Neutrino and Dark Matter Detections via Atomic Ionizations at sub-keV Sensitivities

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Henry T. Wong (Academia Sinica & TEXONO)

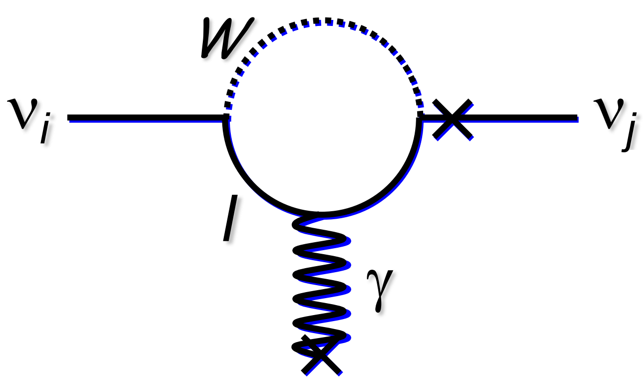
Direct Dark Matter Detection

- Cryogenic detector experiments
  - pure Ge, Si targets
  - operating at very low temperatures
  - CDMS, CDEX, CRESST, EURECA, …
- Noble liquid experiments
  - detect the flash of scintillation light produced by a particle collision in liquid Xe or Ar
  - PANDAX, XENON, ZEPLIN, DEAP, ArDM, WARP, LUX, …

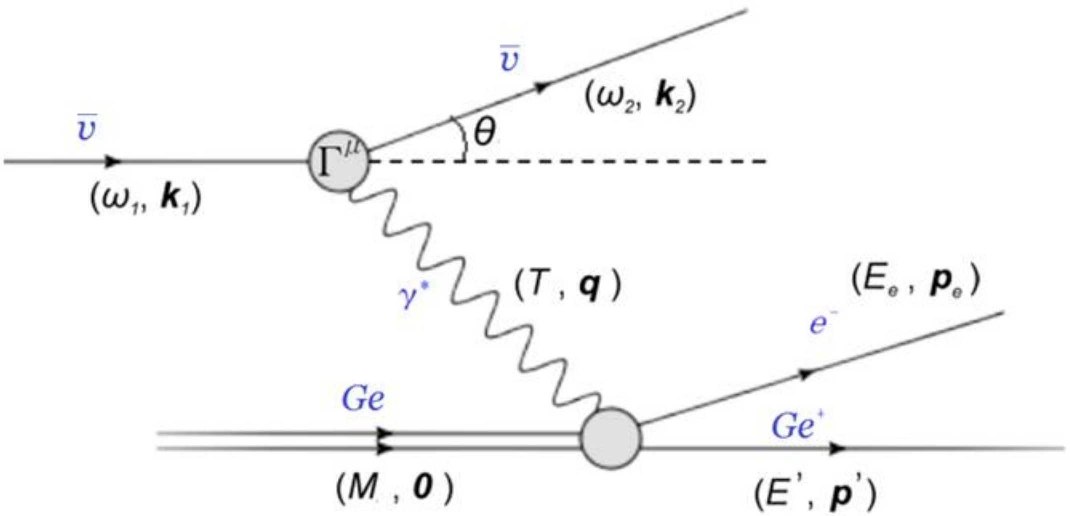
Neutrino EM properties

- ☐ nonzero millicharge exists
- ☐ anomalous magnetic moment exists

- ➢ Finite neutrino masses and mixings
- ➢ Chirality
- ➢ Charge quantization
- ➢ Dirac or Majorana
- ➢ CP phase



ν – Ge Atomic Ionization (AI)

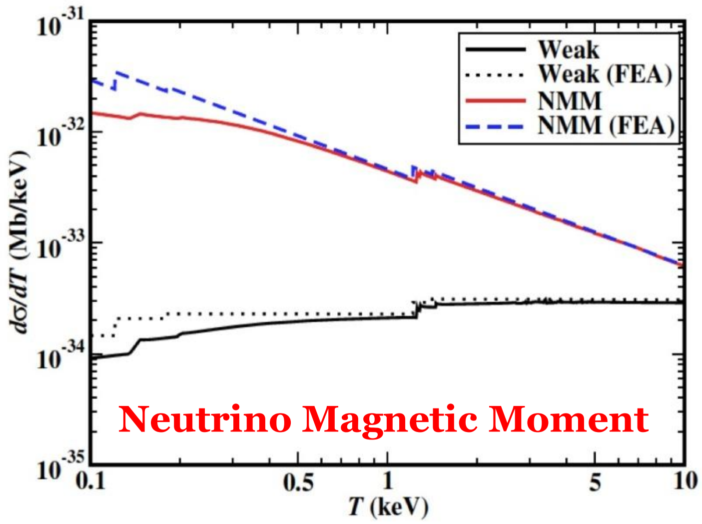


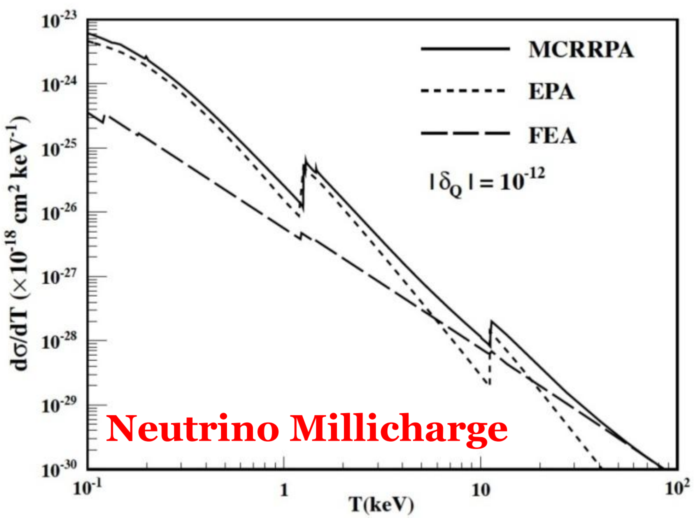
$$\Gamma^{\mu}_{\mathrm{em}} \equiv F_1 \cdot \gamma^{\mu} + F_2 \cdot \sigma^{\mu\nu} \cdot q_{\nu}$$

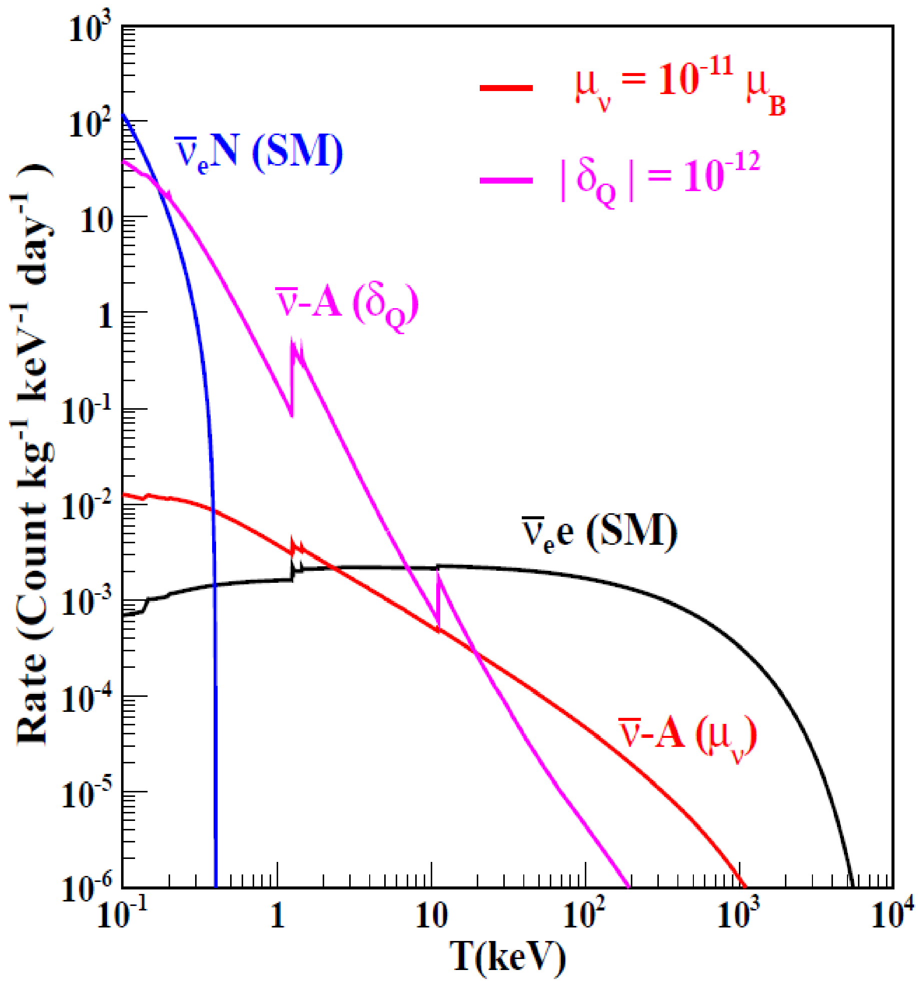
$$F_1 = \delta_{\mathrm{Q}} \cdot e_0$$

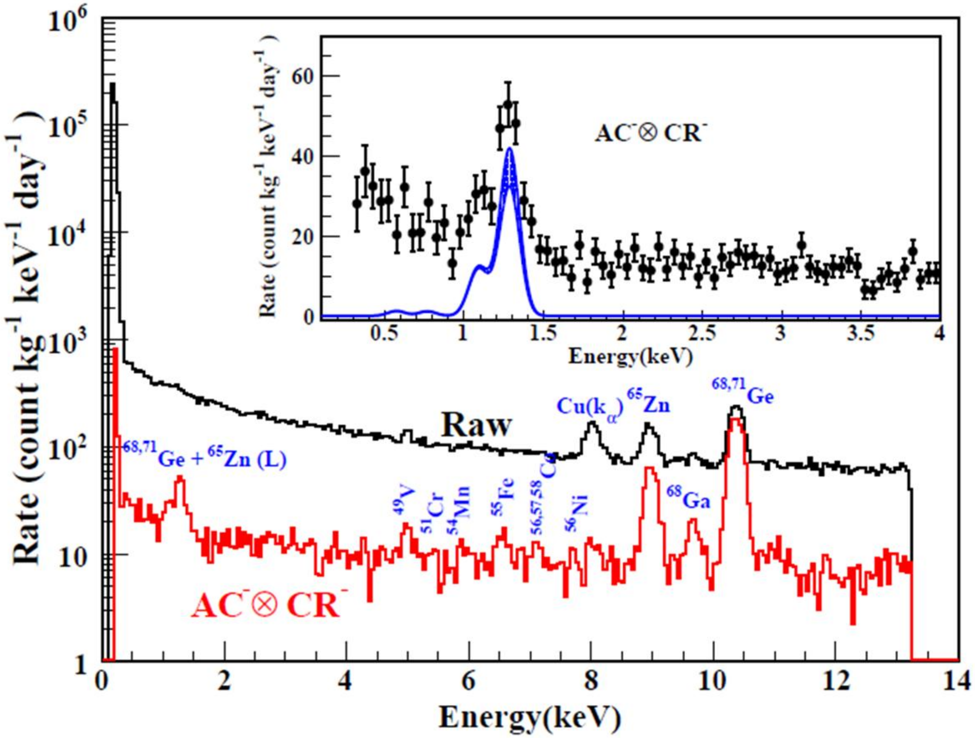
$$F_2 = (-i) \cdot \frac{\mu_{\nu}}{2 \cdot m_e}$$

Two channels for *ν* – Ge Scattering





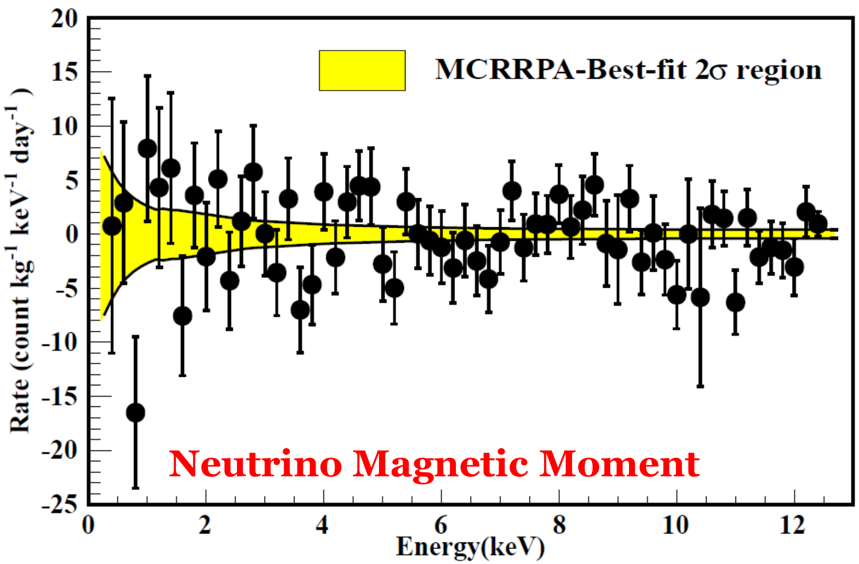


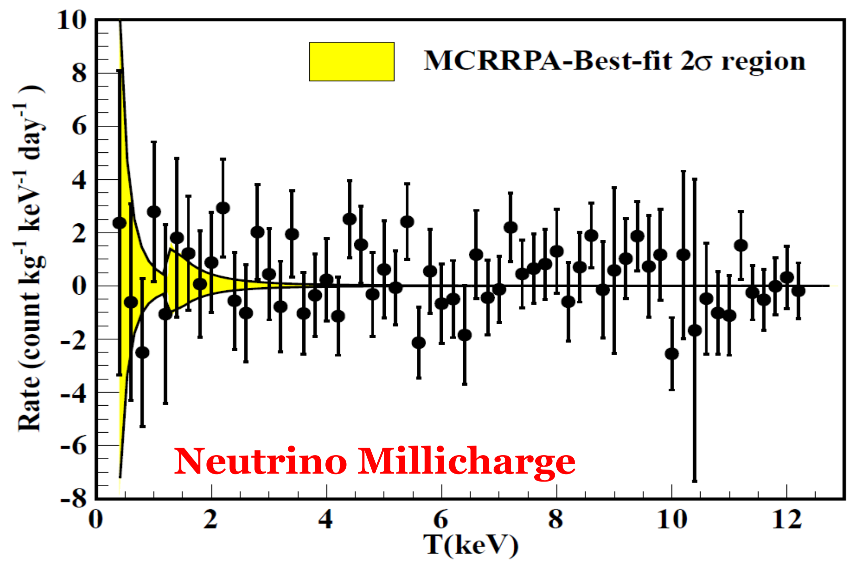


TEXONO Collaboration

@ Kuo-Sheng Nuclear

Power Station in Taiwan





Experimental Limit

Neutrino Magnetic Moment (NMM)

Data	Neutrino Flux ($cm^{-2}s^{-1}$)	Data Strength (kg-day)	Threshold (keV)	NMM Limits at 90% CL (μ_B) FEA	MCRRPA
TEXONO 1kg HPG	6.4×10^{12}	ON/OFF : 570.7/127.8	12	$< 7.4 \times 10^{-11}$	$< 7.4 \times 10^{-11}$
TEXONO 900g PPCGe	6.4×10^{12}	ON : 39.5	0.5	$< 1.6 \times 10^{-10}$	$< 1.6 \times 10^{-10}$
TEXONO 500g PPCGe	6.4×10^{12}	ON/OFF : 25.5/13.4	0.3	$< 3.0 \times 10^{-10}$	$< 3.0 \times 10^{-10}$
GEMMA 1.5 kg HPGe	2.7×10^{13}	ON/OFF : 1133.4/280.4	2.8	$< 2.9 \times 10^{-11}$	$< 2.9 \times 10^{-11}$
PPCGe Projected	6.4×10^{12}	(ON/OFF) : 1500/ 500	0.3	$< 2.3 \times 10^{-11}$	$< 2.6 \times 10^{-11}$

Neutrino Millicharge

Data Set	Reactor-$\bar{\nu}_e$ Flux ($\times 10^{13}$ $cm^{-2}s^{-1}$)	Data Strength Reactor ON/OFF (kg-days)	Analysis Threshold (keV)	$\lvert\delta_Q\rvert$ 90% CL Limits ($< \times 10^{-12}$) Previous Analysis FEA	This Work FEA	This Work MCRRPA
TEXONO 1 kg Ge [17]	0.64	570.7/127.8	12	3.7 [15]	14	8.8
GEMMA 1.5 kg Ge [18]	2.7	755.6/187	2.8	1.5 [16]	2.1	1.1
TEXONO Point-Contact Ge [24]	0.64	124.2/70.3	0.3	–	–	2.1
Projected Point-Contact Ge	2.7	800/200	0.1	–	–	~0.06

Ab initio MCRRPA Theory for Atomic Ionization

MCRRPA: multiconfiguration relativistic random phase approximation

Hartree-Fock : Solve self consistently by reducing the N-body system to single-particle problem by effective mean field

↓

RPA: Include particle-hole excitation diagram

D. Bohm and D. Pines (1952)

↓

RRPA: Describe heavy noble gas (Dirac Eq.)

W.R. Johnson, C.D. Lin and A. Dalgarno (1976)

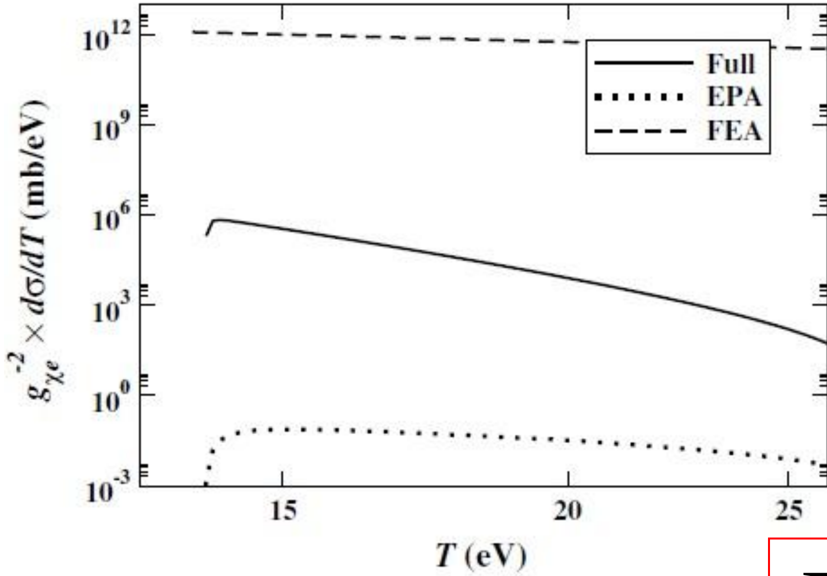
↓

MCRRPA: More than one configuration.
Important for open shell system, like Ge,
where energy gap $<$ closed shell

K.-N. Huang and W.R. Johnson (1982)

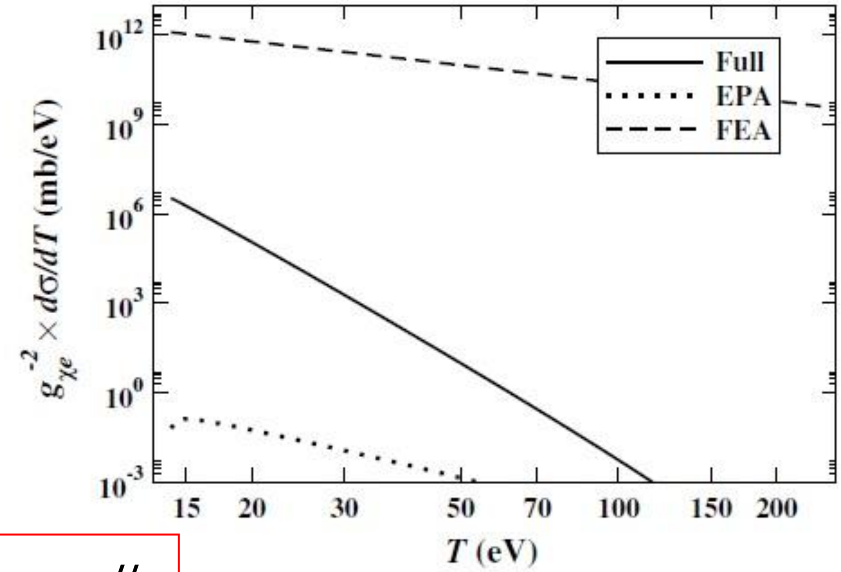
Atomic Ionization by Dark Matters

- Assuming some processes for interactions between DM and atoms, then we can make some constraints through the direct detection. For example: exchanging a massive boson.
- Note the WIMP scattering is the most kinematics-sensitive case, and both FEA & EPA fails badly.
- 1 GeV and 50 MeV mass light DM are examined in short and long interaction.

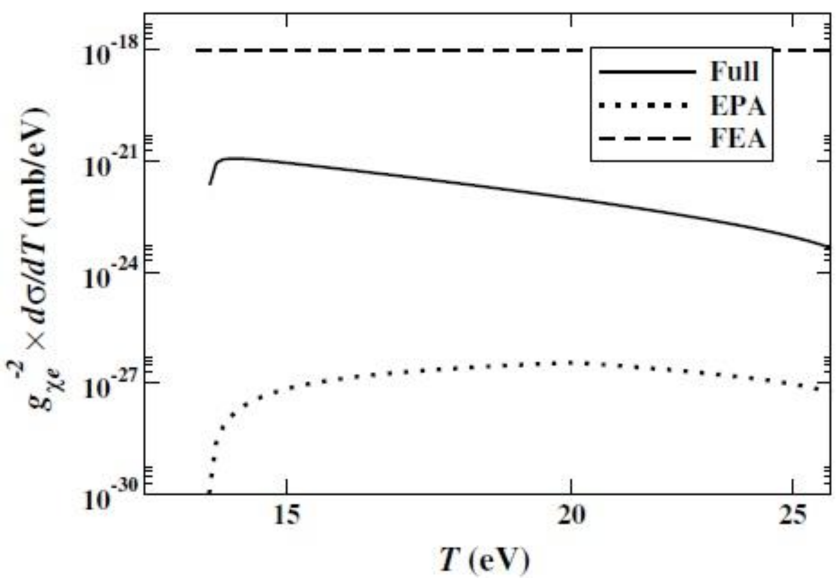


(a) $m_\chi = 0.1$ GeV, $m_b = 0$

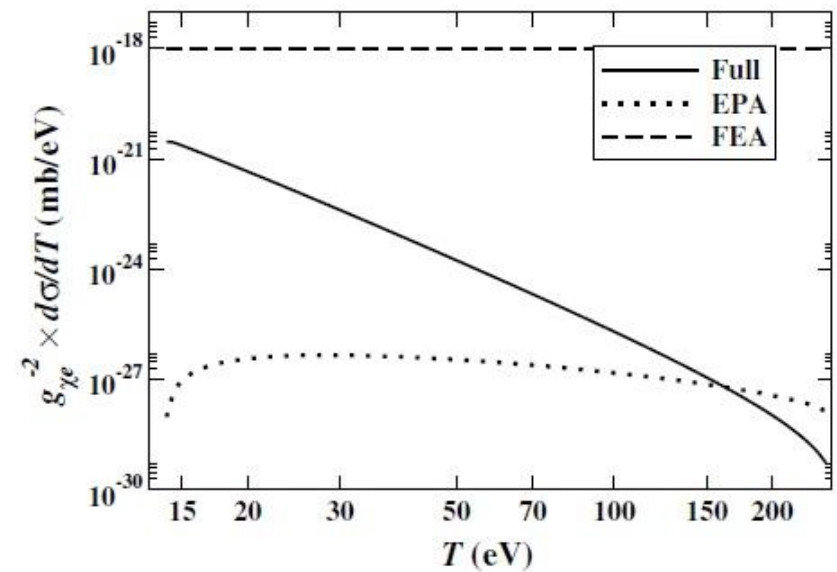
$F_1 : \gamma^\mu$



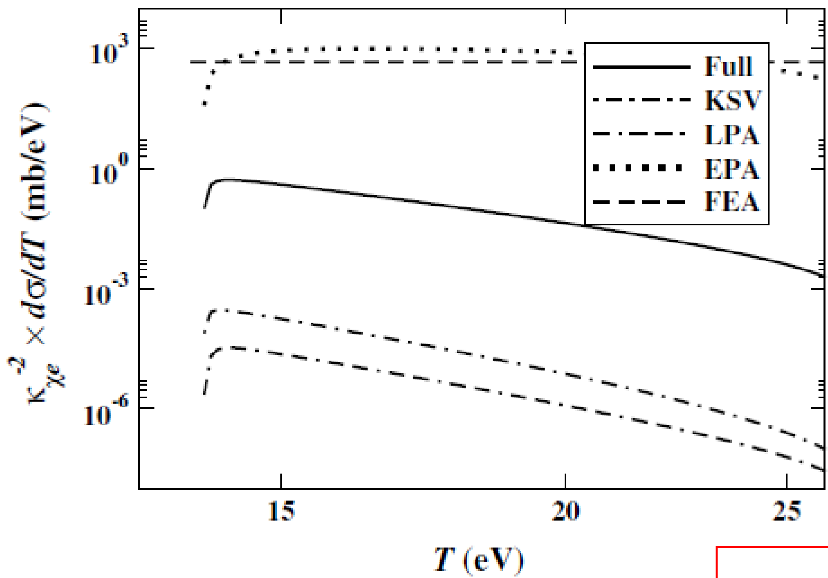
(b) $m_\chi = 1$ GeV, $m_b = 0$



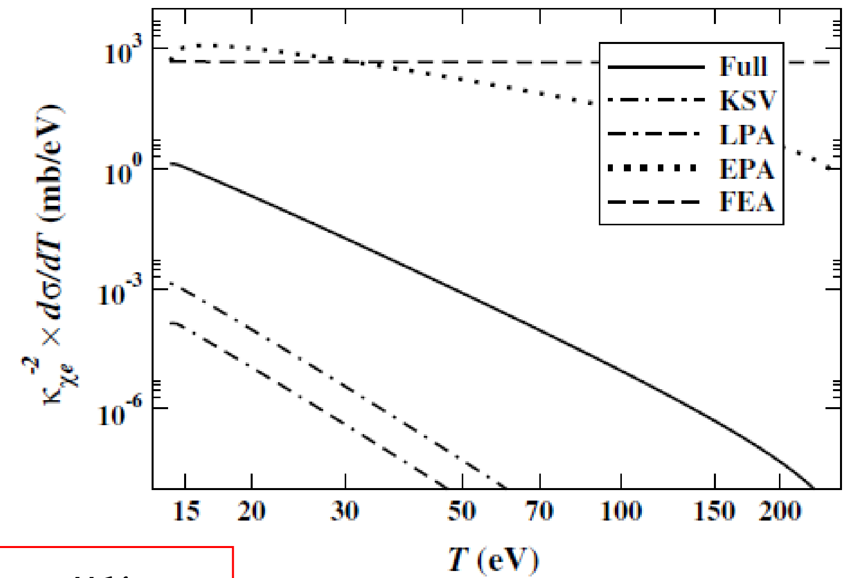
(c) $m_\chi = 0.1$ GeV, $m_b = 125$ GeV



(d) $m_\chi = 1$ GeV, $m_b = 125$ GeV

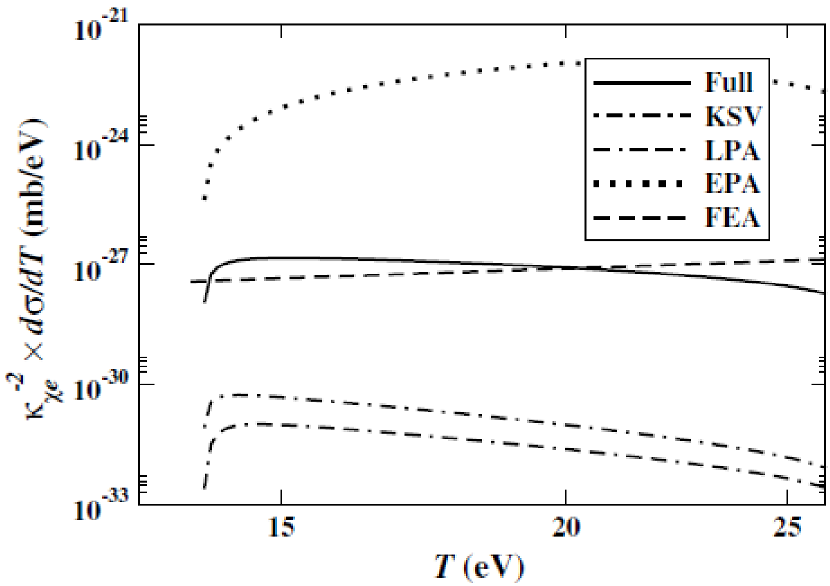


(a)

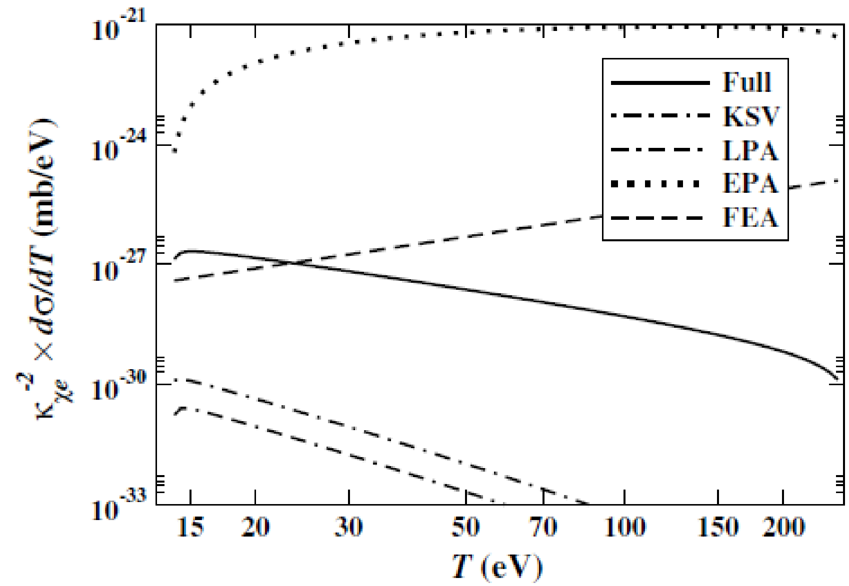


(b)

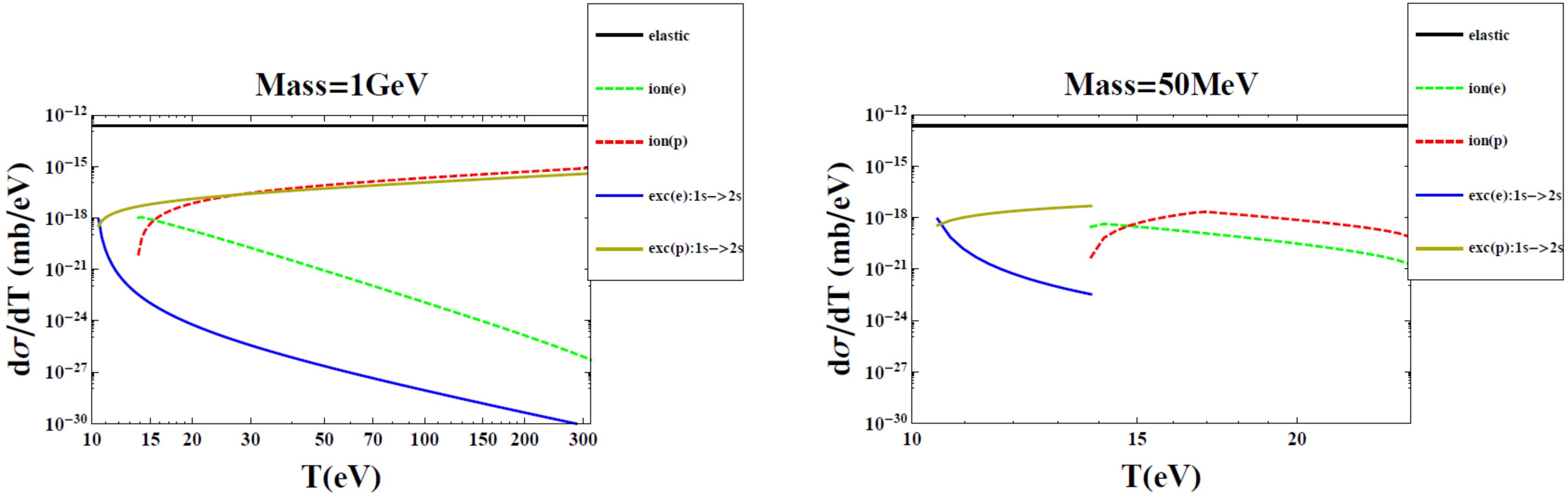
$F_2 : \sigma^{\mu\nu} q_\nu$



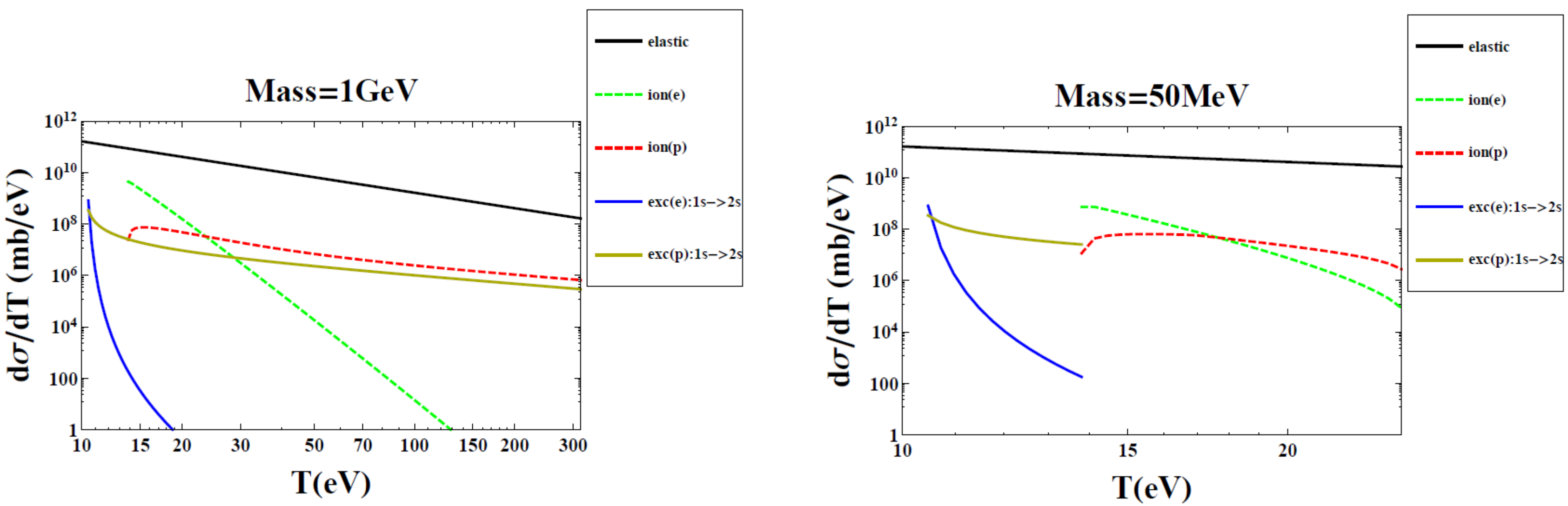
(c)



(d)



Short range interaction: exchanging Higgs-like gauge boson.



Long range interaction: exchanging photon-like boson.

Other Interesting Topics

- Other Ionization Process for Detectors: Besides the interactions mentioned above, there are many possibilities like producing light or heat for a more complex detector.
- Sterile Neutrino: A candidate of light DM, probably can oscillate to ordinary neutrinos.
- Other Neutrino Sources: Tritium beta decay, Low energy solar neutrinos

Reference:

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K.-N. Huang and W. R. Johnson, Phys. Rev. A **25**, 634 (1982). [MCRRPA Theory]

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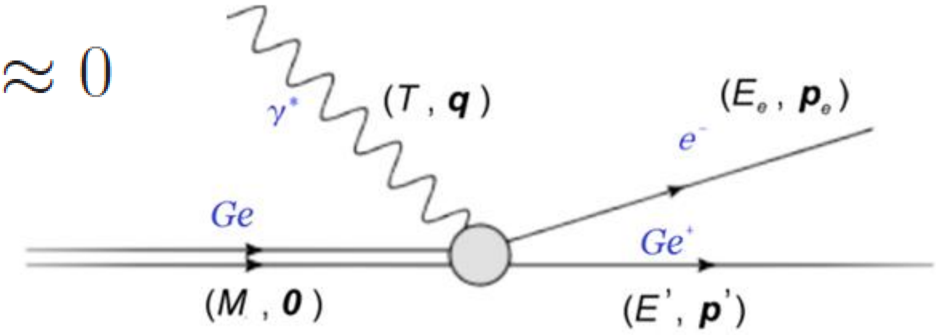
Thanks for your attention!

BACKUP SLIDES

Two Approximations --- I

Equivalent Photon Approx.

$Q^2 \approx 0$

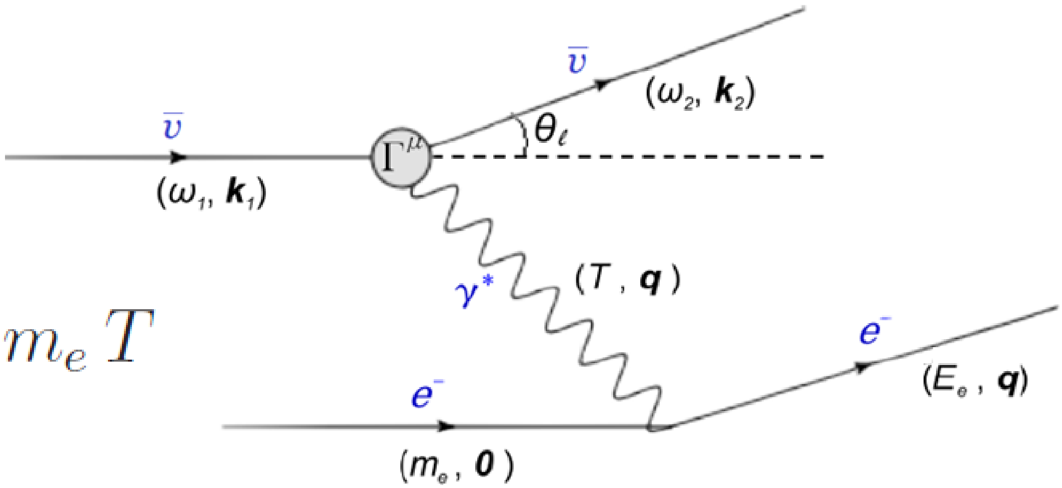


$$\left.\frac{d\sigma}{dT}\right|_{\mathrm{EPA}} = \int d\cos\theta \, \frac{2\,\pi\,\alpha^2}{Q^4} \frac{k_2}{k_1} \left[V_T \left(\frac{T}{2\,\pi^2\,\alpha} \sigma_\gamma(T) \right) \right]$$

$$= \frac{1}{T} \sigma_\gamma(T) \underbrace{\frac{\alpha}{\pi} \frac{k_2}{k_1} T^2 \int d\cos\theta \, \frac{V_T}{Q^4}}_{\text{energy spectrum of equivalent photon}}$$

Two Approximations --- II

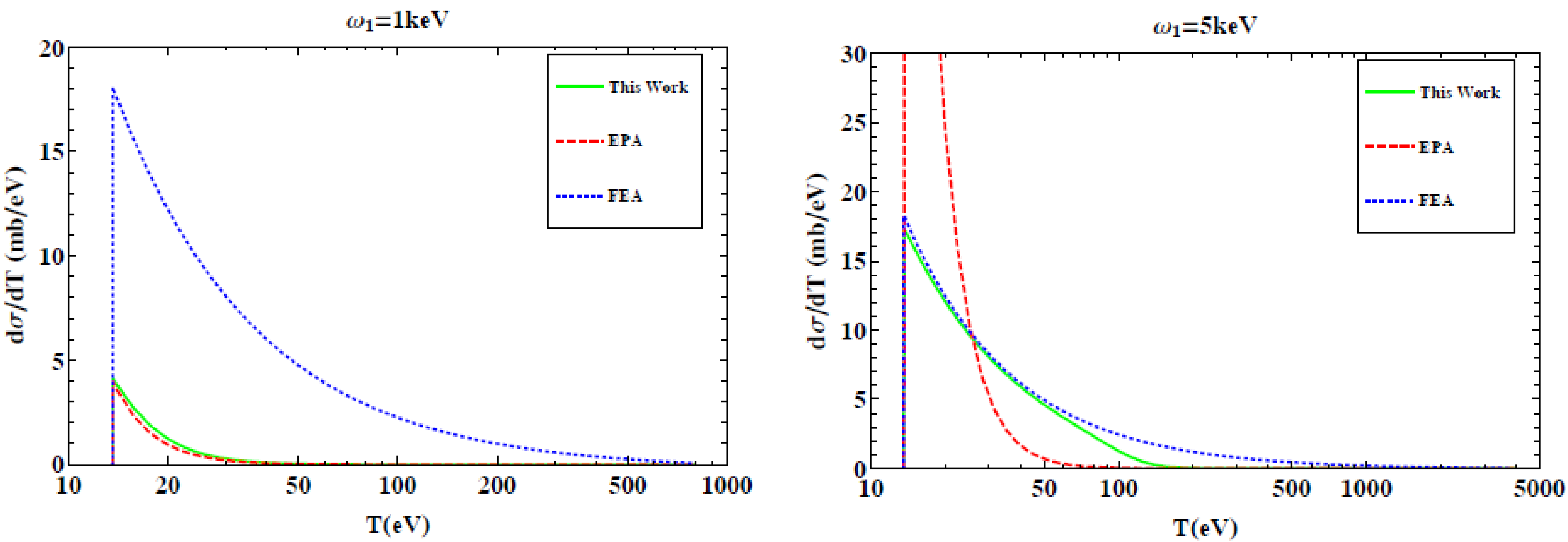
Free Electron Approx.



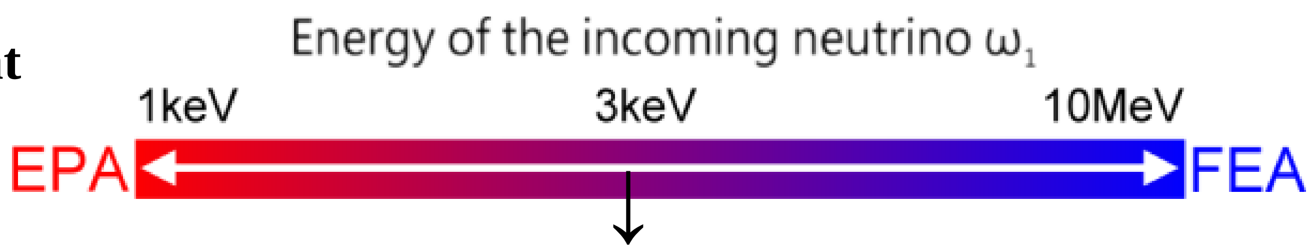
$$Q^2 = -2\, m_e\, T$$

$$\left.\frac{d\sigma}{dT}\right|_{FEA} = \sum_{i=1}^{Z} \theta(T - B_i)\, \left.\frac{d\sigma}{dT}\right|_{q^2=-2m_eT}$$

Toy: ν-H atomic ionization, exact result obtained



Equivalent Photon Approx.



Free Electron Approx.

binding momentum of hydrogen: αm_e

Ab initio MCRRPA Theory for Atomic Ionization

MCRRPA: multiconfiguration relativistic random phase approximation

Hartree-Fock : Solve self consistently by reducing the N-body system to single-particle problem by effective mean field

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Important for open shell system,
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K.-N. Huang and W.R. Johnson (1982)

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

Hamiltonian of an Electron + Atomic Coulomb interaction

Time-dependent interaction

$$V_I(t) = \sum_i [v(\vec{r}_i)\, e^{-i\omega t} + \overline{v}(\vec{r}_i)\, e^{i\omega t}]$$

$\psi(t)$ is a Slater determinant of one-electron orbitals $u_a(\vec{r},t)$ and

invoke variational principle $\delta\langle\overline{\psi}(t)|\, i\frac{\partial}{\partial t} - H - V_I(t)\,|\psi(t)\rangle = 0$

to obtain equations for $u_a(\vec{r},t)$.

RPA: Expand $u_a(\vec{r},t)$ into time-indep. orbitals in power of external potential

$$u_a(\vec{r},t) = e^{i\varepsilon_a t}[u_a(\vec{r}) + w_{a+}(\vec{r})e^{-i\omega t} + w_{a-}(\vec{r})e^{i\omega t} + \ldots]$$

MCRRPA: Approximate the many-body wave function $\Psi(t)$ by a superposition of configuration functions $\psi_\alpha(t)$

$$\Psi(t) = \sum_\alpha C_\alpha(t)\,\psi_\alpha(t)$$

MCRRPA Equations

$$\Psi(t) = \sum_a C_a(t)\psi_a(t)$$

Normalization

$$\langle \Psi(t) | \Psi(t) \rangle = 1$$

$$\langle u_\alpha(t) | u_\beta(t) \rangle = \delta_{\alpha\beta}$$

$$\langle \psi_a(t) | \psi_b(t) \rangle = \delta_{ab}$$

$$\sum_a C_a^\star(t) C_a(t) = 1$$

Slater determinant

$$u_\alpha(t)$$

time-dependent external perturbation:

$$V(t) = \sum_{i=1}^{N} v_+(\mathbf{r}_i)e^{-i\omega t} + \sum_{i=1}^{N} v_-(\mathbf{r}_i)e^{+i\omega t}$$

Multipole expansion

$$v_+ = \sum_{JM\lambda} v_{JM}^{(\lambda)}$$

$$C_a(t) = C_a + [C_a]_+ \, e^{-i\omega t} + [C_a]_- \, e^{+i\omega t} \ldots$$

$$u_\alpha(t) = u_\alpha + w_{\alpha+}e^{-i\omega t} + w_{\alpha-}e^{+i\omega t} + \ldots$$

Transition amplitude:

$$T_J^{(\lambda)} = \sum_\alpha \left[\left\langle w_{\alpha+} \left| v_{JM}^{(\lambda)} \right| u_\alpha \right\rangle + \left\langle u_\alpha \left| v_{JM}^{(\lambda)} \right| w_{\alpha-} \right\rangle \right] + \sum_{ab} \left([C_a]_+^* C_b + C_a^* [C_b]_- \right) \left\langle \psi_a \left| v_{JM}^{(\lambda)} \right| \psi_b \right\rangle$$

Atomic Structure of Ge

$$\Psi = C_1 \left(4p_{1/2}^2\right)_0 + C_2 \left(4p_{3/2}^2\right)_0$$

Valence Configuration	Configuration Weight	Precentage
$4p_{1/2}^2$	0.84939	72.15
$4p_{3/2}^2$	0.52776	27.85

Angular Momentum Selection Rule:

$$|j - J| \leqslant j' \leqslant |j + J|$$

Parity Selection Rule:

$$l + l' + J + \lambda - 1 = \text{even.}$$

For J=1, λ=1

Selection Rules:

$$4p_{1/2} \to \epsilon s_{1/2},$$

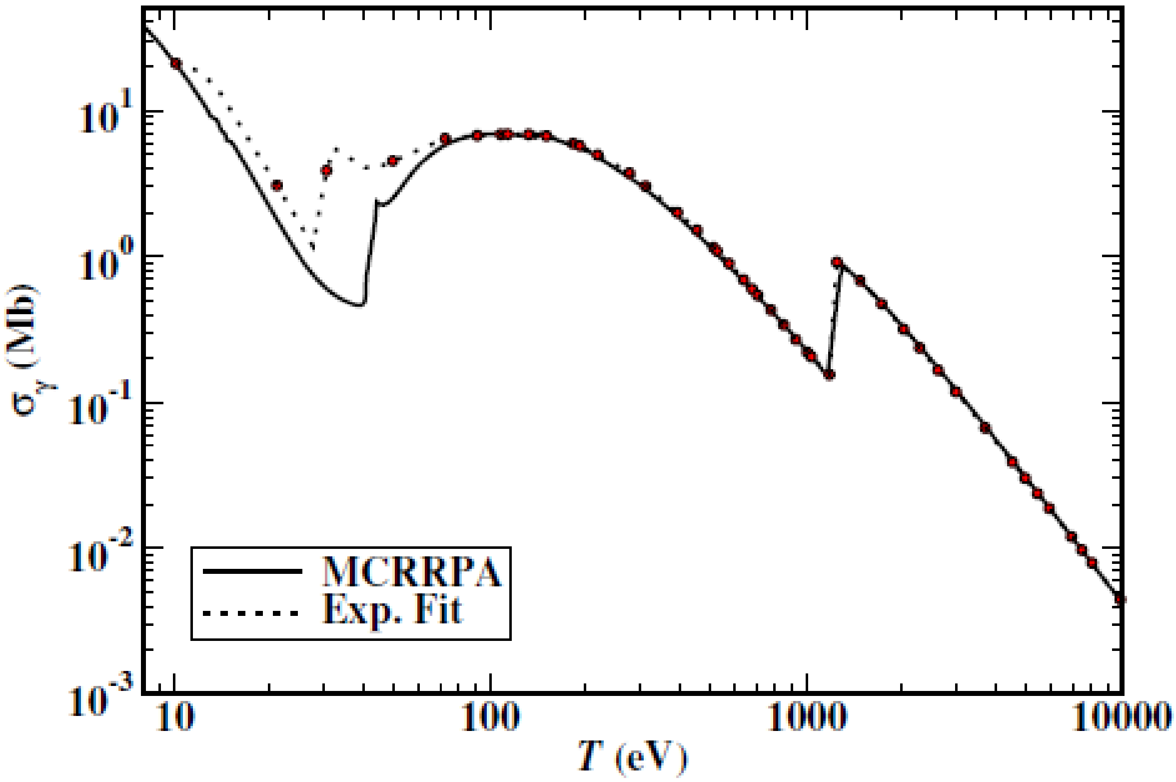
$$4p_{1/2} \to \epsilon d_{3/2},$$

$$4p_{3/2} \to \epsilon s_{1/2},$$

$$4p_{3/2} \to \epsilon d_{3/2},$$

$$4p_{3/2} \to \epsilon d_{5/2}.$$

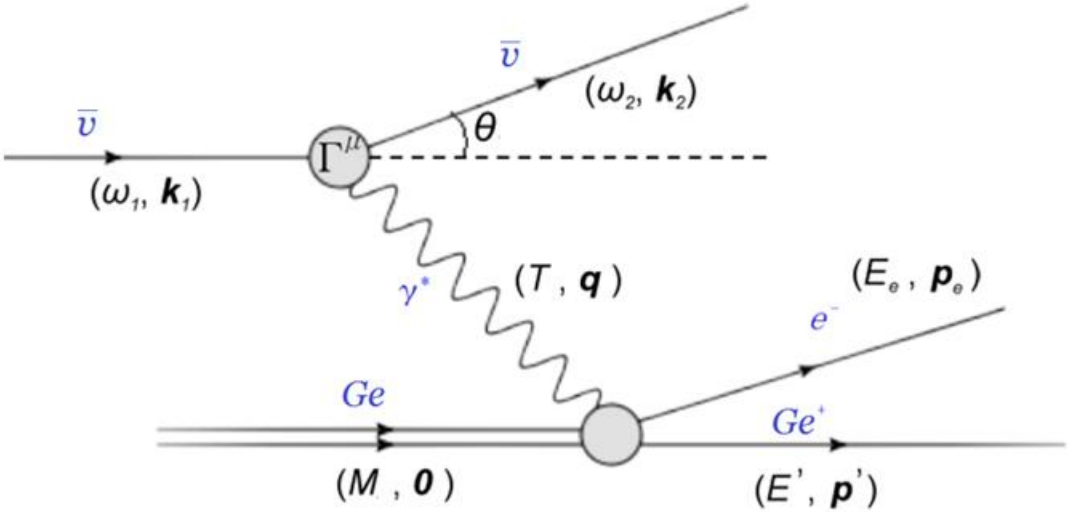
Benchmark: Ge Photoionization



Exp. data: Ge solid

Theory: Ge atom (gas) Above 80 eV error under 5%.

ν – Ge Atomic Ionization (AI)



$$\Gamma^{\mu}_{\mathrm{em}} \equiv F_1 \cdot \gamma^{\mu} + F_2 \cdot \sigma^{\mu\nu} \cdot q_{\nu}$$

$$F_1 = \delta_{\mathrm{Q}} \cdot e_0$$

$$F_2 = (-i) \cdot \frac{\mu_{\nu}}{2 \cdot m_e}$$

ν – Ge Kinematic Function

$$d\sigma = \frac{\pi}{|\vec{k}_1|}\frac{(4\,\pi\,\alpha)^2}{Q^4}\sum_{X=L,T}\left[\left(e_l^2\,V_X^{(F_1)} + \frac{\kappa_l^2}{(2\,m_e)^2}\,V_X^{(F_2)}\right)\,R_X\right]\frac{d^3\vec{k}_2}{(2\,\pi)^3\,2\,\omega_2}$$

$$V_L^{(F_1)} = \frac{Q^4}{q^4}[(\omega_1+\omega_2)^2 - q^2],$$

$$V_T^{(F_1)} = -\left[\frac{Q^2(Q^2+4\omega_1\omega_2)}{2\,q^2} + Q^2 + 2m_l^2\right]$$

$$V_L^{(F_2)} = \frac{-Q^4}{q^4}\left[(\omega_1+\omega_2)^2\,Q^2 + 4\,m_l^2\,q^2\right],$$

$$V_T^{(F_2)} = \frac{Q^2}{2\,q^2}\left[Q^2(Q^2+4\,\omega_1\,\omega_2) - 4\,m_l^2\,q^2\right]$$

ν – Ge Response Function

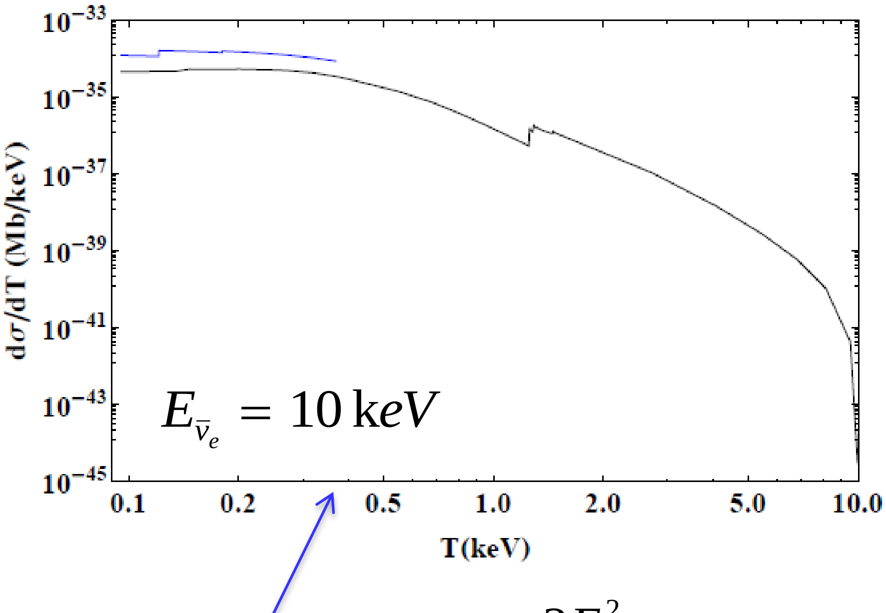
$$d\sigma = \frac{\pi}{|\vec{k}_1|}\frac{(4\,\pi\,\alpha)^2}{Q^4}\sum_{X=L,T}\left[\left(e_l^2\,V_X^{(F_1)} + \frac{\kappa_l^2}{(2\,m_e)^2}\,V_X^{(F_2)}\right)\,R_X\right]\frac{d^3\vec{k}_2}{(2\,\pi)^3\,2\,\omega_2}$$

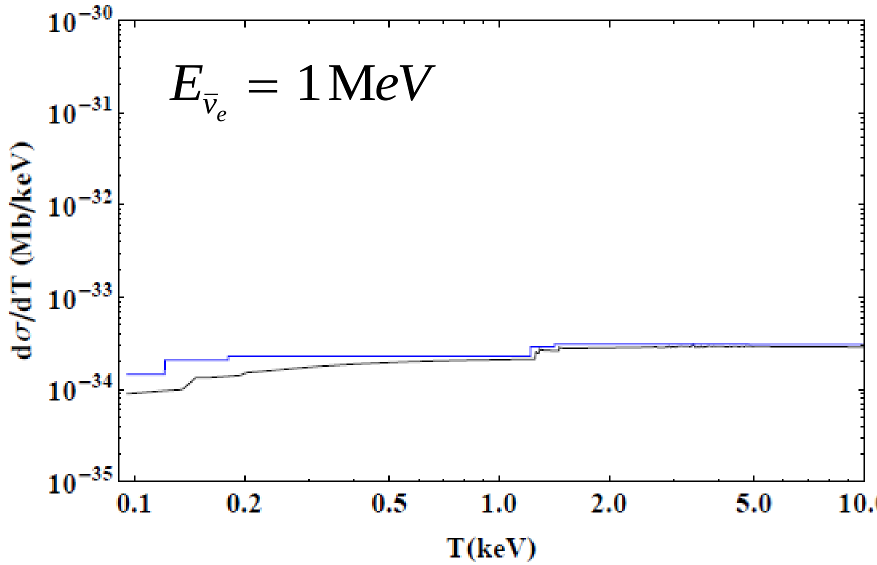
$$R_L \equiv \sum_{m_{j_f}}\overline{\sum_{m_{j_i}}}\int\frac{d^3\vec{p}_r}{(2\,\pi)^3}|\langle f|\rho^{(A)}(\vec{q})|i\rangle|^2\delta\left(T - B - \frac{q^2}{2M} - \frac{p_r^2}{2\,\mu_{red}}\right)$$

$$R_T \equiv \sum_{m_{j_f}}\overline{\sum_{m_{j_i}}}\int\frac{d^3\vec{p}_r}{(2\,\pi)^3}|\langle f|j_\perp^{(A)}(\vec{q})|i\rangle|^2\delta\left(T - B - \frac{q^2}{2M} - \frac{p_r^2}{2\,\mu_{red}}\right)$$

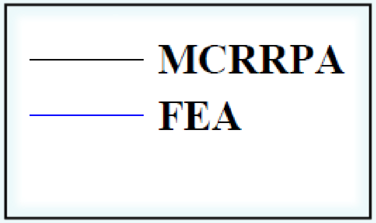
$$\rho^{(A)}(\vec{q}) = -\,e^{i\,\vec{q}\cdot(\vec{R}+\vec{r})}\,,\quad \vec{j}^{(A)}(\vec{q}) = \frac{-1}{2\,m_e}\,e^{i\,\vec{q}\cdot(\vec{R}+\vec{r})}\,(\vec{q} + 2\,\vec{p}_r + i\;\vec{\sigma}_e\times\vec{q}).$$

Numerical Results: Weak Interaction



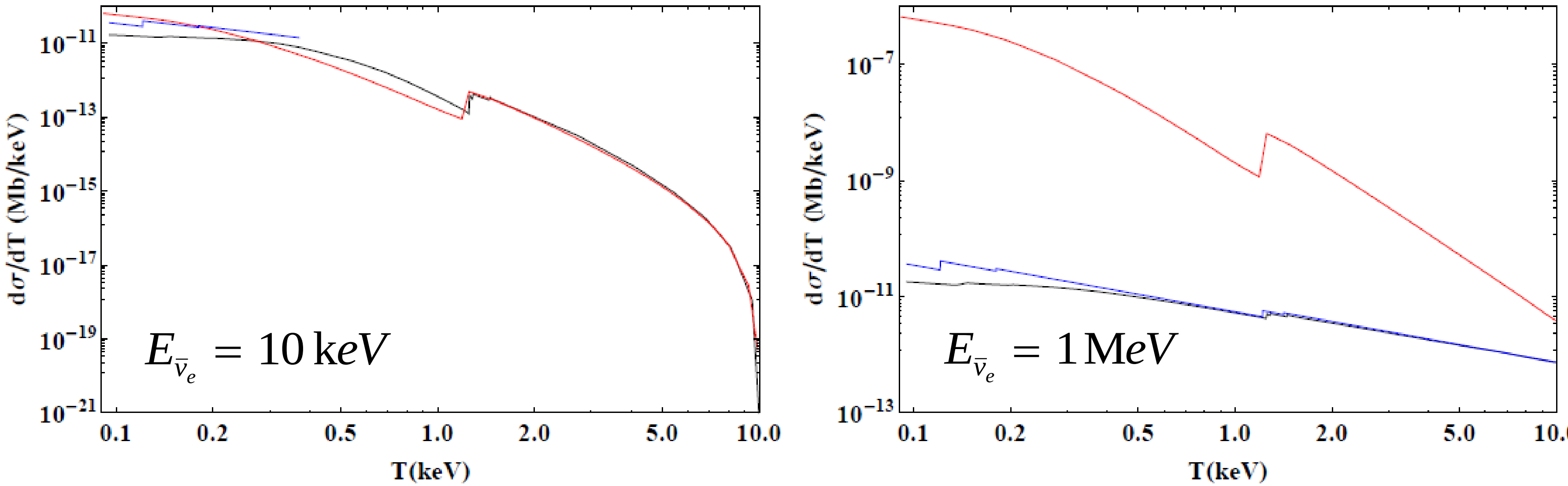


$$\text{cutoff}: T_{\text{Max}} = \frac{2E_{\bar{\nu}_e}^2}{E_{\bar{\nu}_e} + m_e} \approx 0.38\,keV$$



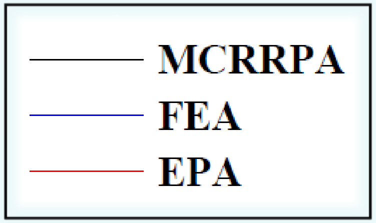
High E_ν & T, ours agreed with FEA.

Numerical Results: NMM

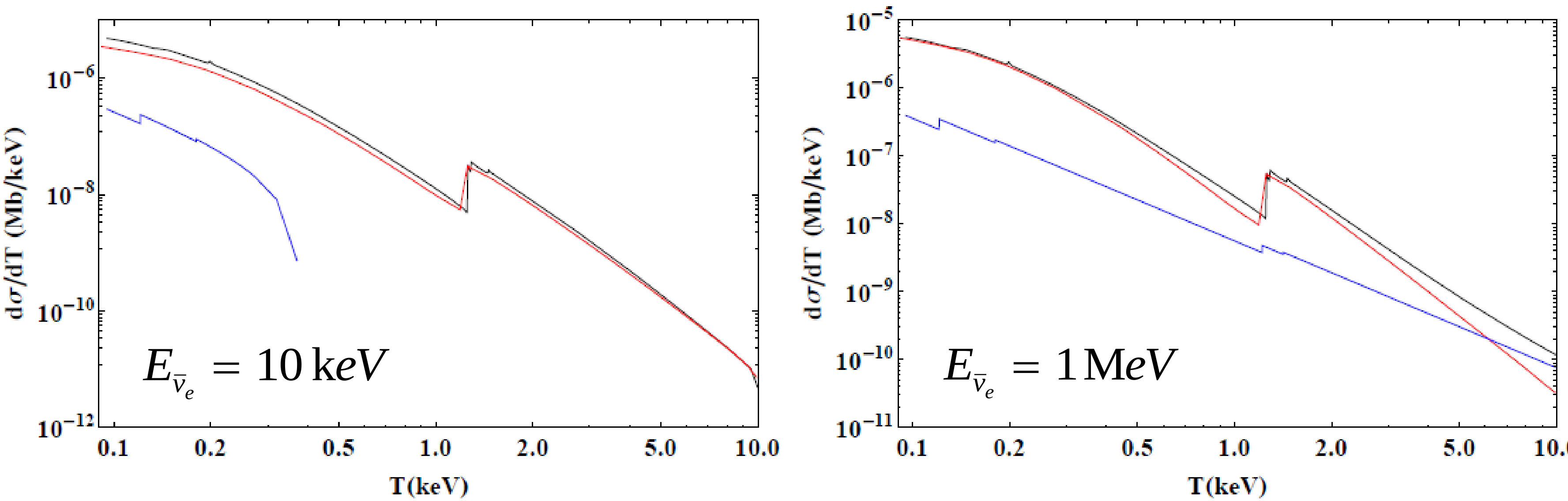


EPA failed at High E_{ν}.

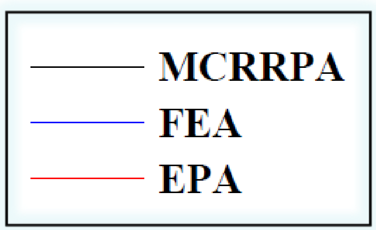
Ours is ~50% smaller than FEA at sub-keV.



Numerical Results: Millicharge



$$m_{\bar{\nu}_e} = 0.2\,eV$$



EPA worked well due to kinematic factors of F_1 form factor receive a strong weight at peripheral scattering angles.