Organic Scintillator Crystals for sub-GeV Daily Modulation Searches

Yoni Kahn
University of Illinois Urbana-Champaign

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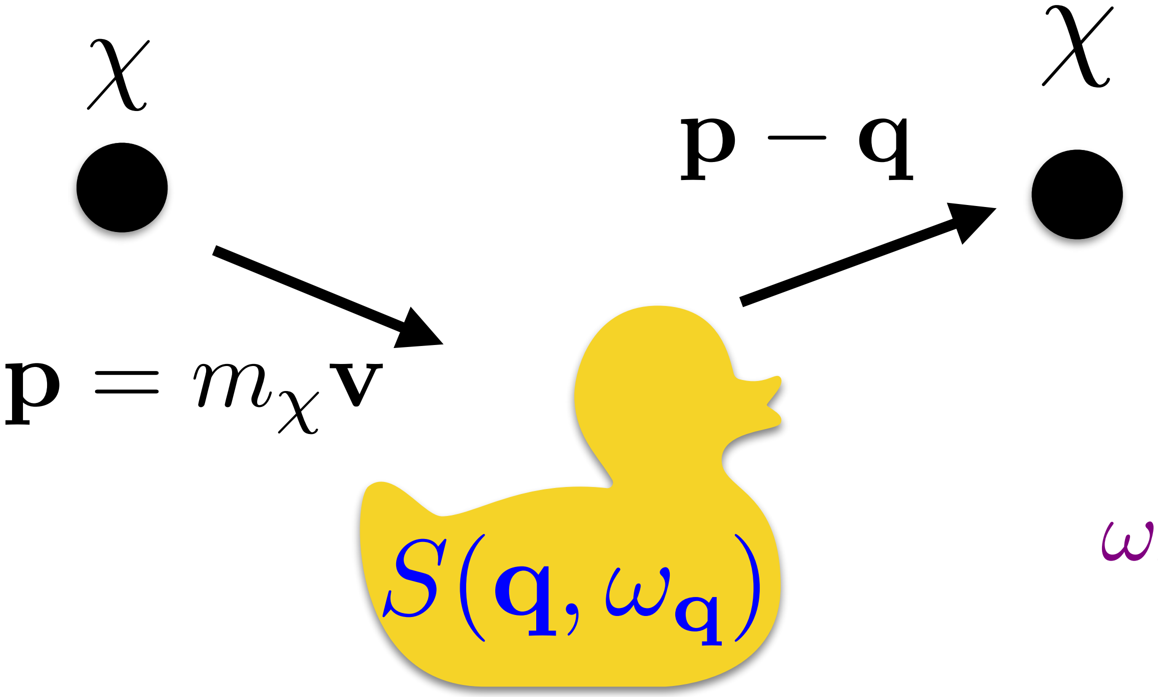
DEPARTMENT OF ENERGY
UNITED STATES OF AMERICA

Scattering response functions



χ

χ

$\mathbf{p} - \mathbf{q}$

$\mathbf{p} = m_\chi \mathbf{v}$

$S(\mathbf{q}, \omega_\mathbf{q})$

does the target have
an energy eigenstate at $\omega_\mathbf{q}$?

Energy deposited by DM:

$$\omega_\mathbf{q} = \frac{\mathbf{p}^2}{2m_\chi} - \frac{(\mathbf{p}-\mathbf{q})^2}{2m_\chi} = \mathbf{q}\cdot\mathbf{v} - \frac{q^2}{2m_\chi}$$

$$S(\mathbf{q}, \omega_\mathbf{q}) \propto \sum_f |\langle f| \sum_j e^{i\mathbf{q}\cdot\mathbf{r}_j} |i\rangle|^2 \delta(\omega_f - \omega_\mathbf{q})$$

$$R \sim \int d^3\mathbf{v}\, f(\mathbf{v}) \int d^3\mathbf{q}\, F^2(\mathbf{q}) S(\mathbf{q}, \omega_\mathbf{q})$$

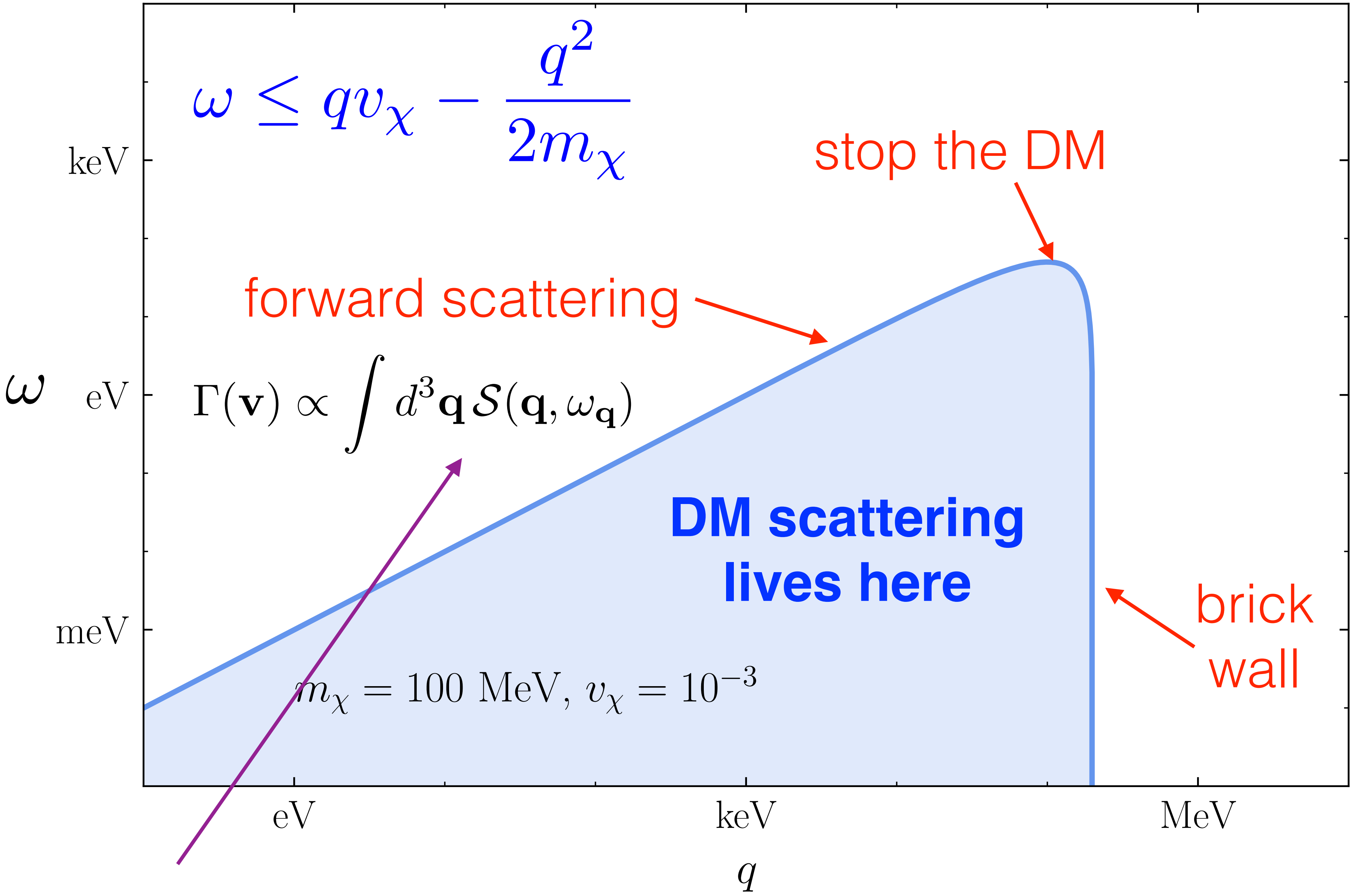
DM properties

Material properties

General framework that works for **any** target and material

[Trickle, Zhang, Zurek, Inzani, Griffin, JHEP 2020; **YK** and Lin, Rep. Prog. Phys. 2022]

Sub-GeV DM kinematics



$$\omega \leq q v_\chi - \frac{q^2}{2m_\chi}$$

stop the DM

forward scattering

$$\Gamma(\mathbf{v}) \propto \int d^3\mathbf{q}\, \mathcal{S}(\mathbf{q}, \omega_{\mathbf{q}})$$

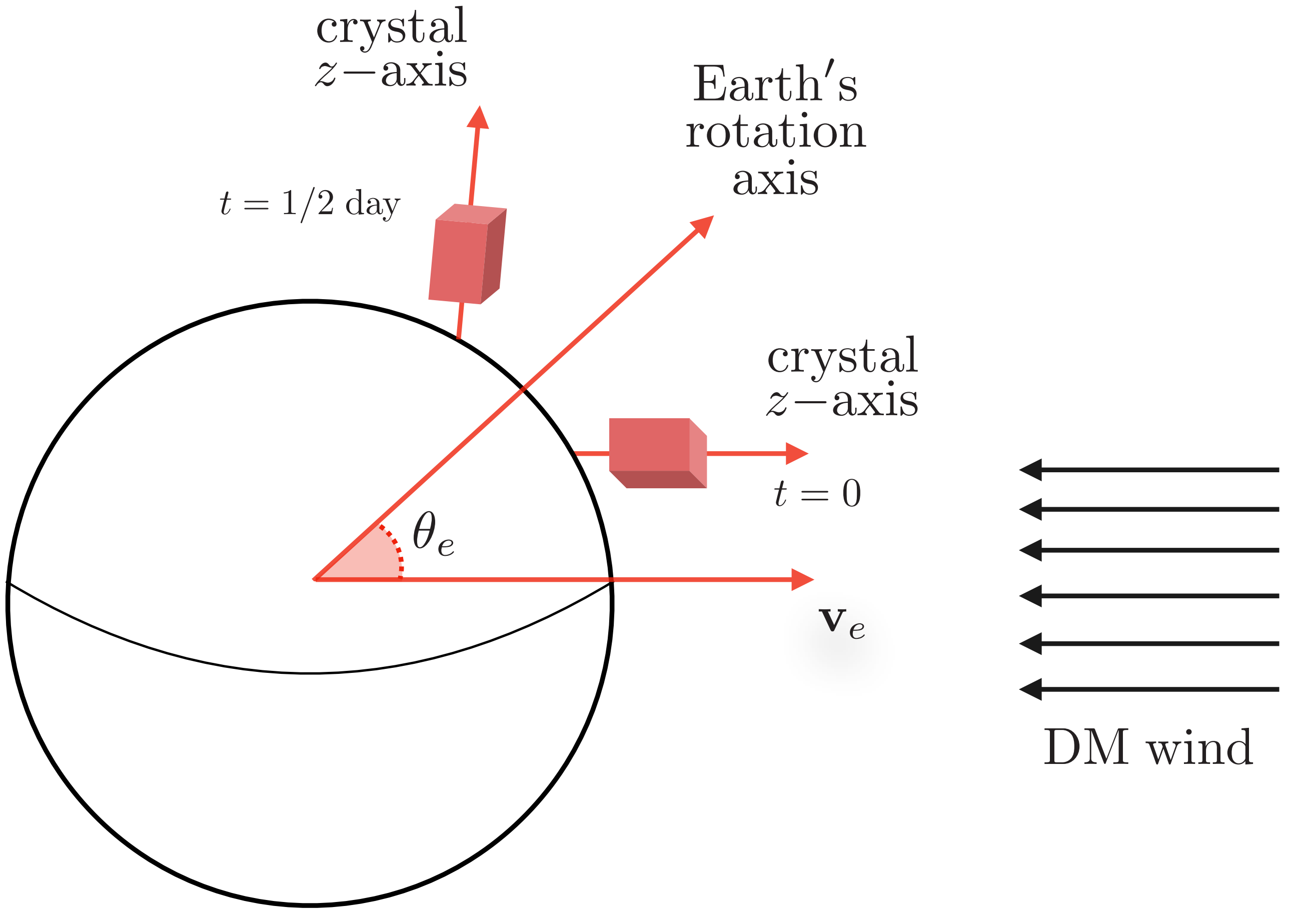
DM scattering lives here

brick wall

$m_\chi = 100$ MeV, $v_\chi = 10^{-3}$

Goal: maximize the response function inside the DM parabola

Daily modulation



$$R(t) \sim \int d^3v\, d^3q\, f_\chi(\mathbf{v},t)\, \mathcal{S}(\mathbf{q},\omega_\mathbf{q}) \qquad \omega_\mathbf{q} = \mathbf{q}\cdot\mathbf{v} - \frac{q^2}{2m_\chi}$$

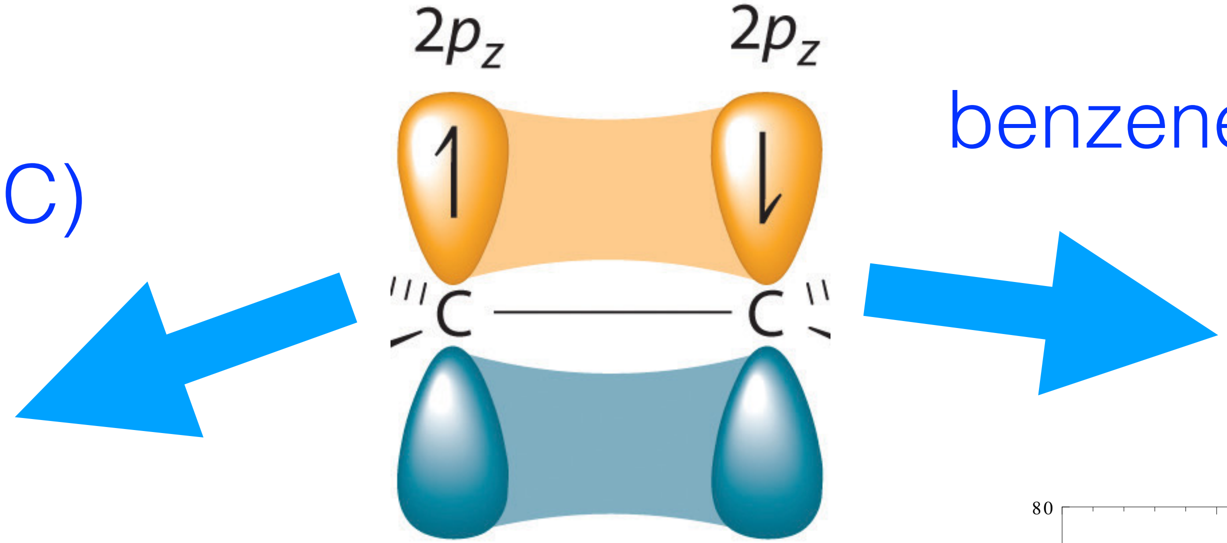
If S is peaked in particular directions of **q**, R will change periodically over 24 hours as $\langle \mathbf{v} \rangle$ rotates in lab frame

Smoking gun for DM signal!

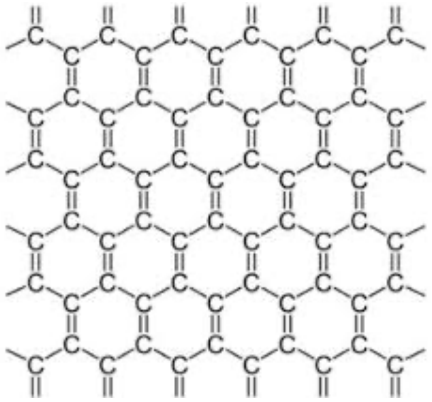
[Spergel, PRD 1988; Coskuner, Mitridate, Olivares, Zurek, PRD 2021]

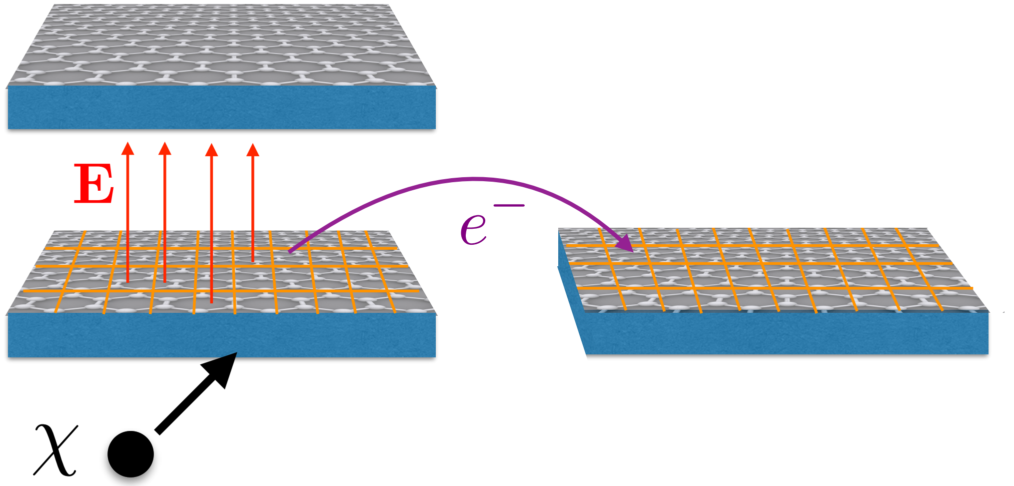
Carbon-based detectors

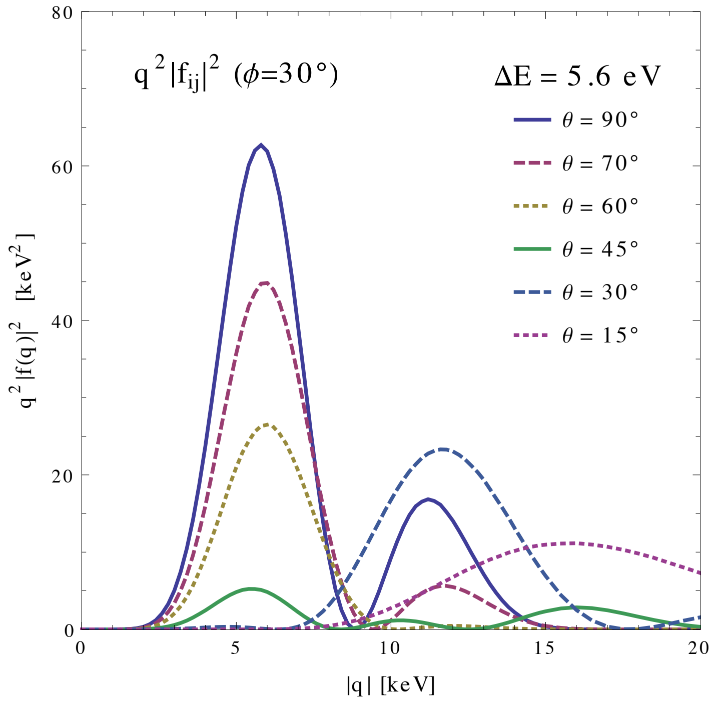
graphene
(1 atom thick of C)



benzene (bonded with H)





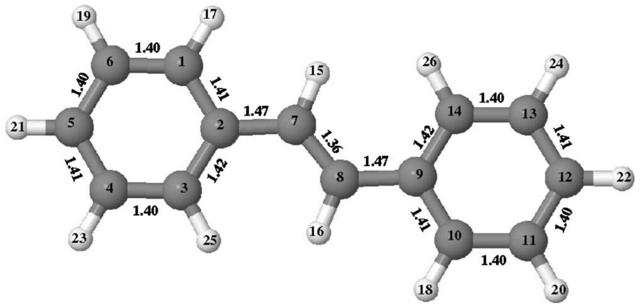


Scattered electron direction correlated with incoming DM. But 1 kg is hard (though, neat ideas at LNGS with nanotubes)

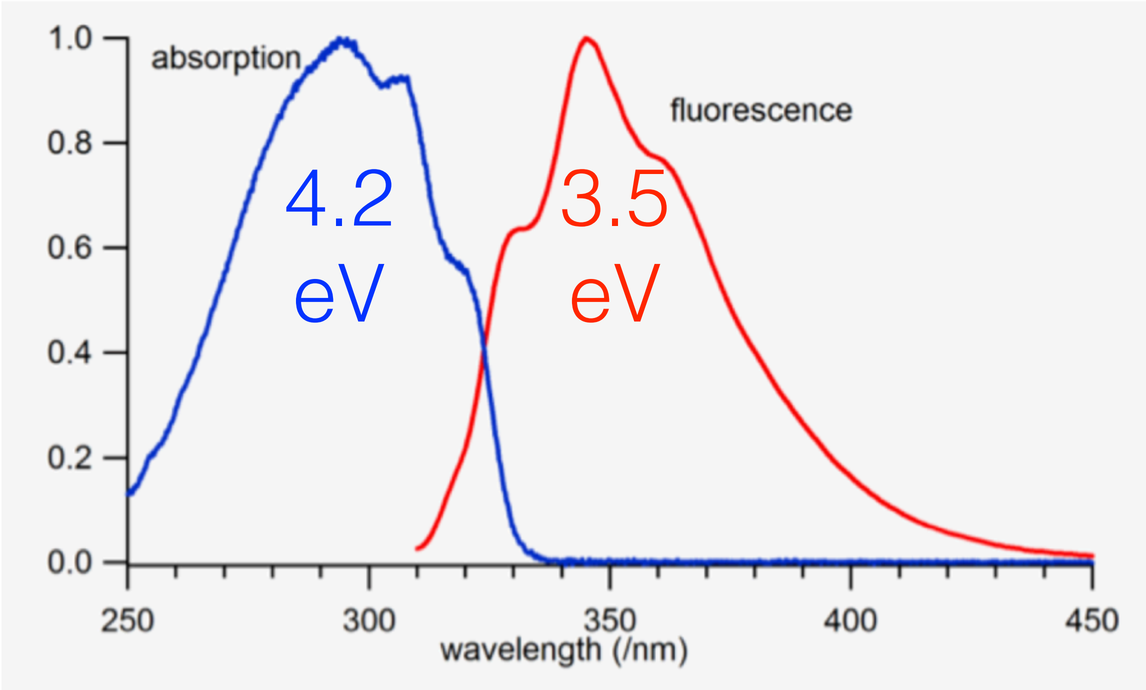
Scintillates, and commercially available! But molecules are randomly oriented in liquid

[Hochberg, **YK**, Lisanti, Tully, Zurek, PLB 2017; Blanco, Collar, **YK**, Lillard, PRD 2020]

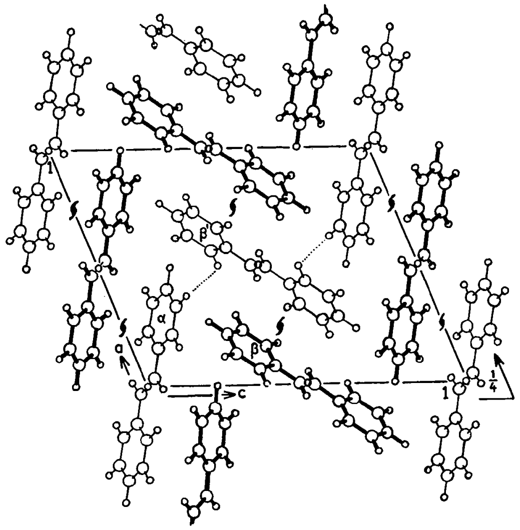
Organic scintillator crystals



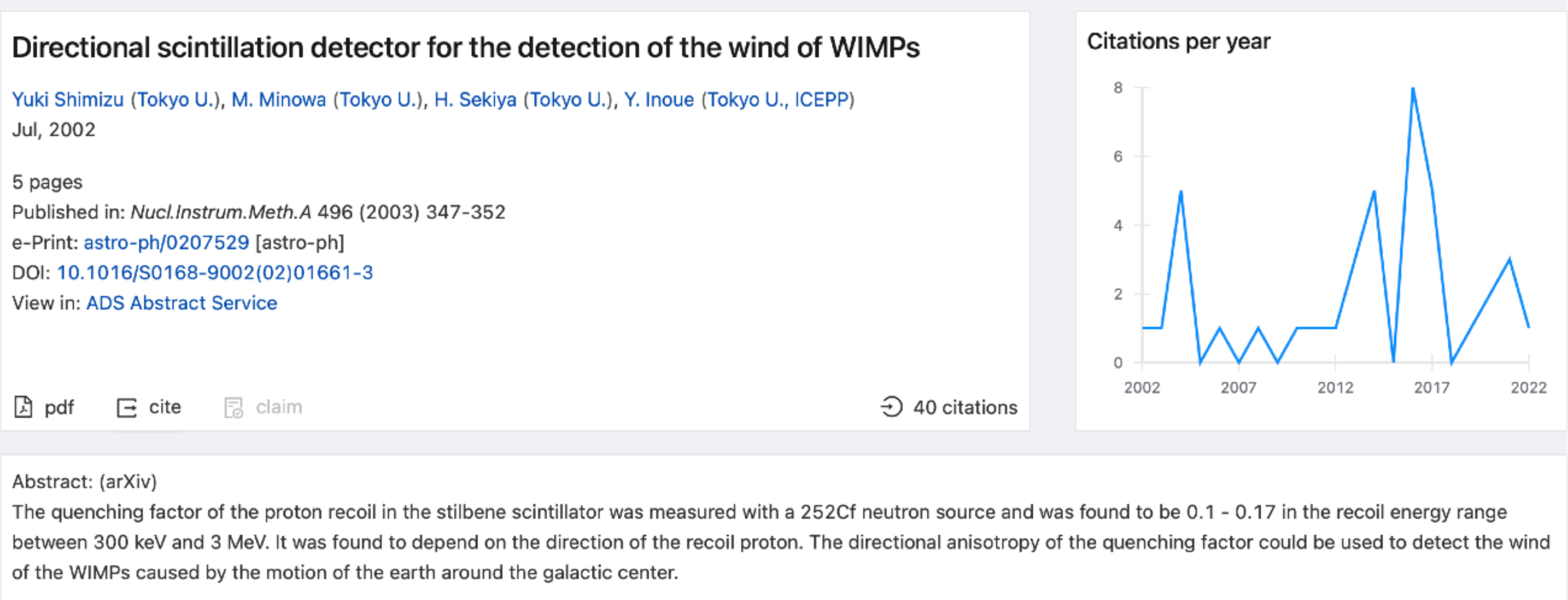
trans-stilbene
($C_{14}H_{12}$)



wavelength shifting = excellent quantum efficiency



4 molecules per unit cell, very weak intermolecular forces



Directional scintillation detector for the detection of the wind of WIMPs

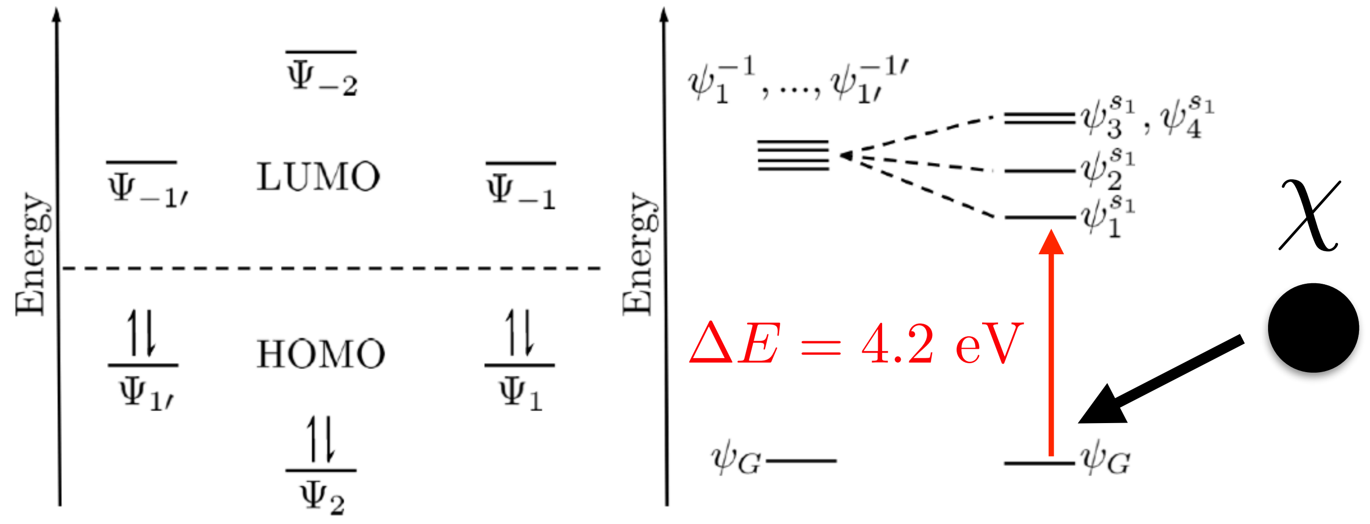
Yuki Shimizu (Tokyo U.), M. Minowa (Tokyo U.), H. Sekiya (Tokyo U.), Y. Inoue (Tokyo U., ICEPP)
Jul, 2002

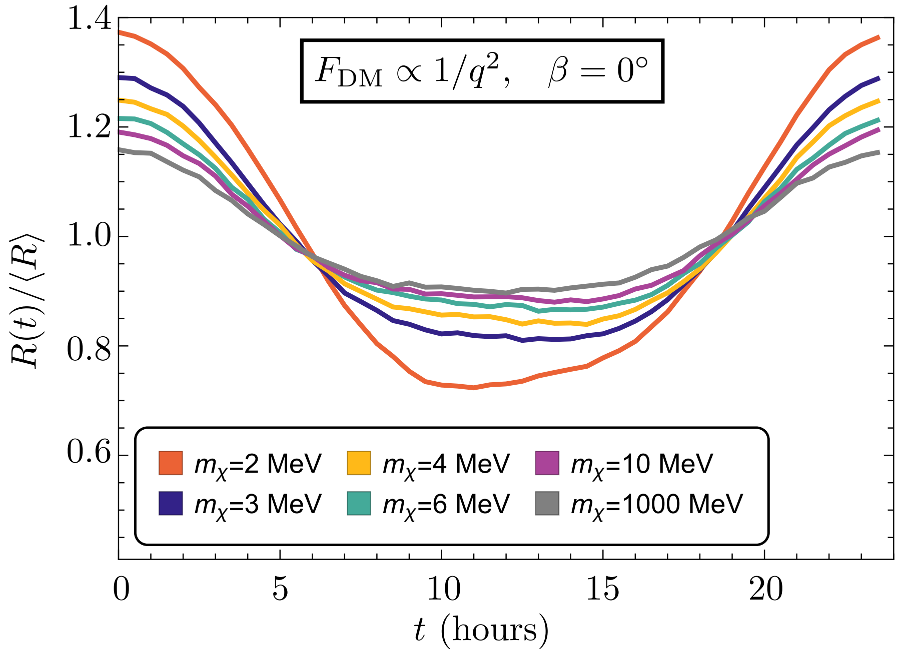
5 pages
Published in: *Nucl.Instrum.Meth.A* 496 (2003) 347-352
e-Print: astro-ph/0207529 [astro-ph]
DOI: 10.1016/S0168-9002(02)01661-3
View in: ADS Abstract Service

Abstract: (arXiv)
The quenching factor of the proton recoil in the stilbene scintillator was measured with a 252Cf neutron source and was found to be 0.1 - 0.17 in the recoil energy range between 300 keV and 3 MeV. It was found to depend on the direction of the recoil proton. The directional anisotropy of the quenching factor could be used to detect the wind of the WIMPs caused by the motion of the earth around the galactic center.

anisotropy already used for WIMP experiment!

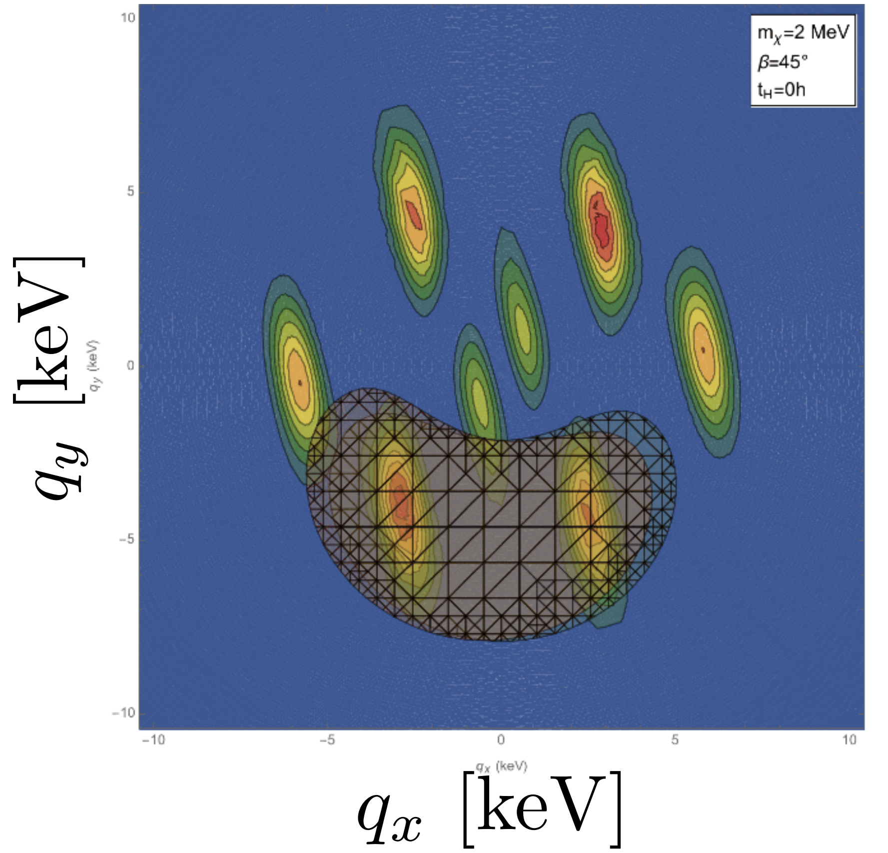
Daily modulation for DM-e

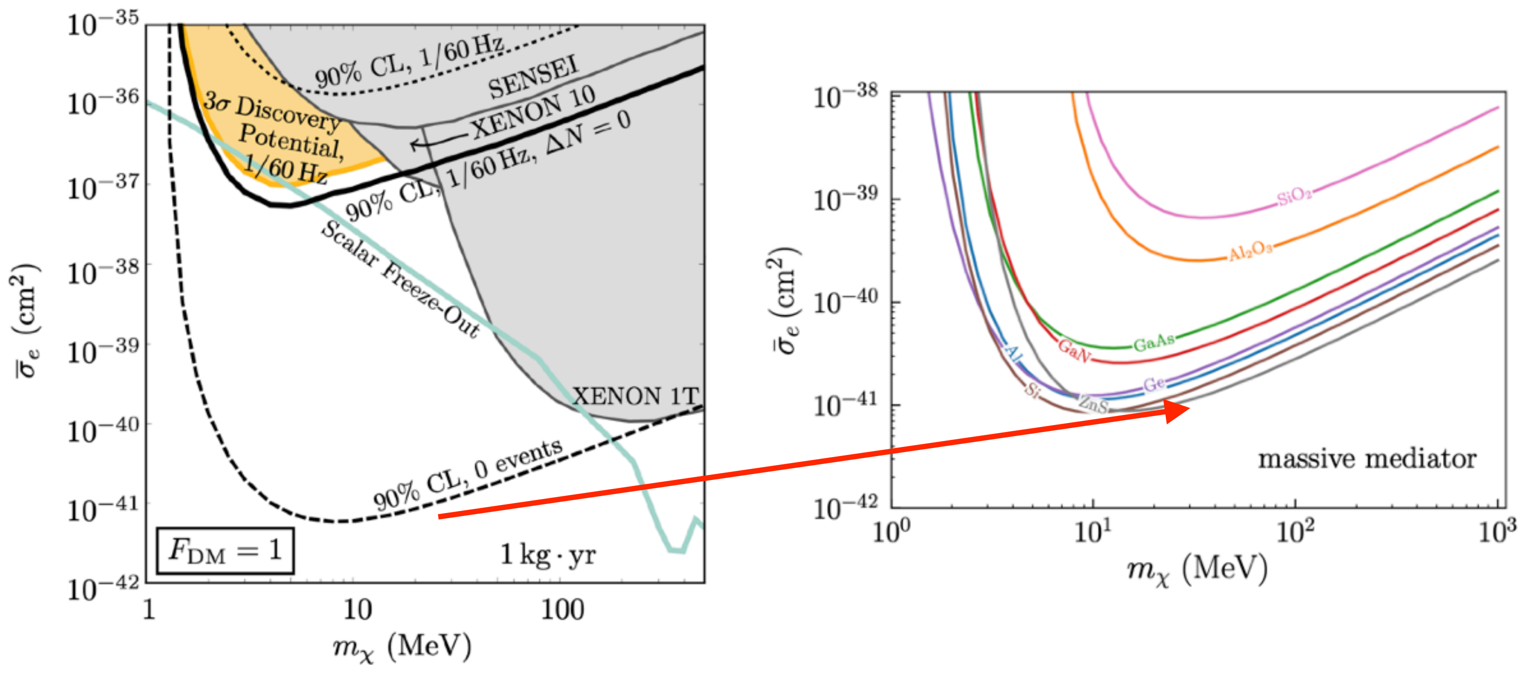




20% daily modulation!

$S(q_x, q_y, q_z = 0; \Delta E)$

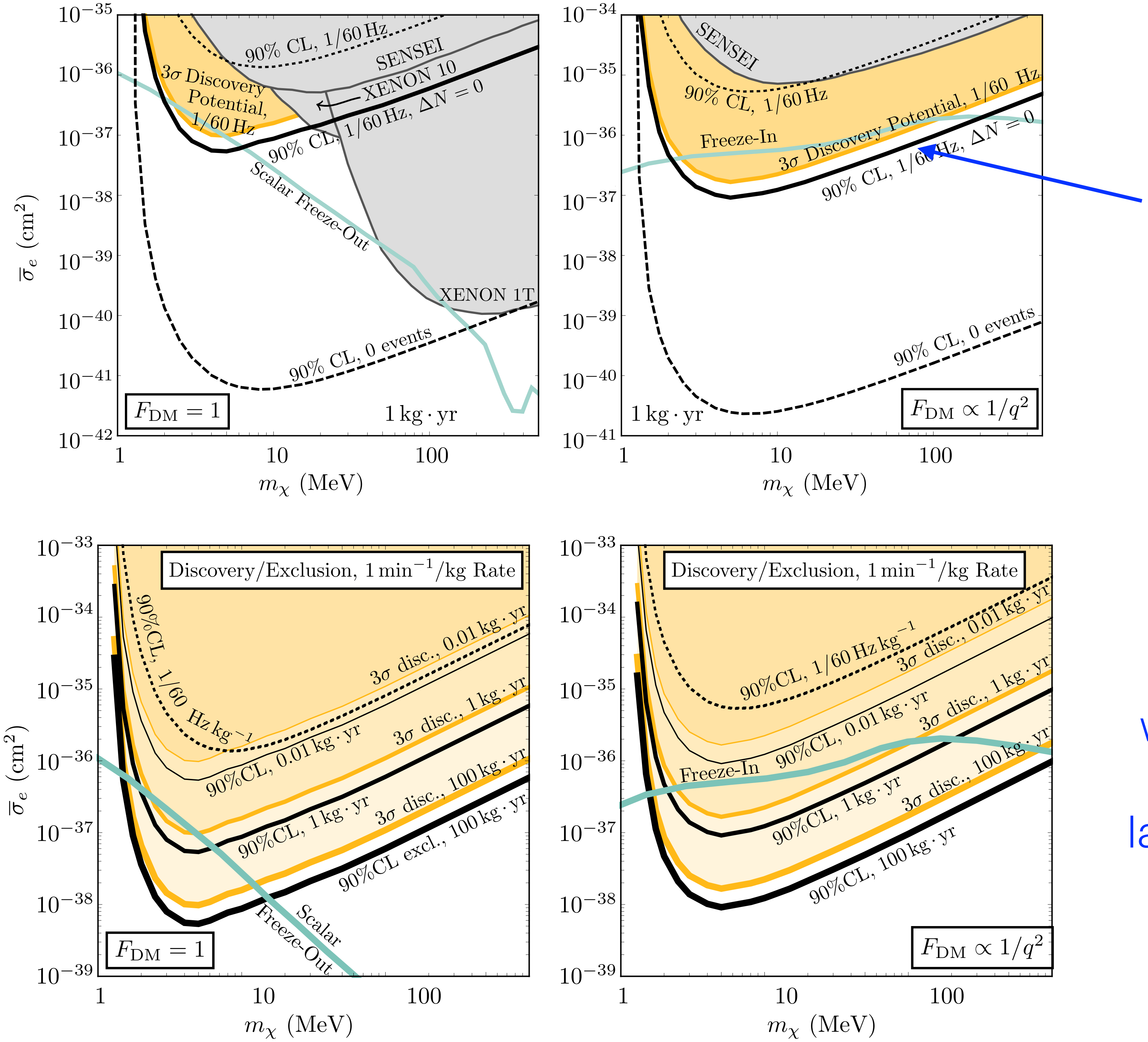




kg for kg, same reach as Si, Ge

[Blanco, **YK**, Lillard, McDermott, PRD 2021; Knapen, Kozaczuk, Lin, PRD 2022]

The power of daily modulation

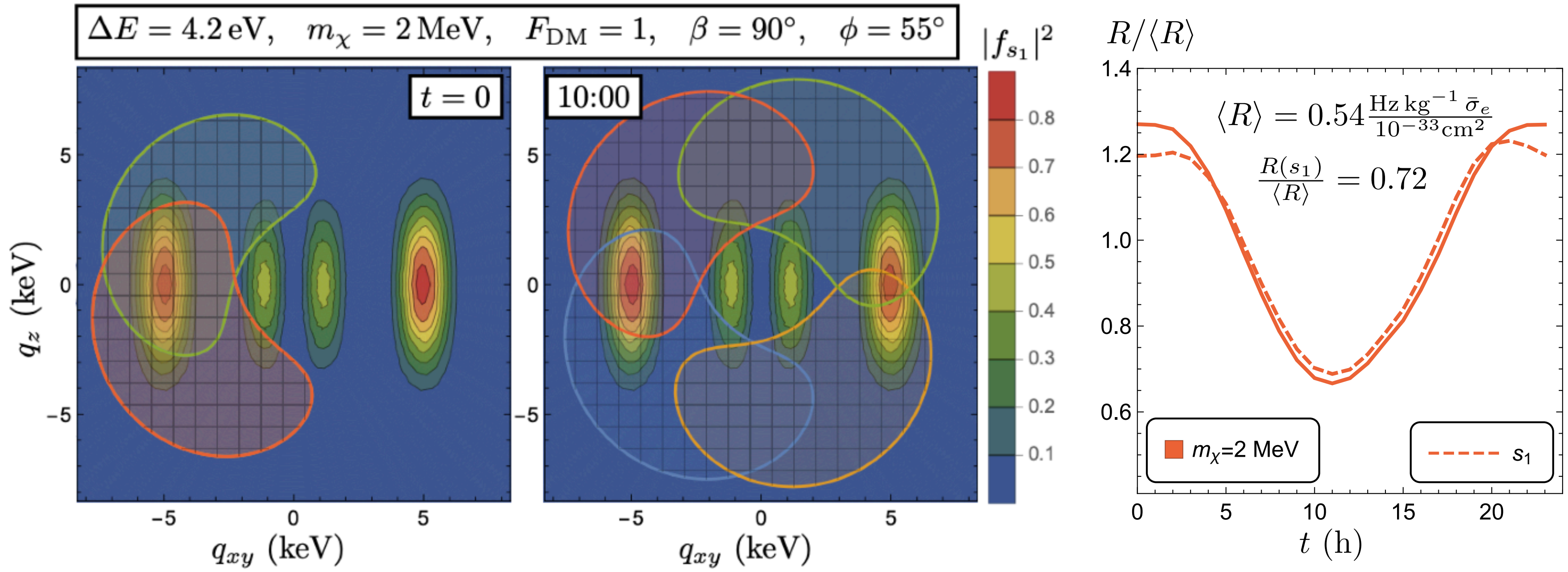


Freeze-in discoverable with 1/min background, but only in modulation analysis!

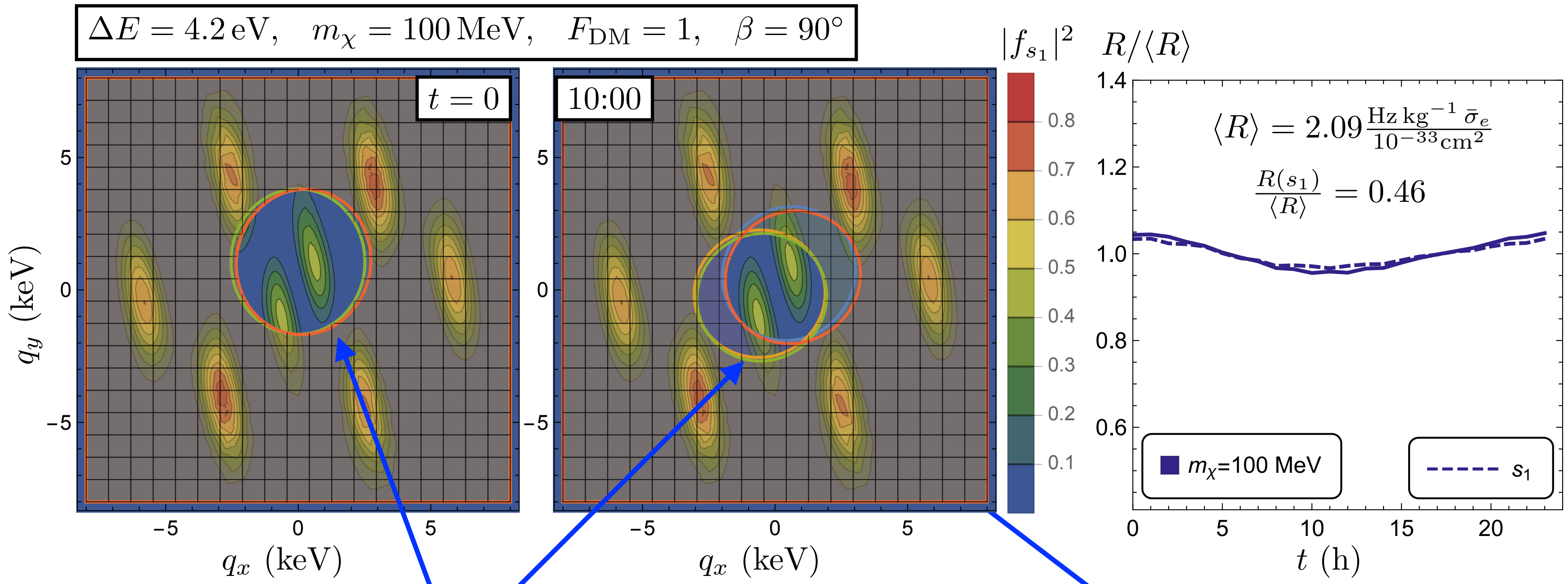
Reach keeps improving with exposure, even with large (constant) background

[Blanco, **YK**, Lillard, McDermott, PRD 2021]

Why can't we do better?



Low masses:
kinematically-allowed "beans" traverse peaks of response function

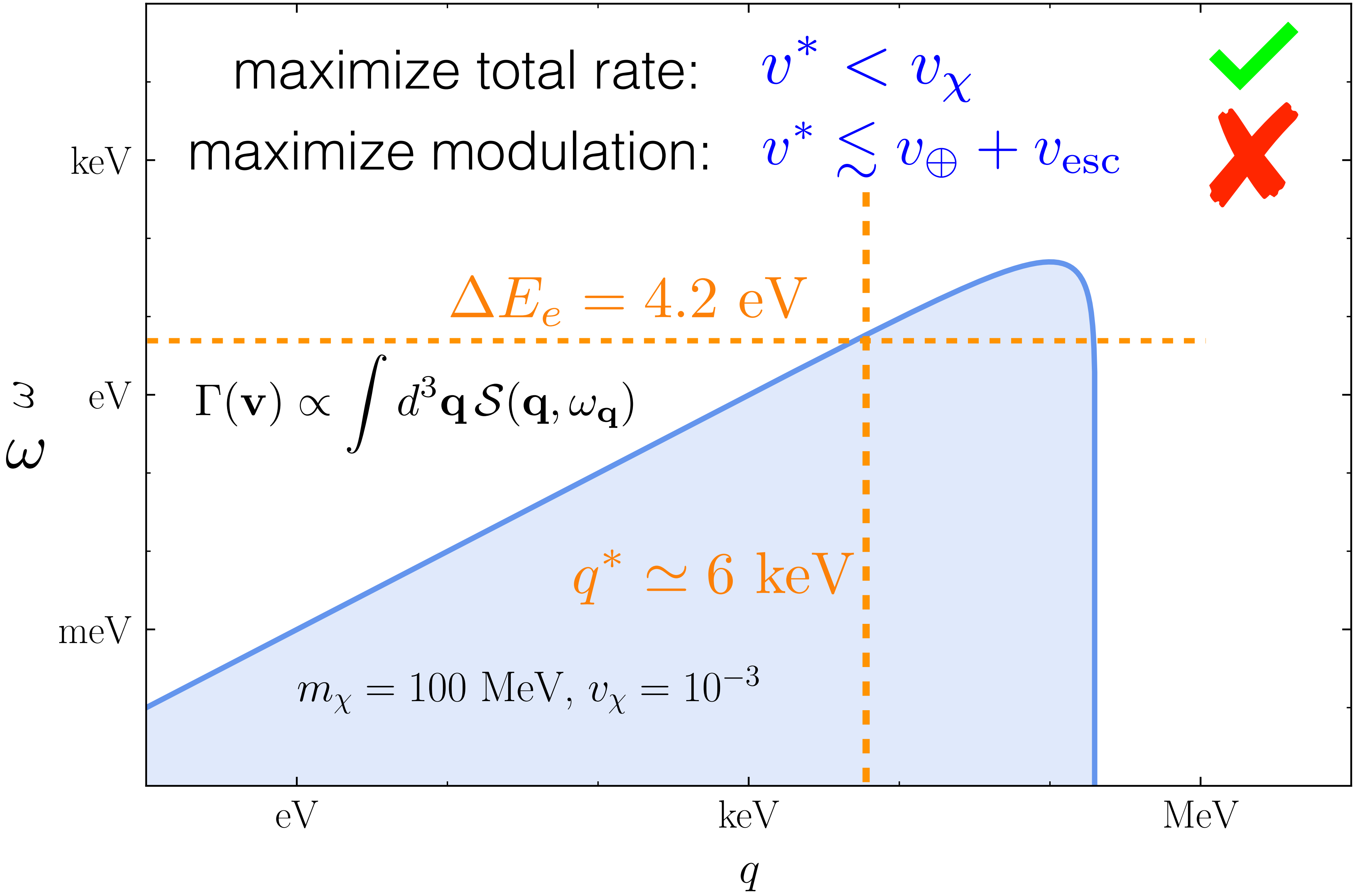


High masses:
peaks are always accessible, residual modulation driven by secondary peaks

$q_{\min} = \Delta E / v_{\max}$ $\quad$ $v^* \equiv \Delta E / q^* \simeq 200 \text{ km/s}$

[Blanco, **YK**, Lillard, McDermott, PRD 2021]

Why can't we do better?



maximize total rate: $v^* < v_\chi$ ✓

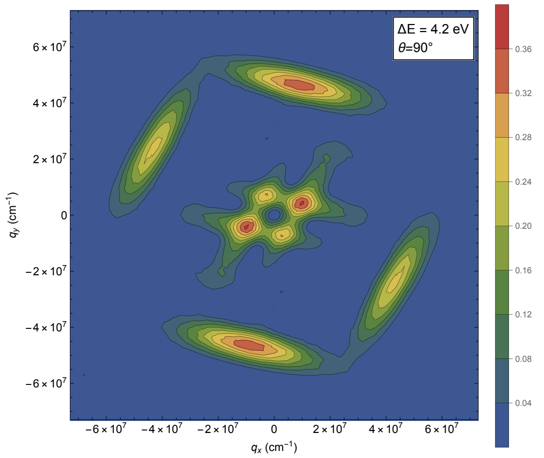
maximize modulation: $v^* \lesssim v_\oplus + v_{\mathrm{esc}}$ ✗

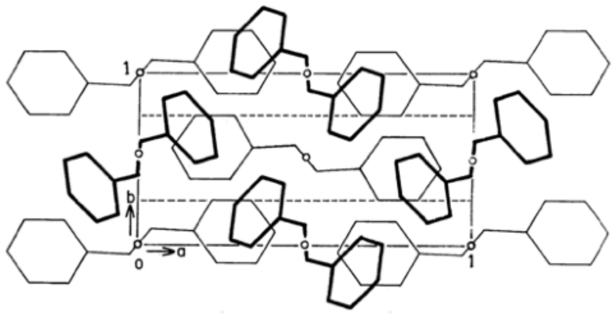
v* controls both total rate and modulation!
Looking at "designer molecules" to optimize

[Blanco, **YK**, Lillard, McDermott, PRD 2021]

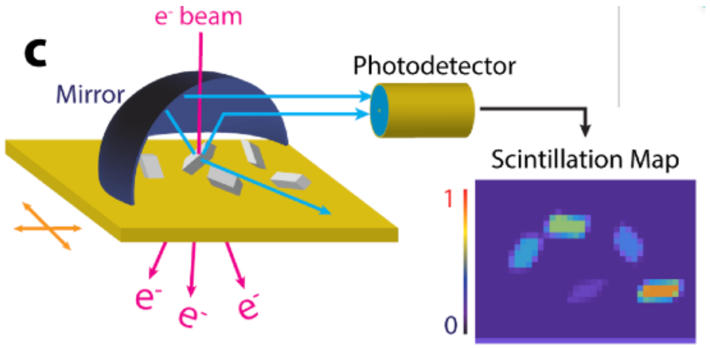
Designing an experiment

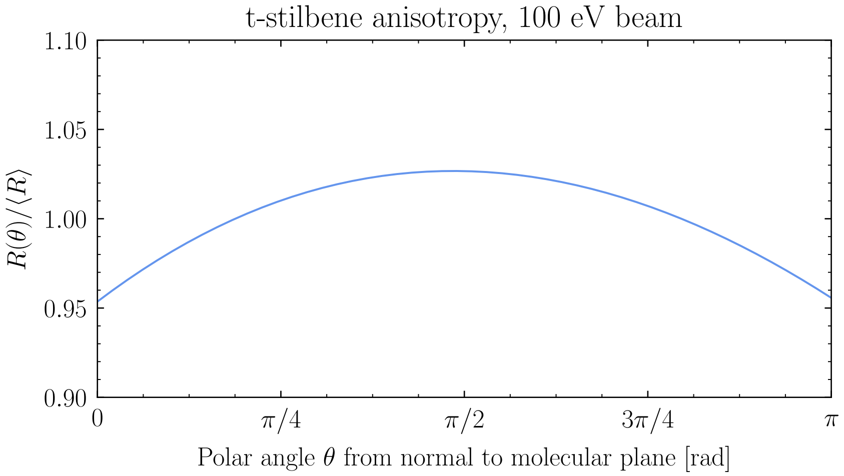
1. Measure response functions of several organic scintillators with X-ray scattering



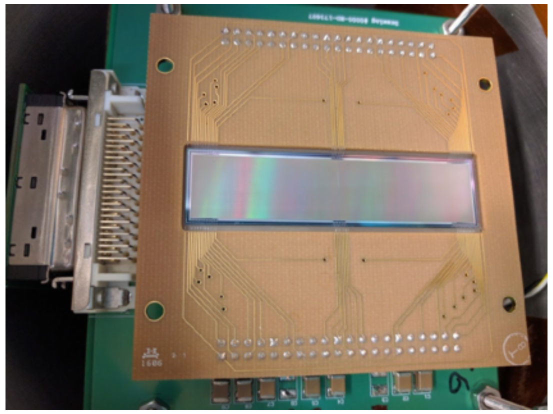


2. Demonstrate anisotropic light yield w/ incident ~100 eV electrons (approved for first measurement at LBNL)





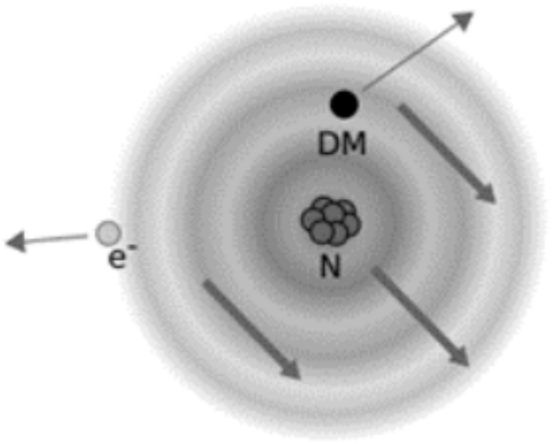
3. Couple a suite of crystal samples to a back-thinned CCD and make a prototype



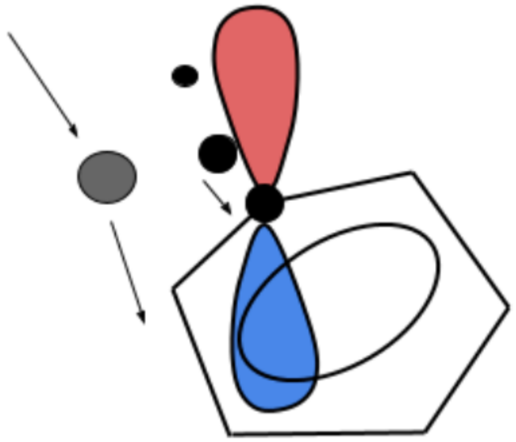
[**YK +** Abbamonte, Baxter, Blanco, Freedman, Liang, Lillard, Rondinelli, Von Kugelgen]

DM-N via Migdal effect

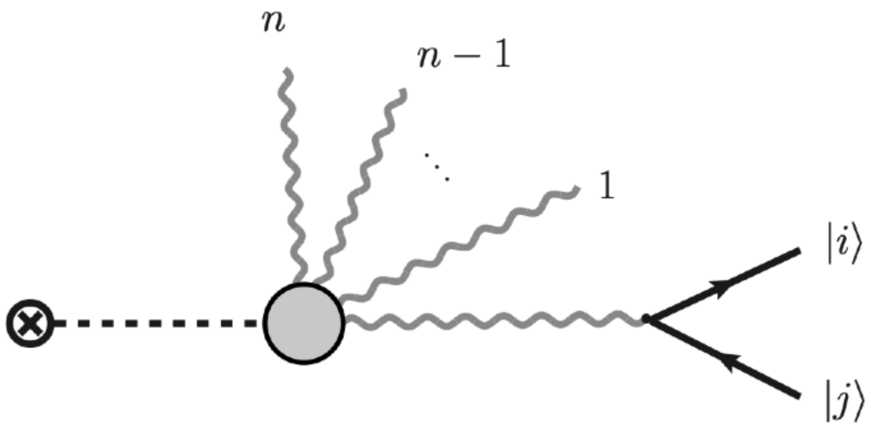
Electrons and nuclei are always coupled!
Whack a nucleus, QM says that electrons can transition



atom



molecule

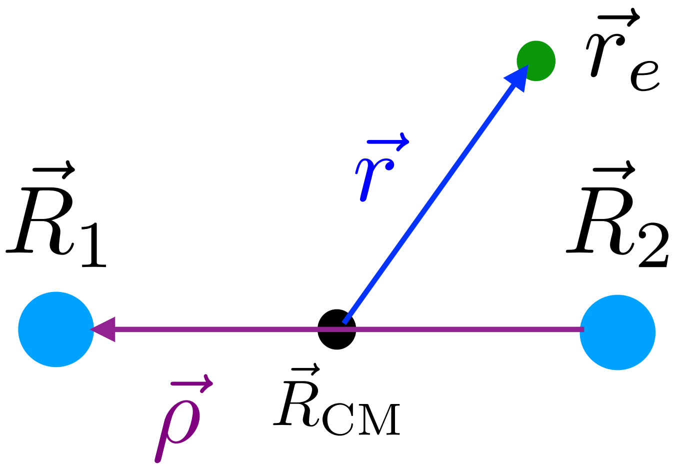


semiconductor
(phonon-mediated)

Charge signal from nuclear scattering — avoid threshold!
Fascinating new area of research: effects usually ignored in CM

[Dolan, Kahlhoefer, McCabe, PRL 2018; Liang et al, arXiv:2205.03395;
Blanco, Harris, **YK**, Lillard, Perez Rios, arXiv:2208.09002]

TWO Migdal effects in molecules!



$$\Psi_0(\vec{R}_1, \vec{R}_2, \vec{r}_e) = \chi_0(\vec{\rho})\left(\overbrace{\psi_0(\vec{r}_e)}^{\text{Born-Oppenheimer}} + \mathcal{O}\left(\frac{m_e}{m_N}\right)\psi'(\vec{r}_e)\right)$$

$$S_M(\vec{q}, \omega) \supset |\langle \Psi' | e^{i\vec{q}\cdot\vec{R}_1} + e^{i\vec{q}\cdot\vec{R}_2} | \Psi_0 \rangle|^2 \delta(\omega - \omega')$$

$$\vec{R}_i \supset \frac{m_e}{m_N}\vec{r}$$

$$\langle \Psi' | \supset \langle \psi' |$$

$$\propto q^2 \left(\frac{m_e}{m_N}\right)^2 |\langle \psi' | \hat{r} | \psi_0 \rangle|^2$$

$$\propto q^2 \left(\frac{m_e}{m_N}\right)^2 |\langle \psi' | \nabla_{\hat{\rho}} \psi_0 \rangle|^2$$

"center of mass recoil" (CMR)

"non-adiabatic coupling" (NAC)

Parametrically identical but orthogonal selection rules!

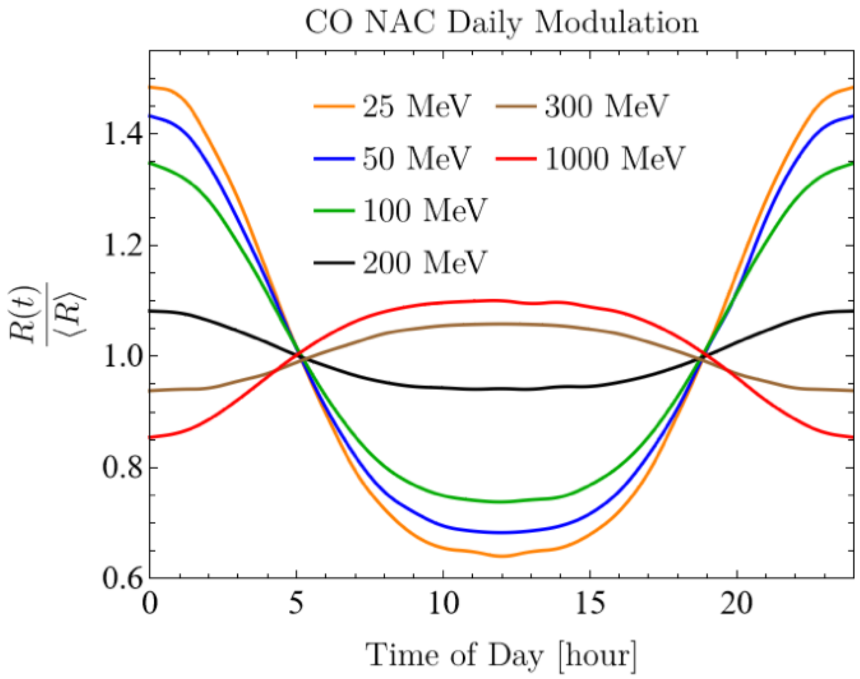
[Lovesey, Bowman, Johnson, Z. Phys. B Cond. Mat. 1982; Colognesi, Physica B 2004;
Blanco, Harris, **YK**, Lillard, Perez Rios, arXiv:2208.09002]

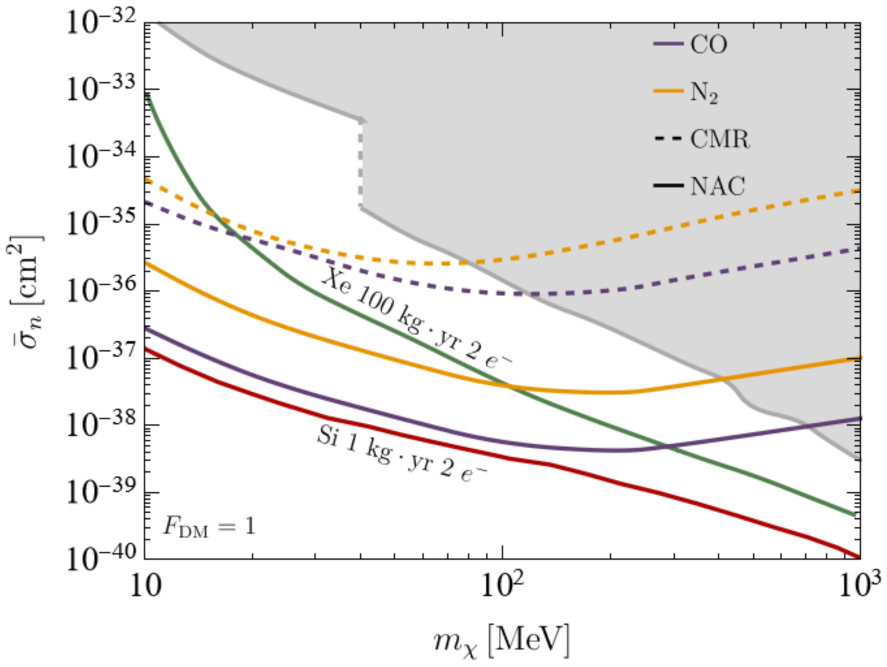
Migdal effect in diatomic molecules (toy example)

For fixed orientation, nuclear matrix elements are also directional:

$$|\langle \chi' | (\hat{q} \cdot \hat{\rho}) \sin(\vec{q} \cdot \vec{\rho}) | \chi_0 \rangle|^2 \sim (\hat{q} \cdot \hat{\rho})^2 \exp\left(-\frac{q^2}{m_N \omega_{\rm vib}} (\hat{q} \cdot \hat{\rho})^2 \right)$$

$\mathcal{O}(1)$ for 100 MeV DM



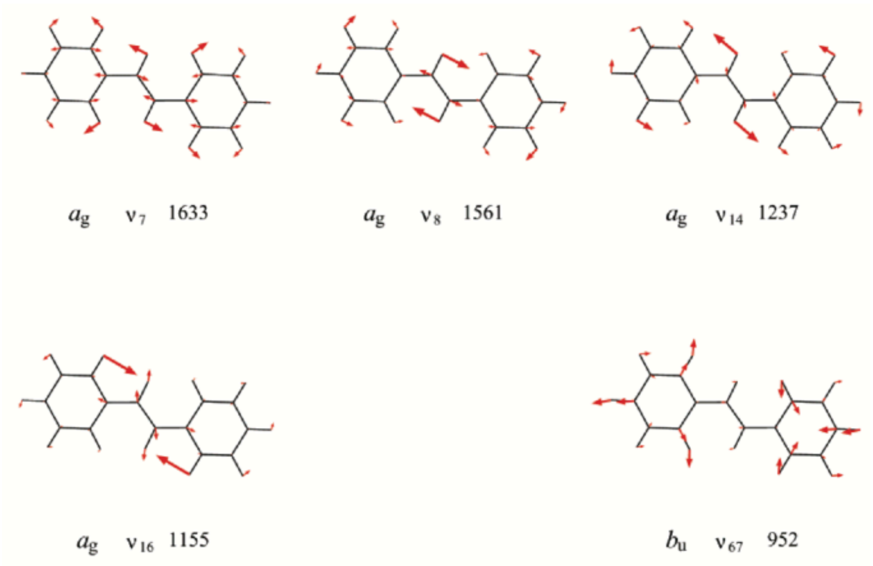


At least 15% daily modulation over entire MeV-GeV range

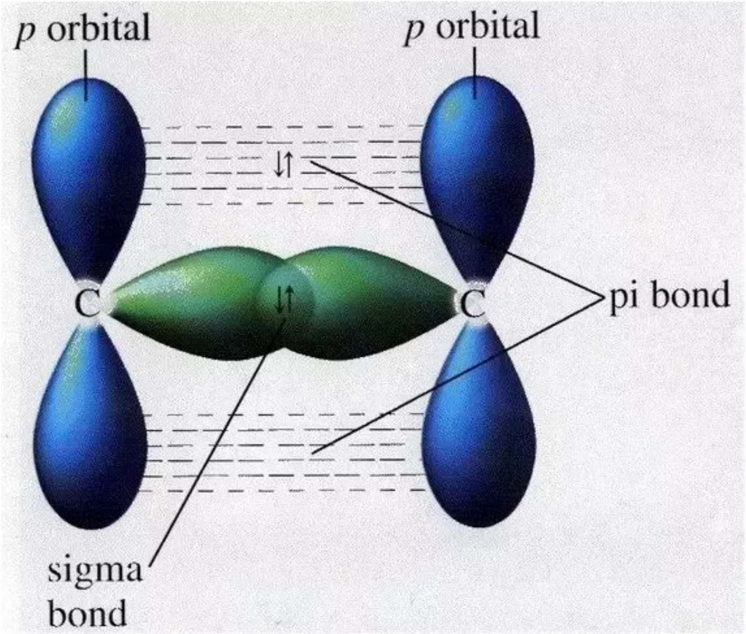
NAC beats CMR by orders of magnitude! Kg for kg, comparable to Si

[Blanco, Harris, **YK**, Lillard, Perez Rios, arXiv:2208.09002]

Generalizing to organic crystals



More normal modes:
NAC should dominate
more over CMR,
more intricate daily
modulation pattern

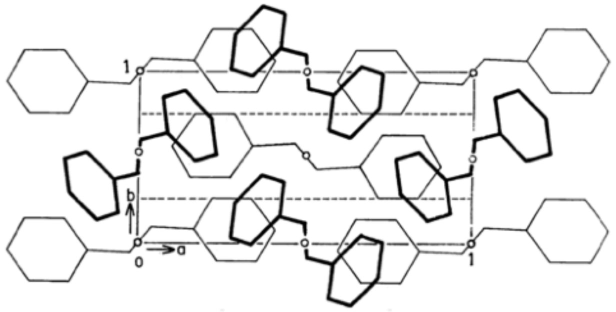


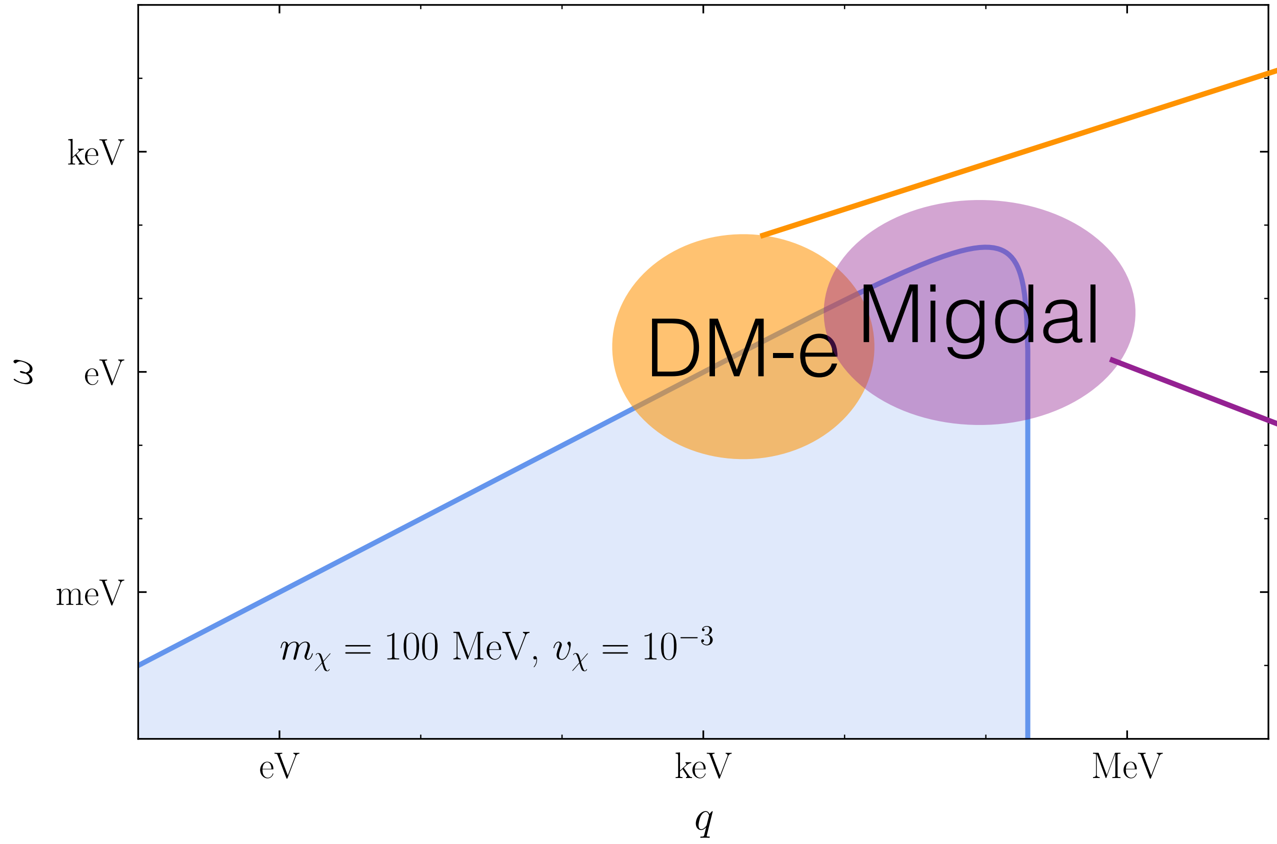
Aromatic bonds are not structural:
excited electron states have similar
nuclear separations, thus large
nuclear matrix elements

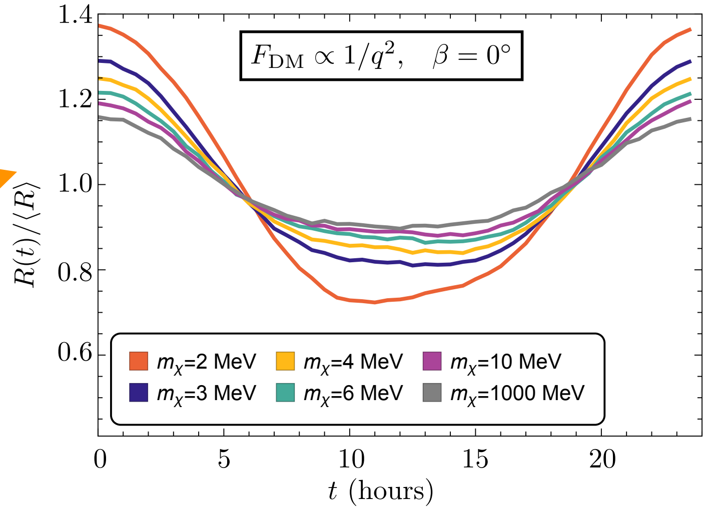
Expect large Migdal rate and large daily modulation in organic scintillators: stay tuned!

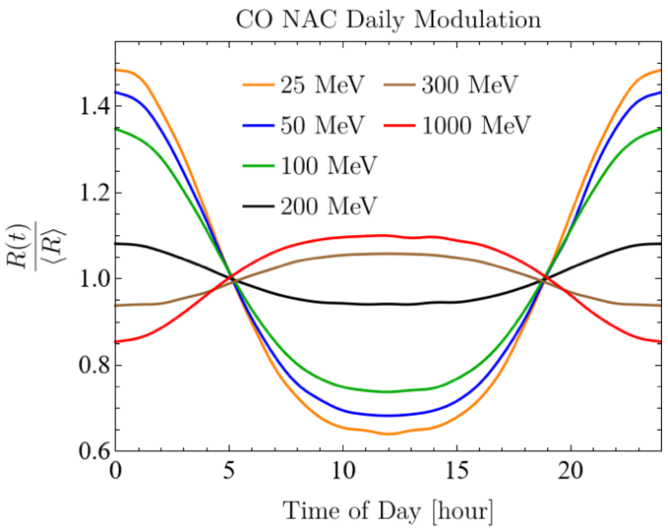
[Blanco, Harris, **YK**, Lillard, Perez Rios, arXiv:2208.09002;
Watanabe et al., J. Phys. Chem. A 2002]

Summary









Organic scintillators are the ideal follow-up experiment to Si and Ge.
Nearly identical DM-e and Migdal sensitivity, plus 20% daily modulation.
Only way to confirm a DM signal!