New dark matter direct detection signals

Josef Pradler

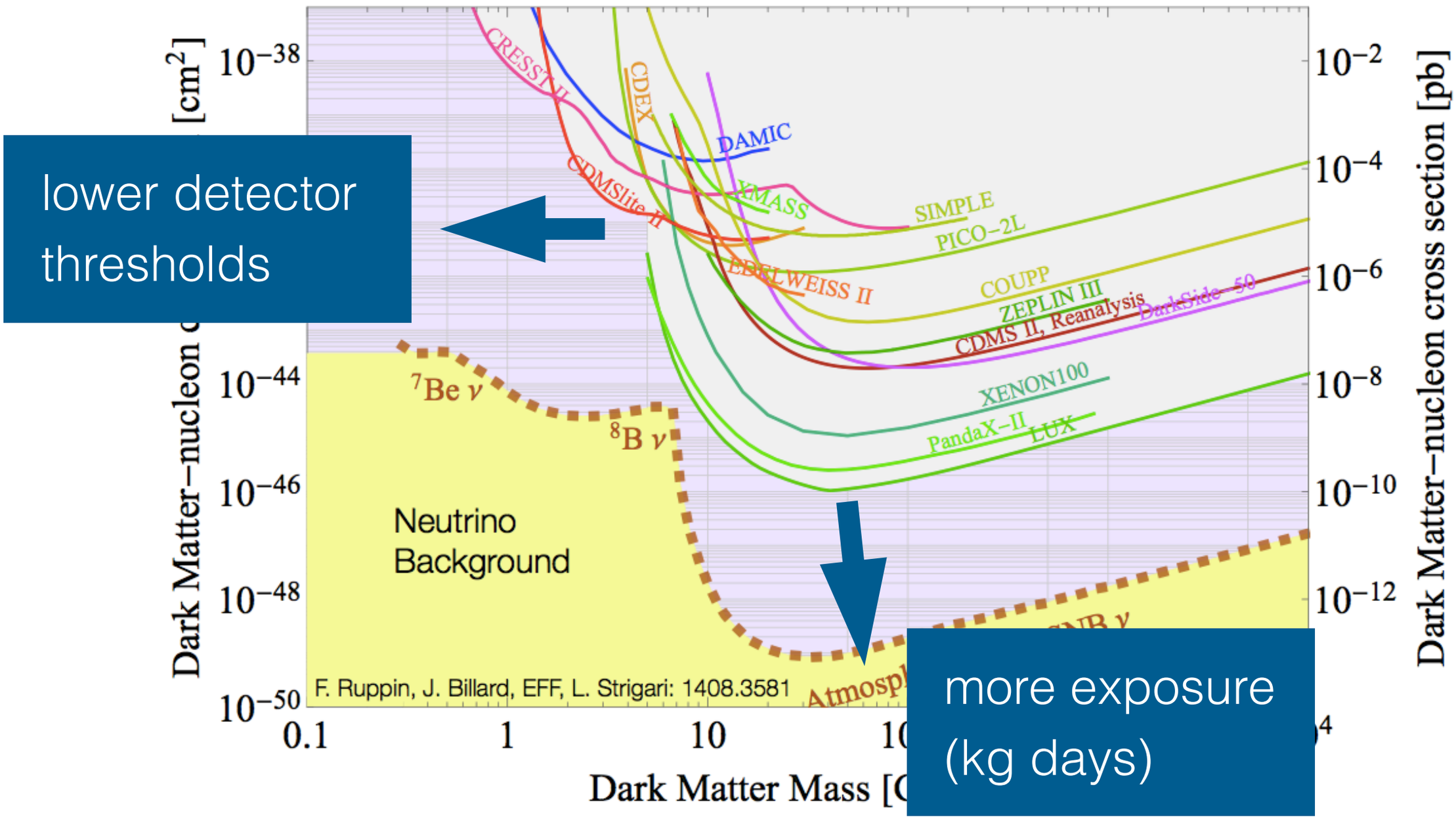
ÖAW AUSTRIAN ACADEMY OF SCIENCES

HEPHY INSTITUTE OF HIGH ENERGY PHYSICS

Pacific 2018 conferernce

Feb 15 2018

A (partial) summary of 2 decades of experimental effort

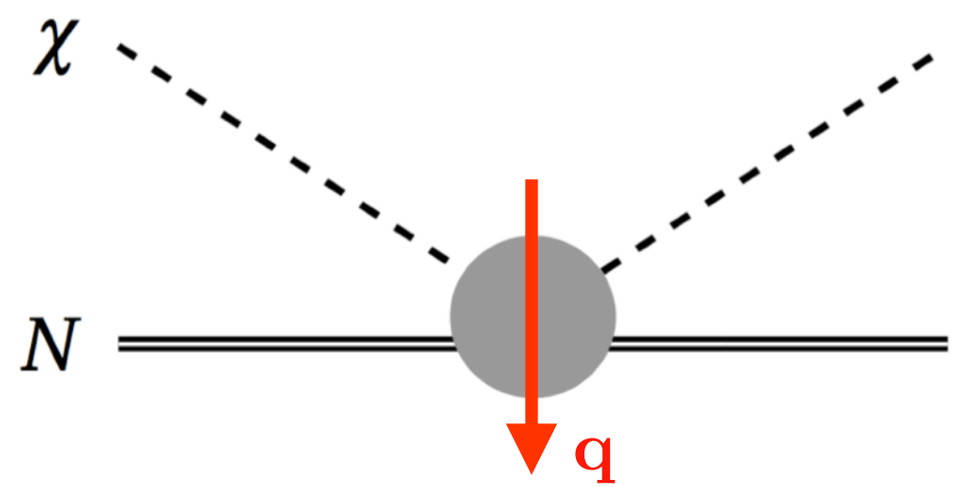


CF1 Snowmass report, Ruppin et al 2014

Direct Detection of “light DM”

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

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

=> 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”

Direct Detection of “light DM”

Nuclear kinetic recoil energy

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=> A given recoil, demands a *minim*

experimental alternatives:

Dark Matter-electron scattering

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

new detection methods (many examples mentioned already)

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“kinematical no-go theorem”

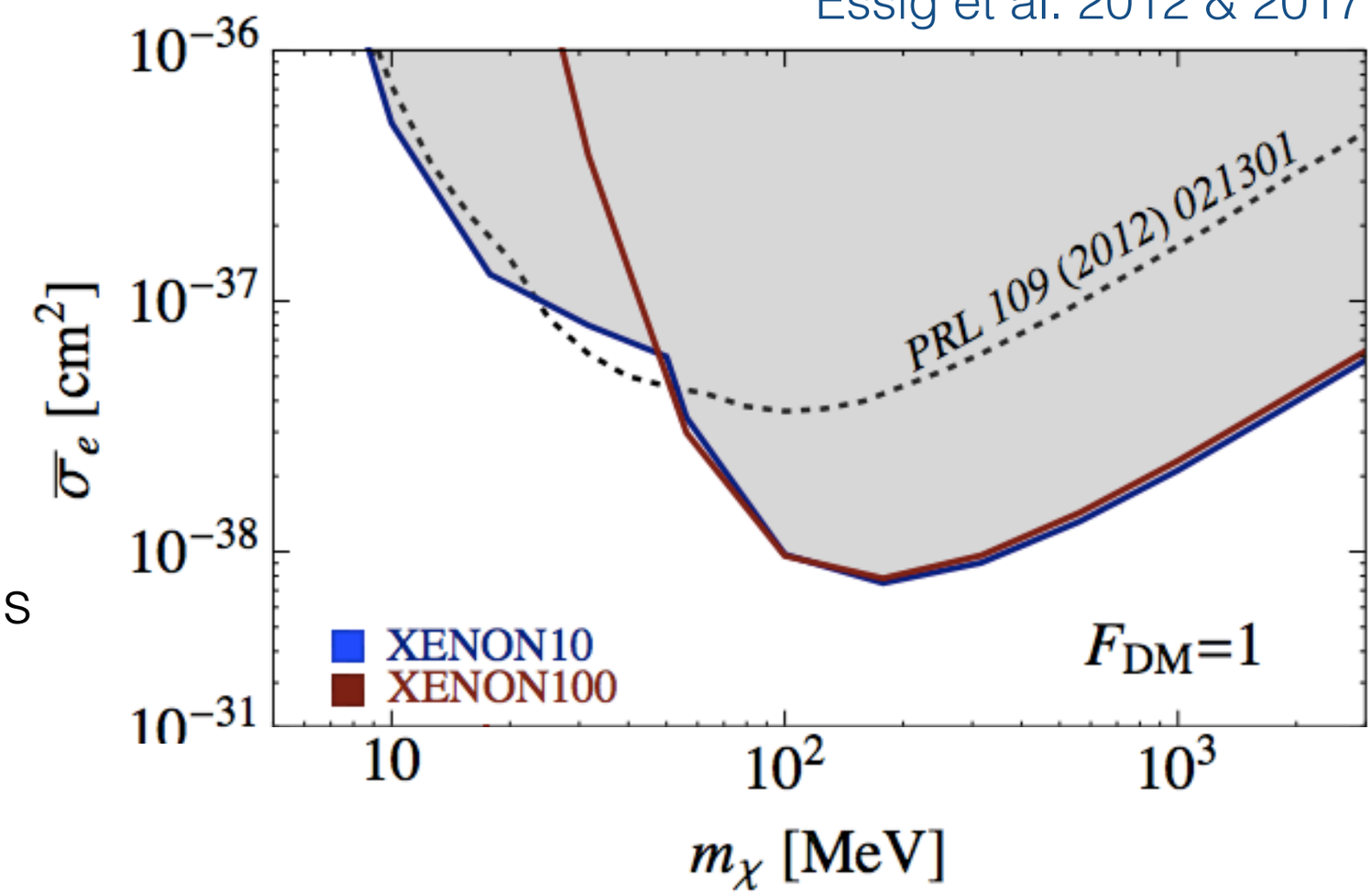
1 DM-electron scattering

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

Ordinary detectors lose sensitivity below few MeV mass

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

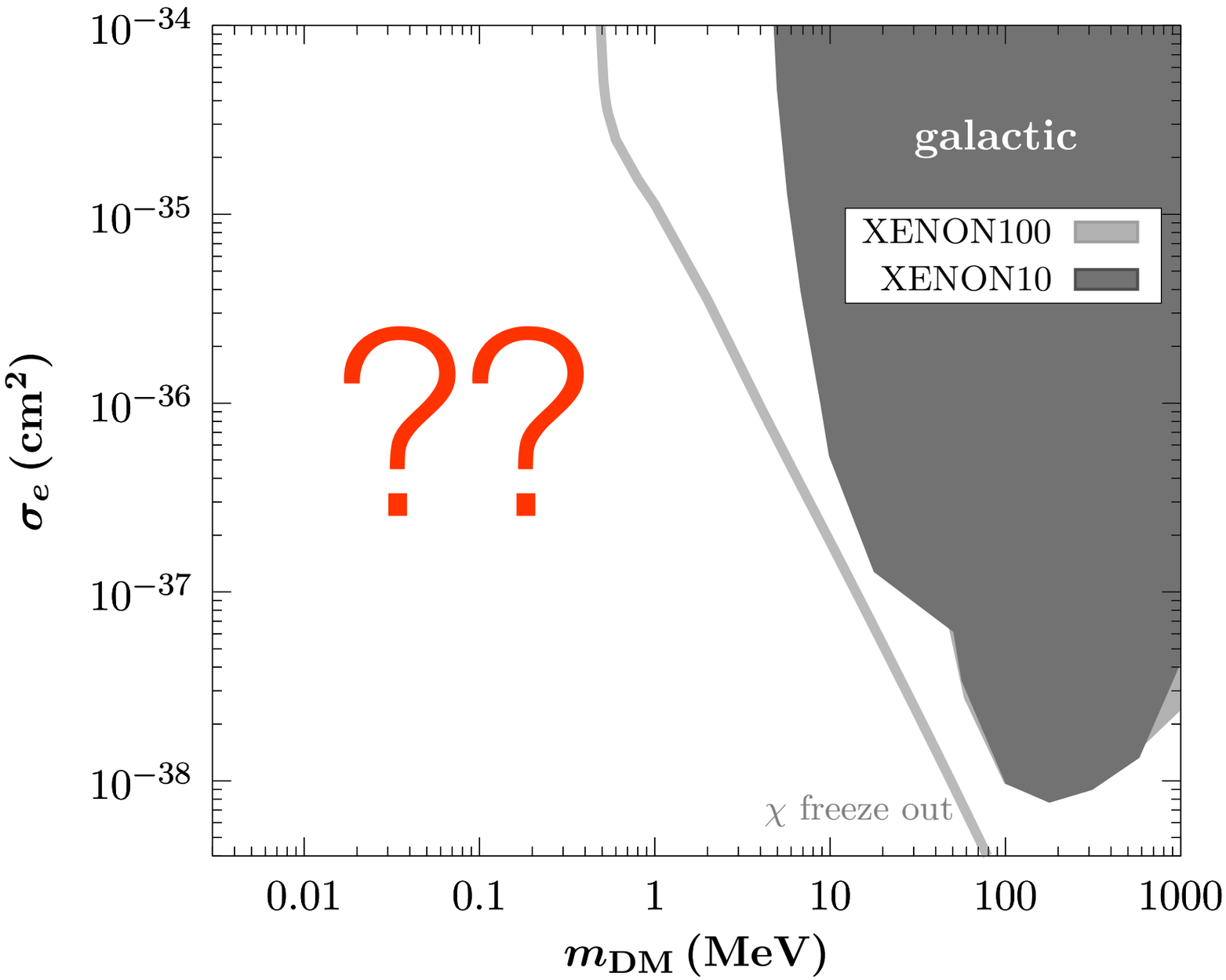
Essig et al. 2012 & 2017



=> 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

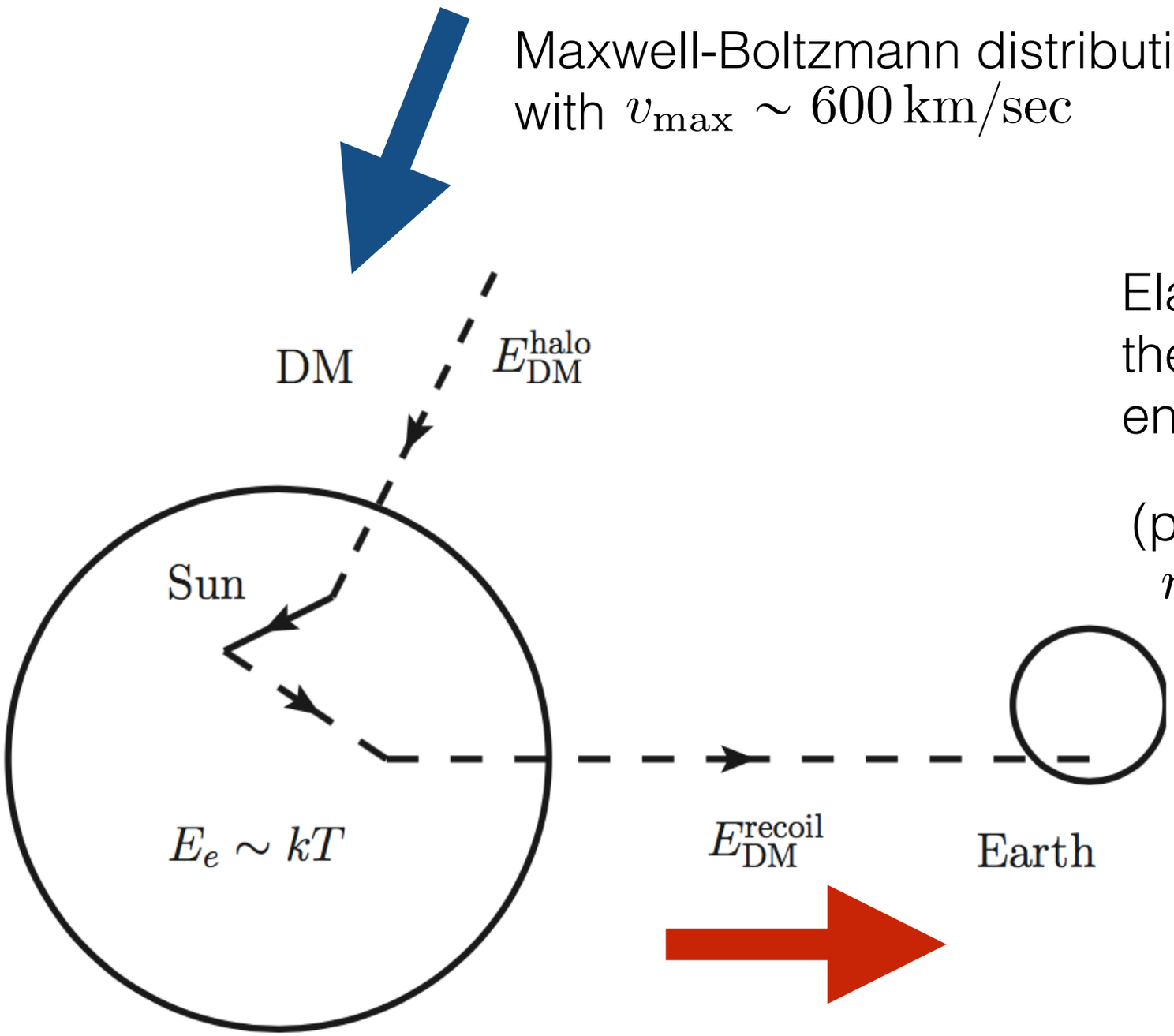
DM-electron scattering



Many ideas for new detector technology, but what can we say *now*?

1 The sun as particle accelerator

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



reflected spectrum

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

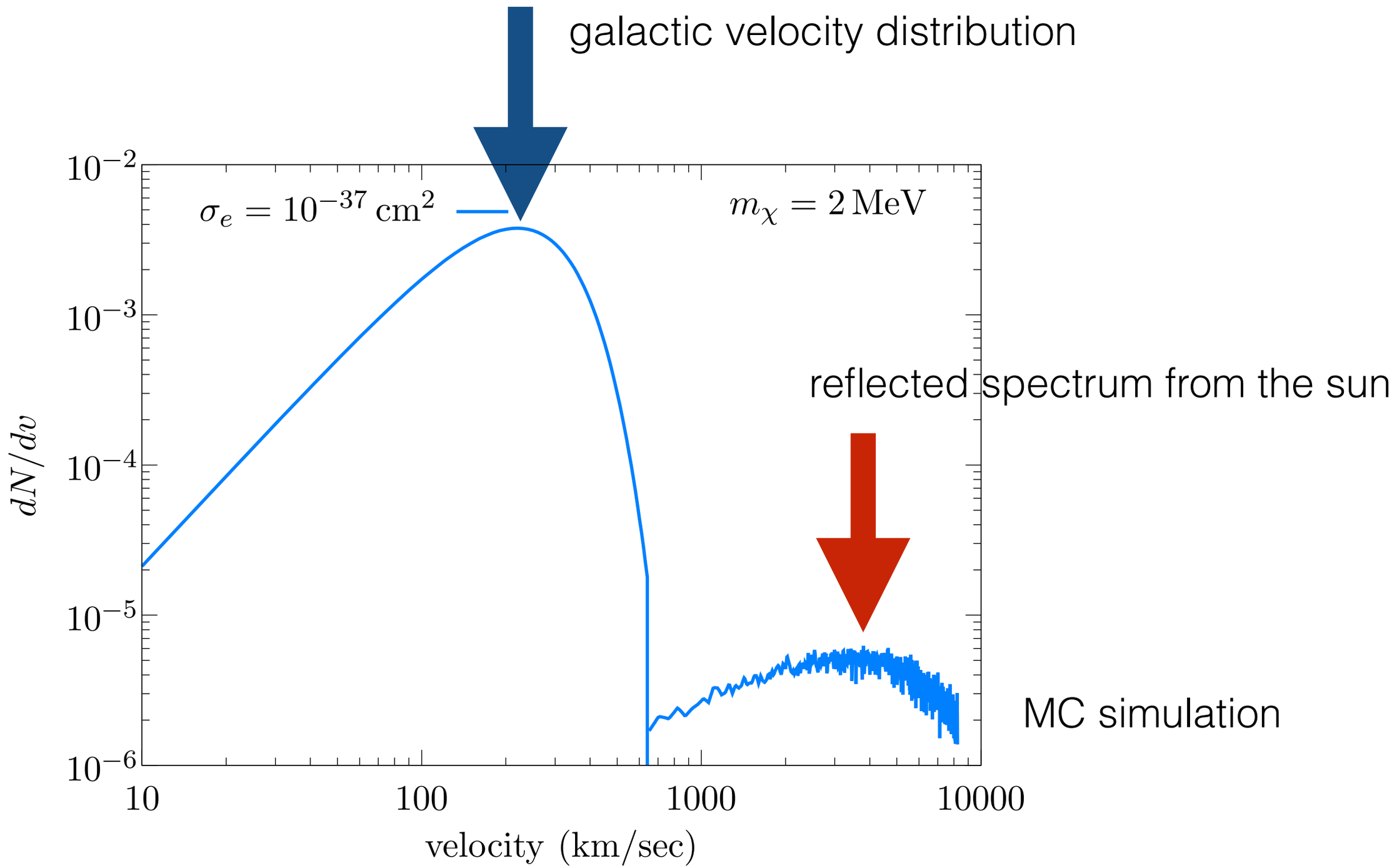
(process most efficient for $m_e = m_{\mathrm{DM}}$)

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

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

An, Pospelov, JP, Ritz arXiv:1708.03642

The sun as particle accelerator



The sun as particle accelerator

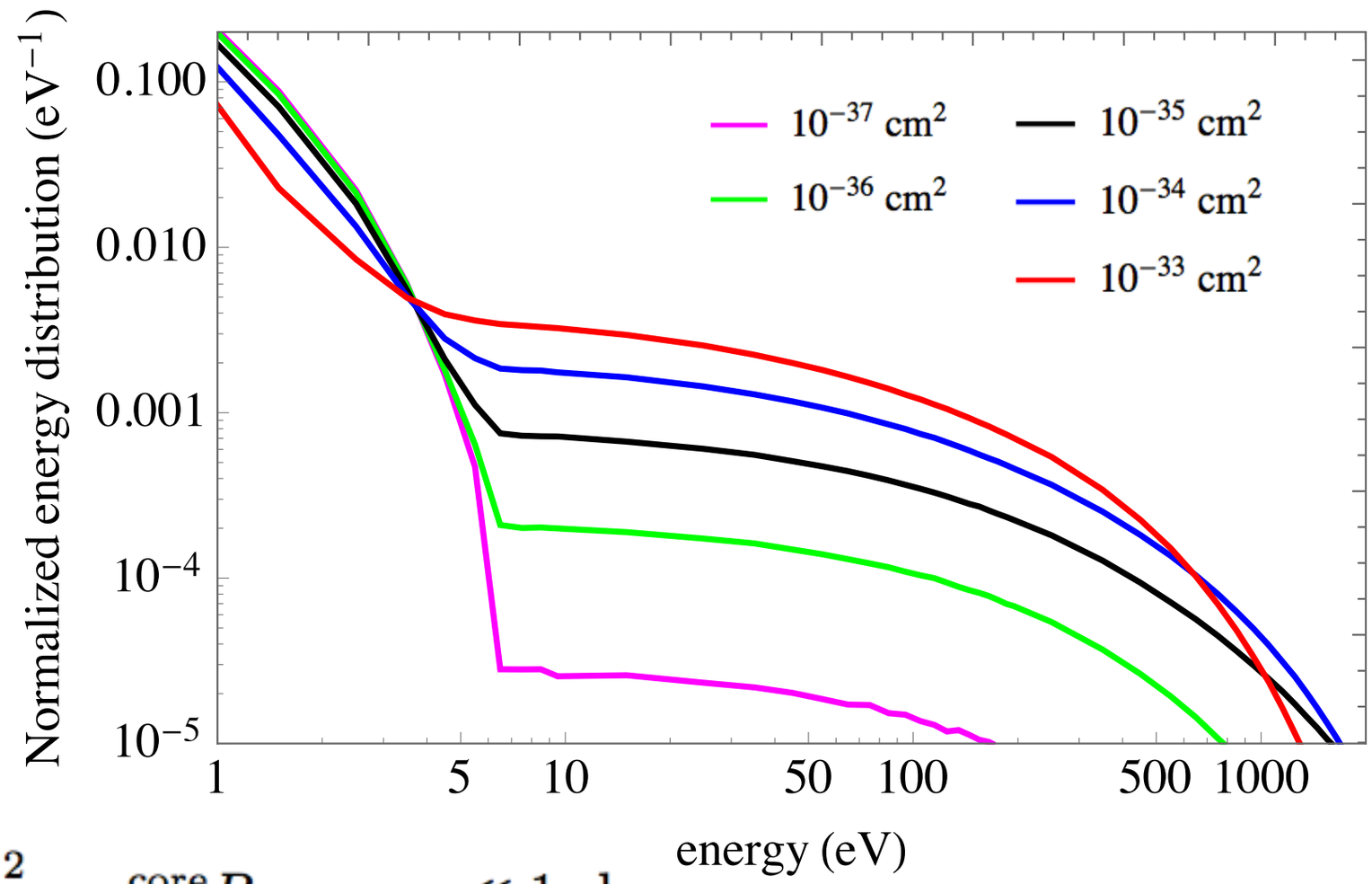
maximal flux from the sun is a factor

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

smaller than the galactic DM flux

sun becomes optically thick for

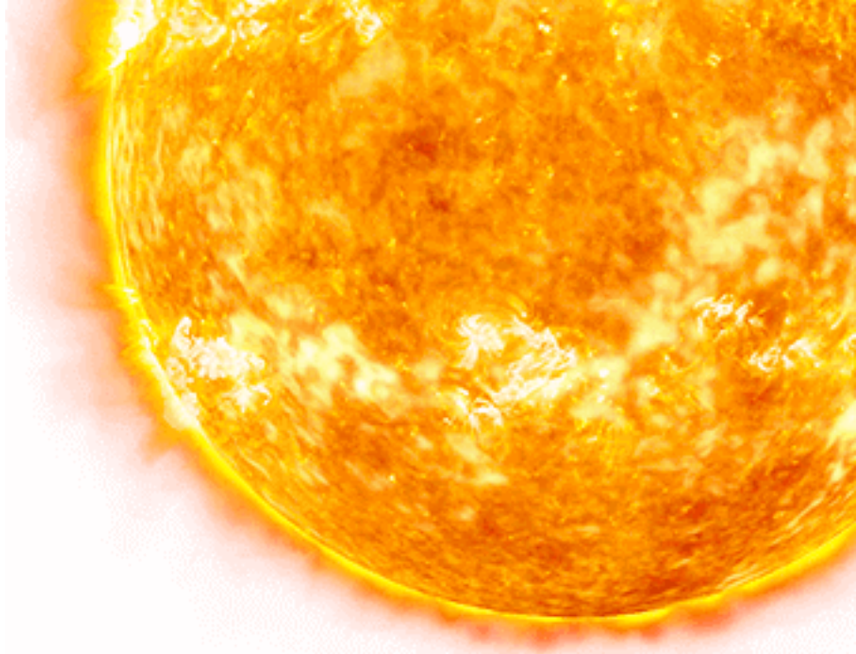
$\sigma_e \gg 10^{-36}\,\mathrm{cm}^2$



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

NB: our Monte Carlo simulation included gravitational focussing and “ISW” after reflection when particles travels to earth

Any influence on the structure of the sun?



Simple estimate show that that energy loss from / heat transfer inside the sun is very small (for the parameter region of interest)

Radius of reflection can be estimated from the optical depth

$$\tau(z_{\rm refl.}) = \int_0^{z_{\rm refl.}} dz\, \sigma_e n_e (R_\odot - z) = 1$$

Maximum heat flow estimated as

$$J \lesssim T(R_{\rm refl.}) \times \frac{\rho_{\rm DM}}{m_{\rm DM}} v \times \pi R_{\rm refl.}^2 \sim 10^{16}\,{\rm W} \times \frac{\rm MeV}{m_{\rm DM}} \frac{T(R_{\rm refl.})}{\rm keV} \left(\frac{R_{\rm refl.}}{R_\odot}\right)^2$$

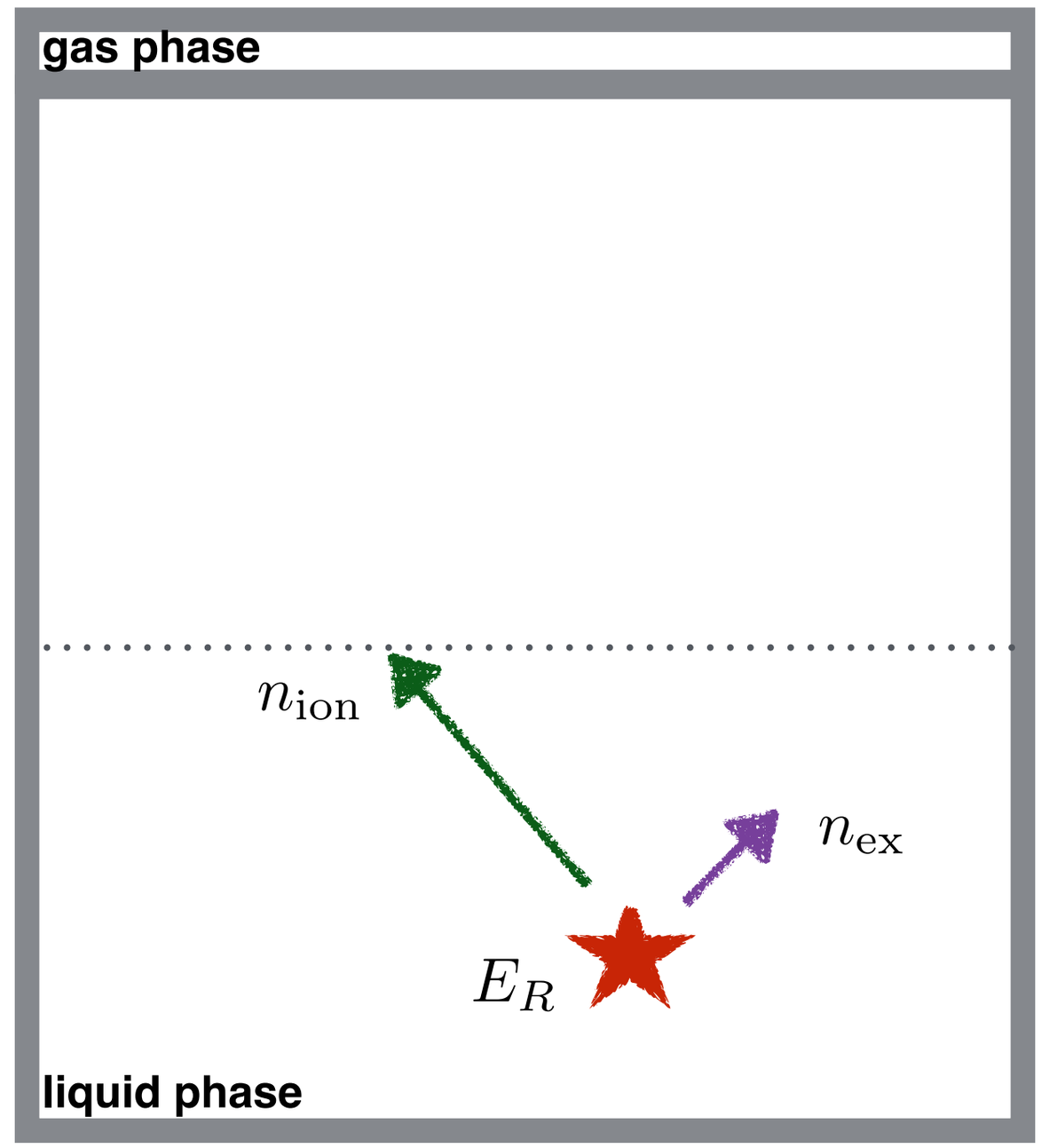
This is to be compared to the total solar luminosity $J_\odot \simeq 10^{26}\,{\rm W}$

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

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

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

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

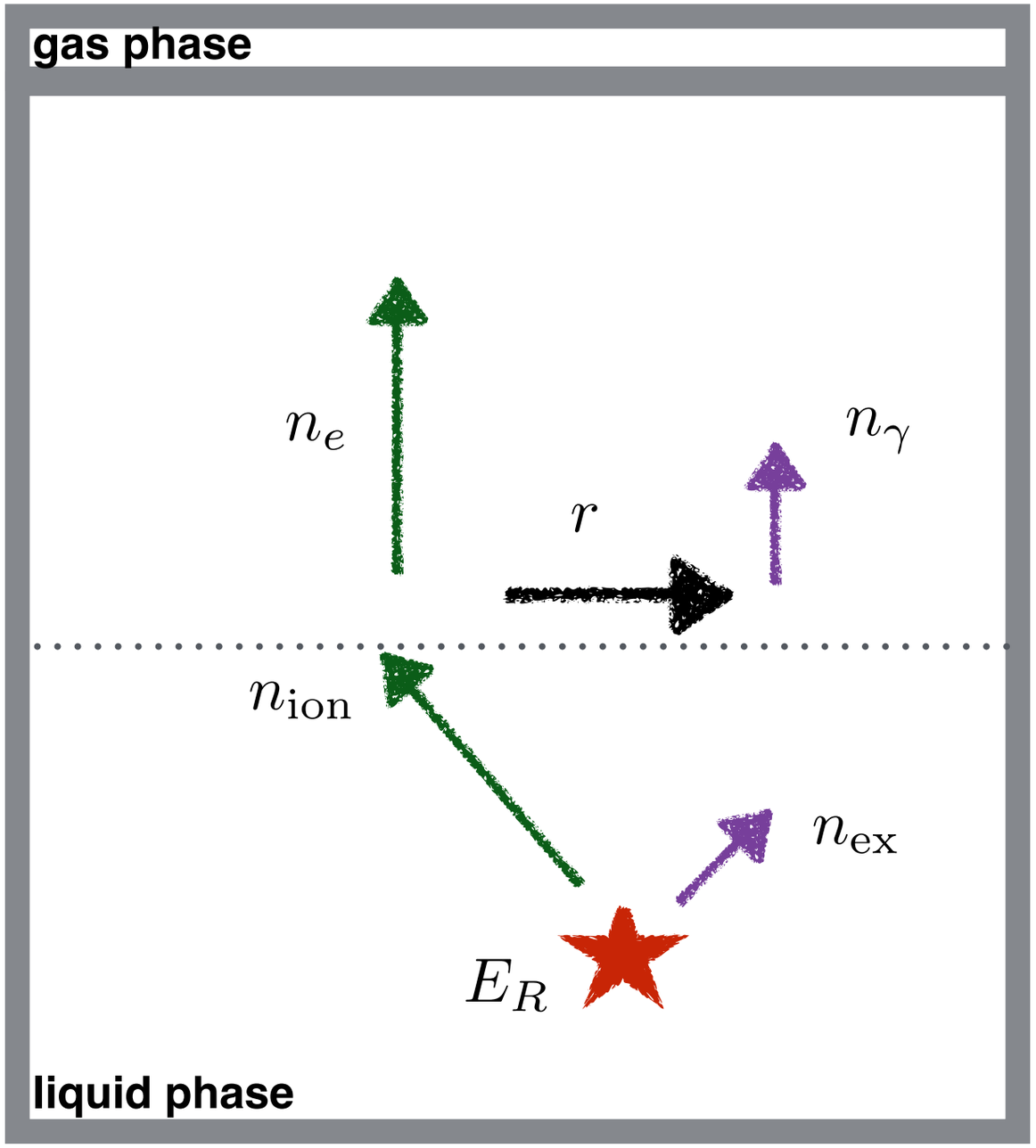


How does an “electron recoil” signal look in a LXE detector?

$$N_Q = \frac{E_R}{W} = n_{\text{ion}} + n_{\text{ex}}$$
$$= n_\gamma + n_e$$

$$n_e = n_{\text{ion}}(1 - r), \quad n_\gamma = n_{\text{ion}} r + n_{\text{ex}}$$

Measurable: de-excitation photons from initial and recombined excitons n_γ and electrons that escape recombination n_e



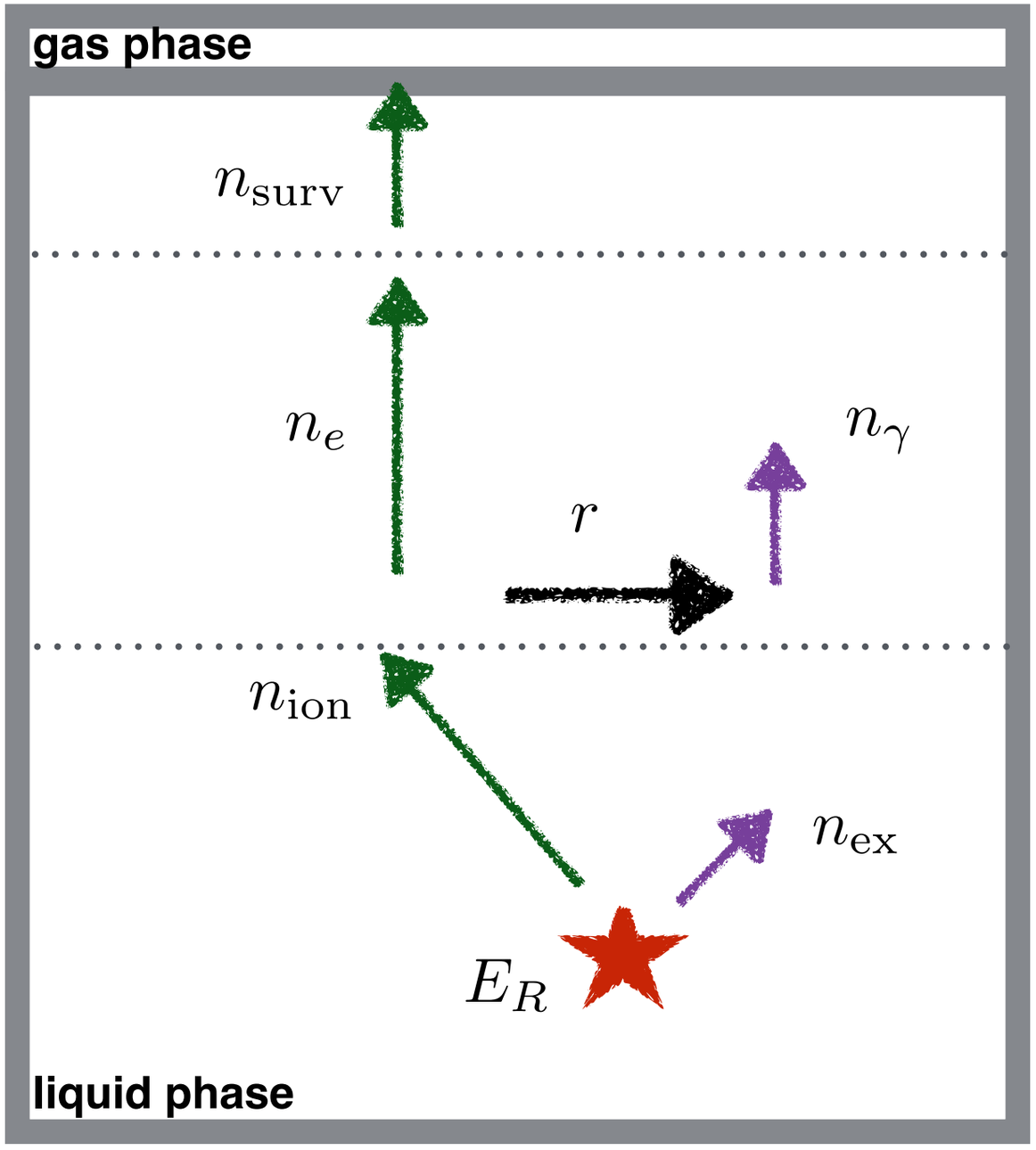
How does an “electron recoil” signal look in a LXE detector?

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

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

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

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

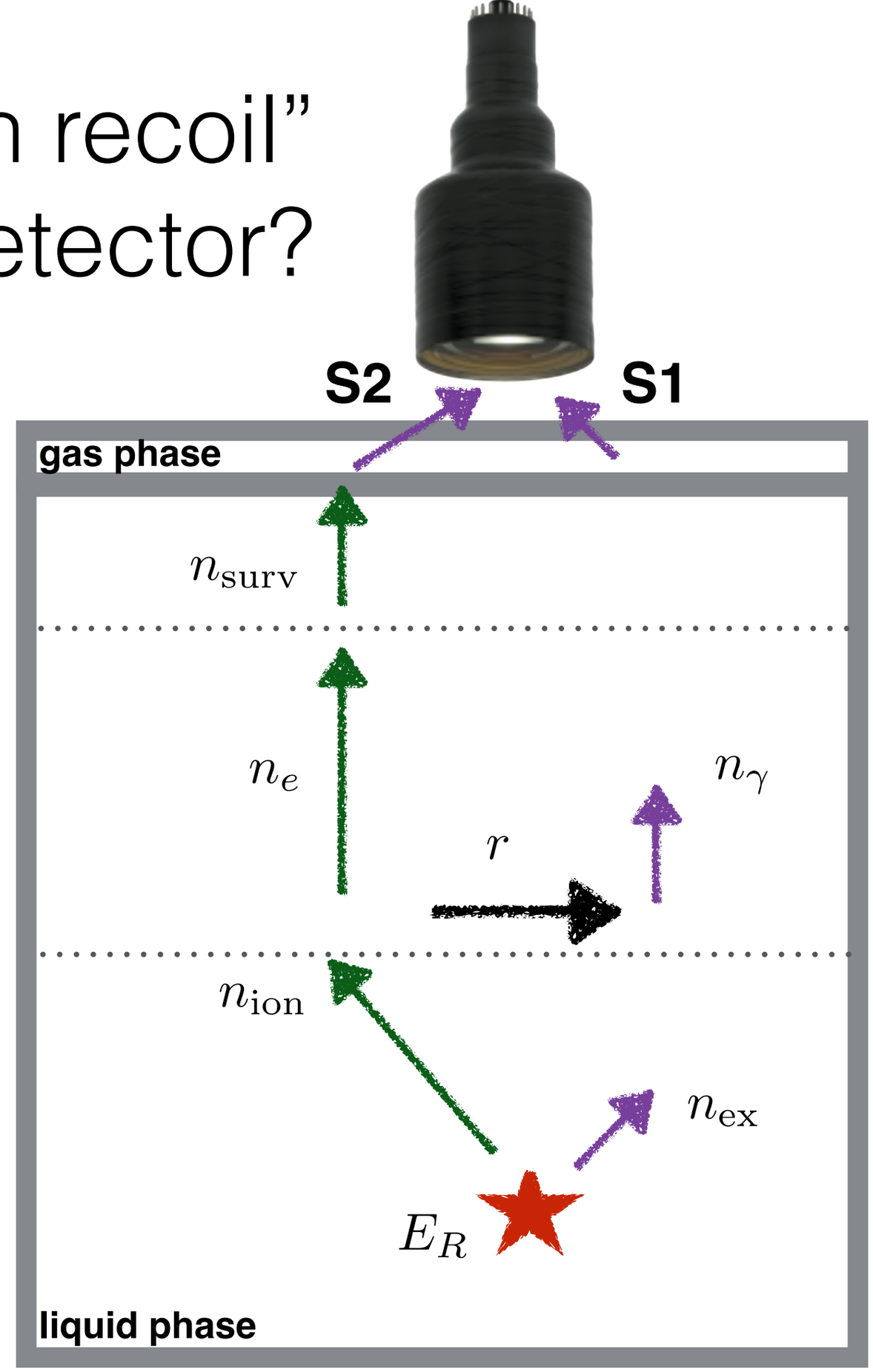


How does an “electron recoil” signal look in a LXE detector?

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

$$g_1 \simeq 0.1, \quad g_2 \simeq 10 - 50$$

An electron reaching the liquid-gas interface creates about O(10) PE (S2); it takes on average 10 scintillation photons to collect 1 PE (S1)



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

detector specific

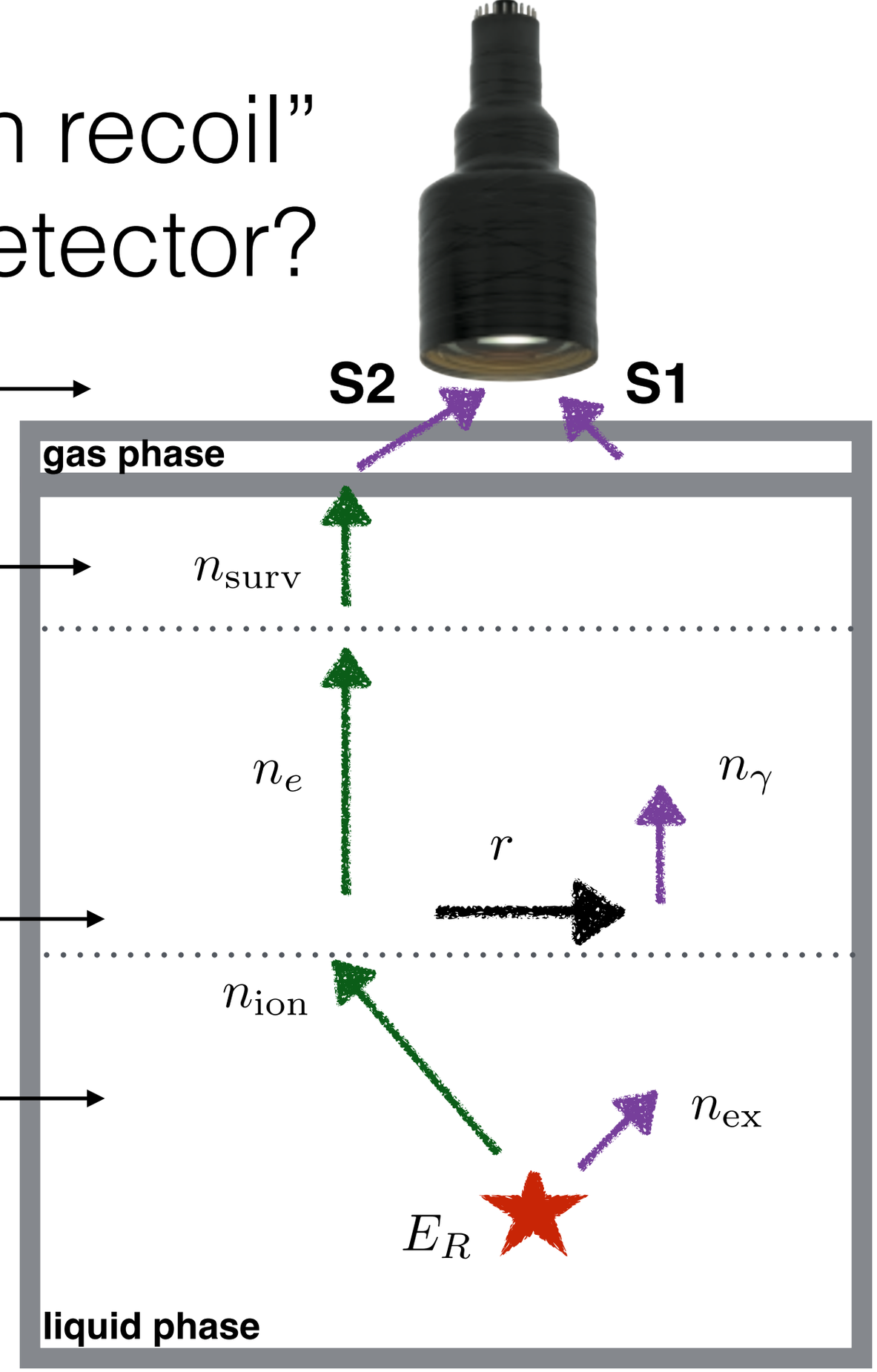
fluctuates

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

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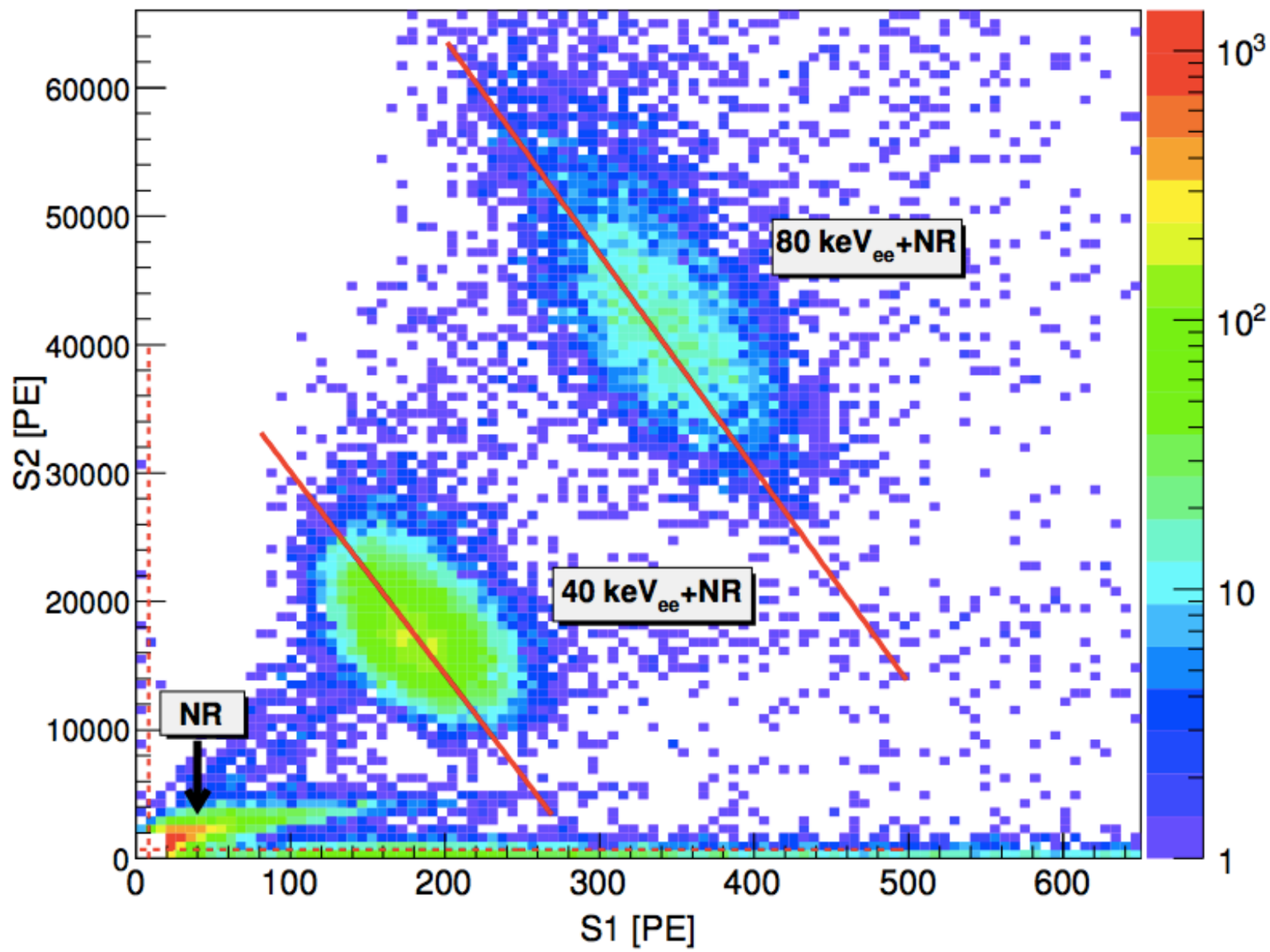
$$= \frac{S1}{g_1} + \frac{S2}{g_2}$$



note the anti-correlation between S1 and S2

Electron vs. nuclear recoils

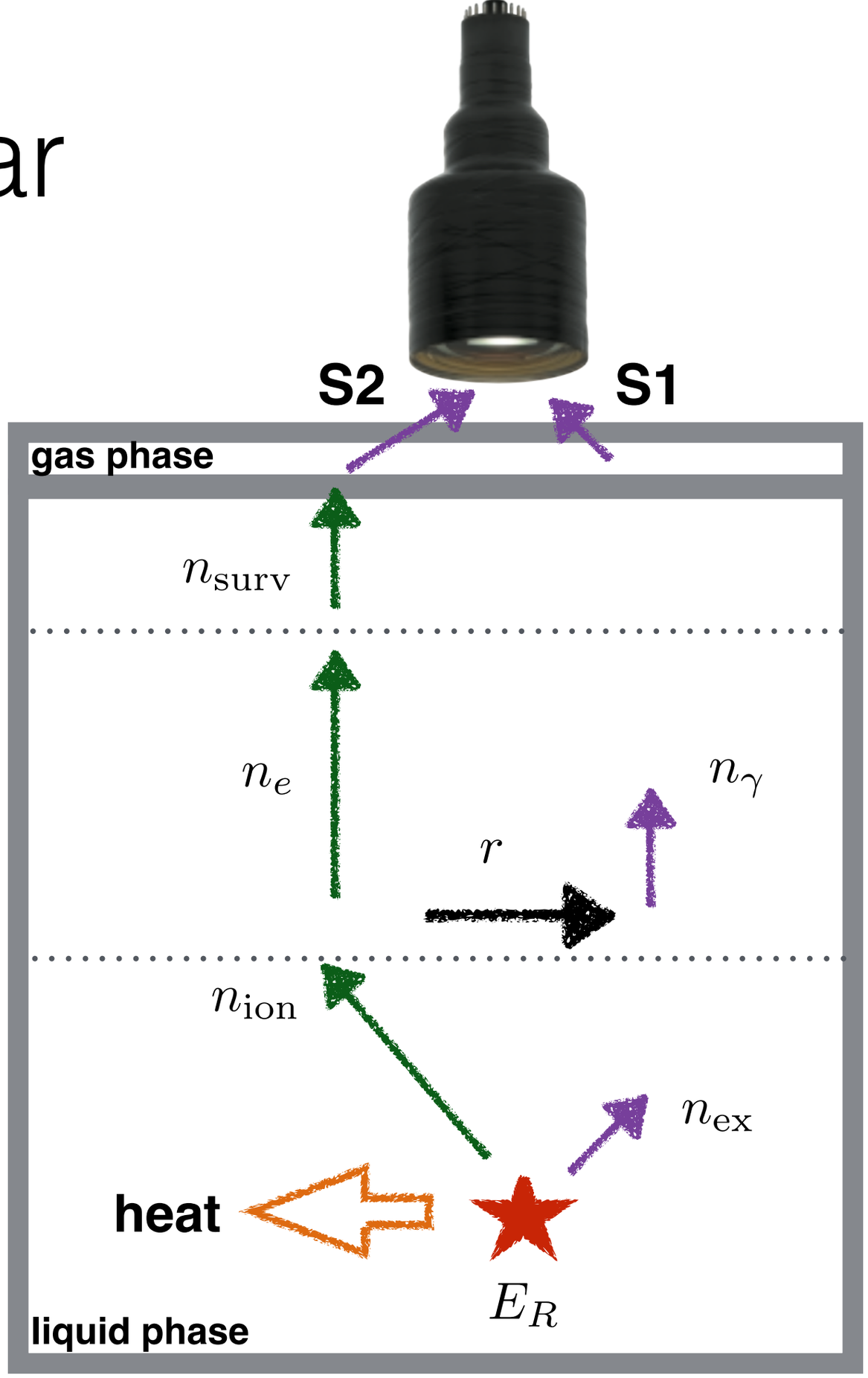
$$N_Q^{\mathrm{ER}} = \frac{E_{R,e}}{W}$$

In electron recoils, heat losses are negligible but not so in nuclear recoils:

$$N_Q^{\mathrm{NR}} = E_R[L_y(E_R) + Q_y(E_R)]$$

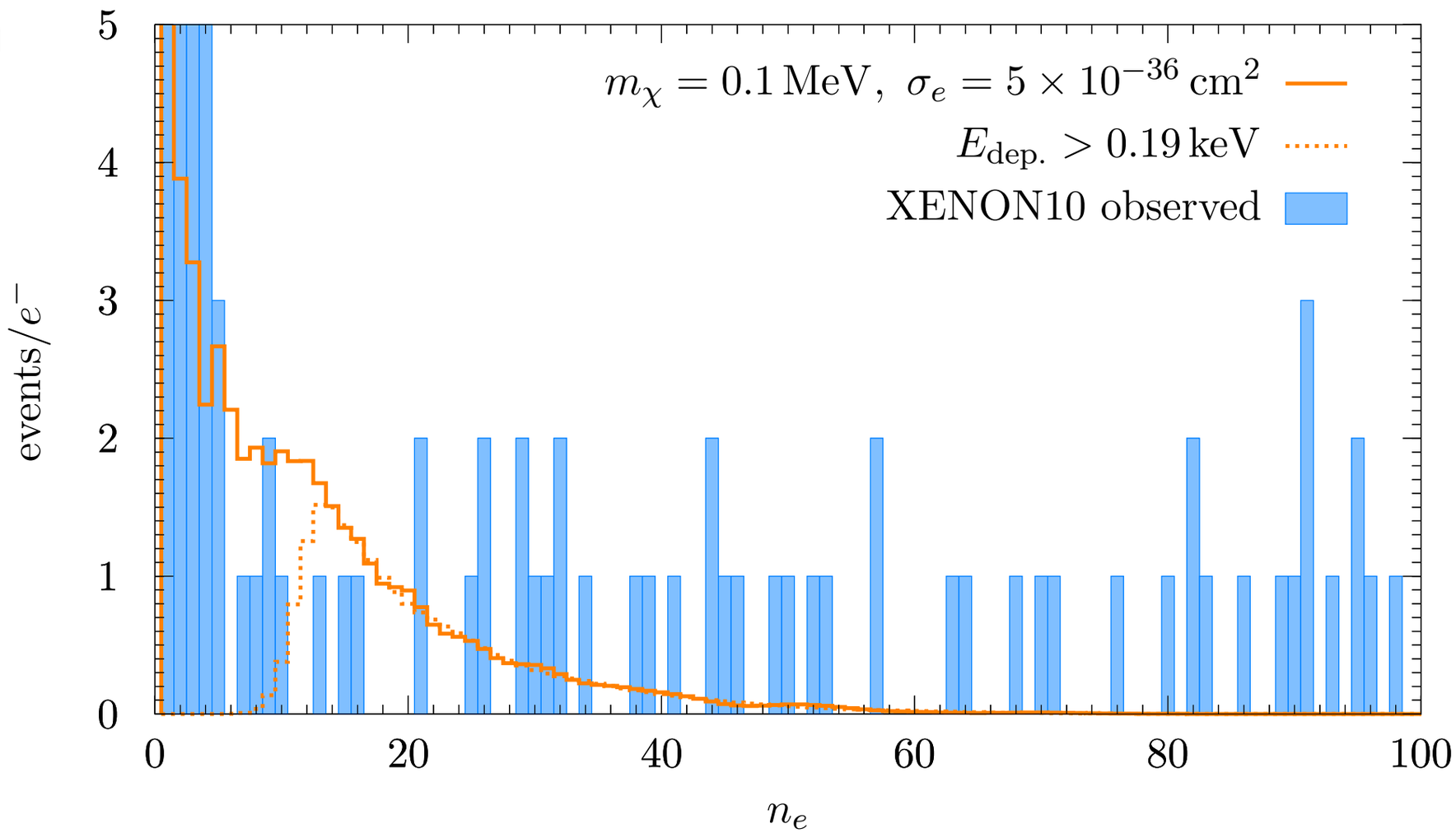
$$N_Q^{\mathrm{NR}} < N_Q^{\mathrm{ER}}$$

NR signal is quenched; additional source of fluctuations



Current sensitivity to sub-MeV DM

Ionization spectrum from DM electron scattering in XENON10



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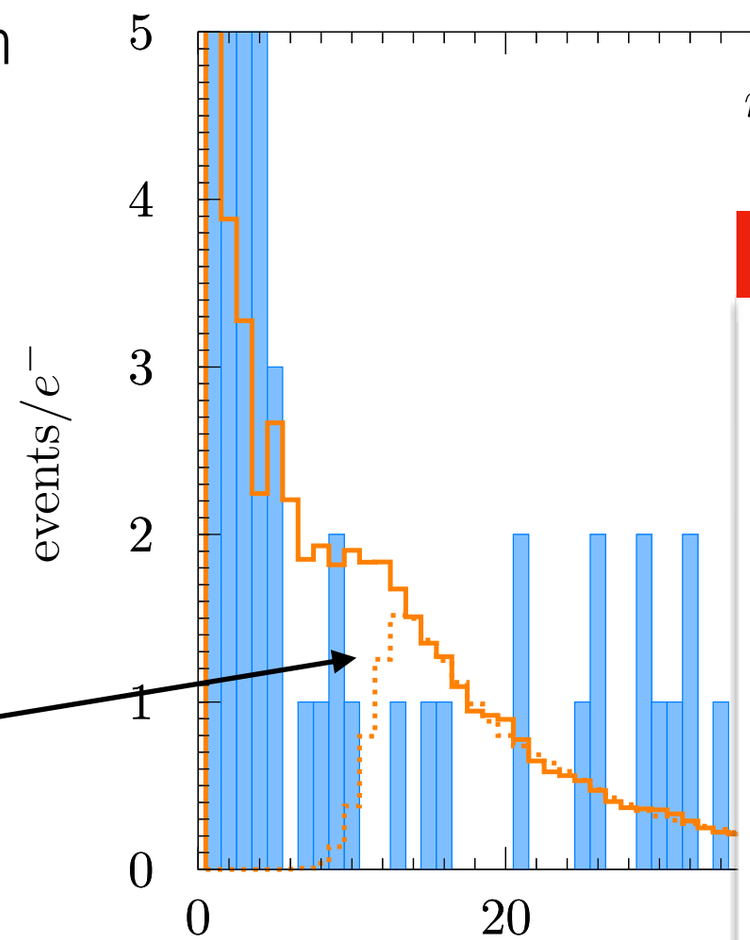
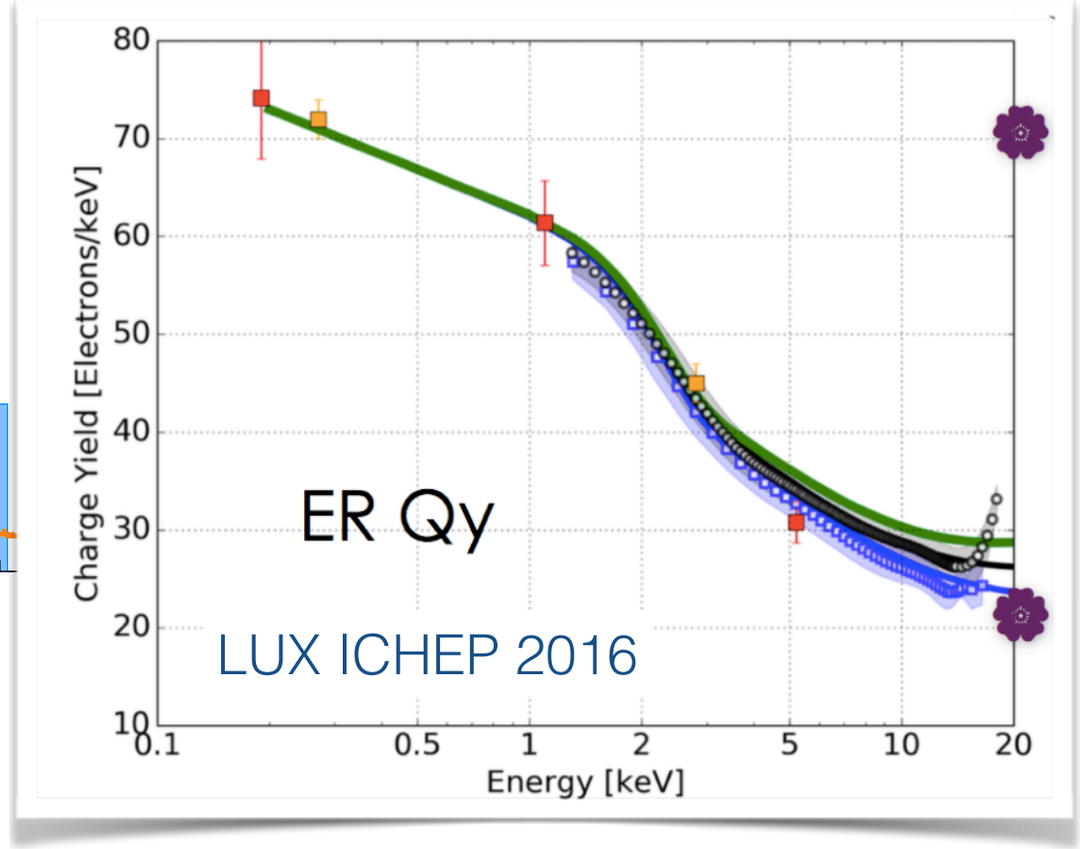


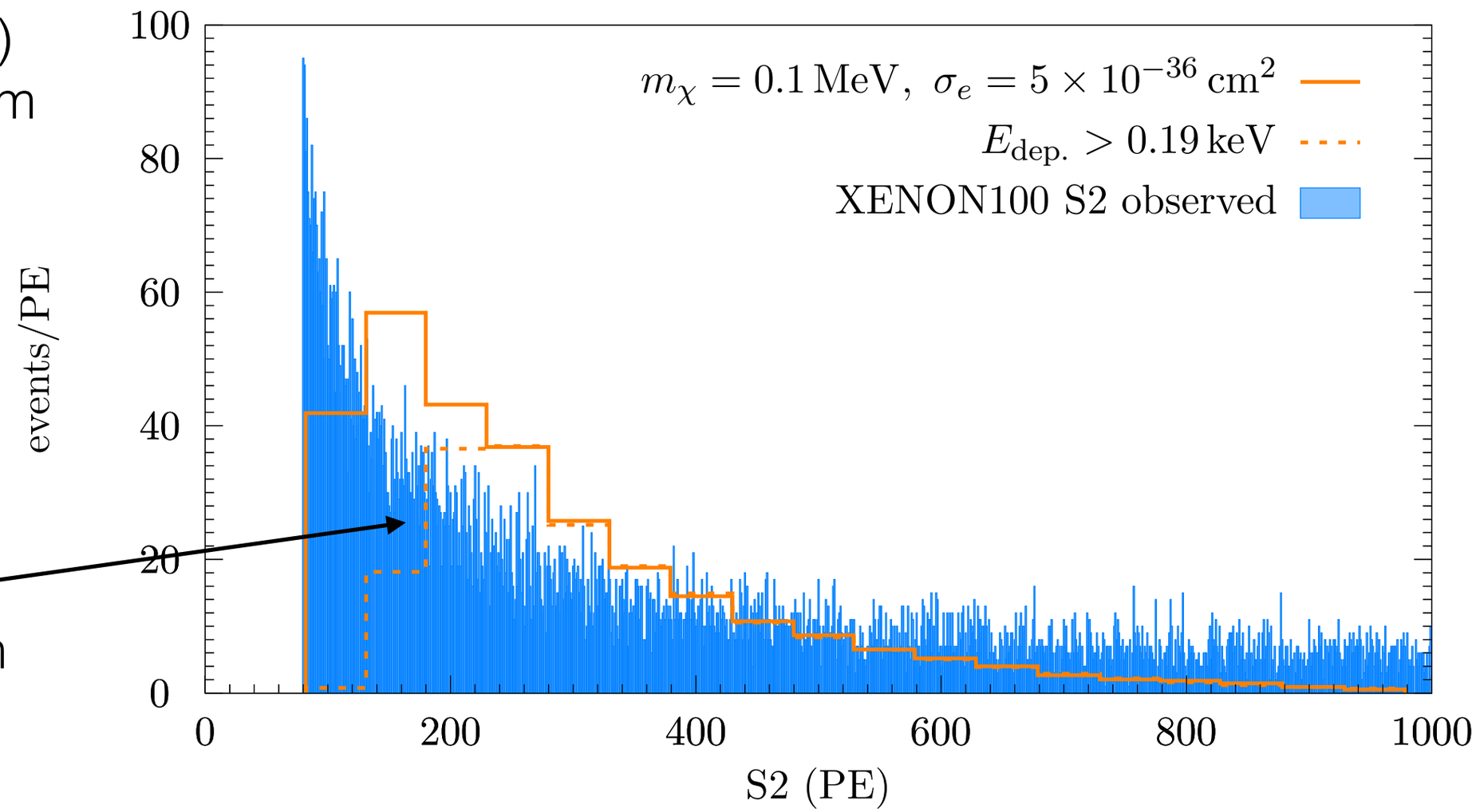
for expt. limits: demand minimum deposited energy of 0.19 keV => data driven approach

Charge yield measured to 0.19 keV



Current sensitivity to sub-MeV DM

XENON100 (2016)
ionization spectrum



for expt. limits:
demand minimum
deposited energy
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 plane or Coulomb waves are used for $|\mathbf{p}'_e\rangle$, numerically, the overlap with HF-bound w.f. can be non-zero

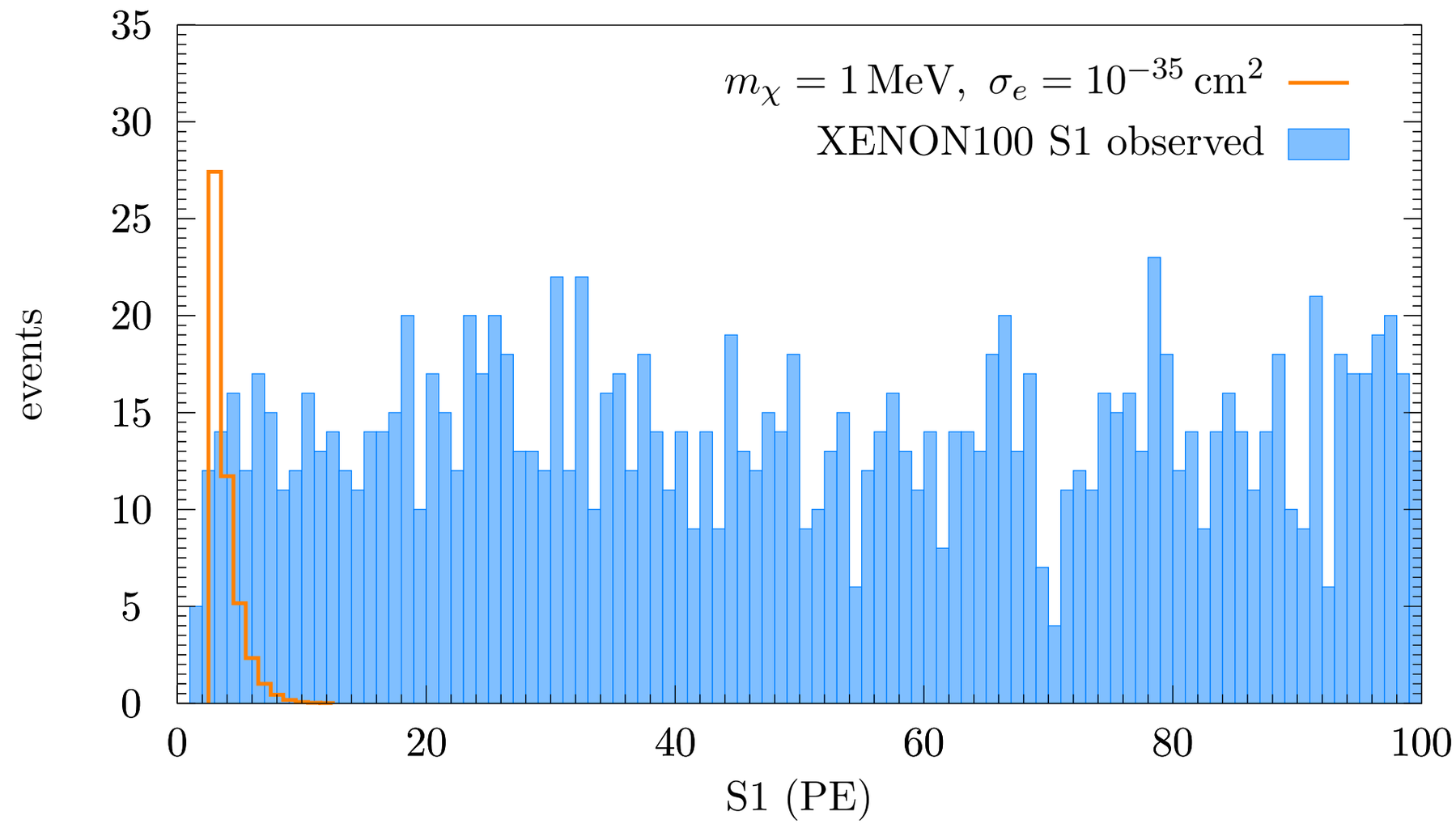
=> we subtract the unity operator in the atomic form factor when the relativistic limit when $\mathbf{q} \cdot \mathbf{r} \ll 1$

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

Current sensitivity to sub-MeV DM

S1-scintillation spectrum in XENON100

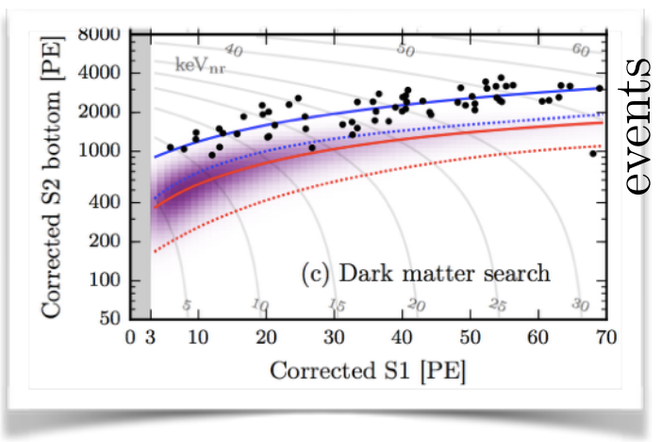
(detected S1 reduces backgrounds through volume fiducialization)



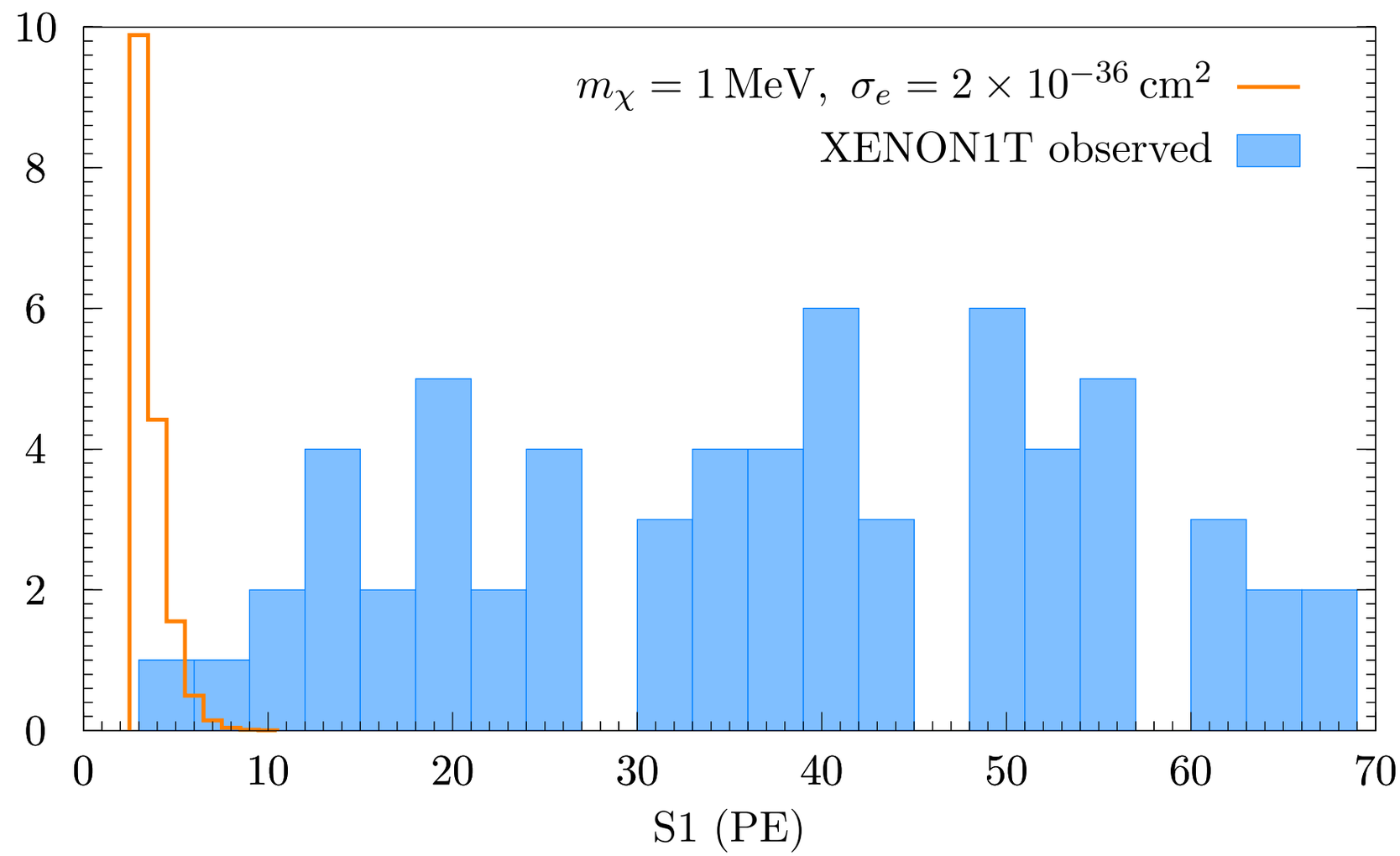
reflected spectrum extends into keV-range => scintillation detectable (benefit of background suppression)

Current sensitivity to sub-MeV DM

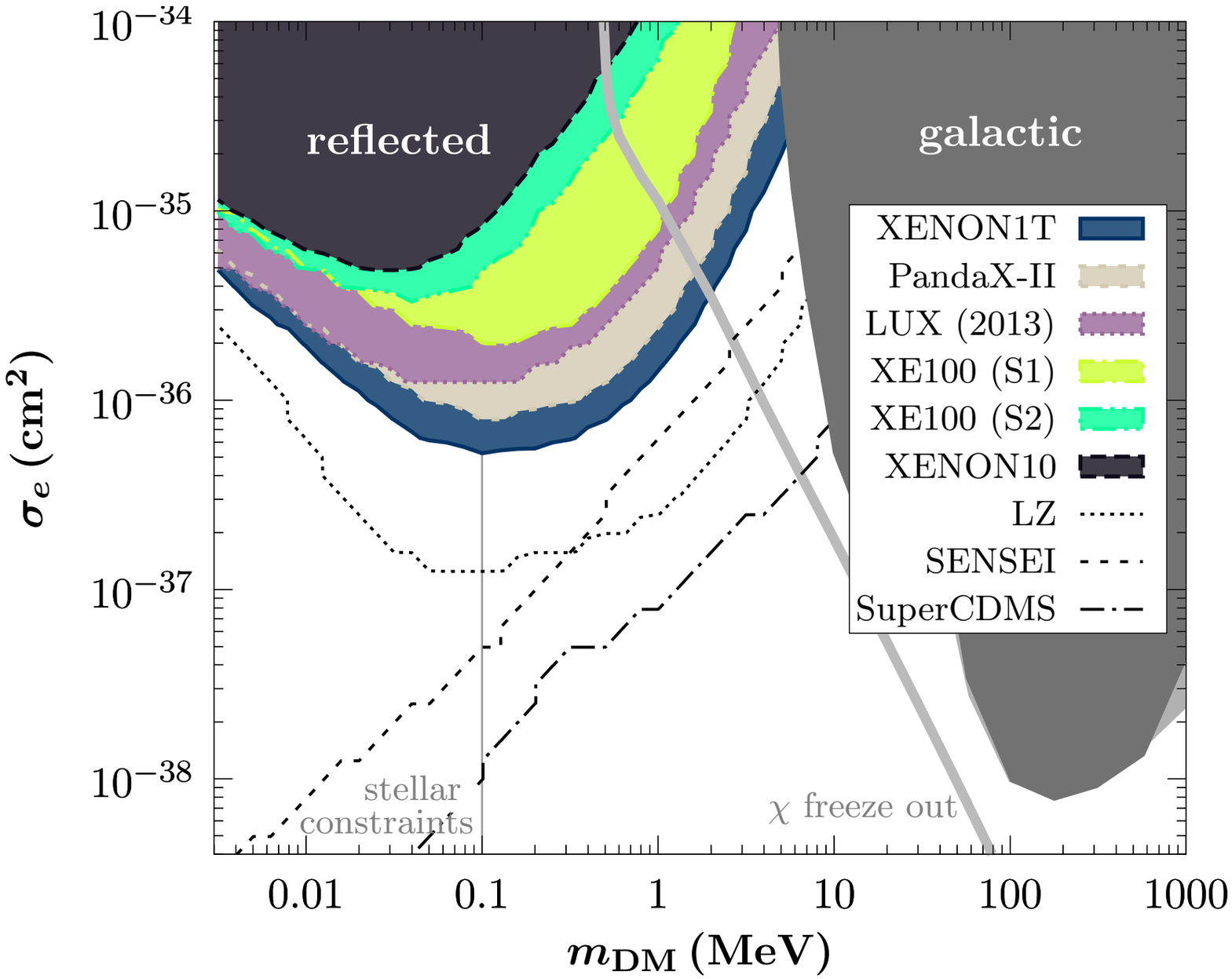
first results from XENON1T



[Aprile et al 2017]

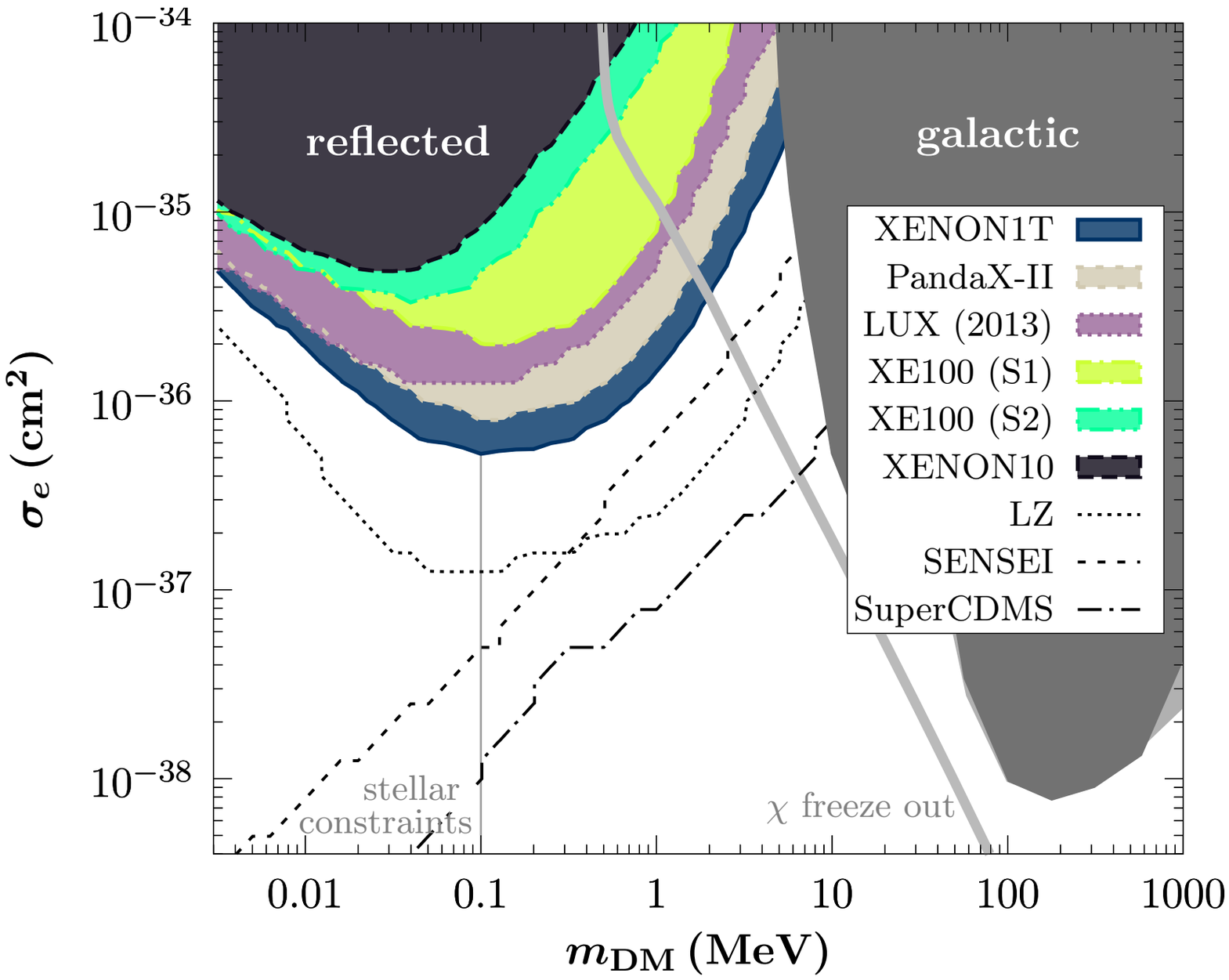


Direct Detection of sub-MeV DM



=> 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!

Direct Detection of sub-MeV DM

Example of a successful model (UV completed through Z')

$$\mathcal{L}_{\rm int} = G_{\chi e} \times (\bar{e}\gamma^\mu e)(i\chi^* \partial_\mu \chi - i\chi \partial_\mu \chi^*)$$

relic density is set via p-wave annihilation
=> safe from CMB constraints on energy injection; Neff contributions are model dependent

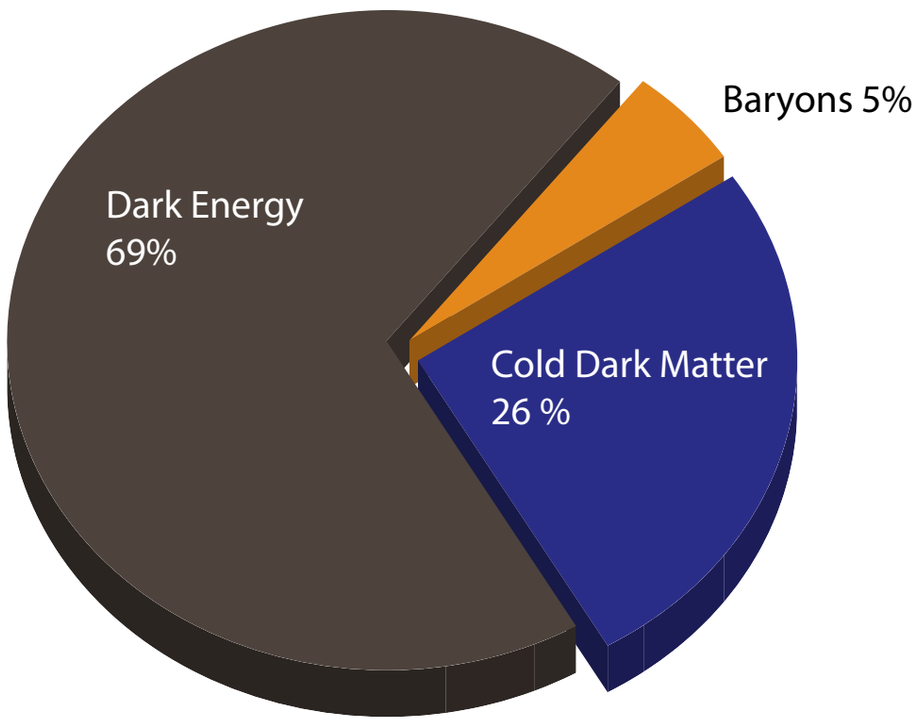
$$\sigma_{\rm ann} v = v^2 \times \frac{G_{\chi e}^2}{12\pi}(m_e^2 + 2m_\chi^2)\sqrt{1 - \frac{m_e^2}{m_\chi^2}}$$

=> First direct test of such DM model

$$\sigma_e = \frac{1}{\pi} G_{\chi e}^2 \mu_{\chi,e}^2 \;\rightarrow\; (8{-}9) \times 10^{-35}\,{\rm cm}^2 \;\times\; \frac{2\mu_{\chi,e}^2}{(2m_\chi^2 + m_e^2)v_e}$$

2 Non-gravitational signatures of a relativistic cosmic background

Cui, Pospelov, JP, **1711.04531**



CMB

$$N_{\rm eff} = 3.04 \pm 0.33$$

$$\Rightarrow \quad \rho_{\rm DR}/\rho_\gamma < 0.15$$

Planck 2015

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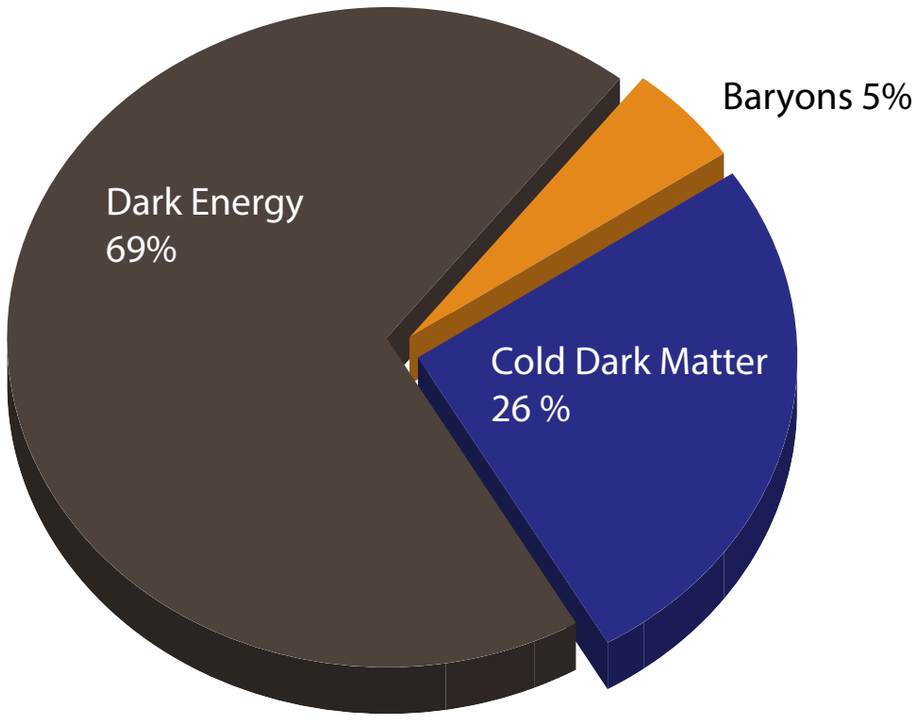
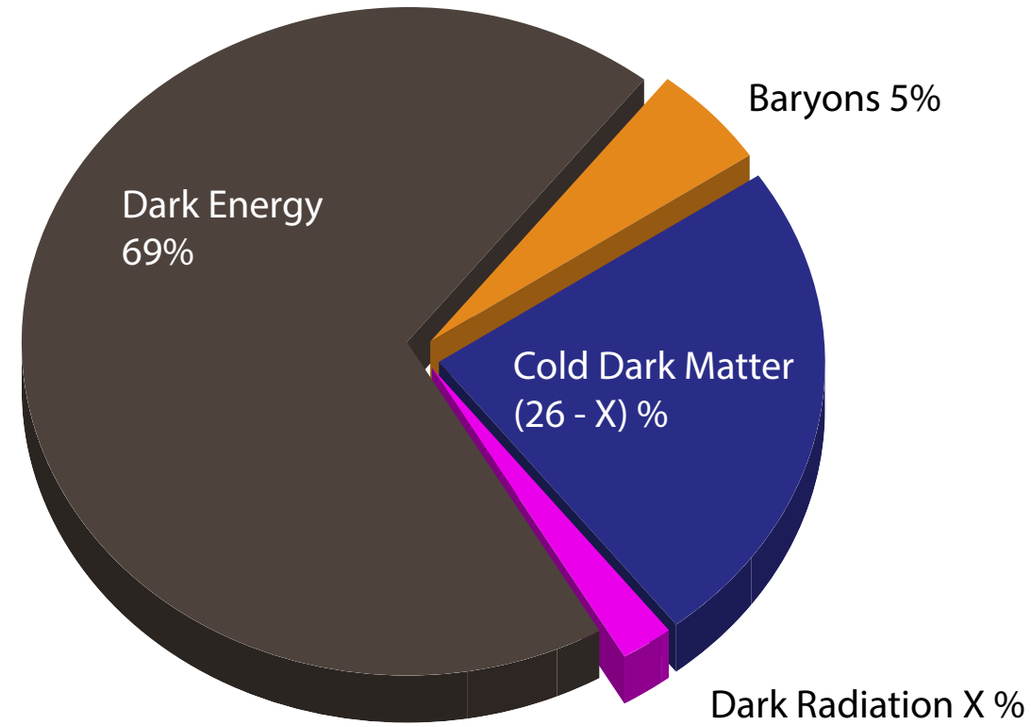


=>



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Planck 2015

Low redshift Universe

Dark radiation (DR):
boosted states in the hidden sector

see, e.g. Agashe et al. 2014

Late Dark Radiation (DR)

Late DR can be sourced by the decay or annihilation of DM.

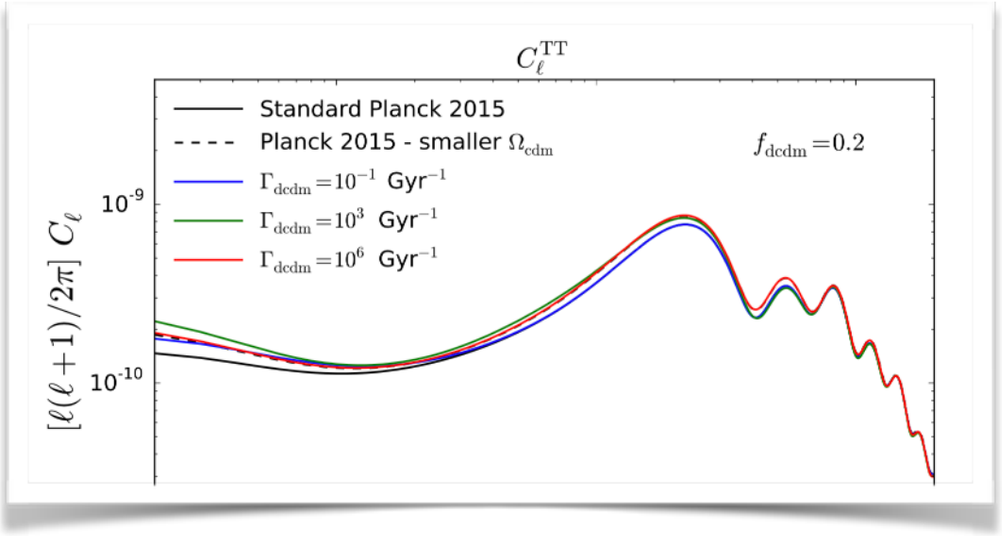
Here we consider DM decay (=most efficient progenitor for a relativistic flux) of a sub-dominant species with lifetime (broadly log-centred) around $H_0^{-1} \sim 10\,\mathrm{Gyr}$

General setup:

$$n_{\mathrm{DR}} \ll n_\gamma, \quad E_{\mathrm{DR}} \gg E_\gamma$$

CMB constraint from late-time ISW and lensing $\rho_{\mathrm{DR}} < 0.1\rho_{\mathrm{DM}}$

e.g. Poulin, Serpico, Lesgourges 2016



NB: there are also constraints on structure formation with residual “kicked DM state” in place

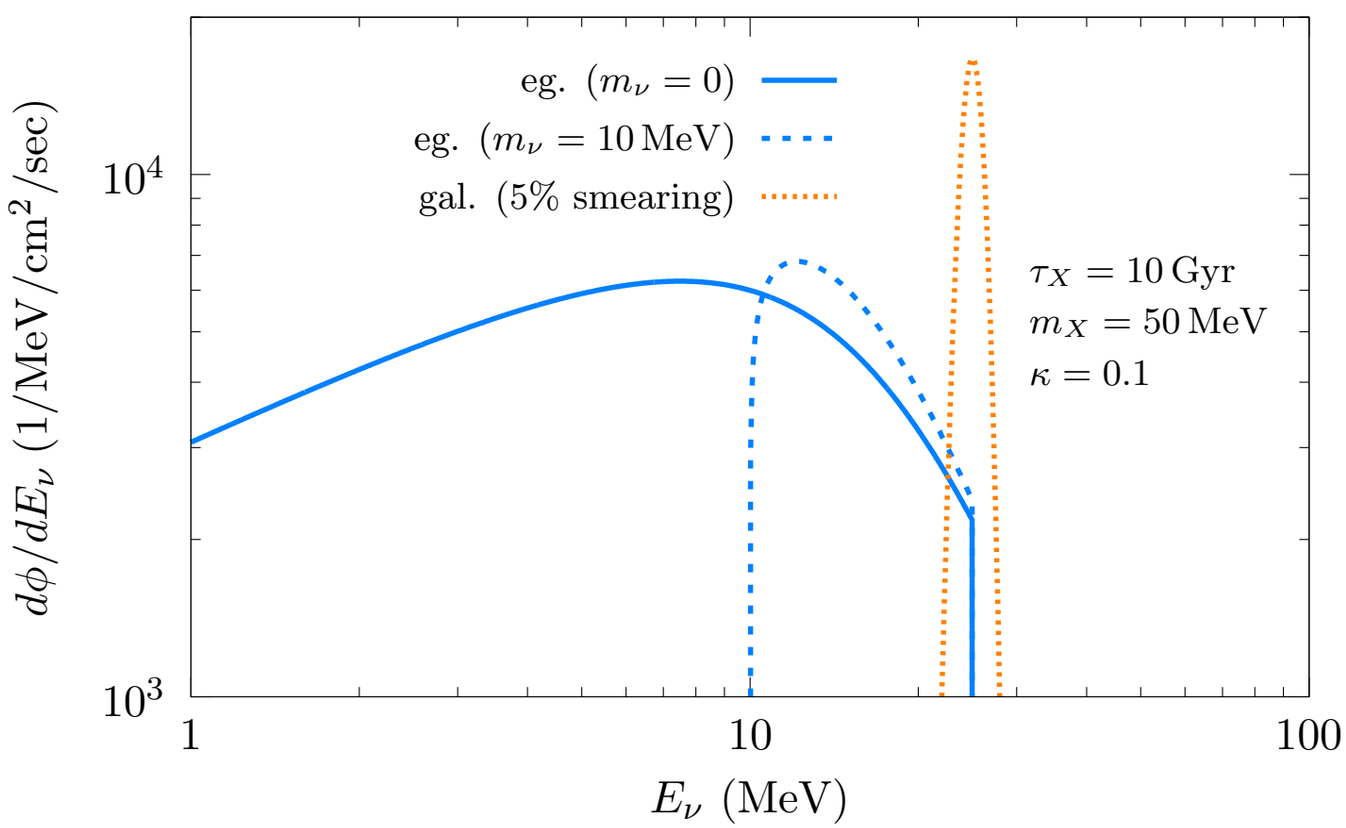
e.g. Wang, Peter at al. 2014

Maximum fluxes of DR

Galactic and extragalactic contributions to the flux

galactic $$\frac{d\phi_{\rm gal}}{dE_\nu} = \frac{\kappa {\rm Br}_\nu e^{-t_0/\tau_X}}{\tau_X m_X} \frac{dN}{dE_\nu} \times R_{\rm sol}\rho_{\rm sol}\langle J\rangle$$

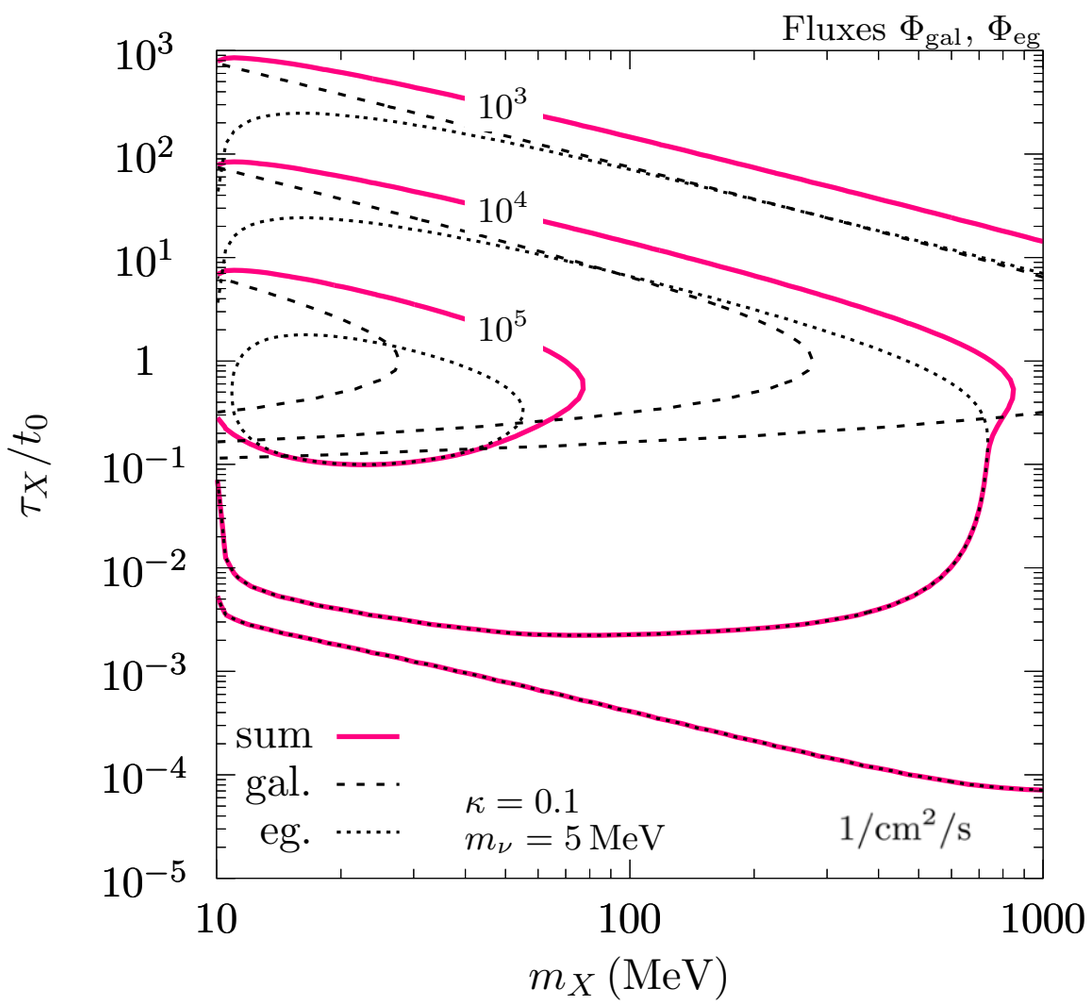
extragalactic $$\frac{d\phi_{\rm e.g.}}{dE_\nu} = \frac{\kappa {\rm Br}_\nu \Omega_{\rm dm}\rho_c}{\tau_X m_X} \int_0^{z_f} dz\, \frac{e^{-t(z)/\tau_X}}{H(z)} \frac{dN[E_{\rm em}(z)]}{dE_\nu} v_{\rm em}(z)$$



example for 2-body injection

Maximum fluxes of DR

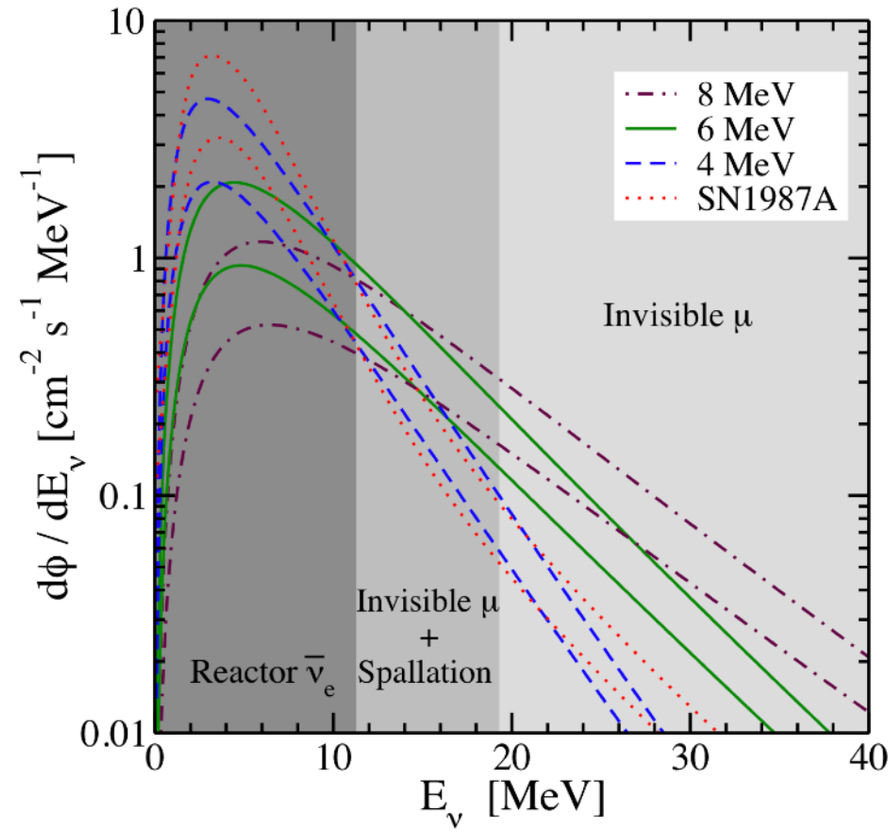
Galactic and extragalactic contributions to the flux



here: 10% decaying DM component

Maximum flux $\Phi_{\rm tot}^{\rm max} \sim \frac{10\,\mathrm{MeV}}{m_X} \times 10^6\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

much in excess of atmospheric nu-flux and DSNB at ~ 10 - 100 MeV



compare with DSNB (Beacom 2010)

Late Dark Radiation *in SM neutrinos*

Option 1: DR are Standard Model neutrinos

Benefits: no Neff constraints for direct decay, interactions within SM are known, minimal setup

Decaying progenitor motivated by certain neutrino mass generation mechanism
Majoron $\phi \to \nu\nu \ (\bar{\nu}\bar{\nu})$

Φ breaks global lepton number, Goldstone mode is ϕ

$$\mathcal{L} = y_1 \bar{L}^c H S_R + y_2 \Phi \bar{S}_L^c S_R + h.c. \quad => \quad \mathcal{L}_{\phi\nu\nu} = i \frac{m_\nu^2}{\langle H \rangle^2} \frac{y_2}{y_1^2} (\nu\nu - \nu^c \nu^c)\phi \qquad m_\nu = \frac{y_1^2 \langle H \rangle^2}{y_2 \langle \Phi \rangle}$$

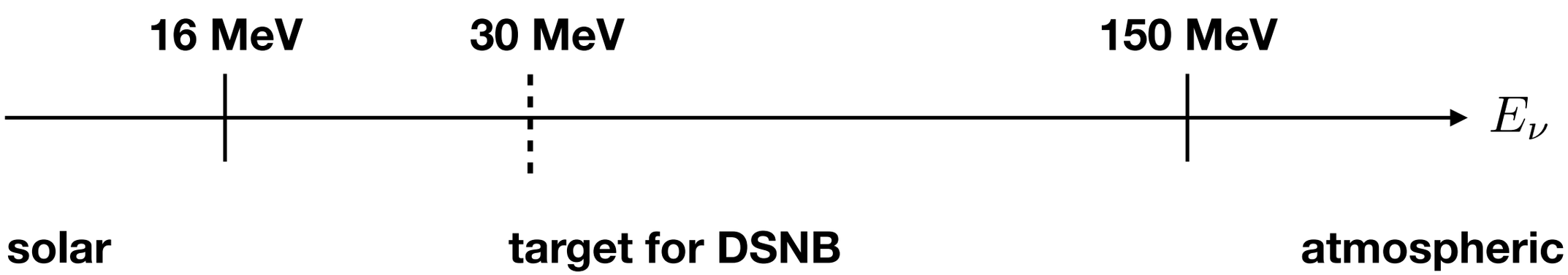
Chikashige, Mohapatra, Peccei 1981

Mass of ϕ as pseudo-Goldstone uncertain, with contributions from Planck-scale suppressed operators; we take it $\mathrm{O}(10)\ \mathrm{MeV}$ noting a non-standard thermal history e.g. Berezinsky, Valle 1993

Late Dark Radiation in SM neutrinos

Measurements / Constraints:

- E < 16 MeV: signal dominated by solar neutrinos (8B flux) in CC and NC scattering on electrons
- 16 MeV < E < 30 MeV: inverse beta decay $p + \bar{\nu}_e \to n + e^+$ with large visible energy
- 30 MeV < E < 150 MeV: reactions with neutrons inside nuclei no longer kinematically suppressed, e.g. $^{16}\mathrm{O} + \nu_e \to {}^{16}\mathrm{F} + e$
- E > 150 MeV: atmospheric neutrino flux well measured and concordant



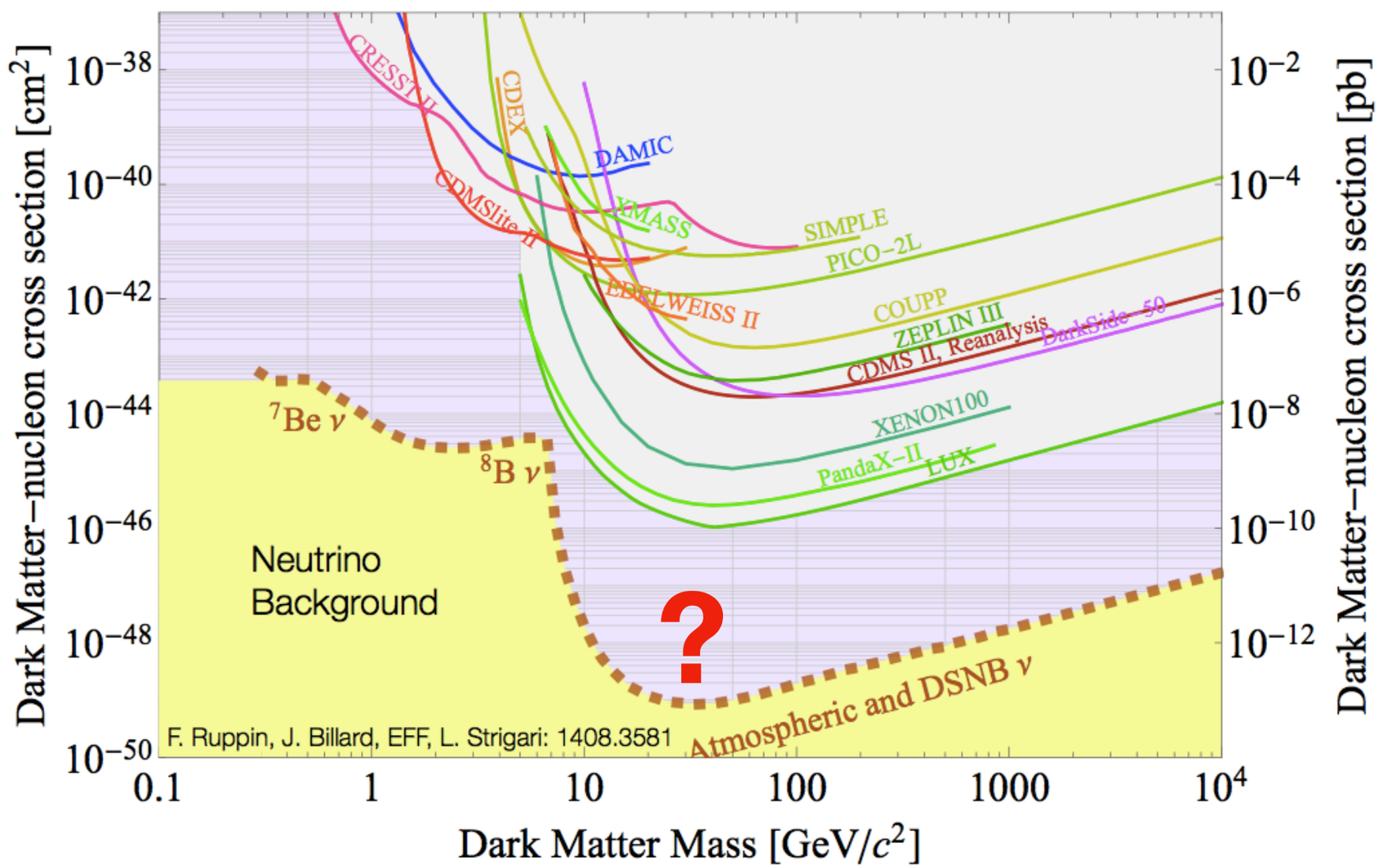
Late Dark Radiation *in SM neutrinos*

Option 1: DR are Standard Model neutrinos

Opportunity: Injection of neutrinos at few 10's of MeV poorly constrained

A 30 MeV neutrino gives signals in direct detection right in the region of largest sensitivity.

Neutrino floor can be raised in models that inject ν but not excessively $\bar{\nu}$



Late Dark Radiation *in new physics*

Option 2: DR are new (semi-)relativistic states that interact with SM

Benefits: more possibilities, stronger signals are possible (here we restrict ourselves to the MeV-scale again). For example,

$$X \to \chi + \chi, \text{ or } X \to Y + \chi, \text{ or } X \to \mathrm{SM} + \chi \qquad X,\ Y = \mathrm{DM} \quad \chi = \mathrm{DR}$$

NB: χ can be a sterile neutrino mixing with ν, recovering Option 1

Option 2.1: χ boson => *absorption signals*

standard cases include χ being a dark photon or axion-like particle; absorption signals have been worked out for direct detection

It turns out that it is difficult to detect bosonic DR that is sourced by sub-keV progenitors, as severe astrophysical constraints apply

Late Dark Radiation *in new physics*

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NB: χ can be a sterile neutrino mixing with ν, recovering Option 1

Option 2.2: χ fermion => *scattering signals*

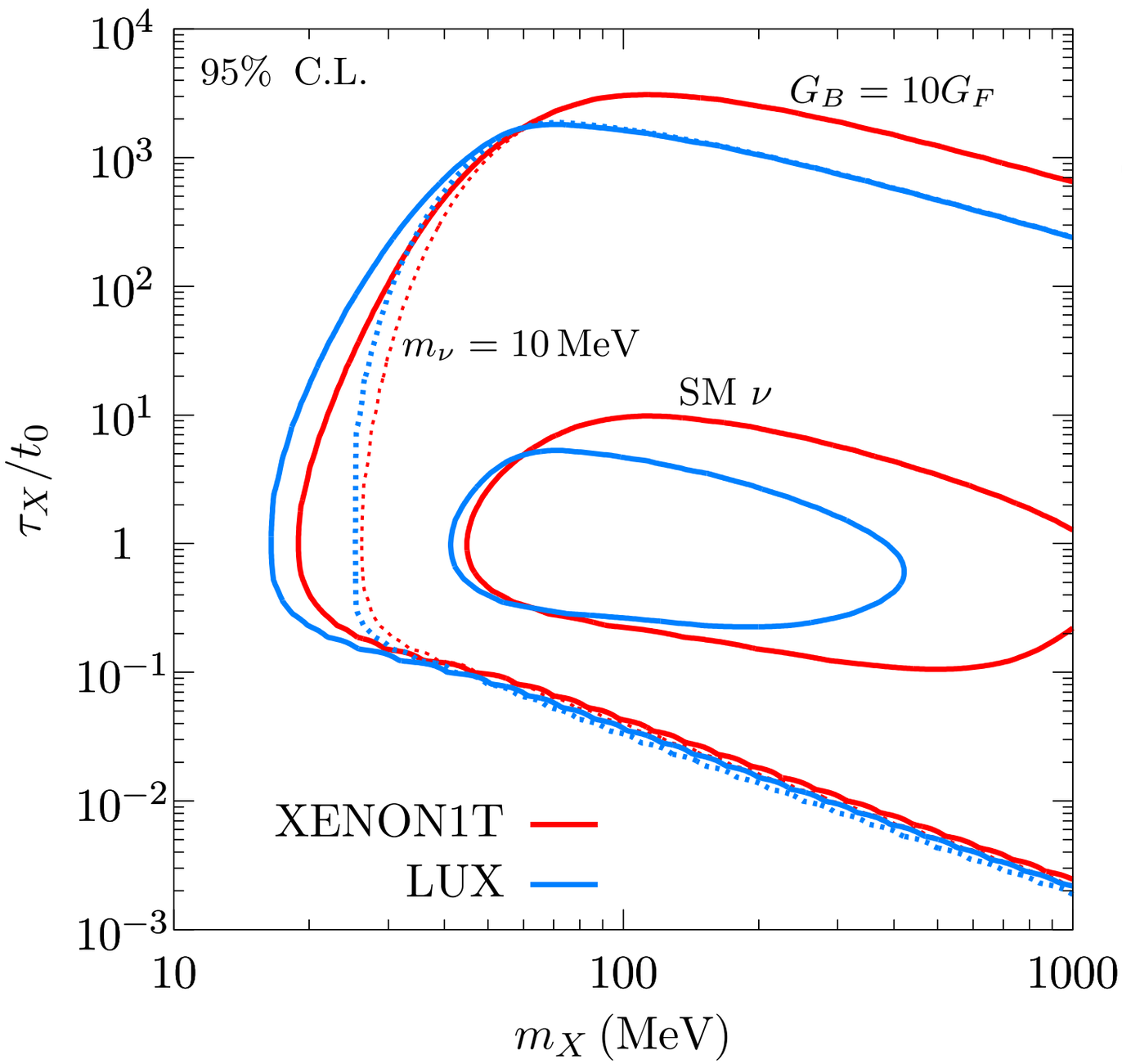
E.g. well motivated and studied case:

$$(\bar{\chi}\Gamma\chi) \times O_b^{\mathrm{SM}} = (\bar{\chi}\gamma_\nu\chi) \times (G_V J^\nu_{EM} + G_B J^\nu_B)$$

$$J^\nu_{EM} = \bar{e}\gamma^\nu e + \bar{p}\gamma^\nu p; \quad J^\nu_B = \bar{n}\gamma^\nu n + \bar{p}\gamma^\nu p$$

Much milder astro-constraints; Neff can be better avoided when coupled to baryons

Direct detection sensitivity to DR



<= Option 2.2. scattering with stronger than SM interactions

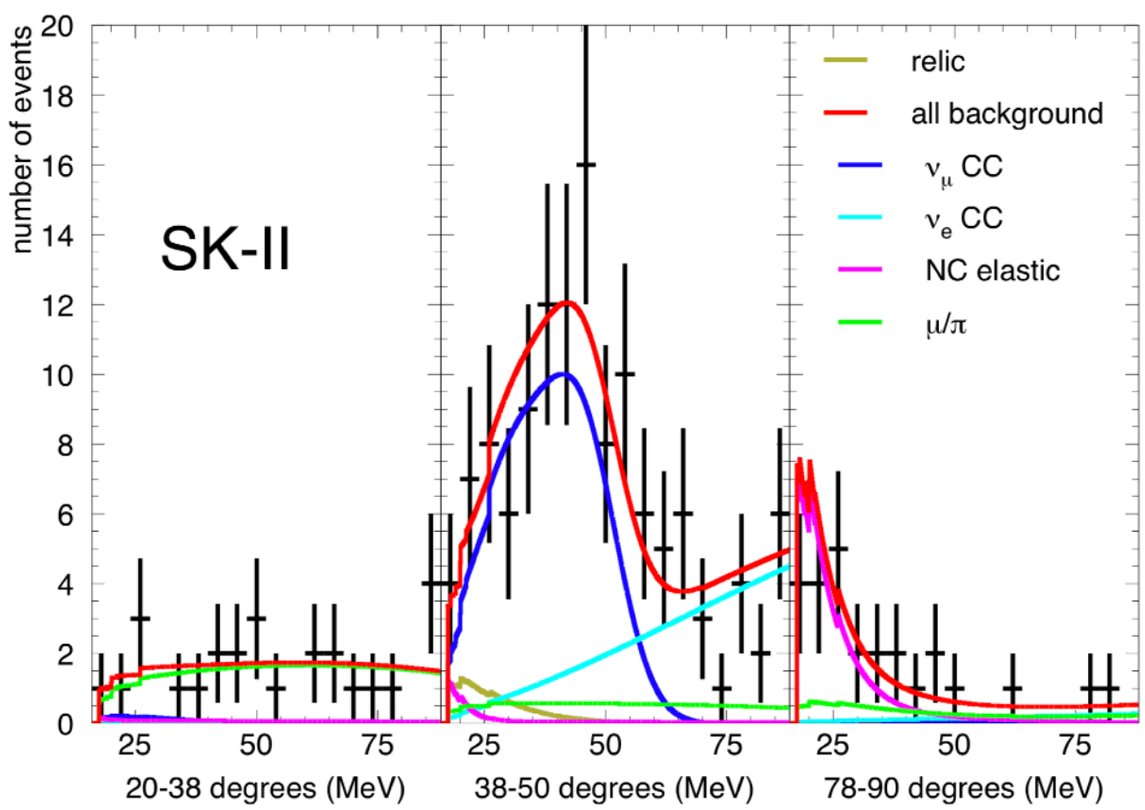
<= Option 1. Decay into SM neutrinos

Neutrino experiments will provide constraints…

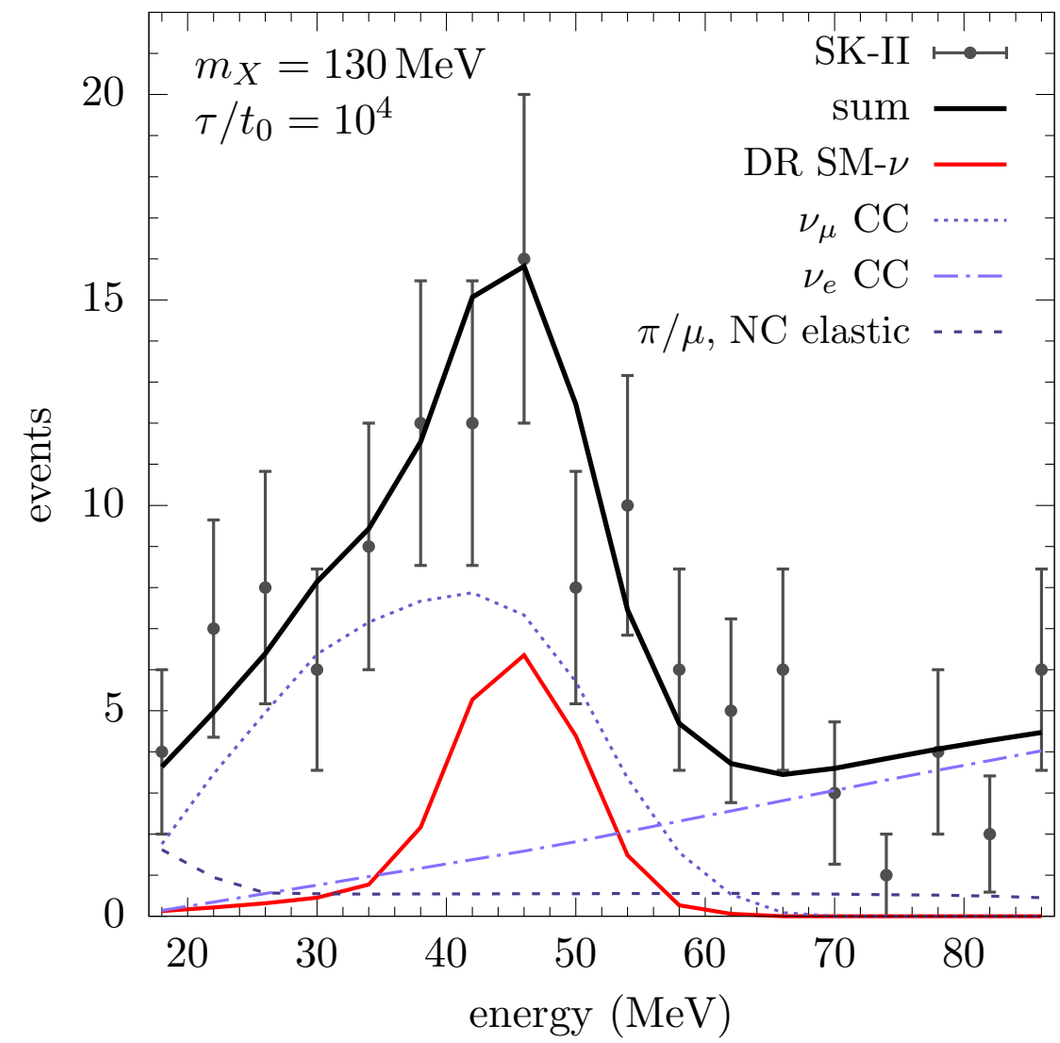
Constraints from neutrino expts.

e.g. recasted Super-Kamiokande search for DSNB neutrinos

Super-K collaboration 2011



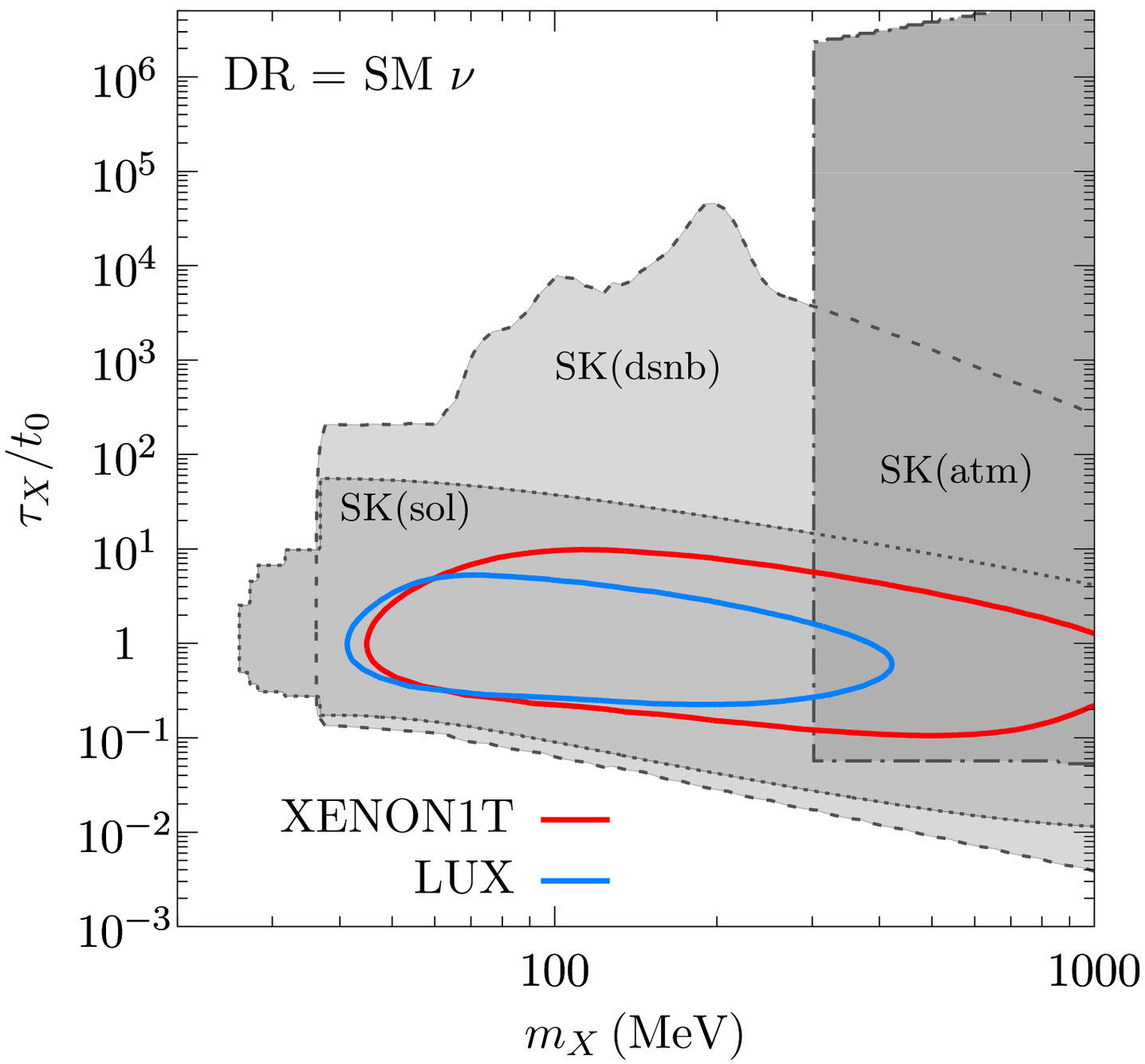
=>



sideband | search-region with fitted bkg. | sideband

e.g. $\phi_\nu(E_\nu \simeq 25\,\mathrm{MeV}) < 5 \times 10^2\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$

Summary - DR in DM neutrinos



Option 1

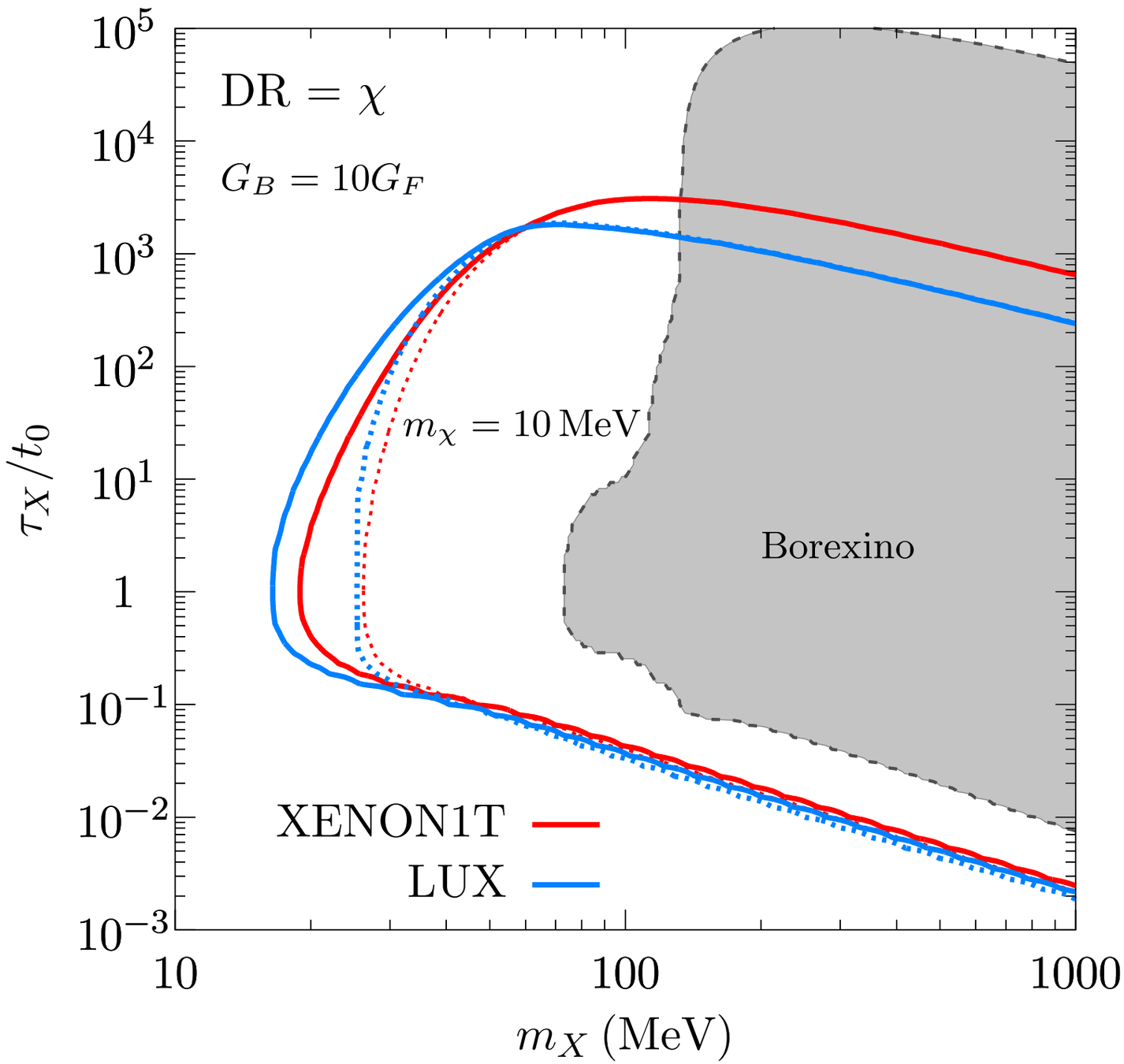
DR in SM neutrinos ν

=> if flux is saturated then neutrino floor ~2 orders of magnitude away from current direct detection sensitivity

=> neutrino floor is raised to by ~2 orders of magnitude for a 30 GeV WIMP

(Nikolic, JP in prep)

Summary - DR in a new species

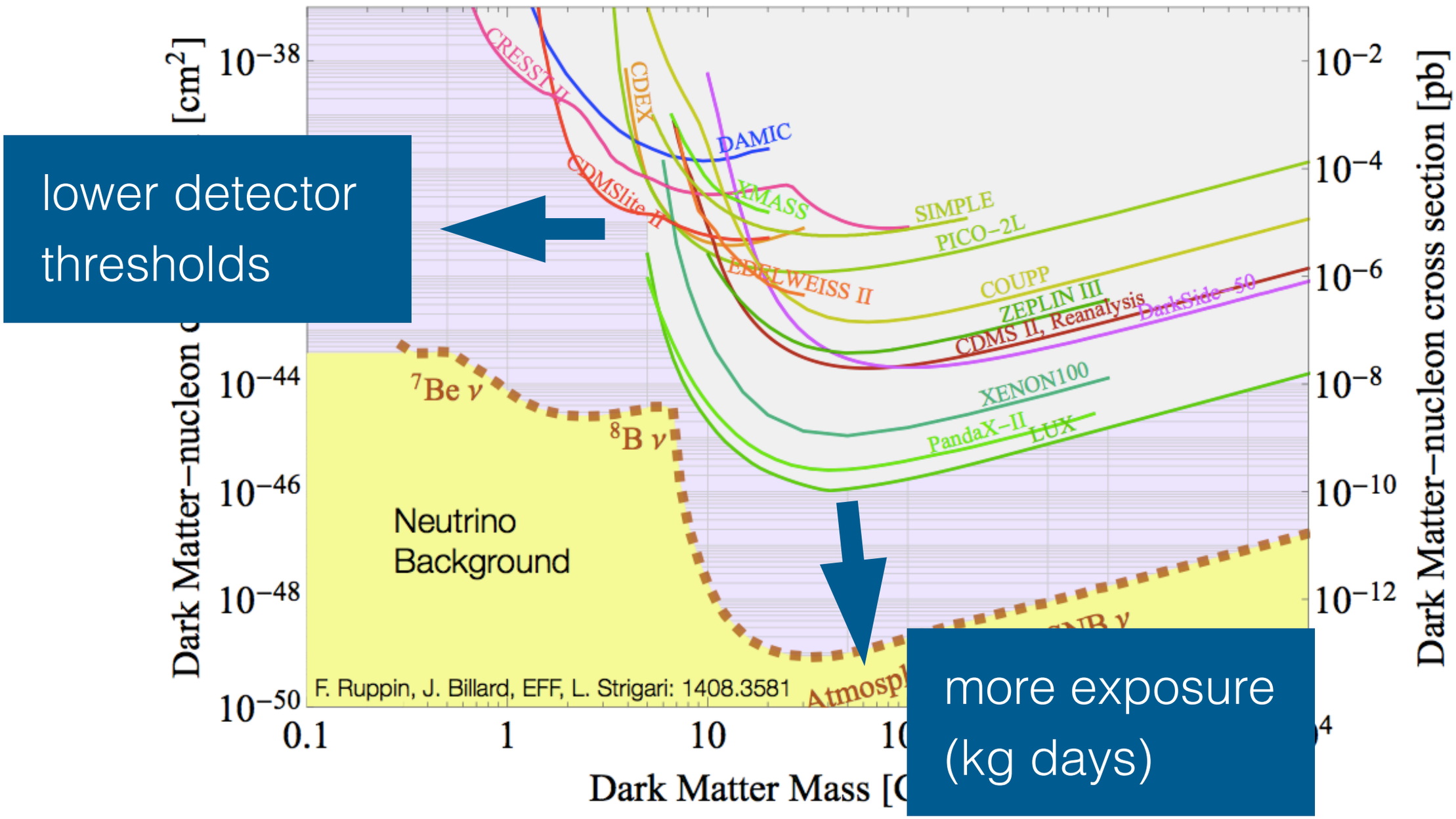


Option 2

new neutrino interacting with baryonic current

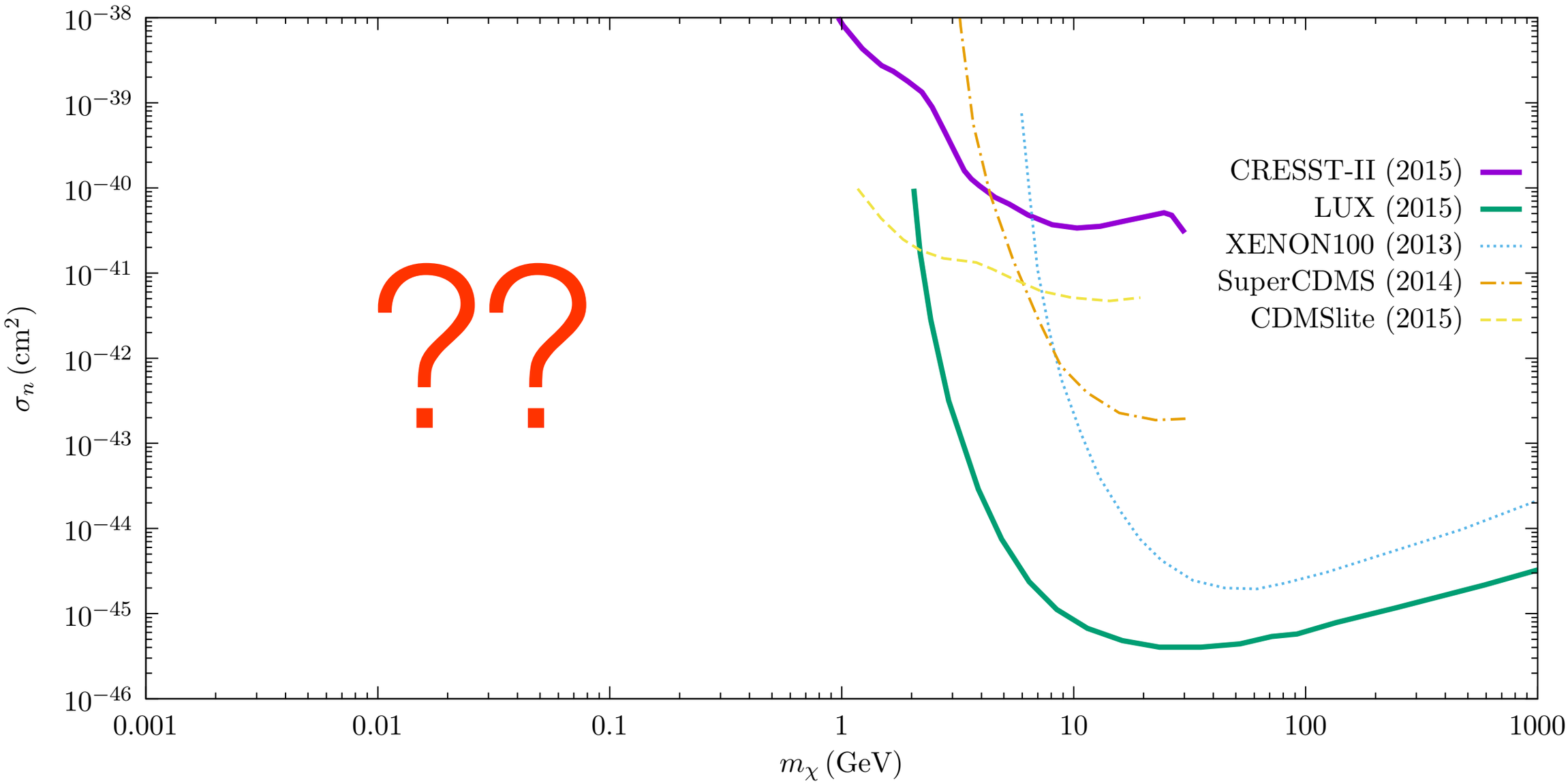
Borexino limit derived from elastic scattering on protons

A (partial) summary of 2 decades of experimental effort



CF1 Snowmass report, Ruppin et al 2014

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



"light Dark Matter"

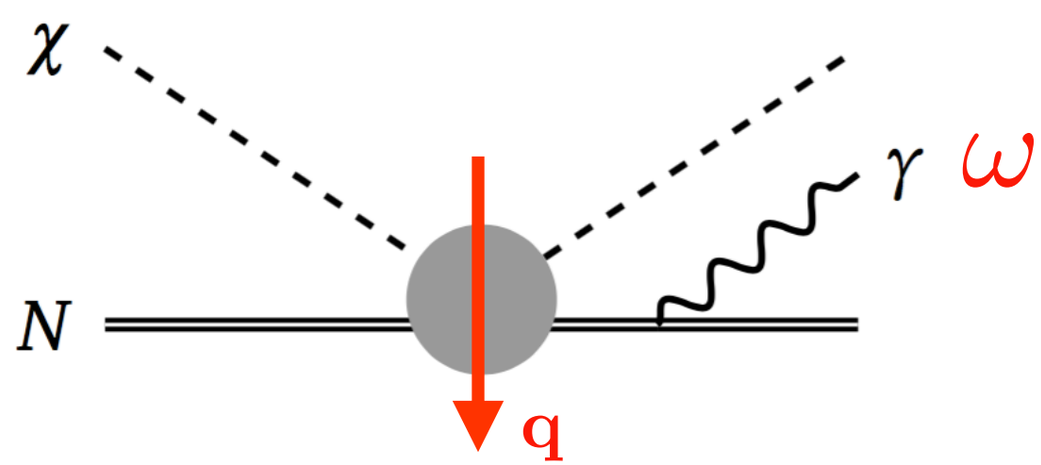
WIMPs

3

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

Kouvaris, JP, **PRL 2017**

Inelastic channel of photon emission from the nucleus



Maximum photon energy

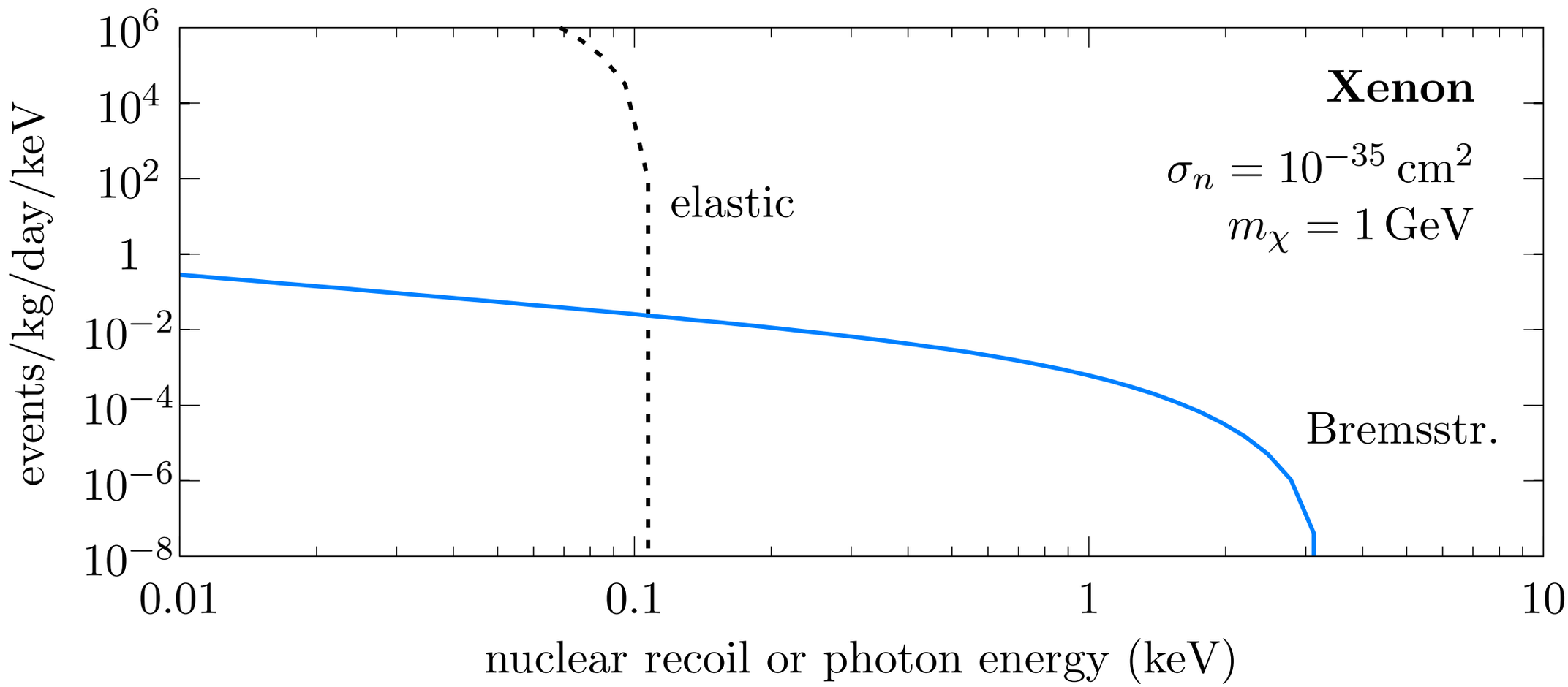
$$\omega_{\max} \simeq \mu_N v^2/2 \simeq m_\chi v^2/2$$

$$\simeq 0.5\,\mathrm{keV}\,\frac{m_\chi}{100\,\mathrm{MeV}}$$

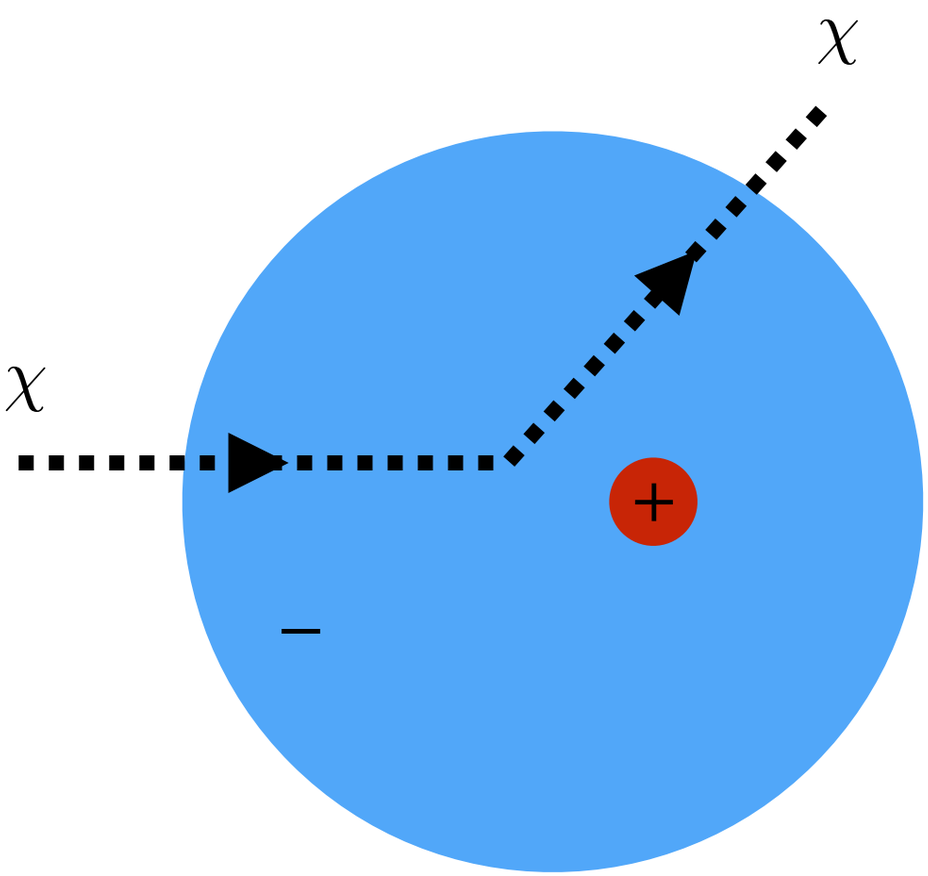
Key I: $E_{R,\max} = 4(m_\chi/m_N)\omega_{\max} \ll \omega_{\max} \quad (m_\chi \ll m_N)$

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

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



Atomic physics picture of photon-emission



"Polarized Atom"

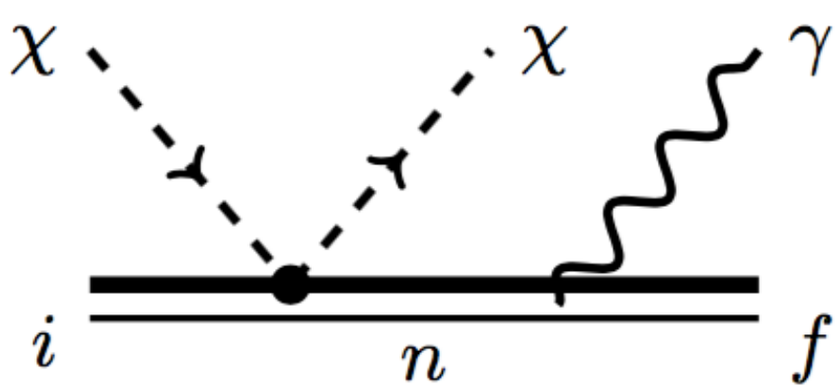
The naive treatment of Bremsstrahlung scales as 1/ω all the way to lowest energies

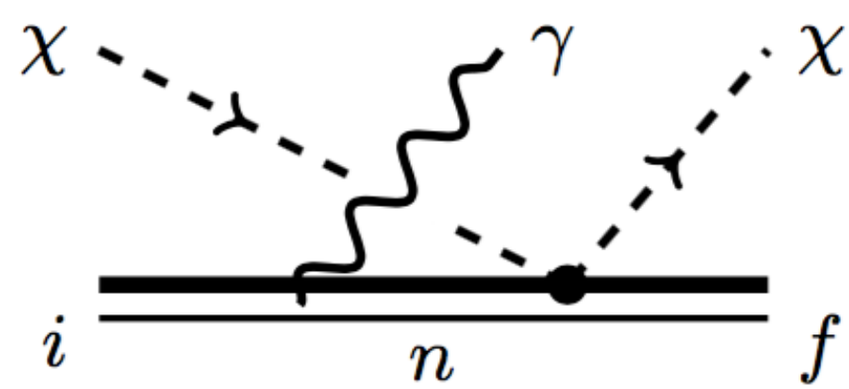
=> After the nucleus gets a kick, in the limit that the DM-nucleus interaction time $\tau_\chi \sim R_N/v_\chi$ is fast compared to the orbital time of electrons, $\tau_\alpha \sim |\mathbf{r}_\alpha|/v_\alpha$, the Atom becomes polarized

for inner shell electrons

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

Atomic physics modification





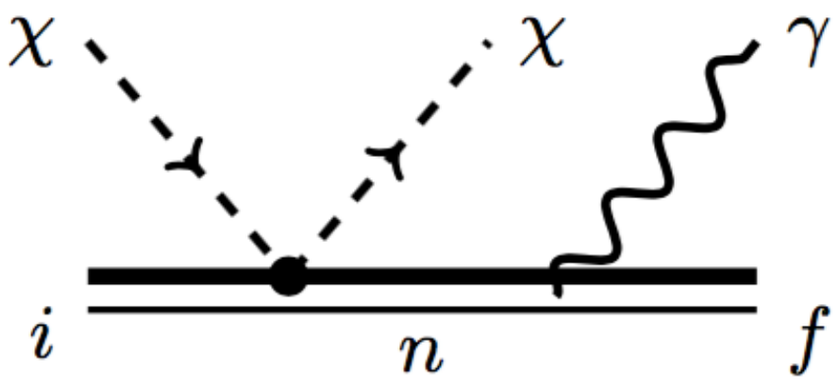
=> QM calculation

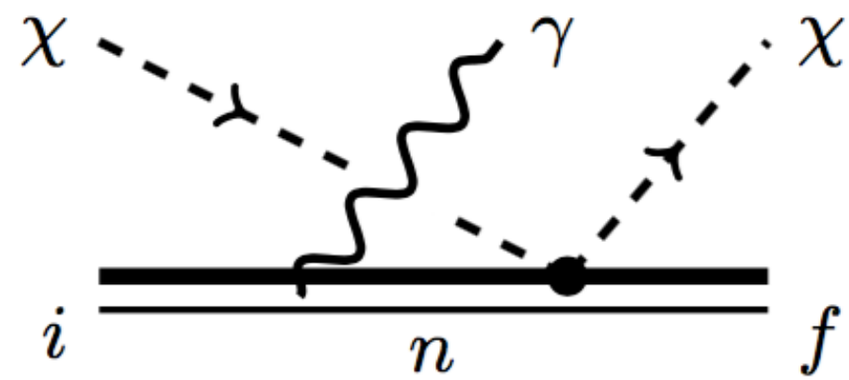
$$|V_{fi}|^2 = 2\pi\omega|M_{\rm el}|^2 \left| \sum_{n\neq i,f} \left[\frac{(\mathbf{d}_{fn}\cdot\hat{\mathbf{e}}^*)\,\langle n|e^{-i\frac{m_e}{m_N}\mathbf{q}\cdot\sum_\alpha \mathbf{r}_\alpha}|i\rangle}{\omega_{ni}-\omega} + \frac{(\mathbf{d}_{ni}\cdot\hat{\mathbf{e}}^*)\,\langle f|e^{-i\frac{m_e}{m_N}\mathbf{q}\cdot\sum_\alpha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

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:

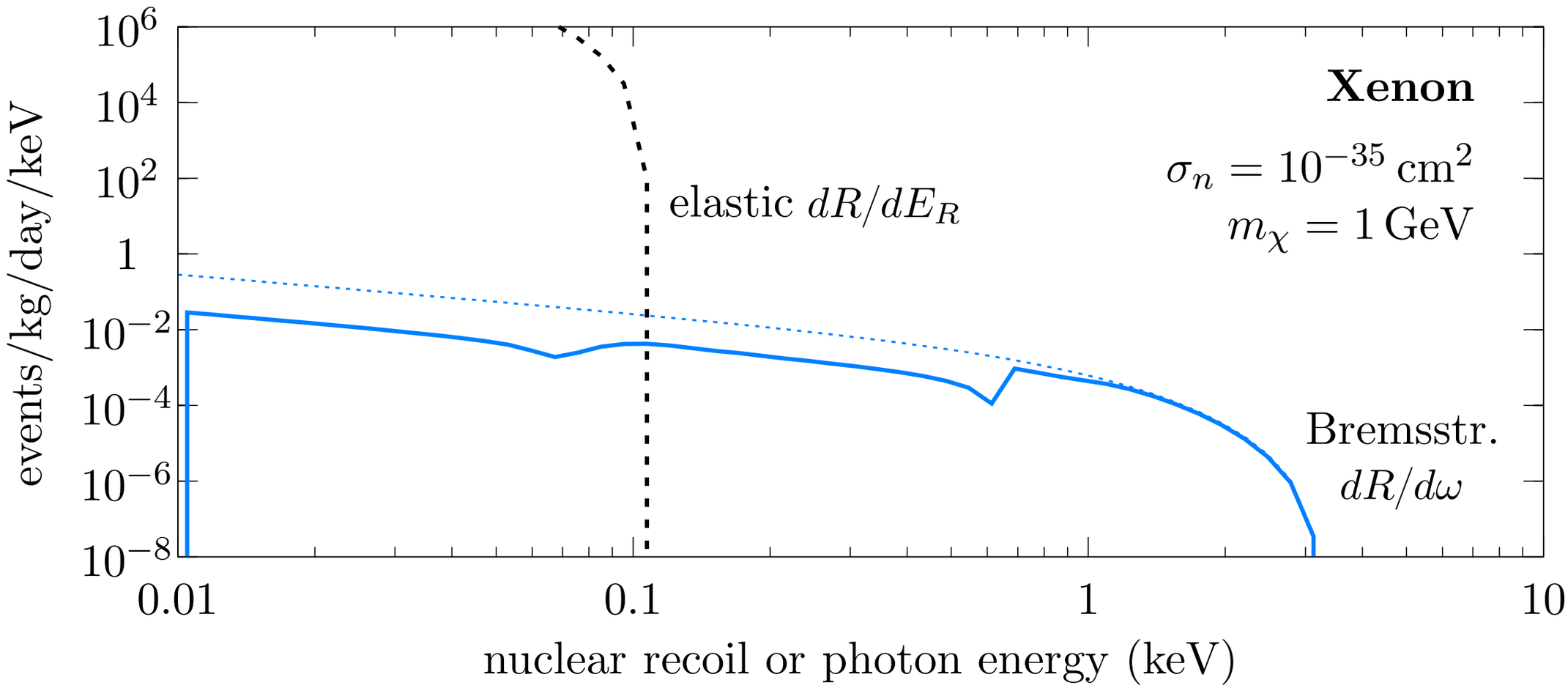
$$\frac{d\sigma}{d\omega dE_R} \propto \omega^3 \times |\alpha(\omega)|^2 \times \frac{E_R}{m_N} \times \frac{d\sigma}{dE_R}$$

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

for large ω naive result is recovered ✓

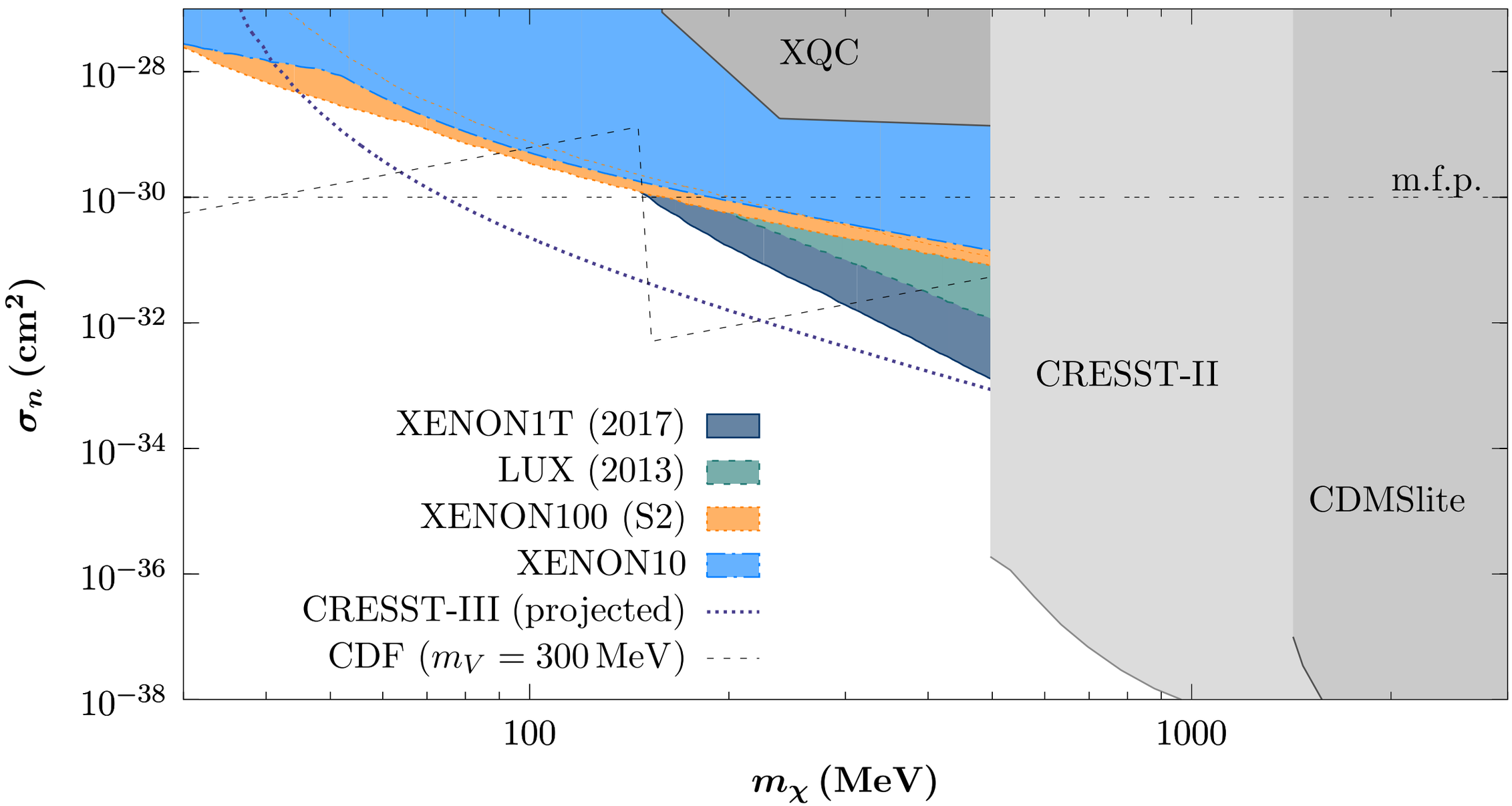
Gaining access to sub-GeV Dark Matter *through nuclear recoils*

including atomic physics modification



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

Current limits + projections



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

Conclusions

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

  Nuclear recoils
  => if MeV-scale DM decays into dark radiation states, direct detection can become competitive with neutrino experiments in the new physics sector; neutrino floor can be raised

  => break the "no-go" theorem from kinematics by going to the inelastic channel of photon emission with higher endpoint energies

  Electron recoils
  => break the "no-go" theorem from kinematics by using the sun as particle accelerator