Theoretical Calculations for sub-GeV Dark Matter Detection

Jiunn-Wei Chen
National Taiwan U.

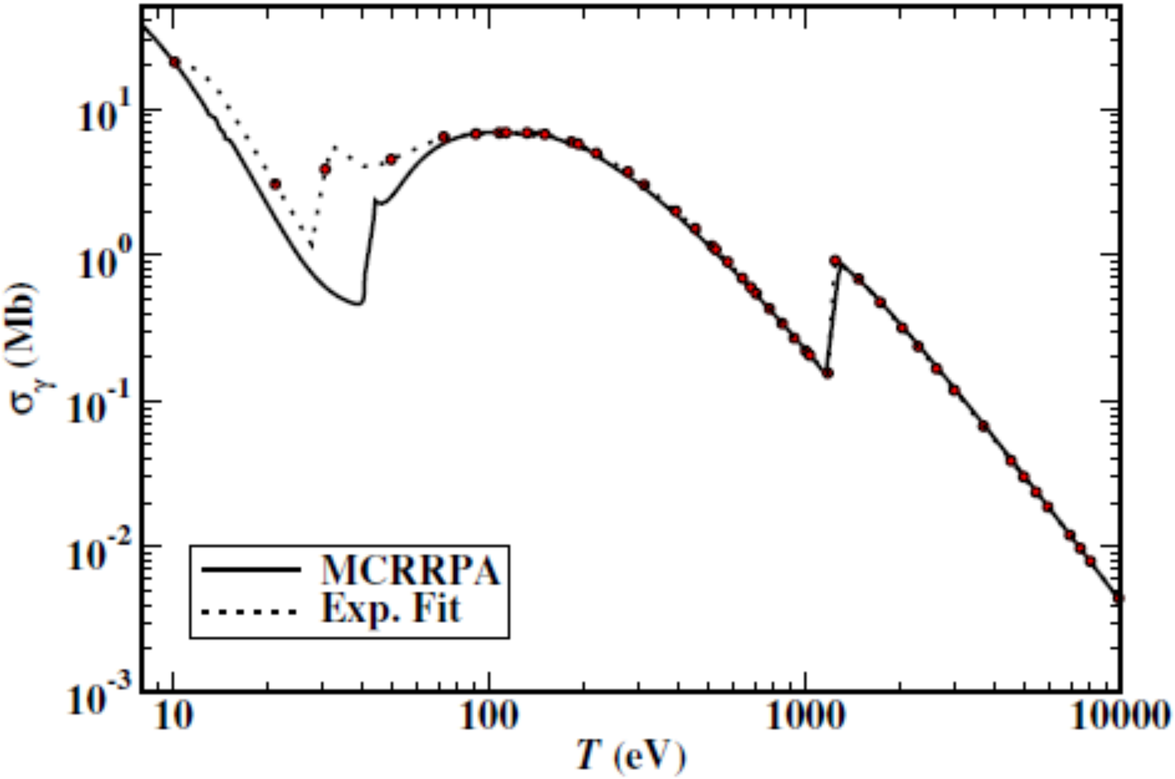
Collaborators:

Chih-Pang Wu (Montreal), Chung-Chun Hsieh, Mukesh Pandey (NTU) Chen-Pang Liu, Hsin-Chang Chih (NDHU) Henry T. Wong, Lakhwinder Singh (AS) Keh-Ning Huang, Hao-Tse Shiao, Hao-Bin Li (AS), Chih-Liang Wu (MIT)

Sub-GeV Dark Matter

- Energy transfer might be more efficient with electron recoils (EC) than nuclear recoils (NC)
- DM: direct detection, velocity slow (~ 1/1000), max energy 1 keV for mass 1 GeV DM.
- Opportunity: Applying atomic physics at keV (low for nuclear physics but high for atomic physics)

Benchmark: Ge Photoionization



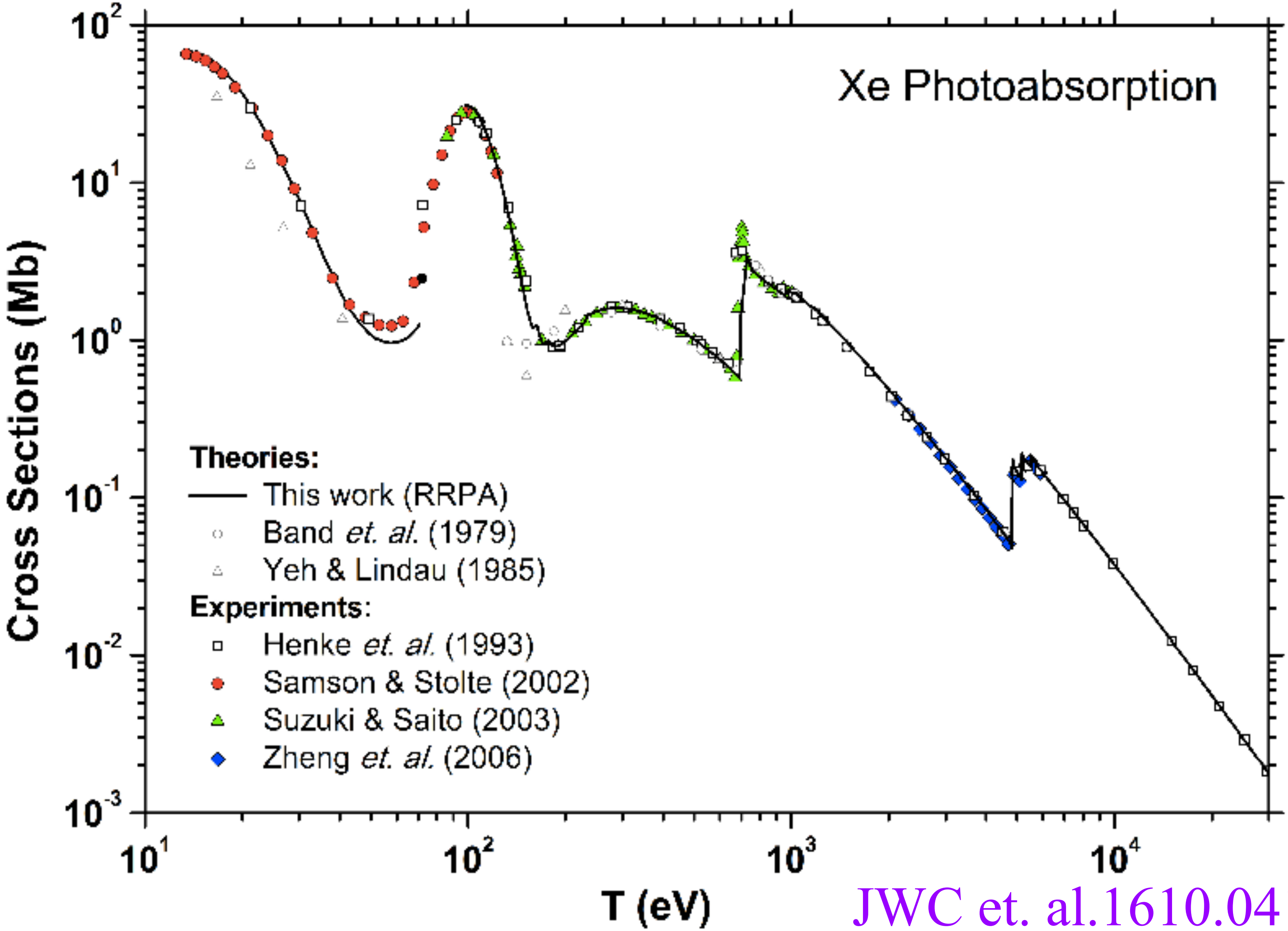
Exp. data: Ge solid

Theory: Ge atom (gas)

Above 100 eV error under 5%.

JWC et. al.
arXiv: 1311.5294

Benchmark: Xe Photoionization



JWC et. al.1610.04177

ab initio MCRRPA Theory

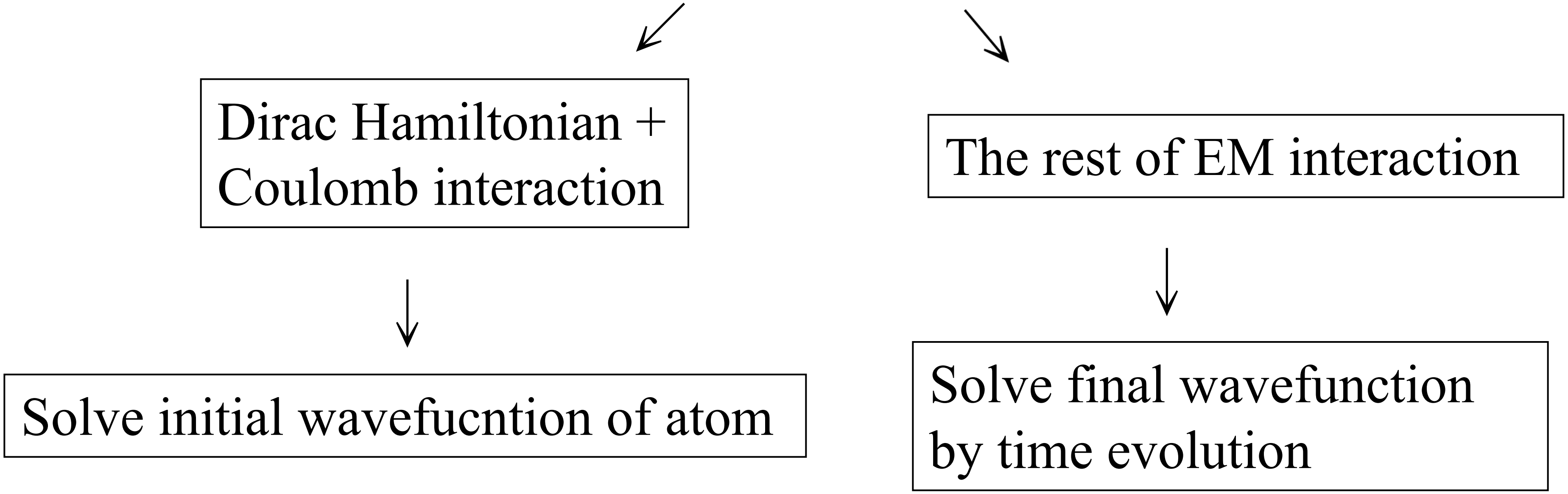
- MCRRPA: multiconfiguration relativistic random phase approx.

Hartree-Fock :	Reducing the N-body problem to a 1-body problem by solving the 1-body effective potential self consistently.
↓	
RPA:	Including 2 particle 2 hole excitations
↓	
RRPA:	Correcting the relativistic effect
↓	
MCRRPA:	More than one configurations in Hartree-Fock; Important for open shell system like Ge where the energy gap is smaller than the closed shell case

MCRRPA Theory

N-electron relativistic Hamiltonian

$$\mathcal{H}(t) = H + V(t)$$



Dirac Hamiltonian + Coulomb interaction

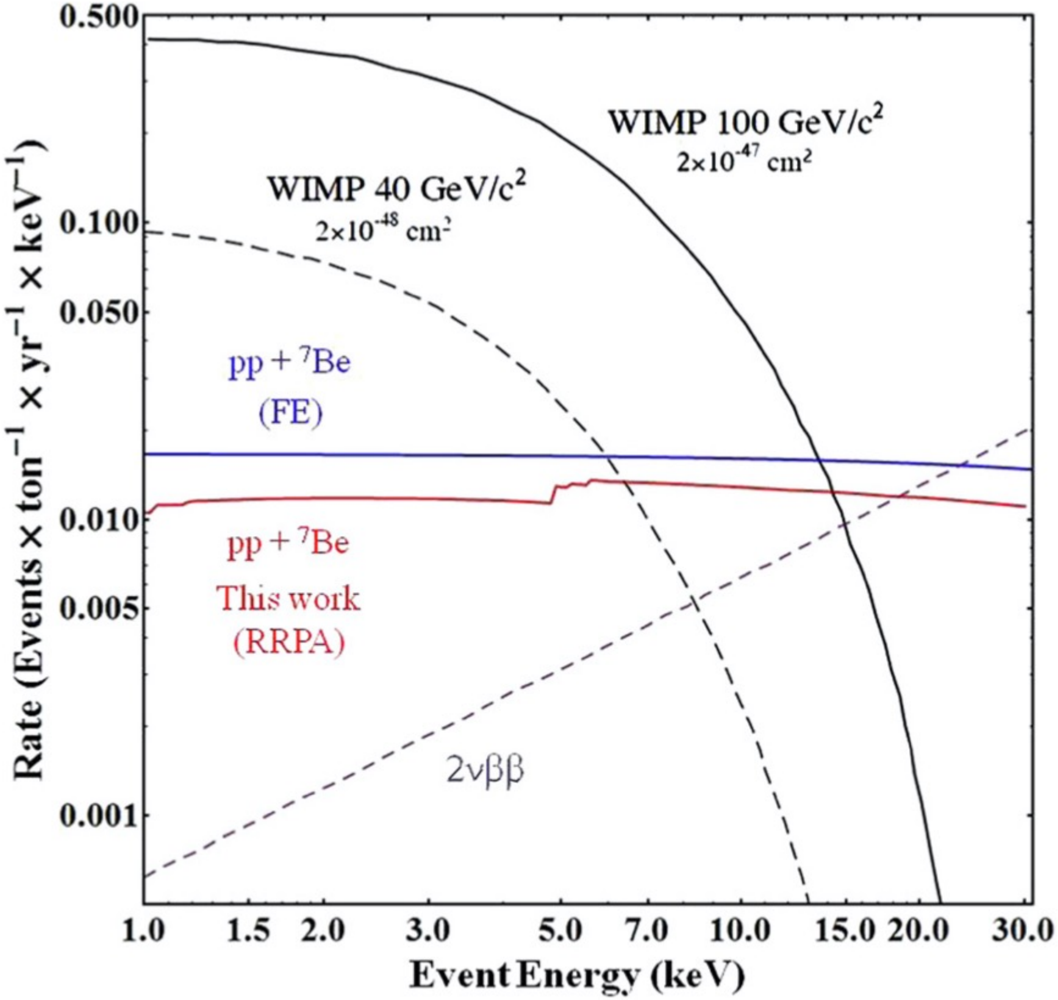
Solve initial wavefucntion of atom

The rest of EM interaction

Solve final wavefunction by time evolution

A small detour to neutrino physics…

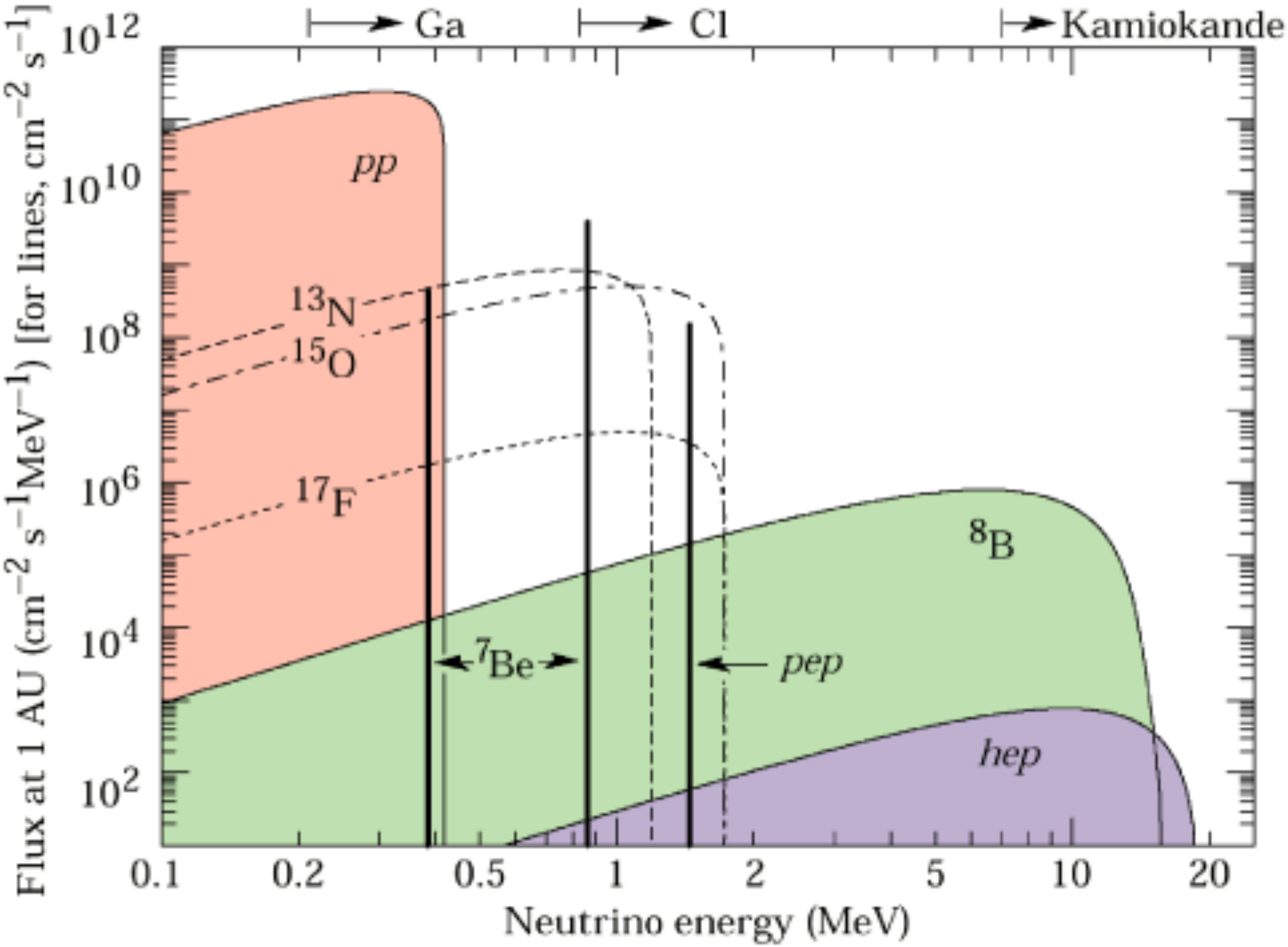
$\nu + A \to \nu' + A^+ + e^-$ EC Background for DARWIN (LXe) 2-30 keV, Error 2-3%



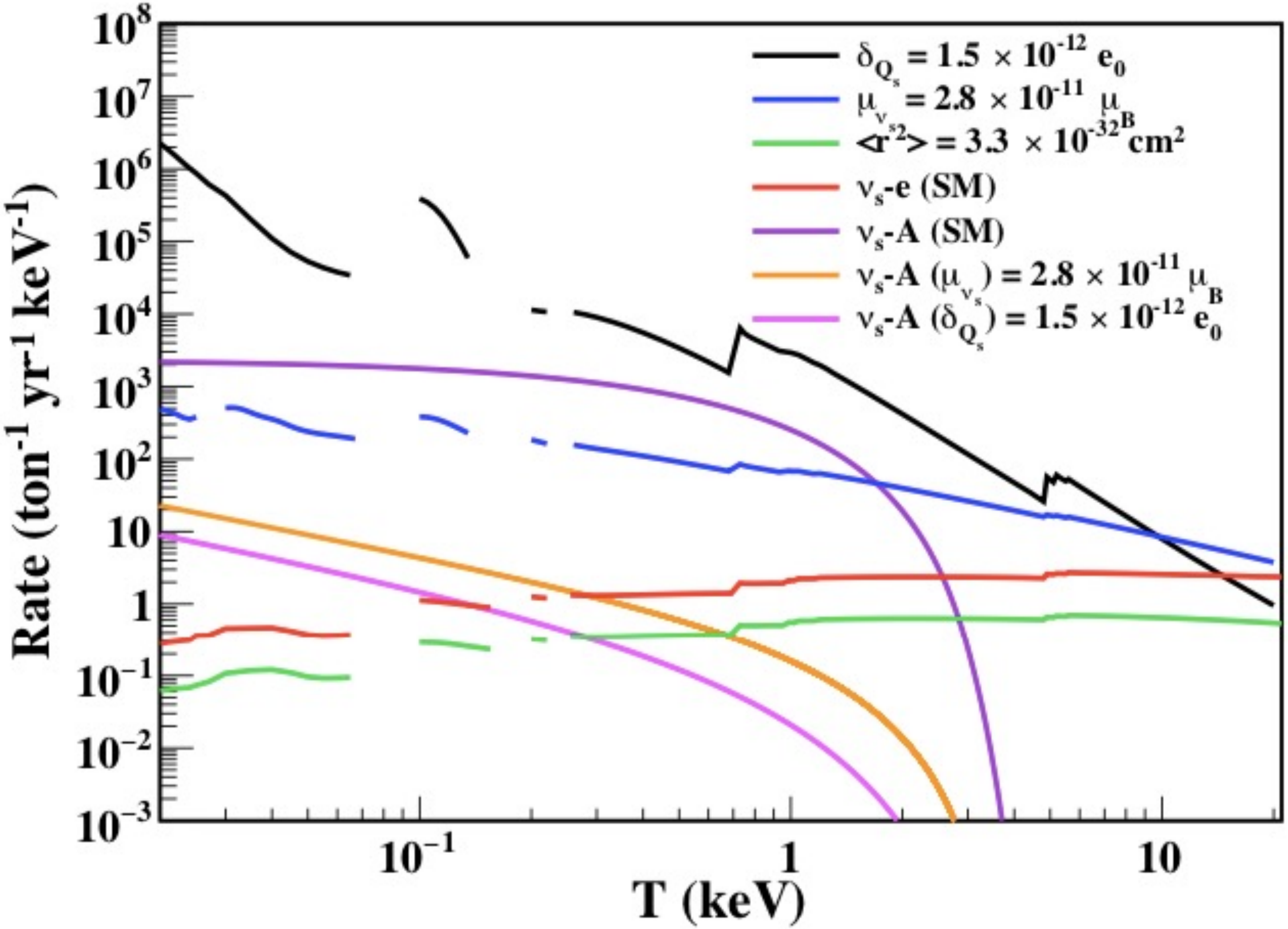
99.5% ER Rejection, 50% NR acceptance

JWC et. al. 1610.04177

Solar Neutrino Flux



Xe atomic ionization with ab initio MCRRPA Theory



CC Hsieh et. al. 1903.06085

Multi-ton LXe detectors are also excellent solar neutrino detectors!

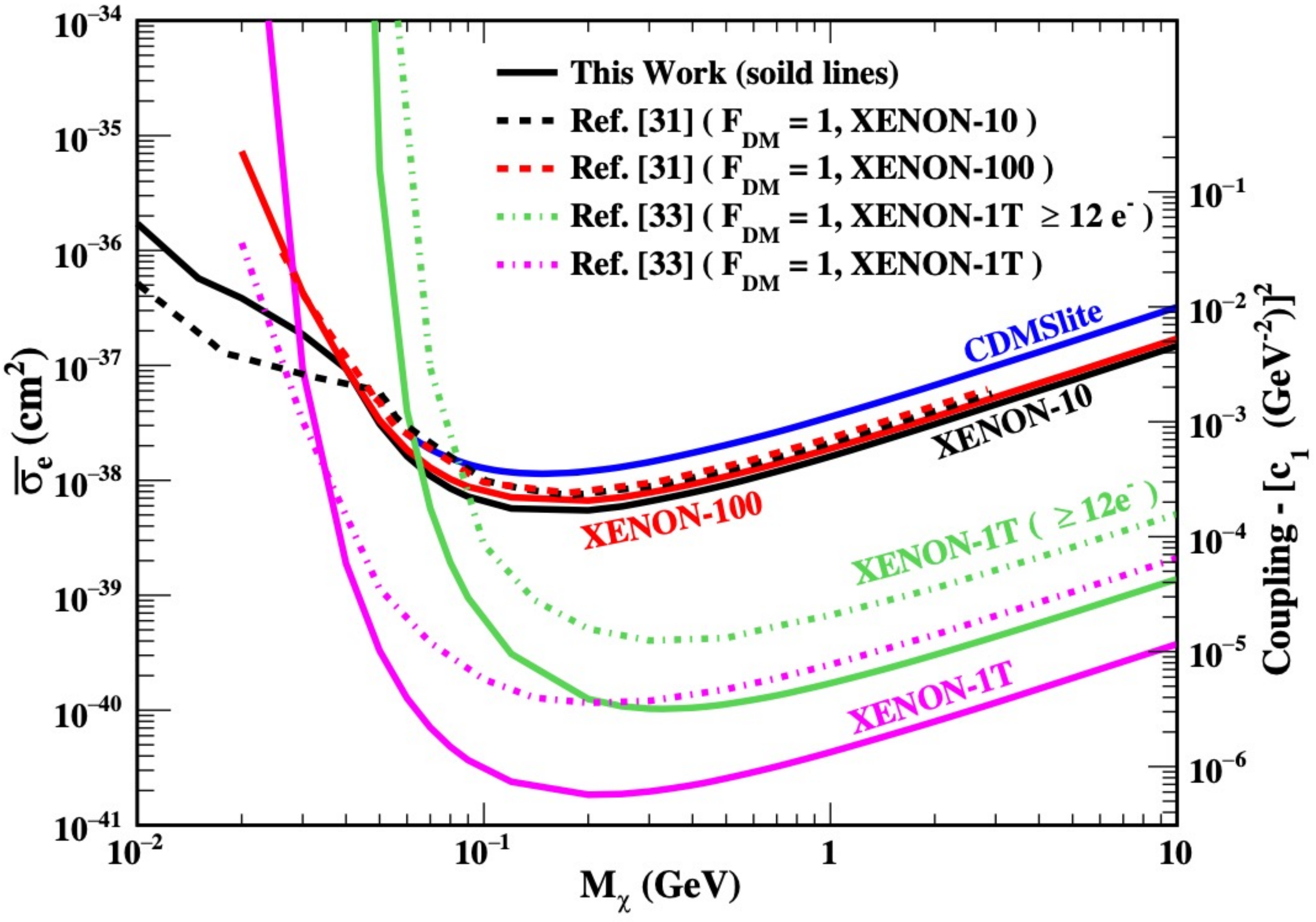
Direct Light Dark Matter Detection

$$\chi + A \to \chi' + A^+ + e^-$$

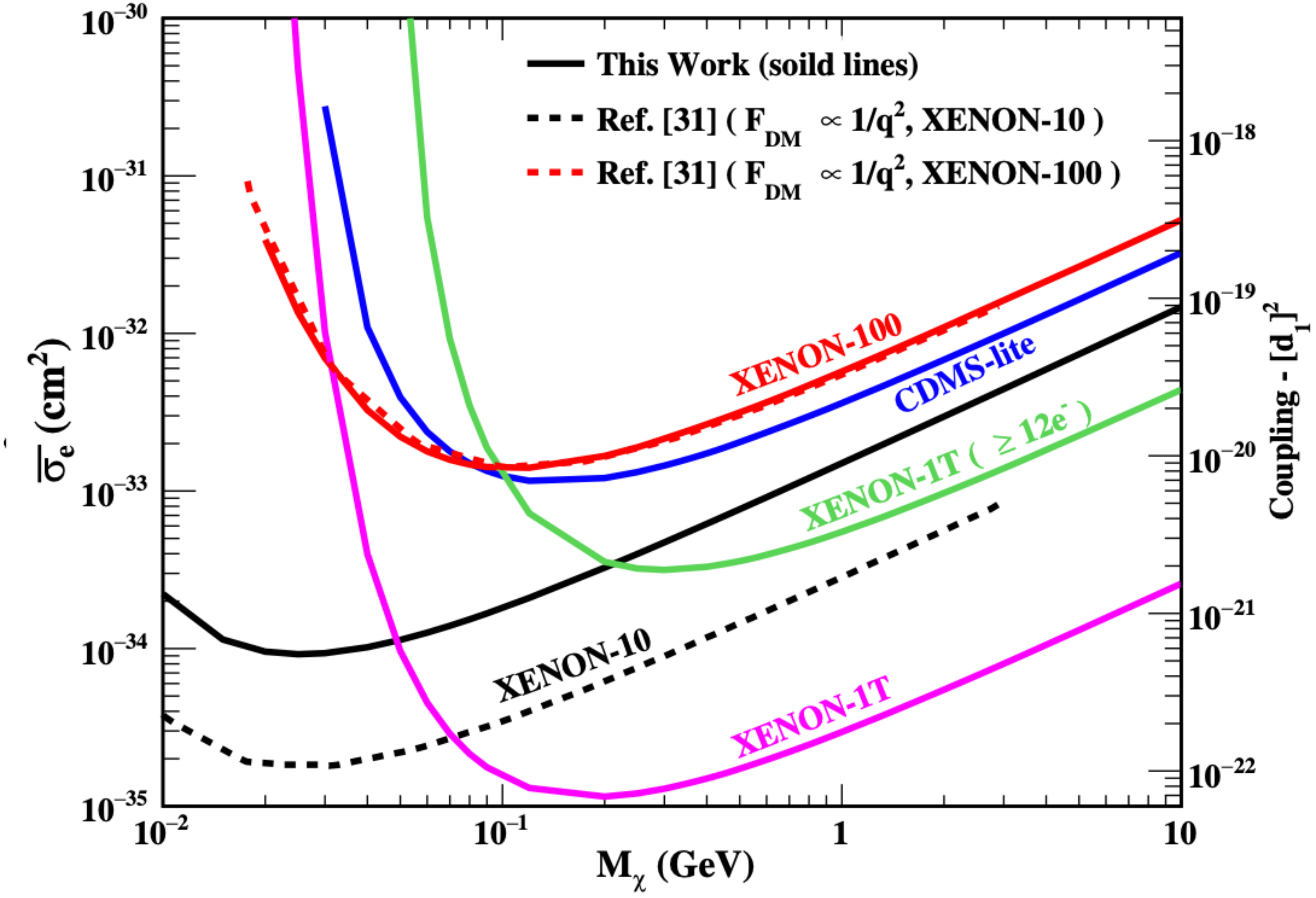
$$\mathcal{L}_{\mathrm{SI}}^{(\mathrm{LO})} = c_1 (\chi^\dagger \chi)(e^\dagger e) + d_1 \frac{1}{q^2} (\chi^\dagger \chi)(e^\dagger e)$$

MK Pandey et. al. 1903.06085

Bounds on Short Range Spin Independent DM-e Coupling



Bounds on Long Range Spin Independent DM-e Coupling

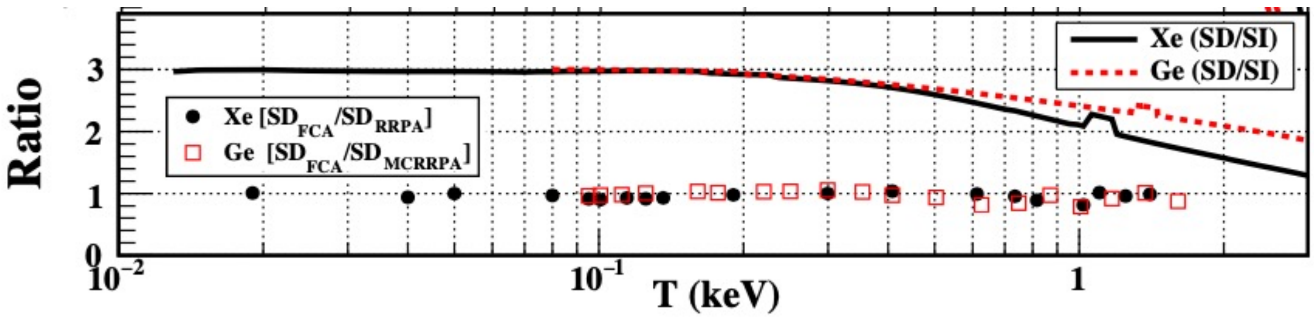


Spin Dependent Cases

$$\mathcal{L}_{\rm SI}^{(\rm LO)} = c_1(\chi^\dagger\chi)(e^\dagger e) + d_1\frac{1}{q^2}(\chi^\dagger\chi)(e^\dagger e)$$

$$\mathscr{L}_{\rm SD}^{(\rm LO)} = (c_4 + d_4/q^2)\left(\chi^\dagger\vec{S}_\chi\chi\right)\cdot\left(e^\dagger\vec{S}_e e\right)$$

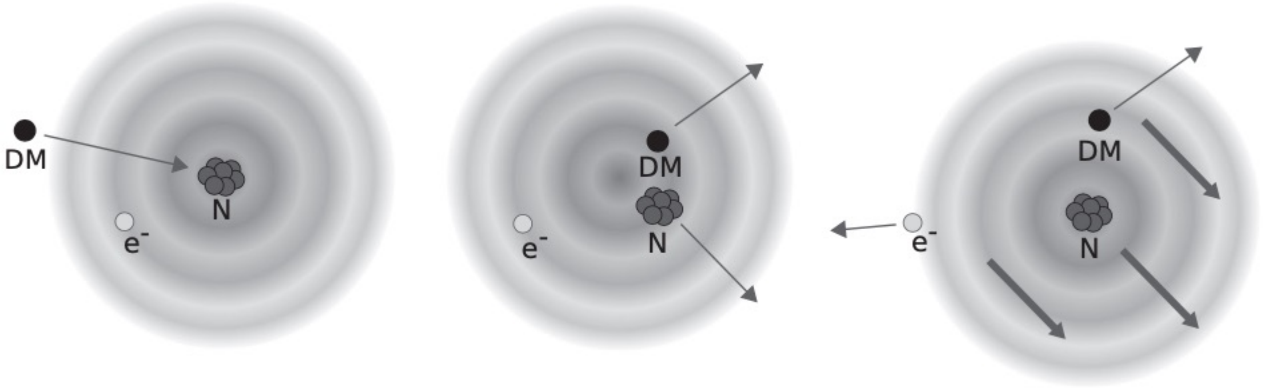
$$\xi = R_{\rm SD}^{(\rm ion)}/R_{\rm SI}^{(\rm ion)}$$



CP Liu et. al. 2106.16214

Migdal effect

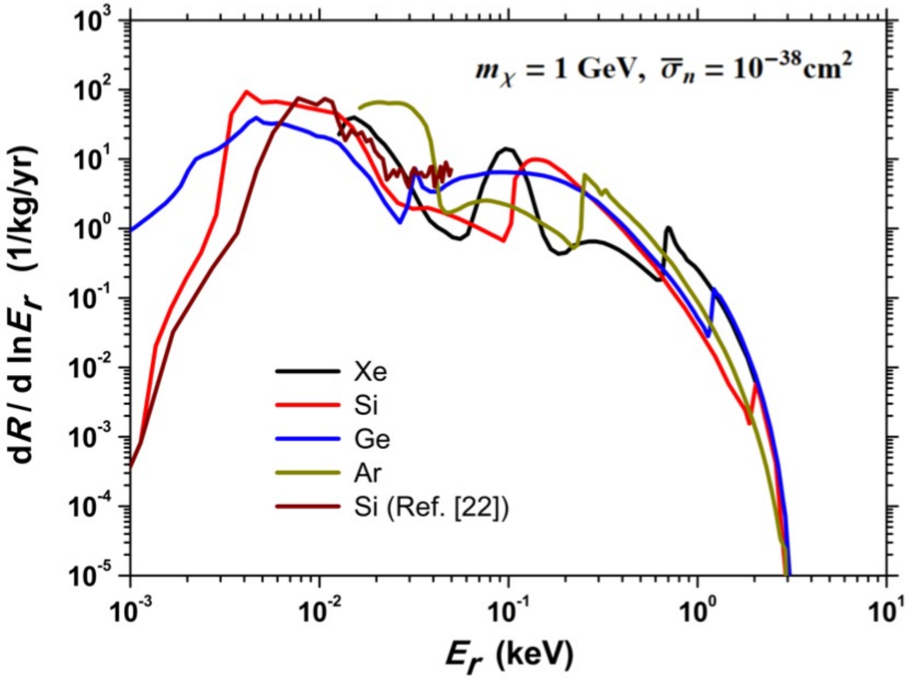
- EC signal below NC threshold (Dolan, Kahlhoefer, McCabe, ‘18)



Migdal effect via photoabsorption

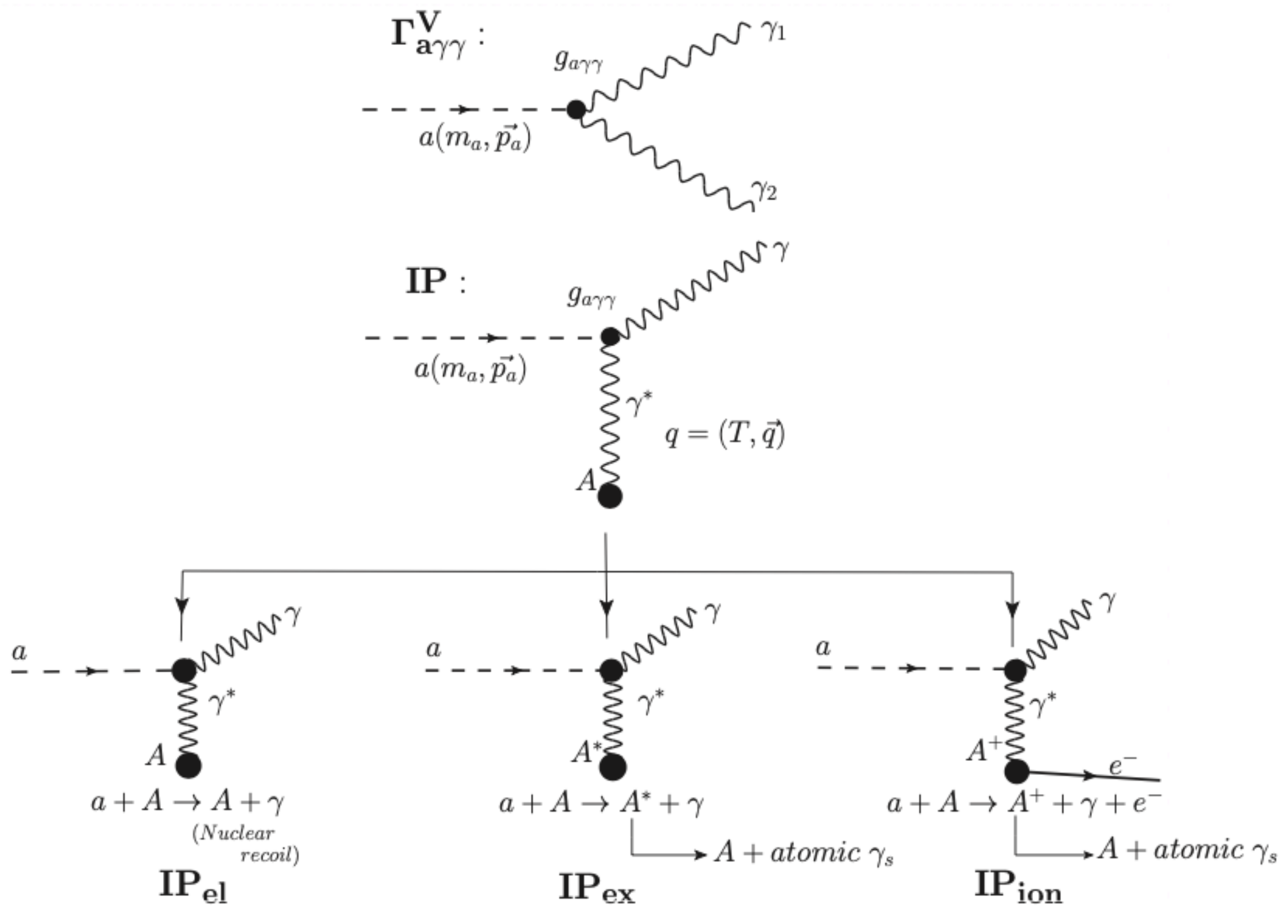
- CP Liu et al.: 2007.10965

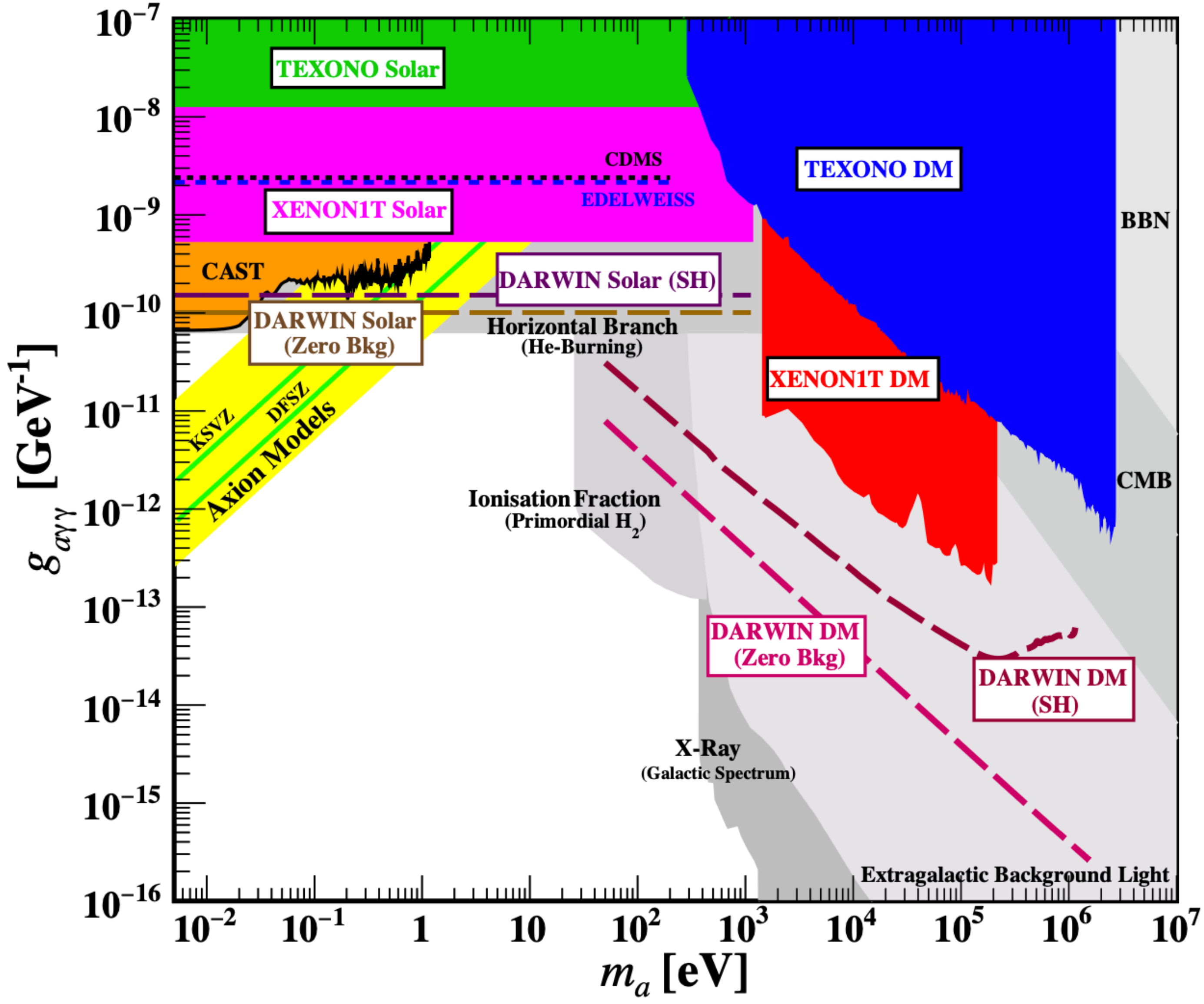
$$\frac{d\sigma^{(\mathrm{MPA})}}{dE_R dE_r} = \frac{m_e^2}{\mu_N^2 v_\chi^2} \tilde{\sigma}_N(q_A) \frac{E_R}{E_r} \frac{\sigma_\gamma(E_r)}{4\pi^2\alpha}$$



New Limits on Axionlike Particle Coupling with the Photons

- C.-P. Wu et al.: 2206.07878





C.-P. Wu et al.: 2206.07878

Summary

- Ab initio atomic tool indispensible to study DM detector response to light DM signal and neutrino background.
- Multi-ton LXe detectors could be very good solar neutrino detectors to measure pp flux to a few percent accuracy (limited by theory error) and constrain exotic neutrino electromagnetic properties with high precision.

Backup slides

Backup slides

SI DM-e comparison