# What Can Atomic Physics Contribute to Neutrino and Light Dark Matter Detections?

Jiunn-Wei Chen

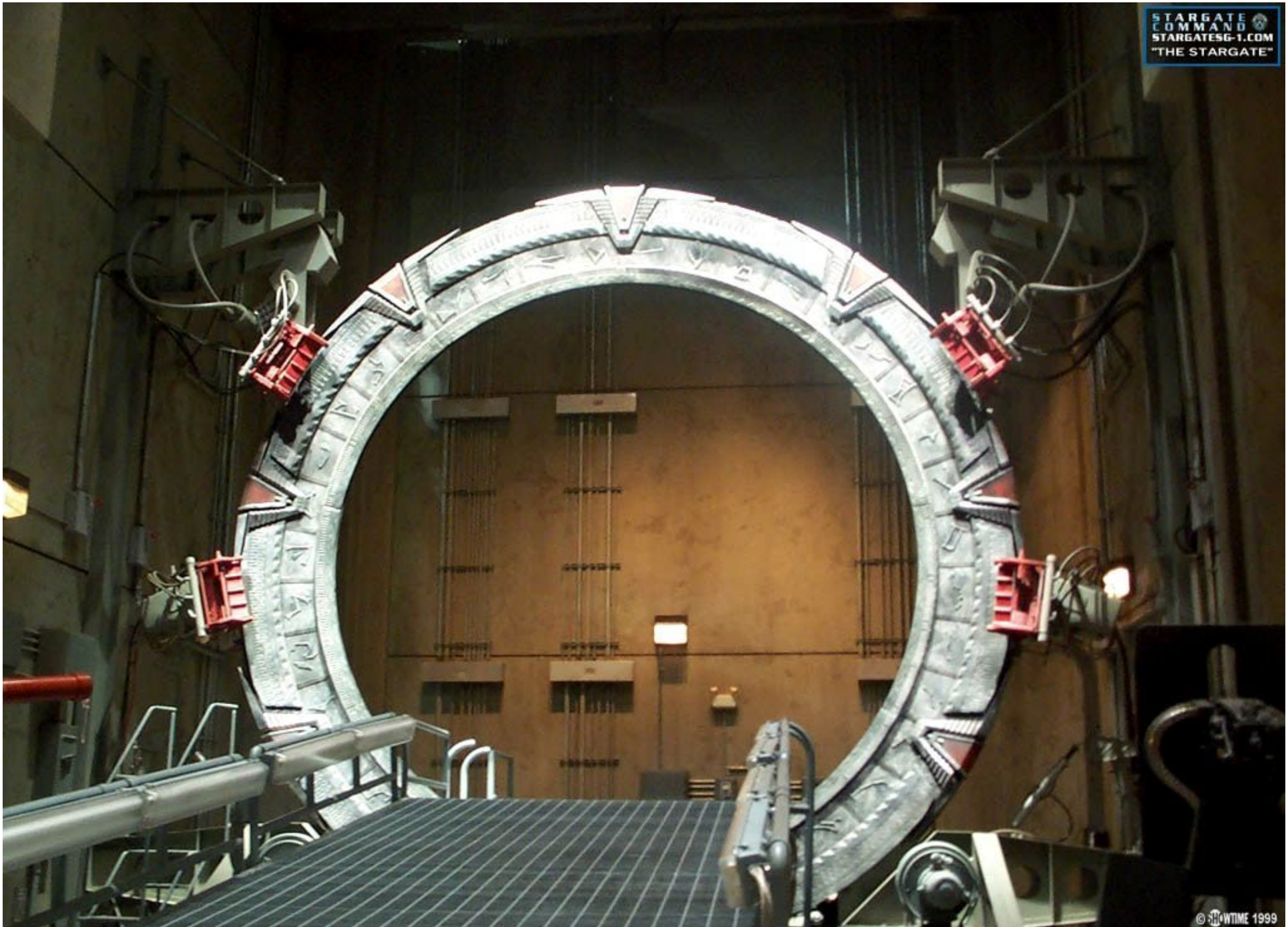
National Taiwan U. / MIT

Collaborators:

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

# Why Bother?

# Neutrino and Dark Matter are Portals to New Physics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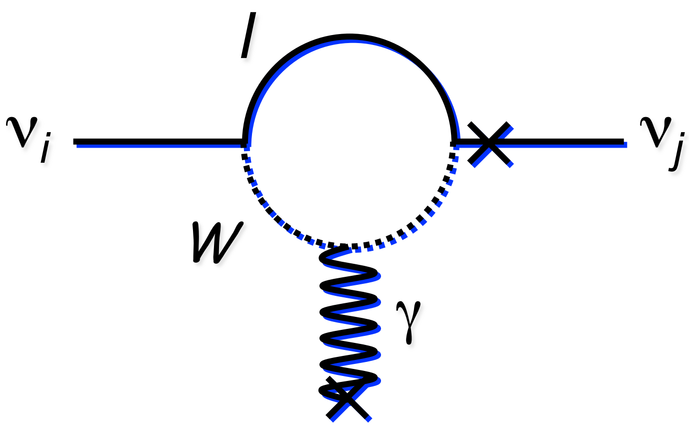
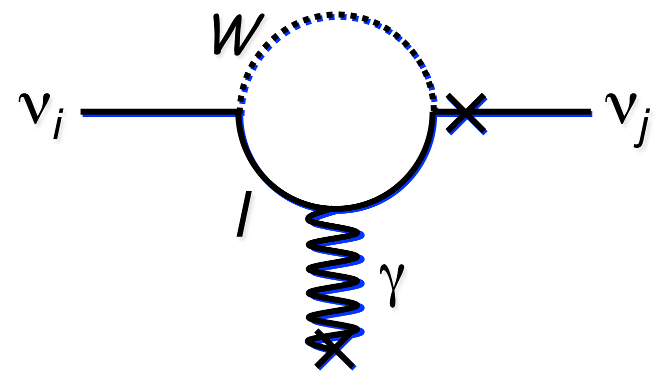
# Neutrino: Challenges and Opportunities

- Mass: hierarchy and absolute values
- Dirac or Majorana?
- CP phase(s)
- Sterile neutrinos?
- Electromagnetic properties: magnetic moments? Charge Radius?...

Those are probes of new physics!

# How neutrino magnetic moment arises in SM?




$$\mu_\nu \approx 10^{-19} \mu_B \cdot \left( \frac{m_\nu}{1\,\mathrm{eV}} \right)$$

A probe of new physics!

# Dark Matter (DM)

- Bigger density than the visible Universe
- Its existence hints that there might be a dark sector

# Portals to the Dark Sector

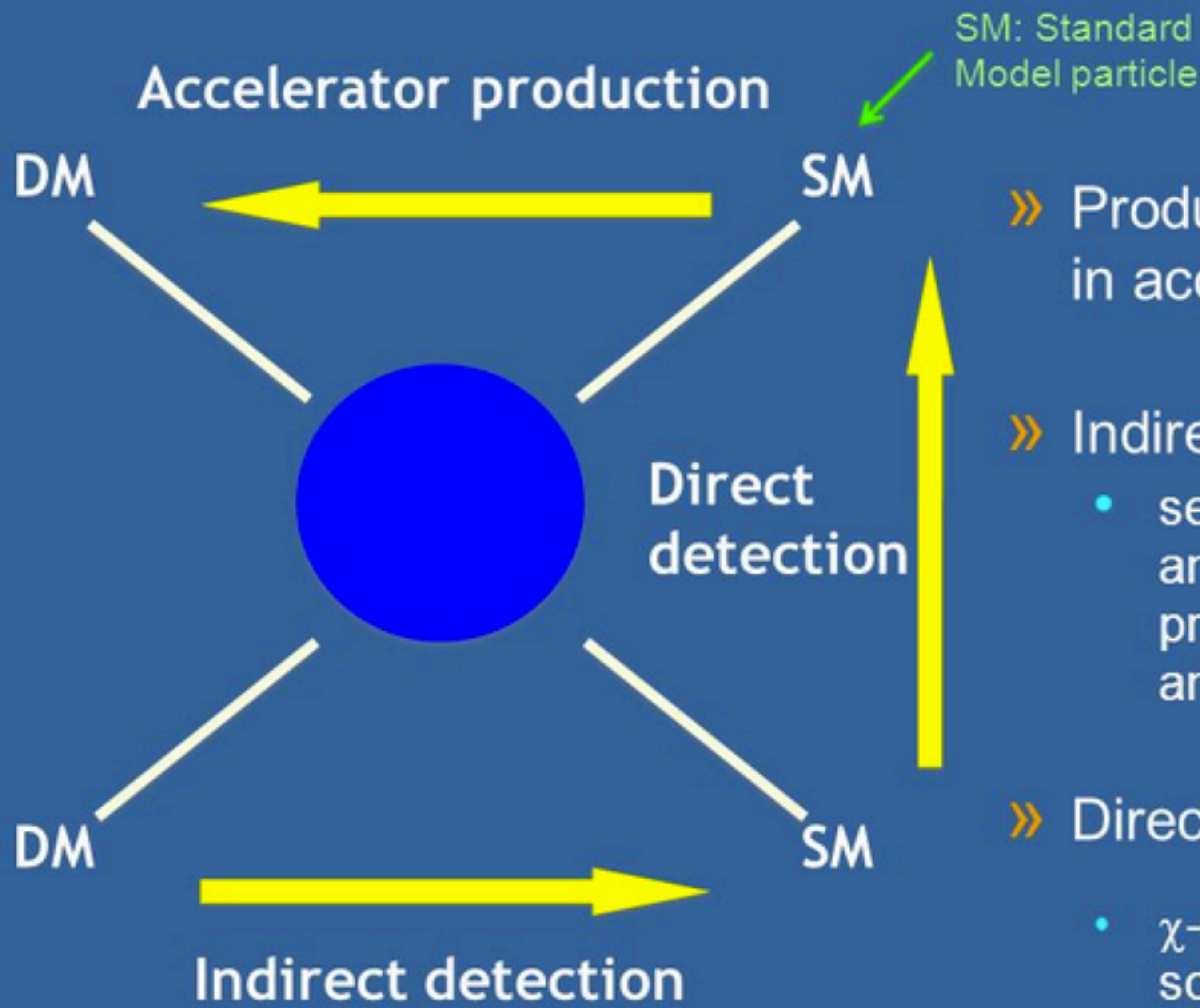
| Portal | Particles | Operator(s) |
|---|---|---|
| "Vector" | Dark photons | $-\frac{\epsilon}{2\cos\theta_W} B_{\mu\nu} F'^{\mu\nu}$ |
| "Axion" | Pseudoscalars | $\frac{a}{f_a} F_{\mu\nu} \widetilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i\mu\nu} \widetilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a} \overline{\psi} \gamma^\mu \gamma^5 \psi$ |
| "Higgs" | Dark scalars | $(\mu S + \lambda S^2) H^\dagger H$ |
| "Neutrino" | Sterile neutrinos | $y_N L H N$ |

- Other dark matter candidates include

  MACHOs: MAssive Compact Halo Objects

  WIMPs: Weakly Interacting Massive Particles

# Strategies: search for Dark Matter




- » Production in accelarators (LHC)
- » Indirect detection:
  - search for annihilation/decay products of $\chi$'s (self-antiparticle)
- » Direct detection:
  - $\chi$-nucleus elastic scattering

# Why Atomic Physics?

# Why Atomic Physics?

- Energy scales: Atomic (~ eV) Reactor neutrino (~ MeV) WIMP (~ GeV)
- Neutrino: NNM atomic ionization signal larger at lower energy scattering (current Ge detector threshold 0.1 keV)
- 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)

# Case Study: Neutrino Magnetic Moment

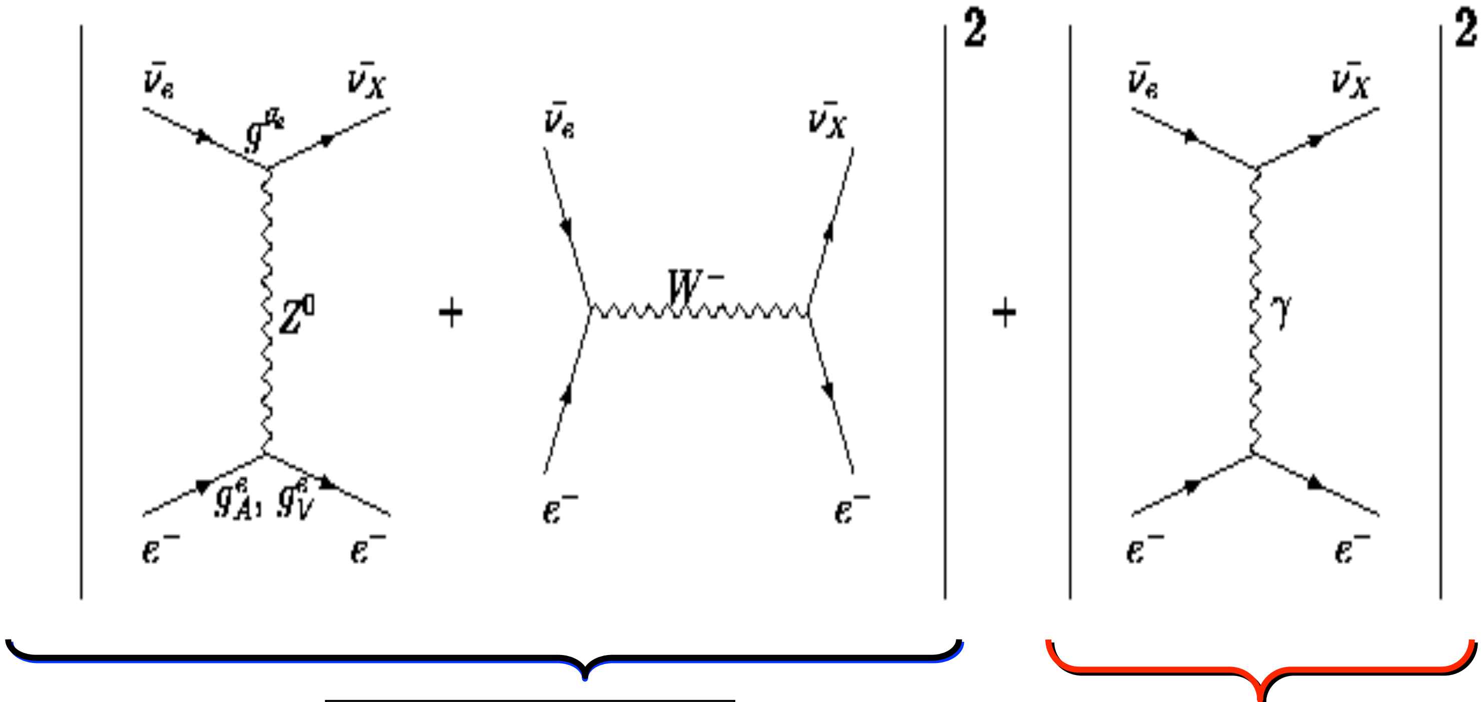
# Neutrino Atomic Ionization

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

- The complete set of neutrino electromagnetic form factors is:

$$j_\mu^{(\gamma)} = \bar{\nu}(k_2, s_2)[F_1(q^2)\gamma_\mu - i(F_2(q^2) + iF_E(q^2)\gamma_5)\sigma_{\mu\nu}q^\nu + F_A(q^2)(q^2\gamma_\mu - \not{q}q_\mu)\gamma_5]\nu(k_1, s_1), \tag{7}$$

## $\bar{\nu}_e e^- \rightarrow \bar{\nu}_x e^-$ **scattering**




Weak Interaction

Magnetic moment

# $\bar{\nu}_e e^- \to \bar{\nu}_x e^-$ **scattering**

$$\underbrace{\frac{d\sigma}{dT} = \frac{G_F{}^2 m_e}{2\pi}\left[(g_V - g_A)^2 + (g_V + g_A + 2)^2\left(1 - \frac{T}{E_\nu}\right)^2 + \left((g_A+1)^2 - (g_V+1)^2\right)\frac{m_e T}{E_\nu^2}\right]}_{\boxed{\text{Weak Interaction}}}$$

$$g_A = 1/2$$

$$g_v = 2\sin\theta_w + 1/2$$

$$\underbrace{+\frac{\pi\alpha^2\mu_\nu^2}{m_e^2}\left(\frac{1}{T} - \frac{1}{E_\nu}\right)}_{\boxed{\text{Magnetic moment}}}$$

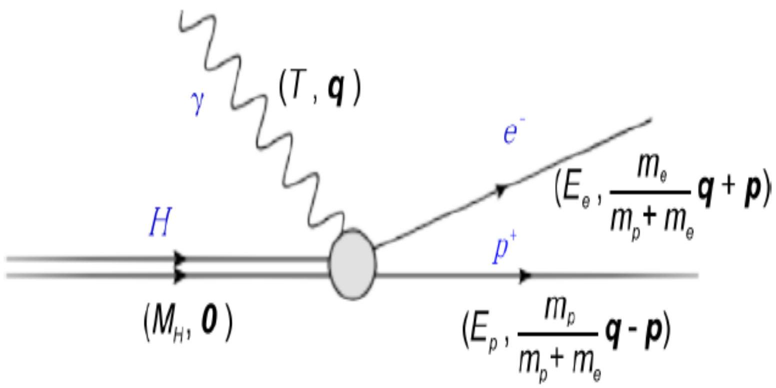
Should go for low T (energy transferred)!

Mini-charge term: $1/T^2$ dependence!

# A Grand Debate on PRL

# Two Approximations ---I

**Equivalent Photon Approx.**

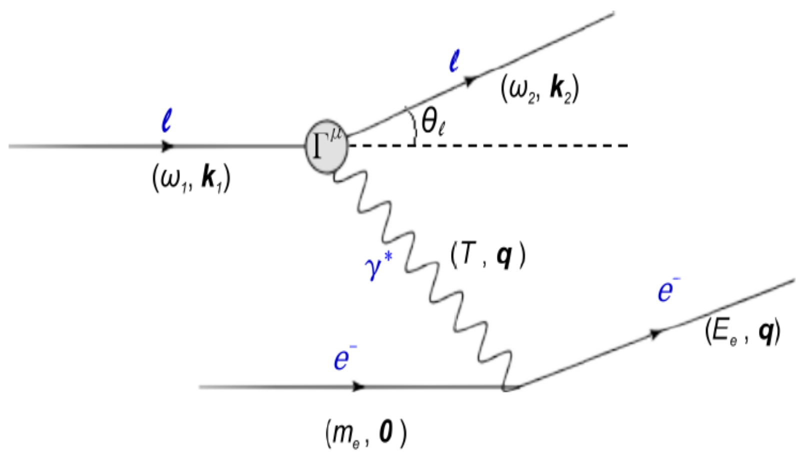



- proposed by Henry Wong et al. ( PRL 105 061801)
- photon $q^2 \sim 0$ : relativistic beam or soft photons $q^\mu \sim 0$
- several orders of magnitude enhancement

→ tighen the $\mu_\nu$ constraint with the same set of data

# Two Approximations --- II

**Free Electron Approx.**




- revisited by Voloshin et al. ( PRL 105 201801)
- sum rule and Hydrogen-like calculation
- FEA works well at sub-keV regime

# A Toy Model Study

# Toy: ν-H atomic ionization, exact result obtained (1307.2857)

# two Approximations

**Free Electron Approx.**
**(revisited by Voloshin et.al)**

**Equivalent Photon Approx.**


binding momentum of hydrogen: $\alpha m_e$

# Settling the Debate

# Ge atomic ionization: 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 1 particle 1 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

↓

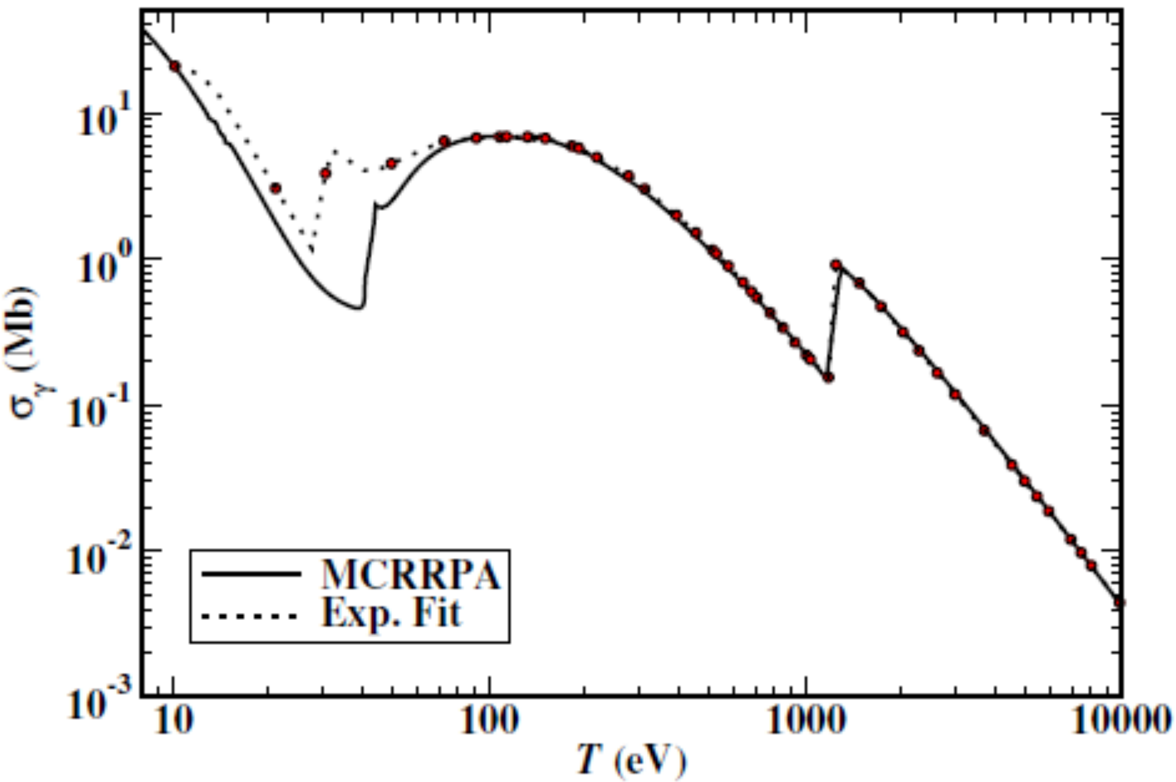
Solve initial wavefucntion of atom

The rest of EM interaction

↓

Solve final wavefunction by time evolution

# Benchmark: Ge Photoionization



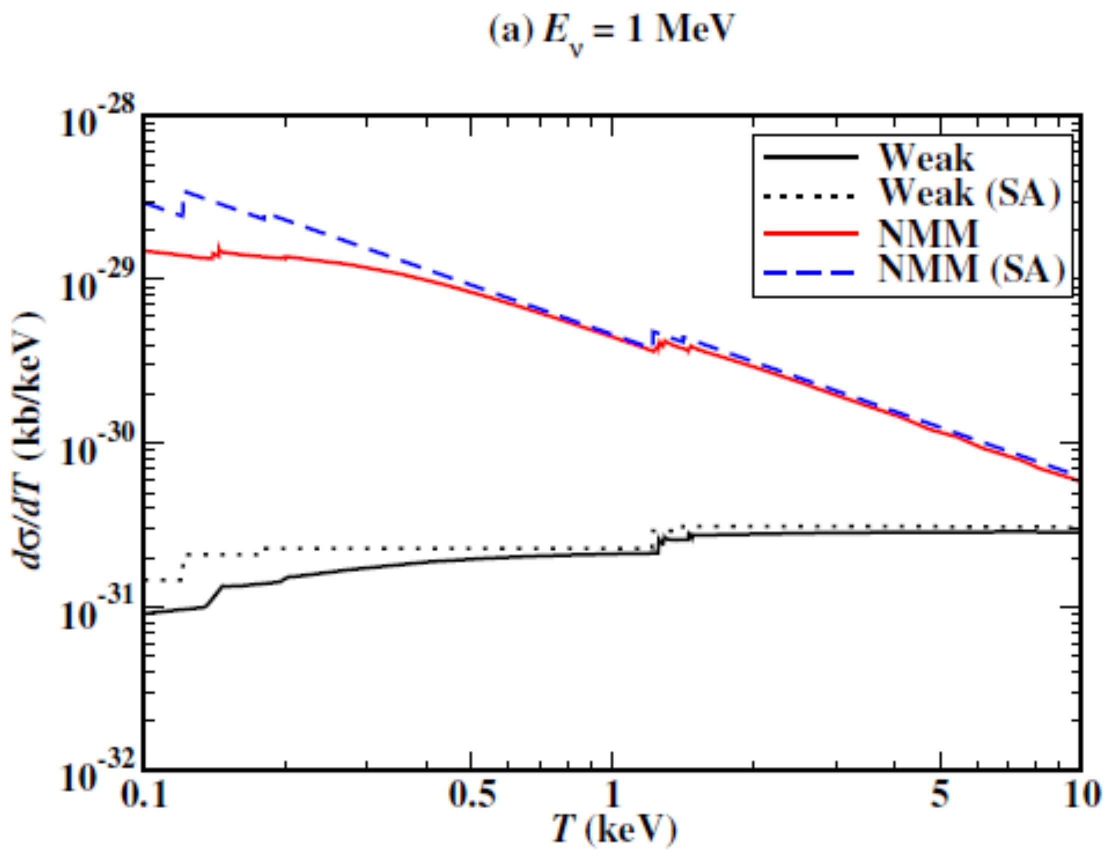

Exp. data: Ge solid

Theory: Ge atom (gas)

Above 100 eV error under 5%.

JWC et. al.
arXiv: 1311.5294

# Ge atomic ionization with ab initio MCRRPA Theory




$$\mu_{\bar{\nu}_e} = 2.9 \times 10^{-11}\, \mu_B$$

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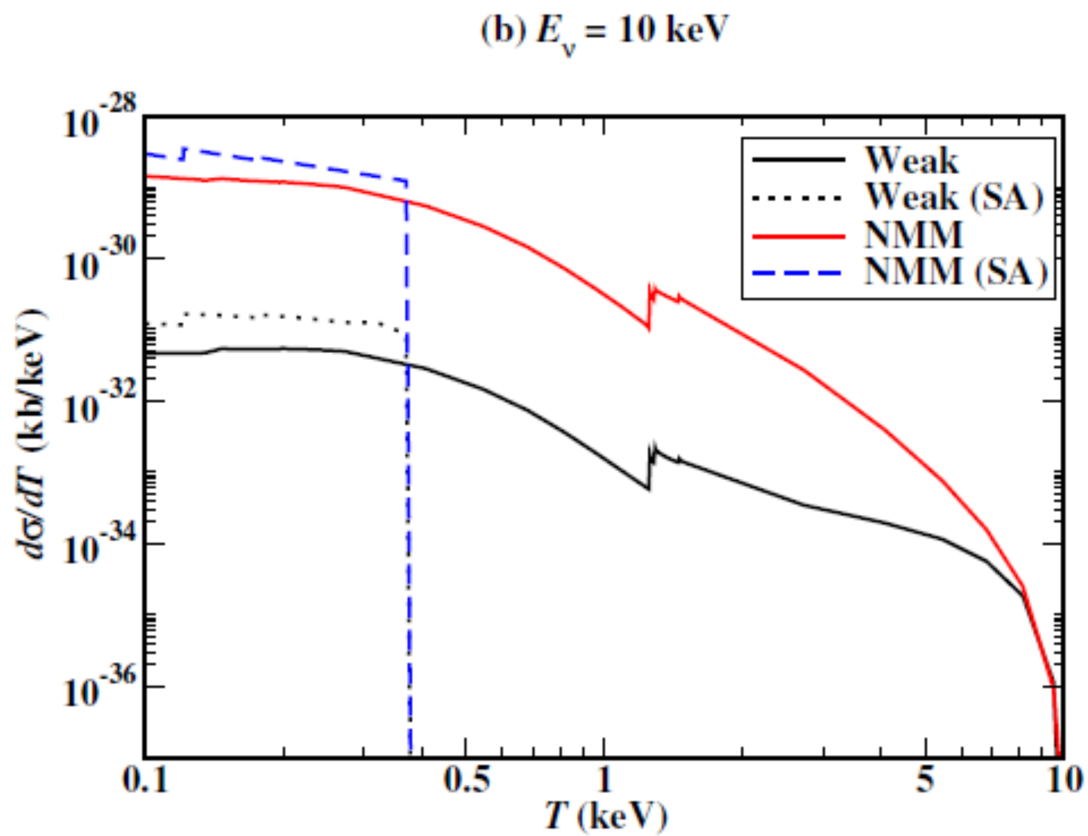


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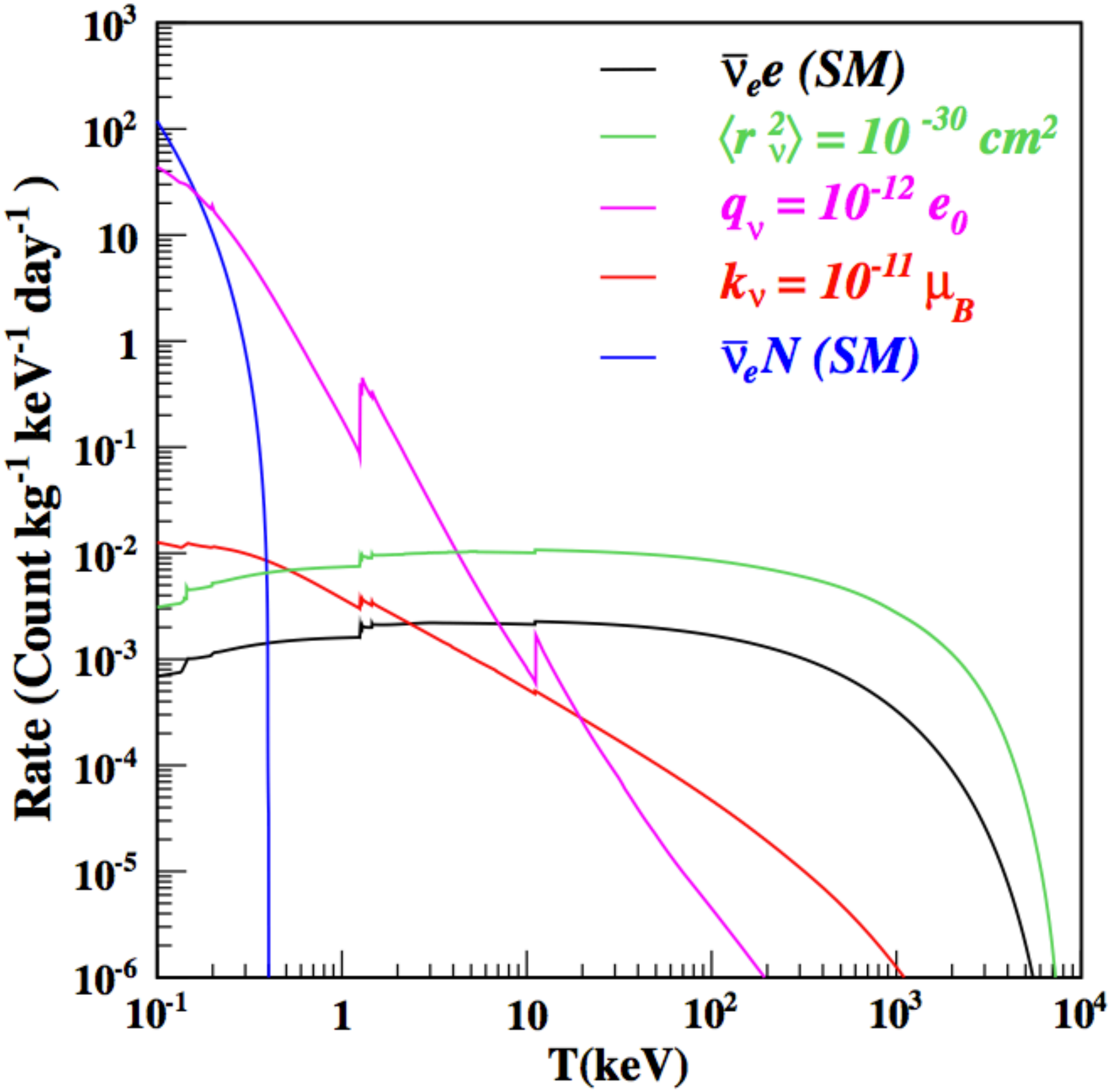



JWC et. al.
1411.0574

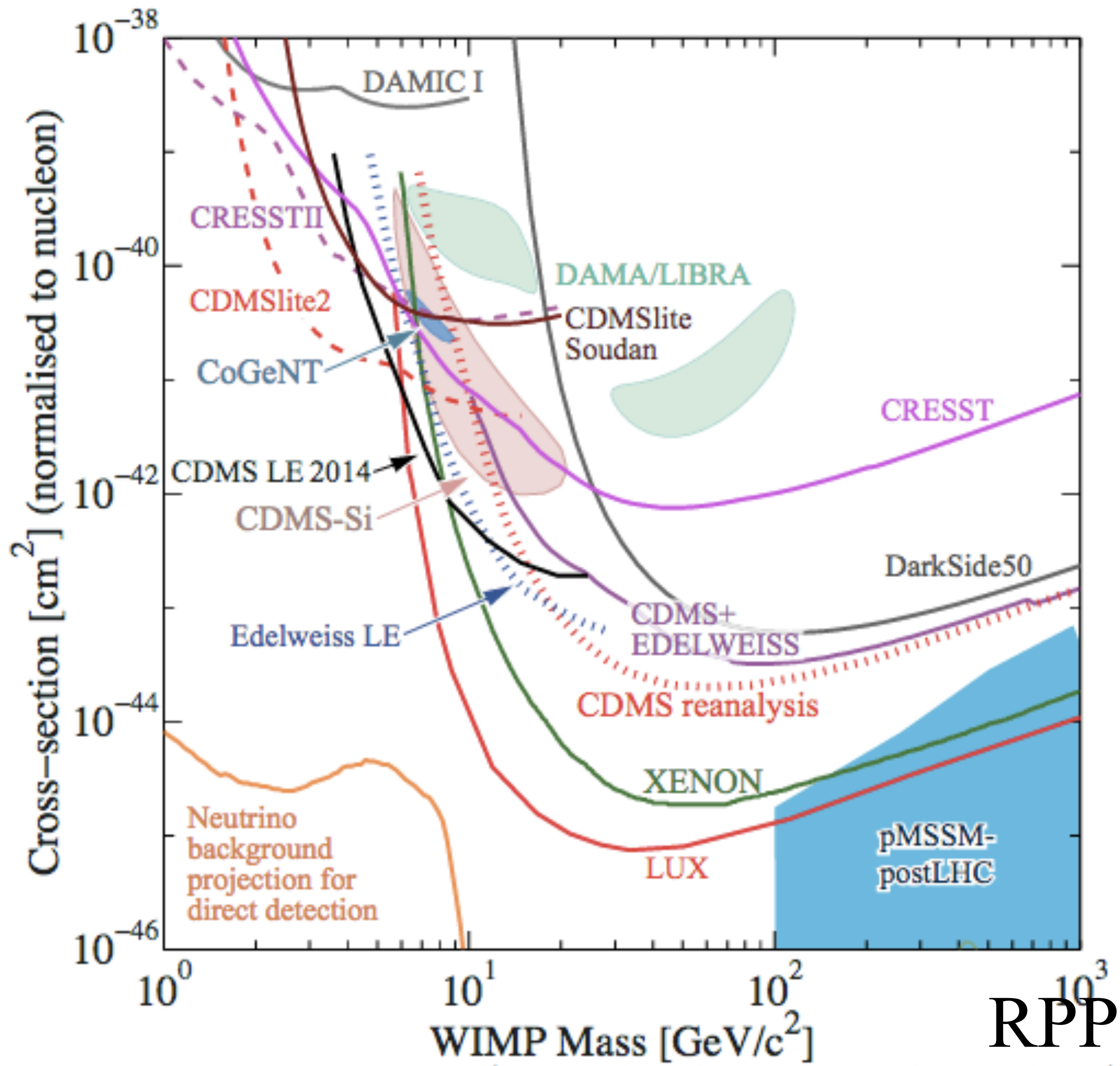
TABLE III. Summary of experimental limits at 90% C.L. on the various neutrino electromagnetic parameters studied in this work by using selected reactor neutrino data. The projected sensitivities of measurements at the specified realistic experimental parameters are also shown. The last row illustrates the effective lower bounds to the sensitivities when a 1% measurement of the SM cross section could be achieved, at a threshold of 0.1 keV for $\kappa_{\bar{\nu}_e}^{(\mathrm{eff})}$ and $\mathbb{q}_{\bar{\nu}_e}$ and 3 MeV for $\langle \mathbb{r}_{\bar{\nu}_e}^2 \rangle^{(\mathrm{eff})}$, respectively.

| Data set | Reactor-$\bar{\nu}_e$ Flux ($\times 10^{13}$ cm$^{-2}$ s$^{-1}$) | Data strength Reactor on/off (kg-days) | Analysis Threshold (keV) | Bounds at 90% C.L. $\kappa_{\bar{\nu}_e}^{(\mathrm{eff})}$ ($\times 10^{-11} \mu_B$) | $\mathbb{q}_{\bar{\nu}_e}$ ($\times 10^{-12}$) | $\langle \mathbb{r}_{\bar{\nu}_e}^2 \rangle^{(\mathrm{eff})}$ ($\times 10^{-30}$ cm$^2$) |
|---|---|---|---|---|---|---|
| TEXONO 187 kg CsI [9] | 0.64 | 29882.0/7369.0 | 3000 | $< 22.0$ | $< 170$ | $< 0.033$ |
| TEXONO 1 kg Ge [5,6] | 0.64 | 570.7/127.8 | 12 | $< 7.4$ | $< 8.8$ | $< 1.40$ |
| GEMMA 1.5 kg Ge [7,8] | 2.7 | 1133.4/280.4 | 2.8 | $< 2.9$ | $< 1.1$ | $< 0.80$ |
| TEXONO point-contact Ge [4,17] | 0.64 | 124.2/70.3 | 0.3 | $< 26.0$ | $< 2.1$ | $< 3.20$ |
| Projected point-contact Ge | 2.7 | 800/200 | 0.1 | $< 1.7$ | $< 0.06$ | $< 0.74$ |
| Sensitivity at 1% of SM | ··· | ··· | ··· | $\sim 0.023$ | $\sim 0.0004$ | $\sim 0.0014$ |

JWC et. al. arXiv: 1411.0574

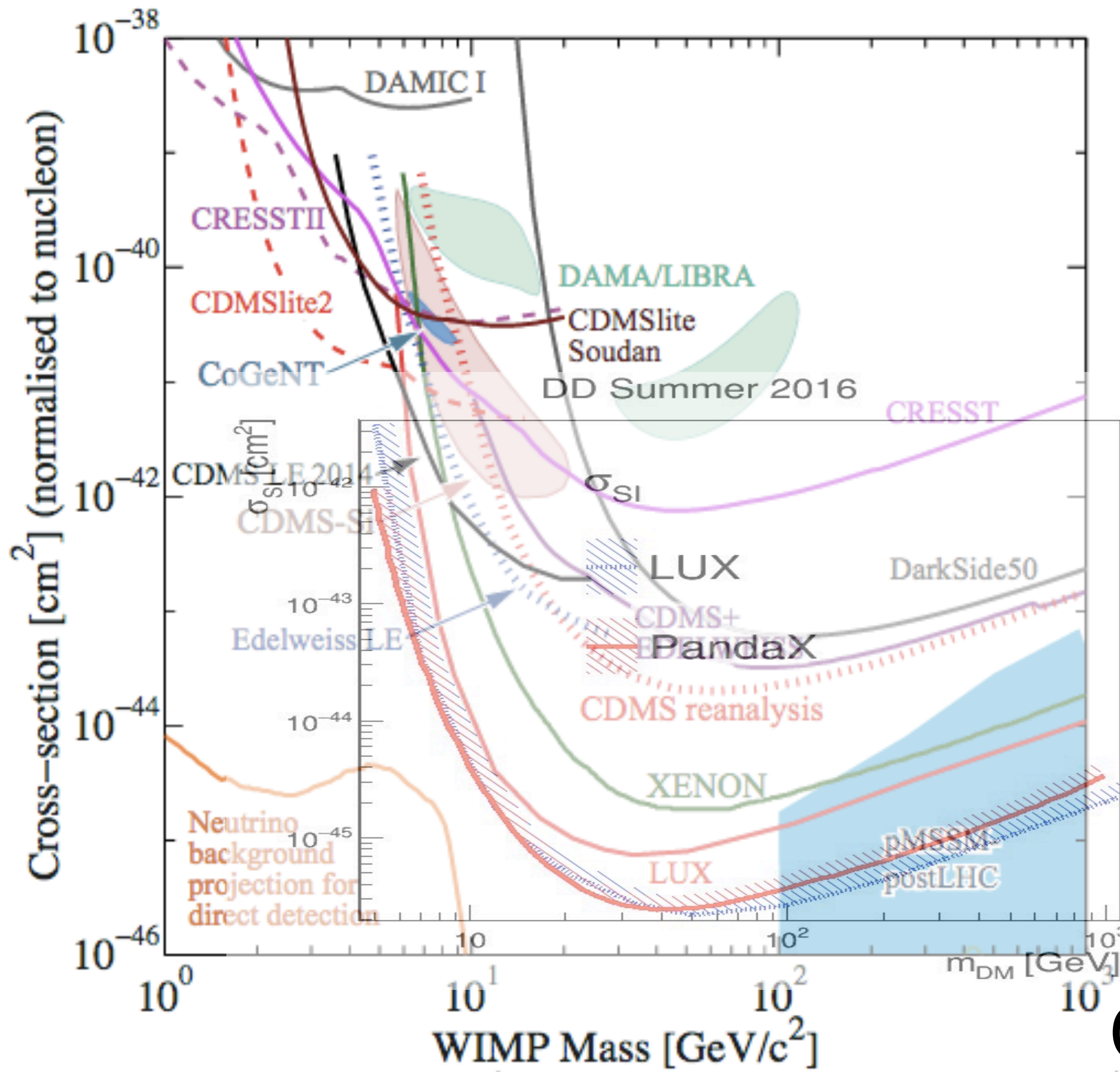
# Turning to the Dark Side

# Direct Dark Matter Detection



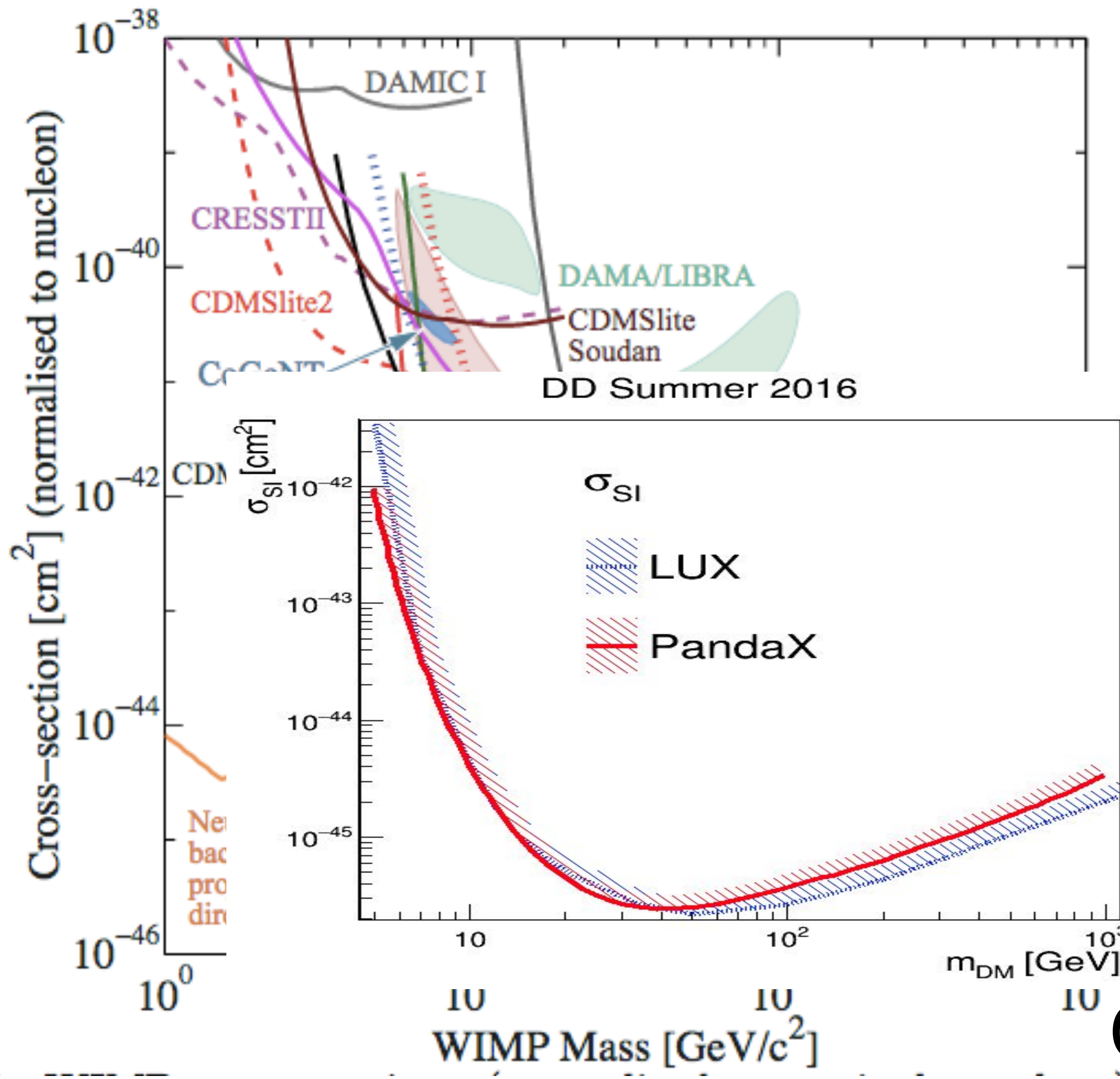

RPP 02/2016

# Direct Dark Matter Detection




07/2016

# Direct Dark Matter Detection




07/2016

# What Can Atomic Physics Contribute?

- Light dark matter detection:

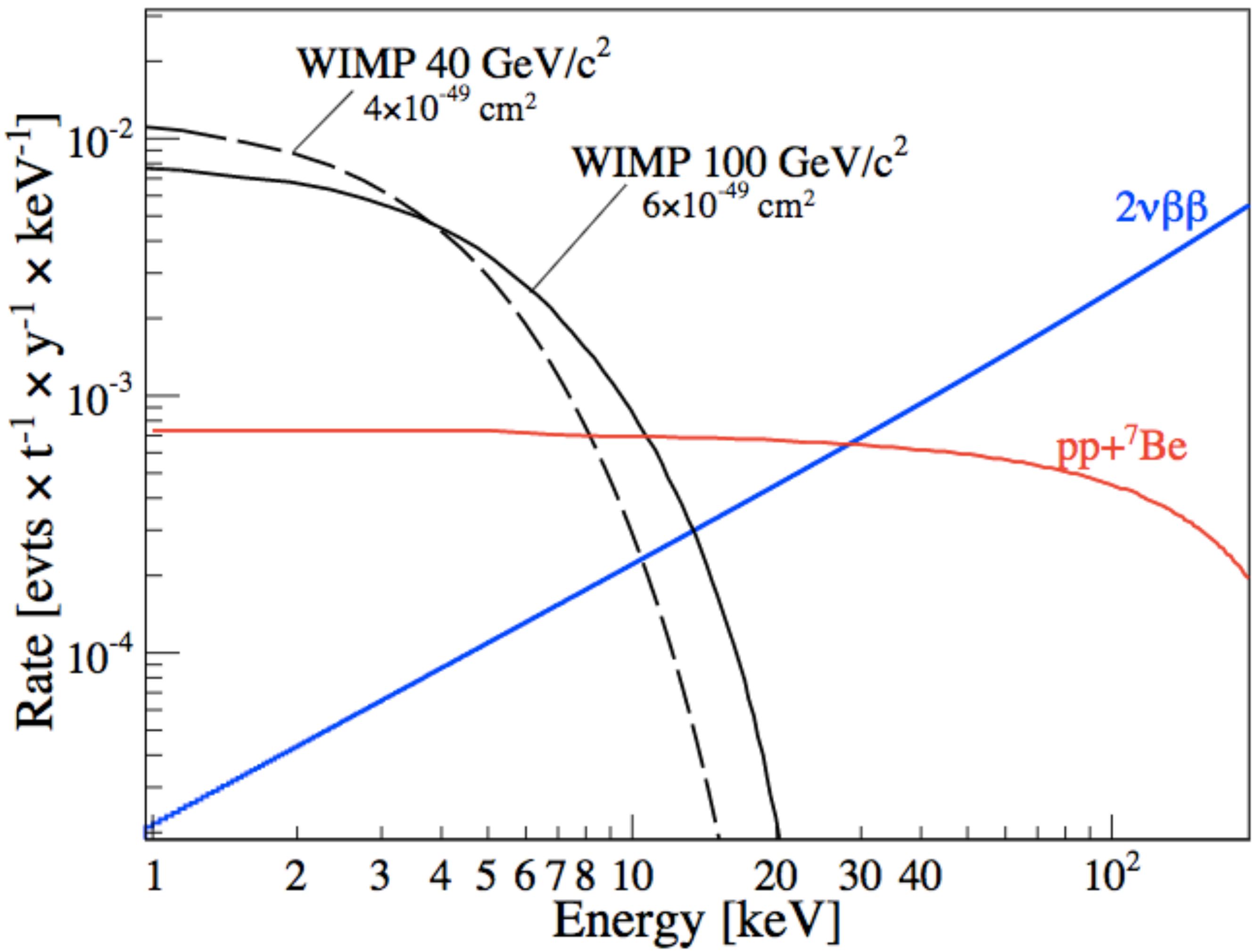
$$\chi + A \rightarrow \chi' + A^+ + e^-$$

- Electron recoil background from solar neutrinos for a LXe detector

$$\nu + A \rightarrow \nu' + A^+ + e^-$$

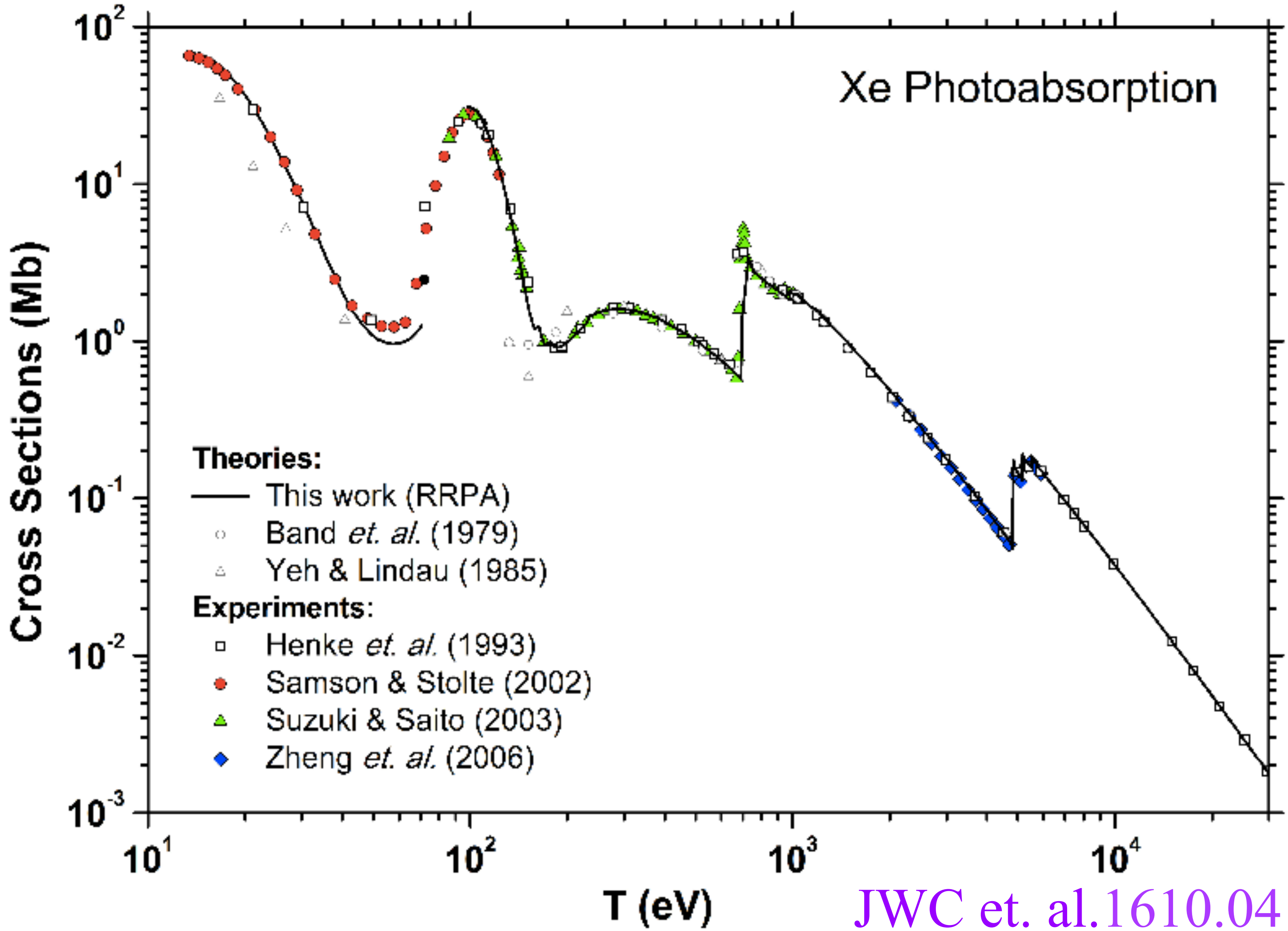
- Large LXe detectors can be used as a neutrino detectors as well (w/ or w/o a source nearby)

# Electron Recoil Background for DARWIN (LXe)



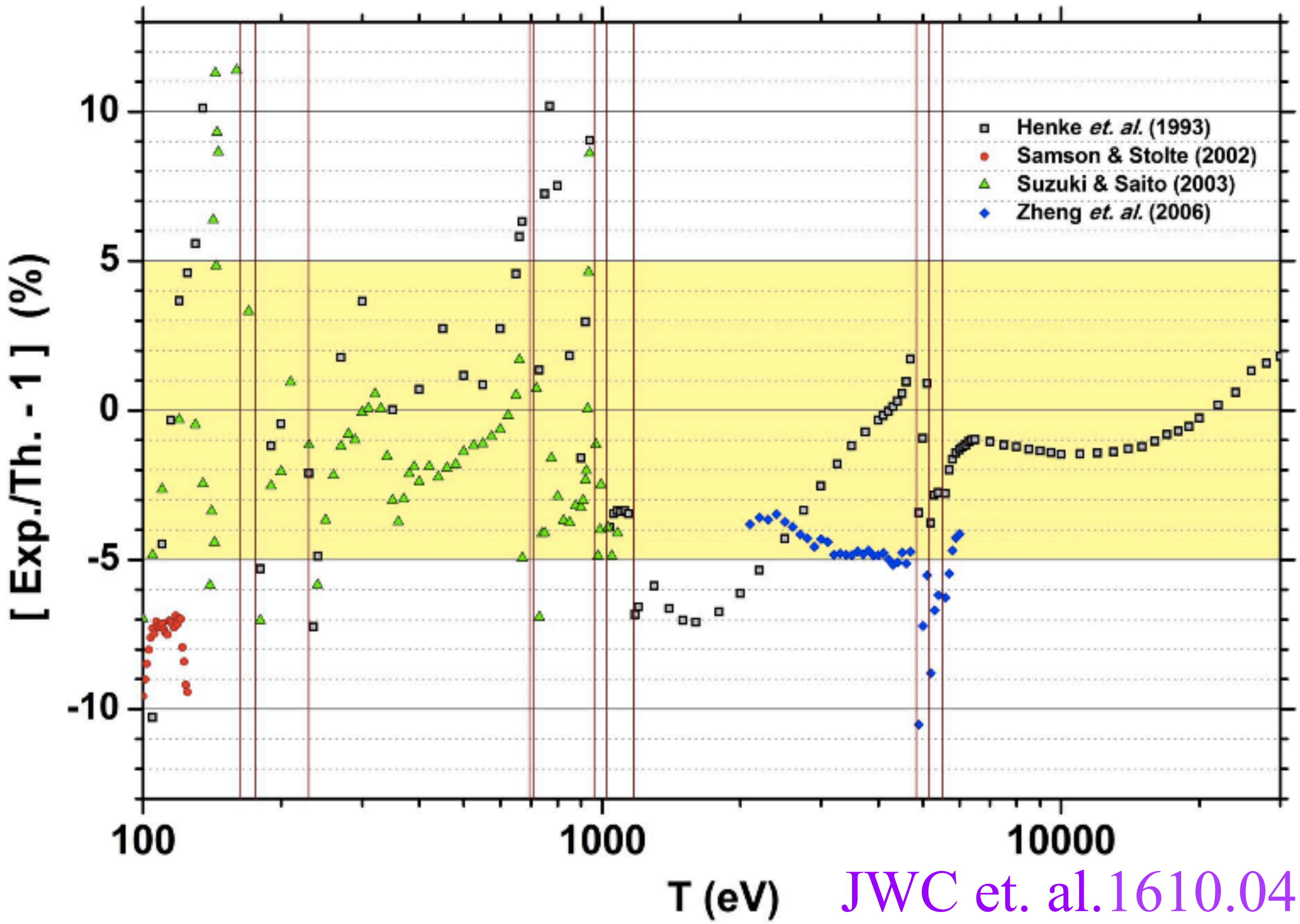

J. Aalbers et al. 1606.07001

# Benchmark: Xe Photoionization




JWC et. al.1610.04177

# Benchmark: Xe Photoionization 2-30 keV, Error 2-3%




JWC et. al.1610.04177

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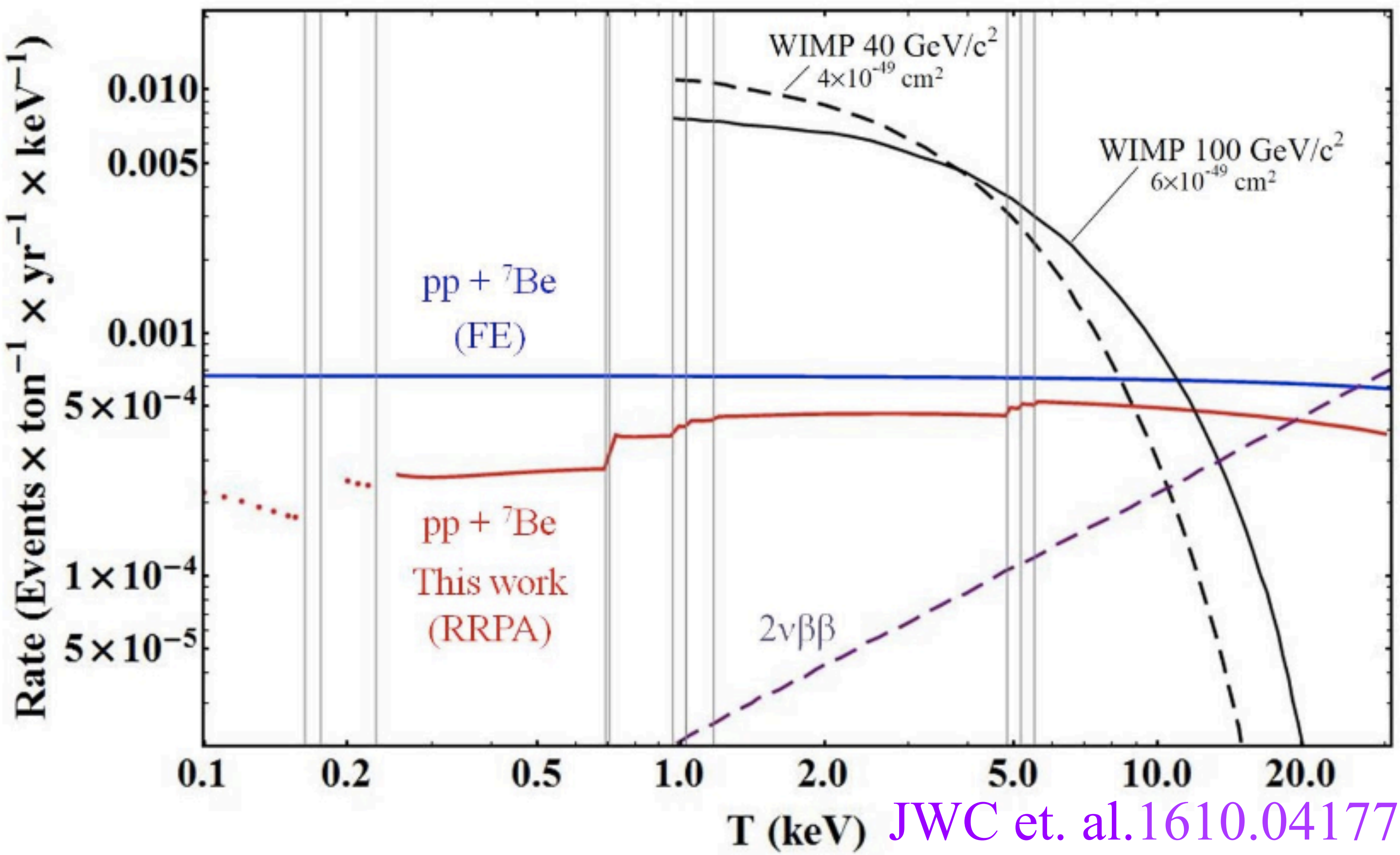
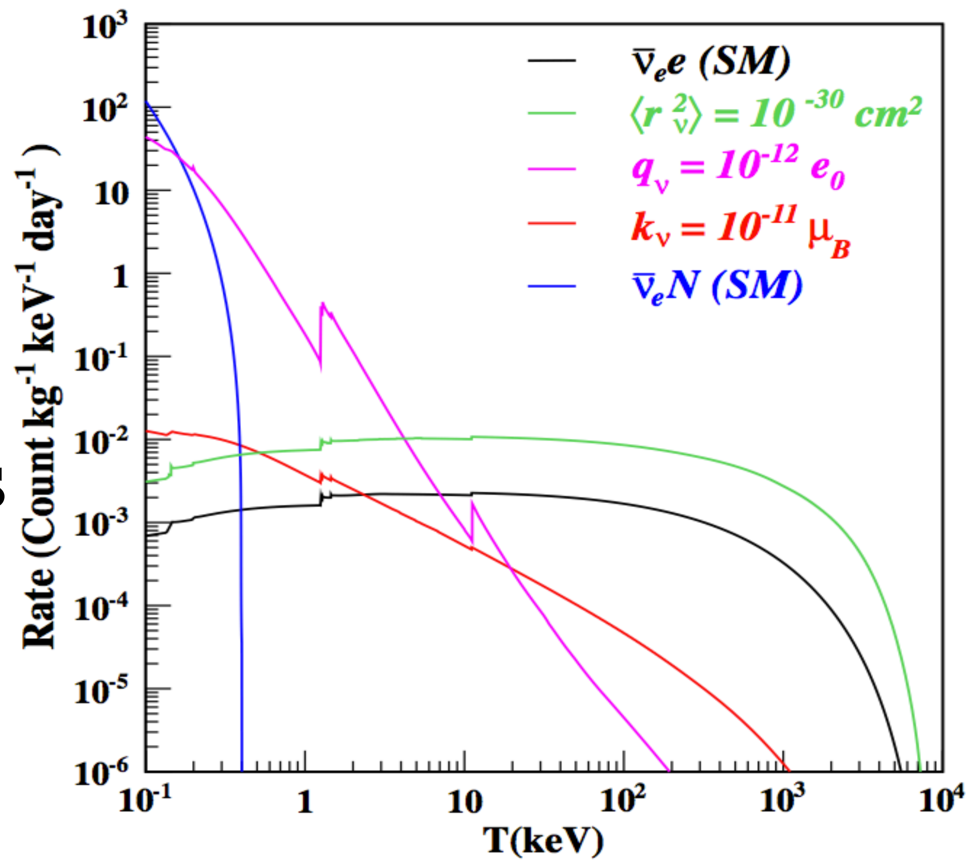



JWC et. al.1610.04177

# Turning a LXe Dark Matter Detector into a Neutrino Detector

- 70 ton-yr exposure gives ~1% stat error on pp flux (~6000 events; theory error 2-3%)---a real time detection
- Imagine what it can do in constraining neutrino properties ---using solar neutrinos as the source.



# Summary

- Neutrinos and dark matter particles are portals to new physics
- 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

# Neutrino Magnetic Moment (NMM)

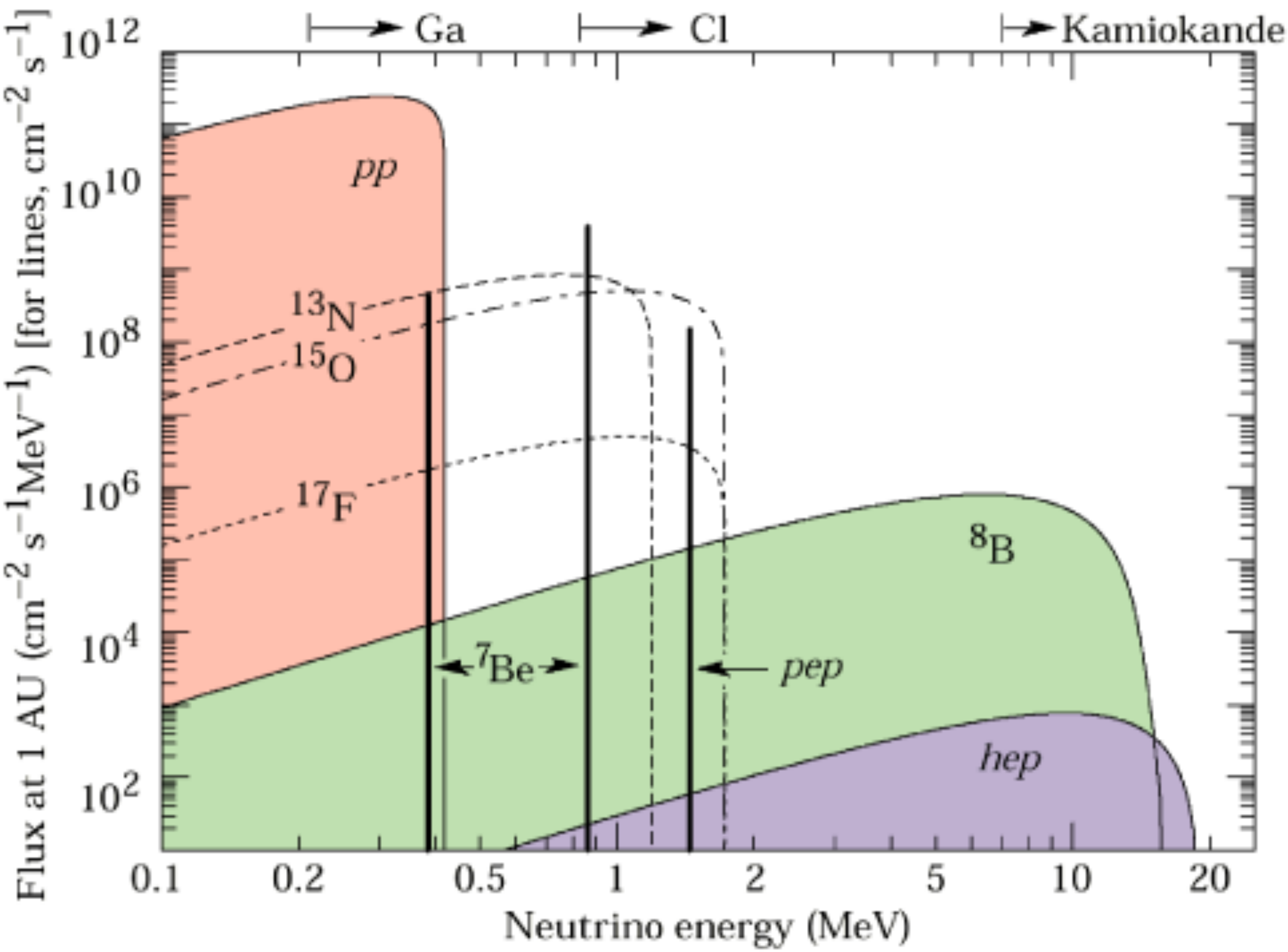
| | Flavor changing MM | Flavor unchanging MM |
|---|---|---|
| Dirac | ○ | ○ |
| Majorana | ○ | × |

(forbiden by CTP)

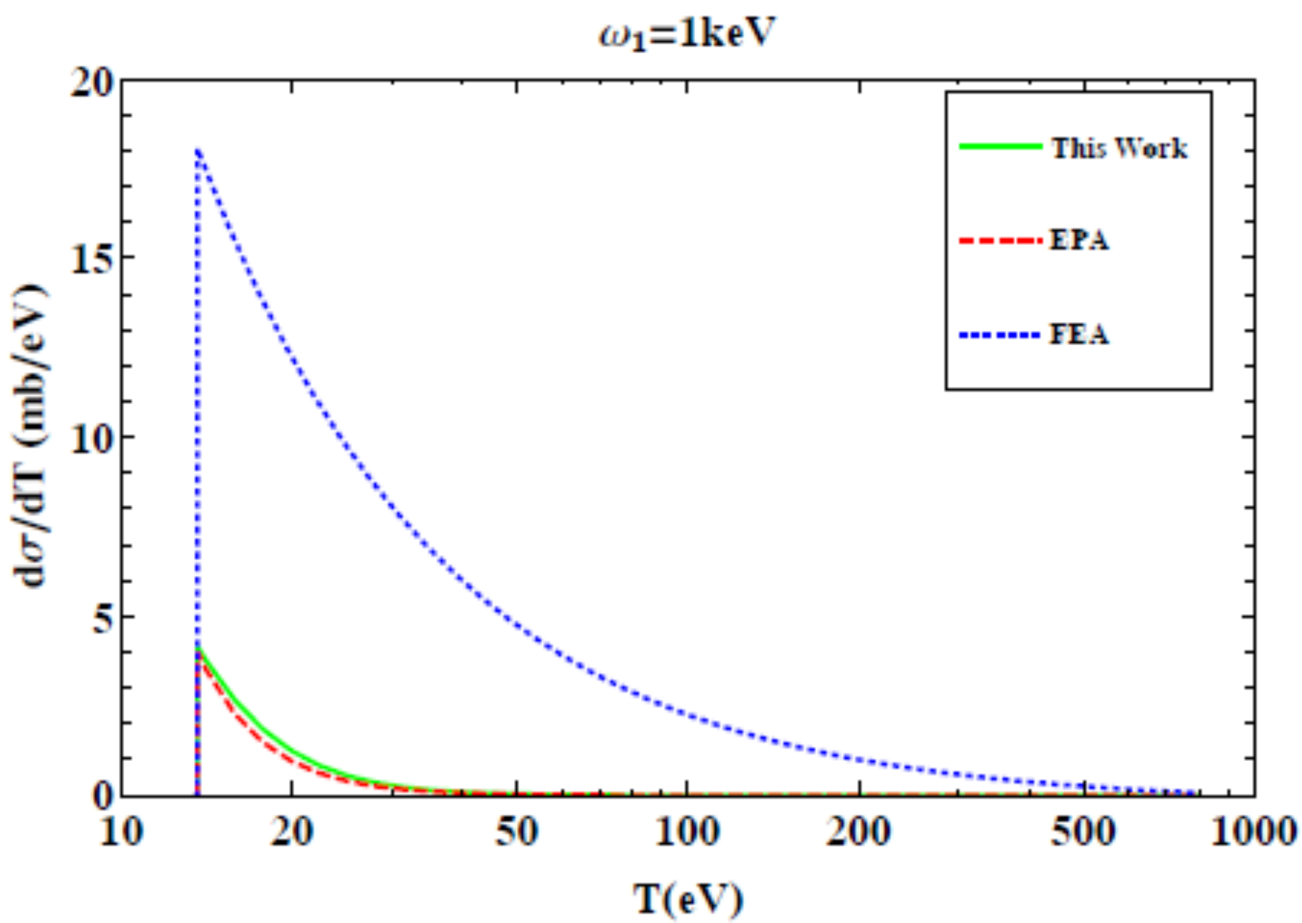
$$\mu_\nu \approx 10^{-19} \mu_B \cdot \left( \frac{m_\nu}{1\,\mathrm{eV}} \right)$$

A probe of new physics!

# Solar Neutrino Flux



# Toy: ν-H atomic ionization, exact result obtained (1307.2857)



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