Electromagnetic Interactions of Neutrinos

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Outline

- Motivation & Introduction
- Exp. Searches & Status
- Many-Body Physics (needed in low-E Exp.)
- Summary

★ For things can not be covered, see, e.g., Giunti & Studenikin, RMP **87**, 531(2015)

Motivation & Introduction

Why Study Neutrino EM?

- Basic properties of elementary particles
- Potential new physics
- Implication for astrophysics & cosmology

EM Form Factors (spin-1/2)

$$\langle p'|j_\mu^{(\gamma)}(0)|p\rangle = \bar{u}(p')\Big[\underbrace{F_1(q^2)}_{\text{charge}}\gamma_\mu - i\underbrace{F_2(q^2)}_{\text{anomalous mag. dipole}}\sigma_{\mu\nu}q^\nu$$
$$+ \underbrace{F_A(q^2)}_{\text{anapole}}\left(q^2\gamma_\mu - \not{q}q_\mu\right)\gamma_5 + \underbrace{F_E(q^2)}_{\text{el. dipole}}\sigma_{\mu\nu}q^\nu\gamma_5\Big]u(p)$$

- For ν's and q^2=0:
  F_1=mQ; F_2=MM; F_A=AM; F_E=EDM;

- ν charge radius squared:
  6 dF_1/dq^2=CR

EM Form Factors (spin-1/2)

$$
{}_f\langle p'|j_\mu^{(\gamma)}(0)|p\rangle_i = \bar{u}(p')\Big[\overbrace{F_1}^{\text{charge}}(q^2)\gamma_\mu - i\overbrace{F_2}^{\text{anomalous mag. dipole}}(q^2)\sigma_{\mu\nu}q^\nu
+ \underbrace{F_A}_{\text{anapole}}(q^2)\left(q^2\gamma_\mu - \not{q}q_\mu\right)\gamma_5 + \underbrace{F_E}_{\text{el. dipole}}(q^2)\sigma_{\mu\nu}q^\nu\gamma_5\Big]u(p)
$$

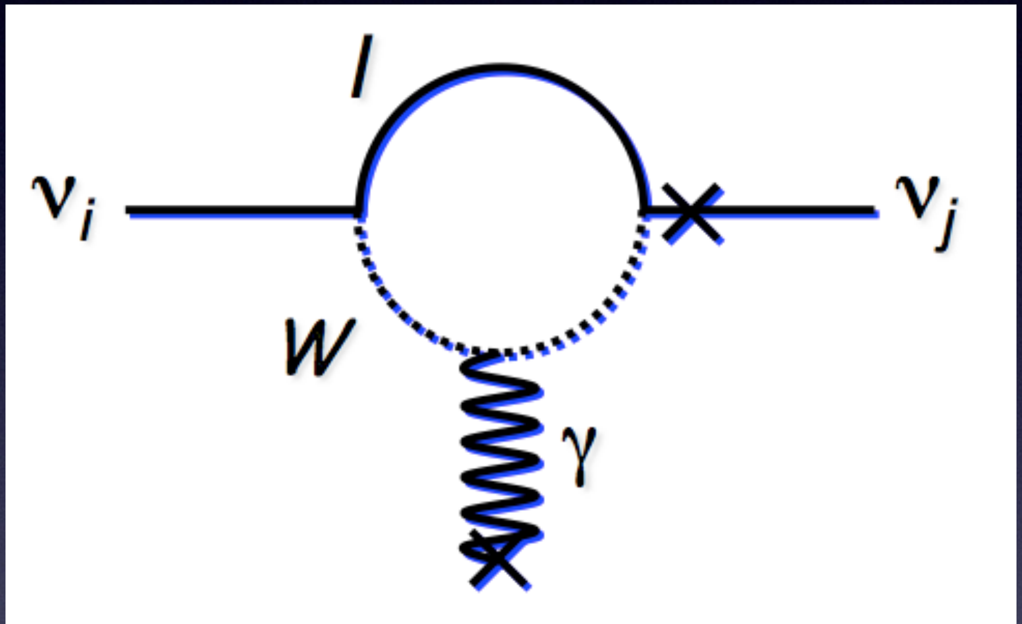
- ν's oscillate; when i=f “static”; i≠f “transition”
- Static moments: Dirac ν's can have all; Majorana ν's can only have anapole [Kayser, PRD, ’82]

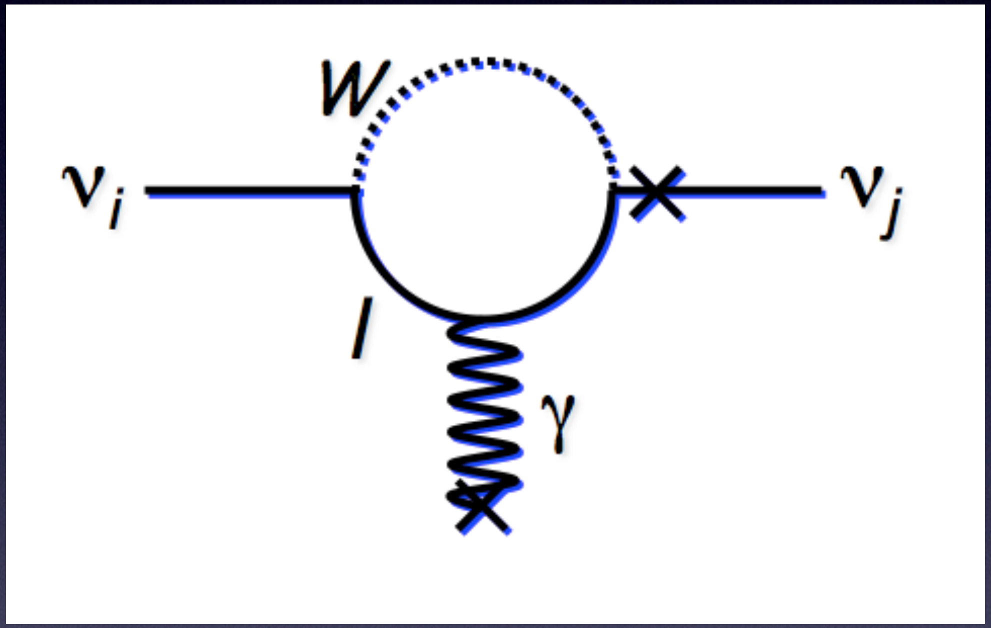
Neutrino EMs in the SM

- Charge: zero by construct
- Other moments: tiny from radiative corrections
- If neutrinos are reported to be milli-charged or have anomaly big EM moments: something “new”, “wrong”, or “background”?!

ν's MM and EDM in the SM

- Consider a Dirac neutrino case:





- Naive dimensional analysis

$$\begin{array}{l} \text{MM} \\ \text{EDM} \end{array} \sim \frac{e}{4\pi}\frac{G_F}{\sqrt{2}}m_\nu \sim \begin{array}{l} 5\times 10^{-19}\,\mu_B \\ 5\times 10^{-30}\,e\,\text{cm} \end{array}$$

AP and Cosmo. Implication

- Star (Sun, red giant, white dwarf etc.) cooling

$$\gamma^* \rightarrow \nu + \bar{\nu}$$

- Supernova explosion and neutron star cooling
- Big bang nucleosynthesis d.o.f.? $\nu_L \leftrightarrow \nu_R$
- What if a primordial magnetic field exists?
- What if a neutrino decay radiatively? $\nu_i \rightarrow \nu_f + \gamma$

Exp. Searches & Status

Primary Detection Channel

- Electron recoil from neutrino-electron scattering

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

- Analysis by change in diff. count rate

$$\frac{d}{dT}R = \frac{d}{dT}R^{(w)} + \frac{d}{dT}R^{(\gamma)}$$

- Electrons are bound, so in fact neutrino-ionization

$$\nu + A(e^-) \rightarrow \nu + A^+ + e^-$$

- Binding effects could be important at low energies

Neutrino-Electron Scattering

- A notable feature:

$$\frac{d\sigma}{dT}^{(0)} \propto \overset{\text{W,CR}}{T^0}, \quad \overset{\text{MM}}{T^{-1}}, \quad \overset{\text{mQ}}{T^{-2}}$$

- Sensitivities to MM and mQ gained by lowering the detector threshold

- Mainstream detectors
  - Semi-cond. germanium: sub-keV — few keV
  - Liquid xenon: ~ few keV
  - Liquid scintillator: 100 keV — MeV
  - Water Cherenkov: ~ few MeV

Differential Rate

$$\frac{d}{dT}R = \rho_e \int dE_\nu \left[\frac{d\sigma}{dT}\right]\left[\frac{d\phi}{dE_\nu}\right]$$

- Need diff. cross section
- Need neutrino energy spectra from sources like
  - reactor: ~ MeV
  - solar: 100 keV — 20 MeV
  - accelerator: vary
- For long-baseline exps., oscillation effects needed

Effective Neutrino EM Moments

★ Because neutrinos oscillate and final-state neutrinos are not detected, experiments constrain effective EM moments, which are combinations of static and transition moments

- e.g. effective MM:

$$\mu^2_{\nu_\ell}(L, E_\nu) = \sum_j \left| \sum_k U^*_{\ell k} e^{-i\Delta m^2_{kj} L/2E_\nu} \left(\mu_{jk} - i\epsilon_{jk}\right) \right|^2$$

- In scatteirng, MM & EDM; CR & AM are barely distinguishable at the $m_\nu \to 0$ limit

Direct Limits on MM

Method	Experiment	Limit	CL	Reference
Reactor $\bar{\nu}_e$-e^-	Krasnoyarsk	$\mu_{\nu_e} < 2.4 \times 10^{-10}\ \mu_B$	90%	Vidyakin *et al.* (1992)
	Rovno	$\mu_{\nu_e} < 1.9 \times 10^{-10}\ \mu_B$	95%	Derbin *et al.* (1993)
	MUNU	$\mu_{\nu_e} < 0.9 \times 10^{-10}\ \mu_B$	90%	Daraktchieva *et al.* (2005)
	TEXONO	$\mu_{\nu_e} < 7.4 \times 10^{-11}\ \mu_B$	90%	Wong *et al.* (2007)
	GEMMA	$\mu_{\nu_e} < 2.9 \times 10^{-11}\ \mu_B$	90%	Beda *et al.* (2012)
Accelerator ν_e-e^-	LAMPF	$\mu_{\nu_e} < 10.8 \times 10^{-10}\ \mu_B$	90%	Allen *et al.* (1993)
Accelerator $(\nu_\mu, \bar{\nu}_\mu)$-e^-	BNL-E734	$\mu_{\nu_\mu} < 8.5 \times 10^{-10}\ \mu_B$	90%	Ahrens *et al.* (1990)
	LAMPF	$\mu_{\nu_\mu} < 7.4 \times 10^{-10}\ \mu_B$	90%	Allen *et al.* (1993)
	LSND	$\mu_{\nu_\mu} < 6.8 \times 10^{-10}\ \mu_B$	90%	Auerbach *et al.* (2001)
Accelerator $(\nu_\tau, \bar{\nu}_\tau)$-$e^-$	DONUT	$\mu_{\nu_\tau} < 3.9 \times 10^{-7}\ \mu_B$	90%	Schwienhorst *et al.* (2001)
Solar ν_e-e^-	Super-Kamiokande	$\mu_S(E_\nu \gtrsim 5\,\mathrm{MeV}) < 1.1 \times 10^{-10}\ \mu_B$	90%	Liu *et al.* (2004)
	Borexino	$\mu_S(E_\nu \lesssim 1\,\mathrm{MeV}) < 5.4 \times 10^{-11}\ \mu_B$	90%	Arpesella *et al.* (2008)

[Giunti & Studenikin, RMP 87, 531(2015)]

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- PDG (2017) adopted

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- Both use low-threshold Ge detector
- Threshold: 2.5 (GEMMA) and 5 (TEXONO) keV

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- Water Cherenkov vs. Liquid Scintillator
- Recent update to 3.1×10^{-11} using Borexino data [Cañas et al. ’16]

Direct Limits on mQ

ν CHARGE

VALUE (units: electron charge)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<3 \times 10^{-8}$	95	[1] DELLA-VALLE	16	PVLA	Magnetic dichroism
$<2.1 \times 10^{-12}$	90	[2] CHEN	14A	TEXO	Nuclear reactor
$<1.5 \times 10^{-12}$	90	[3] STUDENIKIN	14		Nuclear reactor
$<3.7 \times 10^{-12}$	90	[4] GNINENKO	07	RVUE	Nuclear reactor
$<2 \times 10^{-14}$		[5] RAFFELT	99	ASTR	Red giant luminosity
$<6 \times 10^{-14}$		[6] RAFFELT	99	ASTR	Solar cooling

- All use data taken by low-threshold Ge detectors
- Indirect astrophysical limits are generally stronger

Direct Limits on CR

VALUE (10^{-32} cm^2)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
−2.1 to 3.3	90	[1] DENIZ	10	TEXO	Reactor $\overline{\nu}_e e$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
−0.53 to 0.68	90	[2] HIRSCH	03		$\nu_\mu e$ scat.
−8.2 to 9.9	90	[3] HIRSCH	03		anomalous $e^+ e^- \to \nu\overline{\nu}\gamma$
−2.97 to 4.14	90	[4] AUERBACH	01	LSND	$\nu_e e \to \nu_e e$
−0.6 to 0.6	90	VILAIN	95B	CHM2	$\nu_\mu e$ elastic scat.

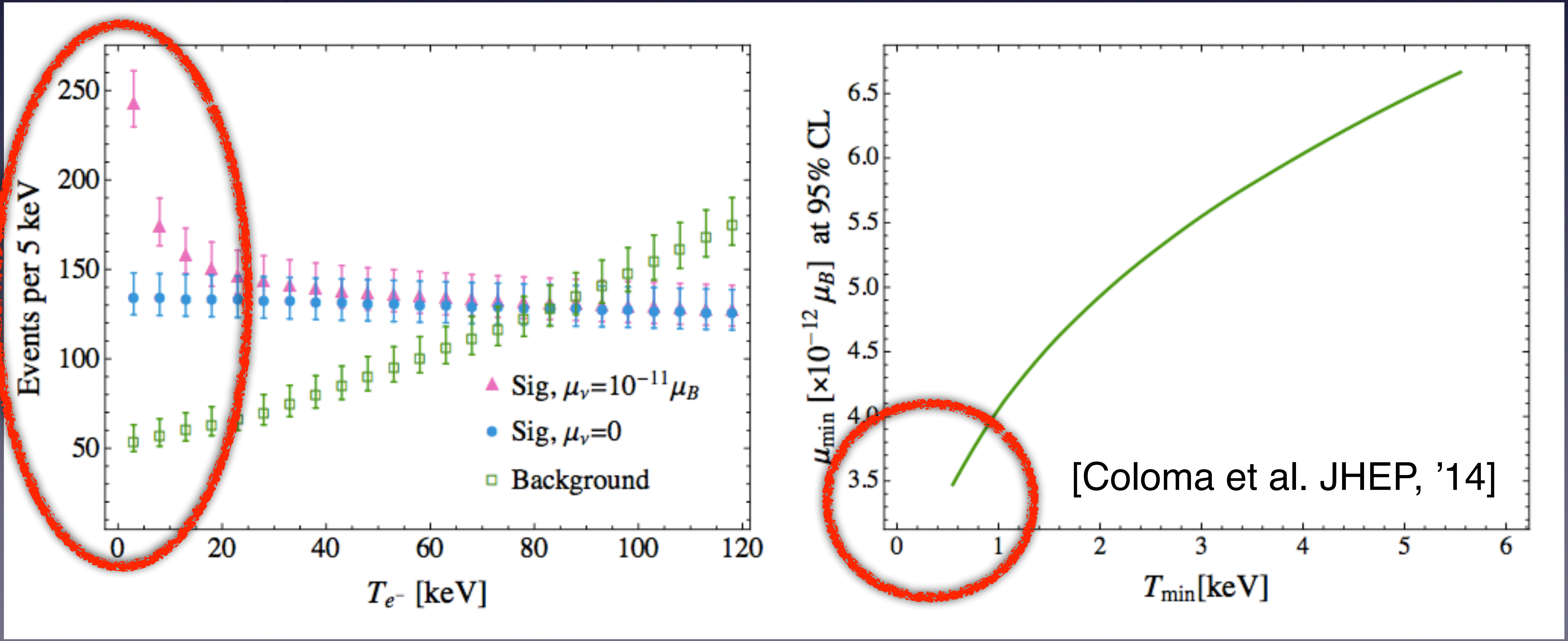
- TEXONO data taken by CsI in 3-8 MeV range
- Low-threshold detectors not competitive on CR

Future Improvements

- Bigger detector mass
- Longer detecting time
- Smaller background
- More intense beam
- Lower detector threshold

Case 1: Lux-Zeplin

- Turning a multi-ton-scale LXe detector for DM to a precision low-E neutrino detector
- Search mode: electron recoil by ^{51}Cr neutrinos



Case 2: COHERENT (SNS)

- Multi-detectors aim at measuring coherent elastic neutrino-nucleus scattering
- Search mode: nuclear recoil by stop-pion neutrinos

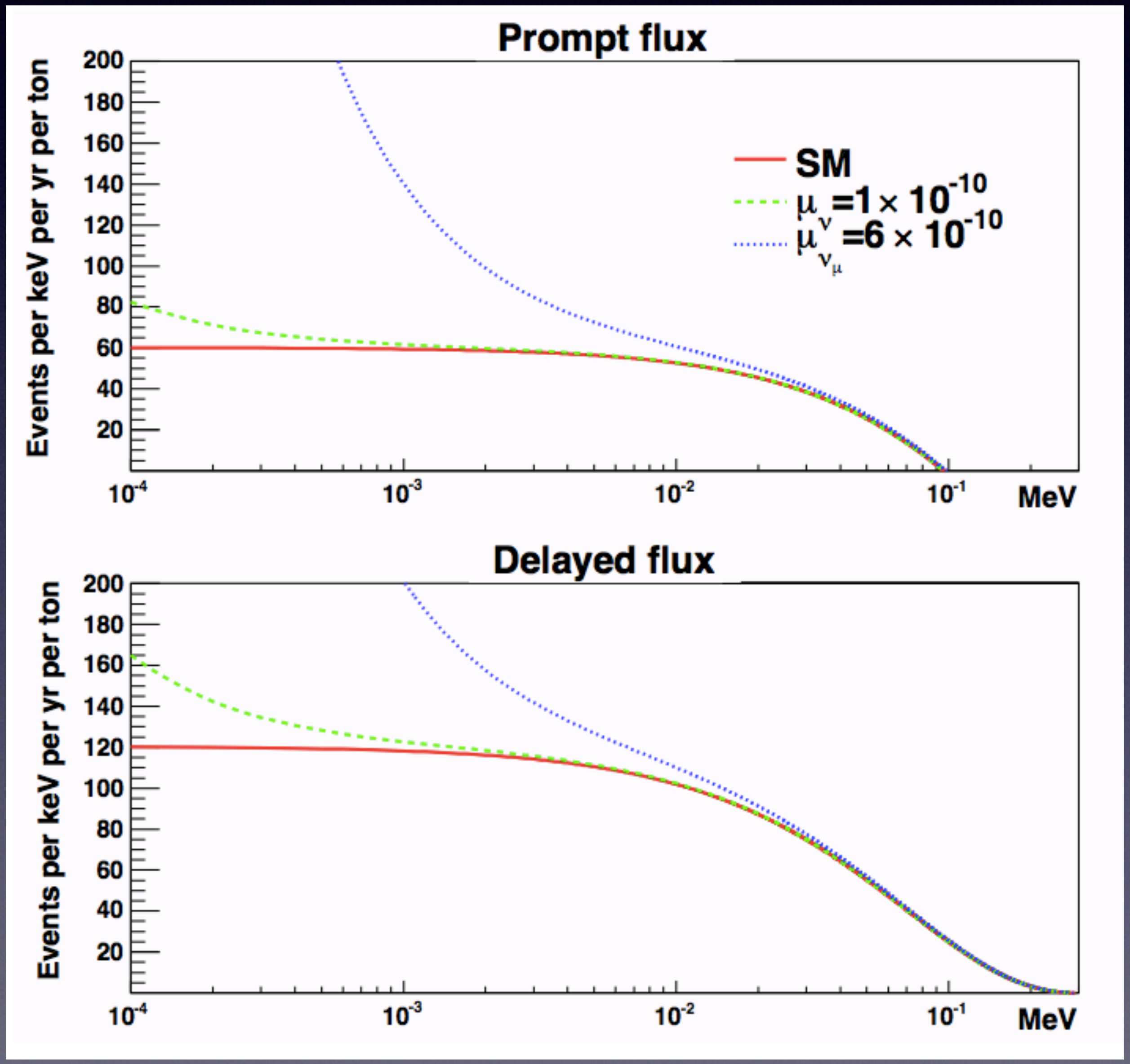
Nucleus	^{20}Ne	^{40}Ar	^{76}Ge	^{132}Xe
μ_{ν_μ}	9.09 [2.31]	9.30 [2.47]	8.37 [2.54]	12.94 [2.54]
$\mu_{\bar{\nu}_\mu}$	10.28 [2.53]	10.46 [2.69]	9.39 [2.75]	14.96 [2.74]
μ_{ν_e}	10.22 [2.44]	10.55 [2.60]	9.46 [2.68]	15.20 [2.68]
$\mu_{\nu_\mu}^{\mathrm{comb}}$	8.07 [2.02]	8.24 [2.16]	7.41 [2.22]	11.58 [2.21]

in $10^{-10}\ \mu_B$

[Kosmas et al. PRD, '15]

Case 2: COHERENT (SNS)

- Challenge: Coh. SM b.g. vs. incoh. MM signal



- Calculation done with Ne
  [Scholberg, PRD '06]

- Need sub-MeV threshold!

- Might have a better shot with mQ (coherent)

Example 3: JUNO/DUNE

- Both multi-purpose neutrino experiments
- MM of solar neutrinos (JUNO)
- Search for core collapse supernova neutrinos (JUNO/DUNE), which indirectly put limits on MM

Future Improvements

- Bigger detector mass
- Longer detecting time
- Smaller background
- More intense beam
- Lower detector threshold!

Important Physical Scales

- For reactor/solar/supernova neutrinos:
  $E_\nu \sim 100$ keV - 20 MeV

- Max. energy deposition by m_ν to m_A:
  $2E_\nu^2/(m_A+2E_\nu) < 10$ keV (if elastic)

- Atomic scales with effective charge Z_{eff} (shell-dep.):
  $p_e \sim Z_{eff}\, m_e\alpha$, $E_\chi \sim Z_{eff}\, m_e\alpha^2$, $m_e\alpha = 3.7$ keV

- Atomic effects important for low-E neutrino detection!

Many-Body Physics
(needed in Low-E Exp.)

What Are Needed?

- Differential cross sections: $d\sigma/\mathrm{d}T$ for weak and EM interactions (MM, mQ, CR)
- Most difficult: transition matrix elements $\langle f|j_\mu^{(w,\gamma)}|i\rangle$ where both *i* and *f* are many-body states
- Are there good approximations or MB problems need to be solved?

Free Electron Approximation

$$\left.\frac{d\sigma}{dT}\right|_{\text{FEA}} = \sum_{i=1}^{Z} \theta(T - B_i) \frac{d\sigma}{dT}^{(0)}$$

T>Bi atomic shell open

free scat.

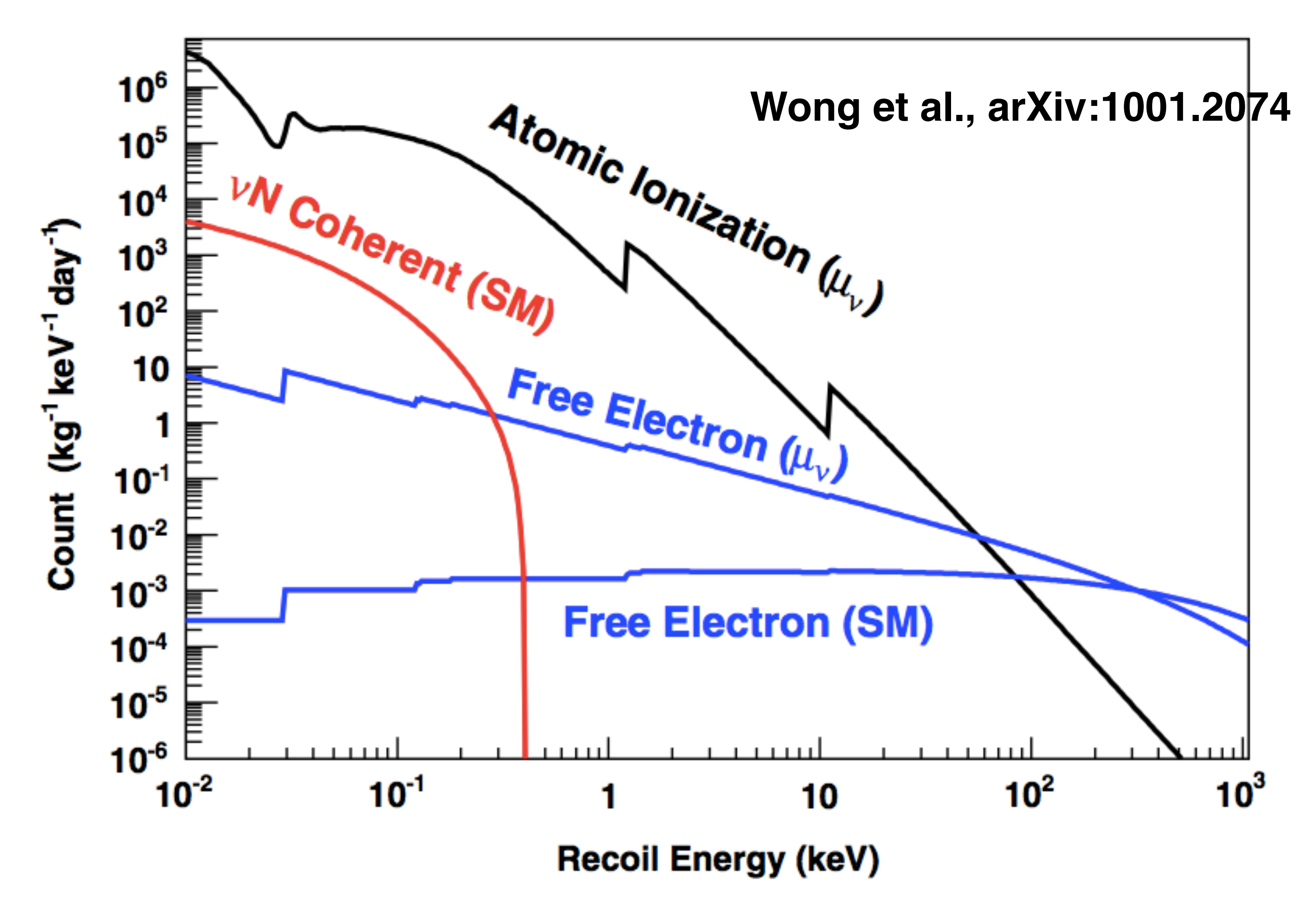
- No atomic calculation needed (almost)
- Validity at sub-keV regimes needs justification

Equivalent Photon Approximation

$$\left.\frac{d\sigma}{dT}\right|_{\text{EPA}} = \sigma_\gamma(T) N_\gamma(T)$$

from exps. from kinematics

- AP built-in in exp. data
- MM sensitivity gain?
- Not really
  Voloshin ’10; …
- Reason: improper $N_\gamma(T)$
  Chen, CPL, et al, ’13



Many-Body Calculations

- Hartree-Fock (fitted local ex.)

  Fayans, et al., ’92; ’01; Kopeikin, et al., ’97; ’03

- FEA + WKB + 2e correlation

  Kouzakov, Studenikin, et al., ’11; ’12; ’14

- Multi-configuration radom phase approximation

  Chen, Chi, CPL, et al., ’14; ’15

Our Method: MCRRPA

An *ab initio* method based on Hatree-Fock (full ex. treatment) with refinements:

- MC [multi-configuration]: open-shell atoms have more than one g-s configuration
  for Ge: $|J=0\rangle = c_1\ |[\mathrm{Zn}]4p^2_{1/2}\rangle + c_2\ |[\mathrm{Zn}]4p^2_{3/2}\rangle$
- R [relativistic]: $Z\alpha \sim 1/4$ for Ge
- RPA [random phase approximation]: residual 2e correlation is important for atomic excited states (in our case $\mathrm{Ge}^+ + e^-$)

Our Results for Ge

- Chen et al., Phys. Rev. D **88**, 033006 (2013)
- Chen et al., Phys. Lett. B **731**, 159 (2014)
- Chen et al., Phys. Rev. D **90**, 011301(R) (2014)
- Chen et al., Phys. Rev. D **91**, 013005 (2015)

Collaborators: J.-W. Chen, H.-C. Chi, K.-N. Huang, H.-B. Li, C.-F. Liu, H.-T. Shiao, L. Singh, H. T. Wong, C.-L. Wu, C.-P. Wu

Benchmark I: Ge Ground State

- First ion. E: 7.899 eV (exp) vs. 7.856 eV (th.)

Valence configuration	Configuration weight	Percentage
$4p_{1/2}^2$	0.84939	72.15%
$4p_{3/2}^2$	0.52776	27.85%

MC is needed!

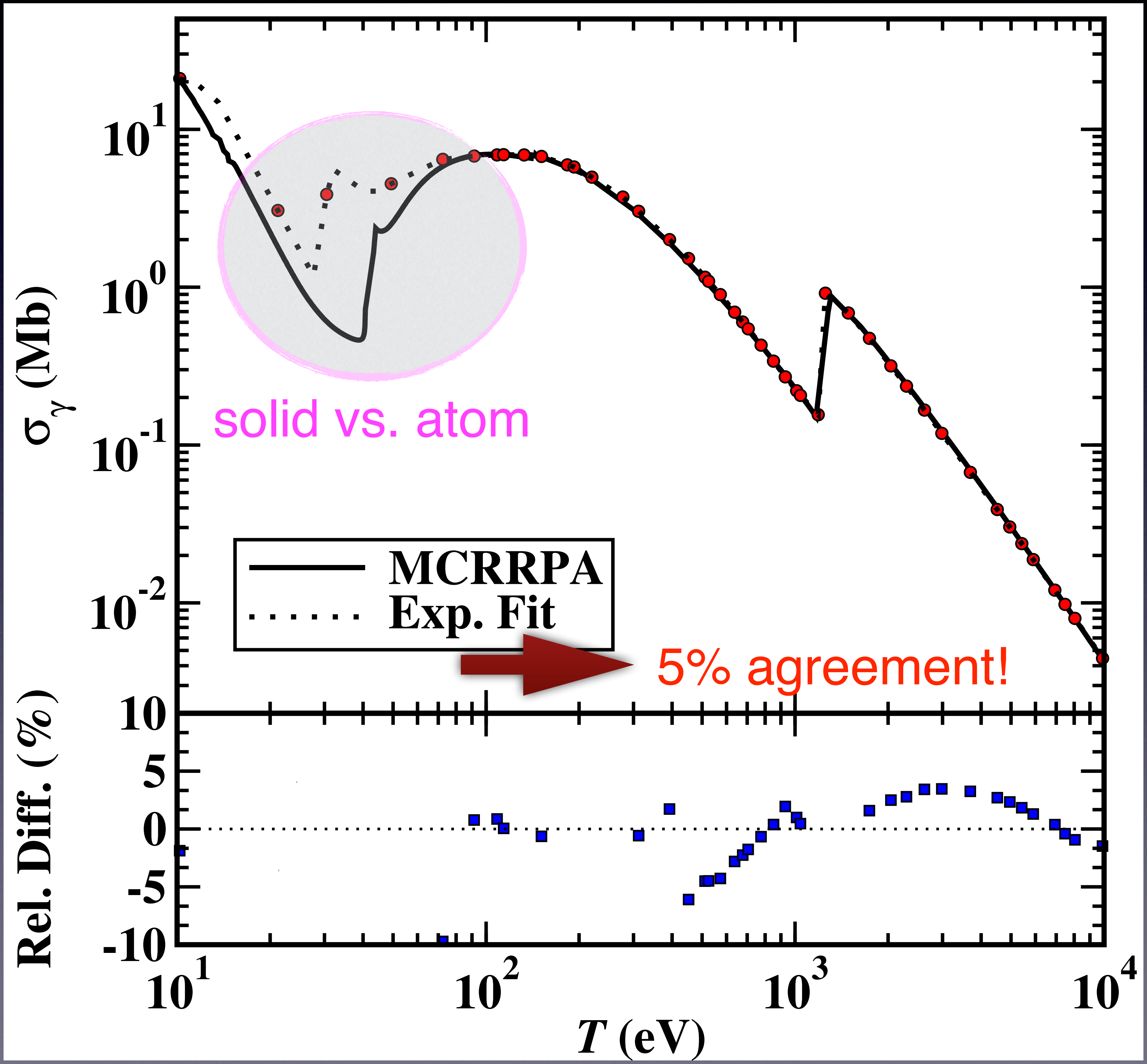
- Single particle energies of subshells:

	$K(1s_{\frac{1}{2}})$	$L_I(2s_{\frac{1}{2}})$	$L_{II}(2p_{\frac{1}{2}})$	$L_{III}(2p_{\frac{3}{2}})$	$M_I(3s_{\frac{1}{2}})$	$M_{II}(3p_{\frac{1}{2}})$	$M_{III}(3p_{\frac{3}{2}})$	$M_{IV}(3d_{\frac{3}{2}})$	$M_V(3d_{\frac{5}{2}})$	$N_I(4s_{\frac{1}{2}})$	$N_{II}(4p_{\frac{3}{2}})$	$N_{III}(4p_{\frac{1}{2}})$
s.p.	11 185.5	1454.4	1287.9	1255.6	201.5	144.8	140.1	43.8	43.1	15.4	8.0	7.8
edge	11 103.1	1414.6	1248.1	1217.0	180.1	124.9	120.8	29.9	29.3			

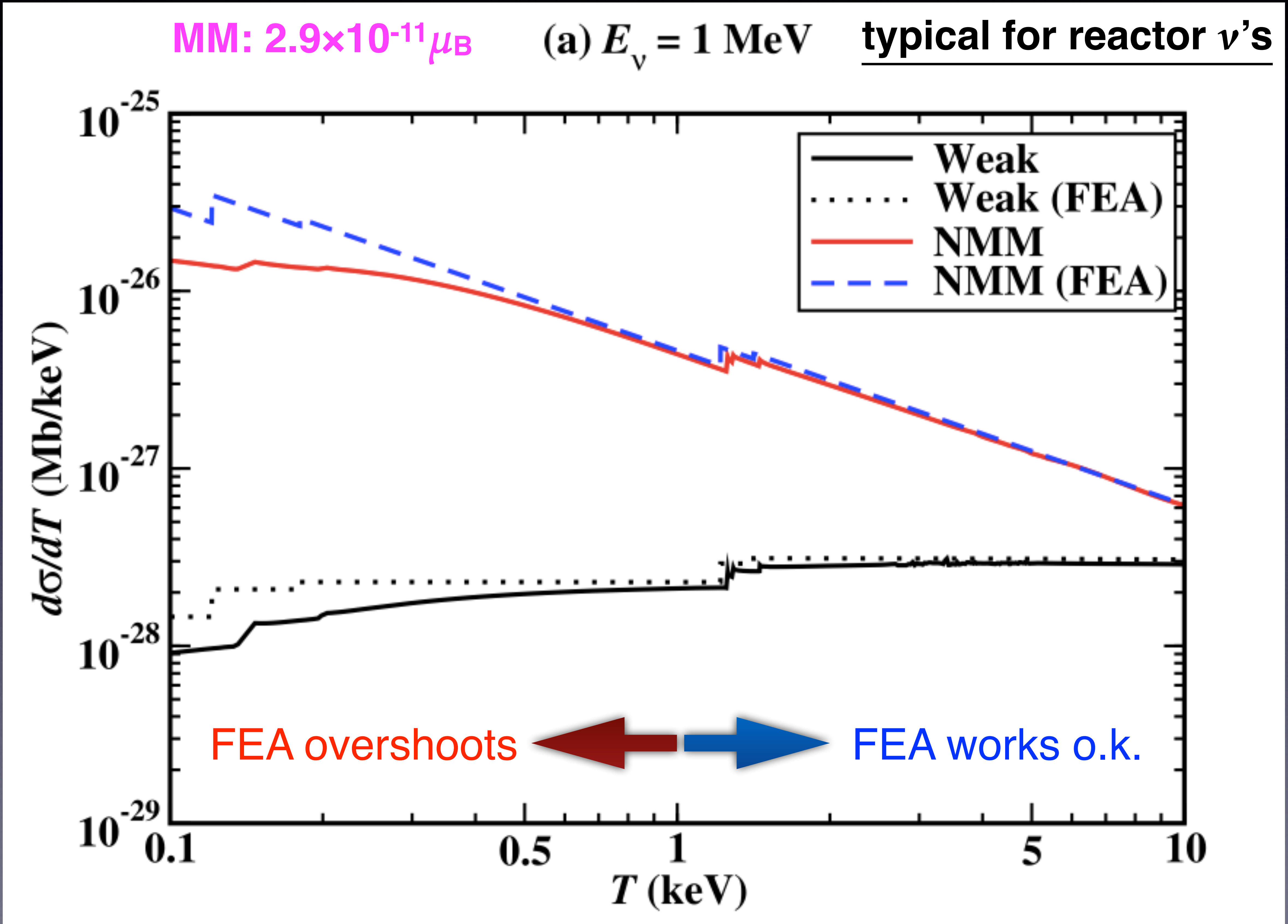
Rel. effect

- To test Ge ex. states, we chose photoionization

Benchmark II: Ge Photoionization

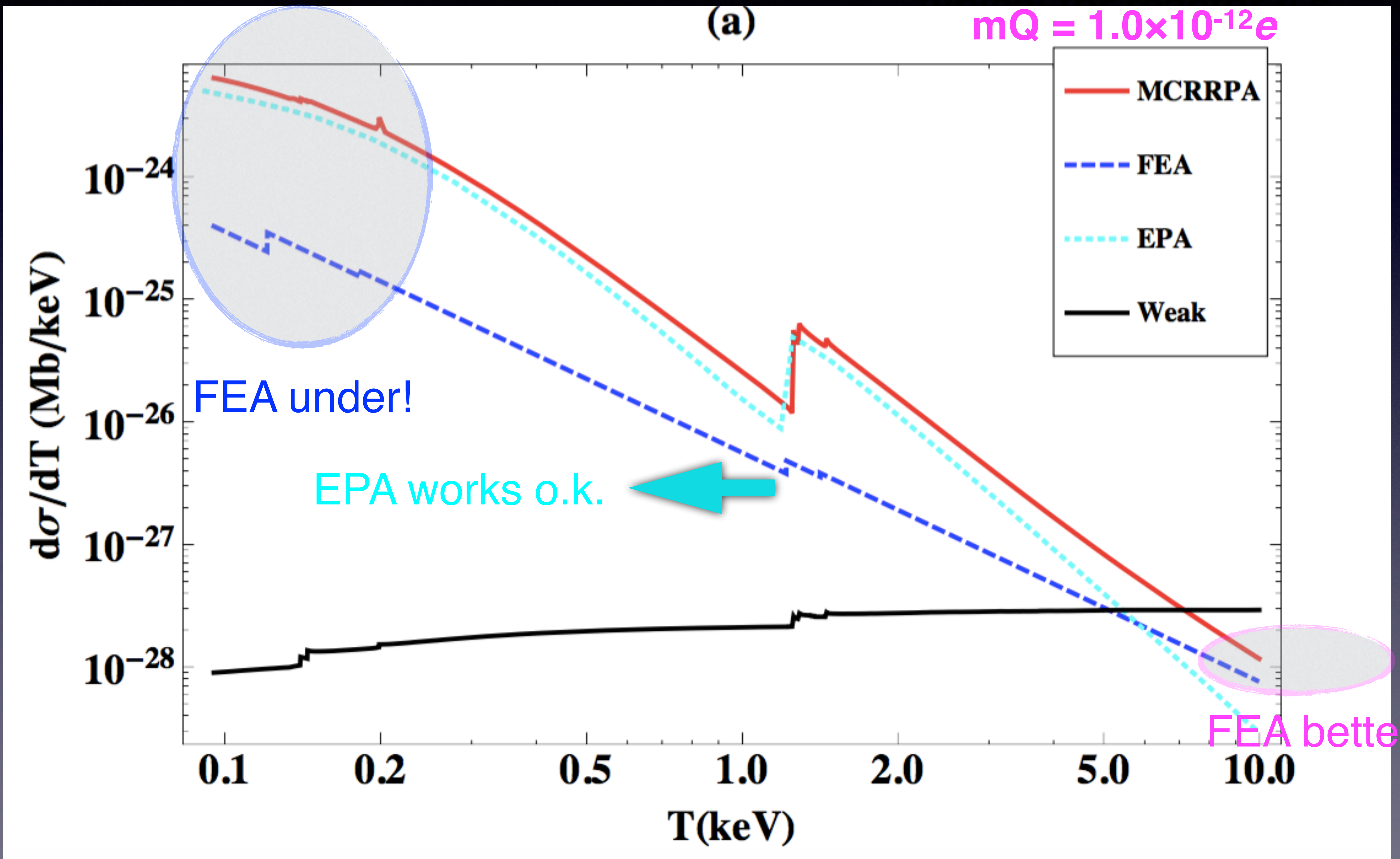


Ge AI by MM



MM: 2.9×10-11μB
(a) Eν = 1 MeV
typical for reactor ν's
Weak
Weak (FEA)
NMM
NMM (FEA)
dσ/dT (Mb/keV)
T (keV)
10-25
10-26
10-27
10-28
10-29
0.1
0.5
1
5
10
FEA overshoots
FEA works o.k.

Ge AI by mQ


(a)
mQ = 1.0×10-12e
MCRRPA
FEA
EPA
Weak
dσ/dT (Mb/keV)
10−24
10−25
10−26
10−27
10−28
0.1
0.2
0.5
1.0
2.0
5.0
10.0
T(keV)
FEA under!
EPA works o.k.
FEA better

Implication

Compared with FEA, atomic effects of Ge at keV lead to

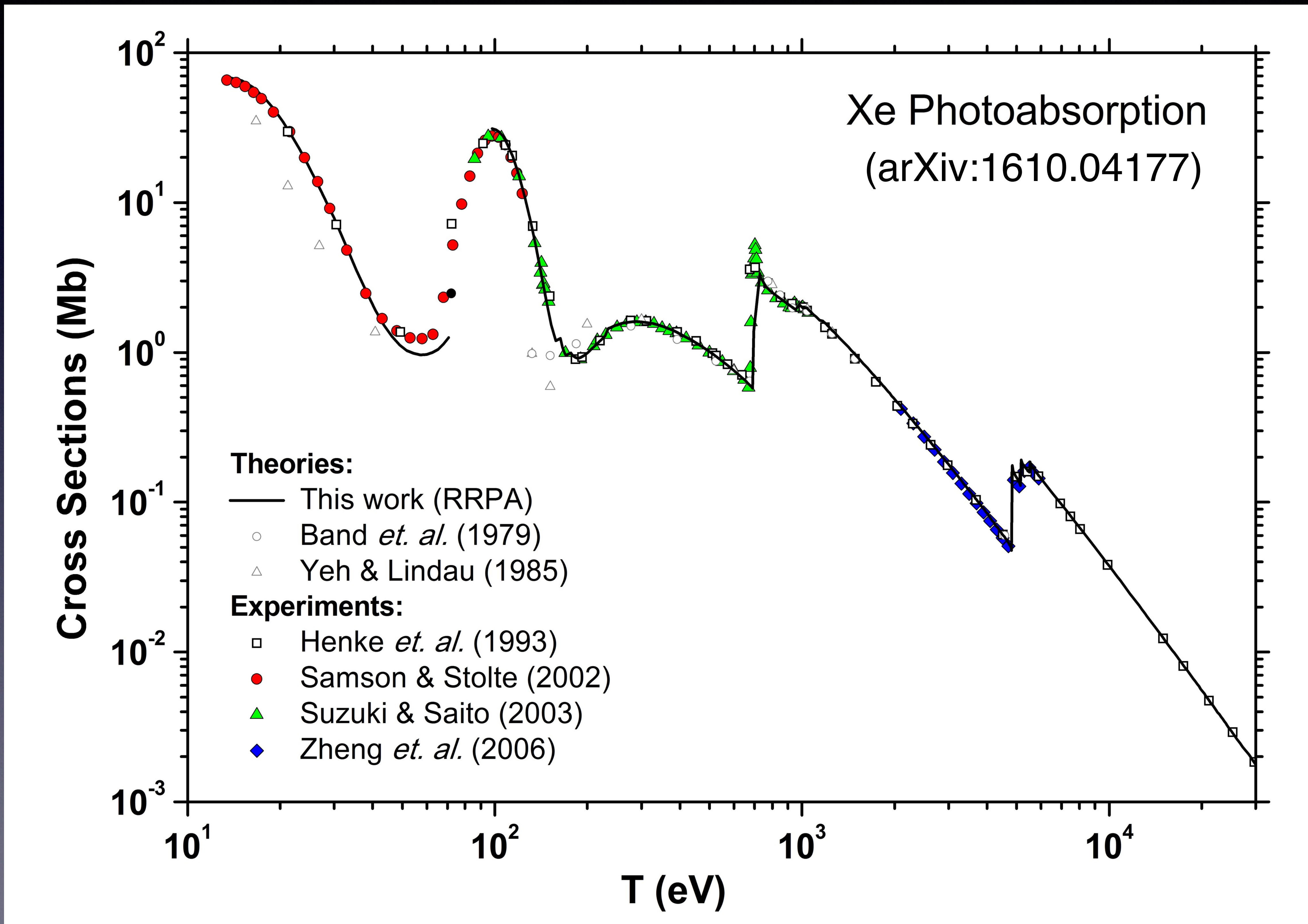
- a slightly weaker limit on MM (but more reliable)
- a much stronger upper limit on mQ

★ (Low-E) Ge data not competitive to CsI data in CR

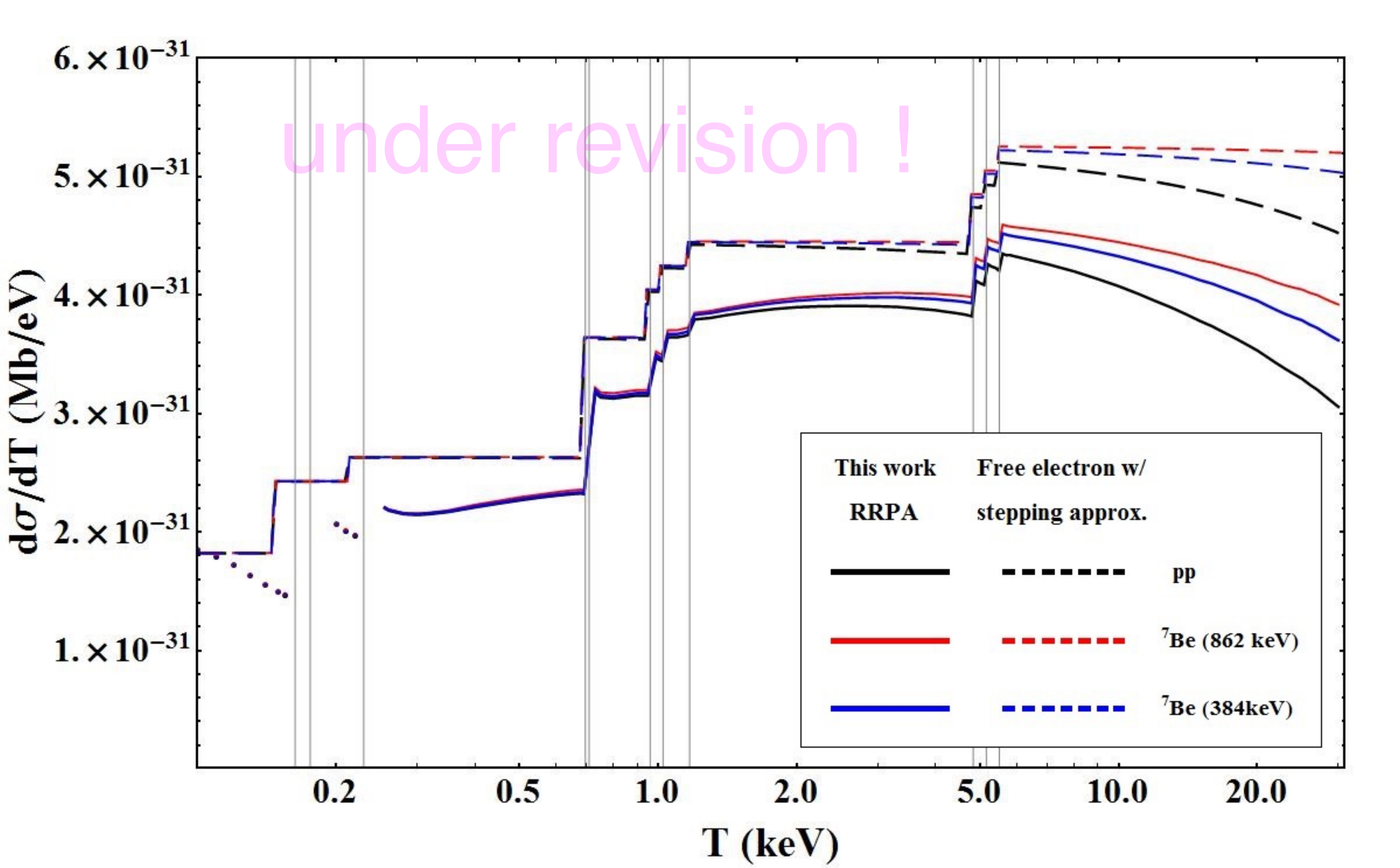
Recent Work on Xe

- Chen et al., arXiv:1610.04177

Benchmark: Xe Photoionization



Solar Neutrino-Xenon Scattering



Low-E Solar Neutrino Rate

Assume 1-ton liquid xenon & 1-year exposure

Physics channel	Low-energy ν measurement			Dark matter search		
Energy range	2–30 keV			2–10 keV		
Assumptions	No ER/NR discrimination			99.98% ER rejection, 30% NR acceptance		
Model	FE	RRPA	Diff.	FE	RRPA	Diff.
Solar *pp* neutrinos	80.7	57.8	−28%	4.8×10^{-3}	3.6×10^{-3}	−25%
Solar ^{7}Be neutrinos	7.1	5.4	−24%	4.1×10^{-4}	3.2×10^{-4}	−23%
Total	87.8	63.2	−28%	5.2×10^{-3}	3.9×10^{-3}	−24%

under revision !

FE overestimate!

Summary

Conclusions

- Neutrino EM properties could be windows for new physics.
- Low-threshold detectors is an efficient way to increase sensitivity.
- Atomic binding effects are important at low energies and can be calculated reliably.
- Similar studies can be applied to light dark matter detection.