Atomic Aspects of Light Dark Matter Searches

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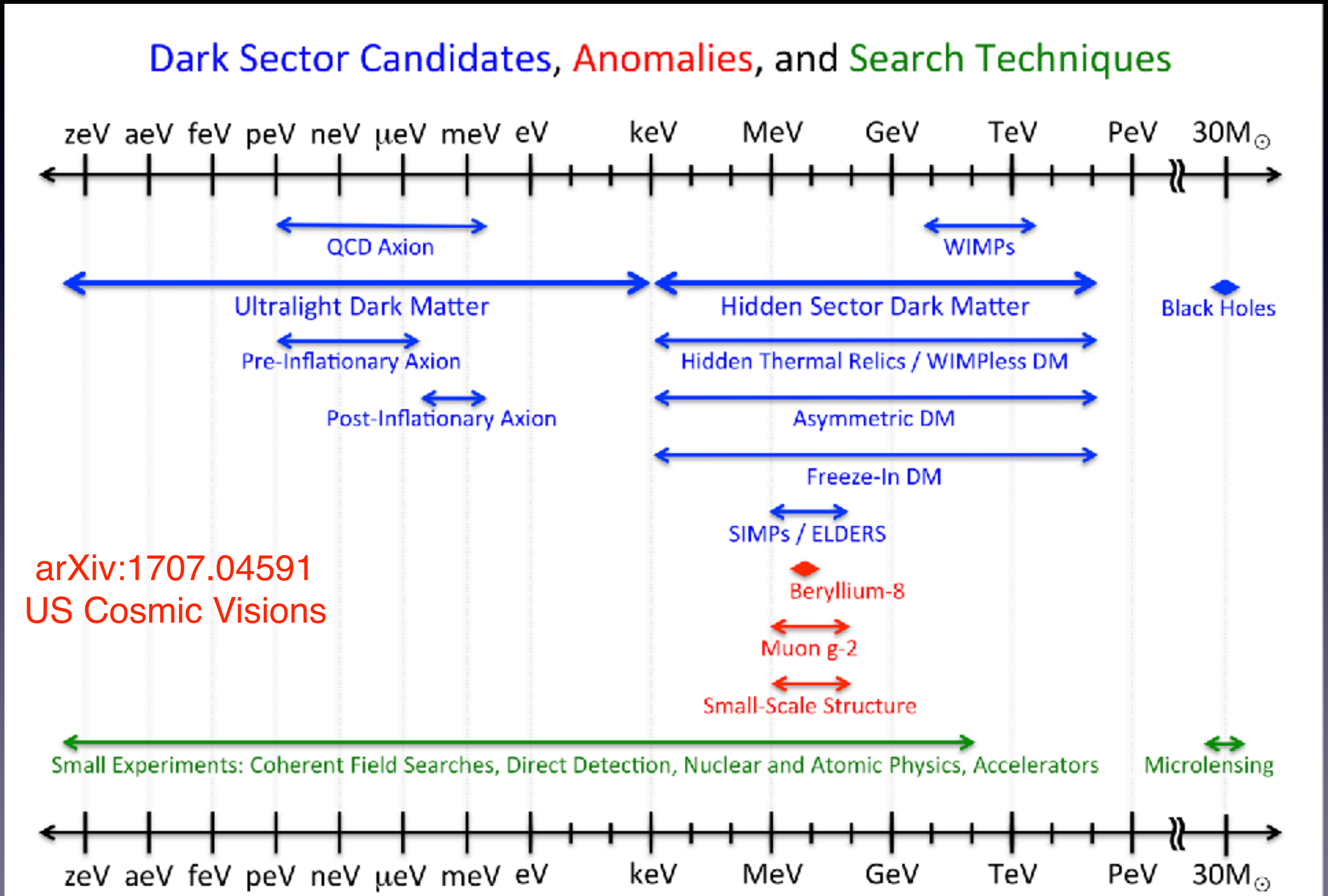
Identification of Dark Matter 2018
Brown U., Providence, USA

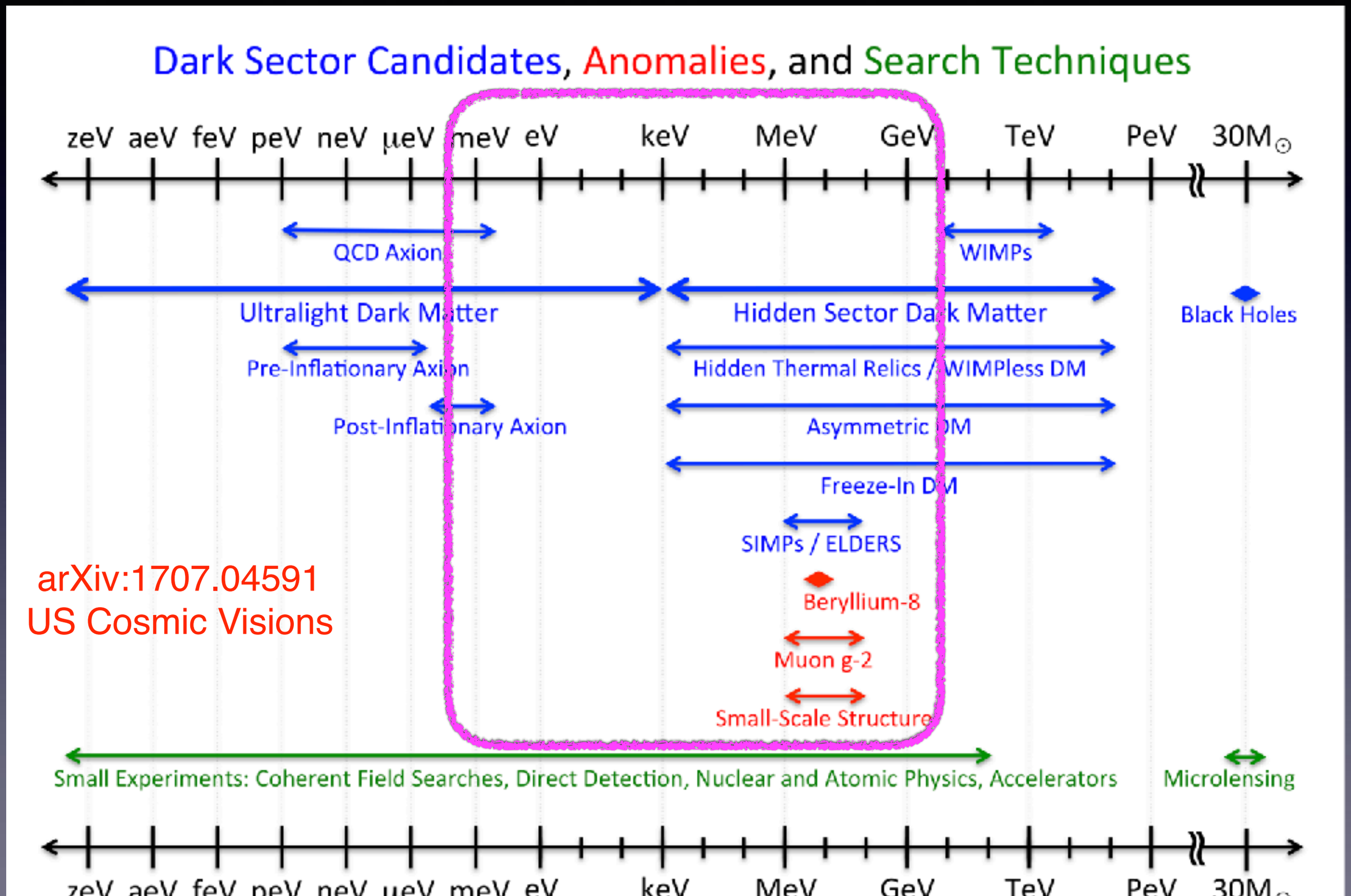
Why Bother?

To Cover a Wide DM Mass Range

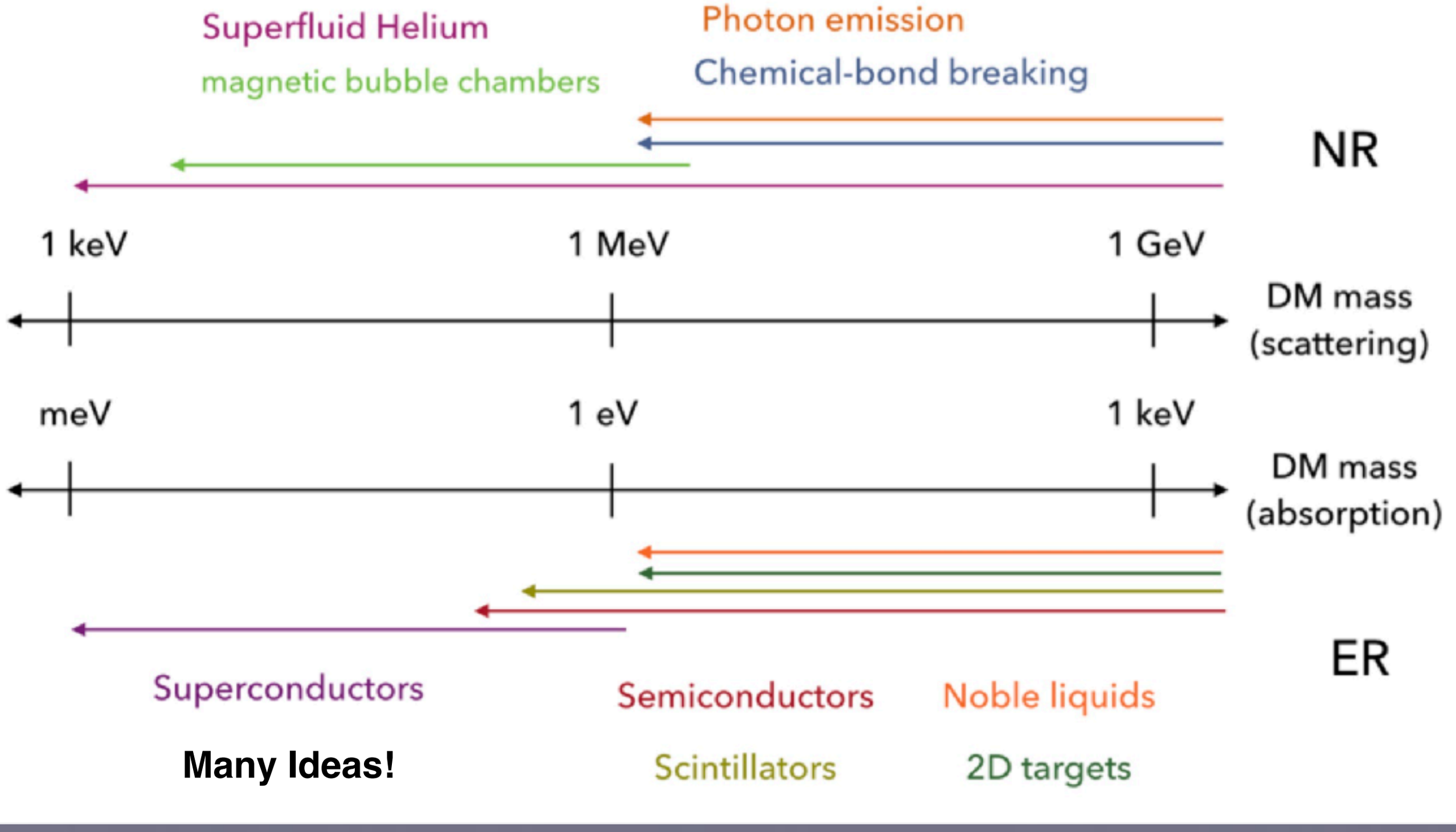


arXiv:1707.04591
US Cosmic Visions

To Cover a Wide DM Mass Range

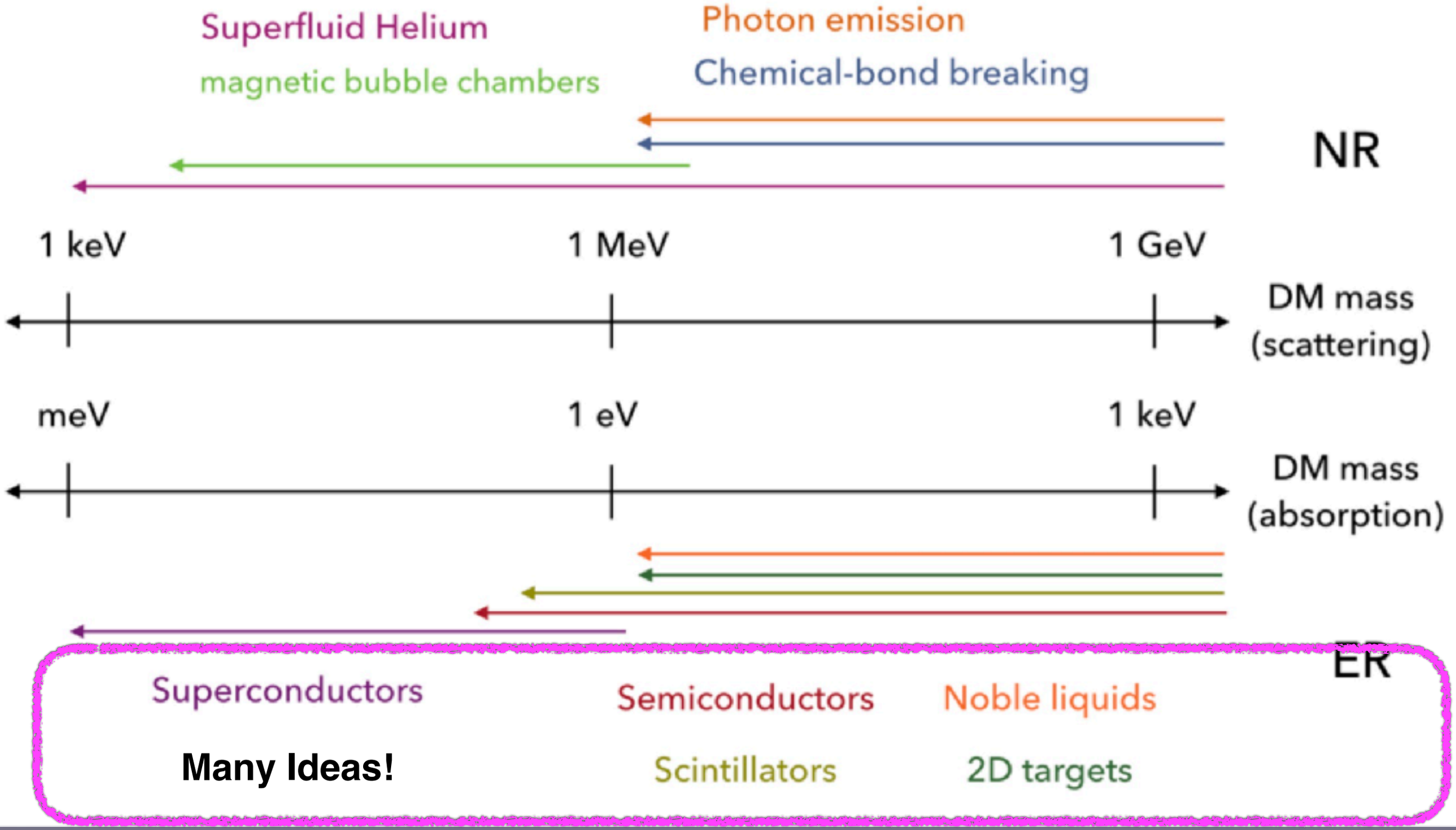


Direct Search in meV-GeV Range



Many Ideas!

Direct Search in meV-GeV Range



Relevant Physical Scales

- For NR ($v/c \sim 10^{-3}$) LDM ($m_\chi \leq 10$ GeV):
  $p_\chi \leq 10$ MeV, $E_\chi \leq 5$ keV

- Max. energy deposition by m_χ to m_A:
  $4m_\chi m_A/(m_\chi+m_A)^2\, E_\chi < 2$ 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

- Current lowest detector thresholds:
  $T_{min} \sim$ keV (nuclear), ~100 eV (electronic)

- Atomic effects important for LDM detection!

Potential Enhancement / Filter

Nuclei and atoms have rich structure, e.g., each energy level has its own specific quantum numbers, it can provide potential

- enhancement (resonance scattering …)
- filter (selection rules in angular momentum, parity, isospin …)

to experimental observables.

To Interpret a Direct Exp. Reliably…

Important Issues

- Can a scattering event be constructed as completely as possible?
- If not, how is a detector observable related to the primary scattering event?
- Is the primary event predicted by theory reliable?

Theoretical Inputs

- HEP: DM-matter interaction (model-driven / EFT) $\mathscr{L}_{\text{int}}$
- HEP/NP/AP: Differential cross section $d\sigma/\mathrm{d}T$
- AstroP: DM energy / velocity spectrum $\phi(\vec{\mathrm{v}})$
- Exp-Th: Energy loss of DM in detectors

EFT DM-matter Lagrangian

- Leading-Order

$$\mathscr{L}_{\text{int}}^{(\text{LO})} = \sum_{f=e,p,n} \left\{ \underbrace{c_1^{(f)}(\chi^\dagger\chi)(f^\dagger f)}_{\text{SI}} + \underbrace{c_4^{(f)}(\chi^\dagger\vec{S}_\chi\chi)\cdot(f^\dagger\vec{S}_f f)}_{\text{SD}} \right\} \leftarrow \text{SR}$$

$$+ d_1^{(f)}\frac{1}{q^2}(\chi^\dagger\chi)(f^\dagger f) + d_4^{(f)}\frac{1}{q^2}(\chi^\dagger\vec{S}_\chi\chi)\cdot(f^\dagger\vec{S}_f f) \Big\} \leftarrow \text{LR}$$

- Next-to-Leading-Order $O(q)$

$$\mathscr{L}_{\text{int}}^{(\text{NLO})} = \sum_{f=e,p,n} \left\{ c_{10}^{(f)}(\chi^\dagger\chi)(f^\dagger i\vec{\sigma}_f\cdot\vec{q}f) + c_{11}^{(f)}(\chi^\dagger i\vec{\sigma}_\chi\cdot\vec{q}\chi)(f^\dagger f) \right.$$

$$\left. + d_{10}^{(f)}\frac{1}{q^2}(\chi^\dagger\chi)(f^\dagger i\vec{\sigma}_f\cdot\vec{q}f) + d_{11}^{(f)}\frac{1}{q^2}(\chi^\dagger i\vec{\sigma}_\chi\cdot\vec{q}\chi)(f^\dagger f) \right\} + \cdots$$

Refs: Fan et. al., JCAP11(2010) 042; Fitzpatrick et. al., JCAP02(2013) 004

Reaction Channels

- Elastic: DM + A → DM + A (2-body)
- Discrete excitation: DM + A → DM + A* (2-body)
- Ionization: DM + A → DM + e^- + A^+ (3-body, our focus)
- Channel separation is not trivial

Differential Cross Section

Example: a $c_1^{(e)}$ type interaction with NR DM

$$d\sigma|_{c_1^{(e)}} = \frac{2\pi}{v_\chi} \sum_F \overline{\sum_I} |\langle F|c_1^{(e)} \rho(\vec{q})|I\rangle|^2 \delta(T - E_{\mathrm{CM}} - (E_F - E_I)) \frac{d^3k_2}{(2\pi)^3}$$

- All dynamical information in response functions
- E_{CM} for CM recoil, E_F-E_I for internal state change
- Biggest challenge: many-body wave functions for the initial and final states

Baseline:
Free Electron Approximation

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

T>Bi atomic shell open

free scat.

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

Our MB Approach: MCRRPA

An *ab initio* method improved upon Hartree-Fock theory

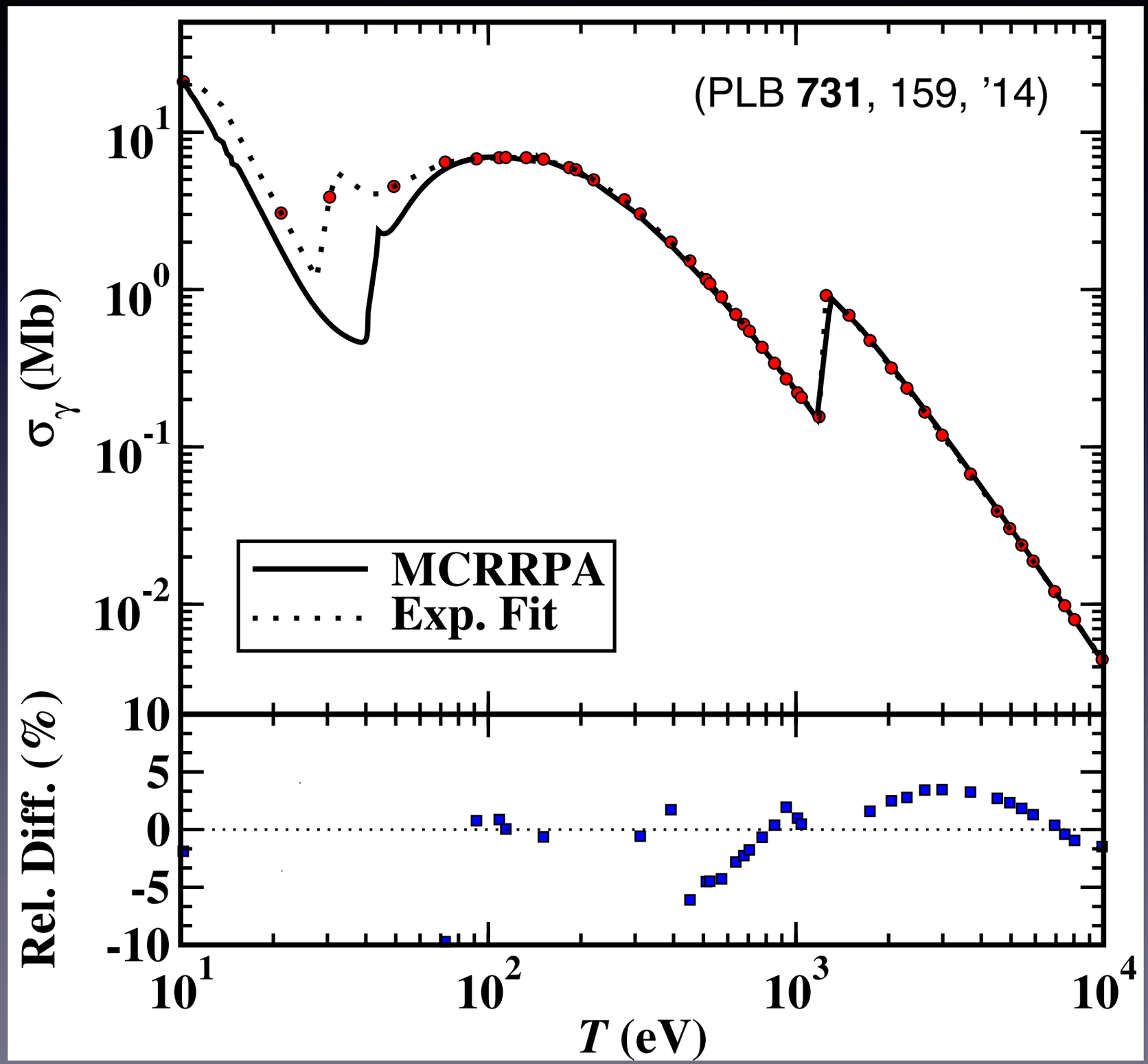
- MC [multi-configuration]: open-shell atoms have more than one ground-state configuration. Eg. for Ge:

$$|J=0\rangle = c_1\,|[\mathrm{Zn}]4p_{1/2}^2\rangle + c_2\,|[\mathrm{Zn}]4p_{3/2}^2\rangle$$

- R [relativistic]: $Z\alpha$~0.25(Ge) / 0.4(Xe)

- RPA [random phase approximation]: residual 2e correlation is important for atomic excited / ionized states

Benchmark: Ge Photoionization



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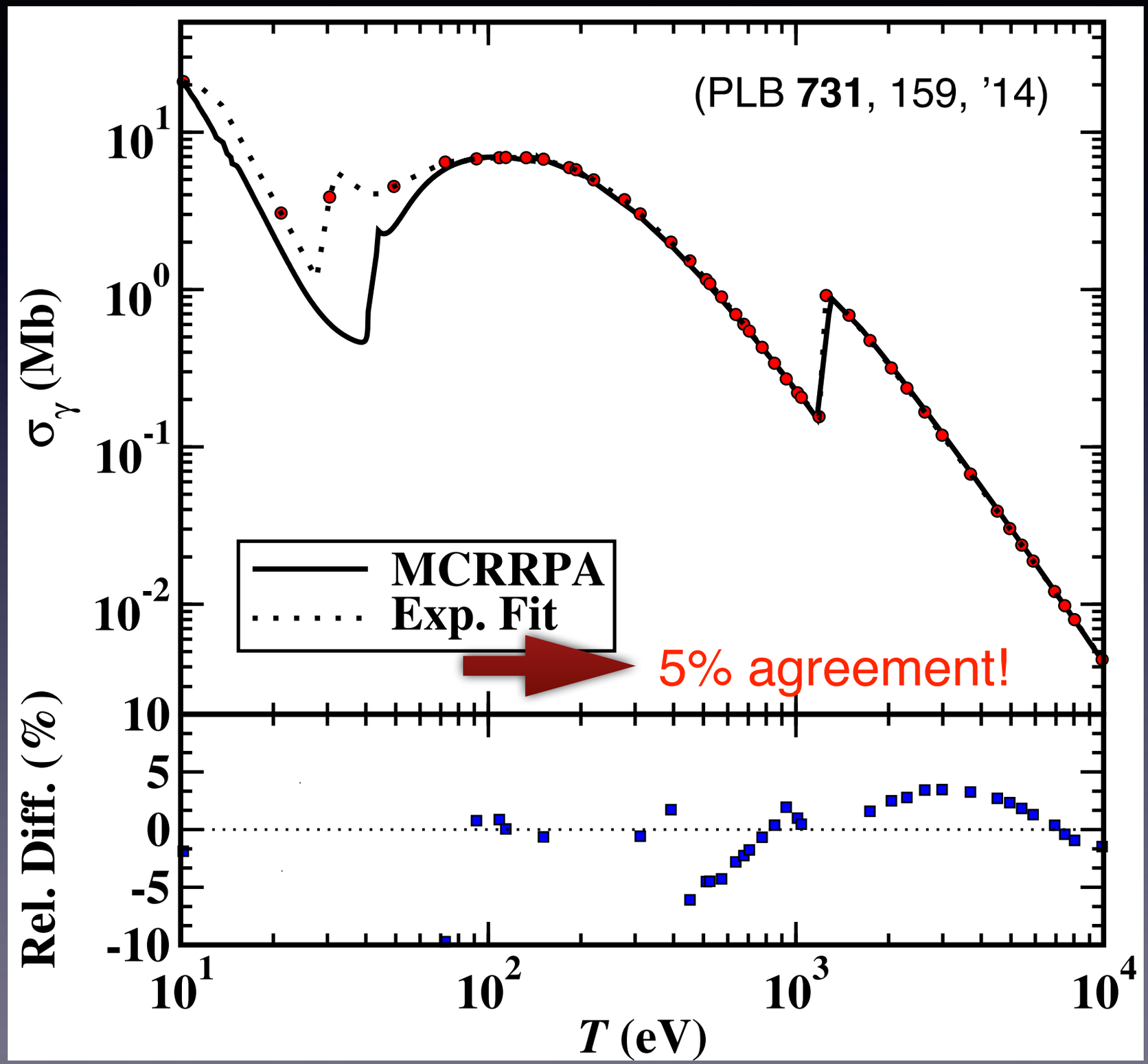

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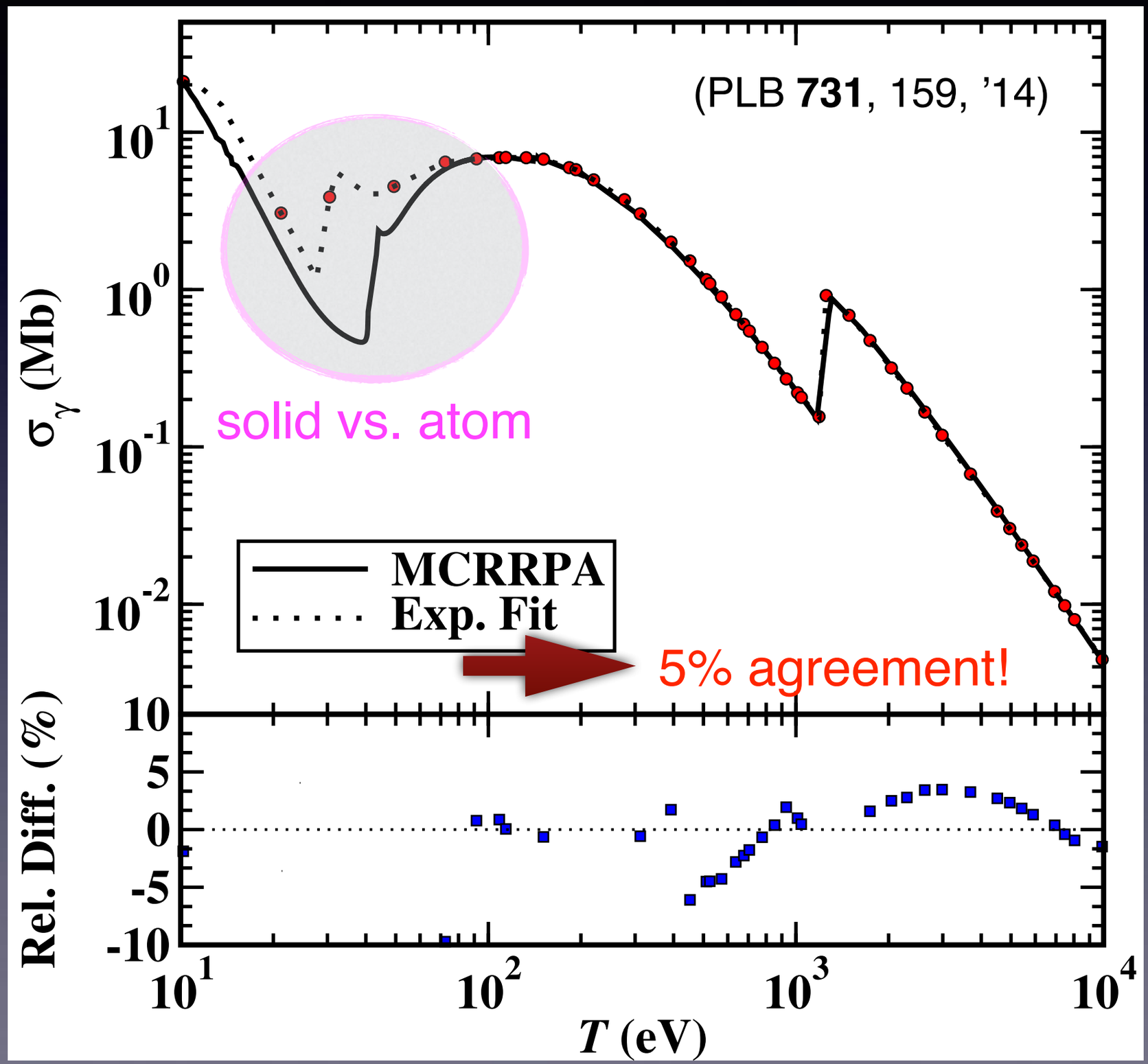
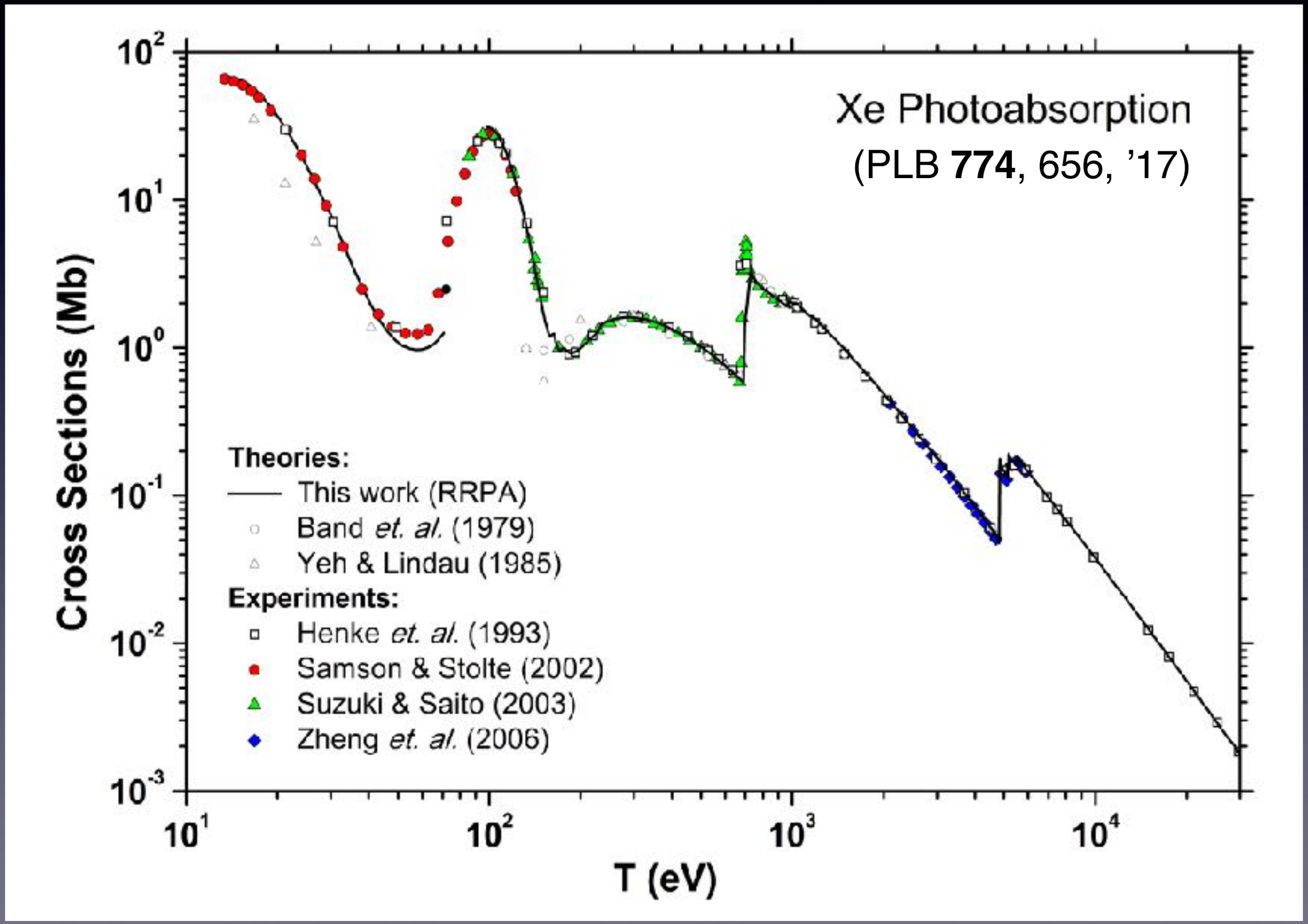


Benchmark: Xe Photoionization



Applying high-quality atomic MB w.fs. to

Neutrino EM Moments

(PLB **731**, 159, ’14; PRD **90**, 011301(R), ’14; PRD **91**, 013005, ’15)

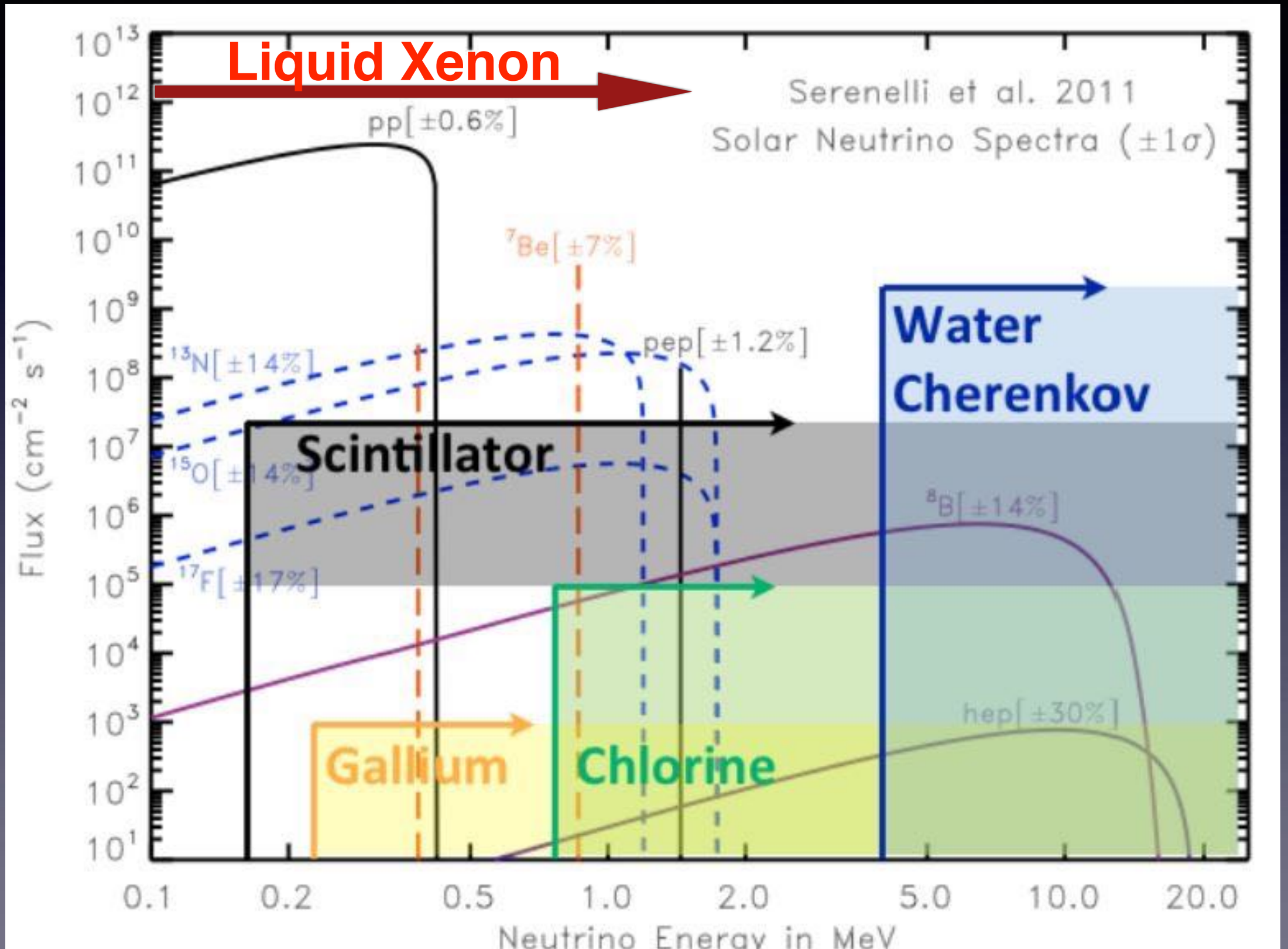
- Enhanced sensitivity at low energies (1/T for mag. moment and 1/T^2 for milli-charge)

- Done w. Ge detectors for reactor anti-neutrinos, now working on Xe detectors for solar neutrinos

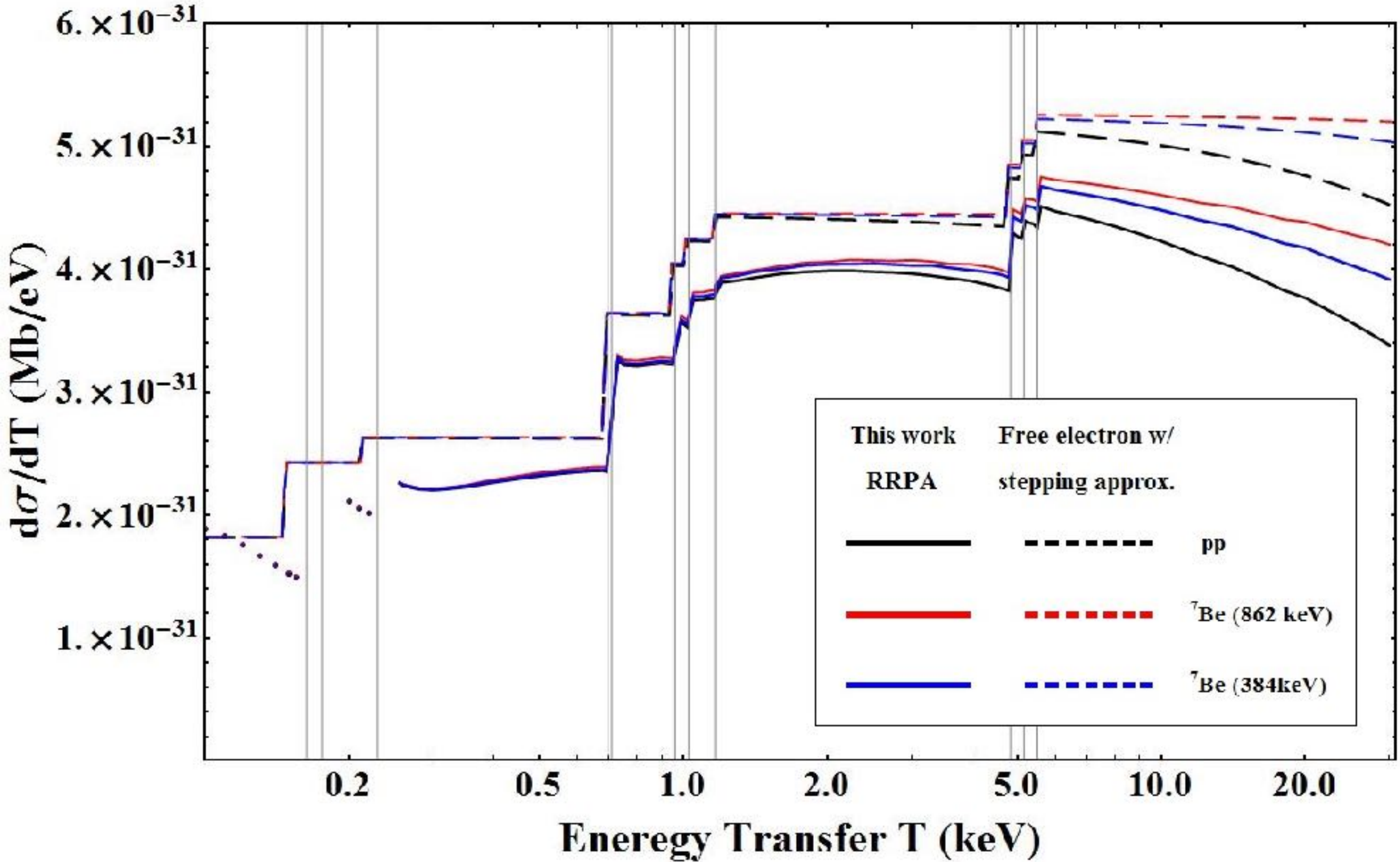
Low-E Solar Neutrinos (PLB **774**, 656, ’17)

- *pp* neutrinos (~hundreds of keV) still not fully observed
- Multi-ton scale LXe (Xenon1T, LZ, DARWIN) detectors are capable (through electron recoil with sub-keV th.)
- Can test solar models to 1% level (~100 ton-yr)
- Important for DM detection background

Solar Neutrinos Detection



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			99.5% ER rejection, 50% NR acceptance		
Model	FE	RRPA	Diff.	FE	RRPA	Diff.
Solar *pp* neutrinos	80.7	61.9	−23%	0.120	0.093	−23%
Solar ^{7}Be neutrinos	7.1	5.7	−20%	0.010	0.008	−21%
Total	87.8	67.6	−23%	0.130	0.101	−22%

FE overestimate!

LDM Searches (in progress)

- Currently concentrate on Ge and Xe
- Can do other 4A (C, Si) and noble-gas (He, Ne, Ar) elements too
- Use EFT framework (c1, d1, c4, and d4 at LO)

M_χ = 1 GeV; c1 = 1 GeV $^{-2}$

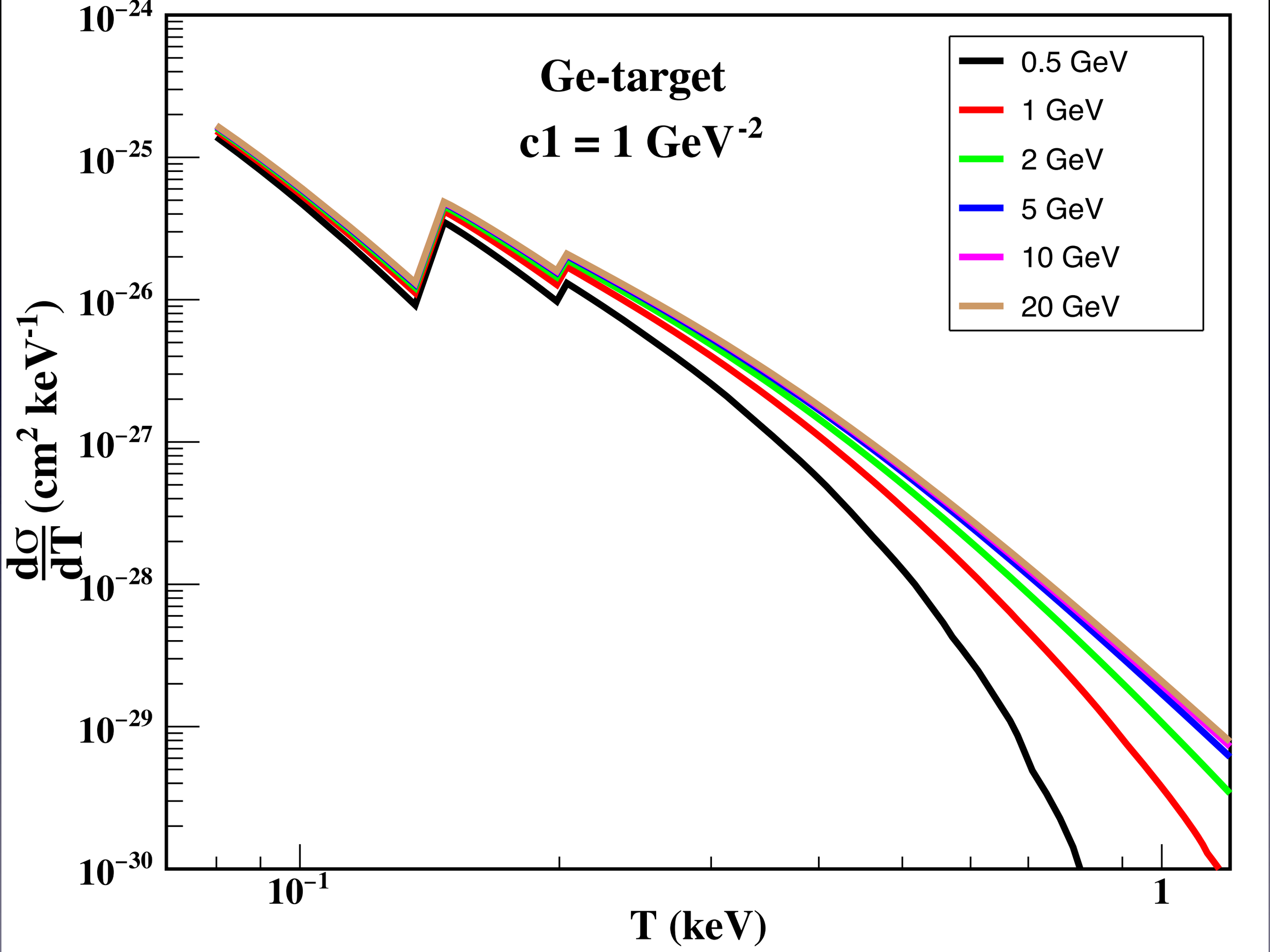
Ge-target

Xe-target

$\frac{d\sigma}{dT}$ (cm^2 keV^{-1})

T (keV)

10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
10^{-30}
10^{-31}
10^{-2}
10^{-1}
1


Ge-target
c1 = 1 GeV-2
0.5 GeV
1 GeV
2 GeV
5 GeV
10 GeV
20 GeV
dσ/dT (cm2 keV-1)
10−24
10−25
10−26
10−27
10−28
10−29
10−30
10−1
1
T (keV)

Ge-target

$c1 = 1\ GeV^{-2}$

$d1 = 1 \times 10^{-9}$

$\frac{d\sigma}{dT}$ ($cm^2\ keV^{-1}$)

10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
10^{-30}
10^{-31}
10^{-32}
10^{-33}
10^{-34}
10^{-35}

10^{-1}

1

T (keV)

Conclusions

- DM (& neutrino) physics is interdisciplinary.
- Many-body problem is essential for sub-keV detectors for DM (& neutrino).
- High-quality many-body calculations can substantially reduce theoretical errors.
- Energy loss mechanism still needs better understanding.

Collaborators

A collaboration consists of NP/HEP theorists, atomic theorists, and experimentalists.

- Jiunn-Wei Chen (Nat'l Taiwan U.)
- Hsin-Chang Chi (Nat'l Dong Hwa U.)
- Mukesh Pandy (Nat'l Taiwan U.)
- Lakhwinder Singh (TEXONO, Academia Sinica)
- Henry T. Wong (TEXONO, Academia Sinica)
- Chih-Pan Wu (Nat'l Taiwan U.),
- Chih-Liang Wu (Nat'l Taiwan U., now MIT)

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Thanks!