ICRR
Institute for Cosmic Ray Research
University of Tokyo

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Migdal effect in Dark Matter Direct Detection Experiments

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In collaboration with M. Ibe, W. Nakano, K. Suzuki

Contents

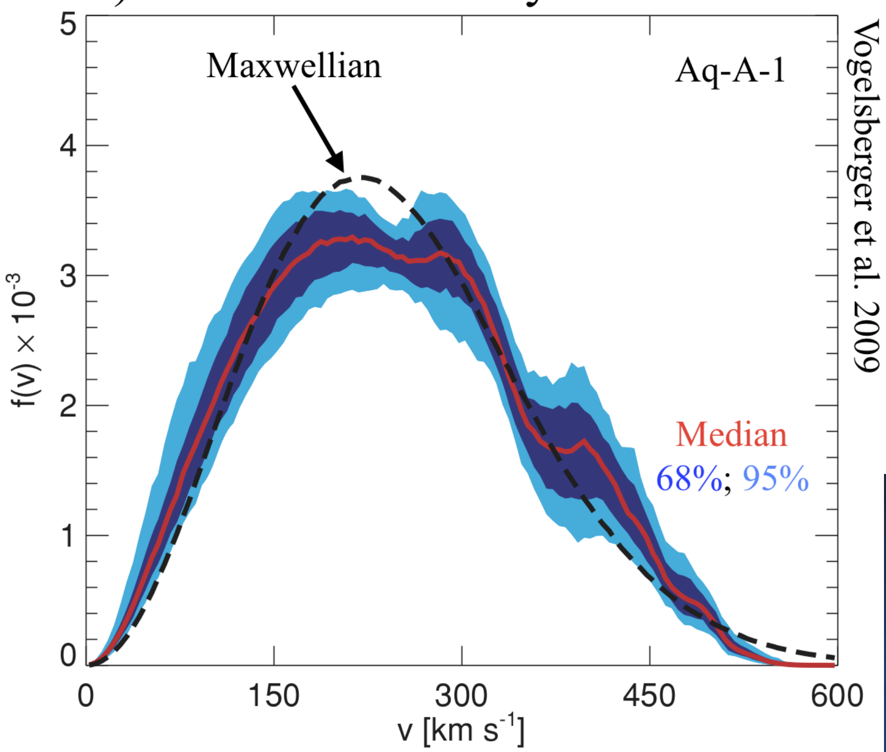
Introduction

Dark matter

- accounts for 26.8% of the total energy density of the Universe
- is invisible
- has the gravitational interaction
- can have additional interactions with SM particles
- has not been directly observed

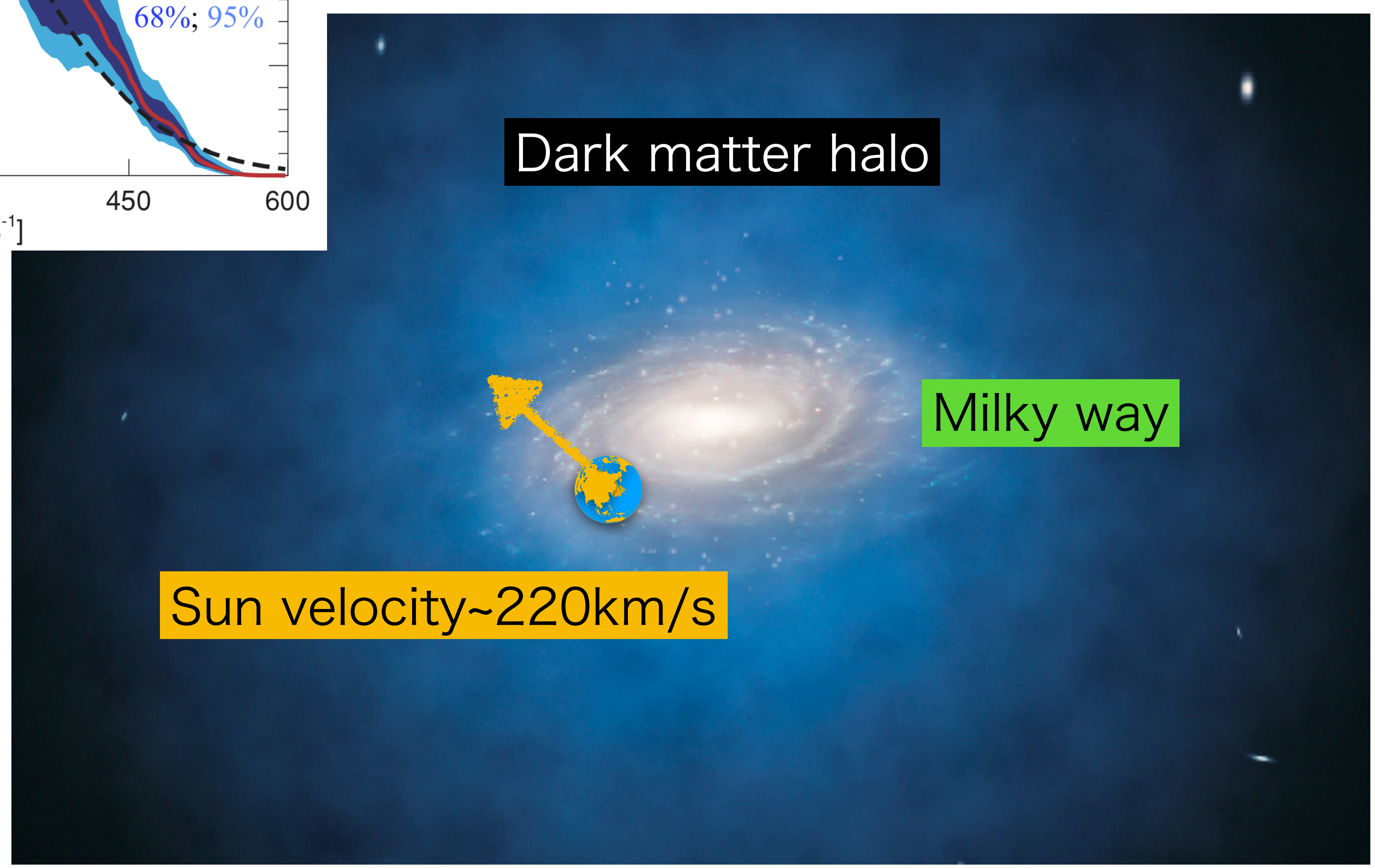
Moving in a DM Halo

d) Local DM velocity PDF (around our solar system)



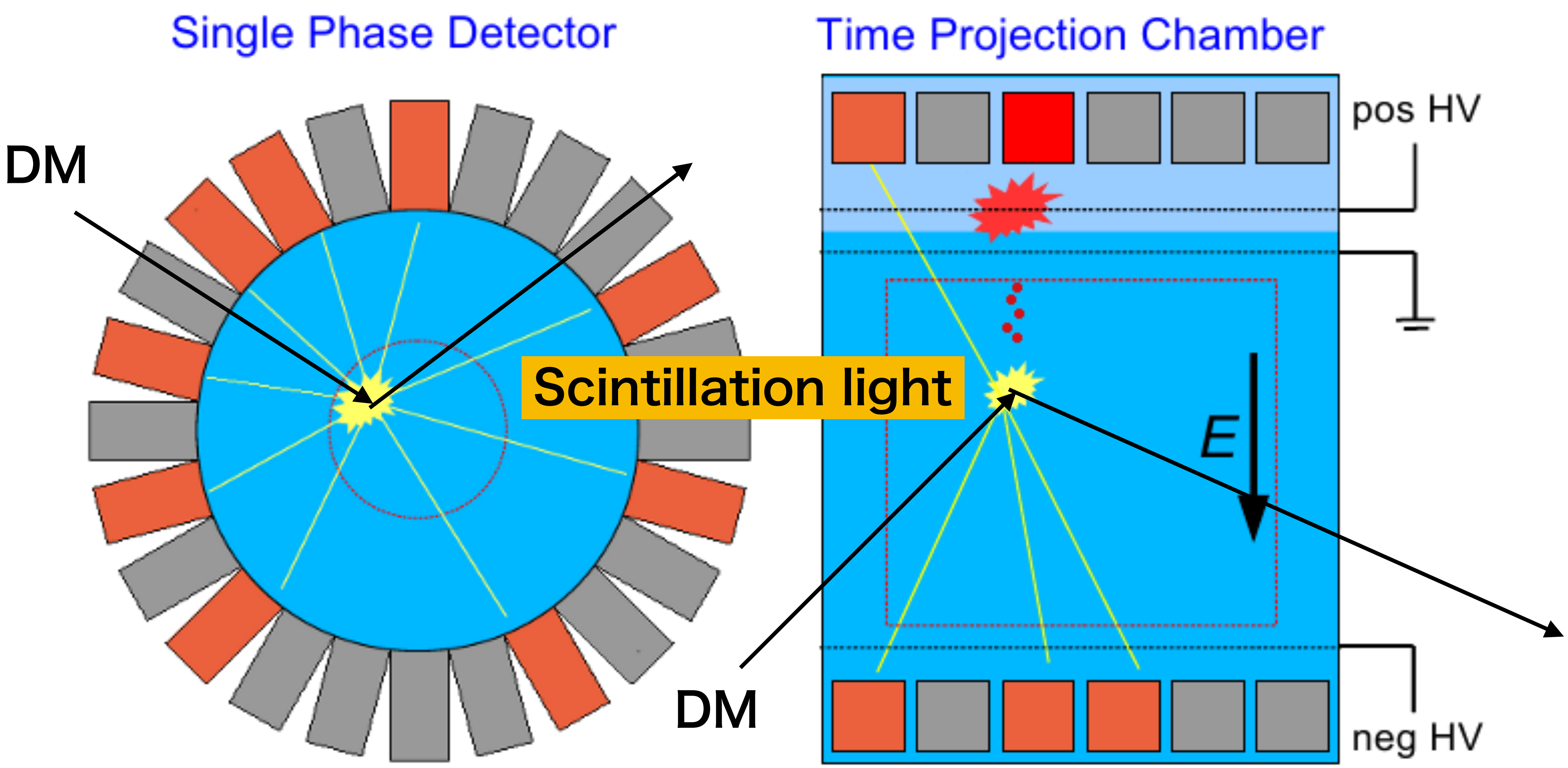
Aquarius Aq-A-1 DMO cosmological simulation
(Dark Matter Only)

We approximate it with the truncated Maxwell distribution $v_0 = 220\,\mathrm{km/s}, v_{\rm esc} = 544\,\mathrm{km/s}.$



Direct Detection

(with scintillator)

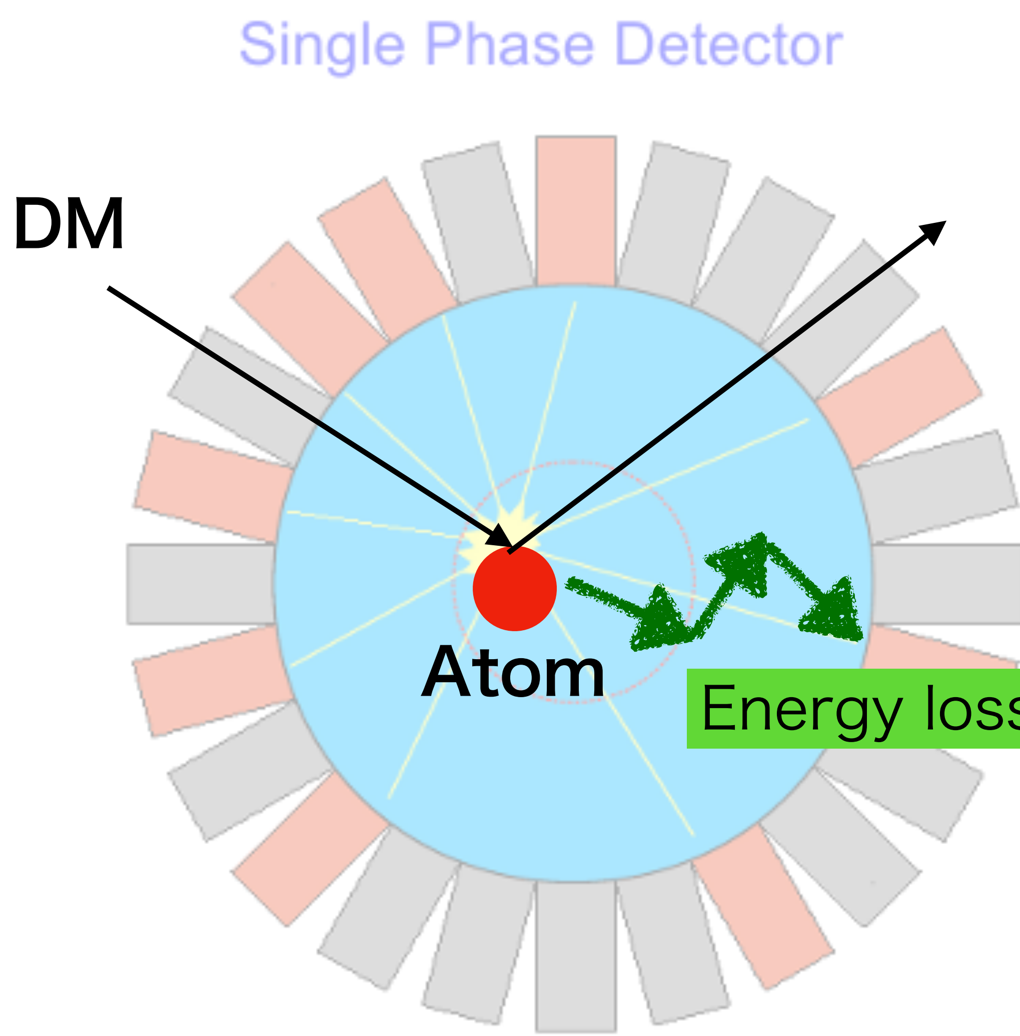


EPJ Web Conf. 96 (2015) 01027

Direct Detection

(with scintillator)

<u>Usually, we assume the scattered atom is not excited or ionized</u>



Heat

↑ 80-90%

Energy loss due to (in-)elastic scattering with other atoms

↓ 10-20%

Electronic excitations

↓

Scintillation

Only a small amount of recoil energy is used for scintillation

Direct Detection

(with scintillator)

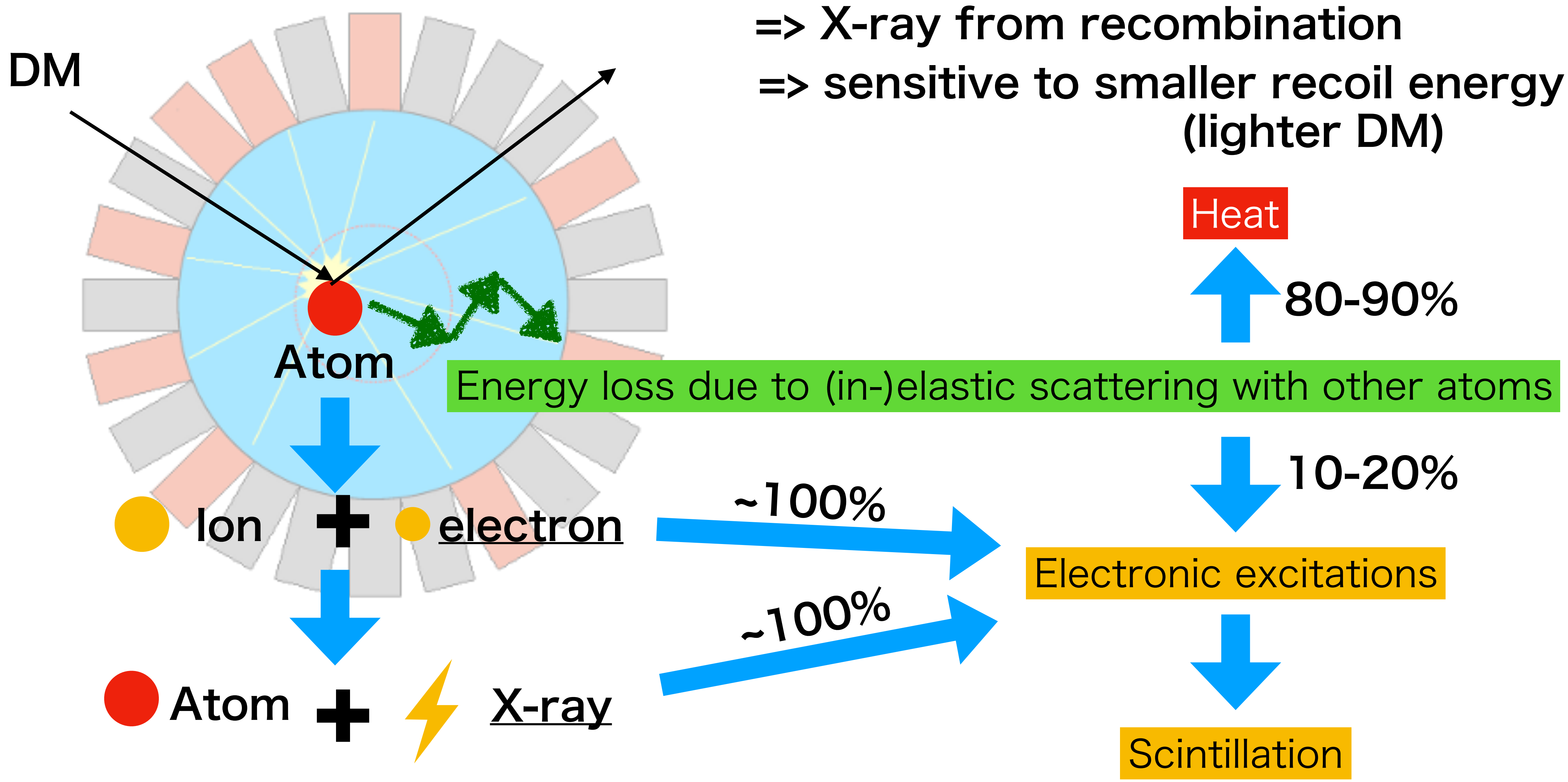
Usually, we assume the scattered atom is not excited or ionized

Single Phase Detector

If the atom is ionized,···

=> X-ray from recombination

=> sensitive to smaller recoil energy (lighter DM)



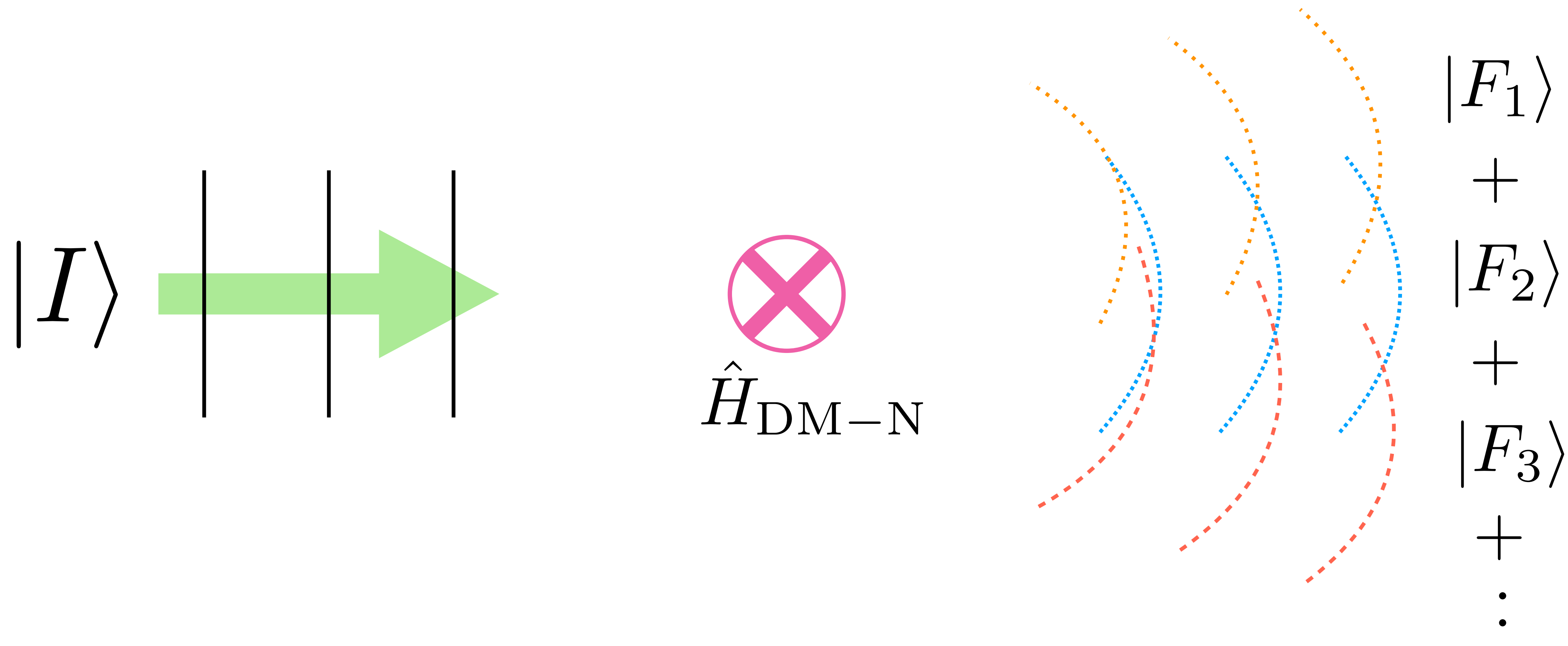
[J. D. Vergados, H. Ejiri, '05; R. Bernabei et al, '07]

Formulation

T-matrix

$$T_{FI} \simeq -2\pi\delta(E_F - E_I)\langle F|\hat{H}_{\mathrm{DM-N}}|I\rangle$$

$|F \text{ or } I\rangle = |\mathrm{DM}\rangle \otimes |\mathrm{atom}\rangle$: energy eigenstate



atomic states

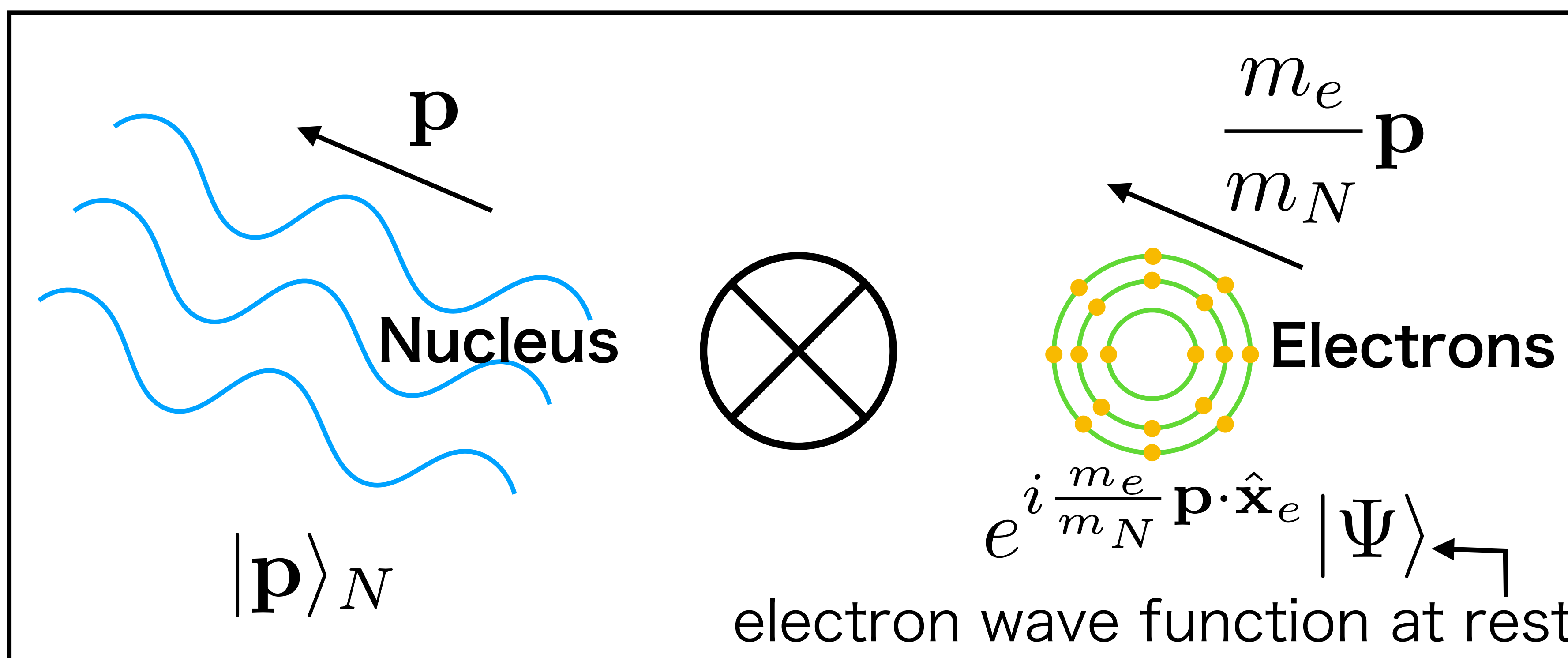
$$T_{FI} \simeq -2\pi\delta(E_F - E_I)\langle F|\hat{H}_{\mathrm{DM-N}}|I\rangle$$

$|F \text{ or } I\rangle = |\mathrm{DM}\rangle \otimes |\mathrm{atom}\rangle$: energy eigenstate

$|\mathrm{DM}\rangle$: **Plane wave of DM**

$|\mathrm{atom}\rangle$: **"Plane wave" of an atom**

$e^{-i\hat{\mathbf{x}}_N \cdot \hat{\mathbf{p}}_e} \times$



gives an approximate energy eigenstate of the total Hamiltonian

Atomic cross section

$$T_{FI} \simeq -2\pi\delta(E_F - E_I)\langle F|\hat{H}_{\mathrm{DM-N}}|I\rangle$$

We assume a contact interaction

$$\frac{d\sigma}{dE_R} \simeq \sum_{E_{ec}^F} \frac{1}{2}\frac{m_A}{\mu_N^2 v_{DM}^2}|F_A(q_A^2)|^2\bar{\sigma}_N|Z_{FI}(q_e)|^2 \ ,$$

recoil energy

$$Z_{FI}(q_e) = \langle\Psi_F|e^{-i\mathbf{q}_e\cdot\hat{\mathbf{x}}}|\Psi_I\rangle$$

$$q_e = \frac{m_e}{m_A}q_A$$

$$\bar{\sigma}_N \simeq \frac{1}{16\pi}\frac{|\mathcal{M}_{\mathrm{nuc}}(q\to 0)|^2}{(m_N + m_{\mathrm{DM}})^2}$$: DM-Nucleus X-sec.

$F_A(q_A^2)$: Nucleus form factor

$$\mu_N = \frac{m_N m_{DM}}{m_N + m_{DM}}$$: Reduced mass

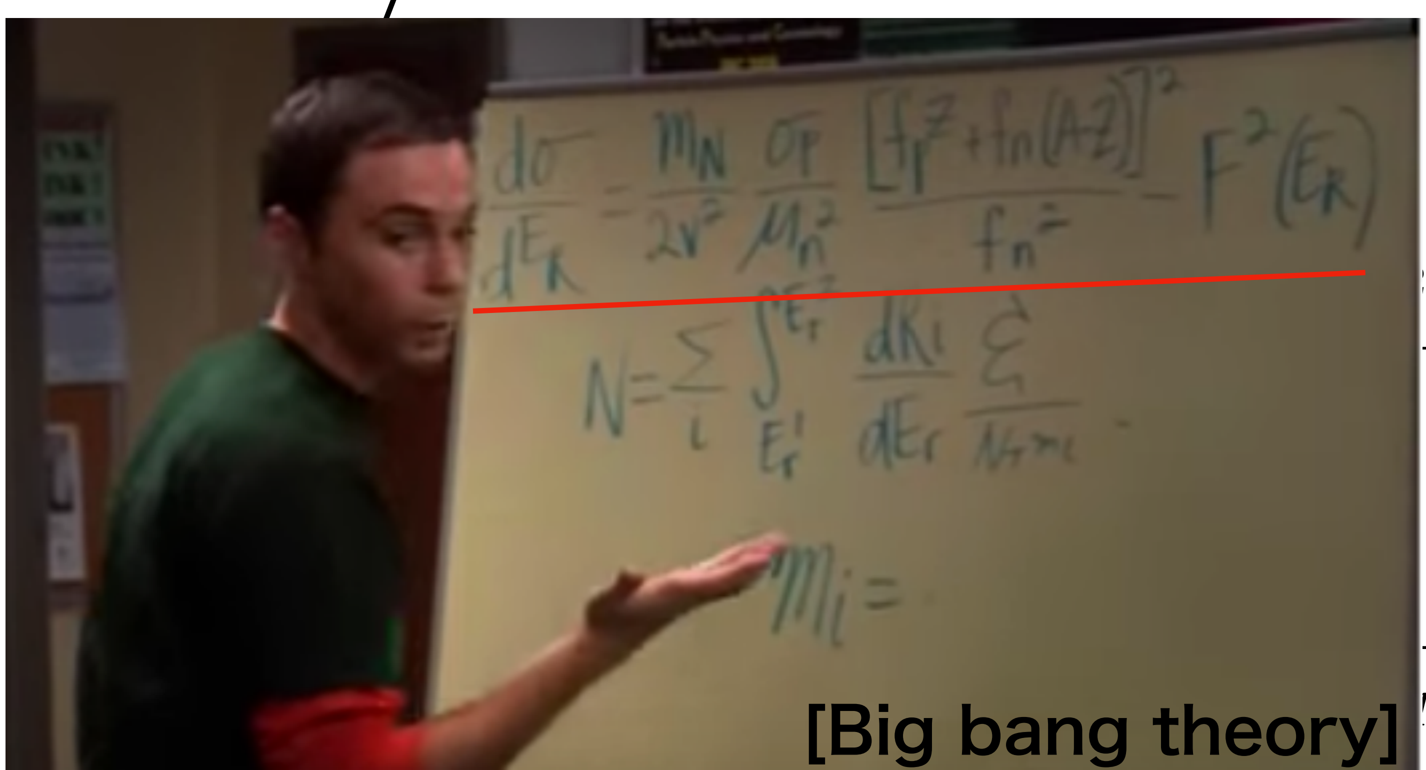
Atomic cross section

$$T_{FI} \simeq -2\pi\delta(E_F - E_I)\langle F|\hat{H}_{\mathrm{DM-N}}|I\rangle$$

We assume a contact interaction

Migdal factor

$$\frac{d\sigma}{dE_R} \simeq \sum_{E_{ec}^F} \frac{1}{2}\frac{m_A}{\mu_N^2 v_{DM}^2}|F_A(q_A^2)|^2\bar{\sigma}_N|Z_{FI}(q_e)|^2,$$



[Big bang theory]

$$Z_{FI}(q_e) = \langle\Psi_F|e^{-i\mathbf{q}_e\cdot\hat{\mathbf{x}}}|\Psi_I\rangle$$

$$q_e = \frac{m_e}{m_A}q_A$$

: DM-Nucleus X-sec.

: Nucleus form factor

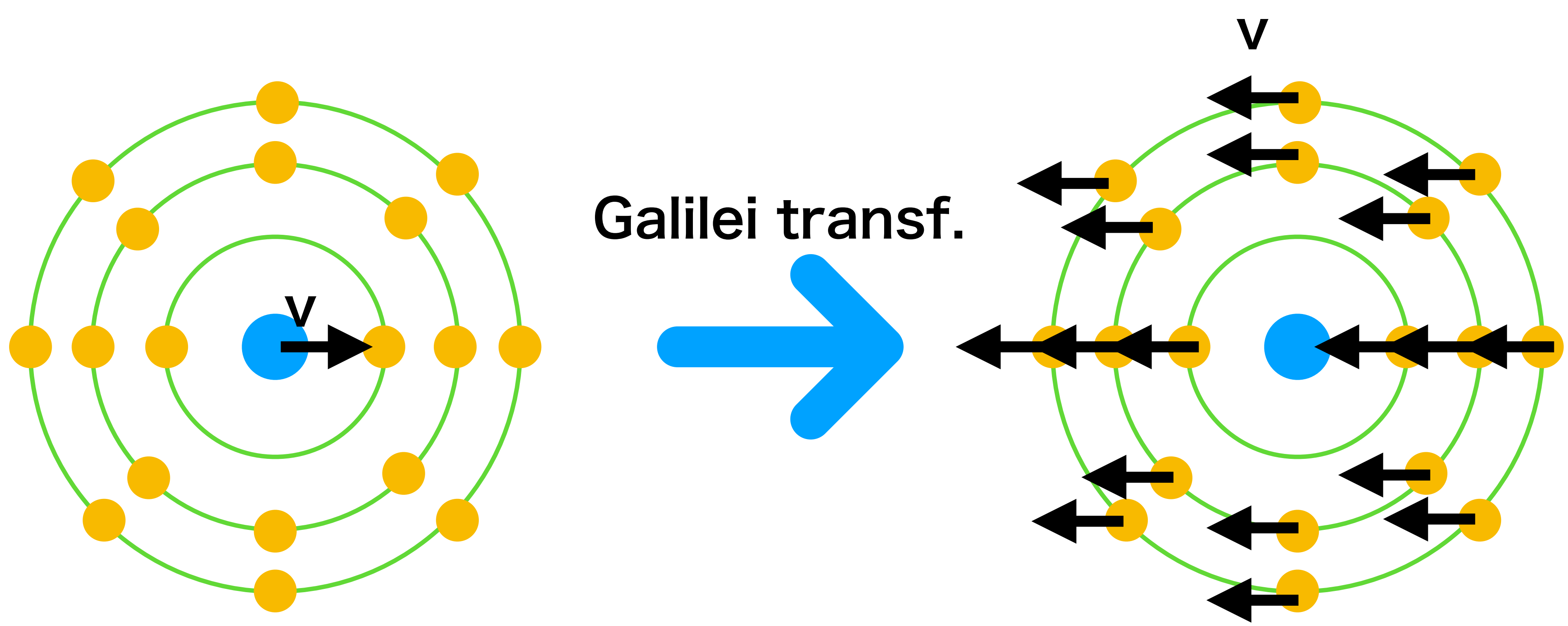
: Reduced mass

Migdal effect

[A. B. Migdal; 1939]

$$Z_{FI}(q_e) = \langle \Psi_F | e^{-i\mathbf{q}_e \cdot \hat{\mathbf{x}}} | \Psi_I \rangle$$

electron wave functions



Lab. frame

$$|\Psi_I\rangle$$

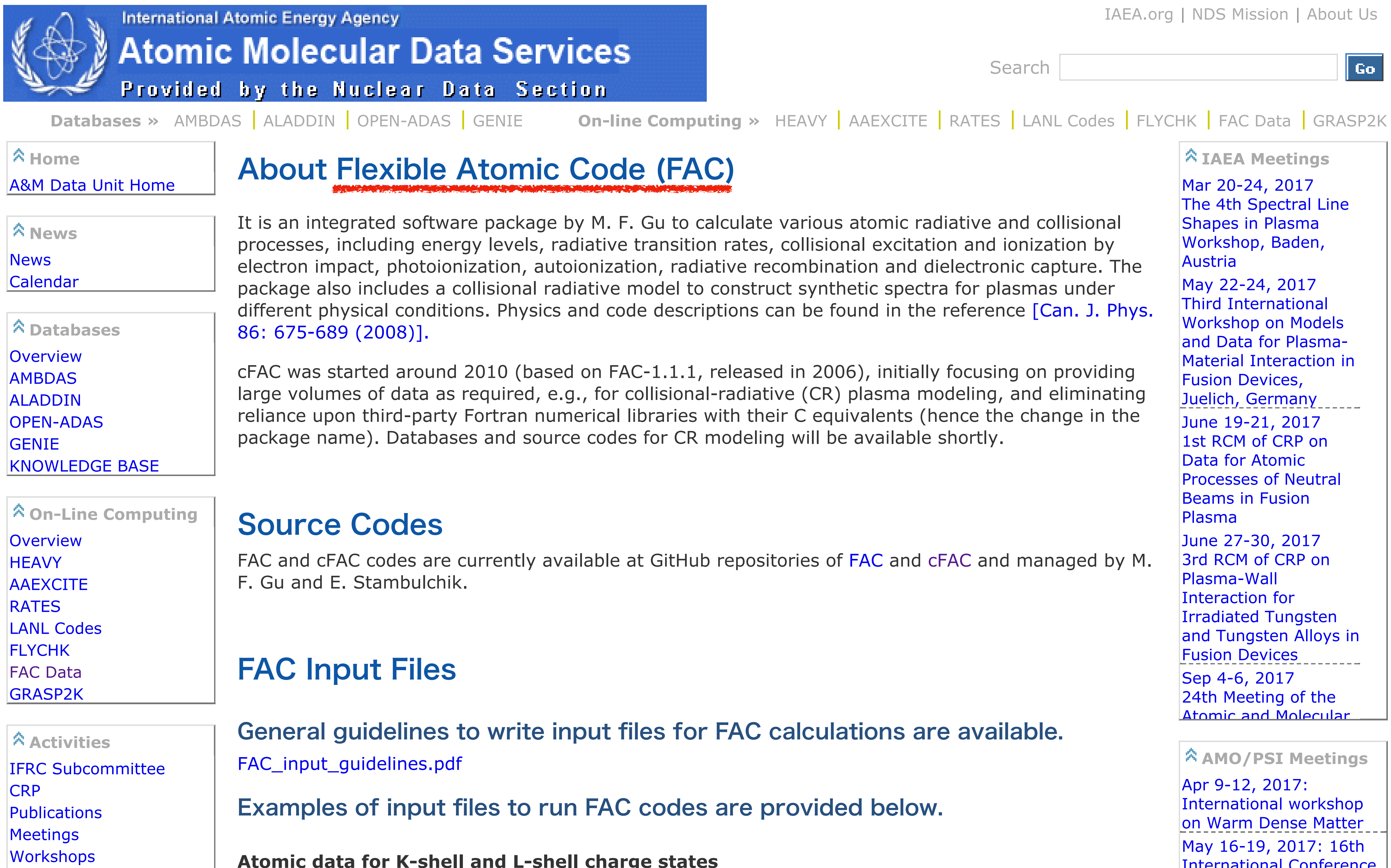
Nucleus rest frame

$$e^{-i\mathbf{q}_e \cdot \hat{\mathbf{x}}} |\Psi_I\rangle$$

$$\mathbf{q}_e = m_e \mathbf{v}$$

Electron wave functions

(Dirac-Hartree-Fock)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About Flexible Atomic Code (FAC)

It is an integrated software package by M. F. Gu to calculate various atomic radiative and collisional processes, including energy levels, radiative transition rates, collisional excitation and ionization by electron impact, photoionization, autoionization, radiative recombination and dielectronic capture. The package also includes a collisional radiative model to construct synthetic spectra for plasmas under different physical conditions. Physics and code descriptions can be found in the reference [Can. J. Phys. 86: 675-689 (2008)].

cFAC was started around 2010 (based on FAC-1.1.1, released in 2006), initially focusing on providing large volumes of data as required, e.g., for collisional-radiative (CR) plasma modeling, and eliminating reliance upon third-party Fortran numerical libraries with their C equivalents (hence the change in the package name). Databases and source codes for CR modeling will be available shortly.

Source Codes

FAC and cFAC codes are currently available at GitHub repositories of FAC and cFAC and managed by M. F. Gu and E. Stambulchik.

FAC Input Files

General guidelines to write input files for FAC calculations are available.

FAC_input_guidelines.pdf

Examples of input files to run FAC codes are provided below.

Atomic data for K-shell and L-shell charge states

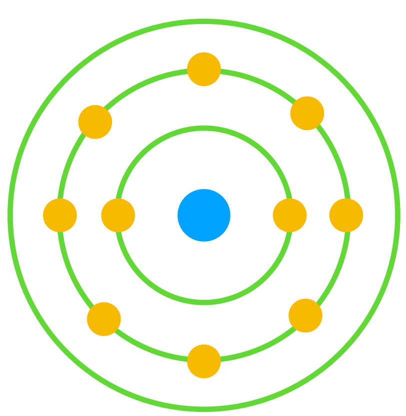
IAEA Meetings
Mar 20-24, 2017
The 4th Spectral Line Shapes in Plasma Workshop, Baden, Austria
May 22-24, 2017
Third International Workshop on Models and Data for Plasma-Material Interaction in Fusion Devices, Juelich, Germany
June 19-21, 2017
1st RCM of CRP on Data for Atomic Processes of Neutral Beams in Fusion Plasma
June 27-30, 2017
3rd RCM of CRP on Plasma-Wall Interaction for Irradiated Tungsten and Tungsten Alloys in Fusion Devices
Sep 4-6, 2017
24th Meeting of the Atomic and Molecular

AMO/PSI Meetings
Apr 9-12, 2017: International workshop on Warm Dense Matter
May 16-19, 2017: 16th International Conference

Initial/Final states

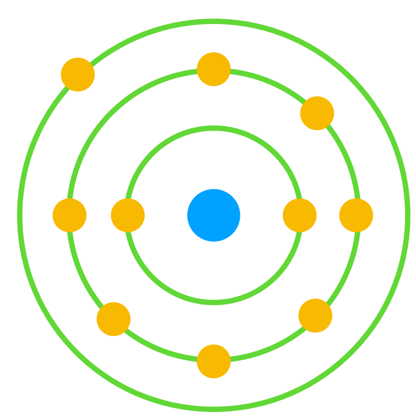
$$|\Psi_F\rangle$$

Ground state $= |\Psi_I\rangle$

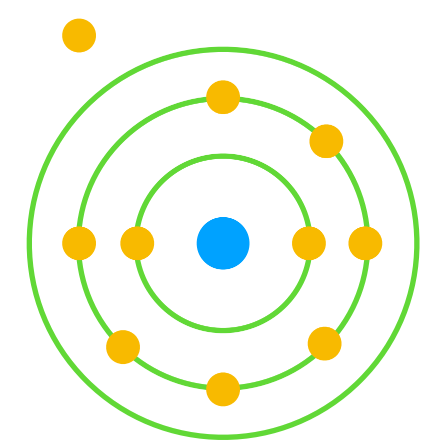


(Including an exchange of electrons)

Excited state (single electron)



Ionized state (single electron)



Migdal factor

$$|Z_{FI}(q_e)|^2 = |\langle \Psi_F | e^{-i\mathbf{q}_e \cdot \hat{\mathbf{x}}} | \Psi_I \rangle|^2 \simeq |\langle \Psi_F | \mathbf{q}_e \cdot \hat{\mathbf{x}} | \Psi_I \rangle|^2$$

$(F \neq I)$

Xe $(q_e = m_e \times 10^{-3})$

Excitation

Ionization

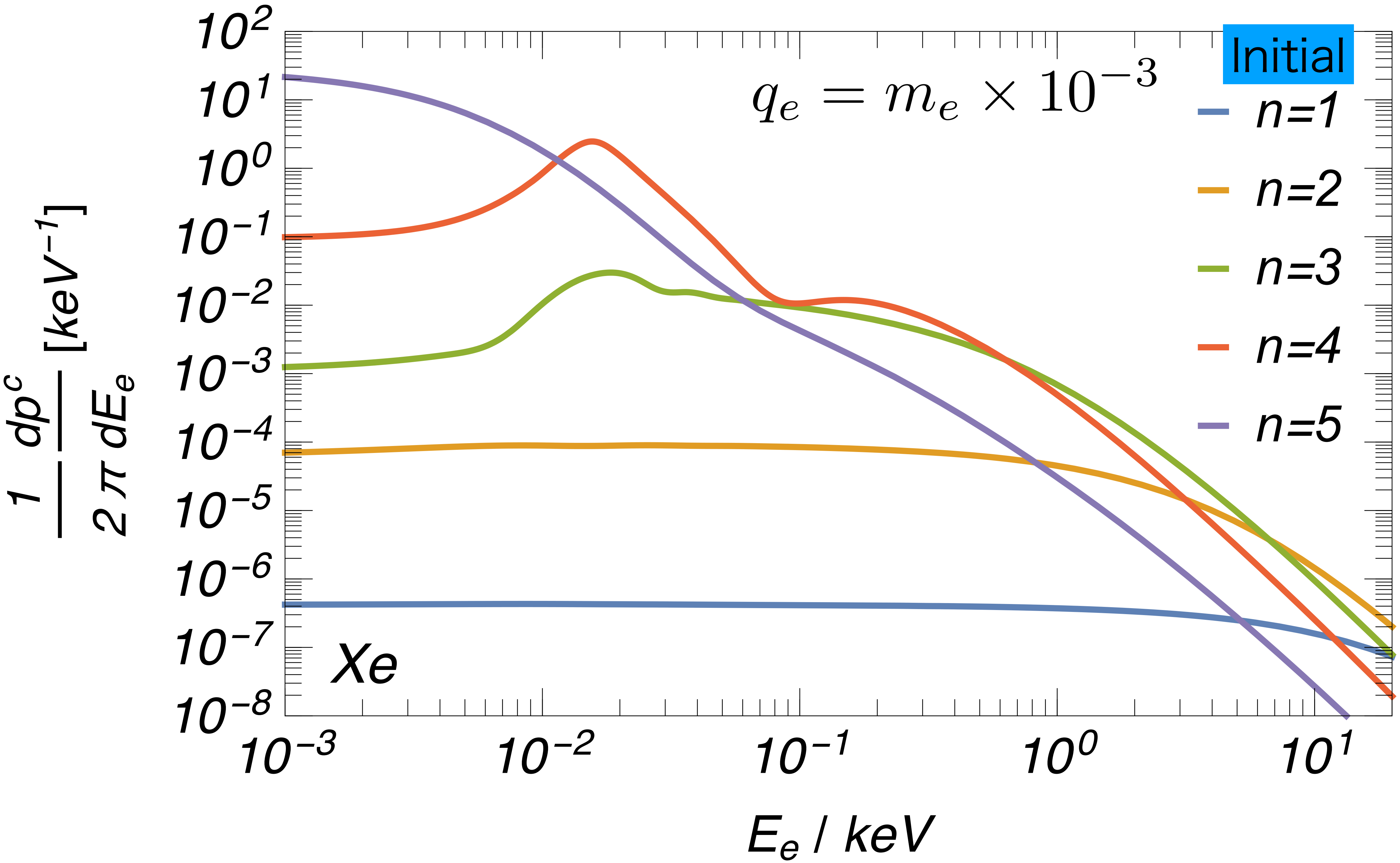
Initial

(n, ℓ)	$\mathcal{P}_{\to 4f}$	$\mathcal{P}_{\to 5d}$	$\mathcal{P}_{\to 6s}$	$\mathcal{P}_{\to 6p}$	$E_{n\ell}$ [eV]	$\frac{1}{2\pi}\int dE_e \frac{dp^c}{dE_e}$
1s	–	–	–	7.3×10^{-10}	3.5×10^4	4.6×10^{-6}
2s	–	–	–	1.8×10^{-8}	5.4×10^3	2.9×10^{-5}
2p	–	3.0×10^{-8}	6.5×10^{-9}	–	4.9×10^3	1.3×10^{-4}
3s	–	–	–	2.7×10^{-7}	1.1×10^3	8.7×10^{-5}
3p	–	3.4×10^{-7}	4.0×10^{-7}	–	9.3×10^2	5.2×10^{-4}
3d	2.3×10^{-9}	–	–	4.3×10^{-7}	6.6×10^2	3.5×10^{-3}
4s	–	–	–	3.1×10^{-6}	2.0×10^2	3.4×10^{-4}
4p	–	4.1×10^{-8}	3.0×10^{-5}	–	1.4×10^2	1.4×10^{-3}
4d	7.0×10^{-7}	–	–	1.5×10^{-4}	6.1×10	3.4×10^{-2}
5s	–	–	–	1.2×10^{-4}	2.1×10	4.1×10^{-4}
5p	–	3.6×10^{-2}	2.1×10^{-2}	–	9.8	1.0×10^{-1}

(n, ℓ)	$4f$	$5d$	$6s$	$6p$
$E_{n\ell}$[eV]	0.85	1.6	3.3	2.2

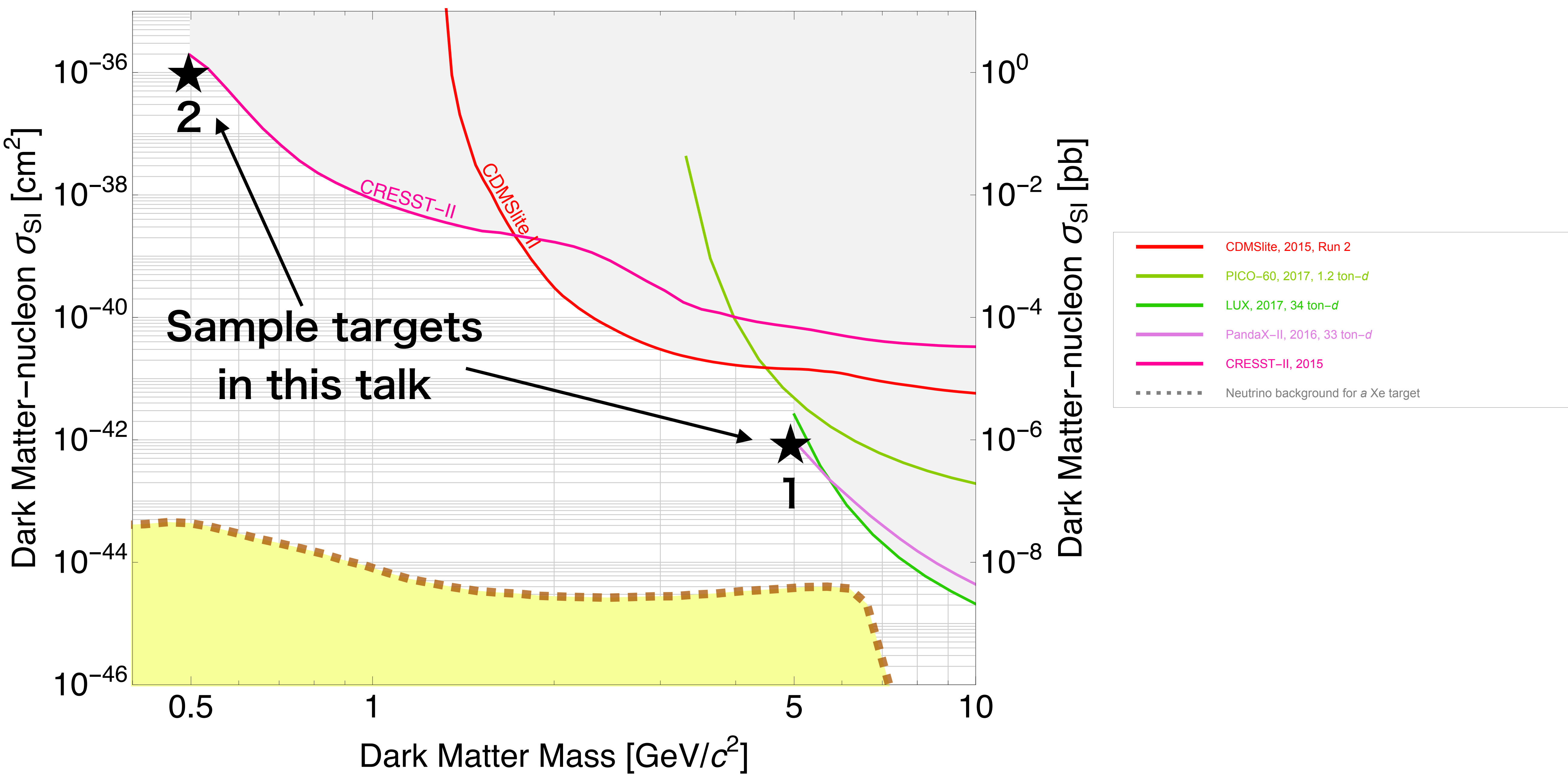
Spectrum of ionized electron

$$|Z_{FI}(q_e)|^2 = |\langle \Psi_F | e^{-i\mathbf{q}_e \cdot \hat{\mathbf{x}}} | \Psi_I \rangle|^2 \simeq |\langle \Psi_F | \mathbf{q}_e \cdot \hat{\mathbf{x}} | \Psi_I \rangle|^2 \quad (F \neq I)$$



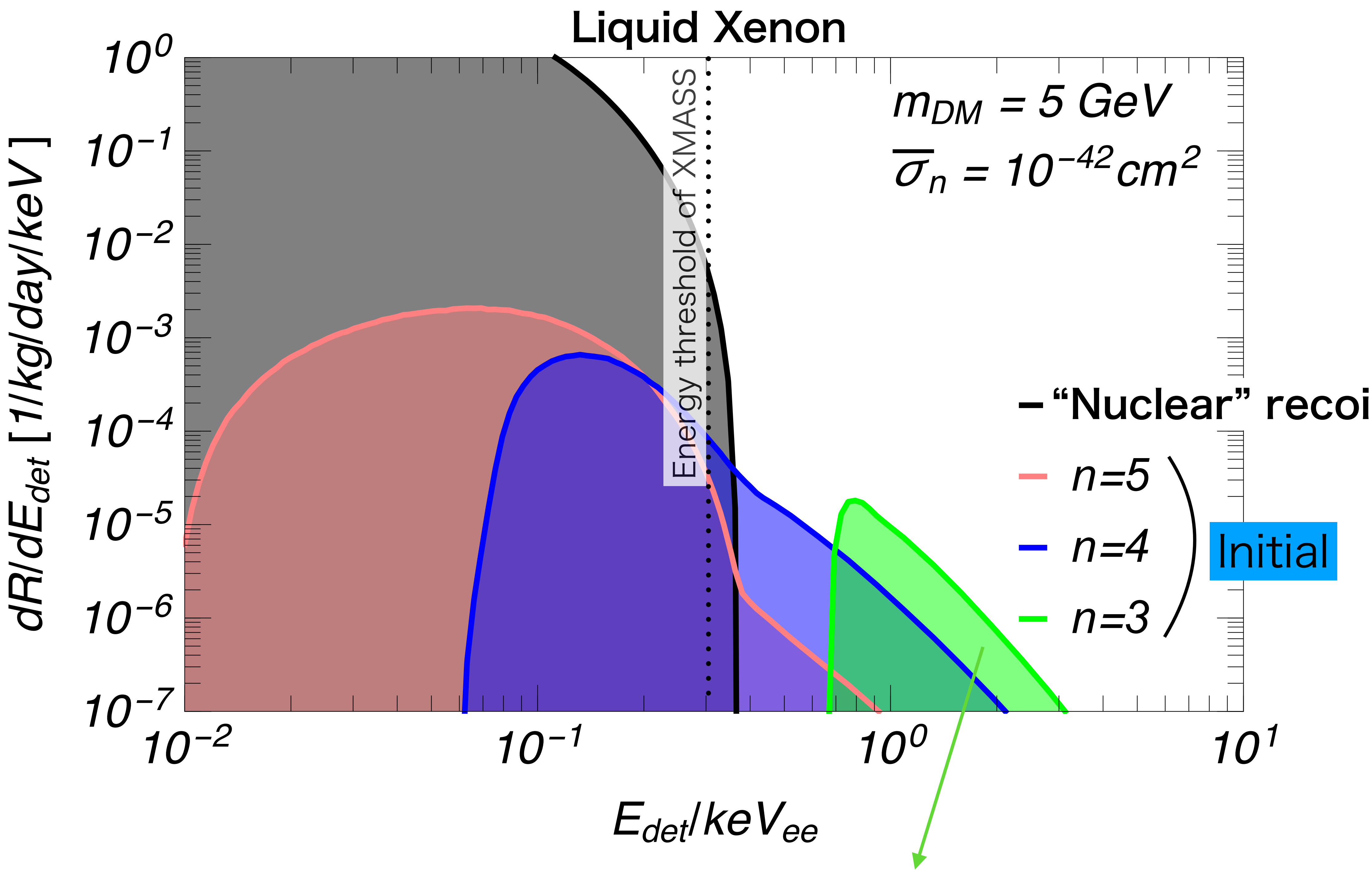
Results

DD of light DM



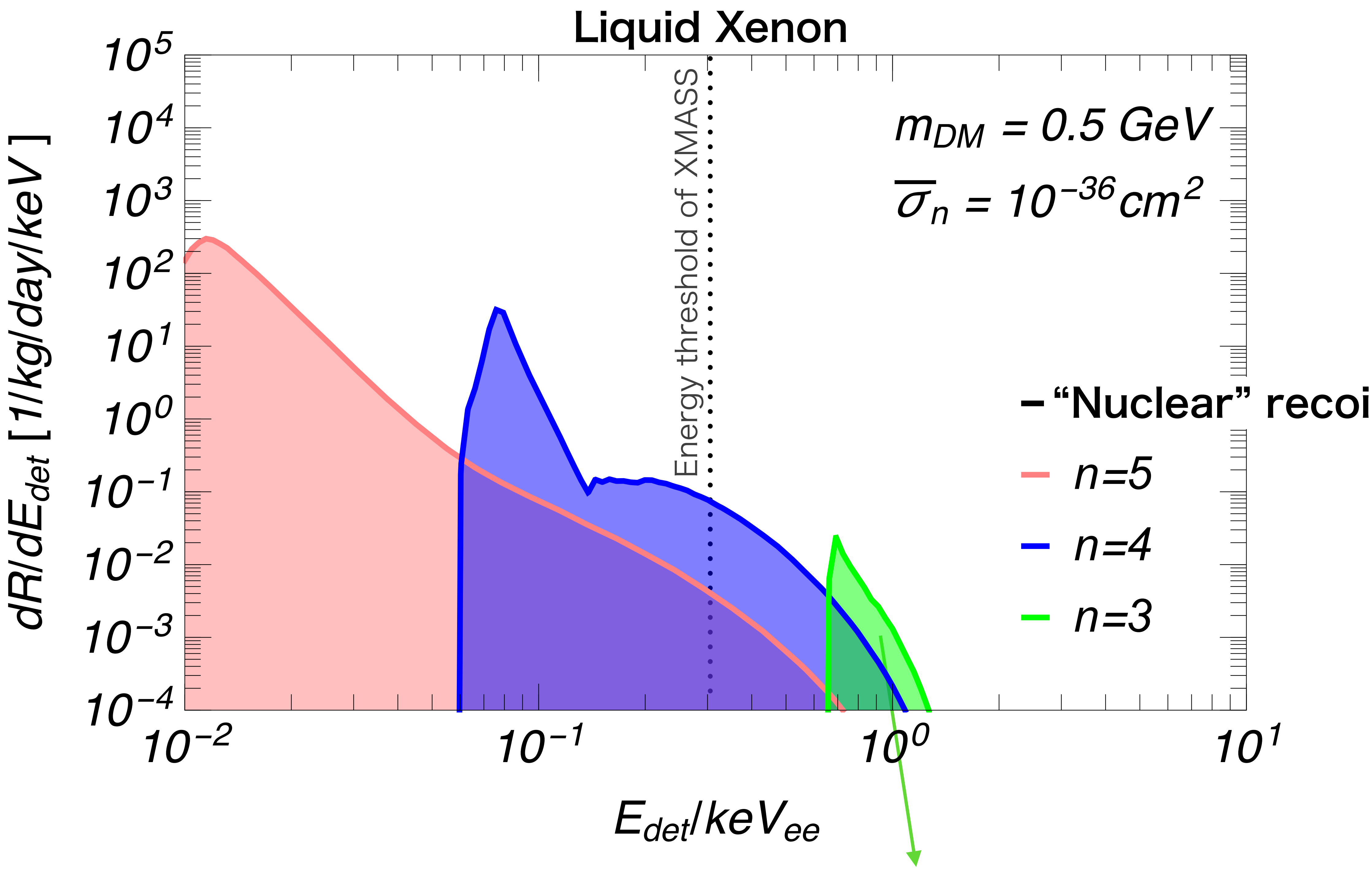
WIMP Limit Plotter

Result 1



a few events expected for 10^5 kg days

Result 2

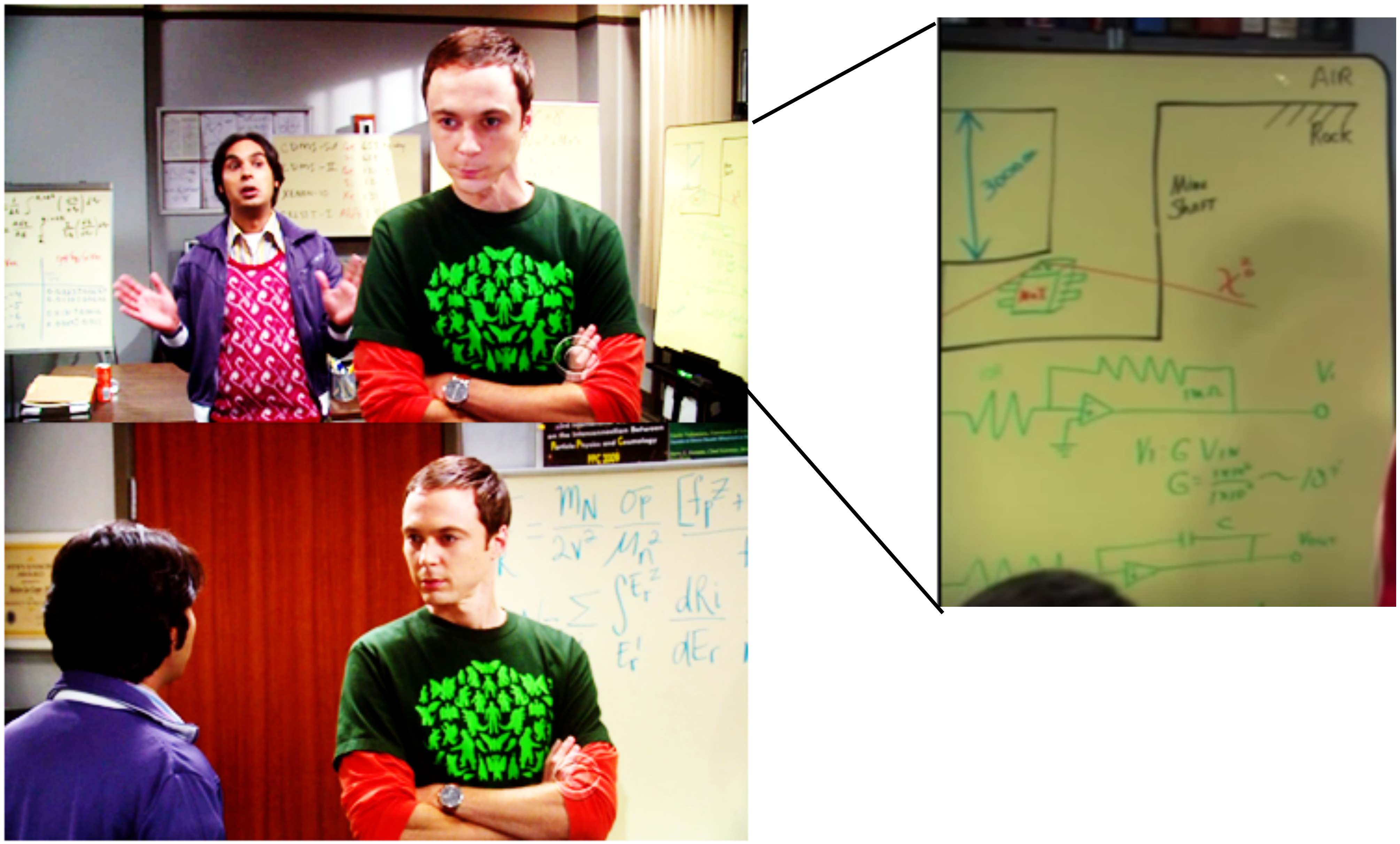


a few hundred events expected for 10^5 kg days

Summary

- When we discuss the direct detection of DM, we usually assume that the recoil atom is not excited or ionized.
- If we consider excitation and ionization, we expect more efficient scintillation due to emitted electrons and photons from the recoil atom.
- We re-formulated the scattering of DM and an atom with the utmost care to the transition rates of electrons, which is not correctly discussed in the previous works.
- Including the excitation/ionization effects, we can search for dark matter with a few or sub- GeV mass even with existing detectors.

Thank you!



RAJ; Oooh, dark matter! We better bring a flashlight. ...I was making a joke.

SHELDON; I'm the boss. I make the jokes.

[Big bang theory]