Neutrinoless double-beta decay

Status, overview and outlook

Simon JM Peeters

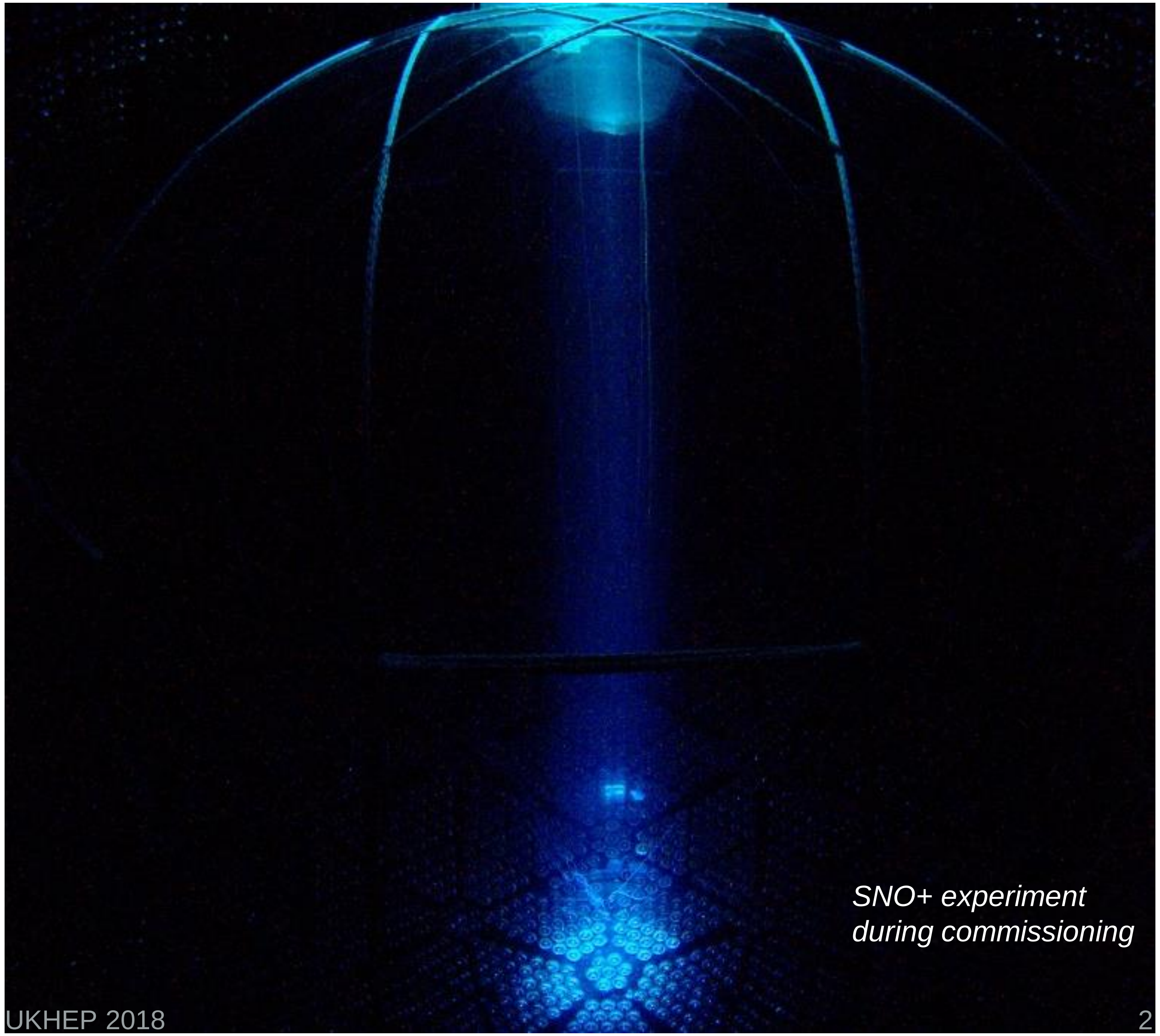
SPICE OF FLAVOUR, UKHEP FORUM

December 2018

UNIVERSITY OF SUSSEX

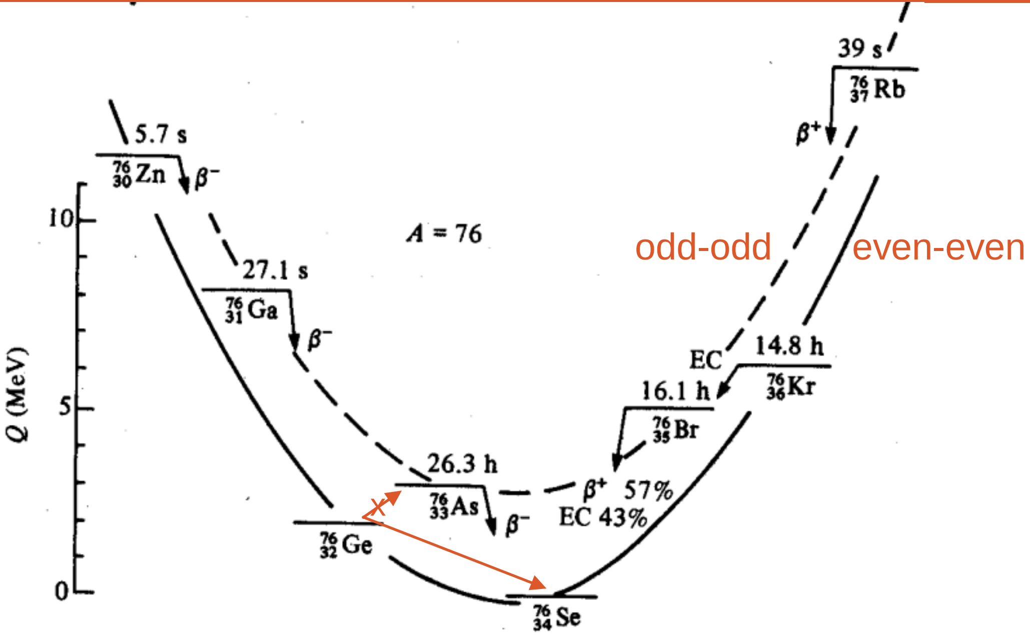
A spotlight on 0νββ

- Neutrinoless double-beta decay: *Why & how?*
- Global picture
- Experiments with UK involvement
- Outlook

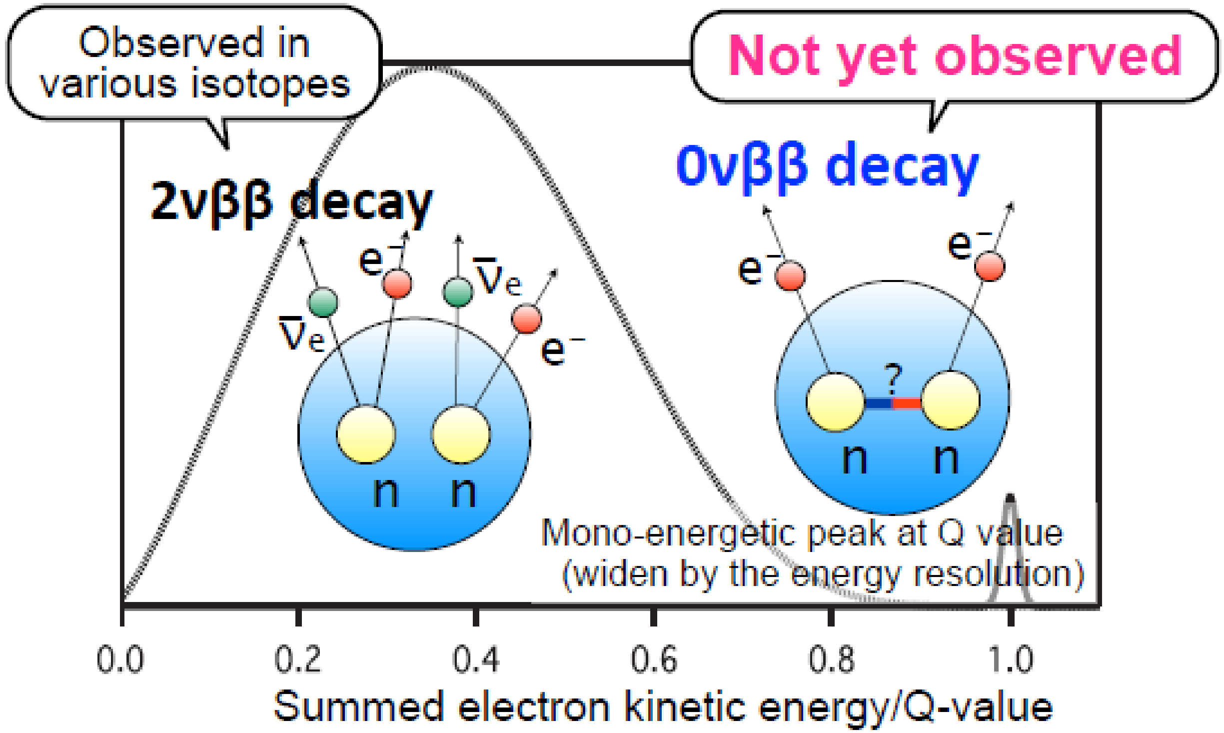


SNO+ experiment during commissioning

Neutrinoless double-beta decay



Isotope	Nat ab.	$Q_{\beta\beta}$ [keV]
^{48}Ca	0.19 %	4262.96(84)
^{76}Ge	7.6%	2039.04(16)
^{82}Se	8.7%	2997.9(3)
^{96}Zr	2.8%	3356.097(86)
^{100}Mo	9.6%	3034.40(17)
^{116}Cd	7.5%	2813.50(13)
^{130}Te	34.5%	2526.97(23)
^{136}Xe	8.9%	2457.83(37)
^{150}Nd	5.6%	3371.38(20)



UNIVERSITY OF SUSSEX

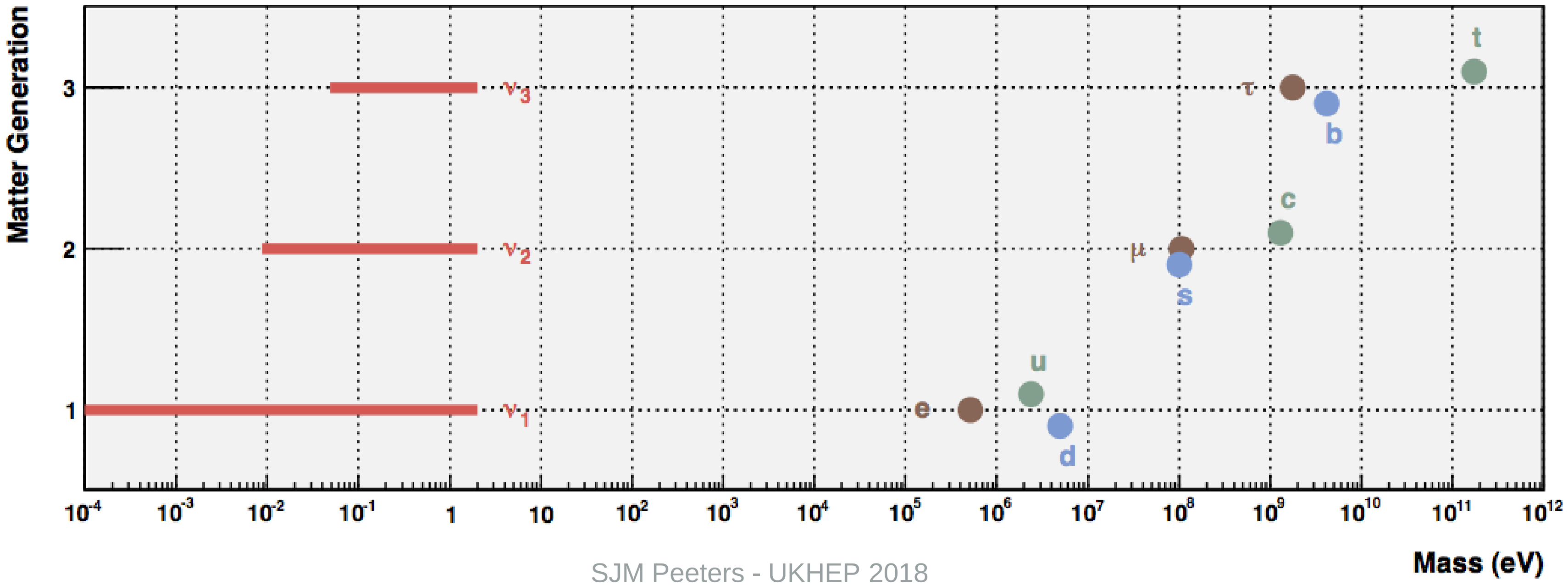
0νββ provides unique information

Observation would imply:

- Violation of lepton number (by 2!)
- Neutrinos have Majorana masses (different than quarks and leptons, Schlechter and Valle, 1982)
- New physics!

It would inform us about:

- An explanation why neutrinos are so much lighter than other particles
- Leptogenesis, a possible origin of the baryon-antibaryon asymmetry ***if neutrinos violate CP (DUNE/HK)***
- Neutrino absolute mass scale



0νββ decay

$$\tau_{0\nu}^{-1} = G_{0\nu}(Q,Z)\left|M^{0\nu}\right|^2 \langle m_{ee}\rangle^2$$

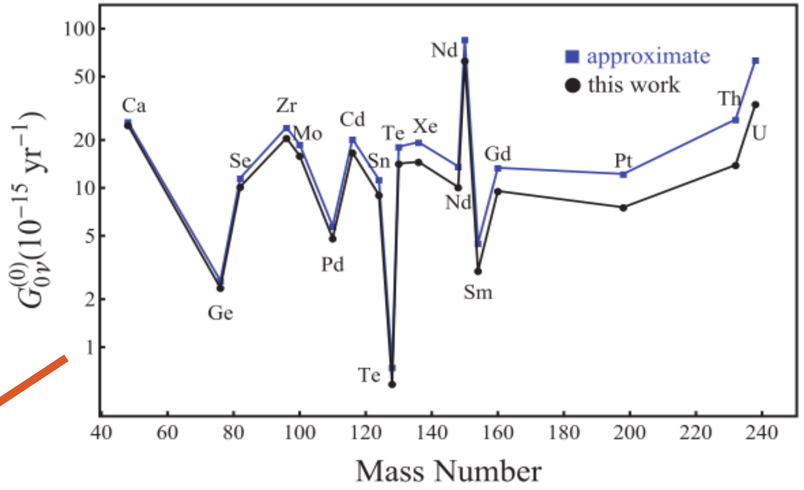
$$\langle m_{ee}\rangle = \sum_k U_{ek}^2 m_k$$
$$= \cos^2\theta_{12}\cos^2\theta_{13} m_1 + \sin^2\theta_{12}\cos^2\theta_{13} e^{i\alpha} m_2 + \sin^2\theta_{13} e^{i\beta} m_3$$

UNIVERSITY OF SUSSEX

$\langle m_{ee}\rangle = \langle m_{\beta\beta}\rangle$

0νββ decay

J. Kotila and F. Iachello, Phys. Rev. C 85, 034316 (2012)



$$\tau_{0\nu}^{-1} = G_{0\nu}(Q,Z)\left|M^{0\nu}\right|^2 \langle m_{ee}\rangle^2$$

(g_A in matrix element)

$$\langle m_{ee}\rangle = \sum_k U_{ek}^2 m_k$$

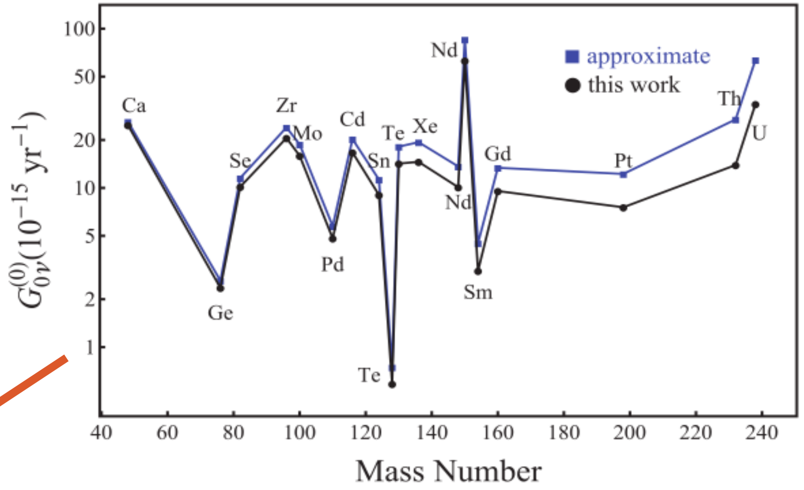
$$= \cos^2\theta_{12}\cos^2\theta_{13}m_1 + \sin^2\theta_{12}\cos^2\theta_{13}e^{i\alpha}m_2 + \sin^2\theta_{13}e^{i\beta}m_3$$

$\langle m_{ee}\rangle = \langle m_{\beta\beta}\rangle$

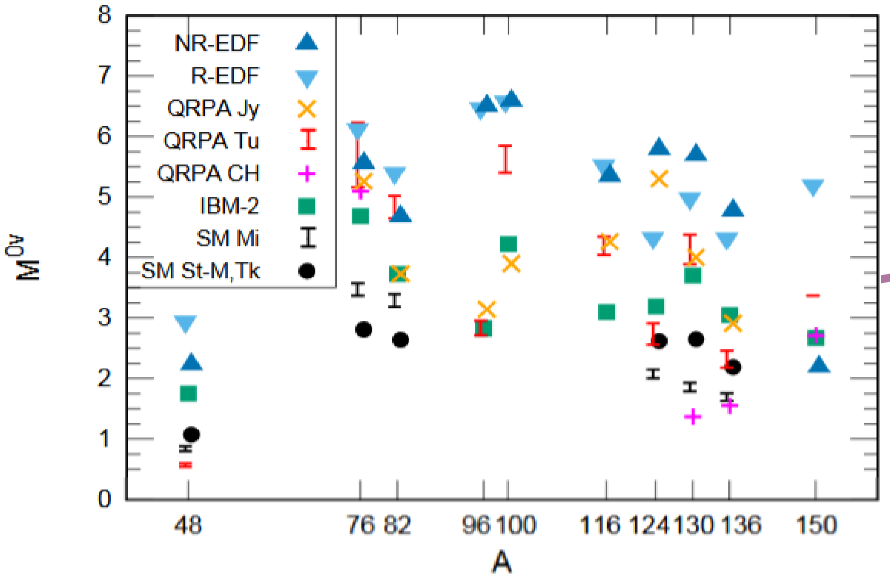
UNIVERSITY OF SUSSEX

0νββ decay

J. Kotila and F. Iachello, Phys. Rev. C 85, 034316 (2012)



Rep. Progr. Phys. 80, 046301 (2017)



$$\tau_{0\nu}^{-1} = G_{0\nu}(Q,Z)\left|M^{0\nu}\right|^2 \langle m_{ee}\rangle^2$$

(g_A in matrix element)

$$\langle m_{ee}\rangle = \sum_k U_{ek}^2 m_k$$

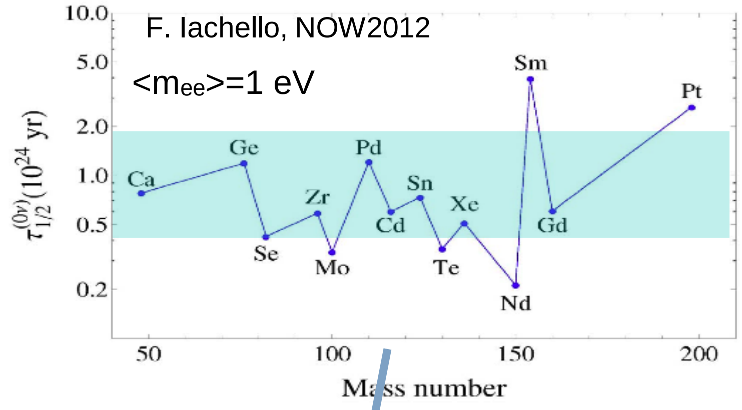
$$= \cos^2\theta_{12}\cos^2\theta_{13}m_1 + \sin^2\theta_{12}\cos^2\theta_{13}e^{i\alpha}m_2 + \sin^2\theta_{13}e^{i\beta}m_3$$

UNIVERSITY OF SUSSEX

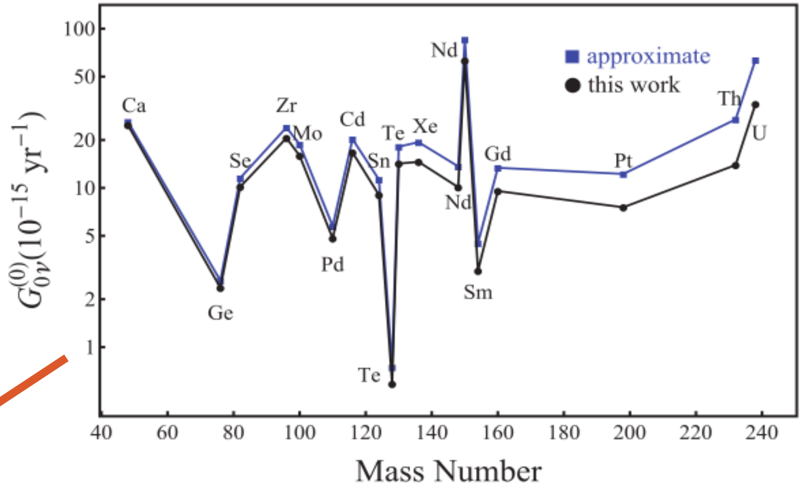
$\langle m_{ee}\rangle = \langle m_{\beta\beta}\rangle$

0νββ decay

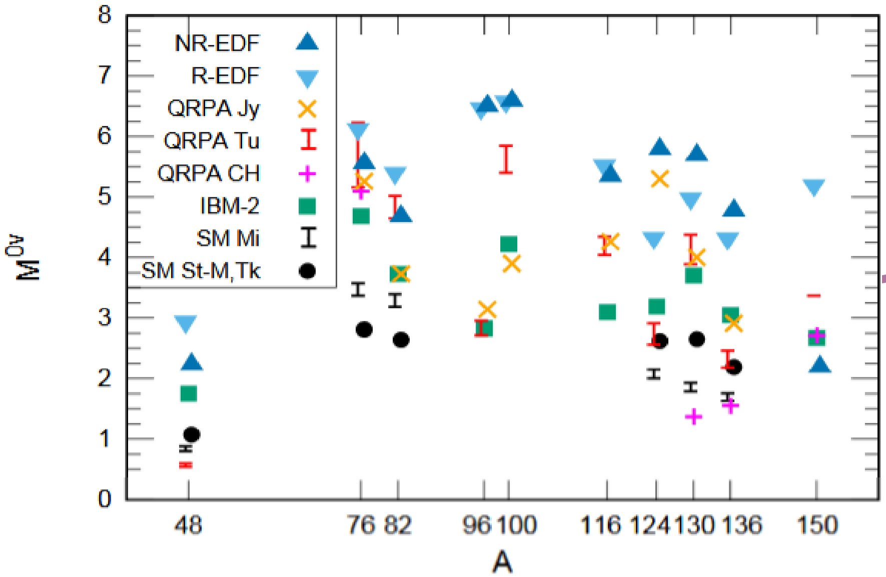
Combining NME with PSF we obtain the expected half-lives



J. Kotila and F. Iachello, Phys. Rev. C 85, 034316 (2012)



Rep. Progr. Phys. 80, 046301 (2017)



$$\tau_{0\nu}^{-1} = G_{0\nu}(Q,Z)\left|M^{0\nu}\right|^2 \langle m_{ee}\rangle^2$$

(g_A in matrix element)

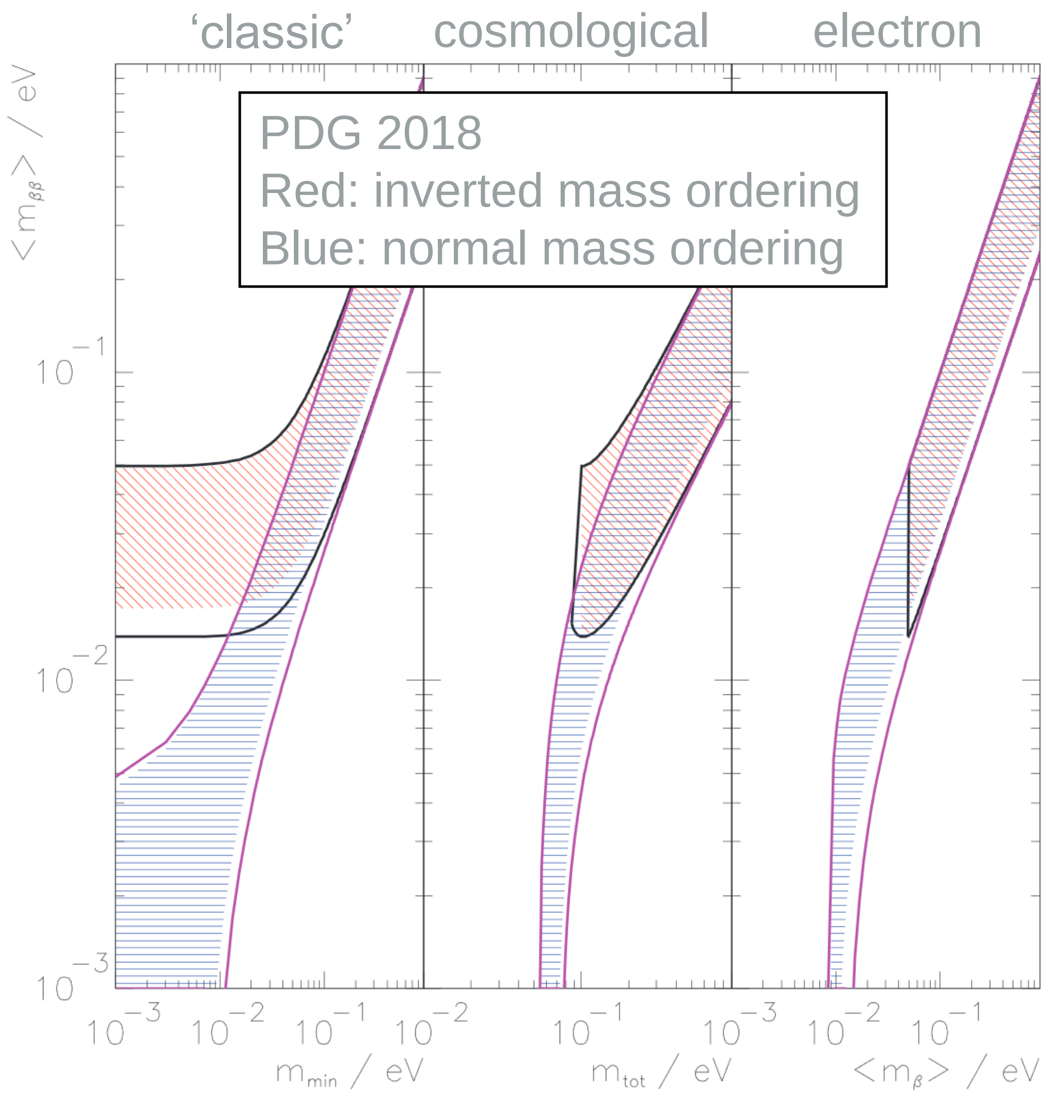
$$\langle m_{ee}\rangle = \sum_k U_{ek}^2 m_k$$

$$= \cos^2\theta_{12}\cos^2\theta_{13}m_1 + \sin^2\theta_{12}\cos^2\theta_{13}e^{i\alpha}m_2 + \sin^2\theta_{13}e^{i\beta}m_3$$

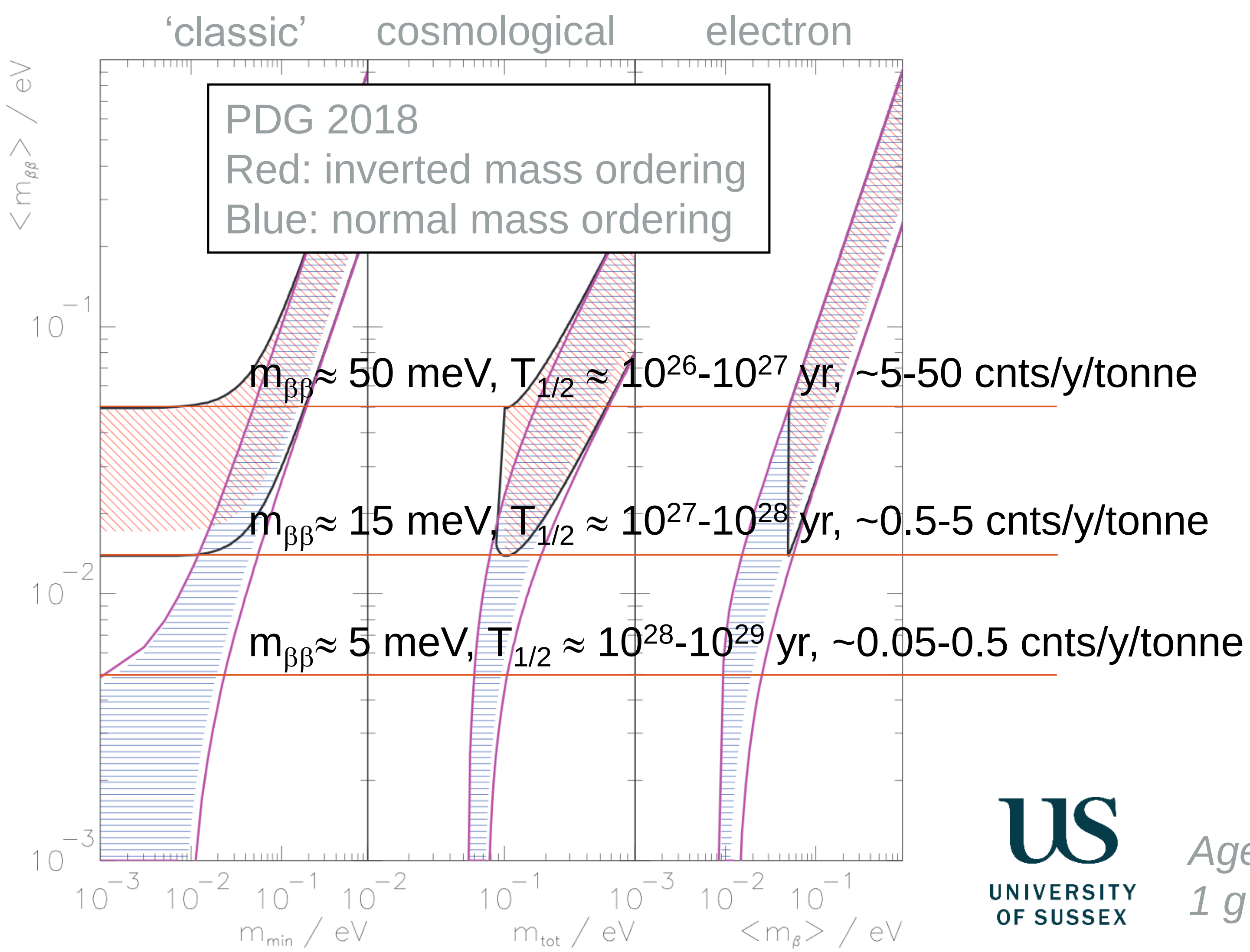
UNIVERSITY OF SUSSEX

$<m_{ee}> = <m_{\beta\beta}>$

Parameter space



Parameter space

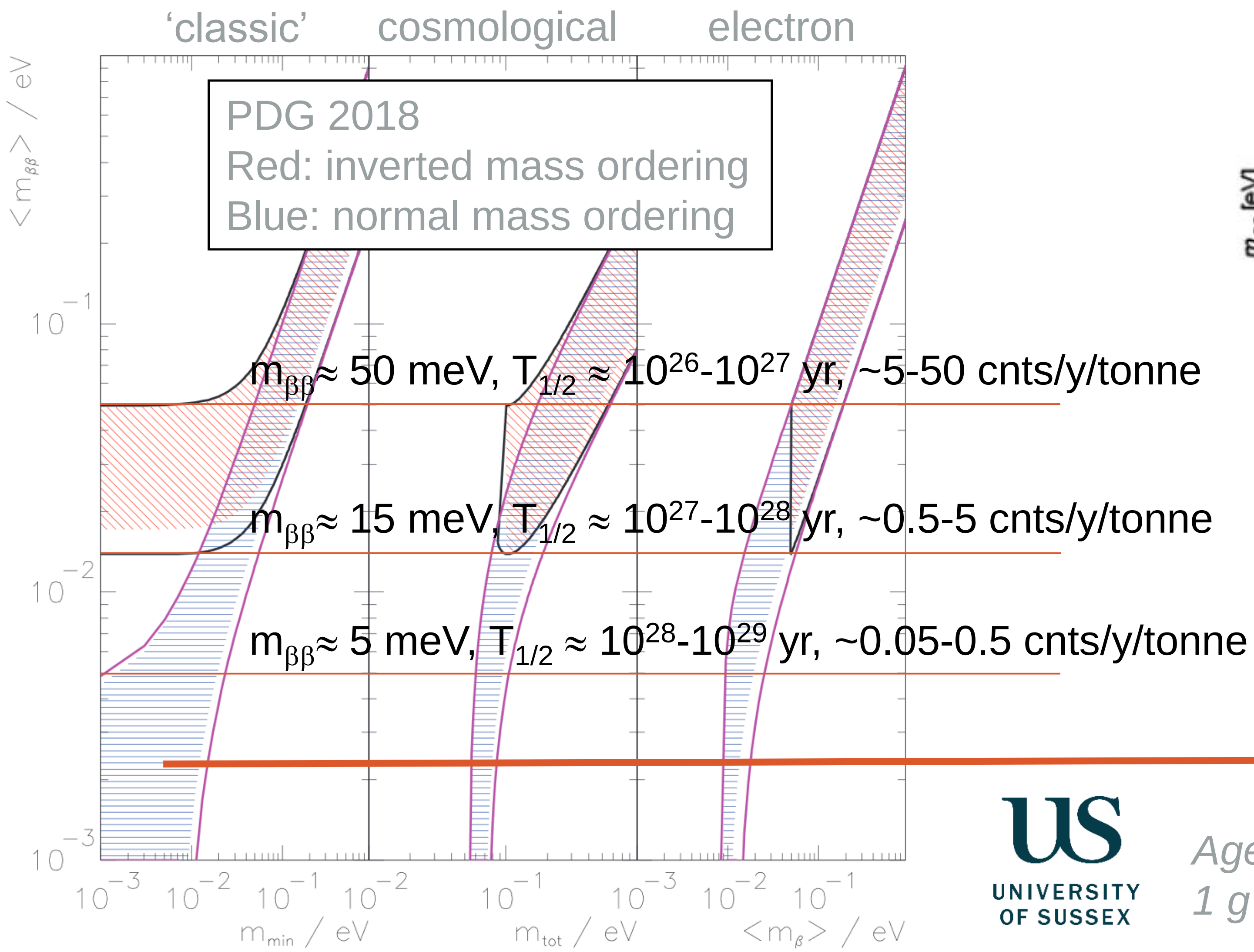


UNIVERSITY OF SUSSEX

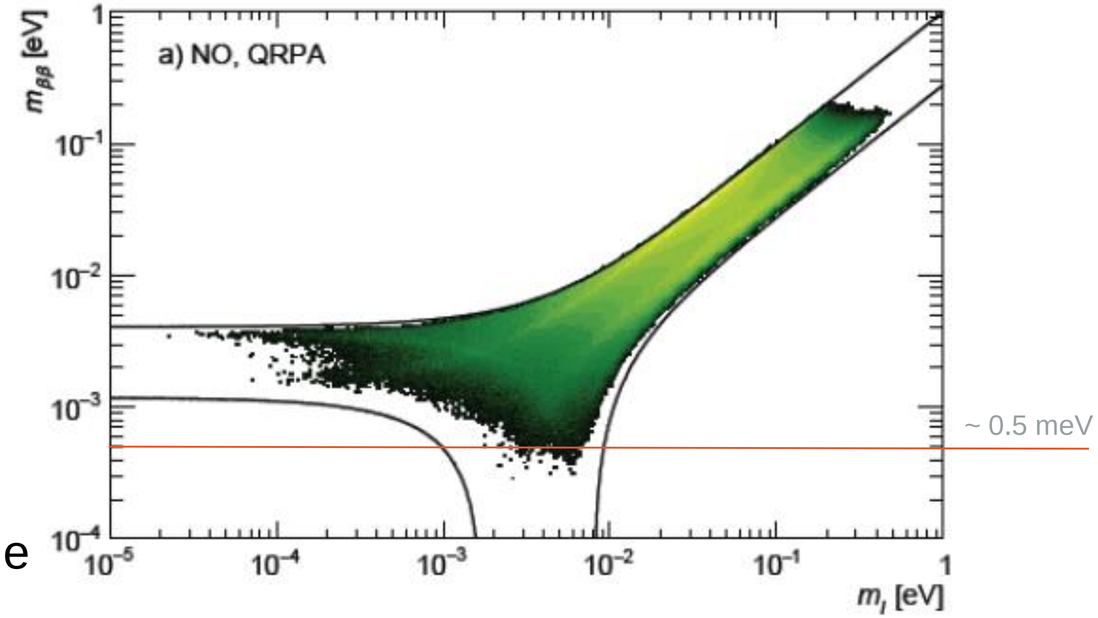
Age of the Universe: 13.8 x 10^9 y

1 g rock (~1 ppm U/Th) gives about 500,000 cnts / y

Parameter space



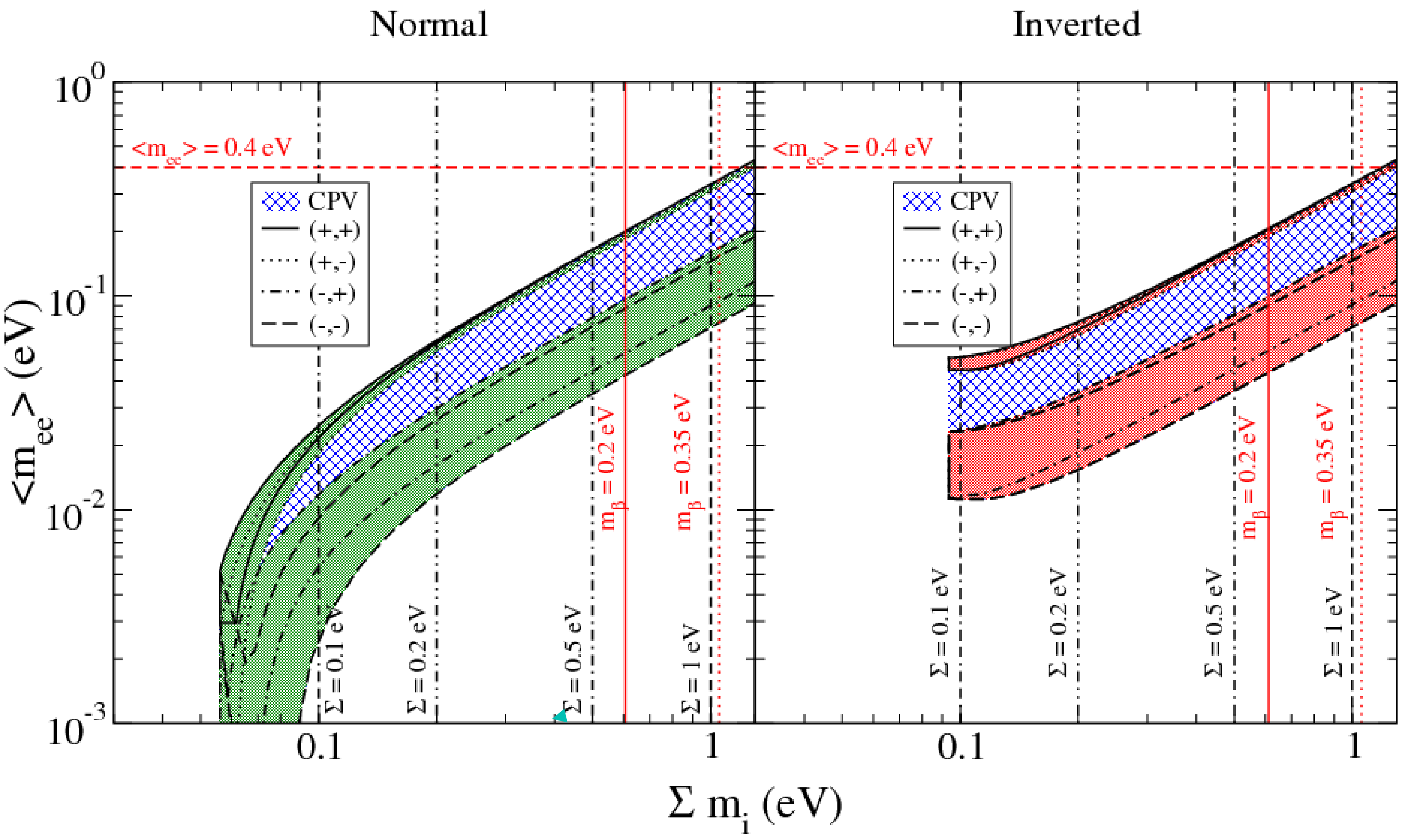
Phys. Rev. D **96**, 053001 (2017)
Global Bayesian analysis including ν-oscillation, m_β,$m_{\beta\beta}$,Σ
Priors:
- Majorana phases (flat)
- m_1 (scale invariant)



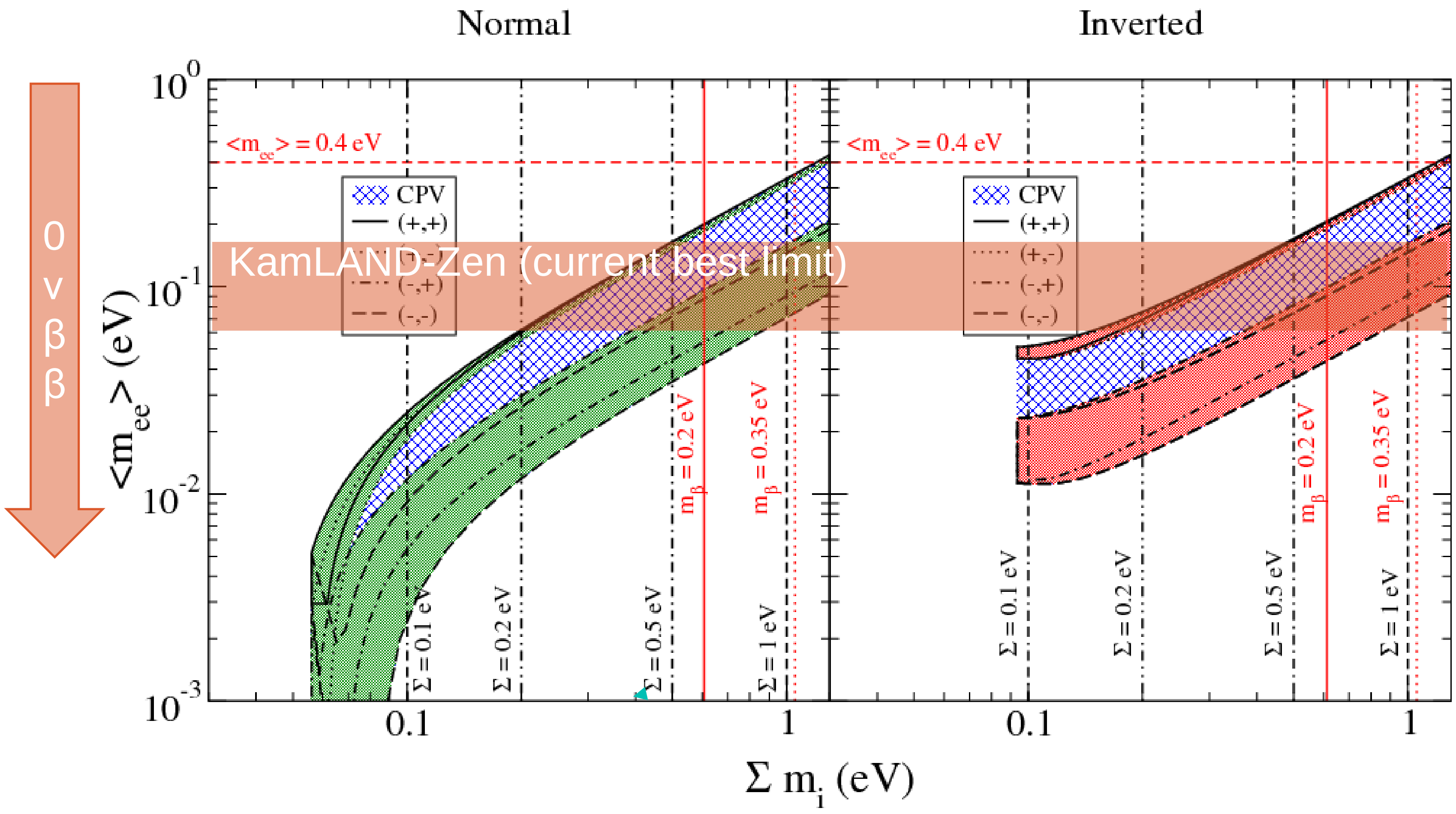
Limited parameter space!

Age of the Universe: 13.8 x 10^9 y
1 g rock (~1 ppm U/Th) gives about 500,000 cnts / y

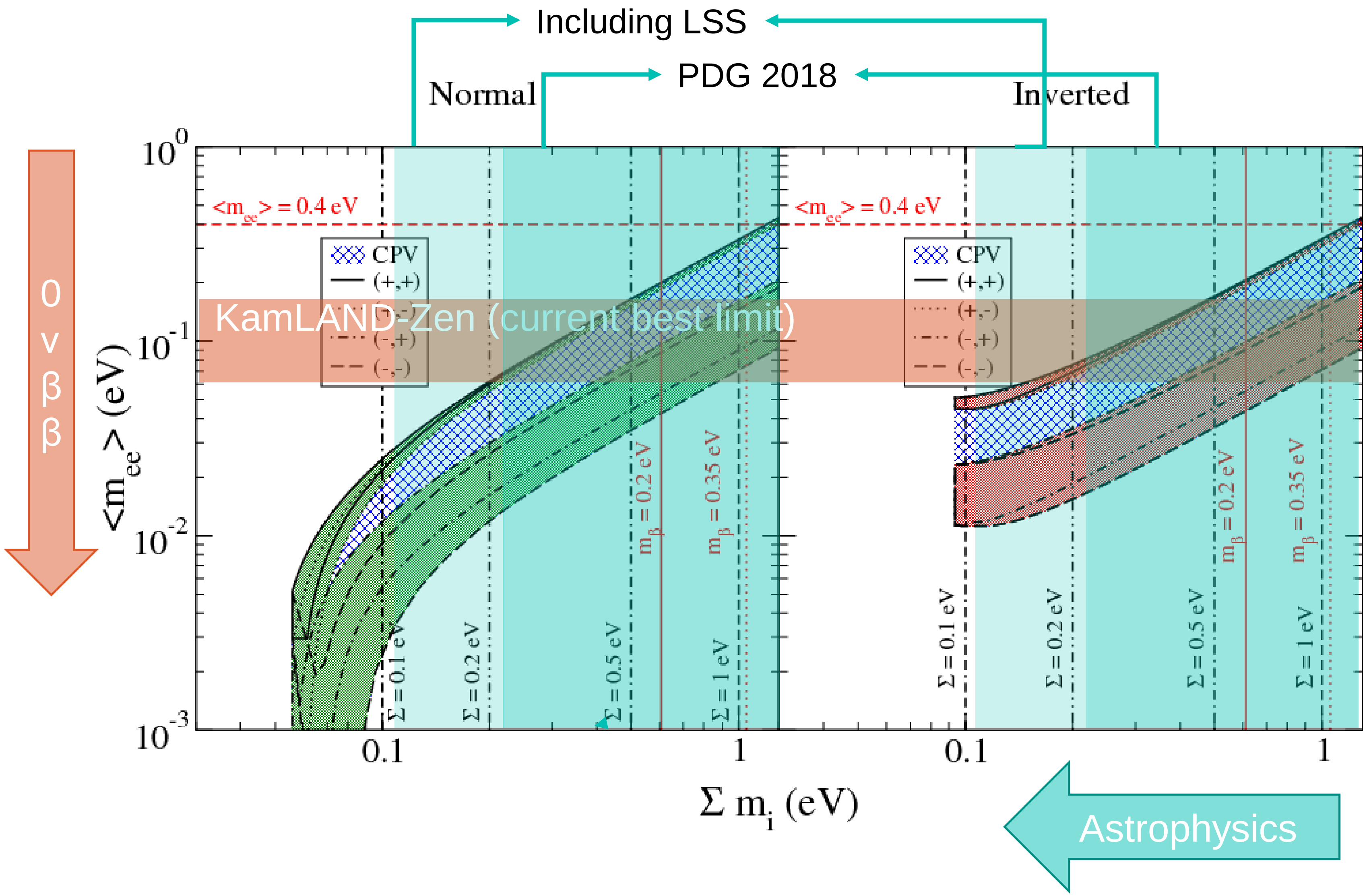
Current status of the parameter space



Current status of the parameter space



Current status of the parameter space

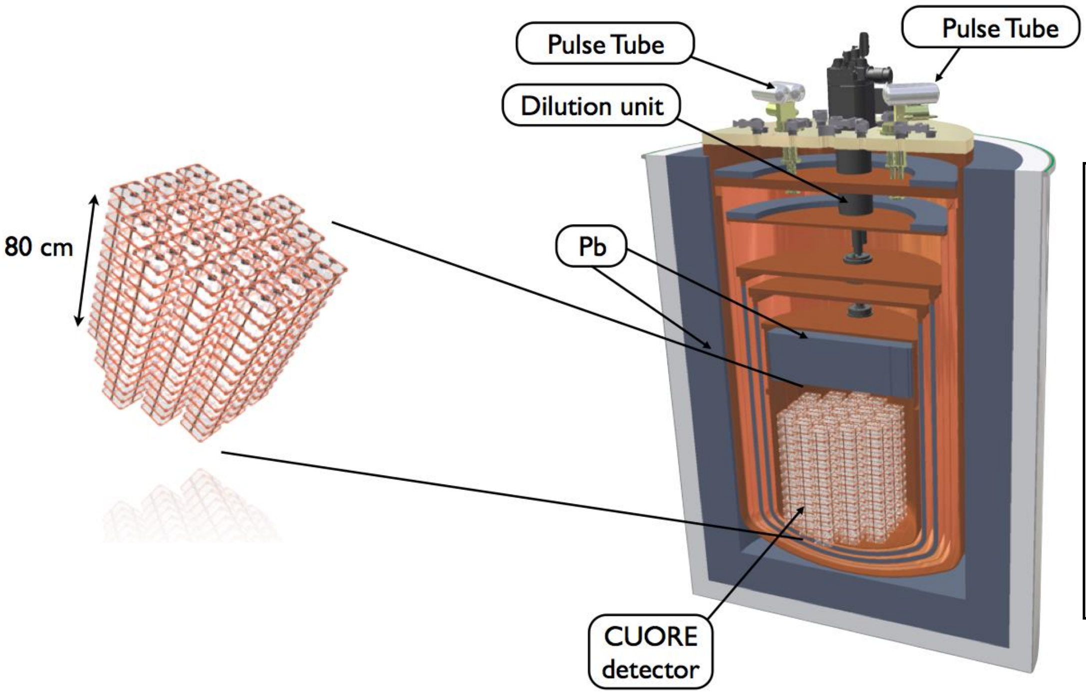


Global activity

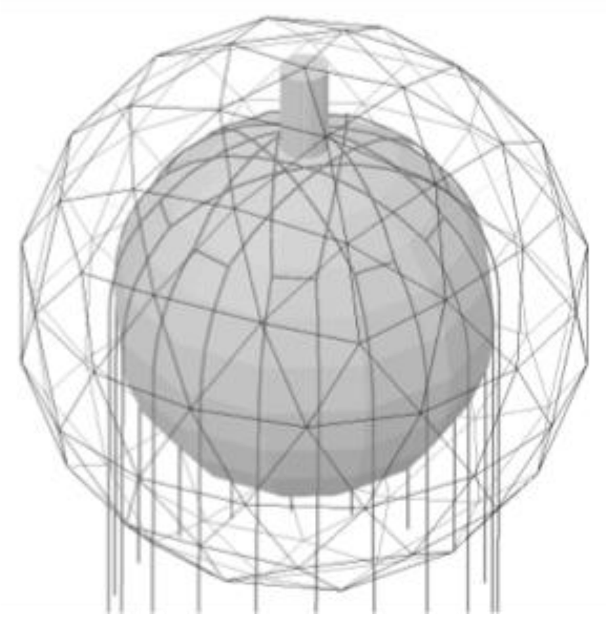
Different approaches

Modular (CUORE,LEGEND)

Monolithic (SNO+,LXe)



NSAC review (US) Nov 2015:
"The modular and monolithic approaches both offer advantages and disadvantages. However, it is not possible to firmly conclude which approach will be optimal at this point"



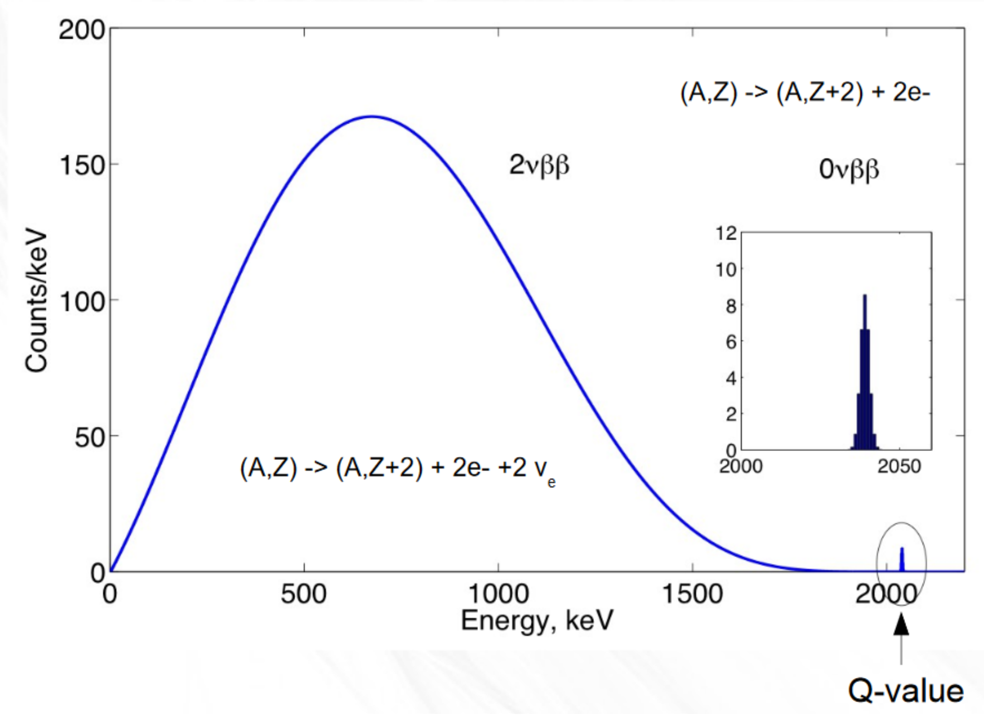
UNIVERSITY OF SUSSEX

Tracking/PID will become important to suppress backgrounds and for interpretation, in case of an observation.

Scaling argument

$$\sigma T_{\frac{1}{2}} = \frac{S}{\sqrt{B_{\text{total}}}} = \frac{Mt}{\sqrt{B_i \Delta E t}} \qquad \left(T_{\frac{1}{2}} \propto m_{\beta\beta}^2\right)$$

Background: $B_i \Delta E = (bM + c)\,\Delta E$



UNIVERSITY OF SUSSEX

Scaling argument

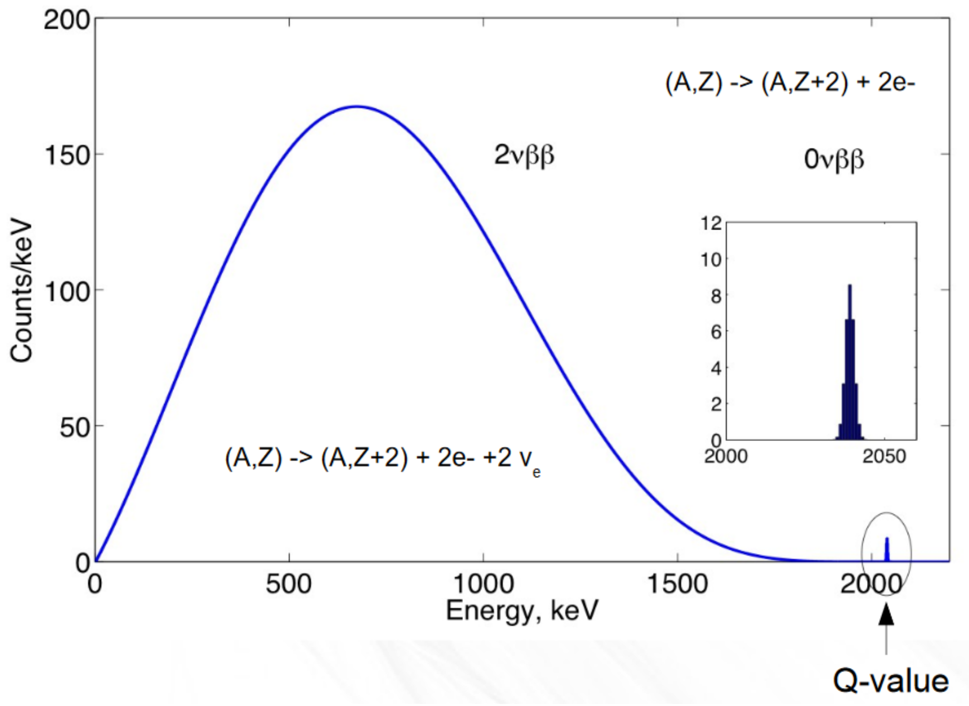
$$\sigma_{T_{\frac{1}{2}}} = \frac{S}{\sqrt{B_{\mathrm{total}}}} = \frac{Mt}{\sqrt{B_i \Delta E t}} \qquad \left(T_{\frac{1}{2}} \propto m_{\beta\beta}^2\right)$$

Background: $$B_i \Delta E = (bM + c)\,\Delta E$$

Background scales with isotope mass

(b dominant):

$$m_{\beta\beta} \propto M^{1/4}$$



UNIVERSITY OF SUSSEX

Scaling argument

$$\sigma_{T_{\frac{1}{2}}} = \frac{S}{\sqrt{B_{\text{total}}}} = \frac{Mt}{\sqrt{B_i \Delta E t}} \qquad \left(T_{\frac{1}{2}} \propto m_{\beta\beta}^2\right)$$

Background: $$B_i \Delta E = (bM + c)\,\Delta E$$

Background scales with isotope mass

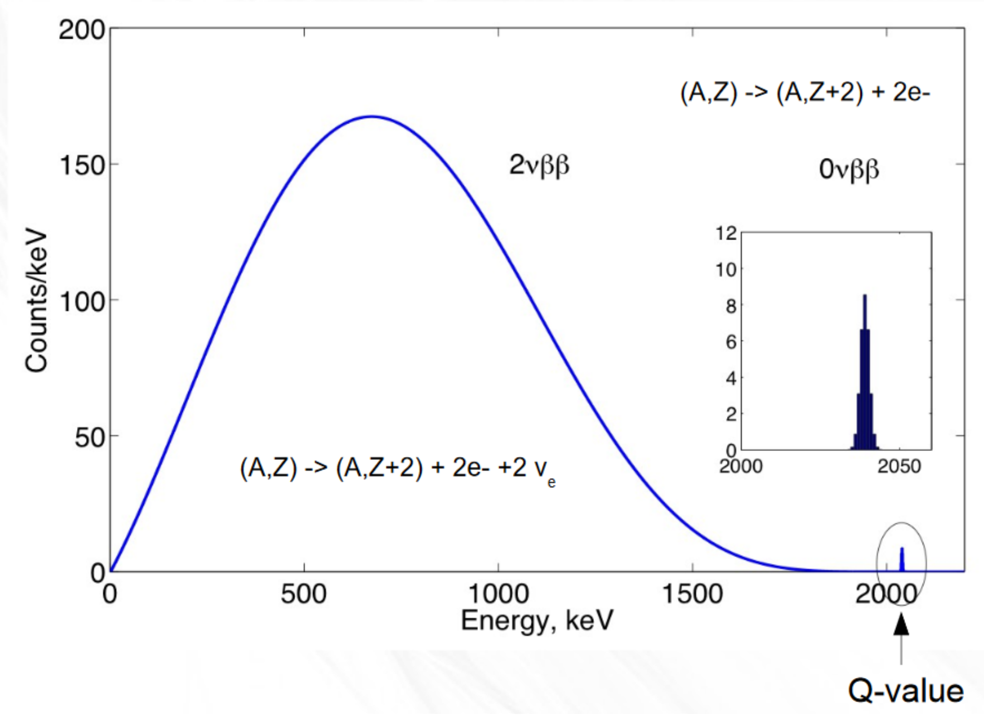
(b dominant):

$$m_{\beta\beta} \propto M^{1/4}$$

Background does not scale with isotope mass

(c dominant):

$$m_{\beta\beta} \propto M^{1/2}$$



Scaling argument

$$\sigma_{T_{\frac{1}{2}}} = \frac{S}{\sqrt{B_{\text{total}}}} = \frac{Mt}{\sqrt{B_i \Delta E t}} \qquad \left(T_{\frac{1}{2}} \propto m_{\beta\beta}^2\right)$$

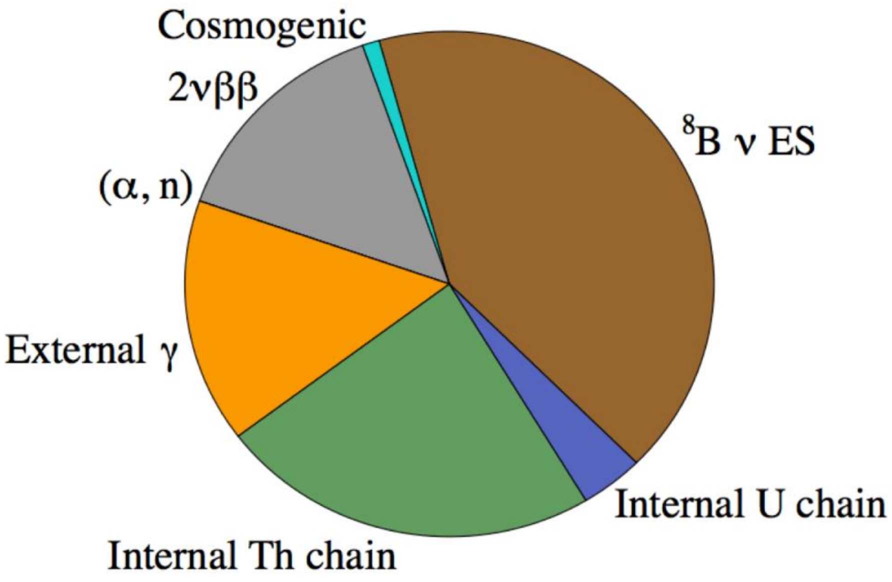
Background: $B_i \Delta E = (bM + c)\,\Delta E$

Background scales with isotope mass (*b dominant*)**:**

$$m_{\beta\beta} \propto M^{1/4}$$

Background does not scale with isotope mass (*c dominant*)**:**

$$m_{\beta\beta} \propto M^{1/2}$$



UNIVERSITY OF SUSSEX

GERDA/MAJORANA to LEGEND

^{76}Ge

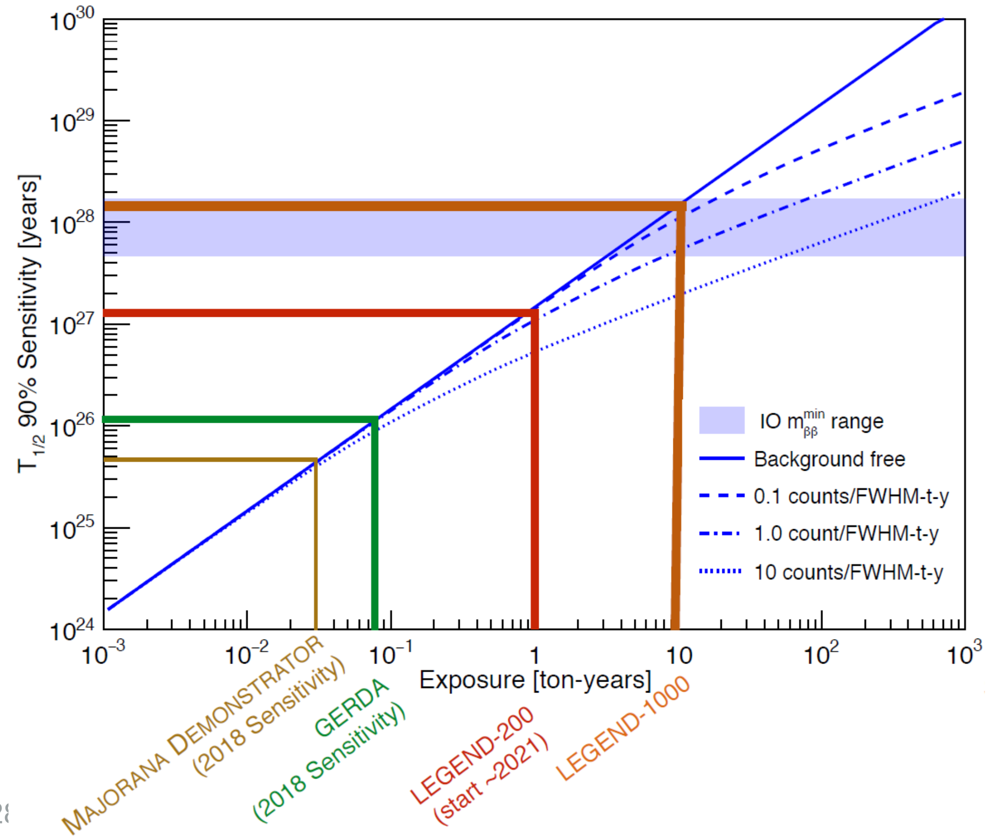
(neutrino2018) GERDA

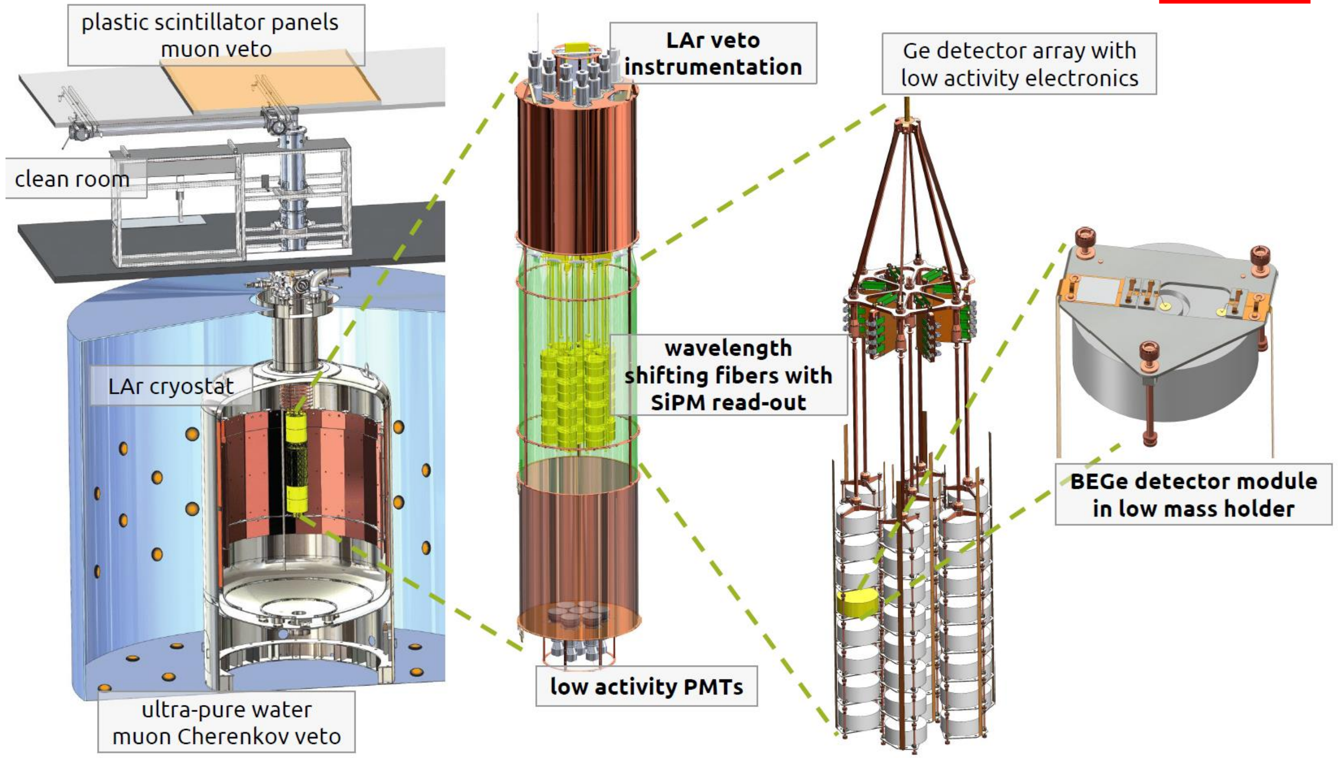
$T_{1/2}$ >0.9×10^{25} years (90% CL),

$m_{\beta\beta}$ < (110,260) meV (84.2 kg y)

MAJORANA demonstrator

$T_{1/2}$ >2.7×10^{25} years (90% CL)





7 strings with 40 HPGe detectors (43.2 kg)

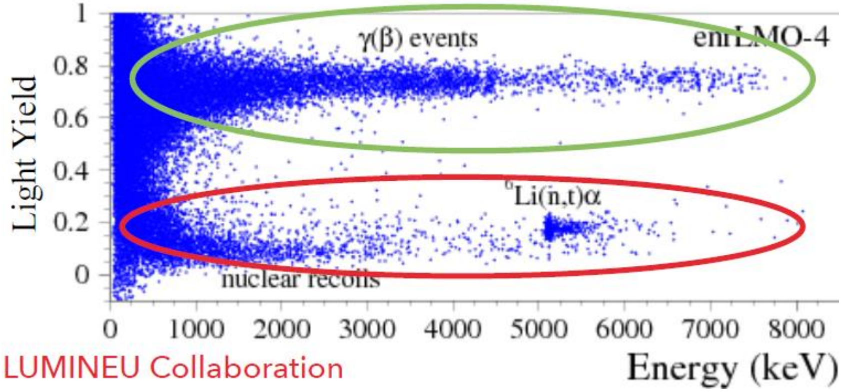
UNIVERSITY OF SUSSEX

Ge

CUORE

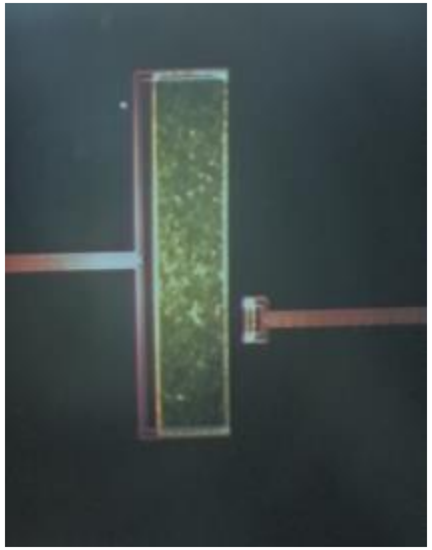
Arxiv:1710.07988 $T_{1/2}$ *>1.5×10^{25}* years (90% CL), $m_{\beta\beta}$ *< (110,520) meV (7 weeks)*

- Upgraded cryostat and improving energy resolution
- Taking more data since May 2018
- Upgrade to CUPID, adding light detectors allowing PID, reduce backgrounds
- Aim is to go to near the bottom of the IH region (6-20 meV)

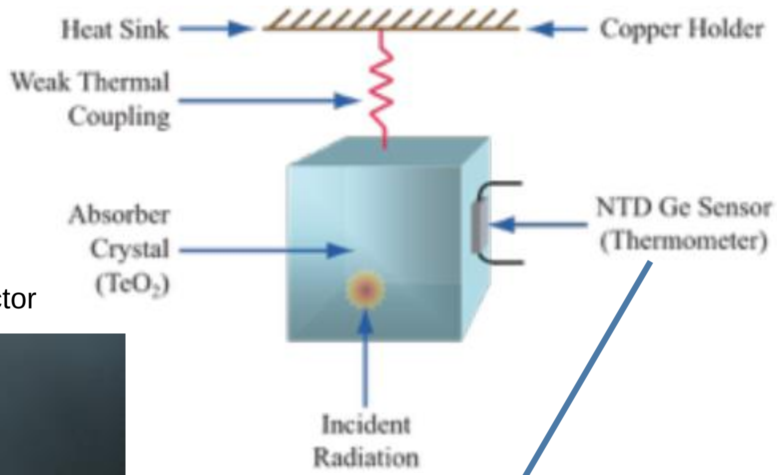


LUMINEU Collaboration

Neganov-Luke and TES based light detector



Cryogenic bolometers

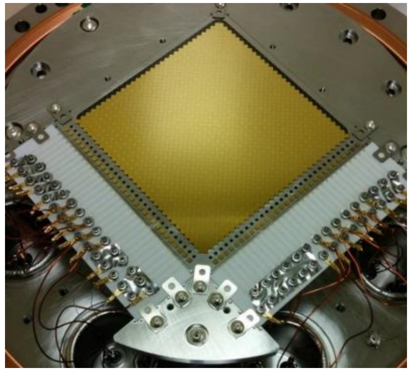


EXO-200 and nEXO

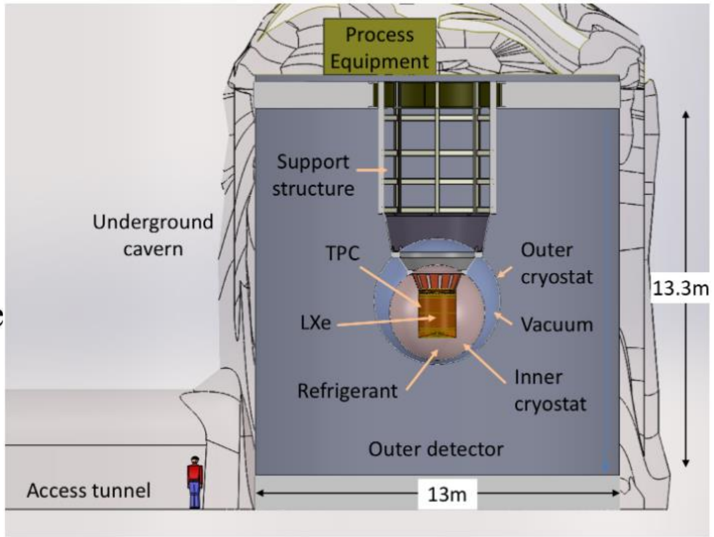
(PRL 120 072701 (2018)) EXO-200 phase I: $T_{1/2}$ *>1.8×10^25* years (90% CL), $m_{\beta\beta}$ < *(147,398) meV*
(phase II expected to end this month)
nEXO : $T_{1/2}$ ~ 10^{28} years, covering IH region – Ba tagging to exceed this.

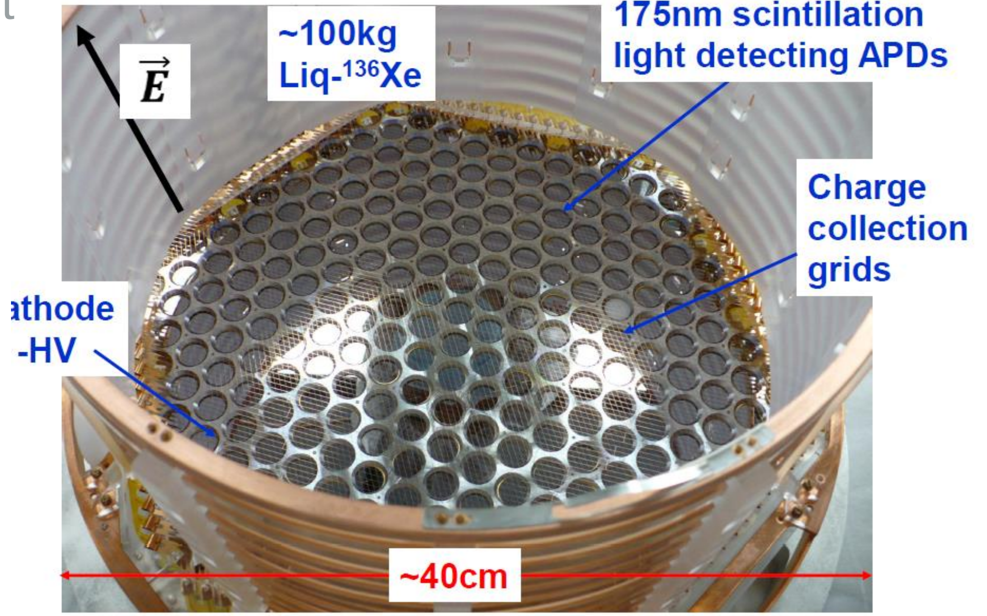
^{136}Xe

SiPM



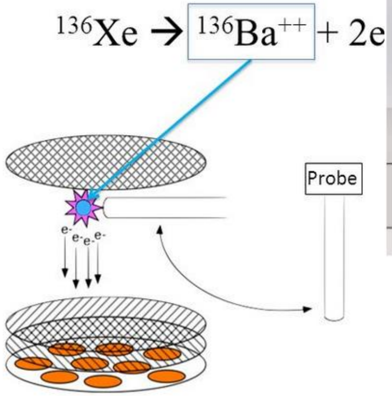
nEXO pre-Conceptual Design Report
ArXiv:1805.11142





EXO-200 TPC

1. Detect and localize decay (like in EXO-200)
2. Send probe in to region of decay
3. Confine the Ba^{++} on probe
4. Remove the probe
5. Identify the barium



KamLAND-Zen

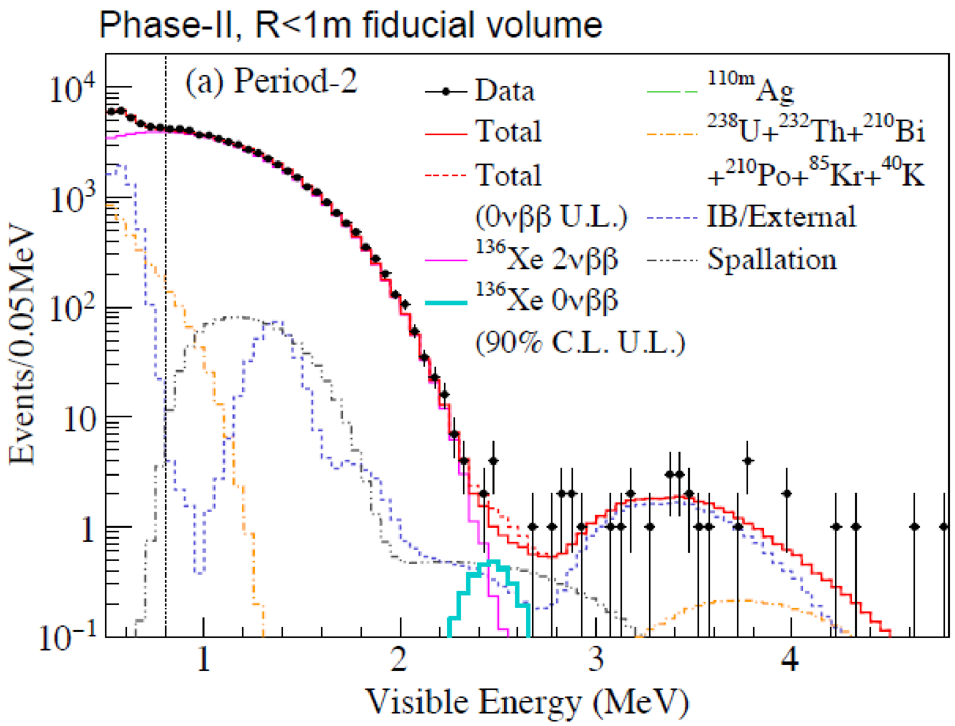
(PRL 117 082503 (2016)) phase II: $T_{1/2}$ *>9.2×10^{25}* years (90% CL), *$m_{\beta\beta}$ < (61,156) meV (126 kg yr)*
(KamLAND-ZEN 800 data taking to be expected to start / have started – target 40 meV)

^{136}Xe

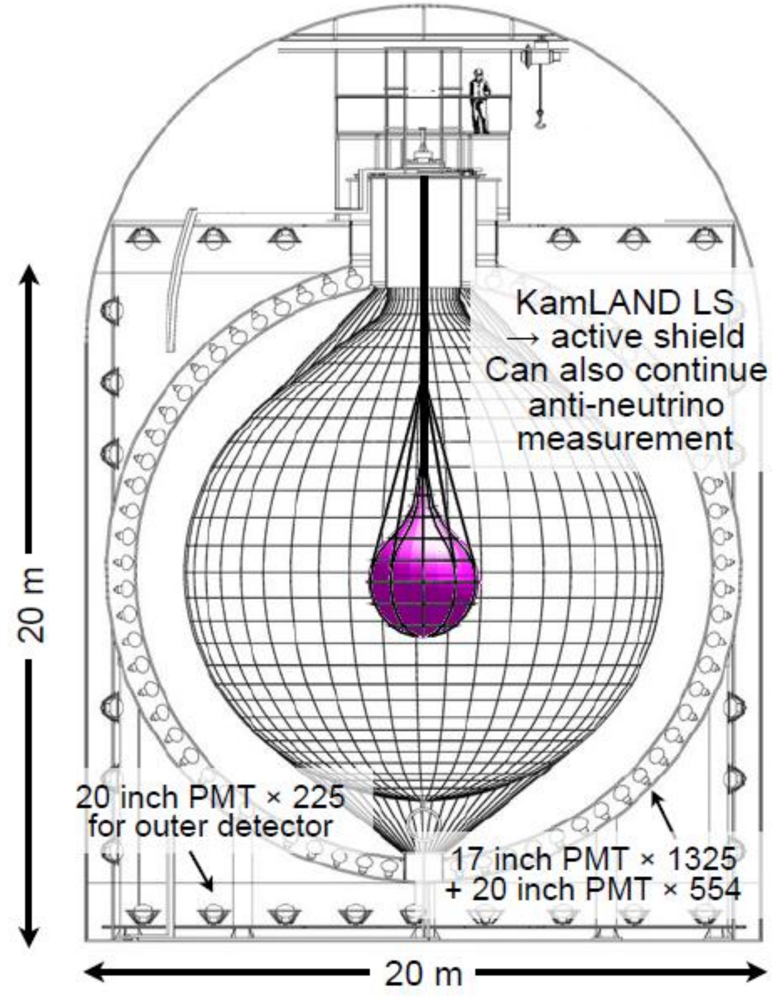
R&D underway for KamLAND2-Zen:

- 1 tonne of 136Xe
- Light concentrators,
- new LAB-based LS

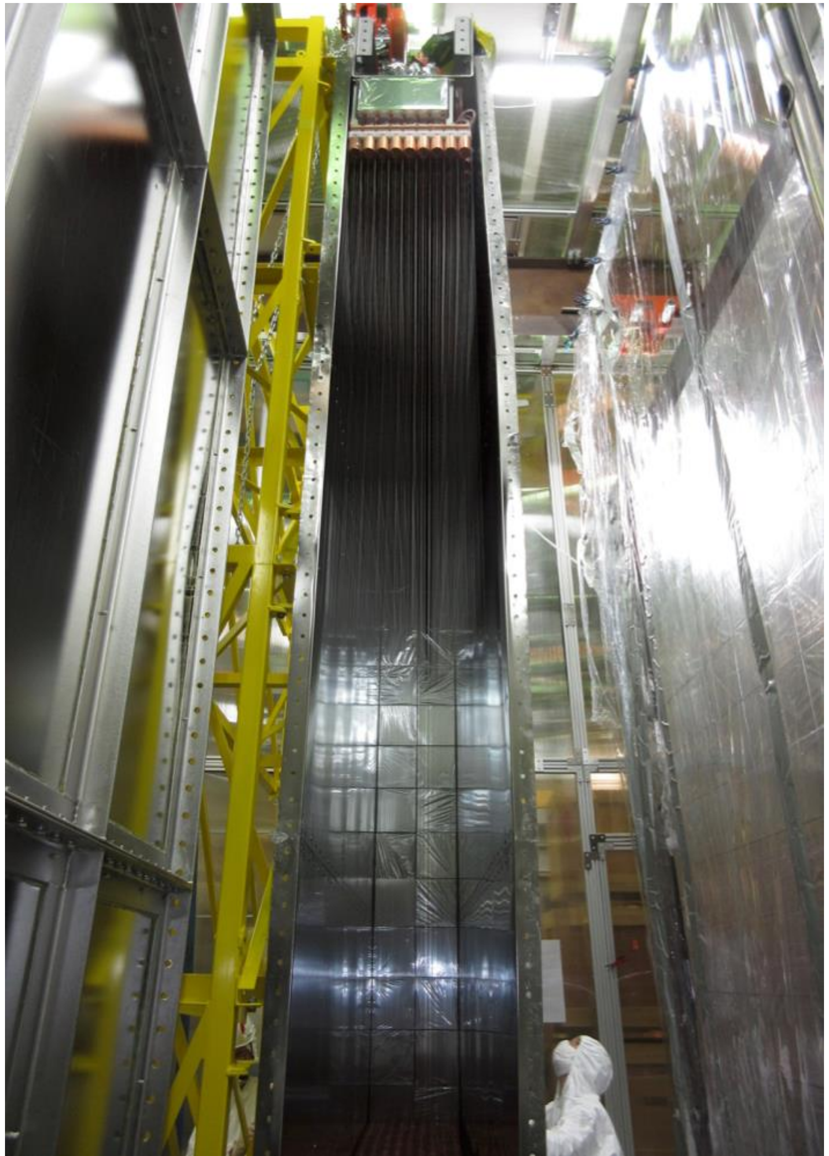
aiming for ~20 meV in 5 yrs



UNIVERSITY OF SUSSEX



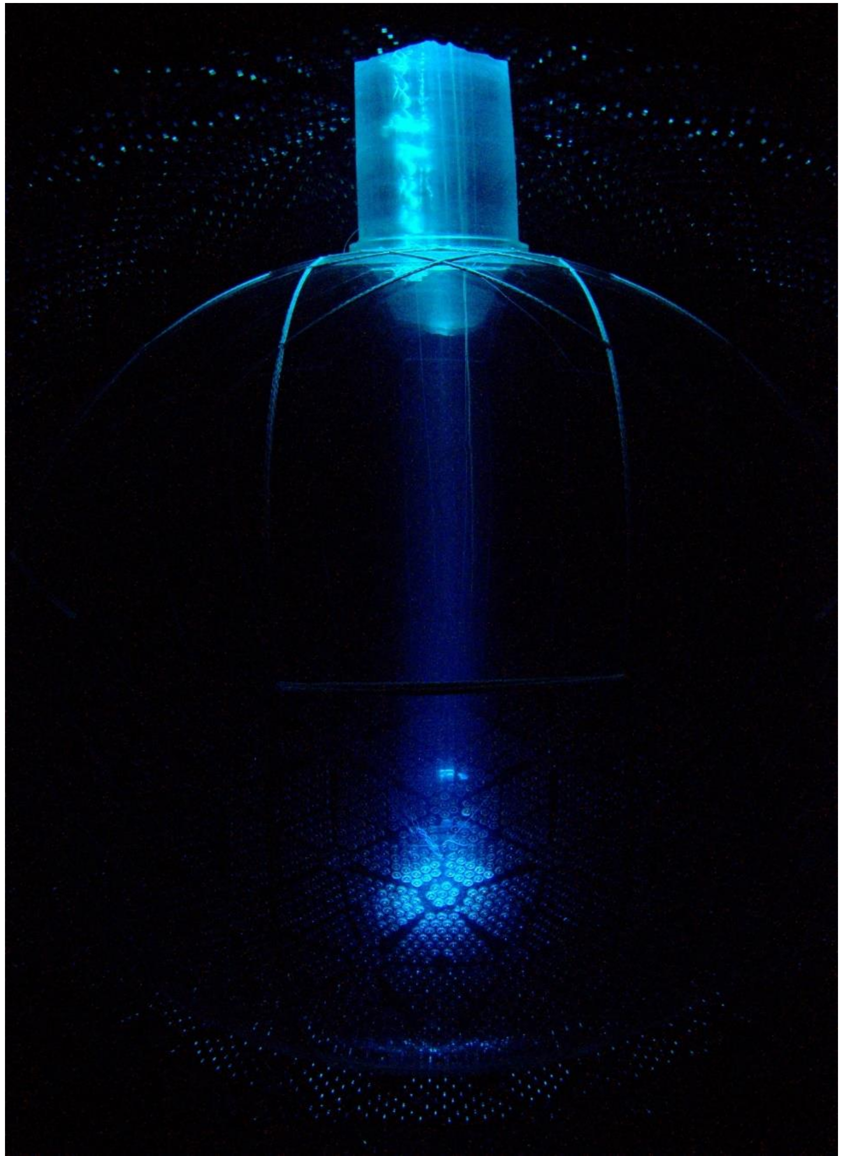
UK



Xe DM

LEGEND

Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

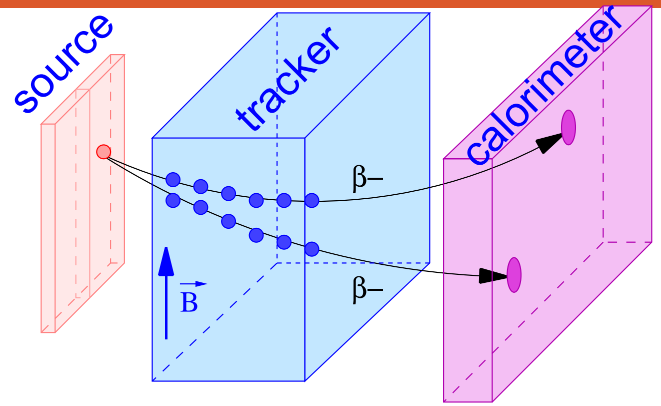


The tracker-calorimeter technique

Source separated from detector: (almost) any solid isotope can be hosted

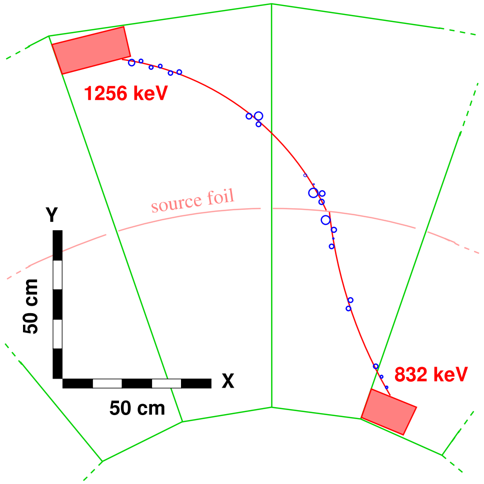
Full topological event reconstruction including $e^{\pm}$, γ-ray and α-particle identification ➞ strong background control & mechanism probe

Successfully exploited by NEMO-3 experiment: 0νββ limits and 2νββ $T_{1/2}$ for several isotopes



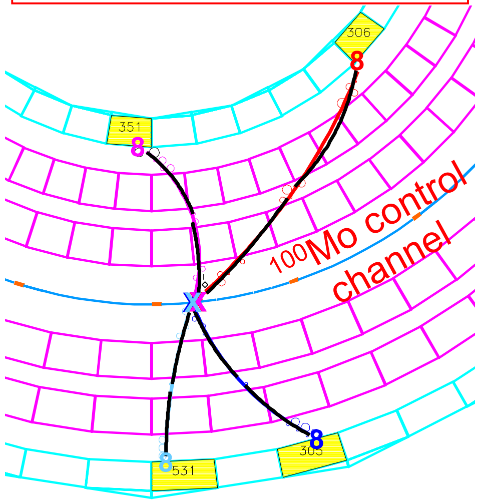
10^{24} year limit with just 7kg of ^{100}Mo

PRD 92, 072011 (2015)



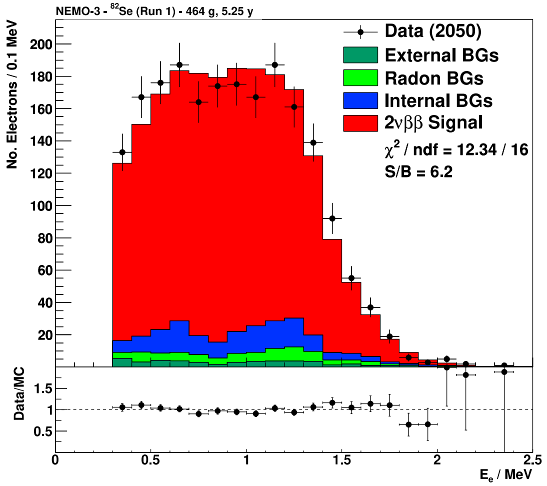
Access unique signatures, e.g. 0ν4β

PRL 119, 041801 (2017)



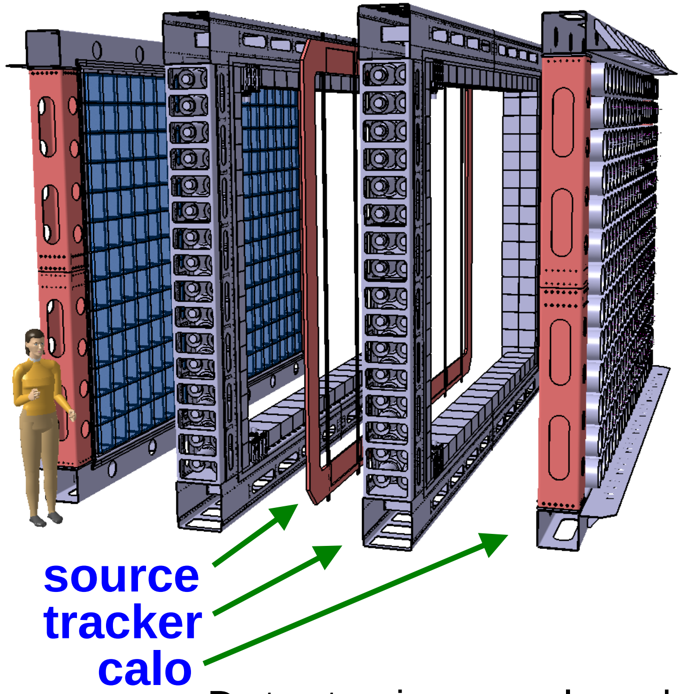
Kinematic probes of DBD mechanism (SSD/HSD)

EPJ C78, 821 (2018)



(Justin Evans)

SuperNEMO



Detector is now closed up and final cabling is taking place

Tracker: 2,034 Geiger cells; 95% He, 1% Ar, 4% alcohol; 44 mm cell diameter

Calorimeter: 712 scintillator blocks with energy resolution 4% FWHM at 3 MeV

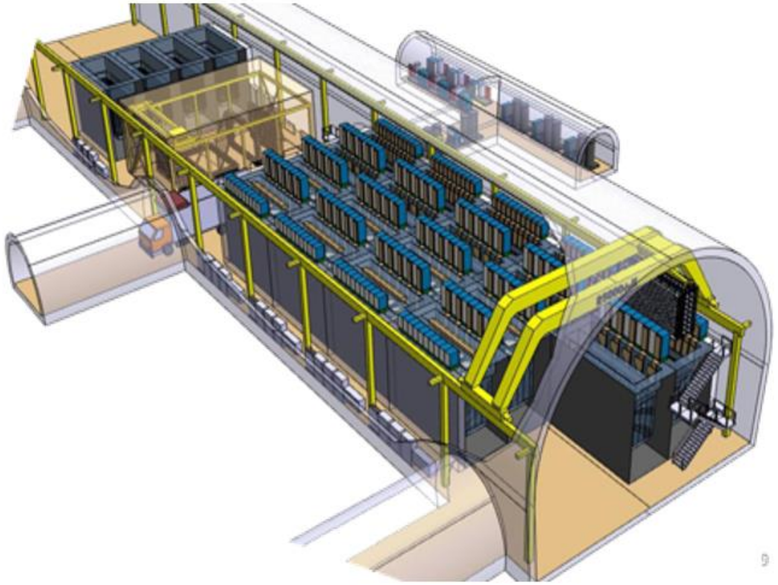
Source: 7 kg ^{82}Se

Demonstrator module sensitivity: $T_{1/2}^{0\nu} > 6.5\times10^{24}$ yr; $\langle m_\nu \rangle < 0.20 – 0.40$ eV

Experience from the Demonstrator Module suggests a 100 kg, 10^{26} yr class experiment ('full SuperNEMO') is possible

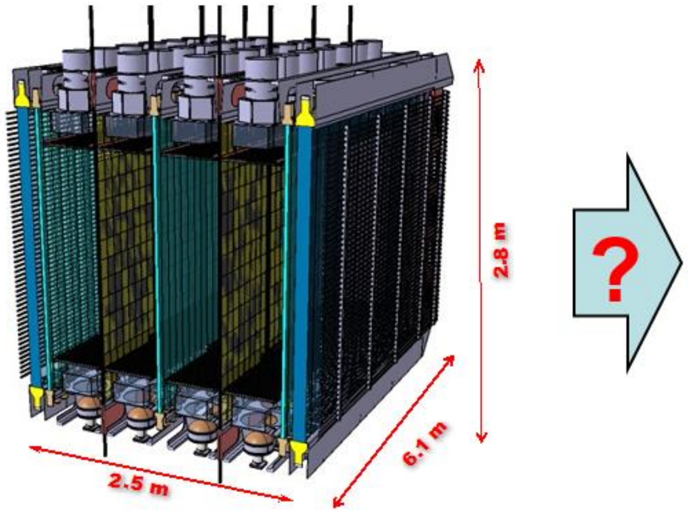
SuperNEMO

- Possible future scenarios for the SuperNEMO technology :
- Build additional Demonstrator-style modules :
  - ✓ We have demonstrated the ability to do this. So far we have met all of the background & performance requirements for SuperNEMO.
  - ✓ Can reach 10^{26} years (~50 meV) with 100 kg × 5 yrs.
  - ✓ Very strongly motivated if there is a discovery "soon" in another $0\nu\beta\beta$ experiment.
  - ✗ Costly.



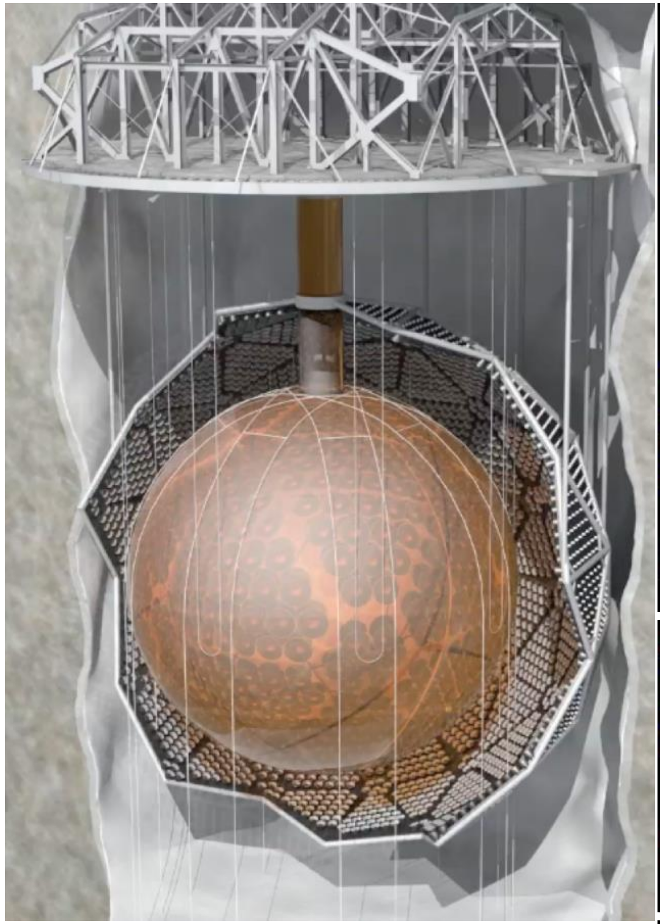
SuperNEMO

- <u>Consider alternative designs :</u>
  - Cheaper with no significant reduction in performance.
  - Enter the regime cost(detector) ≤ cost(enriched isotope) which is the ultimate requirement for all techniques using enriched isotopes.
  - Look at alternative designs & sites, including Boulby in the UK.

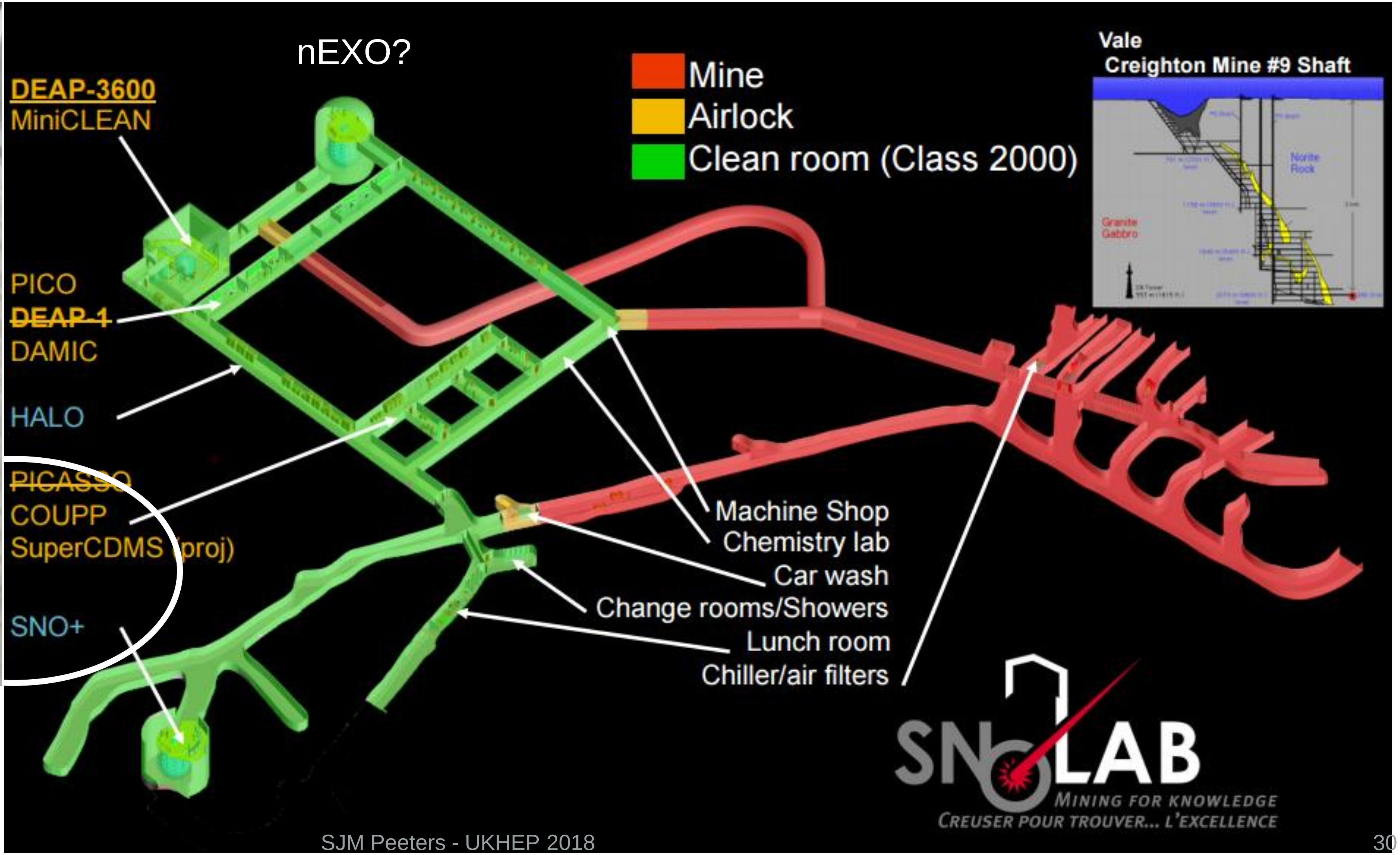


- Can we extend the technique another order of magnitude ?

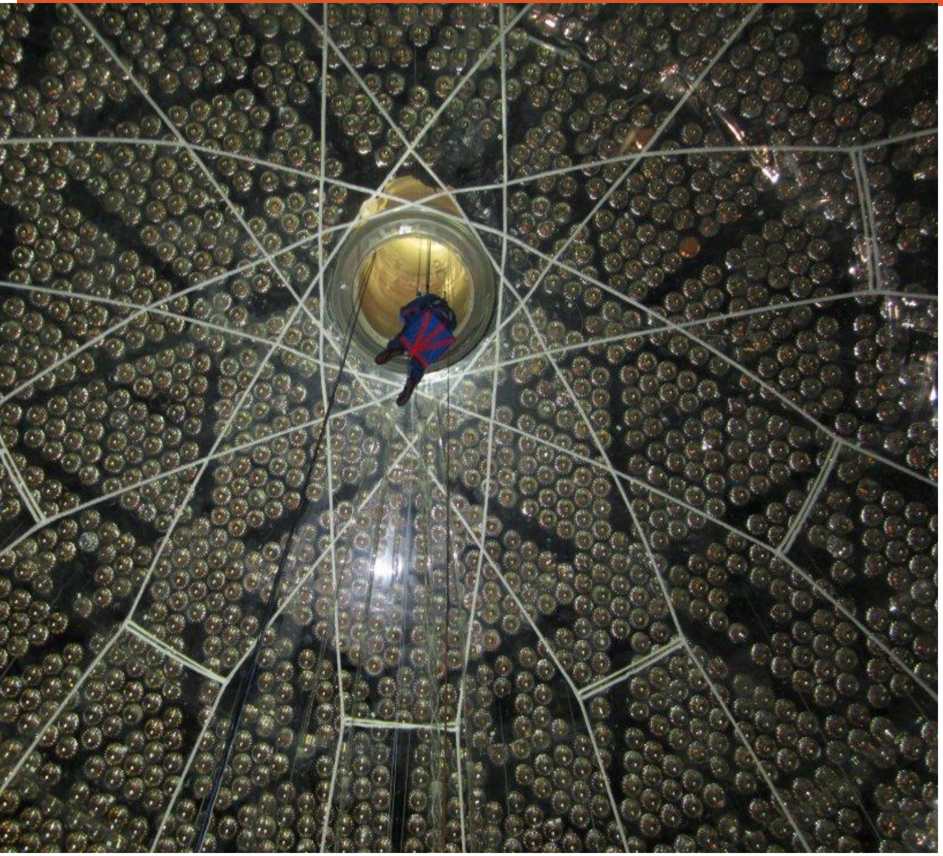
SNO+ @ SNOLAB (ON, Canada)
Building on the success of SNO

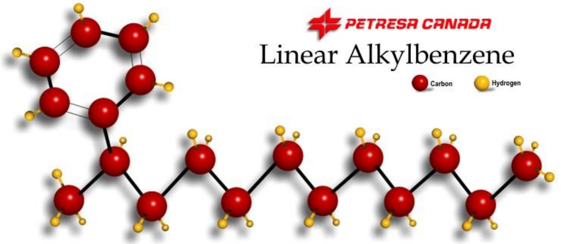


6 m radius acrylic vessel with
780 tonne LAB/PPO (2 g/l),
9400 10” PMTs with light concentrators



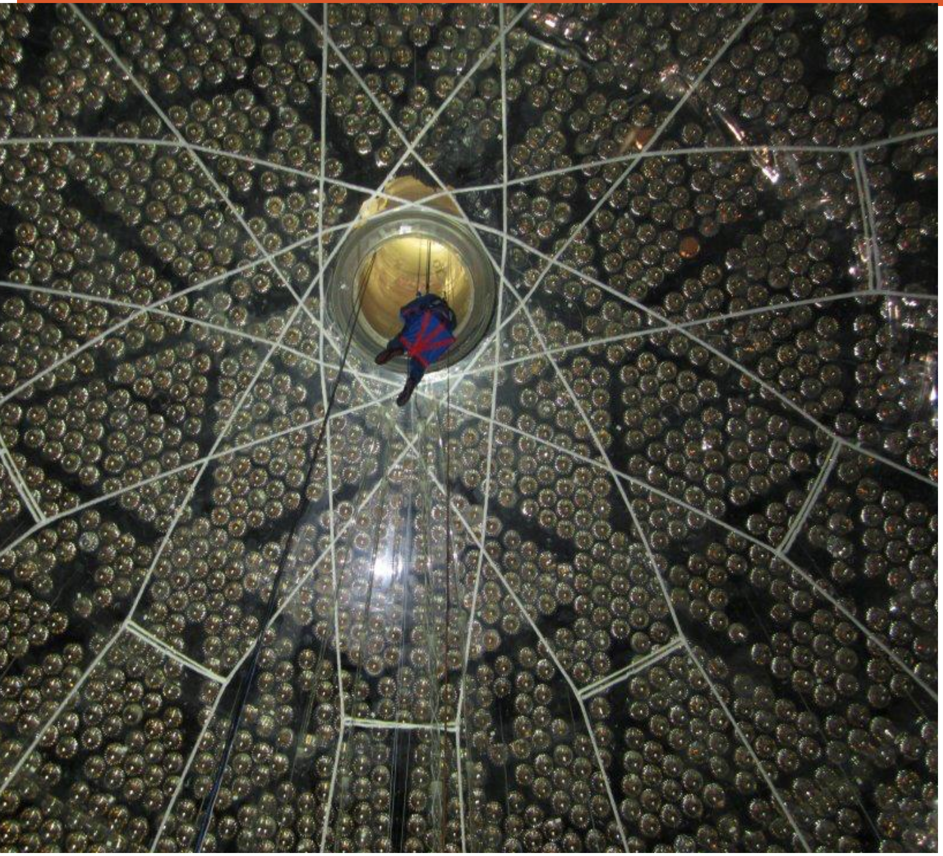
Experiment refurbishment

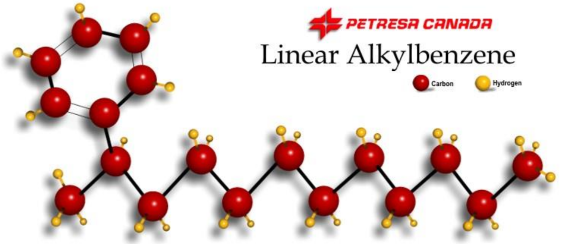




UNIVERSITY OF SUSSEX

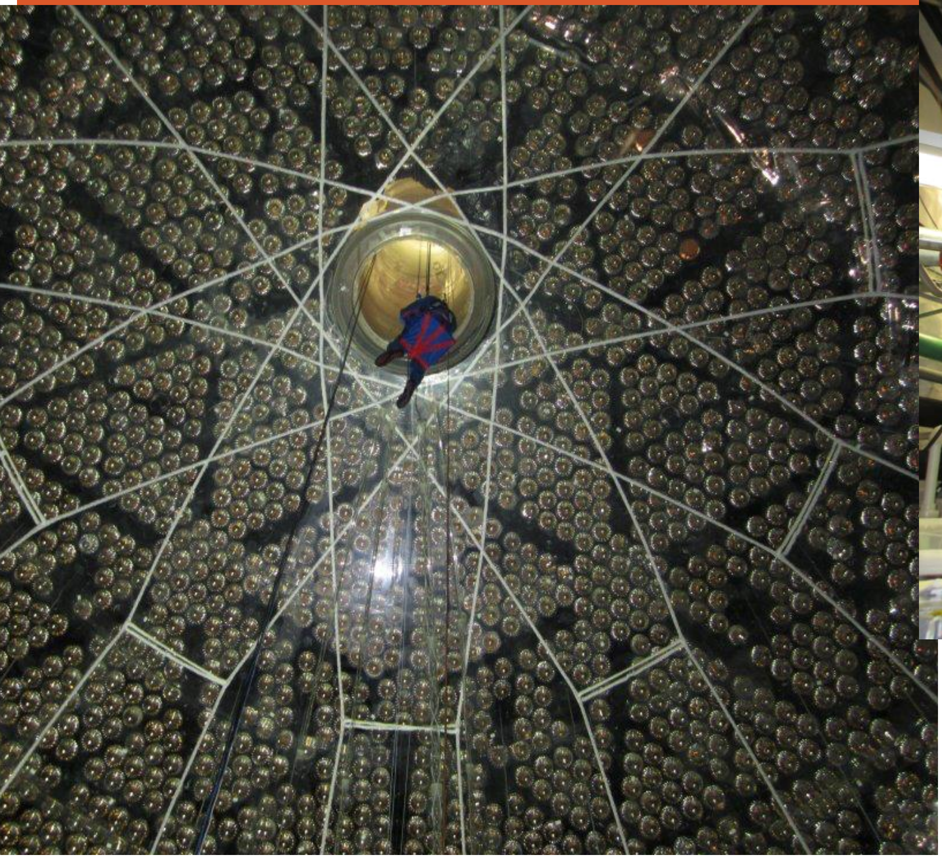
Experiment refurbishment

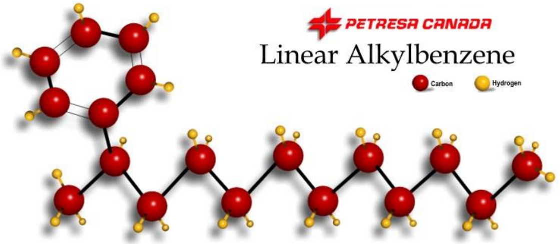




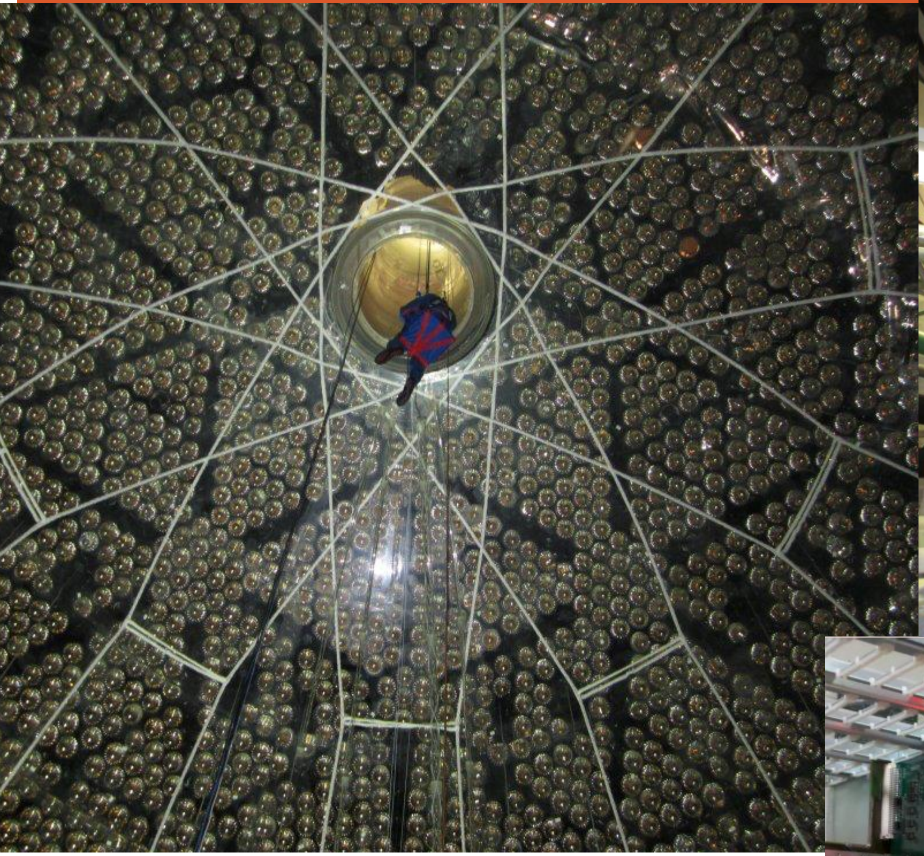
UNIVERSITY OF SUSSEX

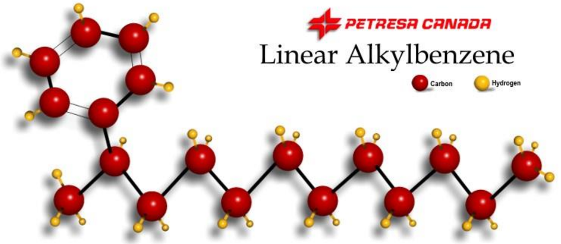
Experiment refurbishment





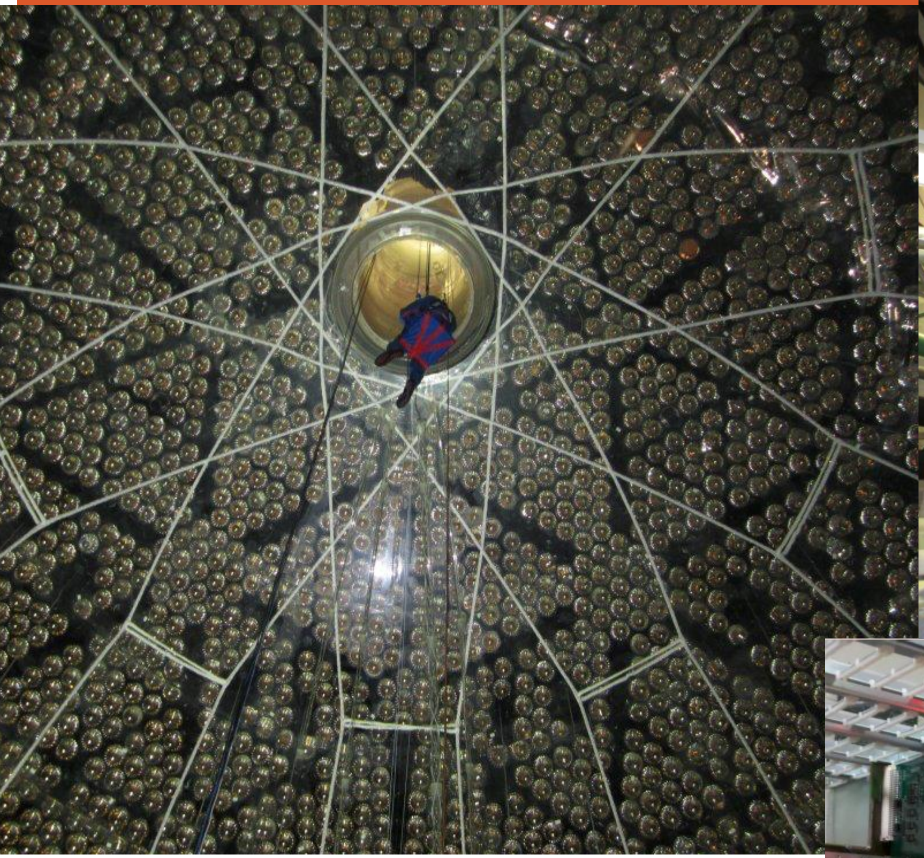
Experiment refurbishment

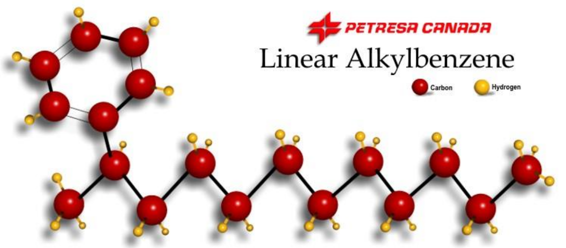


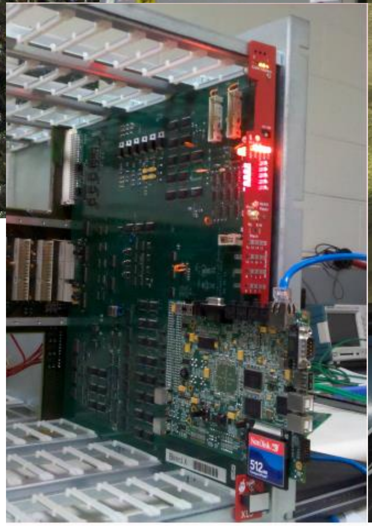


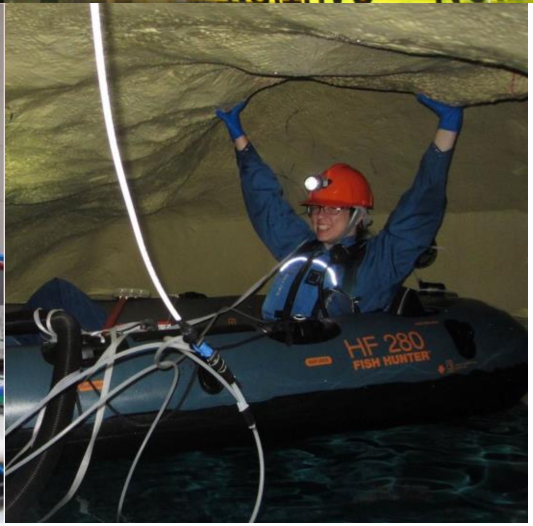
UNIVERSITY OF SUSSEX

Experiment refurbishment

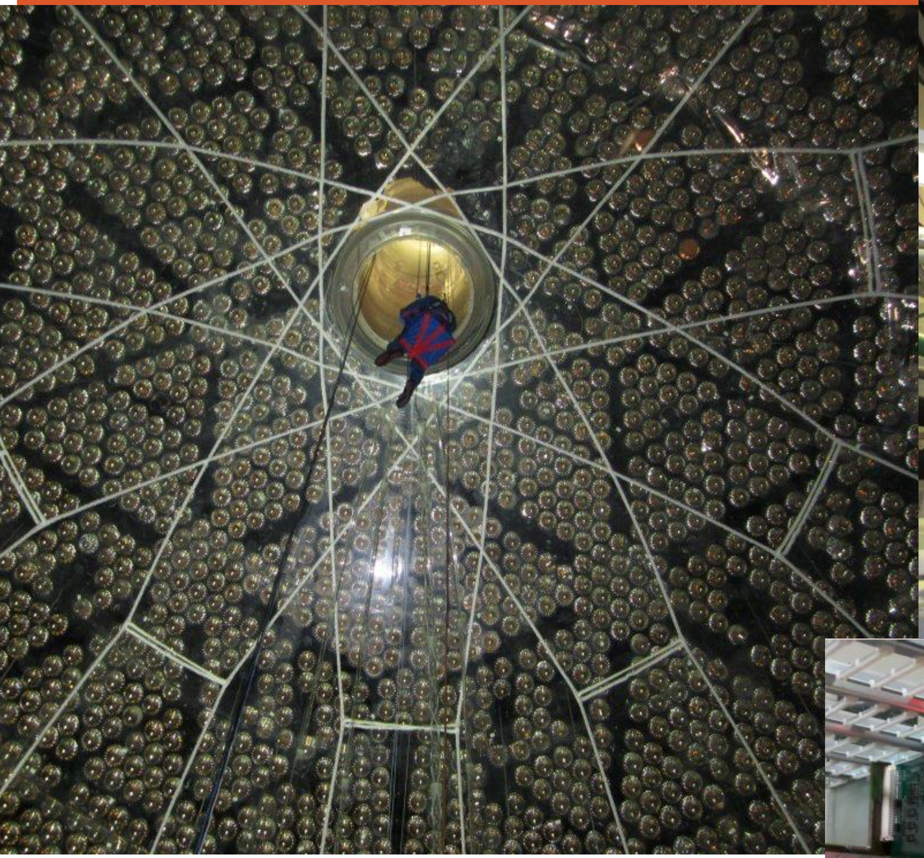


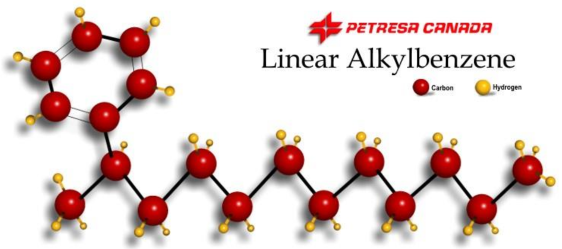


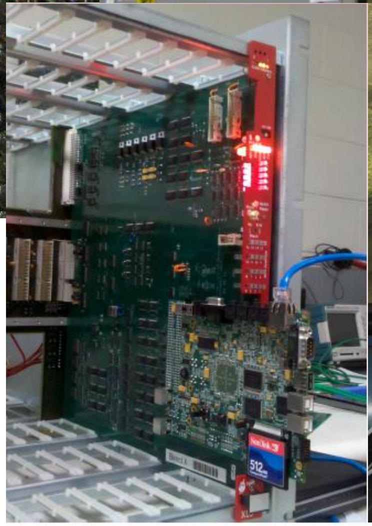


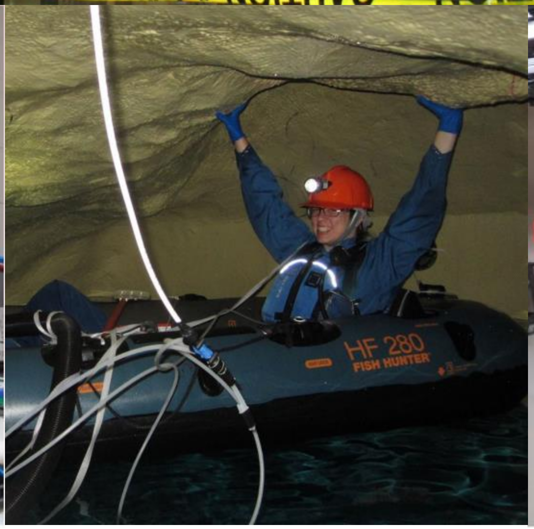


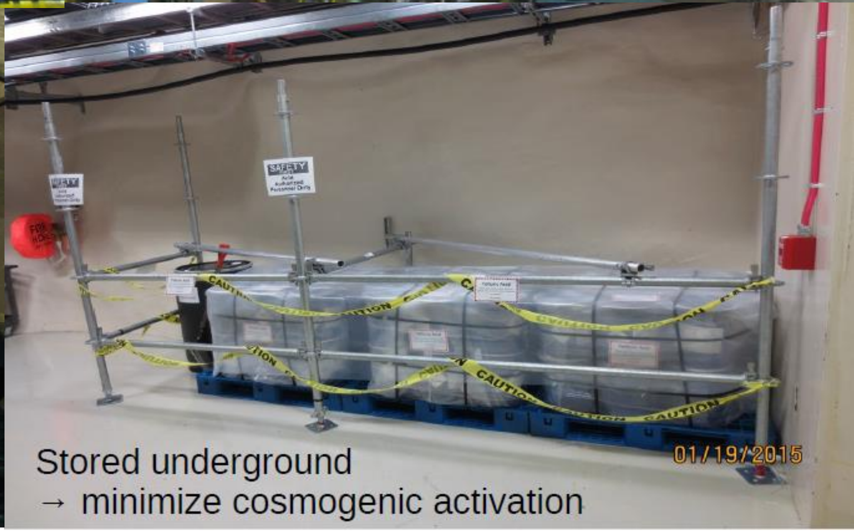
Experiment refurbishment









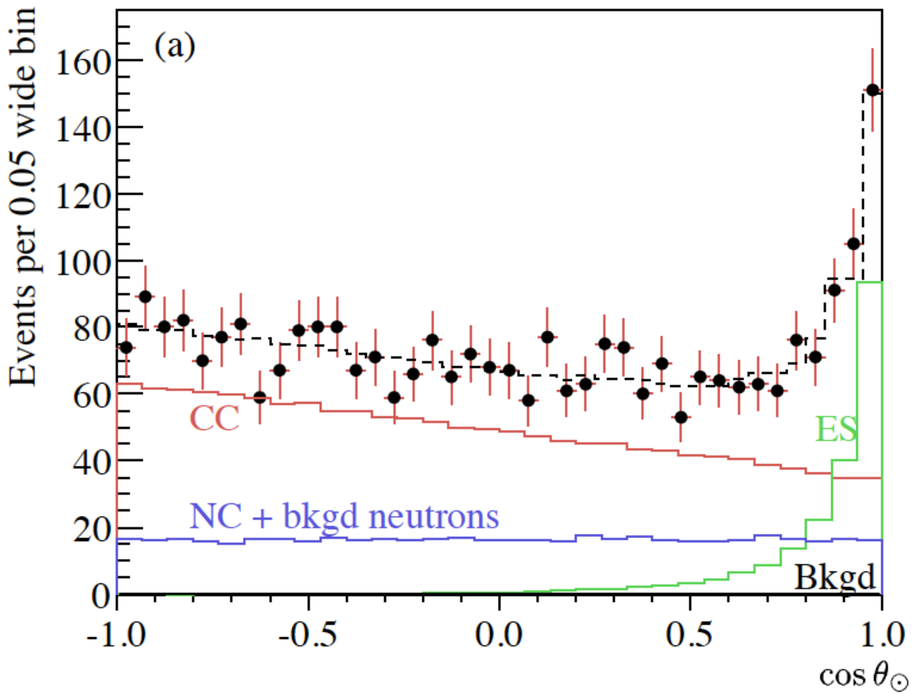


Stored underground
→ minimize cosmogenic activation

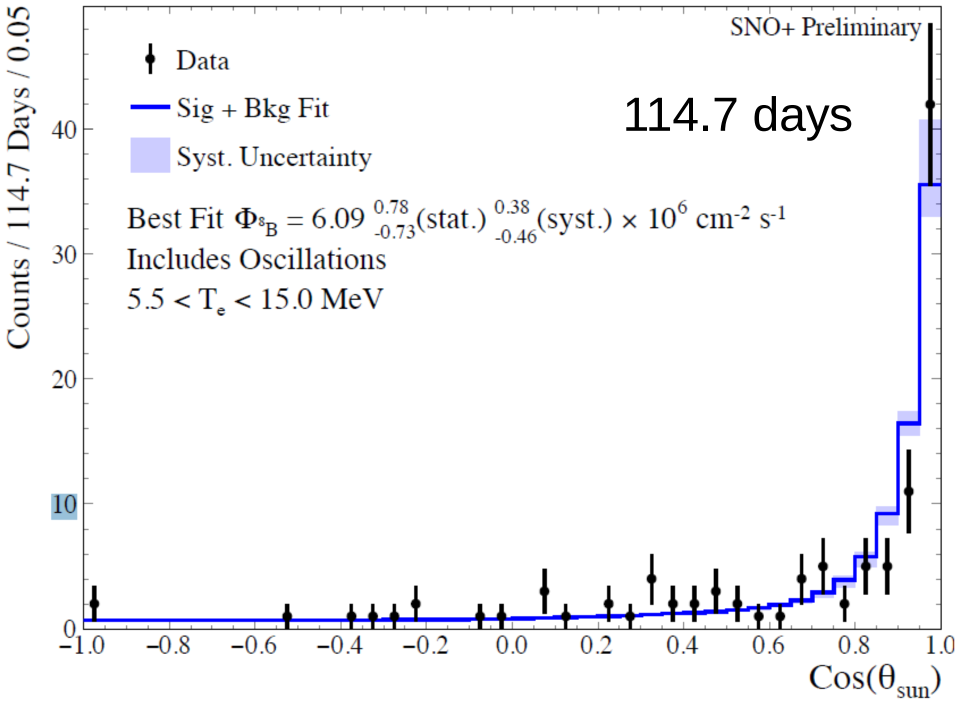
Three phases: water, scintillator, loaded scintillator

We are here

SNO (D_2O)



SNO+ (H_2O)



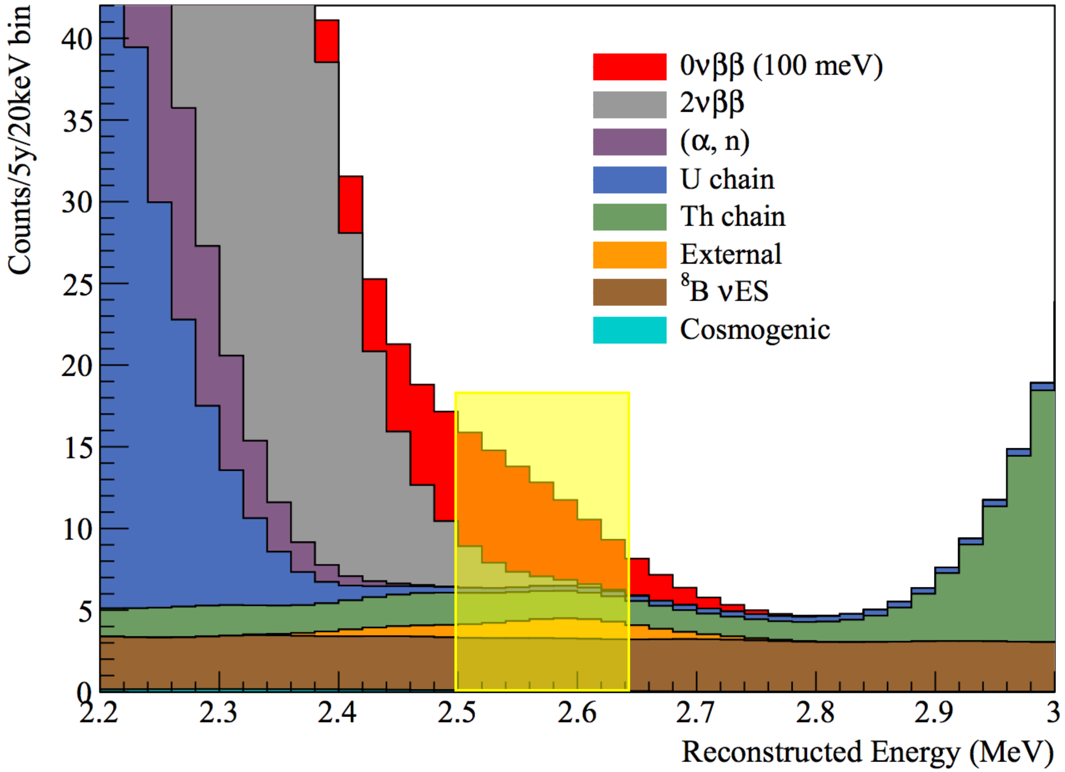
Background levels consistent with or below "nominal" value used for sensitivity projections

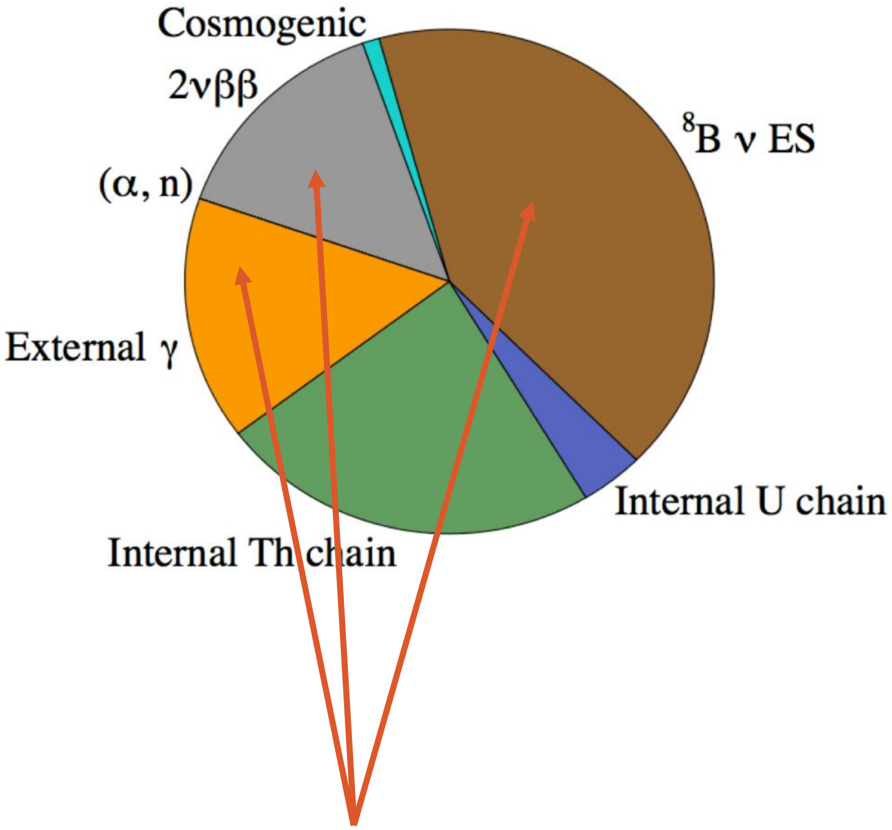
UNIVERSITY OF SUSSEX

SNO+ projections

0.5% Te loading, 5 yrs live time, 3.3 m fiducial volume (17%)

$T_{1/2}$ > 1.9 x10^{26} yrs (90% CL)





ROI: -0.5 - 1.5 σ (2.49-2.65 MeV)
Predict 12.4 counts/yr in yr 1
~10^{-6}/keV.kg.yr

UNIVERSITY OF SUSSEX

Dominant backgrounds measured

Future directions

0.5% run: prototype for multi-tonne experiment

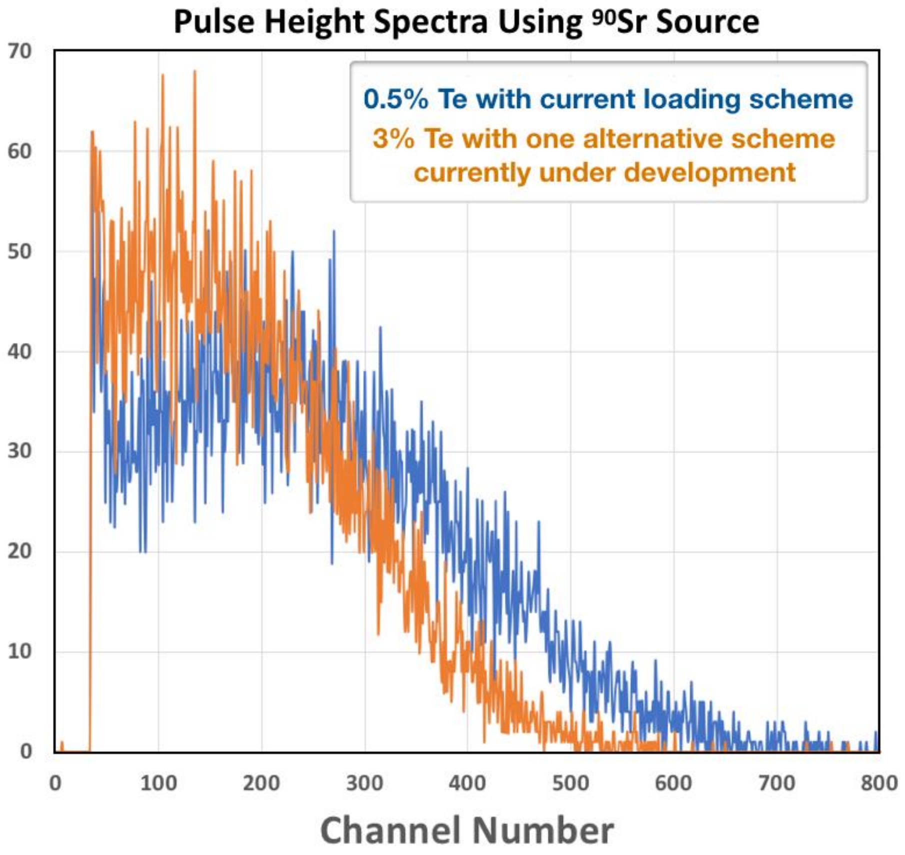
- Dominant backgrounds not correlated with loading
- Higher loading to increase sensitivity

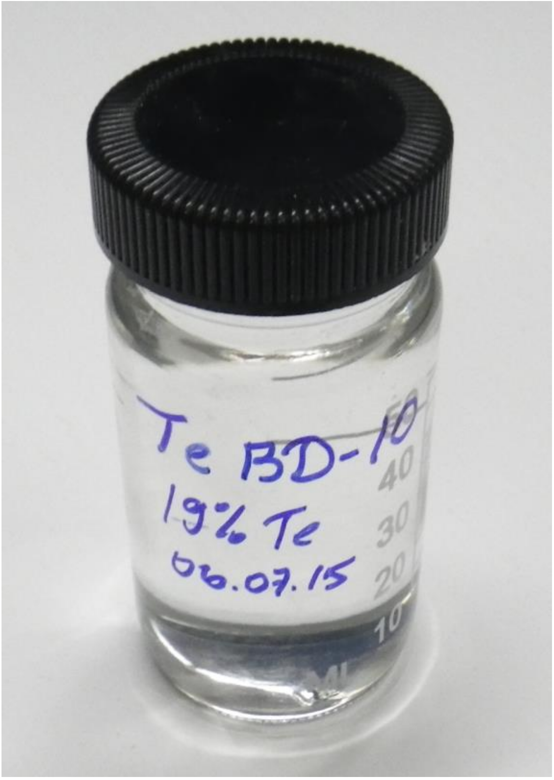
Metal loading R&D

- Increase light yield
- High transparency achieved at high loadings

Detector upgrade path

- New PMTs e.g. R5912-HQE (34% QE)
- Replace concentrators
- Contain isotope in a bag
- Enrichment





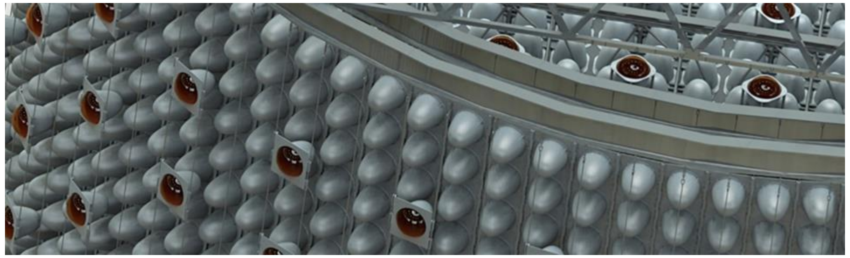
UNIVERSITY OF SUSSEX

20% less light with 6 x more loading!

Advanced scintillator detector concept – beyond SNO+(+)

Concept studies underway for large scale scintillator detectors with the possibility of multi-tonne loading, using separation of scintillation and Cherenkov light (removing backgrounds, in particular ^{8}B).

WATCHMAN – a 1 ktonne prototype closely associated with this – will be constructed in Boulby.



THEIA, see Arxiv:1504.08284

Also: Arxiv:1306.5654

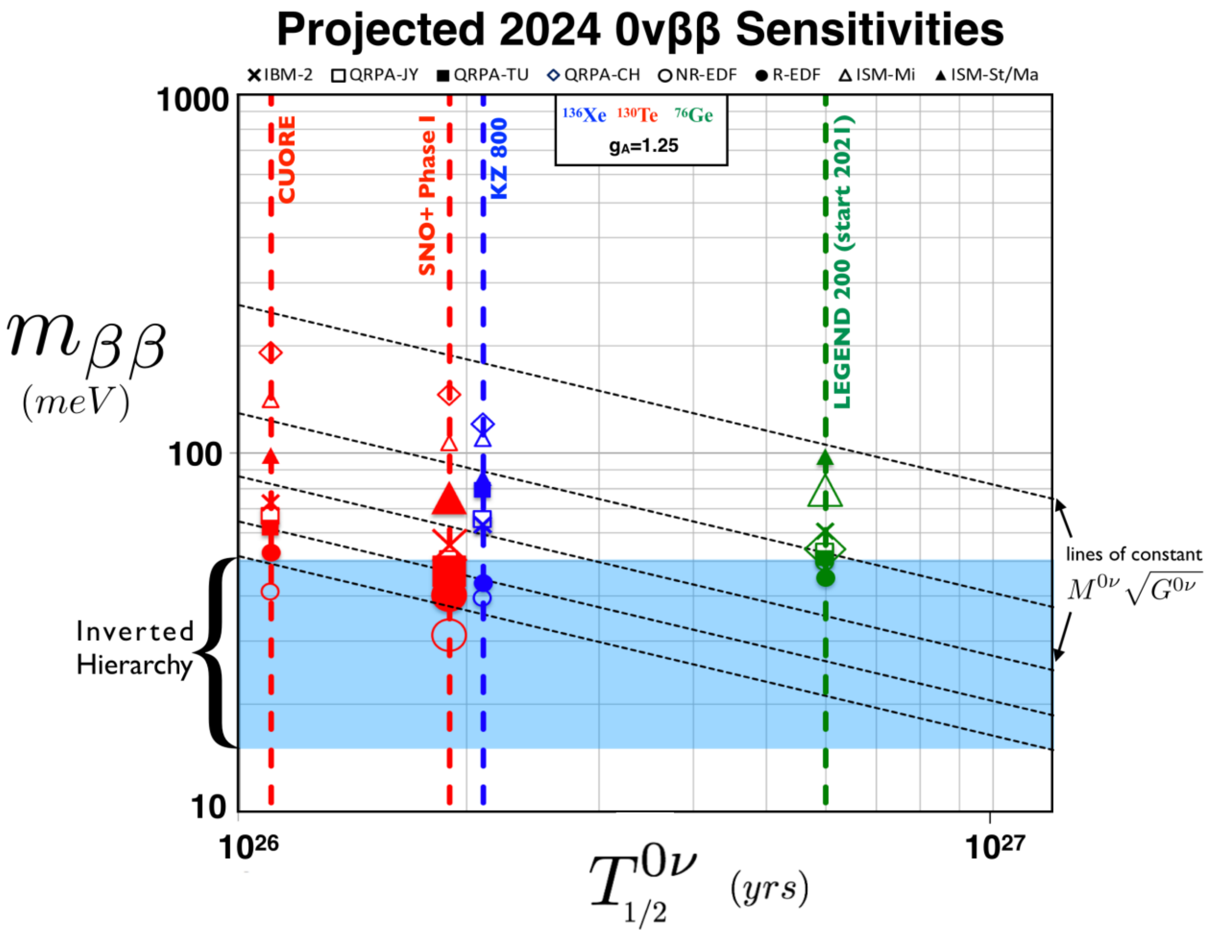
Facility

- Geo and reactor anti-neutrinos
- Solar neutrinos
- Supernovae neutrinos
- DSNB
- Nucleon decay
- Sterile neutrinos

UNIVERSITY OF SUSSEX

Summary

Neutrinoless double-beta decay is a vibrant field with the potential to deliver exciting new insights, with a bright future ahead.



UNIVERSITY OF SUSSEX