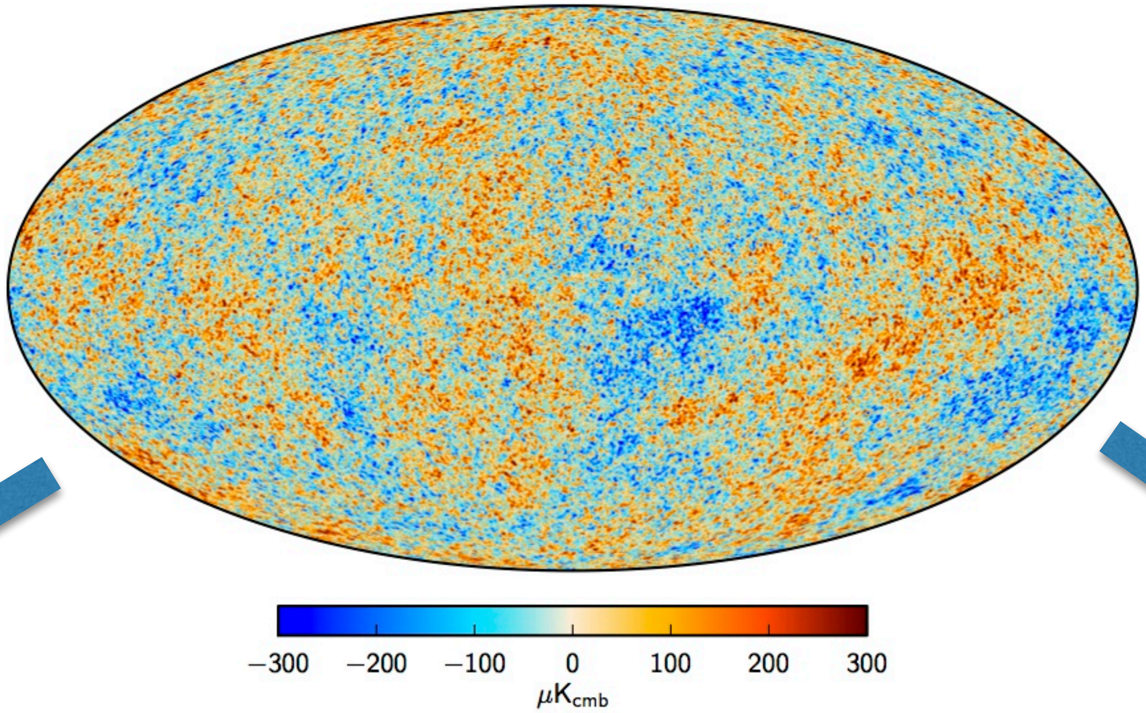
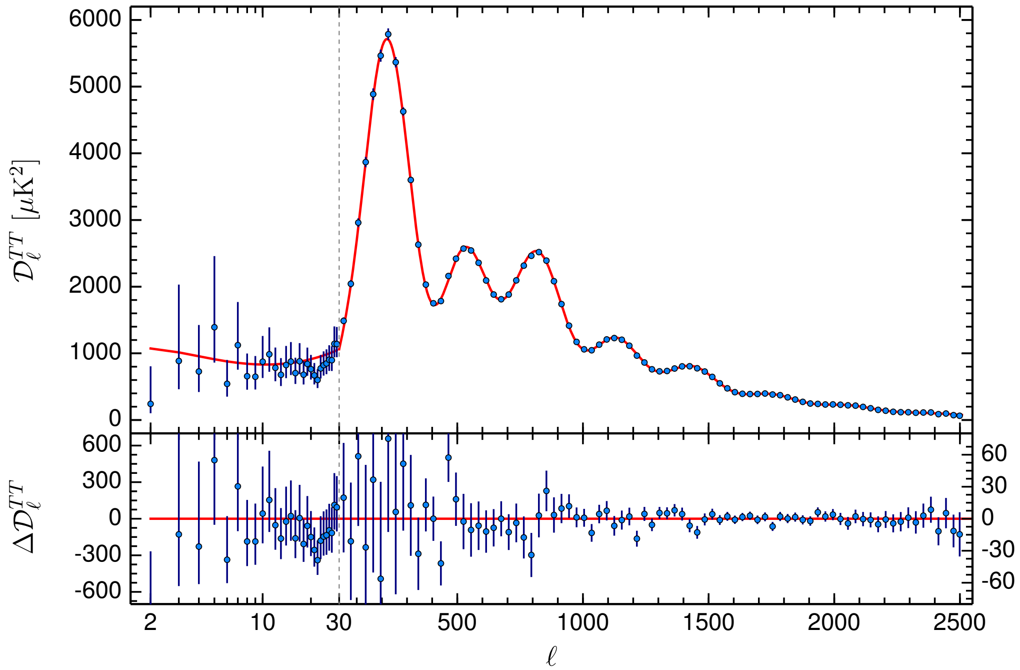
New Approaches to Dark Matter Direct Detection

Yoni Kahn (UIUC)

PHENO 2022, 5/11/22

Dark matter exists!





Parameter	[1] *Planck* TT+lowP
$\Omega_b h^2$	0.02222 ± 0.00023
$\Omega_c h^2$	0.1197 ± 0.0022
$100\theta_{MC}$	1.04085 ± 0.00047
τ	0.078 ± 0.019
$\ln(10^{10} A_s)$	3.089 ± 0.036
n_s	0.9655 ± 0.0062
H_0	67.31 ± 0.96
Ω_m	0.315 ± 0.013
σ_8	0.829 ± 0.014
$10^9 A_s e^{-2\tau}$	1.880 ± 0.014

We have never observed a dark matter particle.

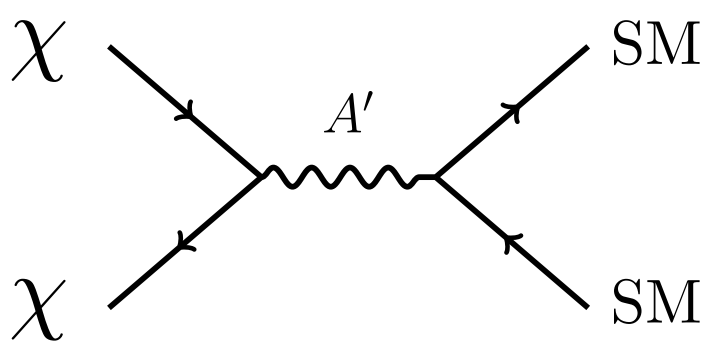
[Planck collab., A&A 2016]

Open questions about DM

What is its mass?

Does it interact non-gravitationally?

How was it made in the early universe?

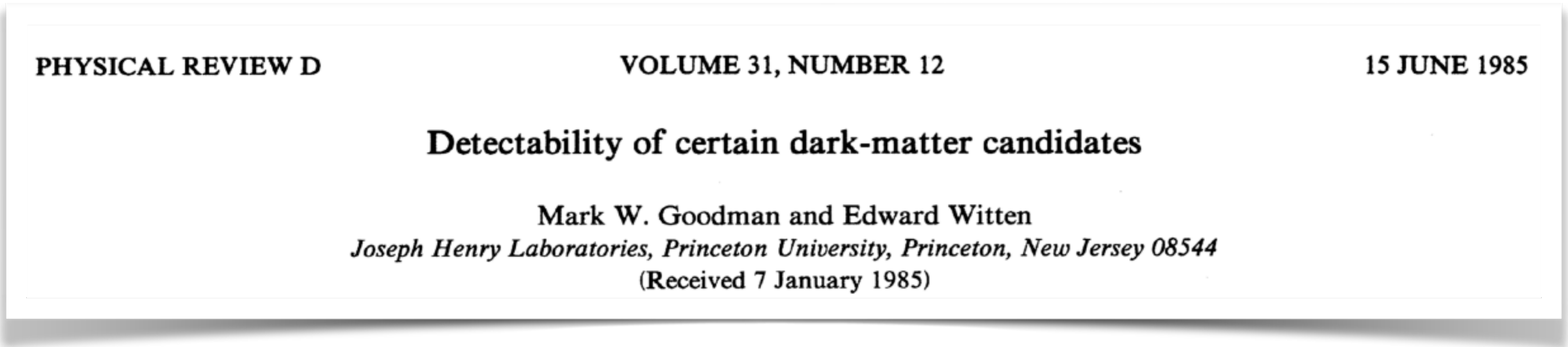


postulate some answers
(viable benchmark models)

How can we detect galactic DM on Earth?

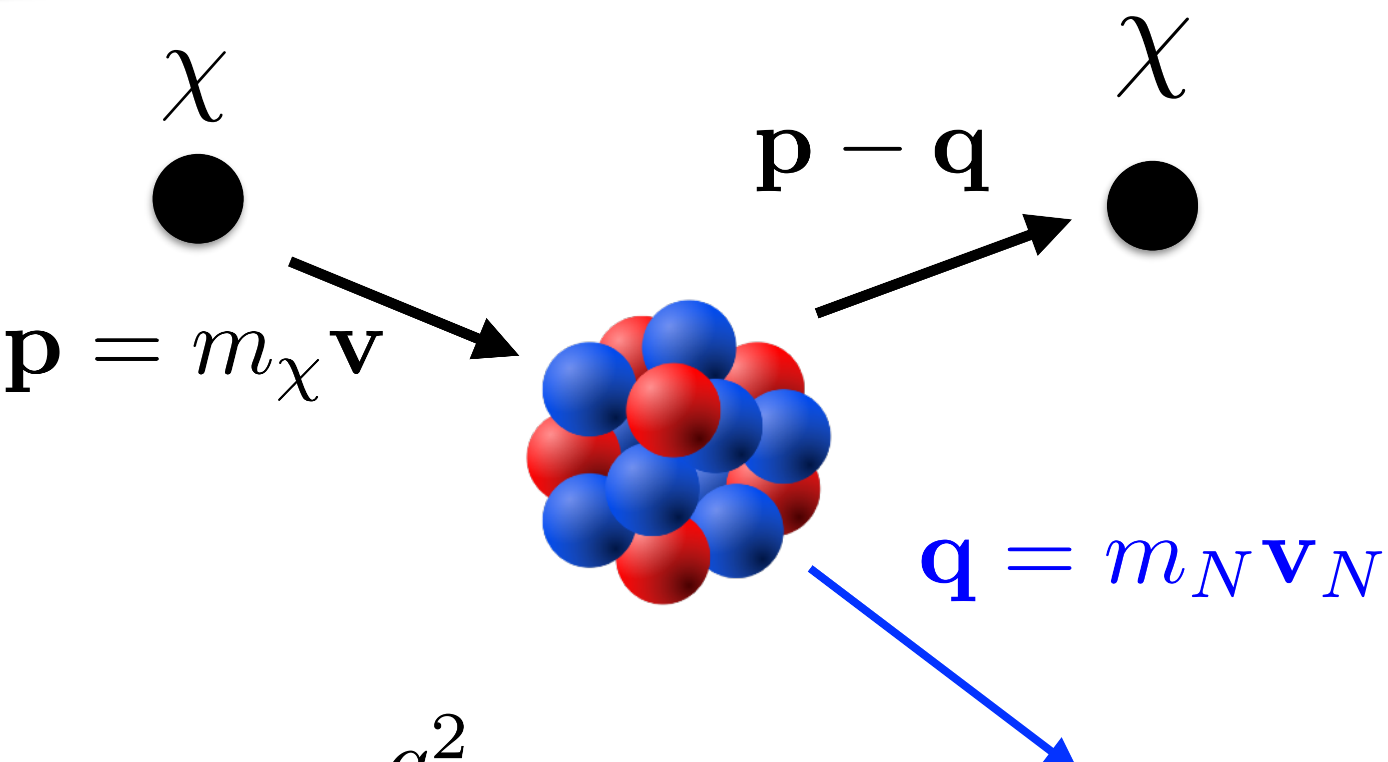
Use tools from high-energy physics plus condensed matter, atomic physics, materials science, quantum information, …
to understand **DM interactions in terrestrial detectors**

DM-nuclear scattering


PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)



$$E_N = \frac{q^2}{2m_N}, \quad q_{\max} = 2\mu_{\chi N} v$$

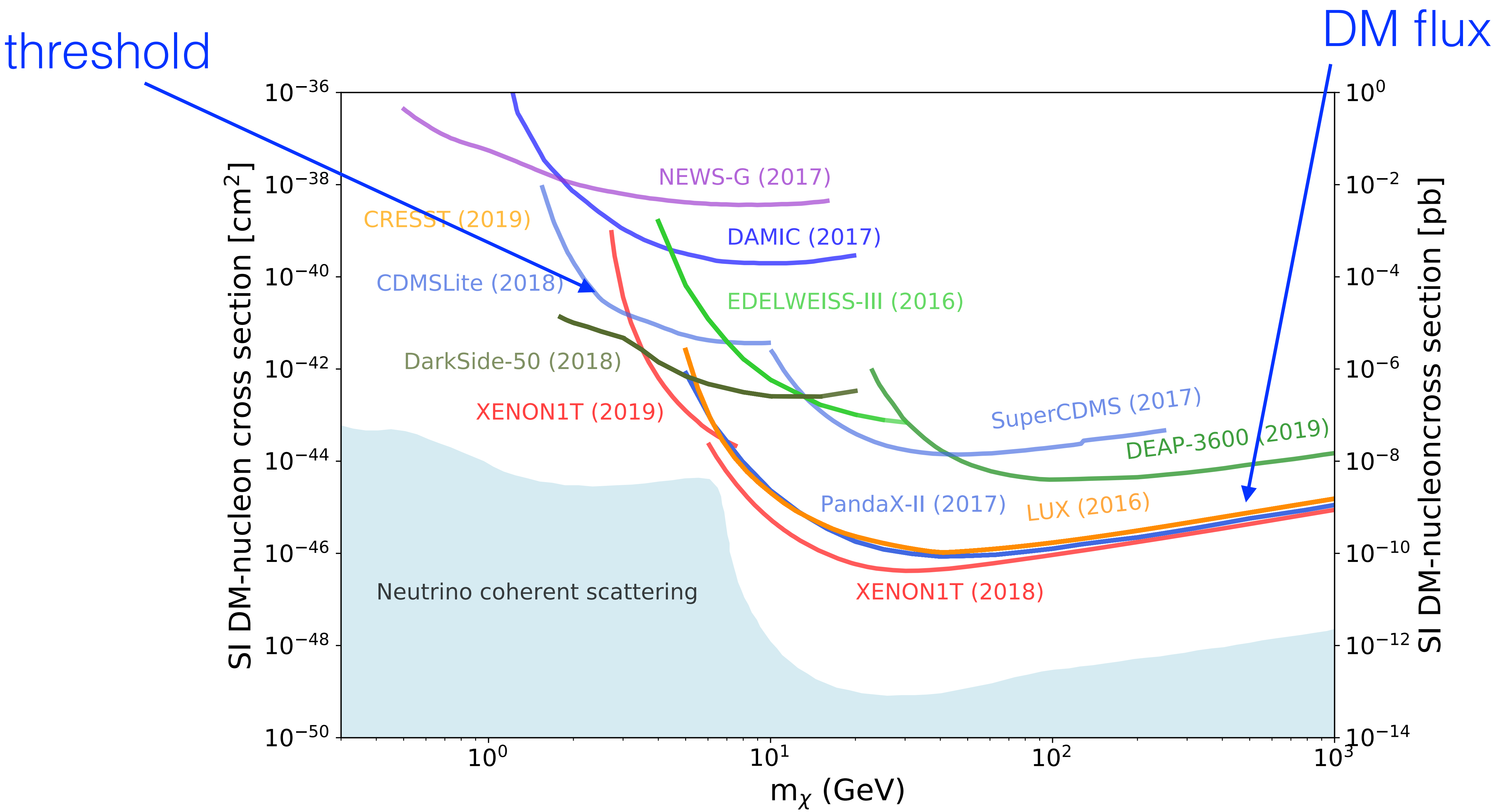
$m_\chi \simeq m_N$
(10-100 GeV)

$m_\chi \gg m_N$
(100 GeV - 1 TeV)

Strategy: fill a giant tank with e.g. liquid xenon, bury it under a mountain or in a mine, look for nuclear recoil energy deposited by DM

 [Goodman & Witten PRD 1985]

The landscape so far



Zero background with multi-ton detectors,
a stunning technical achievement. But all null results so far!

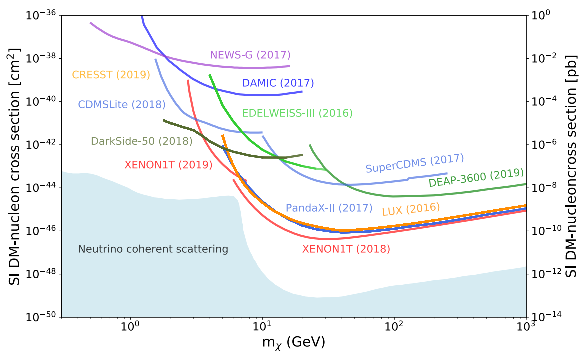
50 orders of magnitude!

Wavelength fits in a galaxy

Elementary particle

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

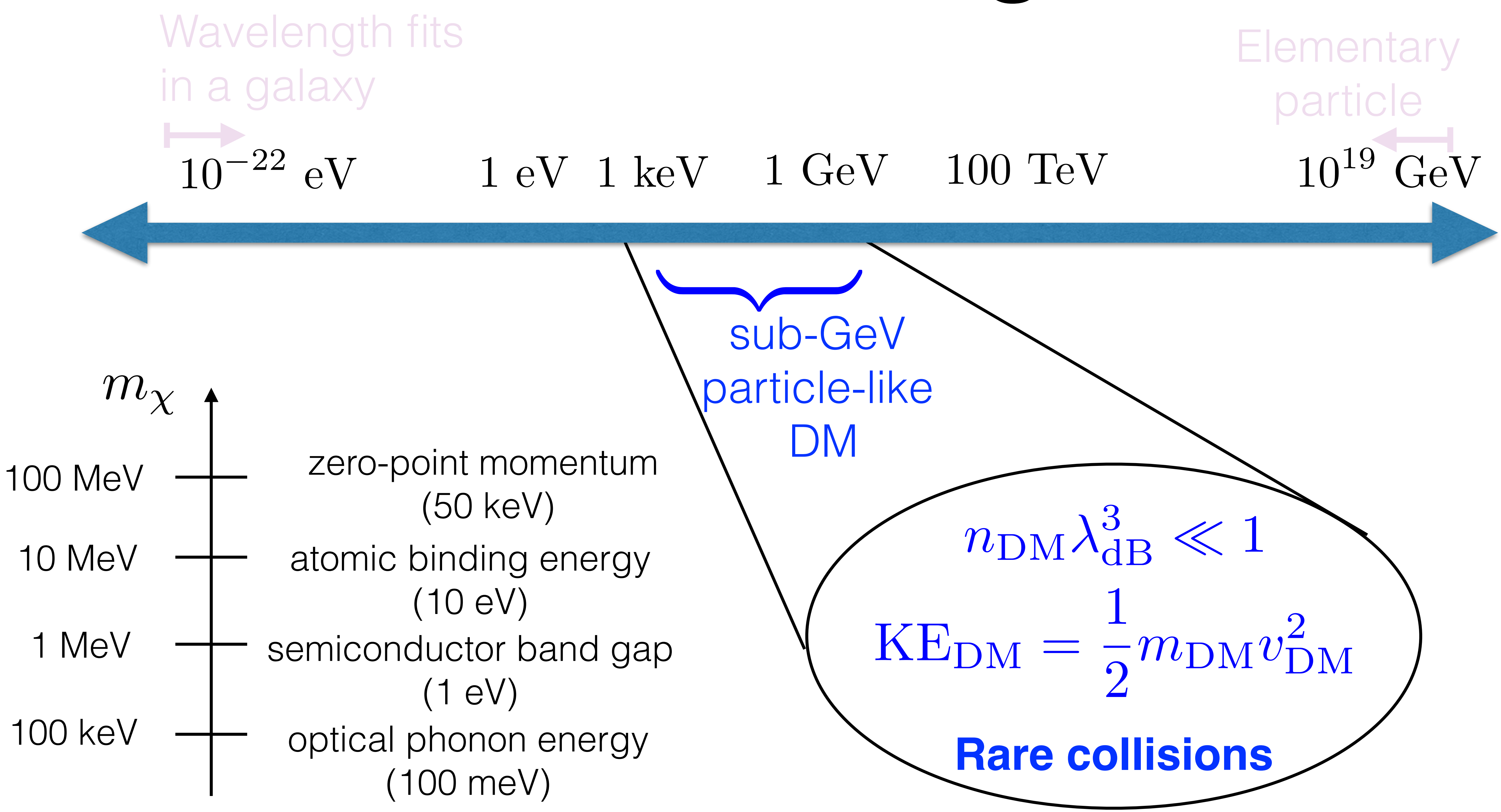
WIMPS



we have only looked in a small part of this huge parameter space! (though see D. Hooper talk for motivation)

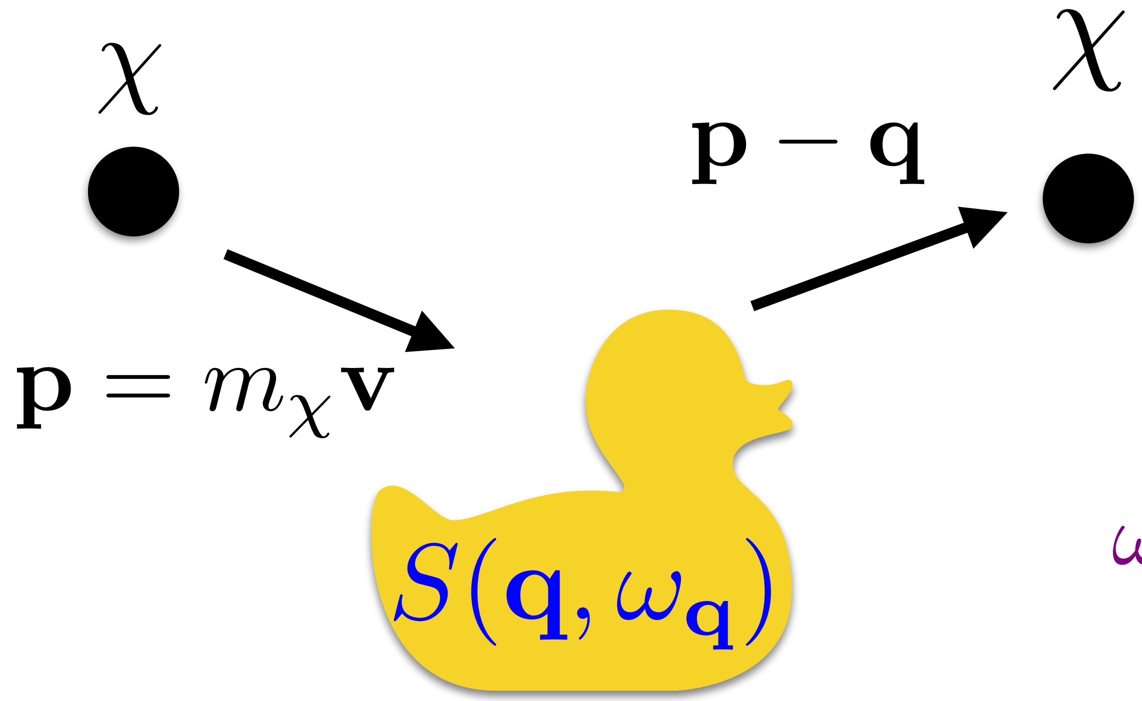
This talk: some fun and exciting new approaches (non-exhaustive!) to covering the rest of it

50 orders of magnitude



Detector is not a bag of free particles: condensed matter physics mandatory!
(c.f. M. Sholapulkar talk from Monday)

Response functions



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

Energy deposited by DM:

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

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

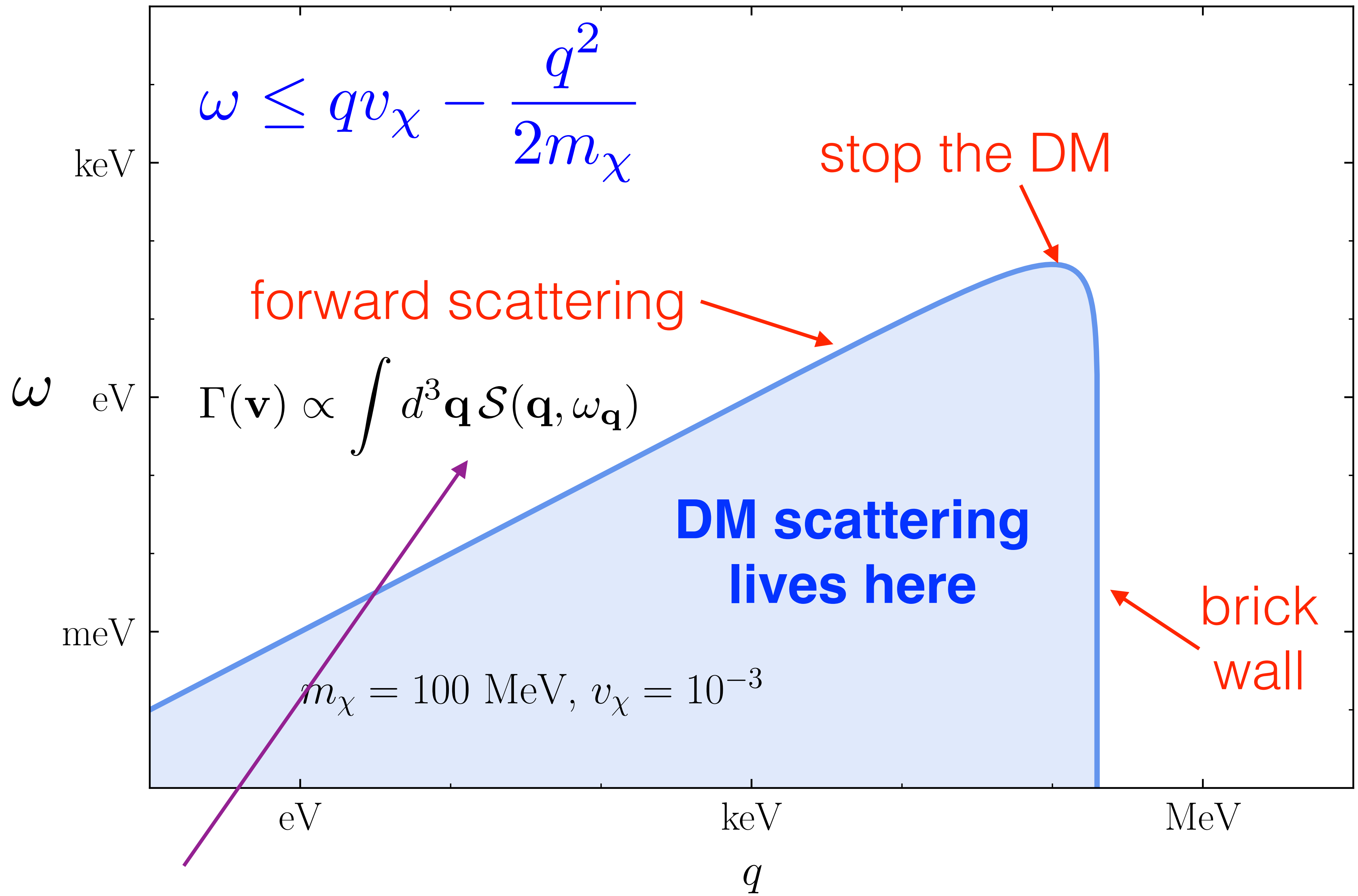
$$R \sim \int d^3\mathbf{v}\, f(\mathbf{v}) \int d^3\mathbf{q}\, F^2(\mathbf{q}) S(\mathbf{q}, \omega_\mathbf{q})$$

DM properties — Material properties

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

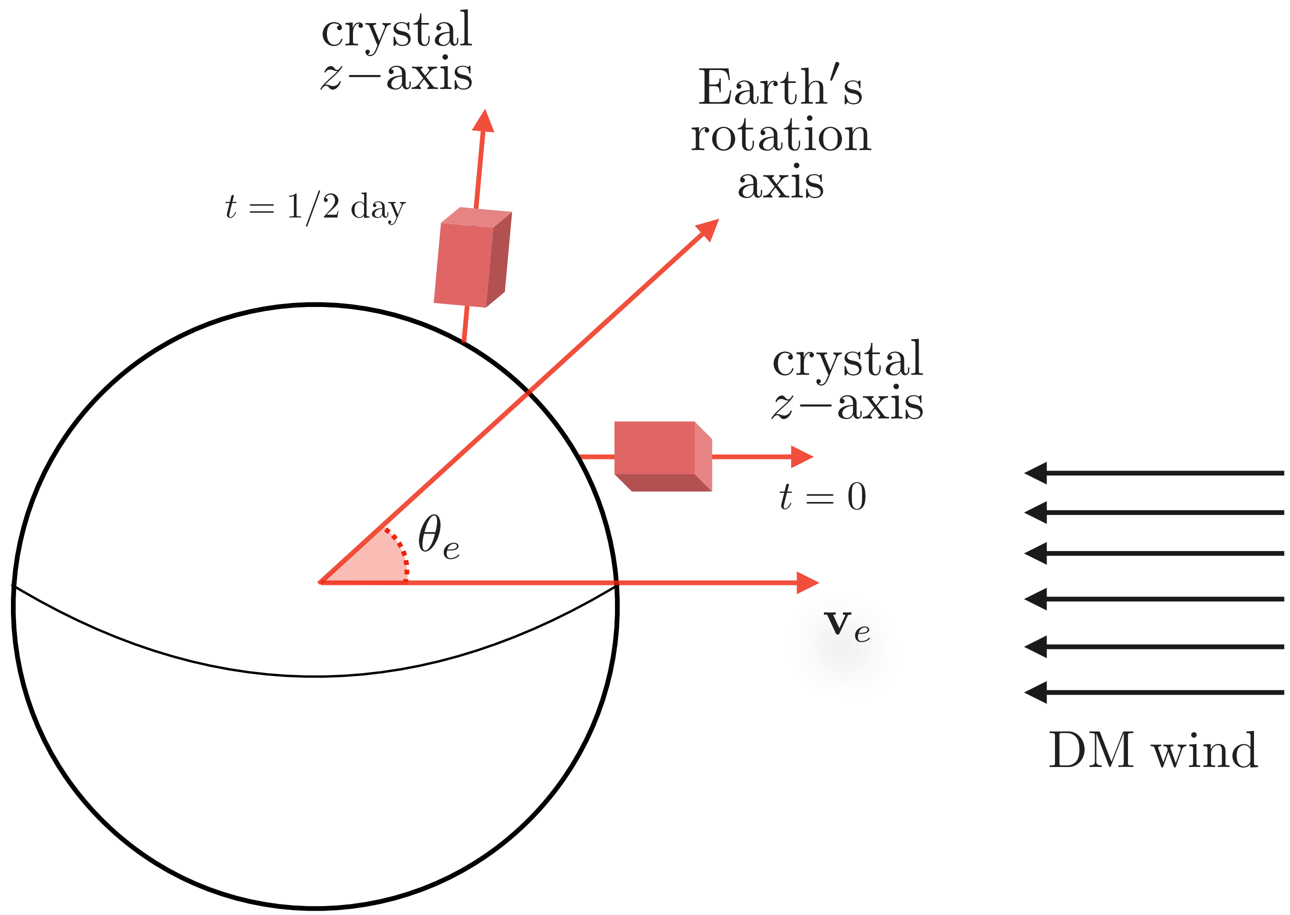
[Trickle, Zhang, Zurek, Inzani, Griffin, JHEP 2020; **YK** and Lin, arXiv:2108.03239]

Sub-GeV DM kinematics



Goal: maximize the response function inside the DM parabola

Daily modulation



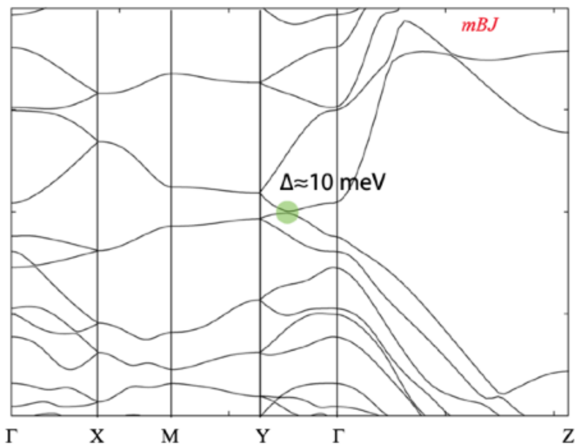
$$R(t) \sim \int d^3v\, d^3q\, f_\chi(\mathbf{v}, t)\, \mathcal{S}(\mathbf{q}, \omega_\mathbf{q}) \qquad \omega_\mathbf{q} = \mathbf{q} \cdot \mathbf{v} - \frac{q^2}{2m_\chi}$$

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

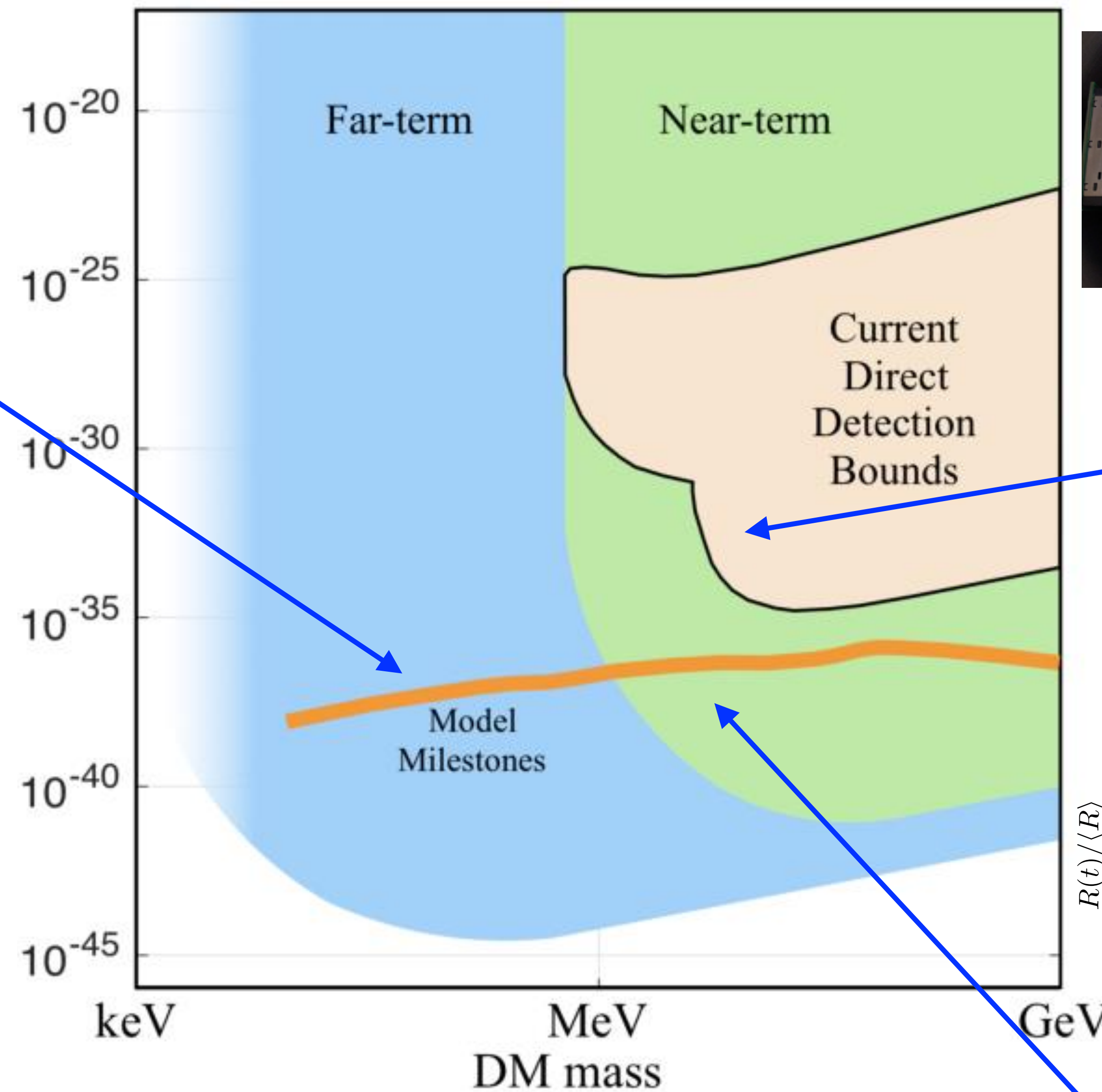
Smoking gun for DM signal!

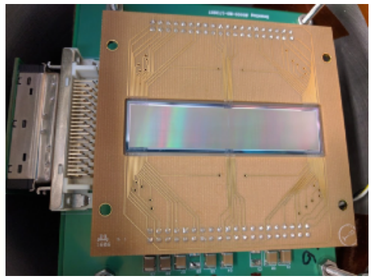
[Spergel, PRD 1988; cartoon from Coskuner, Mitridate, Olivares, Zurek, 1909.09170]

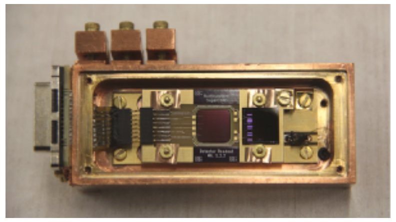
DM-electron scattering



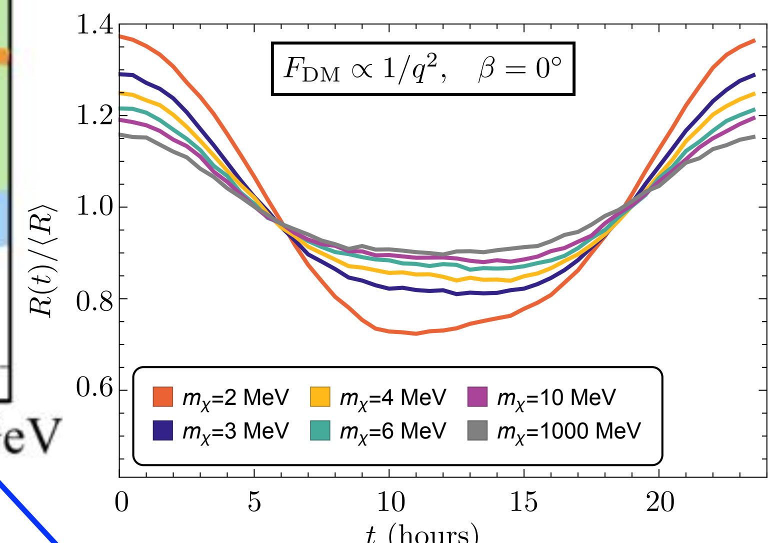
Low-gap materials (e.g. $Eu_5In_2Sb_6$) for sub-MeV DM







Single e/h excitation in semiconductors: now running!



Molecular excitation: daily modulation

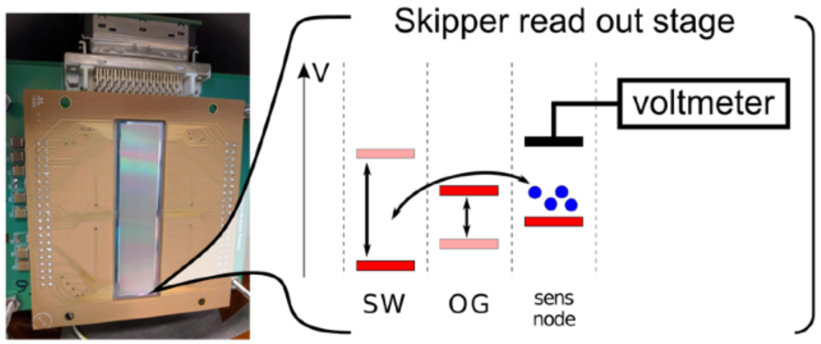
Sensitivity driven by electron energy gap: $\frac{1}{2} m_{\rm DM} v_{\rm DM}^2 = \Delta E_e$

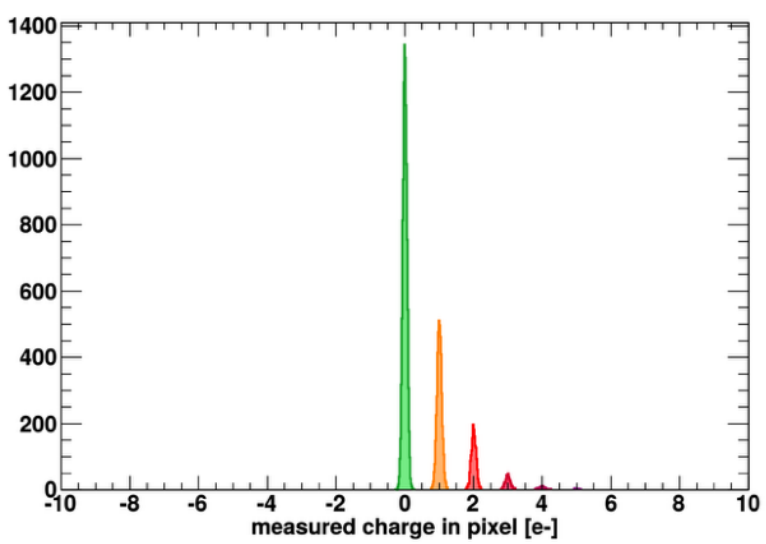
[Barak et al. (SENSEI collab.), PRL 2020; Amaral et al. (SuperCDMS collab.), PRD 2020; Blanco, **YK**, Lillard, McDermott, PRD 2021; SPLENDOR collab; DOE BRN report]

Single-electron detection

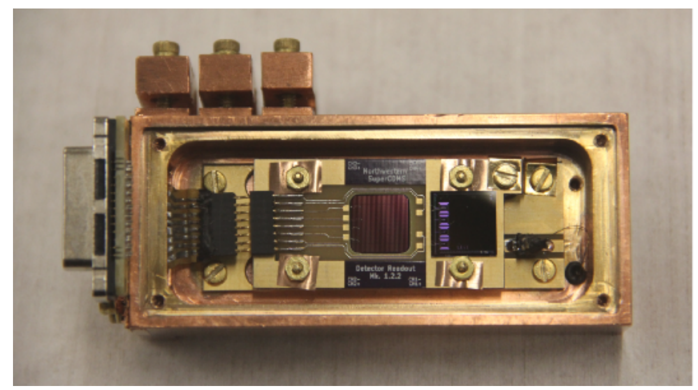
Harness amazing industrial/technological development of ultra-pure Si:

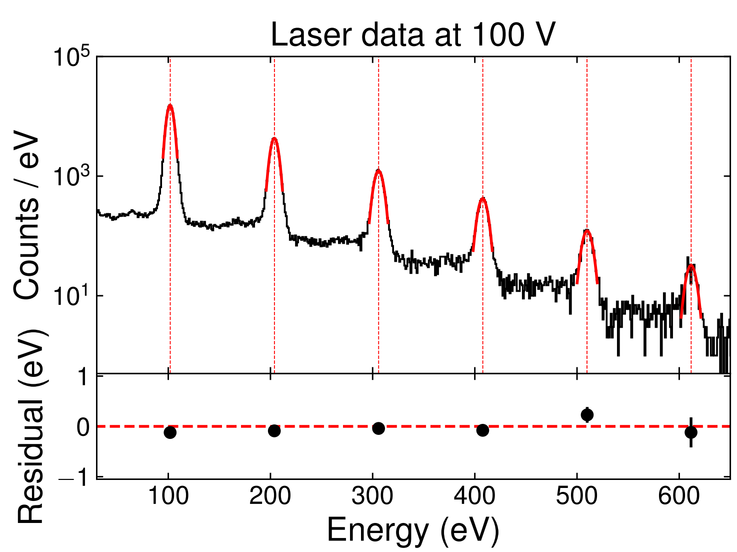
SENSEI
(2 grams):

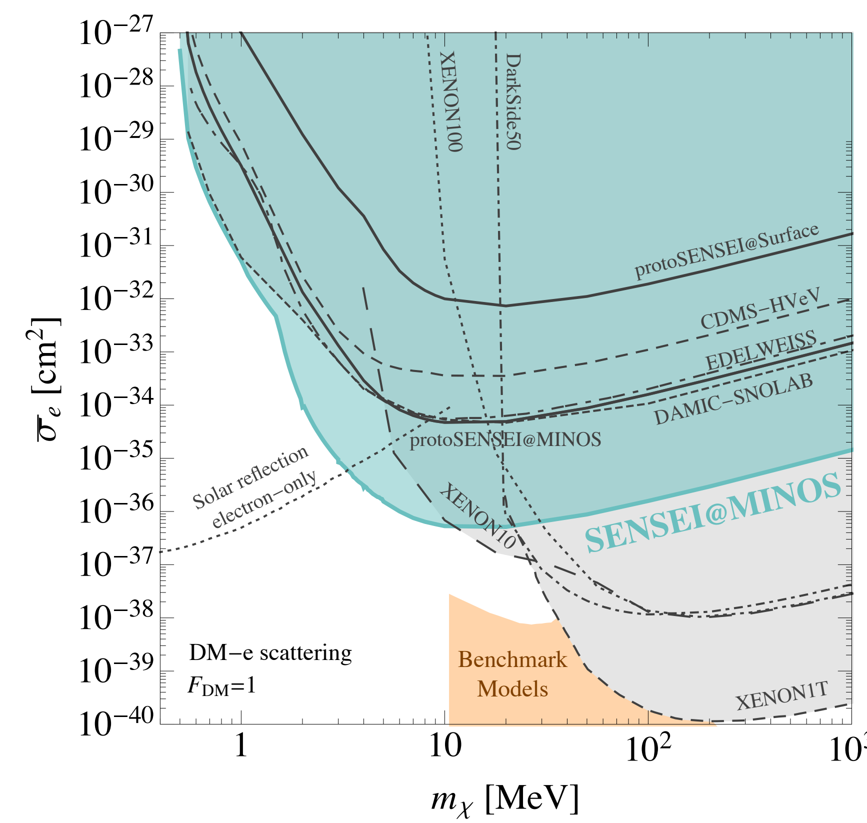




SuperCDMS HVeV
(0.93 grams):





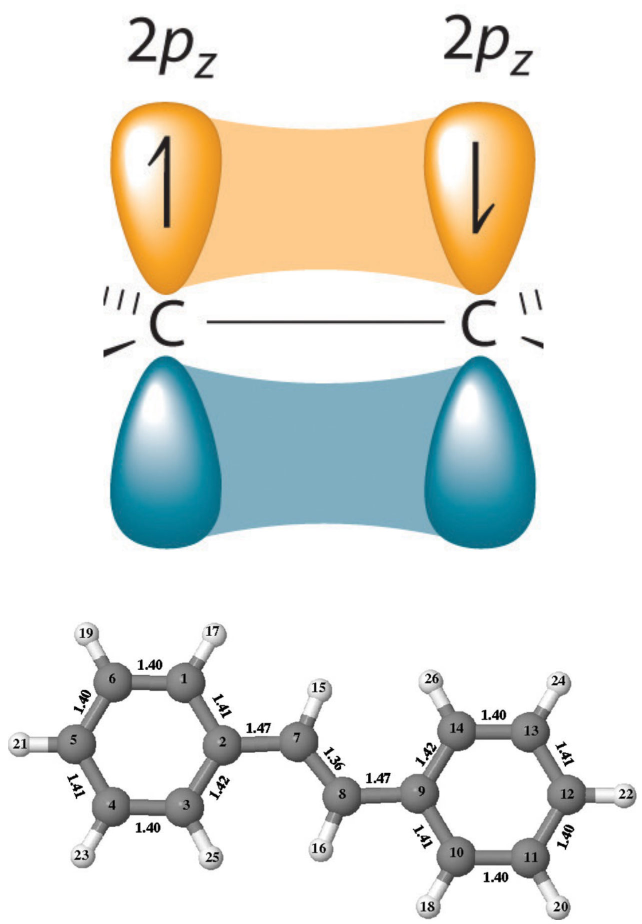


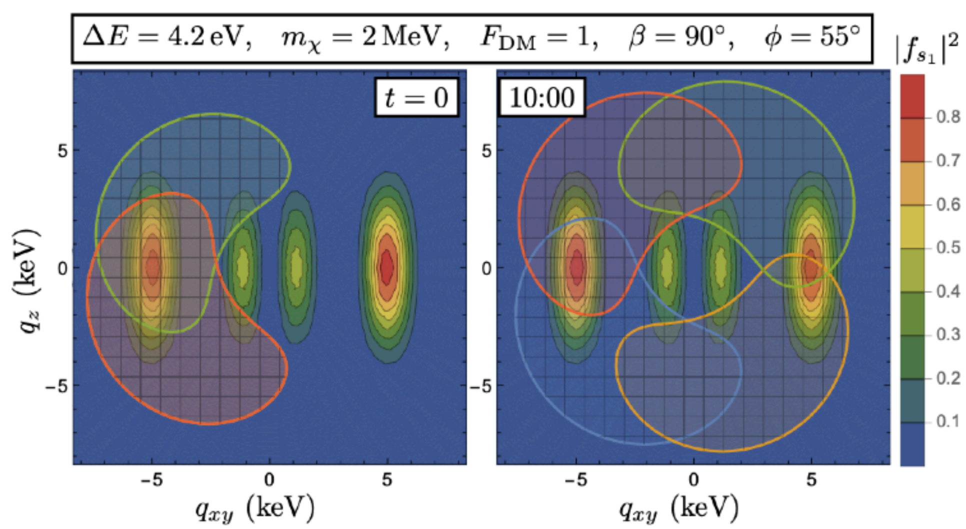
Well-motivated parameter space is very close:
reliable estimate of the signal in solid-state detectors is crucial!

[Barak et al. (SENSEI collab.), PRL 2020; Amaral et al. (SuperCDMS collab.), PRD 2020]

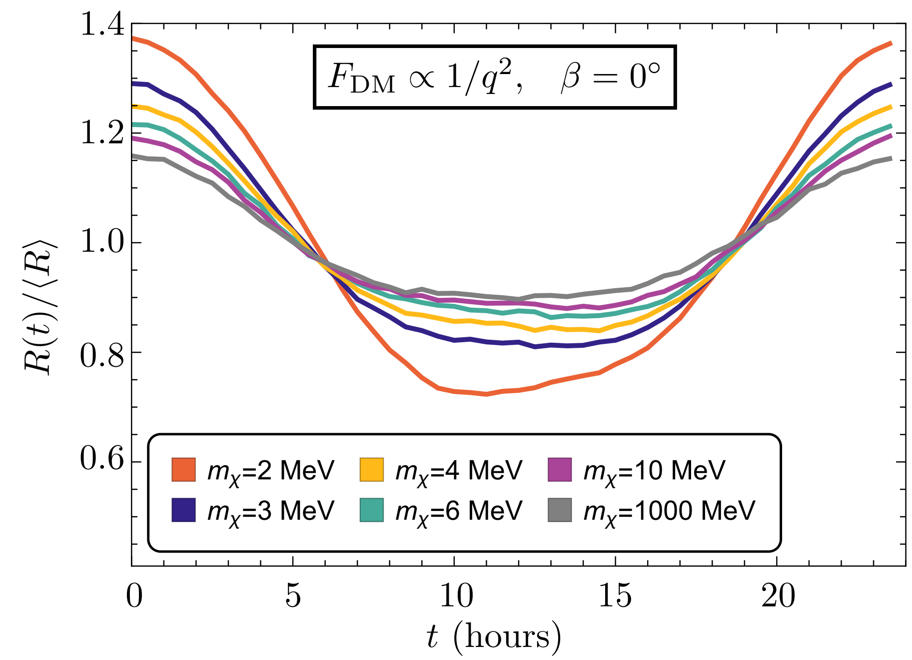
Organic crystals

Carbon bonds give eV-scale energy gaps, anisotropic response





response function
(lowest transition)

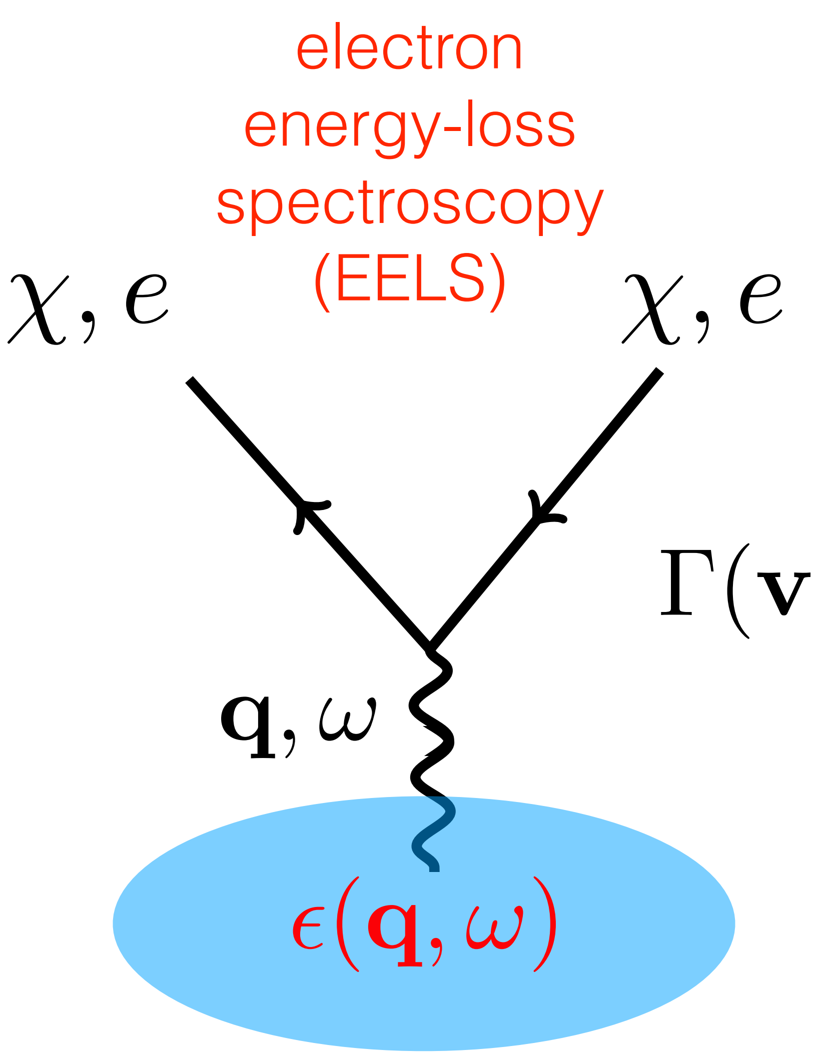


20% daily modulation!

Kg for kg, same total rate as Si,
but modulation means discovery does not require zero background

Measuring electron response

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



DM-electron interaction (assumed spin-independent)

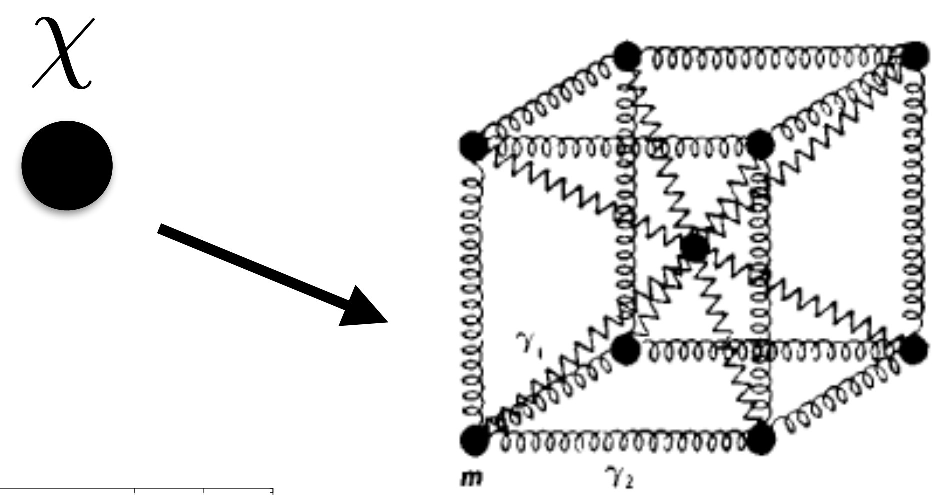
Response function (dielectric, for electrons)

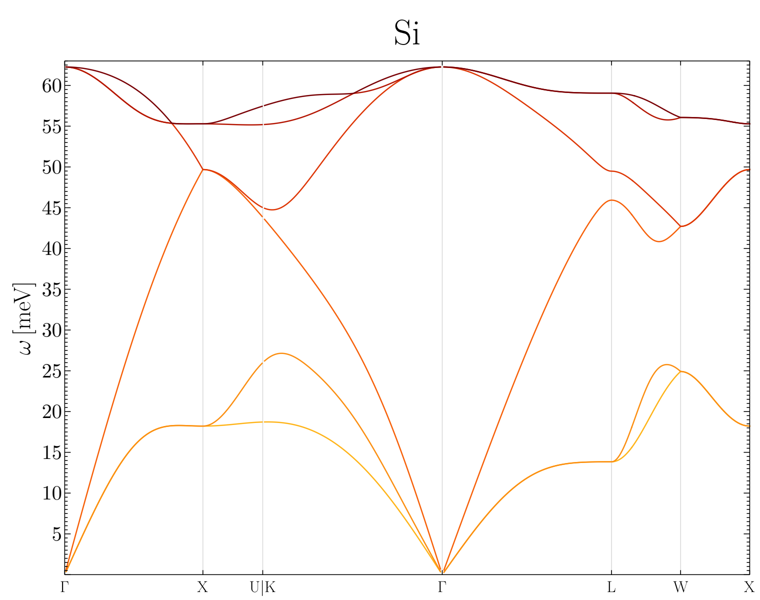
$$\Gamma(\mathbf{v}) = \int \frac{d^3\mathbf{q}}{(2\pi)^3} |V(\mathbf{q})|^2 \left[\frac{q^2}{e^2} 2\,\mathrm{Im}\left(-\frac{1}{\epsilon(\mathbf{q}, \omega)}\right)\right]$$

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]

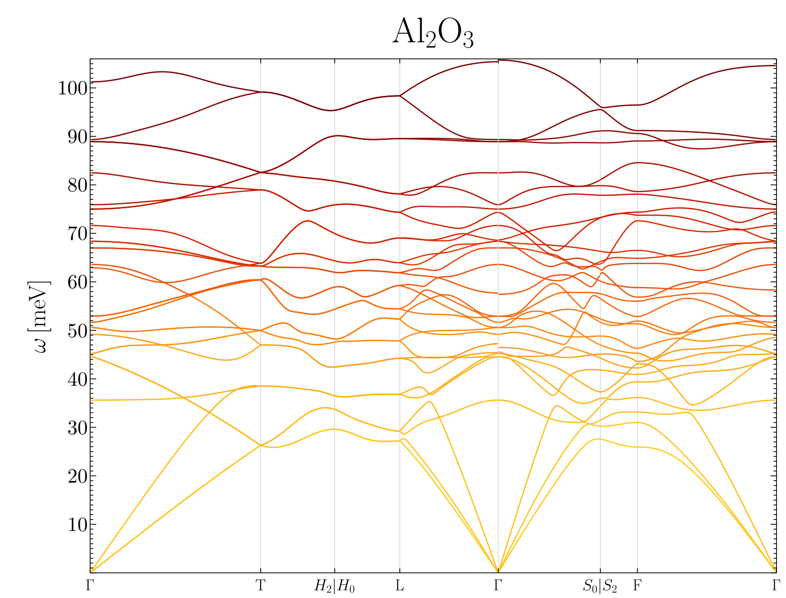
From nuclei to phonons





$$q \simeq \mathrm{eV} - \mathrm{keV}$$

$$\omega \simeq 1 - 100\ \mathrm{meV}$$



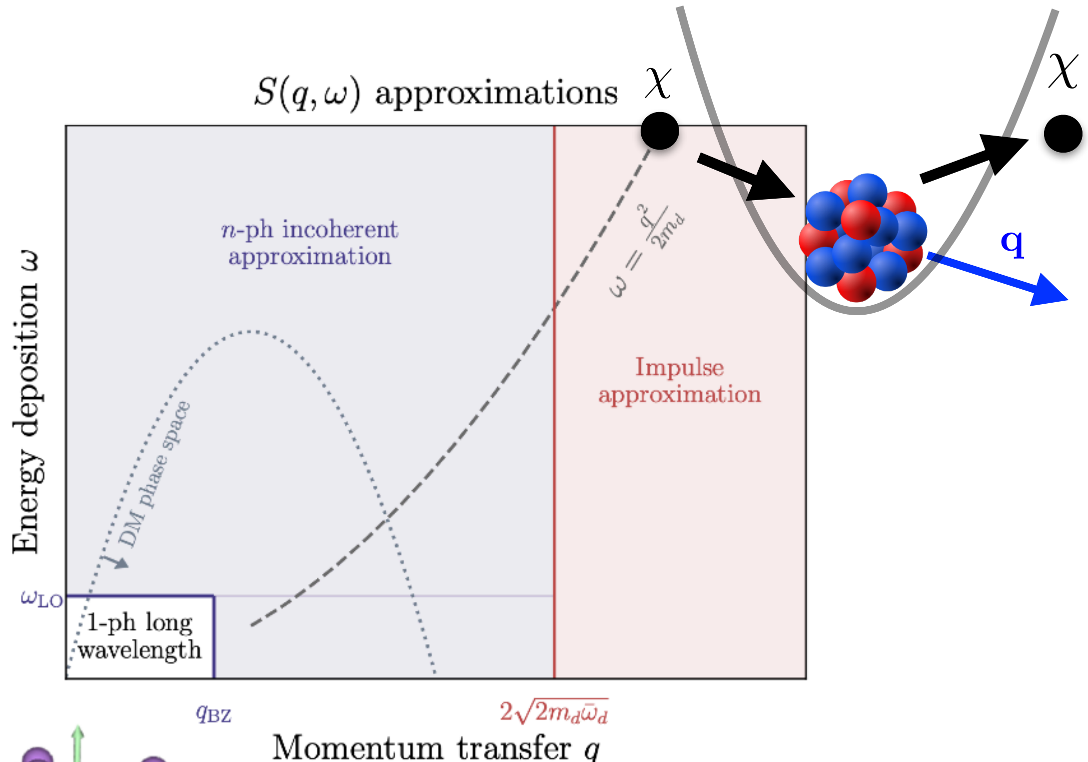
Each line is a dispersion relation $\omega(\mathbf{q})$ for a collective oscillation of many nuclei, which contributes to $S(\mathbf{q}, \omega_{\mathbf{q}})$.

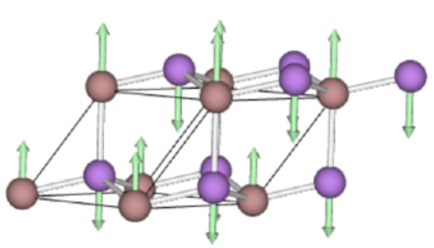
Many more modes than a single free nucleus! Also strong anisotropy

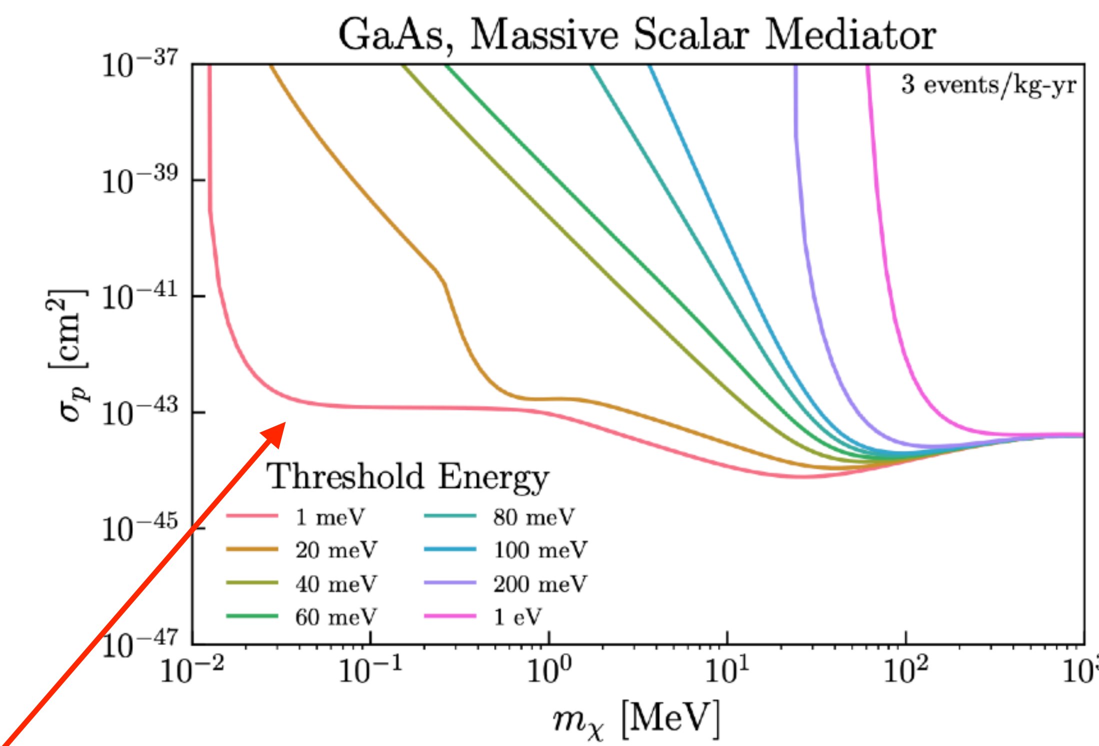
[Griffin, Inzani, Trickle, Zhang, Zurek, PRD 2020]

DM-nuclear scattering

At low momentum transfer, nuclei oscillate collectively: phonons





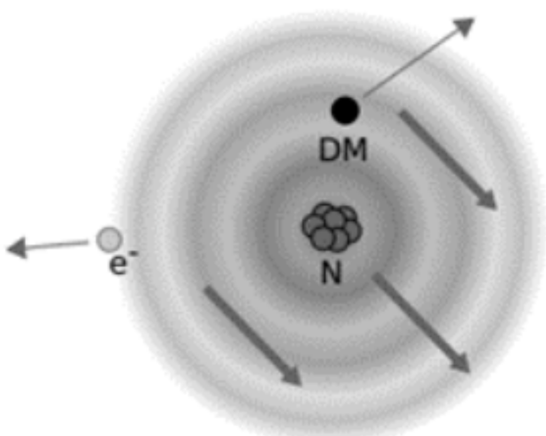


Sensitivity driven by readout: arbitrarily low-energy phonon modes exist, but need to read out at meV thresholds with no background

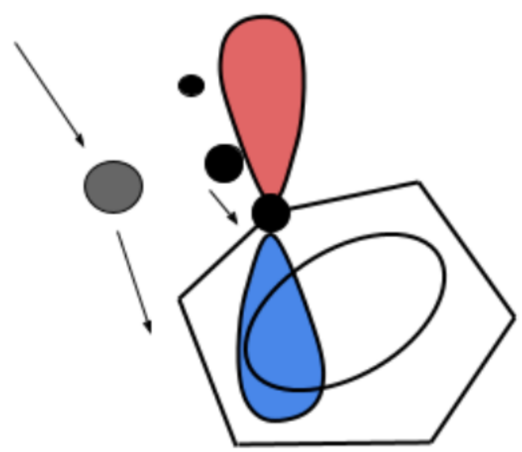
[Campbell-Deem, Knapen, Lin, Villarama, arXiv:2205.02250; Griffin, Knapen, Lin, Zurek, PRD 2018; **YK**, Krnjaic, Mandava, PRL 2021]

Migdal effect

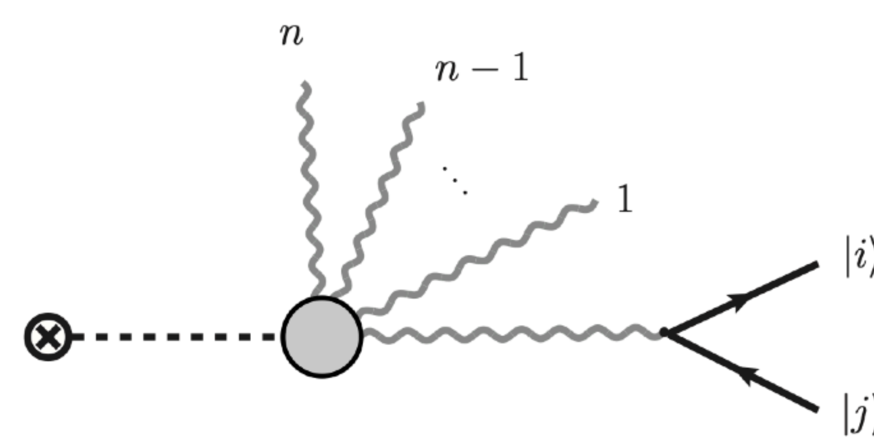
Electrons and nuclei are always coupled!
Whack a nucleus, QM says that electrons can transition



atom



molecule



semiconductor
(phonon-mediated)

Can get charge signal from nuclear scattering (avoid threshold!) and possible daily modulations (c.f. I. Harris and D. Adams talks Tuesday).
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]

Ultralight DM

Wavelength fits in a galaxy

Elementary particle

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

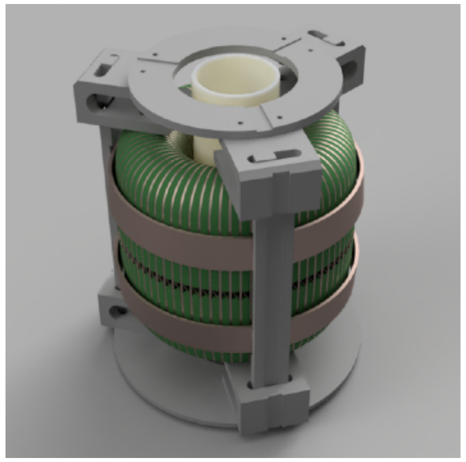
coherent-field bosonic (e.g. axions)

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

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

Behaves as classical field

Magnets, superconducting cavities, atomic clocks…dark matter acts like an oscillating external source of fixed but unknown frequency for any quantum-mechanical system



Axion direct detection

$$a(\mathbf{x},t) = \frac{\sqrt{2\rho_{\rm DM}}}{m_a}\cos(m_a t + \mathcal{O}(v_{\rm DM})\mathbf{x})$$

In axion DM background, get oscillating observables:

$$\nabla \times \mathbf{B}_a = \frac{\partial \mathbf{E}_a}{\partial t} - g_{a\gamma\gamma}\left(\mathbf{E}_0 \times \nabla a - \mathbf{B}_0 \frac{\partial a}{\partial t}\right)$$

$$\nabla \cdot \mathbf{E}_a = -g_{a\gamma\gamma}\mathbf{B}_0 \cdot \nabla a$$

Effective AC charge and current

$$H_N \supset g_{aNN}\nabla a \cdot \vec{\sigma}_N$$

Effective AC magnetic field

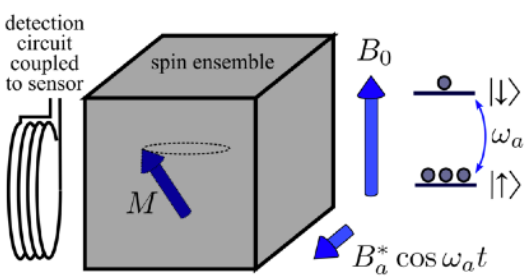
$$d_n = g_d a$$

Time-varying EDM

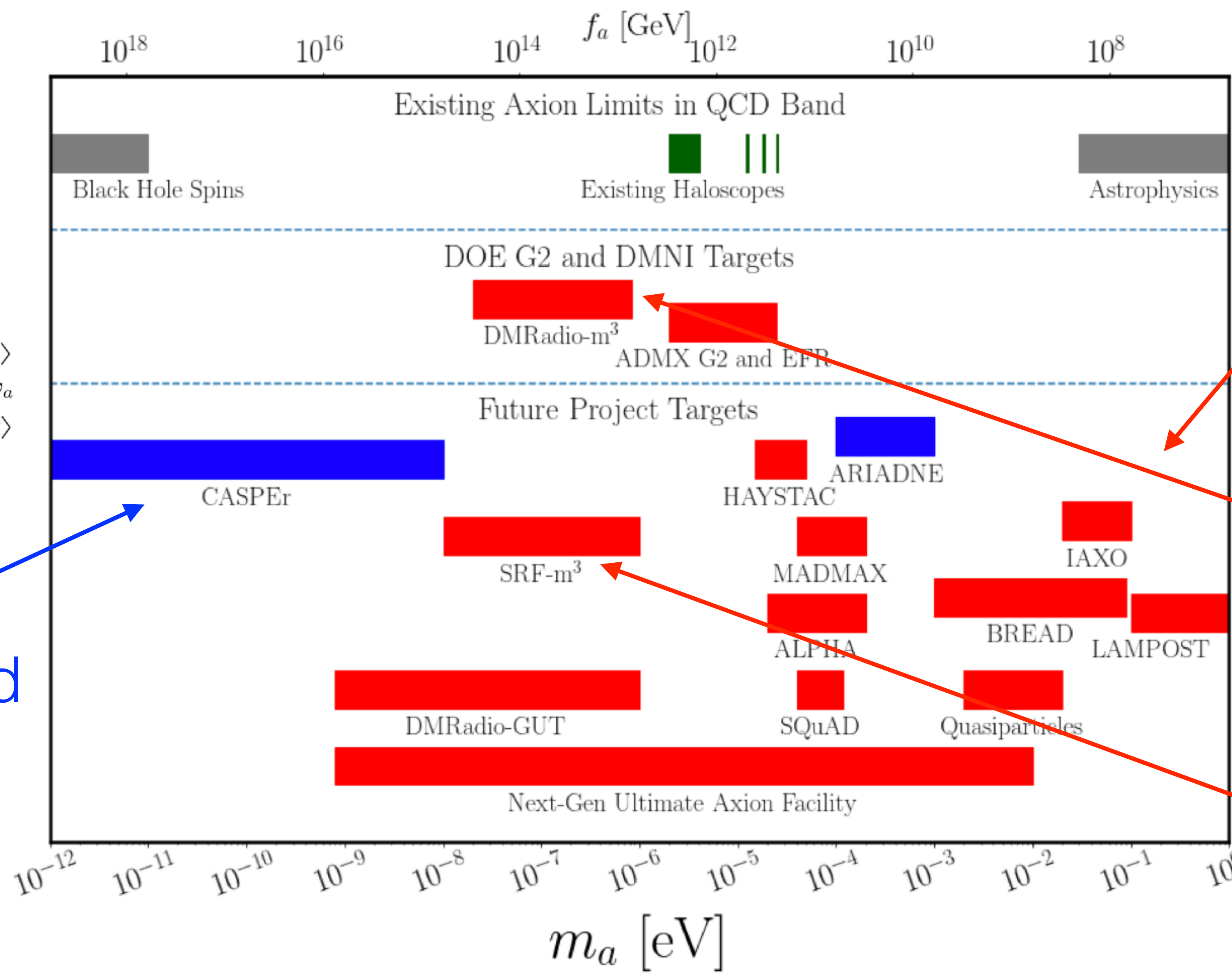
Note: $\nabla a \sim v_{\rm DM} \sim 10^{-3}$ so some are easier than others

[Sikivie, PRL 1983; Graham and Rajendran, PRD 2013]

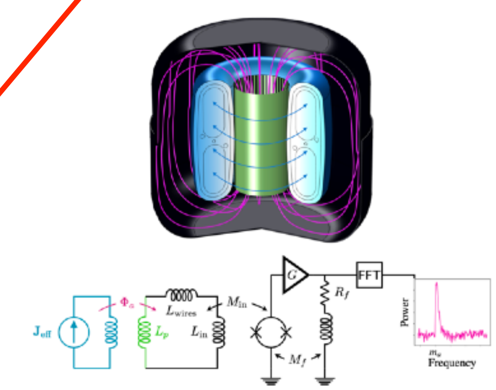
Landscape of axion DM

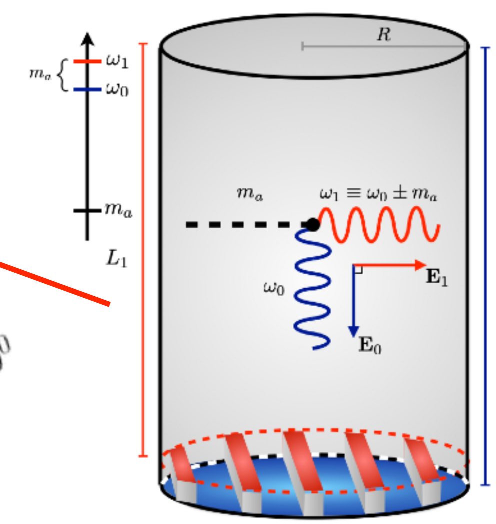


axion = effective B-field



R. Janish's talk Monday





Very very weak continuous signals: quantum-limited readout is key!

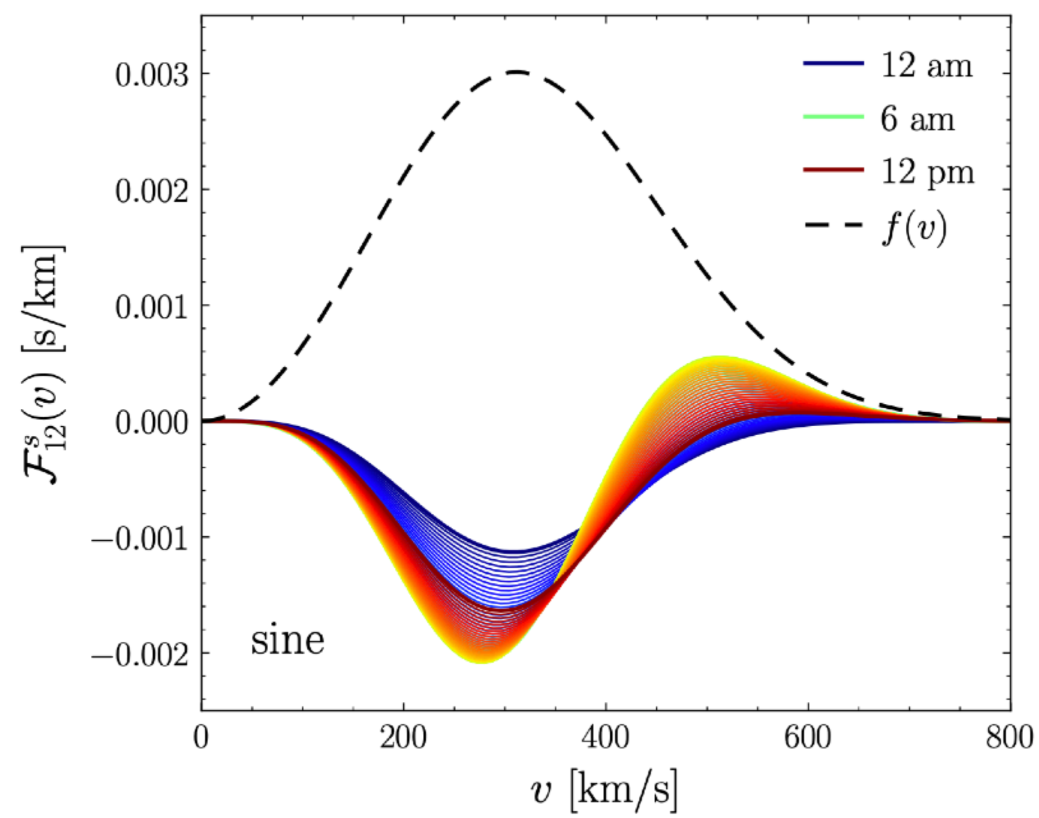
axion = effective current

[Jaeckel, Rybka, Winslow, Snowmass WP arXiv:2203.14923]

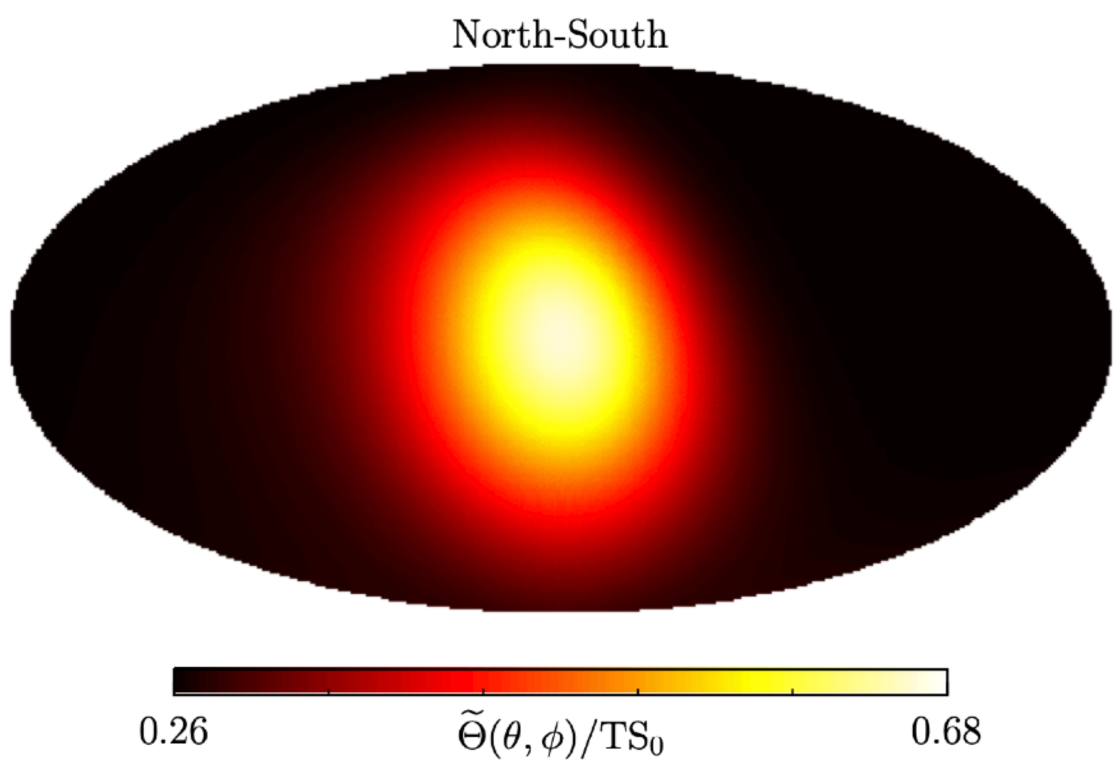
Axion DM interferometry

Covariance between two spatially-separated detectors shows interference effects which modulate over a day

off-diagonal covariance



reconstruction of solar velocity

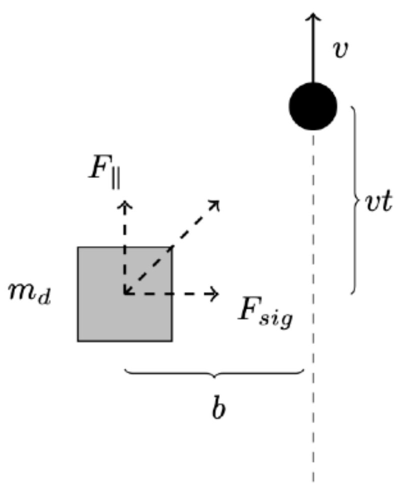


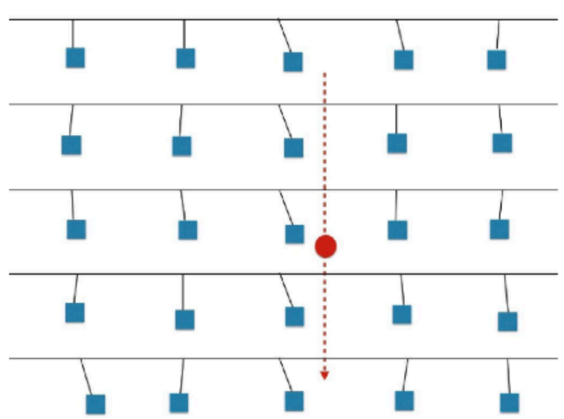
If 1 detector sees a signal, 2 can measure 3-dimensional DM velocity distribution in a day!

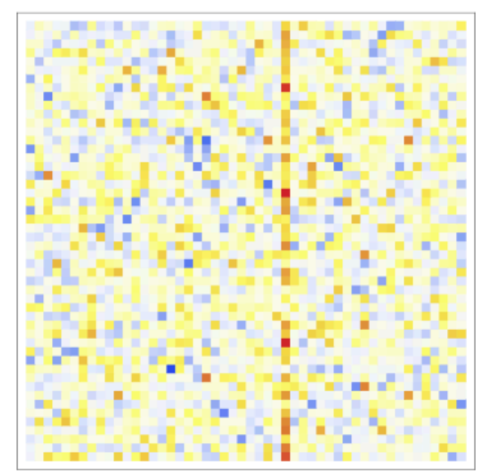
Super-heavy DM

Wavelength fits in a galaxy

Elementary particle







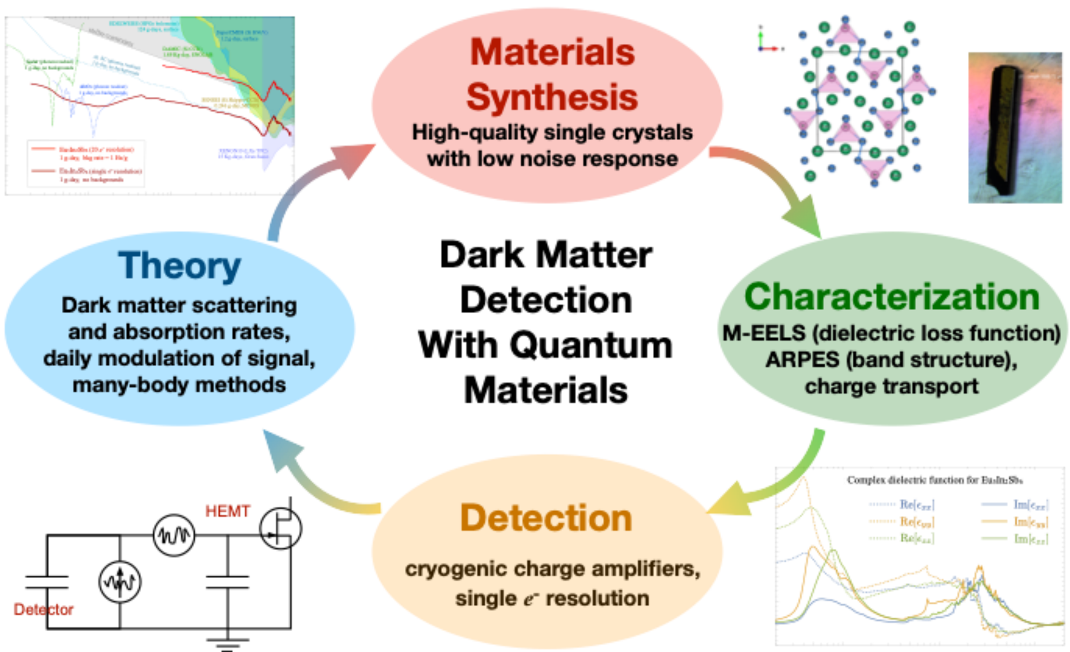
If DM is heavy enough, can (in principle) detect it with only gravitational coupling

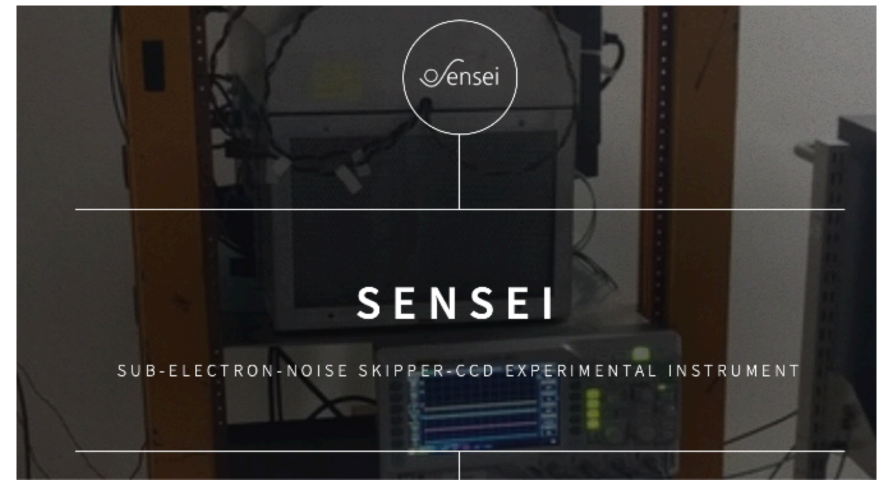
Gravity is weak, but who knows, DM could be purely gravitationally coupled!

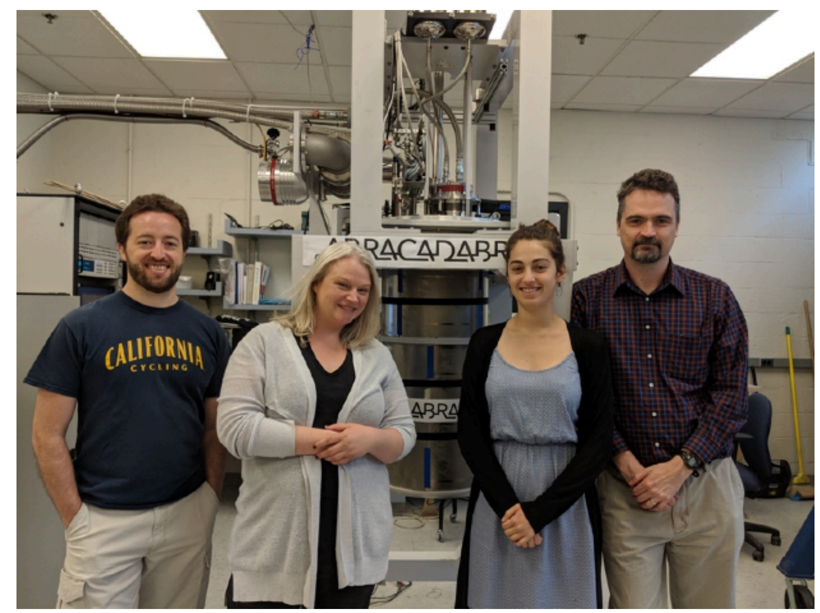
Quantum readout essential

[Carney, Ghosh, Krnjaic, Taylor, PRD 2020]

From theory to the lab







From theory paper to first data possible in **< 5 yrs:**

rapidly-advancing field and much more progress remains to be made!

[SPLENDOR, Windchime, SENSEI, ABRACADABRA collabs.]