The EXO Search for Neutrinoless Double Beta Decay

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CARLETON AND TRIUMF

DBD-16 WORKSHOP

Collaborating Institutions (EXO-200+nEXO)

U of Alabama	Bern	BNL
Cal Tech	Carleton	Colorado State
Drexel	Duke	Erlangen
IHEP (Bejing)	Indiana	Illinois
ITEP (Moscow)	UC Irving	Laurentian
LLNL	UMass	McGill
ORNL	Seoul	South Dakota
SLAC	Stanford	Stony Brook
Tech. Univ. (Munich)	TRIUMF	Maryland

Why Search for DBD

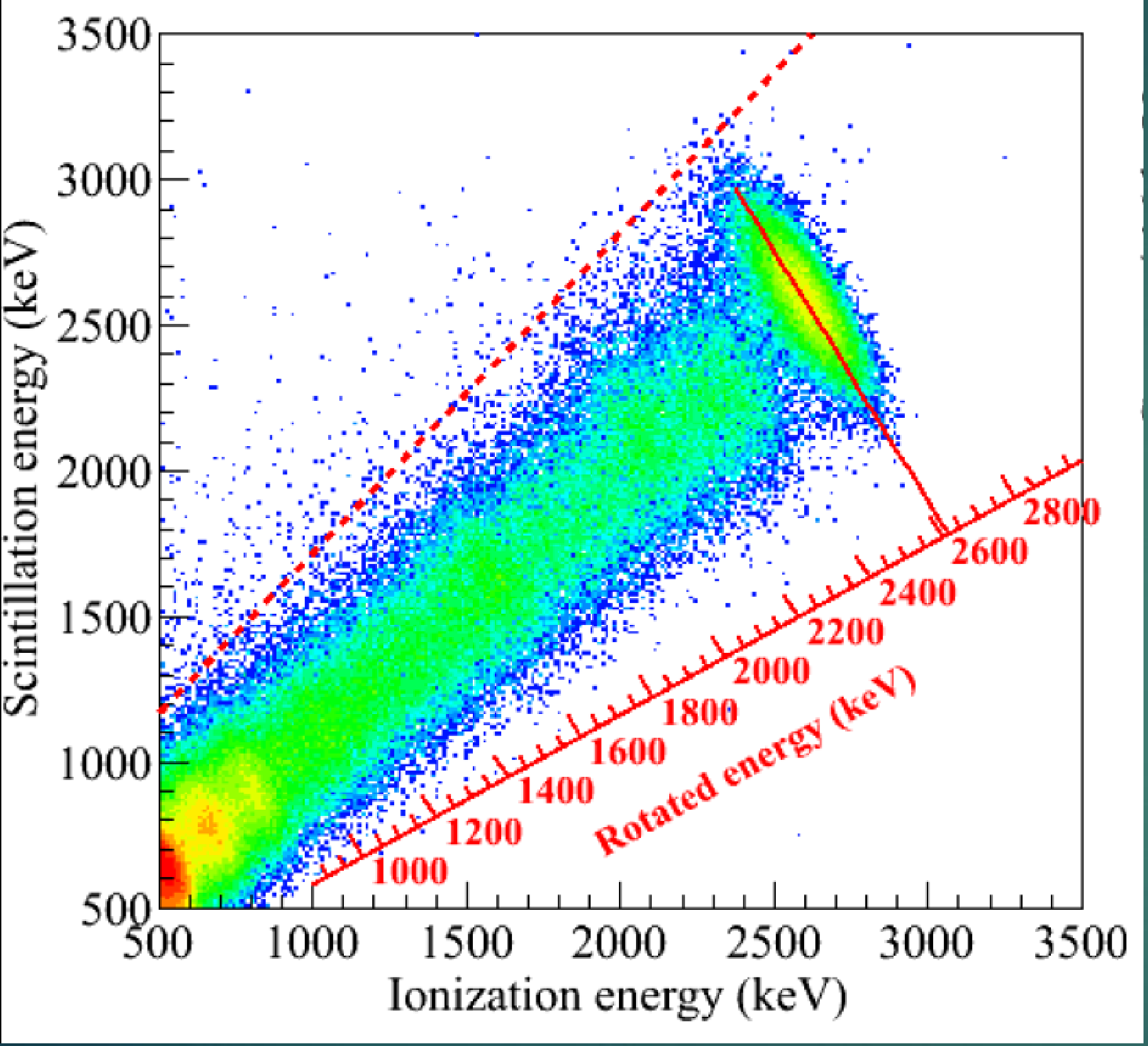
- Following discoveries at Super-K, SNO, Kamland-zen,… we know that neutrinos have mass
- Why do we have a family of particles with such different mass compared with the charged leptons, & charged quarks?
- Following S-K, S & K… we know that neutrinos are strongly mixed
- Does this point to an explanation of the matter dominance of the universe through leptogenesis?
- These are deep and challenging problems. Observing neutrinoless double beta decay would shed some light on the problems and it is one of the very few lampposts we can look under.

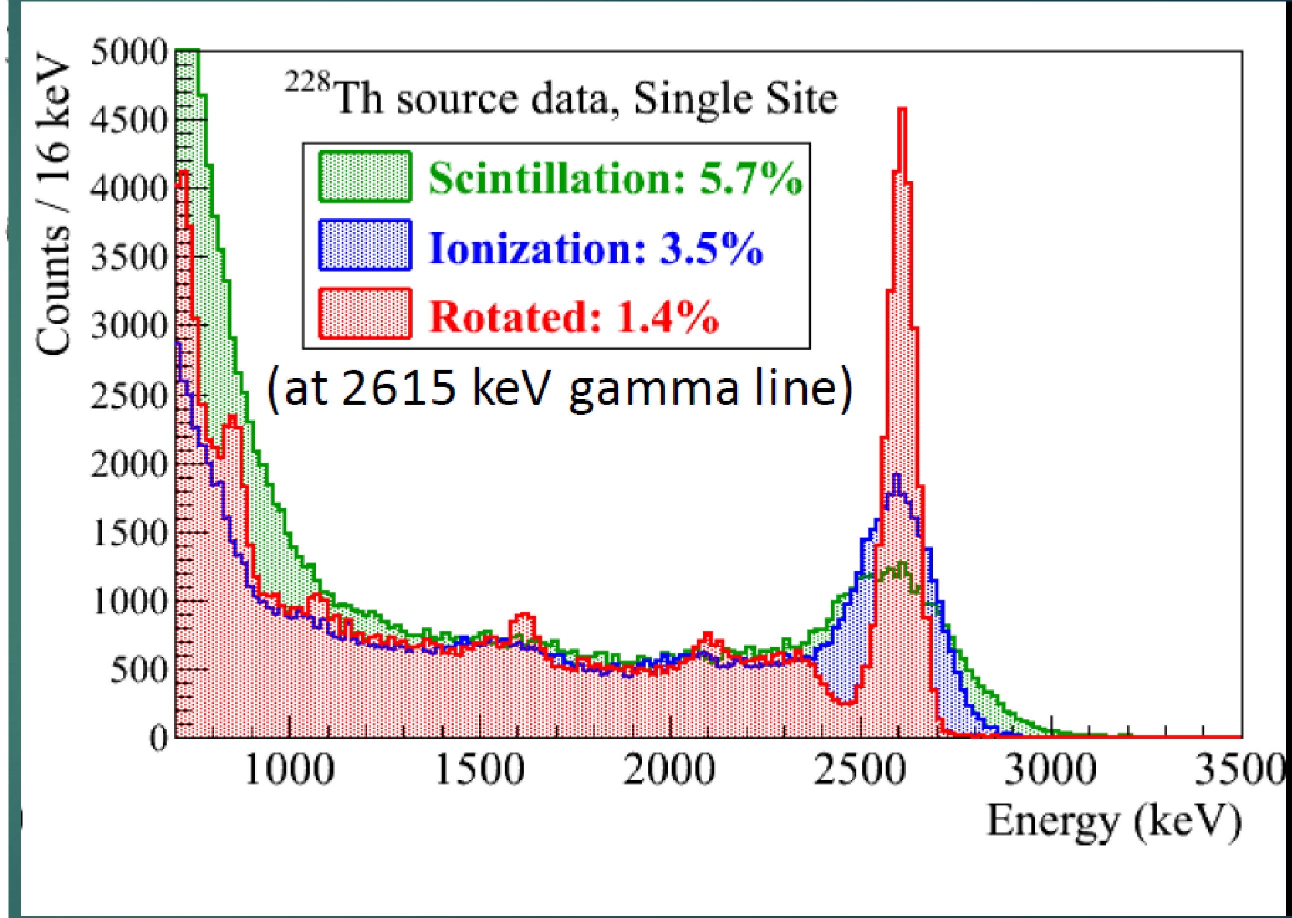
Milestones for N-DBD

- 1) Explore the validity of the Heidelberg-Moscow claim
- 2) Explore the Inverted Hierarchy
- 3) Explore the Normal Hierarchy
- Milestone 1 has been passed
- Milestone 2 is the target of the next generation of experiments
- Milestone 3 should be in our minds as we push towards milestone 2. We should be developing a roadmap to get to step 3 and ensure that we are moving along it.
- In this talk I will suggest one such roadmap.

EXO – Enriched Xenon Observatory

- EXO looks for DBD in liquid xenon enriched in ^{136}Xe
- Energy deposited produces both ionization and scintillation
- Approximately 20 eV per electron or photon
- Must measure both charge and light to get reasonable resolution
- Charge collection efficiency is high, light collection efficiency is low so resolution is most strongly driven by light signal.
- Energy resolution is of order 1% (σ)

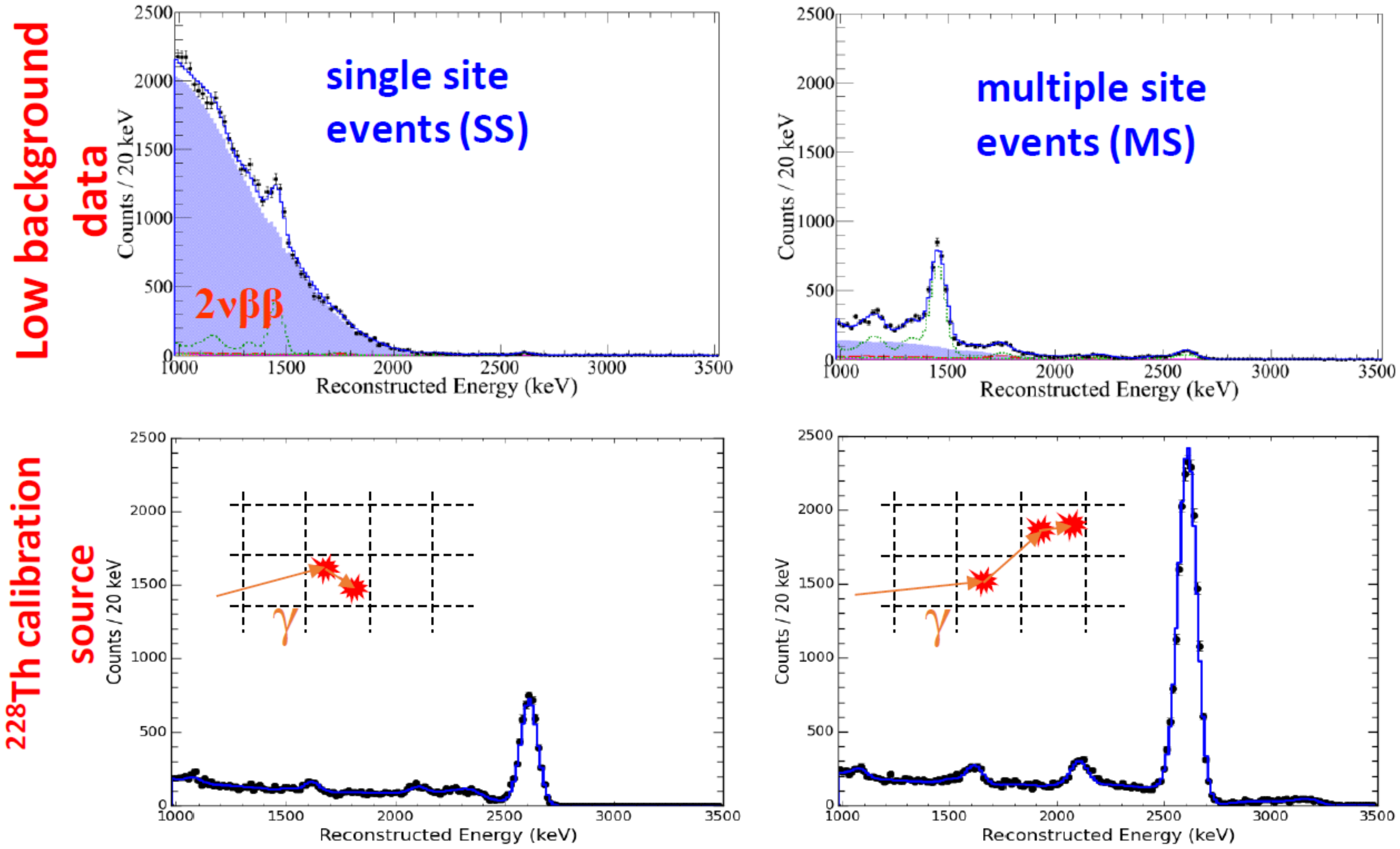

Scintillation energy (keV)
Ionization energy (keV)
Rotated energy (keV)
3500
3000
2500
2000
1500
1000
500
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800


228Th source data, Single Site
Scintillation: 5.7%
Ionization: 3.5%
Rotated: 1.4%
(at 2615 keV gamma line)
Counts / 16 keV
Energy (keV)

EXO is more than a calorimeter

- There is a huge advantage in using a large, homogeneous detector for DBD if one can accurately measure the position of ionizing events
- The only process that can produce a narrow line in the spectrum in such a detector is an external gamma ray. These are strongly attenuated in a dense medium and the dependence of rate on standoff distance is very different from the signals sought
- Gamma rays normally produce more than one ionization cluster (photoelectric to total cross section is 1:40 for 2.614 MeV) allowing identification of these gamma backgrounds
- Weak gamma lines cannot mimic a signal in these detectors!

Topological Event Information



- **TPC allows the rejection of gamma backgrounds because Compton scattering results in multiple energy deposits.**
- **SS/MS discrimination is a powerful tool not only for background rejection, but also for signal discovery.**

Advantages of Xenon for DBD

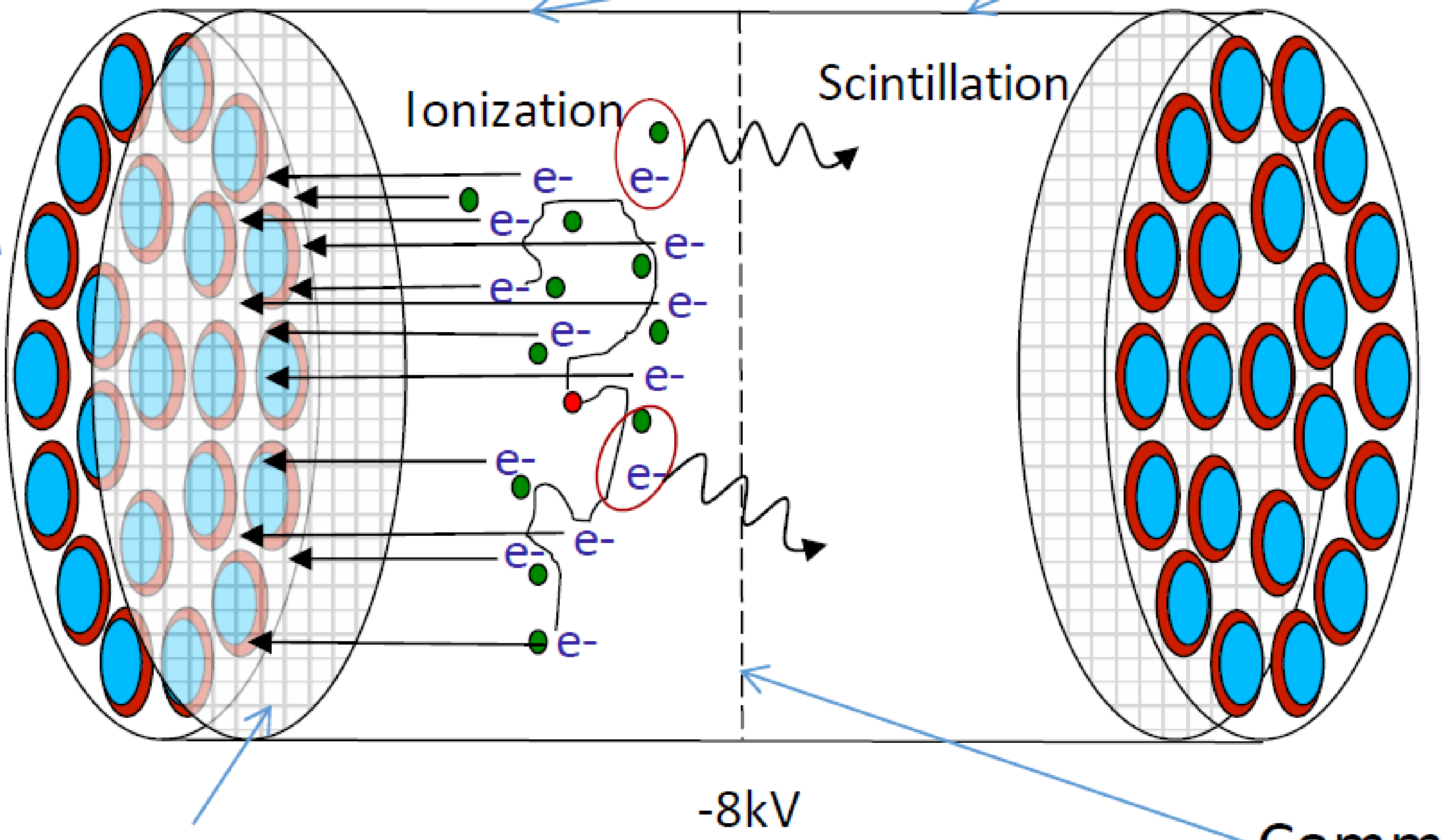
- Xe is easy to purify of all radioactive contaminants except other noble materials
  - Kr lines far from the ^{136}Xe DBD Q value
  - Rn can give backgrounds from non-active regions of the detector but these look like external backgrounds. Alphas can be easily identified
- Xenon is (relatively) easy to enrich isotopically and this leads to a large cost advantage over everything except perhaps Te
- Xenon has no long lived radioactive isotopes

The EXO Program

- EXO-200
  - 200 kg detector located at WIPP in New Mexico, USA
  - In operation since 2011
  - First observation of 2νDBD in ^{136}Xe
  - Most precise measurement of a 2νDBD rate
  - First major challenge to Heidelberg-Moscow claim
- nEXO
  - 5000 kg detector proposed for SNOLAB
  - Sensitive to DBD through the inverted hierarchy

TPC modules

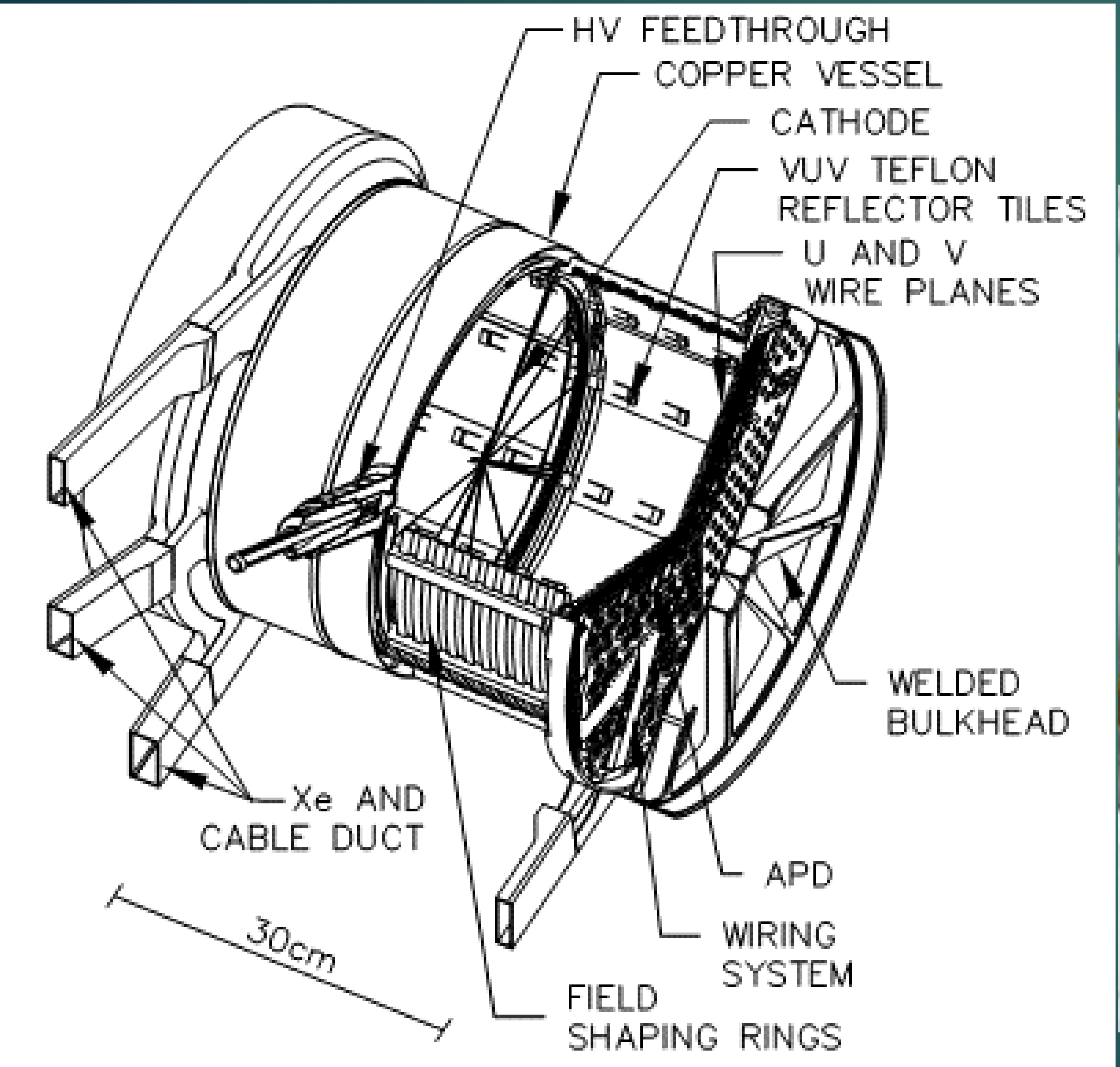
Avalanche photodiode (APD) array observes prompt scintillation

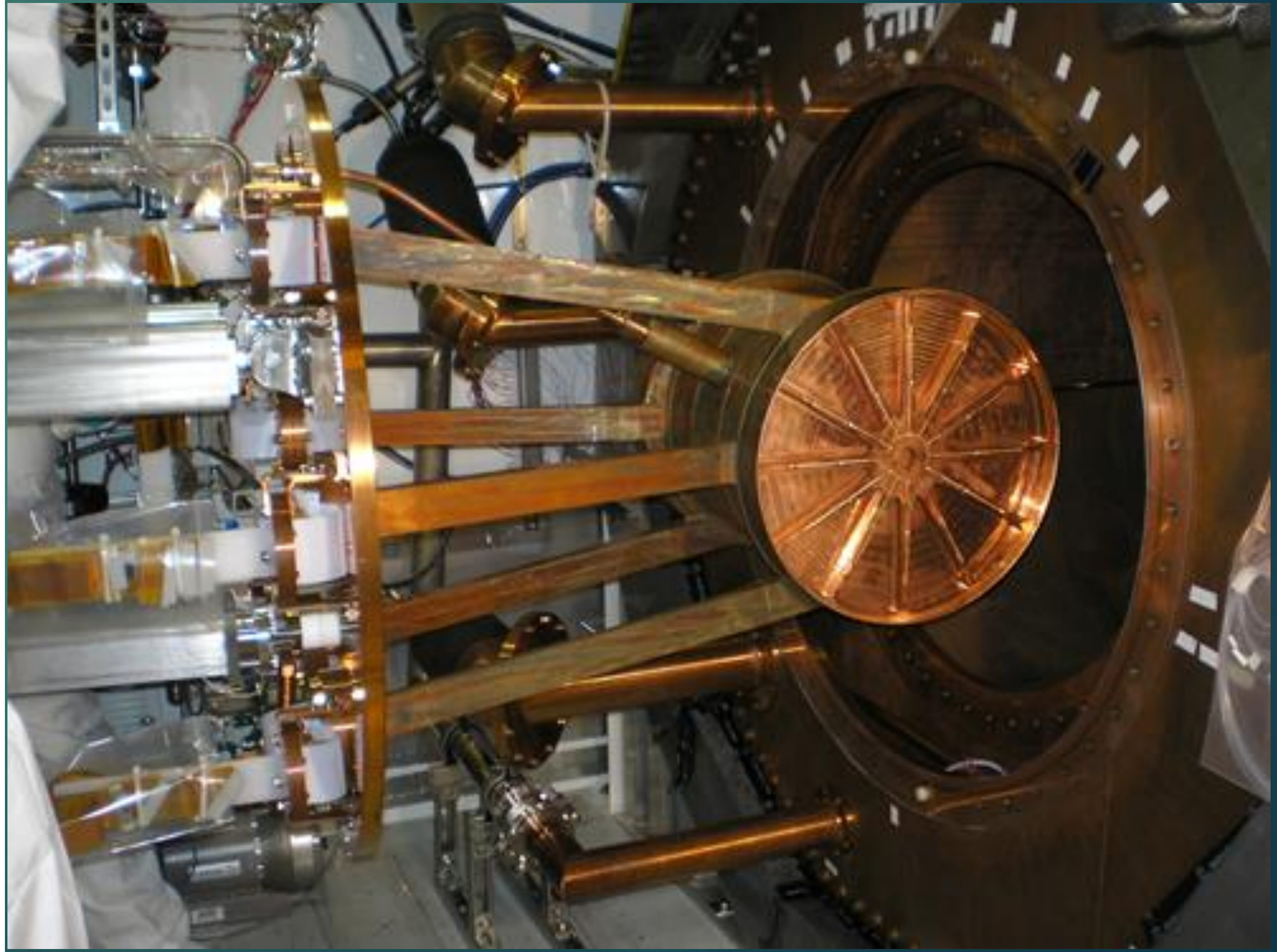


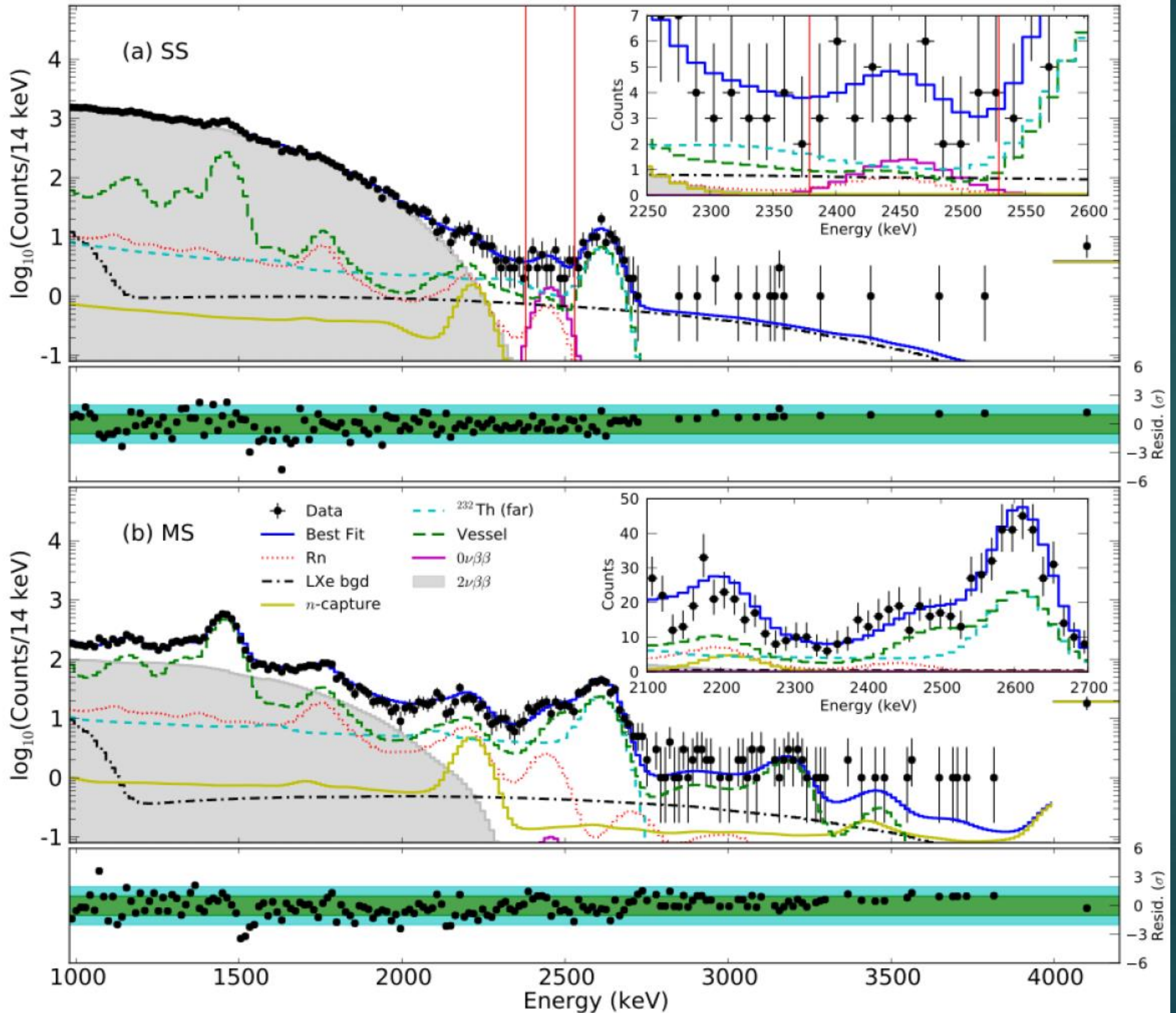
Crossed shielding and charge collection grids give give x,y position

Common cathode

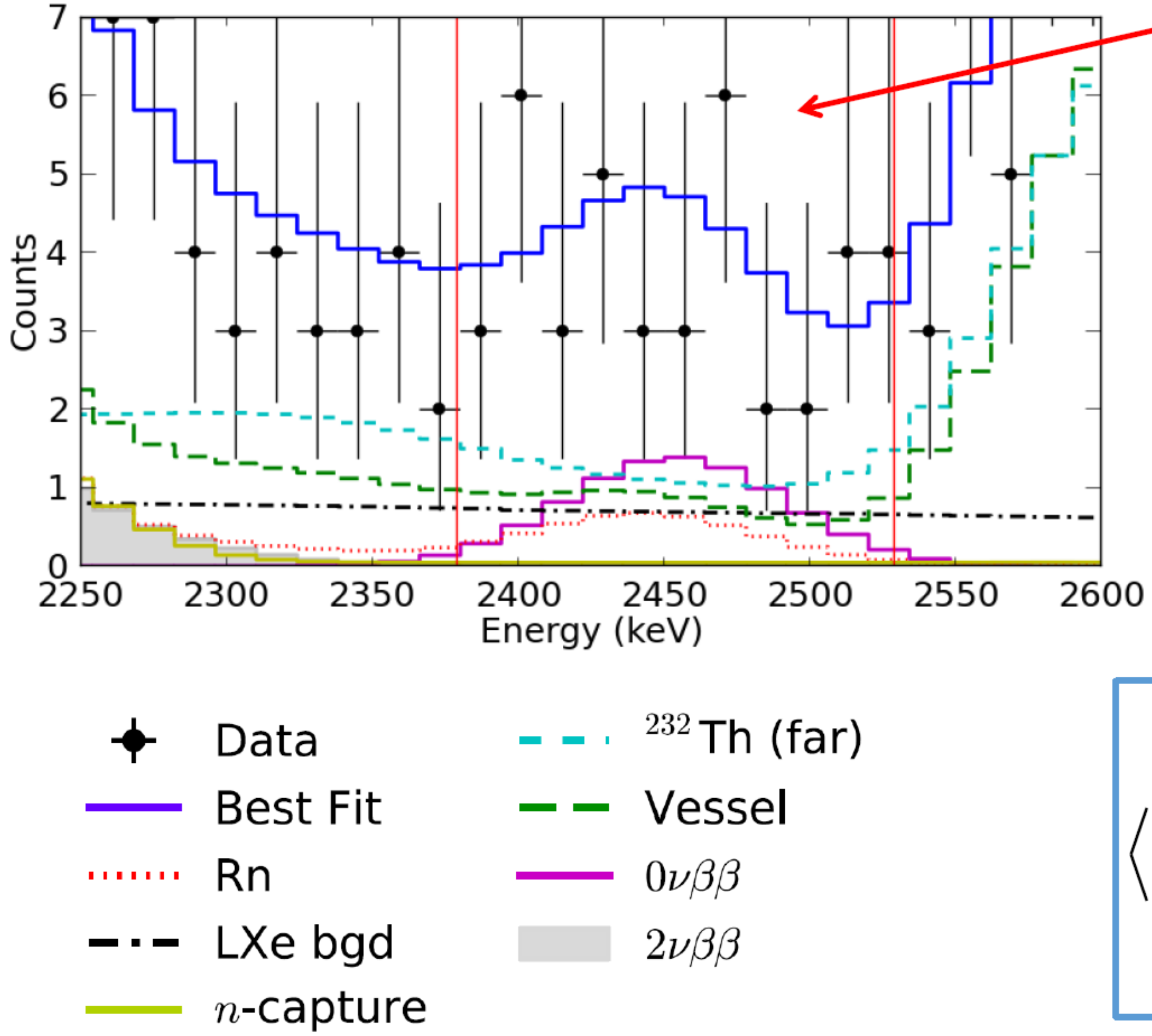
EXO-200


HV FEEDTHROUGH
COPPER VESSEL
CATHODE
VUV TEFLON
REFLECTOR TILES
U AND V
WIRE PLANES
WELDED
BULKHEAD
Xe AND
CABLE DUCT
APD
WIRING
SYSTEM
FIELD
SHAPING RINGS
30cm




(a) SS
(b) MS
log$_{10}$(Counts/14 keV)
Resid. (σ)
Energy (keV)
Counts
Data
Best Fit
Rn
LXe bgd
n-capture
^{232}Th (far)
Vessel
$0\nu\beta\beta$
$2\nu\beta\beta$

Recent 0νββ decay result



Background fit in ±2σ ROI	
^{232}Th	16.0
^{238}U	8.1
^{137}Xe	7.0
Total	**31.1 ± 3.8**

From profile likelihood:

$$T_{1/2}^{0\nu\beta\beta} > 1.1 \cdot 10^{25}\ yr$$

$$\langle m_{\beta\beta} \rangle < 190 - 450\ meV$$

$$(90\%\ C.L.)$$

Nature 510, 229 (2014)

Phys. Rev. Lett. 109, 032505 (2012)

EXO-200 Status

- Access to WIPP lost due to incidents unrelated to EXO
- Detector is now accessible and has been cleaned up and restated
- New electronics to remove coherent noise on APD’s
- Running at higher drift field
- Should allow a factor of 3 improvement in sensitivity in 2 year run

EXO-200 $(0\nu)\beta\beta$ search

2011 First measurement of $2\nu\beta\beta$ in ^{136}Xe [PRL 107, 212501 (2011)]

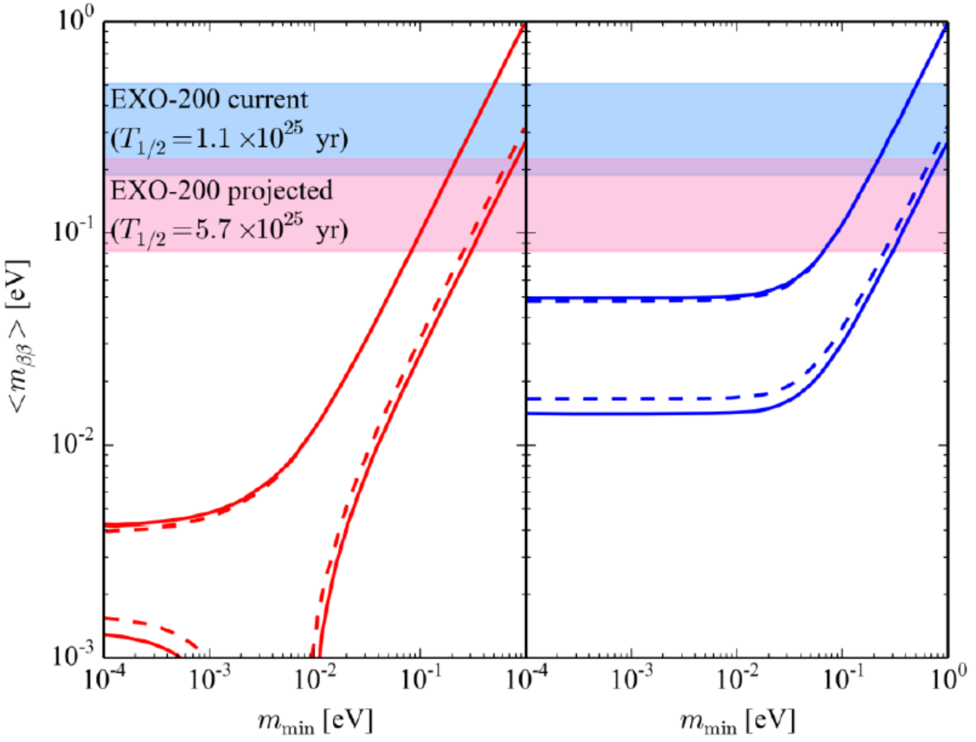
2012 First $0\nu\beta\beta$ result, best $m_{\beta\beta}$ limit [PRL 109, 032505 (2012)]

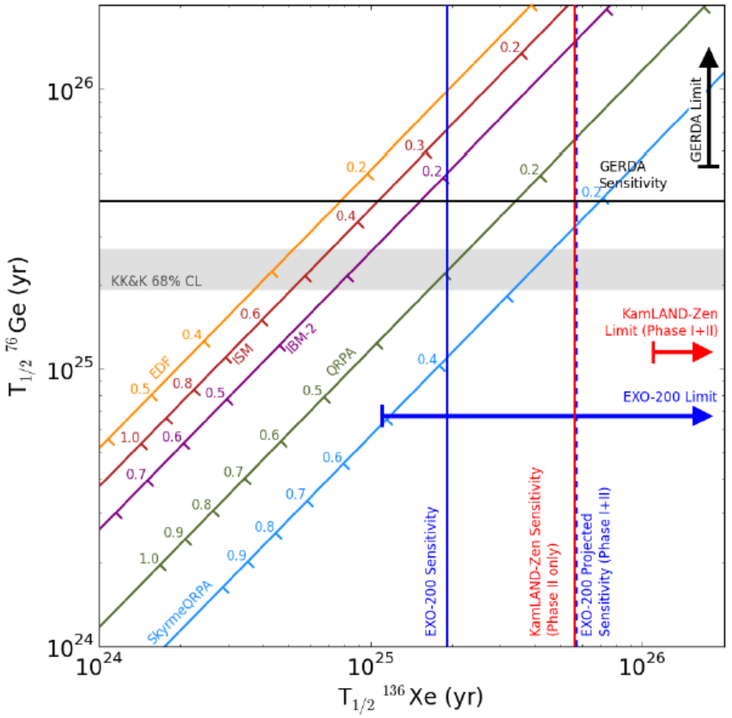
2013 Most precisely measured $2\nu\beta\beta$ rate — and the lowest
→slowest process ever directly measured in nature! [PRC 89, 015502 (2014)]

2014 Improved sensitivity to $m_{\beta\beta}$ [Nature 510, 229 (2014)]

$T_{1/2}^{2\nu\beta\beta} = 2.165 \pm 0.016(stat) \pm 0.059(syst) \times 10^{21}$ yr

$T_{1/2}^{0\nu\beta\beta} > 1.1\times 10^{25}$ yr @ 90% C.L.

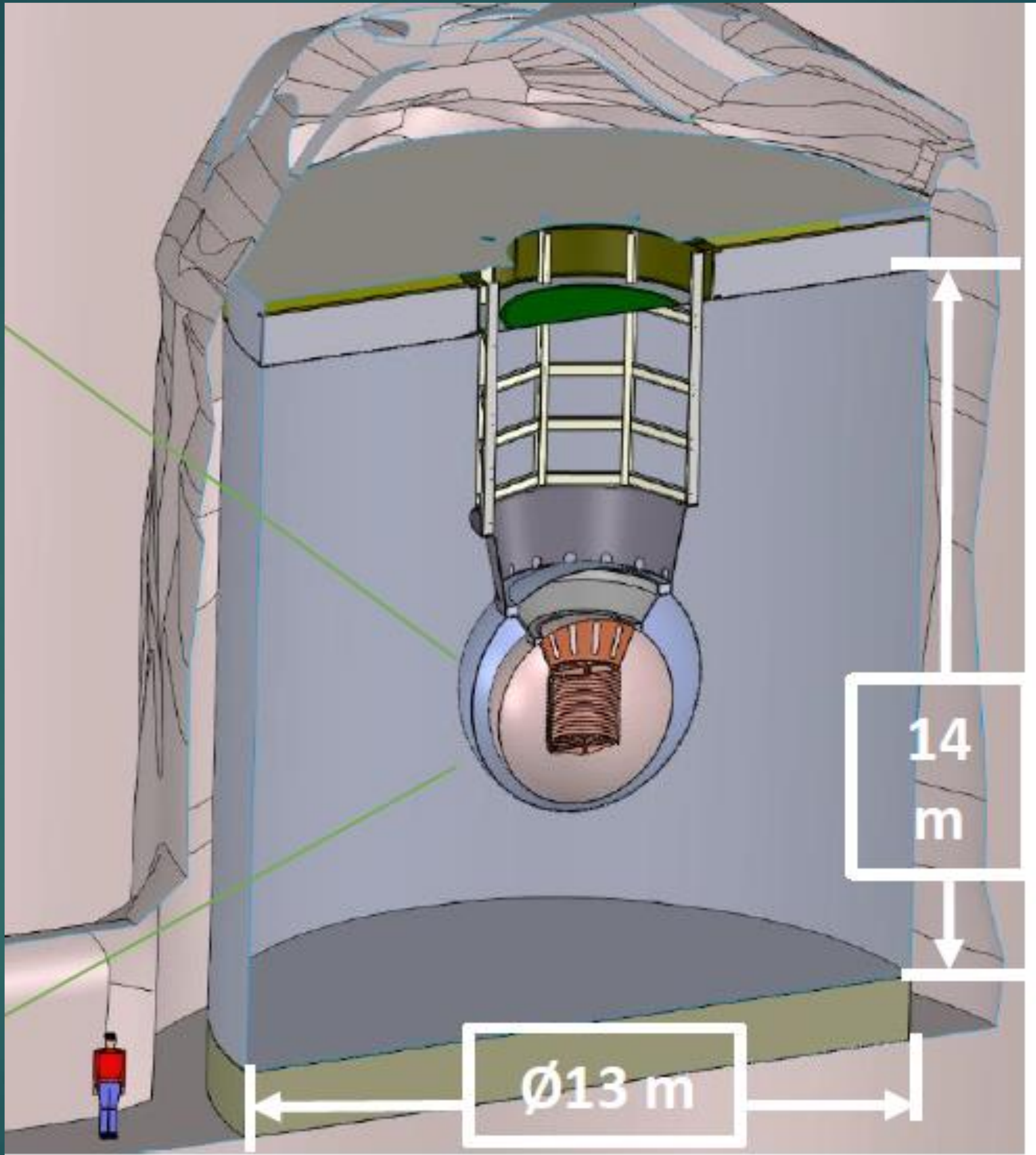




KamLAND ZEN [arXiv:1605.02889]
GERDA [PRL 111, 122503 (2013)]

nEXO

- Build on the technology of EXO-200 to make a 5000 kg detector
- Improve design in areas where scaling is not attractive
- Improve design where technology has advanced to allow it
- Move to much deeper site to reduce the cosmogenic backgrounds
- Change to water shielding to kill the environmental backgrounds
- Continue to use HFE as a heat transfer fluid and inner shield



nEXO at the SNOlab Cryopit

EXO-200 -> nEXO : Location

- EXO-200 is at WIPP
- Depth is too shallow for a larger detector
- Salt creeps!
- Lead used for shielding
- nEXO is expected to be at SNOLAB
- Negligible cosmogenic production
- Water shield kills local neutrons, gammas

EXO-200 -> nEXO: Design Concepts

- EXO-200 has two back-to-back TPCs with central cathode
- nEXO has a single TPC with diameter = height
- This gives best, homogeneous and shielded conditions
- nEXO has much longer drift length
  - EXO-200 had excellent electron lifetime (~3 ms) but nEXO must be better
  - Eliminate plastics wherever possible
  - (EXO-200 used SNO acrylic to support the field cage and clean Teflon as a reflector to enhance photon collection. Must find fused silica or something to replace the acrylic and eliminate the Teflon)

EXO-200 -> nEXO: Light Sensors

- In EXO-200 LAAPDs are used for light detection.
- The units we used are not available
- Need high voltage (~2 kV)
- Noise a problem – low gain
- nEXO -
- Use SiPMs and cover the barrel (4 m^2)
- Better light collection -> better resolution
- Need SiPMs sensitive to 172 nm light (ε> 15%)
- Need operation at -100°, Low dark noise, Low cross talk, etc.

EXO-200 -> nEXO: Electronics

- EXO-200 uses a small number of channels
- Electronics is external to the detector and at room temperature
- nEXO –
- Far more channels required
- Electronics must be local (capacitance issues and cable issues)
- Electronics must operate cold

EXO-200 -> nEXO : Charge readout

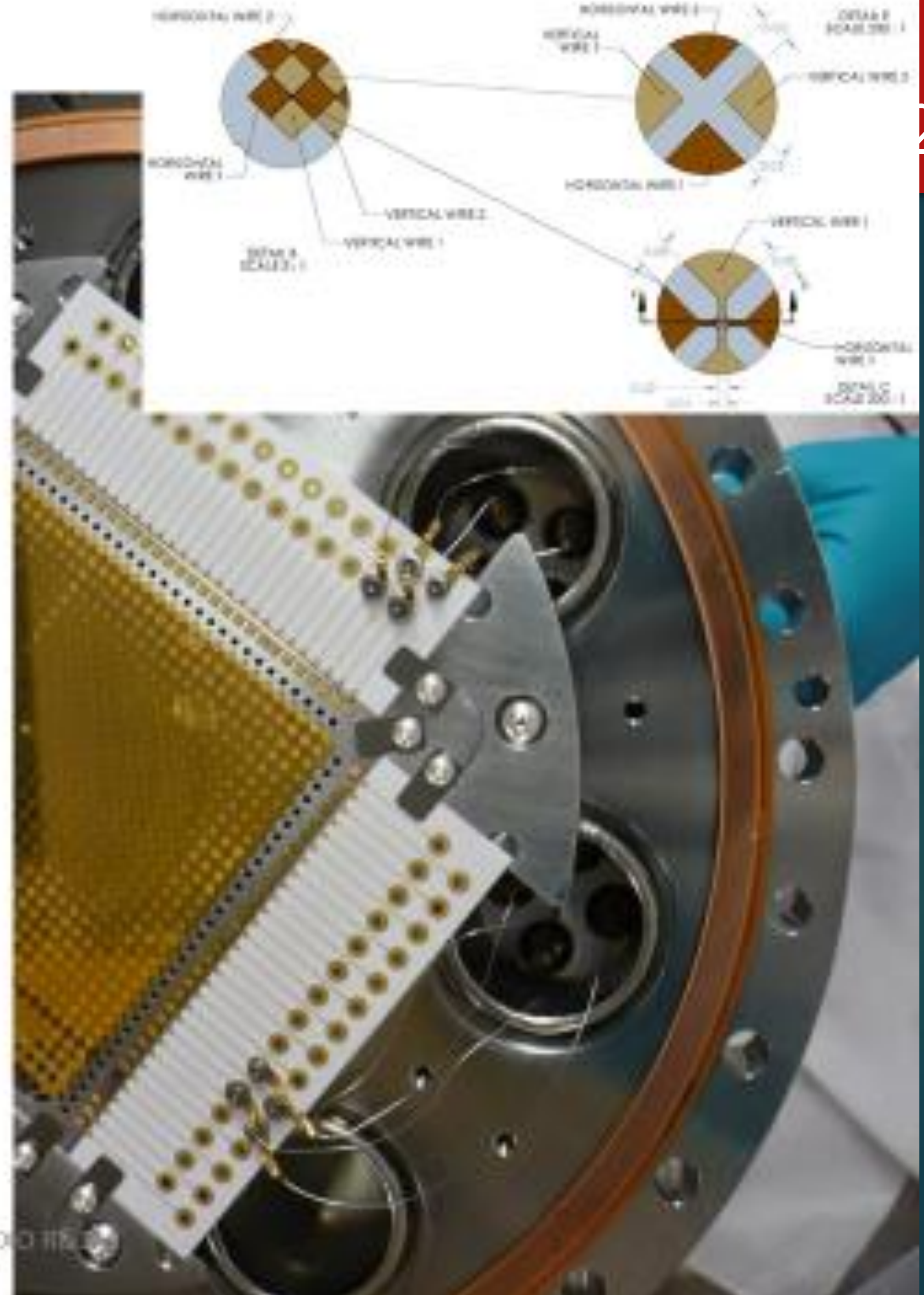
- In EXO-200 charge is read out by wires – one induction plane and one charge collection plane
- nEXO will use pads
- Wire planes do not scale nicely with size (mass α R^5)
- Wire planes need high voltage
- Wires have high capacitance

4) Novel Low Background TPC Concepts

3mm pitch, crossed strip, full coverage, quartz- or sapphire-supported charge collection/readout tile. Produced by IHEP; functional testing in LXe in the US.

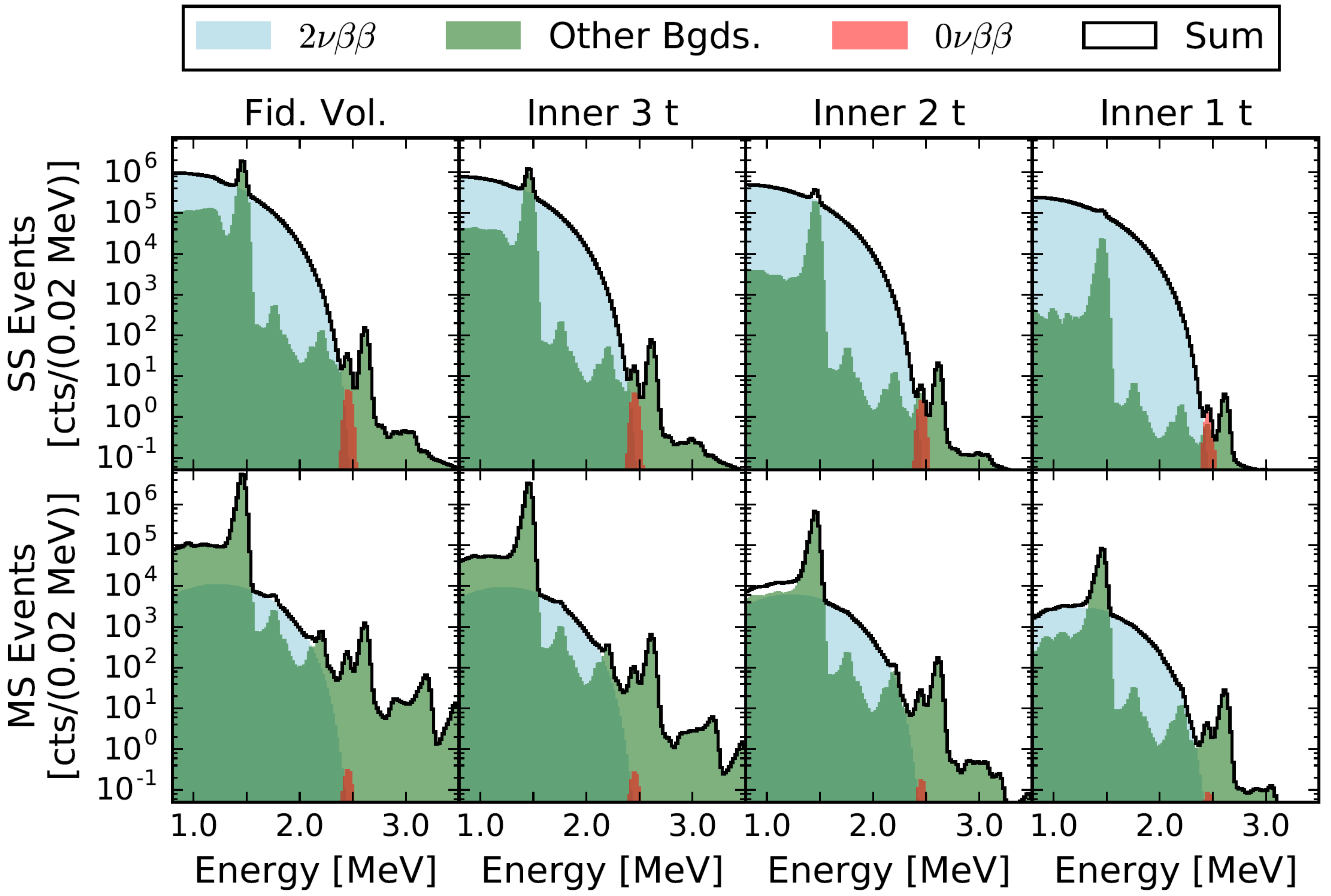
The prototype to the right uses a quartz substrate.

External readout is coupled with ceramic interface boards for the test.   In "real life" the readout chip will be mounted directly onto the tile.

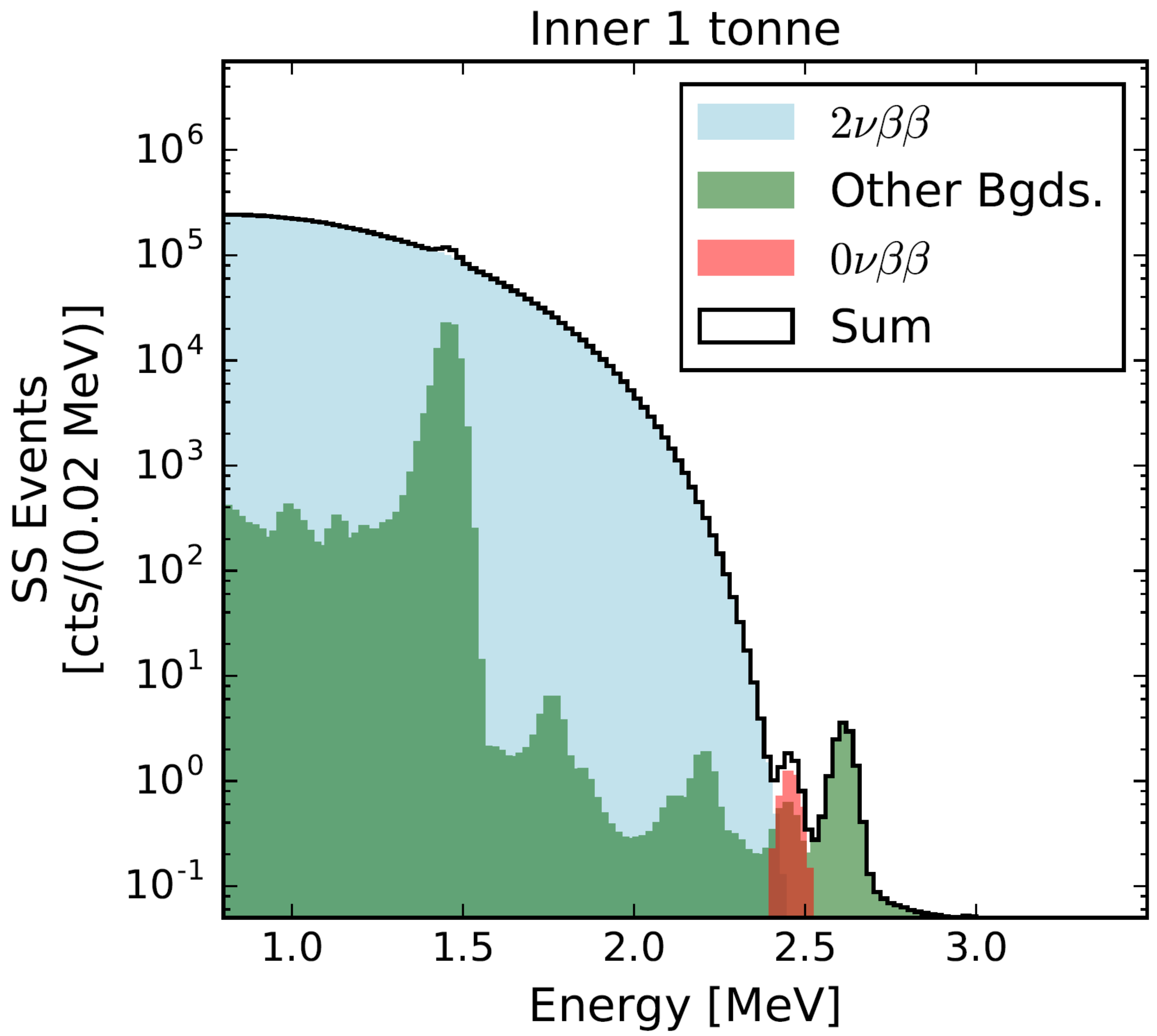


Expected sensitivity for nEXO

- Extensive and detailed Monte Carlo simulations have been made to estimate the sensitivity and discovery potential for nEXO
- All activity levels are based on measurement and experience with EXO-200

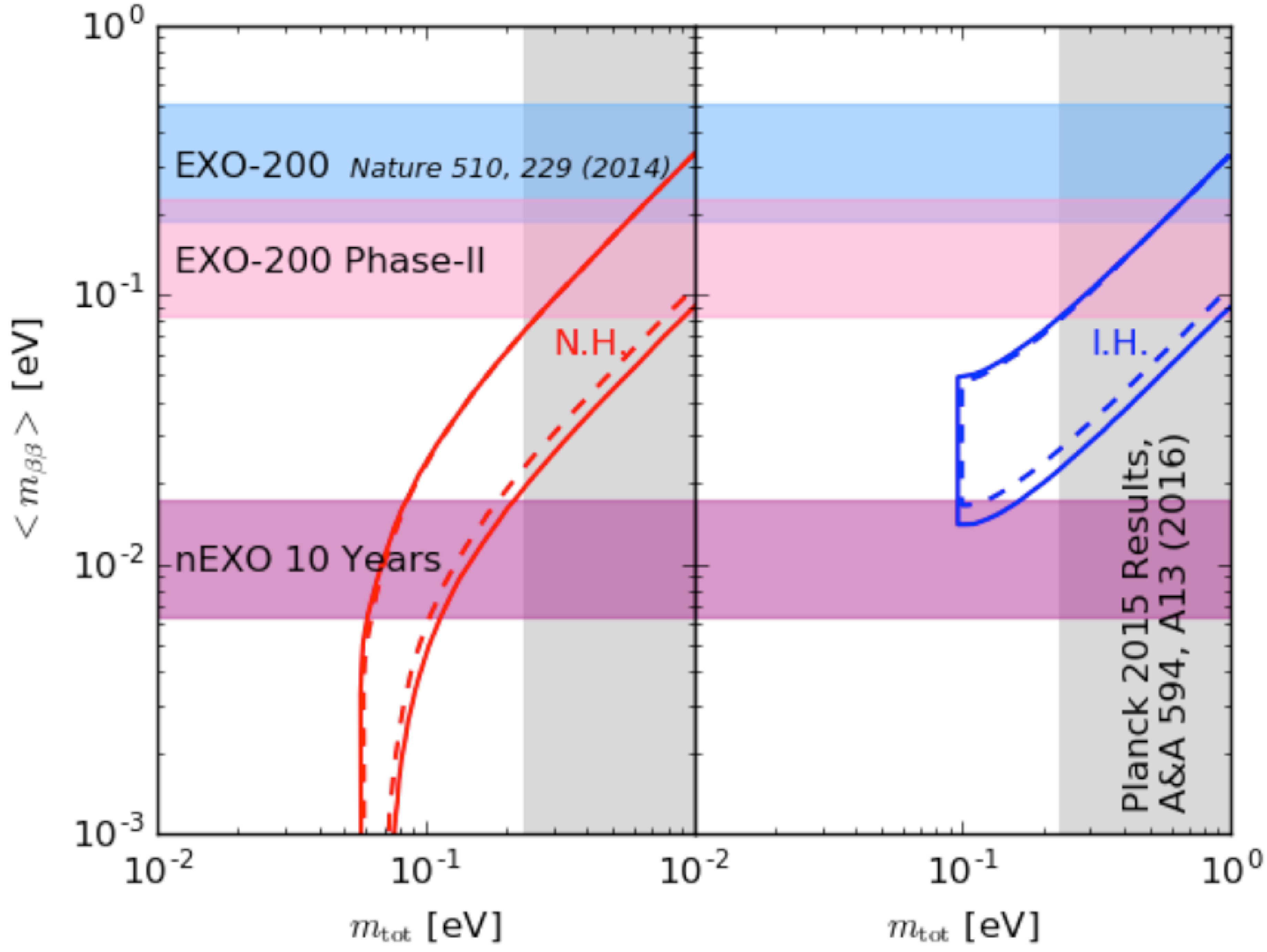


$2\nu\beta\beta$
Other Bgds.
$0\nu\beta\beta$
Sum
Fid. Vol.
Inner 3 t
Inner 2 t
Inner 1 t
SS Events [cts/(0.02 MeV)]
MS Events [cts/(0.02 MeV)]
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
1.0
2.0
3.0
Energy [MeV]



Expected data for 10 years

Discovery potential limit
5.5×10^{27} yr

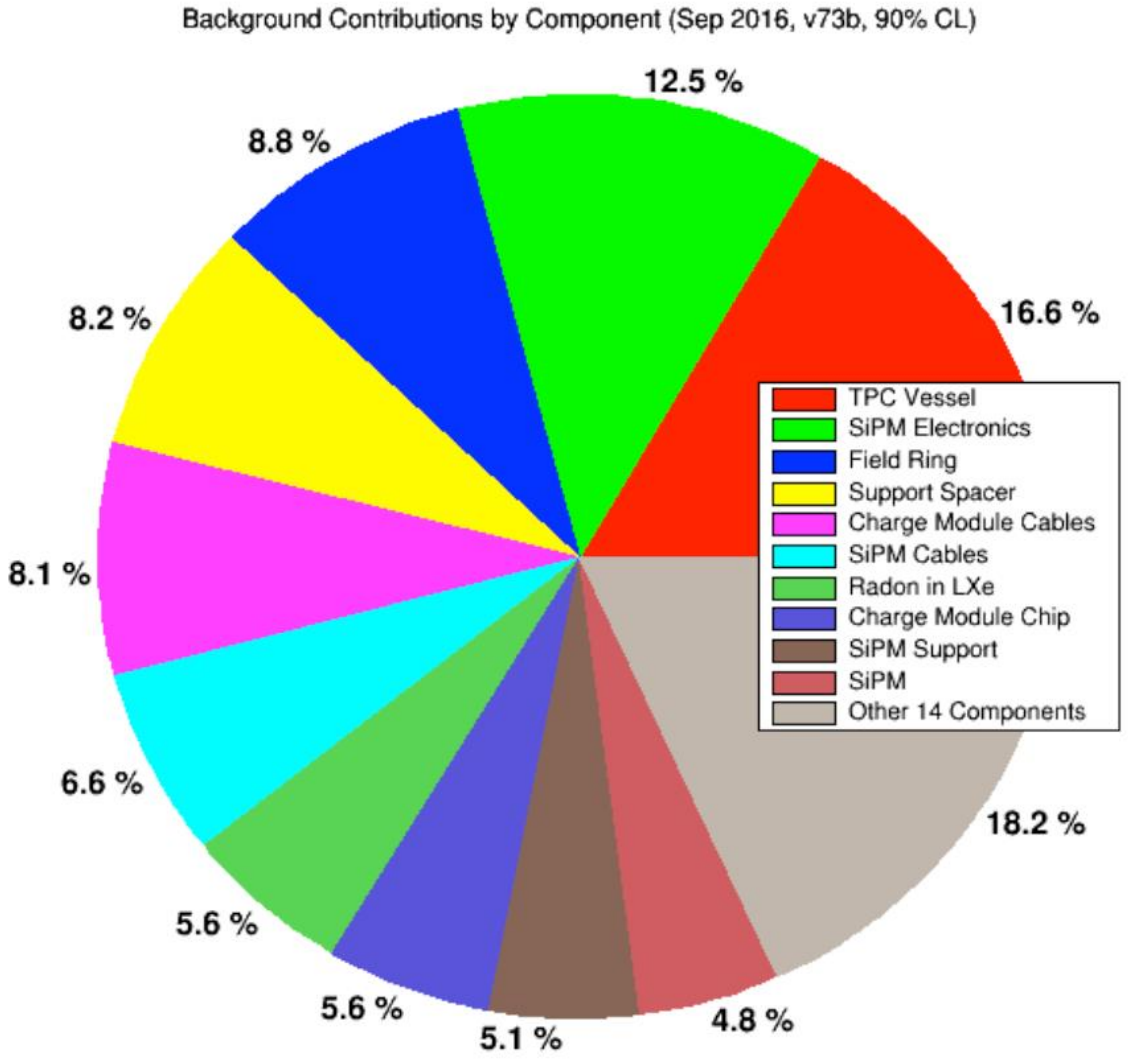


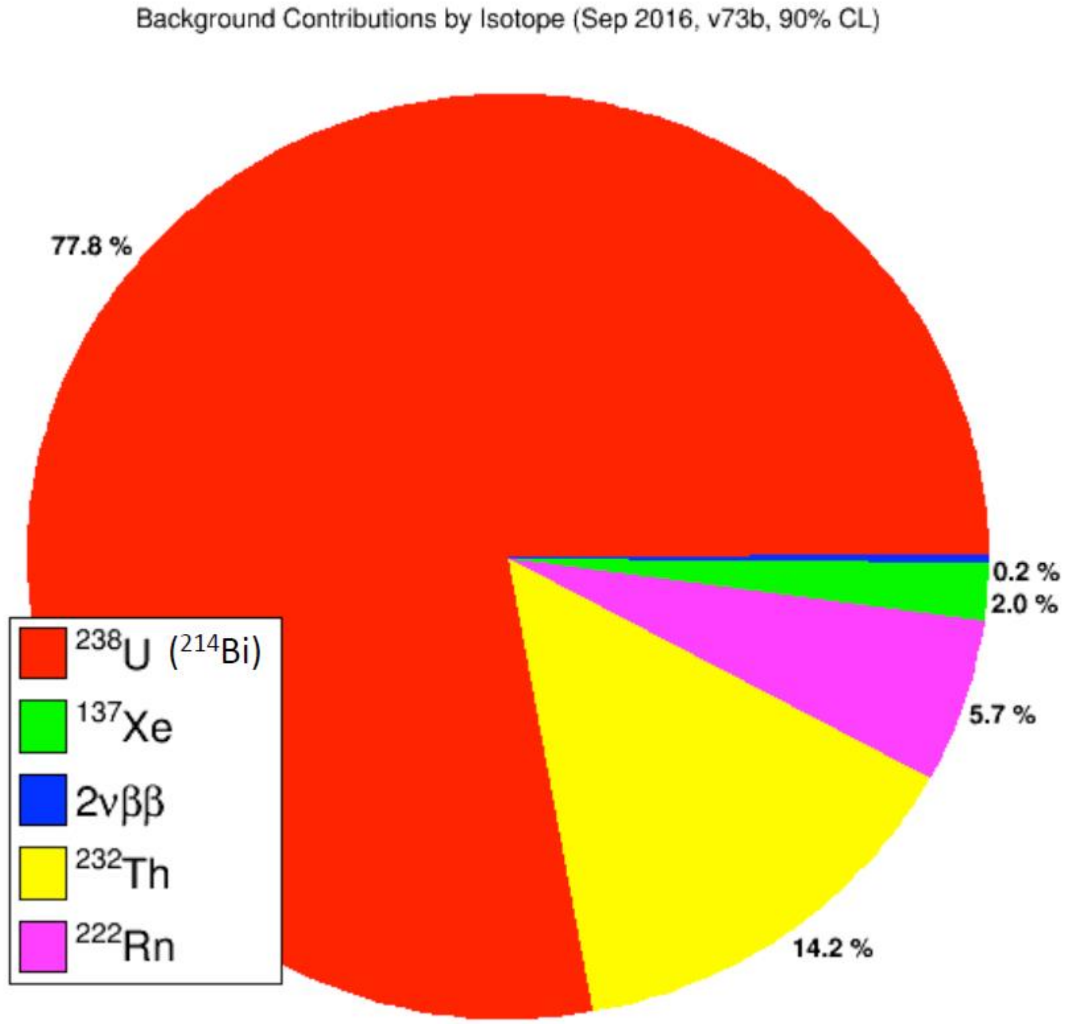
EXO-200 Nature 510, 229 (2014)
EXO-200 Phase-II
nEXO 10 Years
N.H.
I.H.
Planck 2015 Results, A&A 594, A13 (2016)
$< m_{\beta\beta} >$ [eV]
m_{tot} [eV]
m_{tot} [eV]
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
10^{-2}
10^{-1}
10^{0}

On to the Normal Hierarchy

- Note: EXO does not have a collective opinion on this – the ideas expressed are my own
- nEXO is background limited.
- The backgrounds are dominantly external gamma rays
- There are two approaches to follow:
- Eliminate the backgrounds by barium tagging
- Reduce the backgrounds by better gamma discrimination
- For nEXO, the 10 year background free sensitivity (Feldman Cousins) is 3.5 x 10^{28}yrs. Our target is about 10^{29}yrs. So we need to increase target exposure (tons or years or both) in addition to background surpression

Background Budgets (90% U.L.)

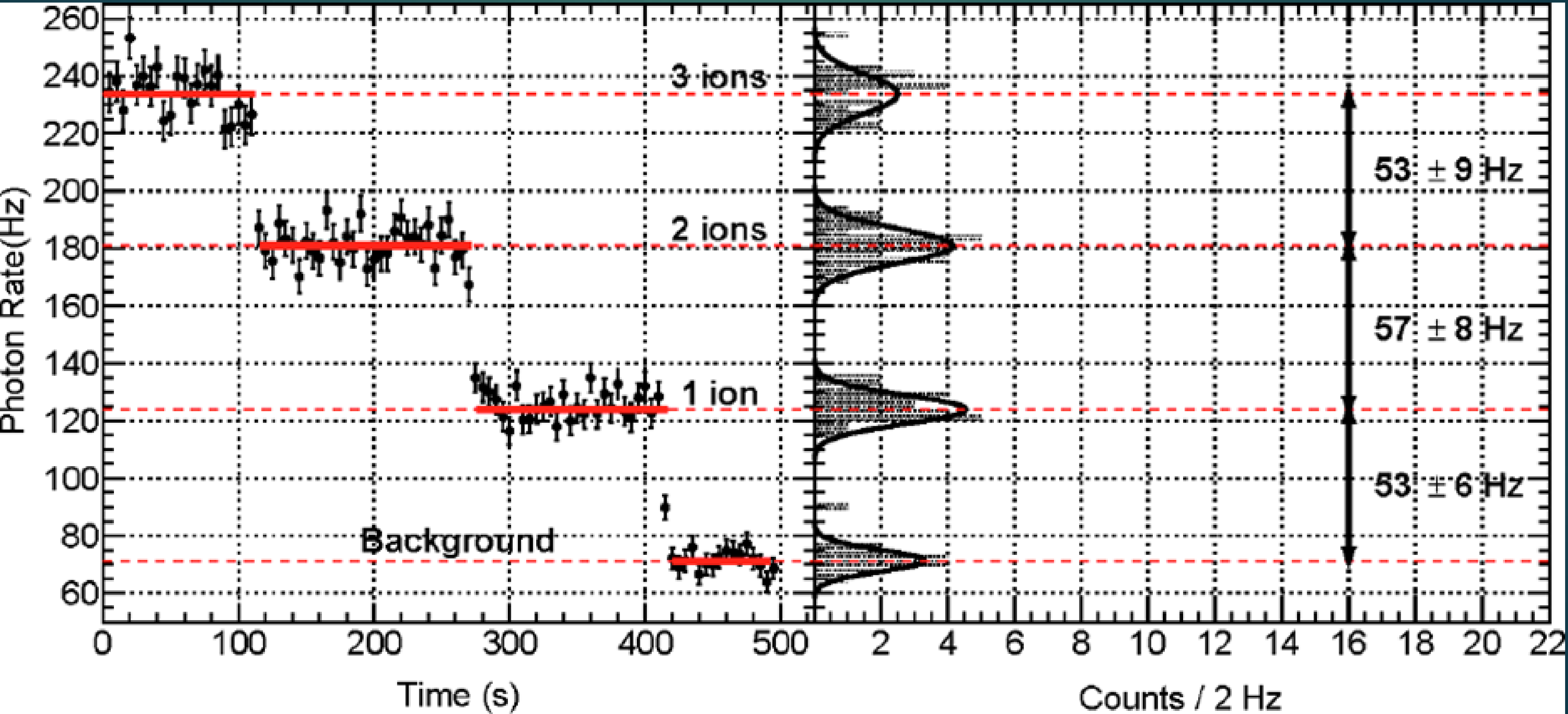




Barium tagging

- Barium tagging (ie look for Ba ion production at the time/location of an observed event) would eliminate all backgrounds except the 2 neutrino events
- Original idea from Mike Moe
- Concepts are been developed for extraction of ions from gas and liquid followed by laser fluorescence
- Good progress has also been made for freezing ions in xenon ice and looking at fluorescence in the ice

Barium ions identified in a linear trap (Ryan Killick)



Alternative approach to background reduction

- Our background is almost all external gammas
- We identify gammas by multi-site nature of multiple Compton gamma interactions
- This is extremely valuable but could be much better.
- For 2.614 MeV gammas we get 4:1 MS/SS but the photo-electric/total cross section is 40:1
- With much better spatial resolution and lower cluster thresholds we should be able to recover much of this
- In gas gamma rejection of ~30 can be achieved by counting Bragg peaks. Can we get resolution good enough to get some of this?

A possible model for the NH detector

- Use a 2 phase detector such as Xenon, LUX, LZ etc
- Use a new type if SiPM to capture the signal
  - Work on 3D digital SiPMs progressing well
- Note: 2 phase detection with SiPMs is inherently much faster than a charge collection pad system
- Noise which dominates the pad system is essentially eliminated
- Thresholds <<1 keV look possible
- Spatial resolution needs to be demonstrated but should be much higher than pad systems
- Prototype under construction

Can we reduce the cost of enrichment?

- Looking into distillation as a way to enrich Xe
- Will need very tall still (~km)
- Possible in mine shafts?
- Basic data on vapour pressure differences not yet available but theoretical numbers available
- First look at designs from PNNL
- Cryogenic distillation looks to have modest operating costs and feasibility will largely depend on capital costs.
- Work underway to determine the basic data so feasibility and costs can be estimated

Conclusions

- EXO-200 has been a very successful entry into the 100 kg physics of double beta decay
- nEXO has the promise of coverage of the Inverted Hierarchy with a conservative and proven design
- The future to the Normal Hierarchy is challenging but not totally beyond our grasp.
- A very exciting time for neutrinoless double beta decay!