Recent Results of Neutrinoless Double Beta Decay Search in Experiments

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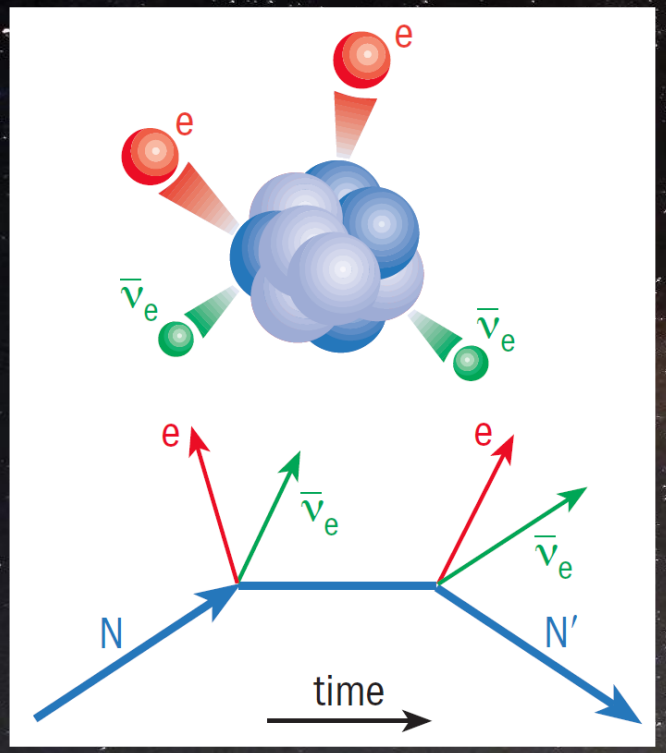
Outline

- Neutrinoless double deta decay ($0\nu\beta\beta$)
- The most stringent limits on $0\nu\beta\beta$ in experiments: ^{130}Te, ^{76}Ge, and ^{136}Xe
- Majorana neutrino search in natural xenon DM experiments (PandaX-4T)
- Summary

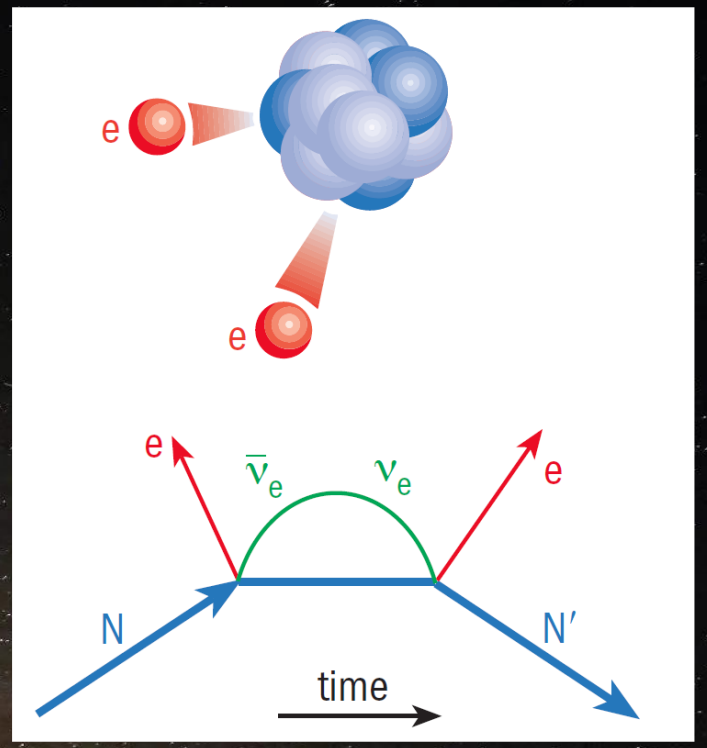
Neutrinoless Double Beta Decay ($0\nu\beta\beta$)



Double Beta Decay ($2\nu\beta\beta$)

$\bar{\nu} = \nu$

Majorana neutrino



Neutrinoless Double Beta Decay ($0\nu\beta\beta$)

Golden channel for Majorana neutrino search

- Majorana or Dirac
- Lepton number violation
- Measures effective Majorana mass: relate $0\nu\beta\beta$ to the neutrino oscillation physics

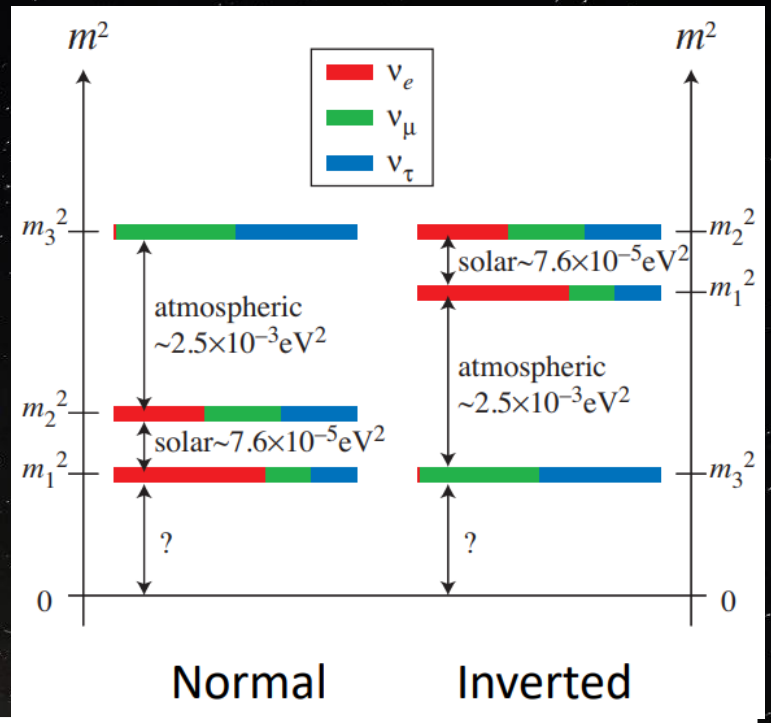
$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\ |M^{0\nu}|^2\ \frac{|\langle m_{\beta\beta}\rangle|^2}{m_e^2}$$

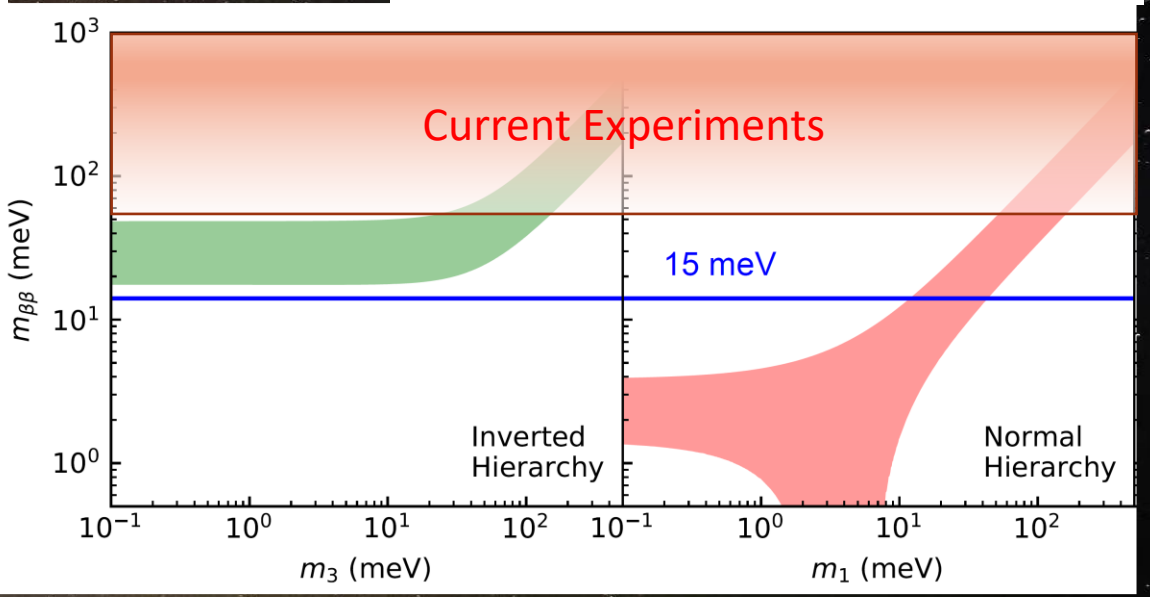
Phase space factor

Nuclear matrix element

Effective Majorana neutrino mass:

$$|\langle m_{\beta\beta}\rangle| = \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right|$$

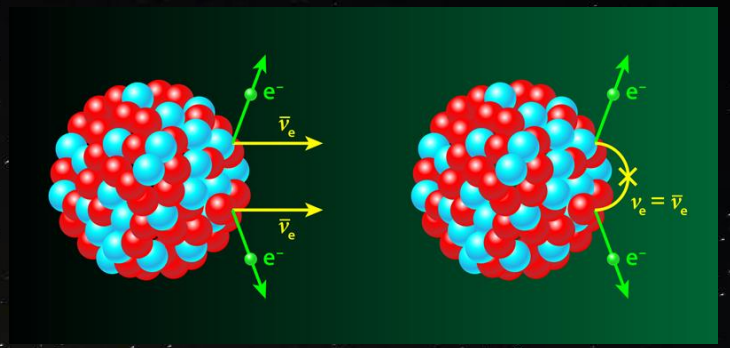


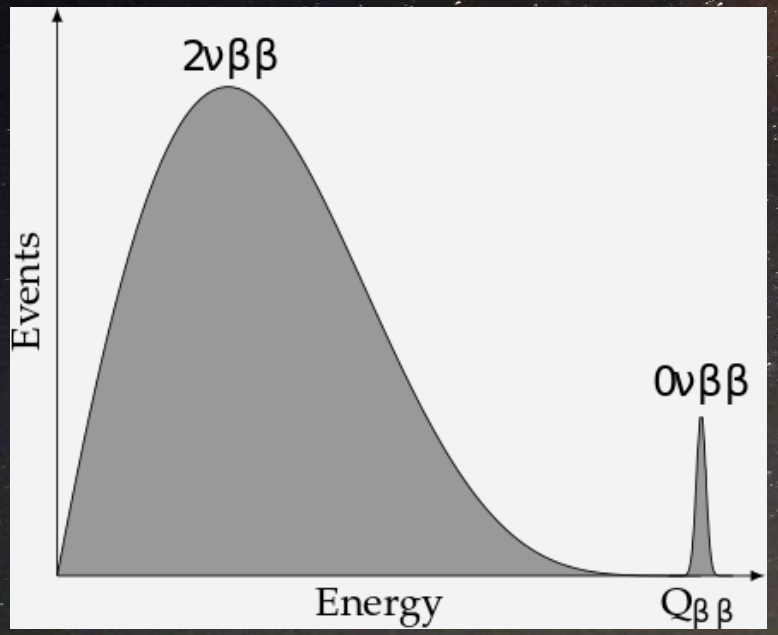


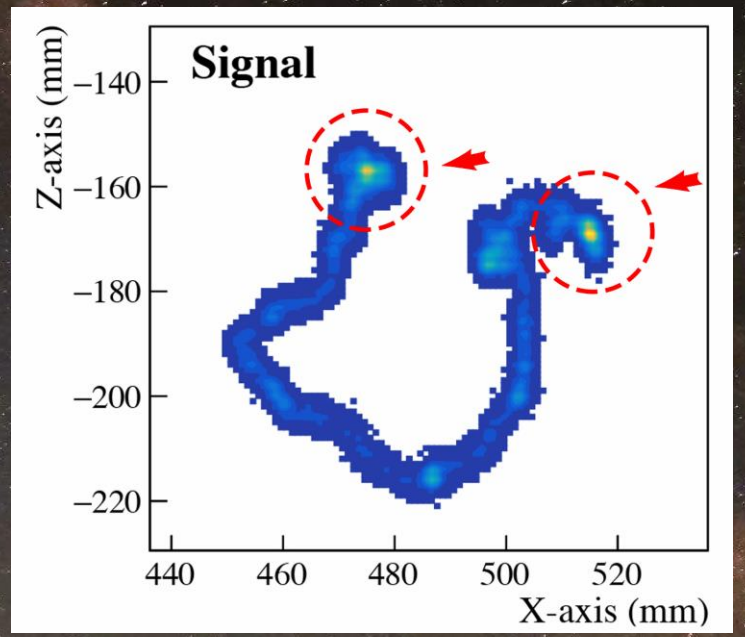
Experimental Searches

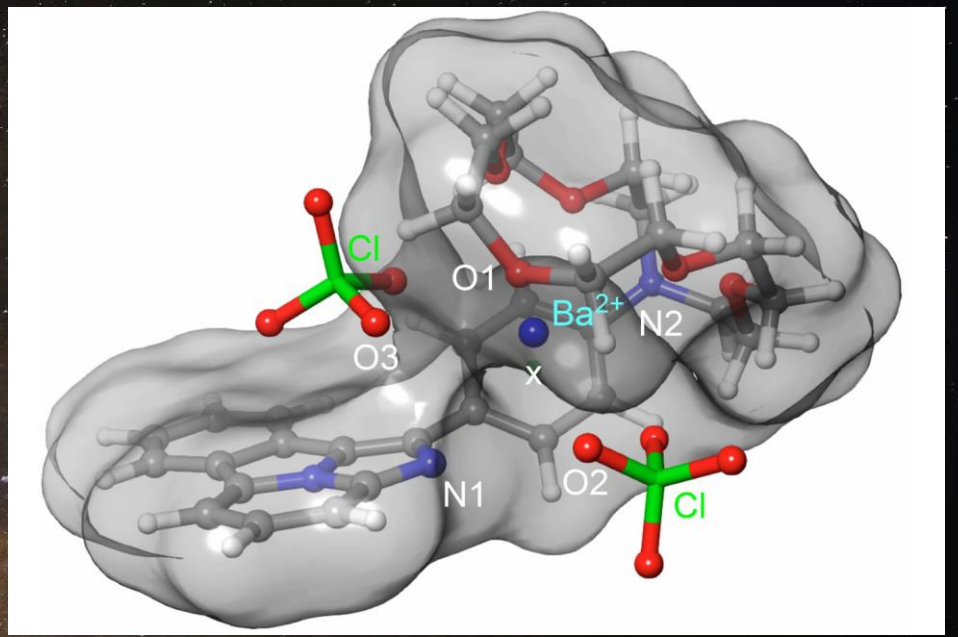
$$^{136}\mathrm{Xe} \rightarrow {}^{136}\mathrm{Ba} + 2\mathrm{e}^{-} + ?\,\nu$$

- Detect the electron
  - Summed energy
  - Trajectories
- Detect the daughter nuclei
  - Geochemical and radiochemical
  - Imaging



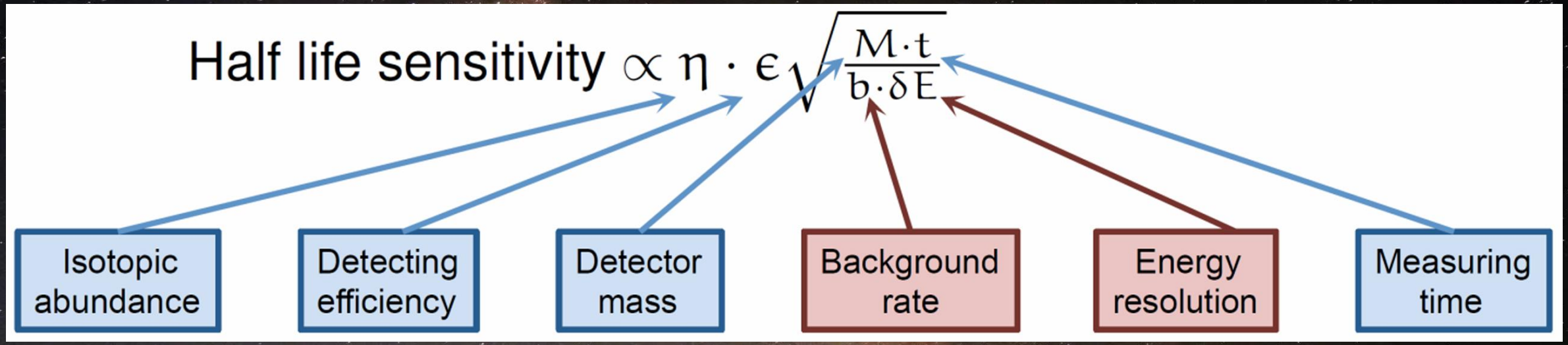




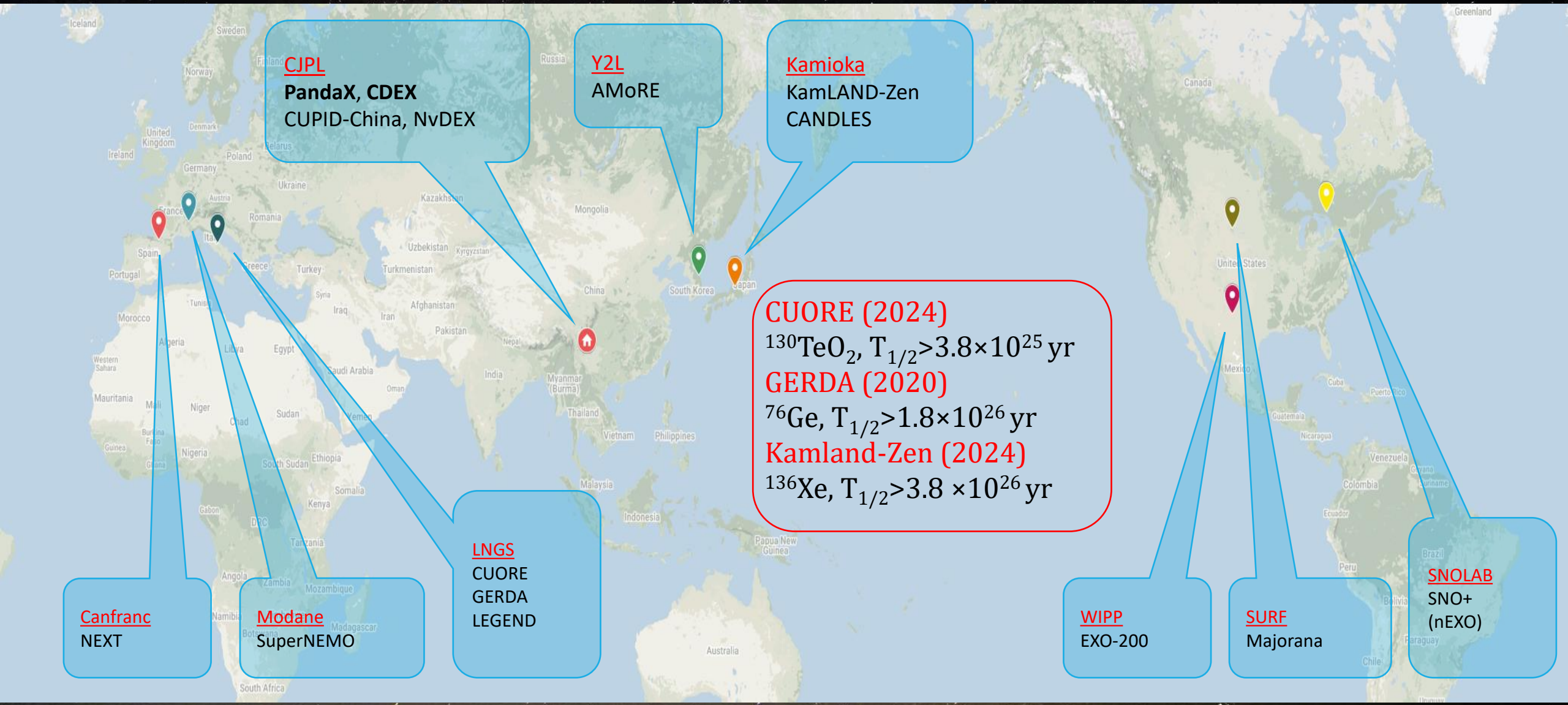


Half-life sensitivity from experiments

- Small signals: Fewer than 1 event/year for ton-scale experiments
- Number of signals over fluctuation of background for possible observation
- Extreme requirements for detector performance and background control

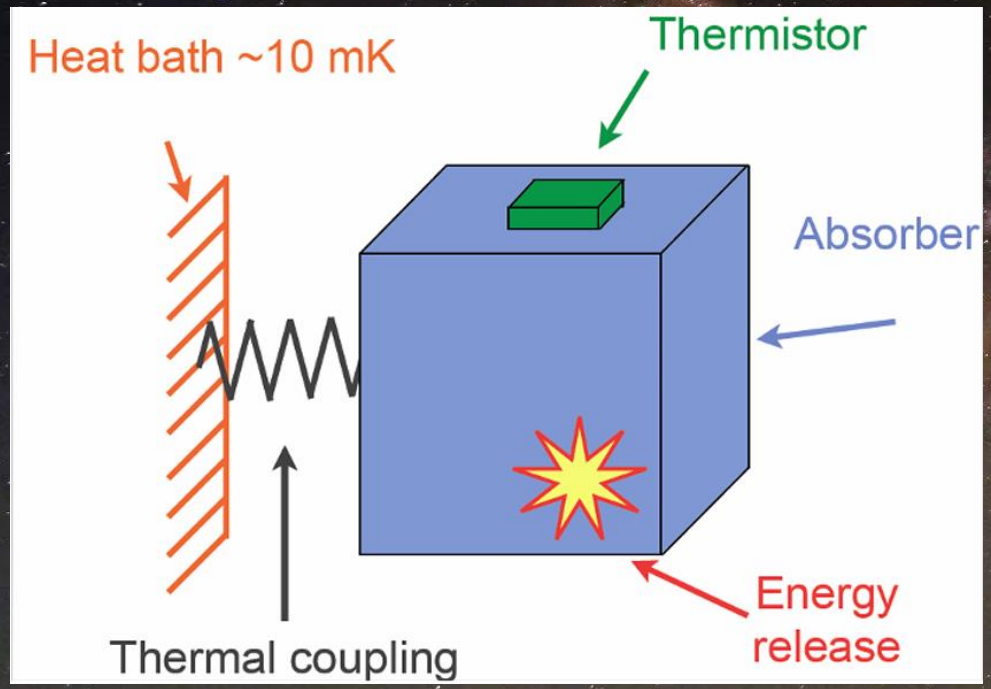


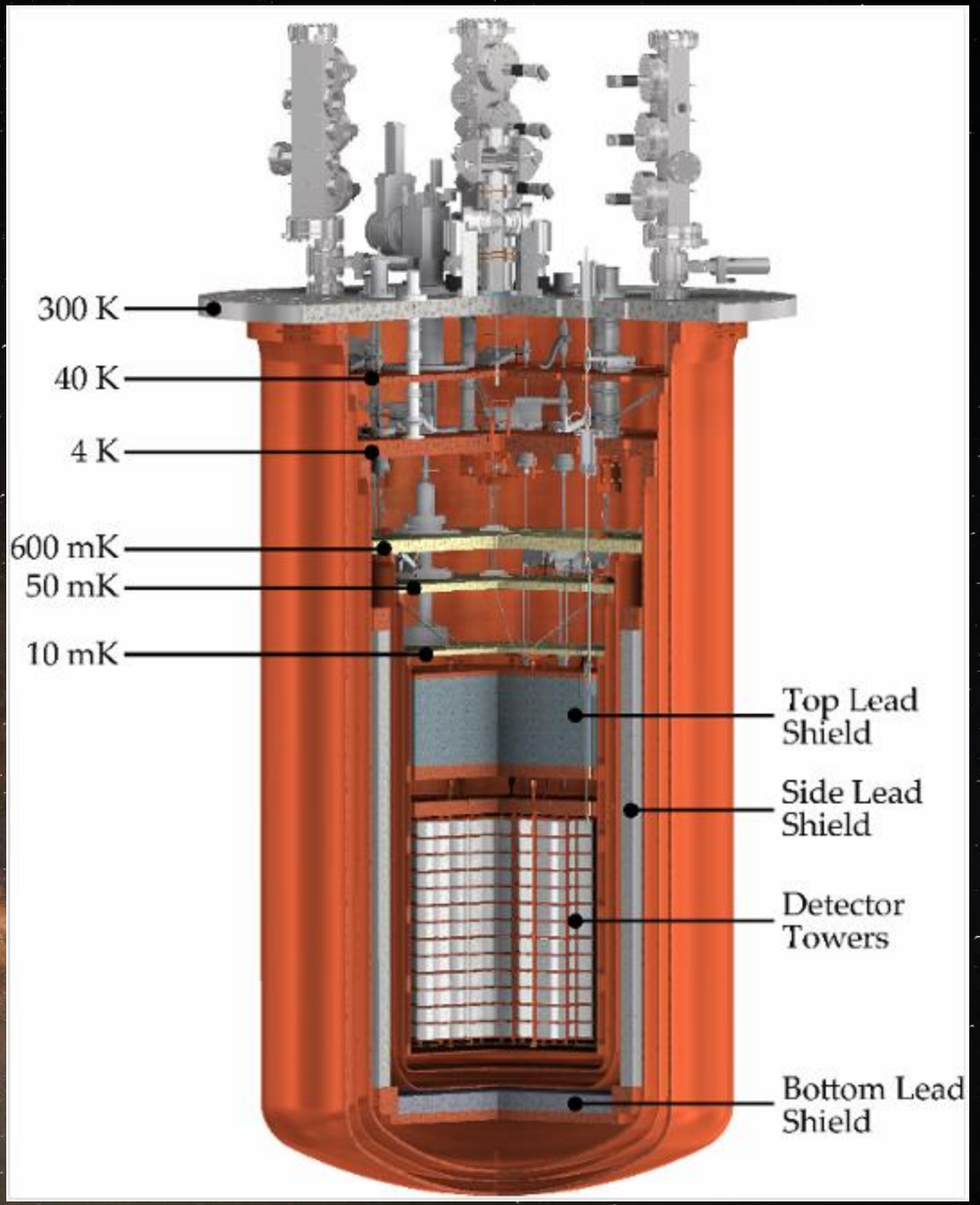
$0\nu\beta\beta$ experiments



CUORE bolometer array

- Search for $0\nu\beta\beta$ of ^{130}Te
- 988 TeO_2 crystals run as a bolometer array
- 10 mK in a custom dilution refrigerator
- Gran Sasso underground lab (LNGS), Italy

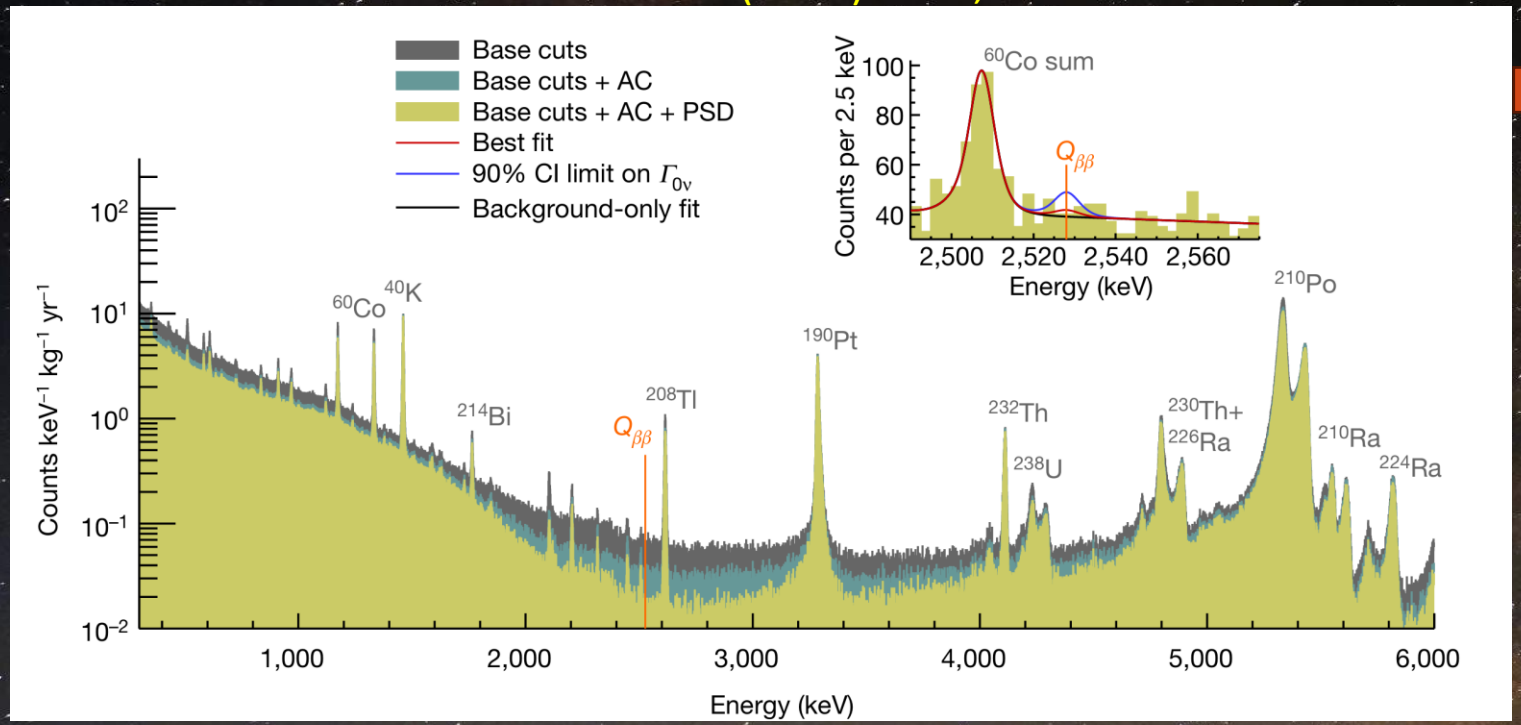




Recent results: ^{130}Te $0\nu\beta\beta$

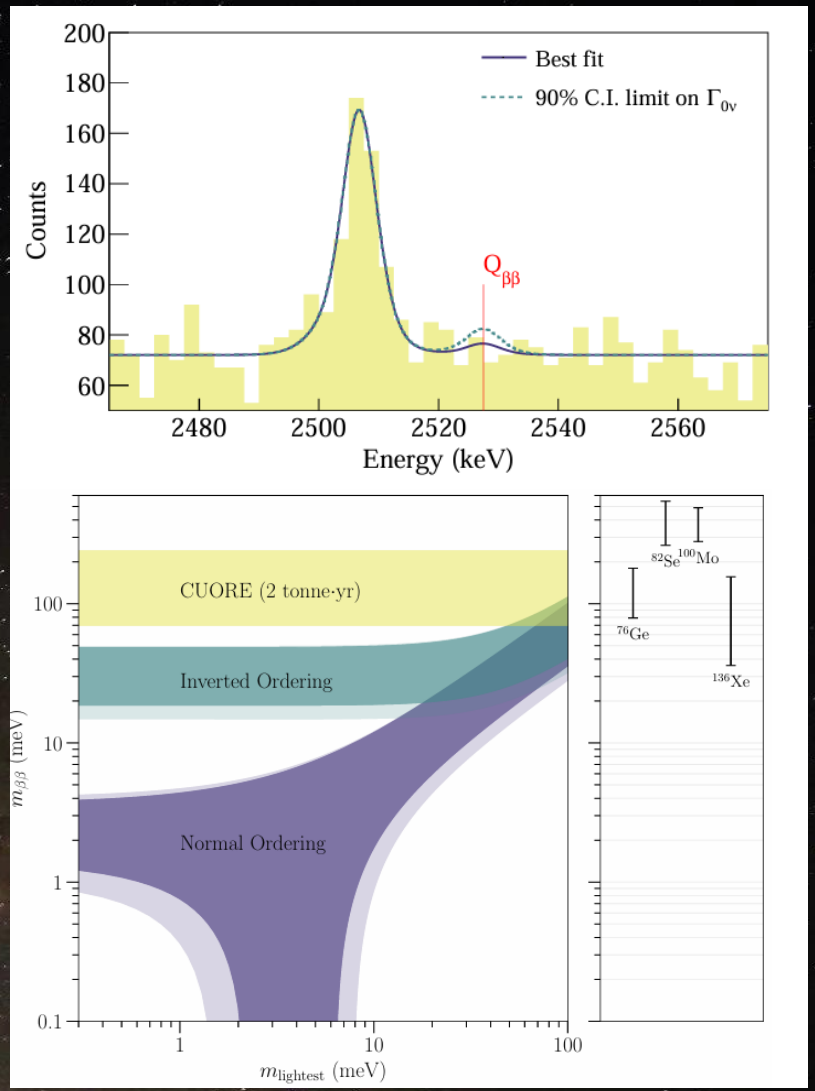
- Stable data taking since 2017
- Excellent energy resolution FWHM (~7.8keV)

Nature 604 (2022) 7904, 53-58



1 tonne·year TeO_2 exposure: >2.2×10^{25} yr

ArXiv: 2404.04453 (2024)

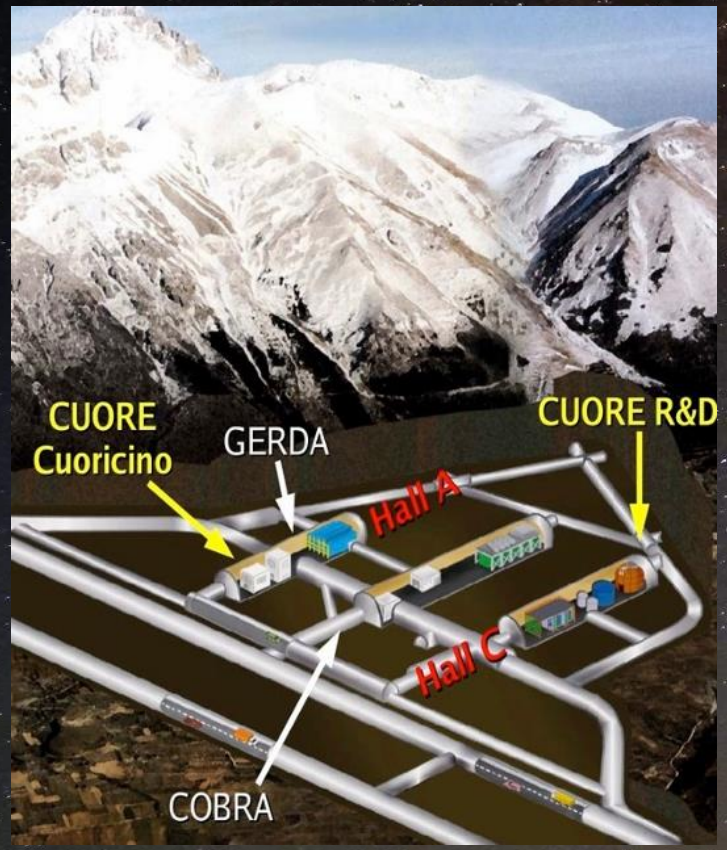


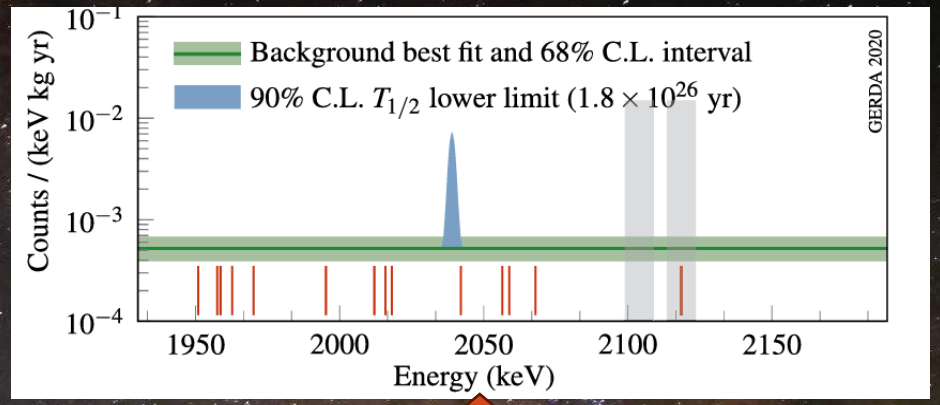
2 tonne·year TeO_2 exposure: >3.8×10^{25} yr

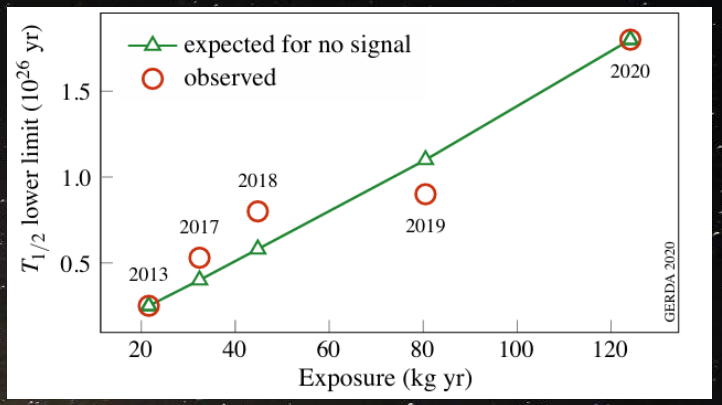
GERDA: HPGe detector

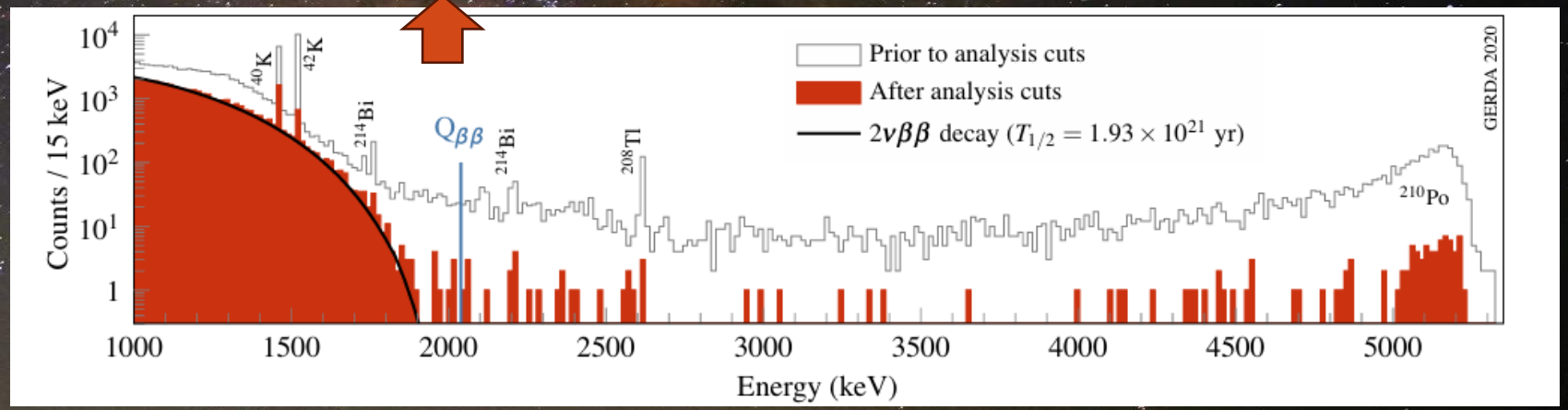
- HPGe detector for ^{76}Ge $0\nu\beta\beta$: very good energy resolution (3keV @ Q value) and background control
- 127.2 kg yr exposure in a background-free regime : >1.8×10^{26}yr

Phys.Rev.Lett. 125 (2020) 25, 252502









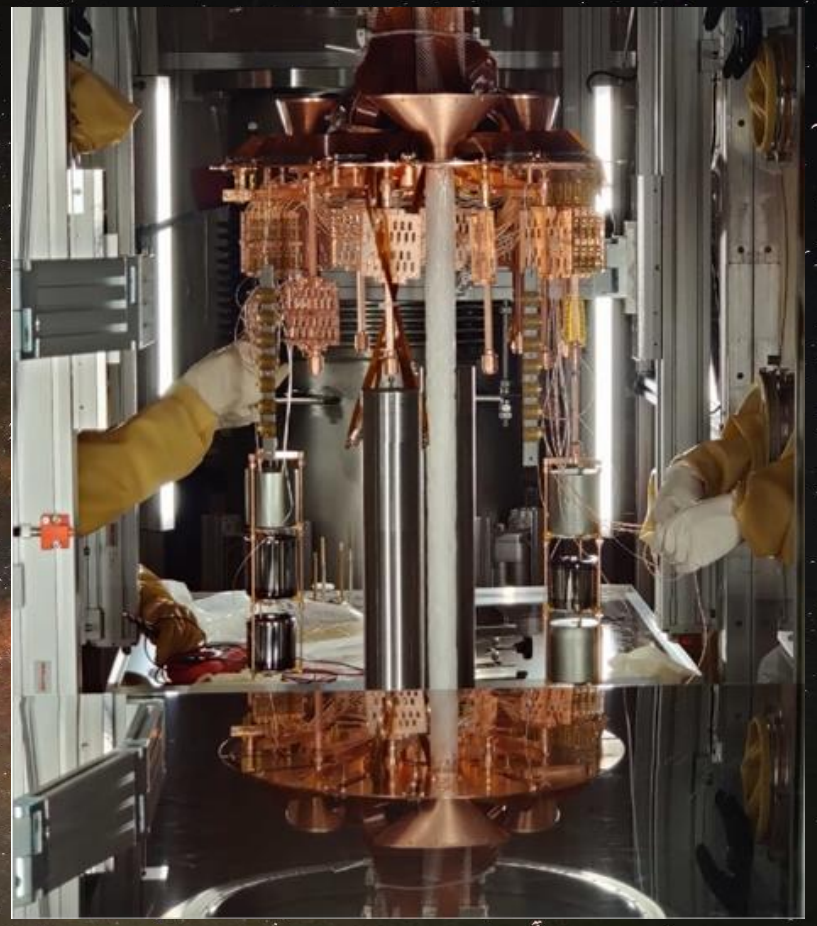
LEGEND-200: Commissioning now at LNGS

- 200 kg mass loading in upgrade of existing GERDA infrastructure at LNGS
- Targeting 2.5 keV FWHM resolution
- Background goal:<0.6 cts/(FWHM t yr)

Discovery sensitivity up to 10^{27} yrs

GERDA

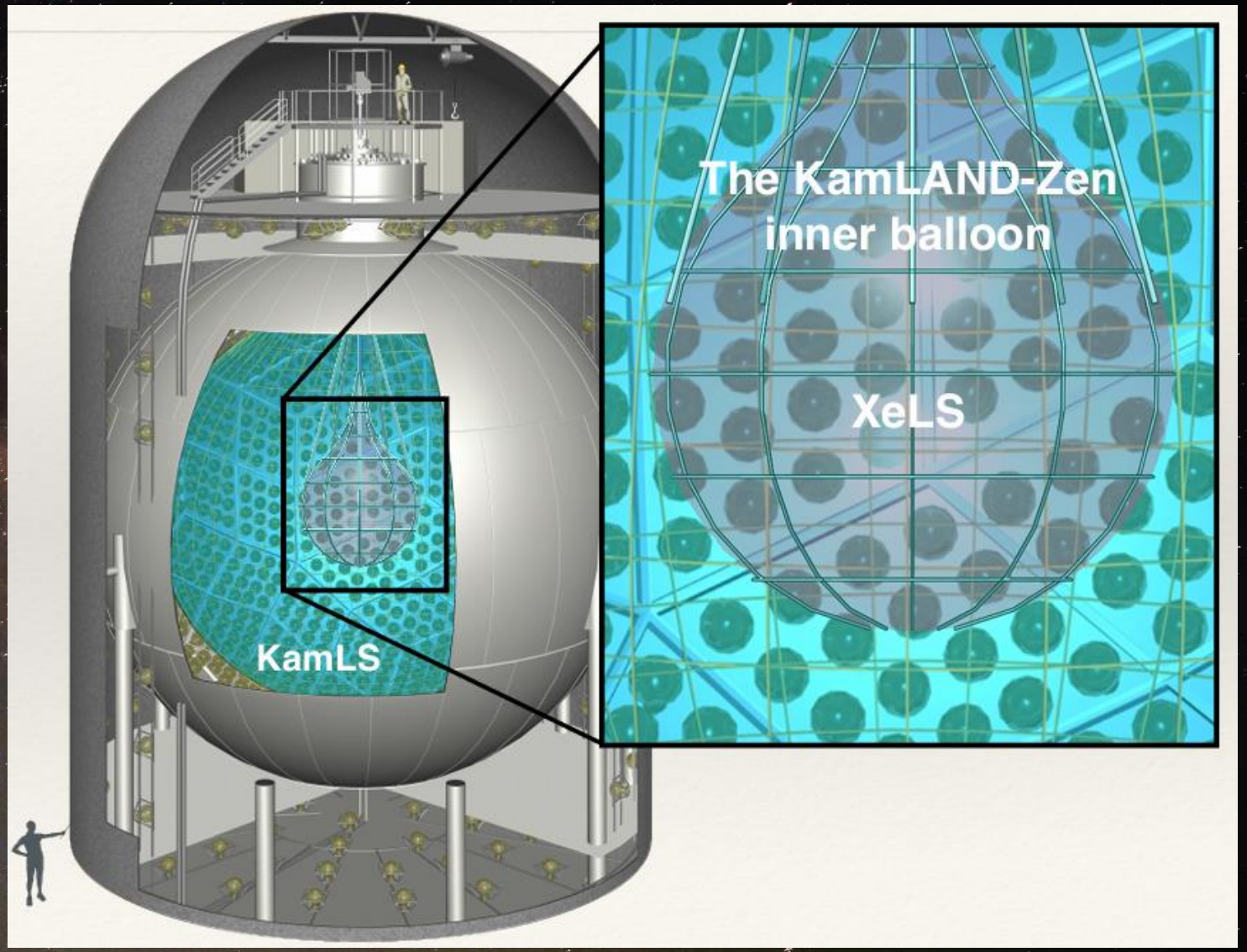
MAJORANA



LEGEND-200

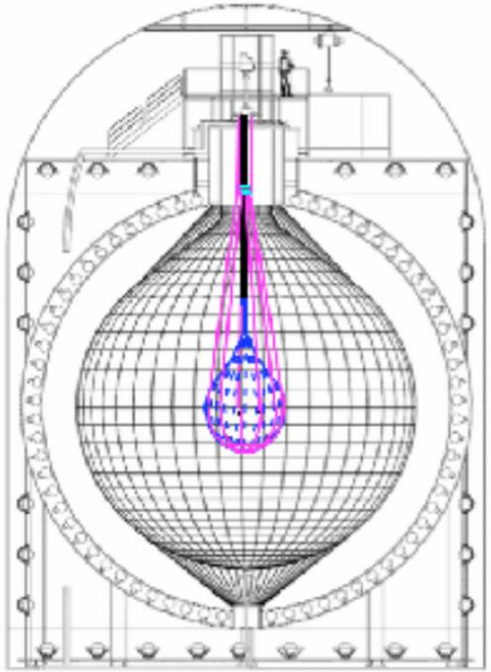
KamLAND-Zen: Xe-loaded LS

- KamLAND: 1 kiloton of ultra low radioactivity liquid scintillator (LS)
- 3% wt xenon soluble in Liquid Scintillator (XeLS)



KamLAND-Zen upgrade path

Past



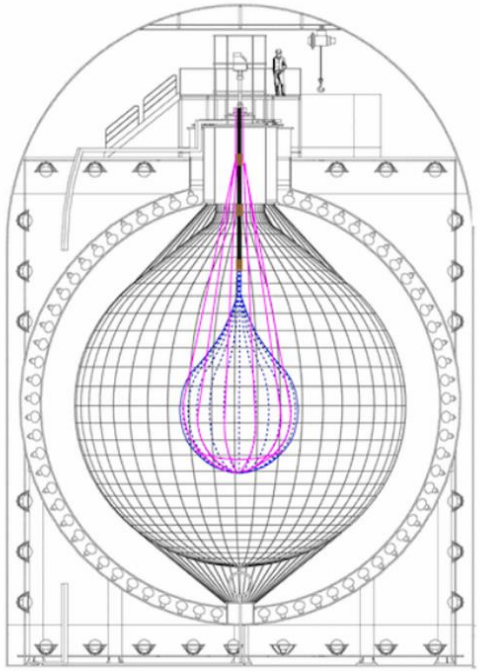
KamLAND-Zen 400

R = 1.54m mini-balloon

Xenon 320 ~ 380 kg

2011 ~ 2015

Ongoing



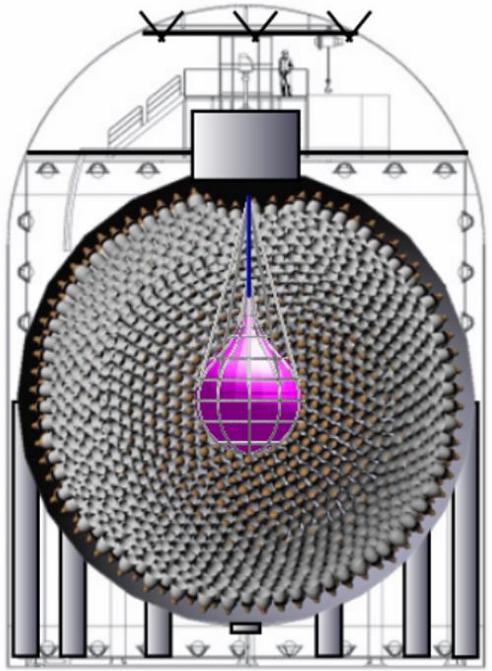
KamLAND-Zen 800

R = 1.90m mini-balloon

Xenon 745 kg

Jan. 22, 2019 ~

Future

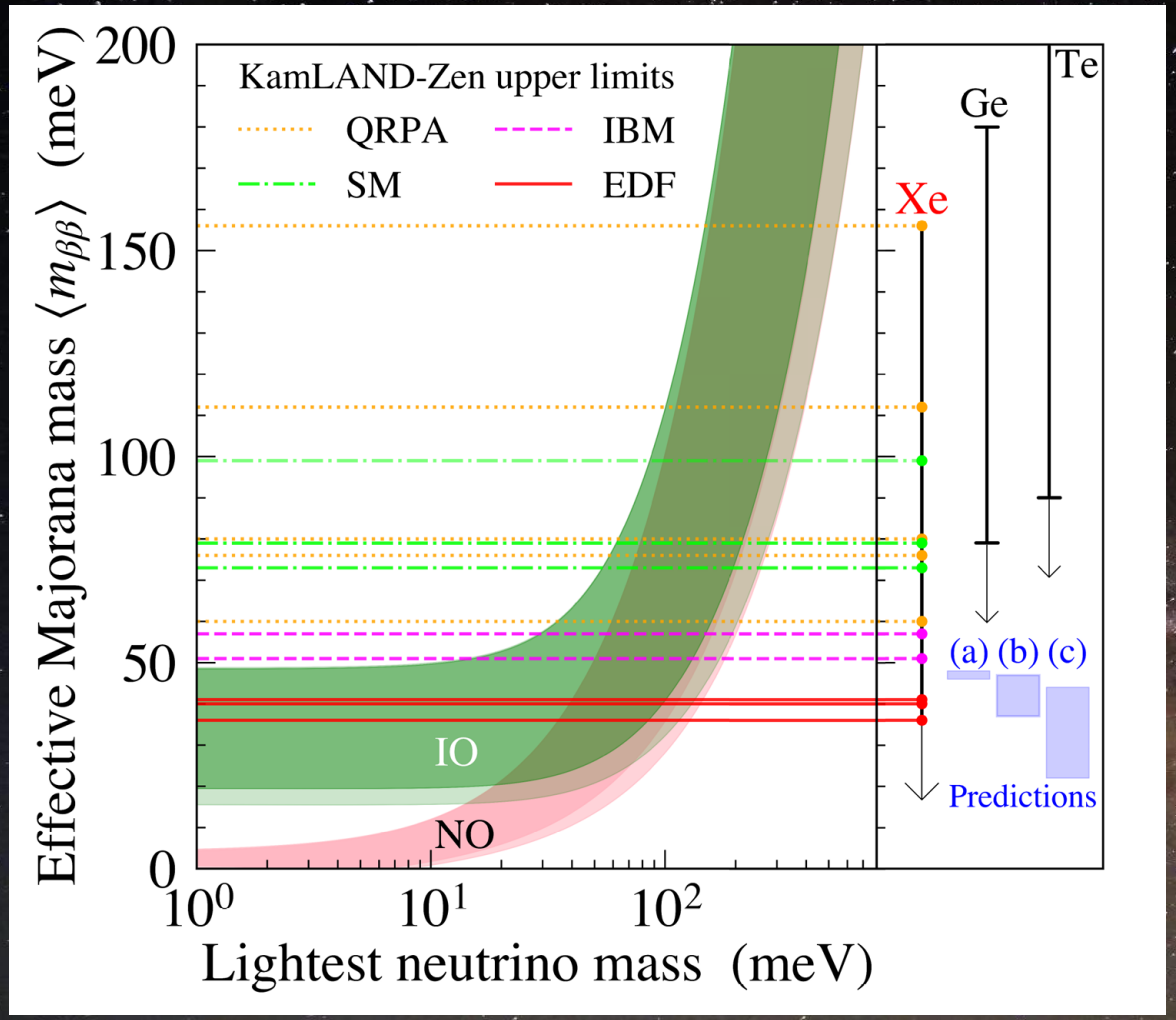


KamLAND2-Zen

Xenon ~ 1 ton

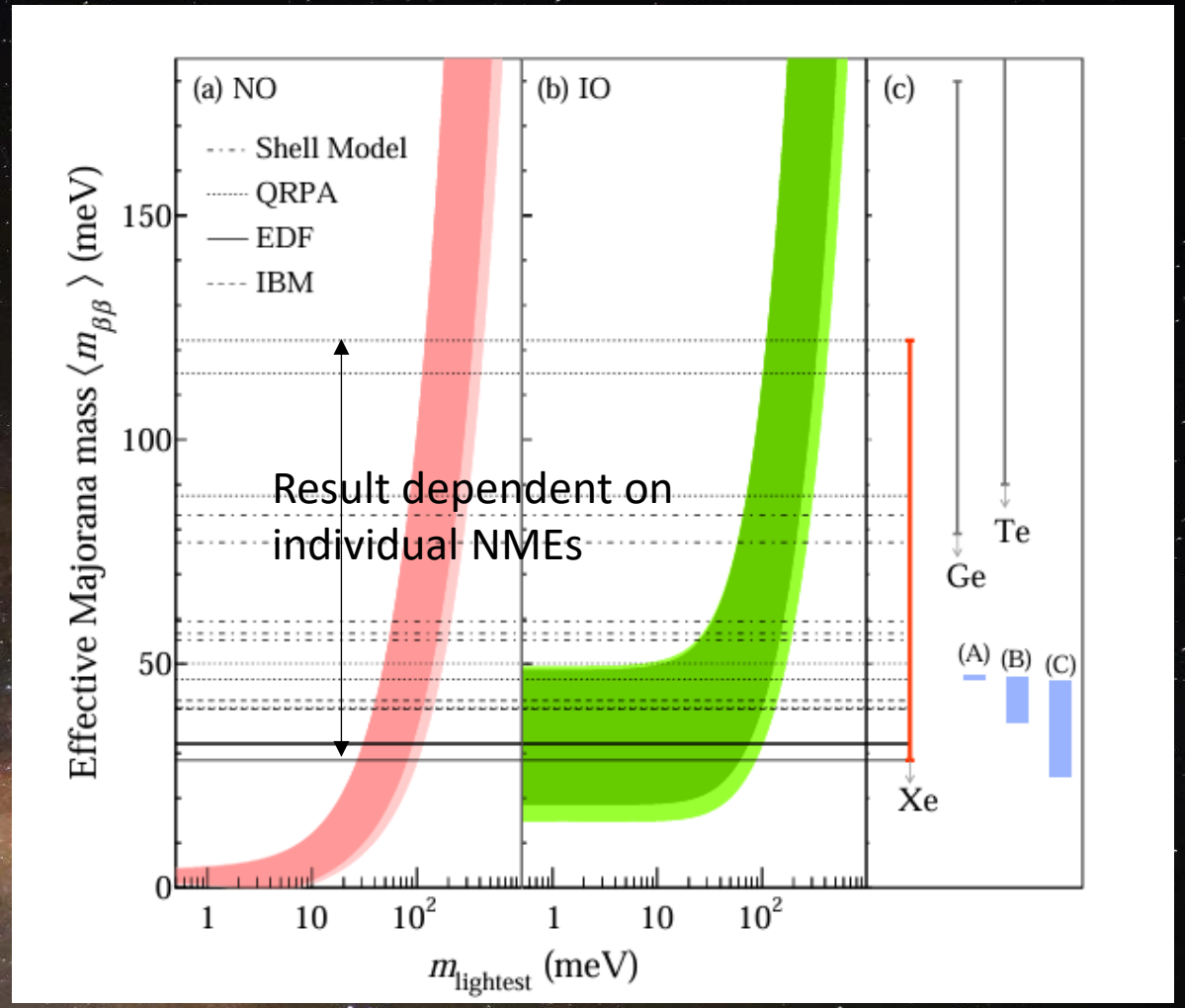
Recent results from KamLAND-Zen 800: ^{136}Xe $0\nu\beta\beta$

Phys.Rev.Lett. 130 (2023) 5, 051801



0.97 ton yr of ^{136}Xe: >2.3×10^{26} yr,
$\langle m_{\beta\beta} \rangle$ < 36−156meV

ArXive: 2406.11438 (2024)

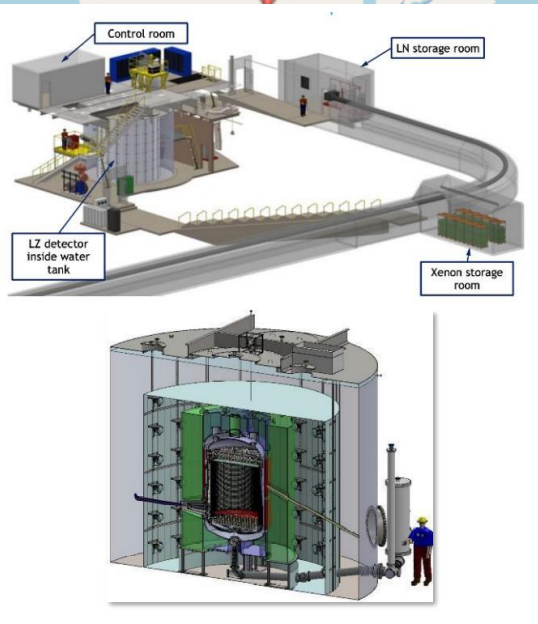


2.097 ton yr of ^{136}Xe: >3.8×10^{26} yr
$\langle m_{\beta\beta} \rangle$ < 28−122meV

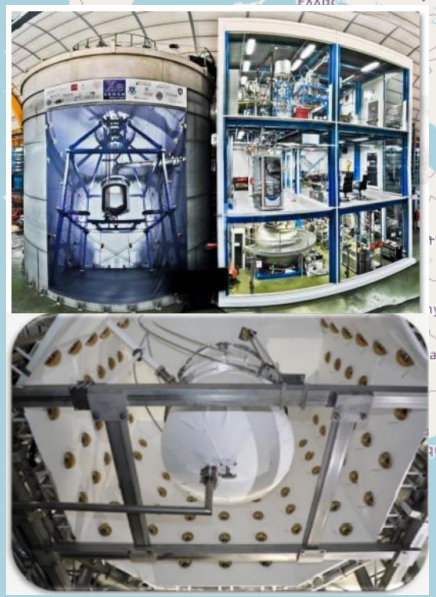
The big three xenon DM experiments

- **Multi-ton natural xenon experiments for DM search**

LZ

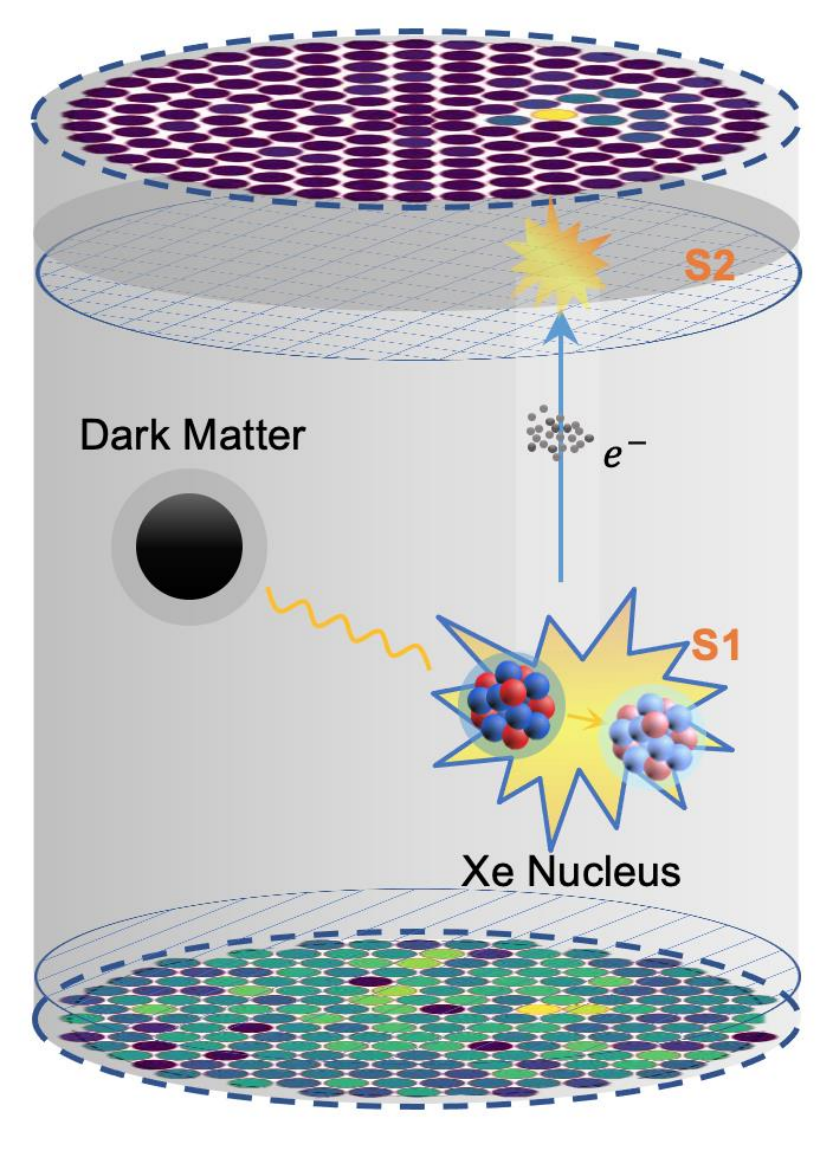


XENON

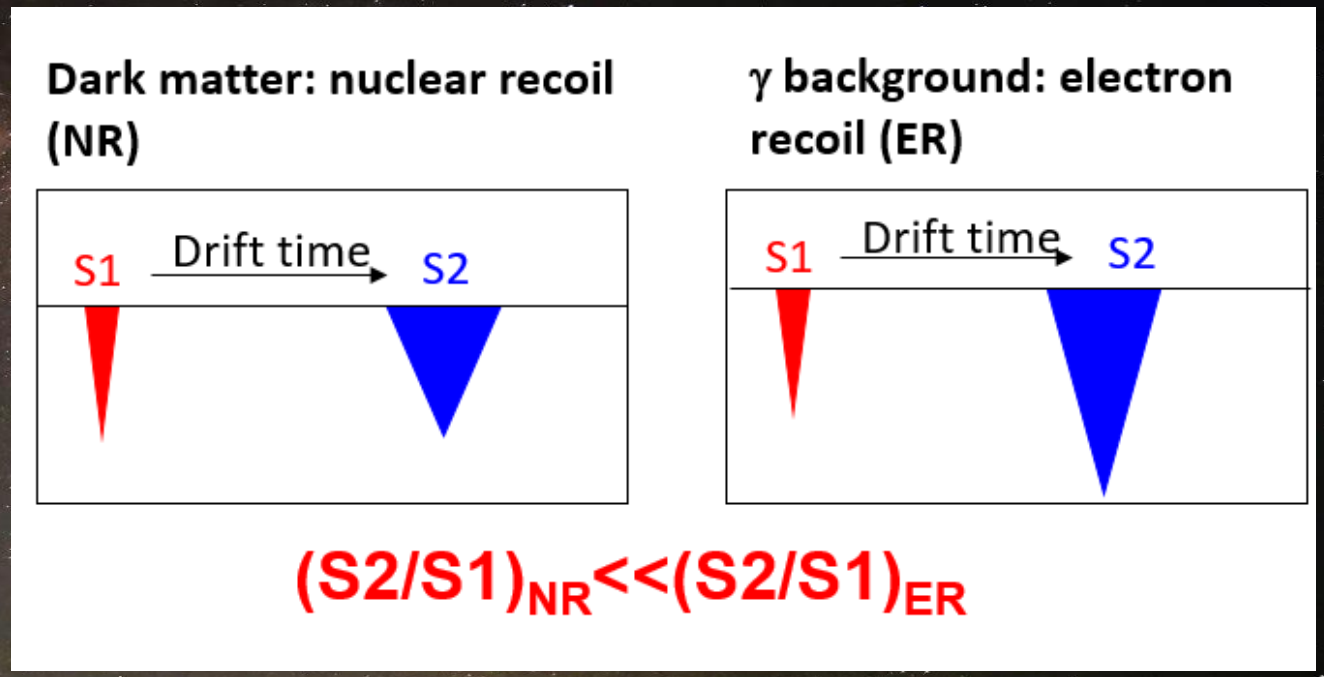


PandaX

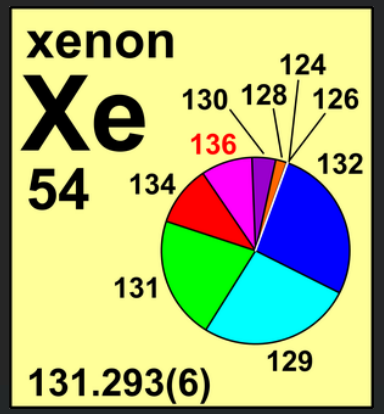
Dual-phase xenon TPC



- **Paired scintillation (S1) and ionization (S2) signals**
  - Precise energy measurement
  - 3D position reconstruction
  - Discrimination between nuclear recoil and electron recoil signals
  - Calorimeter from sub keV to MeV

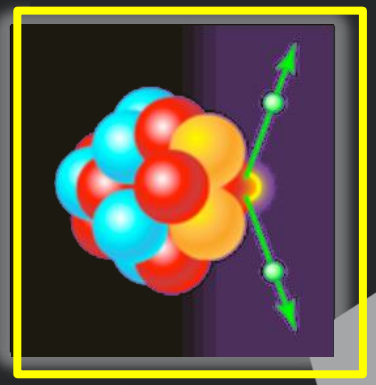


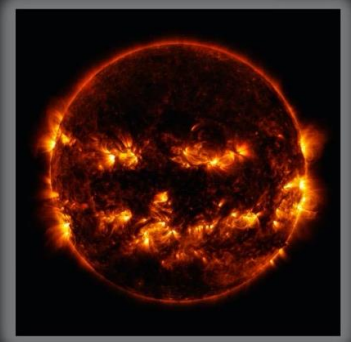
PandaX-4T experiment currently with ~250 days' data



Majorana neutrino
> 2 MeV

Dark Matter
1 keV – 10 keV

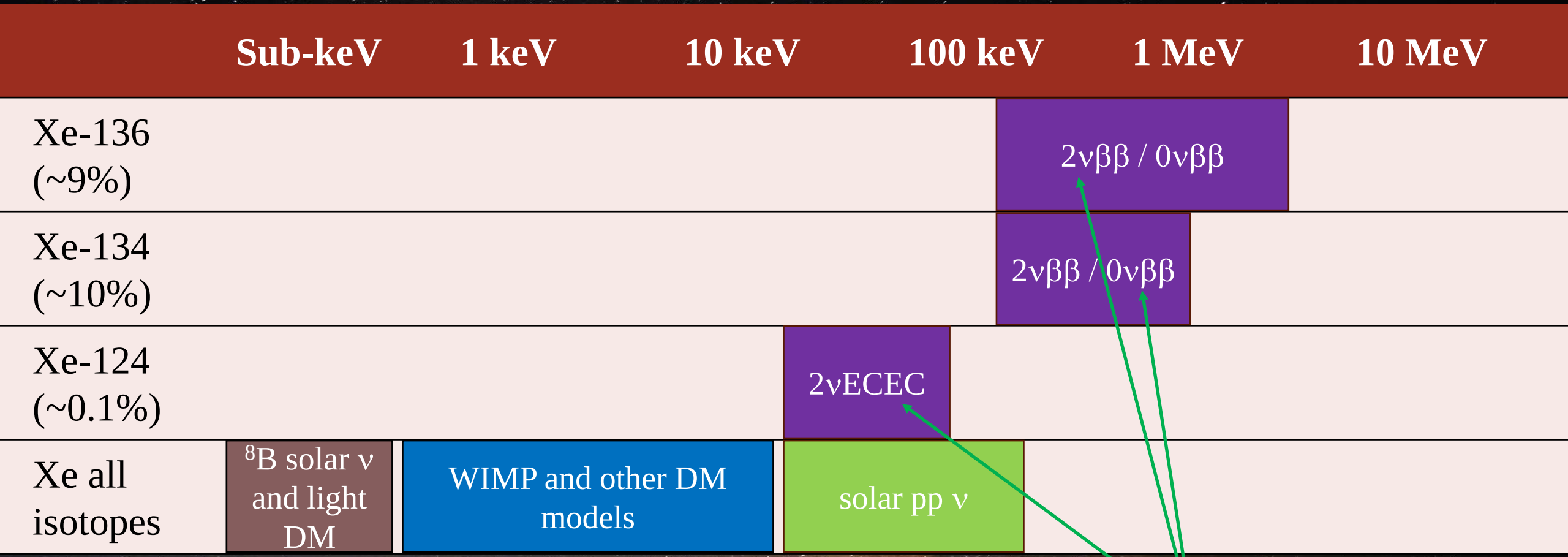




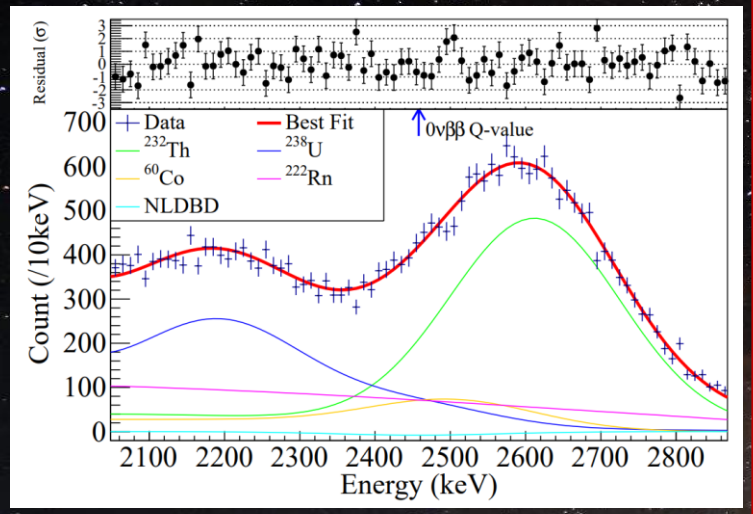
Astrophysics neutrino < 300 keV

- Third generation of the PandaX experiments located at CJPL-II
- A multi-ton dual phase xenon TPC at CJPL
  - Dual-phase Xe TPC: 1.2 m (D) ×1.2 m (H)
  - Sensitive volume: 3.7 ton LXe
  - Total volume: 5.6 ton LXe
- Commissioned since late 2020
- Run 0 (~ 95 d)+Run 1 (~ 154 d)

Multiple physics in a wide energy range



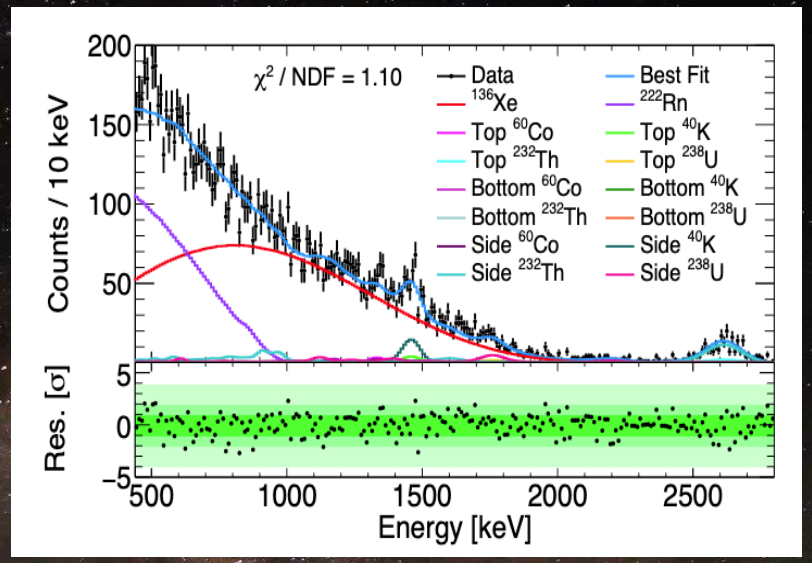
^{136}Xe $0\nu\beta\beta$ search in PandaX experiment

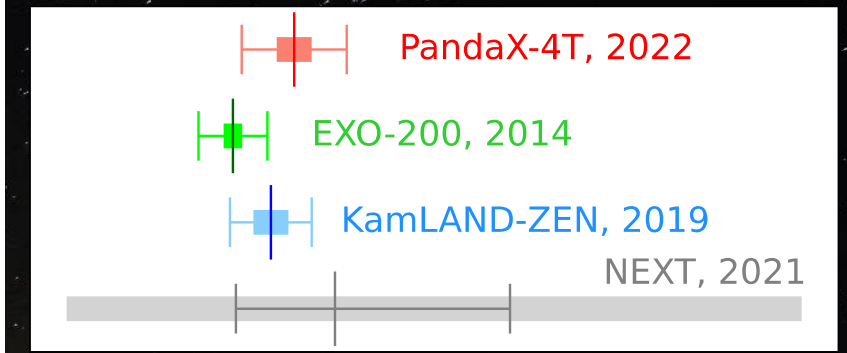


Chinese Physics C 43, 113001 (2019)

^{136}Xe $0\nu\beta\beta$ search by PandaX-II:

- 580kg natural xenon+403.1 day DM data
- First ^{136}Xe $0\nu\beta\beta$ search from a DM detector (2.4×10^{23}yr)
- Verified feasibility and potential of DM detector for $0\nu\beta\beta$ search



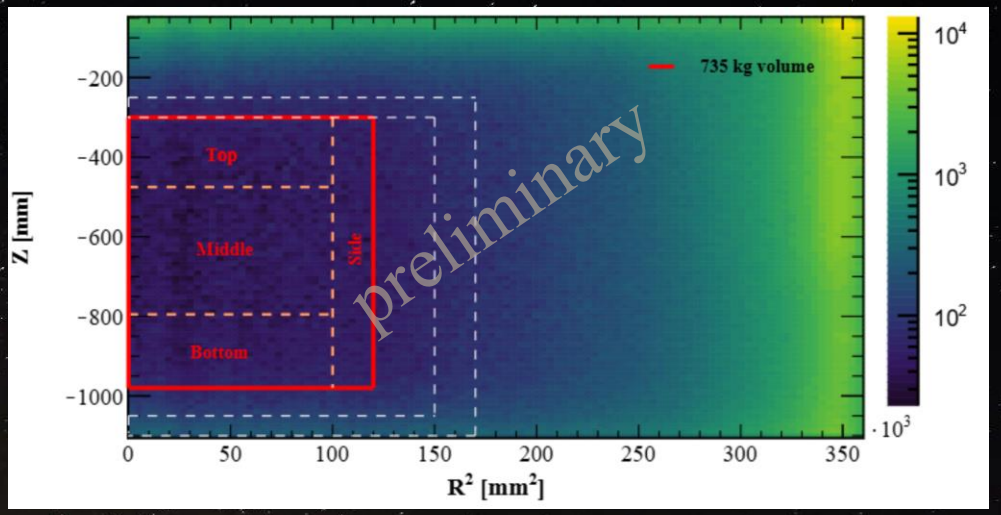


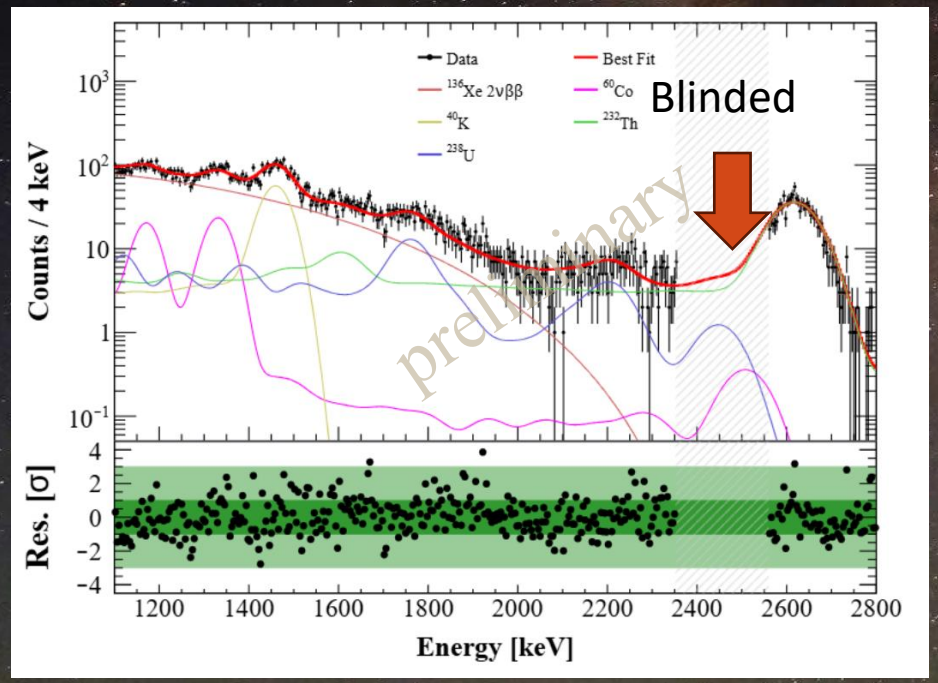
Research 2022 (2022) 9798721

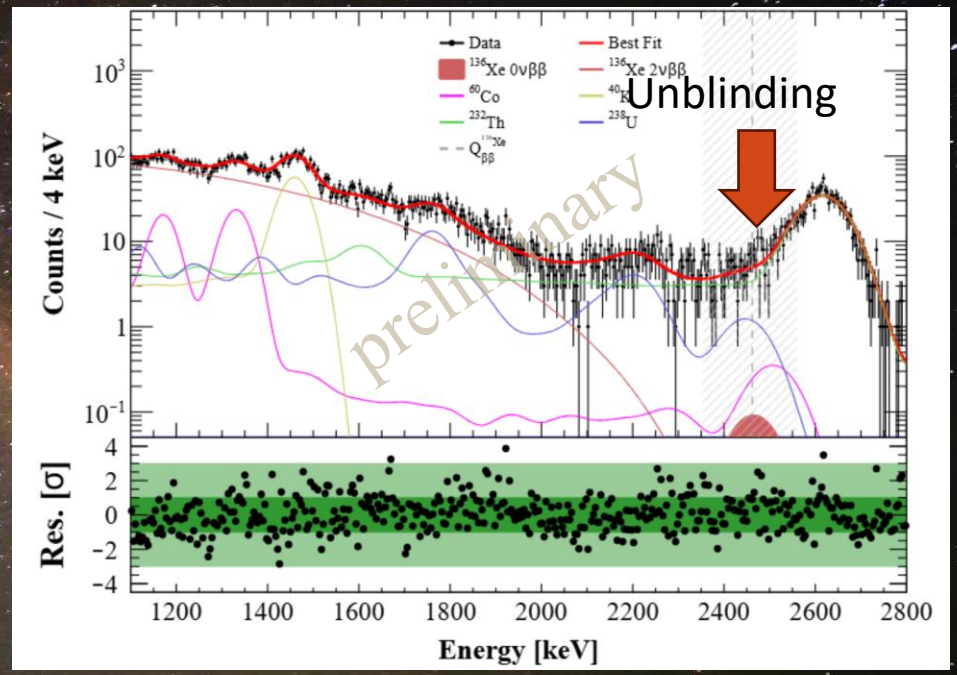
- ^{136}Xe $2\nu\beta\beta$ half-life measured by PandaX-4T: $2.27 \pm 0.03(\text{stat.}) \pm 0.10(\text{syst.}) \times 10^{21}$ yr
- Comparable precision with leading results
- First such measurement from a DM detector with natural xenon
- 440 keV – 2800 keV range is the widest ROI

^{136}Xe $0\nu\beta\beta$ search in PandaX-4T

- Run0+Run1 (~250 days' data) blind analysis
- 735 kg FV in the center
- The region outside the FV for detector response study
- Lower limit (preliminary): >2.1×10^{24} yr



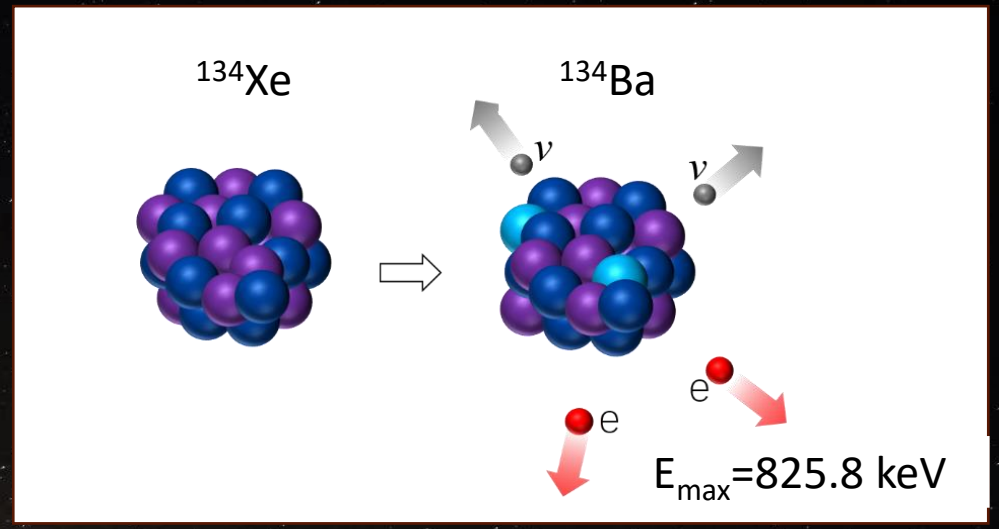




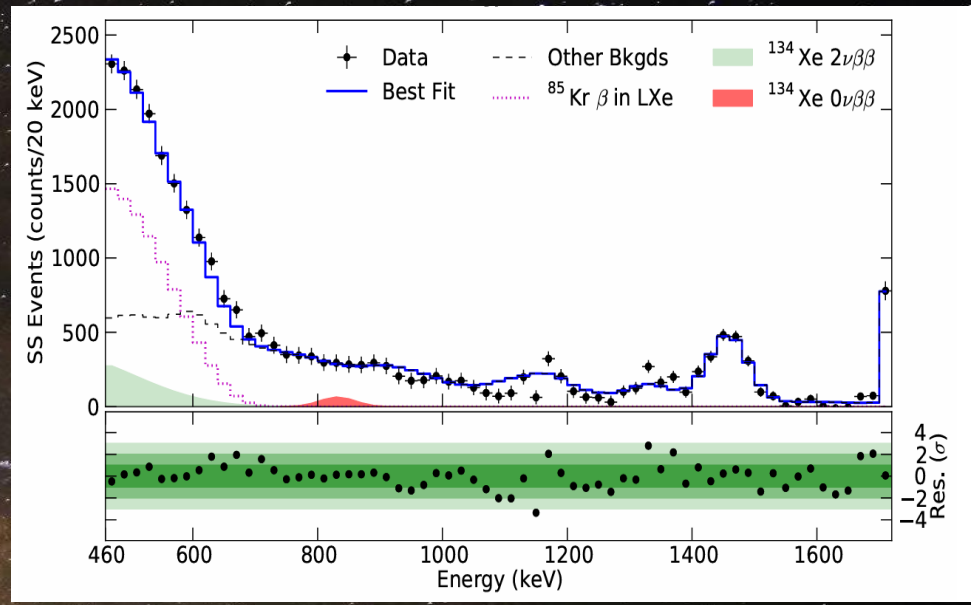
^{134}Xe $2\nu\beta\beta$ and $0\nu\beta\beta$

- Double beta decay of ^{134}Xe into ^{134}Ba:

$$^{134}\mathrm{Xe} \rightarrow ^{134}\mathrm{Ba}^{++} + 2\,e^{-}\,(+2\,\bar{\nu}_e)$$



- Q-value is 825.8±0.9 keV
- Half-life from theoretical predictions: ~10^{24} yr
- Best experiment limits from EXO-200 with 29.6 kg·yr data of ^{134}Xe :
  - $T_{1/2}^{2\nu\beta\beta} > 8.7 \cdot 10^{20}$ yr at 90% CL
  - $T_{1/2}^{0\nu\beta\beta} > 1.1 \cdot 10^{23}$ yr at 90% CL
- Isotopic composition in EXO-200 : 80.7% ^{136} Xe and 19.1% ^{134}Xe
- Energy spectrum: ROI between 460 keV and 740 keV for $2\nu\beta\beta$, energy resolution σ/E=3.56% @825.8 keV

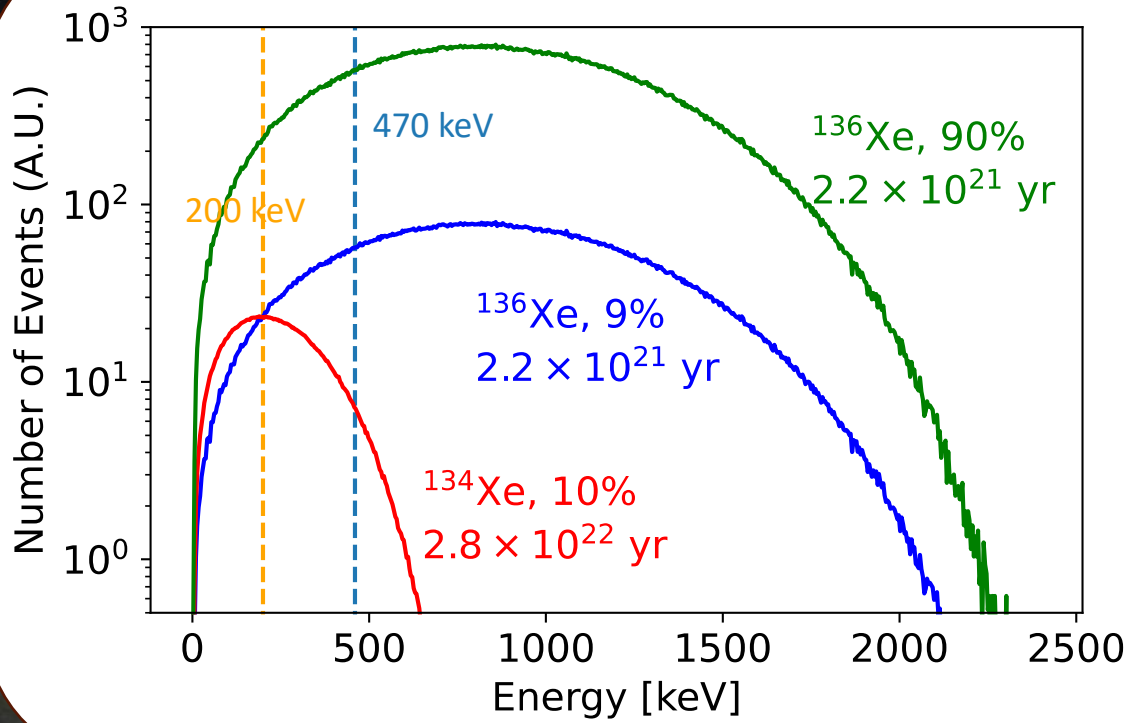


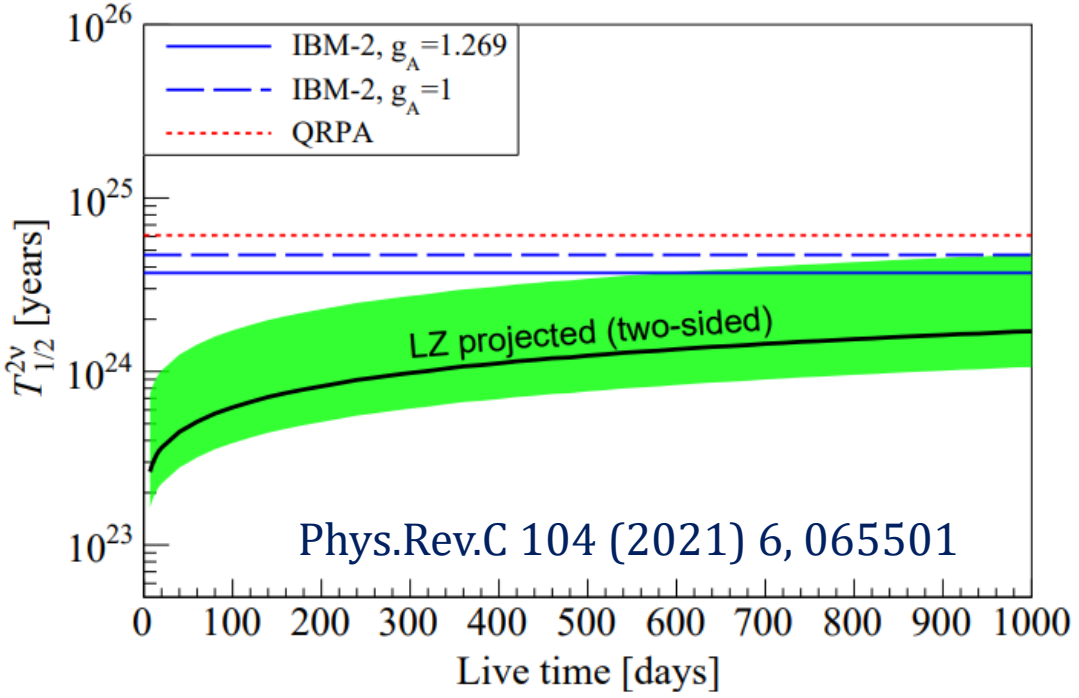
Phys.Rev.D 96 (2017) 9, 092001

^{134}Xe $2\nu\beta\beta$ and $0\nu\beta\beta$ search in PandaX-4T

- PandaX-4T: more ^{134}Xe; much less ^{136}Xe; wider energy range; self shielding effect; potential discovery

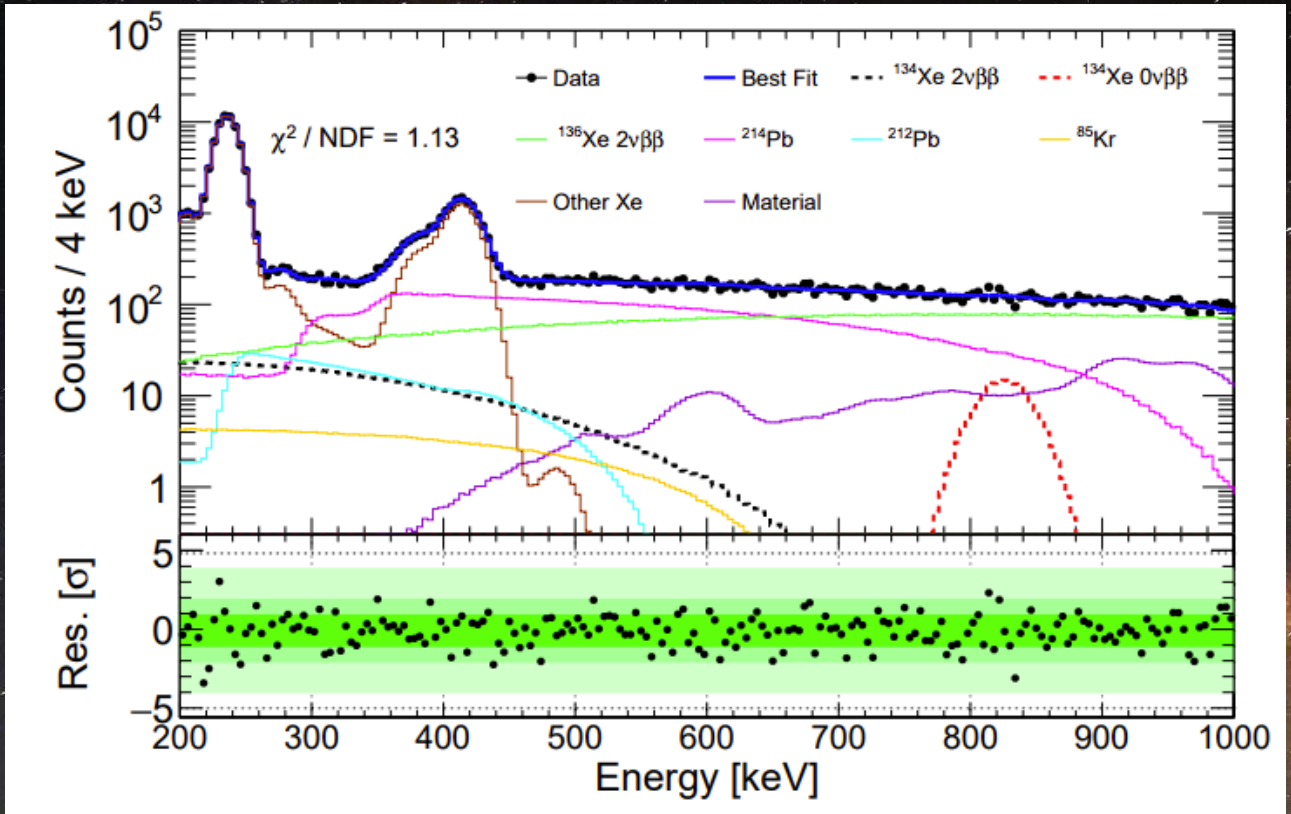
	^{134}Xe mass	^{136}Xe abundance	Analysis threshold	Live Time
PandaX-4T	68.7 kg	8.9%	200 keV	94.9 days
EXO-200	18.1 kg	81%	470 keV	600 days

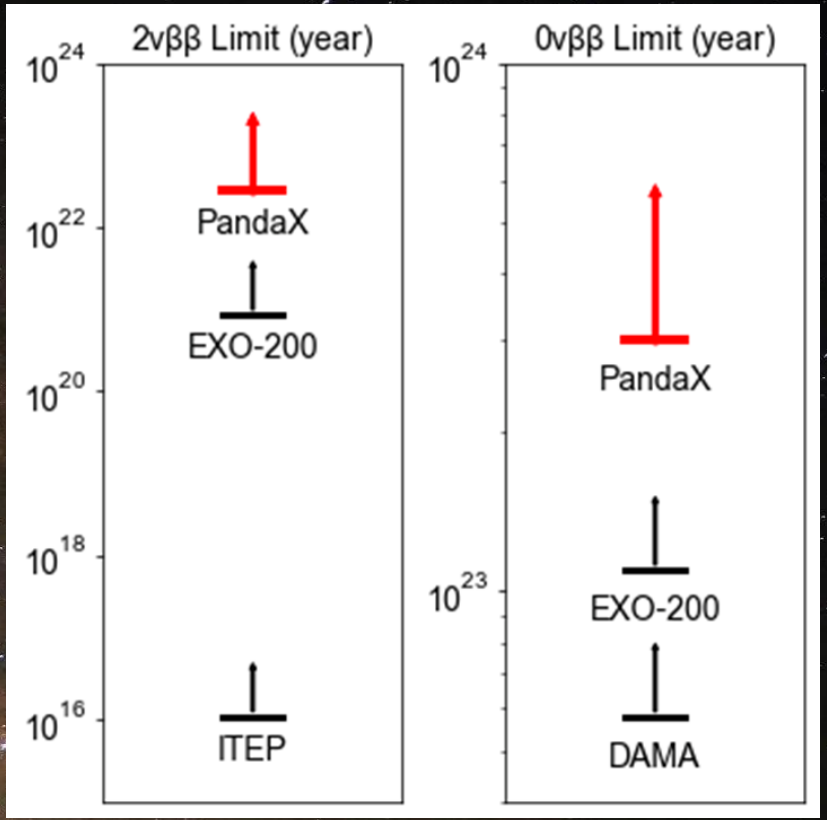




^{134}Xe half-life limits @ PandaX-4T

- Simultaneous fit for ^{134}Xe $2\nu\beta\beta$ and $0\nu\beta\beta$ using Run0
- Final counts of $2\nu\beta\beta$ and $0\nu\beta\beta$: 10±269(stat.)±680(syst.) and 105±48(stat.)±38(syst.)
- 90% CL lower limits on the half-life: $T_{1/2}^{2\nu\beta\beta} > 2.8 \cdot 10^{22}$ yr and $T_{1/2}^{0\nu\beta\beta} > 3.0 \cdot 10^{23}$ yr

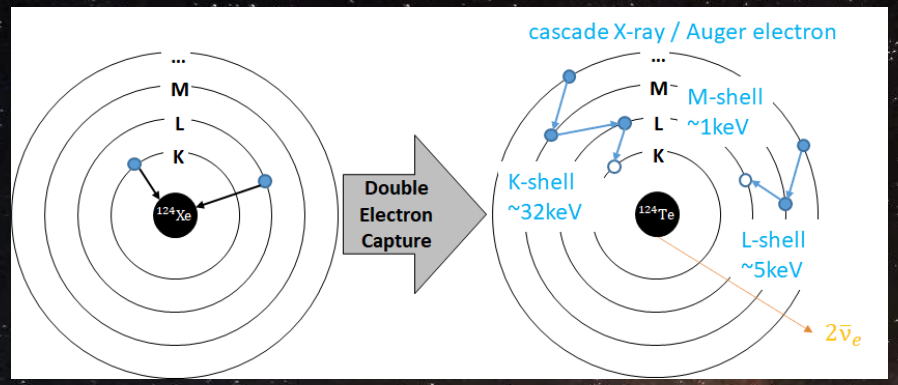


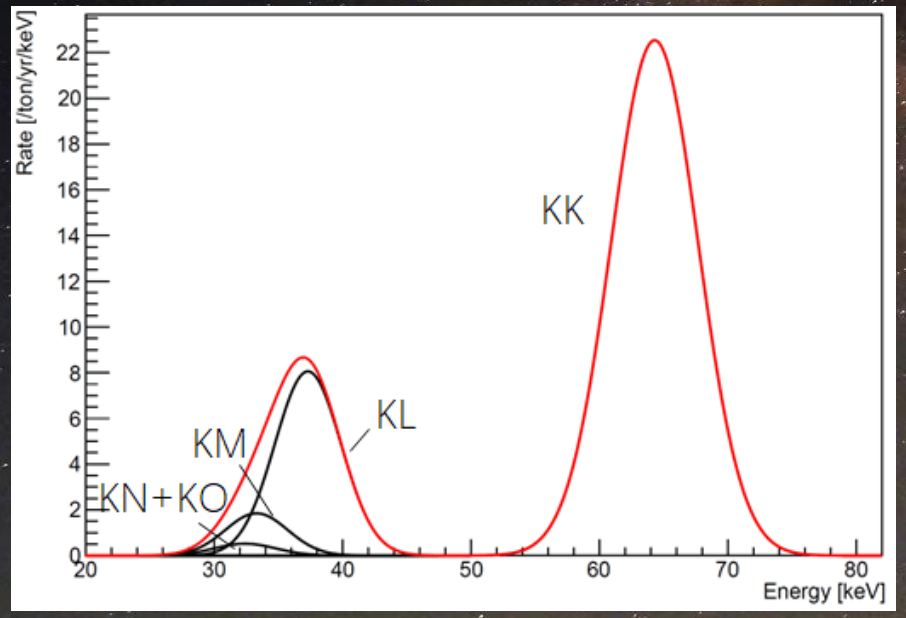


PandaX, Phys.Rev.Lett. 132 (2024) 15, 152502

^{124}Xe 2νECEC half-life measurement

$$(A, Z) + 2e^- \rightarrow (A, Z-2) + (2\nu_e)$$





- 2ν/0ν ECEC
  - Q = 2857 keV
  - Auger electron & X-ray cascades SS events
- 2νECEC is a 2nd order weak process, with a longest measured half-life so far

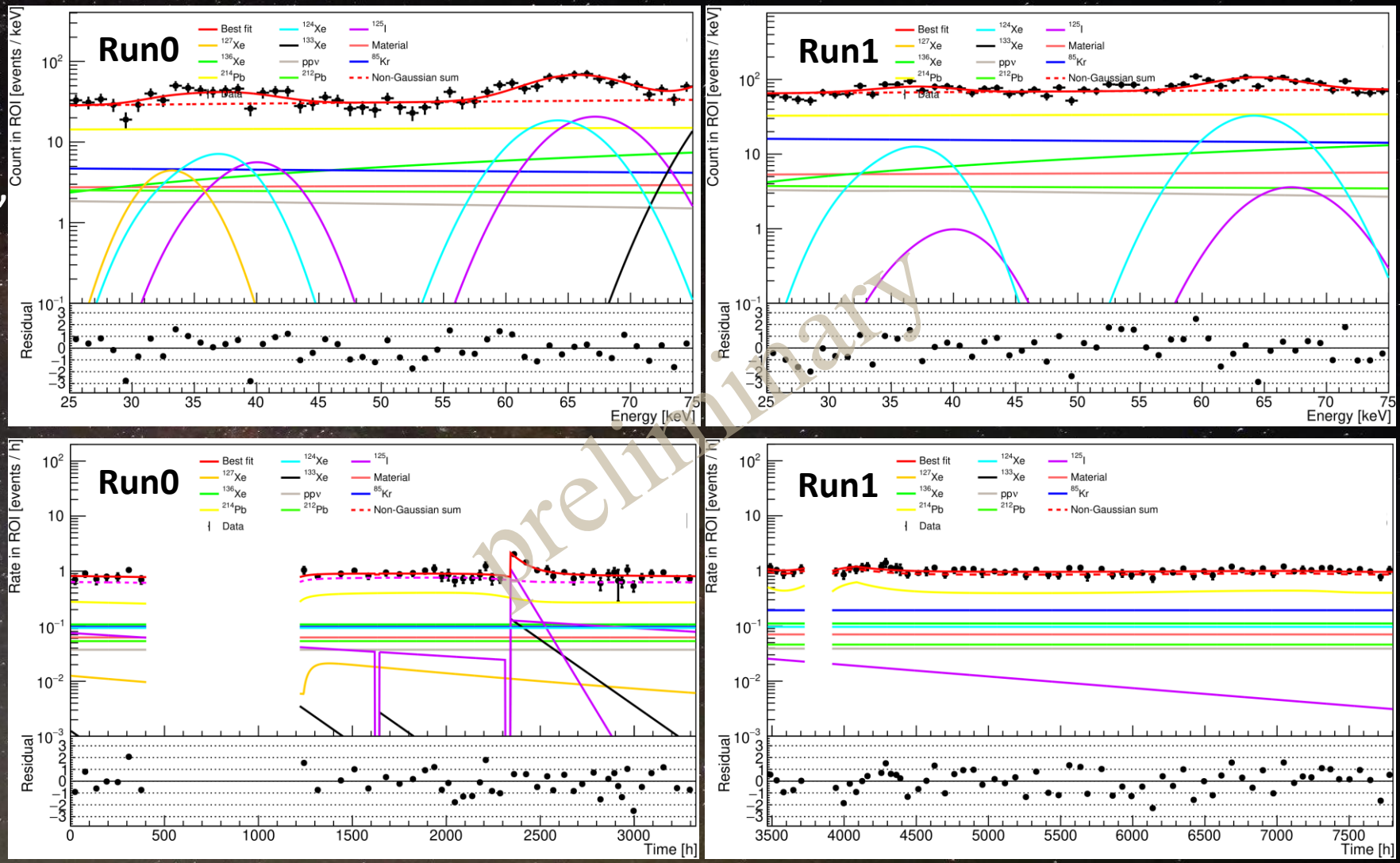
- XENONnT: $T_{1/2} = (1.18 \pm 0.13_{stat} \pm 0.14_{sys}) \times 10^{22}$ yr
  [PRL 129, 161805 (2022)]
- LZ: $T_{1/2} = (1.09 \pm 0.14_{stat} \pm 0.05_{sys}) \times 10^{22}$ yr
  [ArXiv: 2408.17391 (2024)]

Energy spectrum + time evolution likelihood fit

- Unbinned 2D fit to Run0+Run1 data in parameter space of (energy, time) to well model the Iodine background
- Use a profile likelihood ratio (PLR) approach
- Preliminary measurement on ^{124}Xe 2νECEC half-life:

$1.03 \pm 0.15(\text{stat.}) \pm 0.06(\text{syst.}) \times 10^{22}$ yr

Projected spectra and time evolution



Summary

- Searching for $0\nu\beta\beta$ is the most sensitive to probe the nature of neutrino mass and absolute neutrino masses
- The most stringent limits on $0\nu\beta\beta$ in experiments:
  - 3.8×10^{25}yr for ^{130}Te; 1.8×10^{26}yr for ^{76}Ge; 3.8×10^{26}yr for ^{136}Xe
- Majorana neutrino search in Natural xenon DM experiments (PandaX-4T):
  - ^{136}Xe $2\nu\beta\beta$ half-life is precisely measured ($2.27 \pm 0.03(\text{stat.}) \pm 0.10(\text{syst.}) \times 10^{21}$ yr)
  - Limits for ^{134}Xe $2\nu\beta\beta$ and $0\nu\beta\beta$ with 17.9 kg·yr exposure : $T_{1/2}^{2\nu\beta\beta} > 2.8 \cdot 10^{22}$ yr and $T_{1/2}^{0\nu\beta\beta} > 3.0 \cdot 10^{23}$ yr at 90% CL
  - Preliminary result of ^{136}Xe $0\nu\beta\beta$: $T_{1/2}^{0\nu\beta\beta} > 2.1\times10^{24}$ yr
  - Preliminary result of ^{124}Xe 2νECEC: $1.03 \pm 0.15(\text{stat.}) \pm 0.06(\text{syst.}) \times 10^{22}$ yr

Thanks!