Small-Scale Experiments for Light Dark Matter

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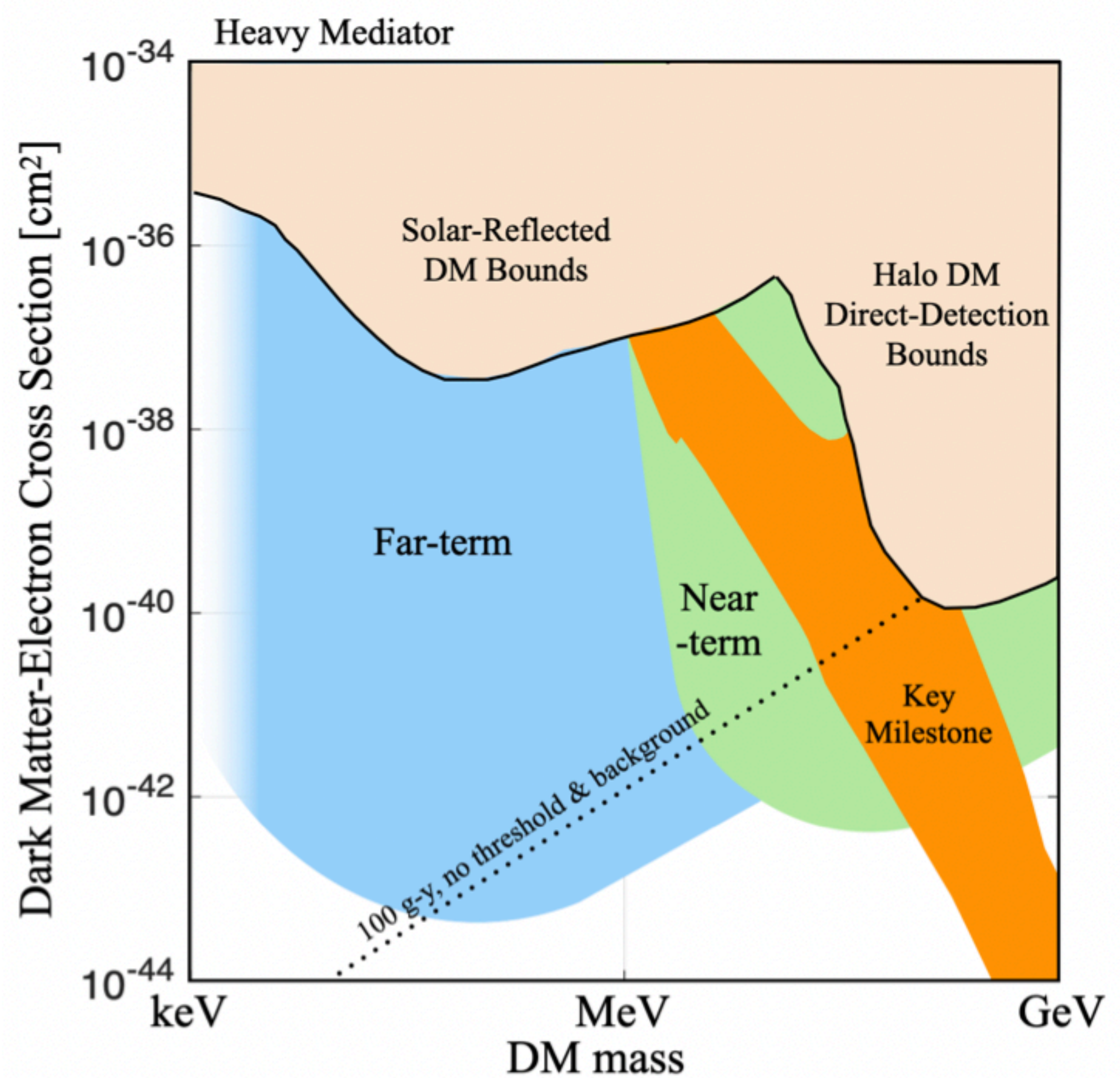
SNOLAB Future Projects Workshop, 4/29/25

UNIVERSITY OF TORONTO

Sub-GeV DM: unexplored frontiers



$$\rho_{\rm DM} \sim 0.3~{\rm GeV/cm^3}$$

$$n_{\rm DM} \propto \frac{1}{m_{\rm DM}}$$

Lighter DM:
smaller detector gives same event rate

100 g rather than 10 tons can make a discovery!
Science per $ is unbeatable:
sharp theory targets, bounded parameter space

[Snowmass CF1 whitepaper, arXiv:2203.08297]

Axion DM: precision quantum science

10^{-22} eV   1 eV   1 keV   1 GeV   100 TeV 10^{19} GeV

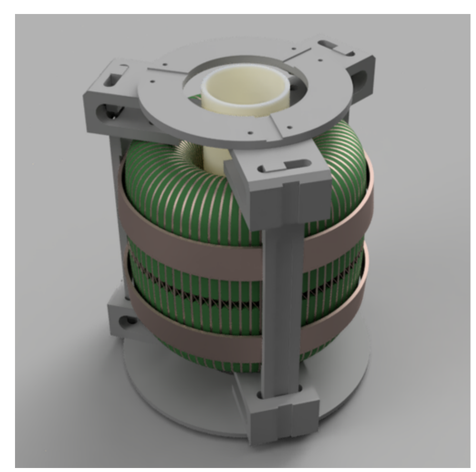
"wave-like" DM

$$n_{\rm DM}\lambda_{\rm dB}^3 \gg 1$$

$$\mathrm{KE}_{\rm DM} = \frac{1}{2} m_{\rm DM} v_{\rm DM}^2 \ll 1\ \mu\mathrm{eV}$$

Behaves as classical field

Superconducting cavities, atomic clocks, nuclear spins… dark matter is an oscillating external source of **fixed but unknown frequency** for any quantum-mechanical system

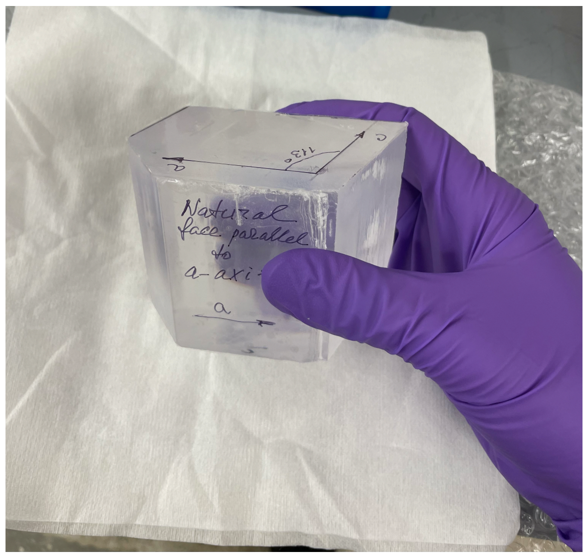


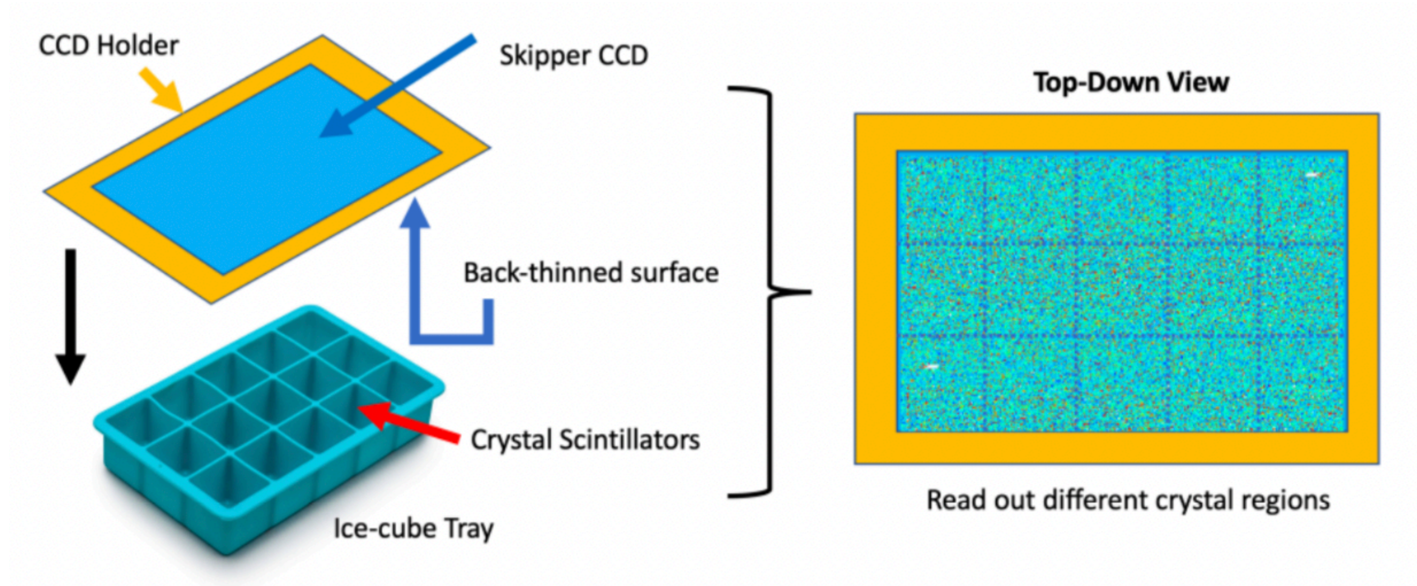
Techniques from quantum information are key to ultimate sensitivity

[ABRACADABRA collab.; ADMX collab.]

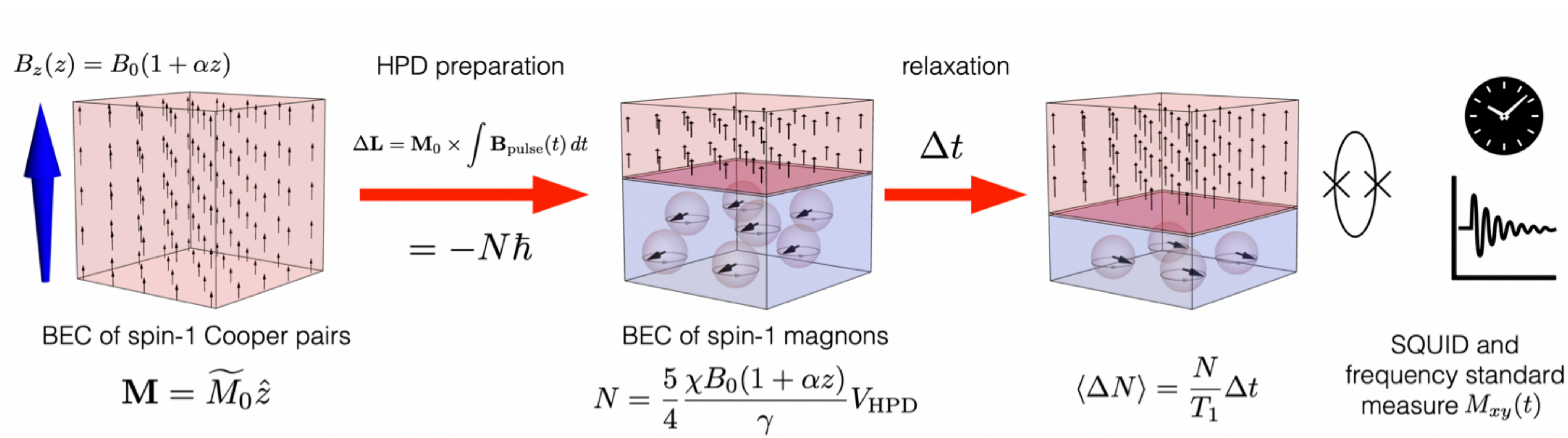
Two small-scale experiments

1. Anisotropic organic scintillators
plus silicon CCDs for MeV-GeV DM

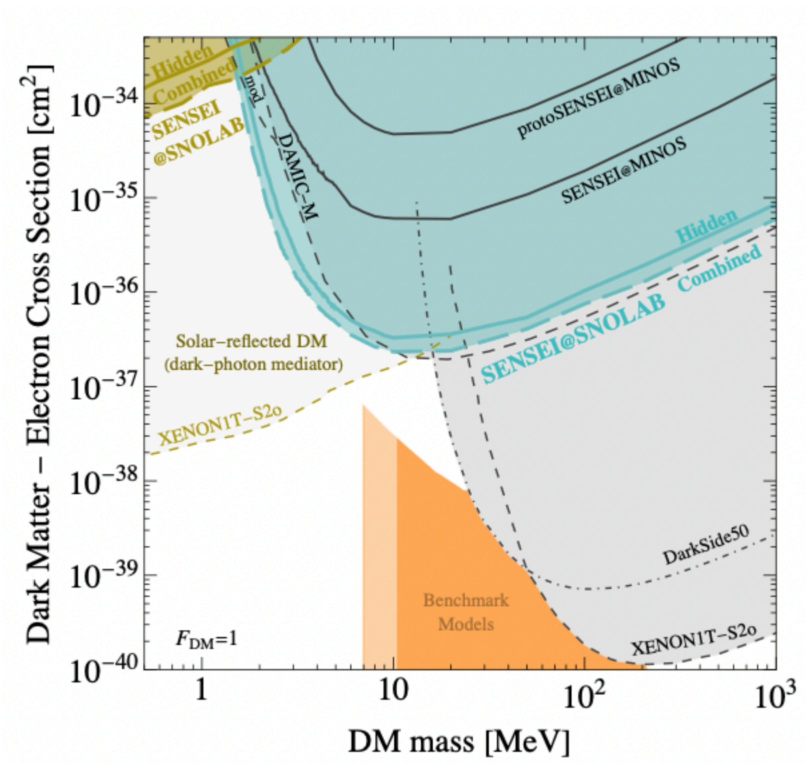


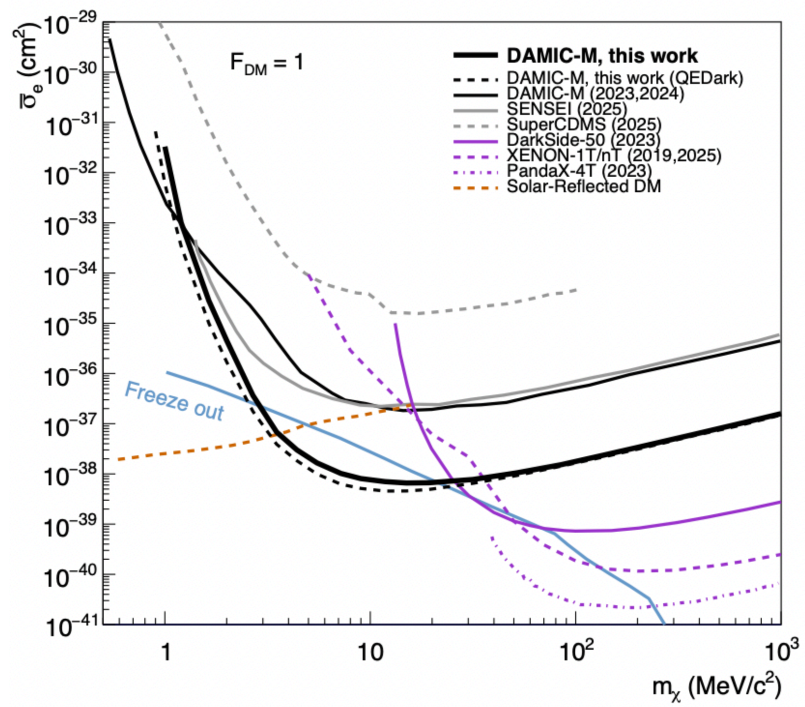


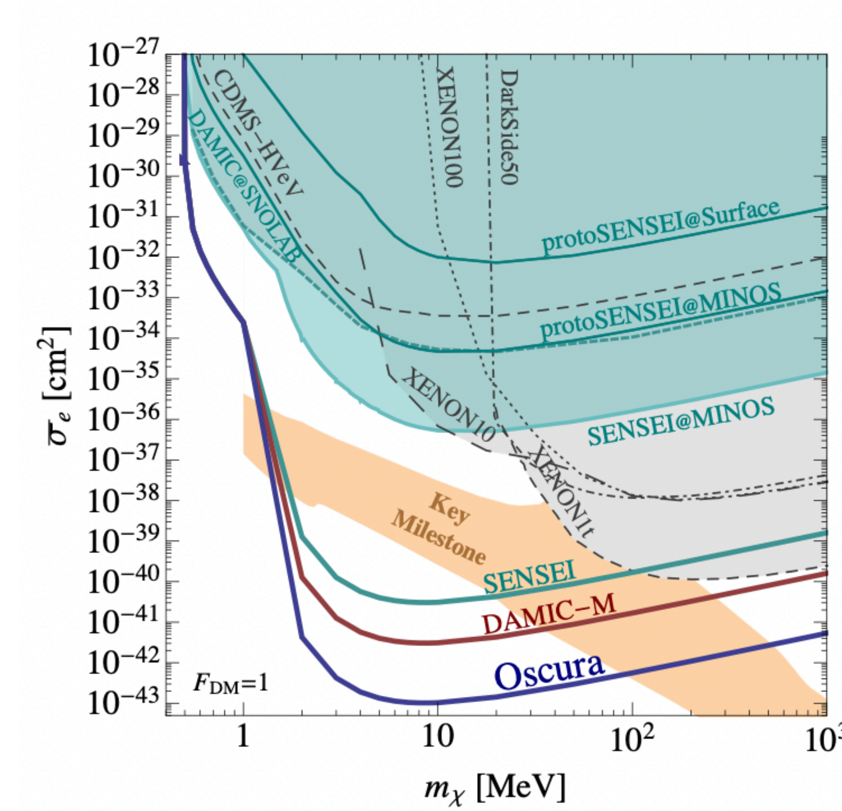
2. Superfluid helium-3 for axion DM



Silicon CCDs for sub-GeV DM







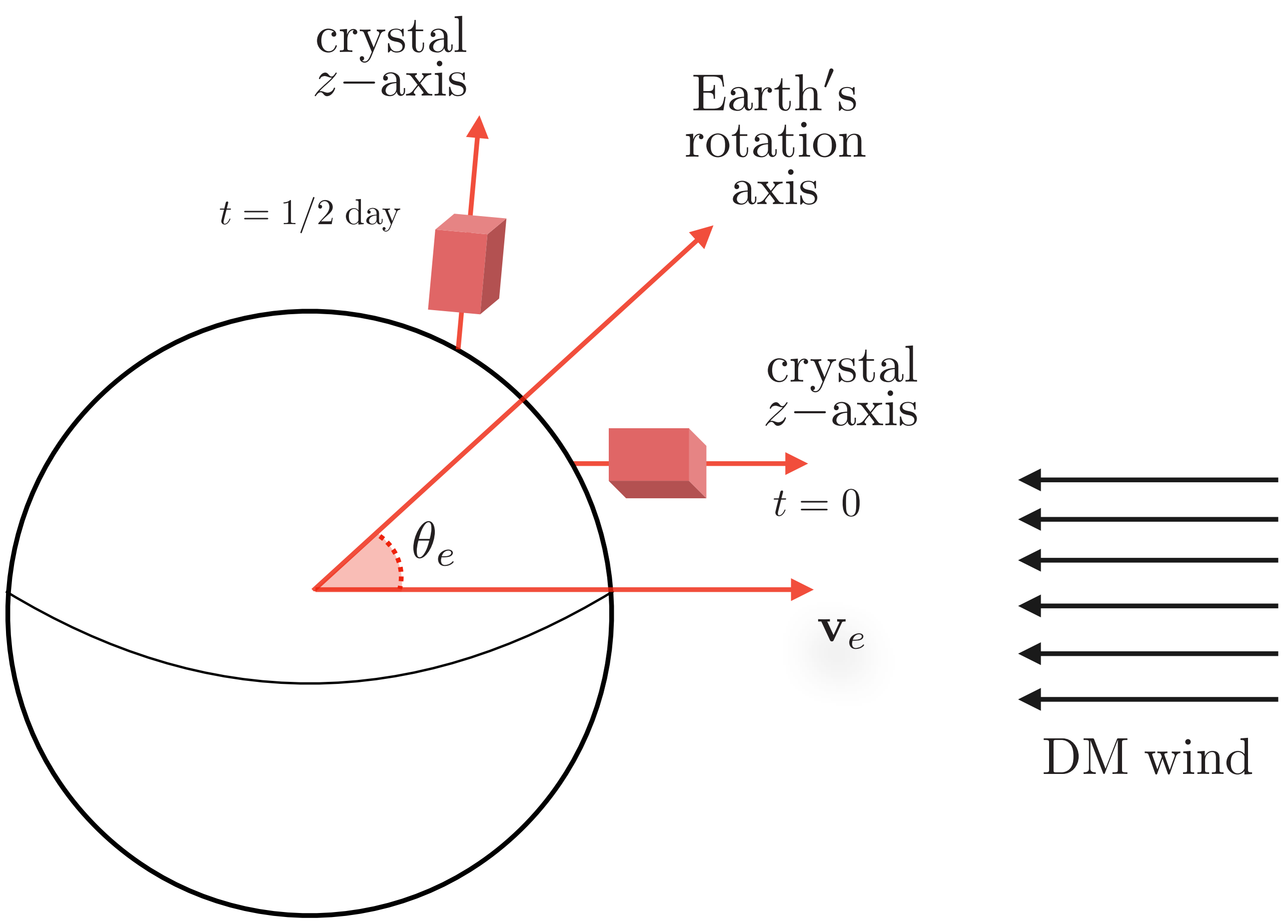
SENSEI: an incredible scientific success for SNOLAB…

now leading constraints from DAMIC-M

…which can continue with the Oscura program

(for other approaches using silicon at SNOLAB, see M. Diamond and Z. Hong's talk Wednesday)

A new handle: daily modulation



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

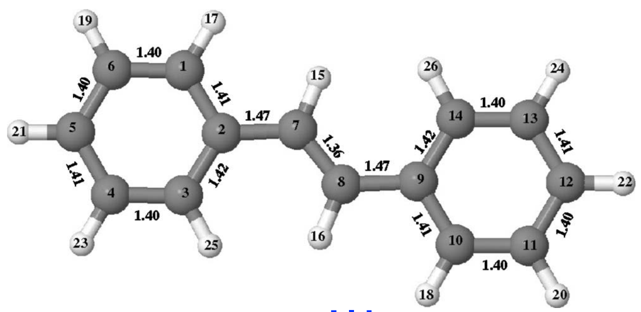
Smoking gun for DM signal!

Anisotropy in material response, **not** directionality of outgoing state

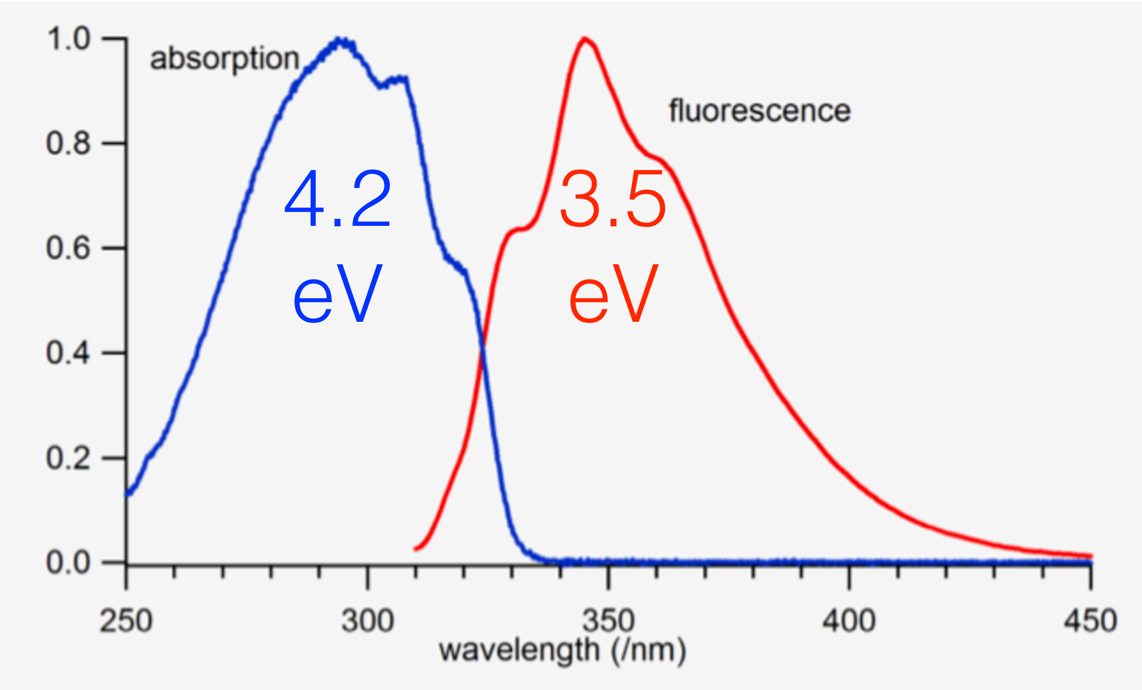
Modulating signal without sacrificing total rate

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

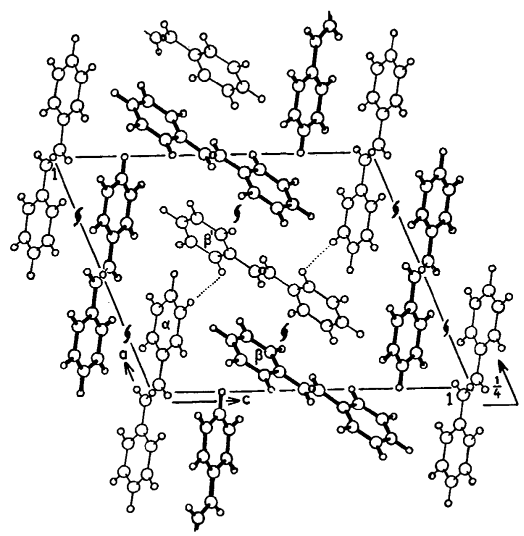
Organic scintillator crystals



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



wavelength shifting = excellent quantum efficiency



planar molecules = anisotropy

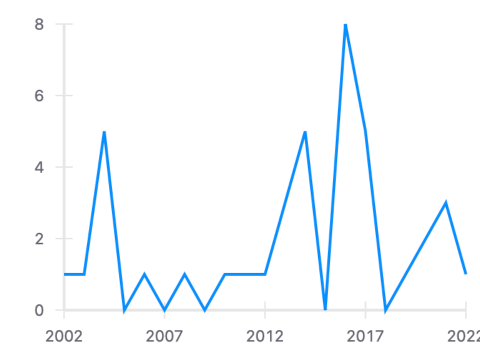
Directional scintillation detector for the detection of the wind of WIMPs

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

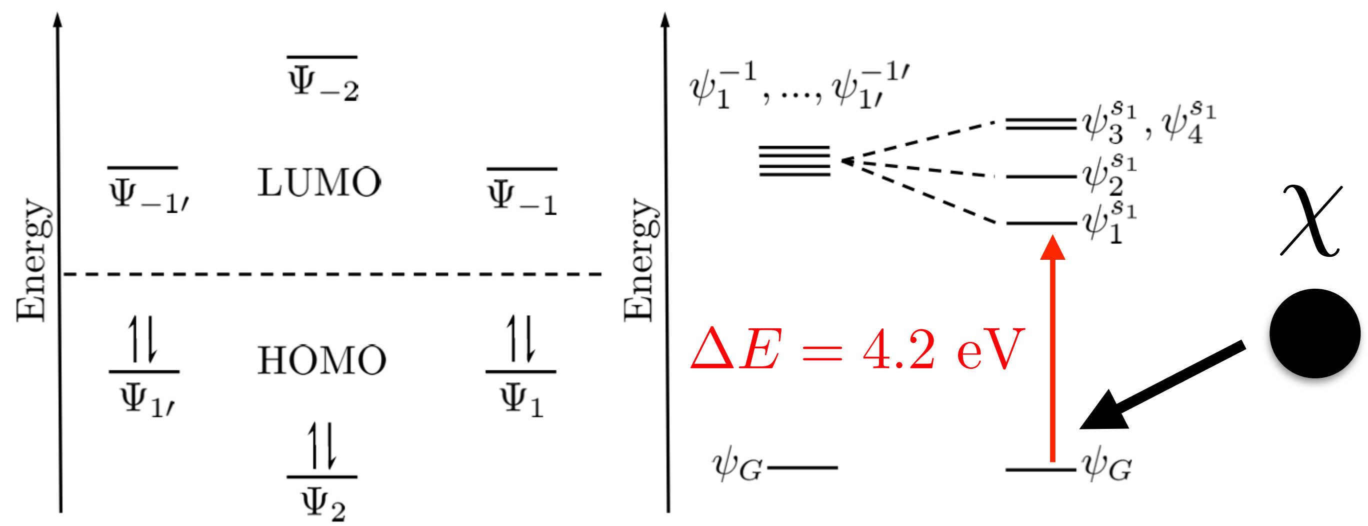
Citations per year



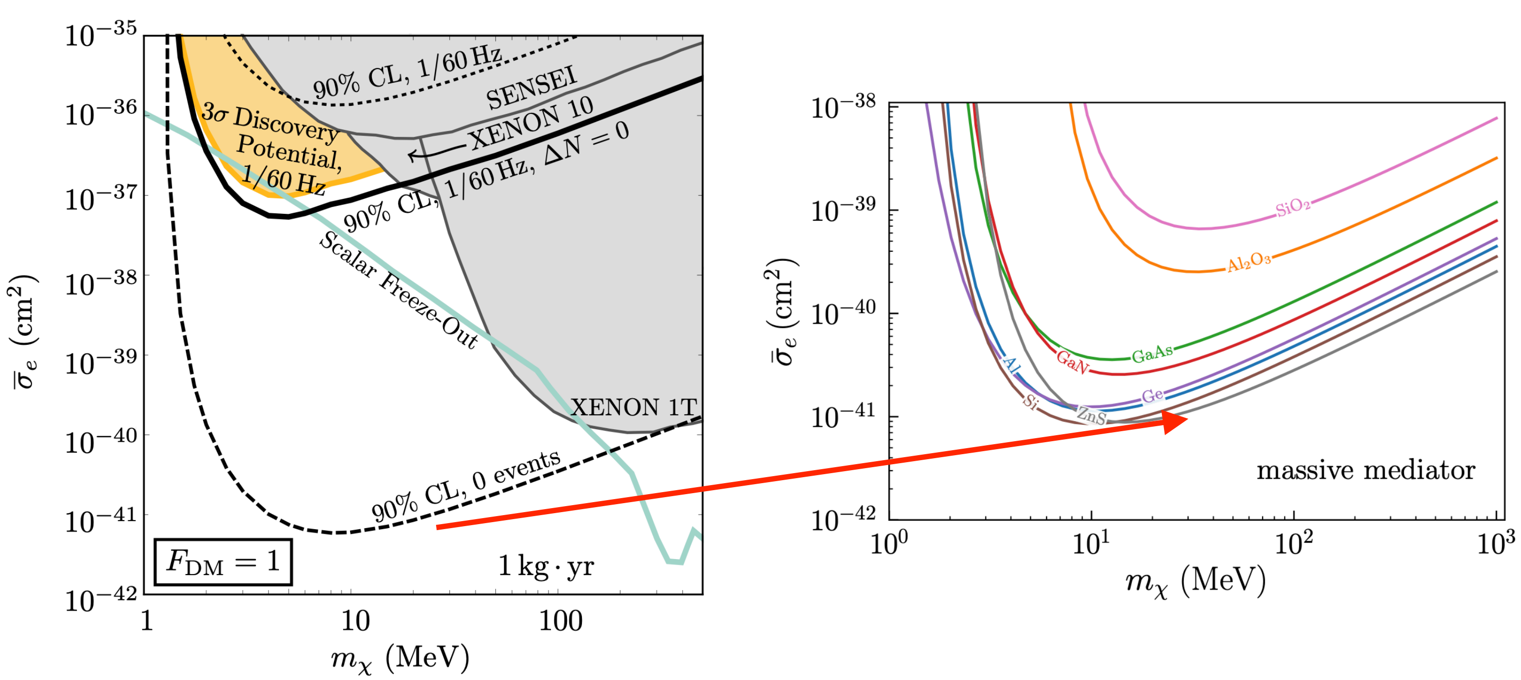
Abstract: (arXiv)
The quenching factor of the proton recoil in the stilbene scintillator was measured with a 252Cf neutron source and was found to be 0.1 - 0.17 in the recoil energy range between 300 keV and 3 MeV. It was found to depend on the direction of the recoil proton. The directional anisotropy 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.

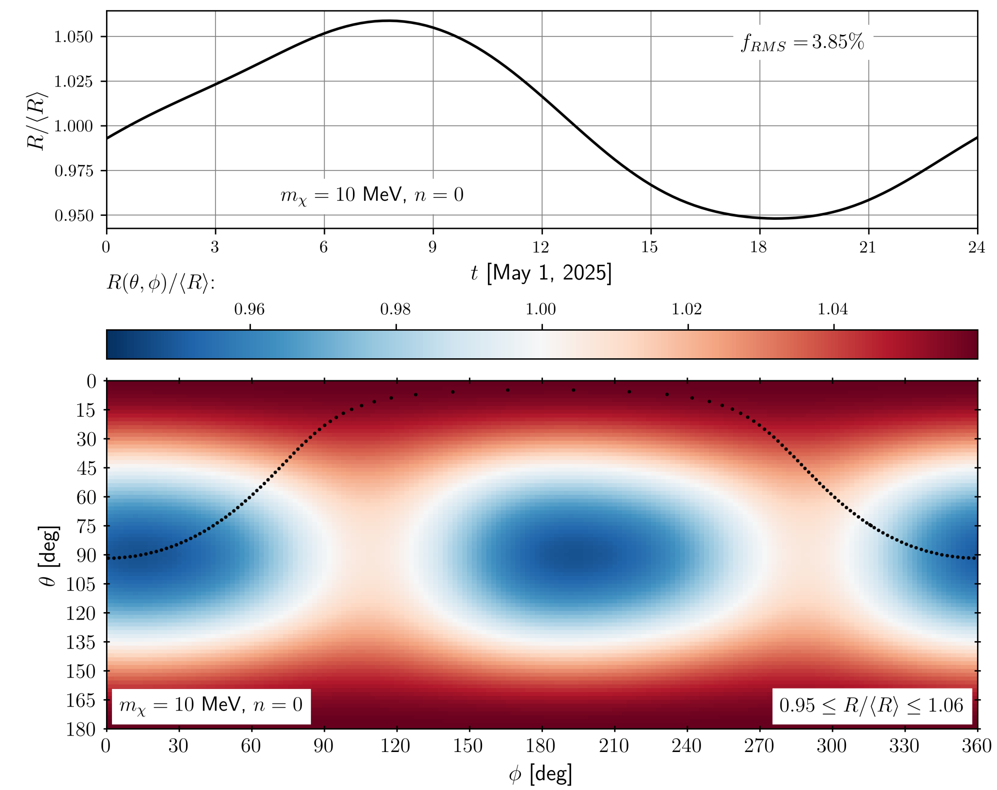
anisotropy already used for WIMP experiment!

Daily modulation for DM-e



signal: scintillation photon following electronic de-excitation



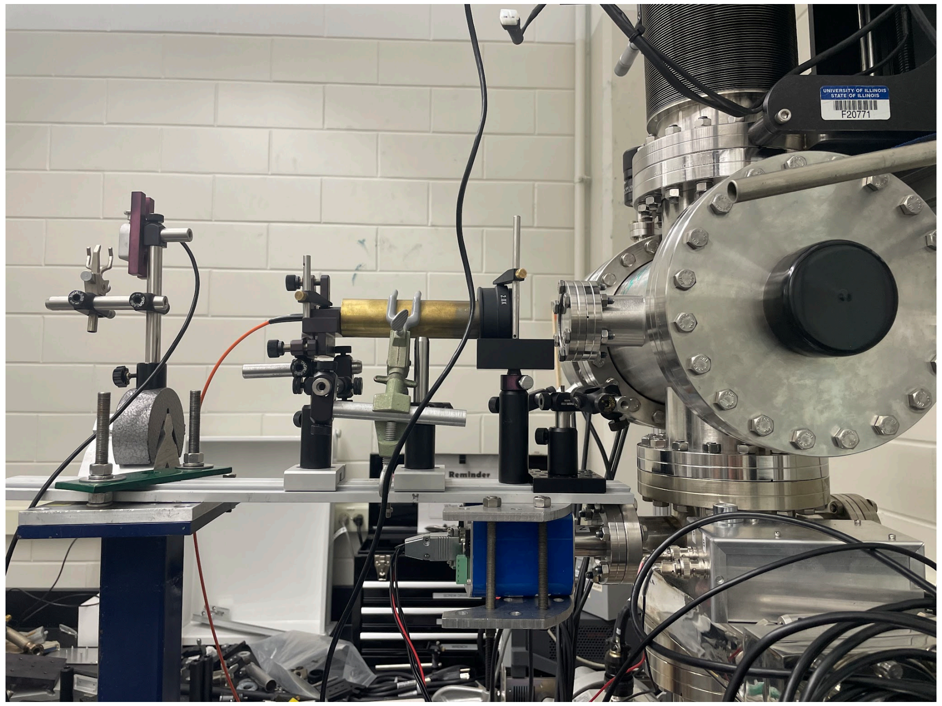


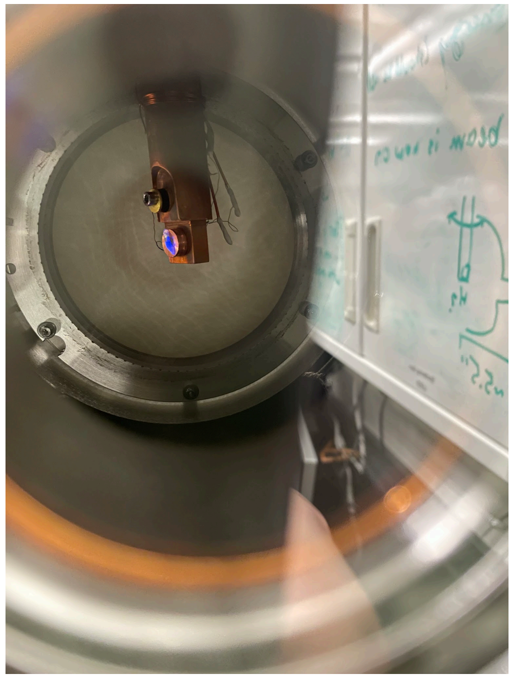
kg for kg, same total rate as Si,
but **decouple target and detector**

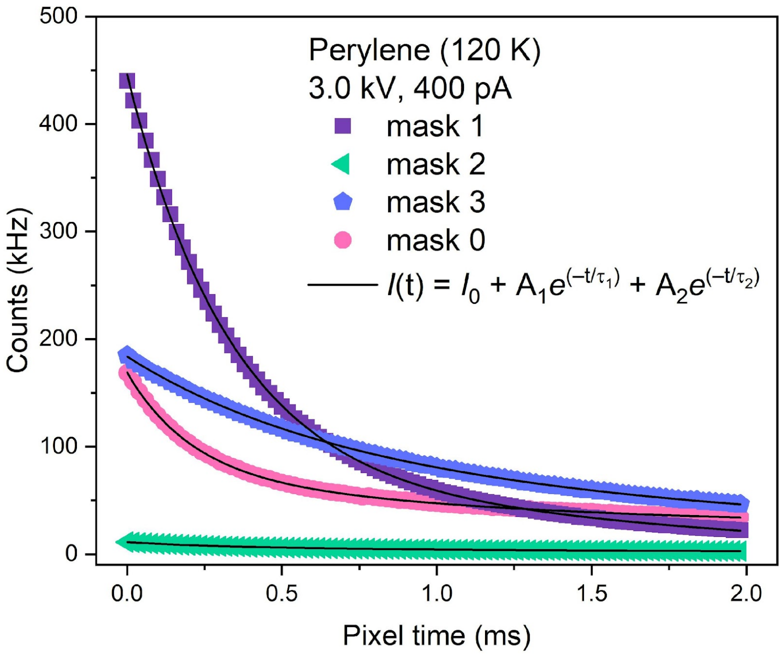
plus daily modulation!

Directional calibration

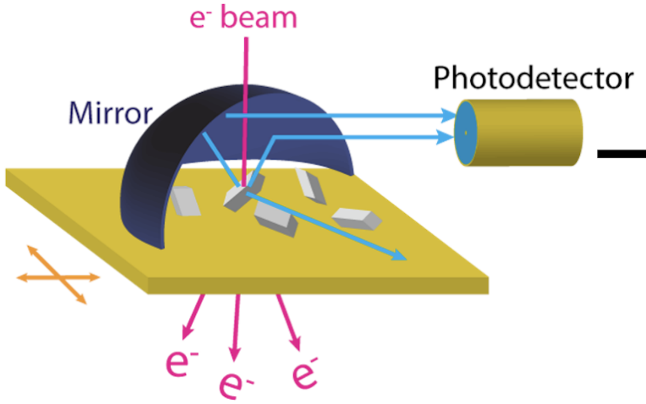
LEED (keV electron gun) at UIUC

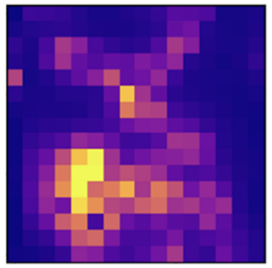




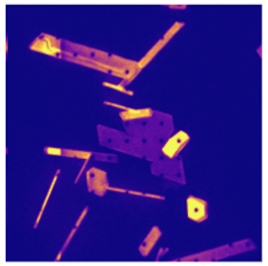


Cathodoluminescence microscope at LBL

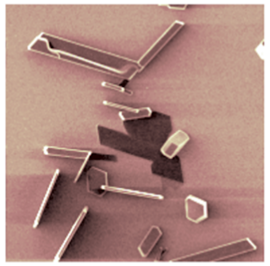




Collect spectral map of microcrystals



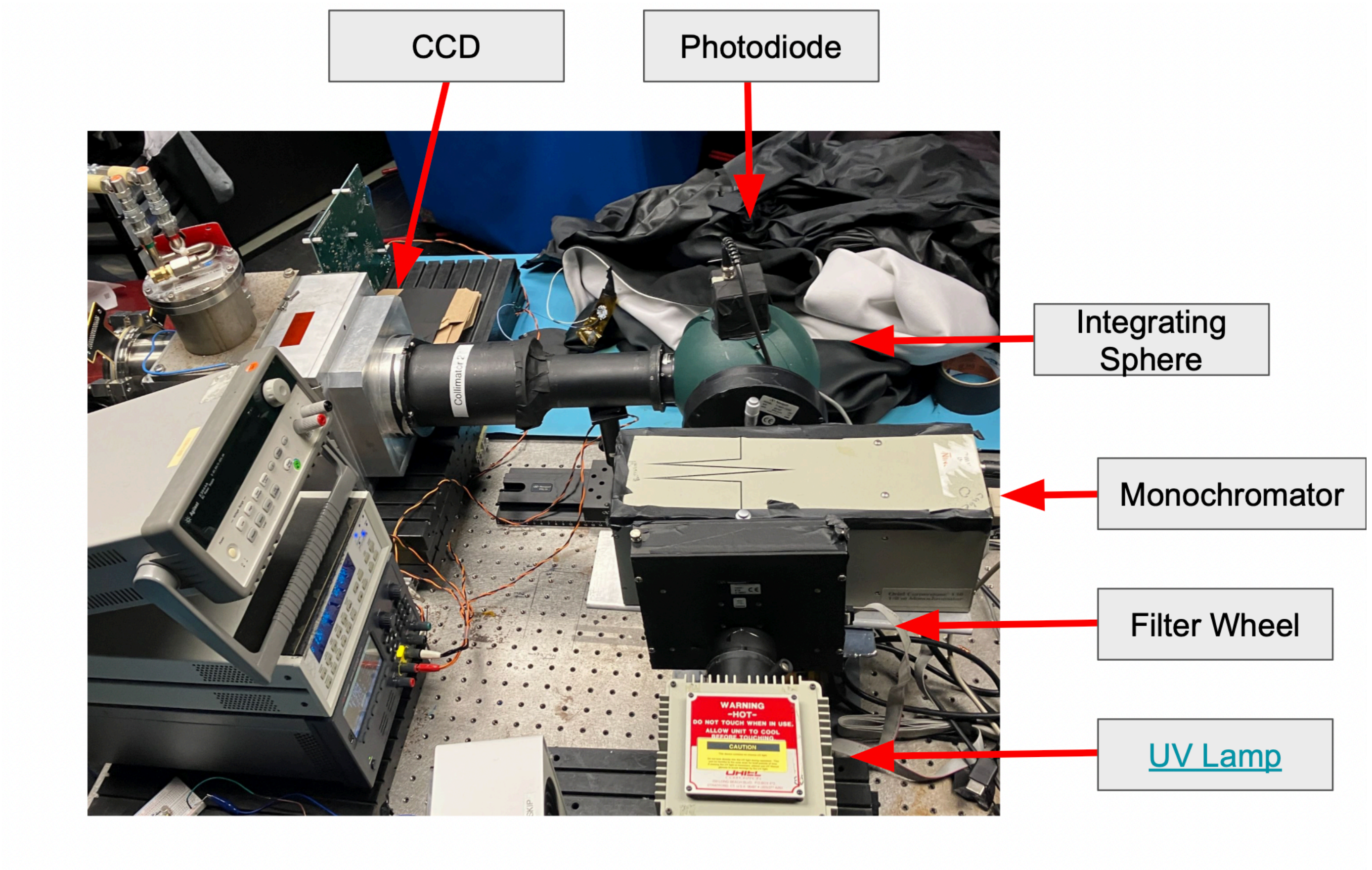
Evaluate damage from e⁻ beam

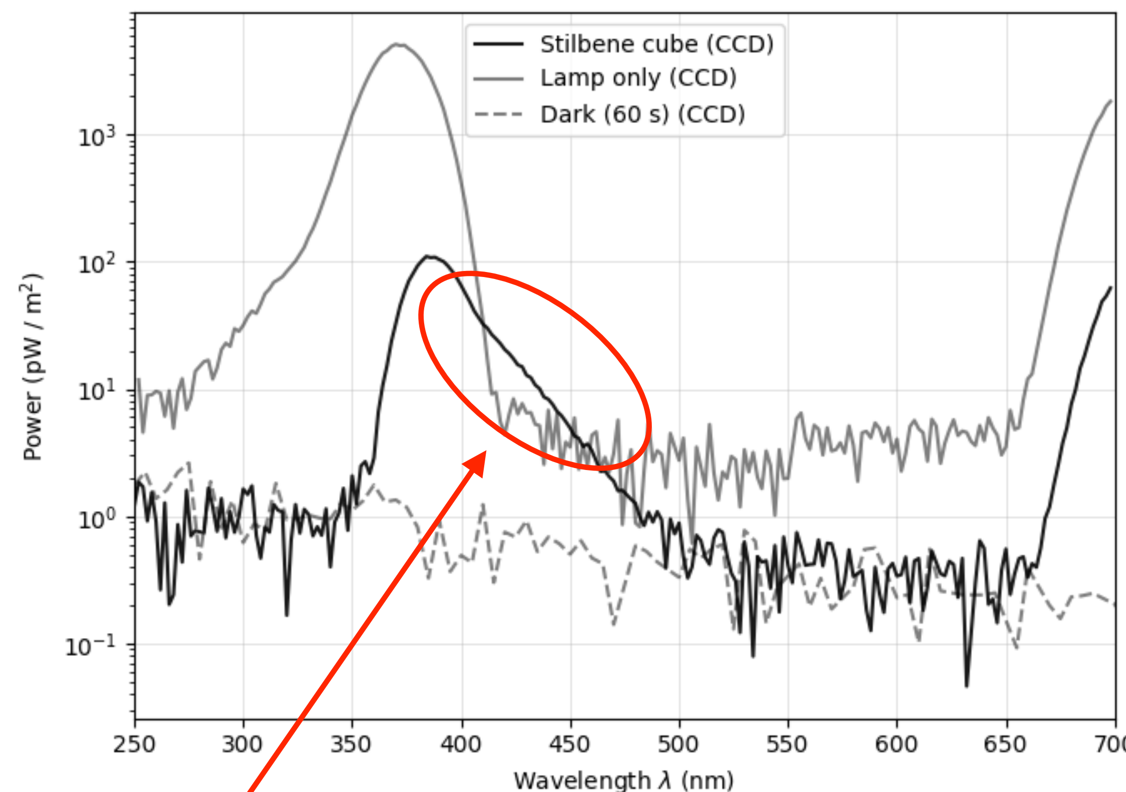


Determine crystal morphology with SEM

Seeing some directional response (PRELIMINARY)

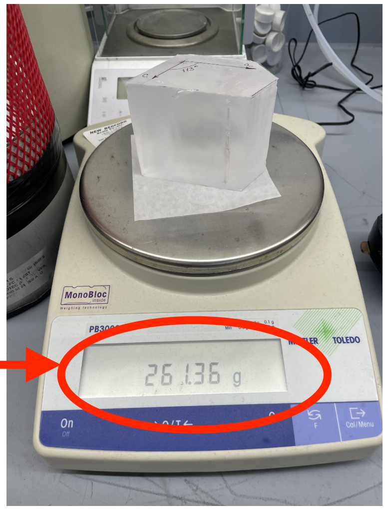
Scintillators + CCDs





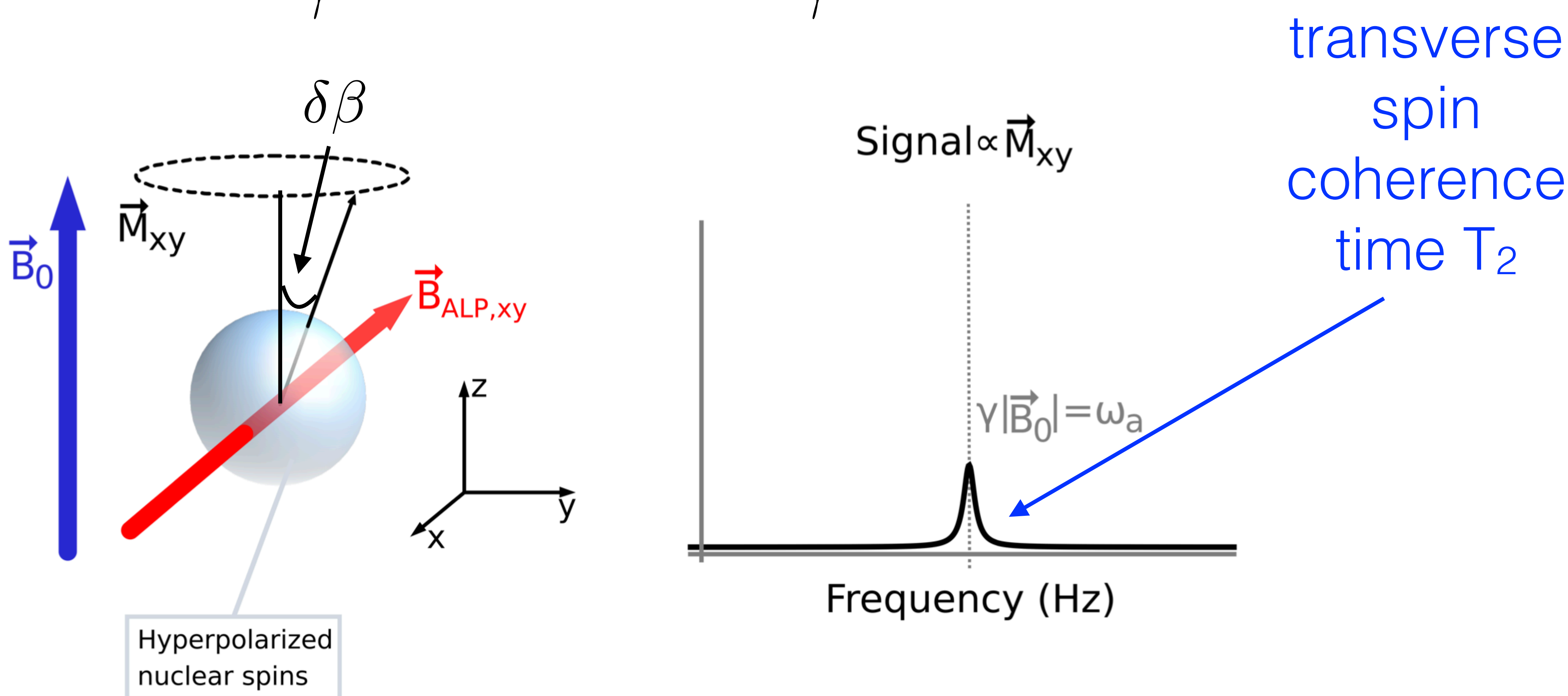
can see stilbene scintillation spectrum with CCD!

Best of both worlds!
Use mature SNOLAB CCD infrastructure for readout/shielding, scale up detector mass to >kg with organic scintillators



Axion detection with nuclear spins

$$\vec{B}_a = \frac{g_{aNN}}{\gamma}\nabla a \simeq g_{aNN}\frac{\sqrt{2\rho_{\rm DM}}}{\gamma}\cos(\omega_a t)\vec{v}_a$$



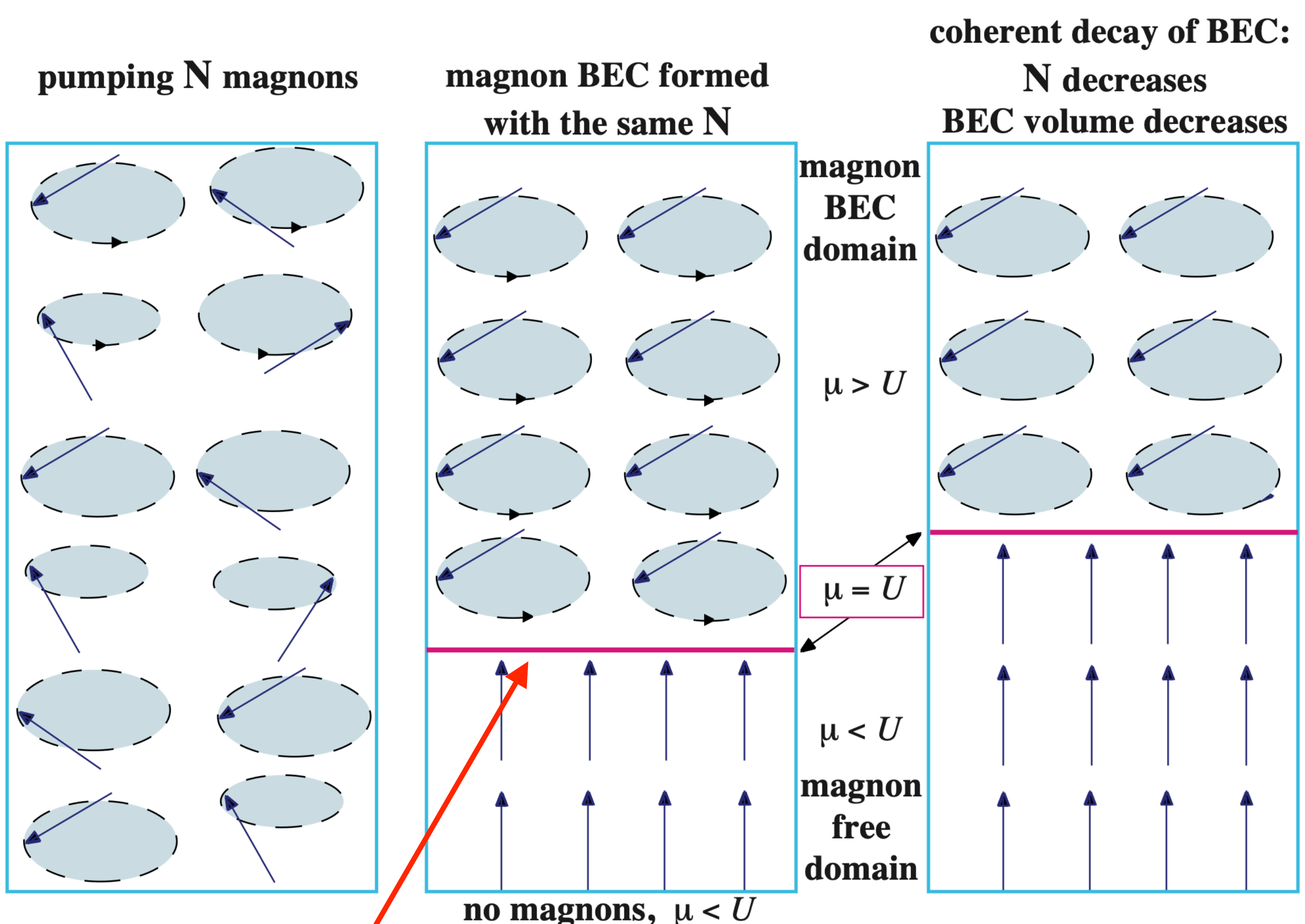
On resonance, $\gamma B_0 = m_a$,linearly growing tip angle:

$$\delta\beta(t) = \gamma B_a t \quad \text{for } t < \min[\tau_a, T_2]$$

Need to scan Larmor frequencies and maintain coherence

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

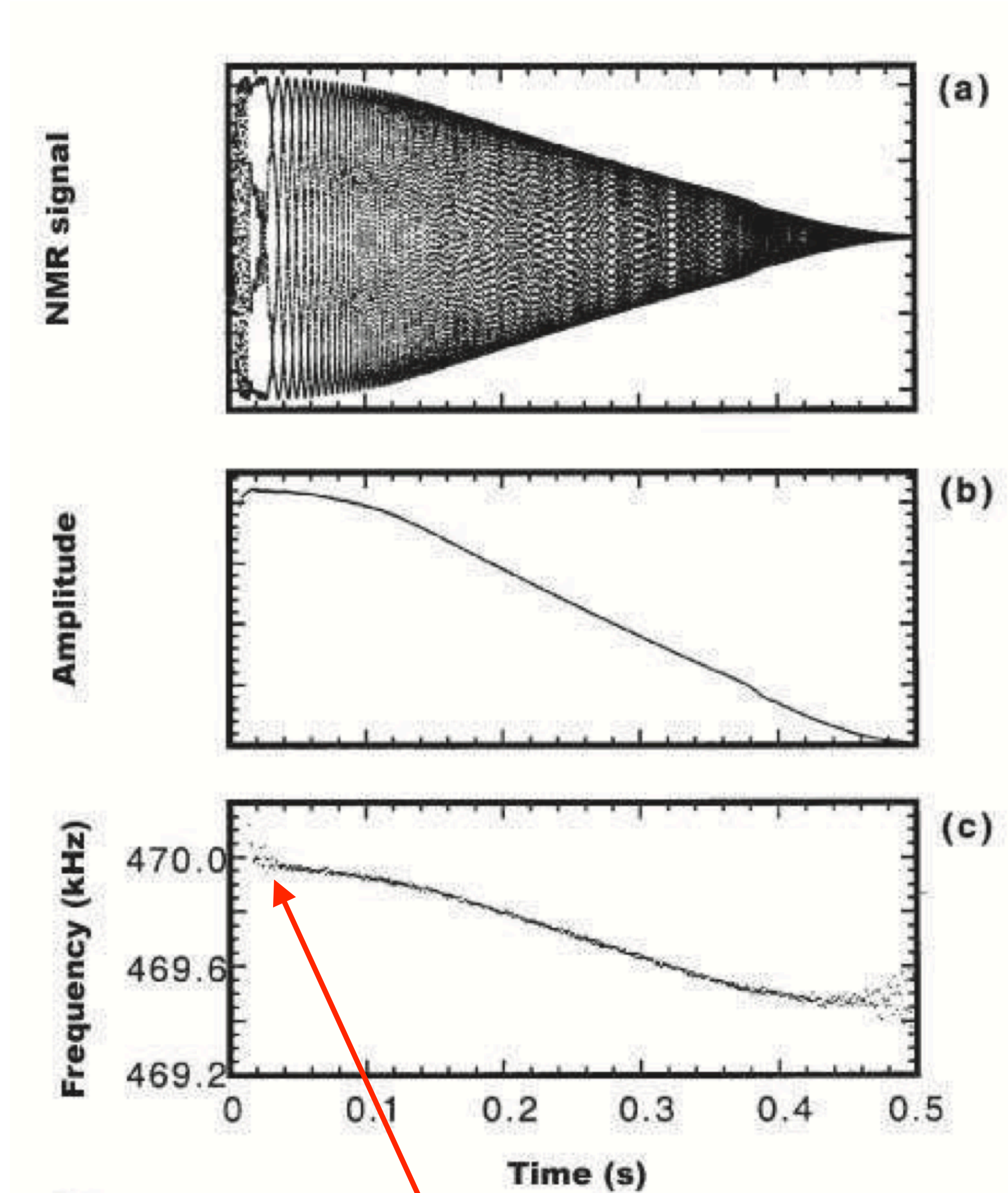
Superfluid 3He-B: Homogenous Precession Domain



$\frac{dB_z}{dz}$

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

$$\omega_L = \gamma B(z)$$

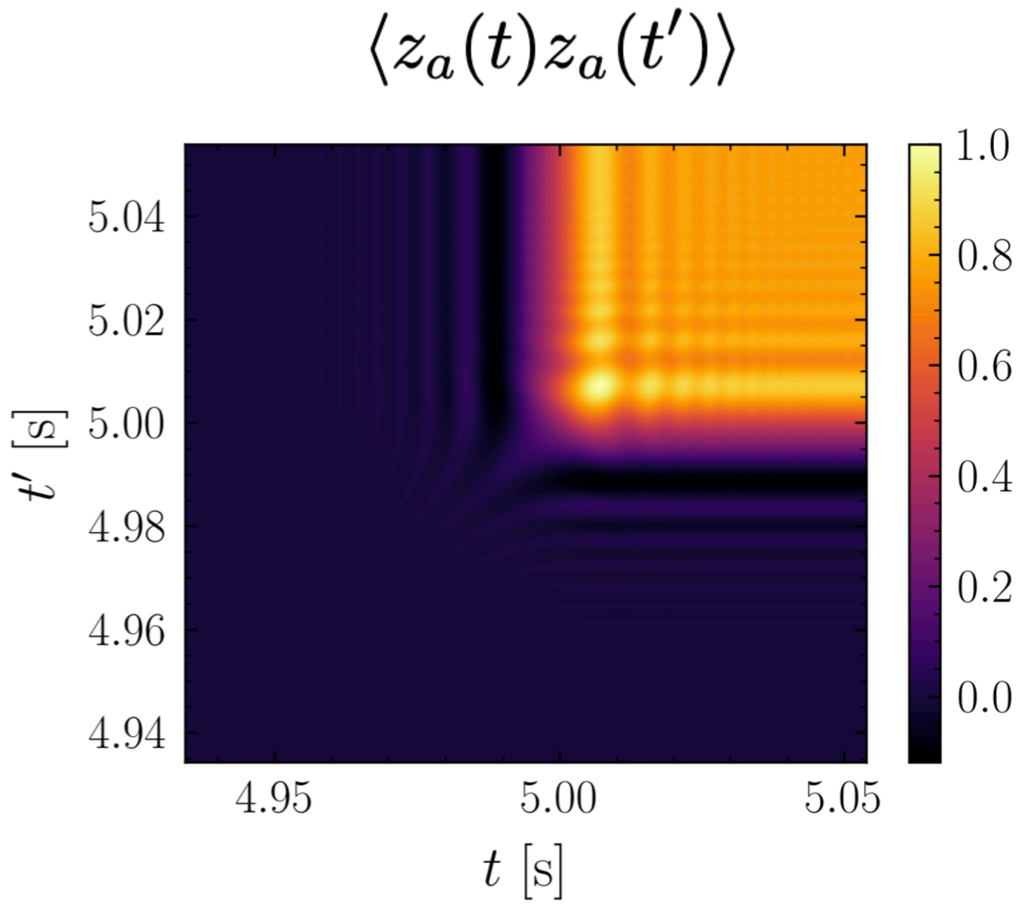


Naturally scans frequencies!

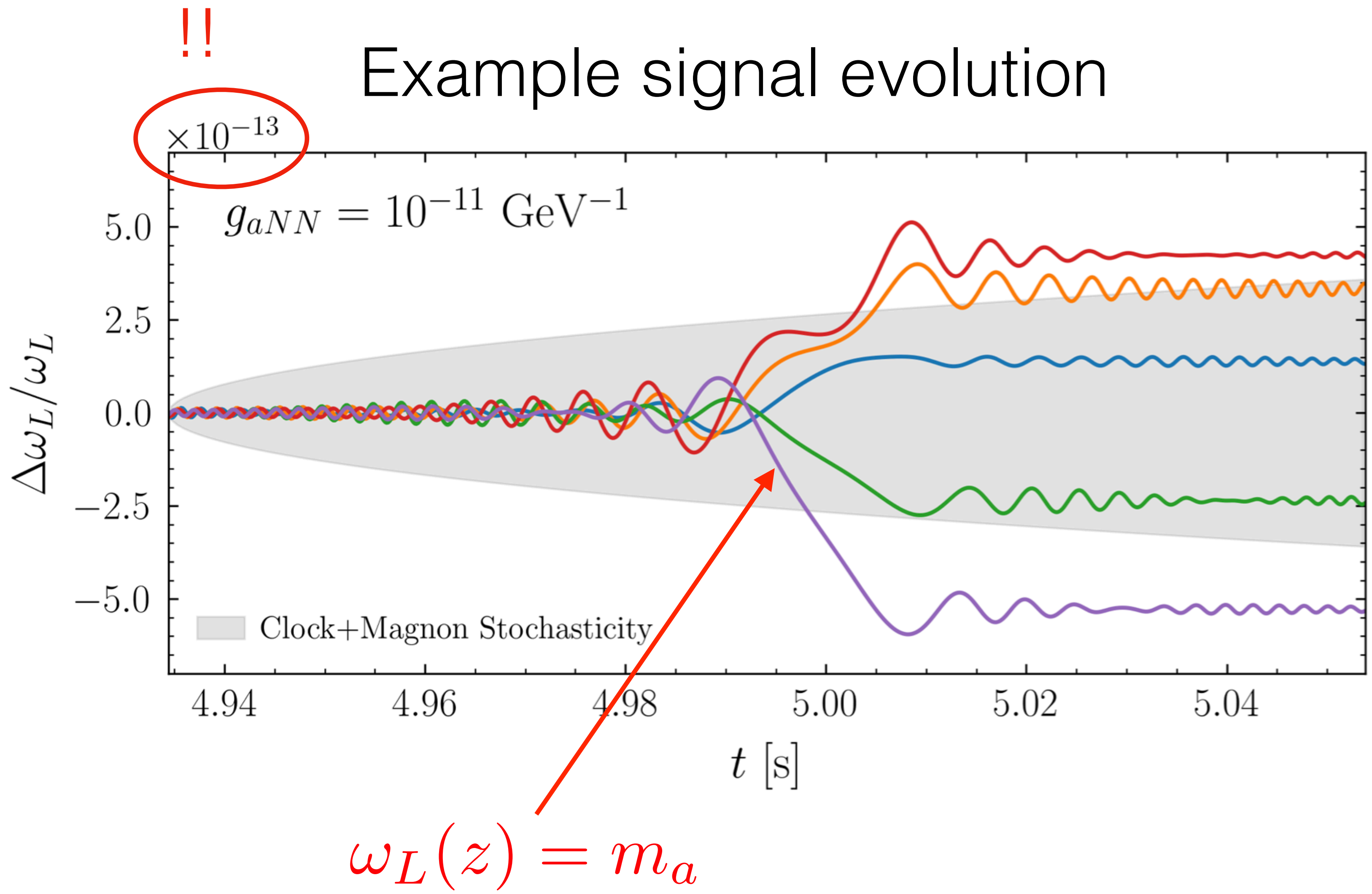
[Fomin, JETP 1985; Bunkov and Volovik, arXiv:0904.3889 and arXiv:1003.4889]

Axion signal

Axion induces small variance in domain wall position,
hence small change in precession frequency drift



Example signal evolution



Need frequency precision to 1 part in 10 trillion (!), but
no information in (large) amplitude. Perfect for quantum readout!

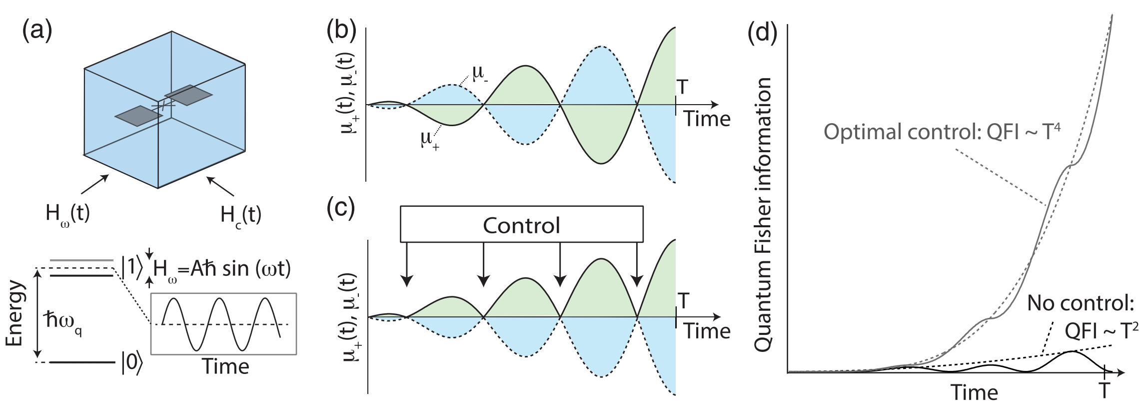
[Gao et al. (**YK**), PRL 2022; Foster et al. (**YK**), PRD 2024]

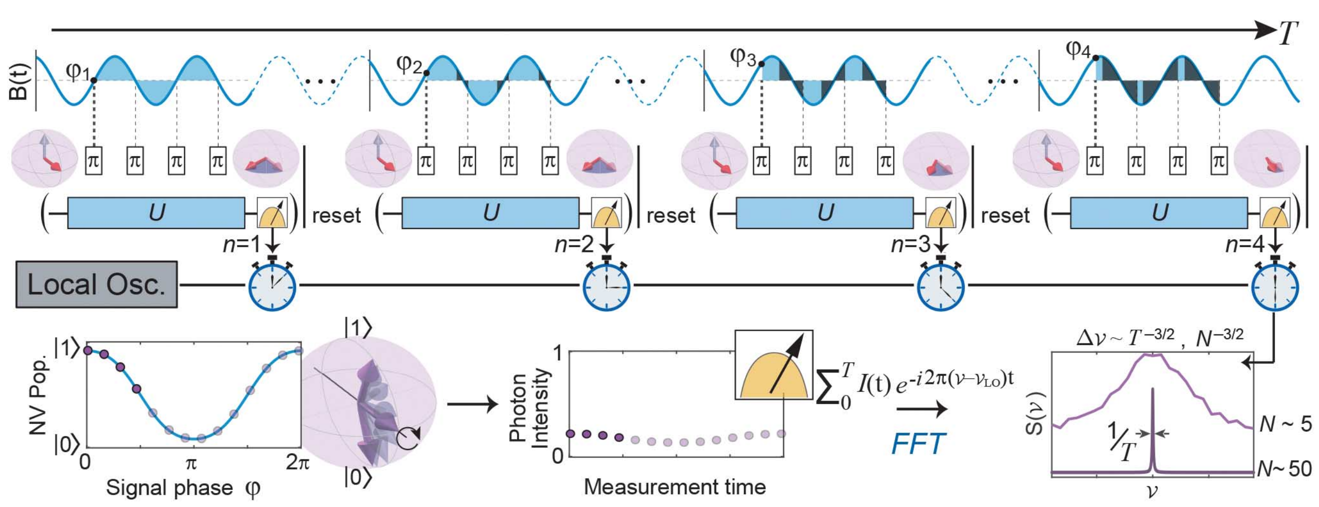
Qubit readout

Precessing HPD read out by flux-sensitive superconducting qubit:

$$H_{\dot\omega}(t) = A\sin(\omega_L t + \dot\omega t^2/2)\frac{\sigma_z}{2}$$

Apply time-dependent control pulses to optimally estimate $\dot\omega$:





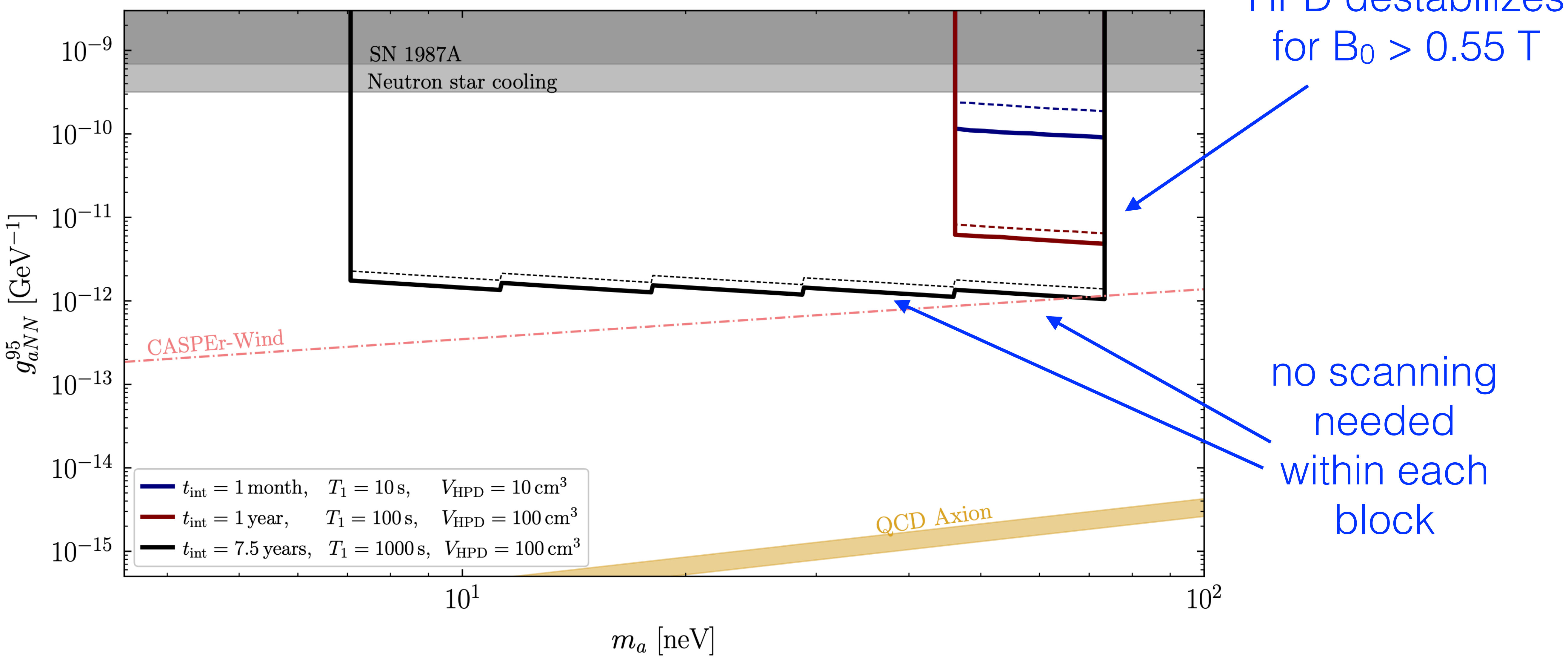
Up to qubit coherence time:

$$\delta\dot\omega \sim T^{-3}$$

Timestamp each readout and correlate:

$$\delta\dot\omega \sim T^{-5/2}\,T_2^{-1/2}$$

Projected HPD sensitivity



World-leading sensitivity with just 10-100 cc's of 3He!
Needs cryogenic infrastructure + RF systems,
but synergistic with SNOLAB's quantum science program
(c.f Marvin Hirschel's talk on Thursday)

[Gao et al. (YK), PRL 2022; Foster et al. (**YK**), PRD 2025]

Summary

Amazing science opportunities with small-scale detectors!
Many other ideas, SNOLAB is the place to make them happen

Scintillator collaboration:
University of Chicago/Fermilab: Brandon Roach, Nora Hoch, Abby Williams, Edgar Marrufo Villalpando, Dan Baxter, Alex Drlica-Wagner
University of Illinois Urbana-Champaign: Peter Abbamonte, David Balut, James Oh, Liam Thompson
MIT: Dane Johnson, Danna Freedman, Lindley Winslow
Penn State: Carlos Blanco
University of Oregon: Aria Radick, Ben Lillard
University of Toronto: Yoni Kahn

3He collaboration: Yoni Kahn **(Toronto);** Christina Gao **(SUST)**; Jan Schütte-Engel **(Berkeley)**; Bill Halperin, Man Nguyen, John William Scott **(Northwestern)**; John Davis **(Alberta);** Josh Foster **(Fermilab/Wisconsin)**