Many-body Physics in Neutrino and Dark Matter Detection

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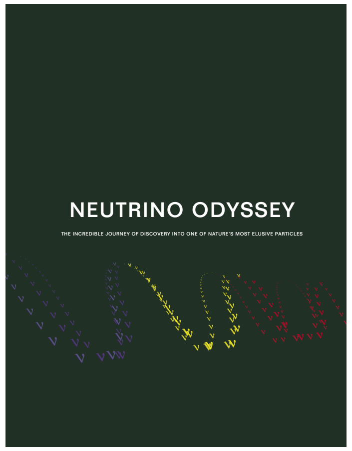
Collaborators

- A collaboration consists of NP/HEP theorists, atomic theorists, and experimentalists.
- Core members: Jiunn-Wei Chen (NTU), Hsin-Chang Chi (NDHU), CPL (NDHU), Lakhwinder Singh (AS), Henry T. Wong (AS), Chih-Pan Wu (NTU)
- Adjunct members: Keh-Ning Huang (Sichuan U.), Shin-Ted Lin (Sichuan U.), Qian Yue (Tsinghua, Beijing)
- Former members: Hao-Tze Hsiao (NTU), Chih-Liang Wu (NTU)
- Supported in part by NCTS-ECP (2015-2018) and MoST

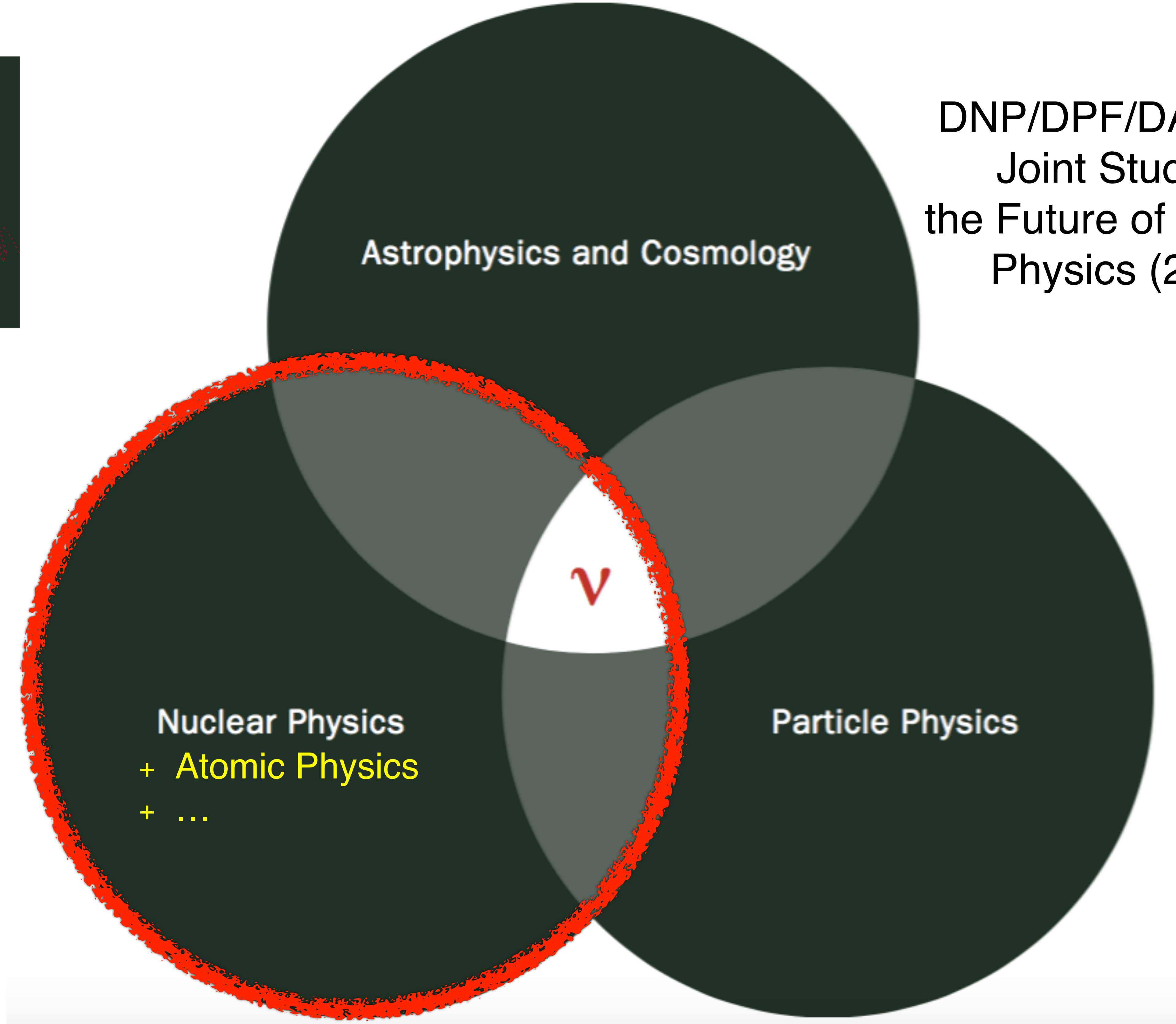
Outline

- Introduction
- Why Bother with Low Energies?
- Theory Basics
- Selected Works
- Summary

Introduction



DNP/DPF/DAP/DPB
Joint Study on
the Future of Neutrino
Physics (2004)



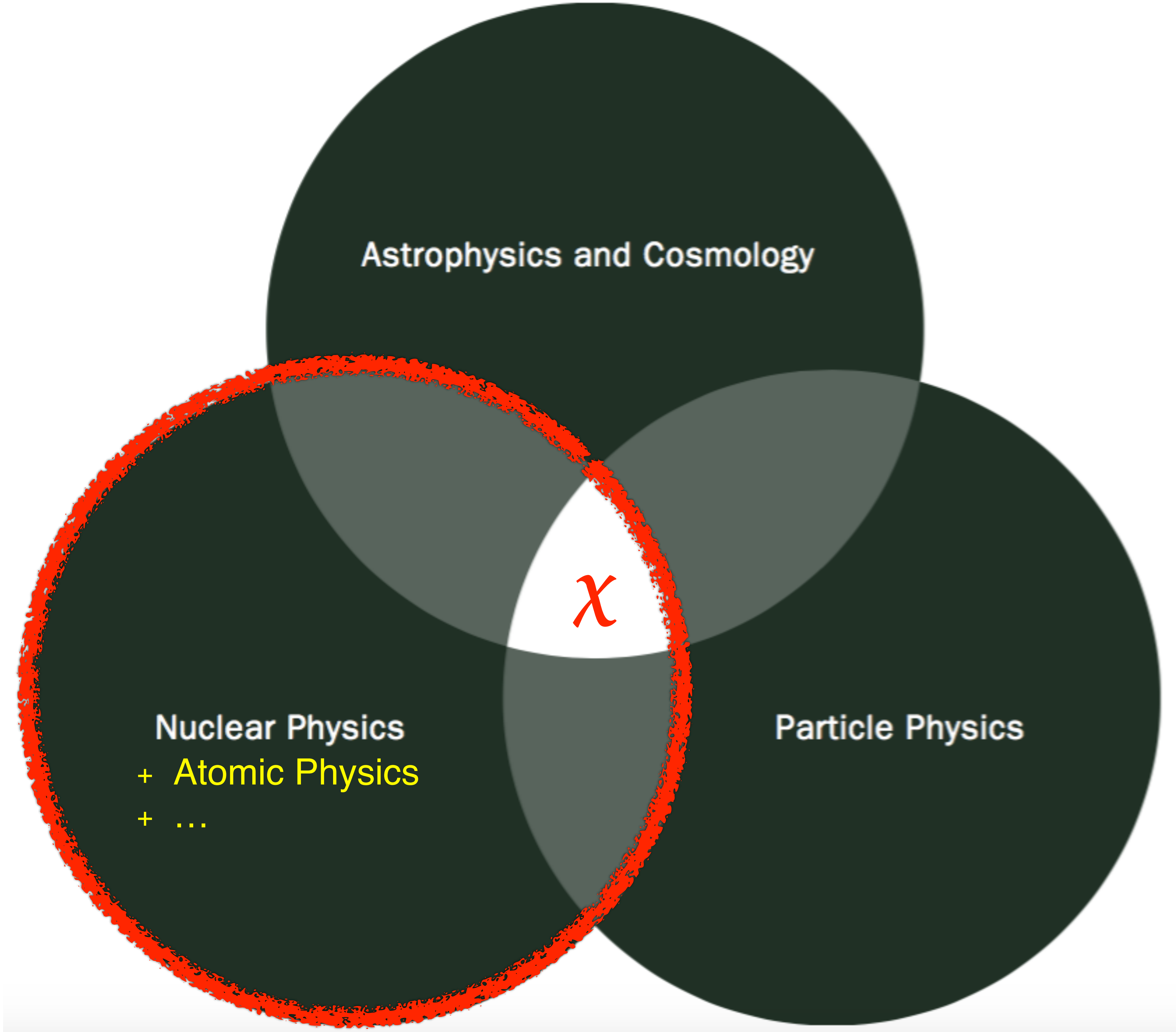
Neutrino Physics
- An Interdisciplinary Study

3 Recommendations (APS 2004)

- ★ A phased program of sensitive searches for neutrinoless nuclear double beta decay
- ★ A comprehensive U.S. program to complete our understanding of neutrino mixing, to determine the character of the neutrino mass spectrum and to search for CP violation among neutrinos
- Development of an experiment to make precise measurements of the low-energy neutrinos from the sun

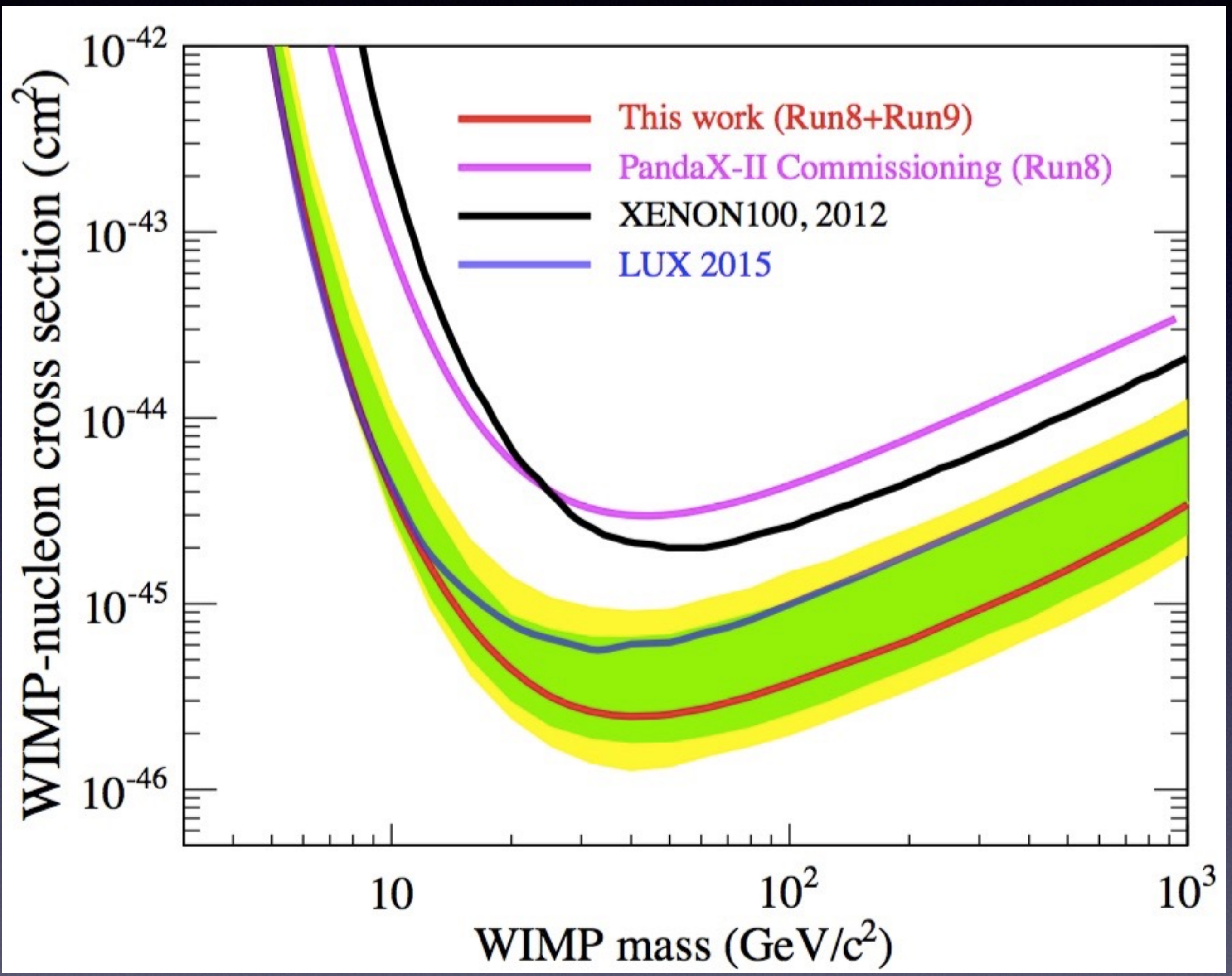
How NP/AP Becomes Relevant?

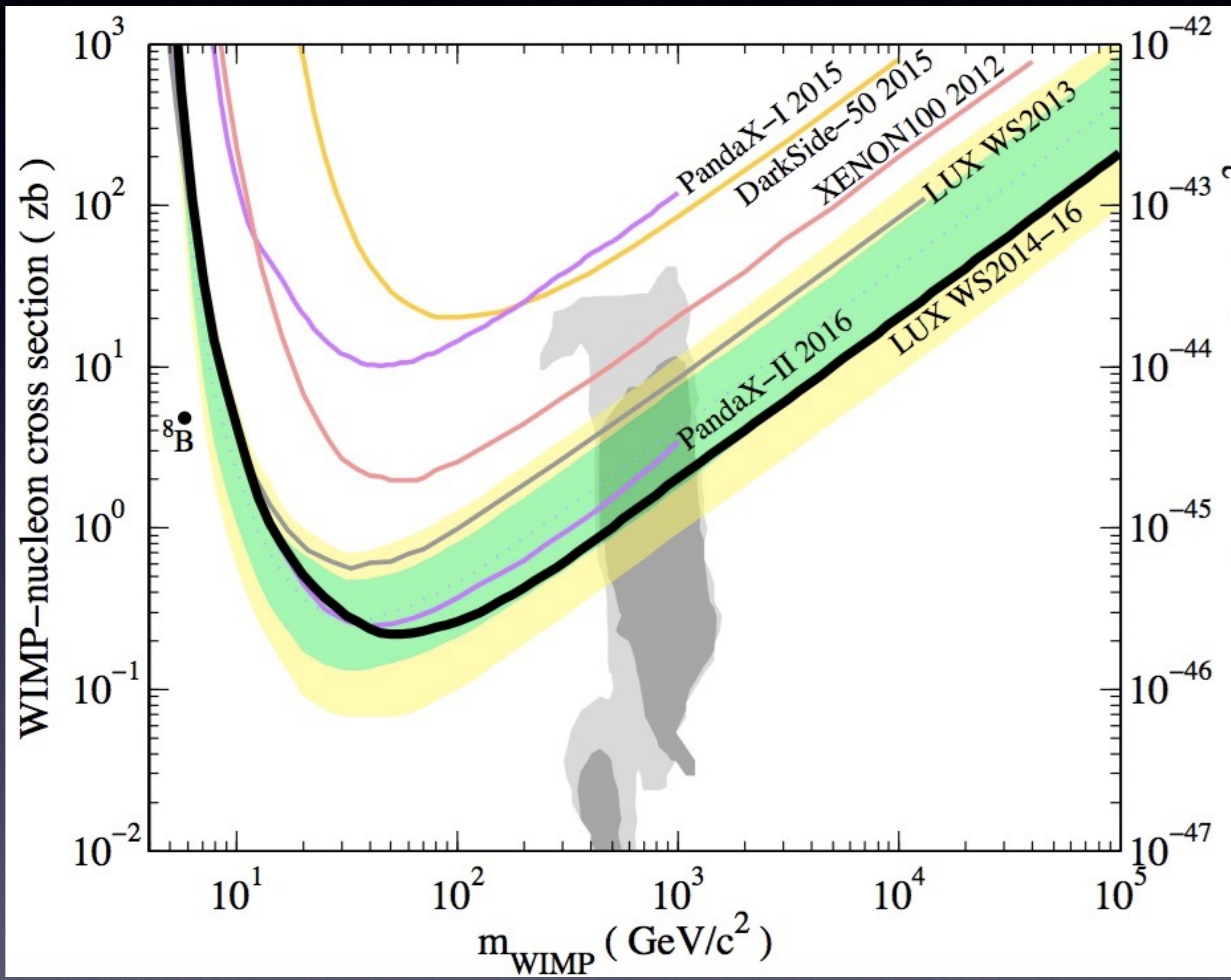
- As sources: beta decay, double beta decay, electron capture …
- As media: the Sun, supernovae, the Earth (atom. & geo.) …
- As detectors: neutrino-nucleus/atom scattering/capture …



Dark Matter Physics
- An Interdisciplinary Study, too!

WIMP Paradigm





PandaX-II (PRL **117**, 121303, '16)

LUX (PRL **118**, 021303, '17)

★ Racing towards the "neutrino floor" !

How about “Light Dark Sector”?

- Snowmass 2013 Rep. “Dark Sectors and New, Light, Weakly-Coupled Particles” (arXiv:1311.0029), compelling cases:
  - Axions and Axion-Like Particles (<1eV)
  - Dark Photons (masses vary)
  - Light Dark Matter (sub-GeV, neutral/milli-charged)
- Anomalies in X-ray (~keV) and γ-ray (~MeV–GeV) lines indirectly point to potential LDM particles.

How NP/AP Becomes Relevant?

- As detectors: DM-nucleus/atom scattering/capture …
- As media: DM captured/boosted, decay/annihilate in stellar environments …
- As sources: dark bound states, mirror DM (dark nuclei, atoms etc.) …

In this talk, focus on the detector aspect in direct detection

Important Issues

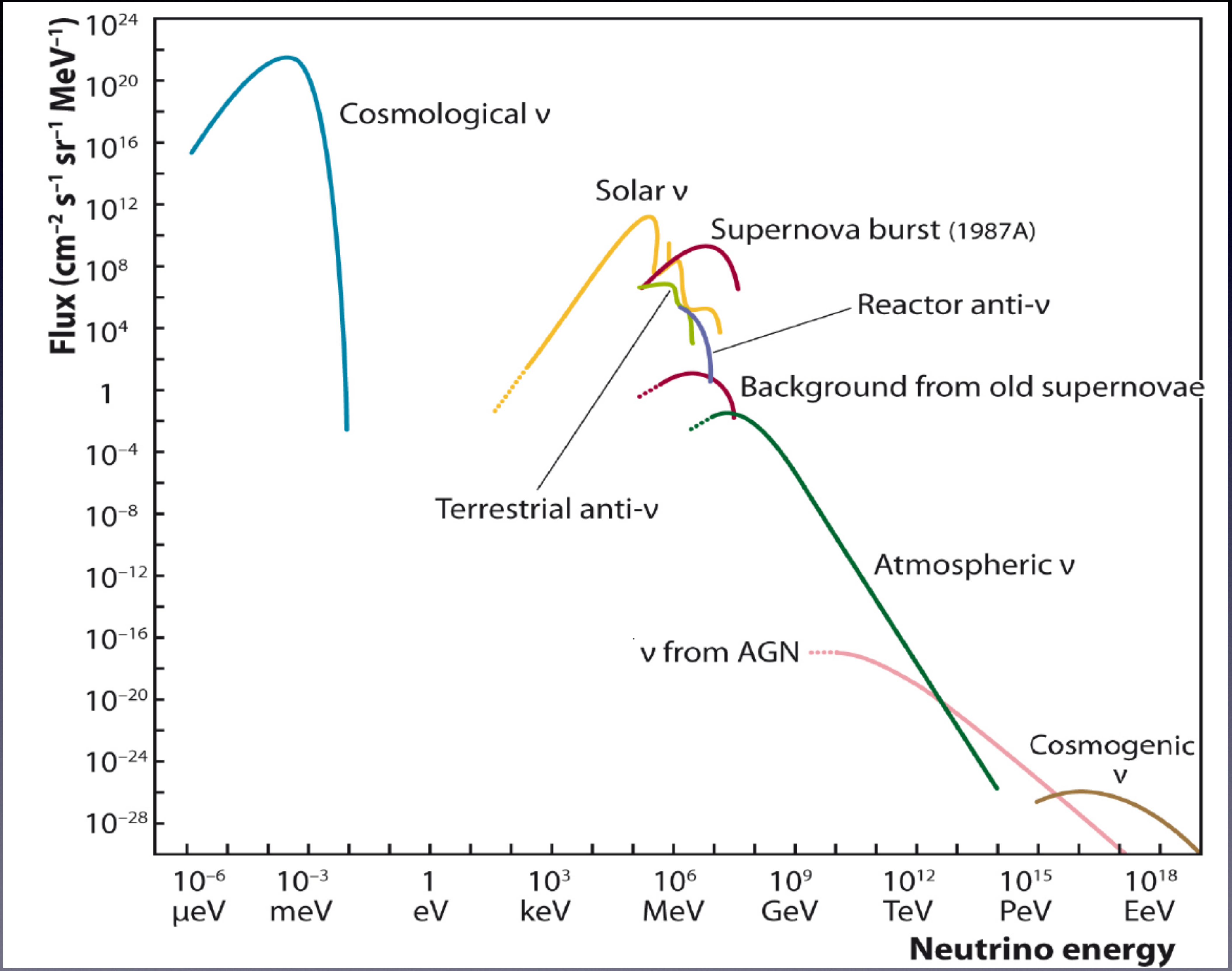
- Can a scattering event be constructed as completely as possible?
- If not, how is a detector observable related to the primary scattering event?
- Is the primary event predicted by theory reliable?

Why Low Energies?

Where Interests Are

- Solar, supernova, reactor, geo-neutrinos (keV-MeV)
- Sterile neutrinos (eV or keV)
- Relic neutrinos (sub-eV)
- Light DM (sub-GeV)

Fluxes Are Big



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.

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

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

★ Atomic effects important for low-E neutrino detection!

Important Physical Scales

- For NR ($v/c \sim 10^{-3}$), LDM ($m_\chi \lesssim 10$ GeV):
  $p_\chi \lesssim 10$ MeV, $E_\chi \lesssim 5$ keV
- Max. energy deposition by m_χ to m_A:
  $4 m_\chi m_A / (m_\chi + m_A)^2 \, E_\chi < 2$ keV (if elastic)
- Atomic scales with effective charge Z_{eff} (shell-dep.):
  $p_e \sim Z_{\text{eff}}\, m_e \alpha$, $E_\chi \sim Z_{\text{eff}}\, m_e \alpha^2$, $m_e \alpha = 3.7$ keV
- Current lowest detector thresholds:
  $T_{\text{min}} \sim$ keV (nuclear), ~100 eV (electronic)
- Atomic effects important for LDM detection!

Theory Basics

What Are Needed?

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

Neutrino EM Interactions

- General EM current for spin-1/2 particles:

$$\langle p'|j_\mu^{(\gamma)}(0)|p\rangle = \bar{u}(p')\Big[\underbrace{F_1}_{\text{charge}}(q^2)\gamma_\mu - i\underbrace{F_2}_{\text{anomalous mag. dipole}}(q^2)\sigma_{\mu\nu}q^\nu$$

$$+ \underbrace{F_A}_{\text{anapole}}(q^2)\left(q^2\gamma_\mu - \not{q}q_\mu\right)\gamma_5 + \underbrace{F_E}_{\text{el. dipole}}(q^2)\sigma_{\mu\nu}q^\nu\gamma_5\Big]u(p)$$

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

EFT DM-matter Lagrangian

- Leading-Order

SI SD

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

$$\left. + d_1^{(f)} \frac{1}{q^2} (\chi^\dagger \chi)(f^\dagger f) + d_4^{(f)} \frac{1}{q^2} (\chi^\dagger \vec{S}_\chi \chi) \cdot (f^\dagger \vec{S}_f f) \right\}$$ 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: ν/χ + A → ν/χ + A (2-body)
- Discrete excitation: ν/χ + A → ν/χ + A* (2-body)
- Ionization: ν/χ + A → ν/χ + e^- + A^+ (3-body, our focus)
- Channel separation is not trivial

Differential Cross Section

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

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

- 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

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

T>Bi atomic shell open

free scat.

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

Our MB Approach: MCRRPA

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

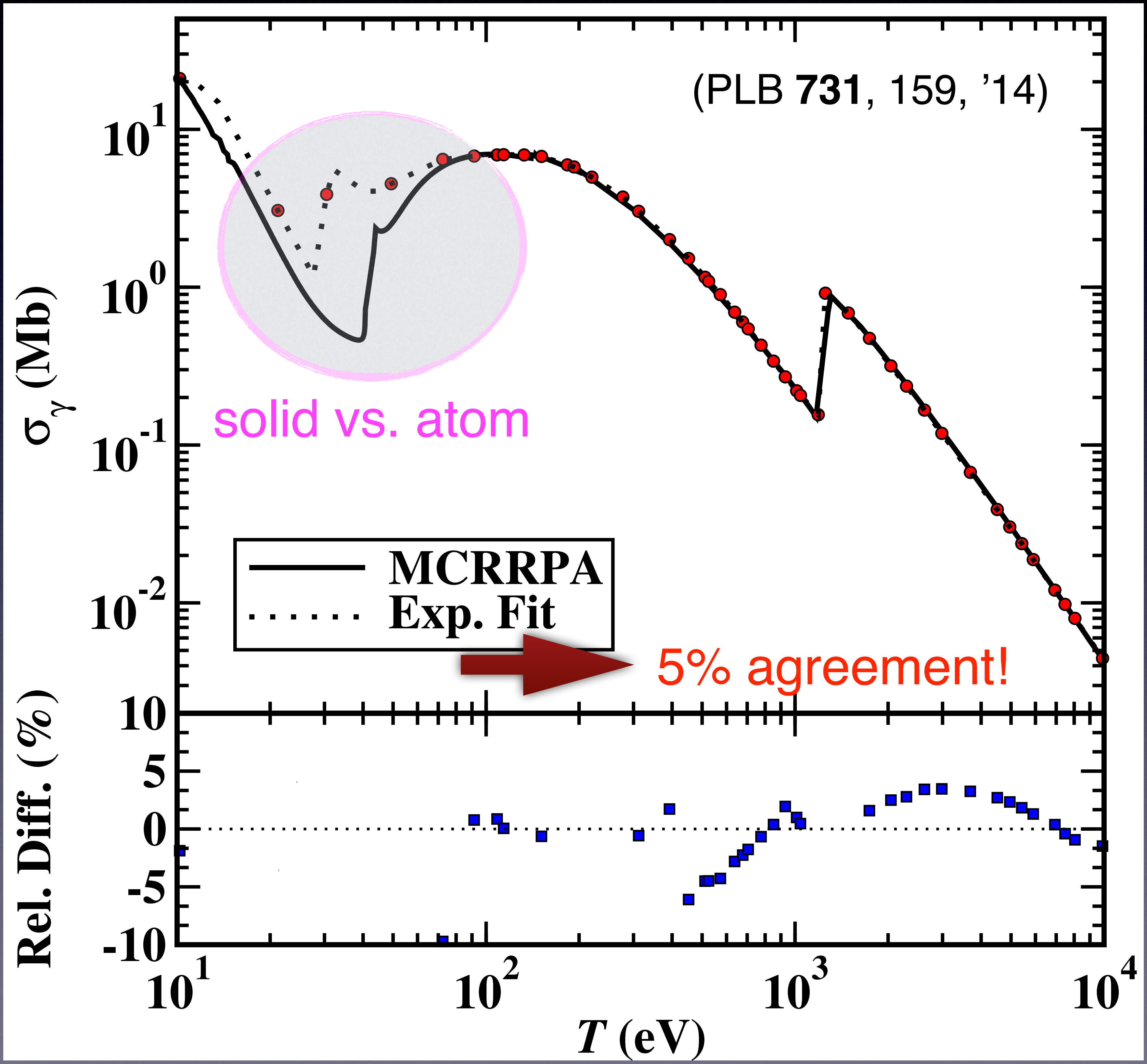
- MC [multi-configuration]: open-shell atoms have more than one ground-state configuration. Eg. for Ge:

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

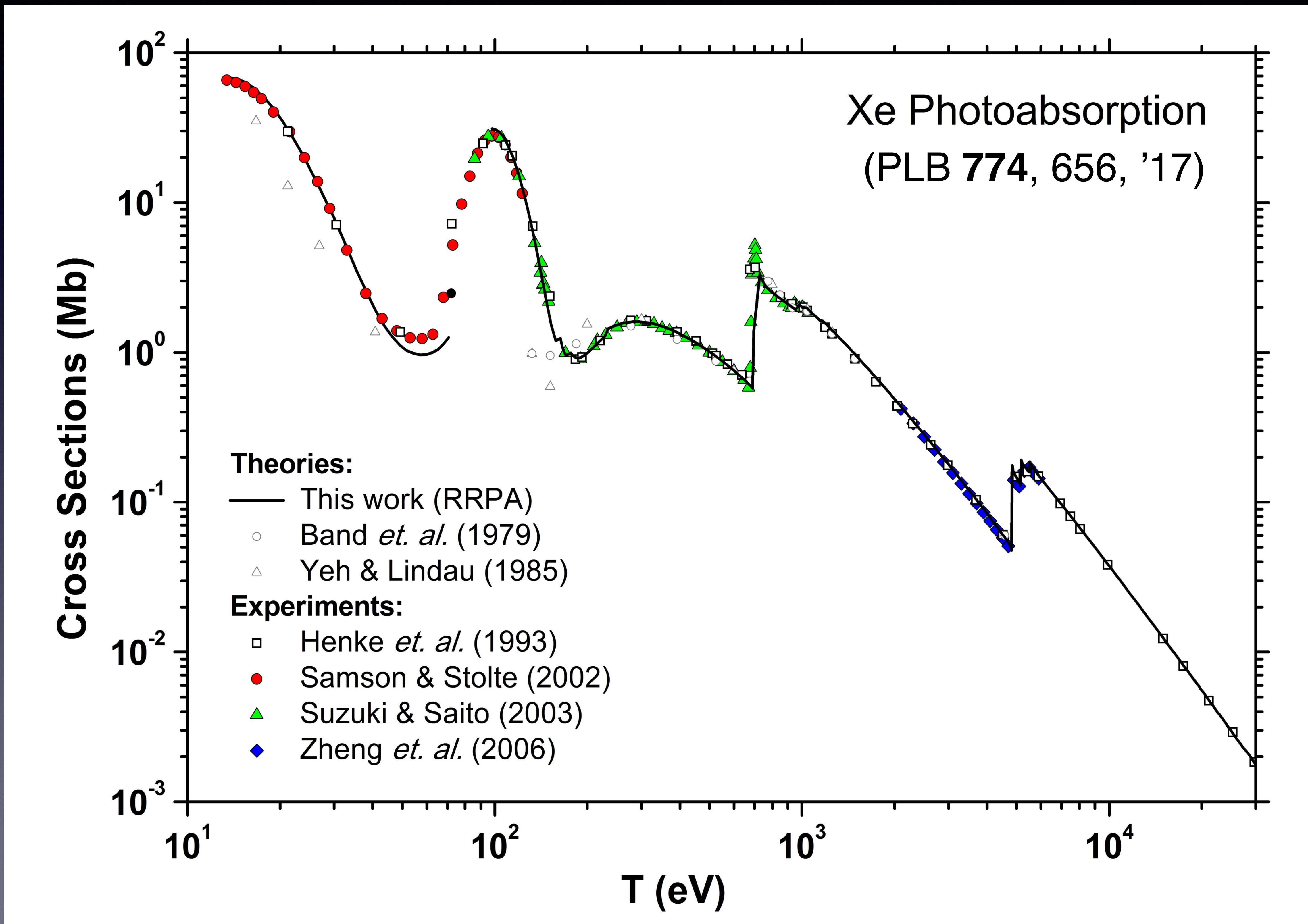
- R [relativistic]: $Z\alpha$~0.25(Ge) / 0.4(Xe)

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

Benchmark: Ge Photoionization



Benchmark: Xe Photoionization



Selected Works

Neutrino EM Moments

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

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

Beauty of Low-T Detectors

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

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

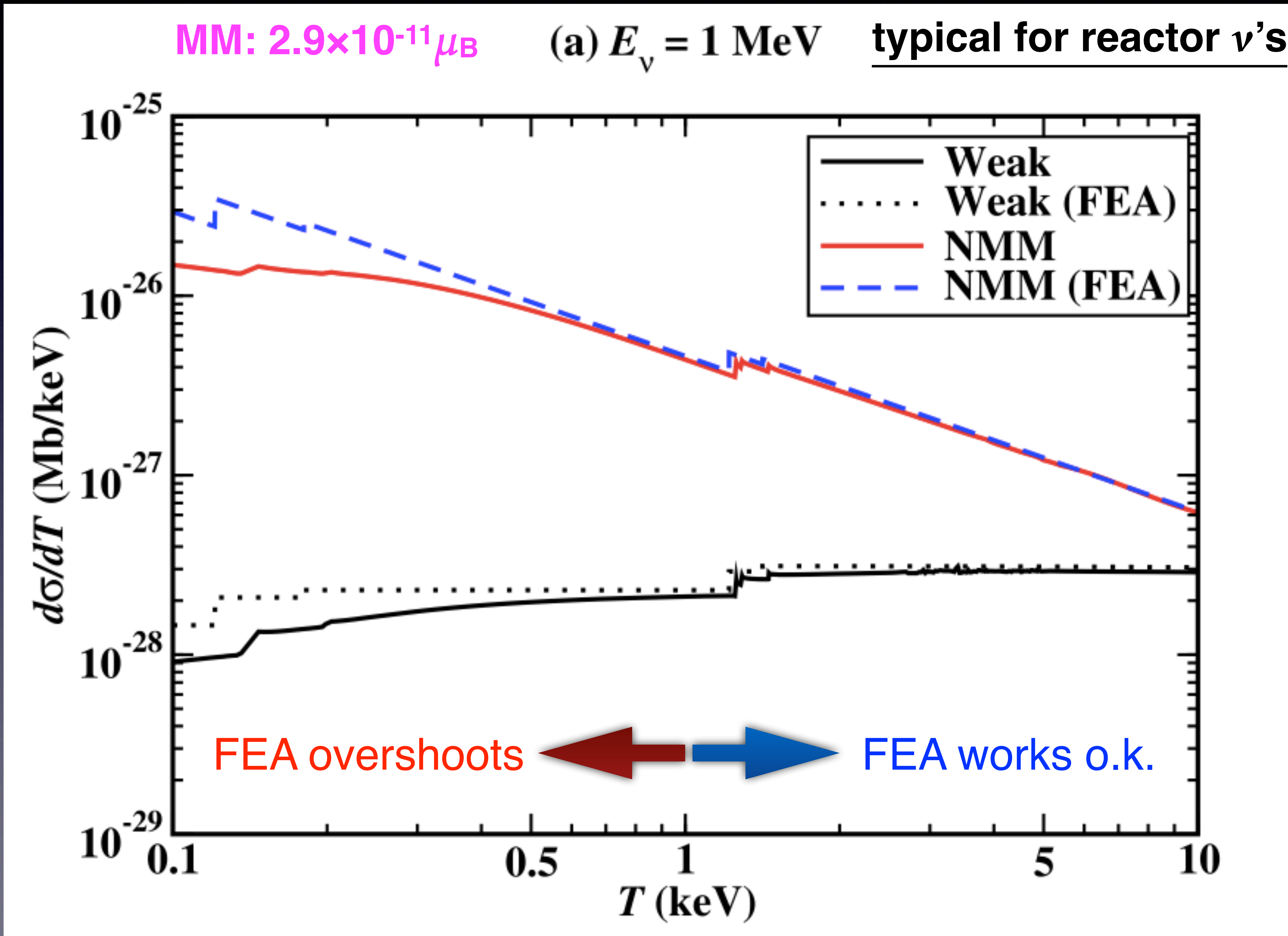
- Low threshold detectors:

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

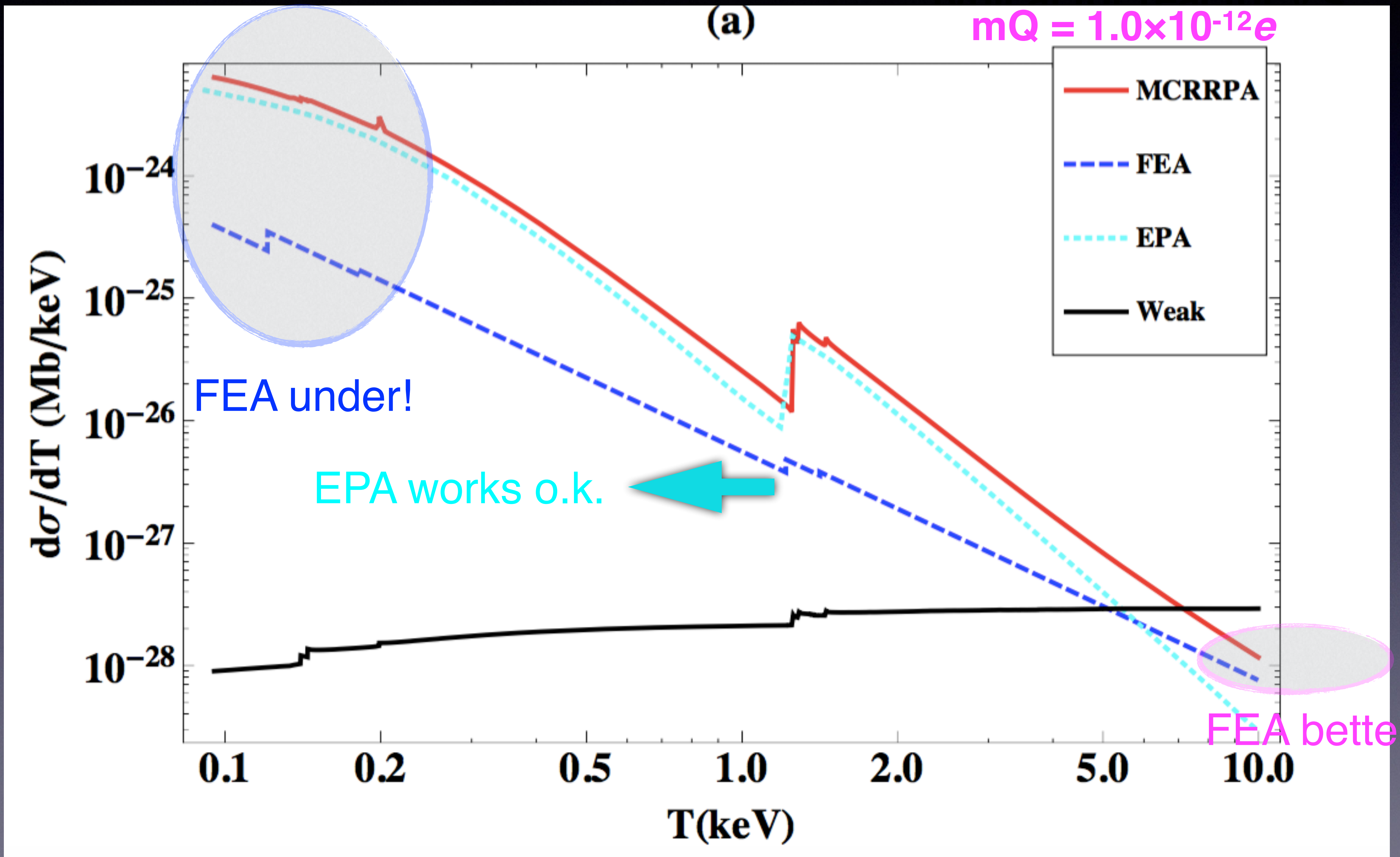
- Price to pay:

Atomic binding effects!

Ge AI by MM


MM: 2.9×10^-11 μB
(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^-12 e
MCRRPA
FEA
EPA
Weak
FEA under!
EPA works o.k.
FEA better
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)

Current Direct Limits

From PDG 2016

- MM: $2.9\times10^{-11}\mu_B$ (GEMMA ’13); $7.4\times10^{-11}\mu_B$ (TEXONO ’07)
- mQ: [$1.5\times10^{-12}e$ (from GEMMA); $2.1\times10^{-12}e$ (from TEXONO)]

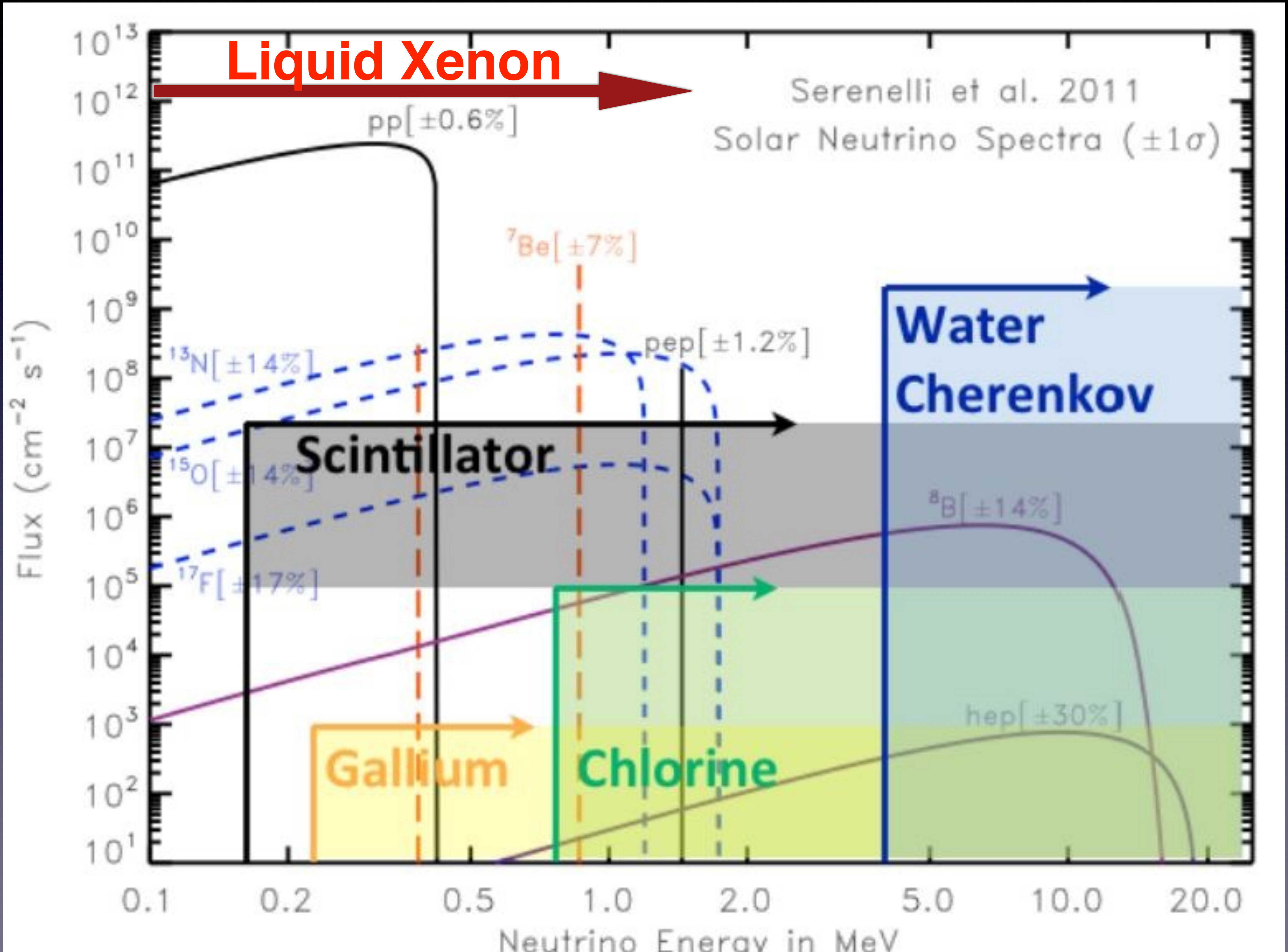
ν CHARGE

VALUE (units: electron charge)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<2.1\times10^{-12}$	90	[1] CHEN	14A	TEXO	Nuclear reactor
$<1.5\times10^{-12}$	90	[2] STUDENIKIN	14		Nuclear reactor
$<3.7\times10^{-12}$	90	[3] GNINENKO	07	RVUE	Nuclear reactor

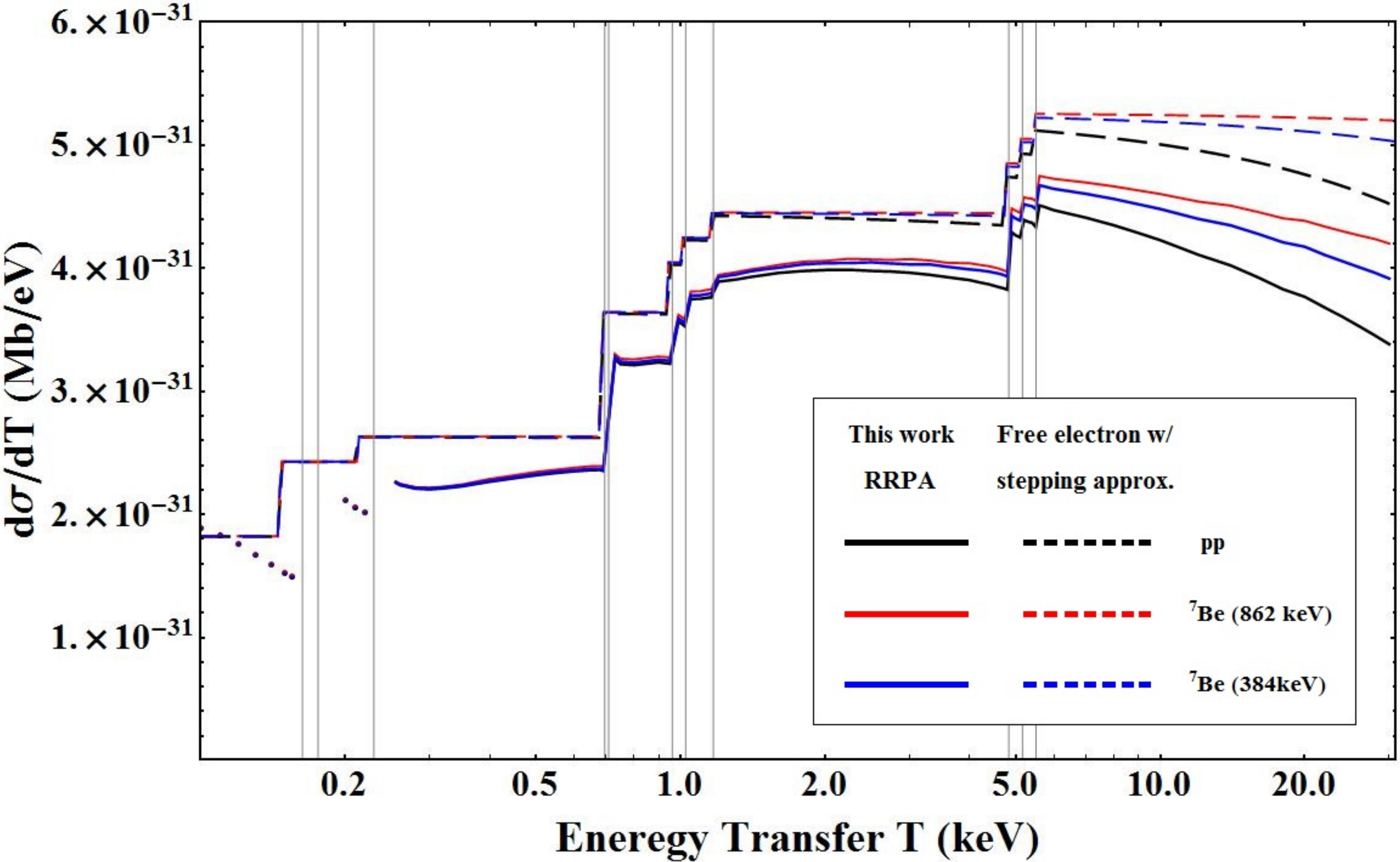
Low-E Solar Neutrinos (PLB **774**, 656, ’17)

- *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!

Summary

Conclusions

- Neutrino & DM physics is interdisciplinary.
- Many-body physics is essential for sub-keV detectors of neutrinos and dark matter.
- High-quality many-body calculations can substantially reduce theoretical errors.
- Energy loss mechanism still needs better understanding.

Thanks!