New Materials for Light DM Detection

Yoni Kahn
University of Illinois at Urbana-Champaign

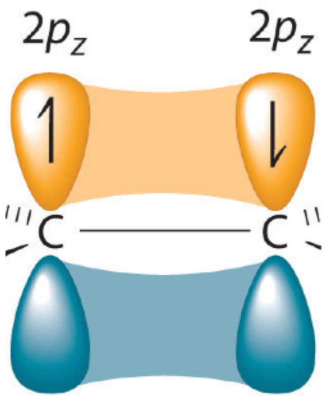
Rencontres de Blois 2022, 5/23/22

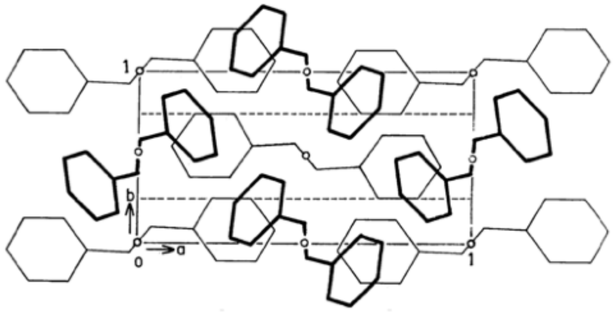
Los Alamos
NATIONAL LABORATORY

DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

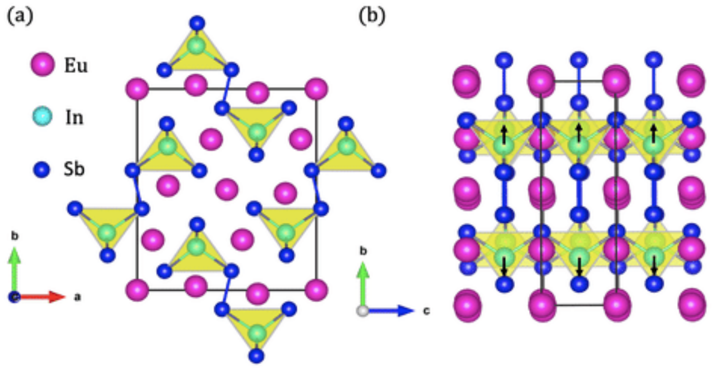
4 new materials:

Organic scintillator crystals for MeV-GeV DM

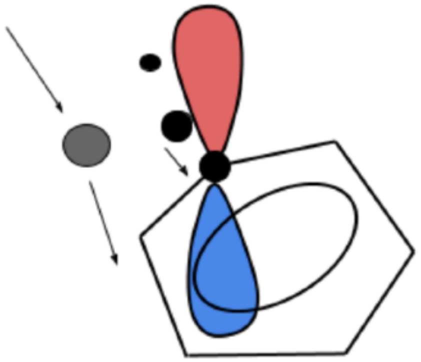




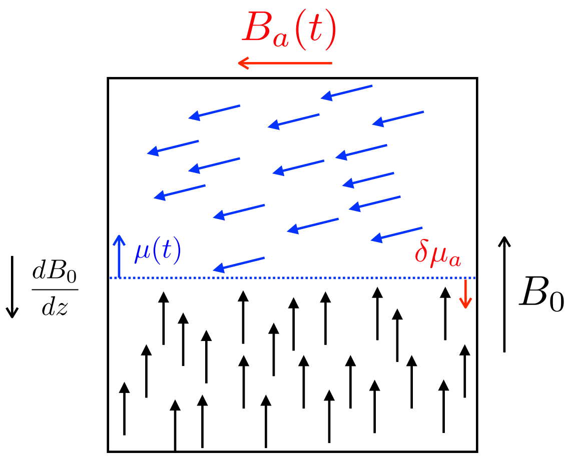
Narrow-gap semiconductors for keV-MeV DM



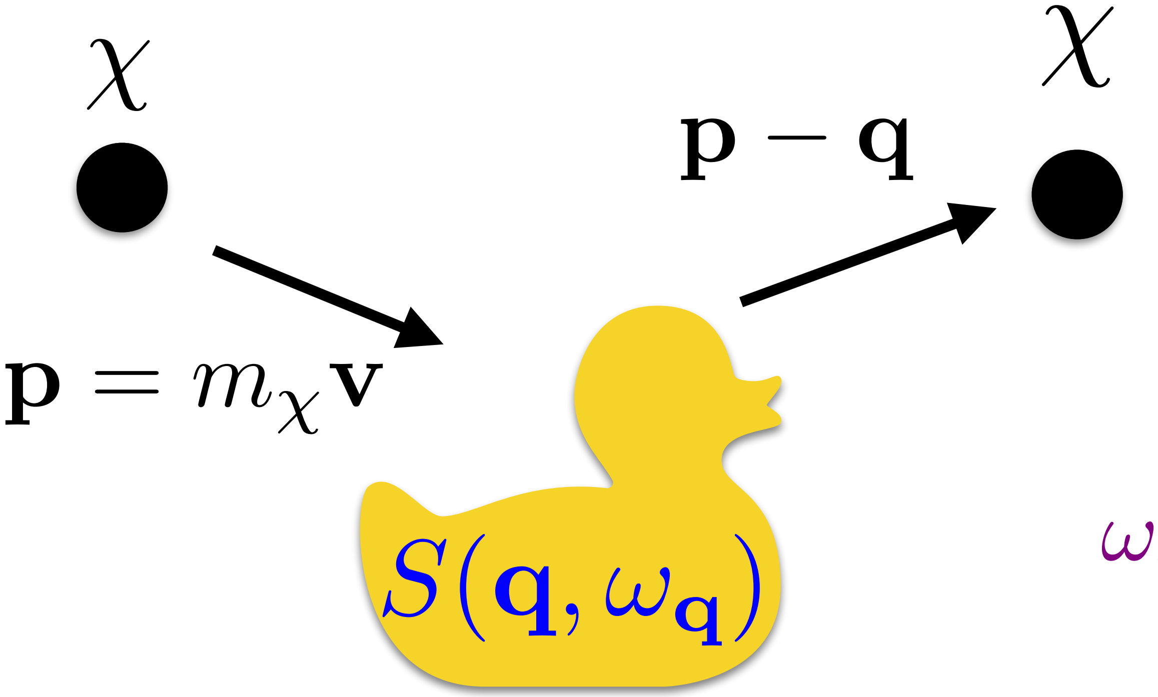
Molecules for Migdal effect



Superfluid 3He-B for axions



Scattering response functions



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

Energy deposited by DM:

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

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

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

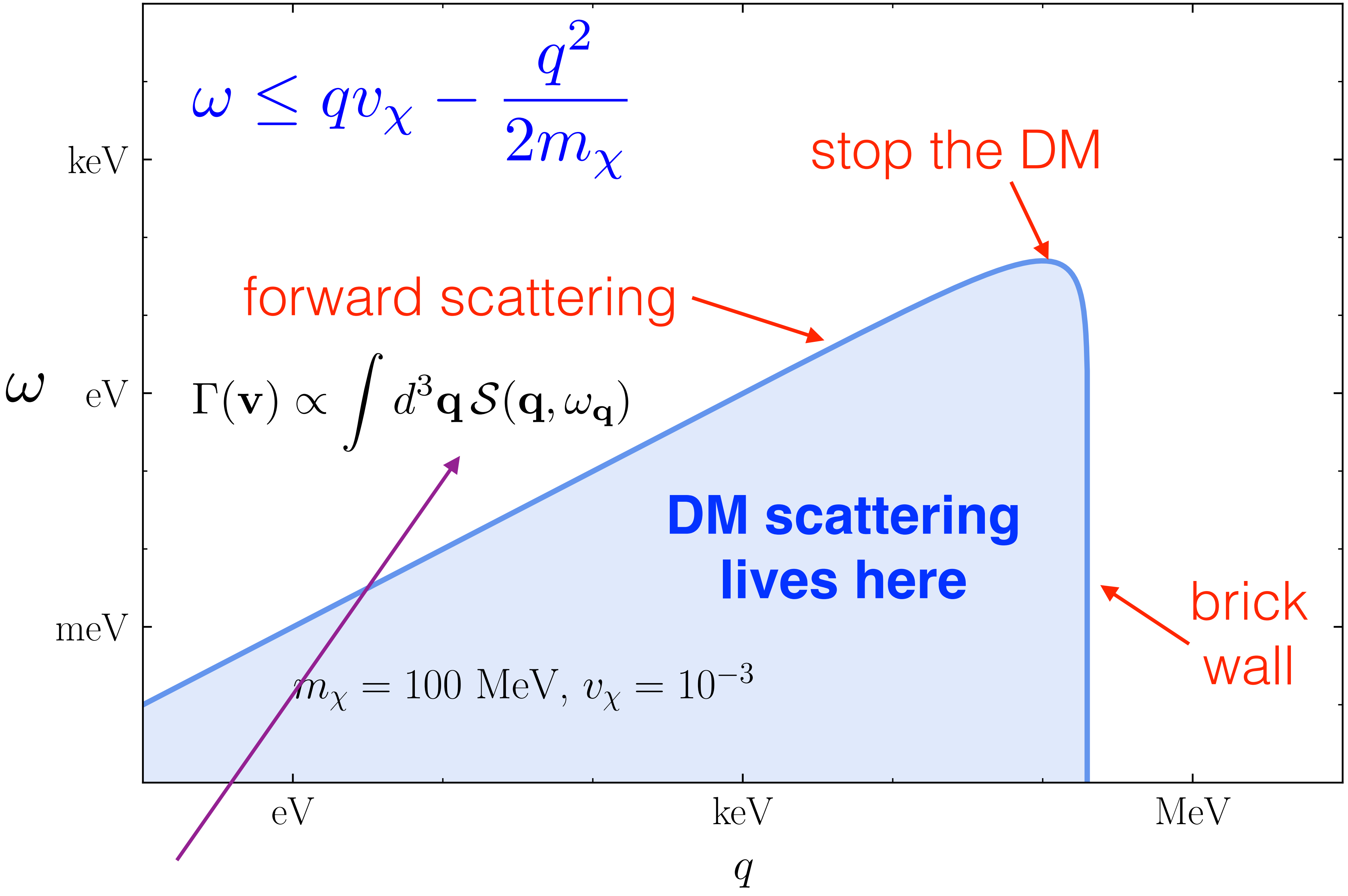
DM properties

Material properties

General framework that works for **any** many-body system

[Trickle, Zhang, Zurek, Inzani, Griffin, JHEP 2020; **YK** and Lin, arXiv:2108.03239]

Sub-GeV DM kinematics



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

stop the DM

forward scattering

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

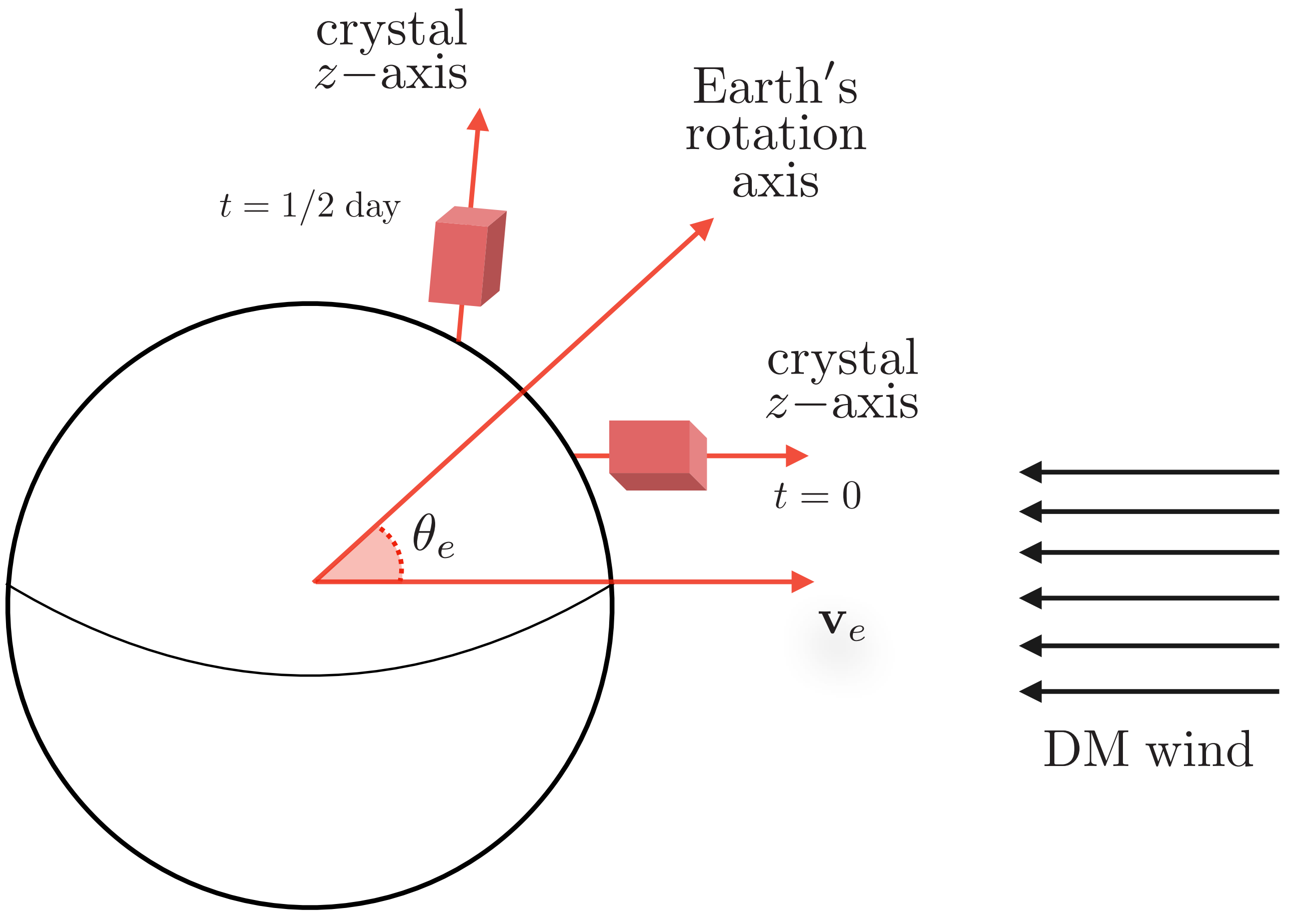
DM scattering lives here

brick wall

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

Goal: maximize the response function inside the DM parabola

Daily modulation



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

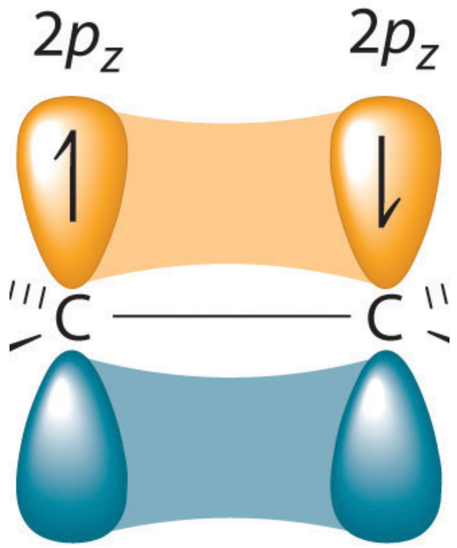
If S is peaked in particular directions of **q**, R will change periodically over 24 hours as $\langle \mathbf{v} \rangle$ rotates in lab frame

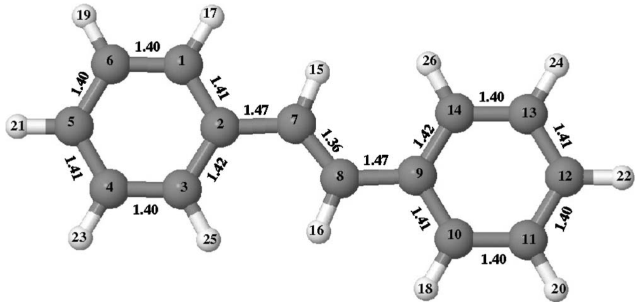
Smoking gun for DM signal!

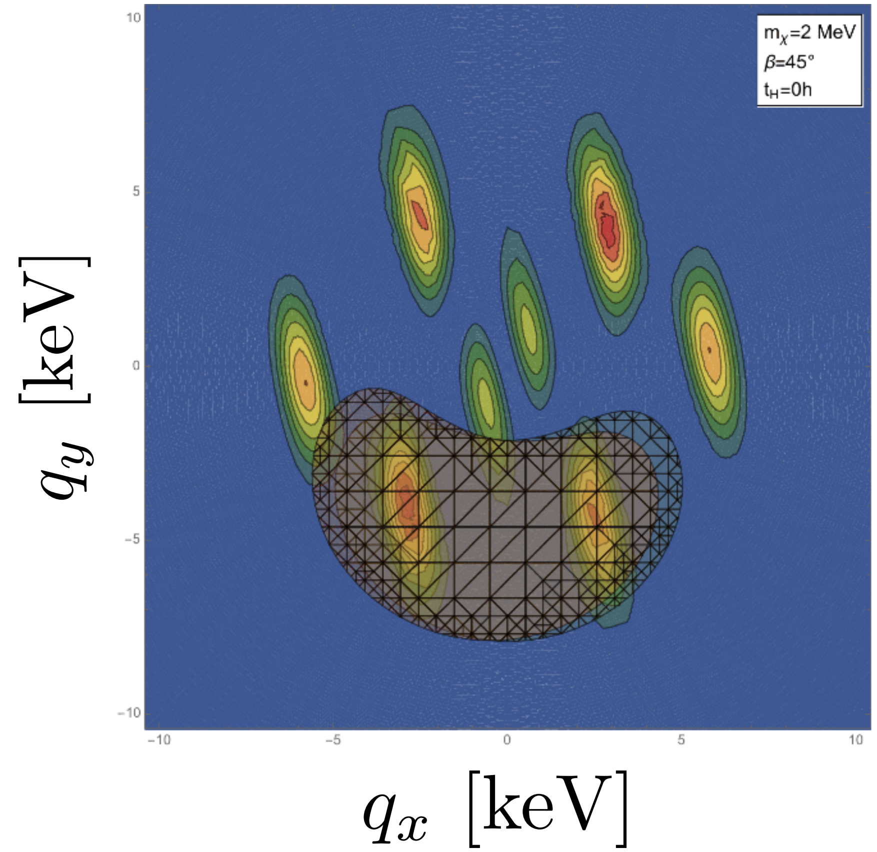
[Spergel, PRD 1988; Coskuner, Mitridate, Olivares, Zurek, PRD 2021]

Organic crystals

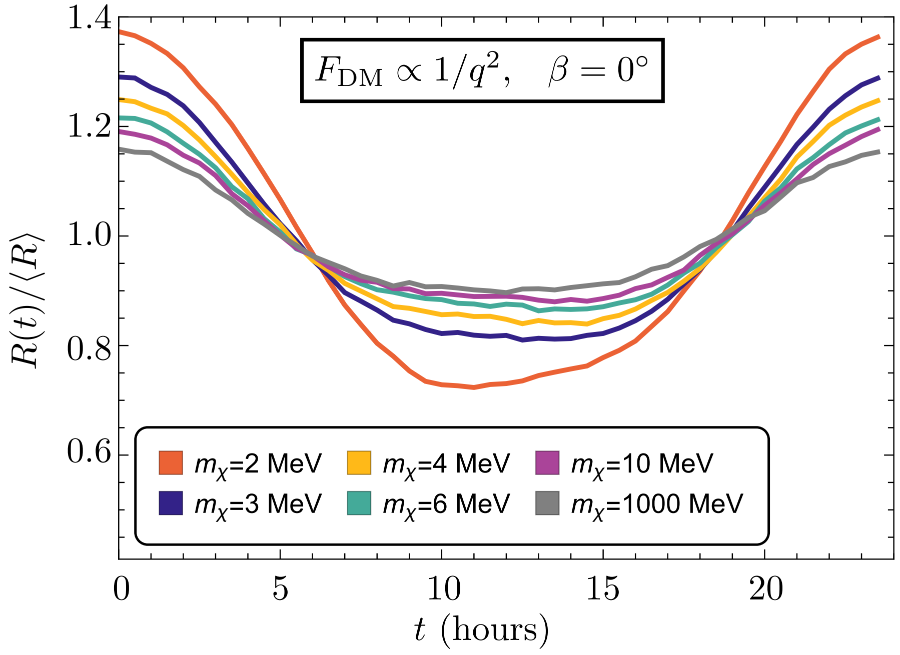
Carbon bonds give eV-scale energy gaps, anisotropic response







response function
(lowest transition)



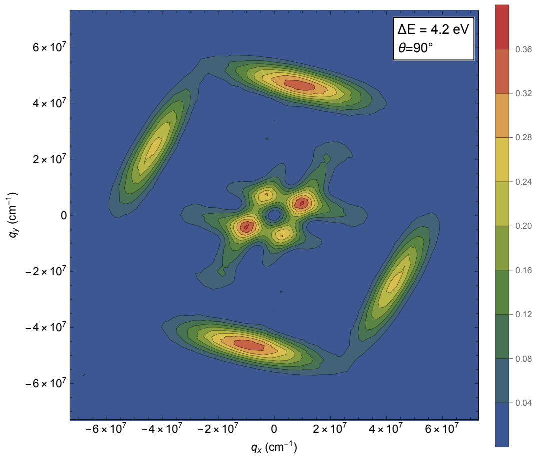
20% daily modulation!

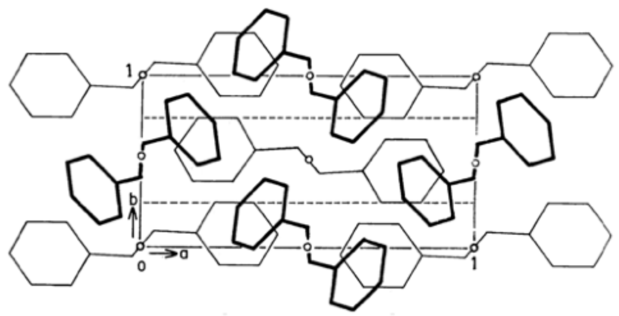
Kg for kg, same total rate as Si (see T. Volansky talk),
but modulation means discovery does not require zero background

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

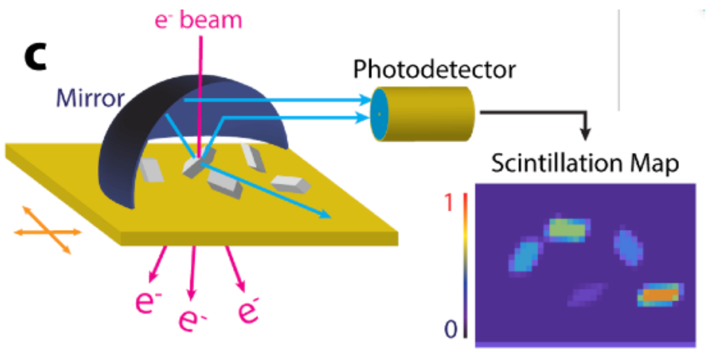
Designing an experiment

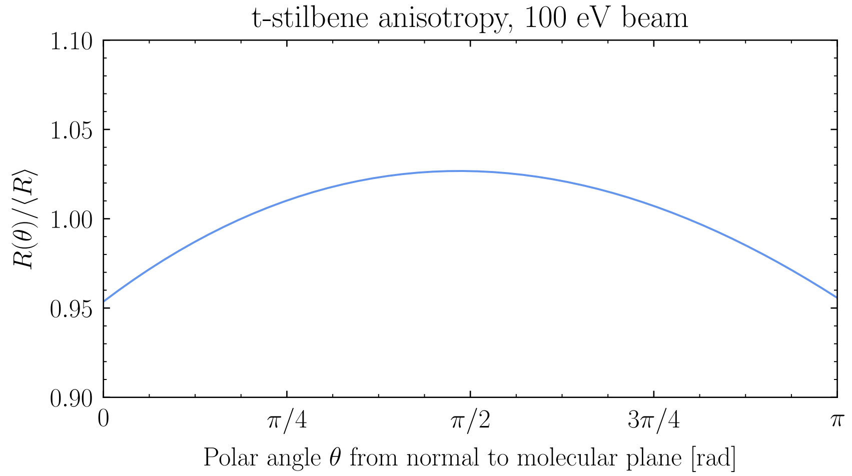
1. Measure response function with electron energy-loss spectroscopy



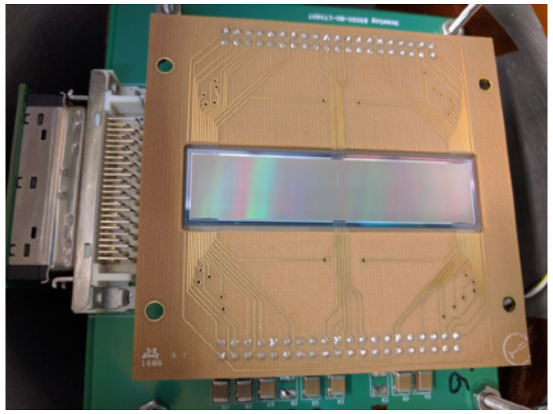


2. Demonstrate anisotropic light yield w/ incident ~100 eV electrons (approved for measurement at LBNL!)



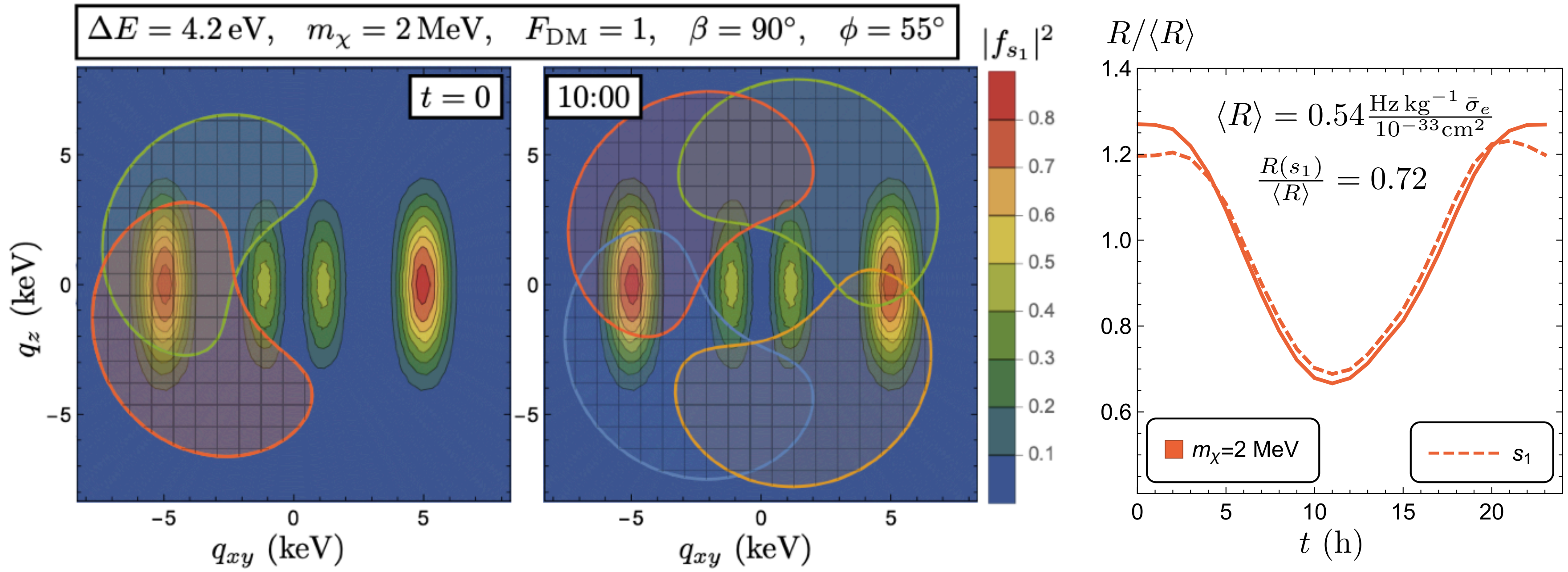


3. Couple a t-stilbene crystal to a CCD and make a prototype

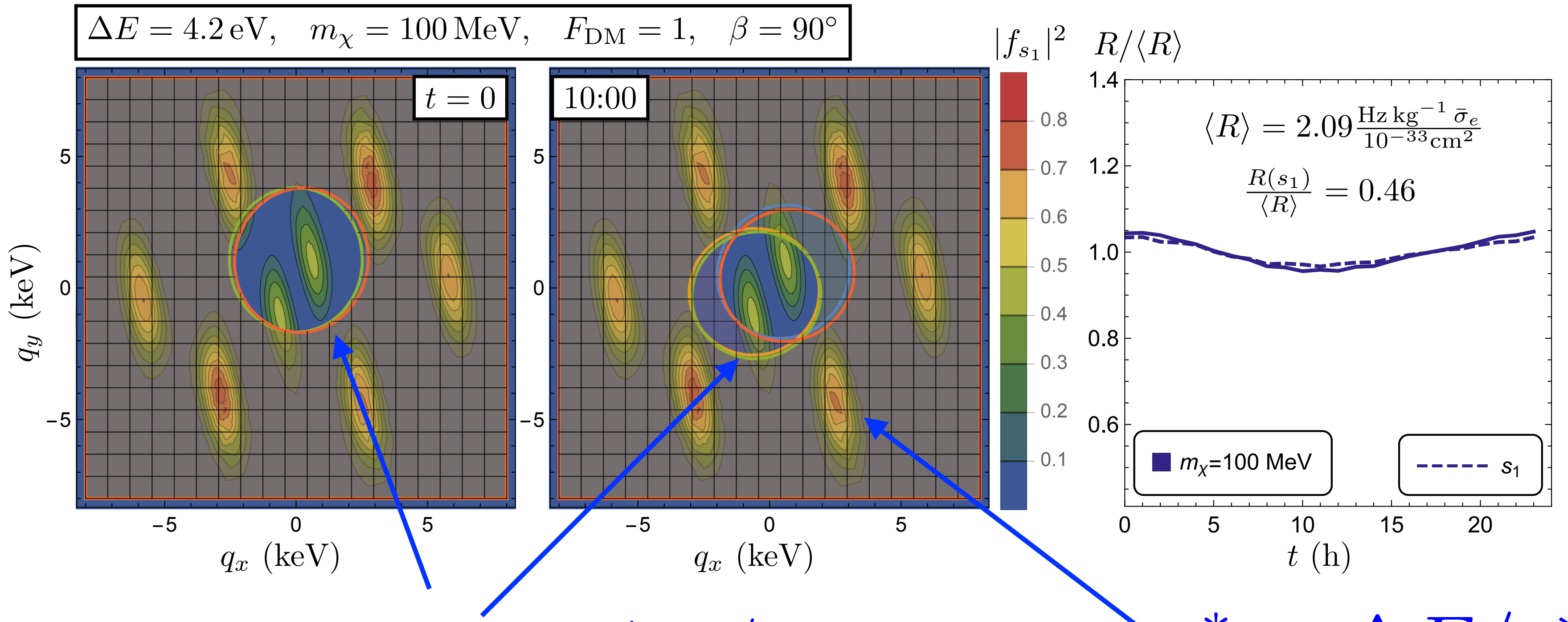


[**YK**, Liang, Lillard, Collar + UIUC/UChicago/Northwestern/Fermilab/Princeton/MIT]

Why can't we do better?



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



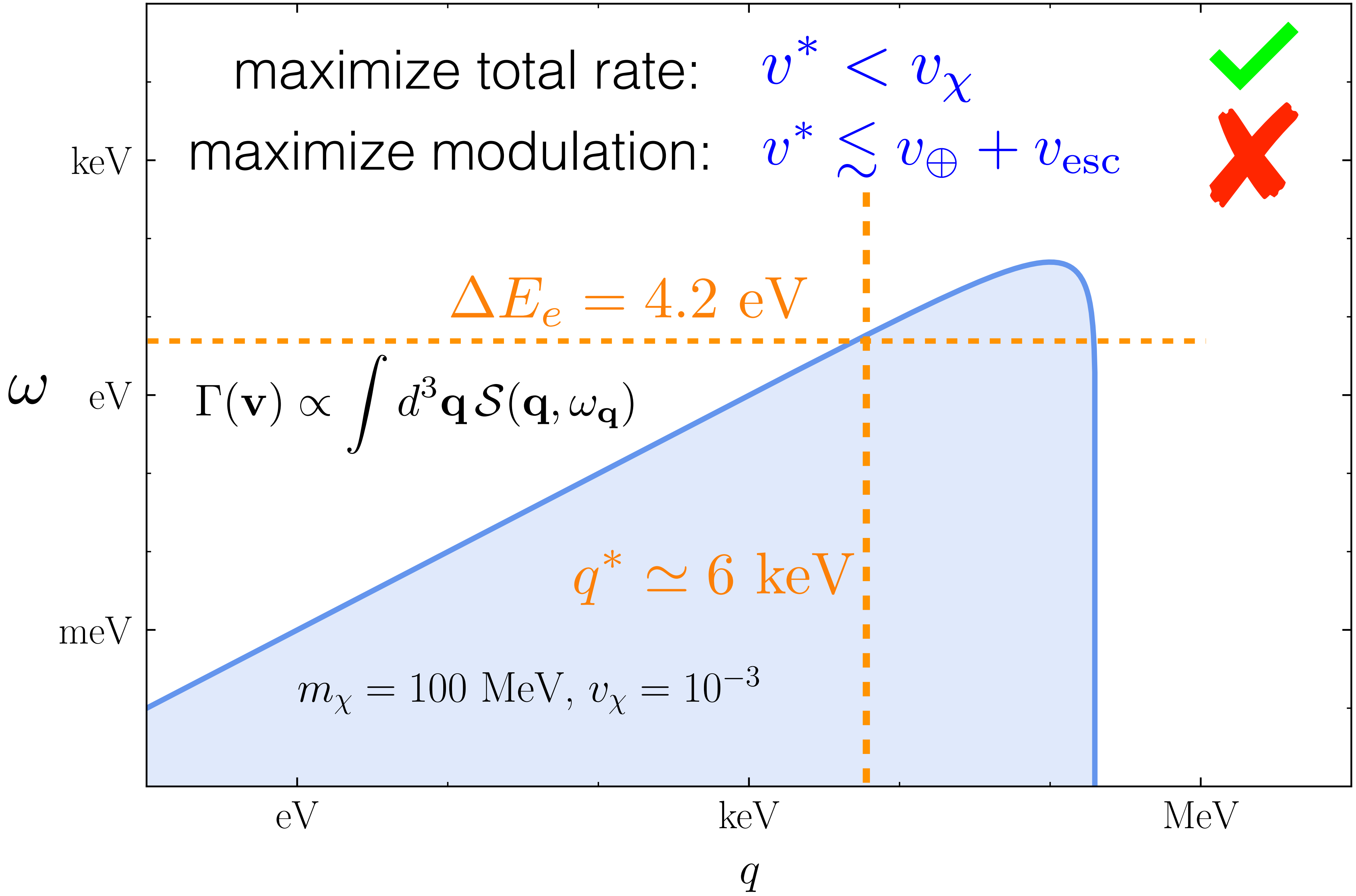
High masses: peaks are always accessible, residual modulation driven by secondary peaks

$q_{\rm min} = \Delta E / v_{\rm max}$

$v^* \equiv \Delta E / q^* \simeq 200\ \mathrm{km/s}$

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

Why can't we do better?

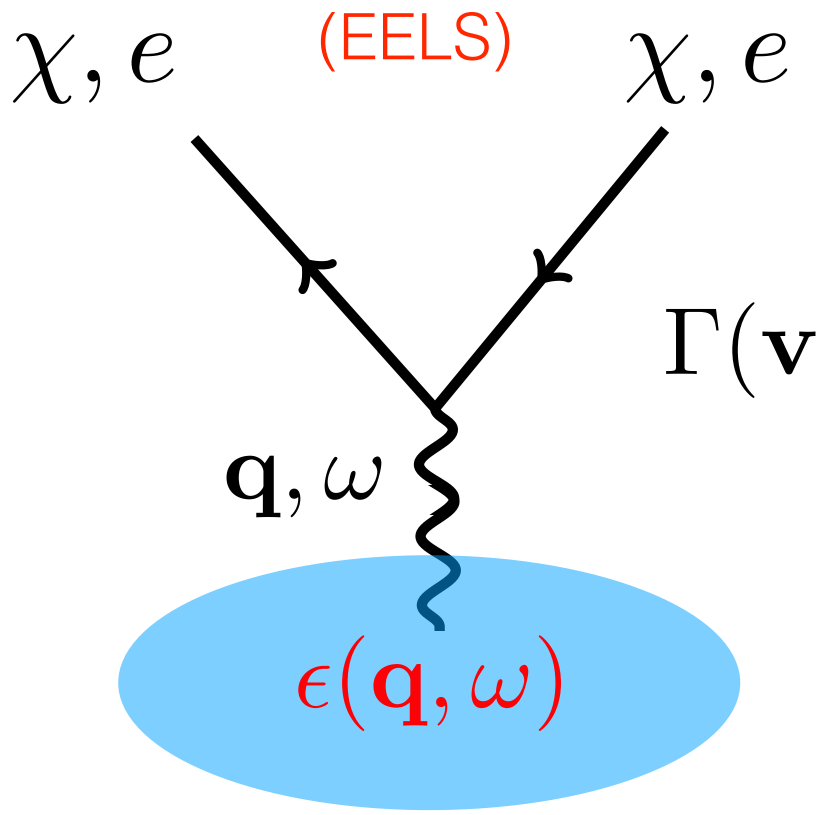


Effective electron velocity controls both total rate and modulation!

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

Measuring electron response

Just like deep inelastic scattering lets us measure strong QCD effects with QED probes, electrons can act as “proxy” for DM



electron energy-loss spectroscopy (EELS)

DM-electron interaction (assumed spin-independent)

Response function (dielectric, for electrons)

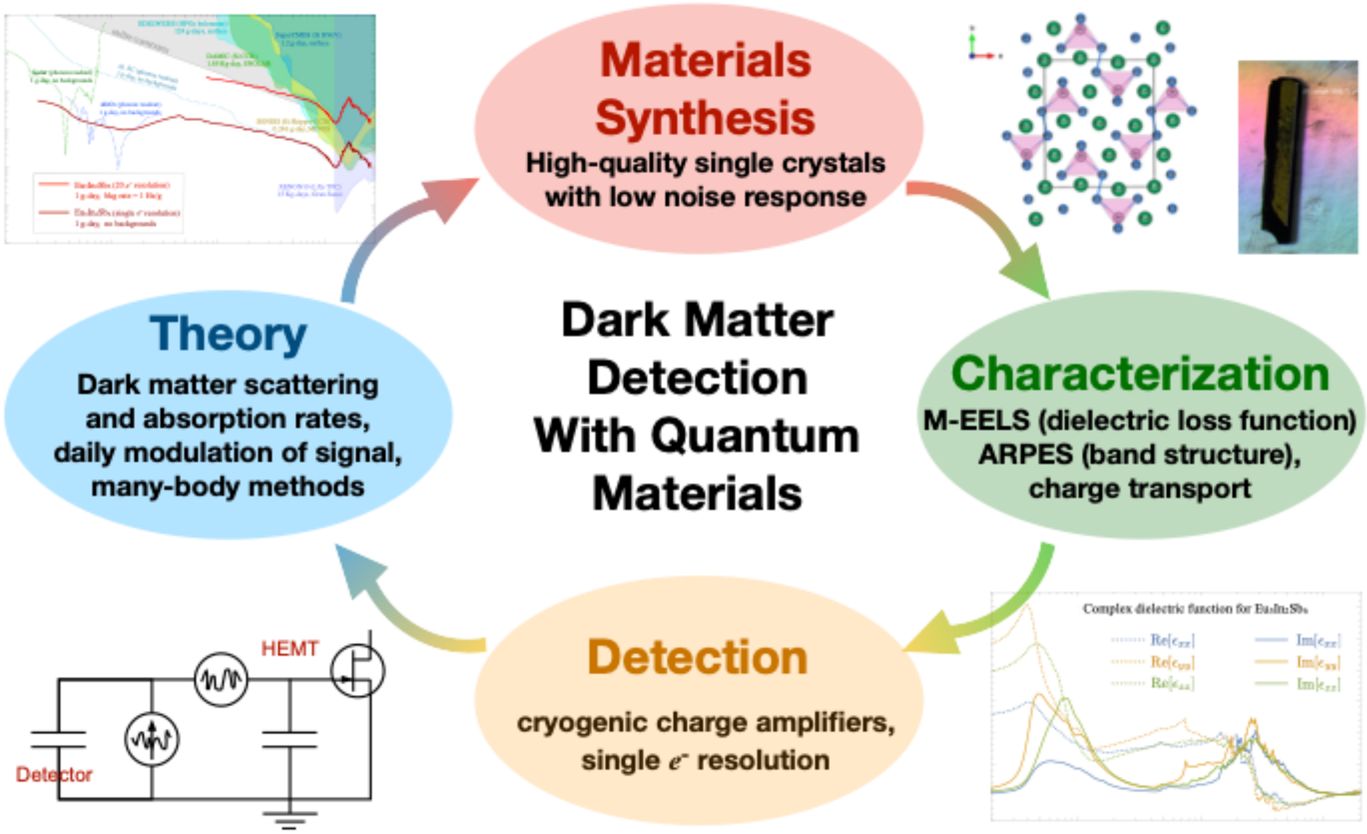
$$\Gamma(\mathbf{v}) = \int \frac{d^3\mathbf{q}}{(2\pi)^3} |V(\mathbf{q})|^2 \left[\frac{q^2}{e^2}\, 2\,\mathrm{Im}\left(-\frac{1}{\epsilon(\mathbf{q},\omega)}\right)\right]$$

Works even for materials too complicated to compute electron wavefunctions directly!

[Pines and Nozieres Phys. Rev. 1959;
Berggren, Hochberg, **YK**, Kurinsky, Lehmann, Yu, PRL 2021]

SPLENDOR

With the loss function in hand, can obtain the expected DM-electron response in a **data-driven** way



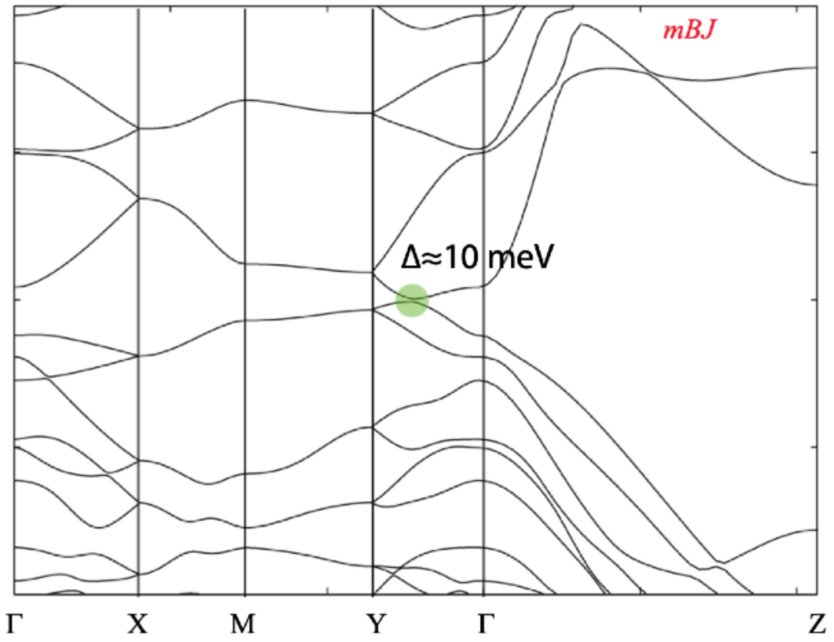
Materials Synthesis
High-quality single crystals with low noise response

Dark Matter Detection With Quantum Materials

Theory
Dark matter scattering and absorption rates, daily modulation of signal, many-body methods

Characterization
M-EELS (dielectric loss function) ARPES (band structure), charge transport

Detection
cryogenic charge amplifiers, single e^- resolution

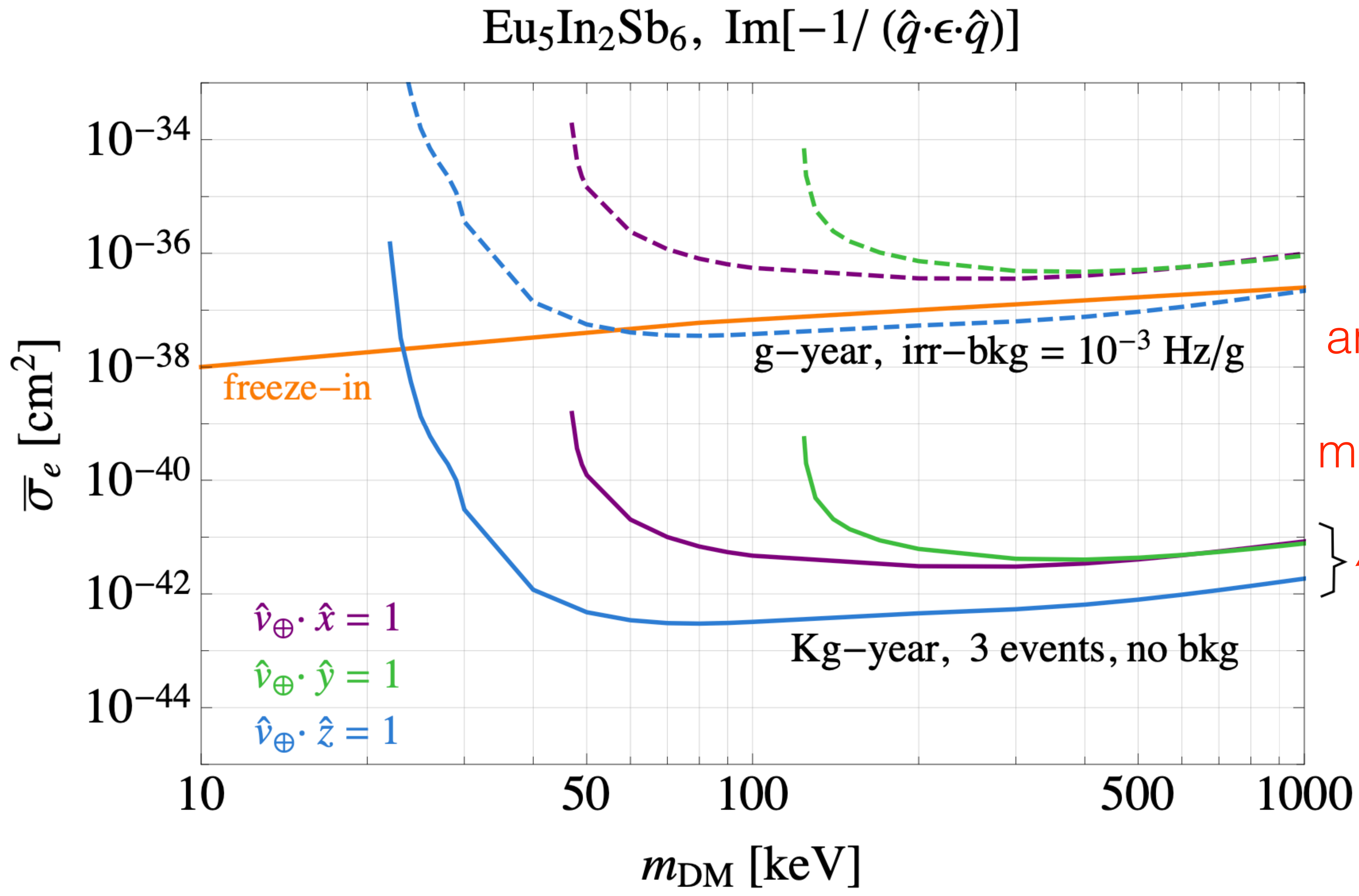


$Eu_5In_2Sb_6$: narrow-gap anisotropic semiconductor

First measurements being performed now, prototype amplifier coming soon!

[SPLENDOR collab. incl. **YK**, LANL/UIUC/SLAC/CSU East Bay]

PRELIMINARY reach

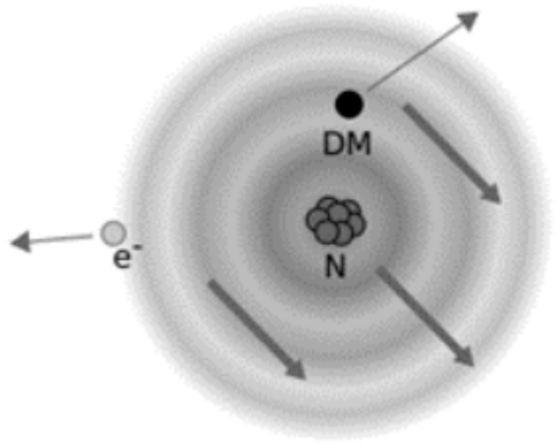


anisotropy:
daily
modulation!

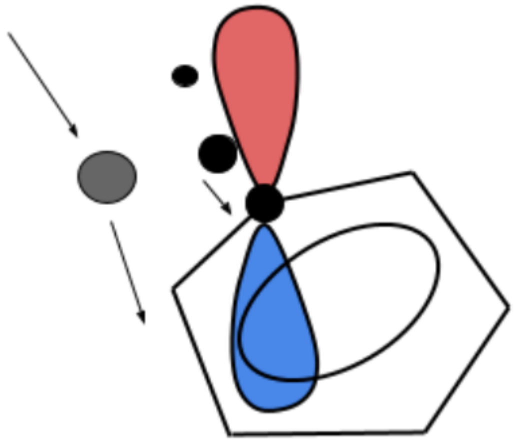
[D. Alves, SPLENDOR collab. incl. **YK**, to appear]

Migdal effect

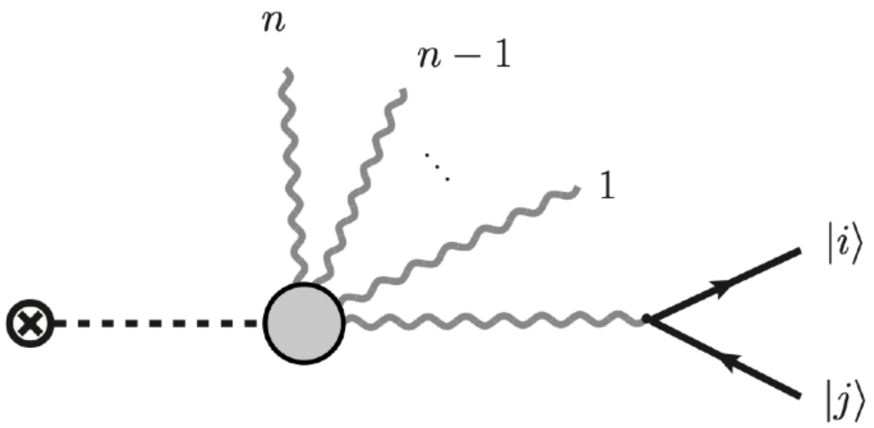
Electrons and nuclei are always coupled!
Whack a nucleus, QM says that electrons can transition



atom



molecule

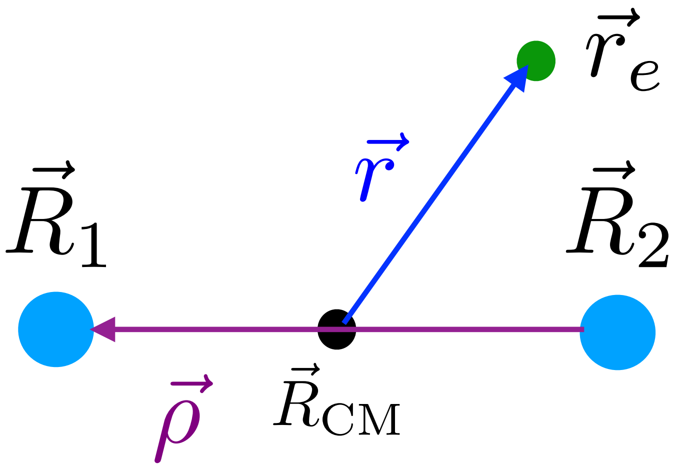


semiconductor
(phonon-mediated)

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

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

TWO Migdal effects in molecules!



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

$$P_M = |\langle \Psi' | e^{i\vec{q}\cdot\vec{R}_1} + e^{i\vec{q}\cdot\vec{R}_2} | \Psi_0 \rangle|^2$$

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

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

"center of mass recoil"

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

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

"non-adiabatic coupling"

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, to appear]

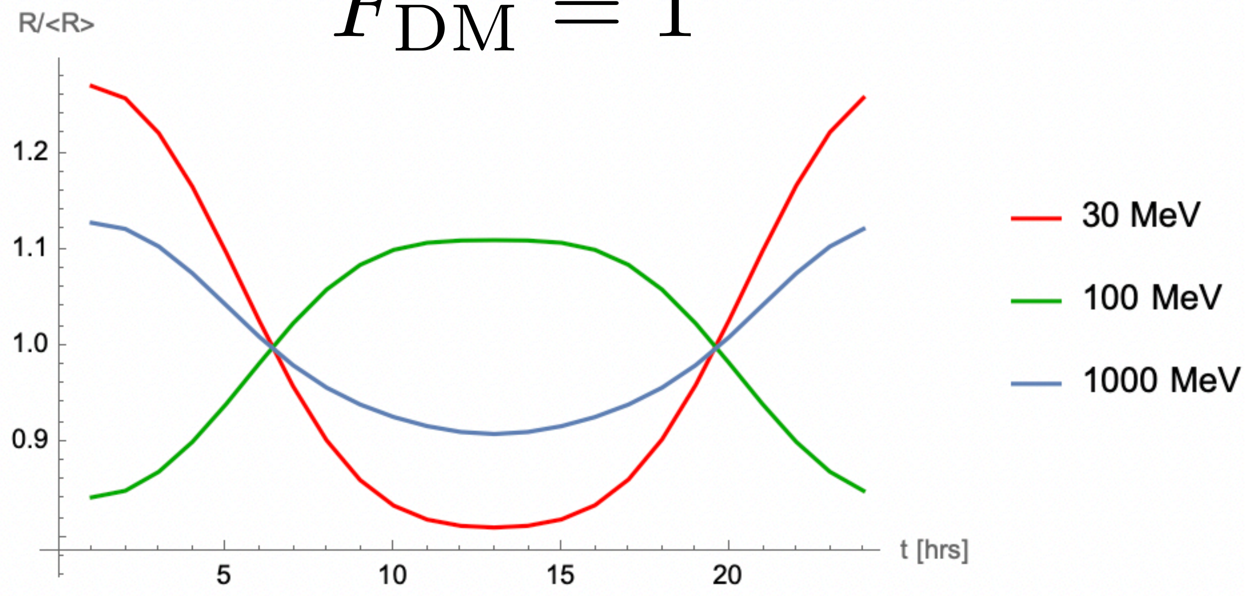
Midgal daily modulation (PRELIMINARY)

For fixed orientation, nuclear matrix elements are also directional:

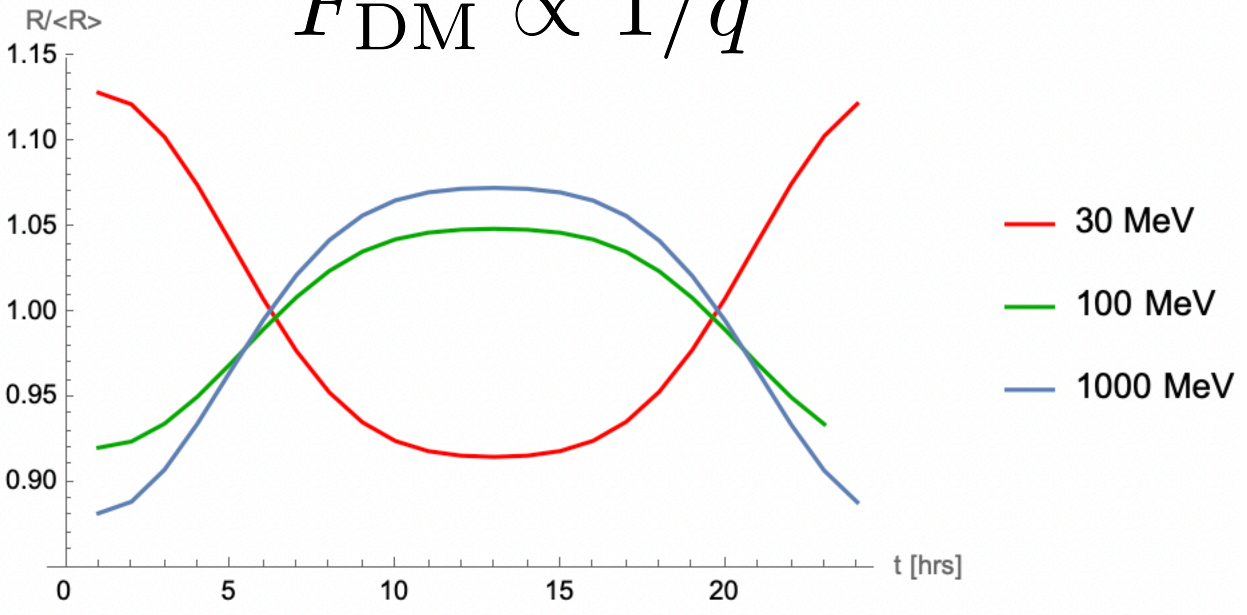
$$|\langle\chi'|(\hat{q}\cdot\hat{\rho})\sin(\vec{q}\cdot\vec{\rho})|\chi_0\rangle|^2 \sim (\hat{q}\cdot\hat{\rho})^2 \exp\left(-\frac{q^2}{m_N\omega_{\text{vib}}}(\hat{q}\cdot\hat{\rho})^2\right)$$

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

$F_{\text{DM}} = 1$

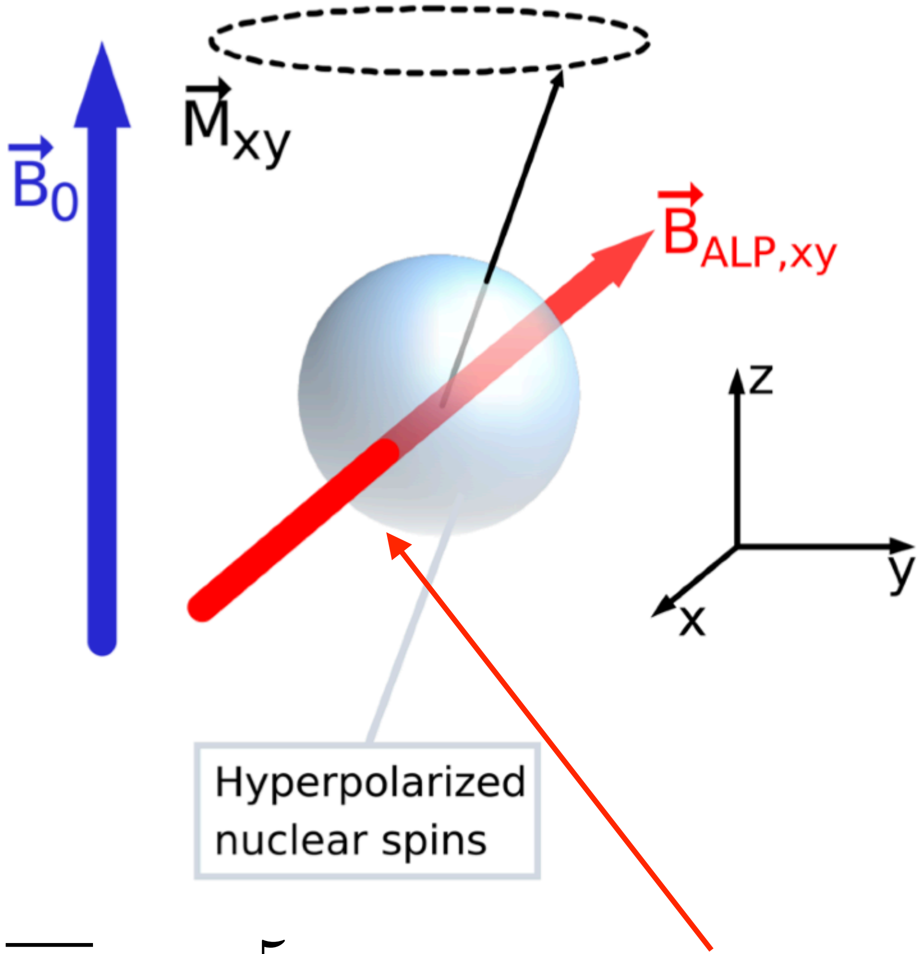


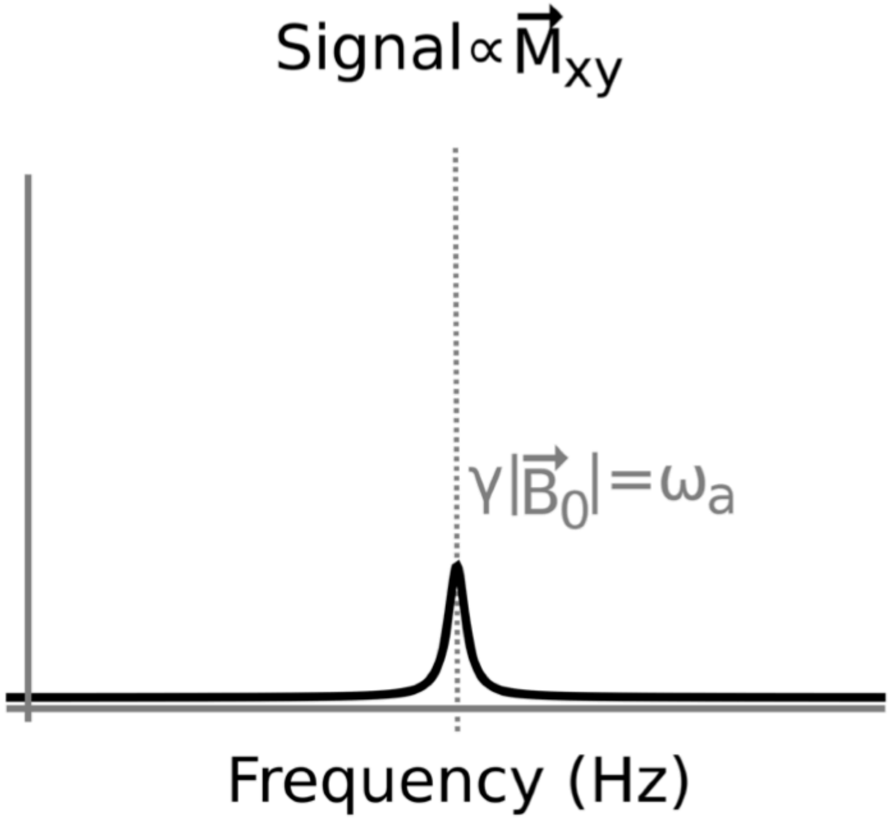
$F_{\text{DM}} \propto 1/q^2$



[Blanco, Harris, **YK**, Lillard, Perez Rios, to appear]

Axion wind with CM systems





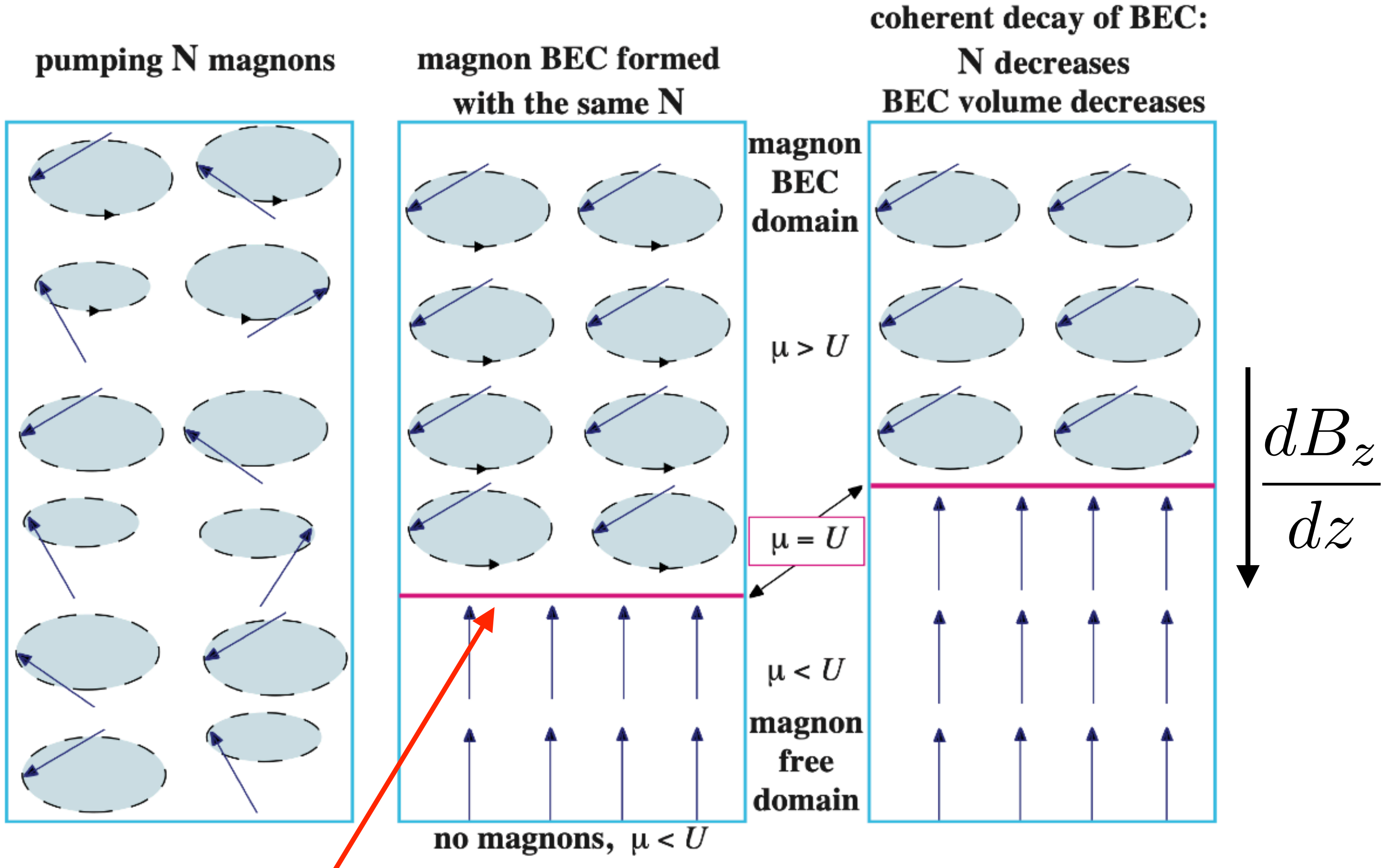
$$g_{aNN}\partial_\mu a \overline{N}\gamma^\mu\gamma^5 N \to g_{aNN}\nabla a \cdot \vec{\sigma}_N$$

tiny signal above noise
at axion frequency

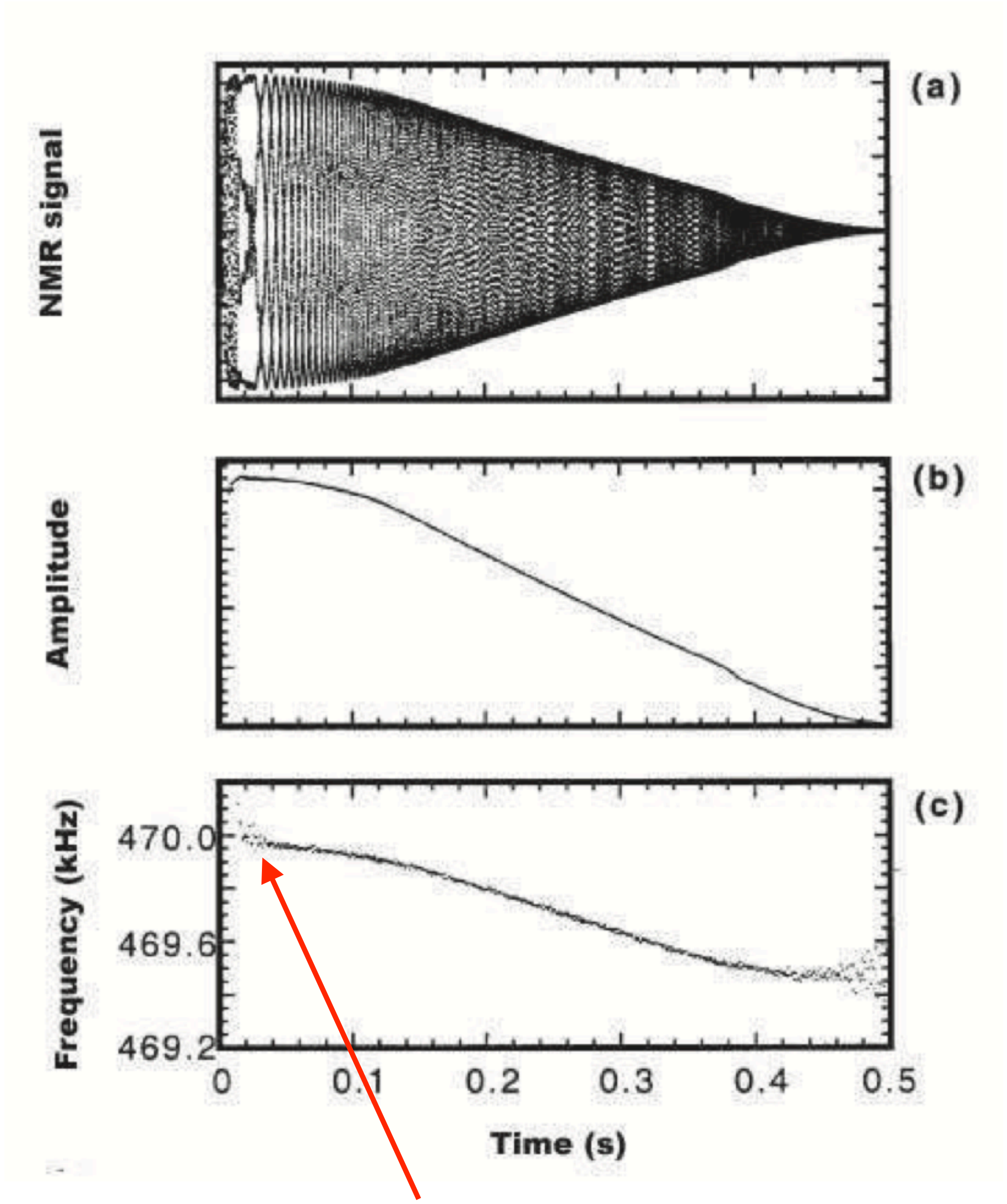
CASPEr: exploit analogy with NMR
But, scanning requires tuning B-field to parts per million

[CASPEr collab; Garcon et al. arXiv:1707.05312]

Superfluid 3He-B:
Homogenous Precession Domain



Macroscopic domain precesses in phase at **local** Larmor frequency

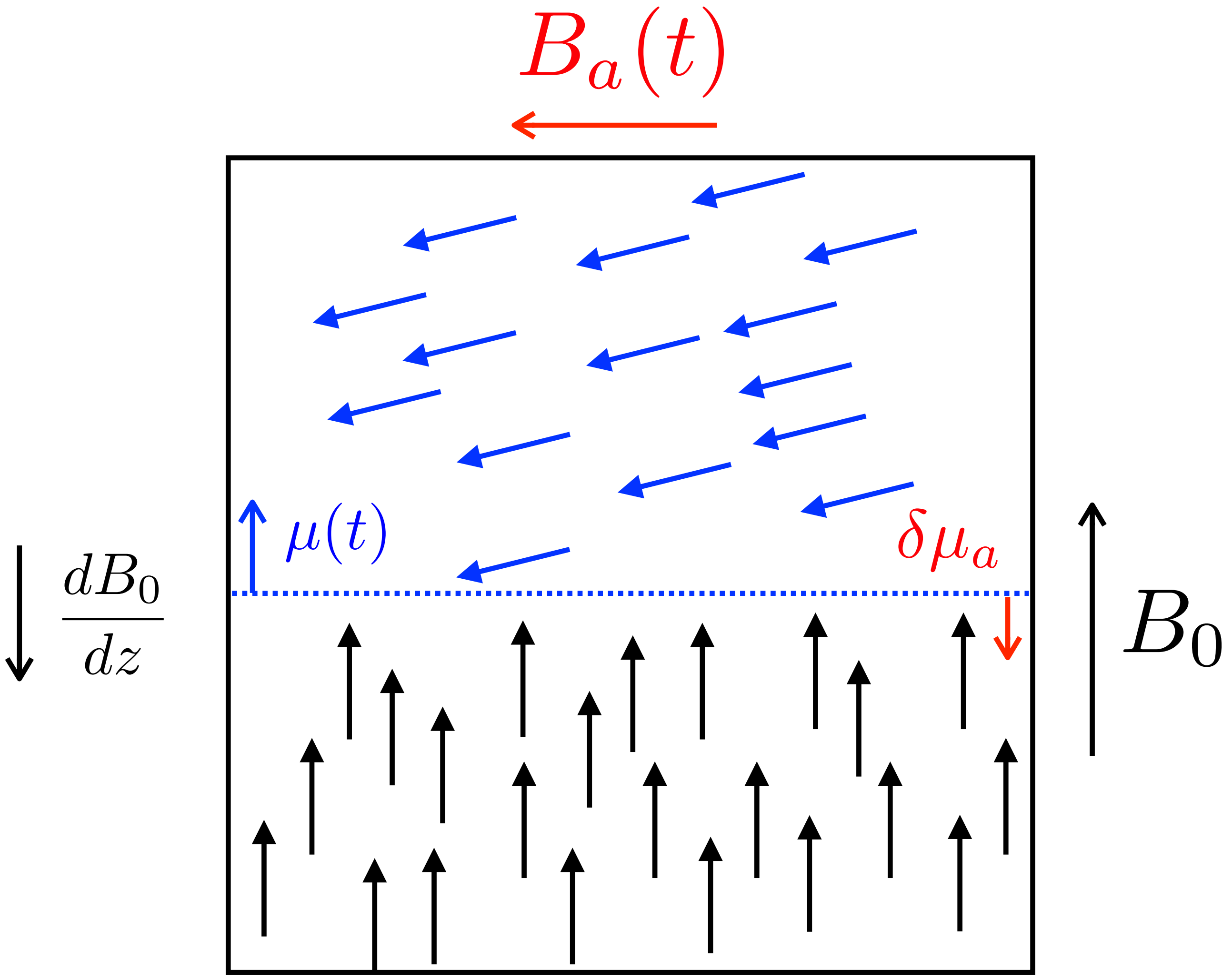


Naturally scans frequencies!

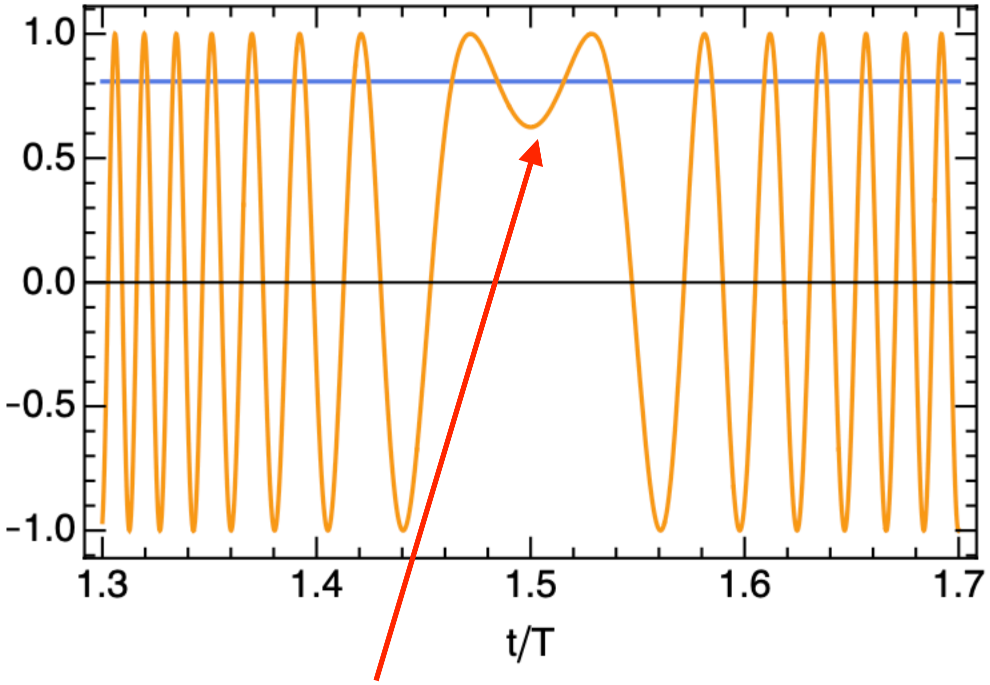
[Bunkov and Volovik, arXiv:0904.3889 and arXiv:1003.4889]

Axion signals in HPD

Axion replenishes magnons, acts as a frictional force on domain wall:



$$\Delta\omega = \int_0^{\tau_a} dt\, \dot{\omega}(t)$$

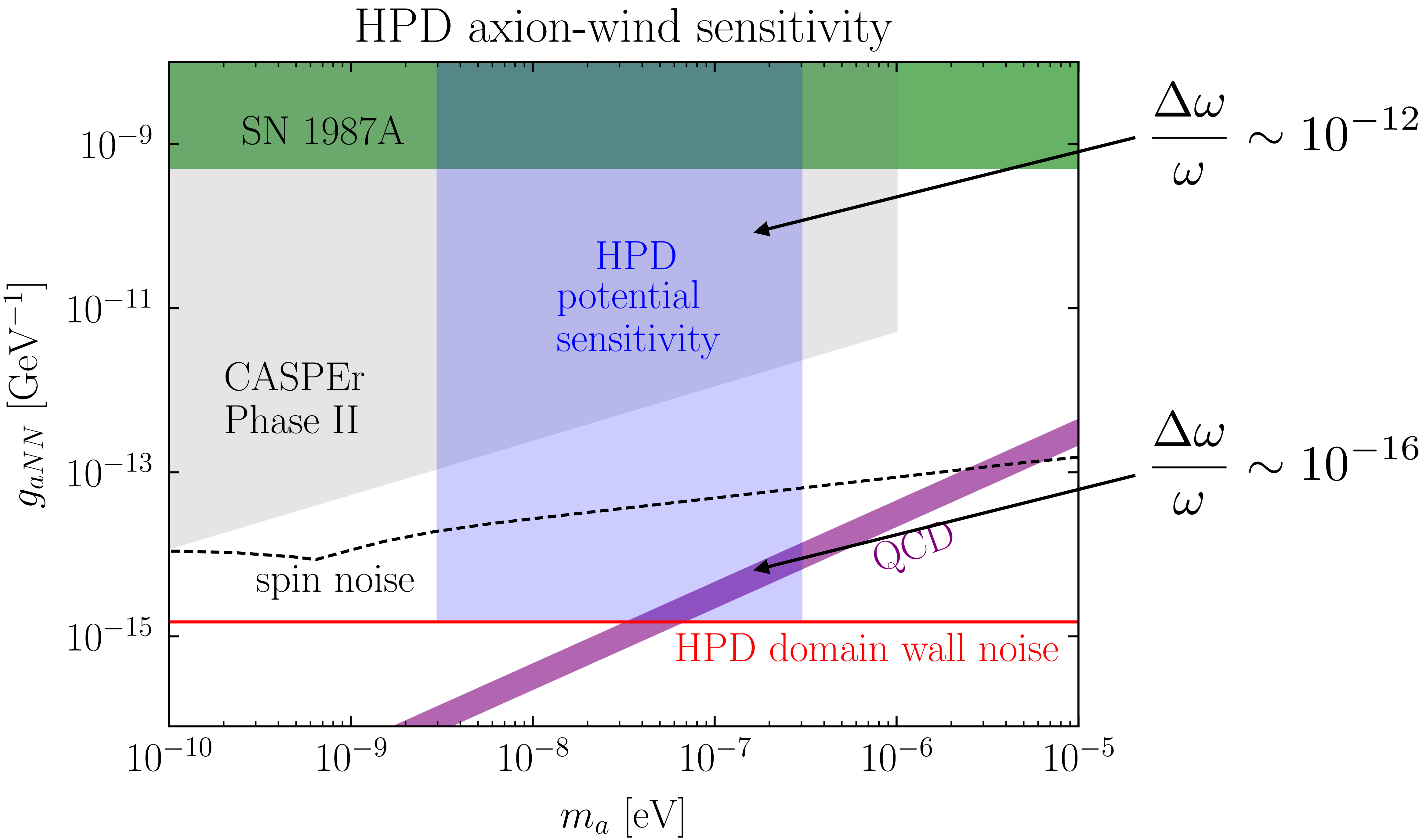


resonance

Looking for a small frequency shift is easier than a small field!
Daily modulation from many sweeps of same masses per day

[Gao, Halperin, **YK**, Nguyen, Schütte-Engel, Scott, to appear]

PRELIMINARY sensitivity

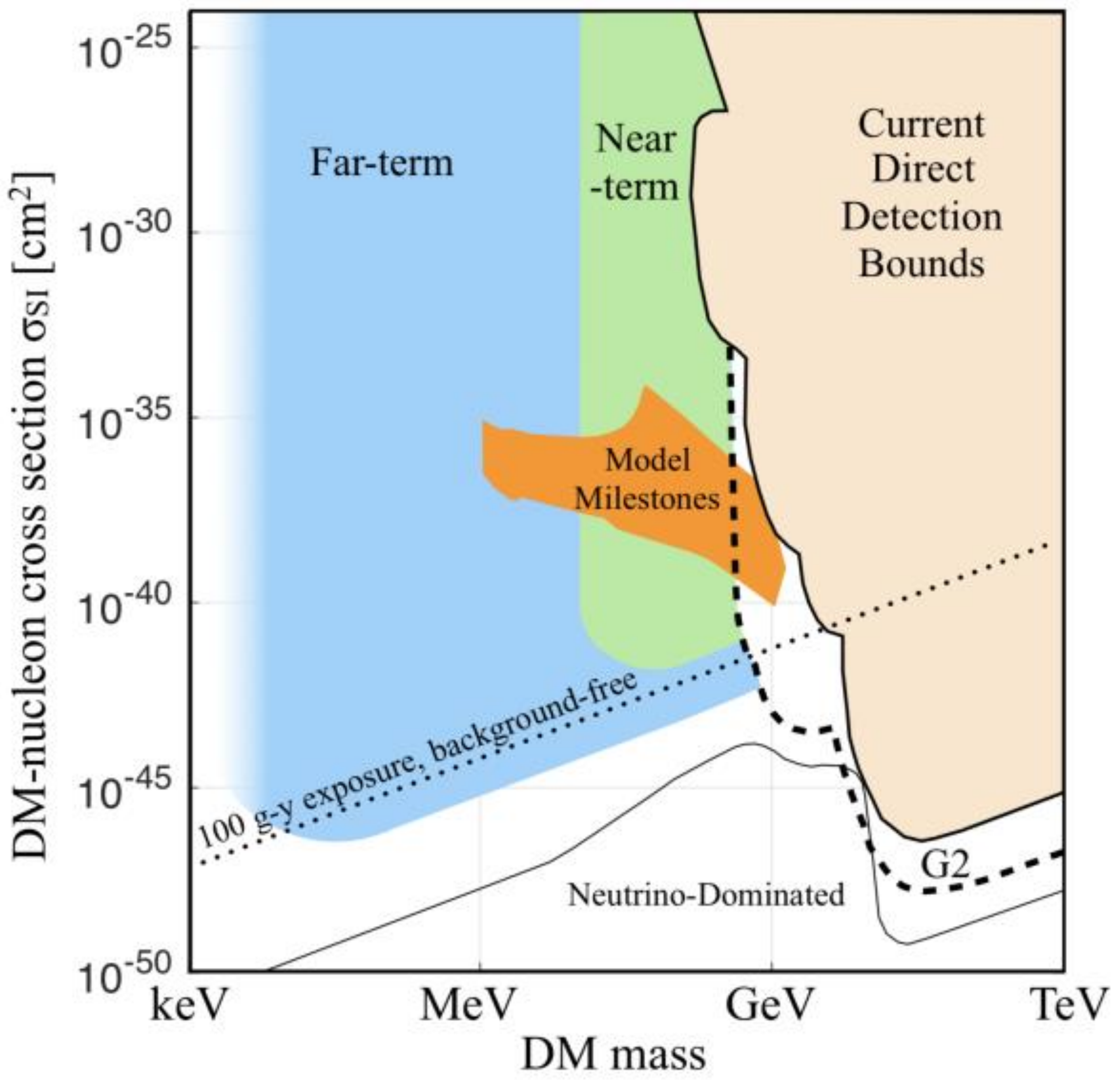


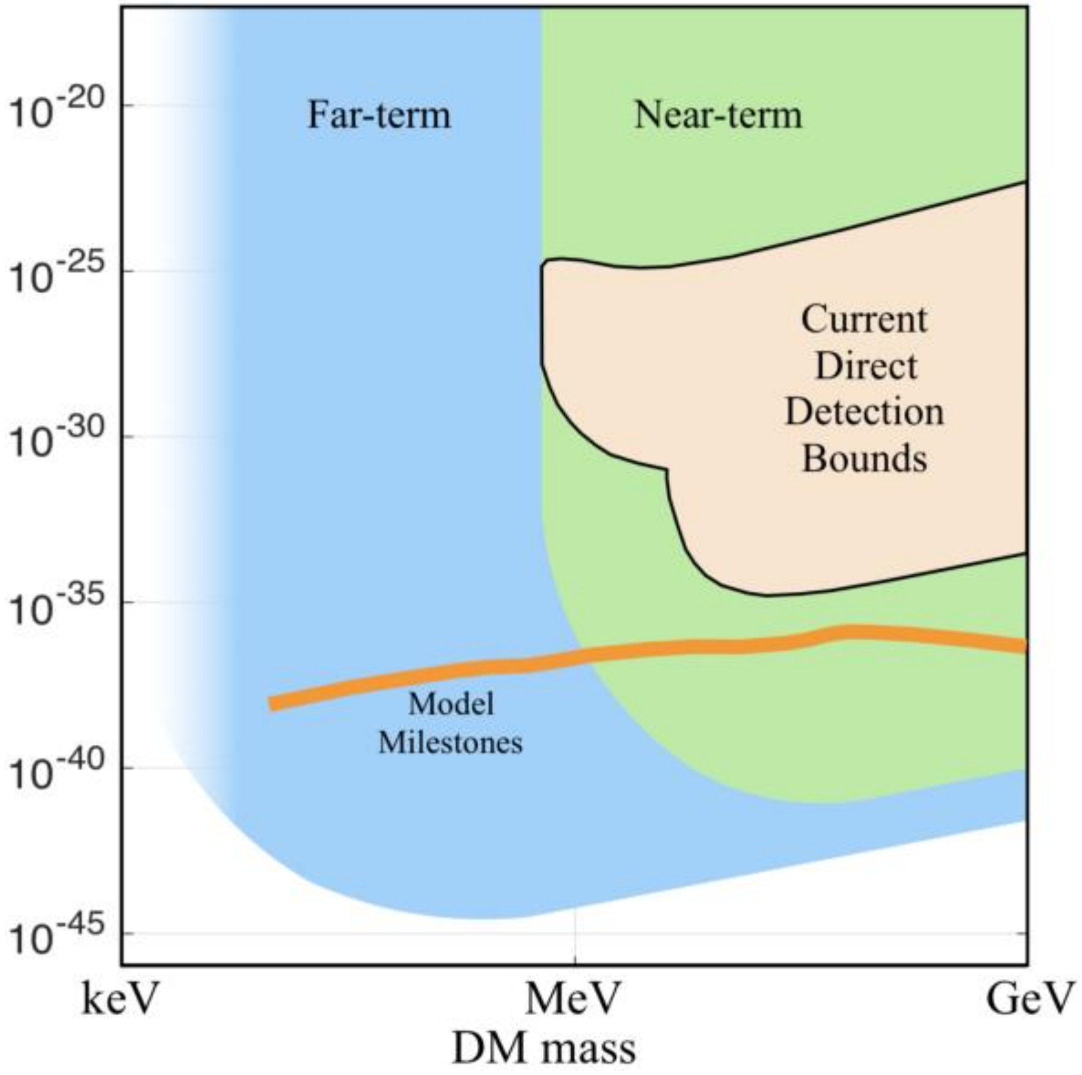
$$\frac{\Delta\omega}{\omega} \sim 10^{-12}$$

$$\frac{\Delta\omega}{\omega} \sim 10^{-16}$$

[Gao, Halperin, **YK**, Nguyen, Schütte-Engel, Scott, to appear]

The future for light DM



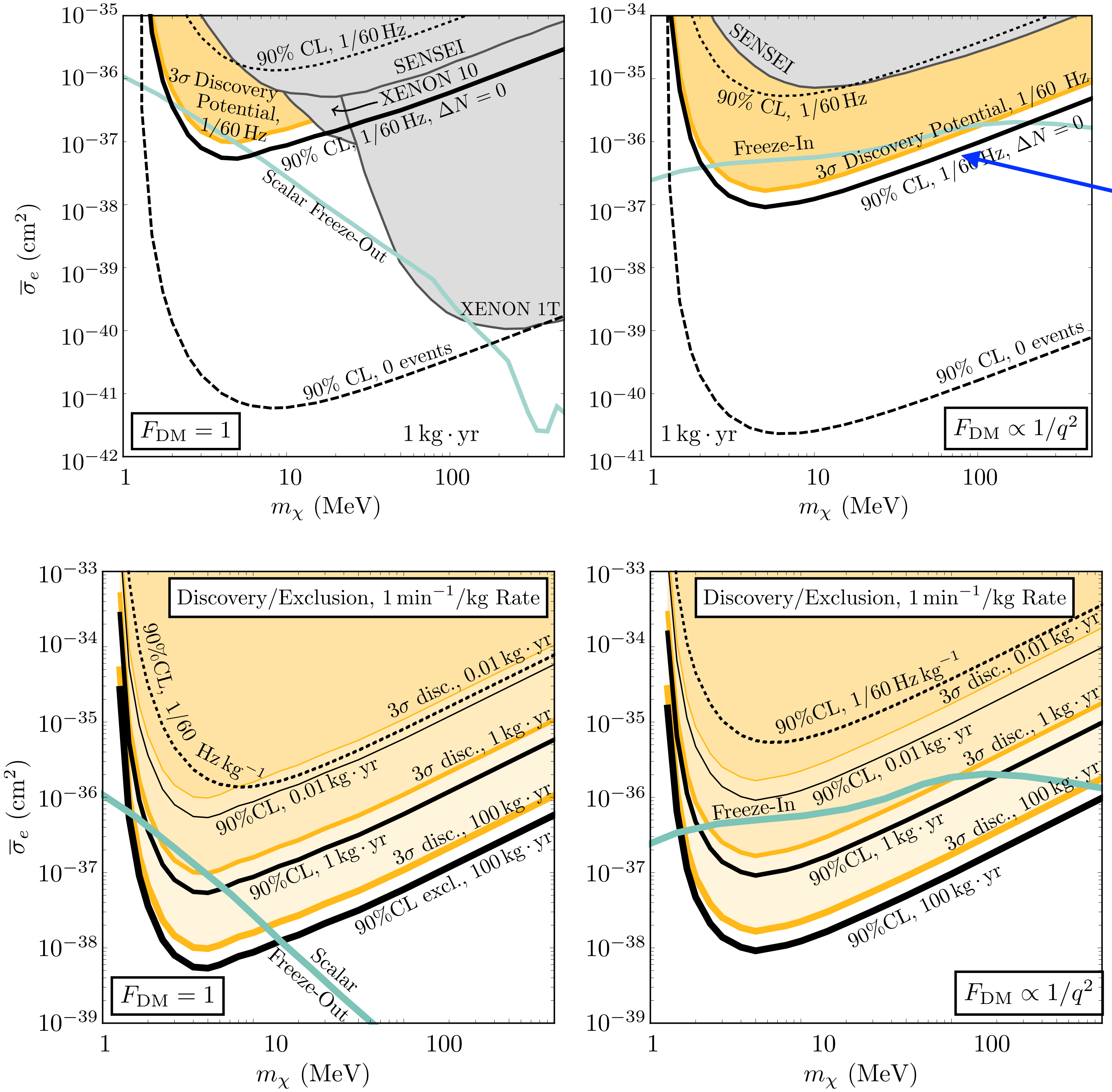


Detectors are uncovering new parameter space every day,
and more on the horizon. CM tools help determine the true sensitivity!

[DOE BRN report]

Backup

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]