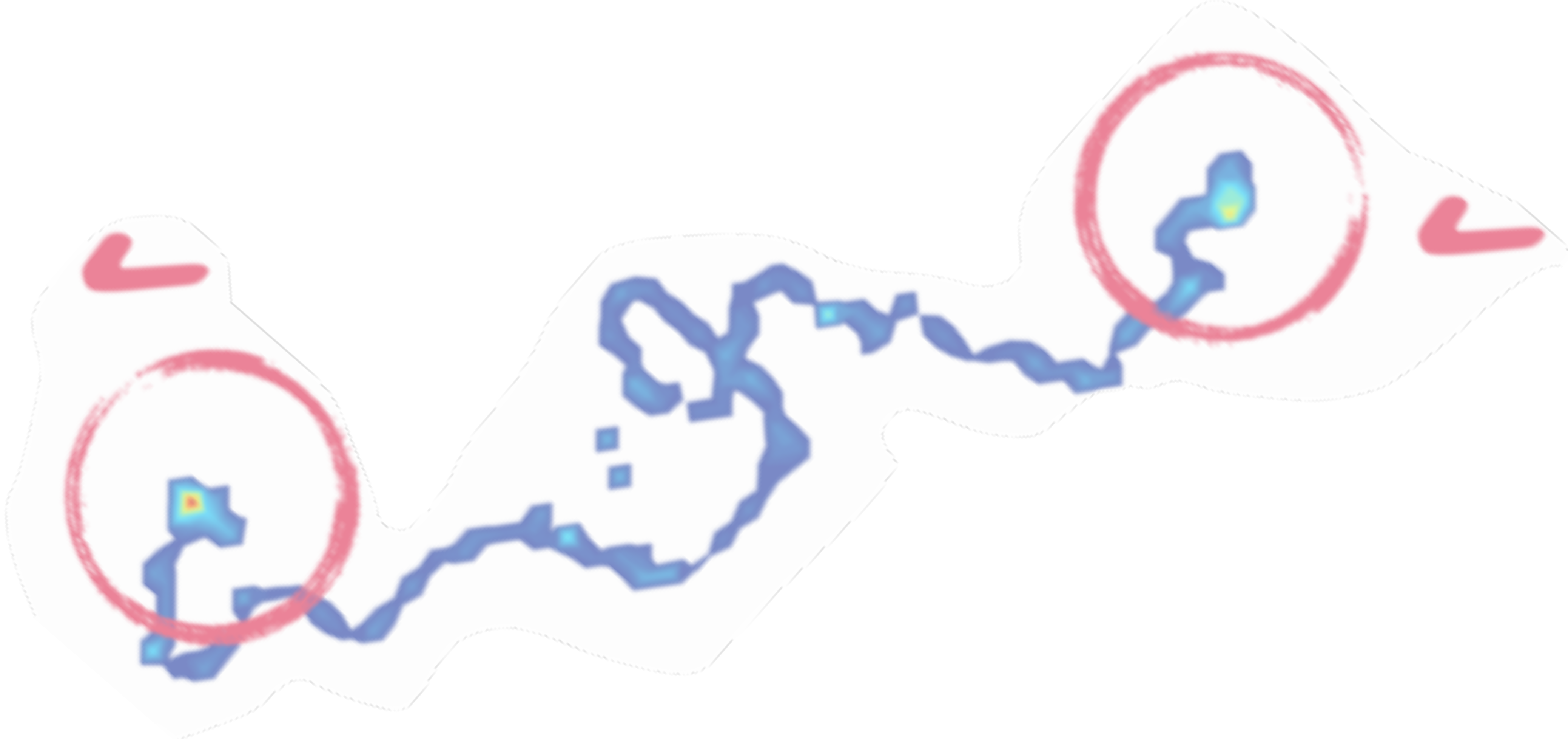


Searching for Majorana neutrinos with NEXT

Roxanne Guenette

The University of Manchester

HEP seminar, University of Warwick
1 February 2024

Brief introduction to neutrinos

- We have known for a while that we have three flavors of neutrinos that only interact weakly
- The biggest discovery for neutrinos was the fact that they oscillate (SuperKamiokande, SNO, KamLand…)
- We "understand" oscillation physics and have measured most of the oscillation parameters with some precision
- Oscillation implies that neutrinos are massive particles, in **contradiction** with the Standard Model
- While massive neutrinos are a first glimpse of new physics, many open questions of neutrinos could lead to paradigm shifting discoveries!

How to give mass to the neutrinos

In Standard Model:

- ✓ Neutrinos are created exclusively via weak interactions
- ✓ The charged boson $W^{\pm}$ only couples to left-handed particles (right-handed antiparticles)
- ✓ All neutrinos (antineutrinos) and produced left-handed (right-handed)
- ✓ No evidence of right-handed neutrinos
- ✓ Without right-handed fields, neutrinos remain massless

How to give mass to the neutrinos

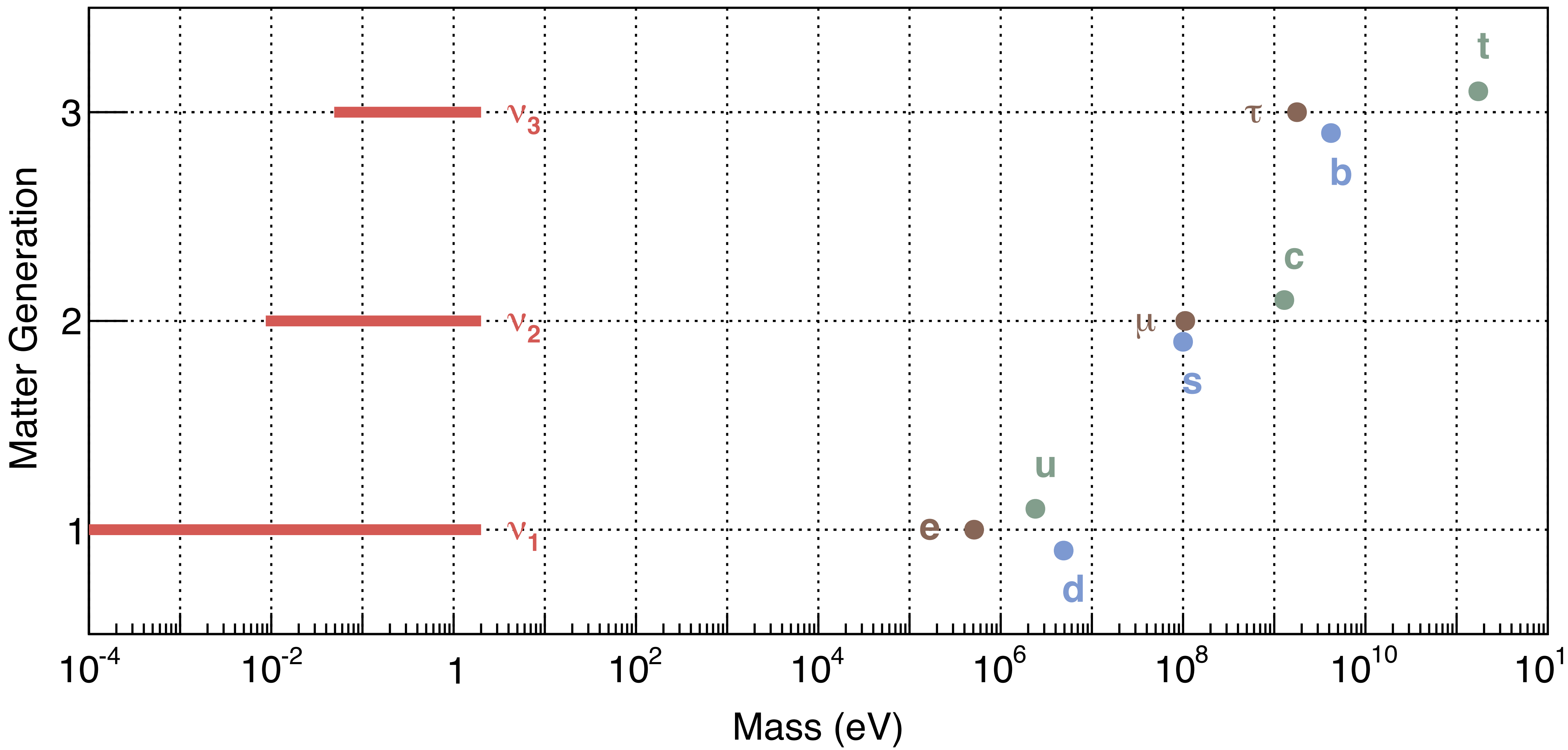
- Simplest: **extend** particle content of SM to add right-handed neutrino fields

$$-\mathcal{L}_{H,\ell} = \frac{y^\ell v}{\sqrt{2}} \overline{\ell_L}\, \ell_R + \frac{y^\nu v}{\sqrt{2}} \overline{\nu_L}\, \nu_R + \frac{y^\ell}{\sqrt{2}} \overline{\ell_L}\, \ell_R H + \frac{y^\nu}{\sqrt{2}} \overline{\nu_L}\, \nu_R H + \text{H.c.}$$

$$m_\ell = y^\ell \frac{v}{\sqrt{2}} \qquad m_\nu = y^\nu \frac{v}{\sqrt{2}}$$

$$y^\nu \lesssim 10^{-11} \ll y^e \sim 10^{-6}$$

How to give mass to the neutrinos



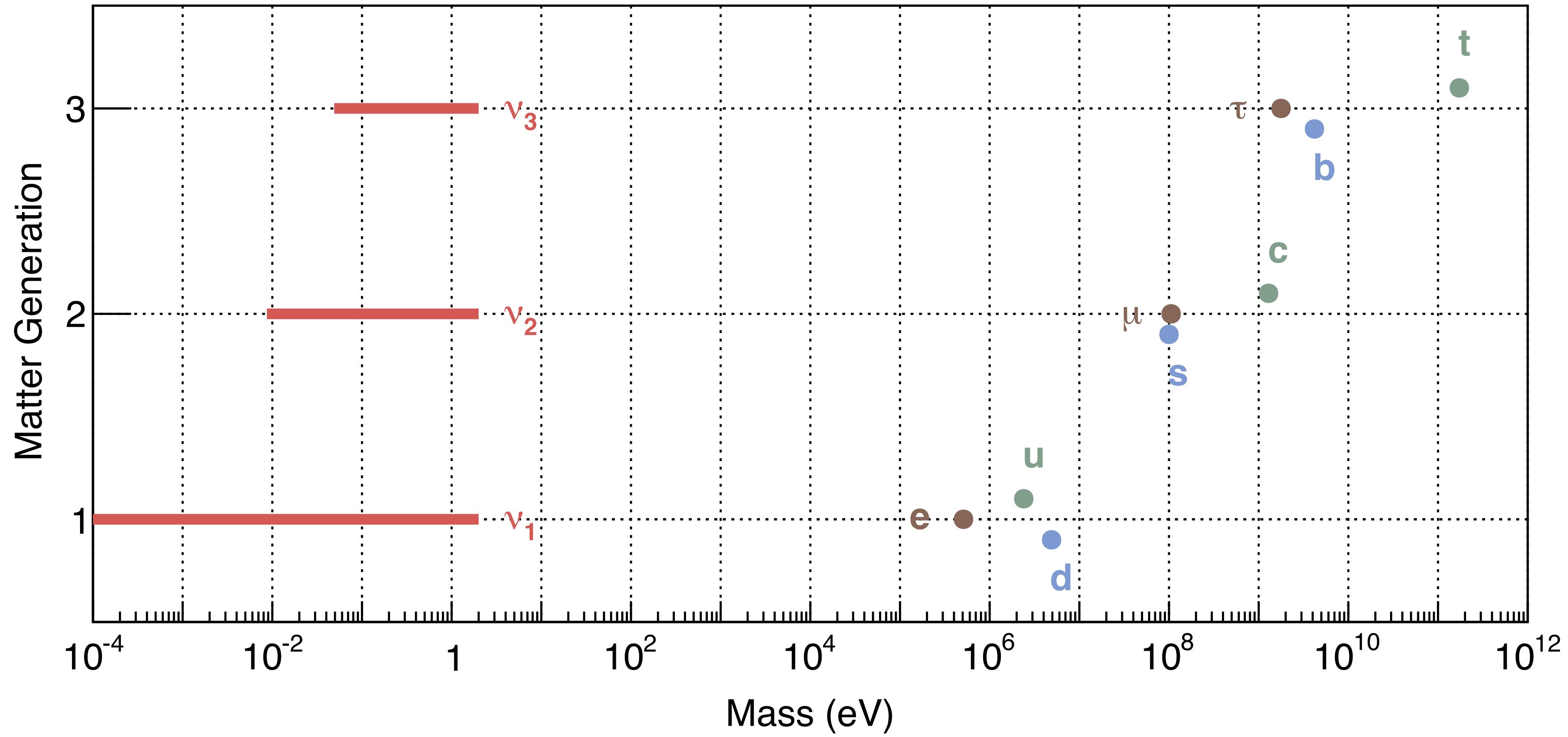
This doesn't seem *natural*…

What we know we don't know

- What are the absolute neutrino masses?
- What is the mass hierarchy (ordering)
- Is there CP violation? What is δ_{CP}?
- What is the nature of neutrinos (Dirac or Majorana)?
- Are there sterile neutrinos?

What we know we don't know

What are the absolute neutrino masses?

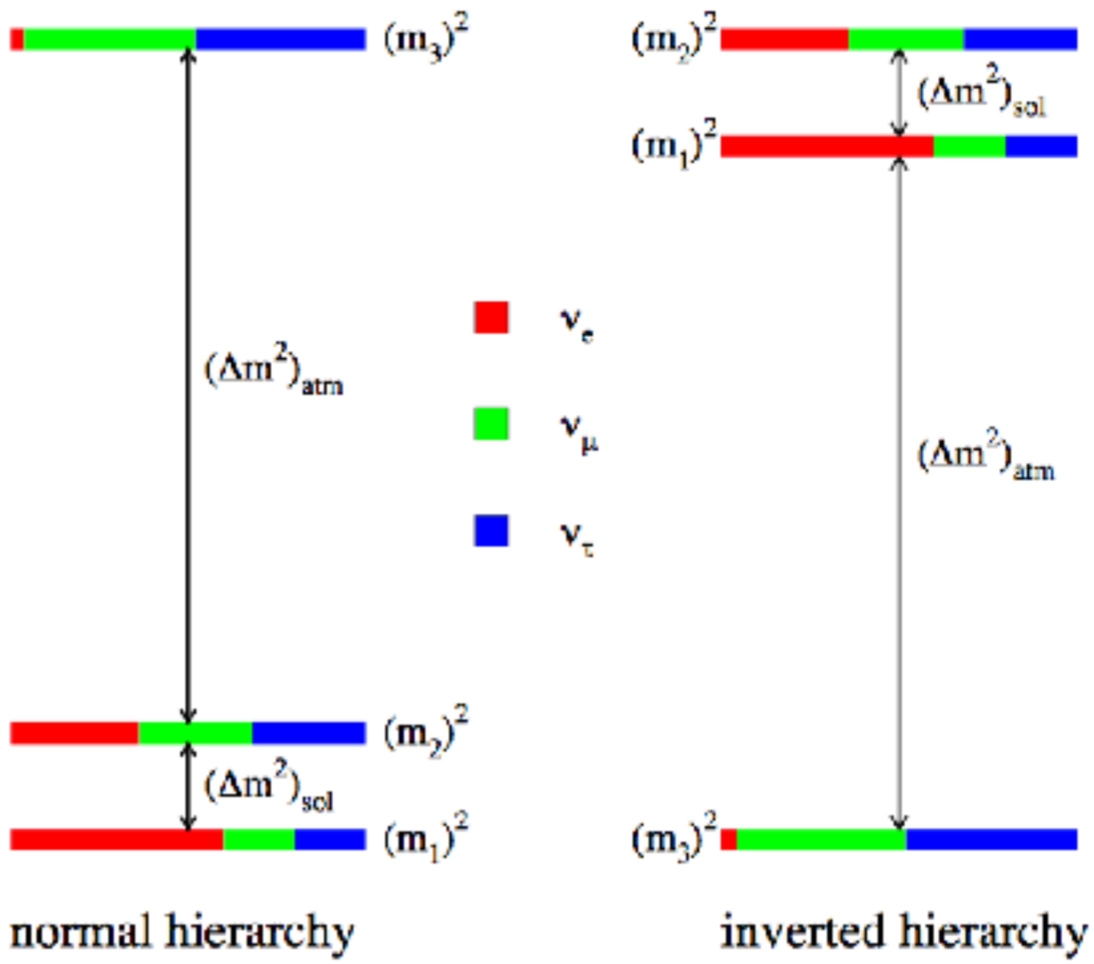


What we know we don't know

What is the masse ordering?

$(\Delta m^2)_{sol} \sim 10^{-5}\ eV^2$

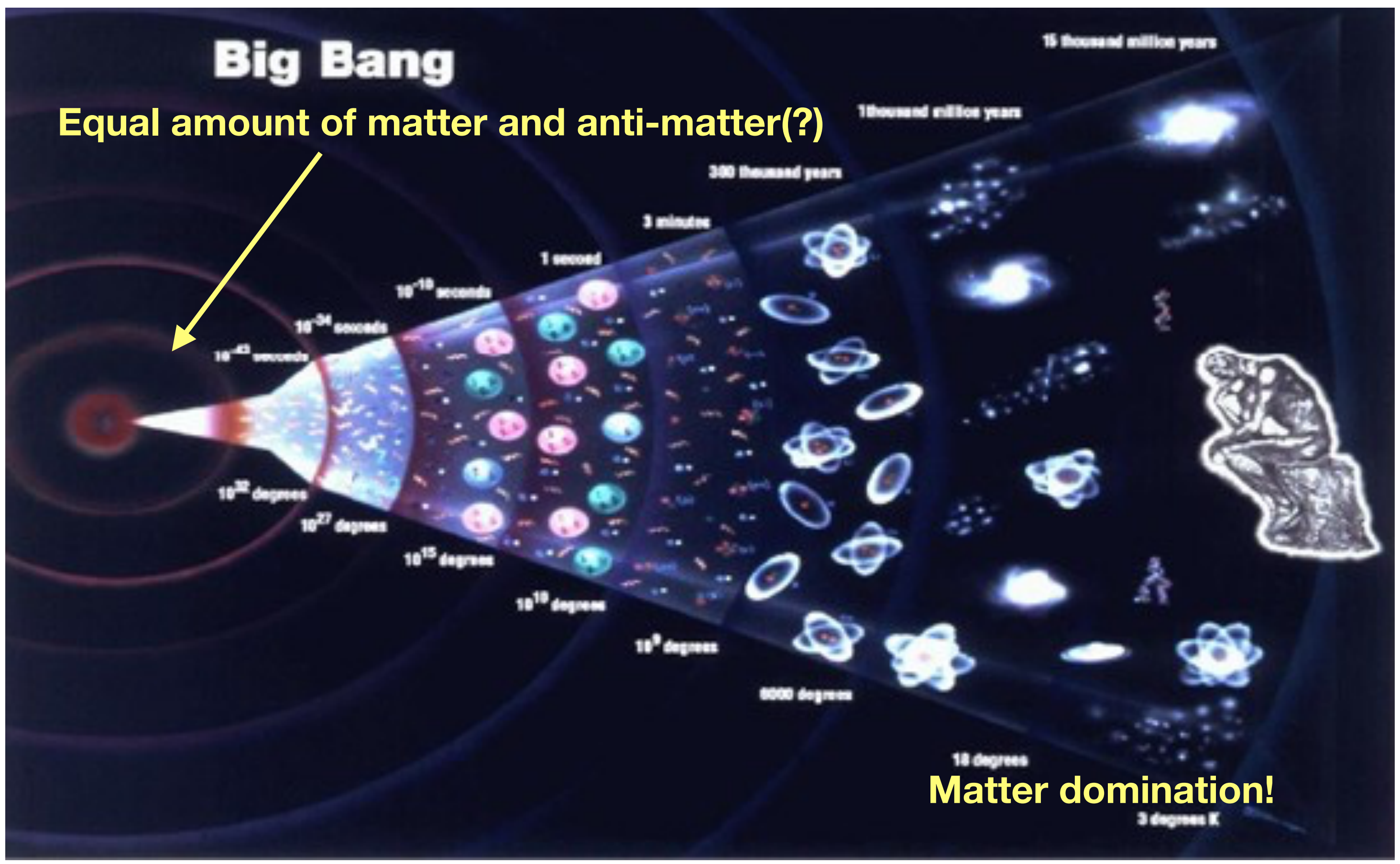
$(\Delta m^2)_{atmo} \sim 10^{-3}\ eV^2$



- ➡ Simplify oscillation predictions significantly
- ➡ Constrain GUT
- ➡ Guidance to $0\nu\beta\beta$ experiments

What we know we don't know

Is there CP violation? What is δ_{CP}?



Anti-Matter ⇒ Matter ???

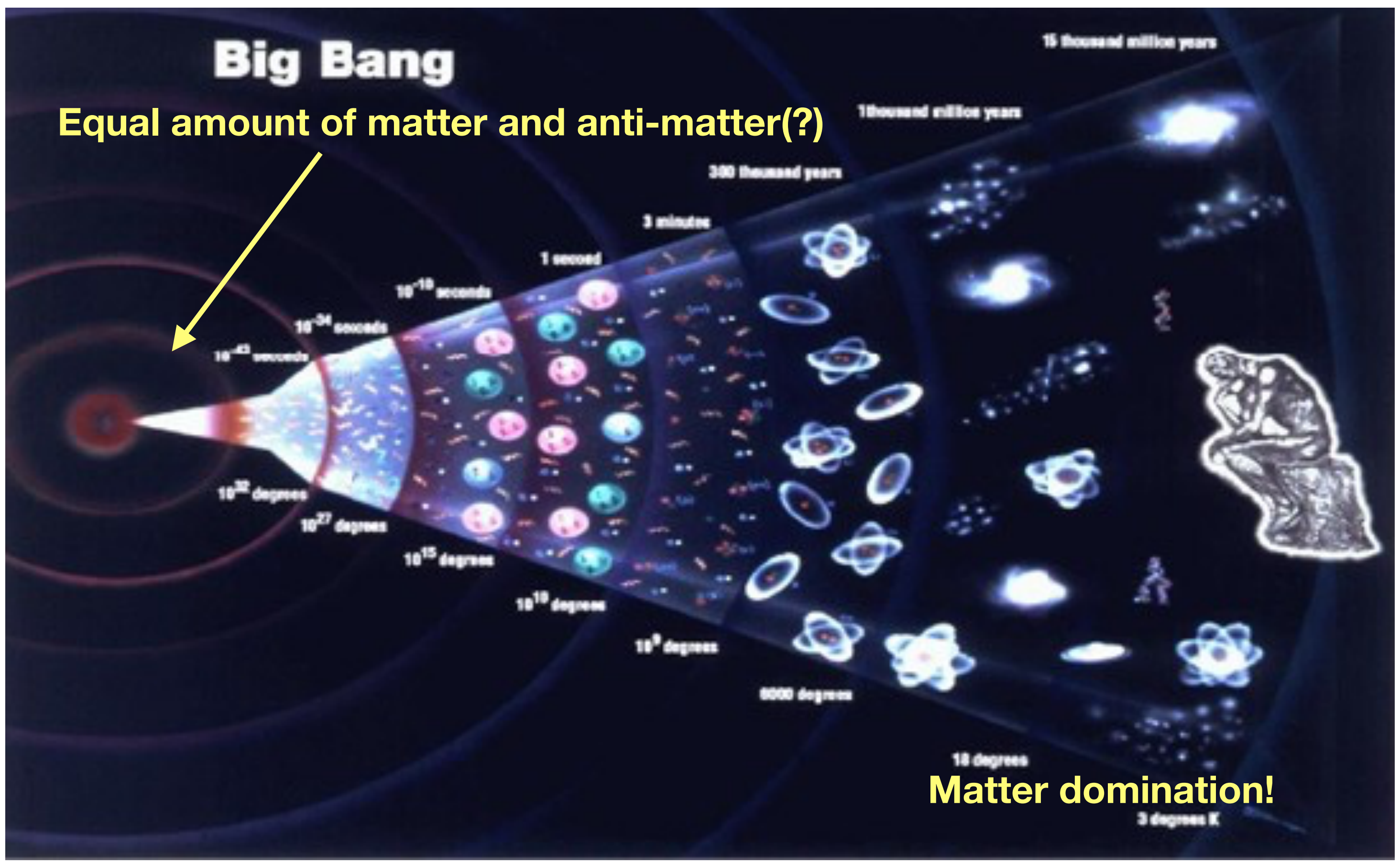
CP violation!

C: Particle → Antiparticle

P: Helicity → Reversed helicity

What we know we don't know

Is there CP violation? What is δ_{CP}?



Anti-Matter ⇒ Matter ???

CP violation!

C: Particle ⟶ Antiparticle

P: Helicity ⟶ Reversed helicity

$\overline{\nu}$(right-handed) = CP[ν(left-handed)]

$$P(\overline{\nu_\alpha} \rightarrow \overline{\nu_\beta}) \neq P(\nu_\alpha \rightarrow \nu_\beta)$$

What we know we don't know

What is the nature of neutrinos (Dirac or Majorana)?

Dirac fermion $\overline{\nu} \neq \nu$

$$-\mathcal{L}_{\mathrm{D}} = m_\nu \, \overline{\nu_L} \, \nu_R + \mathrm{H.c}$$

4 degrees of freedom:
- LH particle
- RH particle
- LH anti-particle
- RH anti-particle

Majorana fermion $\overline{\nu} = \nu$

$$-\mathcal{L}_{\mathrm{M}} = m_\nu \, \overline{\nu_L} \, \nu_L^c + \mathrm{H.c}$$

2 degrees of freedom:
- LH particle/antiparticle
- RH particle/antiparticle

Getting the big picture out of the answers

Absolute Mass

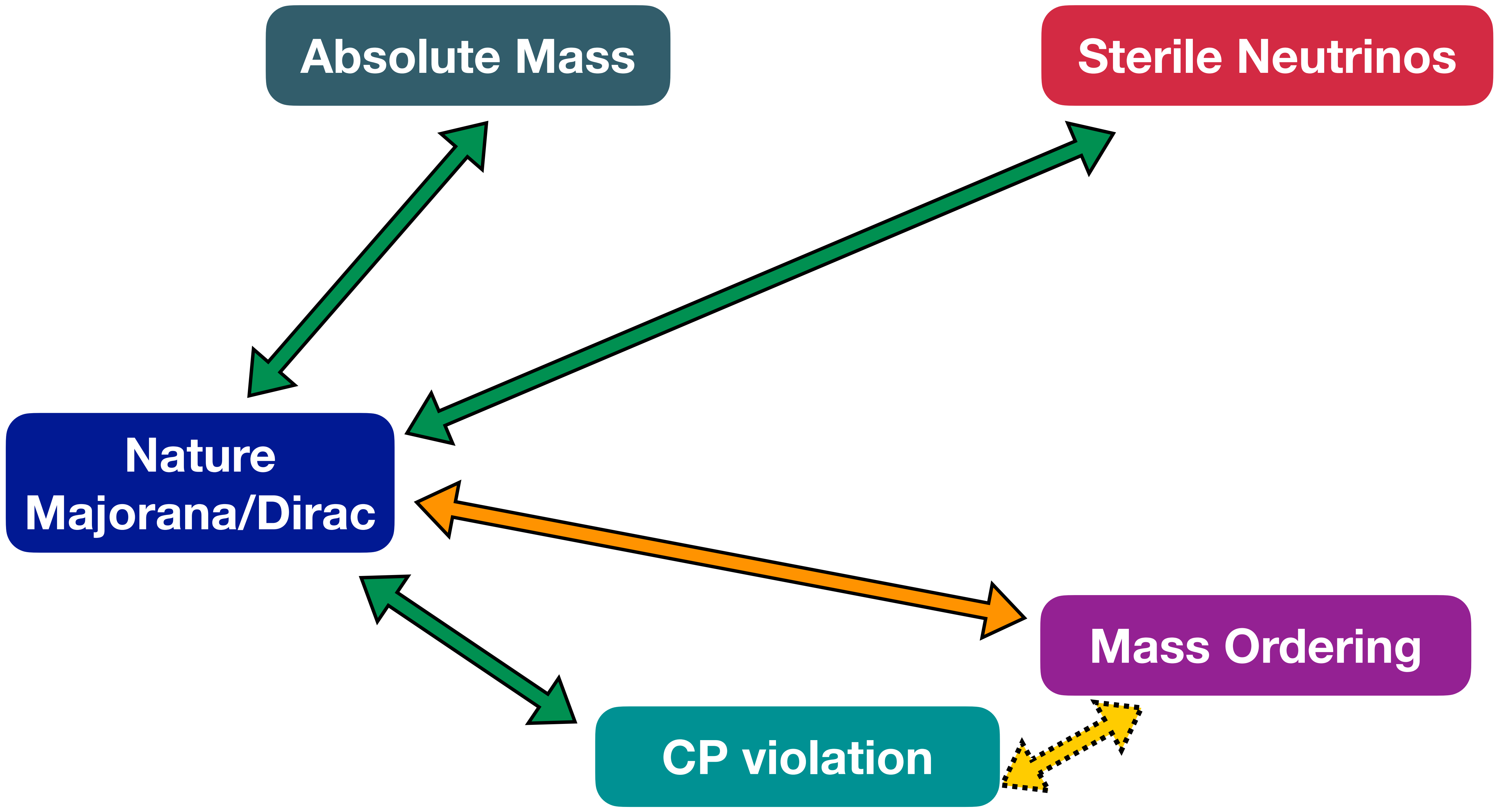
Sterile Neutrinos

Nature Majorana/Dirac

Mass Ordering

CP violation

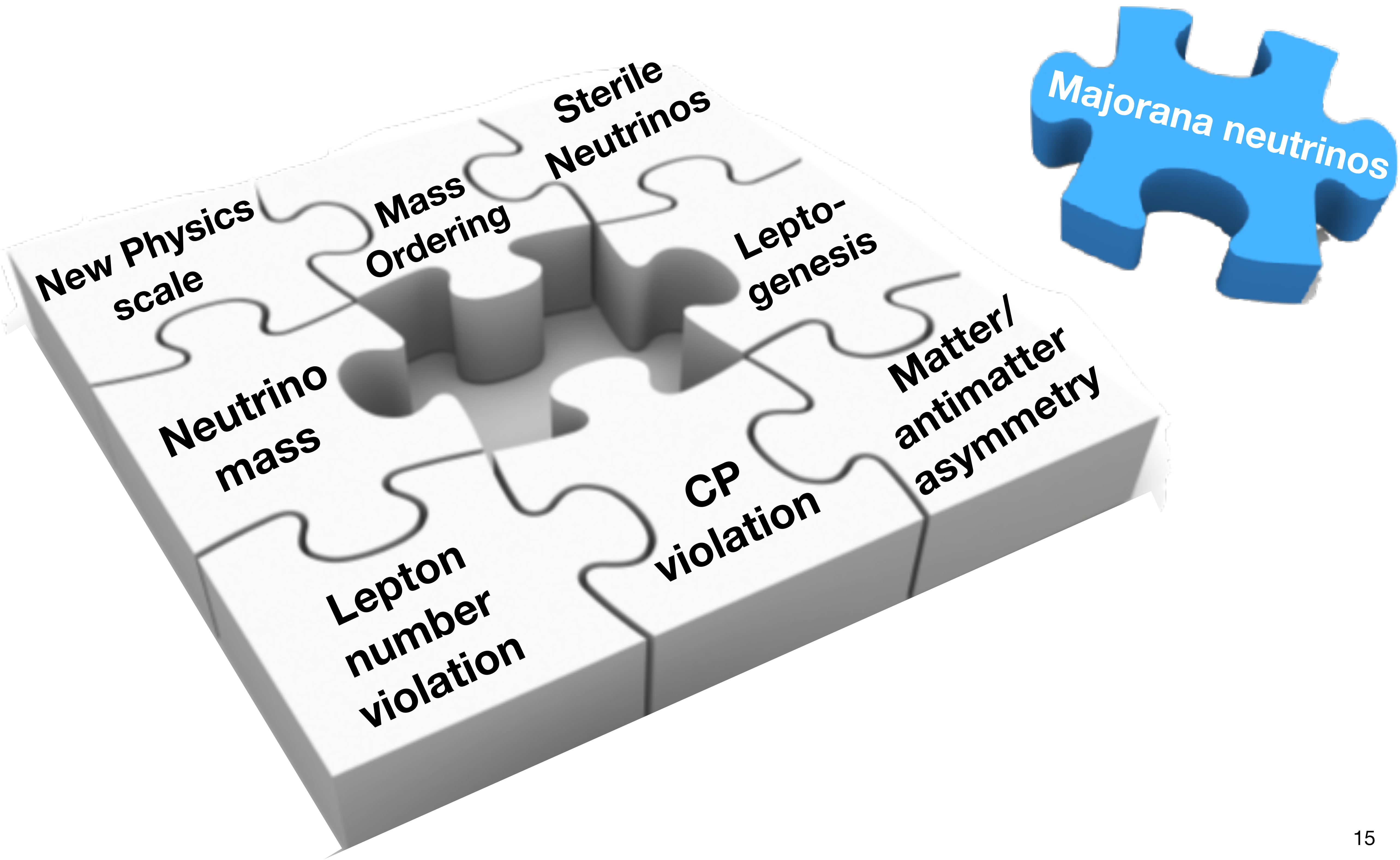
Getting the big picture out of the answers

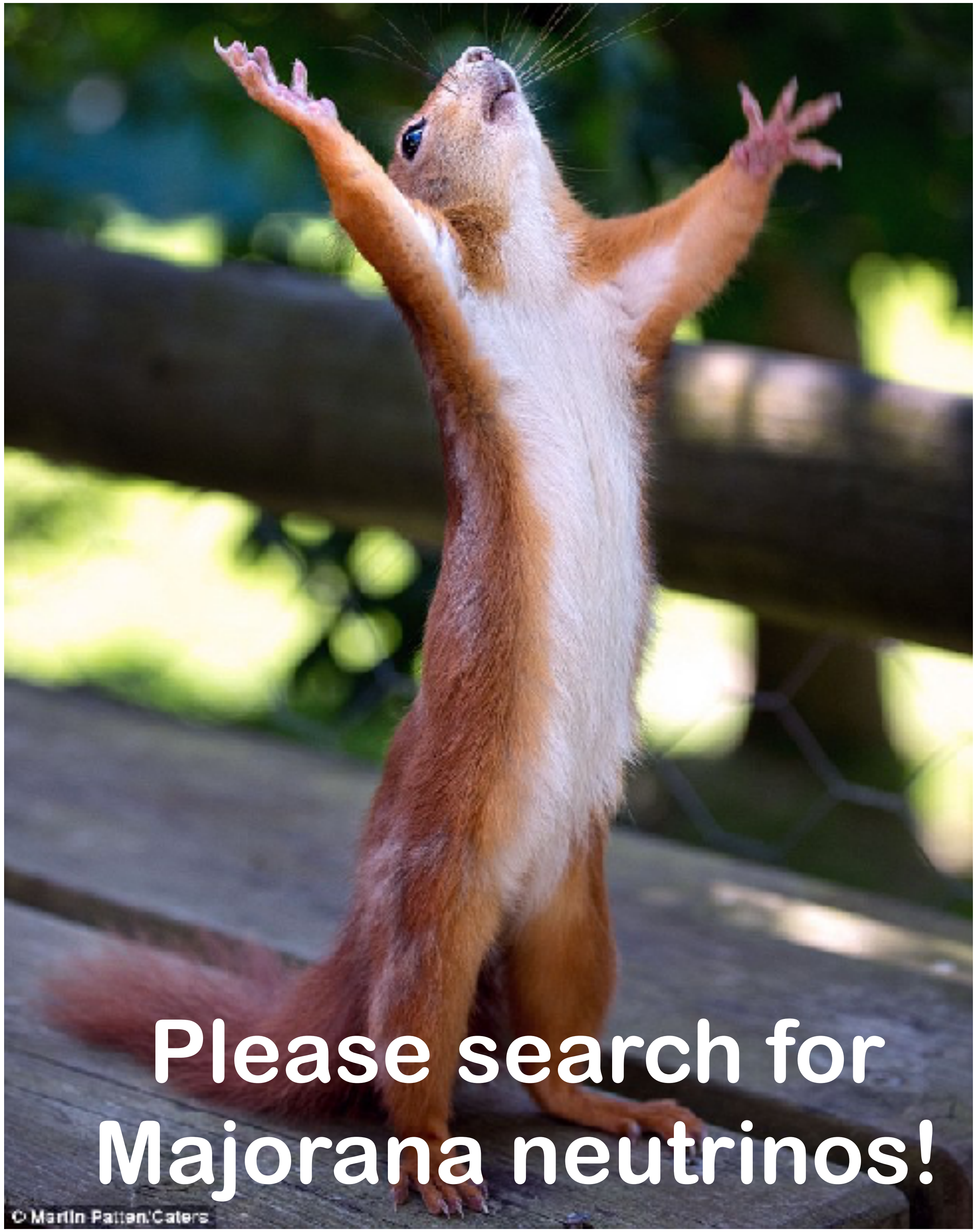


What if neutrinos are Majorana particles?

- That makes neutrinos even more special!
- It could give constraints for the absolute neutrino mass
- It provides strong basis on neutrino mass mechanism (new mechanism beside Higgs one)
- It give serious ground to *Leptogenesis* (Majorana neutrinos are an excellent ingredient)
- It proves that the Standard Model is only a low-energy effective theory AND it gives the scale of new physics!

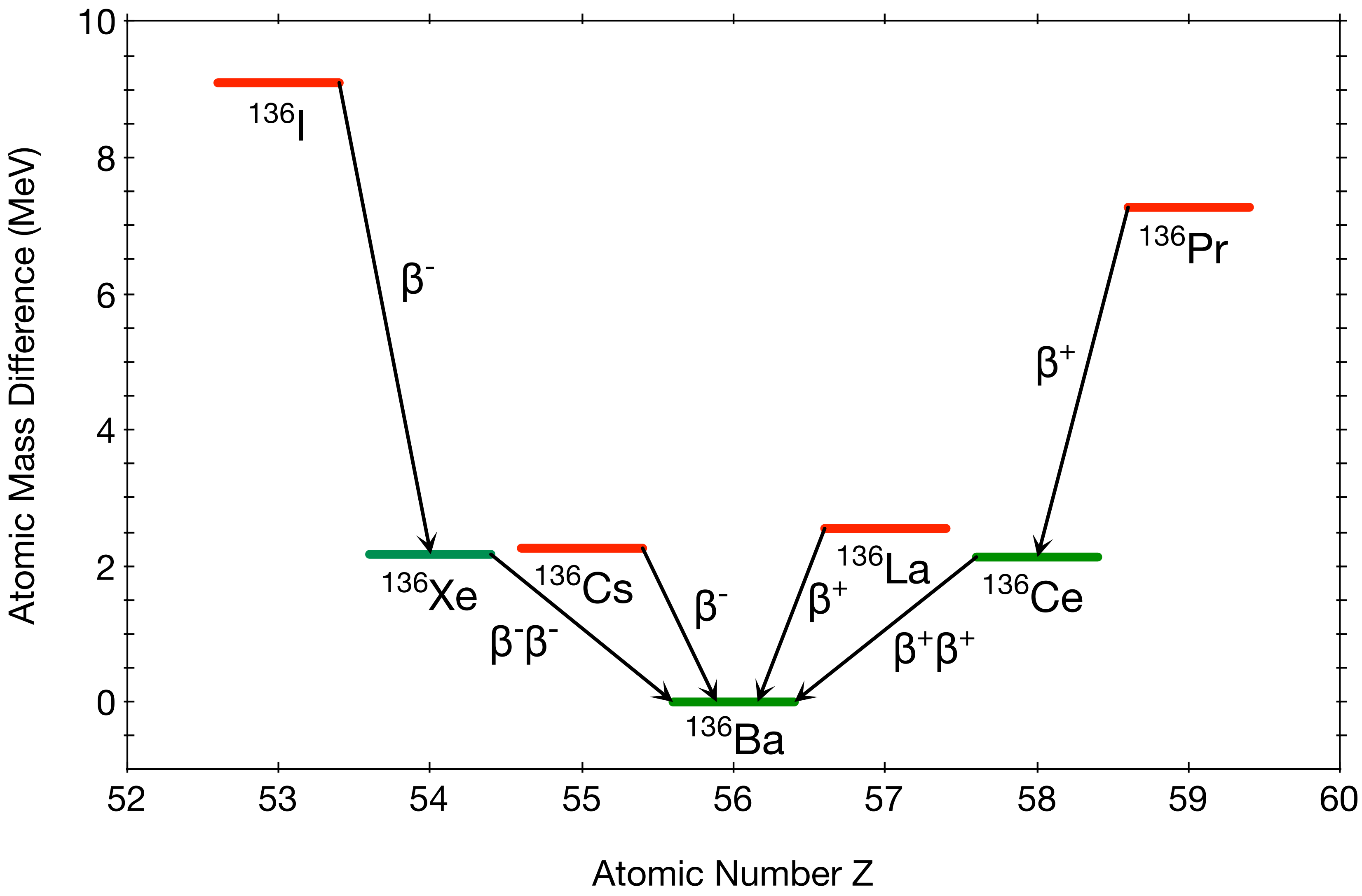
Searching for Majorana neutrinos

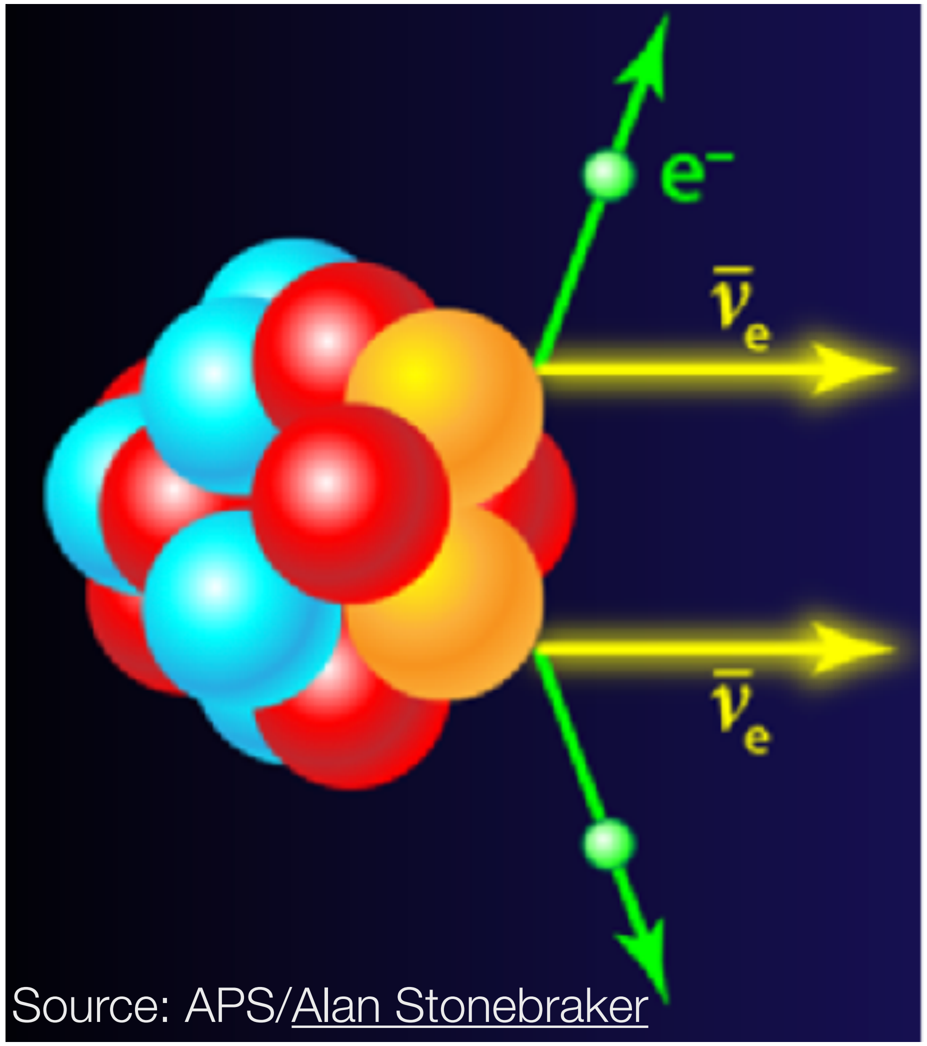



Please search for
Majorana neutrinos!
© Martin Patten/Caters

How to find a Majorana neutrino?

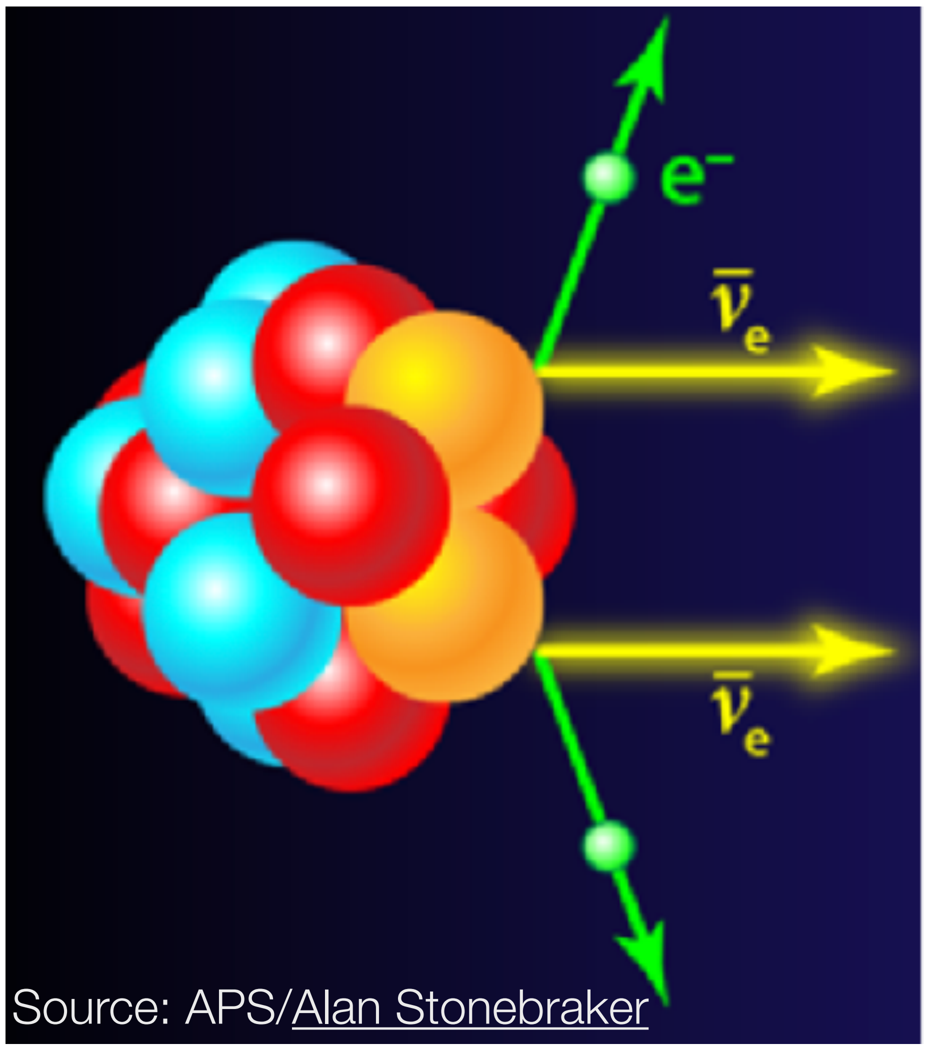
The only *known* way to search for Majorana neutrinos is studying **double beta decays**





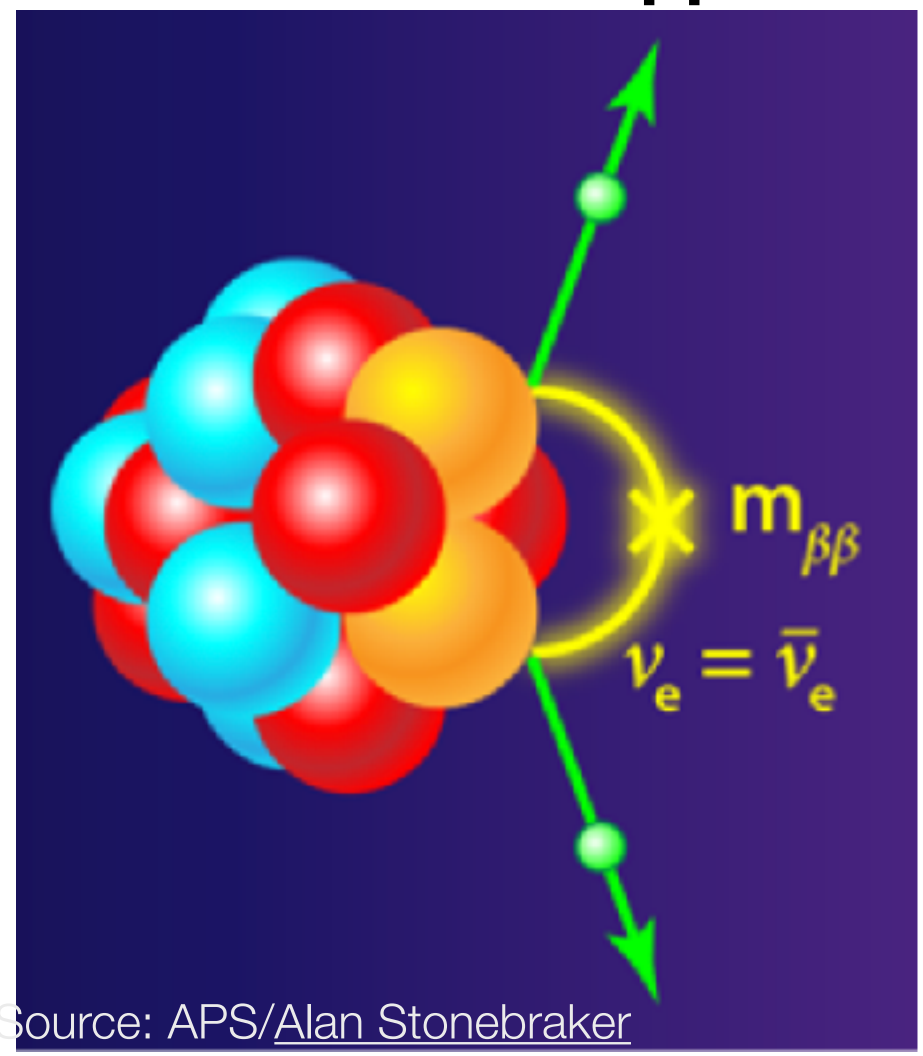
What about double beta decay?

Allowed regular ββ



Source: APS/Alan Stonebraker

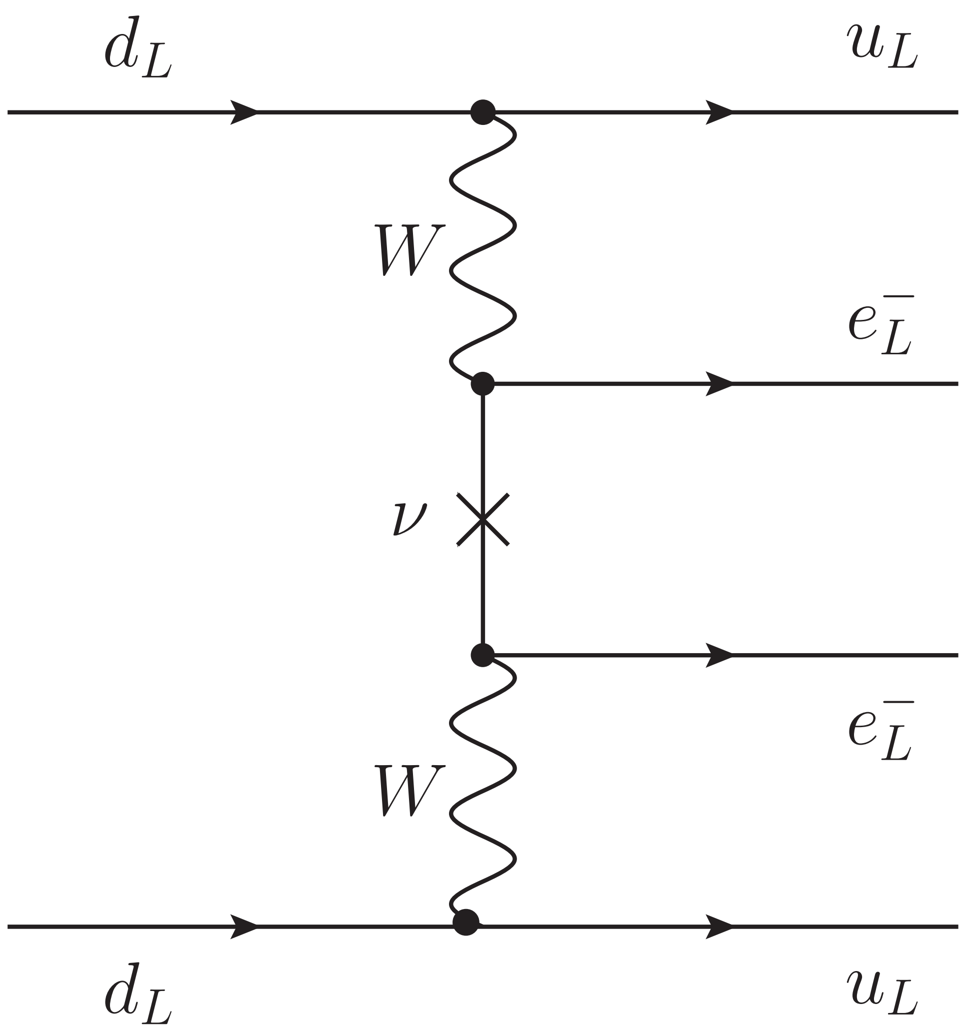
Neutrinoless ββ



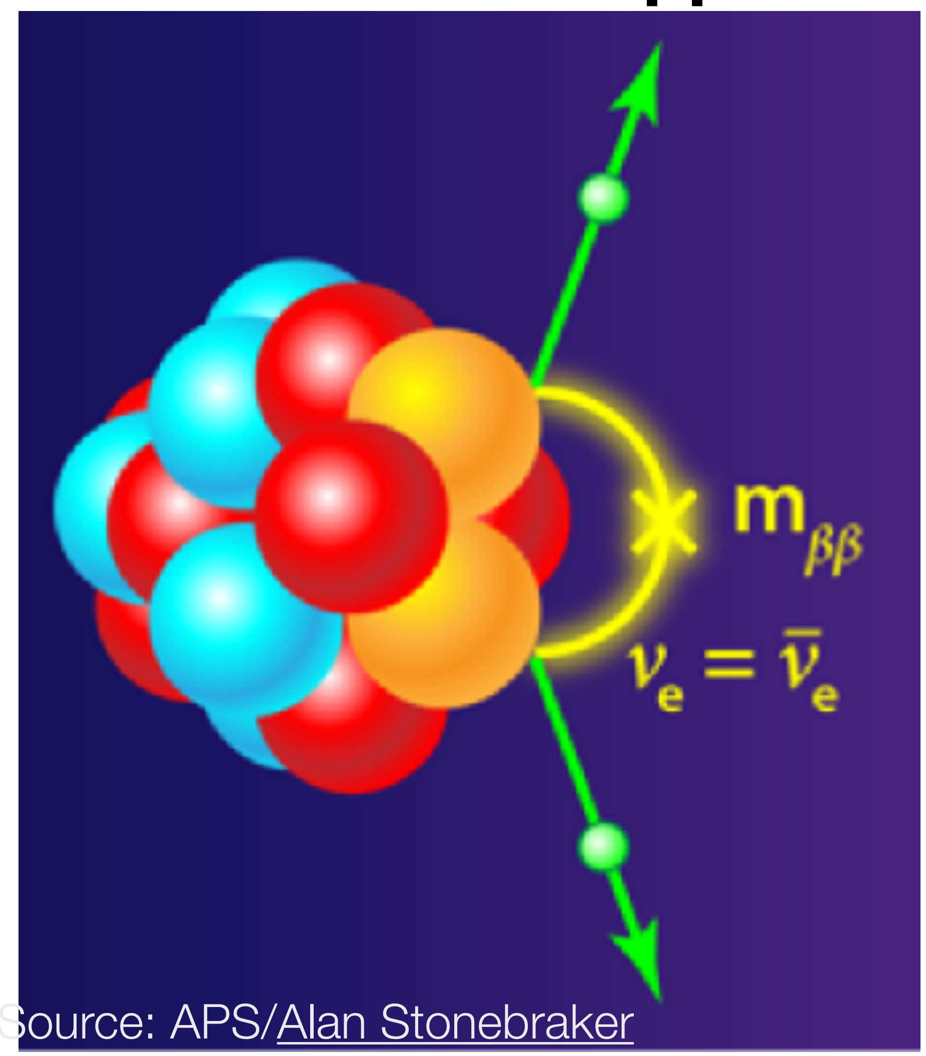
Source: APS/Alan Stonebraker

What about double beta decay?

One example of Majorana mechanism



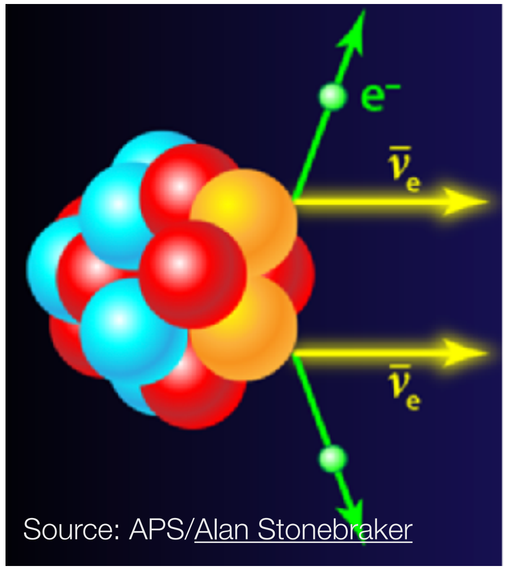
Neutrinoless ββ



Then let's do it! Yes, but….

- These decays are rare!
- Allowed regular decays have half-life $T_{½} \sim 10^{19\text{-}21}$ y
- For neutrinoless double beta decay ($0\nu\beta\beta$):

Allowed regular ββ

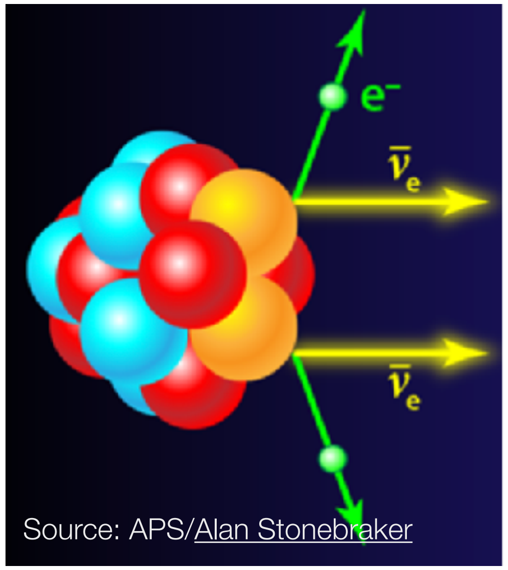


$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}\,\left|M^{0\nu}\right|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

Then let's do it! Yes, but….

- These decays are rare!
- Allowed regular decays have half-life $T_{½} \sim 10^{19\text{-}21}$ y
- For neutrinoless double beta decay (0νββ):

Allowed regular ββ



$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}\ \left|M^{0\nu}\right|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

At least 5 orders of magnitudes smaller!

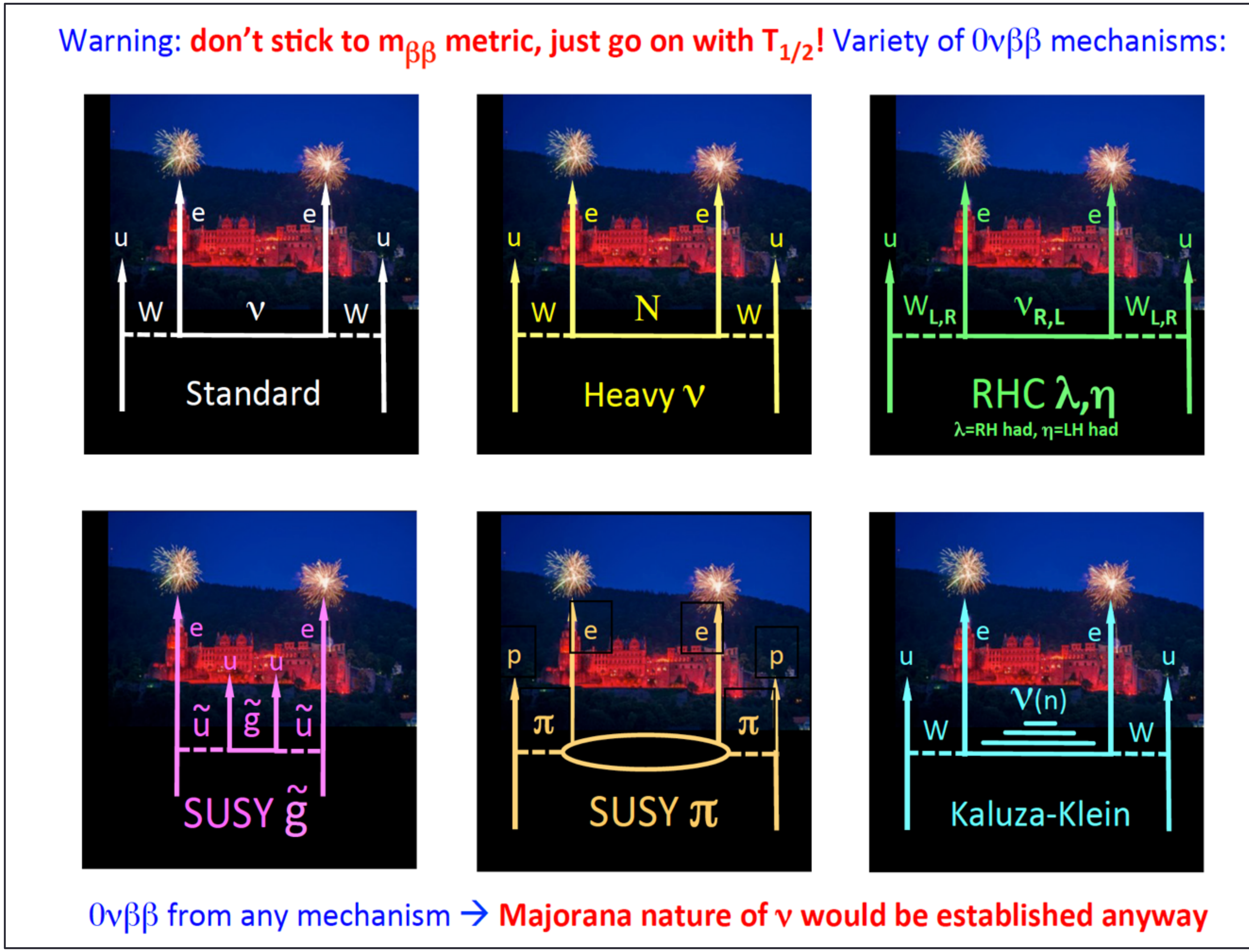
Expected signal region

- Pick a model

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu} \left|M^{0\nu}\right|^{2} \boxed{\left(\frac{m_{\beta\beta}}{m_e}\right)}^{2}$$

Expected signal region

- Pick a model (**note**: there are several models!)



Slide from The Mid and Long Term Future of Neutrinoless Double Beta Decay, Andrea Giuliani, Neutrinno2018, https://doi.org/10.5281/zenodo.1286915

Expected signal region

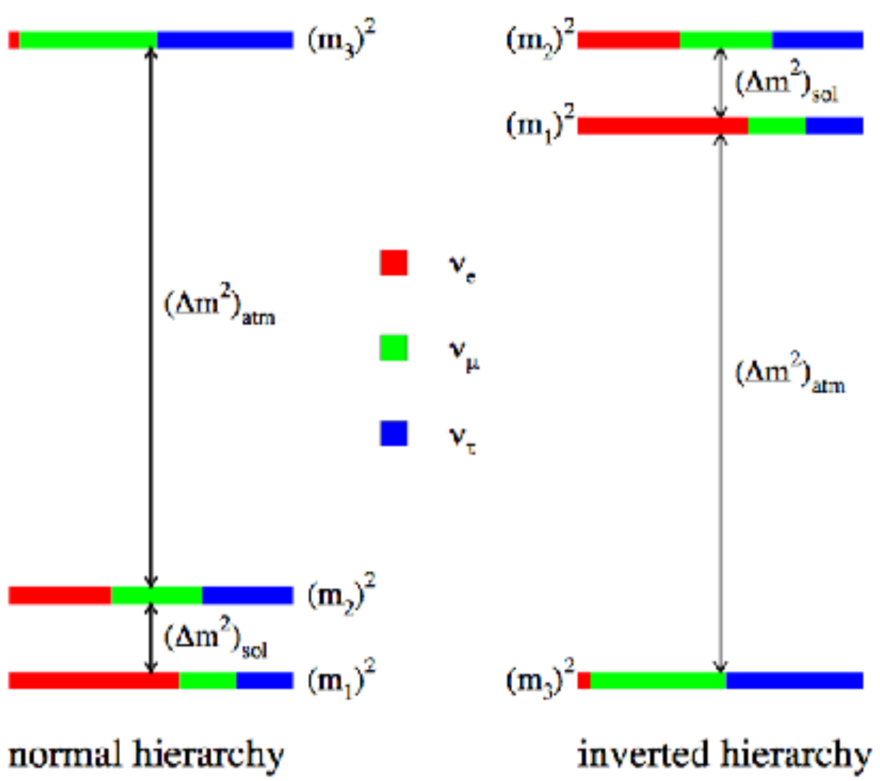
- Pick a model
  (**note**: there are several models!)

$$\left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu}\ \left|M^{0\nu}\right|^2 \boxed{\left(\frac{m_{\beta\beta}}{m_e}\right)}^2$$

Oscillation parameters (from PMNS)

$$m_{\beta\beta} \equiv \left| \mathrm{e}^{i\alpha_1} \boxed{|U_{ei}^2|}\, \boxed{m_1} + \mathrm{e}^{i\alpha_2} \boxed{|U_{e2}^2|}\, \boxed{m_2} + \boxed{|U_{e3}^2|}\, \boxed{m_3} \right|$$

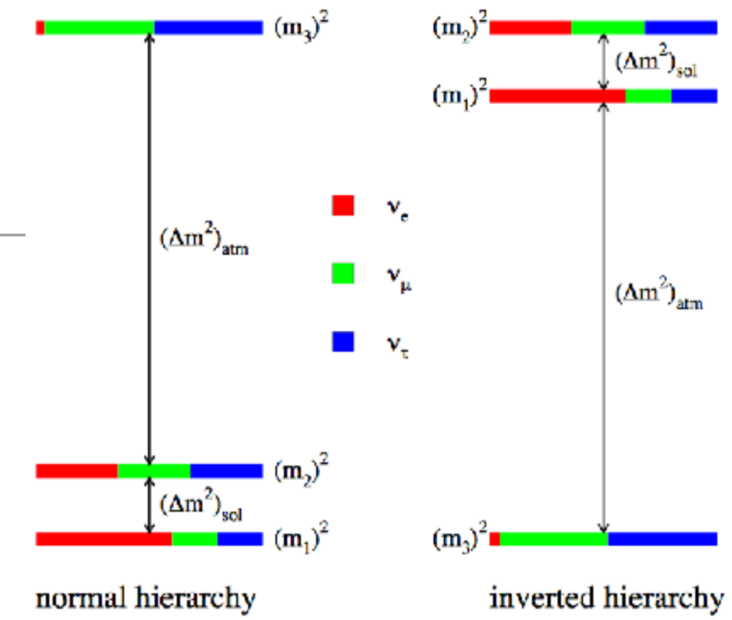
Mass, depends on mass ordering



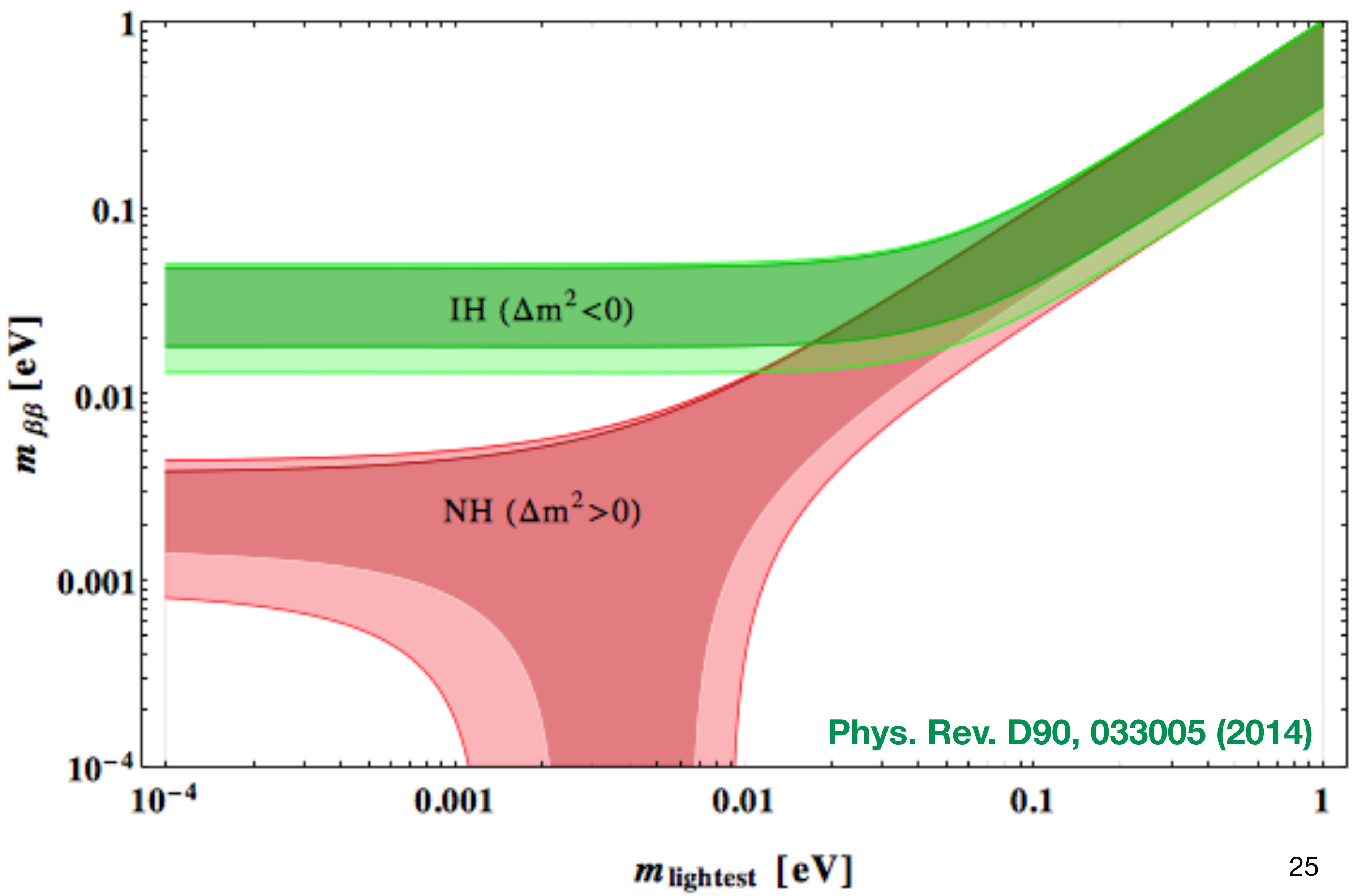
Expected signal region

- Pick a model (**note**: there are several models!)

$$m_{\beta\beta} \equiv \left| e^{i\alpha_1}|U_{ei}^2|m_1 + e^{i\alpha_2}|U_{e2}^2|m_2 + |U_{e3}^2|m_3 \right|$$



- Draw the parameter space (**note**: there are many uncertainties!)



Expected signal region

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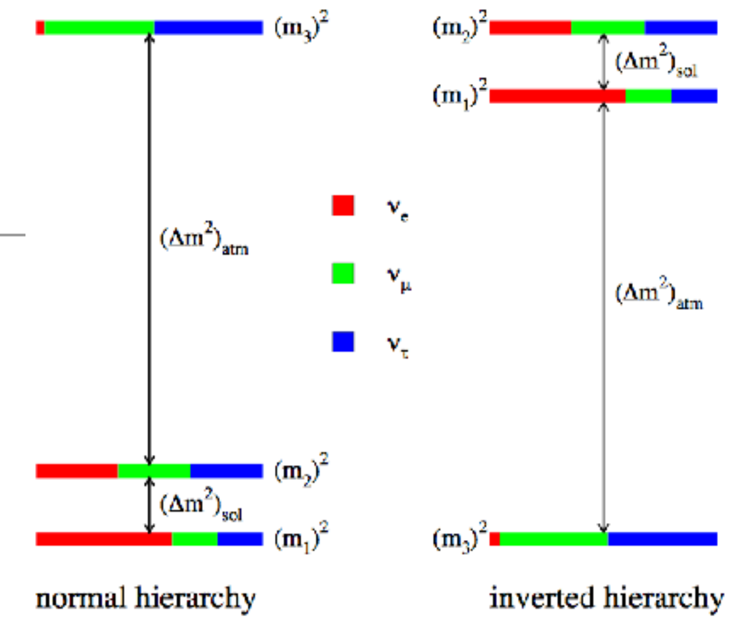
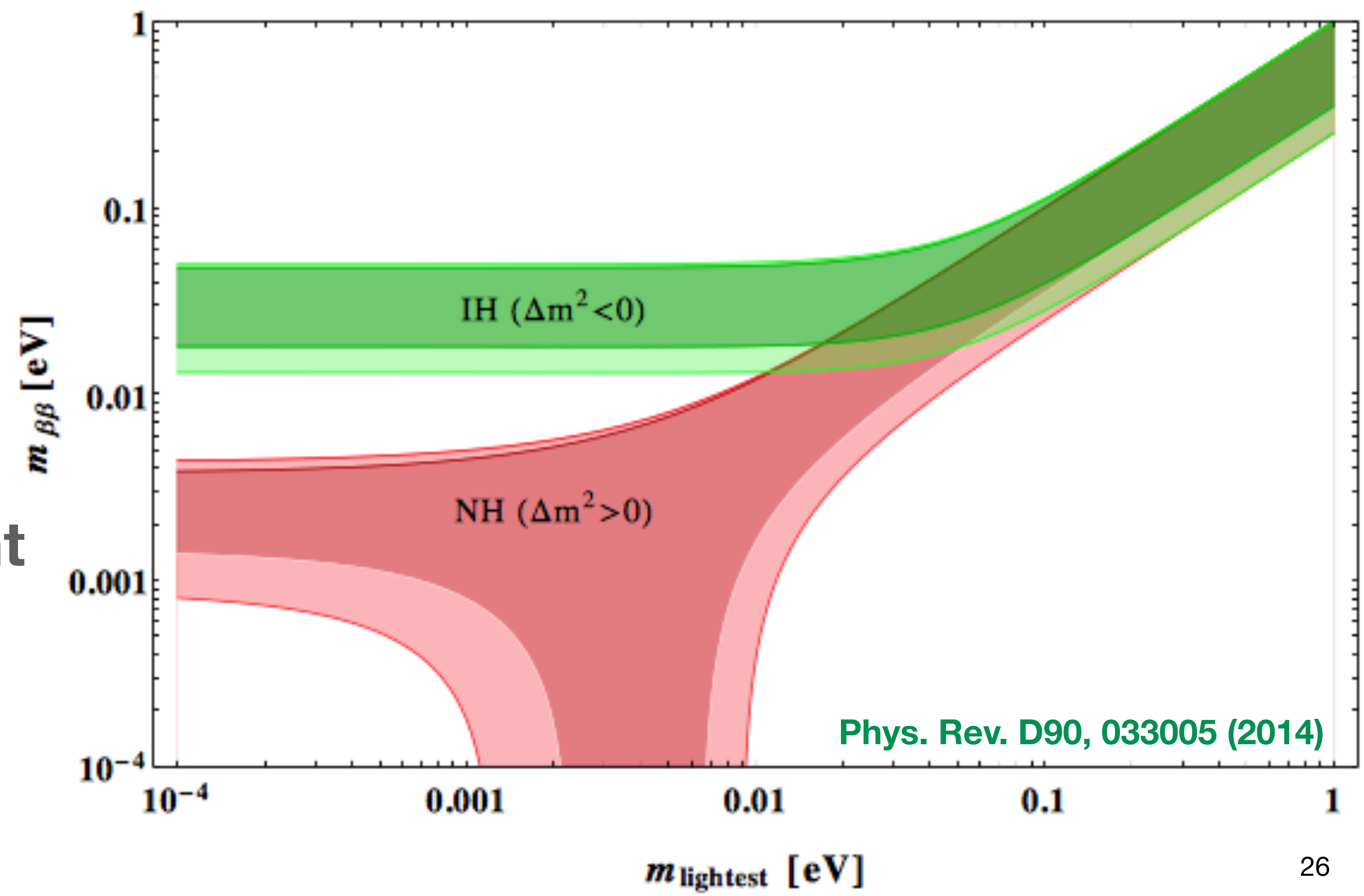
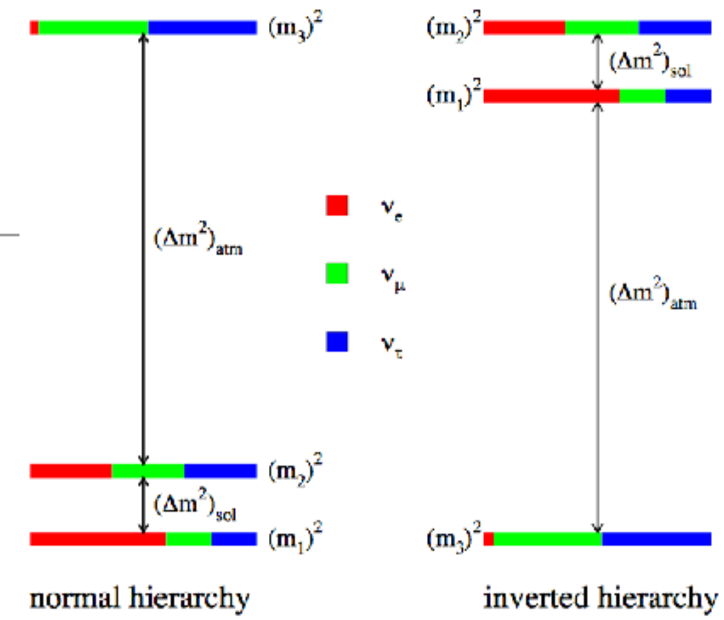


- Pick a model (**note**: there are several models!)
- Draw the parameter space (**note**: there are many uncertainties!)
- This is just a **very model-dependent** way to represent the search, but we need something



Expected signal region



- Pick a model (**note**: there are several models!)

$$m_{\beta\beta} \equiv \left| e^{i\alpha_1}|U_{ei}^2|m_1 + e^{i\alpha_2}|U_{e2}^2|m_2 + |U_{e3}^2|m_3 \right|$$

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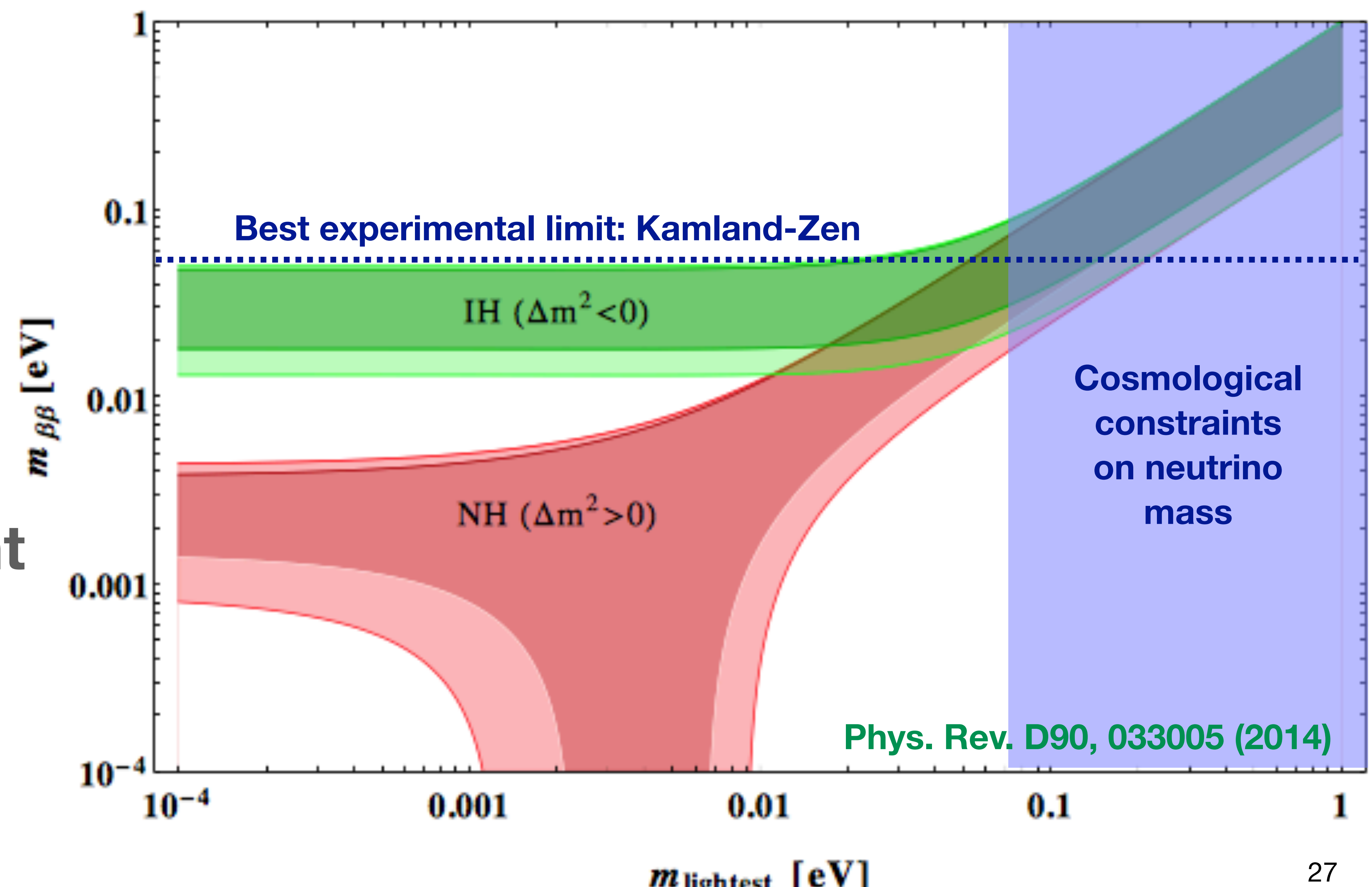
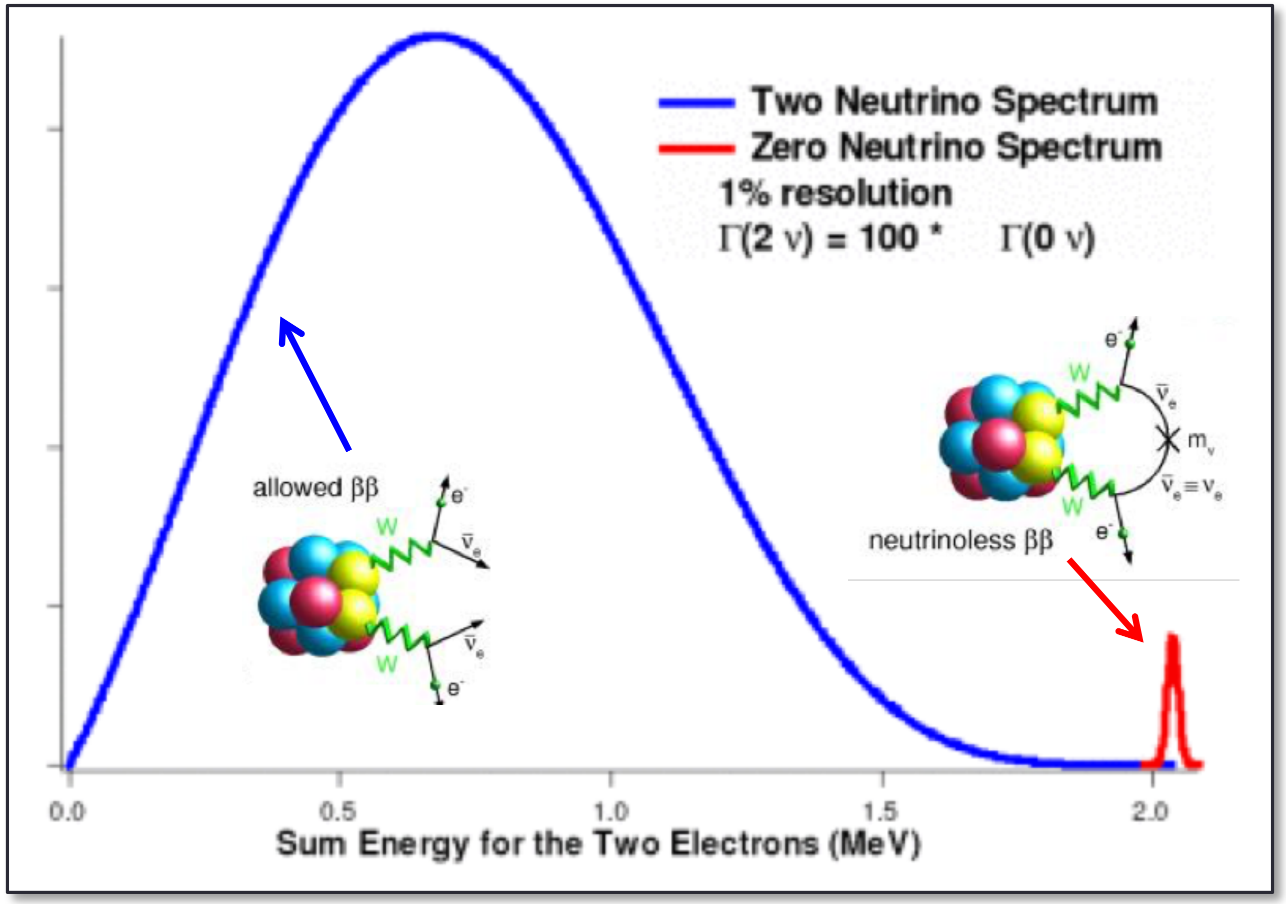


Looking for $0\nu\beta\beta$ experimentally

We are going to be looking at **extremely rare events** ($T_{½} > 10^{25}$ y) that have a very **specific energy**



1. **Great energy resolution**
   (to identify the $0\nu\beta\beta$ over the regular $2\nu\beta\beta$)

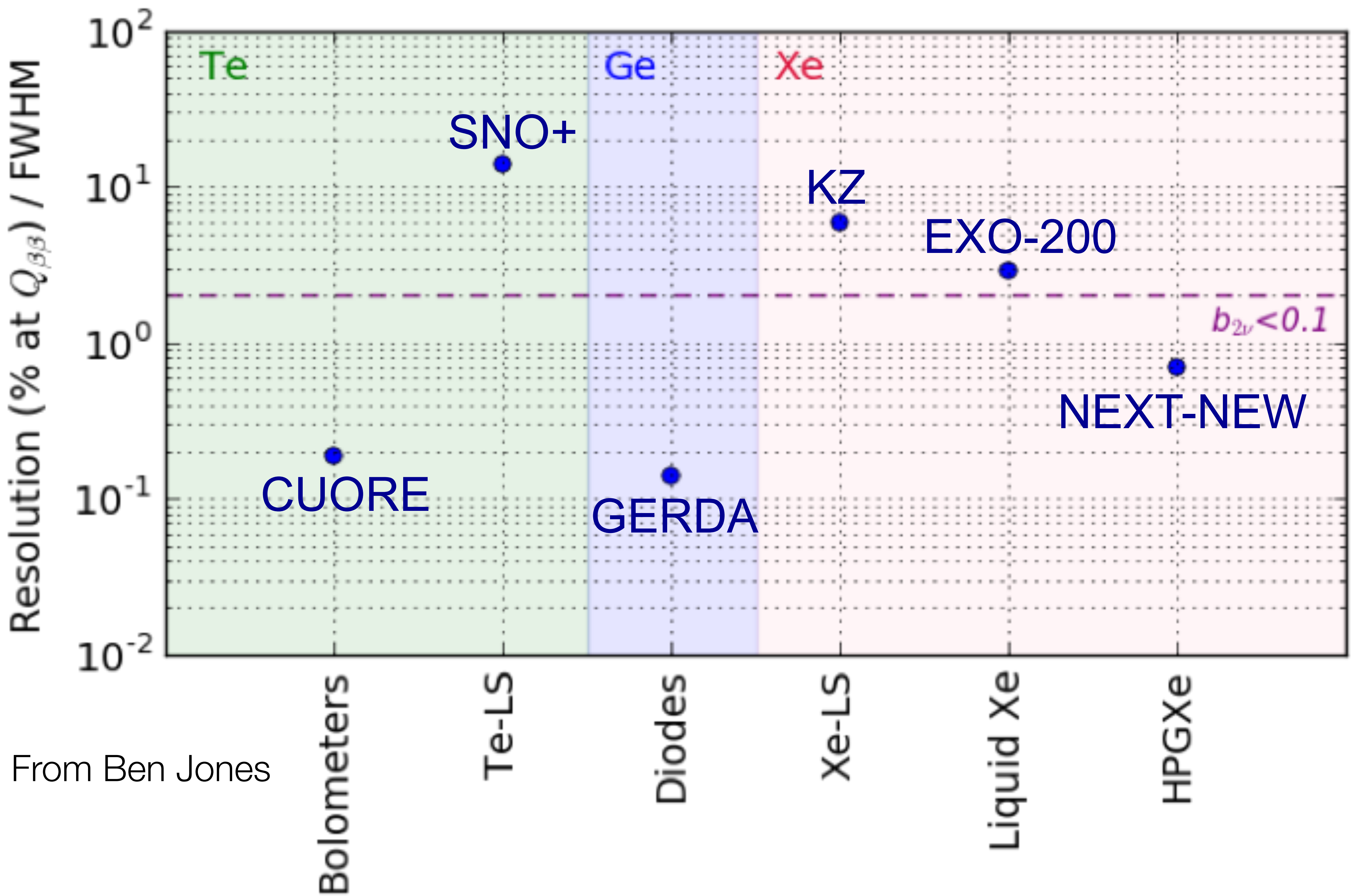
2. **Extremely low background**
   (to see the very rare signal over radioactive events)

3. **Scalability**

Easier said than done!

Current status of experiments (demonstrated)

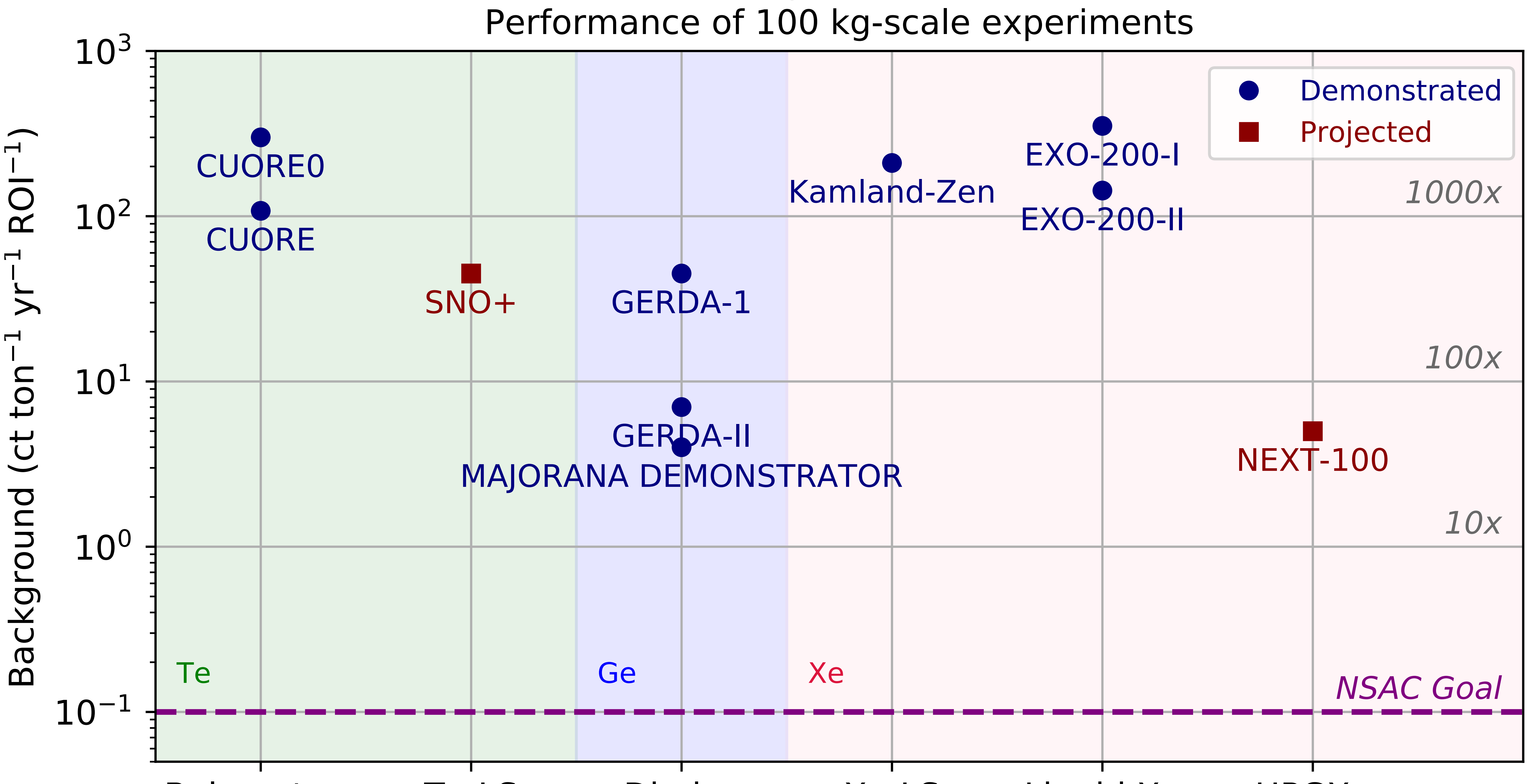
Energy resolution



From Ben Jones

Easier said than done!

Current status of experiments (demonstrated and projected)
Backgrounds

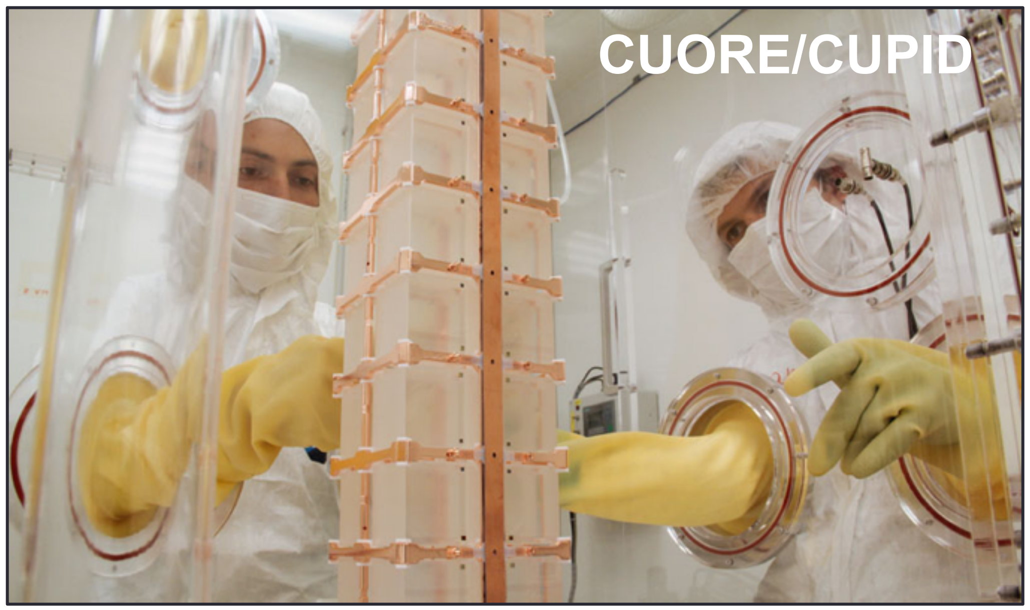


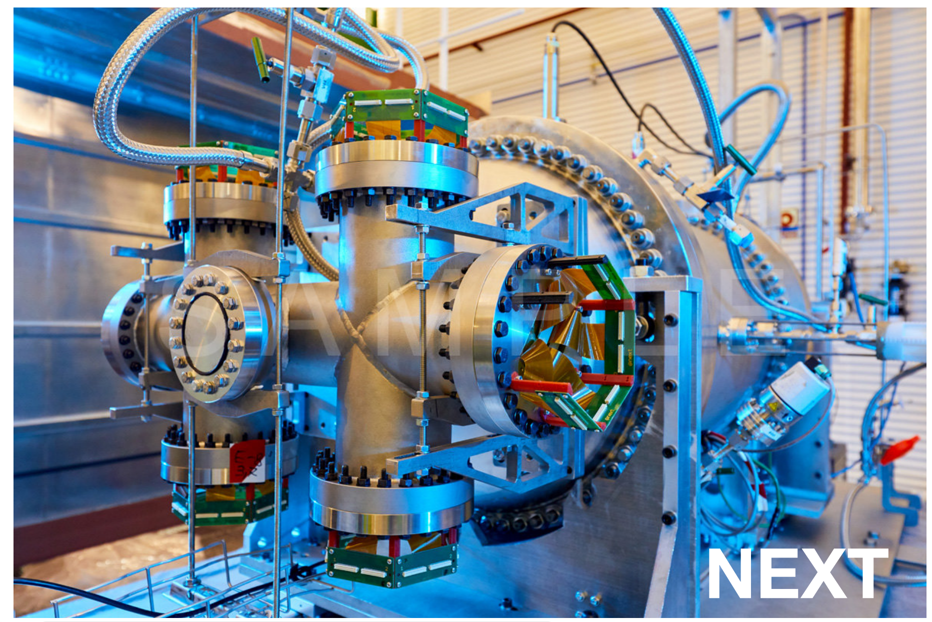
From Ben Jones

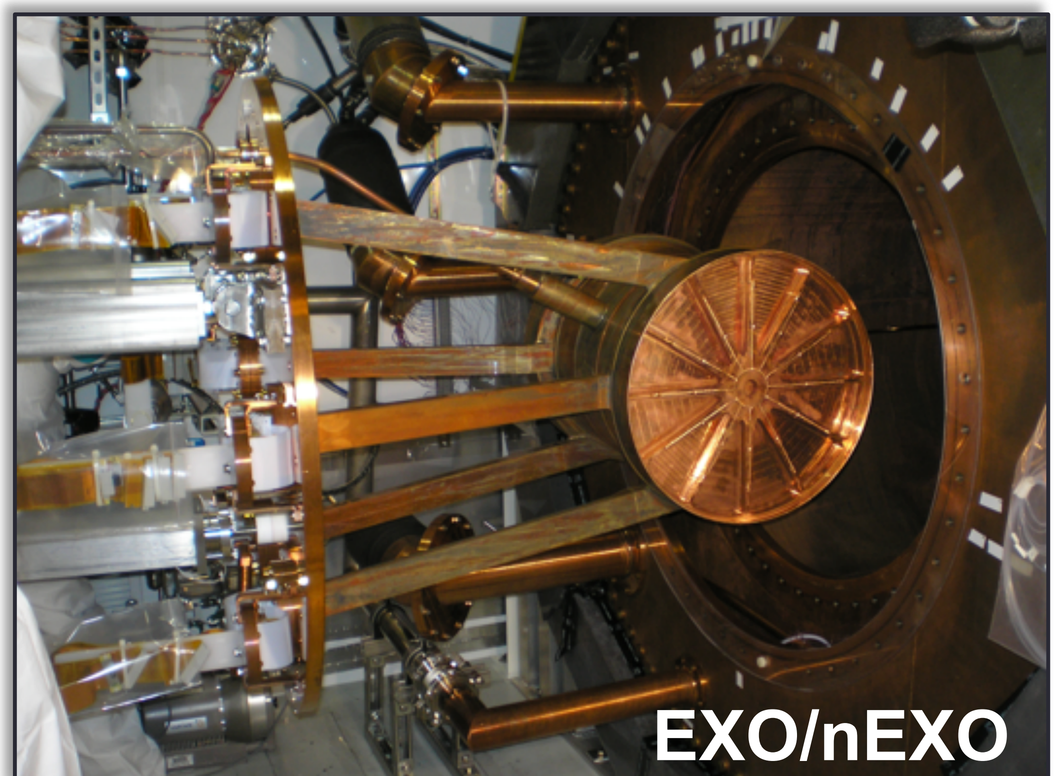
Current experimental efforts

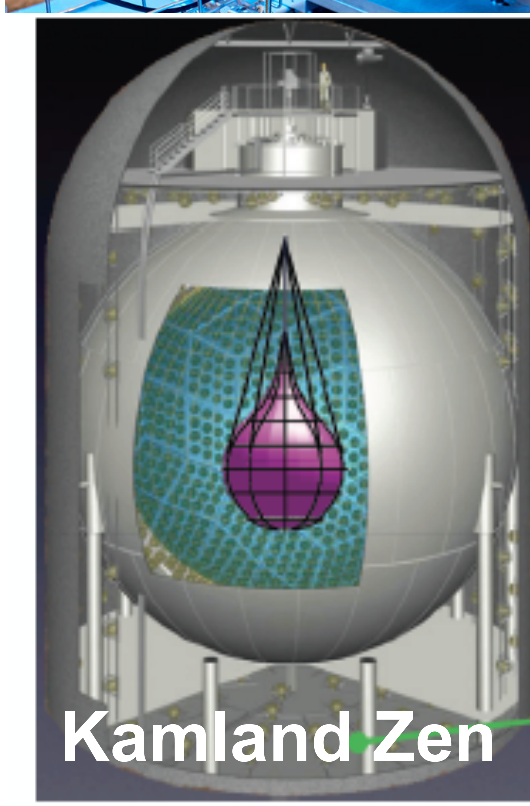
Many cutting edge technologies

Several different approaches



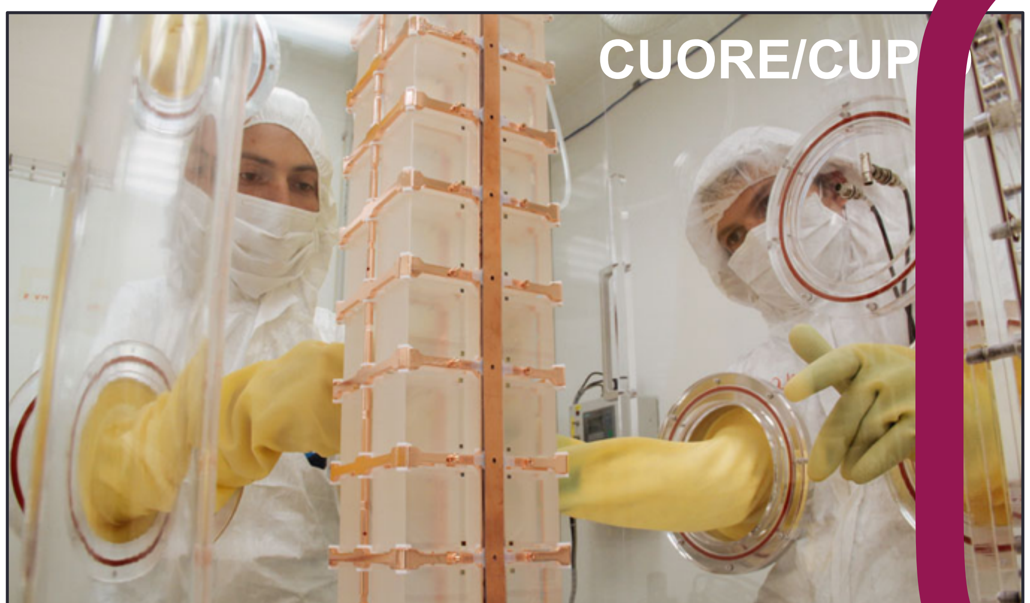


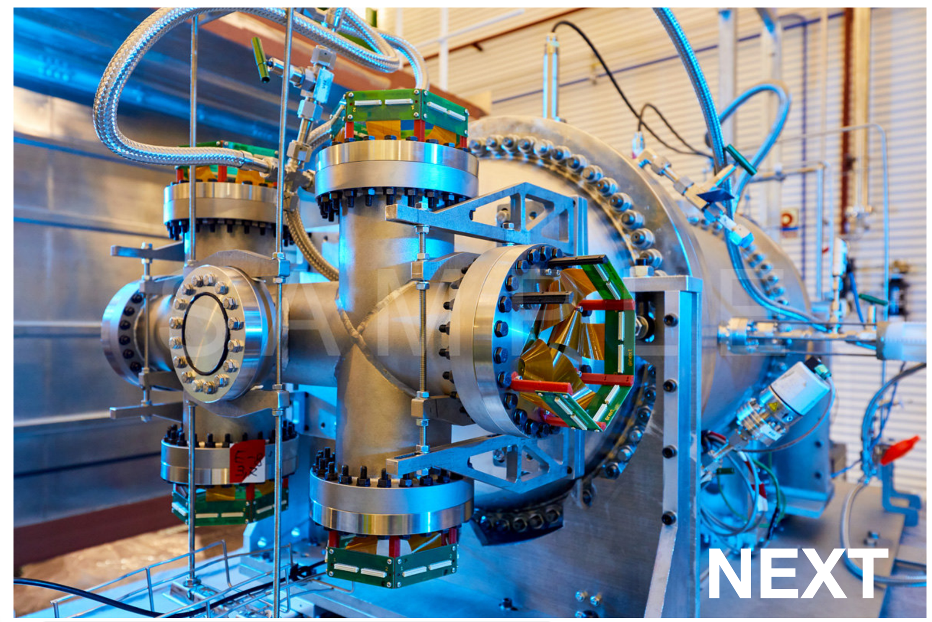


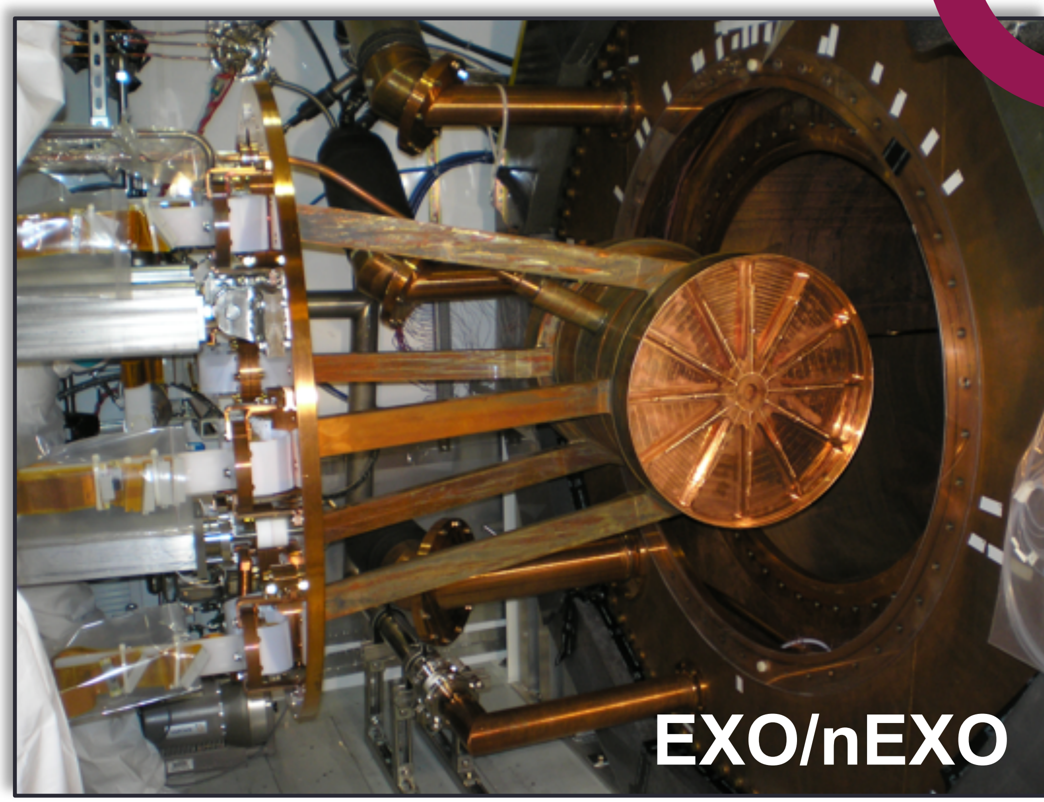


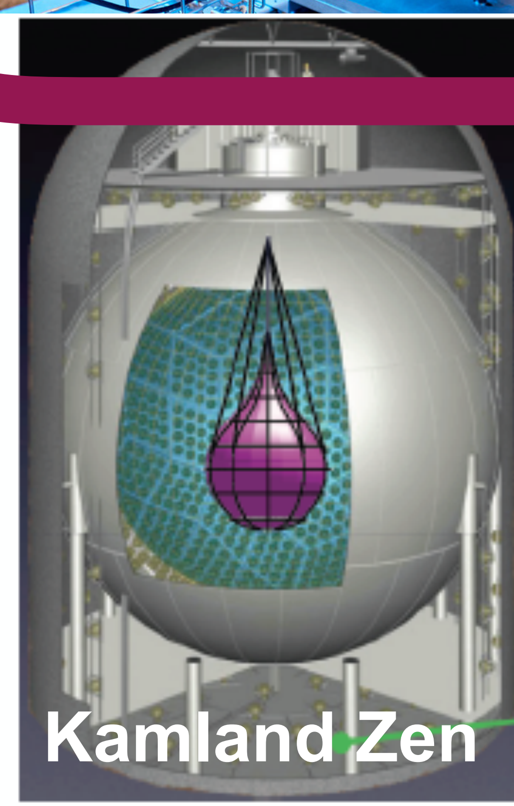
Current experimental efforts

Many cutting edge technologies
Several different approaches



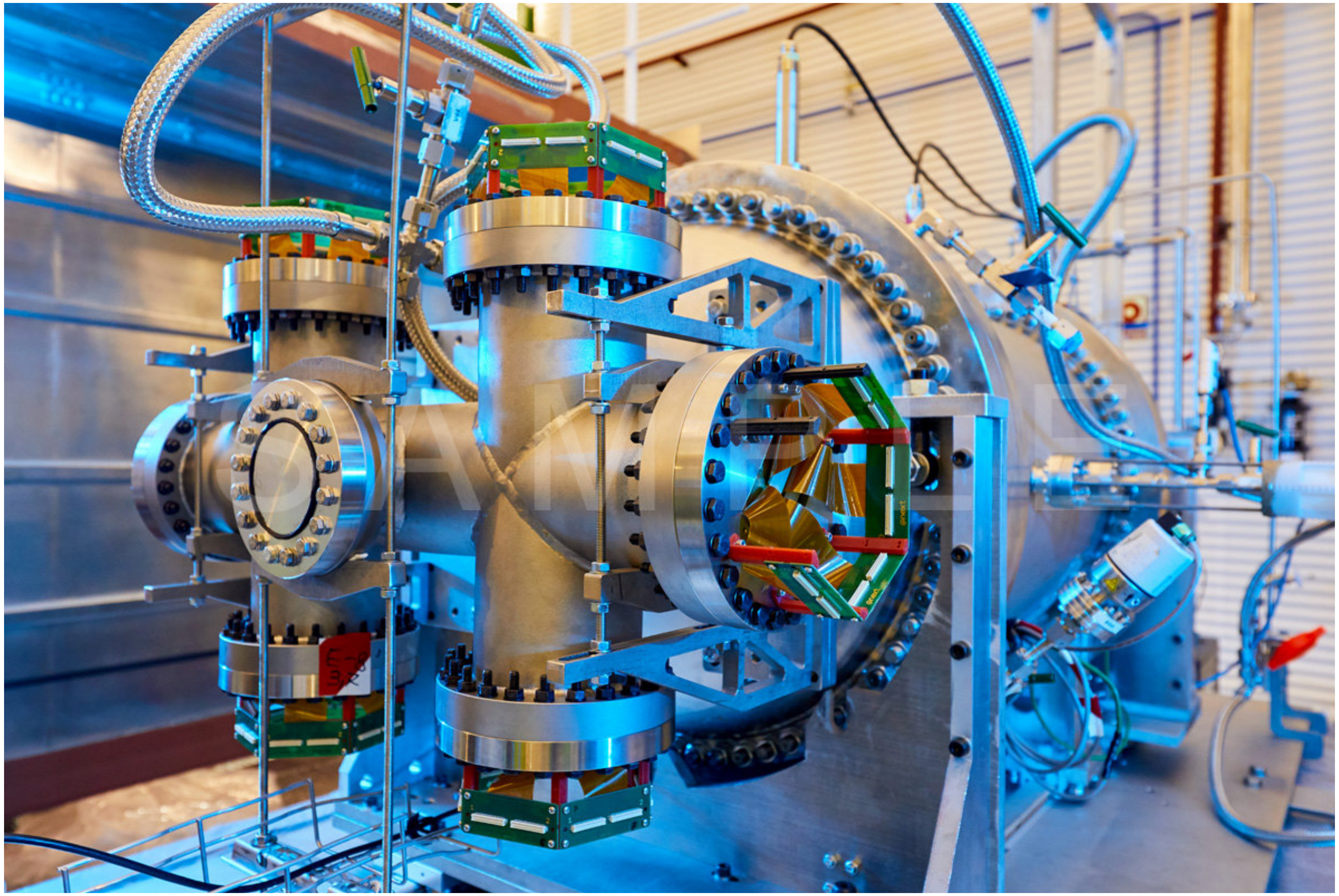






NEXT (Neutrino Experiment with Xenon TPC)

High-pressure gas Xenon Time Projection Chamber



NEXT (Neutrino Experiment with Xenon TPC)

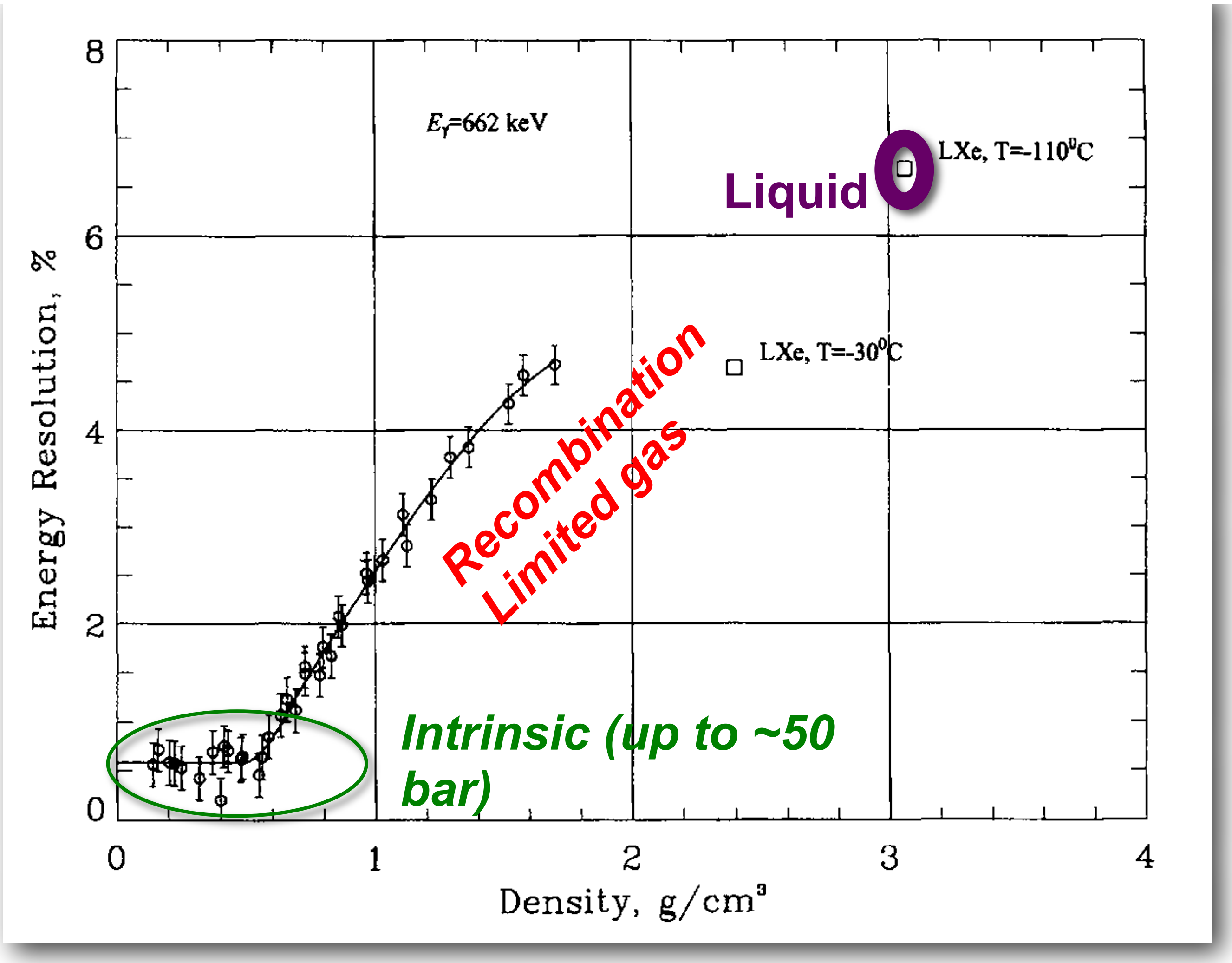
High-pressure gas Xenon Time Projection Chamber

Density: Higher pressure means more isotope in same volume

NEXT (Neutrino Experiment with Xenon TPC)

High-pressure gas Xenon Time Projection Chamber

- **Energy resolution:** Great intrinsic energy resolution in gas



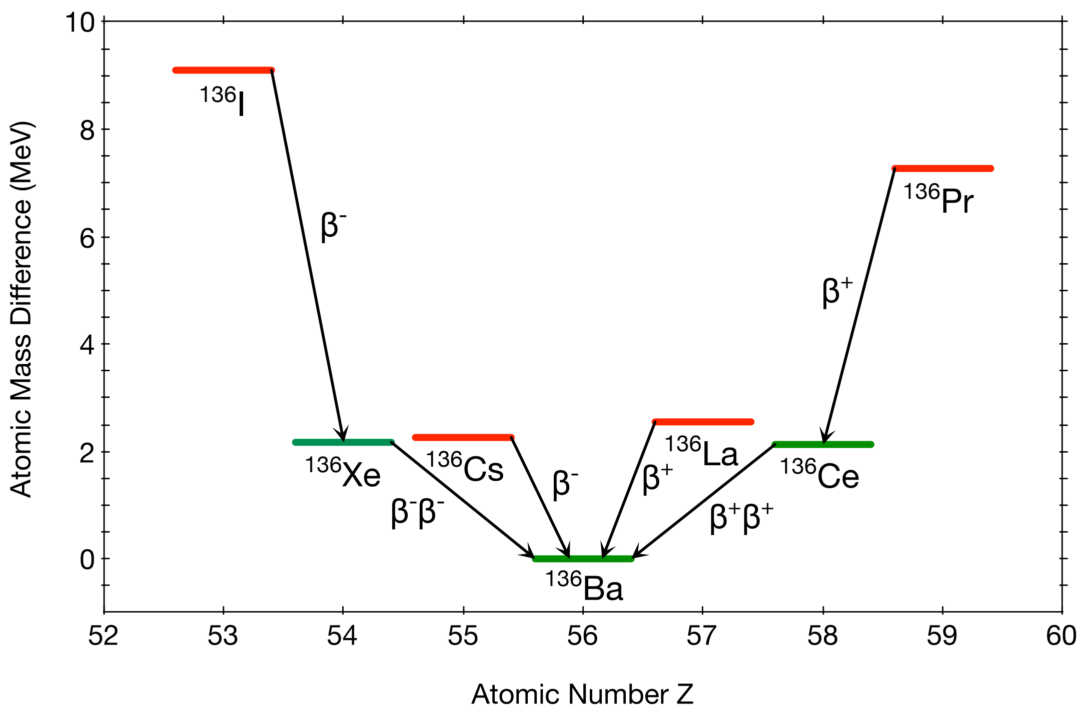
Bolotnikov and Ramsey. "The spectroscopic properties of high-pressure xenon."NIM *A* 396.3 (1997): 360-370

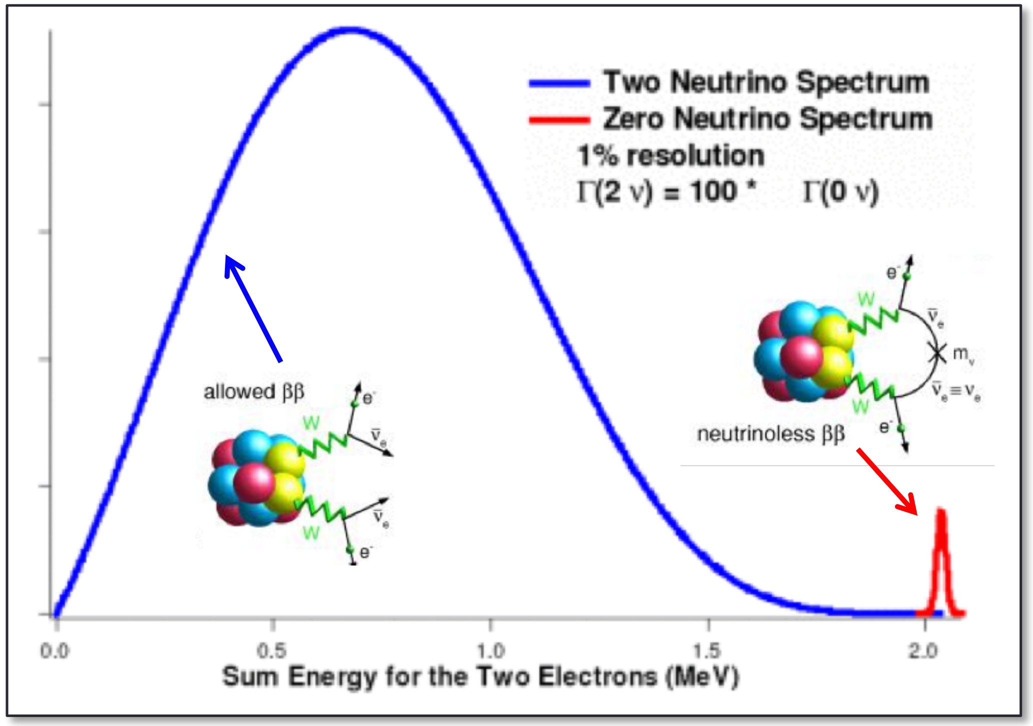
NEXT (Neutrino Experiment with Xenon TPC)

High-pressure gas Xenon Time Projection Chamber

1. **Isotope:** High enough abundance, $Q_{\beta\beta}$ = 2.5 MeV
2. **Noble gas:** Ideally suited to detection technology (TPC)

Source = detector!





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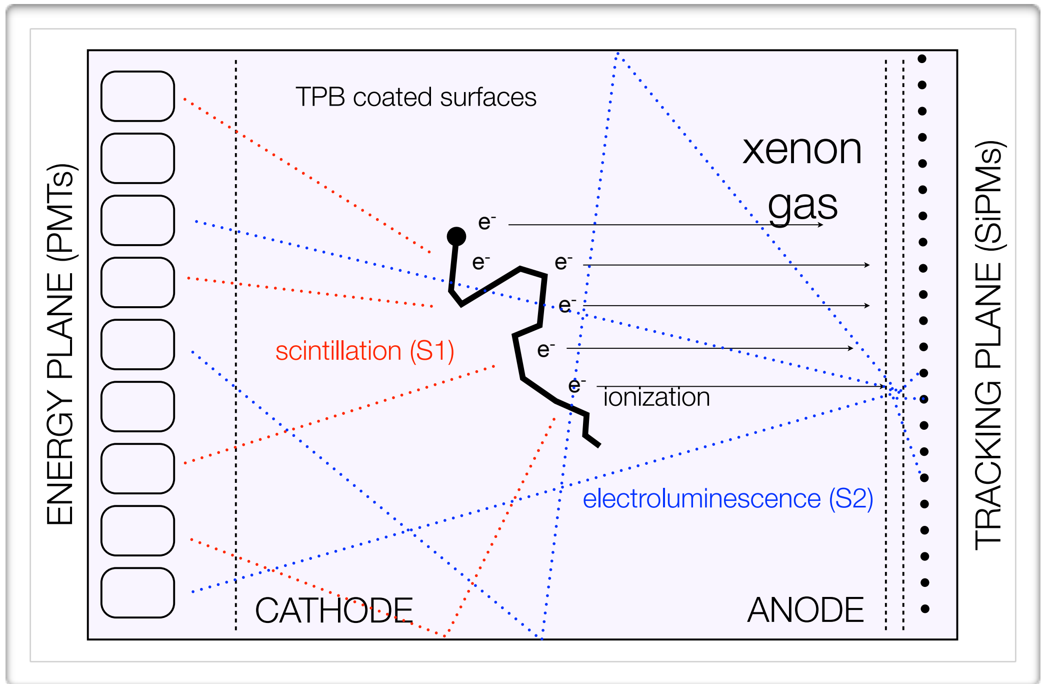
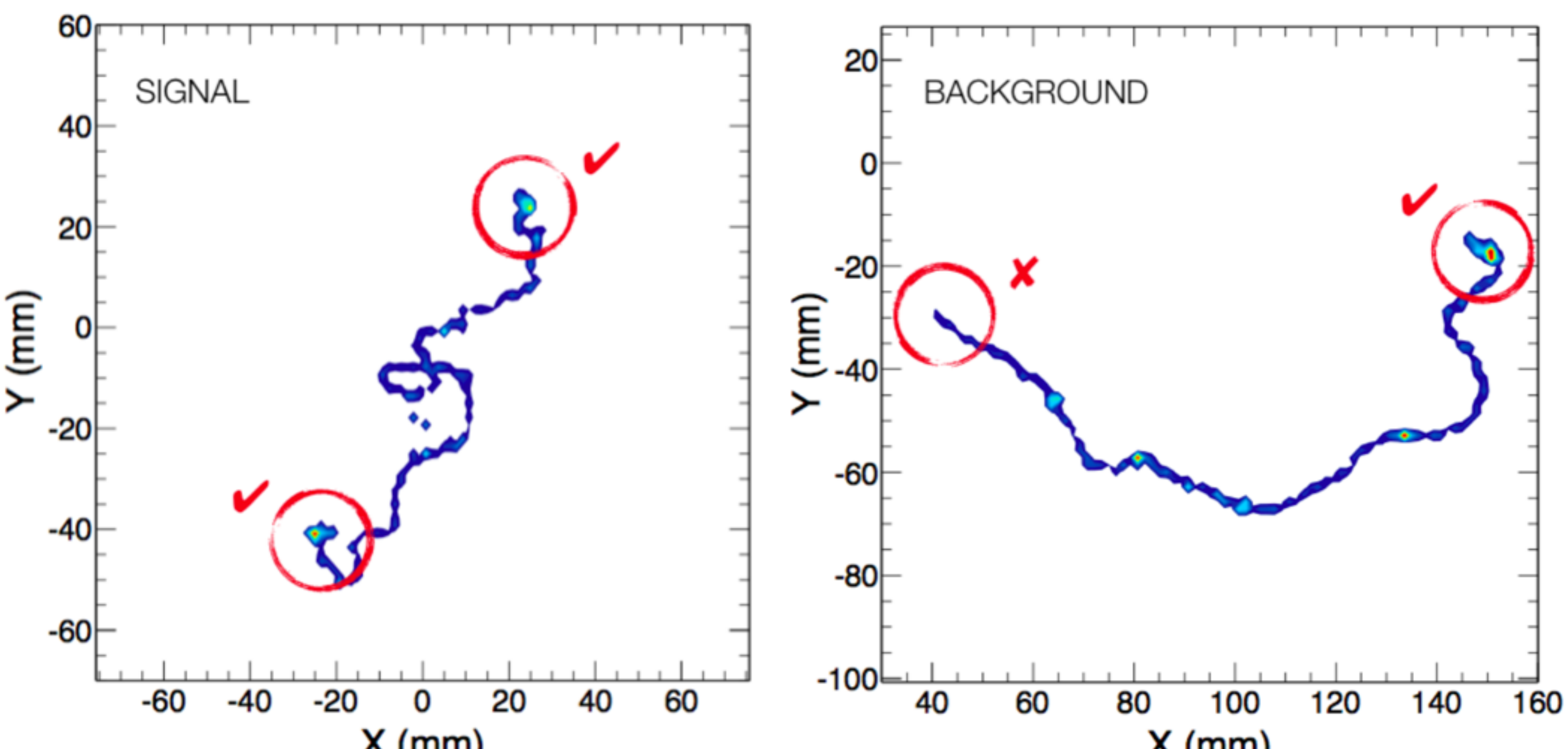
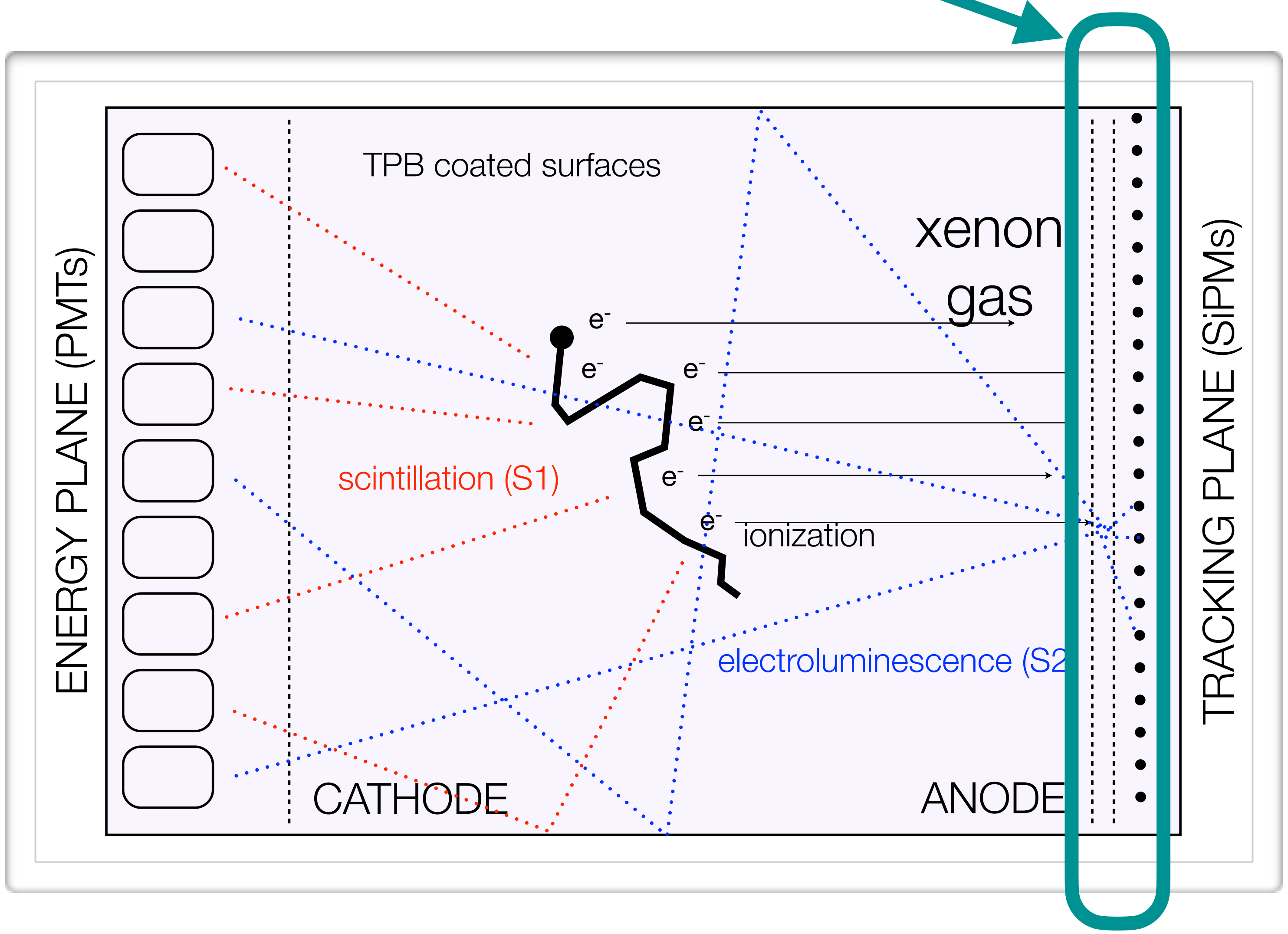


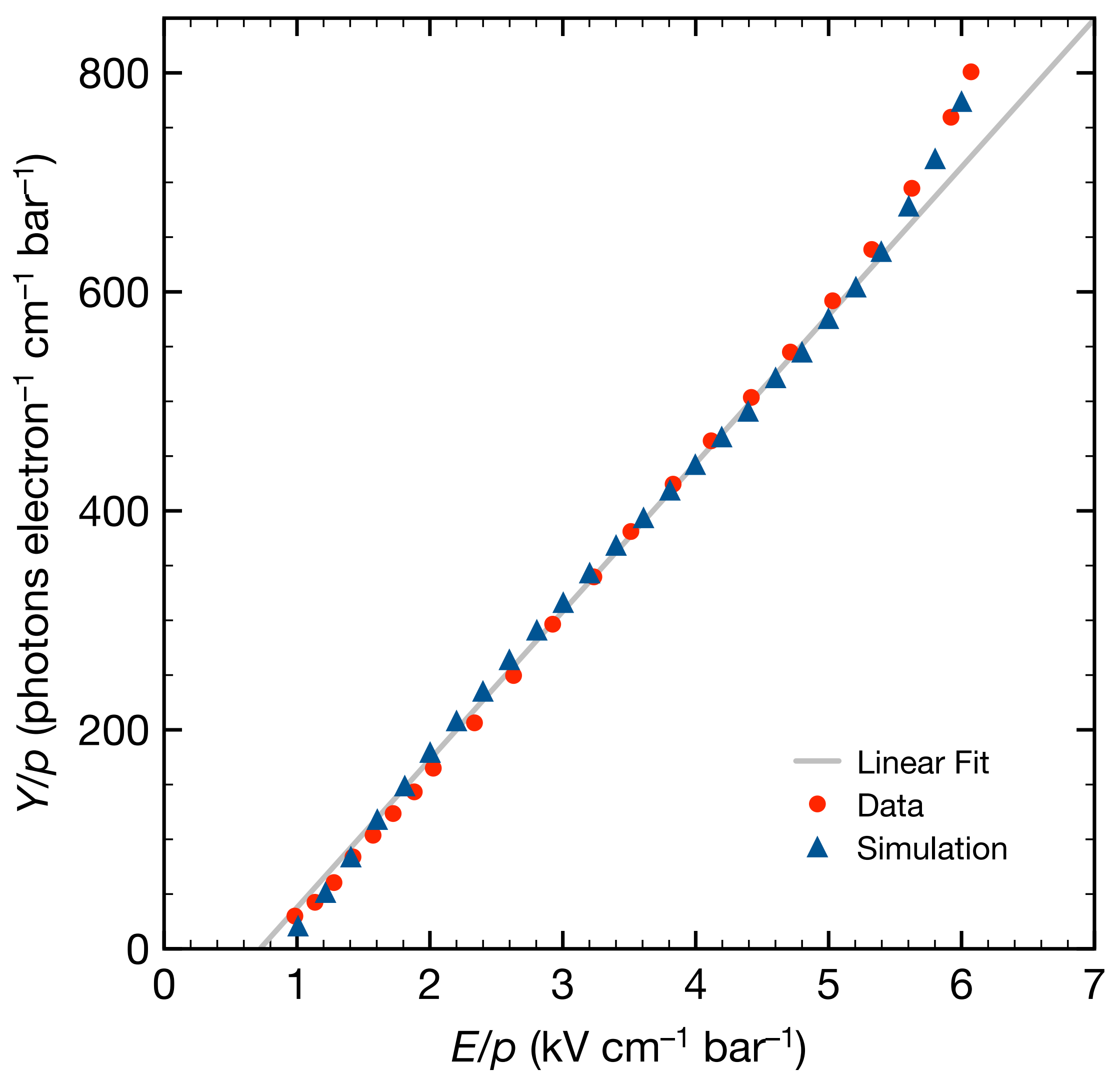


Topology: TPC offers high quality images of events

NEXT (Neutrino Experiment with Xenon TPC)

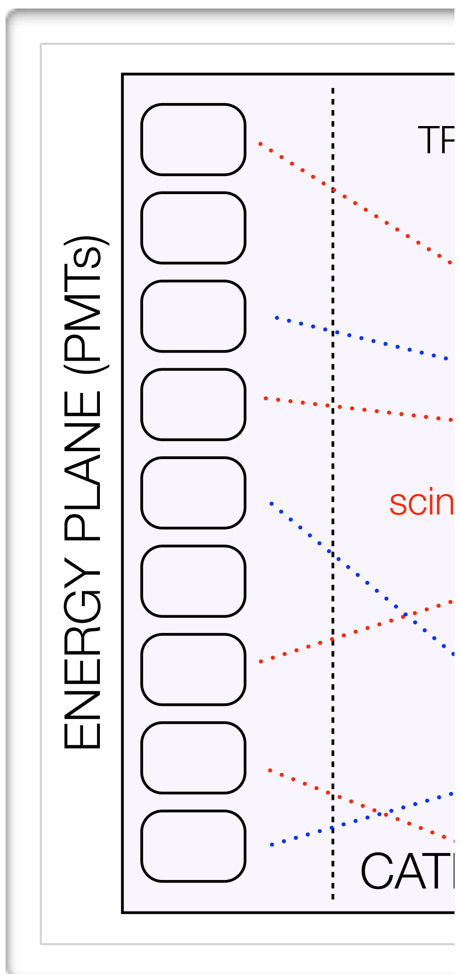
Electroluminescence

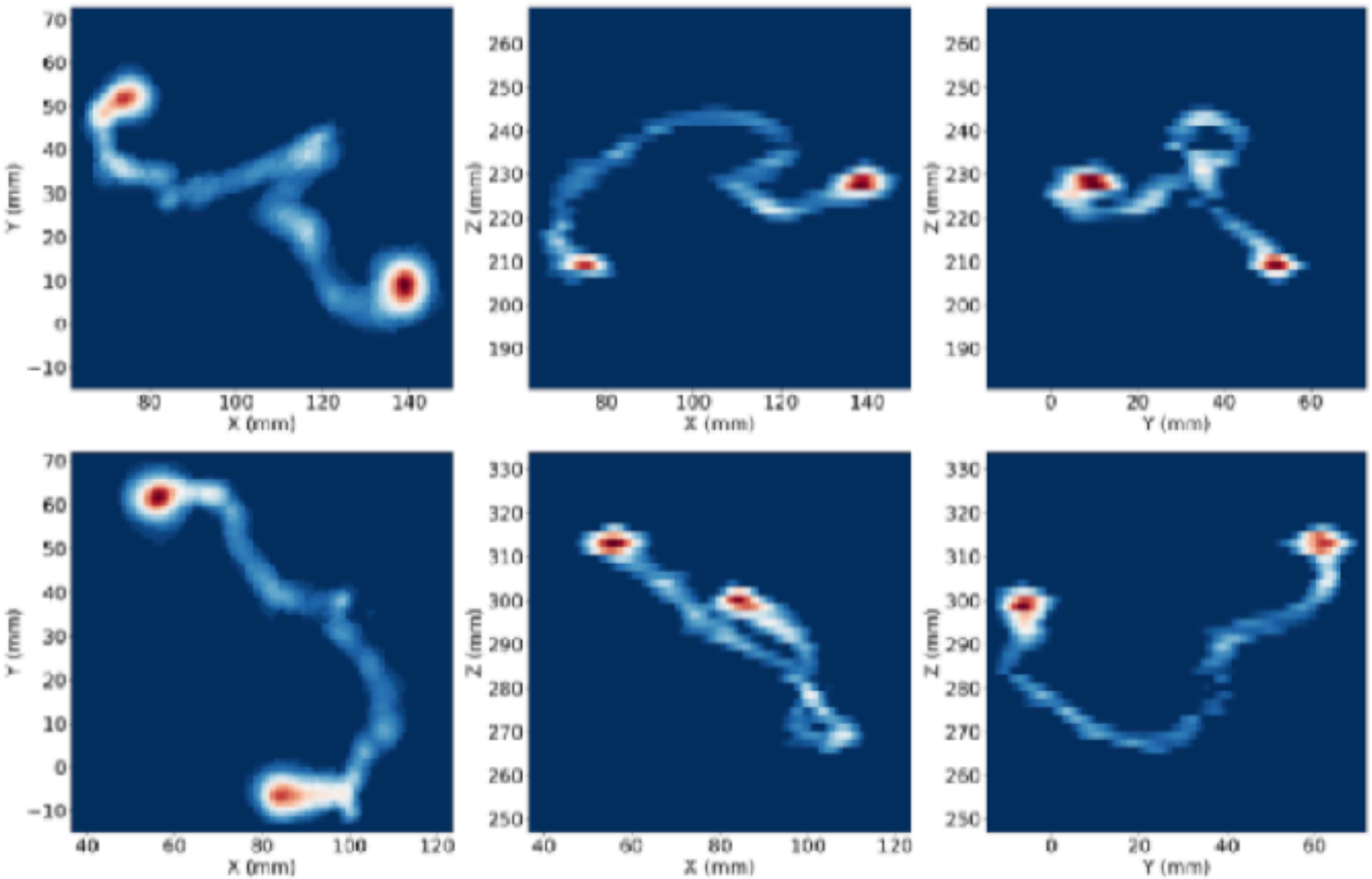


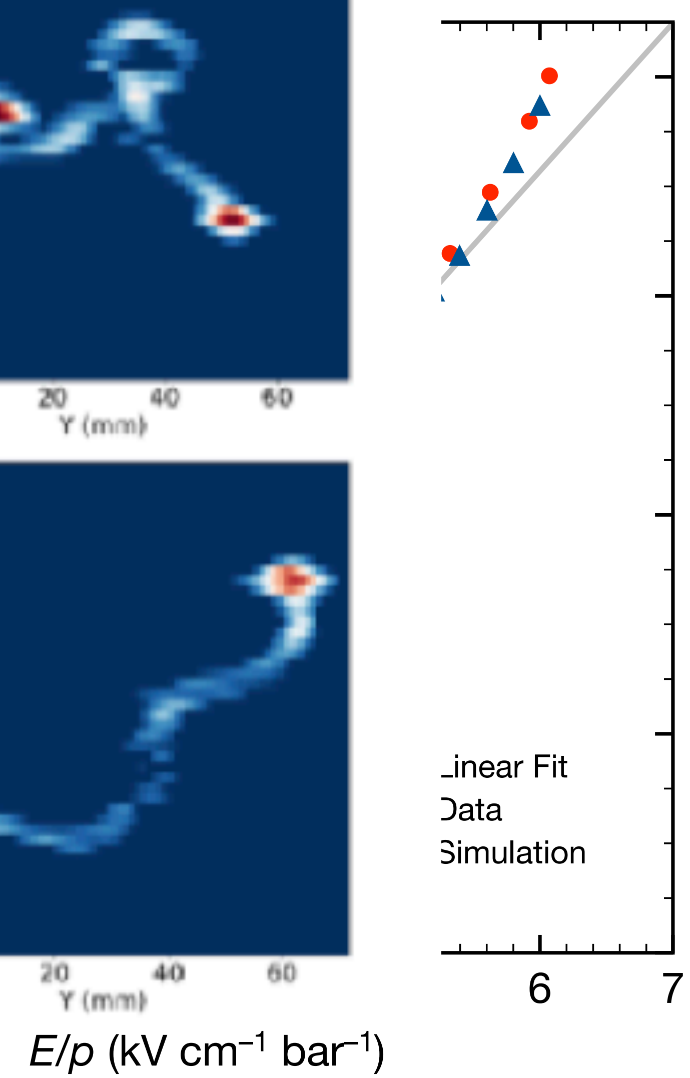


NEXT (Neutrino Experiment with Xenon TPC)

Electroluminescence







The NEXT project

(2010–2014)
Prototyping of detector concept

(2015–2021)
Test underground, radiopure operation

(2024–2027)
Neutrinoless double beta decay searches

(2027– …)
Discovery?

LSC (Canfranc)

???

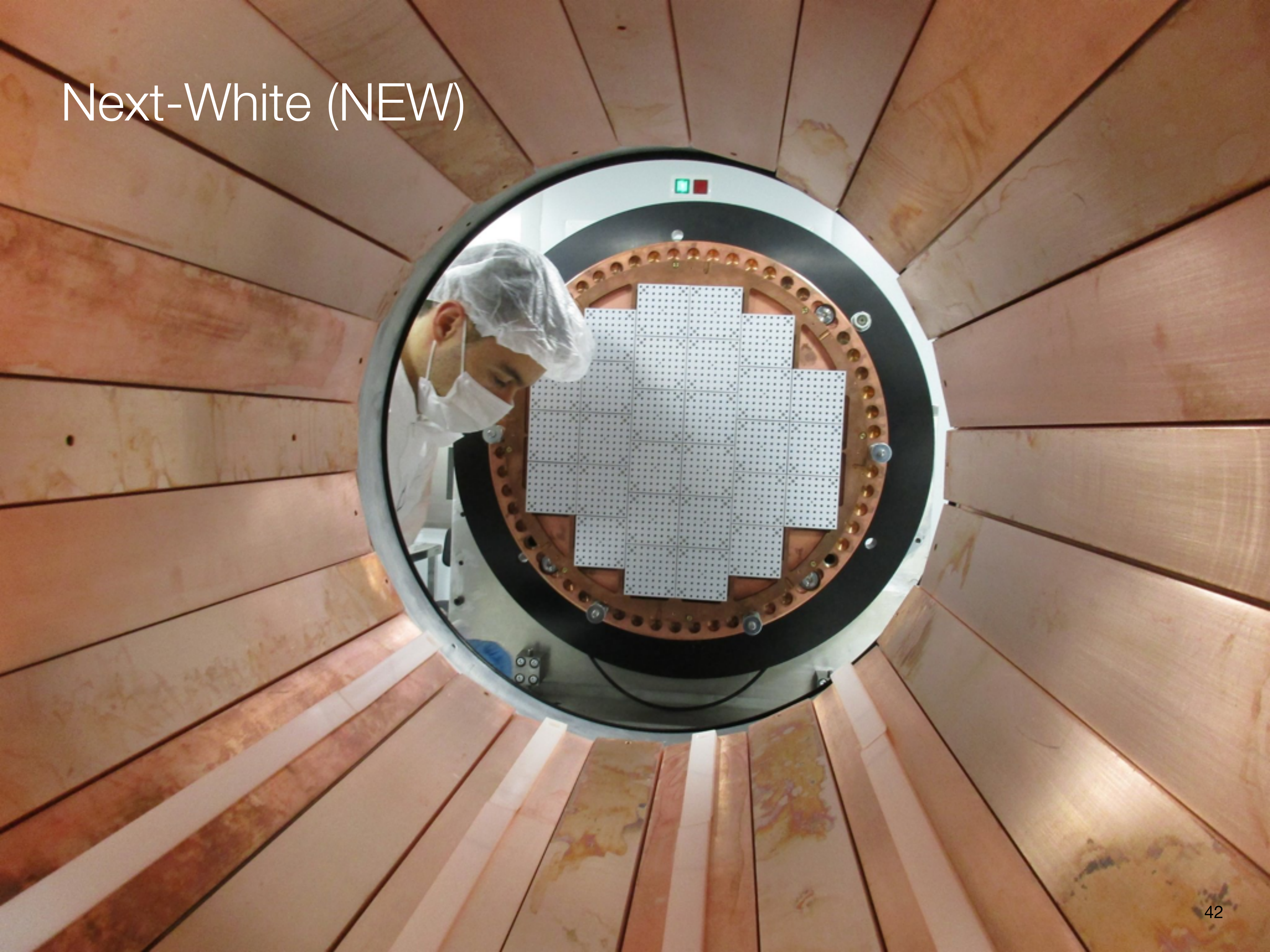
The NEXT project

Many great results

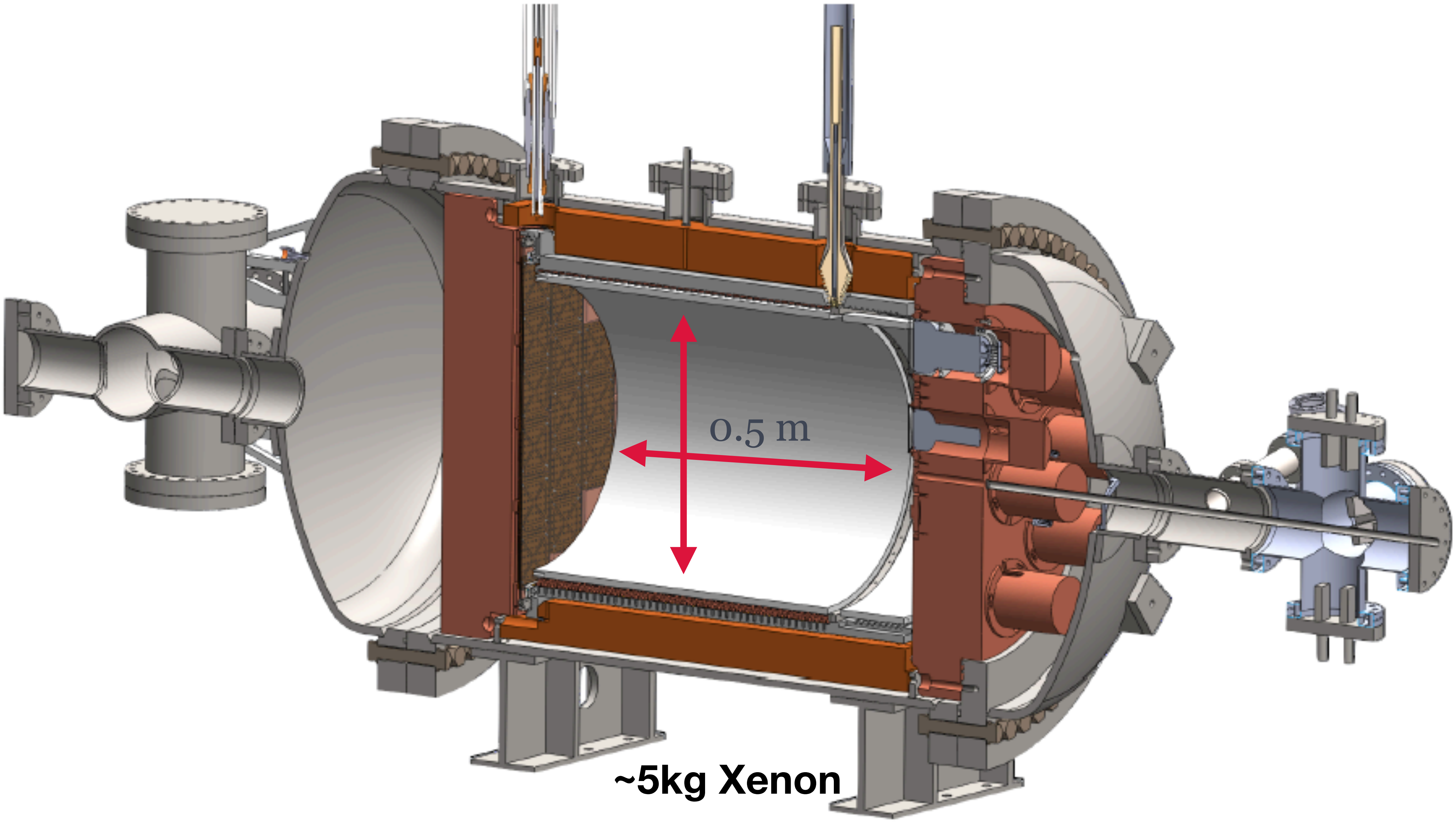
Demonstration of technology

Construction completed in Fall 2023!

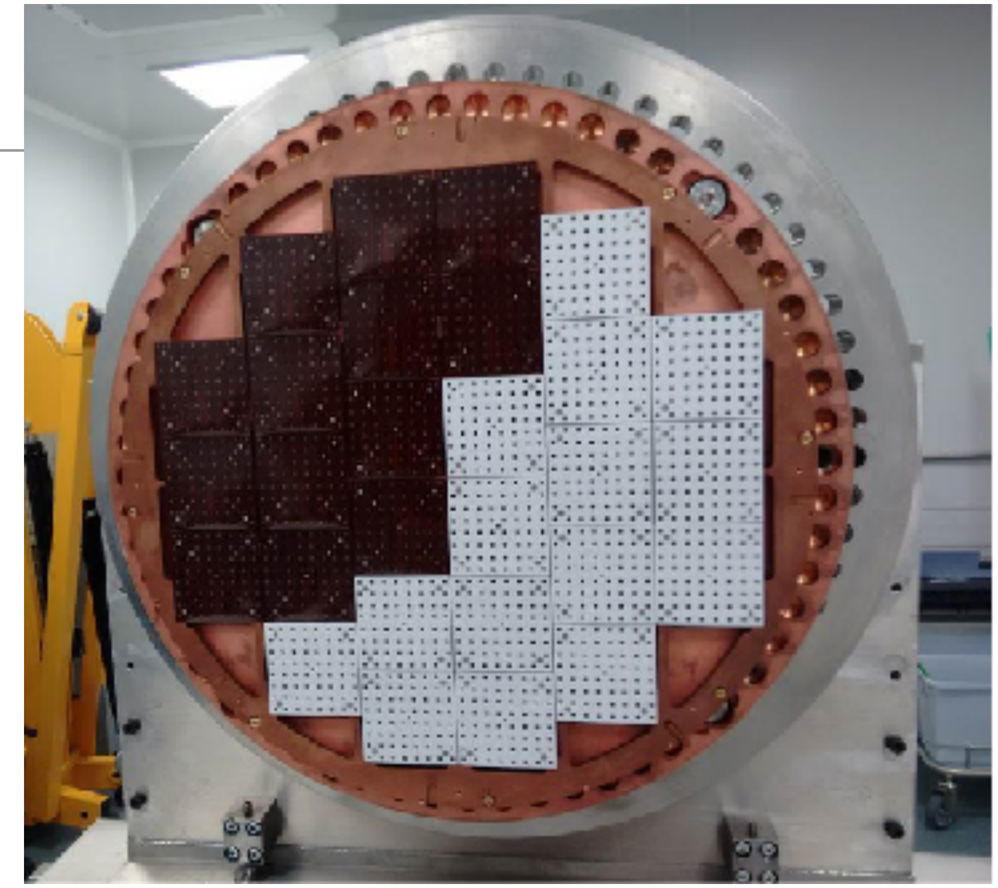
Next-White (NEW)

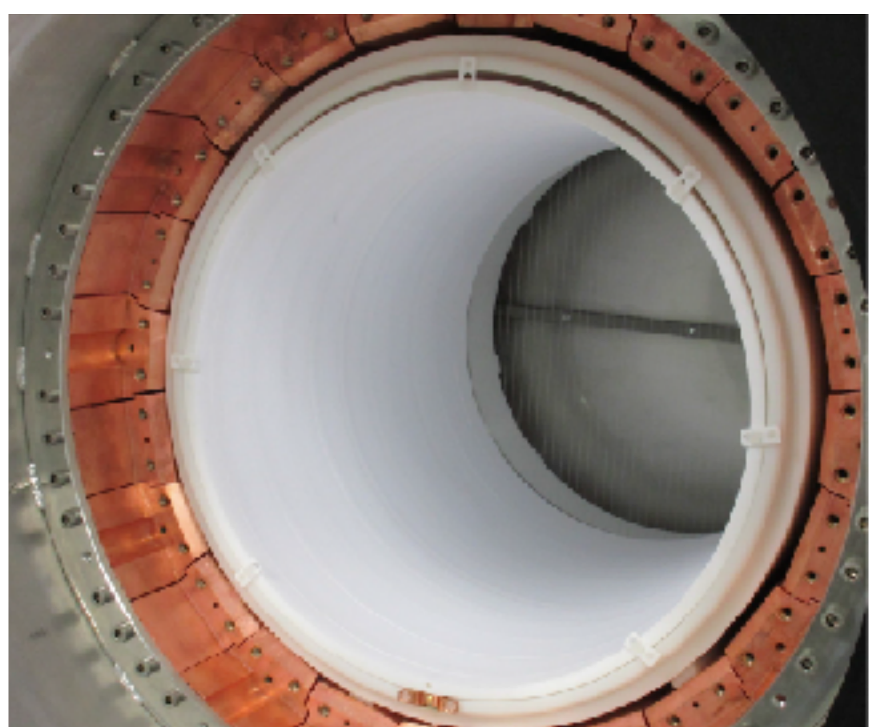


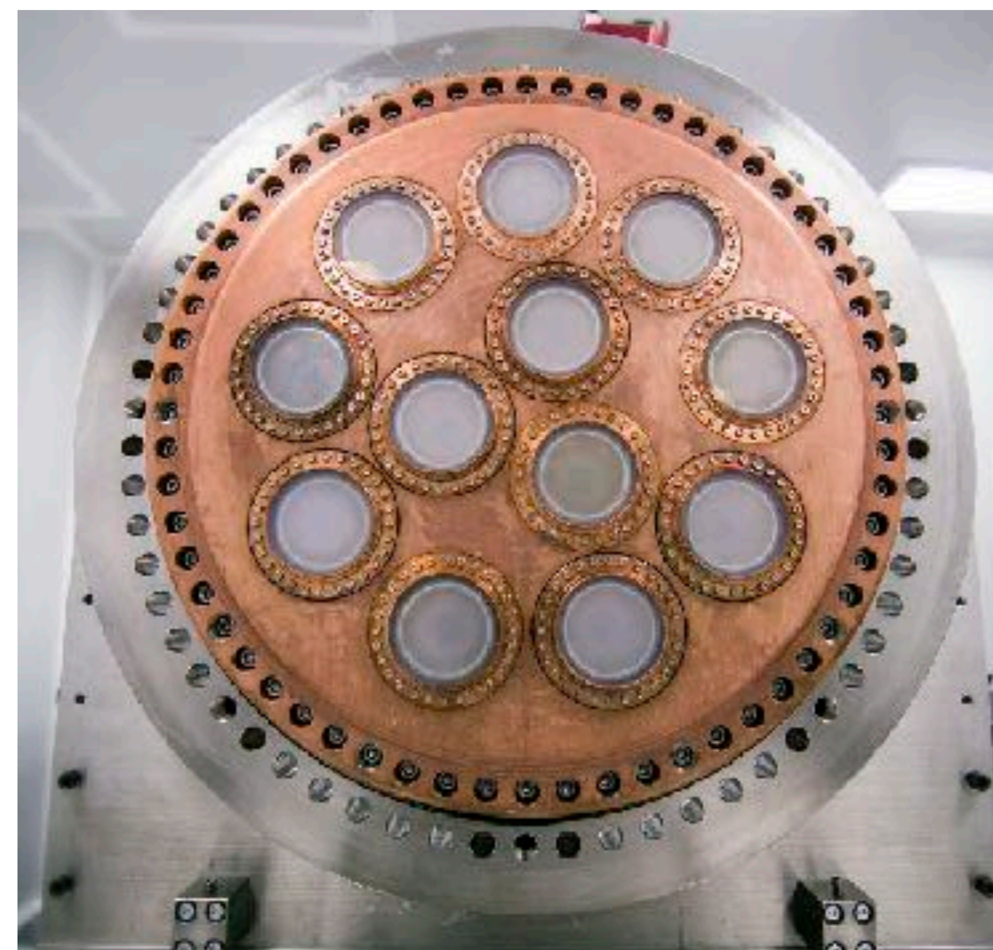
NEW detector



NEW detector

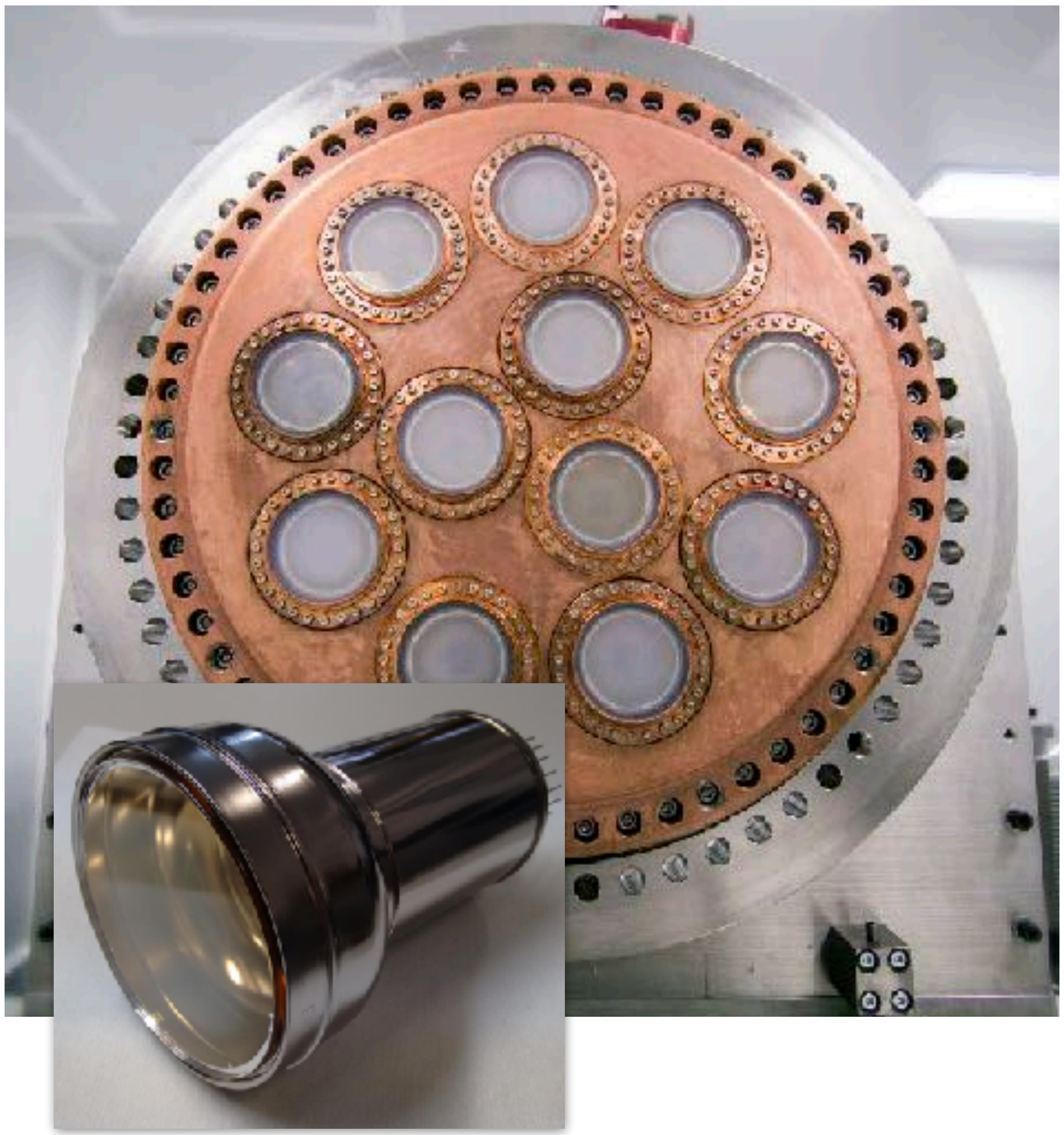






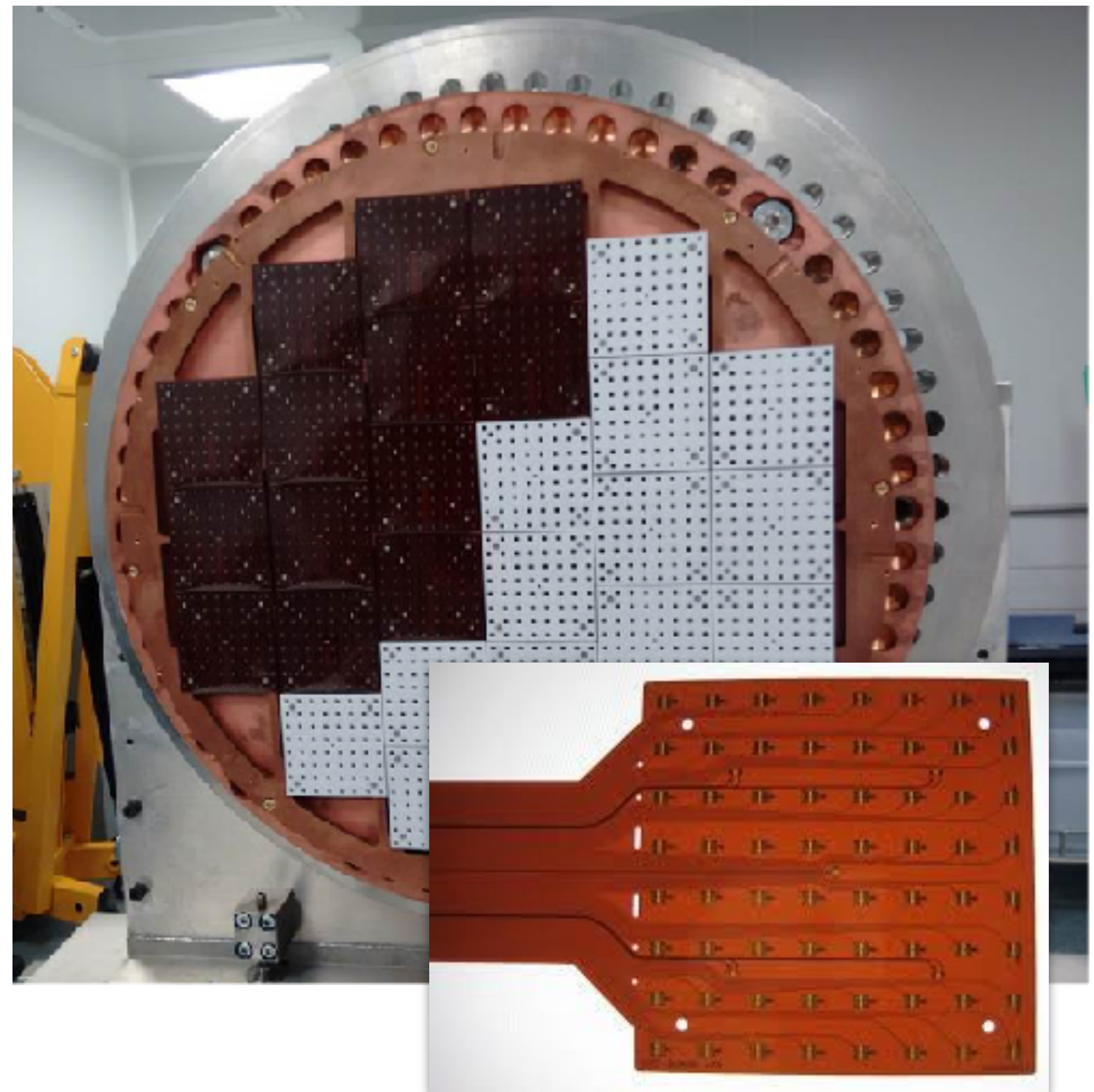
NEW readout

Energy plane



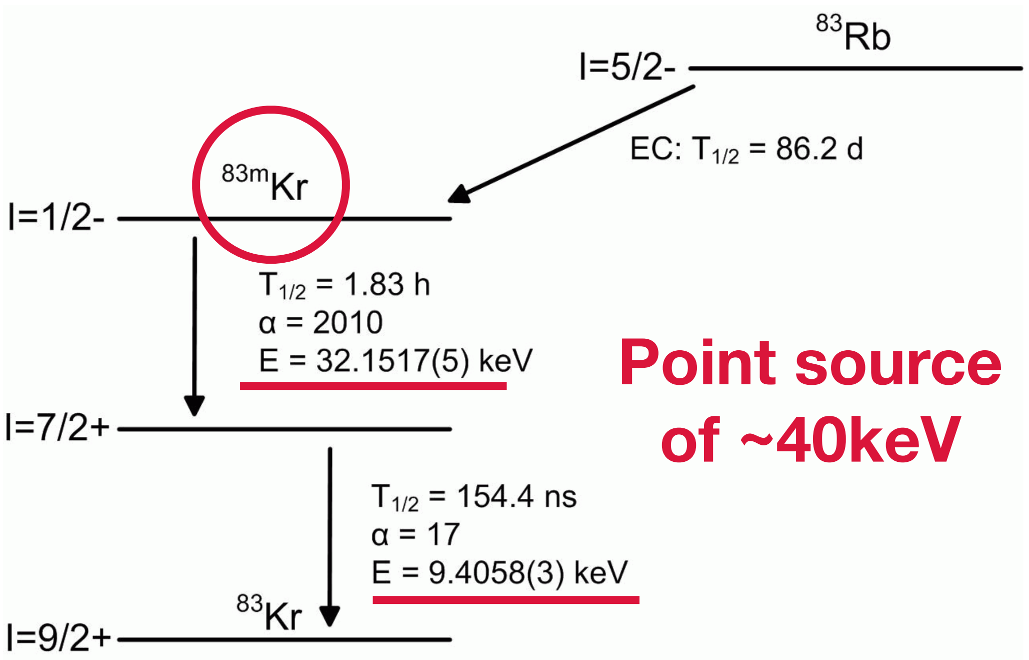
12 Hamamatsu R11410

Tracking plane

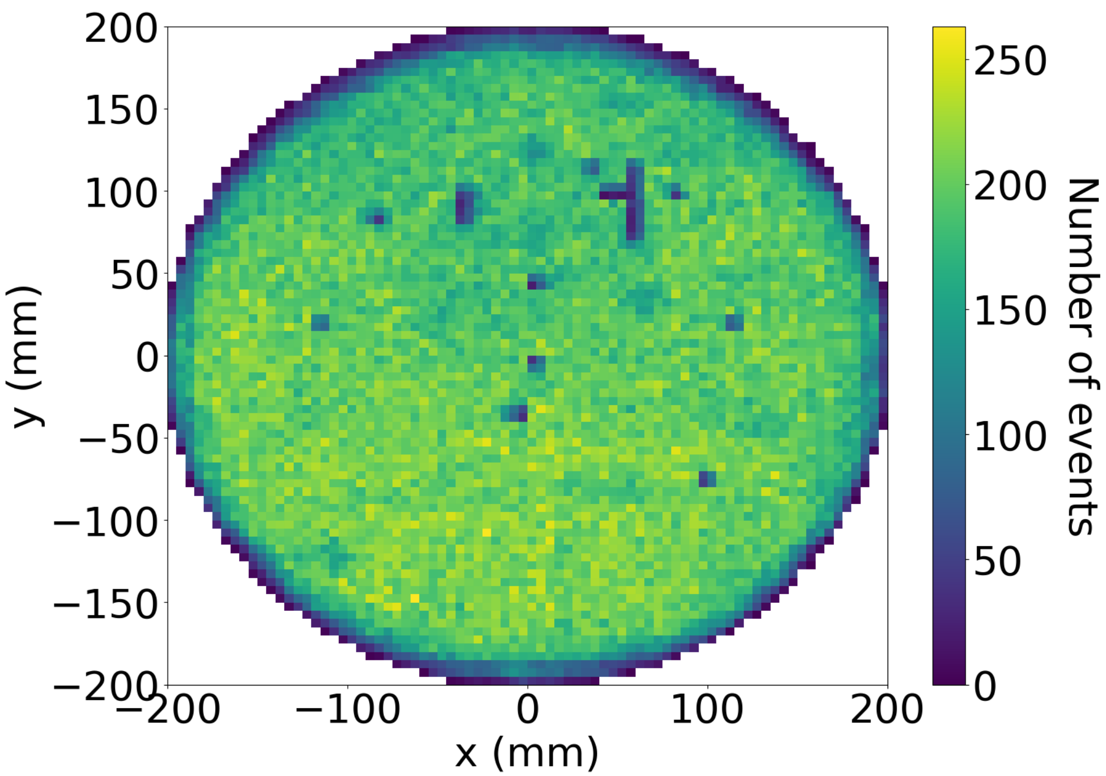


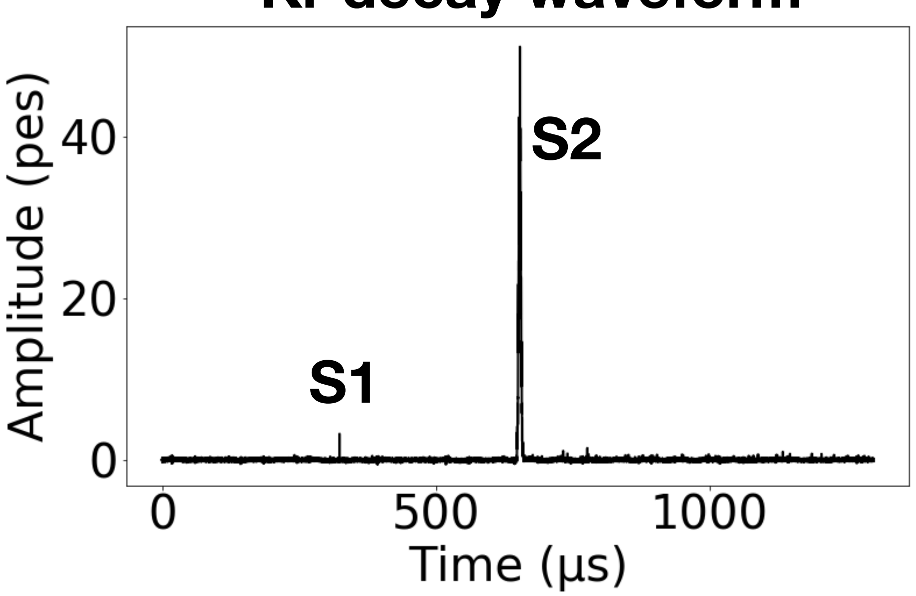
~2000 SensL 1-mm² SiPMs

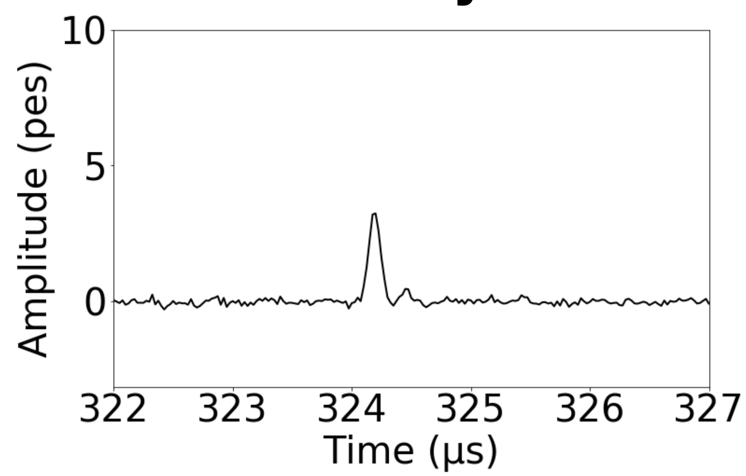
NEW calibration with Krypton-83

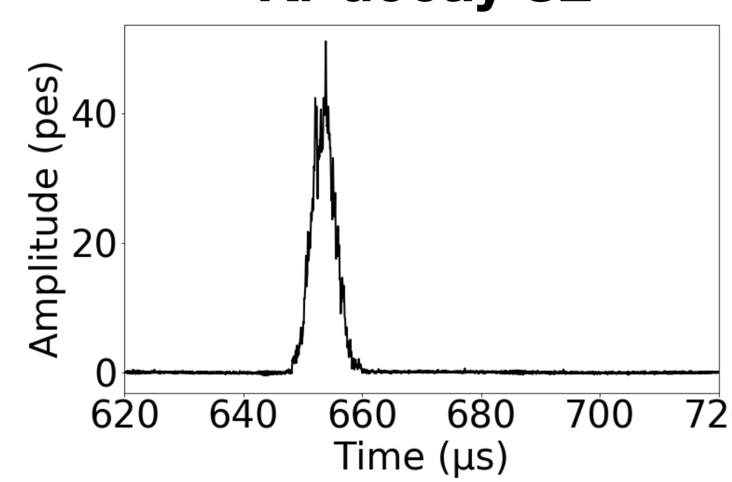


Point source of ~40keV



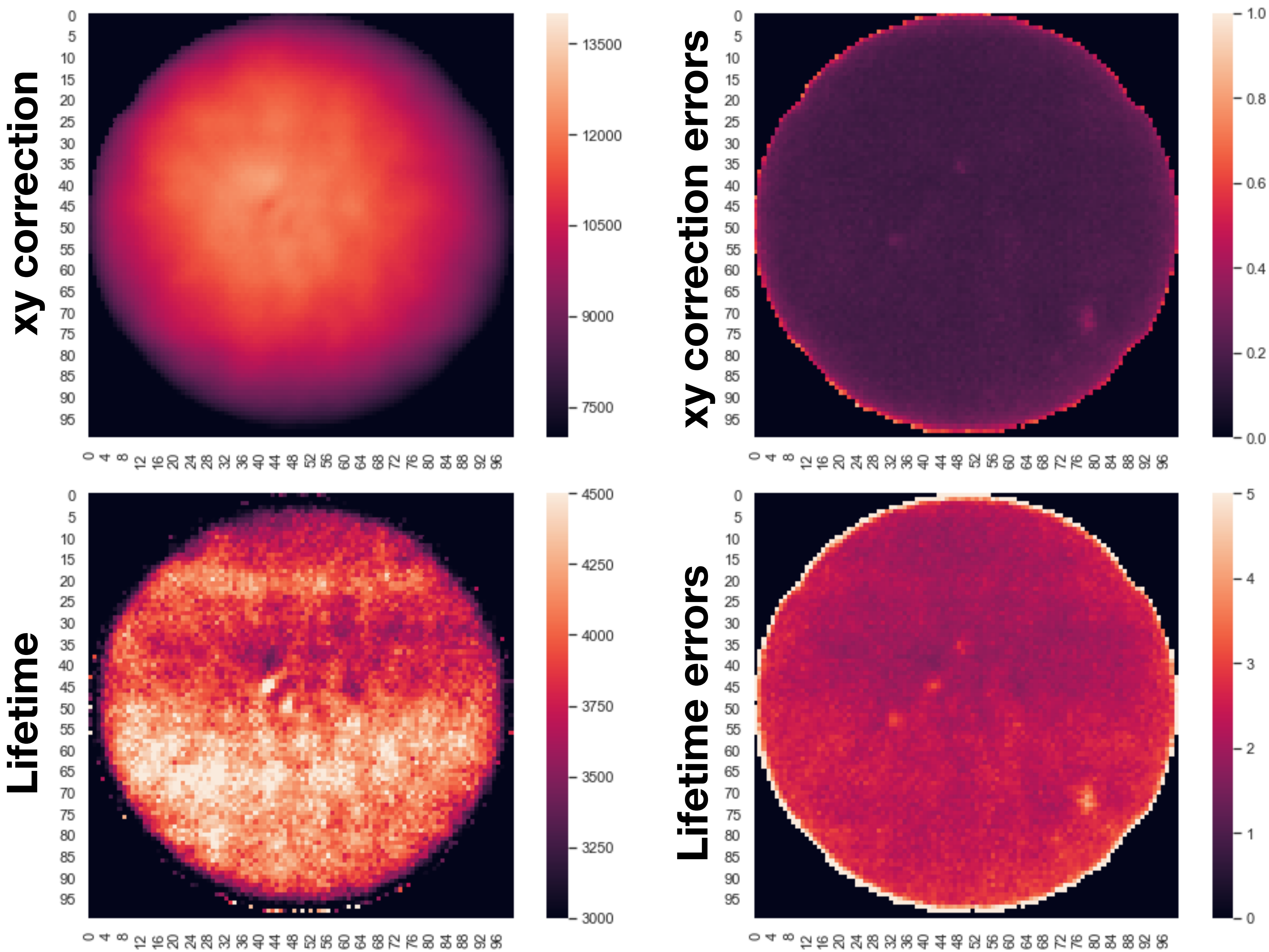






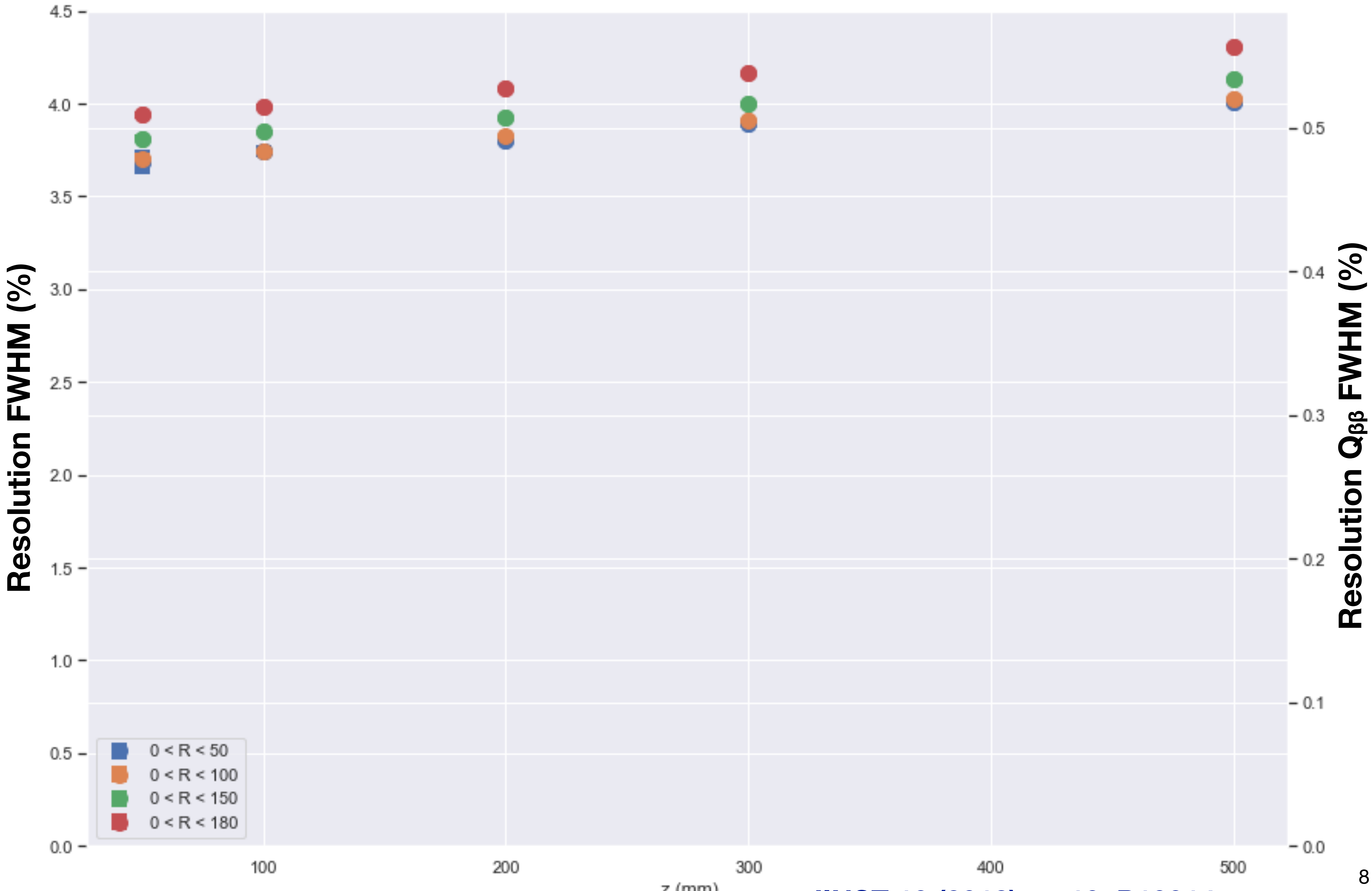
NEXT Collaboration, *JINST* **13** (2018) P10014

NEW calibration with Krypton-83



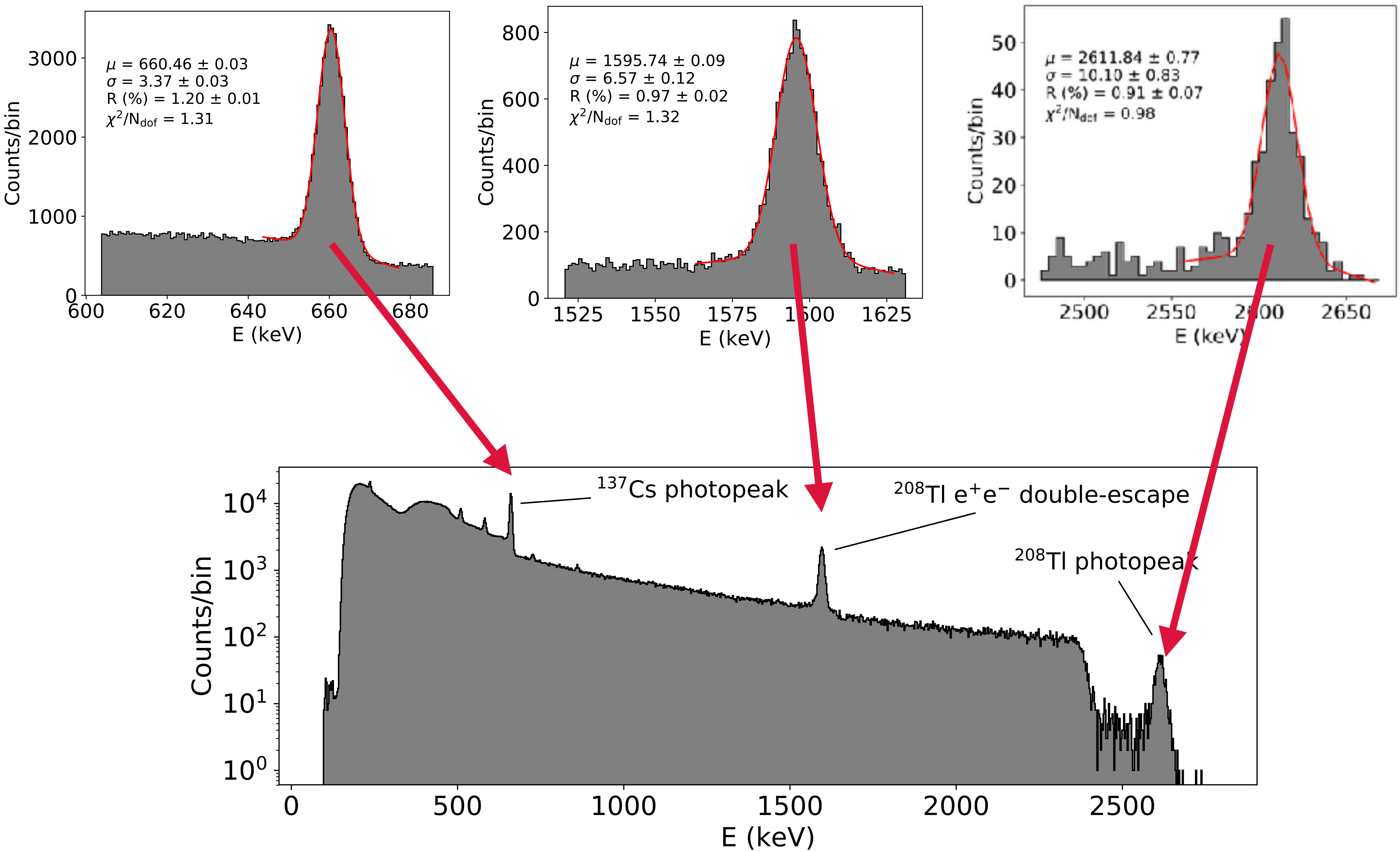
NEXT Collaboration, *JINST* **13** (2018) P10014

NEW calibration with Krypton-83



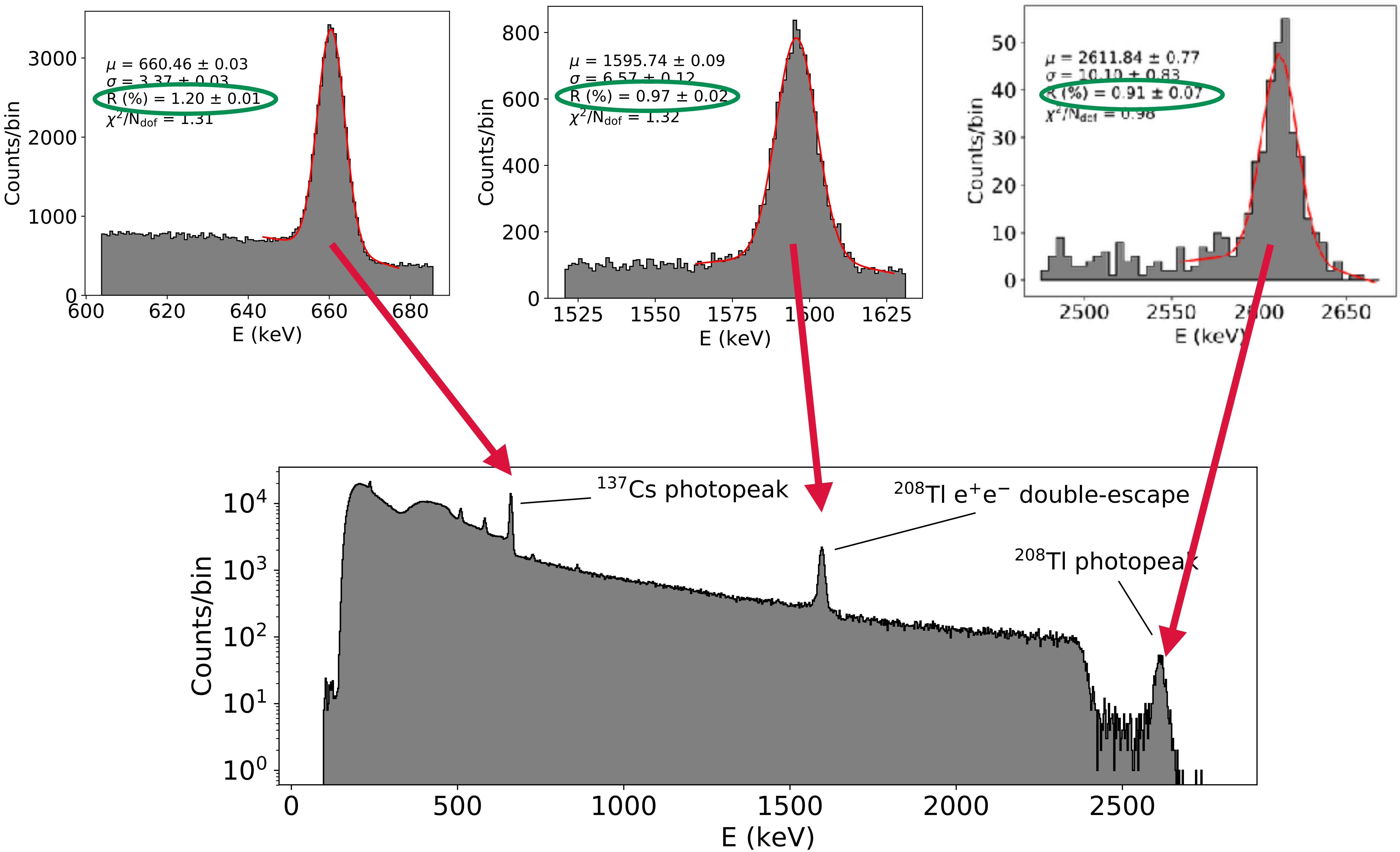
JINST 13 (2018) no.10, P10014

NEW energy resolution (calibration sources)



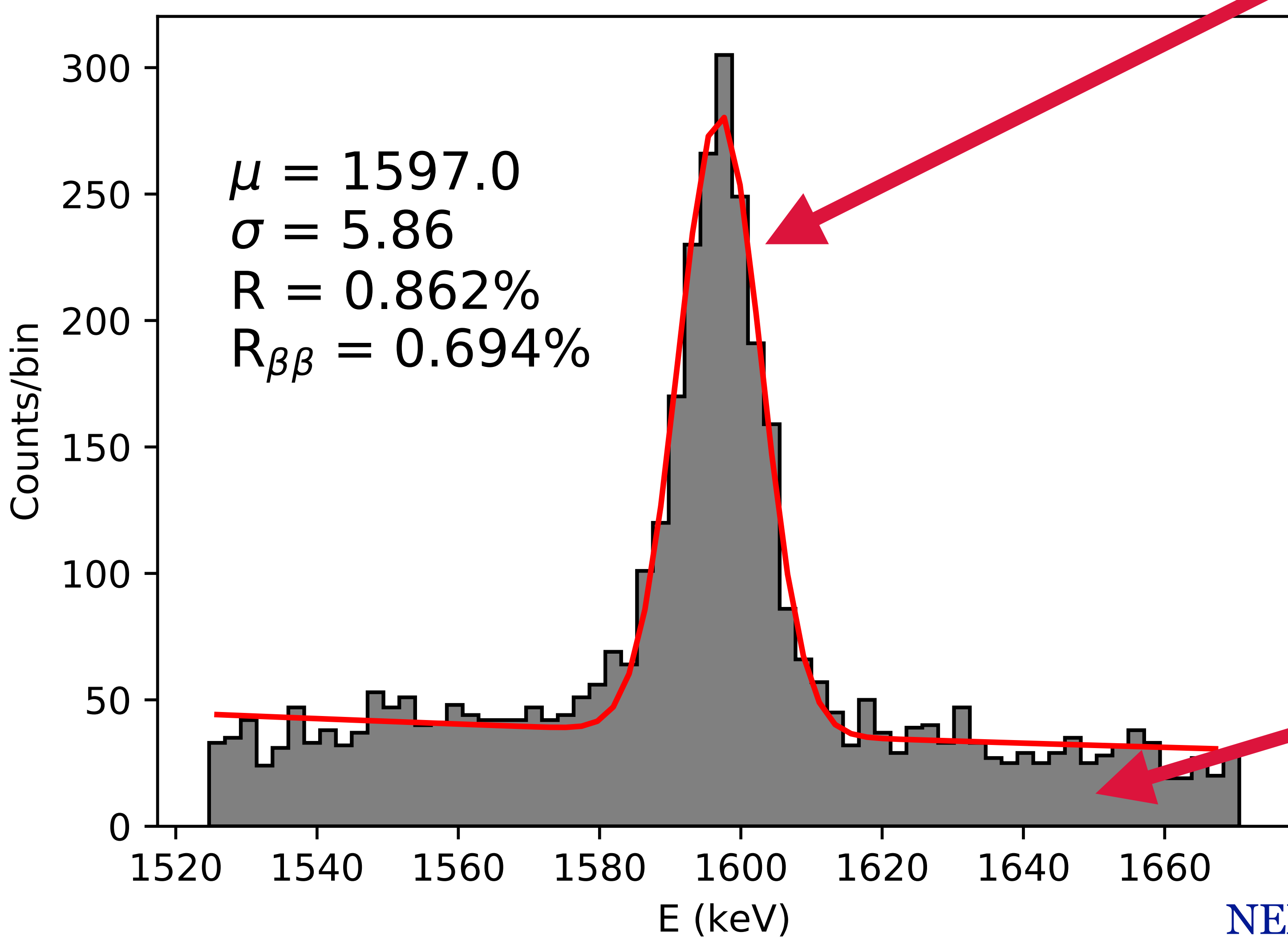
NEXT Collaboration, *JHEP* 10 (2019) 230

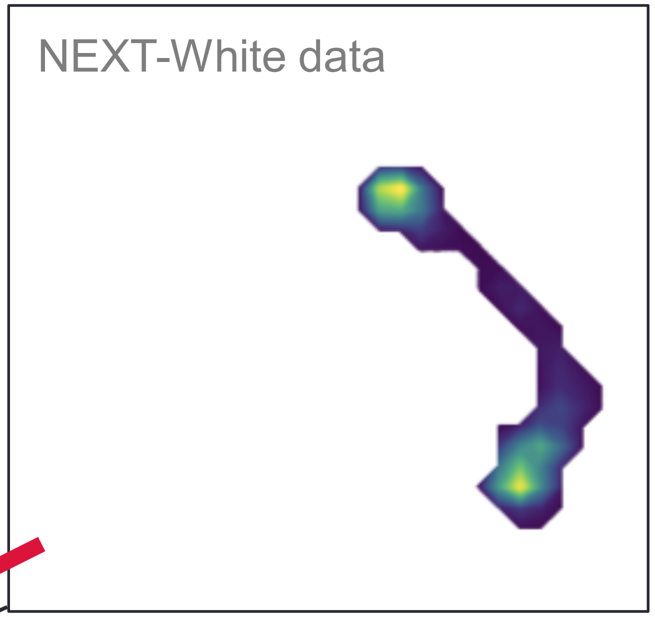
NEW energy resolution (calibration sources)



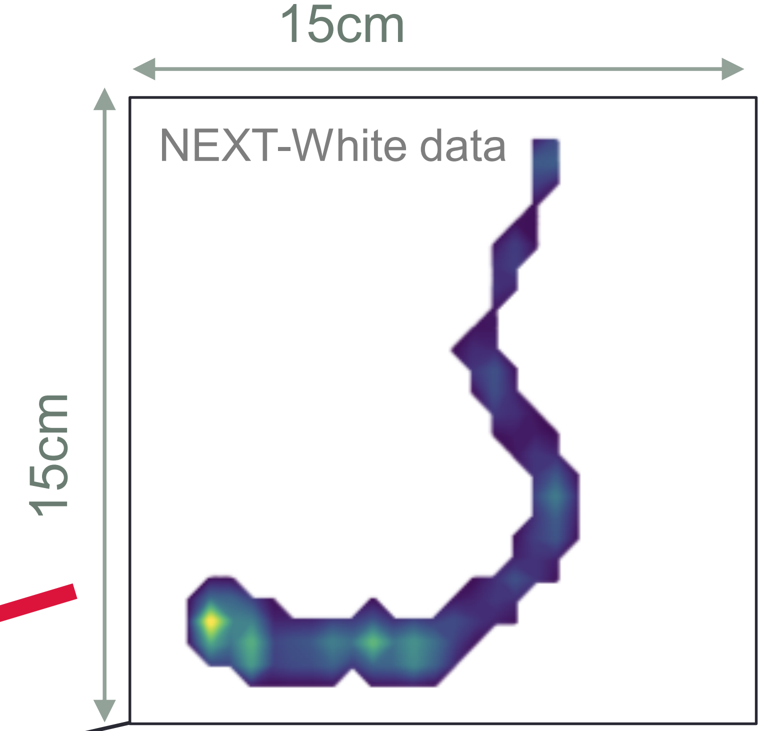
NEXT Collaboration, *JHEP* 10 (2019) 230

NEW topology





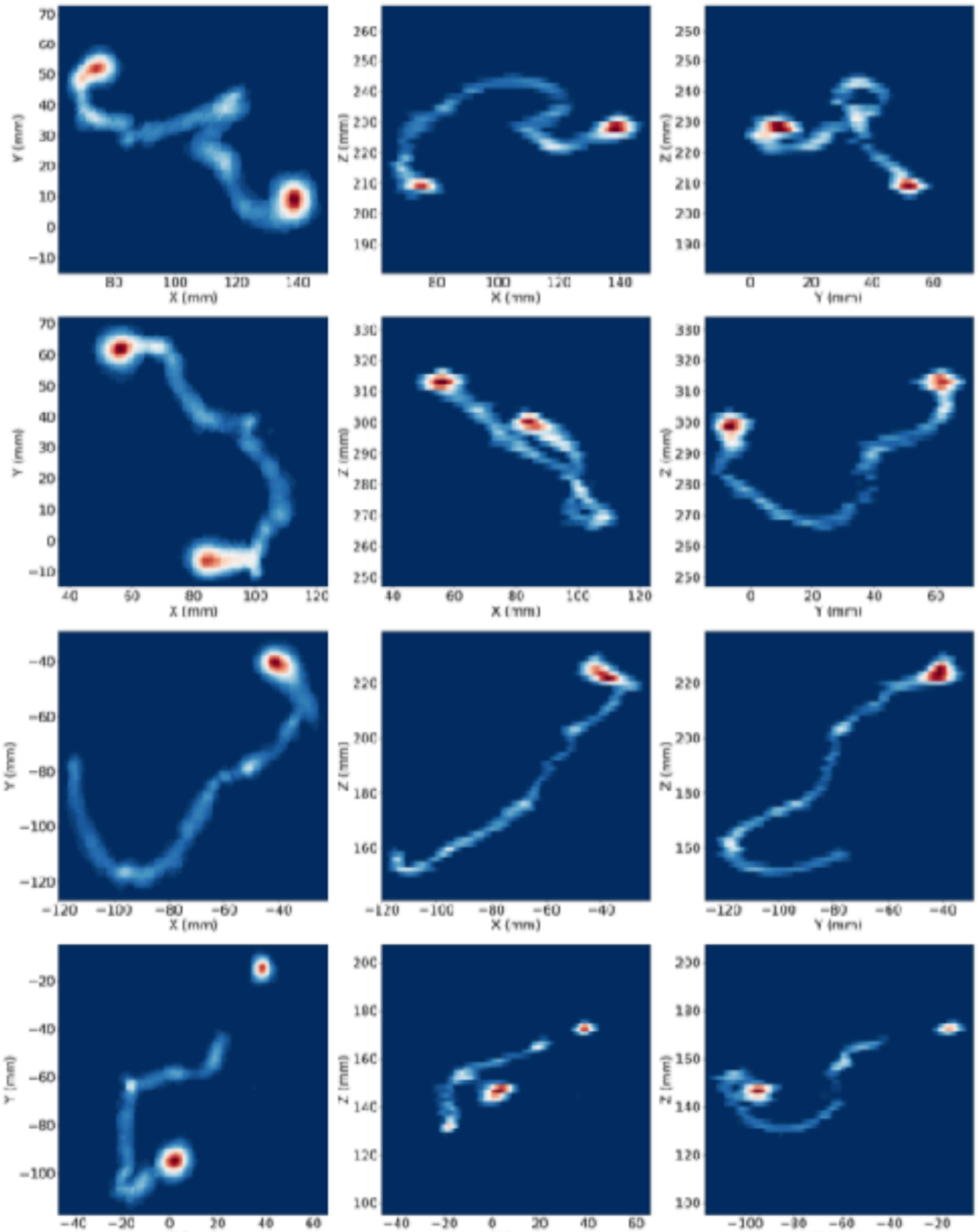
On double escape peak



Off double escape peak

NEXT Collaboration, *JHEP* 10 (2019) 052

NEW topology

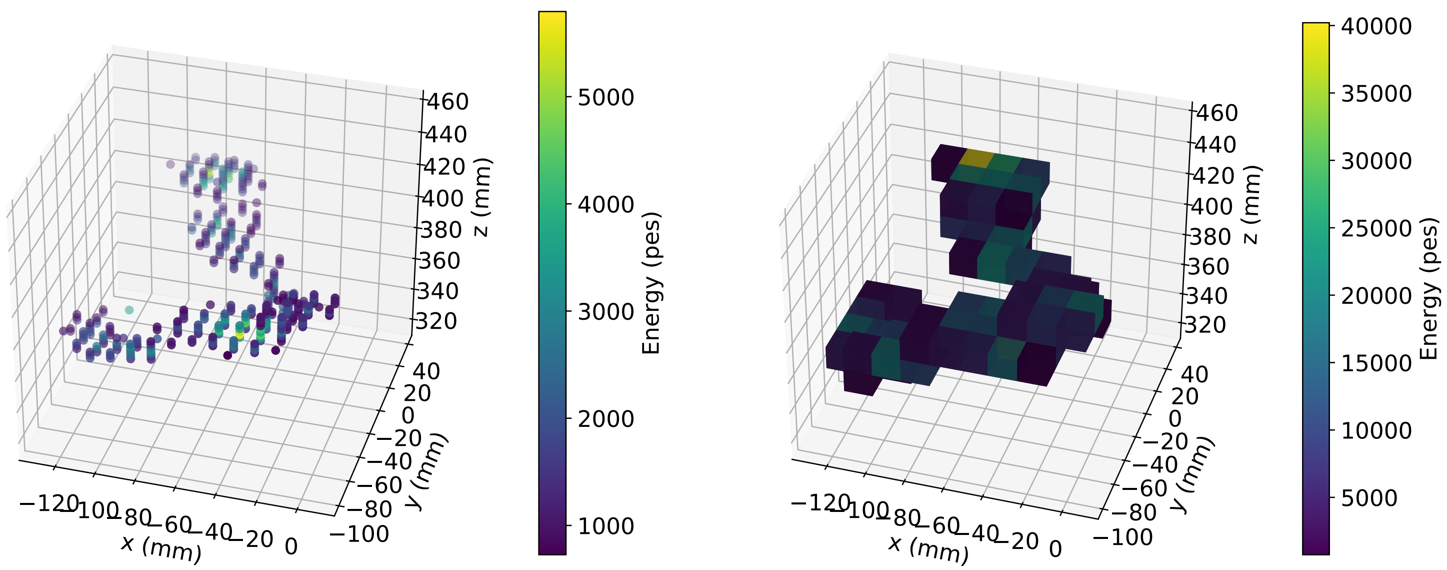


NEXT Collaboration, *JHEP* 07 (2021) 146

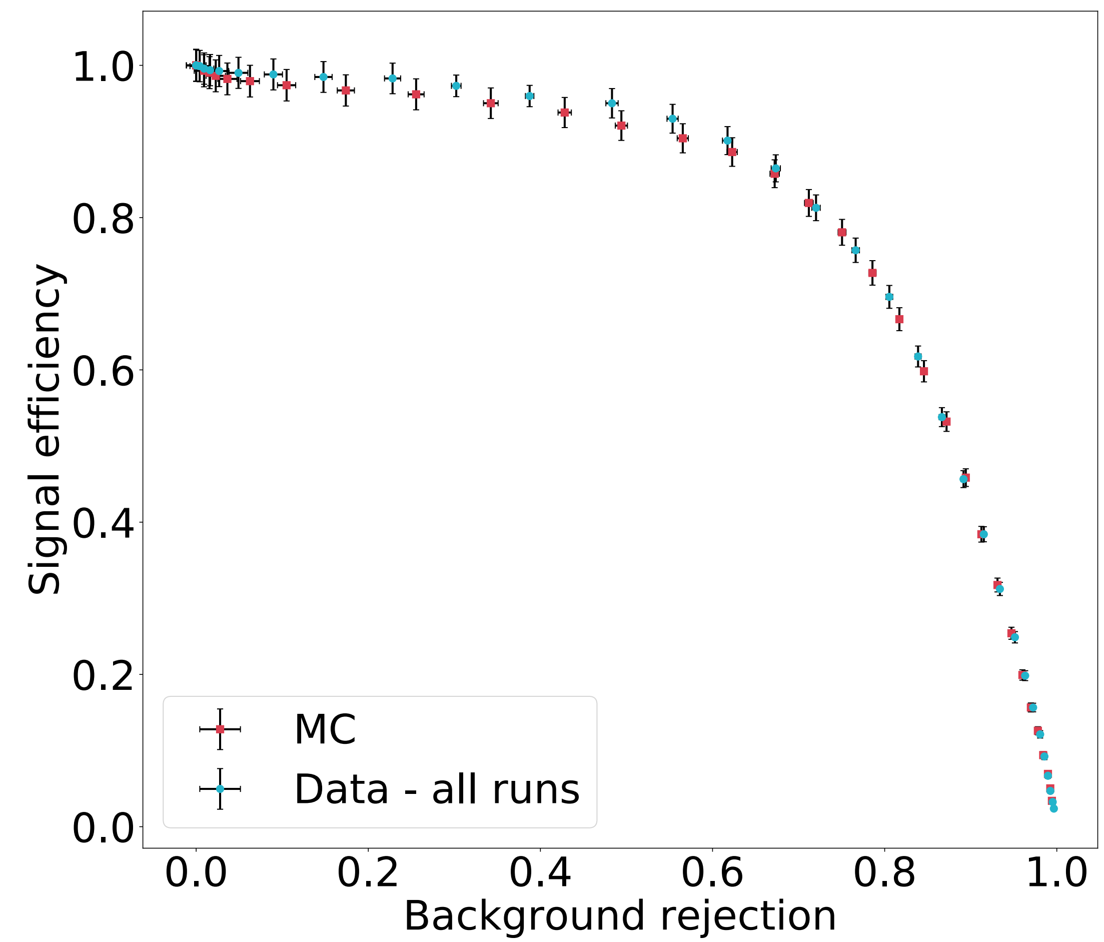
NEW topology

Topological separation

- Cut-based analysis



NEXT Collaboration, “*Demonstration of the event identification capabilities of the NEXT-White detector*” *JHEP* 10 (2019) 052

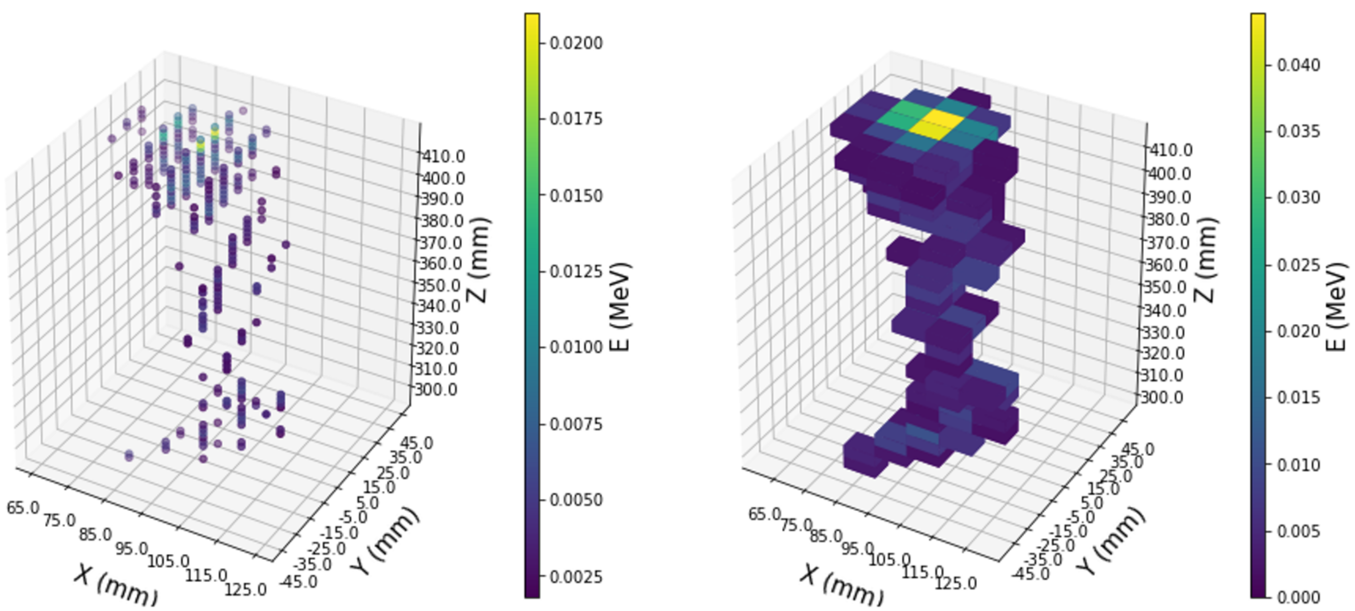


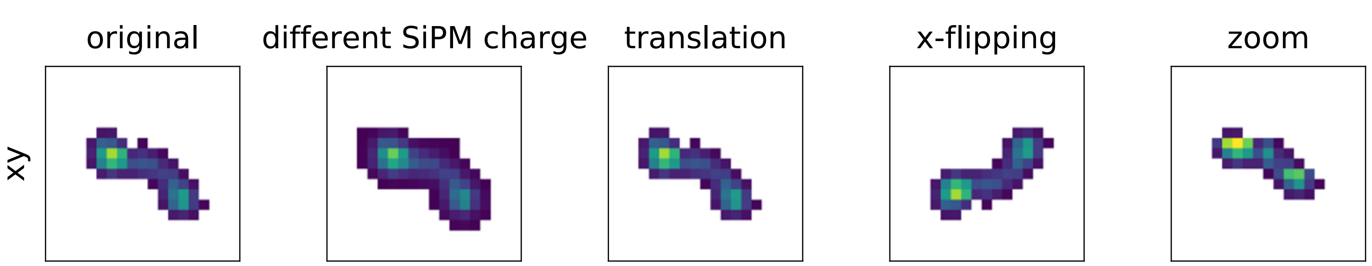
~70% efficiency
~20% bkg contamination

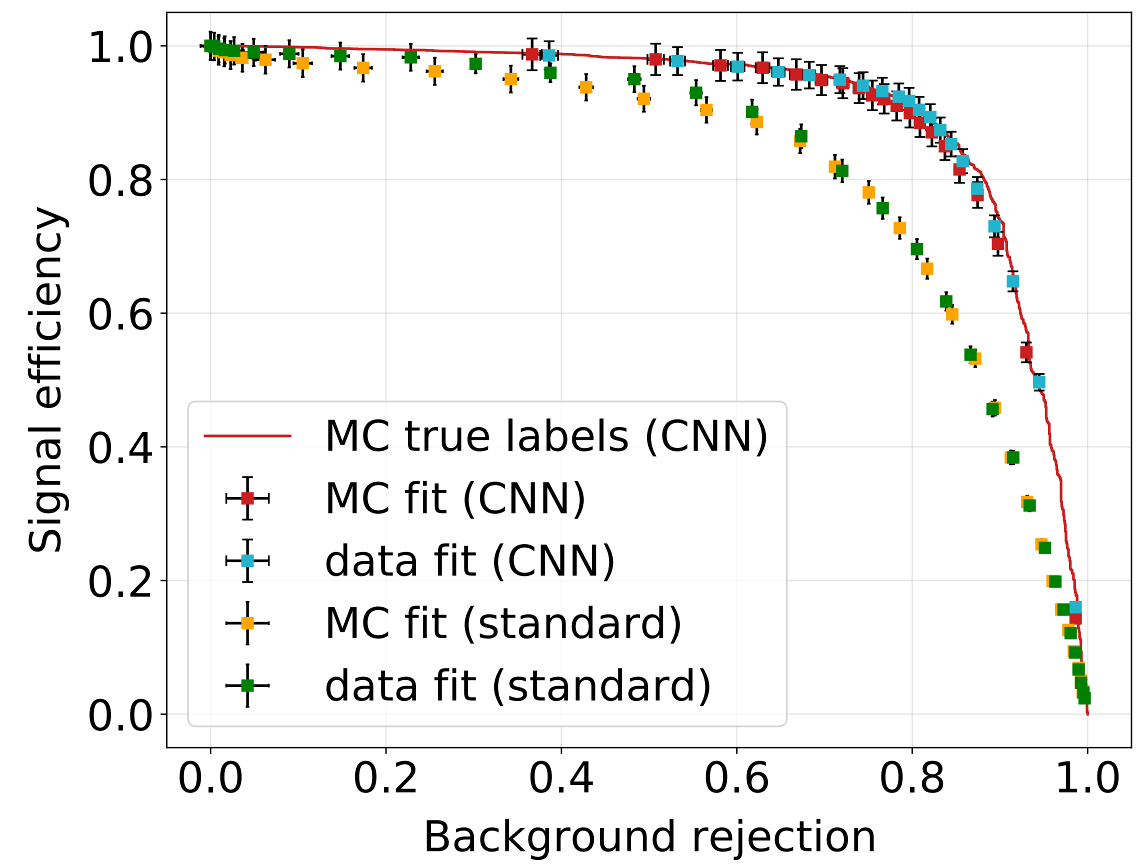
NEW topology

Topological separation

- DNN analysis







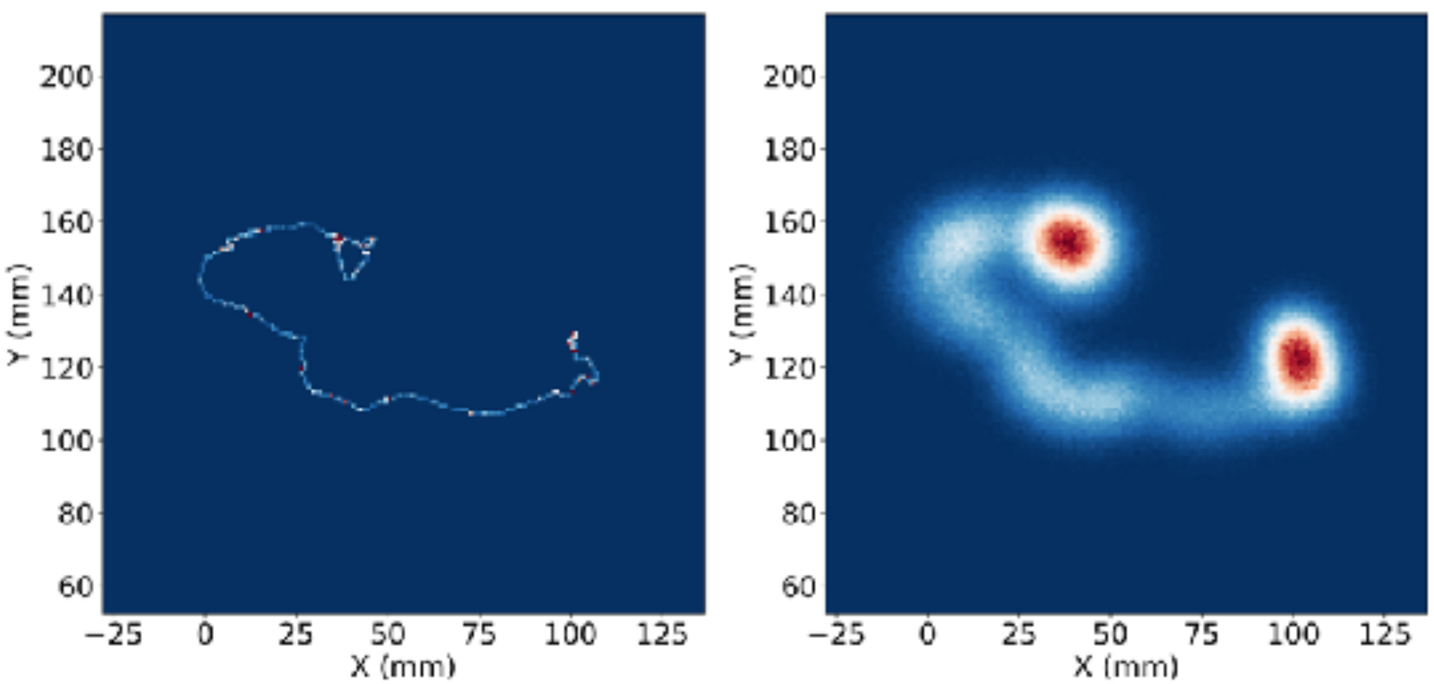
~65% efficiency
~10% bkg contamination

NEXT Collaboration, "*Demonstration of background rejection using deep convolutional neural networks in the NEXT experiment*", *JHEP* 01 (2021) 189

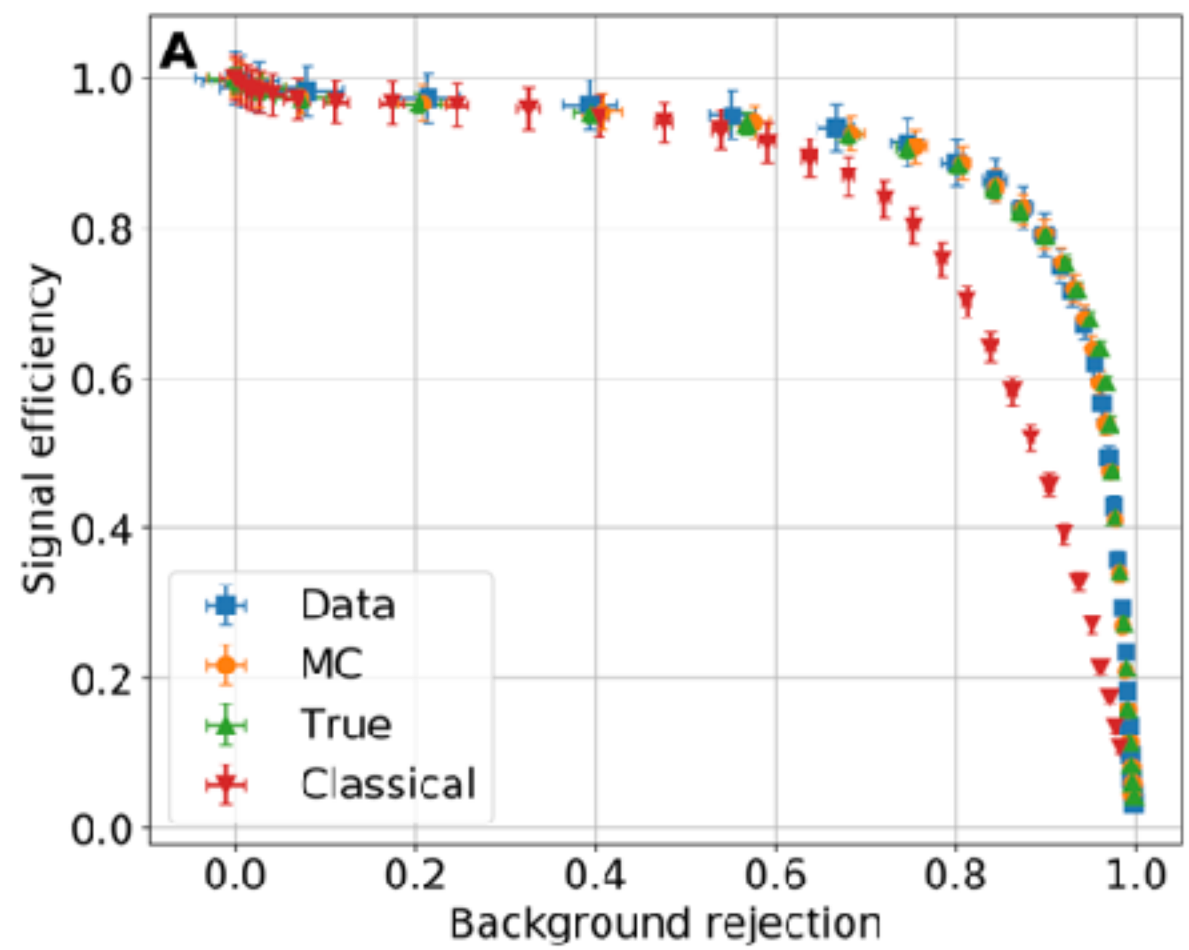
NEW topology

Topological separation

- Richardson-Lucy deconvolution analysis



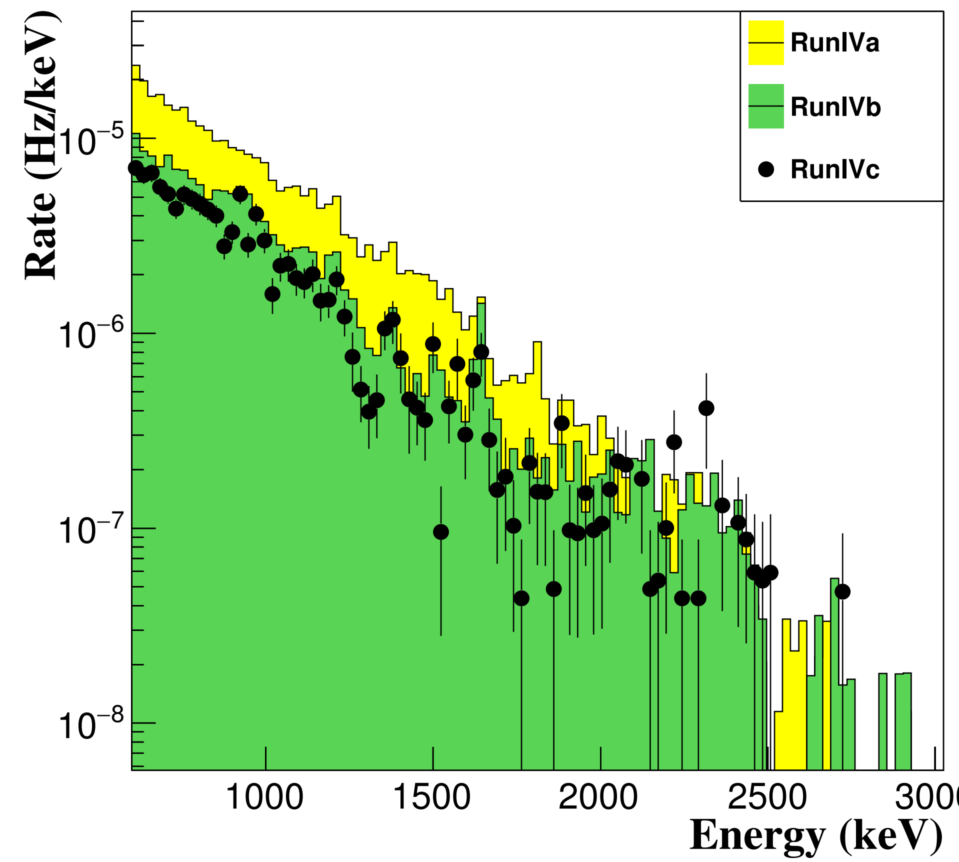
NEXT Collaboration, "*Boosting background suppression in the NEXT experiment through Richardson-Lucy deconvolution*", *JHEP* 07 (2021) 146



~56% efficiency
~4% bkg contamination

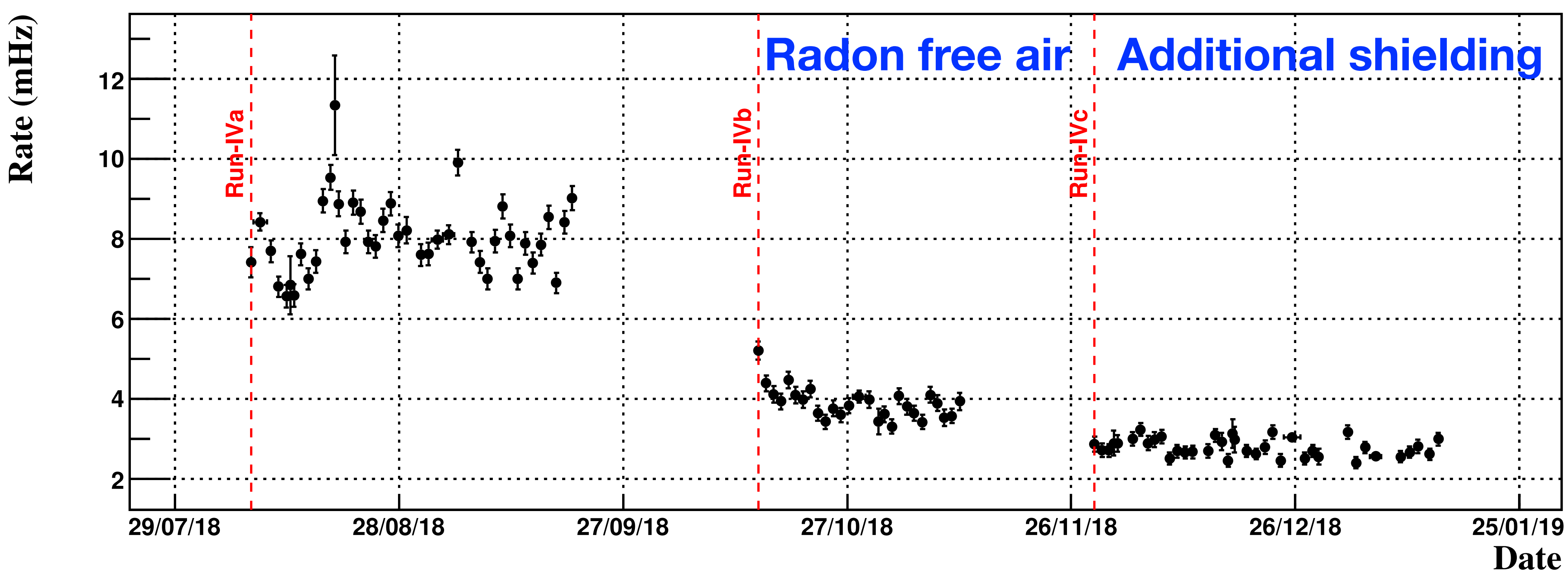
NEW backgrounds

Low-background data taking proceeding after detector calibration campaign. NEXT background model assessed using these data.



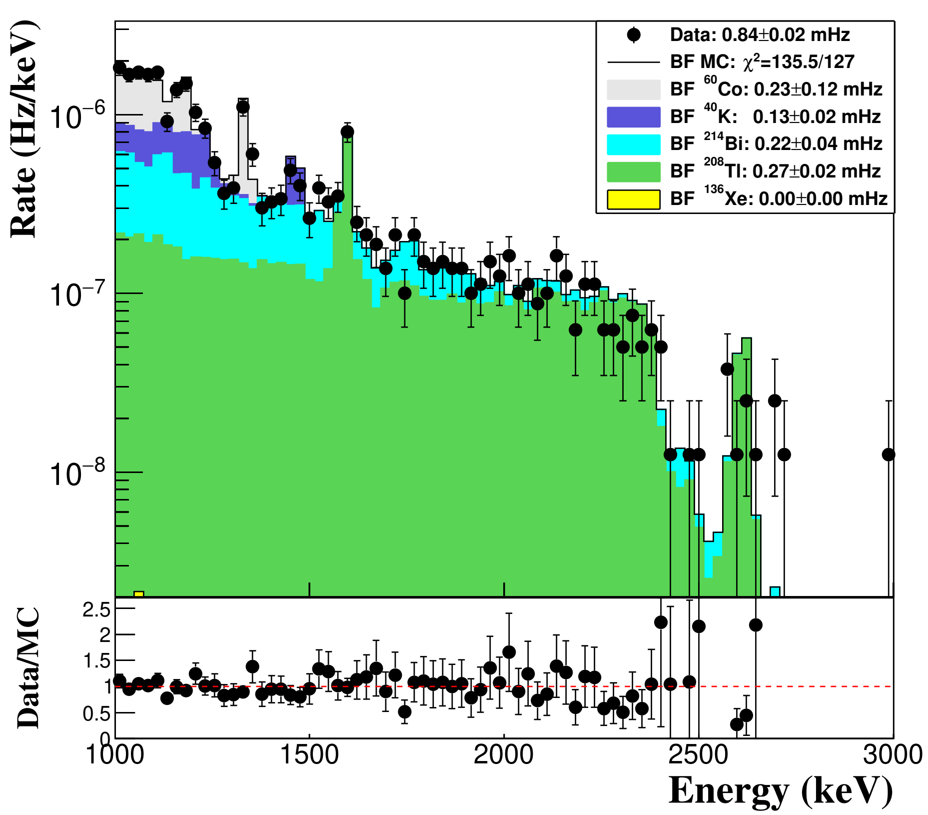
Several improvements in the setup have reduced backgrounds by a factor of ~4:

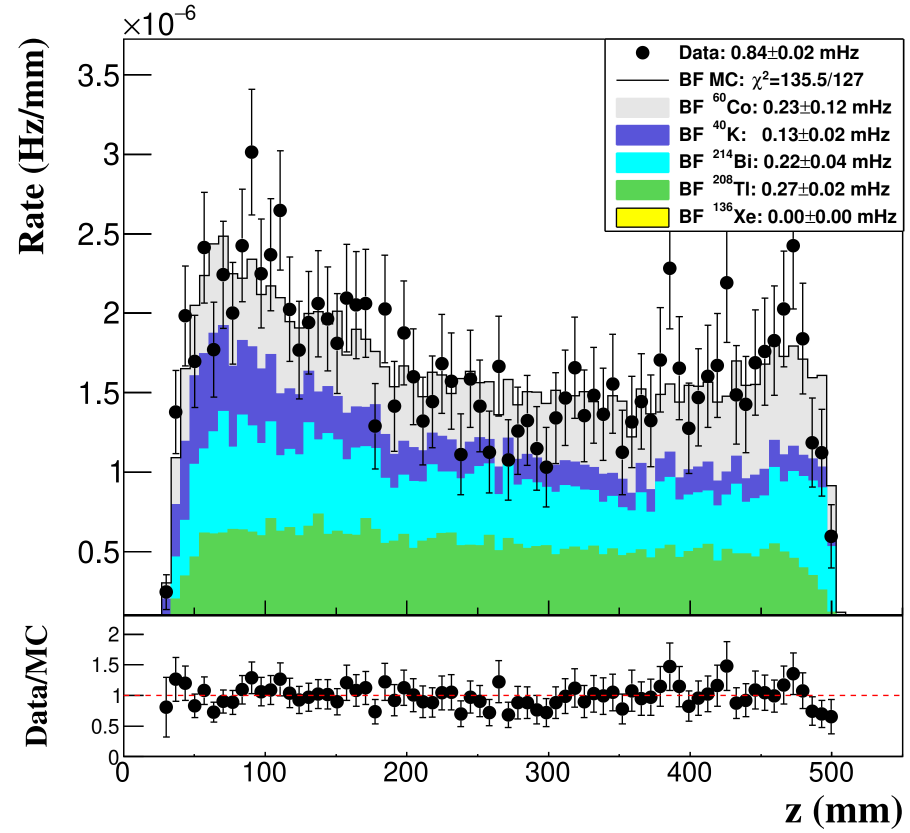
- New radiopure components in field cage.
- Radon-free air introduced in lead shielding.
- Additional layer of shielding added.

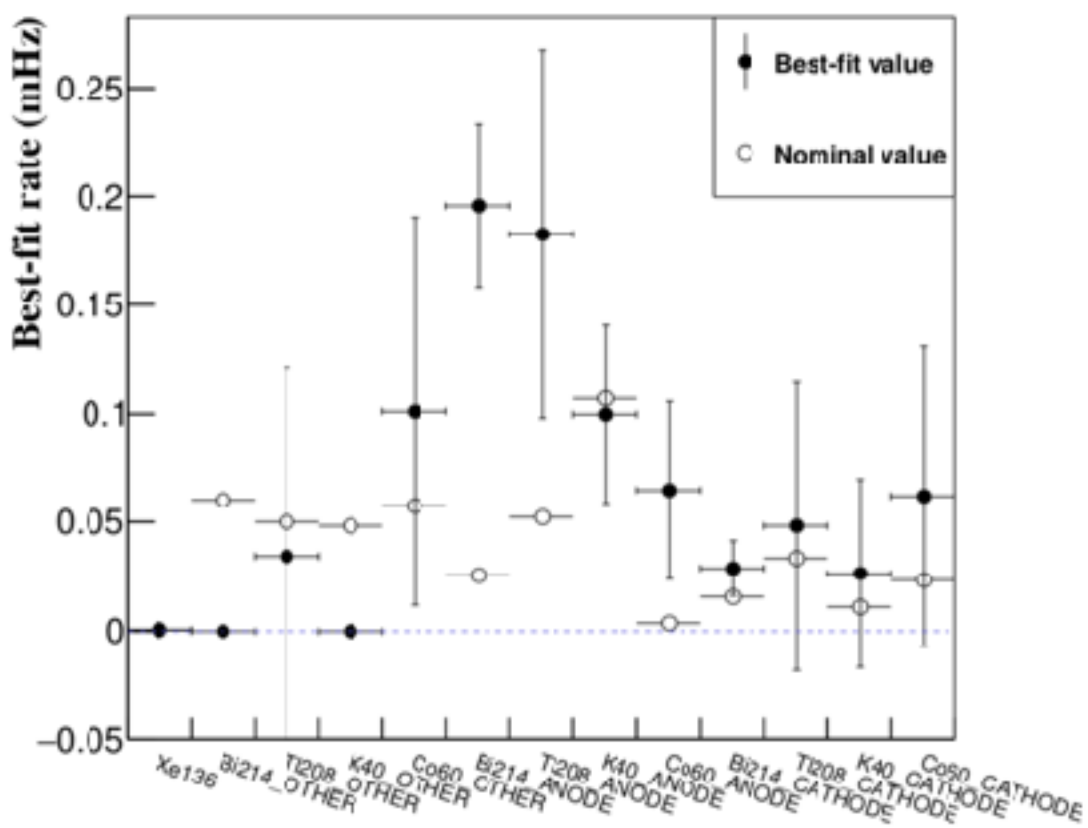


NEXT Collaboration, *JHEP* 10 (2019) 51

NEW backgrounds







NEXT Collaboration, *JHEP* 10 (2019) 51

Summary of NEW results

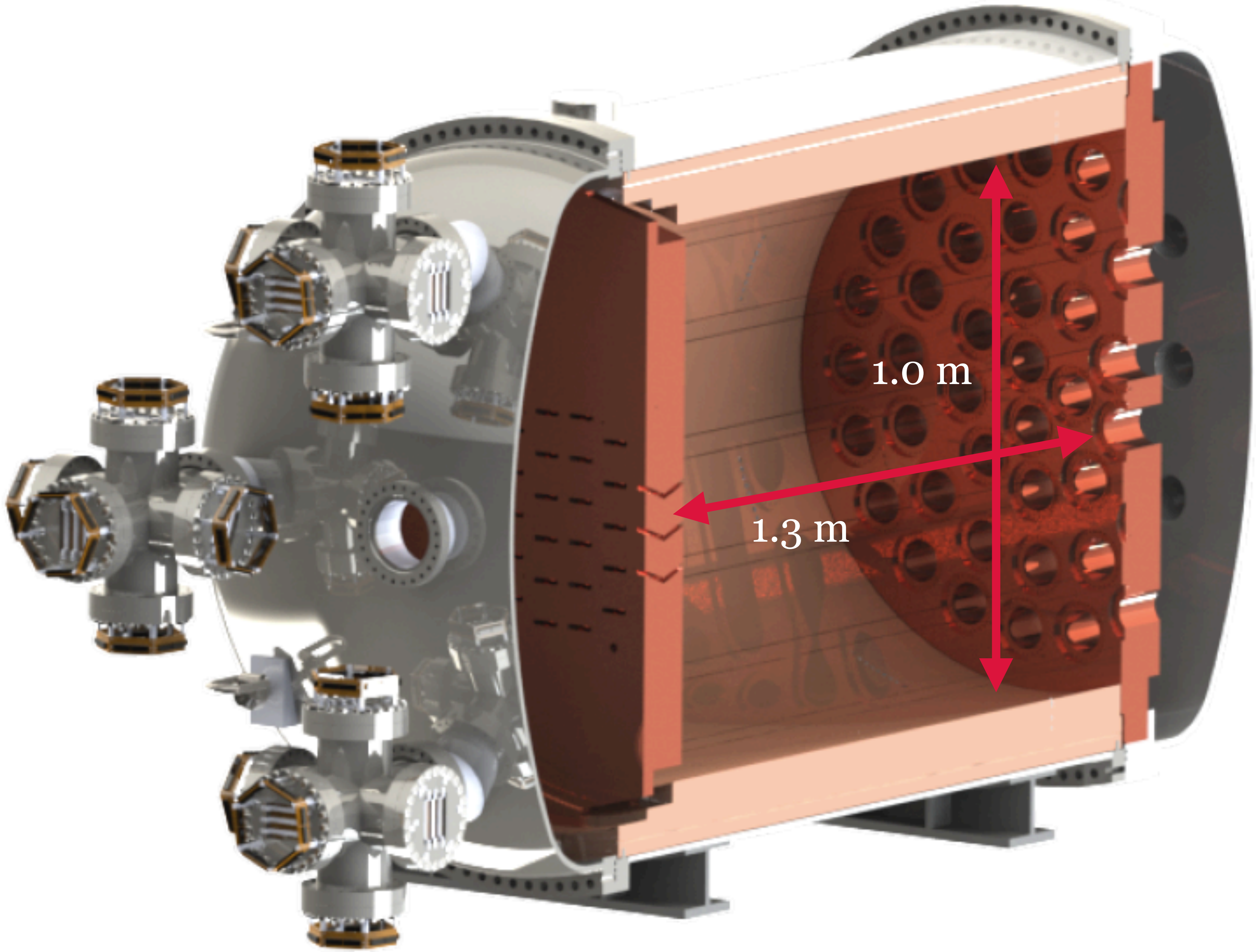
1. **Great energy resolution** ✓
   - With several calibration sources (different energies), energy resolution better than 1% FWHM at $Q_{\beta\beta}$ is achieved

2. **Powerful topology separation** ✓
   - Traditional cut-based and DNN analyses show promising backgrounds ejection power

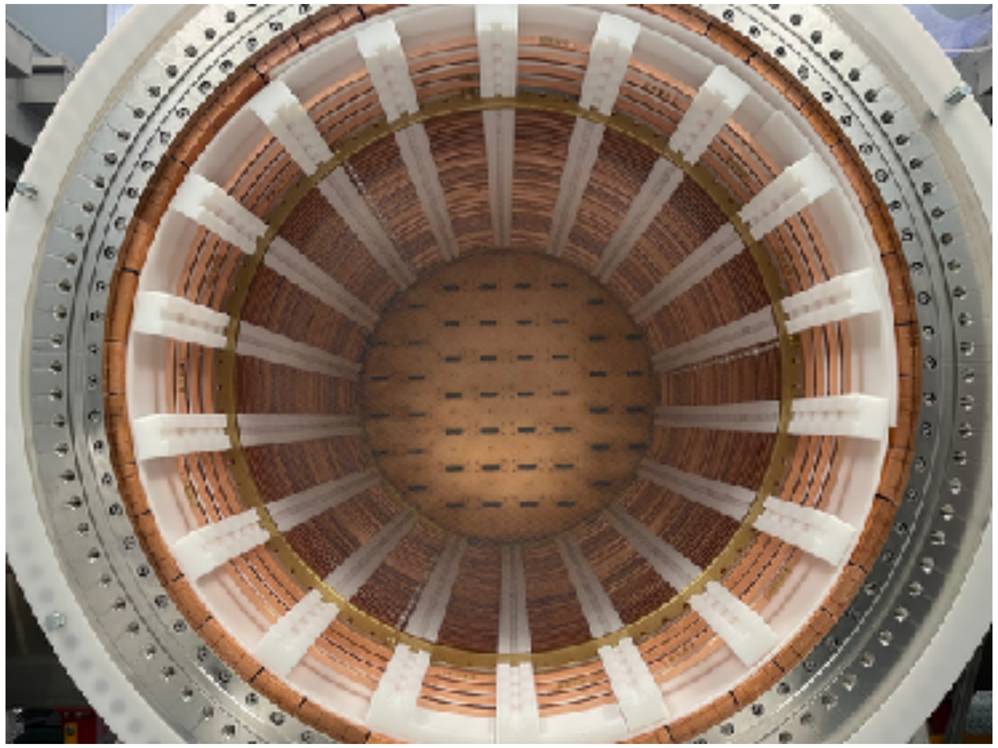
3. **Low background** ✓
   - Backgrounds measured in NEW and used for future predictions
   - Identification of potential improvements

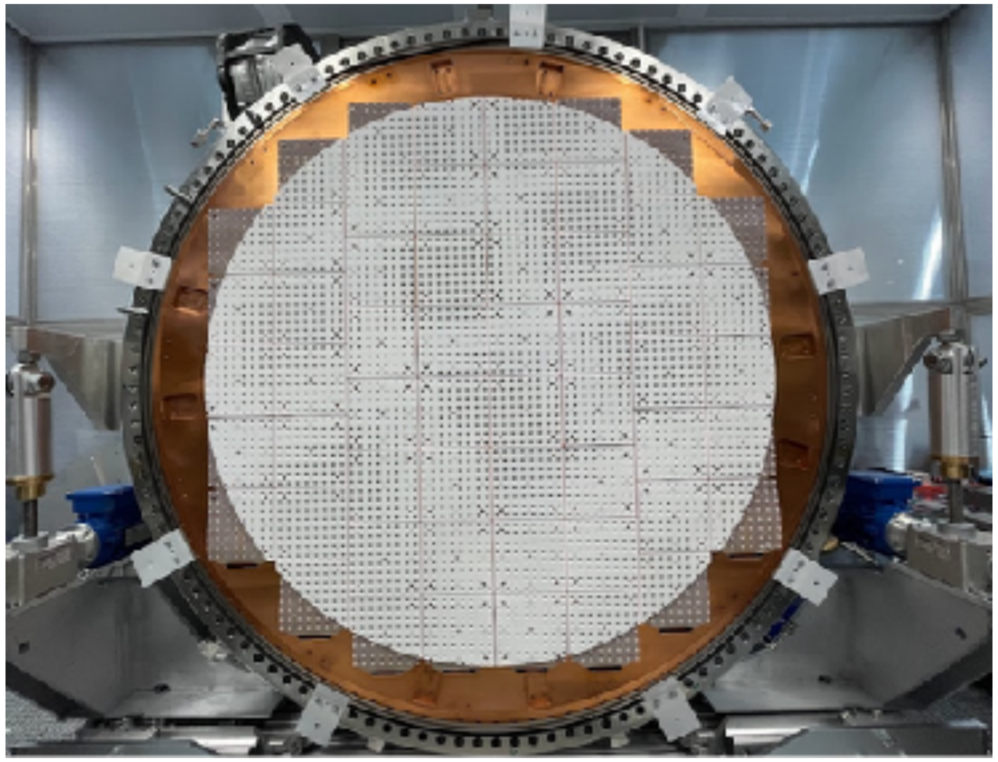
4. **Scalability**
   - NEXT-100

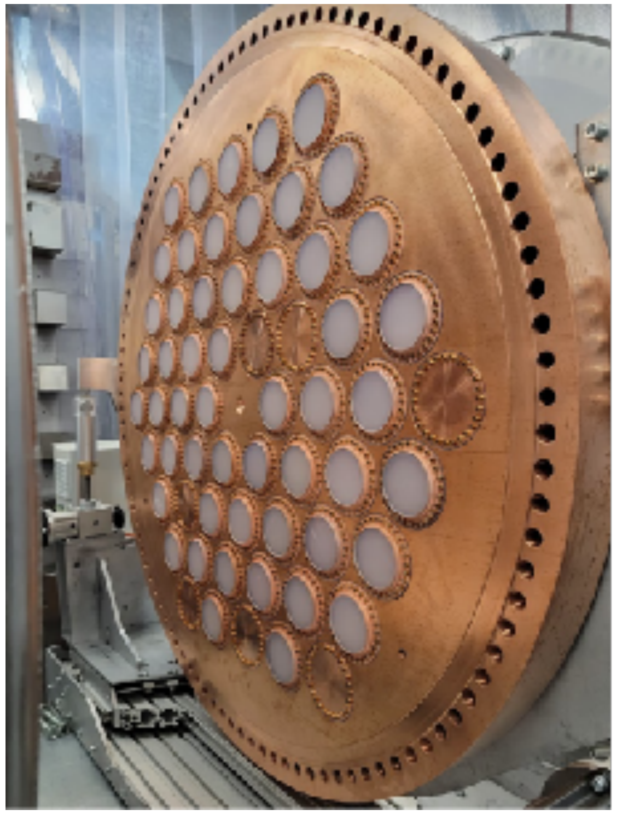
NEXT-100



NEXT-100 is now completed!

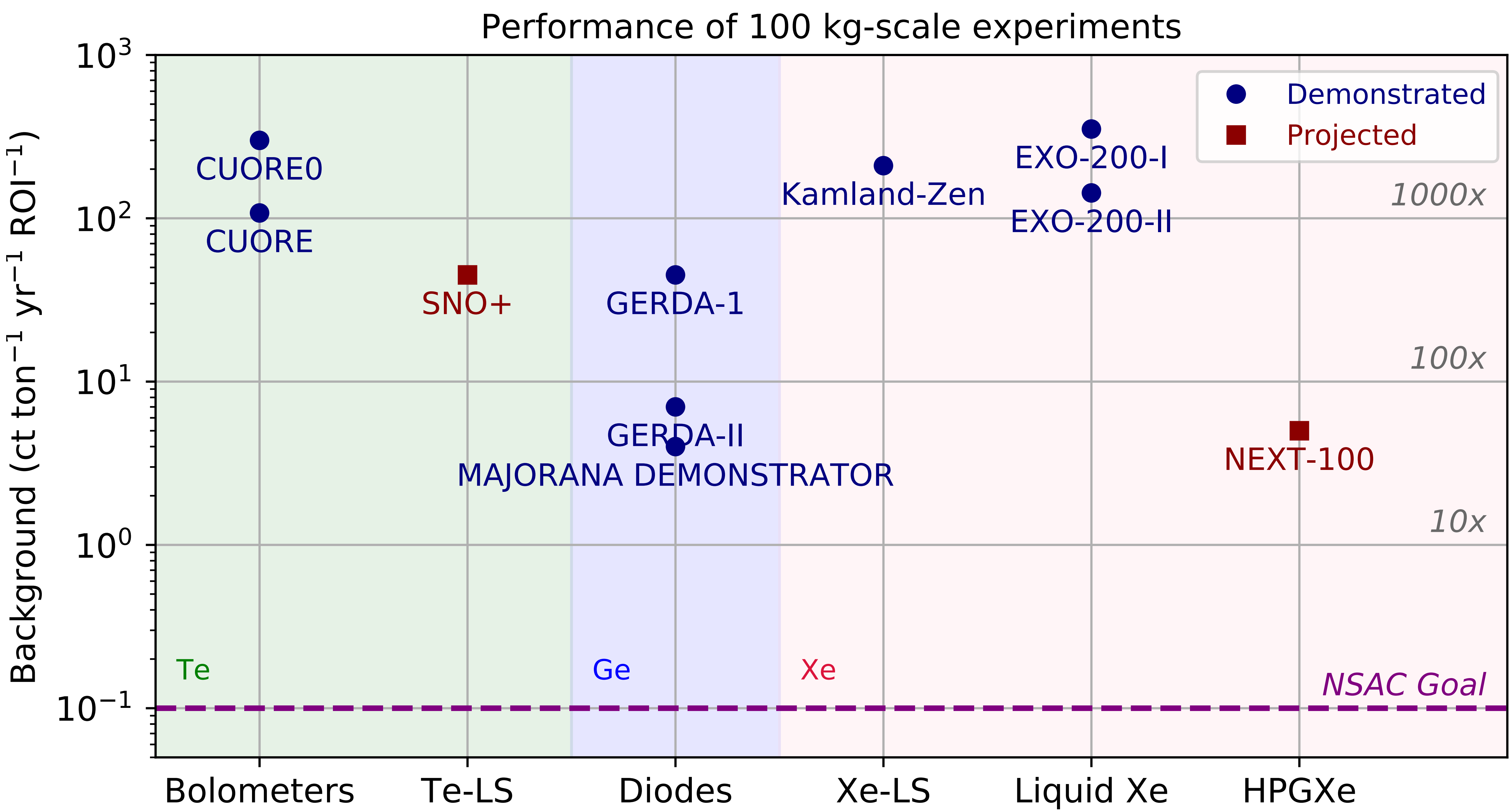






Towards the ton-scale

NEXT-100 should demonstrate a background rate competitive with HPGe detectors: a few counts per ton and year in ROI



From Ben Jones

Towards the ton-scale

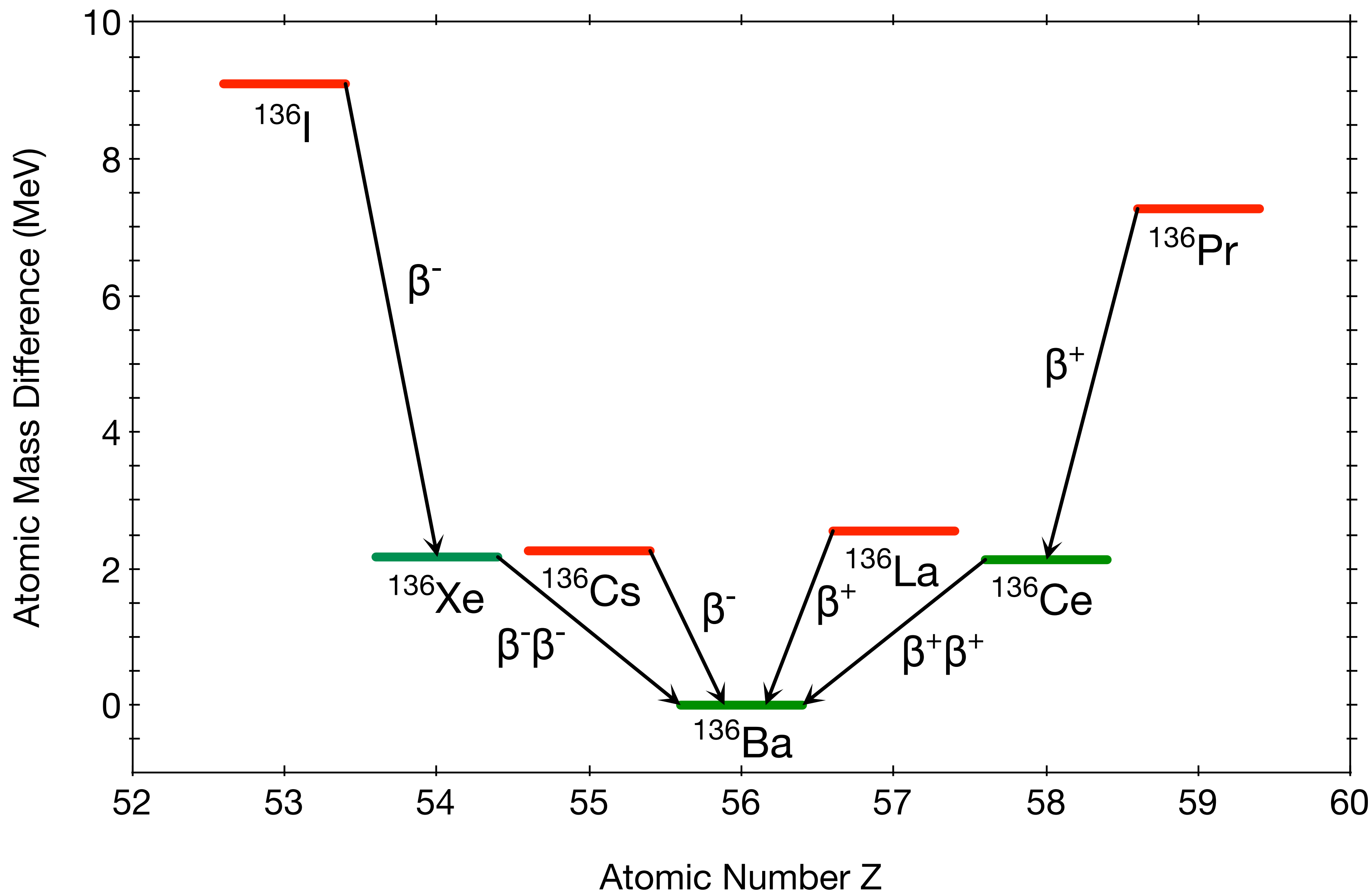
- NEXT-100 should demonstrate a background rate competitive with HPGe detectors: a few counts per ton and year in ROI
- Ample room for improvement in several areas:
  - ✓ Reconstruction algorithms (i.e. better energy resolution and topological discrimination)
  - ✓ Radiopurity (e.g. get rid of PMTs)
  - ✓ Low-diffusion gas mixtures and denser tracking plane to improve tracking signature

Focused R&D devoted to these 3 points!

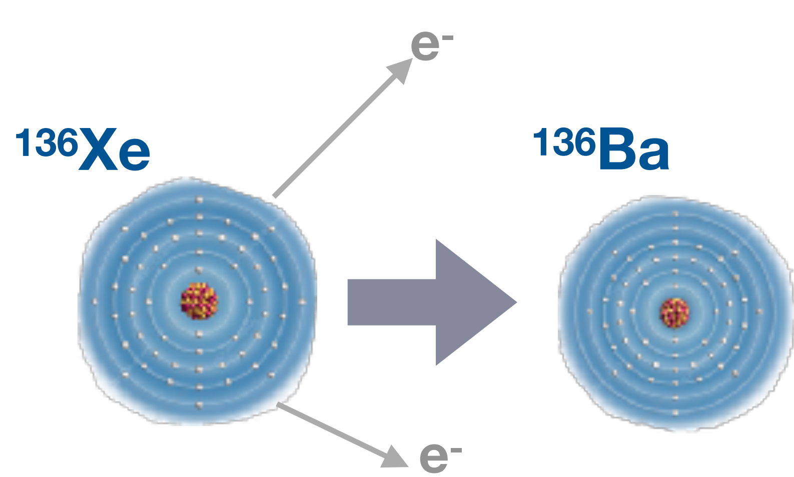
Towards the ton-scale

- NEXT-100 should demonstrate a background rate competitive with HPGe detectors: a few counts per ton and year in ROI
- Ample room for improvement in several areas:
  - ✓ Reconstruction algorithms (i.e. better energy resolution and topological discrimination)
  - ✓ Radiopurity (e.g. get rid of PMTs)
  - ✓ Low-diffusion gas mixtures and denser tracking plane to improve tracking signature
- Last but not least: gaseous xenon could make possible a true background-free experiment via tagging of the barium decay product

Ba tagging

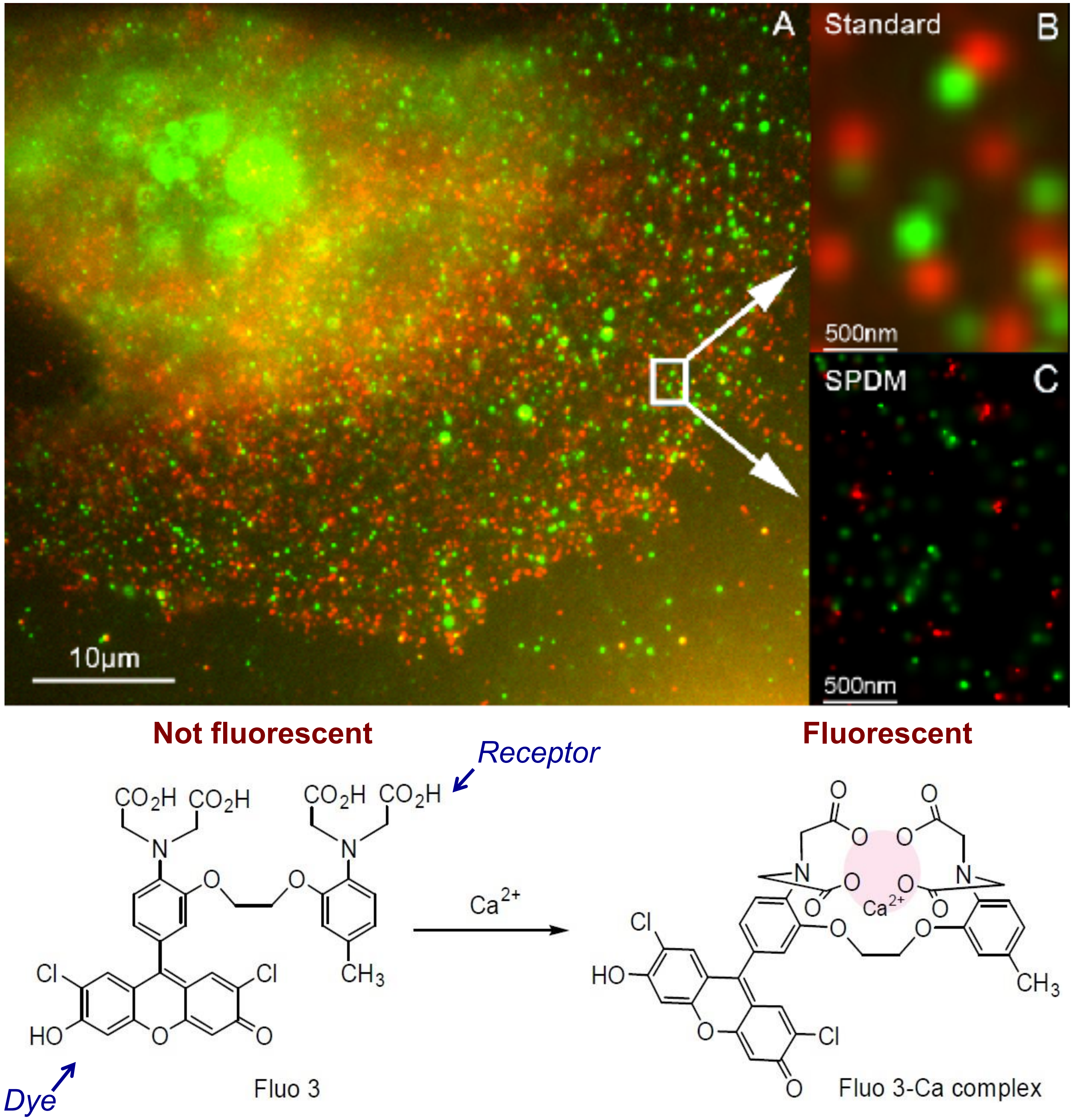


Atomic Mass Difference (MeV)
Atomic Number Z
10
8
6
4
2
0
52
53
54
55
56
57
58
59
60
136I
136Xe
136Cs
136Ba
136La
136Ce
136Pr
β-
β-β-
β-
β+
β+β+
β+



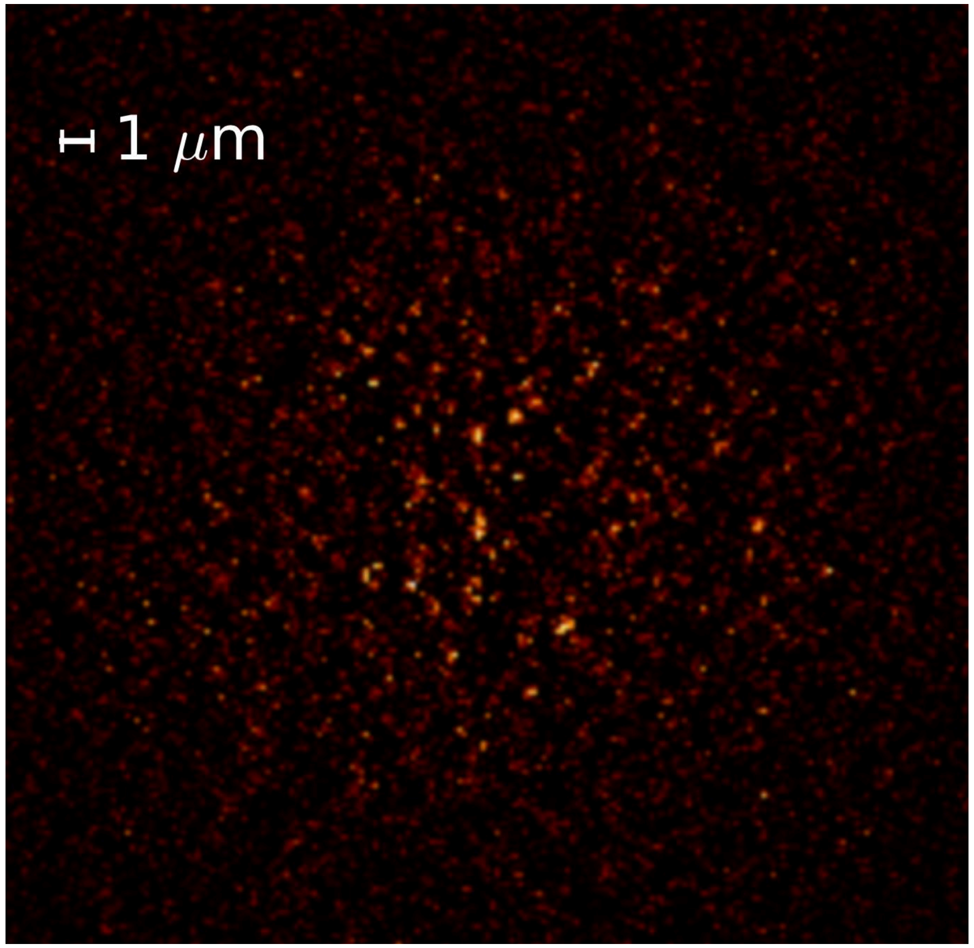
136Xe
136Ba
e-
e-

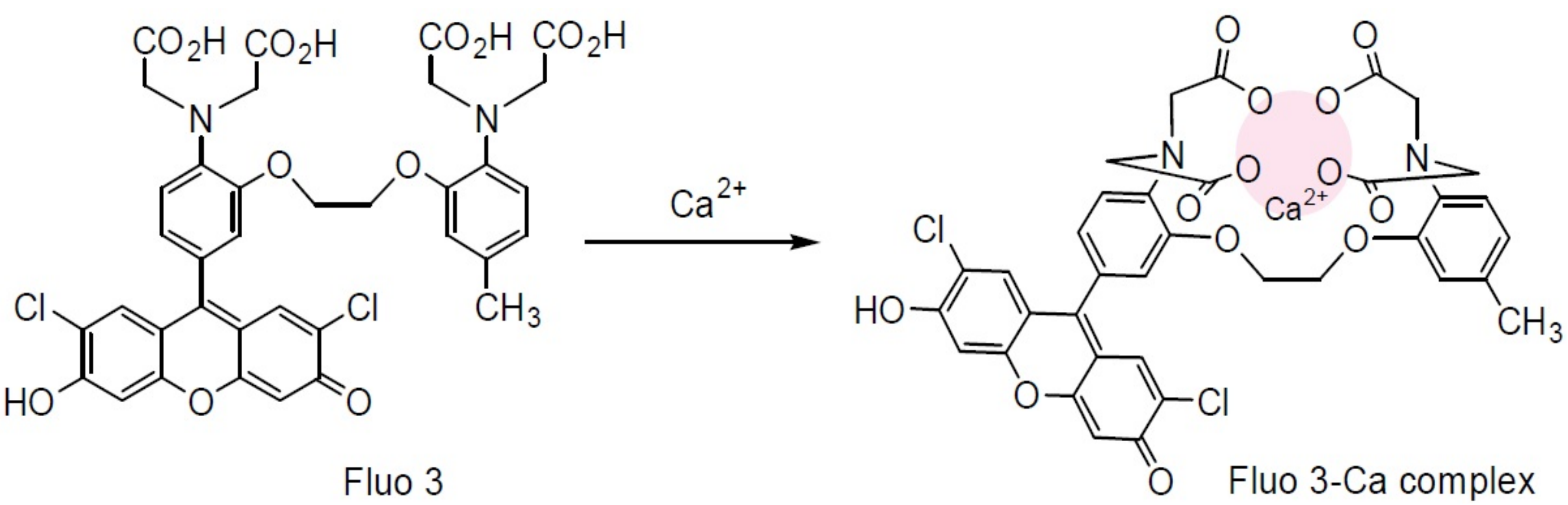
Ba tagging

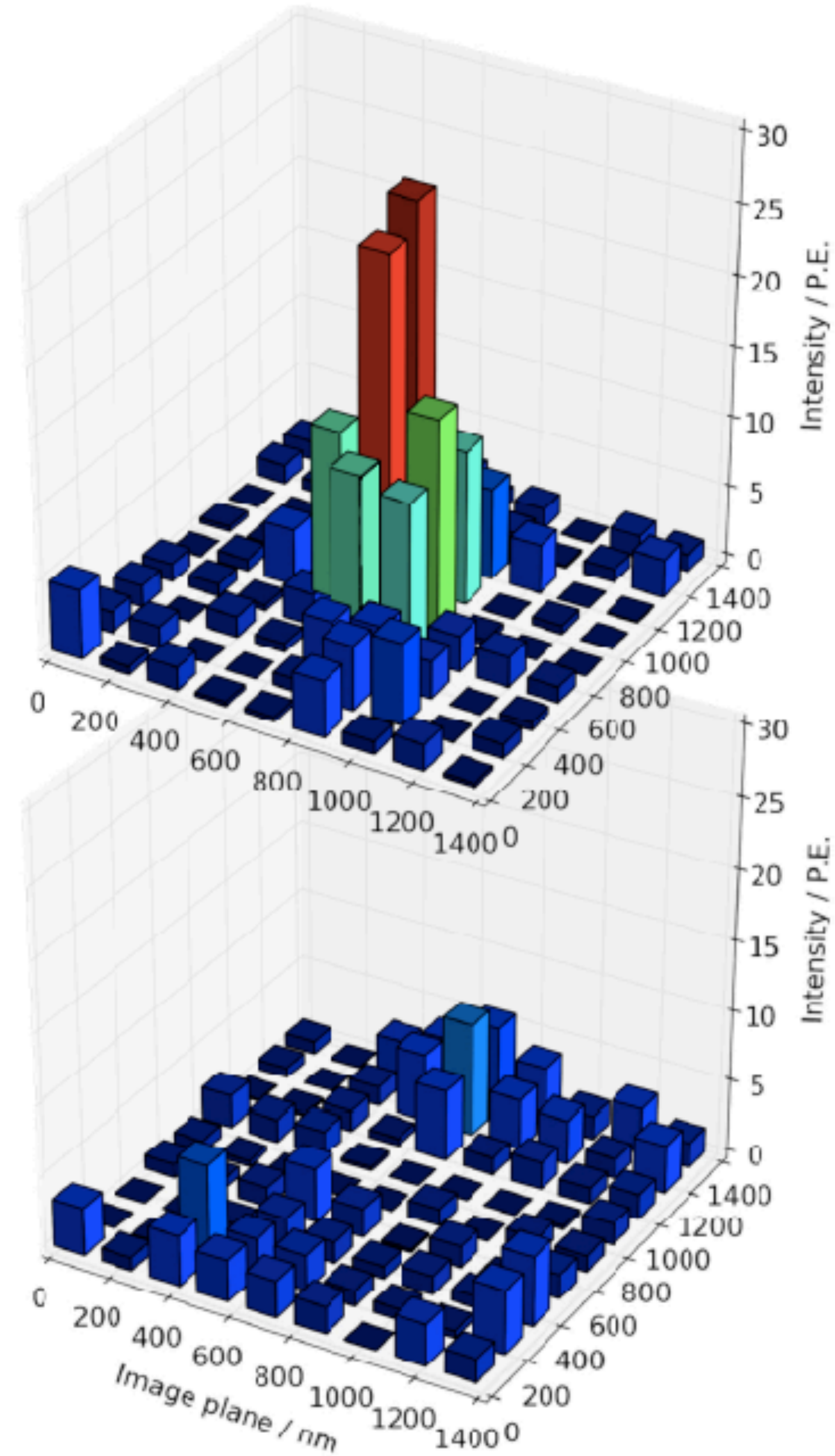


D.R. Nygren, *J. Phys. Conf. Ser.* **650** (2015) 012002

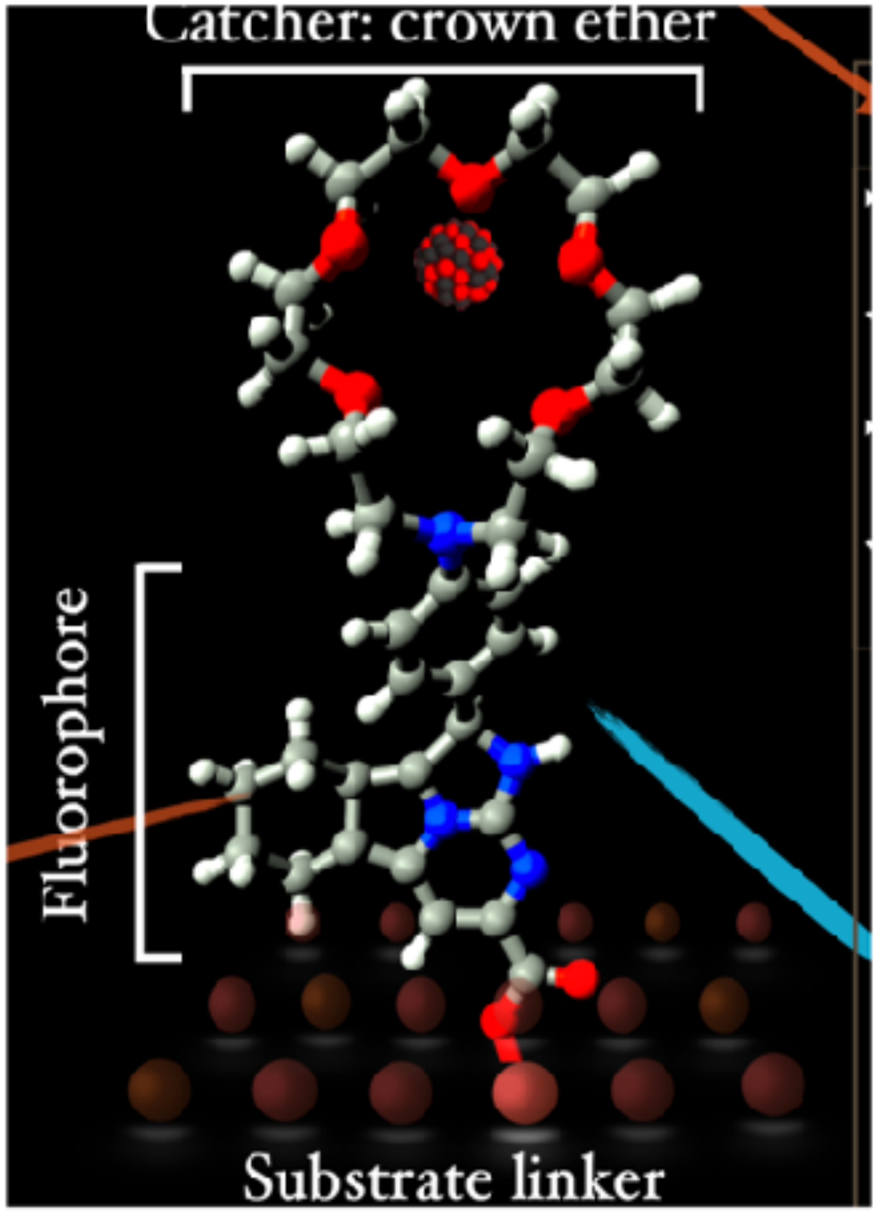
Ba tagging

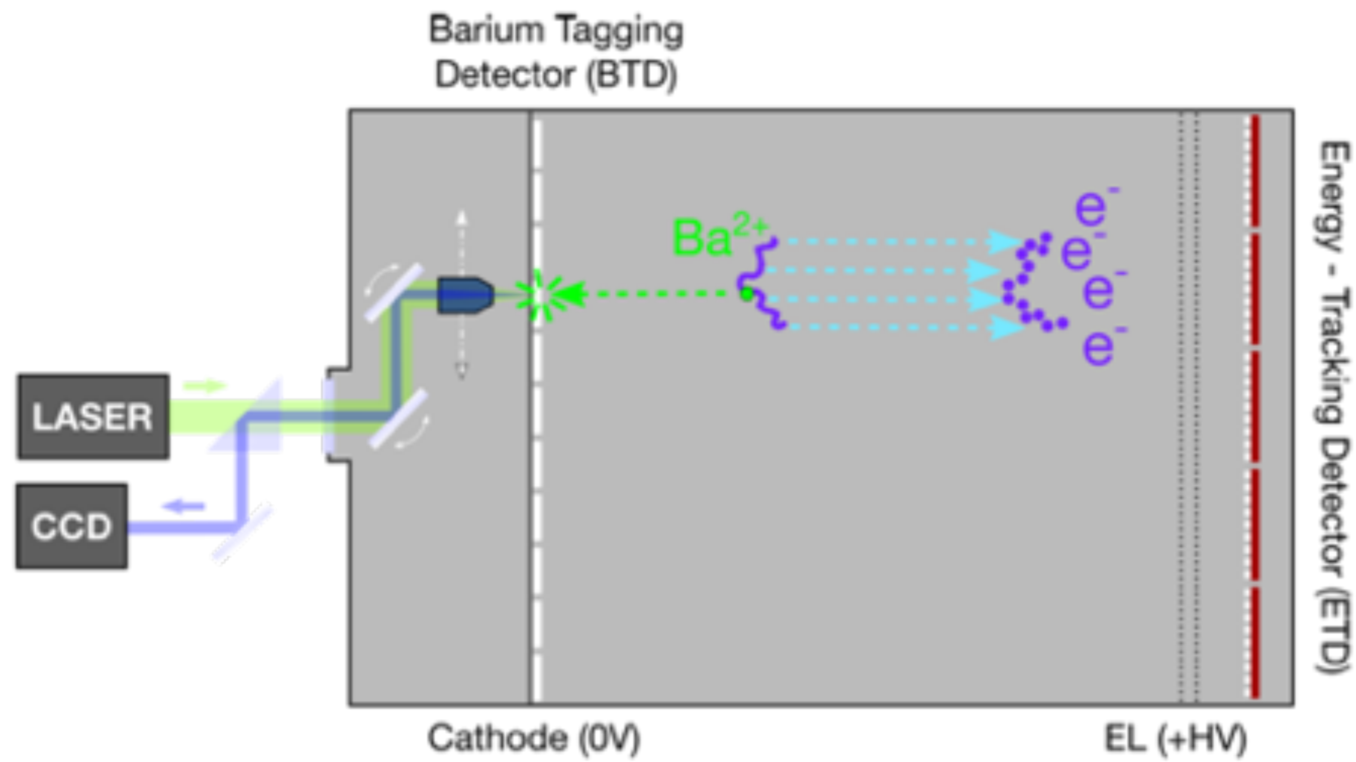

1 μm


CO2H
CO2H
N
O
O
Cl
HO
Cl
O
CH3
Ca2+
Cl
HO
O
Cl
O
N
Ca2+
CH3
Fluo 3
Fluo 3-Ca complex


Intensity / P.E.
Image plane / nm

Ba Tagging





D. Nygren , J.Phys.Conf.Ser. 650 (2015) no.1, 012002
JINST 11 (2016) no.12, P12011

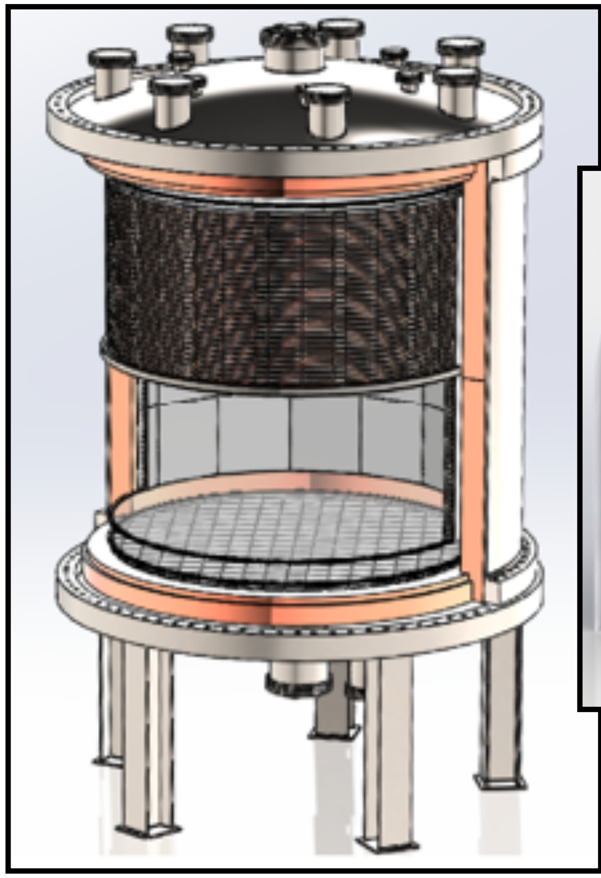
A.D. McDonald *et al.* (NEXT Collaboration)
Phys. Rev. Lett. 120, 132504 (2017)

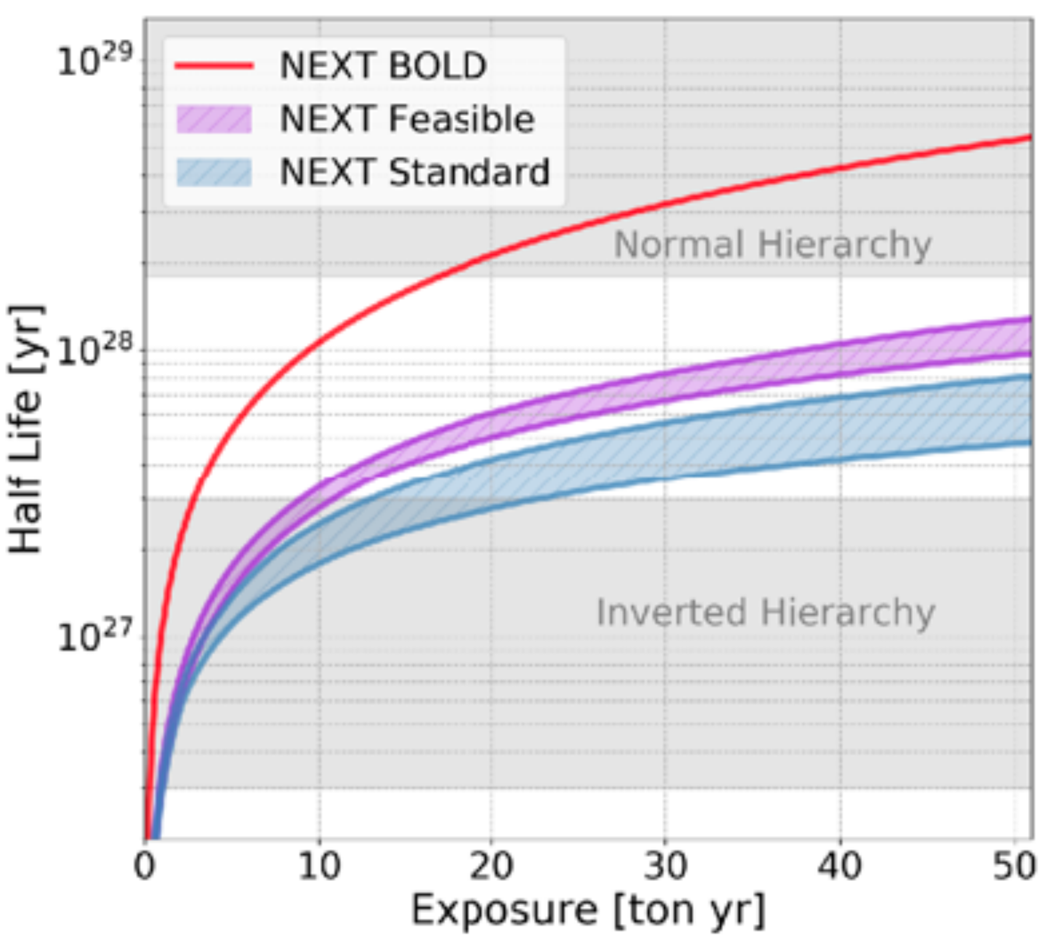
Sci Rep 9, 15097 (2019)

Nature 583, 48–54 (2020)

ACS Sens. 2021, 6, 1, 192–202 (2021)

NEXT-ton (~2025)





Two approaches developed in parallel:

- **NEXT-HD, High Definition: incremental approach, using/improving existing technology.**
- **NEXT-BOLD, Barium Tagging: based on disruptive new concept (SMFI Ba++ tagging).**

Phased approach

- **~1 ton of 136Xe introduced per phase.**
- **Ultra pure materials. SiPMs as the only sensor.**

NEXT-HD:

- **Improves topological signature, improves energy resolution**
- **Reduces radioactive budget (no PMTs)**
- **Energy plane made of large area SiPMs (design similar to that of DarkSide)**
- **Potential to reduce SiPM dark count by cooling detector**
- **Background: 0.39 cts [ton ROI yr]$^{-1}$ *(standard)***
  0.07 cts [ton ROI yr]$^{-1}$ *(feasible)*

NEXT-BOLD:

- **Tracking and energy measured in anode.**
- **Cathode implements Barium Tagging System**
- **Virtually background free**

NEXT Collaboration, *JHEP* 164 (2021) 56

Summary

- HPGTPCs have unique advantages for neutrinoless double-beta decay searches
- NEW demonstrated that topology selection and great energy resolution can be achieved
- NEXT-100, now under commissioning, will demonstrate scalability and will have sensitivity similar to current generation of experiments
- The ton-scale is really where we want to go and NEXT proposes a staged approach with unique potential to reach near the normal mass ordering phase space

Summary

- HPGTPCs have unique advantages for neutrinoless double-beta decay sea

- NEW demo d great energy resolution
- NEXT-100, nonstrate scalability rent generation of experimen
- The ton-sc d NEXT proposes a staged approach with unique potential to reach near the normal mass ordering phase space