Title: Direct detection signals of light dark matter

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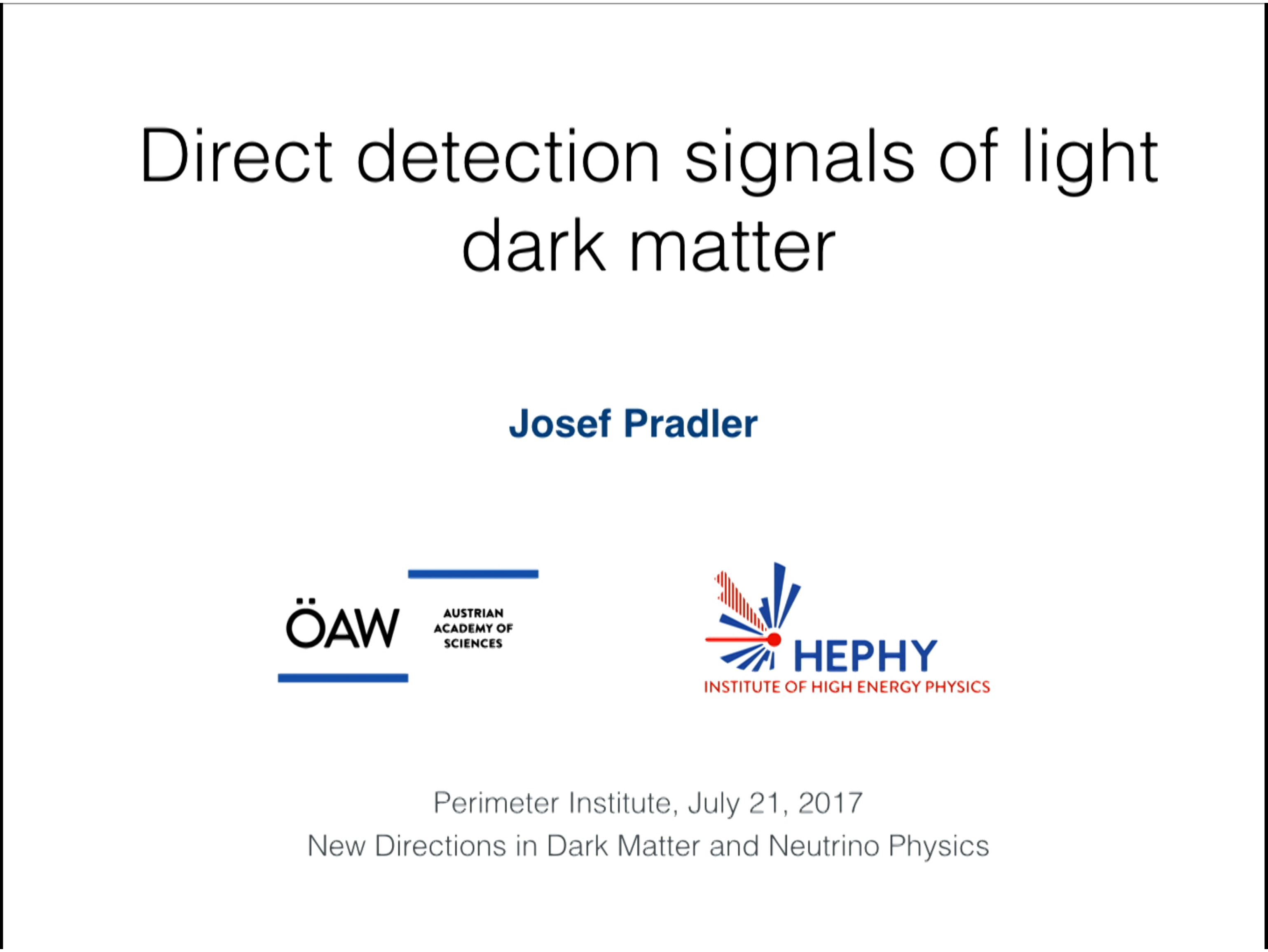
Abstract:



Direct detection signals of light dark matter

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HEPHY INSTITUTE OF HIGH ENERGY PHYSICS

Perimeter Institute, July 21, 2017
New Directions in Dark Matter and Neutrino Physics

Detecting light DM - with existing technology

① **DM-nucleus scattering**

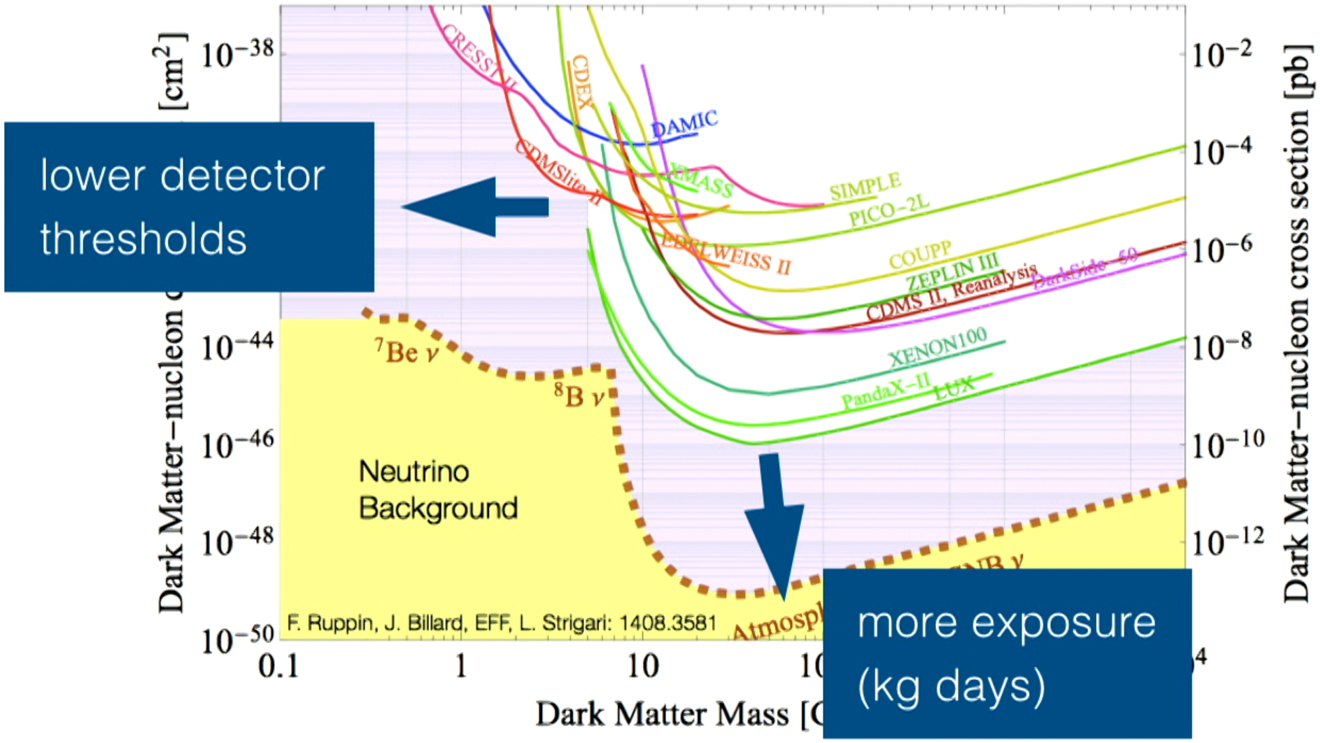
C. Kouvaris and JP
Phys.Rev.Lett. 118, 031803 (2017)

② **DM-electron scattering**

H. An, M. Pospelov, JP, A. Ritz,
in preparation

N. Bernal, X. Chu, JP
Phys.Rev. D95 (2017)

A (partial) summary of 2 decades of experimental effort

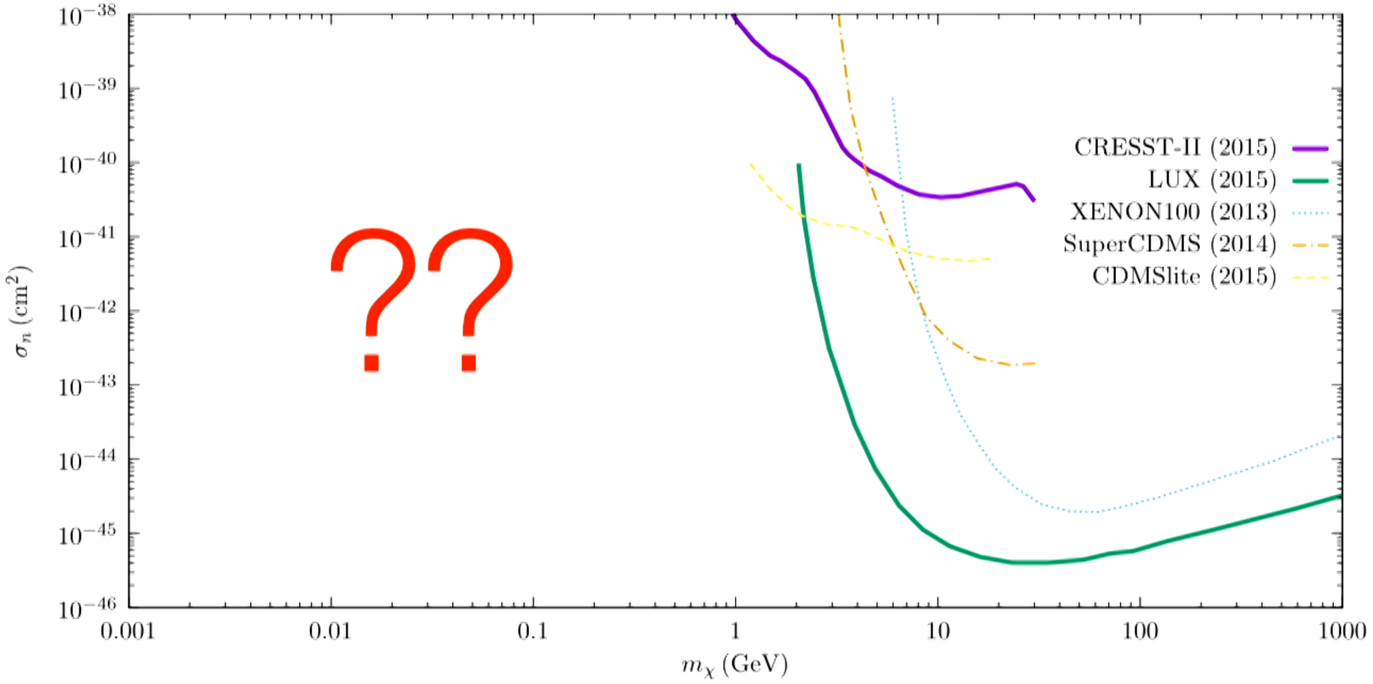


lower detector thresholds

more exposure (kg days)

CF1 Snowmass report, Ruppin et al 2014

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



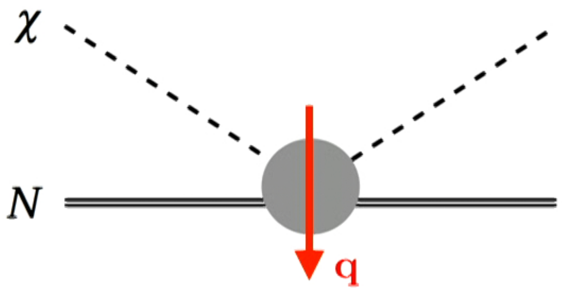
"light Dark Matter"

WIMPs

Direct Detection

Nuclear kinetic recoil energy

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



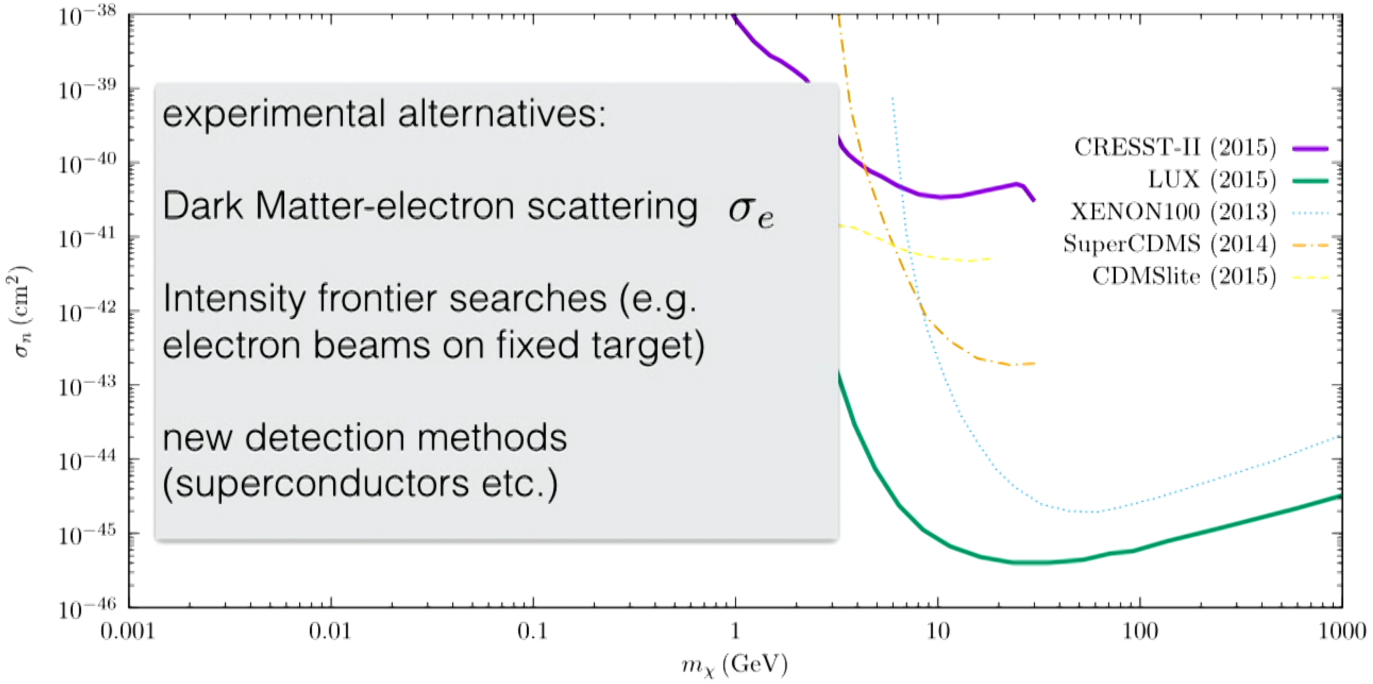
=> A given recoil, demands a *minimum* relative velocity

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

=> 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:

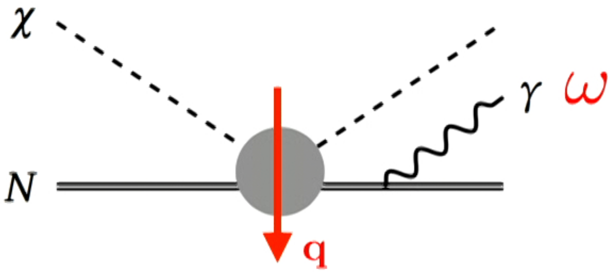
Dark Matter-electron scattering σ_e

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



Inelastic channel of photon emission from the nucleus

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

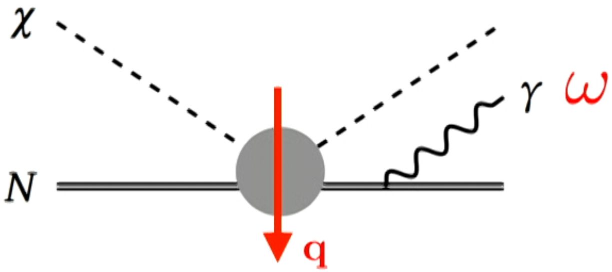
Key II: 0.5 keV nuclear recoil is easily missed,
0.5 keV photon is never missed!

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

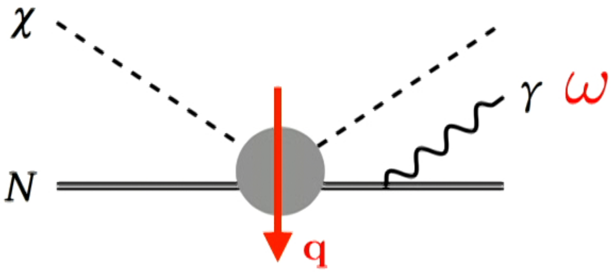
NB: The factorization holds if $\delta\mathbf{q} = (\mathbf{p}'_N - \mathbf{p}_N - \mathbf{k}) - (\mathbf{p}'_N - \mathbf{p}_N)_{\omega=0} \ll \mathbf{q}$

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

①

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

$$\frac{d\sigma}{dE_R d\omega} = \frac{4Z^2\alpha}{3\pi}\frac{1}{\omega}\frac{E_R}{m_N} \times \frac{d\sigma}{dE_R}$$



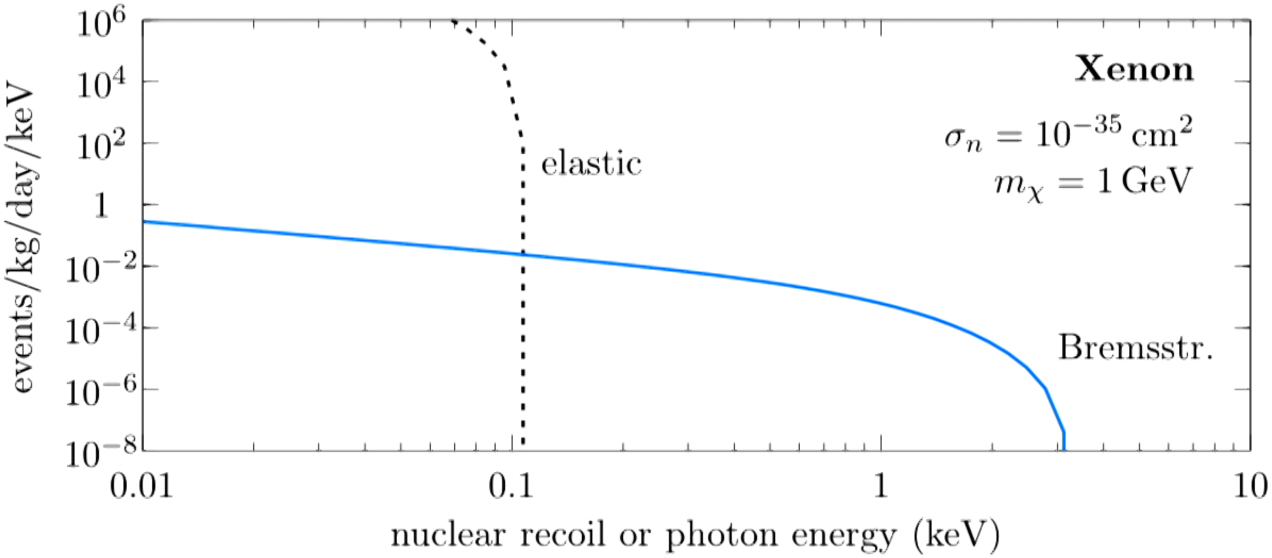
Price to pay

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

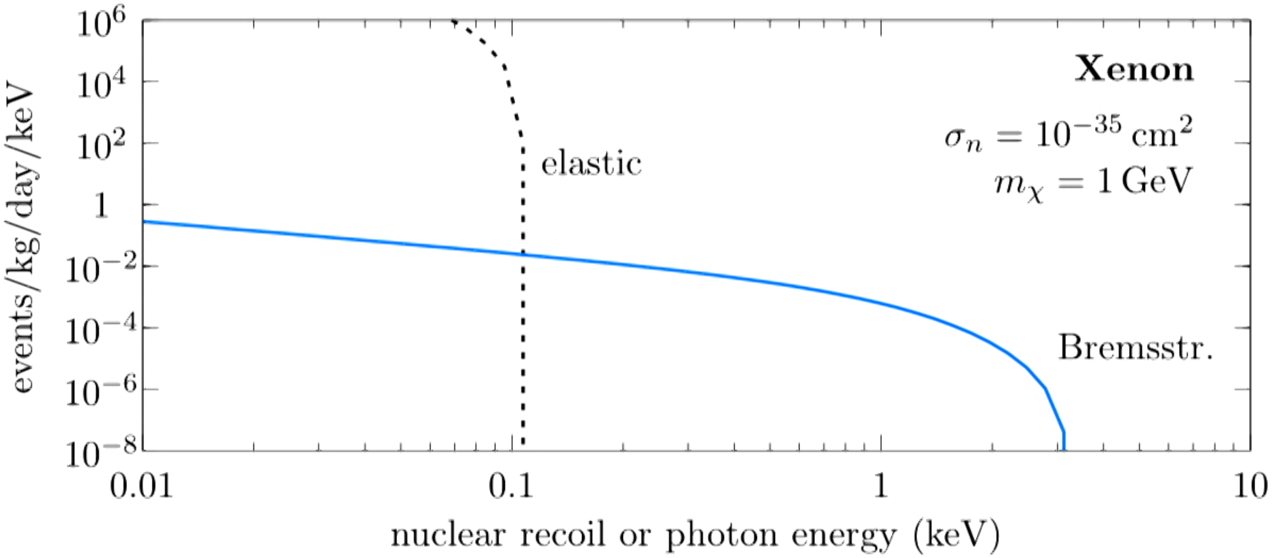
Can we overcome this suppression in rate?

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

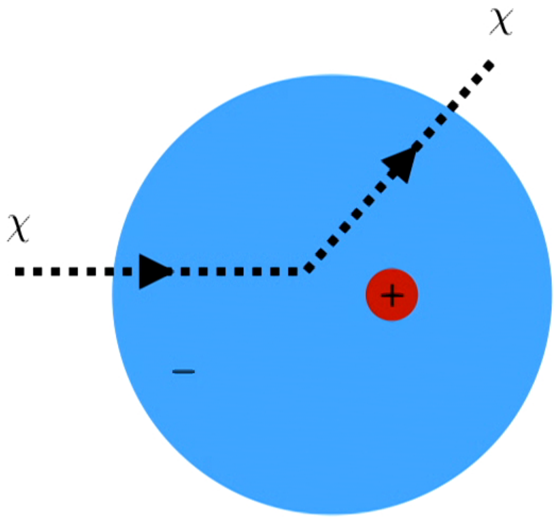
Gaining access to sub-GeV Dark Matter *through nuclear recoils*



Gaining access to sub-GeV Dark Matter through nuclear recoils



Atomic physics picture of photon-emission



“Polarized Atom”

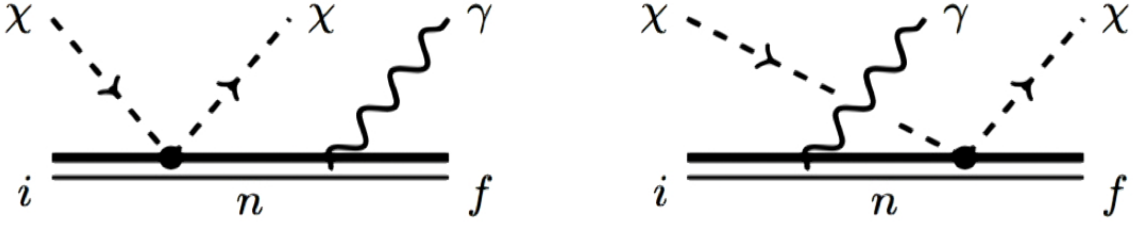
The naive treatment of Bremsstrahlung scales as 1/ω all the way to lowest energies

=> 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



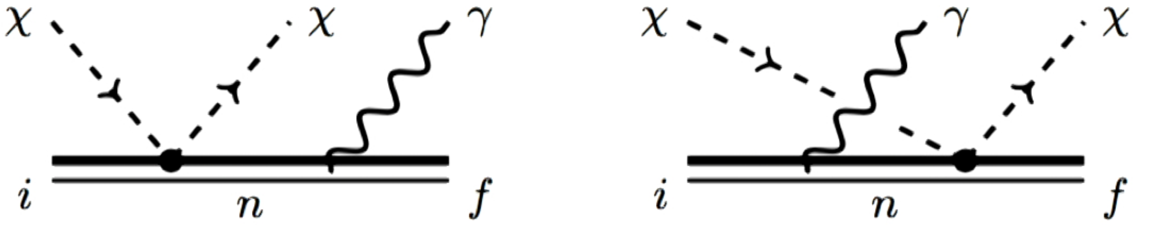
=> QM calculation

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

dipole matrix element for
emission of photon

boost of the electron cloud

Atomic physics picture of photon-emission



dipole emission polarizability of the atom

For f=i:

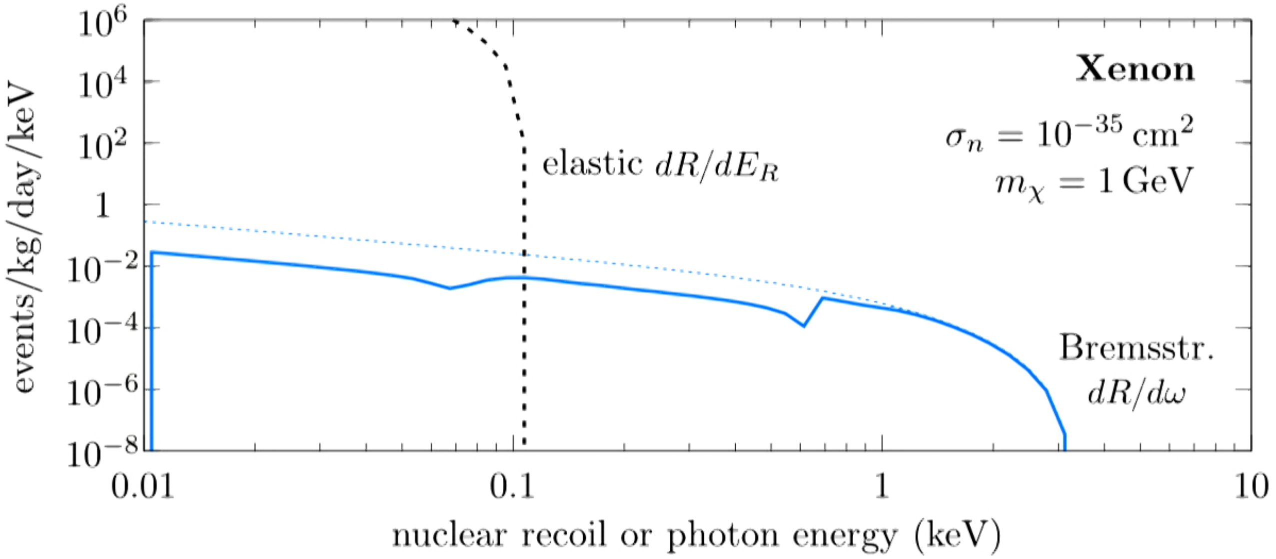
$$\frac{d\sigma}{d\omega dE_R} \propto \omega^3 \times |\alpha(\omega)|^2 \times \frac{E_R}{m_N} \times \frac{d\sigma}{dE_R}$$

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

for large ω naive result is recovered ✓

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

including atomic physics modification



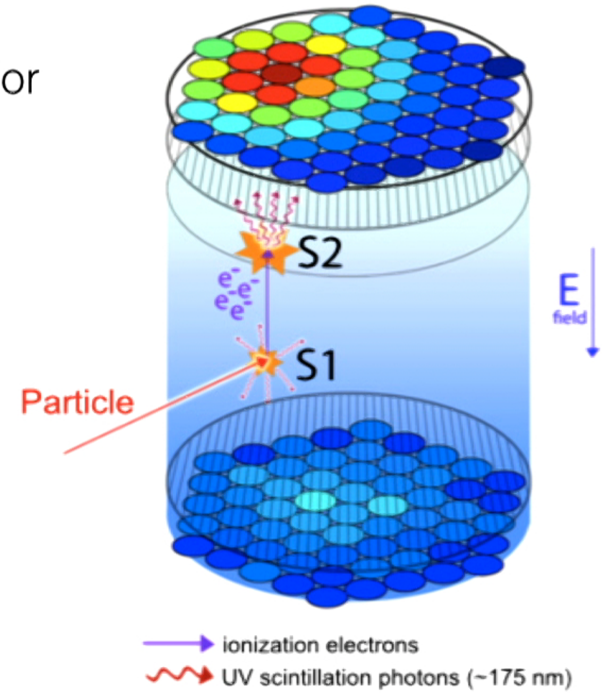
=> importantly, we can draw from atomic data listings for atom polarizabilities!

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

scattering events classify as *"electron recoils"*

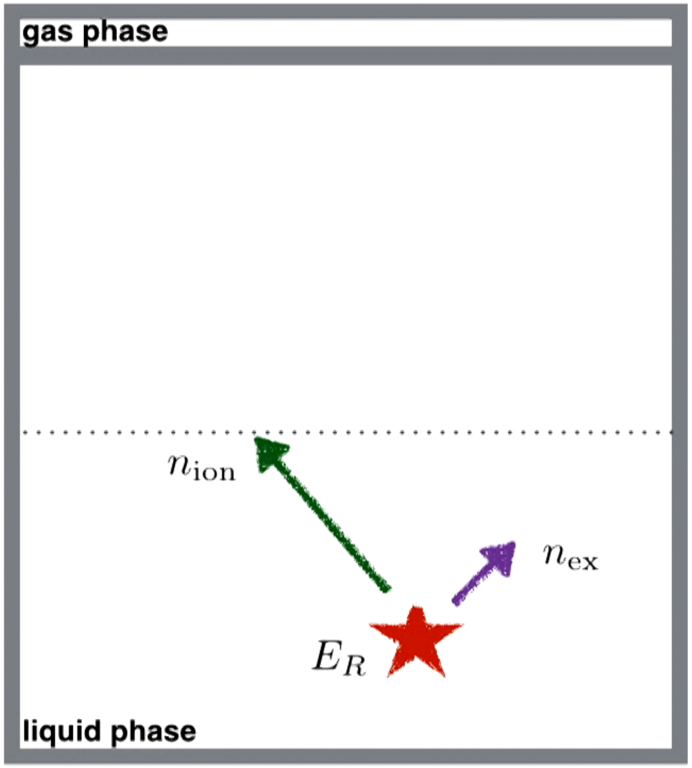


How does an “electron recoil” signal look in a LXE detector?

$$N_Q = \frac{E_R}{W} = n_{\rm ion} + n_{\rm ex}$$

$$W \simeq 13.7\,\mathrm{eV} \qquad n_{\rm ex}/n_{\rm ion} = \text{few}\,\%$$

Given energy deposition E_R, a number of quanta N_Q is produced, distributed in electron-ion pairs and excited atoms $n_{\rm ex}$



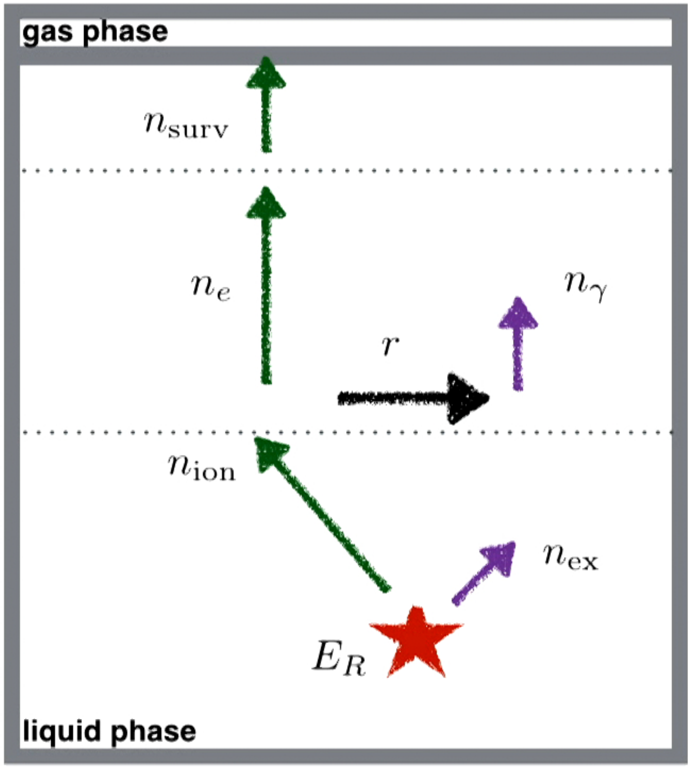
How does an “electron recoil” signal look in a LXE detector?

$$p_{\rm surv} \simeq \exp\left(-\frac{\Delta z}{\tau v_d}\right)$$

$v_d \simeq 1.7 \mathrm{mm}/\mu\mathrm{s} \qquad \tau > 1\,\mathrm{s}$

Electrons are drifted in the electric field towards the liquid-gas interface; depending where they are created, attenuation occurs

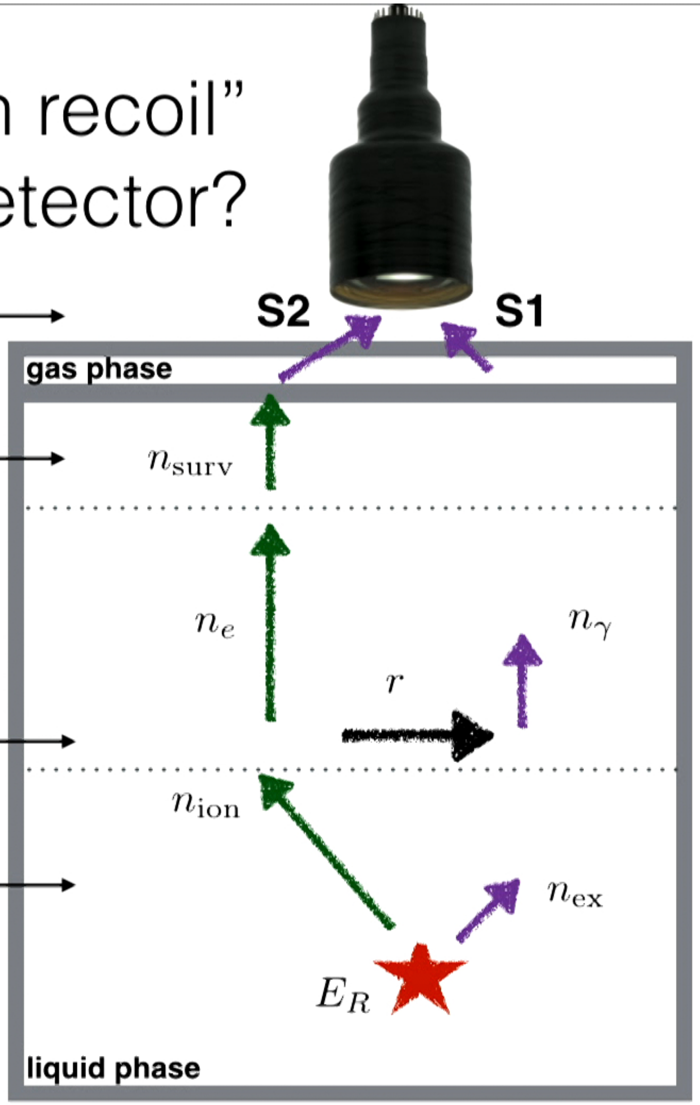
$p_{\rm surv} \sim 0.6 - 0.9$



How does an “electron recoil” signal look in a LXE detector?

detector specific
- fluctuates
- fluctuates

LXE universal (given E-field)
- fluctuates
- fluctuates



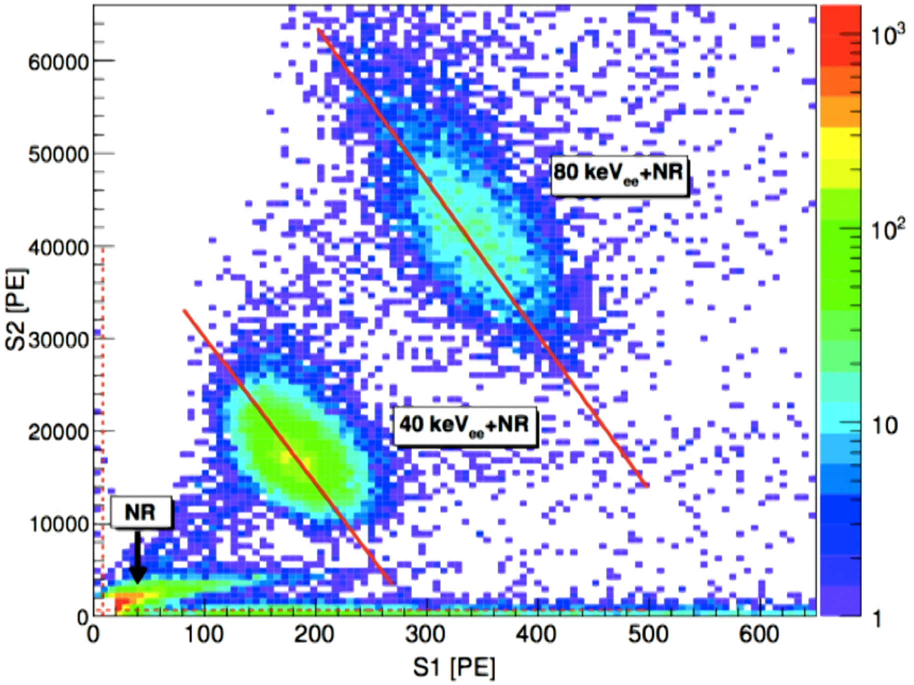
=> derive PDF(S1,S2 | ER)

How does an "electron recoil" signal look in a LXE detector?

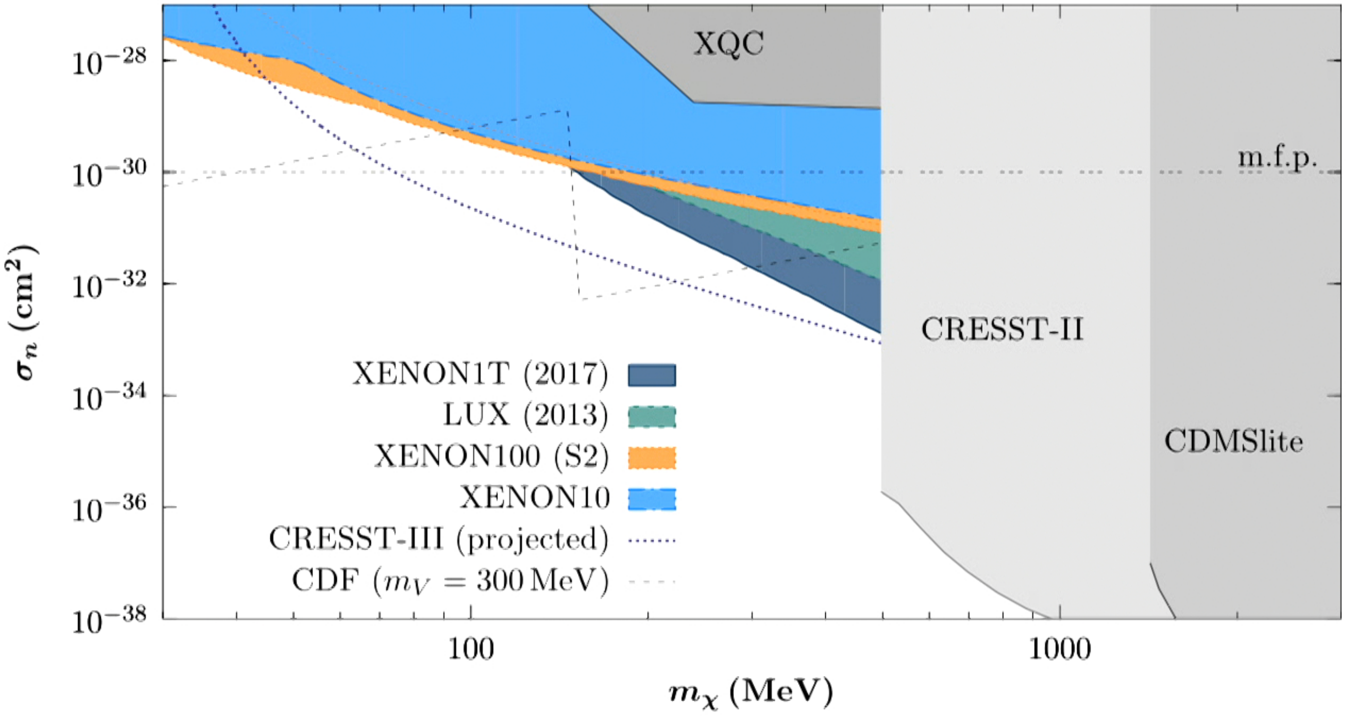
e.g. PandaX

$$N_Q = n_{\rm ion} + n_{\rm ex} \\ = n_\gamma + n_e \\ = \frac{S1}{g_1} + \frac{S2}{g_2}$$

note the anti-correlation between S1 and S2

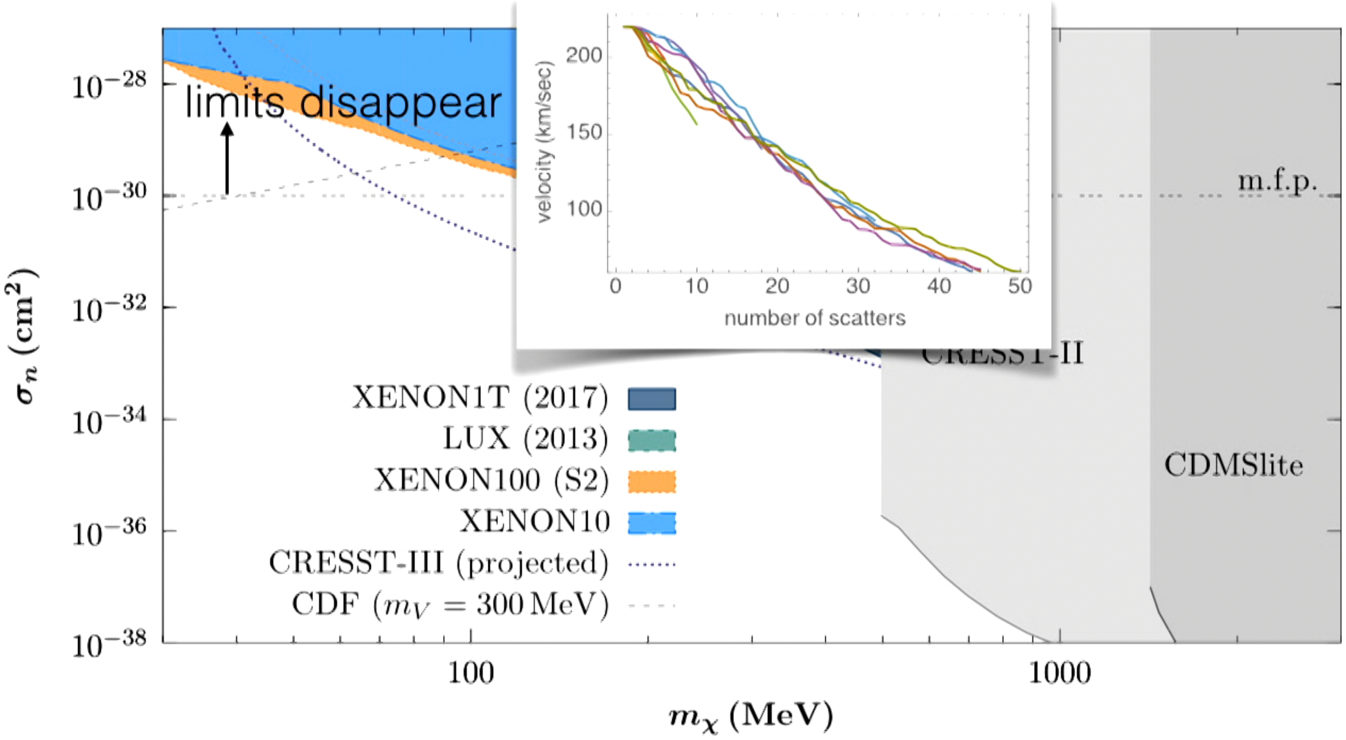


Current limits + projections



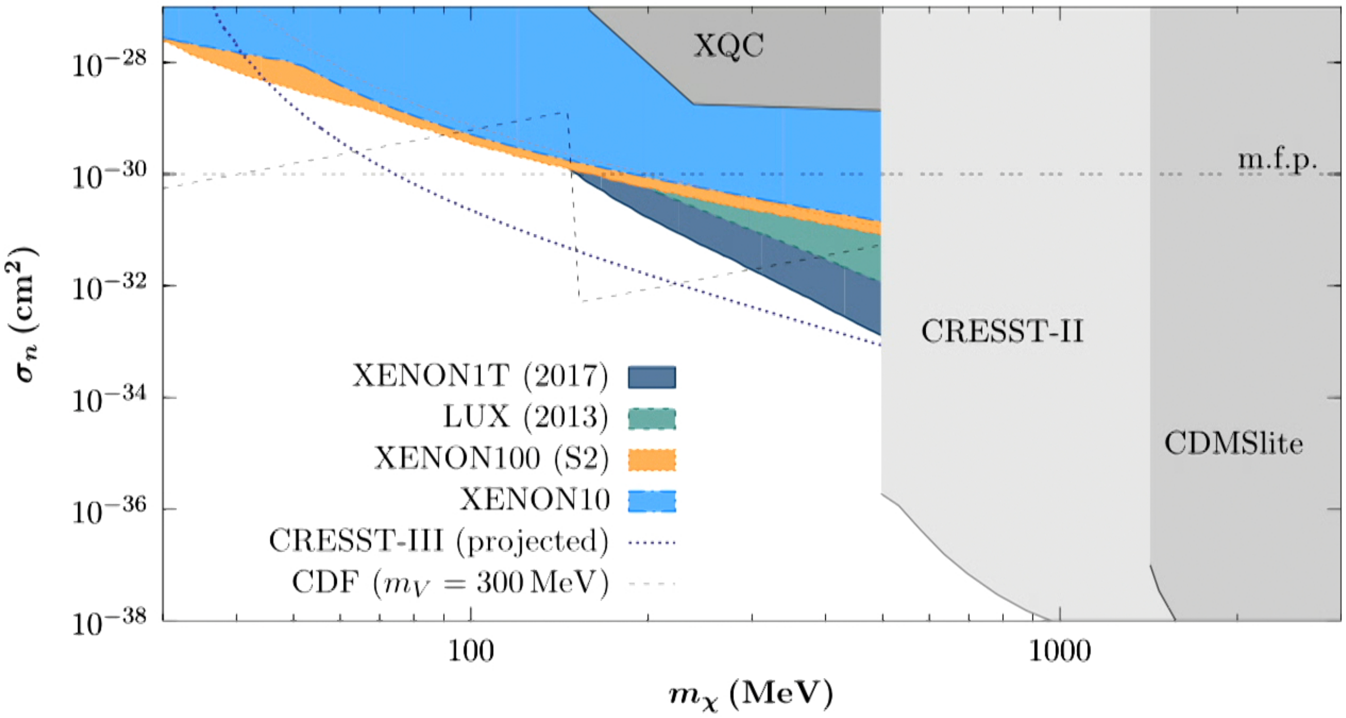
=> First limit on sub-500 MeV DM-nucleon scattering!

Current limits + projections



=> First limit on sub-500 MeV DM-nucleon scattering!

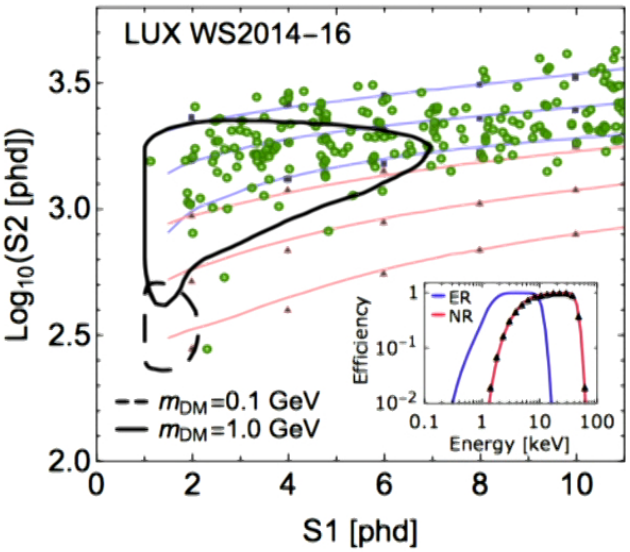
Current limits + projections



=> First limit on sub-500 MeV DM-nucleon scattering!

Detailed signal morphology from DM-induced Bremsstrahlung

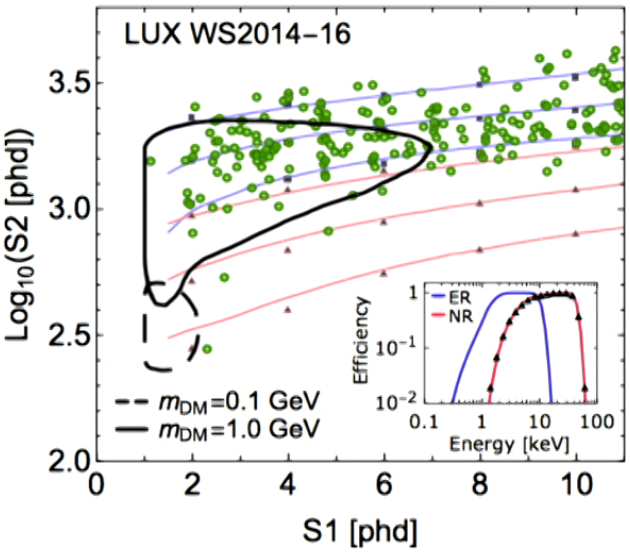
McCabe 2017



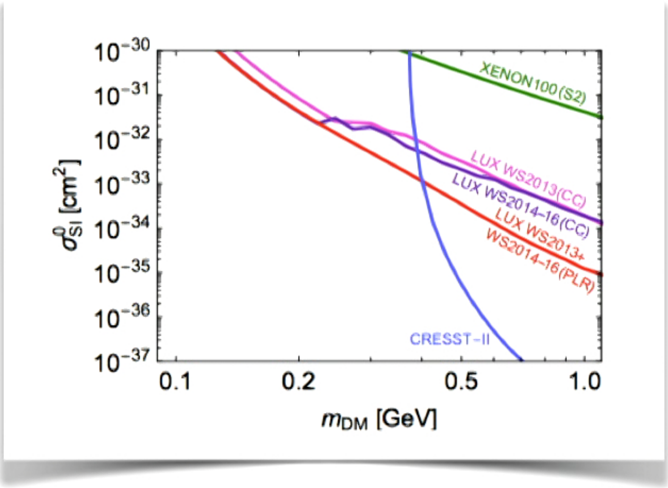
=> limits can be further improved when distribution of S1 vs. S2 is taken into account (signal region appears to slip into the NR-band)

Detailed signal morphology from DM-induced Bremsstrahlung

McCabe 2017



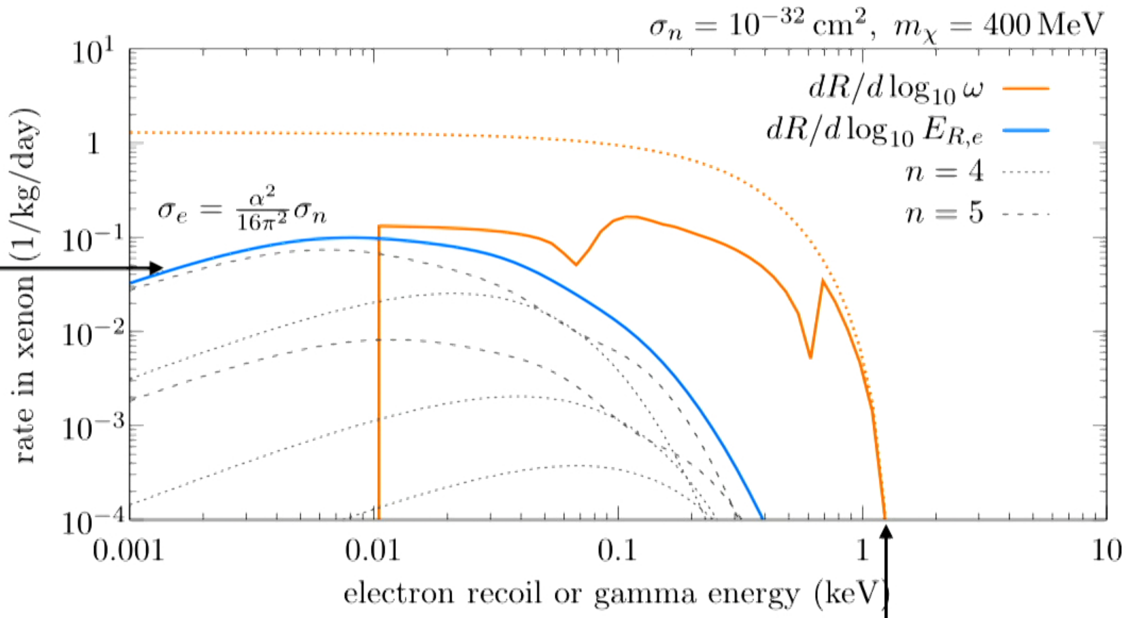
=>



=> limits can be further improved when distribution of S1 vs. S2 is taken into account (signal region appears to slip into the NR-band)

Method favors leptophobic DM models

radiatively
induced
DM-electron
scattering
(DM coupled
to baryonic
current)

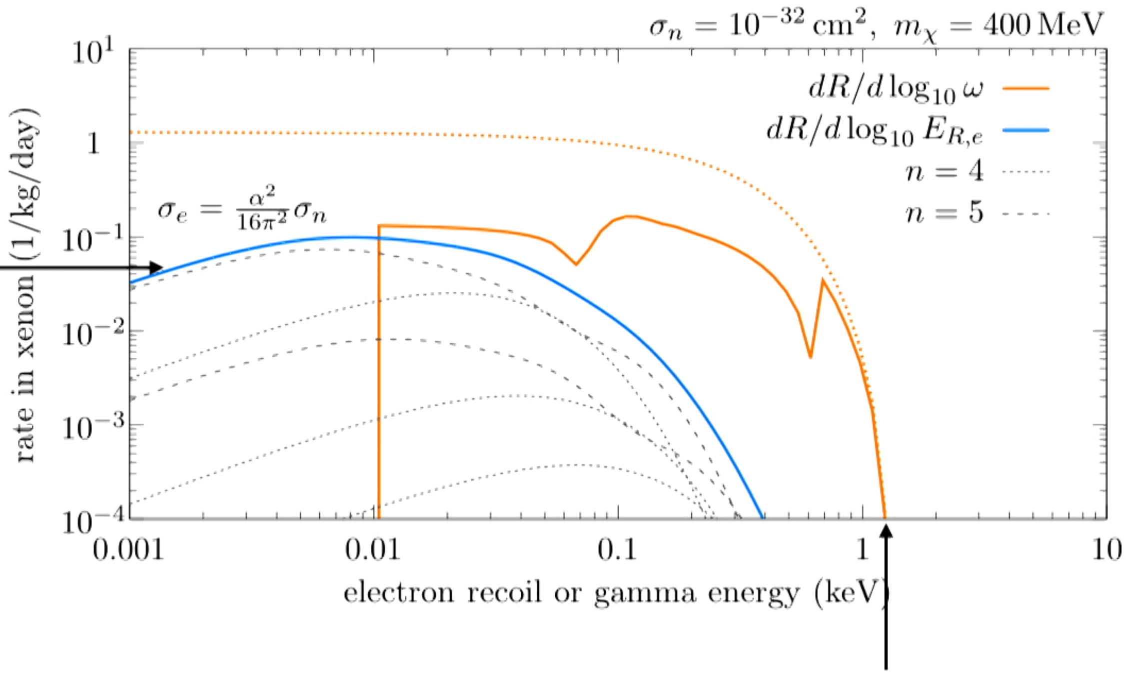


Brems from DM-
nucleus scattering

NB: new limits on non-conserved vector currents constrain size of possible cross sections [Dror, Lasenby, Pospelov; 2017]

Method favors leptophobic DM models

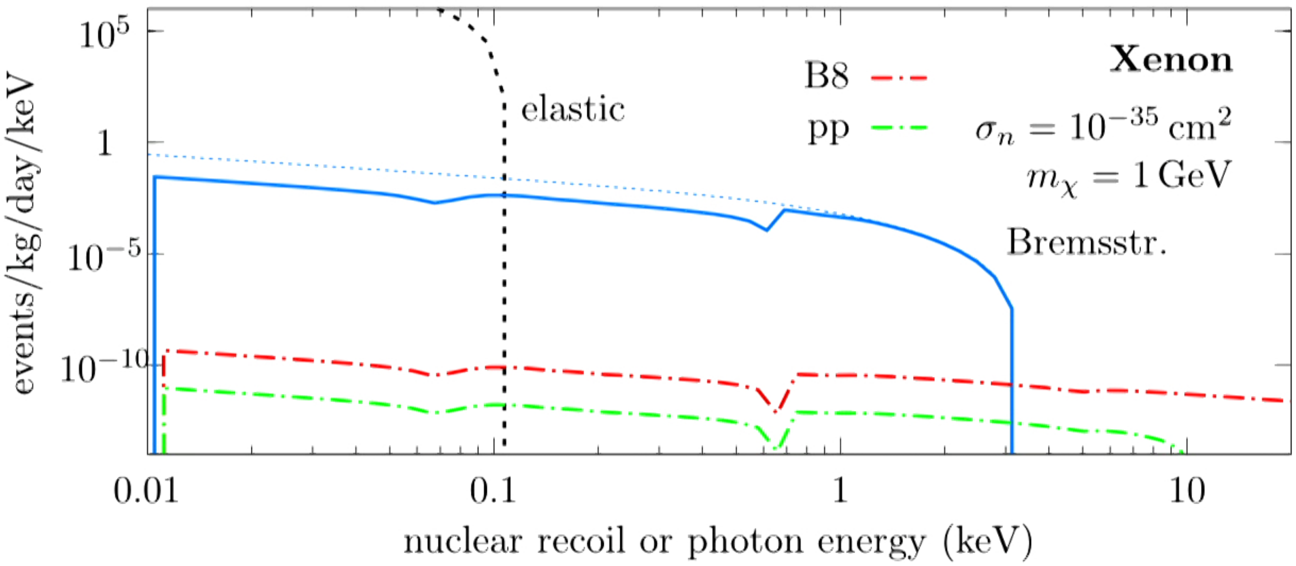
radiatively induced DM-electron scattering (DM coupled to baryonic current)



Brems from DM-nucleus scattering

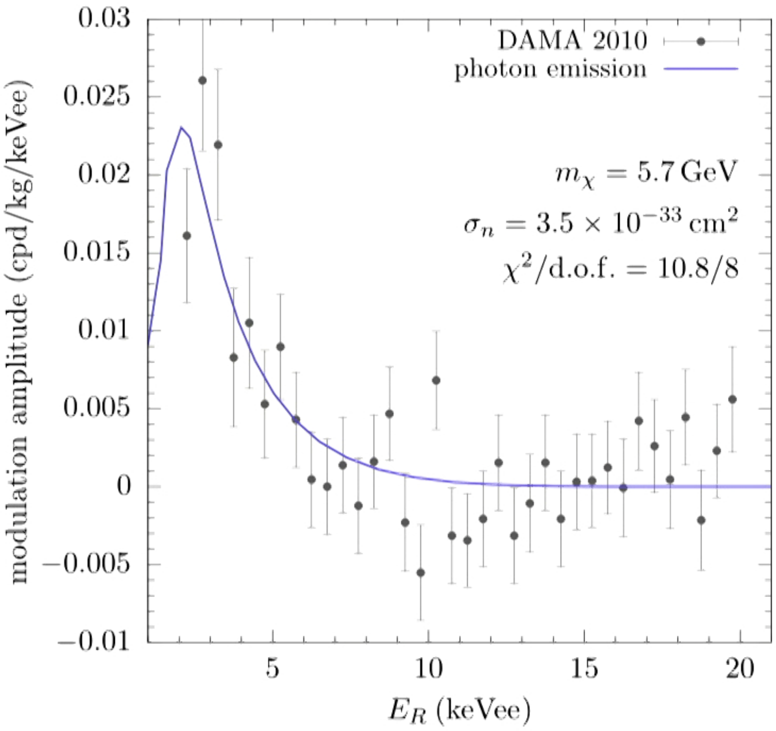
NB: new limits on non-conserved vector currents constrain size of possible cross sections [Dror, Lasenby, Pospelov; 2017]

Bonus Material-1: Solar neutrino induced Brems. signal?



Energetically prospective, but numbers are very small.

Bonus Material-II: Another DAMA favored region

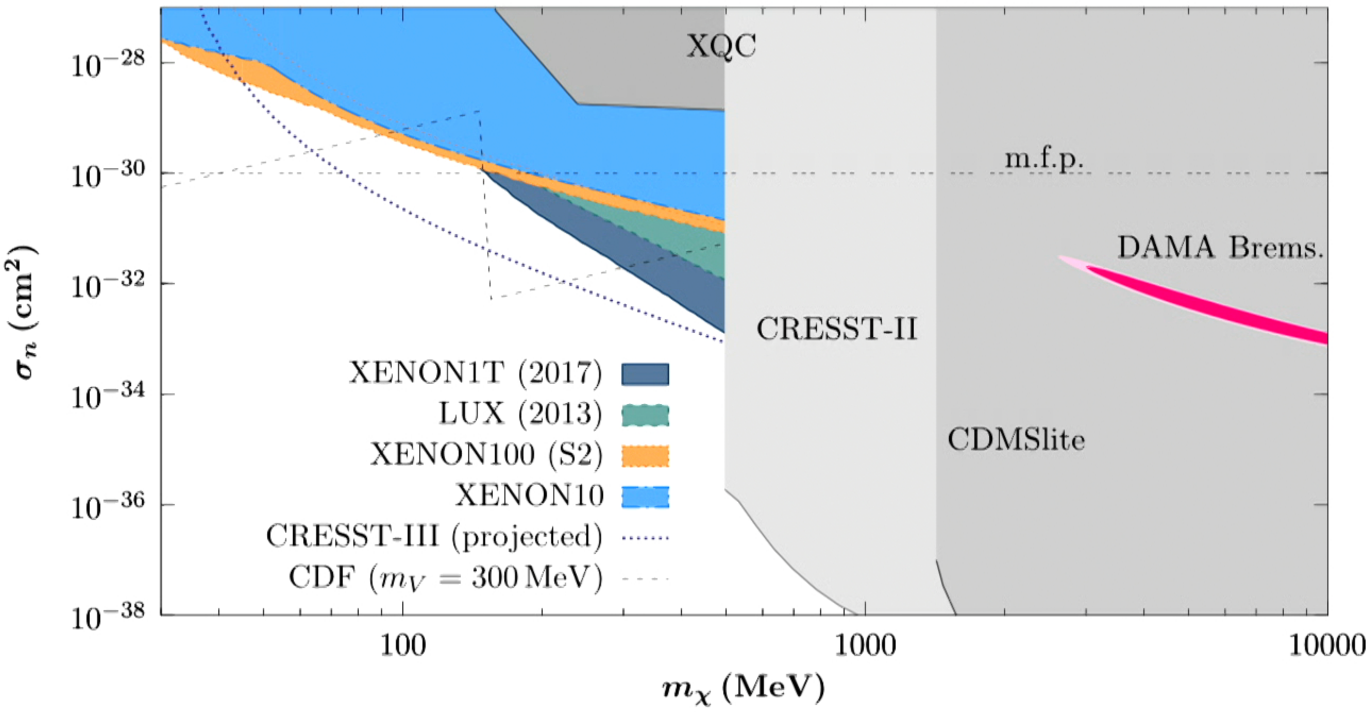


Scintillation light from Na nuclear recoil is quenched (Q~0.2)

modulated Bremsstrahlung is unquenched => lower mass DM induces signal at energies higher than expected from nuclear recoils

=> modulation amplitude can be fitted

Bonus Material-II: Another DAMA favored region



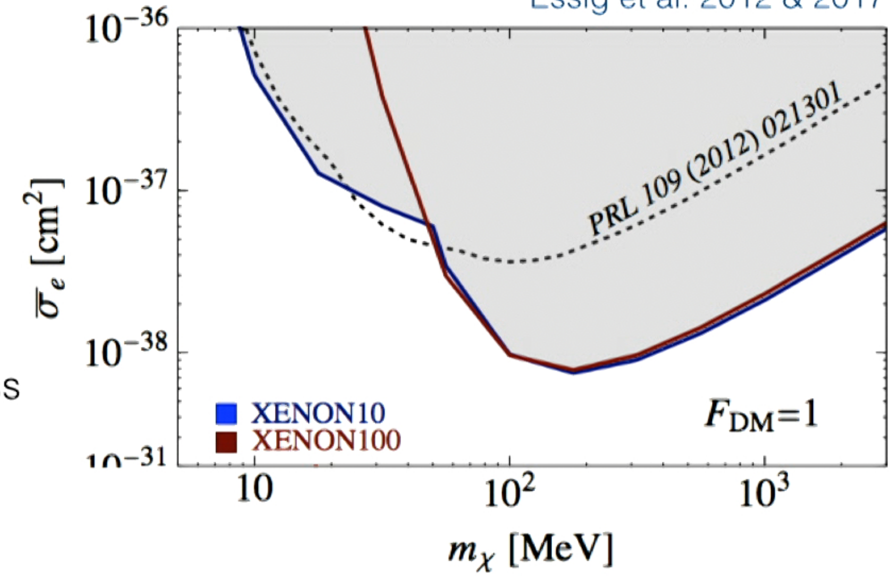
2 DM-electron scattering

DM-electron scattering is a promising experimental avenue for detecting sub-GeV DM

Ordinary detectors lose sensitivity below few MeV mass

$$E_{\rm kin} \sim 5\,{\rm eV} \times \frac{m_{\rm DM}}{10\,{\rm MeV}}$$

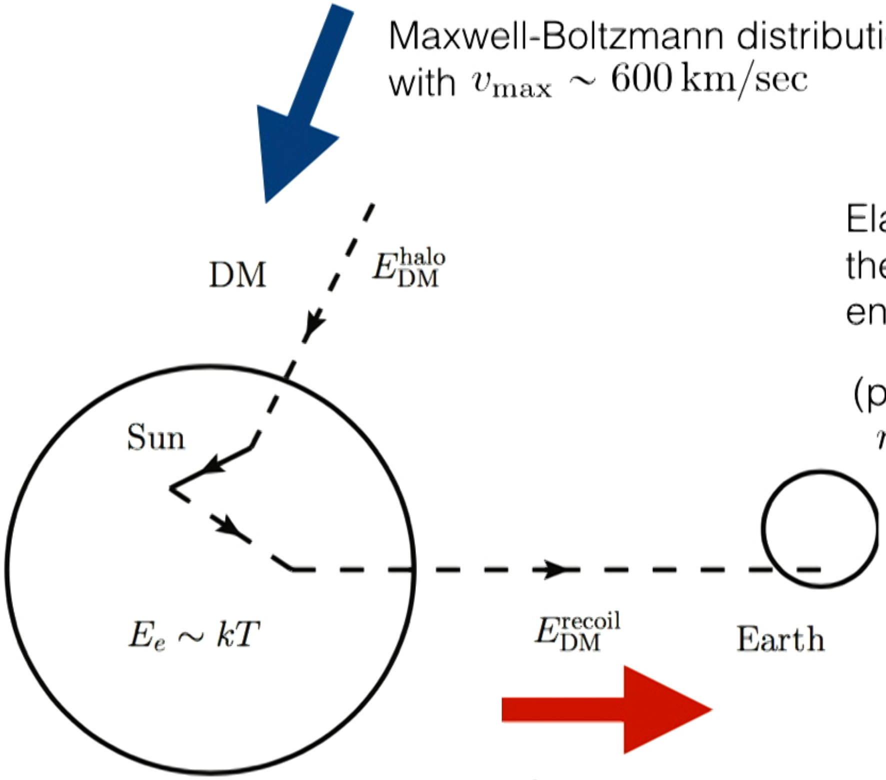
Essig et al. 2012 & 2017



=> if m < 10 MeV, then there are no particles bound to the Galaxy that could ionize an outer shell Xenon electron!

"kinematical no-go theorem" #2

The sun as particle accelerator



Maxwell-Boltzmann distribution
with $v_{\rm max} \sim 600\,{\rm km/sec}$

reflected spectrum

Elastic scattering on electrons in the sun's interior lifts DM kinetic energy into (sub-)keV regime

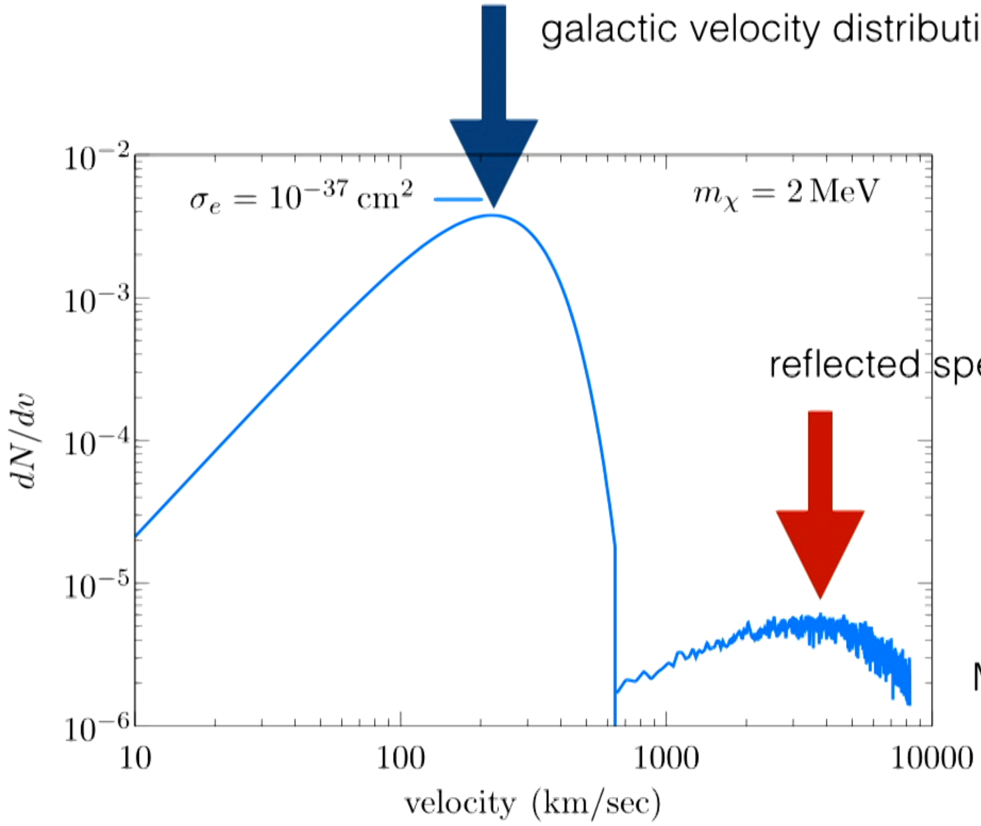
(process most efficient for $m_e = m_{\rm DM}$)

$$E_{\rm DM}^{\rm recoil} \sim T$$

$$v_{\rm max} = \sqrt{2T/m}$$
$$\sim 10^4\,{\rm km/sec} \times \sqrt{1\,{\rm MeV}/m}$$

An, Pospelov, JP, Ritz (in preparation)

The sun as particle accelerator



galactic velocity distribution

reflected spectrum from the sun

MC simulation

The sun as particle accelerator

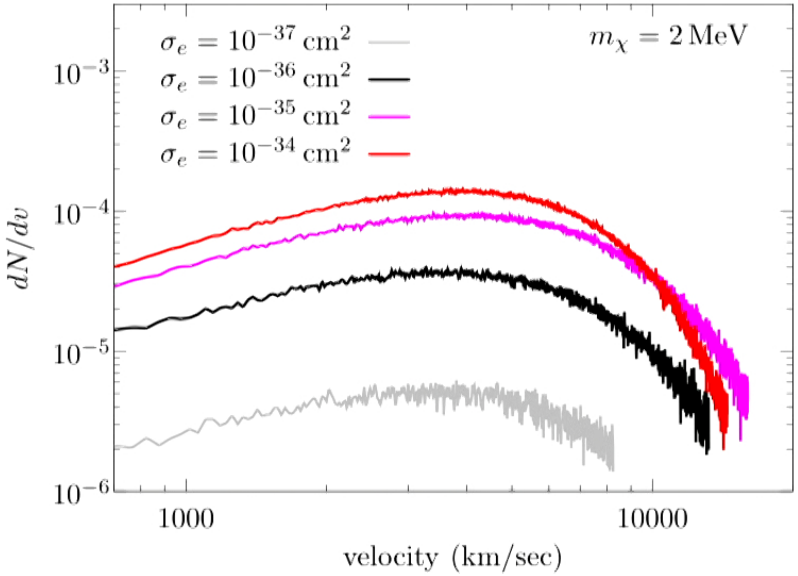
maximal flux from the sun is a factor

$(R_\odot/1\mathrm{A.U.})^2 \simeq 10^{-5}$

smaller than the galactic DM flux

sun becomes optically thick for

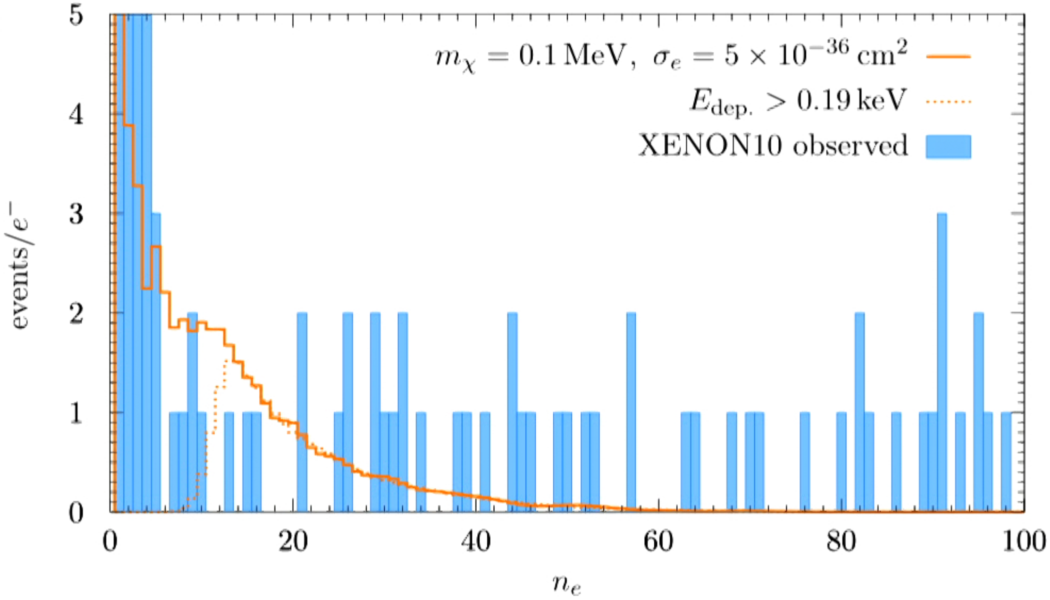
$\sigma_e \gg 10^{-36}\,\mathrm{cm}^2$



$$\Phi_{\text{reflected}} \sim \Phi_h \times \begin{cases} \left(\frac{R_{\text{core}}}{1\,\text{A.U.}}\right)^2 \sigma_e n_e^{\text{core}} R_{\text{core}}, & \sigma_e \ll 1\,\text{pb} \\ \left(\frac{R_{\text{scatt}}}{1\,\text{A.U.}}\right)^2, & \sigma_e \gg 1\,\text{pb} \end{cases}$$

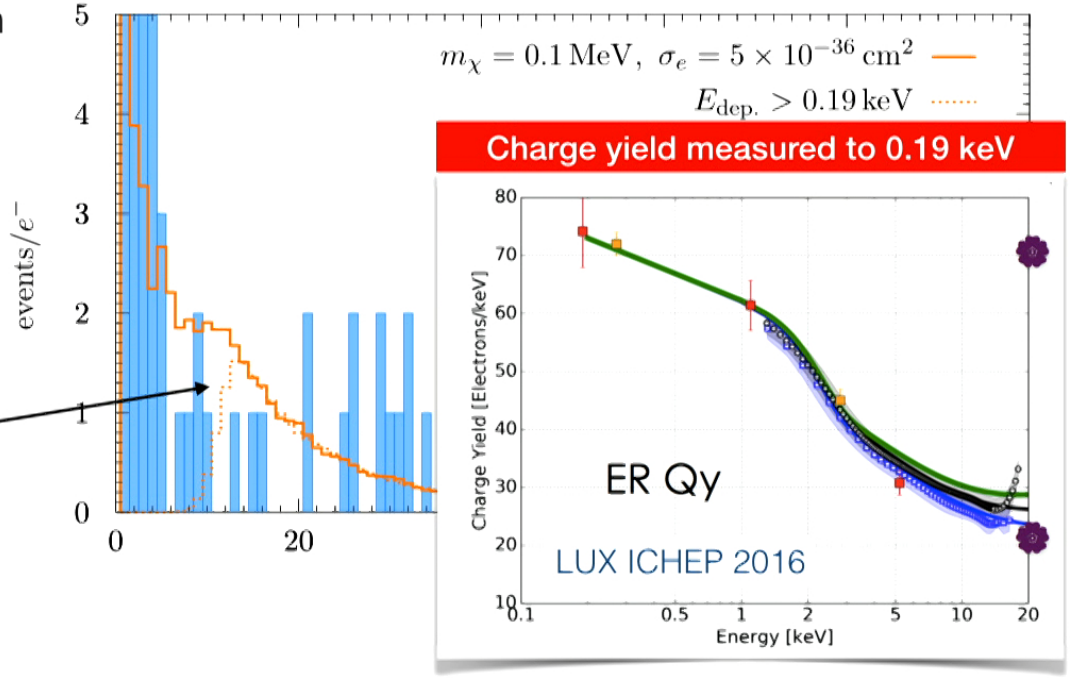
Current sensitivity to sub-MeV DM

Ionization spectrum from DM electron scattering in XENON10



Current sensitivity to sub-MeV DM

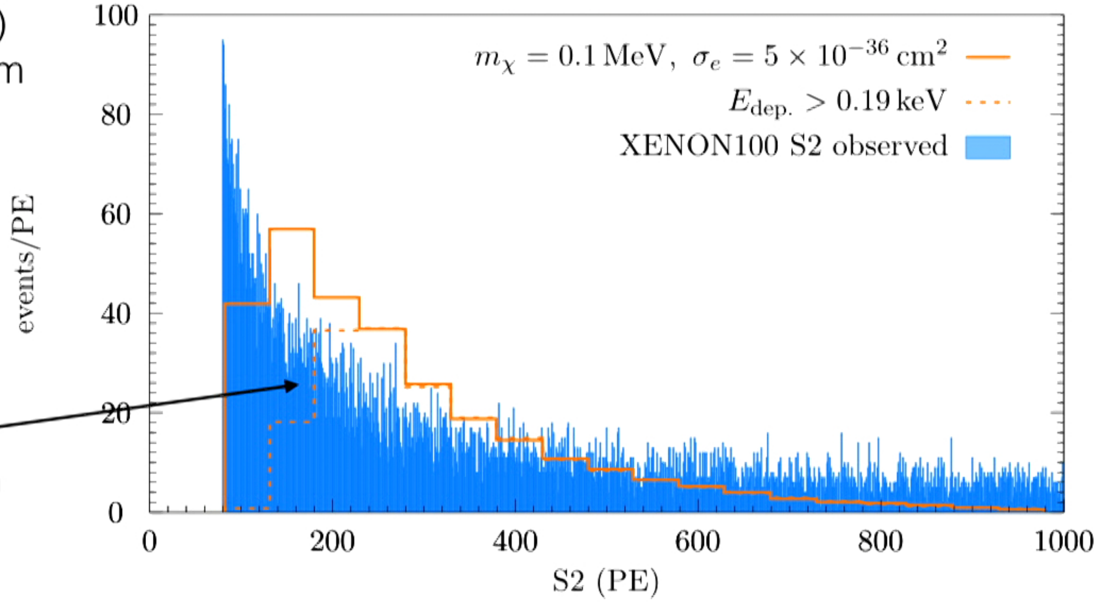
Ionization spectrum from DM electron scattering in XENON10



for expt. limits: demand minimum deposited energy of 0.19 keV => data driven approach

Current sensitivity to sub-MeV DM

XENON100 (2016)
ionization spectrum



for expt. limits:
demand minimum
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of 0.19 keV
=> data driven
approach

Current sensitivity to sub-MeV DM

Technicality: keV-scale reflected particles are relativistic ($T_{\rm core} \sim \rm keV$)

1. relativistic velocity average $\eta(E_\chi^{\rm min}) = \int_{E_\chi^{\rm min}(q)} dE_\chi \, \frac{m_\chi^2}{E_\chi p_\chi} \frac{dN}{dE}$

2. although $\langle \mathbf{p}'_e | nlm \rangle = 0$ by definition, if (Sommerfeld enhanced) plane waves are used for $|\mathbf{p}'_e\rangle$, numerically, the overlap with HF-bound w.f. is non-zero

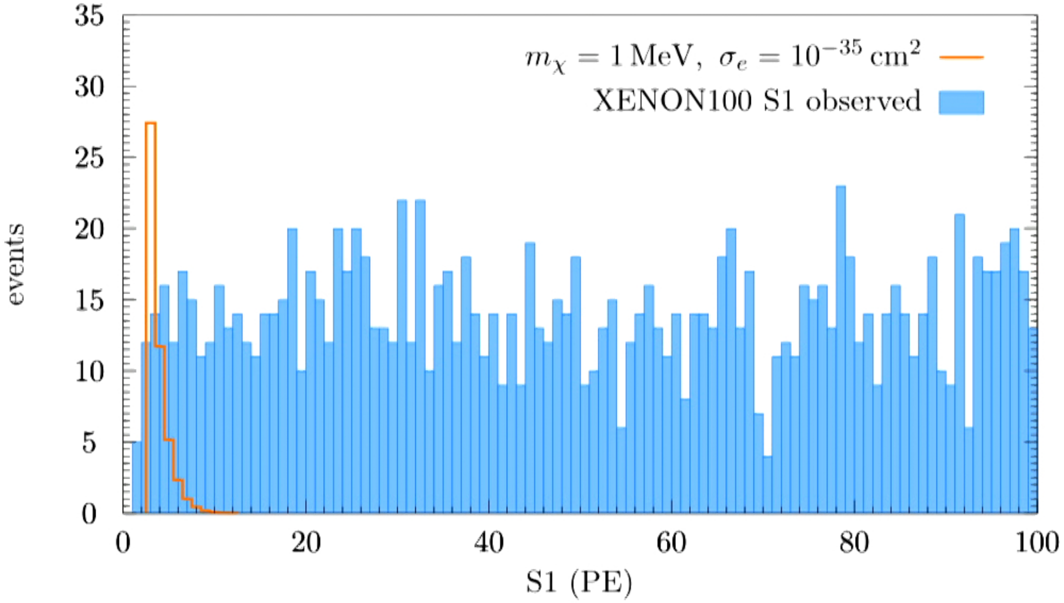
=> we subtract the unity operator in the atomic form factor when the relativistic limit when $\mathbf{q}\cdot\mathbf{r} \ll 1$

$$f(\mathbf{q}) = \langle \mathbf{p}'_e | e^{i\mathbf{q}\cdot\mathbf{r}} | nlm \rangle \qquad \rightarrow \qquad f^{\rm sub}(\mathbf{q}) = \langle \mathbf{p}'_e | e^{i\mathbf{q}\cdot\mathbf{r}} - 1 | nlm \rangle$$

Current sensitivity to sub-MeV DM

S1-scintillation spectrum in XENON100

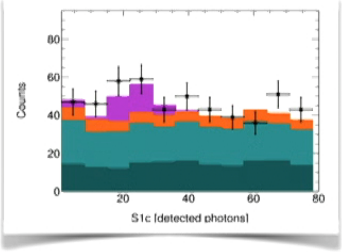
(detected S1 reduces backgrounds through volume fiducialization)



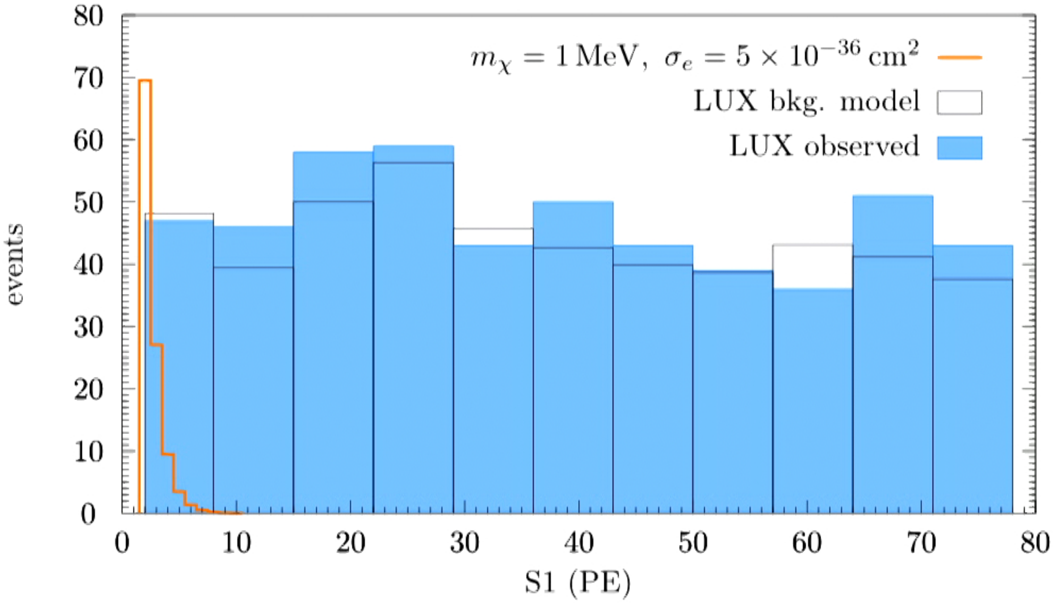
reflected spectrum extends into keV-range => scintillation detectable (benefit of background suppression)

Current sensitivity to sub-MeV DM

LUX 2013 data
(search for axions
and ALPS)

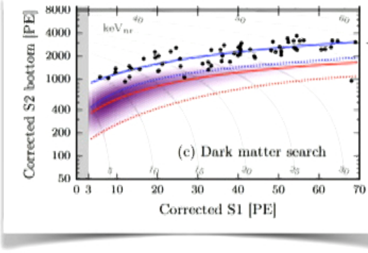


[Akerib et al 2017]

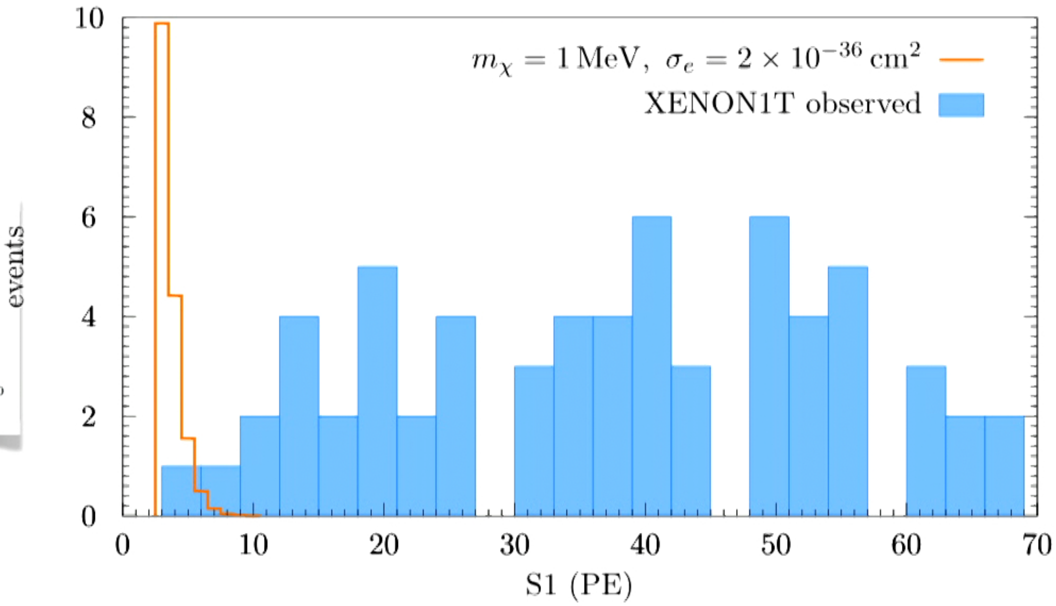


Current sensitivity to sub-MeV DM

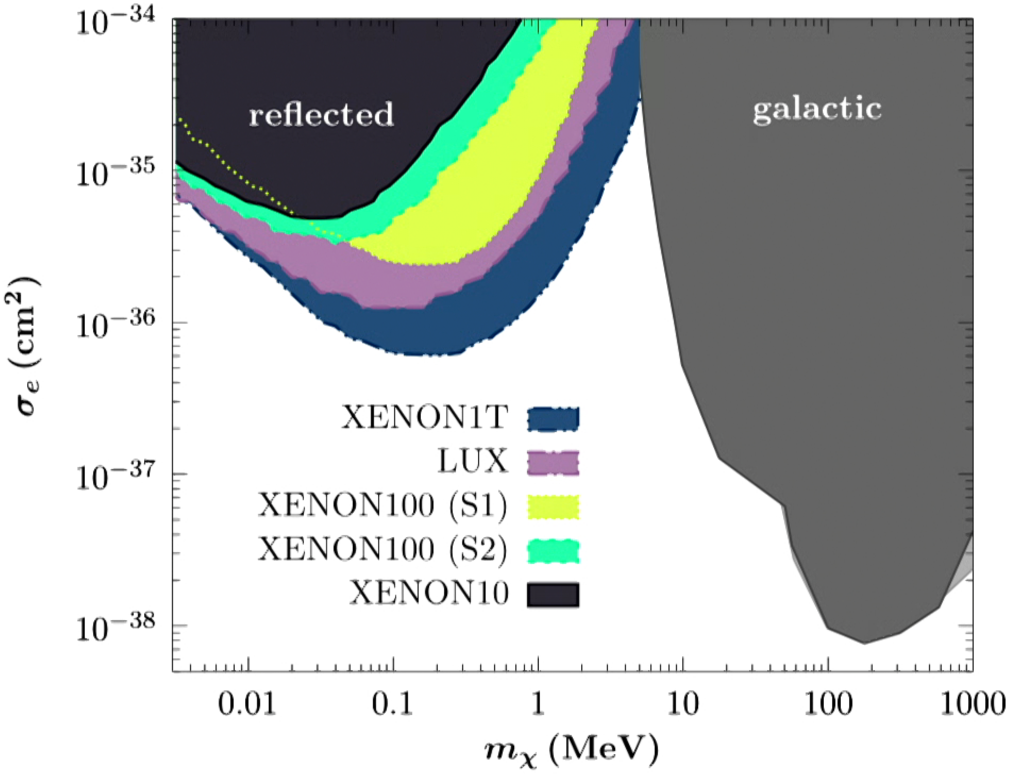
first results from XENON1T



[Aprile et al 2017]

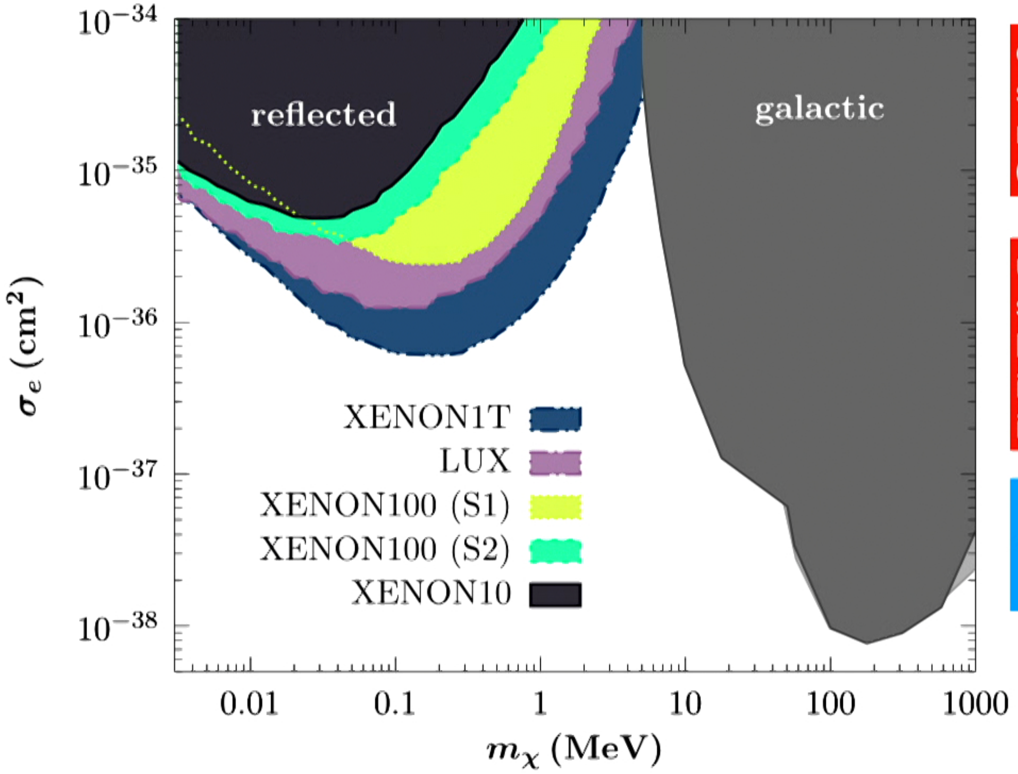


Direct Detection of sub-MeV DM



=> First limit on sub-MeV DM-electron scattering!

Direct Detection of sub-MeV DM



data-driven ionization/ scintillation yield: minmum energy deposit of 0.19 keV required

unlike galactic DM-electron scattering, incoming DM has keV-kinetic energy; ionization from n=4 important

limits may be improved by from PDF(S1,S2|E) [work in progress]

=> First limit on sub-MeV DM-electron scattering!

2b SIMPs => prototypical light DM

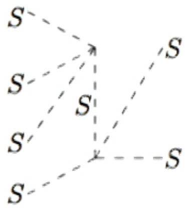
Here, SIMPs are code for particles that annihilate “strongly” through number violating processes, 3 -> 2 or 4 -> 2.

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 $\sigma/m \lesssim 1\,\mathrm{bn/GeV}$

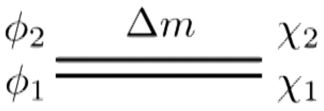
Bernal, Chu, JP 2017

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 $\chi_{1,2}$

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

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

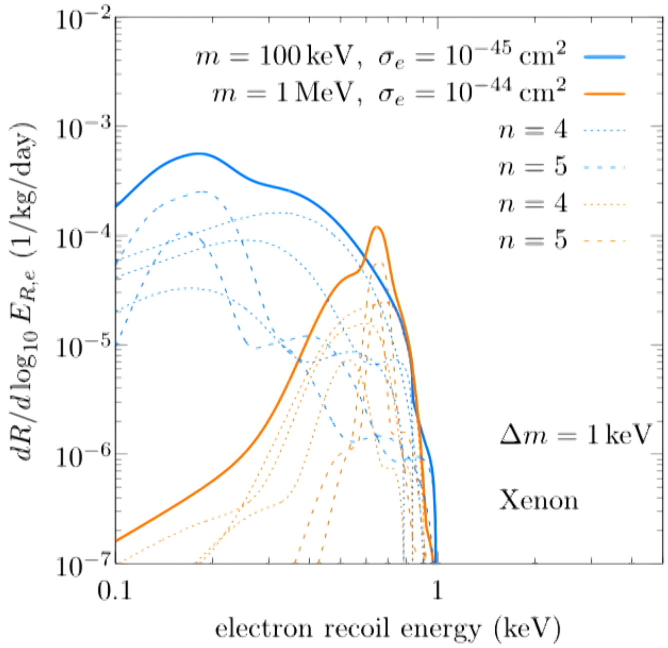
=> if gauged with U(1) “dark photon,” interaction becomes *off-diagonal*

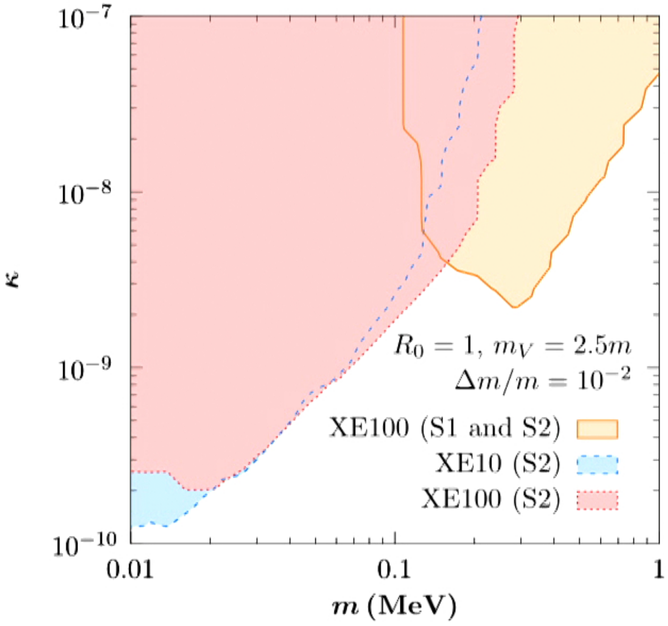
$$\mathcal{L}_{\text{int},\,\phi} = g_V\left(\phi_1\partial^\mu\phi_2 - \phi_2\partial_\mu\phi_1\right)V_\mu + \frac{1}{2}g_V^2\left(\phi_1^2+\phi_2^2\right)V^2 - V_\Phi(\phi_1,\,\phi_2)$$

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

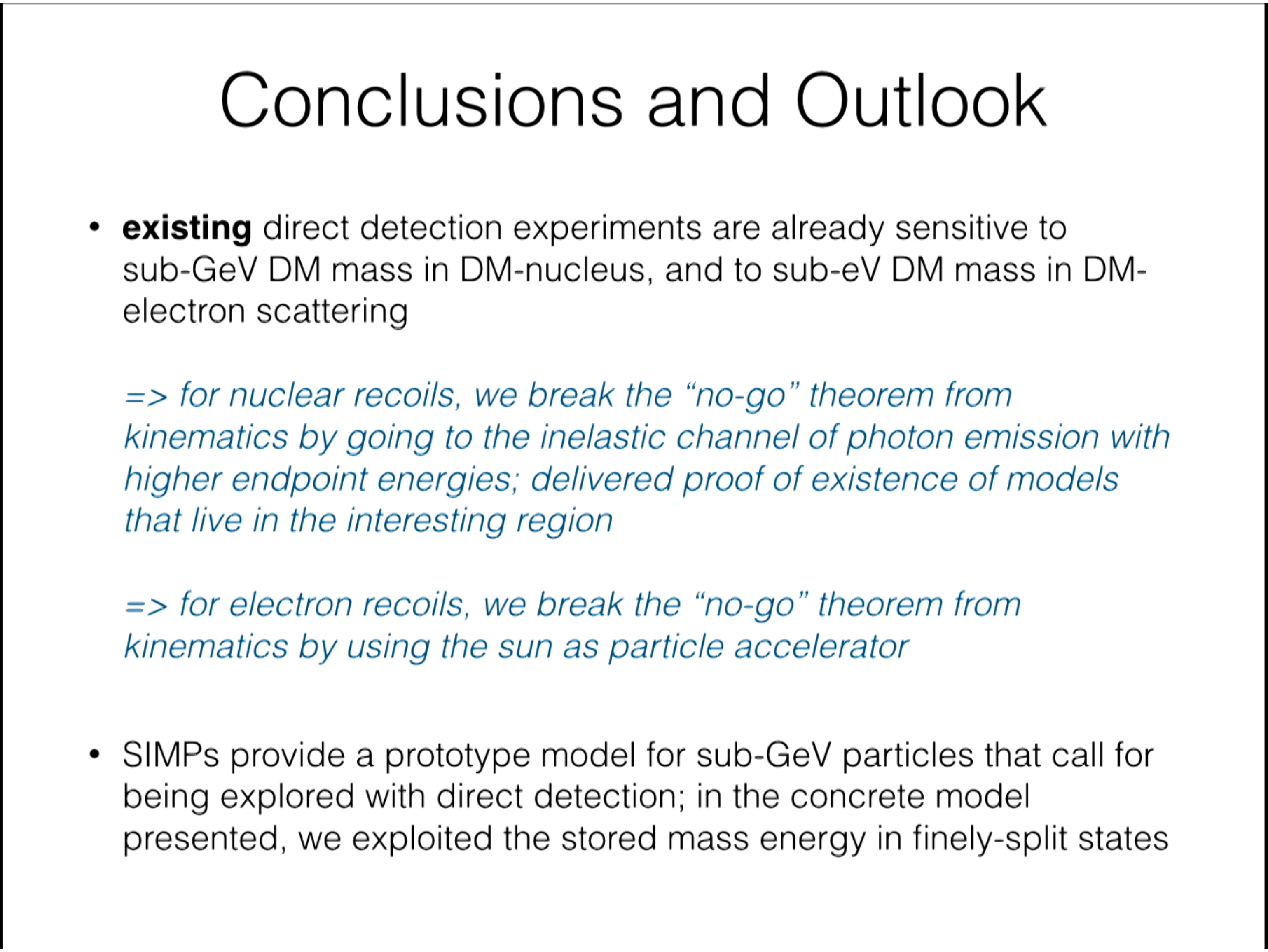
Bernal, Chu, JP 2017

Exothermic DM-electron scattering





once $\Delta m \gtrsim 1\,\mathrm{keV}$, S1-channel accessible (see before)



Conclusions and Outlook

- **existing** direct detection experiments are already sensitive to sub-GeV DM mass in DM-nucleus, and to sub-eV DM mass in DM-electron scattering

  => for nuclear recoils, we break the "no-go" theorem from kinematics 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

  => for electron recoils, we break the "no-go" theorem from kinematics by using the sun as particle accelerator

- 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