Charting Majorana Galaxy with(out) neutrinos

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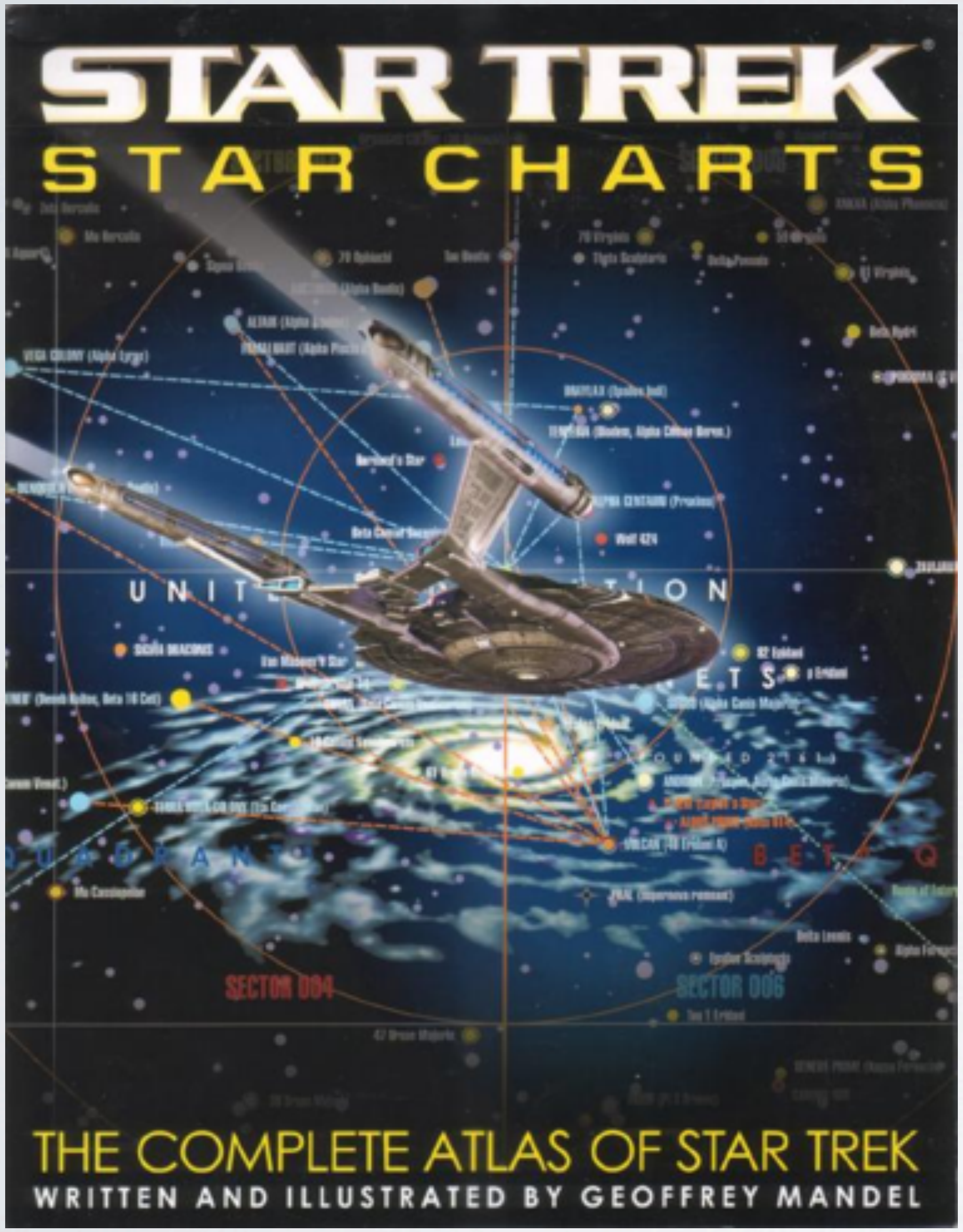
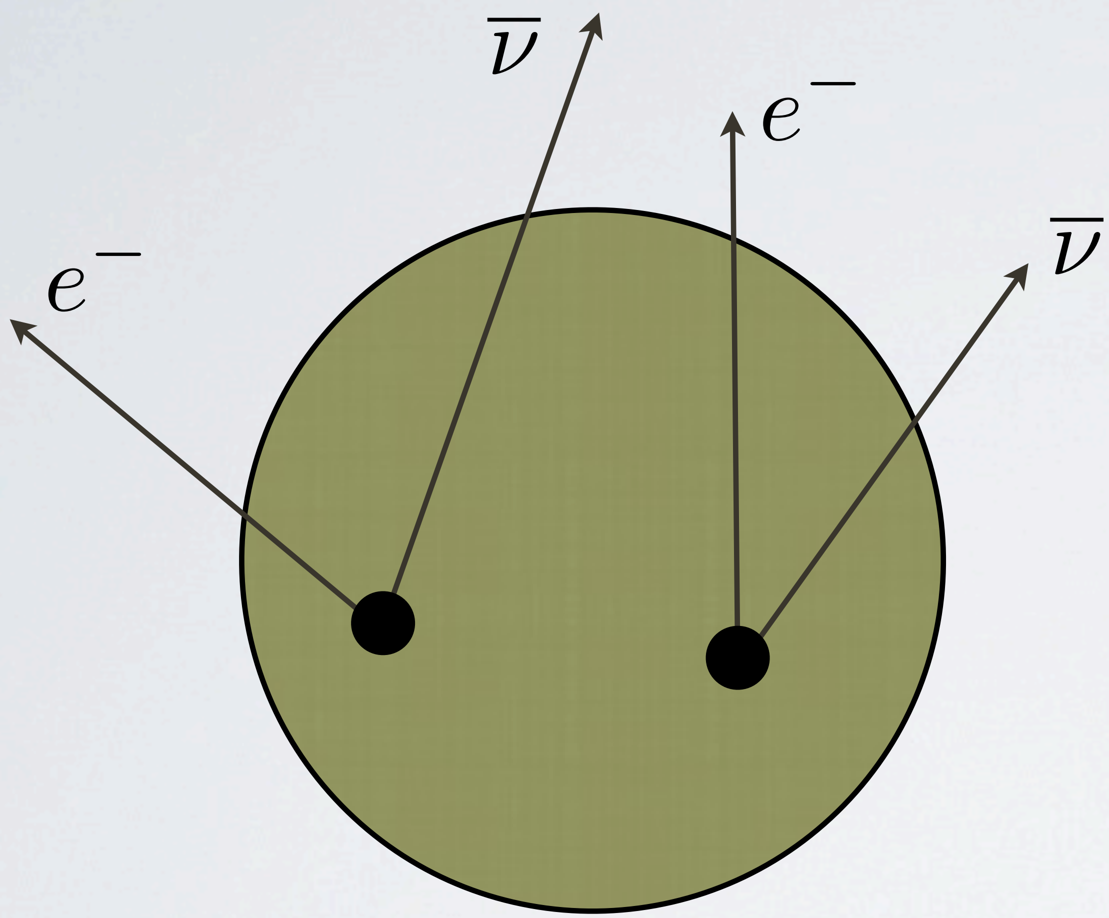
Trieste, October, 2013

To boldly go...



- This is not a review talk. I am not attempting to provide an exhaustive view of the state-of-the-art
- No exclusion plots to be shown!. I rather show you “discoveries”...
- My main goal is to assess how much Majorana territory we can cover with bb0nu experiments. In short, what it takes to boldly go...

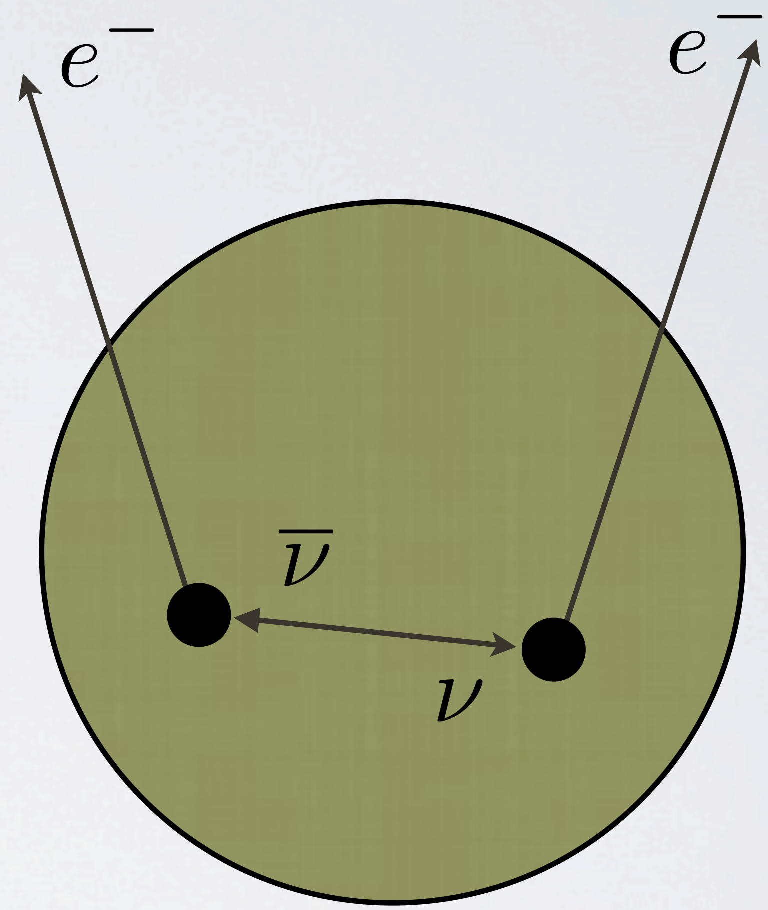
Double beta decay



$\beta\beta 2\nu$

SM-allowed process.
Measured in several nuclei.

$$T_{1/2} \sim 10^{18} - 10^{20} \text{ y}$$



$\beta\beta 0\nu$

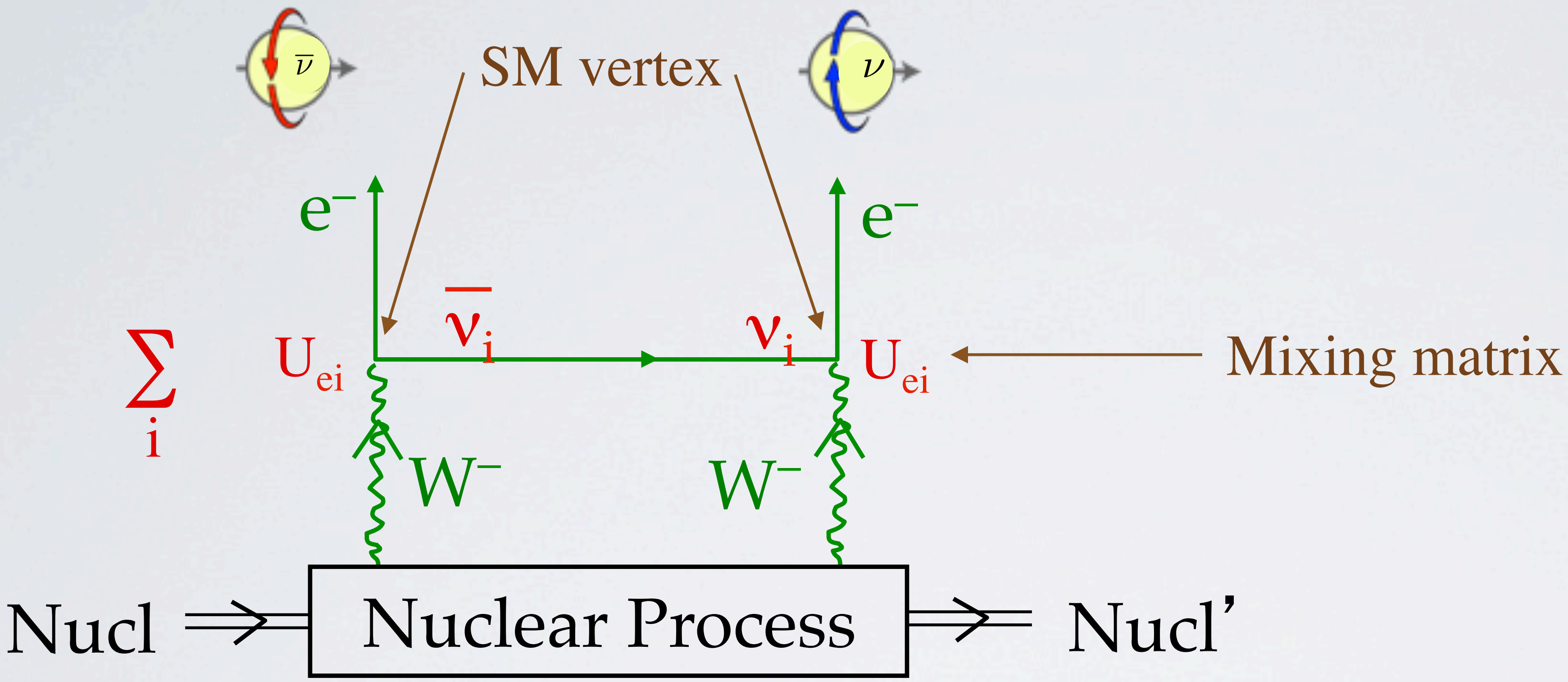
Lepton number violating process.
Requires massive, Majorana neutrinos. Simplest case

$$T_{1/2} > 10^{25} \text{ y}$$

Majorana mass

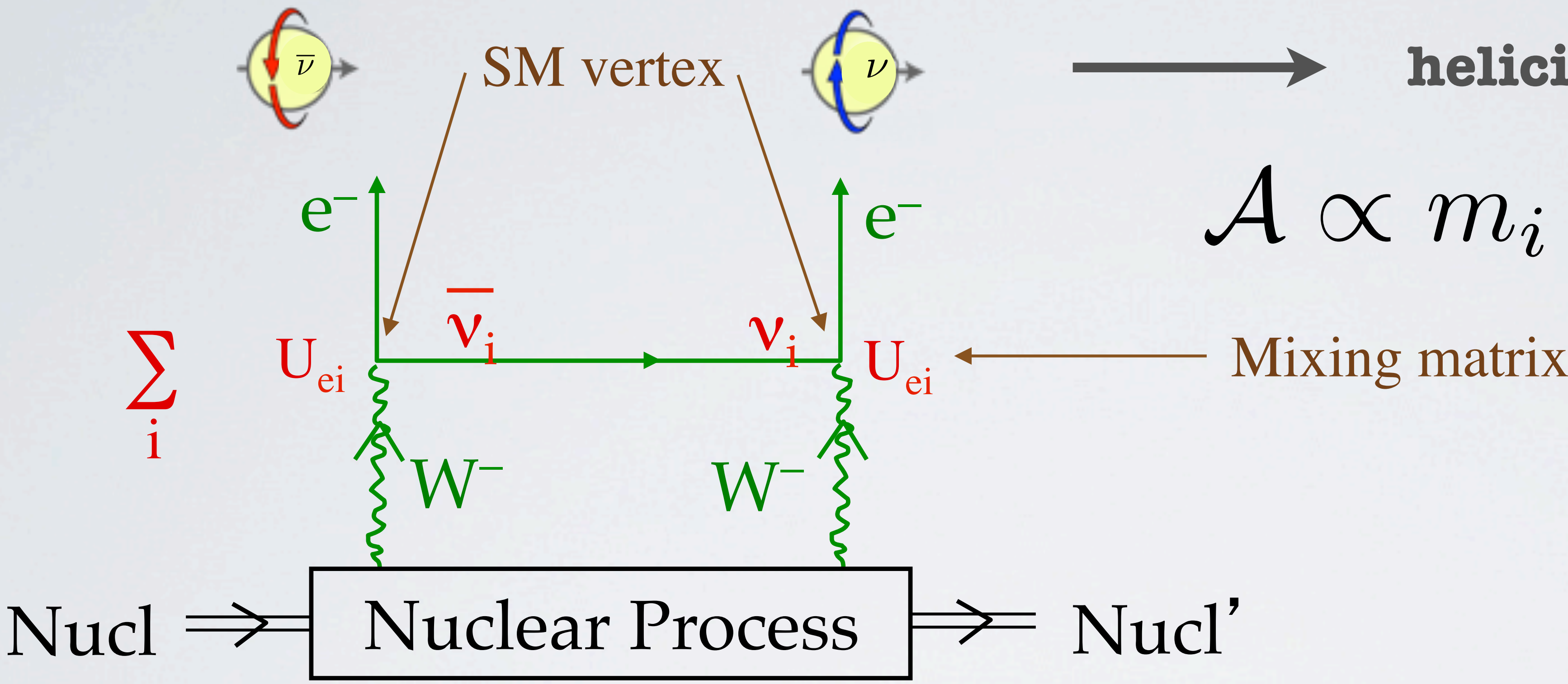
$$m_{\beta\beta} = ||U_{e1}|^2 m_1 + e^{i\alpha_1}|U_{e2}|^2 m_2 + e^{i\alpha_2}|U_{e3}|^2 m_3|$$

Majorana mass



$$m_{\beta\beta} = \left| |U_{e1}|^2 m_1 + e^{i\alpha_1} |U_{e2}|^2 m_2 + e^{i\alpha_2} |U_{e3}|^2 m_3 \right|$$

Majorana mass



helicity flip $\propto \frac{m_i}{E}$

$\mathcal{A} \propto m_i$ **for each** ν_i

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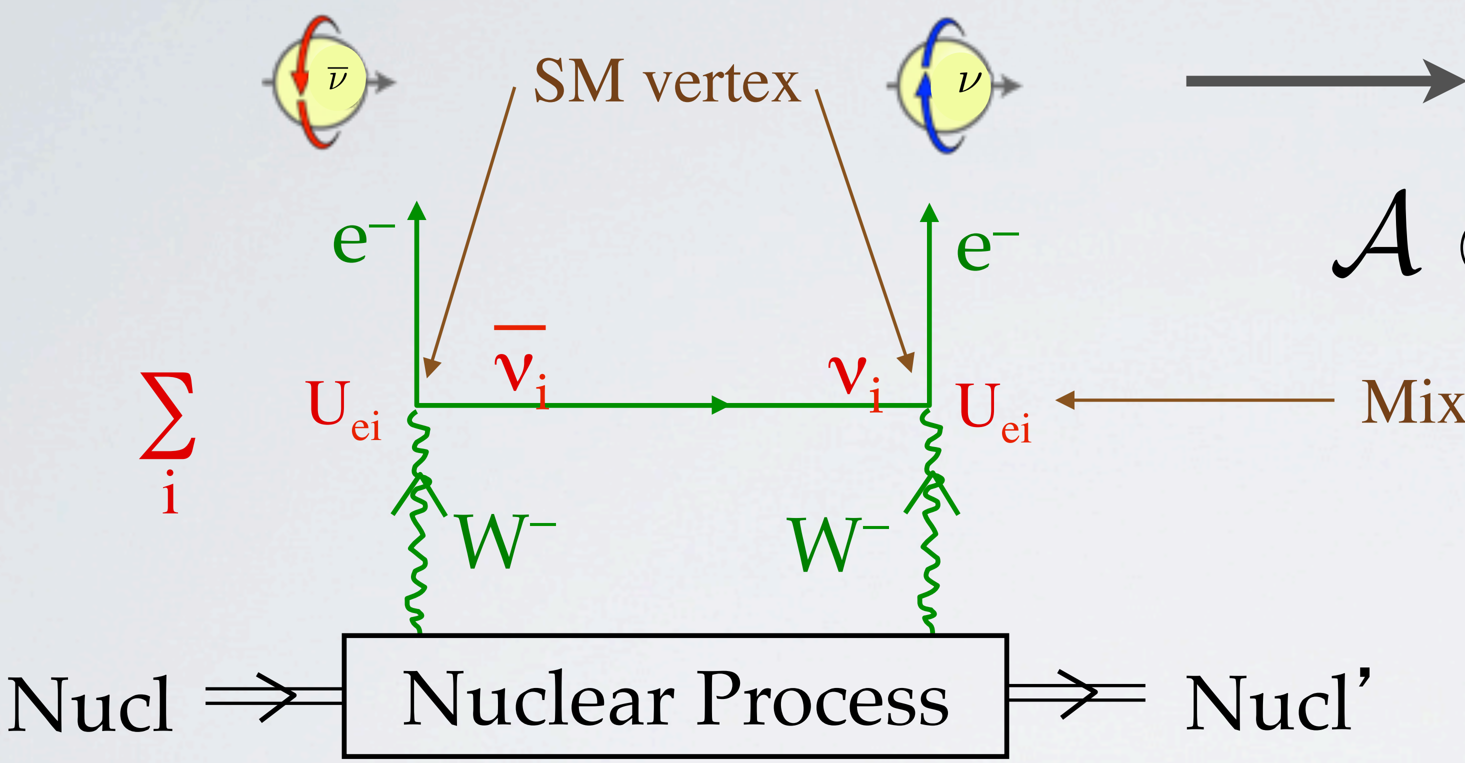
Majorana mass



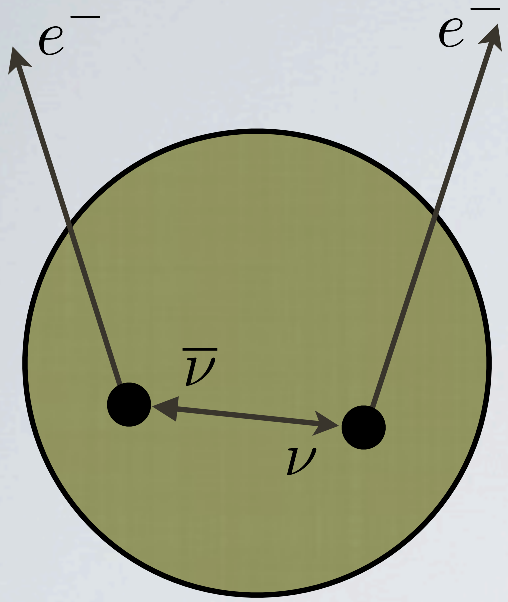
→ **helicity flip** $\propto \frac{m_i}{E}$

$\mathcal{A} \propto m_i$ **for each** ν_i

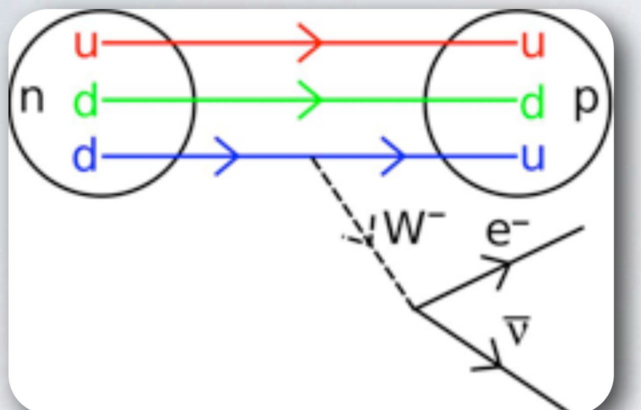
$$m_{\beta\beta} = \left| |U_{e1}|^2 m_1 + e^{i\alpha_1} |U_{e2}|^2 m_2 + e^{i\alpha_2} |U_{e3}|^2 m_3 \right|$$

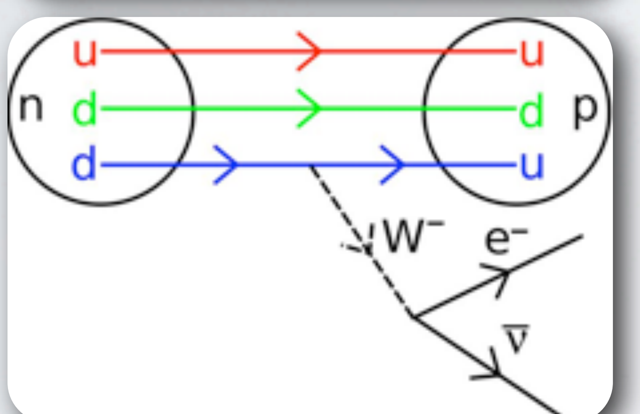
The Uei terms are measured by neutrino oscillation experiments. Nothing is known about the two Majorana phases.

Nuclear physics



$\beta\beta0\nu$



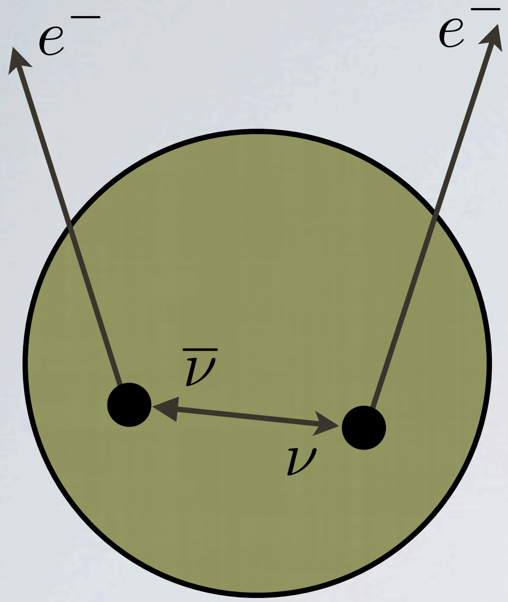


$$(T^{0\nu}_{1/2})^{-1} = \boxed{G^{0\nu}(Q,Z)}\,\boxed{|M^{0\nu}|^2}\,m^2_{\beta\beta}$$

phase-space

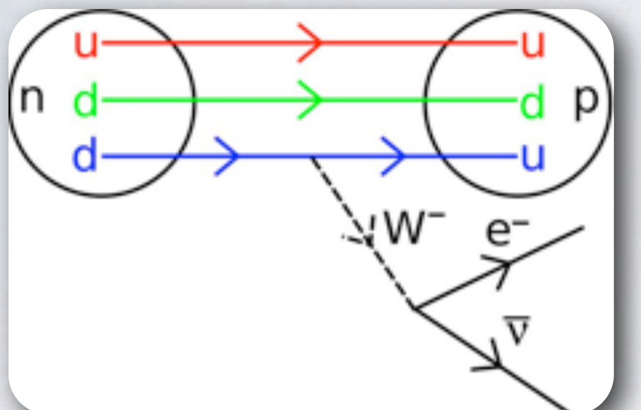
nuclear matrix

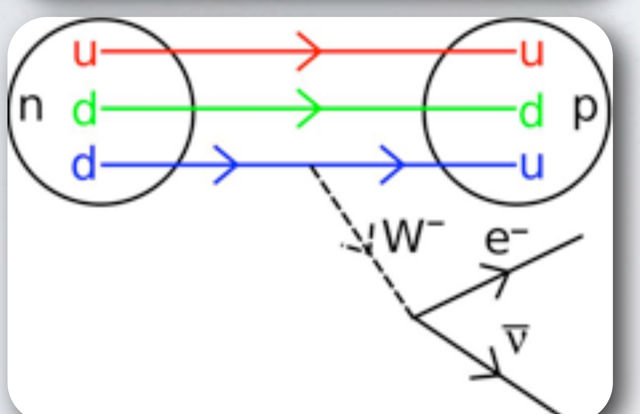
Majorana neutrino



$\beta\beta 0\nu$

Nuclear physics





$$(T^{0\nu}_{1/2})^{-1} = \boxed{G^{0\nu}(Q,Z)}\,\boxed{|M^{0\nu}|^2}\,m^2_{\beta\beta}$$

phase-space

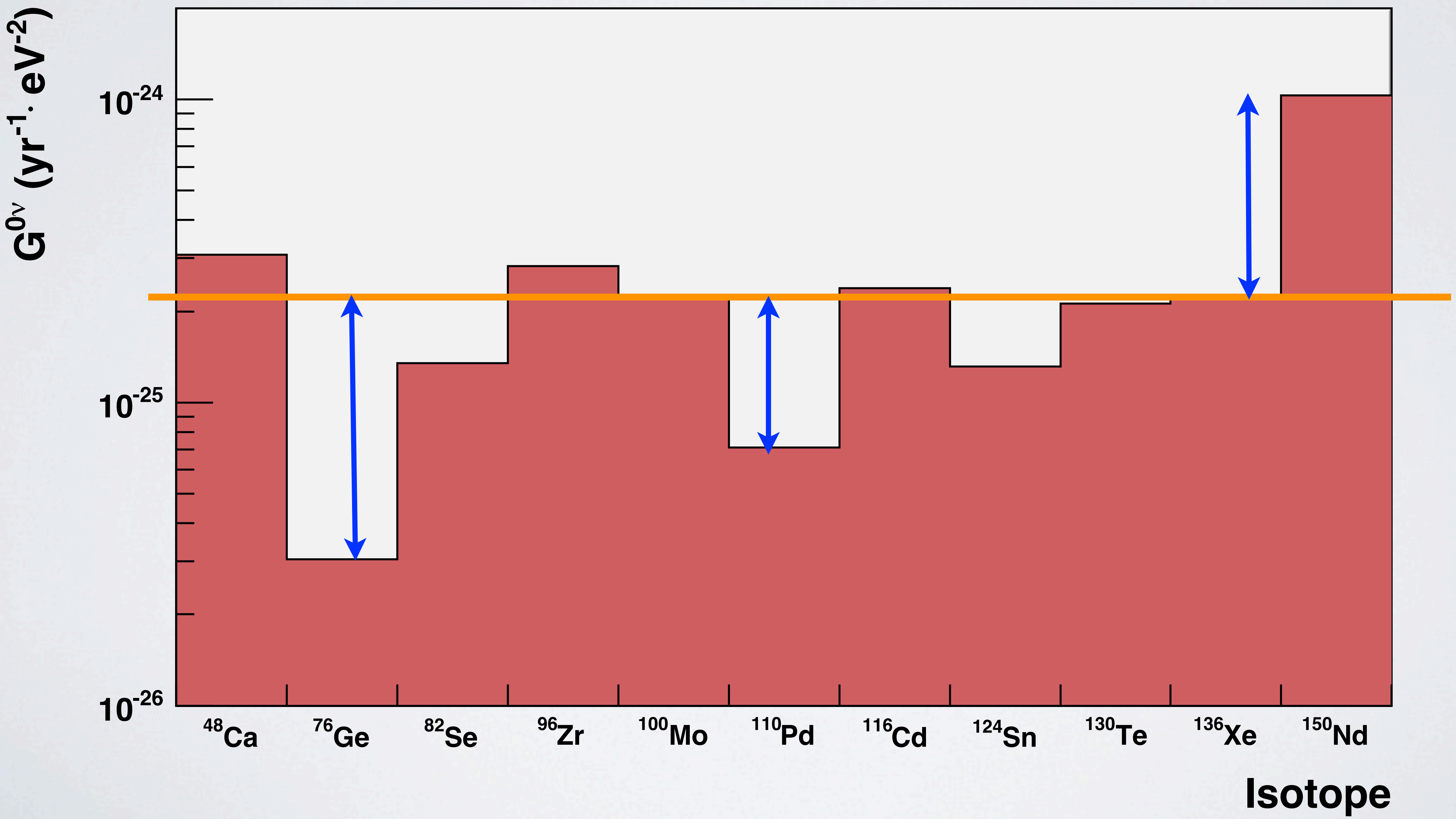
nuclear matrix

Majorana neutrino

Two protons decay simultaneously in a heavy isotope
Nuclear physics results in proportionality constants between period and the inverse of the Majorana mass squared

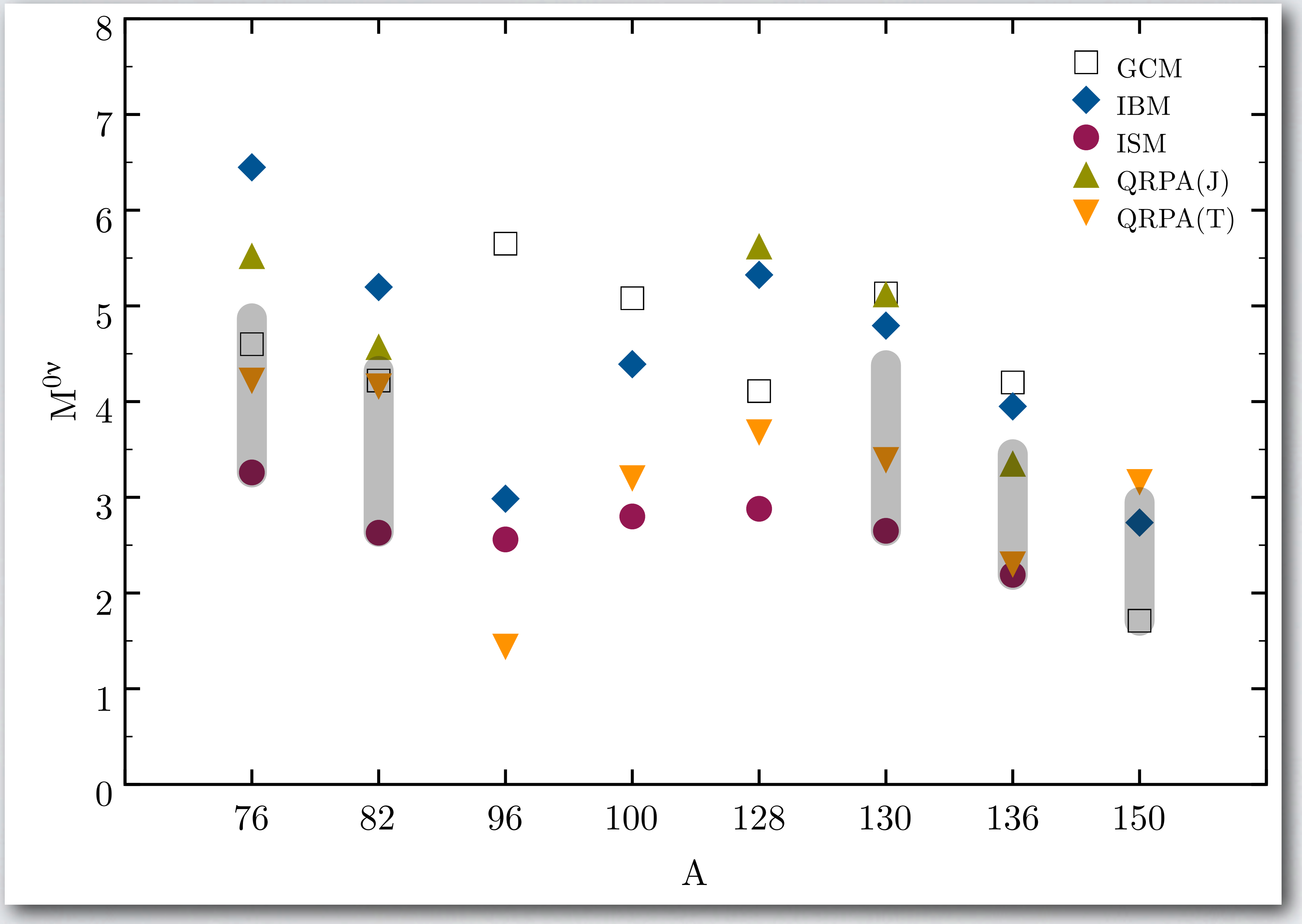
The NME

$$(T^{0\nu}_{1/2})^{-1} = \boxed{G^{0\nu}(Q,Z)}\,\boxed{|M^{0\nu}|^2}\,m^2_{\beta\beta}$$



The NME

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\ |M^{0\nu}|^2\ m^2_{\beta\beta}$$



T^0 to mbb

Isotope	W (g/mol)	$Q_{\beta\beta}$ (keV)	$\|M_{0\nu}\|$	$\|G_{0\nu}\|^{-1}$ (10^{25} y eV^2)	$T^{0\nu}_{1/2}(m_{\beta\beta} = 50$ meV) (10^{27} y)	$N_{0\nu}/N_{0\nu}$(Ge)
^{76}Ge	75.9	2039	4.07	4.09	0.95	1.0
^{82}Se	81.9	2996	3.48	0.93	0.26	3.3
^{130}Te	129.9	2528	3.63	0.59	0.18	3.1
^{136}Xe	135.9	2458	2.82	0.55	0.25	2.1
^{150}Nd	149.9	3368	2.33	0.13	0.15	3.3

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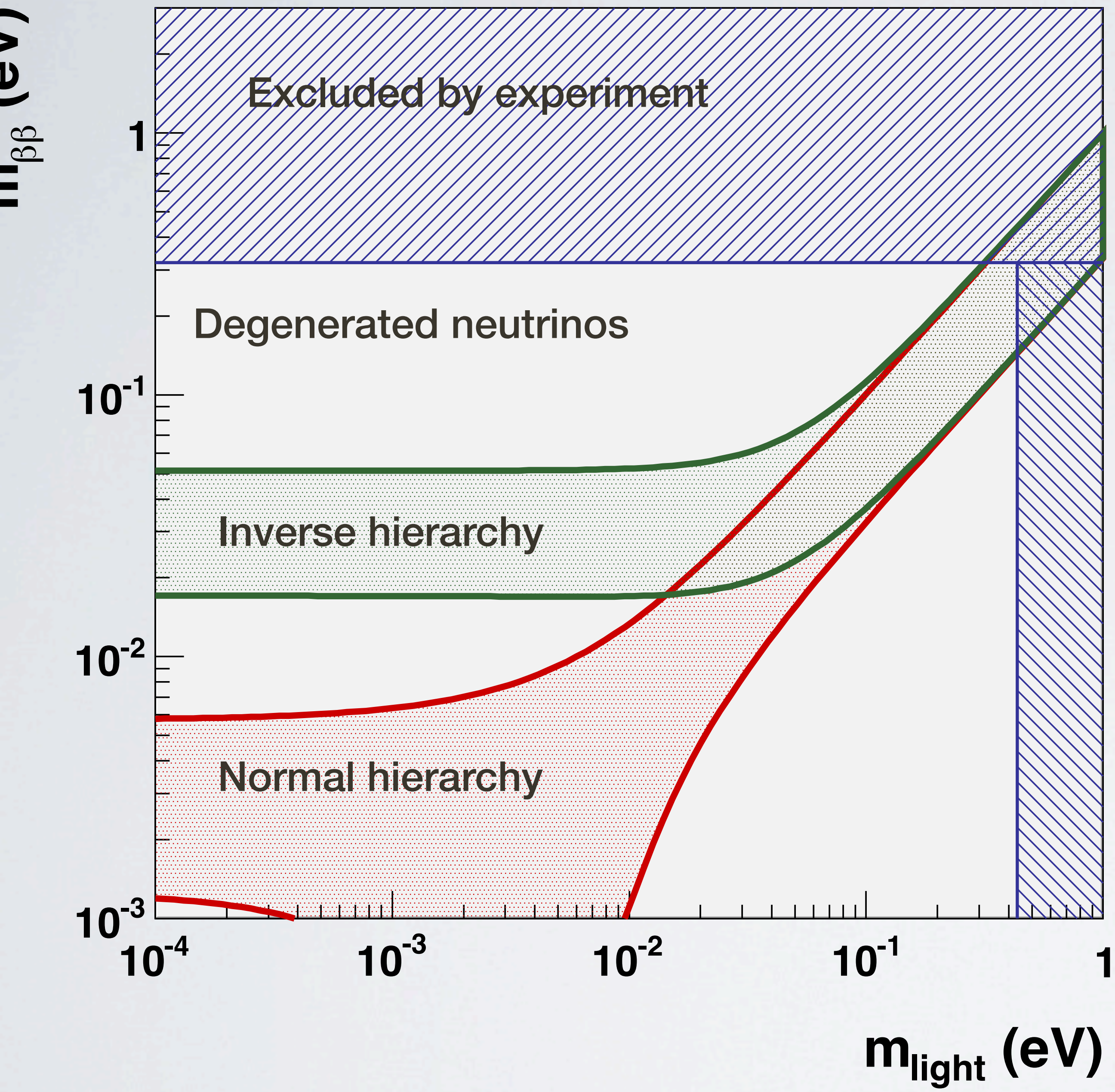
For most of this talk: I take the PMR set (a sort of average between different NME sets). More on that later.

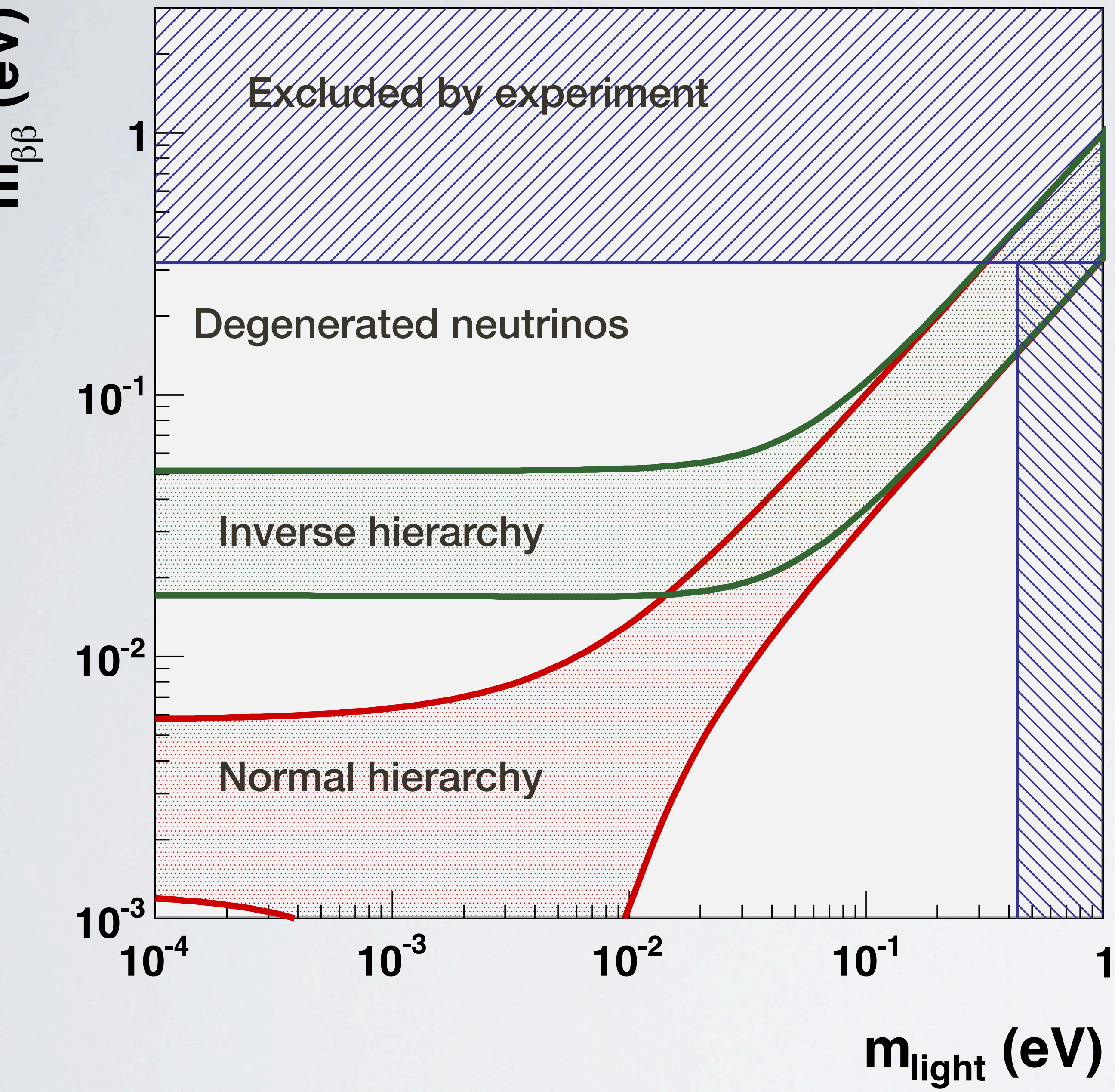
The Majorana landscape

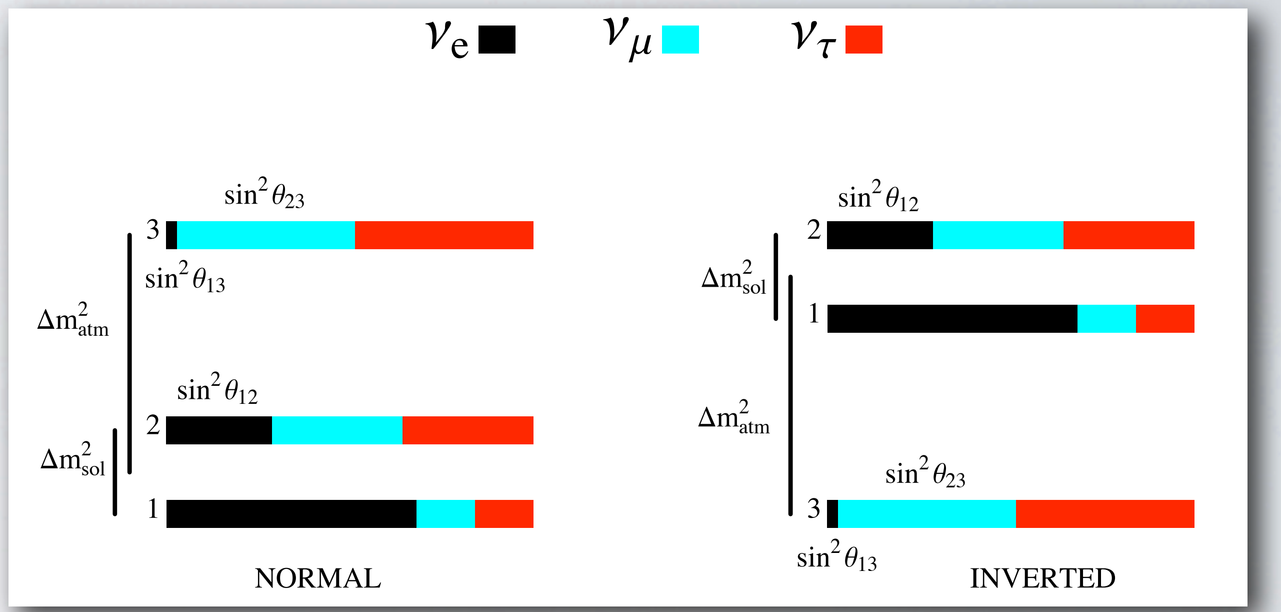


- A sensitivity to mbb~20 meV would result in a discovery if neutrinos are Majorana particles and the hierarchy is inverse.

- If the hierarchy is normal and mbb < 20 meV, cancelations may prevent a discovery even if neutrinos are Majorana particles

The Majorana landscape

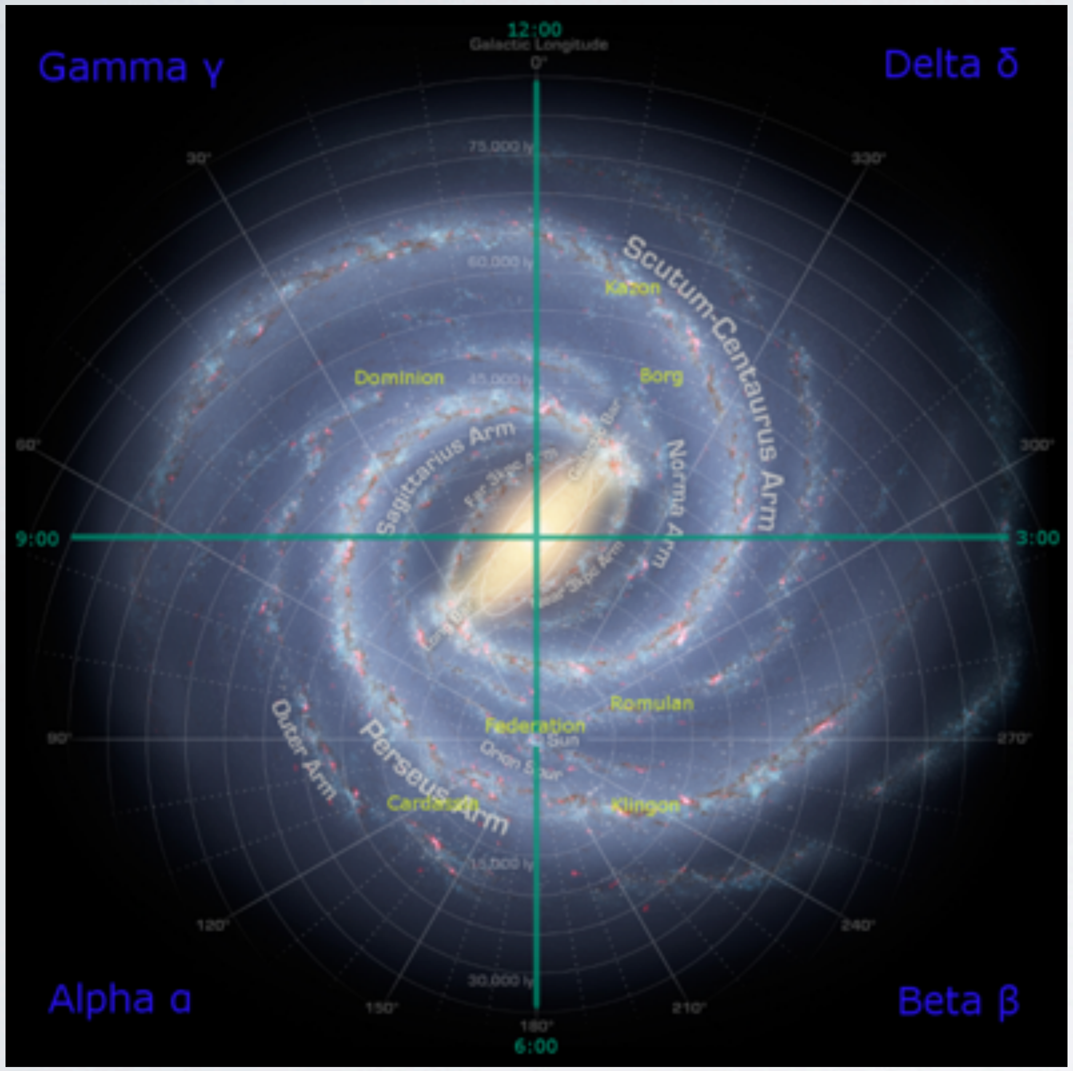


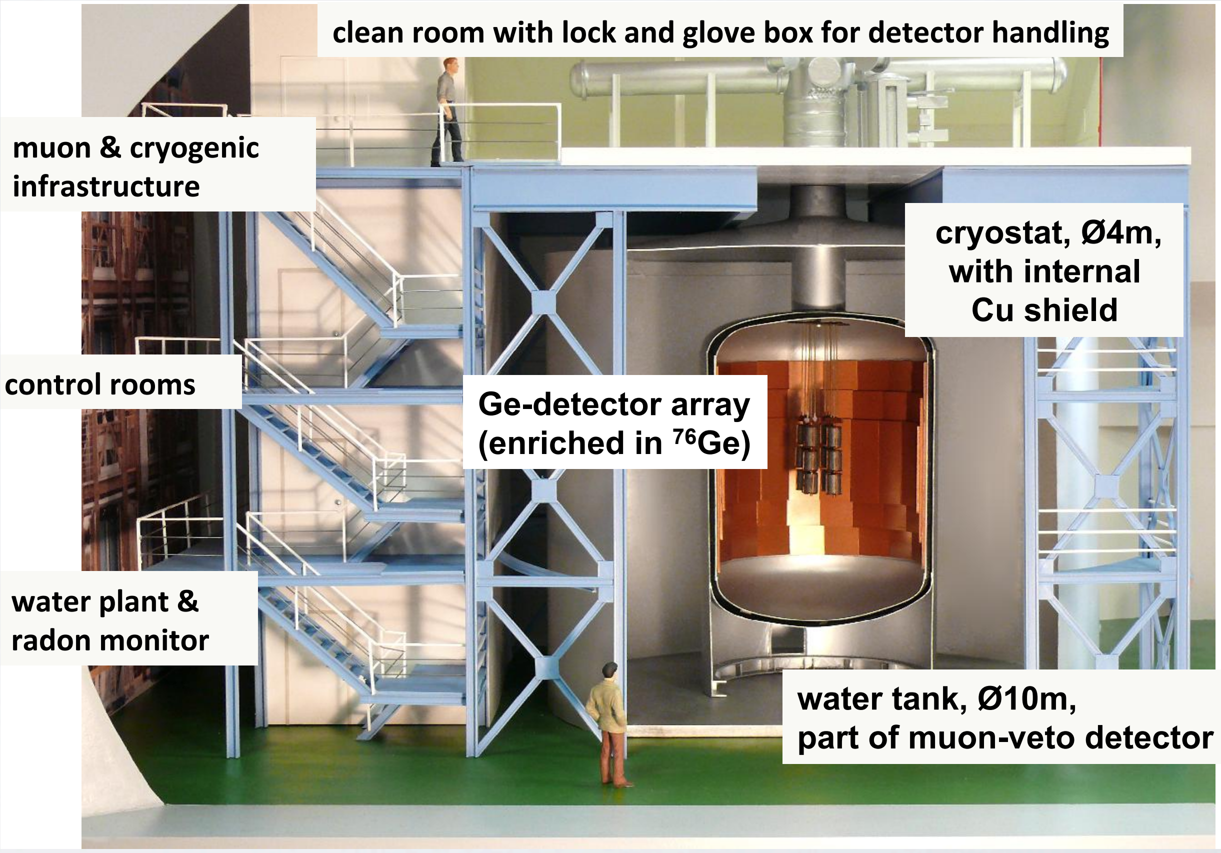


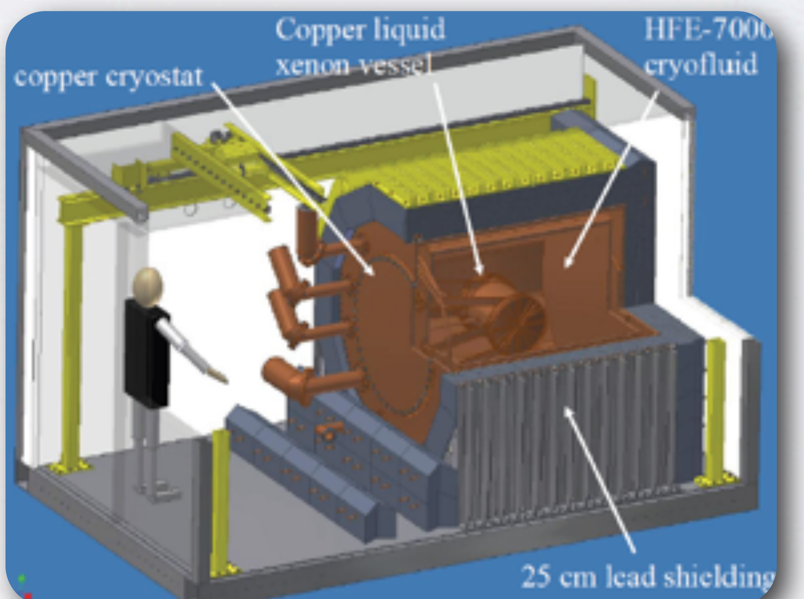
- A sensitivity to mbb~20 meV would result in a discovery if neutrinos are Majorana particles and the hierarchy is inverse.

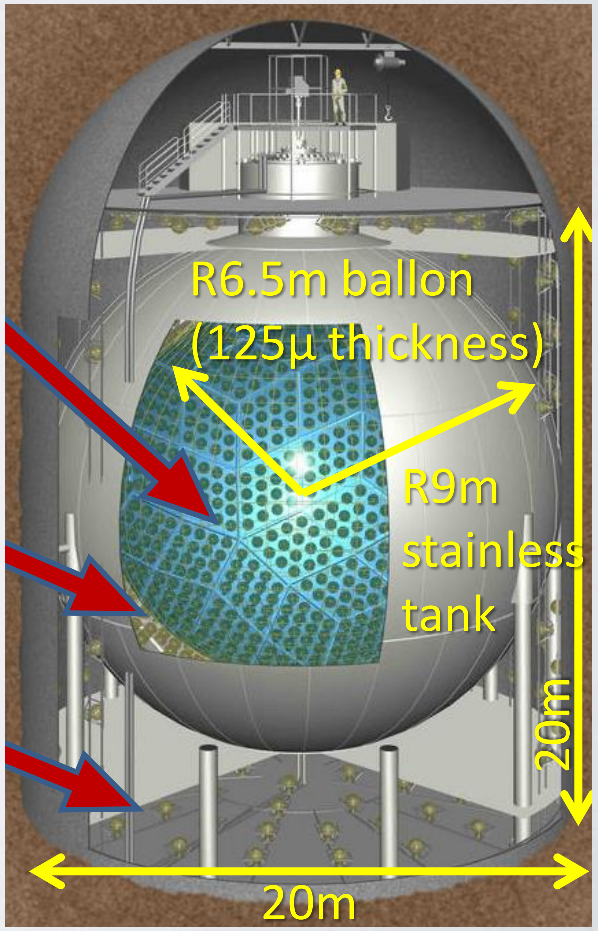
- If the hierarchy is normal and mbb < 20 meV, cancelations may prevent a discovery even if neutrinos are Majorana particles

Charted ground

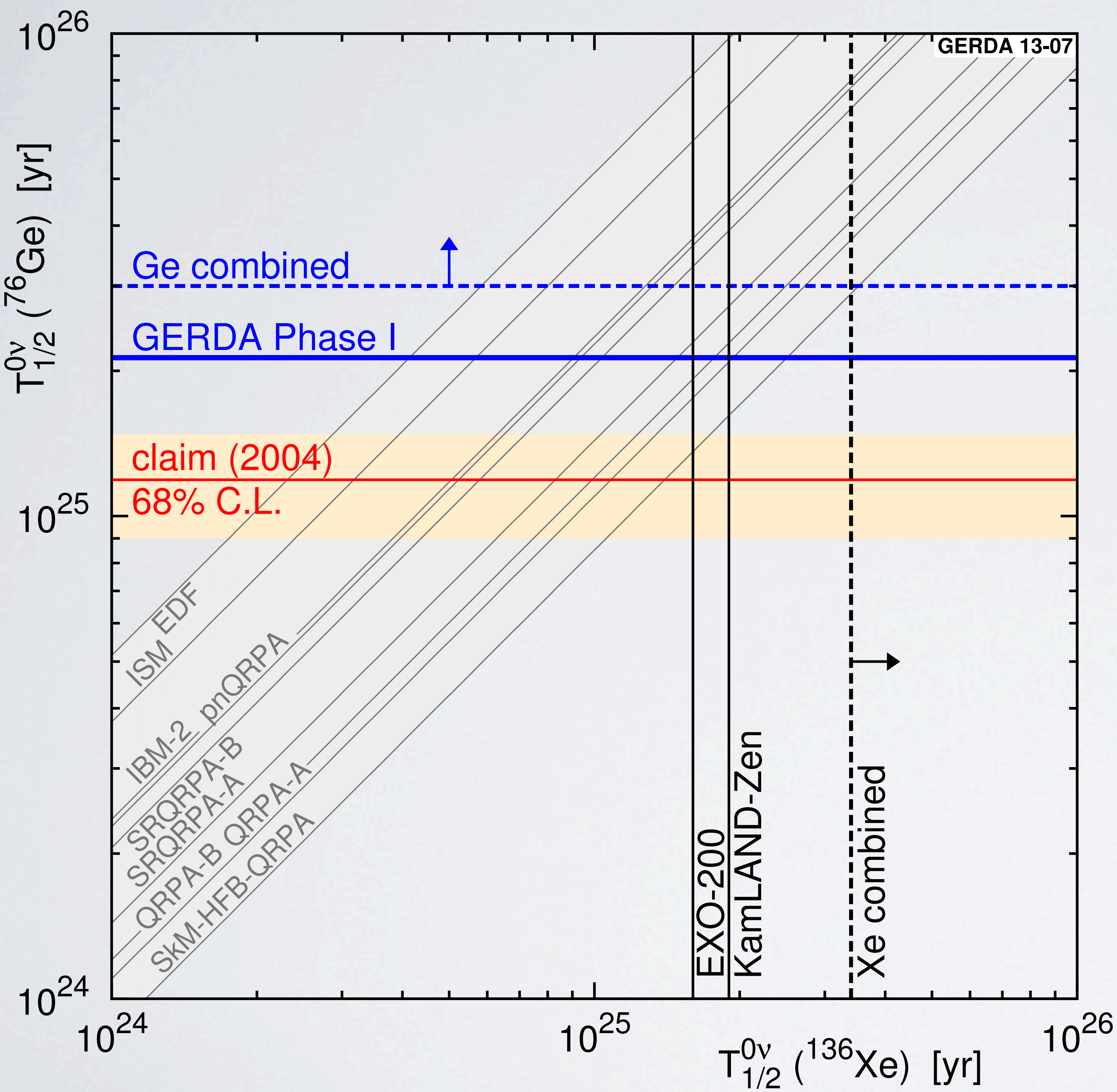






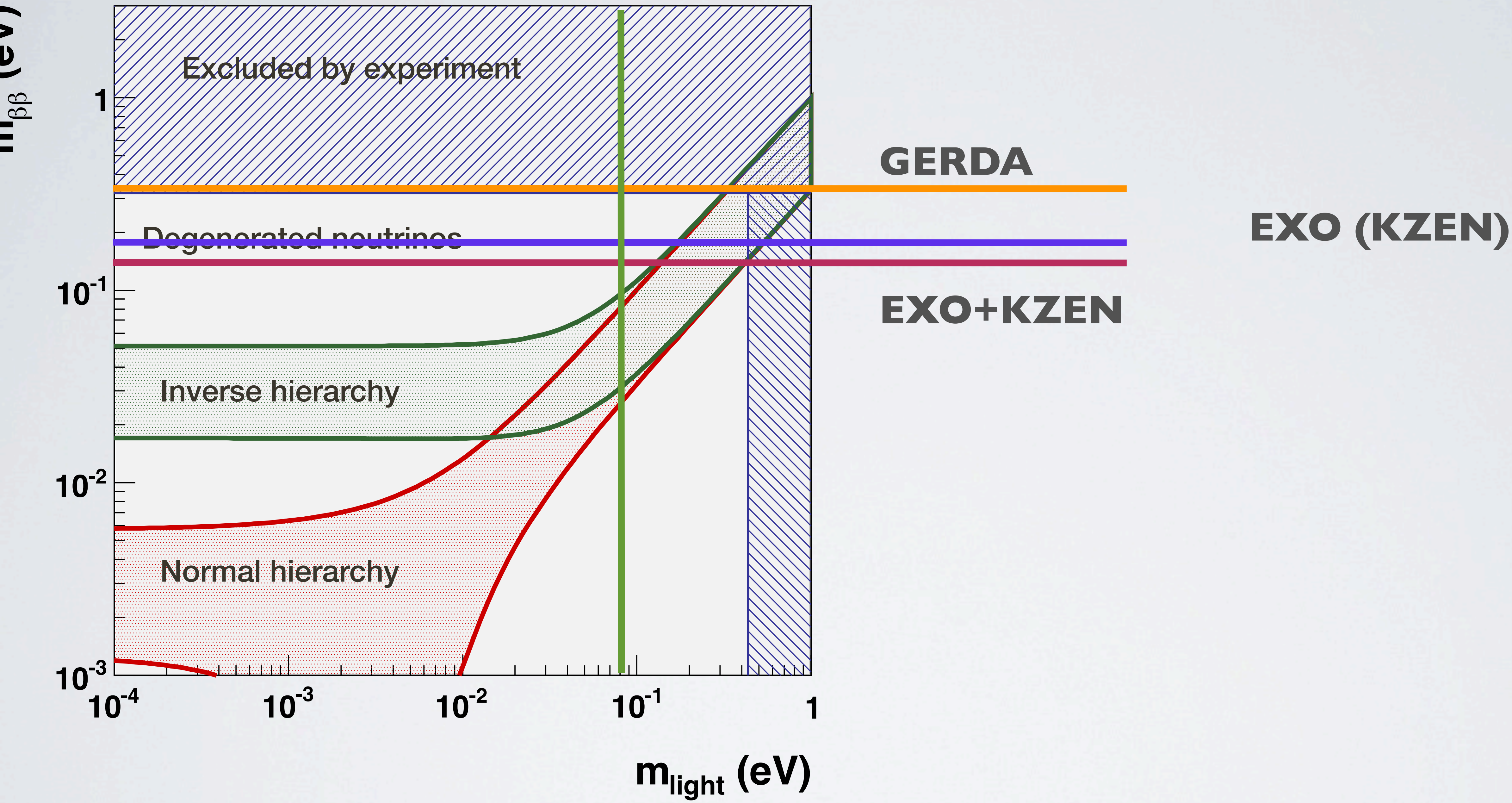


Combined result



- Sensitivity of each experiment T^0 ~2 x 10^{25} y.
- Deployed mass ~20 kg y for Gerda and ~90 kg y (KamLAND-Zen).
- Combined result essentially excludes previous claims of a discovery.

COSMOLOGY (?!)



Excluded by experiment
Degenerated neutrinos
Inverse hierarchy
Normal hierarchy
GERDA
EXO (KZEN)
EXO+KZEN
$m_{\beta\beta}$ (eV)
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
m_{light} (eV)

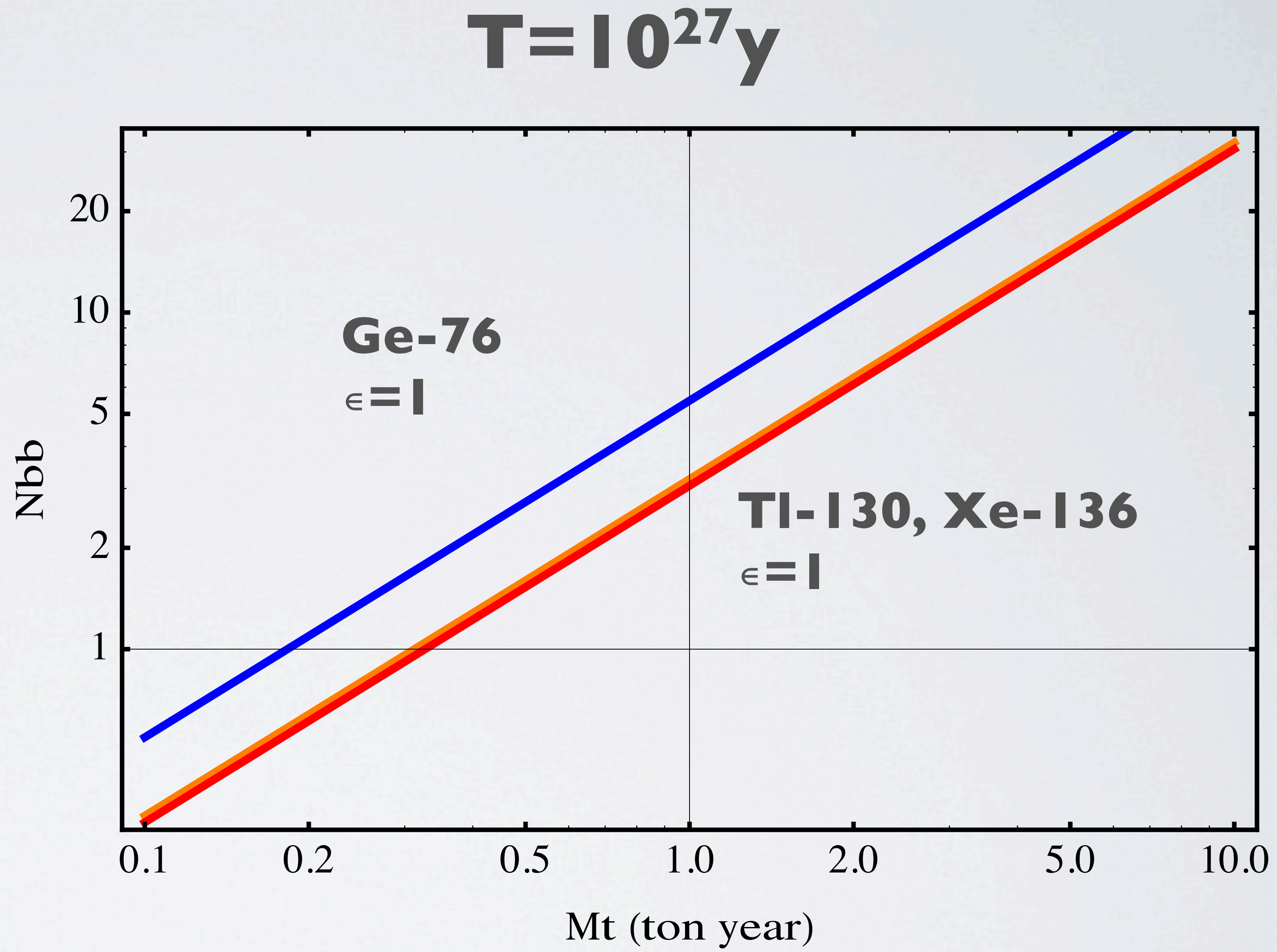
Going into new space

- How much can Gerda, EXO and KZEN improve their sensitivity without major improvements in their setups?
- Who else can join the game in the next few years?
- What would be the sensitivity of the newcomers?

Signal

$$N_{\beta\beta} = \varepsilon \log 2 \frac{N_A M t}{A T^0}$$

- Signal: For a given isotope (A) signal is proportional to detection efficiency and exposure and inversely proportional to period.

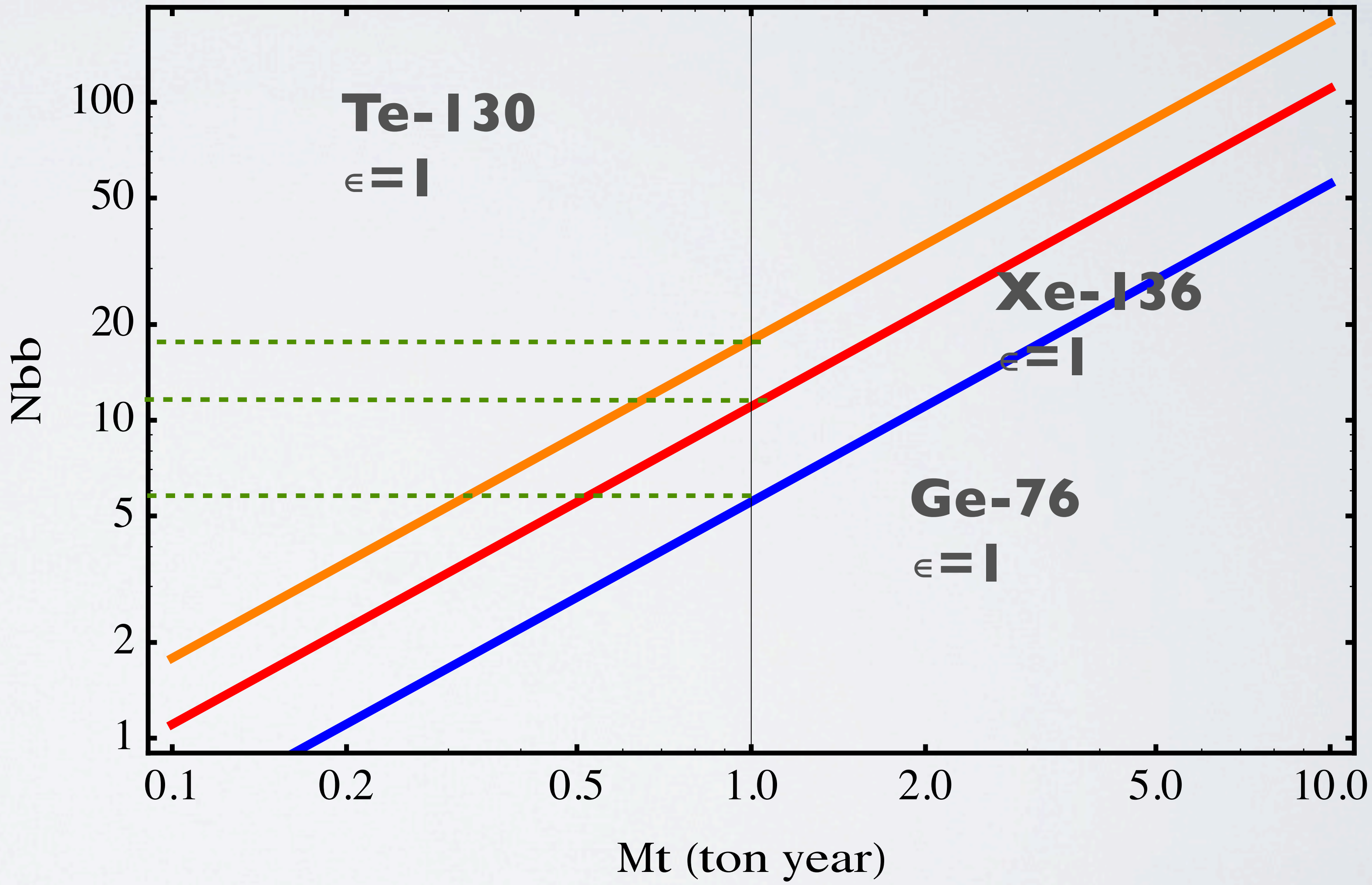


Signal

$$N_{\beta\beta} = \varepsilon \log 2 \frac{N_A M t}{A} \eta \cdot m_{\beta\beta}^2$$

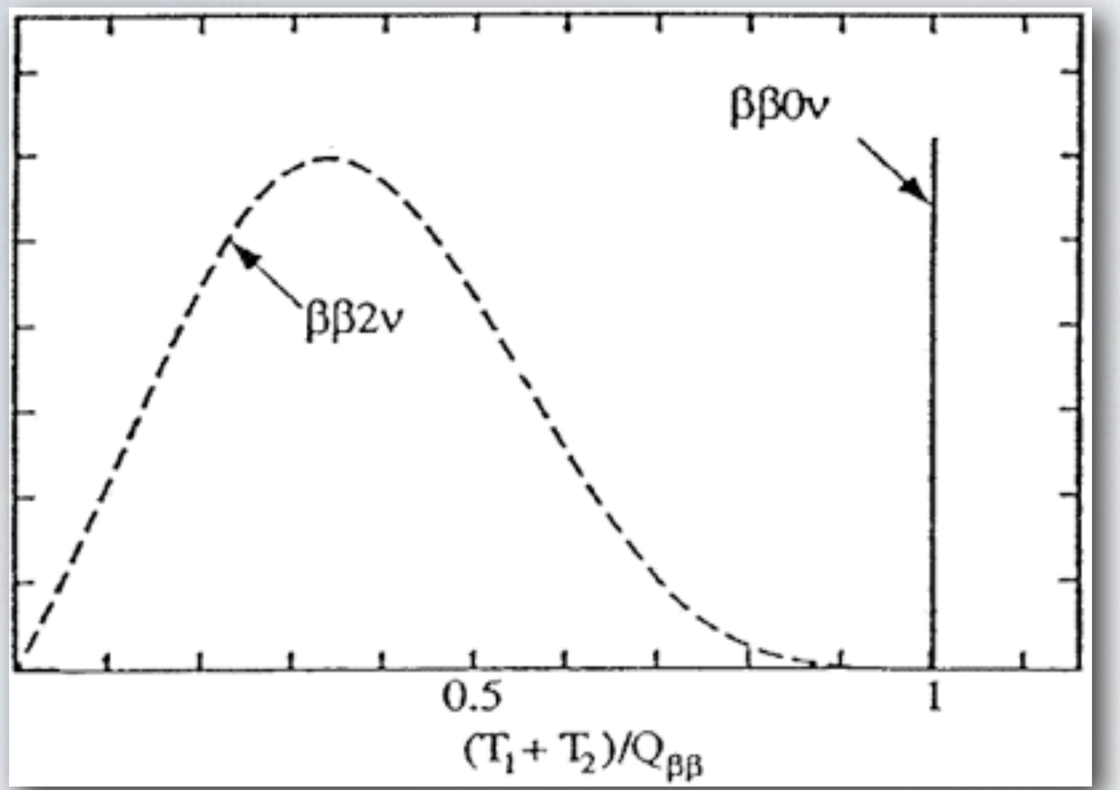
$$\eta = G^{0\nu} \left| M^{0\nu} \right|^2$$

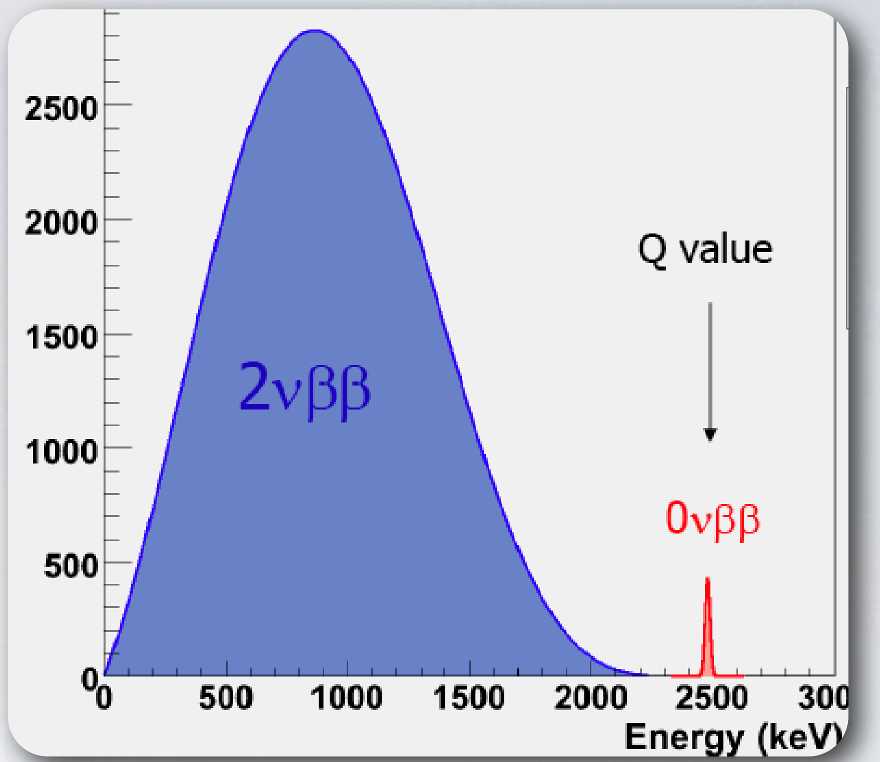
$m_{\beta\beta}$=50 meV



- Signal: For a given isotope (A, η) signal is proportional to detection efficiency and exposure and proportional to $m_{\beta\beta}^2$ (this is what makes bb0nu experiments to difficult)

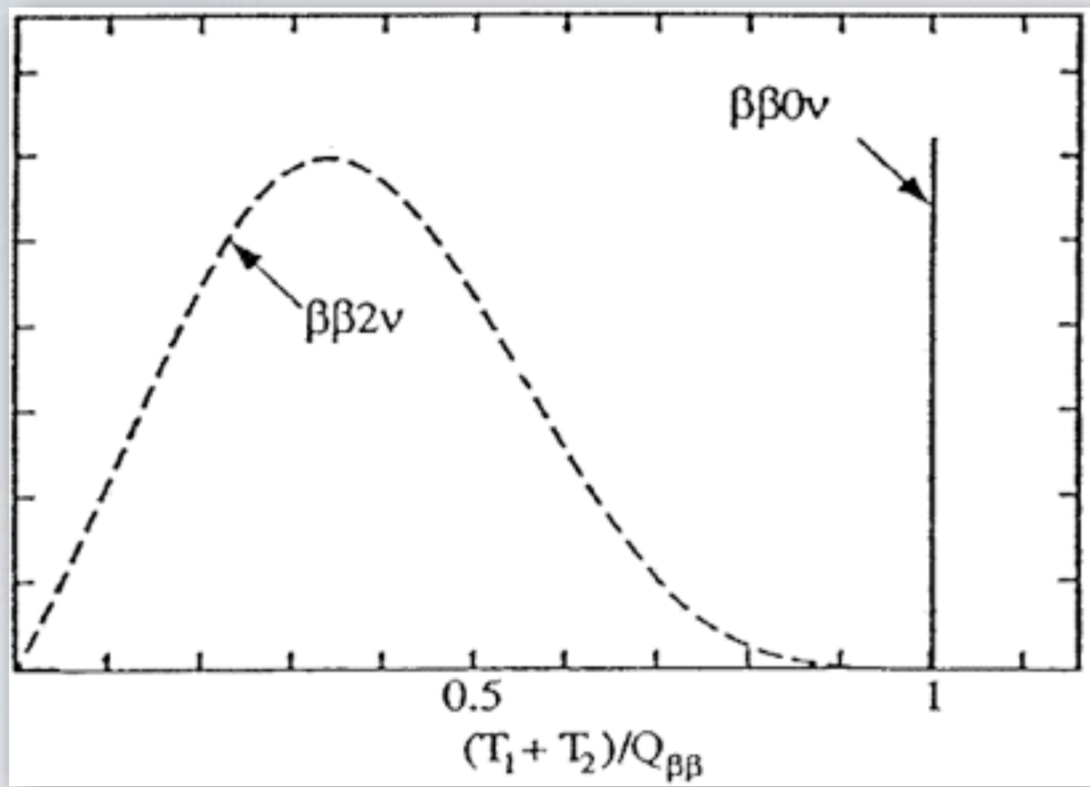
Energy resolution and specific background rate

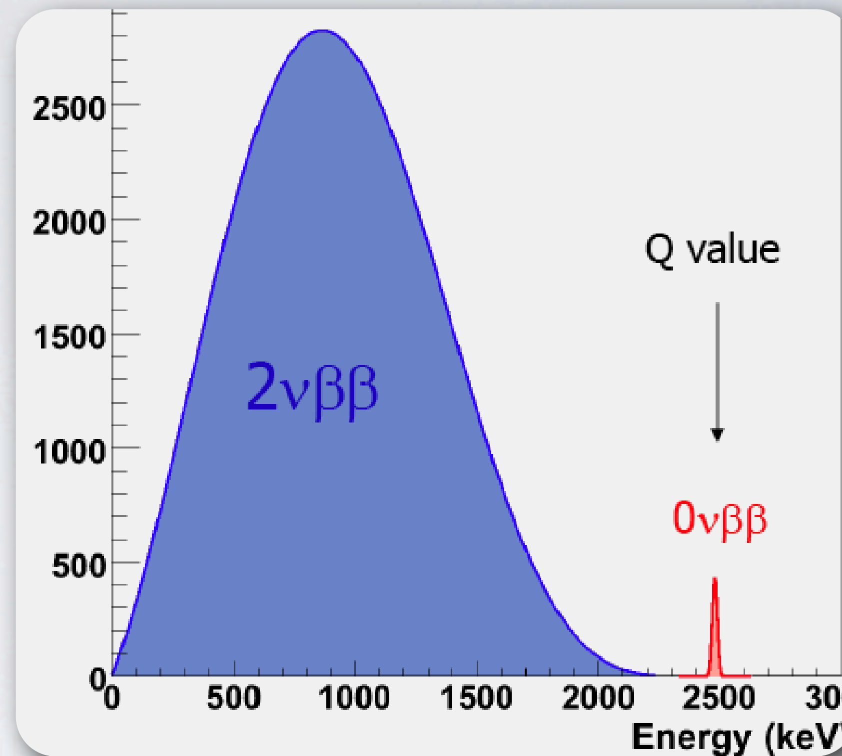


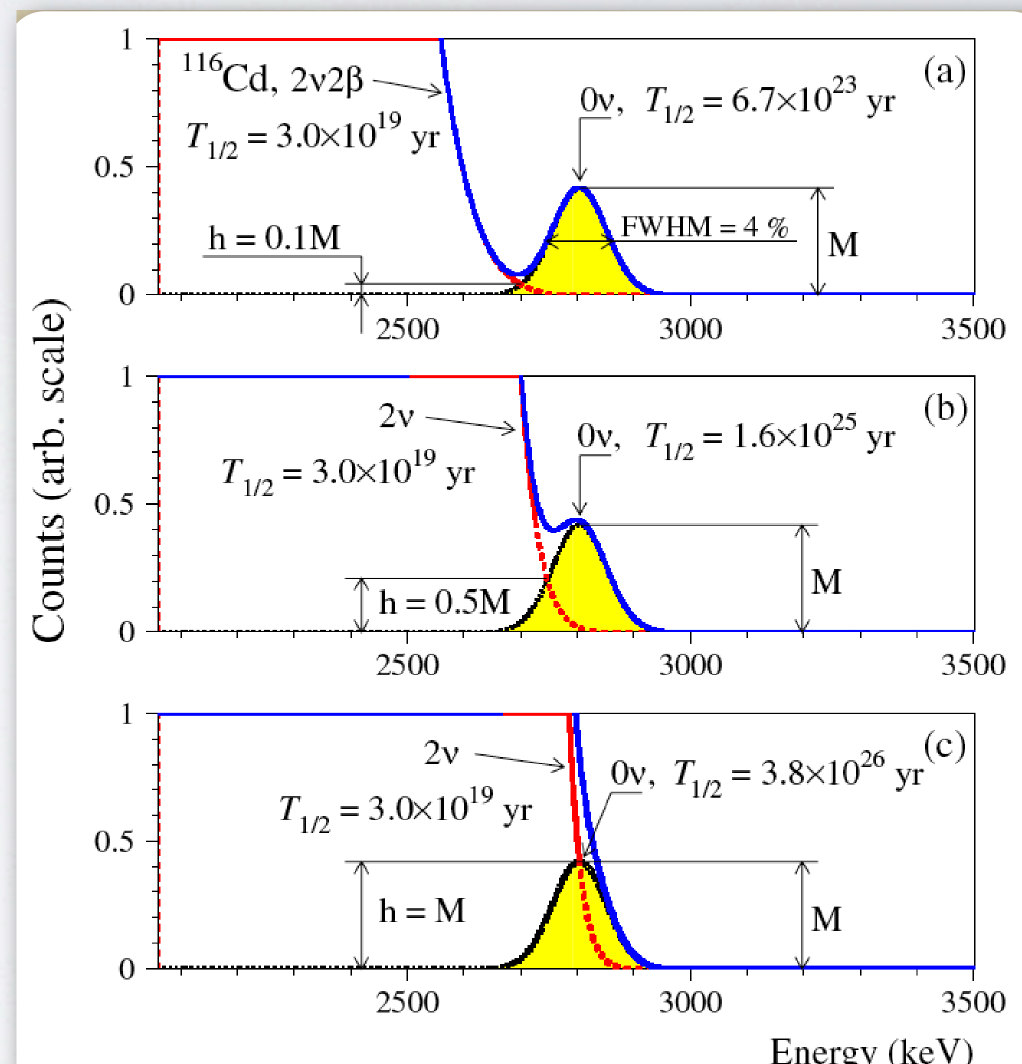


- Signal: Integrate ROI
- Background: cxΔExMt
- where c = counts/(kev kg y), ΔE = energy resolution (in keV) and Mt is exposure

Energy resolution and specific background rate







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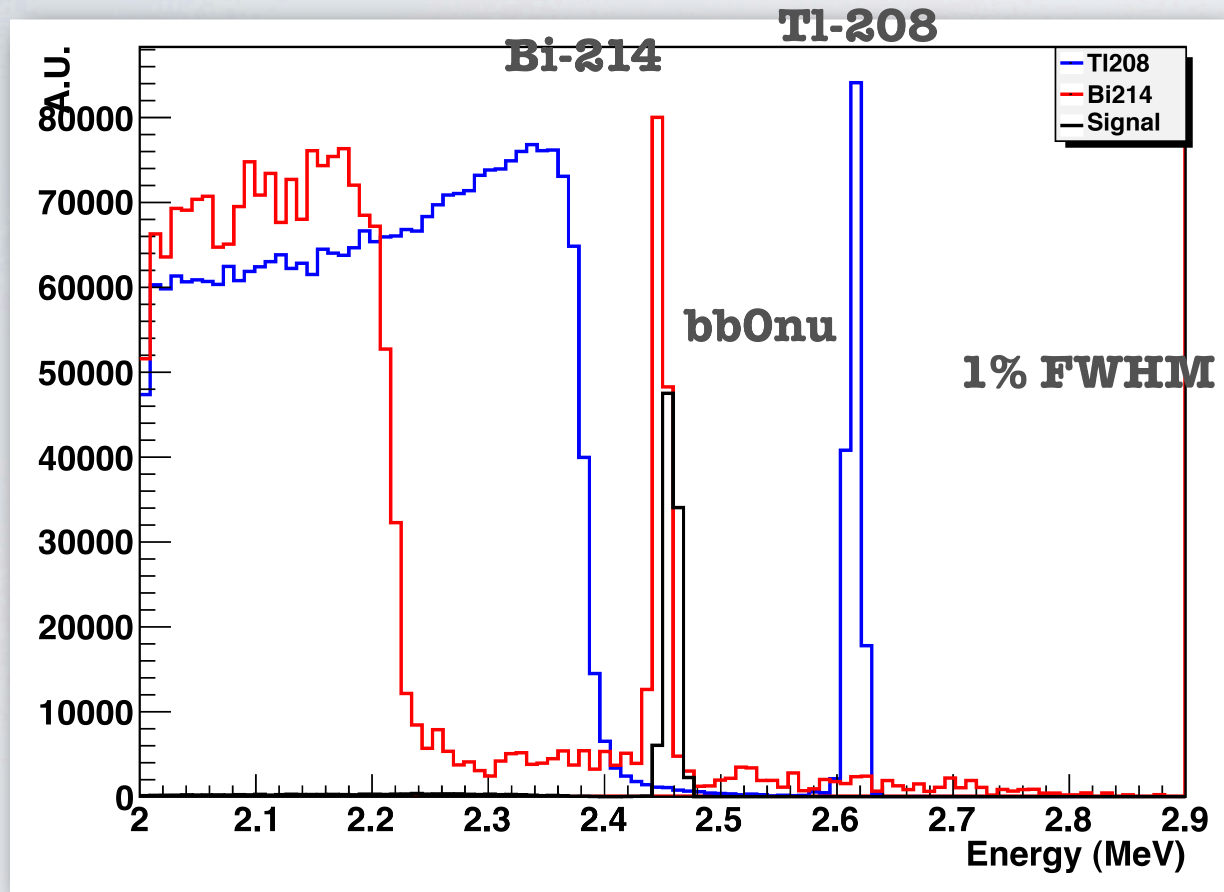
A simple recipe



$$N_{\beta\beta} = \varepsilon \log 2 \frac{N_A M t}{A} \eta \cdot m_{\beta\beta}^2$$

$$\eta = G^{0\nu} \left| M^{0\nu} \right|^2$$

$$N_{bkg} = \Delta E \cdot c \cdot Mt$$

$$S/N = \frac{N_{\beta\beta}}{\sqrt{N_{bkg}}} =$$

$$= \frac{\varepsilon \log 2 \eta N_A}{A} m_{\beta\beta}^2 \sqrt{\frac{Mt}{\Delta E \cdot c}}$$

- Define "discovery" as S/N=5

Experimental parameters

- A given bbonu experiment can be defined in terms of four parameters:
- The source isotope
- The efficiency
- The specific background rate
- The resolution

Exposure: requires cheap isotope and improves if detector scales with volume

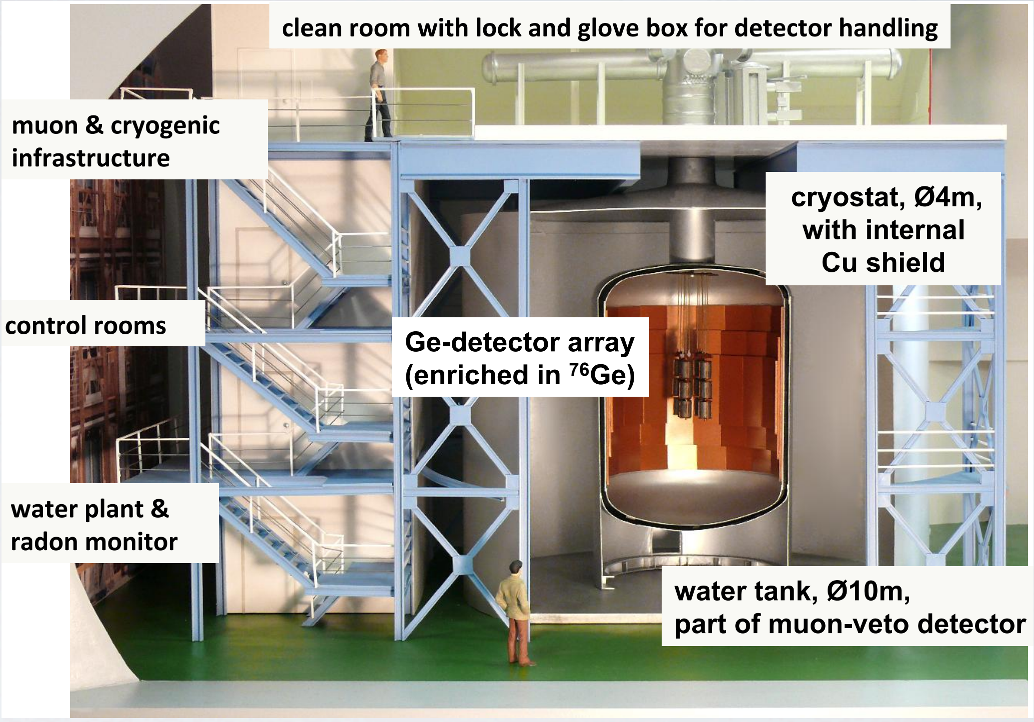
$$S/N = \log 2 N_A m_{\beta\beta}^2 \sqrt{\varepsilon^2 \left(\frac{\eta}{A}\right)^2 \frac{Mt}{\Delta E \cdot c}}$$

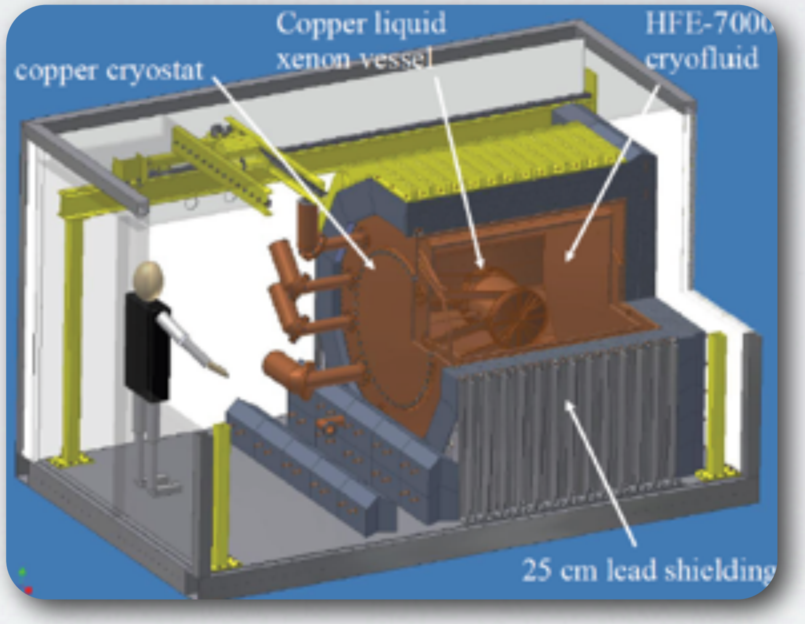
Experimental technique (in practice implies SOURCE = DETECTOR)

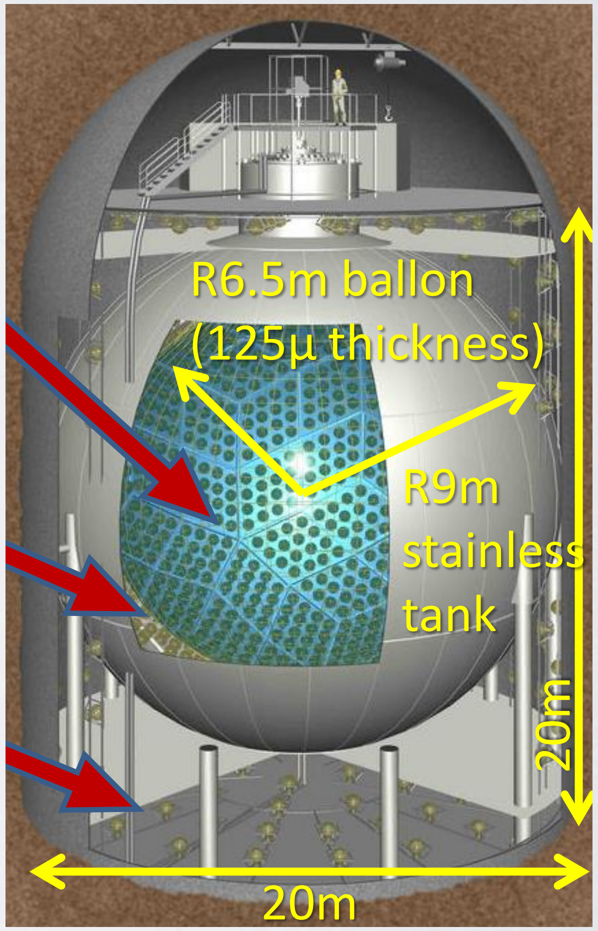
Isotope

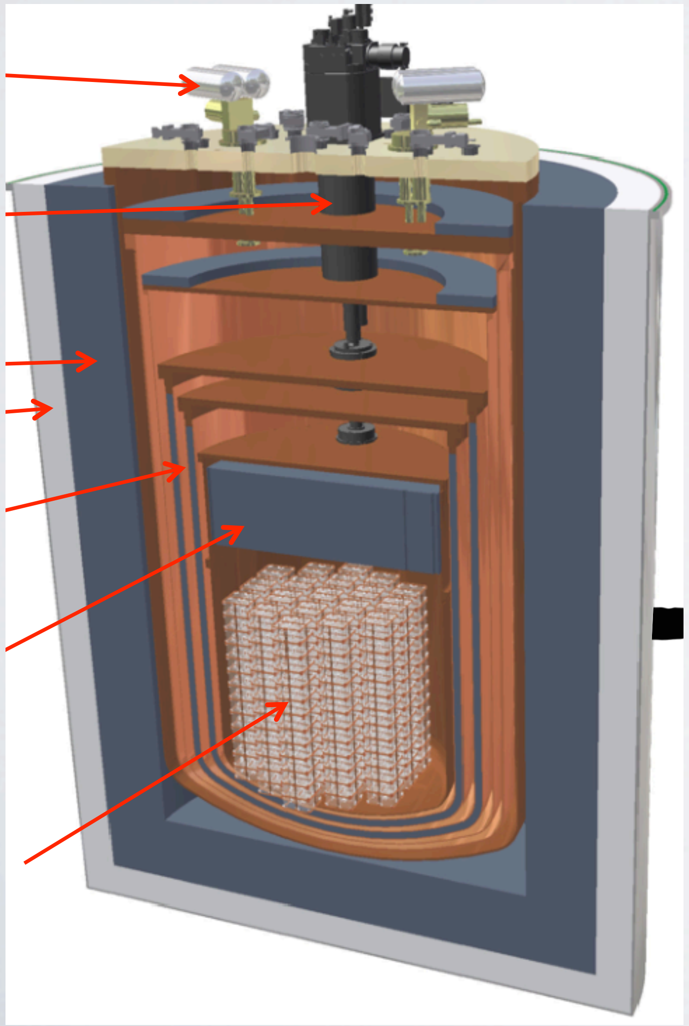
Experimental technique Maximize ΔE, c or both

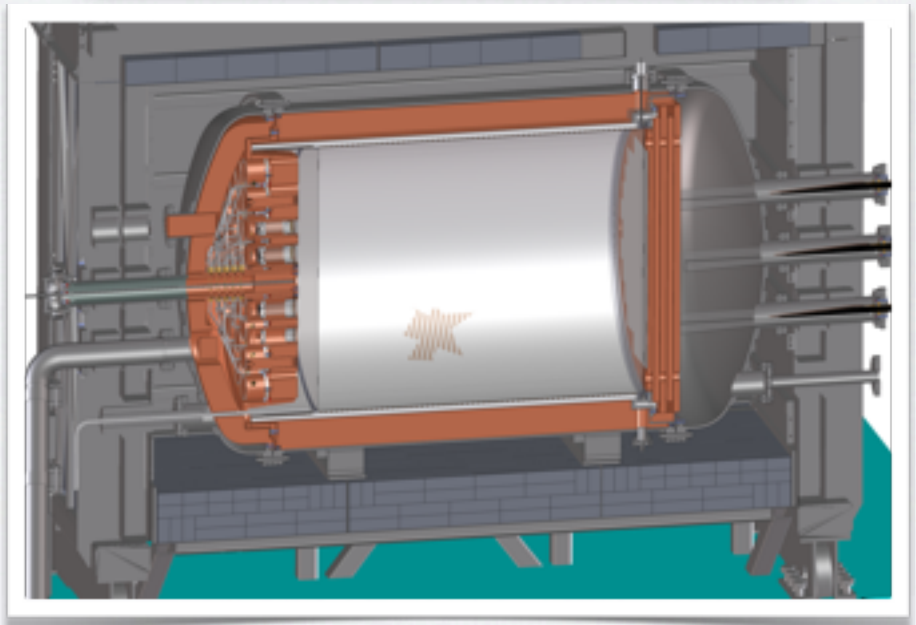
The actors


clean room with lock and glove box for detector handling
muon & cryogenic infrastructure
cryostat, Ø4m, with internal Cu shield
control rooms
Ge-detector array (enriched in ^{76}Ge)
water plant & radon monitor
water tank, Ø10m, part of muon-veto detector


Copper liquid xenon vessel
HFE-7000 cryofluid
copper cryostat
25 cm lead shielding

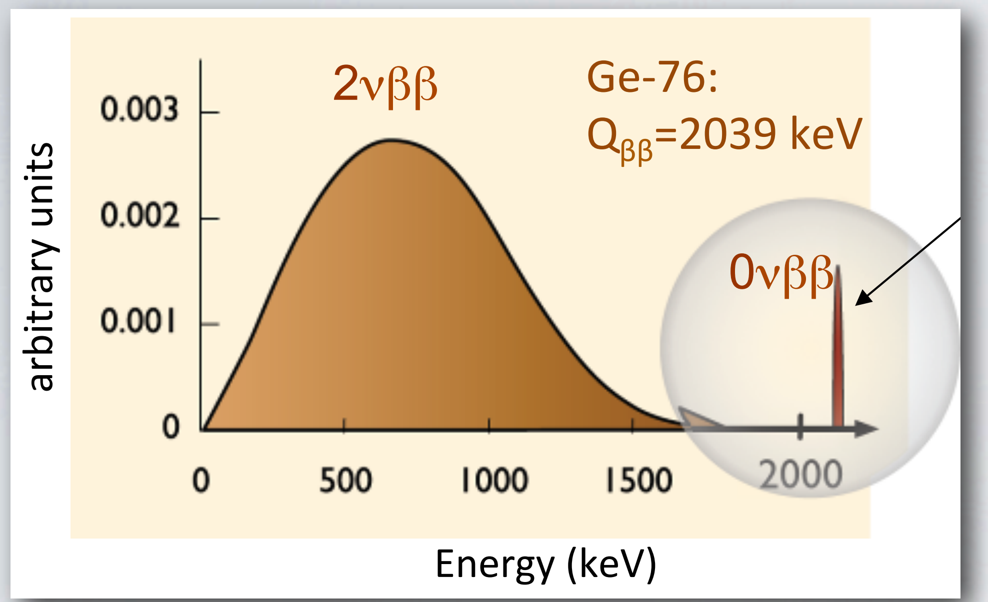

R6.5m ballon (125µ thickness)
R9m stainless tank
20m
20m





Gerda

$$f = \sqrt{\varepsilon^2 \left(\frac{\eta}{A}\right)^2 \frac{Mt}{\Delta E \cdot c}}$$



- Ge diodes
- Detector = Source
- Best ΔE in the market
- Excellent efficiency
- c limited by economy of scale
- MT limited by economy of scale

$\Delta E = 4.4 keV (phase I)$

$\Delta E = 2.5 keV (phase II)$

$c = 10^{-2} ckky (Measured)$

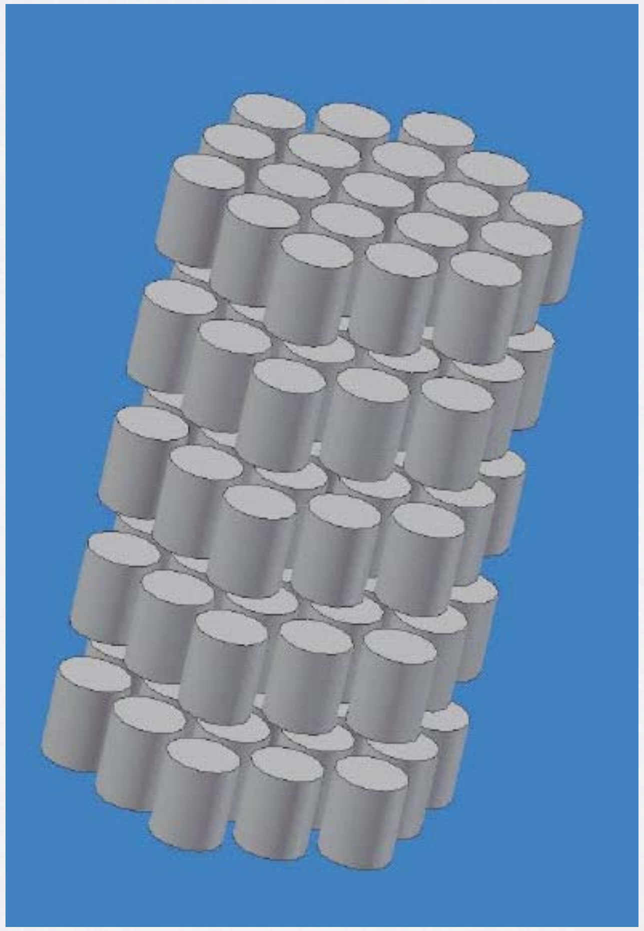
$c = 10^{-3} ckky (Planned)$

$\varepsilon(global) = 62\% (Coax)$

$\varepsilon(global) = 66\% (BEGe)$

FWHM @ Qbb

ckky = counts/(kev kg year)



The problem of economy of scale. S/N does not improve with mass.

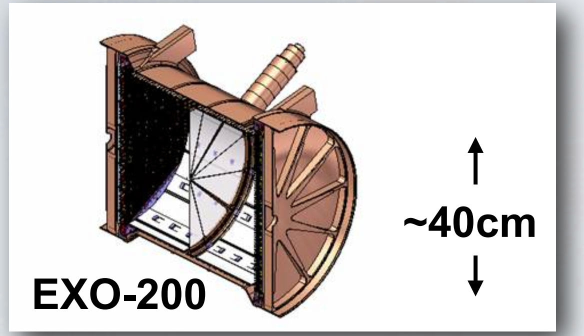
EXO

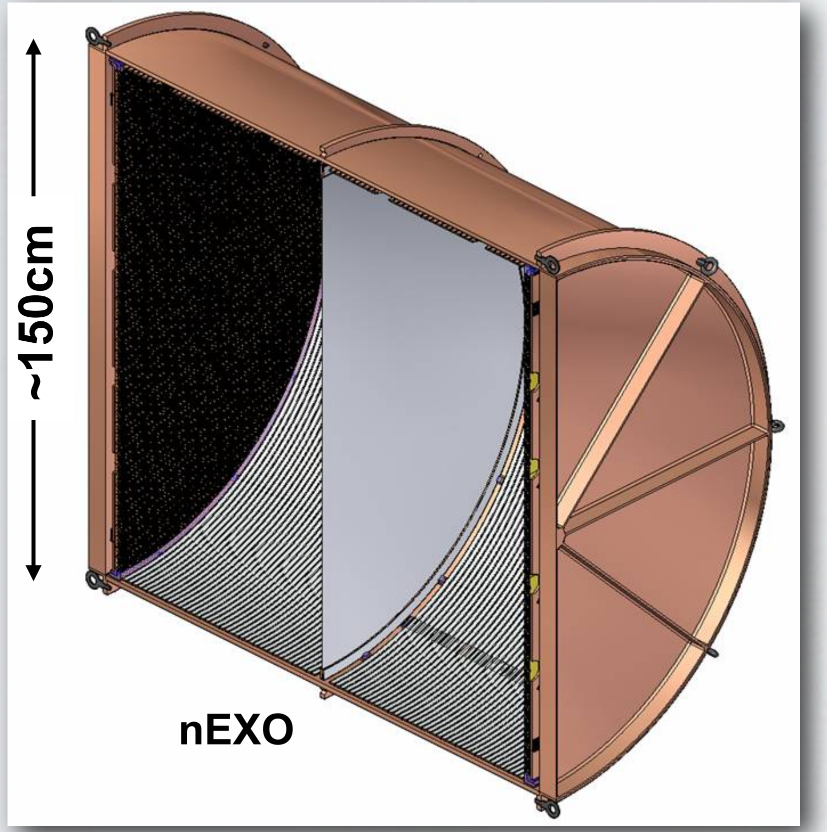
$$c = 1.5 \times 10^{-3}\, ckky$$

$$\Delta E = 96\, keV\, (EXO200)$$

$$\varepsilon(fiducial) = 44\%$$

$$\varepsilon(global) = 38\%$$





- LXe TPC
- Detector = Source
- Mediocre ΔE
- c is good thanks to shelf-shielding (but expensive)
- MT benefits from economy of scale.By making the detector larger S/V goes like 1/L and therefore the backgrounds tend to decrease with L.

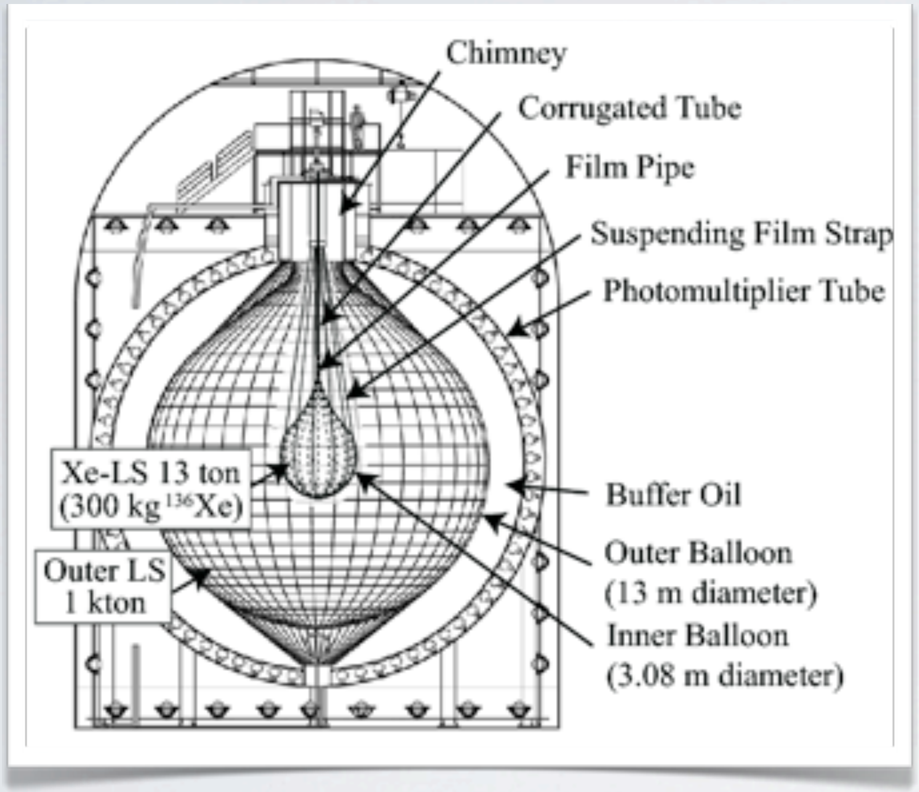
KamLAND-ZEN

$$\Delta E = 250 keV$$

$$c = 1.2 \times 10^{-3} ckky$$

$$\varepsilon(fiducial) = 55\%$$

$$\varepsilon(global) = 50\%$$



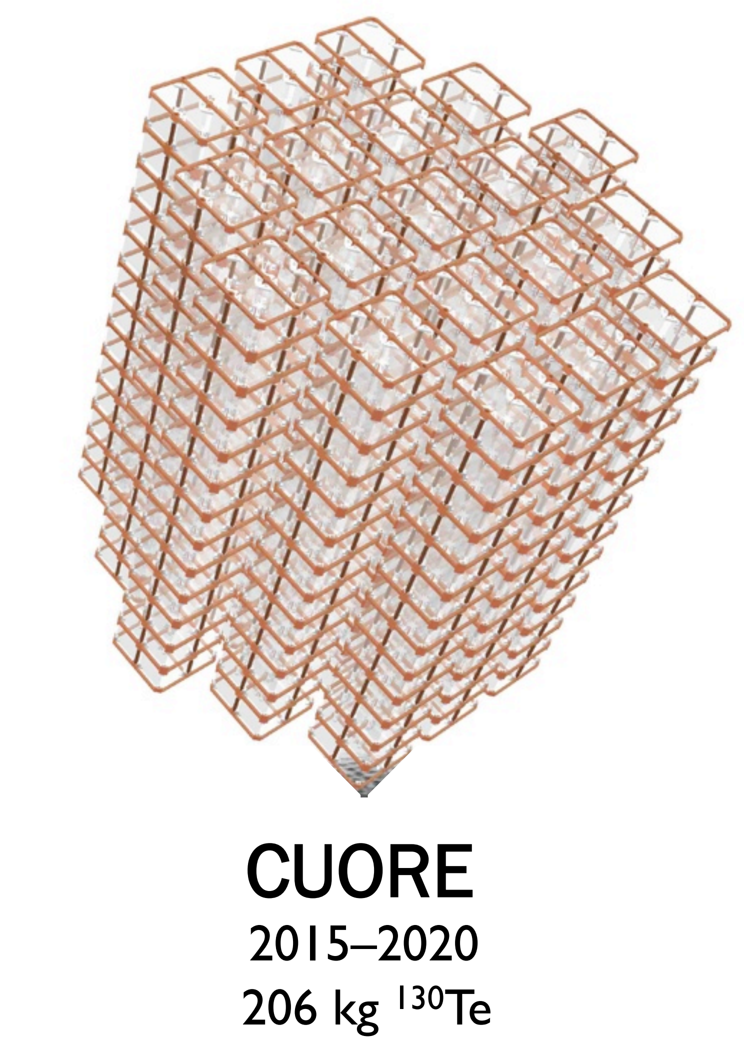
- Xe dissolved in scintillator
- Detector NOT Source
- Poor ΔE
- c is good thanks to shelf-shielding (but lots of passive mass)
- MT benefits (partially) from economy of scale.

Cuore

$$\Delta E = 5 keV$$

$$c \sim 10^{-1} ckky(Measured)$$

$$c = 10^{-2} ckky(Planned)$$



- Te Bolometers. Good isotope!
- Detector = Source
- Excellent ΔE
- Excellent efficiency
- c limited by economy of scale
- MT limited by economy of scale
- Uses natural Te. Mixed blessing (cheaper, but passive mass)

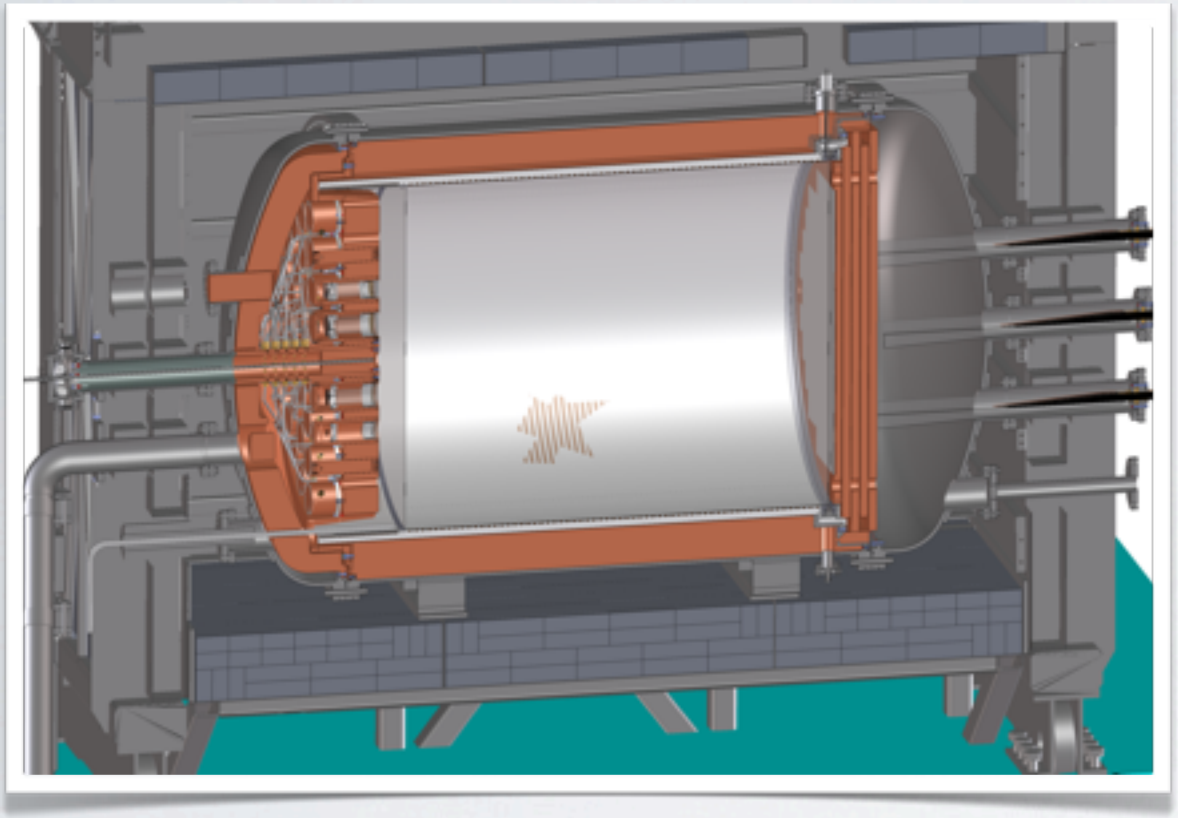
NEXT

$$\varepsilon(global) = 30\%$$

$$\Delta E = 12.5 keV$$

$$c \sim 5 \times 10^{-4}\, ckky(NEXT100)$$

$$c = 10^{-4}\, ckky(Feasible)$$



- HPXe TPC.
- Detector = Source
- Good ΔE
- Moderate efficiency
- c very good thanks to topological signature
- MT benefits by economy of scale
- Technology limit ~few tons

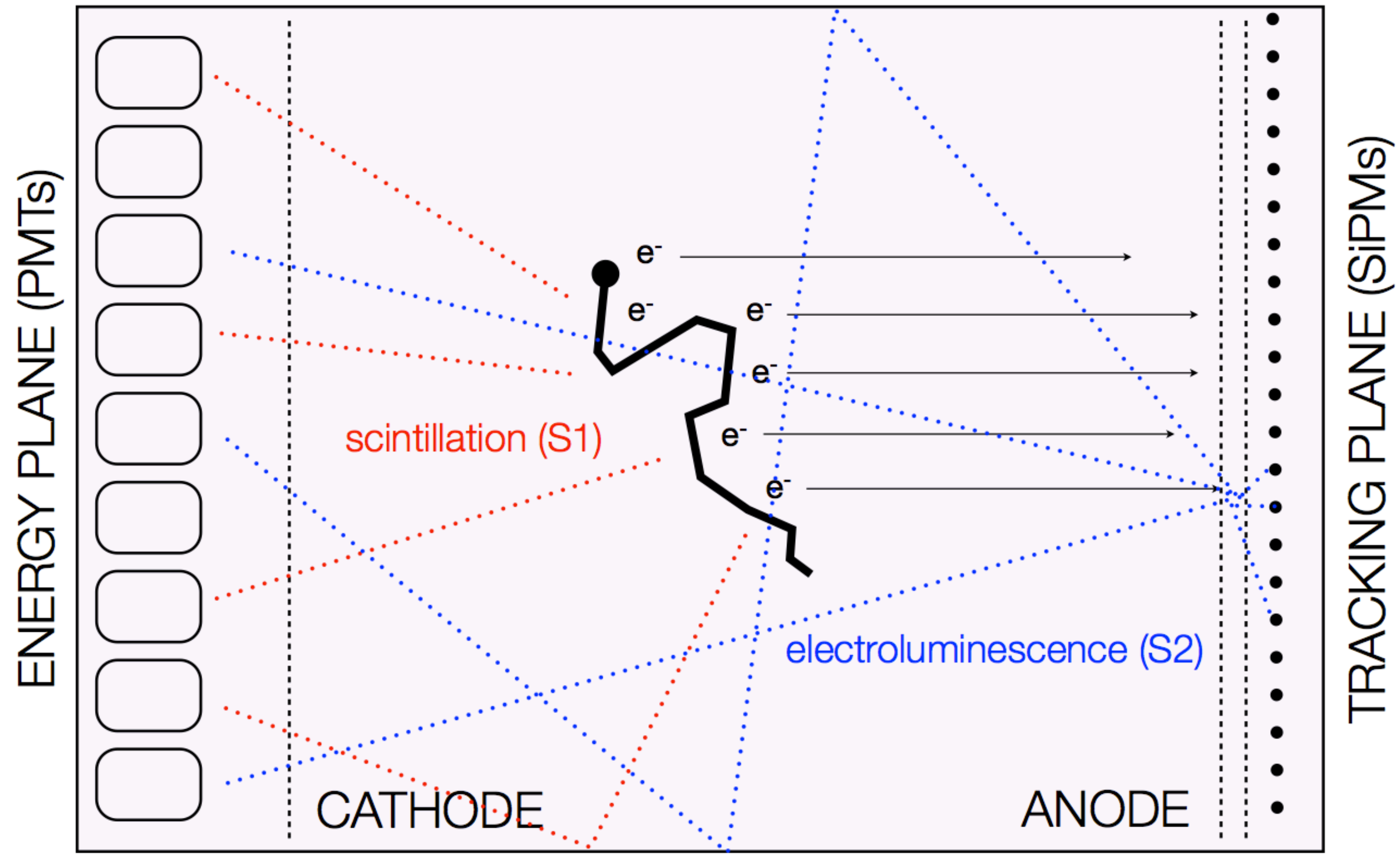
NEXT CONCEPTUAL IDEA, light production

LIGHT PRODUCTION PROCESS

- Electrons excite and ionize Xe
- Excited Xenon emits scintillation light (172nm) that is detected by the PMTs at Energy Plane (SIGNAL 1)
- Electrons from ionization are **drifted** by a weak electric field to the Electro-Luminescence (EL) region
- There, a larger E field accelerate electrons such to excite the Xe, but not enough to ionize it. This process produce a large amount of 172nm photons that will be detected in both photo-sensors planes (SIGNAL 2)

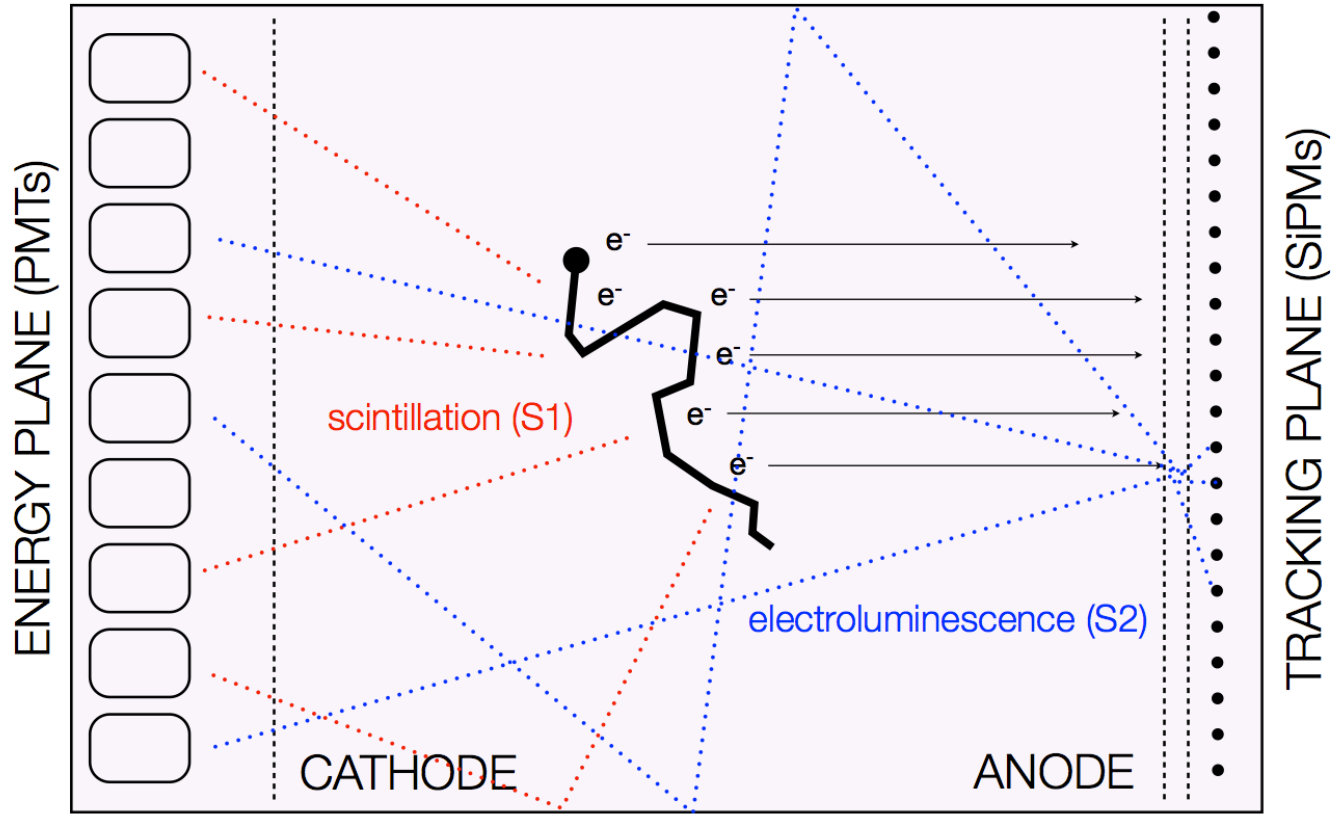
-The **PMTs** in the energy plane will accurately measure the energy

- The **SiPMs** in the tracking plane will allow to reconstruct the track followed by the original particle.

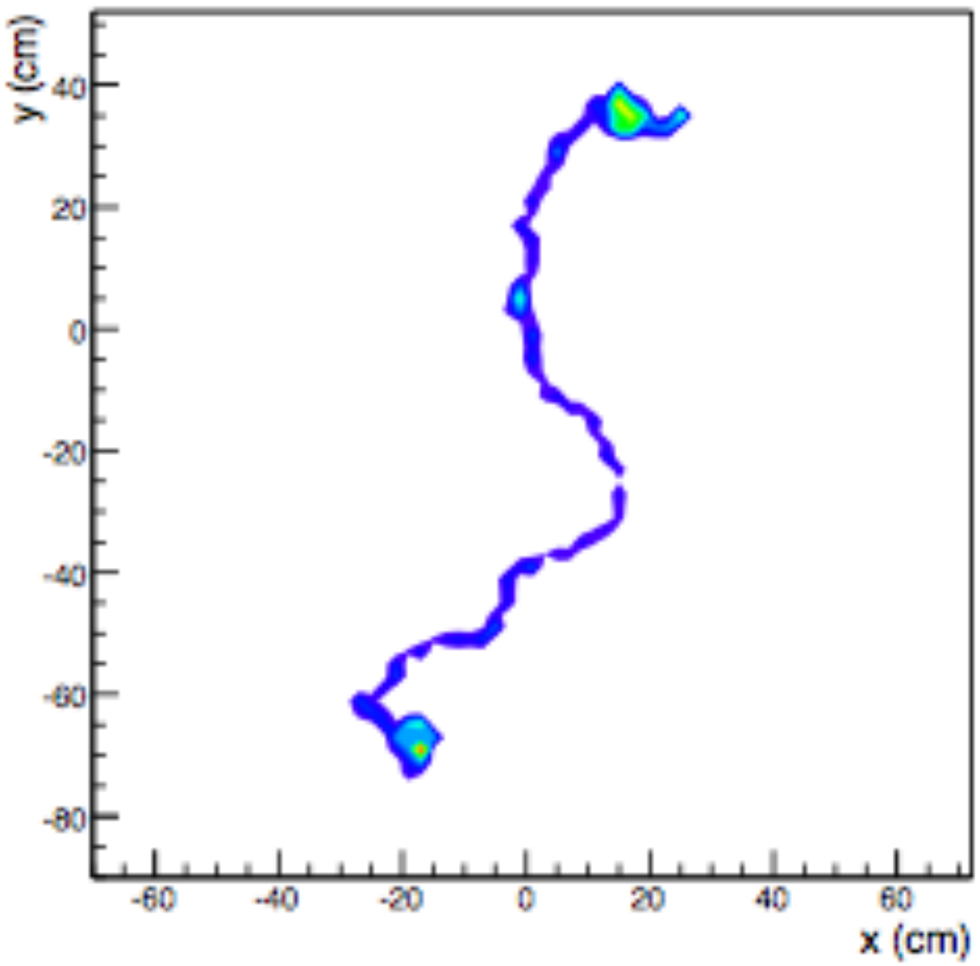


Tetra **P**henyl **B**utadiene (TPB) Wave-Length-Shifter is used to convert the light from UV to 430 nm to make it visible t the SiPMs & increase the number of photons for improving energy resolution

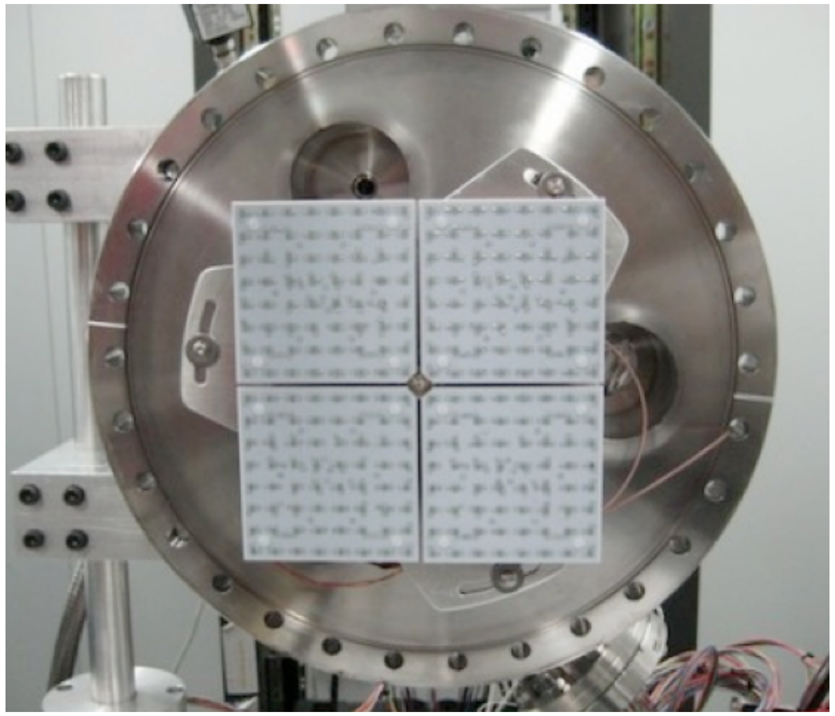
NEXT CONCEPTUAL IDEA, tracking



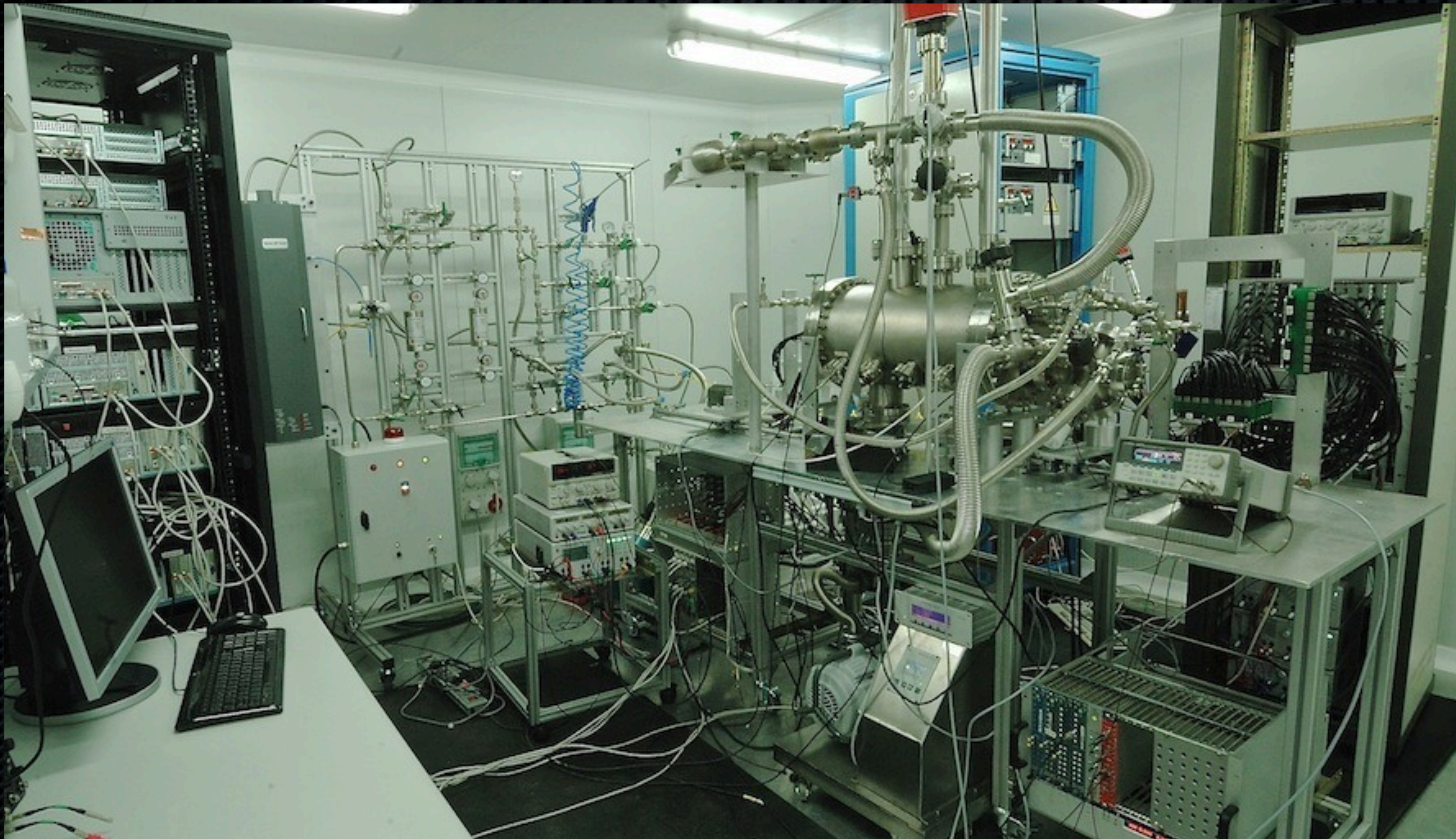
reconstructed tracks from a MC simulated ββ0ν event

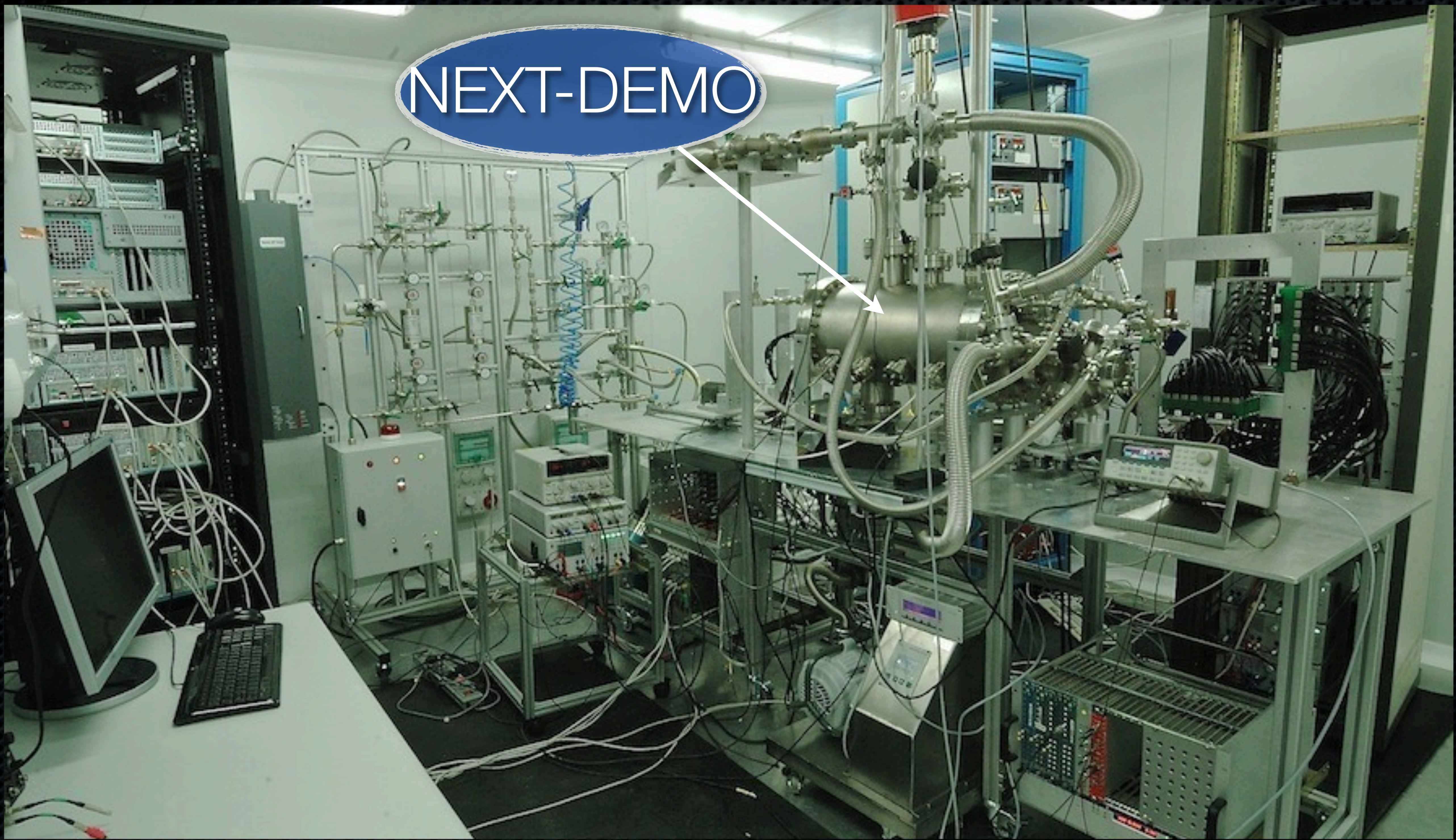


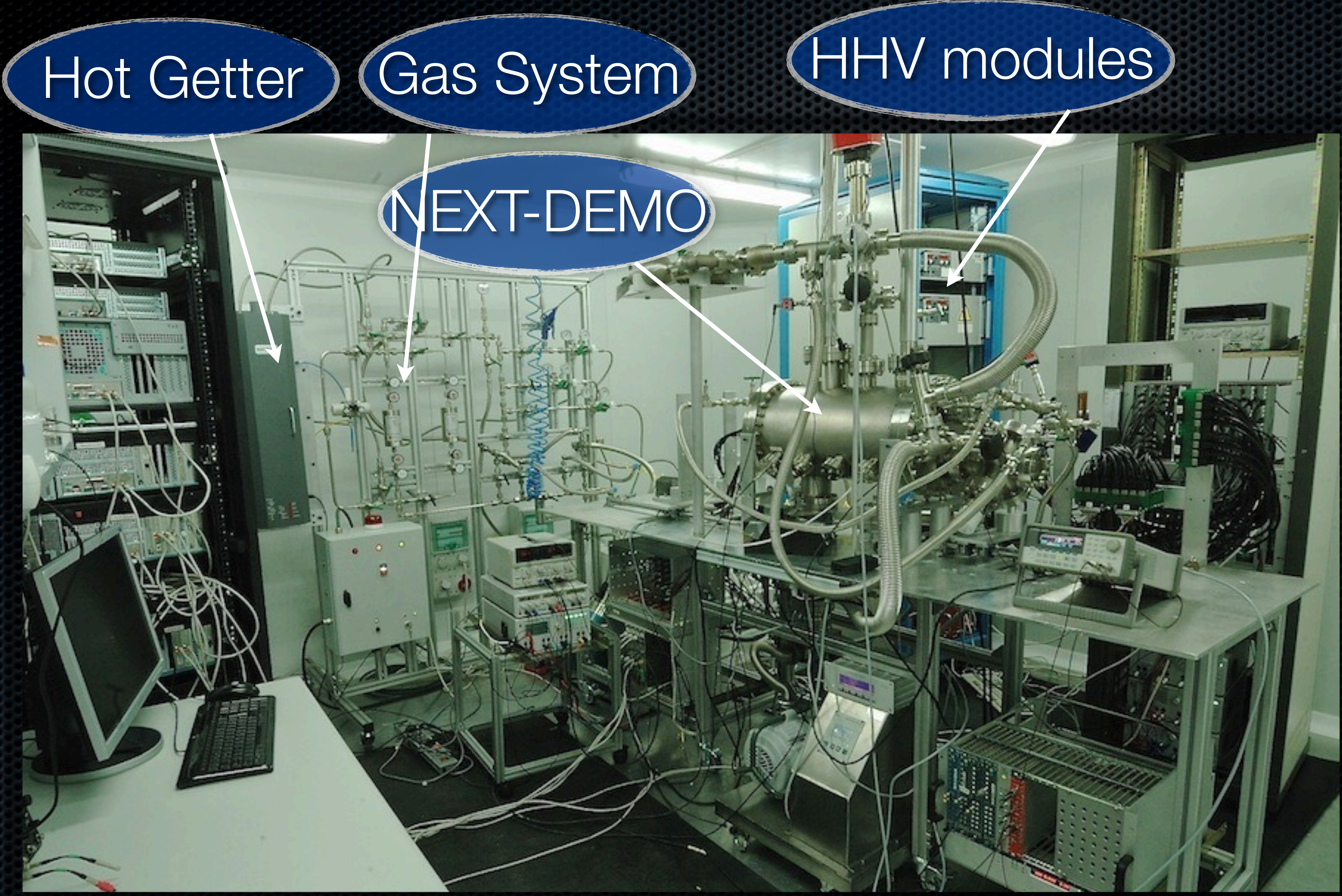
Tracking Plane of NEXT-DEMO, with 256 SiPMs for tracking



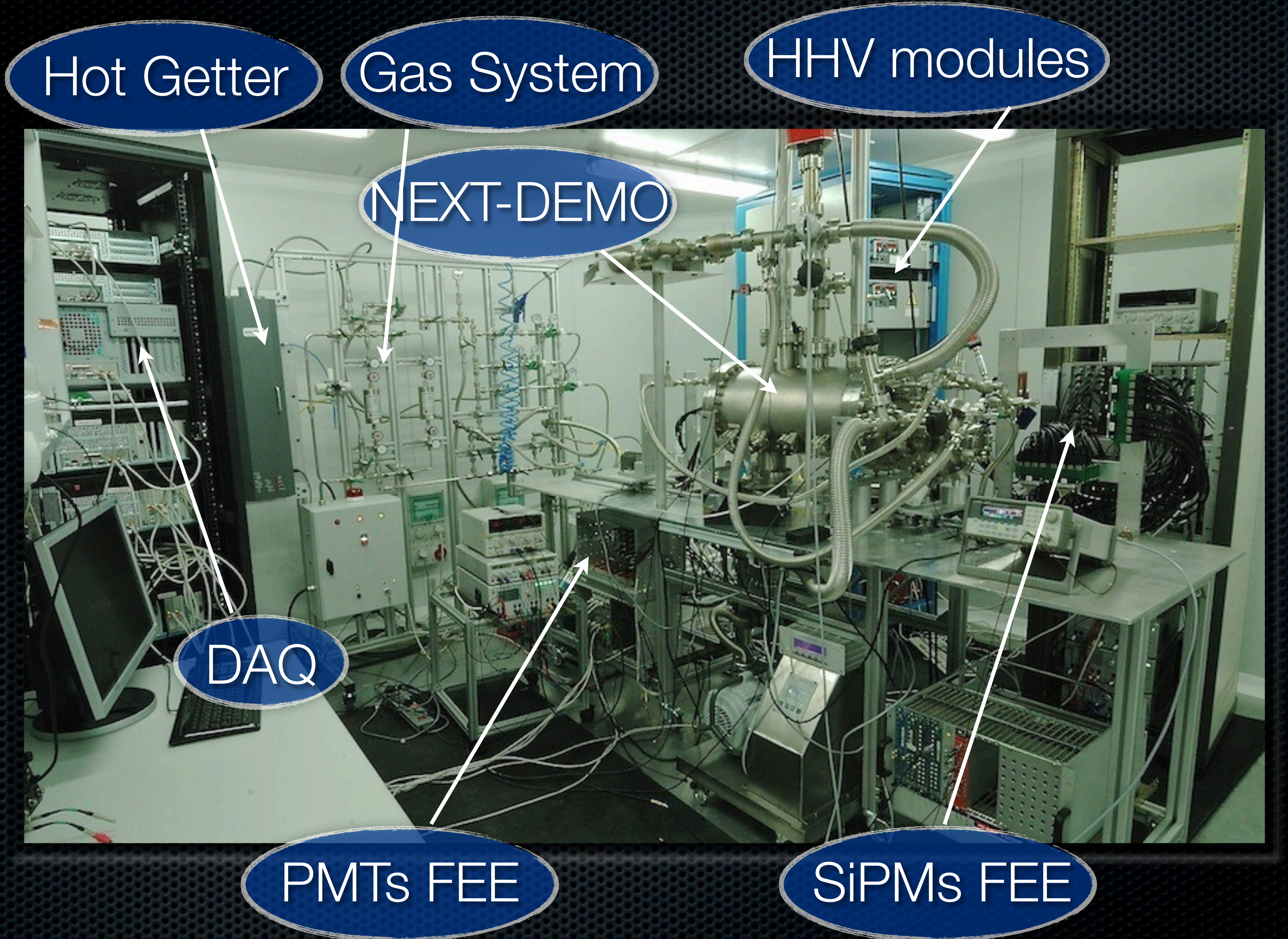
The signature of the electron is a twisted track with a strong energy deposition at its end




NEXT-DEMO



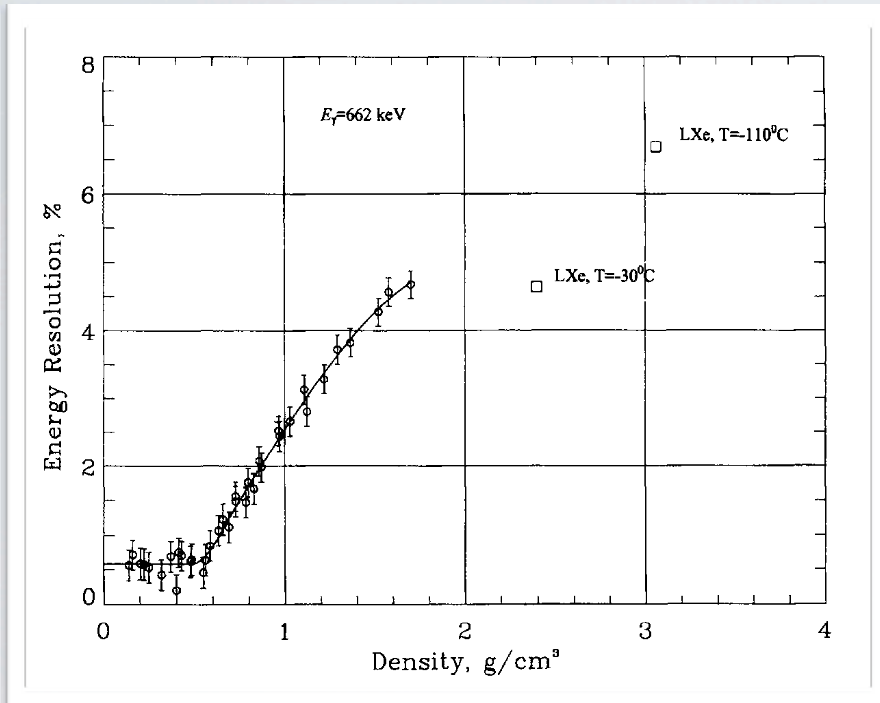
Hot Getter
Gas System
HHV modules
NEXT-DEMO

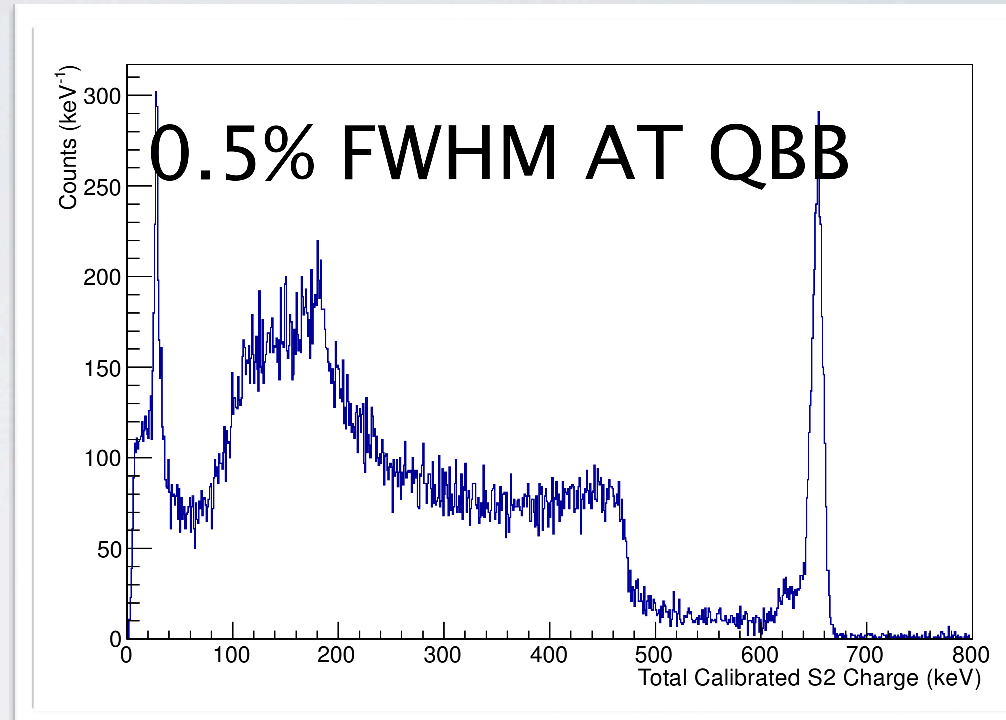

Hot Getter
Gas System
HHV modules
NEXT-DEMO
DAQ
PMTs FEE
SiPMs FEE

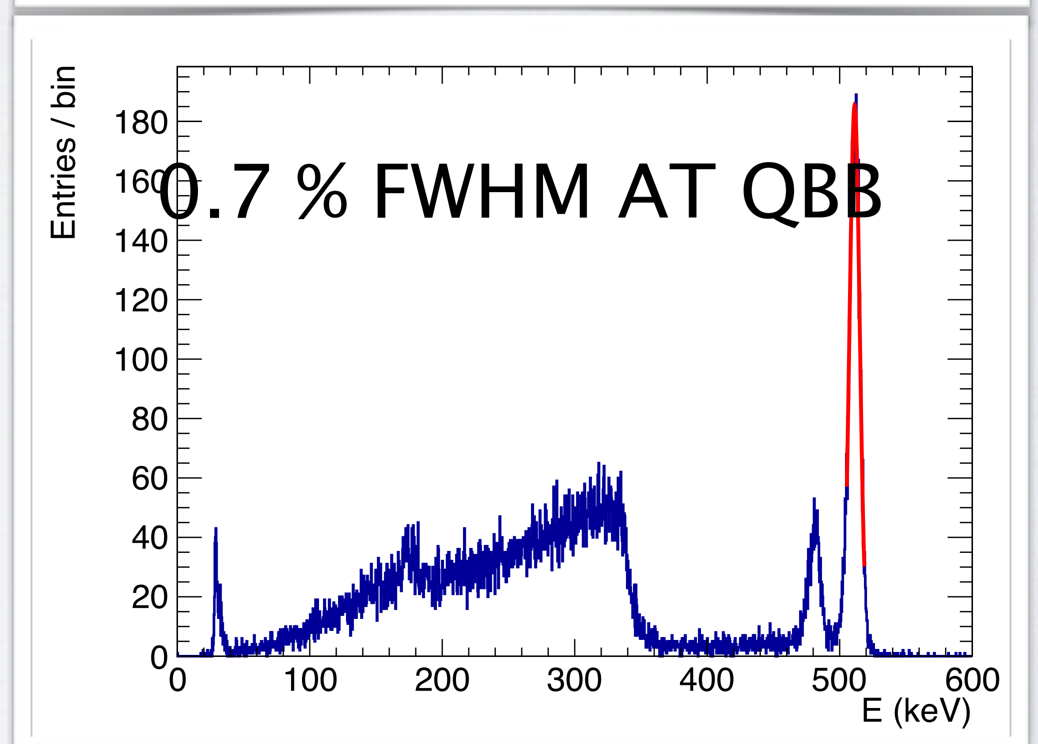

ANODE
EL REGION (5 mm)
GATE
DRIFT REGION (300 mm)
CATHODE
BUFFER REGION (100 mm)
SHIELD

NEXT ENERGY RESOLUTION IS VERY GOOD

Bolotnikov and Ramsey, NIM A 396 (1997)



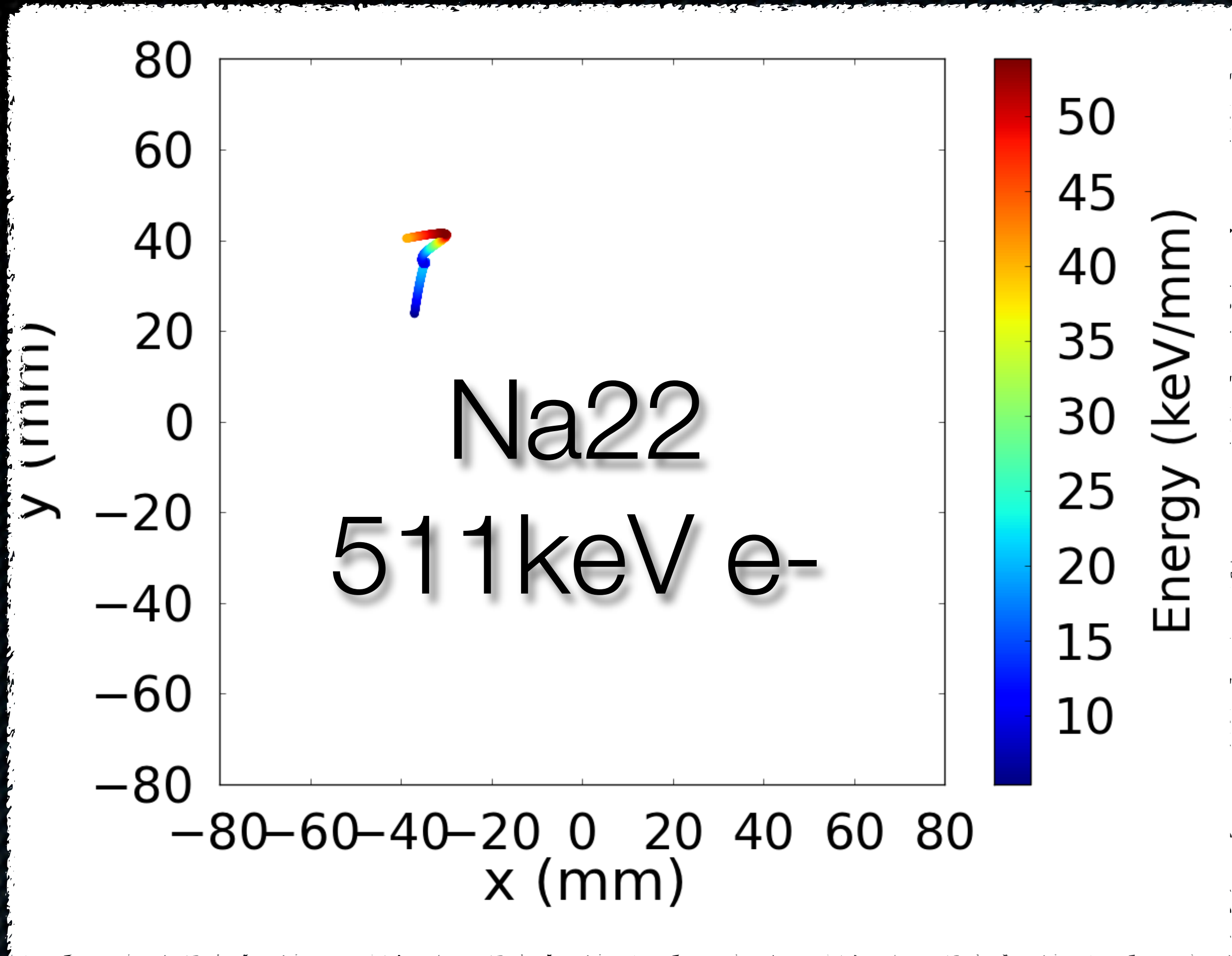


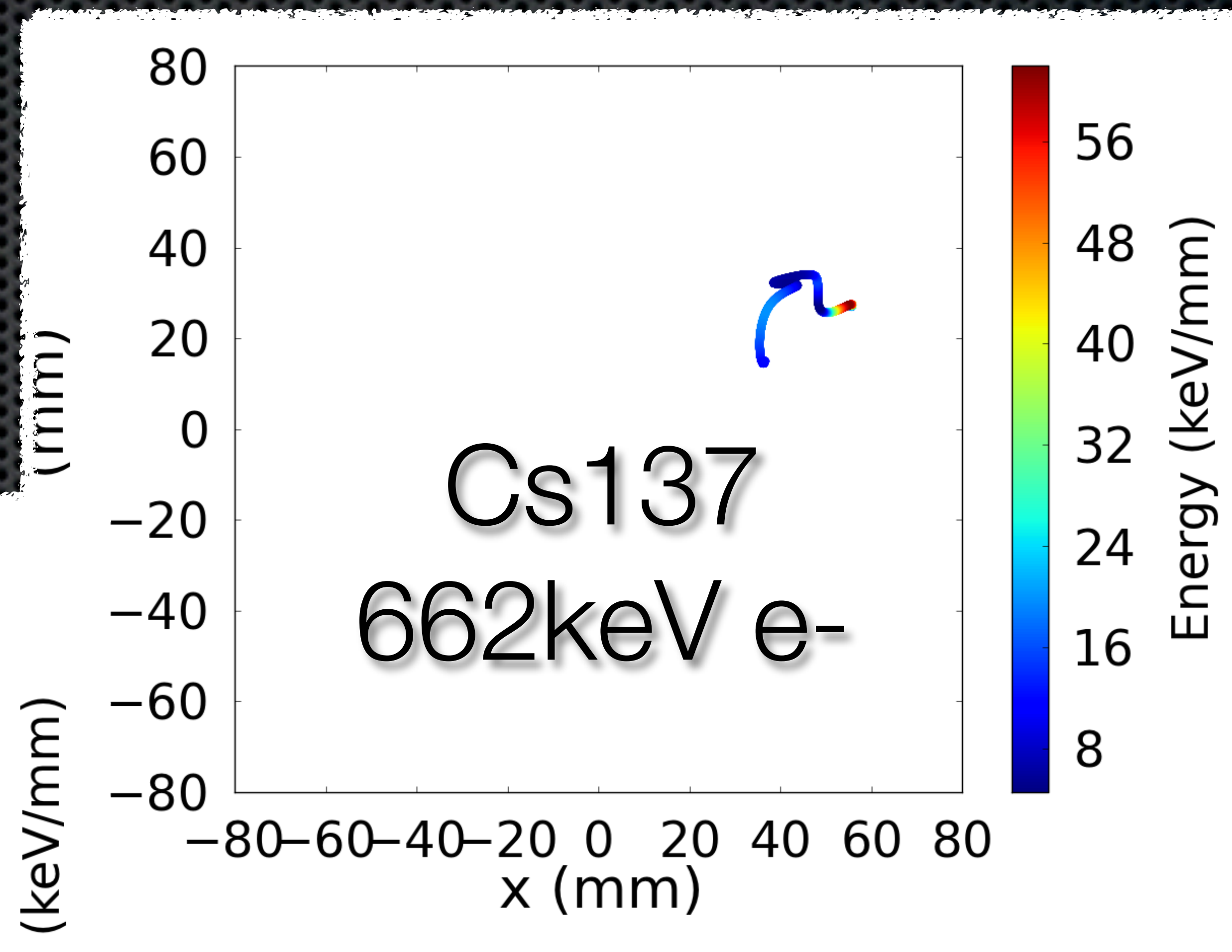


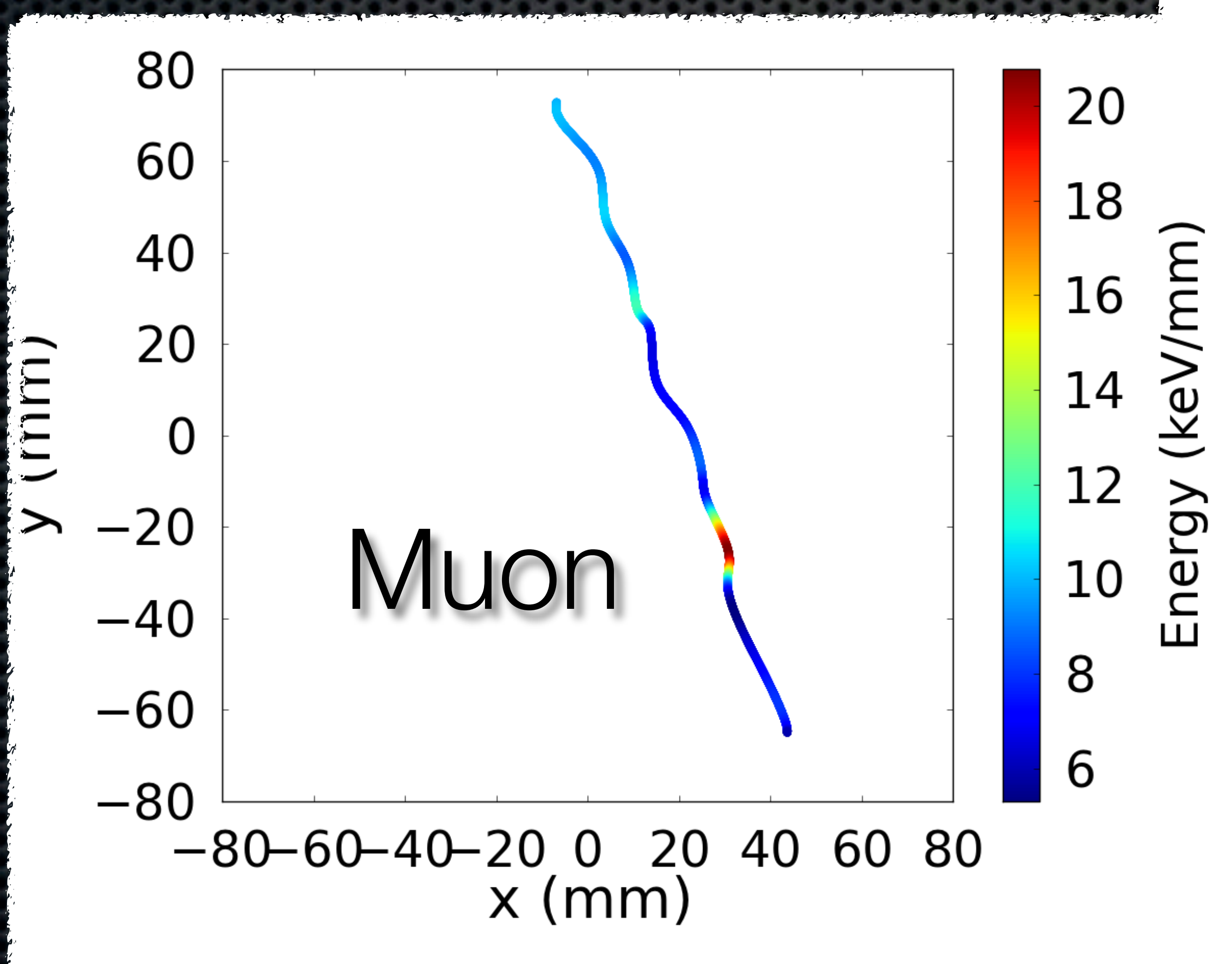
- **V.~Alvarez *et al.* [NEXT Collaboration],** **``Initial results of NEXT-DEMO, a large-scale prototype of the NEXT-100 experiment," arXiv:1211.4838 [physics.ins-det].**

- **V.~Alvarez, *et al.* [NEXT Collaboration],** **"Near-Intrinsic Energy Resolution for 30 to 662 keV Gamma Rays in a High Pressure Xenon Electroluminescent TPC," arXiv:1211.4474 [physics.ins-det].**

Tracks reconstructed for different energies

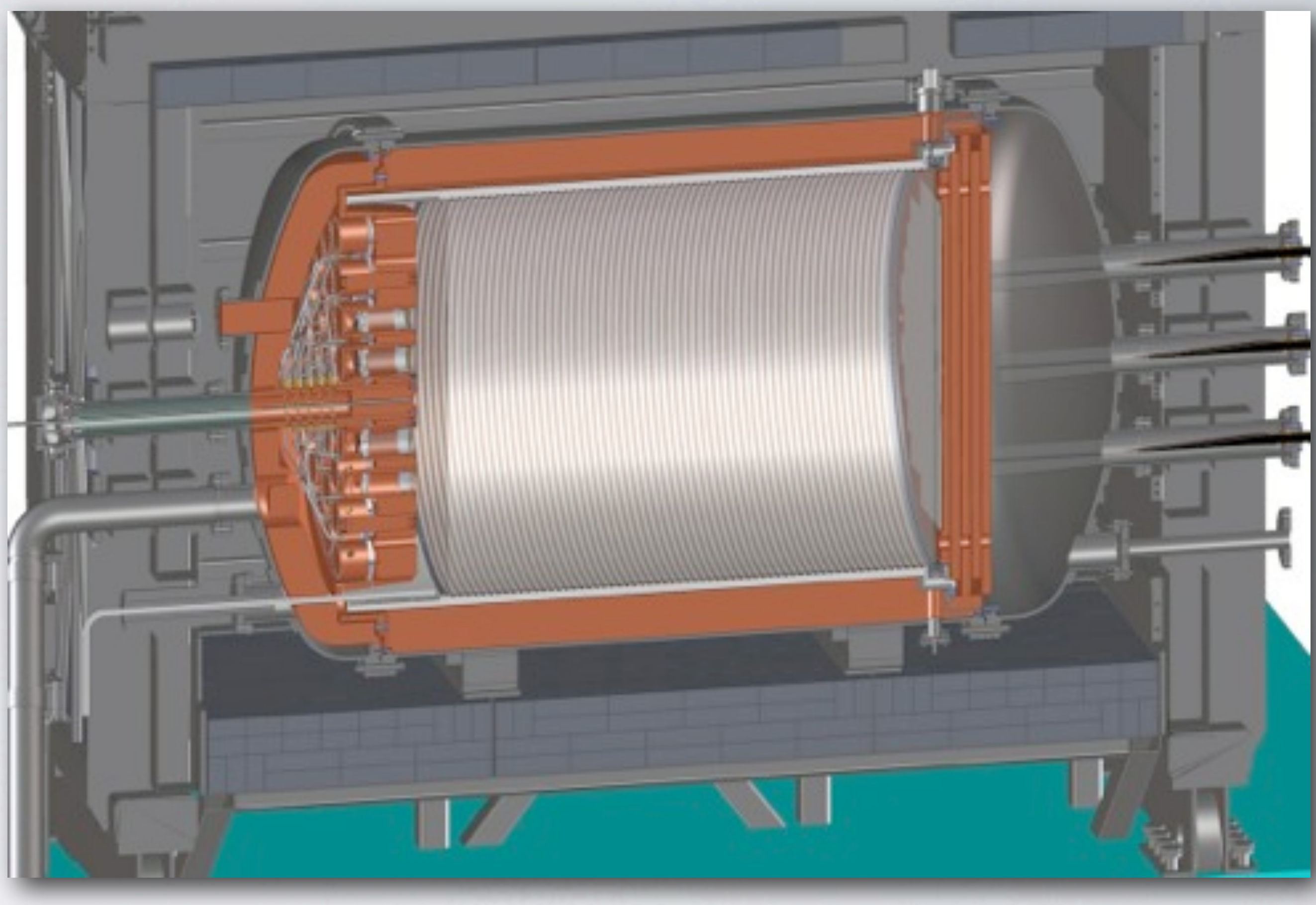


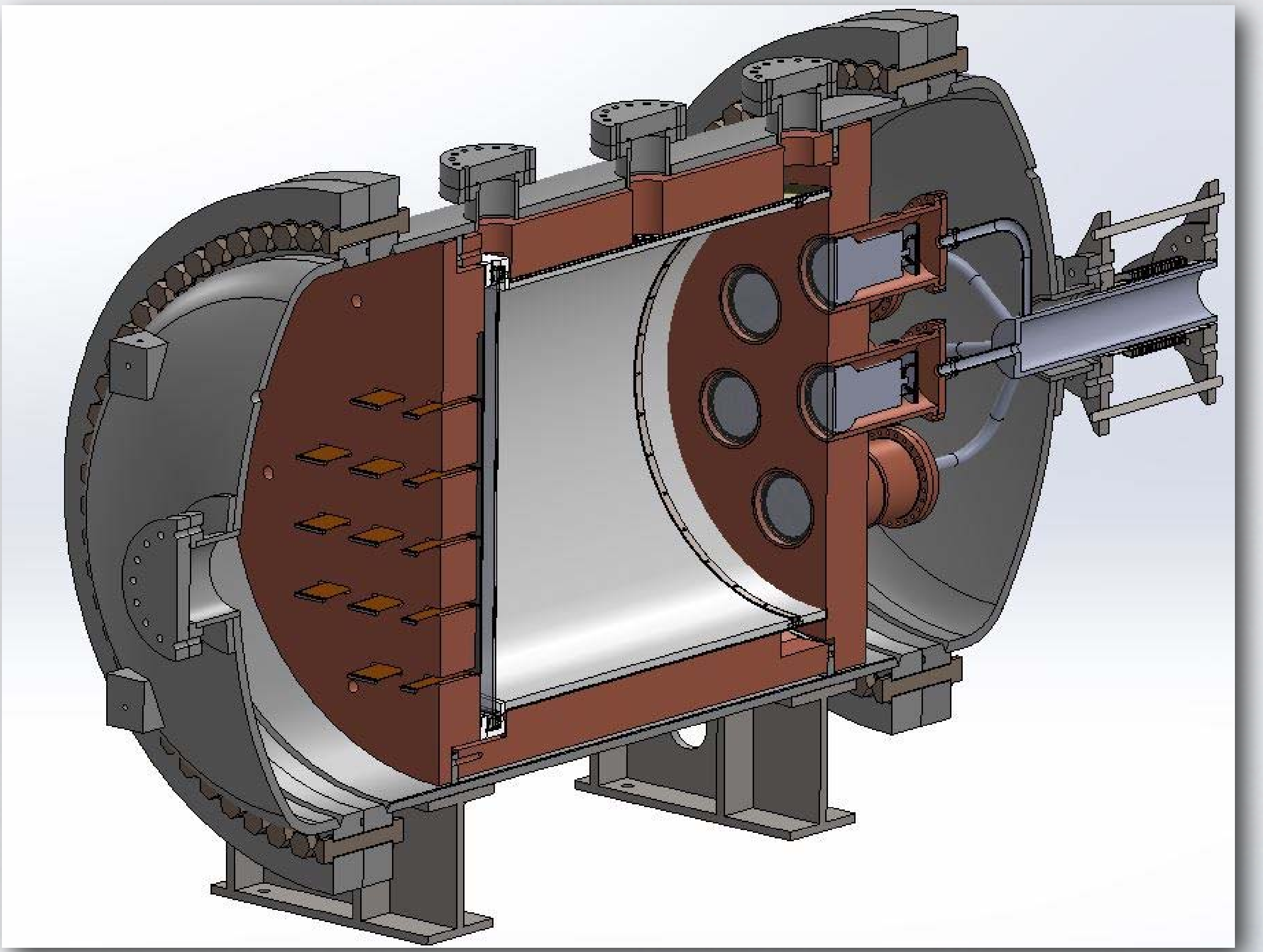




Different behavior between μ and e

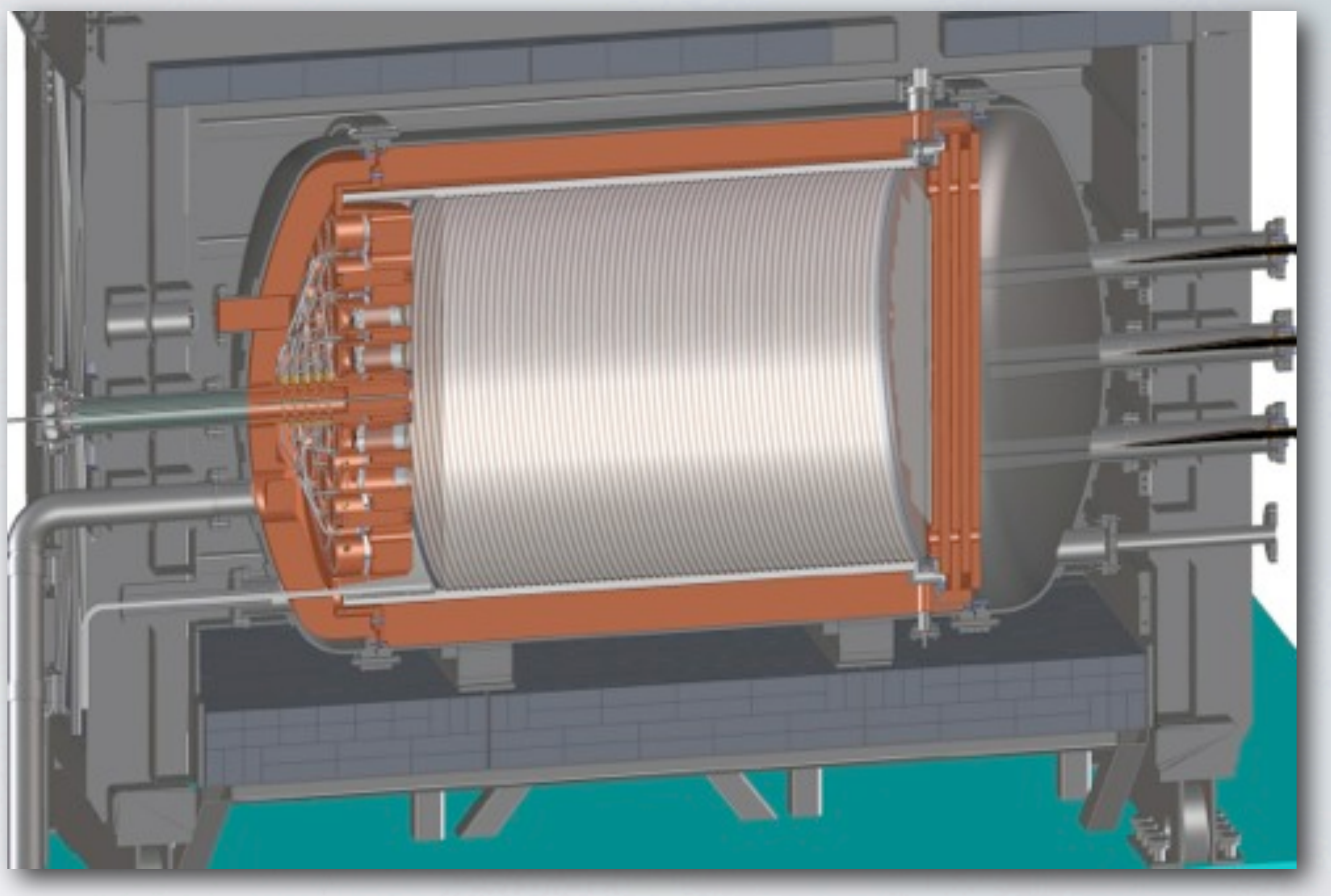
NEXT-WHITE (NEW)

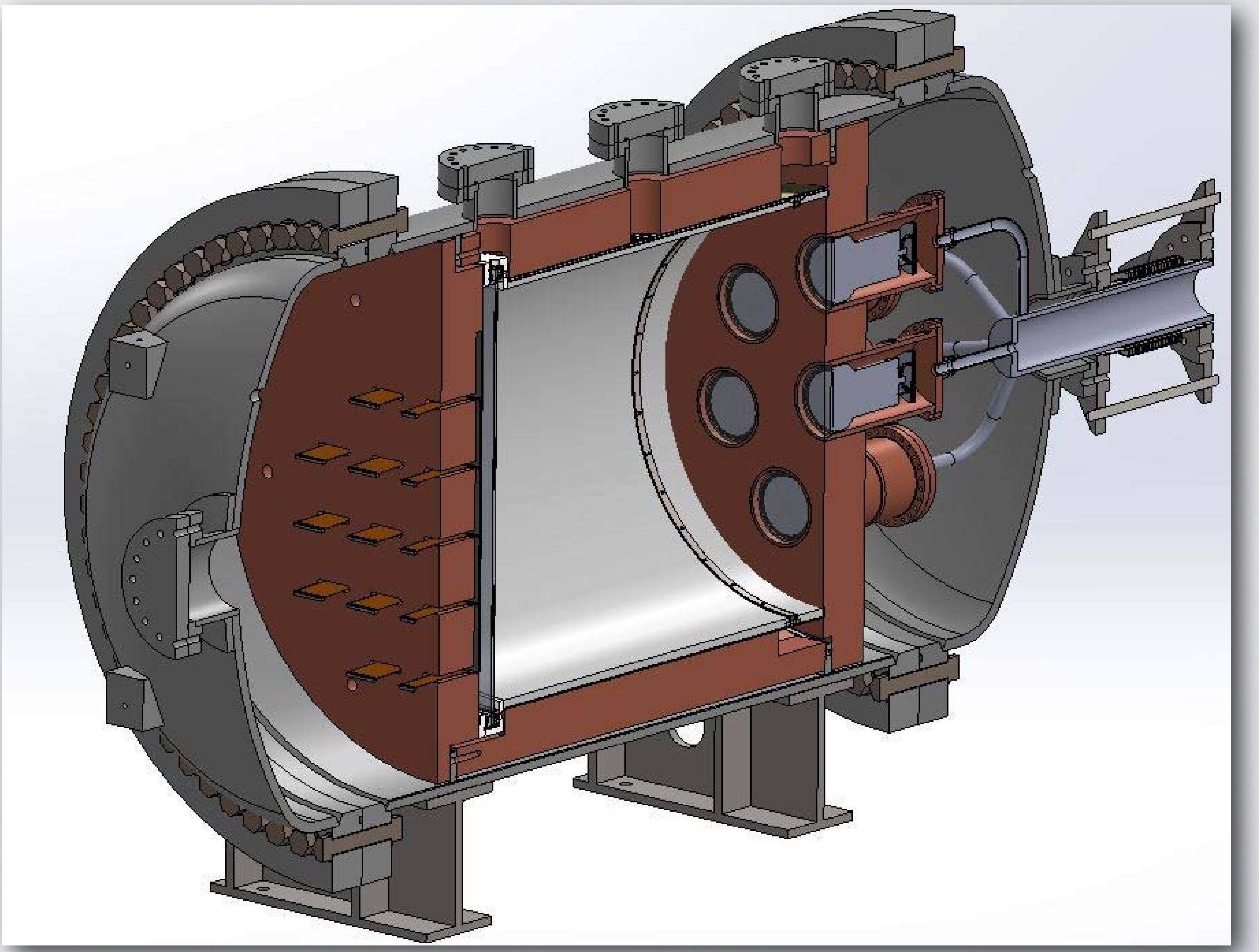




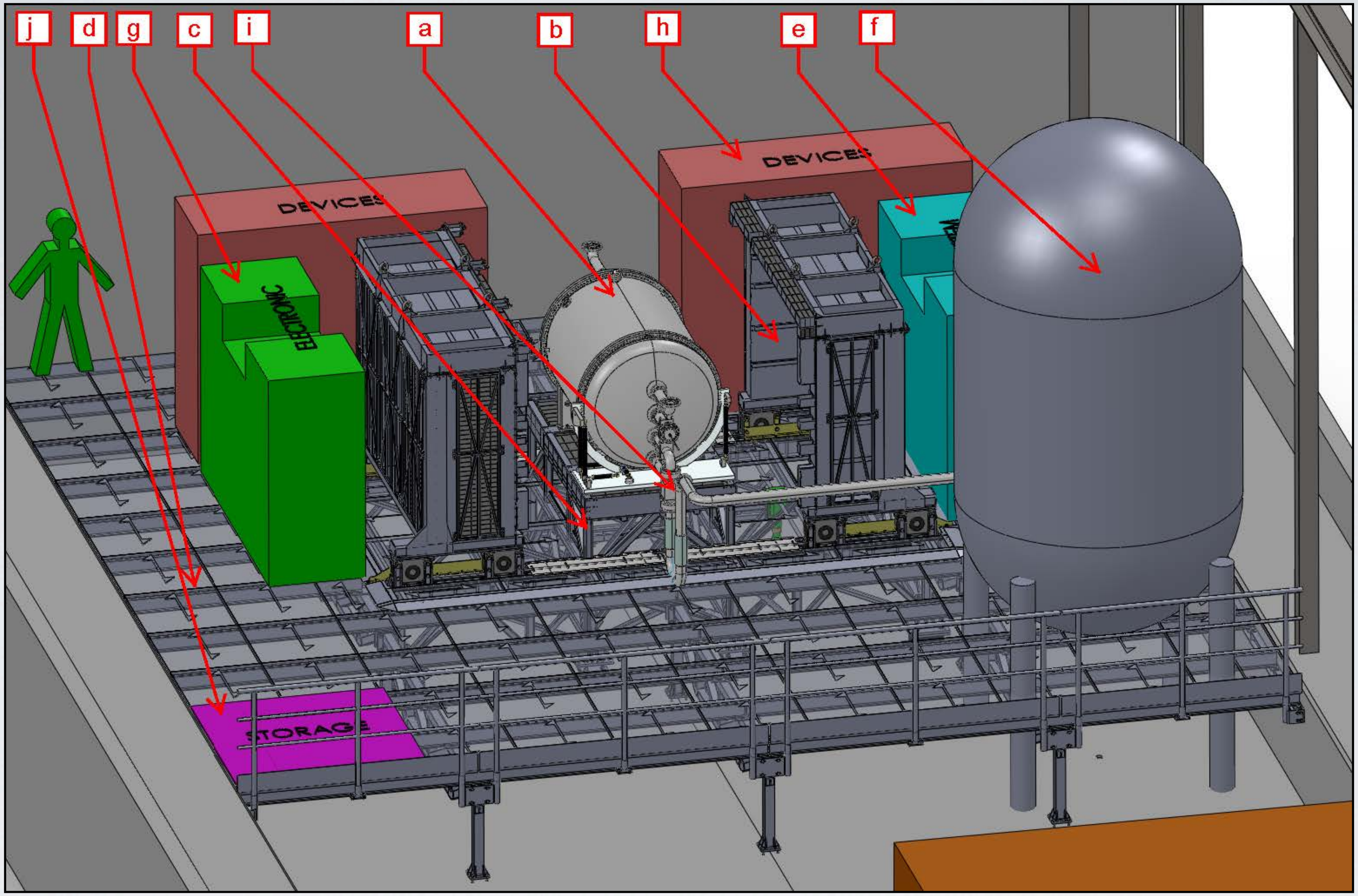
NEXT-WHITE (NEW)

- First phase of NEXT-100 (2014)
- Energy plane with 12 PMTs (20 % of sensors)
- Tracking plane with 23 DBs (20 % of sensors).
- Field cage dimensions: 1:2 NEXT-100
- Mass ~20 kg.
- Radiopure.
- Full validation of background model.
- Measurement of bb2nu mode.
- Topological signal (2 electrons)



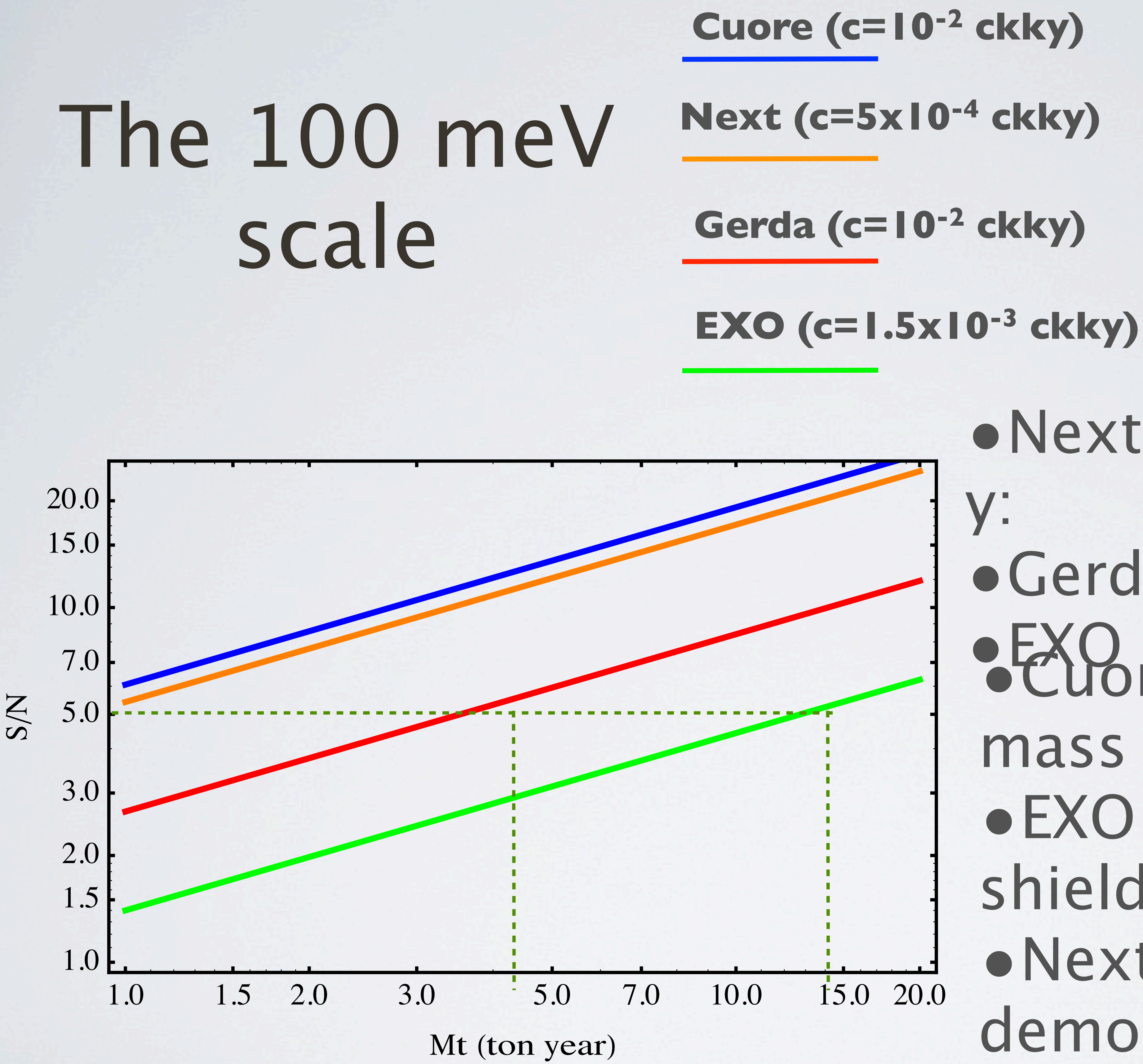


I-Infrastructures at Canfranc Laboratory.



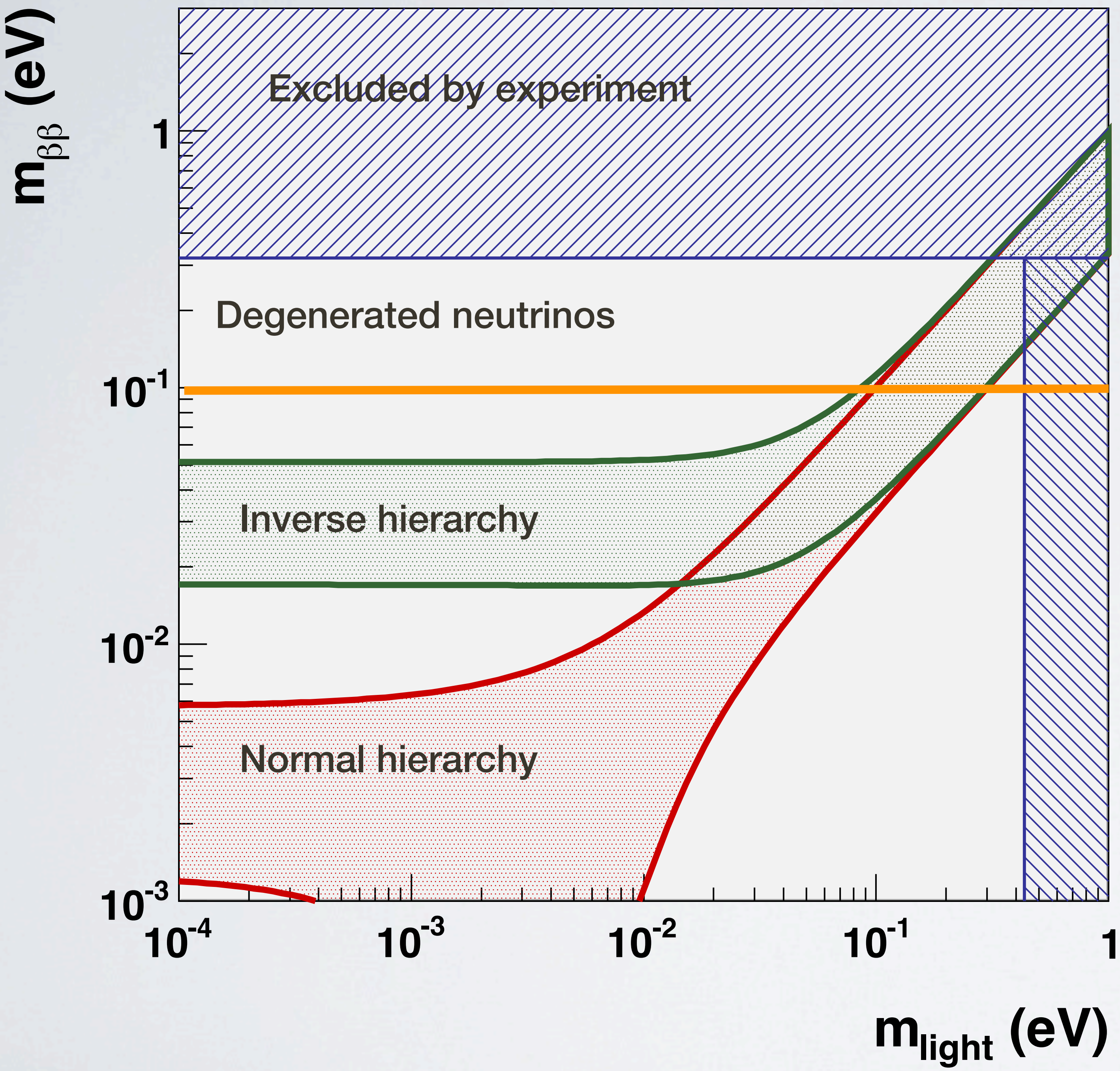
NEXT-100 stage-I (NEW): operation in 2014/2015
Supported by an AdG/ERC grant (awarded in 2013)

The 100 meV scale



- Next & Cuore ~1 ton y:
- Gerda 4.5 ton y
- EXO & KZ 15 ton y
- Cuore: add passive mass
- EXO add self-shielding
- Next & Cuore: demonstrate c

The 100 meV scale



Reaching 100 meV requires already very large exposures which in turn require detector masses of the order of the ton.

The implication is that one must reduce the background rate further before attempting to go to larger masses.

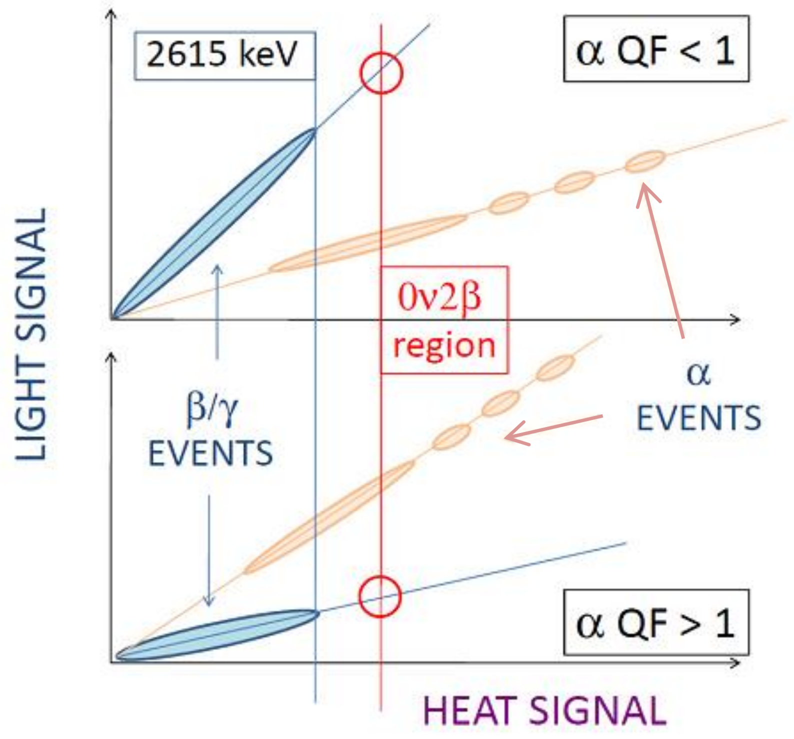
In practice: current generation of experiments are just prototypes of the ton-scale.

Improving the ship

- Ge: 10^{-3} ckky instrumented veto, multi-site
- Bolometers: Cuore --> Lucifer: 10^{-3} ckky by combining scintillation and thermal signal
- Next: full use of topological signal: 10^{-4} ckky
- EXO: more self-shielding: 10^{-4} ckky (at the cost of more wasted enriched xenon)

Lucifer

Advantages of this technique



- Different isotopes can be tested
- Very high efficiency
- Excellent energy resolution (‰)
- Possibility of growing radio—pure crystals.

But…no possibility to tag the event
poor background rejection (α events)

Solution: Scintillating Bolometers!

Based on double read-out: HEAT + LIGHT

e^- and α of the same energy:
- Release the same heat in the bolometer
- Produce a different amount of light → discrimination

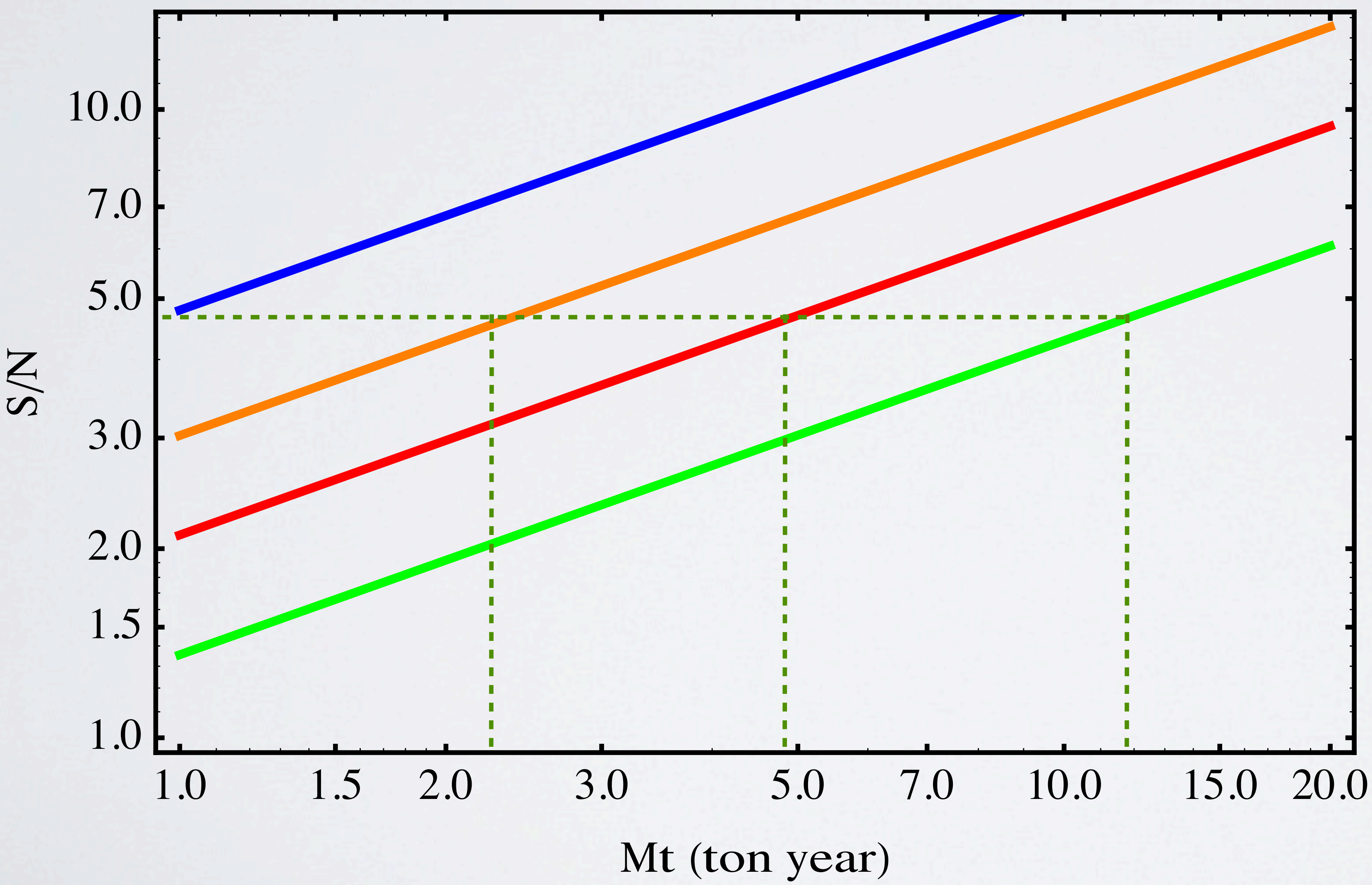
The 50 meV scale

Lucifer (c=10^{-3} ckky)

HPXe (c=10^{-4} ckky)

Gerda/Majorana (c=10^{-3} ckky)

LXe (c=10^{-4} ckky)



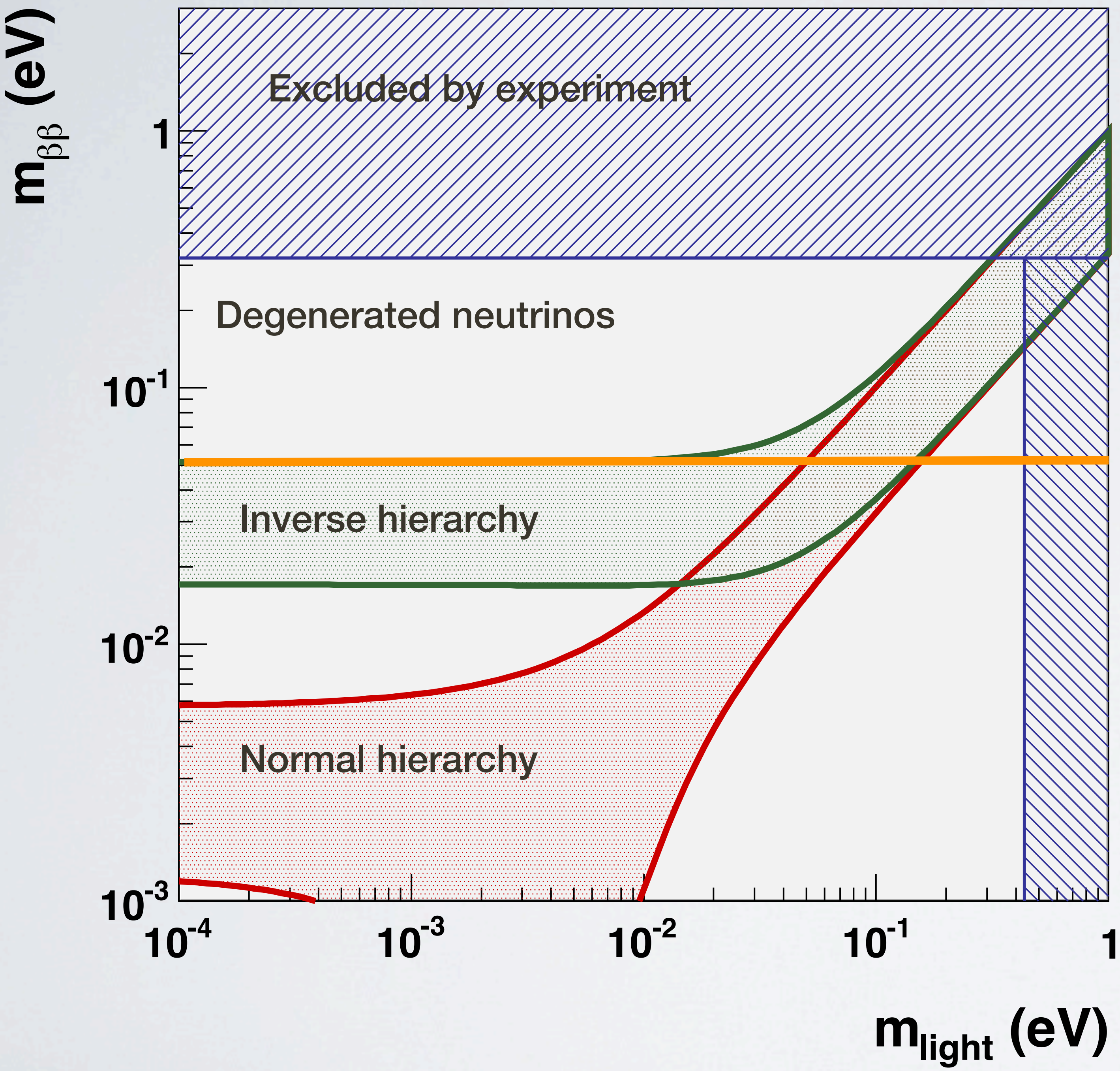
Lucifer: 1 ton year

HPXe: 2 ton year.

Ge: 5 ton year

LXe: 12 ton year + shielf (~20 ton year)

The 50 meV scale



Reaching 50 meV requires masses of the order of 1 ton for bolometers, Ge, HPXe and order 10 ton for LXe.

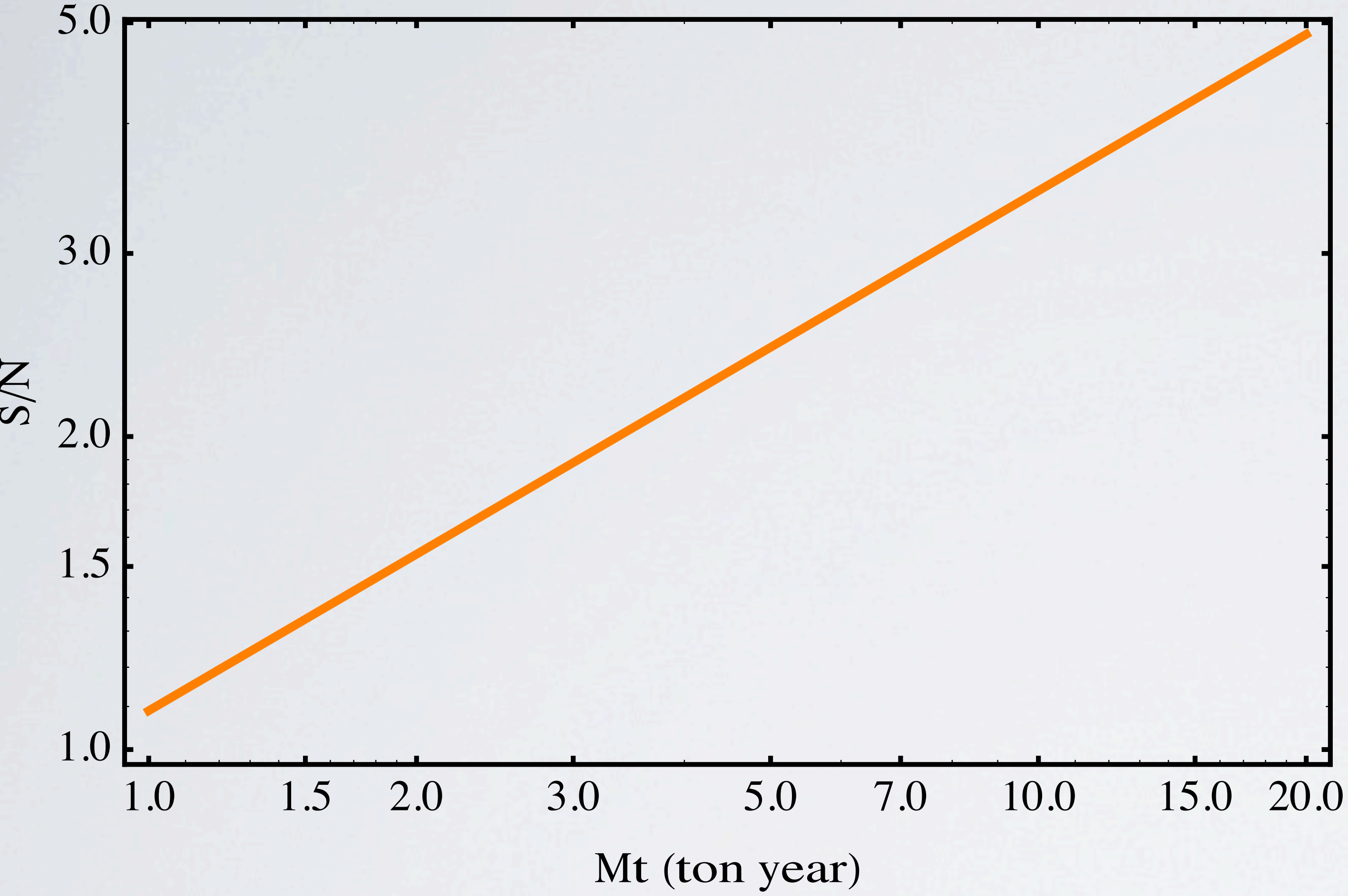
Cost and scalability is a concern. Ge/bolometers cost at least a factor 10 more than Xenon.

Example: Gerda has 30 detectors for 20 kg. Would need 1500 detectors for 1 ton.

LXe needs to deploy very large masses (a factor 10 more than the others).

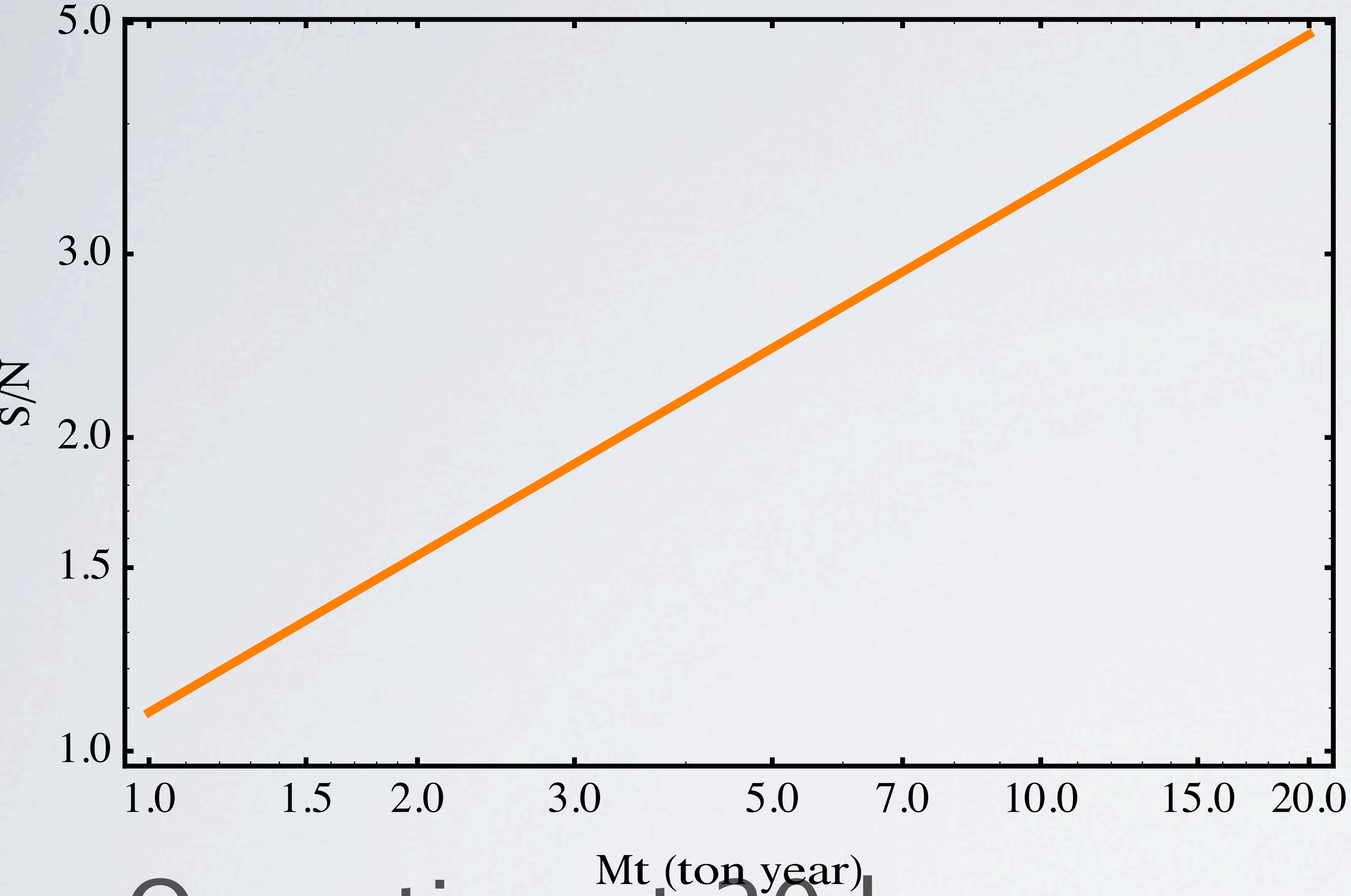
HPXe seems to be capable of striking an acceptable deal between scalability, cost and performance.

The 30 meV scale



- NEXT is scalable (like LXe) but does not need shelf-shielding (uses topology instead).
- Presumably also cheaper than the competition.

The 30 meV scale

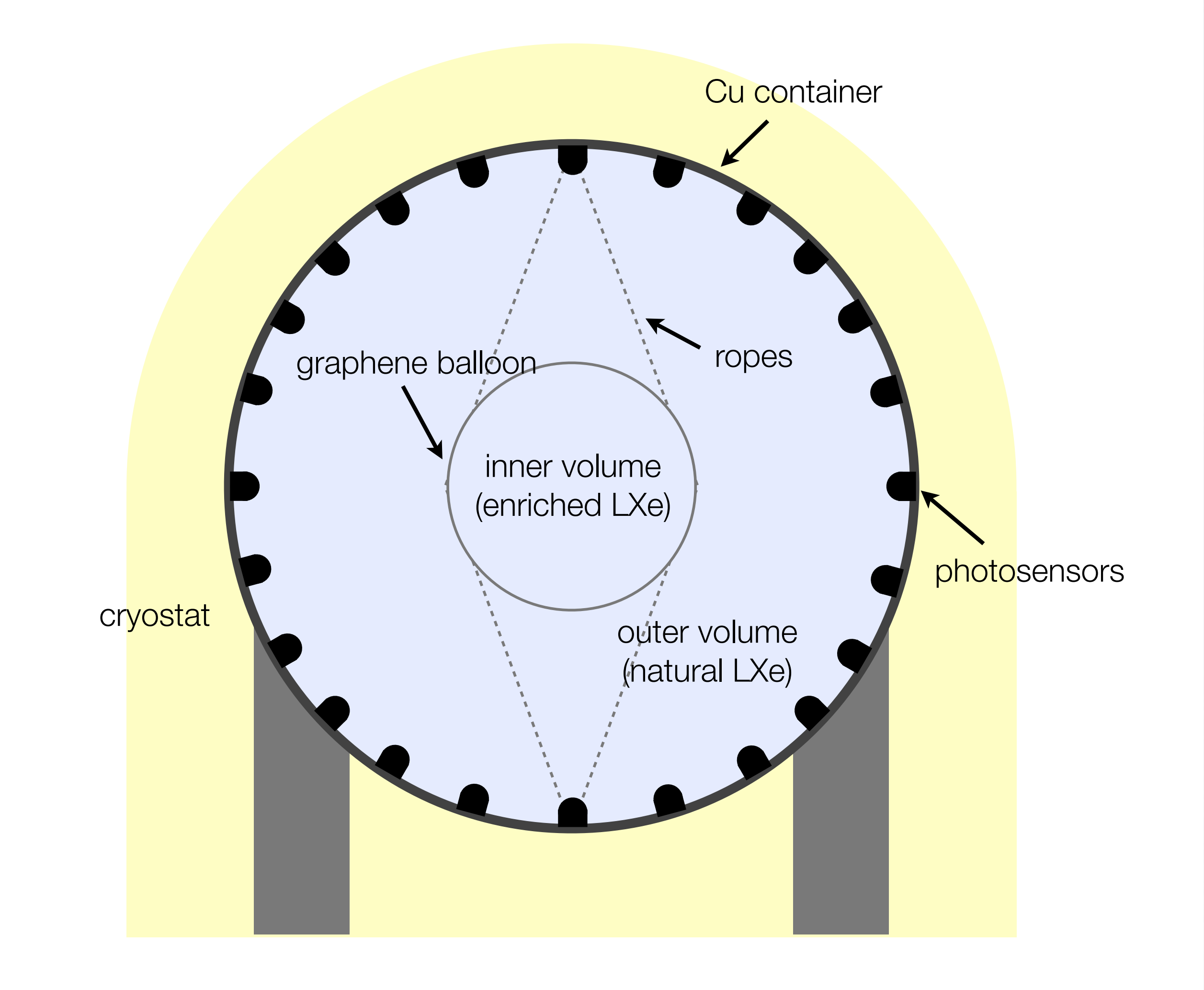


- NEXT is scalable (like LXe) but does not need shelf-shielding (uses topology instead).
- Presumably also cheaper than the competition.

Operating at 20 bar one needs 10 m^3 to fit one ton of xenon.
A symmetric TPC of R=1.5m and L1/2= 1.5 m would contain 20 m^3 or 2 tons.
One could reach 20 tons year (running for a full decade).

GraXe

JCAP 1202 (2012) 037



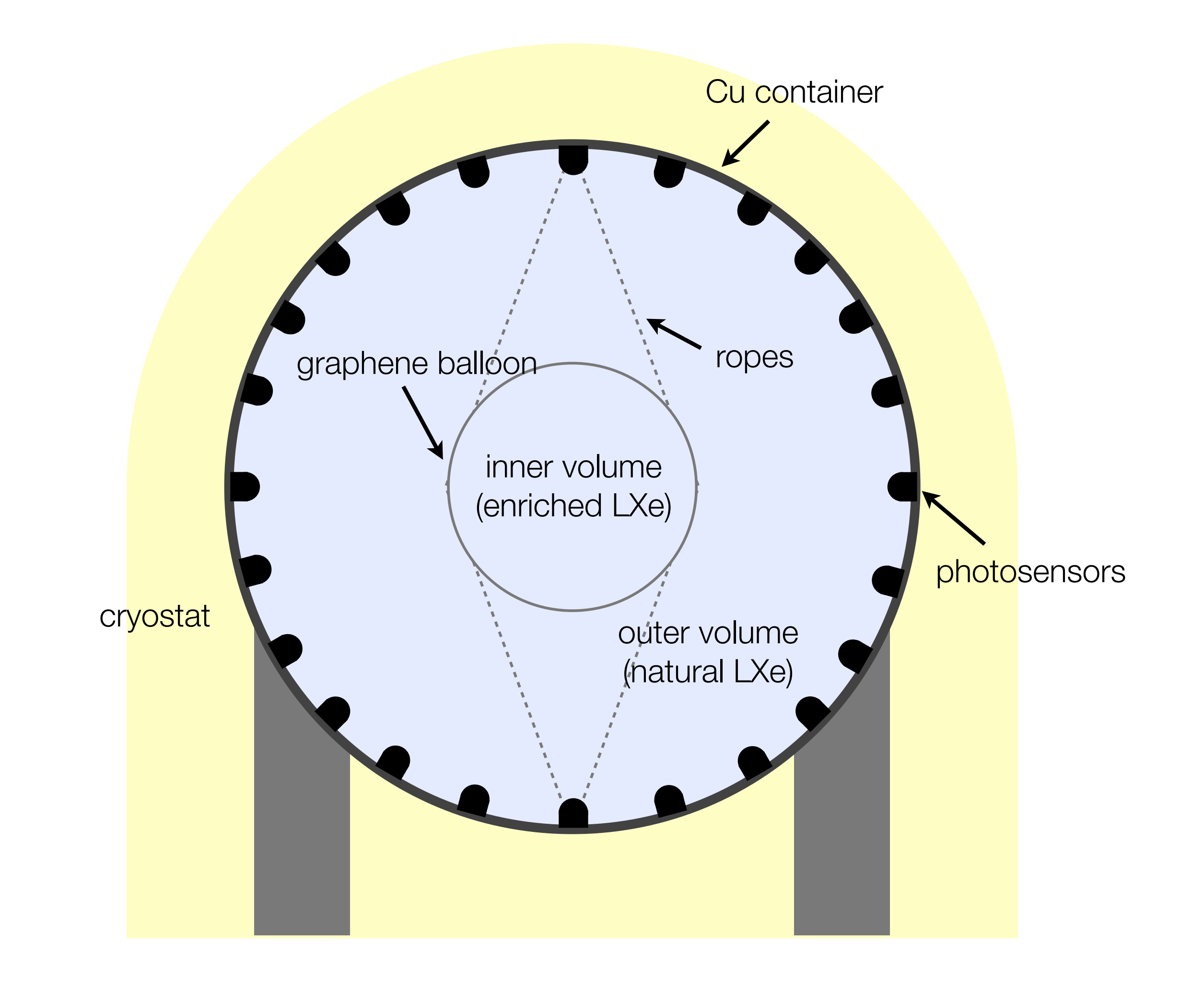
$$c = 10^{-5}\, ckky$$

$$\varepsilon(global) = 60\%$$

$$\Delta E = 96 keV$$

GraXe

JCAP 1202 (2012) 037



$$c = 10^{-5} ckky$$

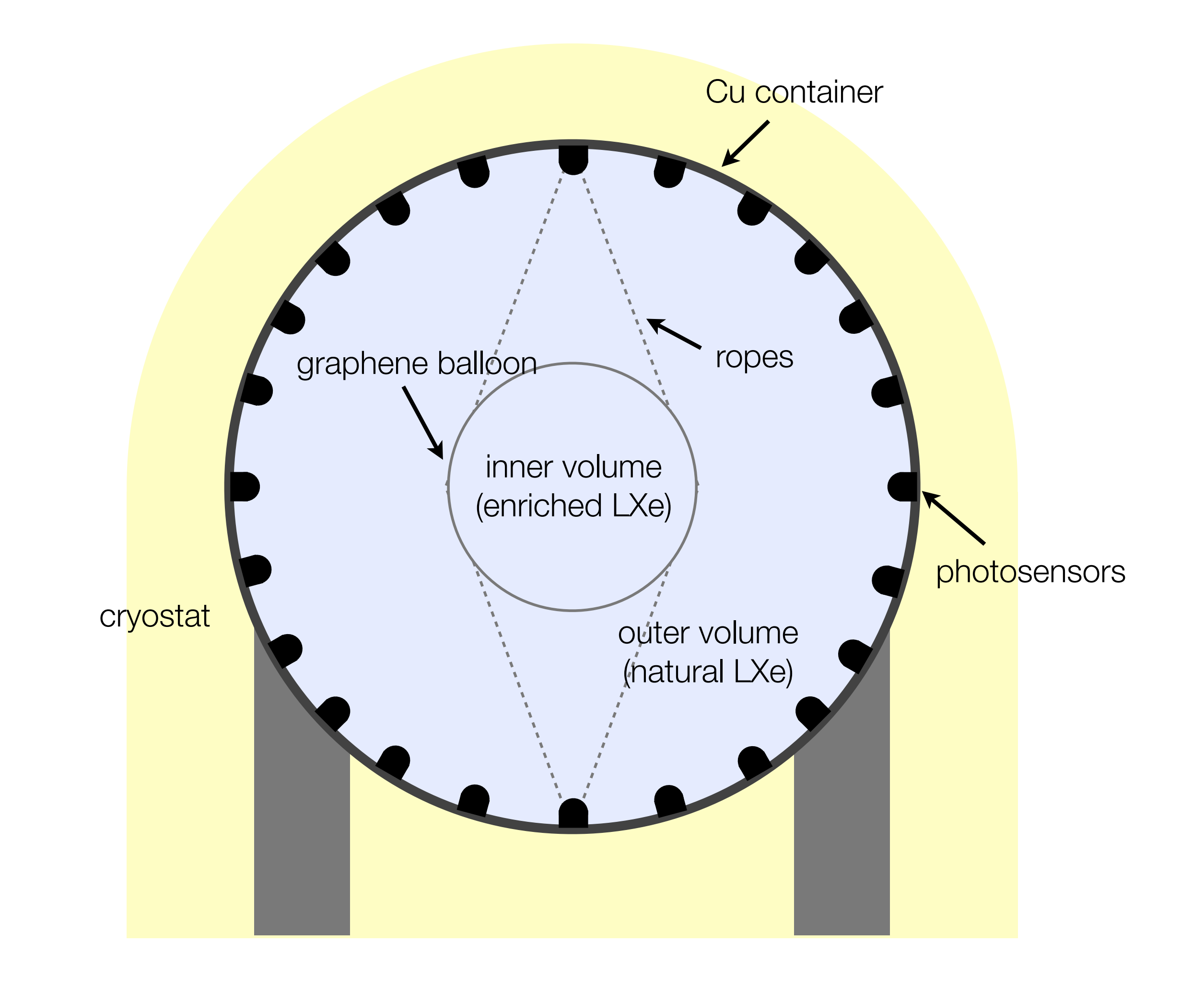
$$\varepsilon(global) = 60\%$$

$$\Delta E = 96 keV$$

- Outer Sphere, made of copper, tiled with PMTs, 1.2 m in radius, contains 20 tons of normal LXe
- Inner sphere, 45 or more cm radius. Graphene Balloon.
- Enriche LXe inside (1-5 ton)
- Graphene: fully metallic, impermeable to LXe, transparent to VUV light, few-layer atoms (no radioactive background)

GraXe

JCAP 1202 (2012) 037



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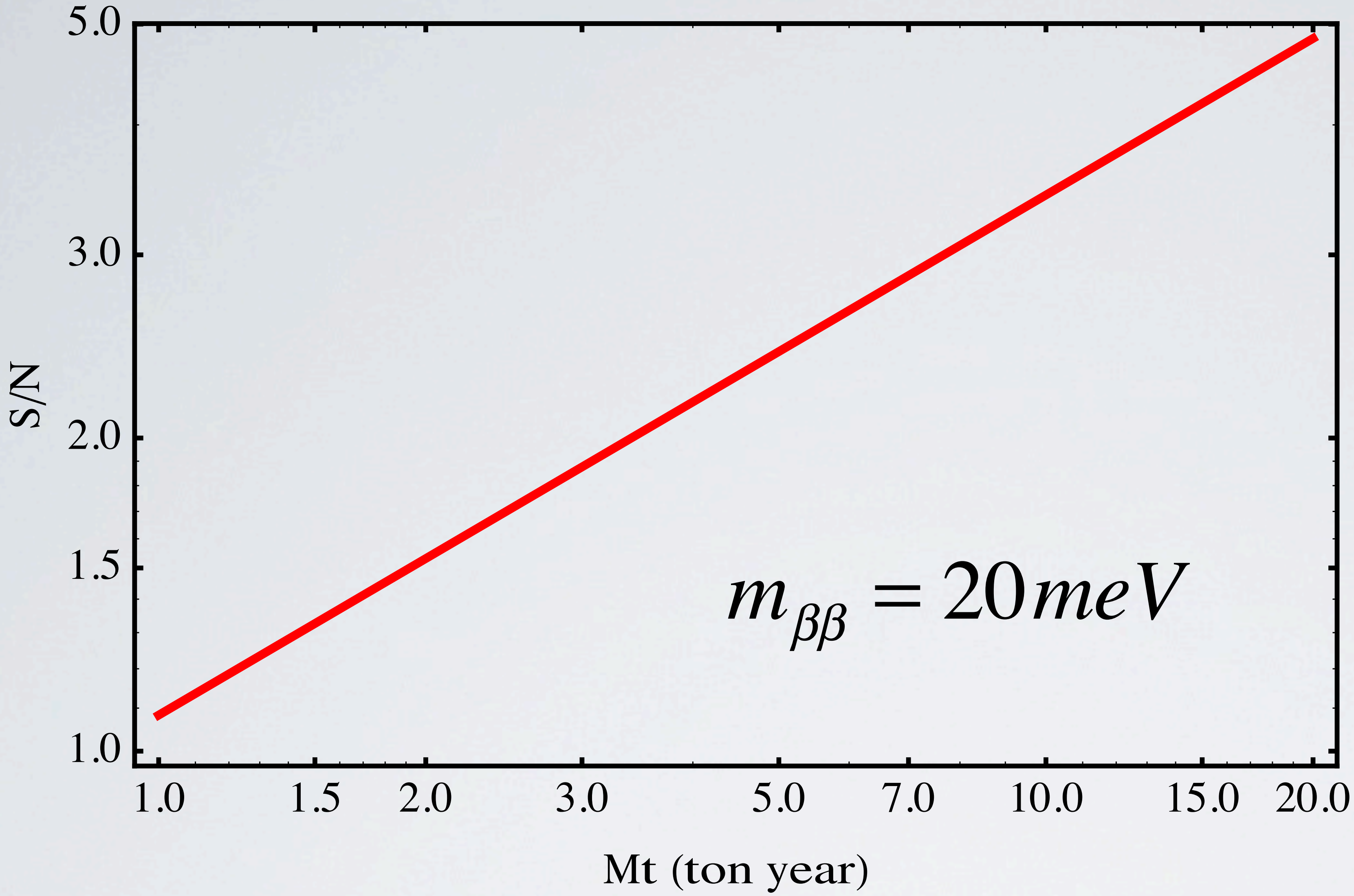
- Graphene: fully metallic, impermeable to LXe, transparent to VUV light, few-layer atoms (no radioactive background)

GraXe: Combines the EXO and KamLAND-Zen approaches thanks to Graphene balloon

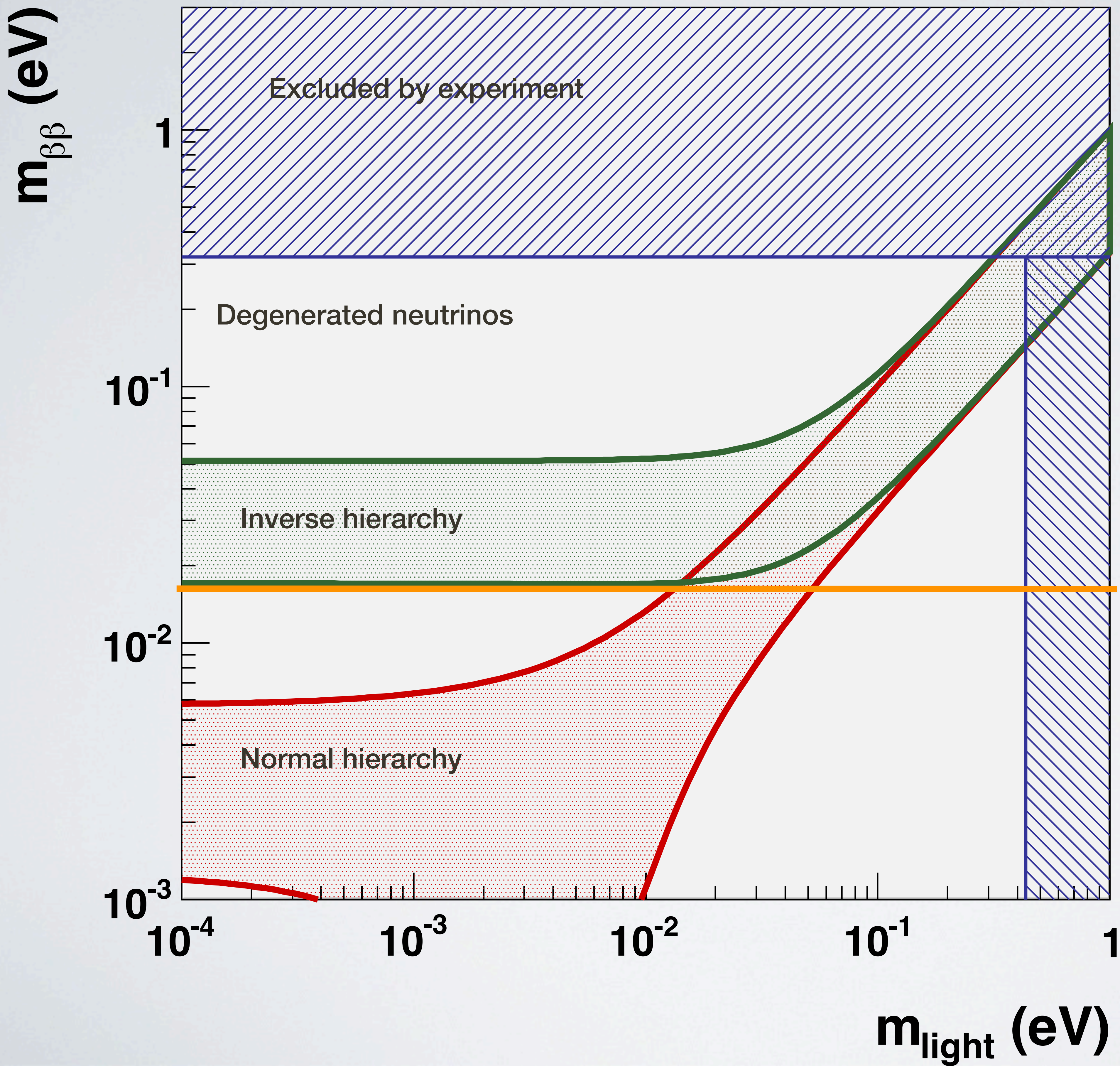


LXe-based detectors may also allow **identification of Ba daughter** nucleus, eliminating all non-ββ backgrounds

see, e.g., M.K. Moe, Phys. Rev. C. 44, R931 (1991)

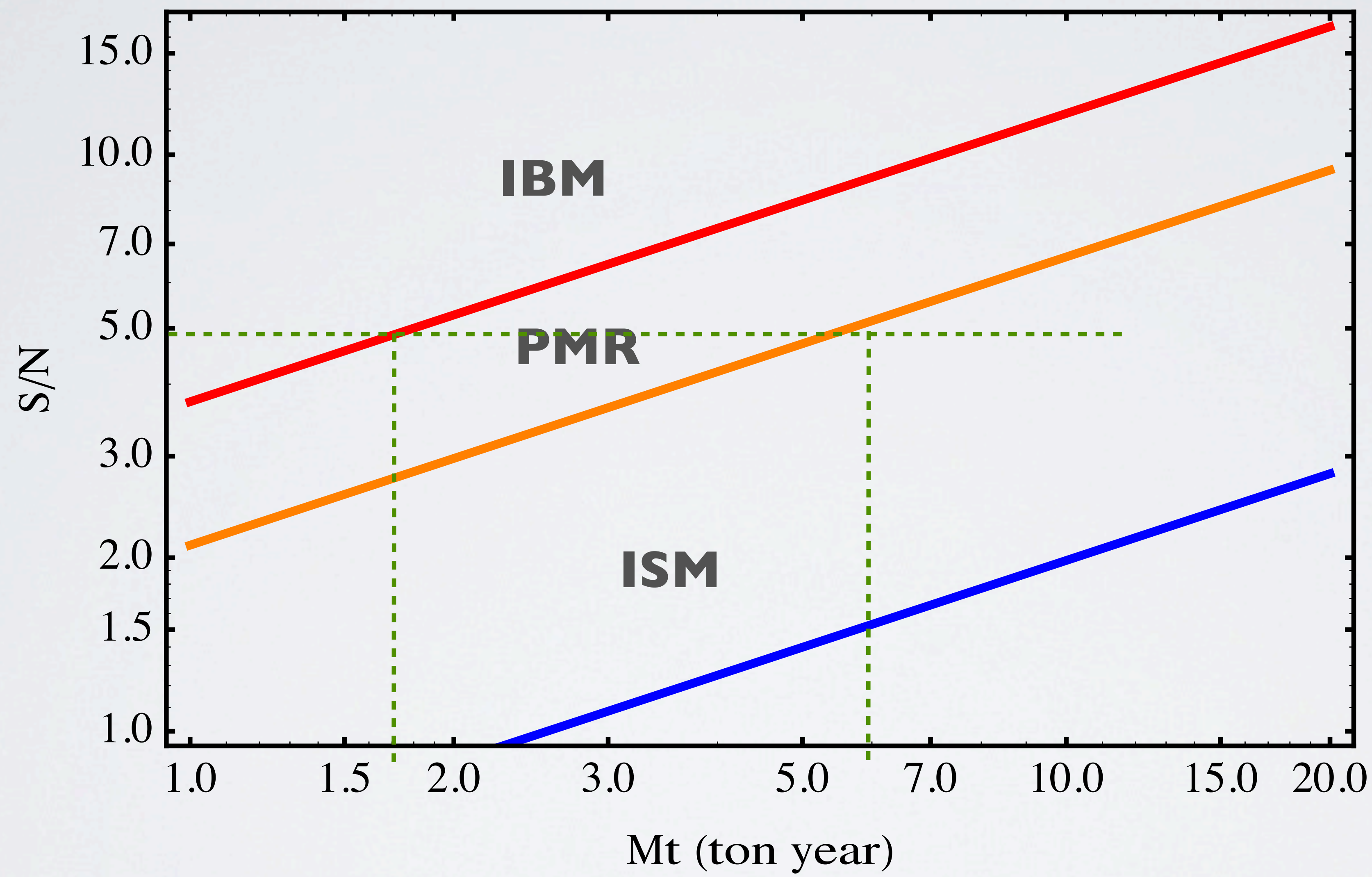
- To cover the inverse hierarchy GraXe needs 20 ton year. This is feasible (the inner balloon can contain a few tons) thanks to the density of LXe. The resolution of LXe is just enough to skirt bb2nu. The extreme self-shielding is achieved at a affordable cost thanks to the graphene technology.

GraXe & 20 meV scale

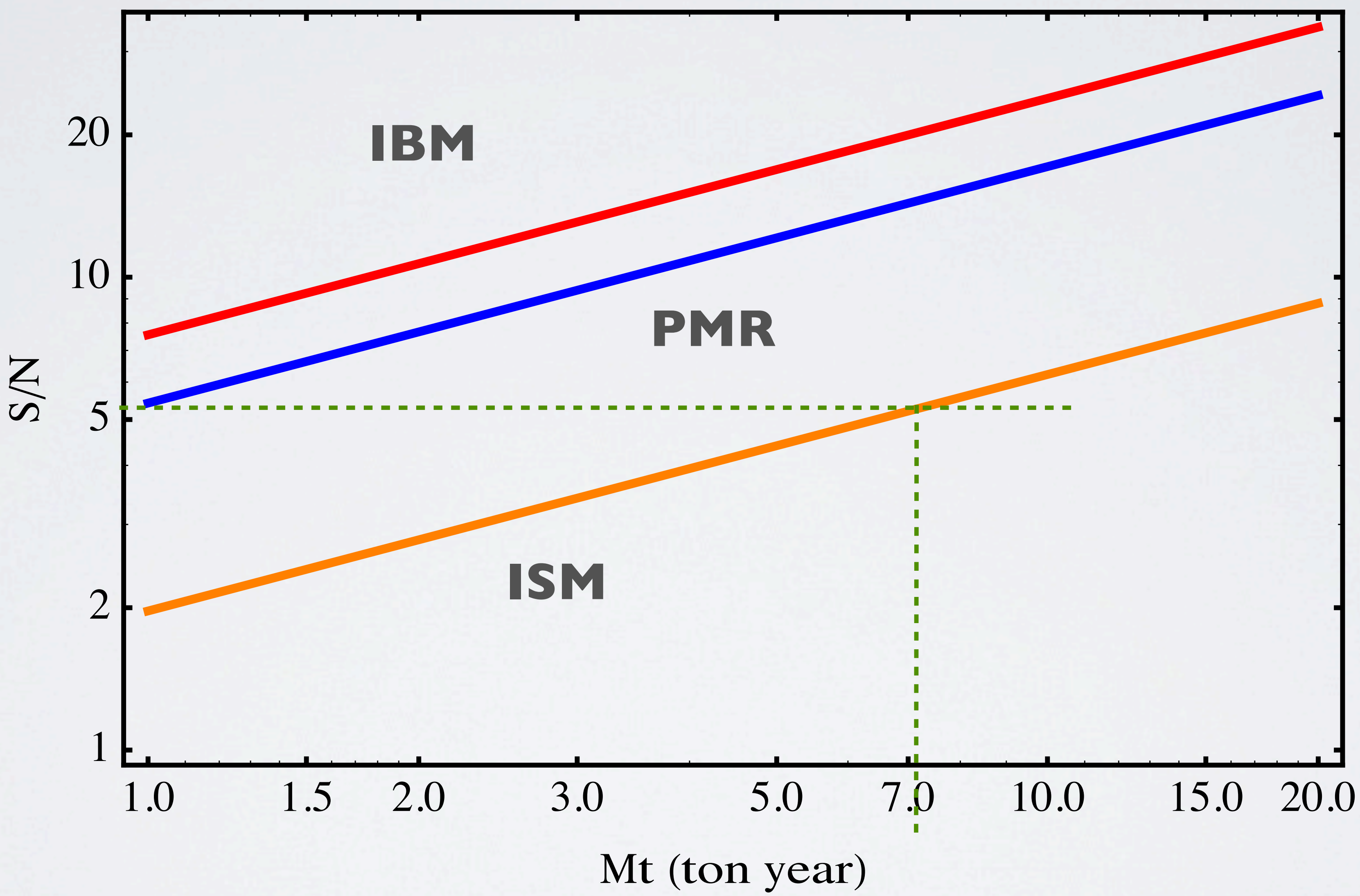


The effect of the NME

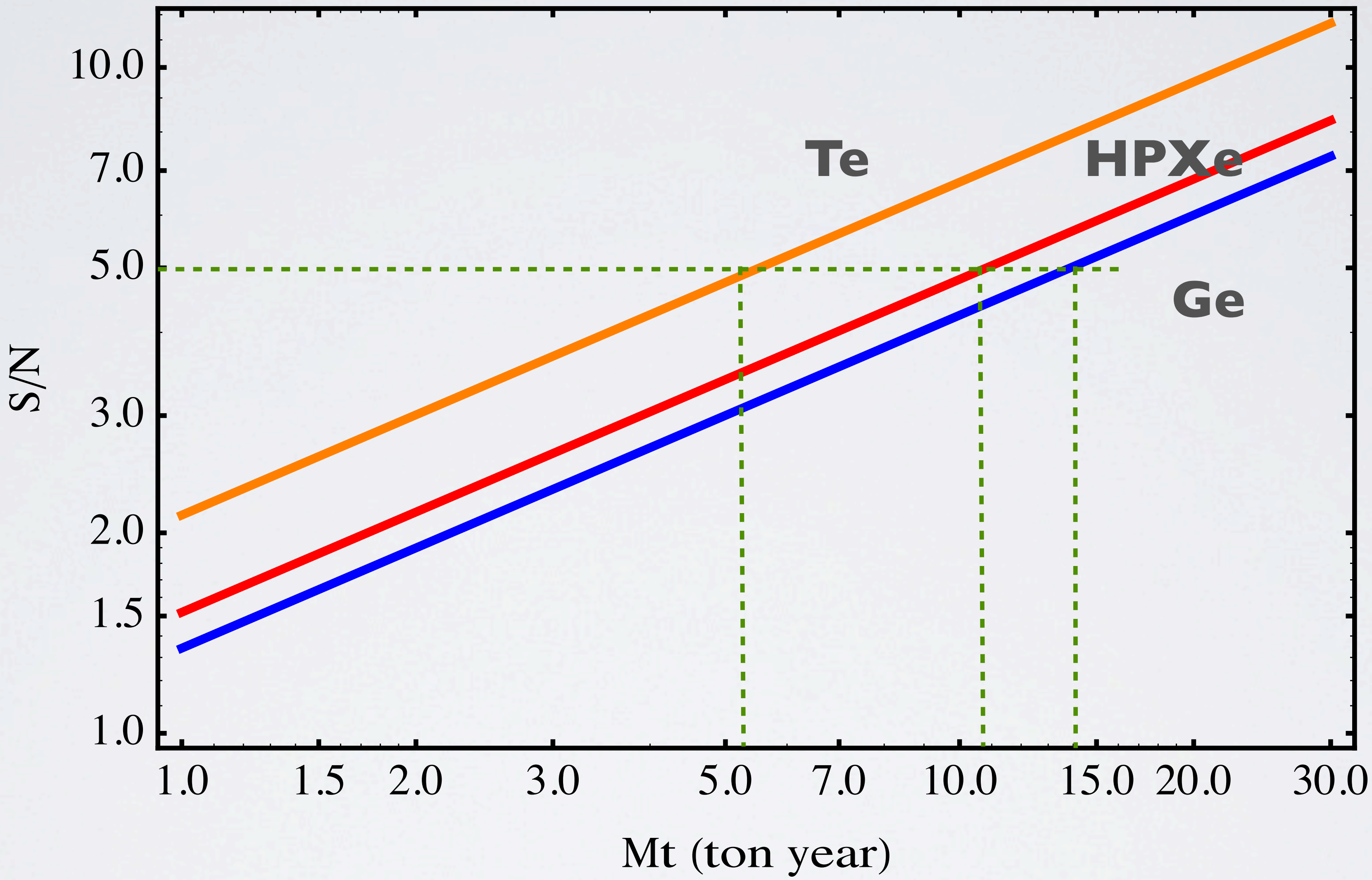
Ge-76
$m_{\beta\beta}$ = 50 meV



Xe-76
$m_{\beta\beta}$ = 50 meV



IBM set
$m_{\beta\beta}$ = 30 meV



The effect of the NME

- Unless dramatic theoretical progress is made, uncertainties associated to our (lack of) knowledge of the NMEs suggest that one should not place all the ships in the same quadrant of the galaxy.
- Searches based in 3 isotopes may very well be the best possible strategy.

Bodly going... beyond?

Bodly going... beyond?

- What if one does not find a signal at the 20 meV level?
- I hope I have convinced you that fully exploring the inverse hierarchy is hard enough.
- One could explore further (at great cost), find nothing... and prove nothing, due to accidental cancelations!
- Even Startrek must watch for black holes!

Captains logbook

- This is good moment for the field, with 3 experiments in the market.
- However, current generation of detectors won't even scratch the inverse hierarchy. To reach 50 meV, one needs to improve background suppression by one order of magnitude and deploy masses of the order of the ton.

Captains logbook

- New ideas are needed. Experiments based on Ge (with full shielding and multi-site detection), scintillating bolometers (a la Lucifer) and HPXe TPCs (a la NEXT) seem capable of reaching the 50 meV mark, provided they can acquire and deploy the mass (this may be easier for HPXe).

- LXe detectors are also a viable path. Improvement there should come either from Ba tagging or by technological break through a la GraXe.

Captains logbook

- The uncertainties in the NMEs suggest that diversifying the fleet (eg using several isotopes) is a wise approach.
- Exploring the inverse hierarchy requires masses in the scale of multiton and background rates extremely small.
- Getting there will take considerable effort. Eventually more than one technique (and more than one isotope) may succeed.
- Europe may lead this exciting field, if we only try...

Captains logbook

- Europe: Gerda, Cuore, NEXT... (GraXe?) can lead this exciting field.

In memoriam, James White

Thanks for your attention