New ideas for the direct detection of light dark matter

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From LHC to Dark Matter and beyond

Outline - light DM

1 **A new, irreducible signal in direct detection experiments**

based on Chris Kouvaris and JP
Phys.Rev.Lett. 118, 031803 (2017)

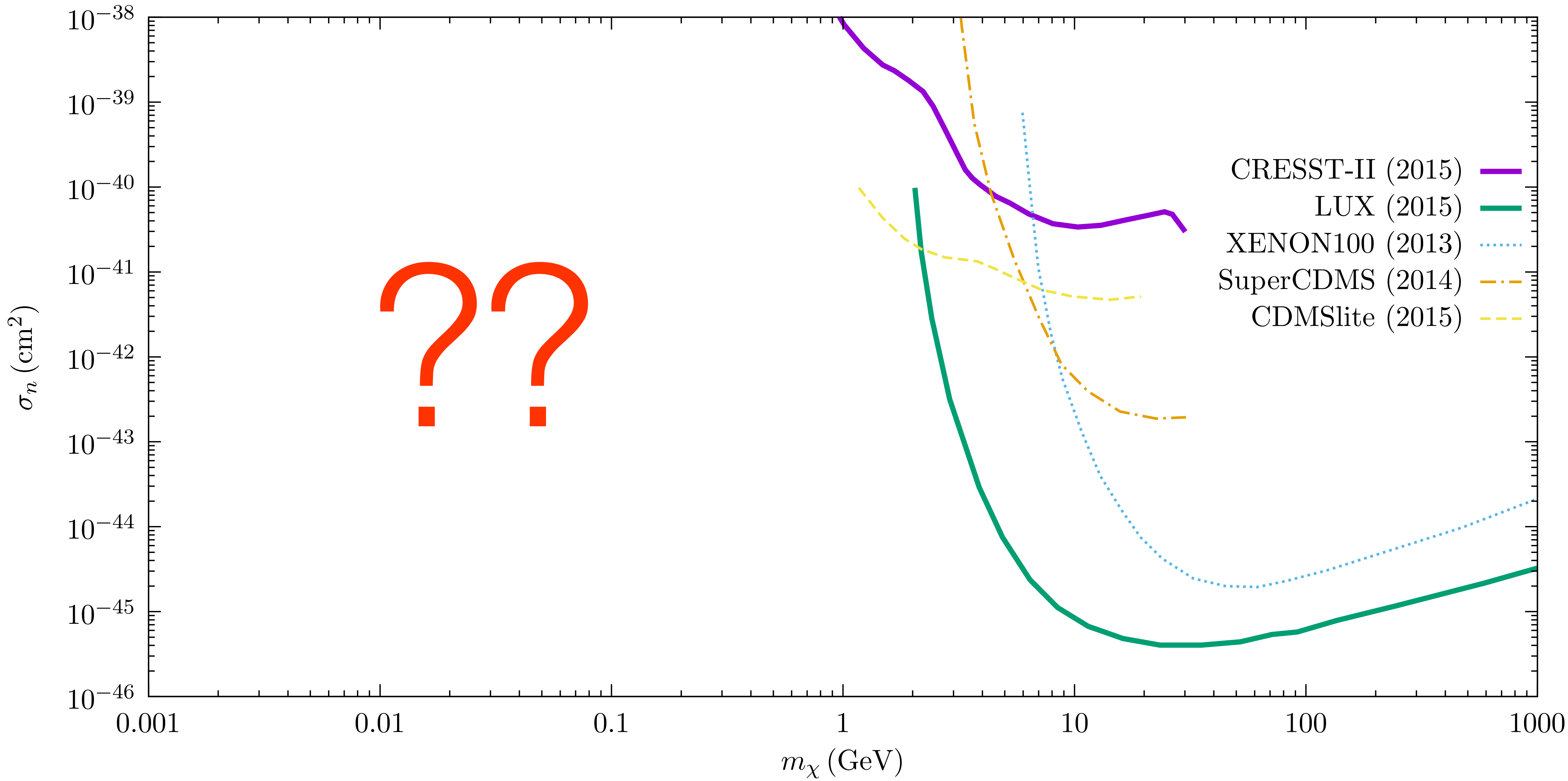
2 **"SIMPs inspired" direct detection of excited states**

based on Nicolás Bernal, Xiaoyong Chu, JP
arXiv:1702.04906 [hep-ph]

A summary of 2 decades of experimental effort

light DM space WIMP-space

How can we make progress in the sub-GeV region?



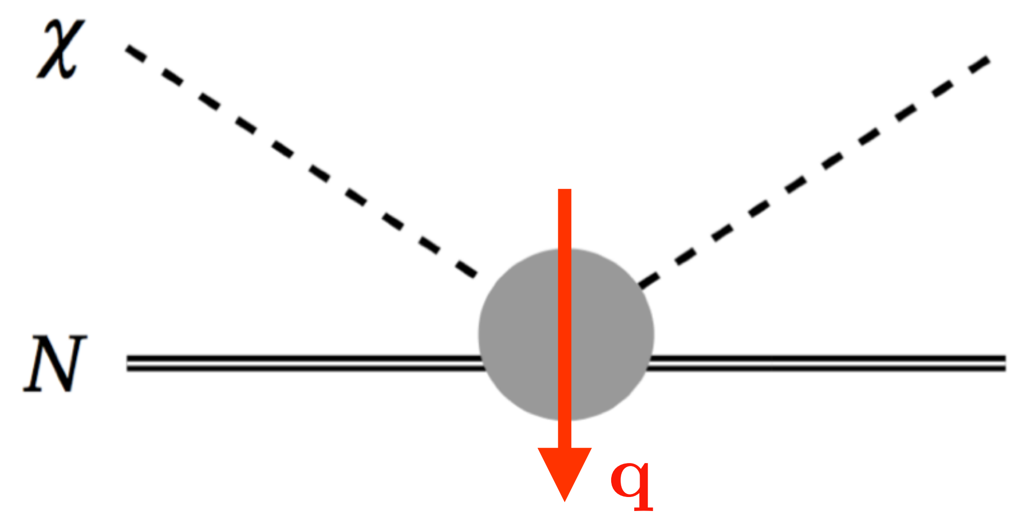
"light Dark Matter"

WIMPs

Direct Detection

Nuclear kinetic recoil energy

$$E_R = \frac{\mathbf{q}^2}{2m_N} = \frac{\mu_N^2 v^2}{m_N}(1 - \cos\theta_*)$$



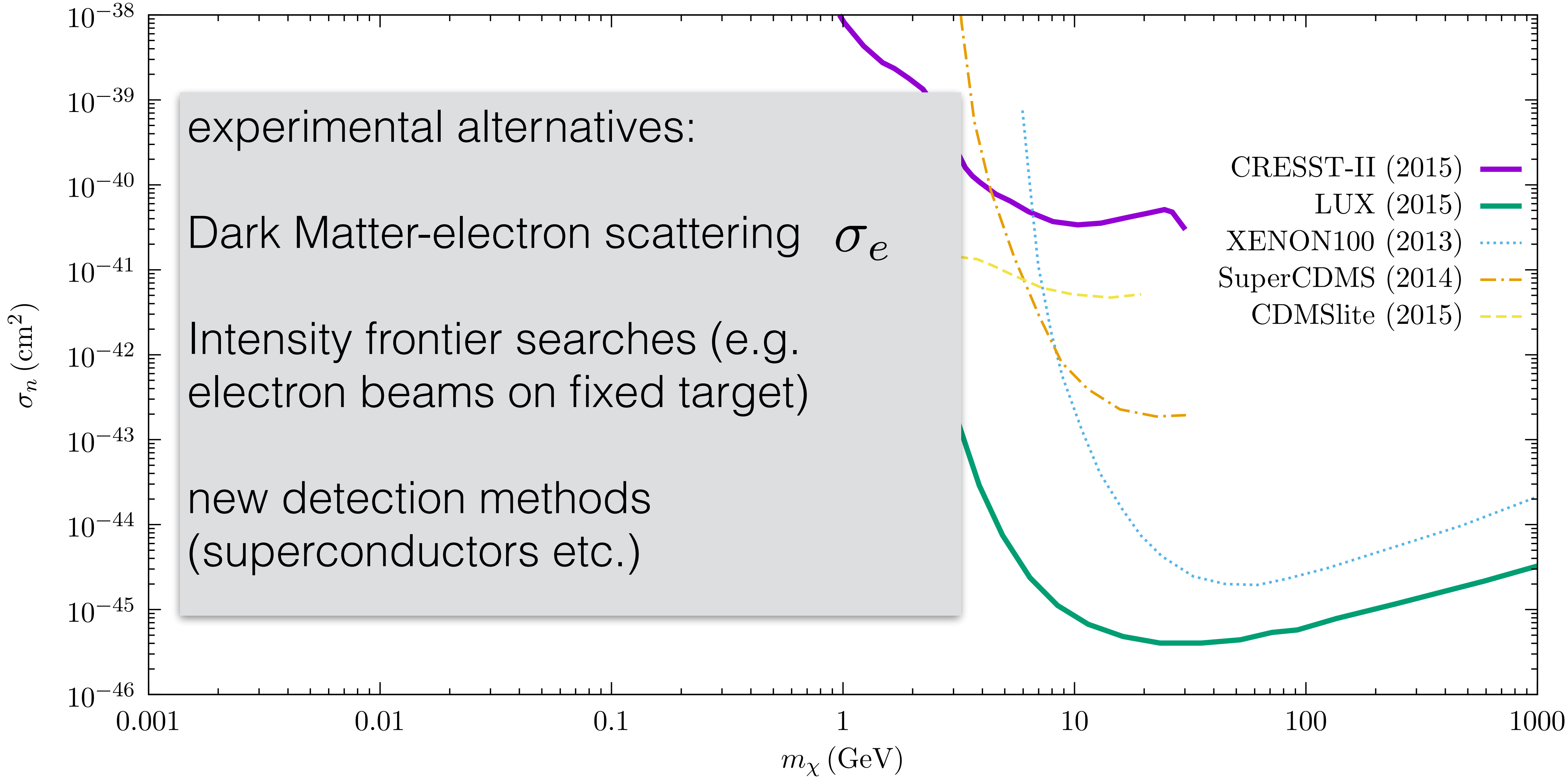
=> A given recoil, demands a *minimum* relative velocity

$$v_{\min} = \sqrt{\frac{m_N E_R}{2\mu_N^2}} \simeq \left(\frac{E_R}{0.5\,\mathrm{keV}}\right)^{1/2} \frac{1\,\mathrm{GeV}}{m_\chi} \times \begin{cases} 1700\,\mathrm{km/s} & \mathrm{Xenon} \\ 600\,\mathrm{km/s} & \mathrm{Oxygen} \end{cases}$$

=> if m < 1 GeV, then there are no particles bound to the Galaxy that could induce a 0.5 keV nuclear recoil on a Xenon atom!

"kinematical no-go theorem"

Gaining access to sub-GeV Dark Matter



experimental alternatives:

Dark Matter-electron scattering σ_e

Intensity frontier searches (e.g. electron beams on fixed target)

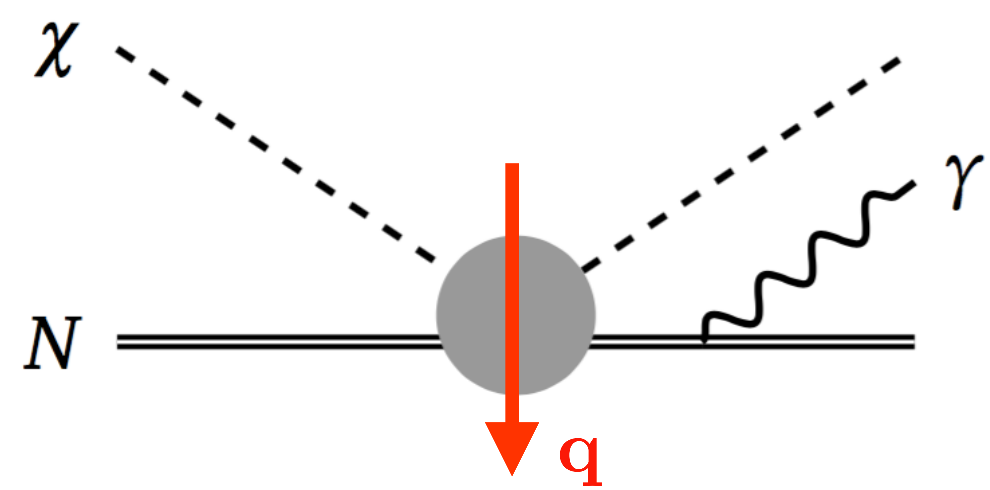
new detection methods (superconductors etc.)

1

Gaining access to sub-GeV Dark Matter *through nuclear recoils*

Matrix element for photon emission

$$M = M_{\rm el} \times Ze \left(\frac{p'_N \cdot \epsilon^*}{p'_N \cdot k} - \frac{p_N \cdot \epsilon^*}{p_N \cdot k} \right)$$



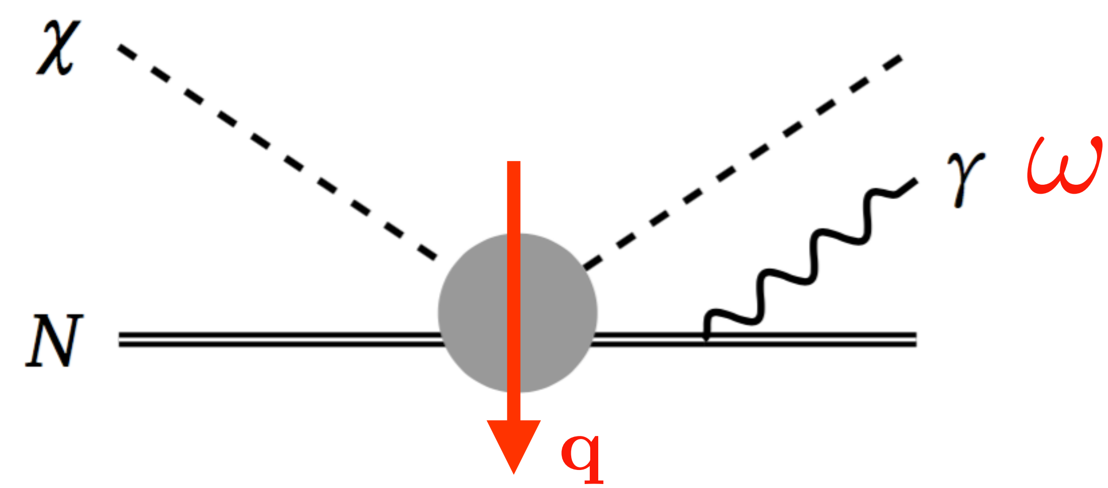
Note: factorization holds for any nuclear spin; semiclassical process where the nucleus moves on a classical trajectory, the emission is quantum

=> cross section factorizes

$$d\sigma = d\sigma_{\rm el} \times (Ze)^2 \left| \frac{p'_N \cdot \epsilon^*}{p'_N \cdot k} - \frac{p_N \cdot \epsilon^*}{p_N \cdot k} \right|^2 \frac{d^3\vec{k}}{(2\pi)^3 2\omega}$$

Gaining access to sub-GeV Dark Matter *through nuclear recoils*

$$\frac{d\sigma}{dE_R d\omega} = \frac{4Z^2\alpha}{3\pi}\frac{1}{\omega}\frac{E_R}{m_N} \times \frac{d\sigma}{dE_R}\Theta(\omega - \omega_{\max})$$



Maximum photon energy

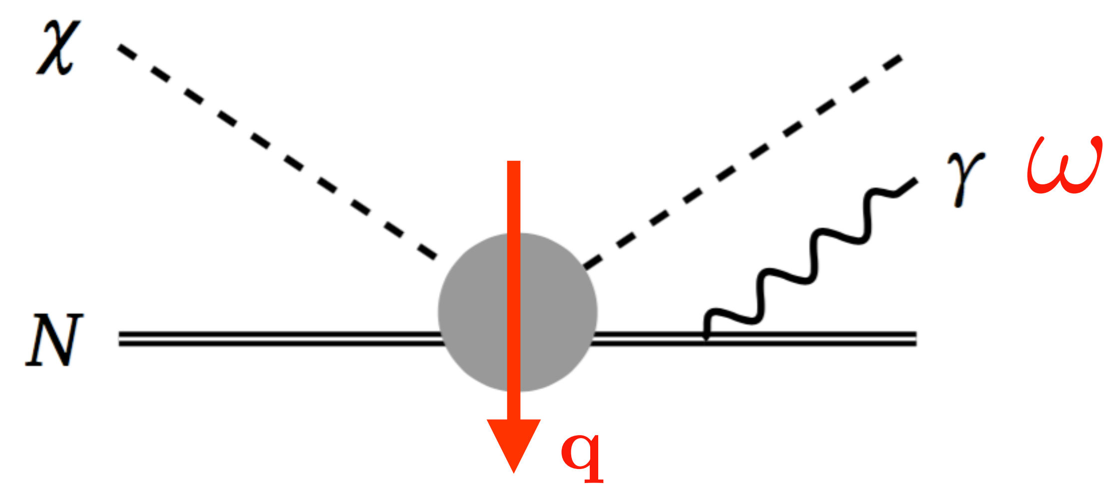
$$\omega_{\max} \simeq \mu_N v^2/2 \simeq m_\chi v^2/2$$
$$\simeq 0.5\,\mathrm{keV}\,\frac{m_\chi}{100\,\mathrm{MeV}}$$

Key I:

$$E_{R,\max} = 4(m_\chi/m_N)\omega_{\max} \ll \omega_{\max} \quad (m_\chi \ll m_N)$$

Gaining access to sub-GeV Dark Matter *through nuclear recoils*

$$\frac{d\sigma}{dE_R d\omega} = \frac{4Z^2\alpha}{3\pi}\frac{1}{\omega}\frac{E_R}{m_N} \times \frac{d\sigma}{dE_R}\Theta(\omega - \omega_{\max})$$



Maximum photon energy

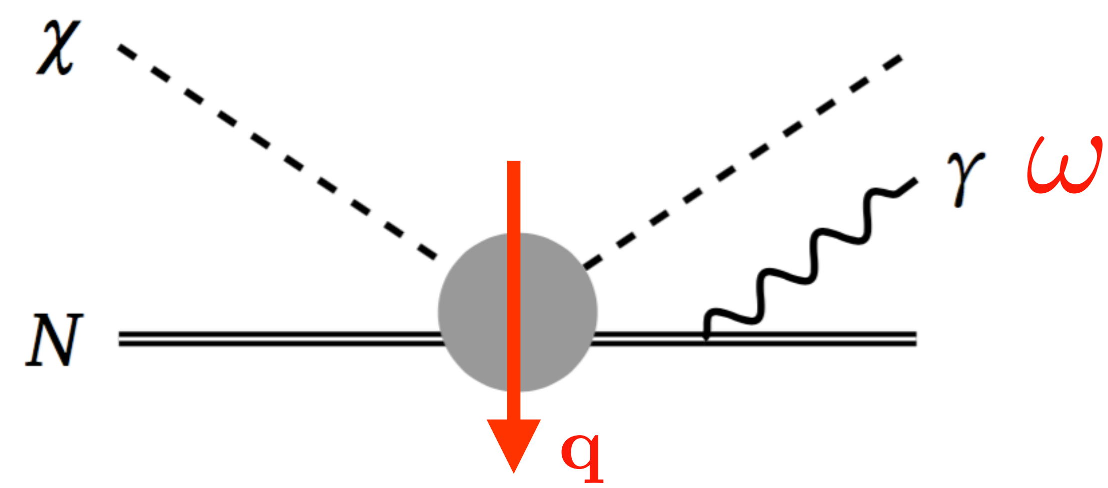
$$\omega_{\max} \simeq \mu_N v^2/2 \simeq m_\chi v^2/2$$
$$\simeq 0.5\,\mathrm{keV}\,\frac{m_\chi}{100\,\mathrm{MeV}}$$

Key II:

0.5 keV nuclear recoil is easily missed,
0.5 keV photon is never missed!

Gaining access to sub-GeV Dark Matter *through nuclear recoils*

$$\frac{d\sigma}{dE_R d\omega} = \frac{4Z^2\alpha}{3\pi}\frac{1}{\omega}\frac{E_R}{m_N} \times \frac{d\sigma}{dE_R}\Theta(\omega - \omega_{\max})$$



Maximum photon energy

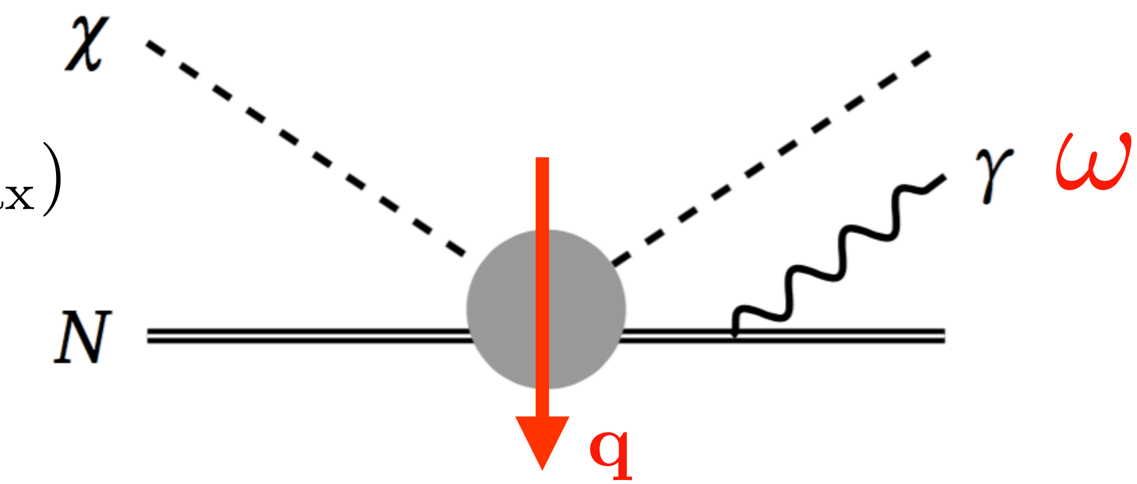
$$\omega_{\max} \simeq \mu_N v^2/2 \simeq m_\chi v^2/2$$
$$\simeq 0.5\,\text{keV}\,\frac{m_\chi}{100\,\text{MeV}}$$

NB: The factorization holds if $\delta\mathbf{q} = (\mathbf{p}'_N - \mathbf{p}_N - \mathbf{k}) - (\mathbf{p}'_N - \mathbf{p}_N)_{\omega=0} \ll \mathbf{q}$

or, equivalently, if $\omega \ll |\mathbf{q}|v = \sqrt{2m_N E_R}v$ ✓

Gaining access to sub-GeV Dark Matter *through nuclear recoils*

$$\frac{d\sigma}{dE_R d\omega} = \frac{4Z^2\alpha}{3\pi}\frac{1}{\omega}\frac{E_R}{m_N} \times \frac{d\sigma}{dE_R}\Theta(\omega - \omega_{\max})$$



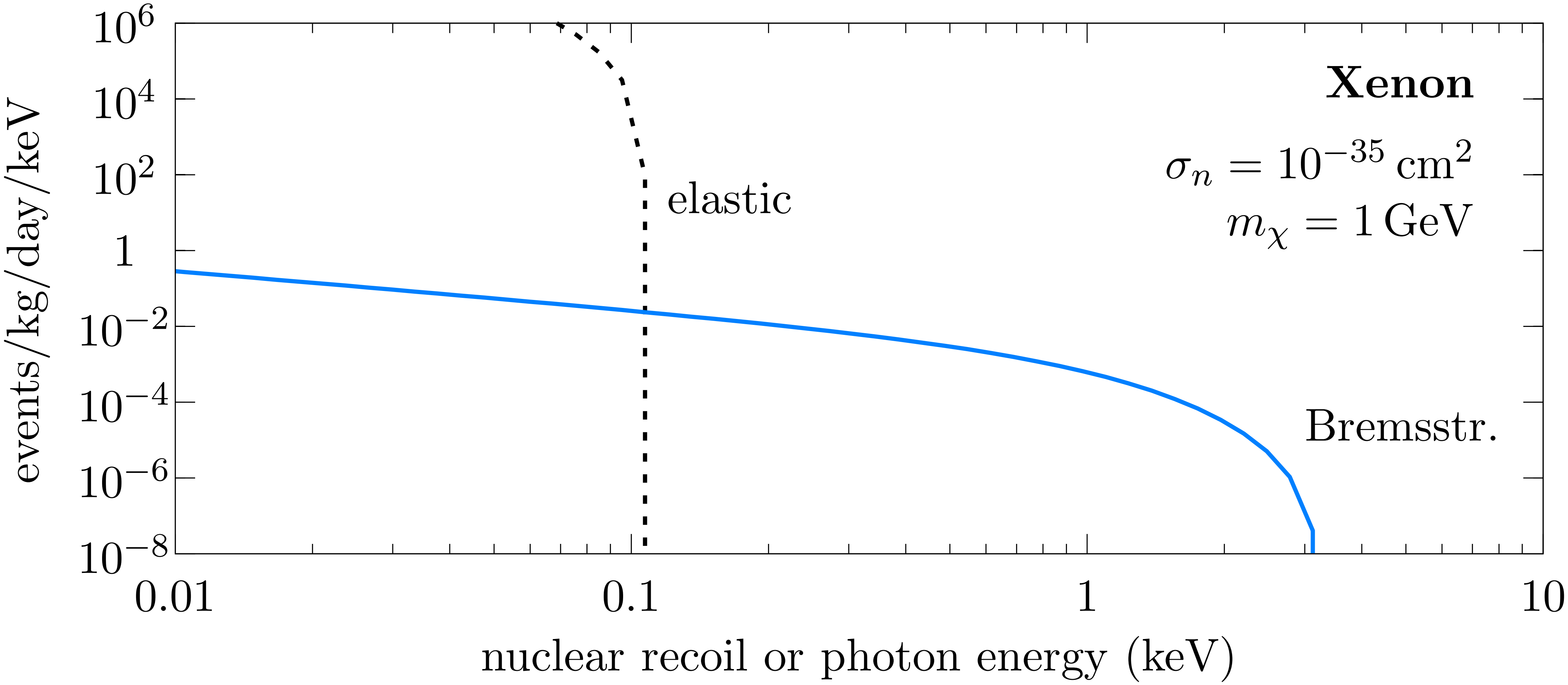
Price to pay

$$\simeq \frac{7\times 10^{-8}}{\omega}\left(\frac{E_R}{1\,\mathrm{keV}}\right) \times \frac{d\sigma}{dE_R} \quad \text{(Xenon)}$$

Can we overcome this suppression in rate?

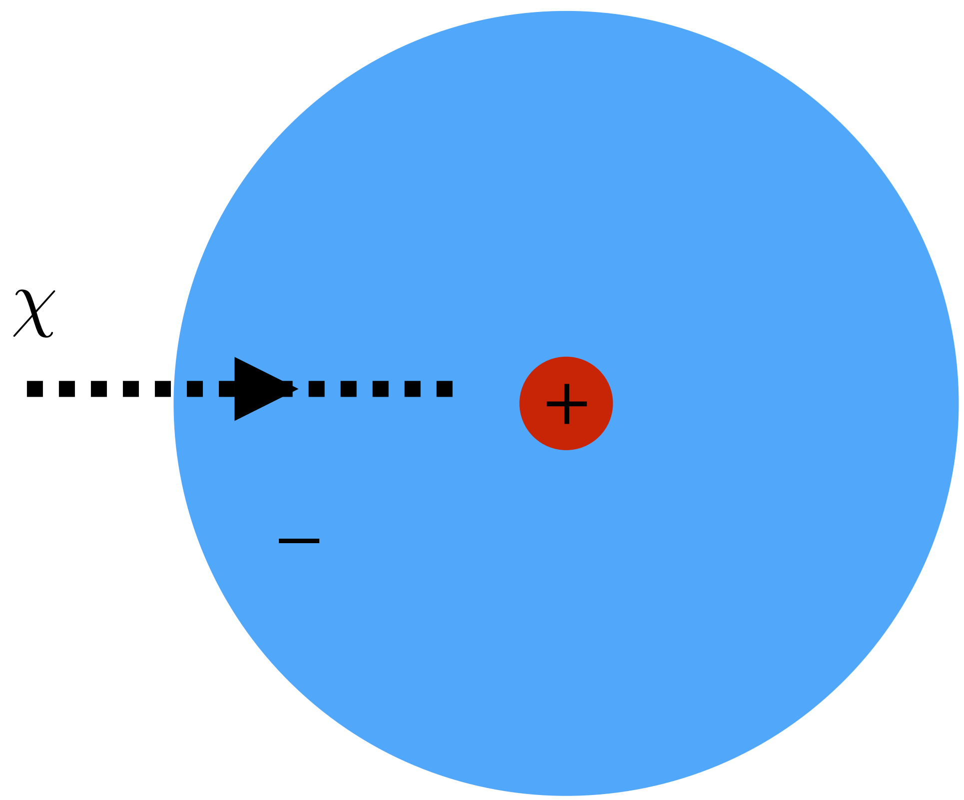
=> yes, because the recoil spectrum is exponentially rising with smaller recoil energy!

Gaining access to sub-GeV Dark Matter *through nuclear recoils*



Maybe we have been
too naive about the process
of photon emission?!

Atomic physics modification

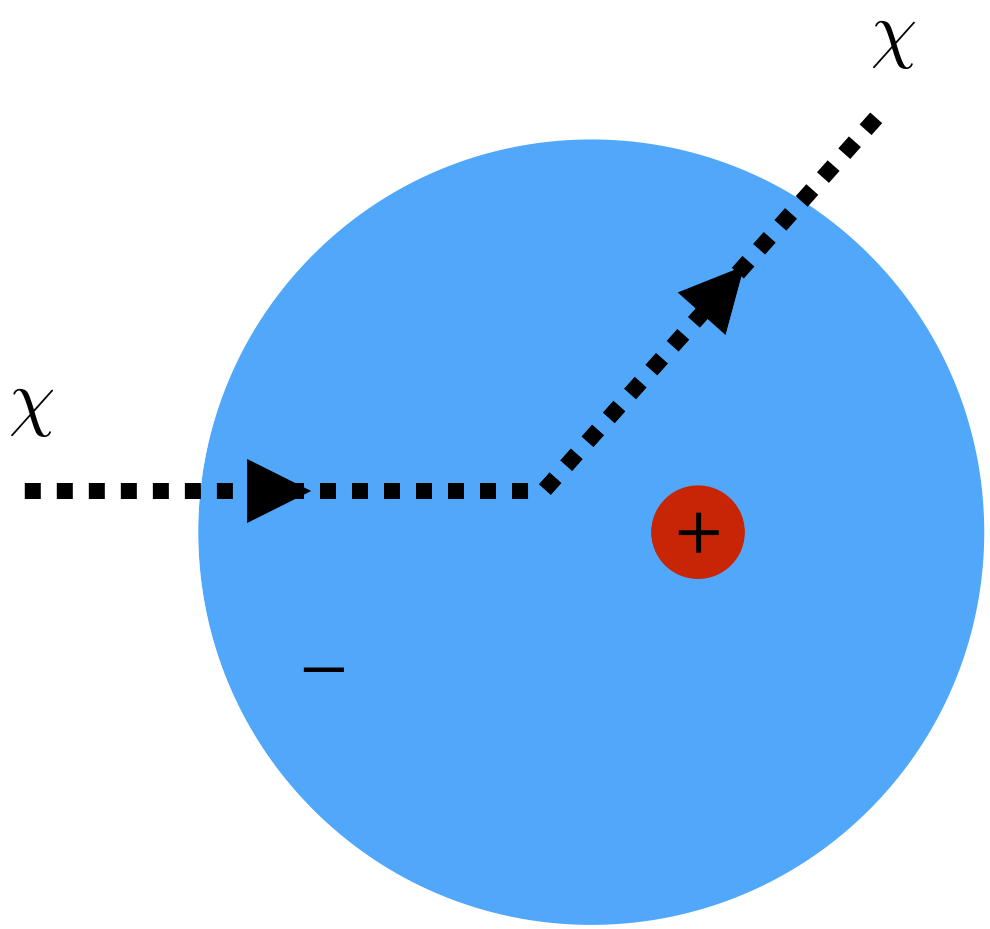


Atom in ground state

The naive treatment of Bremsstrahlung scales as 1/ω all the way to lowest energies

=> this becomes modified by the fact that the nucleus is in a bound state of electrons

Atomic physics modification



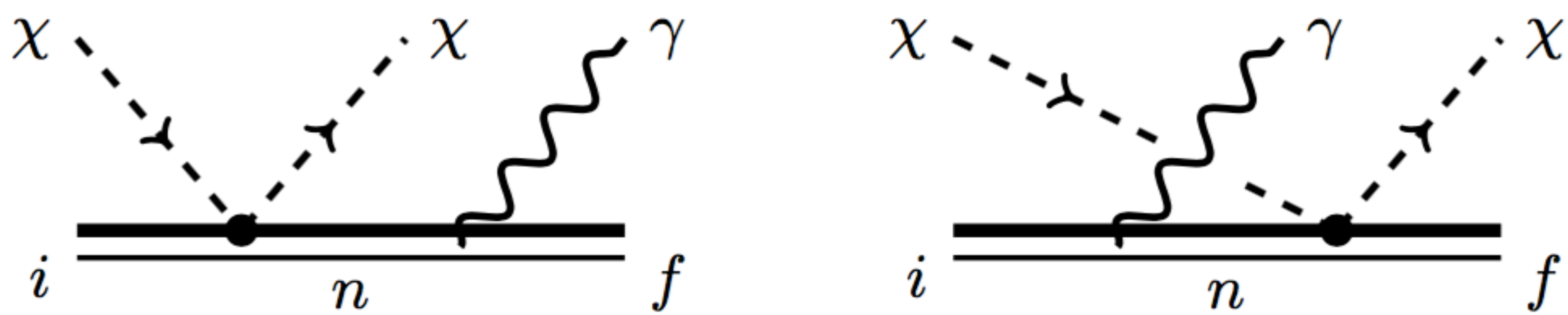
"Polarized Atom"

=> After the nucleus gets a kick, in the limit that the DM-nucleus interaction time $\tau_\chi \sim R_N/v_\chi$ is fast compared to the orbital time of electrons, $\tau_\alpha \sim |\mathbf{r}_\alpha|/v_\alpha$, the Atom becomes polarized

for inner shell electrons

$$\tau_\chi/\tau_\alpha \simeq 10^{-4} A^{1/3} Z^2$$

Atomic physics modification



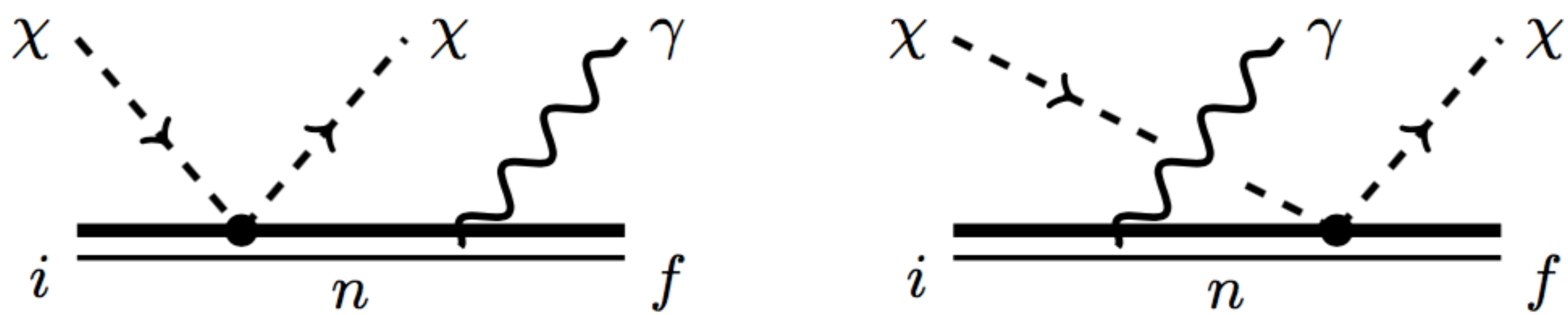
=> QM calculation

$$|V_{fi}|^2 = 2\pi\omega |M_{\mathrm{el}}|^2 \left| \sum_{n\neq i,f} \left[\frac{(\mathbf{d}_{fn}\cdot\hat{\mathbf{e}}^*)\langle n|e^{-i\frac{m_e}{m_N}\mathbf{q}\cdot\sum_\alpha \mathbf{r}_\alpha}|i\rangle}{\omega_{ni}-\omega} + \frac{(\mathbf{d}_{ni}\cdot\hat{\mathbf{e}}^*)\langle f|e^{-i\frac{m_e}{m_N}\mathbf{q}\cdot\sum_\alpha \mathbf{r}_\alpha}|n\rangle}{\omega_{ni}+\omega} \right] \right|^2$$

dipole matrix element for emission of photon

boost of the electron cloud

Atomic physics modification



=> QM calculation

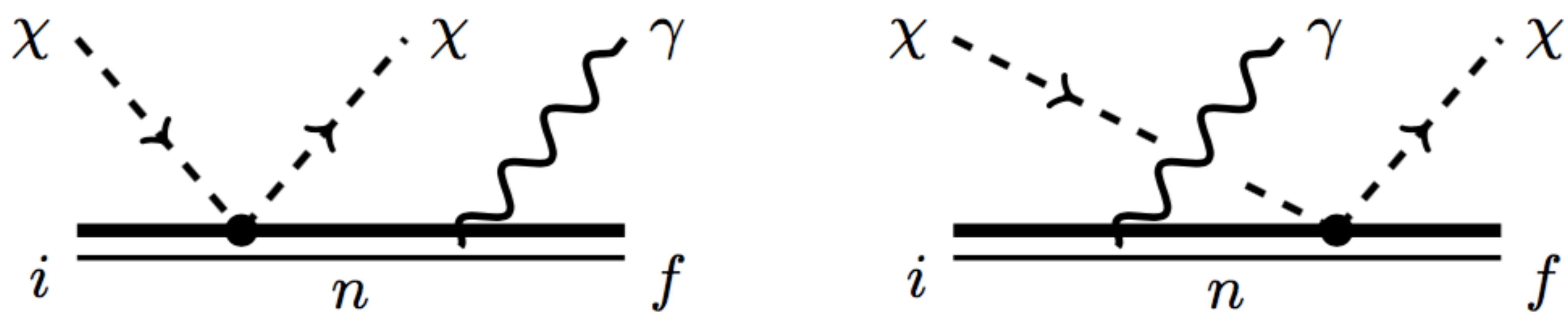
End result for f=i:

$$\frac{d\sigma}{d\omega dE_R} \propto \omega^3 \times |\alpha(\omega)|^2 \times \frac{E_R}{m_N} \times \frac{d\sigma}{dE_R}$$

energy scaling of dipole emission

polarizability of the atom

Atomic physics modification



=> QM calculation

End result for f=i:

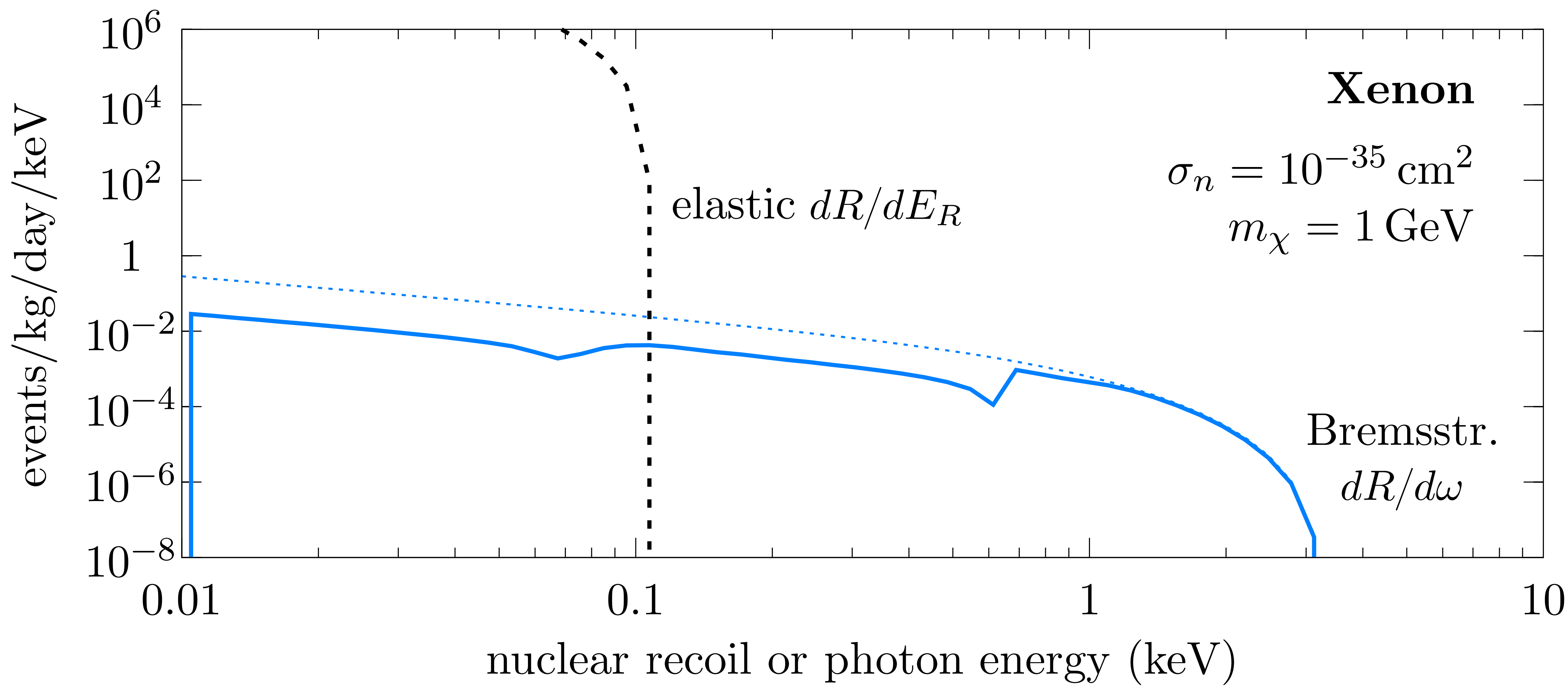
$$\frac{d\sigma}{d\omega dE_R} \propto \omega^3 \times |\alpha(\omega)|^2 \times \frac{E_R}{m_N} \times \frac{d\sigma}{dE_R}$$

$$\rightarrow \frac{Z^2\alpha}{\omega} \times \frac{E_R}{m_N} \times \frac{d\sigma}{dE_R}$$

for large ω naive result is recovered ✓

Gaining access to sub-GeV Dark Matter *through nuclear recoils*

including atomic physics modification



=> importantly, we can draw from atomic data listings!

Detecting Bremsstrahlung

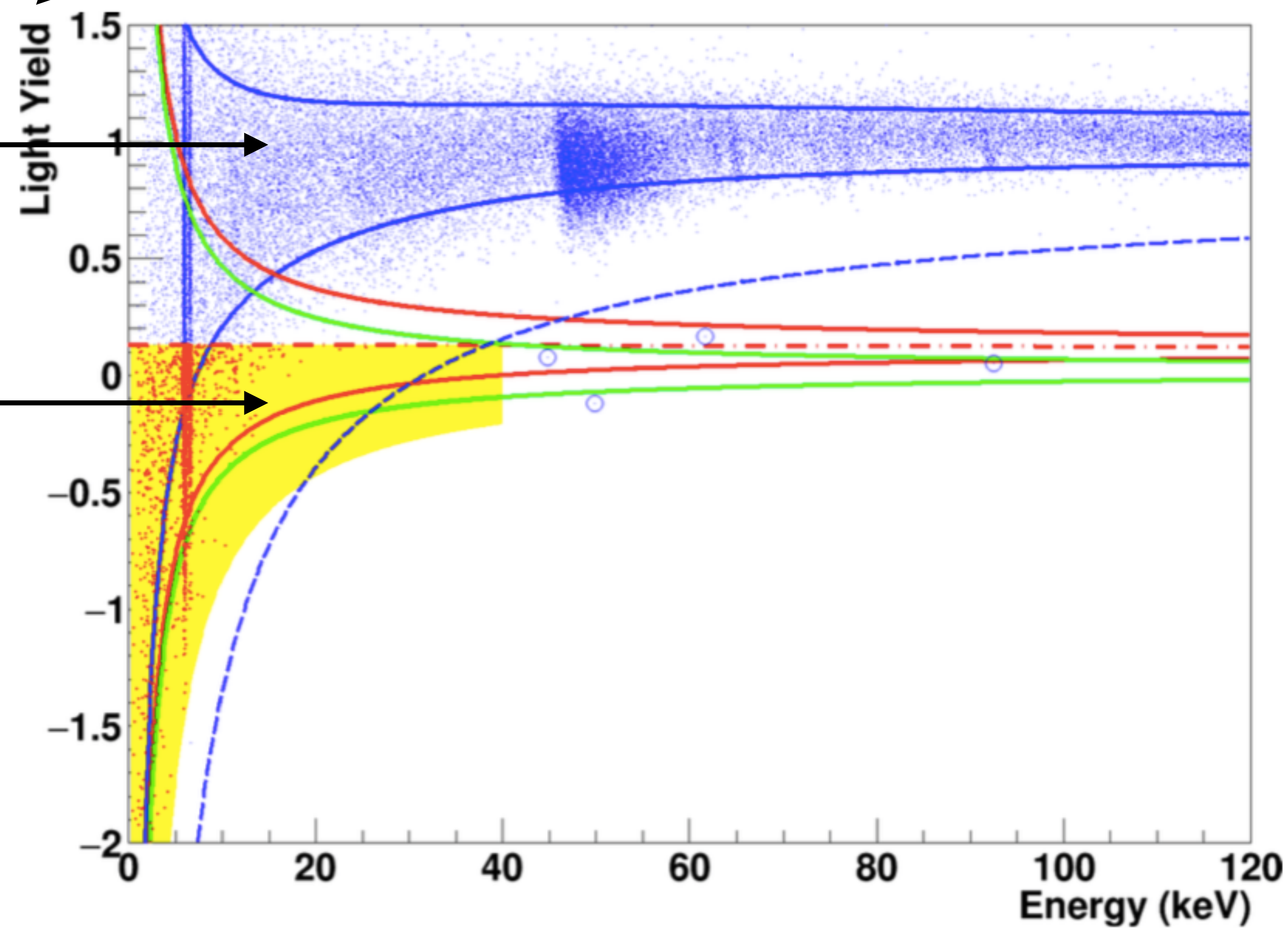
discriminating quantity

"electron recoil band" = crowded

"nuclear recoil band" = clean

+ few 100 eV thresholds

=> solid state detectors are (currently) less suited for this search

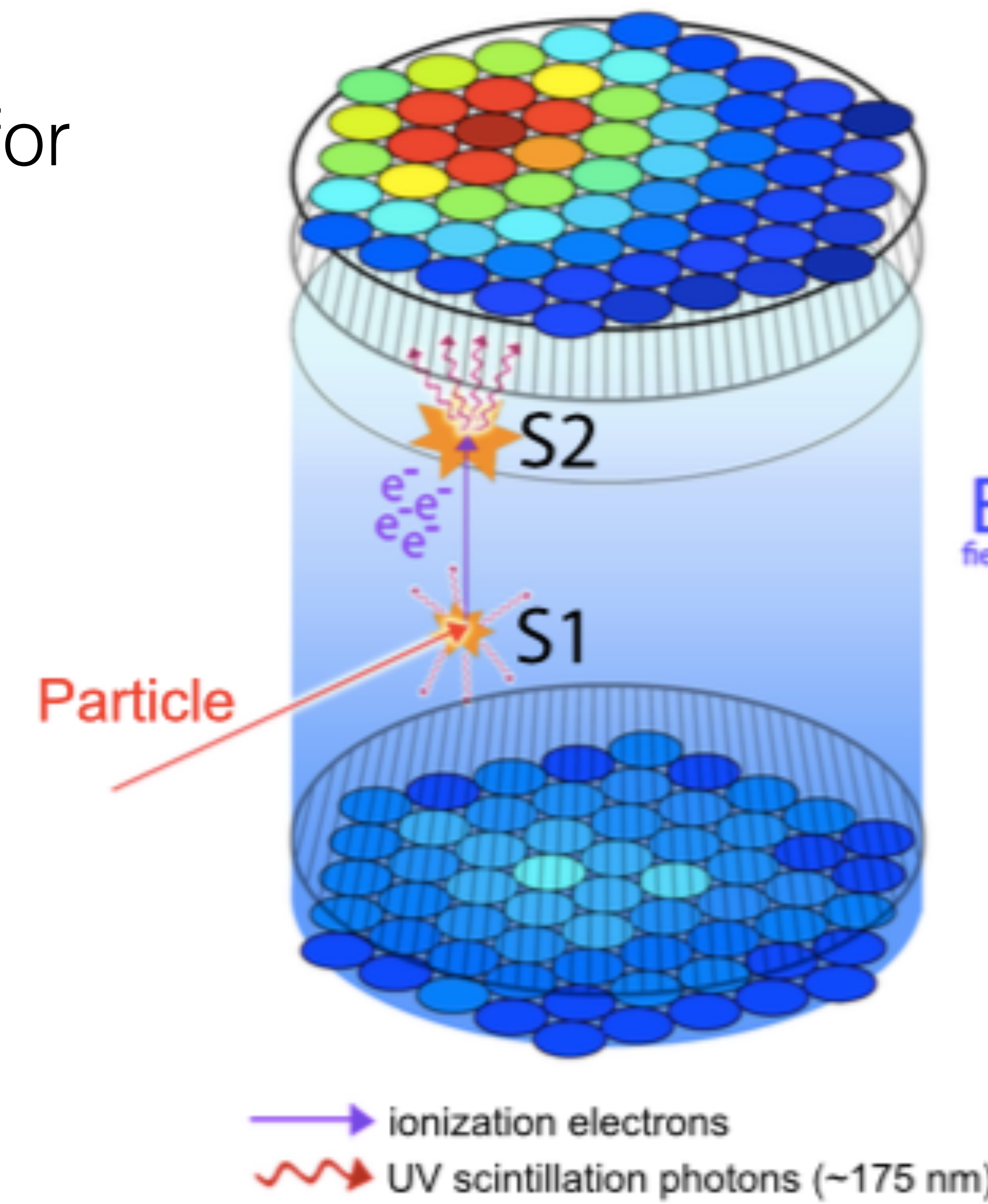


e.g. CRESST 2015

Detecting Bremsstrahlung

=> Liquid scintillators are well suited for detecting the *photon signal through ionization*

A 100 eV photon produces multiple electrons => in principle easily picked up



XENON10 - differential limit

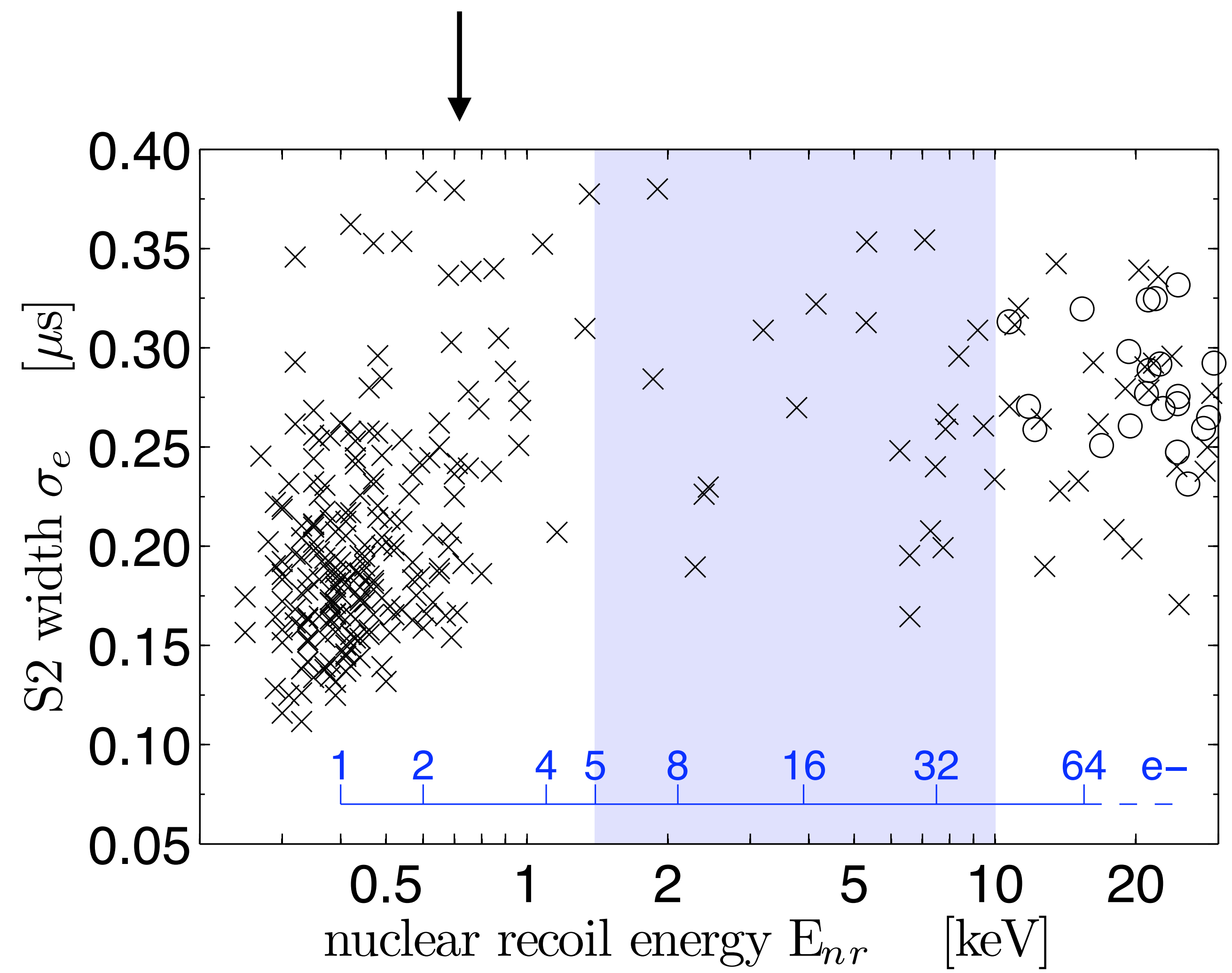
Use differential information of the number of ionized electrons

Primary ionized electron + **secondary electrons** from recoiling primary electron plus from the filling of shell vacancies

At large deposited energies

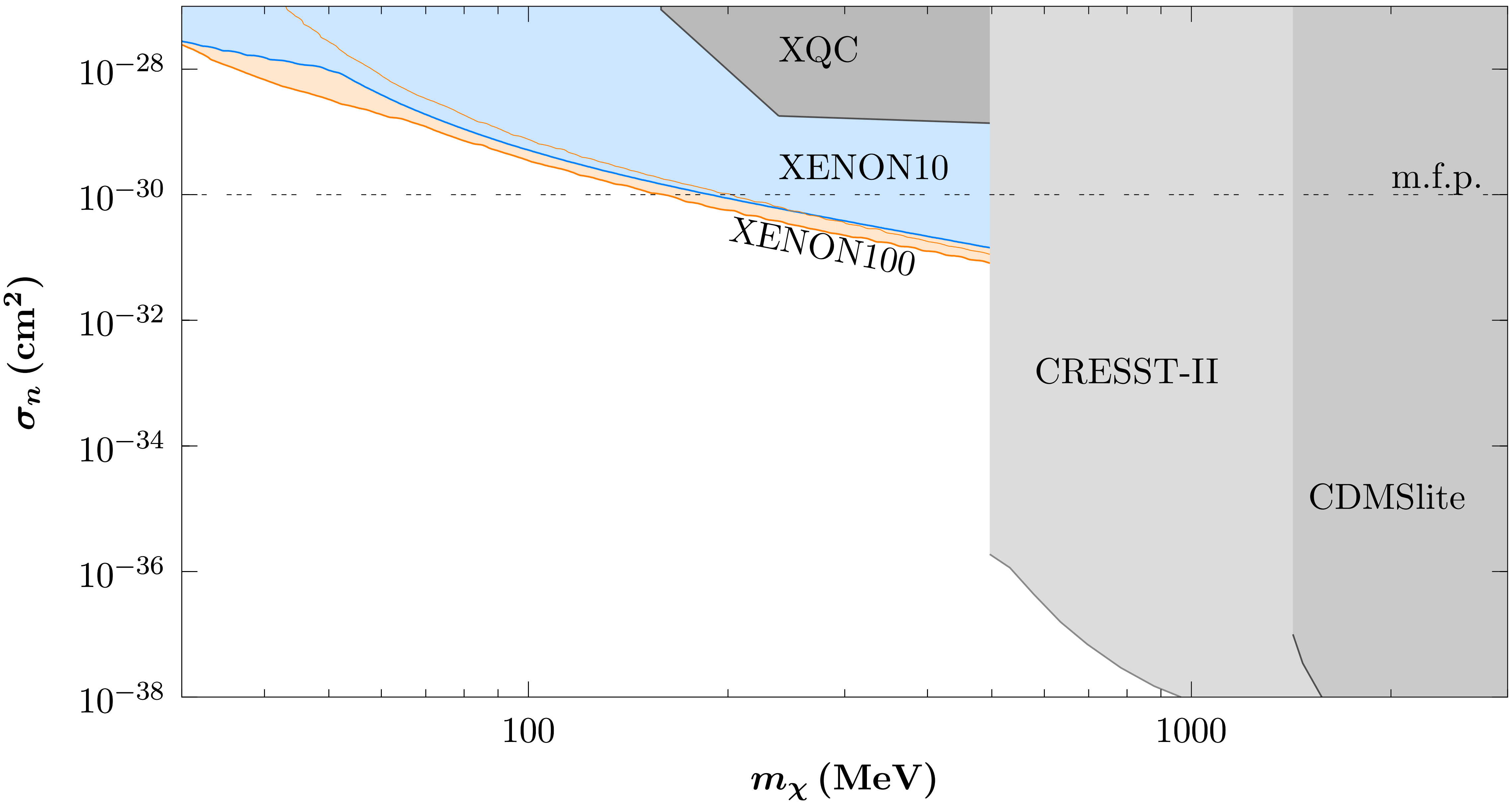
$$n_e \sim \omega/(13.8\text{eV})$$

We follow the statistical model for n_e by Essig et al. 2012



XENON10 collaboration, 2011

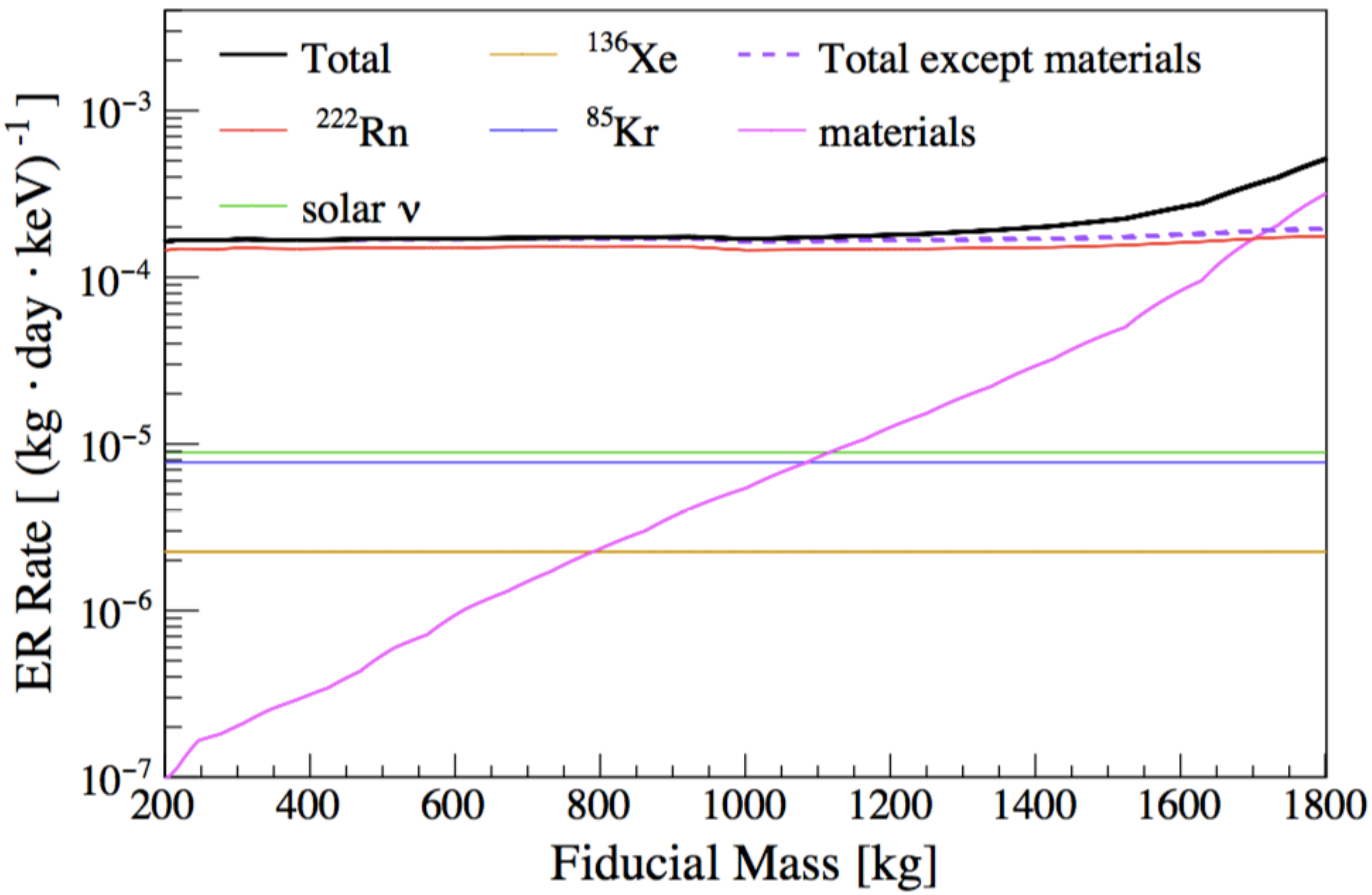
sub-GeV sensitivity to nuclear recoils



=> FIRST limit on DM-nucleus scattering below 500 MeV!

Bringing back S1/
Going forward with LXE

[Aprile et al 2015]

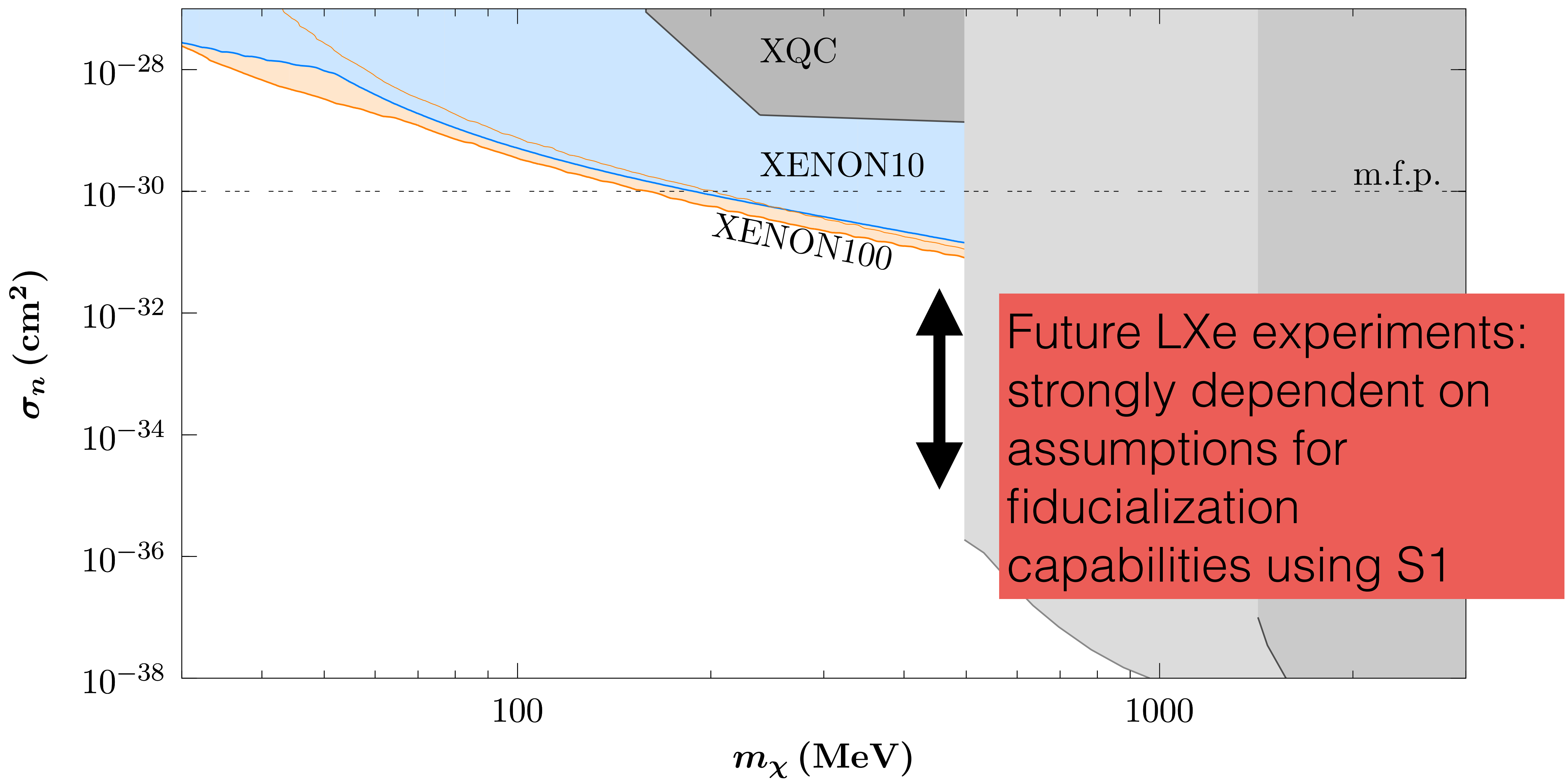


1. What about LUX?

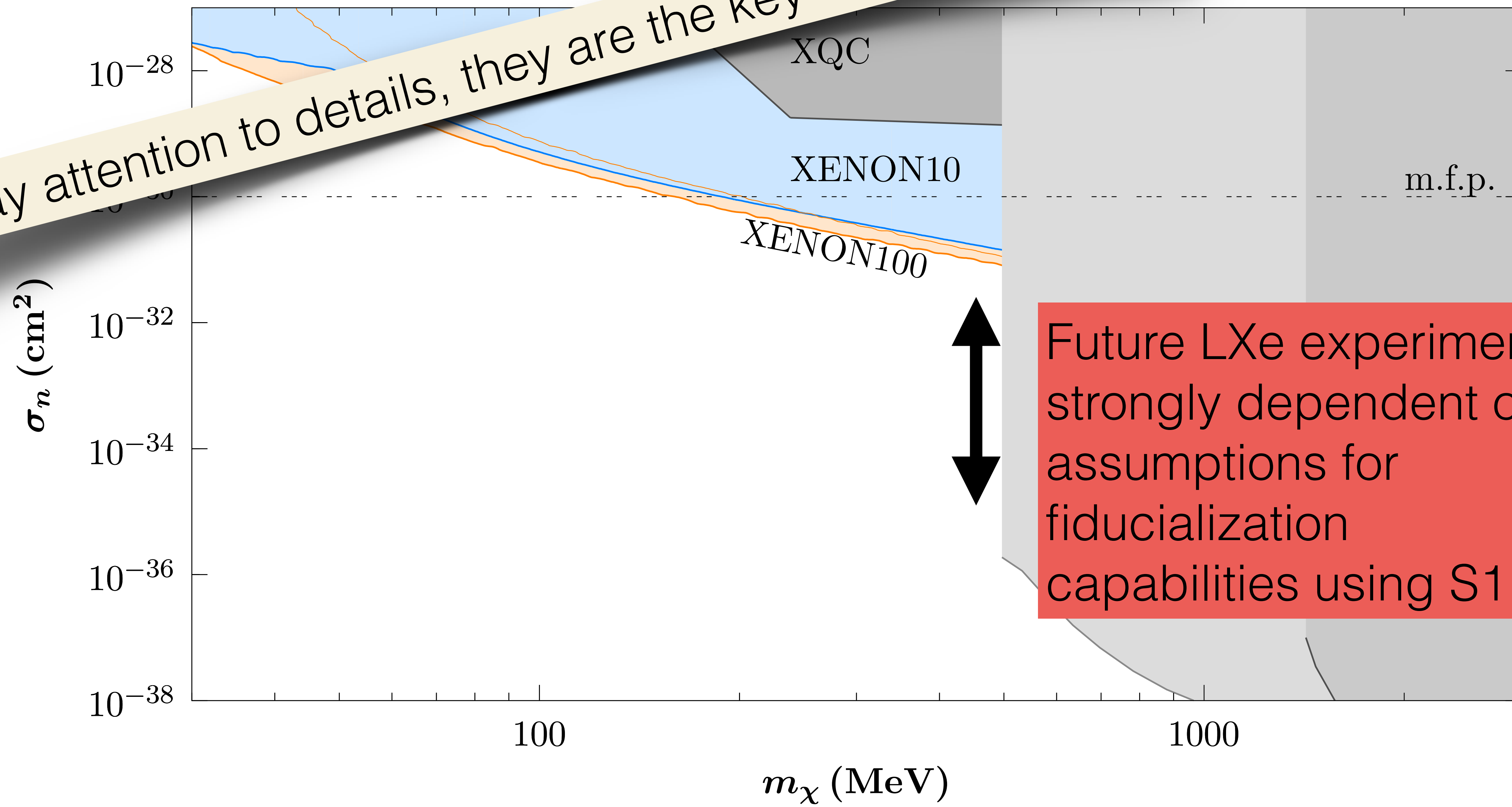
2. XENON1T is running

XENON1T expect a ER background at the of 10^{-4} /kg/day/keV **(in the fiducial volume)**

sub-GeV sensitivity to nuclear recoils



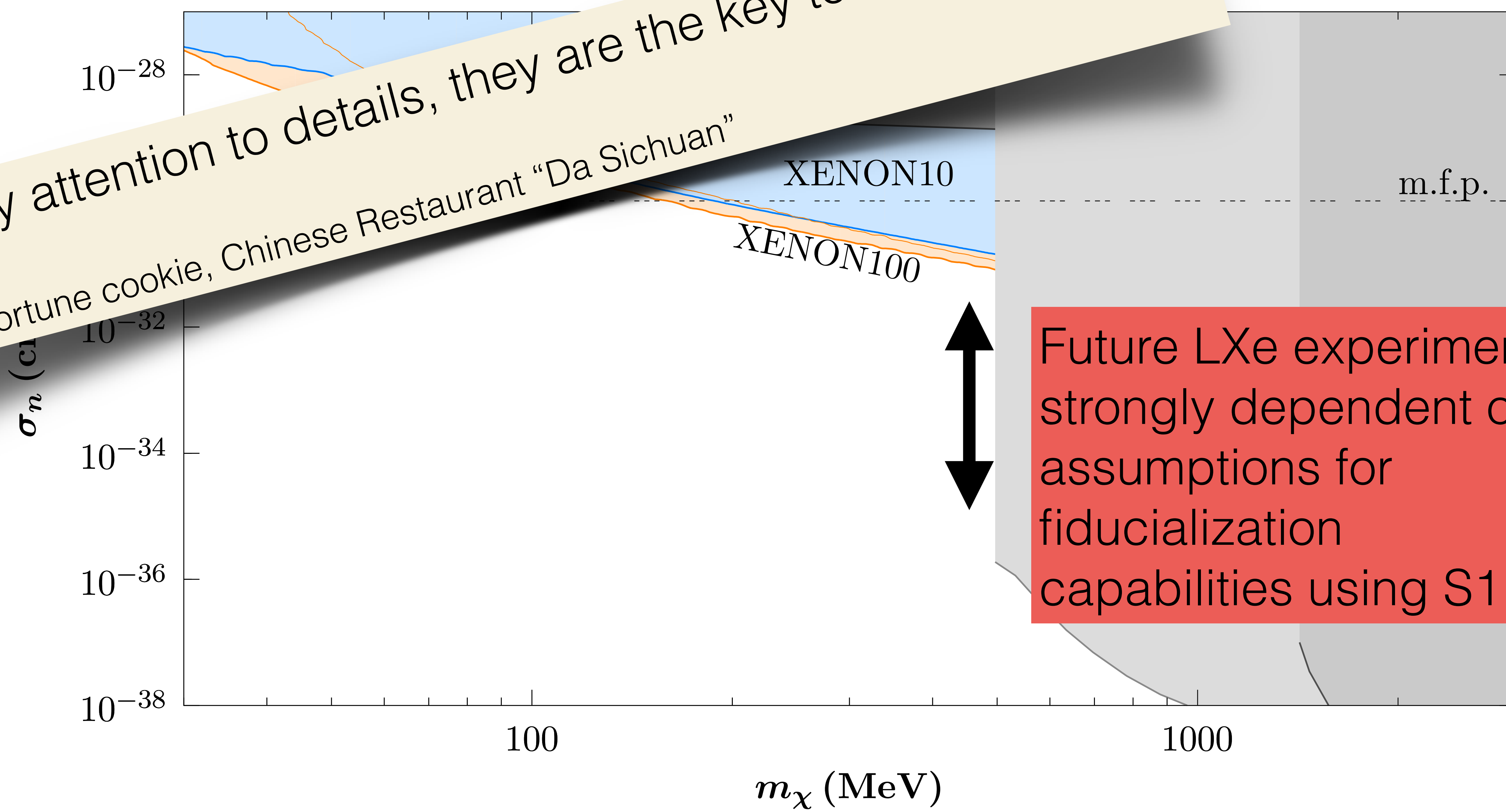
sub-GeV sensitivity to nuclear recoils



"Pay attention to details, they are the key to success"

Future LXe experiments: strongly dependent on assumptions for fiducialization capabilities using S1

sub-GeV sensitivity to nuclear recoils

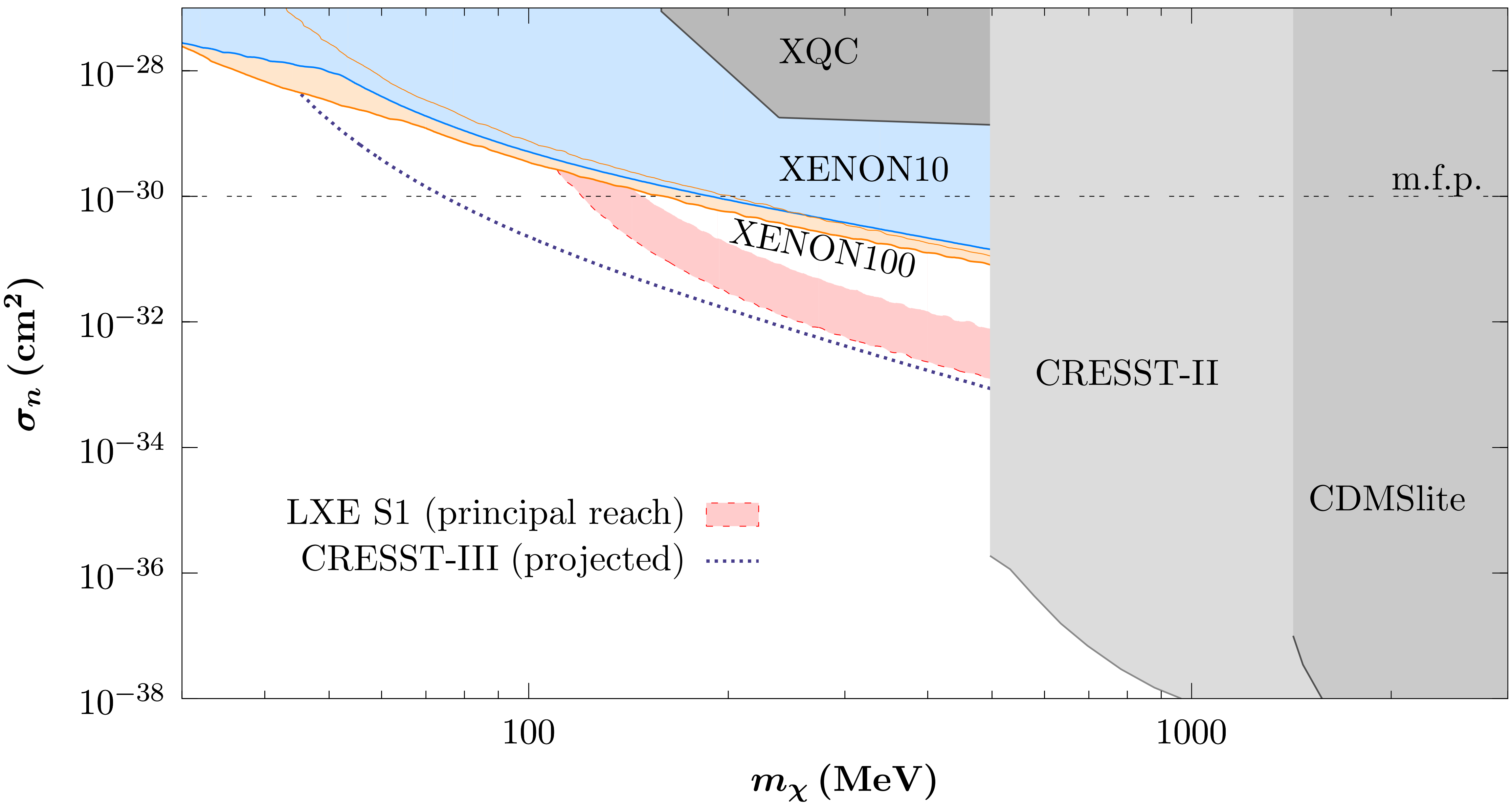


"Pay attention to details, they are the key to success"

Fortune cookie, Chinese Restaurant "Da Sichuan"

Future LXe experiments: strongly dependent on assumptions for fiducialization capabilities using S1

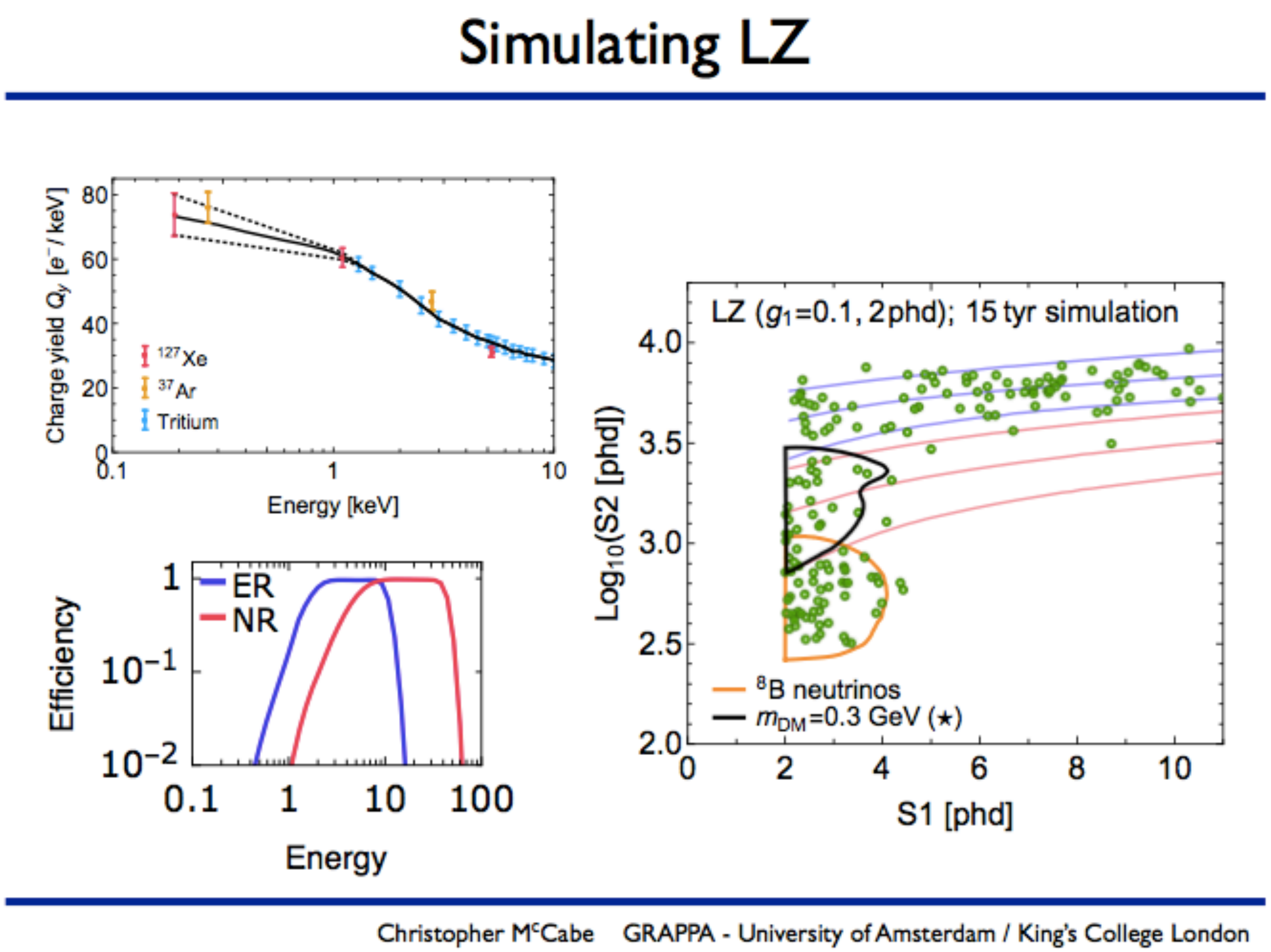
sub-GeV sensitivity to nuclear recoils

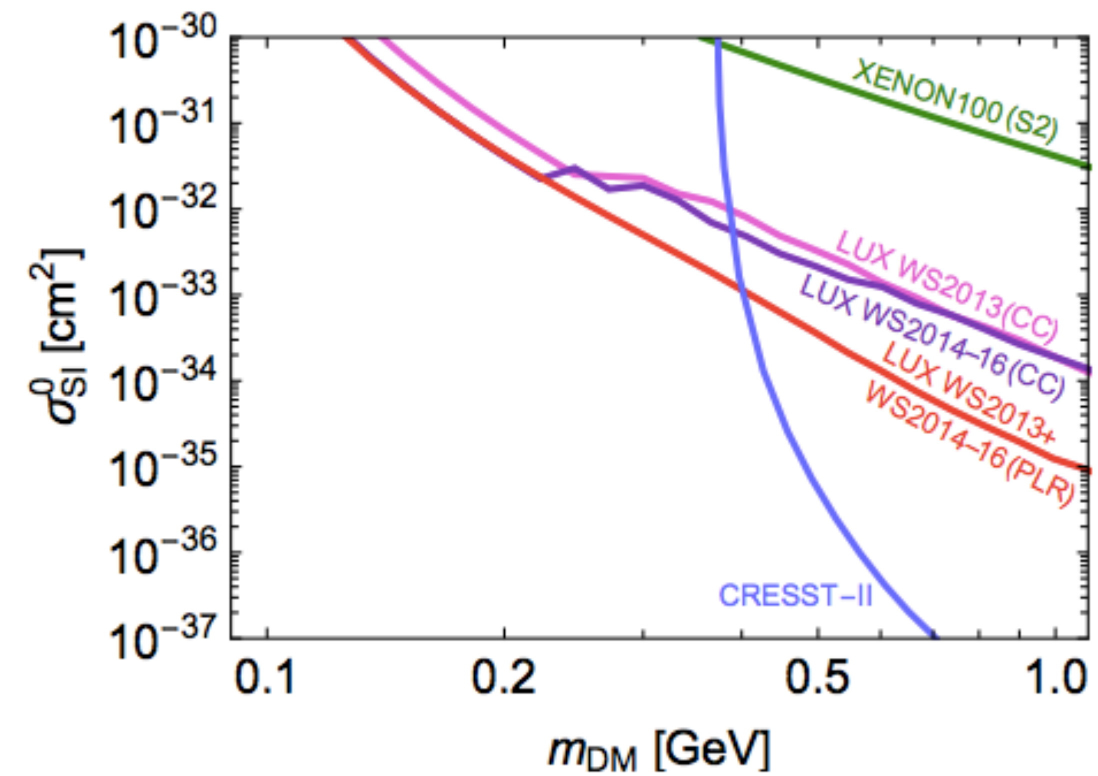


LXE: fiducialization with 2 scintillation photons, each detected with efficiency 40 - 100%
CRESST-III: projection with claimed purity-target of 0.01 events/kg/day/keV and 100 eV threshold

LUX limit from photon emission

McCabe 2017

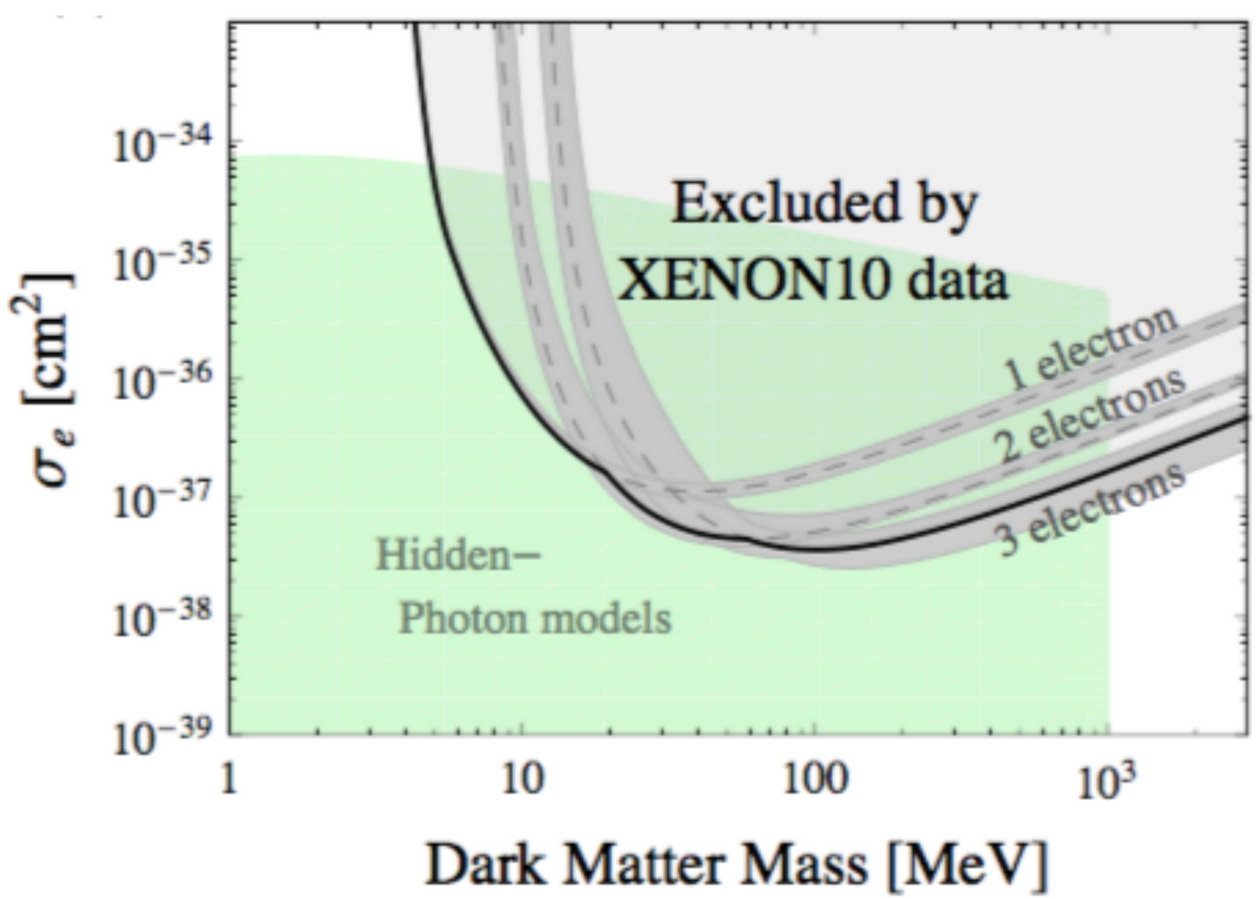




Utilizing the Bremsstrahlung process, LUX yields strongest bounds once bringing back S1

sub-GeV DM already constrained in DM-electron scattering

Essig et al. 2012



=> we may improve on current limits, when DM-electron scattering cross section is at least suppressed

=> “leptophobic” DM models

“Leptophobic” Dark Matter

Consider a very simple form of DM that couples to quarks at tree level through gauged baryon number $U(1)_B$

$$\mathcal{L} = \mathcal{L}_\chi - \frac{1}{4}(V_B^{\mu\nu})^2 + \frac{1}{2}m_V^2(V_B^\mu)^2 - \frac{\kappa}{2}V_B^{\mu\nu}F_{\mu\nu} + g_B V_B^\mu J_\mu^B$$

Baryon current $J_B^\mu \equiv \frac{1}{3}\sum_i \bar{q}_i\gamma^\mu q_i$

Kinetic mixing $\kappa_{\rm tree} = 0$

$$\mathcal{L}_\chi = i\bar{\chi}\not{D}\chi - m_\chi\bar{\chi}\chi, \quad \text{(Dirac DM)},$$
$$\mathcal{L}_\chi = |D_\mu\chi|^2 - m_\chi^2|\chi|^2 \quad \text{(Scalar DM)}.$$

NB: there are various ways to achieve correct relic density, and a sound cosmological scenario (i.e. avoid CMB constraints)

“Leptophobic” Dark Matter

Comparing the total cross sections for DM nucleon vs electron scattering

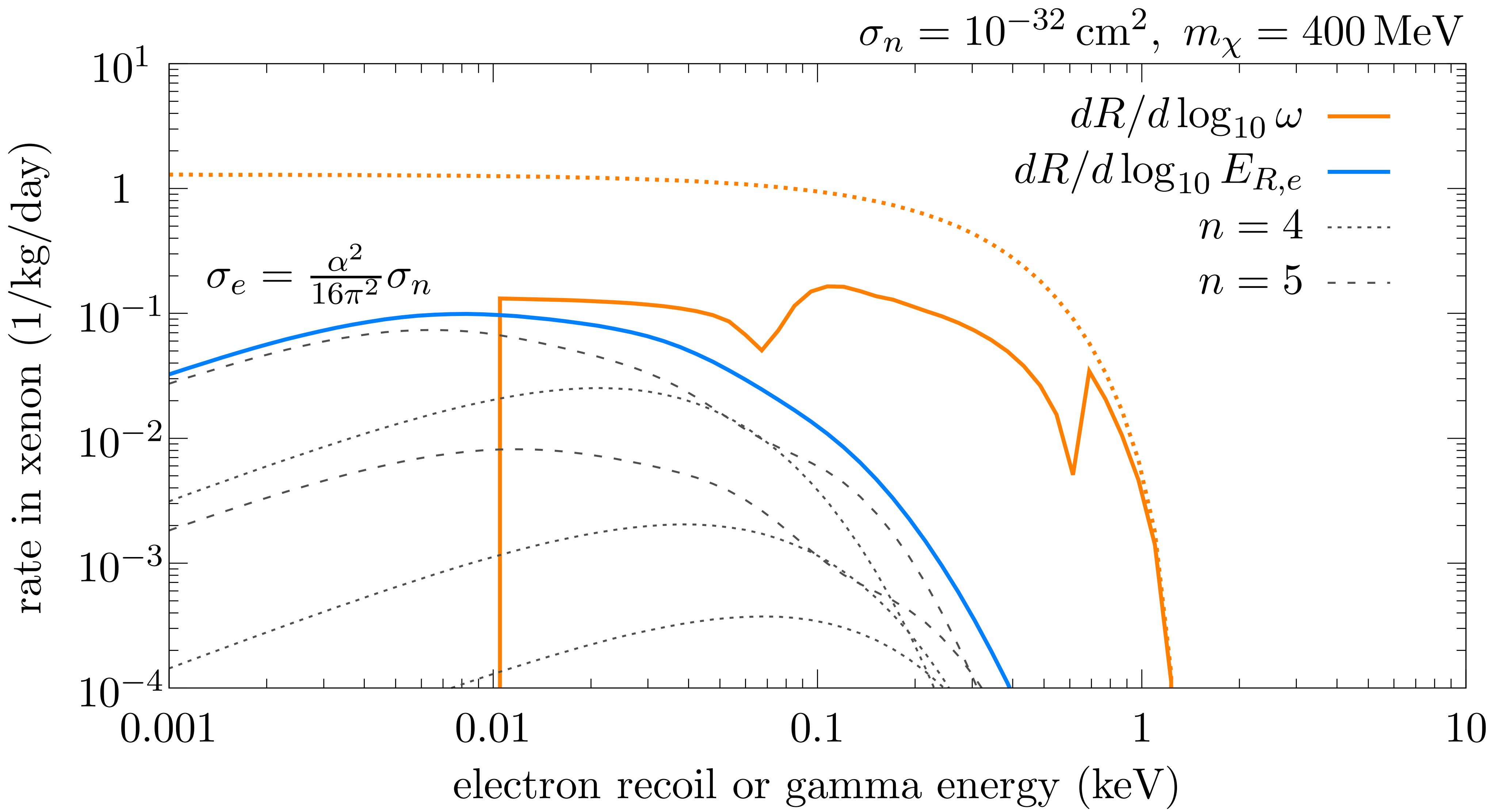
$$\sigma_n \sim \frac{16\pi\alpha_B^2 m_\chi^2}{m_V^4}, \qquad \sigma_e \sim \frac{16\pi\alpha_B \alpha \kappa^2 m_\chi^2}{m_V^4}$$

With radiatively induced kinetic mixing $\kappa_{\rm rad} \sim e g_B/(16\pi^2)$

=> $$\frac{\sigma_e}{\sigma_n} = \frac{\alpha\kappa^2}{\alpha_B} \sim \frac{\alpha^2}{16\pi^2} \sim 3 \times 10^{-7}$$

Large hierarchy is achieved and our method works already in the “vanilla model”. ✓

DM-nucleon vs. DM-electron scattering
new territory is covered



blue: DM-electron scattering

orange: photon emission from DM-nucleus scattering

2 SIMPs => prototypical light DM

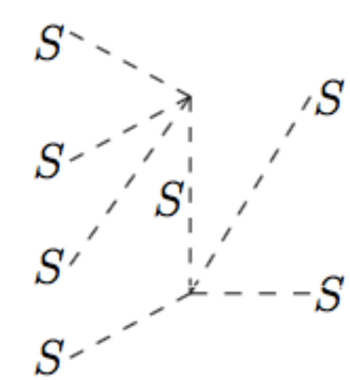
Here, SIMPs are code for particles that annihilate “strongly” through number violating processes, 3 -> 2 or 4 -> 2.

Two canonical incarnations

non-perturbative SIMPs

$$\mathcal{L}_{WZW} = \frac{2N_c}{15\pi^2 f_\pi^5}\varepsilon^{\mu\nu\rho\sigma}\mathrm{Tr}\left[\pi\partial_\mu\pi\partial_\nu\pi\partial_\rho\pi\partial_\sigma\pi\right]$$

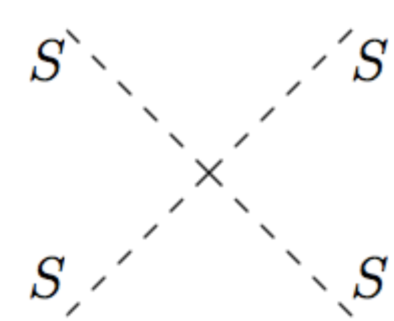
e.g. Hochberg, Kuflik, Volansky, Wacker (2014)



perturbative SIMPs e.g. λS^4

e.g. Bernal, Chu 2016

Interaction demanded by successful relic density put in peril by constraints on 2 -> 2 self-scattering in clusters $\sigma/m \lesssim 1\,\mathrm{bn/GeV}$



Bernal, Chu, JP 2017

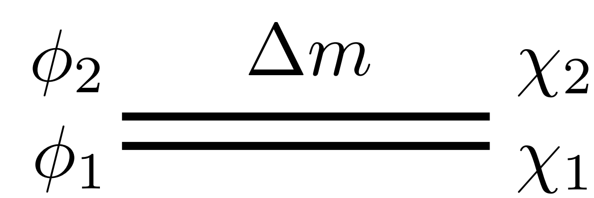
Simply split SIMPs

break tension between freeze-out and self-scattering

Consider complex scalar Φ or Dirac fermion Ψ

=> split real/imaginary and Weyl components by mass terms, such as

$$(m_\phi^2\, \Phi^2 + h.c.)$$



=> finely split states $\phi_{1,2}$ and $\chi_{1,2}$

$$\text{Pseudo-Dirac } \chi_{1,2}: \quad m_{1,2} \simeq M_D \mp \frac{m_L + m_R}{2} + O(\delta)$$

$$\text{Scalar } \phi_{1,2}: \quad m_{1,2}^2 = M^2 \mp m_\phi^2\,.$$

=> if gauged with U(1) "dark photon," interaction becomes *off-diagonal*

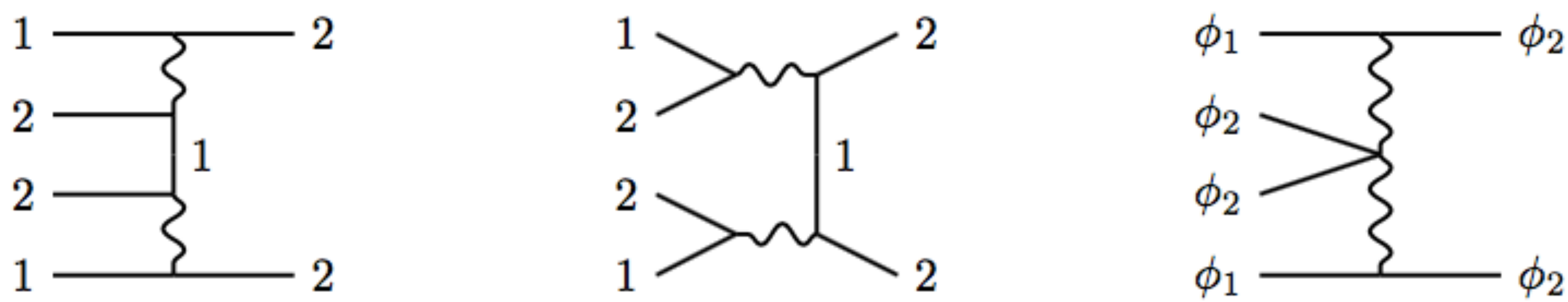
$$\mathcal{L}_{\text{int},\,\phi} = g_V\left(\phi_1 \partial^\mu \phi_2 - \phi_2 \partial_\mu \phi_1\right) V_\mu + \frac{1}{2} g_V^2 \left(\phi_1^2 + \phi_2^2\right) V^2 - V_\Phi(\phi_1,\, \phi_2)$$

$$\mathcal{L}_{\text{int},\,\chi} = i g_V \bar{\chi}_1 \gamma^\mu \chi_2 V_\mu$$

Bernal, Chu, JP 2017

Simply split SIMPs

Annihilation

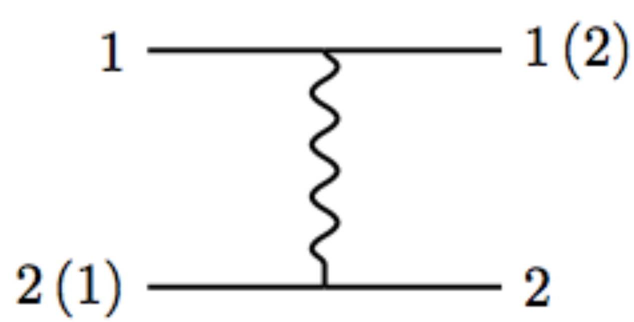


fermions, s-wave: only 1212 possible (Pauli exclusion) => **mass splitting enters** $n_2/n_1 \sim e^{-\Delta m/T'}$

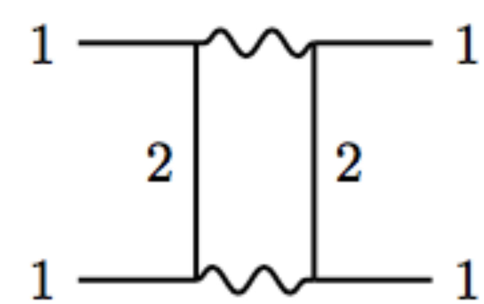
vs. Self-Scattering

regulated by left-over states 2 toady, after kinetic decoupling

$e^{-\Delta m/T_{f,kin}}$, τ_2



suppressed diagonal couplings

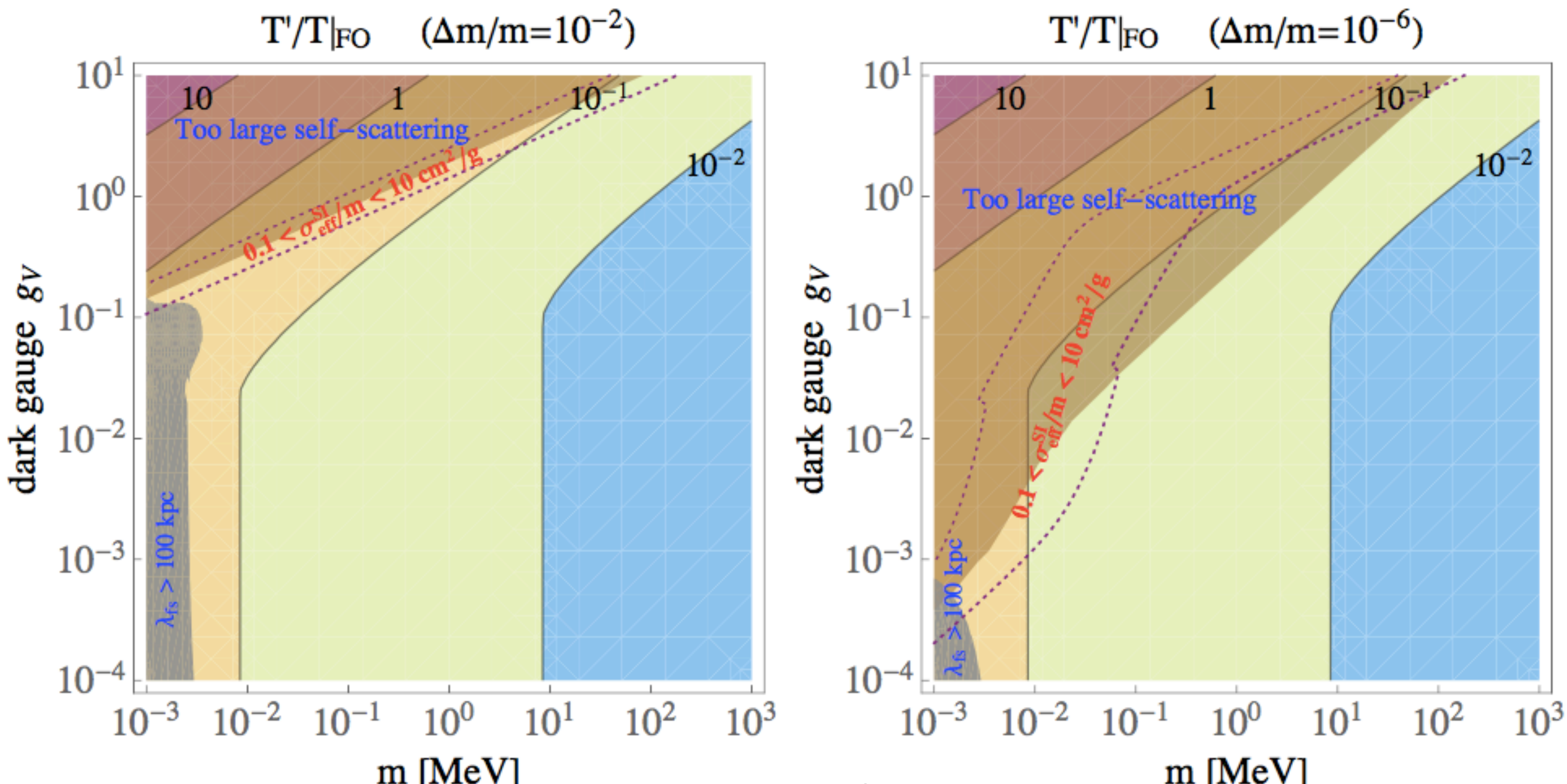


radiatively suppressed scattering

Bernal, Chu, JP 2017

Simply split SIMPs

Parameter space with prospective solutions to small-scale structure problems



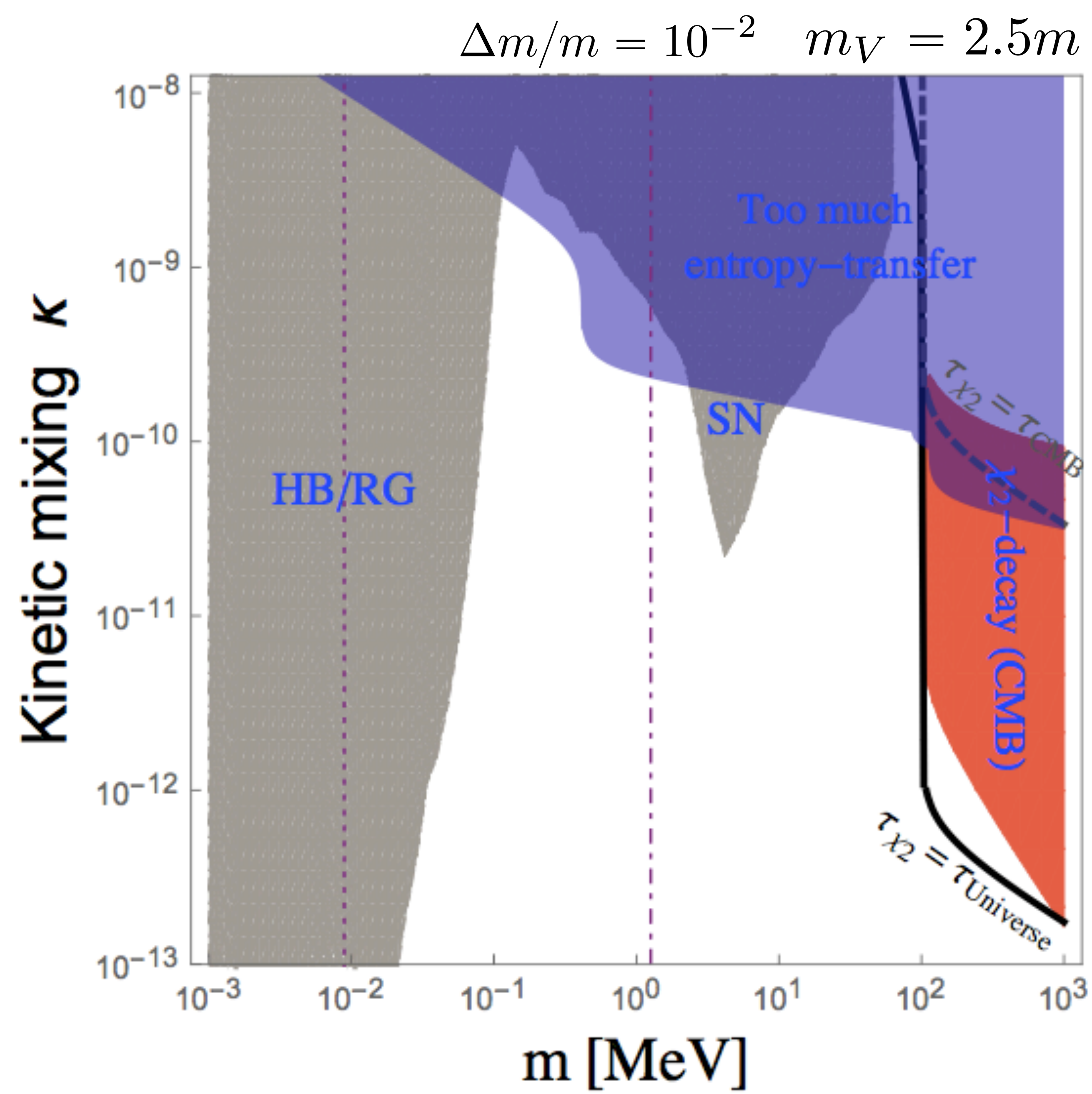
$m_V > 2m$

Bernal, Chu, JP 2017

Door to Phenomenology e.g. though kinetic mixing

In contrast to WIMPs, the prospects of detection of SIMPs are less certain, since their abundance is set in the hidden sector (no *a priori* thermal equilibrium requirement with SM)

=> here we consider kinetic mixing of dark photon V with strength κ



Bernal, Chu, JP 2017

Exothermic DM-electron scattering

$$2 + \mathrm{Atom} \to 1 + \mathrm{X}$$

Excited state 2 can scatter on electrons and/or nuclei. When neglecting kinetic energy of DM => monochromatic energy deposition by Δm

$$\frac{d\sigma v}{d\ln E_{R,e}} = \bar{\sigma}_e \frac{m}{4\,\mu_{\chi e}^2} \times \left[\int d\Omega_{\vec{p}_e'}\, q |F_{\rm DM}(q)|^2 \sum_{\rm deg.\,states} |f_{\rm ion}(q)|^2 \right]_{q=\sqrt{2m\,(\Delta m - E_B - E_{R,e})}}$$

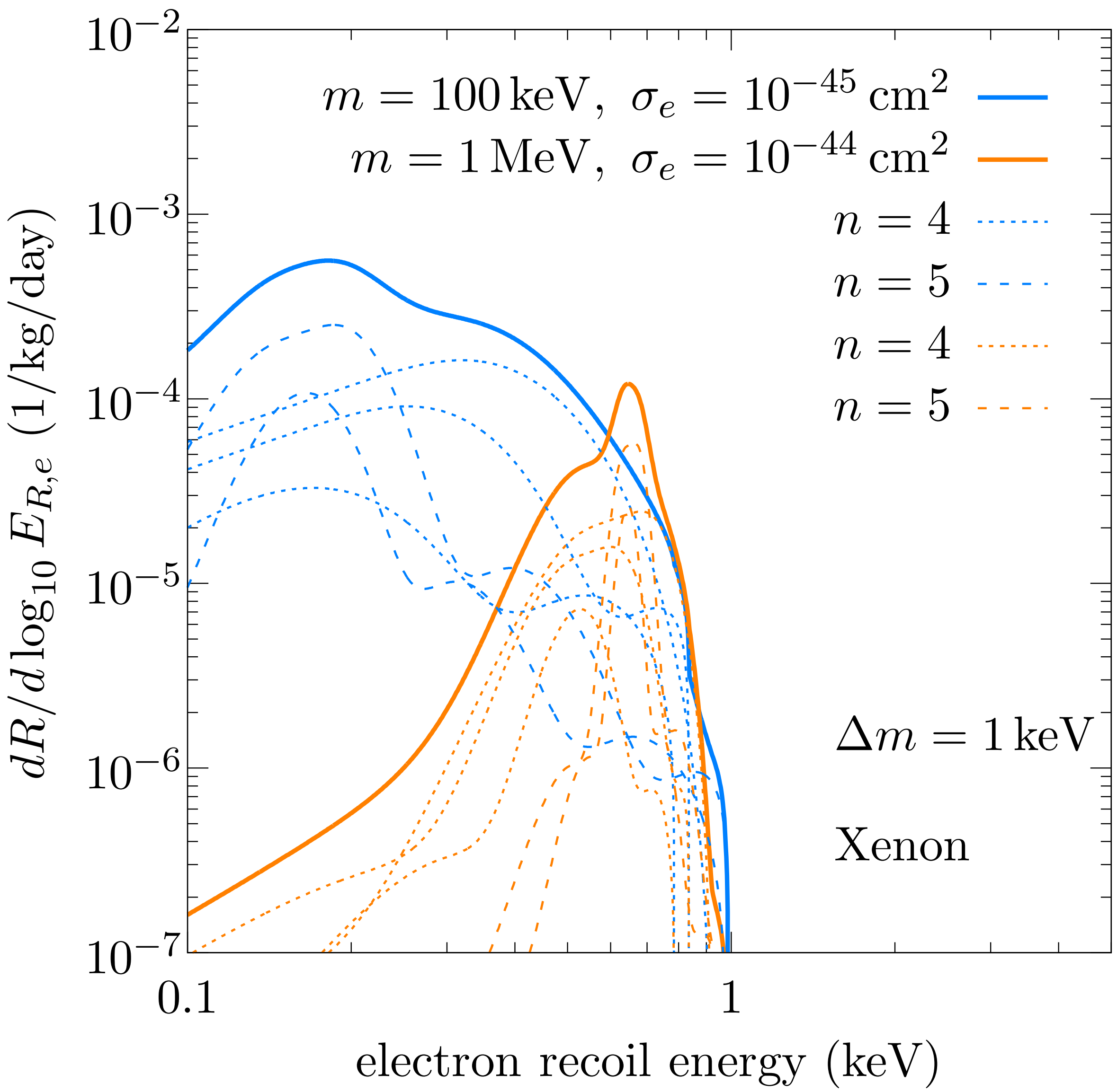
DM-electron c.s. — DM form factor — atomic form factor — momentum transfer

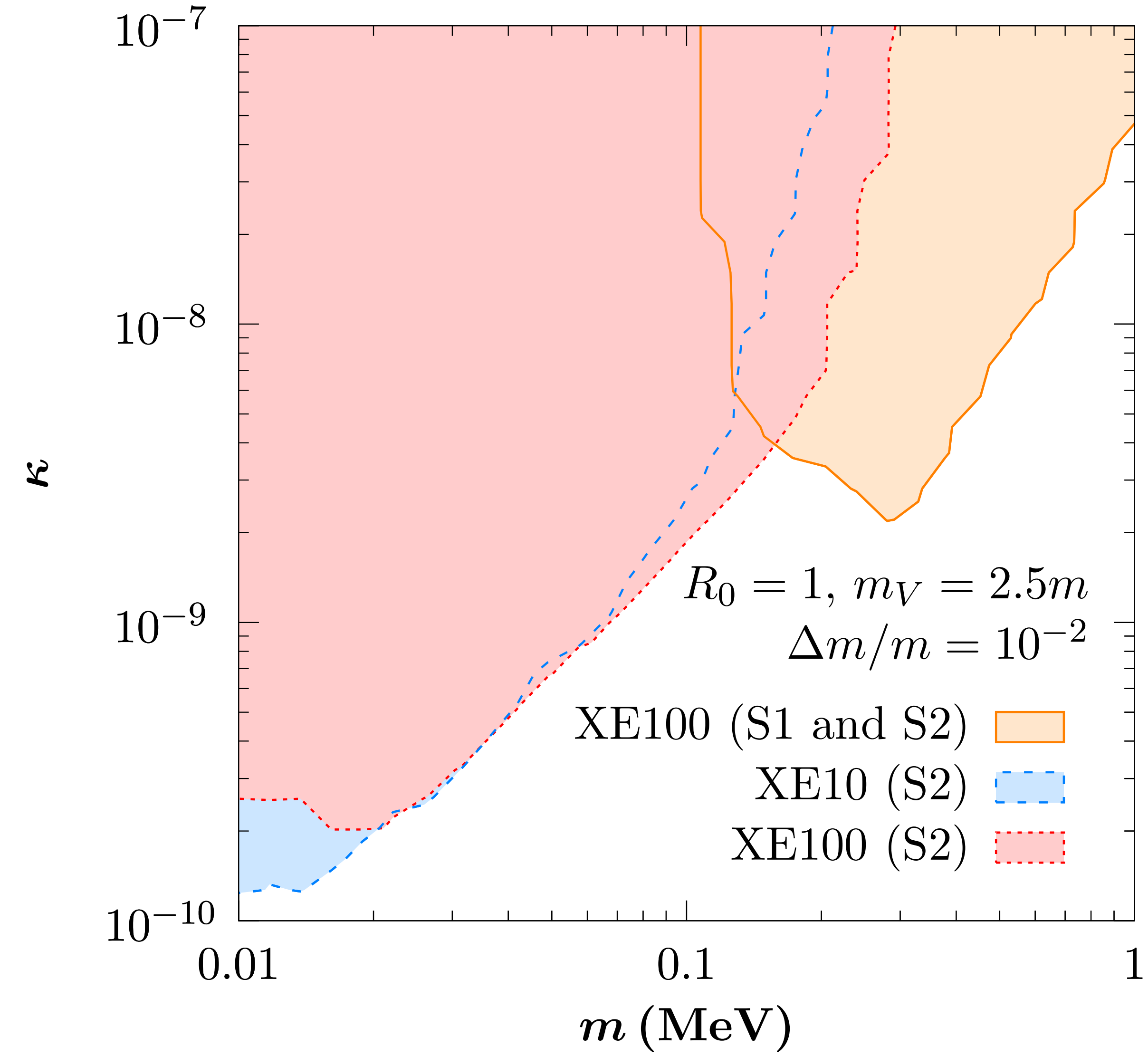
$$\frac{d\sigma_{nl}\, v}{d\ln E_{R,e}} = \bar{\sigma}_e \frac{(2l+1)\, m\, {p_e'}^2}{4\,(2\pi)^3\, \mu_{\chi e}^2} \int_{|p_e' - \sqrt{2m\,(\Delta m - E_B - E_{R,e})}|}^{p_e' + \sqrt{2m\,(\Delta m - E_B - E_{R,e})}} dp'\, p' |\chi_{nl}(p')|^2$$

F.T. of bound e- wave function

Bernal, Chu, JP 2017

Exothermic DM-electron scattering





=> once $\Delta m \gtrsim 1\,\mathrm{keV}$ energy deposition is large enough for reducing the background via the scintillation signal (same theme as before)

Conclusions and Outlook

- **existing** (and upcoming) direct detection experiments already break new ground in the light DM region - sensitivity to MeV-scale (lighter than 0.5 GeV) DM-nucleon interaction is possible
  => we break the "no-go" theorem from kinematics of elastic DM-nucleus scattering by going to the inelastic channel of photon emission with higher endpoint energies
  => delivered proof of existence of models that live in the interesting region
- There are a number of ways to improve on our proposals
  - Direct "shake-off" contribution of electrons + "beyond polarizability" contributions increase charge multiplicity (not a small effect)
  - Spin-dependent scattering: a complete, even loop-induced absence of DM-electron couplings is possible
  - Work out the analog for semiconductor detectors
  - Re-evaluation of the neutrino floor
- SIMPs provide a prototype model for sub-GeV particles that call for being explored with direct detection; in the concrete model presented, we exploited the stored mass energy in finely-split states