Neutrino Mass Searches with Beta Decay Experiments

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University of Sussex

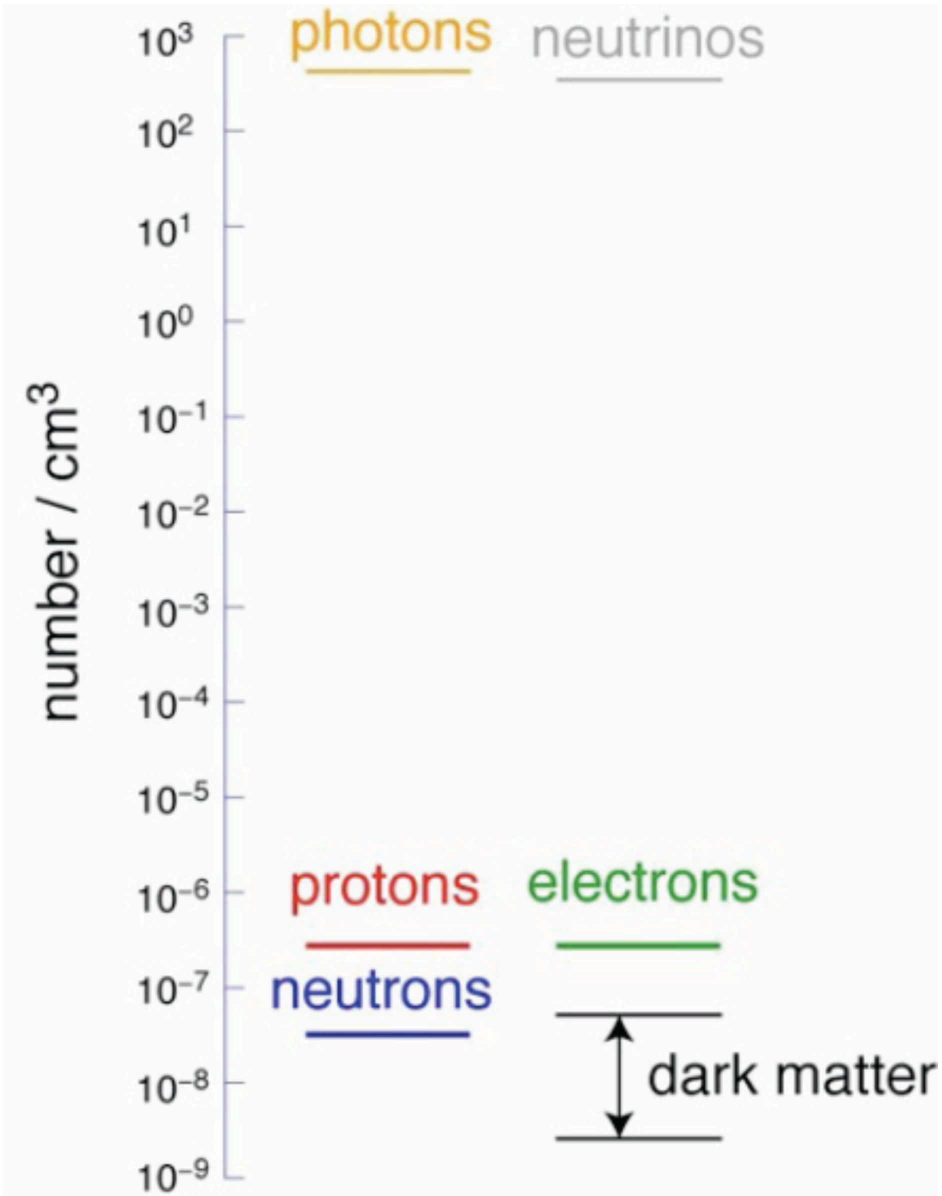
IoP Particle Physics Conference at RHUL

8th April 2014

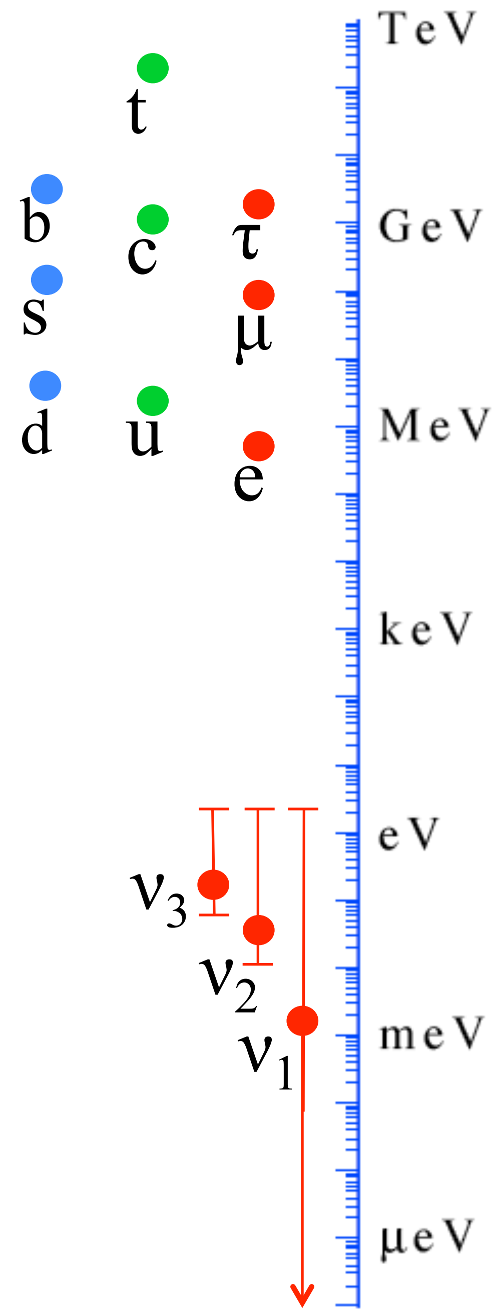
Introduction

- Why study neutrinos?
- Where do we stand on neutrino masses?
- Single Beta-decay
  - Experiments
  - Sensitivities
- Neutrinoless Double Beta Decay (0νββ)
  - Current results
  - Experiments under construction (UK focus)

Why study neutrinos?



Pattern to masses?



Normal hierarchy

Where do we stand on neutrino masses?

Straightforward but detailed picture...

$$\nu_1 \quad \nu_{Heaviest} \quad \nu_3$$

$$\nu_{\beta\beta} \quad \nu_\tau \quad \nu_\mu$$

$$\nu_e \quad \nu_2$$

$$\nu_{Lightest} \quad \sum \nu_i$$

Where do we stand on neutrino masses?

- Upper limits on:
  - ν_e from tritium beta decay
  - sum from cosmology
  - $\nu_{\beta\beta}$ from $0\nu\beta\beta$ (if Majorana)

- Lower limits on:
  - Heaviest two neutrinos from osc. expts

- Bottom Line:
  - Heaviest neutrino: **$0.05 < m_\nu < 2.2$ eV** (0.2 eV cosmology)
  - Lightest neutrino could have zero mass

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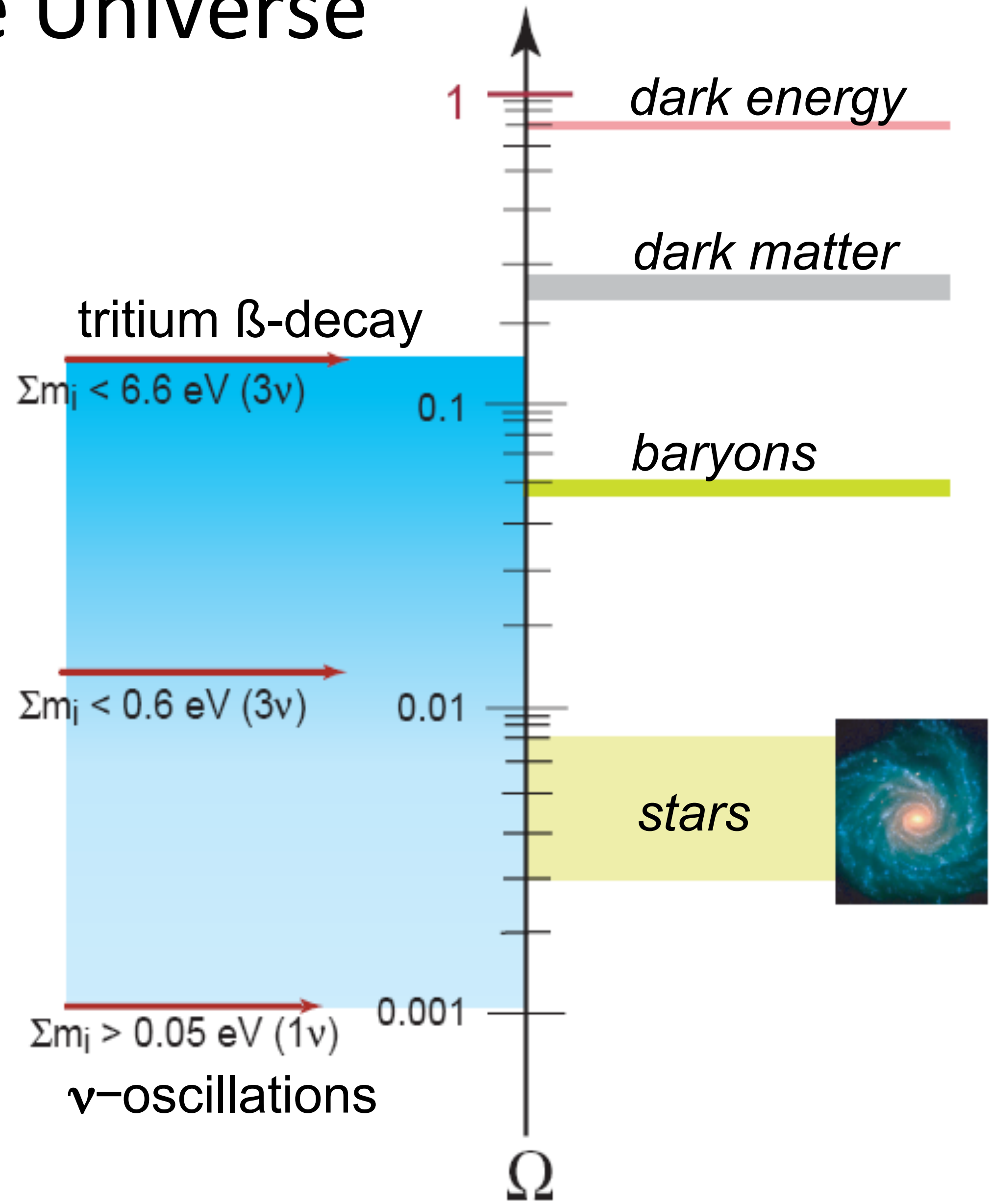
Neutrinos and the Universe



Cosmology:

role of relic-ν´s as hot dark matter (Ω_ν)

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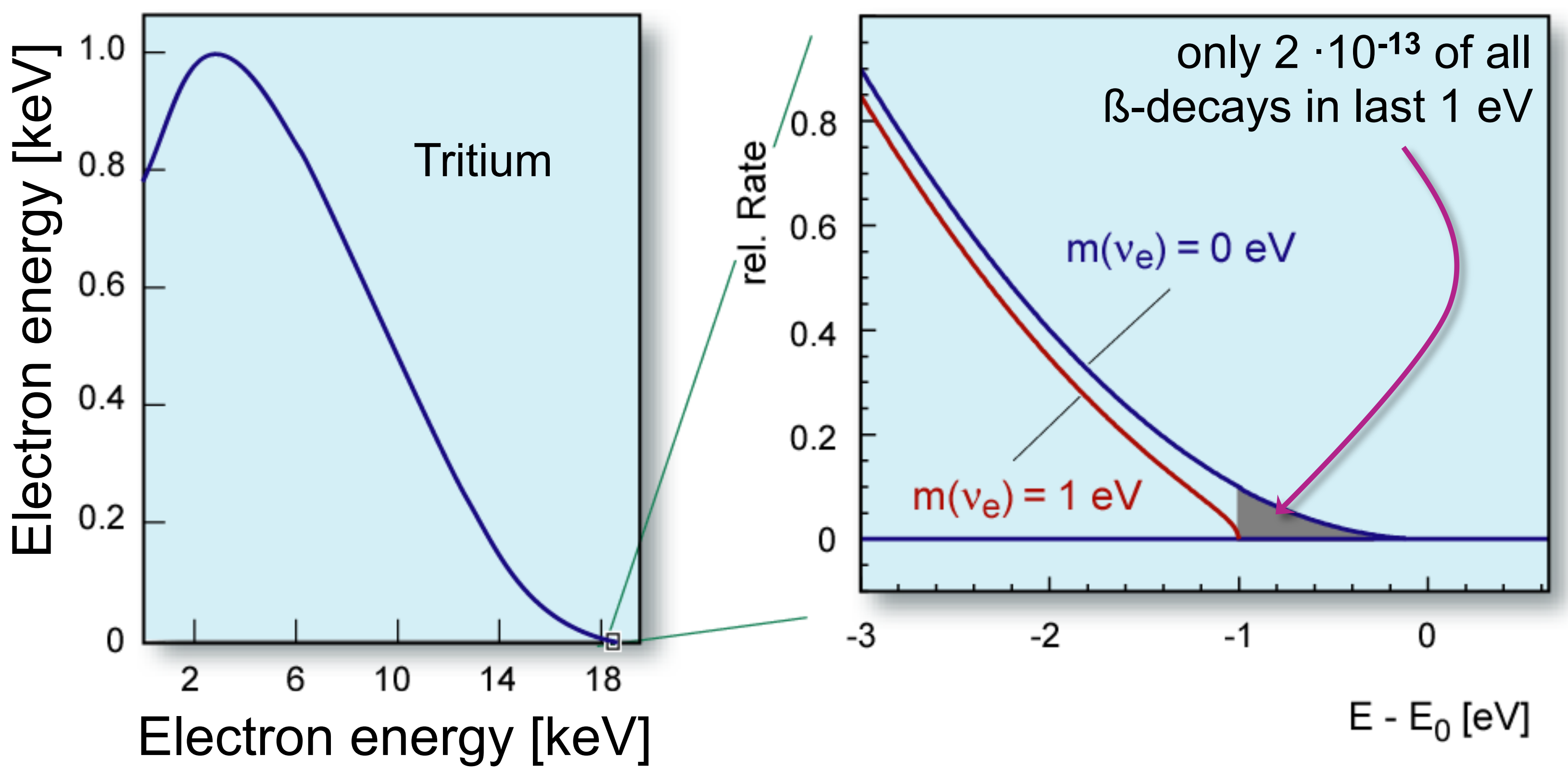
[G. Drexlin – NuPhys2013]

Direct Beta-decay Measurements

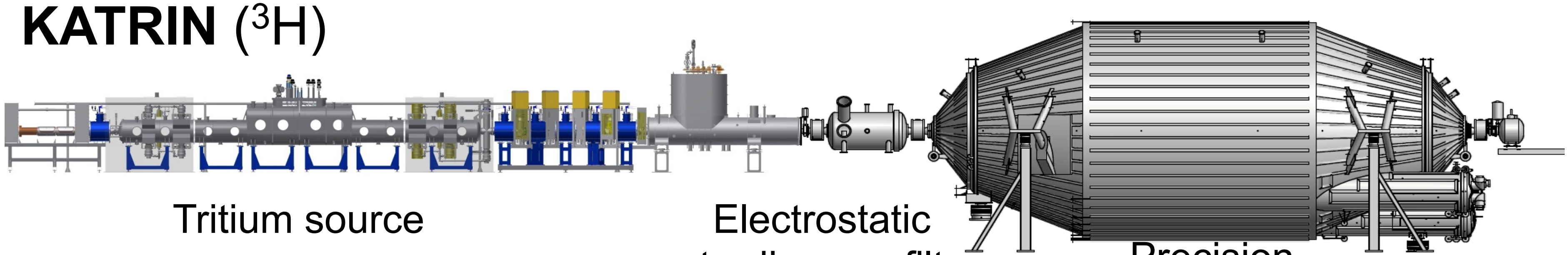
- Model independent measurement of m(ν_e)
  - based solely on **kinematic parameters & energy conservation**



- 2 main expt. approaches: calorimeter or spectrometer

[G. Drexlin – NuPhys2013]

KATRIN (^3H)



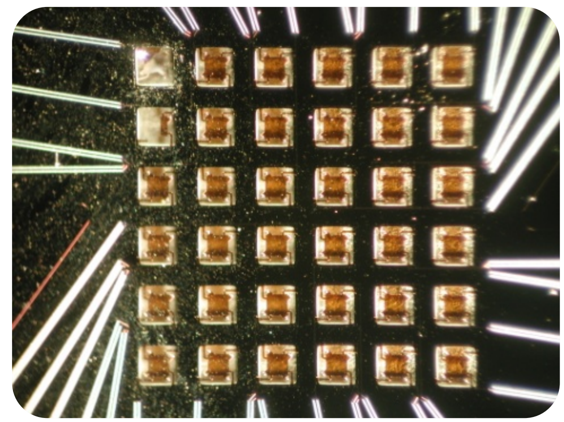
Sensitivity: **$m(\nu_e)$ = 200 meV (90% CL)** / 350 meV (5σ)

Statistics σ_{stat} = 0.018 eV²

Systematics σ_{syst} < 0.017 eV²

Tritium data: mid-2016

MARE (Re)



Deploy large arrays of cryogenic micro-bolometers

Phase-1: sensitivity $m(\nu_e)$ ~ few eV

Phase-2: statistical sensitivity $m(\nu_e)$ ~ 0.1-0.2 eV

Advantage: scalable approach. Needs R&D.

ECHO (Ho)

EC de-excitation spectrum measurement

Project 8 (^3H)

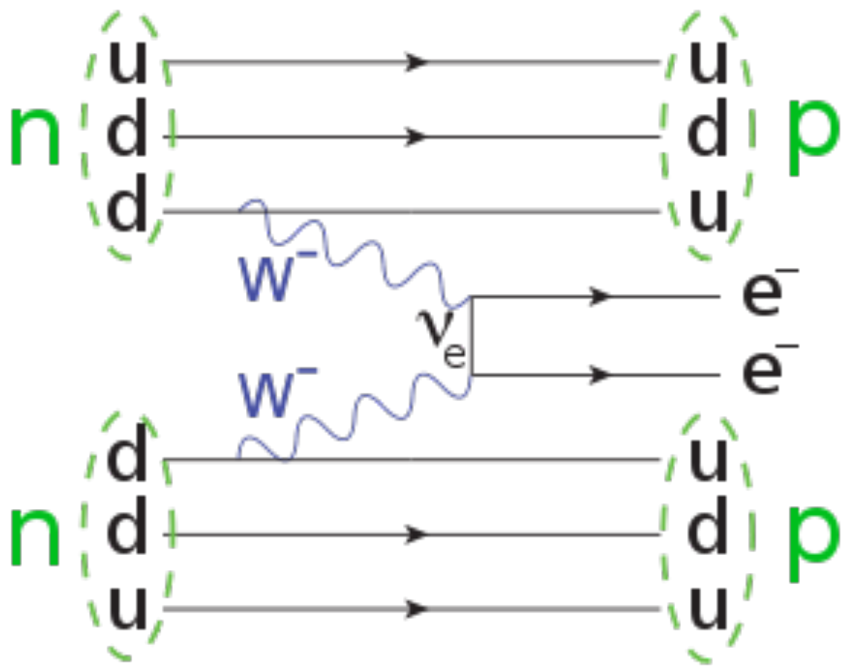
Coherent cyclotron radiation of single e^-

[G. Drexlin – NuPhys2013]

0νββ

(and 2νββ)

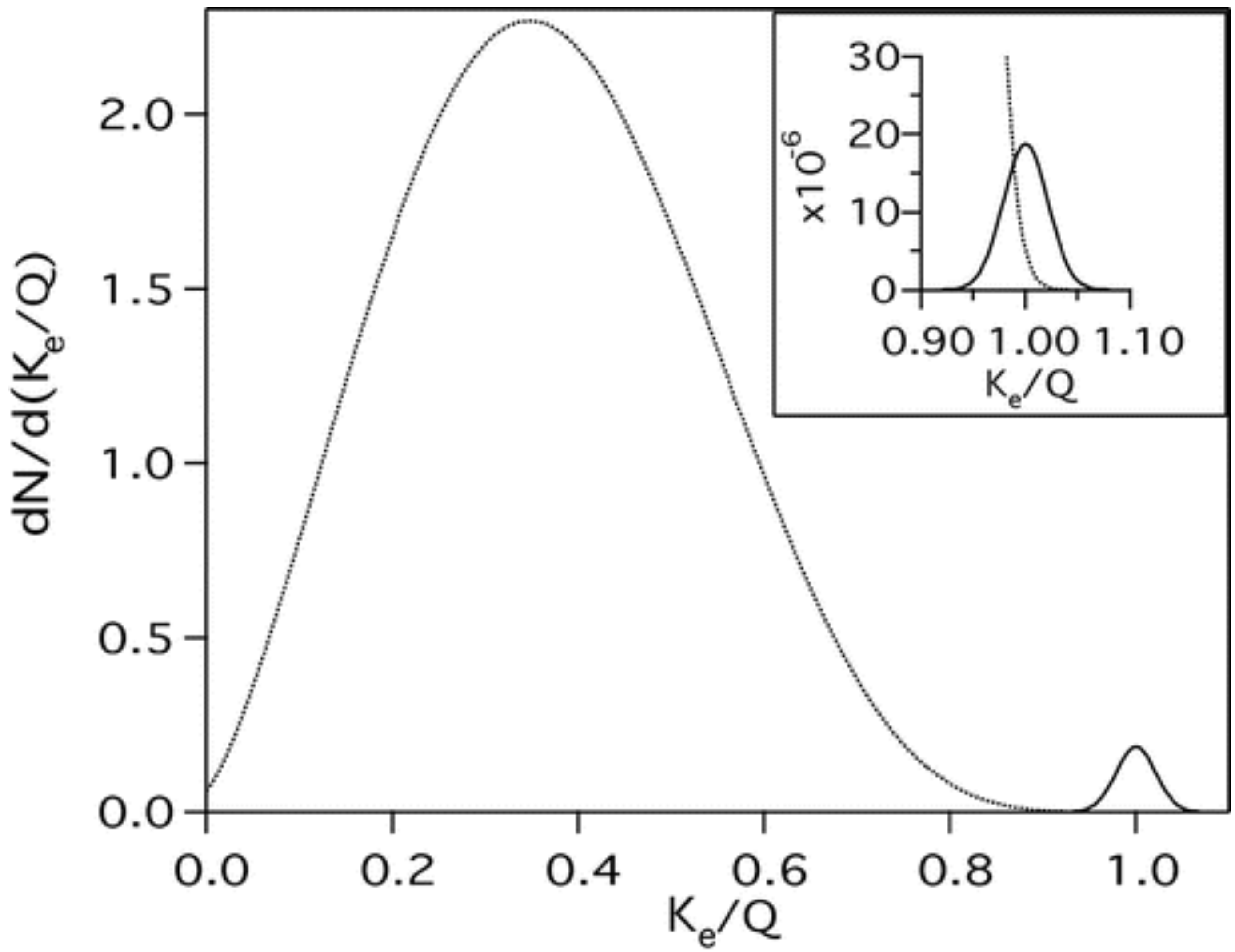
Why look for 0νββ?



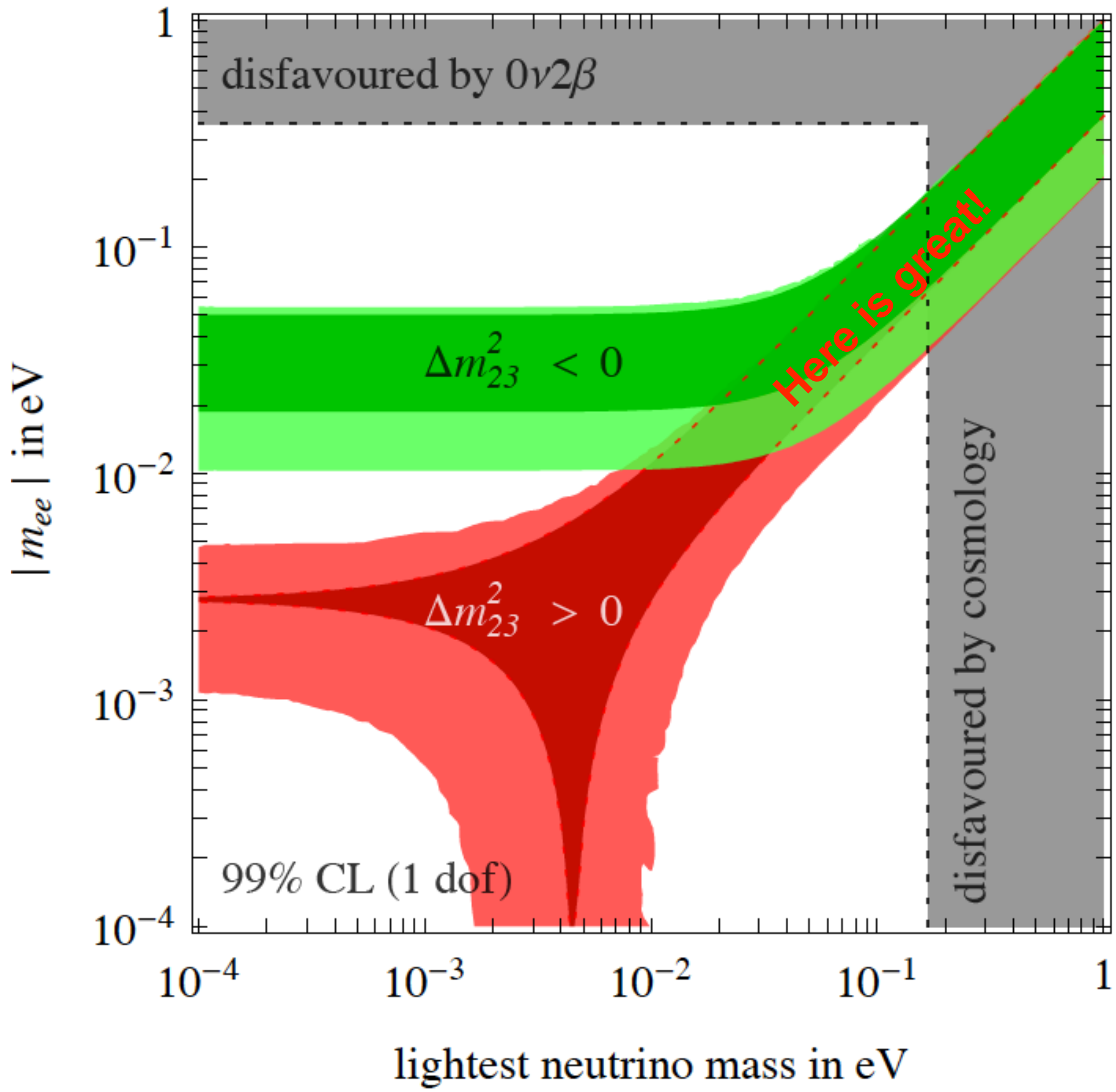
- Is lepton number violated?
- Are neutrinos their own antiparticles?
- What's the absolute neutrino mass scale?

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

0νββ Experimental Signature



Where do we stand on 0νββ neutrino masses?



[hep-ph/0606054]

Synergy with Oscillation Expts

If osc. expts show the mass hierarchy is inverted

AND

$0\nu2\beta$ expts **don't** see a signal for $m_\nu <$ ~15 meV

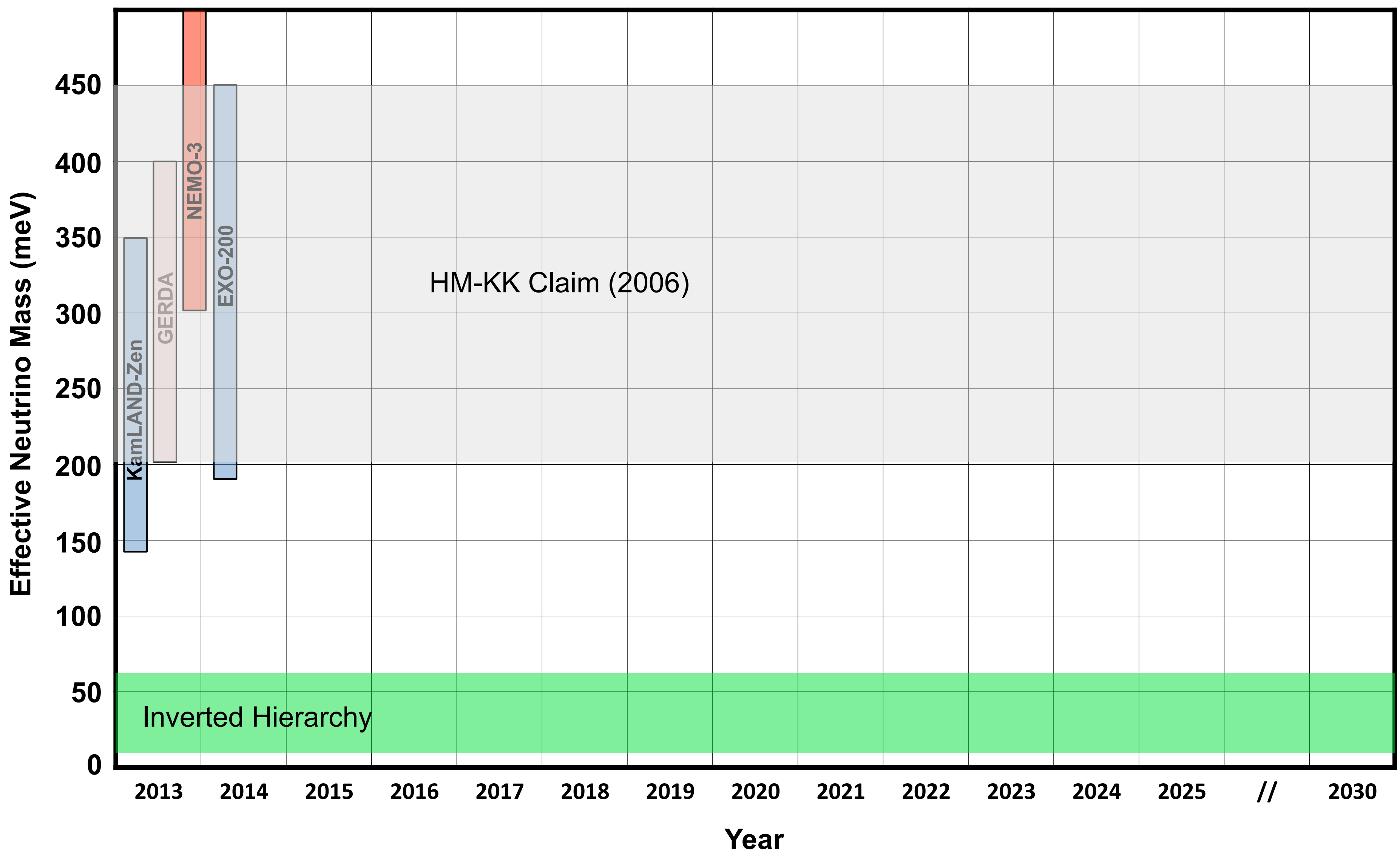
We know neutrinos are Dirac not Majorana
(assuming no extra new physics)

Double Beta Decay Experiments

- Currently running experiments
  - CANDLES
  - KamLAND-Zen (upgrades underway)
  - EXO-200
  - GERDA
- Experiments under construction
  - CUORE (currently running COURE-0)
  - Majorana "Demonstrator"
  - NEXT
  - **SuperNEMO (NEMO3 recently ran)**
  - **SNO+**

[Mark Chen, NuPhys2013]

Current Results

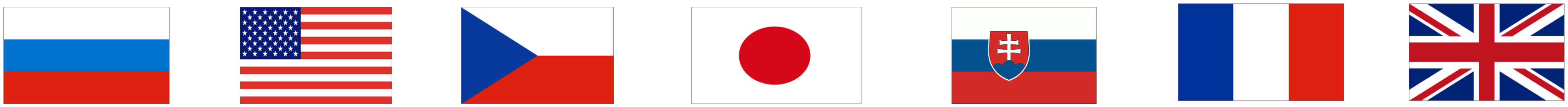


Focus Now on UK Efforts

For more detail see Parallel session 1E
Rare/Precision Lepton Physics
This afternoon at 1pm

NEMO3/SuperNEMO:
Stefano TORRE, Guillaume EURIN, Pawel GUZOWSKI

SNO+:
Philip JONES, Ashley BACK

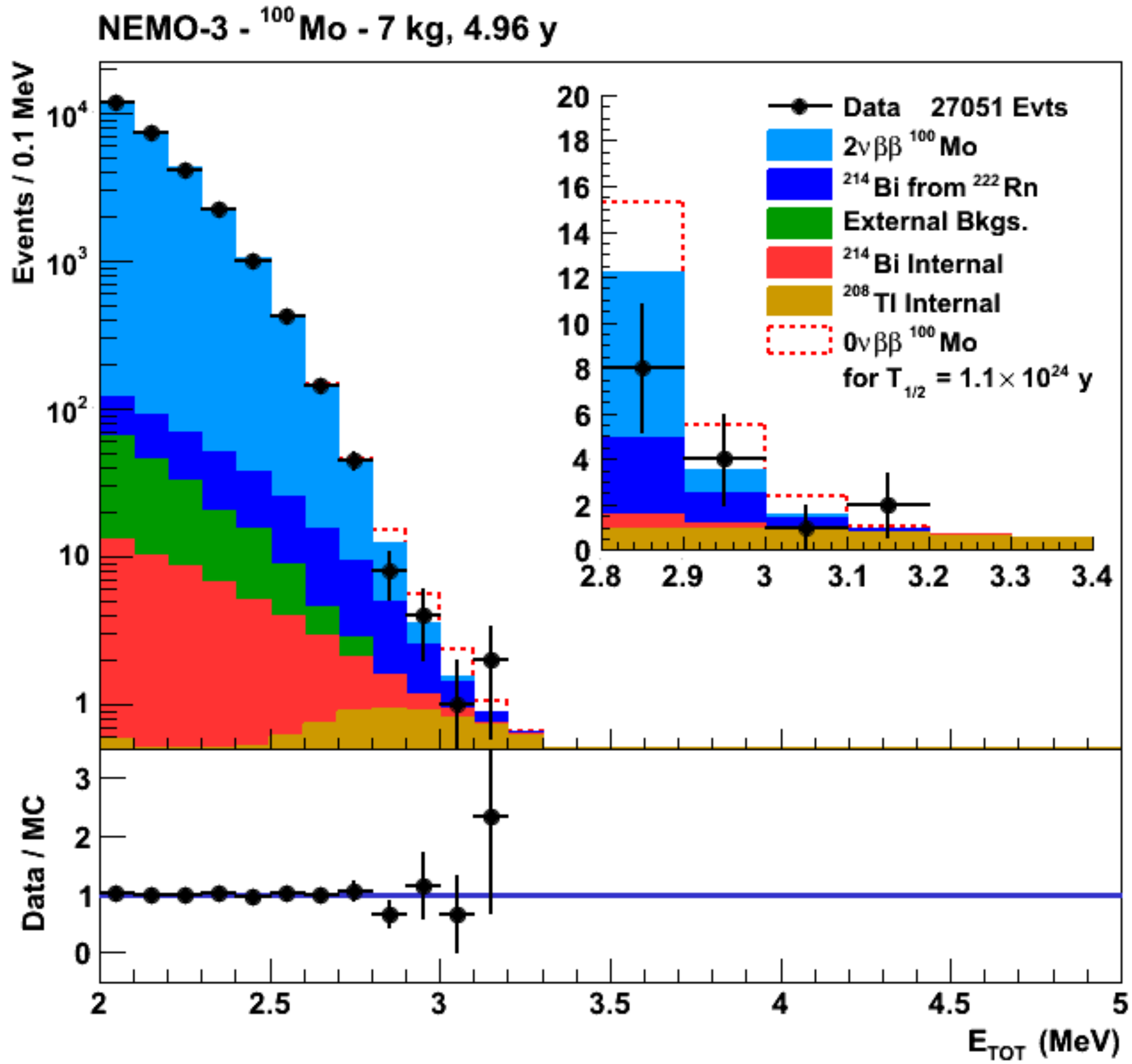


supernemo

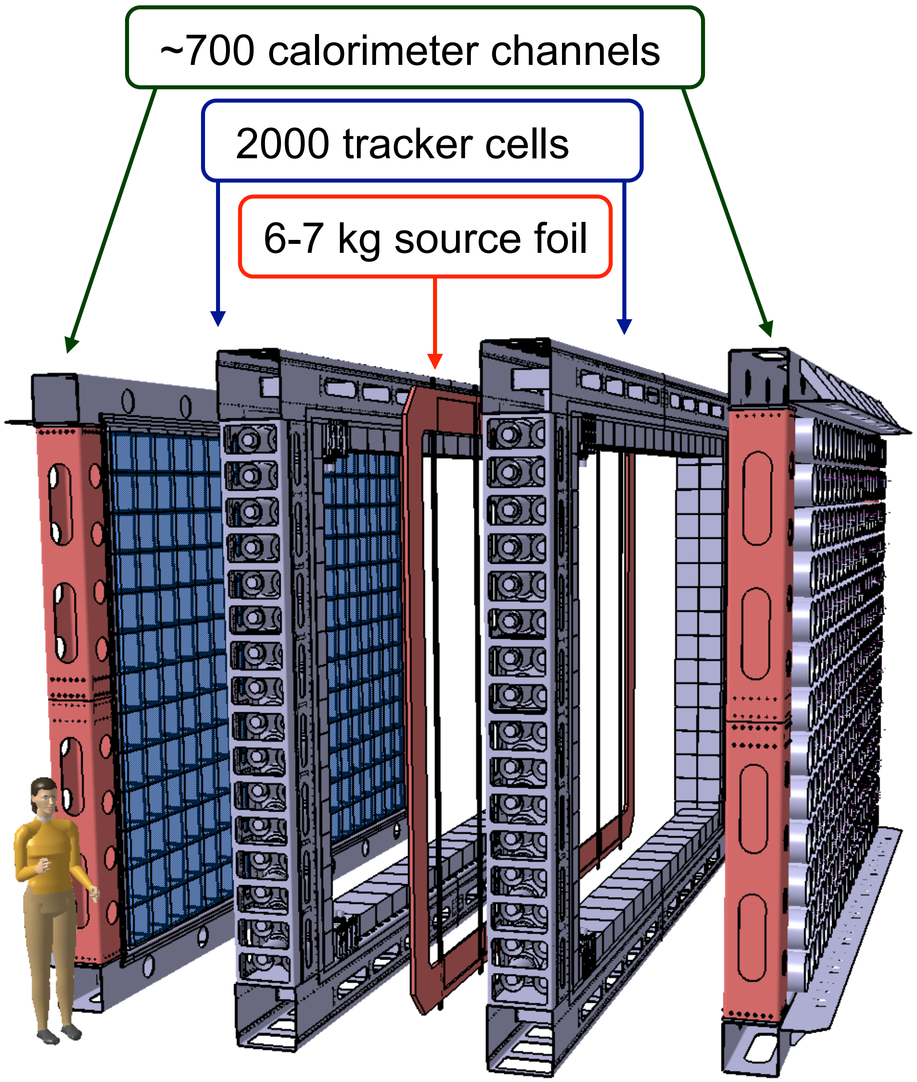
collaboration

UK groups: Imperial, Manchester, UCL, UCL-MSSL, Warwick

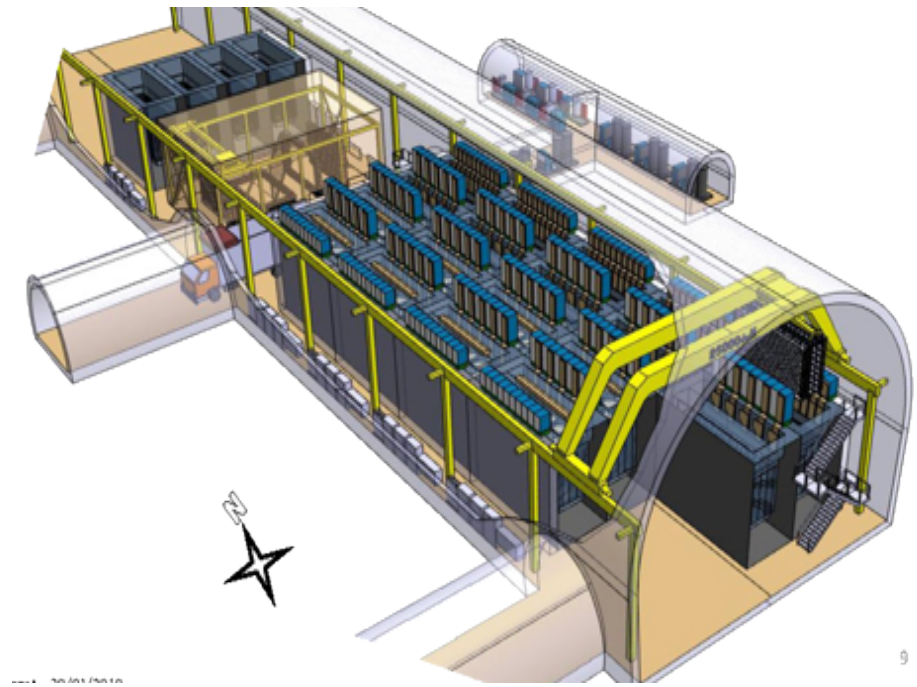
Builds on Successful NEMO-3



SuperNEMO Detector



Demonstrator Module

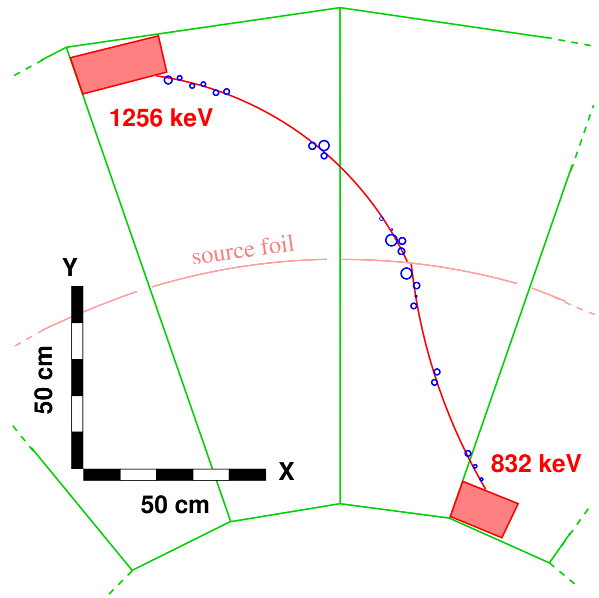


Full SuperNEMO
20 Modules

[Dave Waters, seminar]

SuperNEMO Concept

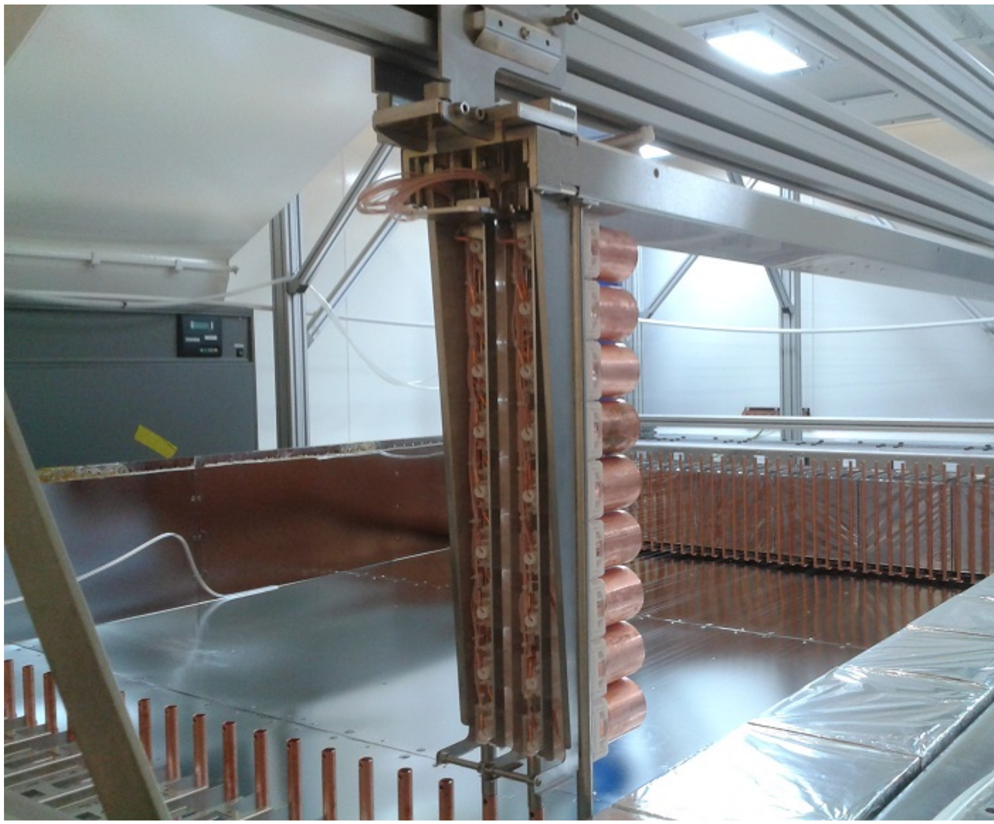
- Tracking-calorimeter
  - Trade off isotope mass for event topology



- Why take this approach?
  - Build on NEMO-3 success
  - Topology very powerful
    - Identify and suppress backgrounds
      - Zero-backgrounds for demonstrator
    - Characterise the mechanism of $0\nu\beta\beta$ decay (on discovery)
  - Flexibility in isotope choice

UK SuperNEMO Contributions

UK building a 2000 channel Geiger-mode tracking detector

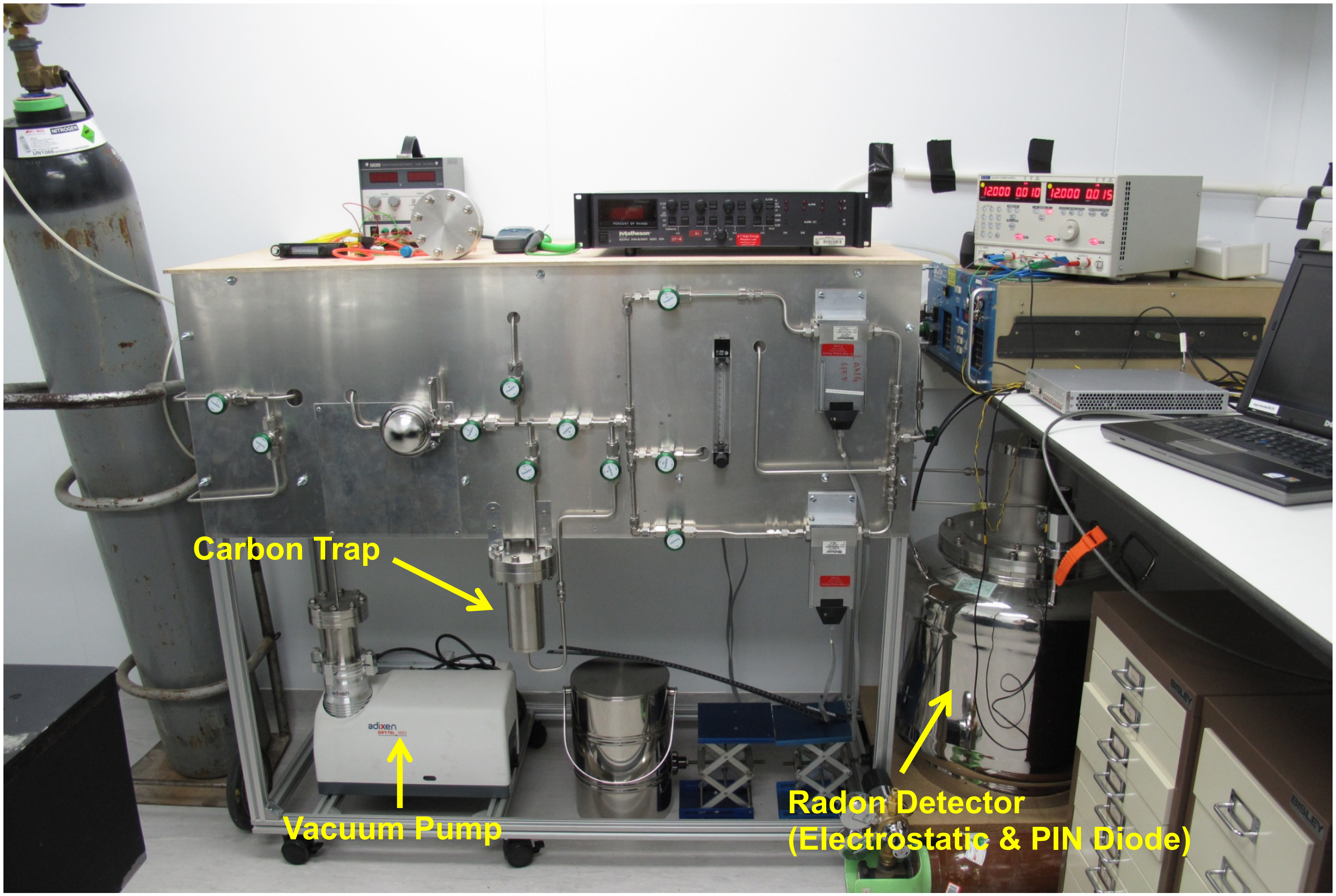


Tracker wiring robot (Manchester)

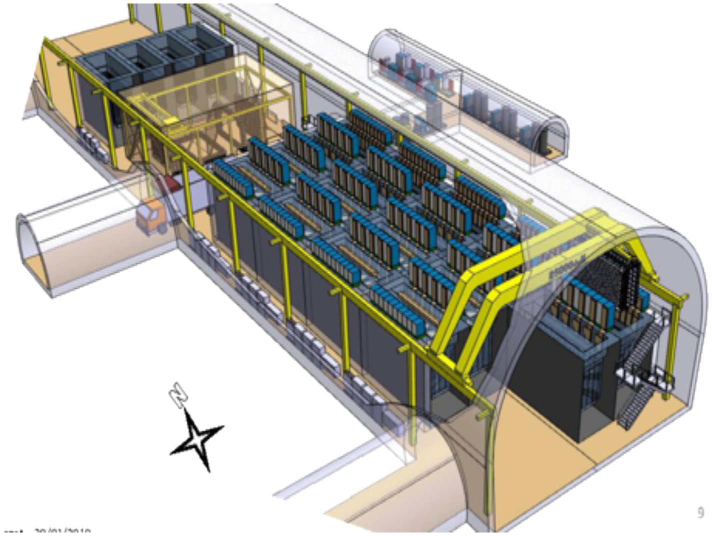
[Dave Waters, seminar]

Radon Concentration Line

- UK built most sensitive radon detector: important technology for many expts
- Need < 100 Rn-atoms/m^3 (!)



SuperNEMO : Timeline



Demonstrator Module Running :
- Prove that we have the lowest background of *any* experiment.
- Competitive limits.
- Unique ββ measurements.

Demonstrator Module construction and commissioning

2012	2013	2014	2015	2016	2017	2018	2019	2020	2020+

Construction and deployment of successive SuperNEMO modules

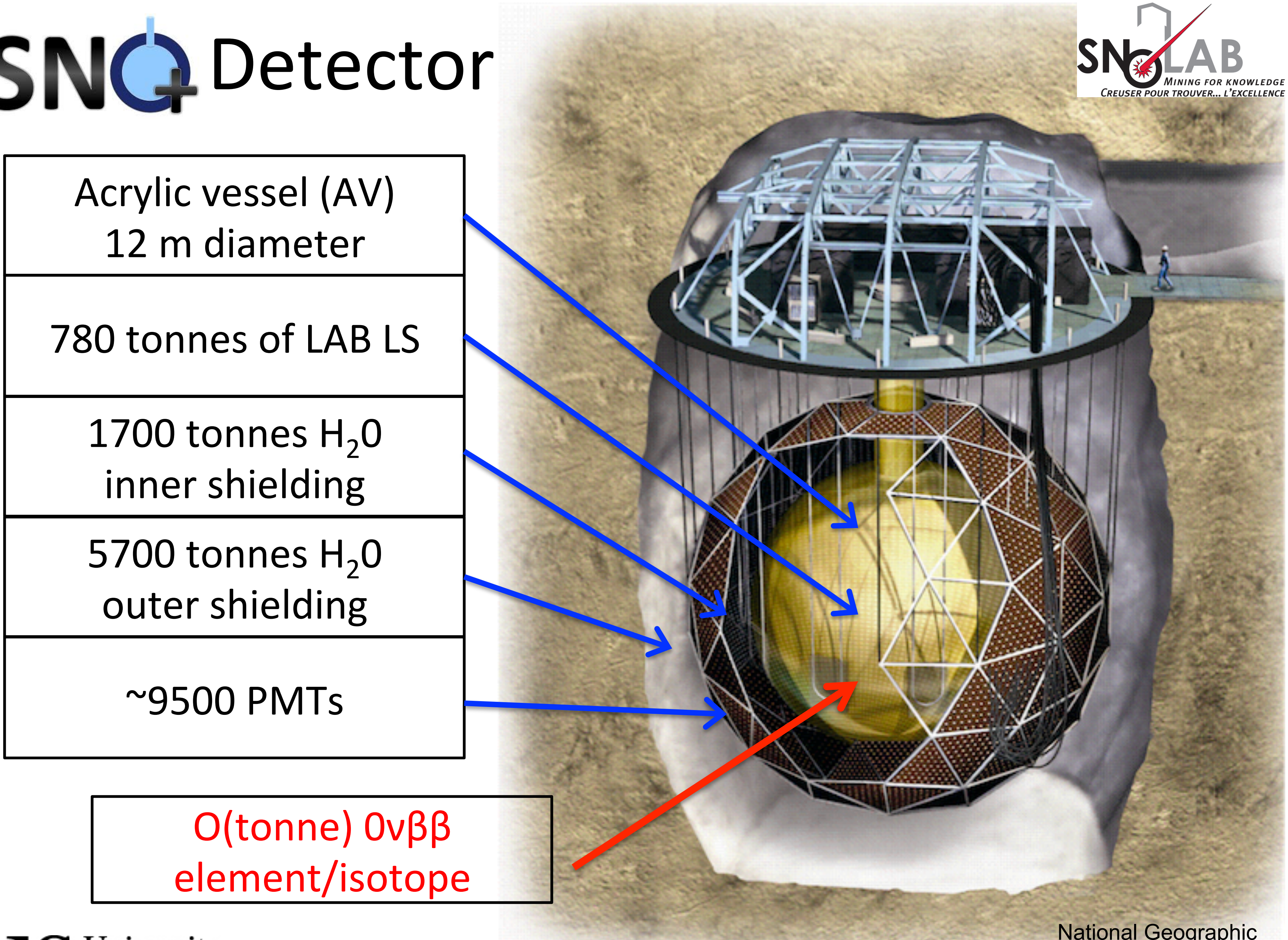
Continuous operation of ≥1 SuperNEMO module

[Dave Waters, seminar]

SNO+

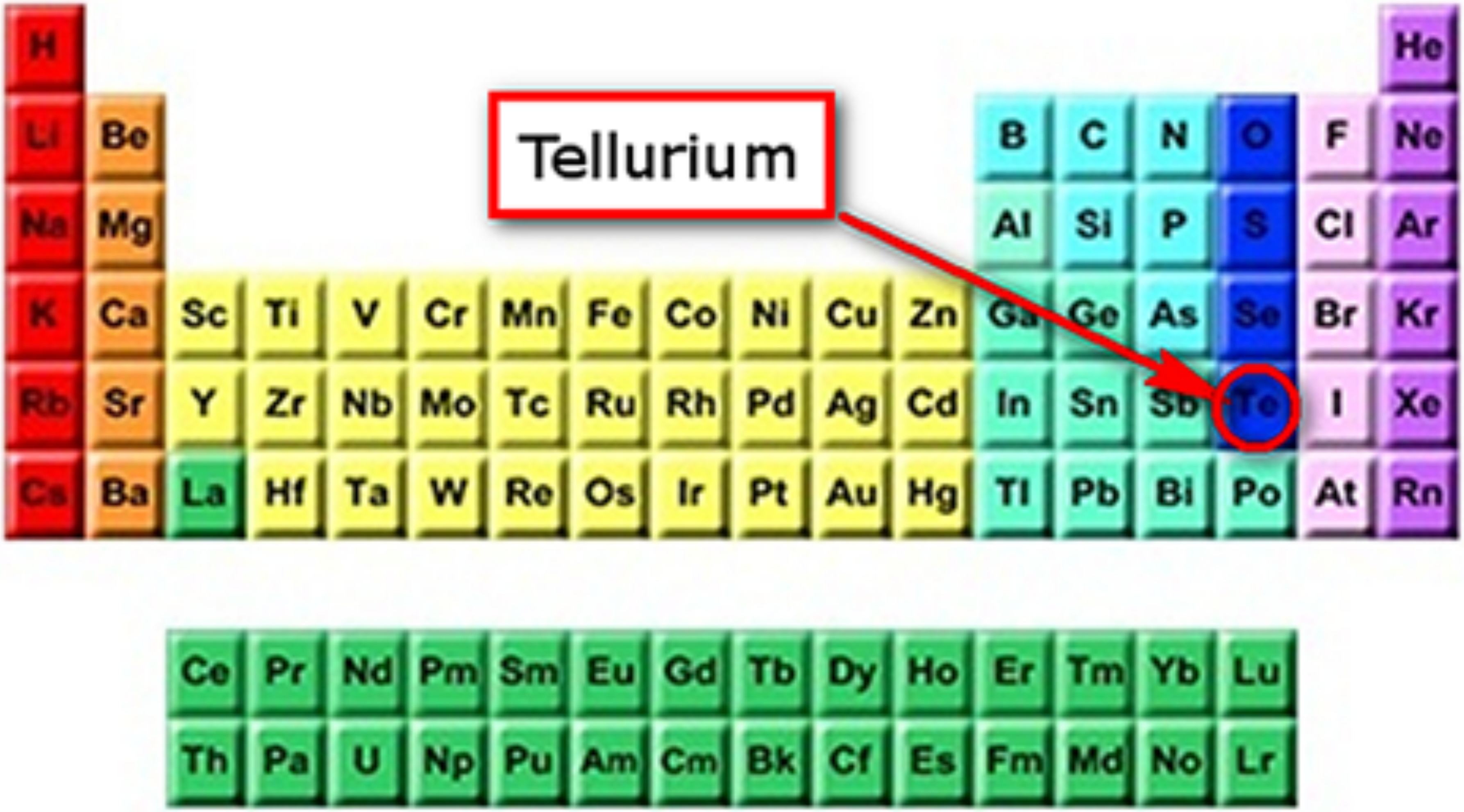
UK groups: Oxford, Sussex, Queen Mary, Liverpool, Sheffield, Lancaster

SNO+ Detector



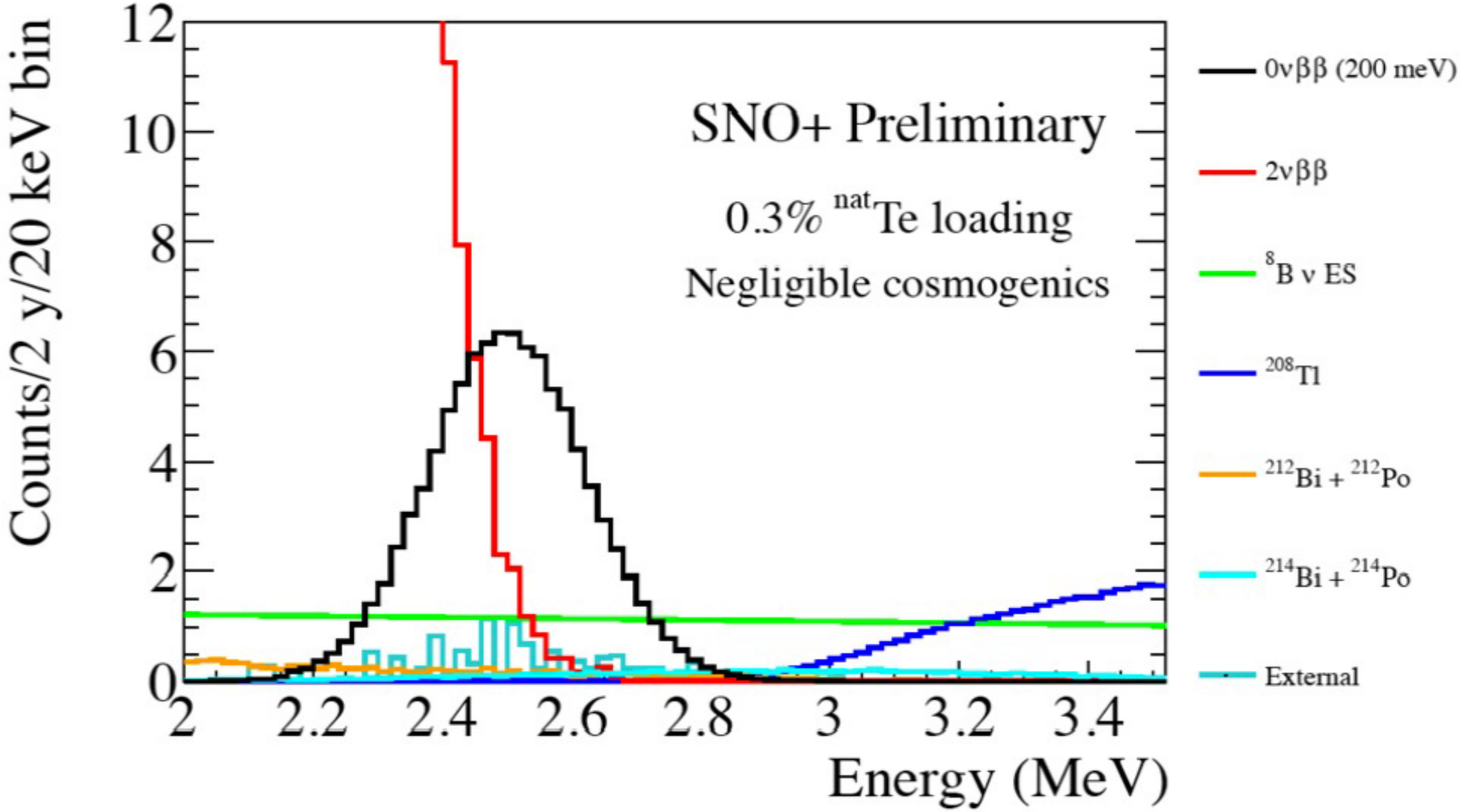
SNO+ Concept

- Load liquid scintillator with 0νββ isotope
  - Trade off energy resolution for higher statistics and lower backgrounds
- Why take this approach?
  - Cost-effective: detector already exists
  - Various isotopes can be used
  - Shielding:
    - Huge external shielding (7400 tonnes H_2O)
    - Self-shielding of scintillator
  - Purification of scintillator by distillation
  - Fast timing to reject Bi-Po backgrounds
  - Flexibility of liquids: loading-level & purification



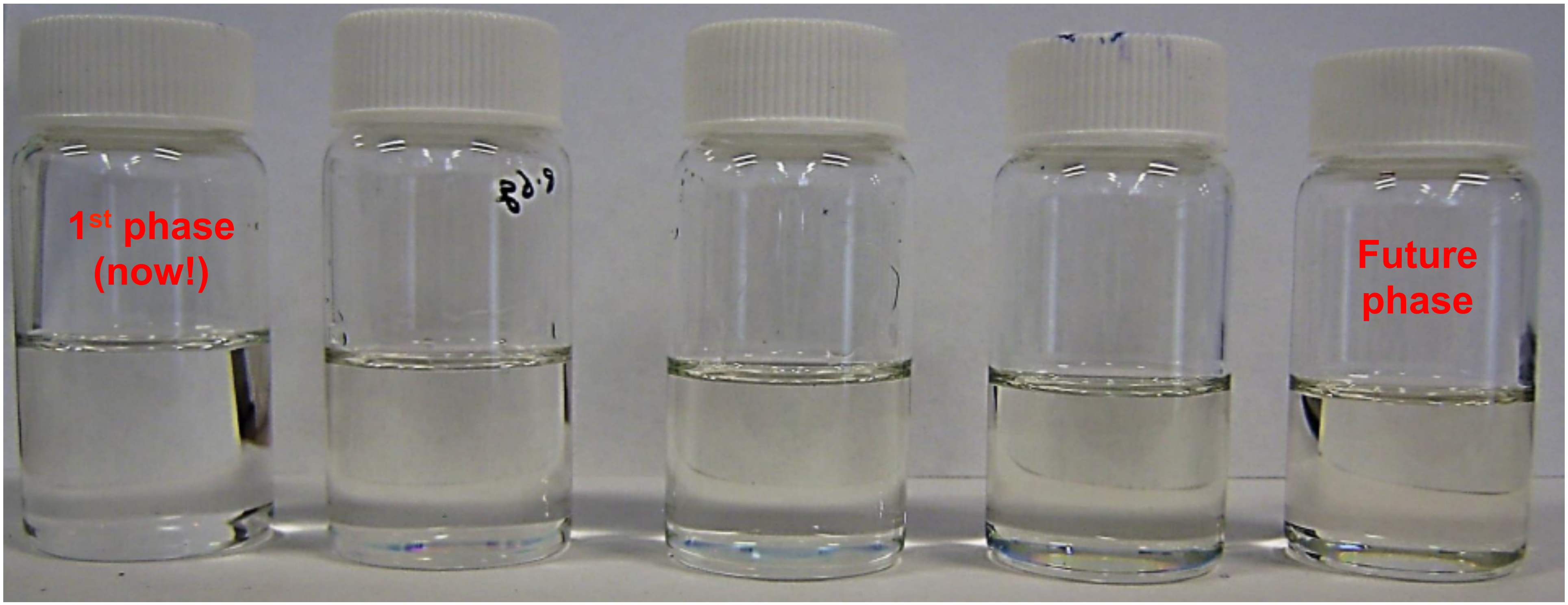
UK order for 1 tonne of Te now placed!

Simulated energy spectrum



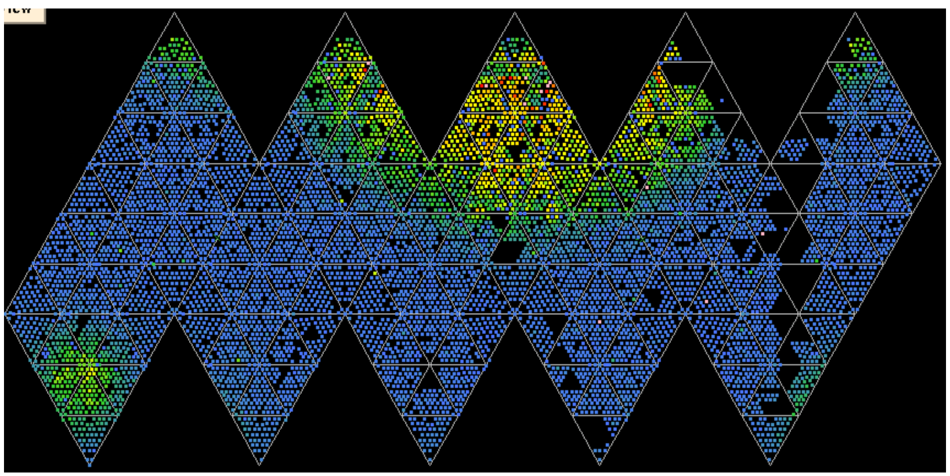
UK Co-leading Development Group

Ongoing R&D towards future SNO+ phases...

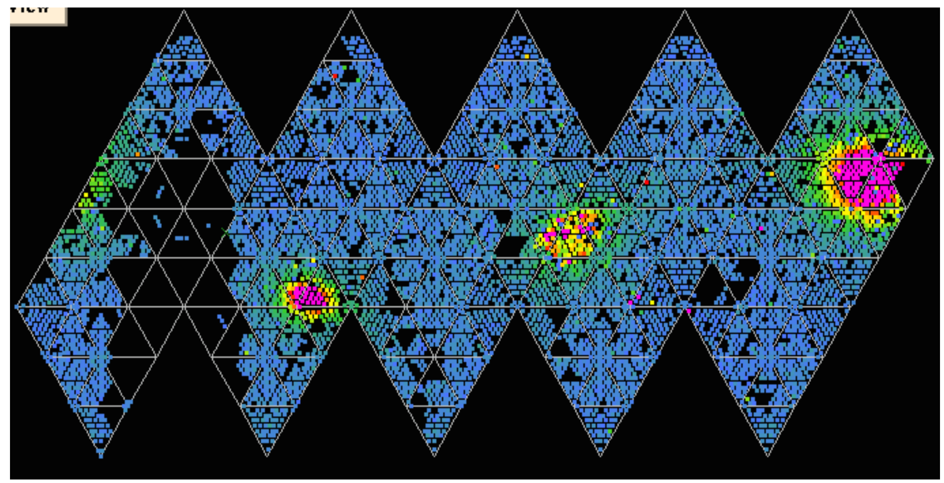


0.3% 0.5% 1% 3% 5%

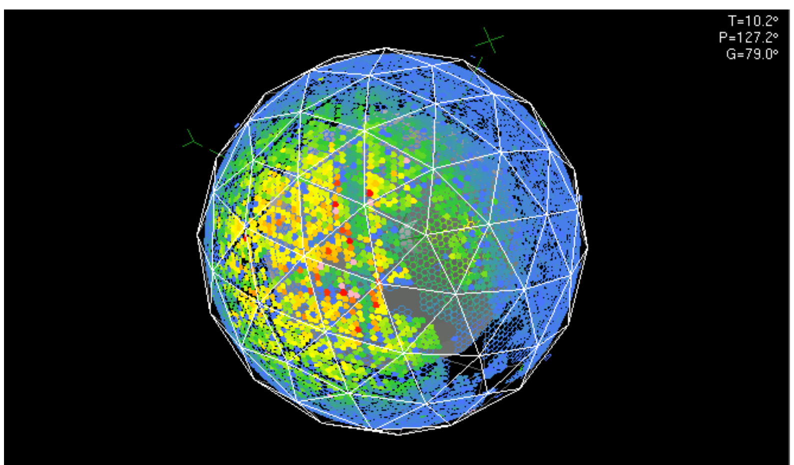
UK/EU Optical Calibration Systems Commissioning in March/14

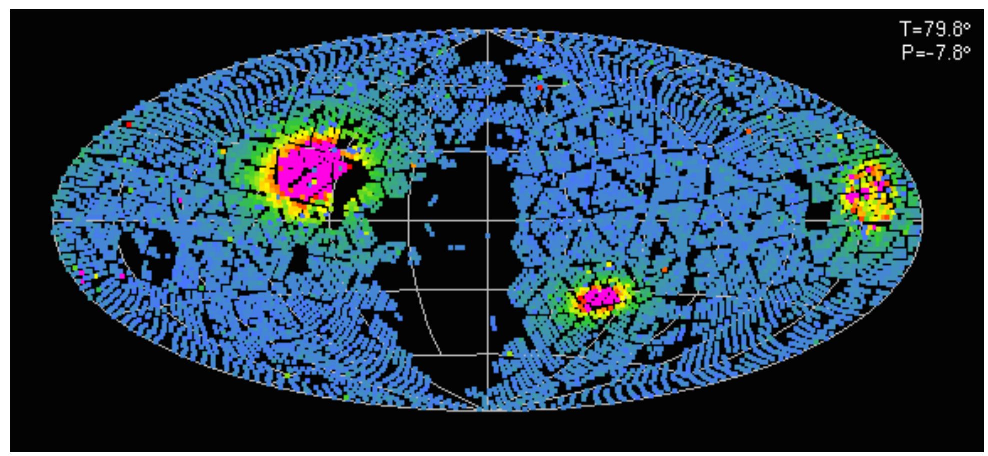


LED-based beams to illuminate entire detector (gain, timing calib)



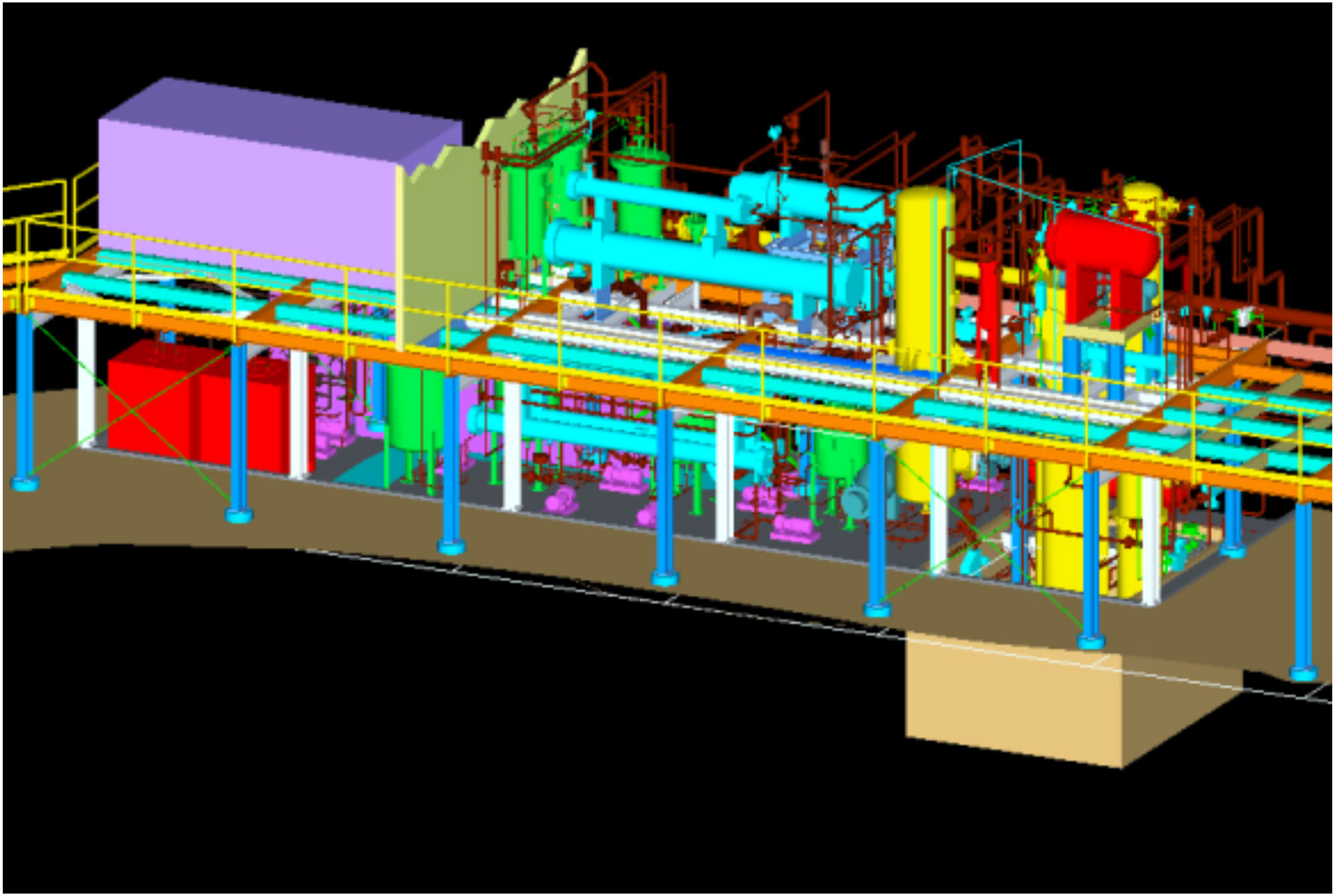
Narrow laser-based beams to study scattering





Lots of progress on-site

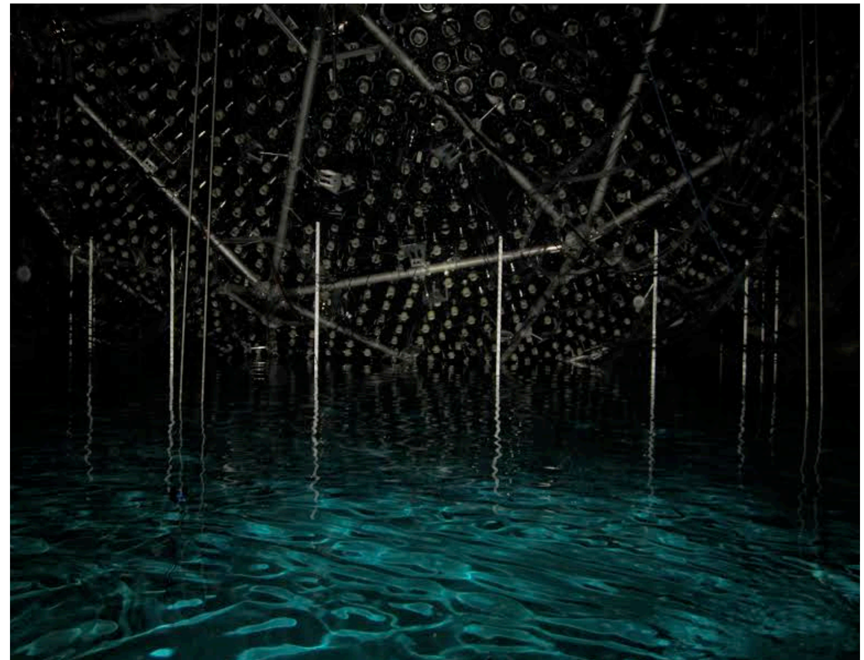
Scintillator processing plant is key



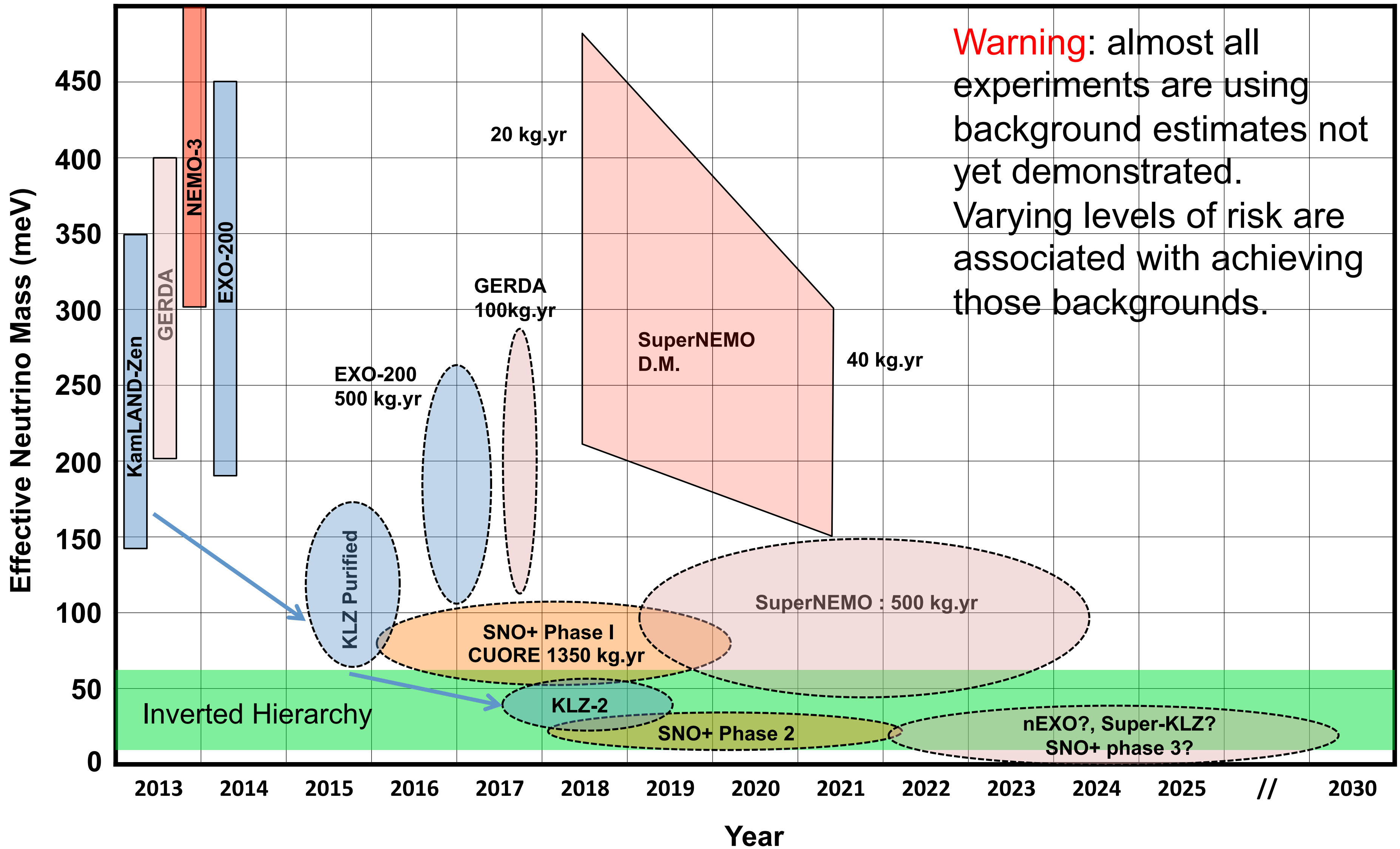
Columns

SNO+ Schedule

- Water fill has begun
- Scintillator process system completion: March 2015
- Detector filled with scintillator: September 2015



Comparing Sensitivities



[Input from D. Waters, S. Biller]

Conclusions

- β-decay and 0νββ address profound questions about the universe
- After a decade of building the next generation experiments... 1st wave of new results:
  - 0νββ: EXO-200, KamLAND-Zen, Gerda, NEMO-3
  - **$m_{\beta\beta}$ < 150 - 350 meV (90% CL)**
- Much more soon to come:
  - β: KATRIN, MARE... ECHO, Project 8
  - 0νββ: SuperNEMO, SNO+, KZ-upgrades, CUORE, EXO-200, Gerda, Majorana demonstrator, NEXT
- Huge windows for discovery opening up
- Stay tuned!

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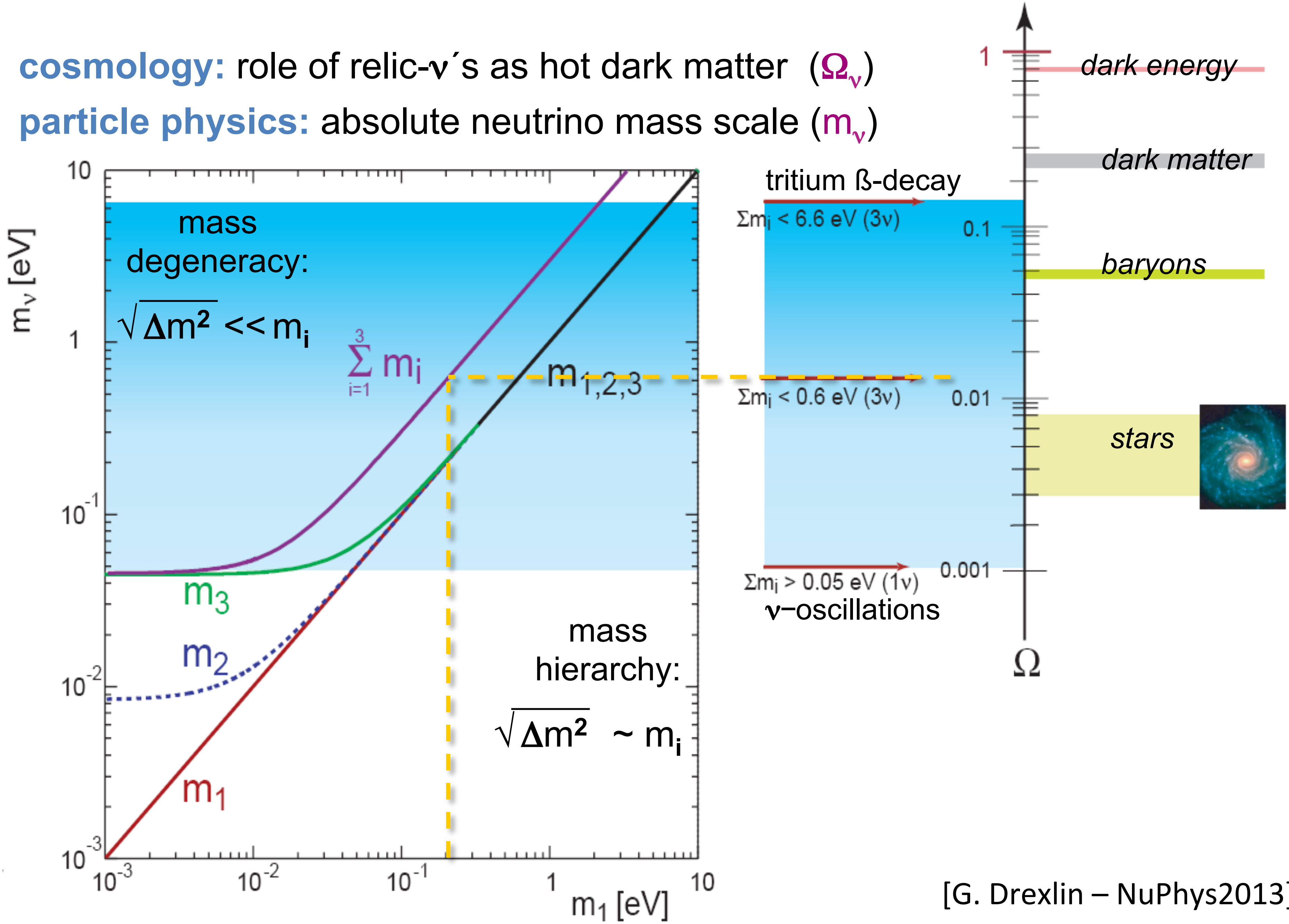
Backup slides

Where do we stand on neutrino masses?

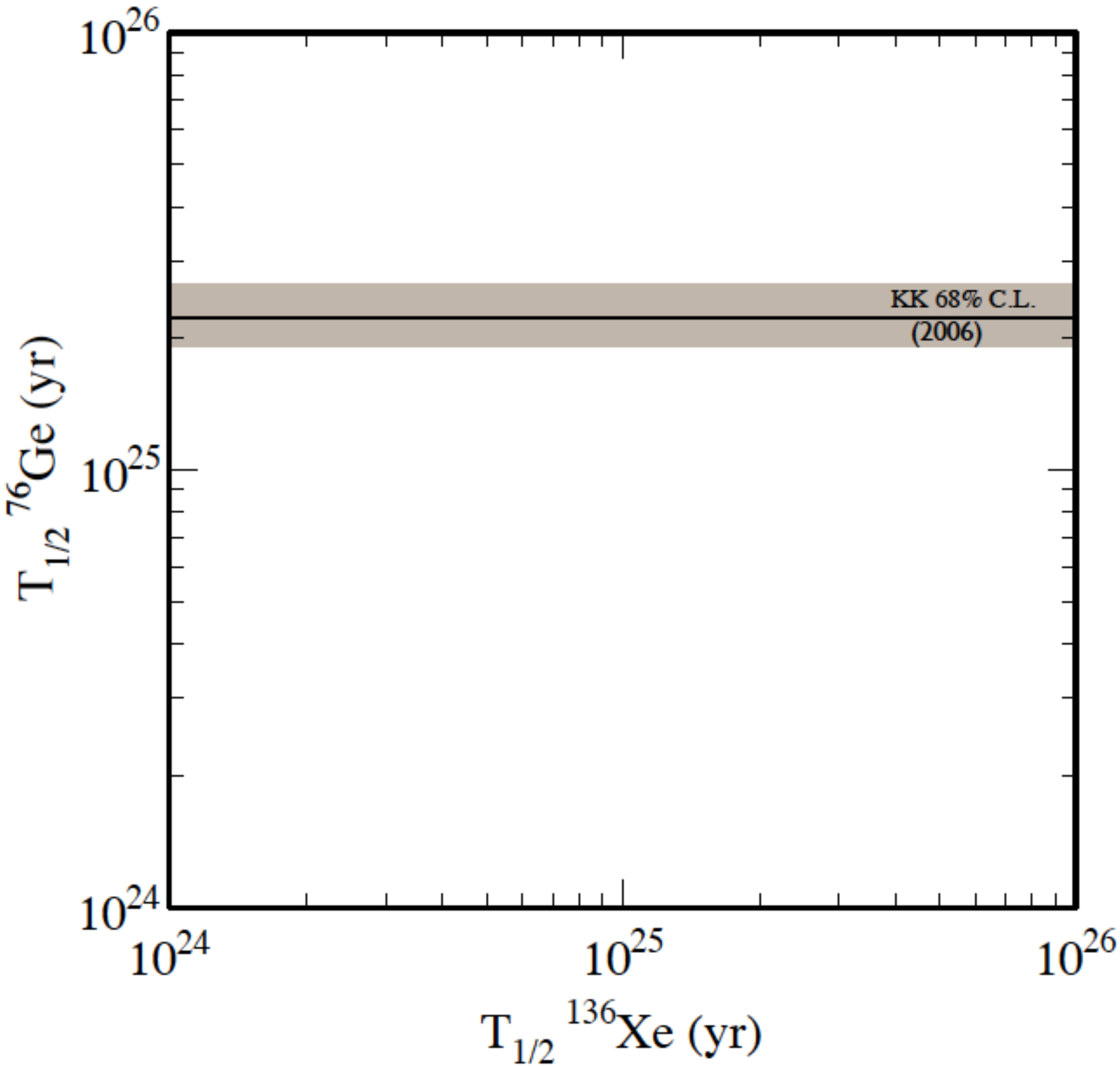
cosmology: role of relic-ν´s as hot dark matter (Ω_ν)

particle physics: absolute neutrino mass scale (m_ν)



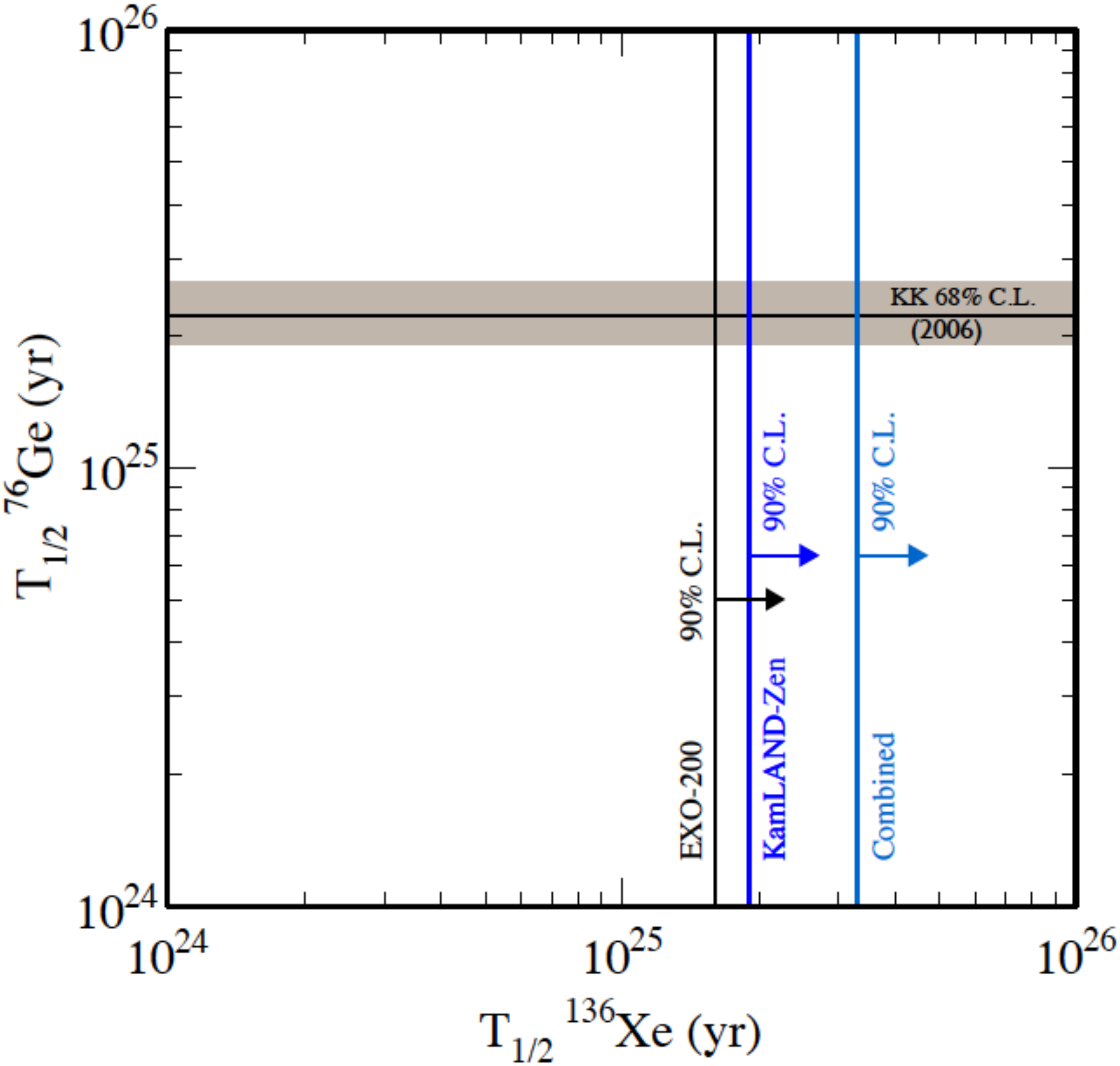
[G. Drexlin – NuPhys2013]

HM-KK Claim



KK 68% C.L.
(2006)
10^{26}
10^{25}
10^{24}
$T_{1/2}$ ^{76}Ge (yr)
10^{24}
10^{25}
10^{26}
$T_{1/2}$ ^{136}Xe (yr)

HM Claim Vs EXO-200 & KamLAND-zen



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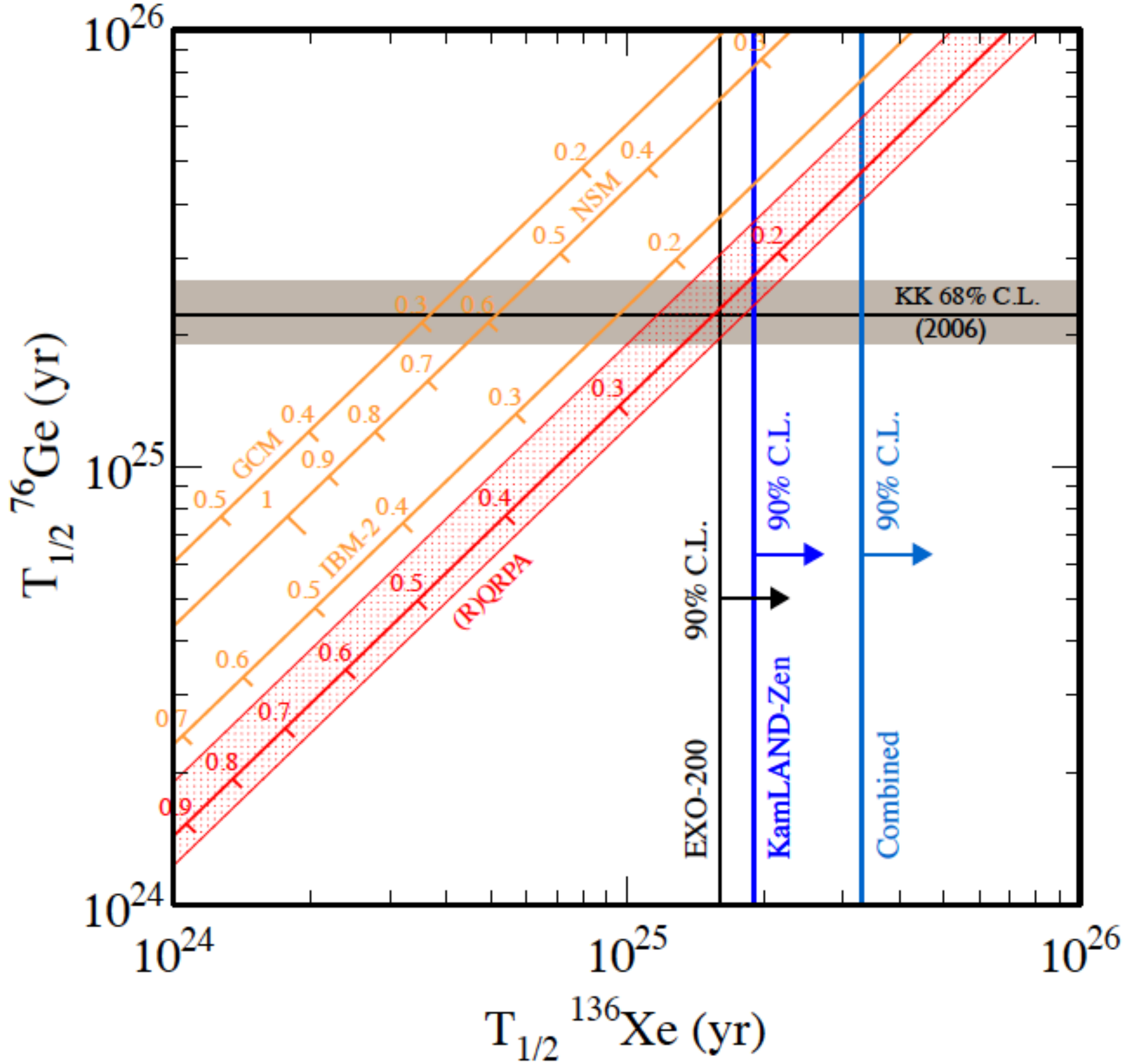
HM Claim Vs EXO-200 & KamLAND-zen



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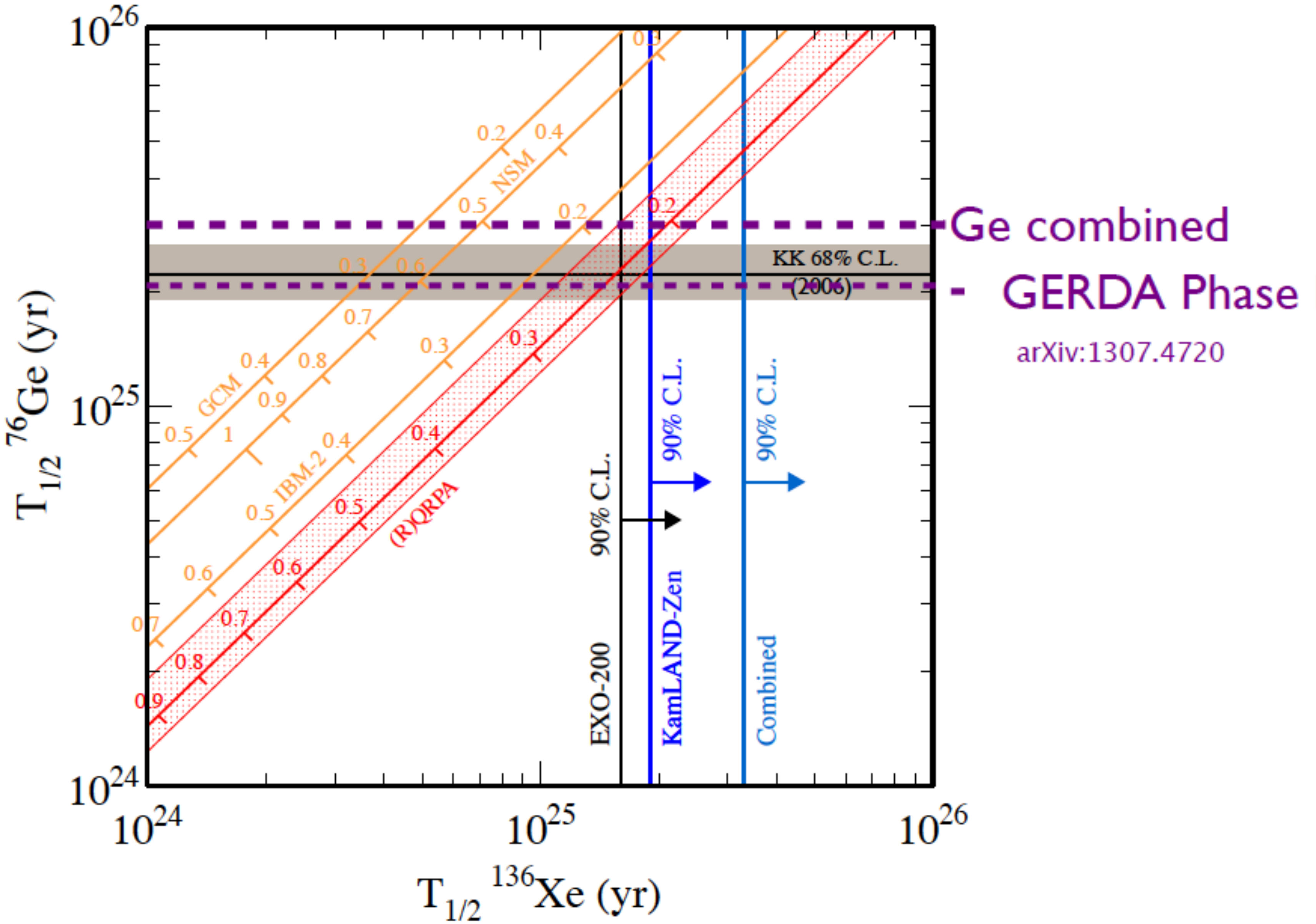
HM Claim Vs EXO-200 & KamLAND-zen



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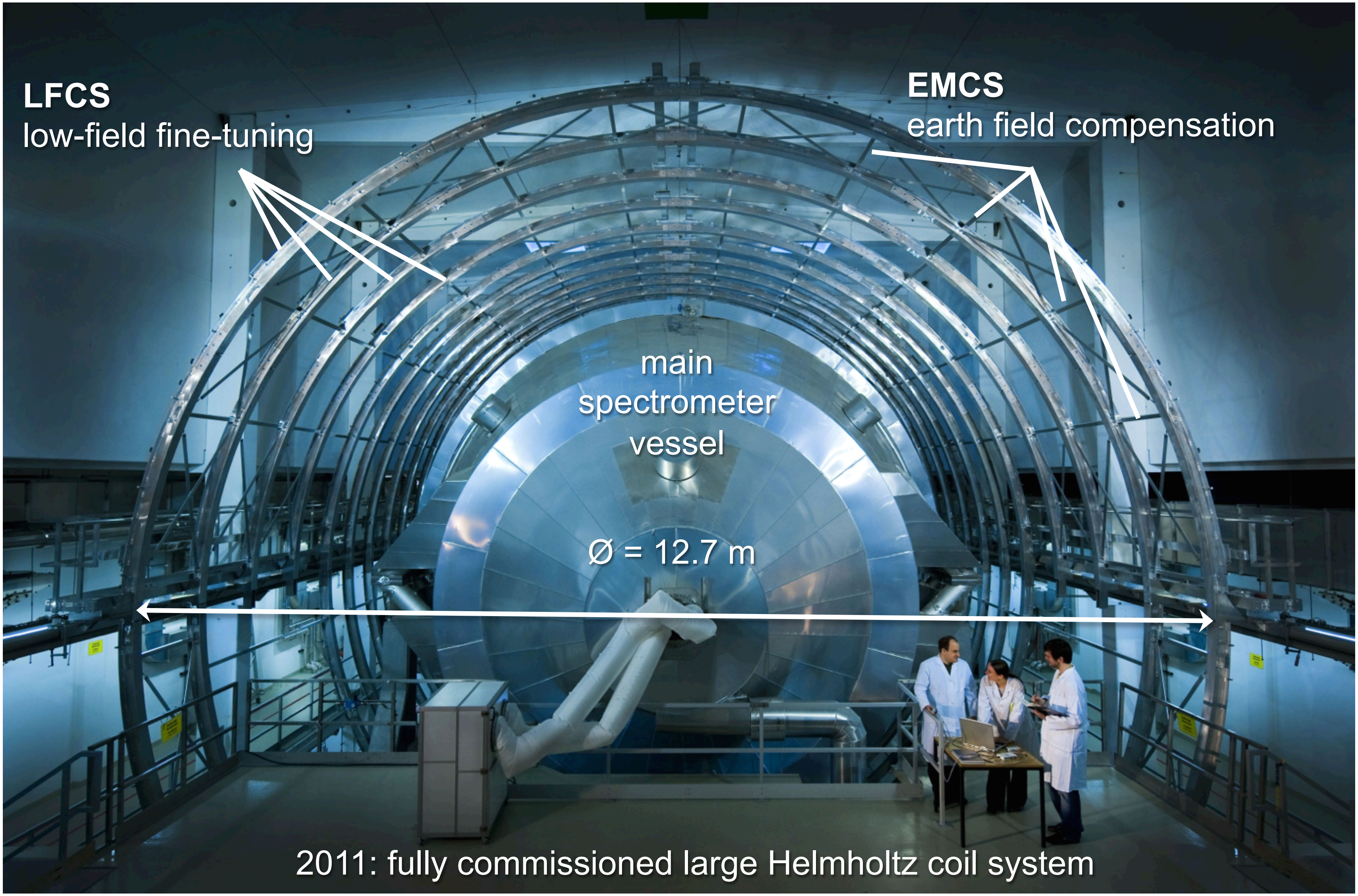
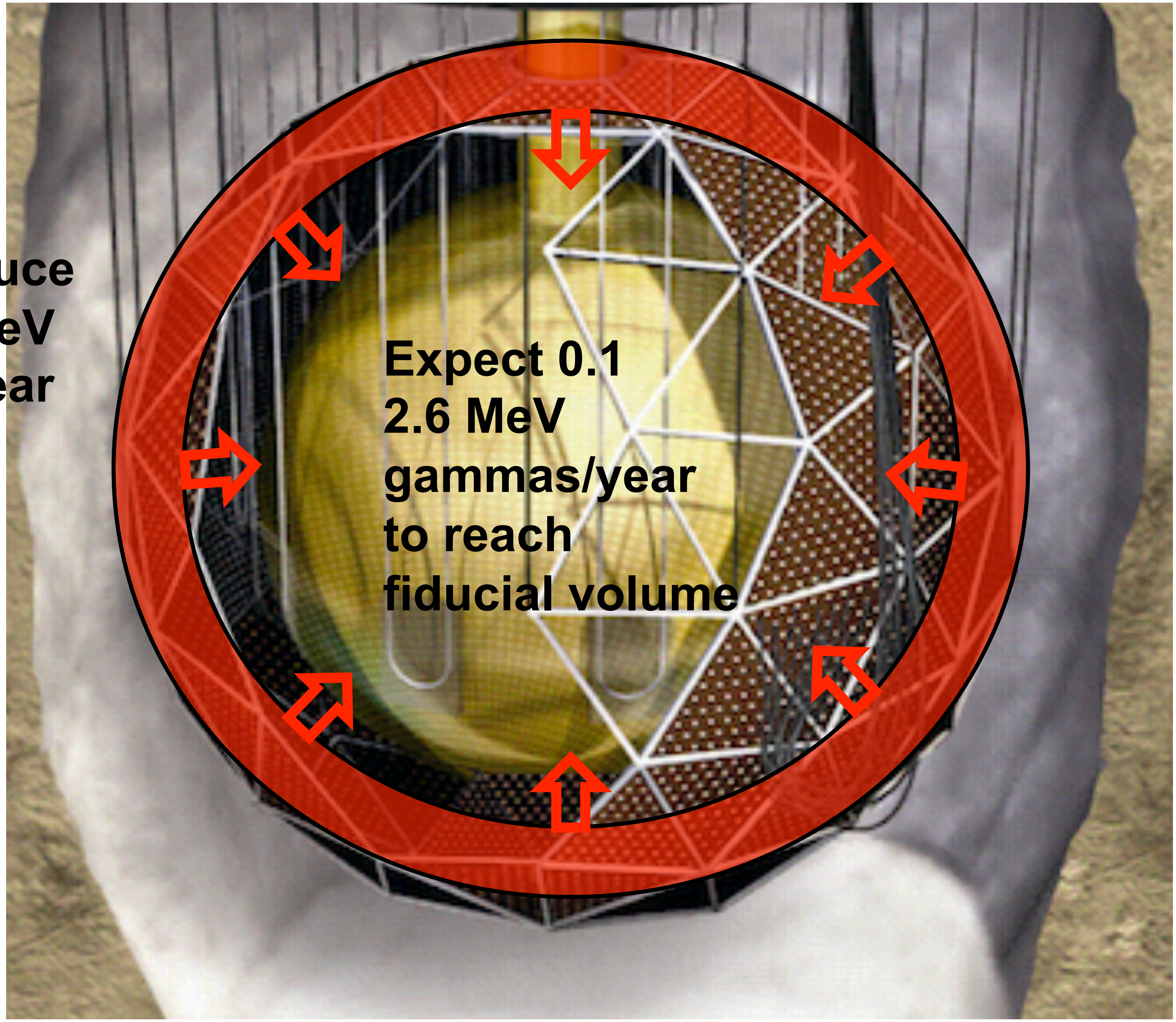


[G. Drexlin – NuPhys2013]

Upper Plant Area

Effect of shielding

PMTs produce $\sim 10^{11}$ 2.6 MeV gammas/year



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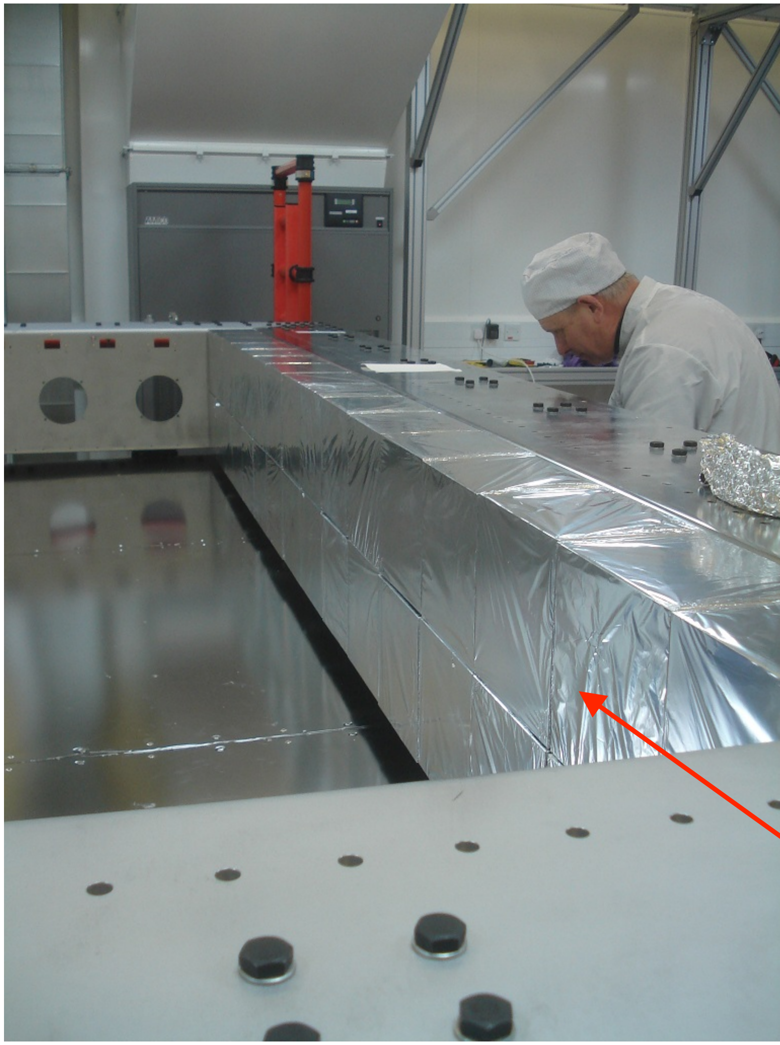
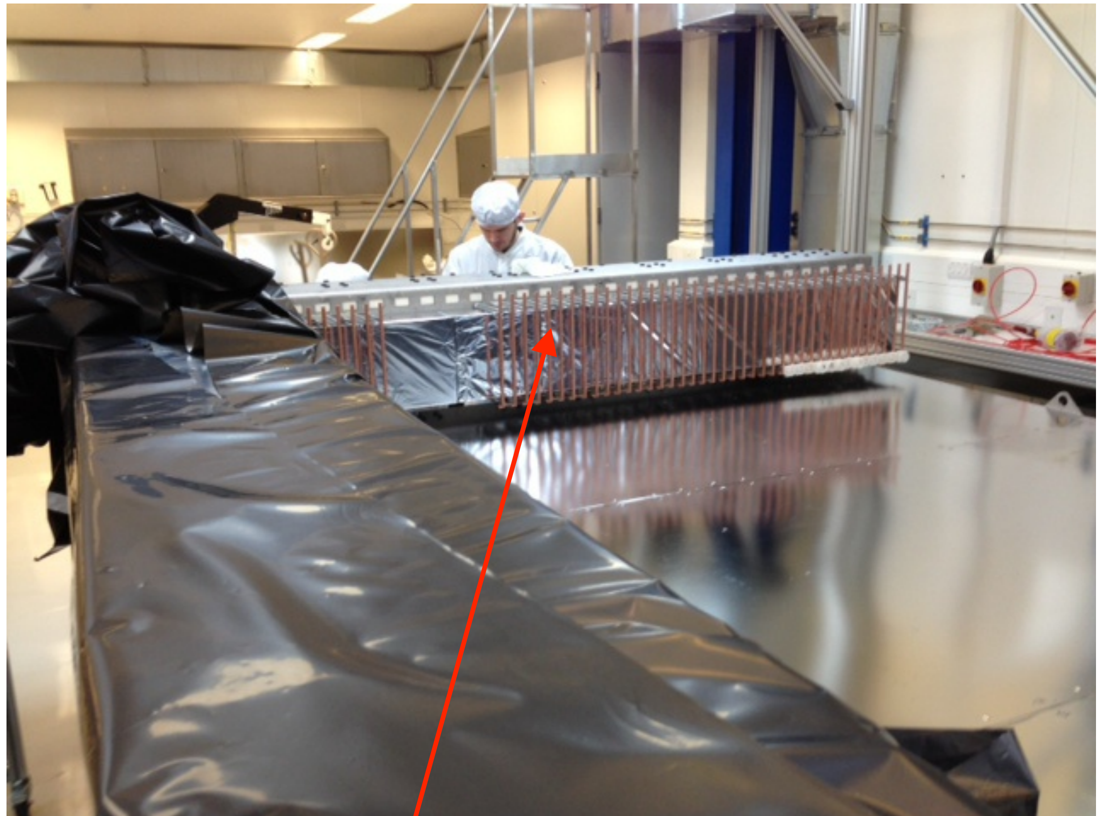
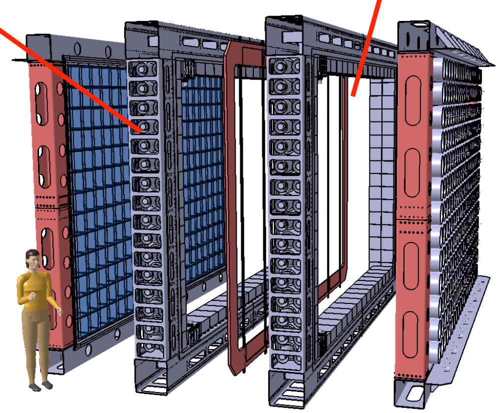
Tracker Frame



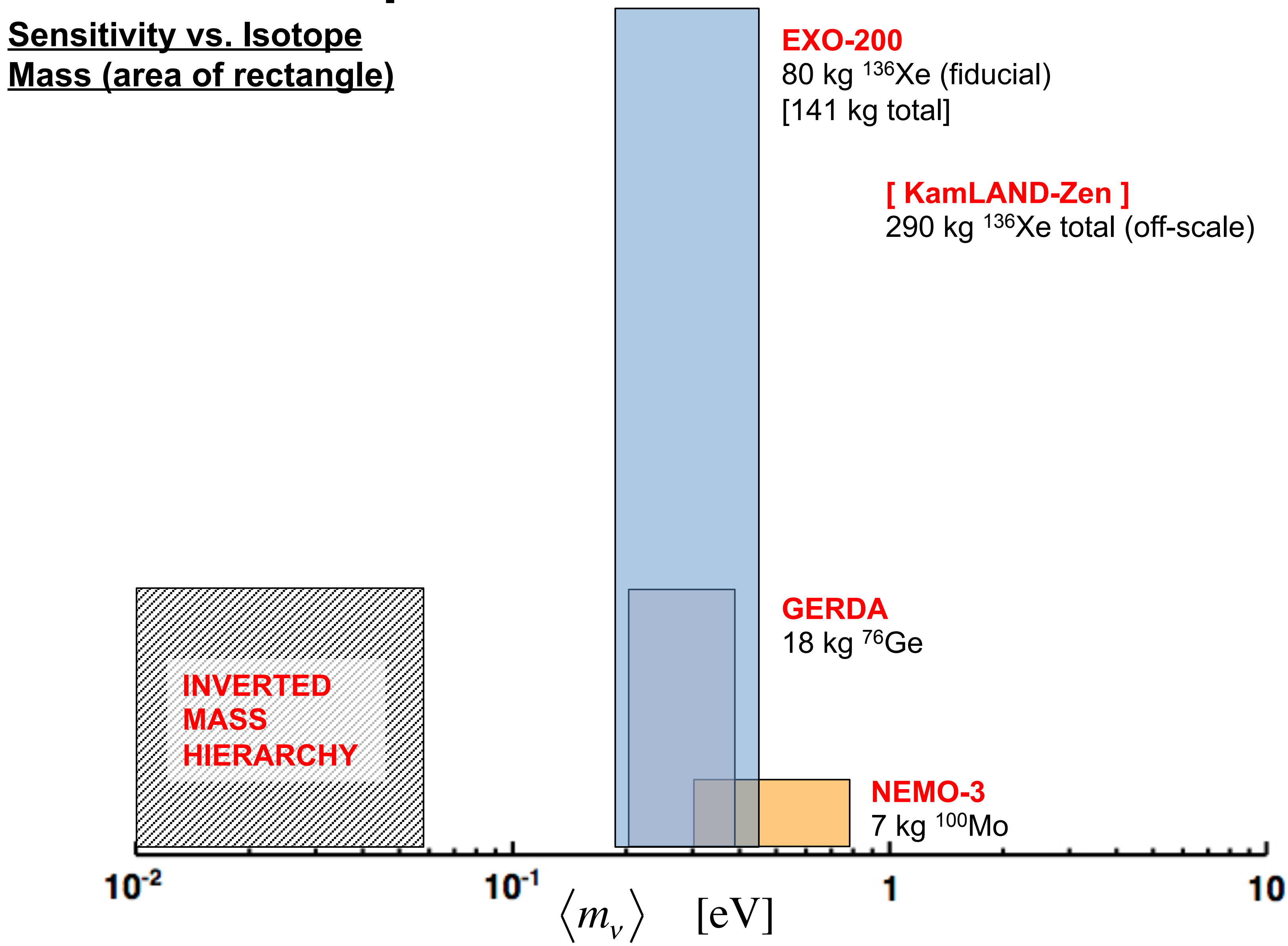




- Insertion of Optical Modules into tracker frame.
- Preparation of cell support structure.

[Dave Waters, seminar]

Comparison with NEMO-3

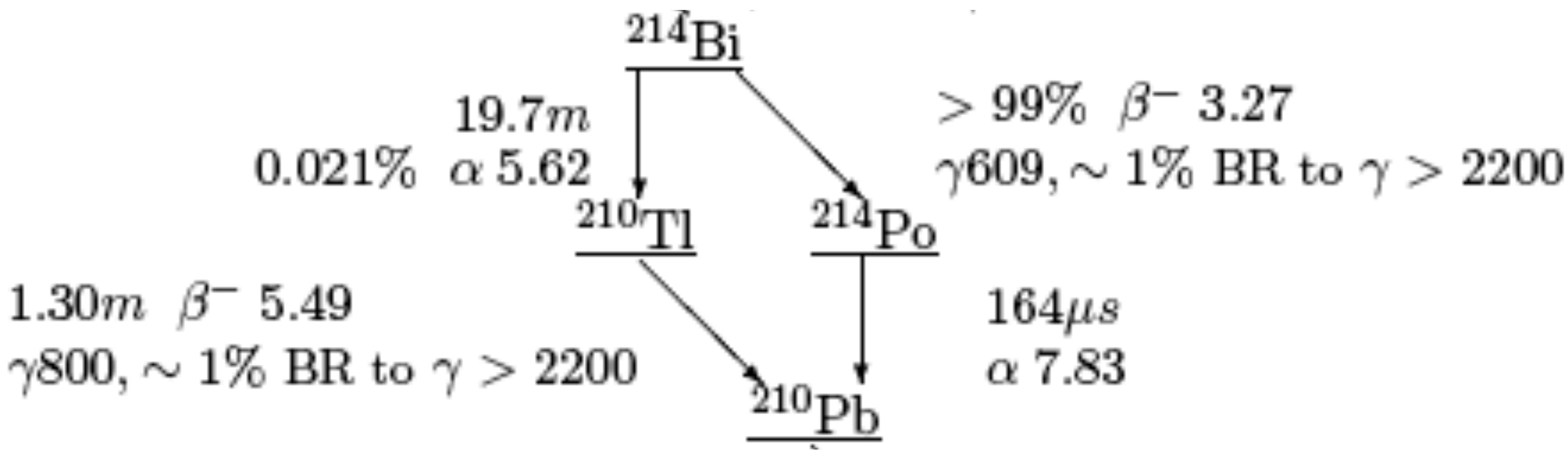


Experiment/ Isotope	Isotope mass (kg)	$T_{1/2}$ sensitivity (yr)	<m_ν> sensitivity (meV)	Expected year of target sensitivity	Comments
EXO-200 ^{136}Xe	160	3.3×10^{25}	110-260	2017	
nEXO ^{136}Xe	5000	1.0×10^{27}	20-47	2027	x20 lower bkg than in EXO-200
GERDA ^{76}Ge	40	1.0×10^{26}	120-280	2017	x10 lower bkg than GERDA-I
Ge-1t ^{76}Ge	1000	2.0×10^{27}	27-63	2030+(?)	Further bkg reduction (x3) or better PSA
CUORE ^{130}Te	200	1.0×10^{26}	50-130	2025	x5-10 lower bkg than currently achieved
SNO+	800	1.0×10^{26}	50-130	2017-20 (?)	[No data]

Why switch to ^{130}Te (from ^{150}Nd)?

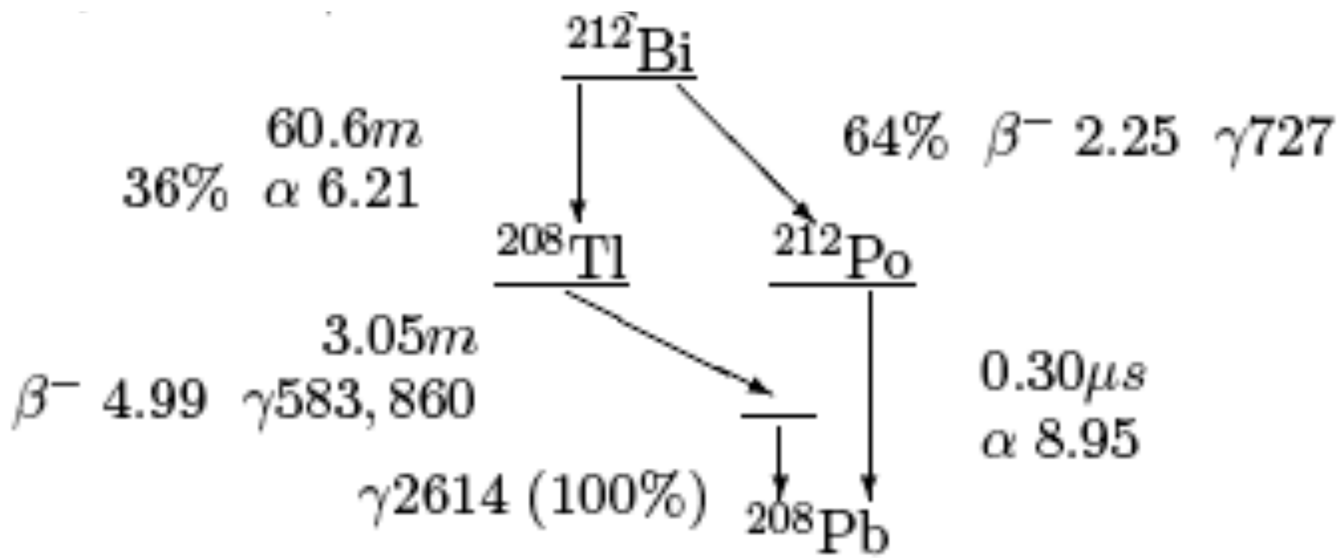
- 34% isotopic abundance
  - 0.3% loading is 810.5 kg of ^{130}Te
- 2νββ half-life of 70×10^{19} years
  - Relative 0ν/2ν rate is ~50 times higher
- Good optical properties
  - Higher loading
- ^{214}Bi tagged down to 10^{-4} level

^{238}U



214Bi
19.7m
0.021% α 5.62
> 99% β⁻ 3.27
γ609, ~ 1% BR to γ > 2200
210Tl
214Po
1.30m β⁻ 5.49
γ800, ~ 1% BR to γ > 2200
164μs
α 7.83
210Pb

^{232}Th



212Bi
60.6m
36% α 6.21
64% β⁻ 2.25 γ727
208Tl
212Po
3.05m
β⁻ 4.99 γ583, 860
0.30μs
α 8.95
γ2614 (100%)
208Pb

How does sensitivity scale?

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

- In a background free experiment measurement of the half-life is linear with exposure (mass x time)
- For 0νββ the neutrino mass sensitivity scales as the sqrt of the half-life. **Harder!**
- With significant backgrounds (that scale with exposure) the half-life sensitivity scales as sqrt of exposure, and neutrino mass scales as 4th root!