Measurements and **ab initio** Calculation of Atomic Compton Scattering

Speaker: Chang-Hao Fang

Outline

- Research background and ab inito calculations
- Experiements and data analysis
- Result and impact on DM background

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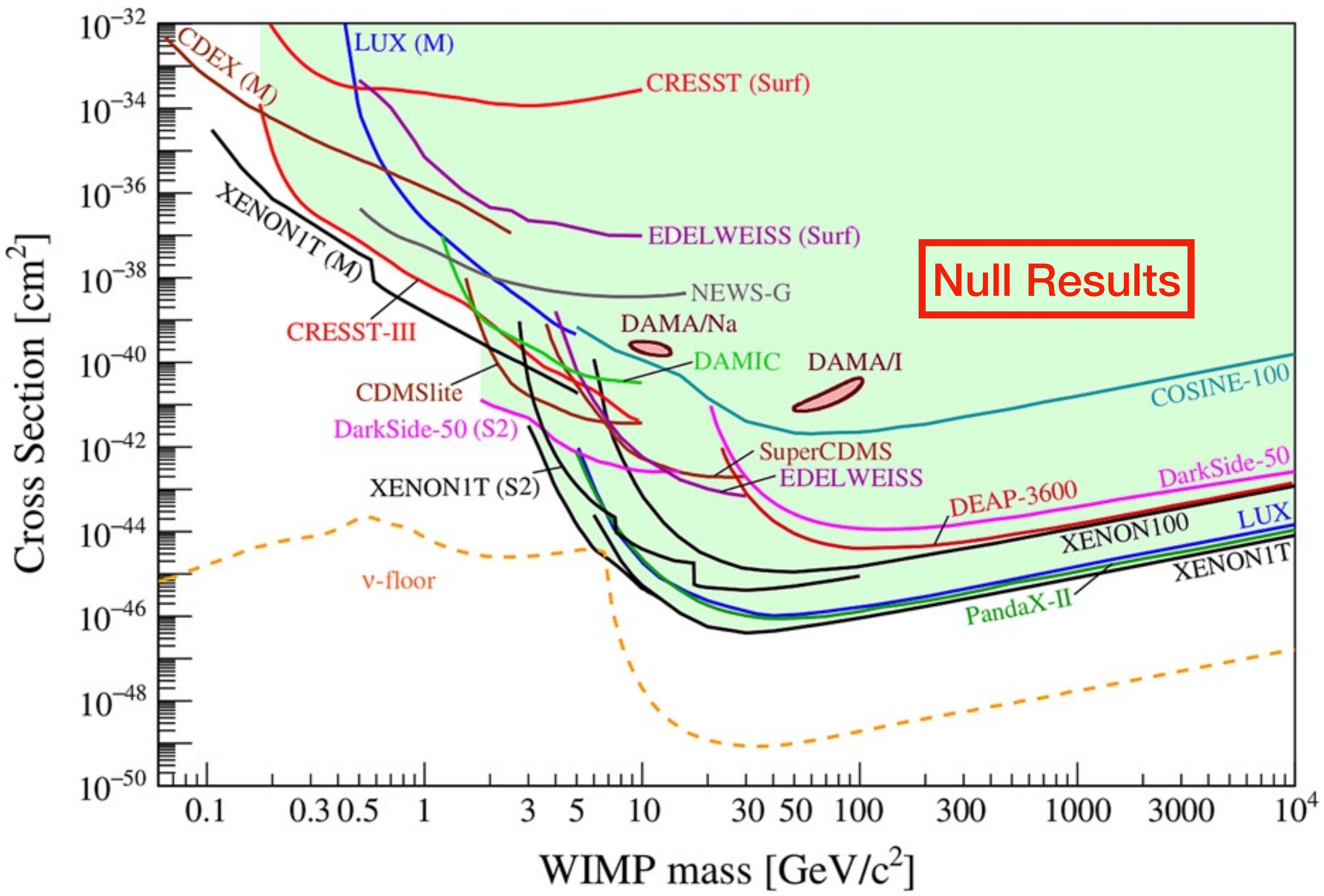
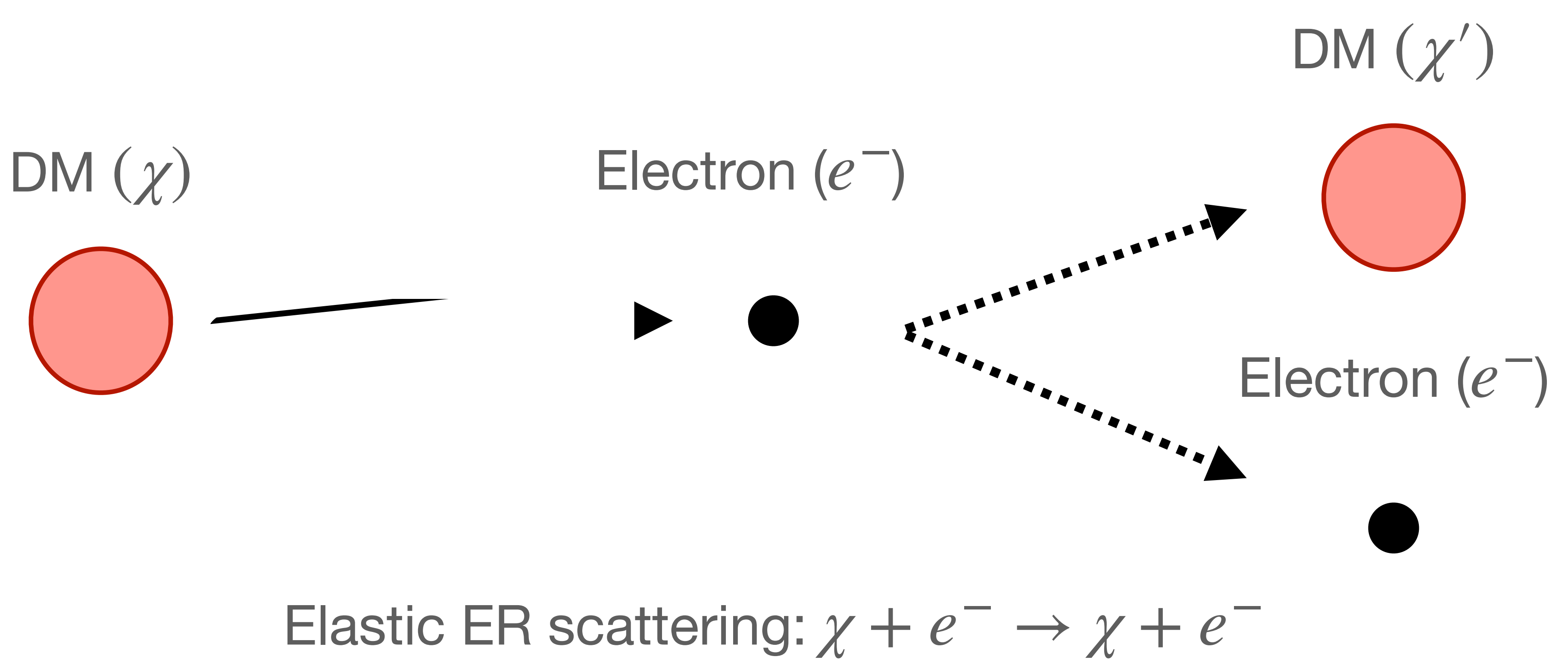
中国暗物质实验

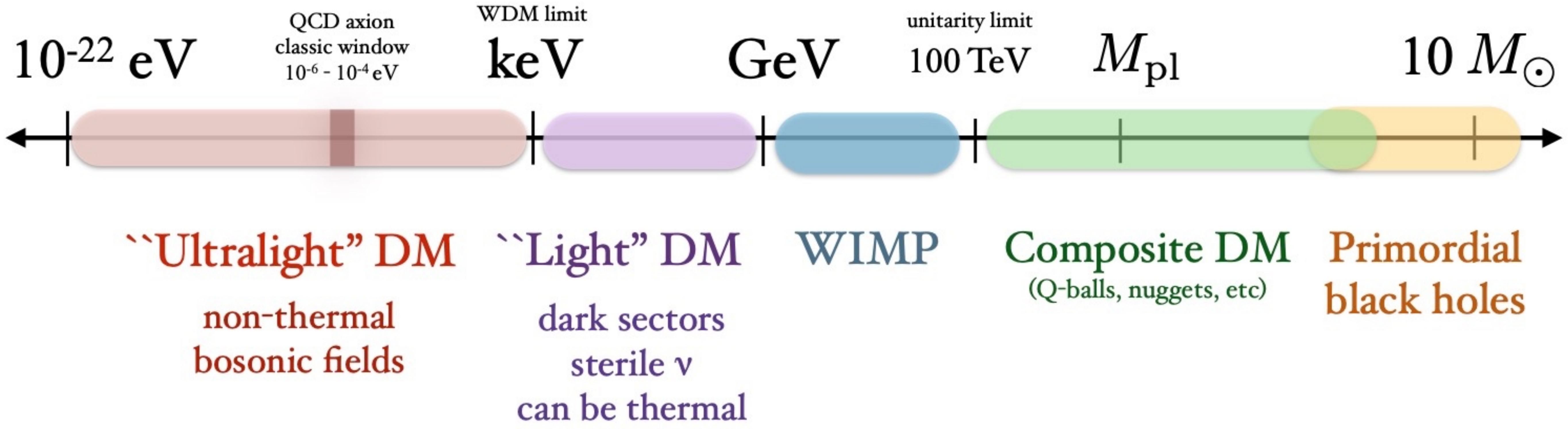
China Dark matter EXperiment

Research Background and ab inito calculation

LDM and Detection Channels



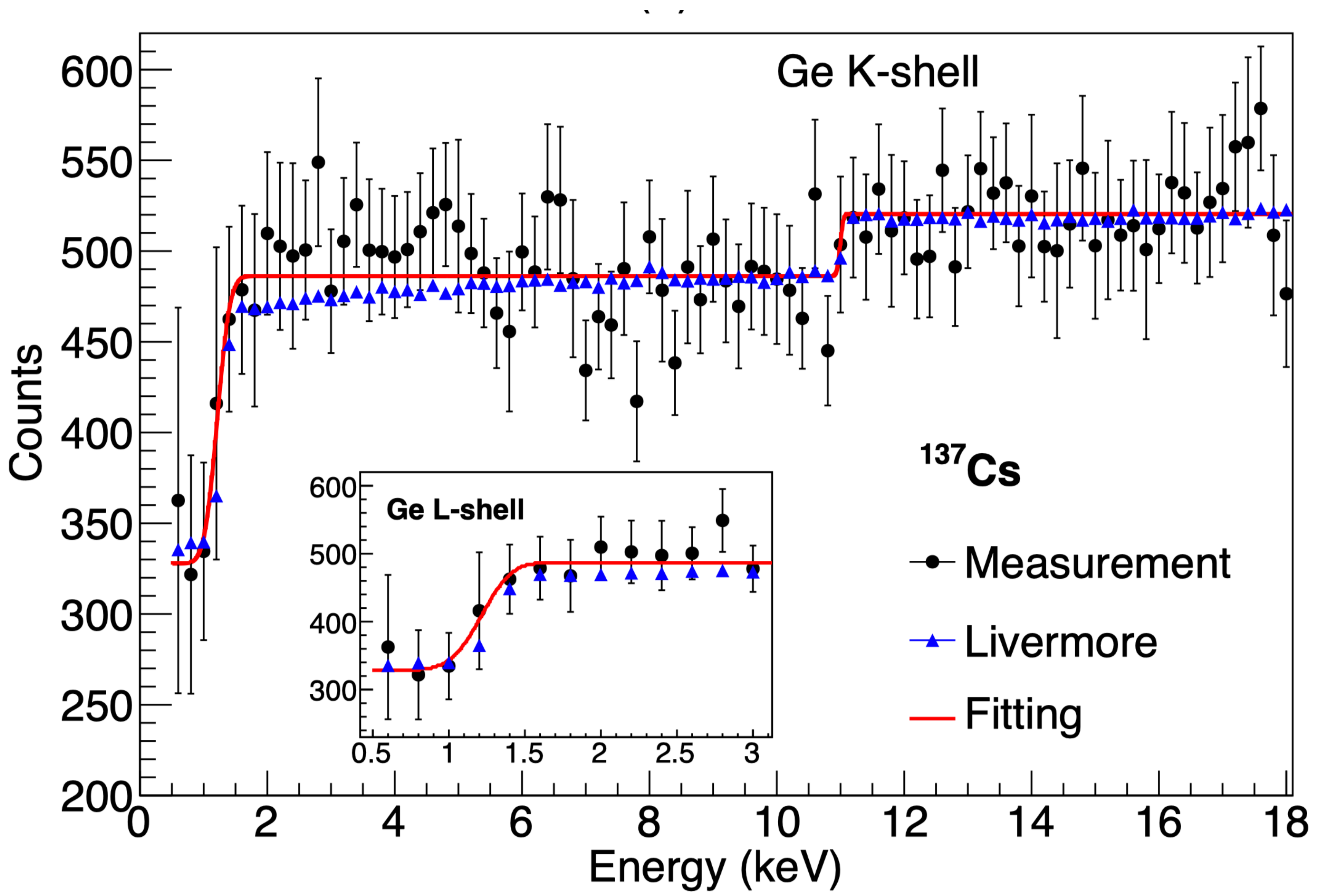




LDM: the Axion-like particles, the vector-like particles model, the dark photon models, the leptophilic dark matter model and WIMPs.

Compton Scattering as Low-Energy Background

- Compton scattering: important ER channels, cannot be discriminated.
  - Step-like structures in the low-energy spectra: atomic binding effects.
- Performing advanced atomic approach with the Multi-configuration Dirac-(Hartree)-Fock (MCDF) method.



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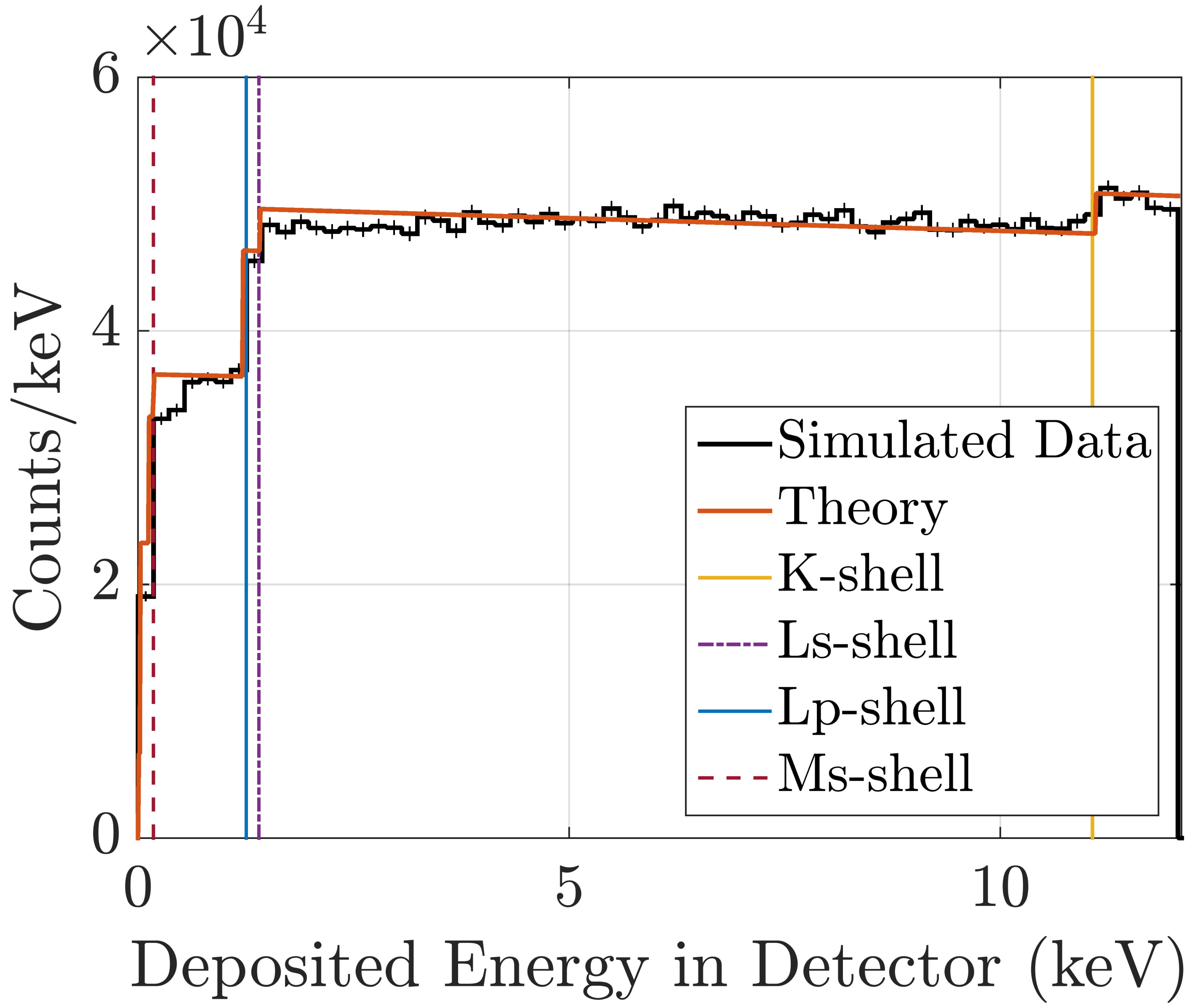


arXiv:1611.05792 [astro-ph, physics:physics] **2016**.

MCDF and RIA in Compton Scattering

- Ab inito calculation of Ge (by MCDF)
  - MCDF vs. HF: Relativistic, many-body (electron correlation, configuration interactions)
- Relativistic Impulse Approximation (RIA) approaches: reduction to a two-body interaction, a photon and an electron with momentum (Compton profile)
- Differential cross-sections

Heaviside step function

$$\left(\frac{d^2\sigma}{d\omega_f d\Omega_f}\right)_{\mathrm{RIA}} = \sum_{njl} Z_{njl}\left(\frac{d^2\sigma_{njl}}{d\omega_f d\Omega_f}\right)_{\mathrm{RIA}} = \frac{r_0^2 m_e^2 c^4 \omega_f}{2}\int_i d^3p_i \frac{X\left(K_i(p_i), K_f(p_f)\right)}{E_i E_f}\delta\left(E_i + \omega_i - E_f - \omega_f\right) \times \sum_{njl} Z_{njl} J_{njl}\left(\boldsymbol{p}_i\right)\Theta\left(\omega_i - \omega_f - B_{njl}\right)$$

Sum over the sub-shells

Kinetic factor

The Compton profile

$$\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{RIA}} = \left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{KN}} \cdot S(\theta, \omega_i)$$

Scattering function (SF), # of activated electrons

$$S(\theta, \omega_i) = \sum_{njl} Z_{njl}\Theta\left(\omega_i - B_{njl}\right)\int_{-\infty}^{p_i^{\max}} J_{njl}(p_z)dp_z$$

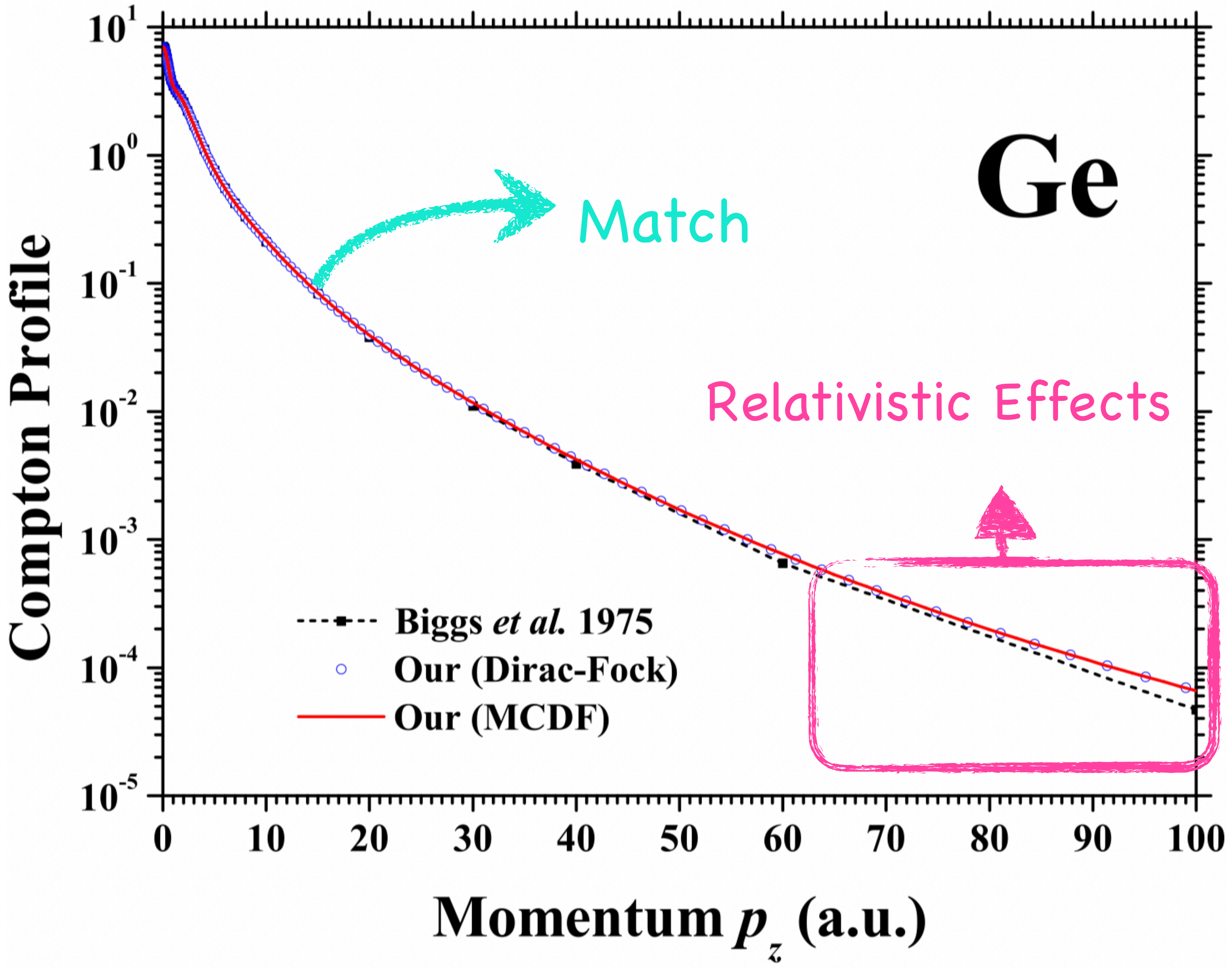
MCDF →
- Ionization energy: wave-function
- Compton profile: distribution of p_e
- SF: Ionization + Compton profile

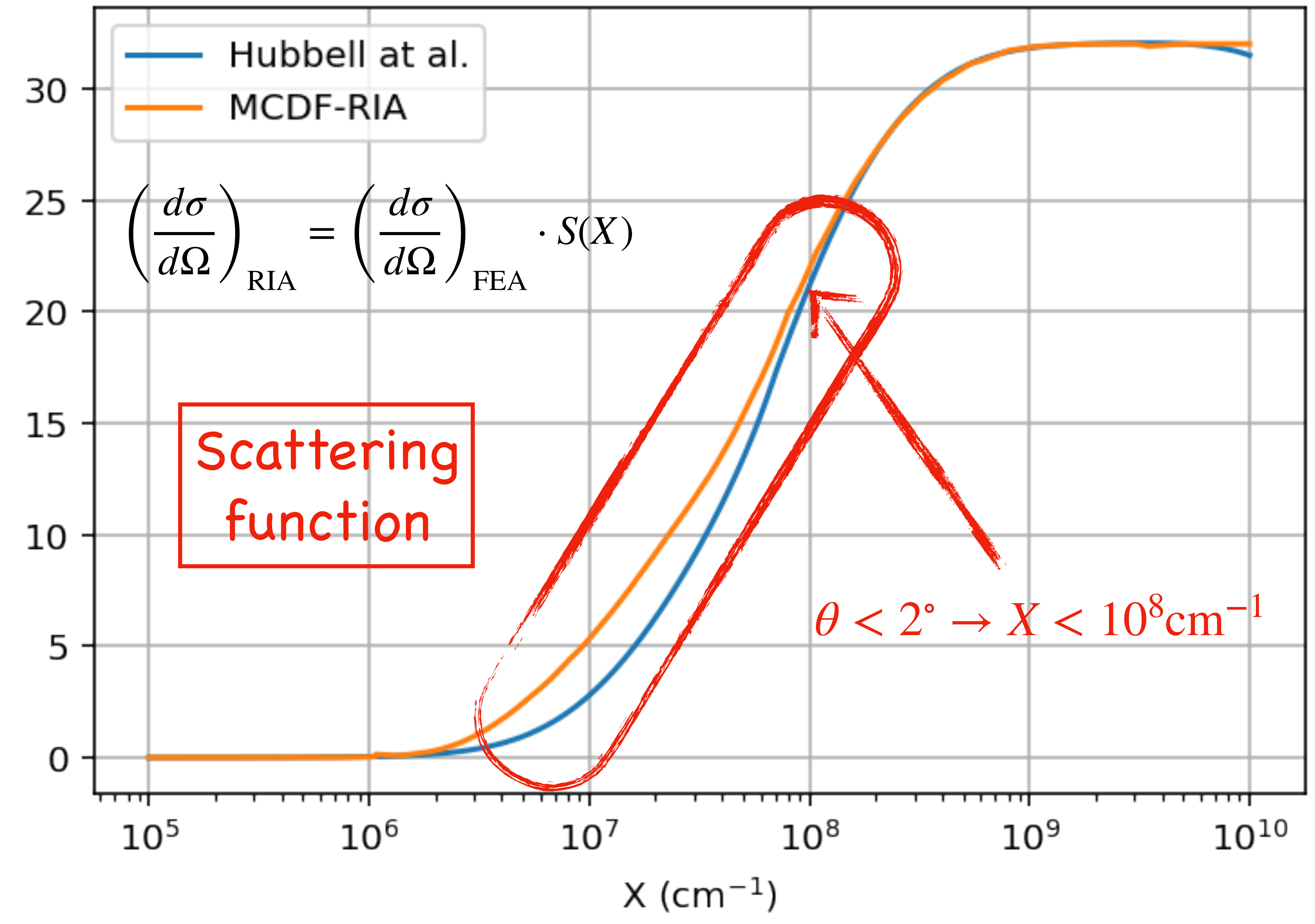
→ MCDF-RIA

MCDF-RIA verus Data in EPDL

Sub-shells	K $1s_{1/2}$	L_{I} $2s_{1/2}$	L_{IIa} $2p_{1/2}$	L_{IIb} $2p_{3/2}$	M_{I} $3s_{1/2}$	M_{IIa} $3p_{1/2}$	M_{IIb} $3p_{3/2}$	M_{IIIa} $3d_{3/2}$	M_{IIIb} $3d_{5/2}$	N_{I} $4s_{1/2}$	N_{IIa} $4p_{1/2}$	N_{IIb} $4p_{3/2}$
MCDF	11119.0	1426.9	1257.3	1226.0	193.3	136.8	132.2	36.5	35.9	14.6	7.8	8.0
HF (EPDL)	11067.0	1402.3	1255.4	—	179.25	129.38	—	38.19	—	14.7	6.5	—
Exp.	11103.1	1414.6	1248.1	1217.0	180.1	124.9	120.8	29.9	29.3	—	7.9	—

MCDF, HF (EPDL), Experimental results [2, 3].



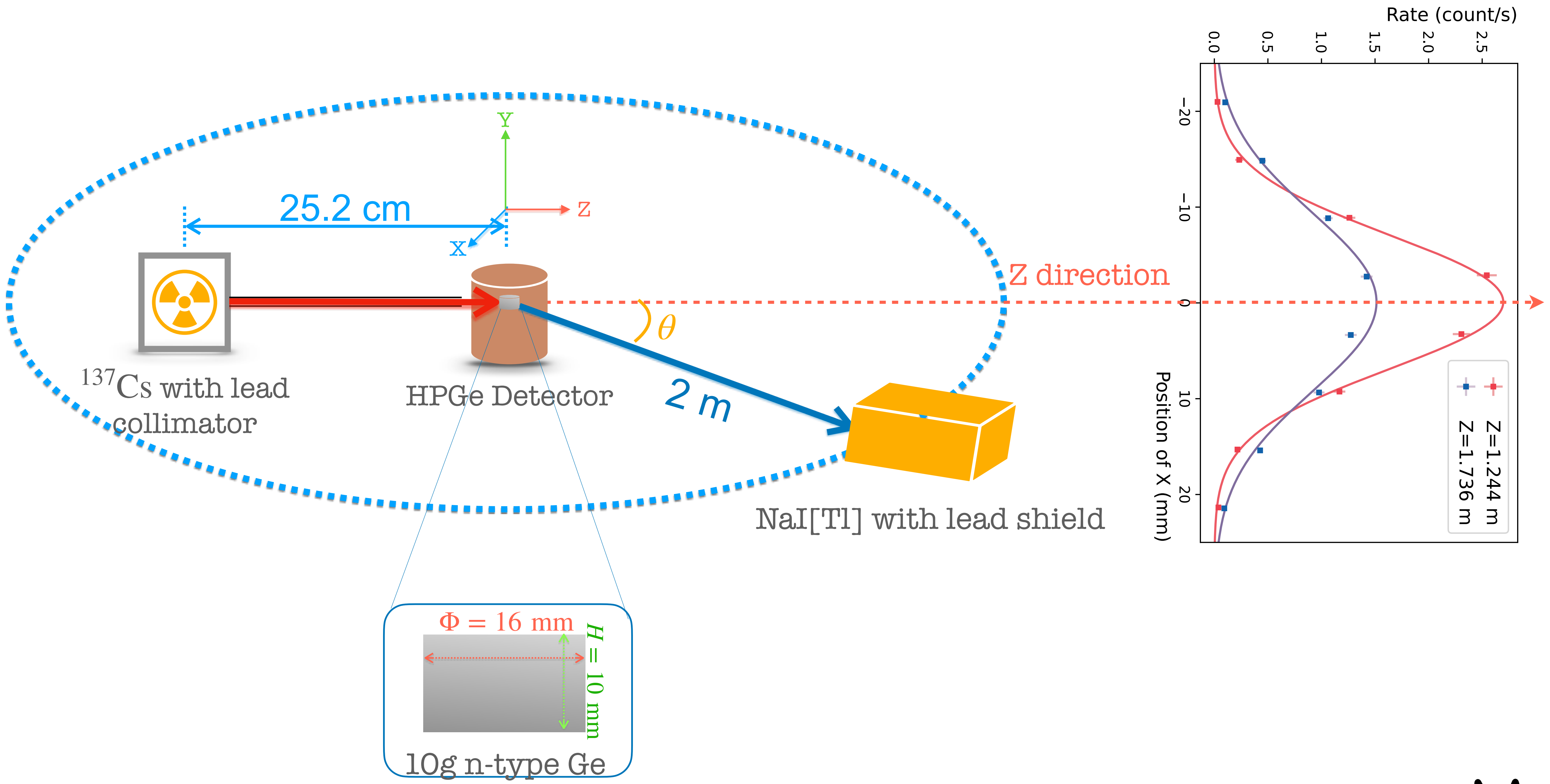


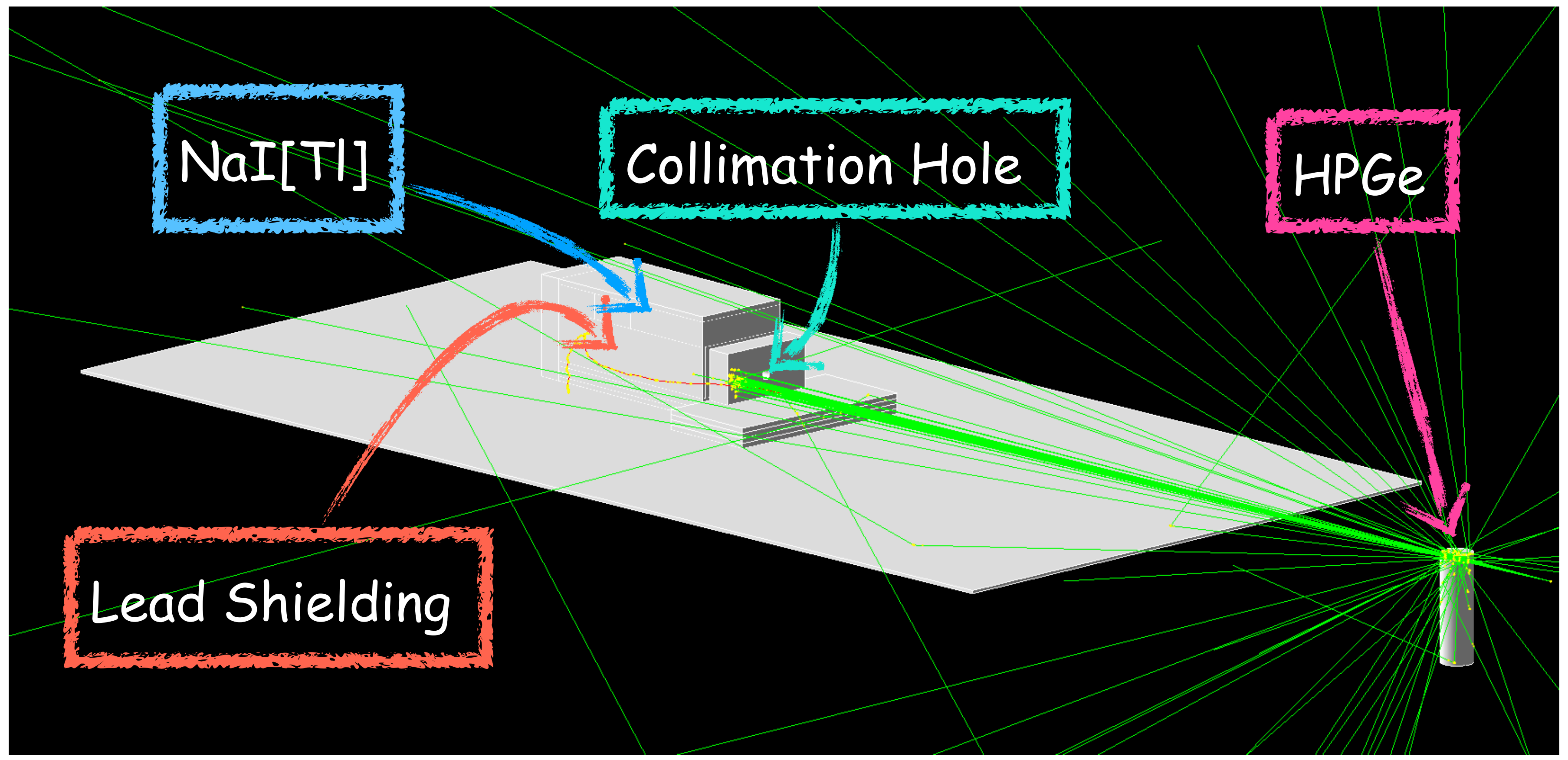
- MCDF-RIA VS. EPDL (Hubbell, Biggs et al.)[1]
  - Ionization energy: MCDF is closer to Exp.
  - Compton profile: match but mildly differ at high p_z.
  - SF (DCS): at most a factor of two difference in the low momentum transfer region.

[1] G4EMLOW8.0
[2] B. Henke, E. Gullikson, and J. Davis, Atomic Data and Nuclear Data Tables 54, 181 (1993).
[3] R. D. Deslattes, E. G. Kessler, P. Indelicato, et al., Reviews of Modern Physics 75, 35 (2003).

Experiments and Data analyses

Experimental Setup





Geometry build in Geant4.

Apparatus	
Source	6.6 mCi 137Cs
Front-end detector	10g n-type HPGe
Back-end detector	NaI[Tl]
Shielding & collimator	5cm Pb + 18 mm hole

- **Measurements:**
  - Energy spectra: $d^2\sigma/(dE d\Omega)$
  - Scattering function

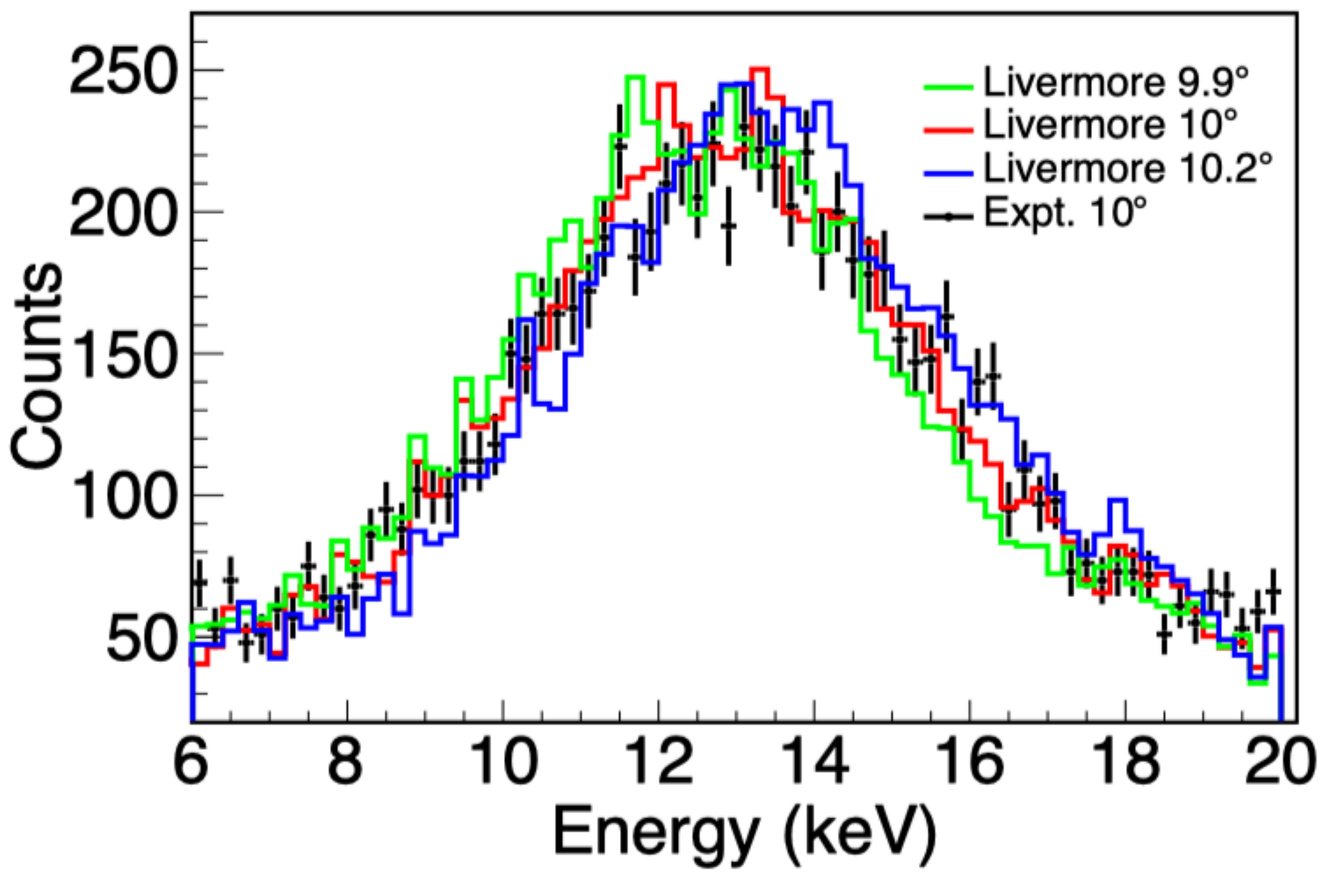
$$S(X)_{\text{s.a.}} = \left[\left(\frac{d\sigma}{d\Omega}\right)_{\text{s.a.}} \Big/ \left(\frac{d\sigma}{d\Omega}\right)_{\text{c.a.}} \right] \cdot S(X)_{\text{c.a.}},$$

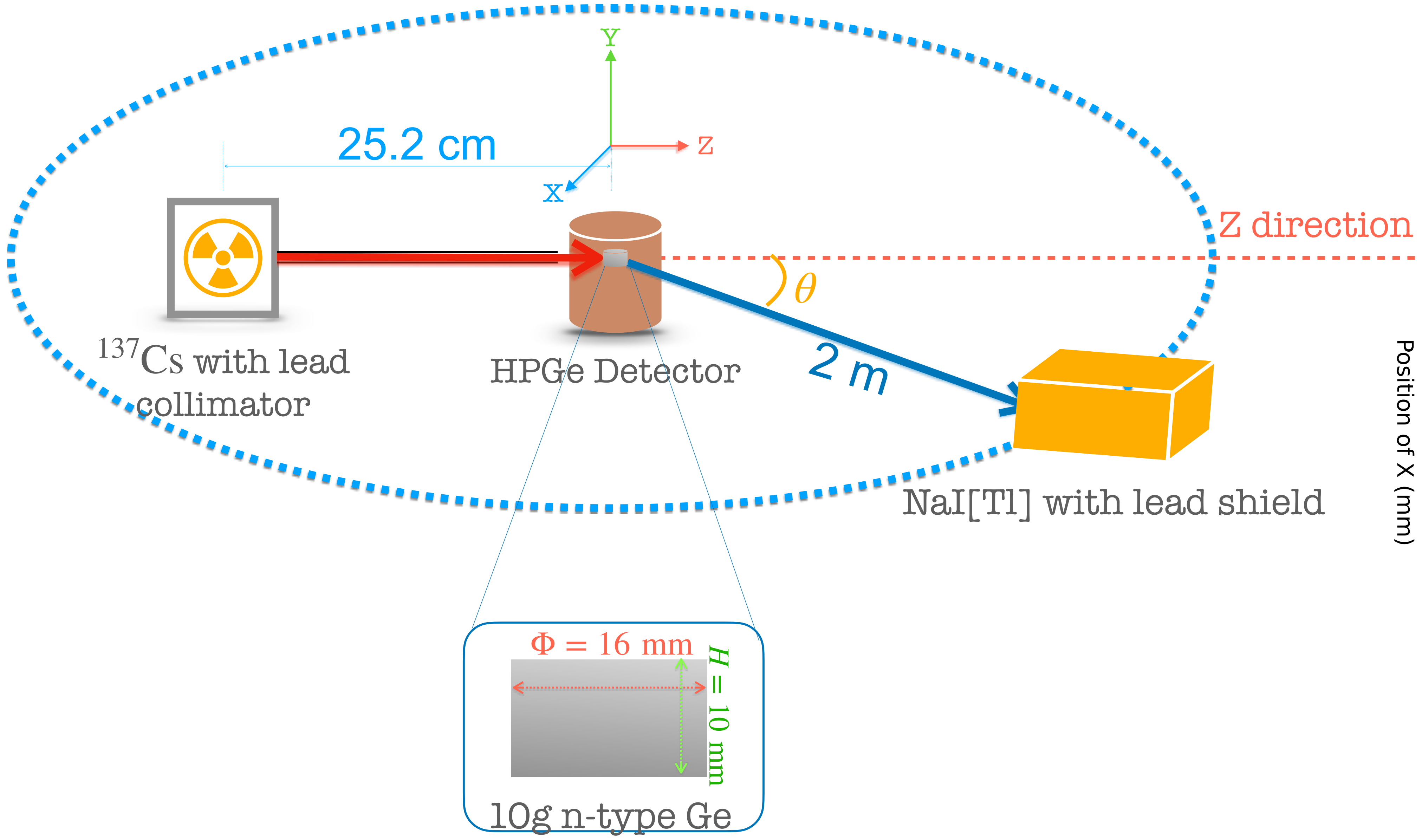
- Key approach: accurate scattering angle calibration.

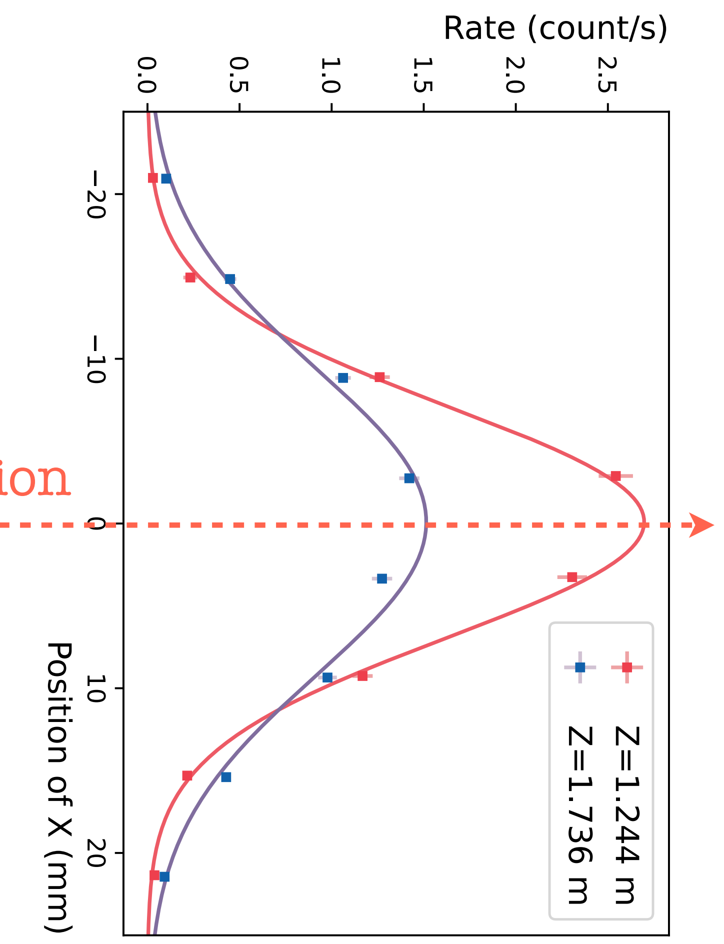
Determination of The Scattering Angle

	error(degree)
scattering angle of 0° error	≤ 0.01
calibrated horizontal plane error	≤ 0.02
arbitrary angle error	≤ 0.02
Total error	≤ 0.03

Geometry error arise from angle calibration

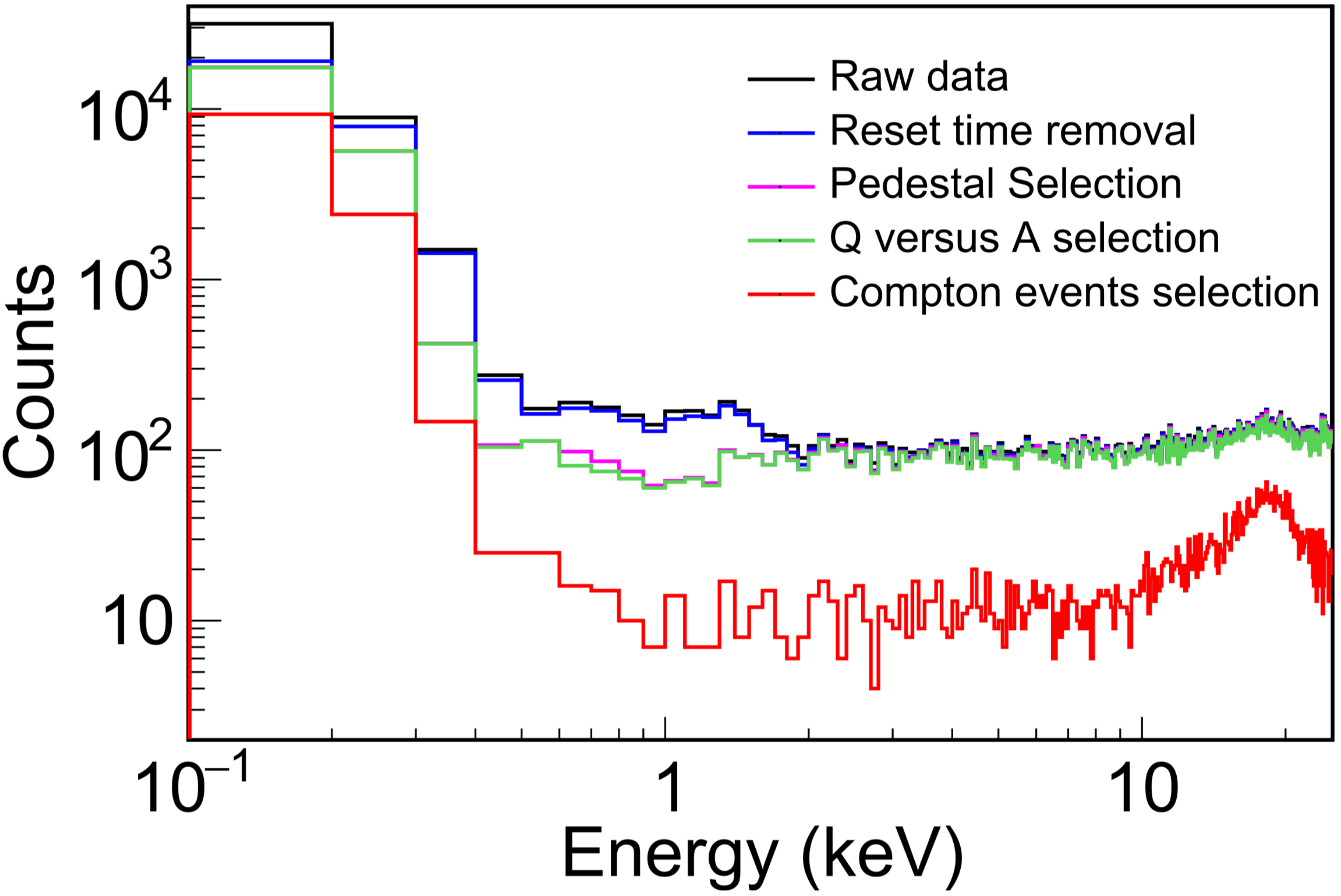


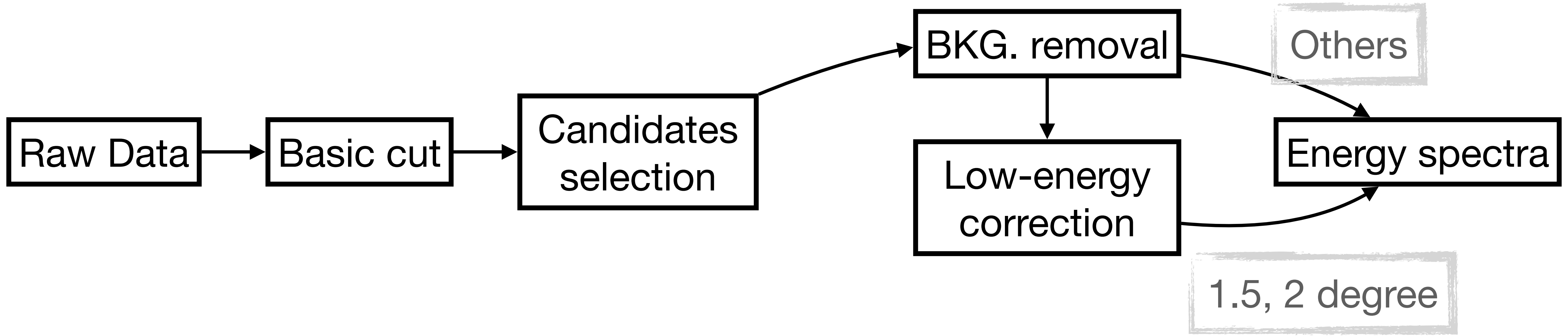




- Scattering angle is determined by calibrating horizontal plane, z-direction and arbitrary scattering angle.
  - Geometric error is within 0.03 degree. Simulations in 2σ: Livermore ($12^{+0.1}_{-0.01}$ °), Monash ($12^{+0.03}_{-0.04}$°)
- UNKNOWN source distribution:-> Measured source separation (0.27±0.01 deg)
- Geometrical scattering angle is **NOT** identical to real scattering angle

Data Analyses: Candidates Selection



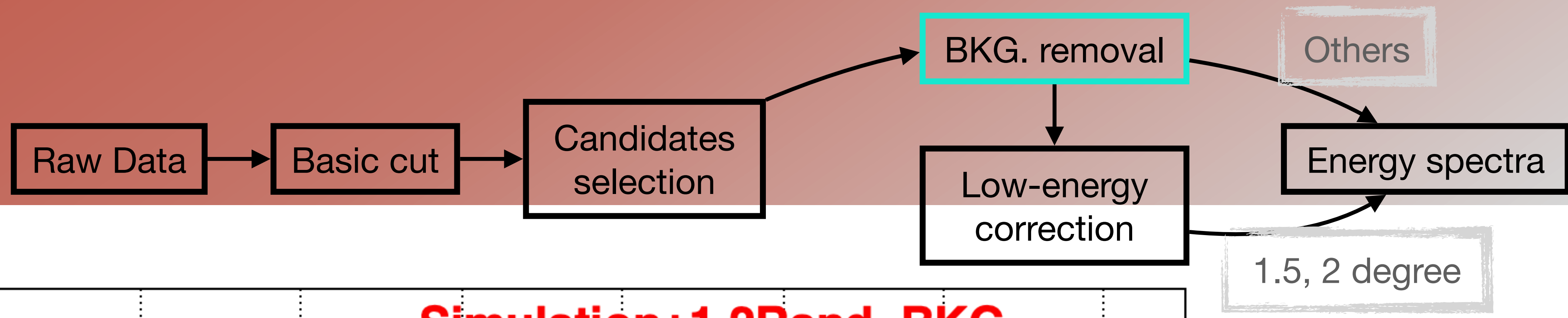


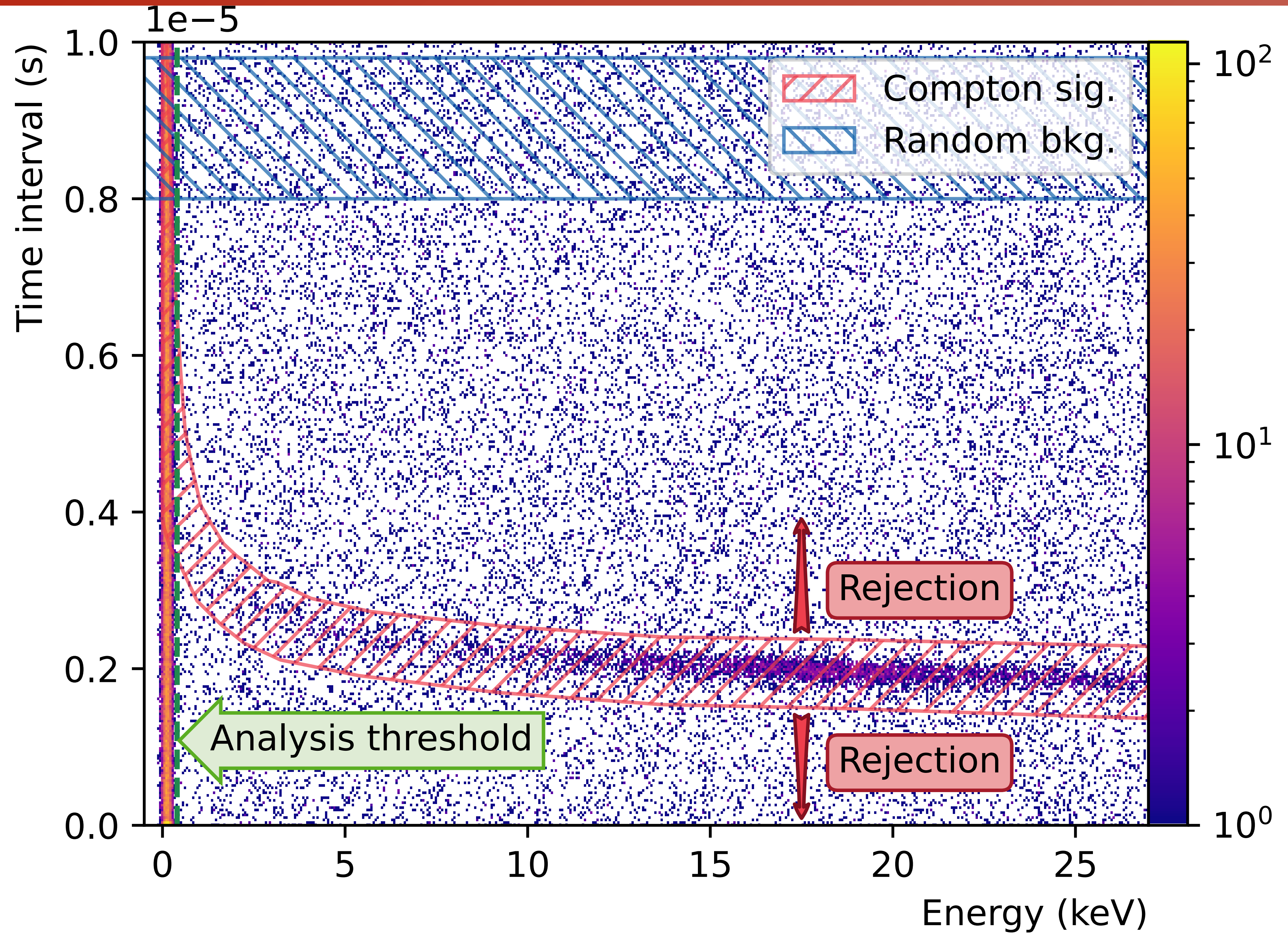
Data processing work flow.

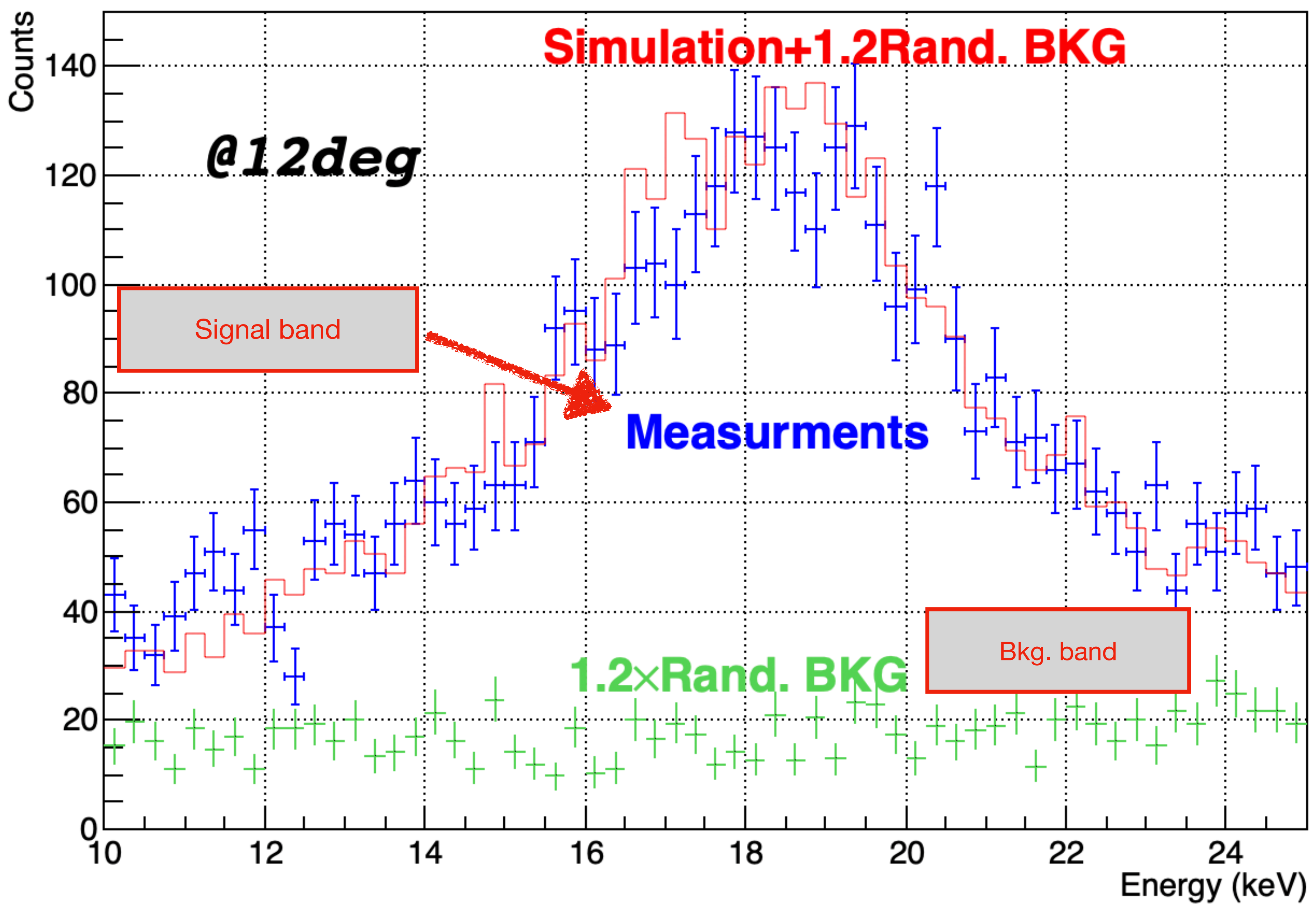
Cuts	Efficiency (%)
DAQ dead time	98.0
Inhibit	99.8
Pedestal	99.6
Q-A	99.7
Candidate selection	99.3
Total	96.4

- Data taking at 12, 5, 4, 3, 2, 1.5 degree.
- Basic cut: INHIBIT, Q-A, Pedestal
- Coincident candidate: Trigger time interval-HPGe energy parameter space

Data Analyses: Background

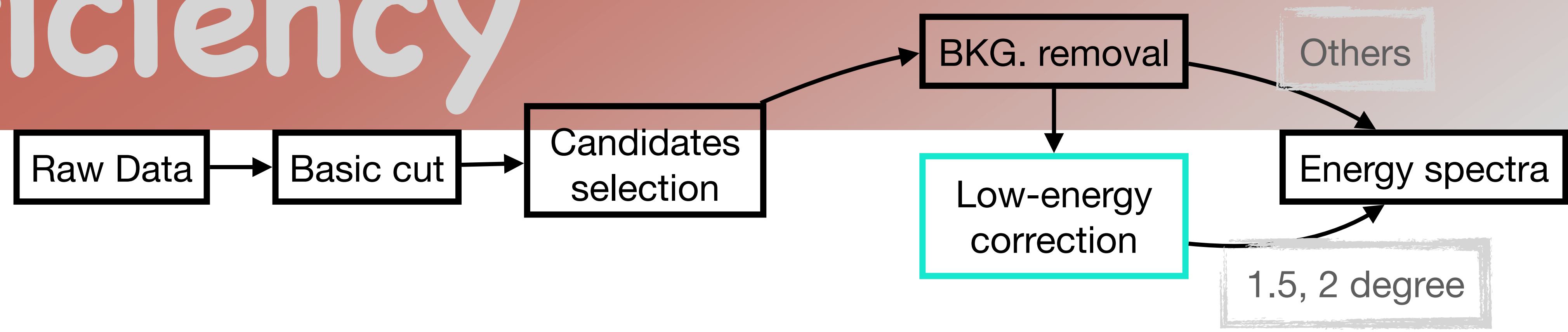


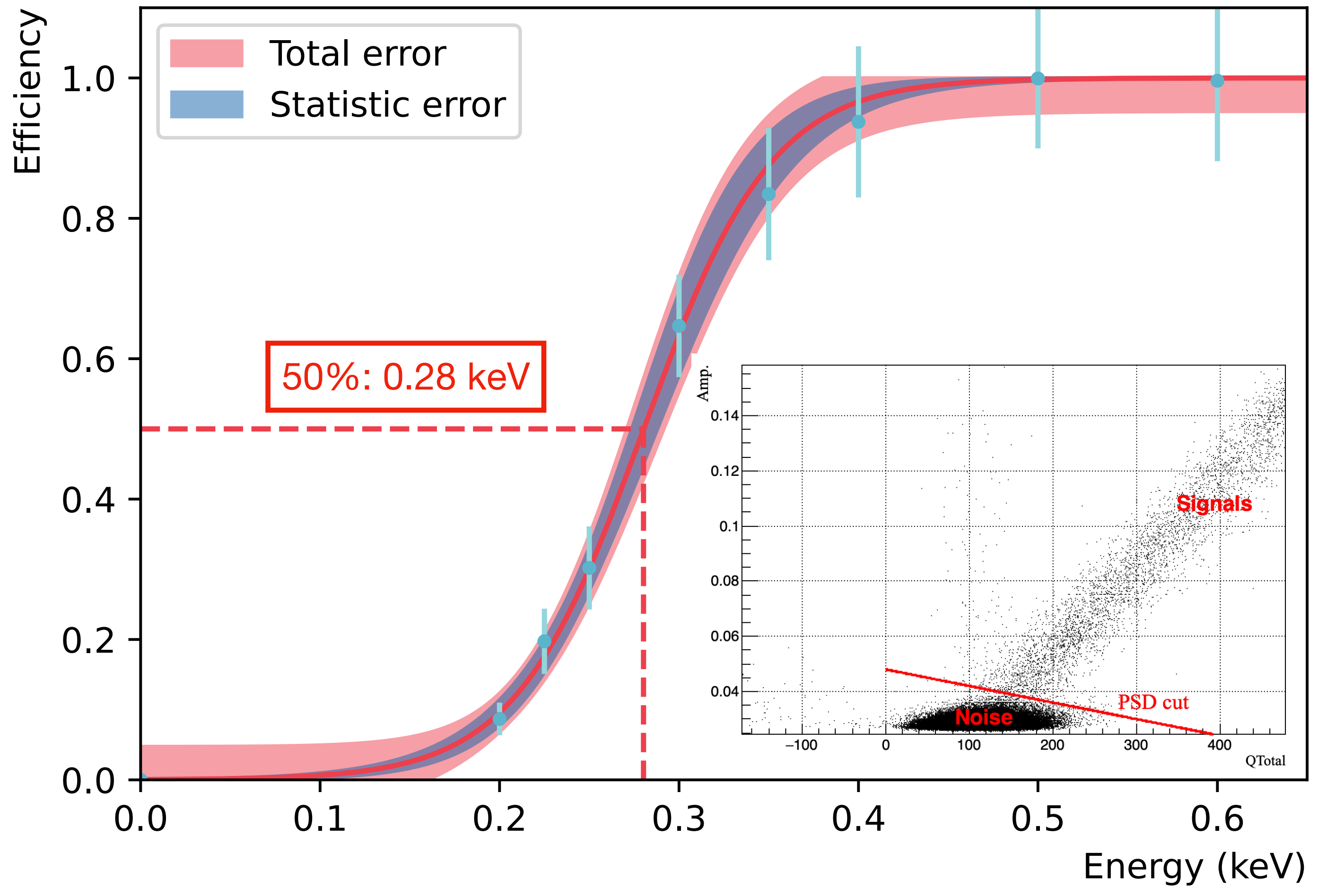




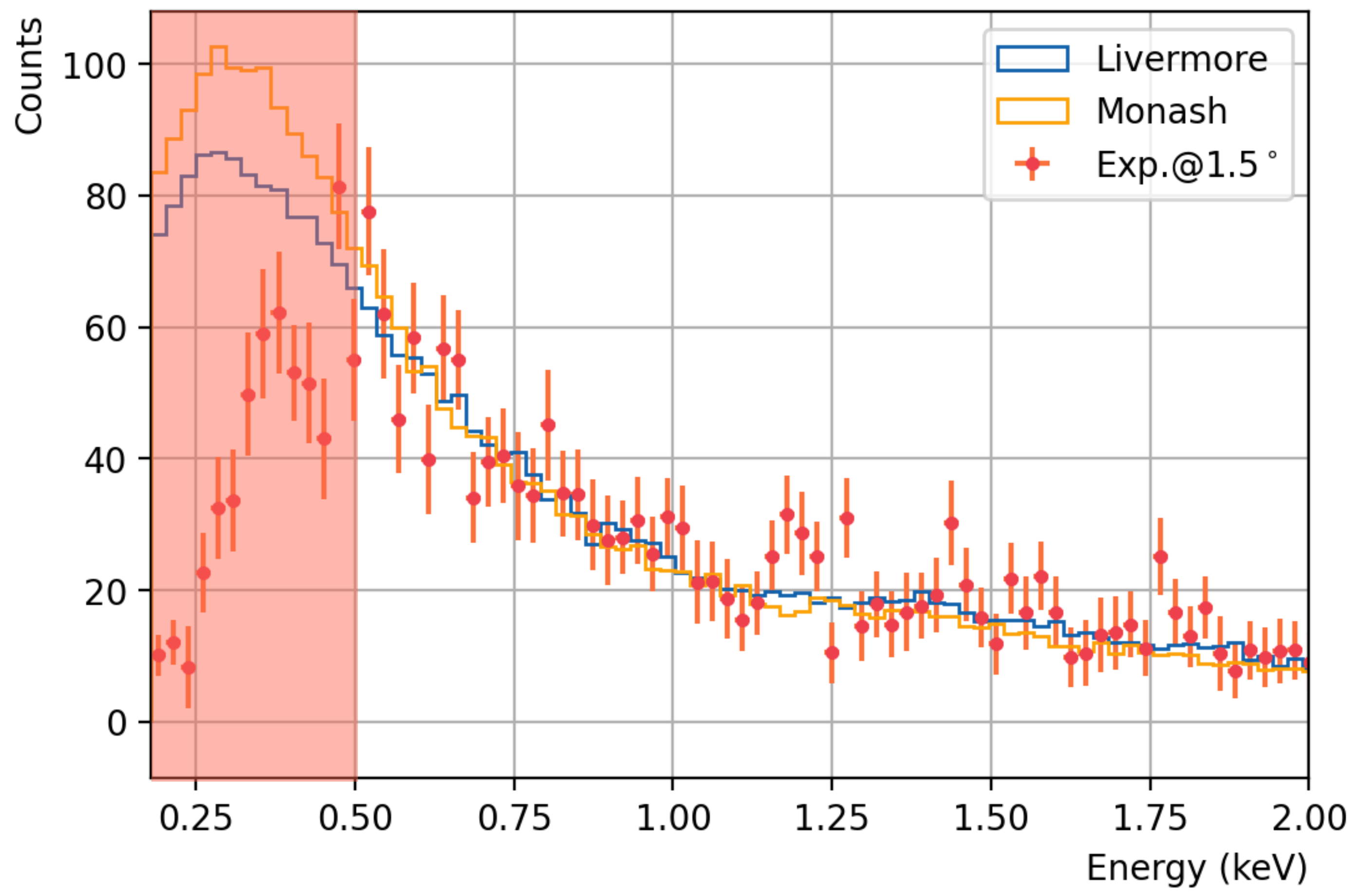
- Background is classified into **two** categories:
  - Accidental coincidence: uniformly distributed in the parameter space; Source related bkg: concentrate at signal region.
- Amount of source related bkg is about 20% of the accidental coincidences background
  - Identified as source contribution and cross-checked with delicate simulations
  - Shape has minor dependence on scattering angles and removed from other angles

Data Analyses: Low-energy Efficiency

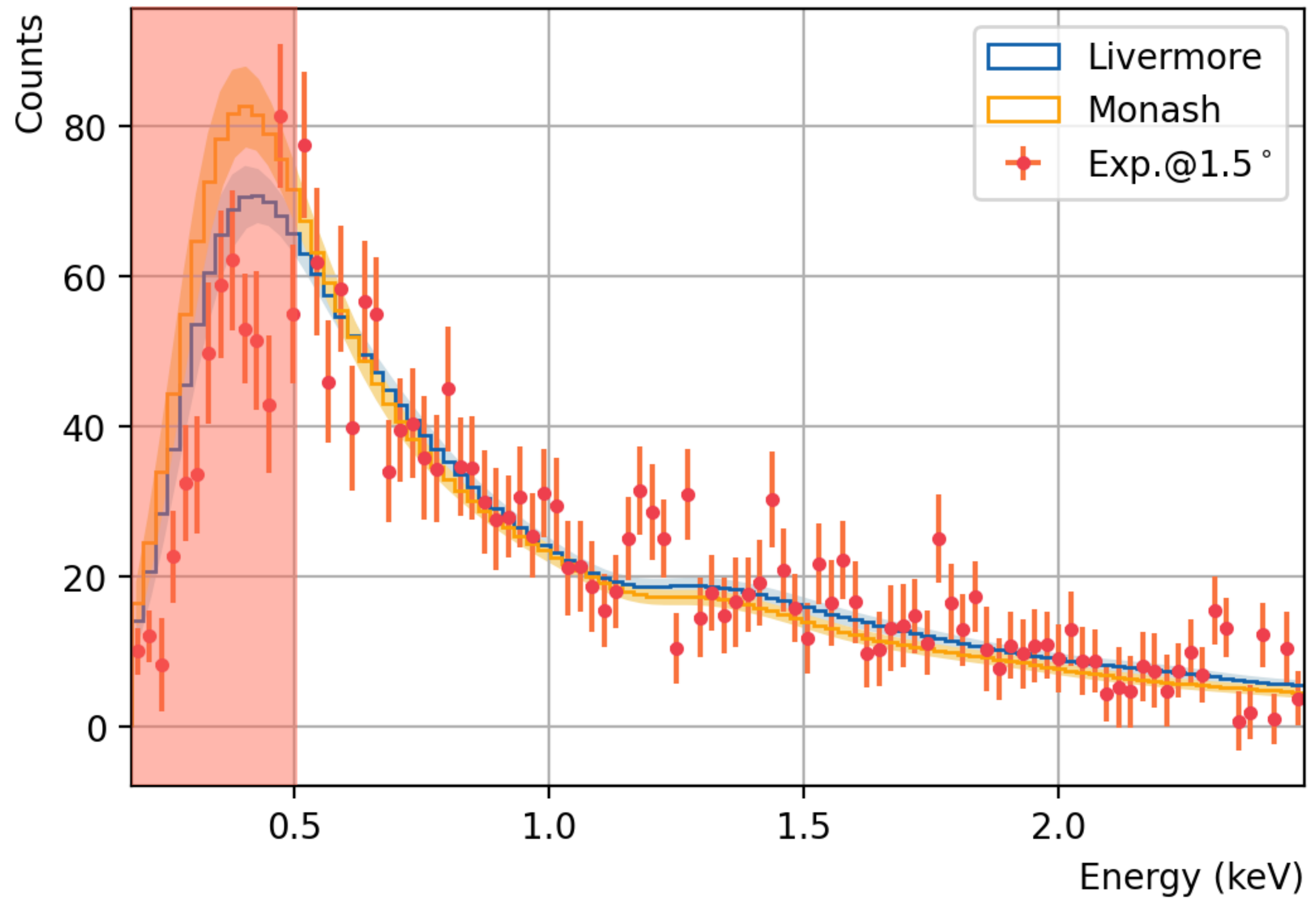




Efficiency function



Spectra before efficiency correction

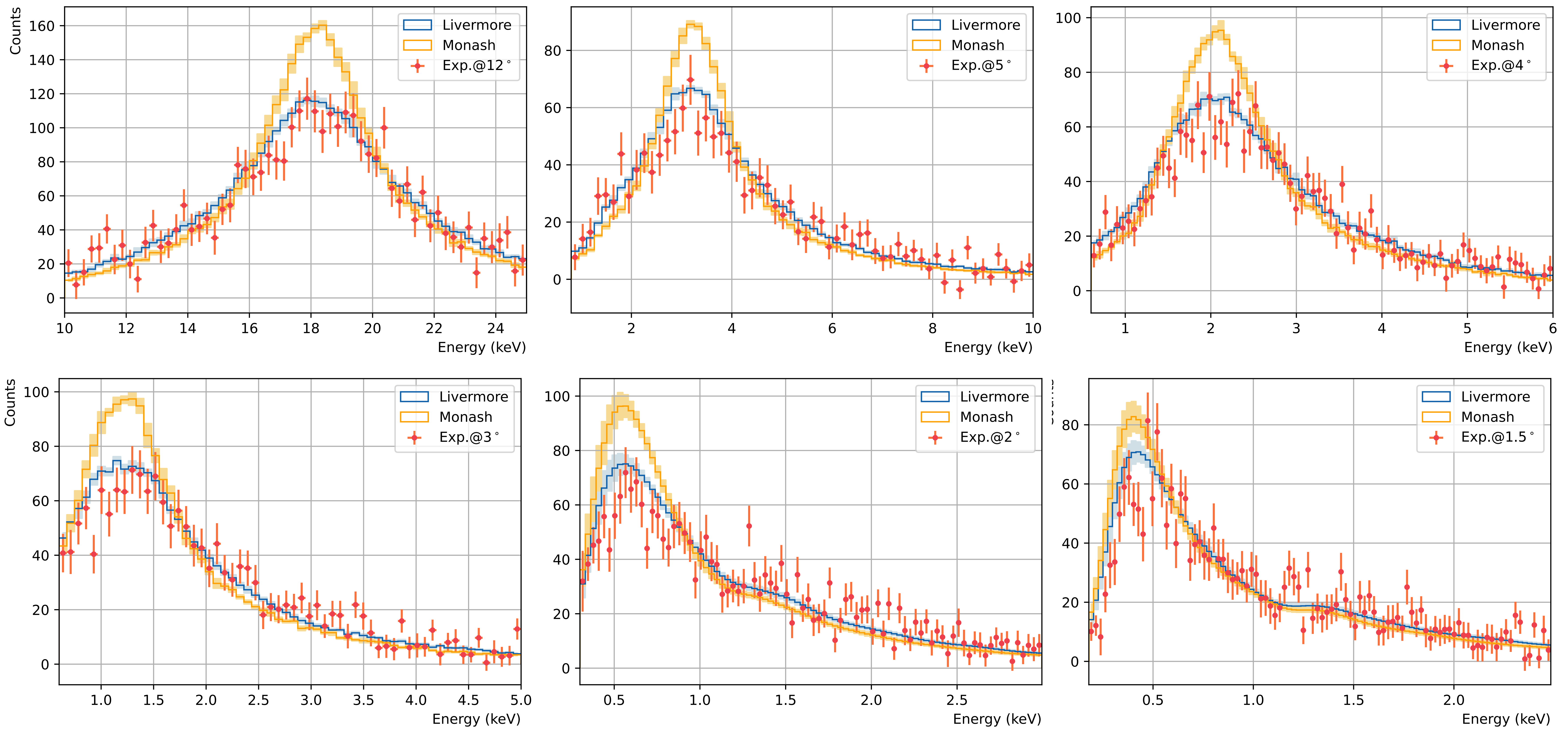


Spectra after efficiency correction

- Compton peak region of 1.5 degree measurement dives into electronic noises.
  - Electronic noise is excluded by PSD cut in A-E(Ge) parameter space and efficiency correction has been applied on the simulated spectra.
- PSD efficiency correction introduces the largest systematic error (low-energy).
- PSD efficiency determine the analysis threshold of 1.5 degree: 180 eV.
- Suppress the investigation to lower momentum transfer region (See SF part).

Experimental Results

Doubly Differential Cross Sections



DDCS spectra: $12^{\circ} \Rightarrow 1.5^{\circ}$

Scat. Ang.	Livermore	Monash
12	49/59	128.72/59
5	50/59	122/59
4	64/79	146/79
3	62/59	145/59
2	102/85	206/85
1.5	110.93/97	164.81/97

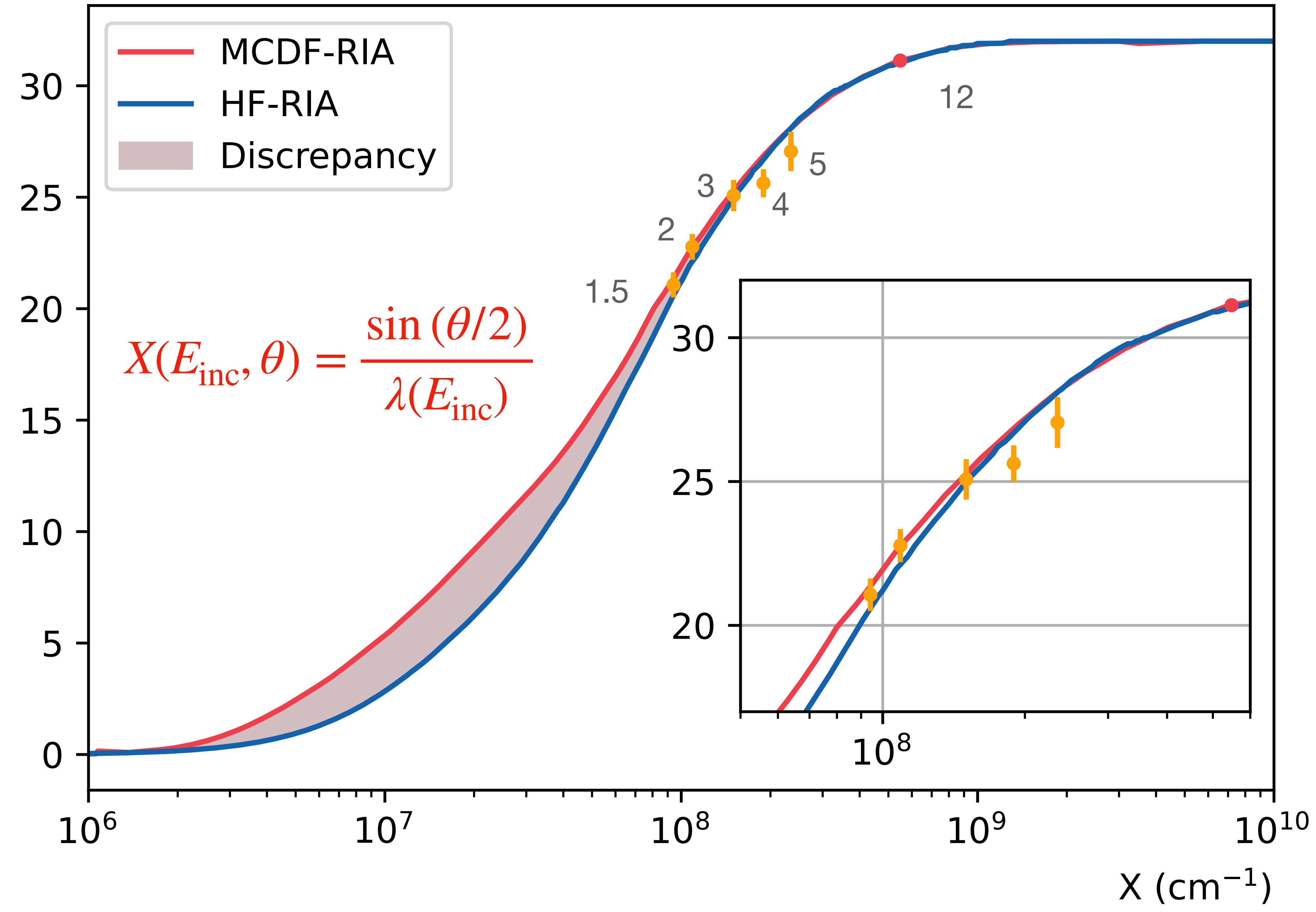
Preliminary

- Penelope, Livermore model match but Monash model does not!
- Data prefers Livermore model. The differences between measurements and Monash model are significant.
  - Monash@12 deg: p-Value: 4.62148e-07. **Beyond 5-sigma!!**

The Scattering Function

Exp.[a] (deg)	1.5	2	3	4	5
Eff.[b] (deg)	2.144	2.575	3.353	4.142	5.158
X[c] (Å)	0.94	1.08	1.50	1.89	2.34

[a]Experimental scattering angle.
[b]Effective scattering angle.
[c]X for Corresponding Effective scattering angle.

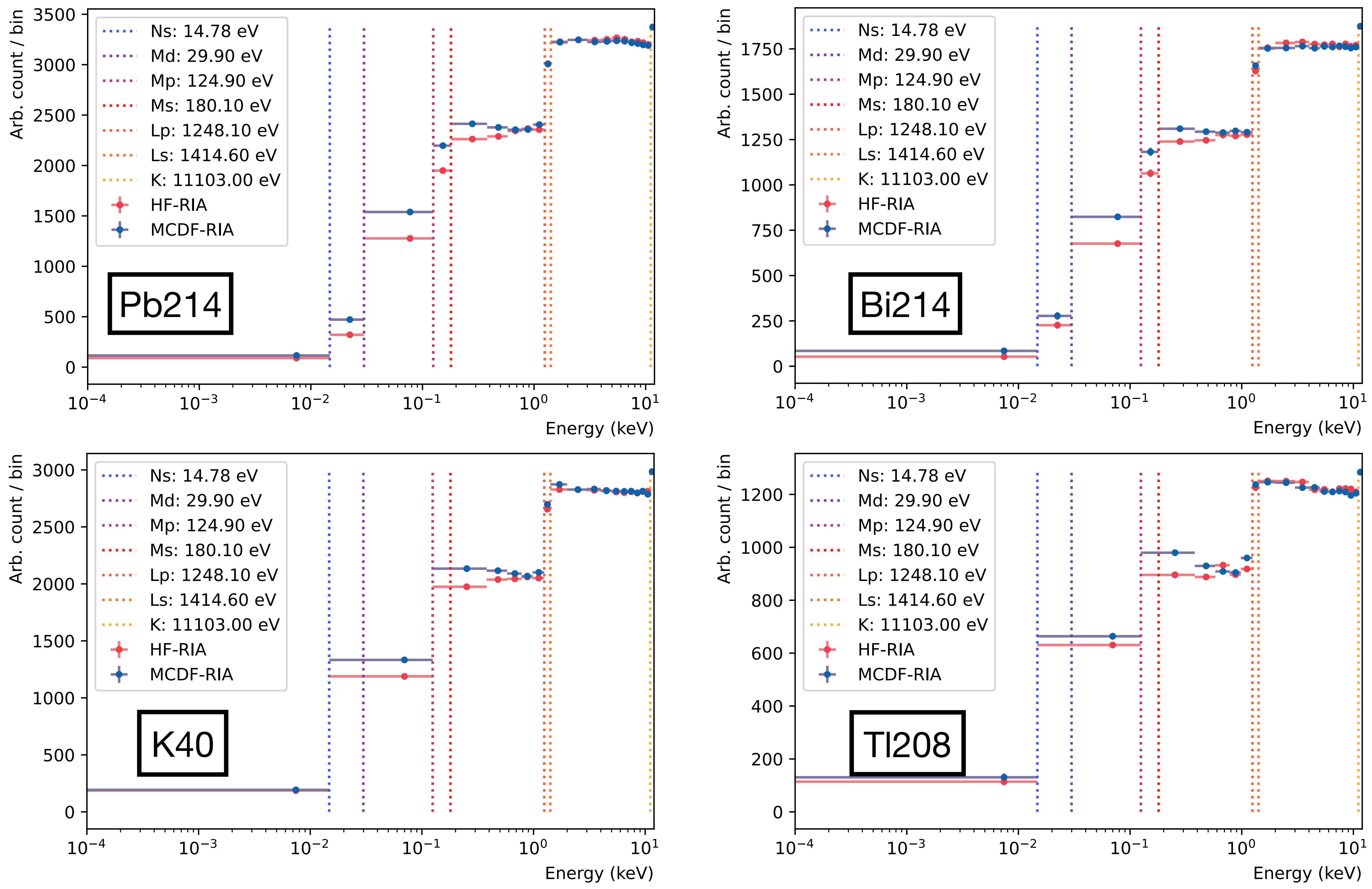


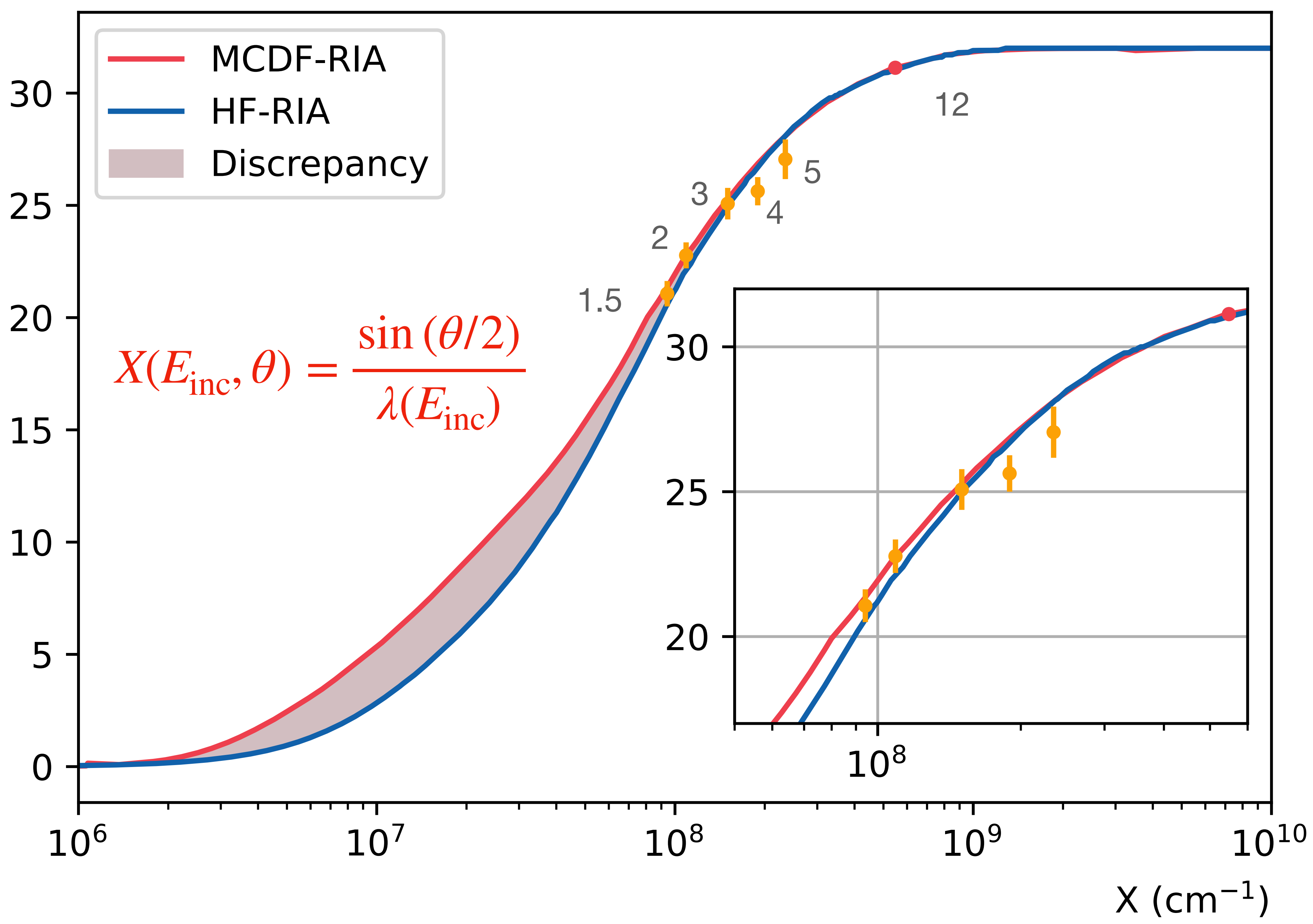
- The effective angles (real scattering angle) were derived from simulations and were found to shift to larger values than the exp calibration.
  - More serious at small angles.
  - Hard to approach lower X region with current setups.
- Measurements are relative closer to our ab initio calculations of SFs at small angles.
  - Current data points cannot tell the difference between Hubbell et al. and MCDF-RIA.

Influence on DM Backgrounds

Compton Background: Scattering Functions

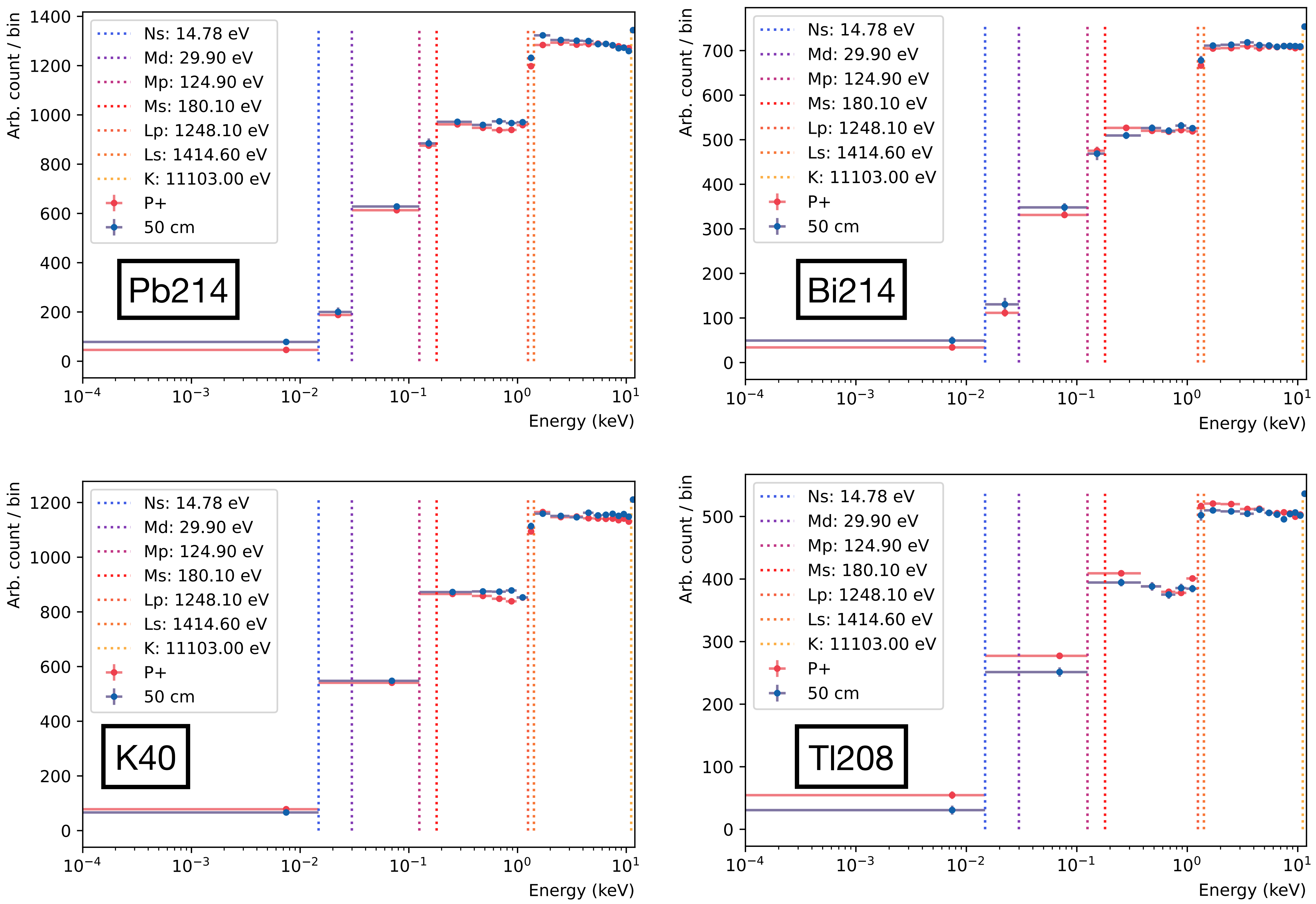
- Environmental gamma sources: ^{214}Pb(352 keV), ^{214}Bi(609 keV), ^{40}K(1461 keV), ^{208}Tl (2614 keV) and etc.
- Test conditions: scattering functions, source position and HPGe mass.
- MCDF-RIA results are 5.3%-7.4% higher than the HF-RIA increasing with incident energy.

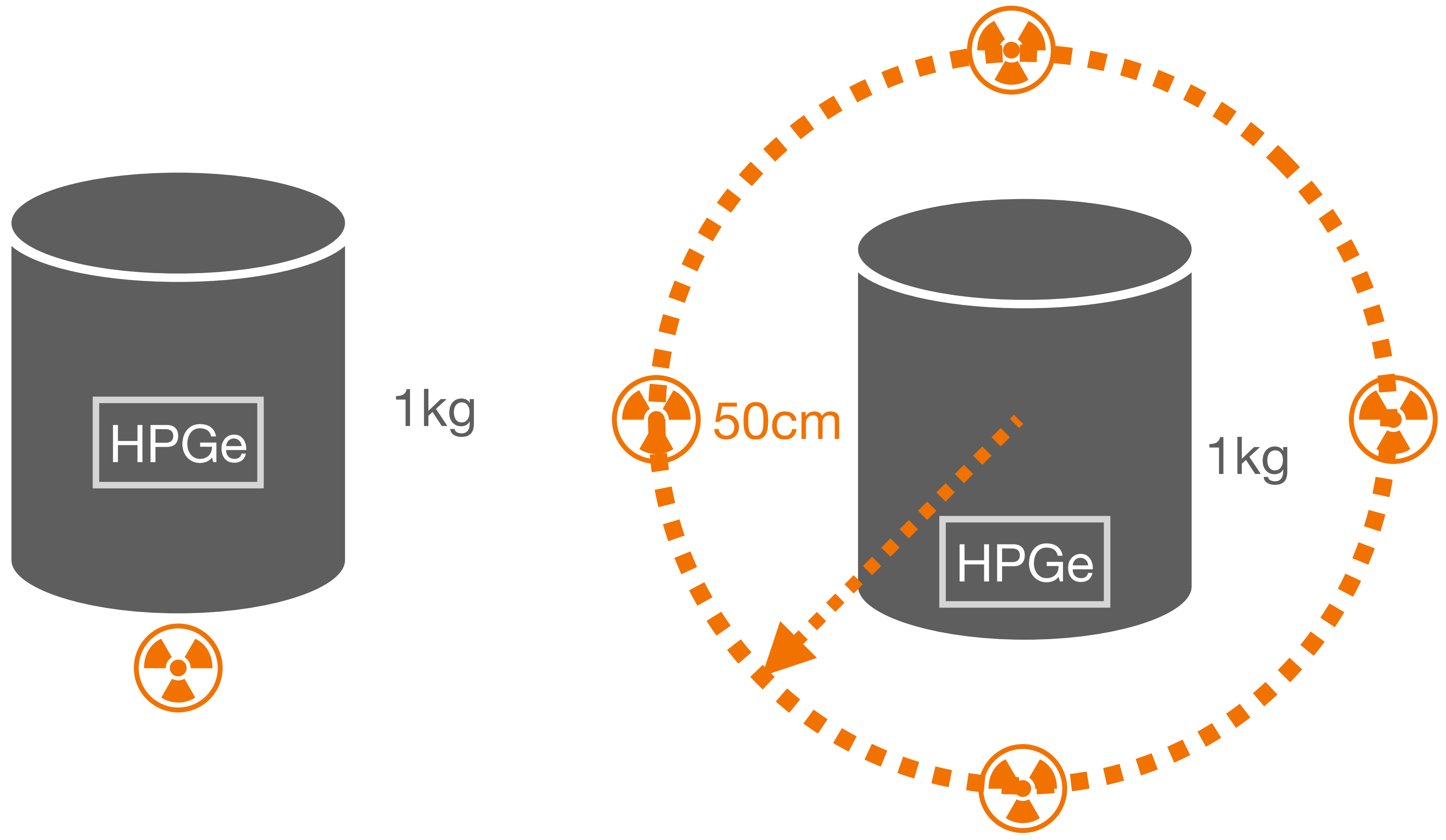




Compton Background: Source Position

- Environmental gamma sources: ^{214}Pb(352 keV), ^{214}Bi(609 keV), ^{40}K(1461 keV), ^{208}Tl (2614 keV)
- Test conditions: scattering functions, source position and HPGe mass.

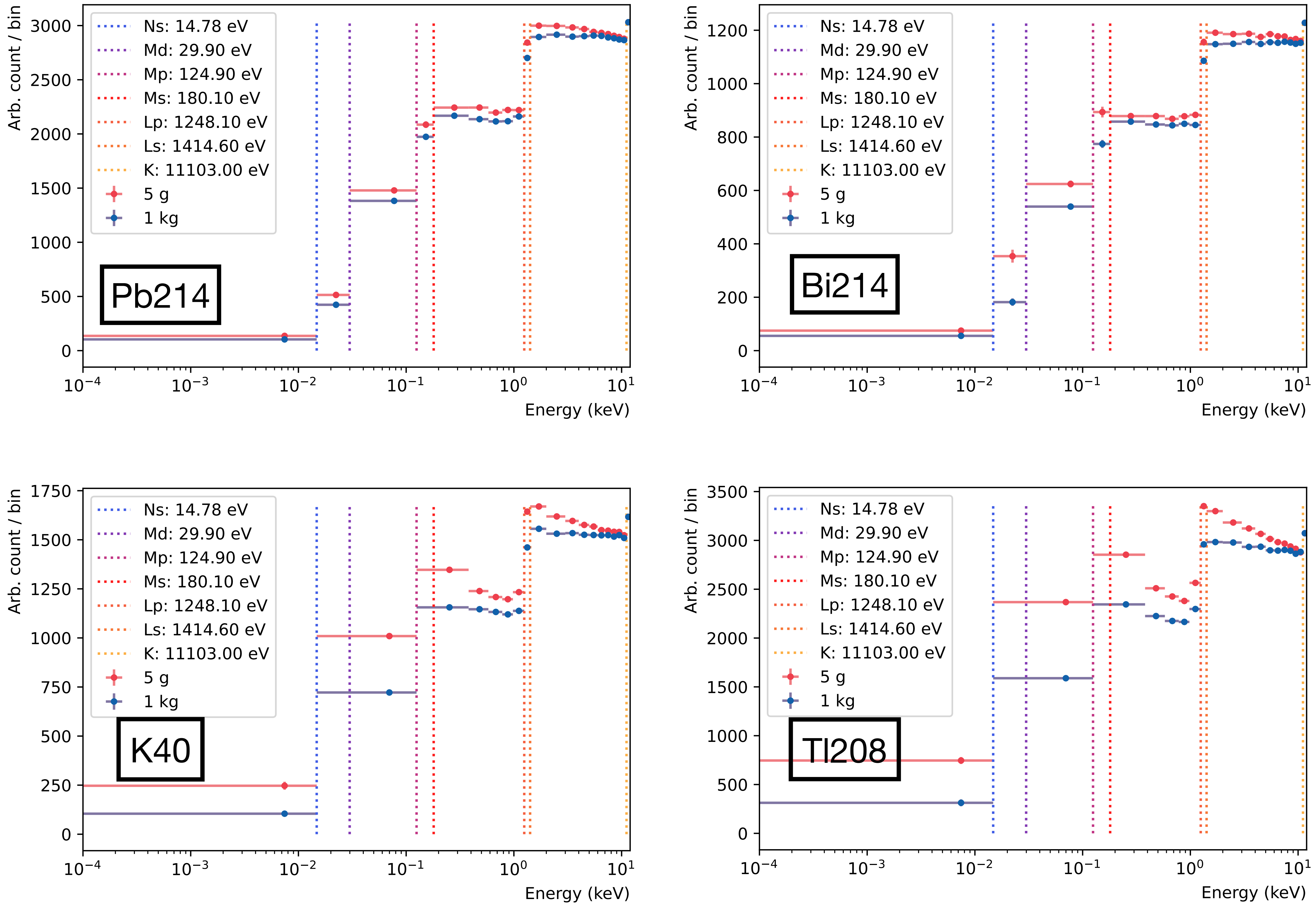


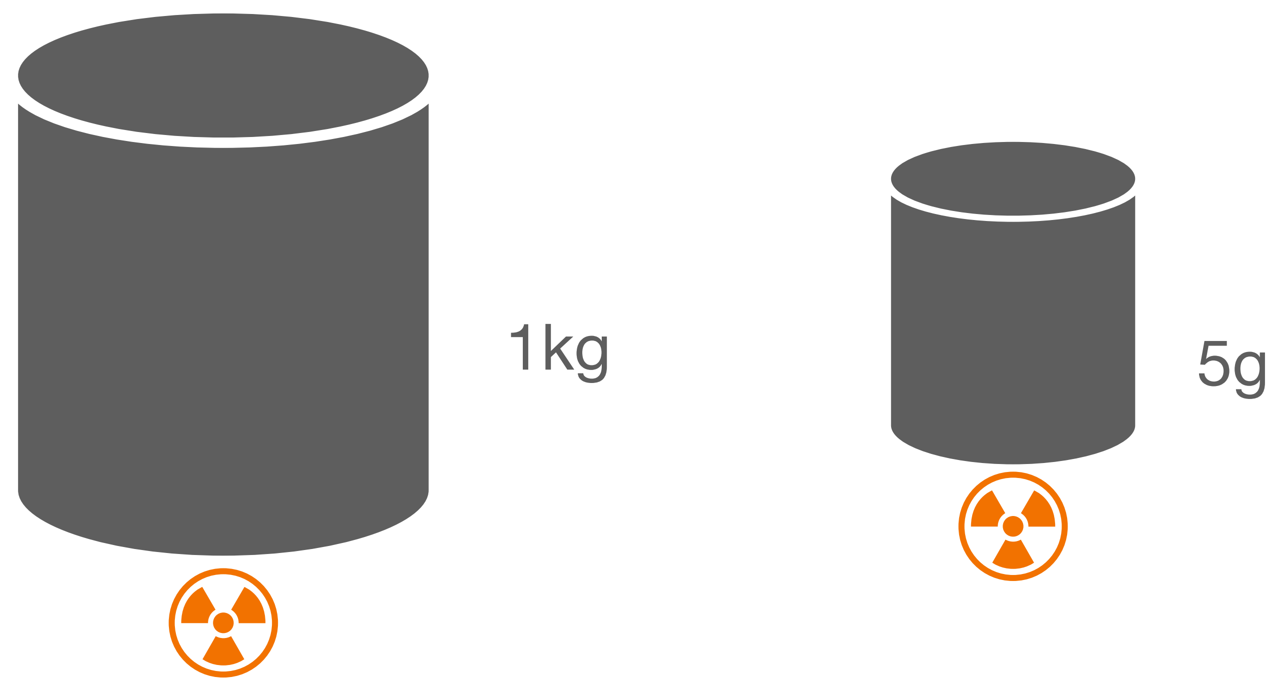


Background different raised by positions within 2.6%.
Minor influence.

Compton Background: Detector Mass

- Environmental gamma sources: ^{214}Pb(352 keV), ^{214}Bi(609 keV), ^{40}K(1461 keV), ^{208}Tl (2614 keV)
- Test conditions: scattering functions, source position and HPGe mass.





- Geometrical effect: suppress the bkg below K-shell ionization threshold for 2.14%–11.97% increasing with incident energy.
- Non-flat structure increasing with incident energy.

Summary

- Performing **ab initio** atomic many-body Compton scattering calculations.
  - MCDF: fully relativistic, many-body effects (electron correlation, configuration interactions)
  - Significant difference on **scattering function** (Differential cross-section) in low-momentum transfer region.
- Experiment to investigate low-momentum transfer Compton scattering behavior is accomplished.
  - Scattering angle is well calibrated and issues are fully concerned.
  - Background, efficiency and systematic errors are concerned.
- Livermore and Monash Compton model in Geant4 are not **identical**.
  - At 12 degrees, the difference with the Monash model exceeds 5 sigma.
- Current experimental setup is hard to clarify the differences on the scattering functions.
- Analyze the influence of SFs, detector mass and source position on Compton scattering for DM experiments with Ge detector.

Thanks for your attention