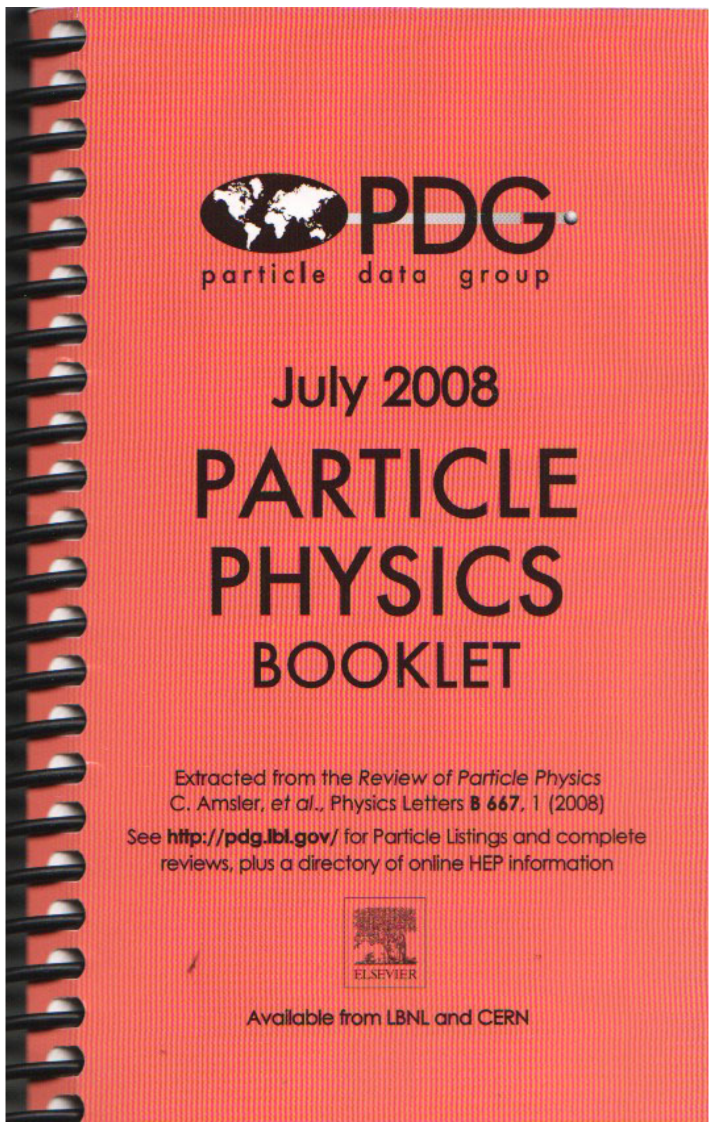
Aspects of dark matter phenomenology

Christopher M^c^Cabe

The local dark matter distribution workshop, Durham, 3rd December 2019

What would we like to know?



Dark Matter Particle (X^0)

X^0 mass: $m = ?$

X^0 spin: $J = ?$

X^0 parity: $P = ?$

X^0 lifetime: $\tau = ?$

X^0 scattering cross-section on nucleons: $?$

X^0 production cross-section in hadron colliders: $?$

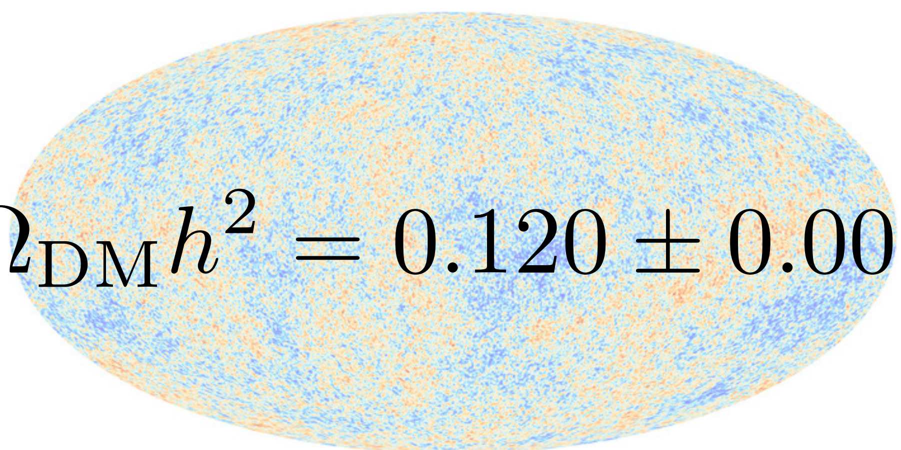
X^0 self-annihilation cross-section: $?$

Why should DM interact with the SM?

"Up to a point the stories of cosmology and particle physics can be told separately. In the end though, they will come together."

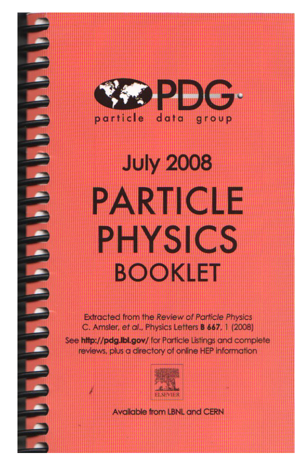
Steven Weinberg

Cosmology



$$\Omega_{\rm DM} h^2 = 0.120 \pm 0.001$$

Particle Physics



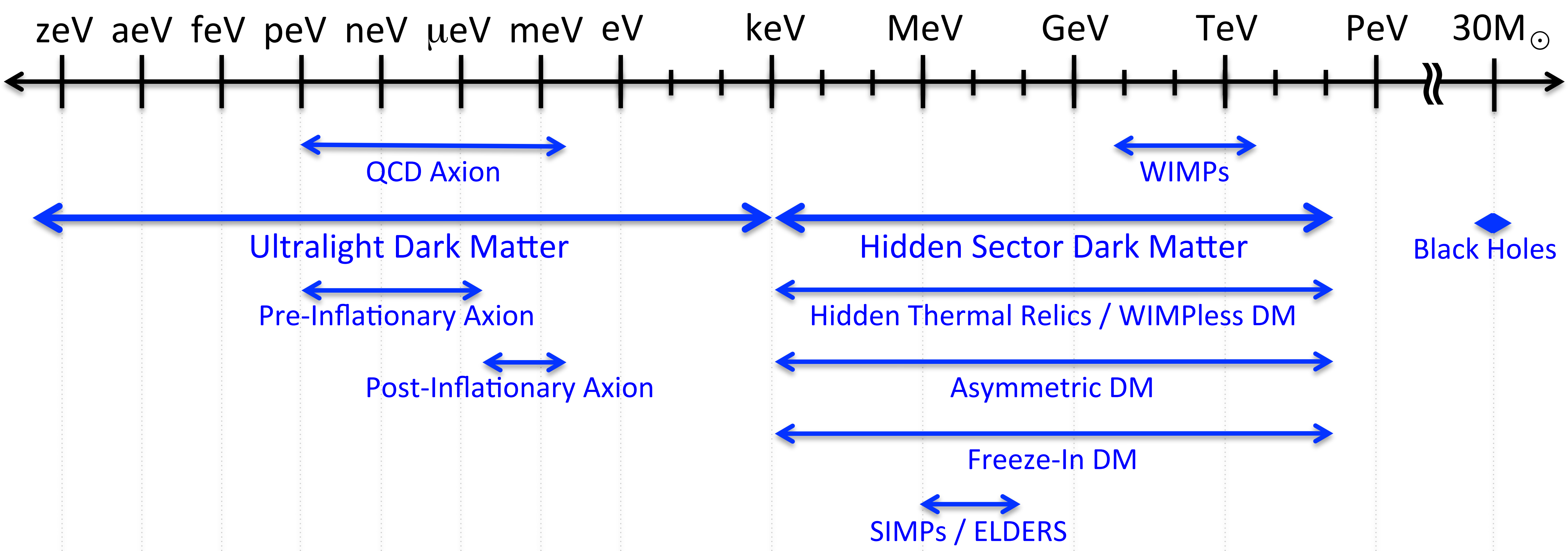
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{m_q}{\Lambda^3}\bar{\chi}\chi\bar{q}q + \cdots$$

Suggests DM - Standard Model interactions are generic

&

informs and limits the possible interactions

Theorists haven't stopped at WIMPs…

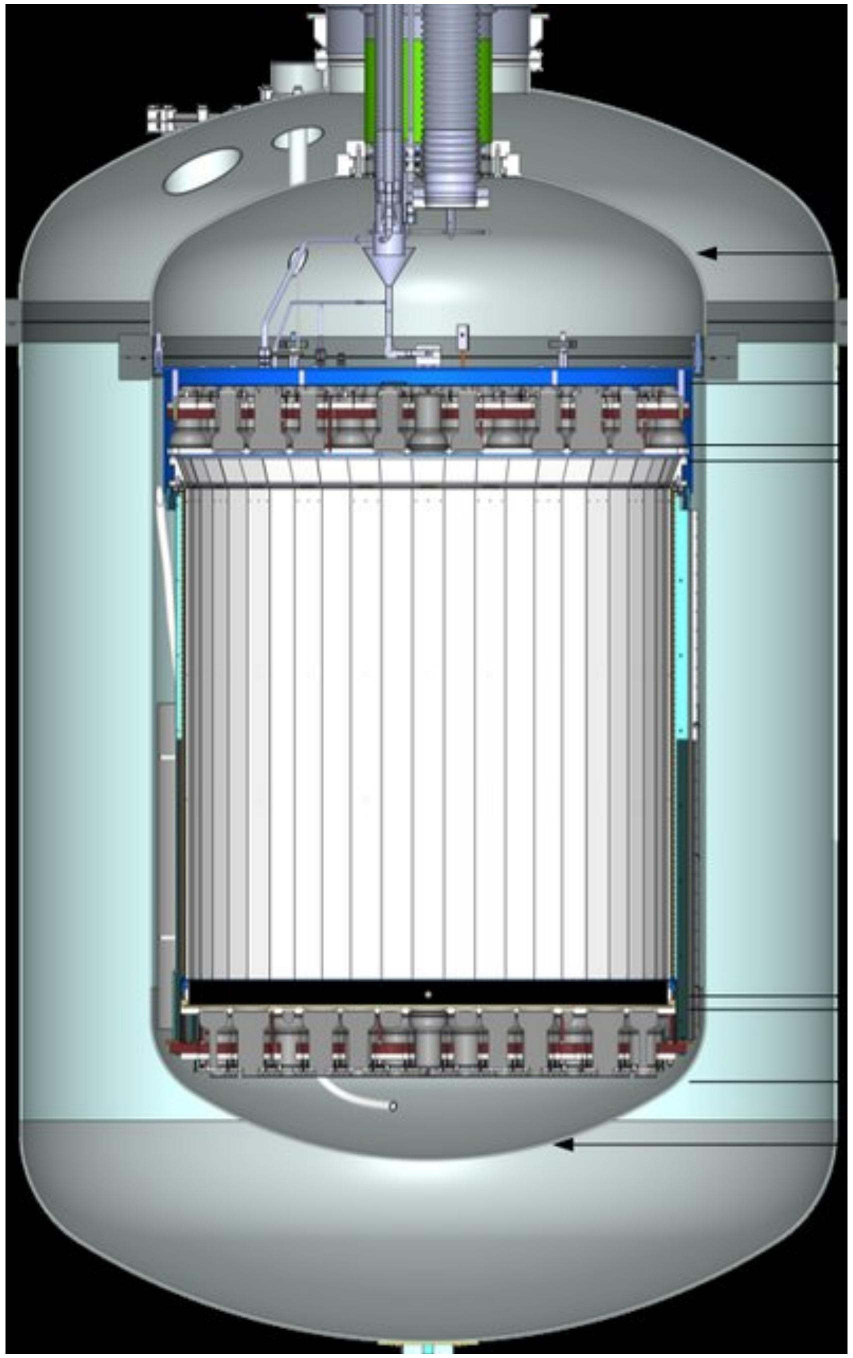


US Cosmic Visions

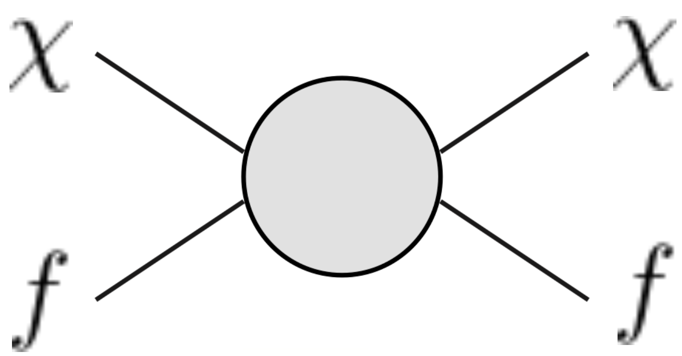
Many candidates outside the WIMP mass range all with SM interactions

Searching for DM - SM interactions

Direct detection unique:
directly probes the galactic dark matter passing through the Earth

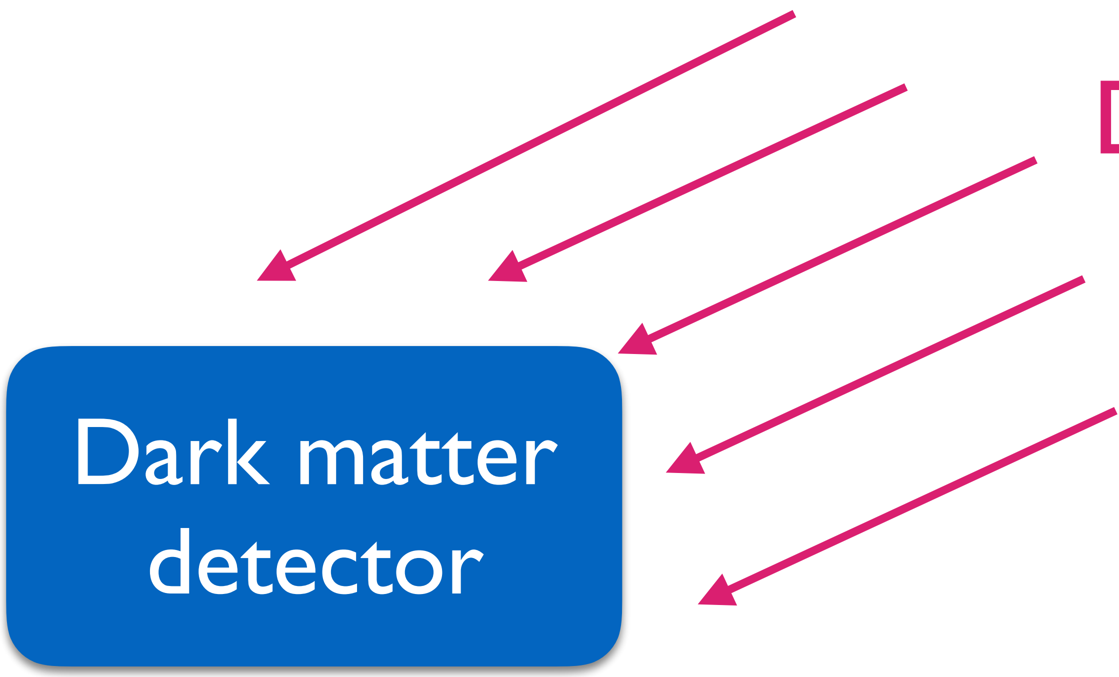


Canonically represented as scattering



…but there are other possibilities

Generic direct detection experiment



Dark matter flux

$$\sim \rho_{\rm DM} \int d^3v \, f_{\rm DM}(\mathbf{v}) \, v$$

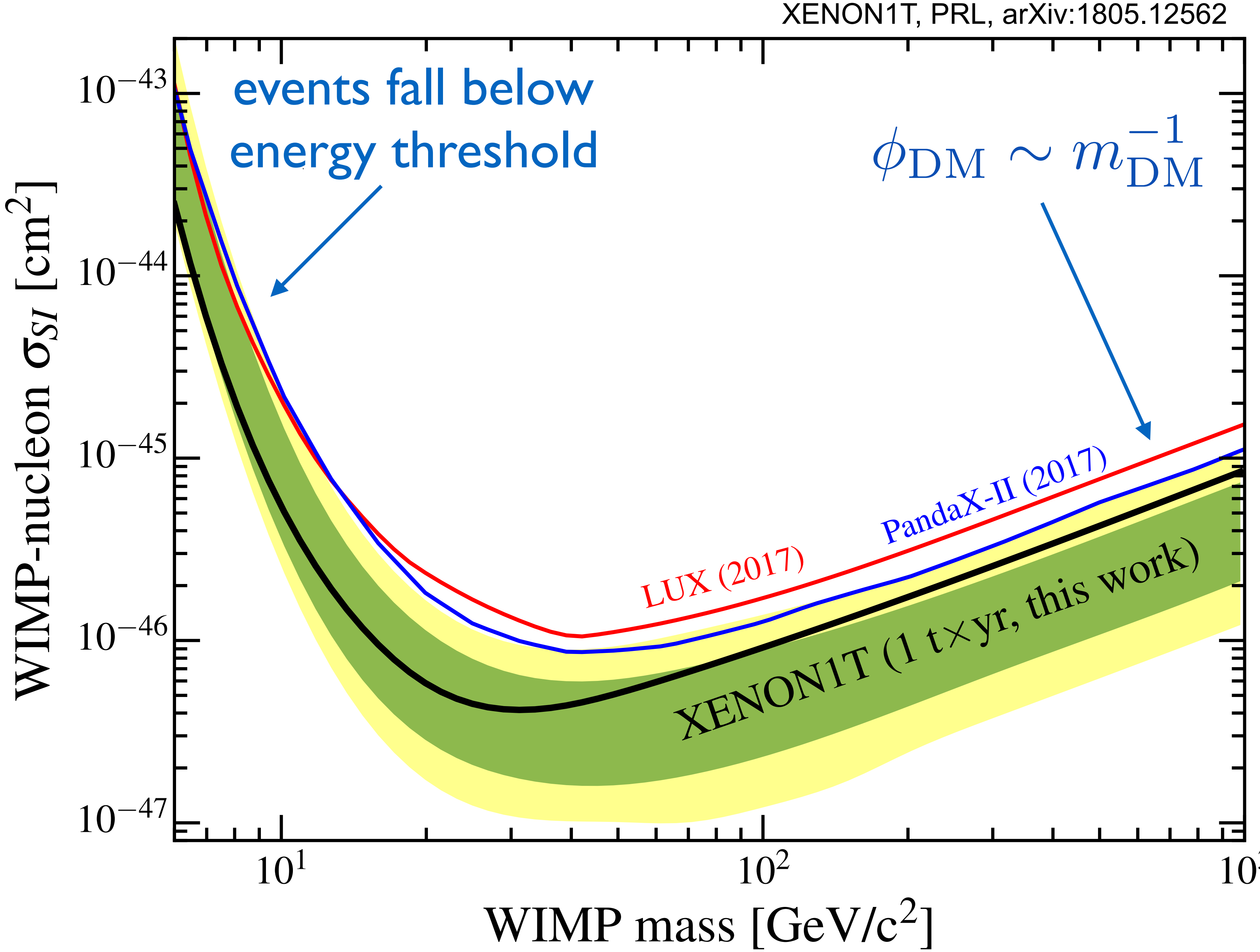
Event rate = DM flux $\times$ *particle physics*

Need to accurately model the DM flux to accurately predict signals

Searching for dark matter

Nuclear recoils: WIMPs to Planck scale relics

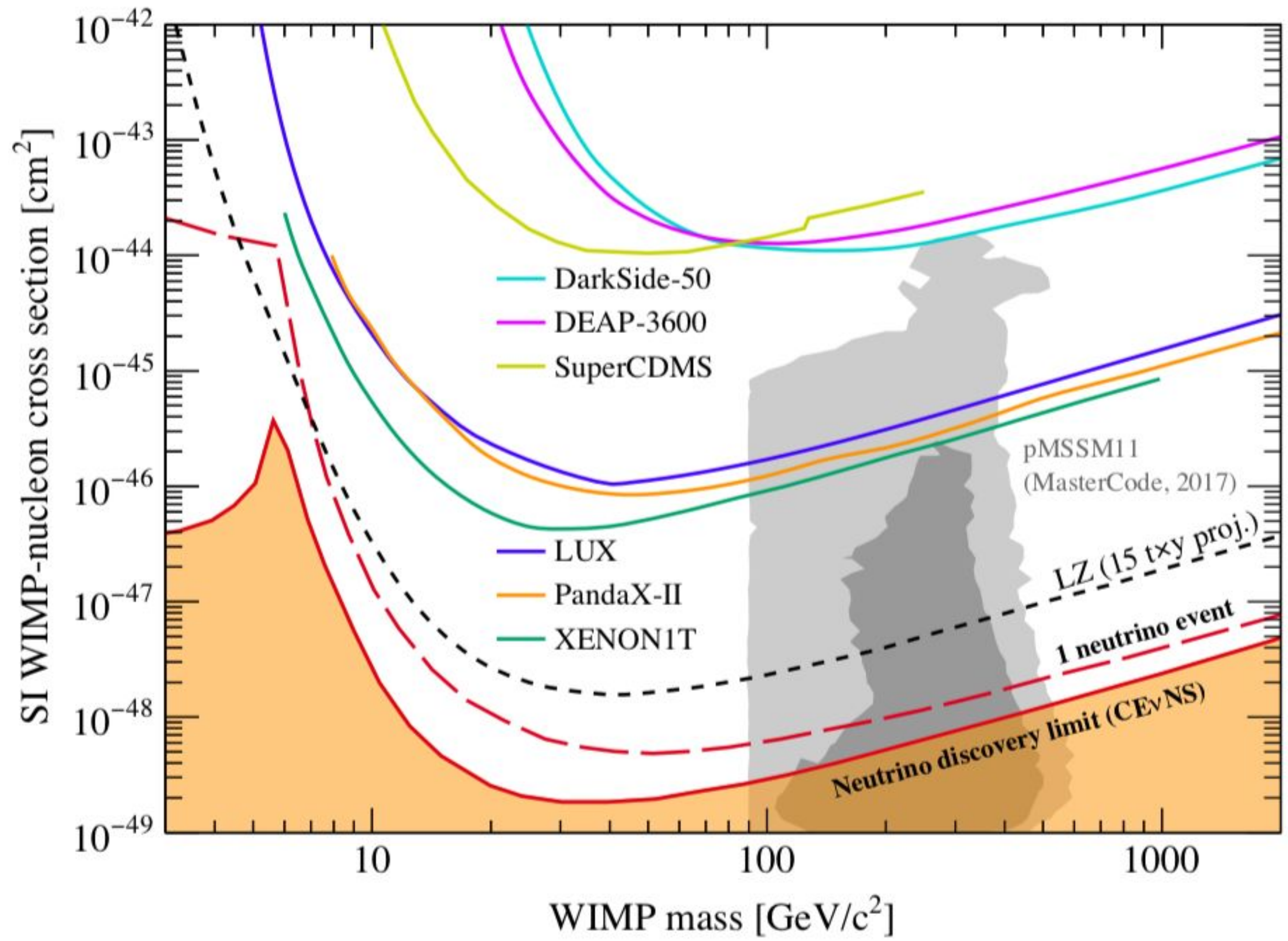
Nuclear recoils: standard WIMP searches

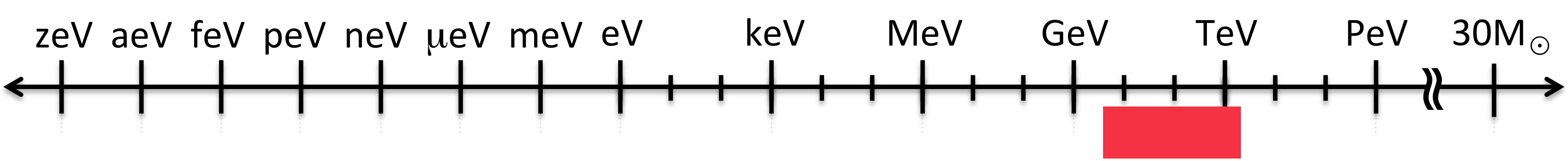


xenon-based experiments

Nuclear recoils: standard WIMP searches

The search for WIMPs continues…



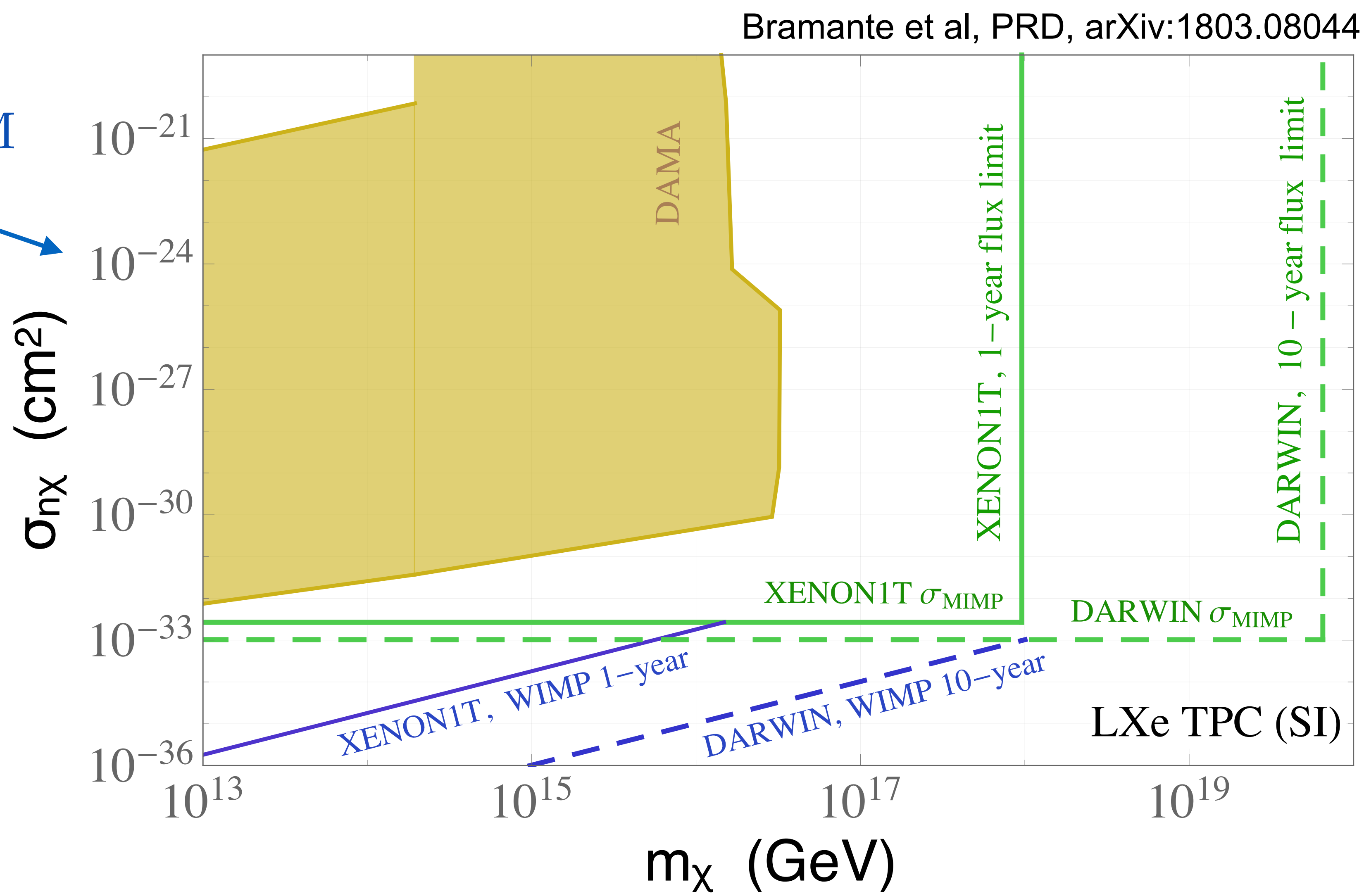


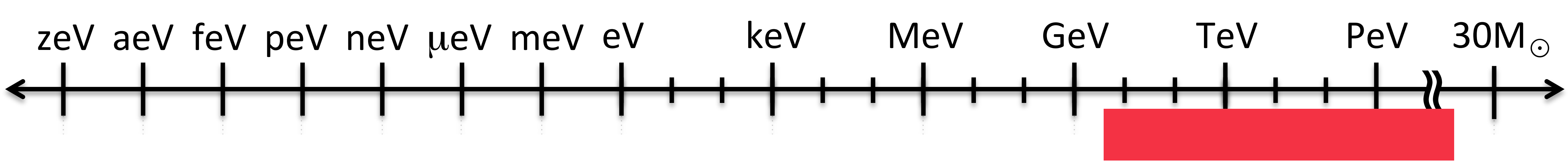
…what happens outside of this normal WIMP mass range?

Nuclear recoils: above the normal WIMP range

Xenon detectors can probe all the way to the Planck scale masses

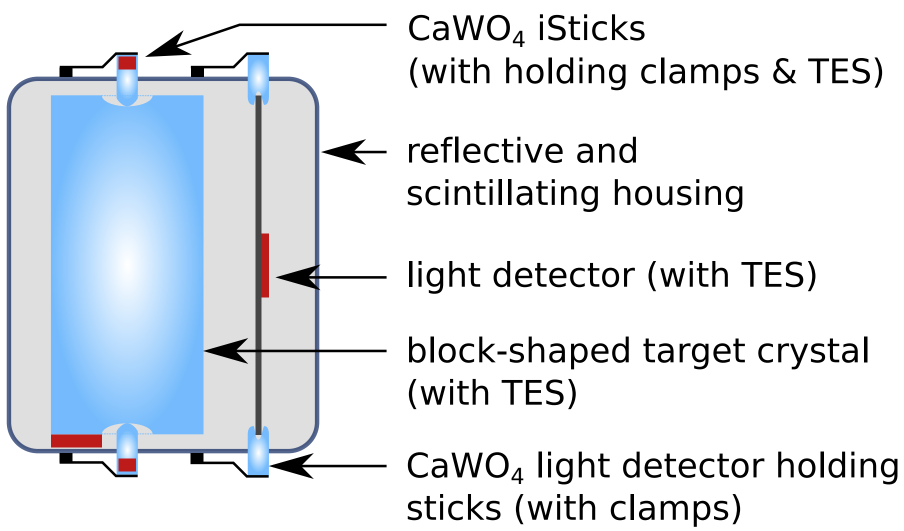
$\phi_{\rm DM} \sim m_{\rm DM}^{-1}$





Nuclear recoils: below the normal WIMP range

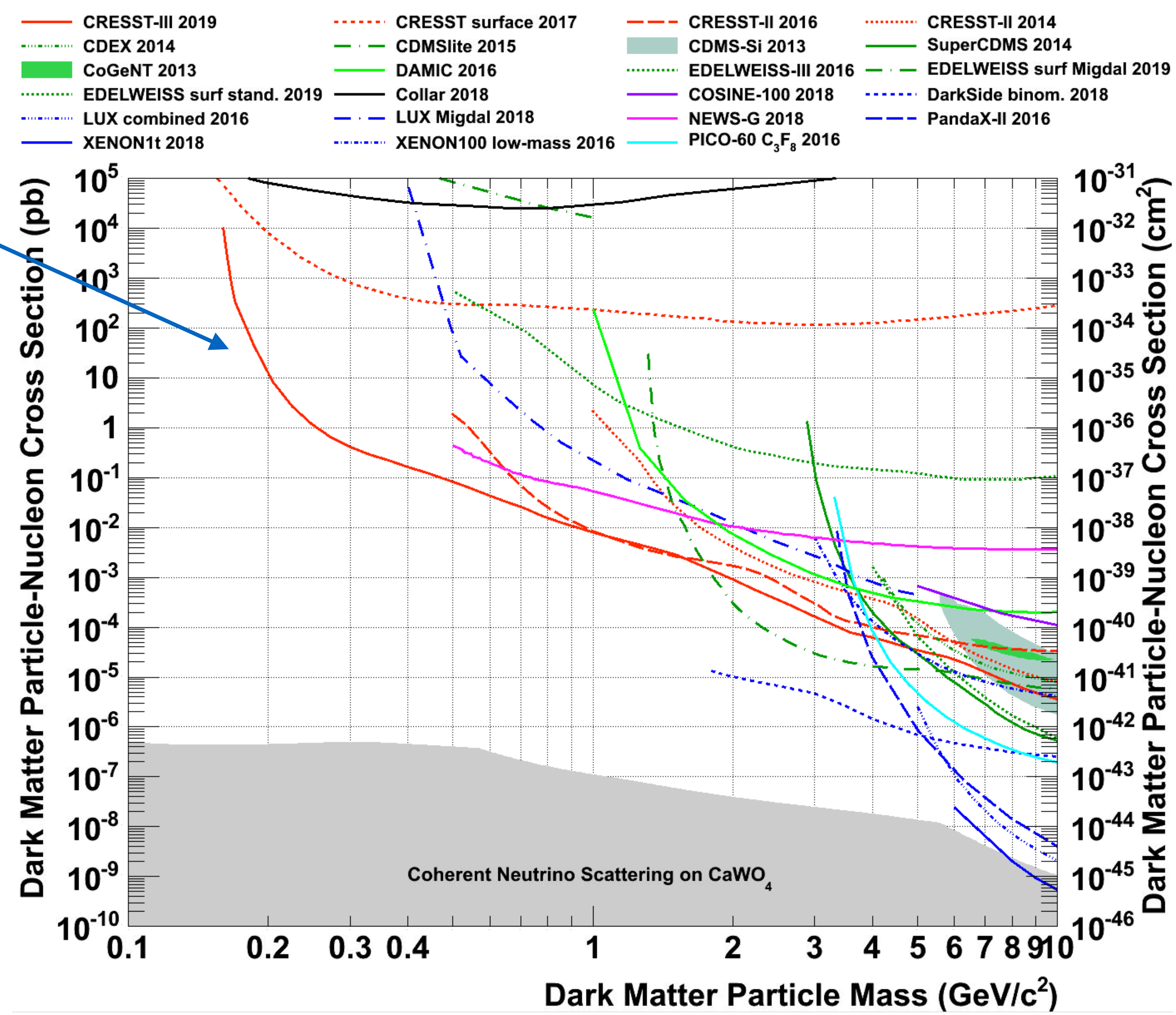
CRESST-III



Detector mass: 24 grams

Detector threshold: 30 eV

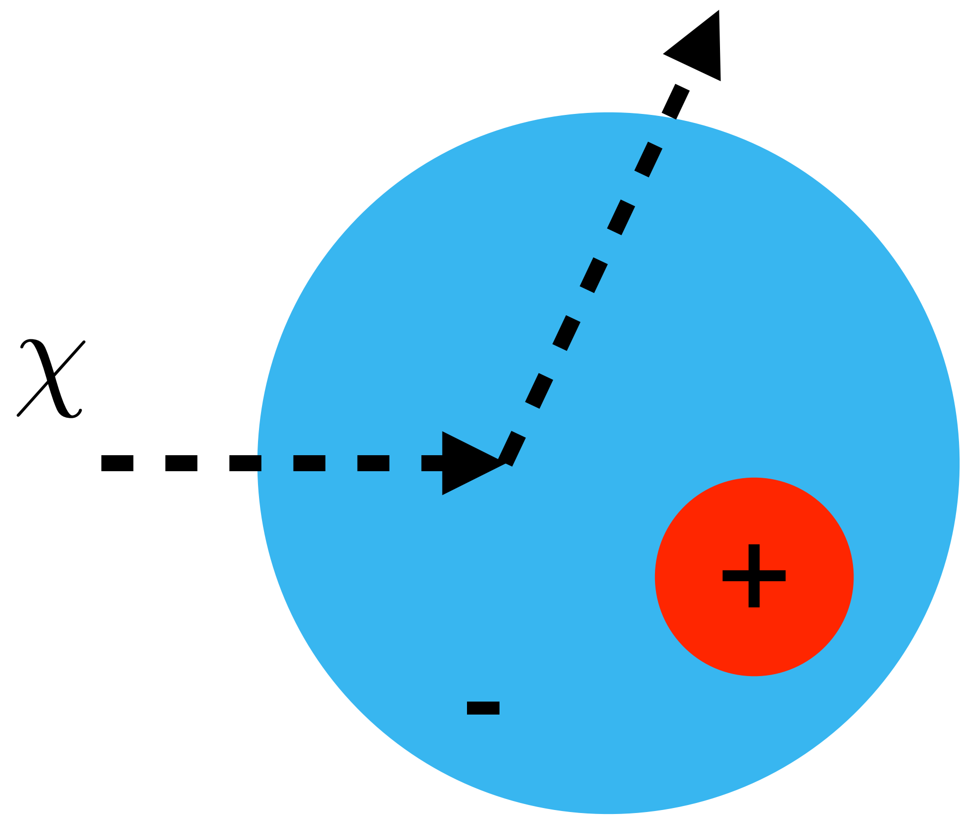
CRESST-III, arXiv:1904.00498



Beyond nuclear recoils: Migdal effect

Emission from the recoiling atom

sub-GeV dark matter in xenon:



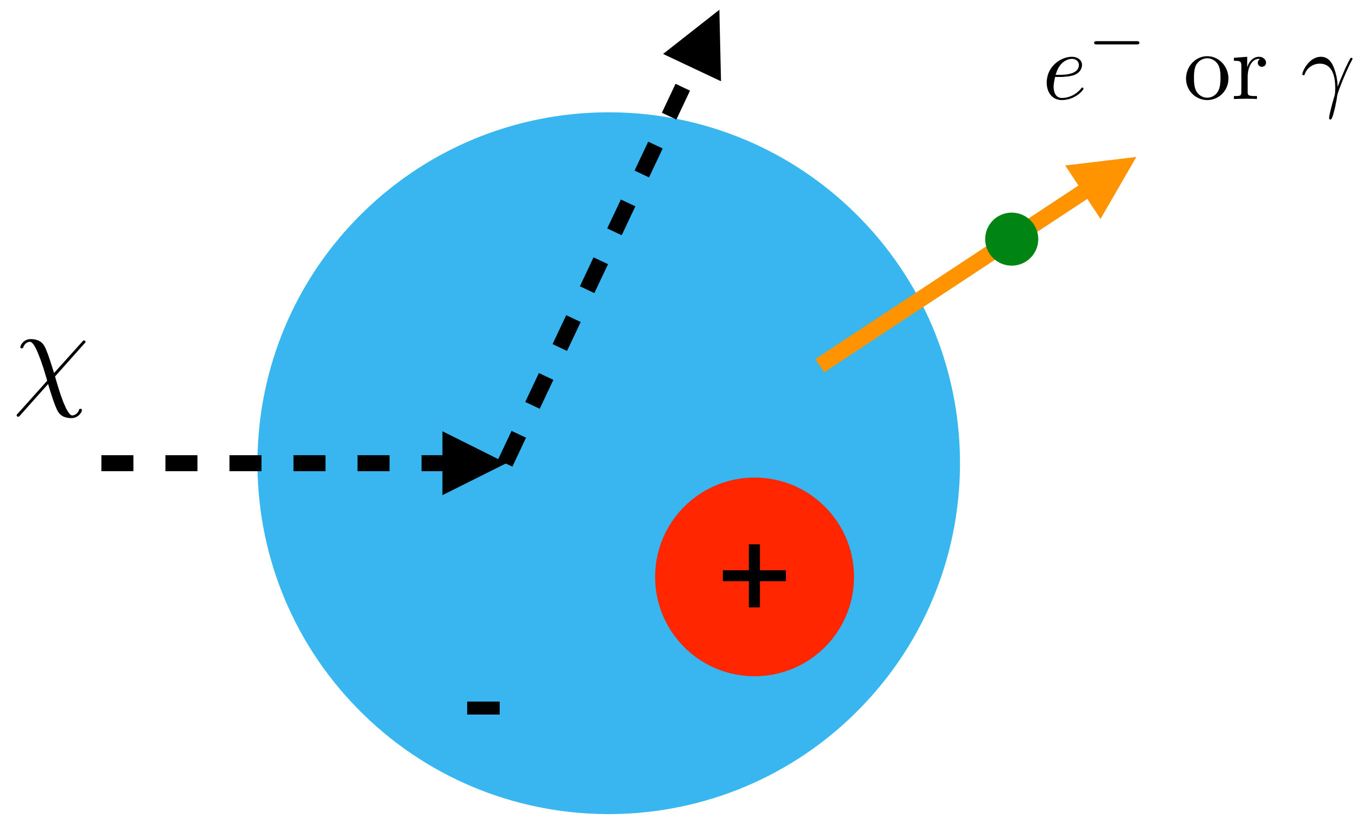
nucleus gets a nudge

$$E_{\rm recoil} \lesssim 0.1~{\rm keV}$$

nuclear recoil below energy threshold

Emission from the recoiling atom

sub-GeV dark matter in xenon:



nucleus gets a nudge

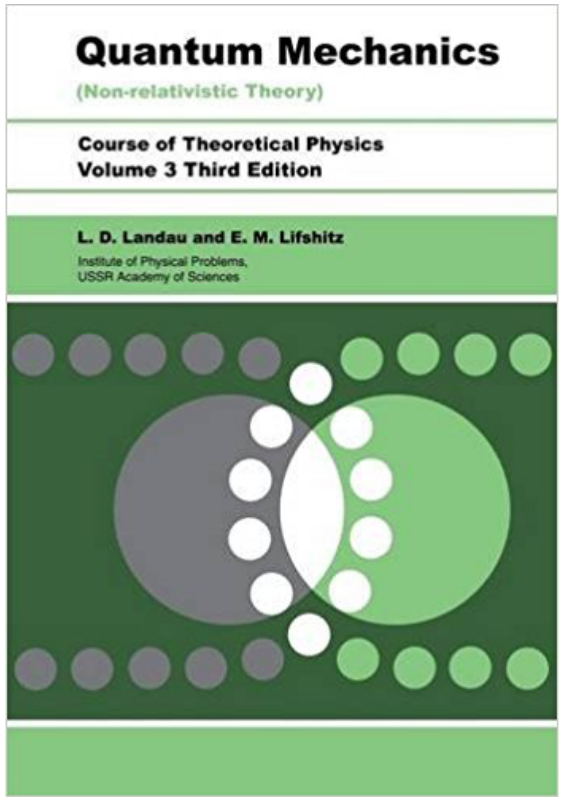
$$E_{\text{recoil}} \lesssim 0.1 \text{ keV}$$

nuclear recoil below energy threshold

...but electrons and photons can be emitted from the atom

Migdal 1939

Electron emission: Migdal effect

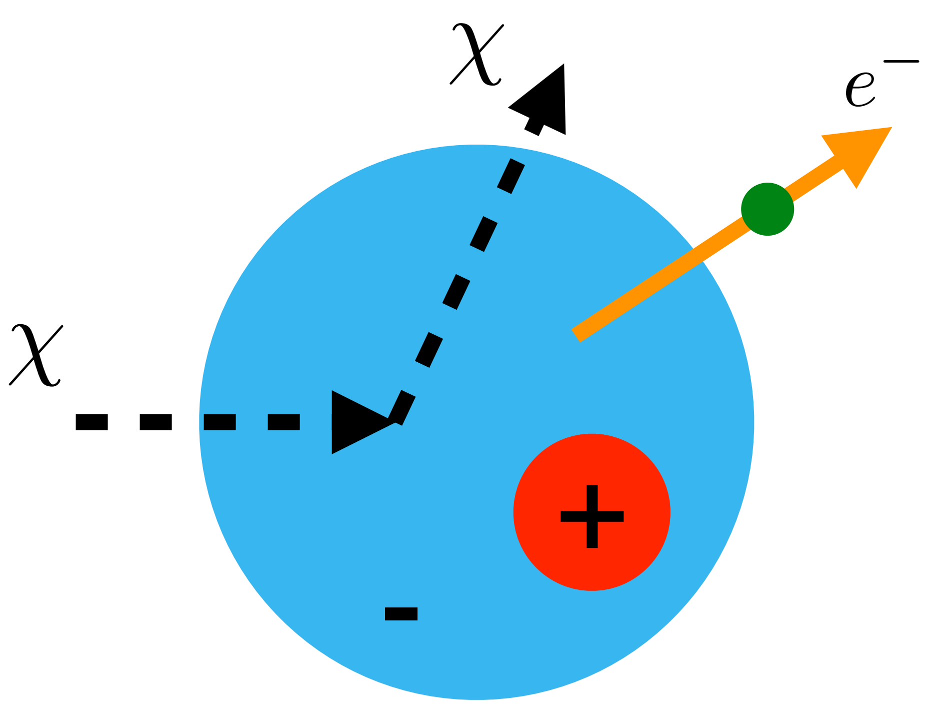


PROBLEM 2. The nucleus of an atom in the normal state receives an impulse which gives it a velocity v; the duration τ of the impulse is assumed short in comparison both with the electron periods and with a/v, where a is the dimension of the atom. Determine the probability of excitation of the atom under the influence of such a "jolt" (A. B. MIGDAL 1939).

SOLUTION. We use a frame of reference K' moving with the nucleus after the impact. By virtue of the condition $\tau \ll a/v$, the nucleus may be regarded as practically stationary during the impact, so that the co-ordinates of the electrons in K' and in the original frame K immediately after the perturbation are the same. The initial wave function in K' is

$$\psi_0' = \psi_0 \exp(-i\mathbf{q} \cdot \sum_a \mathbf{r}_a), \qquad \mathbf{q} = m\mathbf{v}/\hbar,$$

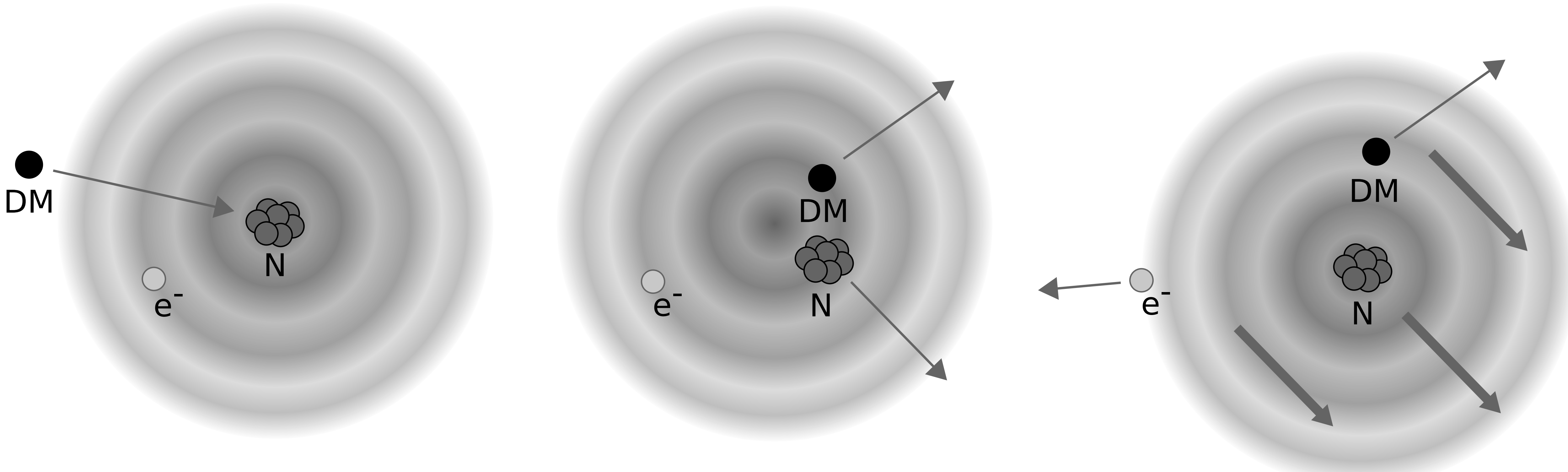
where ψ_0 is the wave function of the normal state with the nucleus at rest, and the summation



Atom emits an electron (Migdal effect)

Ibe, Nakano, Shoji, Suzuki, JHEP, arXiv:1707.07258
Dolan, Kahlhoefer, CM, PRL, arXiv:1711.09906

Migdal effect: updated treatment

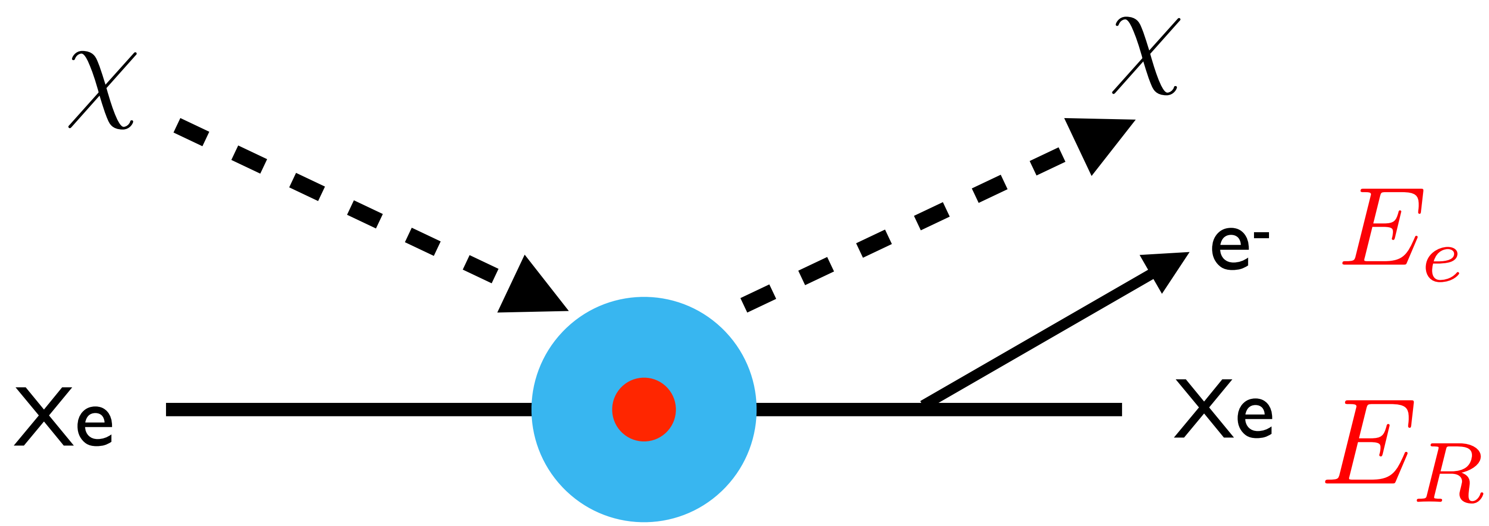


$$|\Phi_{ec}\rangle \qquad |\Phi'_{ec}\rangle = e^{-im_e \sum_i \mathbf{v}\cdot\hat{\mathbf{x}}_i}|\Phi_{ec}\rangle \qquad \mathcal{P} = \left|\langle\Phi^*_{ec}|\Phi'_{ec}\rangle\right|^2$$

"…it takes some time for the electrons to catch up, which causes ionisation of the atom."

Ibe, Nakano, Shoji, Suzuki, JHEP, arXiv:1707.07258
Dolan, Kahlhoefer, CM, PRL, arXiv:1711.09906

Electron emission: Migdal effect



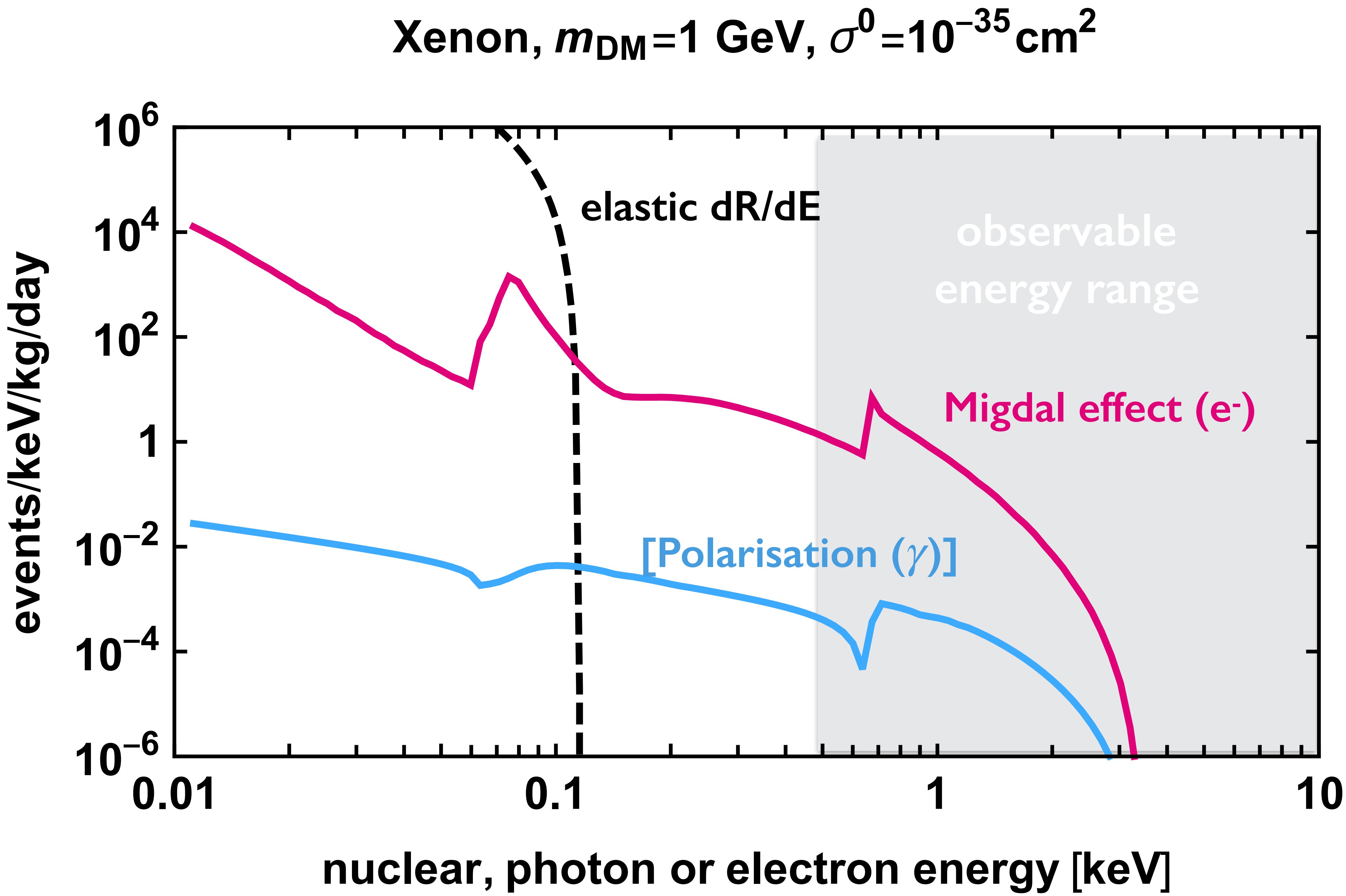
$$\frac{d^2\sigma}{dE_R\,dE_e} = |Z_{\rm ion}(E_e, E_R)|^2 \times \frac{d\sigma}{dE_R}$$

Usual 2->2 cross section

'atomic form factor' ~ $\mathcal{P} = |\,\langle \Phi^*_{ec} | \Phi'_{ec} \rangle\,|^2 \sim 10^{-3}$

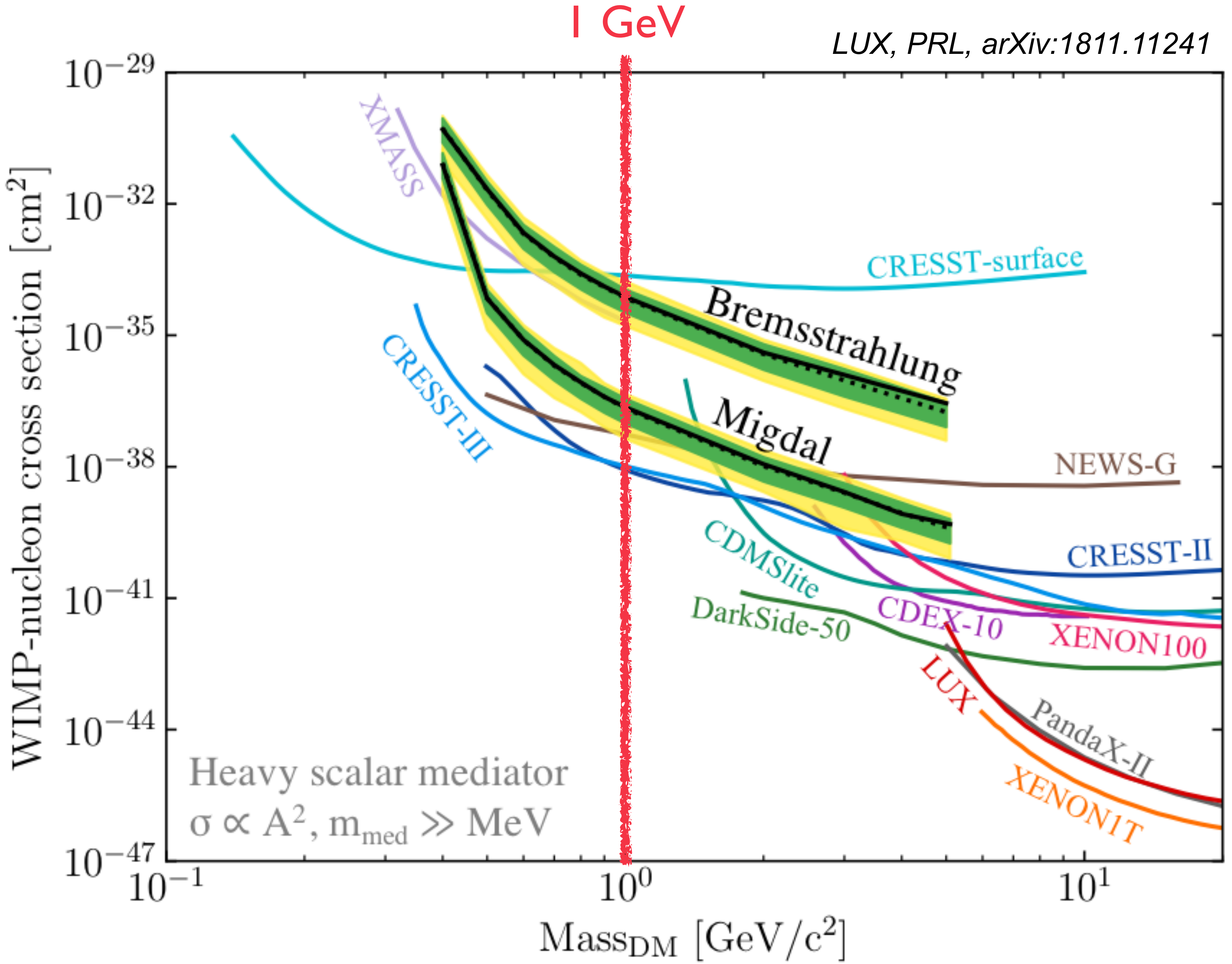
Calculated in Ibe, Nakano, Shoji, Suzuki, JHEP, arXiv:1707.07258 for different elements

sub-GeV DM signals in xenon

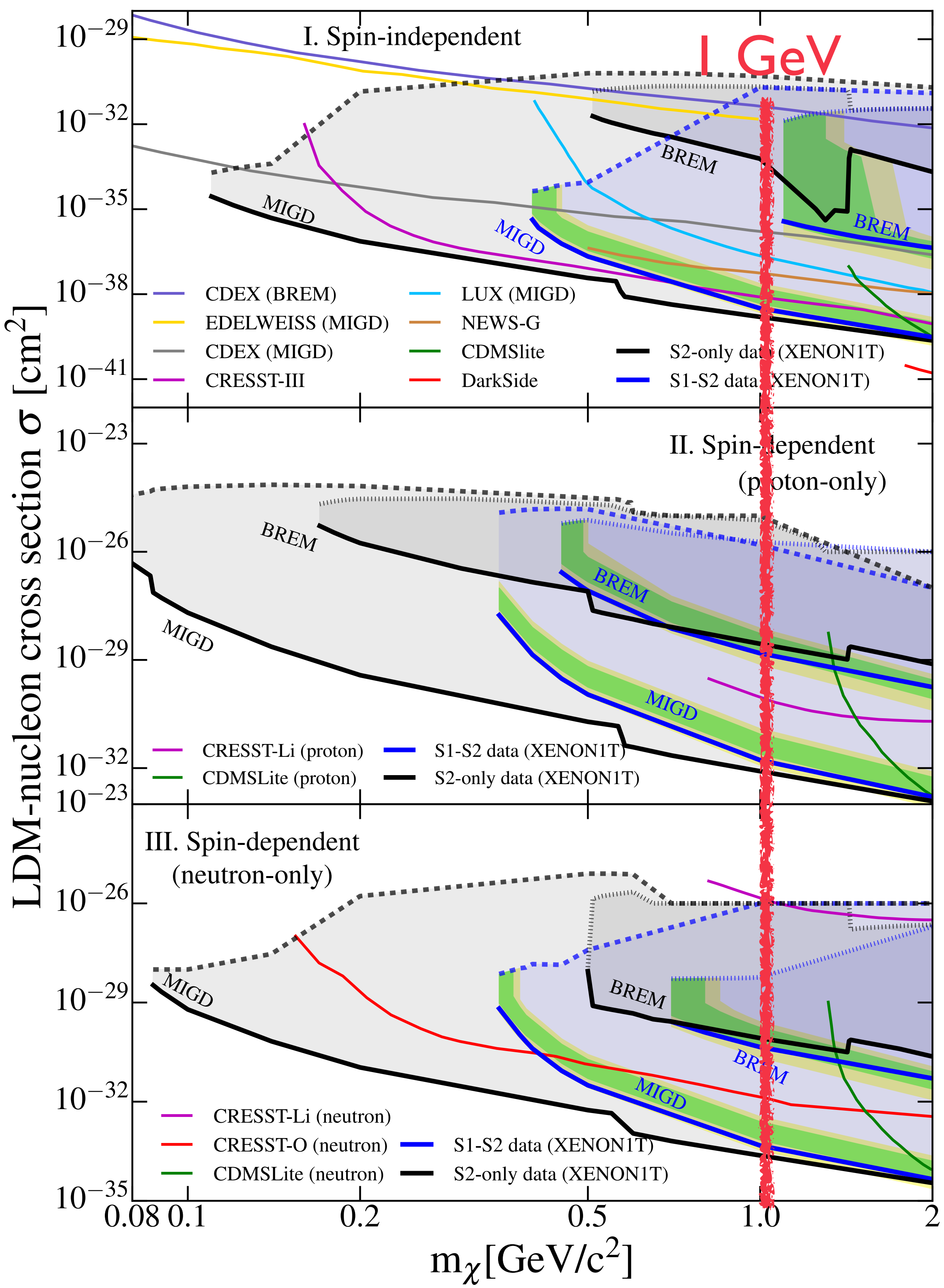


Migdal electrons observable even for $m_{\rm DM} \lesssim 1$ GeV

LUX (Xe) sensitive below 1 GeV

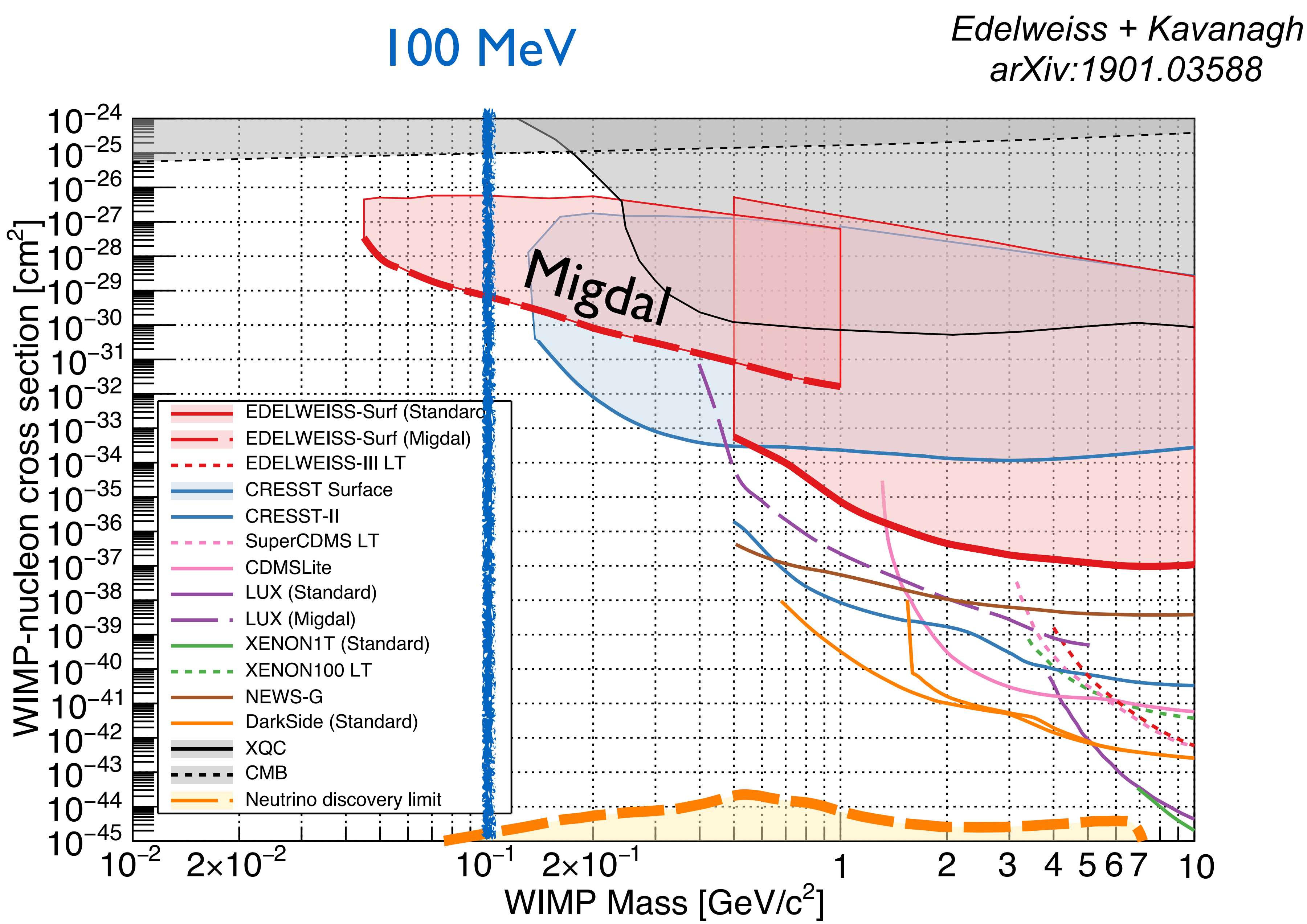


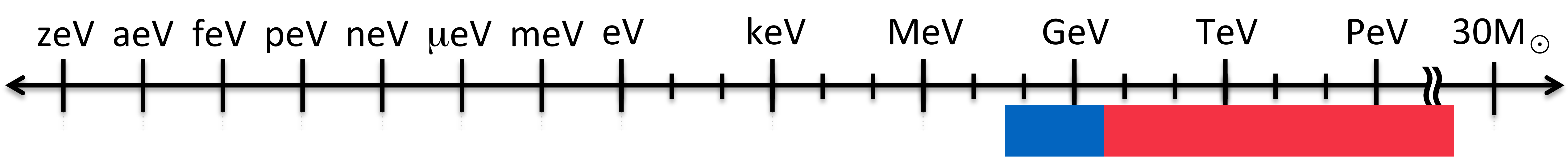
XENON1T sensitive below 1 GeV



XE1T, PRL, arXiv:1907.12771

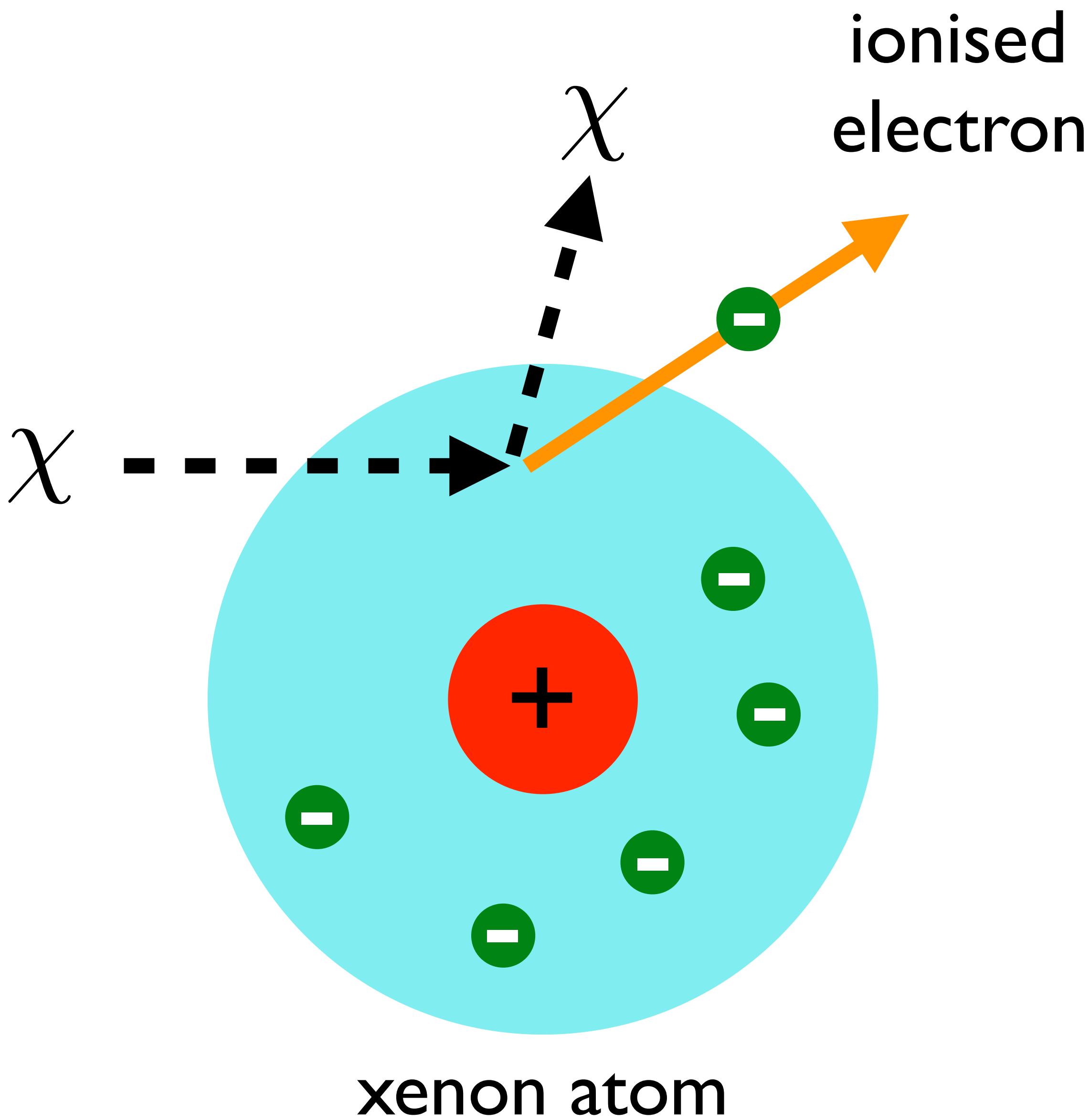
Edelweiss (Ge) sensitive below 100 MeV





Beyond nuclear recoils: electron scattering

Electron-ionisation in atoms



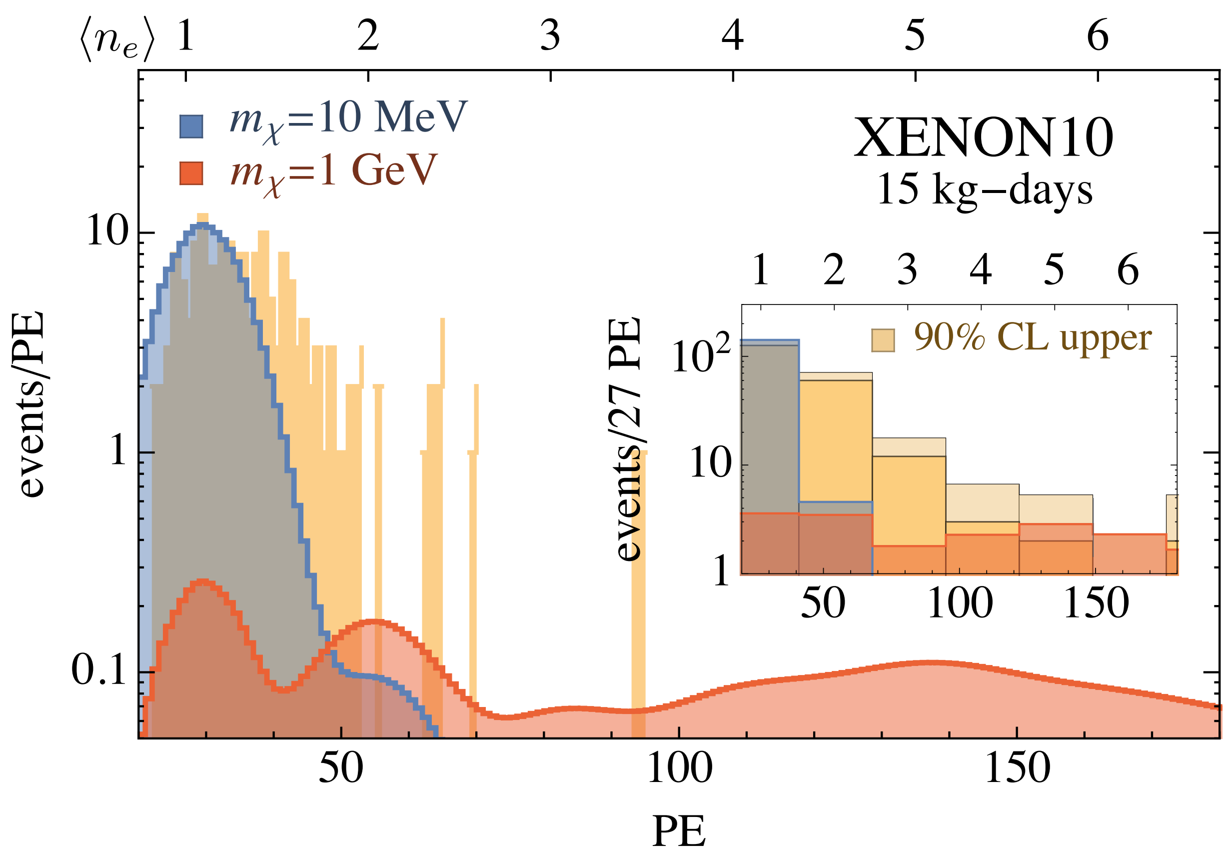
For ionisation, require:

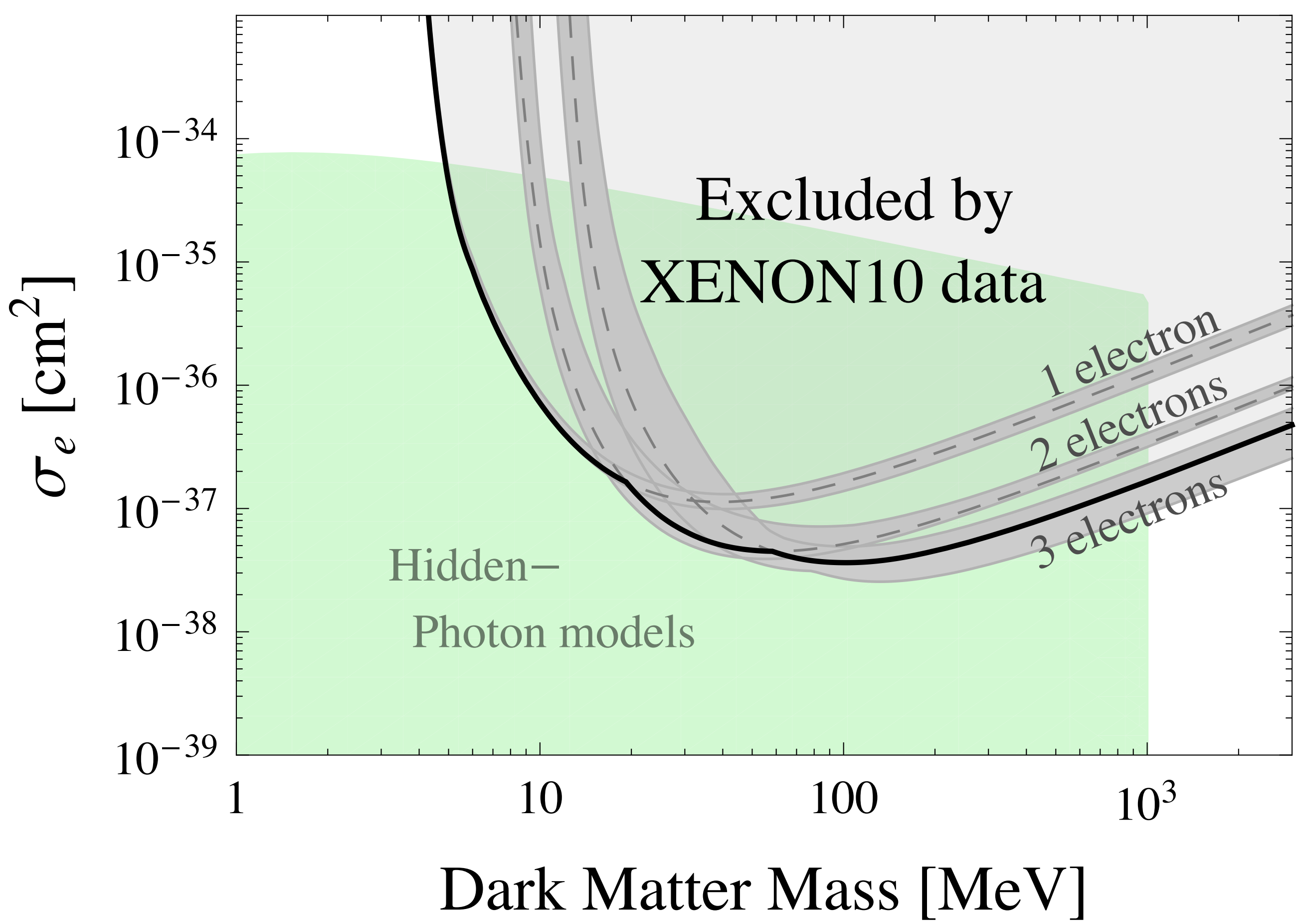
$$\frac{1}{2}m_{\rm DM}v_{\rm DM}^2 \gtrsim E_{\rm binding}(\sim 12~{\rm eV})$$

$$m_{\rm DM} \gtrsim 5~{\rm MeV}$$

Xenon electron-ionisation constraints

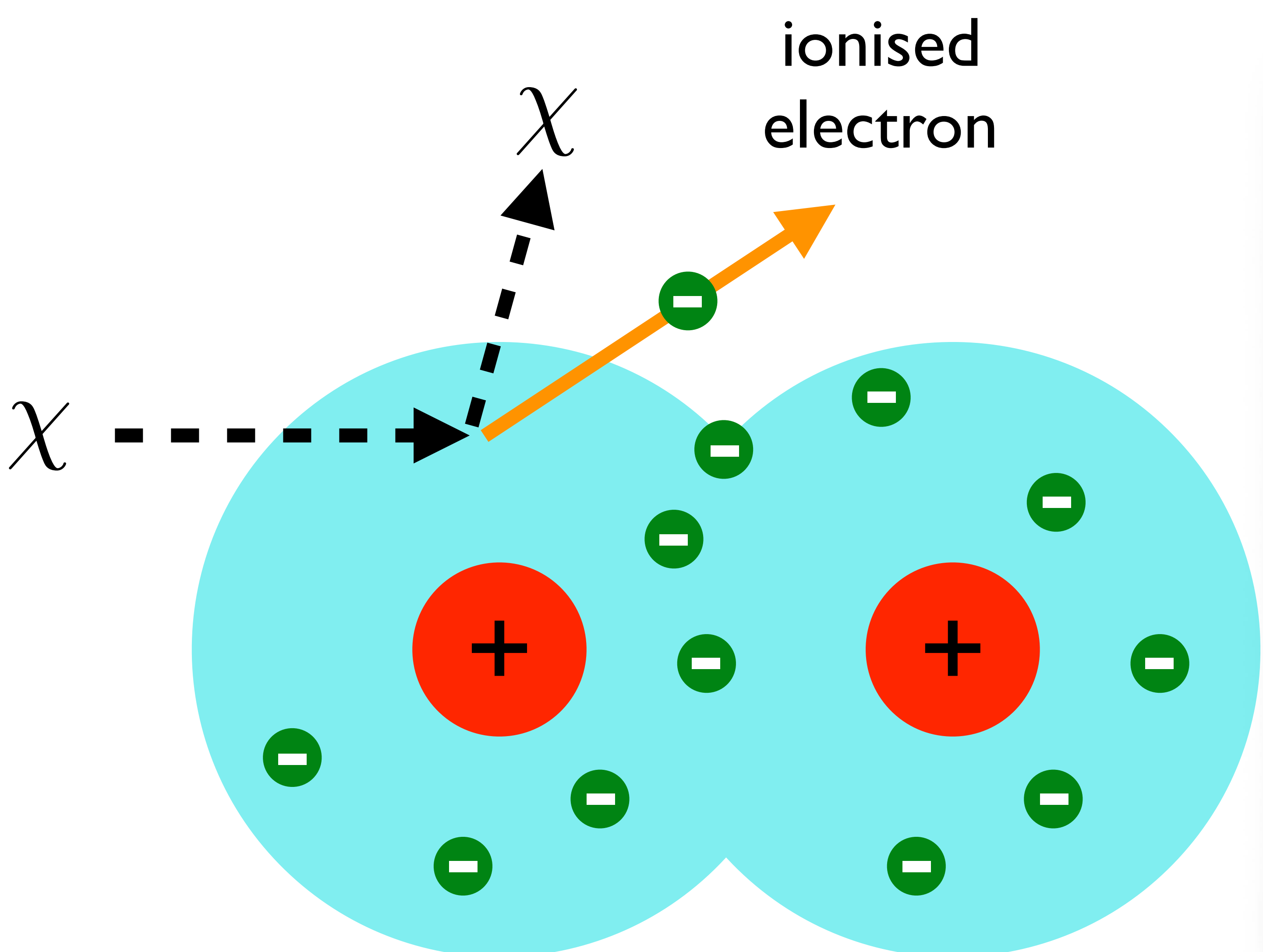
- ZEPLIN, XENON10 & XENON100 can measure single electrons (S2 only)
- *Also possible in argon (e.g. DarkSide-50)*





Essig et al, PRL, arXiv:1206.2644
Essig et al, PRD, arXiv:1703.00910

Electron ionisation in semi-conductors



For ionisation, require:

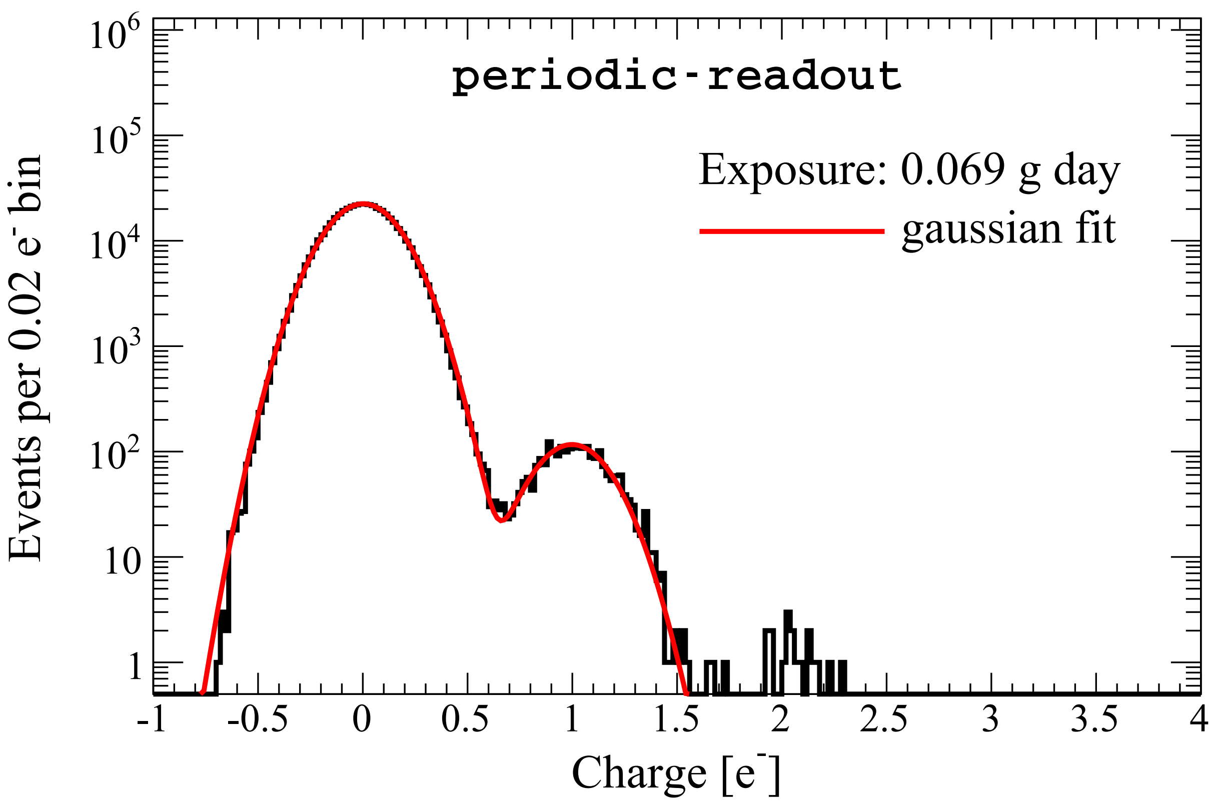
$$\frac{1}{2} m_{\rm DM} v_{\rm DM}^2 \gtrsim E_{\rm binding}$$

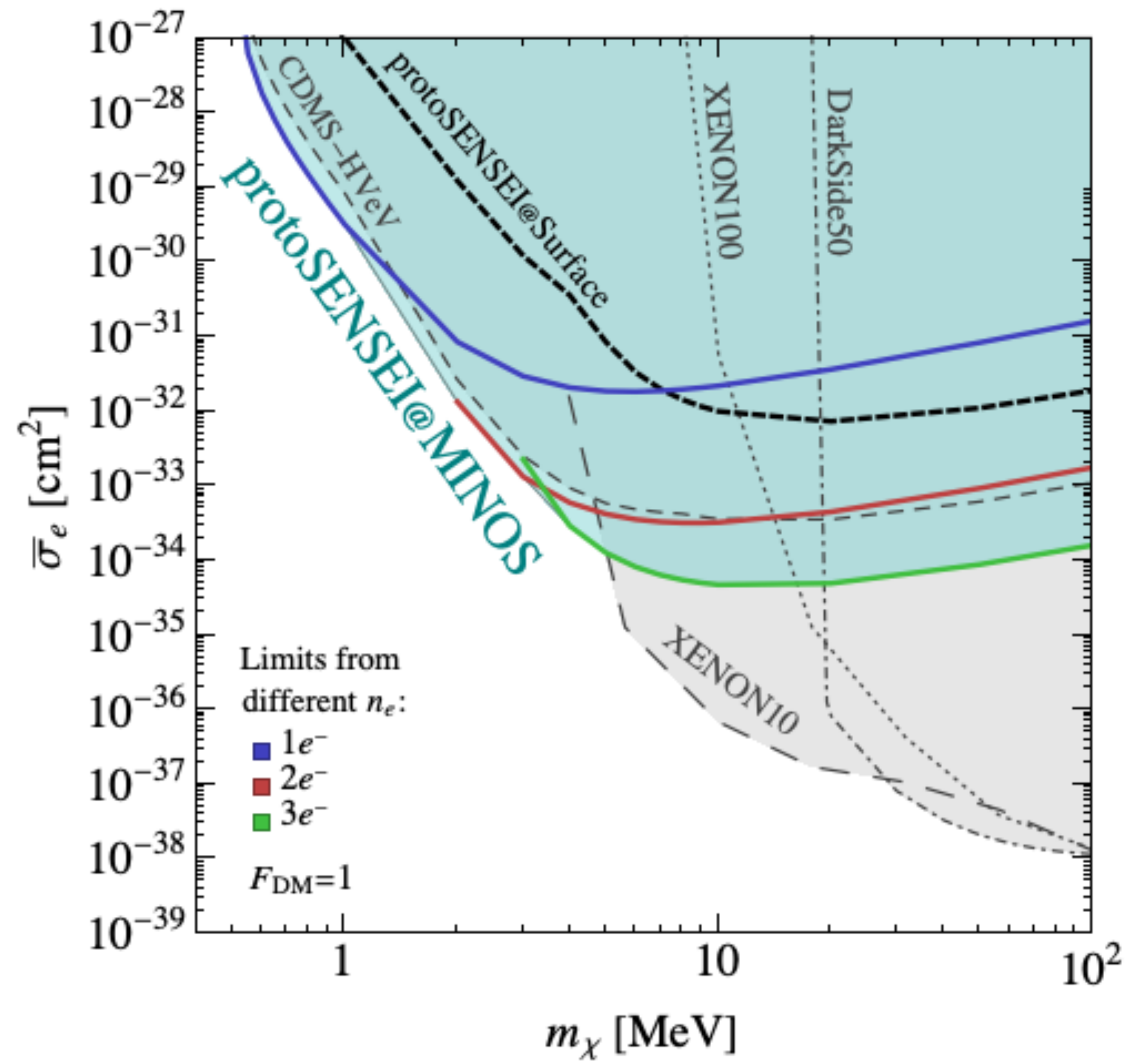
$$E_{\rm binding}^{\rm semi\text{-}conduct} \sim 1~{\rm eV}$$

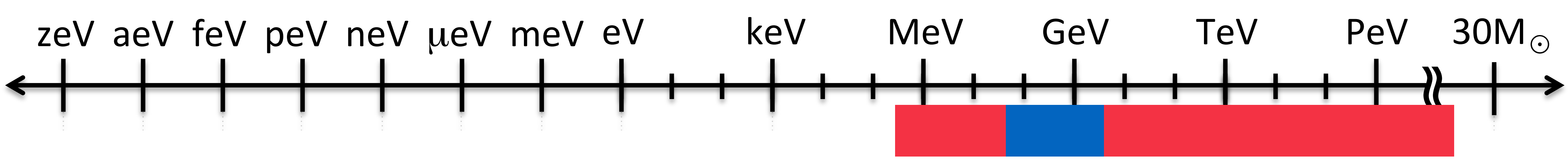
$$m_{\rm DM} \gtrsim 0.5~{\rm MeV}$$

Electron ionisation in semi-conductors

SENSEI, PRL, arXiv:1901.10478



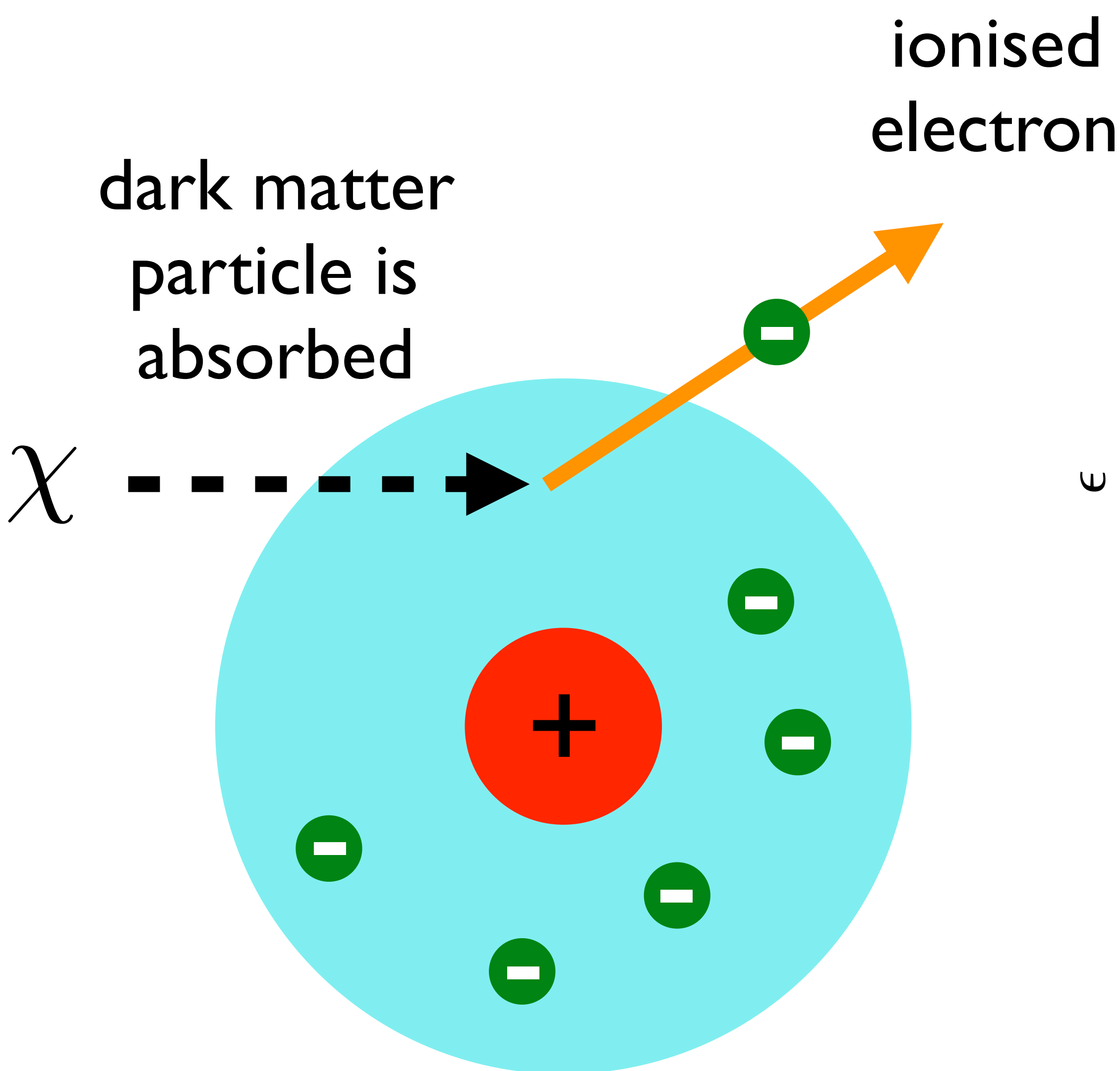




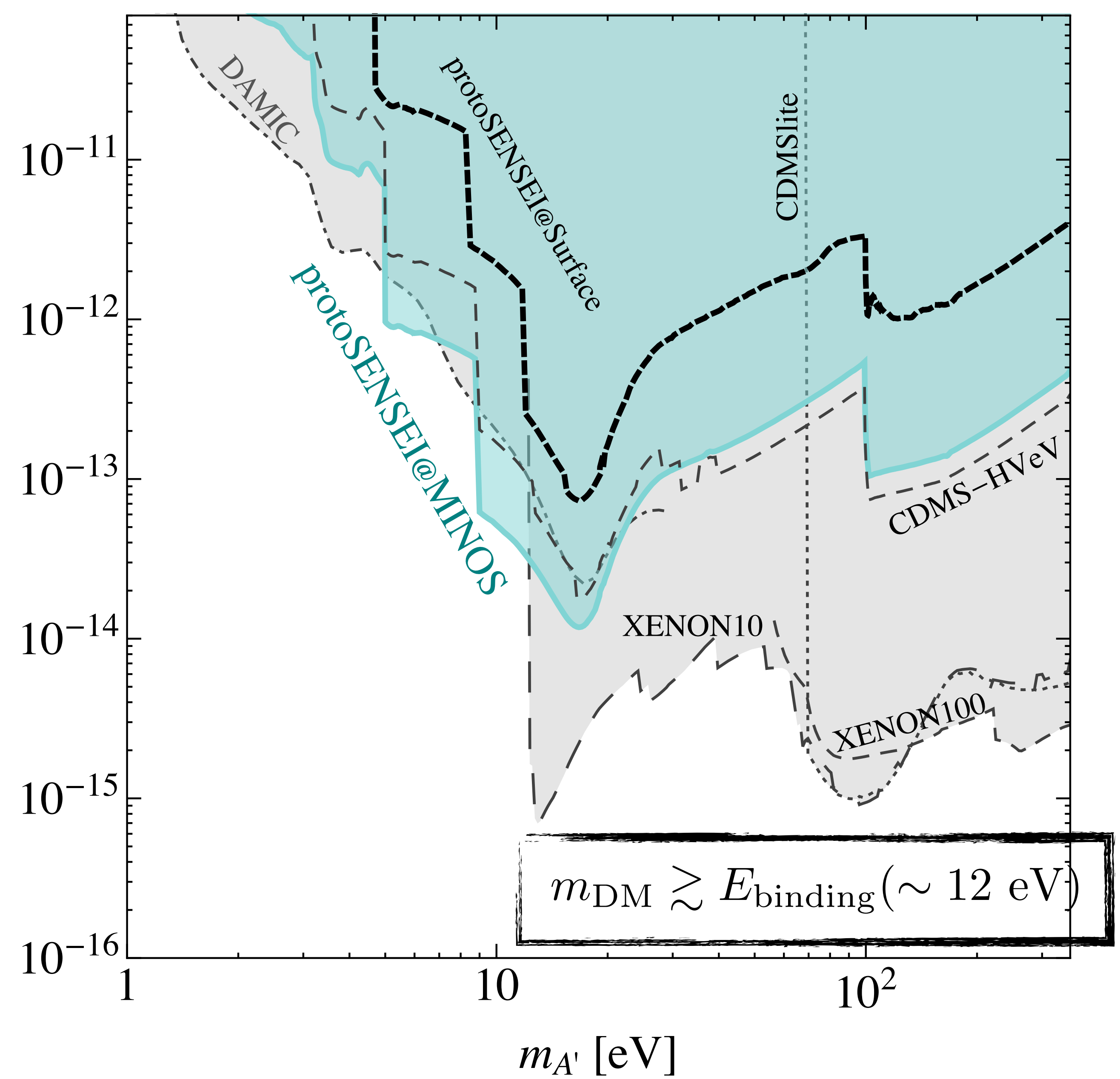
Beyond electron scattering: Dark matter absorption

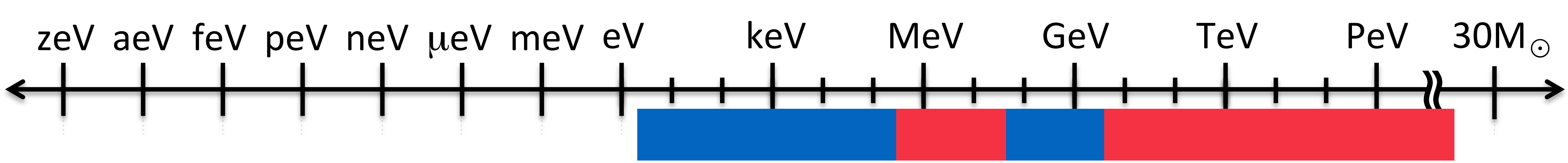
Dark matter absorption

$$\mathcal{L} \supset V_\mu \bar{\psi}_e \gamma^\mu \psi_e \text{ or } A \bar{\psi}_e \gamma^5 \psi_e$$

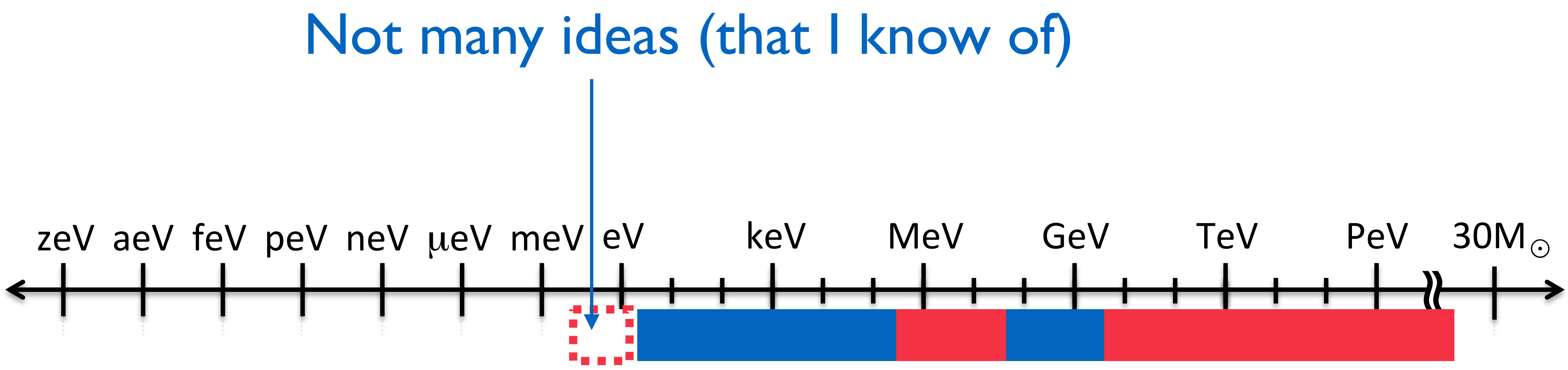


SENSEI, PRL, arXiv:1901.10478





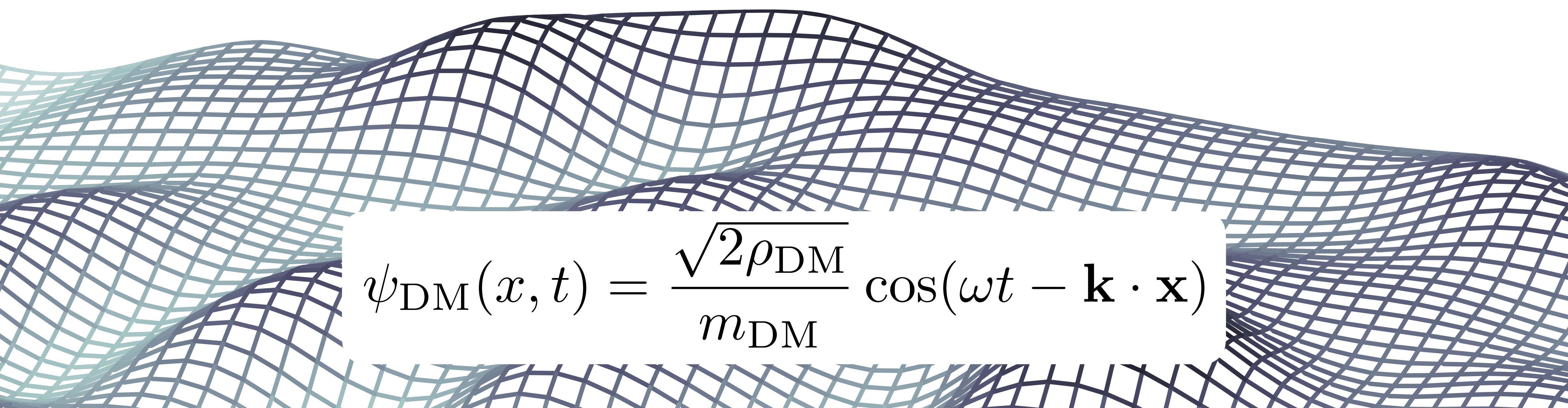
Mind the gap…


Not many ideas (that I know of)
zeV
aeV
feV
peV
neV
μeV
meV
eV
keV
MeV
GeV
TeV
PeV
30M⊙

Quantum Technologies for Fundamental Physics (QTFP) Programme

STFC and EPSRC invite applications for research consortia to apply for funding as part of the Quantum Technologies for Fundamental Physics (QTFP) programme. This is a new programme which, building on the investments of the National Quantum Technology Programme, aims to demonstrate how the application of quantum technologies will advance the understanding of fundamental physics questions.

Dark matter as a wave: axions



$$\psi_{\rm DM}(x,t) = \frac{\sqrt{2\rho_{\rm DM}}}{m_{\rm DM}} \cos(\omega t - \mathbf{k}\cdot\mathbf{x})$$

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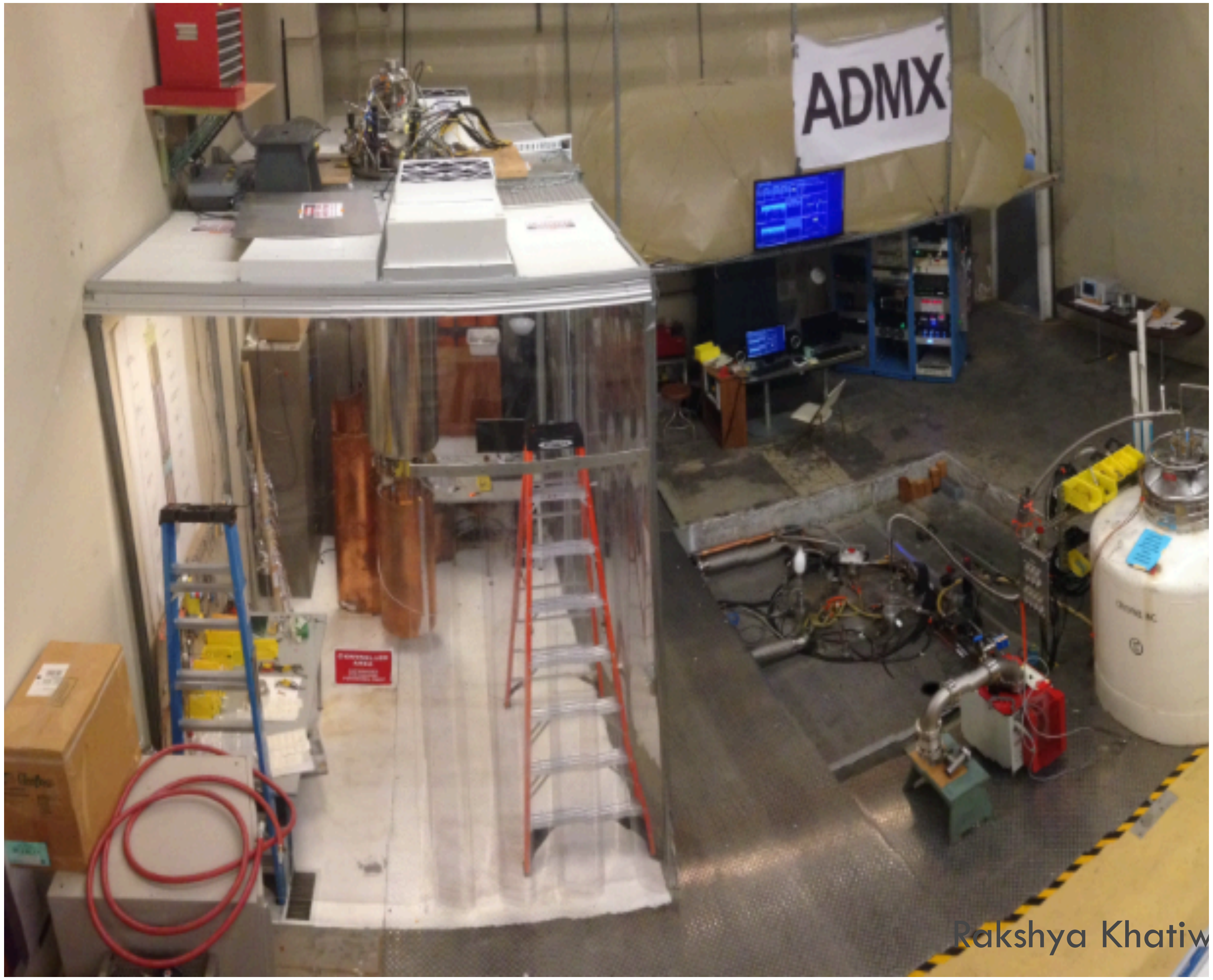
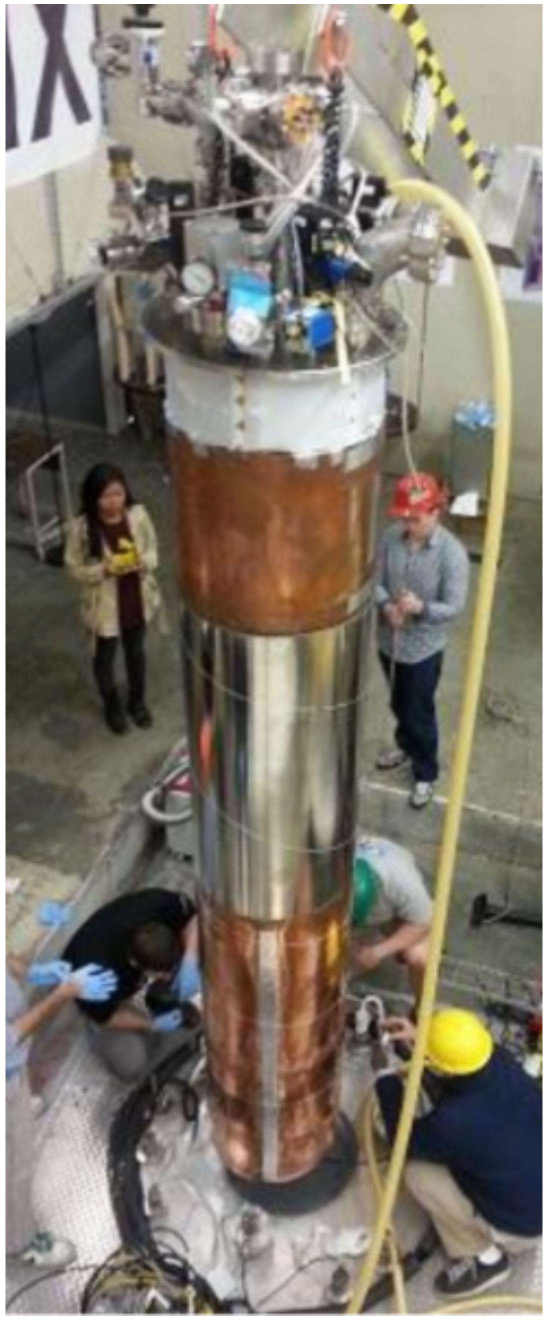
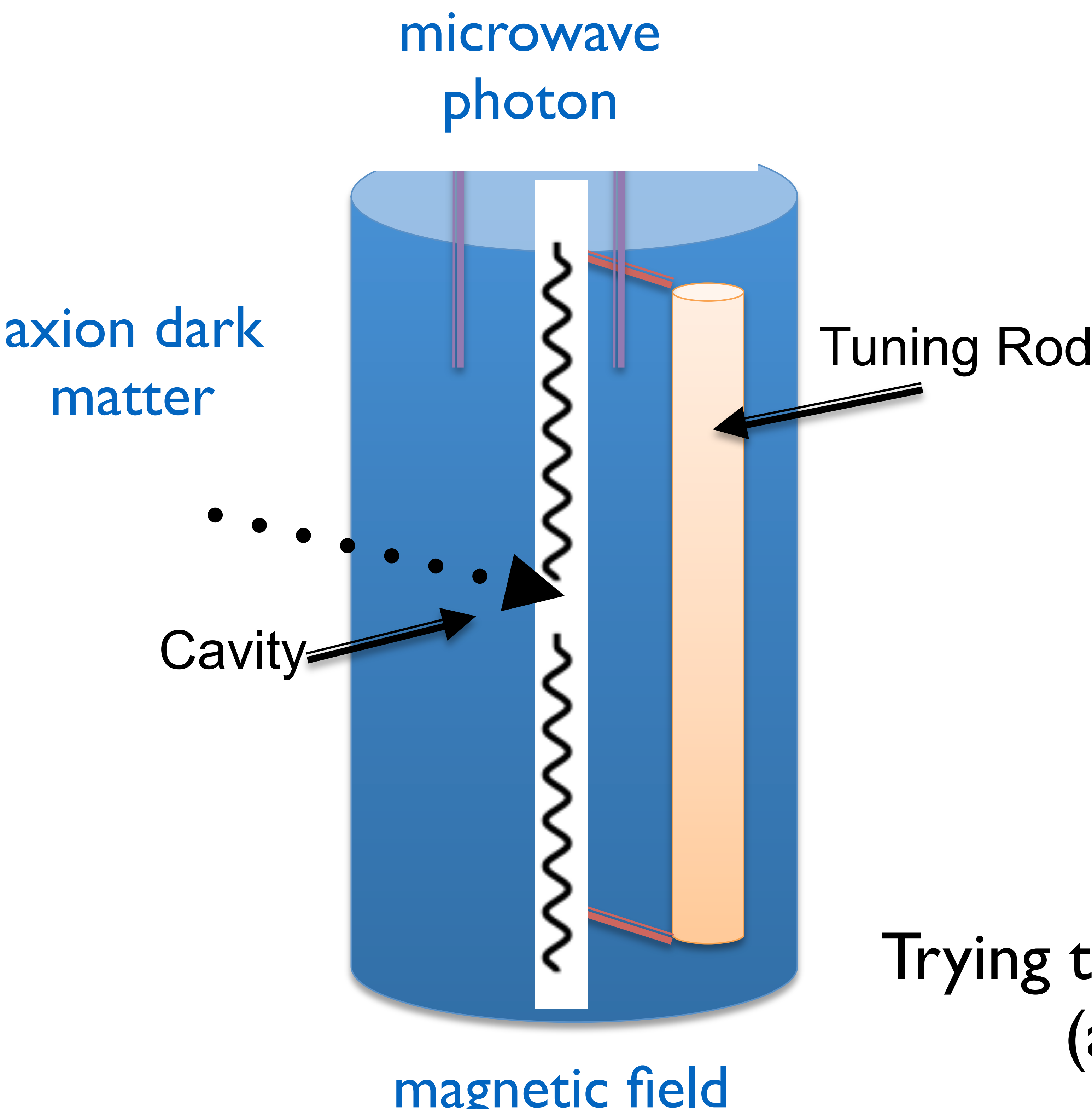
ADMX: Axion Dark Matter eXperiment





University of Sheffield + 8 USA institutions

ADMX: Axion Dark Matter eXperiment

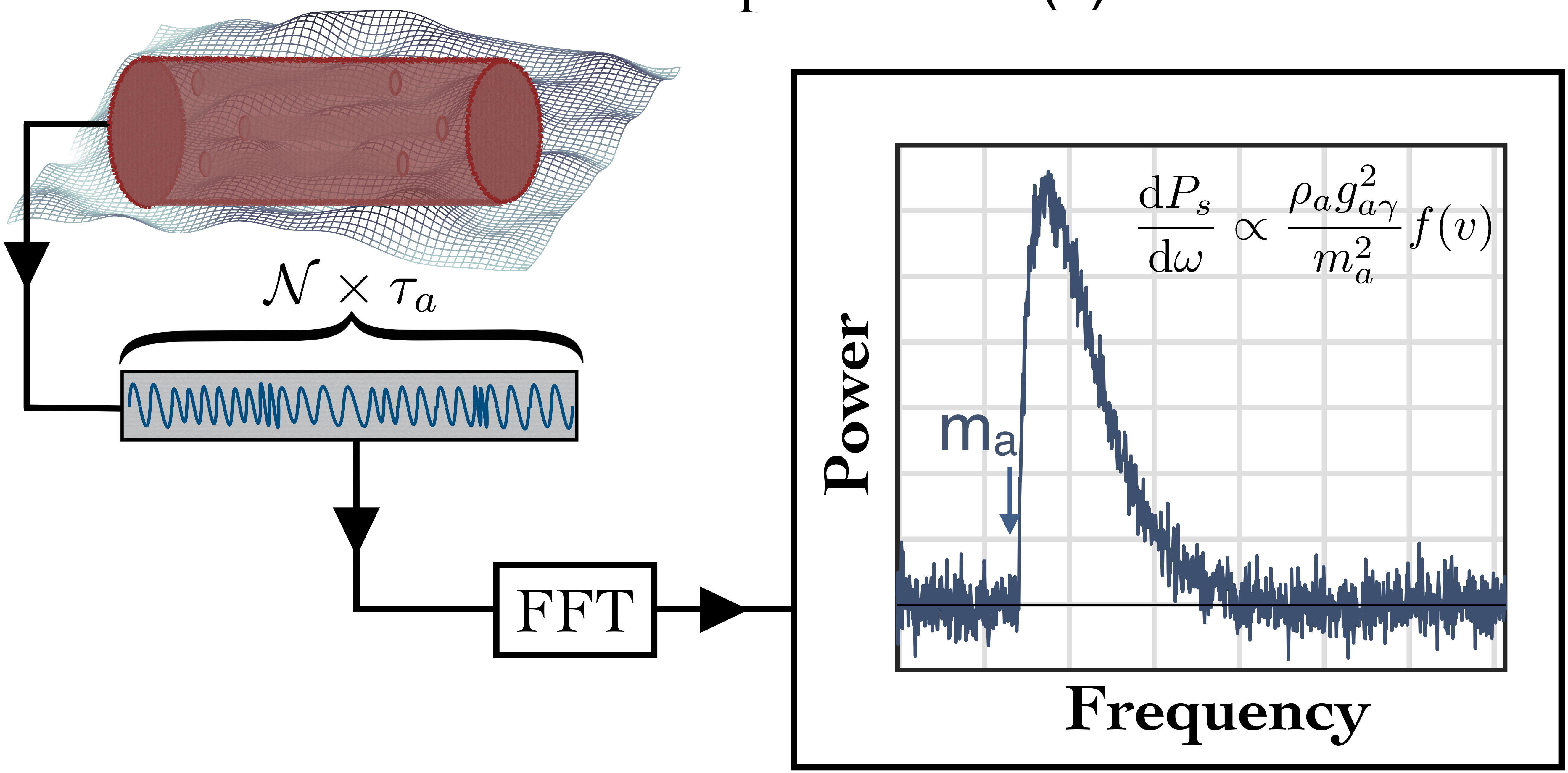


Tuneable cavity:
Trying to tune onto the axion mass
(a dark matter radio?)

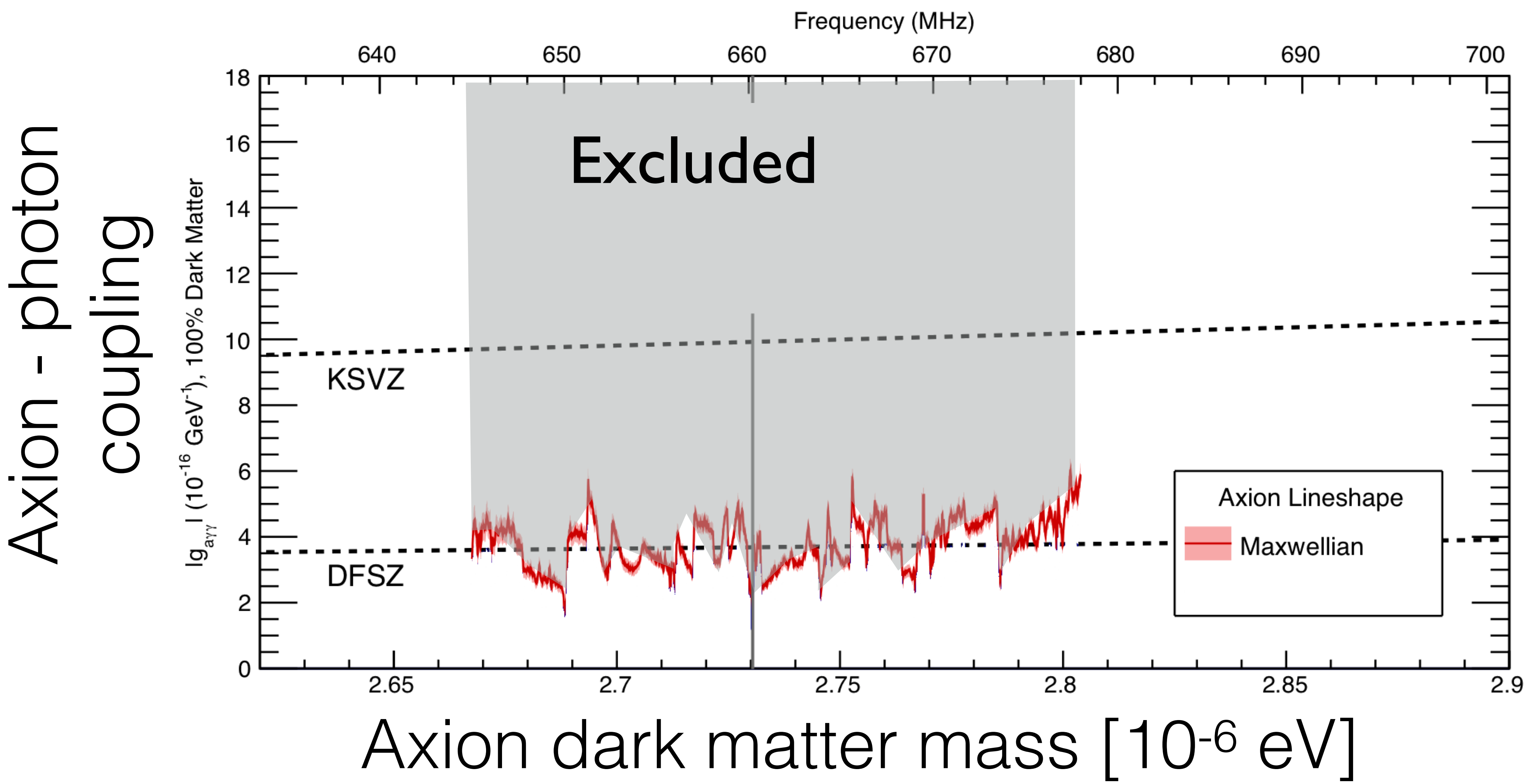
Measuring the axion distribution

Sampling axion field over many, N, coherence times:

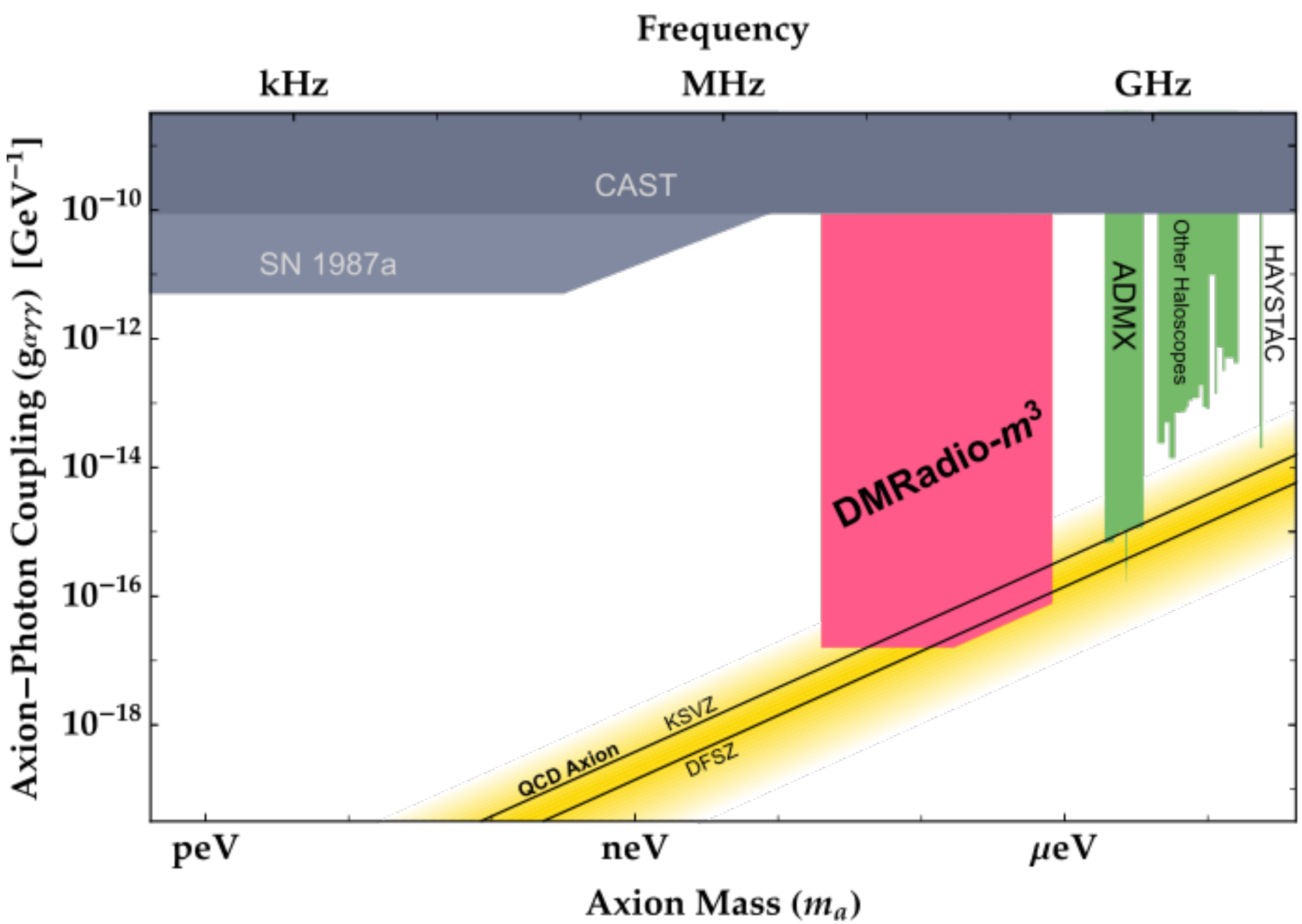
→ Power spectrum ~ f(v)

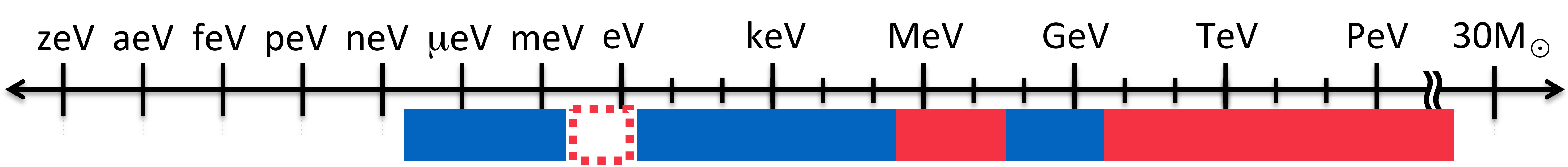


ADMX making good progress



Funded proposals to extend the range further





Dark matter as a wave: interferometers and clocks

Scalar dark matter: $\phi_{\rm DM}(t, \mathbf{x})$

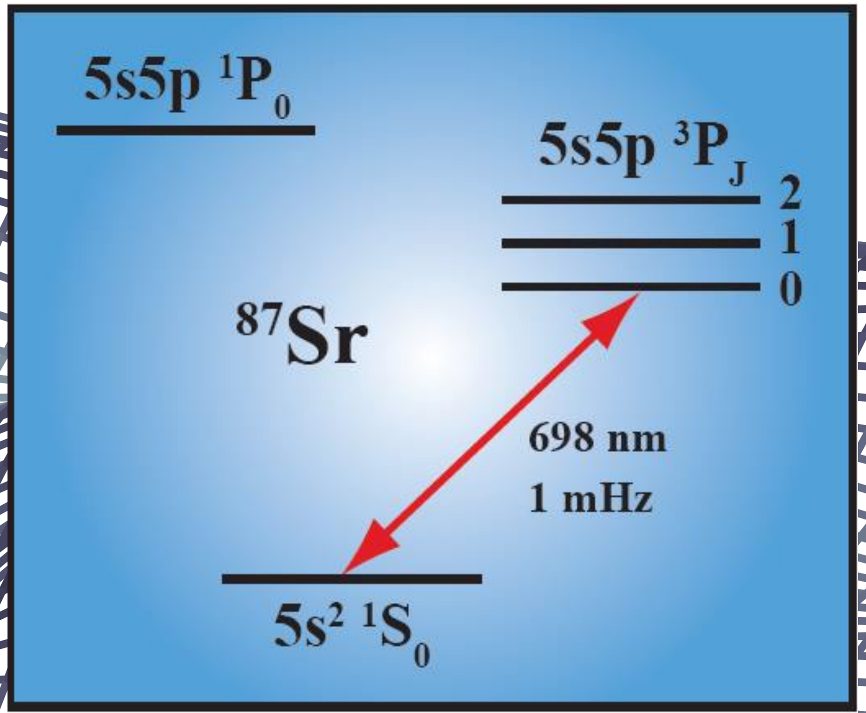
DM-SM interactions induce oscillations in the fundamental 'constants':

$$m_e(t, \mathbf{x}) = m_e \left[1 + \frac{d_{m_e}}{M_{\rm Pl}} \phi(t, \mathbf{x})\right]$$

$$\alpha(t, \mathbf{x}) = \alpha \left[1 + \frac{d_e}{M_{\rm Pl}} \phi(t, \mathbf{x})\right]$$

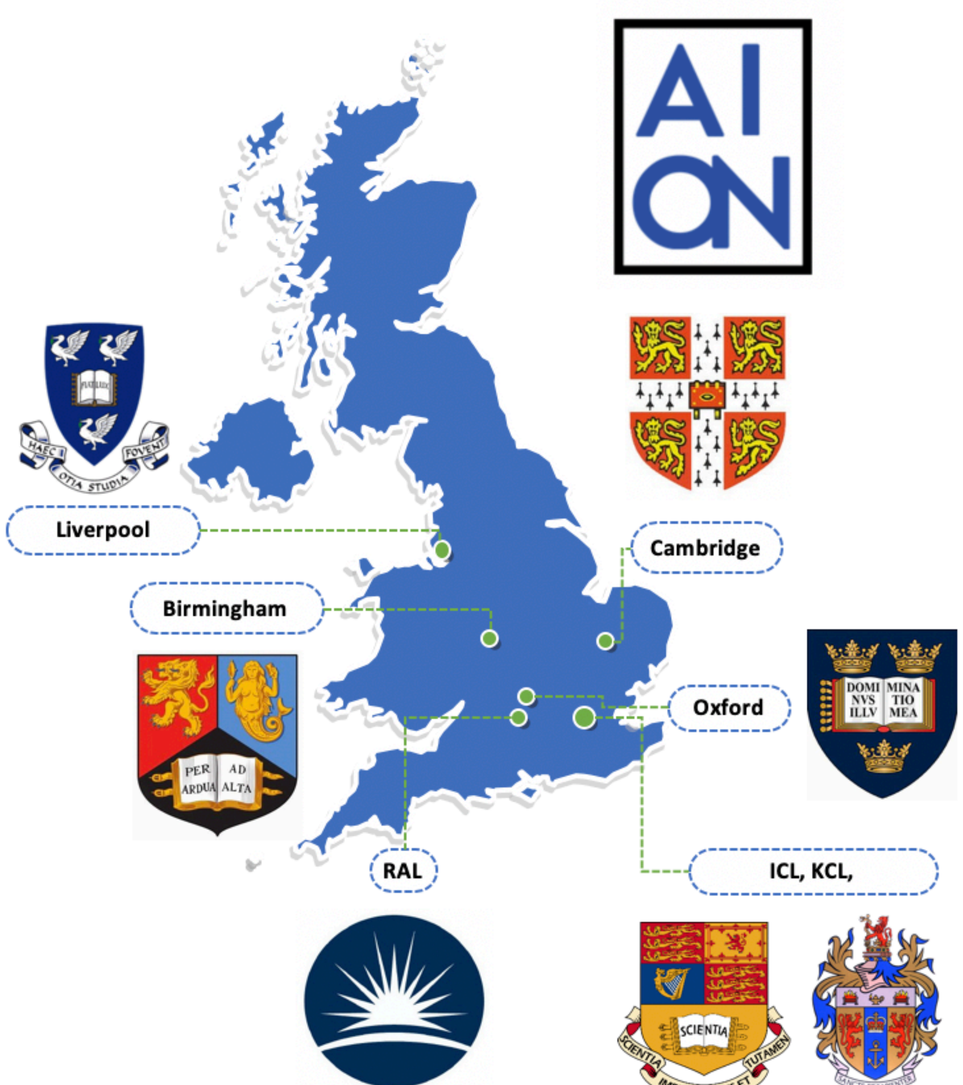
These induce oscillations in electronic transition energies

$$\frac{\delta\omega_{\rm Sr}}{\omega_{\rm Sr}} = \frac{\sqrt{2\rho_{\rm DM}}}{m_{\rm DM}} \frac{(d_{m_e} + \xi d_e)}{M_{\rm Pl}} \cos(m_{\rm DM} t)$$

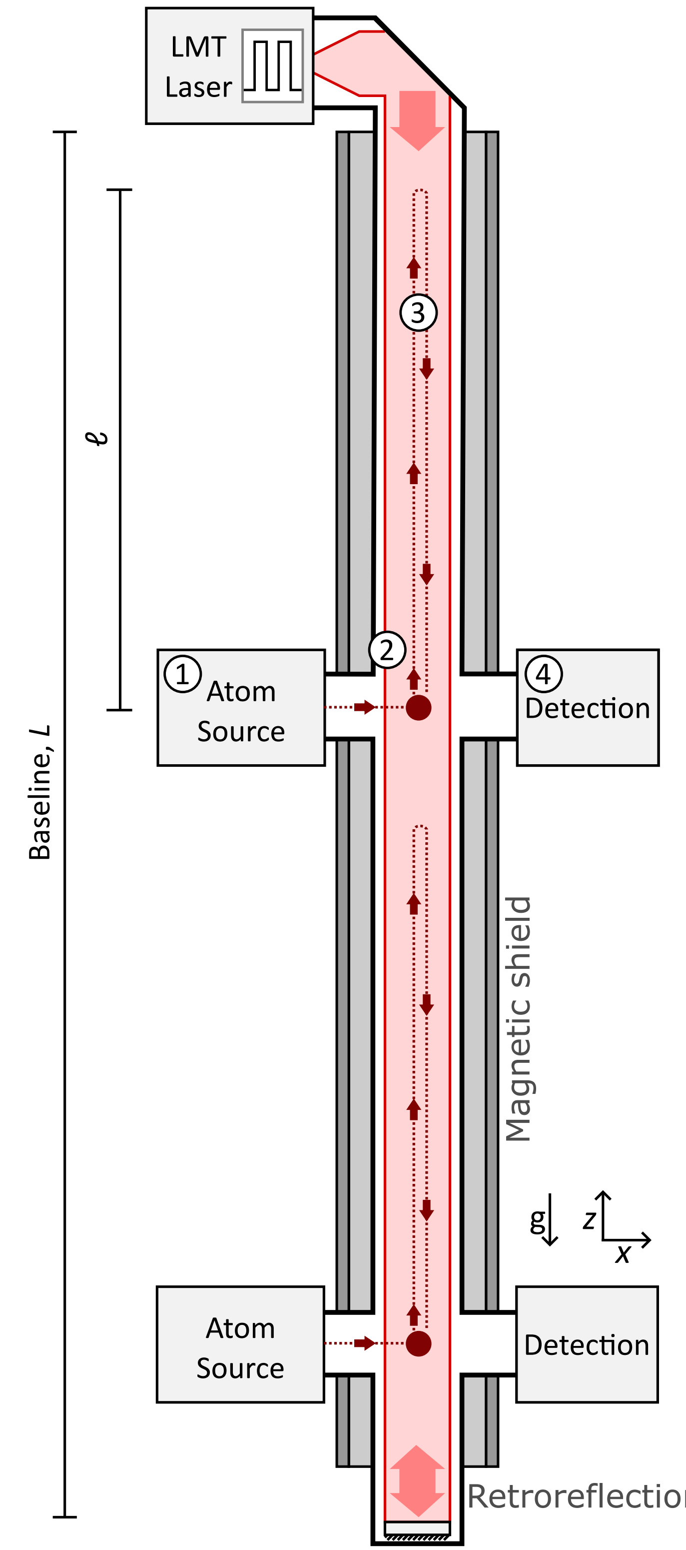


Variations in the constants with AION

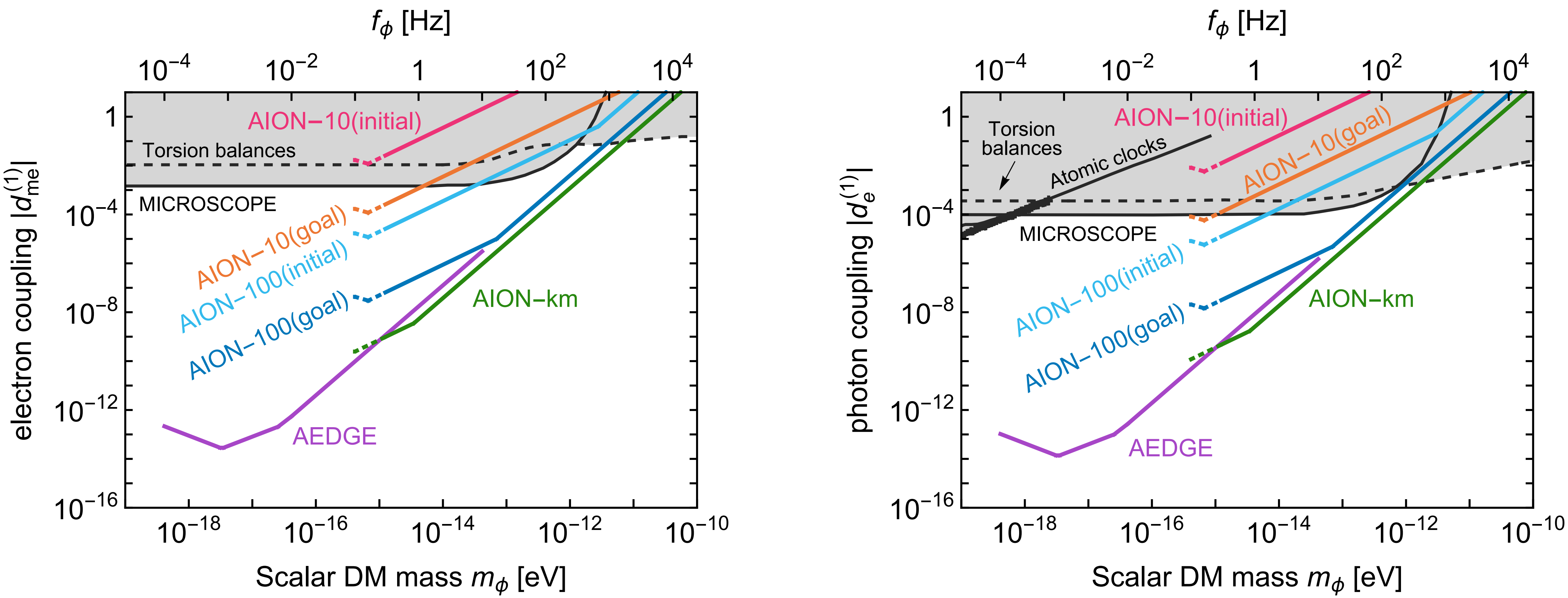
AION:
A UK Atom Interferometer Observatory and Network



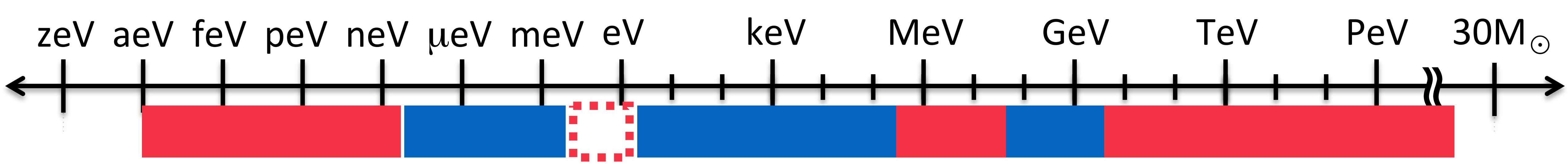
AION, arXiv:1911.11755



Variations in the constants with AION



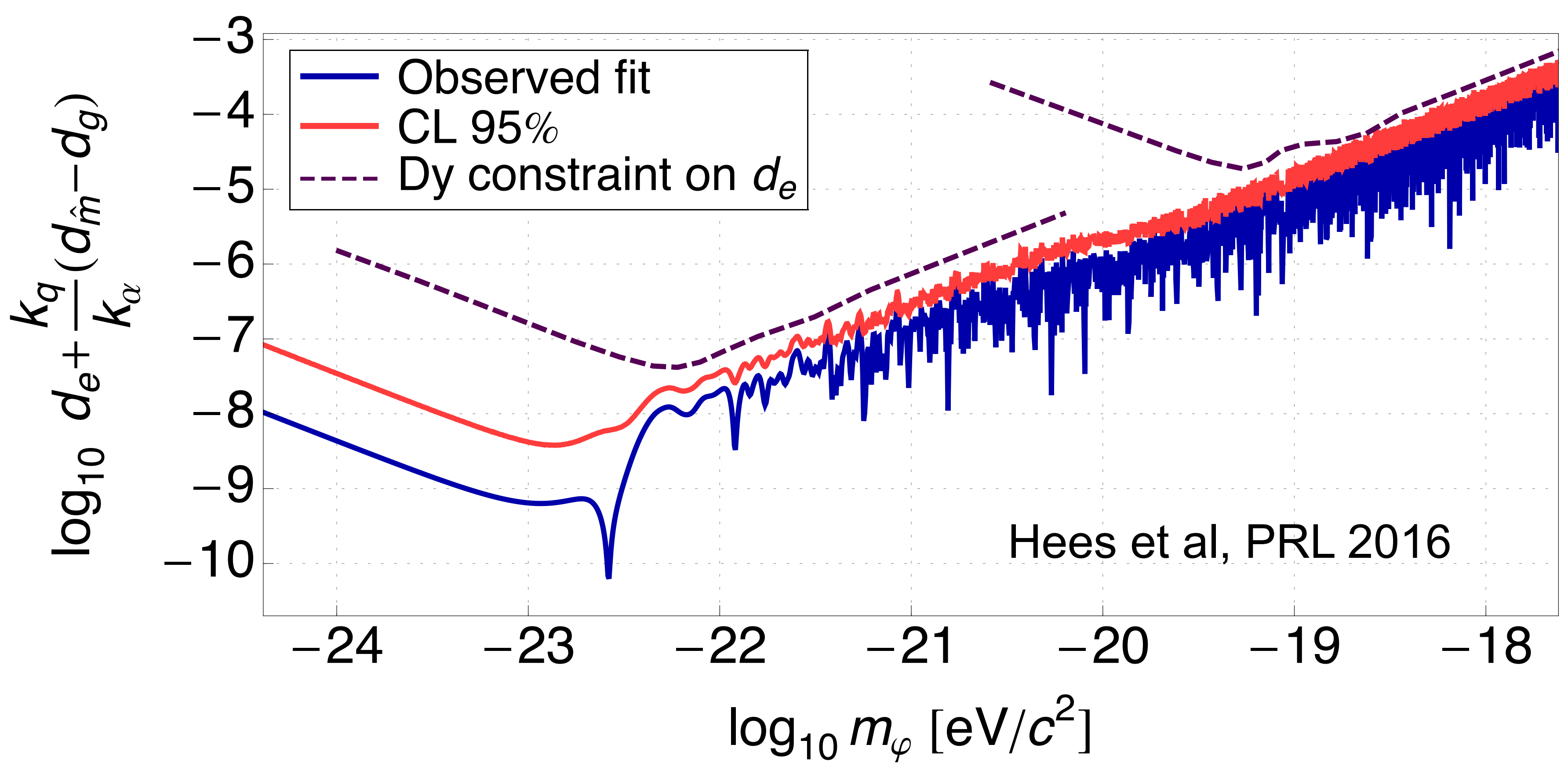
AION, arXiv:1911.11755

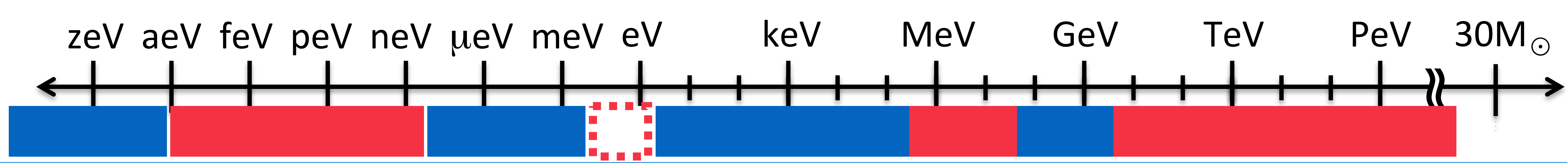


Variations in the constants with atomic clocks

e.g. 6 years precision measurements of the 87Rb/133Cs ground state hyperfine frequency ratio

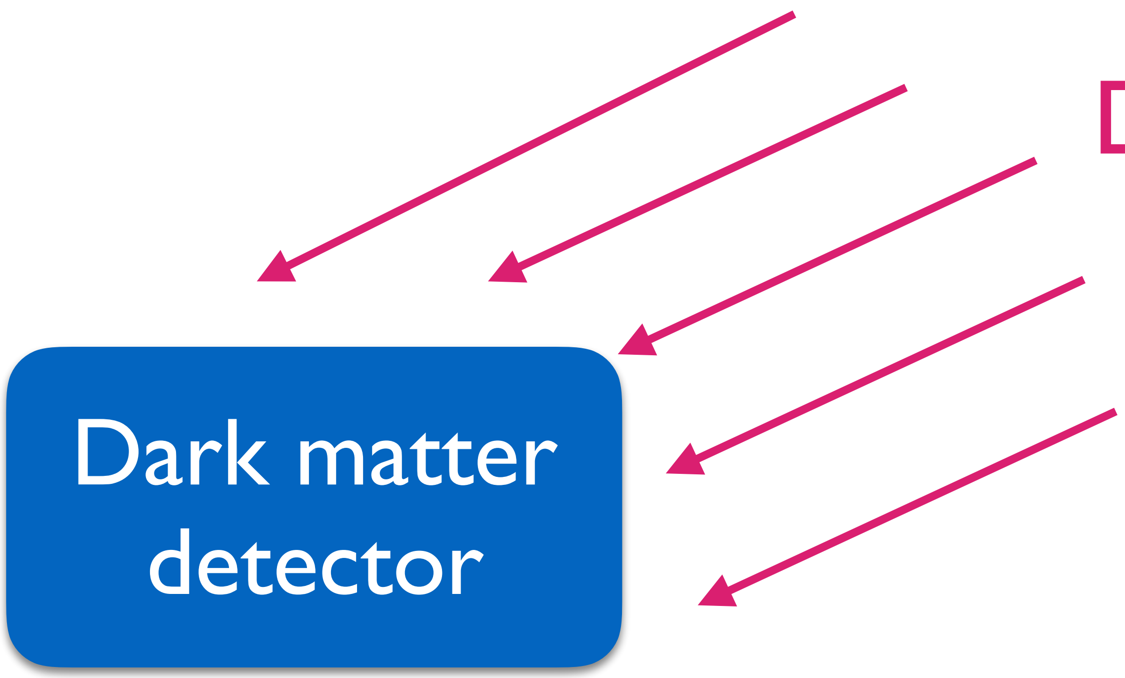
$$\delta\left(\frac{\nu_1}{\nu_2}\right) \propto \cos(m_{\rm DM} t)$$





So what?

Generic direct detection experiment



Dark matter flux

$$\sim \rho_{\rm DM} \int d^3v \, f_{\rm DM}(\mathbf{v}) \, v$$

Event rate = *DM flux* $\times$ *particle physics*

Discussion

- Now experiments probing vast range of dark matter candidates
- Impact of astro uncertainties explored for traditional searches: nuclear recoils and (recently) axion searches
- *Open question: how important for all of the other searches?*