

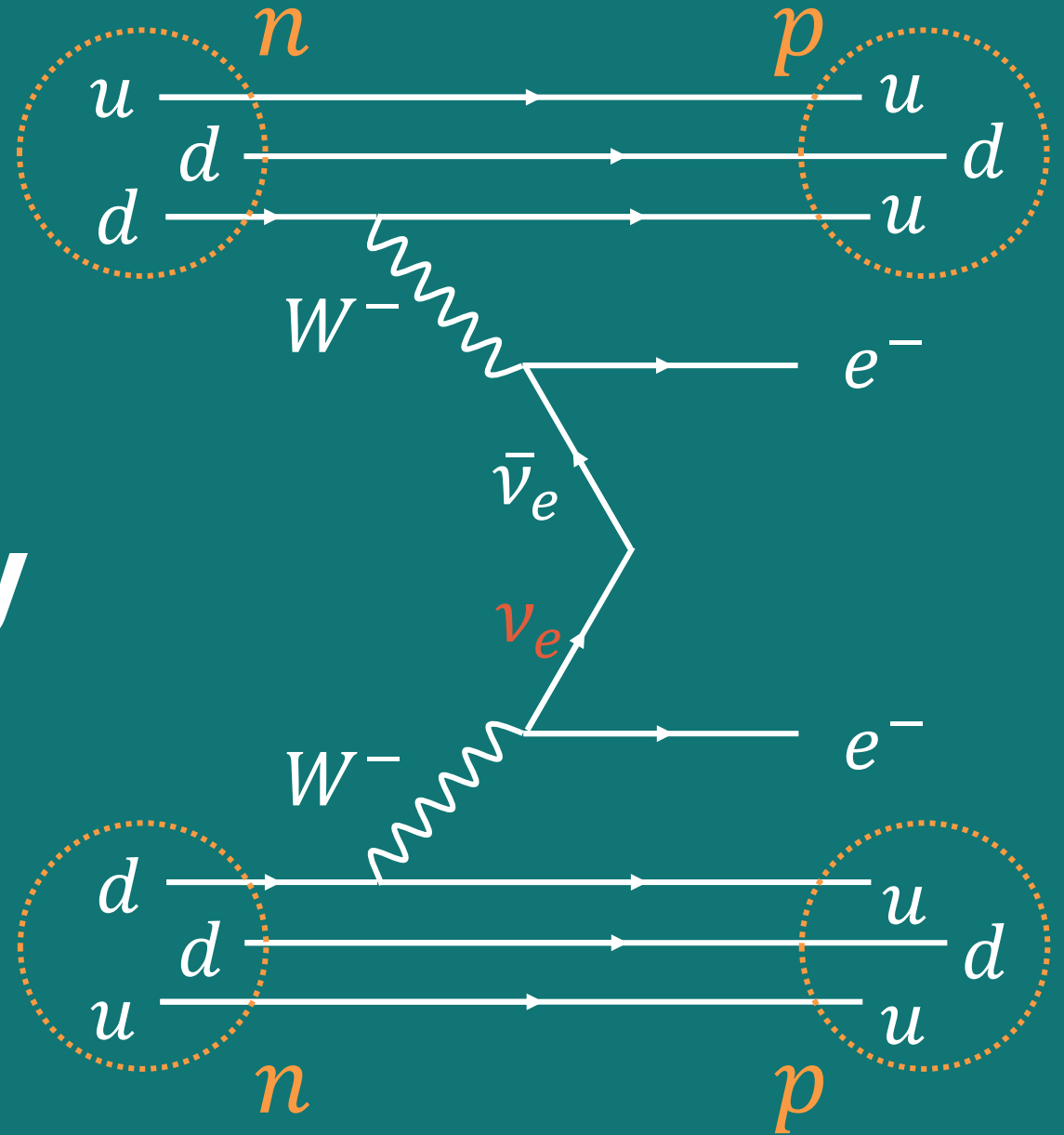
Beta Decay

and

Double Beta Decay

Ke Han (SJTU)

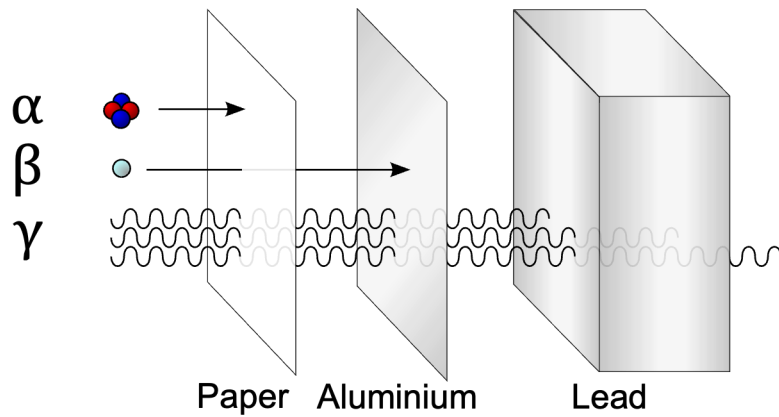
韩柯 (上海交通大学)











Beta decay milestones

Rutherford's identification of alpha/beta-rays

Penetration length; ionization in air

Fermi's theory of beta decay

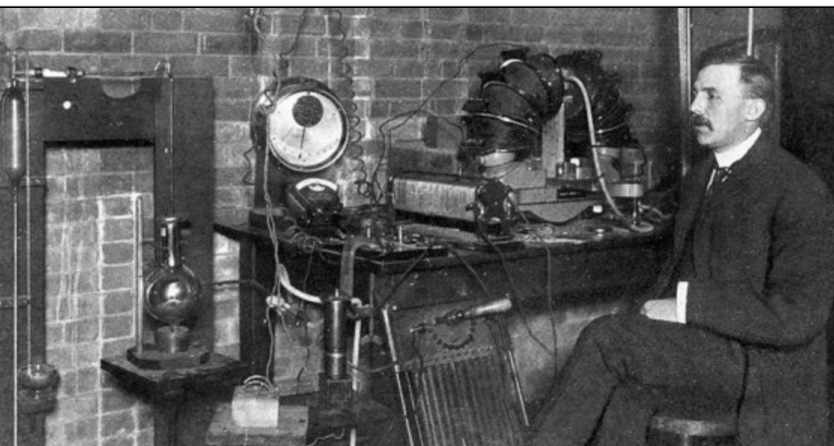
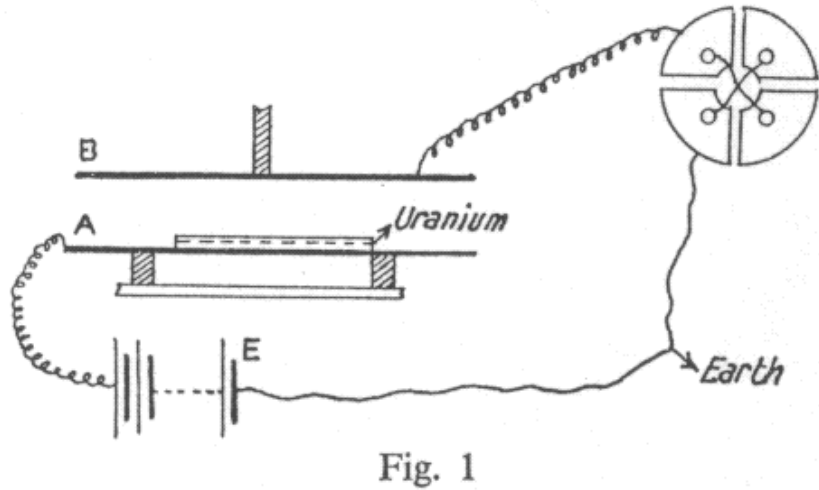
Fermi four-fermion interaction; half-life and spectrum; neutrino

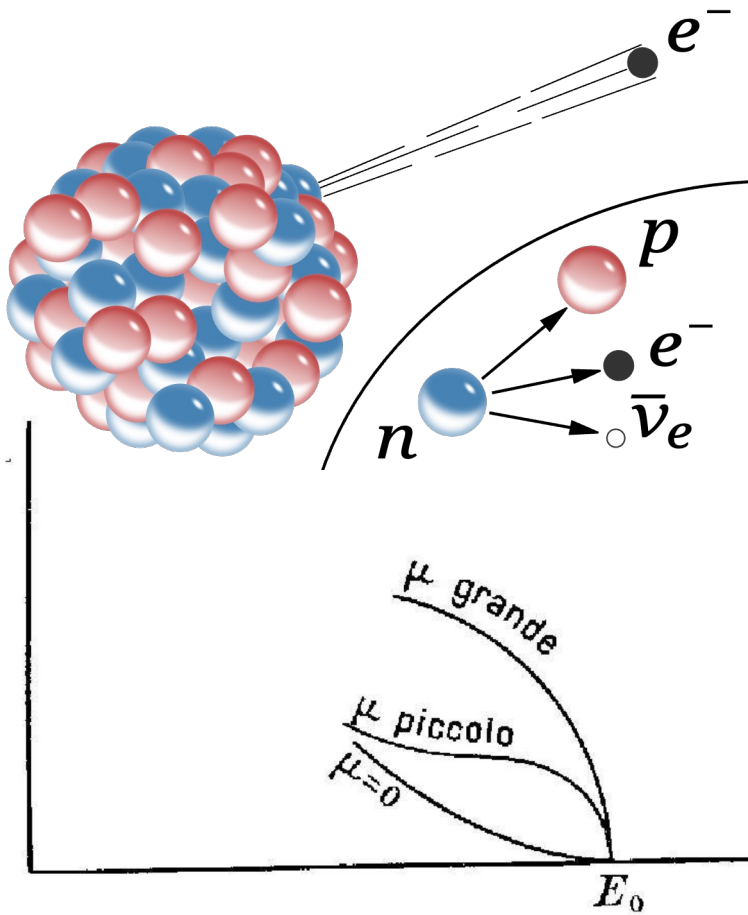
Parity violation (Lee and Yang, with Wu)

Beta asymmetry; gamma anisotropy

Neutrinos!

Source; detection; mass measurement; Majorana neutrinos





Beta decay milestones

Rutherford's identification of alpha/beta-rays

Penetration length; ionization in air

Fermi's theory of beta decay

Fermi four-fermion interaction; half-life and spectrum; neutrino

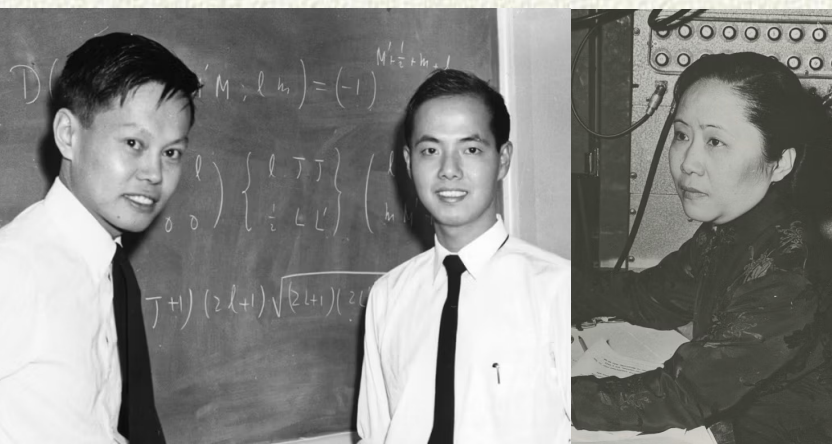
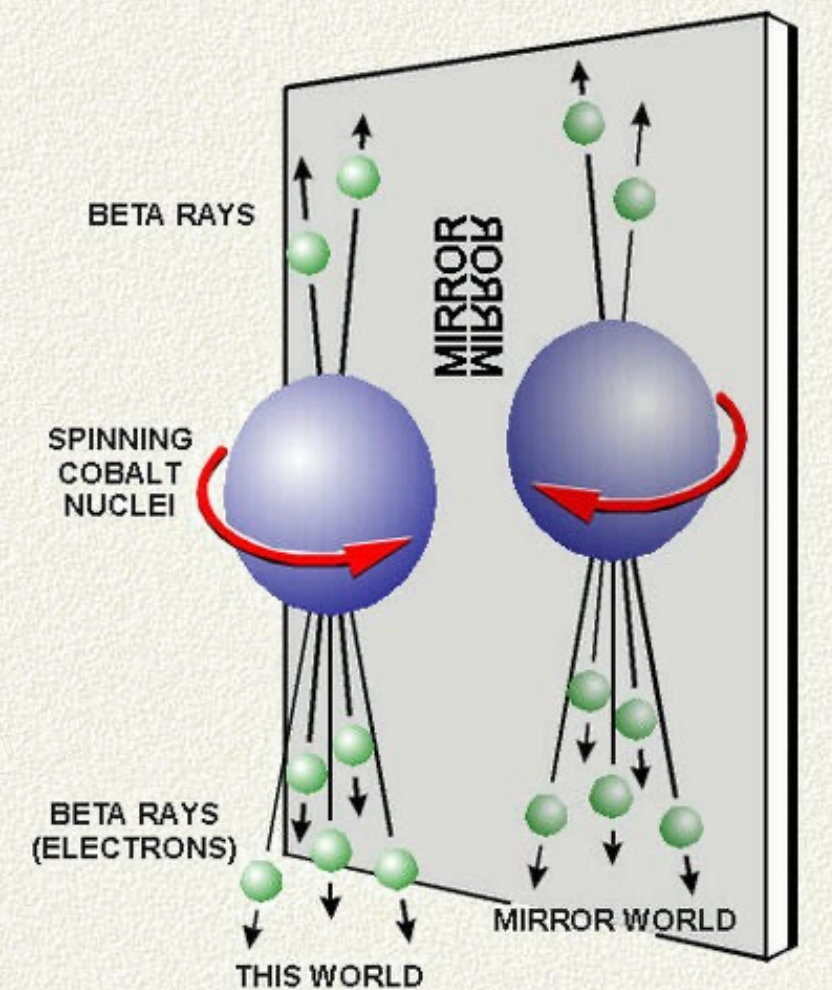
Parity violation (Lee and Yang, with Wu)

Beta asymmetry; gamma anisotropy

Neutrinos!

Source; detection; mass measurement; Majorana neutrinos





Beta decay milestones

Rutherford's identification of alpha/beta-rays

Penetration length; ionization in air

Fermi's theory of beta decay

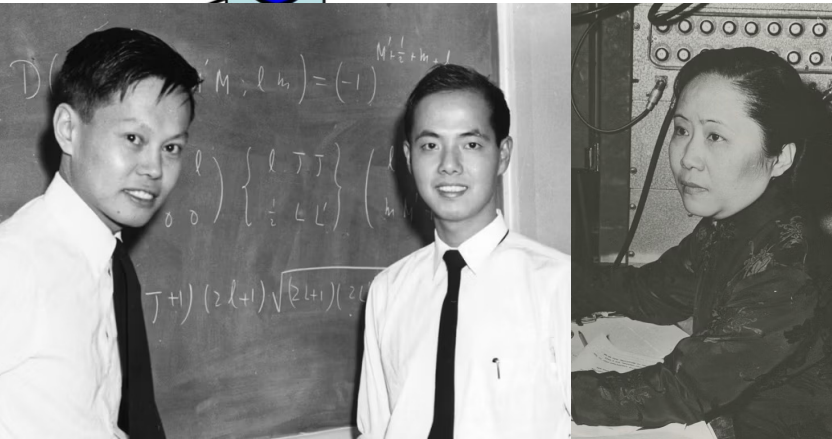
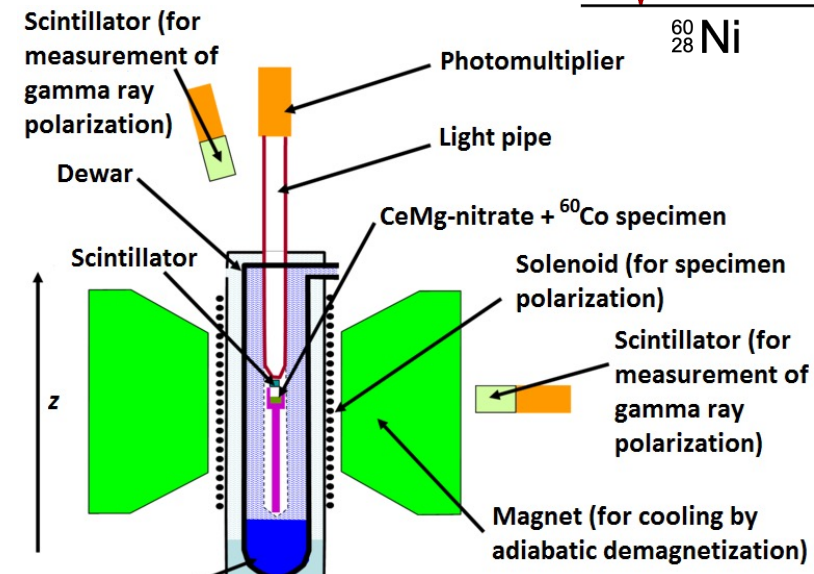
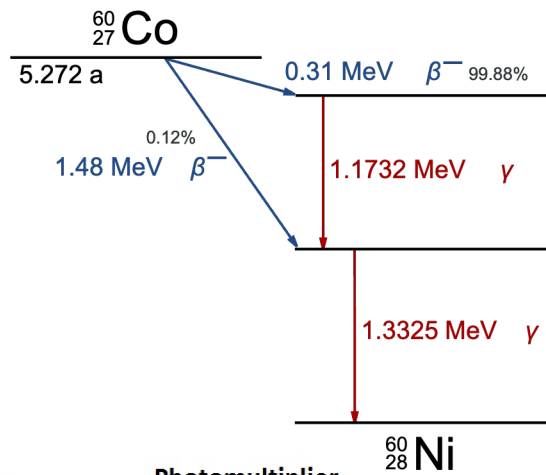
Fermi four-fermion interaction; half-life and spectrum; neutrino

Parity violation (Lee and Yang, with Wu)

Beta asymmetry; gamma anisotropy

Neutrinos!

Source; detection; mass measurement; Majorana neutrinos



Beta decay milestones

Rutherford's identification of alpha/beta-rays

Penetration length; ionization in air

Fermi's theory of beta decay

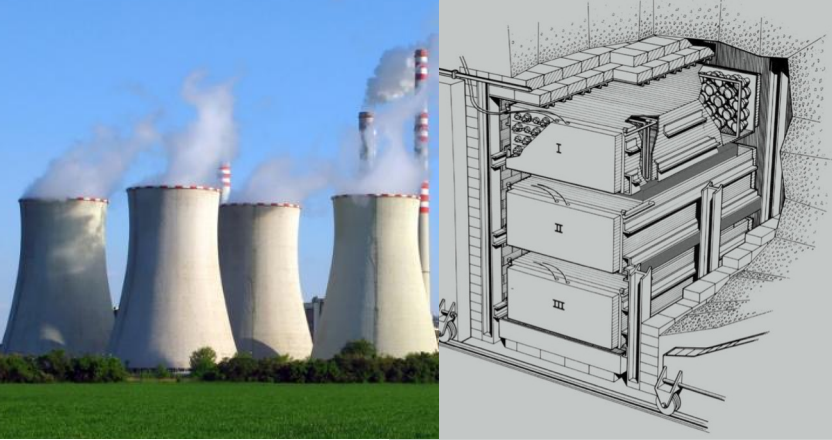
Fermi four-fermion interaction; half-life and spectrum; neutrino

Parity violation (Lee and Yang, with Wu)

Beta asymmetry; gamma anisotropy

Neutrinos!

Source; detection; mass measurement; Majorana neutrinos



Beta decay milestones

Rutherford's identification of alpha/beta-rays

Penetration length; ionization in air

Fermi's theory of beta decay

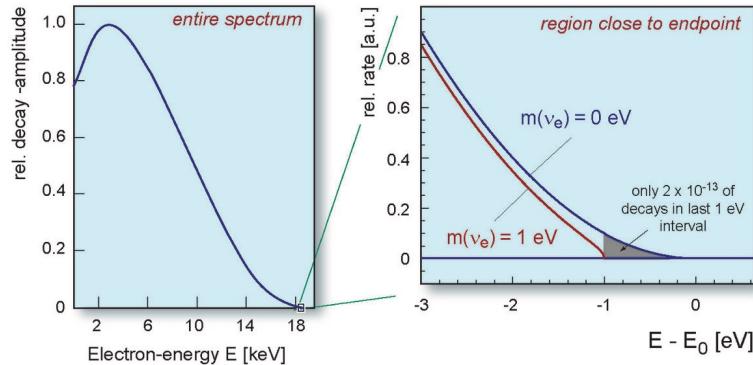
Fermi four-fermion interaction; half-life and spectrum; **neutrino**

Parity violation (Lee and Yang, with Wu)

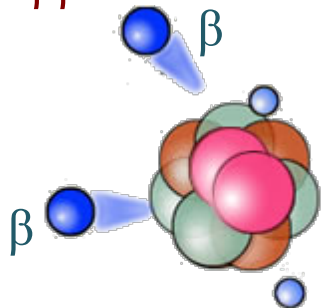
Beta asymmetry; gamma anisotropy

Neutrinos!

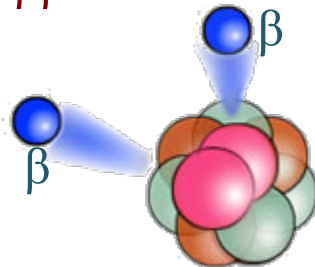
Source; detection; mass measurement; Majorana neutrinos



$2\nu\beta\beta$



$0\nu\beta\beta$

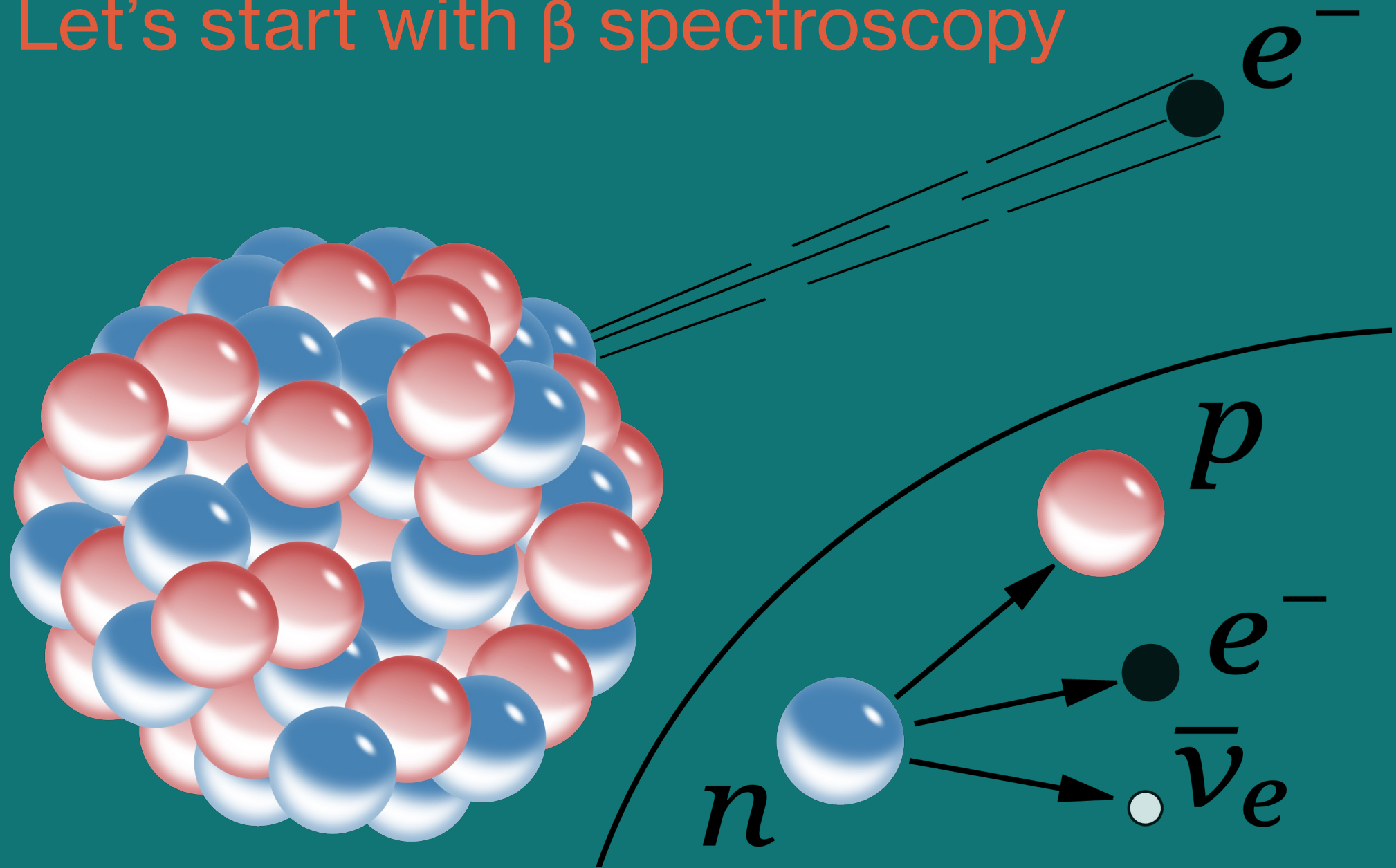


We have studied beta decay for more than a century. What remains to be discovered?

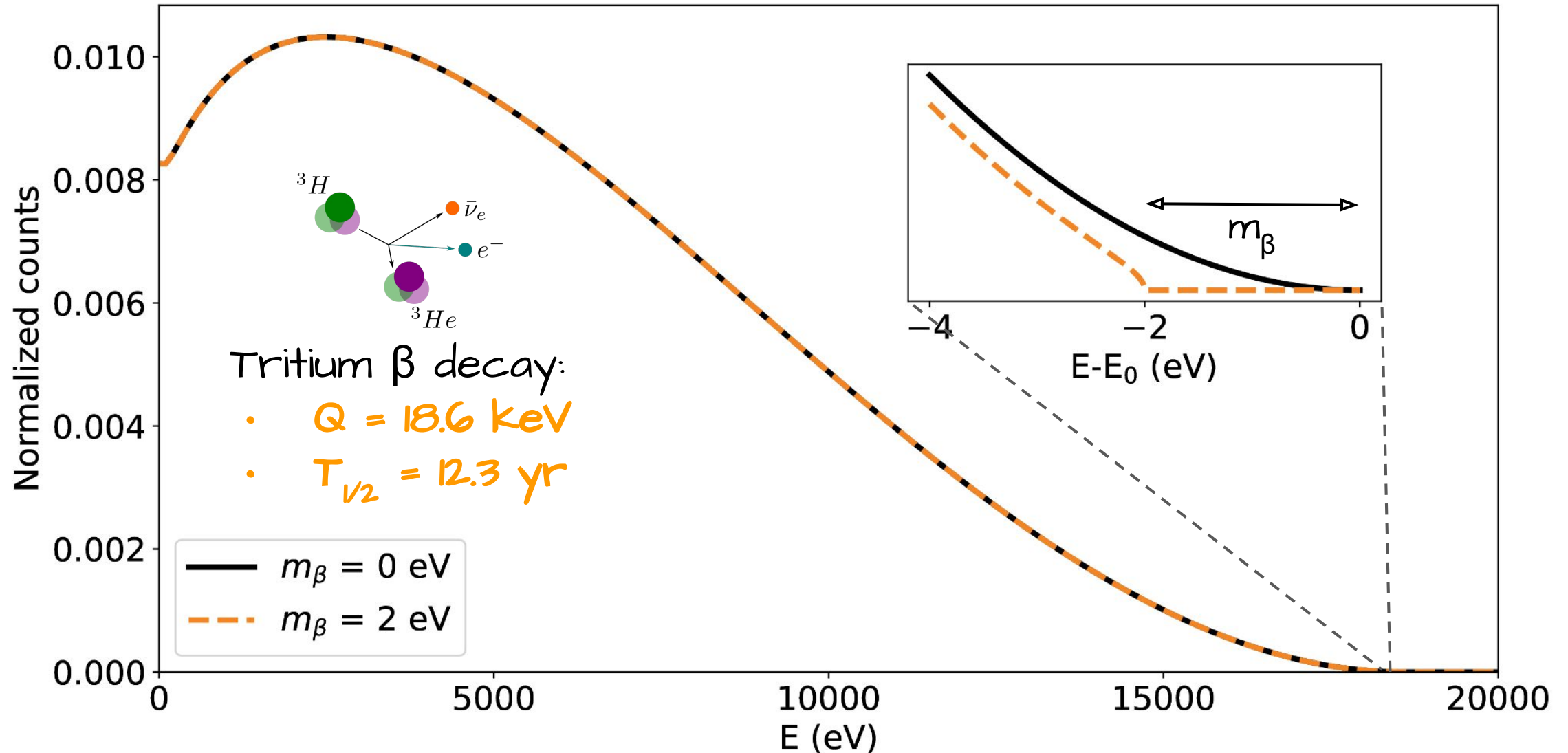
Particle Physicist:

I trust everything in nuclear physics!

Let's start with β spectroscopy

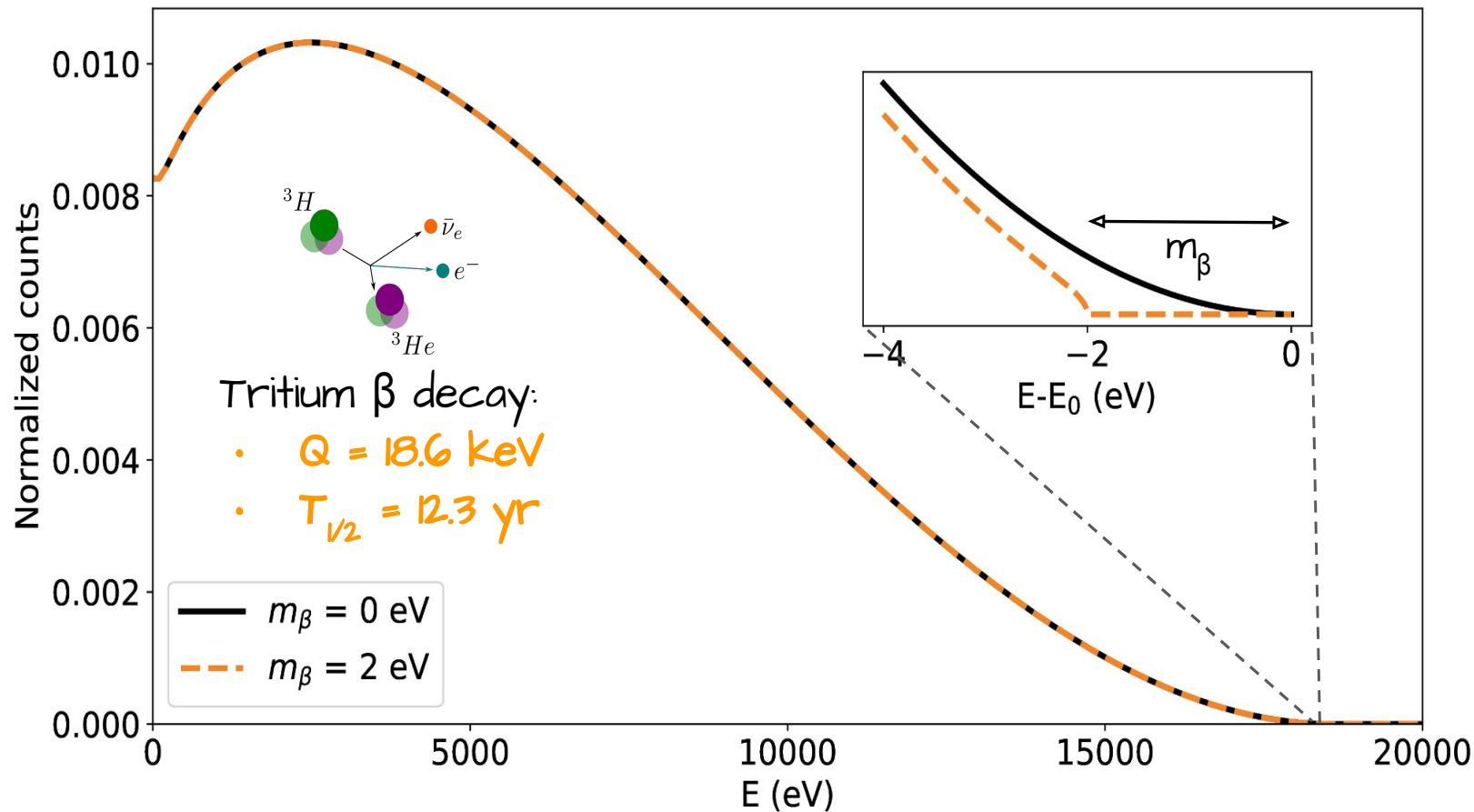


The simple and well-studied β spectrum



From KATRIN

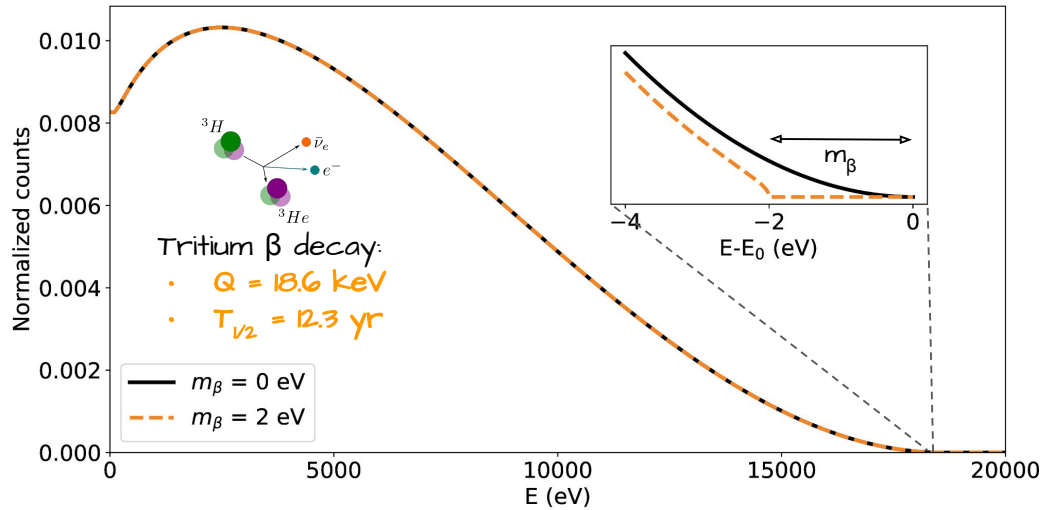
Theoretical β spectrum calculation



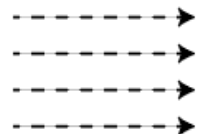
From KATRIN

- Initial and final state
- V-A
- Fermi screening correction
- Weak magnetism current
- Recoiled Coulomb potential
- Finite nuclear size correction
- Radiative correction
- Atomic Quantum Effect (AQE):
 - Exchange of β and e^-

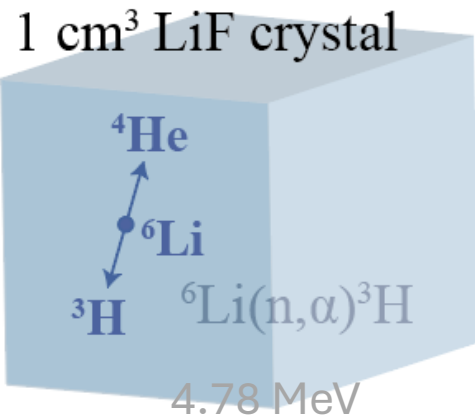
Measured spectrum from 1 keV



Thermal
neutrons

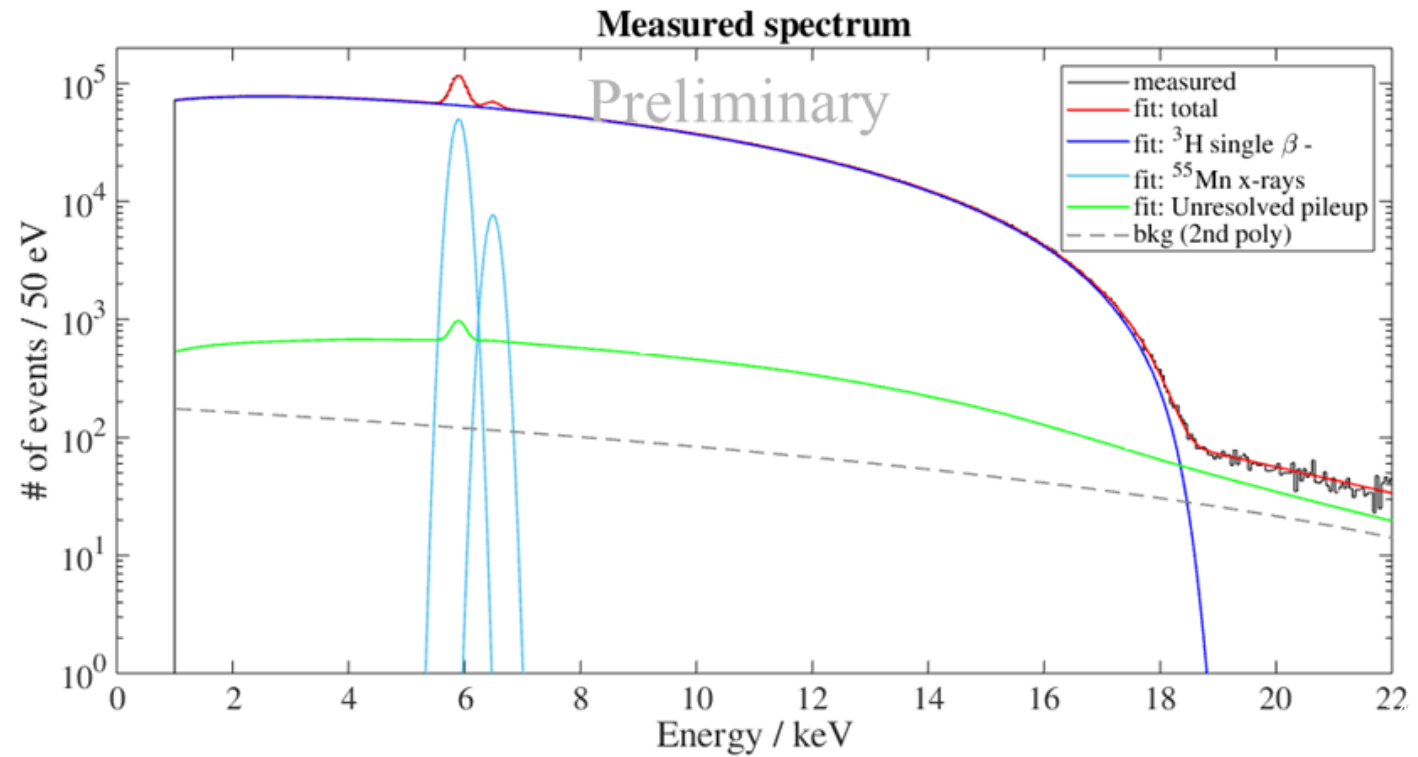
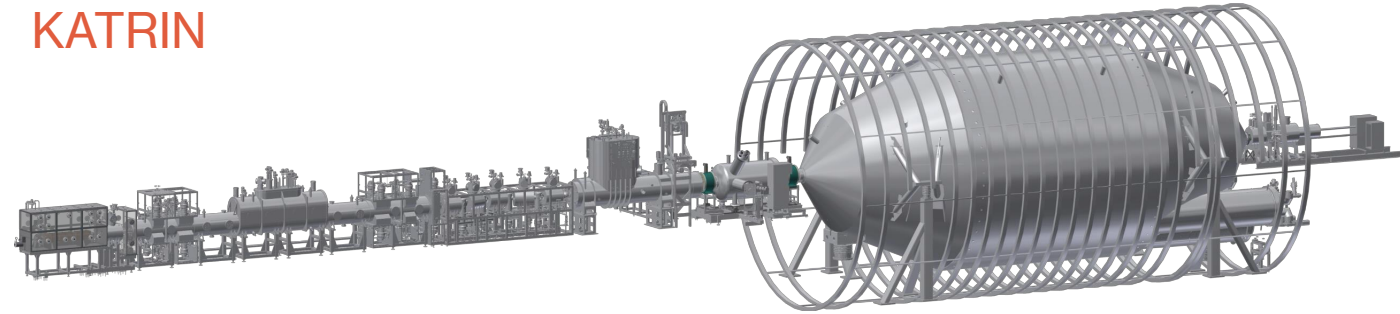


n



From LiFE-SNS

KATRIN



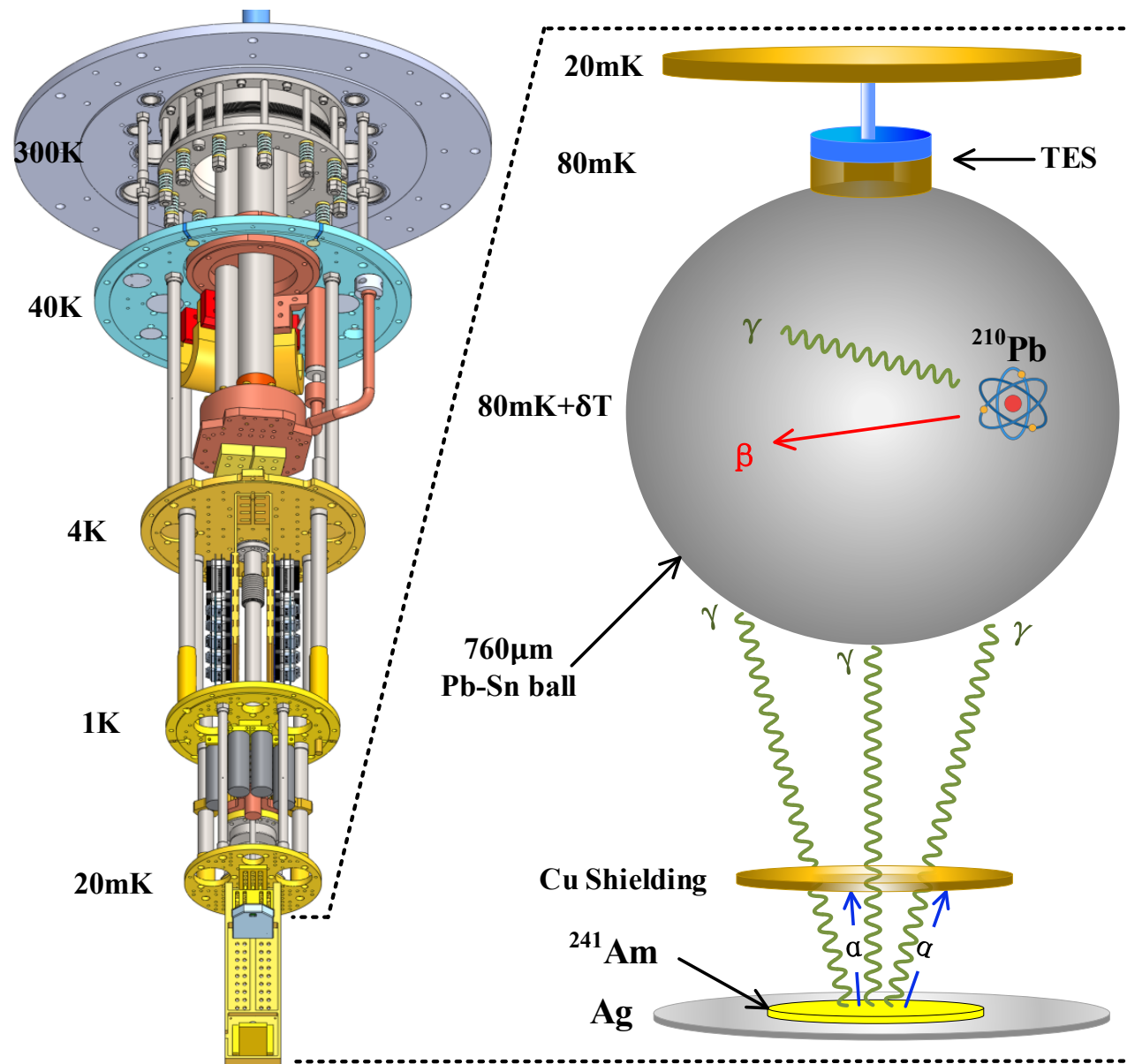
β spectroscopy is straightforward.

Precision β spectroscopy is not.

- ① Energy loss in source
- ② Threshold and energy response in detector
- ③
- ④ Background

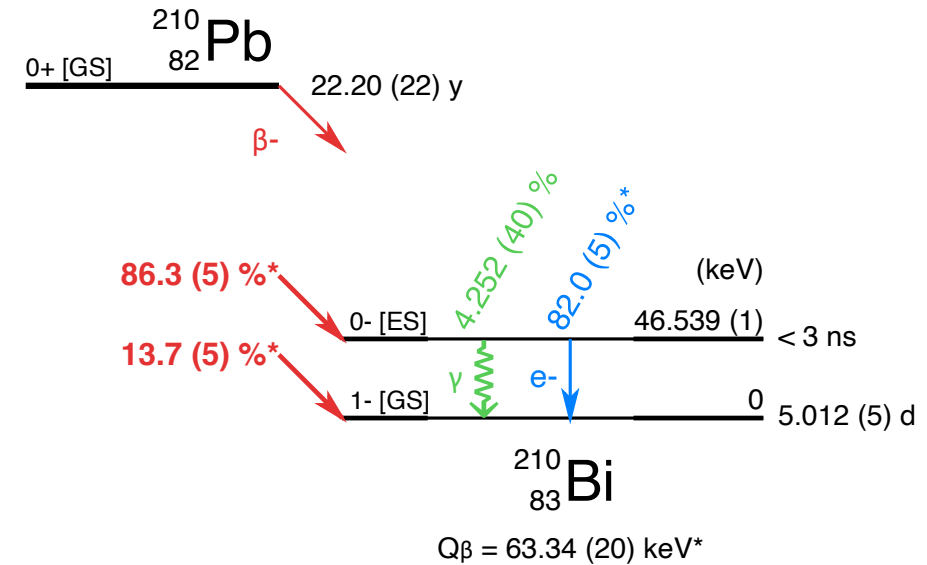
A complete, precise β spectrum has never been measured.

- 1 Energy loss in source
- 2 Threshold and energy response in detector
- 3
- 4 Background



Source = Detector Bolometer

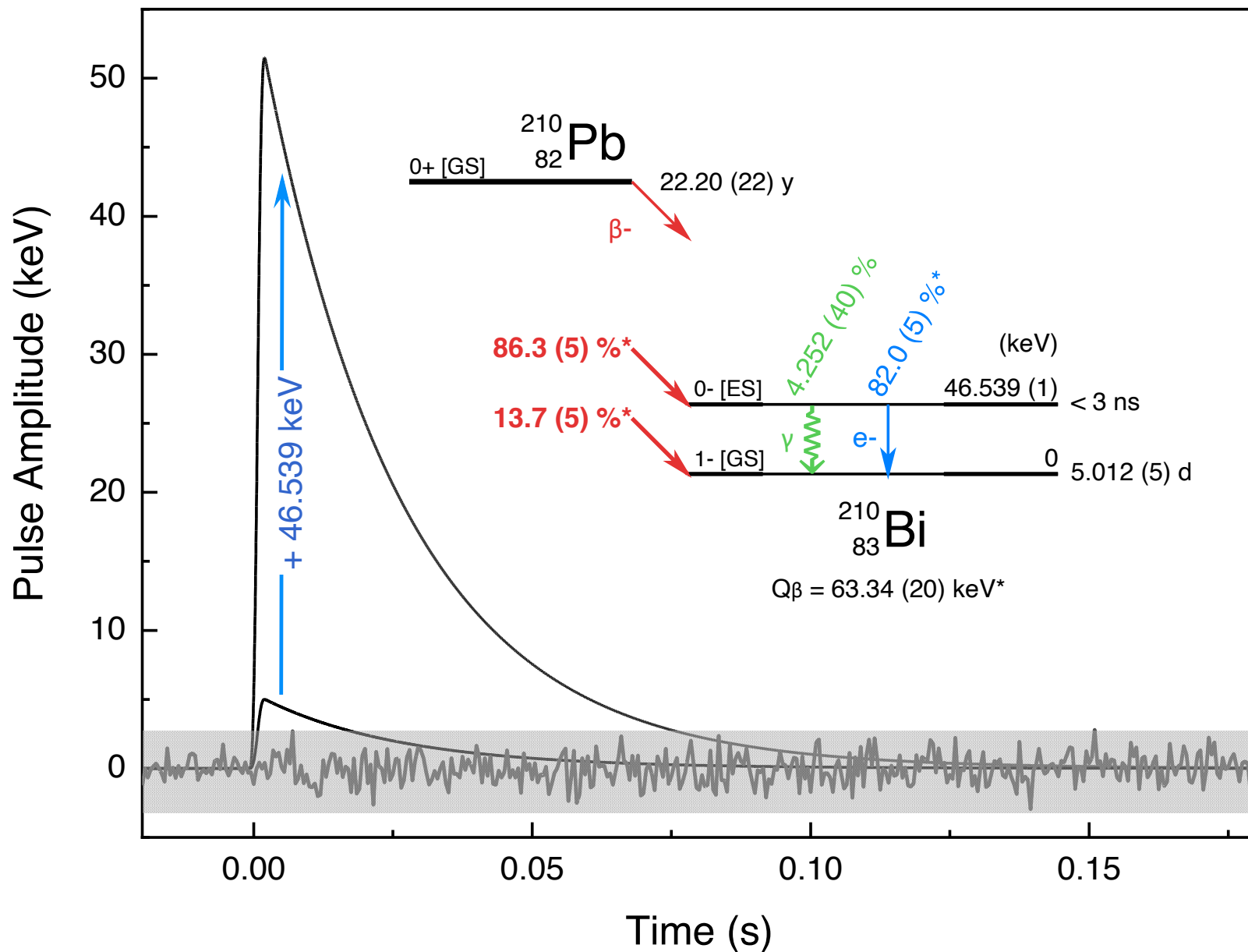
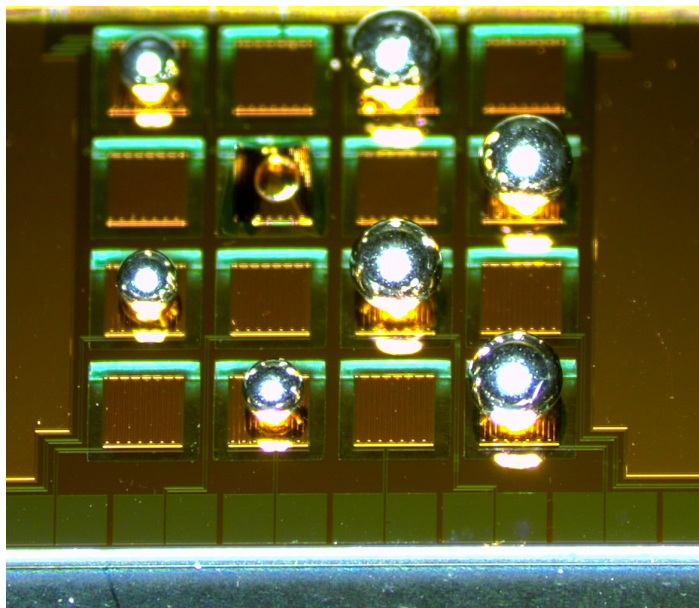
Full energy in detector 😊



Shuo Zhang, Hao-Ran Liu, Ke Han, Xavier Mougeot, Paul-Antoine Hervieux,
et al. [Arxiv:2509.26390](https://arxiv.org/abs/2509.26390)

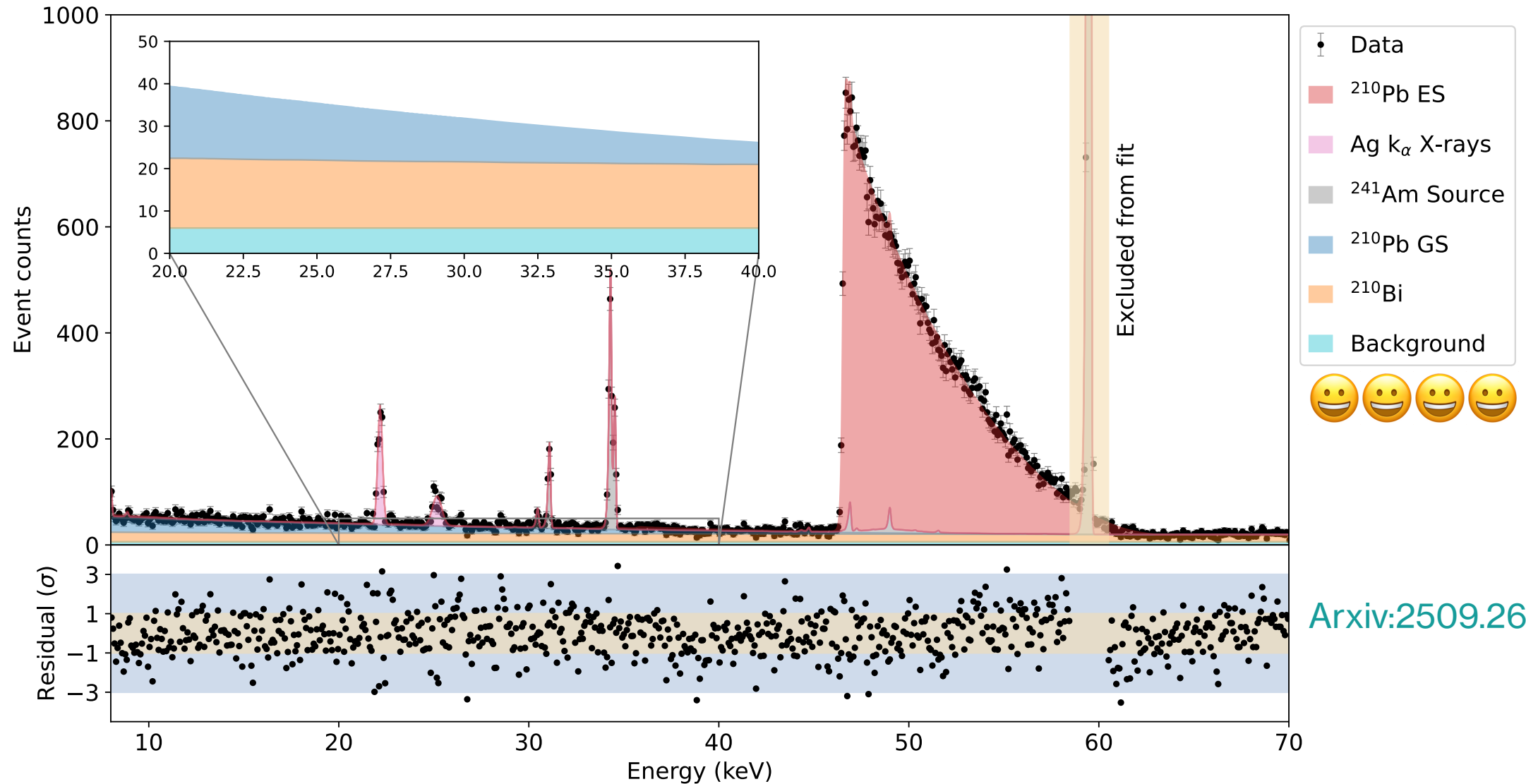
γ coincidence summing

Threshold-Free β measurement 😊😊

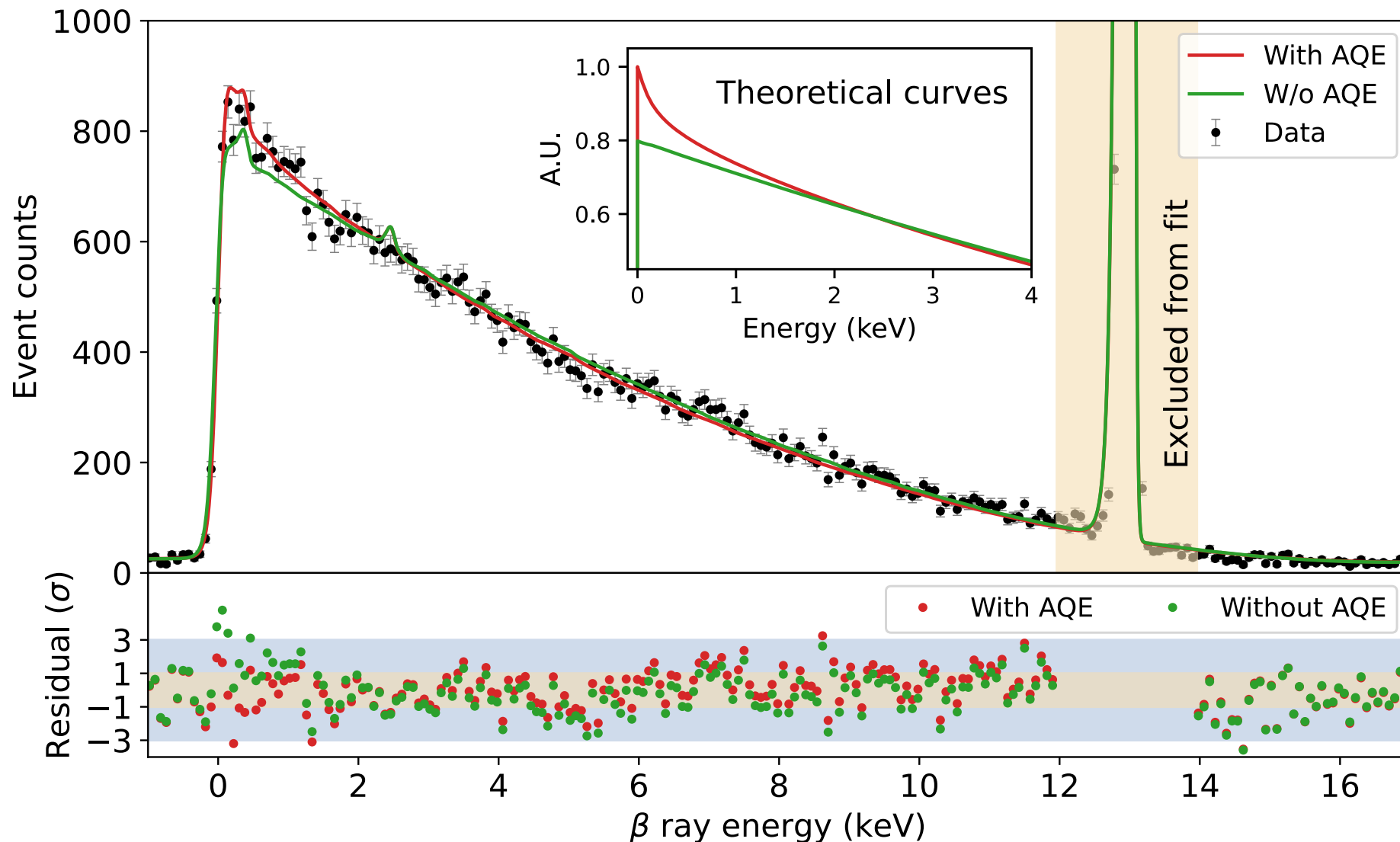


Arxiv:2509.26390

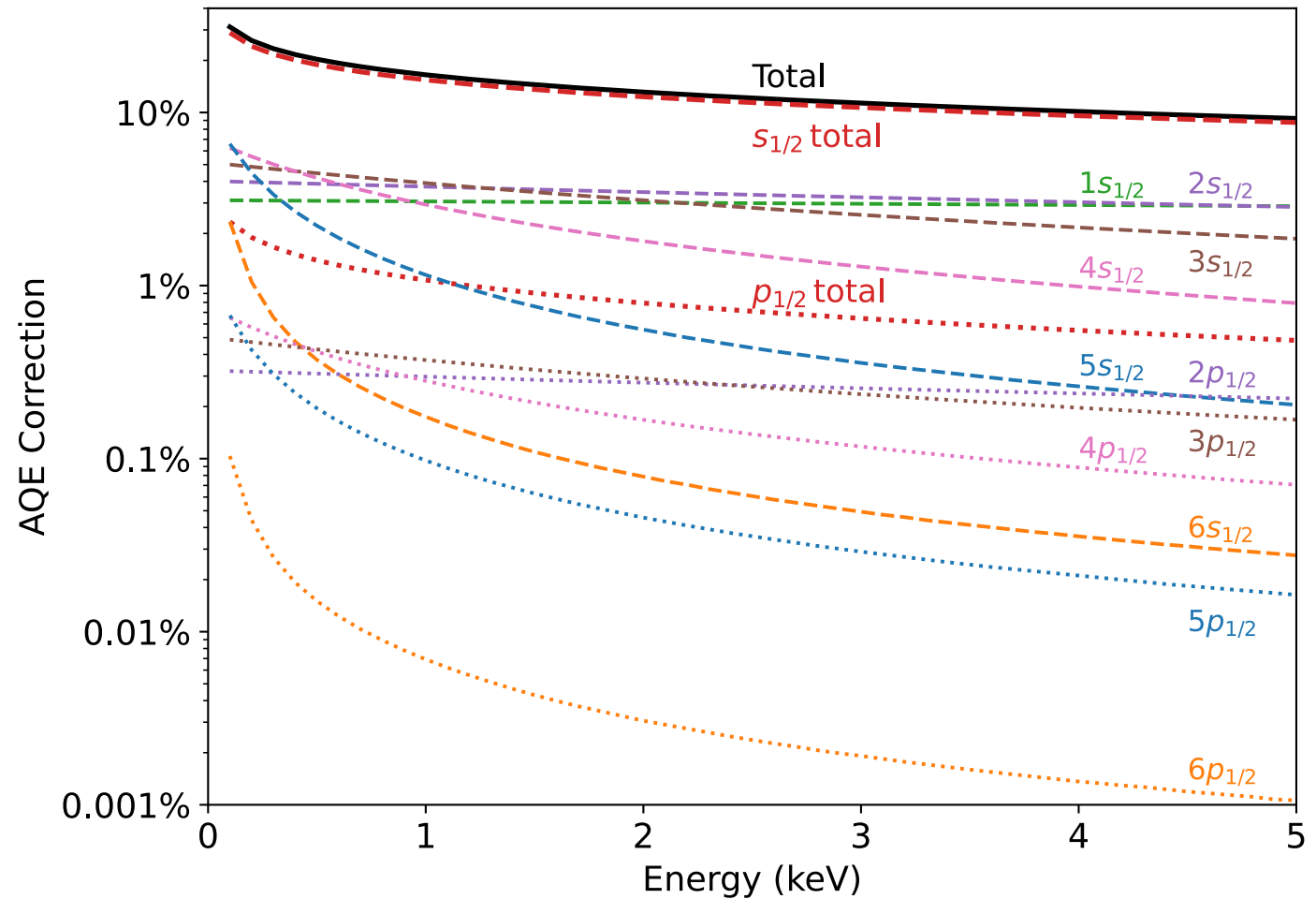
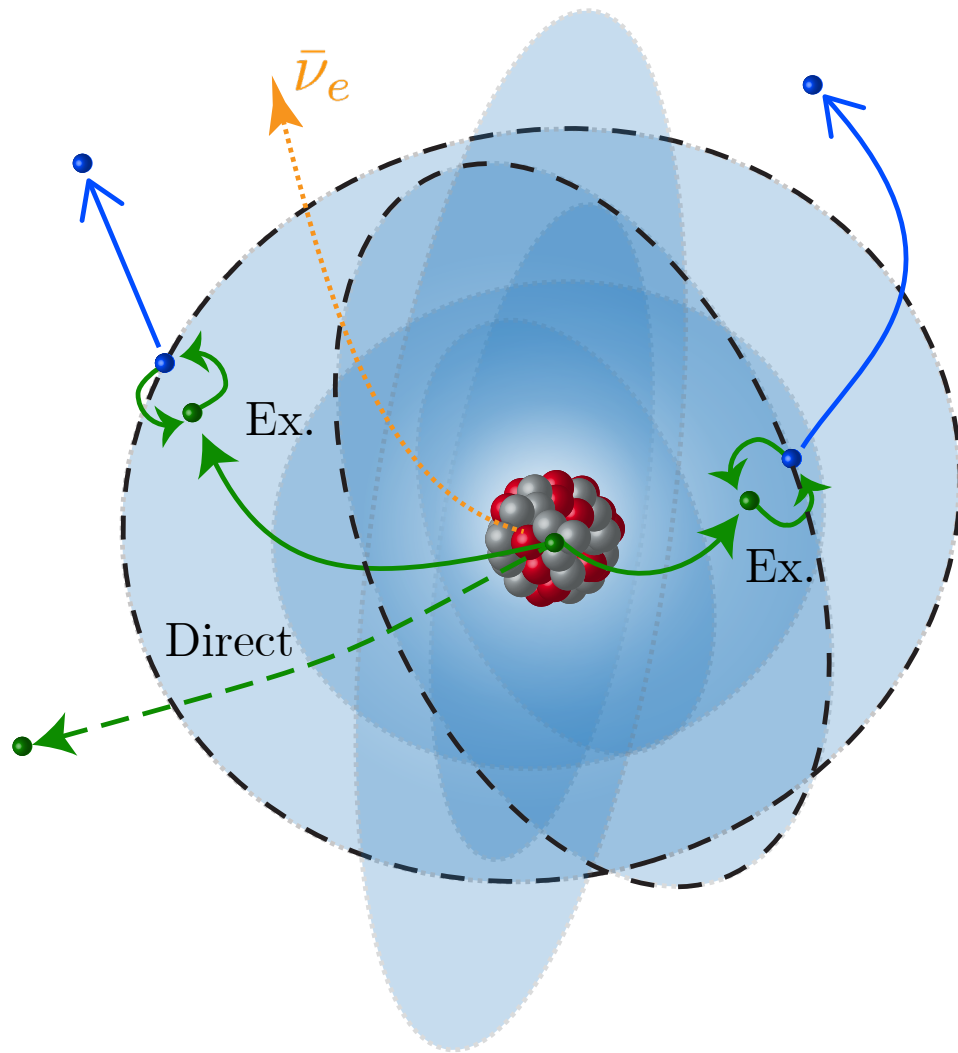
Multiple spectroscopic lines for calibration 😊😊😊



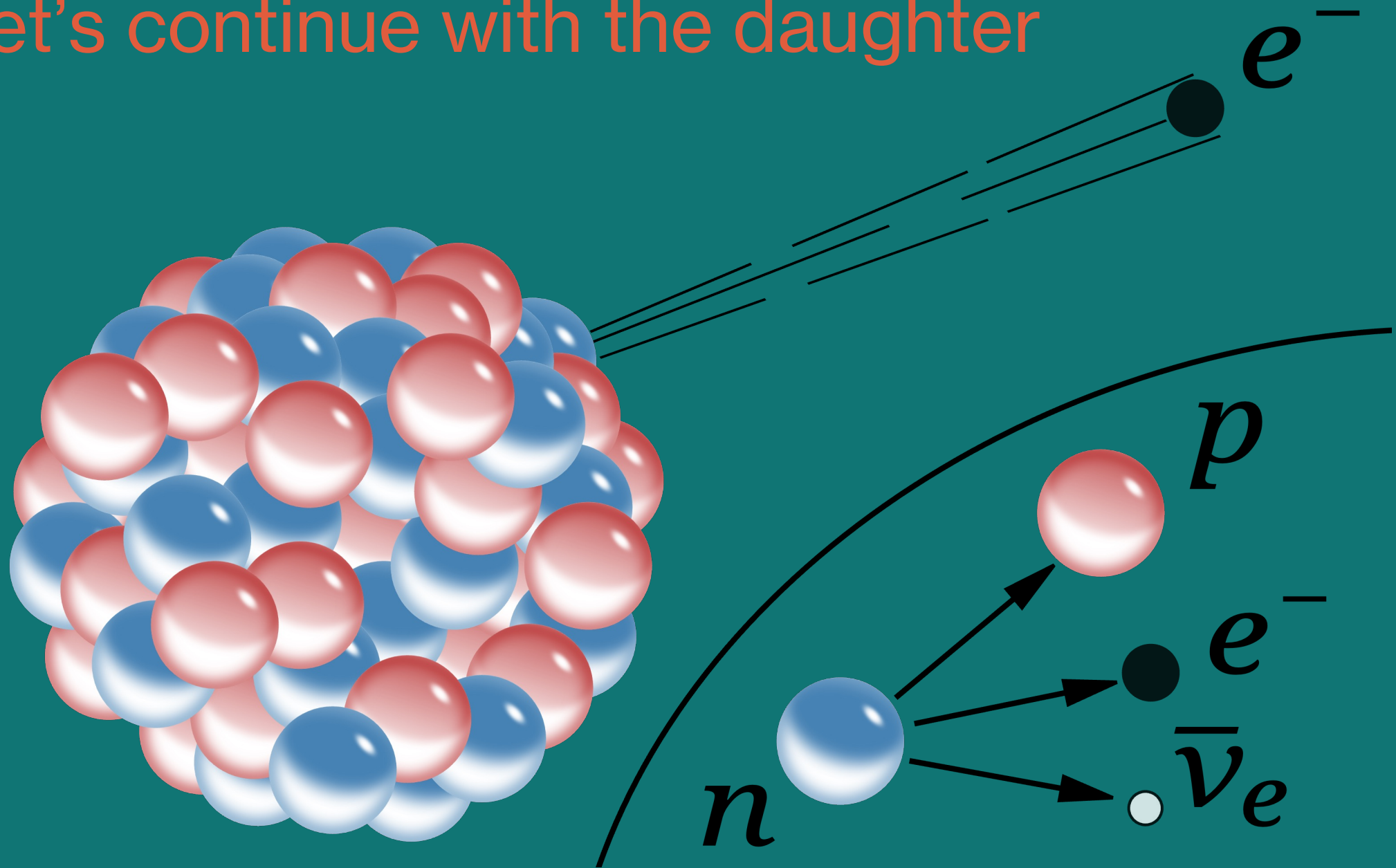
First complete, precision β decay spectrum from 0 keV



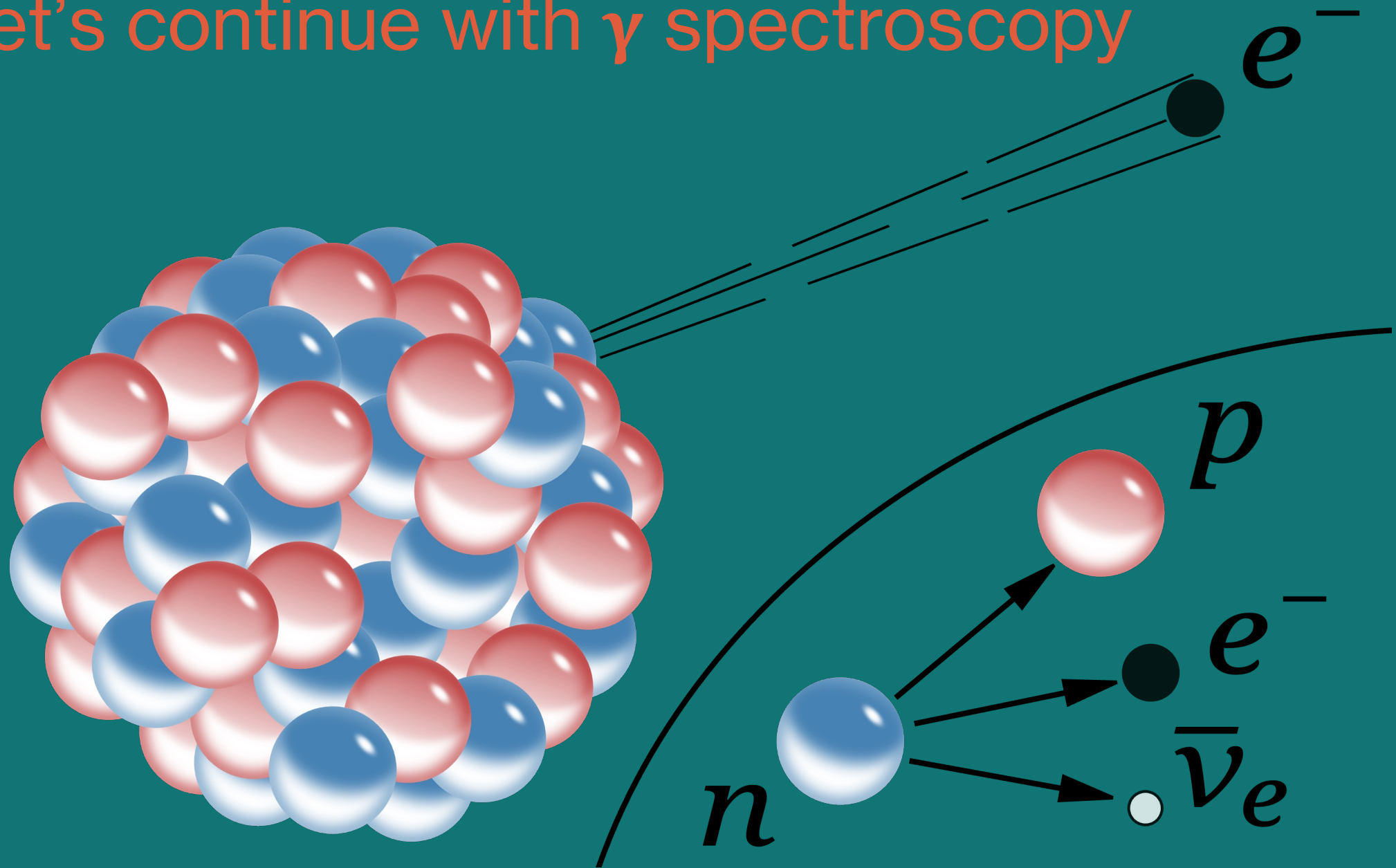
AQE: all orbits contribute positively

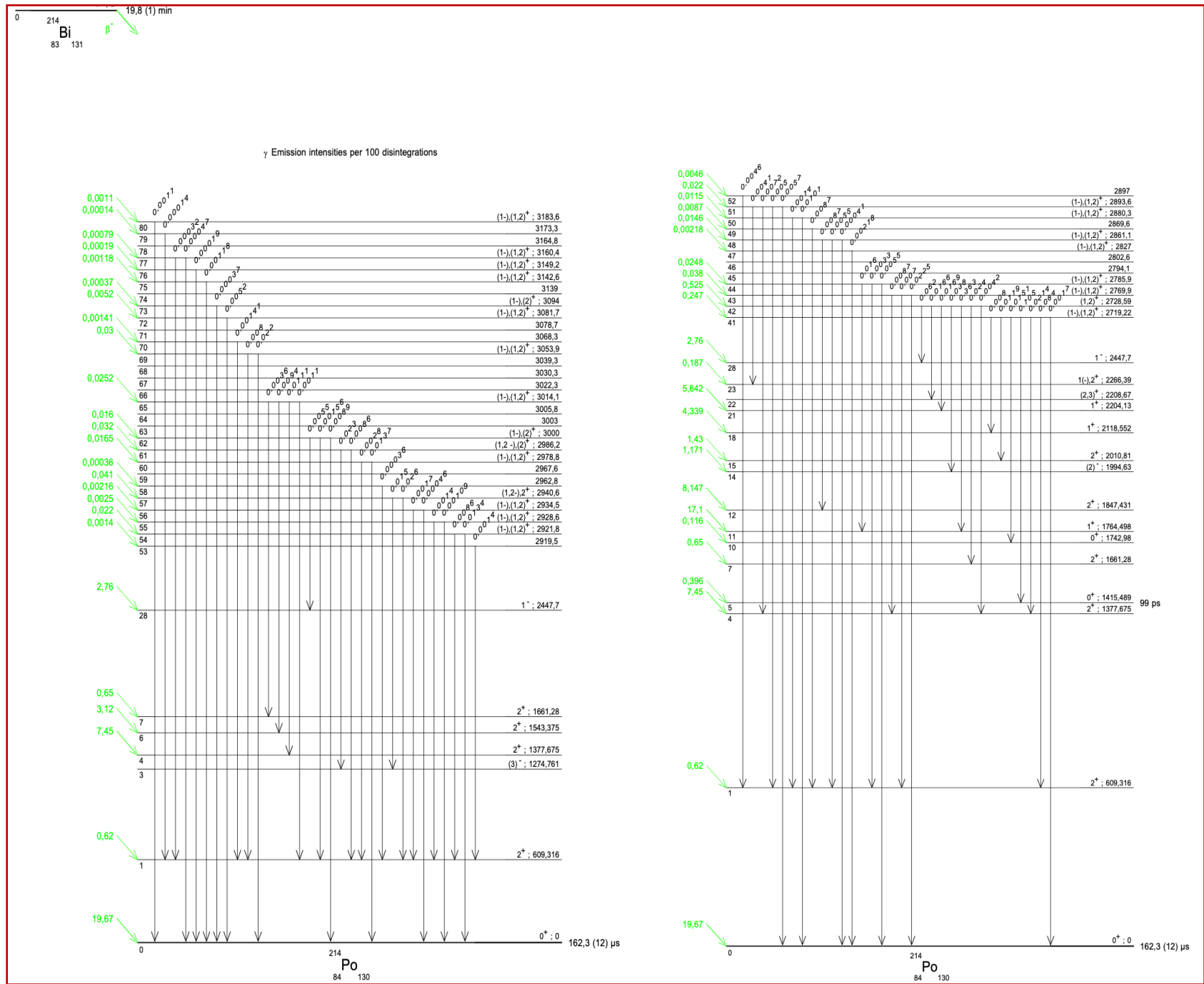
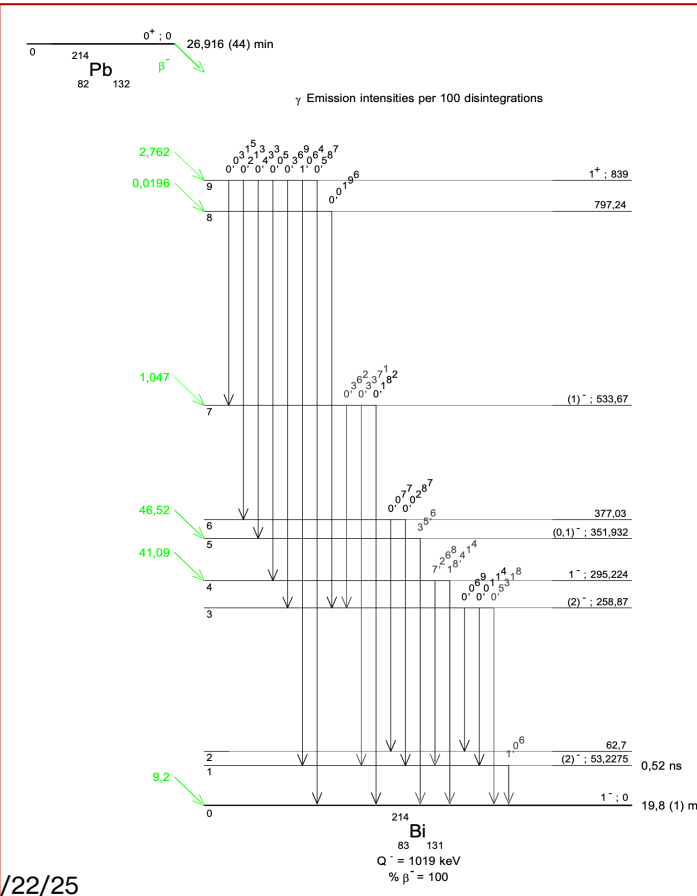


Let's continue with the daughter

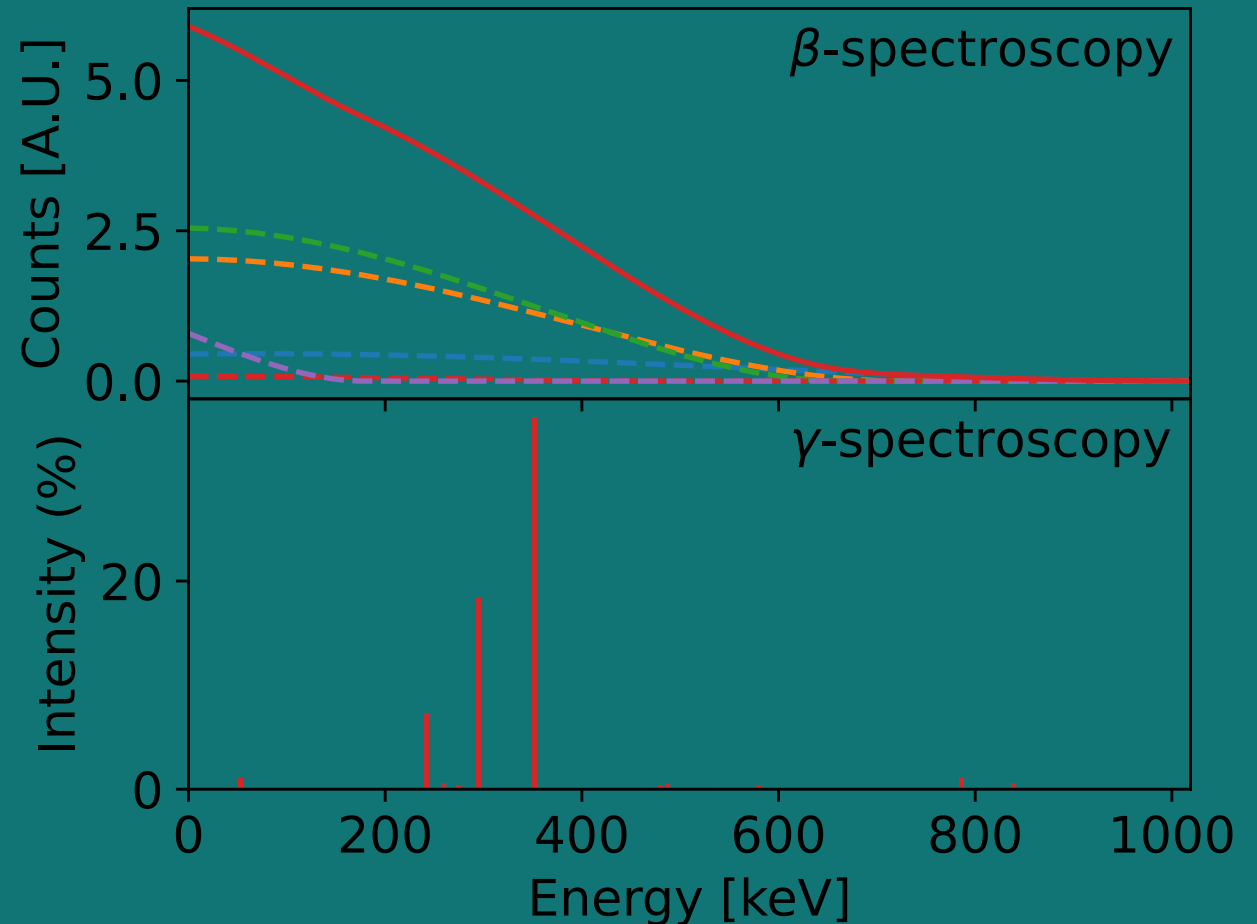
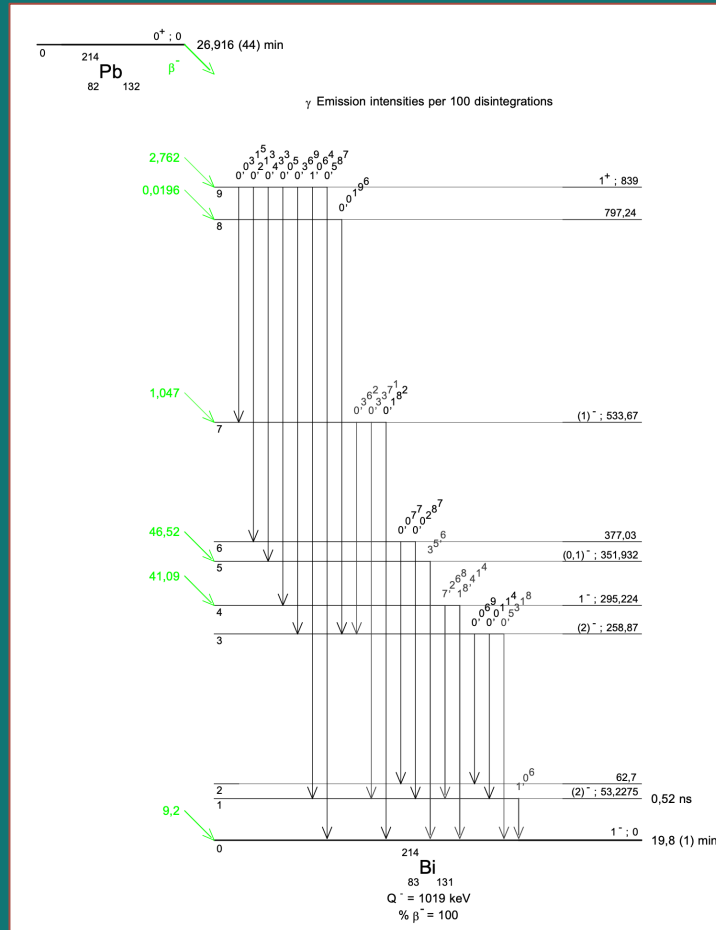


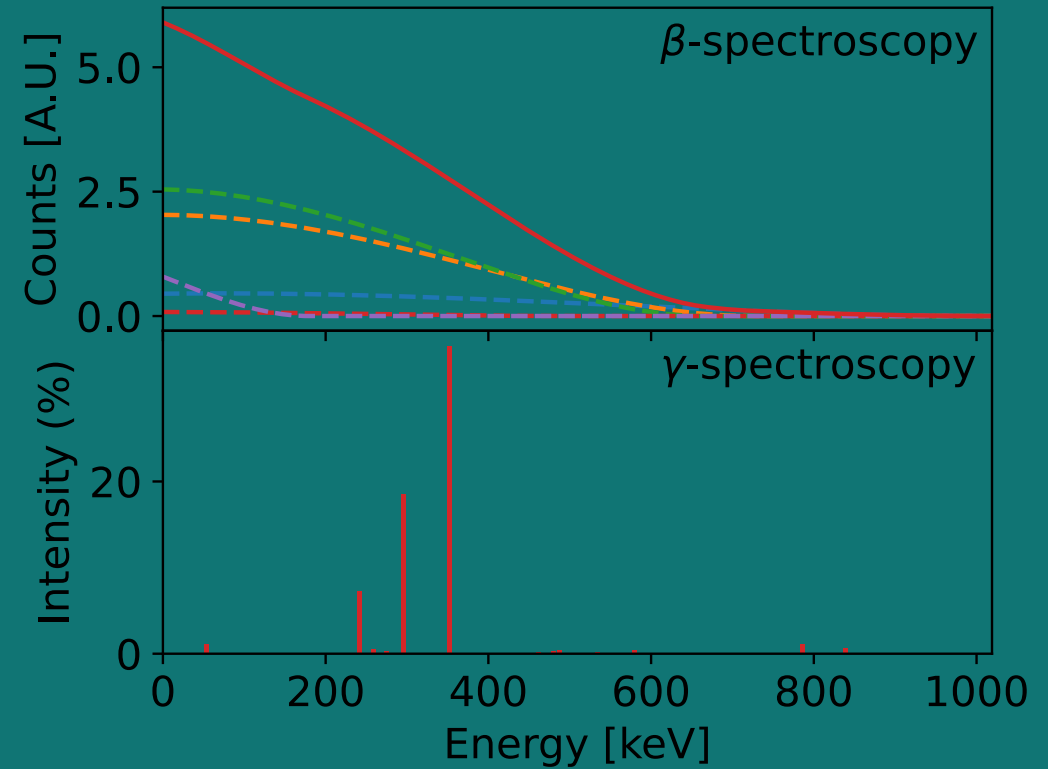
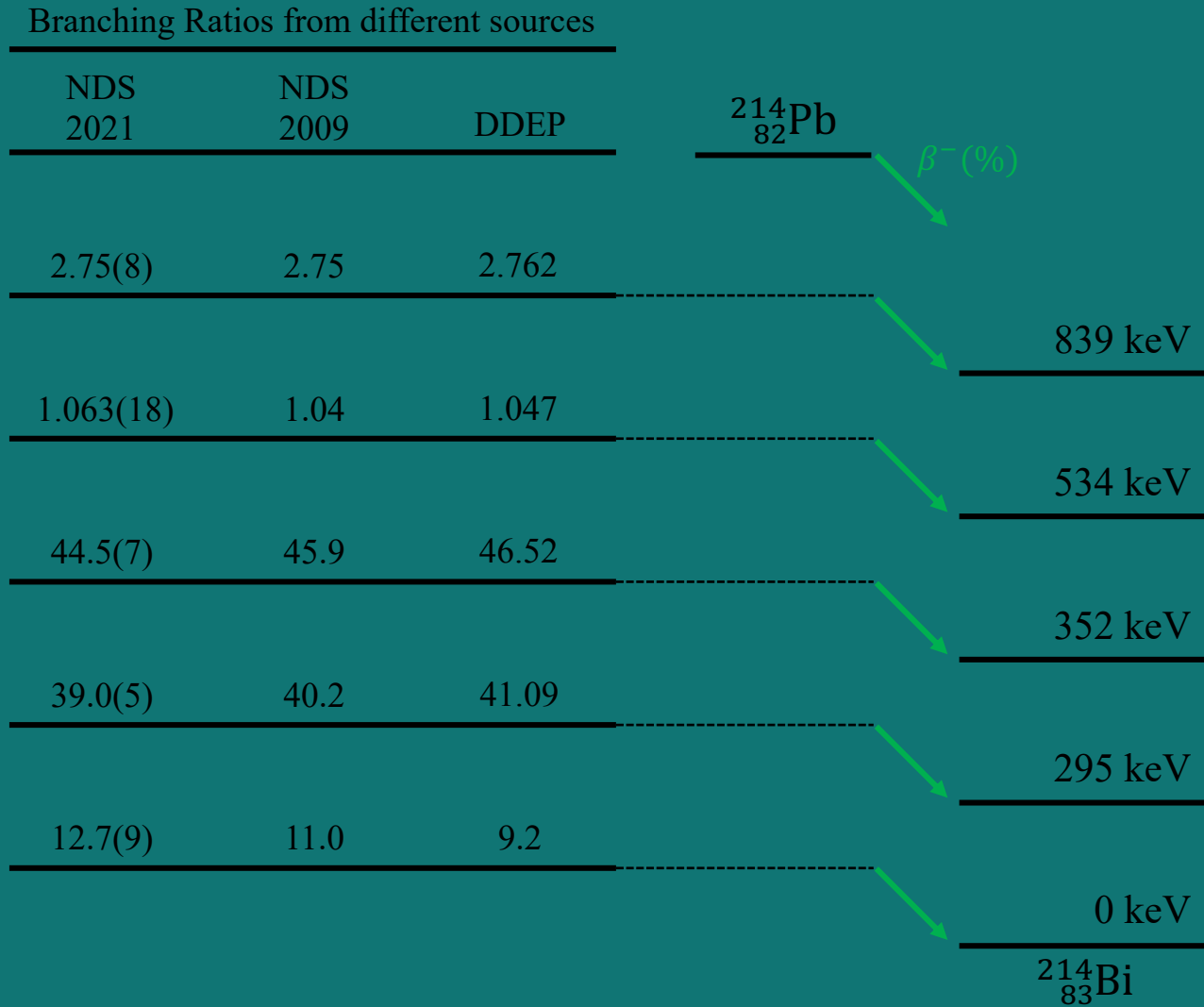
Let's continue with γ spectroscopy

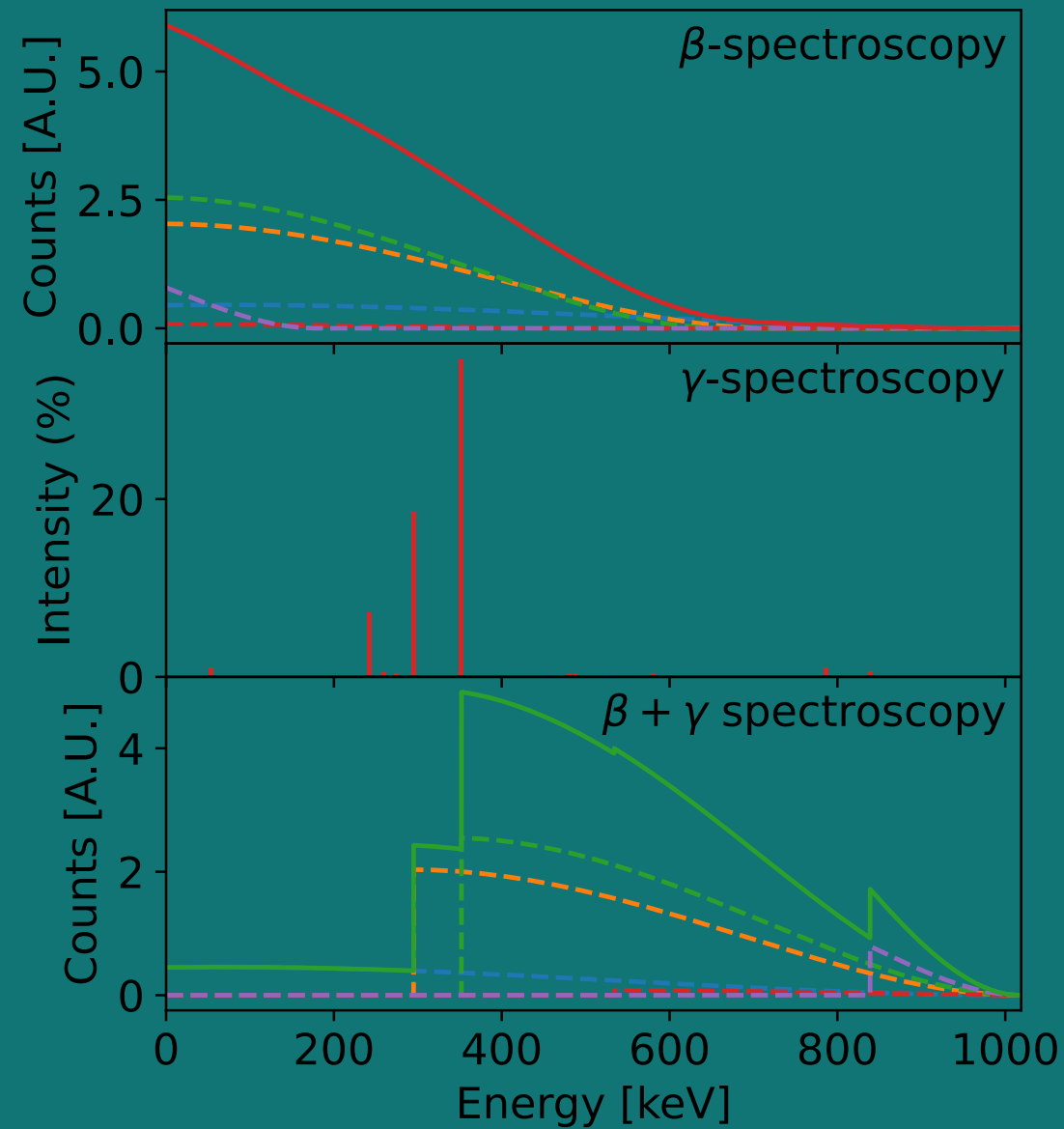
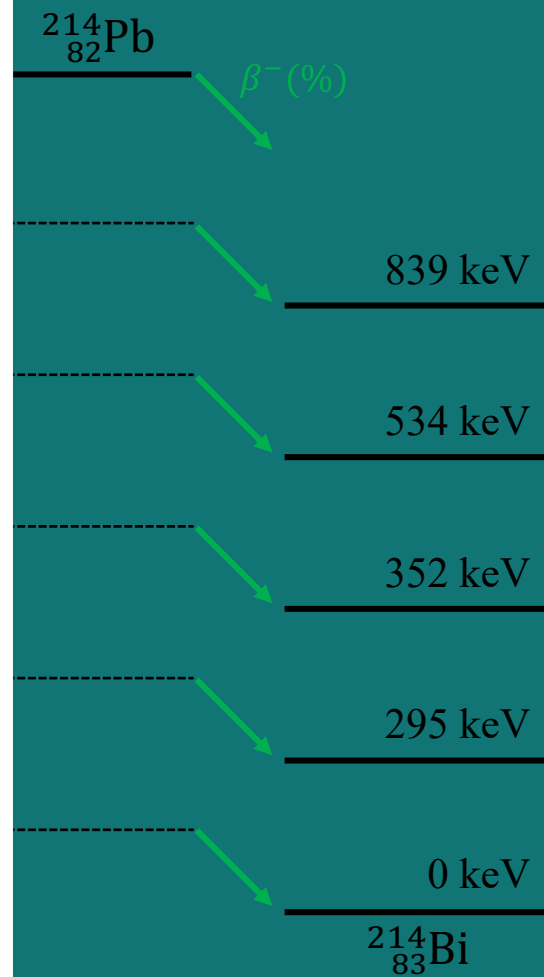
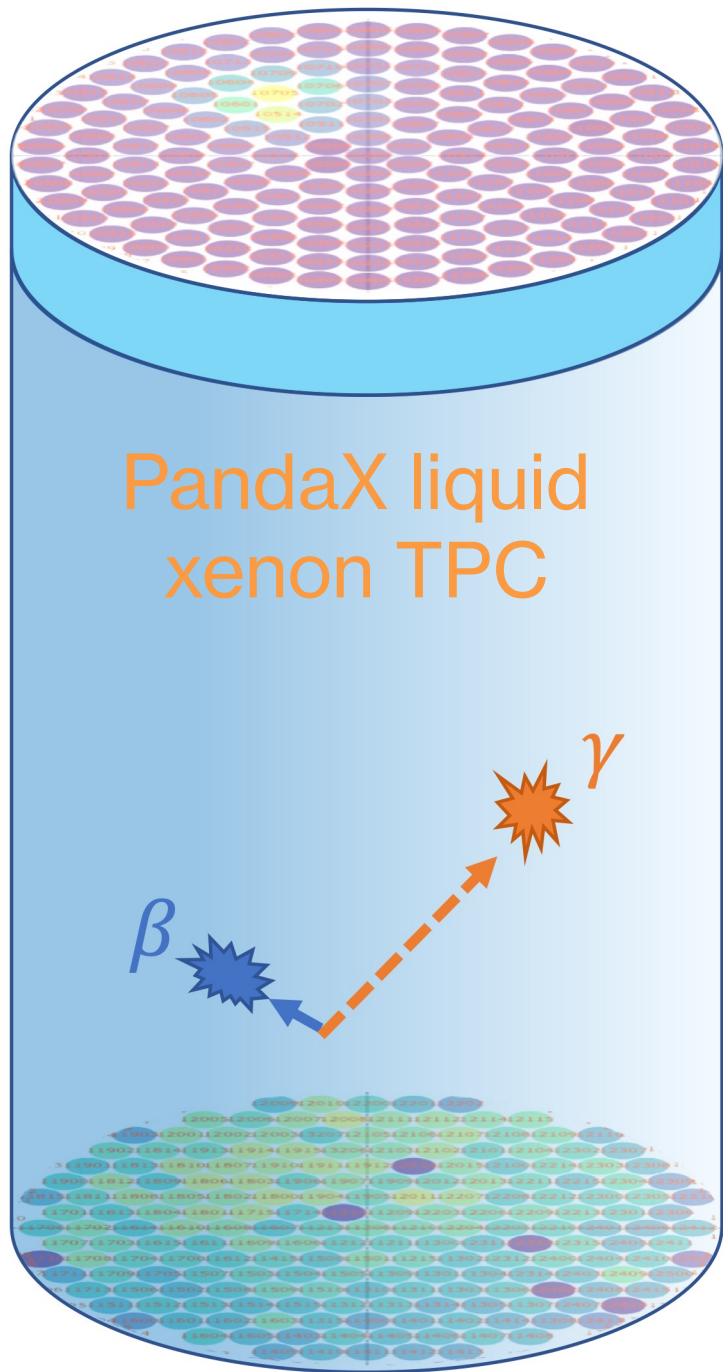




It is challenging to obtain a decay scheme from β spectroscopy or γ spectroscopy

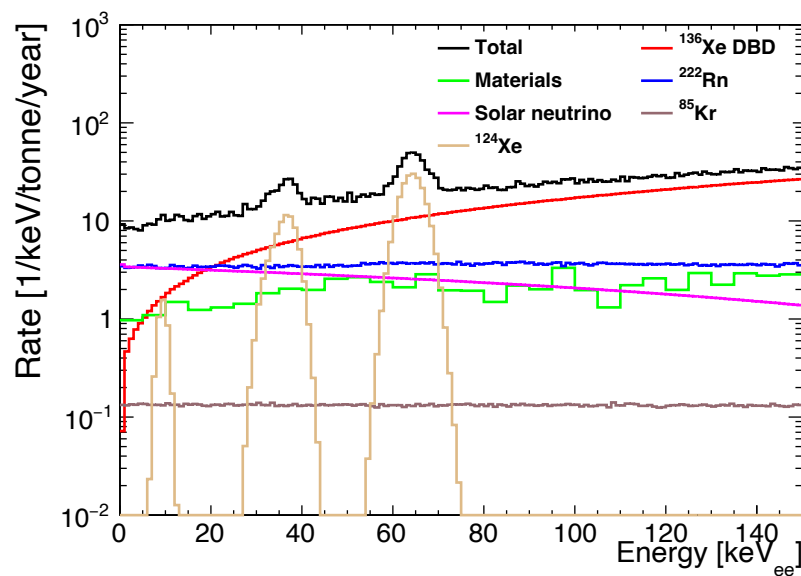




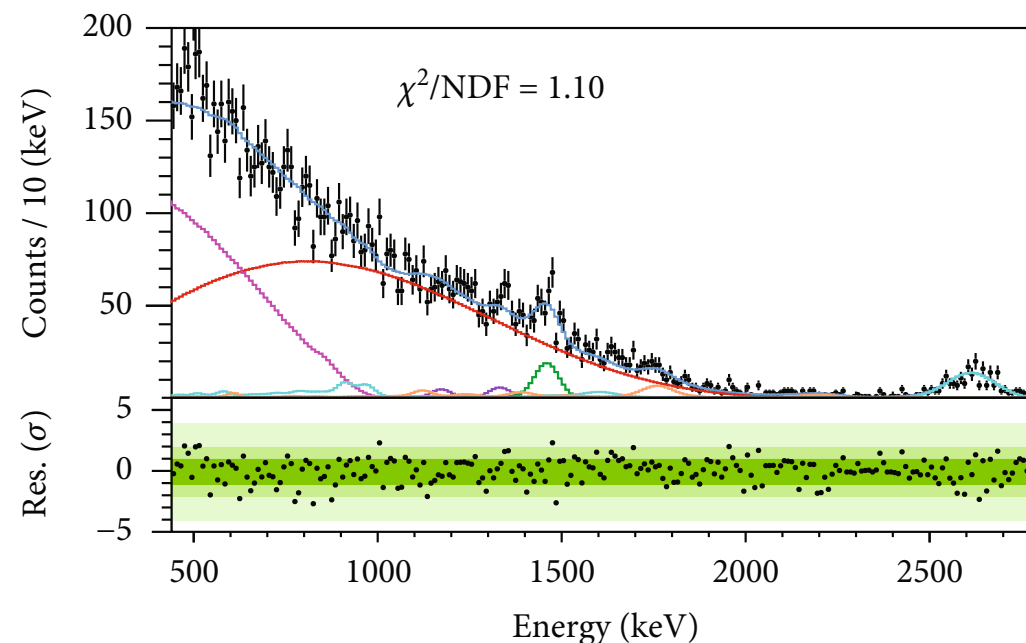


^{214}Pb β decay spectra are critical for LXe TPC

Internal background from ^{222}Rn , can not be removed except distillation



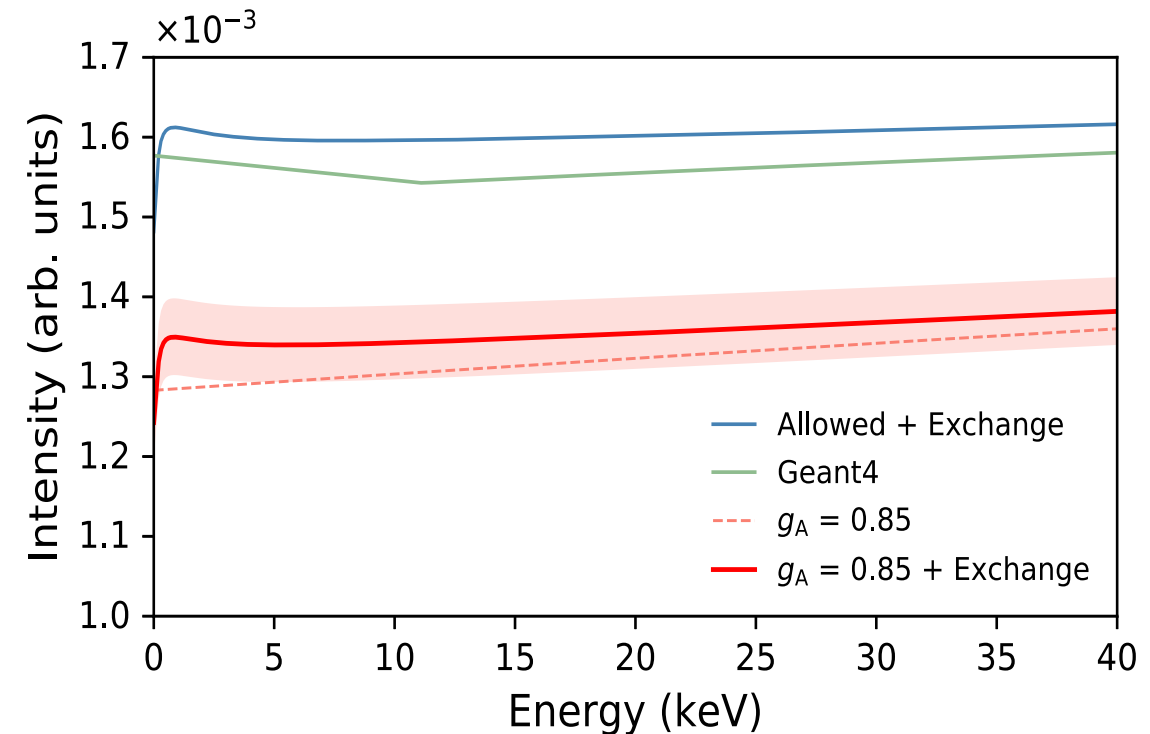
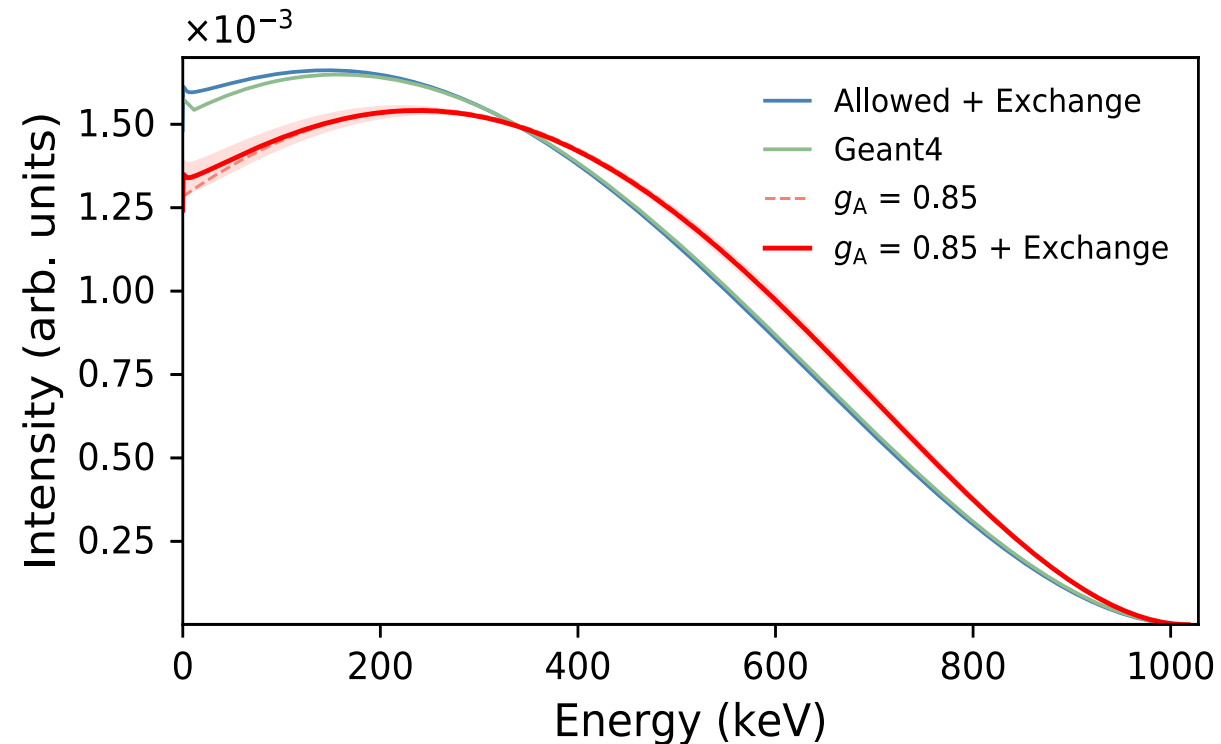
PandaX-xT, assuming $0.5 \mu\text{Bq/kg}$ ^{222}Rn



PandaX-4T DBD fit

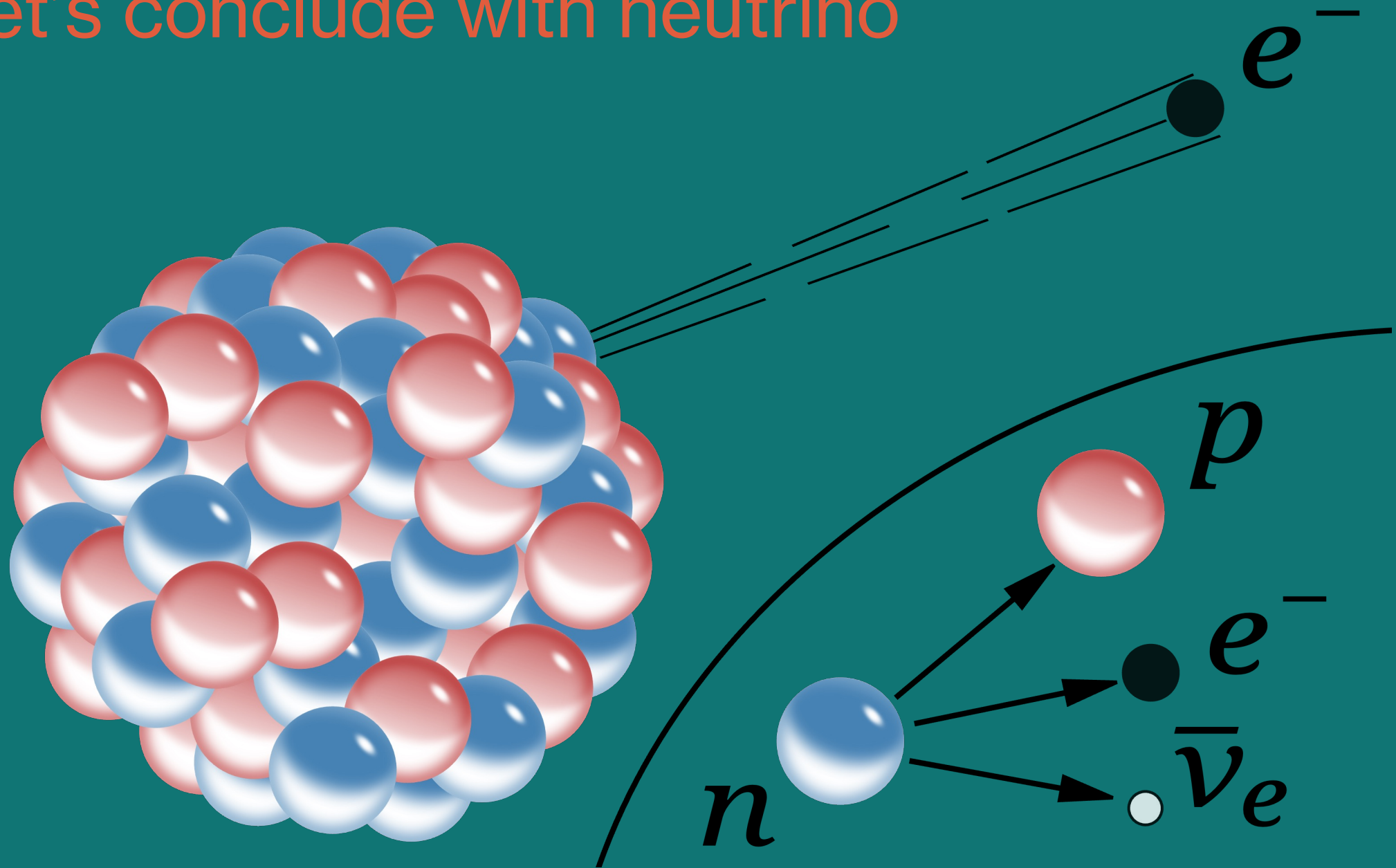
^{214}Pb spectral shape calculation depends on models and experimental inputs

Decays to GS, ES (295 and 534 keV): first-forbidden, non-unique decays

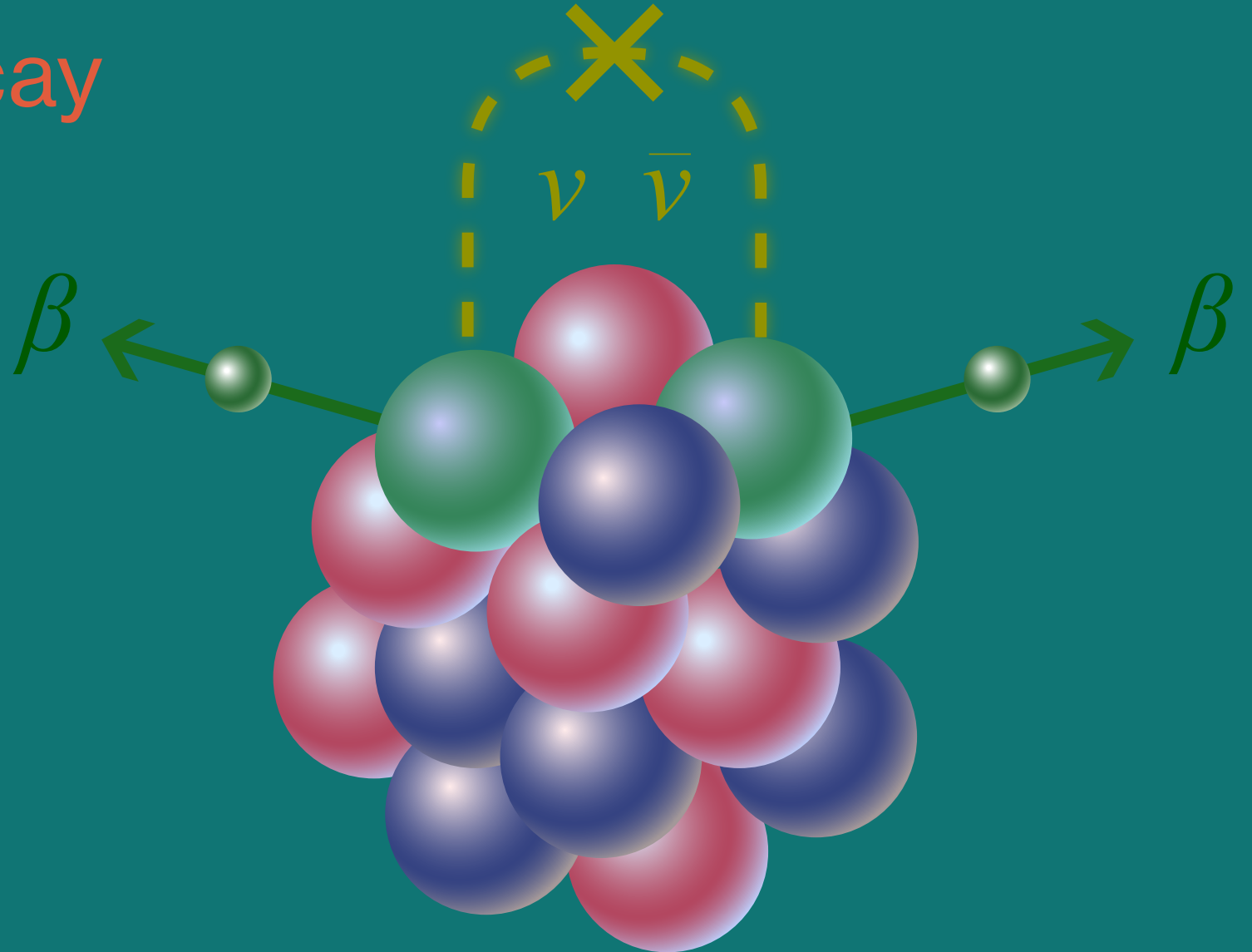


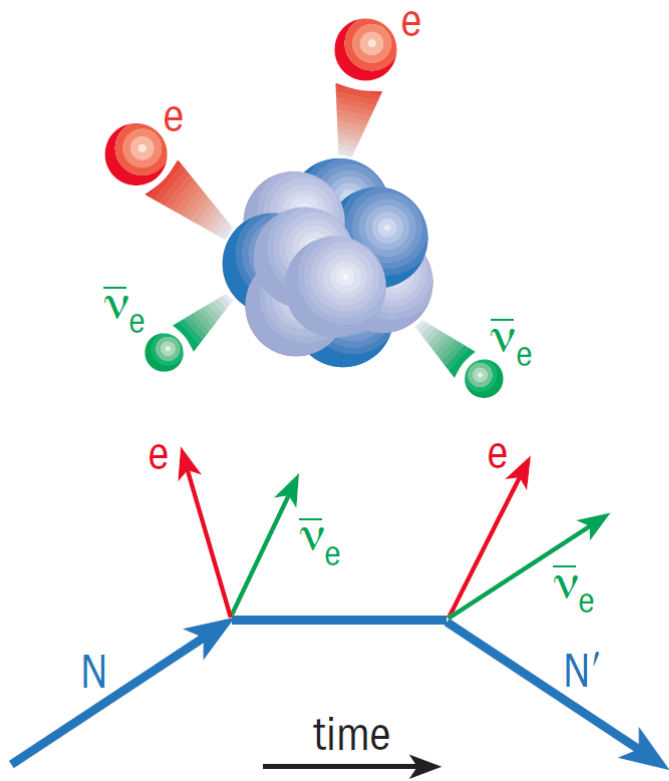
Haselschwardt et al. PRC 102, 065501 (2020) with NDS 2009 br.

Let's conclude with neutrino



Let's conclude with neutrinoless
double beta decay





Double beta decay milestones

Goeppert-Mayer (1935)

2 neutrino Double beta decay

Majorana (1937)

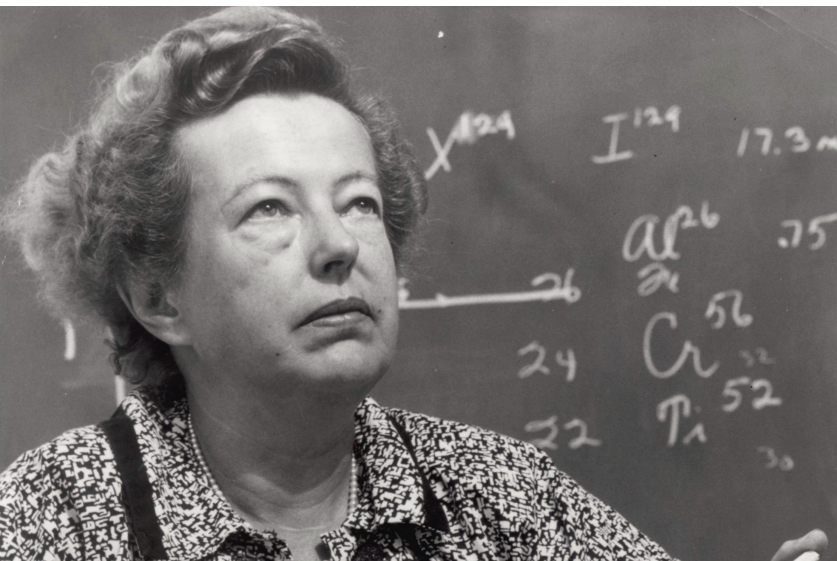
Neutrinos are the antiparticles of themselves

Furry (1939)

Neutrinoless double beta decay

Elliott, Hahn, Moe (1987)

Observation of $2\nu\beta\beta$ in a gas TPC



$$\bar{\nu} = \nu$$



Double beta decay milestones

Goeppert-Mayer (1935)

2 neutrino Double beta decay

Majorana (1937)

Neutrinos are the antiparticles of themselves

Furry (1939)

Neutrinoless double beta decay

Elliott, Hahn, Moe (1987)

Observation of $2\nu\beta\beta$ in a gas TPC

Double beta decay milestones

Goeppert-Mayer (1935)

2 neutrino Double beta decay

Majorana (1937)

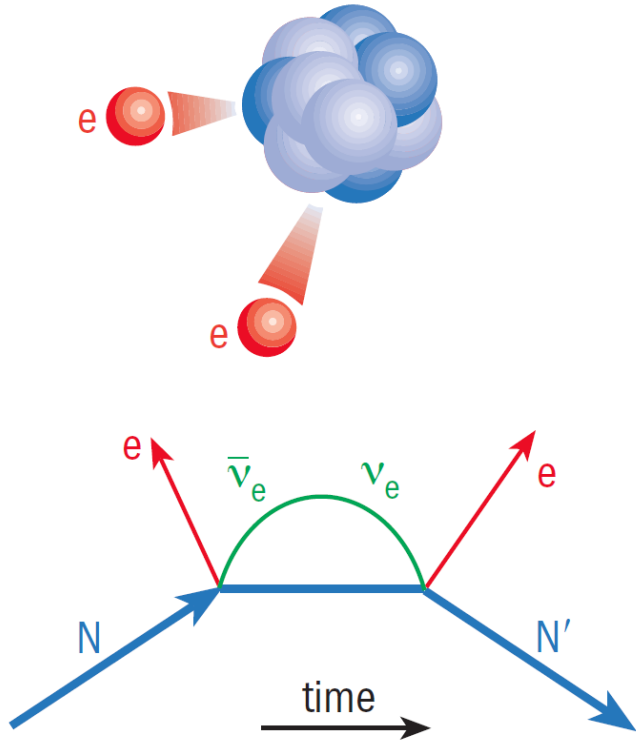
Neutrinos are the antiparticles of themselves

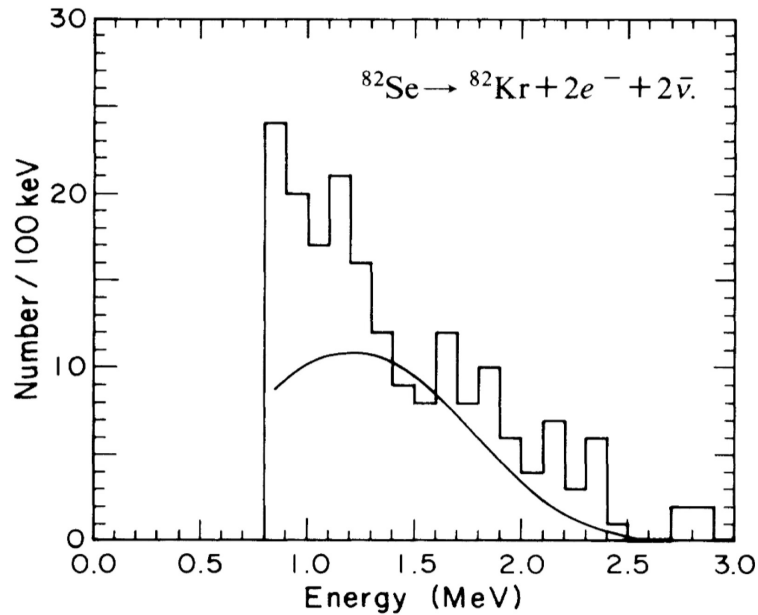
Furry (1939)

Neutrinoless double beta decay

Elliott, Hahn, Moe (1987)

Observation of $2\nu\beta\beta$ in a gas TPC





Double beta decay milestones

Goeppert-Mayer (1935)

2 neutrino Double beta decay

Majorana (1937)

Neutrinos are the antiparticles of themselves

Furry (1939)

Neutrinoless double beta decay

Elliott, Hahn, Moe (1987)

Observation of $2\nu\beta\beta$ in a gas TPC (call back to Wu, $^{214}\text{Pb/Bi}$)



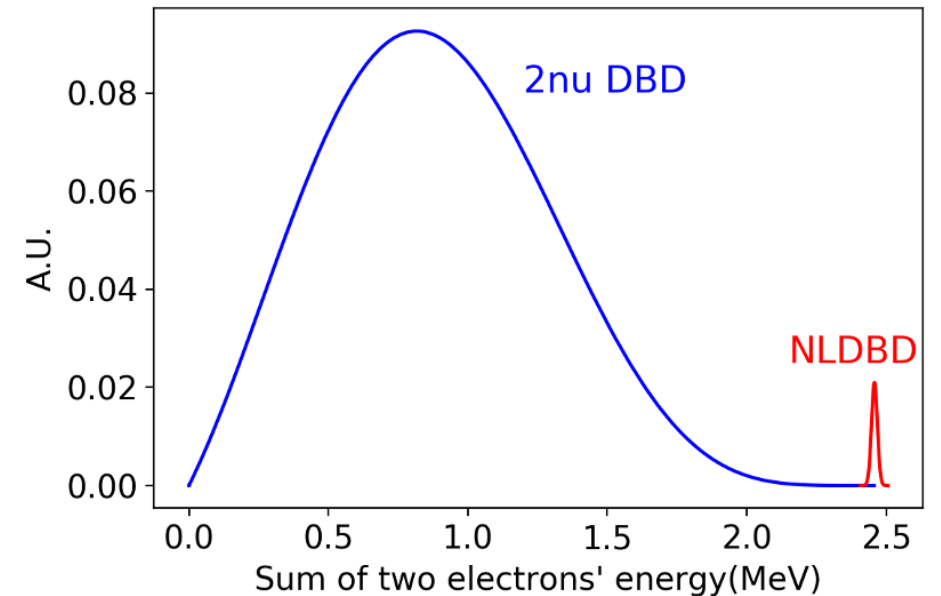
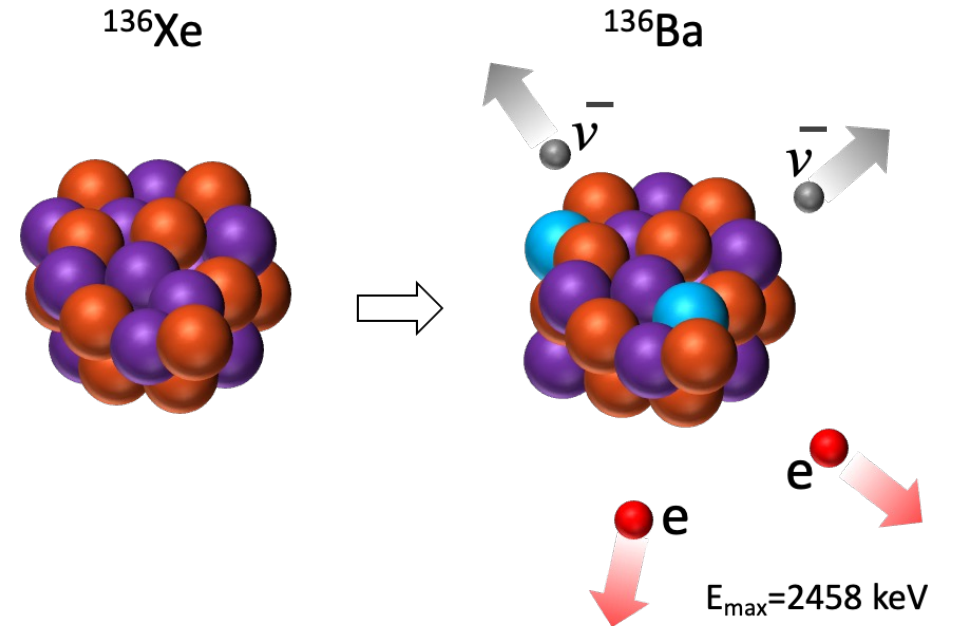
Experimental searches

- Detect the electrons
 - Energy
 - Trajectories
- Detect the daughter nuclei
 - Geochemical and radiochemical
 - Imaging

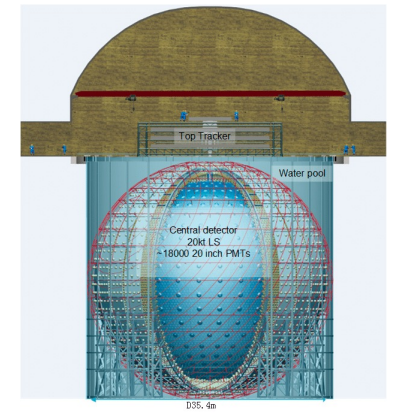
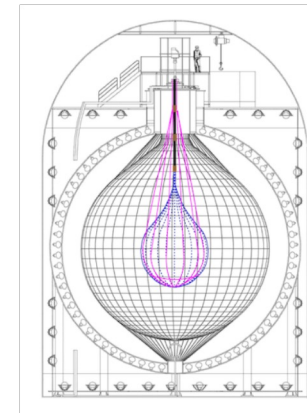
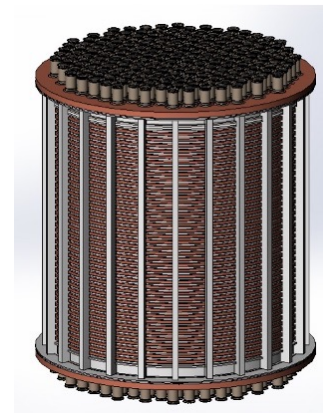
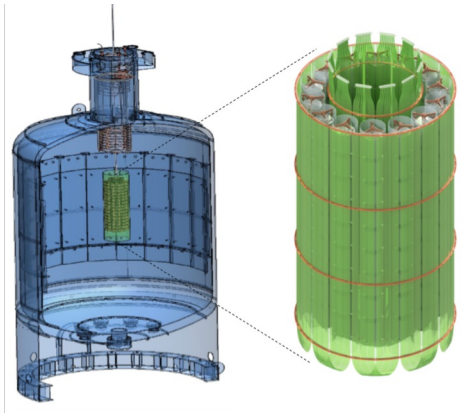
$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu}(Q, Z) |M^{0\nu}|^2 \frac{|\langle m_{\beta\beta} \rangle|^2}{m_e^2}$$

Phase space factor

Nuclear matrix element

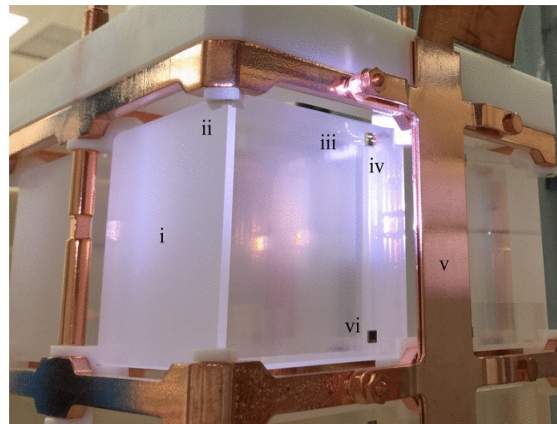
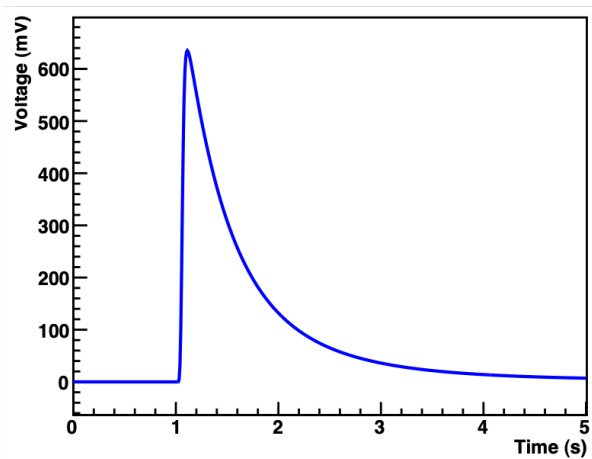


Solid state detector arrays	Gas/liquid detectors
CUORE/CUPID	KamLAND-ZEN
LEGEND	nEXO
CDEX	PandaX
CUPID-CJPL	NvDEX
	JUNO- $0\nu\beta\beta$

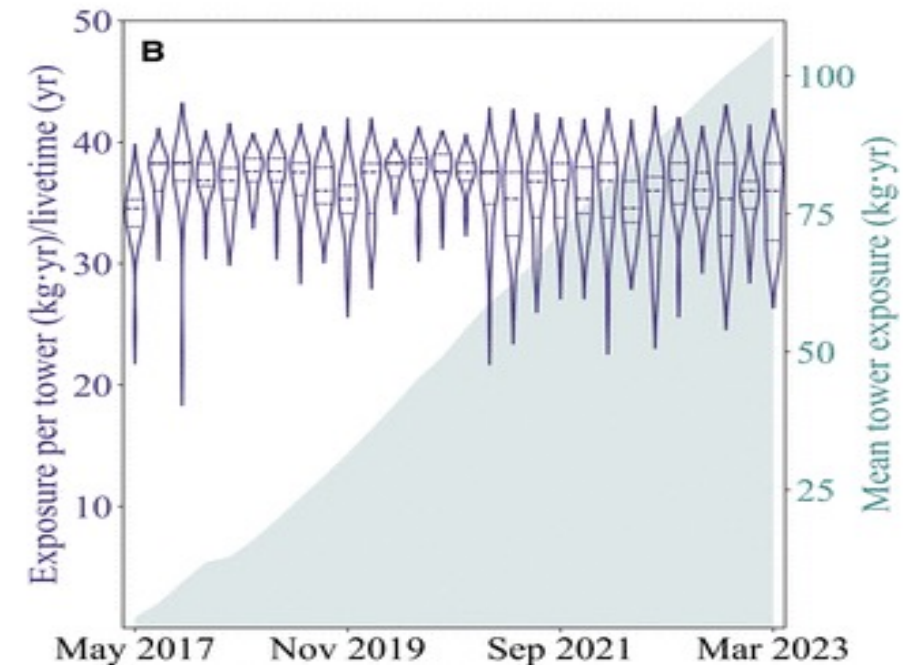
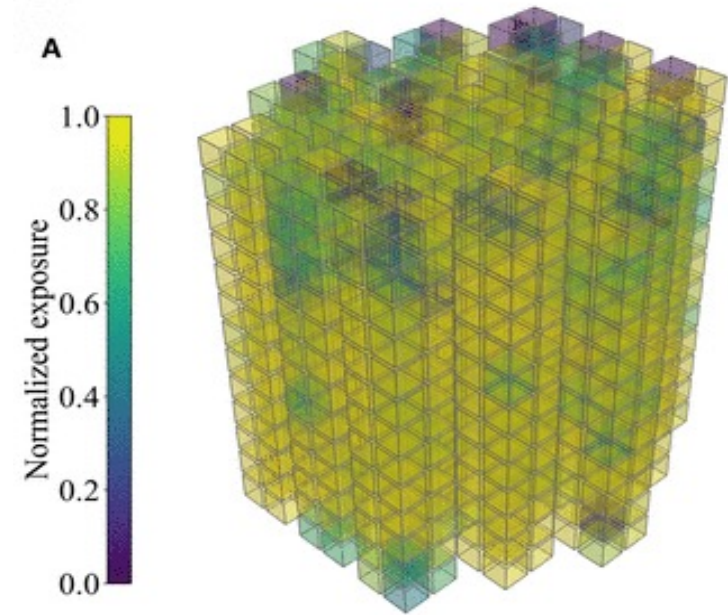


CUORE bolometer array

- Search for $0\nu\beta\beta$ of ^{130}Te
- 988 TeO_2 crystals as a bolometer array
 - 19 Towers
 - 13 floors
 - 4 modules per floor

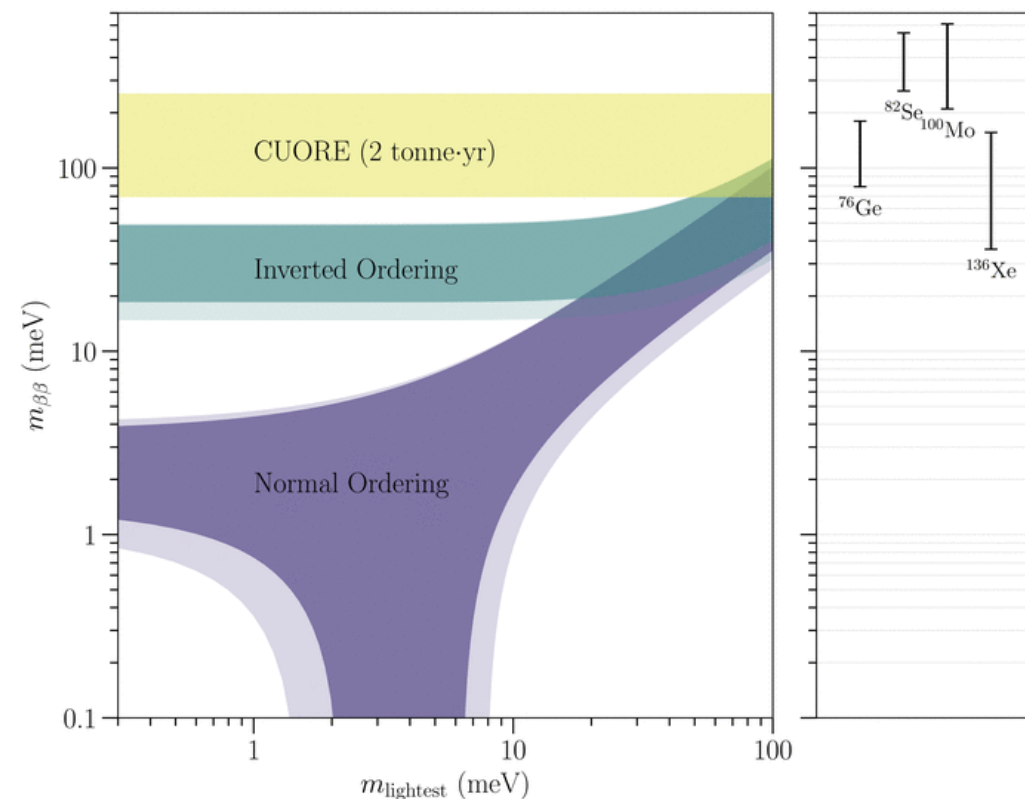
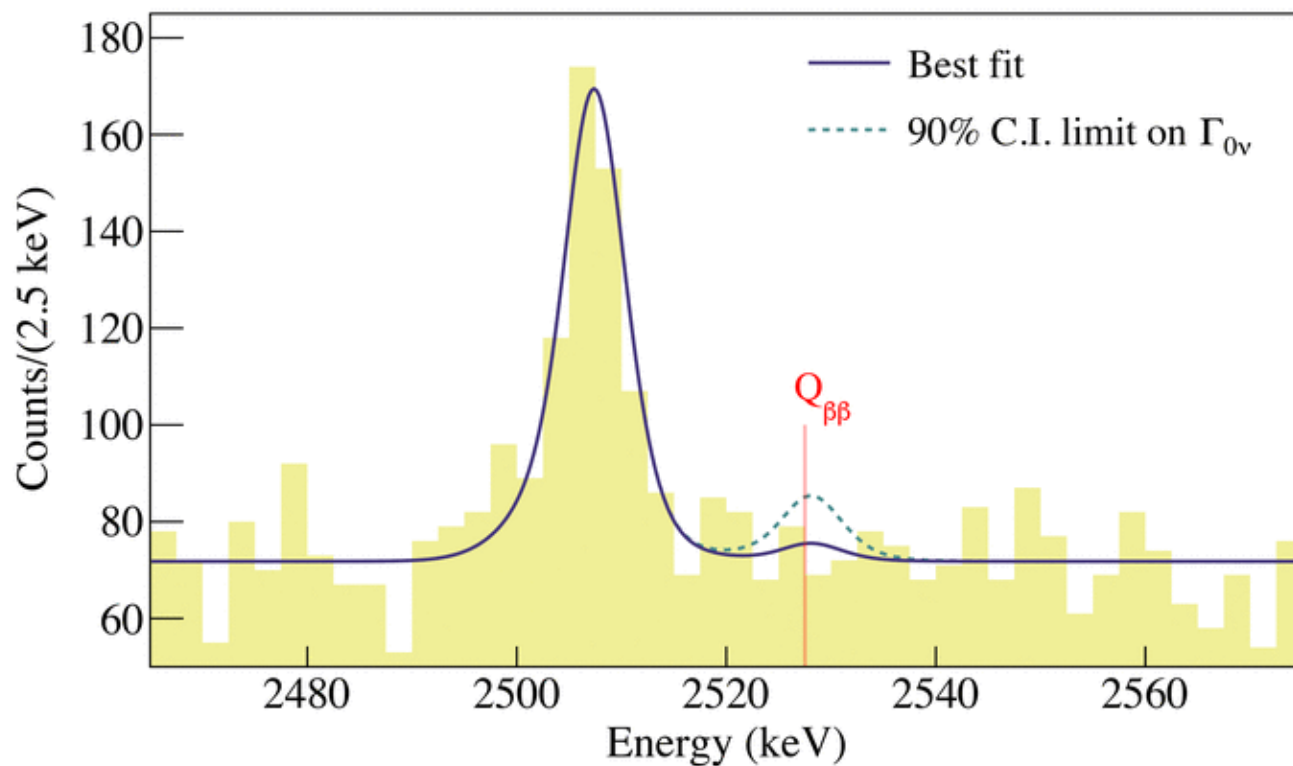


Constraints on lepton number violation with the 2 tonne · year CUORE Dataset, DOI: (10.1126/science.adp6474)



Constraints on lepton number violation with the 2 tonne · year CUORE Dataset

DOI: (10.1126/science.adp6474)



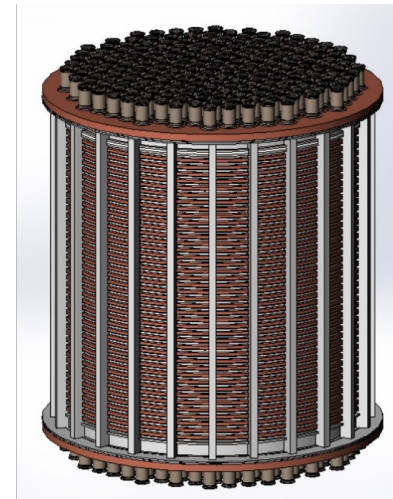
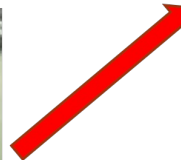
PandaX detectors



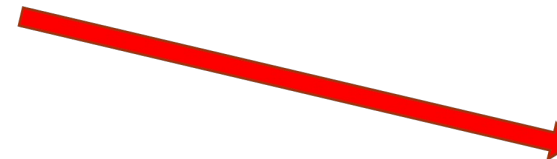
PandaX-I: 120kg
LXe (2009 – 2014)



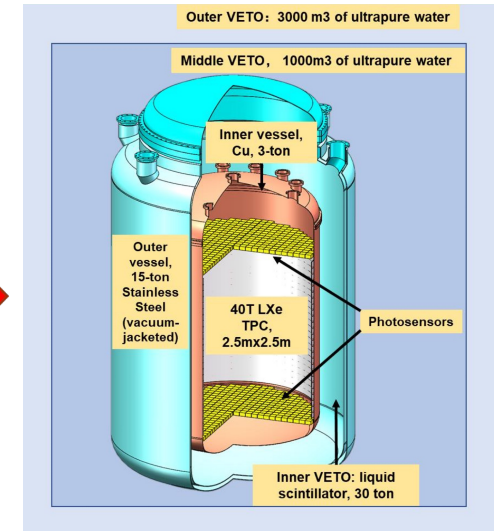
PandaX-II: 500kg
LXe (2014 – 2018)



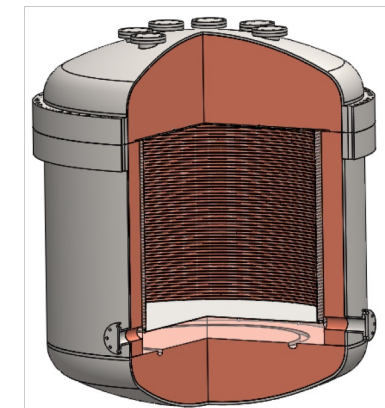
PandaX-4T LXe
(2020-)



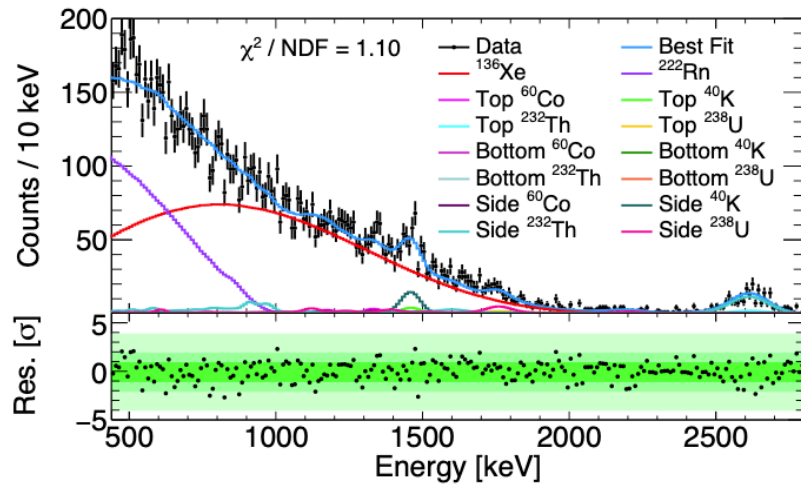
PandaX-III: 100kg - 1 ton
HPXe for $0\nu\beta\beta$ (future)



PandaX-xT LXe
(future)

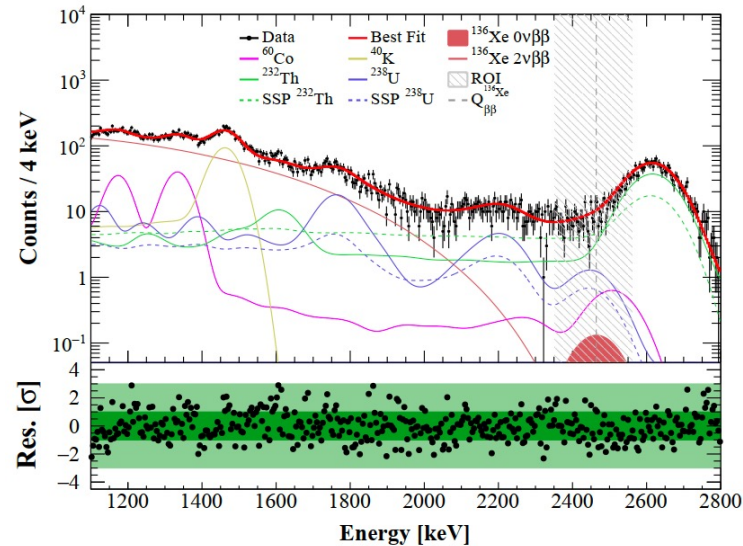


Recent PandaX-4T double beta decay results



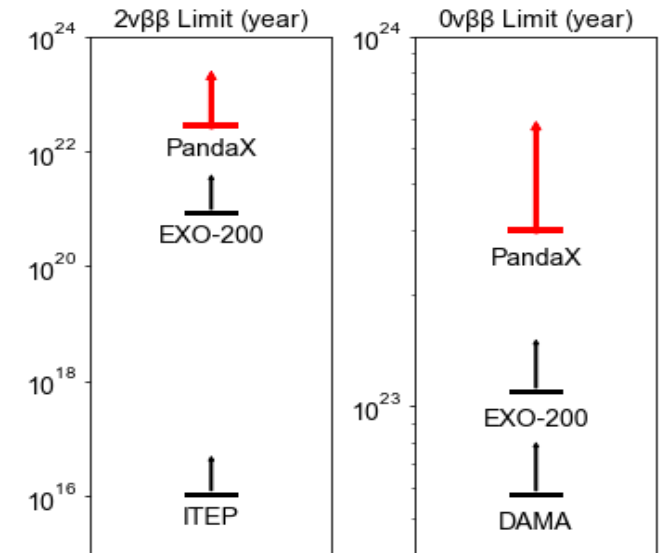
$^{136}\text{Xe } 2\nu\beta\beta$ half-life: $2.27 \pm 0.03(\text{stat.}) \pm 0.09(\text{syst.}) \times 10^{21} \text{ yr}$

Research, 9798721 (2022)



$^{136}\text{Xe } 0\nu\beta\beta$ half-life $> 2.1 \times 10^{24} \text{ yr}$ (90% C.L.)
 $m_{\beta\beta} < (0.4 - 1.6) \text{ eV}$

Science Bulletin 70, 1779 (2025)

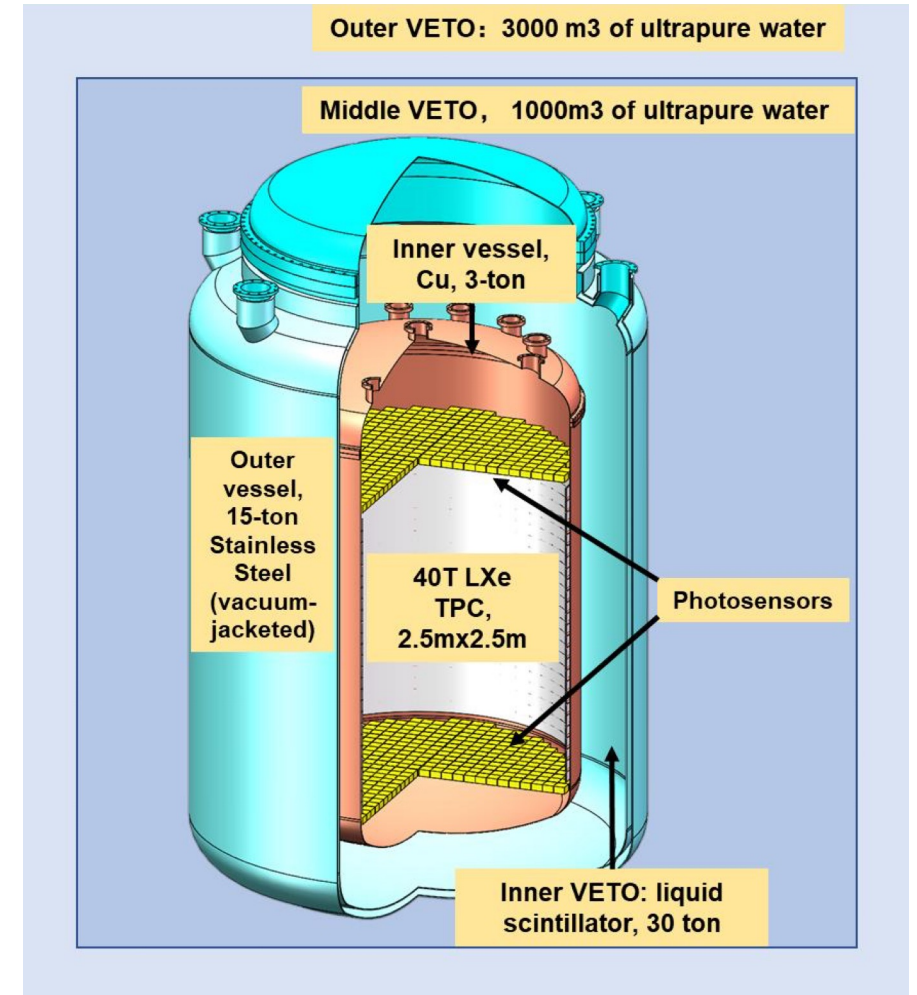


The most stringent ^{136}Xe $2\nu\beta\beta$ and $0\nu\beta\beta$ half-life limits

PRL 132, 152502 (2024)

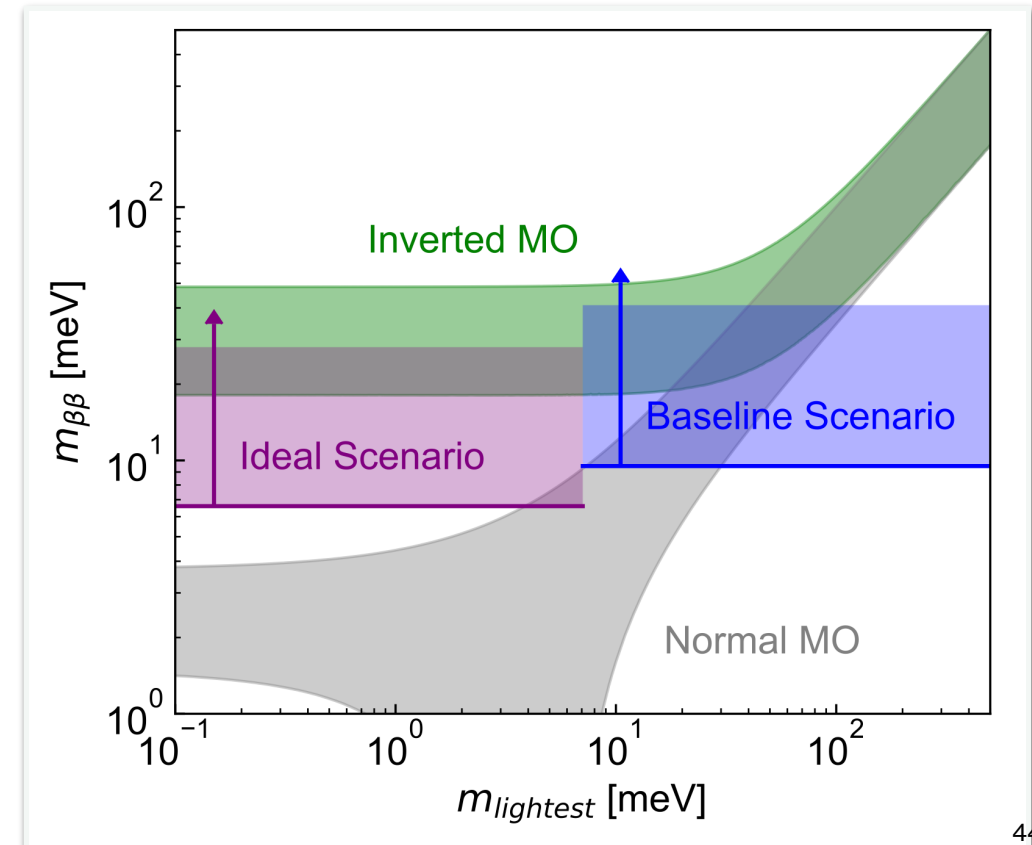
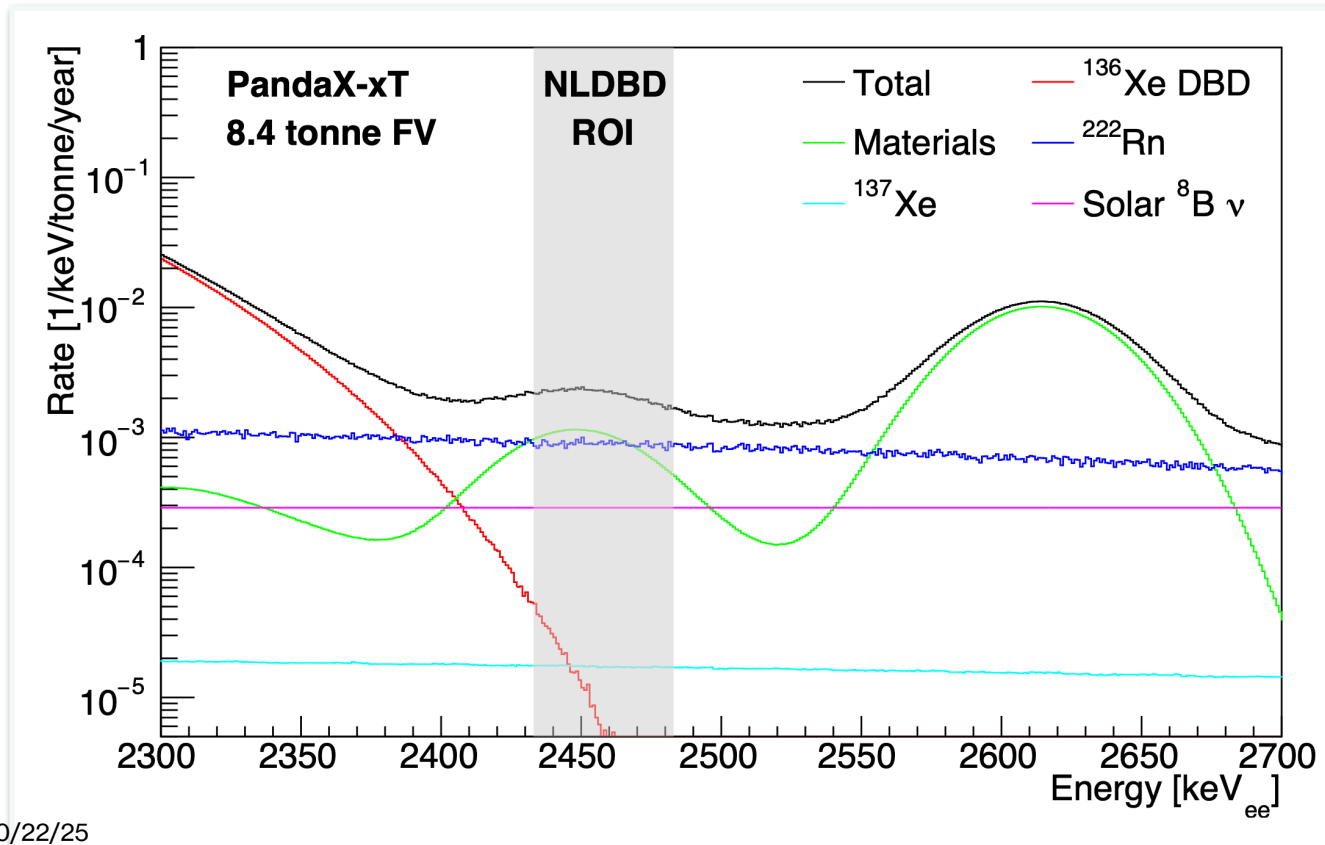
PandaX-xT: Multi-ten-tonne Liquid Xenon Observatory

- Active target: 43 ton of Xenon
 - Decisive test to the WIMP paradigm
 - Explore the Dirac/Majorana nature of neutrino
 - Search for astrophysical or terrestrial neutrinos and other ultra-rare interactions
- Improved PMT, veto, vessel radiopurity, etc
- Staged upgrade utilizing isotopic separation on natural xenon.



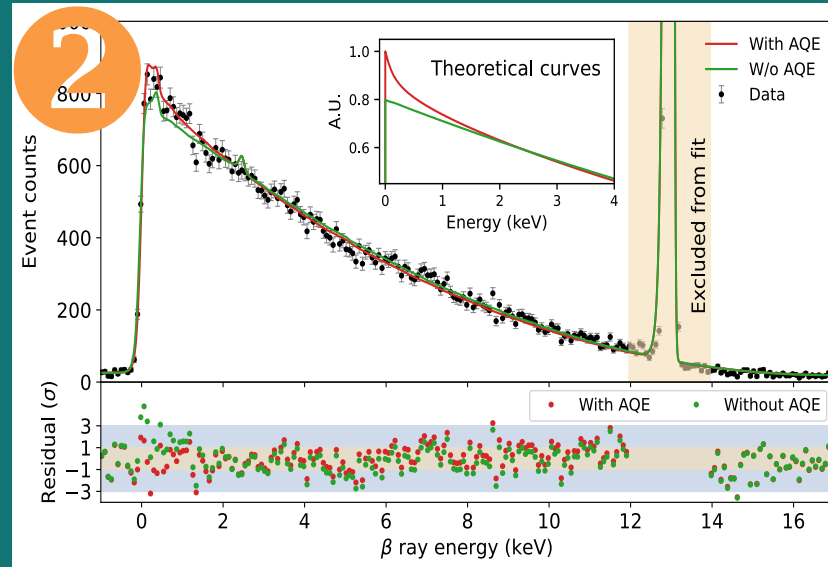
PandaX-xT for $0\nu\beta\beta$

- 4 ton of ^{136}Xe : one of the largest $0\nu\beta\beta$ experiments
- Effective self-shielding: Xenon-related background dominates

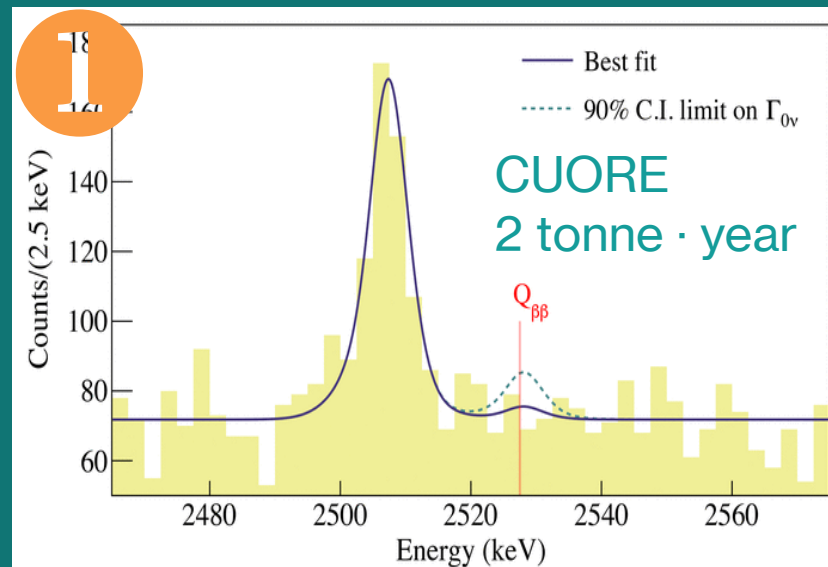


Bolometers

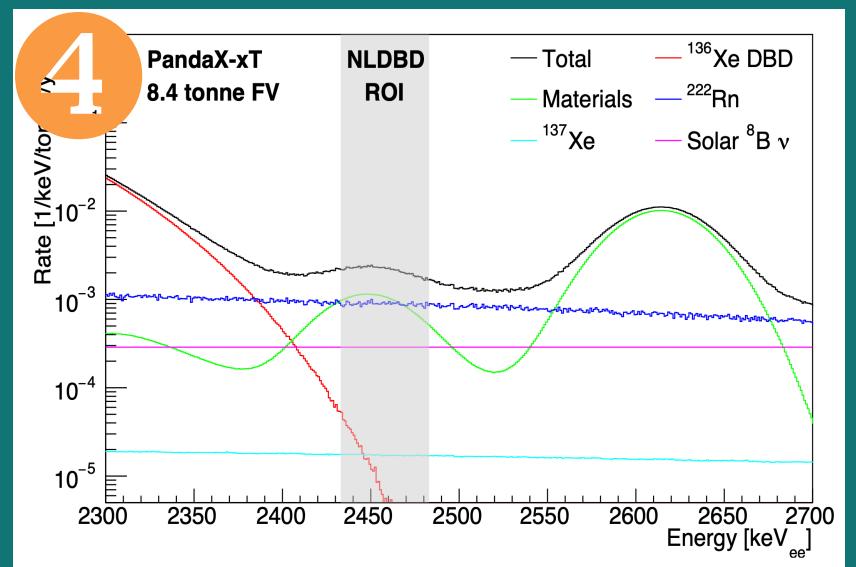
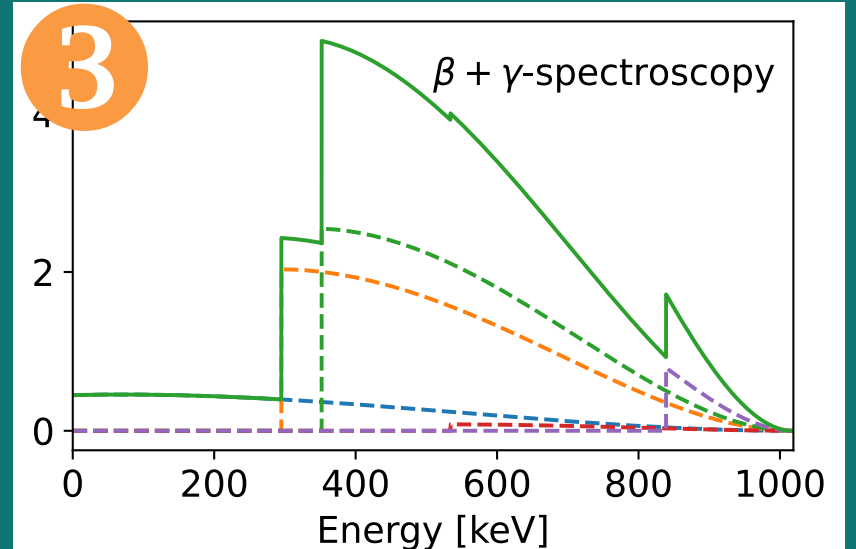
Precision β decay spectroscopy

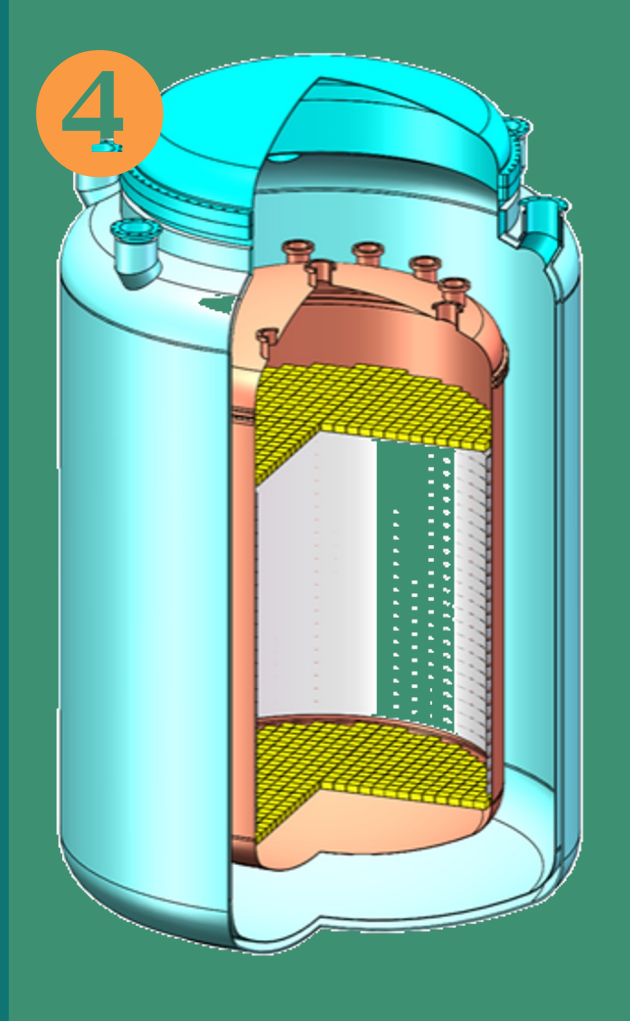
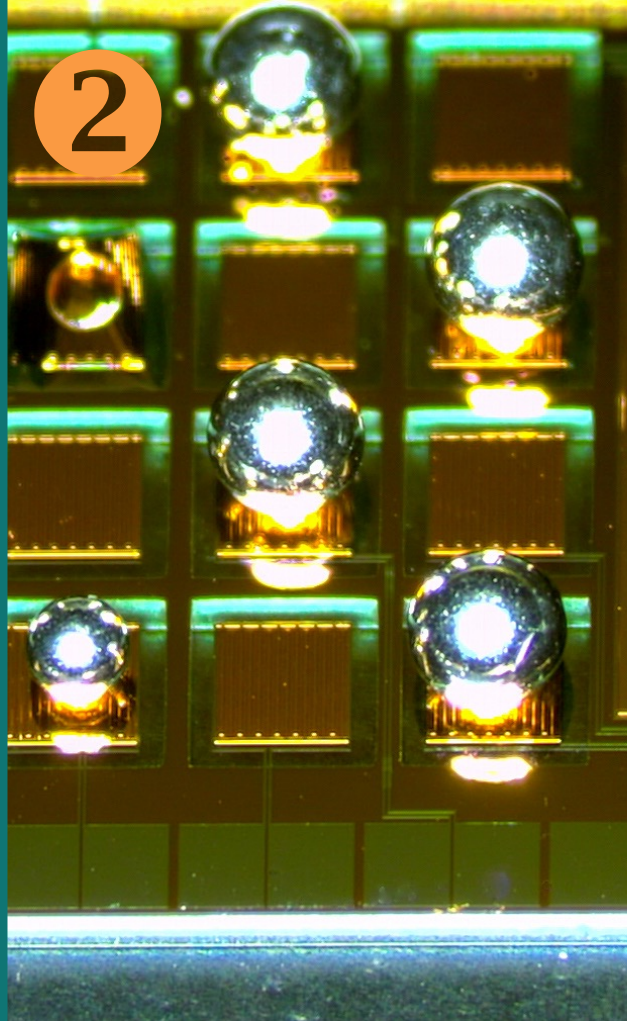
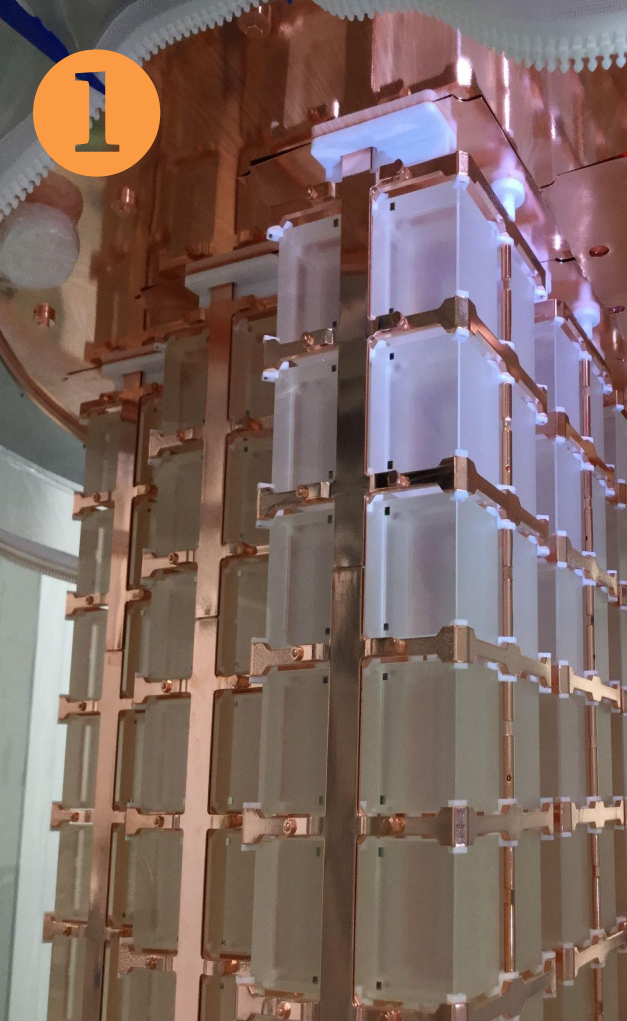


$0\nu\beta\beta$ searches with $\beta\beta$ spectroscopy



Liquid xenon TPC





Thank you!

Ke Han (SJTU)

韩柯 (上海交通大学)