

# Atomic Ionization by Neutrinos at Low Energies

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# Collaborators

A rather unique collaboration consists of **NP/HEP theorists**, **atomic theorists**, and **experimentalists**:

- National Taiwan U.: Jiunn-Wei Chen, Keh-Ning Huang, Chien-Fu Liu, Hao-Tse Shiao, Chih-Liang Wu, Chih-Pan Wu
- National Dong Hwa U.: Hsin-Chang Chi
- Academia Sinica / TEXONO: Hau-Bin Li, Lakhwinder Singh, Henry T. Wong

# References

- 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)

# Motivation & Introduction

# Neutrino EM Moments

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

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  - Potential new physics
  - Implication for astrophysics & cosmology
- 
- ★ Recent review: [Giunti & Studenikin, RMP 87, 531\(2015\)](#)
  - ★ Talks by [A. Studenikin](#), [K. Kouzakov](#), [H.-B. Li](#)

# EM Form Factors (spin-1/2)

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

- For  $\nu$ 's and  $q^2=0$ :  
 $F_1=mQ$ ;  $F_2=MM$ ;  $F_A=AM$ ;  $F_E=EDM$ ;
- $\nu$  charge radius squared:  
 $6 \, dF_1/dq^2=CR$

# Neutrino EMs in the SM

- Charge: zero by construct
- Other moments: tiny from radiative corrections
- If neutrinos are milli-charged or have anomaly big EM moments: could be something “new”, “wrong”, or “background”?!
- Search methods:
  - Direct:  $\nu + e^-(A) \rightarrow \nu + e^- + A^+$
  - Indirect: from astro. and cosmo.

# Current Direct Limits

From PDG 2014

- MM:  $2.9 \times 10^{-11} \mu_B$  (GEMMA '13);  $7.4 \times 10^{-11} \mu_B$  (TEXONO '07)
  - mQ:  $4.7 \times 10^{-12} e$  (from TEXONO '03)
  - CR:  $3.3 \times 10^{-32} \text{cm}^2$  (TEXONO '10)
  - All with reactor anti- $\nu$  sources
- ★ GEMMA & TEXONO both have update!

# Why Low Energy Exps.?

- Neutrinos scatter off free electron with energy deposition  $T$ :

$$\frac{d\sigma^{(0)}}{dT} \propto T^0, T^{-1}, T^{-2}$$

W,CR      MM      mQ

- Low threshold detectors:

GEMMA: Ge @ 1.5 keV; TEXONO: Ge @ 5 keV

- Sub-keV detectors are coming, and atomic physics becomes relevant

# Theory Basics

# What Are Needed?

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

# Free Electron Approximation

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

T > B<sub>i</sub> atomic shell open      free scat.

- No atomic calculation needed (almost)
- Validity at sub-keV regimes needs justification
- ★ Typical atomic scales:  $p \sim Zm_e a$ ;  $E \sim Z^2 m_e a^2$



# 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 random phase approximation

Chen, Chi, CPL, et al., '14; '15

# Our Method: MCRRPA

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

- MC [multi-configuration]: open-shell atoms have more than one g-s configuration  
for Ge:  $|J = 0\rangle = c_1 |[Zn]4p_{1/2}^2\rangle + c_2 |[Zn]4p_{3/2}^2\rangle$
- 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  $Ge^+ + e^-$ )

Our Results for Ge

# Benchmark Calculations

- 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%

- Single particle energies of subshells:

	$K(1s_{1/2})$	$L_I(2s_{1/2})$	$L_{II}(2p_{1/2})$	$L_{III}(2p_{3/2})$	$M_I(3s_{1/2})$	$M_{II}(3p_{1/2})$	$M_{III}(3p_{3/2})$	$M_{IV}(3d_{3/2})$	$M_V(3d_{5/2})$	$N_I(4s_{1/2})$	$N_{II}(4p_{3/2})$	$N_{III}(4p_{1/2})$
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			

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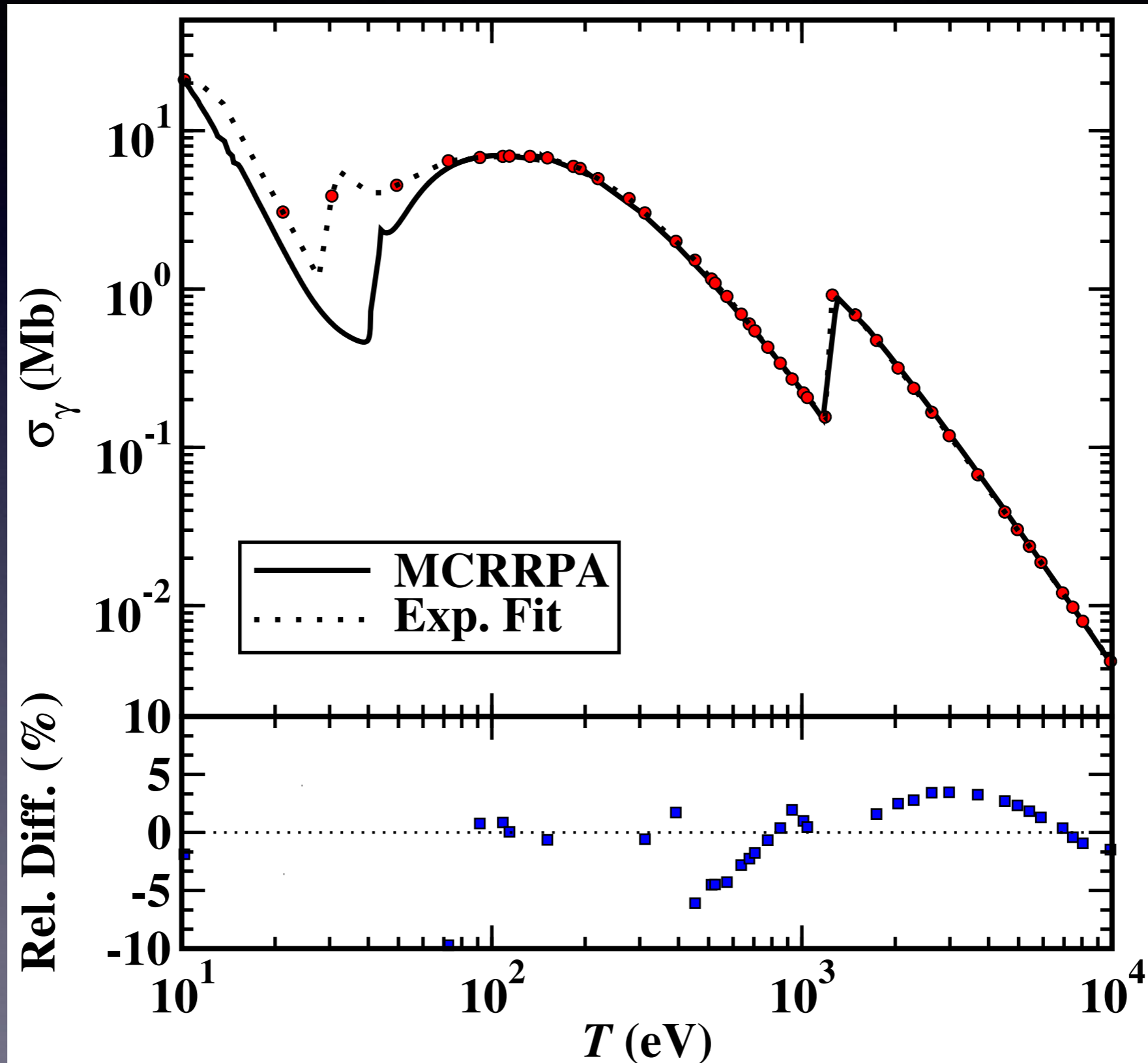
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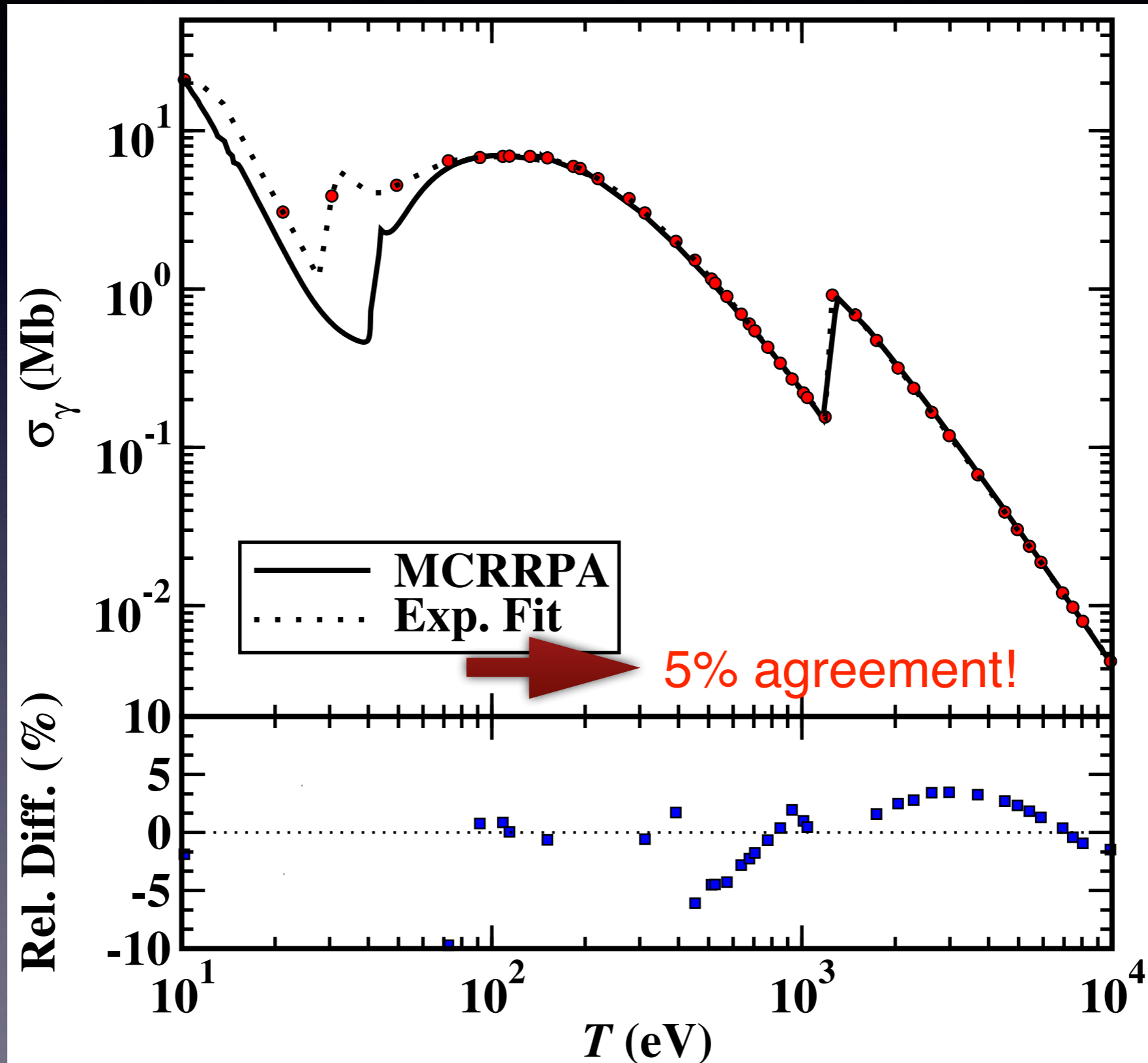
Rel. effect

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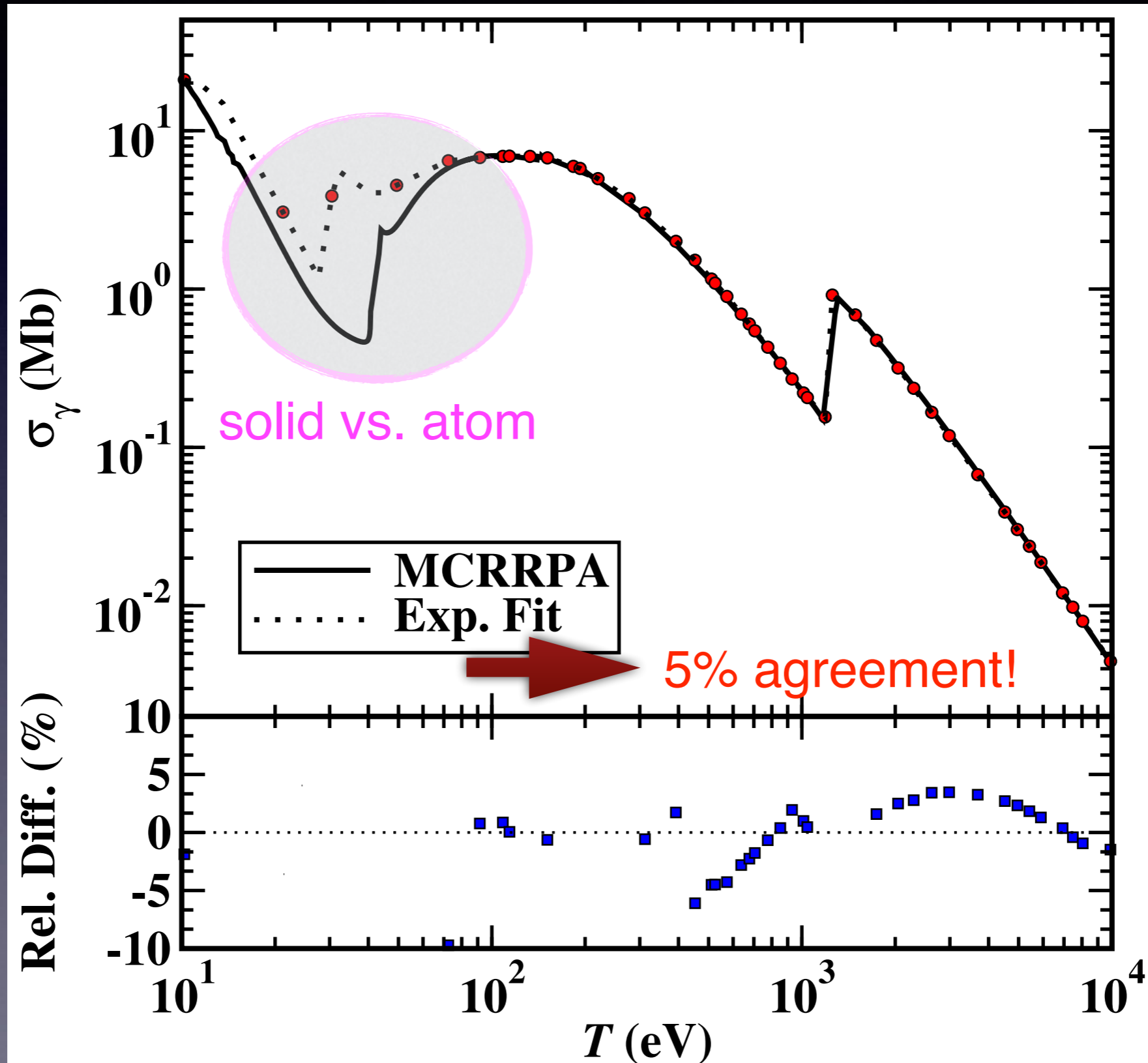
# Ge Photoionization



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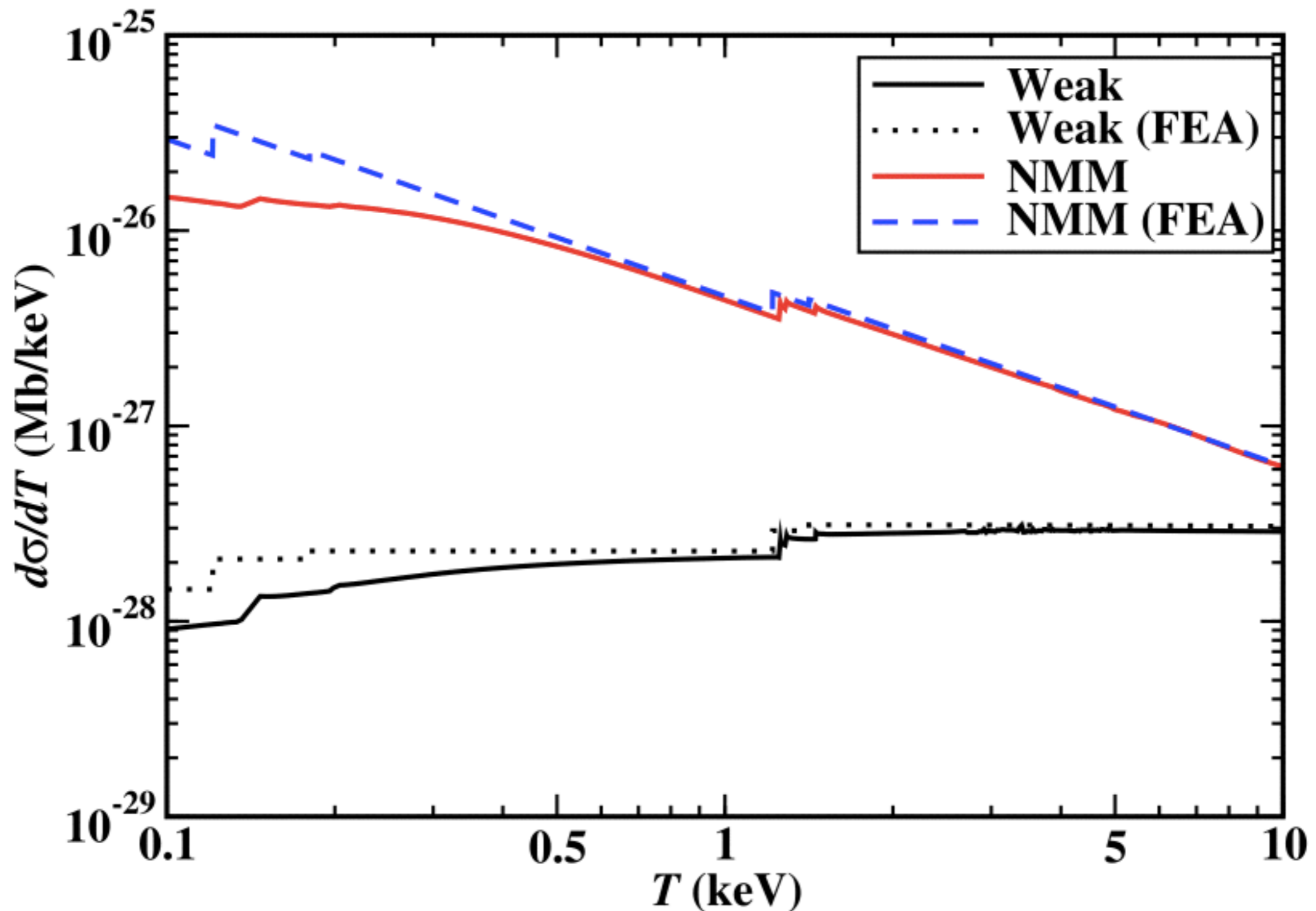


# Ge Al by MM

MM:  $2.9 \times 10^{-11} \mu_B$

(a)  $E_\nu = 1 \text{ MeV}$

typical for reactor  $\nu$ 's

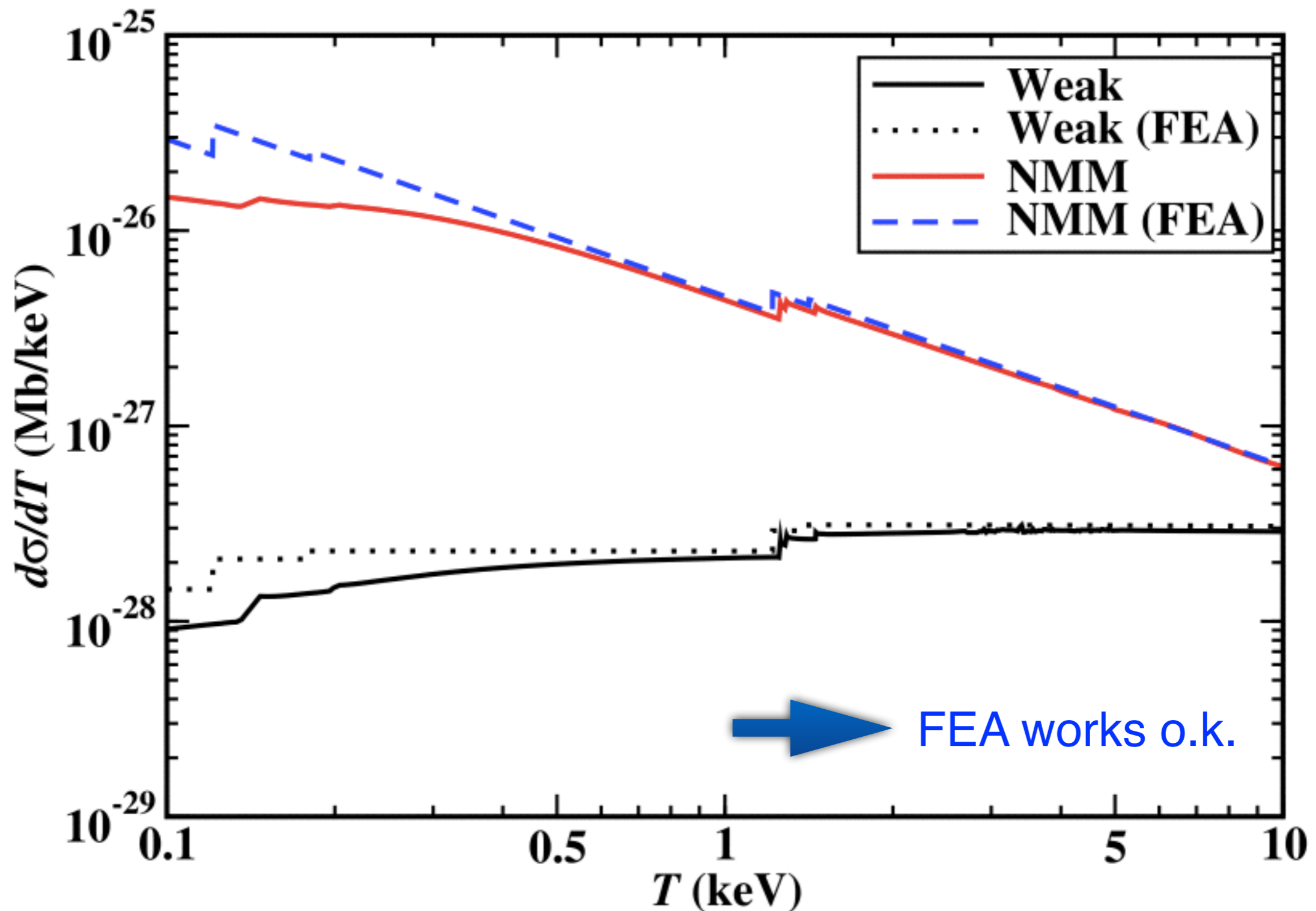


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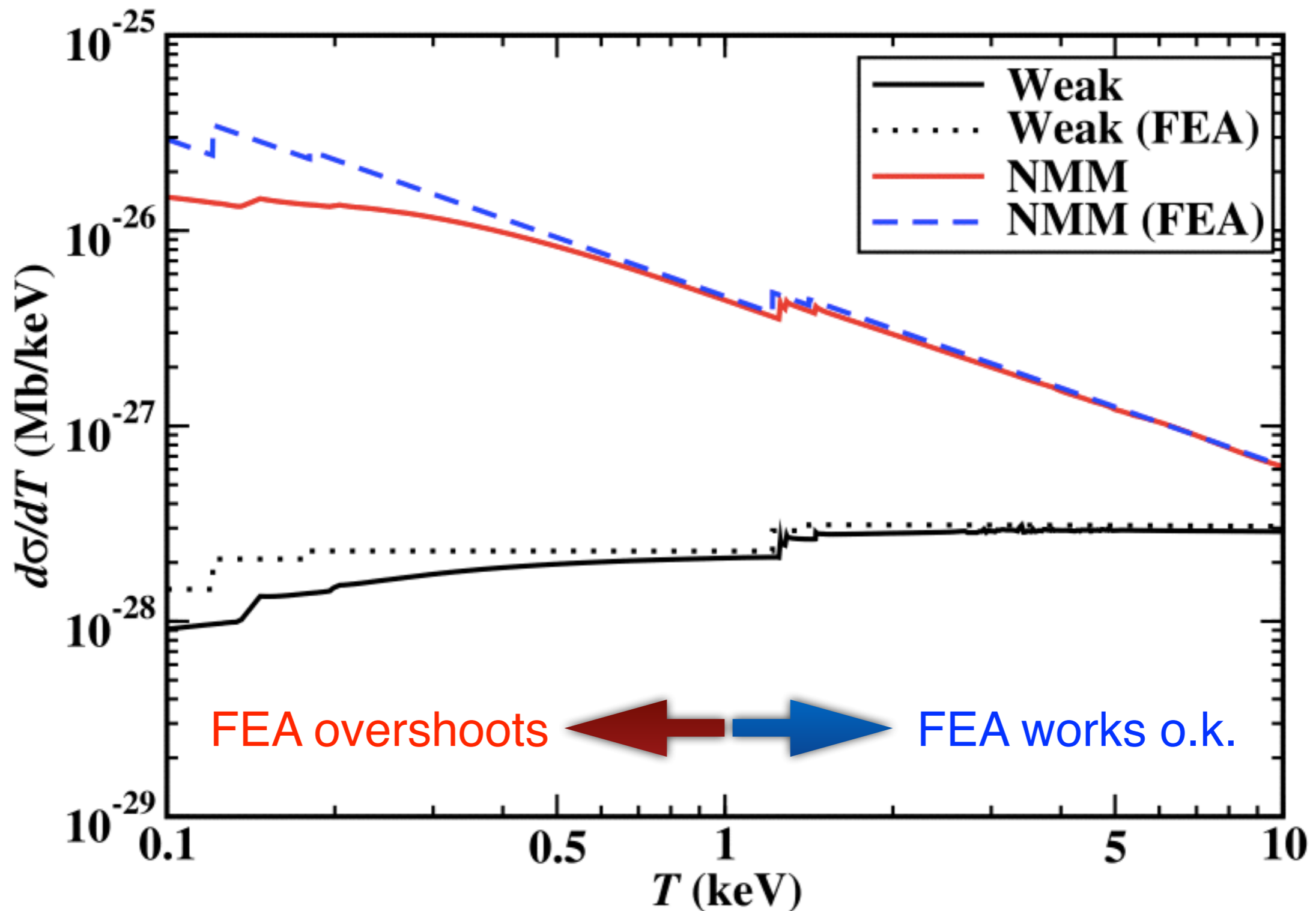


# Ge AI by MM

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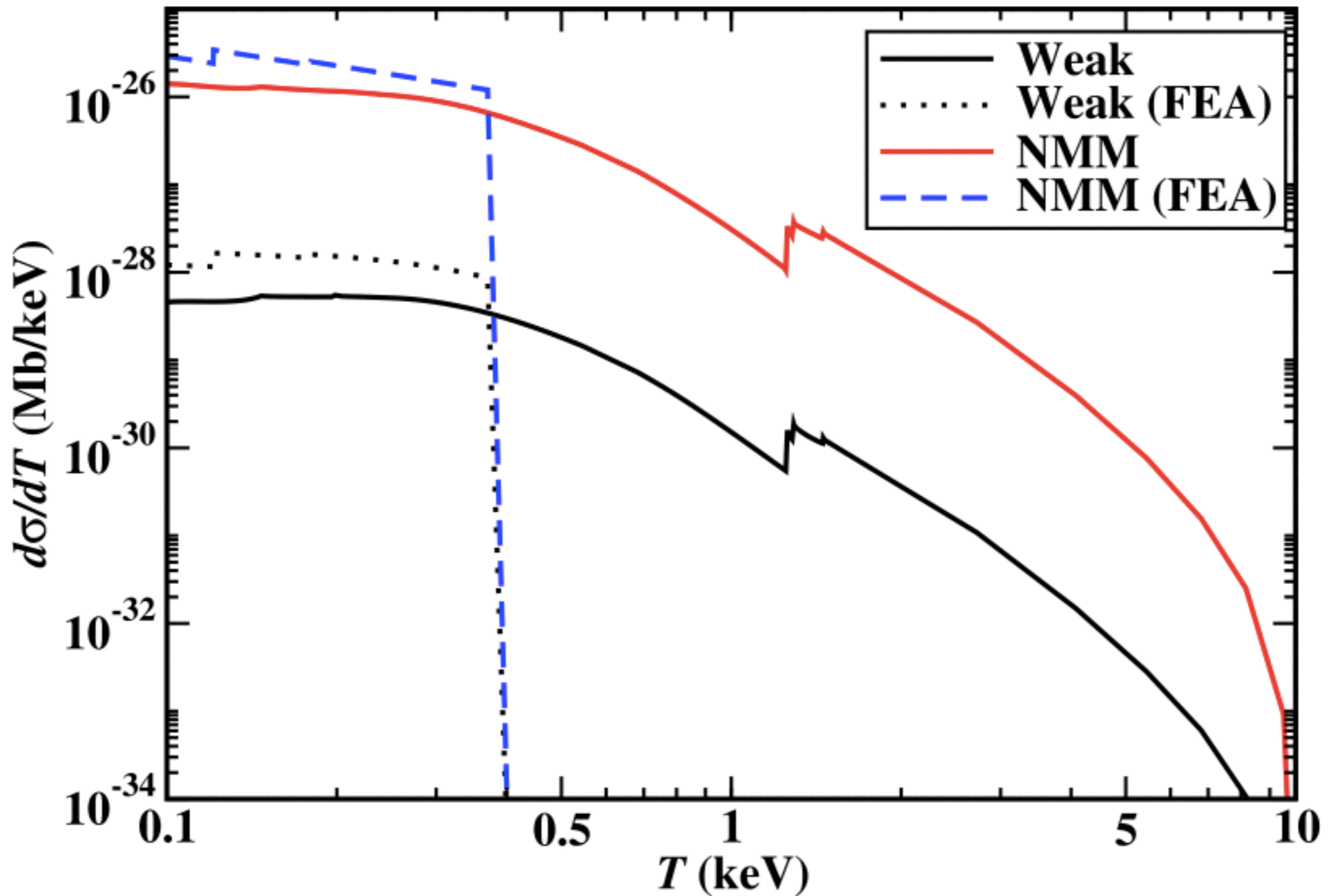


# Ge Al by MM

MM:  $2.9 \times 10^{-11} \mu_B$

(b)  $E_\nu = 10 \text{ keV}$

example of low- $E \nu$ 's

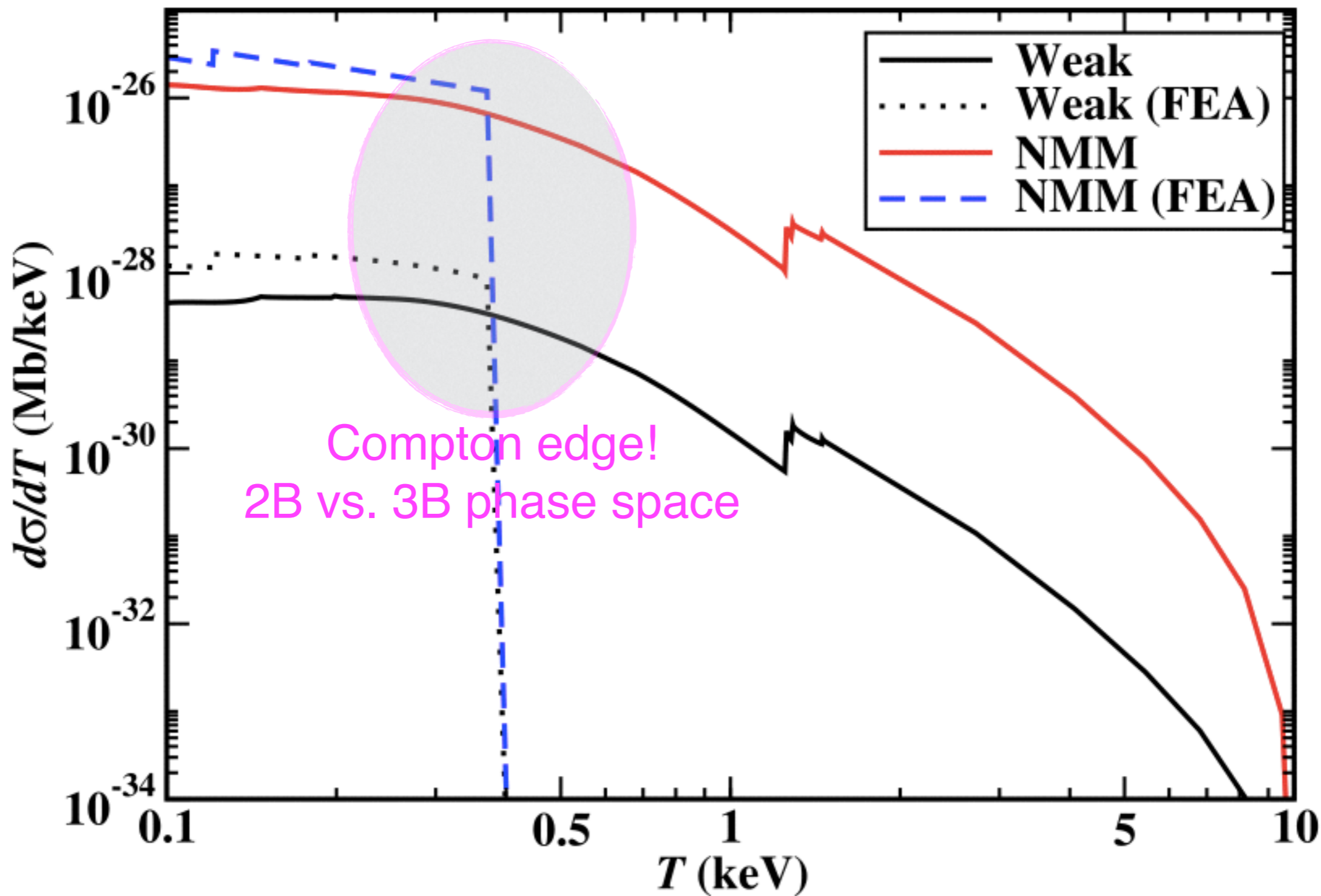


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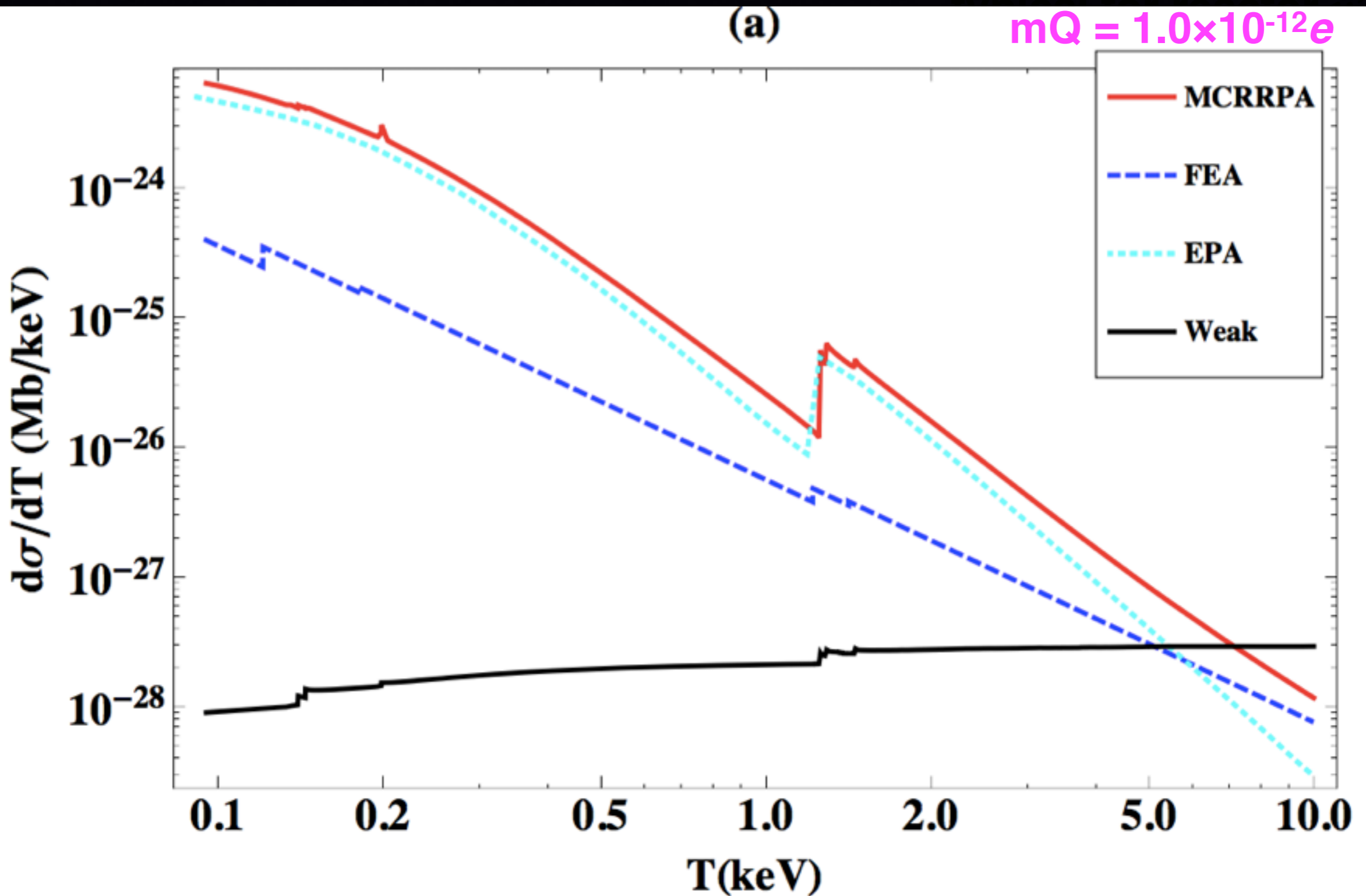
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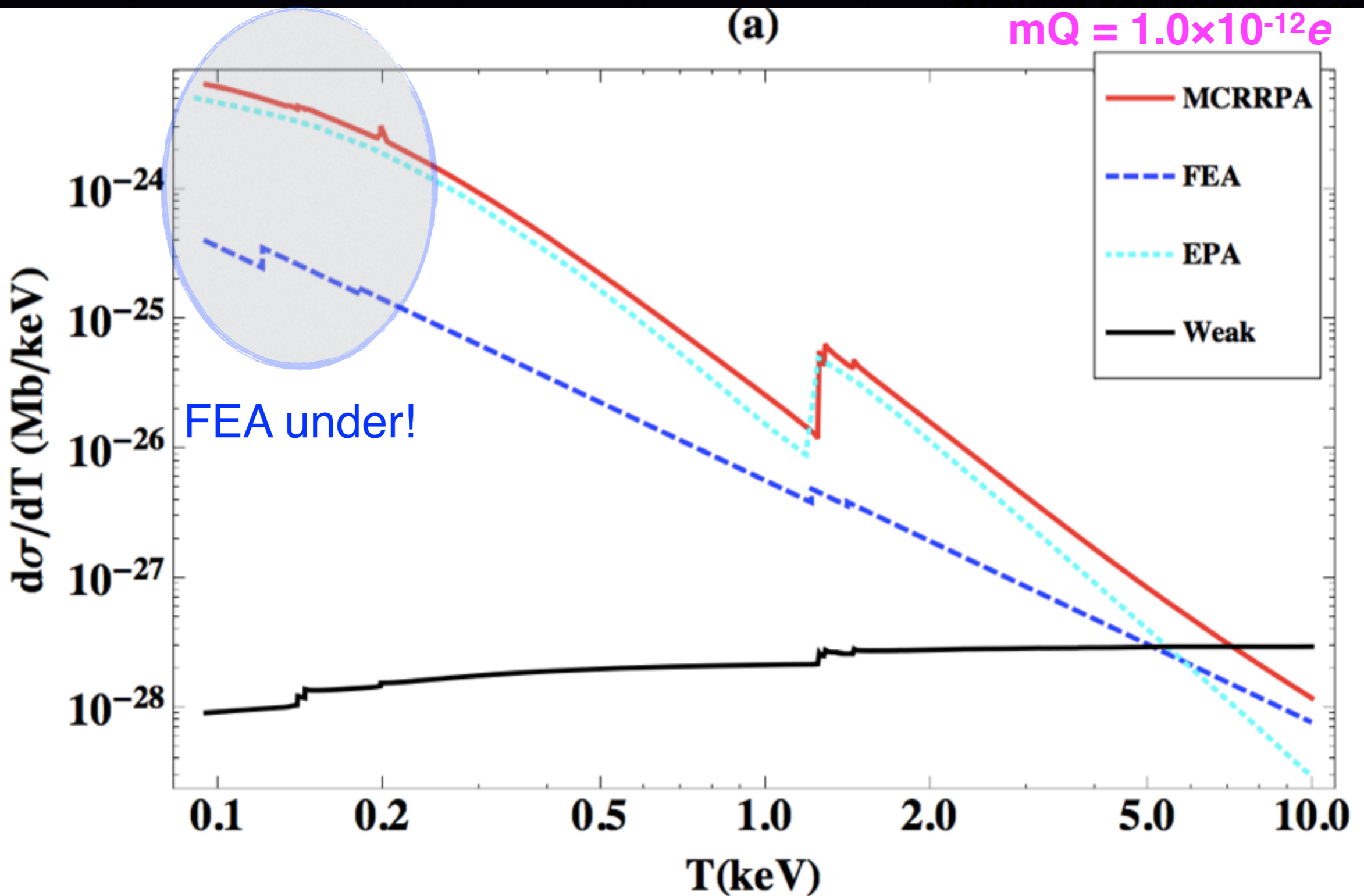
example of low- $E$   $\nu$ 's



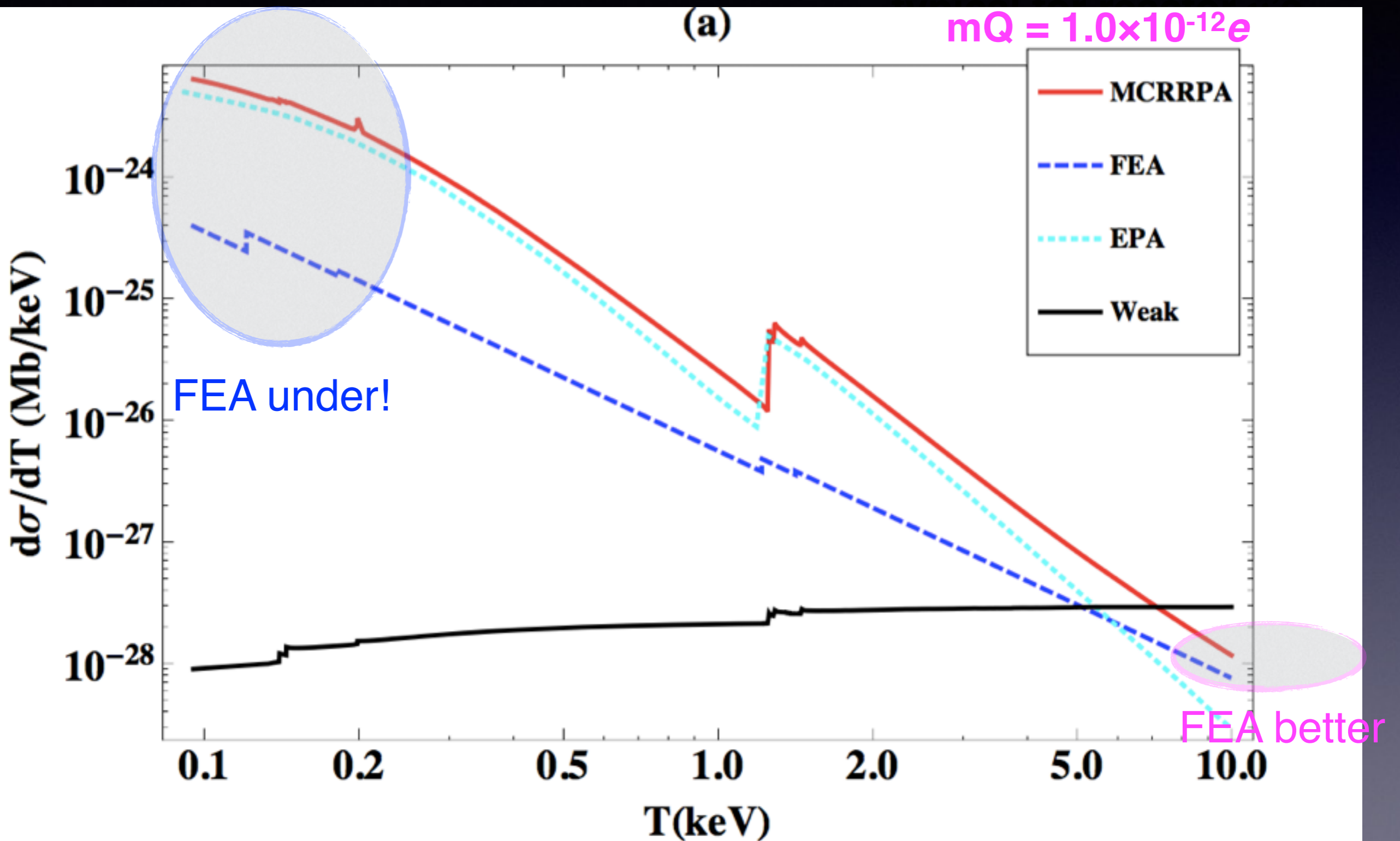
# Ge Al by mQ



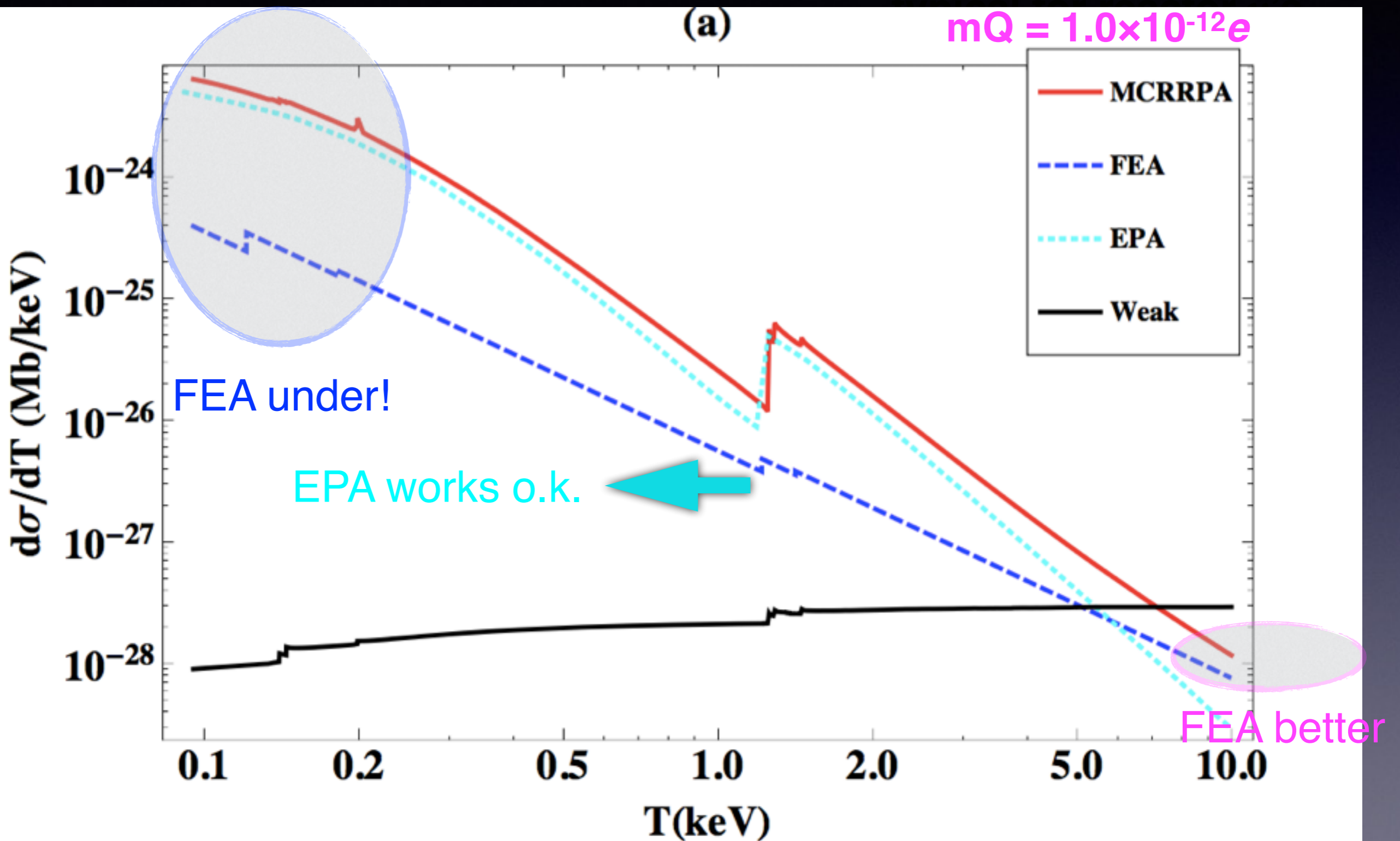
# Ge Al by mQ



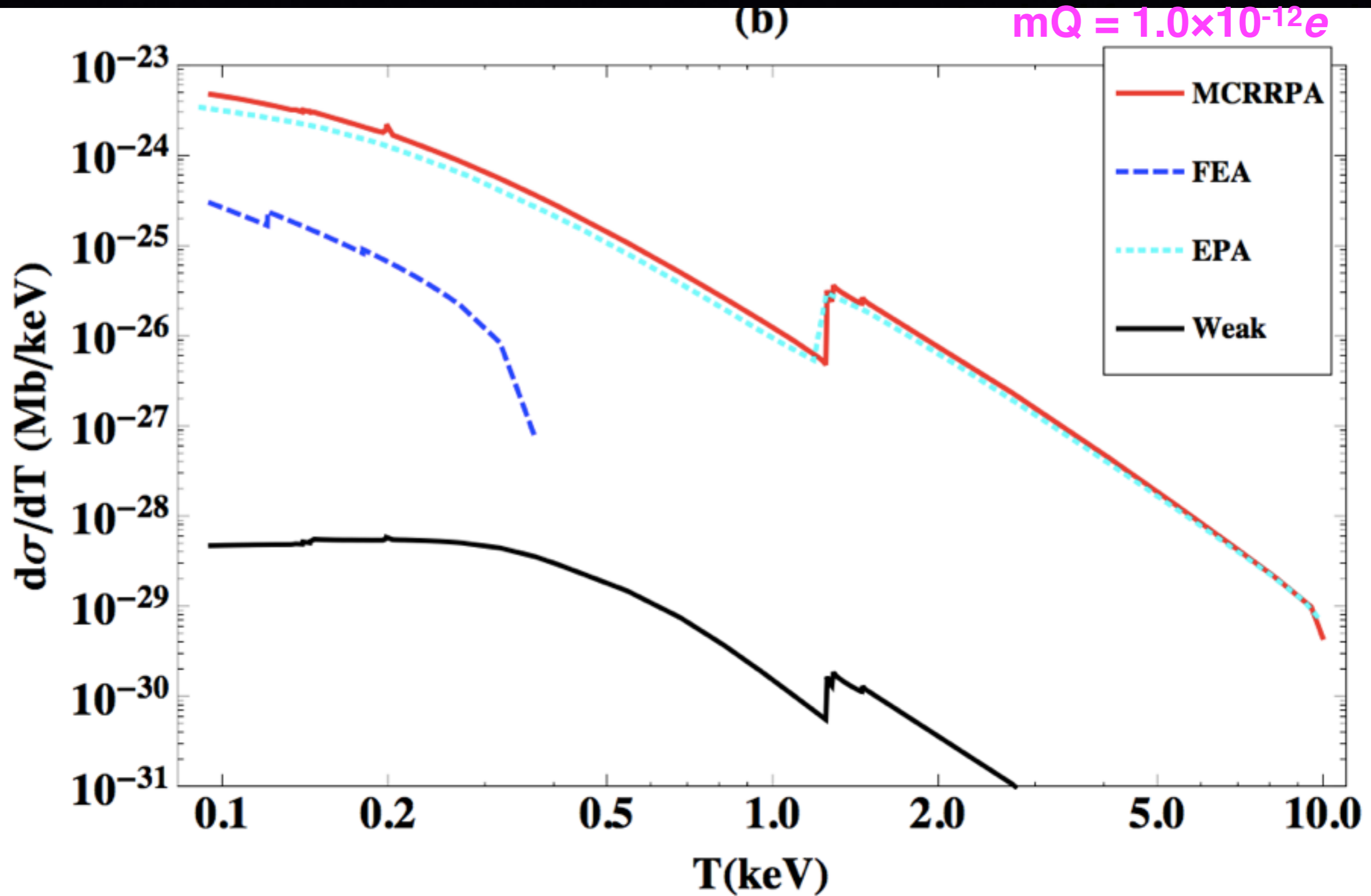
# Ge Al by mQ



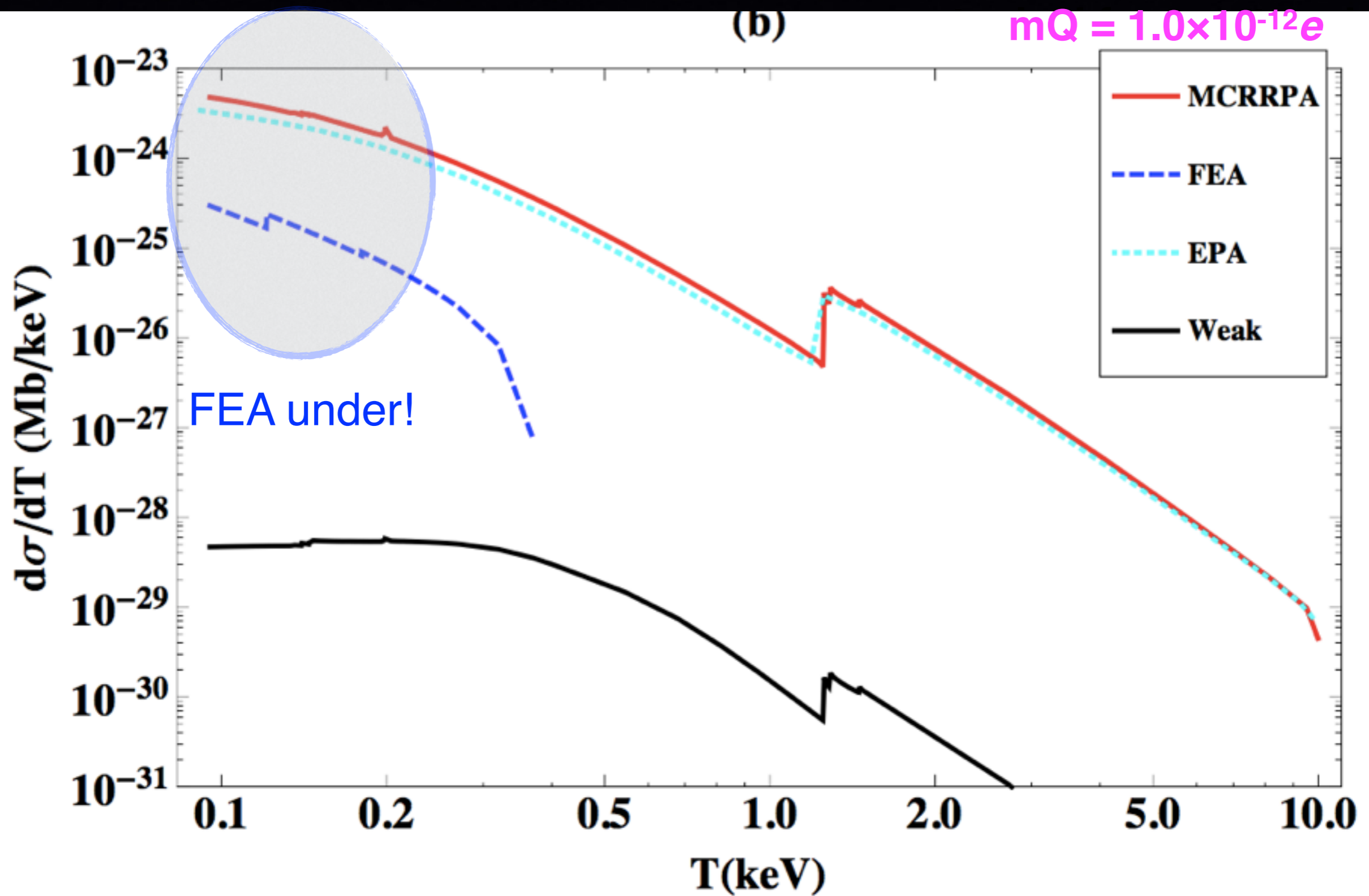
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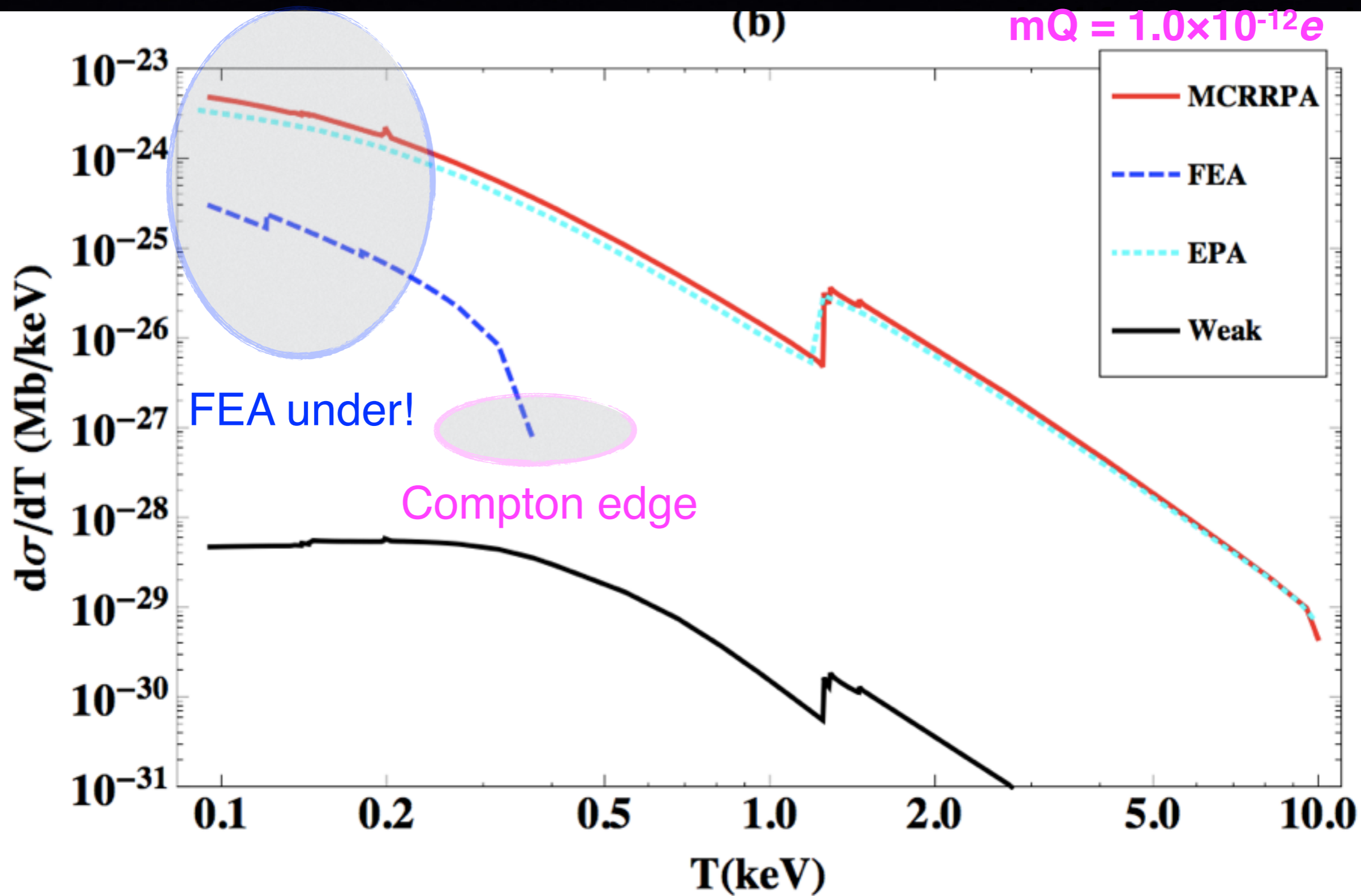
# Ge AI by mQ



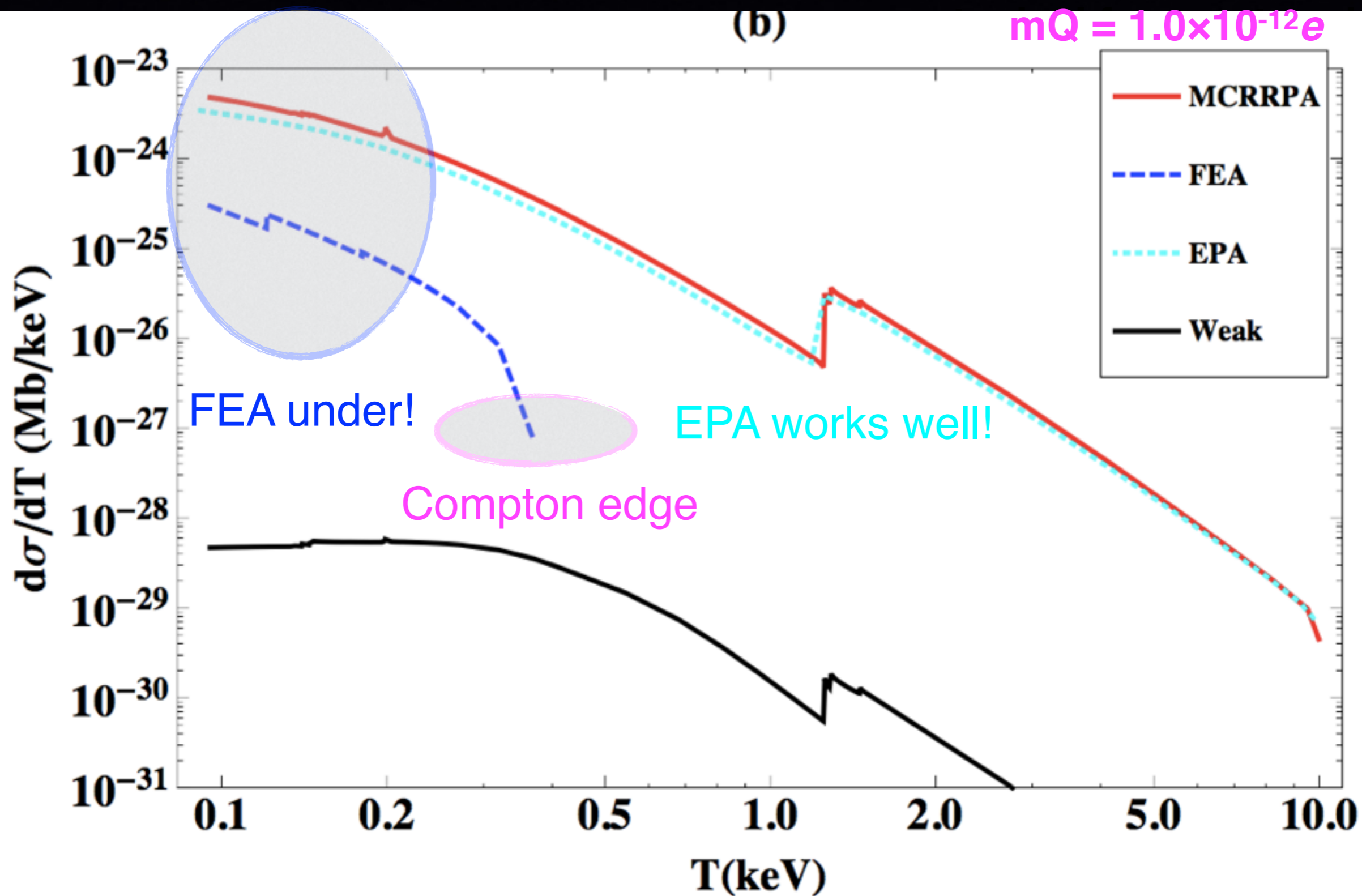
# Ge AI by mQ



# Ge AI by mQ



# Ge AI by mQ



# Implication

Compared with FEA, our results:

- Slightly increase upper limits on MM (but more reliable)
- Substantially improve upper limits on mQ
- ★ (Low-E) Ge data not competitive to CsI data in CR

# Conclusions

- Atomic physics is relevant for sub-keV detectors
- High-quality atomic calculations substantially reduce theoretical errors
- FEA does not work well at sub-keV regime and low- $E \nu$  sources
- Our method is general and can be applied to DM detection  $\chi + e^-(A) \rightarrow \chi + e^- + A^+$  with  $A = \text{Ge, Xe, Ar, etc.}$  **Stay Tuned!**