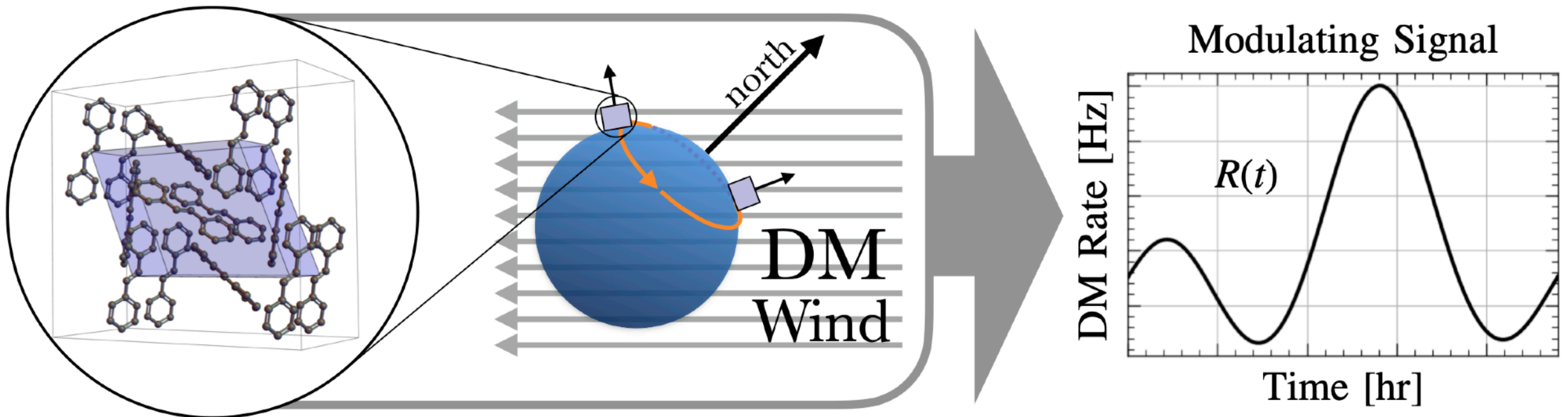
- $\theta_N \approx 42^\circ \pm 6^\circ$
- $v_E \approx 252 \pm 15 \text{ km s}^{-1}$

$t_{\text{sid}} = 23 \text{ h } 56 \text{ m } 4.2 \text{ s}$



Anisotropy for Direct Detection

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



Detector Material:

- anisotropic **response**

DM velocity distribution:

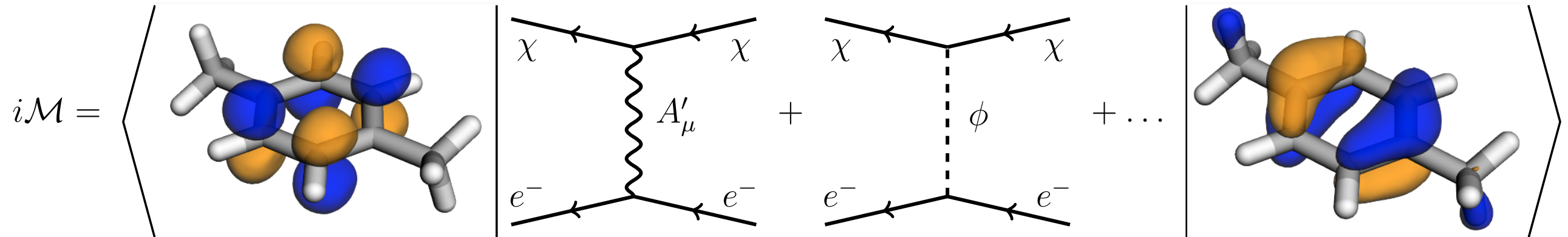
- anisotropic **source**

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...



Molecular Form Factor

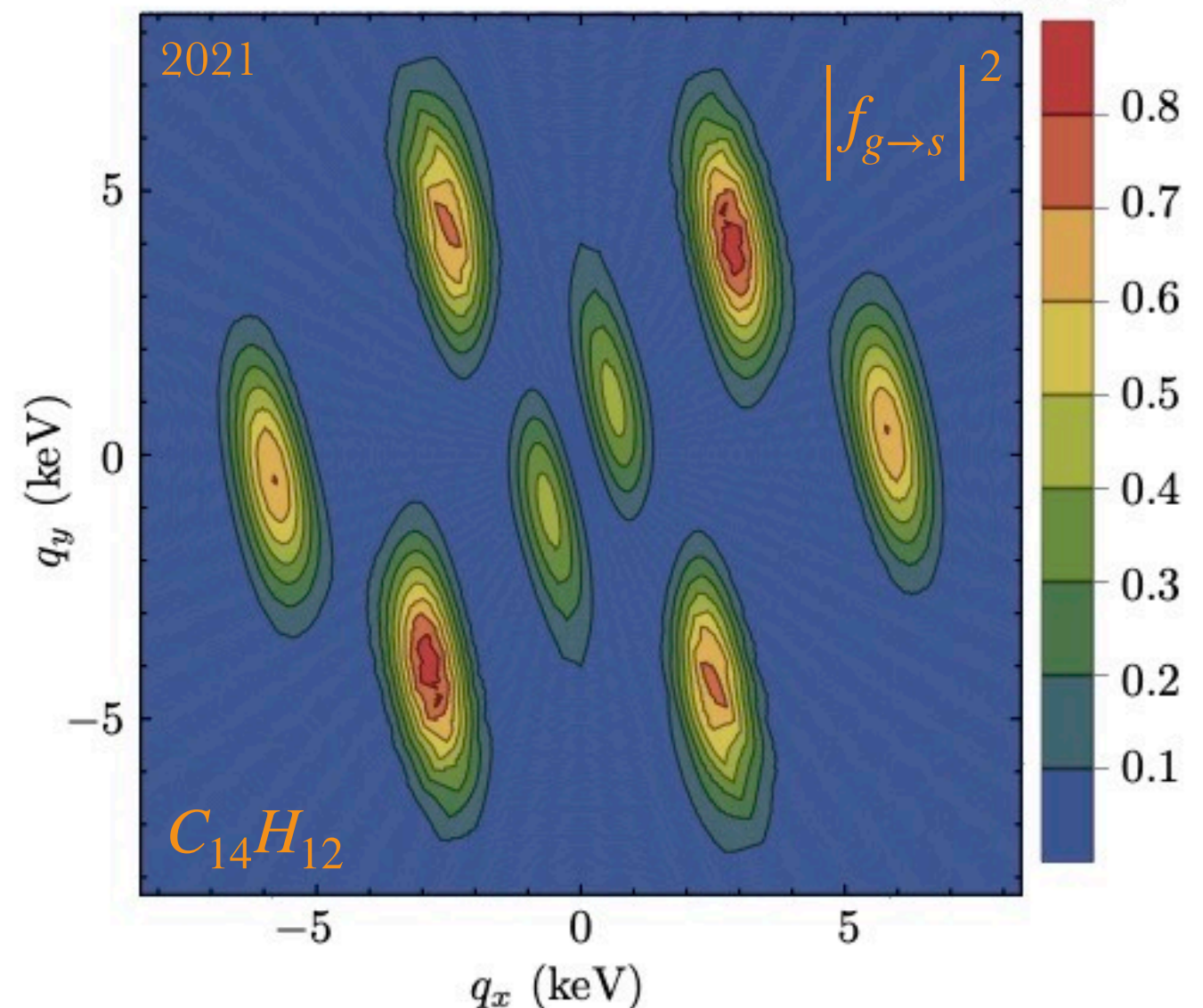


- Probability that DM scattering will excite an electron depends on the **momentum transfer**, $\vec{q}$
- Find the (many-body) ground state and excited states, then calculate:

$$f_{i \rightarrow f}(\mathbf{q}) = \int d^3\mathbf{r} \psi_i(\mathbf{r}) \psi_f^*(\mathbf{r}) e^{i\mathbf{q} \cdot \mathbf{r}}$$

1912.02822: BL, C.Blanco, J.Collar, Y.Kahn

2103.08601: BL, C.Blanco, Y.Kahn, S.McDermott



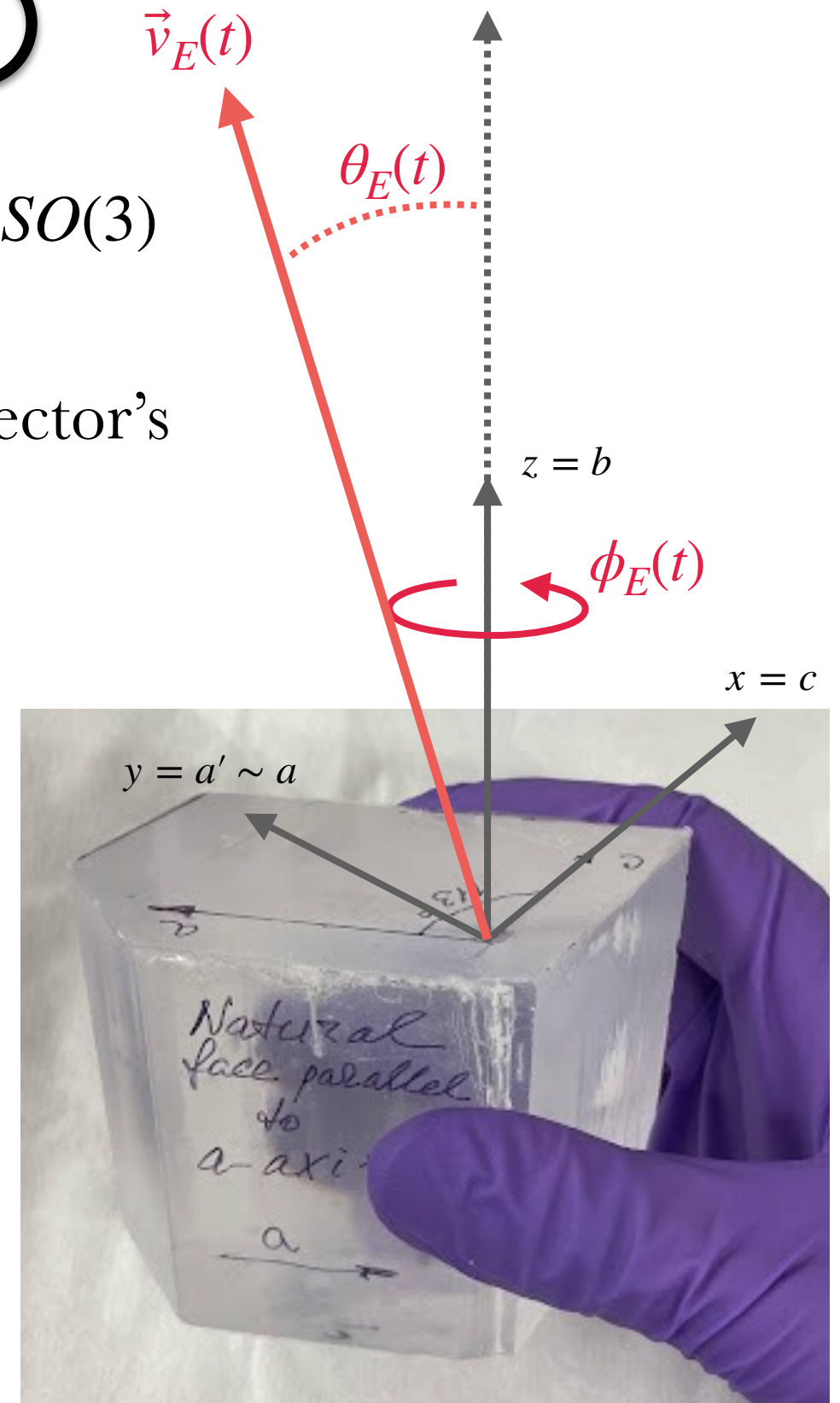
Result: Anisotropic Scattering Rate

- 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 ($SO(3) \rightarrow S^2$)
- $R(\theta_E, \phi_E)$ is measurable, and has **lots of information!**
- **Unique** to each molecule or semiconductor

For fast $R(m_\chi, F_{DM}, \mathcal{R})$ calculations, use the **partial rate matrix:**

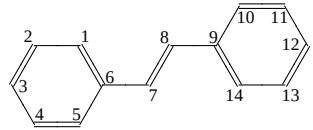
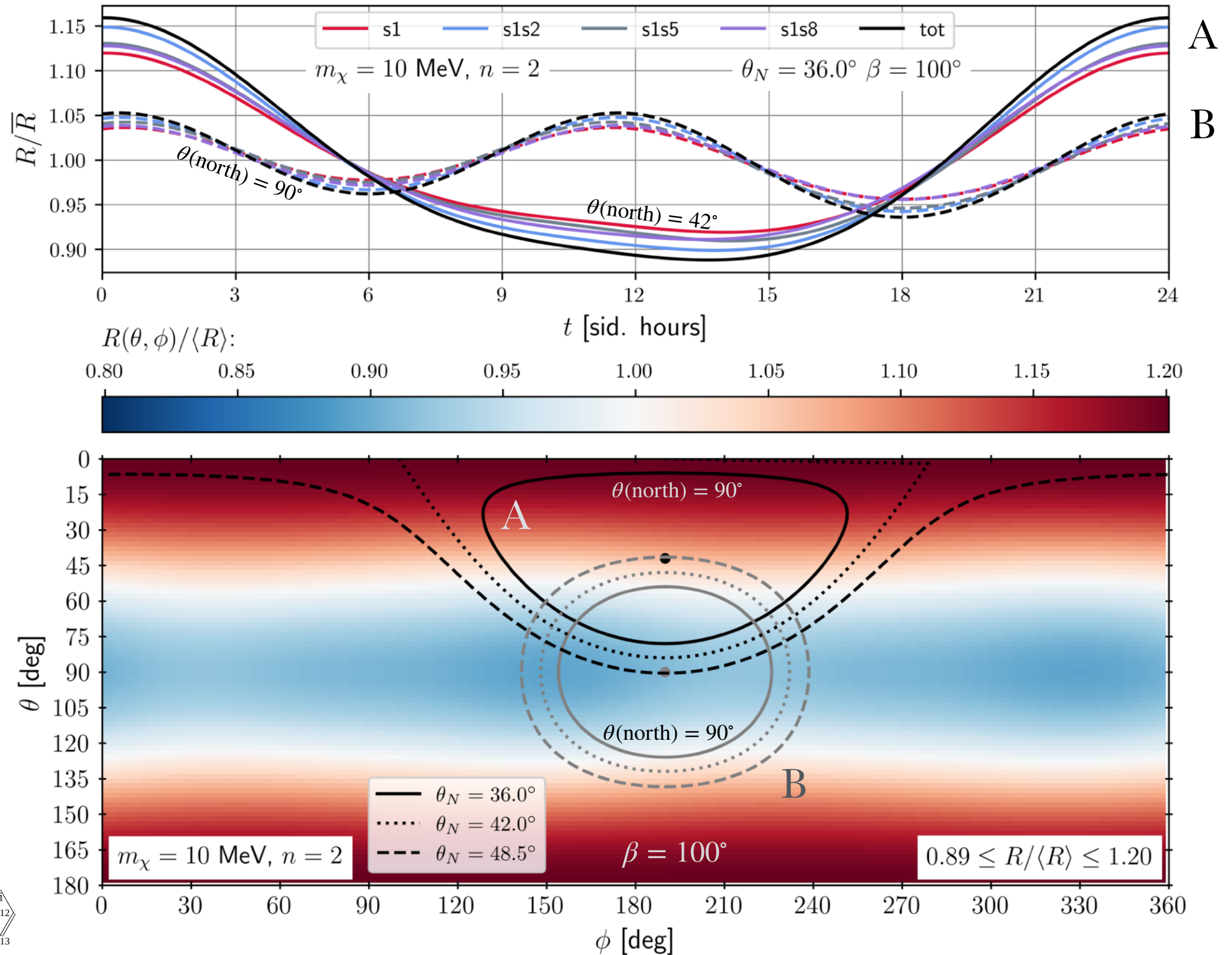
vsdm (Python): `pip install vsdm`

VectorSpaceDarkMatter (Julia)

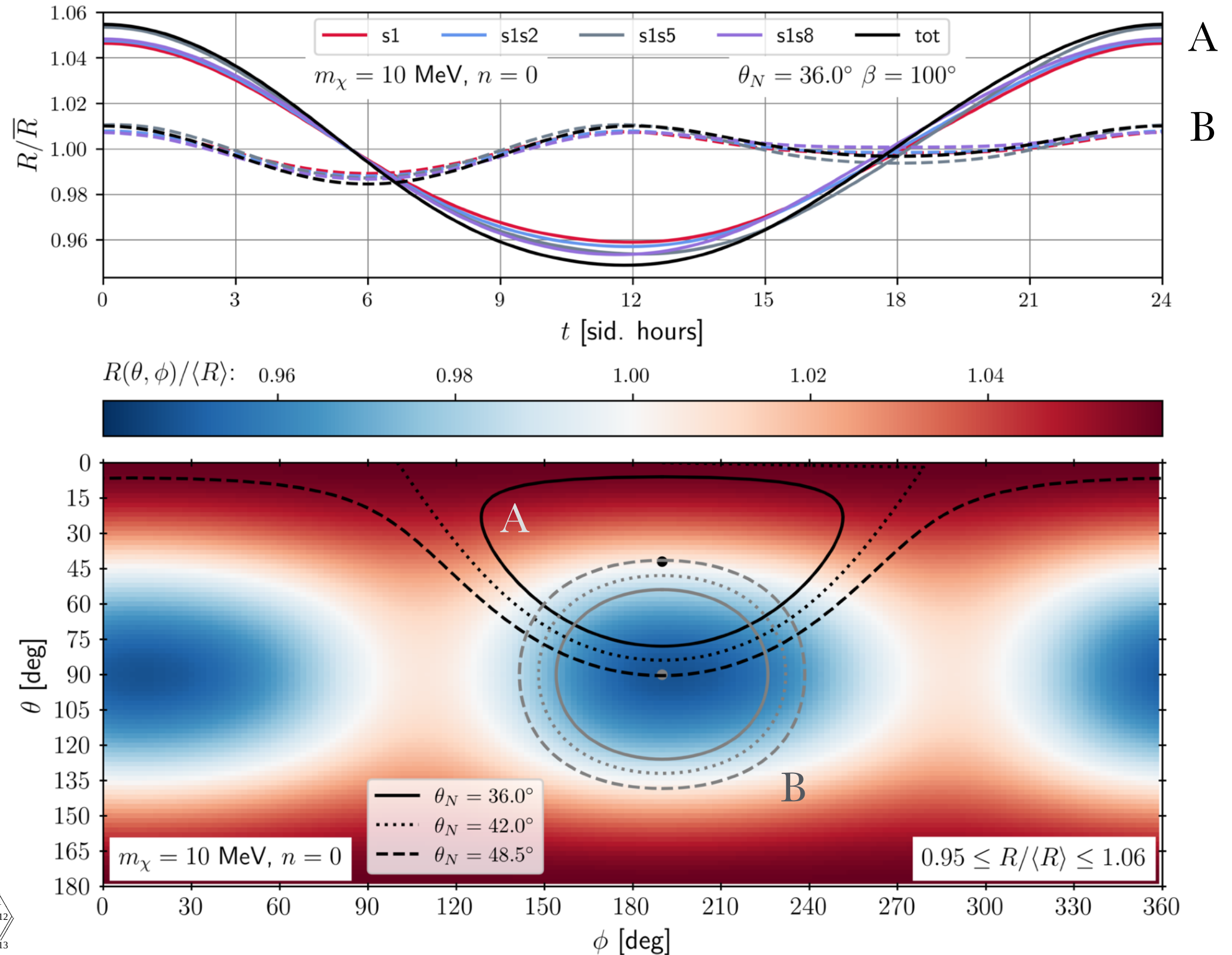


BL and Aria Radick, 2502.17547

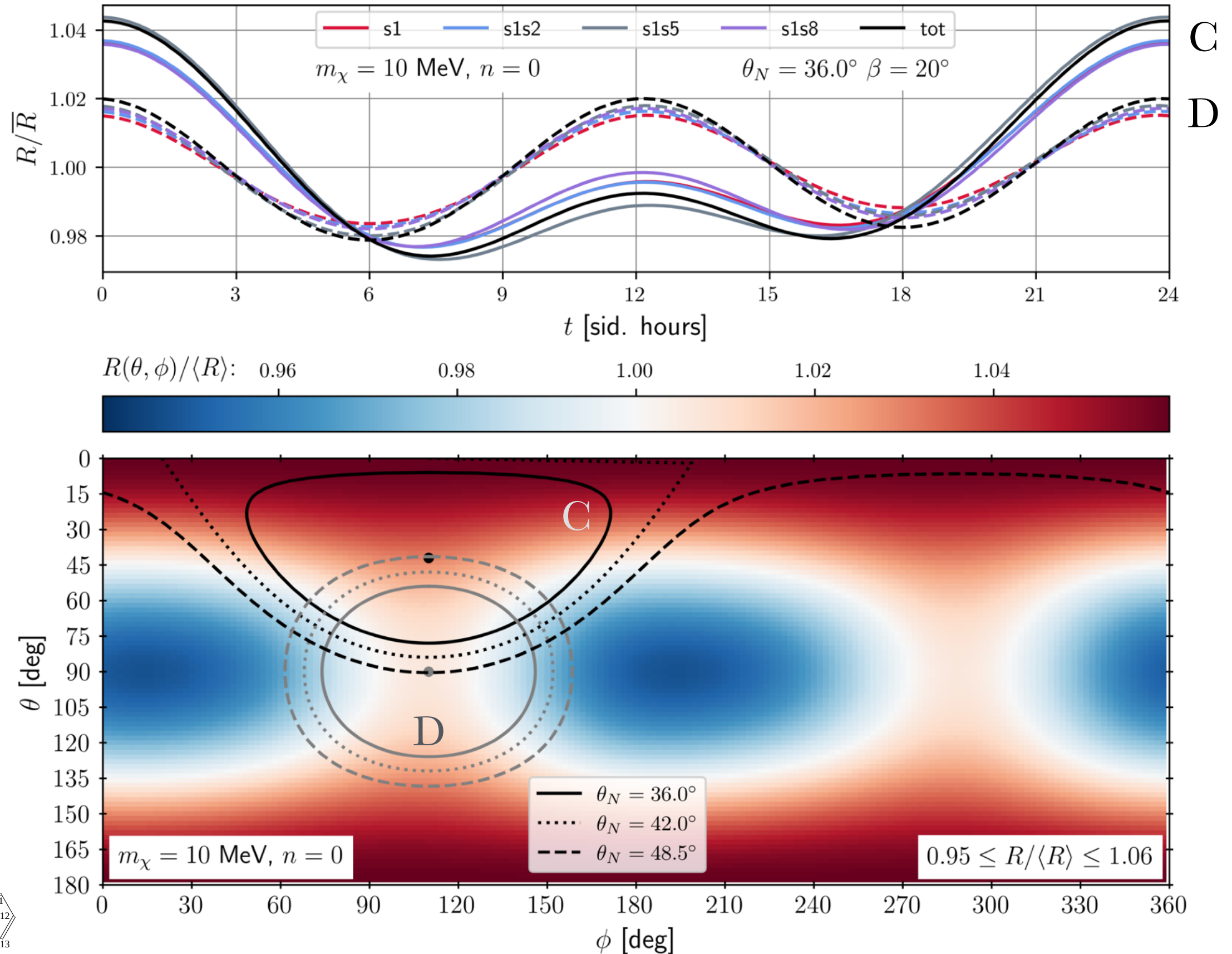
Model 1: 10 MeV DM with **light mediator** (Orientations A,B)



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



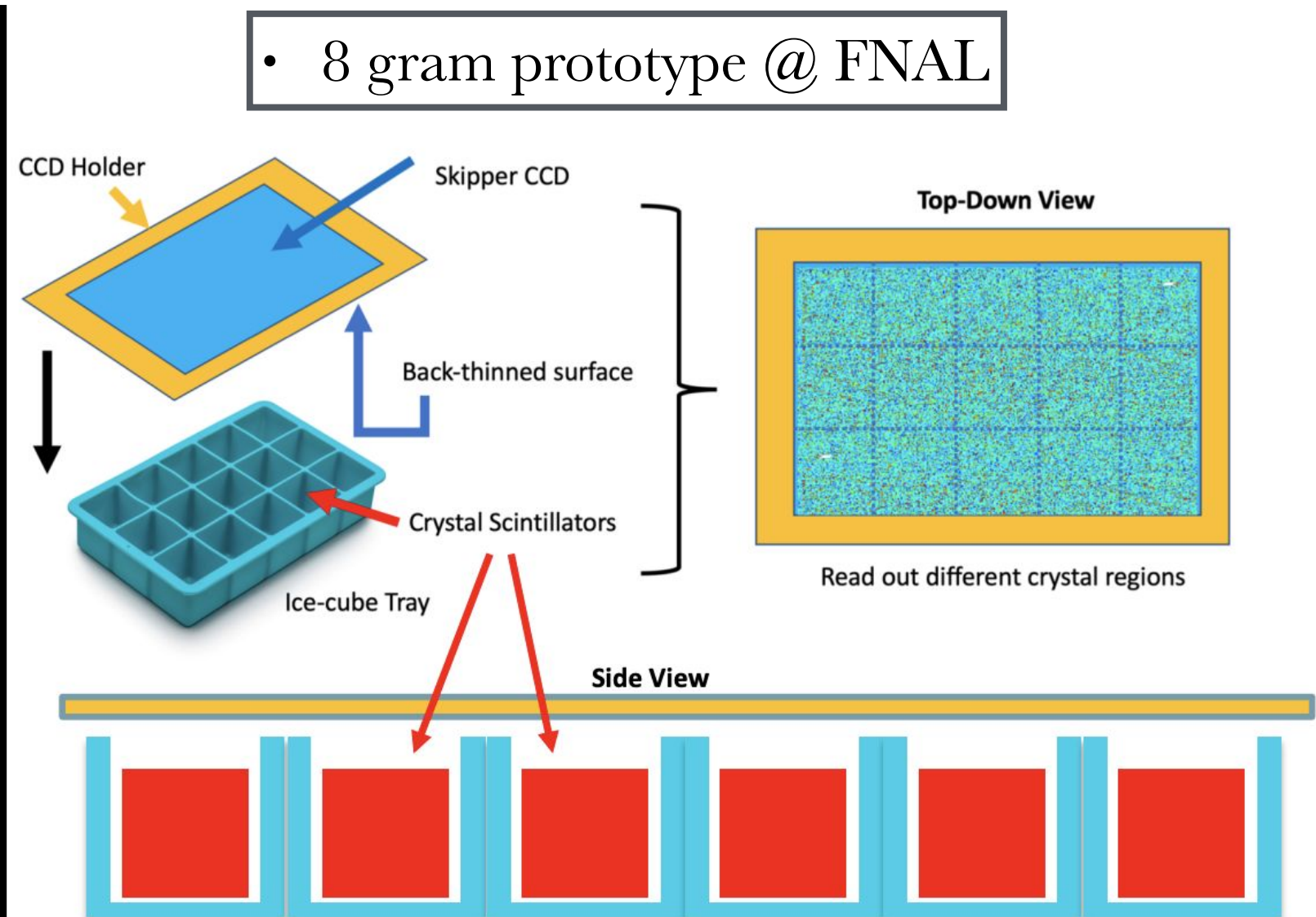
Model 2: 10 MeV DM with **heavy mediator** (Orientations C,D)



Theory-Experiment-Chemistry Collaboration

1. To design, build, and operate a **prototype DM experiment** with crystalline trans-stilbene, using Skipper-CCDs to read out the single photon fluorescence
2. To identify the next generation of **anisotropic target materials**

- Penn State: BL, Carlos Blanco, **Max Smart (Middlebury)**
- Fermilab: Dan Baxter
- U. Chicago: Brandon Roach, **Abby Williams**, Alex Drlica-Wagner
- MIT Chemistry: Danna Freedman, **Dane Johnson**
- MIT Physics: Lindley Winslow, **Nora Hoch**
- U. Toronto: Miriam Diamond, Yoni Kahn, **Martha Yousif**
- UIUC: Peter Abbamonte



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

Design: t-stilbene with Skipper CCDs



- 2026: Operate at surface, then MINOS, with 8g trans-stilbene
- Next Step: radio-purified ~ 1 kg sample for SNOLAB

(More!) 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:

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

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

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

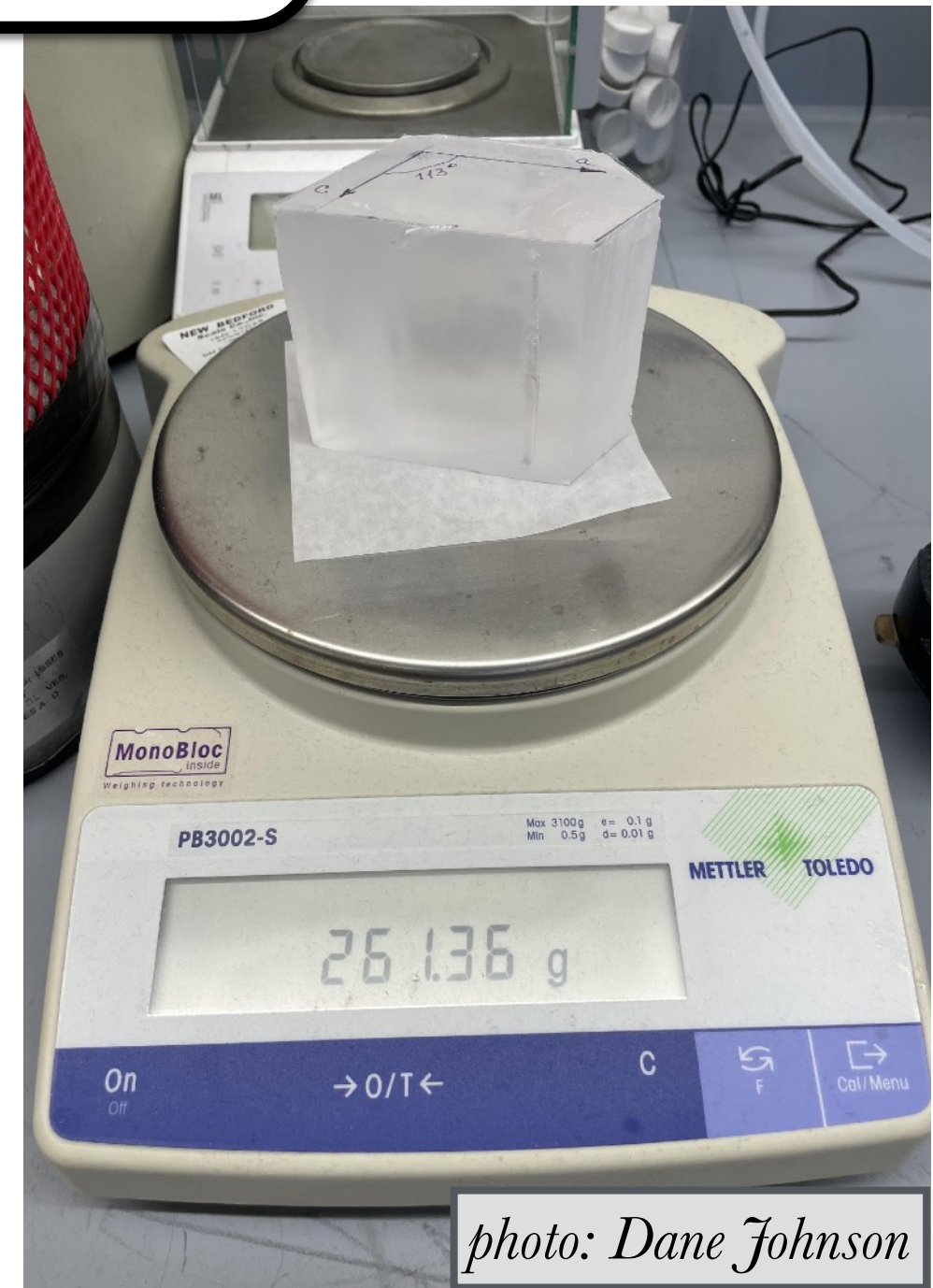


photo: Dane Johnson

Anisotropic Materials

Proposed detector targets include...

- **2d targets:** e.g. graphene
- **Polar semiconductors:**
e.g. Al_2O_3 , SiC , $\text{Eu}_5\text{In}_2\text{Sb}_6$
(SPLENDOR)
- **Dirac materials:** e.g. ZrTe_5
- **Crystalline scintillators:**
e.g. trans-stilbene, many others
- **Migdal effect in molecules:**
DM–nuclear scattering in CO , N_2

$$N_\sigma \sim f_{\text{RMS}} \sqrt{T_{\text{exp}} \langle R(t) \rangle}$$

- How anisotropic?
(include backgrounds!)
- How many 1 kg · year?

Y. Hochberg, Y. Kahn, M. Lisanti, C. G. Tully and K. M. Zurek, *Directional detection of dark matter with two-dimensional targets*, Phys. Lett. B **772**, 239 (2017), doi:[10.1016/j.physletb.2017.06.051](https://doi.org/10.1016/j.physletb.2017.06.051), [1606.08849](https://arxiv.org/abs/1606.08849).

R. Budnik, O. Chesnovsky, O. Slone and T. Volansky, *Direct Detection of Light Dark Matter and Solar Neutrinos via Color Center Production in Crystals*, Phys. Lett. B **782**, 242 (2018), doi:[10.1016/j.physletb.2018.04.063](https://doi.org/10.1016/j.physletb.2018.04.063), [1705.03016](https://arxiv.org/abs/1705.03016).

Y. Hochberg, Y. Kahn, M. Lisanti, K. M. Zurek, A. G. Grushin, R. Ilan, S. M. Griffin, Z.-F. Liu, S. F. Weber and J. B. Neaton, *Detection of sub-MeV Dark Matter with Three-Dimensional Dirac Materials*, Phys. Rev. D **97**(1), 015004 (2018), doi:[10.1103/PhysRevD.97.015004](https://doi.org/10.1103/PhysRevD.97.015004), [1708.08929](https://arxiv.org/abs/1708.08929).

S. Griffin, S. Knapen, T. Lin and K. M. Zurek, *Directional Detection of Light Dark Matter with Polar Materials*, Phys. Rev. D **98**(11), 115034 (2018), doi:[10.1103/PhysRevD.98.115034](https://doi.org/10.1103/PhysRevD.98.115034), [1807.10291](https://arxiv.org/abs/1807.10291).

A. Coskuner, A. Mitridate, A. Olivares and K. M. Zurek, *Directional Dark Matter Detection in Anisotropic Dirac Materials*, Phys. Rev. D **103**(1), 016006 (2021), doi:[10.1103/PhysRevD.103.016006](https://doi.org/10.1103/PhysRevD.103.016006), [1909.09170](https://arxiv.org/abs/1909.09170).

R. M. Geilhufe, F. Kahlhoefer and M. W. Winkler, *Dirac Materials for Sub-MeV Dark Matter Detection: New Targets and Improved Formalism*, Phys. Rev. D **101**(5), 055005 (2020), doi:[10.1103/PhysRevD.101.055005](https://doi.org/10.1103/PhysRevD.101.055005), [1910.02091](https://arxiv.org/abs/1910.02091).

S. M. Griffin, Y. Hochberg, K. Inzani, N. Kurinsky, T. Lin and T. Chin, *Silicon carbide detectors for sub-GeV dark matter*, Phys. Rev. D **103**(7), 075002 (2021), doi:[10.1103/PhysRevD.103.075002](https://doi.org/10.1103/PhysRevD.103.075002), [2008.08560](https://arxiv.org/abs/2008.08560).

C. Blanco, Y. Kahn, B. Lillard and S. D. McDermott, *Dark Matter Daily Modulation With Anisotropic Organic Crystals*, Phys. Rev. D **104**, 036011 (2021), doi:[10.1103/PhysRevD.104.036011](https://doi.org/10.1103/PhysRevD.104.036011), [2103.08601](https://arxiv.org/abs/2103.08601).

A. Coskuner, T. Trickle, Z. Zhang and K. M. Zurek, *Directional detectability of dark matter with single phonon excitations: Target comparison*, Phys. Rev. D **105**(1), 015010 (2022), doi:[10.1103/PhysRevD.105.015010](https://doi.org/10.1103/PhysRevD.105.015010), [2102.09567](https://arxiv.org/abs/2102.09567).

C. Blanco, I. Harris, Y. Kahn, B. Lillard and J. Pérez-Ríos, *Molecular Migdal effect*, Phys. Rev. D **106**(11), 115015 (2022), doi:[10.1103/PhysRevD.106.115015](https://doi.org/10.1103/PhysRevD.106.115015), [2208.09002](https://arxiv.org/abs/2208.09002).

C. Boyd, Y. Hochberg, Y. Kahn, E. D. Kramer, N. Kurinsky, B. V. Lehmann and T. C. Yu, *Directional detection of dark matter with anisotropic response functions* (2022), [2212.04505](https://arxiv.org/abs/2212.04505).

...and more. What else is possible?

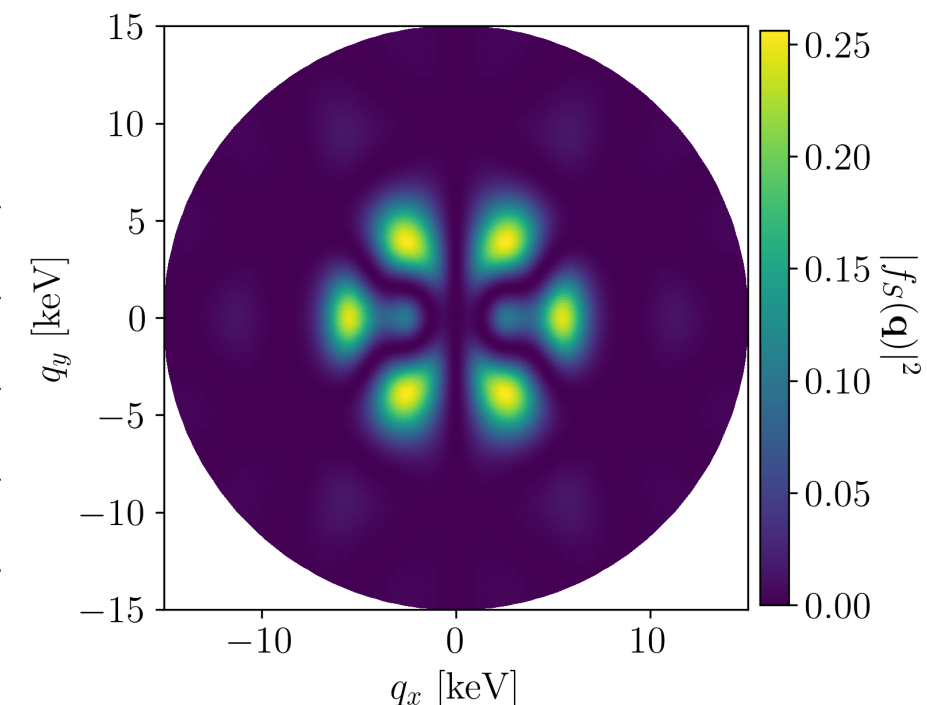
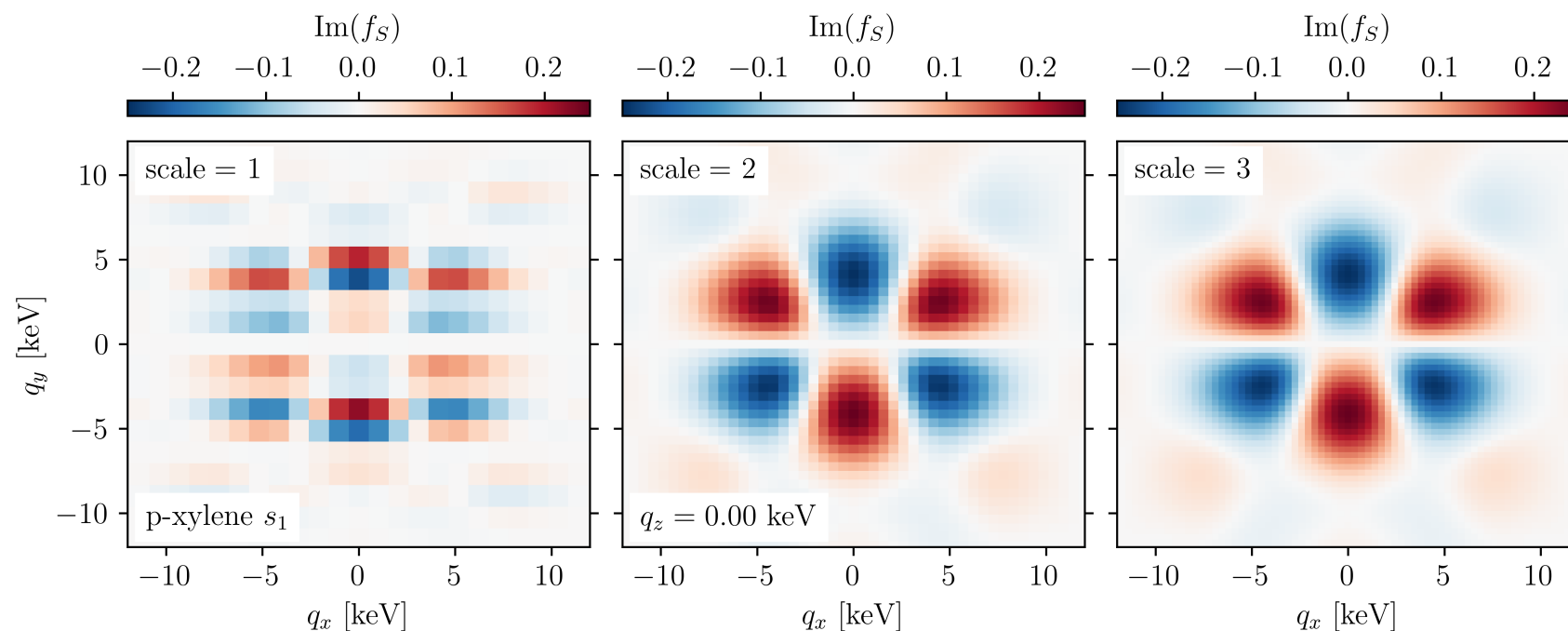
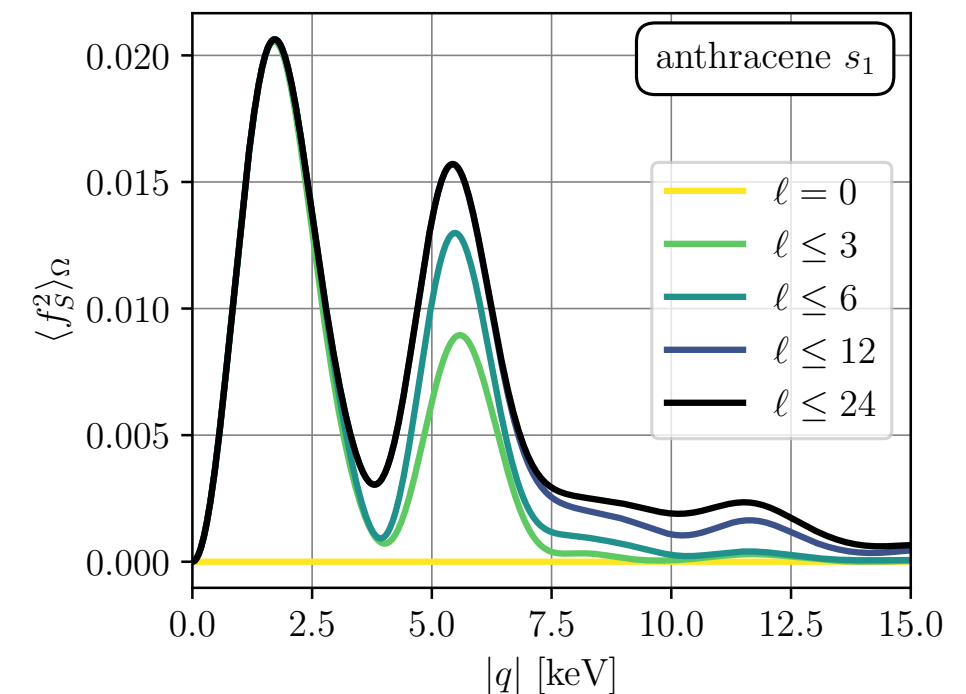
More Anisotropic Detector Targets **with SCarFFF**

with Carlos Blanco and Jack Shergold (arXiv:2512.18010)

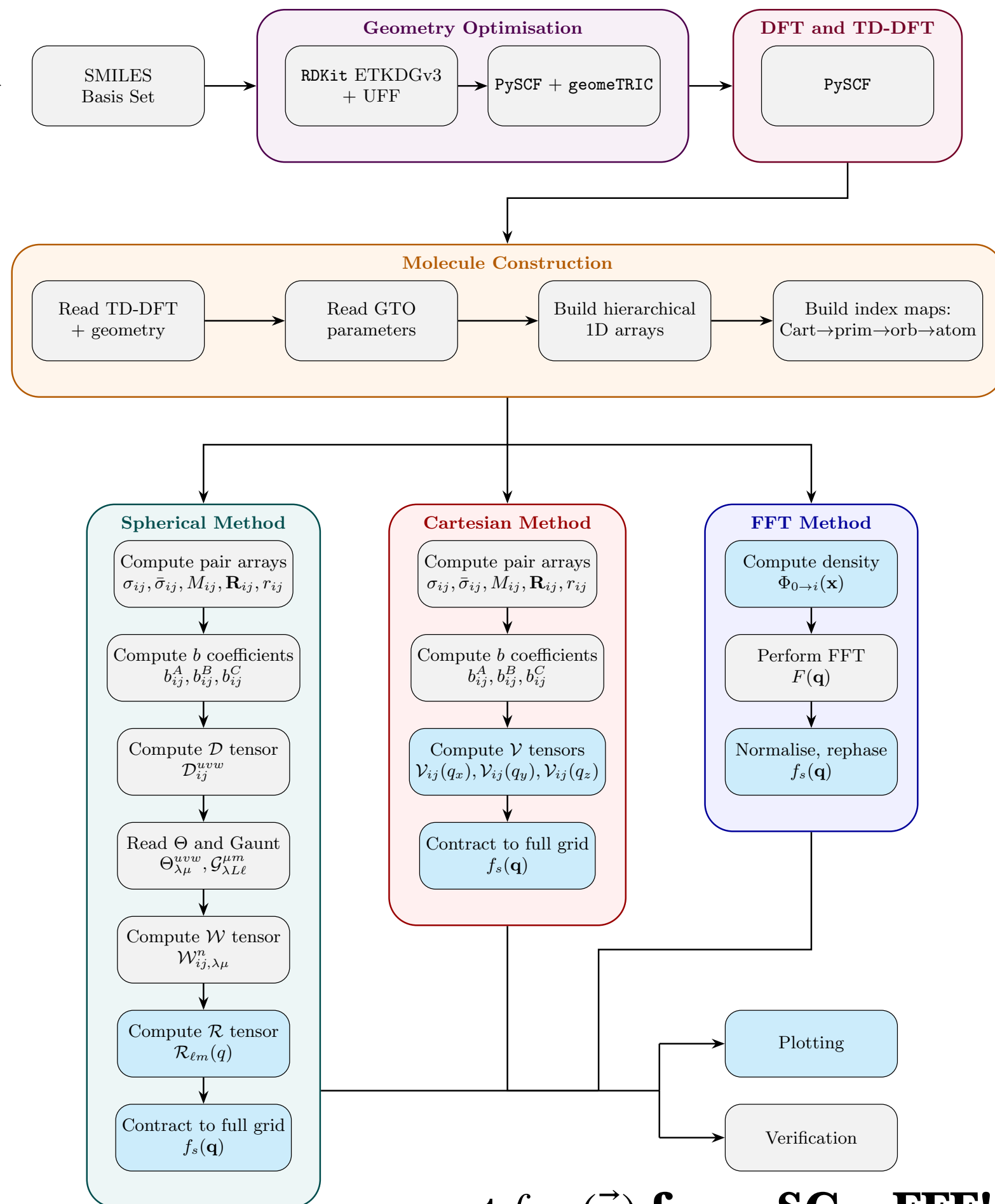
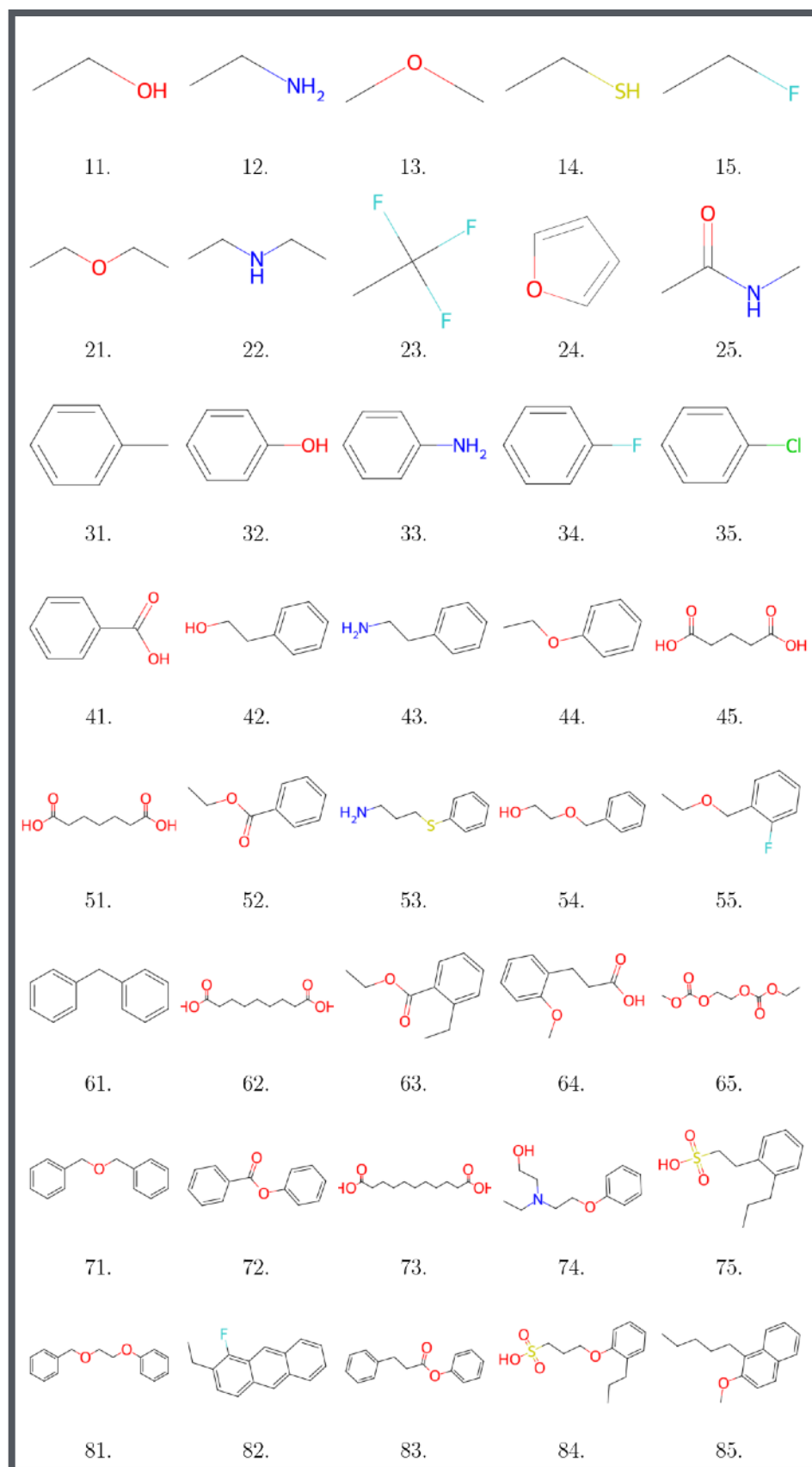
SCarFFF: our **fast** new molecular physics code

***S**calar, **C**artesian, and **F**ourier **F**orm **F**actors*

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



• **pick a molecule...** →



→ **get $f_{g \rightarrow s}(\vec{q})$ from SCarFFF!**

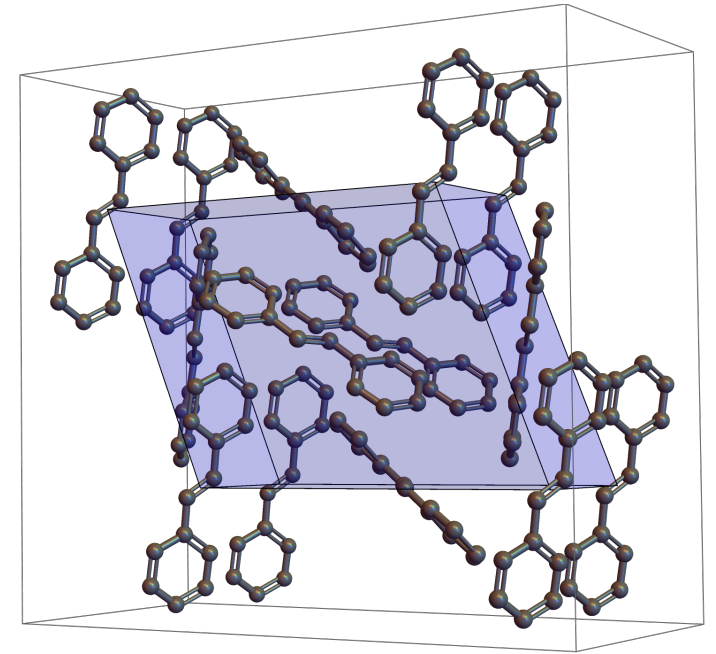
Design Criteria: Crystal Symmetry Groups

with Jack Shergold and Juri Smirnov (arXiv:2607.12036) *see also* arXiv:2310.01480

- The **partial rate matrix** $K_{mm'}^{(\ell)}[g_\chi(\vec{v}), m_\chi, f_s^2(\vec{q}), \dots]$ contains all of the observable information about the DM scattering rate:

$$R(t) = N_{\text{cell}} \rho_\chi \bar{\sigma}_e \sum_{\ell} \sum_{m, m'} G_{mm'}^{(\ell)}(\mathcal{D}(t)) K_{\text{uc}, mm'}^{(\ell)},$$

where $\mathcal{D}(t) \in SO(3)$ is the detector orientation, and $G^{(\ell)}$ is a $(2\ell + 1) \times (2\ell + 1)$ rotation matrix.



Material Response

$$|f_s(\mathbf{q})|^2 = \sum_{\ell, m} f_{s, \ell m}^2(q) Y_{\ell m}(\hat{q}),$$

DM Velocity Distribution

$$g_\chi(\mathbf{v}) = \sum_{\ell, m} g_{\ell m}(v) Y_{\ell m}(\hat{v}),$$

Partial Rate Matrix (*Spin-Independent*)

$$K_{mm'}^{(\ell)} = \int_0^\infty q dq \int_{v_{\min}(q)}^{v_{\max}} v dv P_\ell\left(\frac{v_{\min}(q)}{v}\right) g_{\ell m}(v) \frac{F_{\text{DM}}^2(q, v)}{2\mu_\chi^2 m_\chi} f_{\ell m'}^2(q)$$

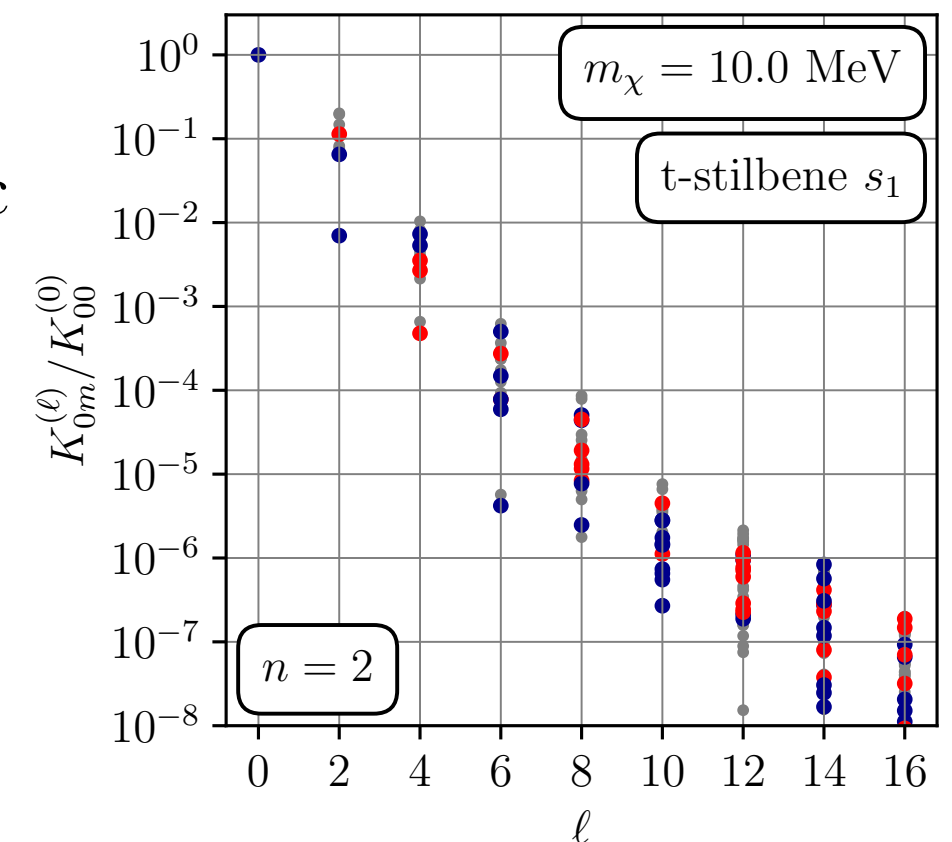
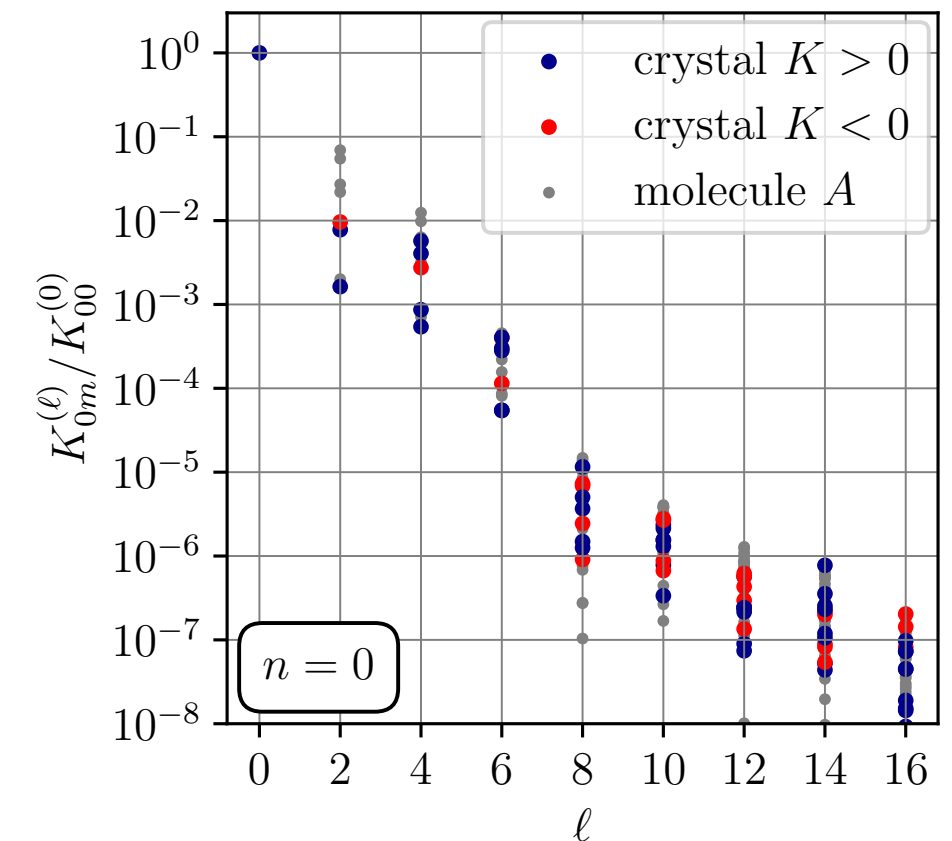
Design Criteria: Crystal Symmetry Groups

with Jack Shergold and Juri Smirnov (arXiv:2607.12036)

$$R(t) = N_{\text{cell}} \rho_{\chi} \bar{\sigma}_e \sum_{\ell} \sum_{m, m'} G_{mm'}^{(\ell)}(\mathcal{D}(t)) K_{\text{uc}, mm'}^{(\ell)},$$

In the Standard Halo Model $g_{\chi}(\vec{v})$, higher harmonic modes ($\ell > 2$) are **exponentially suppressed**:

- $\ell = 0$: isotropic average rate, $\langle R \rangle$
- $\ell = 2$: **leading anisotropy**: $R(t), f_{\text{RMS}}, \dots$
- $\ell \geq 4$: $\mathcal{O}(1\%)$ corrections to $R(t)$



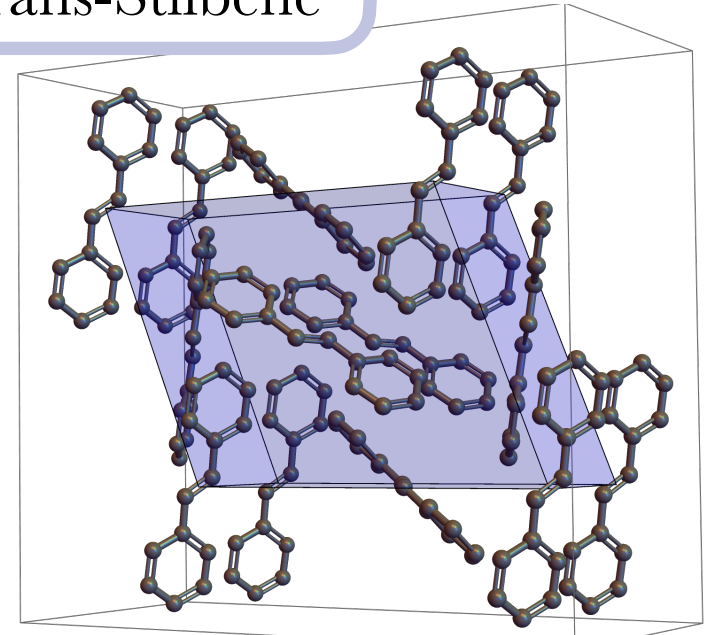
Design Criteria: Quadrupole Survival Classes

with Jack Shergold and Juri Smirnov (arXiv:2607.12036)

- How many $\ell = 2$ modes **can** the material response function have?
 $Q_k : k = 0, 1, 2, 3, 5$.

Survival class	Laue group	Point groups	Space group numbers	$\xi_{\infty}^{(\mathcal{L})}$	CSD frequency
Q_5	<i>Triclinic</i> $\bar{1} (C_i)$	1 (C_1), $\bar{1} (C_i)$	1–2	1	26.26%
Q_3	<i>Monoclinic</i> $2/m (C_{2h})$	2 (C_2), $m (C_s)$, $2/m (C_{2h})$	3–15	1/2	51.32%
Q_2	<i>Orthorhombic</i> $mmm (D_{2h})$	222 (D_2), $mm2 (C_{2v})$, $mmm (D_{2h})$	16–74	1/4	16.90%
Q_1	<i>Tetragonal</i> $4/m (C_{4h})$	4 (C_4), $\bar{4} (S_4)$, $4/m (C_{4h})$	75–88	1/4	1.05%
	<i>Tetragonal</i> $4/mmm (D_{4h})$	422 (D_4), $4mm (C_{4v})$, $\bar{4}2m (D_{2d})$, $4/mmm (D_{4h})$	89–142	1/8	1.17%
	<i>Trigonal</i> $\bar{3} (C_{3i})$	3 (C_3), $\bar{3} (C_{3i})$	143–148	1/3	1.24%
	<i>Trigonal</i> $\bar{3}m (D_{3d})$	32 (D_3), $3m (C_{3v})$, $\bar{3}m (D_{3d})$	149–167	1/6	0.79%
	<i>Hexagonal</i> $6/m (C_{6h})$	6 (C_6), $\bar{6} (C_{3h})$, $6/m (C_{6h})$	168–176	1/6	0.35%
	<i>Hexagonal</i> $6/mmm (D_{6h})$	622 (D_6), $6mm (C_{6v})$, $\bar{6}m2 (D_{3h})$, $6/mmm (D_{6h})$	177–194	1/12	0.23%
Q_0	<i>Cubic</i> $m\bar{3} (T_h)$	23 (T), $m\bar{3} (T_h)$	195–206	1/12	0.26%
	<i>Cubic</i> $m\bar{3}m (O_h)$	432 (O), $\bar{4}3m (T_d)$, $m\bar{3}m (O_h)$	207–230	1/24	0.42%

trans-Stilbene



230 space groups reduce to **five** Q_k classes, ranked by surviving anisotropy

GaAs

Q_0 : no $\ell = 2$

Si, Ge

cf. 2411.03433

Pipeline for Discovery

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

2. Quantum Chemistry Calculation: **SCarFFF**

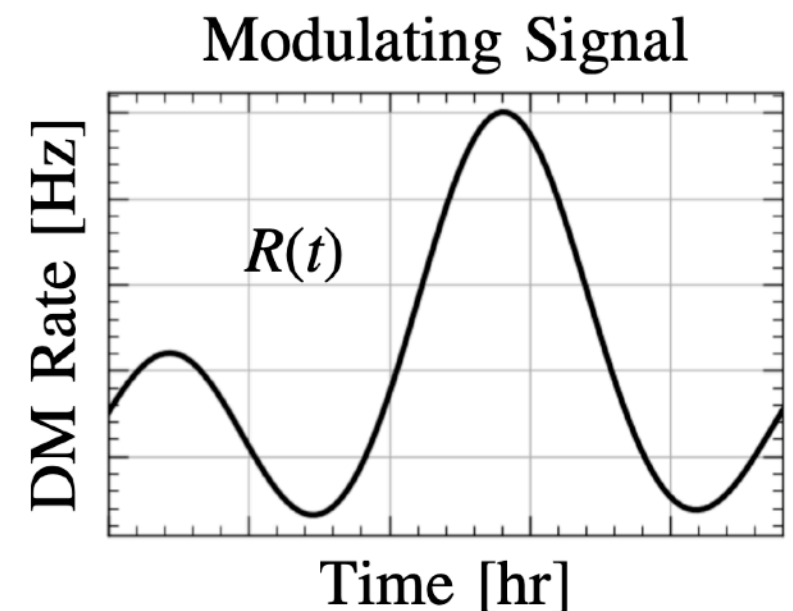
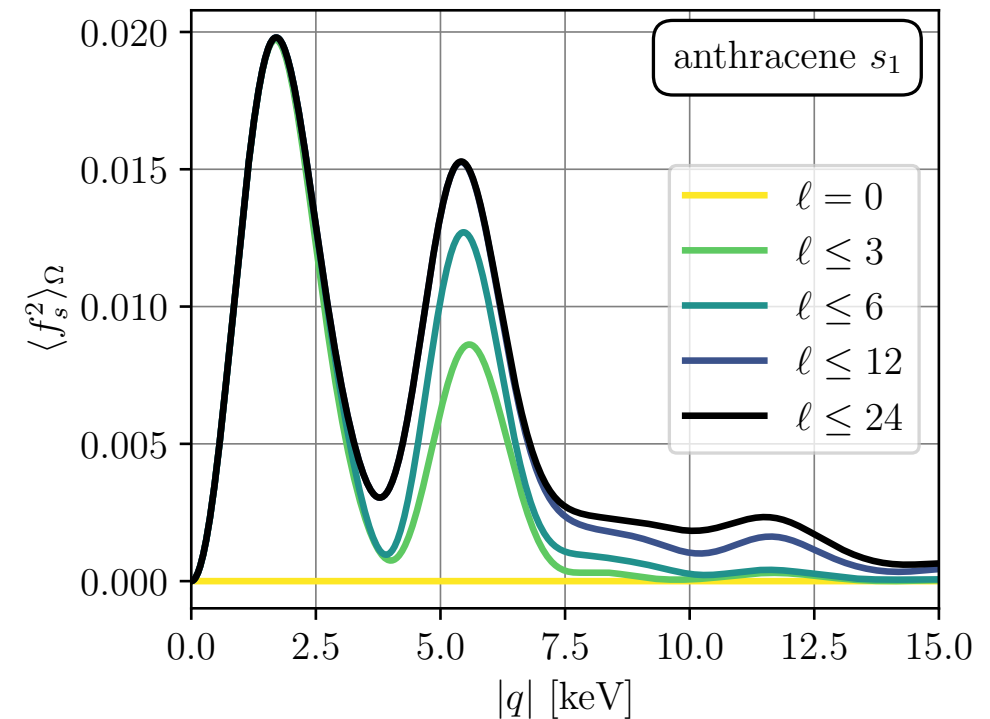
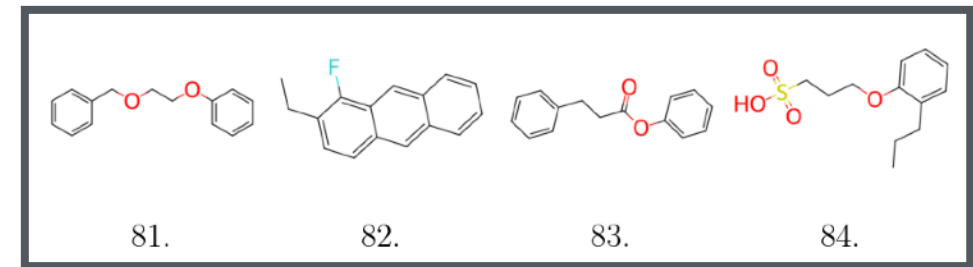
3. Determine the crystal geometry

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



Design Criteria: **Spin Dependence**

with Pierce Giffin, Pankaj Munbodh, and Tien-Tien Yu (arXiv:2511.10764)

Scattering Cross Section

Spin-Independent DM- e^- :
e.g. scalar mediator $\rightarrow B_1(\vec{q})$

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

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

→ **coming soon to SCarFFF**

Design Criteria: **Parity-Breaking Materials**

$$i\mathcal{M} = \left\langle \text{Molecule} \left| \begin{array}{c} \chi \text{---} \chi \\ \text{---} A'_\mu \text{---} \\ e^- \text{---} e^- \end{array} + \begin{array}{c} \chi \text{---} \chi \\ \text{---} \phi \text{---} \\ e^- \text{---} e^- \end{array} + \dots \right| \text{Molecule} \right\rangle$$

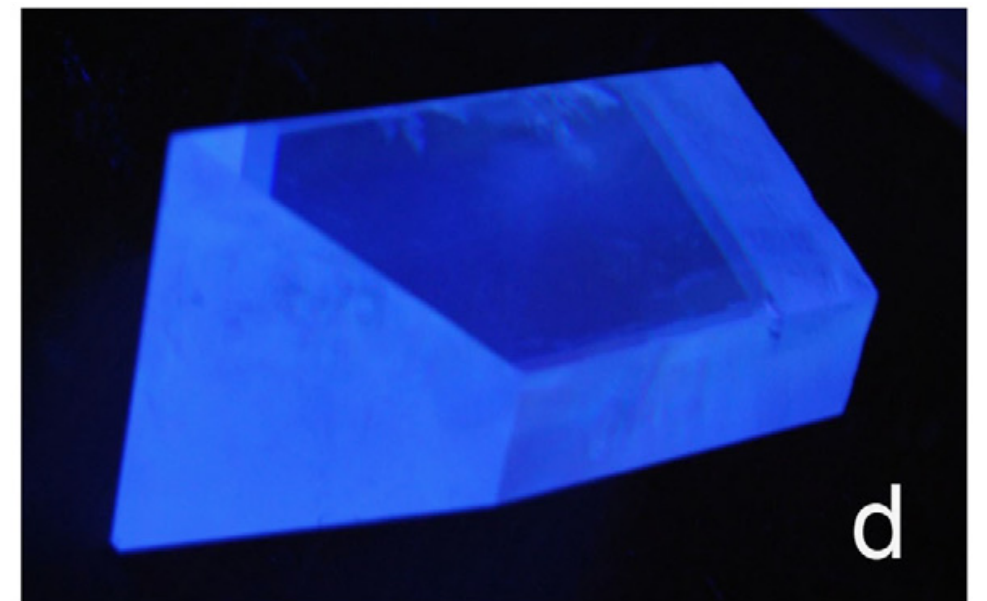
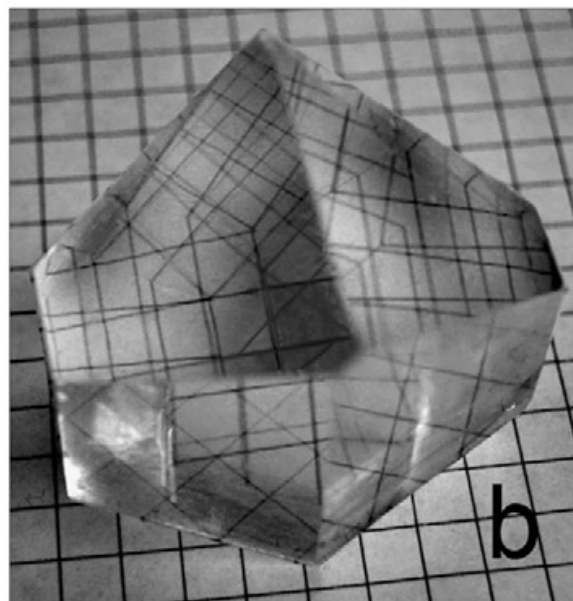
**Parity-Odd, Spin-Dependent
DM-SM interactions**

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

**Parity-Odd Material
Response Functions**

New criterion:

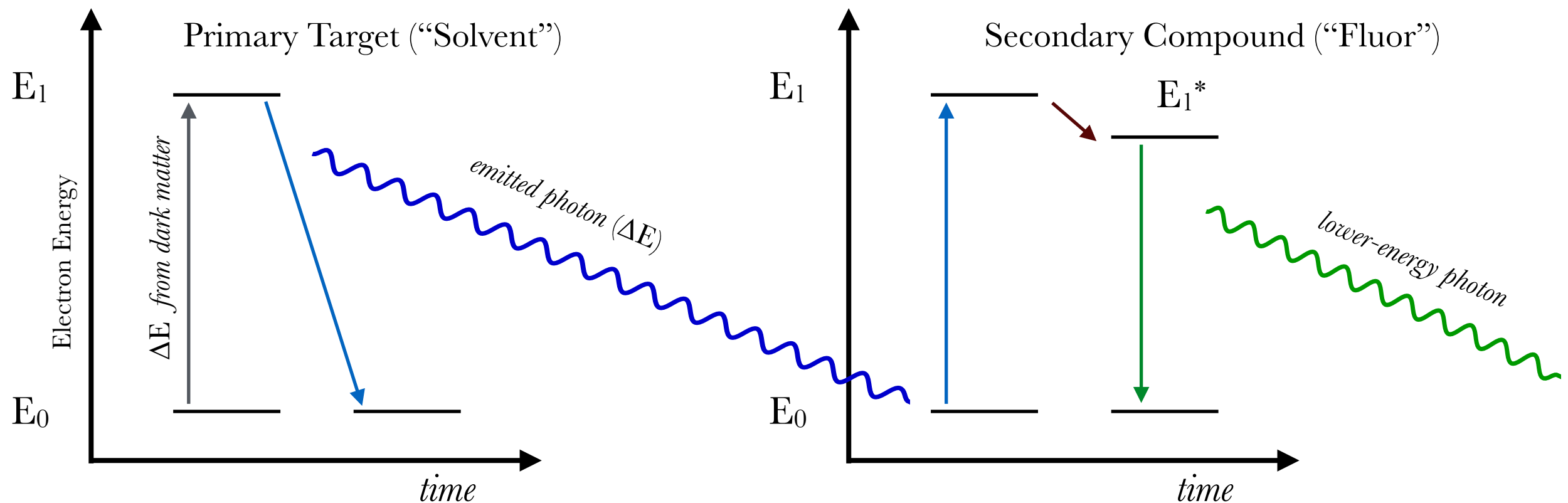
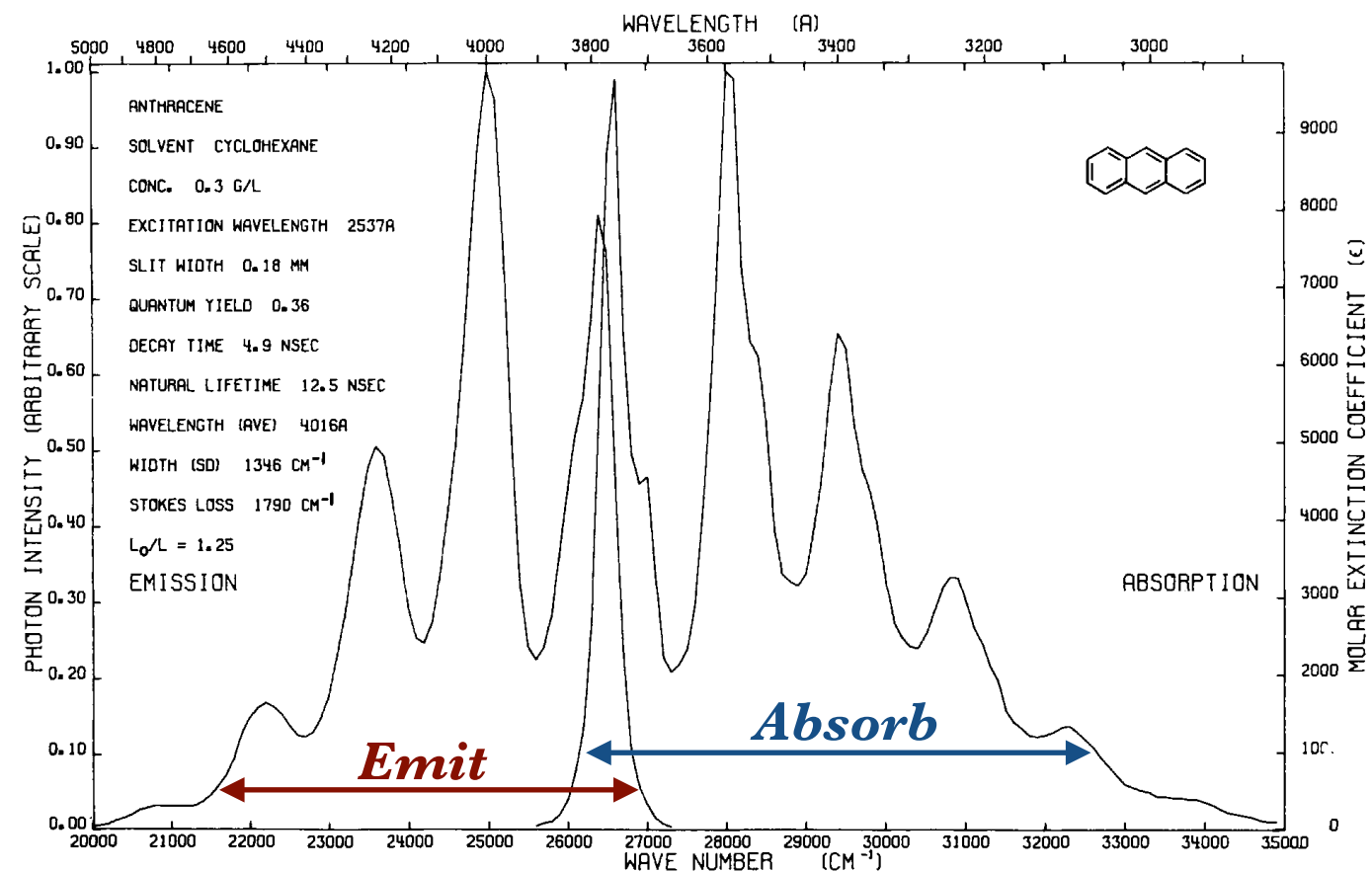
parity-violating materials to discover
parity-violating DM-SM interactions



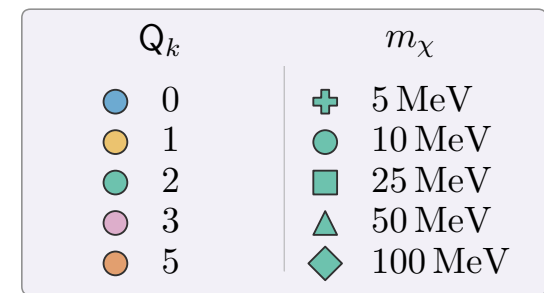
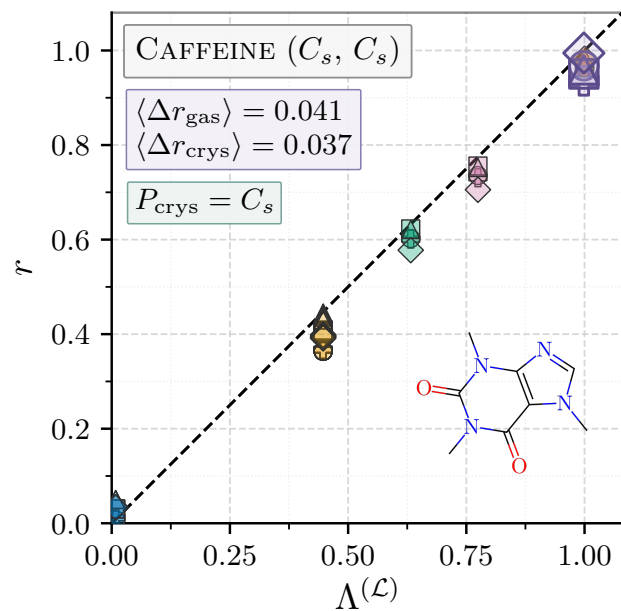
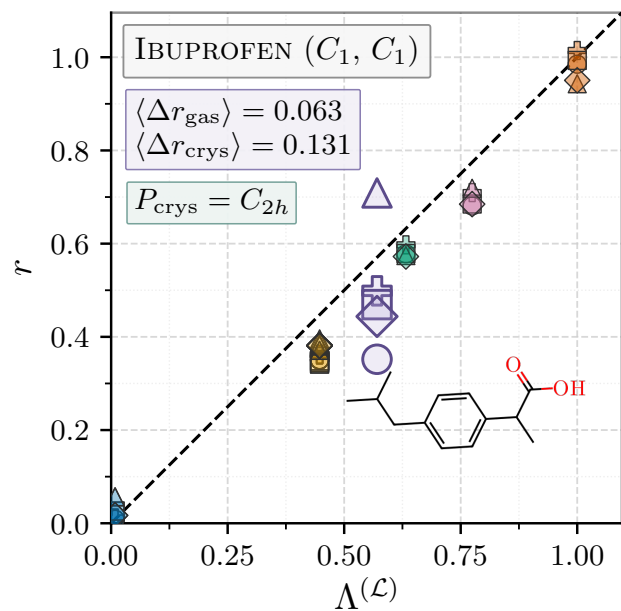
N. Zaitseva et al. / Journal of Crystal Growth 314 (2011) 163–170

Fluorescence:

An offset between the **absorption** spectrum and the **emission** spectrum reduces the frequency of the emitted photon

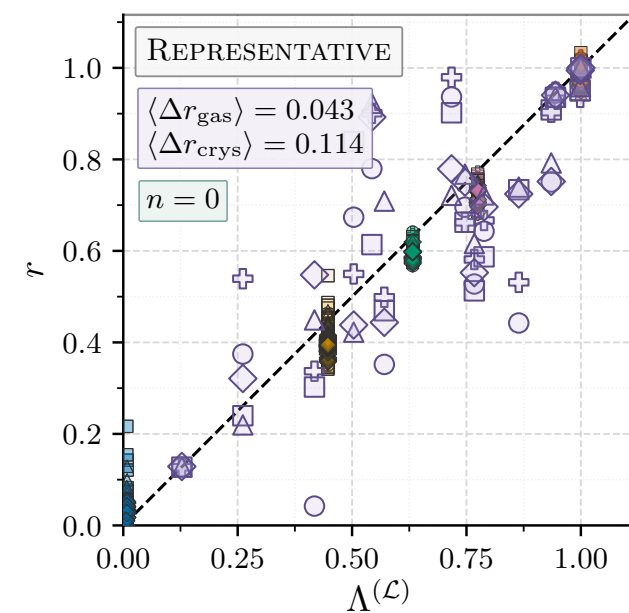
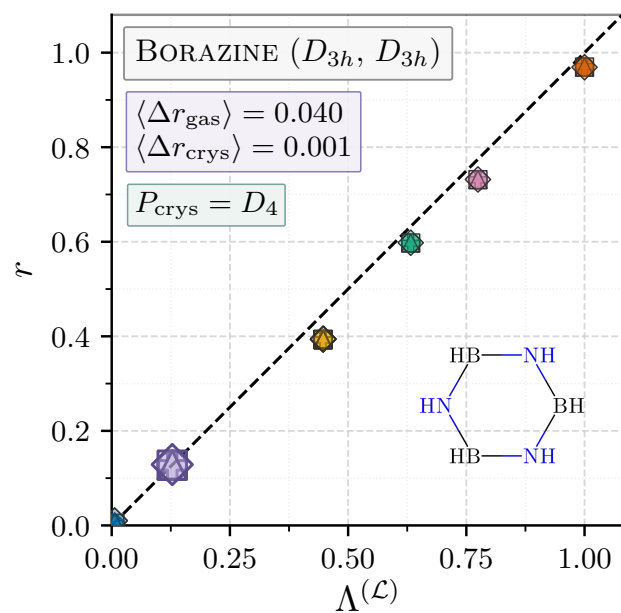
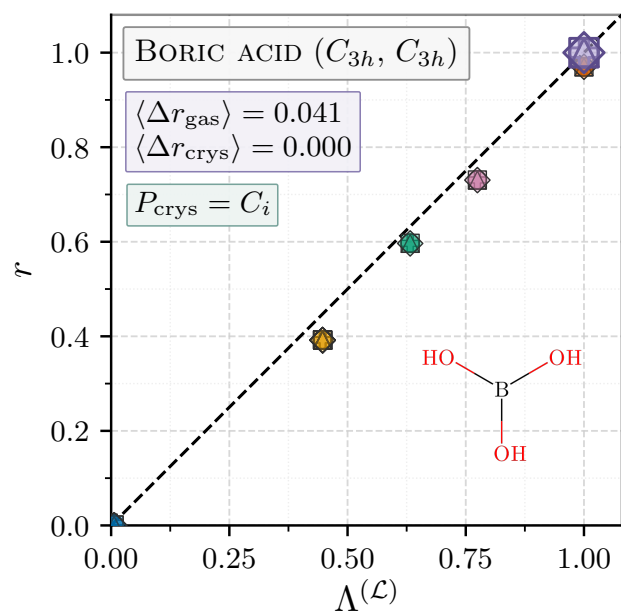
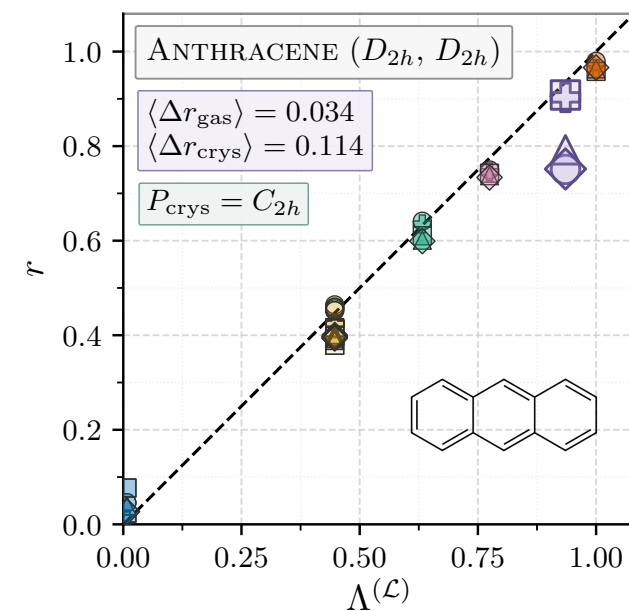
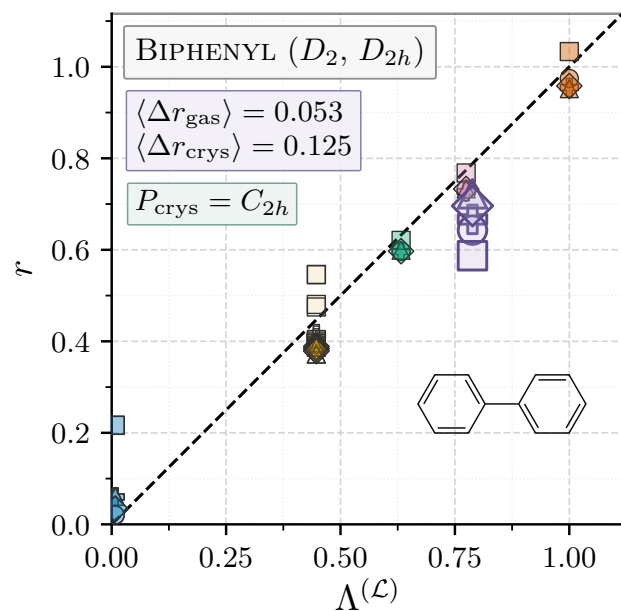
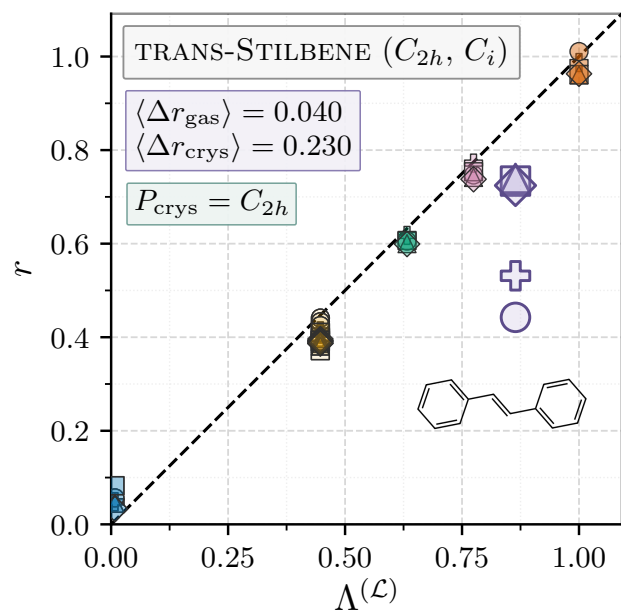


$n = 0$

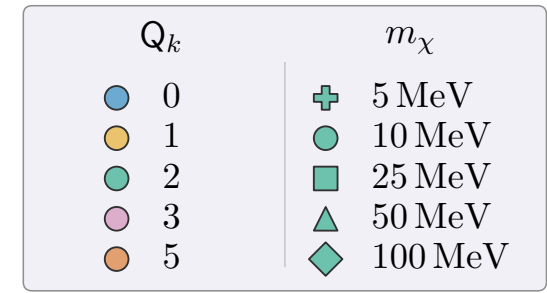
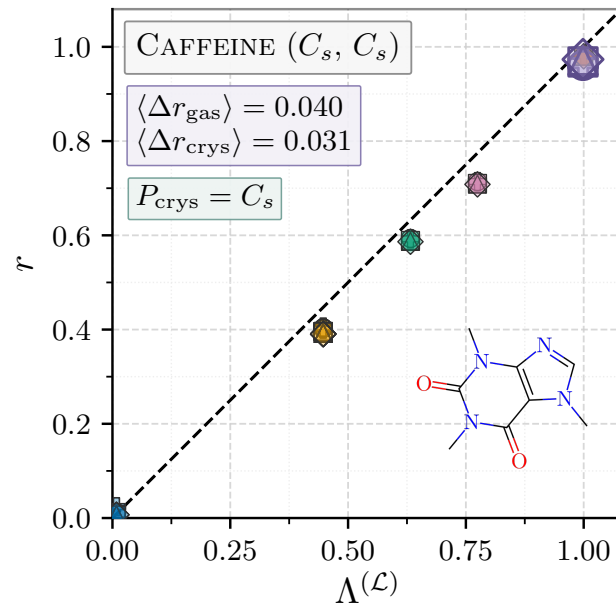
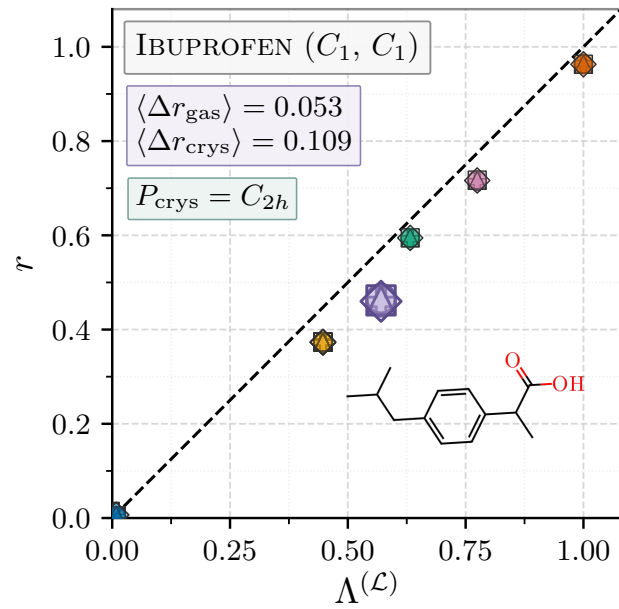


$$r_{\text{gas}} = \frac{\langle f_{\text{RMS}}(\mathcal{L}, H_{\text{gas}}, \mathcal{T}) \rangle_{\mathcal{T}, \mathcal{D}_0}}{\langle f_{\text{RMS}}(C_1, H_{\text{gas}}, \mathbb{I}_3) \rangle_{\mathcal{D}_0}}$$

$$r_{\text{crys}} = \frac{\langle f_{\text{RMS}}(\mathcal{L}, H_{\text{crys}}, \mathcal{T}_{\text{crys}}) \rangle_{\mathcal{D}_0}}{\langle f_{\text{RMS}}(C_1, H_{\text{crys}}, \mathbb{I}_3) \rangle_{\mathcal{D}_0}}$$

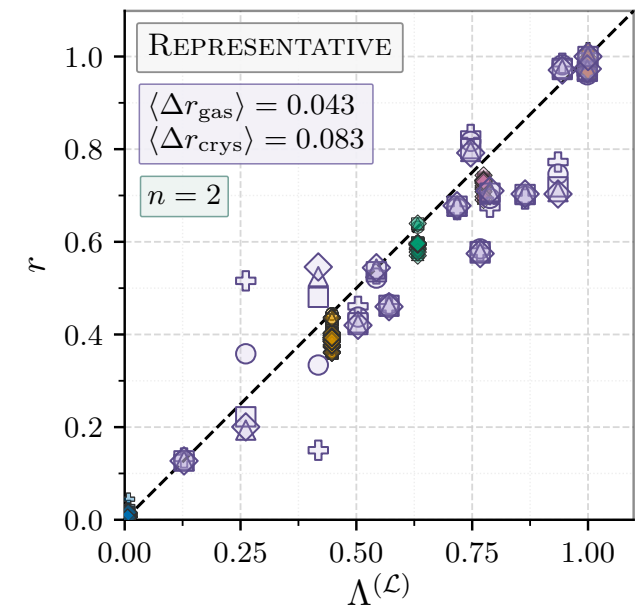
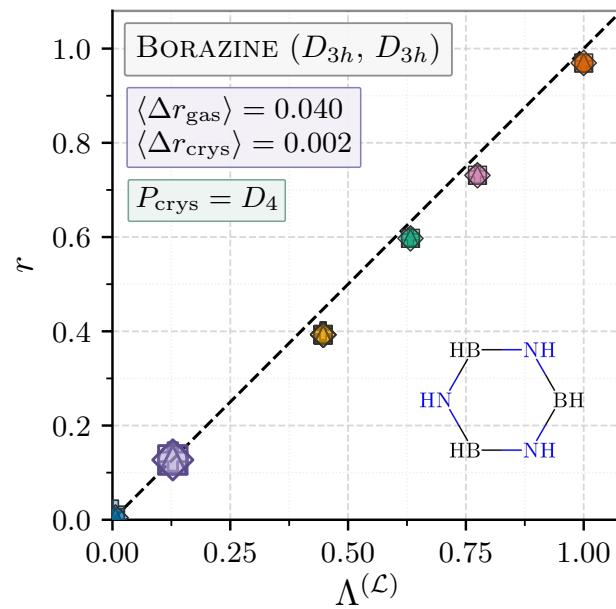
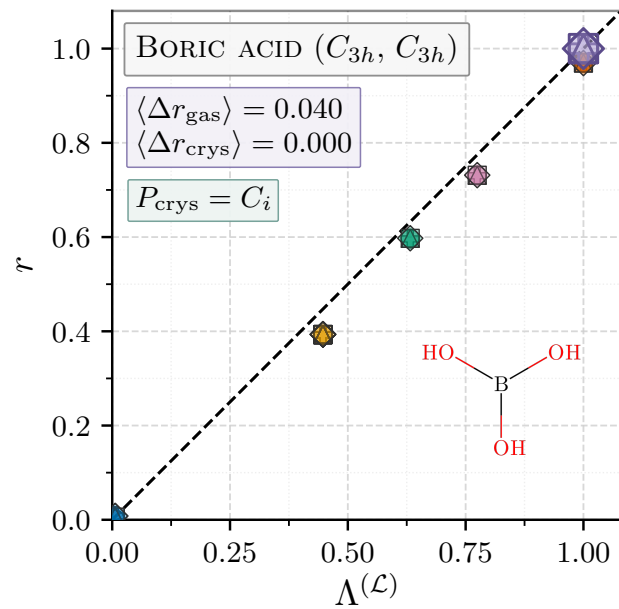
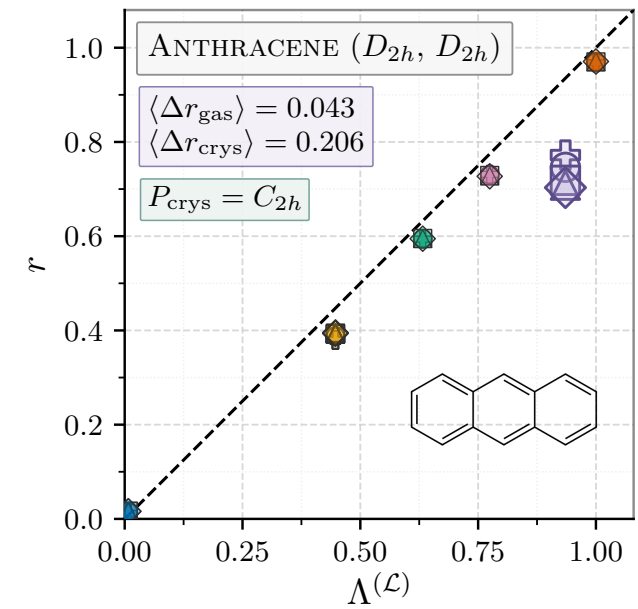
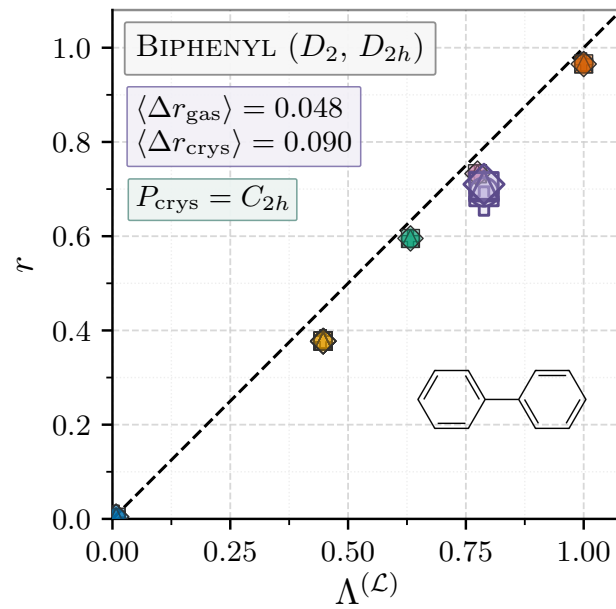
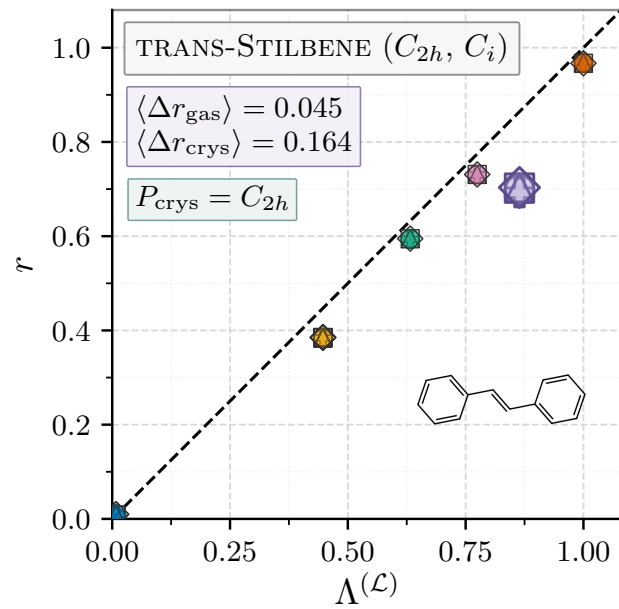


$n = 2$



$$r_{\text{gas}} = \frac{\langle f_{\text{RMS}}(\mathcal{L}, H_{\text{gas}}, \mathcal{T}) \rangle_{\mathcal{T}, \mathcal{D}_0}}{\langle f_{\text{RMS}}(C_1, H_{\text{gas}}, \mathbb{I}_3) \rangle_{\mathcal{D}_0}}$$

$$r_{\text{crys}} = \frac{\langle f_{\text{RMS}}(\mathcal{L}, H_{\text{crys}}, \mathcal{T}_{\text{crys}}) \rangle_{\mathcal{D}_0}}{\langle f_{\text{RMS}}(C_1, H_{\text{crys}}, \mathbb{I}_3) \rangle_{\mathcal{D}_0}}$$



Opportunity: Multiple Materials

- Possible to grow 100g single crystals with high optical quality and anisotropic excitation/fluorescence

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

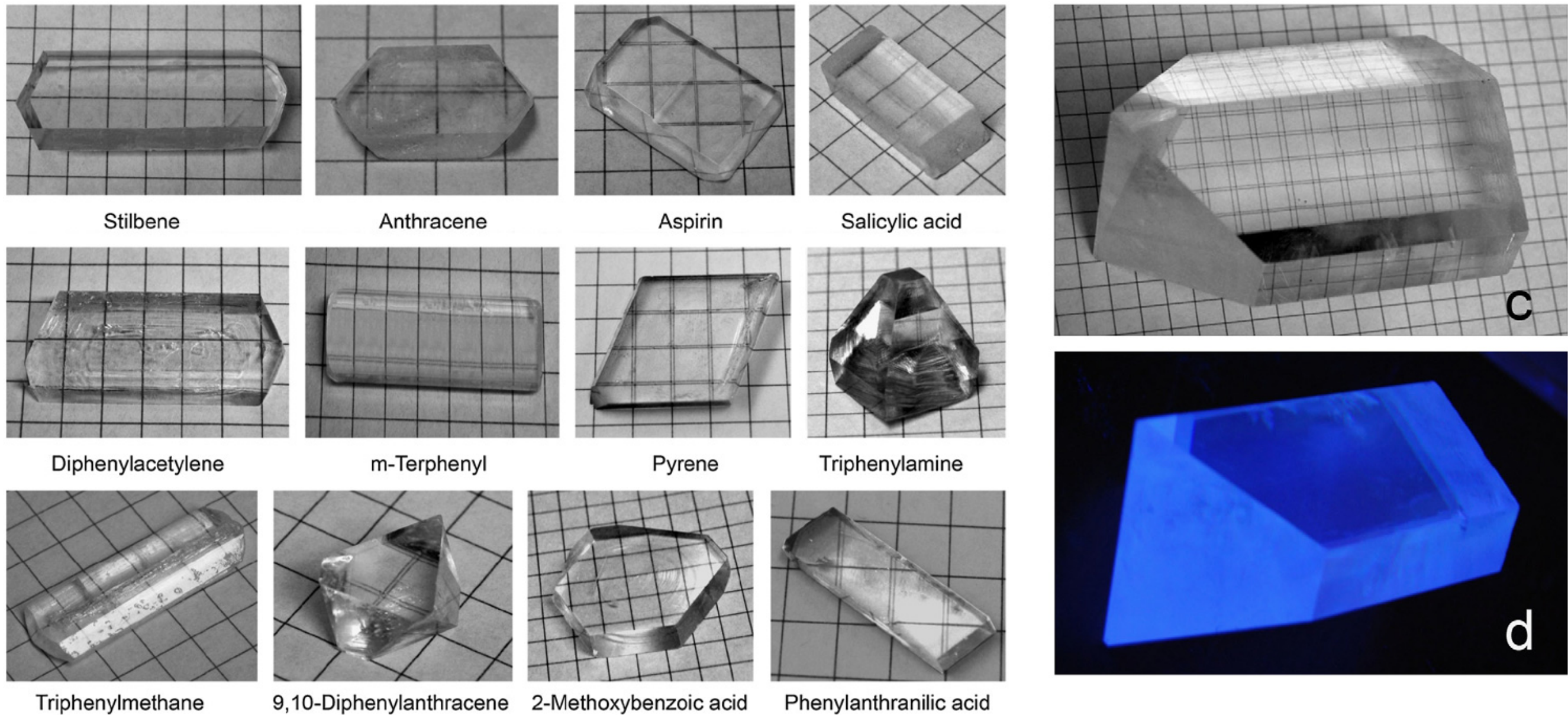
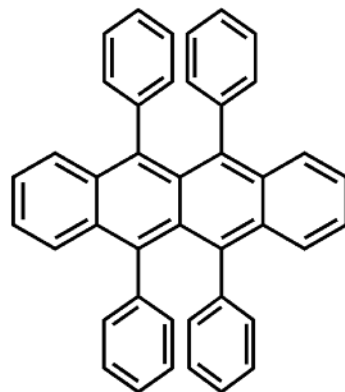
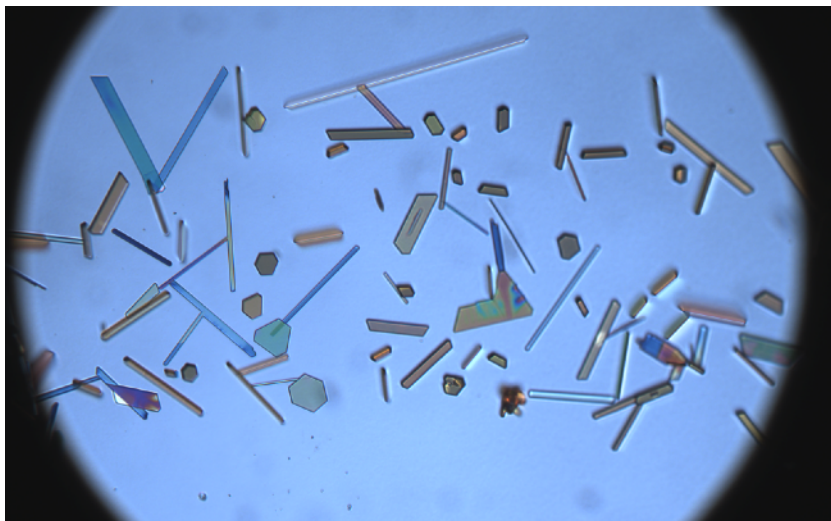
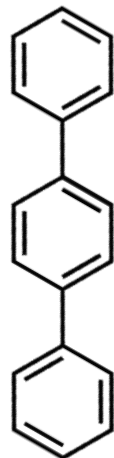
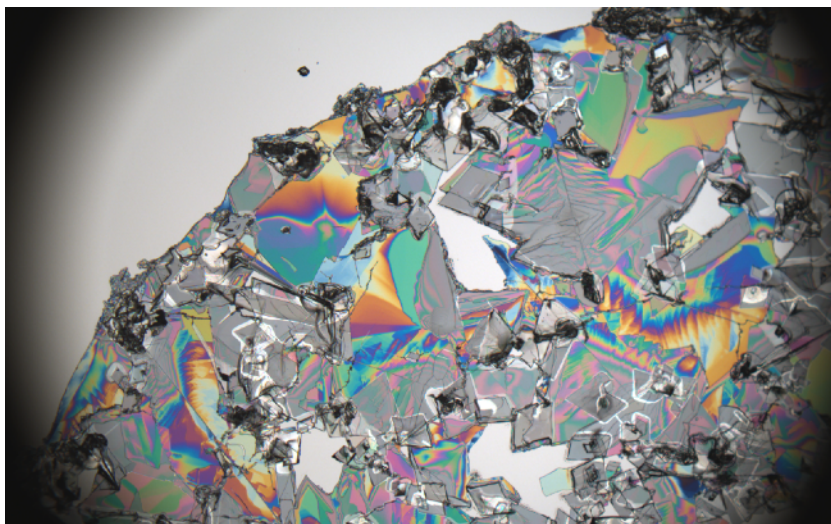
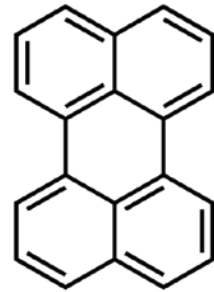
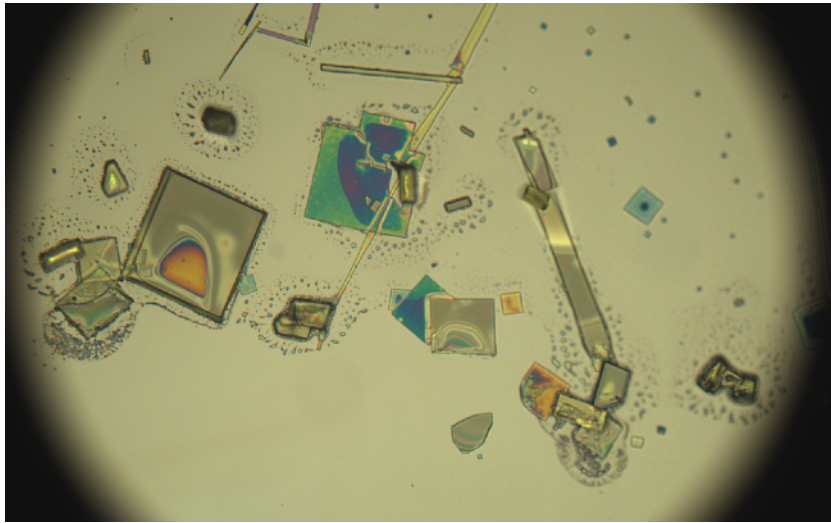


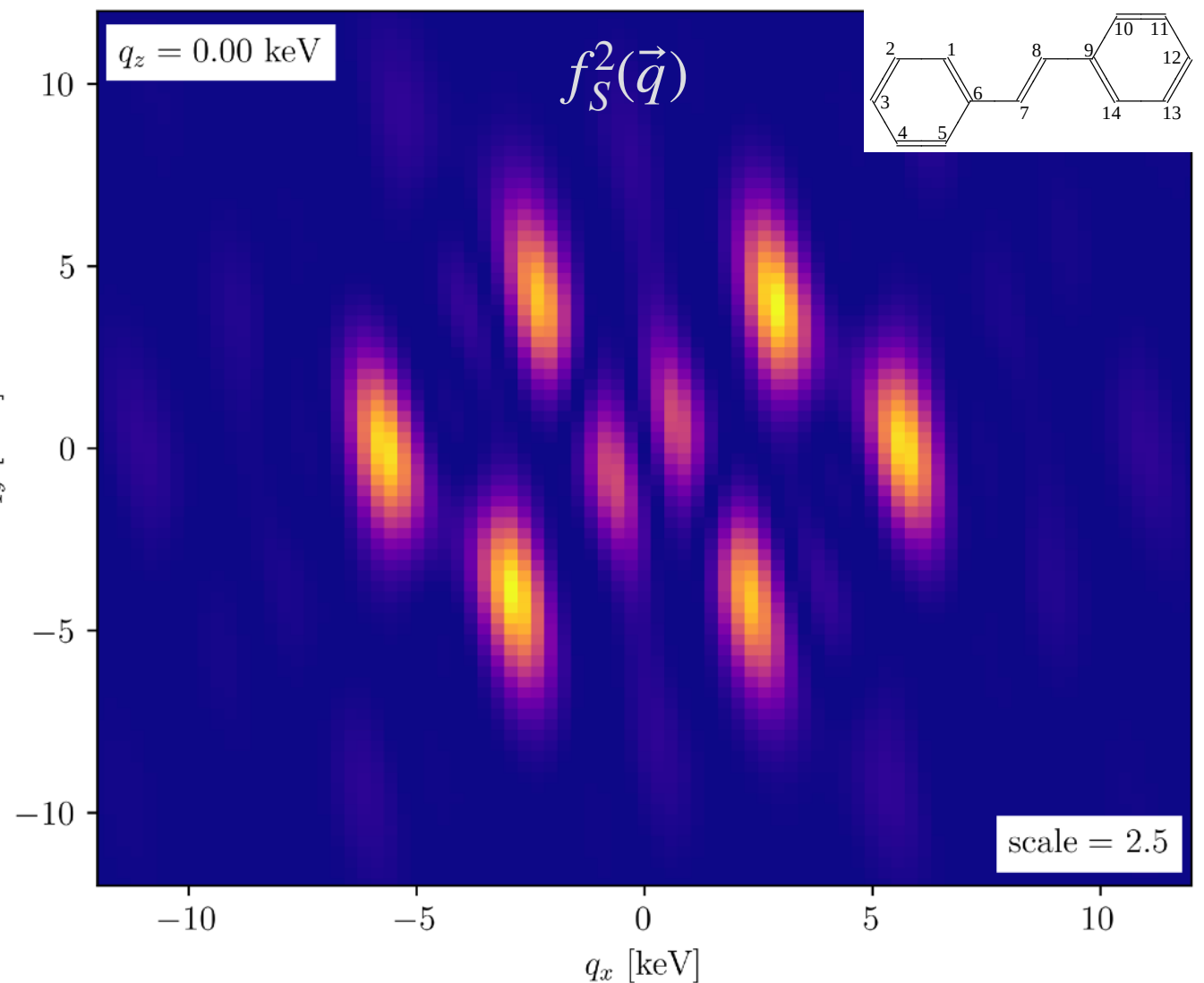
Fig. 1. Organic single crystals grown by slow evaporation method; size of the background square is 6.5 mm.

Opportunity: Multiple Materials



Trans-stilbene is just the beginning

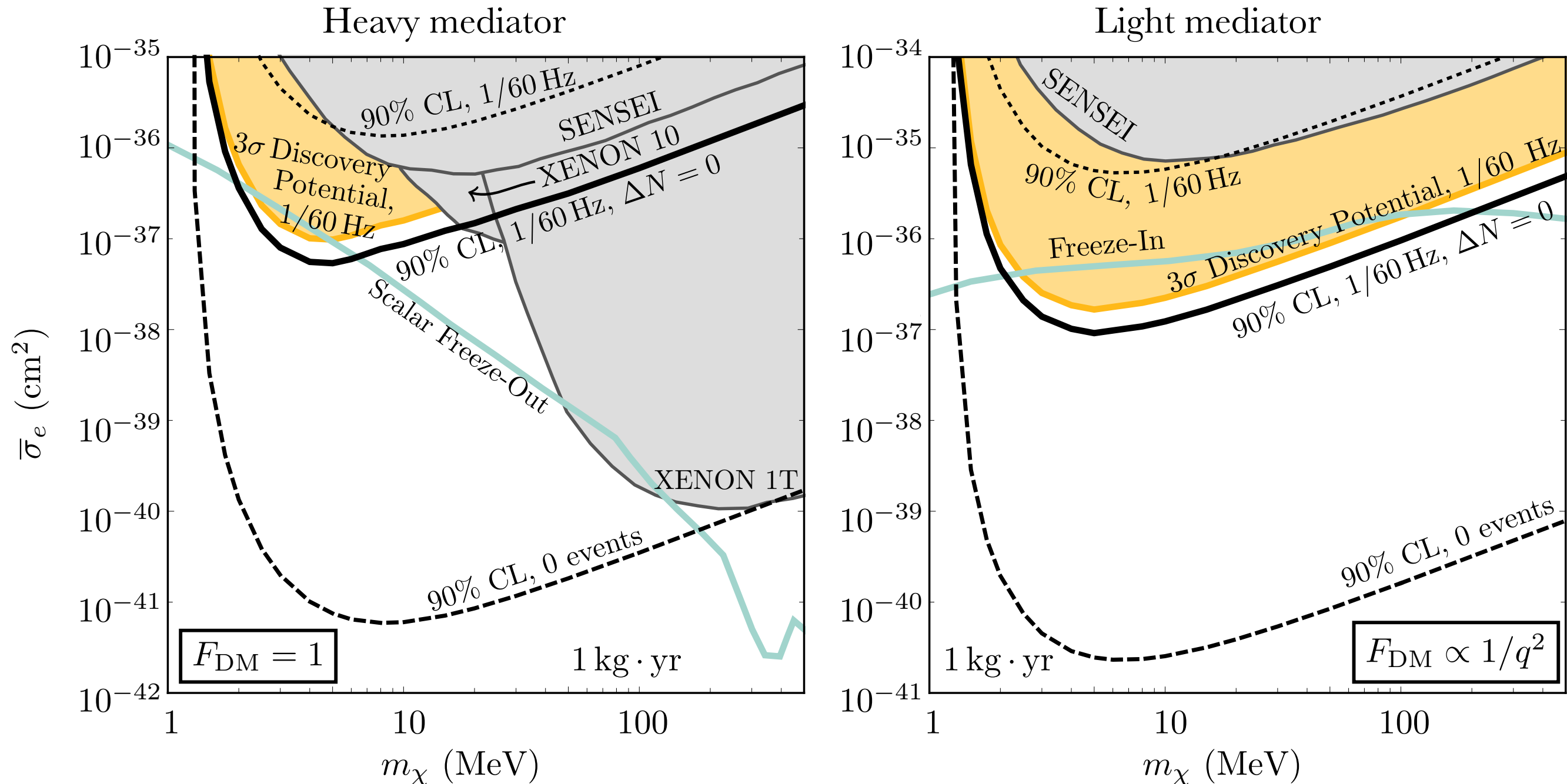
- $C_{14}H_{12}$ was a good first choice, but there are plenty of other molecules.



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

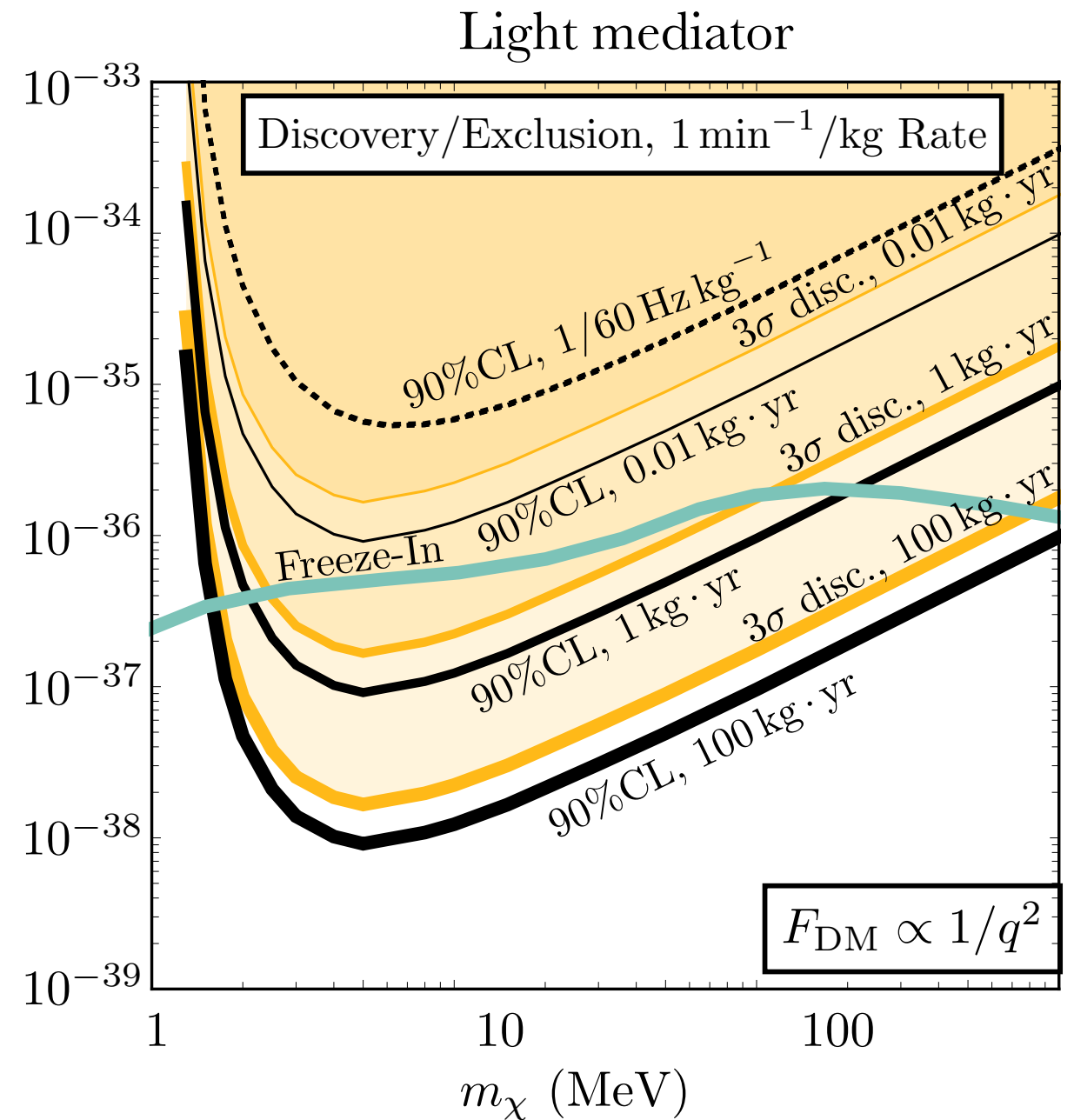
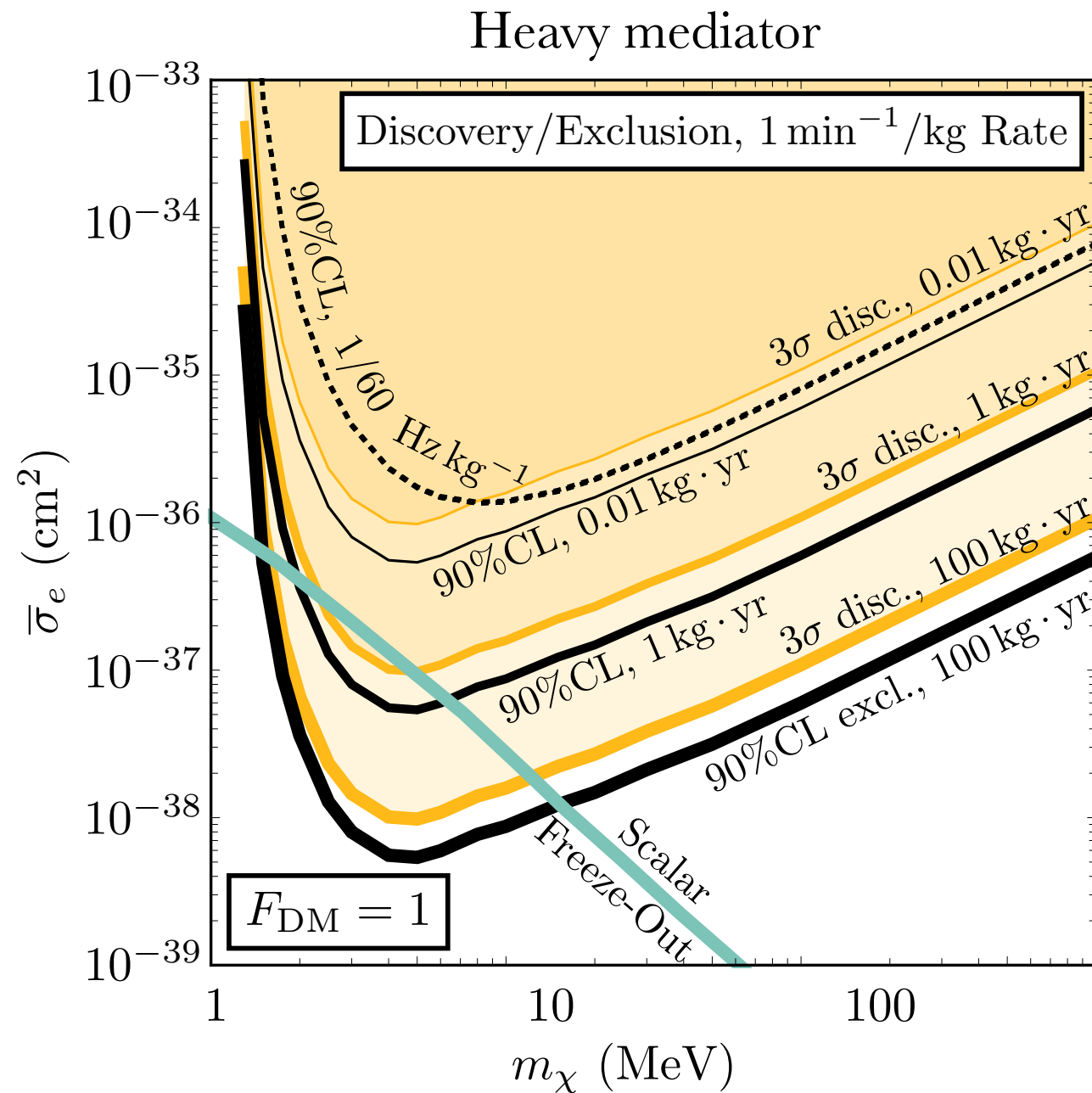
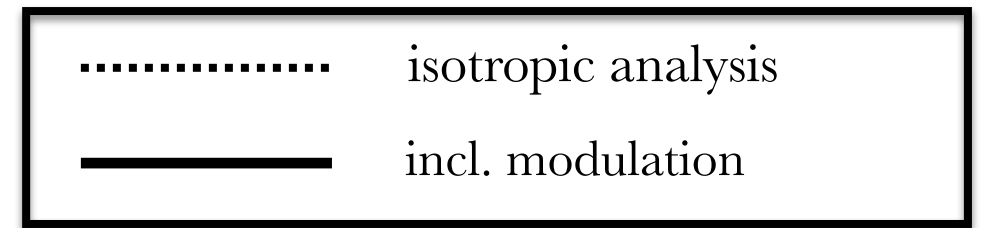


Dark Matter Daily Modulation With Anisotropic Organic Crystals. Carlos Blanco, Yonatan Kahn, BL, Samuel D. McDermott
arXiv:2103.08601

Results

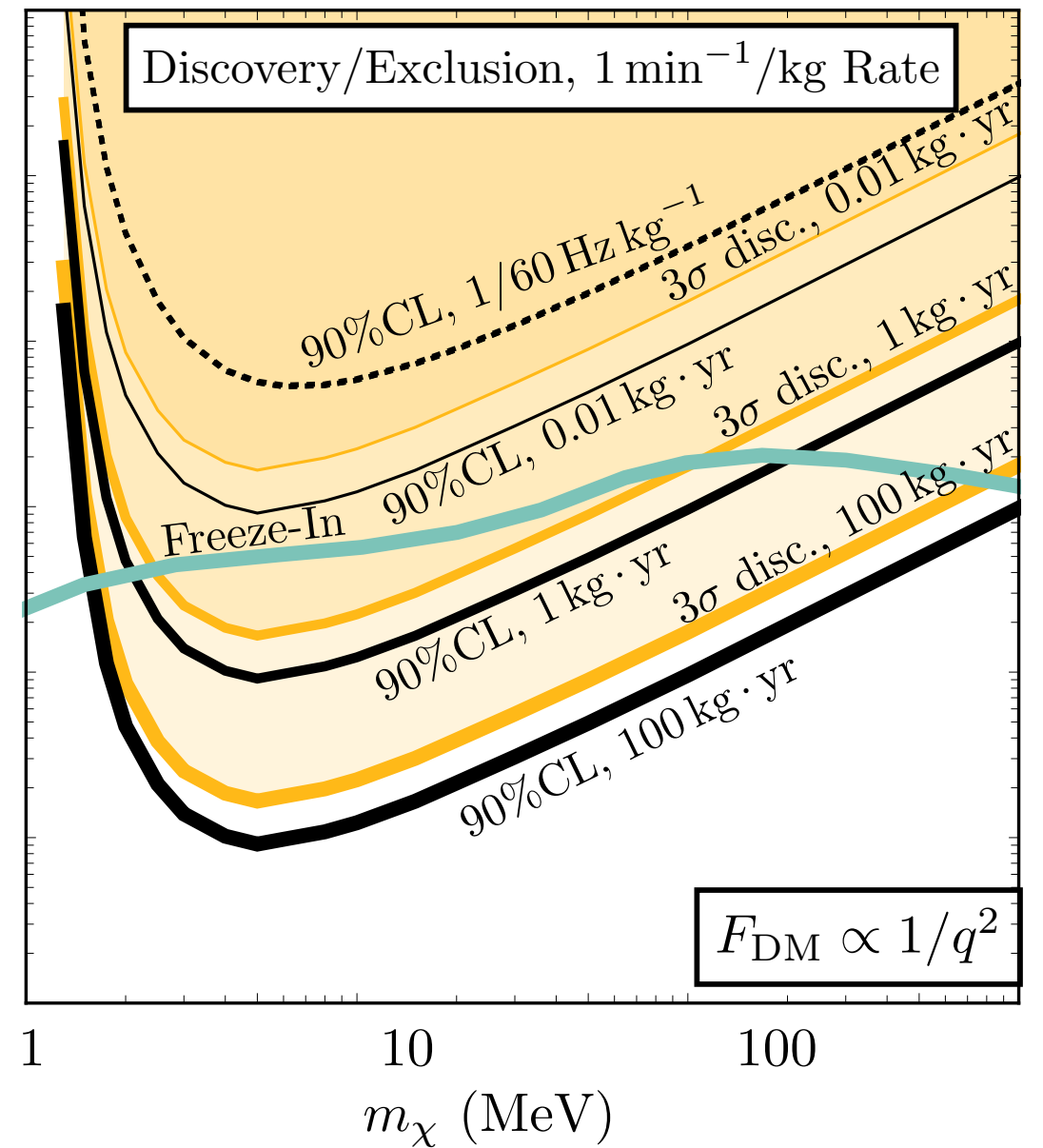
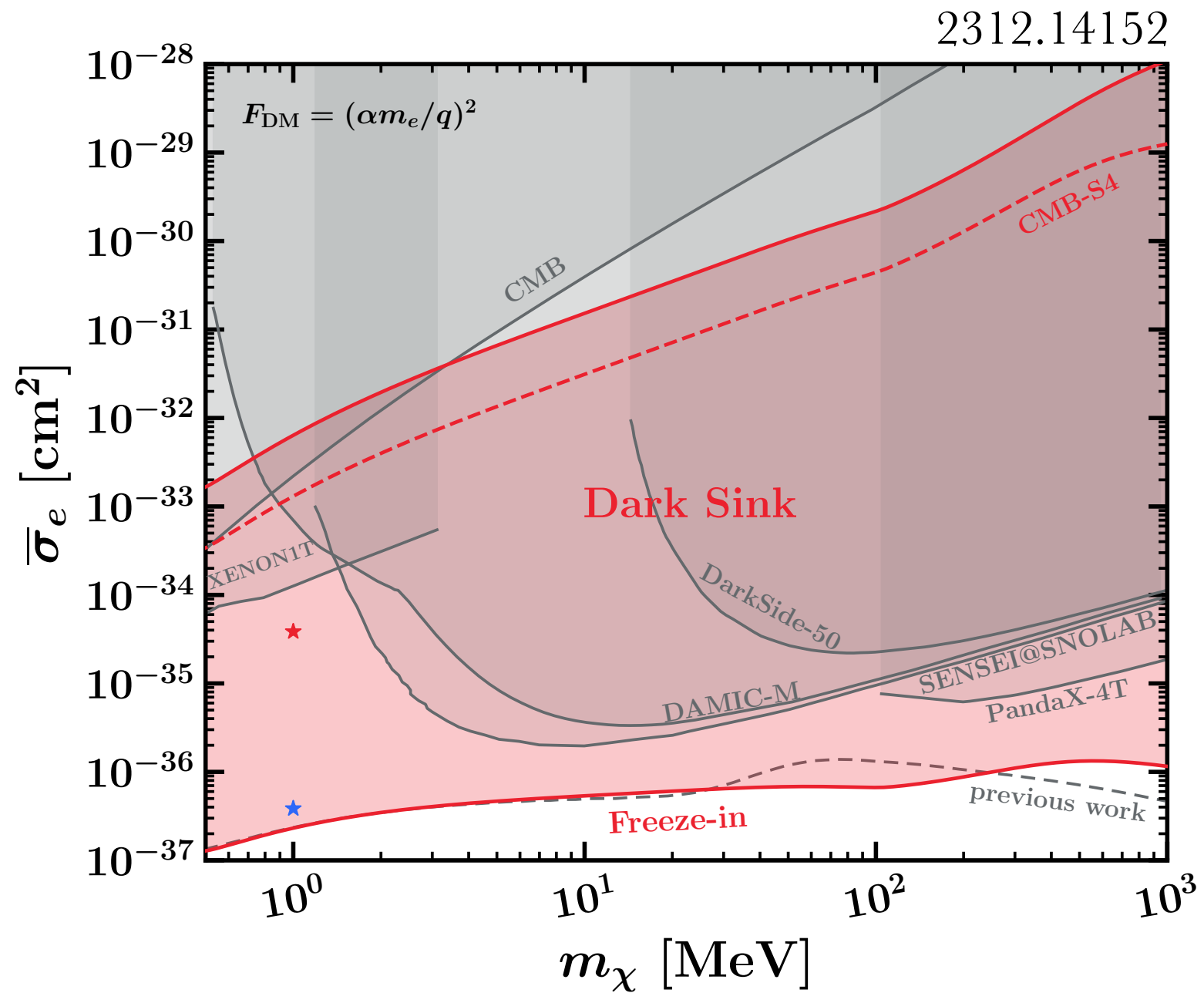
arXiv:2103.08601

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

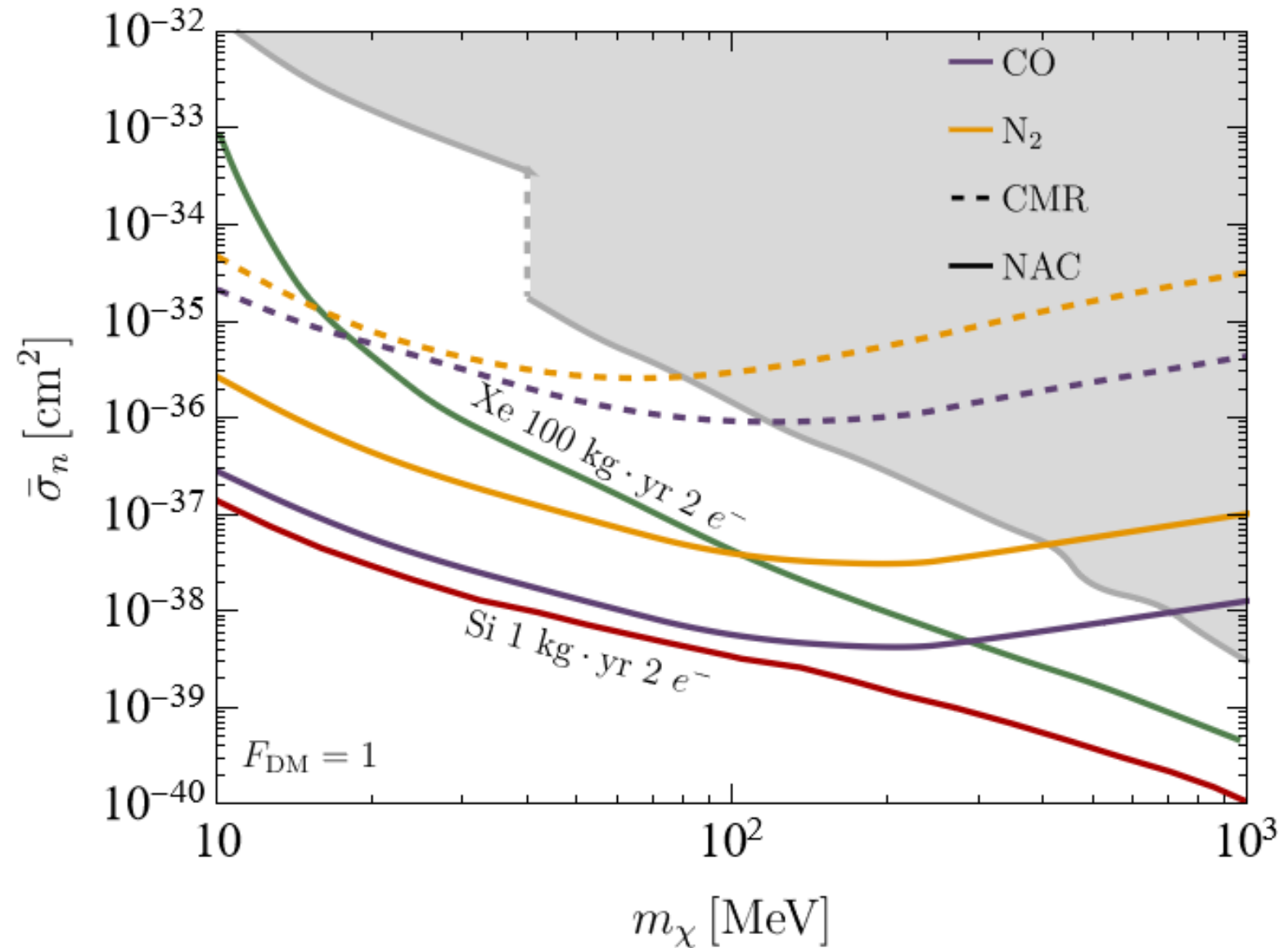
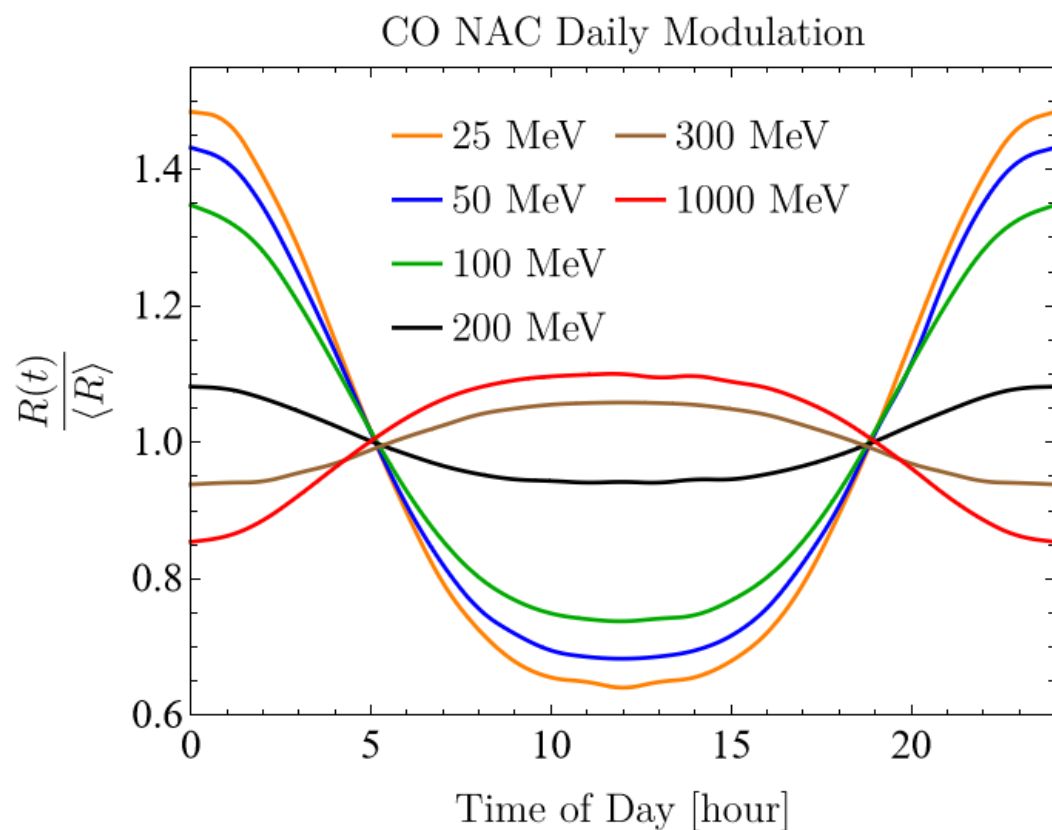
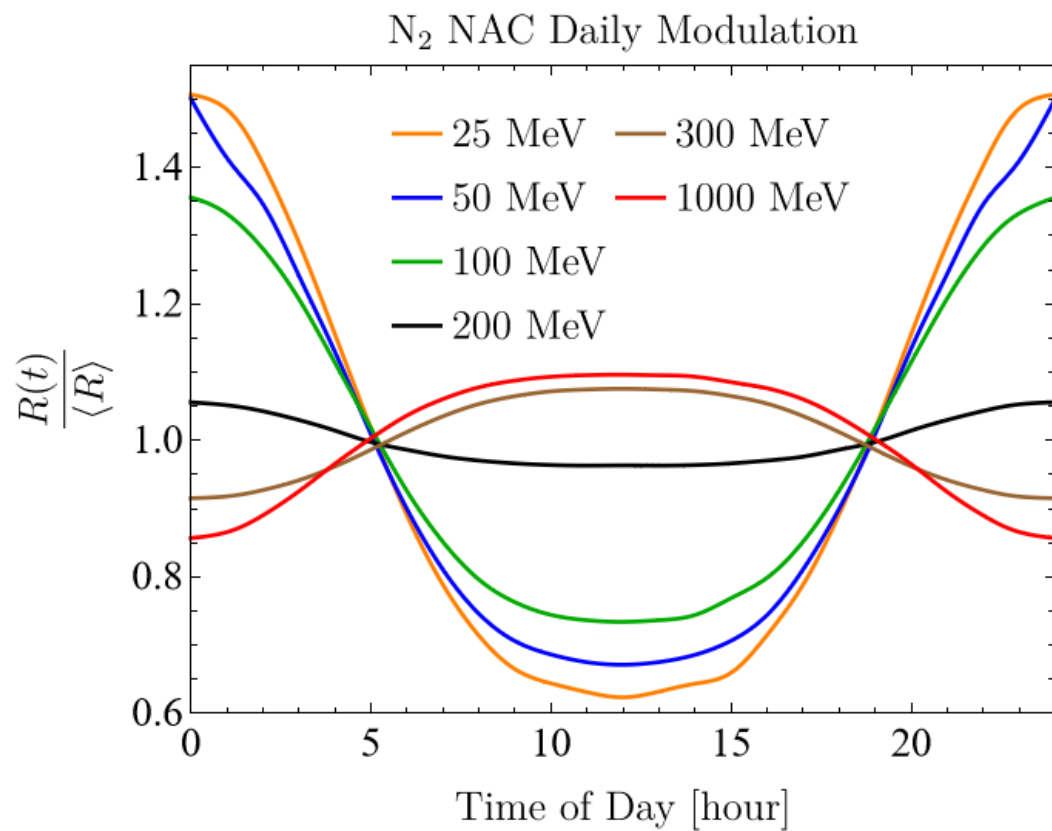


Dark Matter Daily Modulation With Anisotropic Organic Crystals. Carlos Blanco, Yonatan Kahn, BL, Samuel D. McDermott
arXiv:2103.08601

Sub-GeV Dark Sink (Freeze-In)



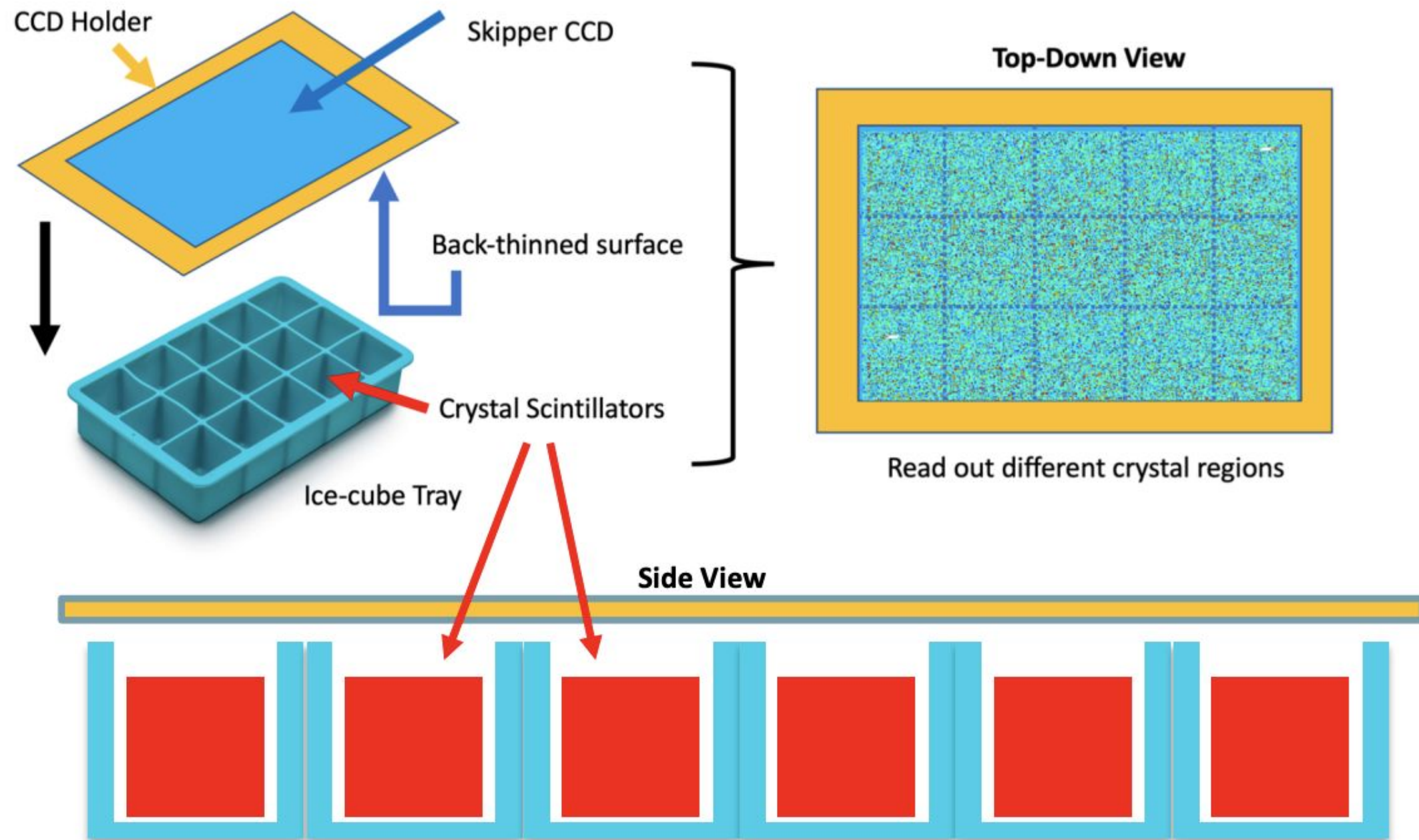
Directionality in Molecular Migdal Effect: (2208.09002)



- Repeat calculation for crystal-forming molecules...

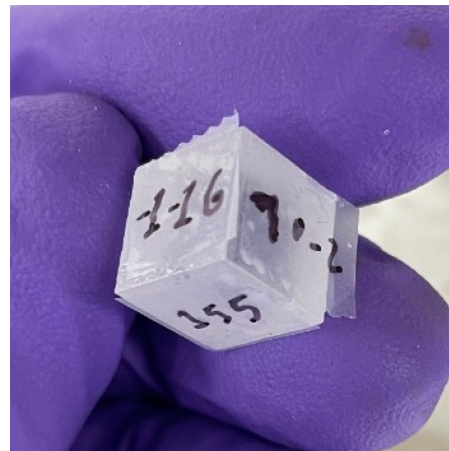
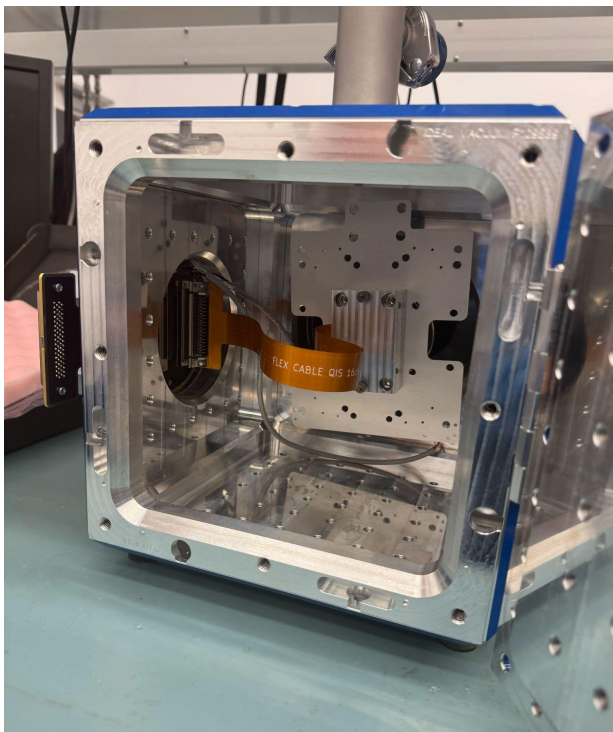
→ ***trans-stilbene...*** ←

Design: t-stilbene with Skipper CCDs

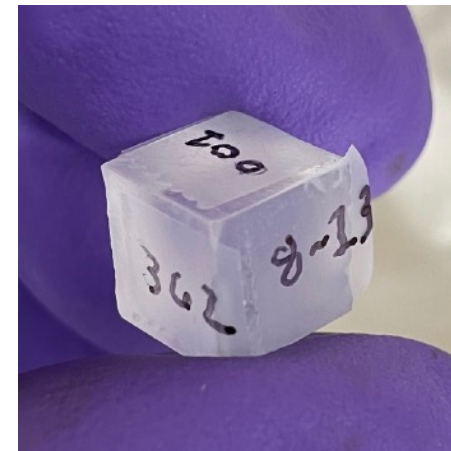


Prototype Experiment at Fermilab!

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



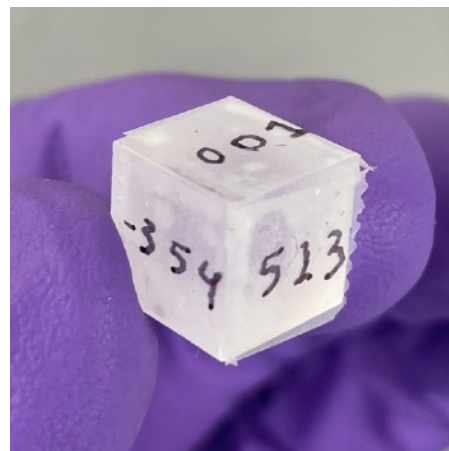
$(-1,-1,6), (7,0,-2), (1,5,5)$



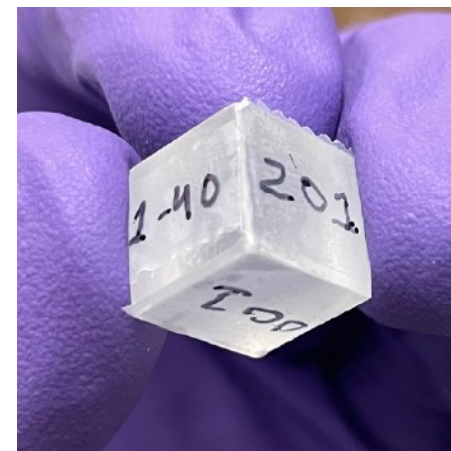
$(0,0,1), (8,-1,3), (3,6,2)$



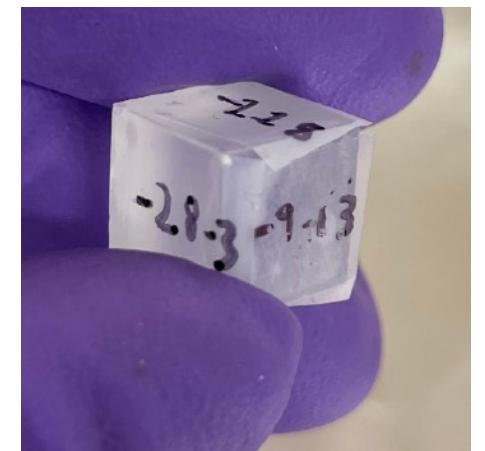
$(-9,0,4), (0,1,7), (-1,5,-3)$



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



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



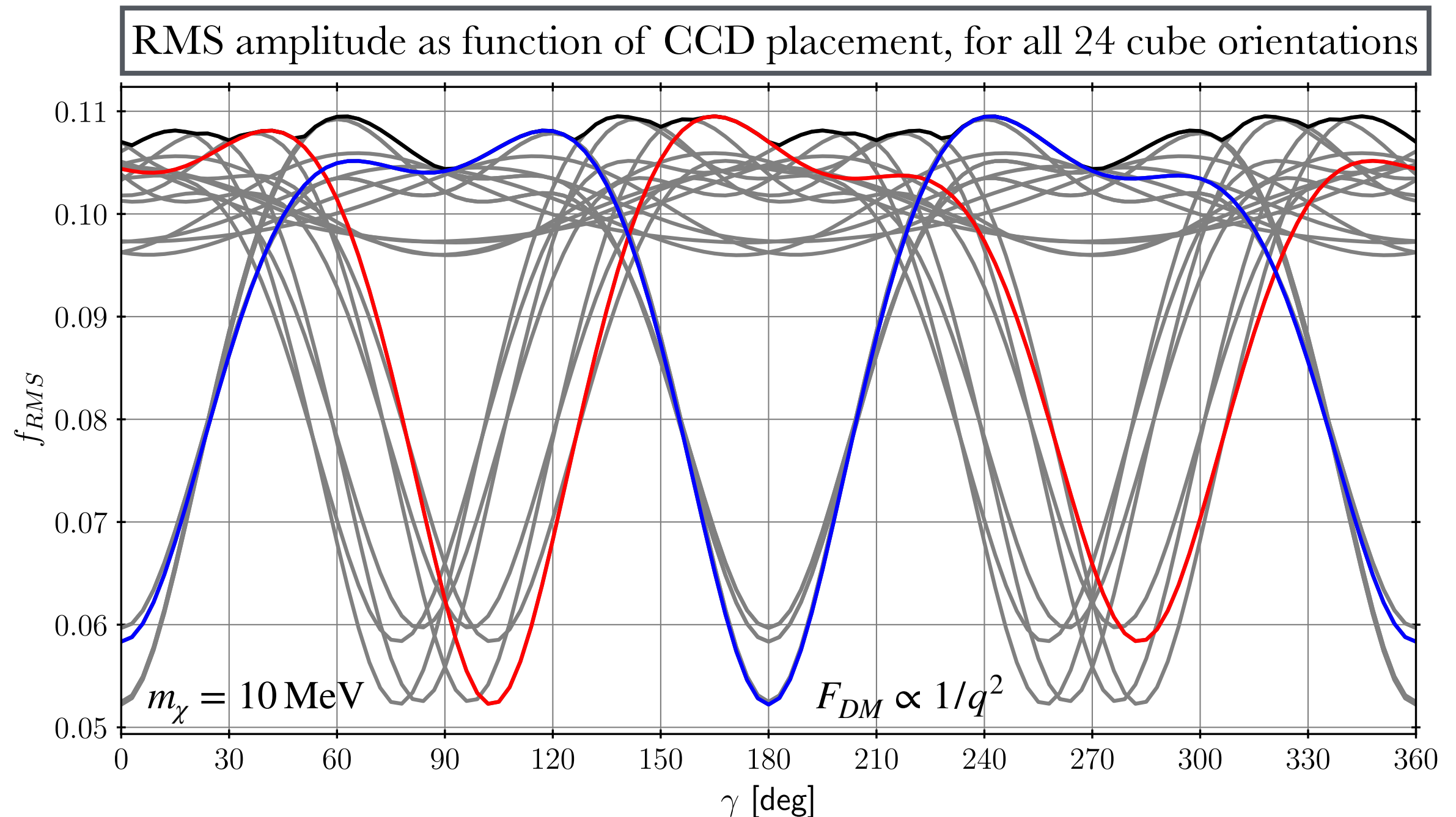
$(-1,1,8), (-9,-1,-3), (-2,8,-3)$

*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

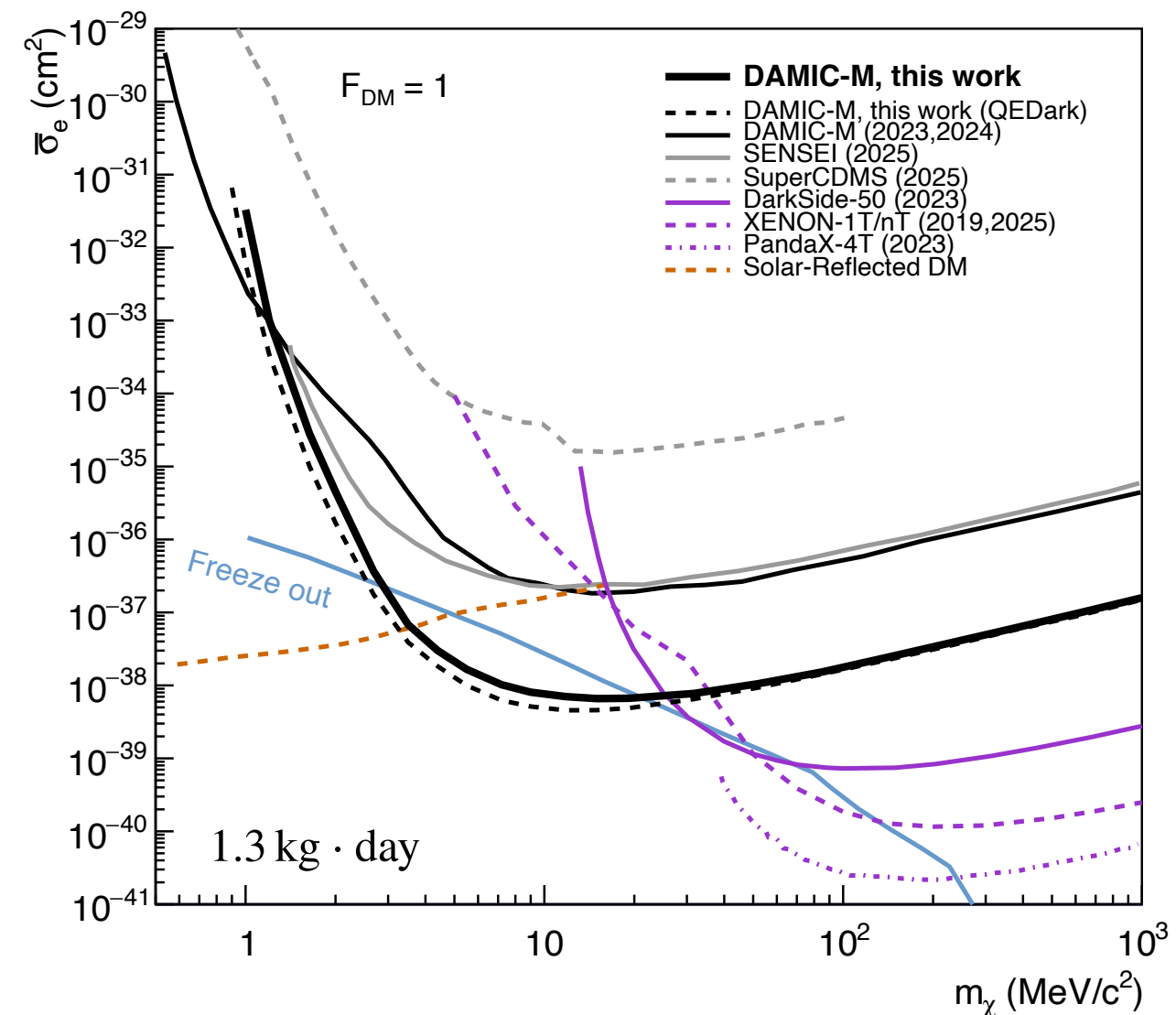
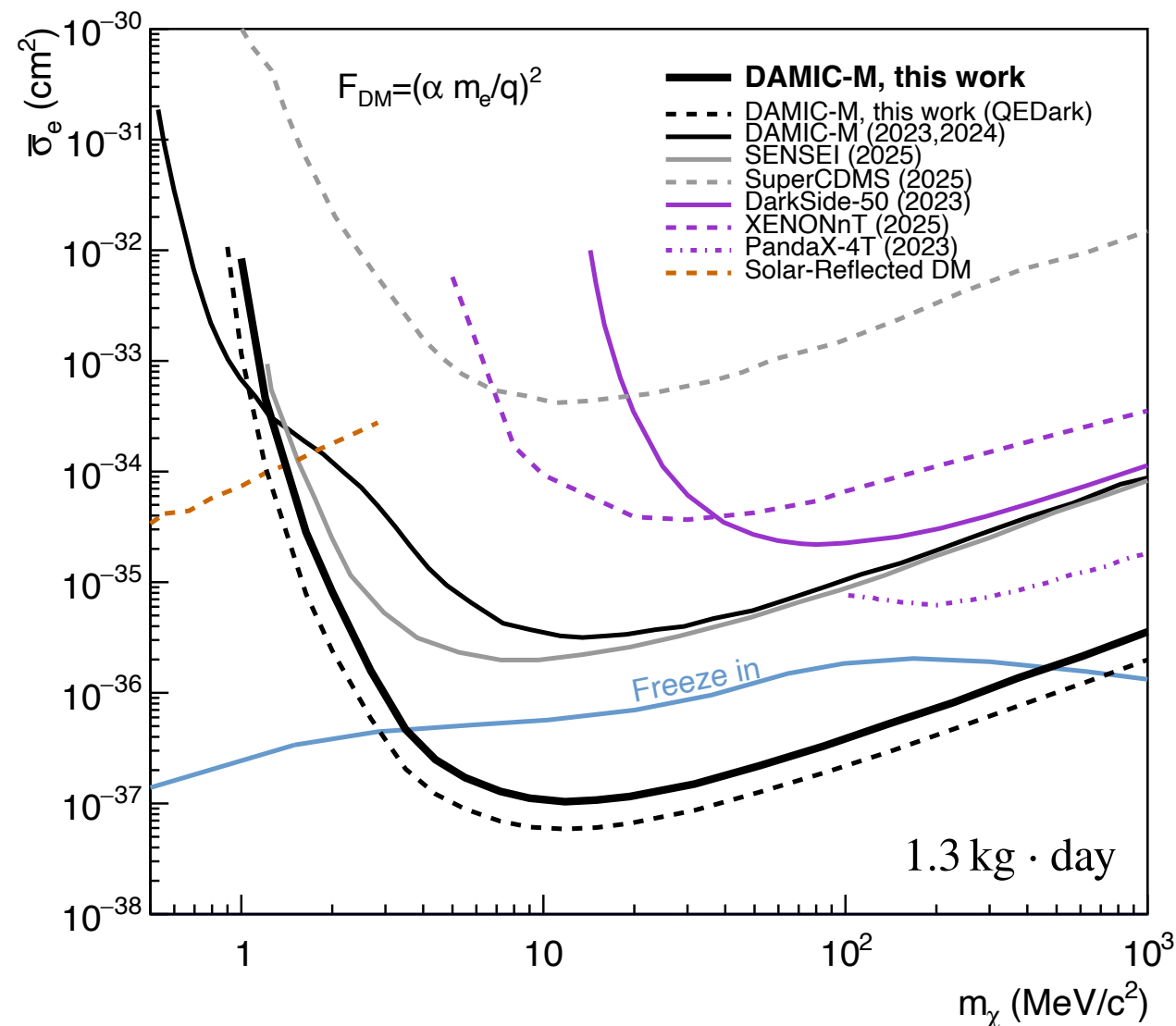


Low Backgrounds in Semiconductors: DAMIC-M

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



Supernova bounds on light mediator

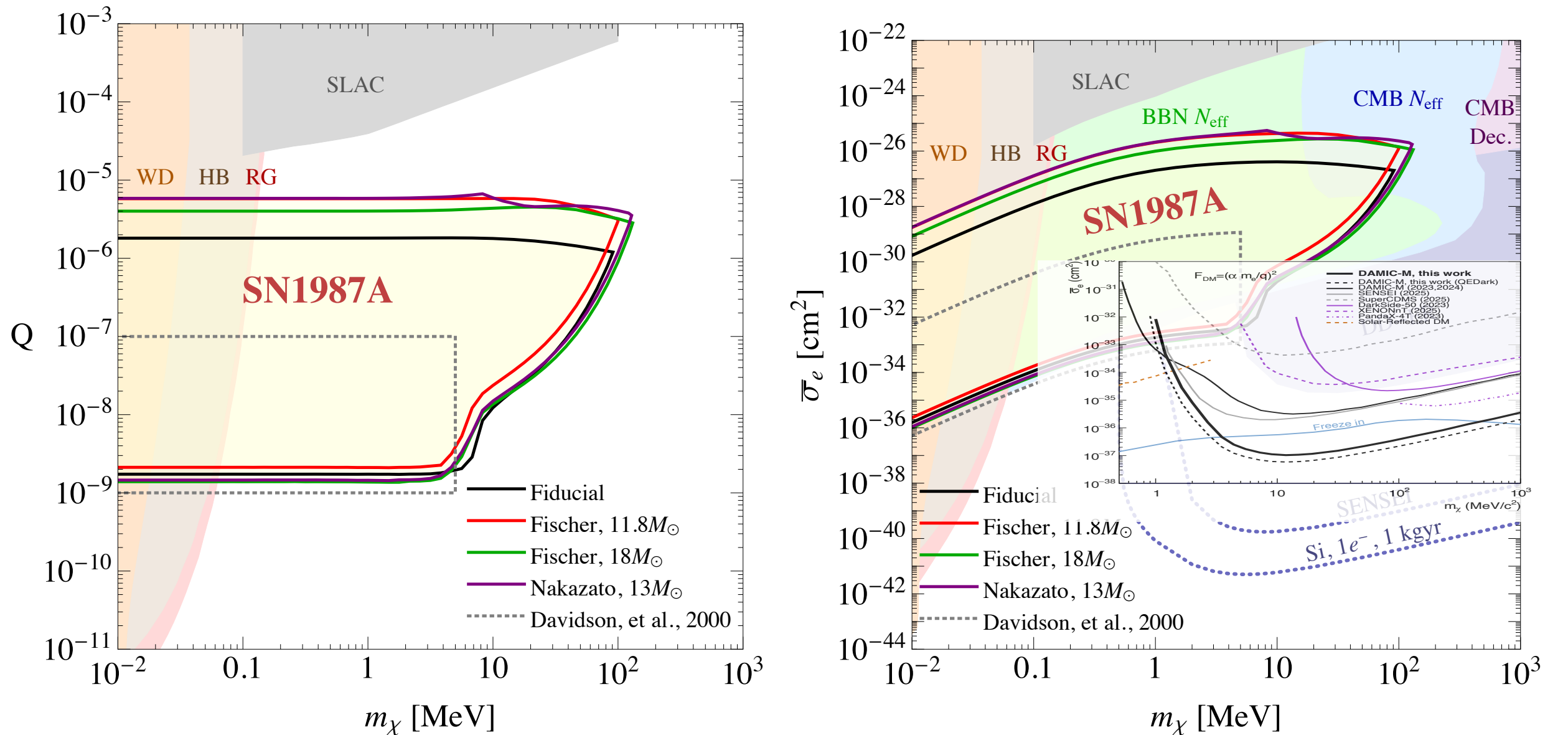


Figure 8. **Left:** Thick solid black, red, green, and red lines show the SN1987A constraints for various temperature and density profiles on millicharged particles, updating the bounds presented in [31] (dotted line).