# Novel decay and scattering signatures of light dark matter

**Josef Pradler**

ÖAW AUSTRIAN ACADEMY OF SCIENCES

HEPHY INSTITUTE OF HIGH ENERGY PHYSICS

PLANCK 2018
Bonn, May 25 2018

# Signatures of DM below and well below the GeV-scale

1 **Decay**

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

Pospelov, JP, Ruderman, Urbano 2018

Cui, Pospelov, JP PRD 2018

2 **Scattering**

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

Kouvaris, JP PRL 2017

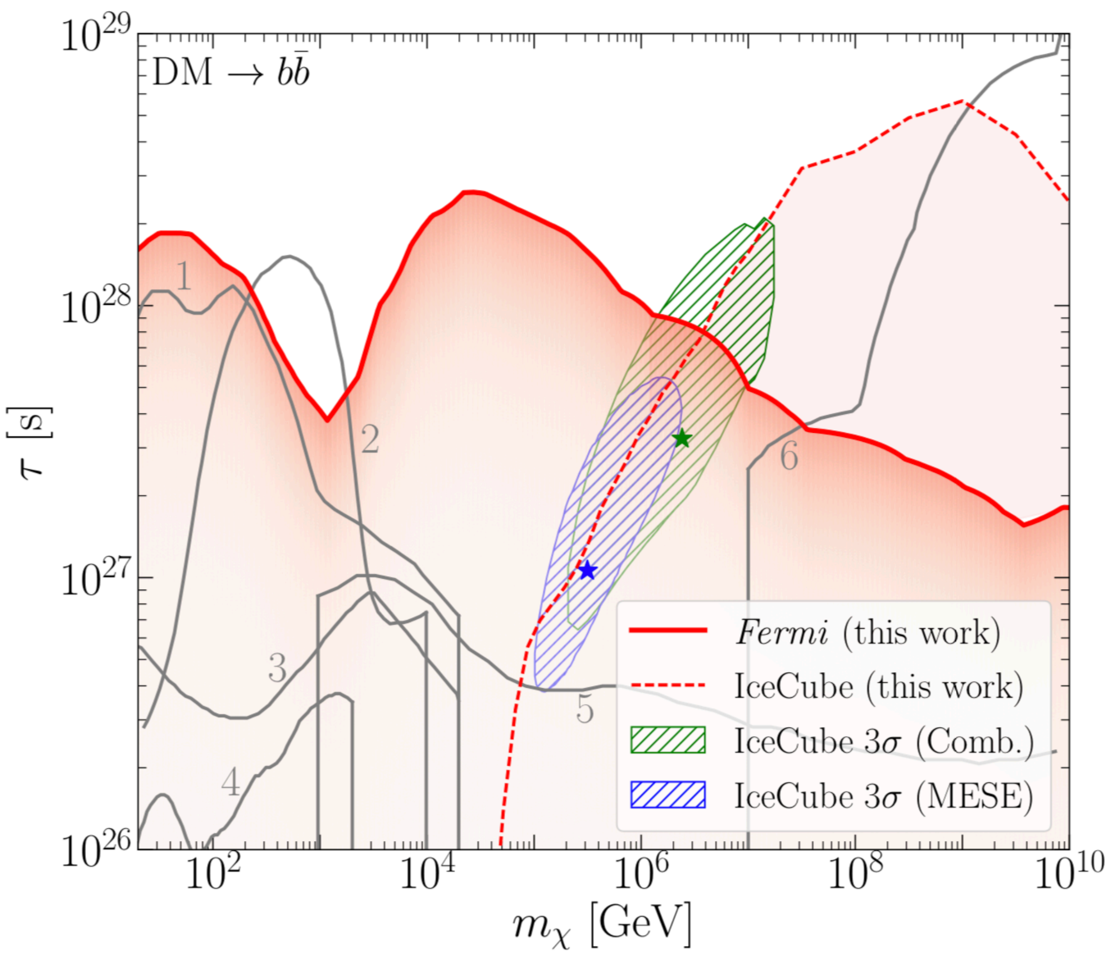
An, Pospelov, JP, Ritz PRL 2018

# 1 DM decay

# DM decay into visible states

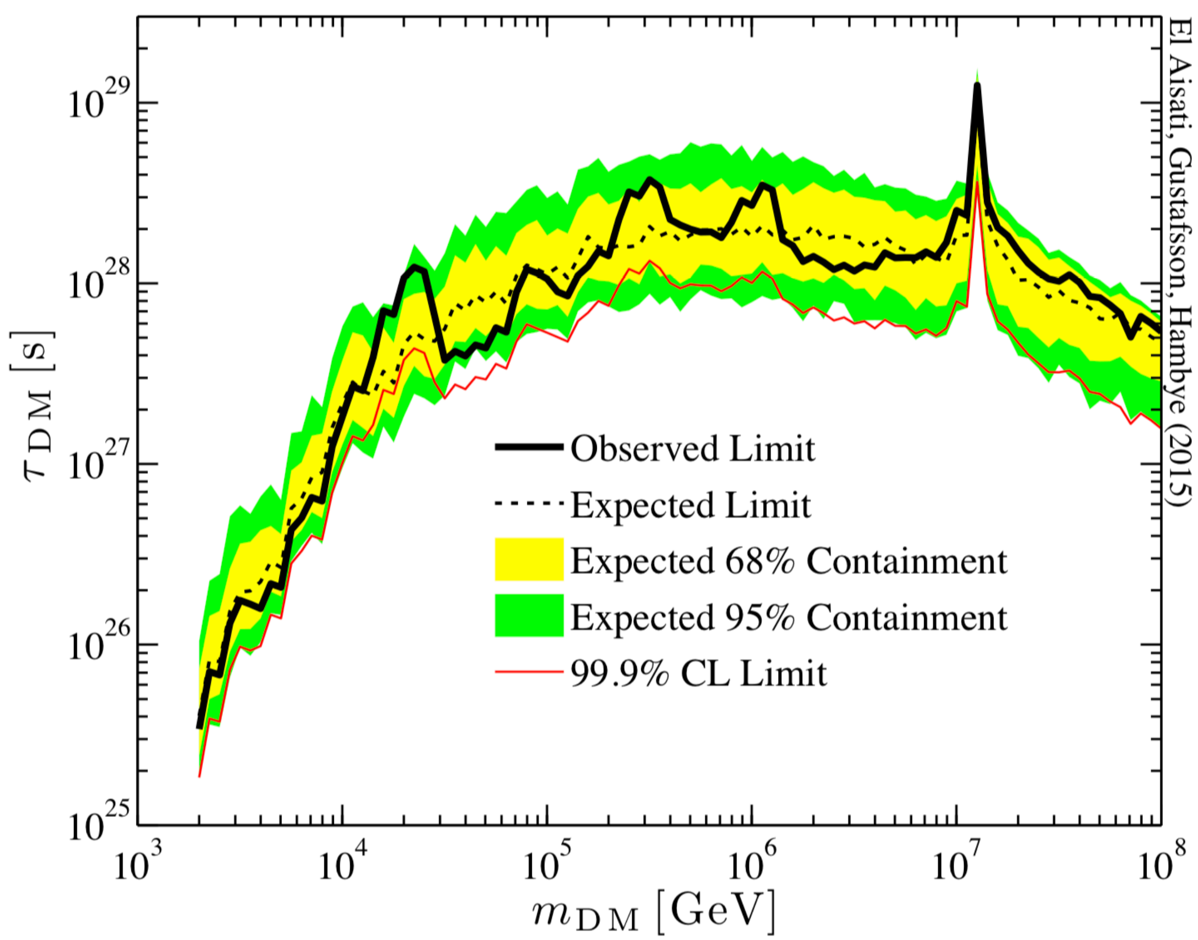
Indirect detection searches require the lifetime of **WIMP-DM** to exceed the age of universe by a large factor, ($10^9$ - $10^{11}$) $t_0$, through visible decay products

gamma-rays




Cohen et al PRL 2016

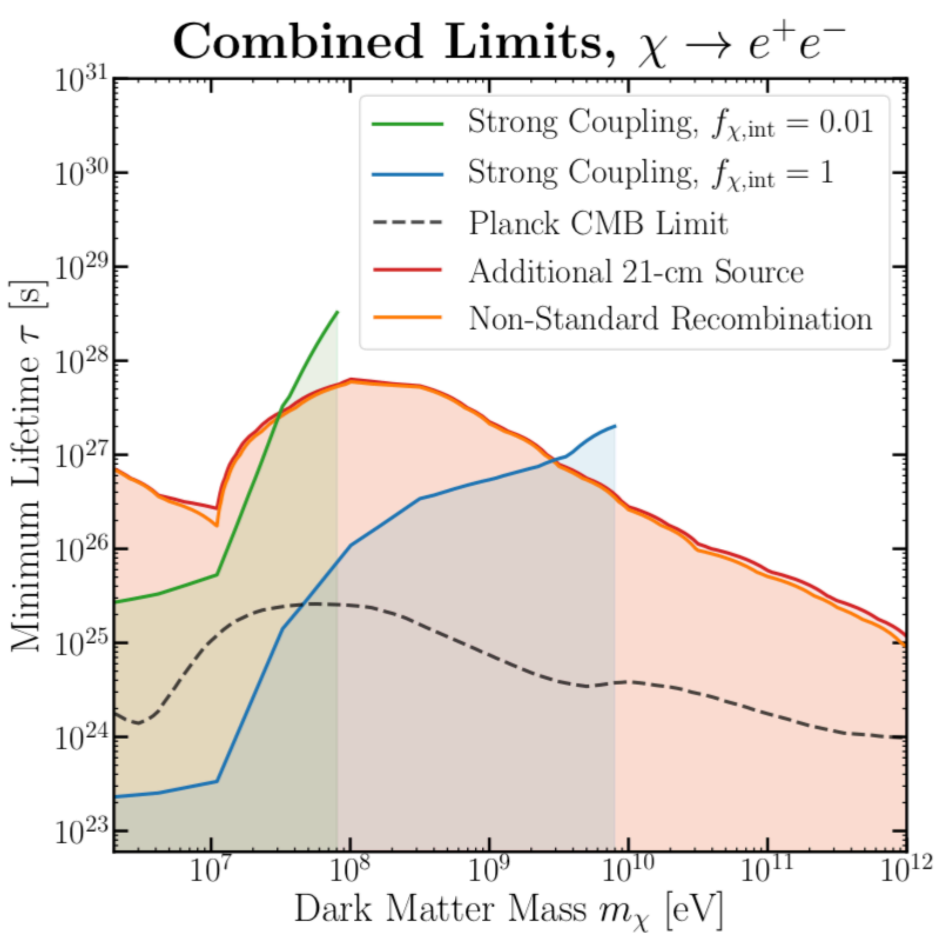
neutrinos

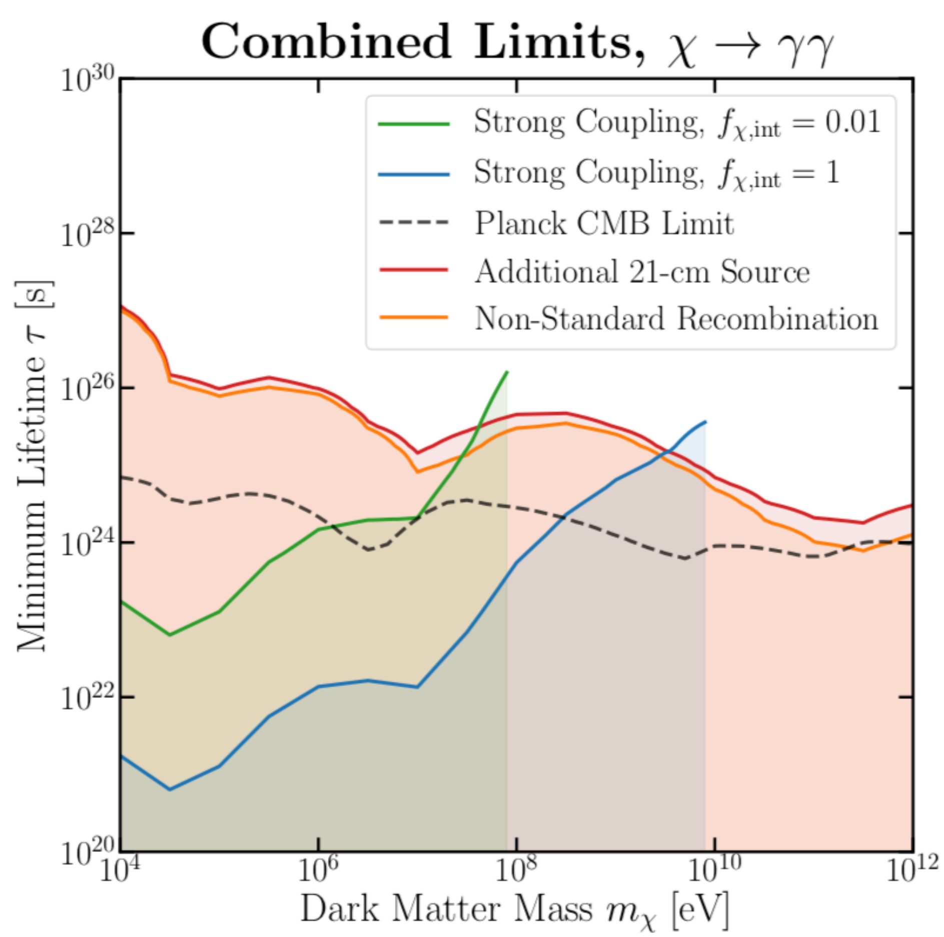



El Aisati, Gustafsson, Hambye PRD 2015

# DM decay into visible states

Since recently, 21cm astronomy (tentatively) requires the lifetime of **sub-GeV DM** to exceed the age of universe by a large factor, $(10^9 - 10^{11})\ t_0$




Liu, Slatyer 2018

see also Clark et al 2018; Mitridate, Podo 2018

# DM decay into *dark states?*

Consider, e.g. DM decay $X \to \chi\bar{\chi}$

**Direct** sensitivity through branching fractions into SM states strongly depend on the details of the model, e.g.

=> $X \to \chi\bar{\chi}e^+e^-$ decay is highly suppressed

$$\mathrm{Br}_{X\to\chi\bar{\chi}e^+e^-} \leq 10^{-3} G_\chi^2 m_X^4 \sim 10^{-13} \quad (m_X = 1\,\mathrm{GeV},\, G_\chi = G_F)$$

Our Universe has the chance to be permeated by **dark radiation** that is sourced by DM decay (or annihilation) at low redshift. What are the direct tests for it?

??

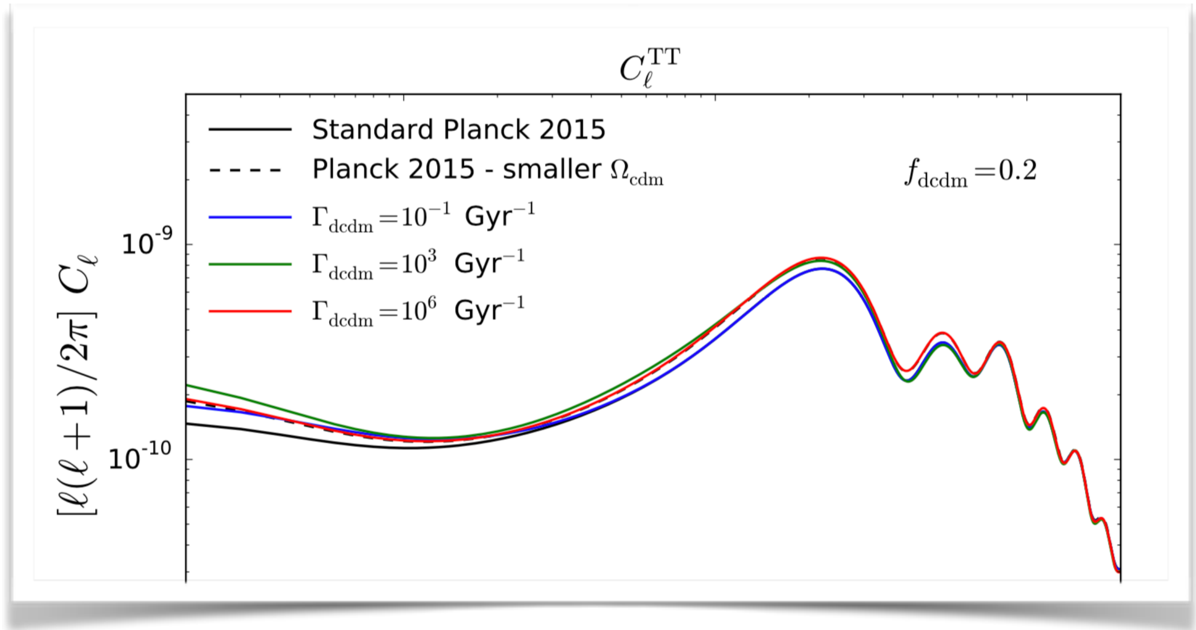
# DM decay into *dark states?*

Cosmology remains a sensitive probe of DM decays, irrespective of DM mass and interaction, but through gravity.

CMB (late-time ISW) and lensing constrains

$$f_{\rm dm} < \text{few}\,\% \qquad (\tau_{\rm dm} < \tau_U)$$
$$f_{\rm dm}/\tau_{\rm dm} \lesssim 1/12\tau_U \qquad (\tau_{\rm dm} > \tau_U)$$

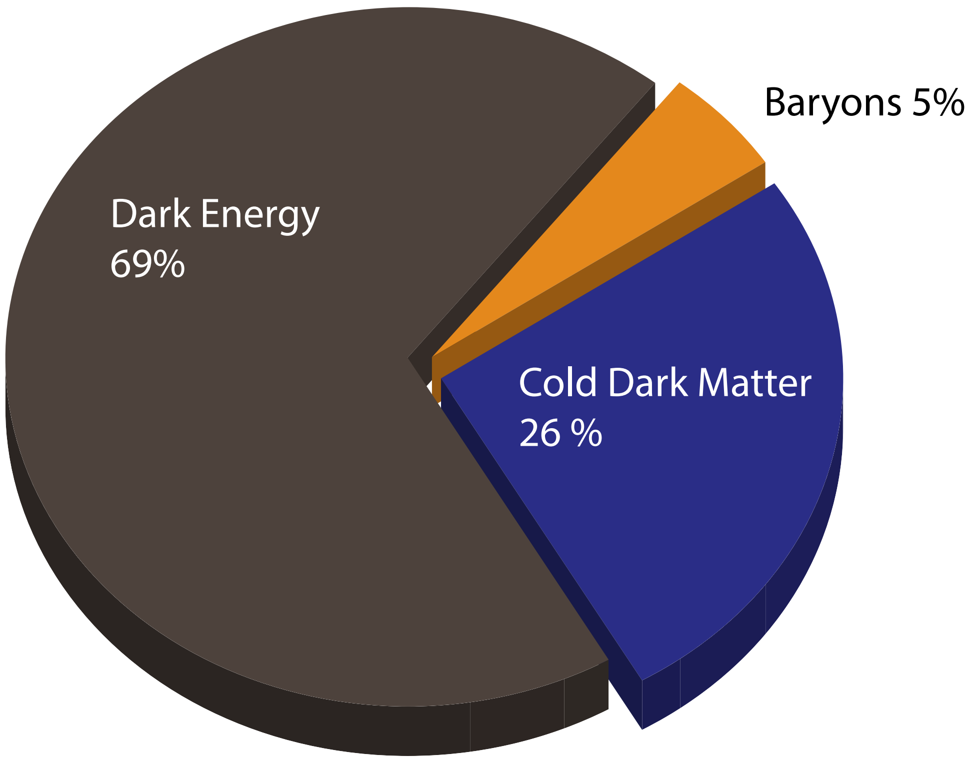
Poulin, Serpico, Lesgourges 2016
see also Berezhiani, Dolgov, Tkachev 2015




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

e.g. Wang, Peter at al. 2014

# Signatures of late dark radiation



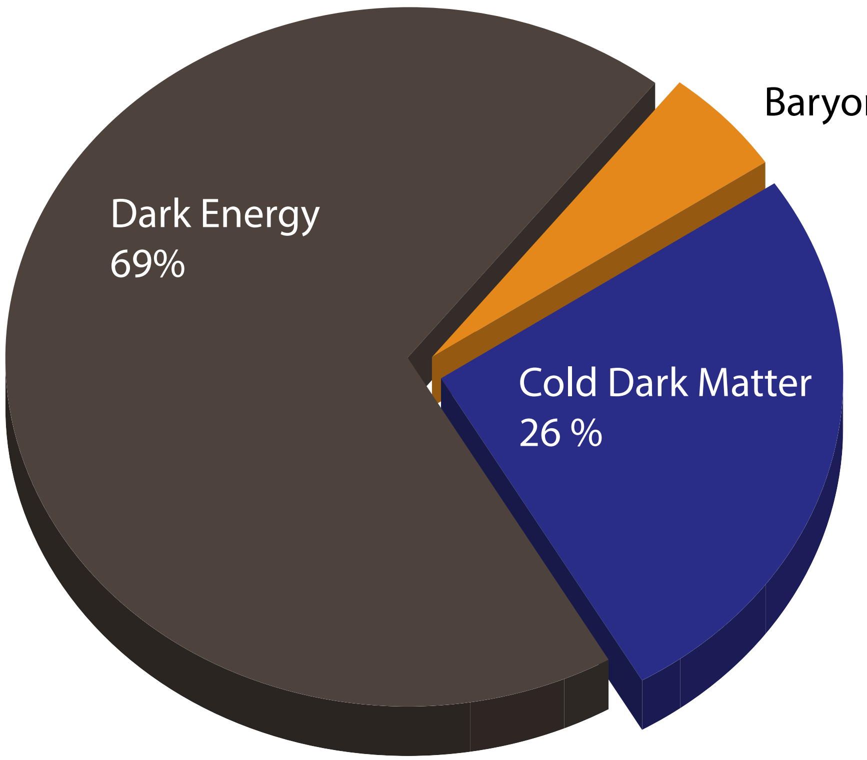

**CMB**

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

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

Planck 2015

# Signatures of late dark radiation




**CMB**

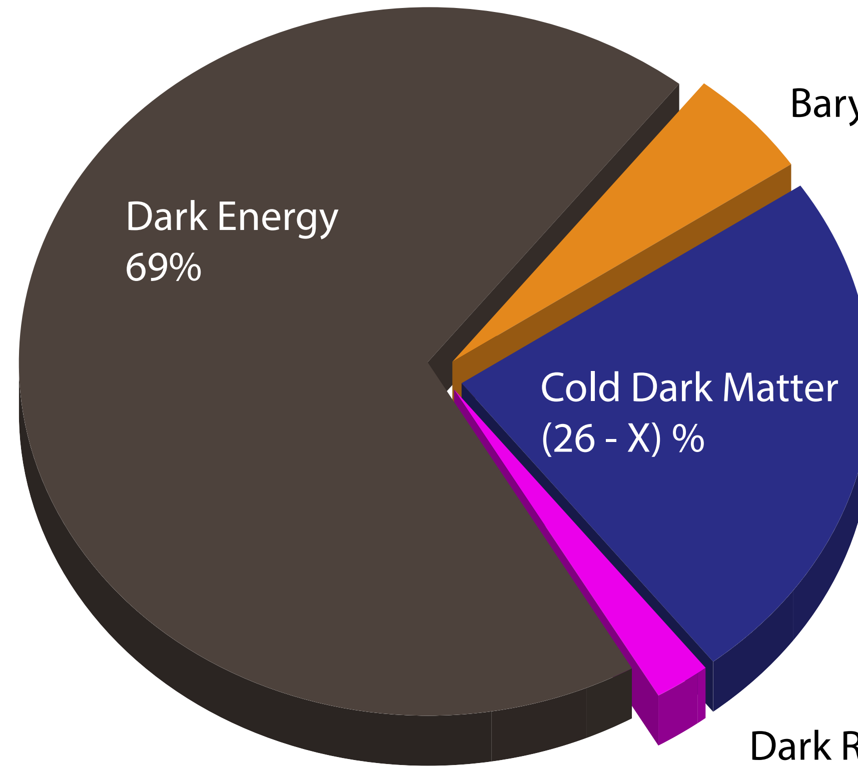
$$N_{\rm eff} = 3.04 \pm 0.33$$

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

Planck 2015

=>

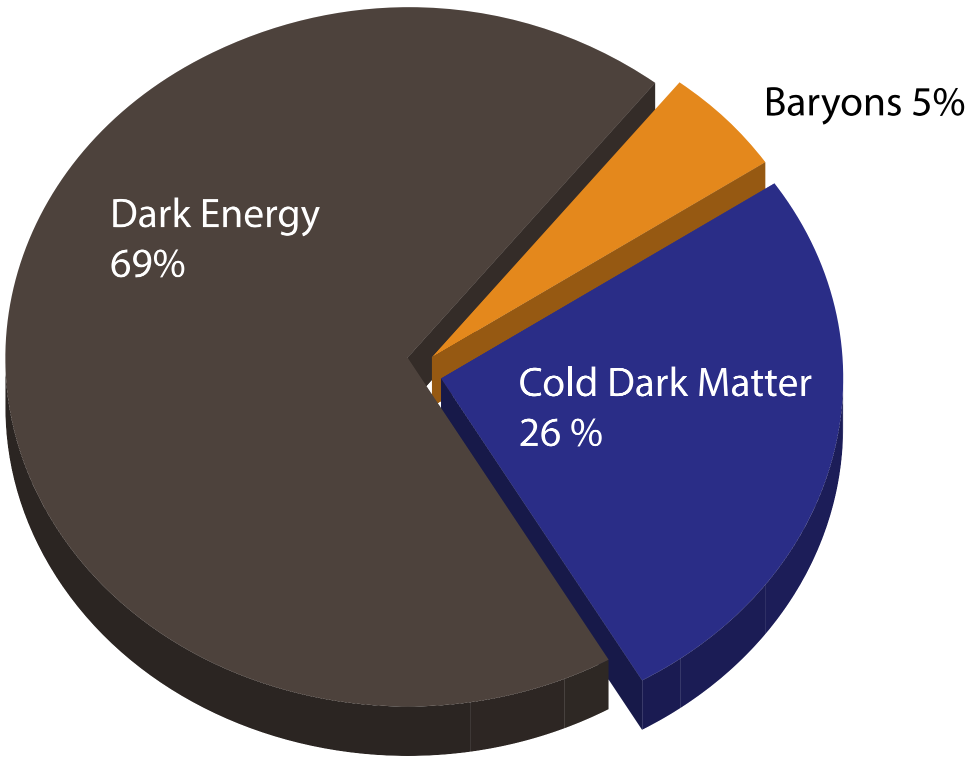
$$\tau_{\rm DM} \gtrsim t_0$$



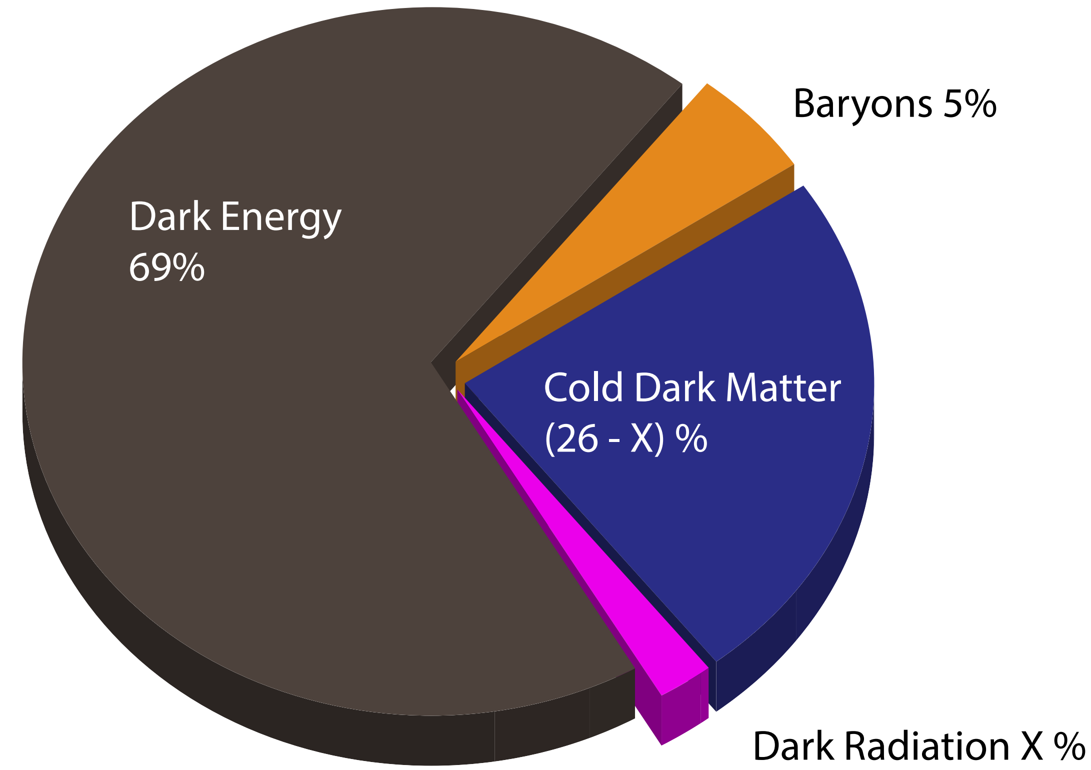

**Low redshift Universe**

# Signatures of late dark radiation

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




=>




**CMB**

**Low redshift Universe**

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

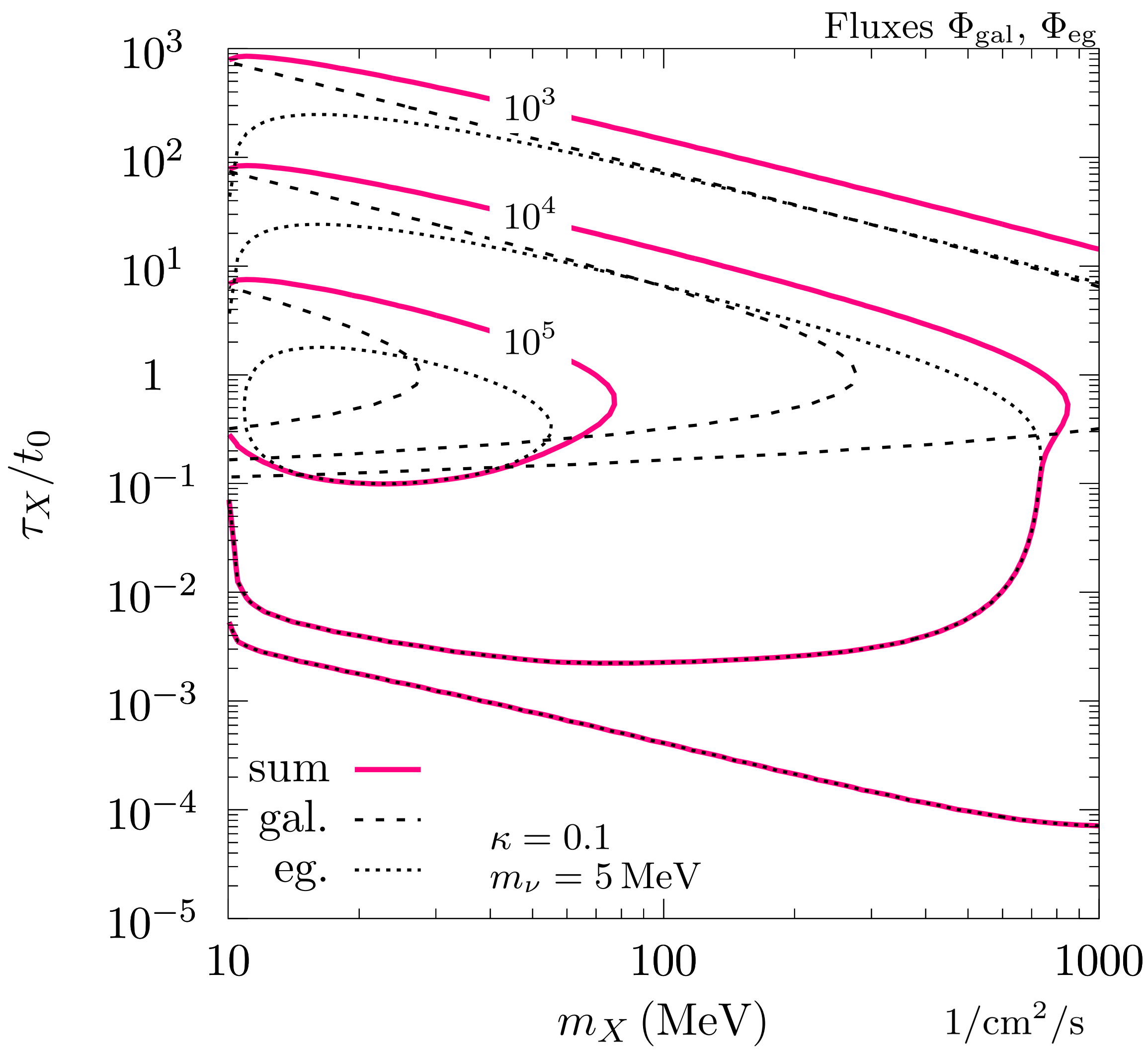
$$\Rightarrow \quad \rho_{\rm DR}/\rho_\gamma < 0.15$$

Planck 2015

**1a**

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

# 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 $\phi \to \nu\nu \; (\bar{\nu}\bar{\nu})$

$\Phi$ breaks global lepton number, Goldstone mode is $\phi$

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

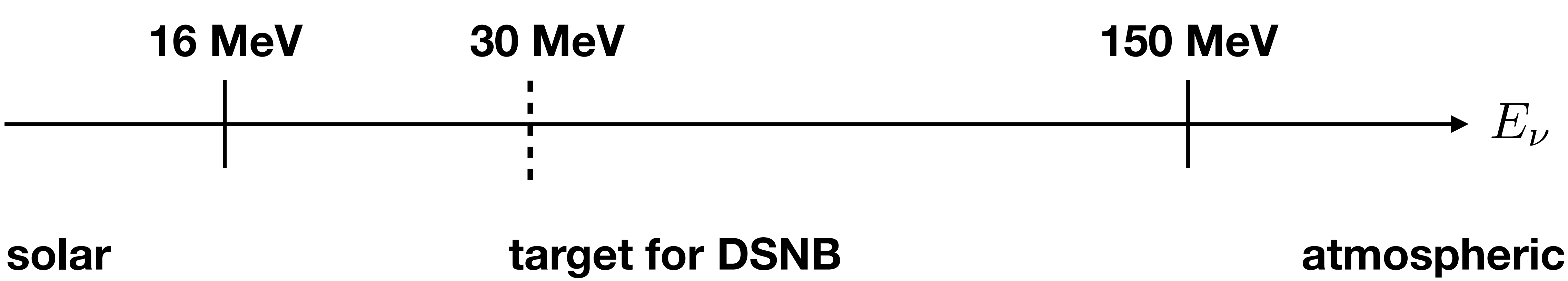
Chikashige, Mohapatra, Peccei 1981

Mass of $\phi$ 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



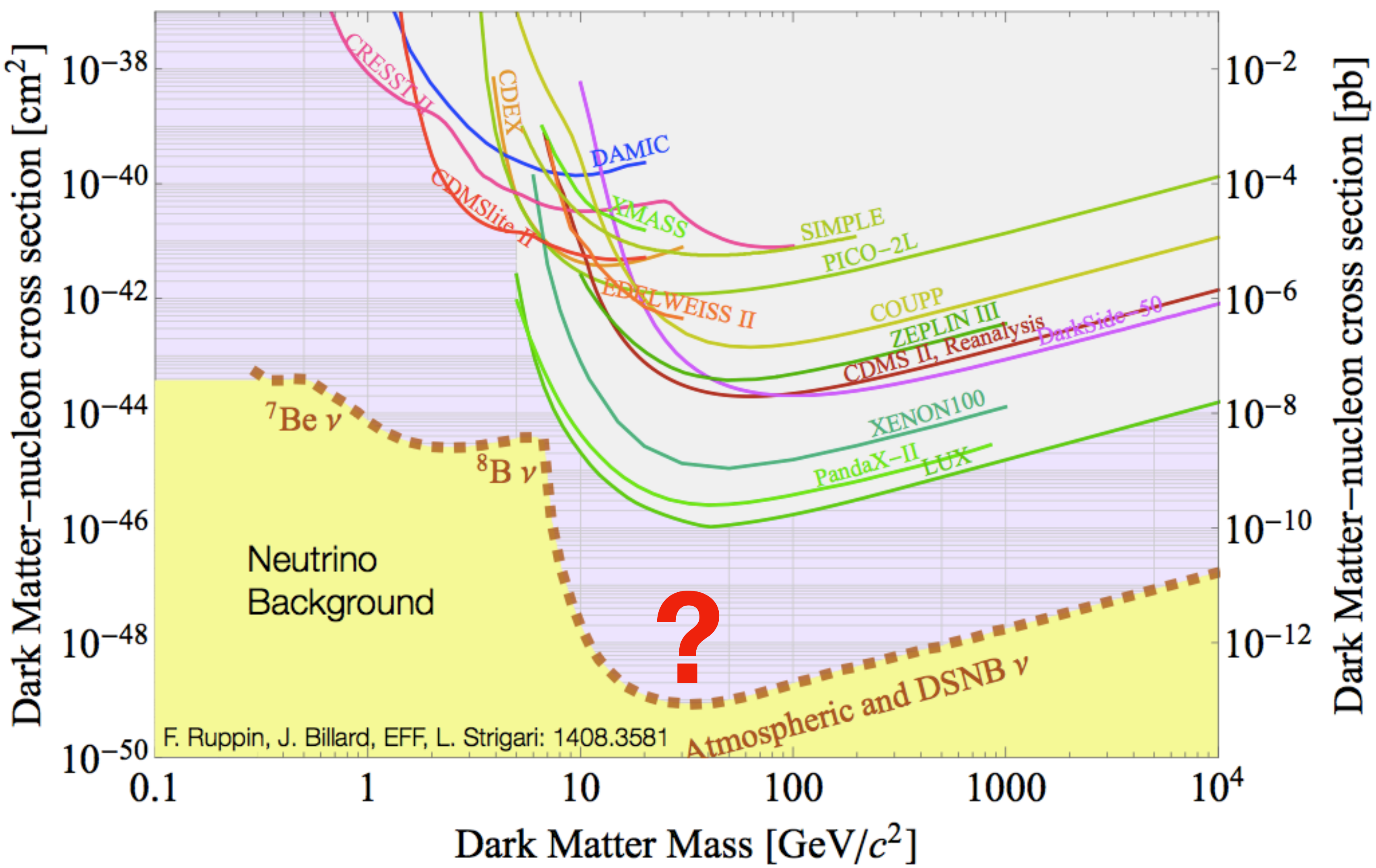
# Late Dark Radiation *in SM neutrinos*

**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.

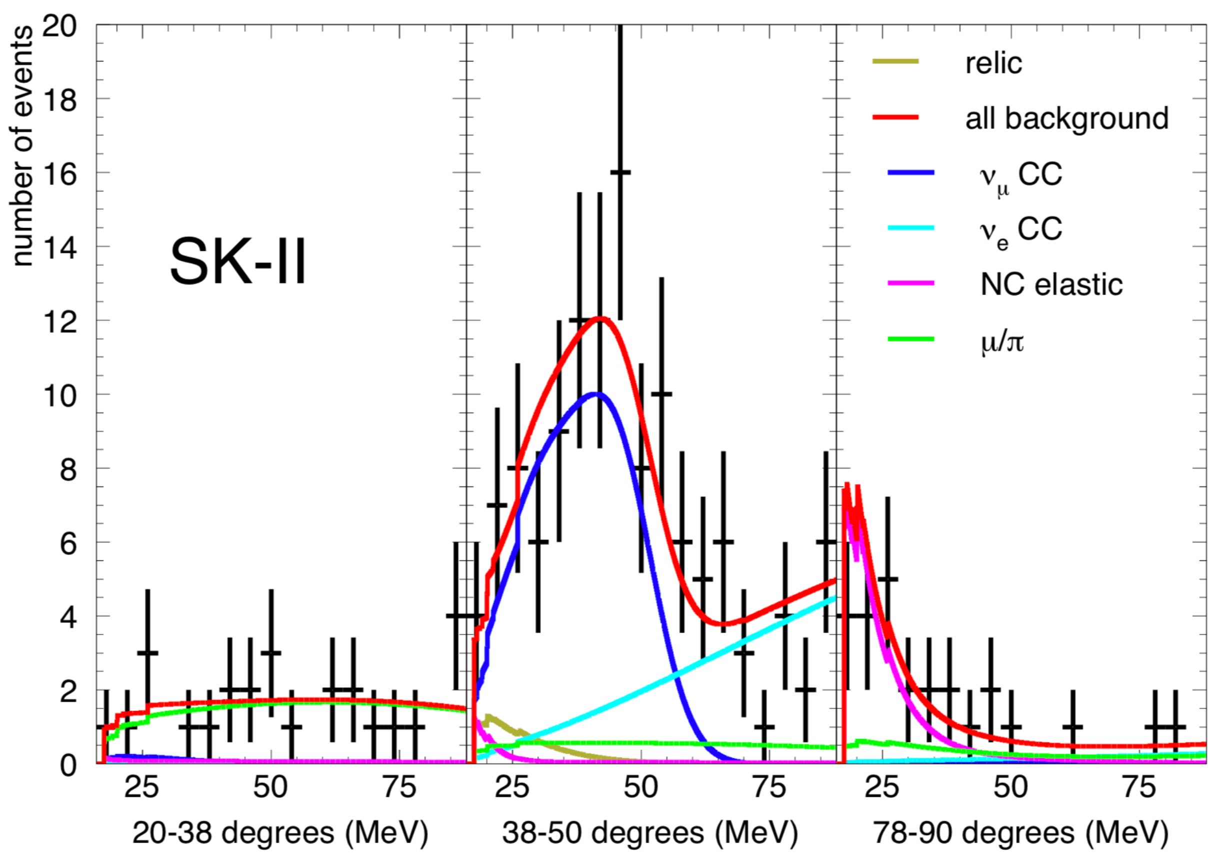
Neutrino floor can be raised in models that inject $\nu$ but not excessively $\bar{\nu}$



# Late Dark Radiation *in SM neutrinos*

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

Super-K collaboration 2011

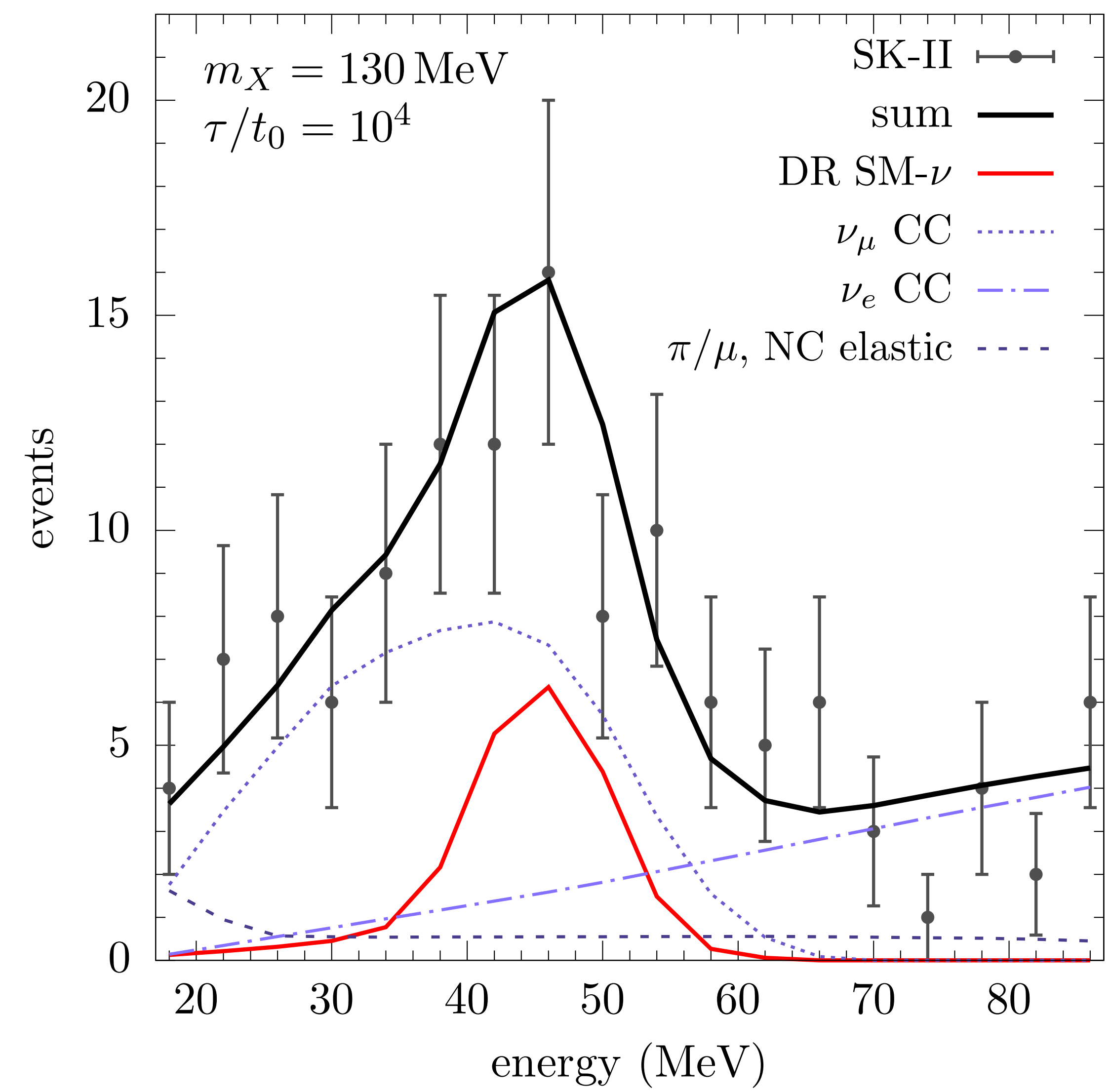



sideband

search-region
with fitted bkg.

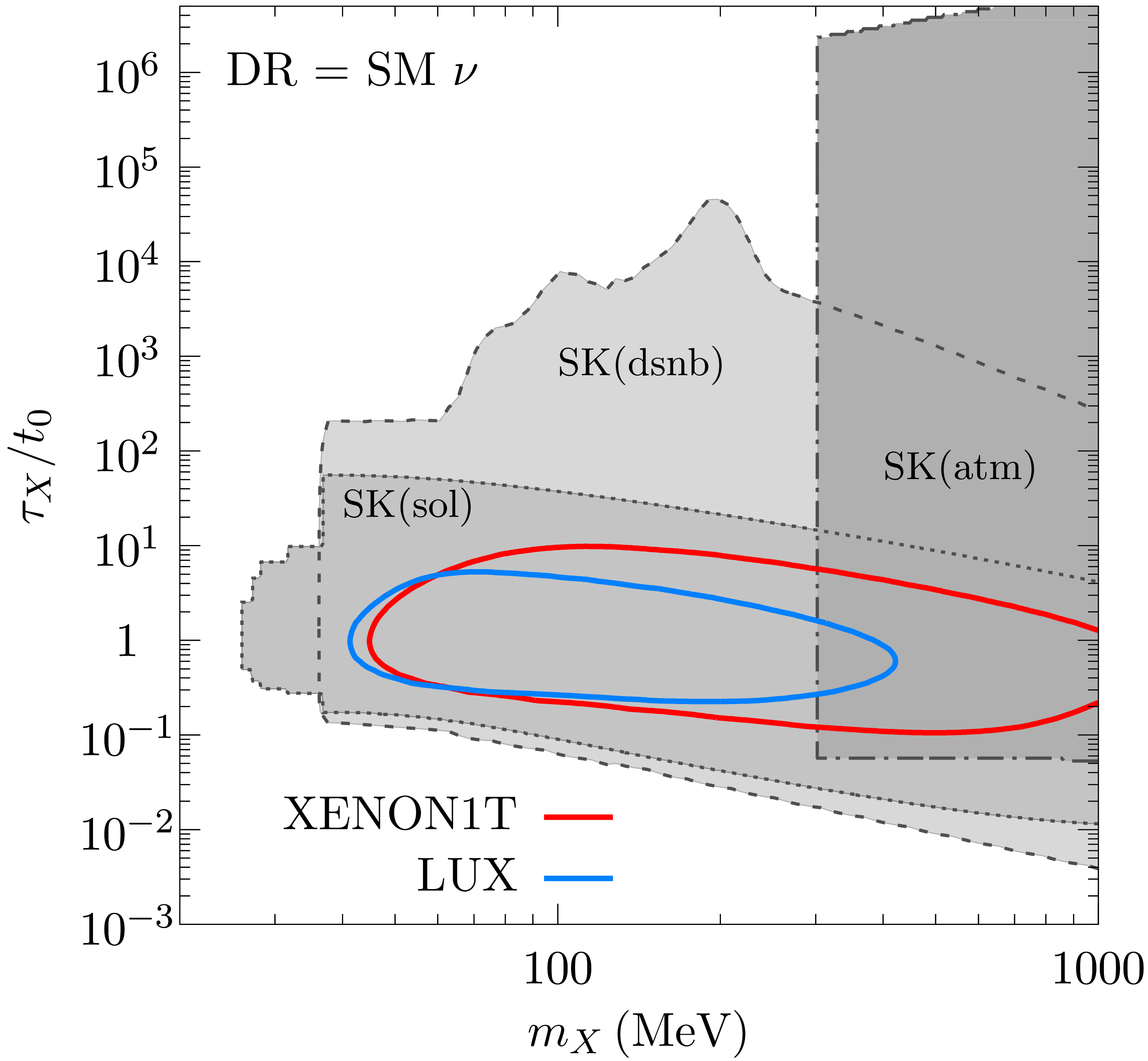
sideband

=>




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

# Late DR in SM neutrinos




**Option 1**

DR in SM neutrinos $\nu$

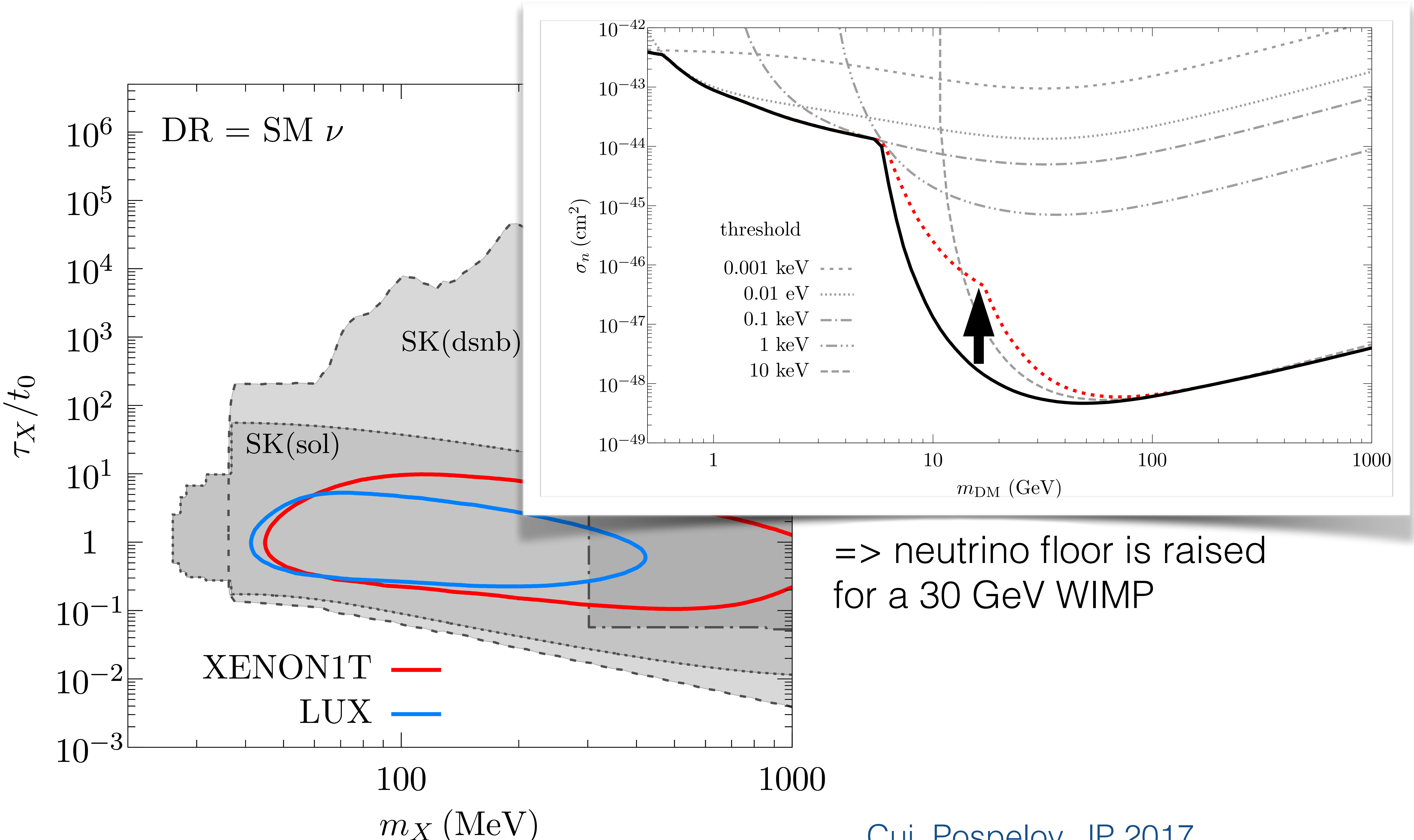
=> if flux is saturated then neutrino floor ~2 orders of magnitude away from current direct detection sensitivity

=> neutrino floor is raised for a 30 GeV WIMP

Cui, Pospelov, JP 2017

# Late DR in SM neutrinos

[Nikolic, JP in prep]




=> neutrino floor is raised for a 30 GeV WIMP

Cui, Pospelov, JP 2017

# 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,

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

NB: $\chi$ can be a sterile neutrino mixing with $\nu$, recovering Option 1

**Option 2.1:** $\chi$ boson => *absorption signals*

standard cases include $\chi$ 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,

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

NB: $\chi$ can be a sterile neutrino mixing with $\nu$, recovering Option 1

**Option 2.2:** $\chi$ fermion => *scattering signals*

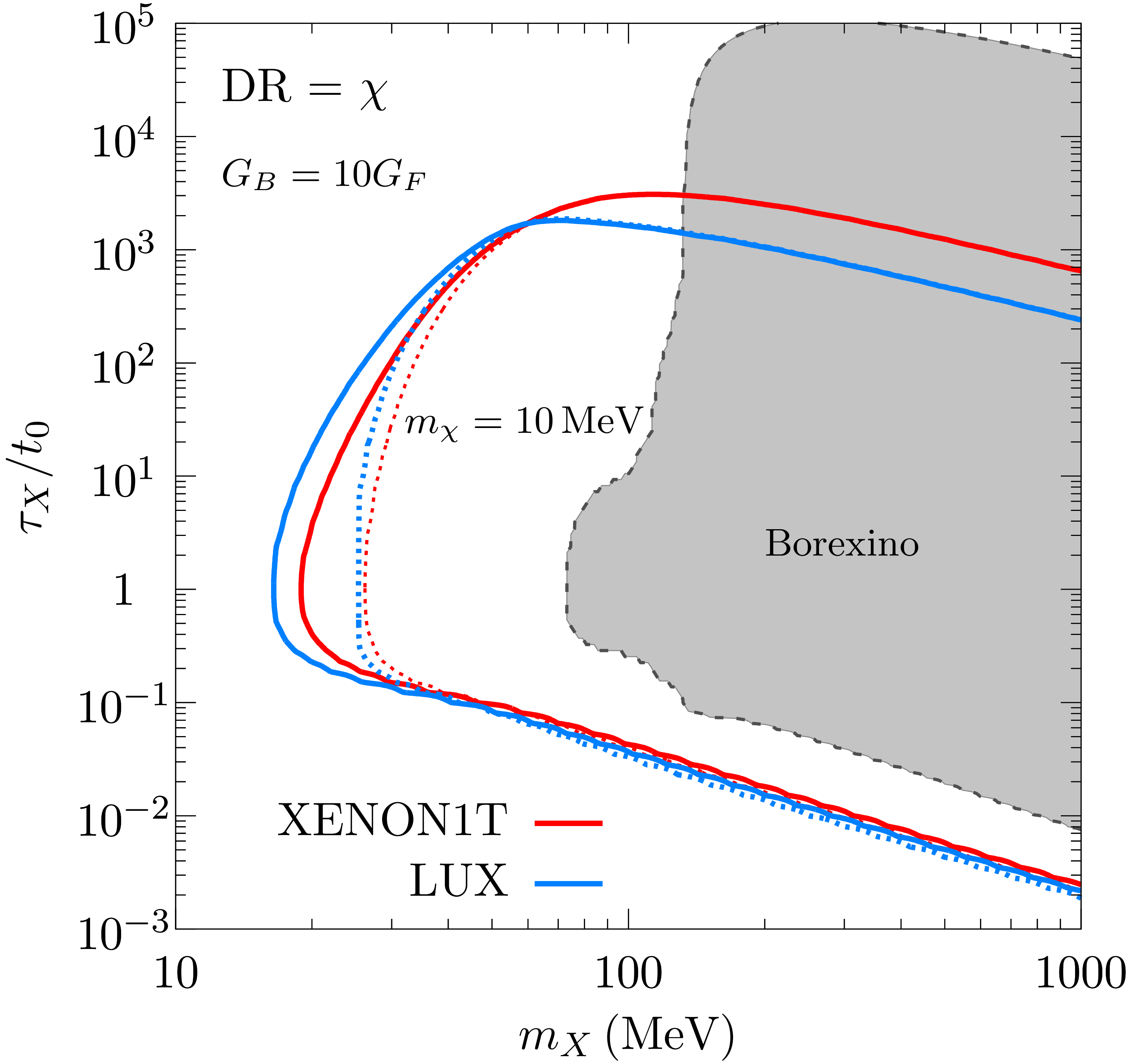
E.g. well motivated and studied case:

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

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

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

# Late DR in a new species




**Option 2**

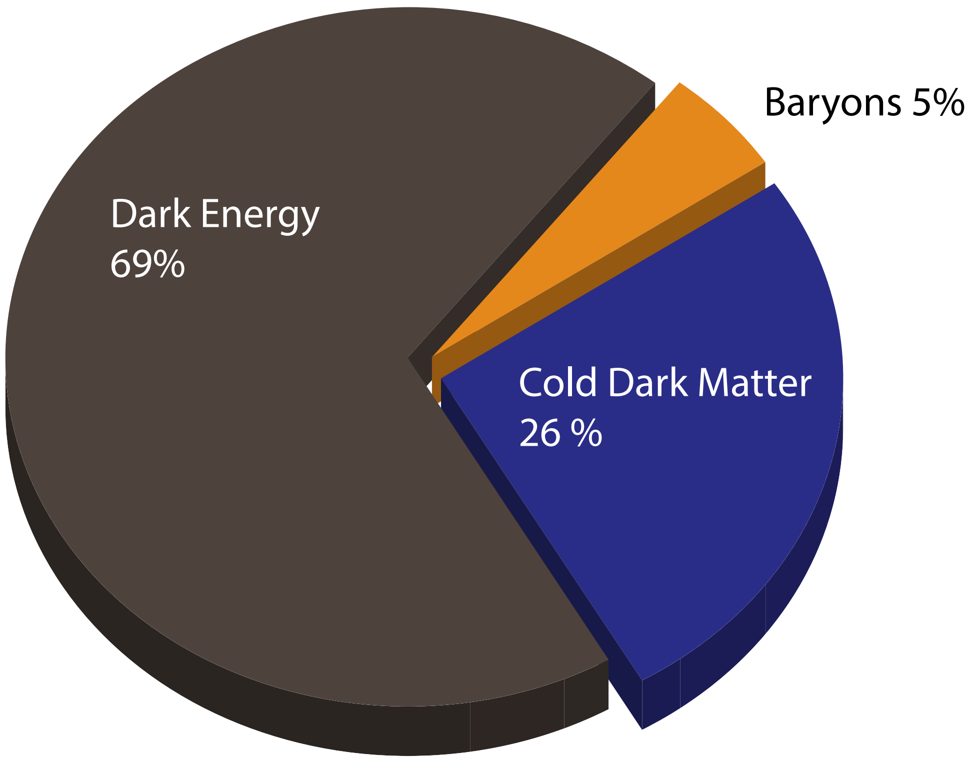
new neutrino interacting with baryonic current

Borexino limit derived from elastic scattering on protons

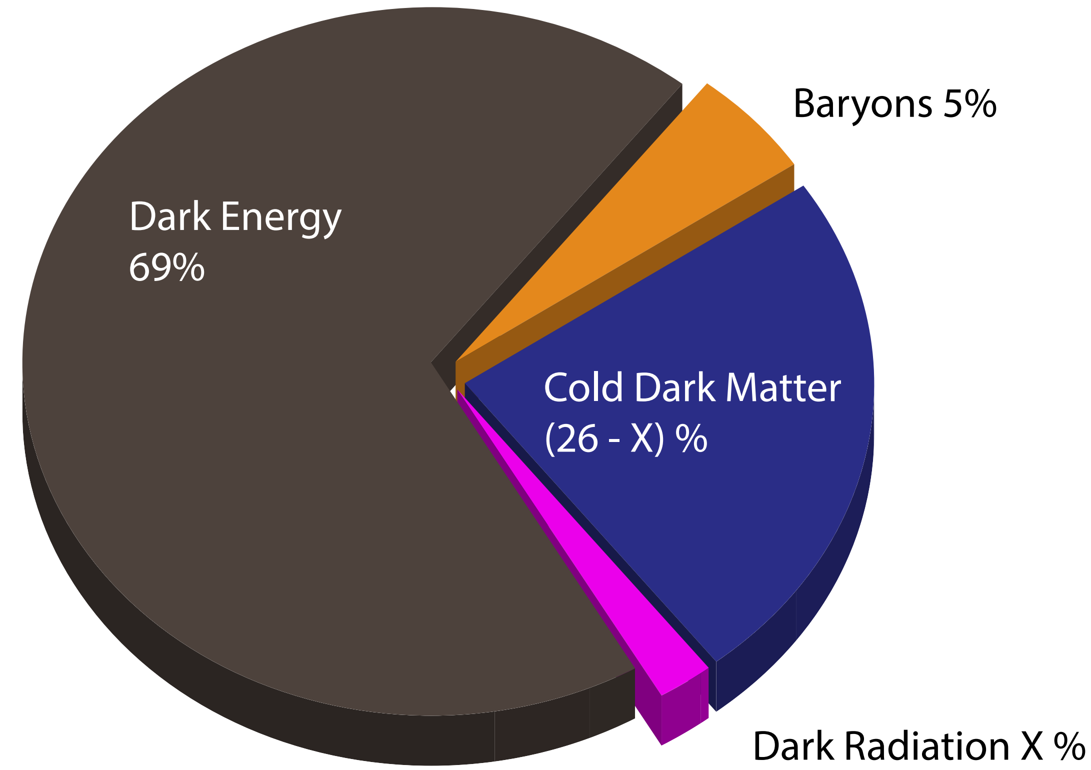
Cui, Pospelov, JP 2017

# Signatures of late dark radiation

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




=>




**CMB**

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

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

Planck 2015

**Low redshift Universe**

**1b**

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

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

# 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 constituents
- Axions with effective dimension 5 interactions with fermions and gauge bosons.

=> This type of dark radiation (DR) very difficult to see directly

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

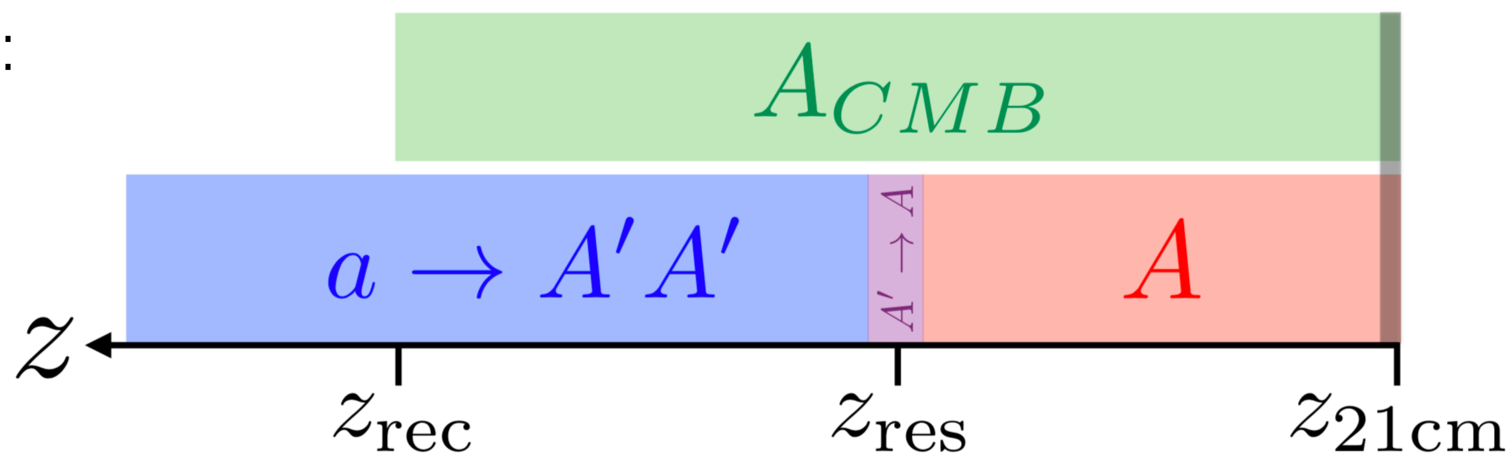
$$n_{\rm RJ} = \frac{1}{\pi^2}\int_0^{\omega_{\rm max}} \frac{\omega^2 d\omega}{\exp[\omega/T]-1} \simeq \frac{T\omega_{\rm max}^2}{2\pi^2} \simeq 0.21\, x_{\rm max}^2\, n_{\rm CMB} \qquad x = \omega/T$$

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

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

# Modification of the RJ tail of the CMB

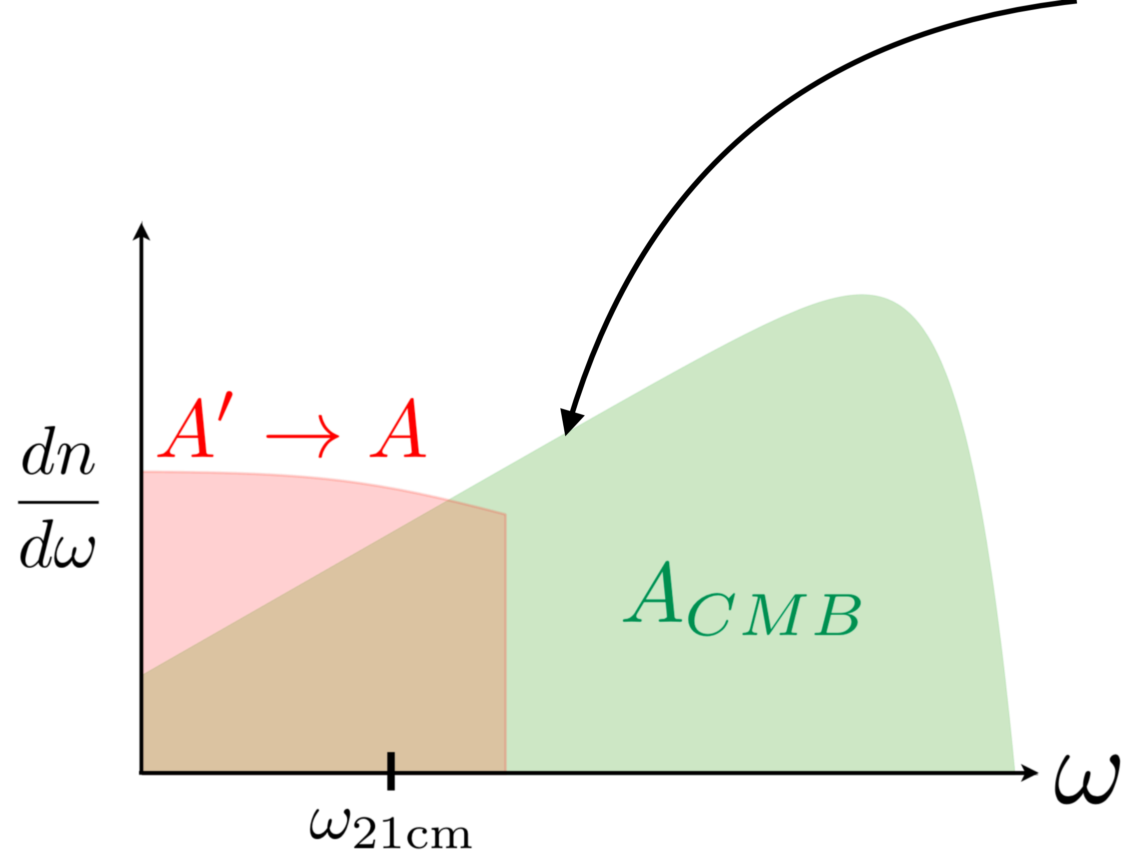
Main idea:




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

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

**=> will change 21 cm cosmo**

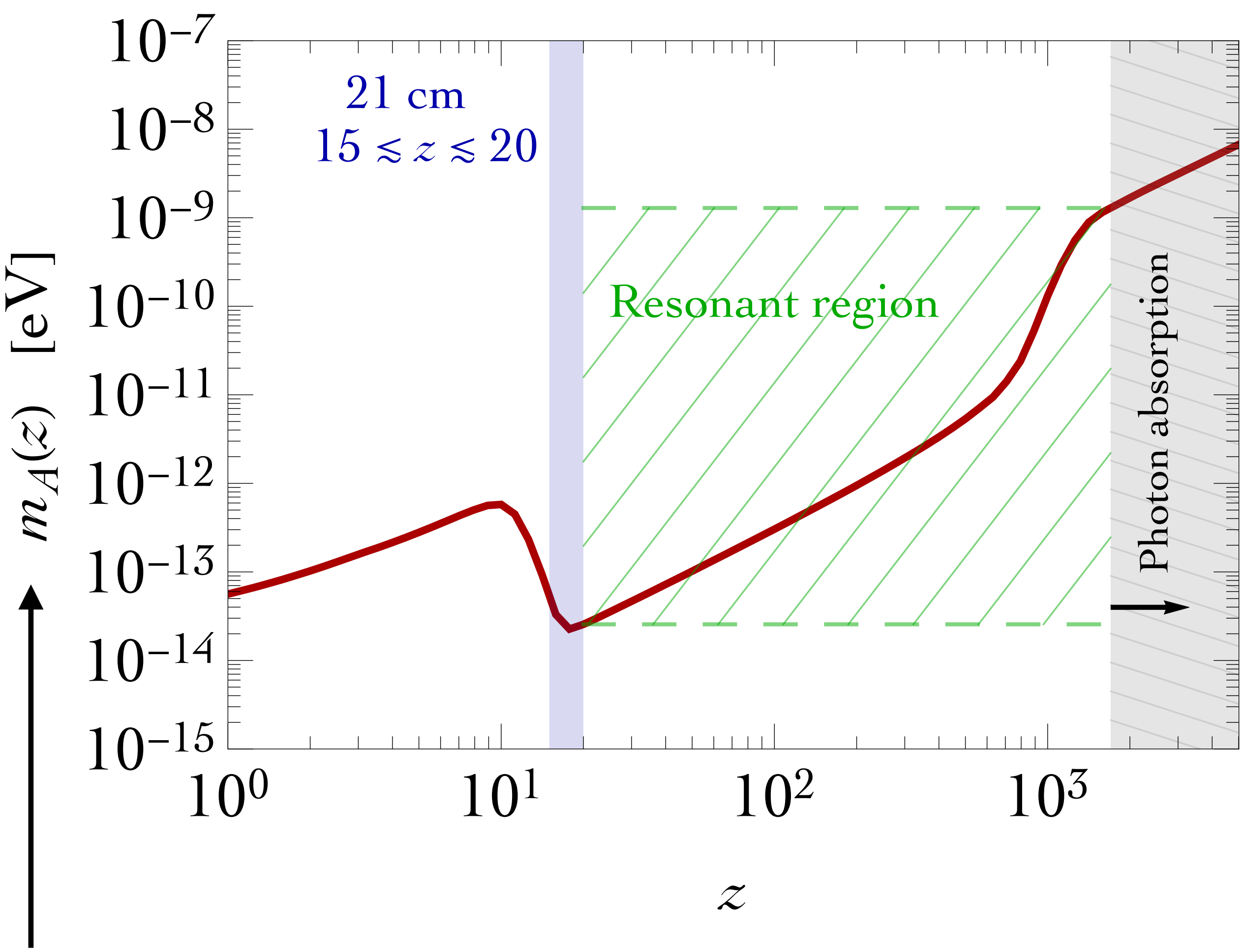


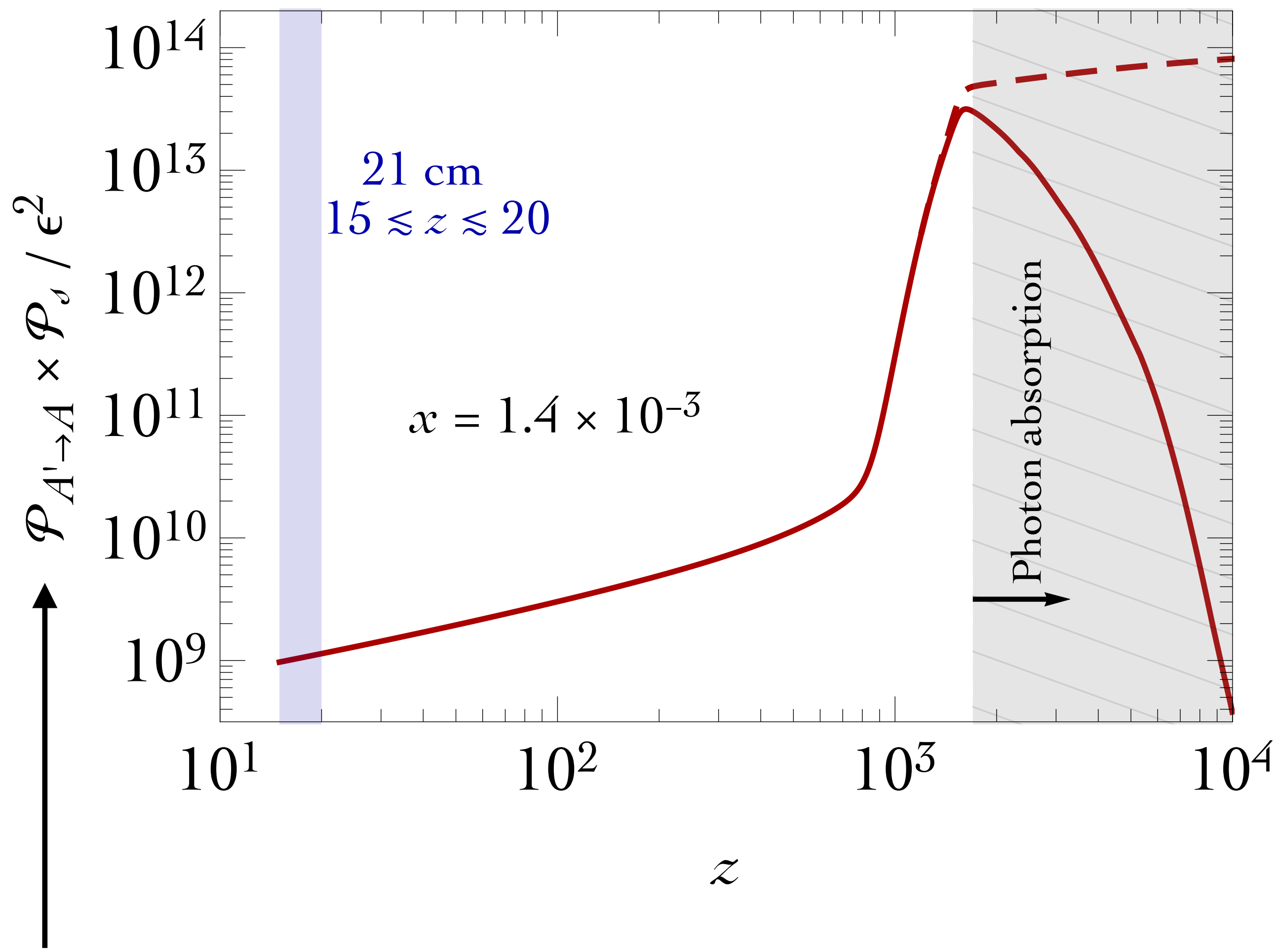

$$\frac{dn_A}{d\omega} \to \frac{dn_A}{d\omega} \times P_{A\to A} + \frac{dn_{A'}}{d\omega} \times P_{A'\to A}$$

Pospelov, JP, Ruderman, Urbano 2018

# Resonant conversion into photons

**vector mass** $m'_A = m_A(z)$ **plasma mass**



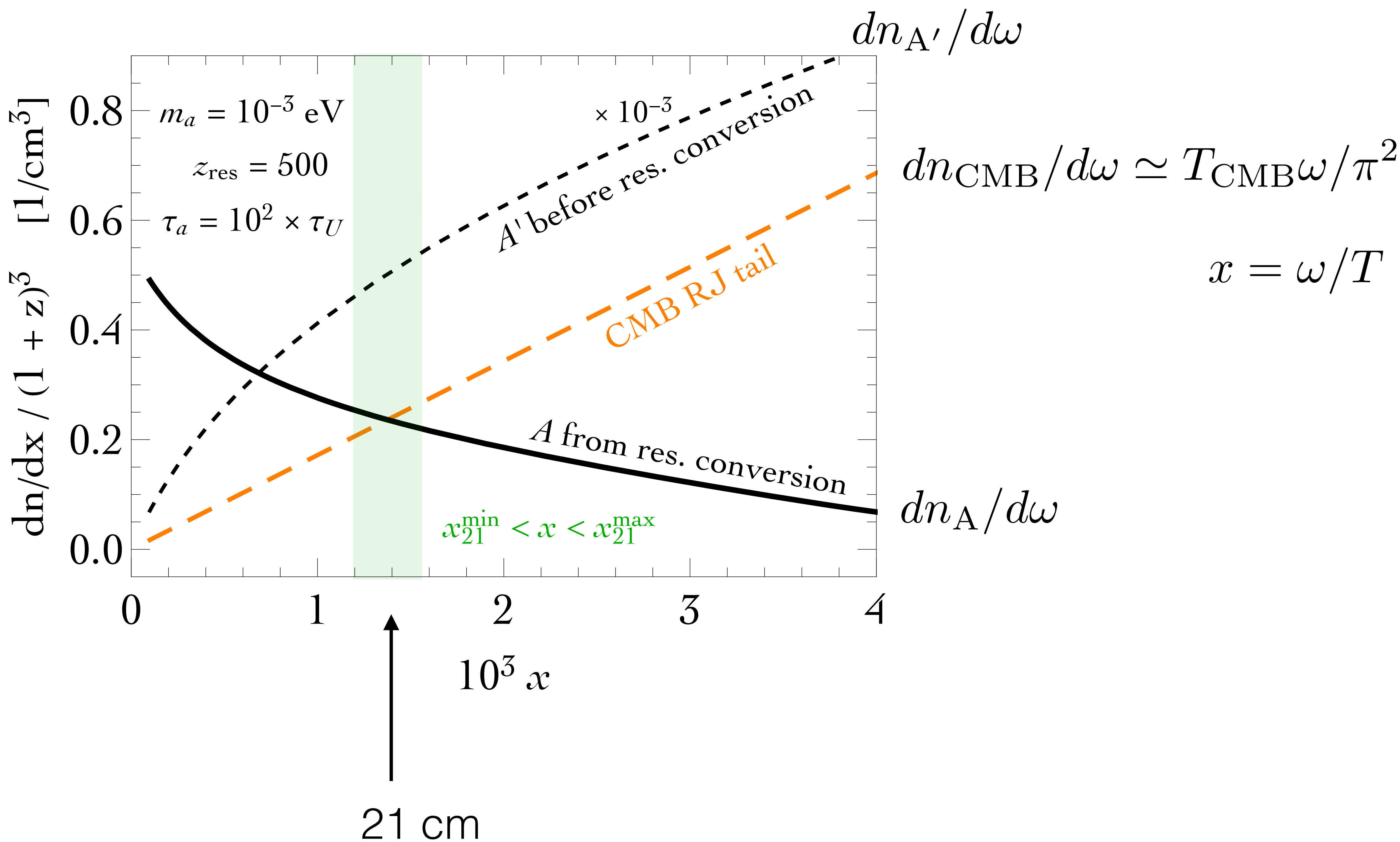

photon plasma freq.

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

transition probability

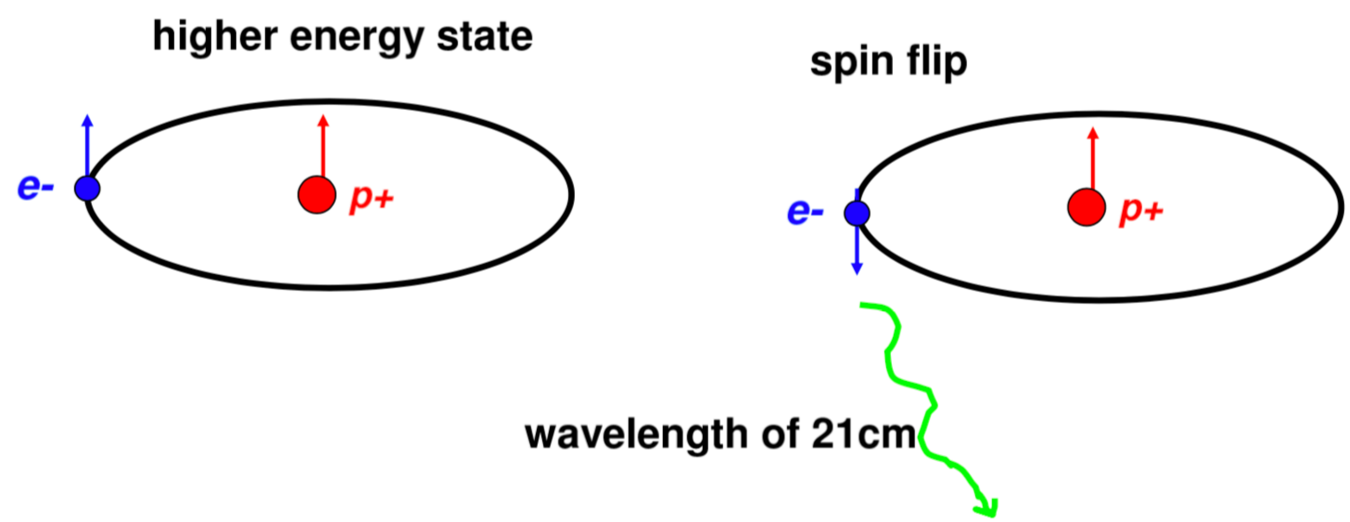
$$P_{A\to A'} = P_{A'\to A} = \frac{\pi \epsilon^2 m_{A'}^2}{\omega} \times \left|\frac{d \log m_A^2}{dt}\right|^{-1}_{t=t_{\rm res}}$$

# (Dark) photon spectra and 21cm



# 21cm and cosmic dawn

$n_1$ $n_0$




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

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

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

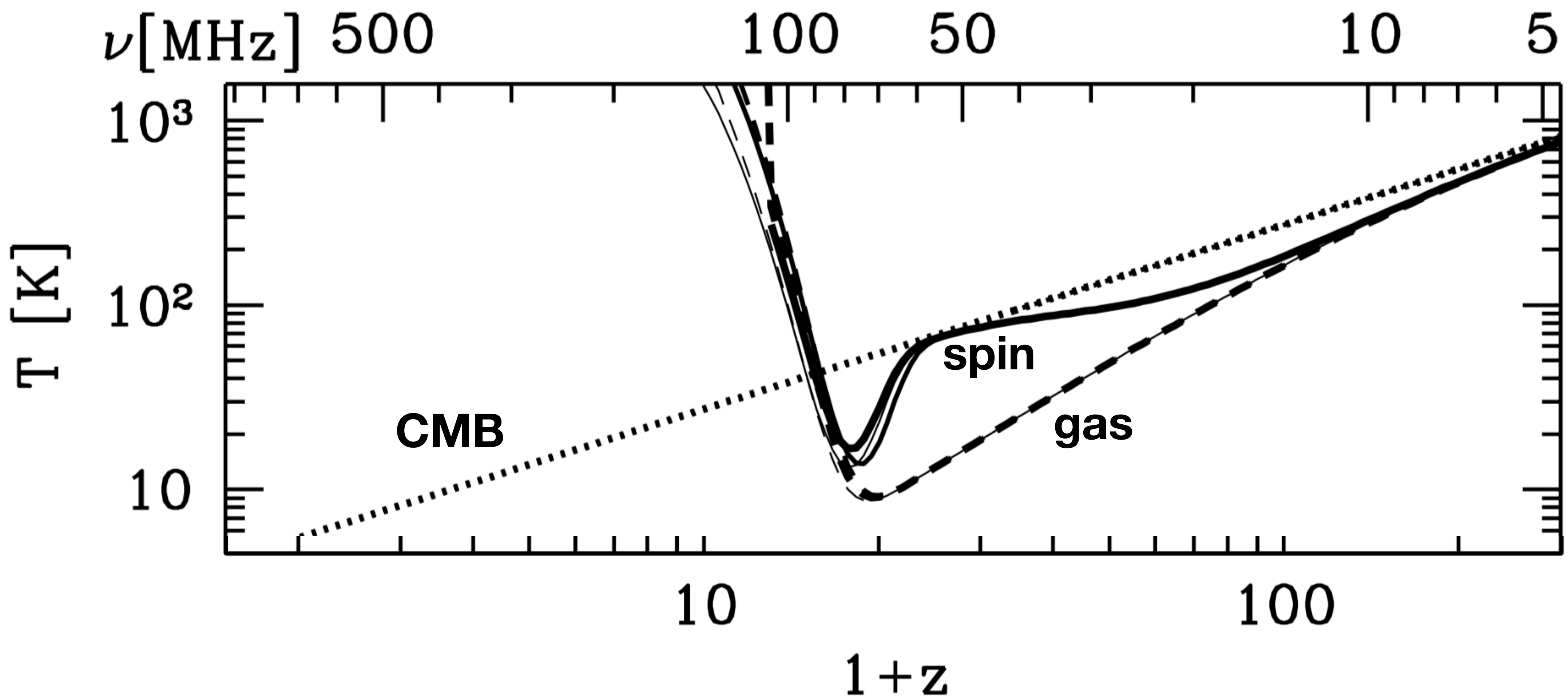
collisions

Einstein coefficients

intensity of photons with 21cm wavelength

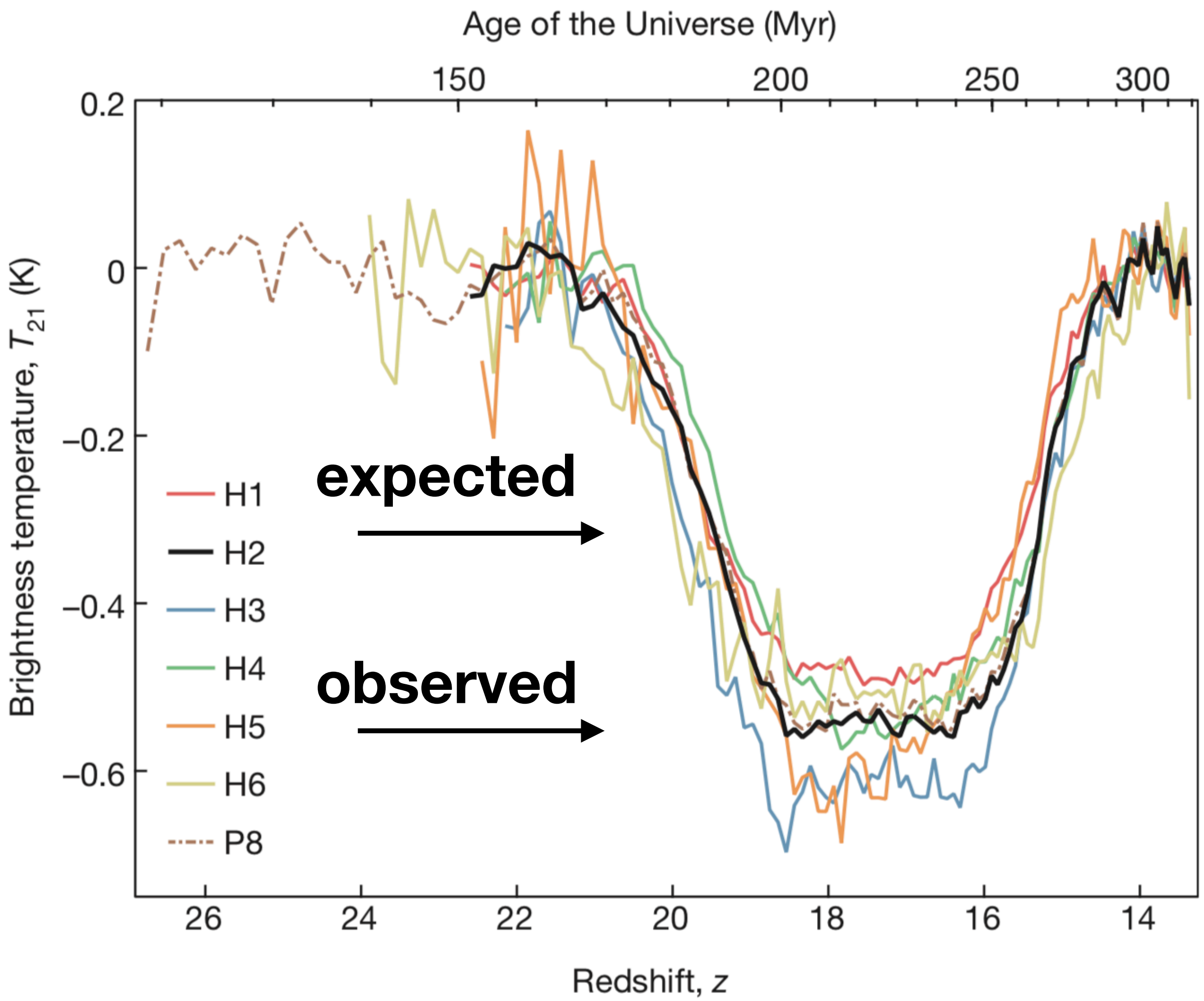
$I_\nu = T\omega^2/2\pi^2 = n_{\mathrm{RJ}}$

# 21cm and cosmic dawn




Loeb, Pritchard 2012

# EDGES result




What is measured in 21 cm astronomy is a brightness temperature

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

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

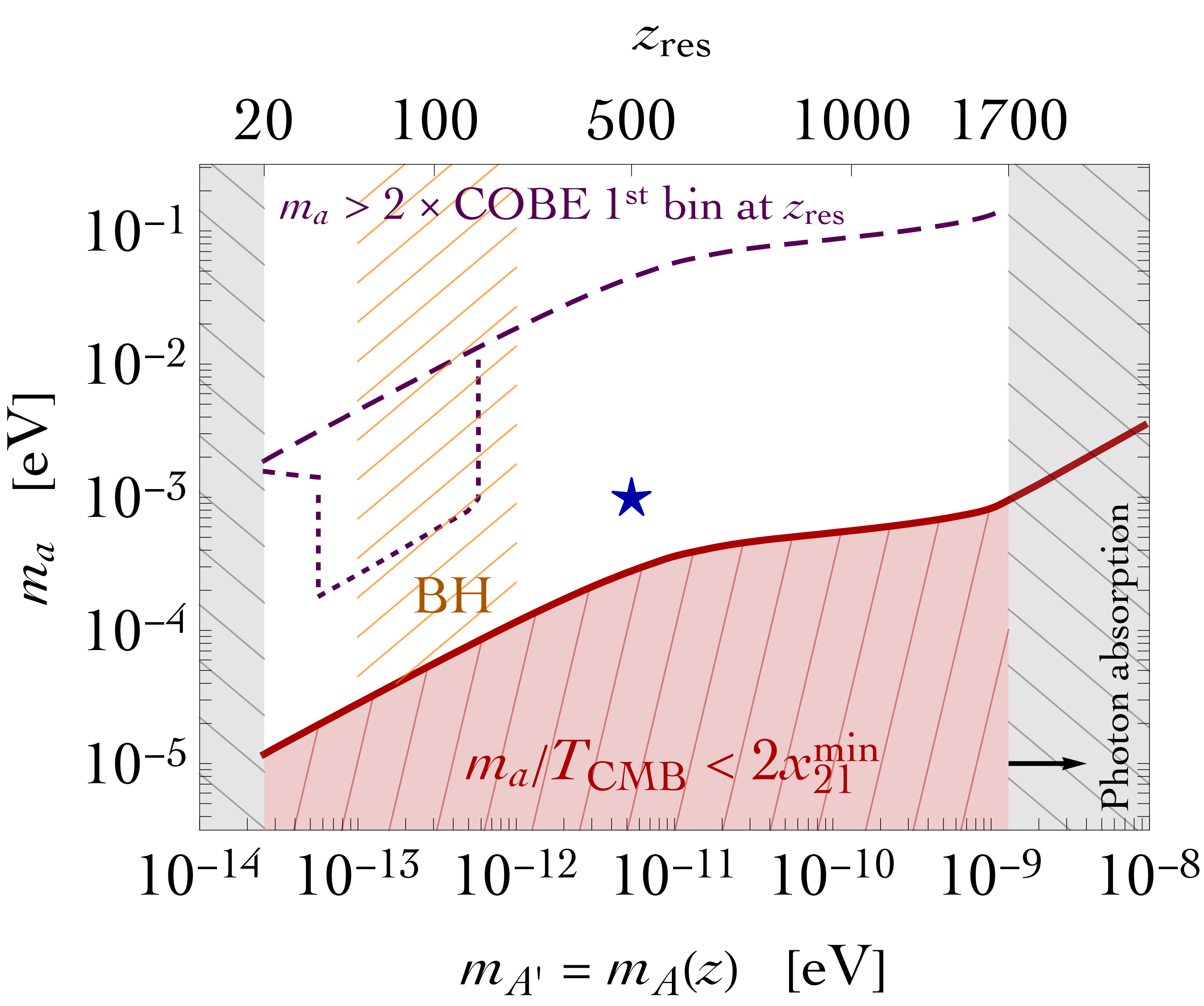
Zaldarriaga, Furlanetto, Hernquist 2004

=> 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

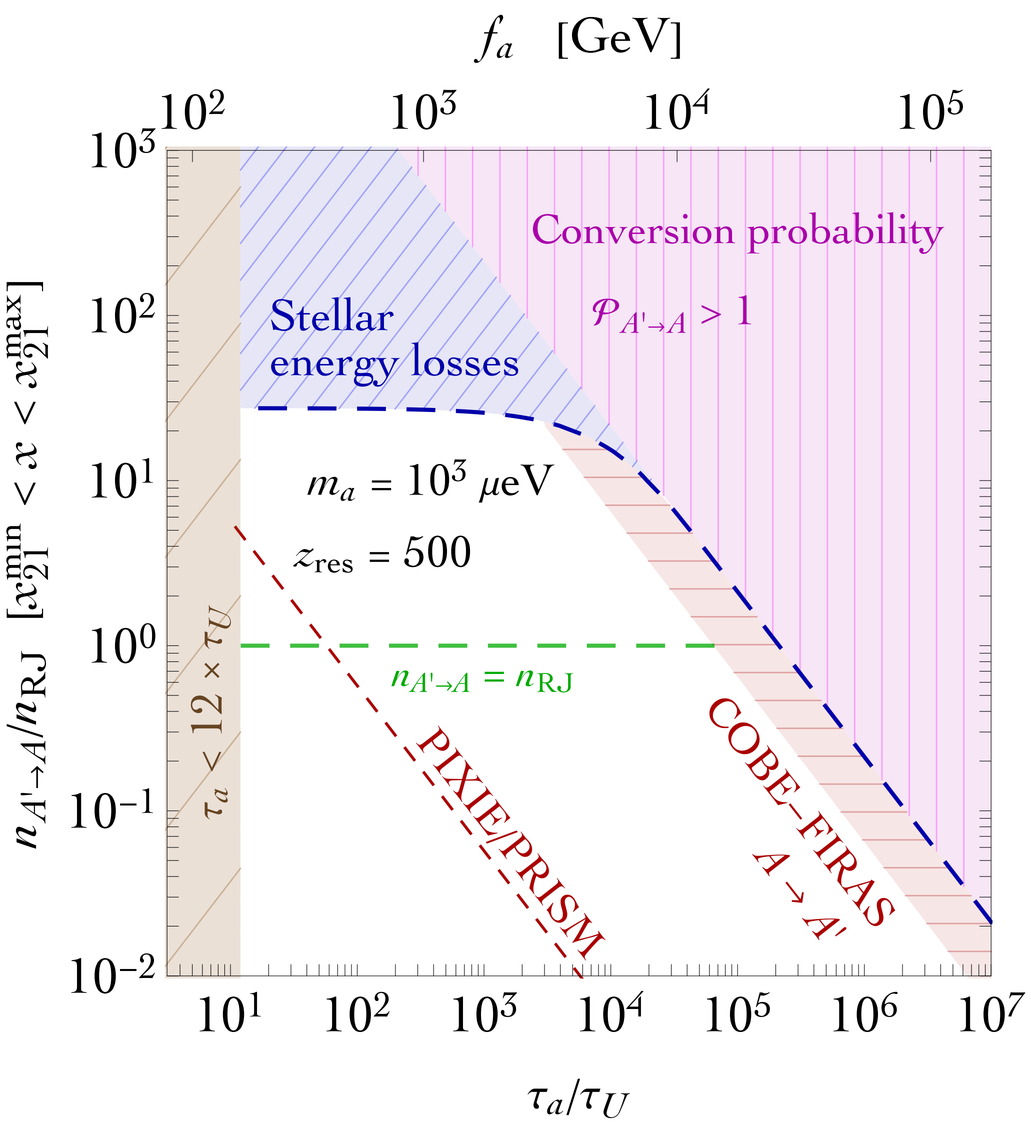
# EDGES result can be explained easily ($n_A \sim n_{RJ}$ is required)

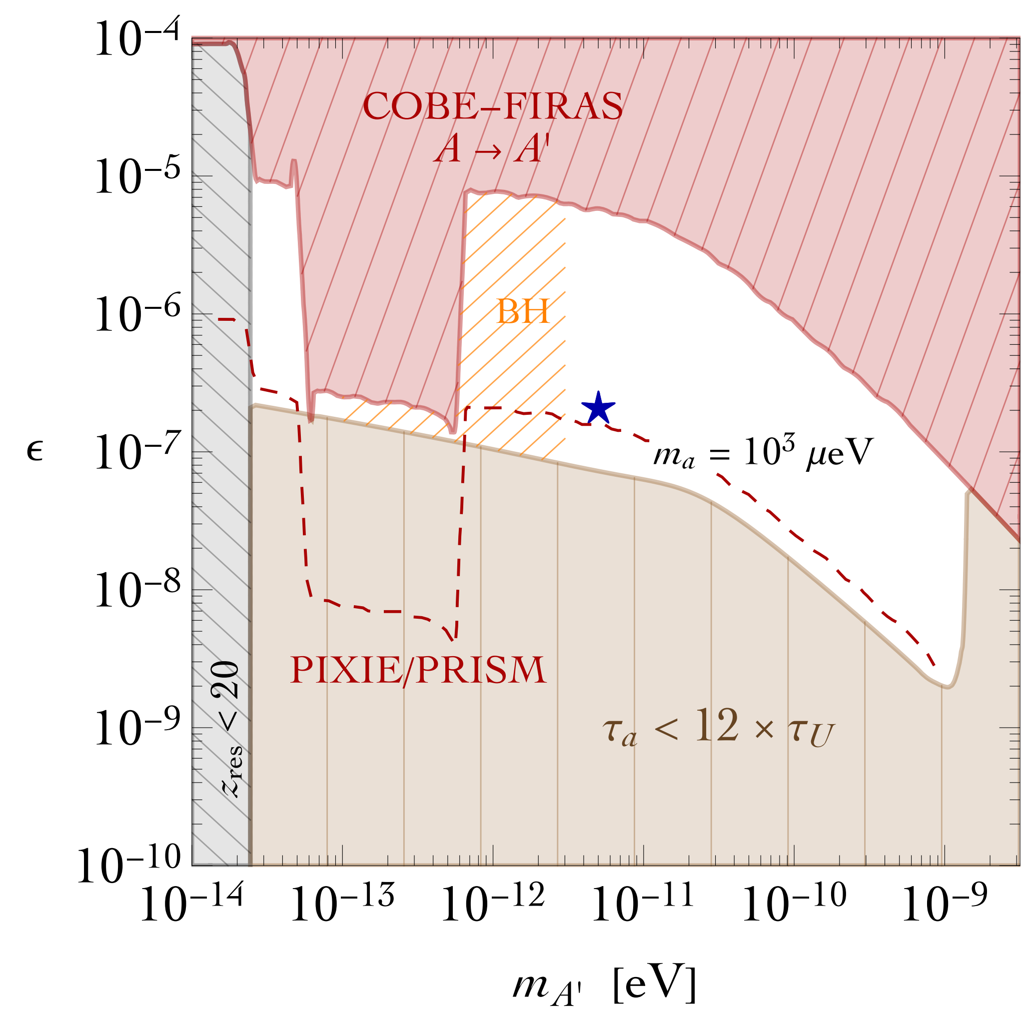



Big parameter space in progenitor mass and dark photon mass for which 21cm band is affected at z ~ 17

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

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



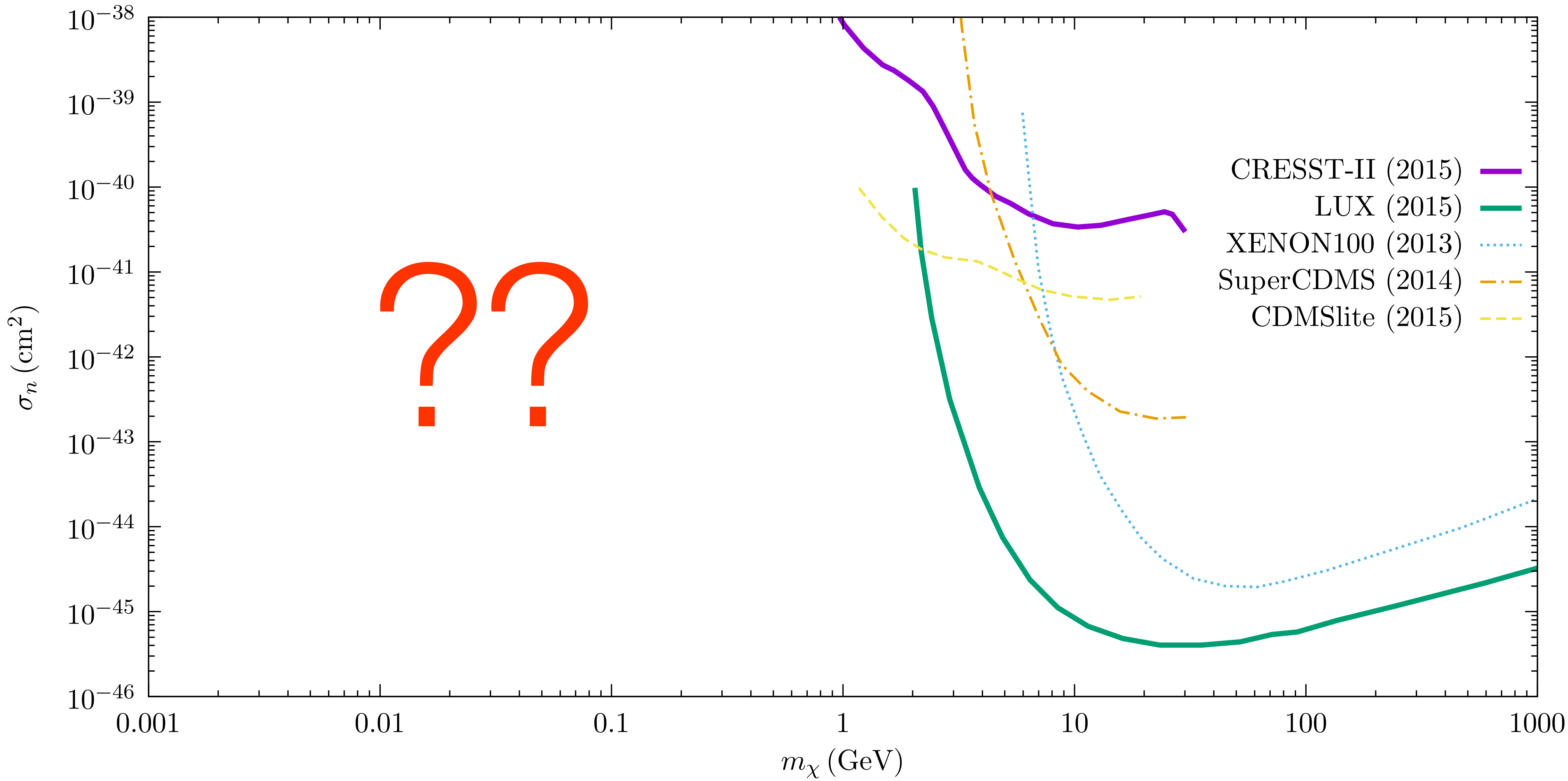

More generally, independently if EDGES result persists, 21 cm astronomy will be sensitive probe of non-standard soft photon population sourced by DM.

NB: similar ideas in follow-ups by Moroi et al. 2018 and Sierra, Fong et al. 2018

2

# DM Scattering on nuclei and electrons

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

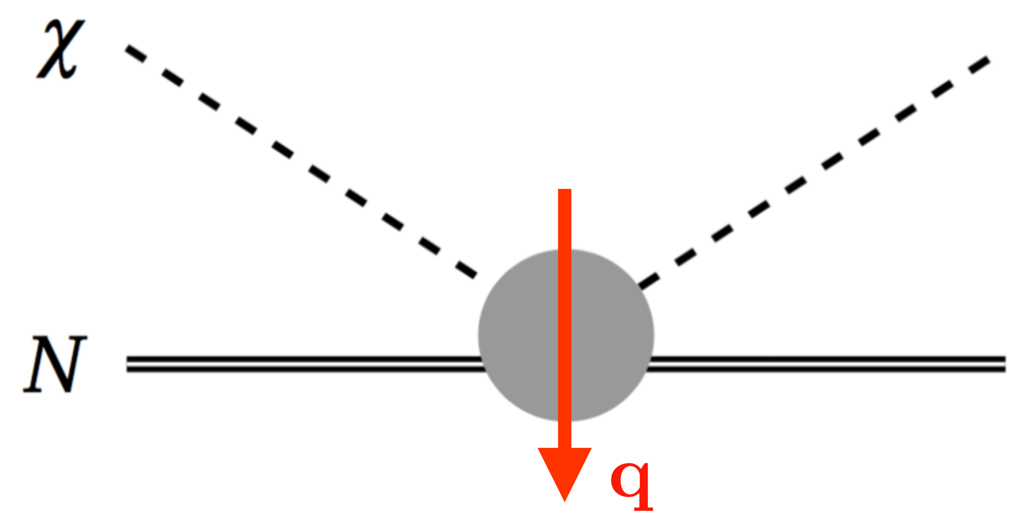



"light Dark Matter" WIMPs

# 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

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

=> 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"

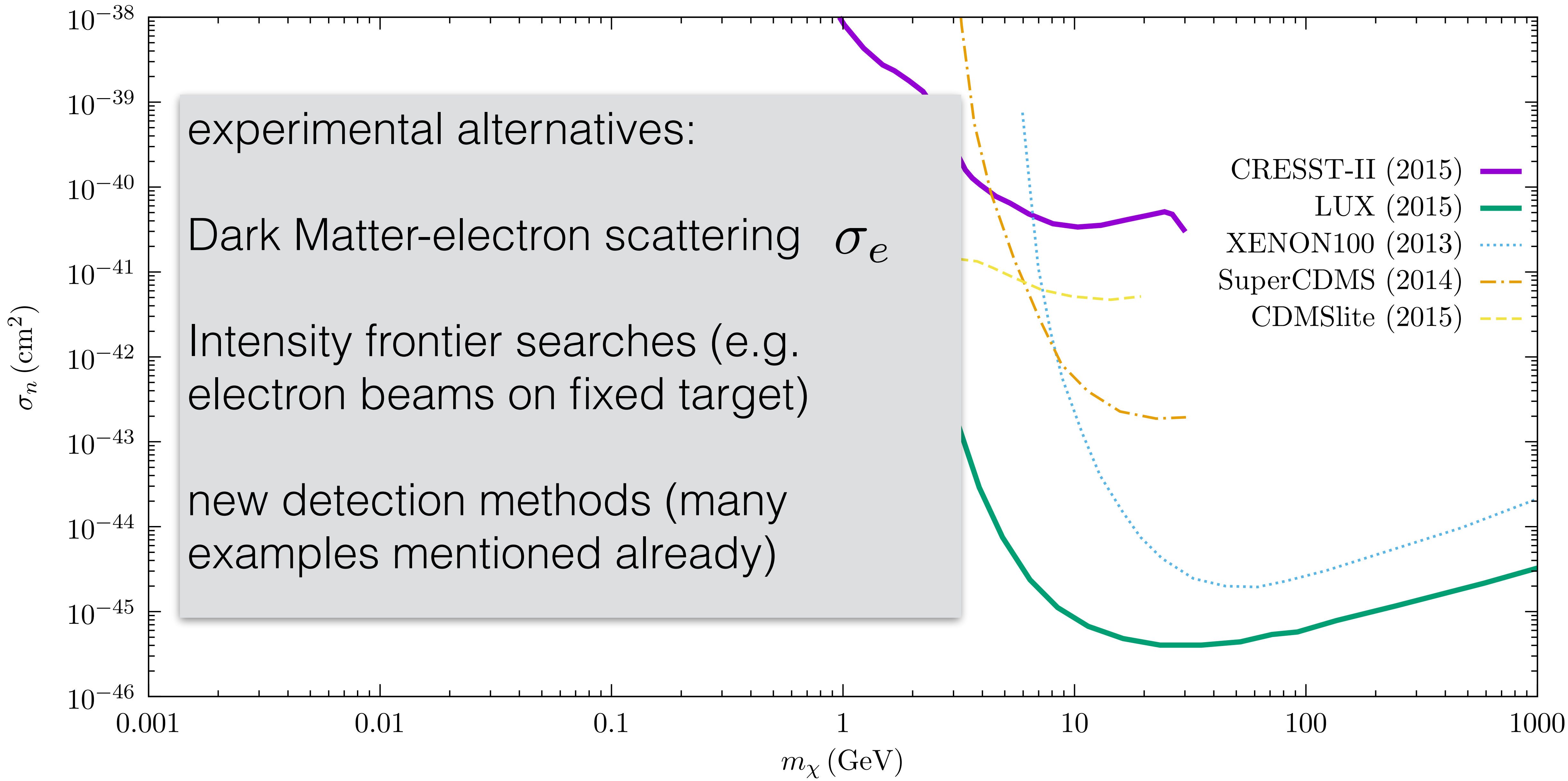
# Gaining access to sub-GeV Dark Matter

experimental alternatives:

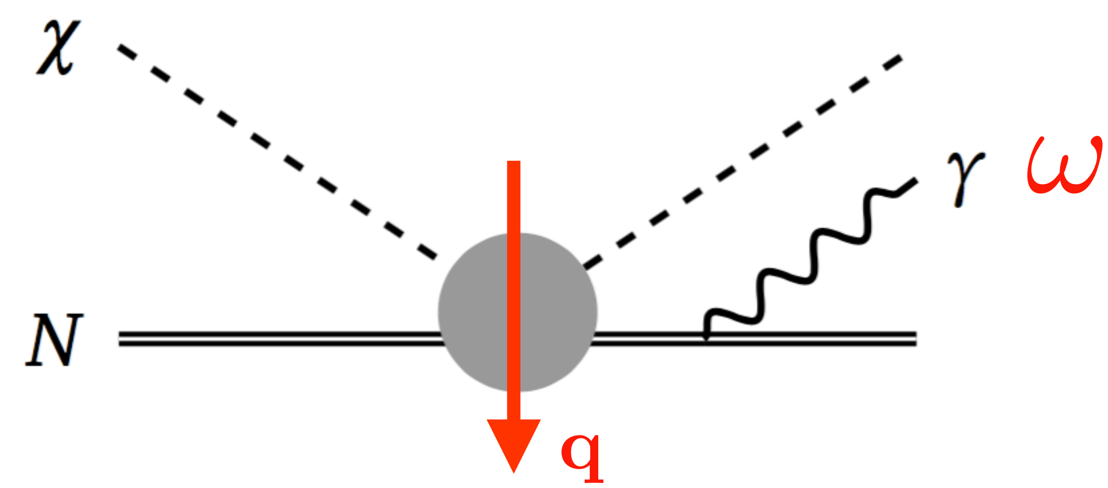
Dark Matter-electron scattering $\sigma_e$

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*



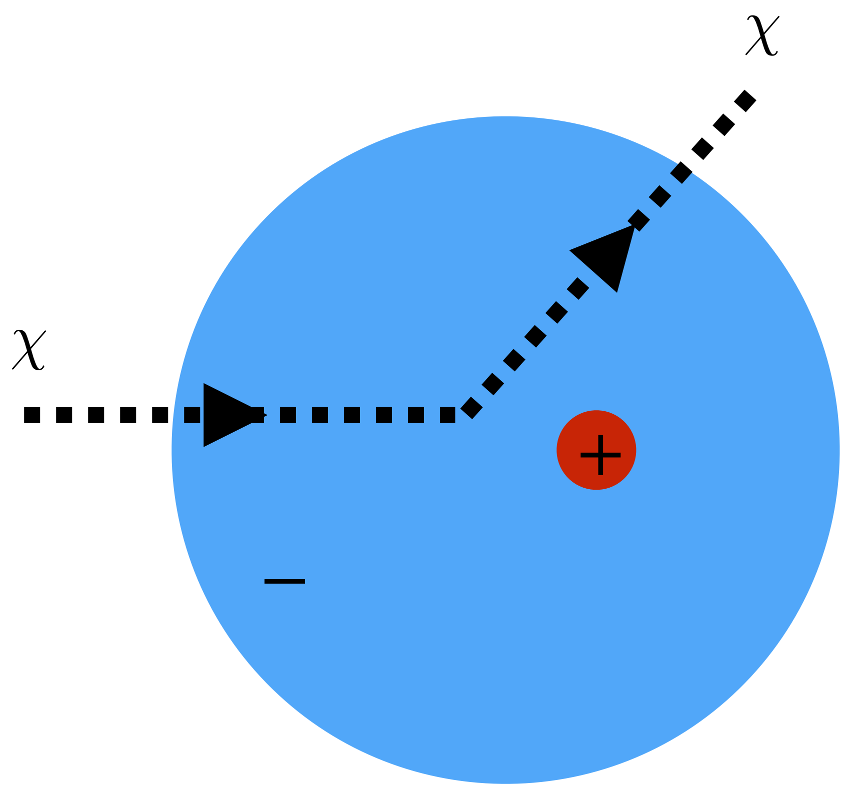

Inelastic channel of photon emission from the nucleus

Maximum photon energy

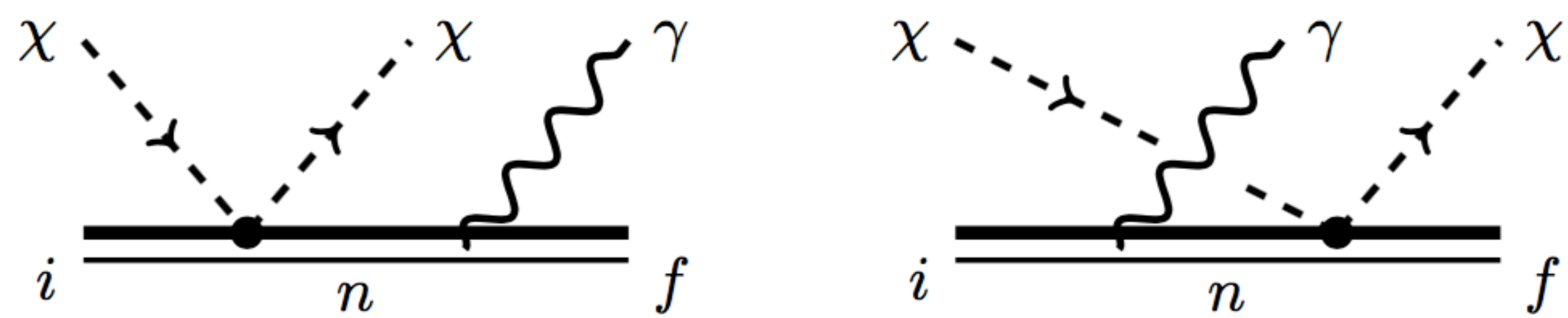
$$\omega_{\max} \simeq \mu_N v^2/2 \simeq m_\chi v^2/2$$
$$\simeq 0.5\,\mathrm{keV}\,\frac{m_\chi}{100\,\mathrm{MeV}}$$

**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!




# Photon-emission from elastic scattering




dipole emission ↓ polarizability of the atom ↓

**For f=i:**

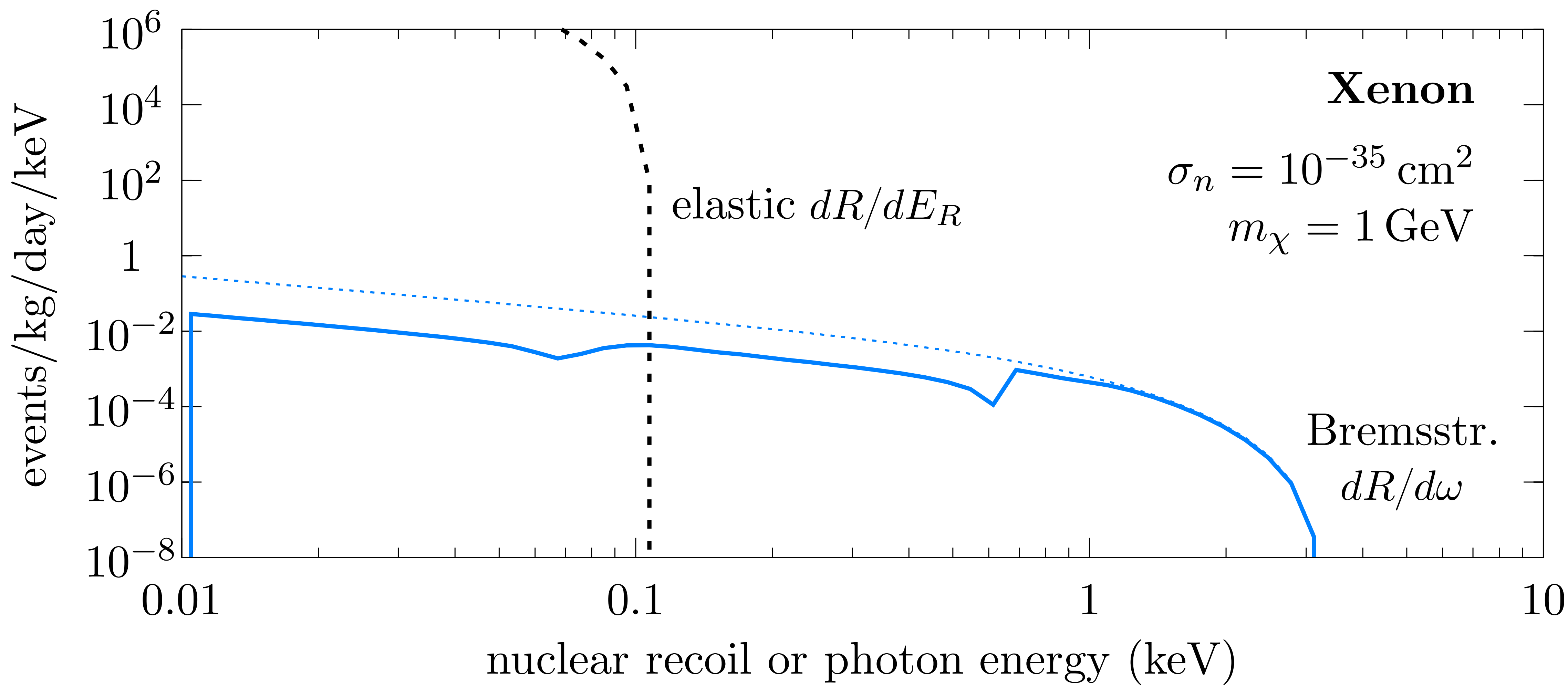
$$\frac{d\sigma}{d\omega dE_R} \propto \omega^3 \times |\alpha(\omega)|^2 \times \frac{E_R}{m_N} \times \frac{d\sigma}{dE_R}$$

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

for large ω naive result is recovered ✓

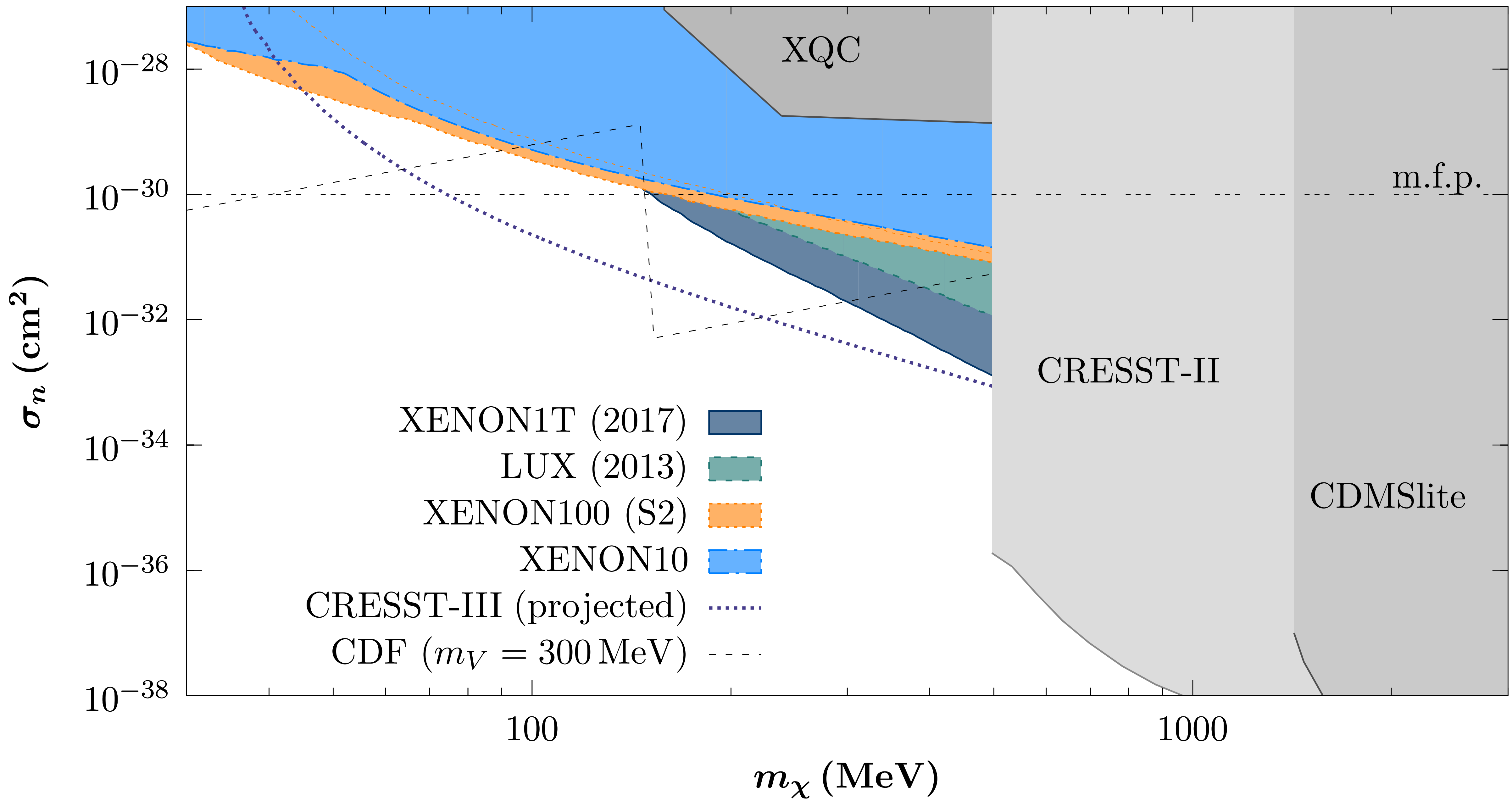
# Gaining access to sub-GeV Dark Matter *through nuclear recoils*

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**

Kouvaris, JP PRL 2016

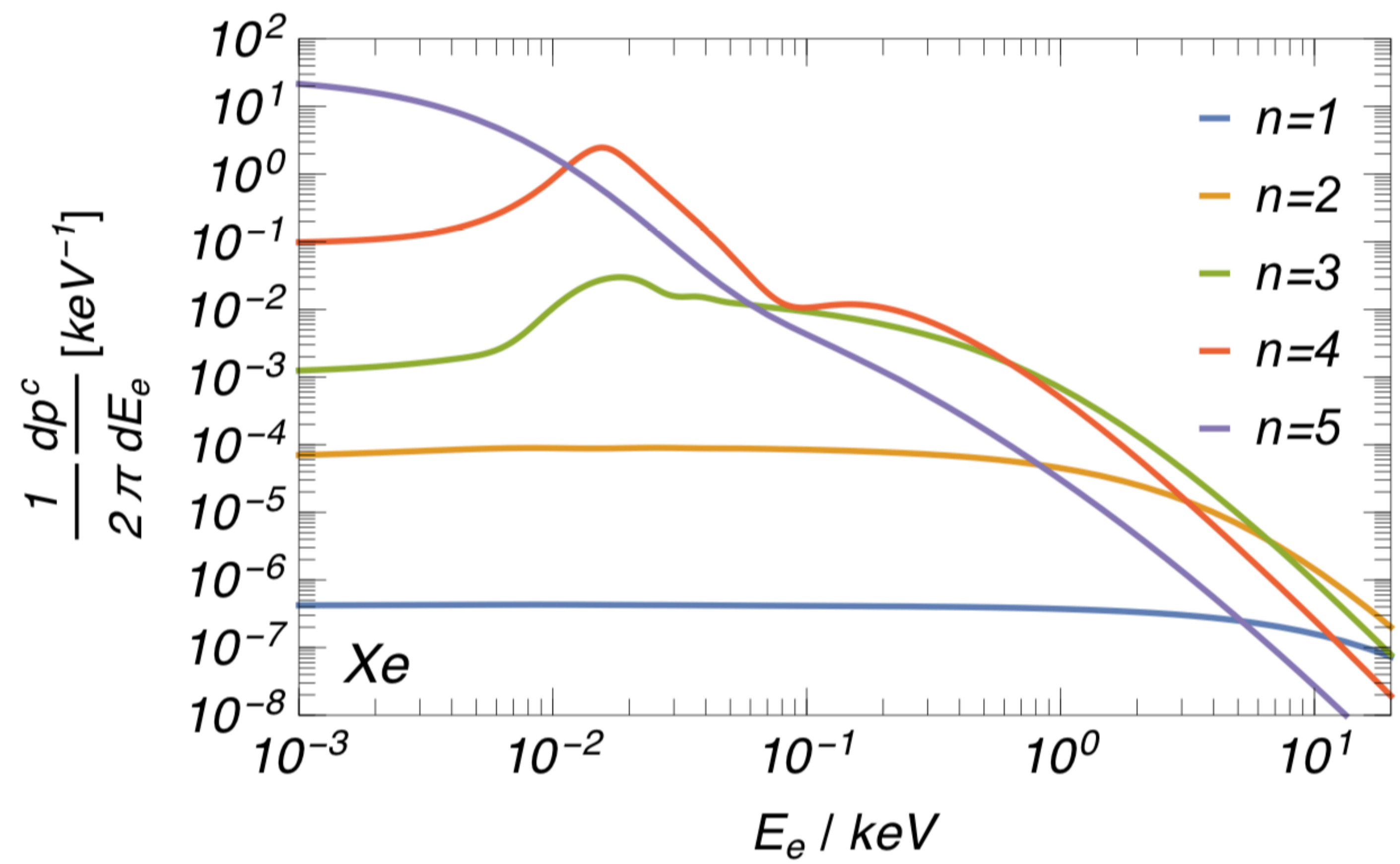
# Direct electron shake off - “Migdal” effect

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

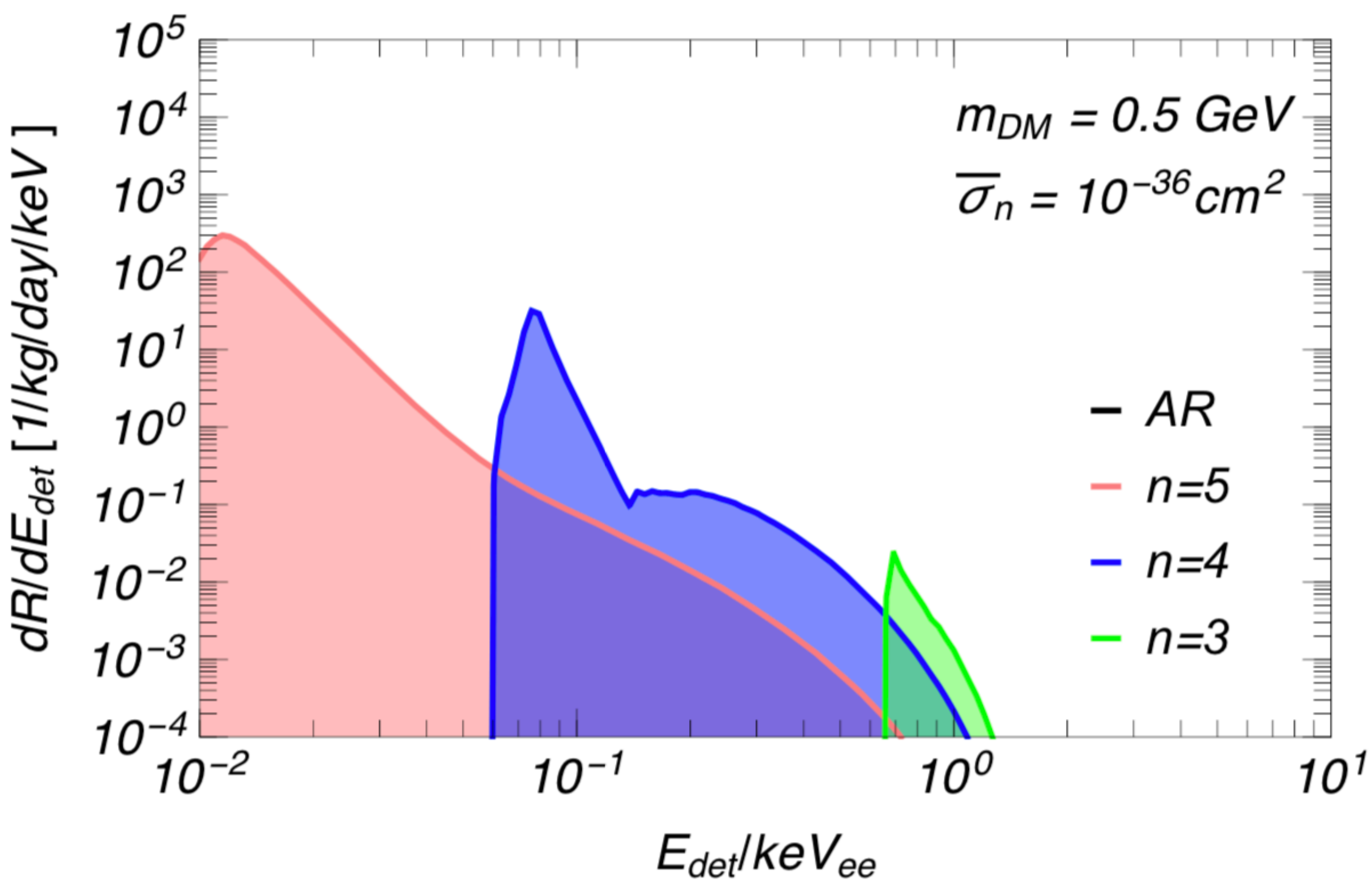
Ibe et al 2017

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)

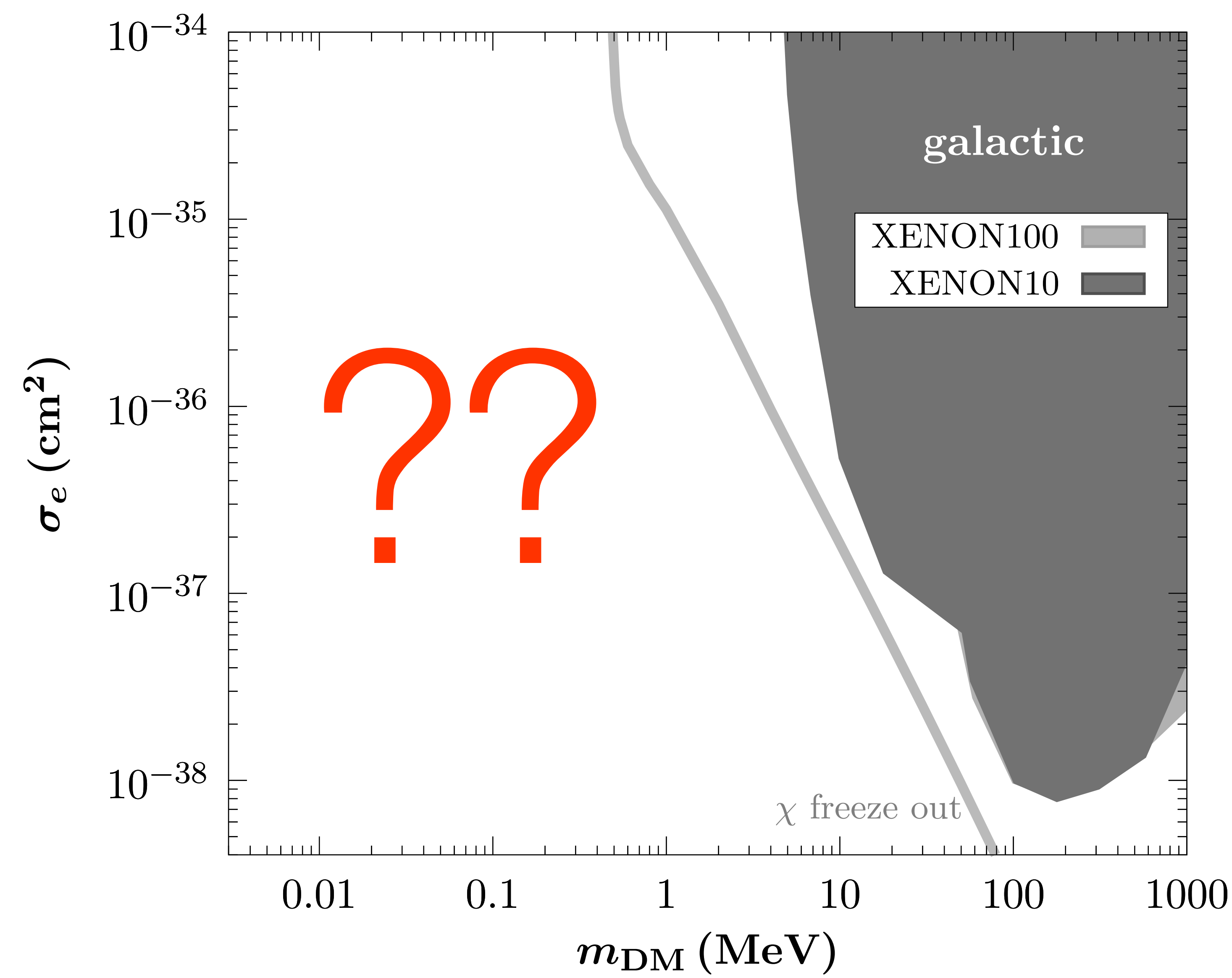



like the Bremsstrahlung, energetically favored for detection over elastic channel

=> 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)

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

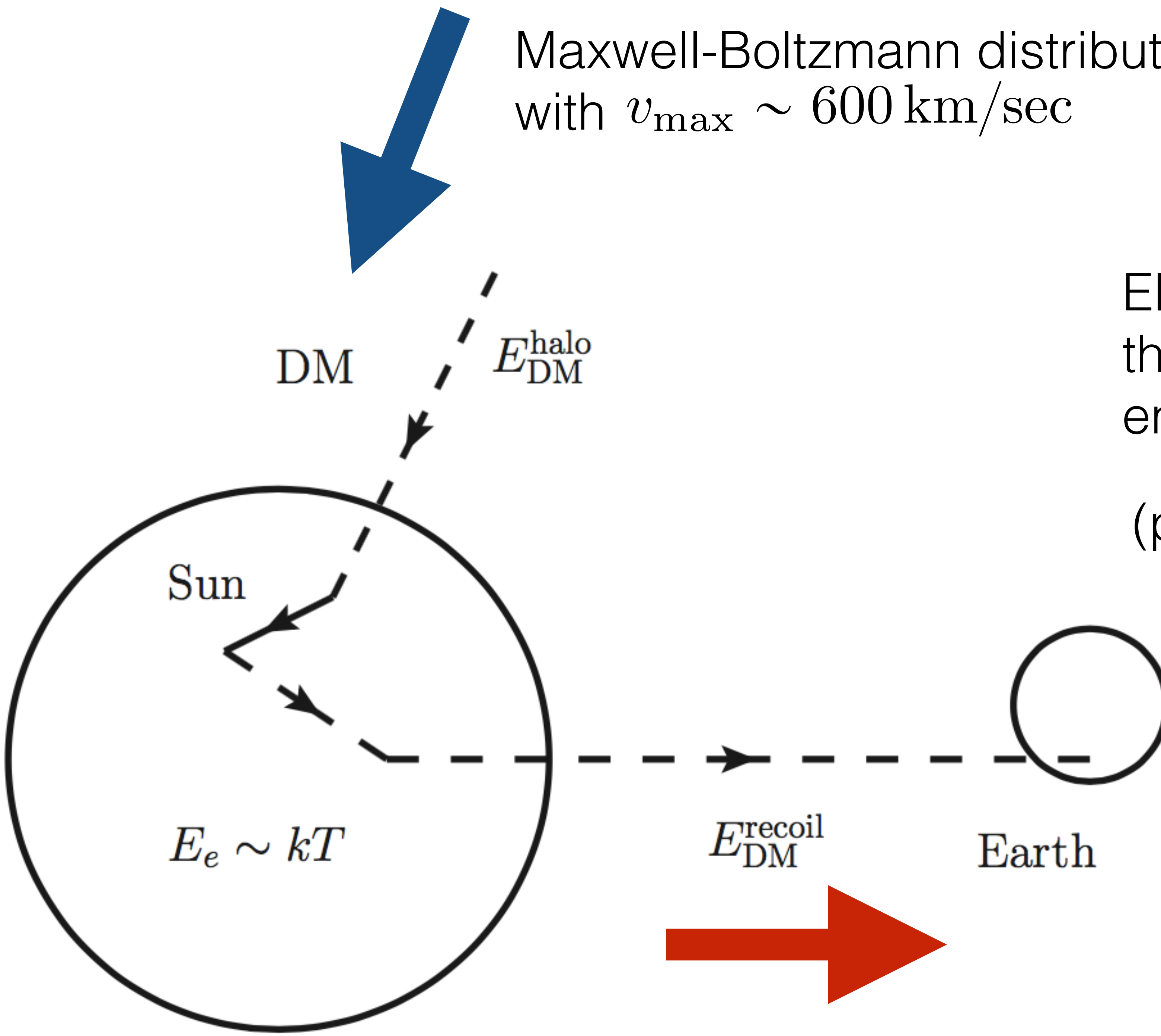
$$\sigma_{\rm ann} v = v^2 \times \frac{G_{\chi e}^2}{12\pi}(m_e^2 + 2m_\chi^2)\sqrt{1 - \frac{m_e^2}{m_\chi^2}}$$

**=> First direct test of such DM model**

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

# The sun as particle accelerator

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




reflected spectrum

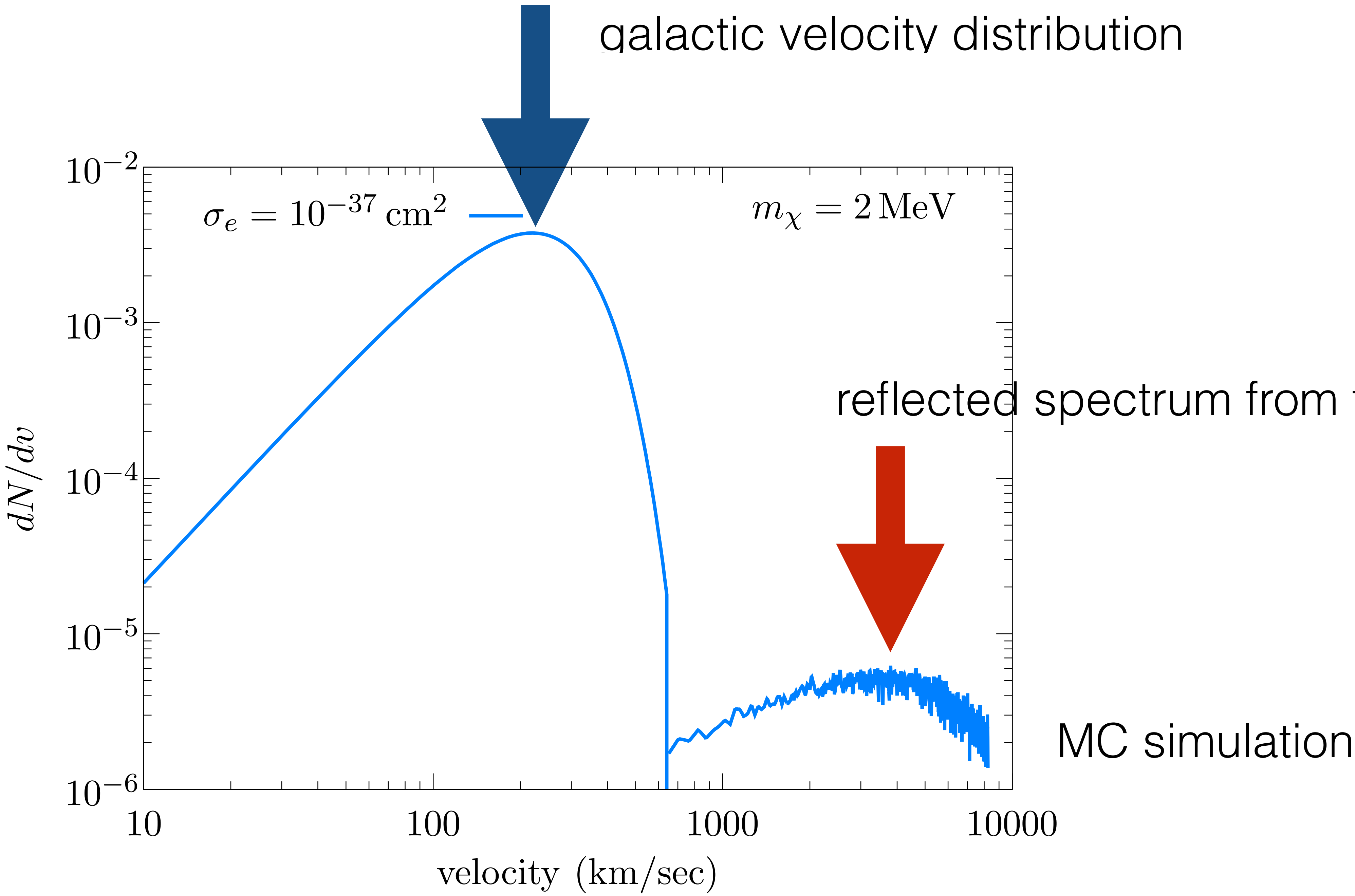
Elastic scattering on electrons in the sun's interior lifts DM kinetic energy into (sub-)keV regime

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

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

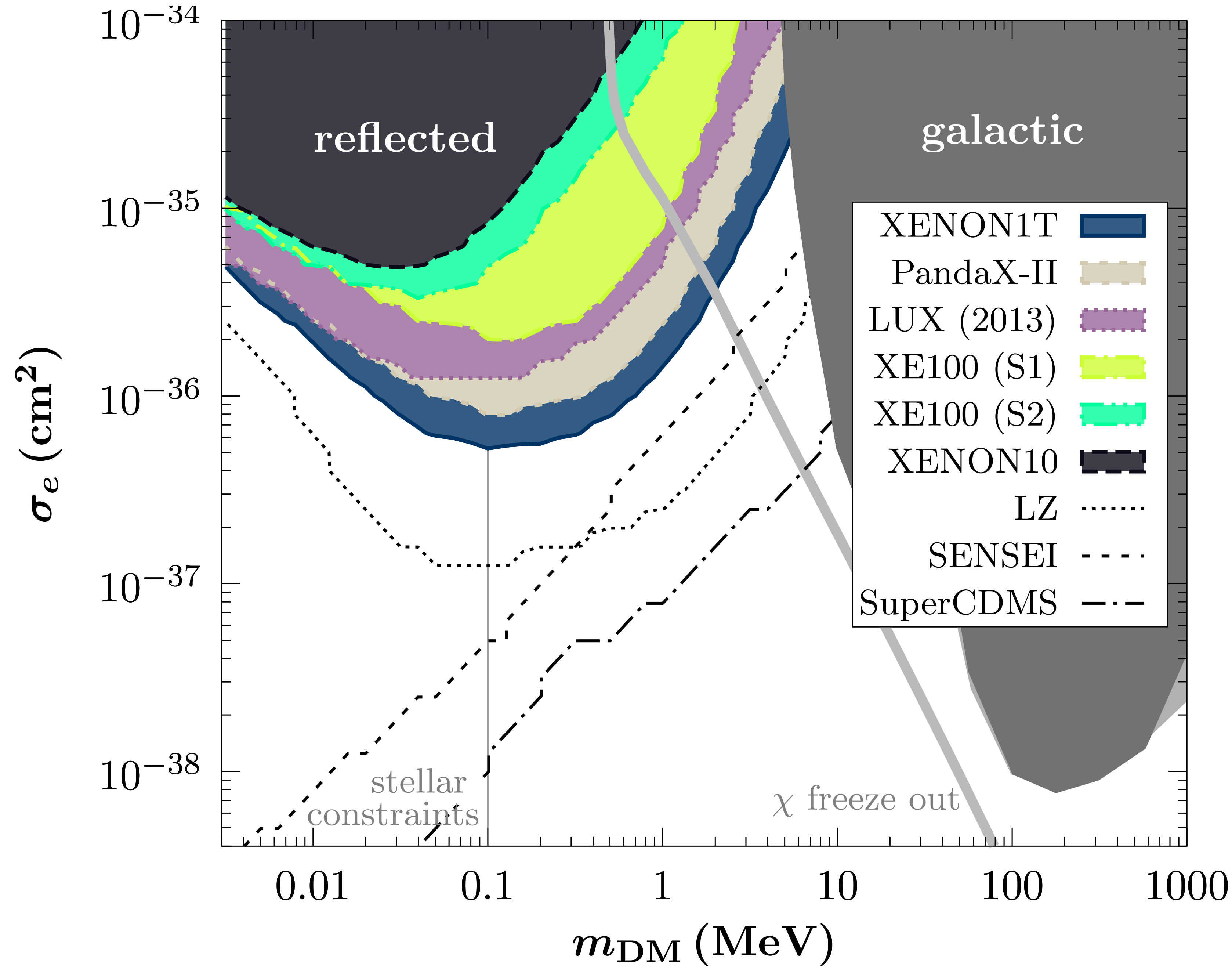
$$v_{\rm max} = \sqrt{2T/m}$$
$$\sim 10^4\,{\rm km/sec} \times \sqrt{1\,{\rm MeV}/m}$$

# The sun as particle accelerator




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

# Direct Detection of sub-MeV DM




An, Pospelov, JP, Ritz PRL 2018

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

# Signatures of DM (well) below the GeV-scale

1

**Decay into dark radiation**

Dark radiation as DM decay product is probed non-gravitationally

- in direct detection when energy is in the 30 MeV ballpark
- in 21 cm cosmology through resonant conversion of very low energetic radiation

2

**DM scattering on electrons and nuclei**

Kinematic no-go theorems in direct detection 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