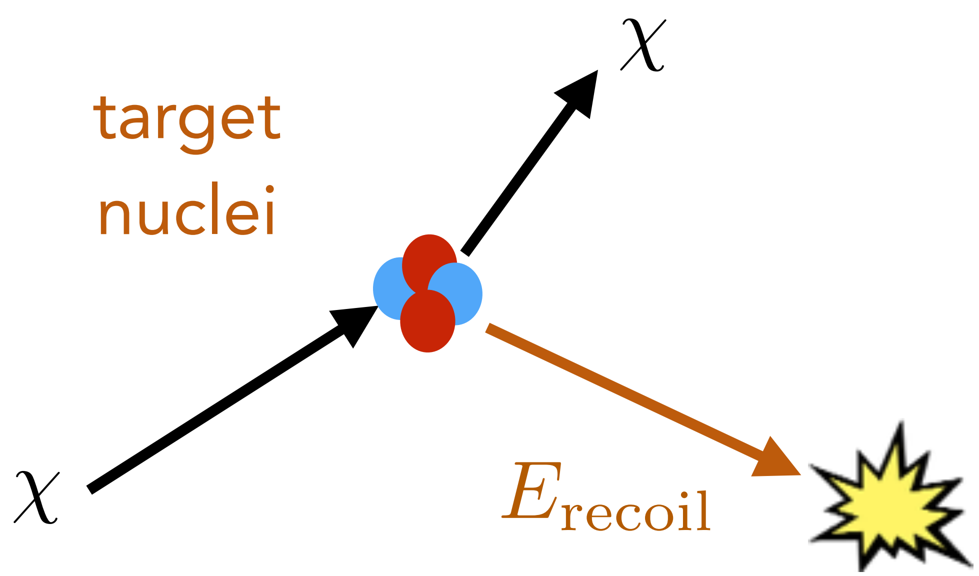
New directions in direct dark matter searches

Tongyan Lin
UC Berkeley & LBNL

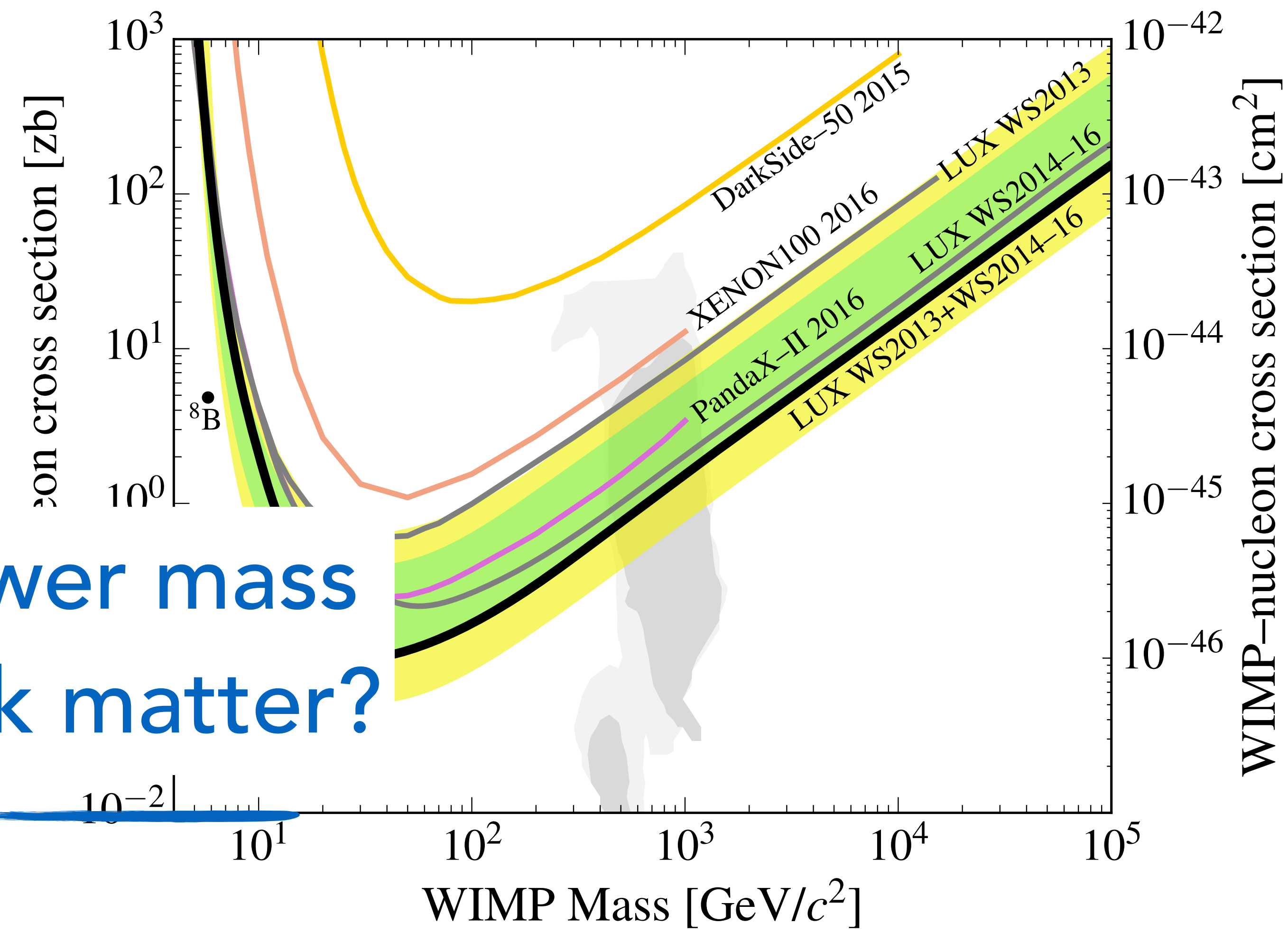
April 4, 2017
DM@LHC 2017, UC Irvine

Direct detection of WIMPs



Heat, ionization, charge
from recoiling nucleus

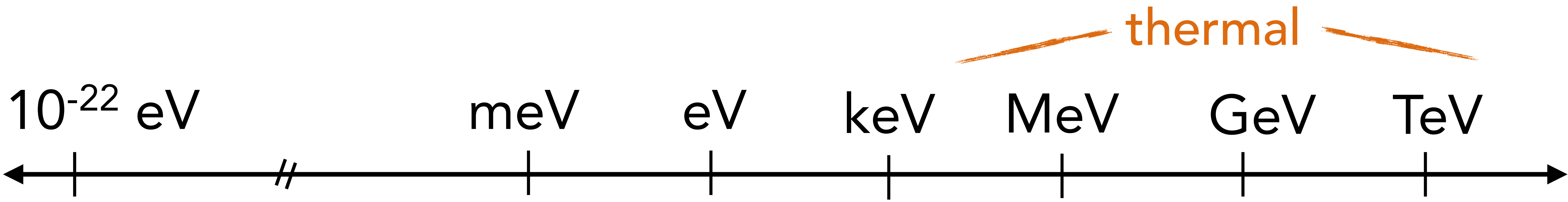
Strongest limits from
Xenon target (Z=54) experiments:



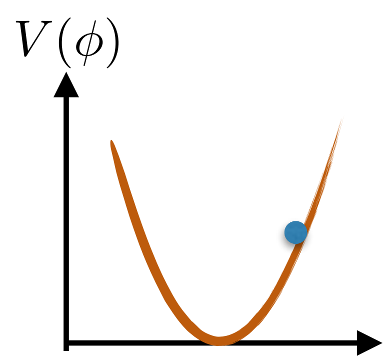
Lower mass
dark matter?

Established program of WIMP searches.
How can we cast a wider net?

Dark matter mass scale



Light bosonic DM



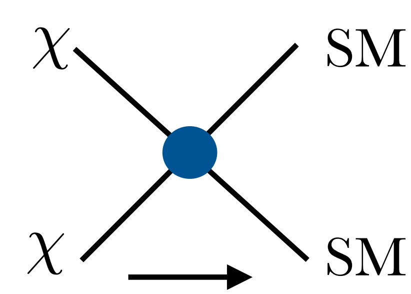
coherent light boson searches
(e.g. ADMX)

Many models

+

Many proposals
for **detection**

WIMP



Nuclear recoil in
direct detection

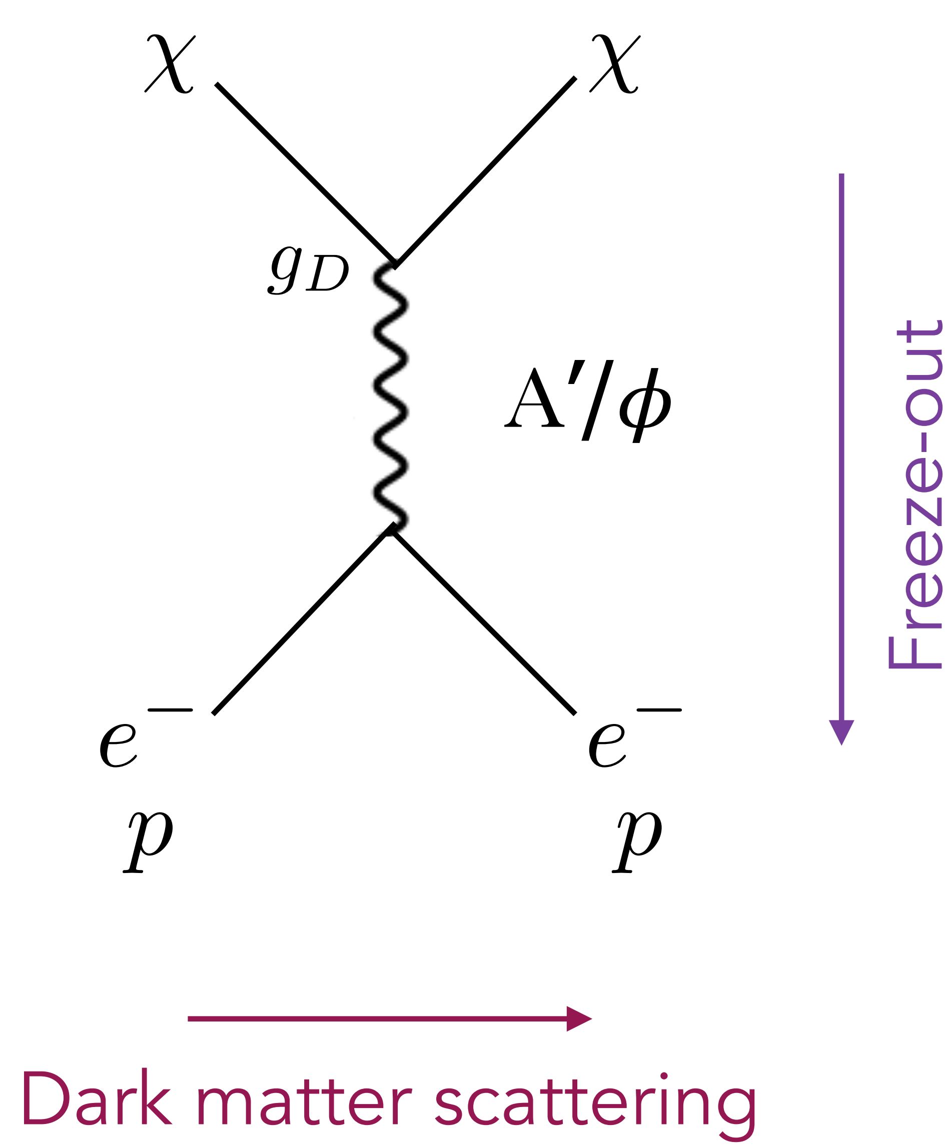
Dark mediators

sub-GeV dark matter

mass scale of mediator similar to (lighter than) χ

thermal freeze-out possible!
(see also, freeze-in)

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$



e.g. WIMPless dark matter
Feng and Kumar 2008

sub-keV bosonic dark matter

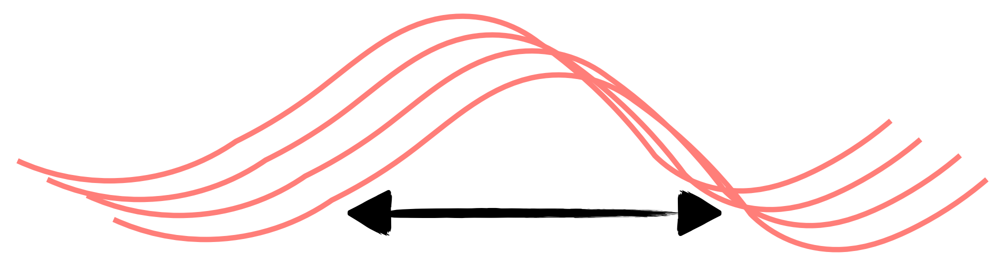
- Candidates:
  - Hidden photon
  - Pseudoscalar (axion)
  - Scalar

  } very weakly coupled!

- Coherent field below *m* ~ eV

Occupation number is high:

$$\frac{\rho_{\rm DM}}{m_{\rm DM}} \gg \lambda_{\rm dB}^{-3}$$

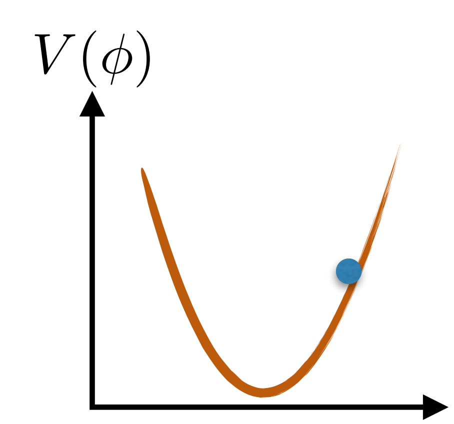


$$\lambda_{\rm de\,Broglie} = \frac{2\pi}{m_{\rm DM} v}$$

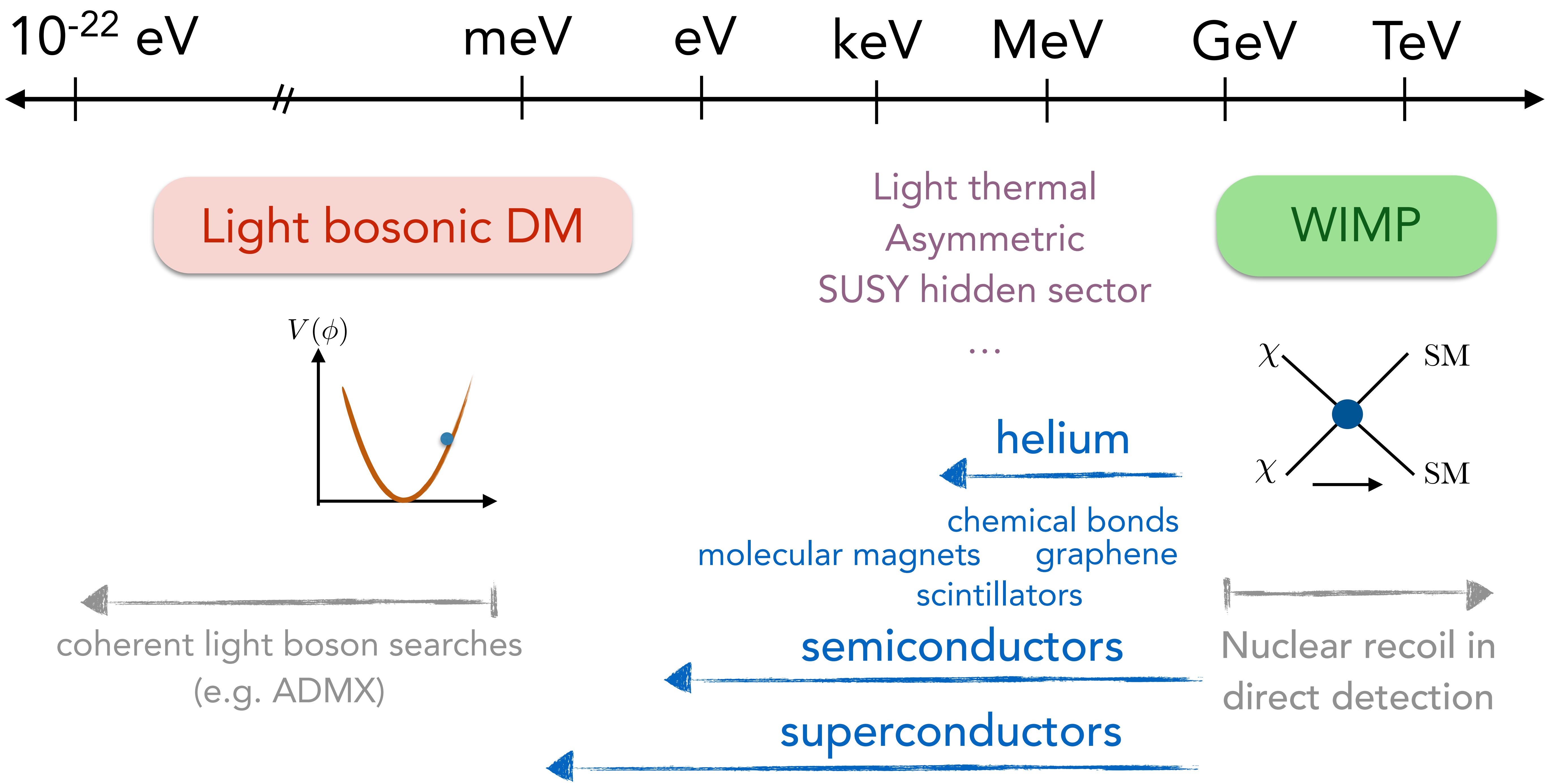
- Non-thermal relic abundance

$$\rho_{\rm DM} = \frac{1}{2} m_{\rm DM}^2 \phi_0^2$$

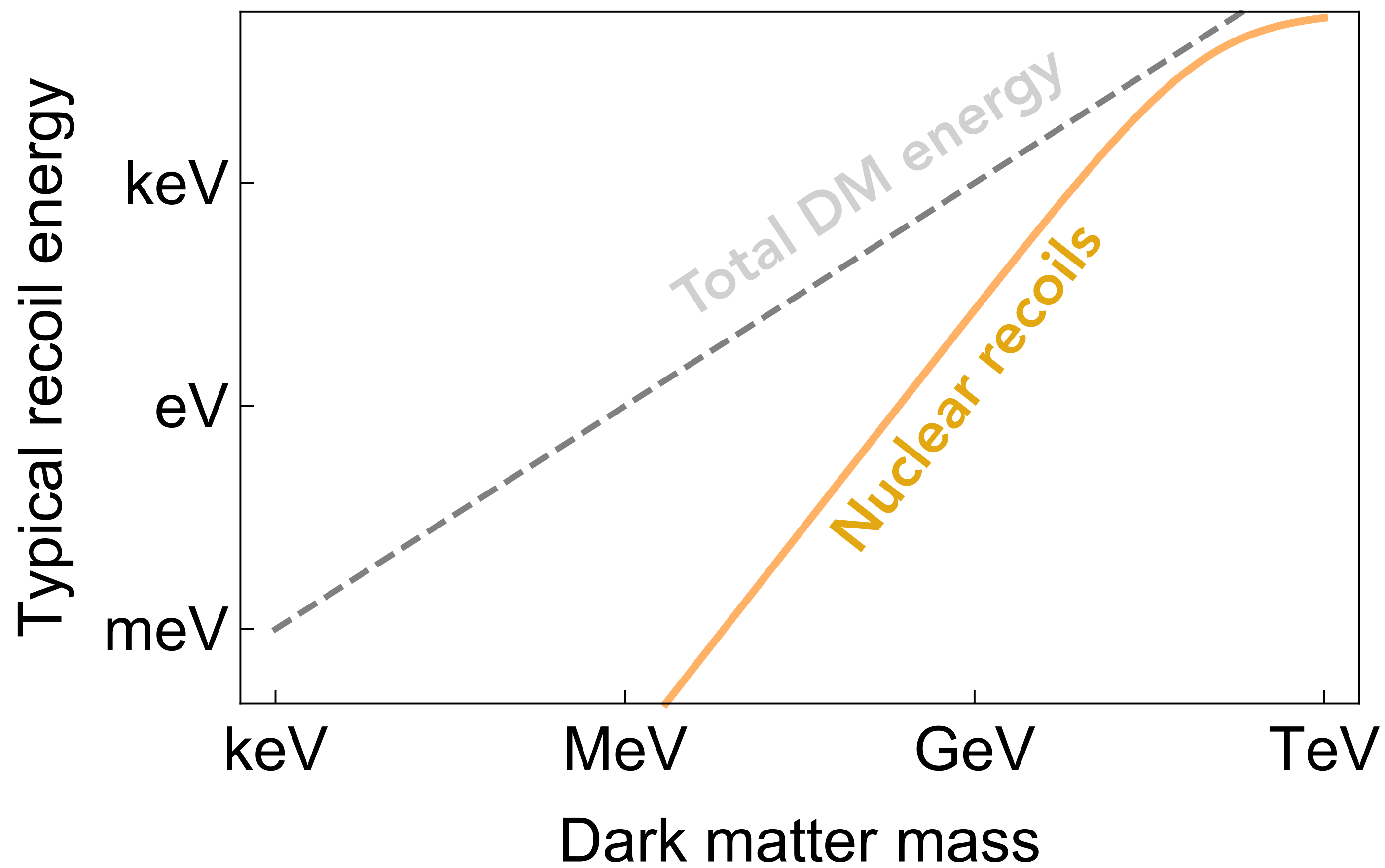
ϕ_0 field value, set by misalignment



Mass scale of dark matter?



Kinematics and thresholds

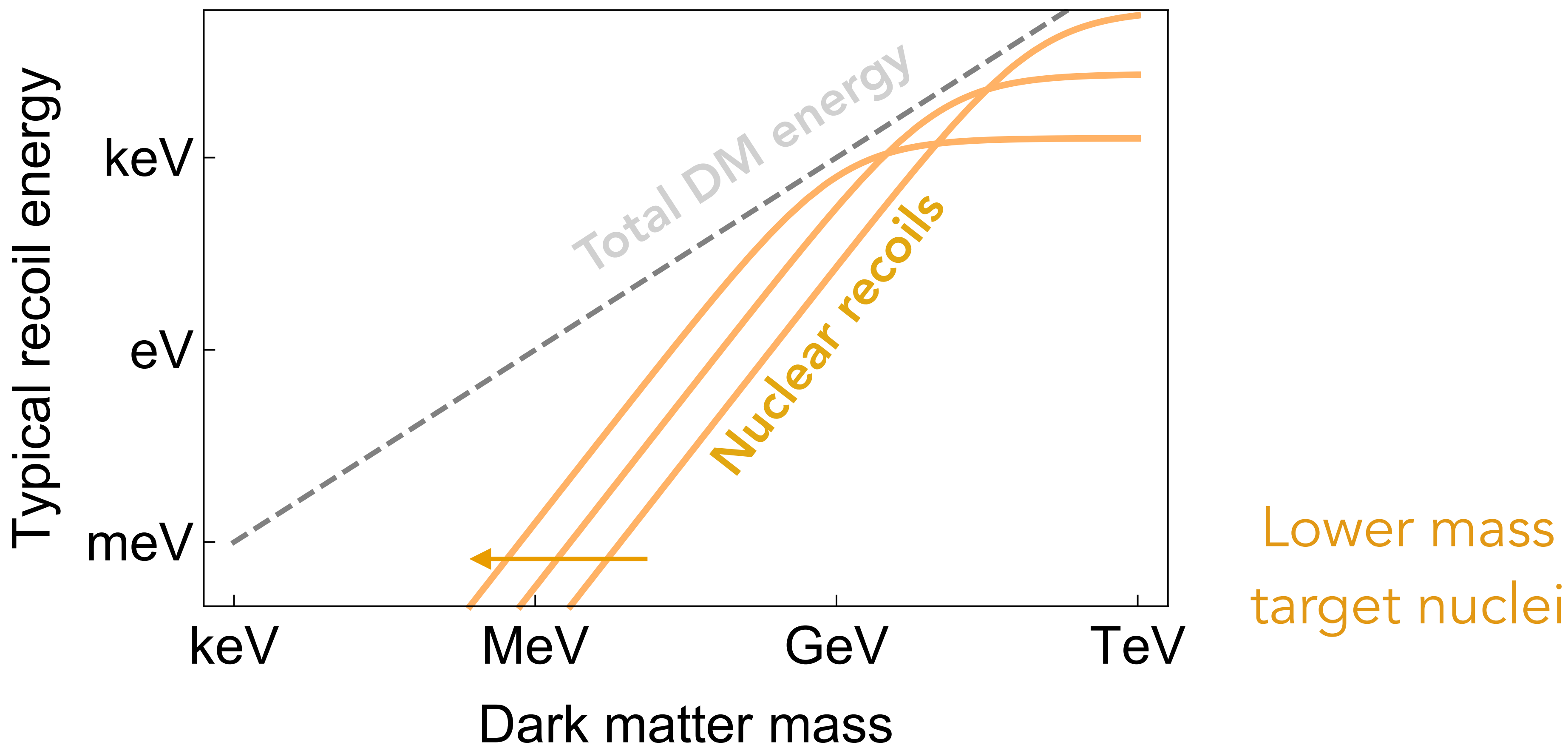


Energy deposited from WIMP in nuclear recoil:

$$E_R \sim \frac{\mu_{\chi N}^2 v^2}{m_N} \sim 1 - 100\,\mathrm{keV}$$

Typical threshold in experiment: > 1 keV nuclear recoil

Kinematics and thresholds



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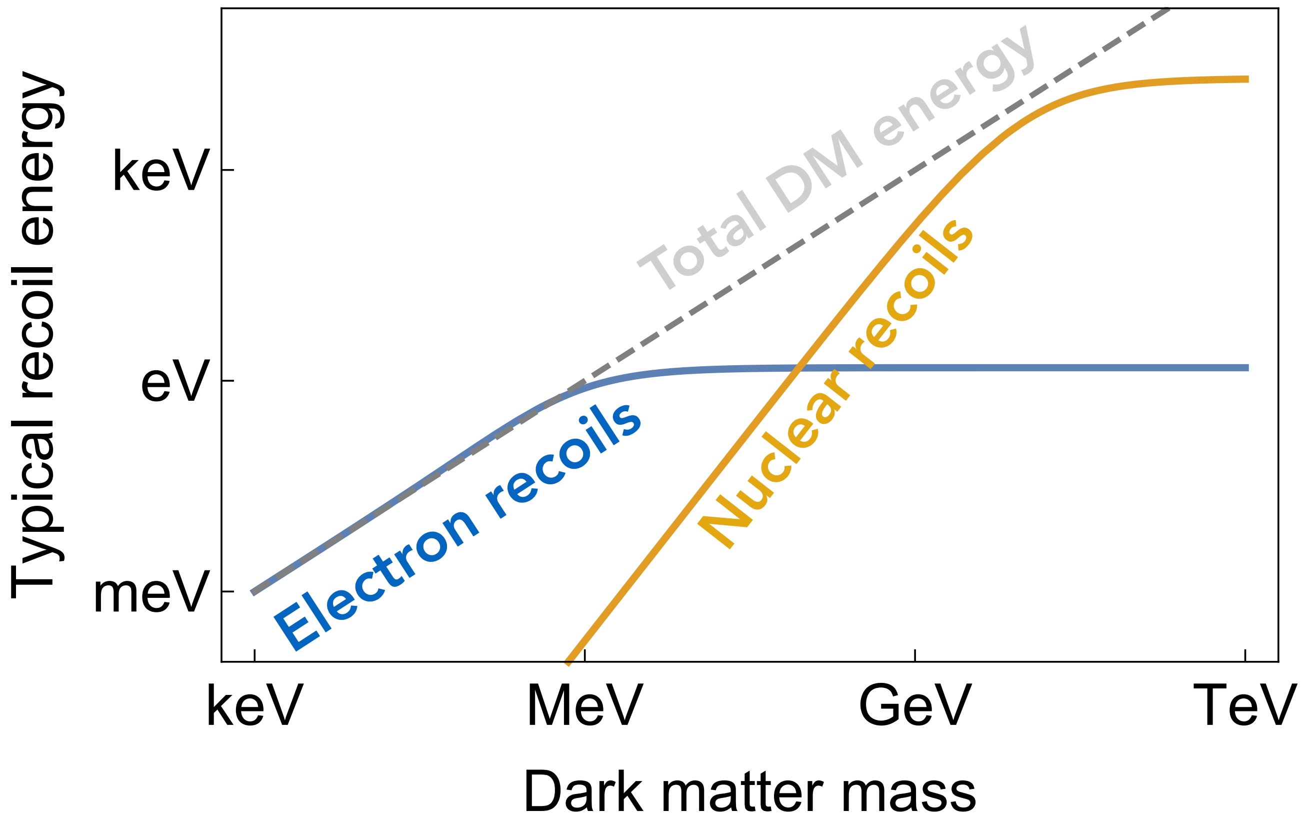
Detecting low mass dark matter

Electron recoils



Goal: sensitivity to ~meV
recoils for keV-MeV dark matter scattering.

Sensitivity to MeV-scale DM
with Xenon10, Xenon100

$E_{th} \gtrsim 12$ eV

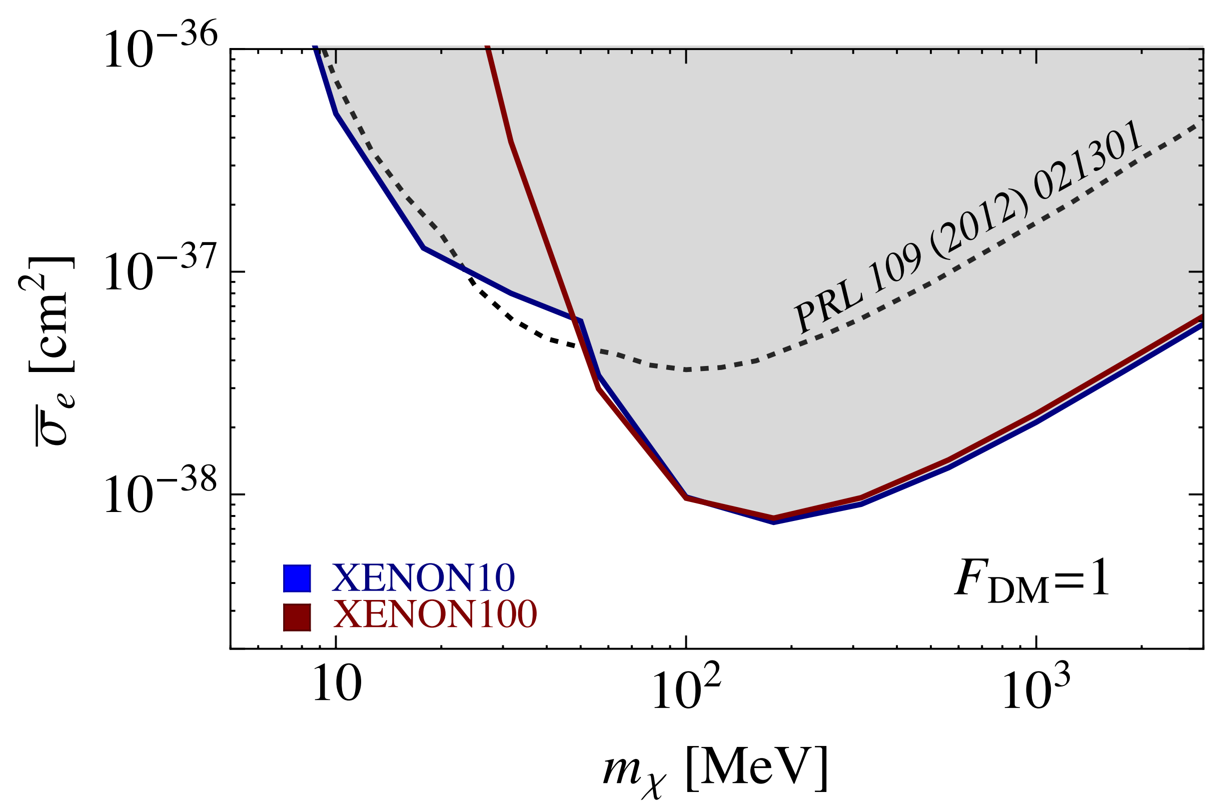


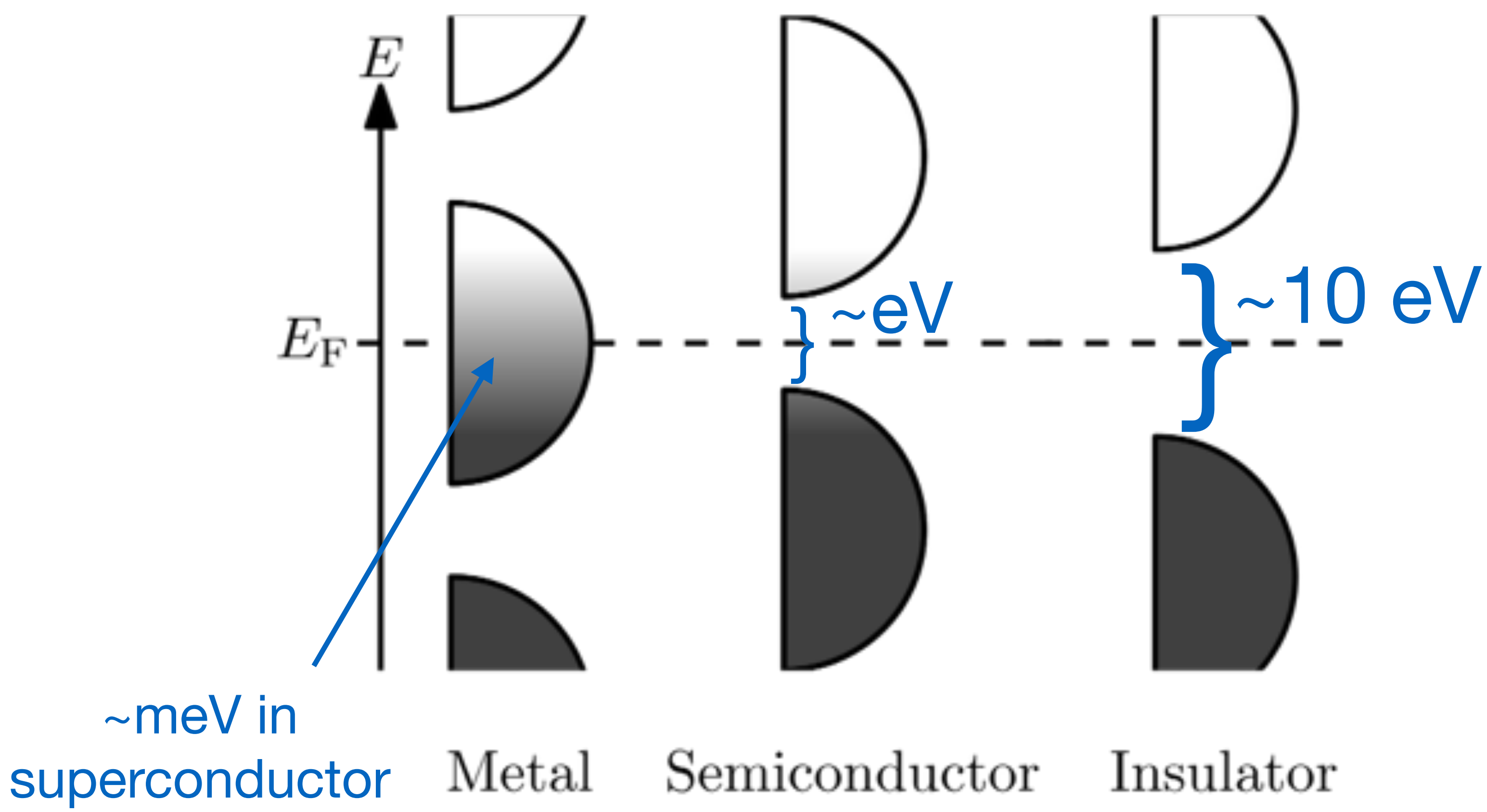
figure from Essig, Volansky, Yu 2017
see also: 1108.5383, 1206.2644

Detecting low mass dark matter

Ideas

Electron recoils with small gap materials

Electronic band structure



Hochberg, **TL**, Zurek 2016/2017;
Essig, Mardon, Volansky; Lee, Lisanti, Mishra-Sharma, Safdi
Essig, Fernandez-Serra, Mardon, Soto, Volansky, Yu
Hochberg, Pyle, Zhao, Zurek;
Hochberg, Kahn, Lisanti, Tully, Zurek

Detecting low mass dark matter

Ideas

Electron recoils with small gap materials

Gapless modes (phonons), vibrational modes

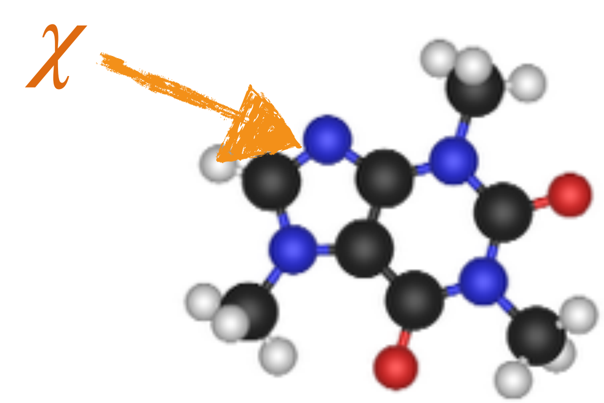
Long wavelength phonons [~meV]:

$$\Omega = c_s|\vec{Q}|$$

$c_s \sim 10^{-5}$ in solid

$c_s \sim 10^{-6}$ in helium

vibrational modes [~meV-eV]



see also: Hochberg, **TL**, Zurek 2016
Essig, Slone, Mardon, Volansky 2016
Bunting, Gratta, Melia, Rajendran 2017

Detecting low mass dark matter

Ideas

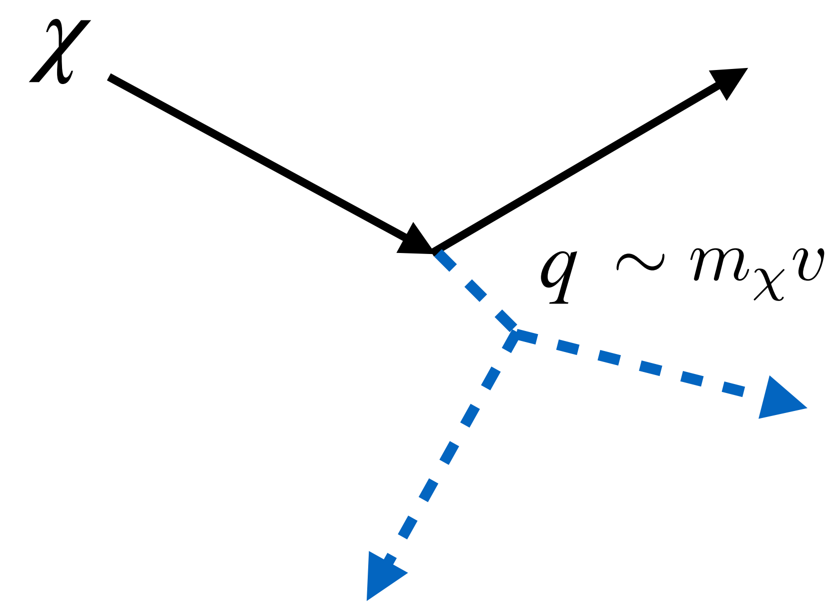
Electron recoils with small gap materials

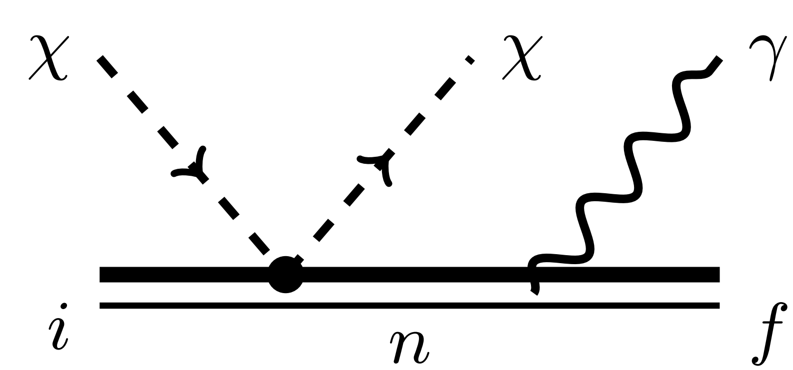
Gapless modes (phonons), vibrational modes

Higher order processes

....

Three-body final states





Schutz and Zurek 2016
Knapen, **TL**, Zurek 2016
McCabe 2017
Kouvaris and Pradler 2016, …

Detecting low mass dark matter

Backgrounds

known

coherent scattering of solar neutrinos

background of O(1-10)/kg-yr/10 eV
(based on DAMIC, SuperCDMS)
1610.00006, 1607.07410

coherent photon scattering
O(1-10)/kg-yr/eV
1610.07656

“dark counts” (fakes) - general challenge

the unknown…

….

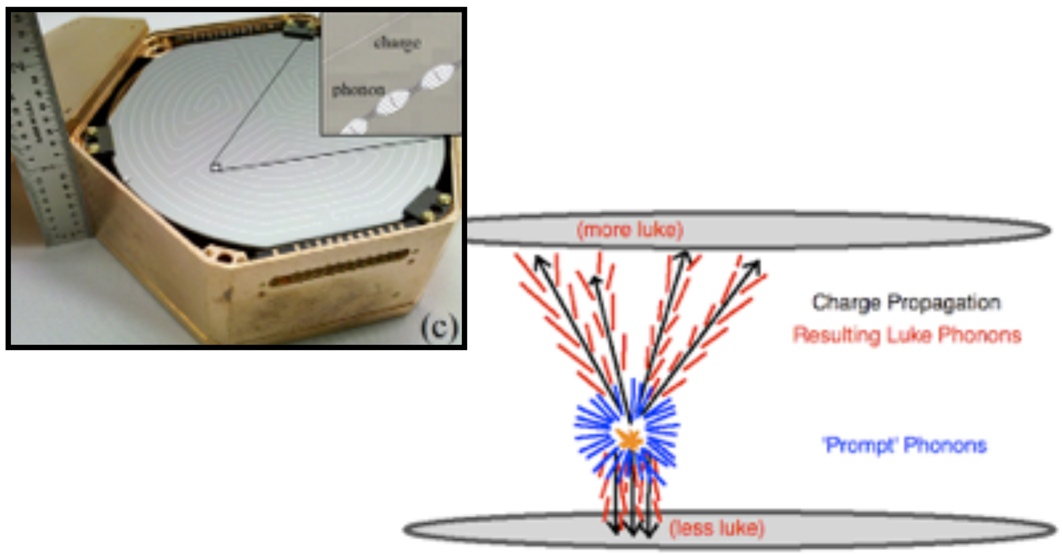
1. Probing low-mass DM with eV-scale thresholds

2. Towards meV-scale thresholds

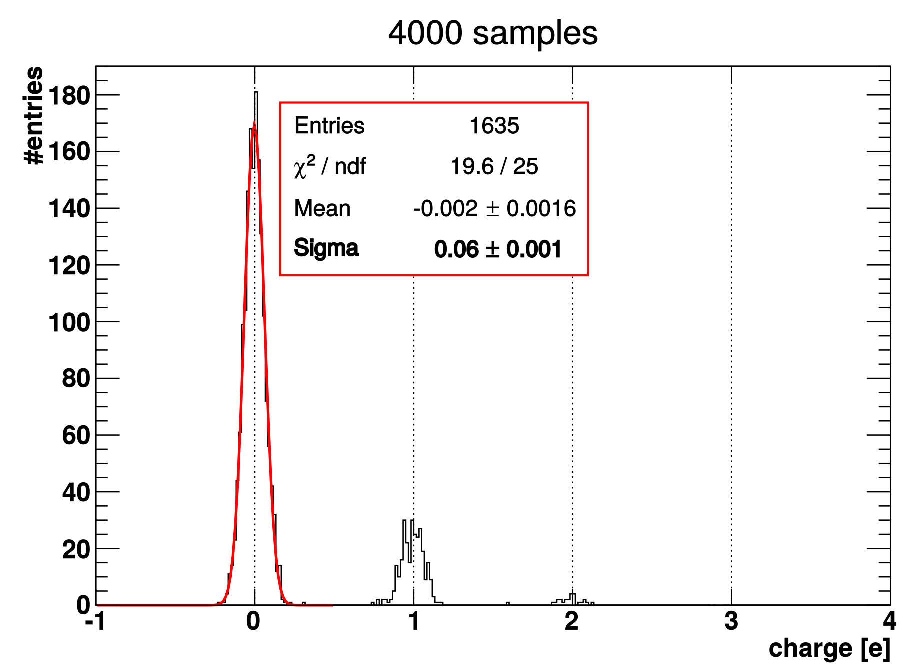
Semiconductor targets

New techniques have led to E_{th}~50 eV electron recoil.

SuperCDMS [Ge, Si]

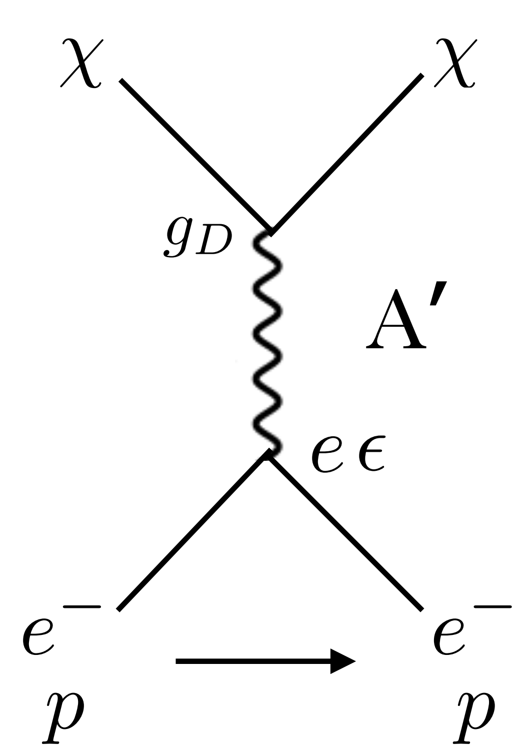


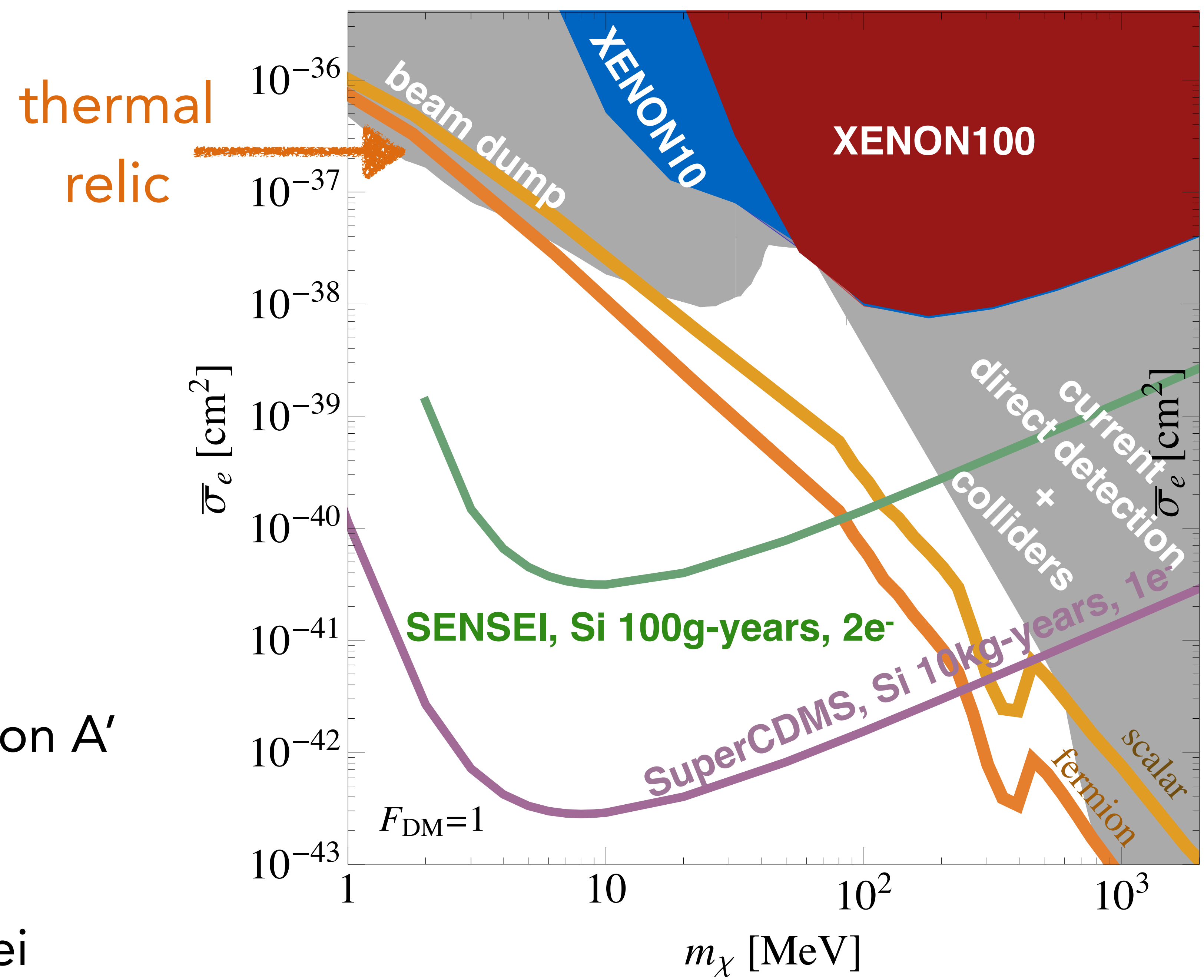
DAMIC, Sensei (Si CCD)



E_{th}~eV (1 or 2 electron sensitivity) can be reached in the near future!
Limited by band gap, dark counts.

Semiconductor targets





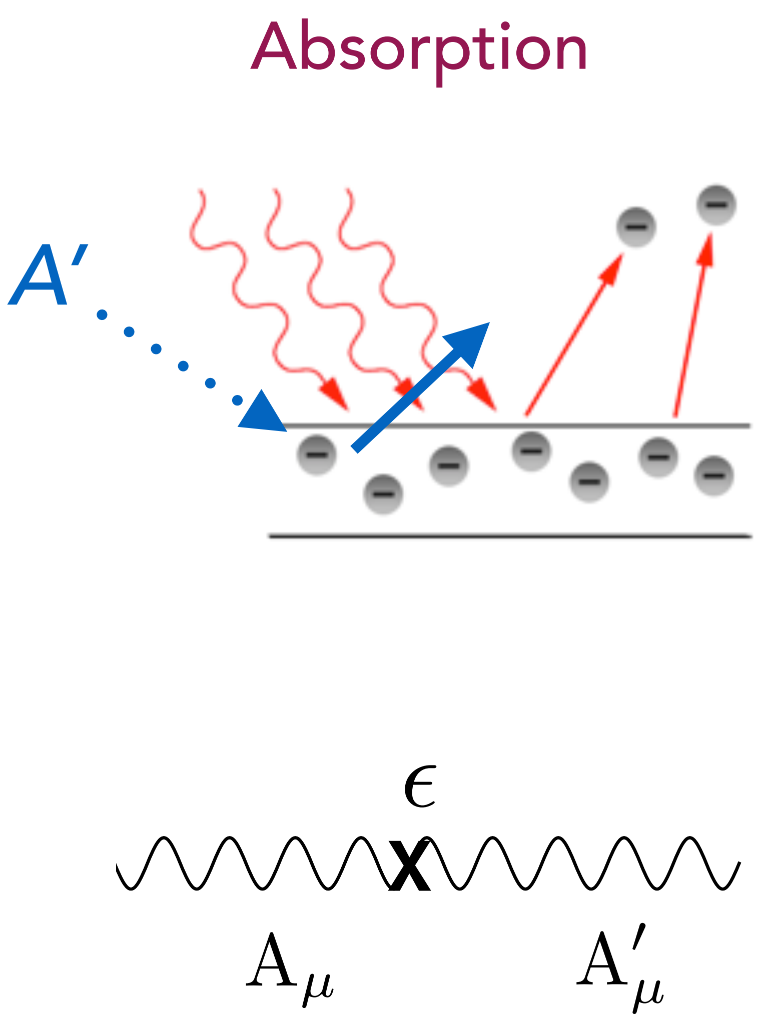
Kinetically mixed hidden photon A′

$$\epsilon e A'_\mu J^\mu_{\rm EM}$$

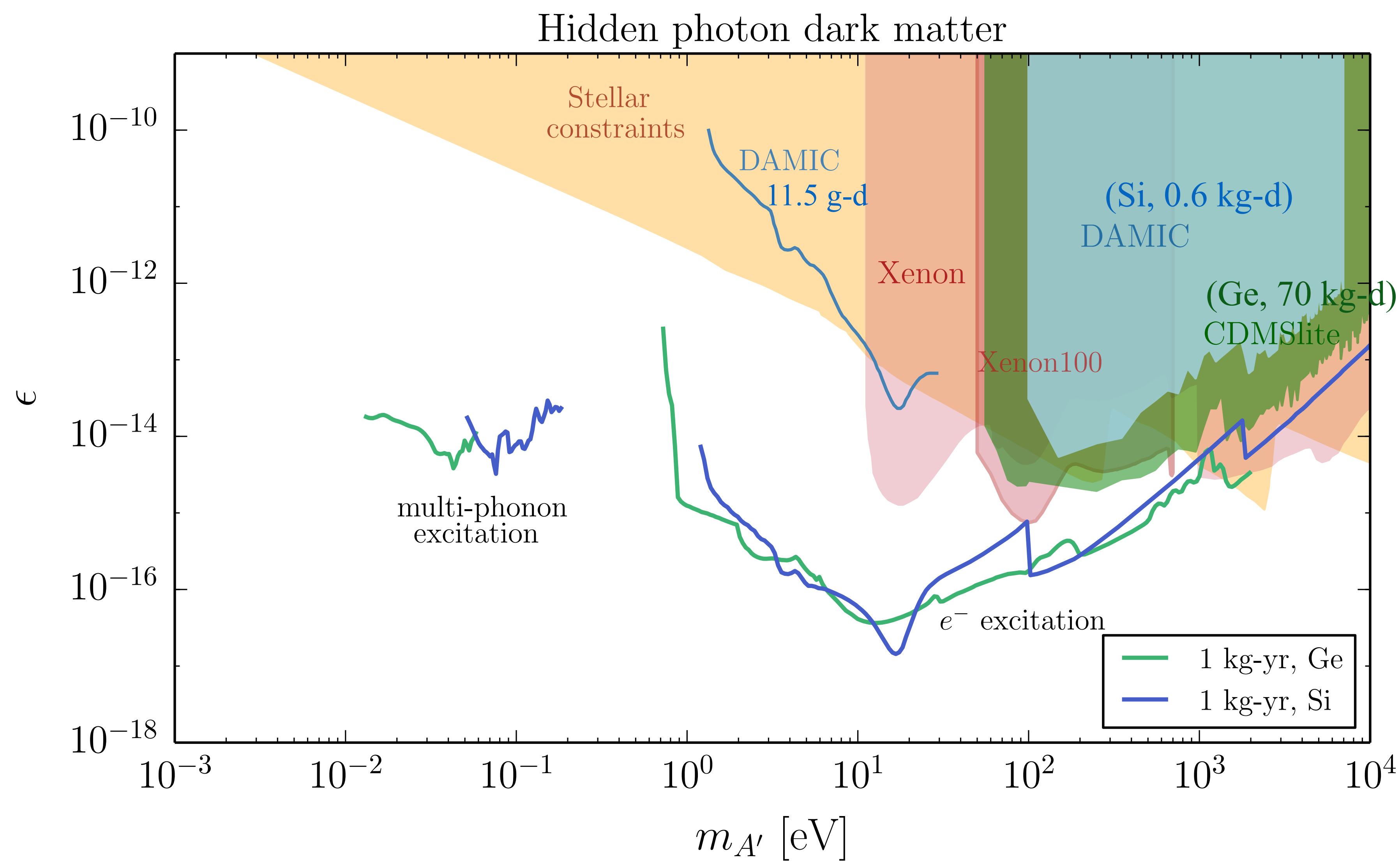
couples to electrons, nuclei

figure from Tien-Tien Yu
(see also Essig et al. 2015)

Absorption of hidden photon DM



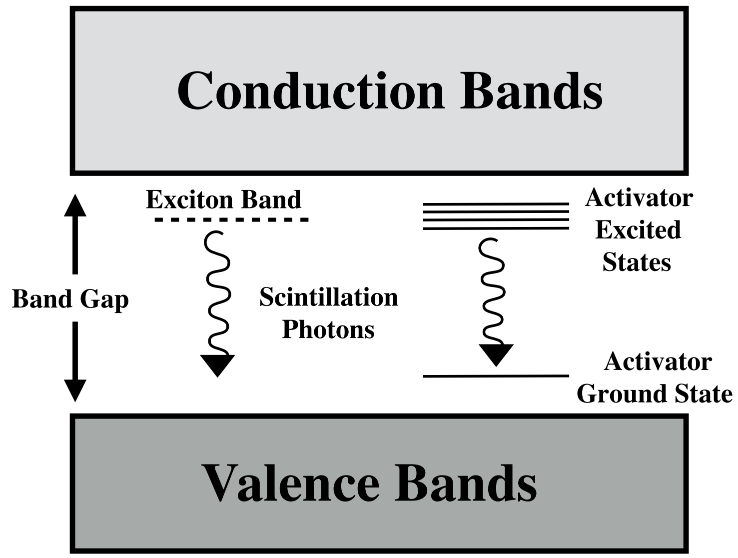
Reach even lighter (eV-scale) bosonic DM:



Hochberg, TL, Zurek 2017
See also: I. Bloch et al. 2016

Stellar, Xenon10 constraints:
An, Pospelov, Pradler 2013, 2014
Redondo & Raffelt 2013

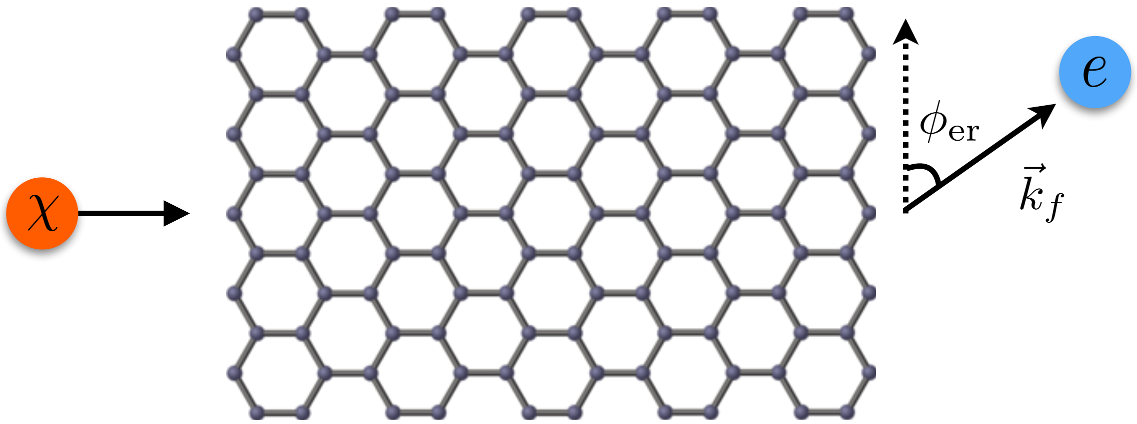
Scintillators



Derenzo, Essig, Massari, Soto, Yu 2016

Aim for detection of single scintillation photons.

Graphene



Hochberg, Kahn, Lisanti, Tully, and Zurek 2016

Idea: use PTOLEMY setup for dark matter. Directionality possible with 2D target.

Reach is similar to semiconductors in both cases.

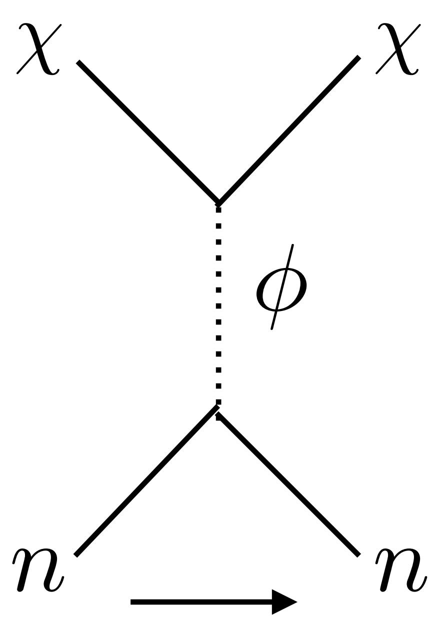
Many exciting developments - each proposal has unique advantages

1. Probing low-mass DM with eV-scale thresholds

2. Towards meV-scale thresholds

Superfluid helium

Sensitive to DM-**nucleon** scattering



For low mass dark matter, the possible momentum transfer is

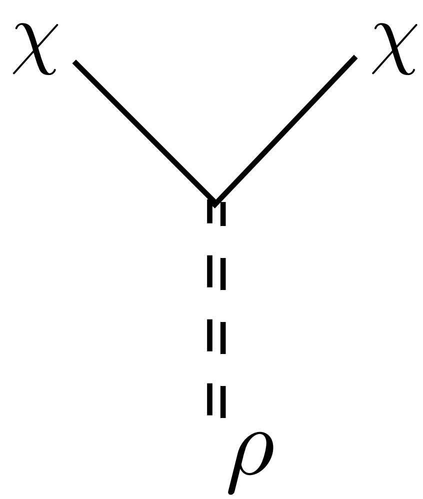
$$Q \sim m_\chi v \sim \text{Angstrom}^{-1}$$

for m_χ = MeV

At these scales, the relevant degree of freedom is a phonon

Superfluid helium

Sensitive to DM-**phonon** scattering



Quasiparticle

For low mass dark matter, the possible momentum transfer is

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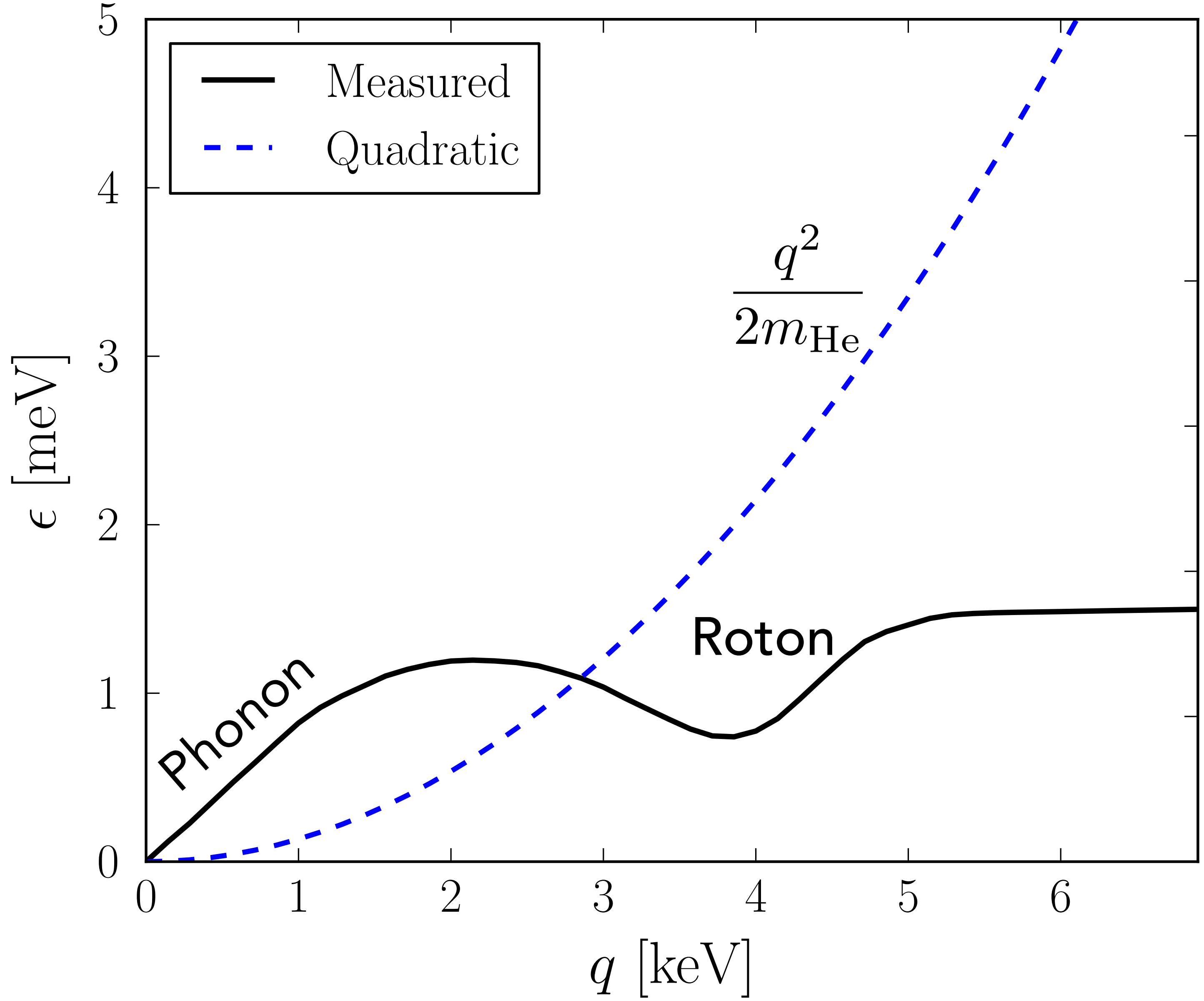
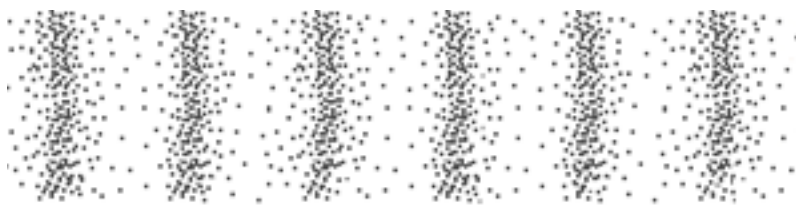
for m_χ = MeV

At these scales, the relevant degree of freedom is a phonon

Superfluid helium



Phonon / density perturbation in He:



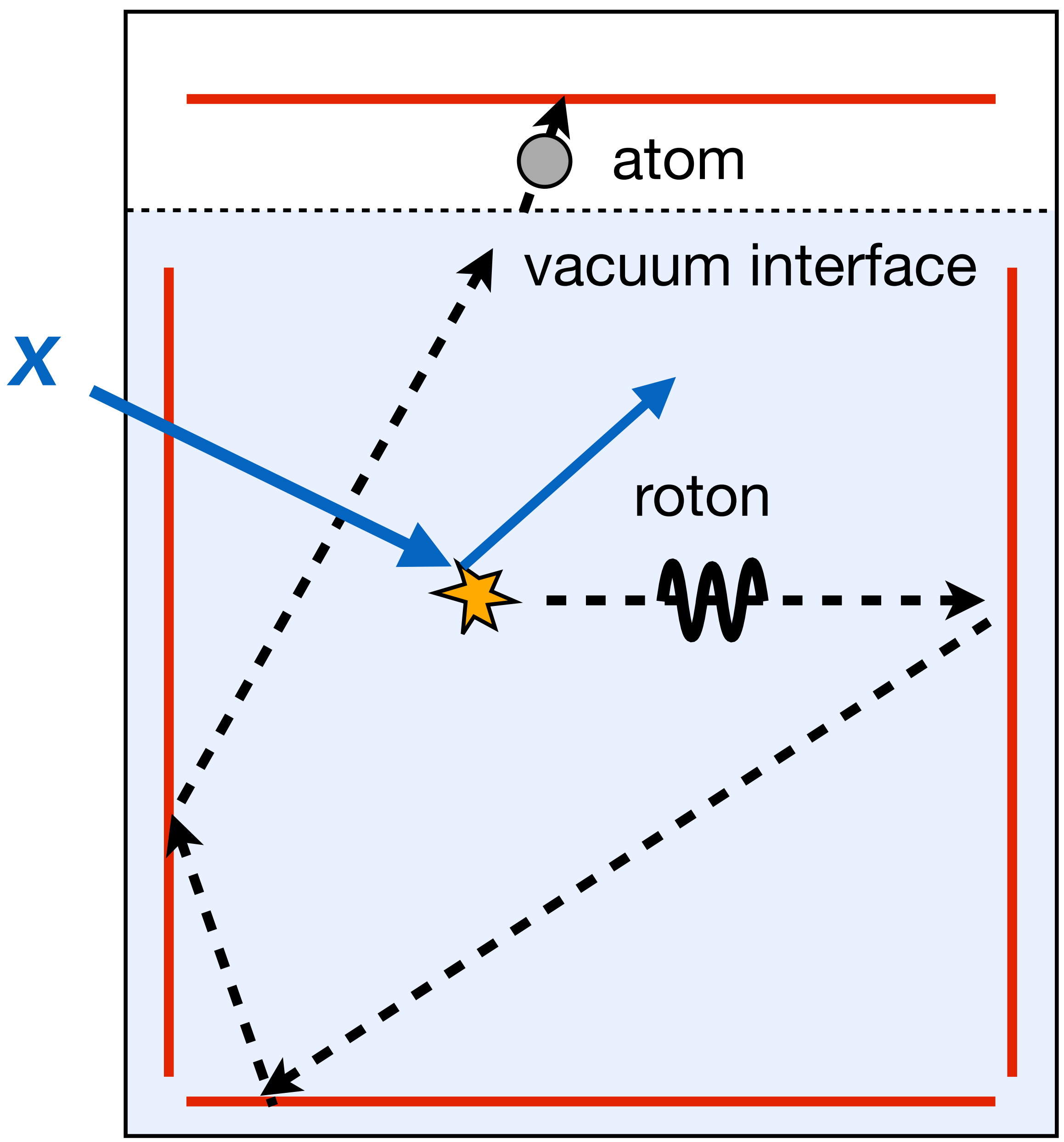
Long lived quasiparticles (stable above 0.8 meV)

Zero viscosity for velocities below critical velocity v_c

Possible ~meV thresholds

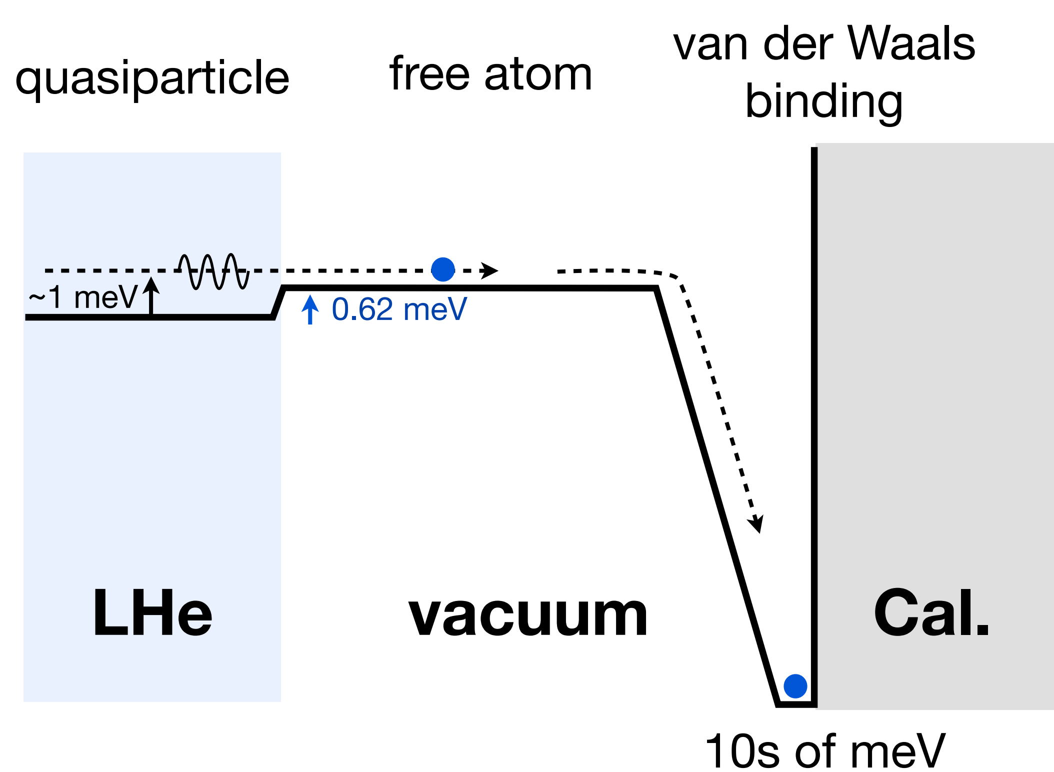
Detector concept

calorimeter



T = 10-100 mK

Evaporation at surface:



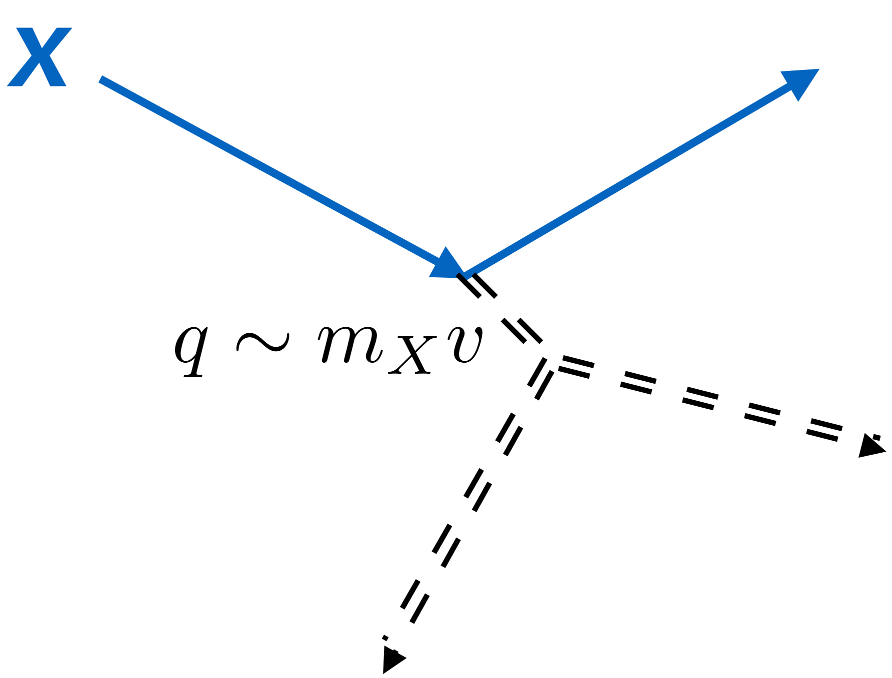
Threshold for evaporation: 0.62 meV

Efficiency: O(10%)

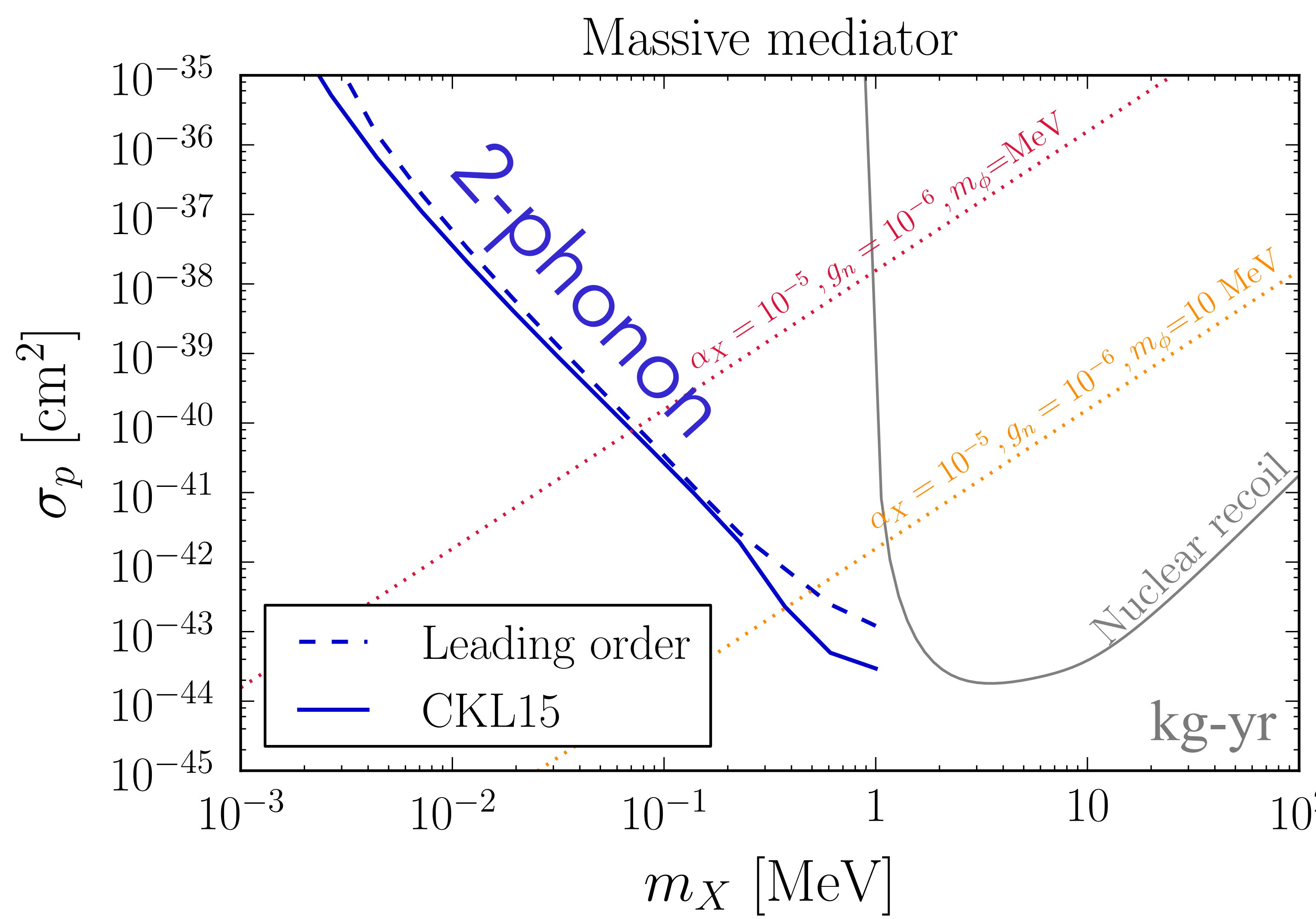
S. Hertel (UMass), D. McKinsey (LBL)

Multi-phonon excitations

2-phonon excitation



Kinematics allows larger energy ω deposited, even for small q

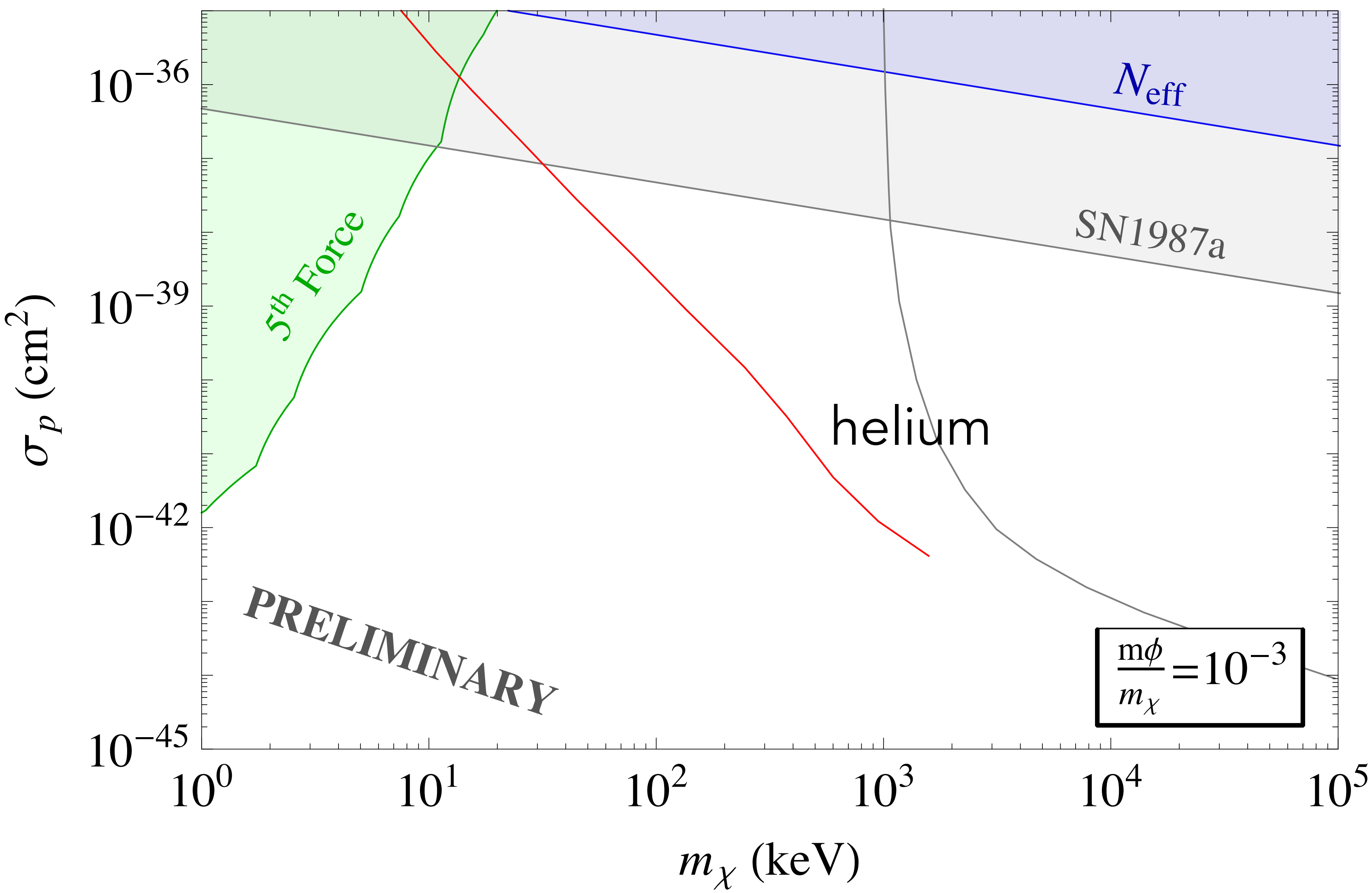


Extends reach to lower mass DM!
(~10 meV resolution)

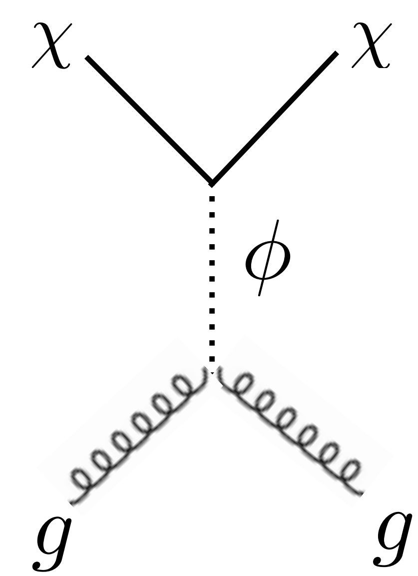
Schutz and Zurek 2016
Knapen, TL, Zurek 2016

Light scalar mediator

Comparison with other constraints:



e.g. DM-nucleon coupling via gluon operator

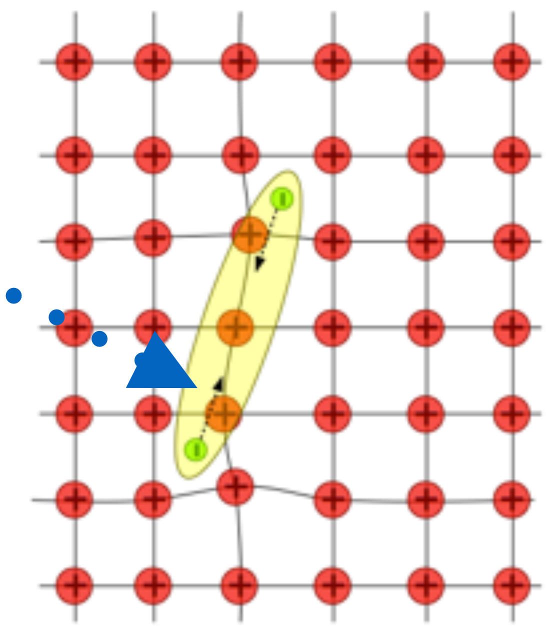


Green, Rajendran 2017, Krnjaic 2015
Knapen, TL, Zurek (work in progress)

Superconductor target

Dark matter processes break apart Cooper pairs:

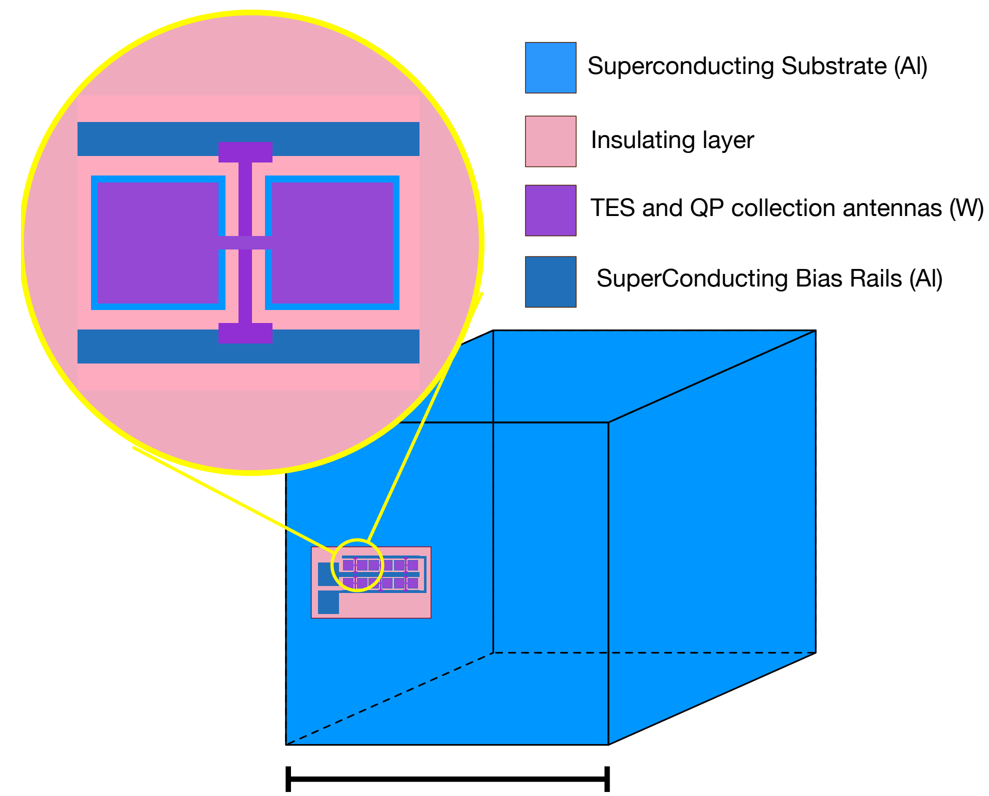
X



$$\Delta = \frac{3}{2} T_c \approx 0.3\,\mathrm{meV}$$

E_{th} ~ meV goal

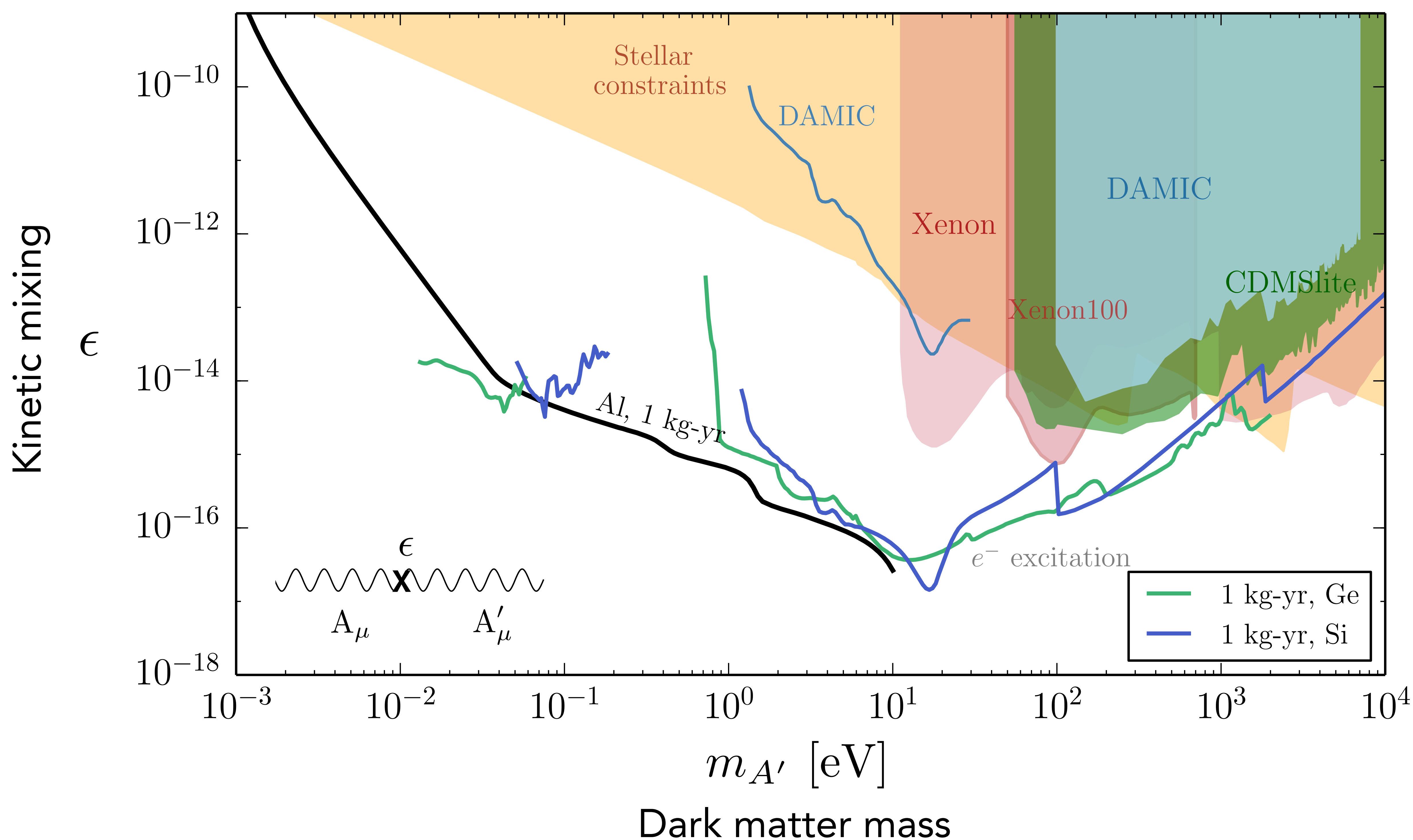
Long-lived excitations can be collected at the surface



5 mm

Hochberg, Zhao, and Zurek 2015
Hochberg, Pyle, Zhao, and Zurek 2015

Absorption of hidden photon DM



Hochberg, **TL**, Zurek 2016

Going Forward

- Multiple detection targets — different systematics, different DM physics.
- Aim for small-scale experiments (~kg target), in addition to WIMP searches
- What other materials and processes can be used? What is the full model space and complementarity with other probes of dark matter?

see talks @ UMD Cosmic Visions 2017, Dark Sectors 2016 report 1608.08632

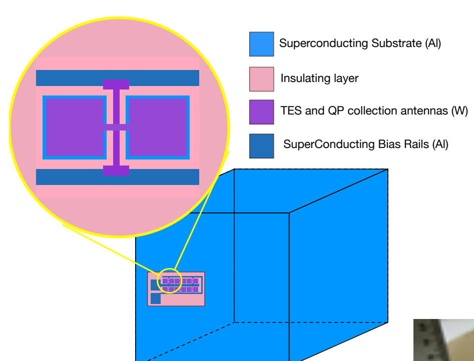
Conclusions

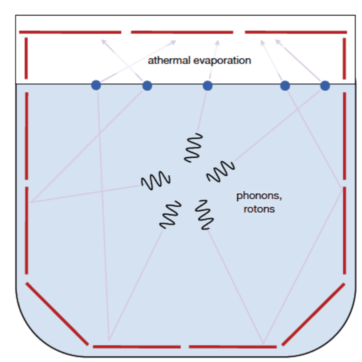
- Current direct detection experiments focus on GeV-TeV scale dark matter. Only scratched the surface for sub-GeV.

- New directions explore many orders of magnitude in mass!

meV eV keV MeV GeV TeV DM mass

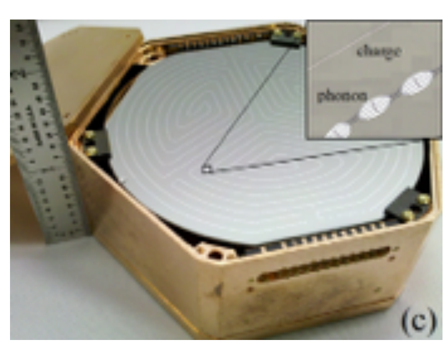
Superconductors





Superfluid He

and many others



Semiconductors

Thanks!