

# Non-Accelerator Neutrino Experiments

**Ruben Saakyan | University College London  
ICHEP-2018, Seoul, Korea  
9-July-2018**

# Starting with disclaimer and apologies

Non-accelerator neutrino physics is a huge field (thanks to many successes over past years). Therefore I had to make some hard choices (undoubtedly biased).

## What is covered

- “Nuclear” aspect of neutrinos from reactors (oscillations discussed in previous two talks)
- Coherent neutrino scattering
- Neutrino mass from  $\beta$ -decay endpoint
- Neutrinoless Double Beta Decay

## What is not covered

- Solar and geo-neutrinos
- Astrophysical and cosmological neutrinos
- Neutrino magnetic moment
- And undoubtedly many more

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Apologies

# Reactor Antineutrino Anomaly (RAA)

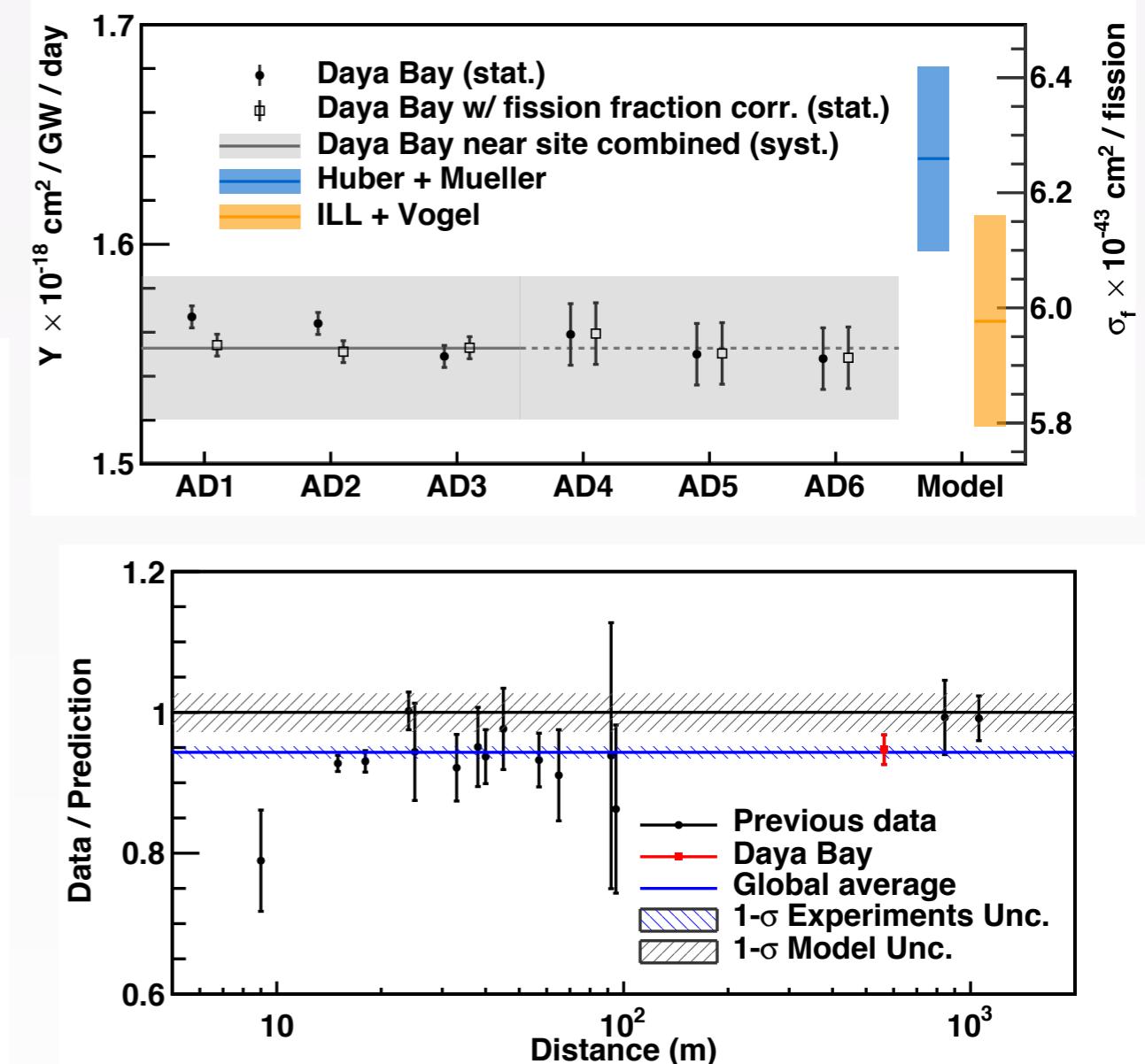
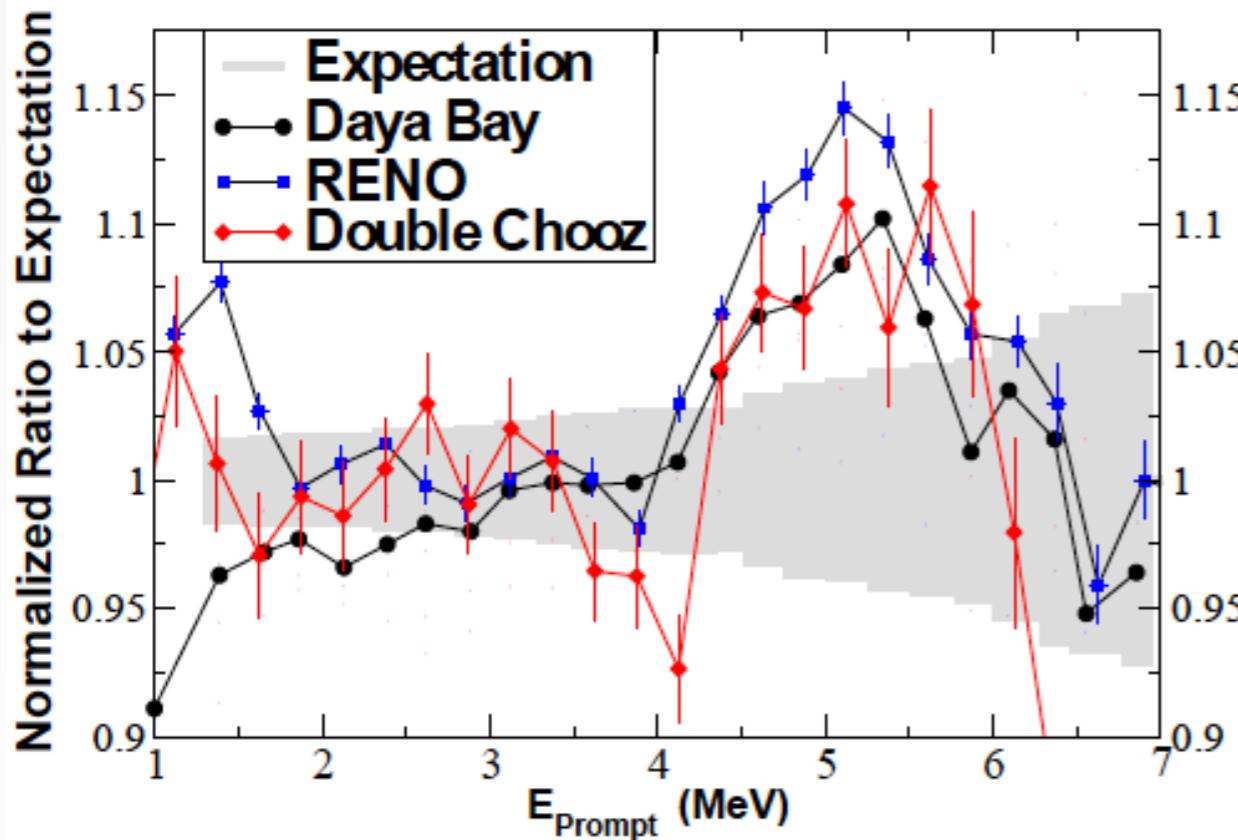
Two anomalies reported in antineutrino nuclear reactor spectra by Daya Bay, RENO and Double Chooz

PRL, 116 (2016) 061801

- ~5% shortfall in antineutrino flux
- “5 MeV” bump in the spectra

A. Hayes, at Neutrino'18

<https://doi.org/10.5281/zenodo.1287950>

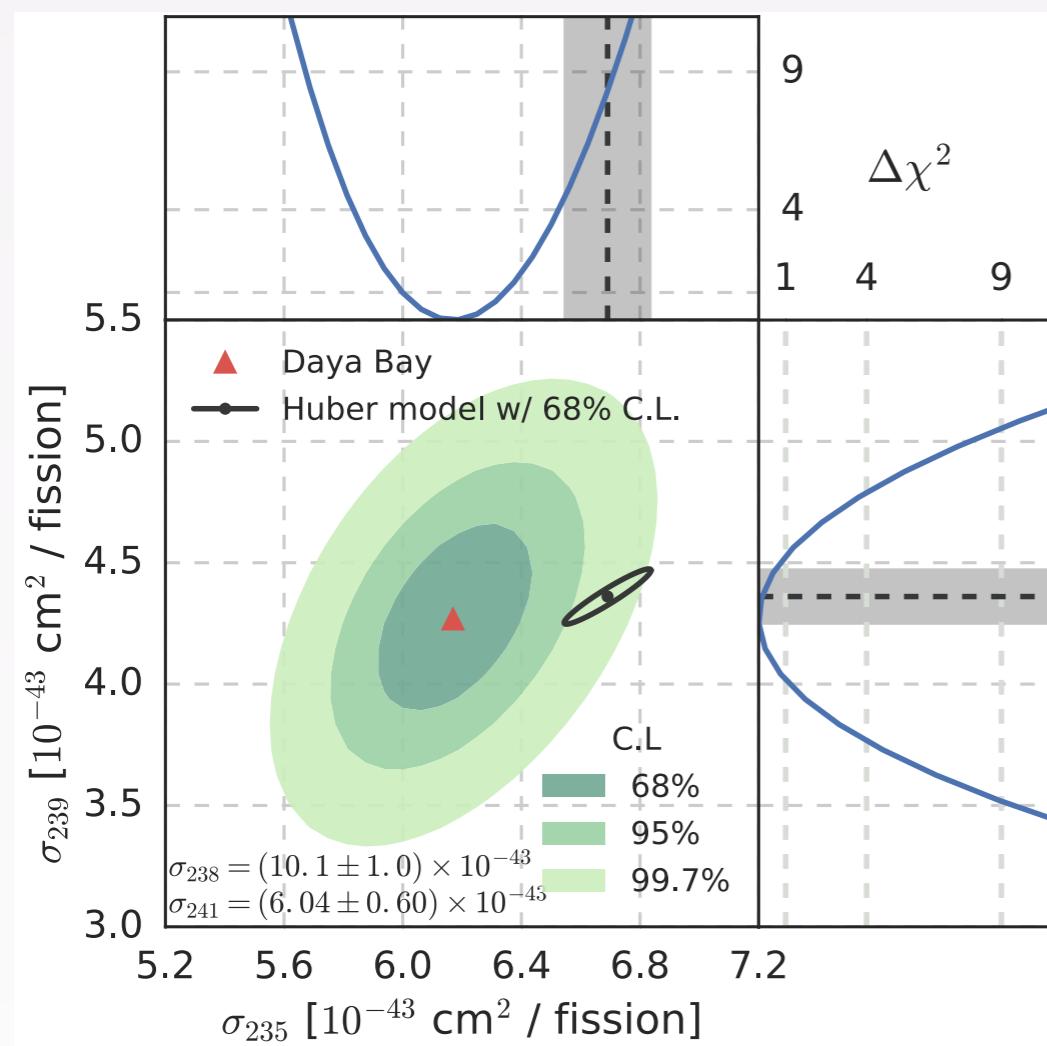


Can nuclear physics account for RAA?

(See previous talk by M. Weber for sterile neutrino discussion)

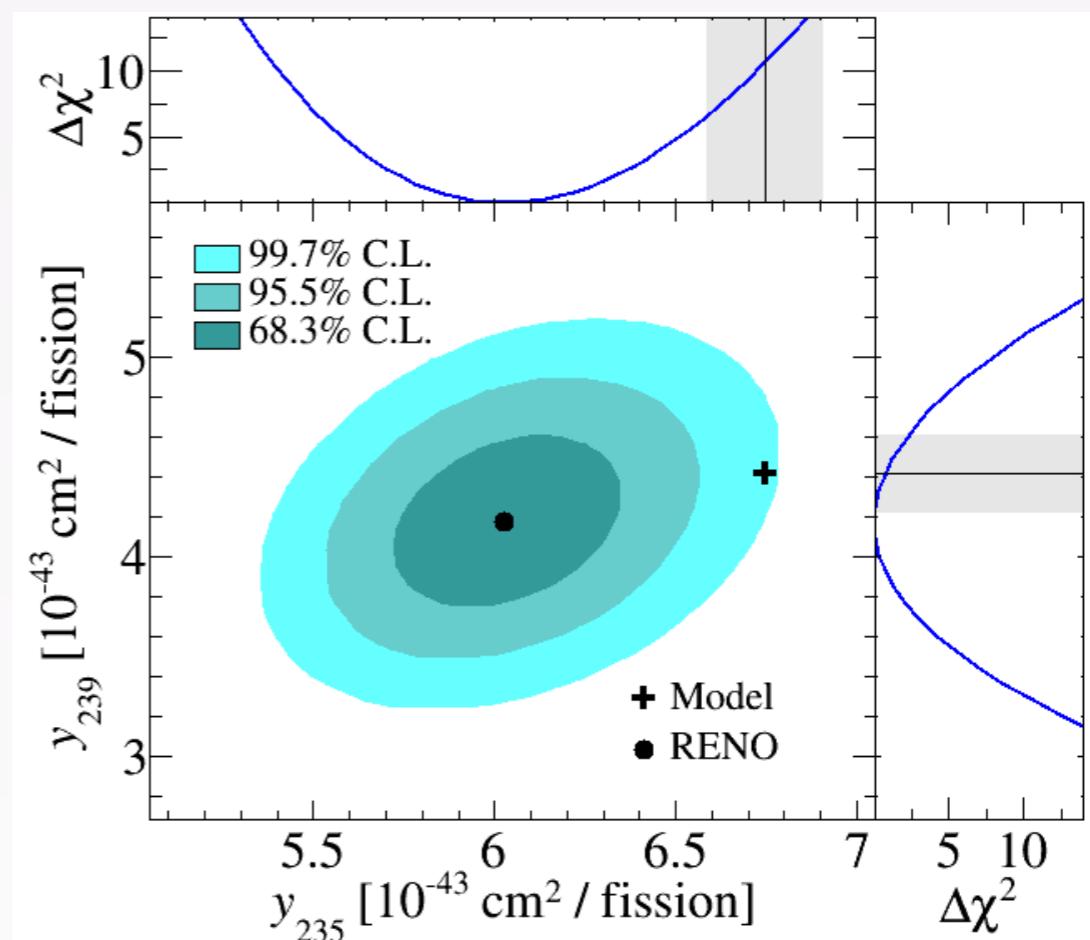
# Reactor Antineutrino Anomaly (RAA)

arXiv:1704.01082



I. Yu at Neutrino'18

<https://doi.org/10.5281/zenodo.1287949>



Analysis of antineutrino flux evolution (fuel burnup) shows deficit of IBD yields per fission for  $^{235}\text{U}$  compared to model

# RAA and nuclear physics

- “5 MeV bump” is likely to have a standard nuclear physics explanation. Discussion underway whether it could be caused by  $^{238}\text{U}$  or  $^{235}\text{U}$ .
  - Current SBL reactor experiments sitting next to HEU reactors should resolve it by observing presence/lack of a bump, e.g. PROSPECT, STEREO, SoLiD.
- Changes in  $Z_{\text{eff}}$  in Fermi function and other corrections may reduce or eliminate existing discrepancy in antineutrino flux

$$S(E_e, Z, A) = \frac{G_F^2}{2\pi^3} p_e E_e (E_0 - E_e)^2 F(E_e, Z, A) (1 + \delta_{\text{corr}}(E_e, Z, A))$$

See A. Hayes talk at Neutrino'18 for details <https://doi.org/10.5281/zenodo.1287950>

# RAA and nuclear physics

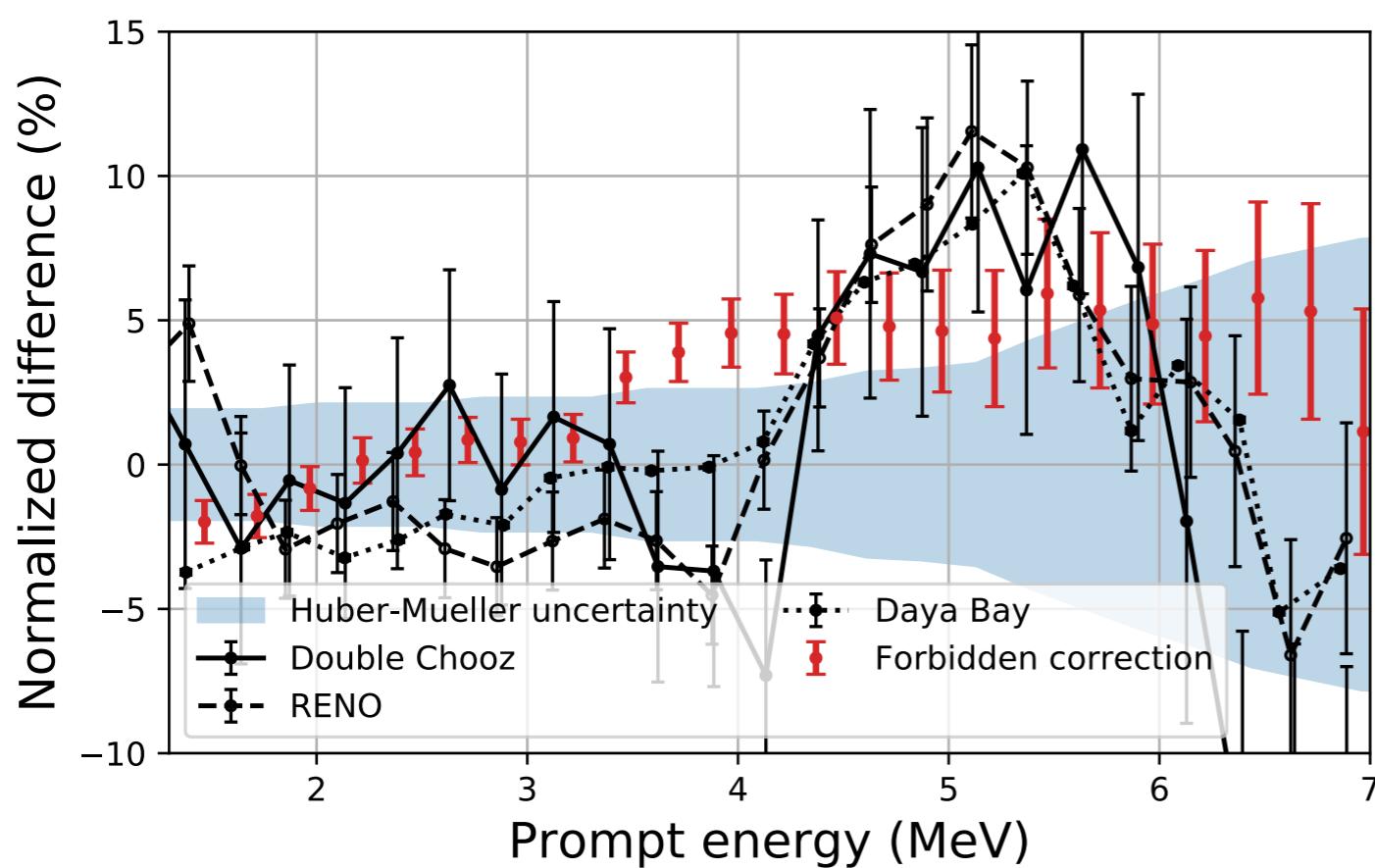
Very recent new suggestion that by using explicit nuclear physics calculations one can eliminate both anomalies: flux and “bump”

$$\frac{dN}{dW} = p W(W - W_0)^2 F(Z, W) C(Z, W) K(Z, W),$$

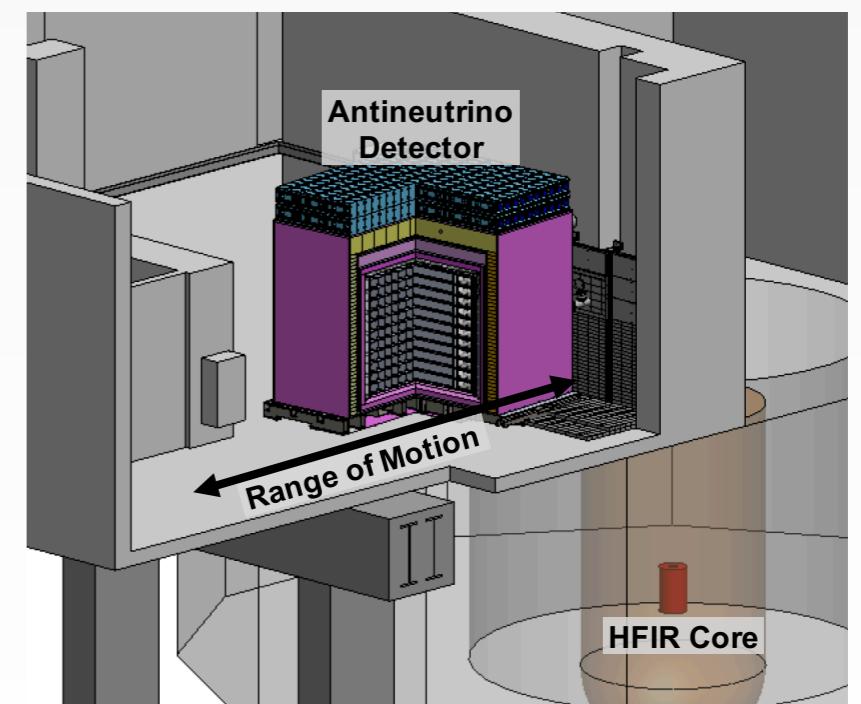
Kinematics      Fermi-function      Shape factor  
 ↓                  ↓                  ↗  
 higher-order corrections

arXiv:1805.12259

Explicitly taken into account for 29 most important forbidden  $\beta$ -decays of fission products

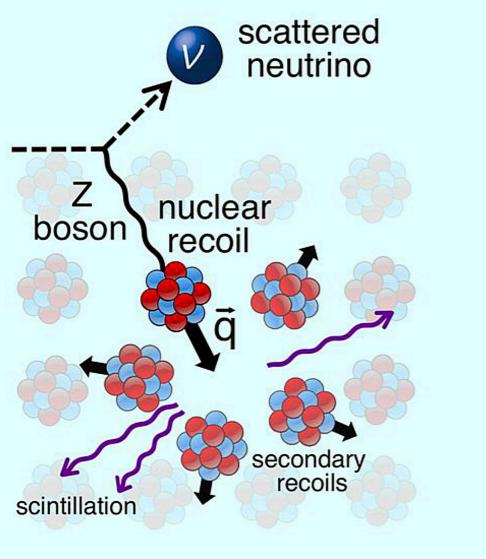


Can be resolved with running/upcoming VSBL reactor experiments.  
 Very good energy resolution ( $\sim 4.5\%/\sqrt{E}$ ), e.g. PROSPECT, is advantage

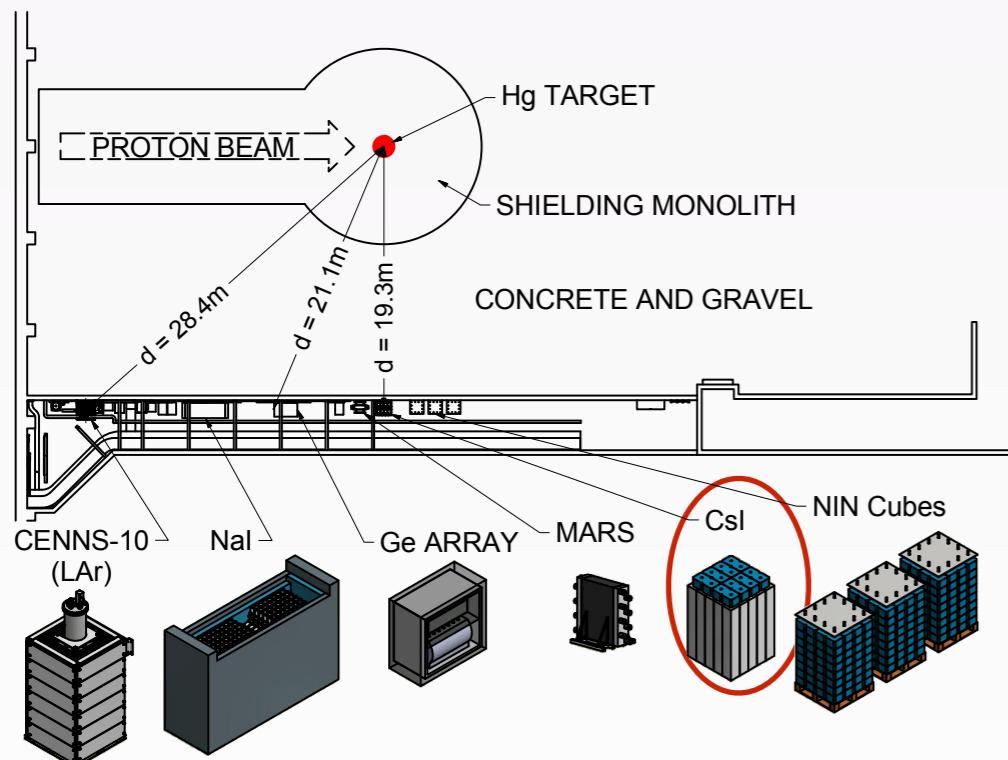


Presented at NDM-2018 Daejeon  
 28 Jun - 4 Jul 2018

# Coherent Elastic neutrino-nucleus scattering — CE $\nu$ NS



$$\sigma \approx \frac{G_F^2 N^2}{4\pi} E_\nu^2$$

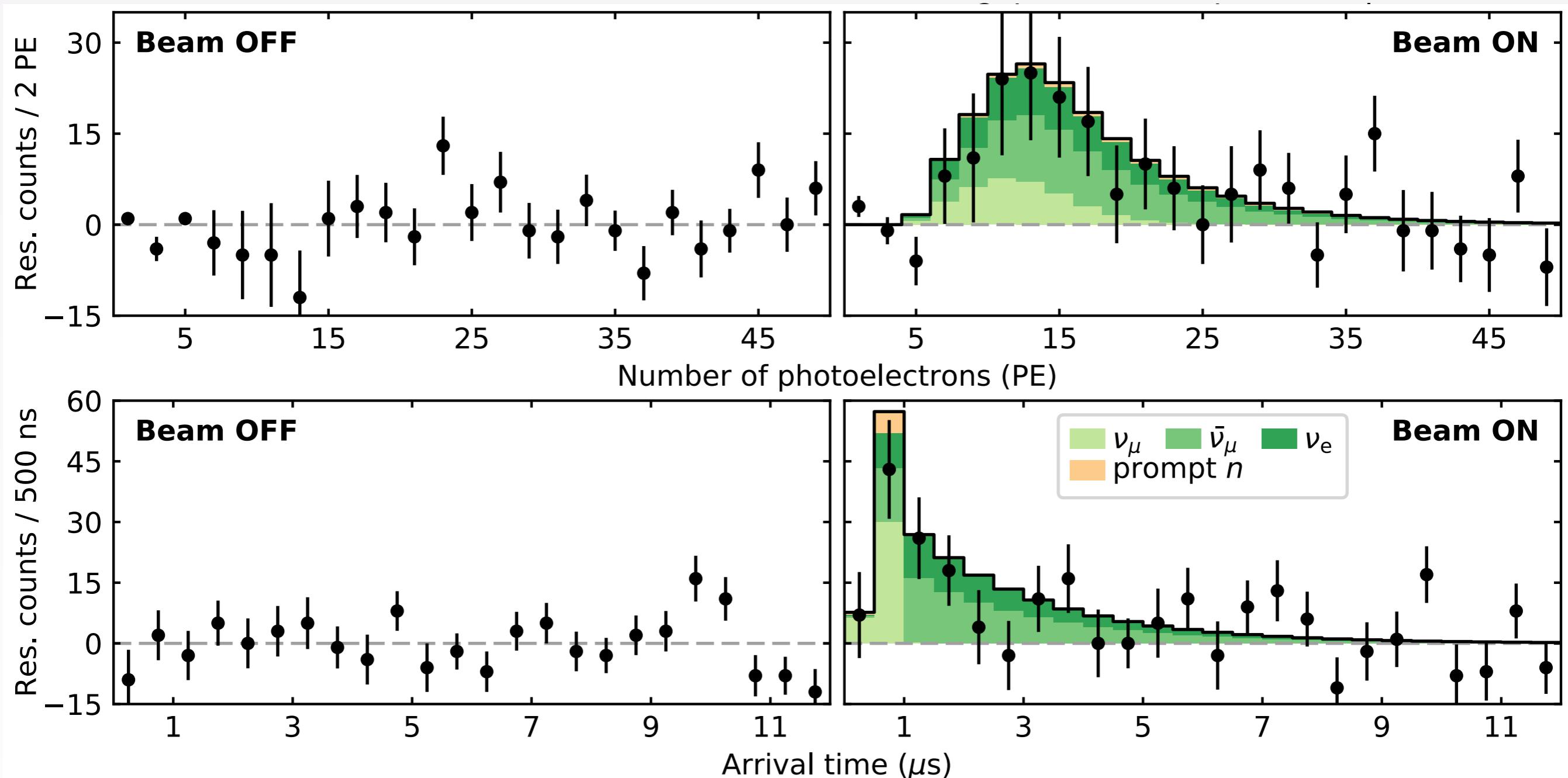


- Coherent scattering on nucleus as a whole
- $p_\nu \sim 1/R_{\text{nuc}} \rightarrow 10's \text{ MeV}$ . Reactors, stopped pions/muons, supernovae
- Cross-section orders of magnitude higher than IBD!
- But tiny nuclear recoil energies must be detected —  $\sim \text{keV}$  scale

- Spallation Neutron Source at Oak Ridge
- $\sim 1 \text{ MW}$  pulsed (60 Hz, 700ns) proton beam (1 GeV)
- Significant background suppression by timing
- Well defined flux from stopped pions and muons

Talk by G.C. Rich (#1032)

# Coherent Elastic neutrino-nucleus scattering — CE $\nu$ NS



First observation of CE $\nu$ NS at  $> 6\sigma$  level !

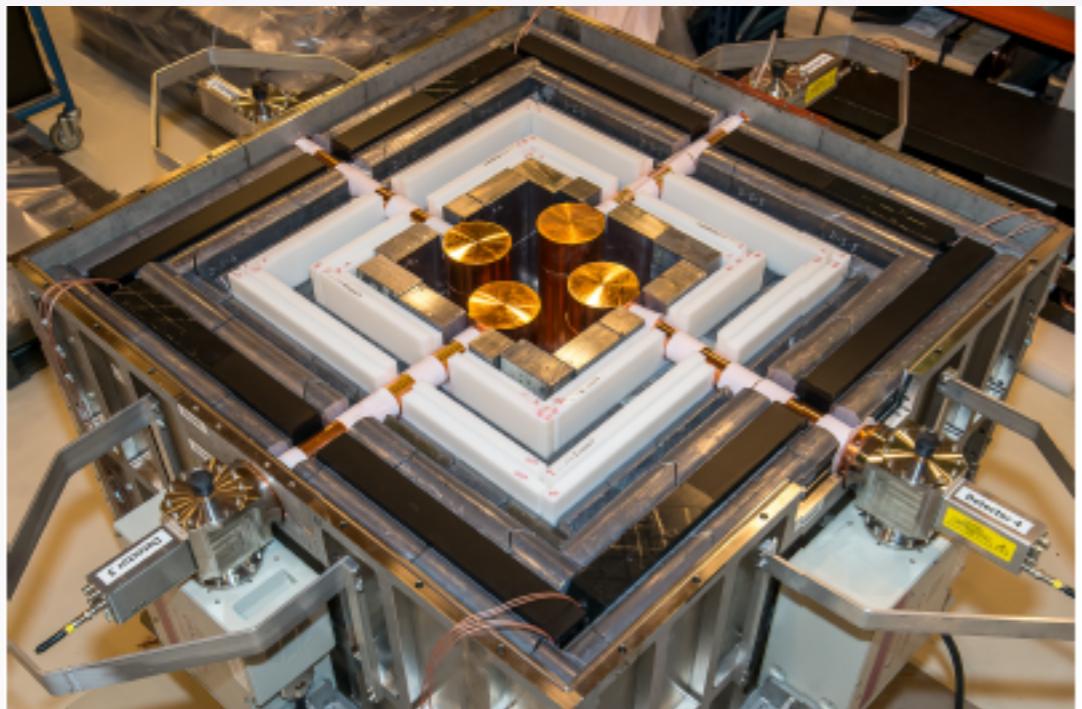
Note the detector size: 14.6kg of CsI(Na)

- Significant new result since last ICHEP
- Exciting opportunities for “table-top” neutrino detectors

Talk by G.C. Rich (#1032)

# Coherent Elastic neutrino-nucleus scattering — CEvNS

**CEvNS@reactors**



**CONUS Experiment at Brokdorf (Germany) nuclear power plant**

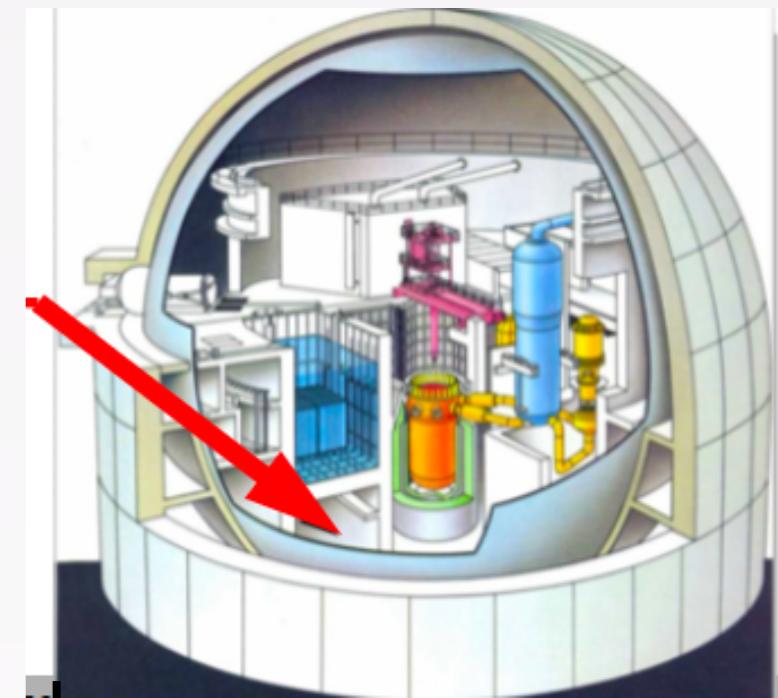
3.9 GW<sub>th</sub>, ν-flux:

$2.4 \times 10^{13} \text{ cm}^{-2} \text{ s}^{-1}$

4 x 1 kg HPGe detectors  
installed at 10-45 m.w.e.  
overburden  
at 17m from core

sub-keV threshold:

$E_\nu = 10 \text{ MeV} \rightarrow E_r = 3 \text{ keV}$   
 $\rightarrow 0.6 \text{ keV with quenching}$



Start data taking Apr'18

Talk by W. Maneschg at Neutrino'18

<https://doi.org/10.5281/zenodo.1286927>

**Rate comparison (all detectors):**

	counts	counts/(d·kg) (*)
reactor OFF (114 kg*d)	582	
reactor ON (112 kg*d)	653	
ON-OFF (exposure corr.)	84	0.94
Significance	<b>2.4 σ</b>	$2.3 \sigma$

(\*) Including stat. uncertainty and above efficiencies

Some systematics  
still under study

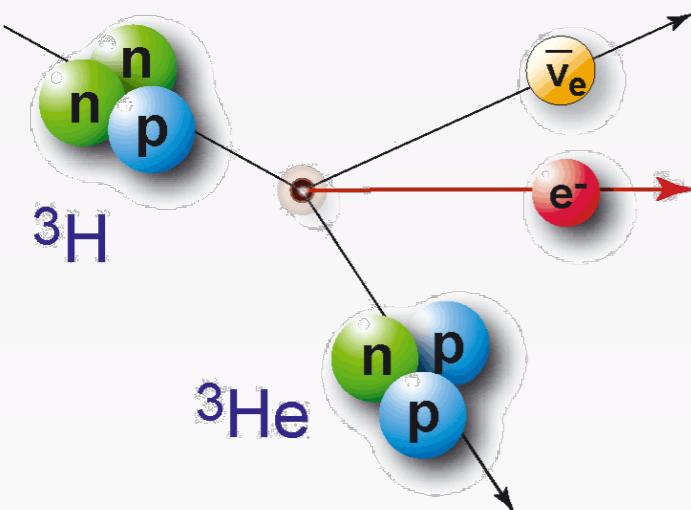
Other experiments: CONNIE,  
MINER, Nu-Cleus, nuGEN,  
RICOCHET, RED-100...

CEvNS: exciting physics  
potential: NSI, oscillations,  
ν-magnetic moment, reactor  
monitoring

See talks by G.C. Rich (#1032),  
D. Aristizabal (#1056) for more

# Neutrino Mass Observables

$\beta$ -decay

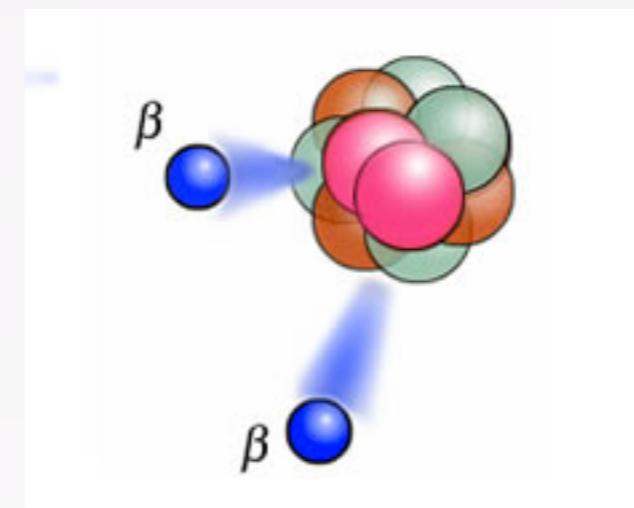


$$m_\beta = \sqrt{\sum_i |U_{ei}|^2 \cdot m_i^2}$$



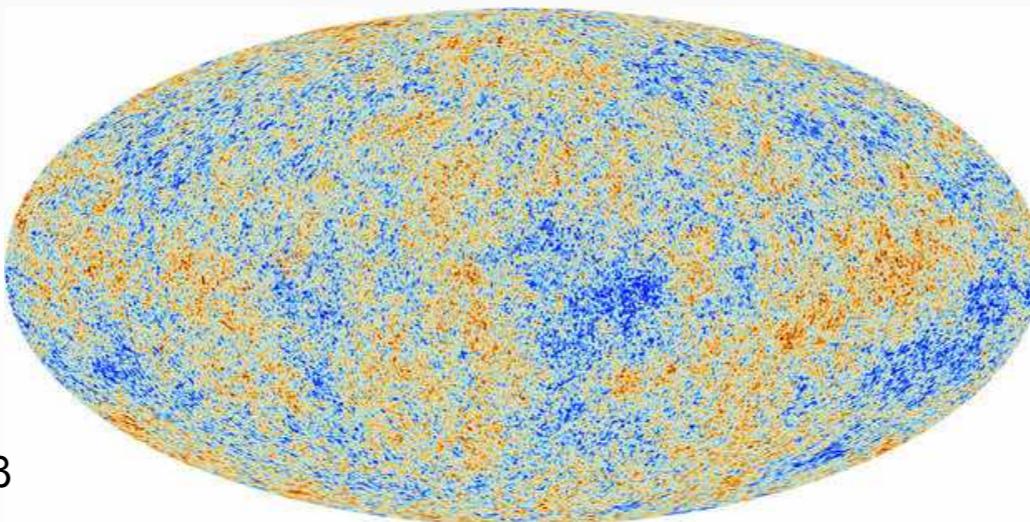
Model independent  
No cancellations for  $m_\beta$

$0\nu\beta\beta$ -decay



$$m_{\beta\beta} = \left| \sum_i U_{ei}^2 m_i \right|$$

Cosmology



$$\sum_i m_i$$

# Neutrino Mass from $\beta$ -decay end-point

E. Fermi, Z. Phys. 88 (1934) 161

Old idea!

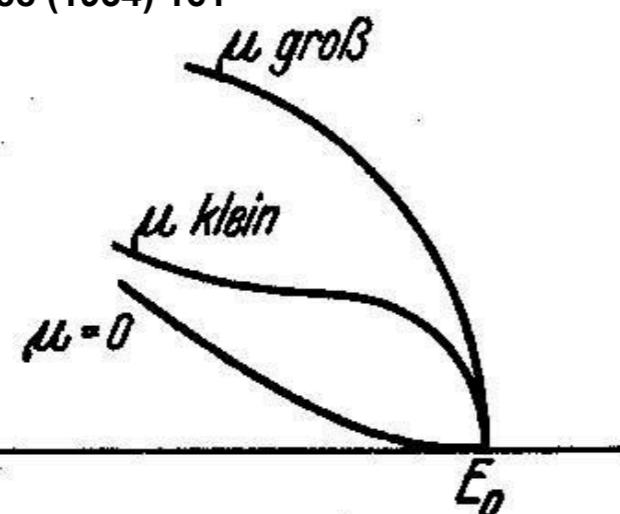
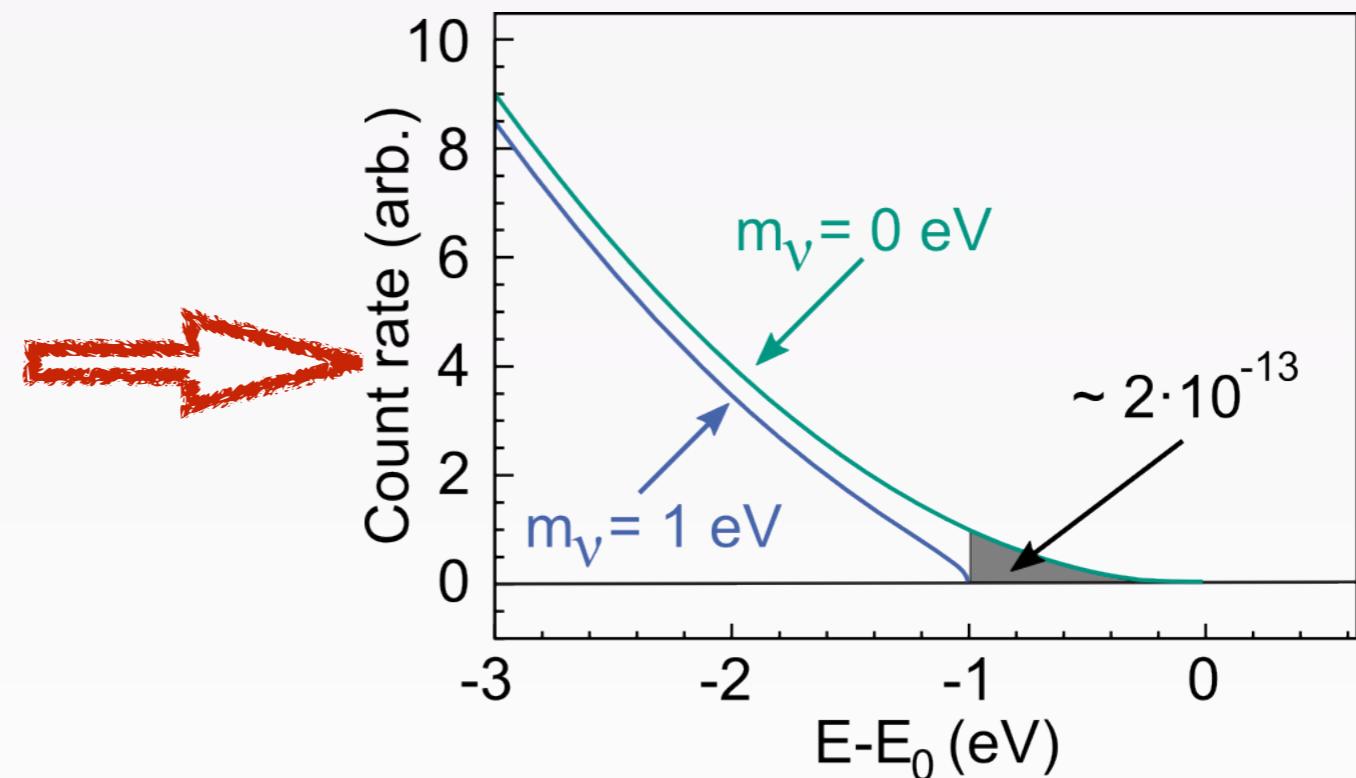


Fig. 1.

Tough Reality

$$\frac{dN}{dE} \propto \sqrt{(E_0 - E)^2 - m_{\bar{\nu}_i}^2 c^4}$$



Best results from  ${}^3\text{H}$   $\beta$ -decay with MAC-E filter technology

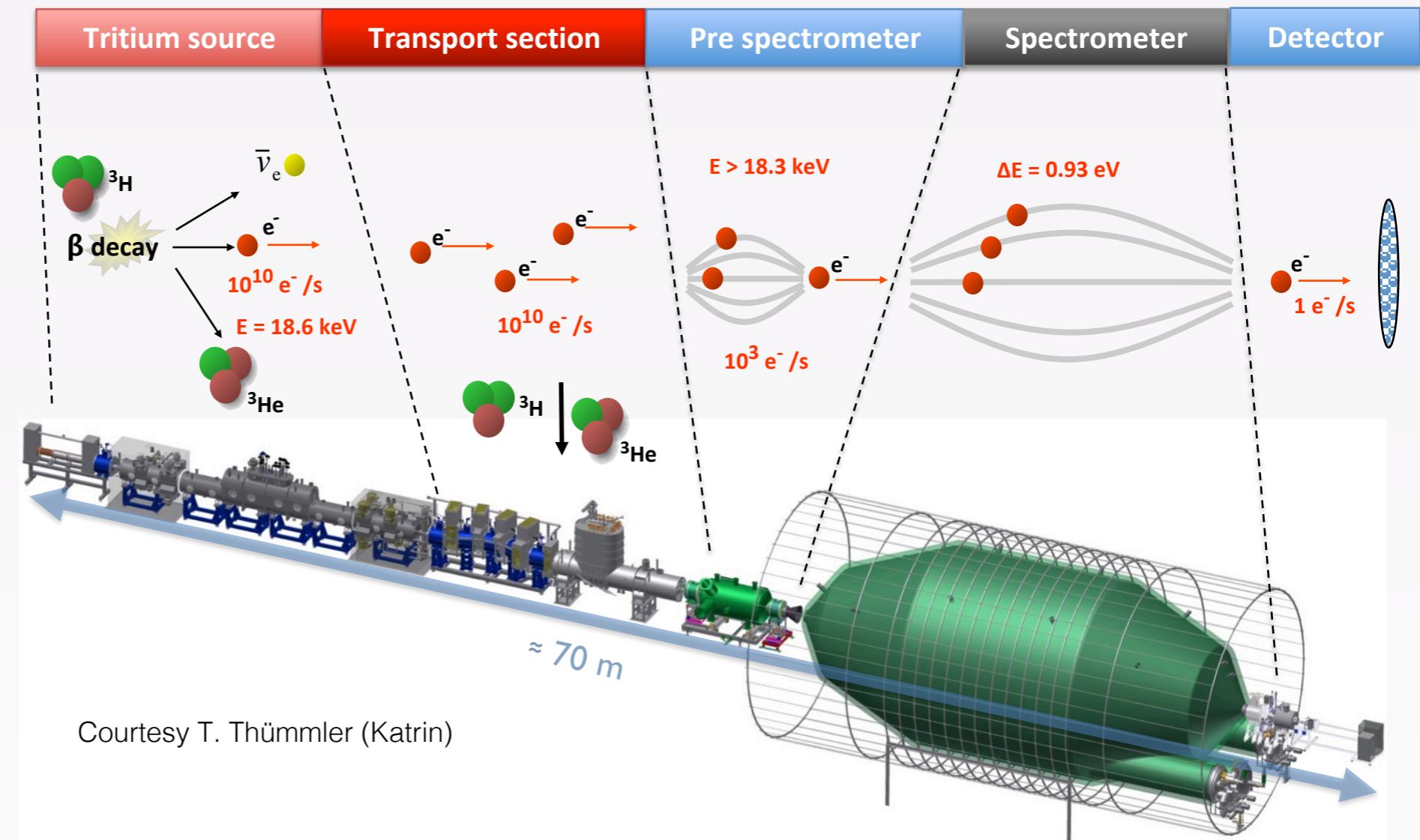
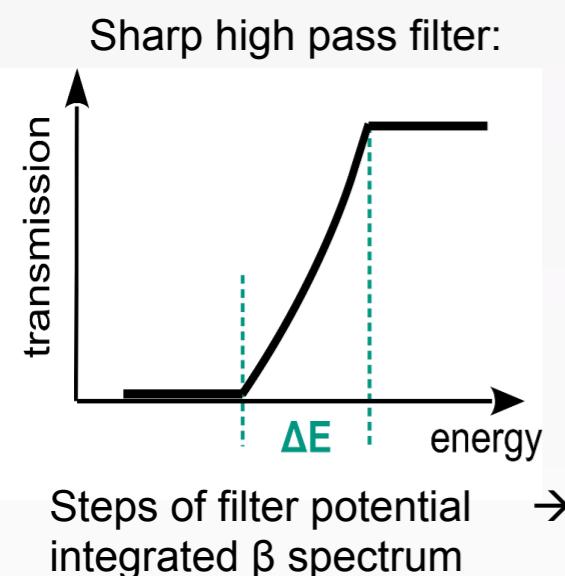
$E_0 = 18.6 \text{ keV}$   
 $T_{1/2} = 12.3 \text{ y}$

$m_\beta < 2 \text{ eV}$

Aim:  $m_\beta < 0.2 \text{ eV}$  (90% C.L.)

# KATRIN Experiment

- Windowless gaseous tritium source
- High  $2\pi$  acceptance
- MAC-E filter: Magnetic Adiabatic Collimation & Electrostatic Filter



$$\frac{\Delta E}{E} = \frac{B_{\min}}{B_{\max}}$$

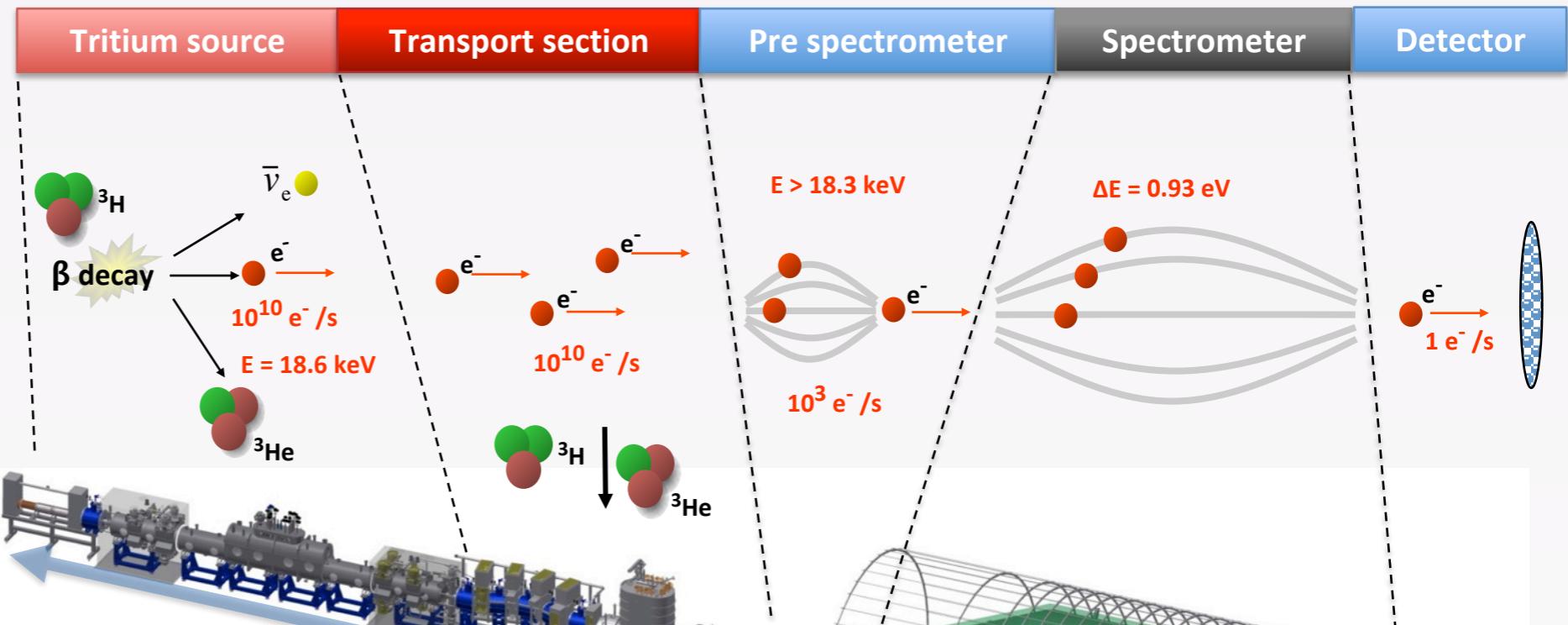
→  $\Delta E < 1 \text{ eV}$  at  $18.6 \text{ keV}$

See talk by M. Schlösser (#317)

# KATRIN Experiment

- Windowless gaseous tritium source
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Sharp high pass filter:



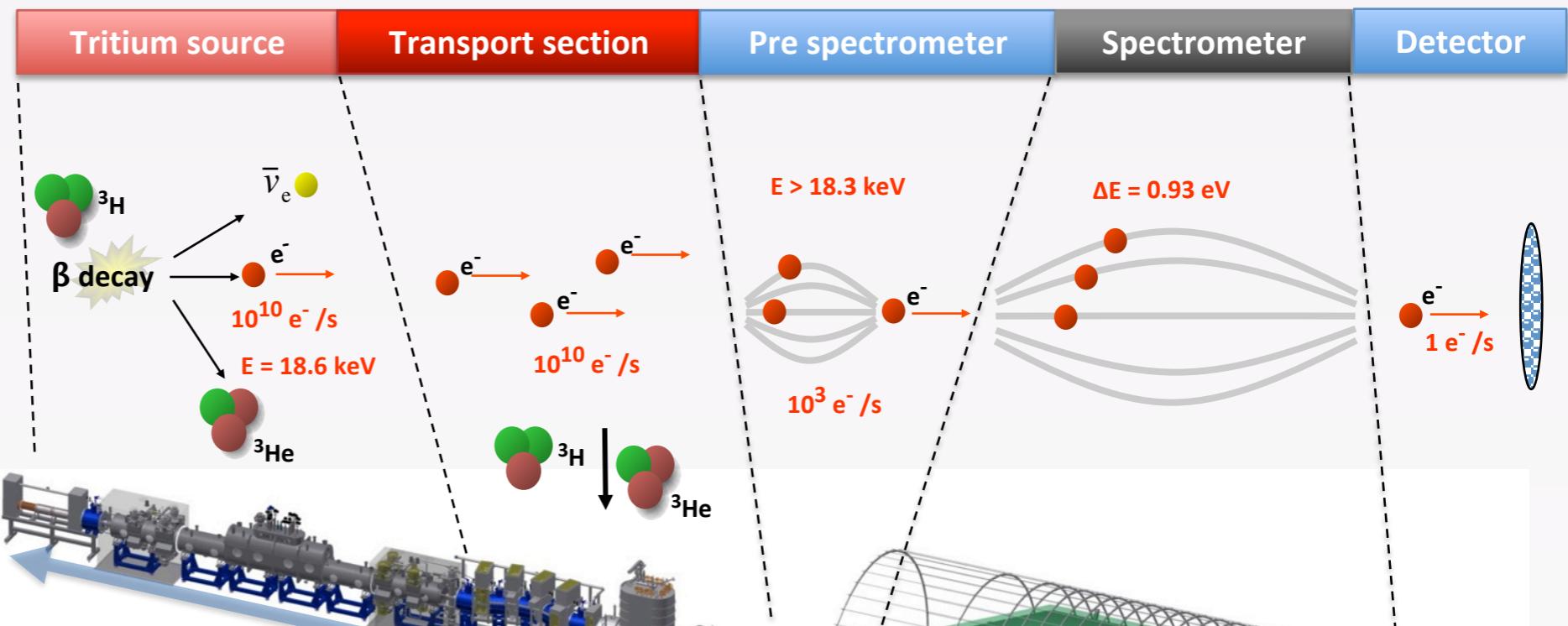
See talk by M. Schlosser (#317)

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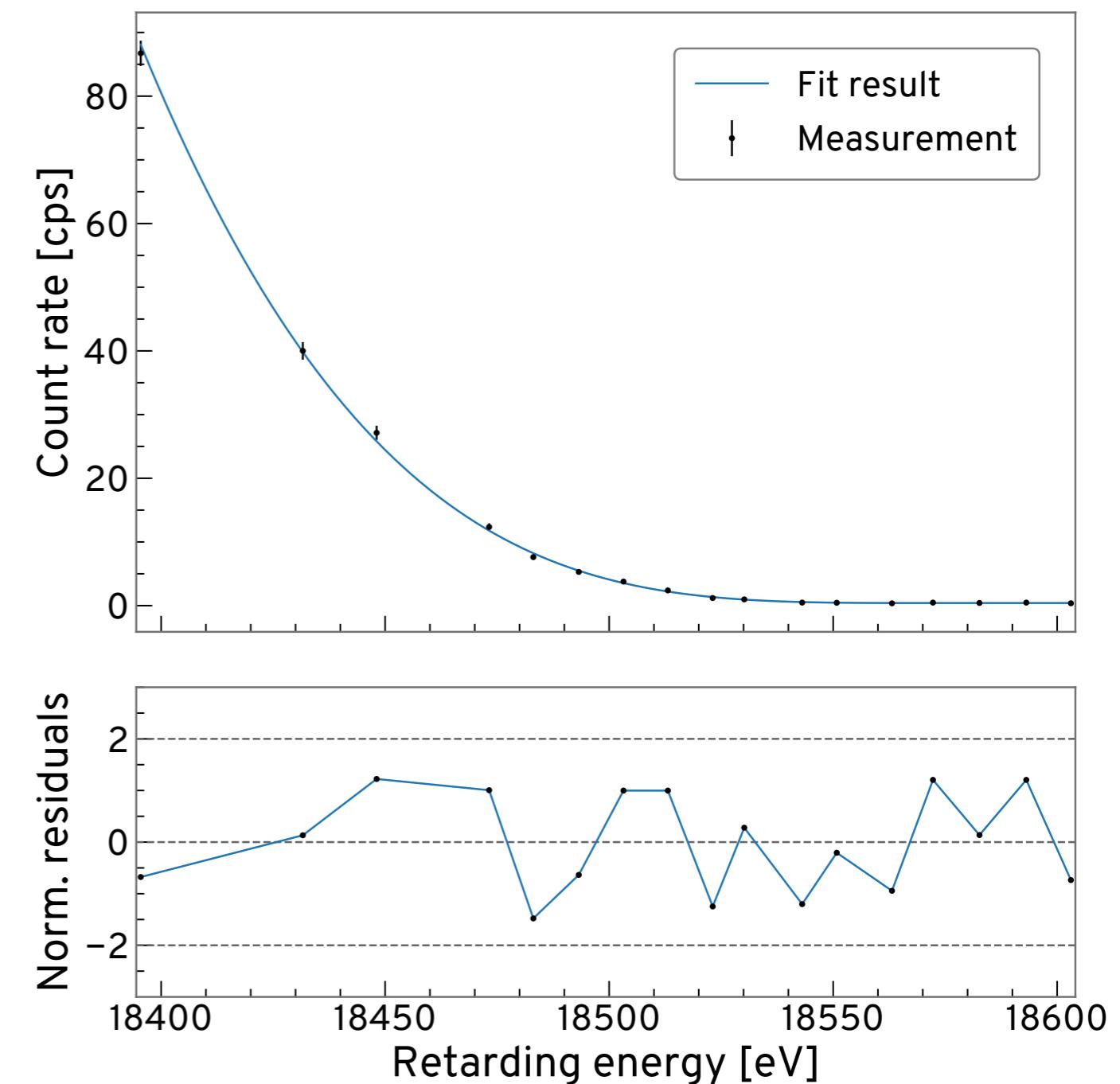
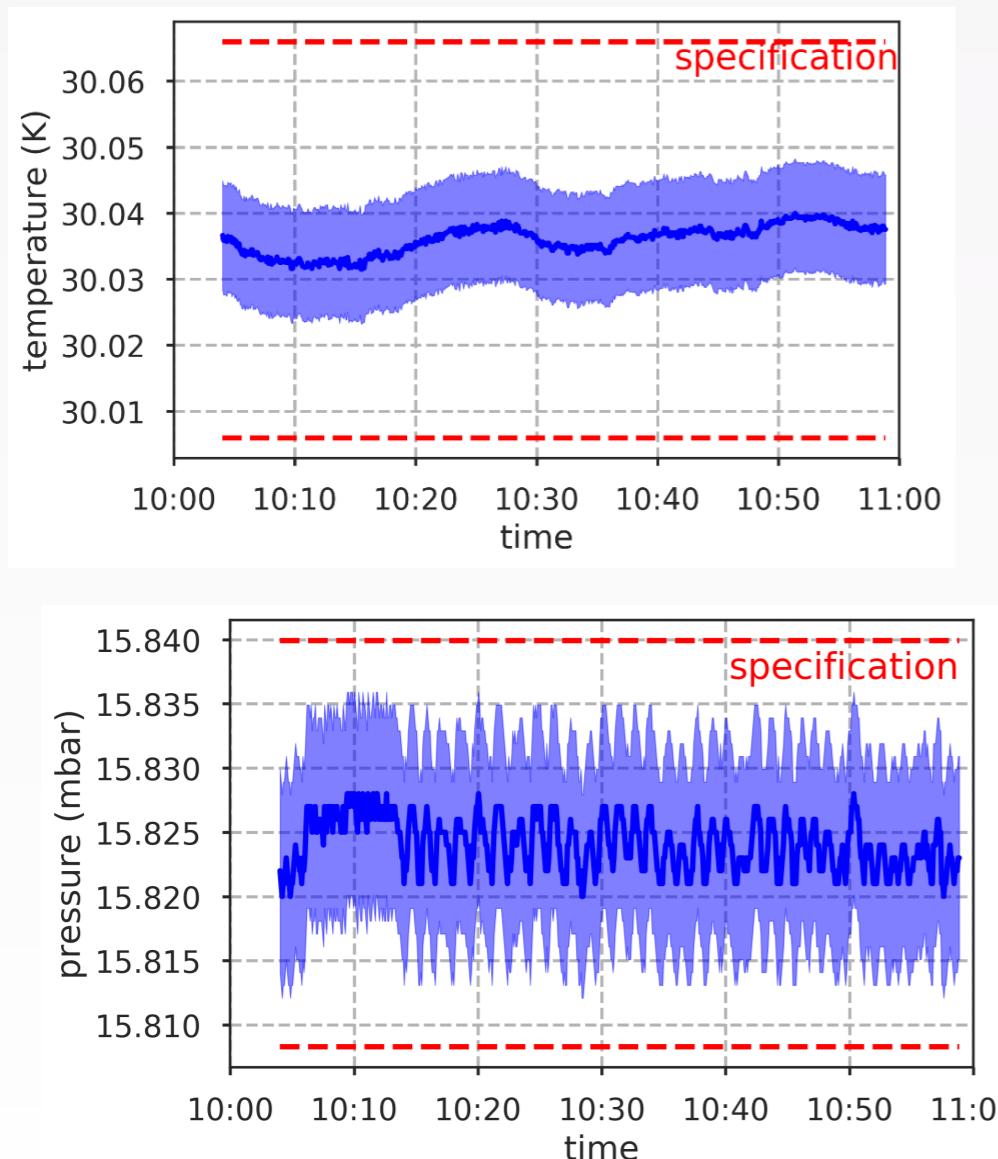
First tritium injection:  
Friday 18 May  
7:48 am UTC



See talk by M. Schlosser (#317)

# KATRIN First Results

- 1% of nominal tritium activity
- Tritium loop operation from 5 June - 18 June (no interruption)
- Source parameters are stable and within specifications



See talk by M. Schlösser (#317)

# How to build on KATRIN success and increase sensitivity to neutrino mass?

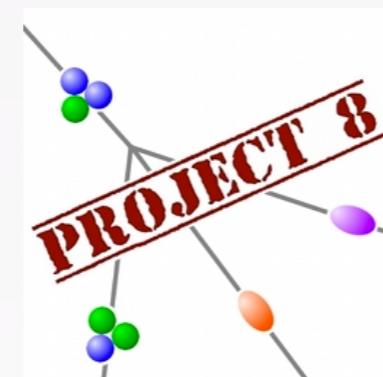
Limitations of  
MAC-E  
technology

$$\frac{\Delta E}{E} \propto \frac{B_{\min}}{B_{\max}}$$

+

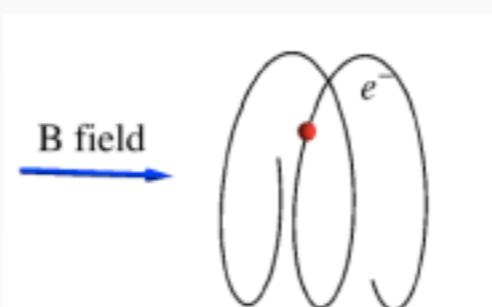
molecular physics  
uncertainties

scales with  
spectrometer size

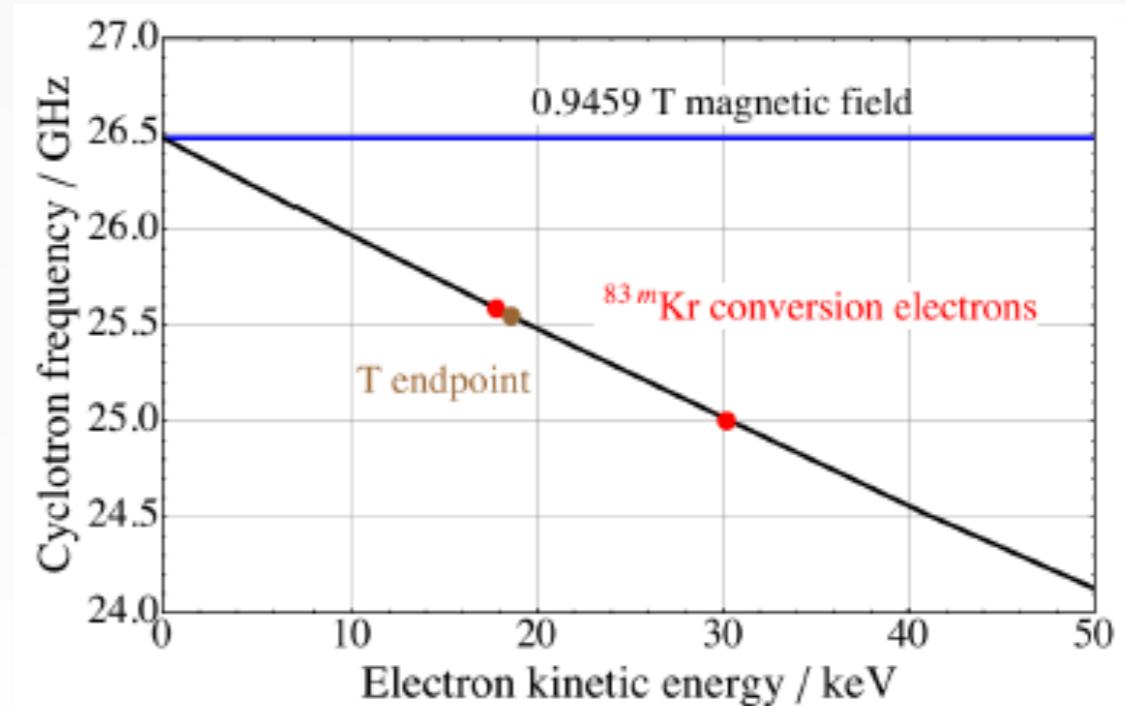
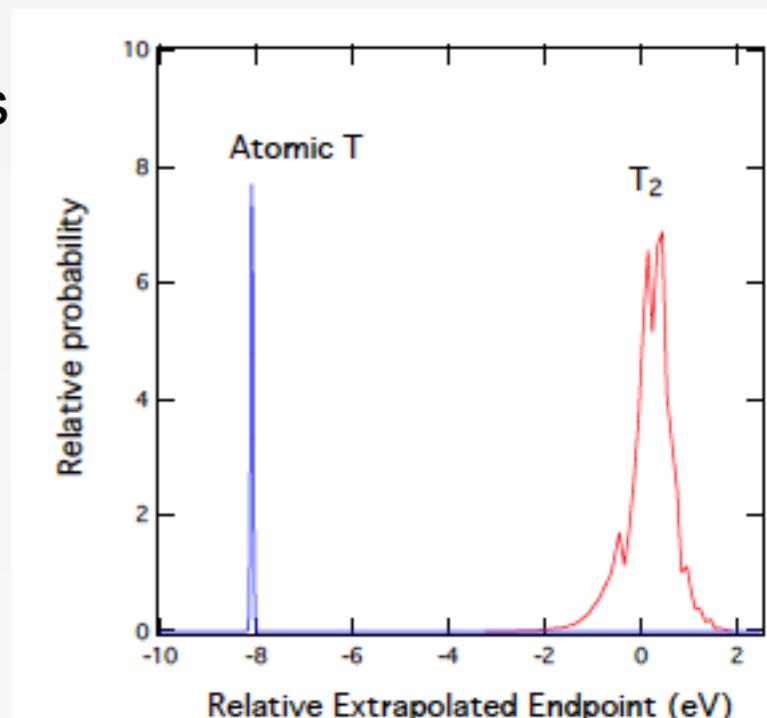


## Concept:

- Electrons moving in B-field emit cyclotron radiation
- Electron cyclotron frequency is related to electron kinetic energy
- Cyclotron frequency is encoded in cyclotron radiation



$$\omega(E_{kin}) = \frac{eB}{E_{kin} + m_e}$$



Talk by G. Rybka at Neutrino'18

<https://doi.org/10.5281/zenodo.1286954>

# How to build on KATRIN success and increase sensitivity to neutrino mass?

Limitations of  
MAC-E  
technology

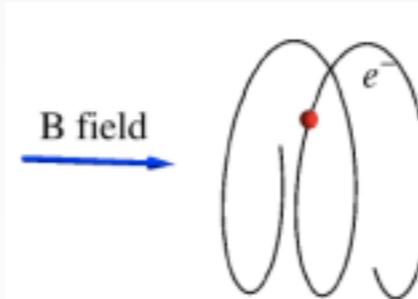
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+  
molecular physics  
uncertainties

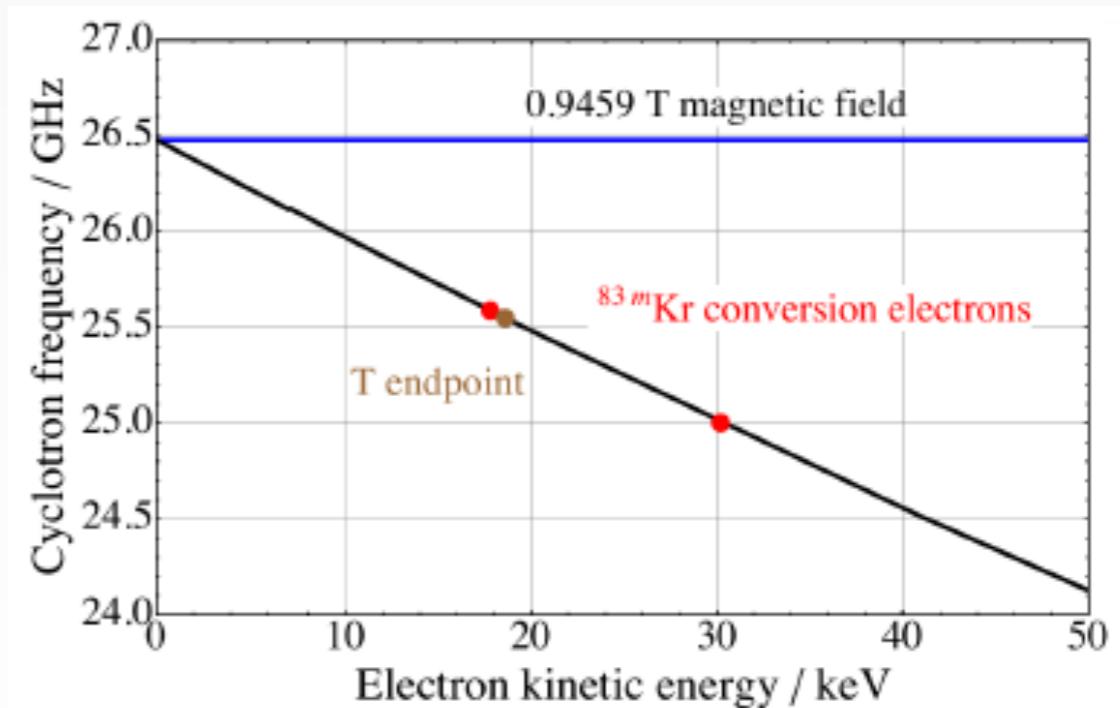
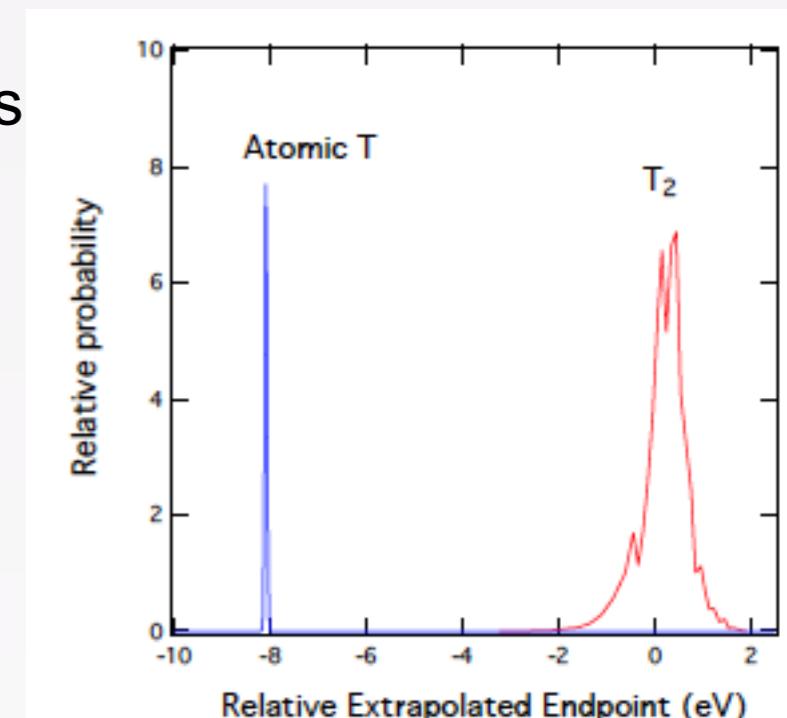
scales with  
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Concept:



$$\omega(E_{kin}) = \frac{eB}{E_{kin} + m_e}$$

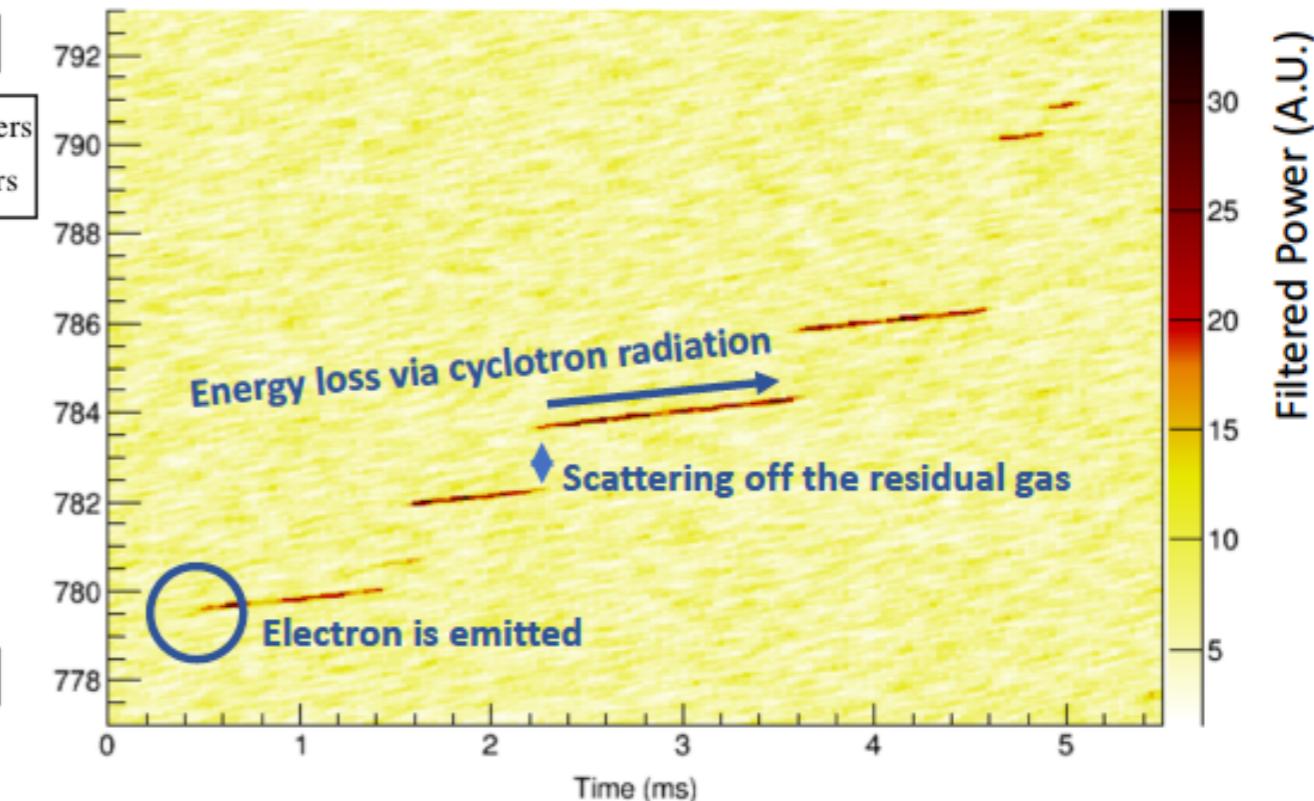
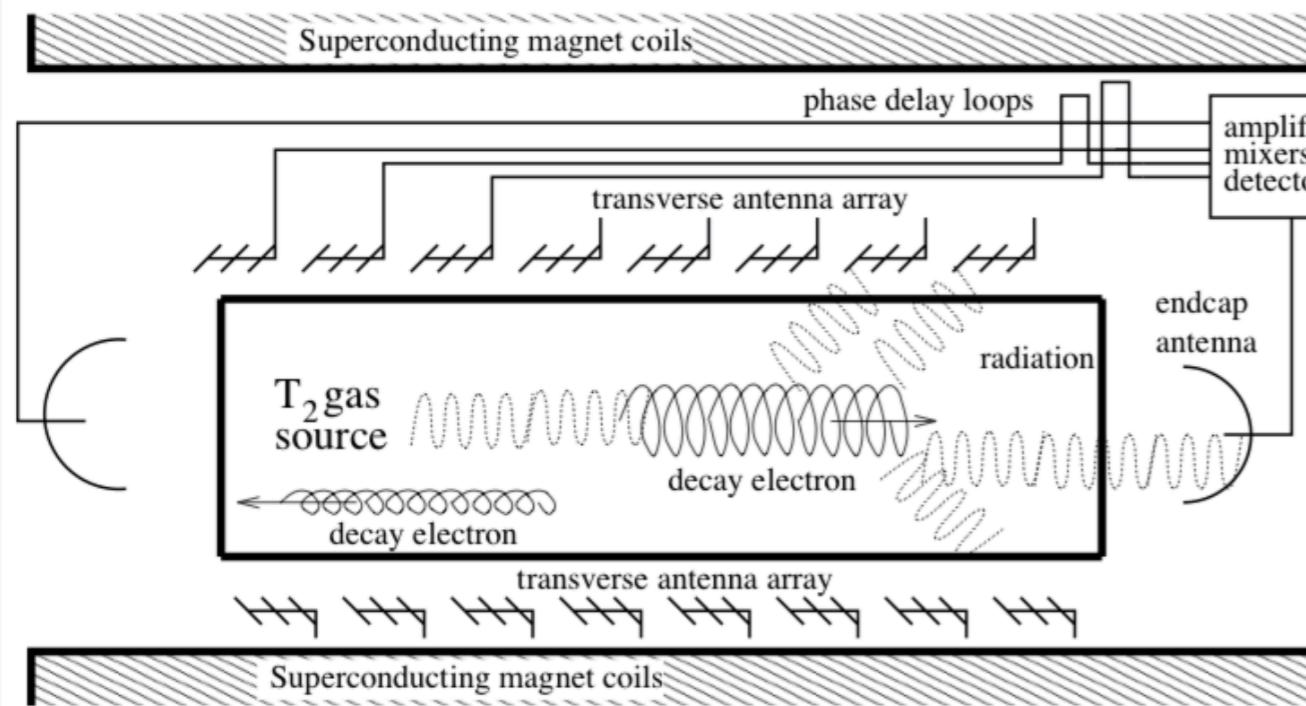


A. Schawlow: “Never measure anything but frequency!”

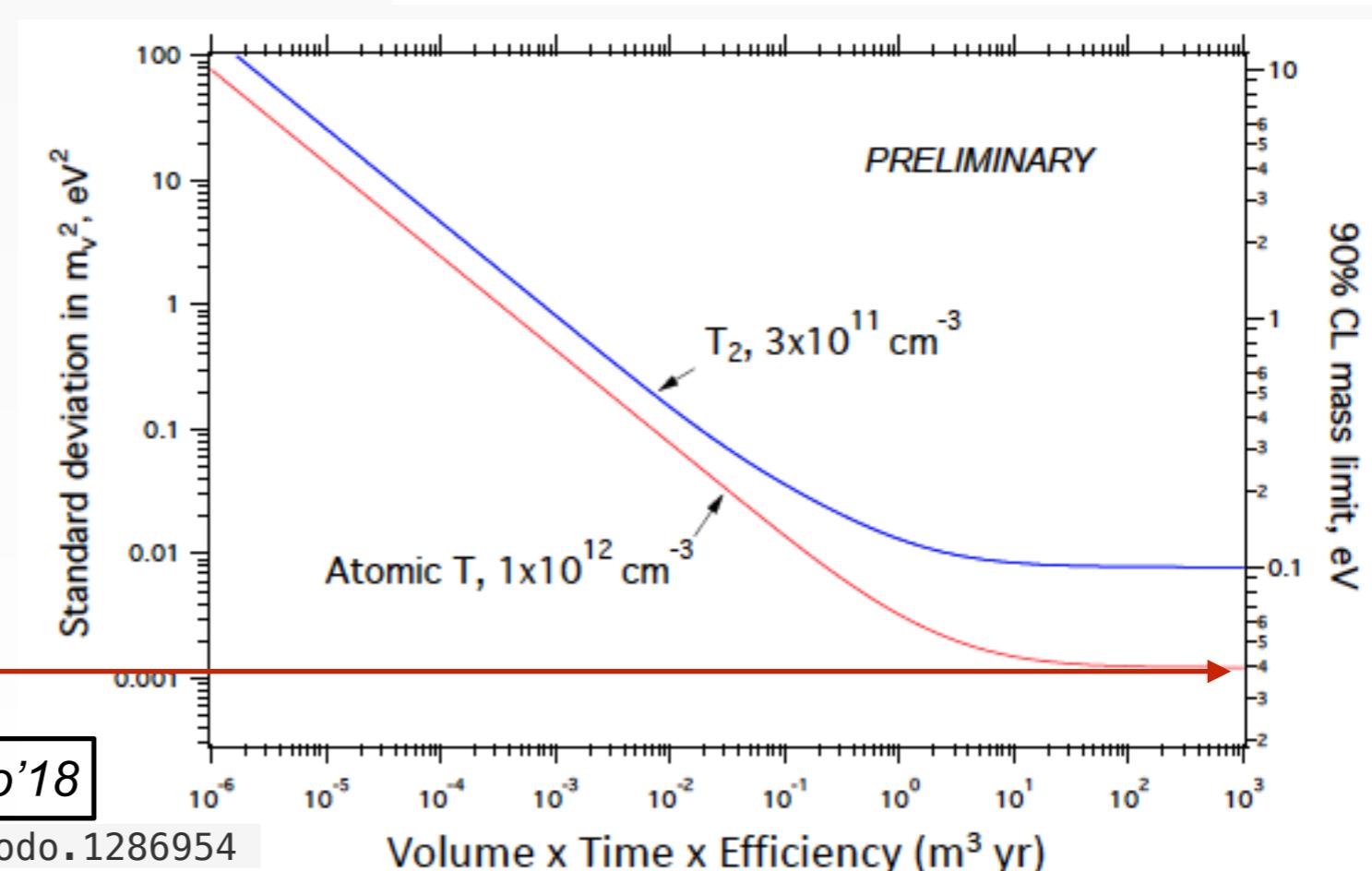
Talk by G. Rybka at Neutrino'18

<https://doi.org/10.5281/zenodo.1286954>

# Measuring ${}^3\text{H}$ $\beta$ -decay end-point in Project 8



- Phased approach
- Start with  $\text{T}_2$  first
- Move to atomic tritium next
- Joffe traps to preserve atomic T (leveraging anti-hydrogen experiments experience)
- **Closing in on guaranteed effect**

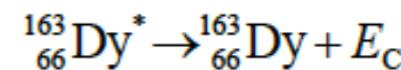
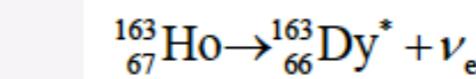
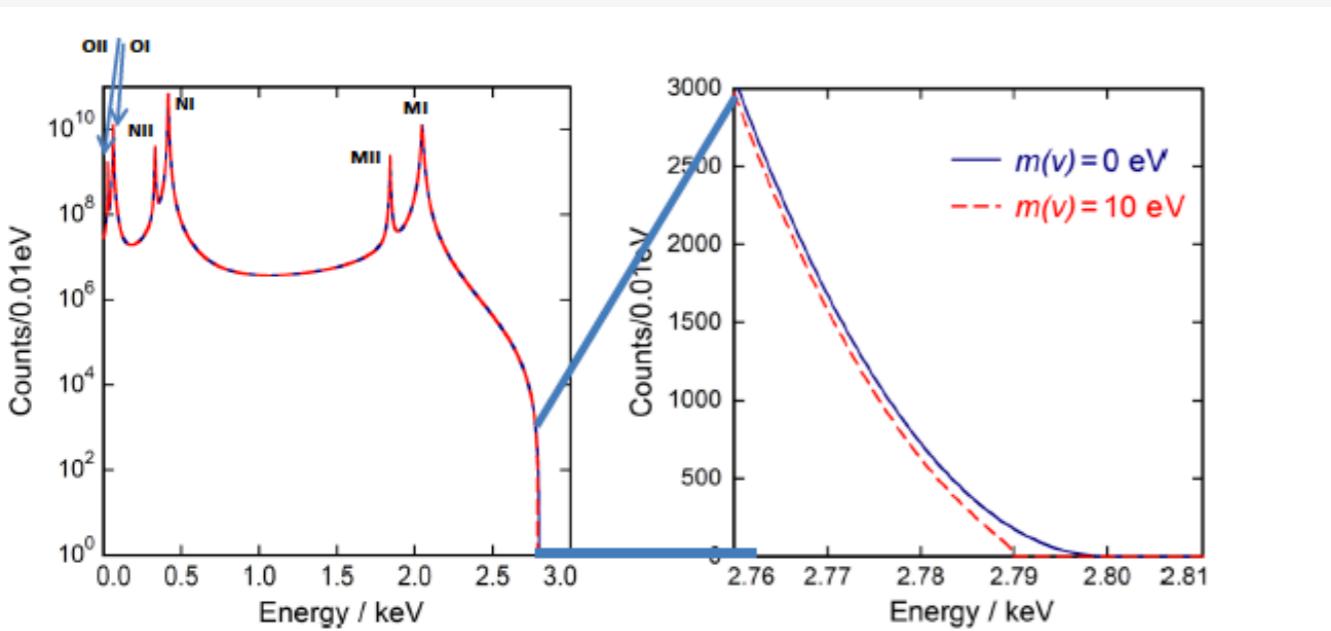


Talk by G. Rybka at Neutrino'18

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# Other Approaches — Micro-calorimeters

- Calorimetric measurement, source inside detector
- No quenching, no unaccounted energy losses
- Measure atomic de-excitation:  
→ X-rays, Auger electrons

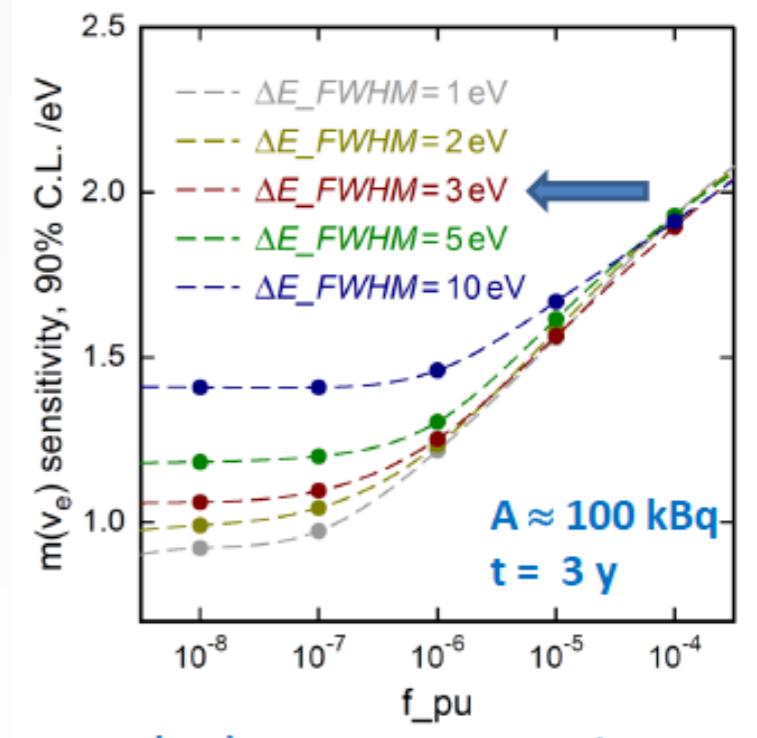


$$Q_{EC} = [2.833 \pm 0.030(\text{stat}) \pm 0.015(\text{syst})] \text{ keV}$$

$$\tau_{1/2} = 4570 \text{ yr}$$

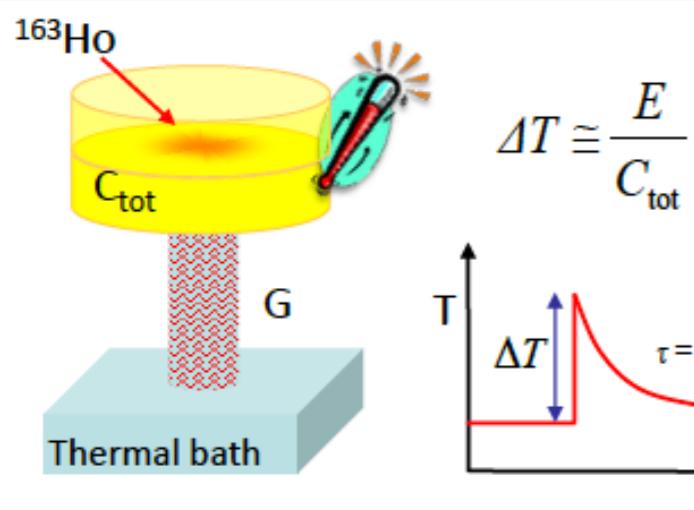
Current sensitivity  $\sim 10 \text{ eV}$

**ECHO-100k (2018 – 2021)**

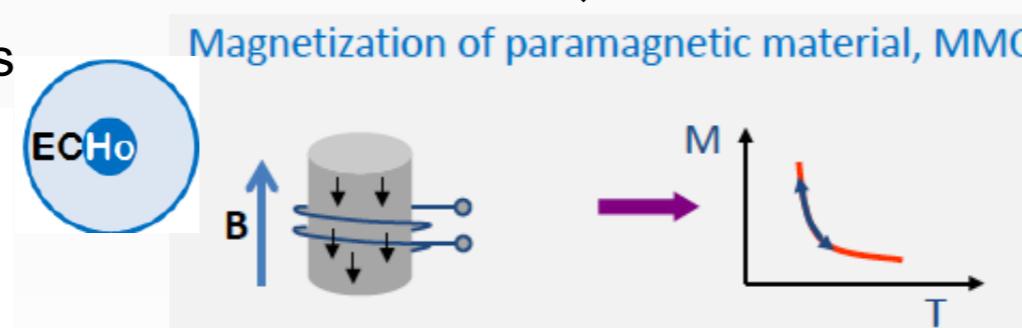
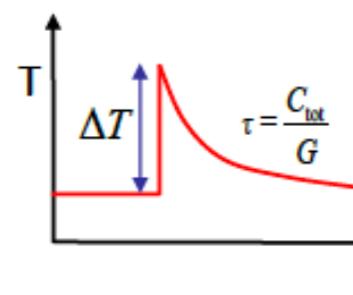


$$m(\nu_e) < 1.5 \text{ eV } 90\% \text{ C.L.}$$

## Low temperature micro-calorimeters



$$\Delta T \approx \frac{E}{C_{tot}}$$



Talk by L. Gastaldo at Neutrino'18

<https://doi.org/10.5281/zenodo.1286950>

# Neutrinoless Double Beta Decay

# Neutrinoless Double Beta Decay

**Short Summary:  
We have not found it yet**

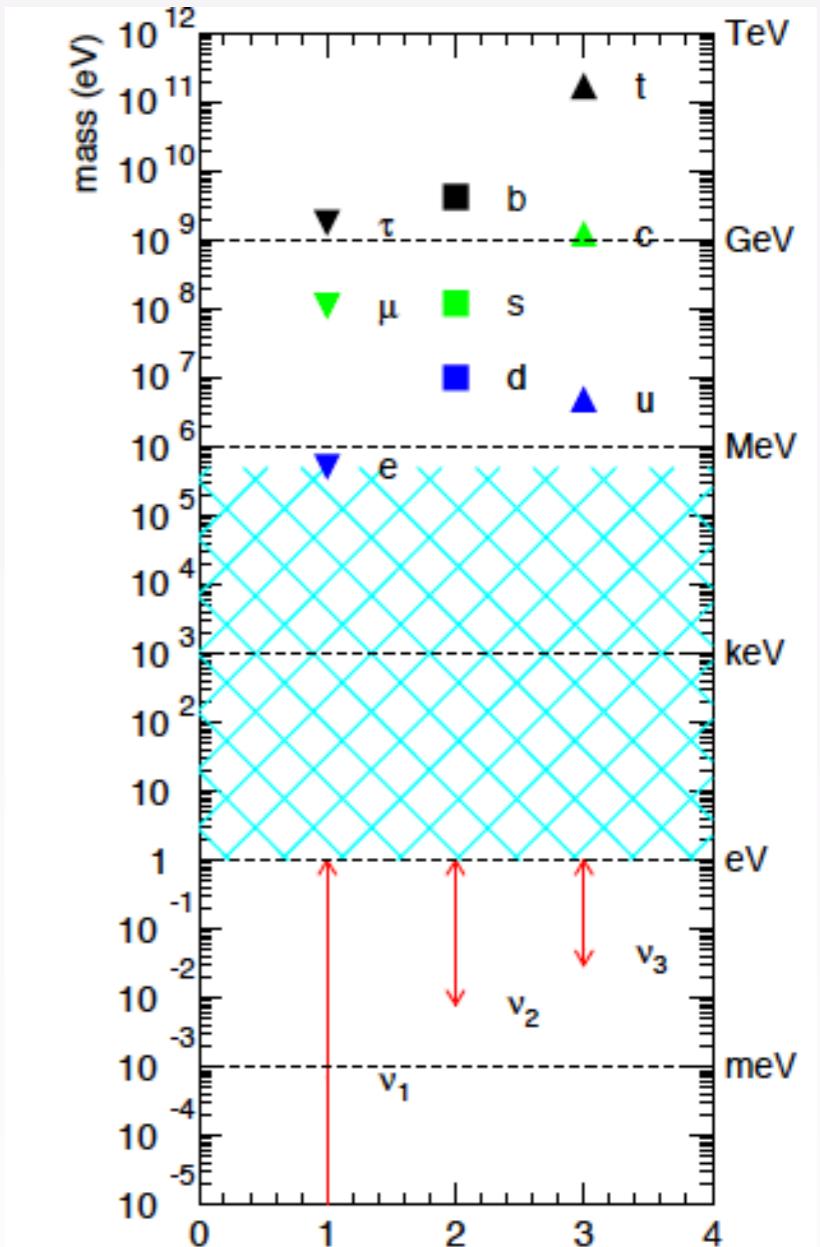
# The Big Picture

- **Neutrinos** provide the only “particle physics evidence” **beyond the SM**
- Remaining **Big Questions:**

- Neutrino mass ordering: **normal** vs **inverted**
- **CP- violation** — Dirac phase
- **Lepton number violation (LNV)**
- **Majorana vs Dirac — mass mechanism**
- CP- violation — Majorana phase
- Neutrino mass ordering: normal vs inverted

addressed by neutrino oscillations

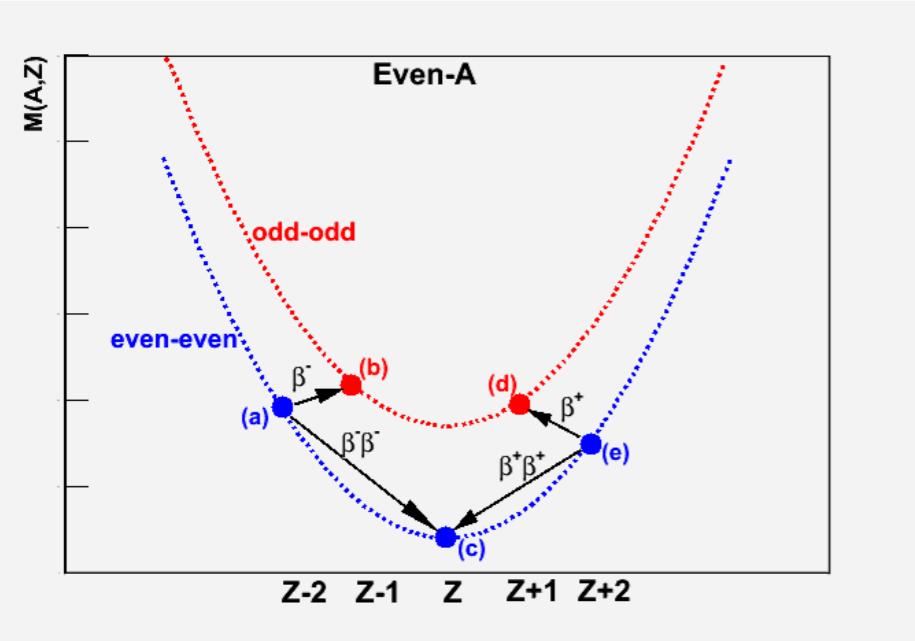
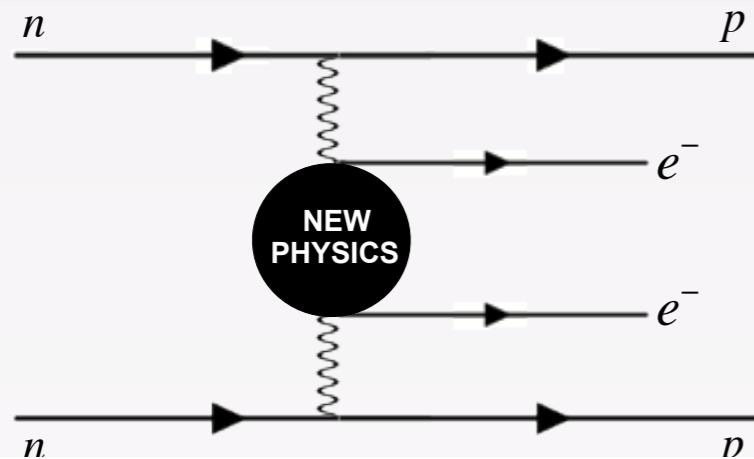
addressed by  $0\nu\beta\beta$



See next talk by S. Petcov

The nuclear process of  $0\nu\beta\beta$  is the **only way** to address **LNV**

# Experimentalist's view on $0\nu\beta\beta$



Over 40 nuclei can undergo  $\beta\beta$ -decay  
Only ~10 experimentally feasible

$\Delta L = 2!$  (a. k. a. Matter Creation)

phase space

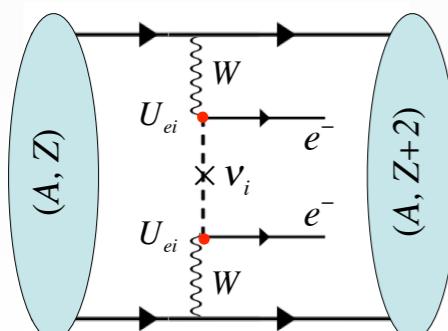
$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}(Q_{\beta\beta}, Z) |M^{0\nu}|^2 \eta^2$$

NME:  
Nasty Nuclear  
Matrix  
Element

LNV parameter

$\eta$  can be due to  $\langle m_\nu \rangle$ , V+A  
Majoron, SUSY, H<sup>-</sup>, leptoquarks,  
or a combination of them

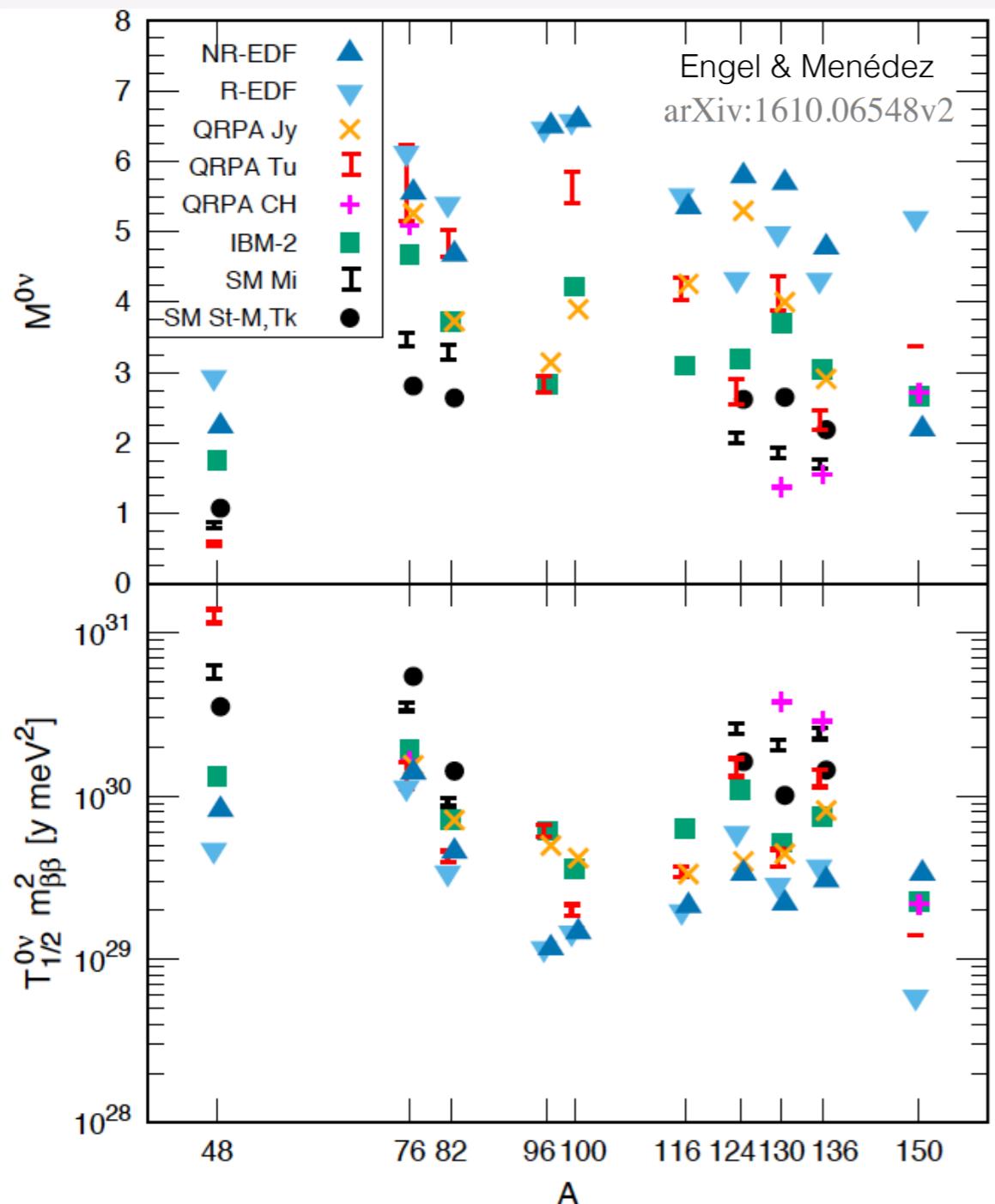
“Popular” scenario - light Majorana mass



Coherent sum over neutrino amplitudes

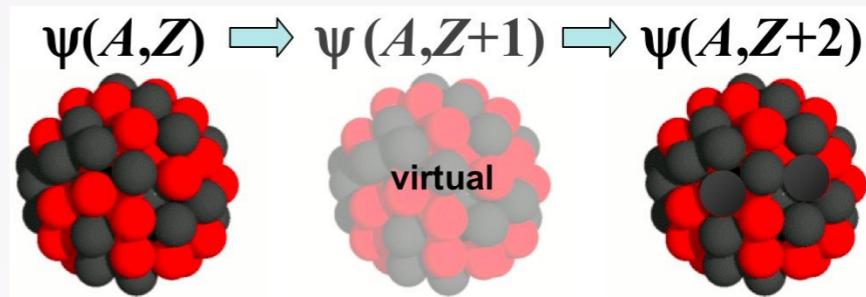
$$\langle m_\nu \rangle = \left| \sum U_{ei}^2 m_i \right| = \left| U_{e1}^2 m_1 + U_{e2}^2 m_2 e^{i\alpha_{21}} + U_{e3}^2 m_3 e^{i\alpha_{31}} \right|$$

# Nuclear Matrix Elements



**Does not affect discovery potential**

$$\Gamma^{0\nu} = G^{0\nu} g_A^4 |M^{0\nu}|^2 \langle m \rangle^2$$



- Significant effort from different groups and different nuclear models
- Question of  $g_A$  quenching under study
- No isotope has clear preference. Choice driven by experimental considerations.
- Experimental input crucial
  - » **2νββ decay**
  - » charge exchange reactions
  - » muon capture

*Talks by S. Stoica #651, M. Murphy #956*

# Standard Model $2\nu\beta\beta$

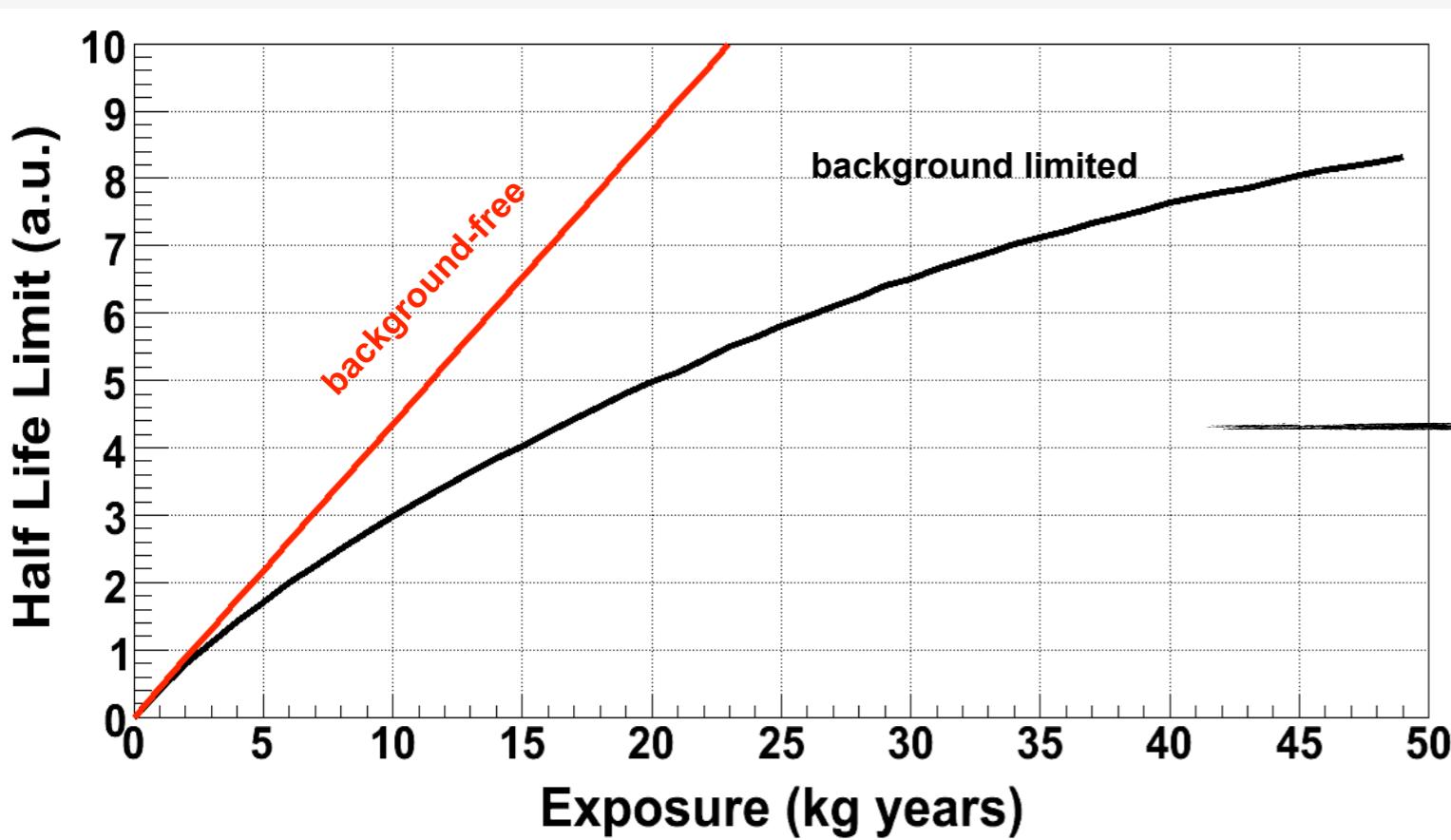
**Observed for 12 nuclei with  $T_{1/2} \sim 10^{18} - 10^{24}$  yr (c.f.  $T_{\text{universe}} \sim 1.4 \times 10^{10}$  yr)**

**Important for**

- (I) **NME calculations. Possible input to  $g_A$  !**
- (II) Ultimate background characterisation
- (III) Sensitive to exotic new physic (Lorentz violation, boson neutrinos,  $G_F$  variation etc)

Isotope	Abundance, %	$Q_{\beta\beta}$ , MeV	$T_{1/2}$ (10 <sup>19</sup> yrs)	Experiment
<sup>48</sup> Ca	0.187	4.274	$6.4 \pm 1.2$	NEMO-3
<sup>76</sup> Ge	7.8	2.039	$192.6 \pm 9.4$	GERDA
<sup>82</sup> Se	9.2	2.996	$9.4 \pm 0.6$	NEMO-3
<sup>96</sup> Zr	2.8	3.348	$2.35 \pm 0.21$	NEMO-3
<sup>100</sup> Mo	9.6	3.035	$0.68 \pm 0.05$	NEMO-3
<sup>116</sup> Cd	7.6	2.809	$2.74 \pm 0.18$	NEMO-3/Aurora
<sup>130</sup> Te	34.08	2.53	$79 \pm 2$	CUORE
<sup>136</sup> Xe	8.9	2.462	$216.5 \pm 6.1$	EXO-200
<sup>150</sup> Nd	5.6	3.367	$0.93 \pm 0.06$	NEMO-3

# Experimental Sensitivity



maximise efficiency & isotope abundance

maximise exposure = mass (isotope)  $\times$  time

$$T_{1/2}^{0\nu} (90\% \text{ C.L.}) = 2.54 \times 10^{26} \text{ y} \left( \frac{\varepsilon \times a}{W} \right) \sqrt{\frac{M \times t}{b \times \Delta E}}$$

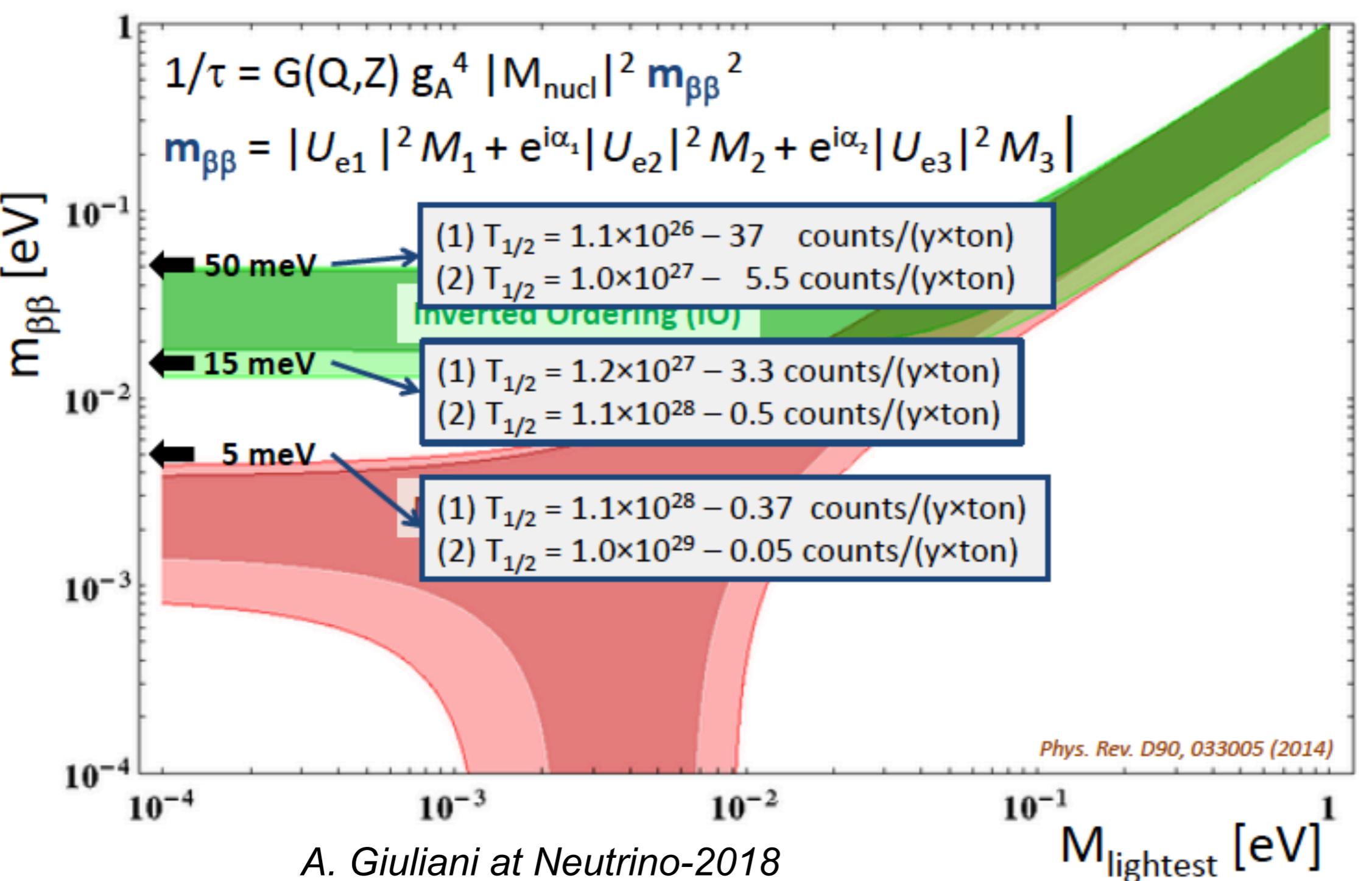
minimise background & energy resolution

$\beta\beta$  is about  
**background suppression!**

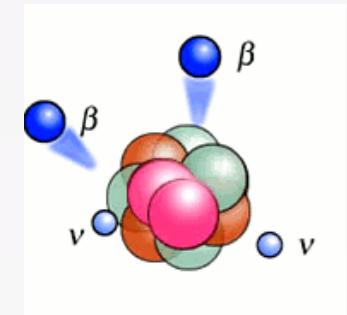
- Backgrounds:**
- Cosmic ray muons (underground is a must)
  - Natural radioactivity  $^{238}\text{U}$ ,  $^{232}\text{Th}$ , etc
  - neutrons
  - $2\nu\beta\beta$

- Take Home Message:**
- Large isotope mass
  - Enrichment opportunities
  - Superior background suppression
  - Good energy resolution

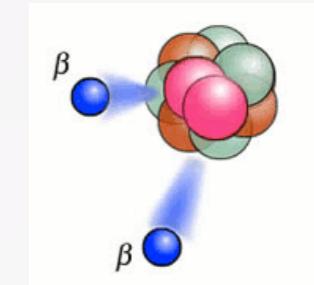
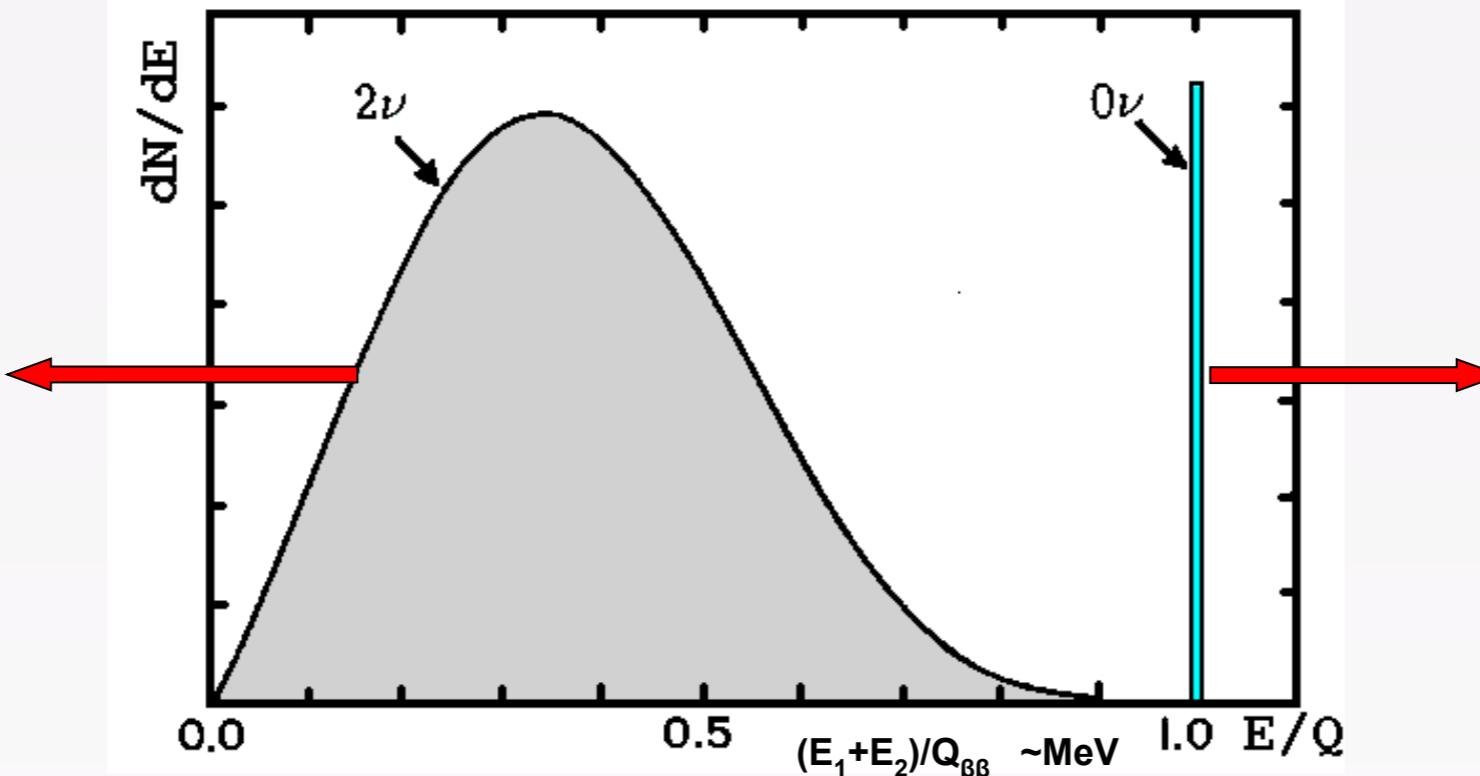
# A tough nut to crack



# Experimental Observables



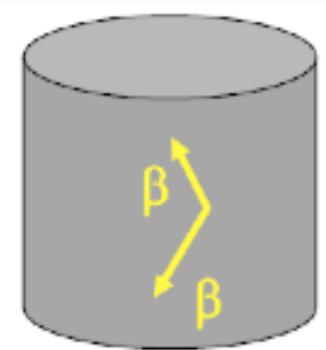
$$(E_1 + E_2) \in [0, Q_{\beta\beta}]$$



$$(E_1 + E_2)/Q_{\beta\beta} \approx 1$$

[ $\otimes$  resolution]

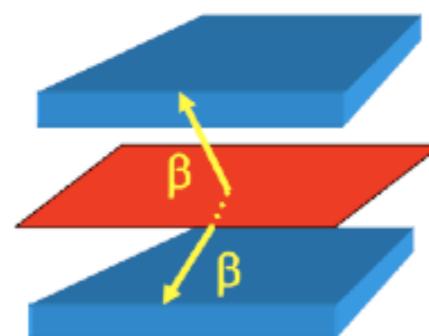
**Homogenous** “source = detector”



Good energy resolution  
Large mass

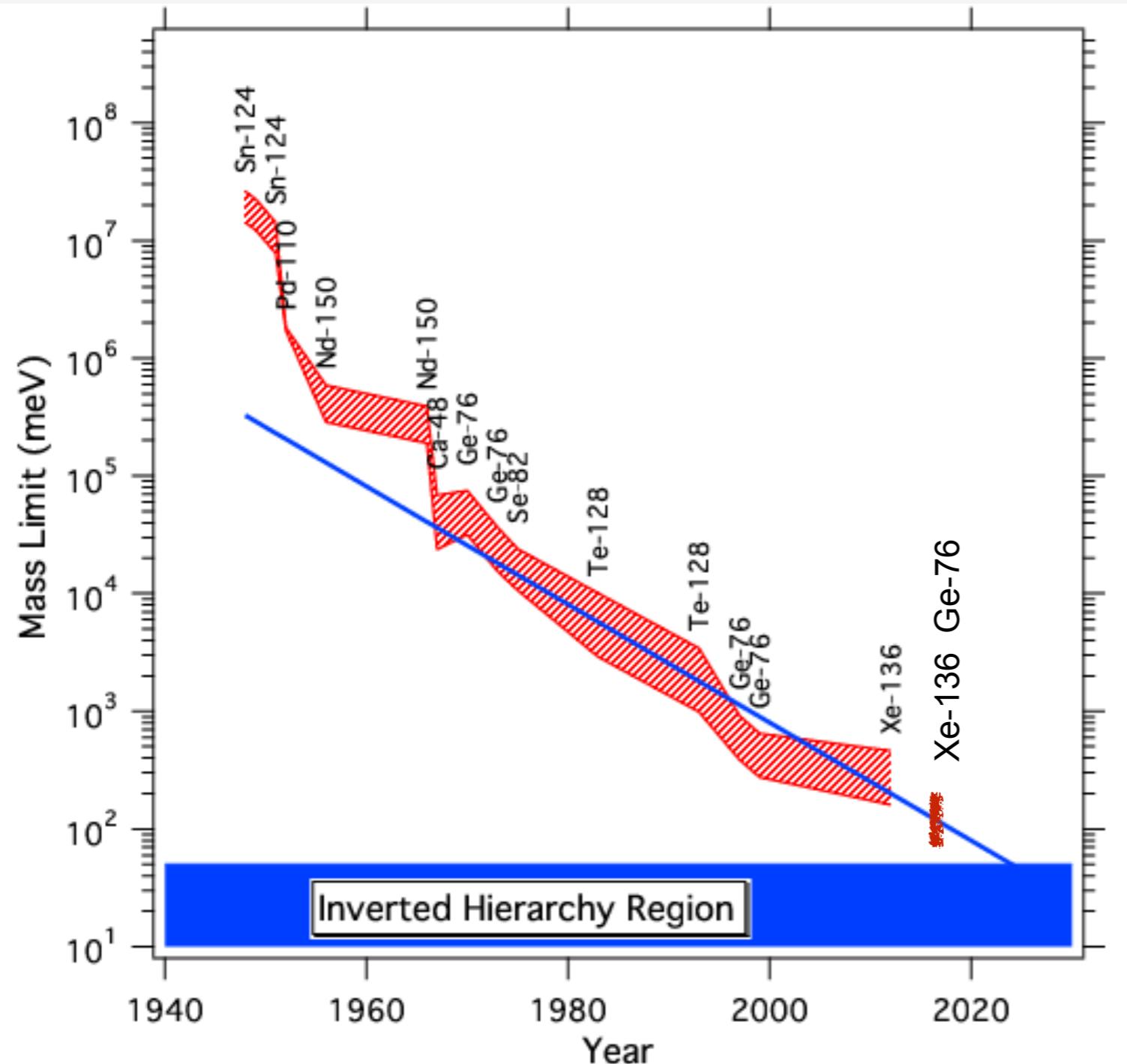
Elements of Both  
**Gaseous Xe TPC**  
**Pixelated CdZnTe**

**Heterogenous** “source  $\neq$  detector”



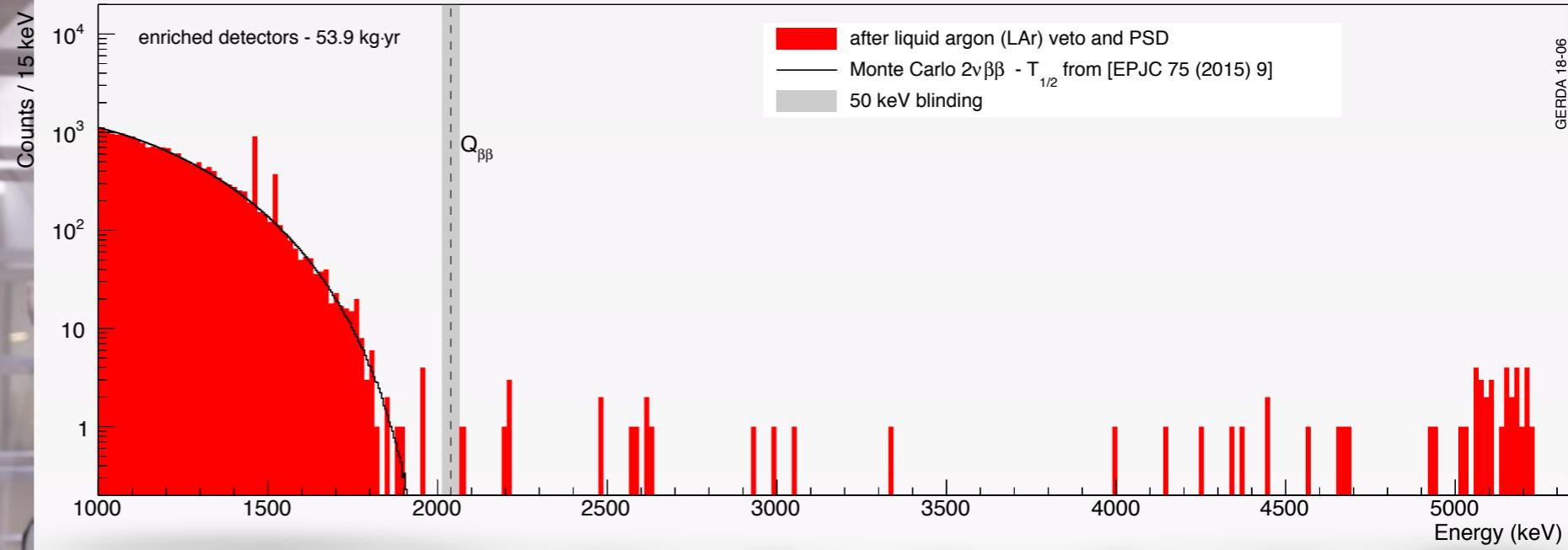
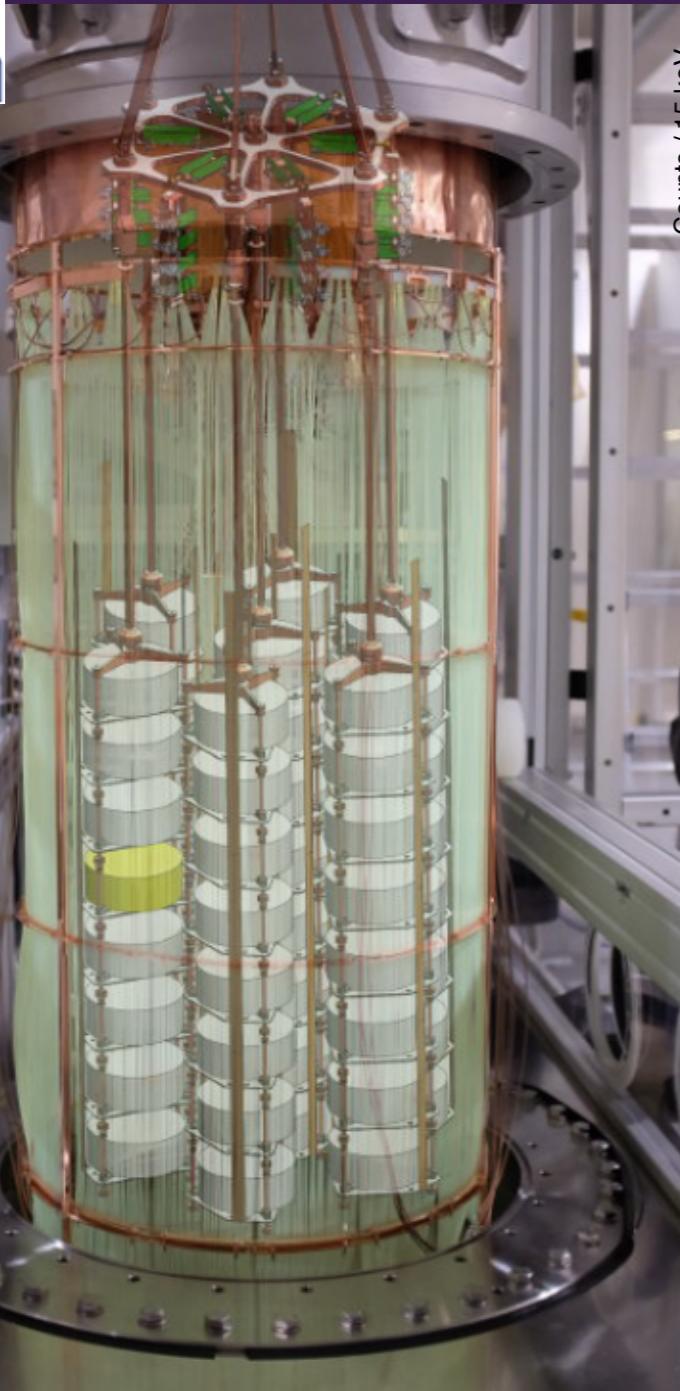
Strong background suppression  
by topology  
Access to underlying physics  
mechanism

# Historical Progress



- Impressive progress due to **dedication, ingenuity and diversity** of the field
- From grams to 100's kgs of isotope
- Innovative methods for background suppression
- Material screening at < ppt level
- Impressive detector capabilities (resolution, particle ID)
- ***Some closing in on “zero background mode”***

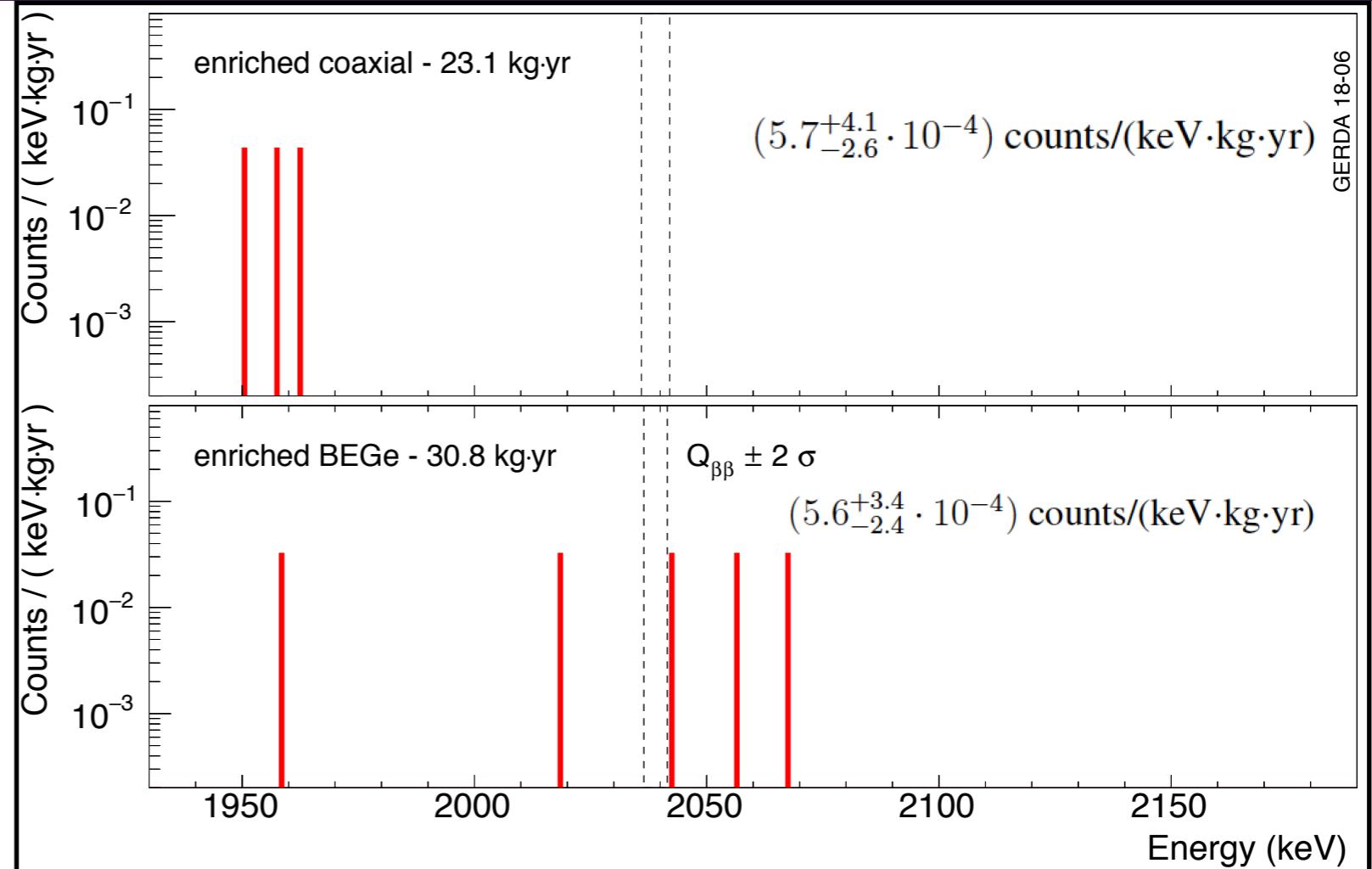
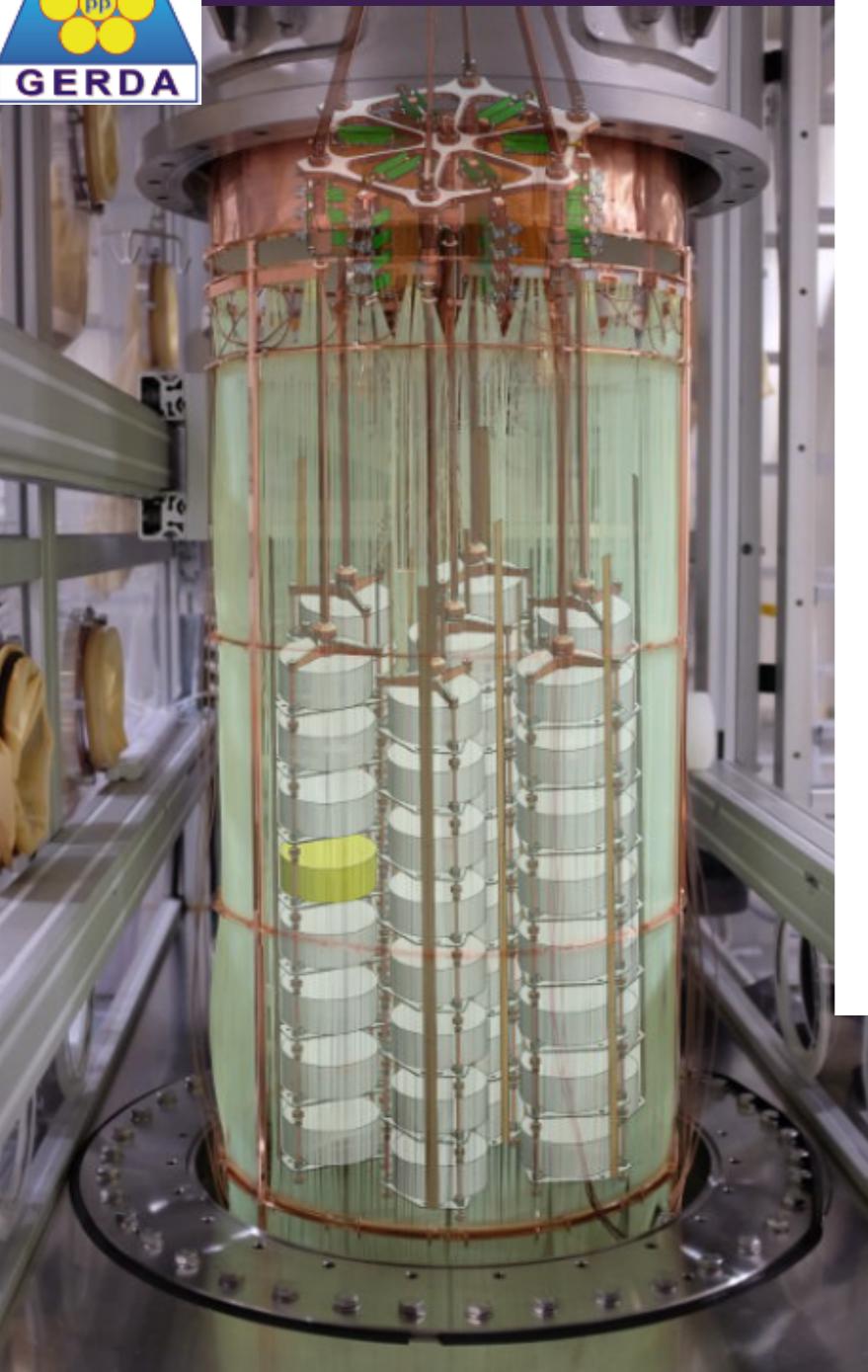
# GERDA ( $^{76}\text{Ge}$ )



*Talk by M. Agostini, #955*



# GERDA ( $^{76}\text{Ge}$ )



**Best fit  $N^{0\nu} = 0$**

$T^{0\nu}_{1/2} > 0.9 \cdot 10^{26} \text{ yr (90\% C.L.)}$

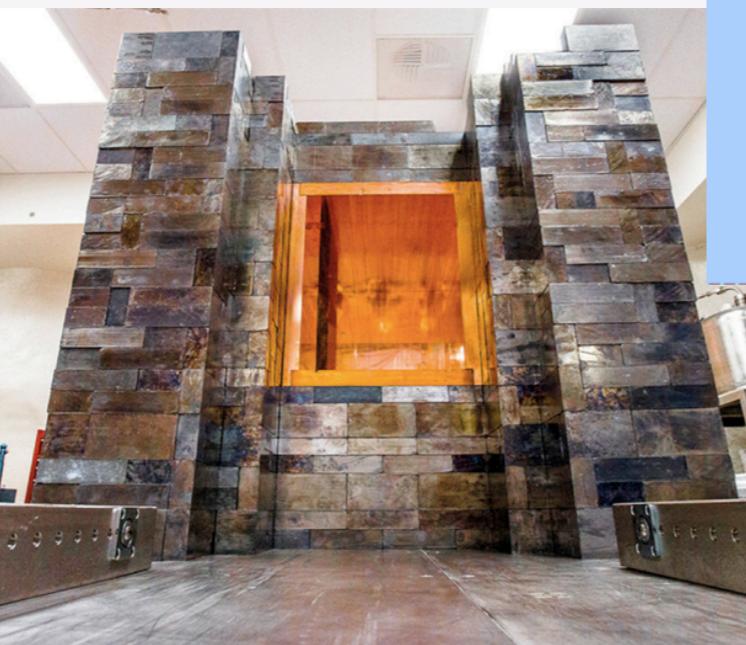
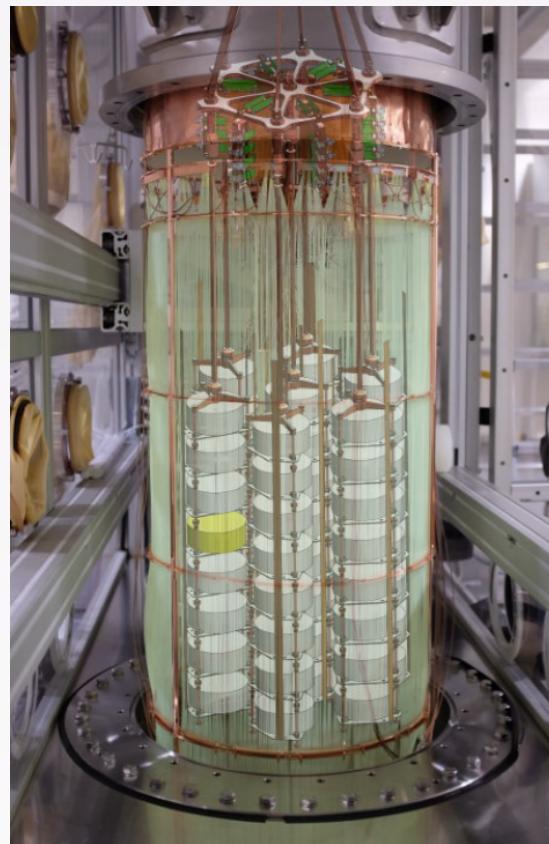
**Median sensitivity (NO Signal)**  $m_{bb} < 0.11 - 0.25 \text{ eV}$

$T^{0\nu}_{1/2} > 1.1 \cdot 10^{26} \text{ yr (90\% C.L.)}$

Just underwent upgrade, will run until end 2019

Talk by M. Agostini, #955

# $^{76}\text{Ge}$ next step — LEGEND



## Phased approach

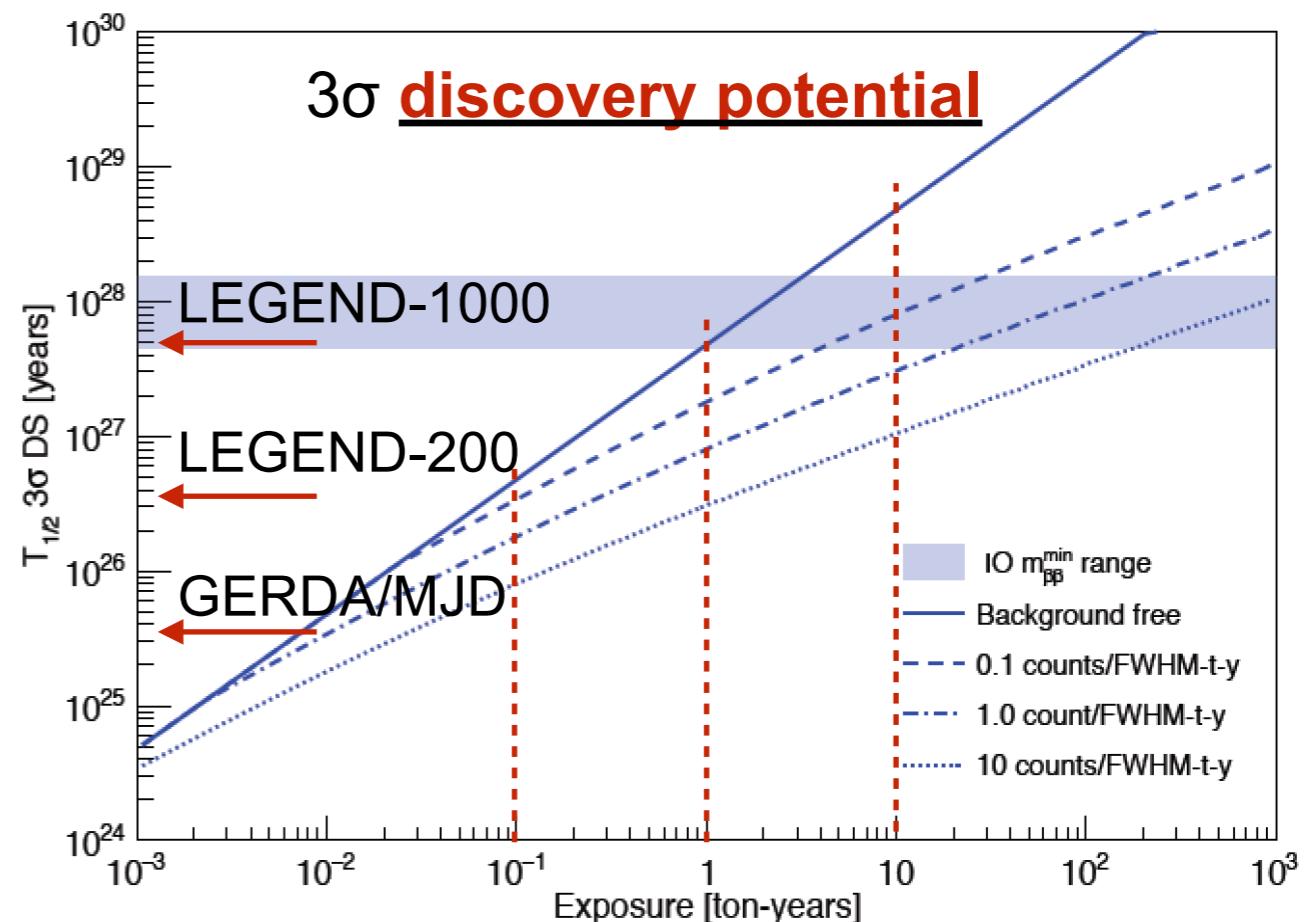
- LEGEND-200 (first phase):
- up to 200 kg of detectors
  - BI  $\sim 0.6$  cts/(FWHM t yr)
  - use existing GERDA infrastructure at LNGS
  - design exposure: 1 t yr
  - Sensitivity  $10^{27}$  yr
  - Isotope procurement ongoing
  - Start in 2021

*Talk by J. Myslik, #810,823*

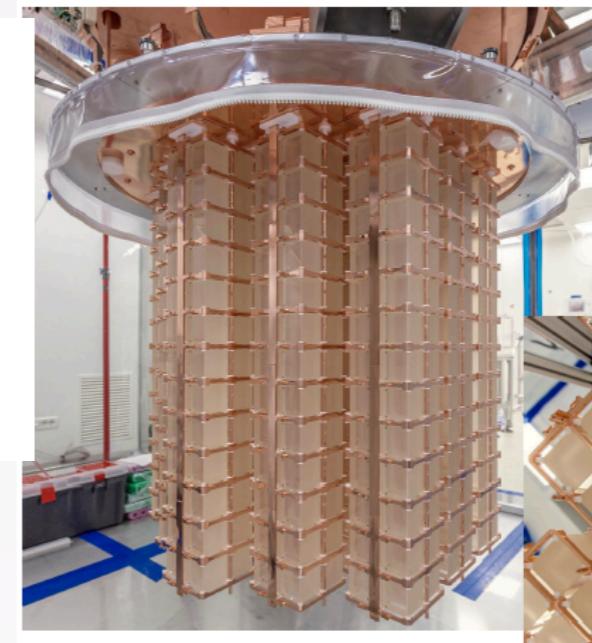
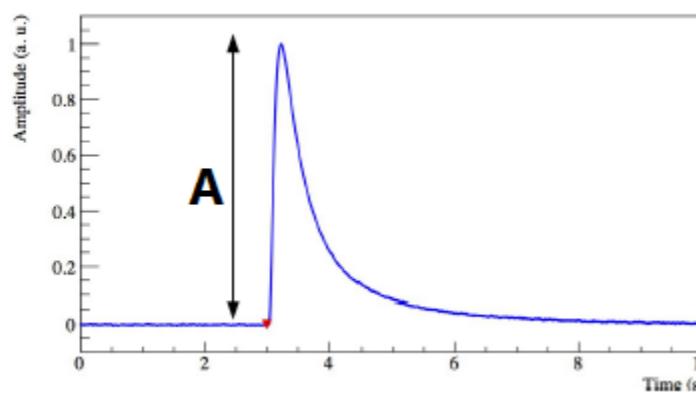
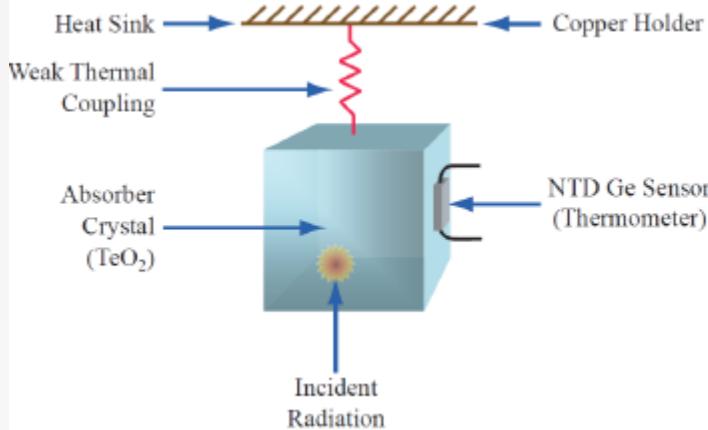
- LEGEND-1000 (second phase):
- 1000 kg of detectors (deployed in stages)
  - BI  $< 0.1$  cts/(FWHM t yr)
  - Location tbd
  - Design exposure 12 t yr
  - $1.2 \times 10^{28}$  yr



Merging the best of GERDA and Majorana:  
E.g. LAr veto of GERDA and ultra-pure copper/electronics of Majorana



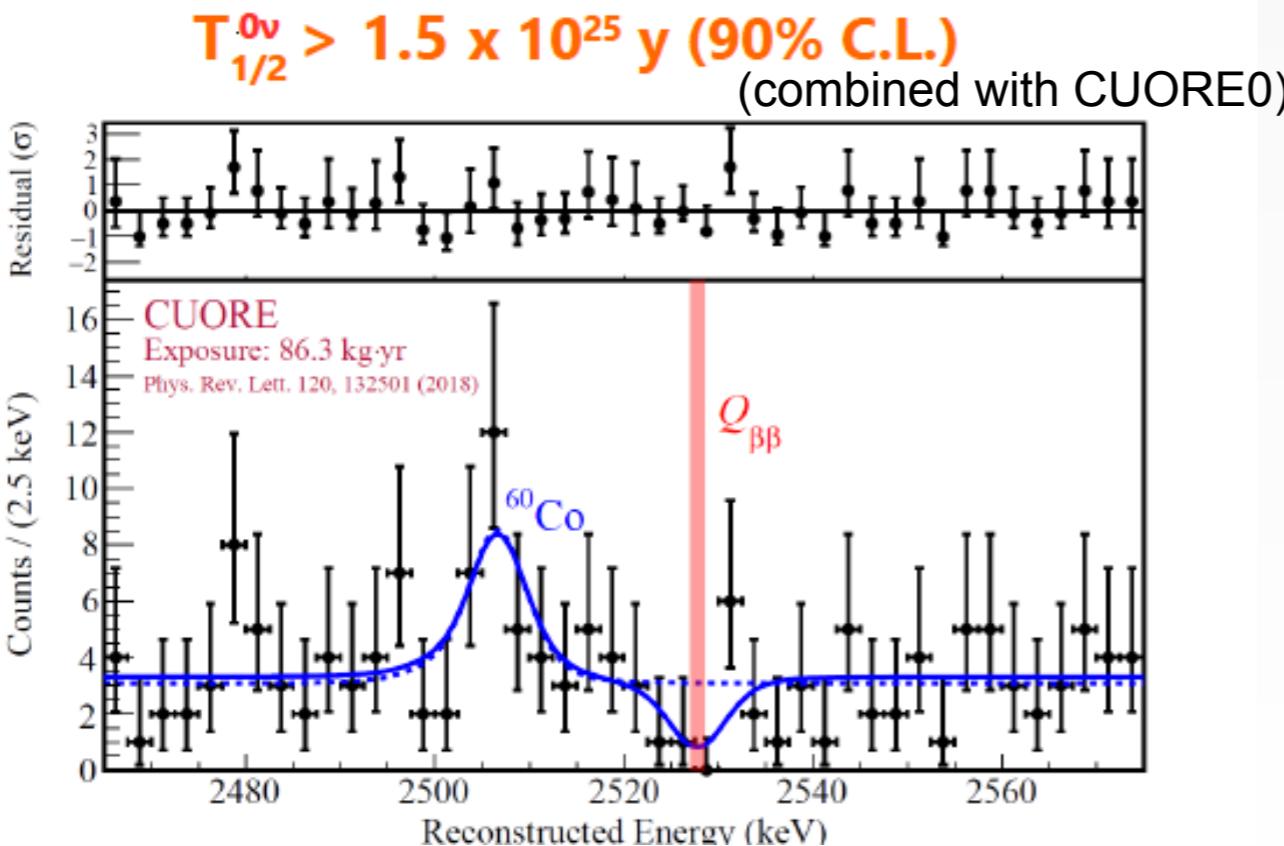
# Bolometers, CUORE



The 19 towers were completely installed in August 2016 in a specially constructed, radon-free clean room

- CUORE with  $^{130}\text{Te}$  (*natural Te due to high abundance*)
- 988  $\text{TeO}_2$   $5 \times 5 \times 5 \text{ cm}^3$  crystals at  $T < 10\text{mK}$
- $^{130}\text{Te}$  mass: 206 kg
- 86.3 kg.yr accumulated in summer 2017
- b.i. =  $(1.4 \pm 0.2) \times 10^{-2}$  counts/(keV.kg.yr)

See talk by S. Pozzi, #98



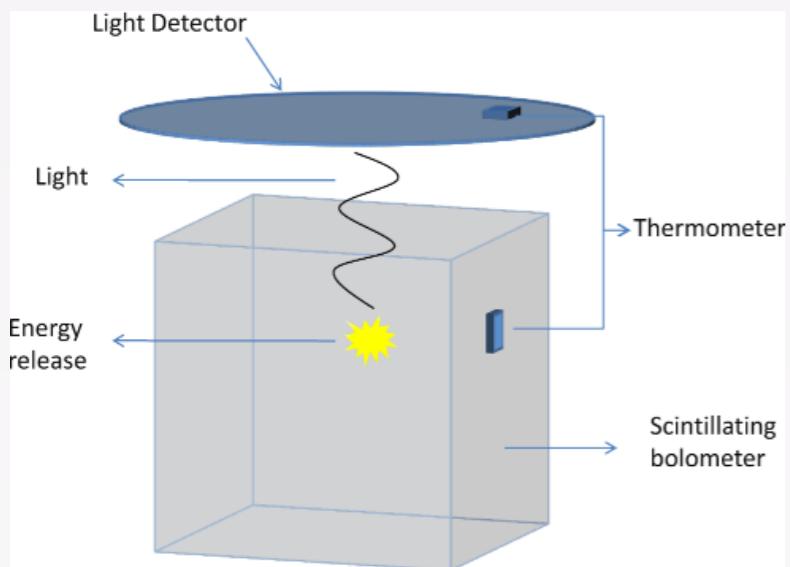
Restarted data taking in May'18  
 $5 \text{ yr of data } T_{1/2}(0\nu) > 9 \times 10^{25} \text{ yr}$

$m_{bb} < 50 - 190 \text{ meV}$

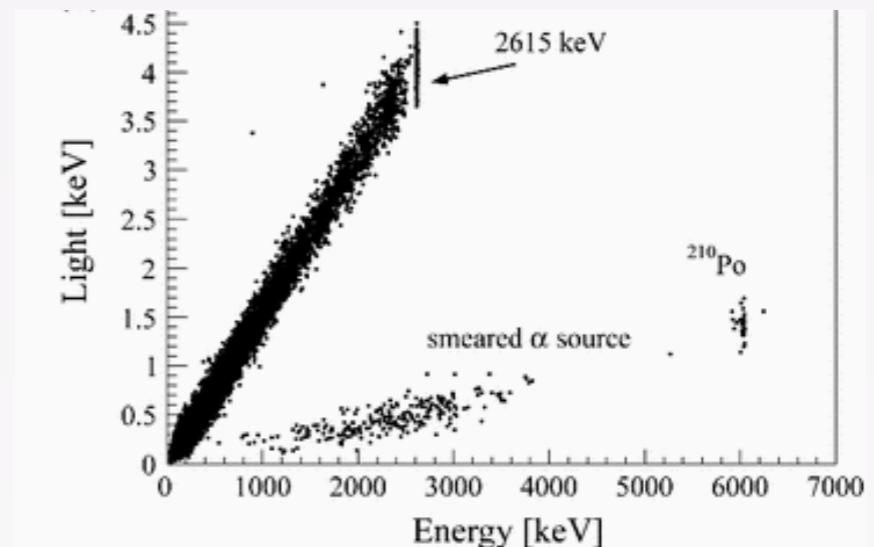
Limitation: background due to surface contamination

scintillating  
bolometers

# Scintillating bolometers



particle  
discrimination



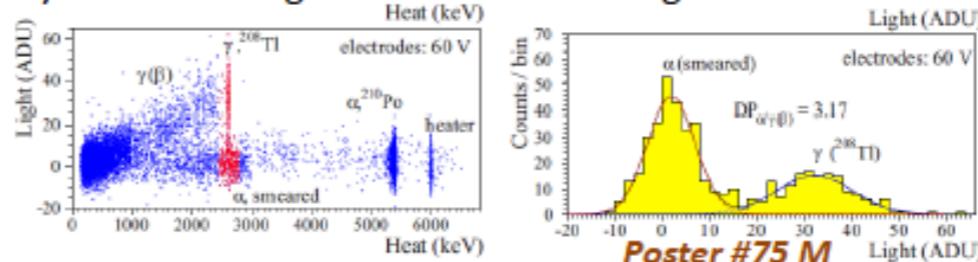
$^{130}\text{TeO}_2 + \text{Cherenkov light}$

Vibrant R&D activities  
(several technologies: NTDs,  
MKIDs, TESs)

**Poster #108 M**

**LSM – France**  $Q=2527 \text{ keV}$

Full  $\alpha/\beta$  separation already achieved with a CUORE-size crystal and a Neganov-Luke assisted light detector – LSM



A. Giuliani at  
Neutrino'18

See talk by  
L. Cardani,  
#932



**CUPID-0 – Zn<sup>82</sup>Se**  $Q=2998 \text{ keV}$

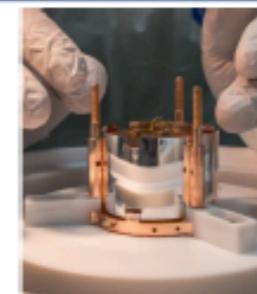
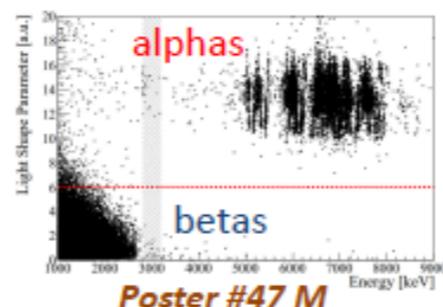
First running demonstrator - LNGS

24 crystals – 5.28 kg <sup>82</sup>Se

Best limit on <sup>82</sup>Se:  $T_{1/2} > 2.4 \times 10^{24} \text{ y}$

Energy resolution:  $\sim 23 \text{ keV FWHM}$

Required improvements in crystal quality and radiopurity



**LNGS – Italy**

**CUPID-Mo – Li<sub>2</sub><sup>100</sup>MoO<sub>4</sub>**  $Q=3034 \text{ keV}$

Phase-I 20 crystals – 2.34 kg <sup>100</sup>Mo

currently in commissioning

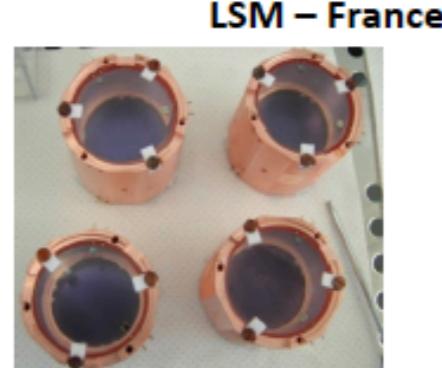
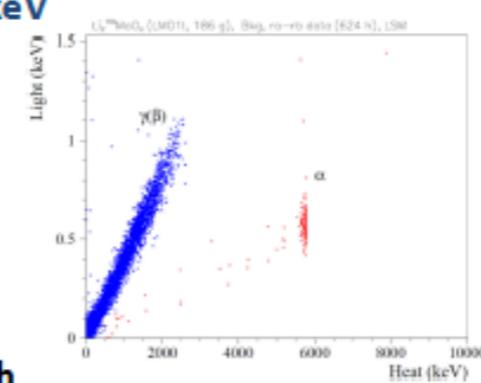
Phase-II

additional 26 crystals – 3.94 kg <sup>100</sup>Mo  
data taking from 2019 – LNGS

Energy resolution:  $\sim 5 \text{ keV FWHM}$

Radiopure high-quality crystals

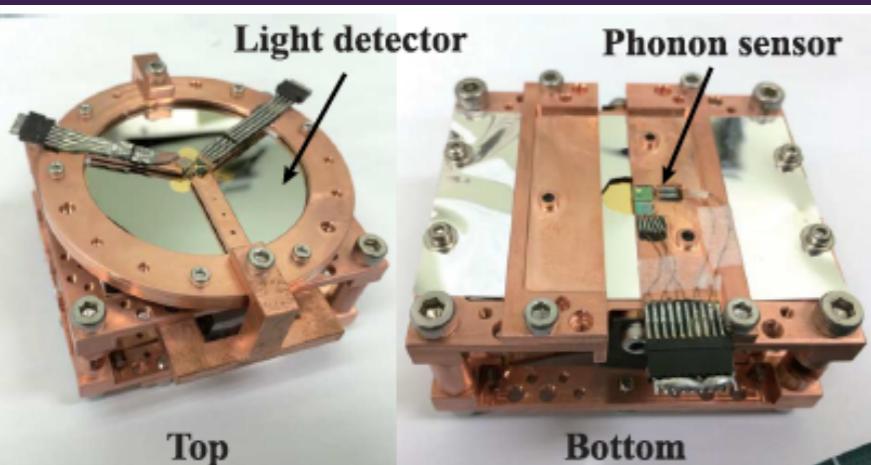
Negligible <sup>100</sup>Mo losses in crystal growth



**LSM – France**

**Poster #76 M**

# Scintillating bolometers

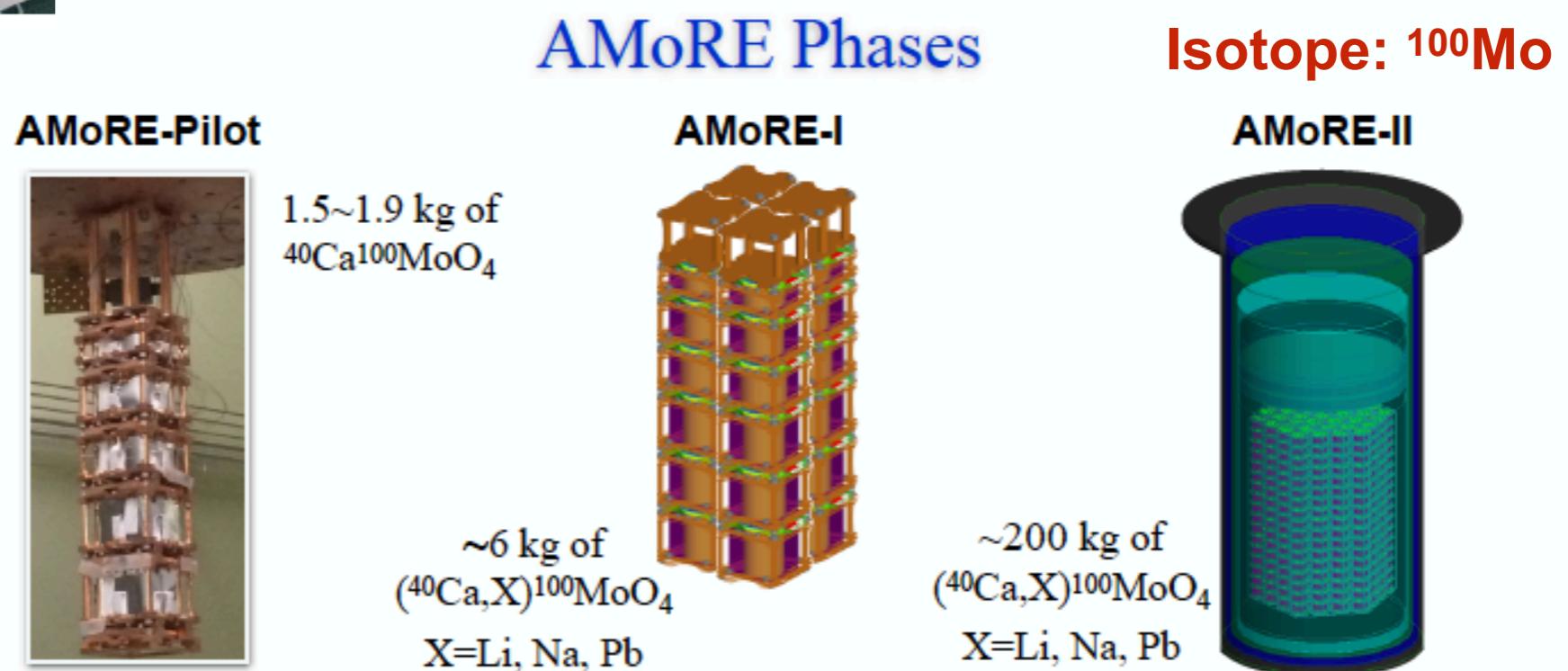


Top

Bottom

MMC — Metallic Magnetic Calorimeter  
faster response → removes pileup from  $2\nu$ -decay  
Initial phase in YangYang Underground Lab in Korea

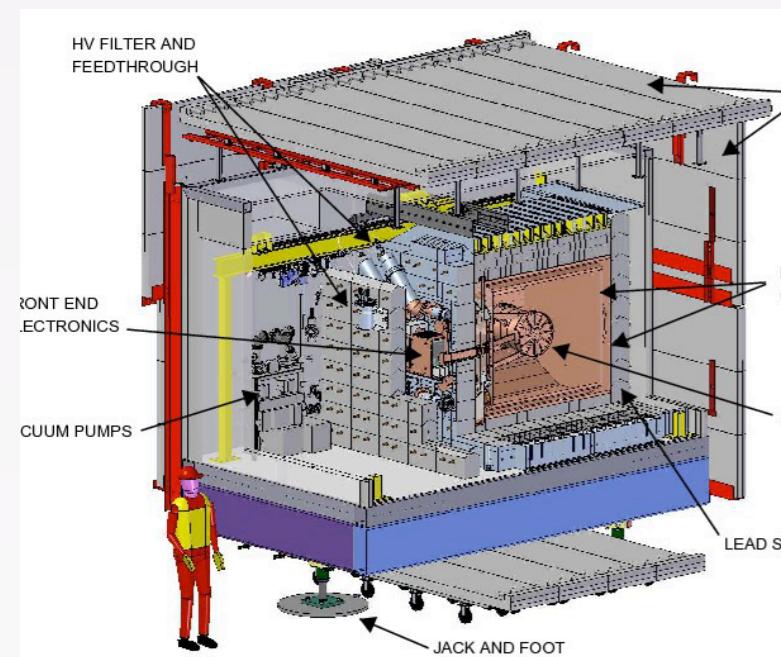
See talk by YS Yoon #677,  
I. Kim, #674  
and posters: #846, 903, 908,  
893, 916, 900, 630



	AMoRE-pilot	AMoRE-I	AMoRE-II
<b>Mass</b>	1.9 kg	6 kg	200 kg
<b>Background goal (keV kg year)<math>^{-1}</math></b>	$\sim 10^{-2}$	$\sim 10^{-3}$	$\sim 10^{-4}$
<b>Expected <math>T_{1/2}</math> sensitivity (years)</b>	$\sim 1 \times 10^{24}$	$8.2 \times 10^{24}$	$8.2 \times 10^{26}$
<b>Expected <math>\langle m_{\beta\beta} \rangle</math> (meV)</b>	380-719	130-250	13-25
<b>Laboratory</b>	Y2L	Y2L	New Lab.
<b>Schedule</b>	2015-2018	2018-2020	2021-

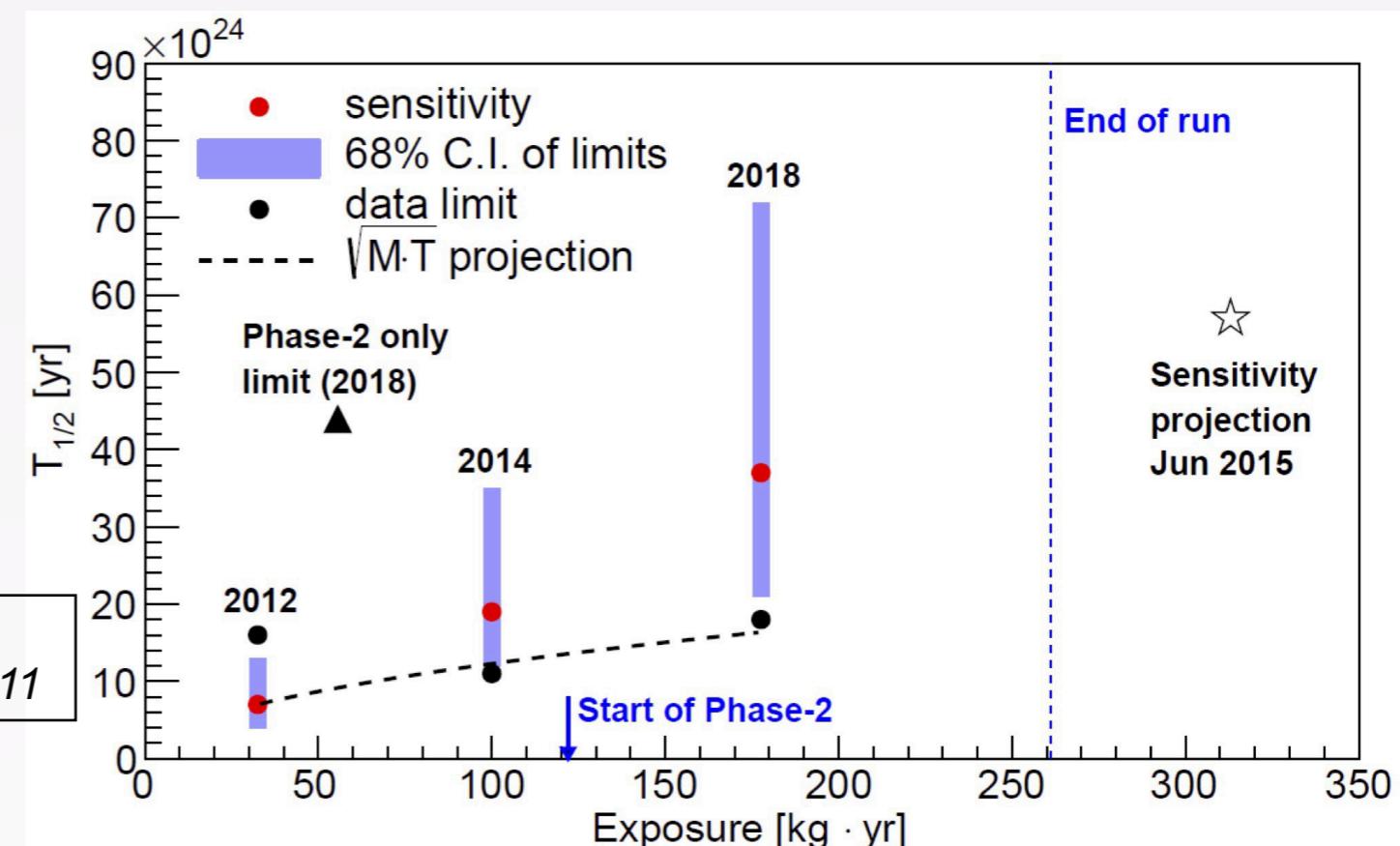
# EXO-200 and nEXO

## EXO-200 at WIPP

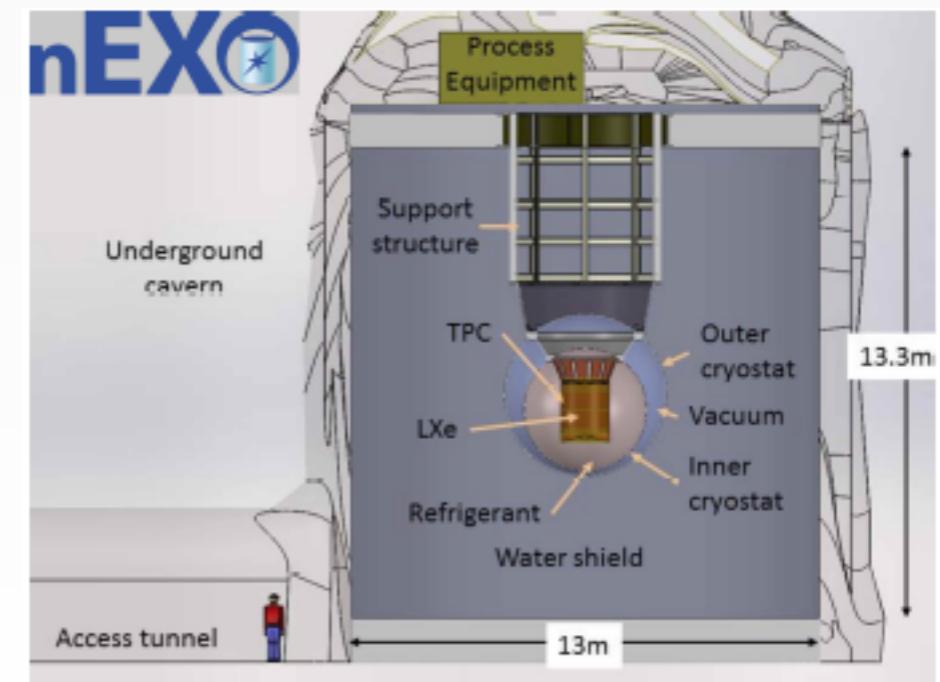
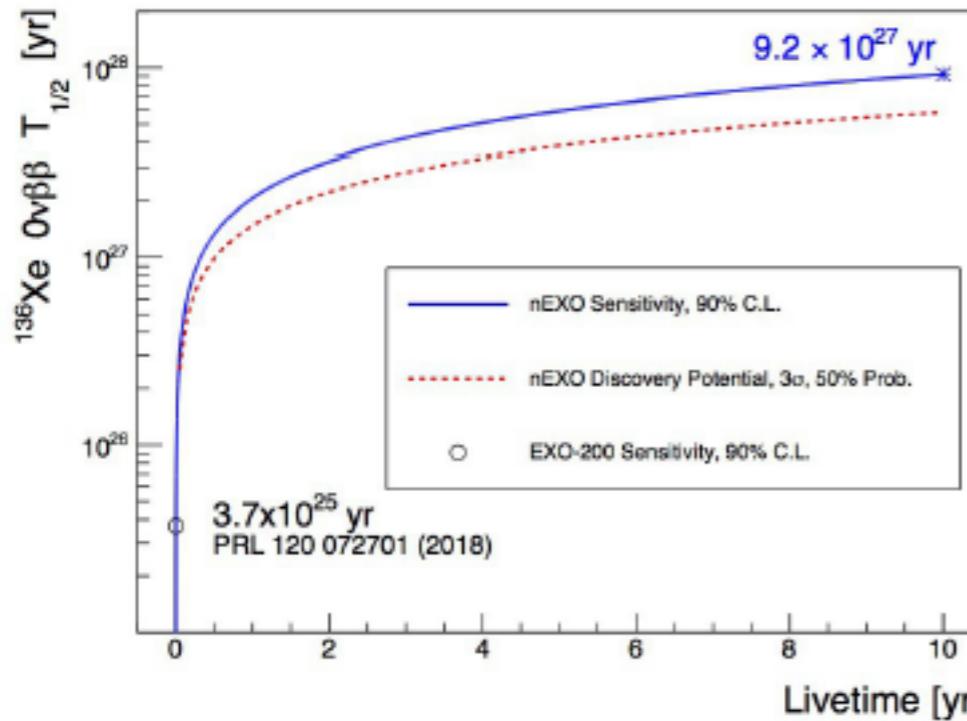


- $^{136}\text{Xe} \rightarrow ^{136}\text{Ba}^{++} + 2\text{e}^{-}$ , Q-value: 2.458 MeV
- Active liquid Xe mass  $\sim 110$  kg

See talk by  
M. Tarka, #911

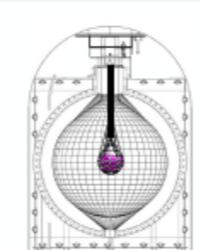
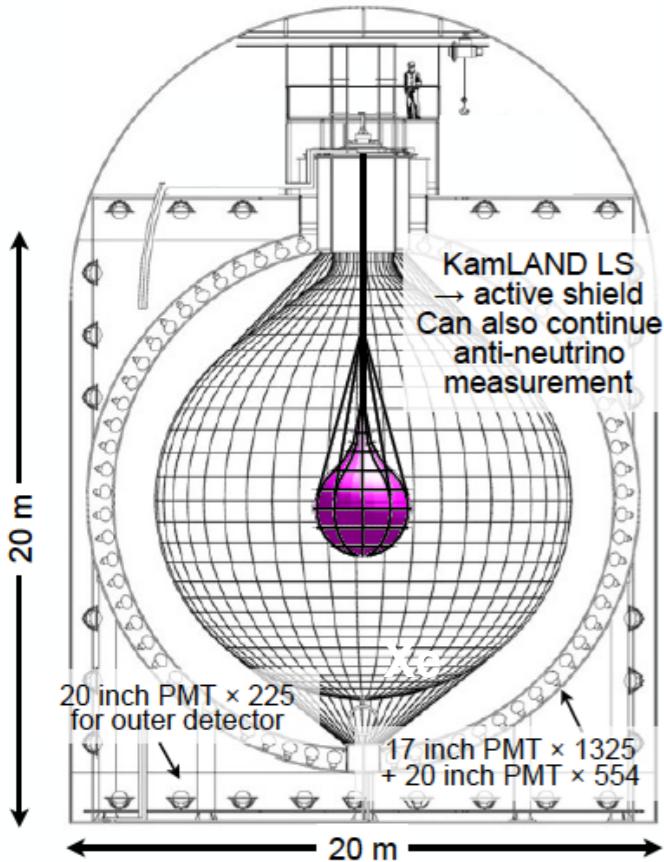


## Future: nEXO at SNOLAB

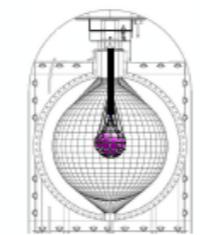


# Large Liquid Scintillator Detectors

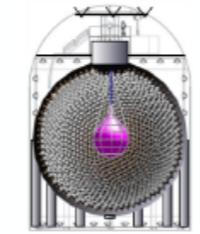
Dissolve  $\beta\beta$  isotope in large volume of very clean liquid scintillator



**Past**  
**KamLAND-Zen 400**  
320-380 kg of Xenon  
Data taking 2011 ~ 2015



**Present**  
**KamLAND-Zen 800**  
~750 kg of Xenon  
DAQ to start in this year



**Future**  
**KamLAND2-Zen**  
~1 ton of  $^{136}\text{Xe}$   
Better energy resolution



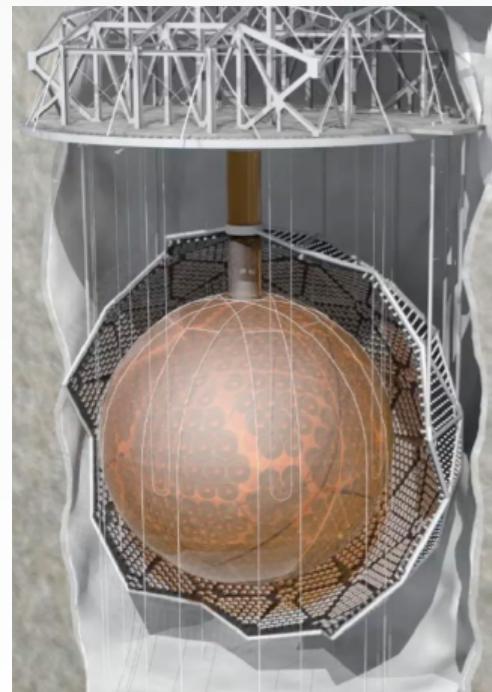
**best constrain**  
 $m_{bb} < 61\text{-}165 \text{ meV}$



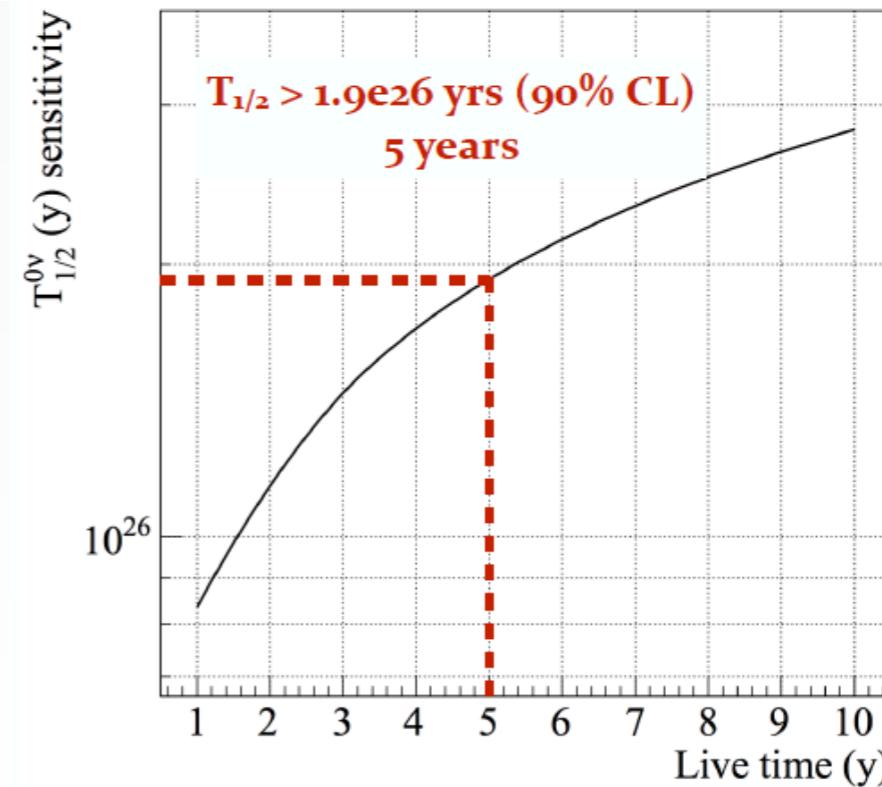
2018  
cleaner balloon with Xe



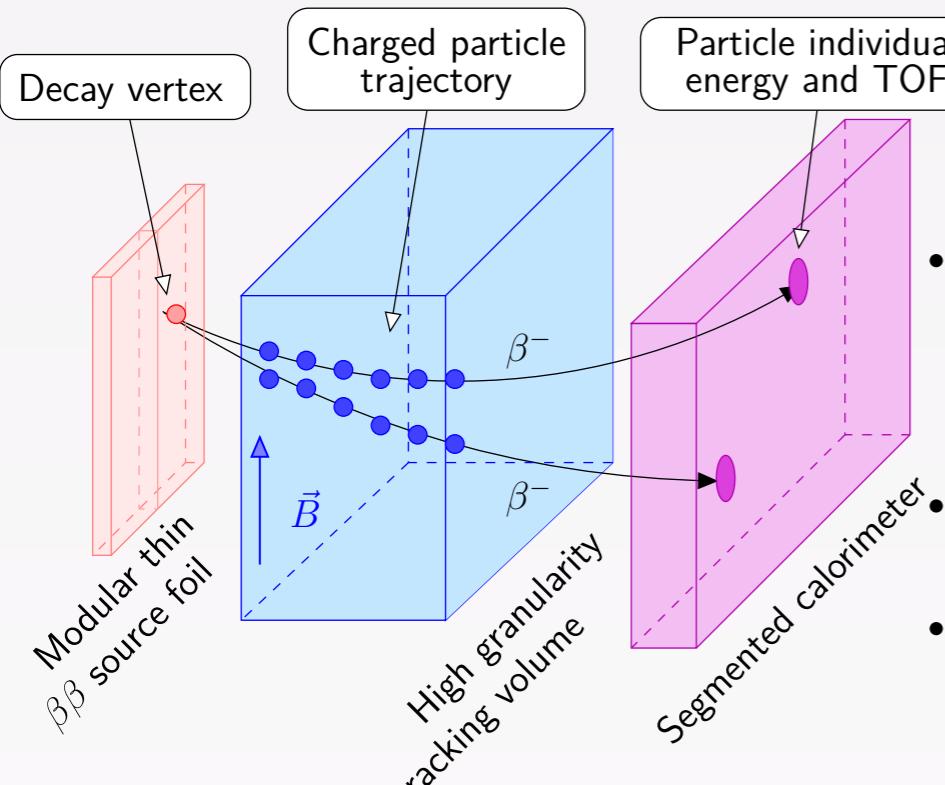
$\sigma(2.6\text{MeV})=4\% \rightarrow < 2.5\%$   
Target  $\langle m_{bb} \rangle \sim 20\text{meV}$  in 5 yrs



- SNO+. Repurposing SNO- detector
- Liquid scintillator fill Jul'18
- Loading Te (natural!) next spring
- Large mass, 0.5% loading  
~ 1t of  $^{130}\text{Te}$
- But fiducialisation needed

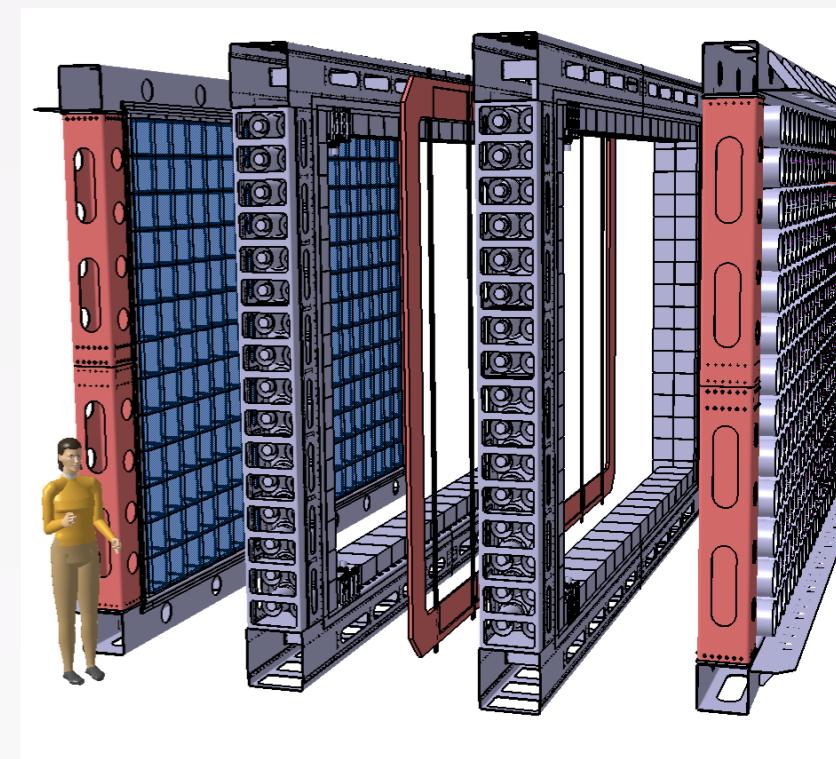


# Topological Reconstruction



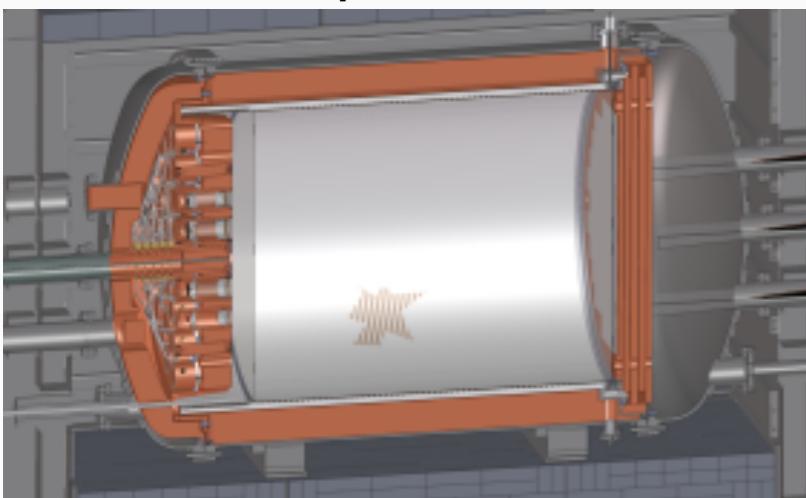
NEMO3 → SuperNEMO

- In the event of a discovery: probe underlying mechanism through angular correlations and individual  $E_e$  distributions
- Smoking gun and multiple isotopes
- Critical input to NME calculations via precise  $2\nu$  measurements

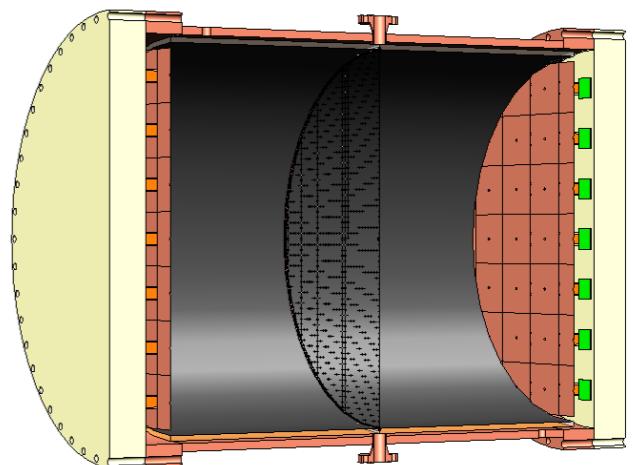
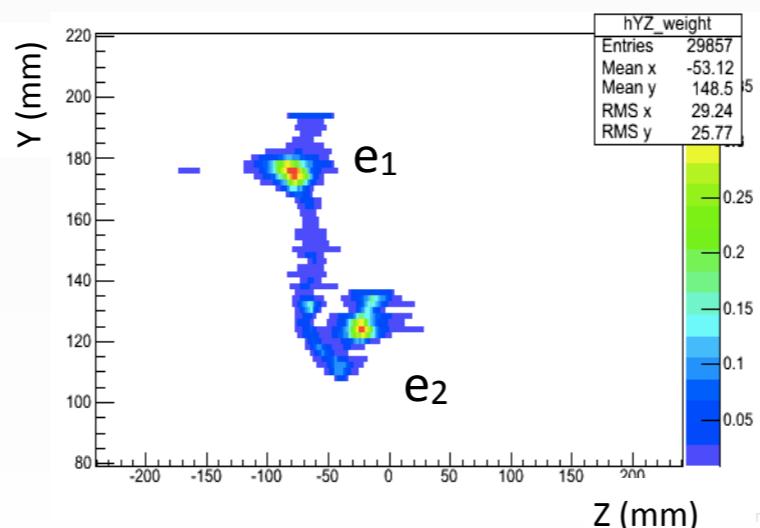


## $^{136}\text{Xe}$ high-pressure (10-15 bar) TPC: NEXT and PandaX

NEXT: Optical TPC



PandaX: Readout with Micromegas

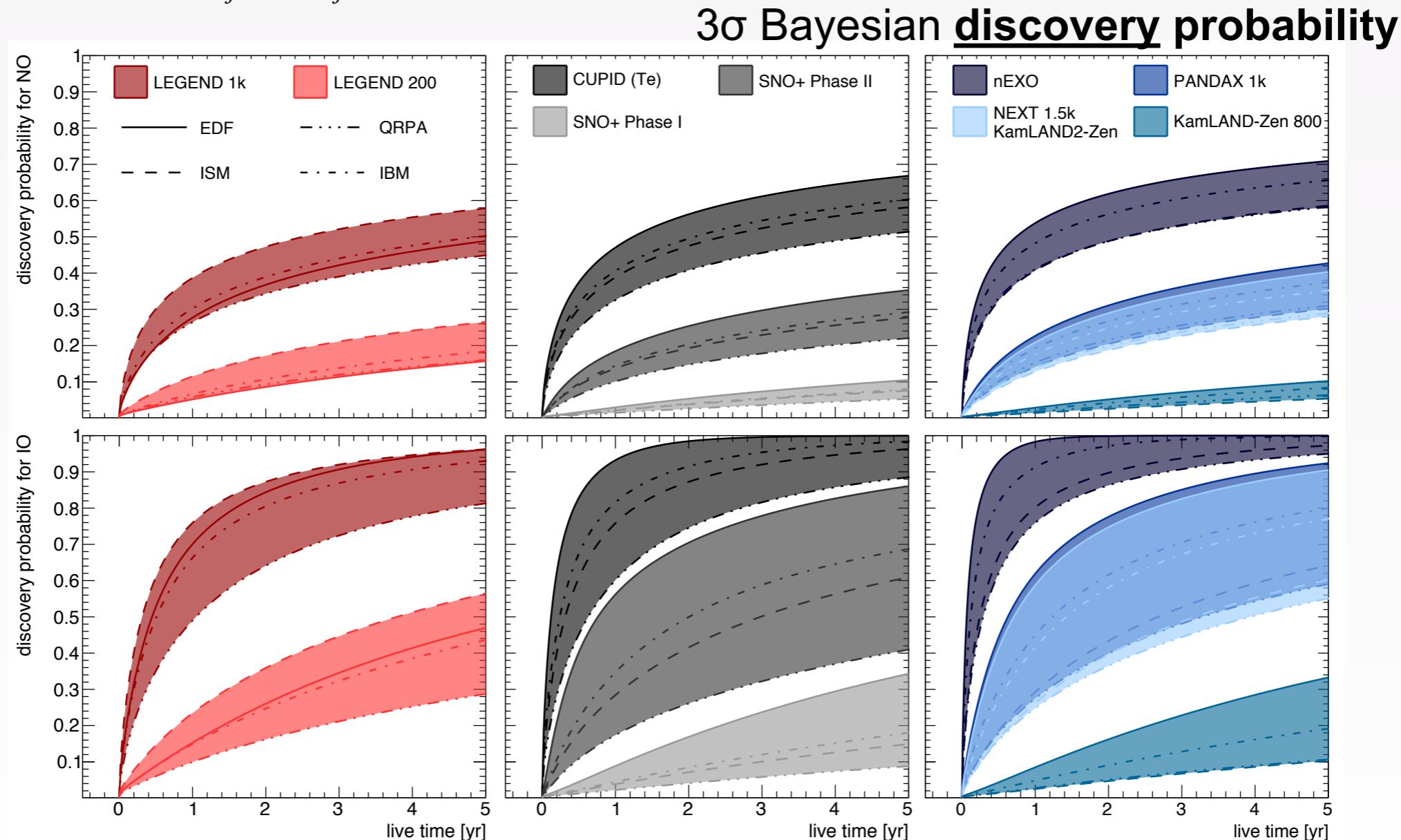


# Outlook into Future Sensitivity

Global Bayesian analysis including neutrino oscillations,  ${}^3\text{H}$   $\beta$ -decay,  $0\nu\beta\beta$  decay, cosmology

Scale-invariant priors:  $\Sigma = m_1 + m_2 + m_3$ ;  $\Delta m_{ij}^2 \rightarrow$  logarithmic

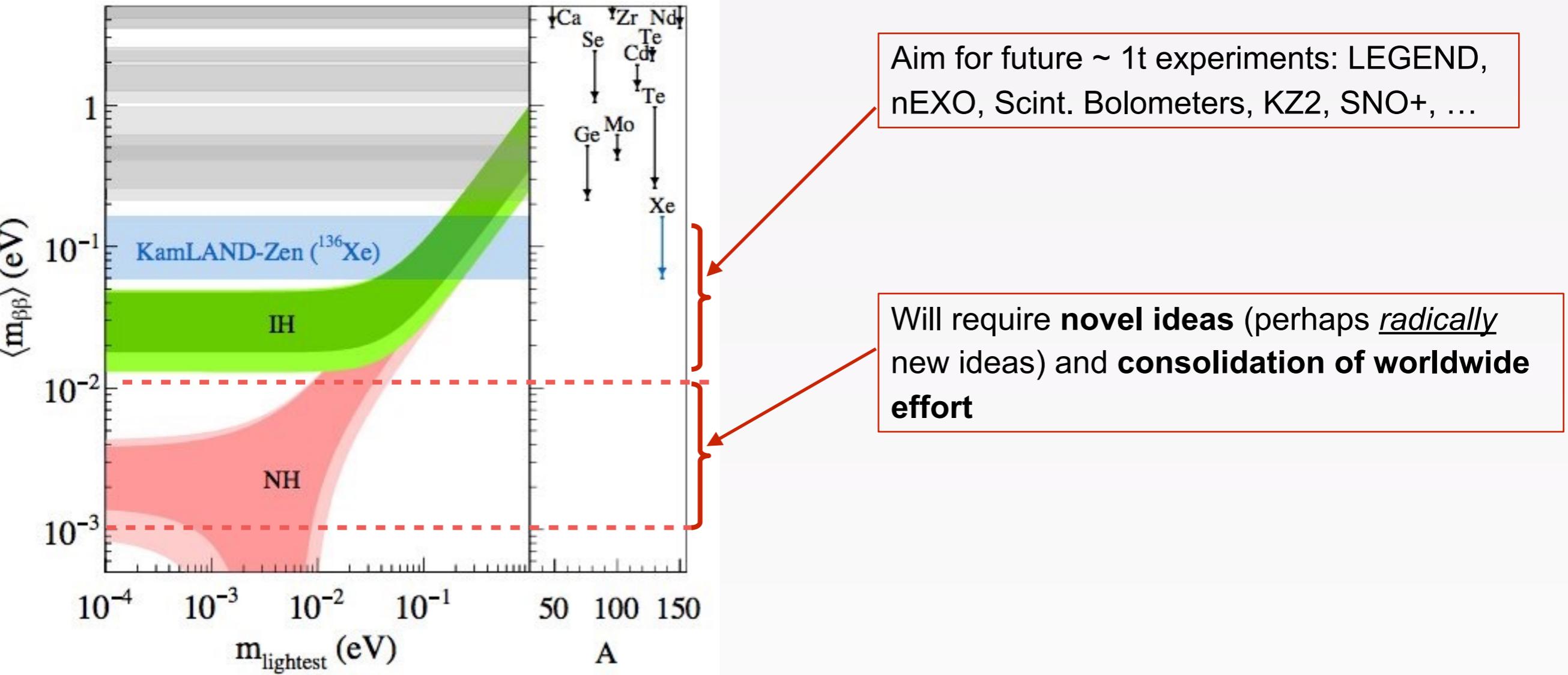
$\theta_{ij}, \delta, \alpha_{ij} \rightarrow$  flat



Phys. Rev. D 96, 053001 (2017)

**Impressive discovery potential of the next generation experiments**

# Concluding Remarks on $0\nu\beta\beta$



- **$0\nu\beta\beta$**  is a quest for **Lepton Number Violation**. The plot above is a good metric but should be understood in a wider context
- Observation of  $0\nu\beta\beta$  will mean neutrino are Majorana but  $\langle m_{bb} \rangle$  may well not be main driving force behind  $0\nu\beta\beta$ .
- Normal Ordering, if confirmed, cannot be a reason to stop searching for **LNV**

# Epilogue

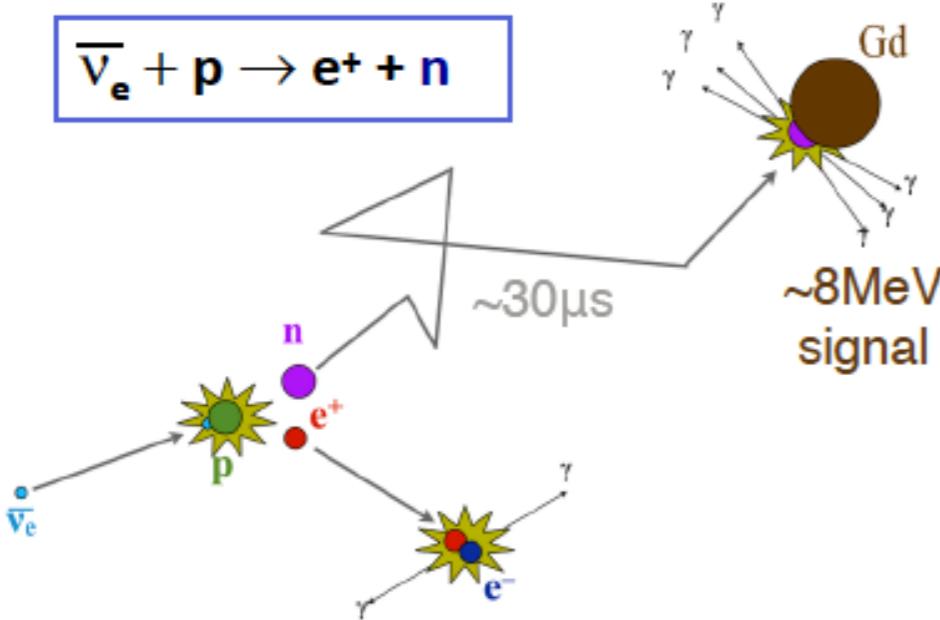
- Non-Accelerator Neutrino Physics has made striking progress, even since ICHEP-2016
  - First Tritium events in KATRIN
  - Ideas to reach the lower bound on  $m_\nu$  with  $\beta$ -decay experiments
  - Zero-background 100 kg scale  $0\nu\beta\beta$  experiments look feasible
  - $0\nu\beta\beta$  community ready to move to ton-scale experiments with reliable extrapolations
  - First observation of Coherent Neutrino Scattering opens new physics and technological opportunities
  - Neutrinos become a tool to understand nuclear reactors
  - ....
- Impossible to do justice to such a vibrant field in 25 min
- Apologies for having to omit many brilliant ideas and experiments

Thank You! 고맙습니다

# BACKUP

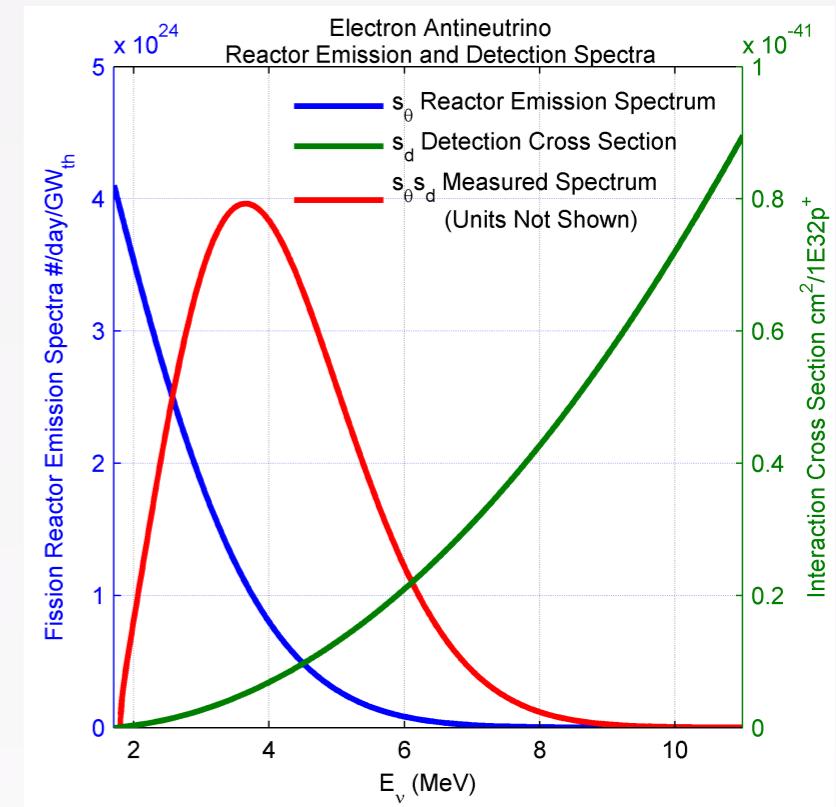
# Detection of Reactor Anti-Neutrinos

## Inverse Beta Decay (IBD)



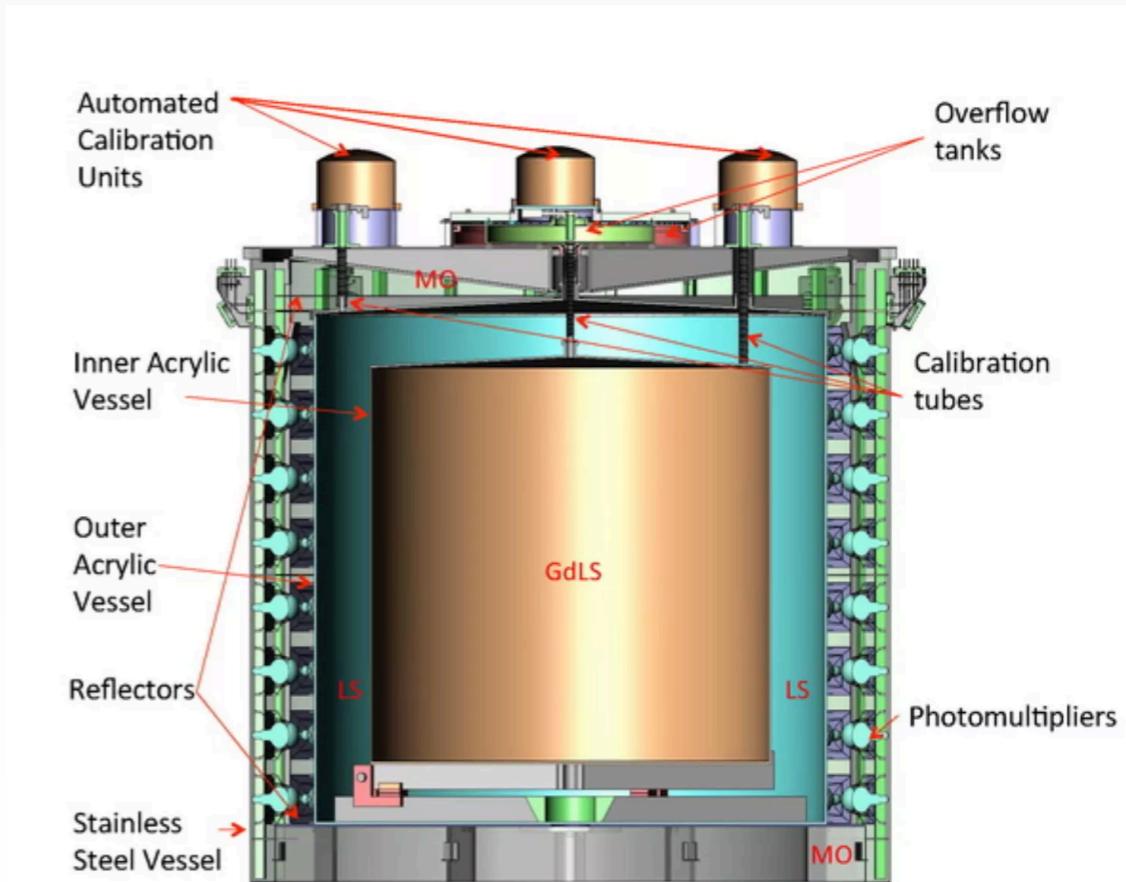
Reactors are reach sources of anti-neutrinos

$$6 \cdot 10^{20} \bar{\nu}_e / \text{GW}_{\text{thermal}}$$



- Delayed Coincidence: powerful background rejection
- Prompt  $e^+$  signal gives energy of  $\bar{\nu}_e$

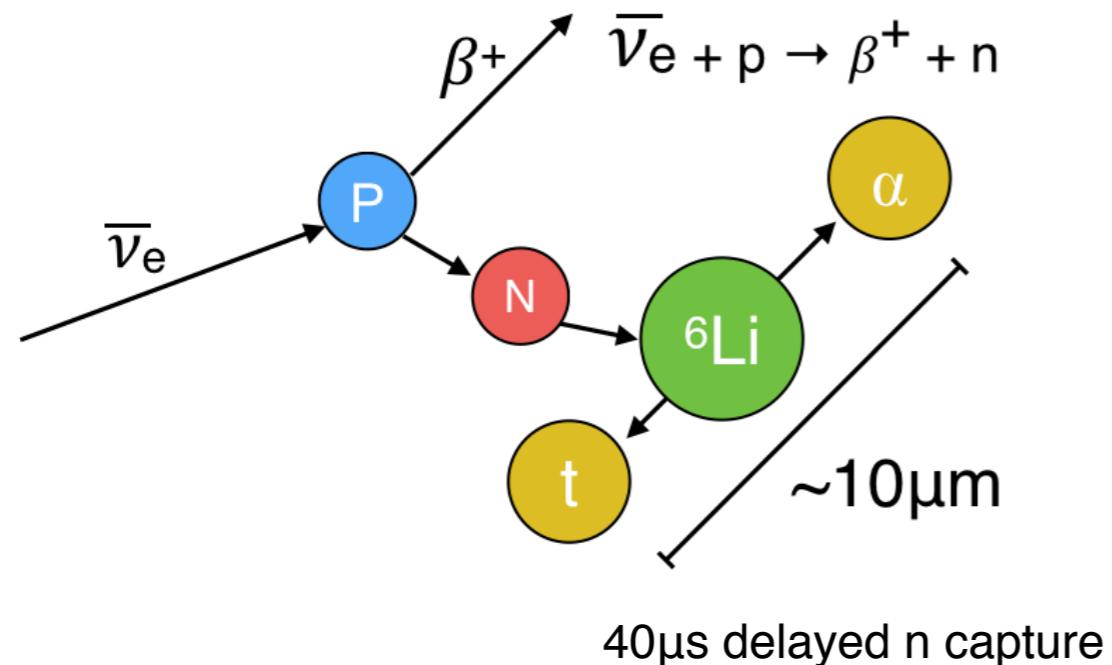
Typical detector:  
Liquid scintillator loaded with a high neutron absorption x-section element, e.g. Gadolinium



# Antineutrino Event Identification with ${}^6\text{Li}$



## Inverse Beta Decay



signal

**inverse beta decay (IBD)**  
 $\gamma$ -like prompt, n-like delay

backgrounds

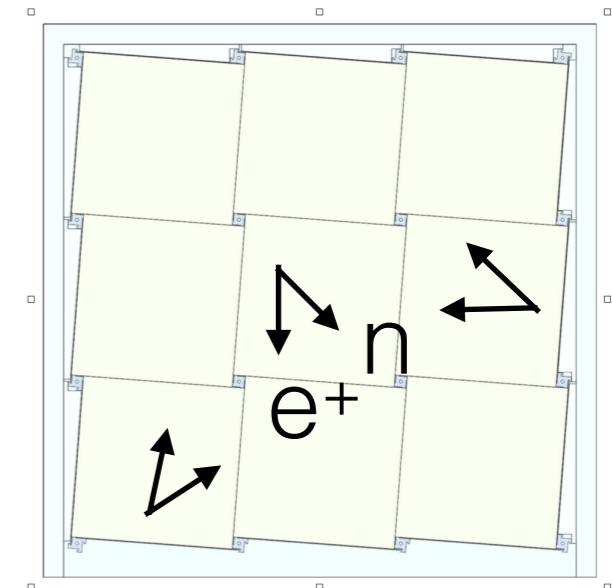
**fast neutron**  
 n-like prompt, n-like delay

**accidental gamma**  
 $\gamma$ -like prompt,  $\gamma$ -like delay

Background reduction is key challenge

Background Reduction  
 detector design & fiducialization

IBD event in  
 segmented  
 ${}^6\text{LiLS}$   
 detector



## Pulse Shape Discrimination

