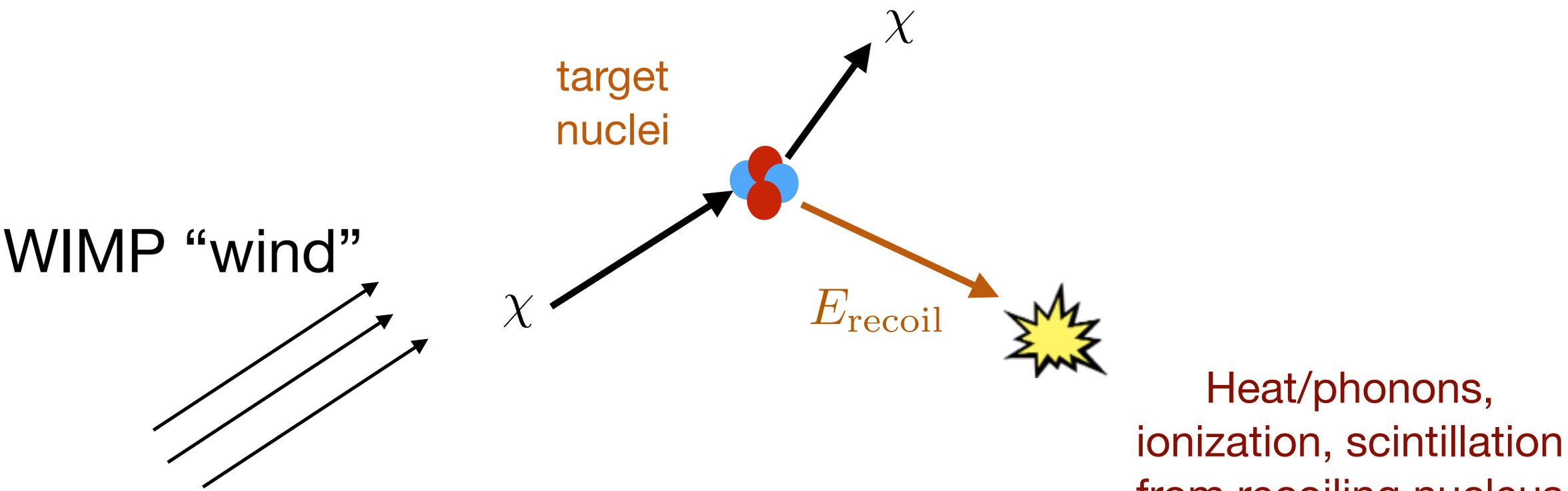
Direct Detection of meV-to-GeV Dark Matter

Tongyan Lin
UC Berkeley & LBNL

March 23, 2017
DOE Cosmic Visions

Direct detection

Key discovery mode for dark matter:

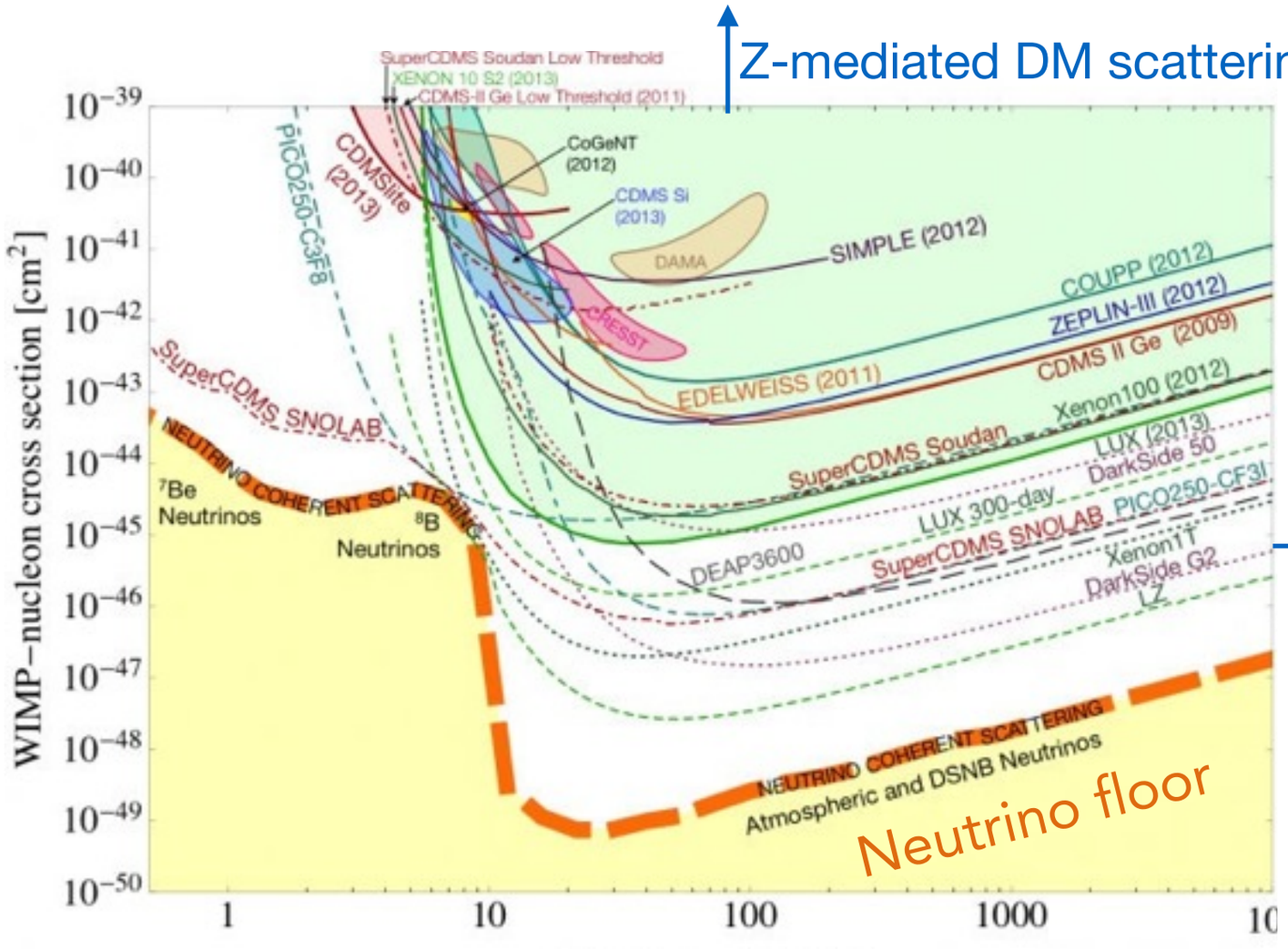


Does dark matter interact with us?

Direct detection

GeV-scale DM

CRESST
EDELWEISS
DAMIC
NEWS
SuperCDMS
…



Higgs-mediated

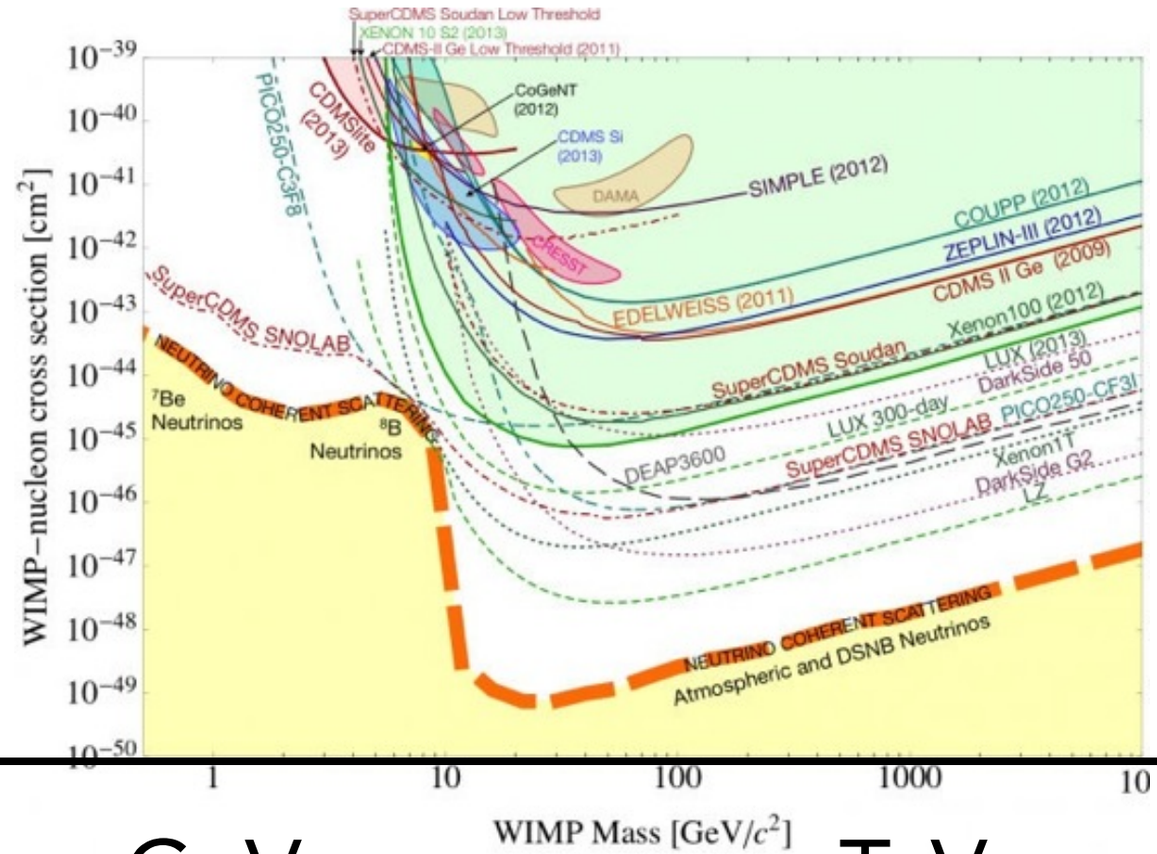
CYGNUS
DarkSide
DEAP
LZ
PICO
PANDAX
Xenon1T
…

Active program of WIMP searches.
Important to cast a wider net!

See WG talks

Unexplored territory

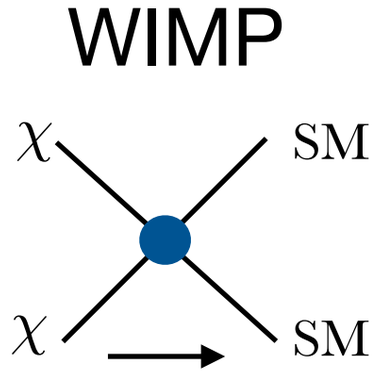
What lives here?
Can we detect
low mass DM?

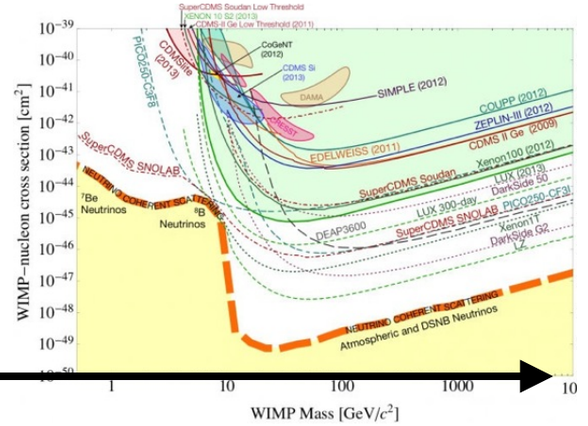


keV MeV GeV TeV

Dark matter mass

Unexplored territory





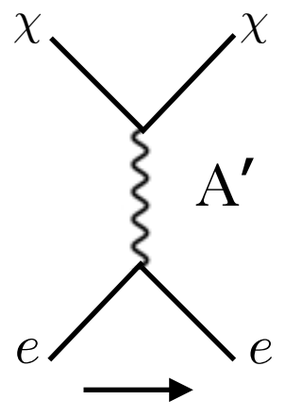
meV eV keV MeV GeV TeV

Dark matter mass

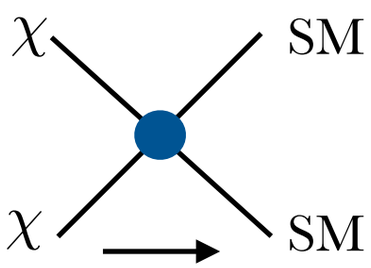
sub-meV coherent bosonic DM (next talk)

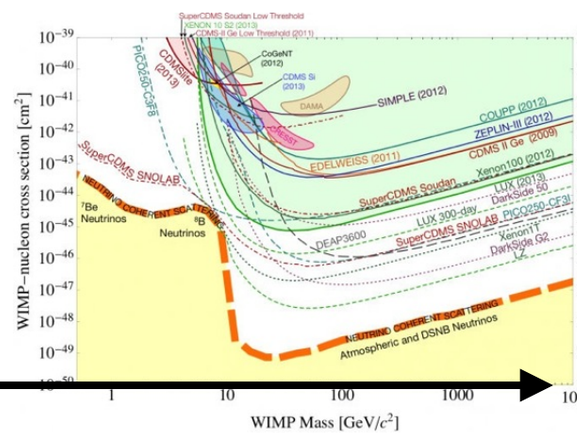
Unexplored territory

Light DM +
light mediators



WIMP





Scattering

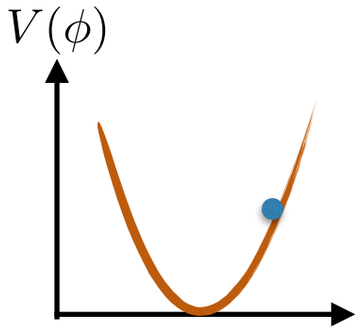
meV eV keV MeV GeV TeV

Dark matter mass

sub-meV coherent
bosonic DM (next talk)

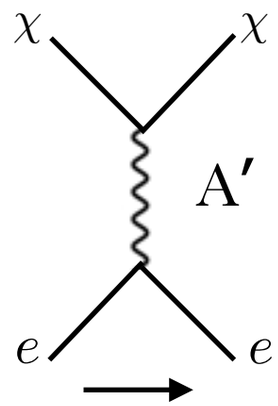
Unexplored territory

Bosonic DM



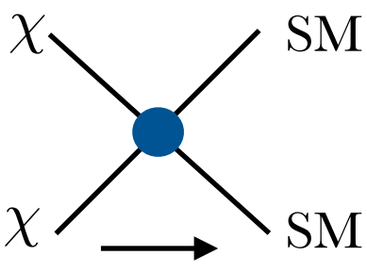
Absorption

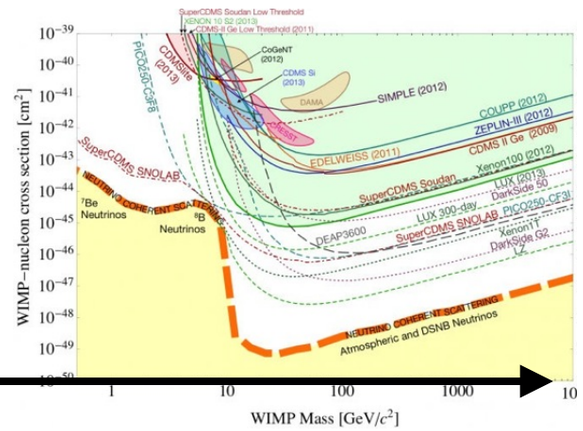
Light DM +
light mediators



Scattering

WIMP



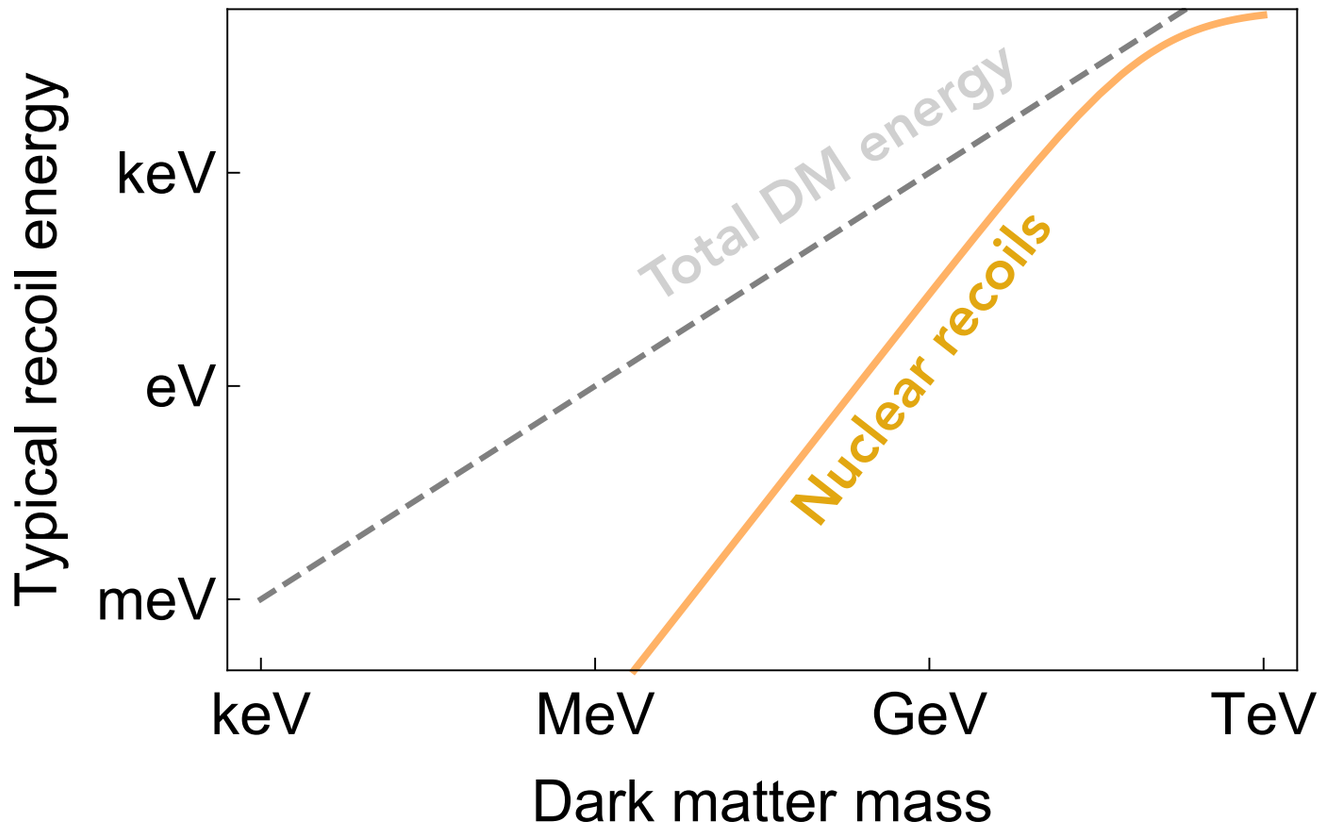


meV eV keV MeV GeV TeV

Dark matter mass

sub-meV coherent
bosonic DM (next talk)

Kinematics and thresholds

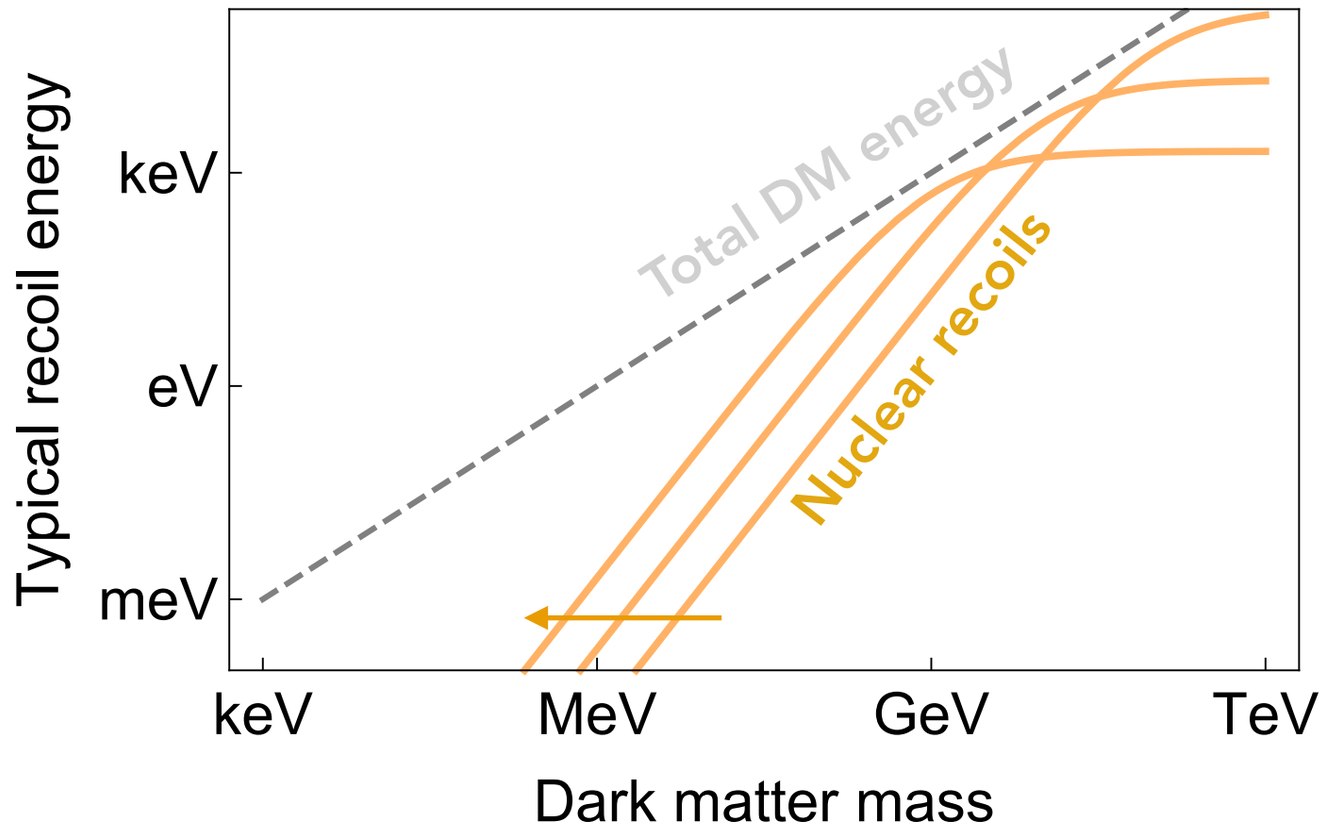


Energy deposited from WIMP in nuclear recoil:

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

Typical threshold in experiment: > 1 keV nuclear recoil

Kinematics and thresholds



Lower mass target nuclei

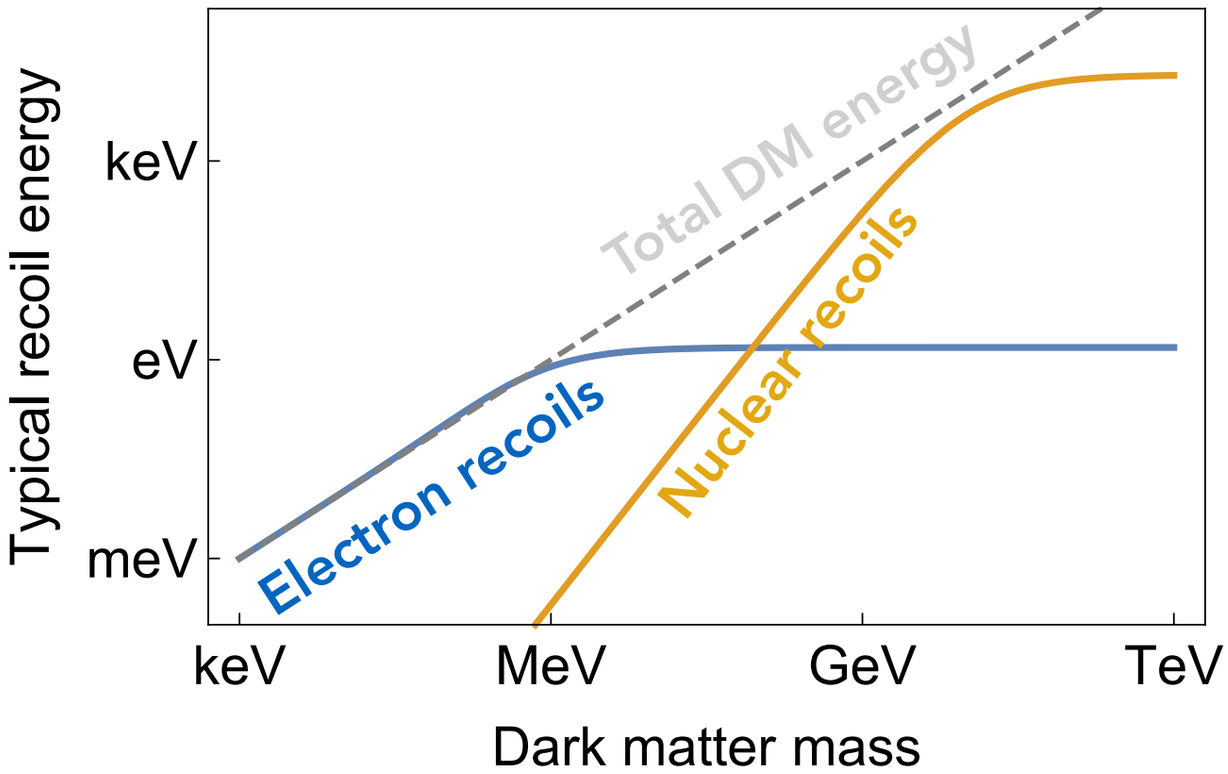
Energy deposited from WIMP in nuclear recoil:

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

Typical threshold in experiment: > 1 keV nuclear recoil

Detecting low mass dark matter

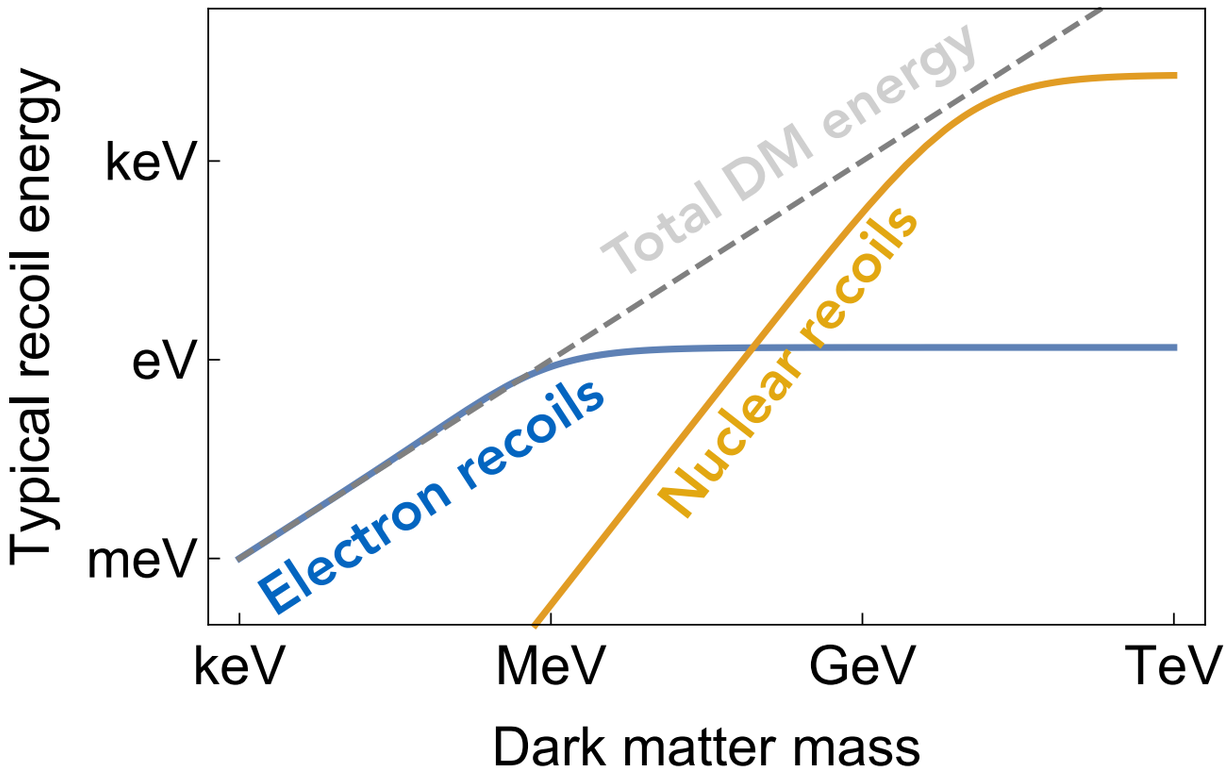
Electron recoils



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

Detecting low mass dark matter

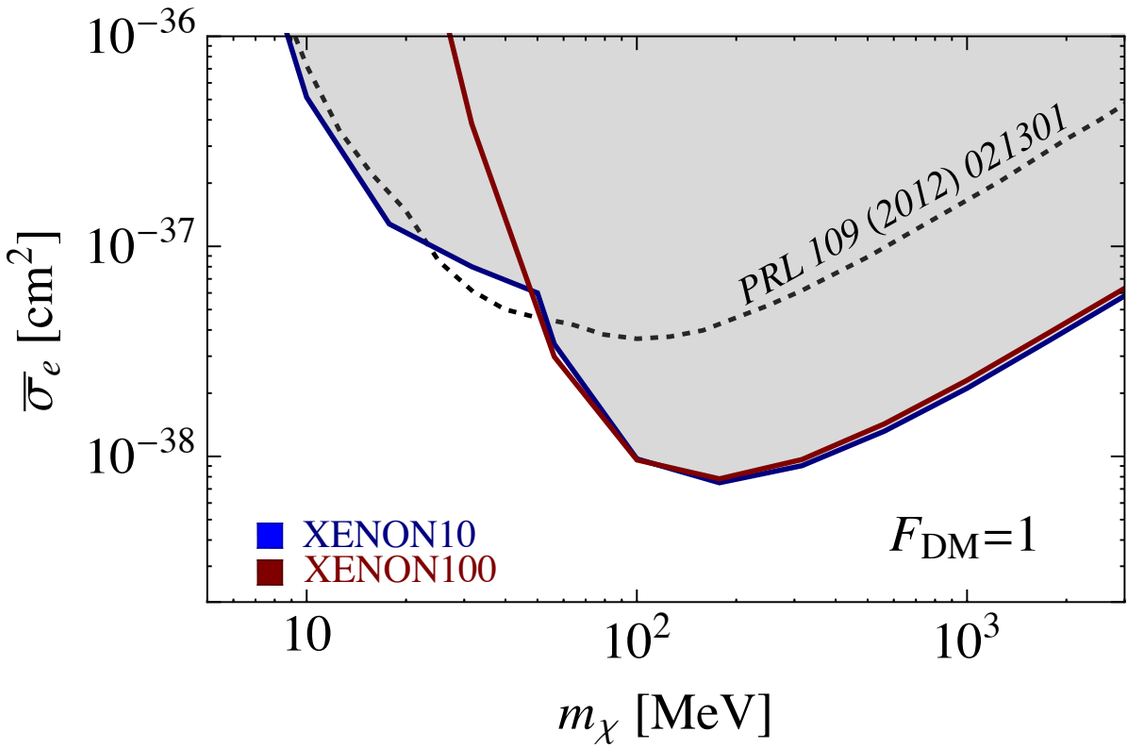
Electron recoils



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

Sensitivity to MeV-scale DM with Xenon10, Xenon100

$E_{th} \gtrsim 12$ eV



See talk by P. Sorensen for future prospects

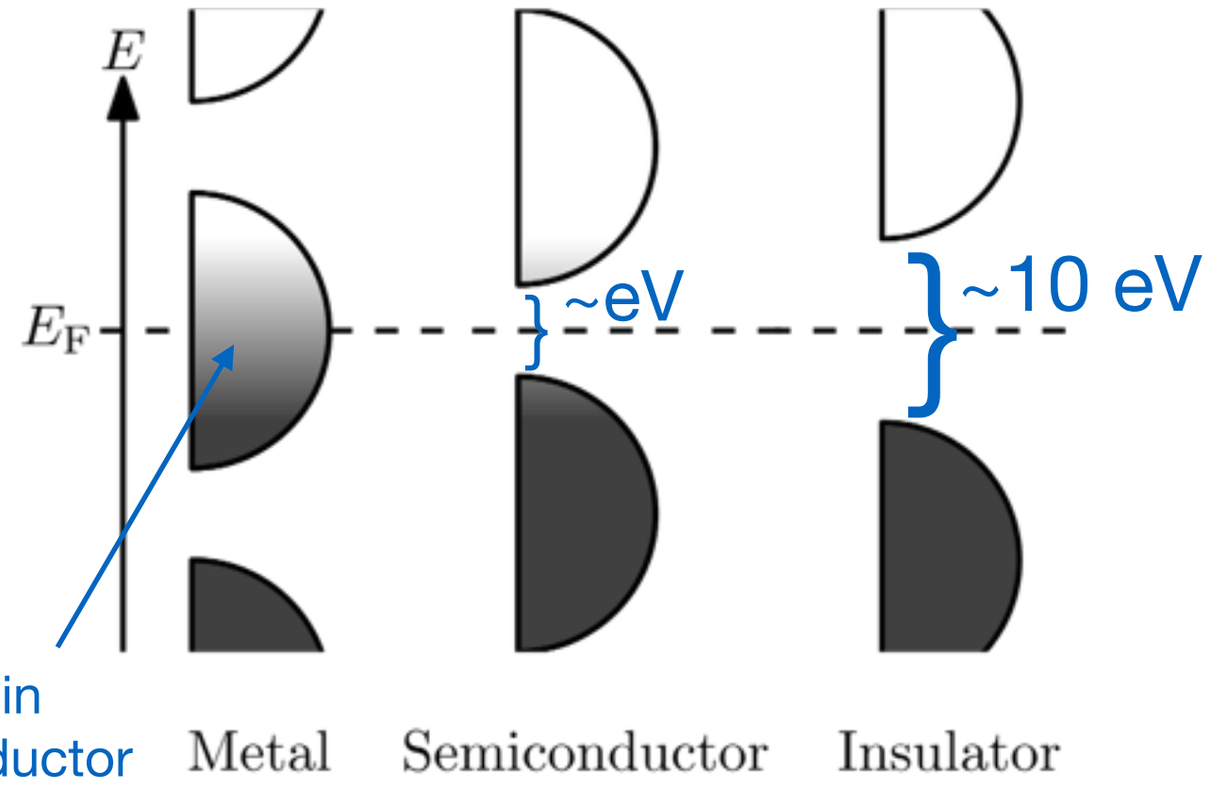
figure from Essig, Volansky, Yu 2017
see also: 1108.5383, 1206.2644

Detecting low mass dark matter

Ideas

Electron recoils with small gap materials

Electronic band structure



See talks by D. Mei, C. Tully, P. Privitera, J. Tiffenberg, T. Yu, Y. Zhao, J. Liu

See WG talks

Many refs; see WG talks

Detecting low mass dark matter

Ideas

Electron recoils with small gap materials

Gapless modes (phonons), vibrational modes

See talks by R. Budnik, S. Knapen, G. Sledel, S. Hertel,

See WG talks

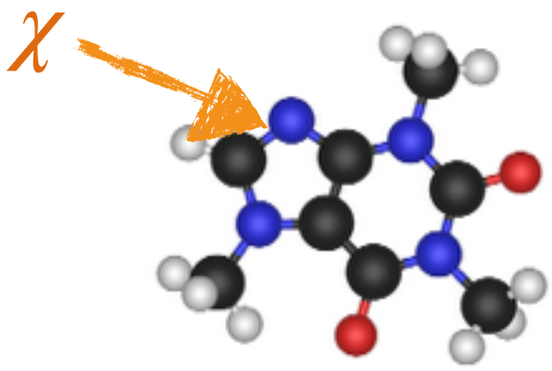
Long wavelength phonons [~meV]:

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

$c_s \sim 10^{-5}$ 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

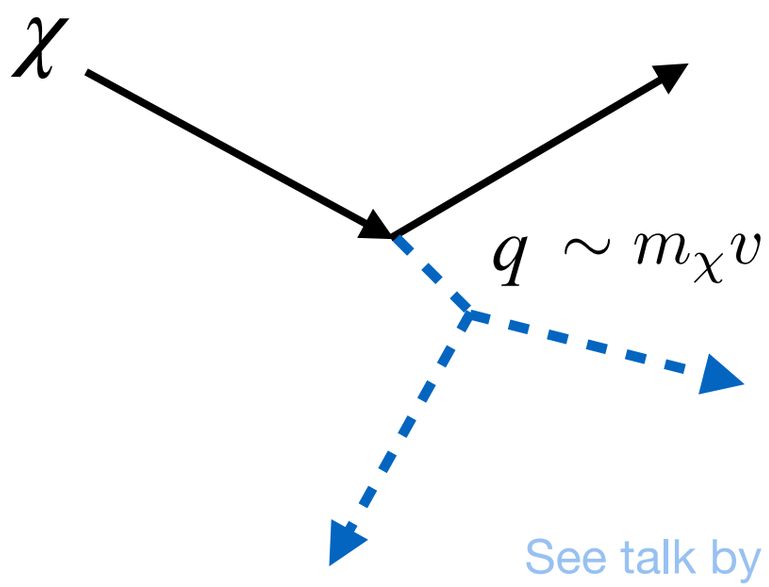
Gapless modes (phonons), vibrational modes

Higher order processes

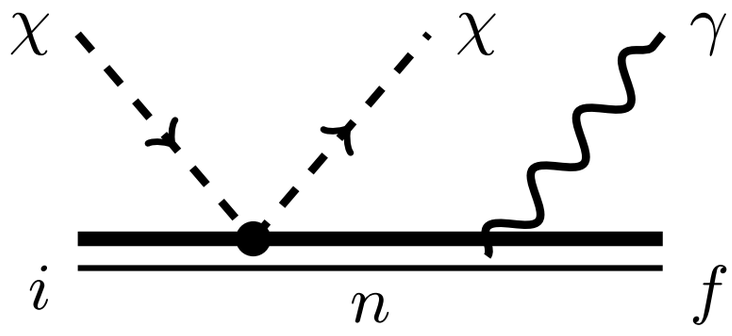
....

See WG talks

Three-body final states



See talk by S. Knapen

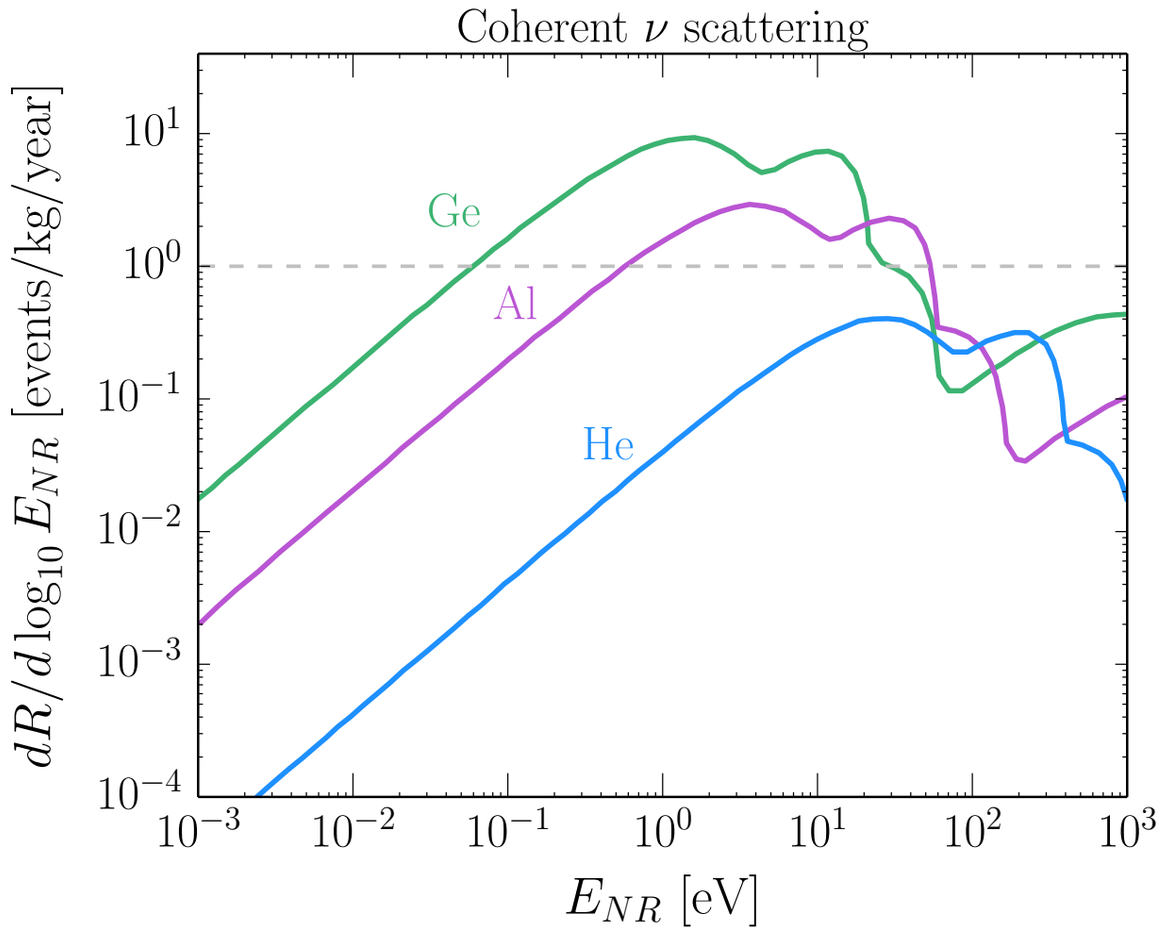


Schutz and Zurek 2016
Knapen, TL, Zurek 2016
McCabe 2017
Kouvaris and Pradler 2016, …

Detecting low mass dark matter

Backgrounds

coherent scattering of solar neutrinos



Events from solar ν with O(kg-year)

See talks by P. Sorensen, L. Strigari, M. Pyle

See WG talks

Detecting low mass dark matter

Backgrounds

coherent scattering of solar neutrinos

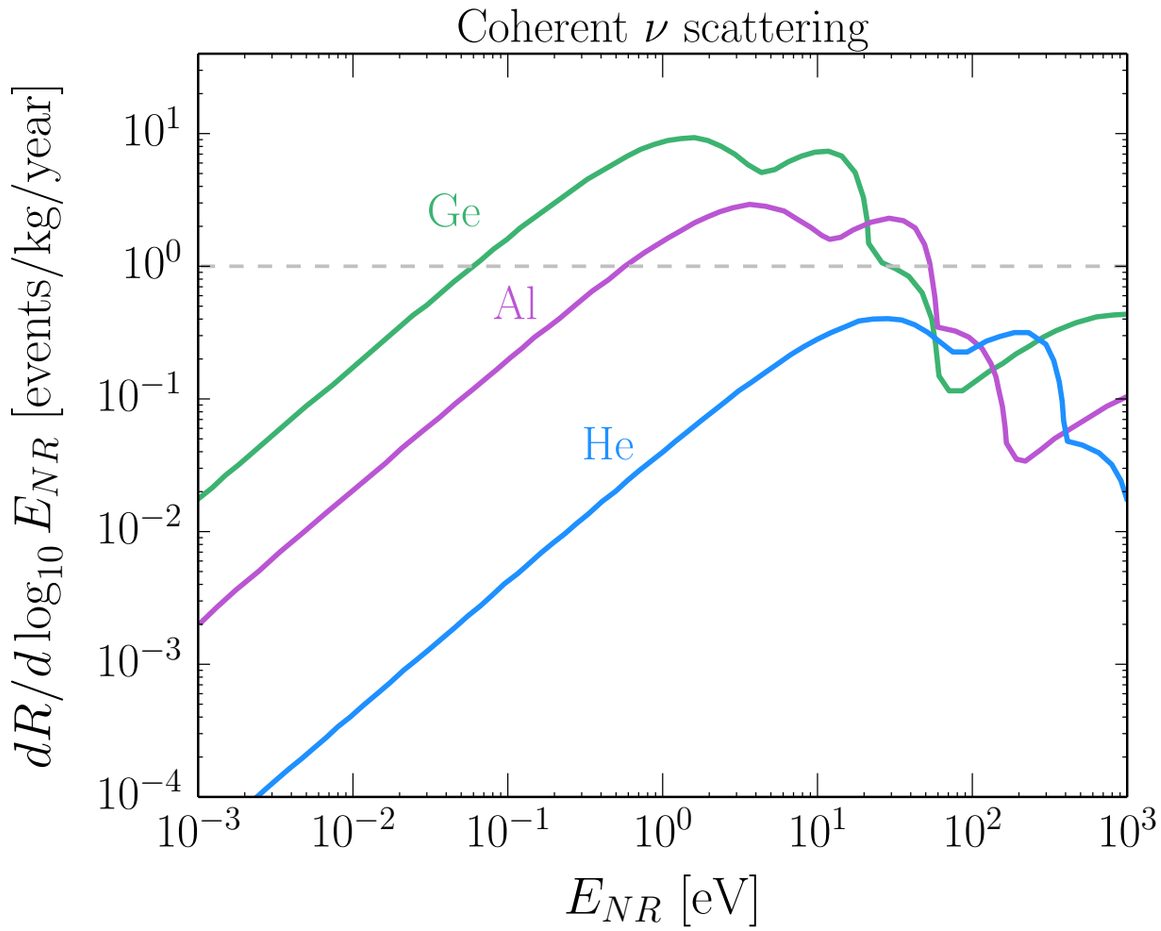
background of O(1-10)/kg-yr/10 eV
(based on DAMIC, SuperCDMS)
1610.00006, 1607.07410

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

...

See talks by P. Sorensen, L. Strigari, M. Pyle

See WG talks



Events from solar ν with O(kg-year)

Benchmarks

1. Scattering of keV-GeV dark matter
   - scalar mediator
   - hidden photon mediator

2. Absorption of meV-keV dark matter
   - hidden photons
   - pseudoscalars/scalars

Light dark matter and light mediators

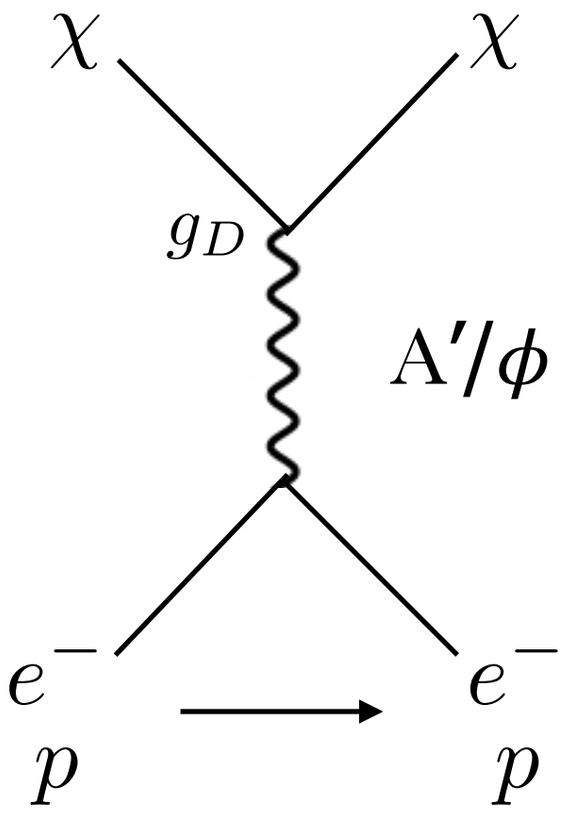
Motivation: low mass dark matter as the lightest stable particle in a dark sector

Mass scale of mediator similar to (lighter than) χ :

- same physics may generate both masses

- annihilation is sufficiently large in the early universe (thermal candidate)

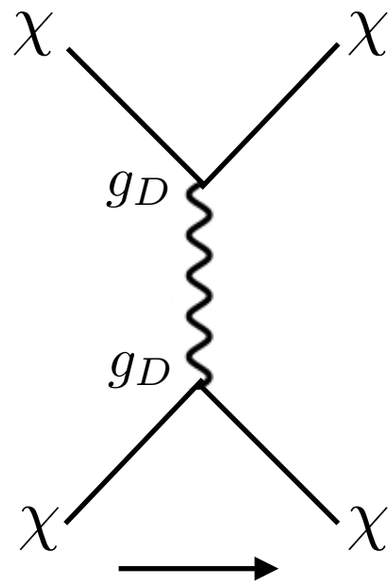
Dark matter scattering



Constraints from cosmology

DM self-interactions gives a bound on g_D:

$$\sigma_T \approx \begin{cases} \frac{4\pi\alpha_D^2 m_\chi^2}{m_{A'}^4}, & m_{A'} \gg m_\chi v \\ \frac{16\pi\alpha_D^2}{m_\chi^2 v^4} \ln\frac{m_\chi v^2}{2m_\phi \alpha_D}, & m_{A'} \ll m_\chi v \end{cases}$$



See talks by A. Peter, M. Kaplinghat, H. Yu

Annihilation of sub-GeV DM is bounded by CMB measurements

See talk by T. Slatyer

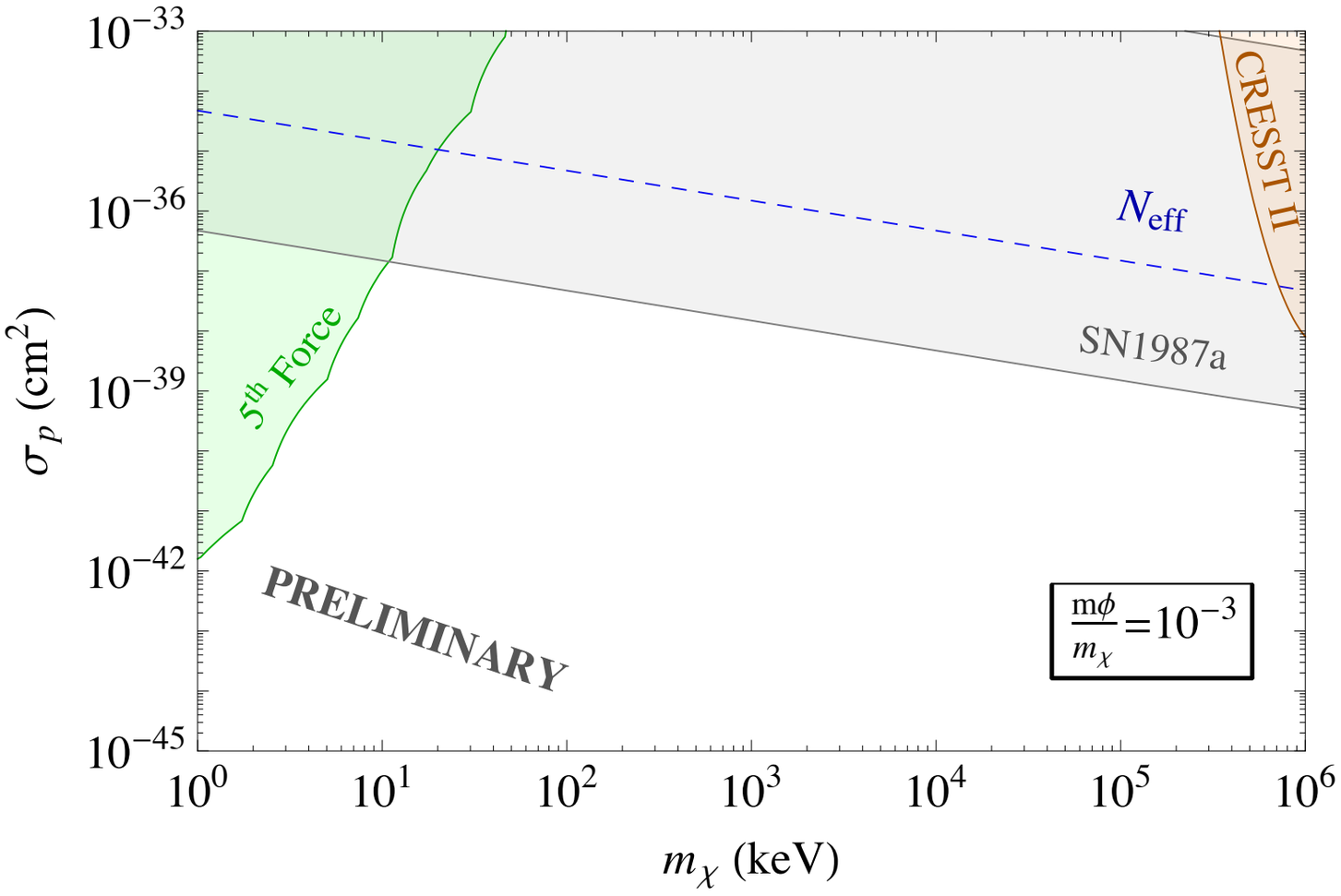
N_{eff} from CMB, BBN also important (model-dependent)

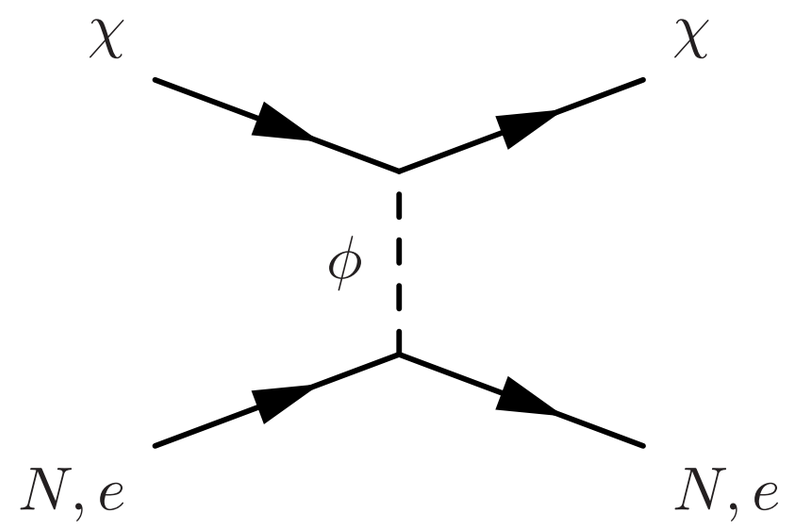
TL Yu Zurek 2011
Boehm Dolan McCabe 2013

Scalar mediator

Coupling to nuclei or electrons

Example: nucleon coupling





see e.g. Hochberg, Pyle, Zhao, Zurek 2016
Green, Rajendran 2017, Krnjaic 2015
Knapen, TL, Zurek (work in progress)

Scalar mediator

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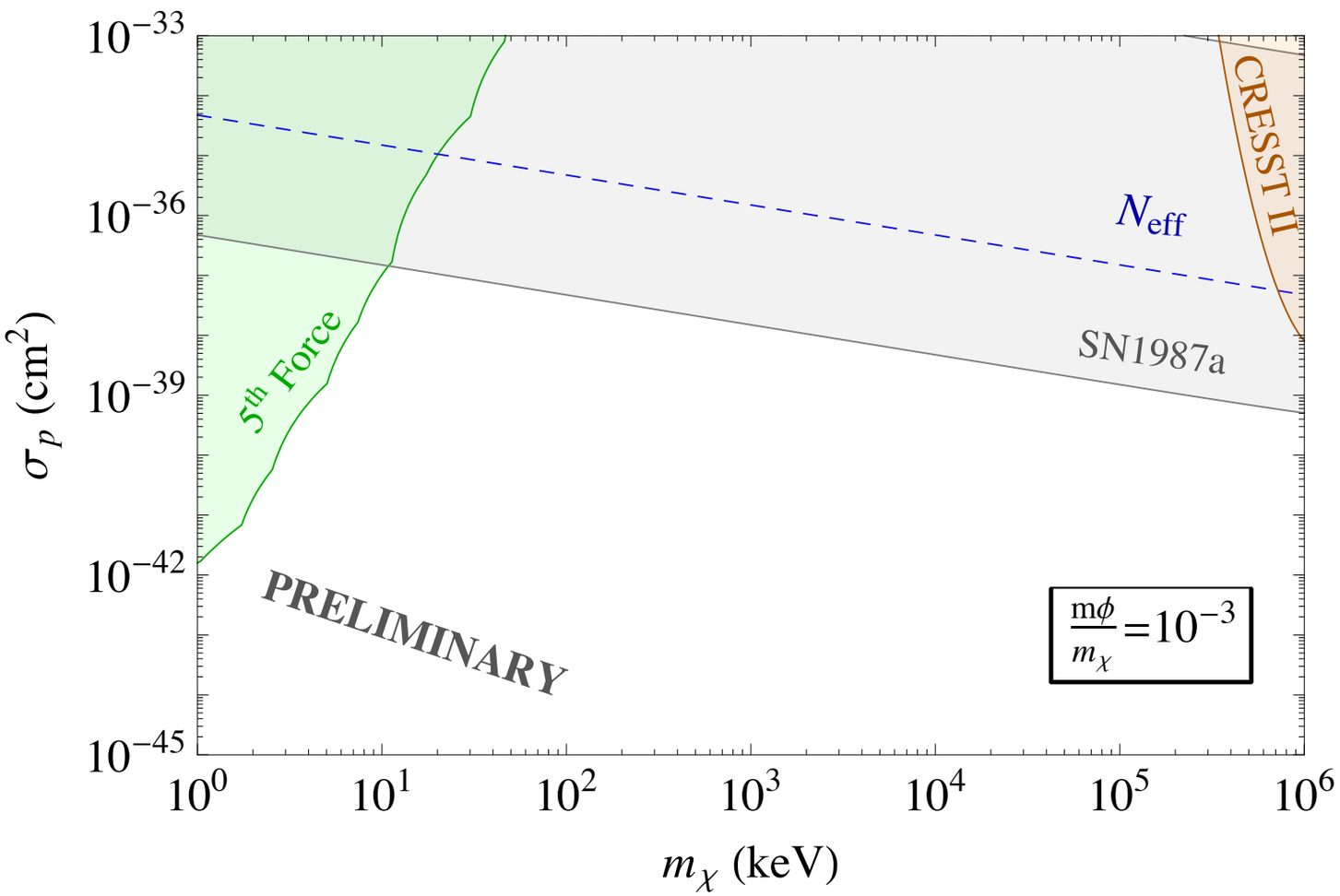
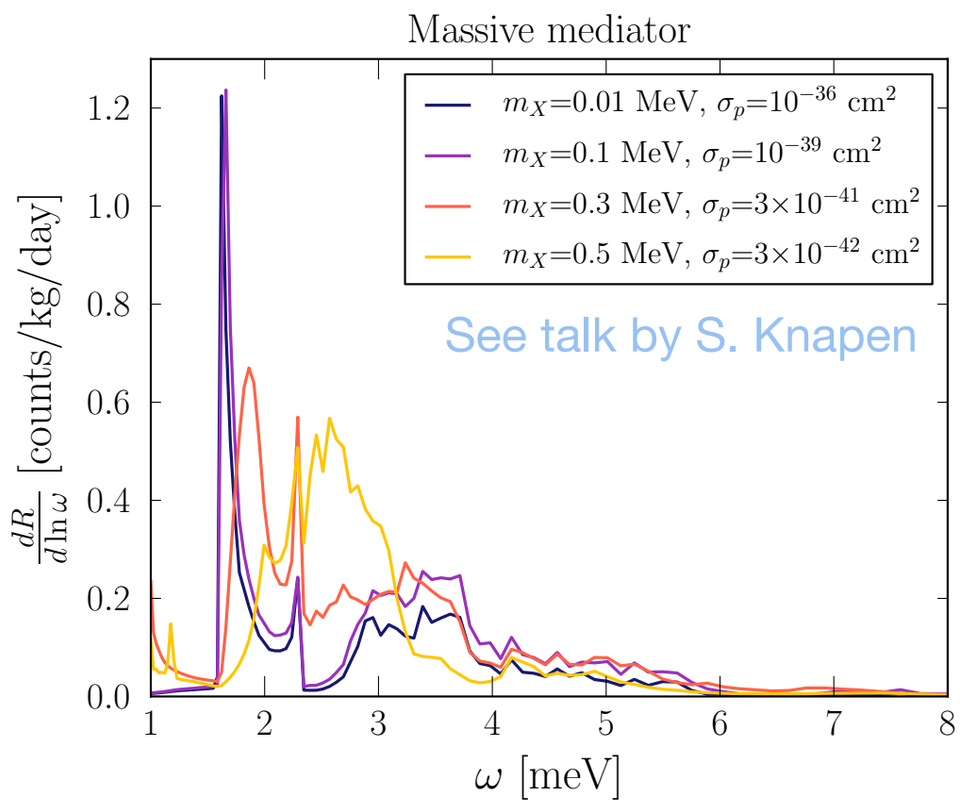


Multi-phonon production in superfluid helium



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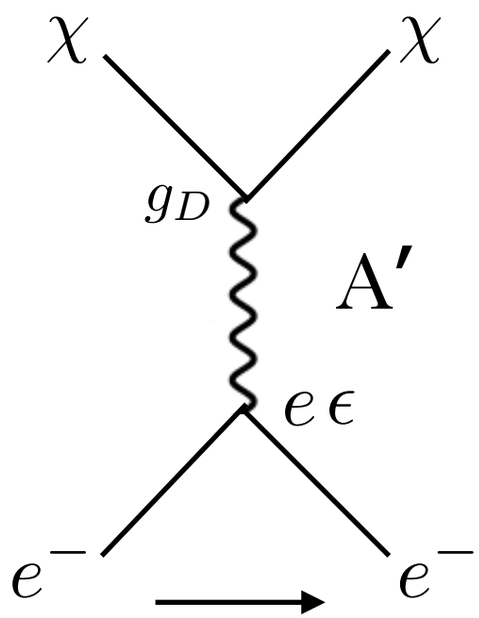
Hidden photon mediator

Kinetically mixed hidden photon A’

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

couples to electrons, nuclei



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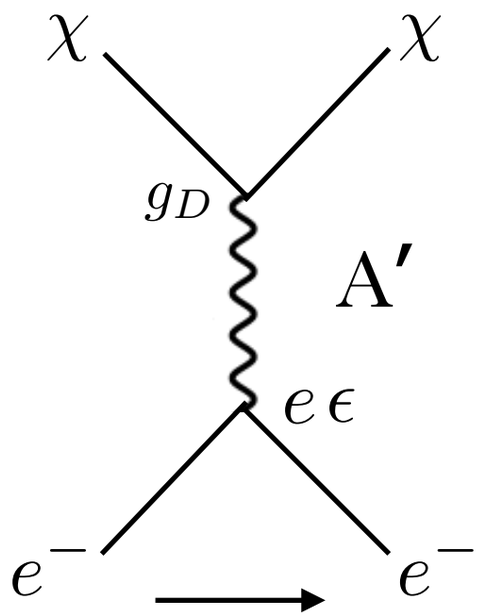


Electron scattering cross section:

massive limit

$$\bar{\sigma}_e \equiv \frac{16\pi\mu_{\chi e}^2 \alpha\epsilon^2\alpha_D}{(m_{A'})^4}$$

massless limit ←

$$m_{A'} \ll \mathrm{keV}$$

$$\bar{\sigma}_e \equiv \frac{16\pi\mu_{\chi e}^2 \alpha\epsilon^2\alpha_D}{(\alpha m_e)^4}$$

Lower thresholds preferred

Recoil spectrum $dR \propto \dfrac{\bar{\sigma}_e}{q^4}$

q: momentum transfer

Massive hidden photon mediator

Targets

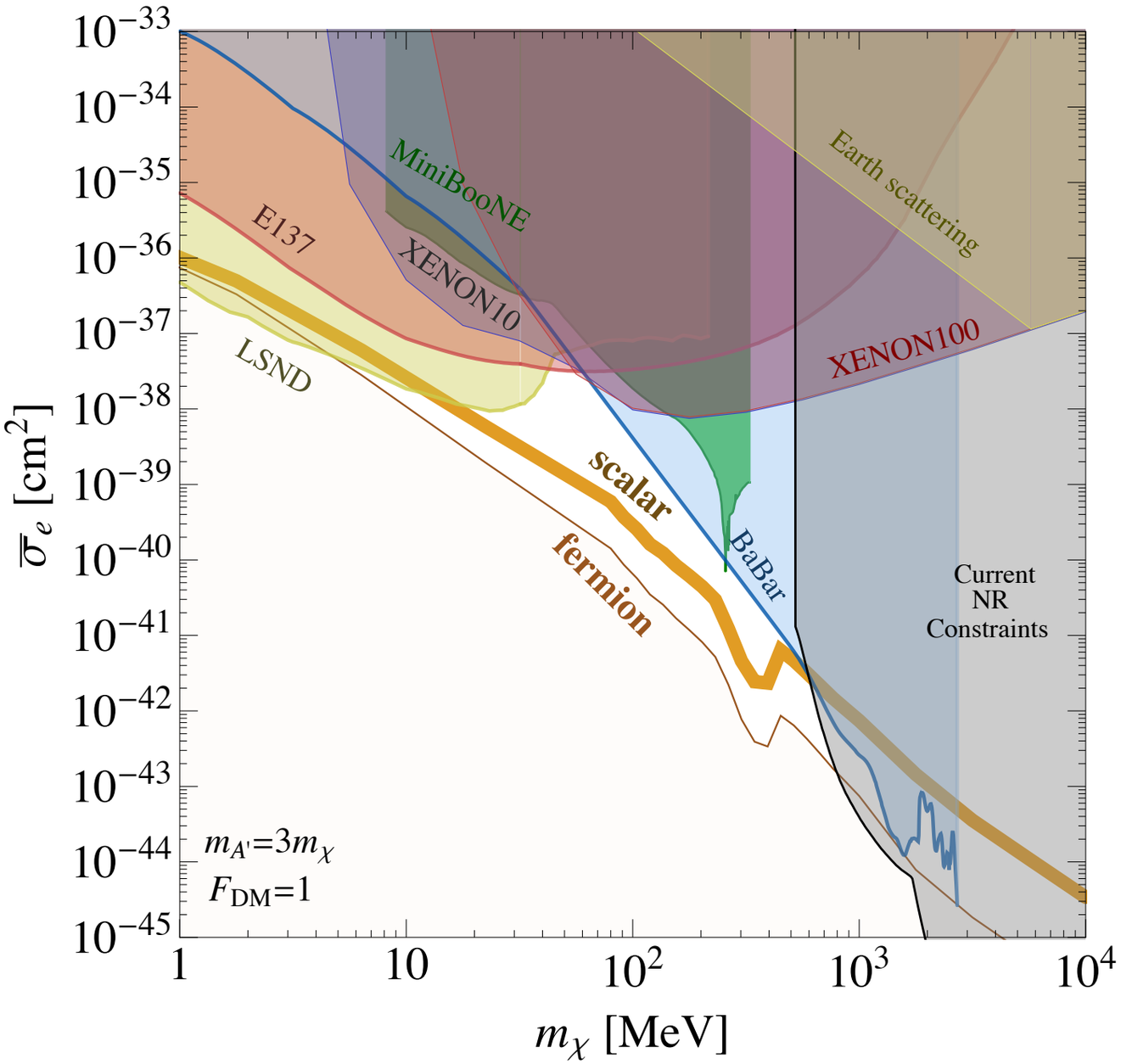
Scalar: thermal relic

Fermion: asymmetric freeze-out

(other mechanisms possible)

Complementary accelerator sensitivity, depending on mass ratio

- $m_{A'} > 2\, m_\chi$ (this plot)
- $m_{A'} < 2\, m_\chi$



Essig et al., 1509.01598,
updated with Essig, Volansky, Yu 2017

Massive hidden photon mediator

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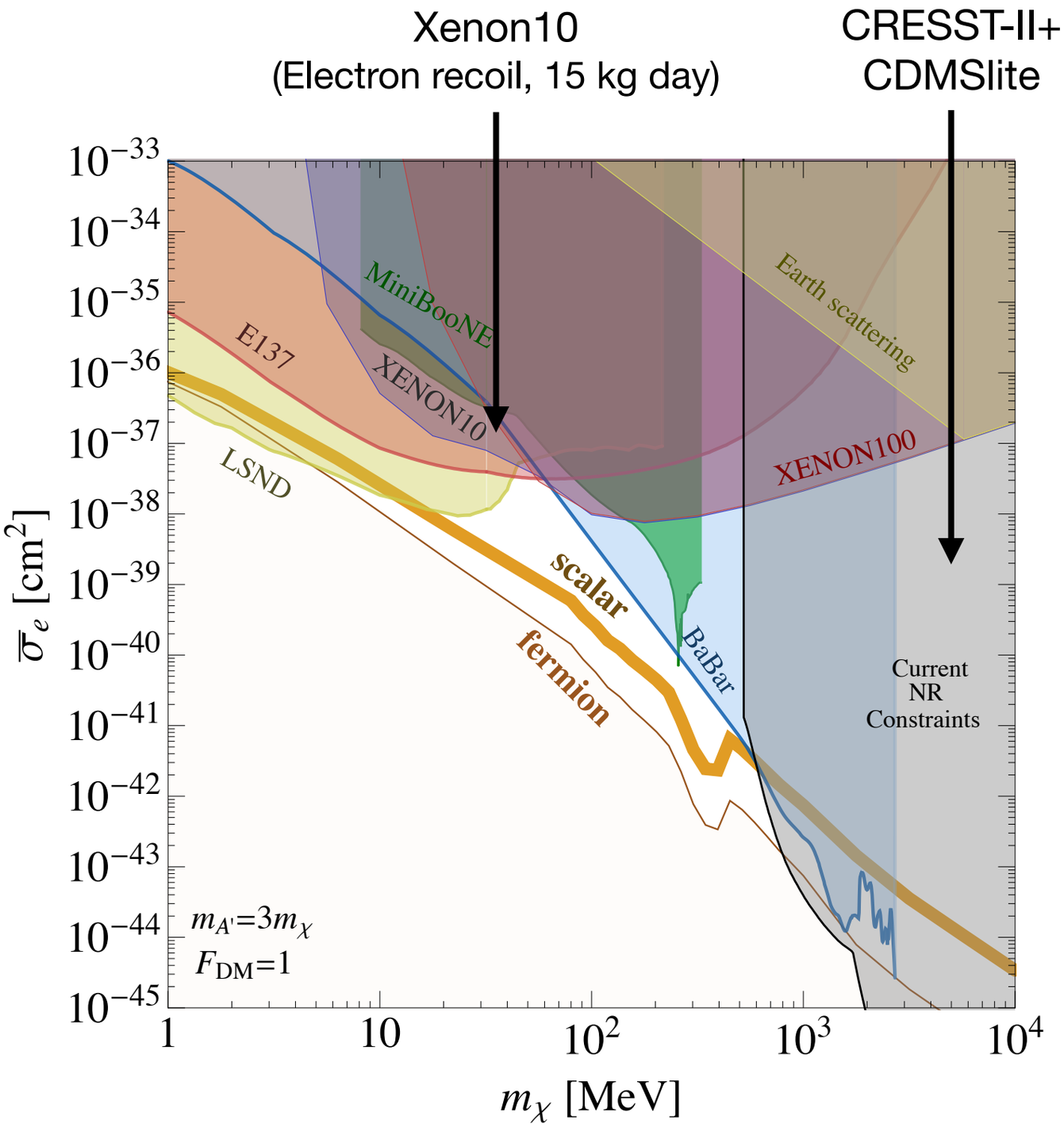


Essig et al., 1509.01598,
updated with Essig, Volansky, Yu 2017

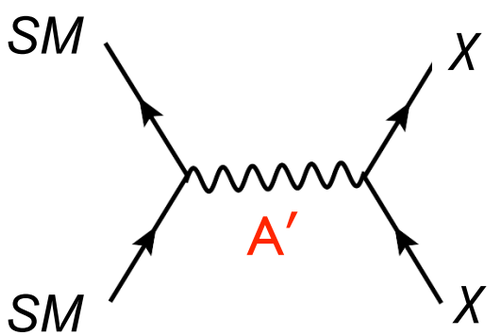
Ultralight hidden photon mediator

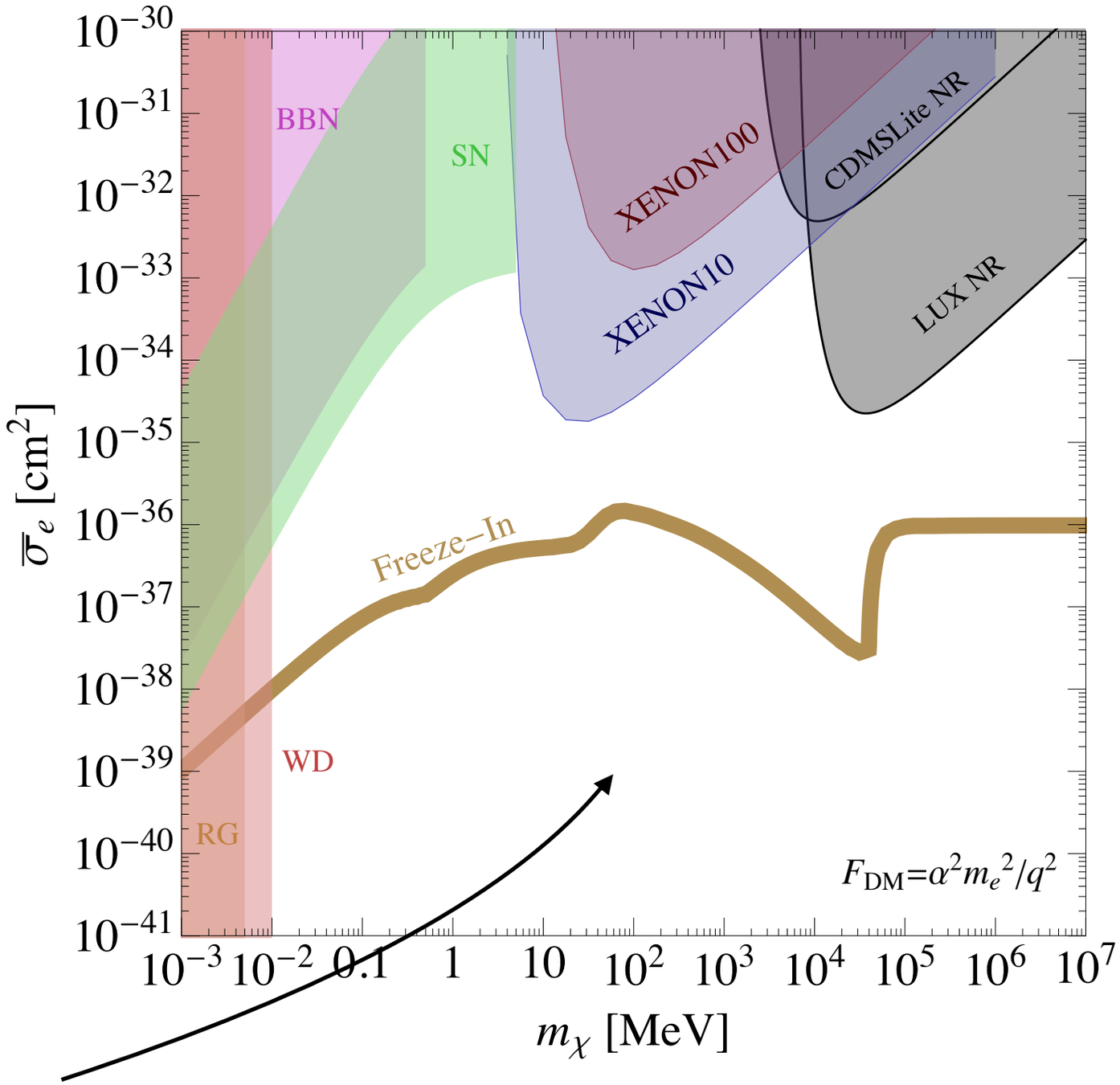
Electron scattering cross section:

$$\bar{\sigma}_e \equiv \frac{16\pi\mu_{\chi e}^2 \alpha \epsilon^2 \alpha_D}{(\alpha m_e)^4}$$

Targets

"Freeze-in"
from SM thermal bath





Asymmetric
thermal freeze-out

Essig Mardon Volansky 2011,
Essig et al., 1509.01598

Benchmarks

1. Scattering of keV-GeV dark matter
   - scalar mediator
   - hidden photon mediator

2. Absorption of meV-keV dark matter
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   - pseudoscalars/scalars

sub-keV bosonic dark matter

- Candidates:
  - **Hidden photon**
  - **Pseudoscalar**
  - **Scalar**

One of the simplest renormalizable couplings to SM:

$$\mathcal{L} \supset -\frac{\kappa}{2} F_{\mu\nu} V^{\mu\nu}$$

Generalization of QCD axion

sub-keV bosonic dark matter

- Candidates:
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  - **Pseudoscalar**
  - **Scalar**

One of the simplest renormalizable couplings to SM:

$$\mathcal{L} \supset -\frac{\kappa}{2} F_{\mu\nu} V^{\mu\nu}$$

Generalization of QCD axion

- Coherent field below $m \sim$ eV

Local DM density: 0.4 GeV/cm^3 $\quad \lambda_{\rm dB} \sim \dfrac{2\pi}{m_{\rm DM} v} \quad v \sim 10^{-3}$

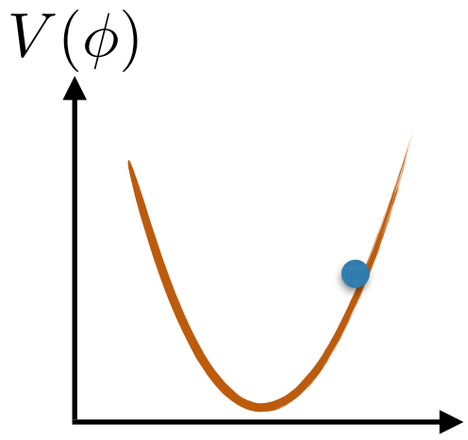
Occupation number is high: $\quad \dfrac{\rho_{\rm DM}}{m_{\rm DM}} \gg \lambda_{\rm dB}^{-3}$

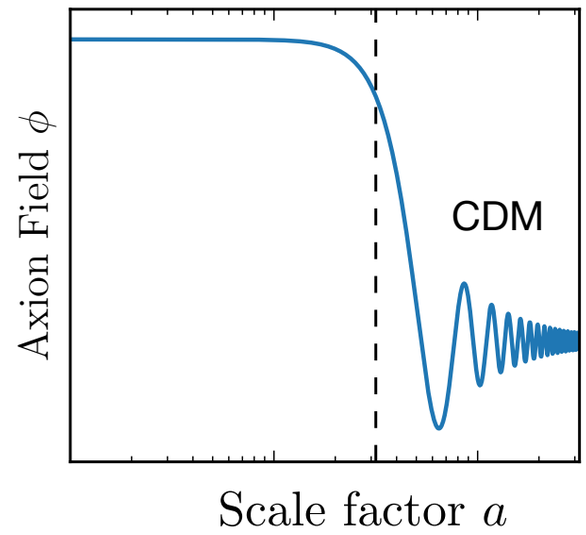
Relic abundance

Non-thermal relic abundance by misalignment mechanism:

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

ϕ_0 — average field today





Correct relic abundance can be achieved via inflationary production of hidden photon (massive vector):

$$m_V \approx 10^{-5}\ \text{eV} \times \left(\frac{10^{14}\ \text{GeV}}{H_{inf}} \right)^4$$

Hubble scale of inflation

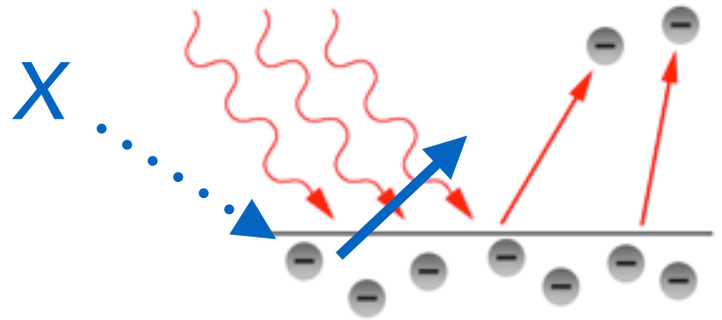
Graham, Mardon, Rajendran 2015

figure from Marsh 2015

DM absorption

Mono-energetic signal from halo DM

- doesn’t require coherent field
- low thresholds needed
- (coupling)^2



Both electron recoils,
phonon modes can be used
to detect DM absorption!

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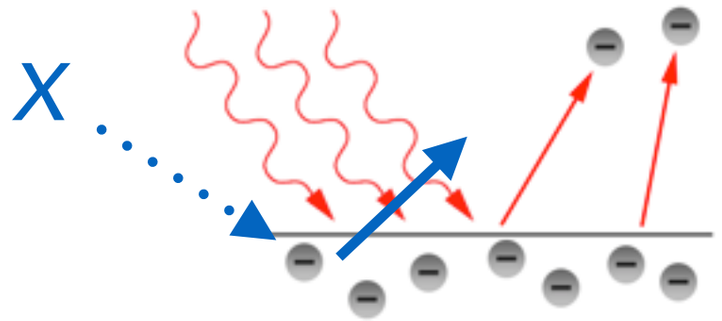


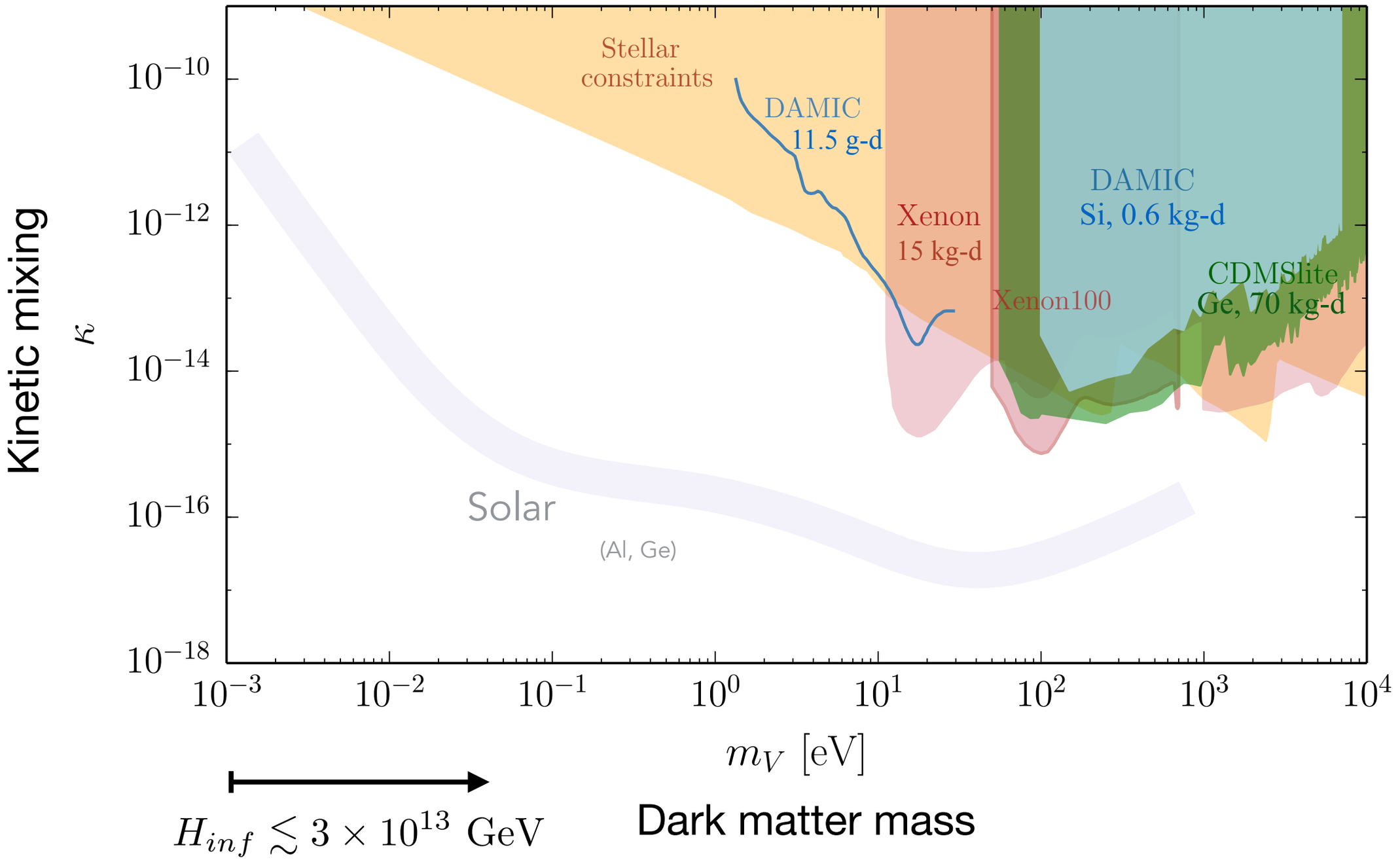
Emission from sun + absorption

- 10-100 eV thresholds sufficient
- (coupling)^4

Both electron recoils, phonon modes can be used to detect DM absorption!

(Stuckelberg mass for hidden photon assumed)

Hidden photon DM

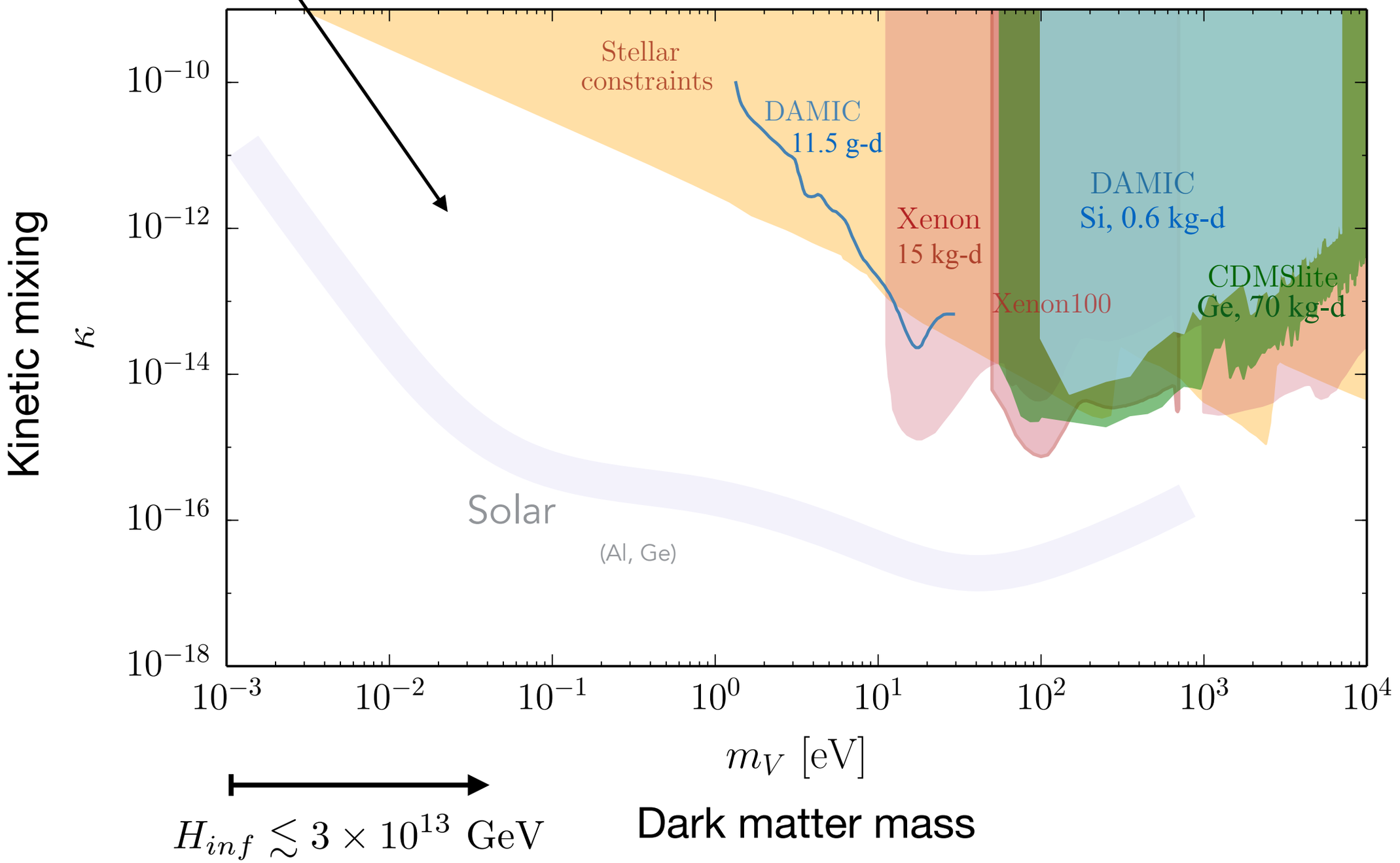


Hochberg, TL, Zurek 2016a, 2016b
An, Pospelov, Pradler 2013, 2014
I. Bloch et al. 2016, DAMIC 1611.03066

(Stuckelberg mass for hidden photon assumed)

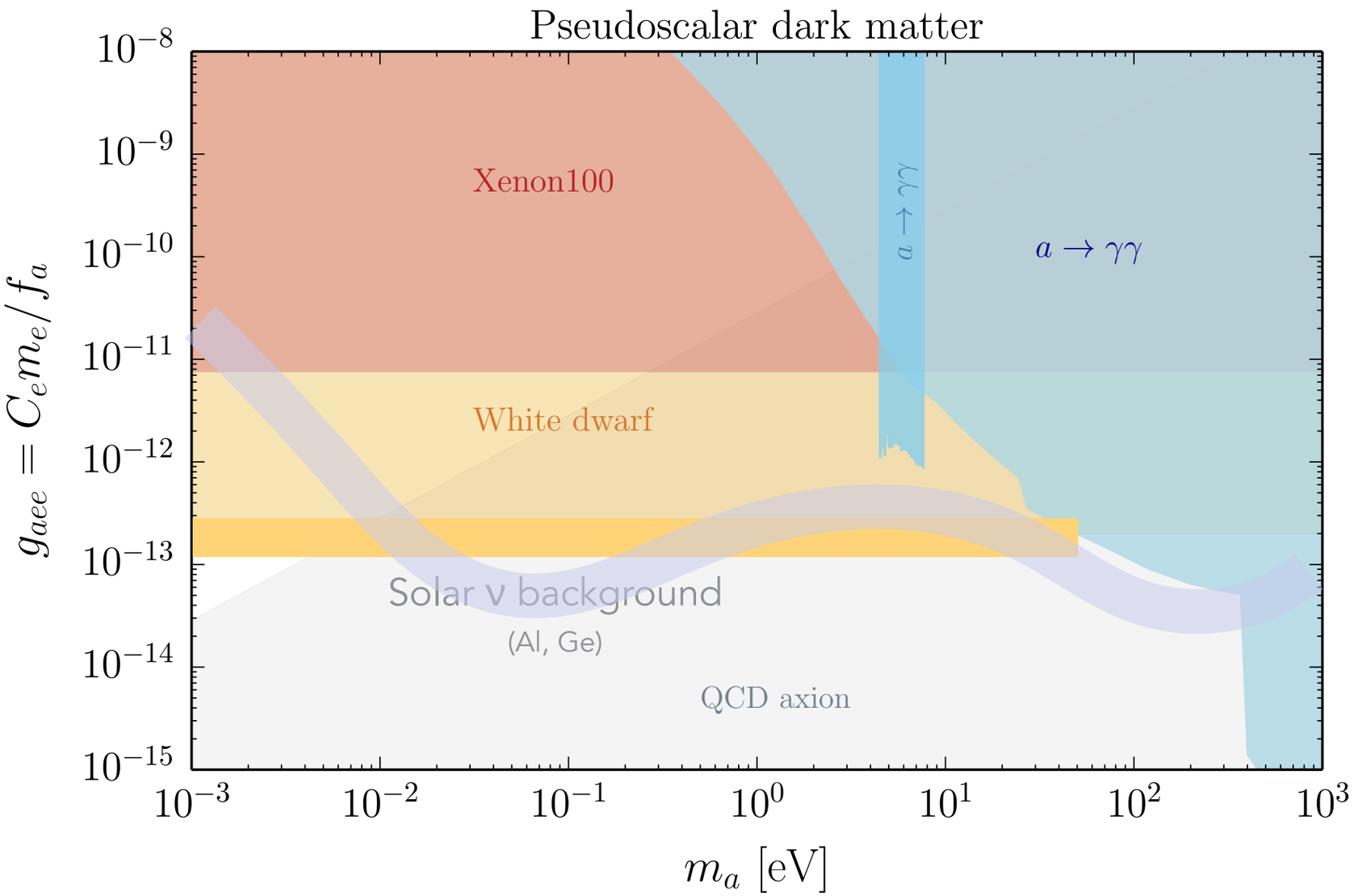
Wide open parameter space, accessible with O(kg-day) exposure

Hidden photon DM



Hochberg, TL, Zurek 2016a, 2016b
An, Pospelov, Pradler 2013, 2014
I. Bloch et al. 2016, DAMIC 1611.03066

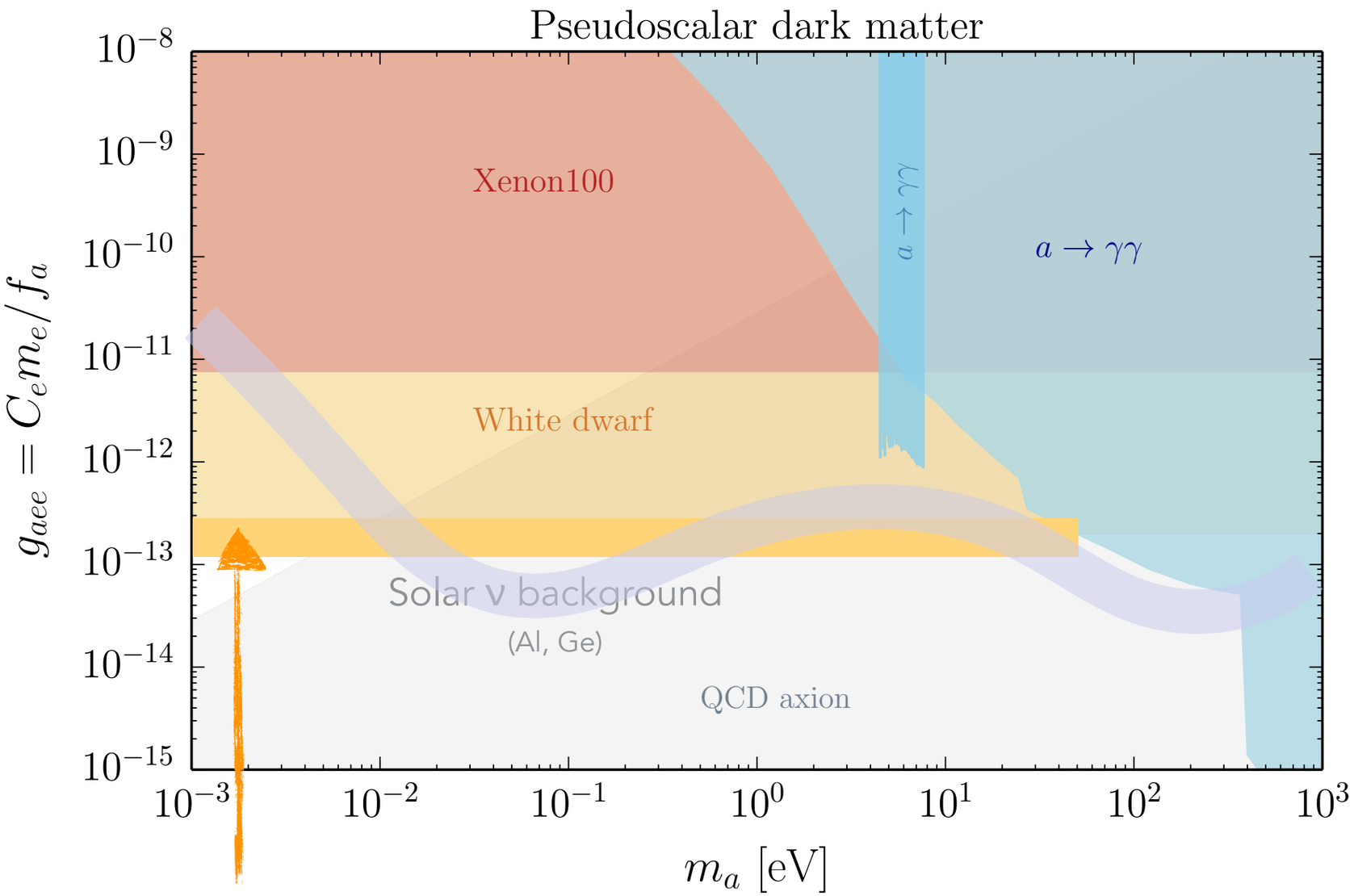
Pseudoscalar DM



Open parameter space accessible with O(kg-year) exposure

Hochberg, TL, Zurek 2016a, 2016b
Arias et al. 2012, I. Bloch et al. 2016

Pseudoscalar DM



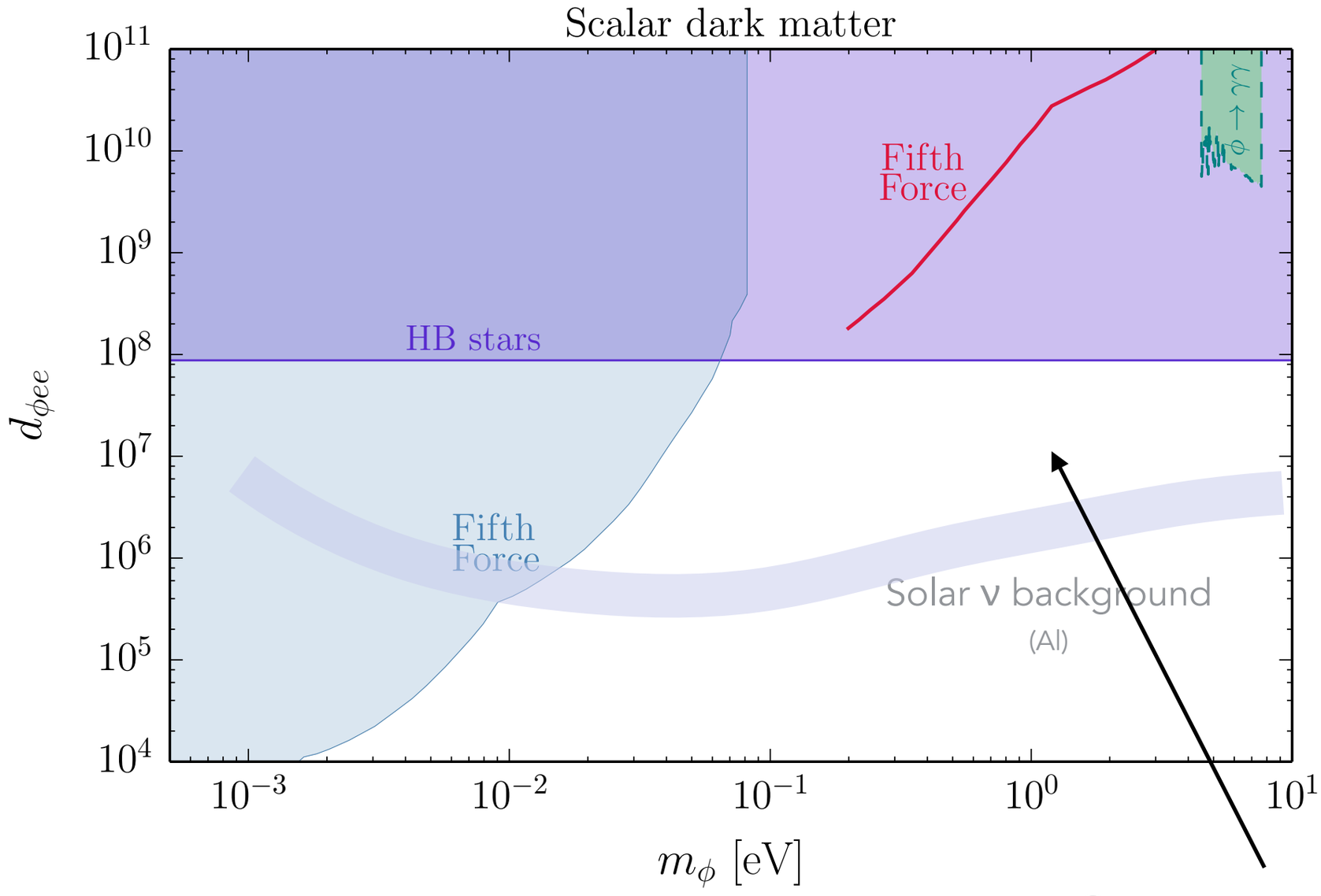
White dwarf cooling hint

Isern et al. 2008;
Giannotti et al. 2015

Open parameter space accessible with O(kg-year) exposure

Hochberg, TL, Zurek 2016a, 2016b
Arias et al. 2012, I. Bloch et al. 2016

Scalar DM



Open parameter space, accessible with O(kg-year) exposure

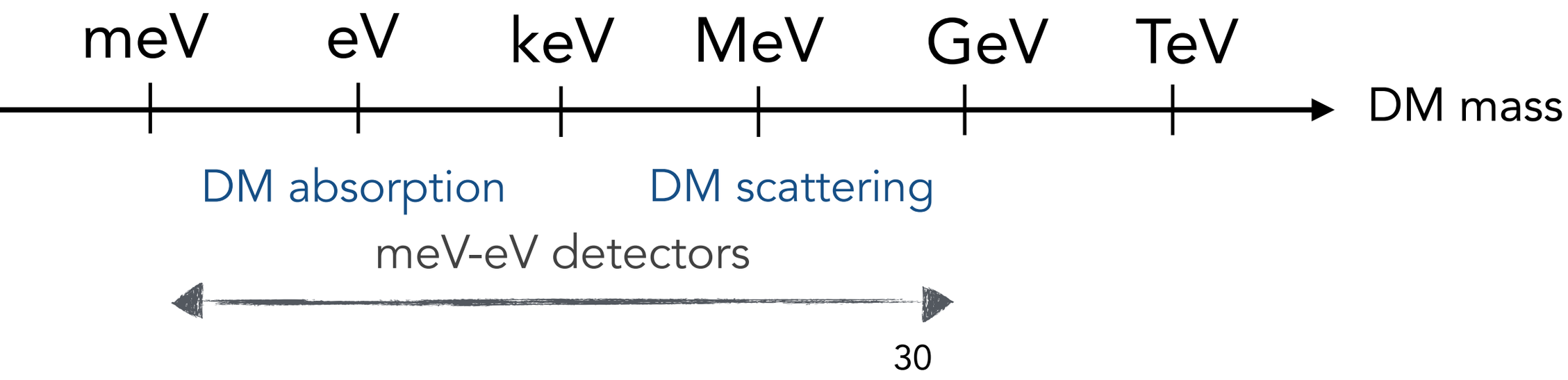
Hochberg, TL, Zurek 2016a, 2016b
Arias et al. 2012, I. Bloch et al. 2016

Conclusions

- Viable and motivated DM candidates in meV-GeV range; variety of well-defined targets in model space

- Many new ideas to reach these with meV-eV threshold detection mechanisms

- Exciting opportunity to cover wide open parameter space, probe MeV thermal relics



Thanks!