

Measurement of Ionisation and Scintillation Yields from ^{214}Bi beta-decay in XENONnT

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LIDINE 2025



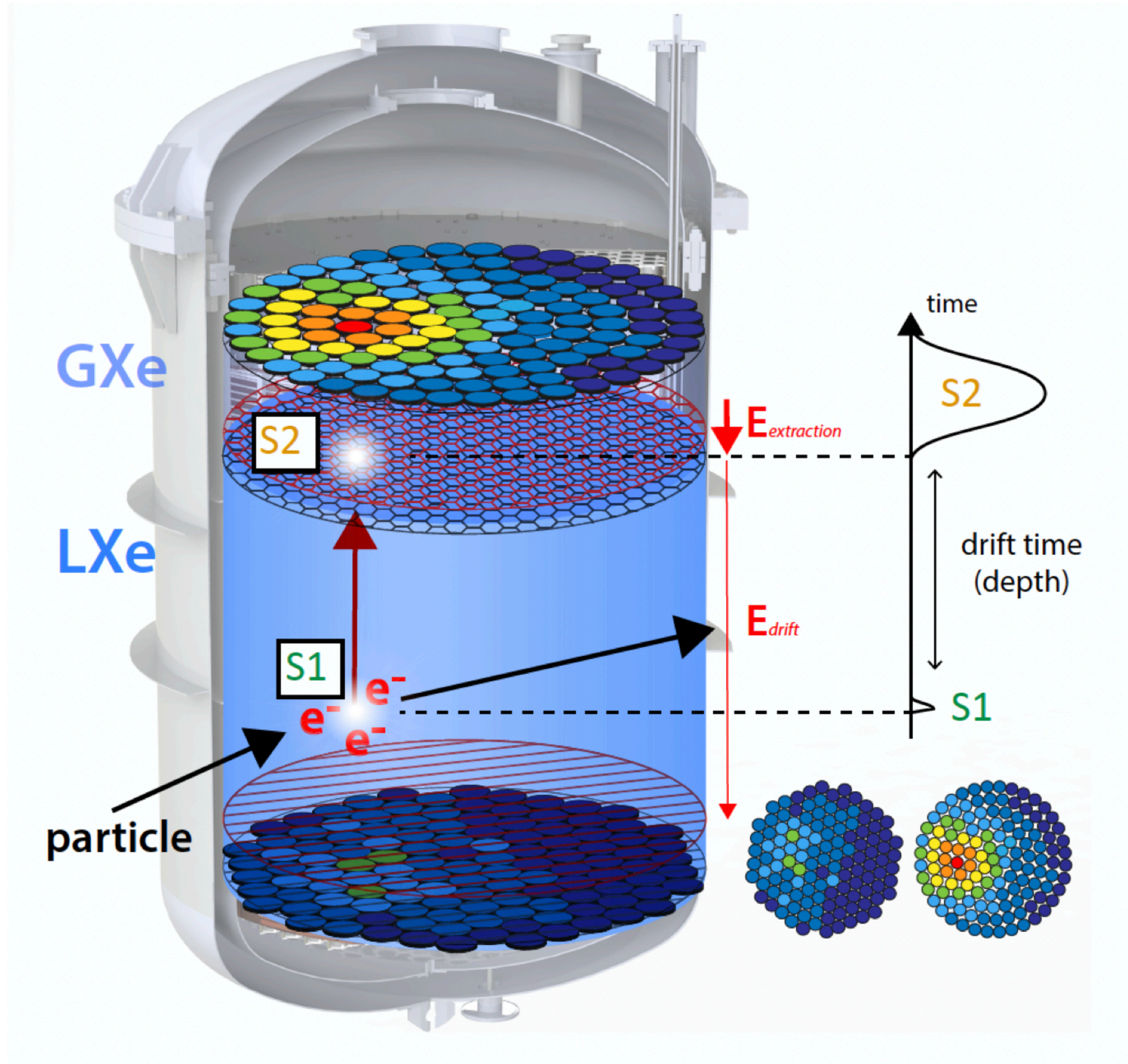
Hong Kong

October 21, 2025



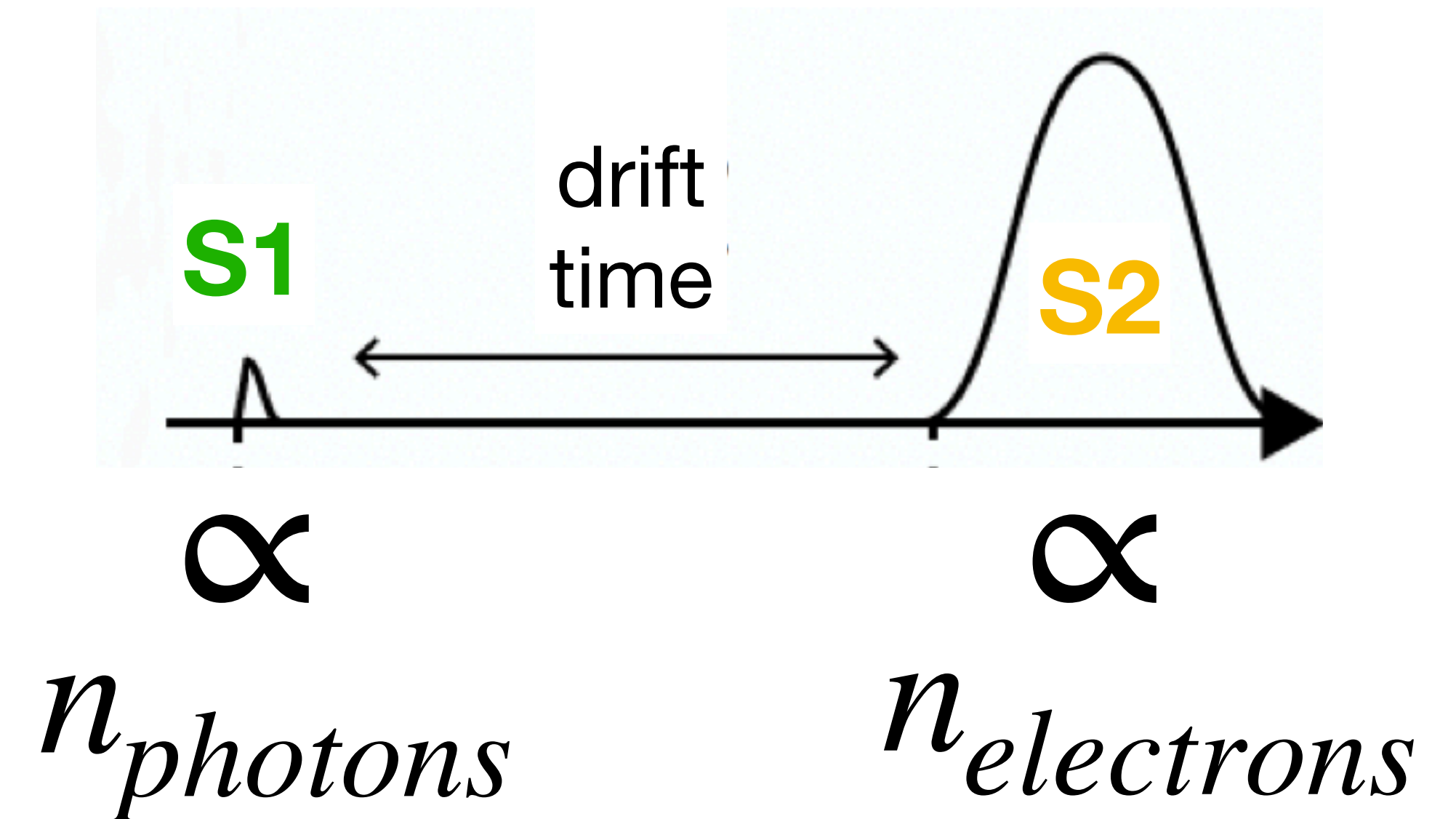
XENON

XENONnT Time Projection Chamber (TPC)



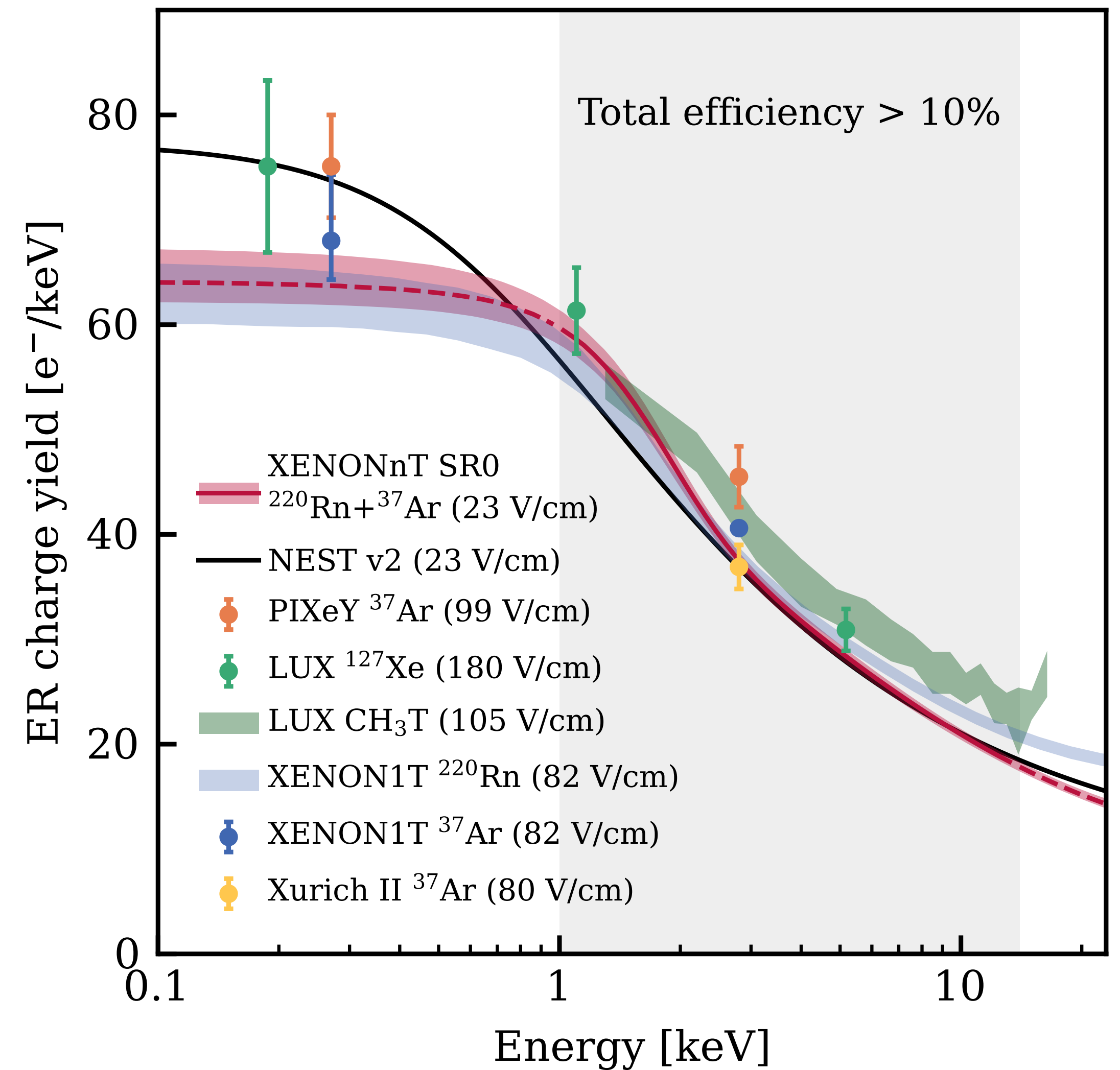
Signals in XENON:

- Each interaction generates two signals:
 - S1** from directly emitted **photons**,
 - S2** from drifted and extracted **electrons**
- Light** and **charge** yields depend on:
 - Drift field (electron-ion recombination)
 - Total interaction energy



Light and Charge yields:

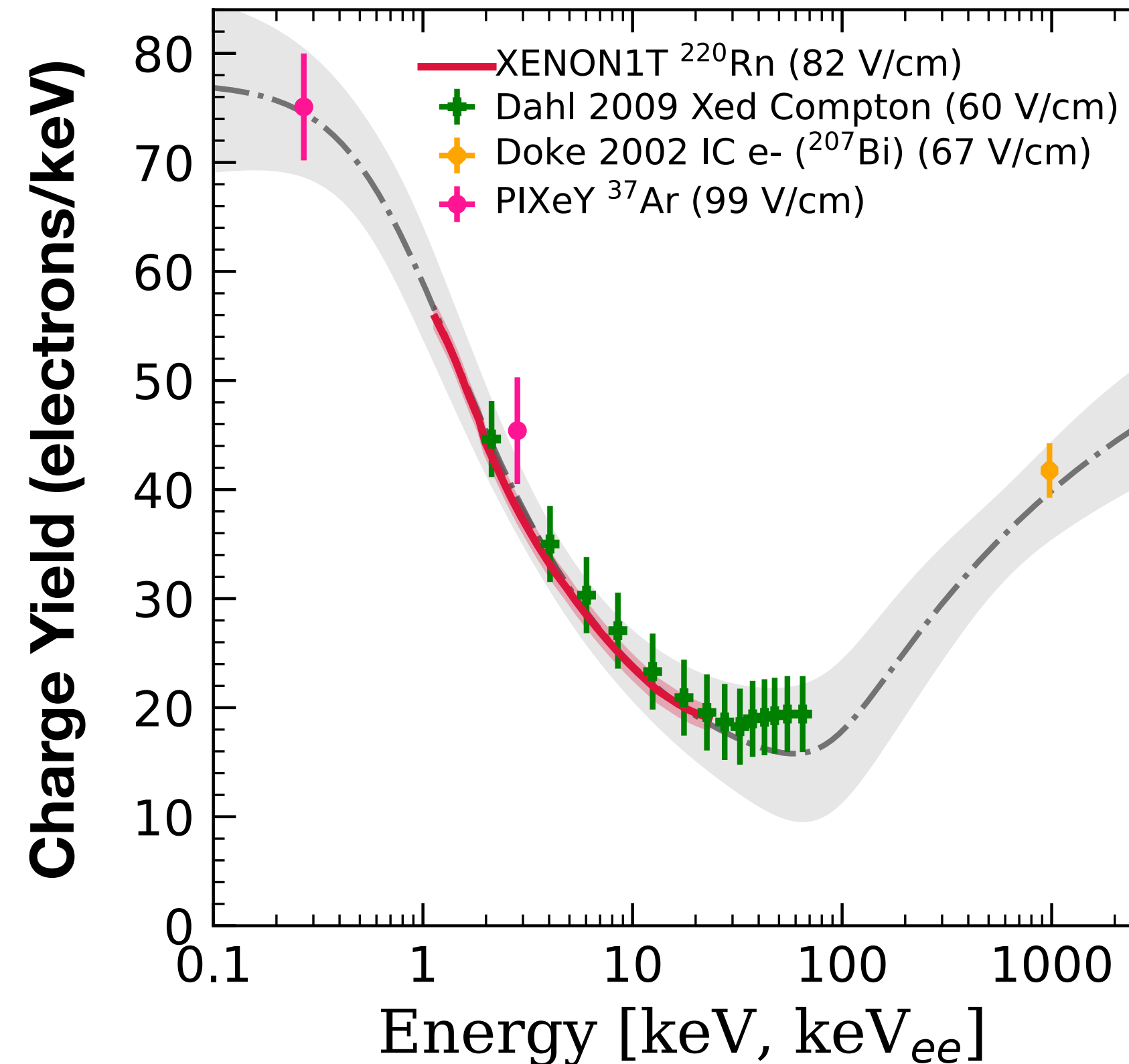
- Precise **modeling of yields** is necessary for any search of rare events in xenon TPCs.
- The **focus** is often limited on a scale between 1 and 10 keV, **really low energies!**
Relevant scale for WIMP or CEvNS scattering, but we want to do much more with our data!
- Many high energy analyses like 2vbb/0vbb and many more, require characterisation of detector response upto **few MeVs**.



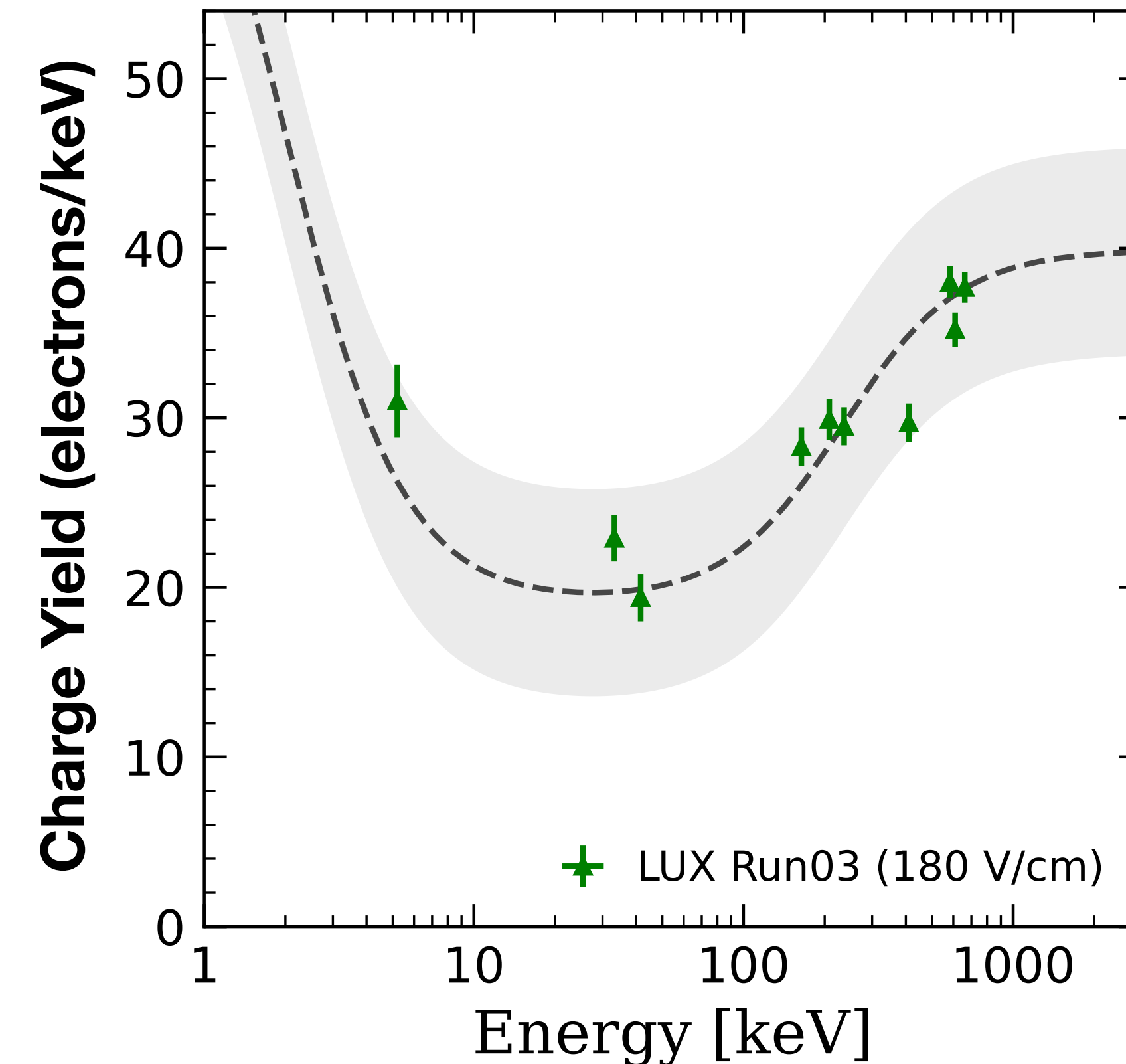
NEST Model:

- Fully empirical, based on combination of Thomas-Imel and Doke-Birks models.
- Aggregates data from many experiments, different fields.
- Separate model for beta and gamma. Compton makes **multiple scatters**, effective lower gamma charge yield.
- Missing data at high energies!

Beta-decays



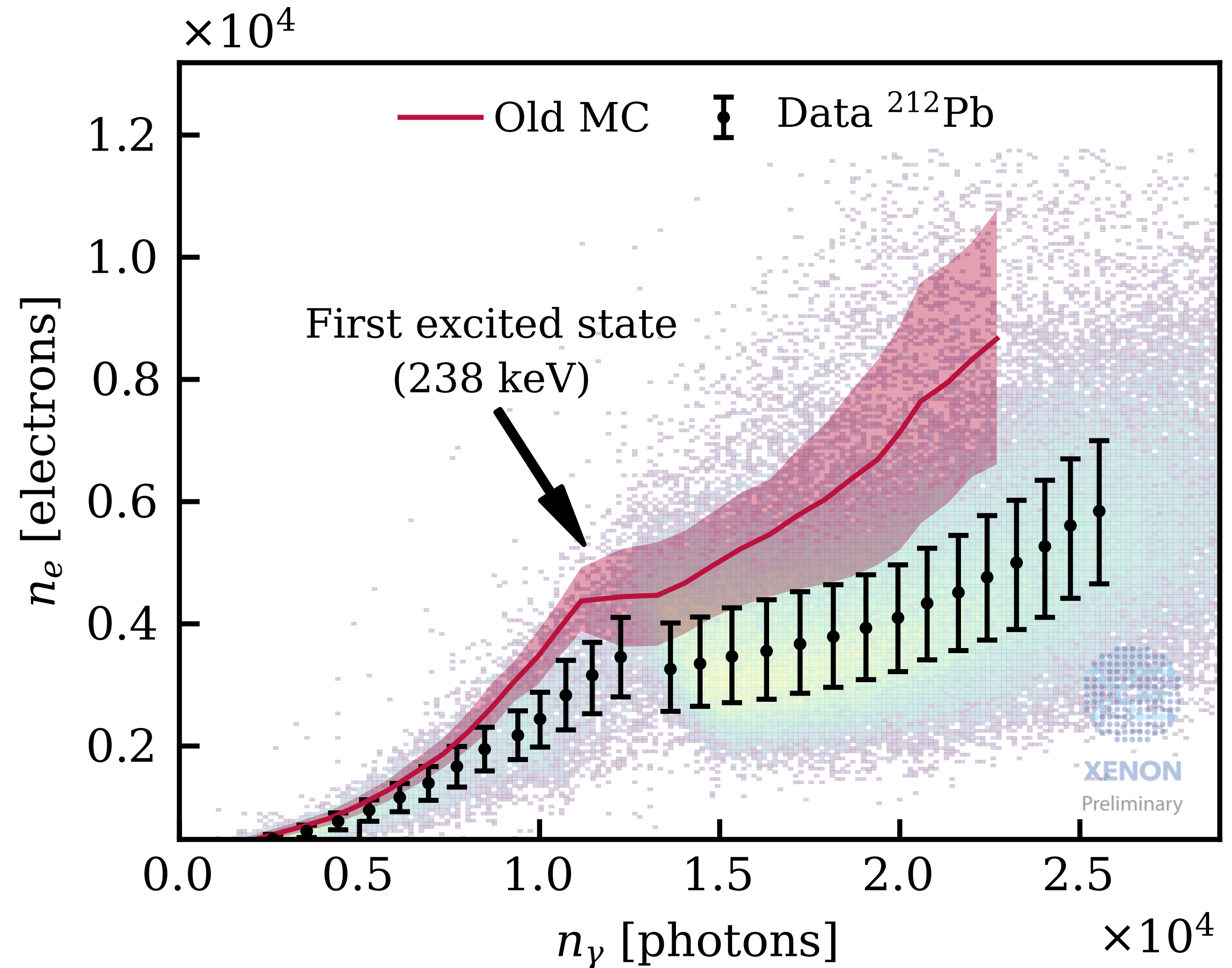
Gamma-decays



How do we model the response at higher energies?

Check on ^{212}Pb data:

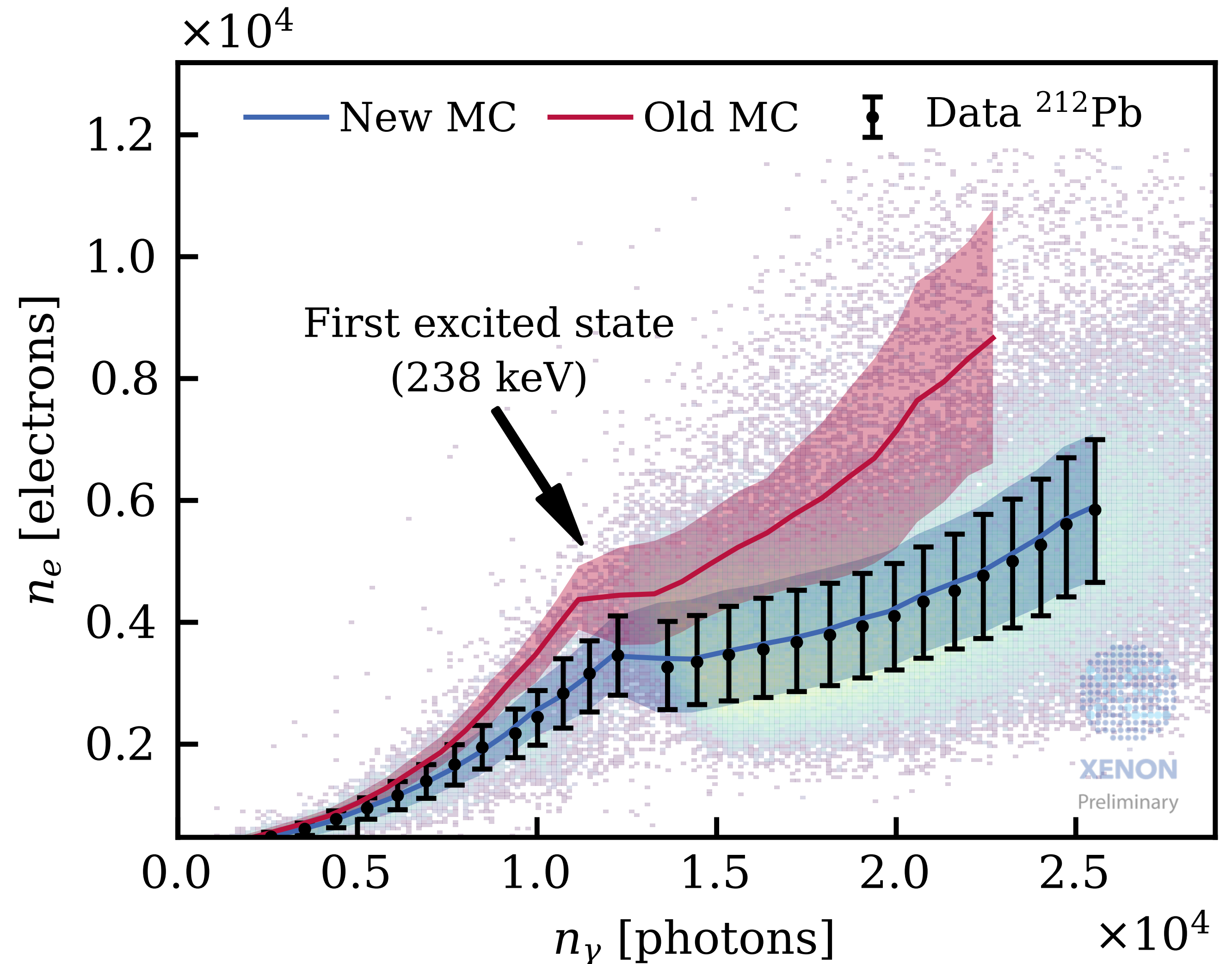
- Compare data and simulations...
- Already at a few hundreds of keV we are completely off!
- Why?
 - No reliable data at energies $>100\text{keV}$
 - Not a lot of data at field $\sim 23\text{V/cm}$
 - Energy deposits in simulations are grouped based on position only!
 - Inconsistency on how NEST yields are extracted and how they are used in simulations.



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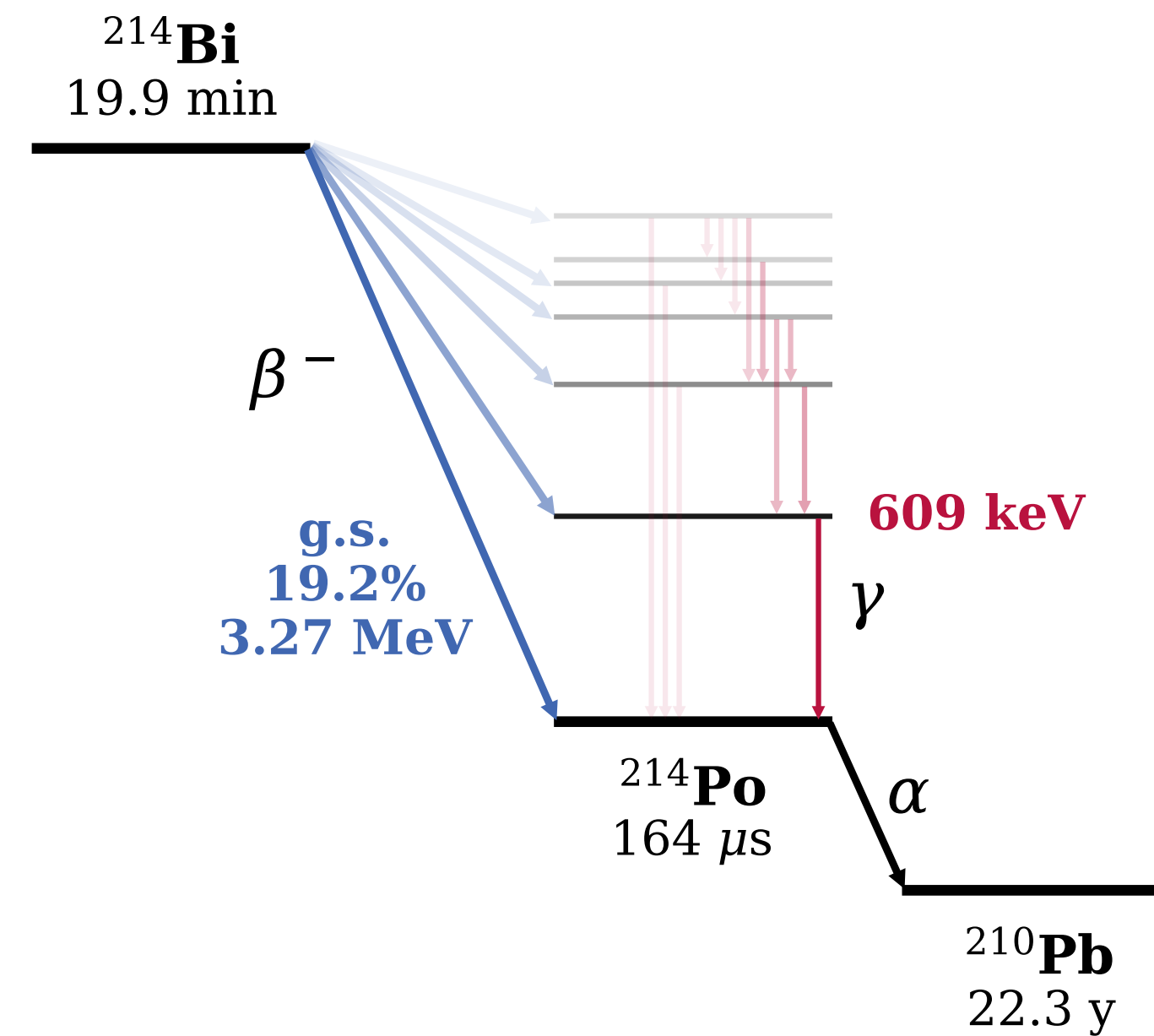
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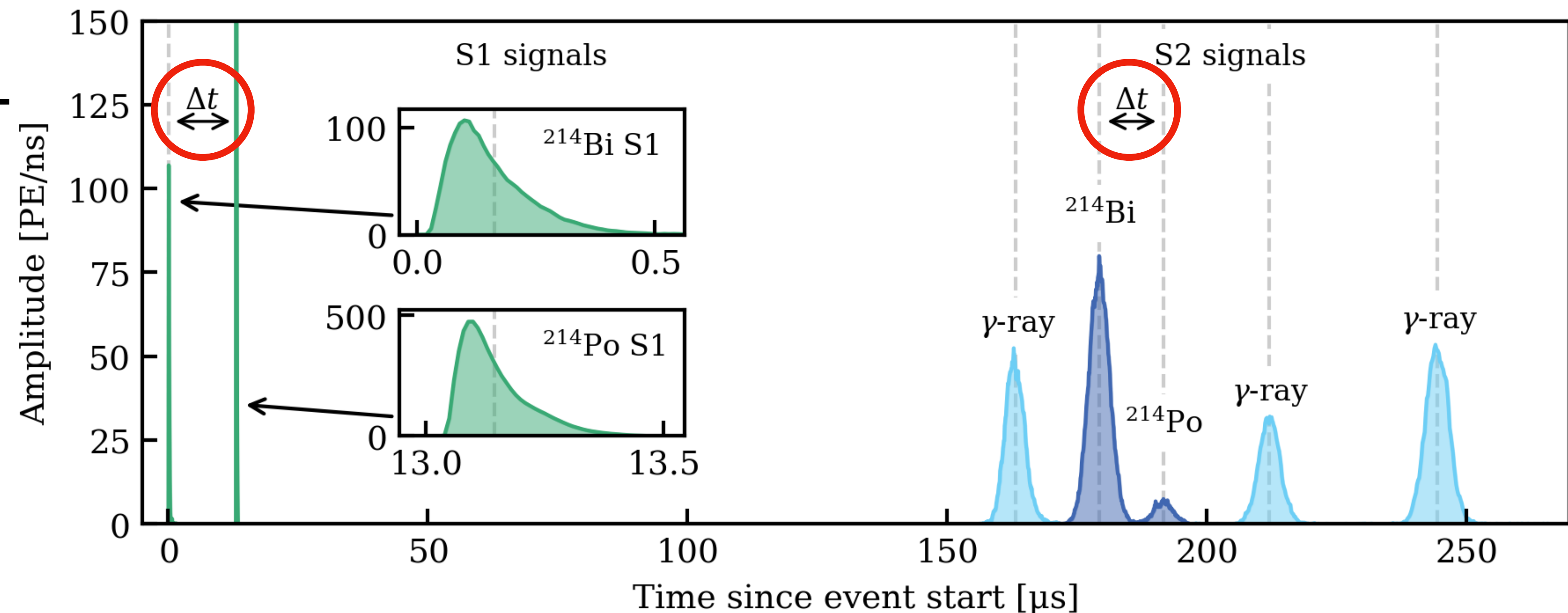
Extracting clean beta decay from background!

XENON arxiv:2510.04846 (2025)



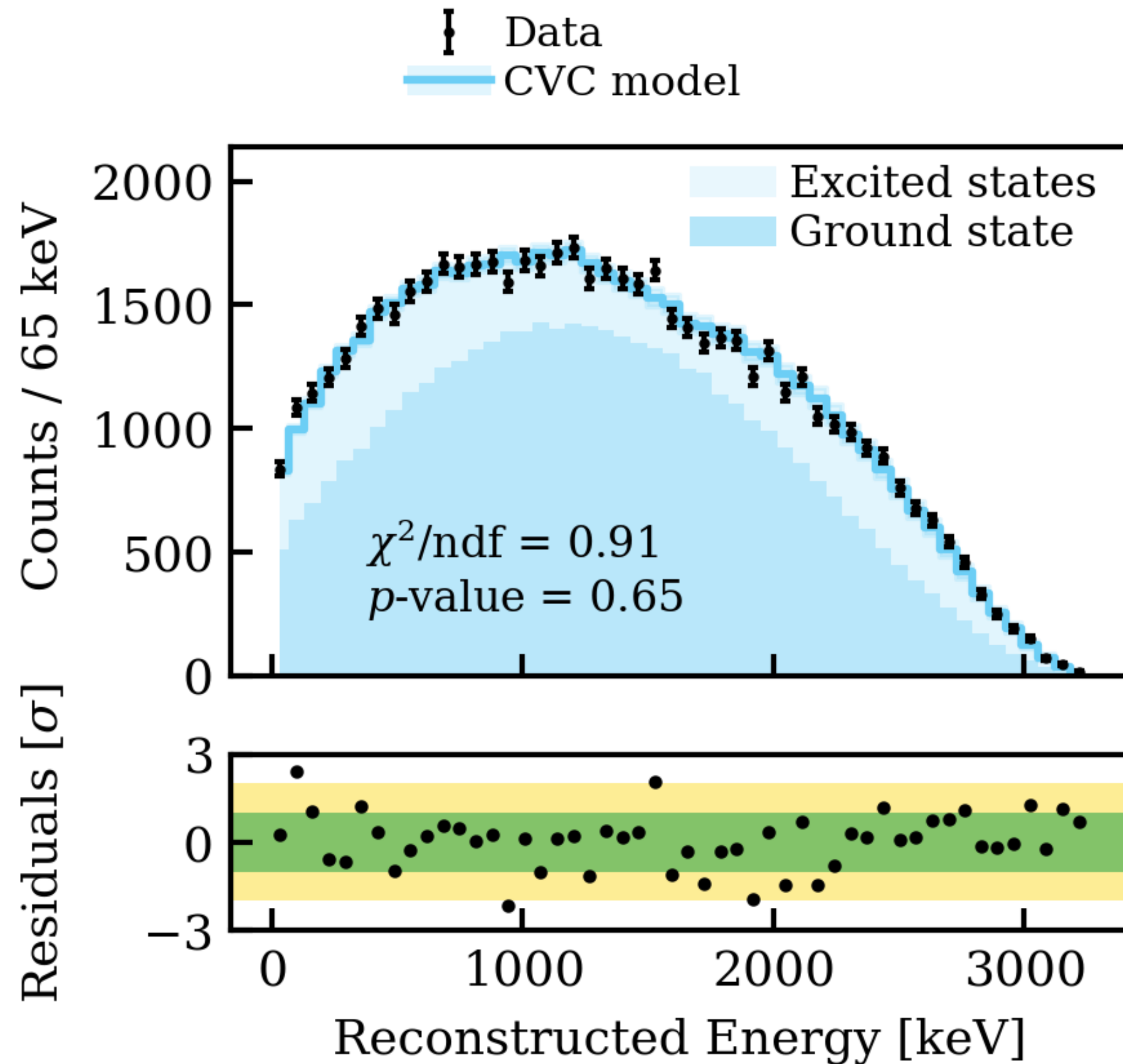
Get clean beta decays from our data:

- Exploit coincidence of ^{214}Bi beta with ^{214}Po alpha: 164 μs half-life
- Isolate direct ground state decays, without gamma peaks
- Build single scatter beta yield model up to 3.27 MeV!



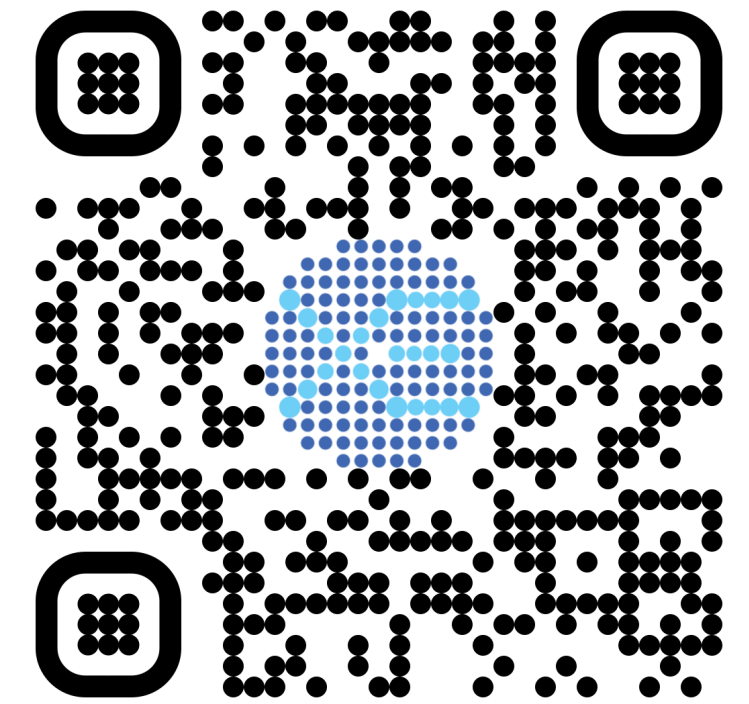
First measurement of ^{214}Bi g.s. beta-spectrum

XENON arxiv:2510.04846 (2025)



THIS IS NOT AN AD.

arXiv:2510.04846

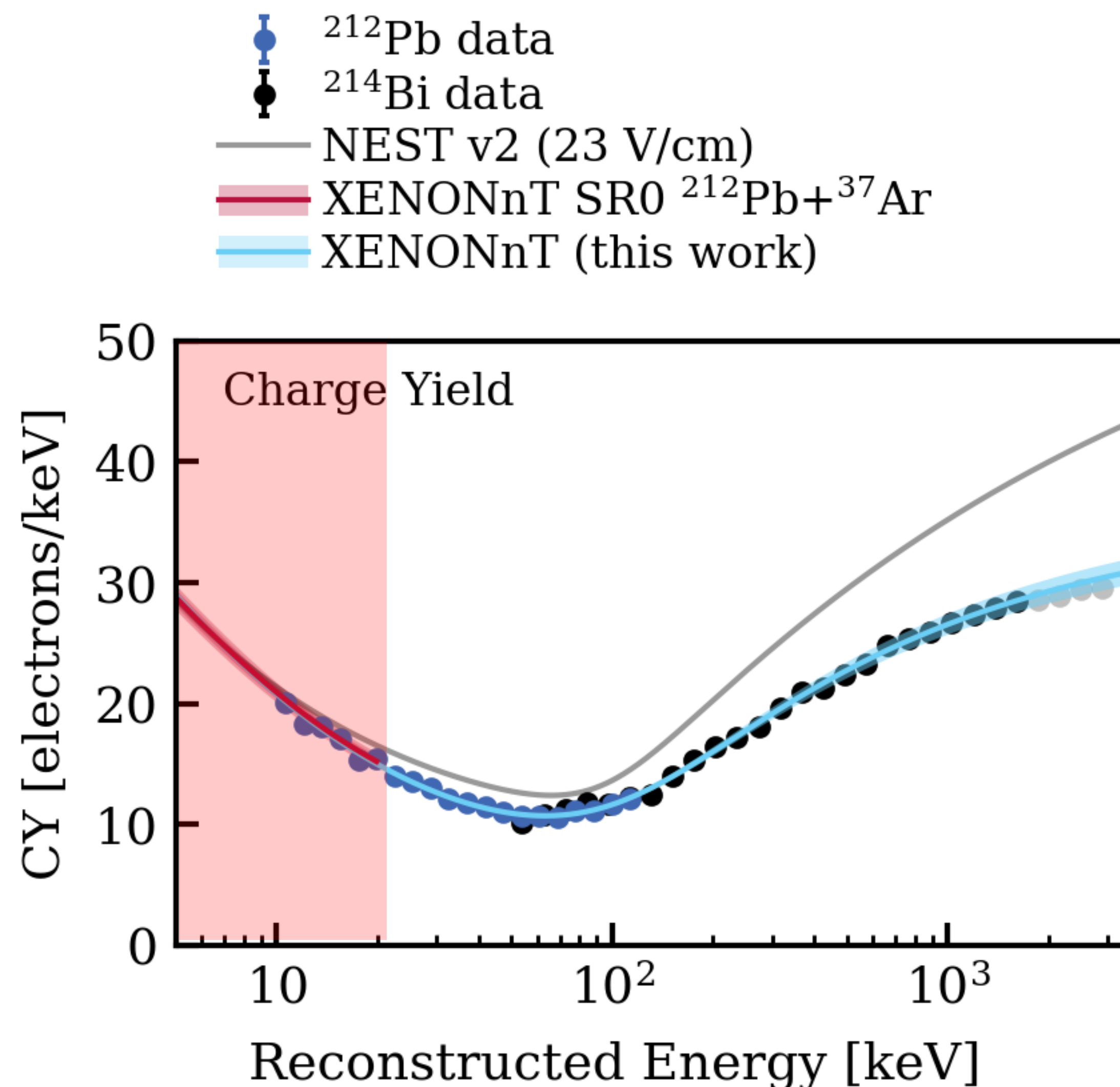


Result of the analysis:

- We can use the extracted sample to perform a **measurement** of the ^{214}Bi ground state decay spectrum.
- It is a first **forbidden non-unique** beta decay, meaning that **nuclear structure** impact the spectral shape.
- Compared spectrum with different theoretical models in recent XENONnT paper.

Extend yield model from 20keV to 3.2 MeV

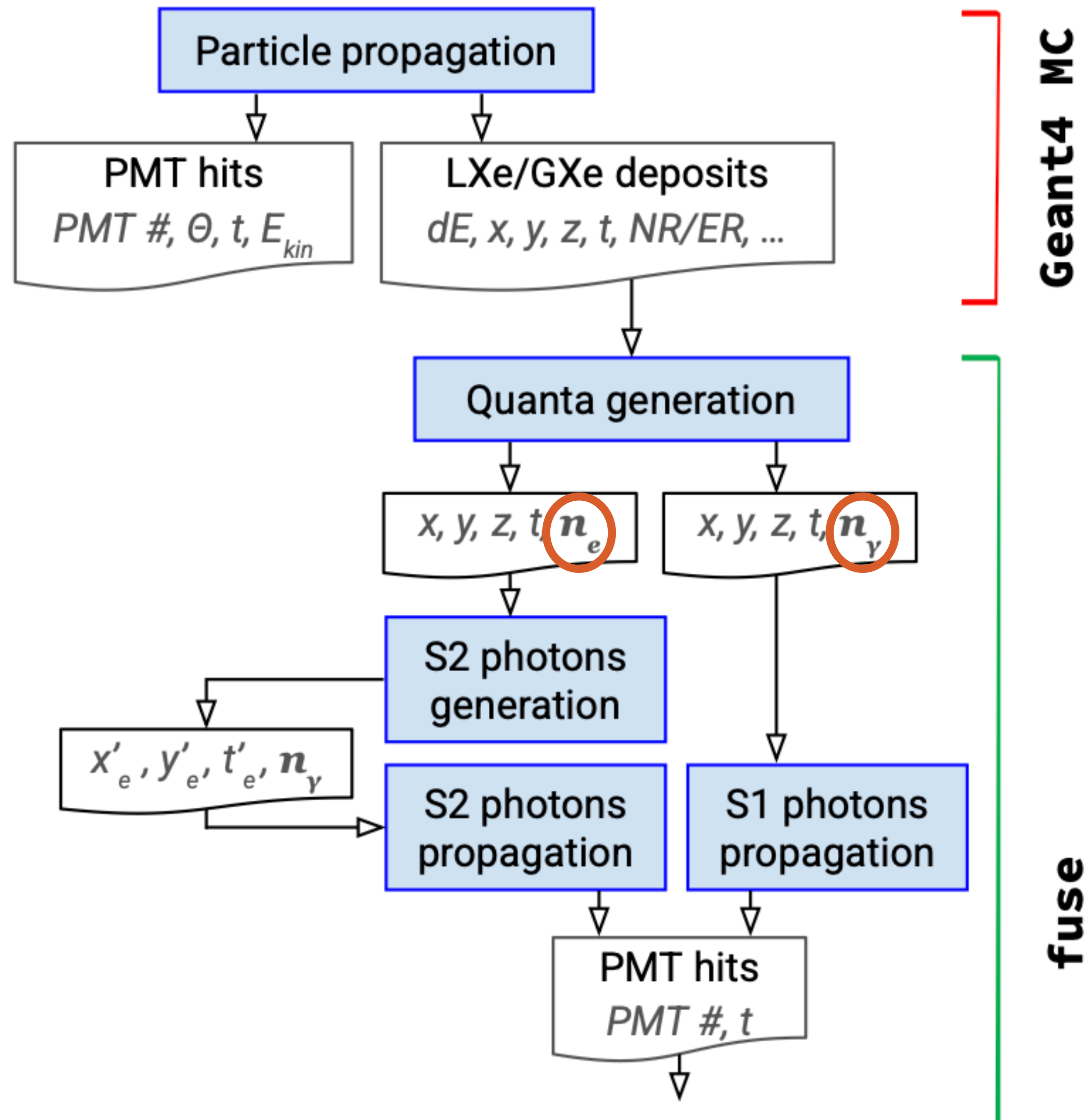
XENON arxiv:2510.04846 (2025)



Data driven high energy yields:

- We obtain the charge (and light) yield from sample of clean single beta decays of ^{214}Bi to ground state, with Q-value of 3.27MeV.
- We estimate and correct for leakage of events containing gammas from excited states or from Brehmstrahlung emission via detailed simulations.
- Shows clear differences with respect to default NEST values, also because of the lack of data at the XENONnT operating drift field of 23V/cm.

XENONnT Simulations Framework: Geant4 + fuse



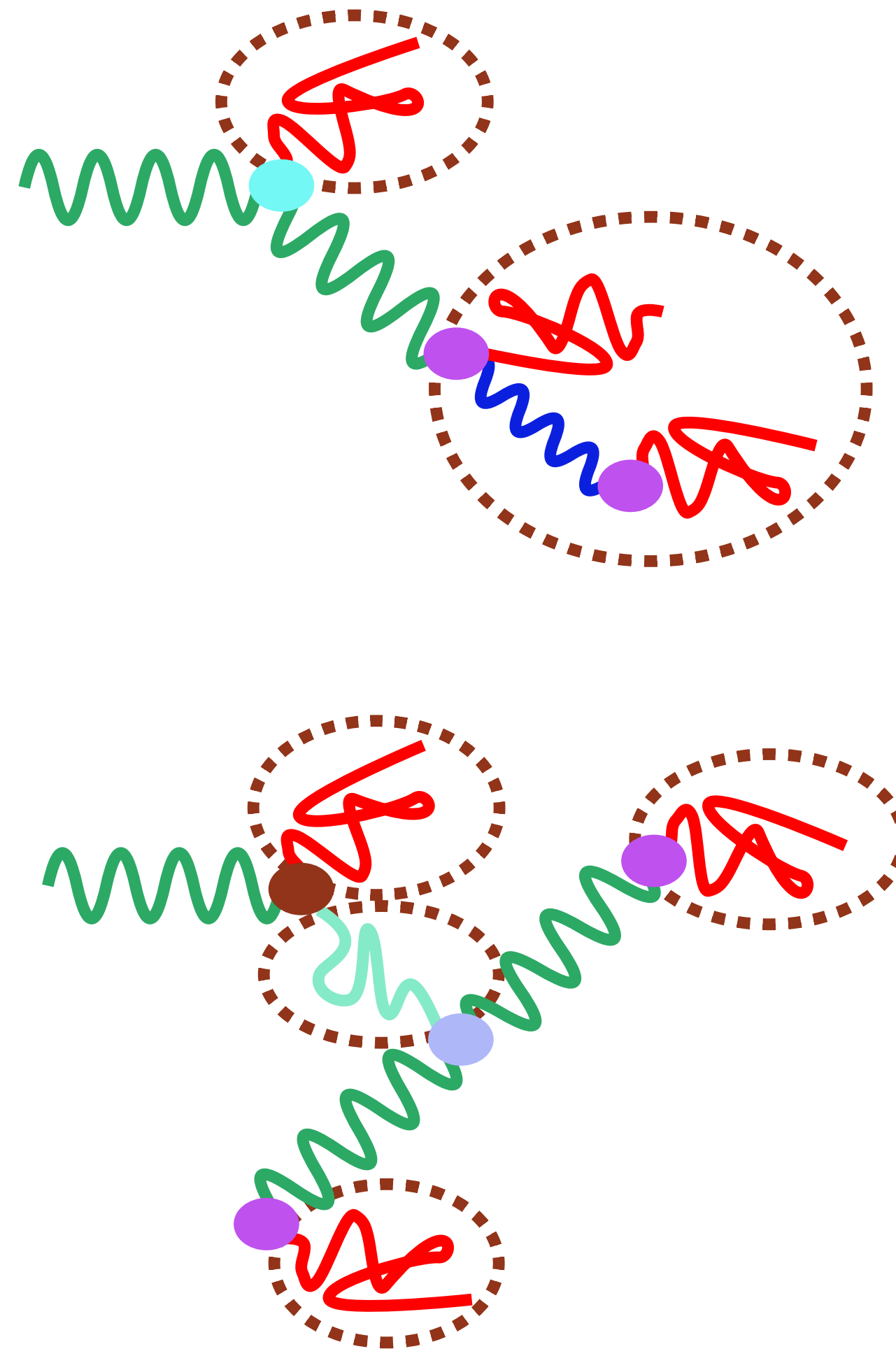
Simulations pipeline:

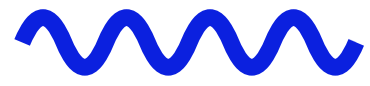
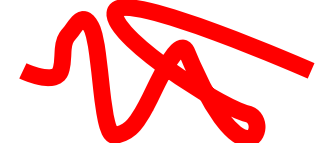
- Start from Geant4 simulation to get energy depositions, very verbose and detailed output
- Group energy deposit in clusters. We need to cluster them into meaningful interaction energies before assigning electrons and photons to each cluster.
- Clustering is now only position and time based algorithm (this works well at low energies, fails when multiple scatters!)
- Then, using NEST framework, assign quanta to each cluster based on interaction energy, interaction type and drift field.
- Propagate photons, drift electrons, make PMT waveforms... all the way to events!

Lineage Clustering Algorithm

First change we need to make:

- We follow the "**lineage**" of each particle, splitting different clusters based on the interaction's physics.
- Rules:
 - **beta-decay** electrons are always one cluster (except Bremsstrahlung)
 - **gamma-rays** make a new cluster at each interaction step
 - **photo-absorption** is always one cluster, including extra gamma-rays and electrons emitted.
- Yields: we use **only one yield model!**



Particles	
	Gamma
	X-ray
	Electron
	Positron

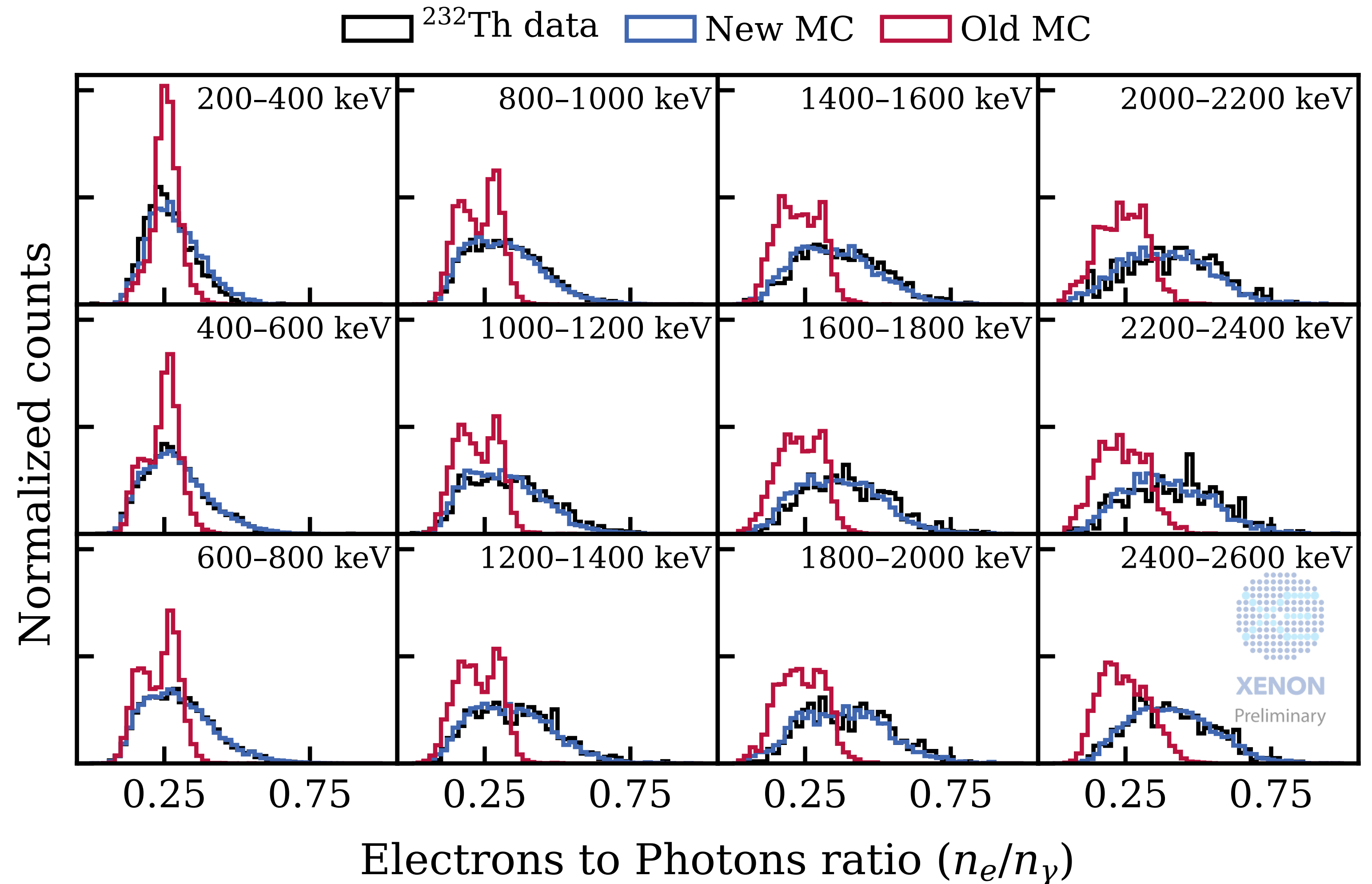
Interactions	
	PhotoAbsorption
	Compton
	Annihilation
	Pair Production

Clusters	
	Beta Yield

Matching Detector Response

High energy gamma-rays:

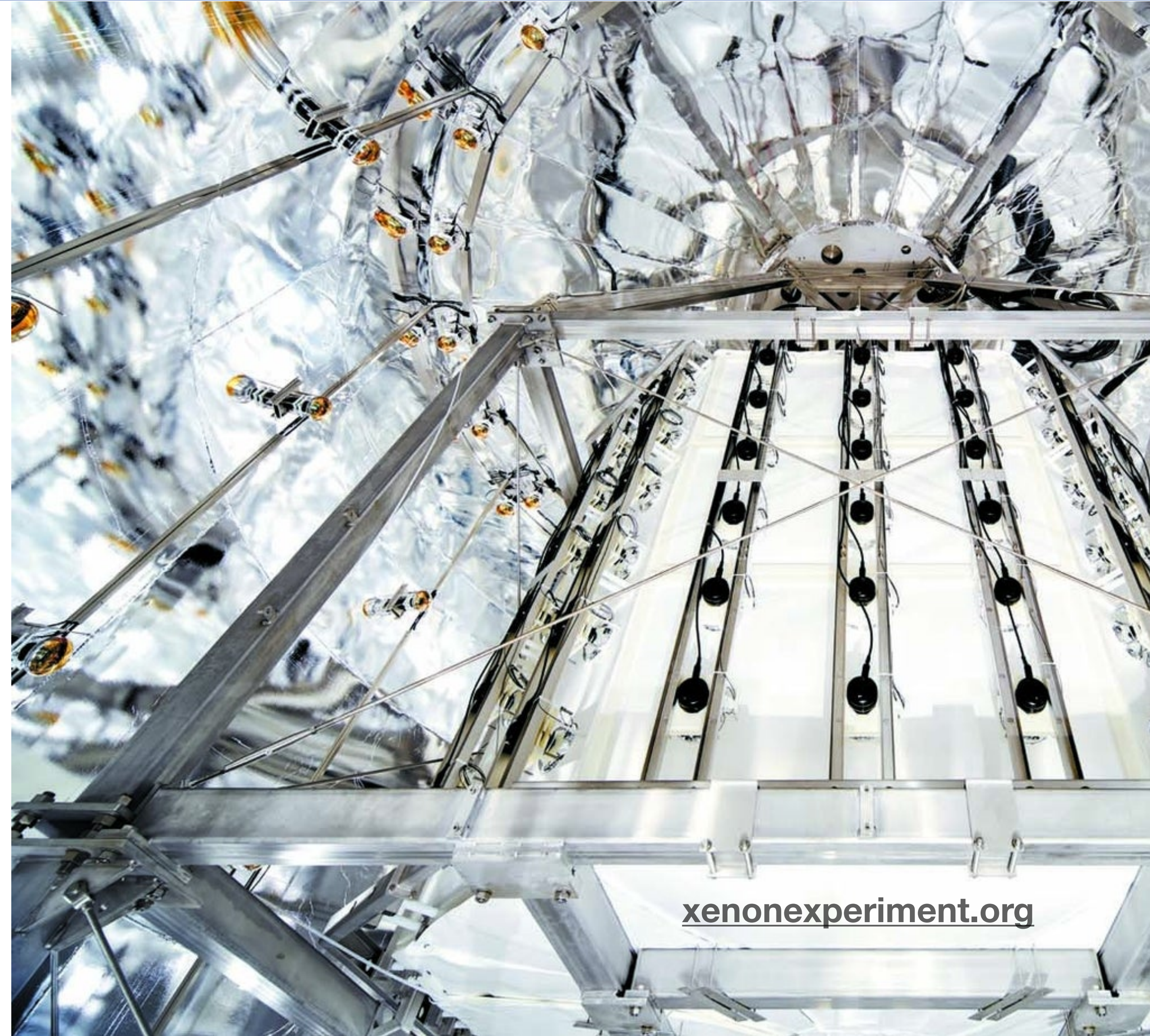
- We use ^{232}Th data to validate the simulations at energies upto 2.6MeV. Population of gamma-rays with many compton scatters and interaction sites.
- We can now reproduce the response of the detector very well in the entire energy range with **one model!**
- We also adjusted the NEST recombination fluctuation model to fix the spread of the distribution.



Thanks for your attention!

Summary:

- We extended the validity of the yield model of XENONnT from $\sim 10\text{keV}$ to $\sim 3\text{MeV}$, using a clean sample of beta decays from ^{214}Bi .
- We introduced a physics based clustering method to properly account for multiple scatters at high energies.
- Combining the two, we are able to match data and simulations, including complicated topologies with mixed betas and gammas in the entire energy range of $0\nu\beta\beta$ searches.

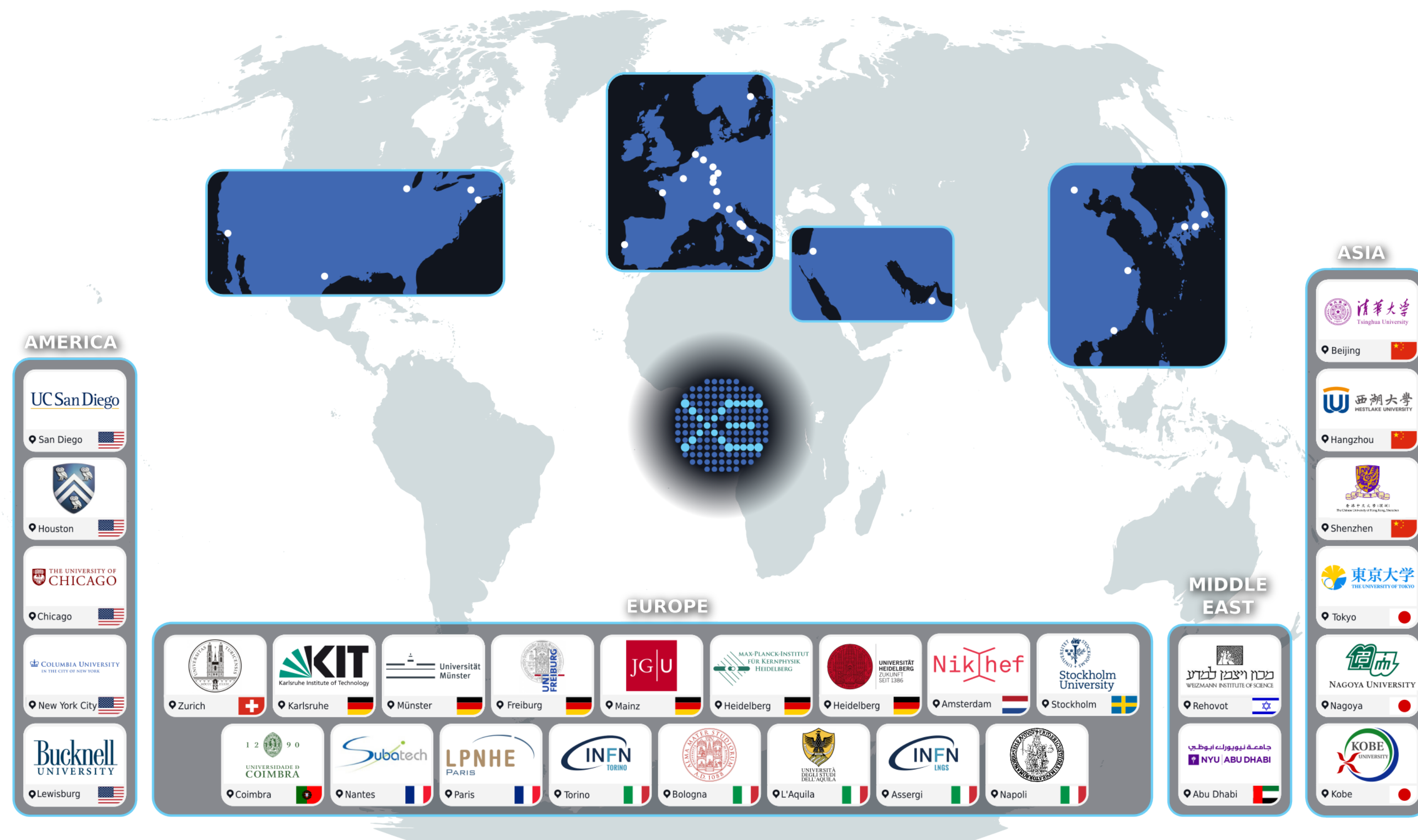


xenonexperiment.org

BACKUP

The XENONnT Collaboration

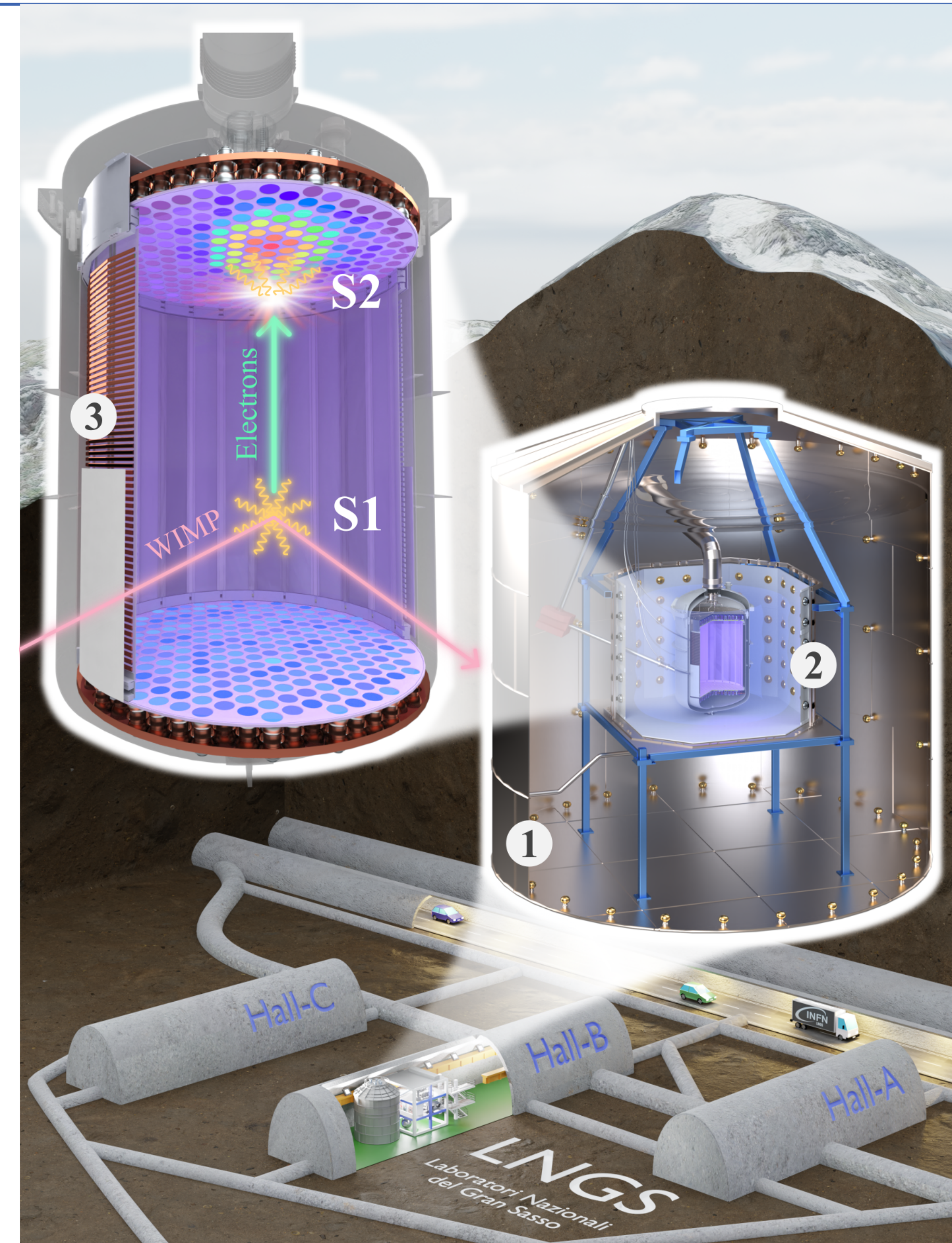
PhysRevX.15.031079 (2025)



Running since
2020

8.6 tonnes
LXe

Lowest Radon
Background



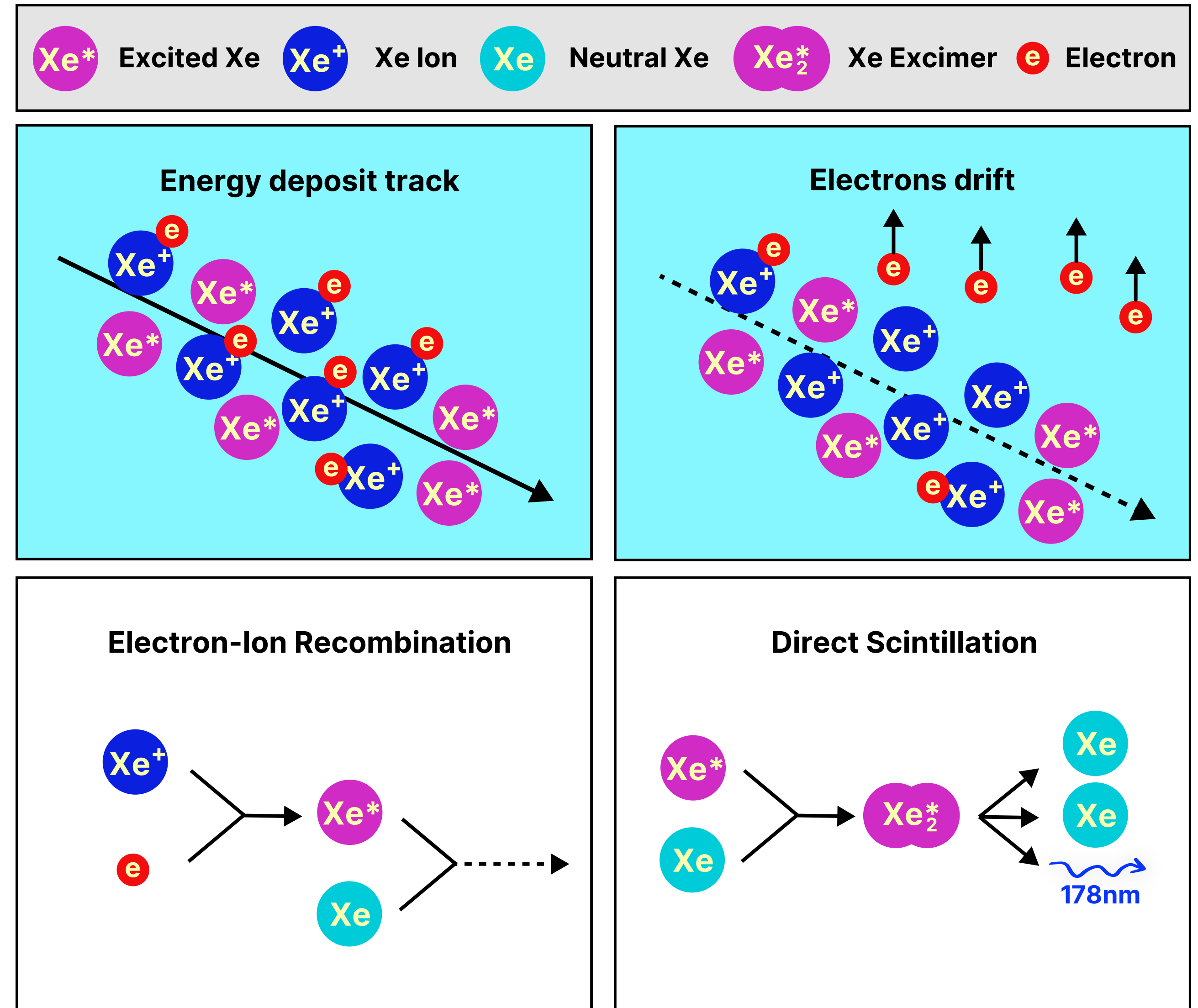
Process of scintillation

Quanta generation:

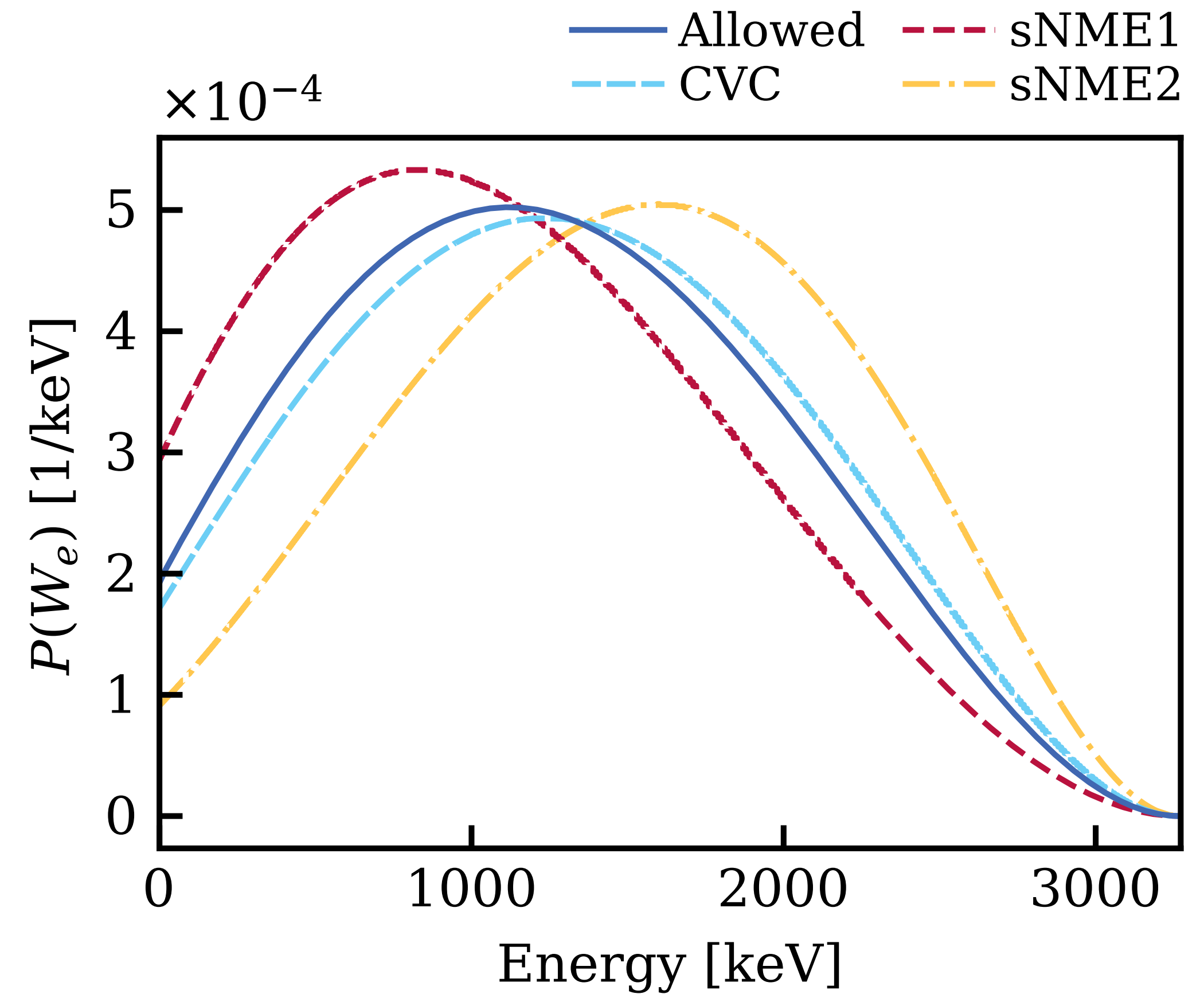
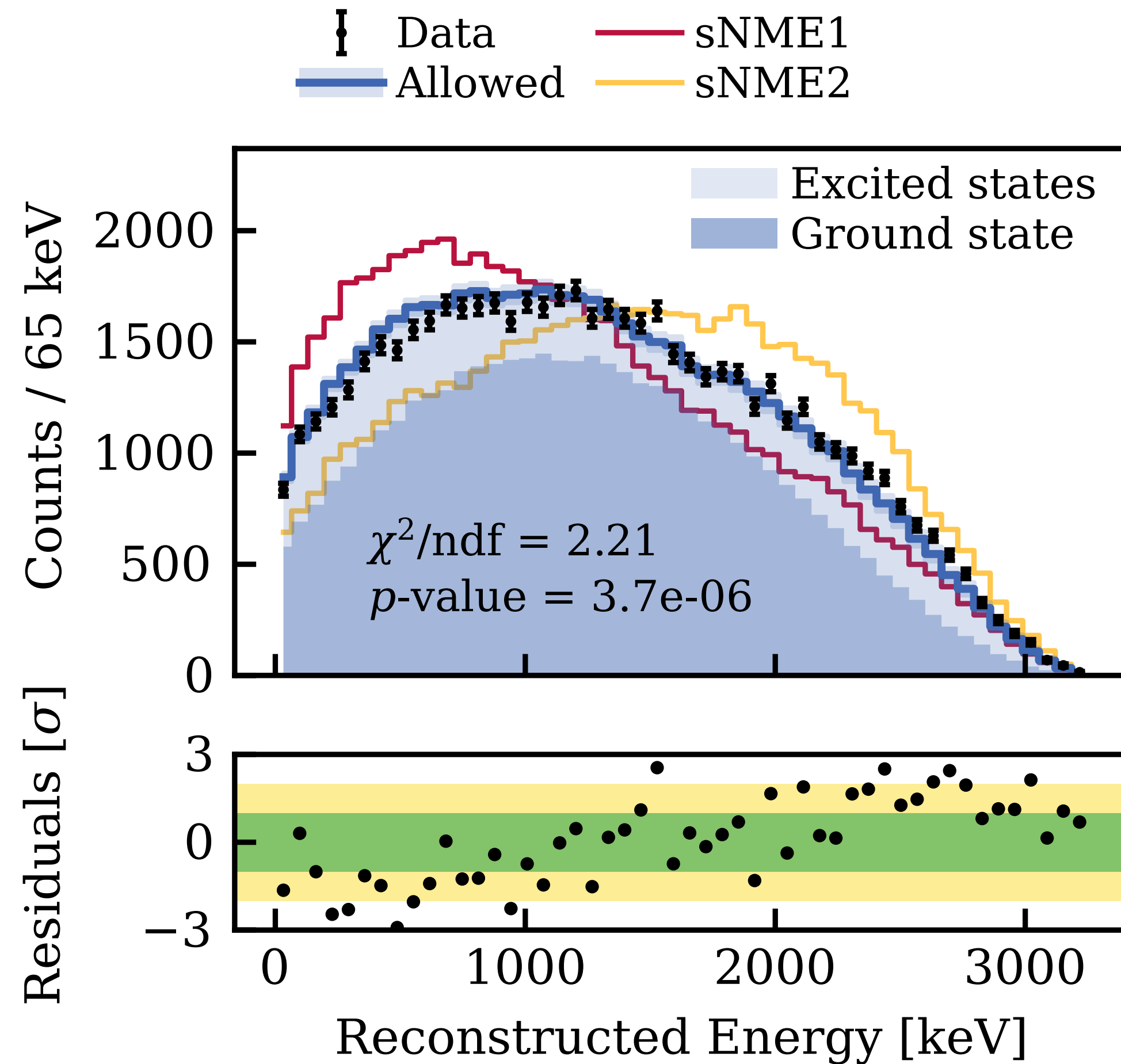
- Total number of **excitons and ions** created is **~constant** (depends slightly on density)
- **Fraction of ions to excitons** depends on the density and on the **energy** of the interaction.
- Fraction of **electrons recombining** depends strongly on **drift field** and **interaction energy**.
- Because with recombination we get one photon from one electron, still **total number of quanta** is **conserved**, and we can reconstruct energy as:

$$E = W (n_{photons} + n_{electrons})$$

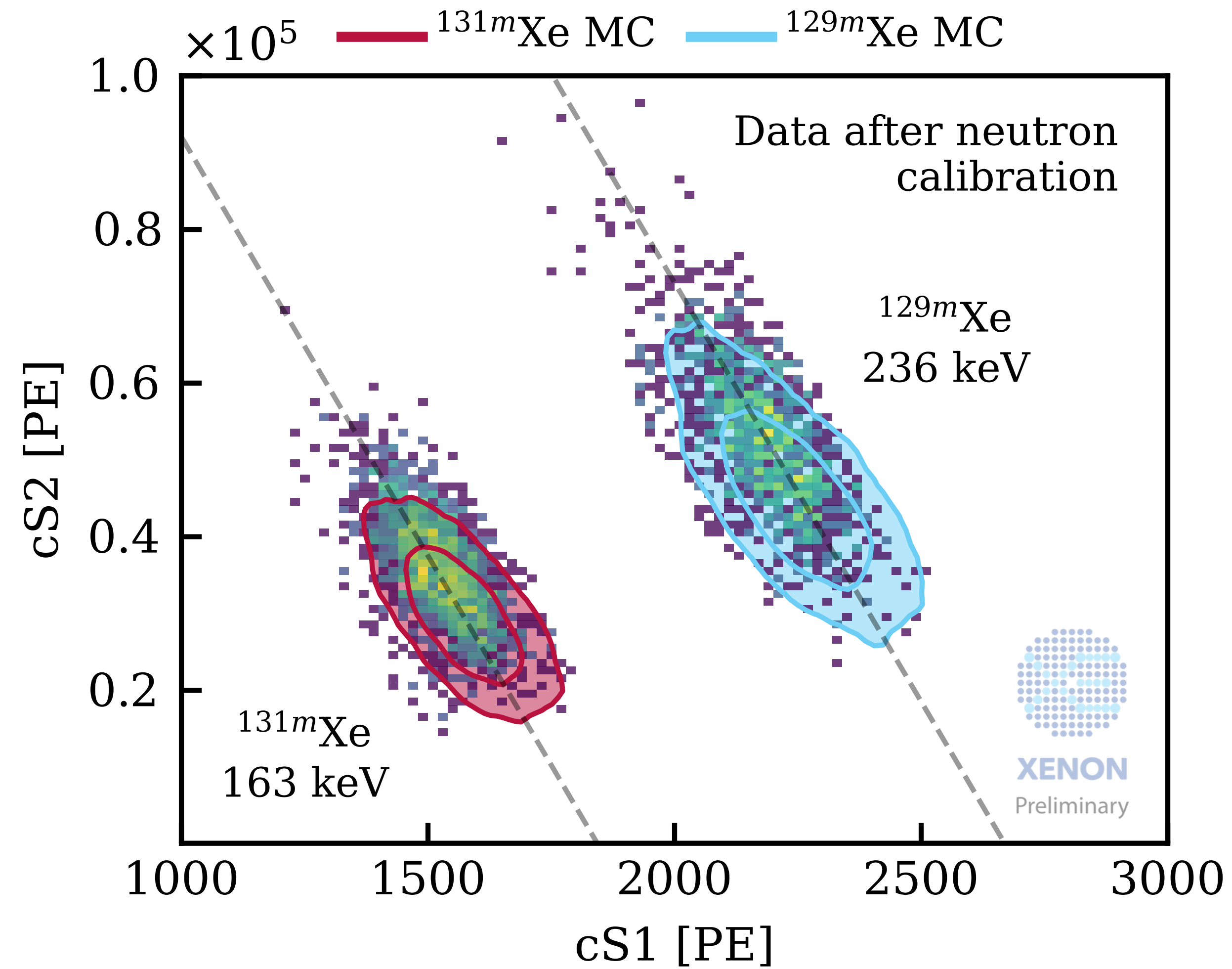
$$W \sim 13.7 \text{ eV / quanta}$$



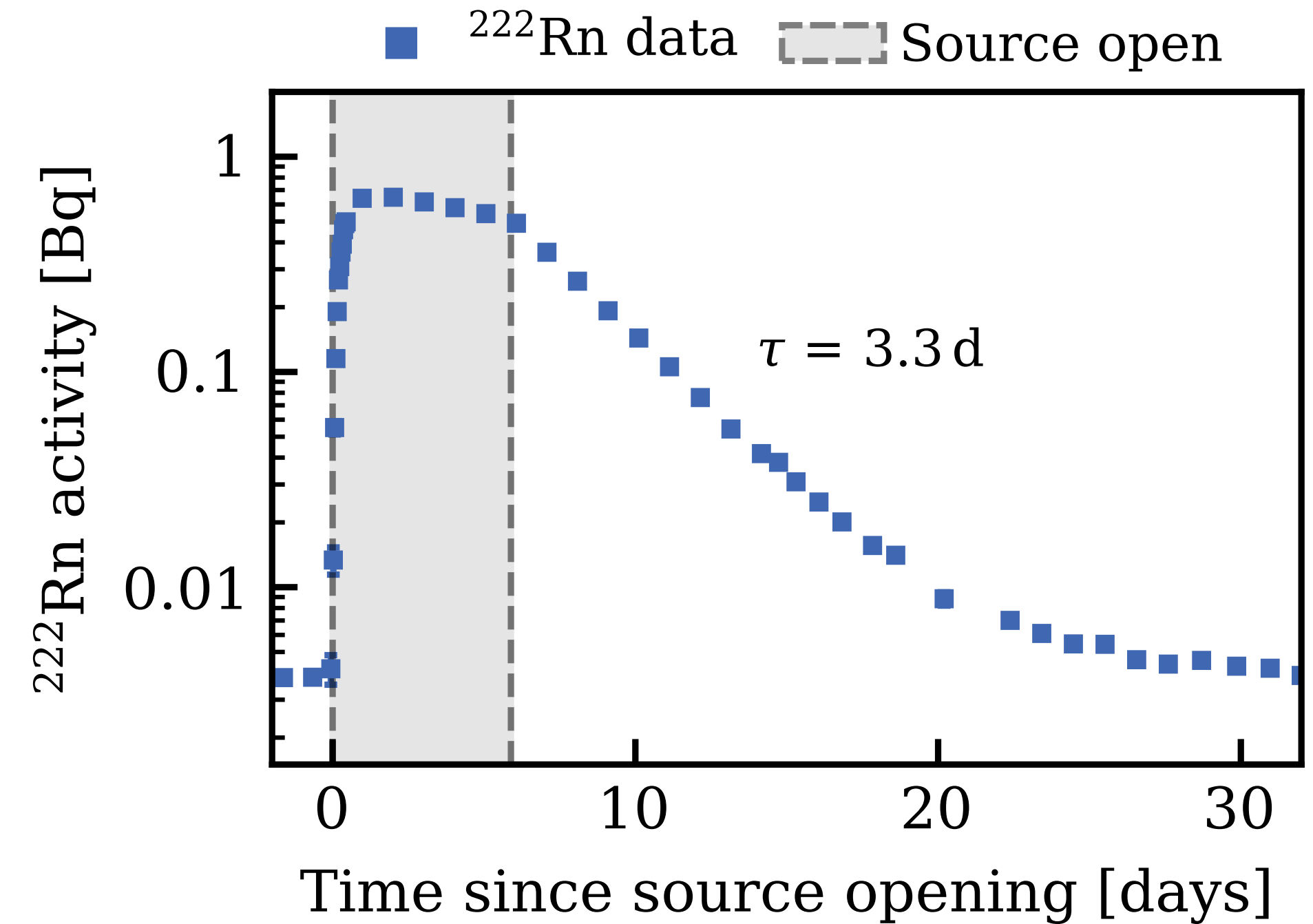
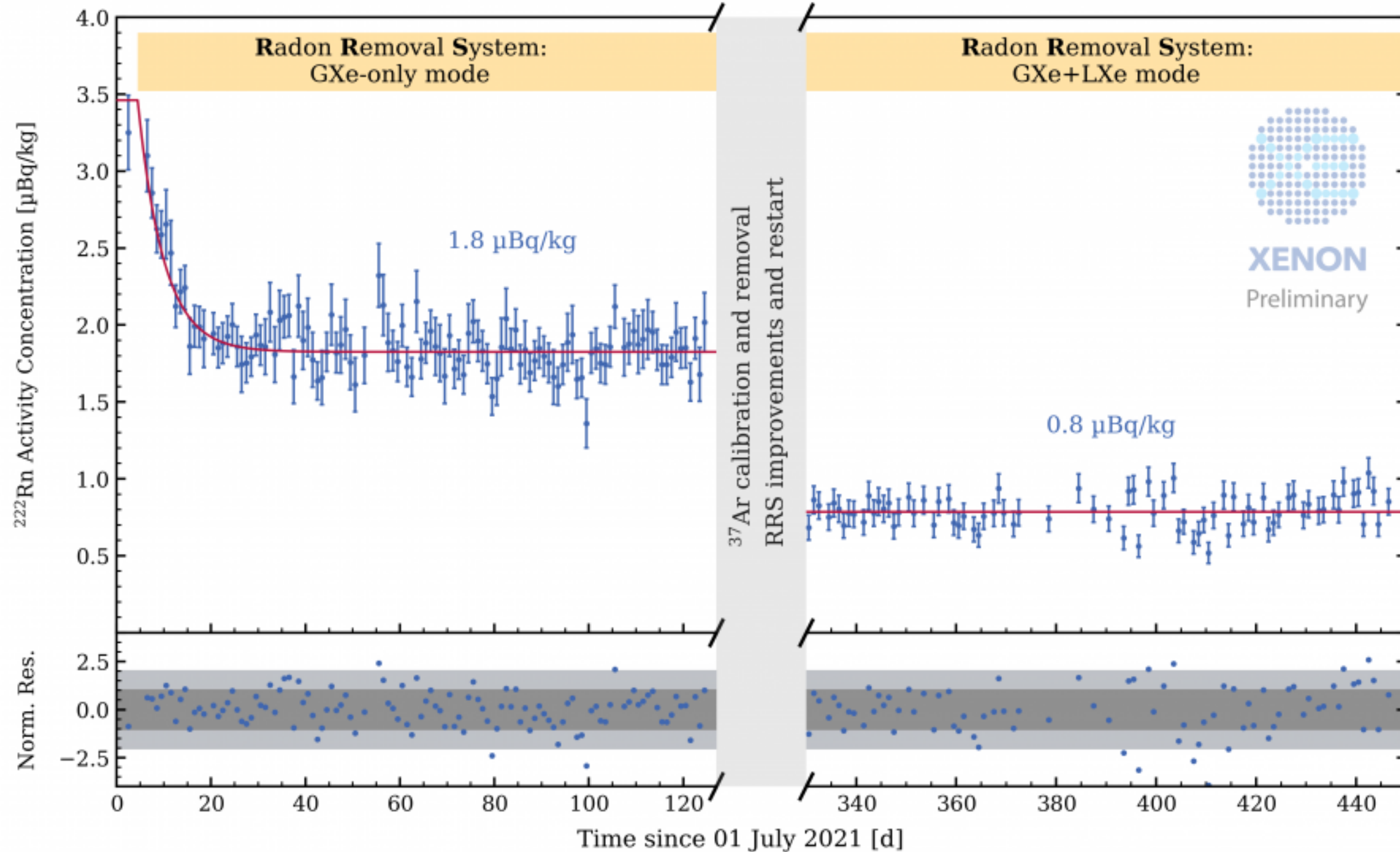
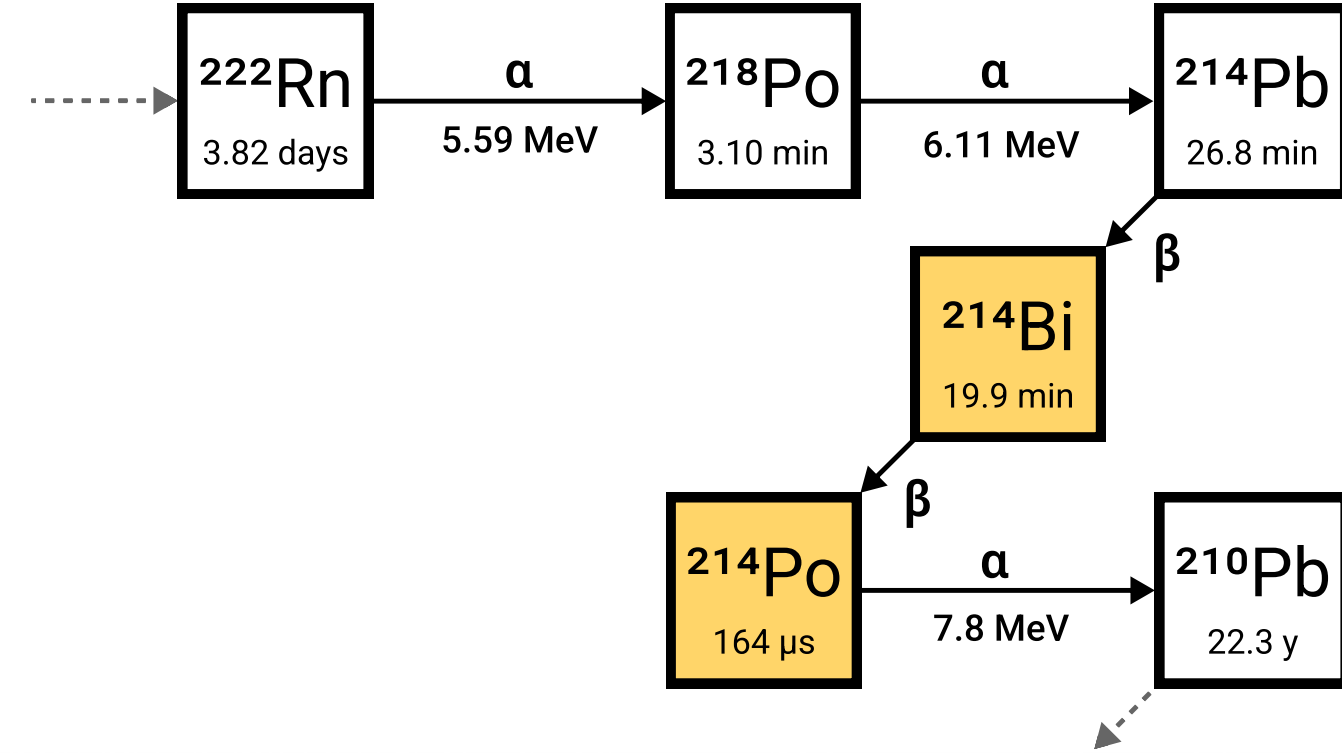
Other models



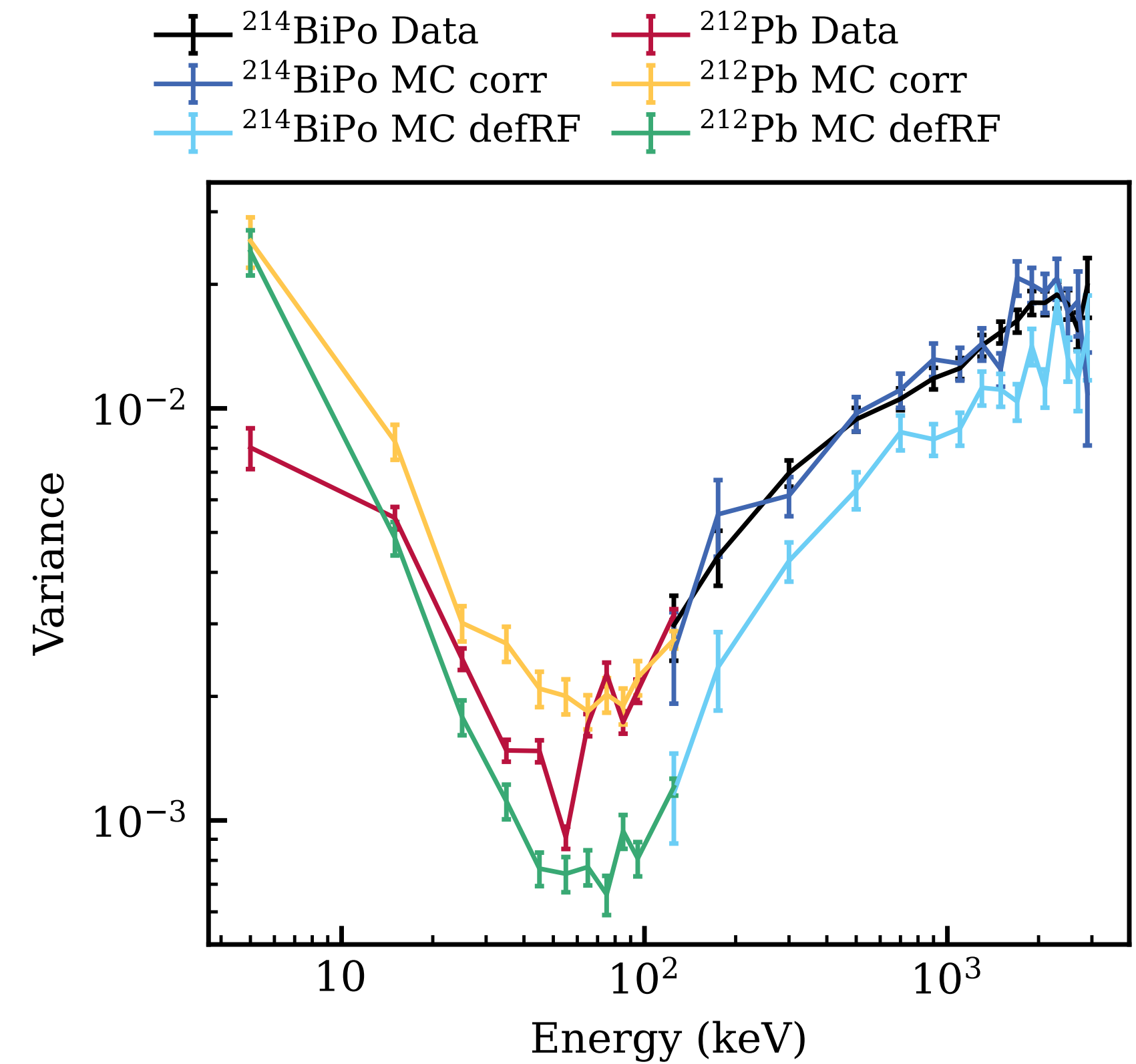
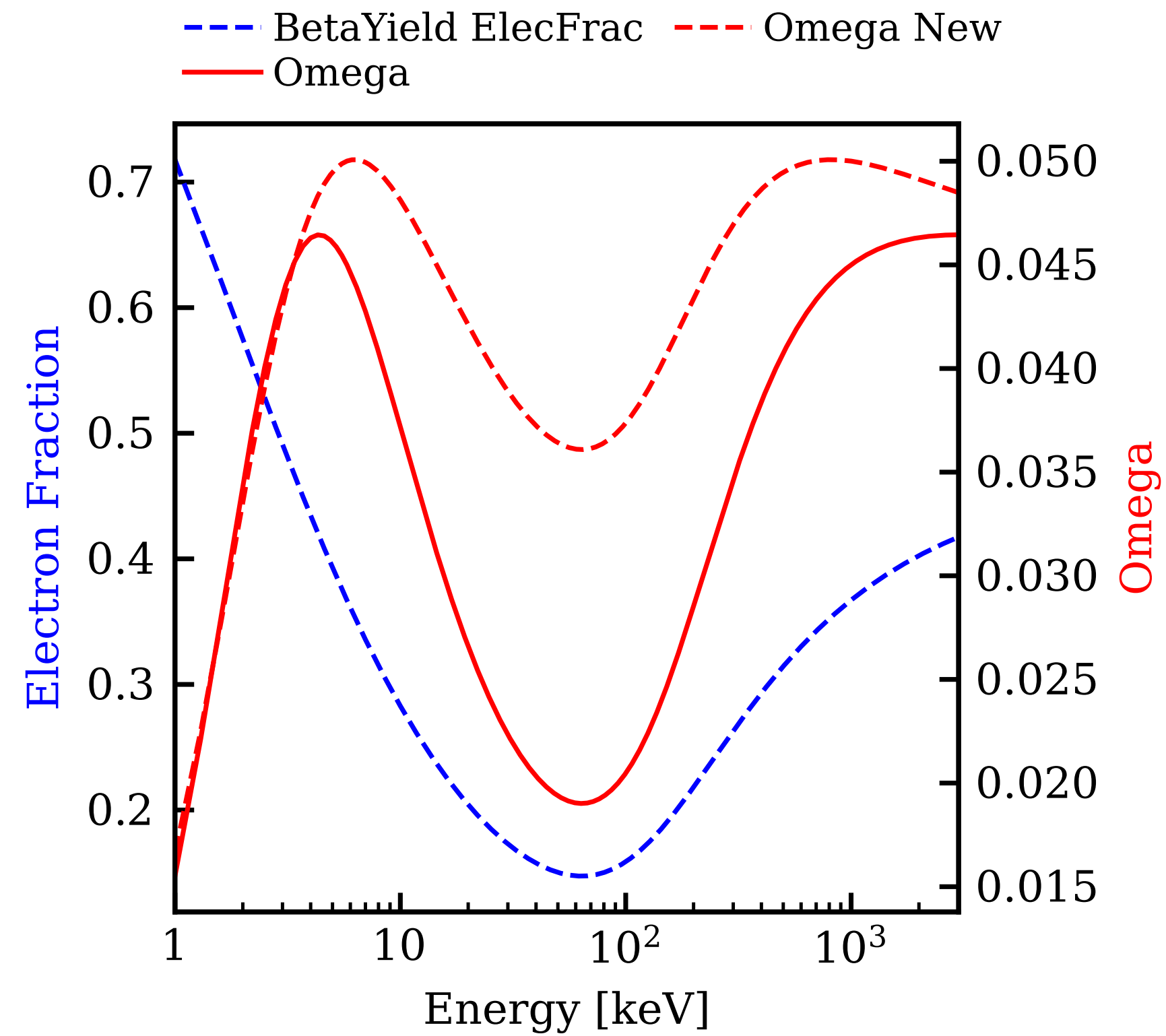
^{129}Xe and ^{131}Xe - IC



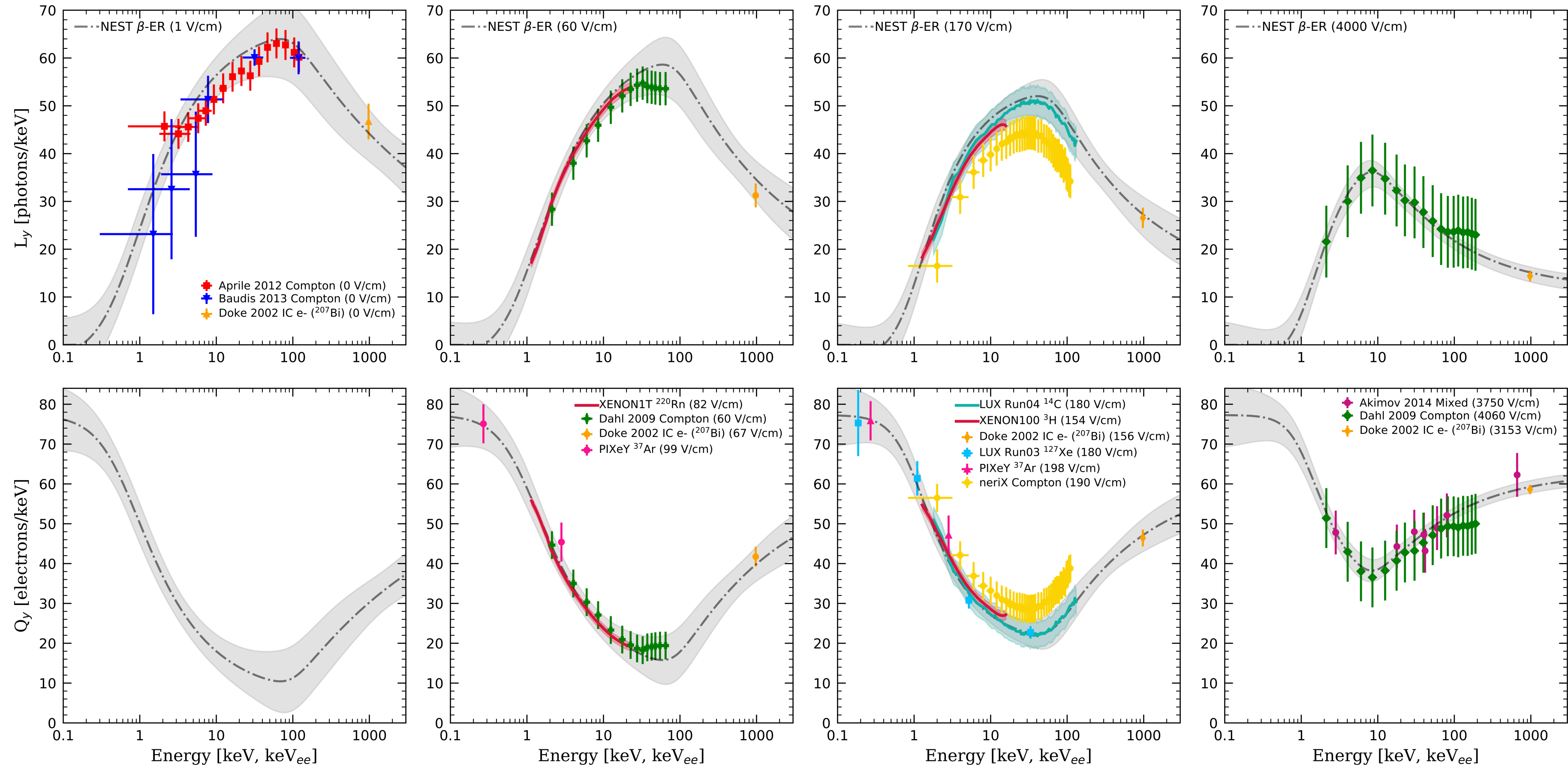
Radon chain backgrounds: the source of our signal



Recombination Fluctuation



NEST Yields: full beta model



$$Q_y(E, \mathcal{E}) = m_1(\mathcal{E}) + \frac{m_2 - m_1(\mathcal{E})}{\left[1 + \left(\frac{E}{m_3(\mathcal{E})}\right)^{m_4(\mathcal{E})}\right]^{m_9}} + m_5(\mathcal{E}) - \frac{m_5(\mathcal{E})}{\left[1 + \left(\frac{E}{m_7(\mathcal{E})}\right)^{m_8}\right]^{m_{10}(\mathcal{E})}}.$$