Signatures of dark matter (well) below the GeV-scale

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Signatures of DM below the GeV-scale

1

Absorption

Dark Photon Dark Matter as a prototype model for atomic absorption in direct detection experiments

An, Pospelov, JP, Ritz PLB 2014

2

Scattering

Sub-GeV and sub-MeV DM-scattering on nuclei and electrons in direct detection

Kouvaris, JP PRL 2017

An, Pospelov, JP, Ritz PRL 2018

3

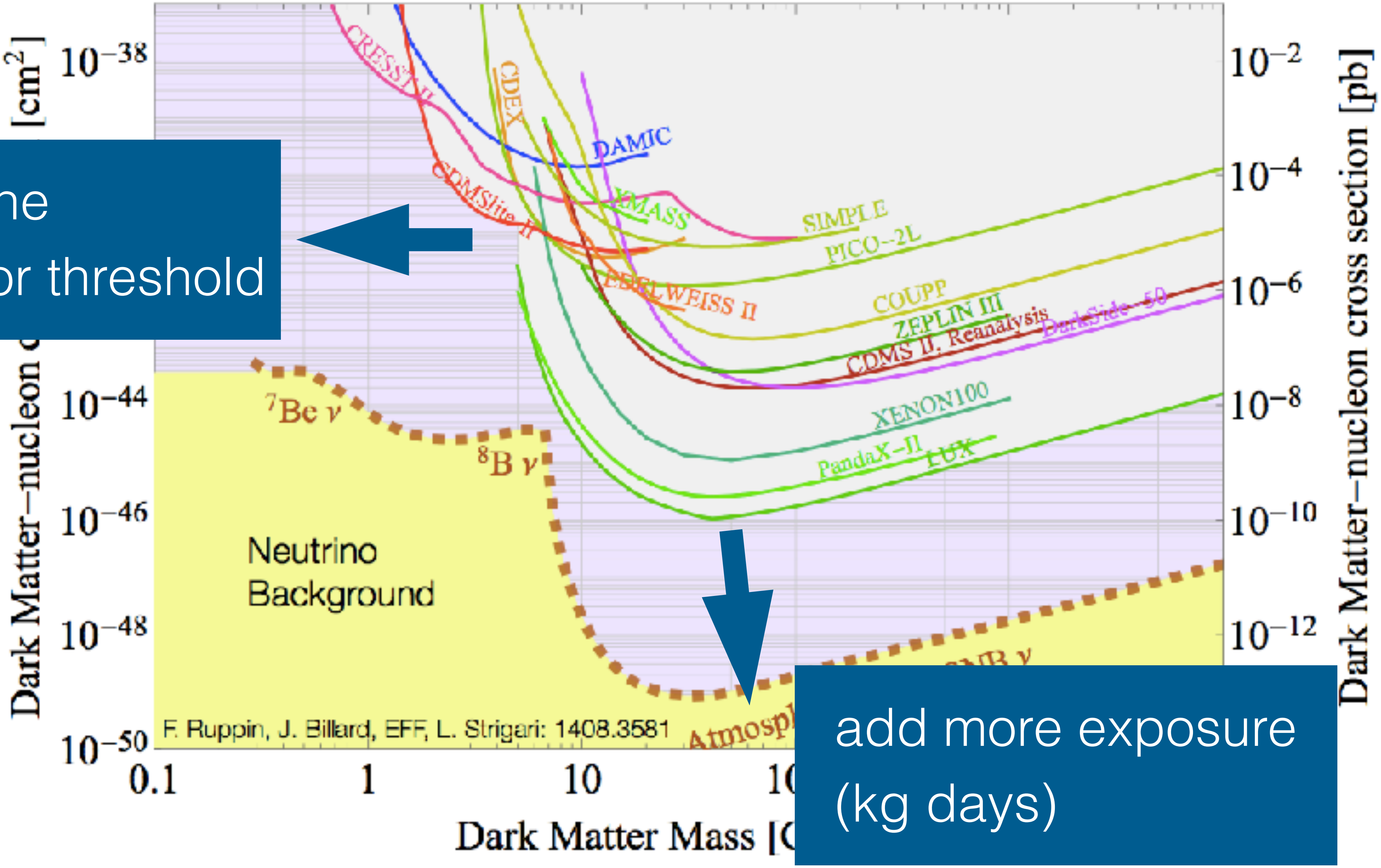
Decay

Non-gravitational signatures of dark radiation as a decay product in direct detection and in 21 cm cosmology

Cui, Pospelov, JP 2017

Pospelov, JP, Ruderman, Urbano 2018

A (partial) summary of 2 decades of experimental effort



lower the detector threshold

add more exposure (kg days)

CF1 Snowmass report, Ruppin et al 2014

+ explore alternative uses of existing data

Light new physics often discussed in terms of the “portal language”

$(H^\dagger H)\,(A\phi + \lambda\phi^2)$	“Higgs Portal” (a minimal model of DM)
$LH\,N$	“Neutrino Portal” likely realized in nature (neutrinos have mass); sterile neutrinos
$F^Y_{\mu\nu}V^{\mu\nu}$	“Vector Portal” kinetic mixing of abelian field strength tensors

① Absorption

Vector portal: Dark Photons

$$\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times U(1)'$$

Standard Model

x “dark sector” with vector particle V^μ

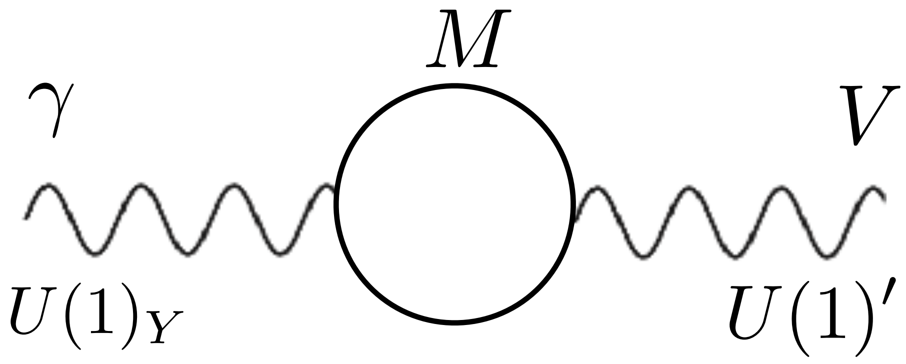
$$-\frac{\kappa'}{2}F^Y_{\mu\nu}V^{\mu\nu} \xrightarrow[\text{energies}]{\text{at low}} -\frac{\kappa}{2}F_{\mu\nu}V^{\mu\nu}$$

hypercharge
field strength

photon
field strength

NB: V_μ must be massive, otherwise κ can be rotated away, unless coupled to DM (“millicharged DM”)

Radiatively induced kinetic mixing



$$\longrightarrow \qquad -\frac{\kappa'}{2}F^{Y}_{\mu\nu}V^{\mu\nu}$$

Assume there are particles charged both under $U(1)_Y$ and $U(1)'$ of *arbitrarily heavy* mass M

$$\kappa \sim \frac{g_Y g'}{16\pi^2} \times \log\left(\frac{\Lambda_{UV}}{M}\right)$$

“non-decoupling” [Holdom ’85]

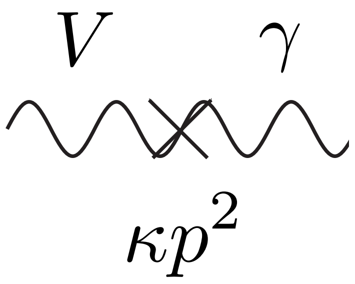
=> kinetic mixing can be a low-energy messenger from high scale

Dark Photons

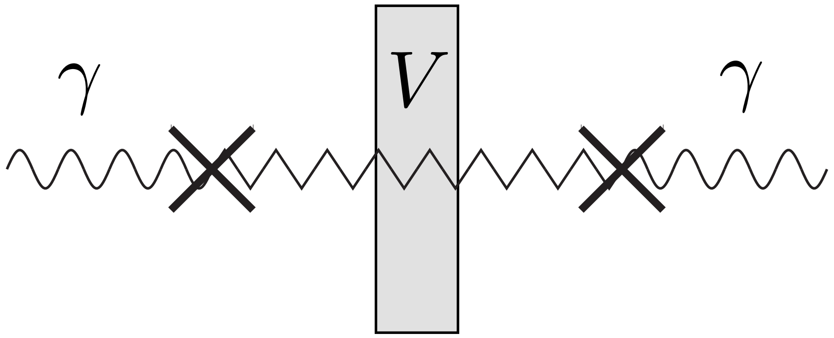
Two equivalent ways to think about $-\frac{\kappa}{2}F_{\mu\nu}V^{\mu\nu}$

A. Keep the mixing as a perturbation:

“Light-shining-through-wall” (LSW) experiments



…suggests…



Photon-Dark Photon mixing manifest

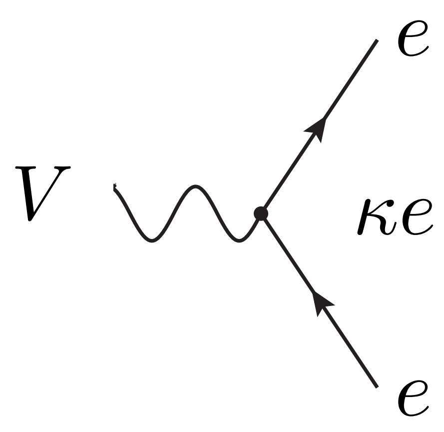
probability $\propto \kappa^4$

sensitivity when $m_V \sim \omega_\gamma$

Dark Photons

Two equivalent ways to think about $-\frac{\kappa}{2}F_{\mu\nu}V^{\mu\nu}$

B. Diagonalize kinetic term:

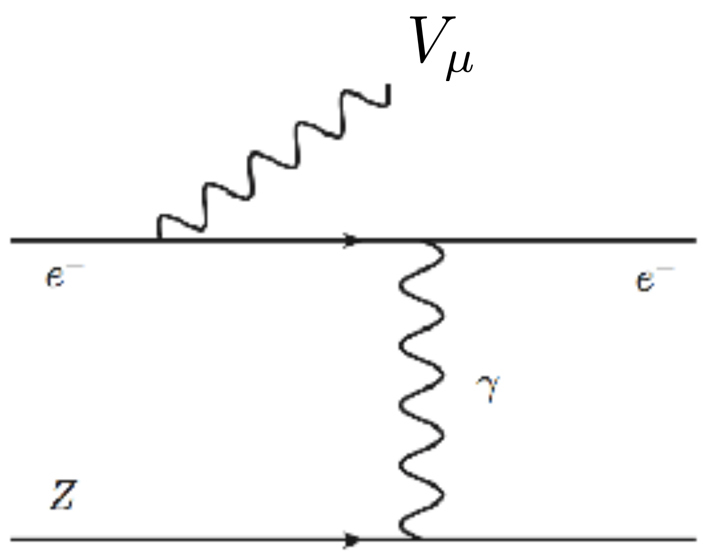


$$eA'_\mu J^\mu_{EM} - \kappa e V'_\mu J^\mu_{EM}$$

Ordinary matter is charged under new force

…suggests…

Direct production in experiment:



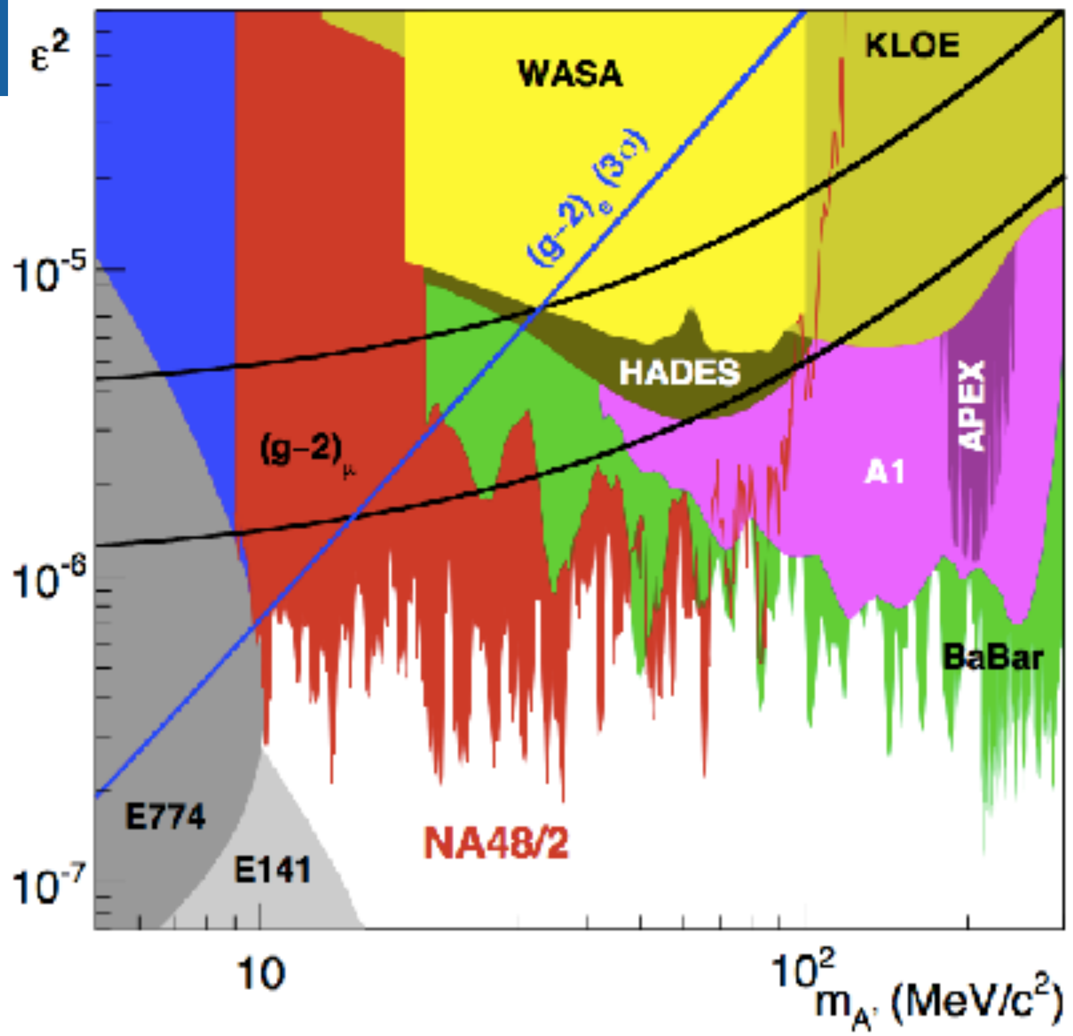
"Intensity Frontier"

Dark Photons

“Intensity Frontier”

precision tests

$(g-2)_e$



beams on fixed target

$$Ze^- \rightarrow Ze^- V \rightarrow Ze^- e^+ e^-$$

flavor factories

$$e^+e^- \rightarrow \gamma V \rightarrow \gamma l^+ l^-$$

$$\pi^0 \rightarrow \gamma V \rightarrow \gamma e^+ e^-$$

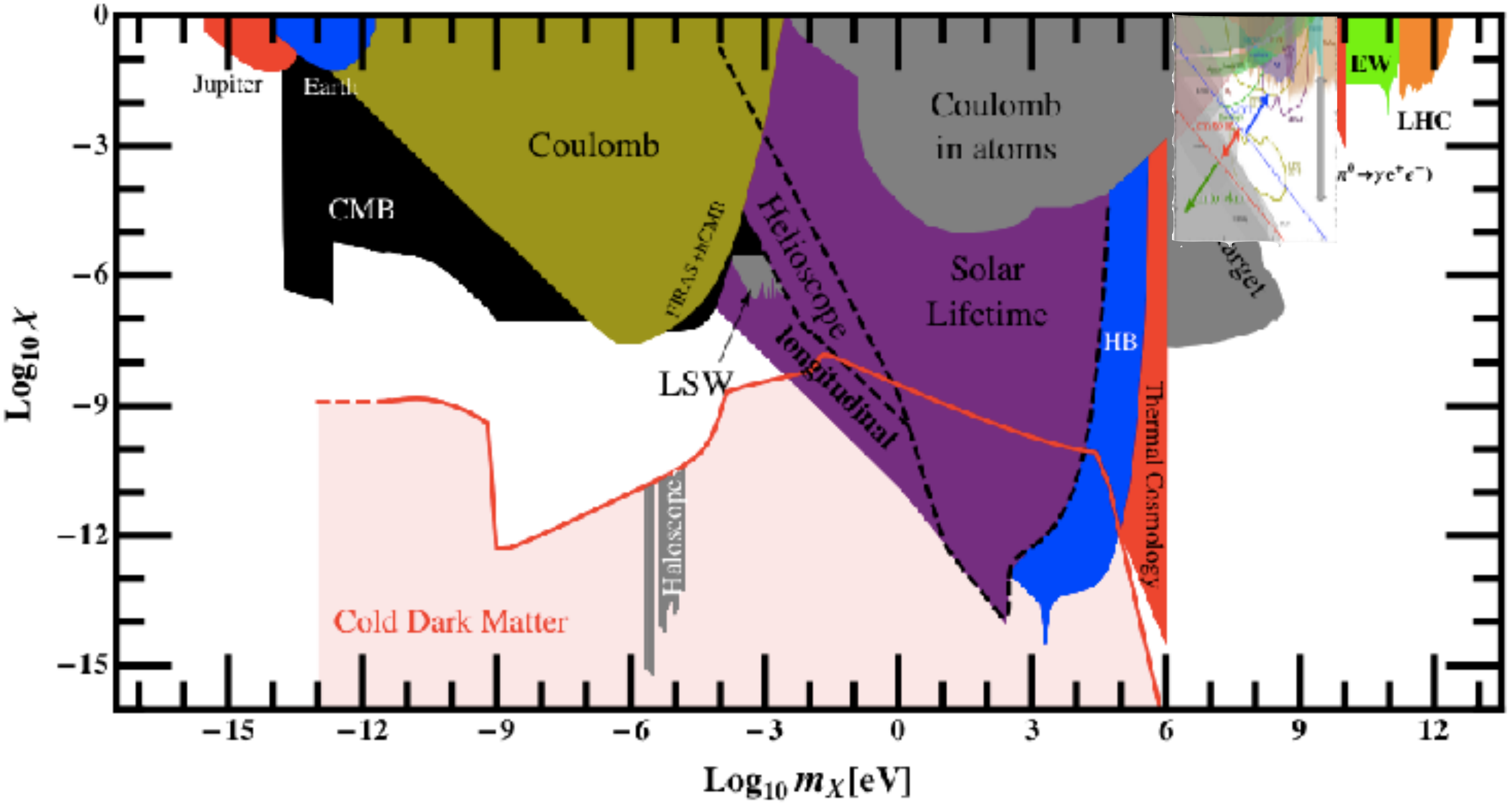
e-beam dumps

$$Ze^- \rightarrow Ze^- V \rightarrow Ze^- e^+ e^-$$

+ results from BaBar, A1, NA48

Future facilities, e.g. HPS, SHiP proposal,…

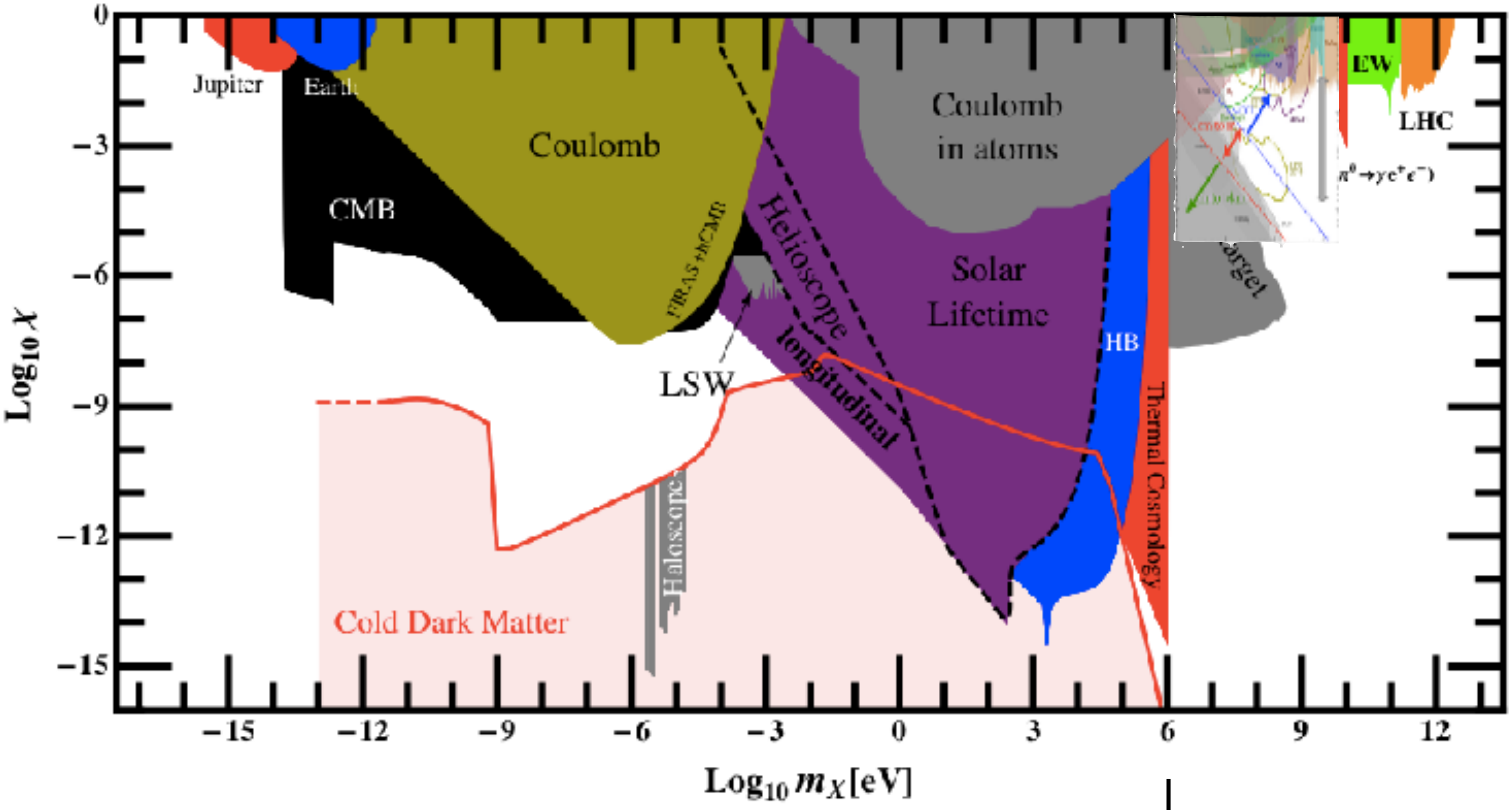
Dark Photon Landscape

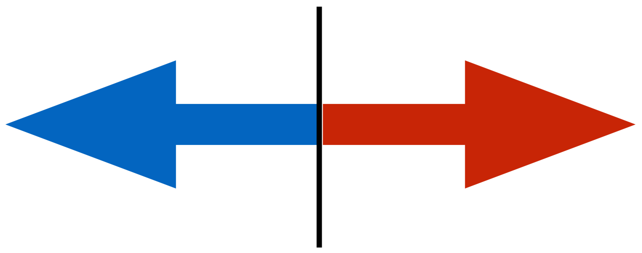


1

(Fig. from Jaeckel 2013)

Dark Photon Landscape





①

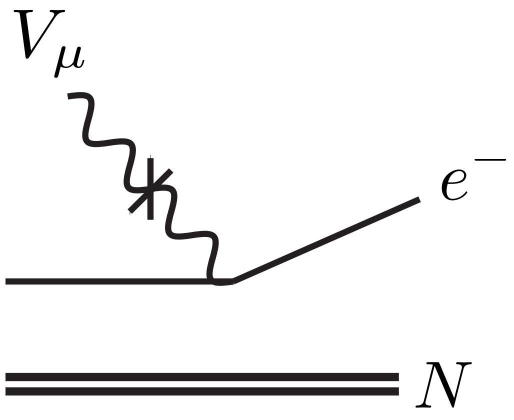
Dark Photon becomes
a dark matter candidate

Decays to
e+ e- possible

(Fig. from Jaeckel 2013)

Absorption-signature

(including medium effects)



$$\frac{\kappa}{2}F_{\mu\nu}V^{\mu\nu} + eJ^\mu_{\rm em}A_\mu \quad \xrightarrow{\text{on-shell V}} \quad \mathcal{L}_{\rm int} = -\kappa m_V^2 A_\mu V^\mu + eJ^\mu_{\rm em}A_\mu$$

Amplitude: $\mathcal{M}_{i\to f+V_{T,L}} = -\frac{e\kappa m_V^2}{m_V^2 - \Pi_{T,L}(q)}\langle p_f|J^\mu_{em}(0)|p_i\rangle\varepsilon^{T,L}_\mu(q)$

Rate: $\Gamma_{T,L} = \frac{e^2}{2\omega}\int d^4x\, e^{iq\cdot x}\kappa^2_{T,L}\varepsilon^*_\mu\varepsilon_\nu\langle p_i|[J^\mu_{em}(x), J^\nu_{em}(0)]|p_i\rangle$

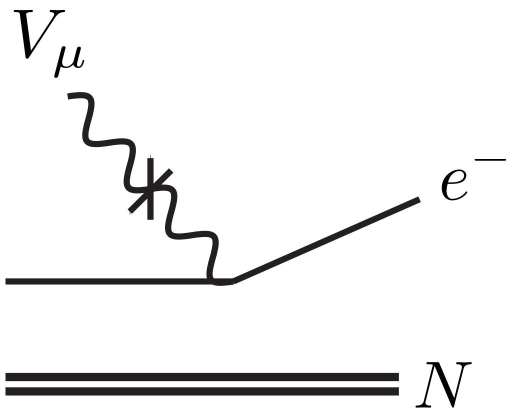
Effective mixing angle inside the medium

$$\kappa^2_{T,L} = \kappa^2 \times \frac{m_V^4}{|m_V^2 - \Pi_{T,L}|^2}$$

Related to the polarization tensor $\Pi_{\mu\nu}$ of the photon in the medium

Absorption-signature

(including medium effects)



$$\frac{\kappa}{2} F_{\mu\nu} V^{\mu\nu} + e J^\mu_{\rm em} A_\mu \xrightarrow{\rm on-shell\ V} \mathcal{L}_{\rm int} = -\kappa m_V^2 A_\mu V^\mu + e J^\mu_{\rm em} A_\mu$$

Amplitude: $\mathcal{M}_{i\to f+V_{T,L}} = -\frac{e\kappa m_V^2}{m_V^2 - \Pi_{T,L}(q)} \langle p_f | J^\mu_{em}(0) | p_i \rangle \varepsilon^{T,L}_\mu(q)$

Rate: $\Gamma_{T,L} = \frac{e^2}{2\omega} \int d^4x\, e^{iq\cdot x} \kappa^2_{T,L} \varepsilon^*_\mu \varepsilon_\nu \langle p_i | [J^\mu_{em}(x), J^\nu_{em}(0)] | p_i \rangle$

$$\Gamma_{T,L} = -\frac{\kappa^2_{T,L}\, \mathrm{Im}\, \Pi_{T,L}}{\omega}$$

Absorption rate given by the imaginary part of the polarization function (optical theorem)

An, Pospelov, JP, PRL 2013
An, Pospelov, JP, Ritz, PLB 2014

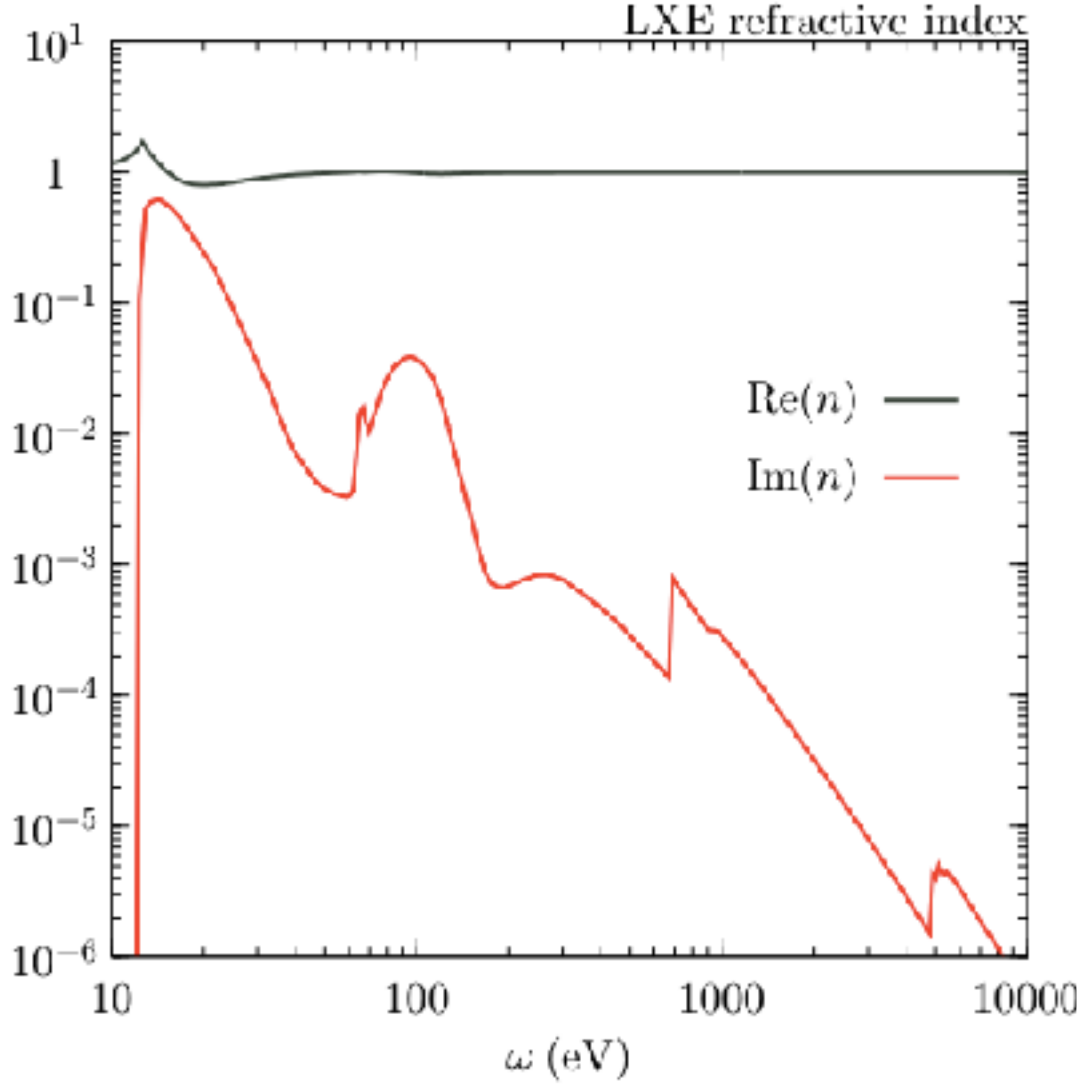
Absorption in Xenon

Compute absorption rate from Xenon *refractive index*

(via tabulated atomic X-ray data, using Kronig-Kramers relations)

$$\Pi_T = \omega^2(1 - n_{\rm refr}^2)$$

$$\Pi_L = (\omega^2 - \vec{q}^2)(1 - n_{\rm refr}^2)$$

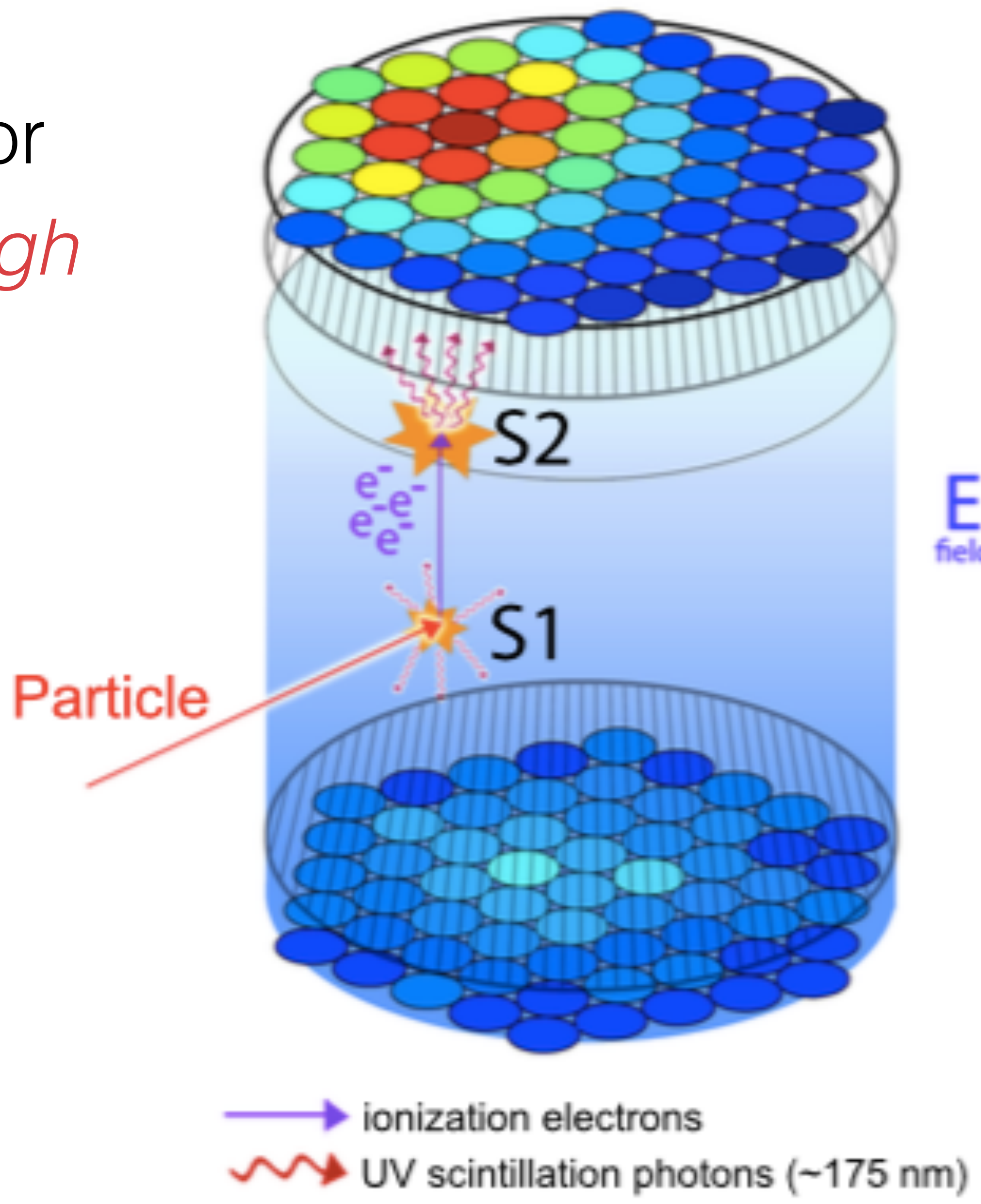


Detecting energy deposits in Liquid Xenon Experiments

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

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

scattering events classify as *“electron recoils”*

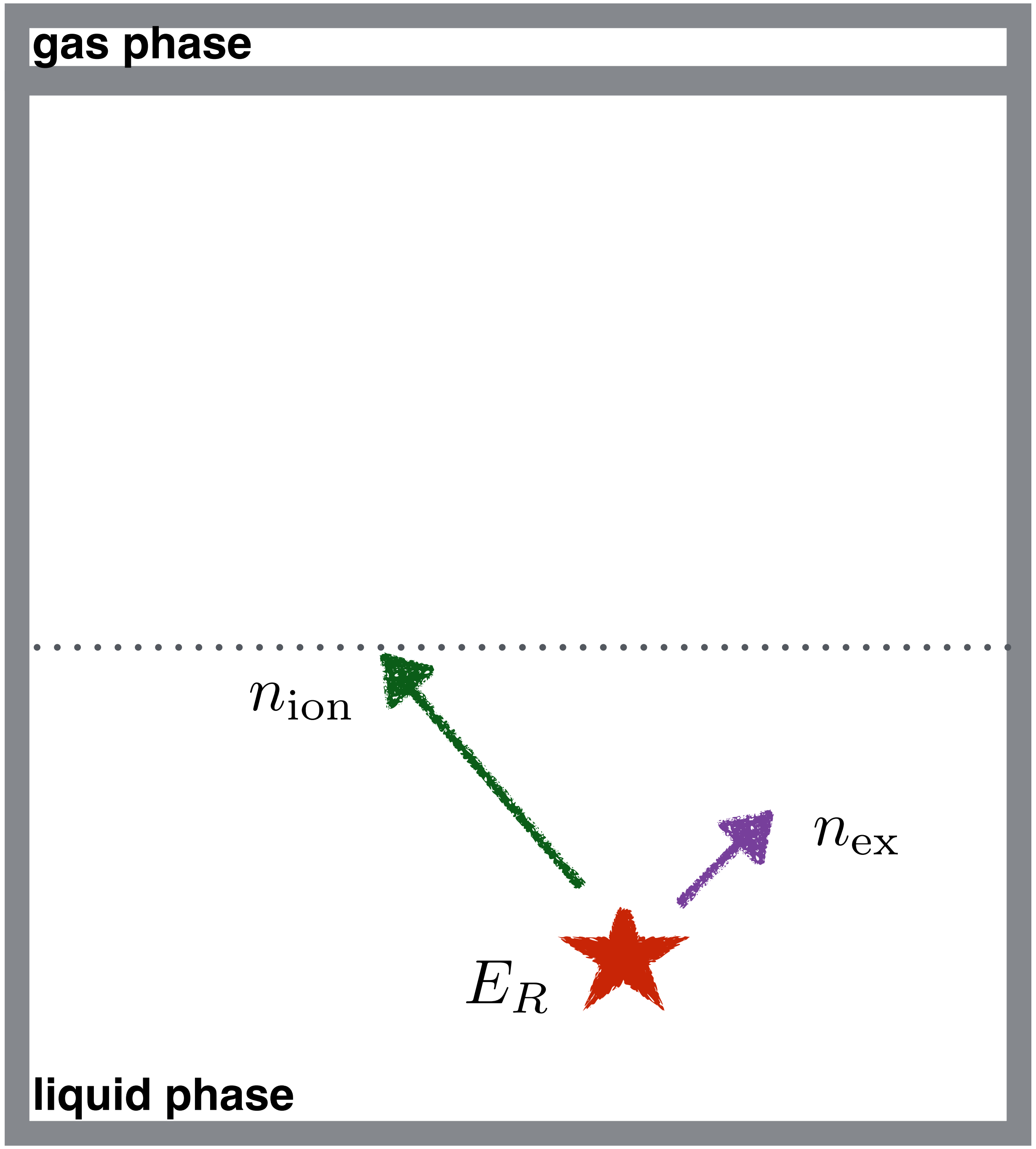


How does an "electron recoil" signal look in a LXE detector?

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

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

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

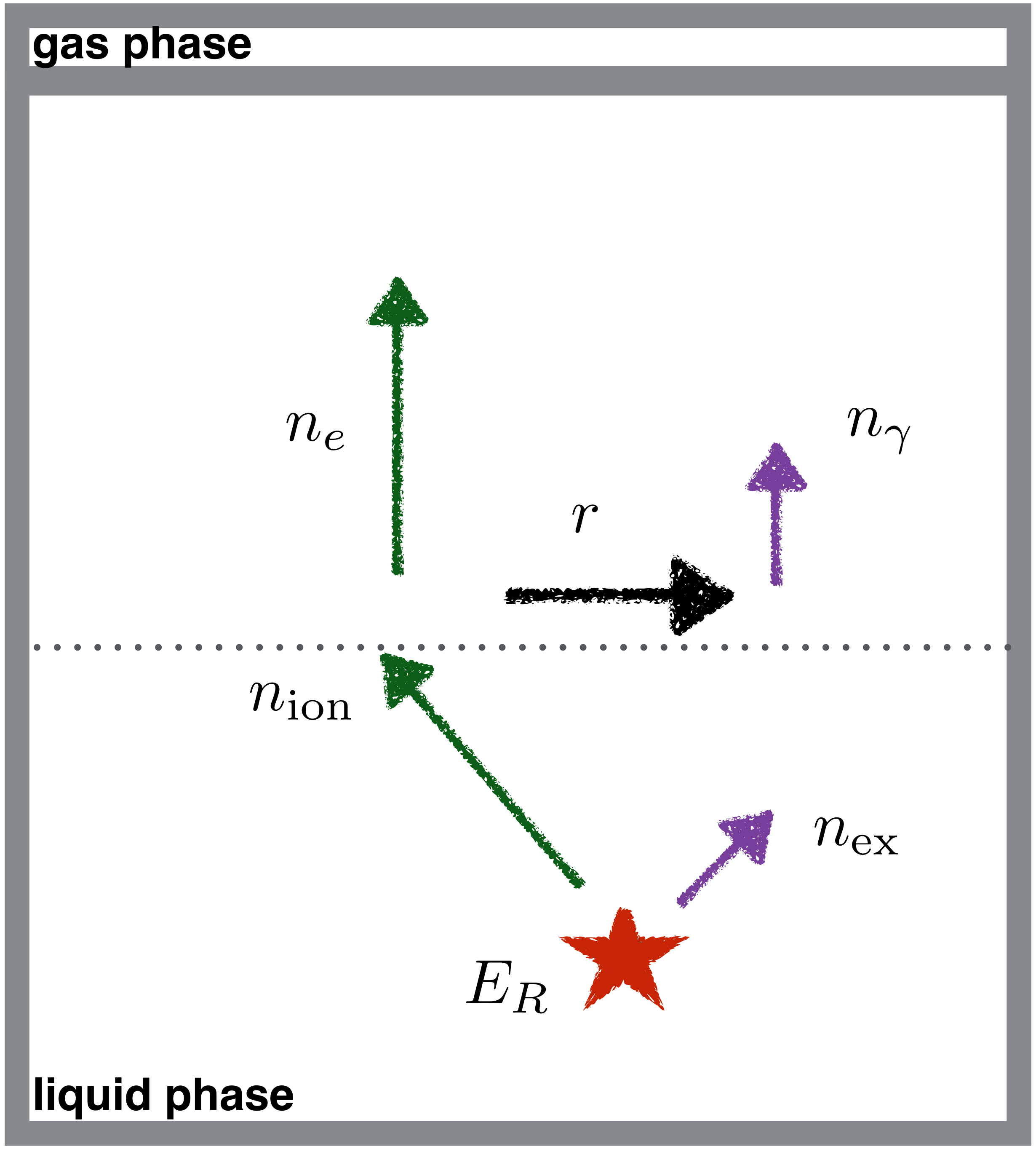


How does an "electron recoil" signal look in a LXE detector?

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

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

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



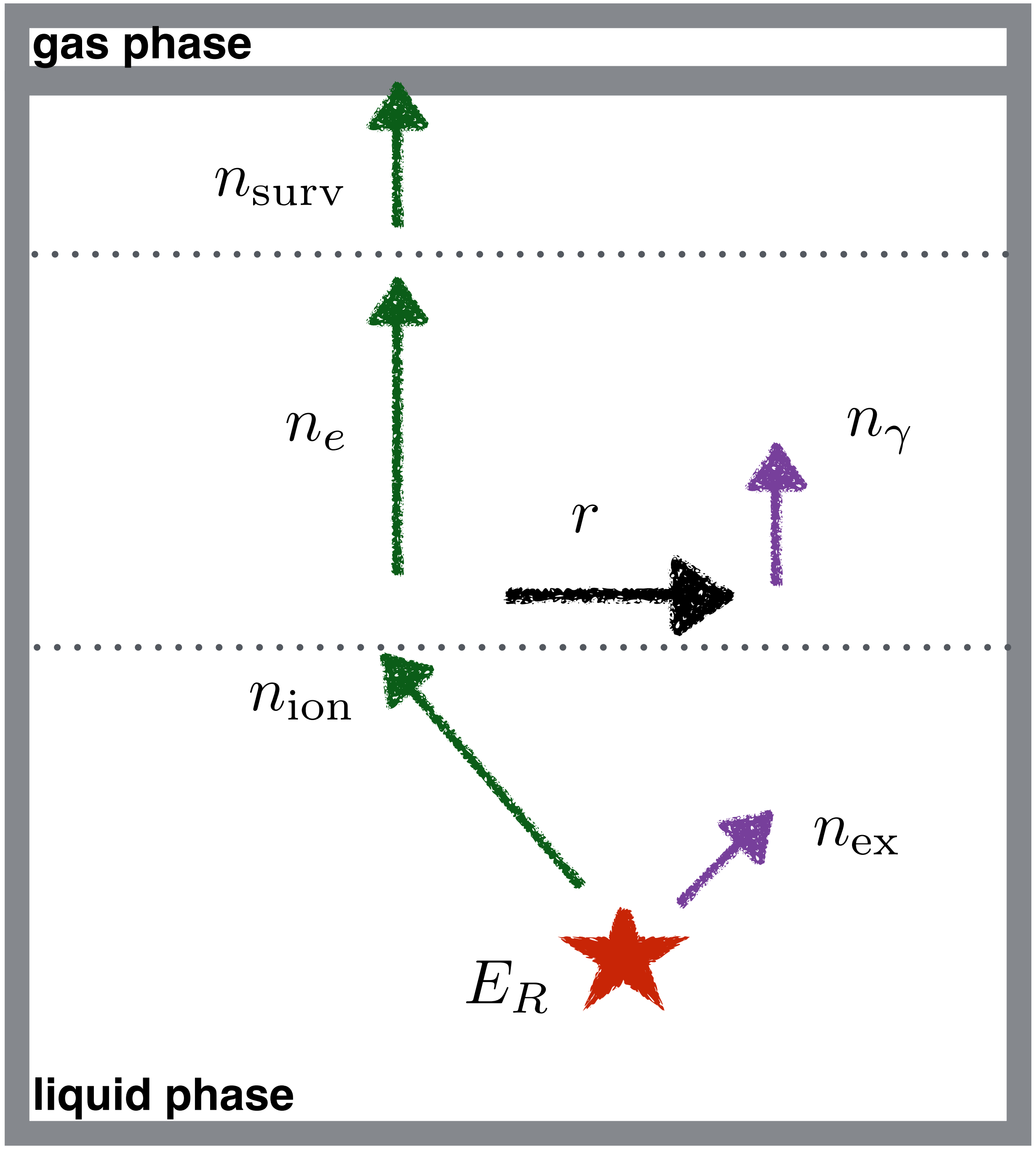
How does an "electron recoil" signal look in a LXE detector?

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

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

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

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

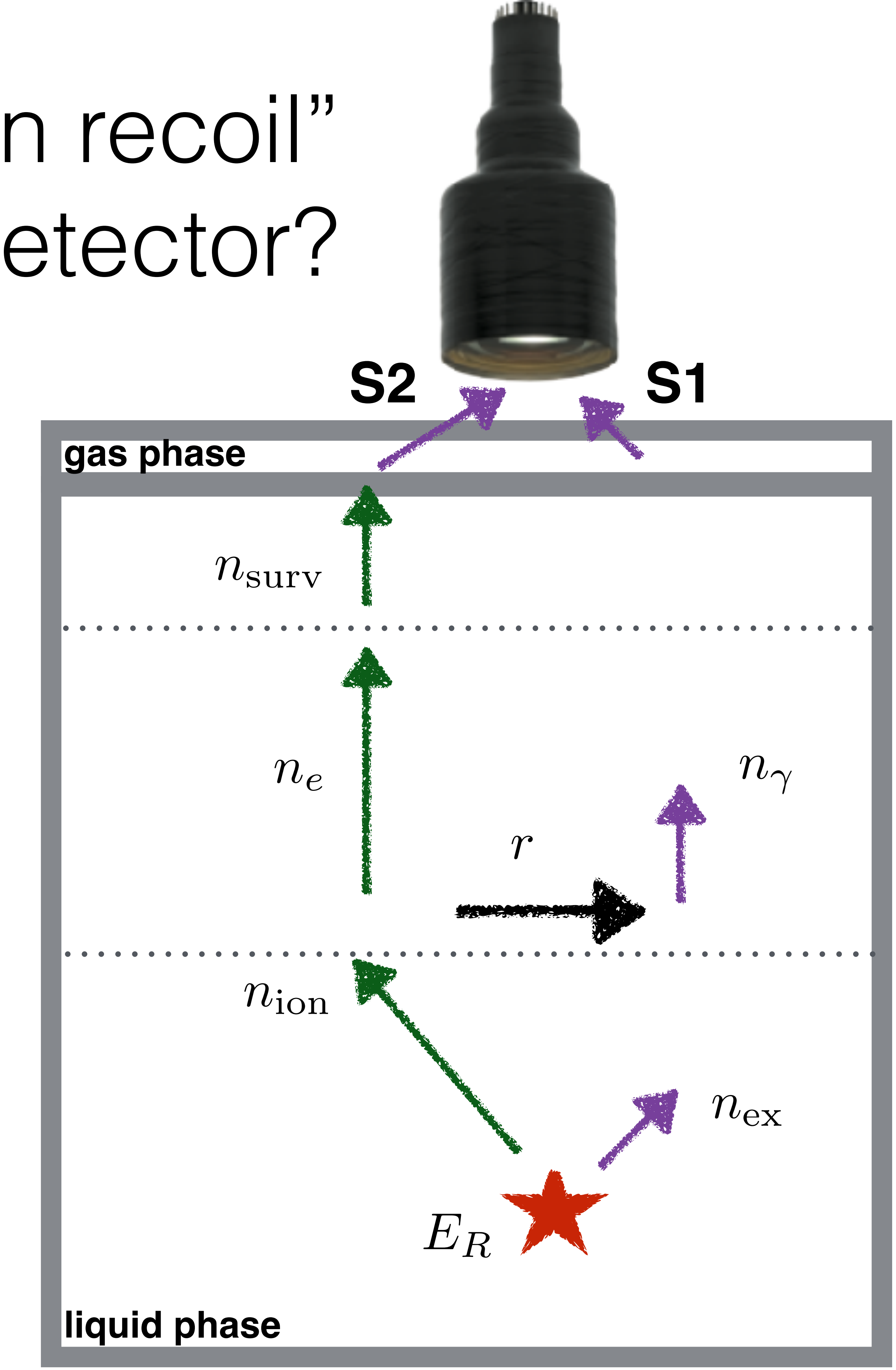


How does an “electron recoil” signal look in a LXE detector?

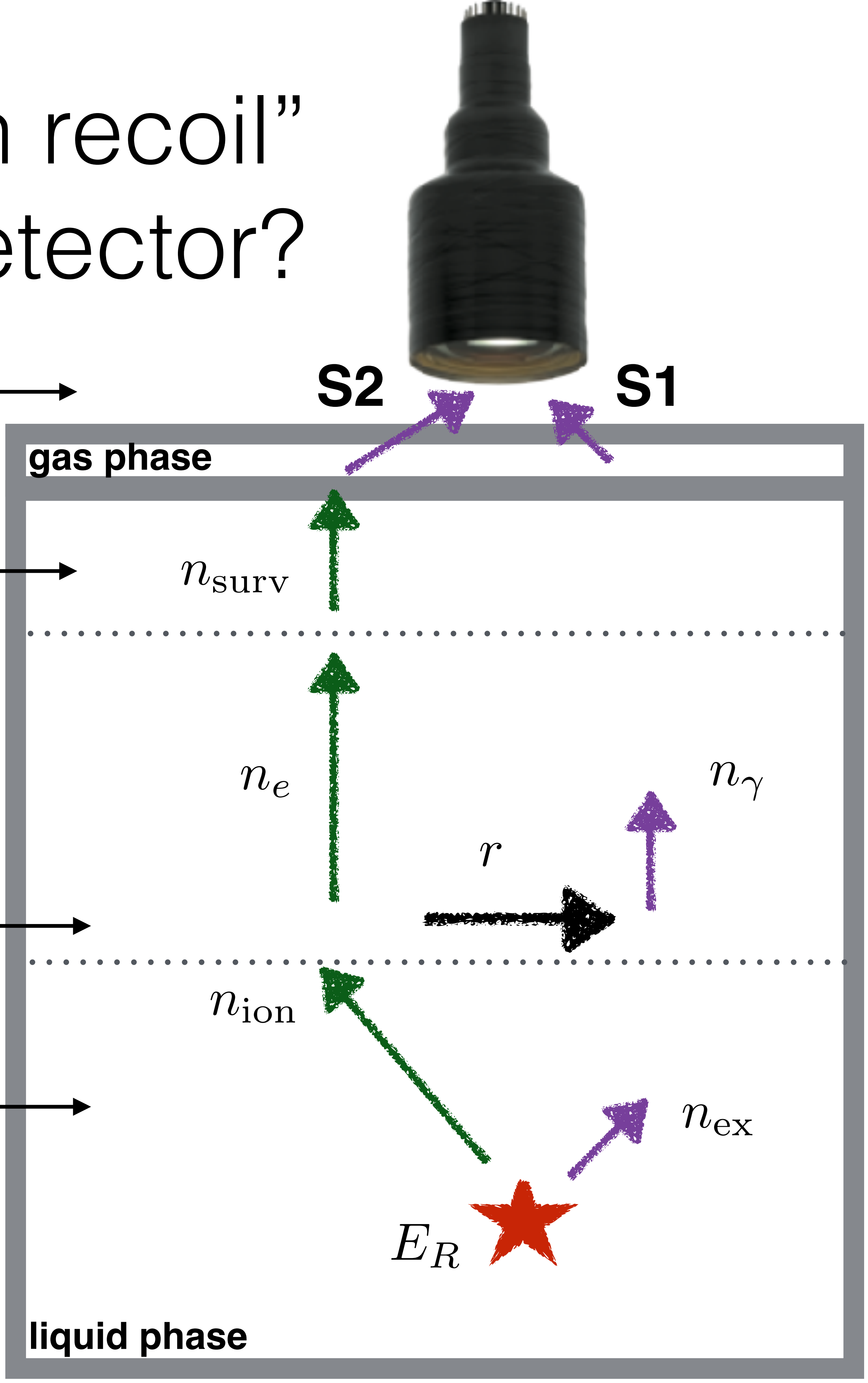
$$\begin{aligned} N_Q &= n_{\rm ion} + n_{\rm ex} \\ &= n_\gamma + n_e \\ &= \frac{S1}{g_1} + \frac{S2}{g_2} \end{aligned}$$

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

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 →

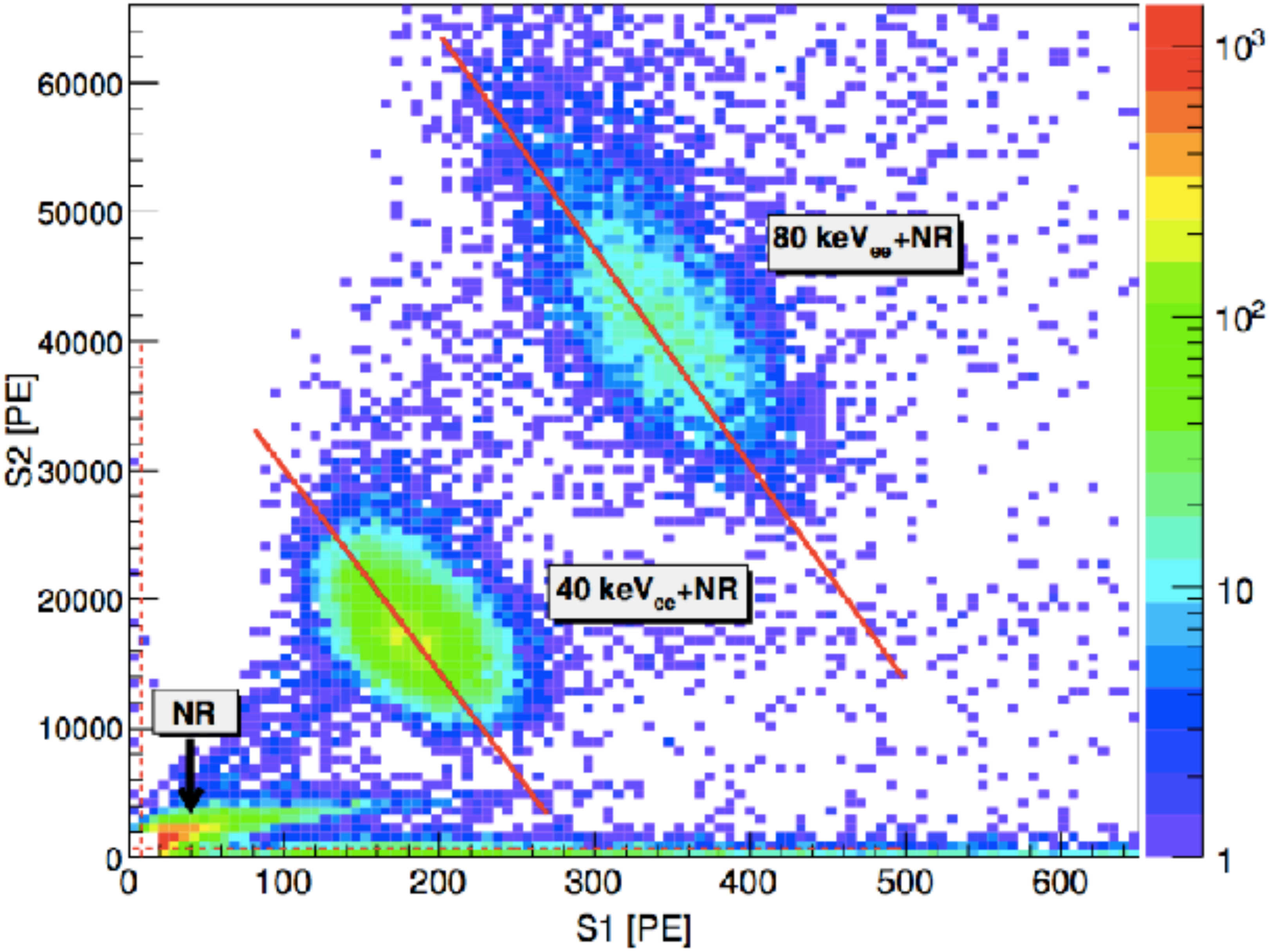
=> derive PDF(S1,S2 | ER)

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

e.g. PandaX

$$
\begin{aligned}
N_Q &= n_{\text{ion}} + n_{\text{ex}} \\
&= n_\gamma + n_e \\
&= \frac{S1}{g_1} + \frac{S2}{g_2}
\end{aligned}
$$

note the anti-correlation between S1 and S2



Electron vs. nuclear recoils

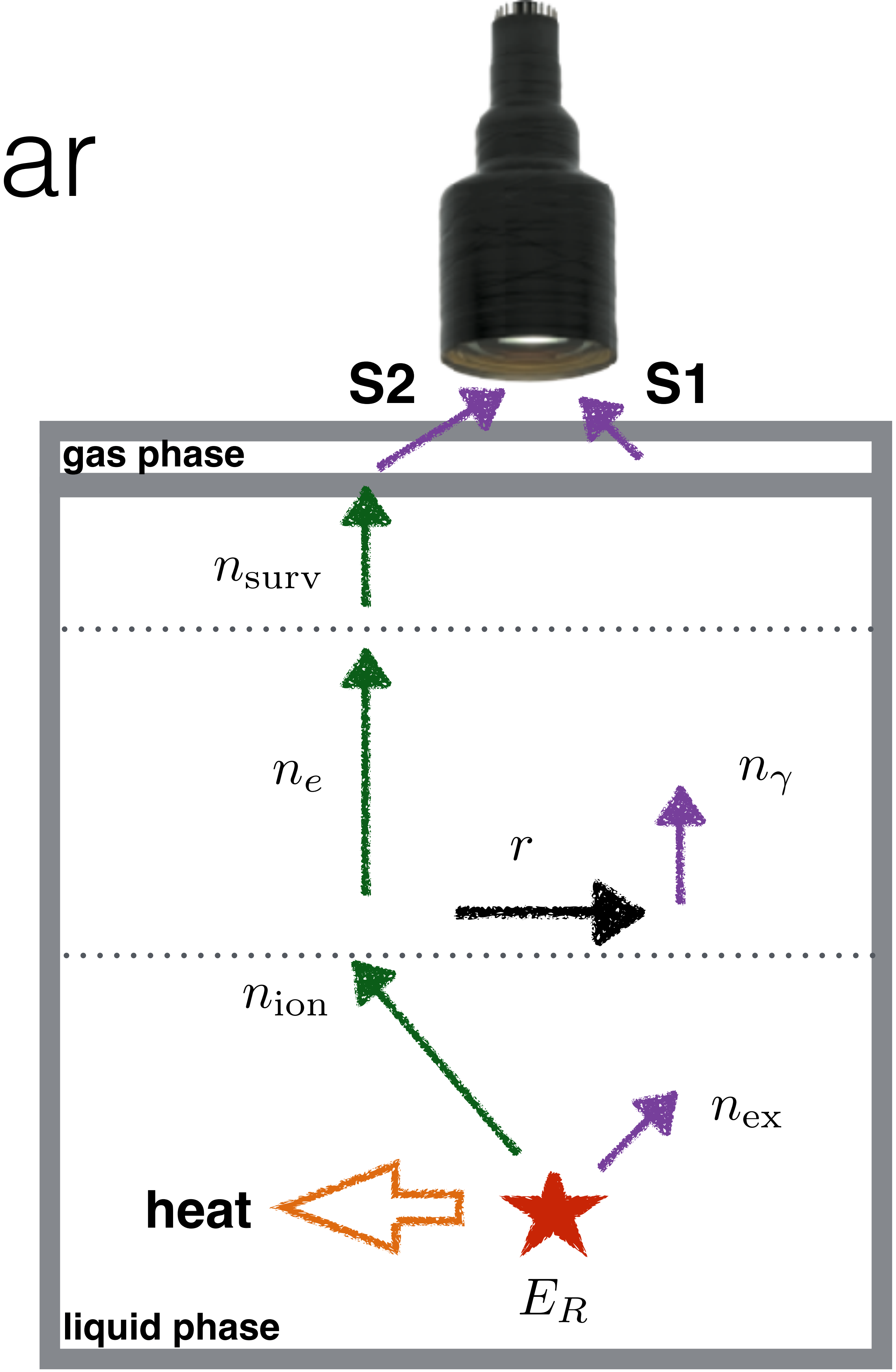
$$N_Q^{\mathrm{ER}} = \frac{E_{R,e}}{W}$$

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

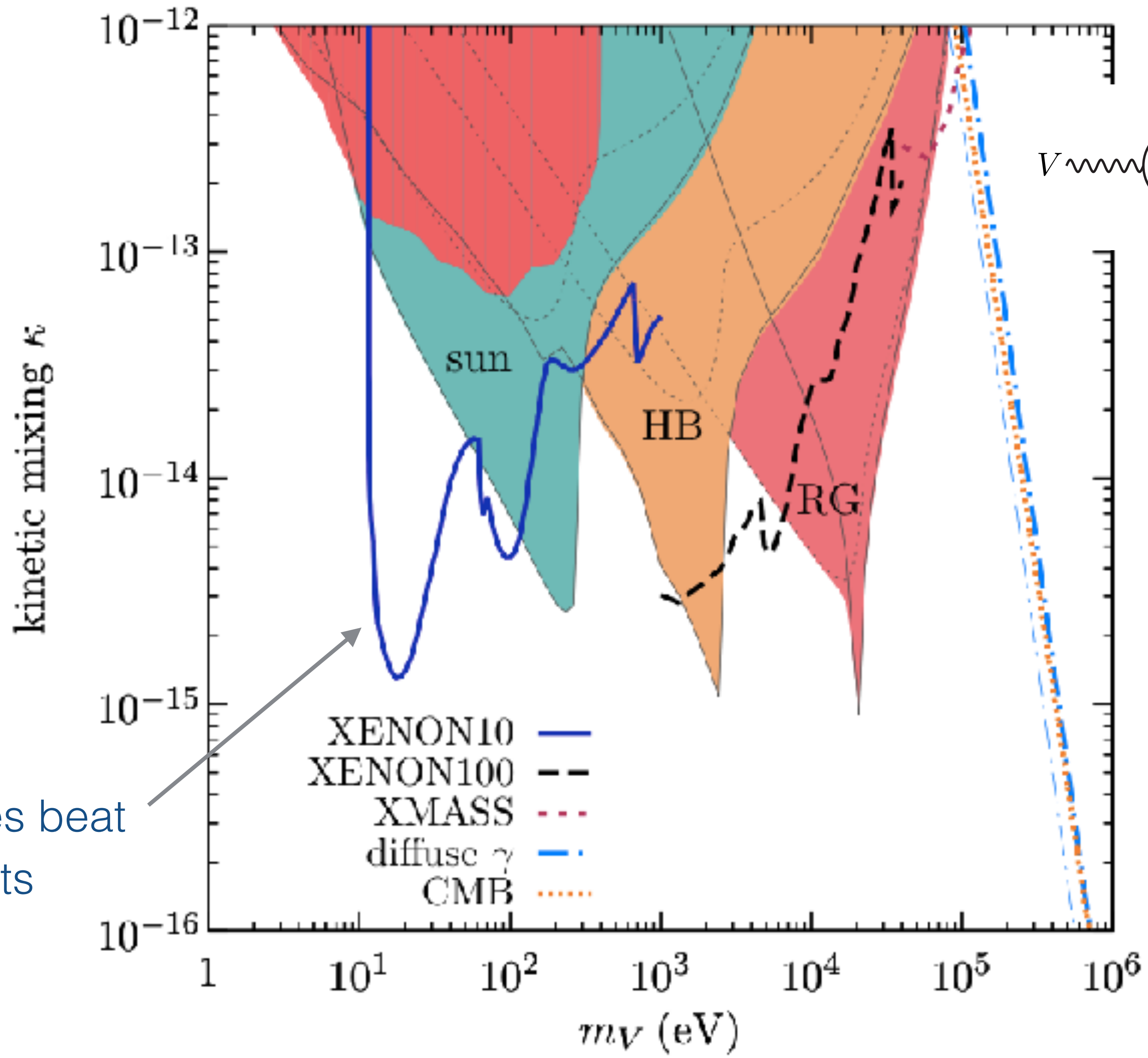
$$N_Q^{\mathrm{NR}} = E_R[L_y(E_R) + Q_y(E_R)]$$

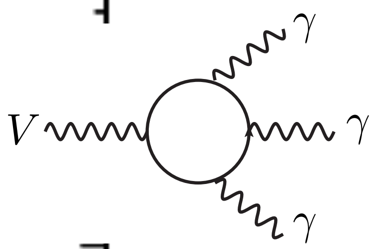
$$N_Q^{\mathrm{NR}} < N_Q^{\mathrm{ER}}$$

NR signal is quenched; additional source of fluctuations



Dark Photon Dark Matter





limits from
gamma rays
and CMB

Laboratory probes beat
astrophysical limits

An, Pospelov, JP, Ritz 2015
see also updates by Bloch et al 2016

“Simplified Models” of Dark Matter absorption

(pseudo)scalar $g_S S\bar{\psi}\psi, \quad g_P P\bar{\psi}\gamma_5\psi,$

(pseudo)vector $g_V V_\mu\bar{\psi}\gamma_\mu\psi,$ ✓ $g_A \mathcal{A}_\mu\bar{\psi}\gamma_\mu\gamma_5\psi,$ $\qquad g_V = e\kappa$

tensor $g_T T_{\mu\nu}\bar{\psi}\sigma_{\mu\nu}\psi, \quad \cdots$ $\qquad \psi$ …electron

If the DM mass is not protected by some symmetry (like for dark photons or axions), loop corrections induce a mass shift

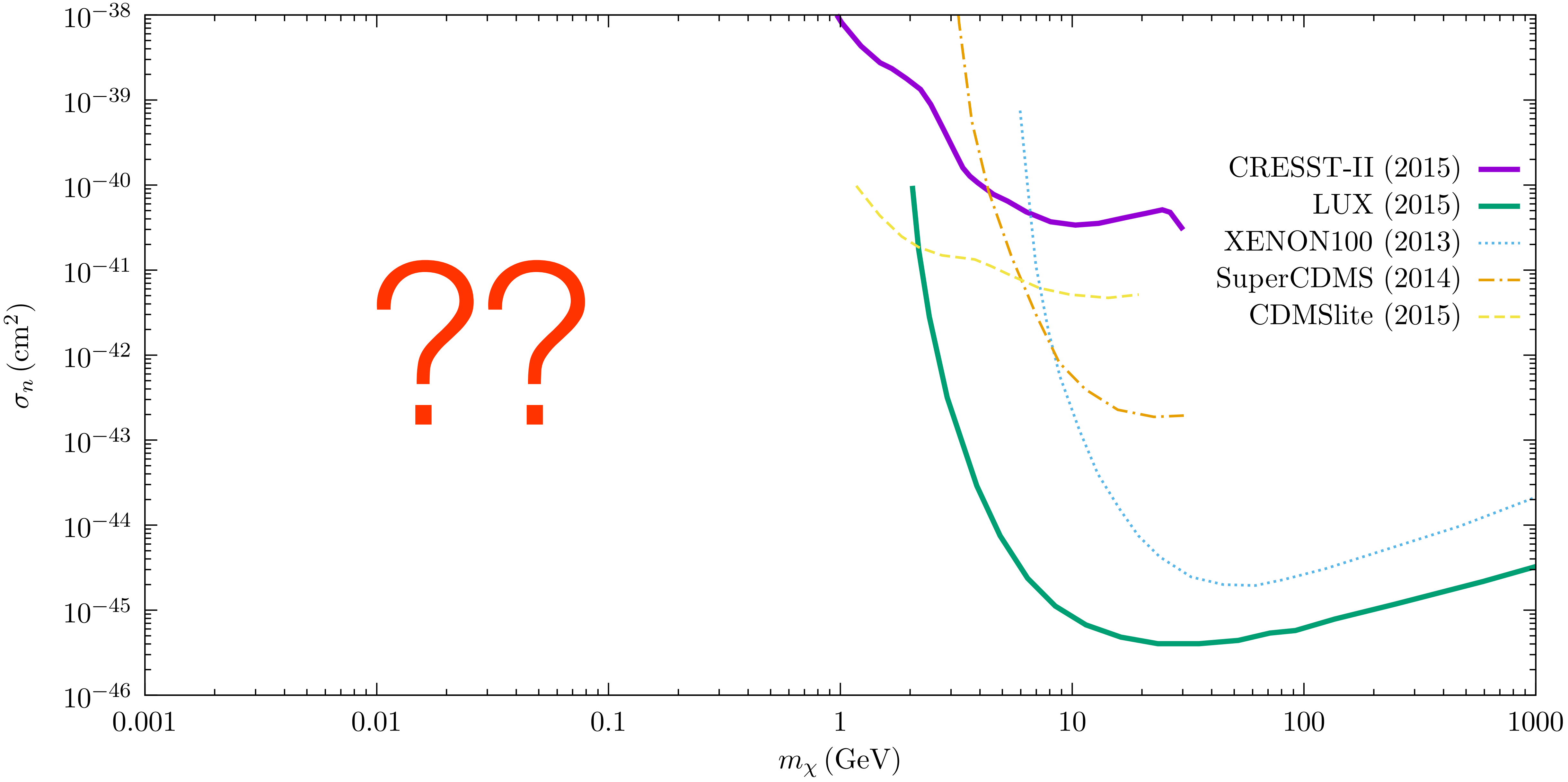
$\Delta m \sim g_i \Lambda_{\rm UV}$ => $g_i \lesssim 10^{-10}$ for $m \sim 100\,{\rm eV}$

As we have just seen, such couplings in the “naturalness regime” are being probed by direct detection

2

Scattering on nuclei

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



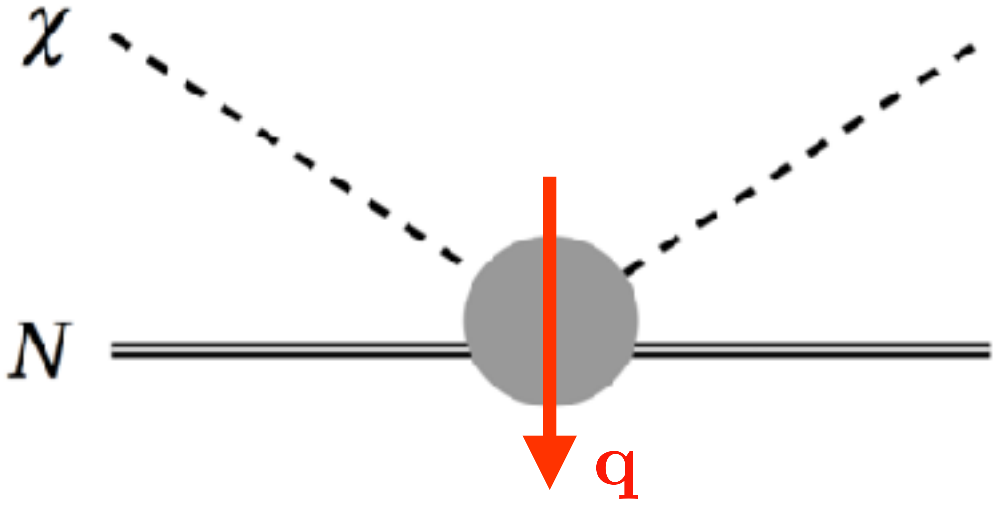
"light Dark Matter"

WIMPs

Direct Detection

Nuclear kinetic recoil energy

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



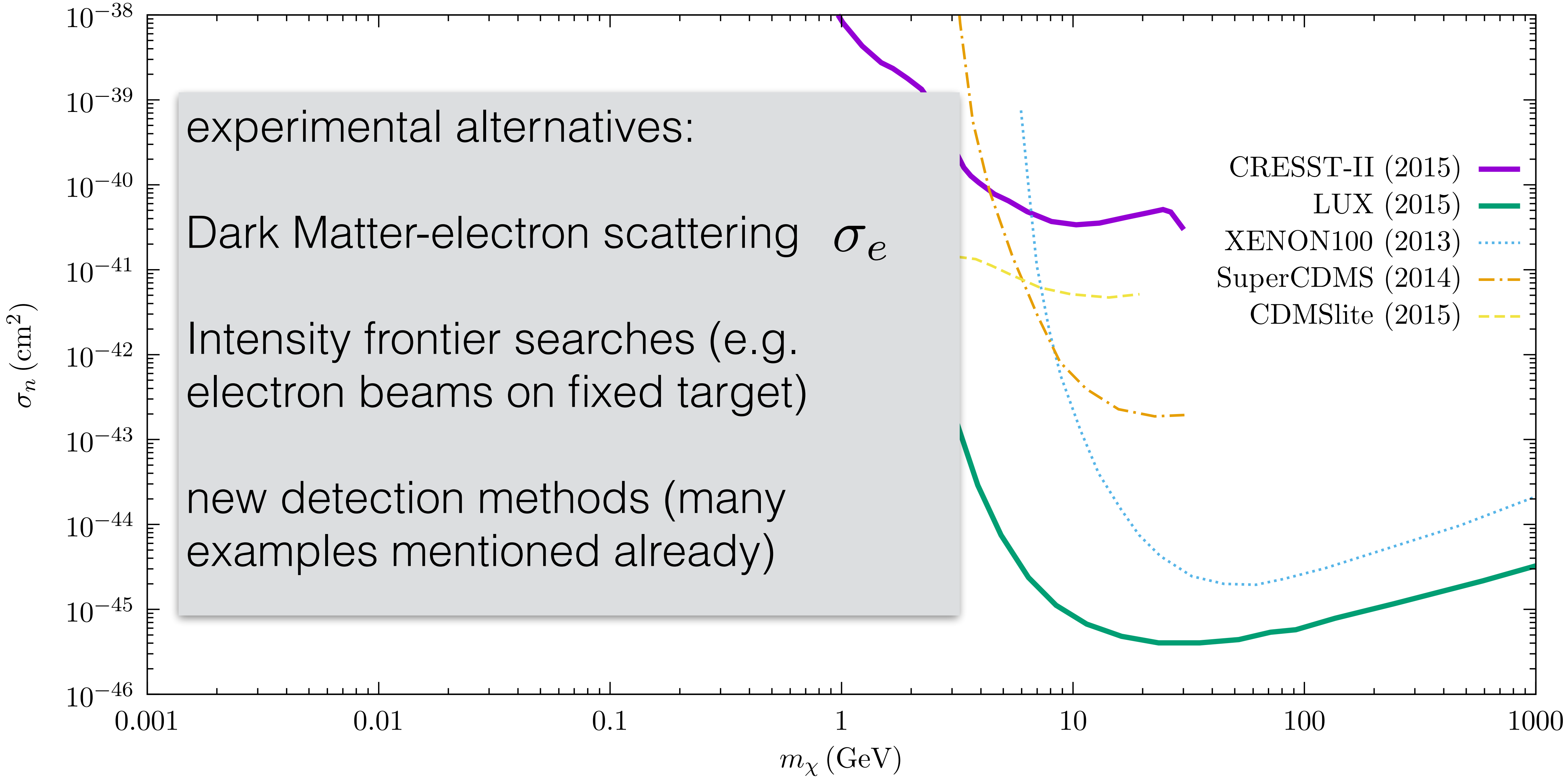
=> A given recoil, demands a *minimum* relative velocity

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

=> 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"

Gaining access to sub-GeV Dark Matter



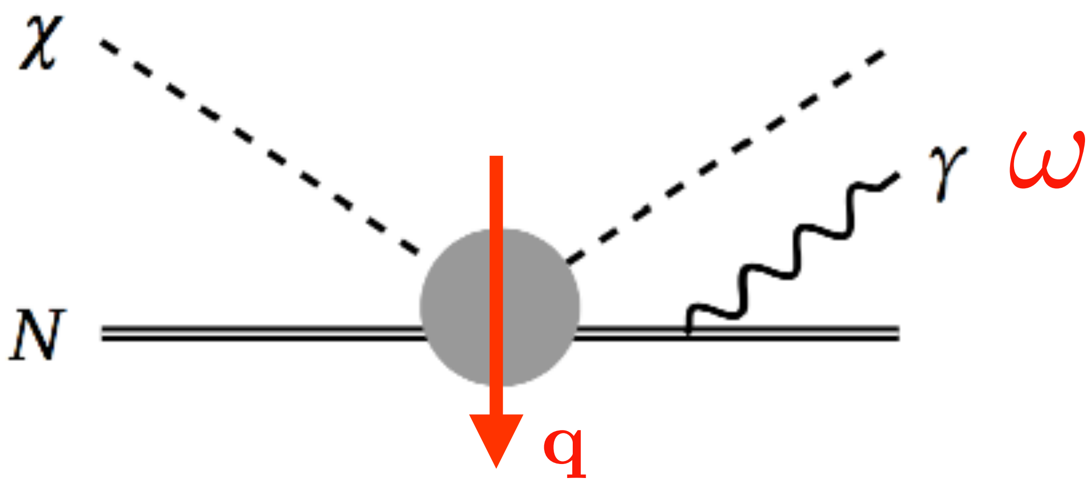
experimental alternatives:

Dark Matter-electron scattering σ_e

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

new detection methods (many examples mentioned already)

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



Inelastic channel of photon emission from the nucleus

Maximum photon energy

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

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

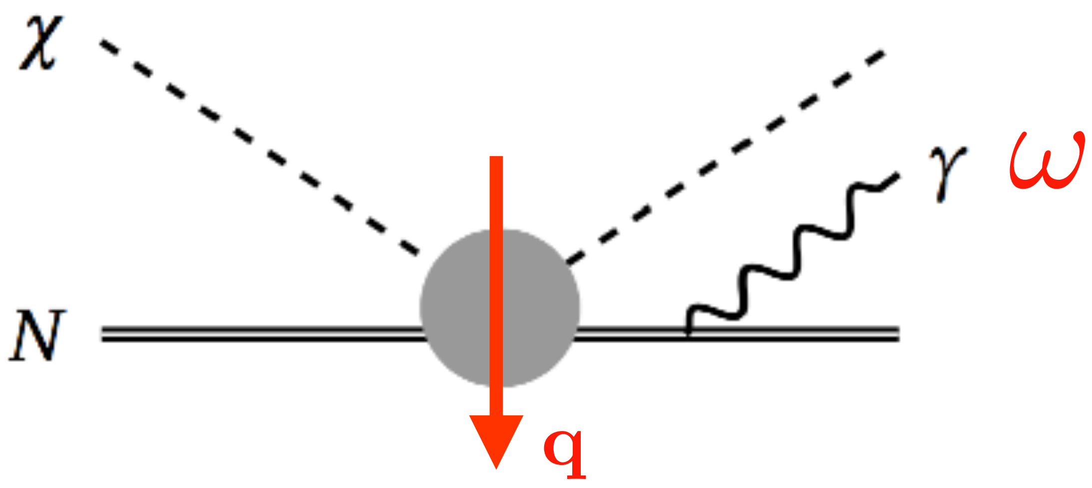
Key I: $E_{R,\max} = 4(m_\chi/m_N)\omega_{\max} \ll \omega_{\max} \quad (m_\chi \ll m_N)$

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

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

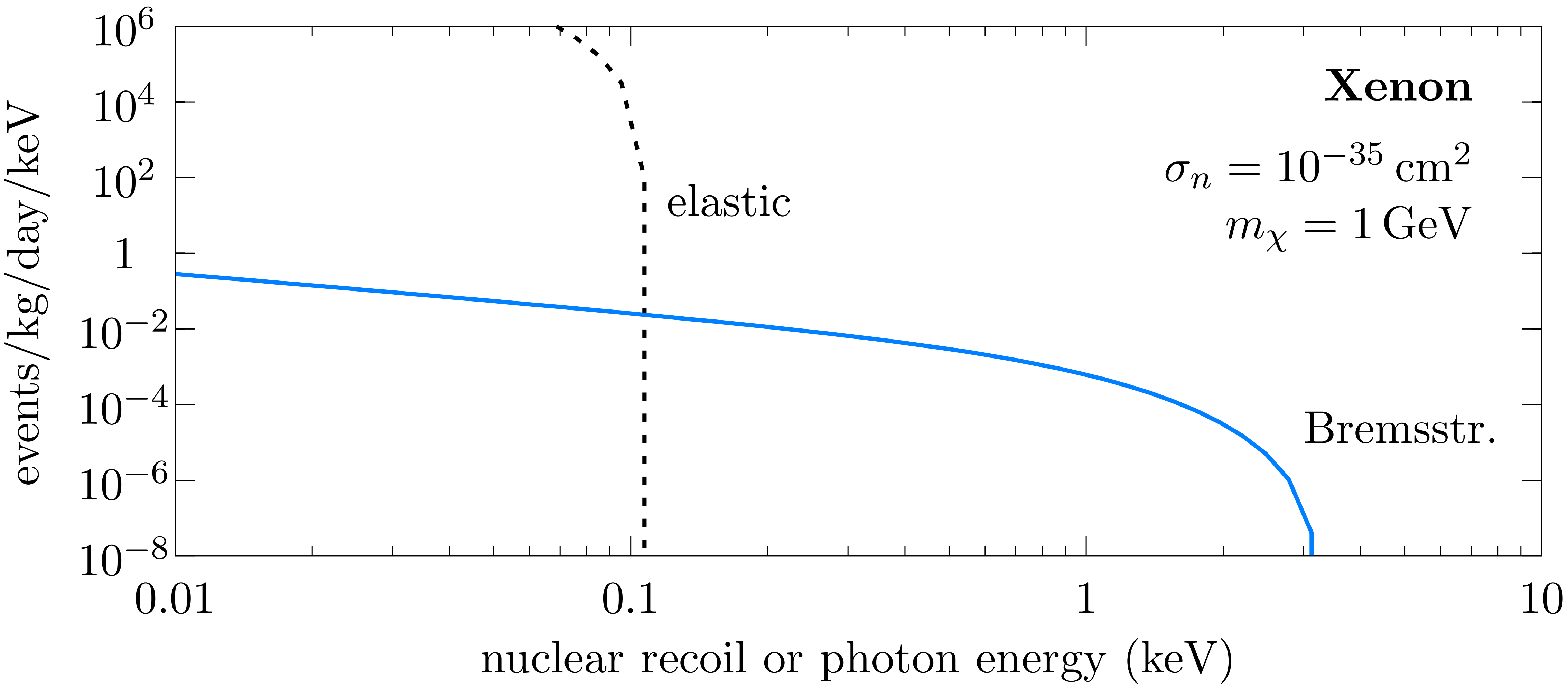


$$\simeq \frac{7\times 10^{-8}}{\omega}\left(\frac{E_R}{1\,\mathrm{keV}}\right) \times \frac{d\sigma}{dE_R} \qquad \text{(Xenon)}$$

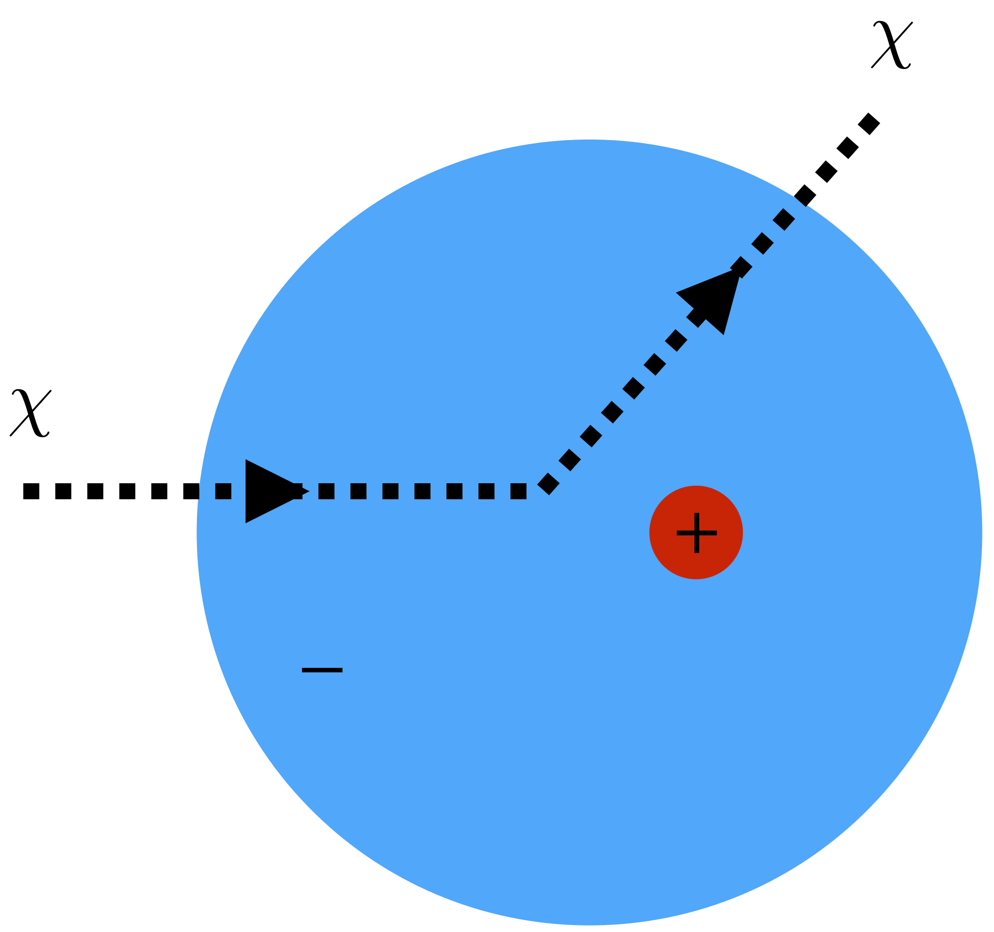
Can we overcome this suppression in rate?

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

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



Atomic physics picture of photon-emission



"Polarized Atom"

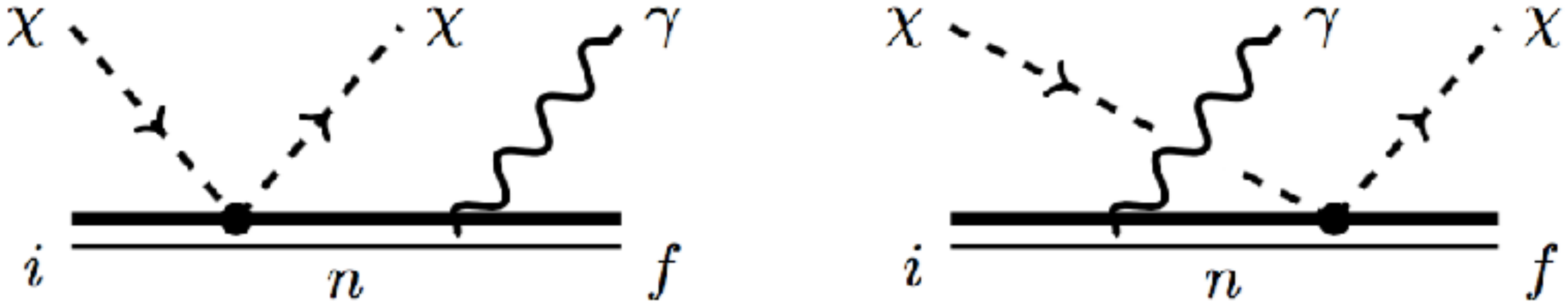
The naive treatment of Bremsstrahlung scales as 1/ω all the way to lowest energies

=> 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 picture of photon-emission



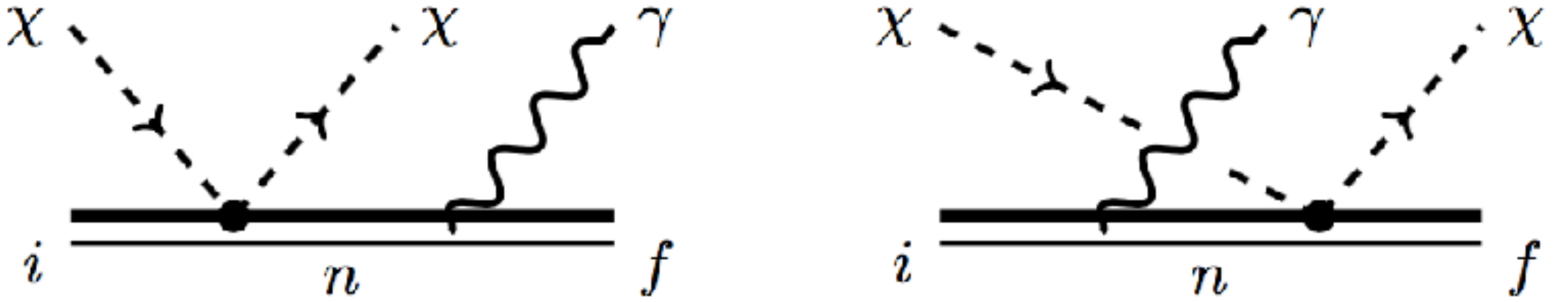
=> QM calculation

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

dipole matrix element for emission of photon

boost of the electron cloud

Atomic physics picture of photon-emission



dipole emission polarizability of the atom

For f=i:

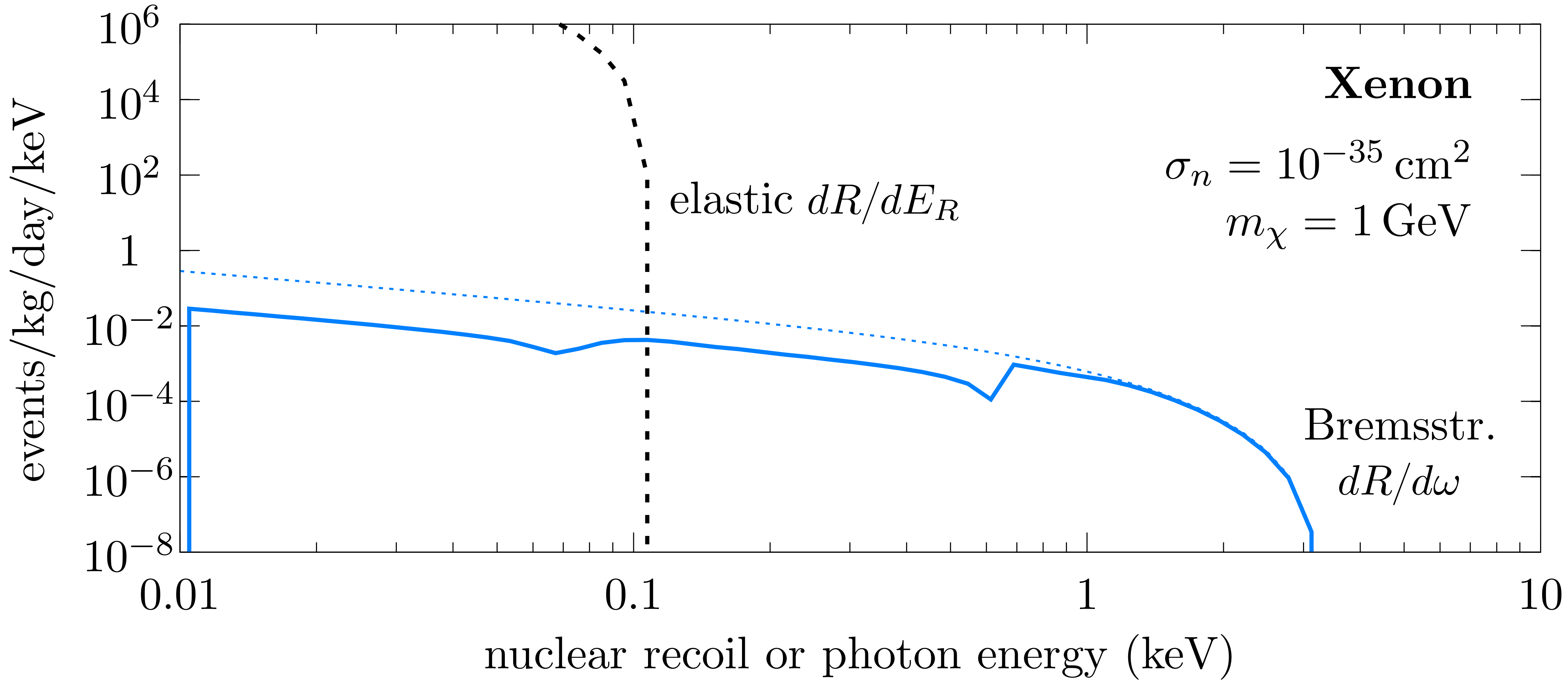
$$\frac{d\sigma}{d\omega dE_R} \propto \omega^3 \times |\alpha(\omega)|^2 \times \frac{E_R}{m_N} \times \frac{d\sigma}{dE_R}$$

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

for large ω naive result is recovered ✓

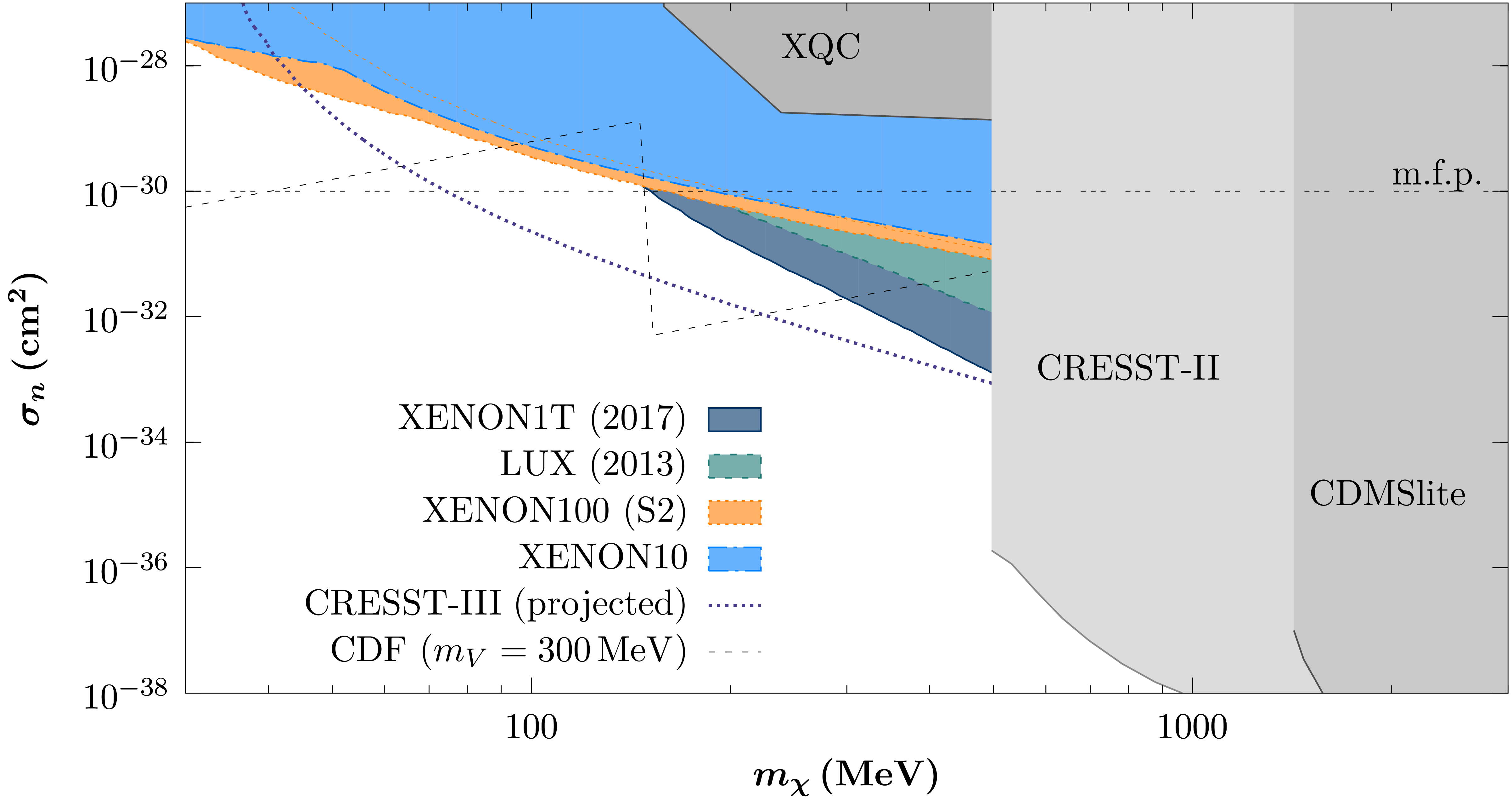
Gaining access to sub-GeV Dark Matter *through nuclear recoils*

including atomic physics modification



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

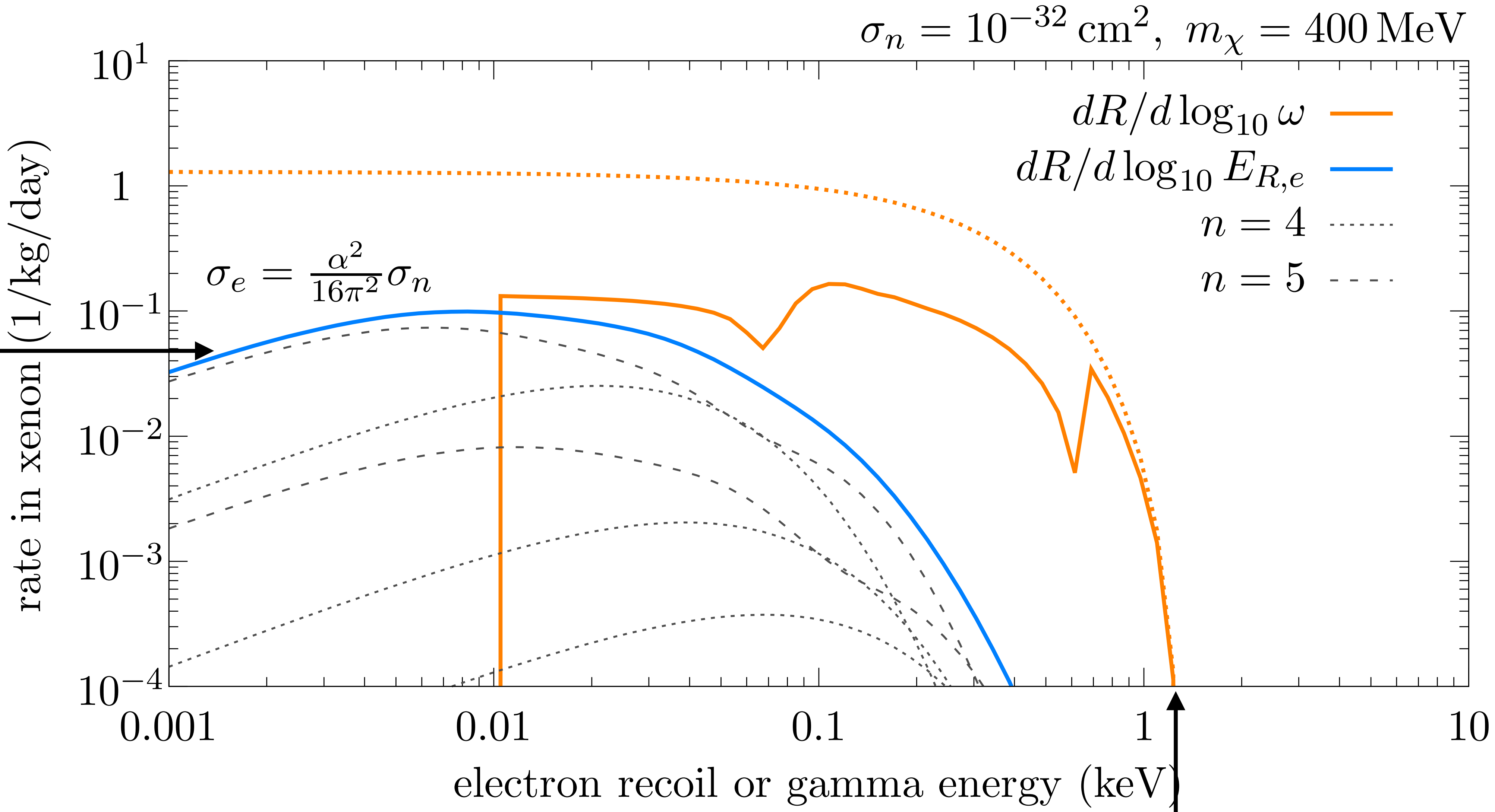
Current limits + projections



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

Kouvaris, JP PRL 2016

Method favors leptophobic DM models



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

Brems from DM-nucleus scattering

e.g. gauged baryon number

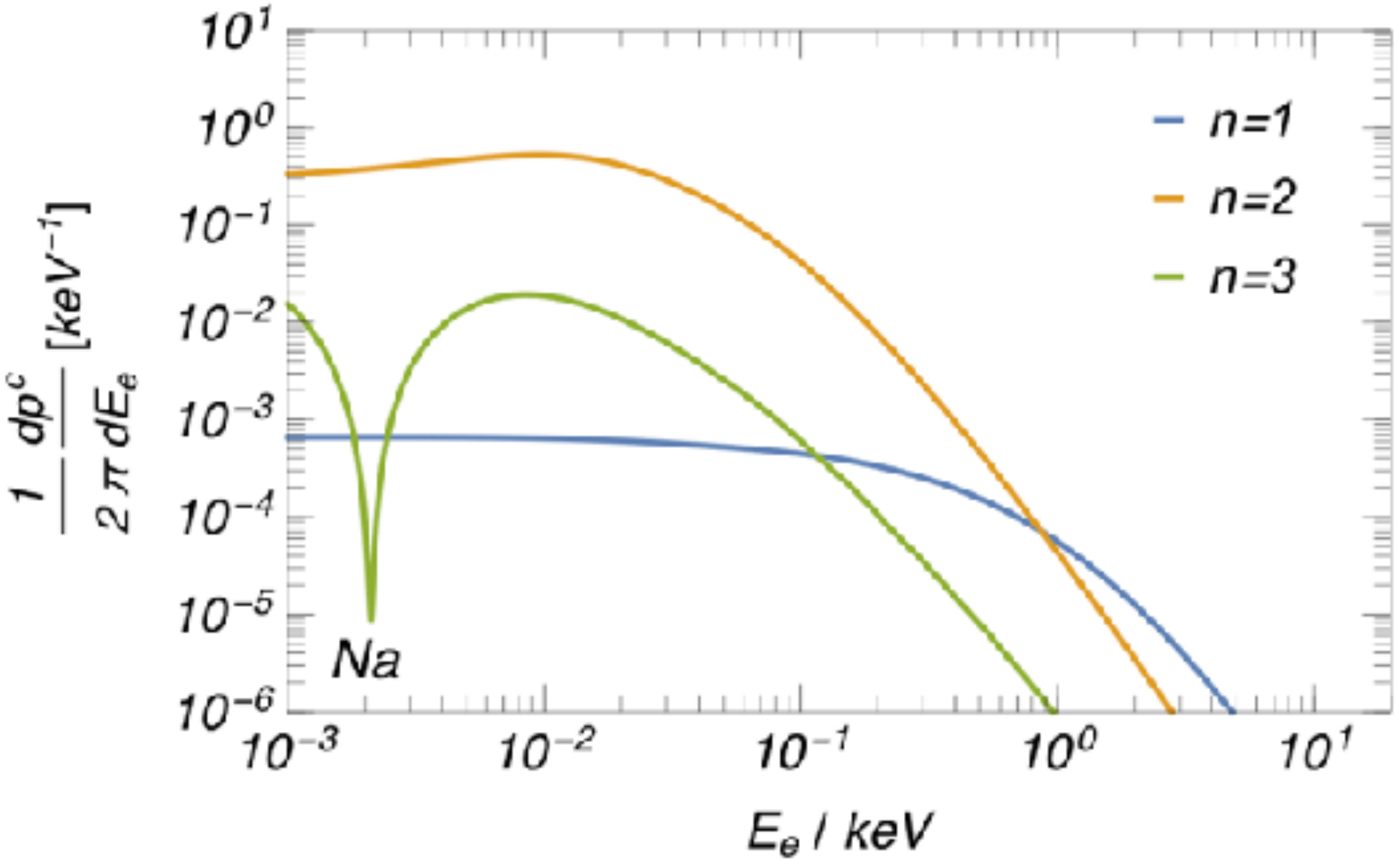
Direct electron shake off - “Migdal” effect

Ibe et al 2017

After DM-nucleus scattering, the electron cloud is boosted relative to the nucleus

$$|\Phi'_{ec}\rangle = e^{-im_e \sum_i \mathbf{v}\cdot\hat{\mathbf{x}}_i}|\Phi_{ec}\rangle$$

Total probability of ionization/excitation $\mathcal{P} = |\langle\Phi^*_{ec}|\Phi'_{ec}\rangle|^2$



(unlike for scintillation, P includes also excitations from inner shell electrons)

Direct electron shake off - “Migdal” effect

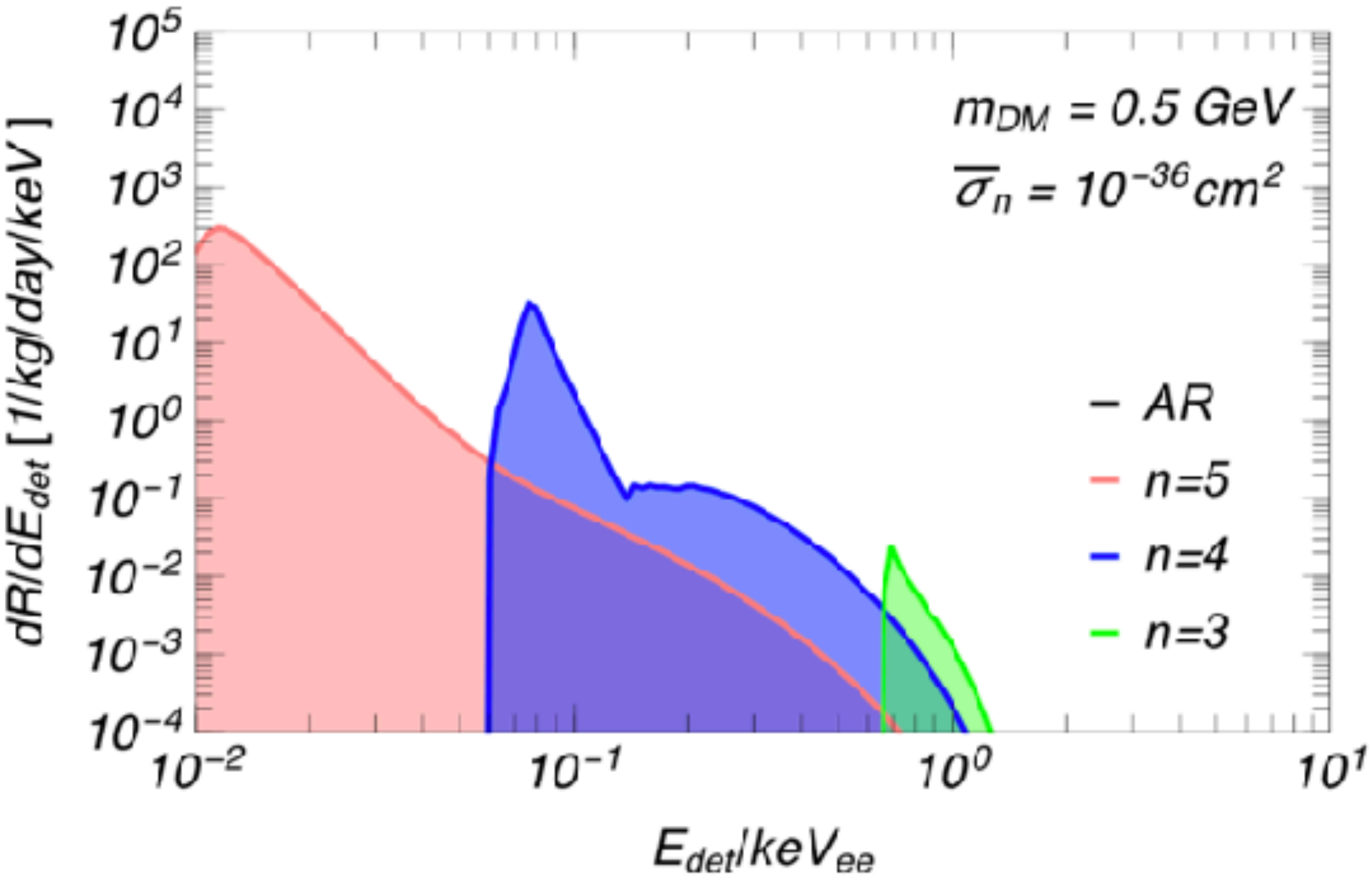
Ibe et al 2017

After DM-nucleus scattering, the electron cloud is boosted relative to the nucleus

$$|\Phi'_{ec}\rangle = e^{-im_e \sum_i \mathbf{v}\cdot\hat{\mathbf{x}}_i}|\Phi_{ec}\rangle$$

Total probability of ionization/excitation $\mathcal{P} = |\langle\Phi^*_{ec}|\Phi'_{ec}\rangle|^2$

(unlike for scintillation, P includes also excitations from inner shell electrons)



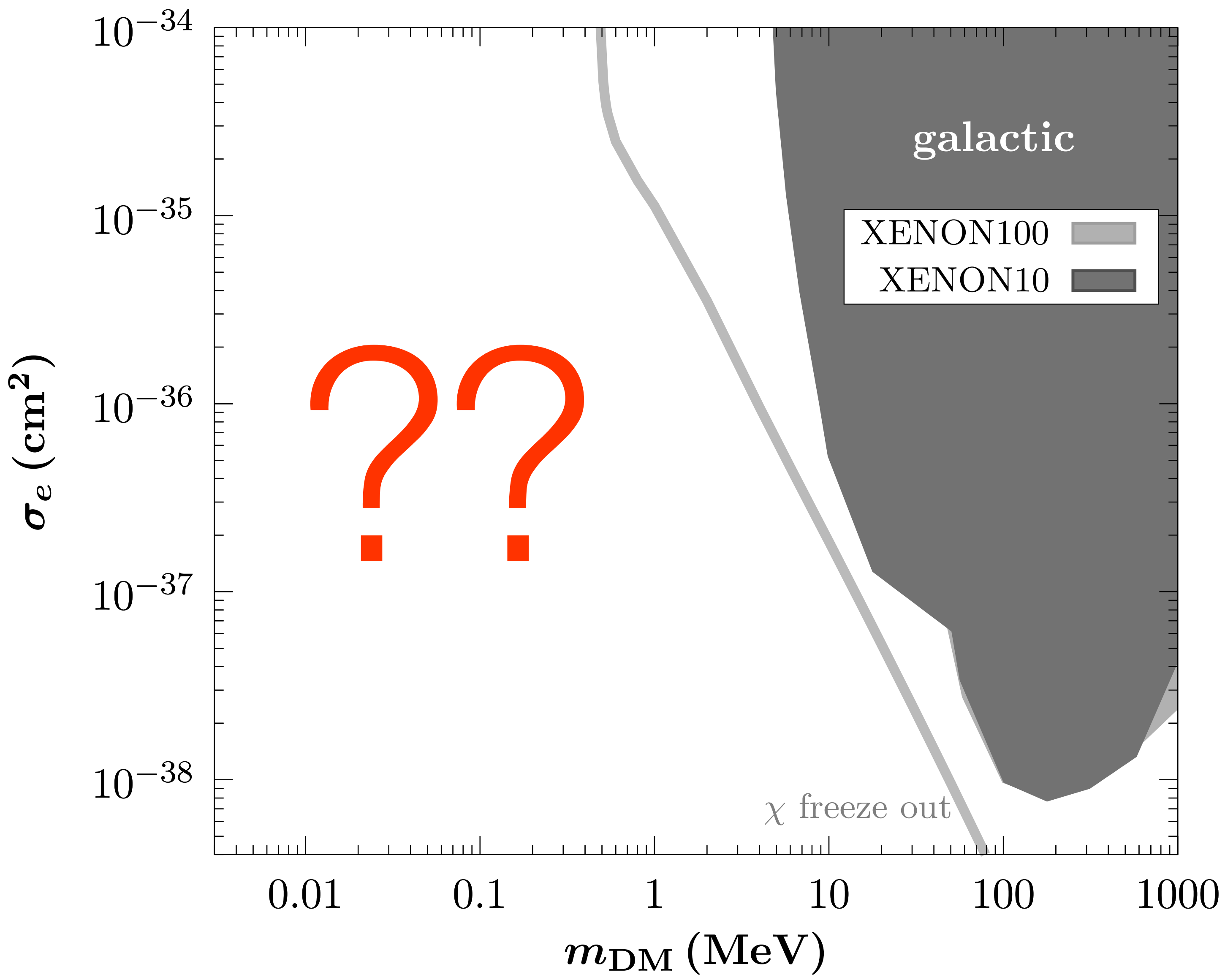
like the Bremsstrahlung, energetically favored for detection over elastic channel

=> employing those results yield improved limits (Dolan et al 2017)

2

Scattering on electrons

DM-electron scattering



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

Direct Detection of sub-MeV DM

Example of a model (UV completed through Z') where relic density is set via p-wave annihilation and safe from CMB constraints on energy injection ($N_{\rm eff}$ contributions are model dependent)

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

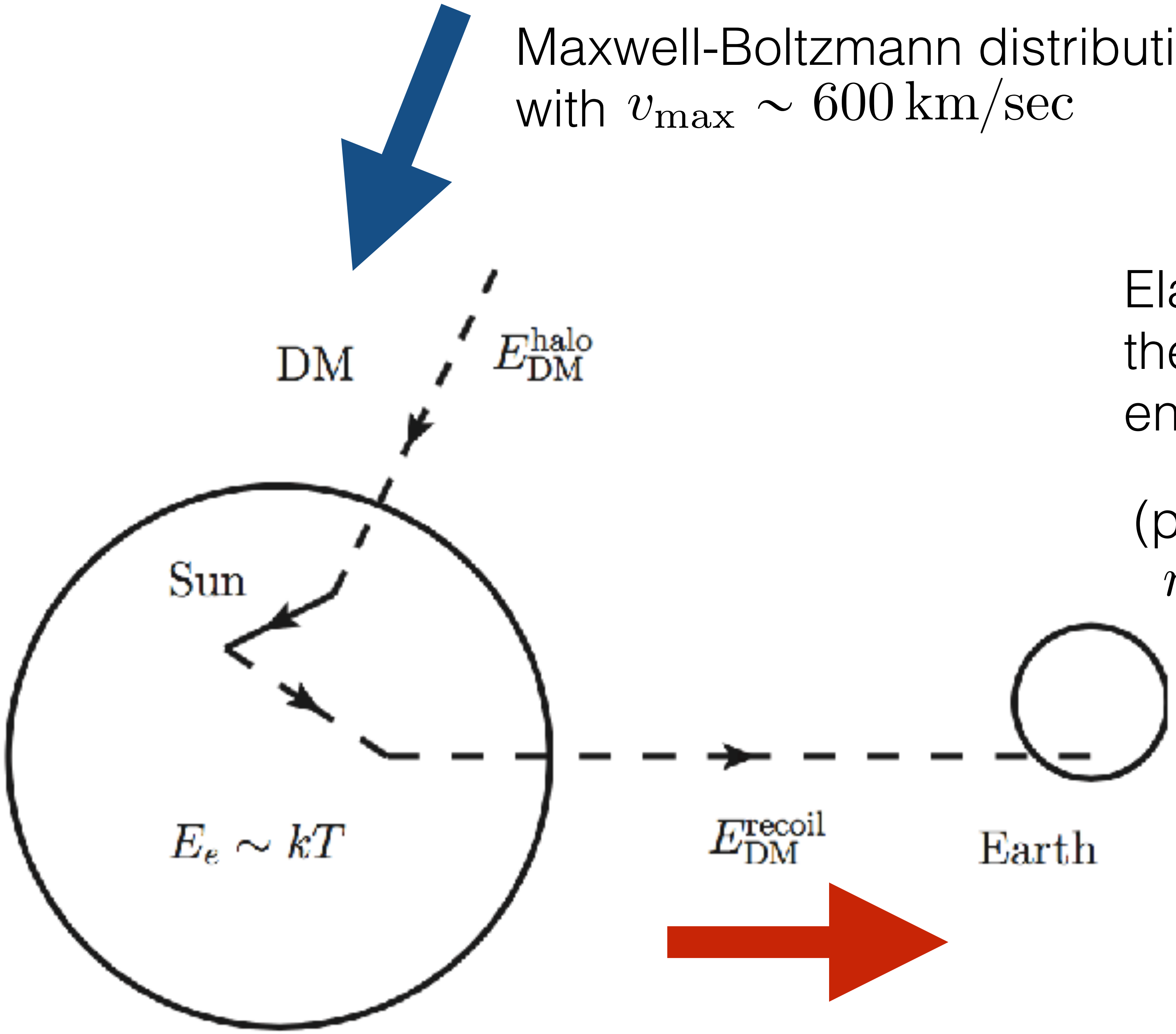
$$\sigma_{\rm ann} v = v^2 \times \frac{G_{\chi e}^2}{12\pi}(m_e^2 + 2m_\chi^2)\sqrt{1 - \frac{m_e^2}{m_\chi^2}}$$

=> First direct test of such DM model

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

The sun as particle accelerator

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



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

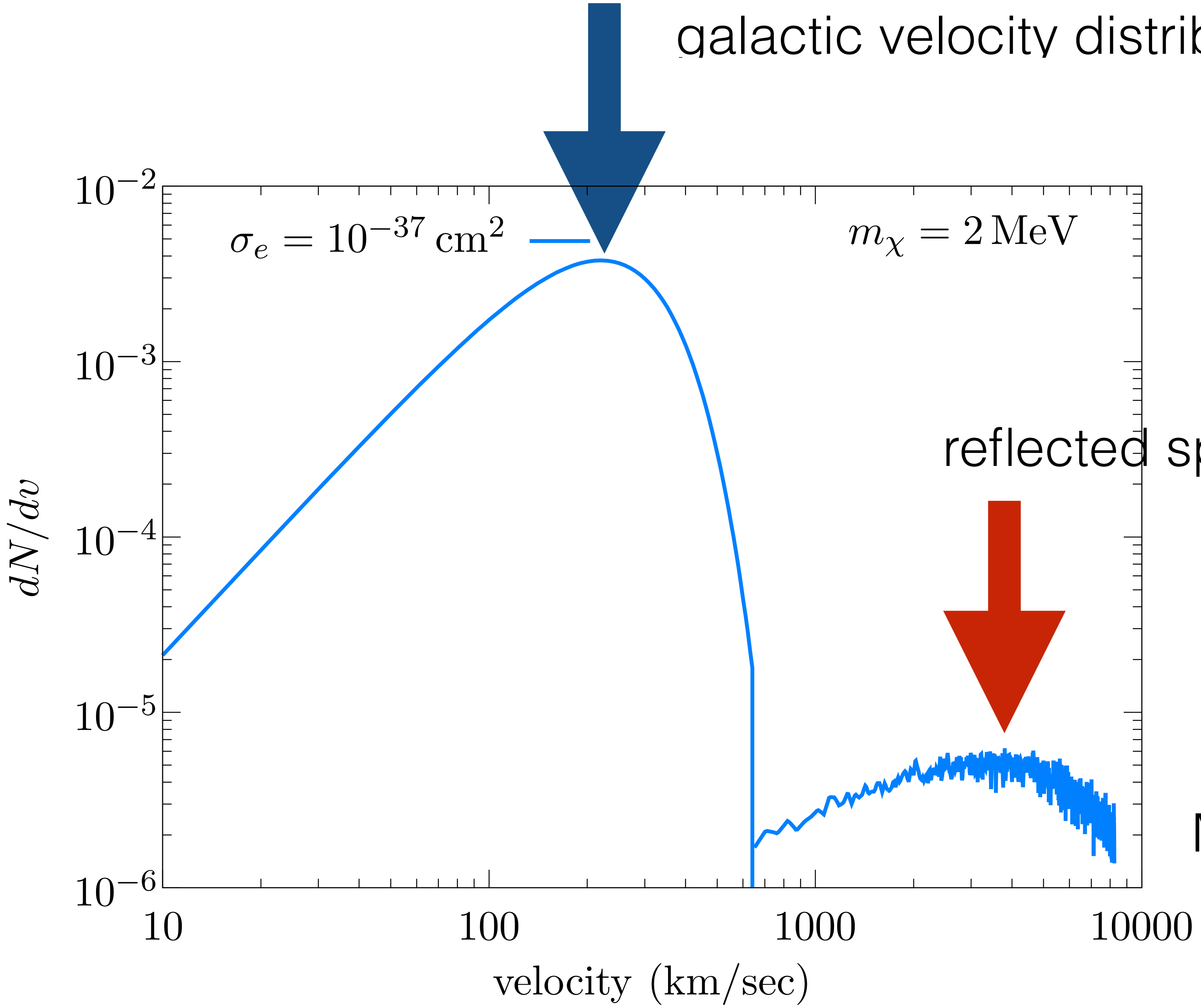
(process most efficient for $m_e = m_{\rm DM}$)

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

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

reflected spectrum

The sun as particle accelerator



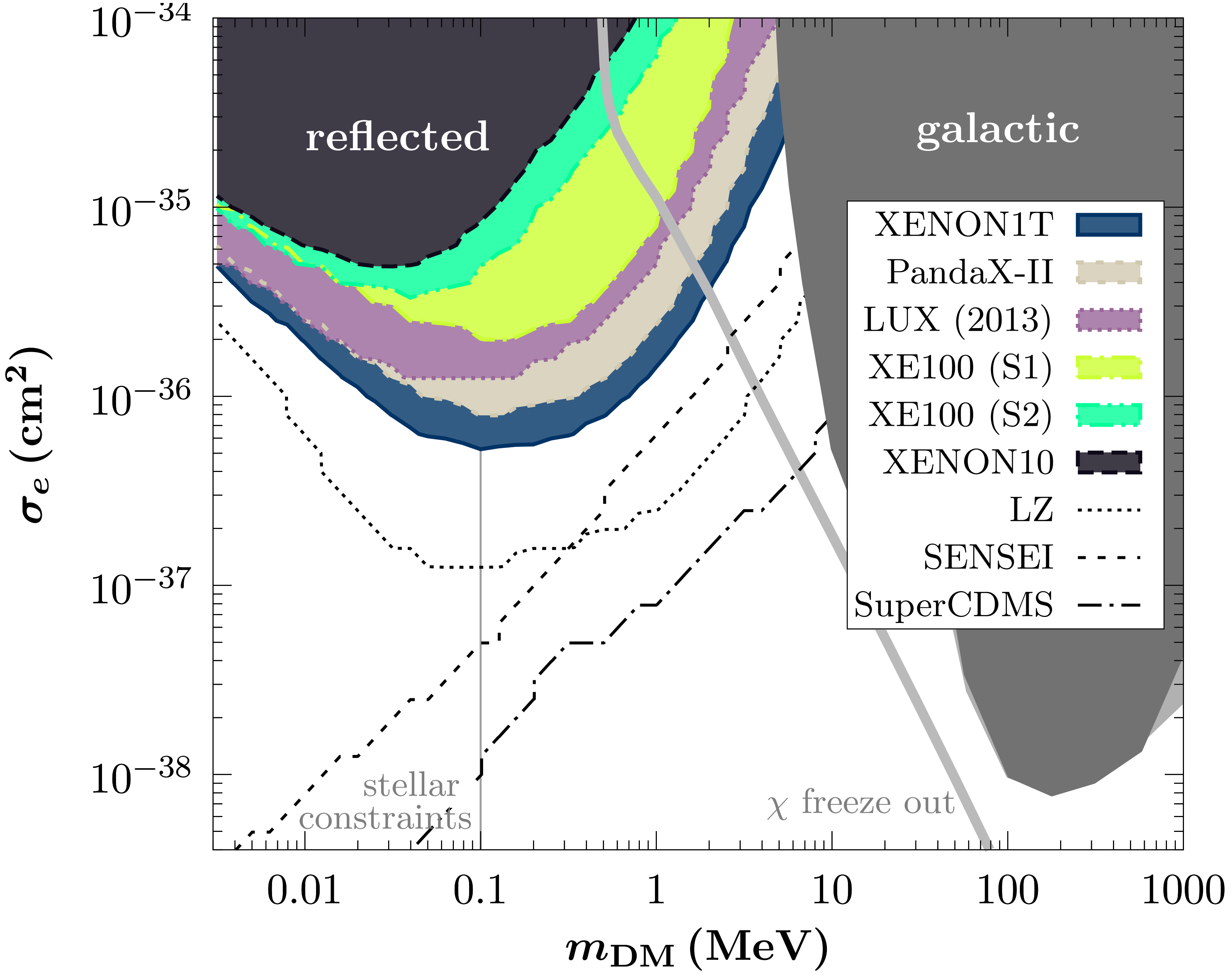
galactic velocity distribution

reflected spectrum from the sun

MC simulation

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

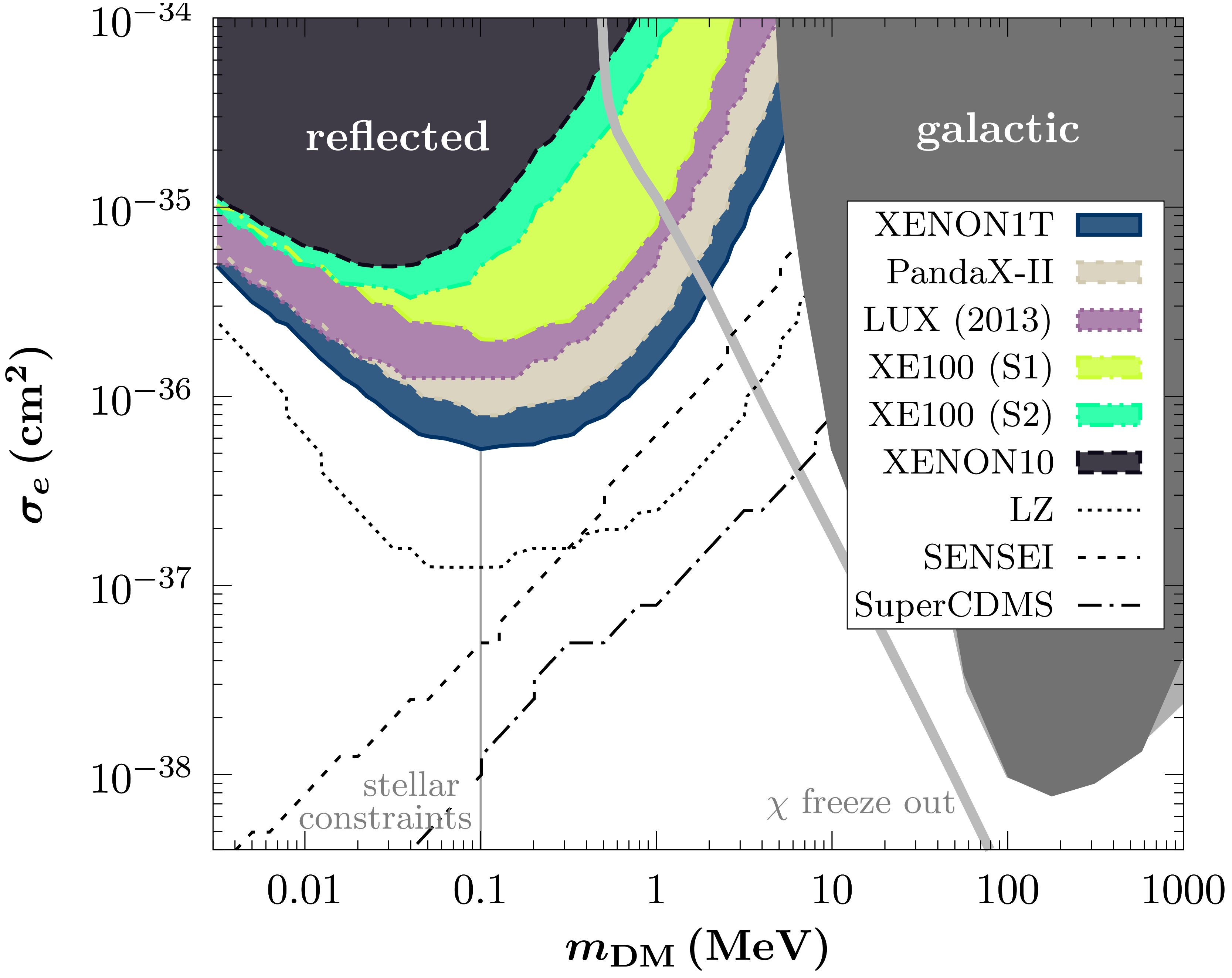
Direct Detection of sub-MeV DM



An, Pospelov, JP, Ritz PRL 2018

=> 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]

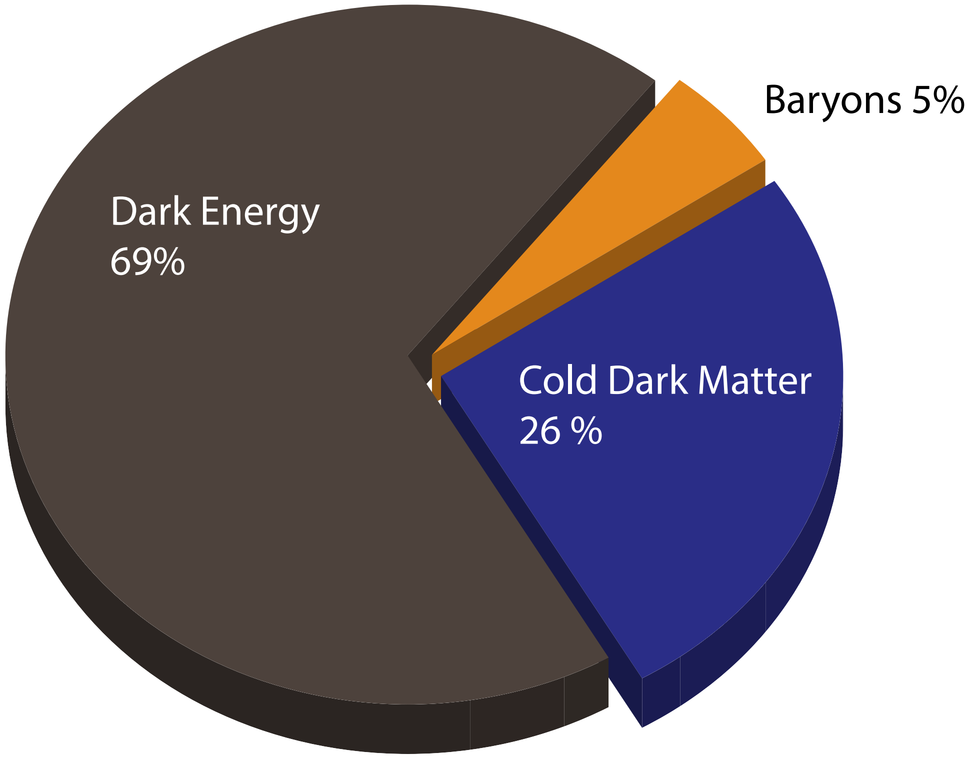
An, Pospelov, JP, Ritz PRL 2018

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

3

Decay into dark radiation

Signatures of late dark radiation



CMB

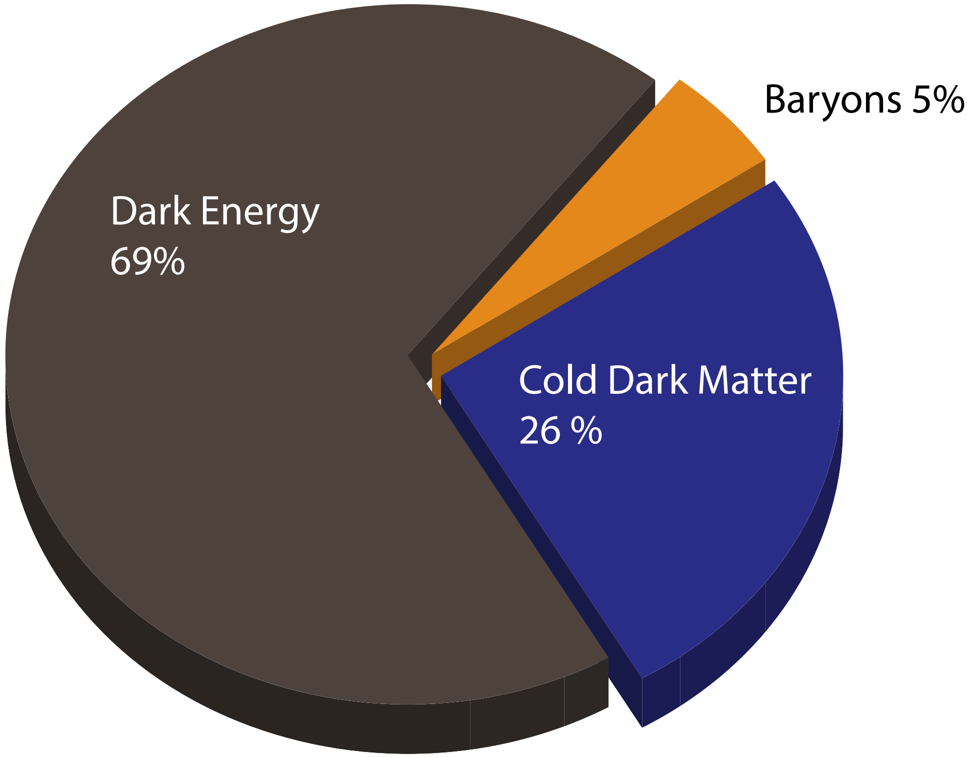
$$N_{\rm eff} = 3.04 \pm 0.33$$

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

Planck 2015

Signatures of late dark radiation

$$\tau_{\rm DM} \gtrsim t_0$$



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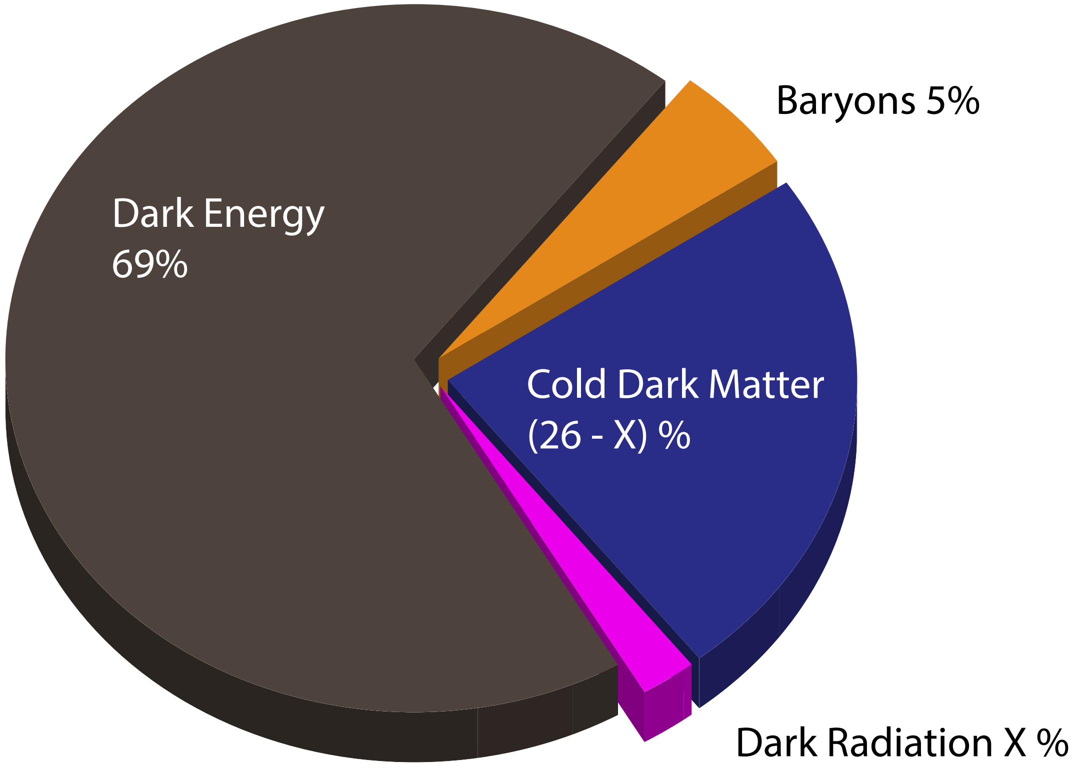


CMB

Low redshift Universe

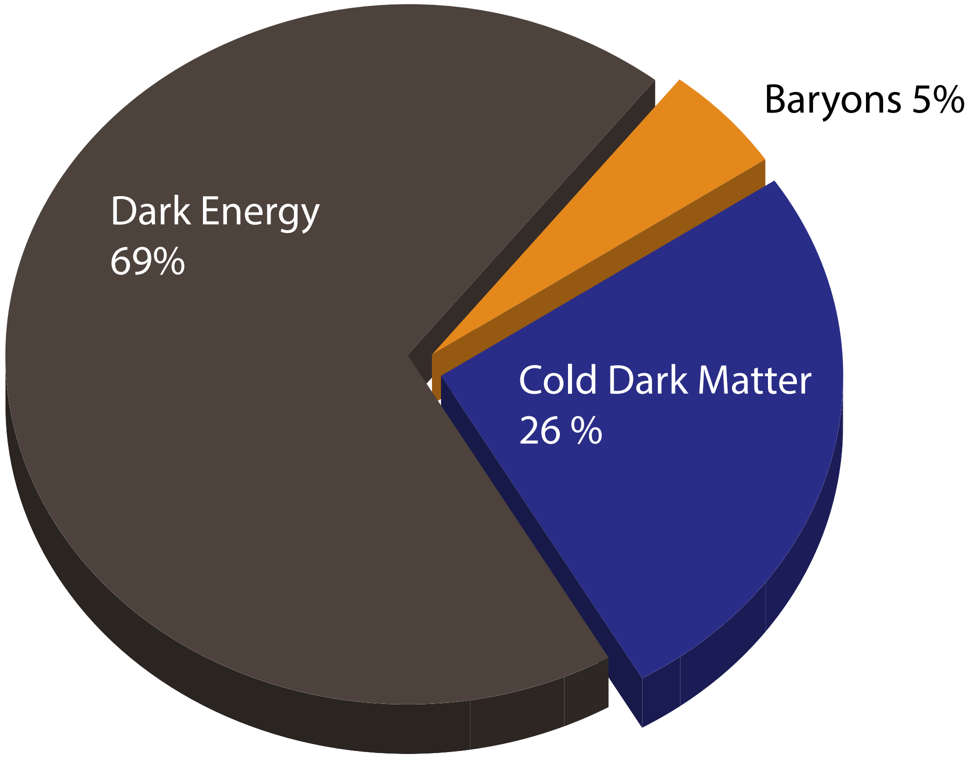
$$N_{\rm eff} = 3.04 \pm 0.33$$

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

Planck 2015

Signatures of late dark radiation

$$\tau_{\rm DM} \gtrsim t_0$$



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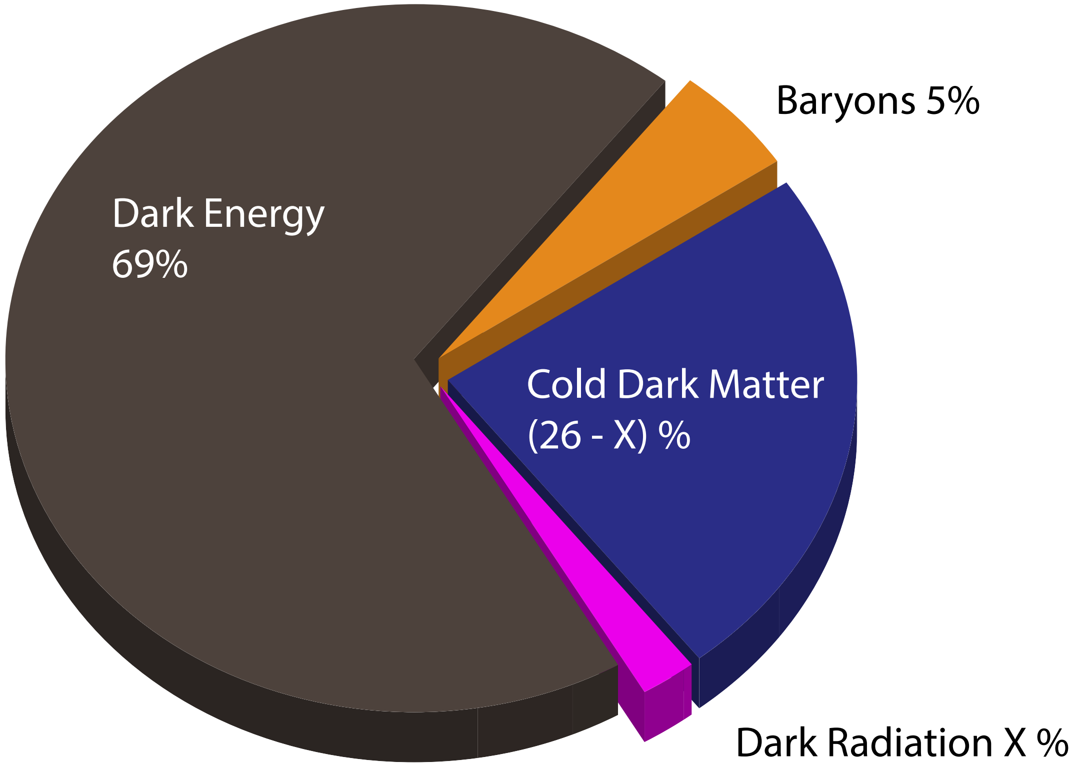


CMB

Low redshift Universe

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

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

Planck 2015

3a

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

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 that decays after CMB decoupling

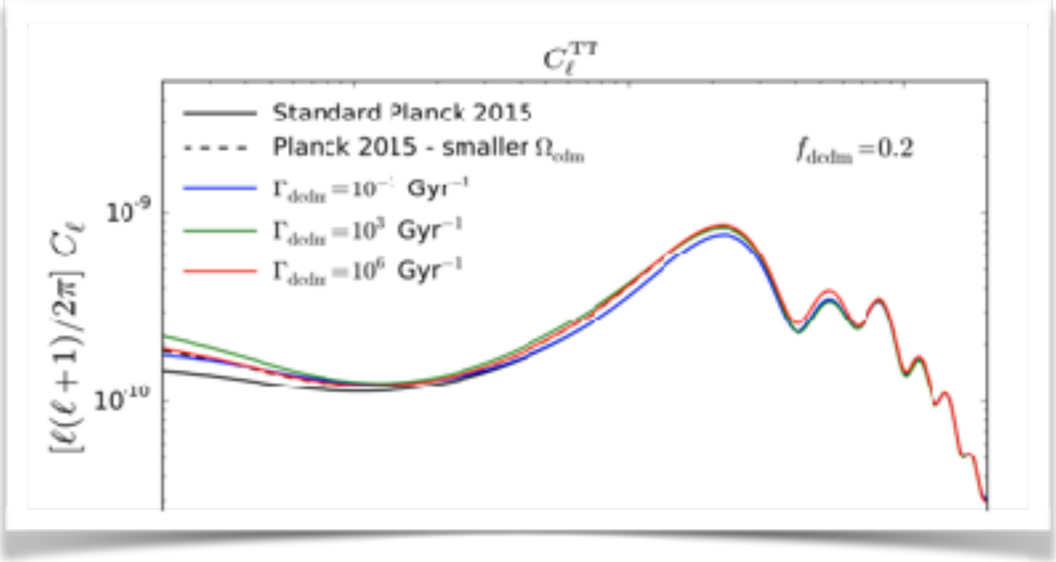
CMB (late-time ISW) and lensing constrains

$$f_{\rm dm} < \text{few}\,\% \qquad (\tau_{\rm dm} < \tau_U)$$

$$f_{\rm dm}/\tau_{\rm dm} \lesssim 1/12\tau_U \qquad (\tau_{\rm dm} > \tau_U)$$

Poulin, Serpico, Lesgourges 2016

see also Berezhiani, Dolgov, Tkachev 2015



There are also constraints on structure formation with residual “kicked DM state” in place

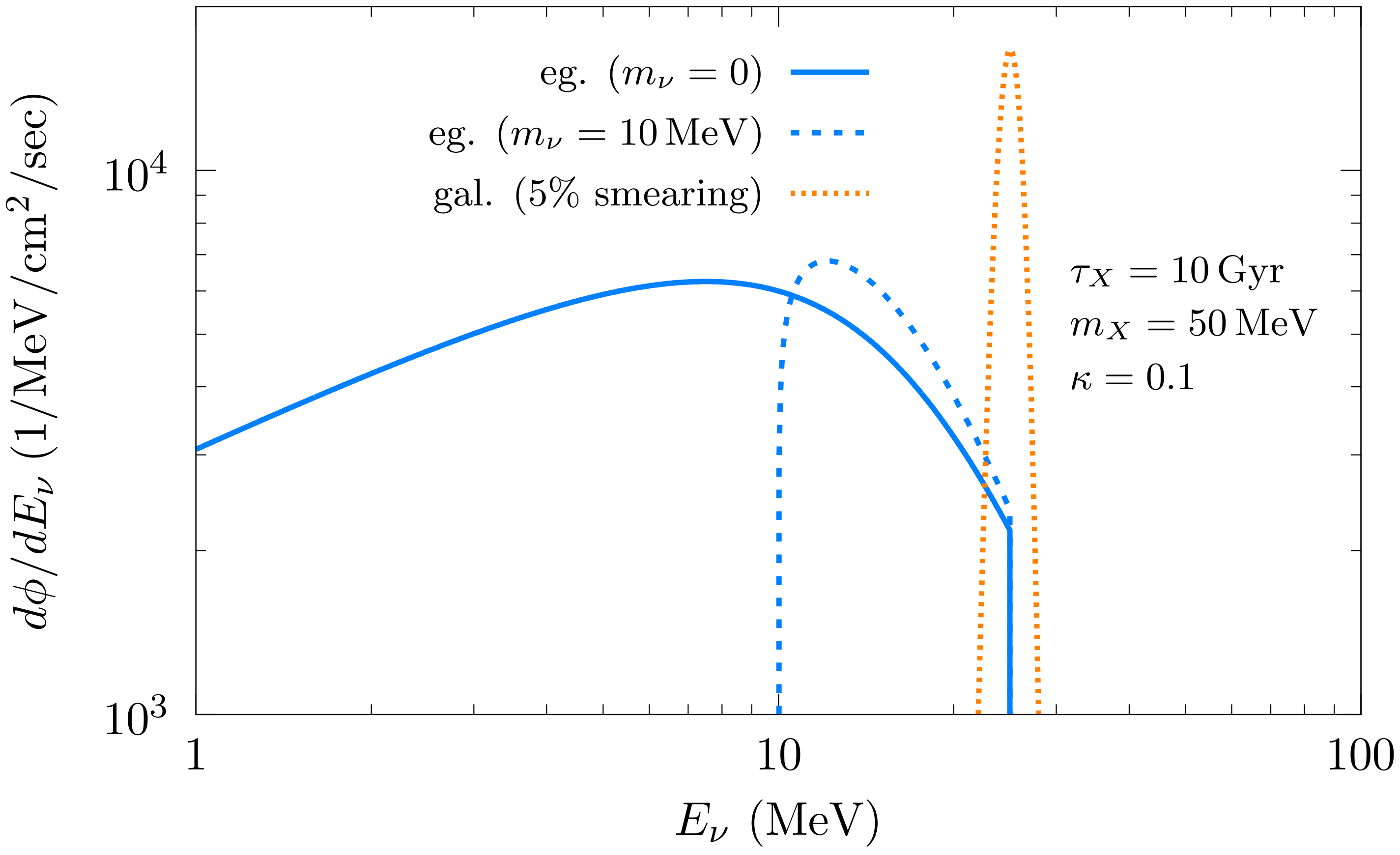
e.g. Wang, Peter at al. 2014

Maximum fluxes of DR

Galactic and extragalactic contributions to the flux

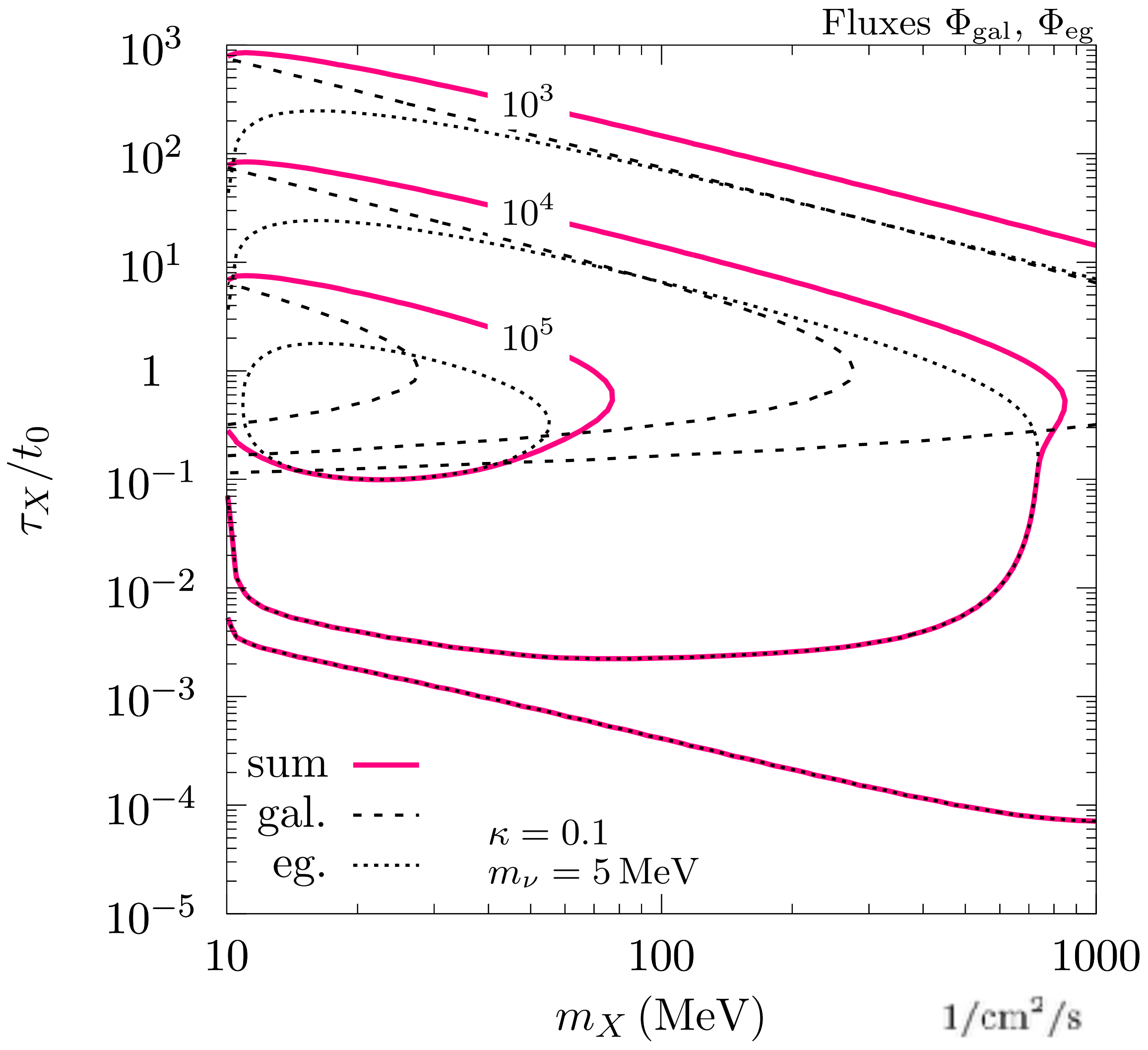
galactic
$$\frac{d\phi_{\rm gal}}{dE_\nu} = \frac{\kappa {\rm Br}_\nu e^{-t_0/\tau_X}}{\tau_X m_X} \frac{dN}{dE_\nu} \times R_{\rm sol}\rho_{\rm sol}\langle J\rangle.$$

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



example for 2-body injection

Maximum fluxes of DR



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

here: 10% decaying DM component

Late Dark Radiation in SM neutrinos

Option 1: DR are Standard Model neutrinos

Benefits: no N_{eff} 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

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

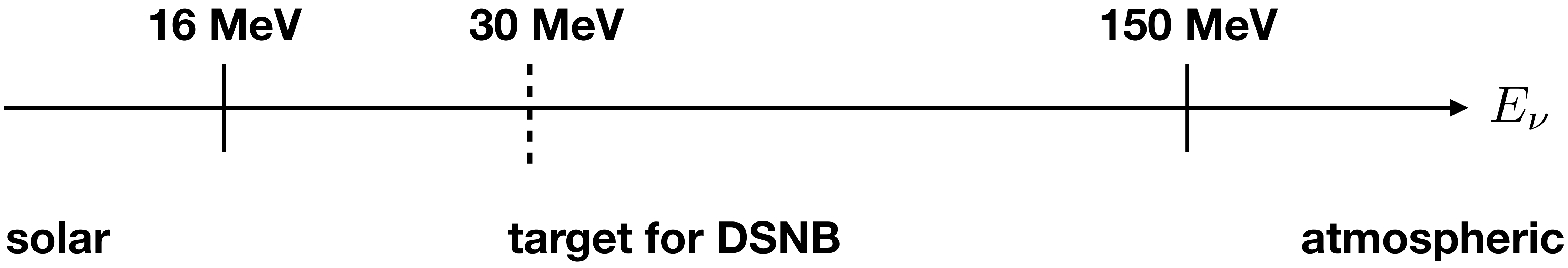
Chikashige, Mohapatra, Peccei 1981

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 $p + \bar{\nu}_e \rightarrow n + e^+$ with large visible energy
- 30 MeV < E < 150 MeV: reactions with neutrons inside nuclei no longer kinematically suppressed, e.g. ${}^{16}\mathrm{O} + \nu_e \rightarrow {}^{16}\mathrm{F} + e$
- E > 150 MeV: atmospheric neutrino flux well measured and concordant


16 MeV **30 MeV** **150 MeV** E_ν

solar **target for DSNB** **atmospheric**

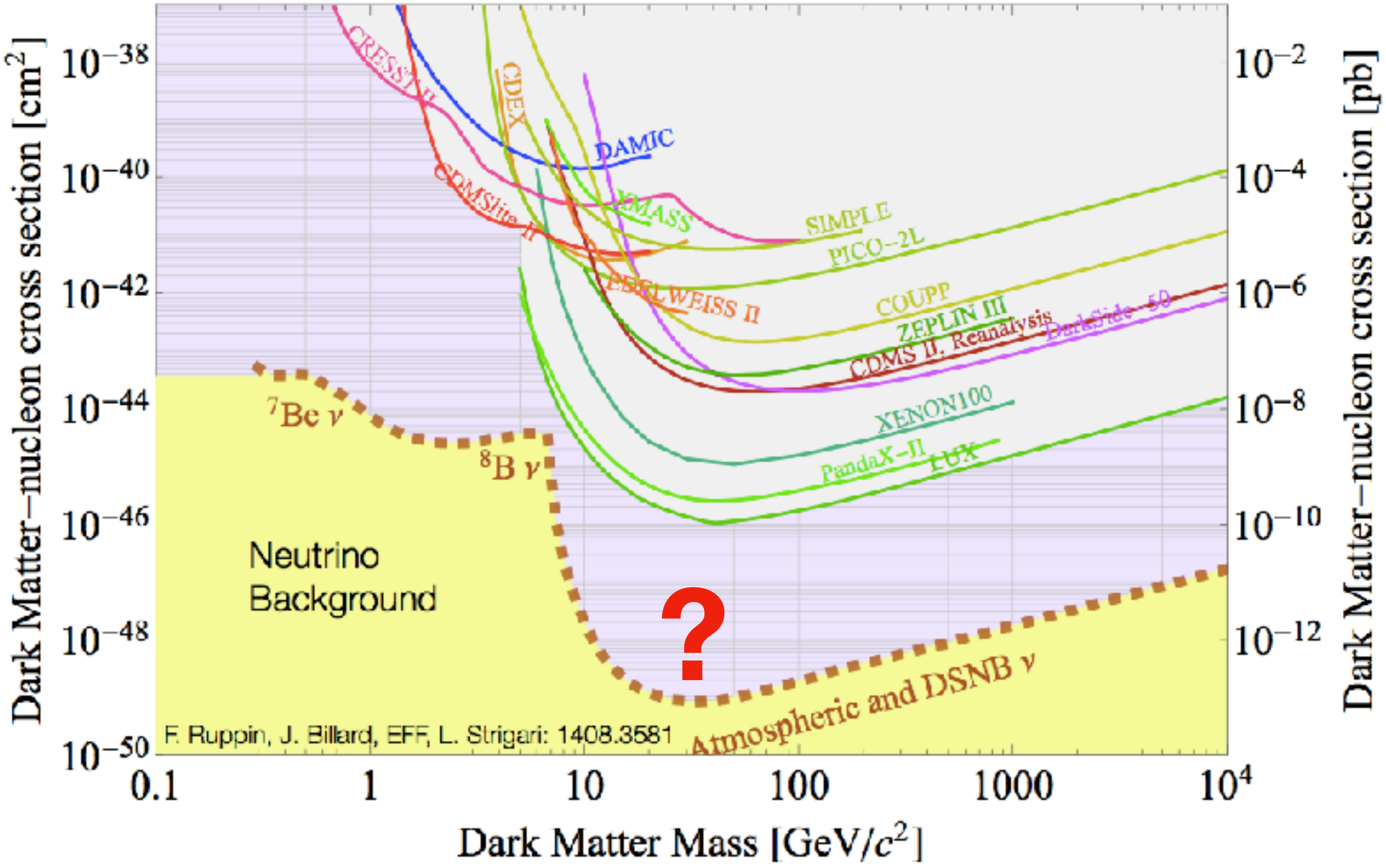
Late Dark Radiation in SM neutrinos

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 $\bar{\nu}$



F. Ruppin, J. Billard, EFF, L. Strigari: 1408.3581

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,

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

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

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,

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

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:

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

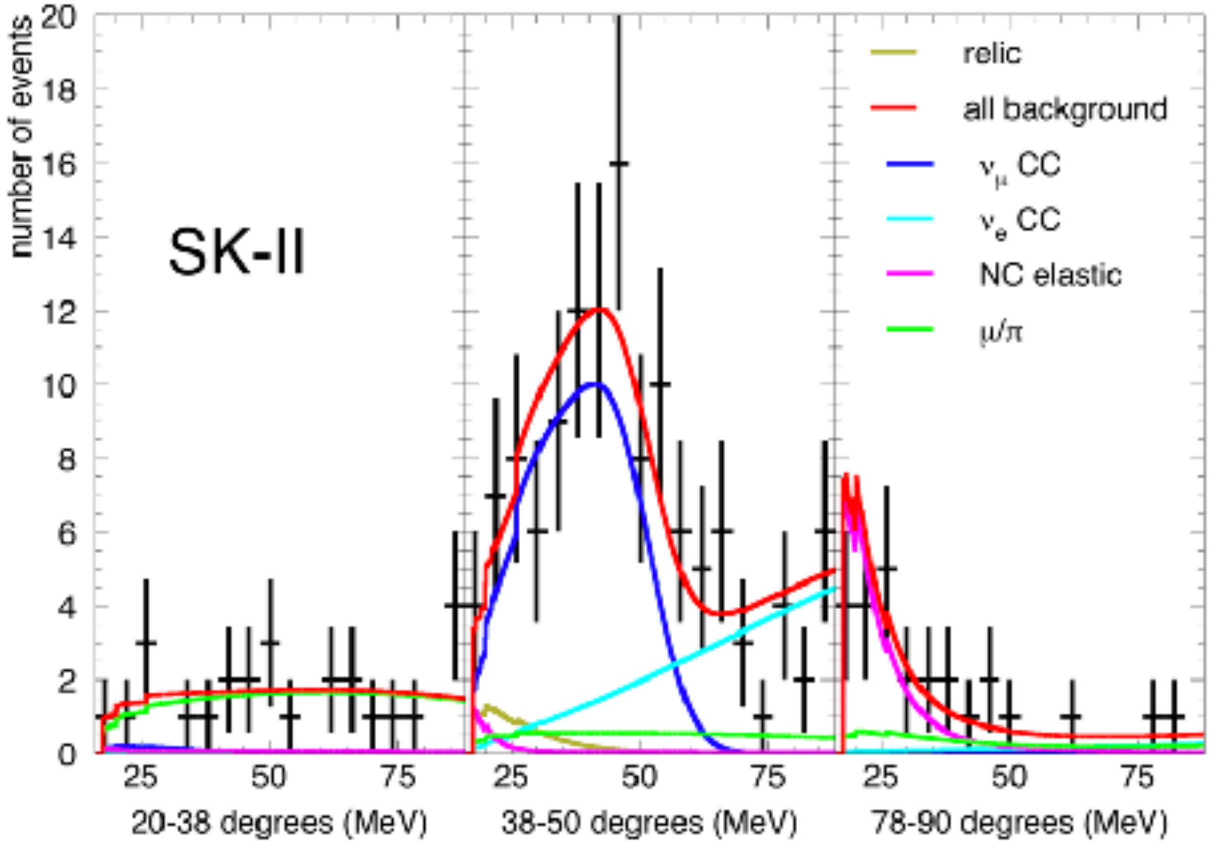
$$J^\nu_{EM} = \bar{e}\gamma^\nu e + \bar{p}\gamma^\nu p; \quad J^\nu_B = \bar{n}\gamma^\nu n + \bar{p}\gamma^\nu p$$

Much milder astro-constraints; N_{eff} can be better avoided when coupled to baryons

Constraints from neutrino expts.

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

Super-K collaboration 2011



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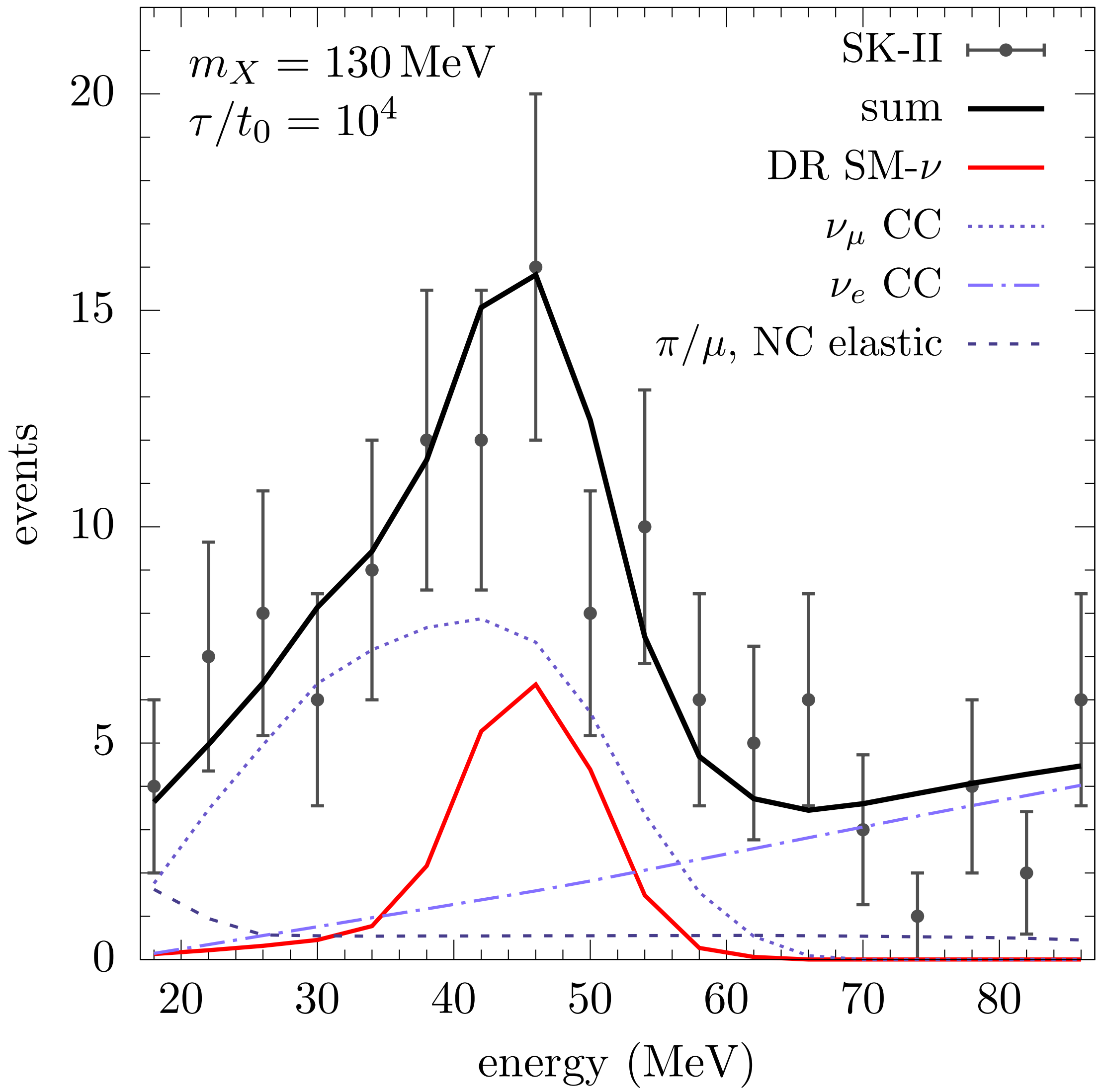


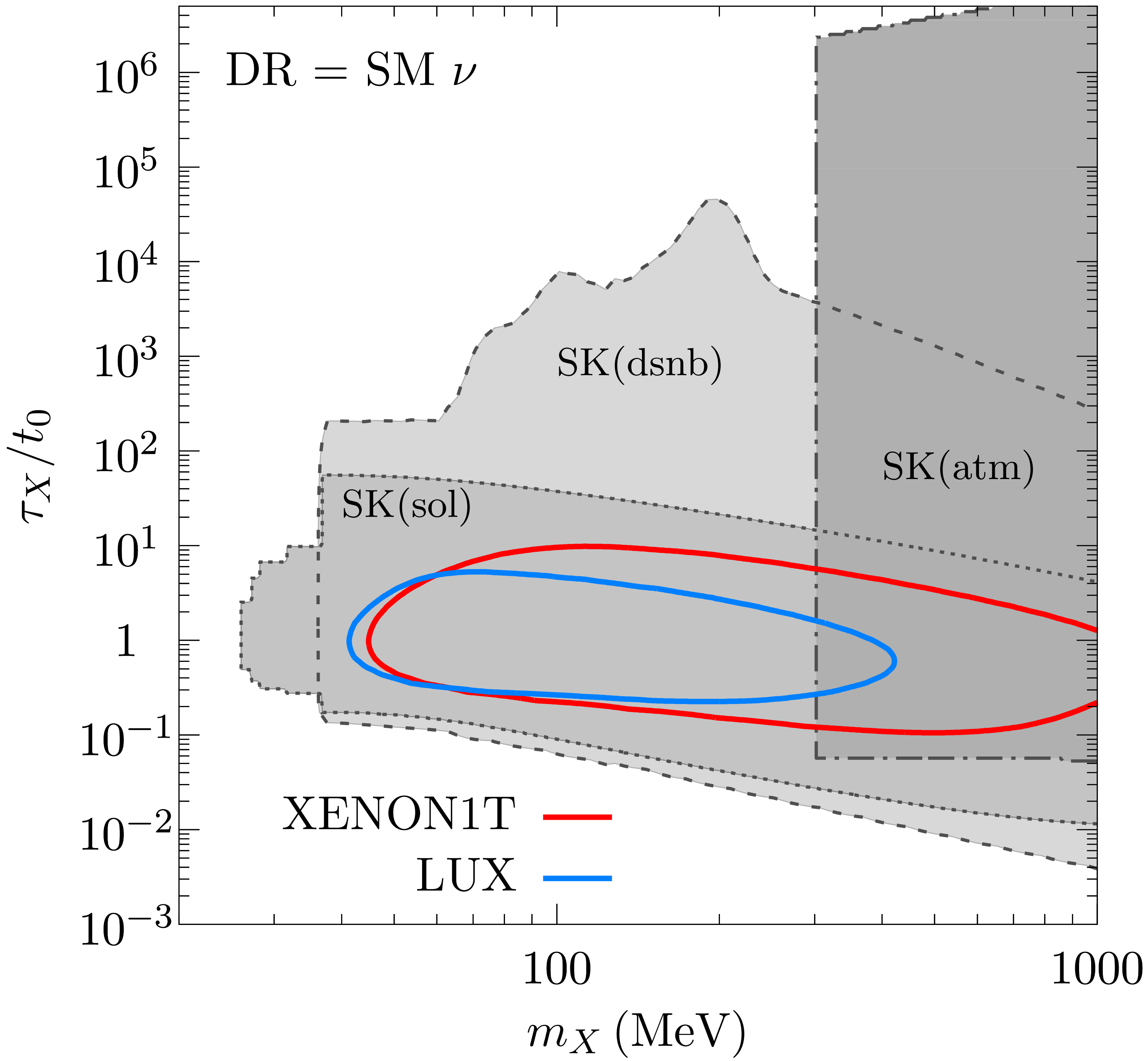
sideband

search-region
with fitted bkg.

sideband

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

Late DR in SM neutrinos



Option 1

DR in SM neutrinos ν

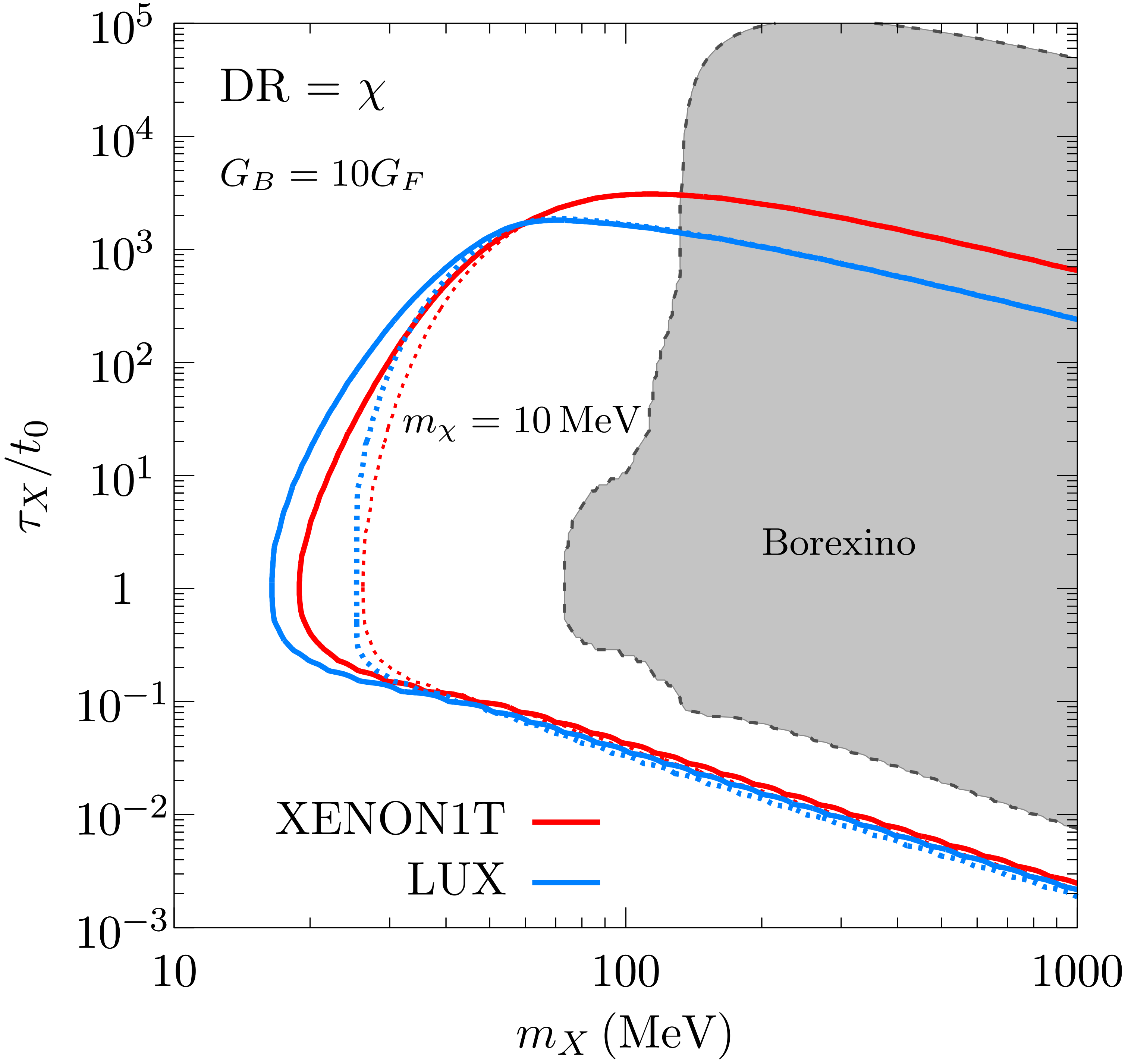
=> if flux is saturated then neutrino floor ~2 orders of magnitude away from current direct detection sensitivity

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

[Nikolic, JP in prep]

Cui, Pospelov, JP 2017

Late DR in a new species



Option 2

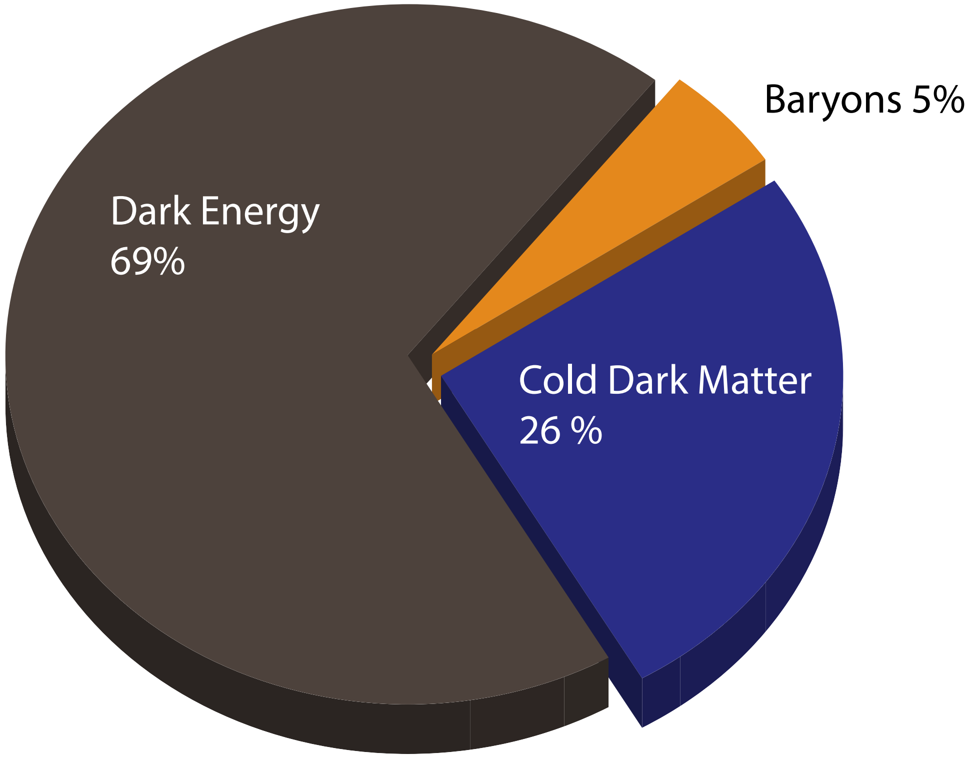
new neutrino interacting with baryonic current

Borexino limit derived from elastic scattering on protons

Cui, Pospelov, JP 2017

Signatures of late dark radiation

$\tau_{\rm DM} \gtrsim t_0$



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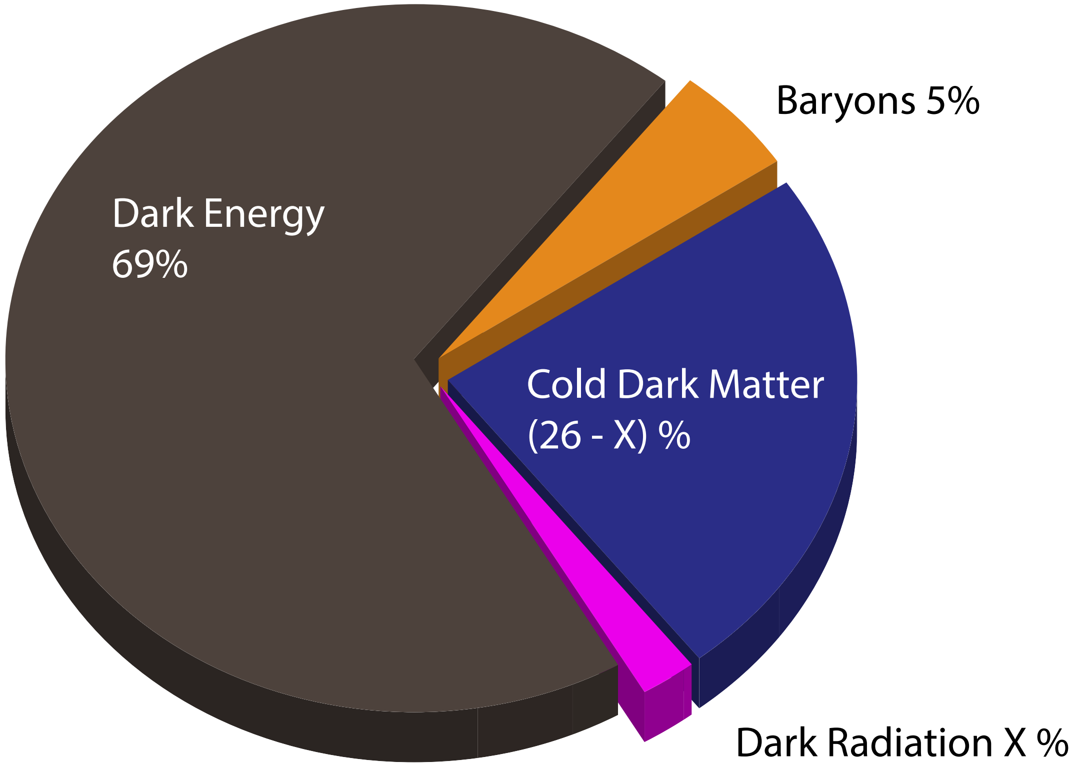


CMB

Low redshift Universe

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

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

Planck 2015

3b

$$\omega_{\rm DR} \ll \omega_{\rm CMB}, \quad n_{\rm DR} > n_{\rm CMB},$$

$$\omega_{\rm DR} n_{\rm DR} \ll \rho_{\rm tot}$$

Prospects of detection

Light fields often have their interactions enhanced at high energies and suppressed at low energies, e.g.

- Neutrinos that have Fermi-type interactions with atomic constituent
- Axions with effective dimension 5 interactions with fermions and gauge bosons.

=> This type of DR very difficult to see directly

However, dark photons can manifest their interactions at low energies and low densities. Moreover, it is possible to have lots of them, compared to CMB

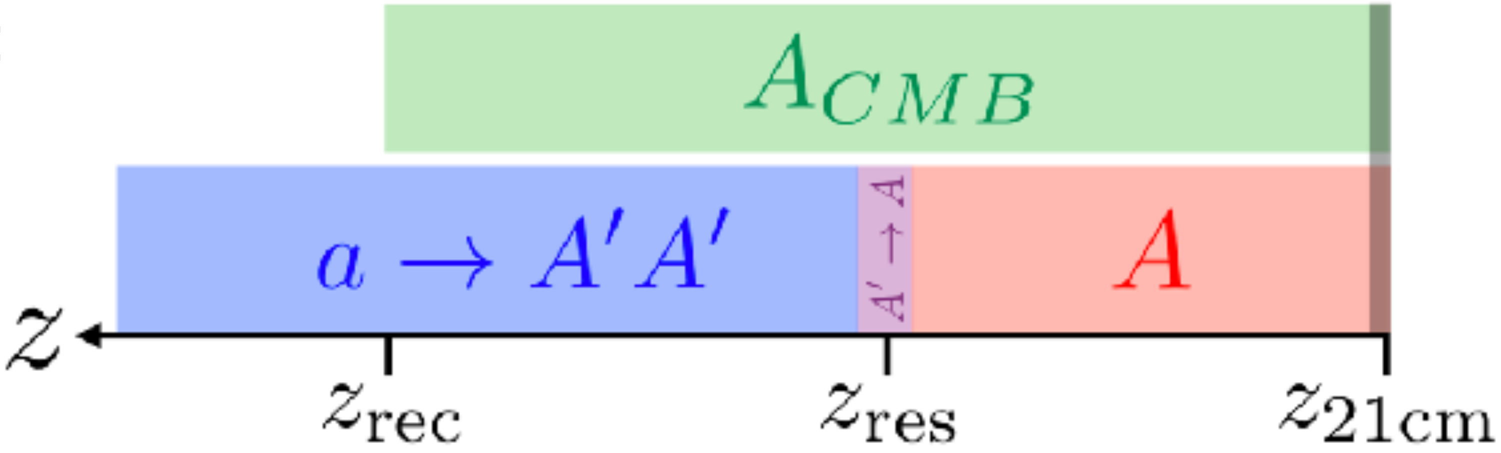
$$n_{\rm RJ} = \frac{1}{\pi^2}\int_0^{\omega_{\rm max}} \frac{\omega^2 d\omega}{\exp[\omega/T]-1} \simeq \frac{T\omega_{\rm max}^2}{2\pi^2} \simeq 0.21\, x_{\rm max}^2\, n_{\rm CMB} \qquad x = \omega/T$$

For example, $x_{\rm max} = 10^{-3}$: $n_{\rm DR} \lesssim 10^2\, n_{\rm CMB}$, early DR with $\Delta{\rm N}_{\rm eff} = 0.5$

$n_{\rm DR} \lesssim 10^5\, n_{\rm CMB}$, late decay of $0.05\,\rho_{\rm DM}$

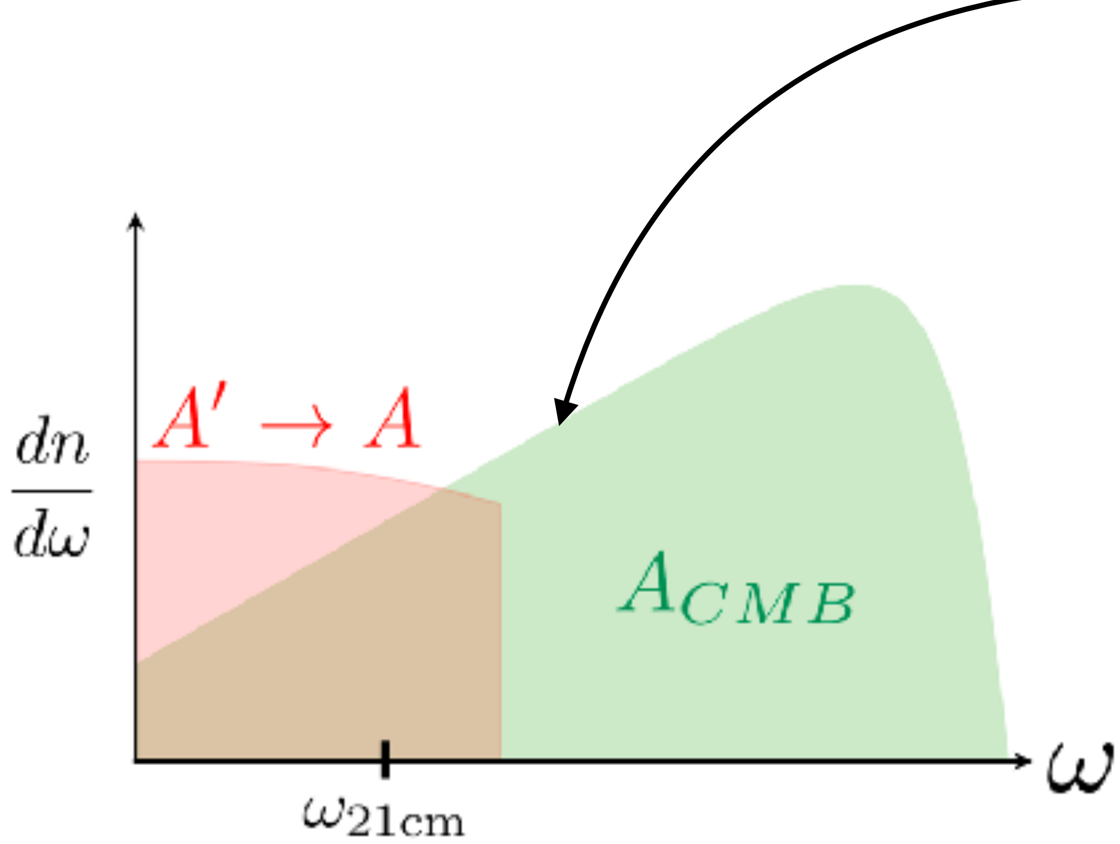
Modification of the RJ tail of the CMB

Main idea:



Rayleigh-Jeans tail $\omega/T \ll 1$

Resonant conversion of Dark Photons into the RJ-tail of the CMB:



$$\frac{dn_A}{d\omega} \to \frac{dn_A}{d\omega} \times P_{A\to A} + \frac{dn_{A'}}{d\omega} \times P_{A'\to A}$$

Pospelov, JP, Ruderman, Urbano 2018

DM decay into dark photons

Axion-like particle together with dark photon:

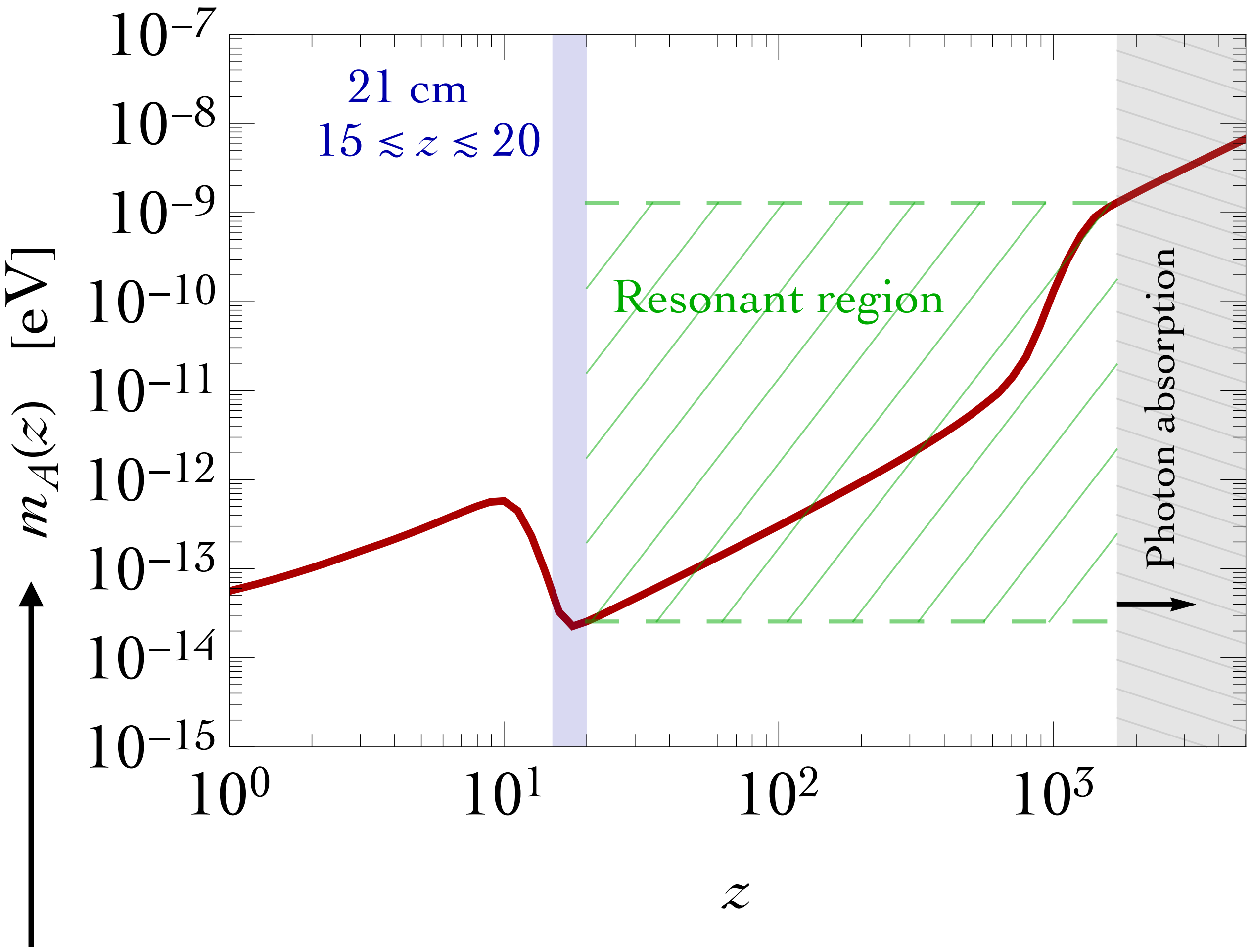
$$\mathcal{L} = \frac{1}{2}(\partial_\mu a)^2 - \frac{m_a^2}{2}a^2 + \frac{a}{4f_a}F'_{\mu\nu}\tilde{F}'^{\mu\nu} + \mathcal{L}_{AA'} \ ,$$

$$\mathcal{L}_{AA'} = -\frac{1}{4}F_{\mu\nu}^2 - \frac{1}{4}(F'_{\mu\nu})^2 - \frac{\epsilon}{2}F_{\mu\nu}F'_{\mu\nu} + \frac{1}{2}m_{A'}^2(A'_\mu)^2$$

Lifetime can be anything from much shorter to much longer than the age of the Universe

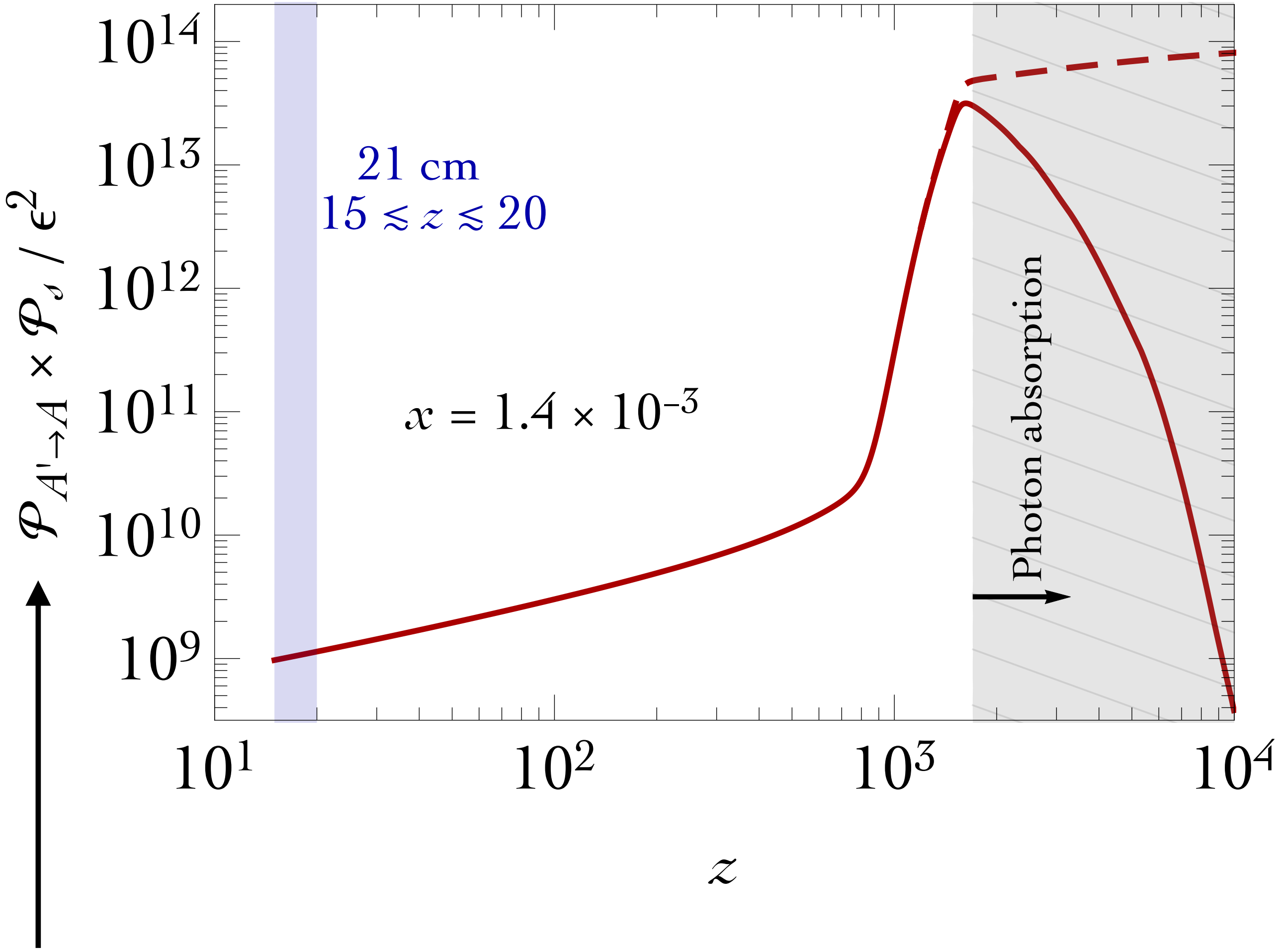
$$\Gamma_a = \frac{m_a^3}{64\pi f_a^2} = \frac{3\times 10^{-4}}{\tau_{\mathrm{U}}}\left(\frac{m_a}{10^{-4}\,\mathrm{eV}}\right)^3\left(\frac{100\,\mathrm{GeV}}{f_a}\right)^2$$

Dark photon - photon conversion



photon plasma freq.

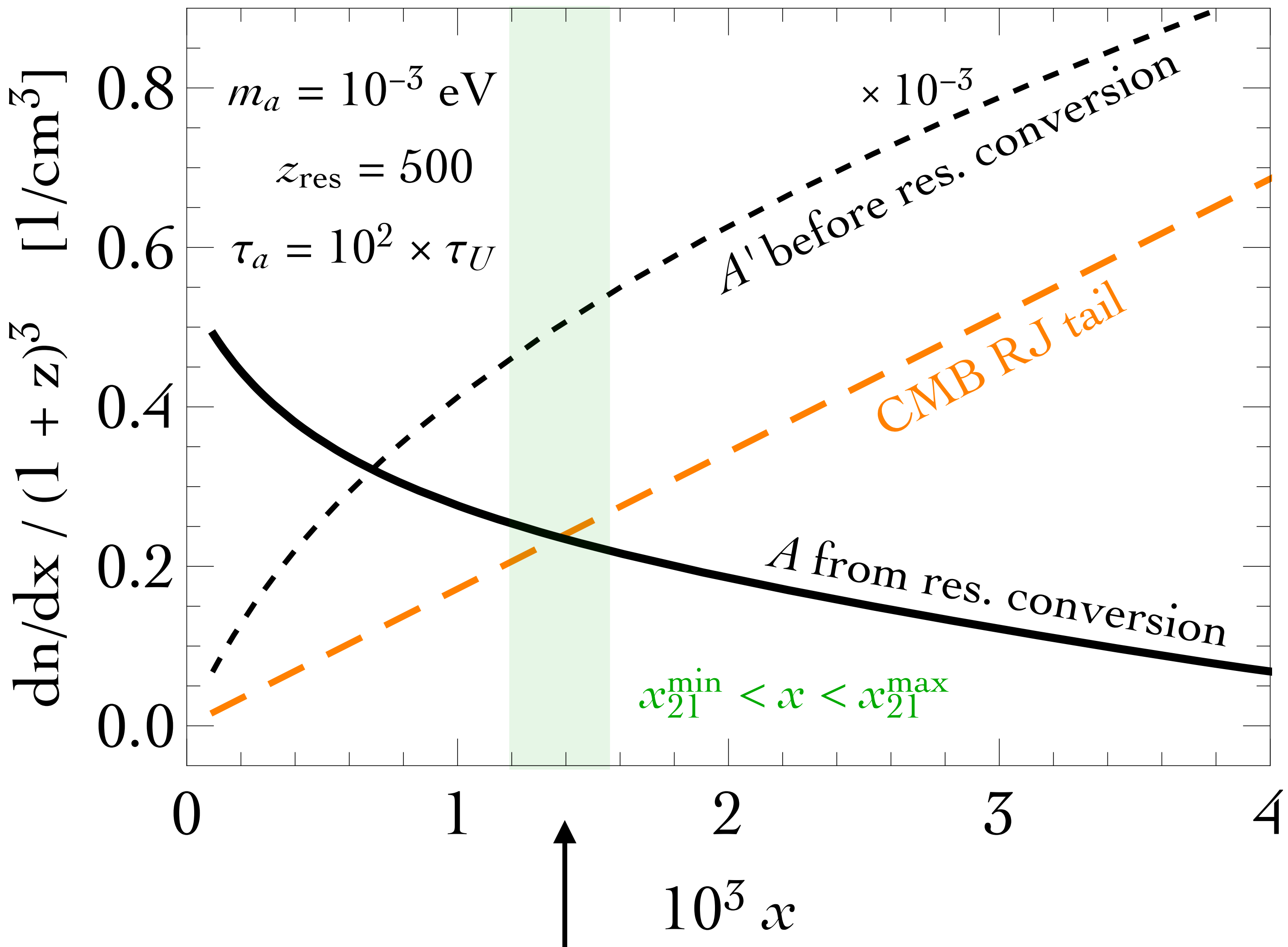
$$m_A(z) \simeq 1.7 \times 10^{-14}\mathrm{eV} \times (1+z)^{3/2} X_e^{1/2}(z)$$



transition probability

$$P_{A\to A'} = P_{A'\to A} = \frac{\pi \epsilon^2 m_{A'}^2}{\omega} \times \left| \frac{d\log m_A^2}{dt} \right|_{t=t_{\mathrm{res}}}^{-1}$$

(Dark) photon spectra and 21cm



$dn_{\rm A'}/d\omega$

$dn_{\rm CMB}/d\omega \simeq T_{\rm CMB}\omega/\pi^2$

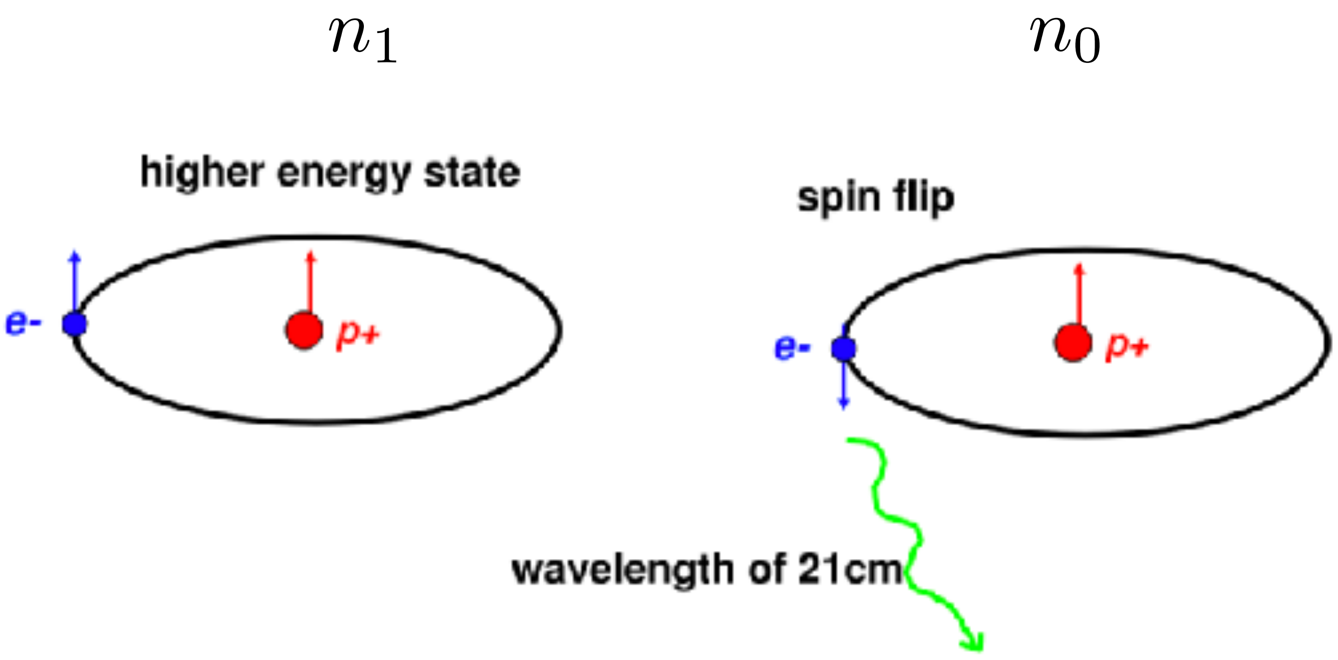
$x = \omega/T$

$dn_{\rm A}/d\omega$

21 cm

21cm and cosmic dawn

$$\frac{n_1}{n_0} = \frac{g_1}{g_0} \exp\left\{-\frac{T_\star}{T_s}\right\}$$



$$21\,\mathrm{cm} \quad \text{or} \quad 1.4\,\mathrm{GHz} \quad \text{or} \quad 6\,\mu\mathrm{eV}$$

$$\dot{n}_0 + 3Hn_0 = -n_0(C_{01} + B_{01}I_\nu) + n_1(C_{10} + A_{10} + B_{10}I_\nu)$$

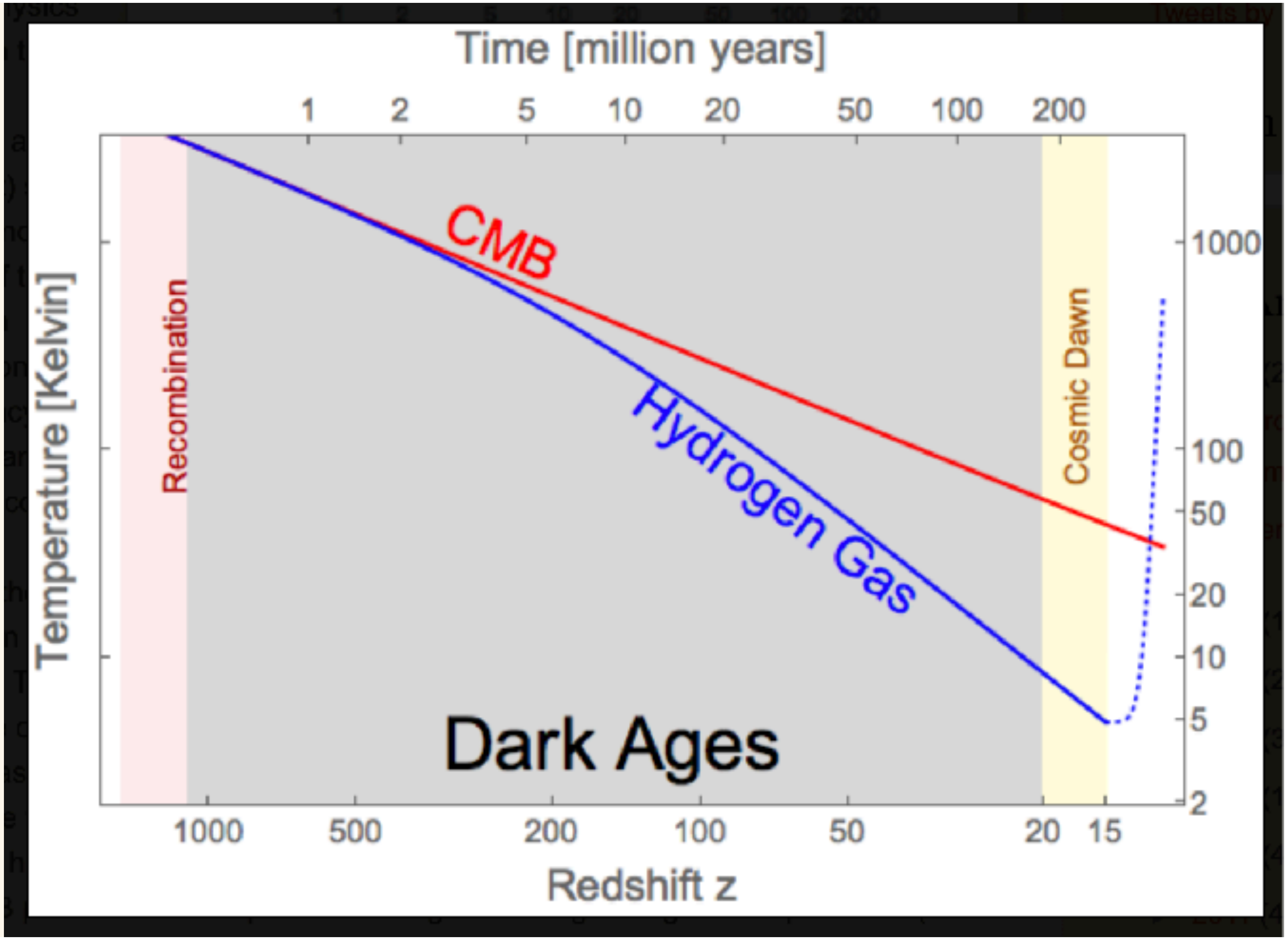
collisions

Einstein coefficients

number of photons with 21cm wavelength

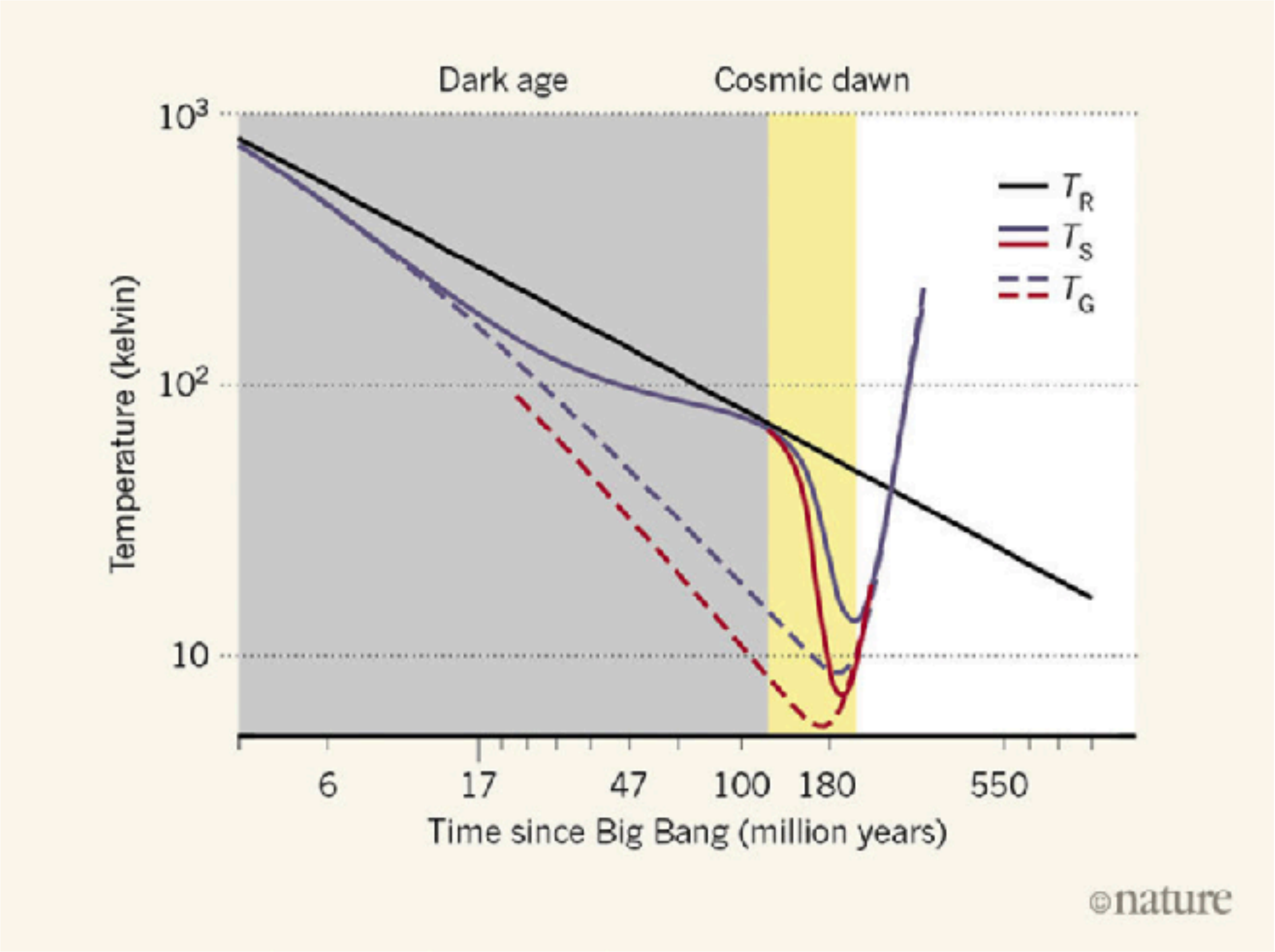
21cm and cosmic dawn

Evolution of CMB, gas, and spin temperature

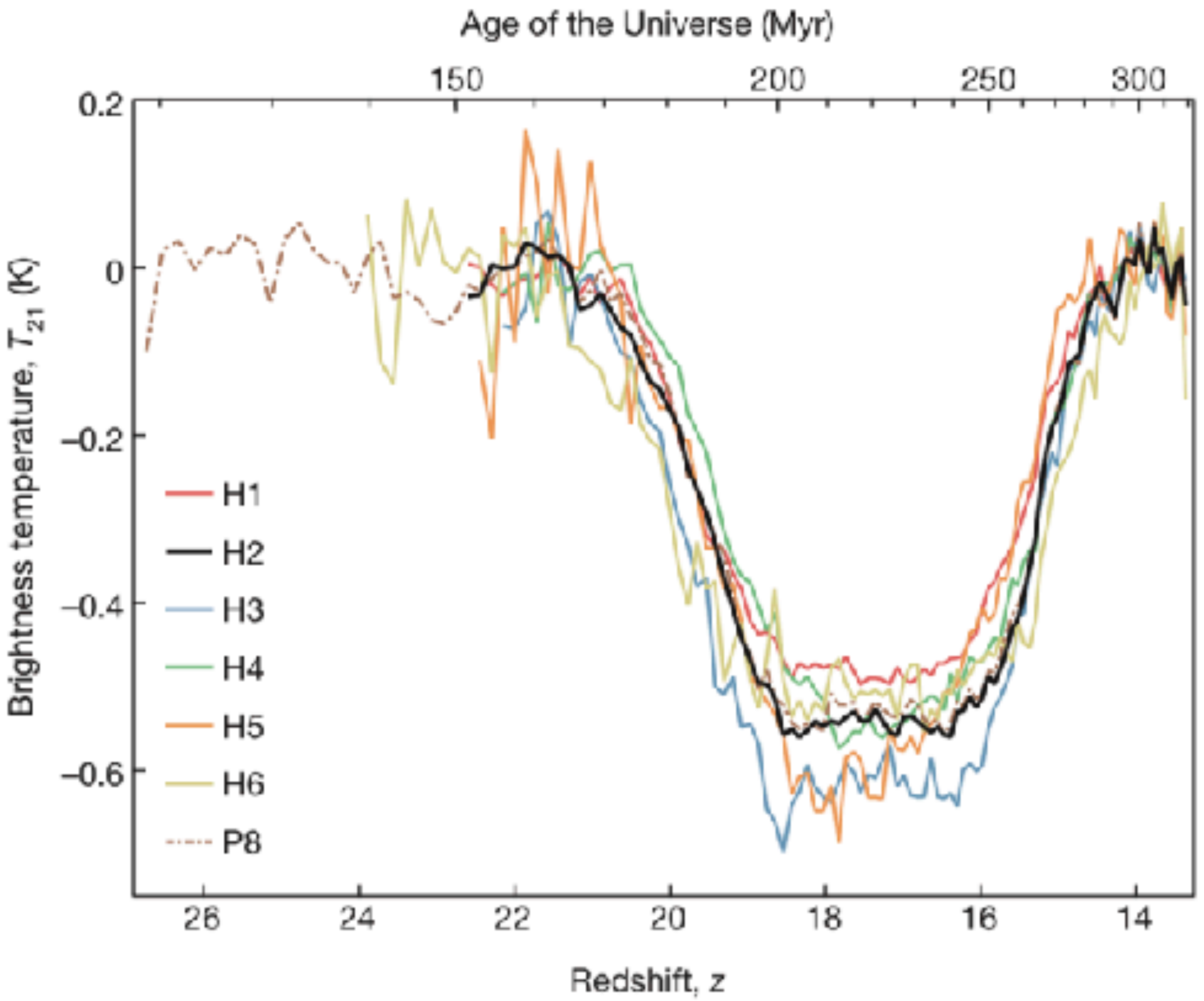


21cm and cosmic dawn

Evolution of CMB, gas, and spin temperature



EDGES result



What is measured in 21 cm astronomy is a brightness temperature

$$T_{21}(z) = \frac{\tau(T_s - T_{\rm r})}{1+z}$$

$$\simeq 23\,{\rm mK}\, x_H(z) \left[1 - \frac{T_r(z)}{T_s(z)}\right] \sqrt{\frac{1+z}{10}}$$

Zaldarriaga, Furlanetto, Hernquist 2004

=> EDGES collaboration has recently measured anomalously low value (3.8 sigma)

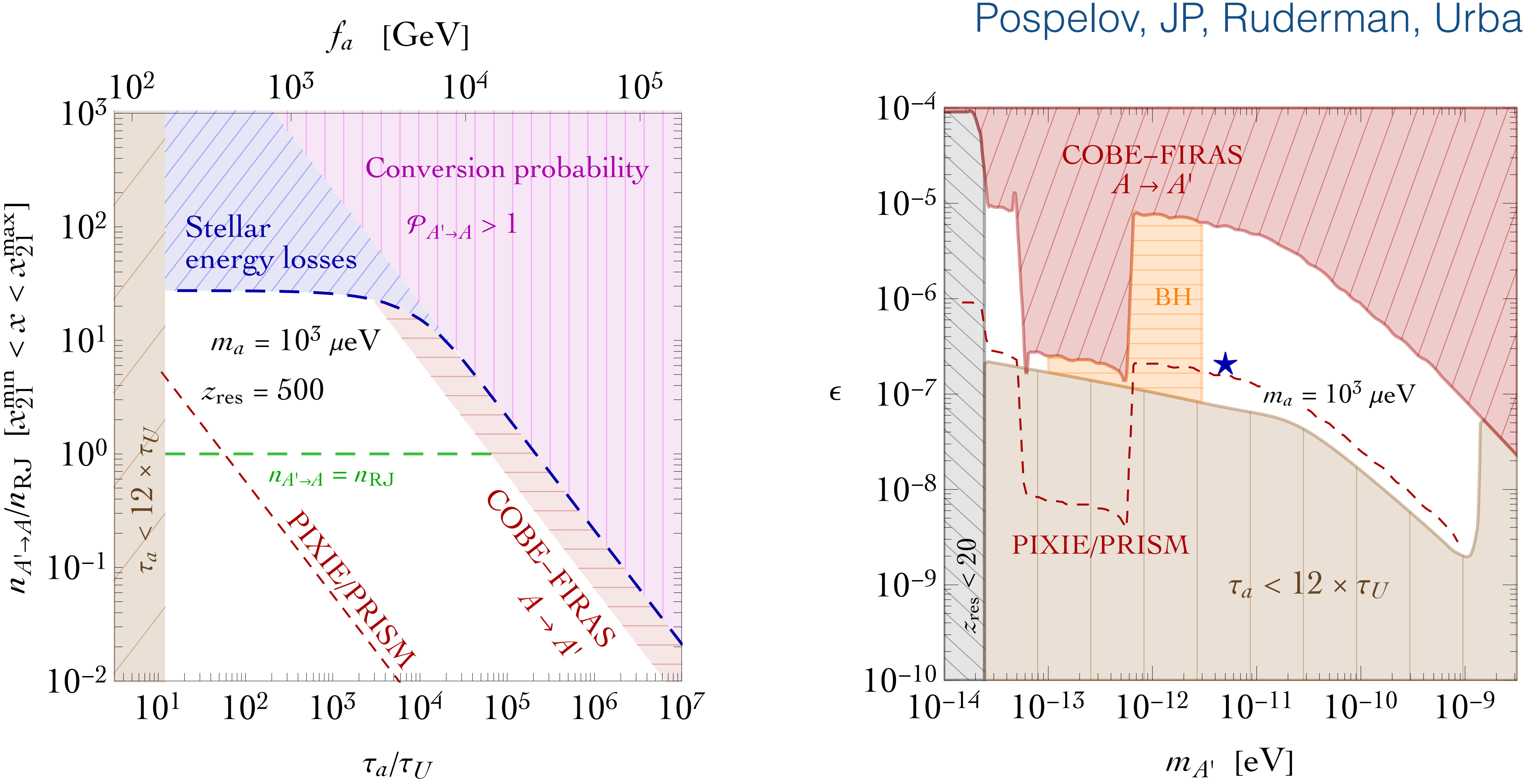
$$T_{21}(z \simeq 17) = -0.5K \quad (16 < z < 20)$$

Bowman et al 2018

EDGES result can be explained easily ($n_A \sim n_{RJ}$ is required)

Example: progenitor $m_a = 10^{-3}\,\mathrm{eV}$

Pospelov, JP, Ruderman, Urbano 2018



More generally, independently if EDGES result persists, 21 cm astronomy will be sensitive probe of non-standard soft photon population sourced by DM.

Signatures of DM (well) below the GeV-scale

1

Absorption

Bosonic DM with mass above 12 eV is probed in current LXE experiments; lower masses to be probed in systems with “smaller gaps”

2

Scattering

Kinematic no-go theorems are avoided

- for sub-GeV DM scattering on nuclei by considering inelastic channel of photon and electron emission
- for sub-MeV DM scattering on electrons use reflected DM flux from the sun

3

Decay

Non-gravitational signatures of dark radiation as a decay product is probed in direct detection when energy is in the 30 MeV ballpark scattering on nuclei and in 21 cm cosmology through resonant conversion of very low energetic radiation