Neutrinomassen & Doppelbetazerfall

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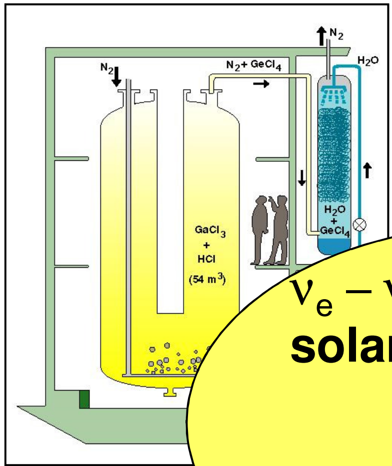
DPG Frühjahrstagung, Mainz
24-28.3.2014

Non-zero neutrino masses established through ν-oscillation experiments



$\nu_e - \nu_{\mu,\tau}$; $\overline{\nu}_e - \overline{\nu}_x$

solar- and reactor-ν's:

™m² ~ 7.5·10⁻⁵ eV² → $™m^2 \sim 7.5 \cdot 10^{-5}$ eV^2

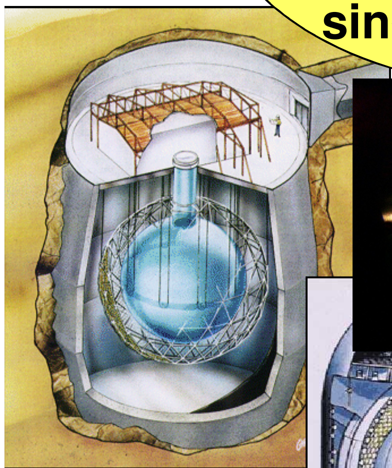
$\sin^2\theta_{12} \sim 0.3$

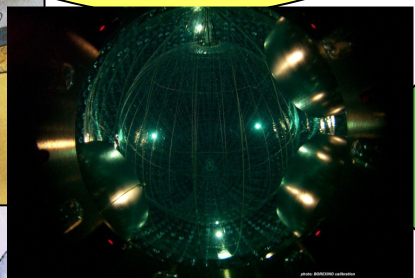
$\nu_\mu - \nu_\tau$

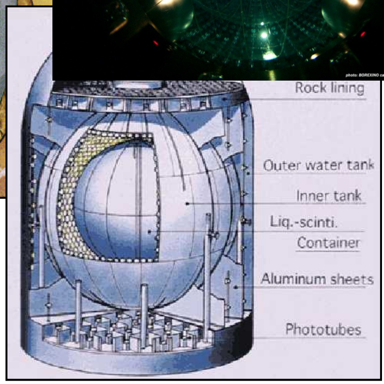
atmospheric- and LBL accelerator-ν's:

$\Delta m^2 \sim 2.4 \cdot 10^{-3}$ eV^2

$\sin^2\theta_{23} \sim 0.43$



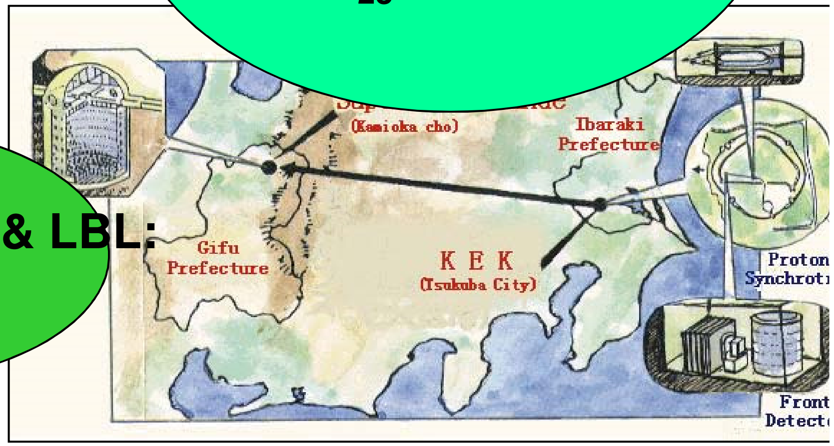




$\overline{\nu}_e - \overline{\nu}_x$

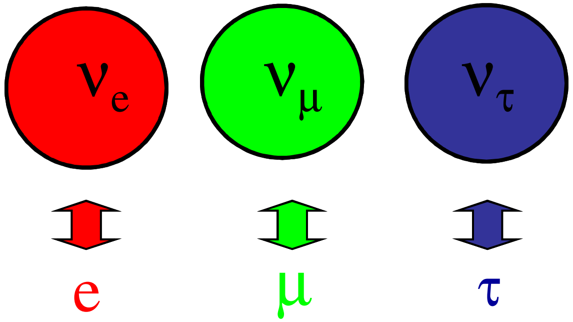
reactor-ν's & LBL:

$\sin^2\theta_{13} \sim 0.023$

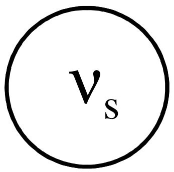


Neutrino flavors & mass eigenstates

Production/detection:
Flavor neutrino states



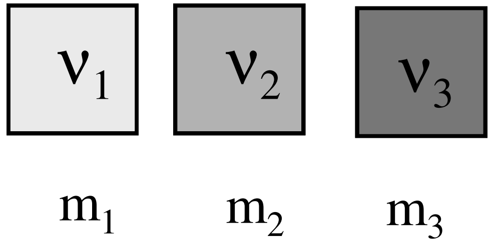
Eigenstates of the
CC weak interactions



Sterile neutrinos?

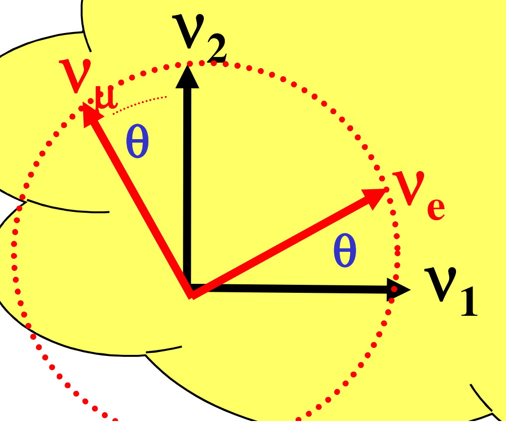
≠

Propagation:
Mass eigenstates



Pontecorvo-Maki-Nagakawa-Sakata (PMNS)

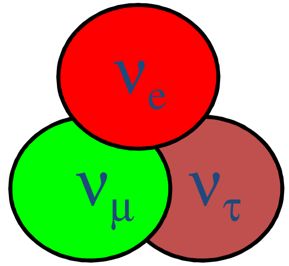
Example: 2 flavor mixing

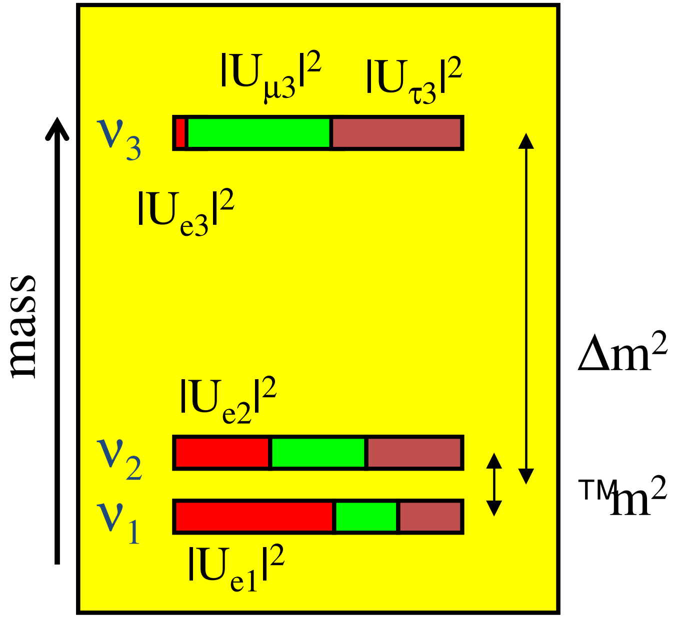


$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

From A. Smirnov

Neutrino mixing





Normal mass hierarchy

$\Delta m^2 = m^2_3 - (m^2_1 + m^2_2)/2$

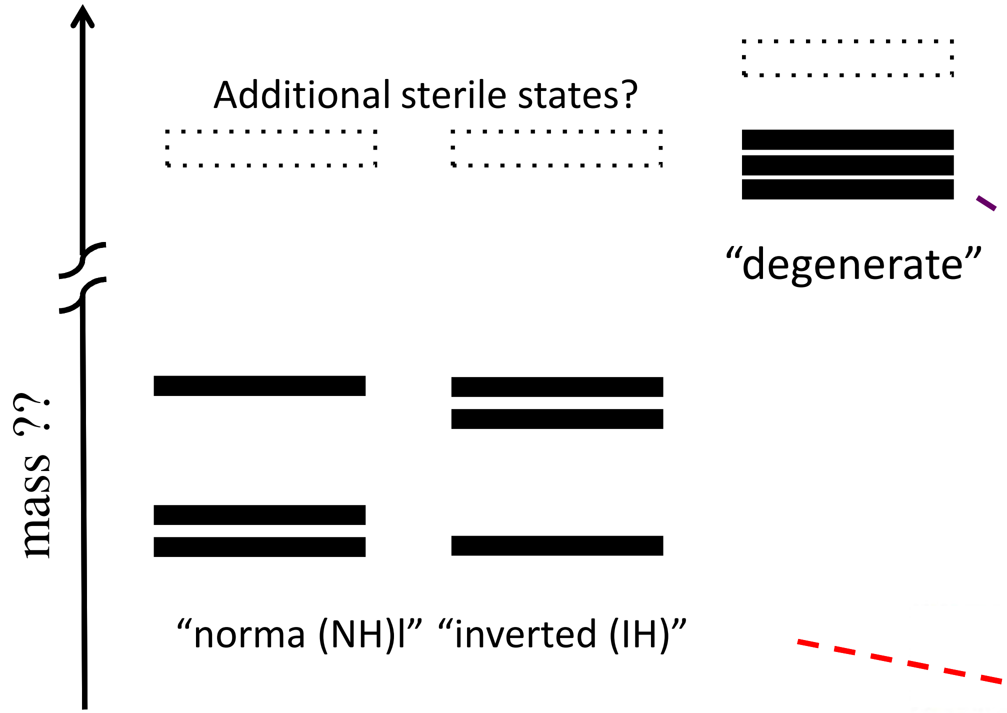
™$m^2 = m^2_2 - m^2_1$

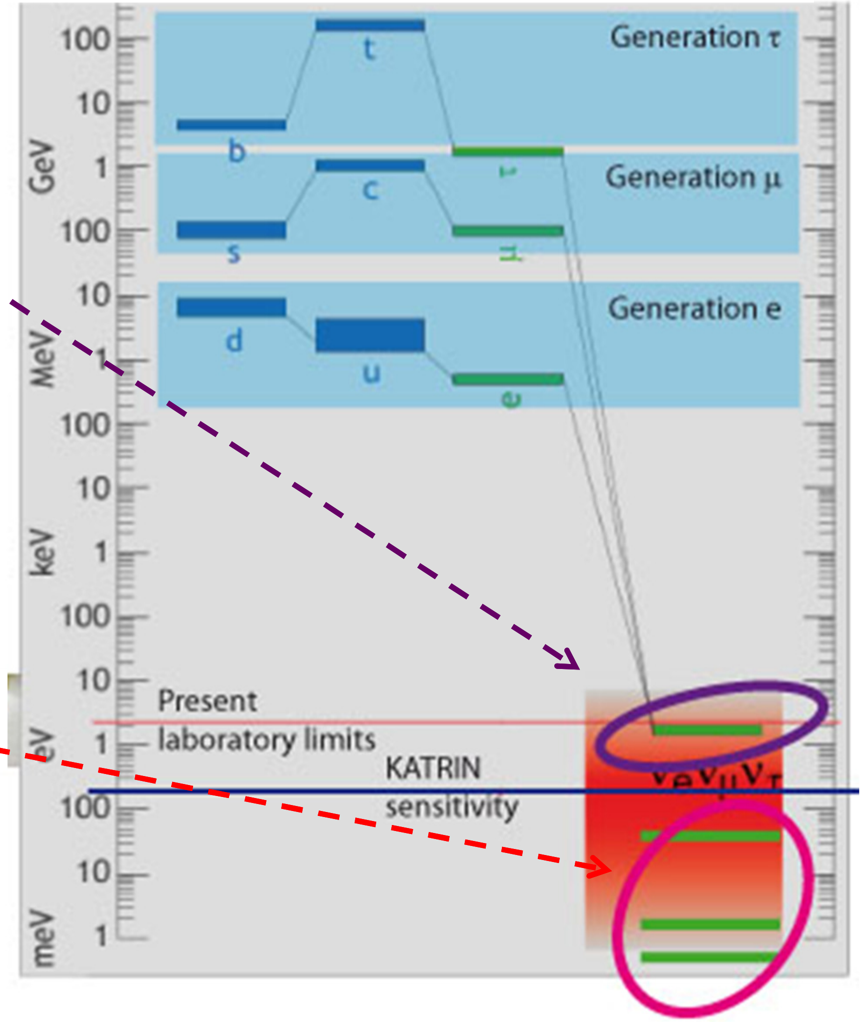
Mixing matrix:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

adopted from A. Smirnov

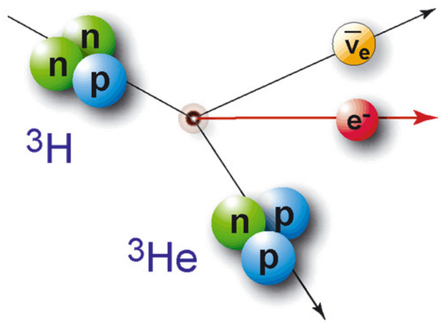
What is the mass scale? Which ordering?





ν-mass observables

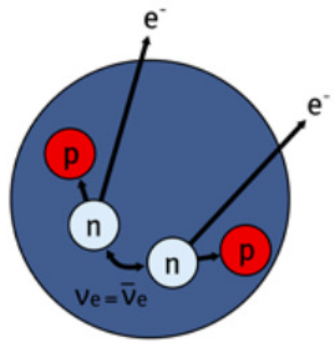
β-decay



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

(Dirac or Majorana)

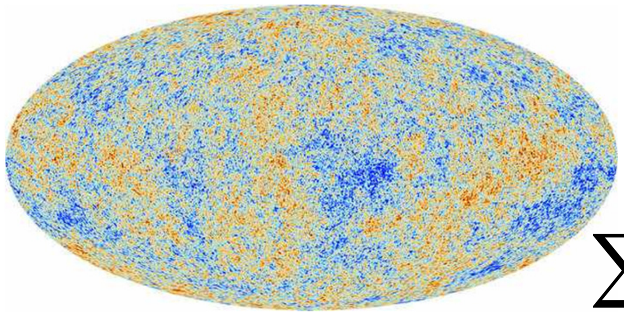
0νββ-decay



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

(Majorana)

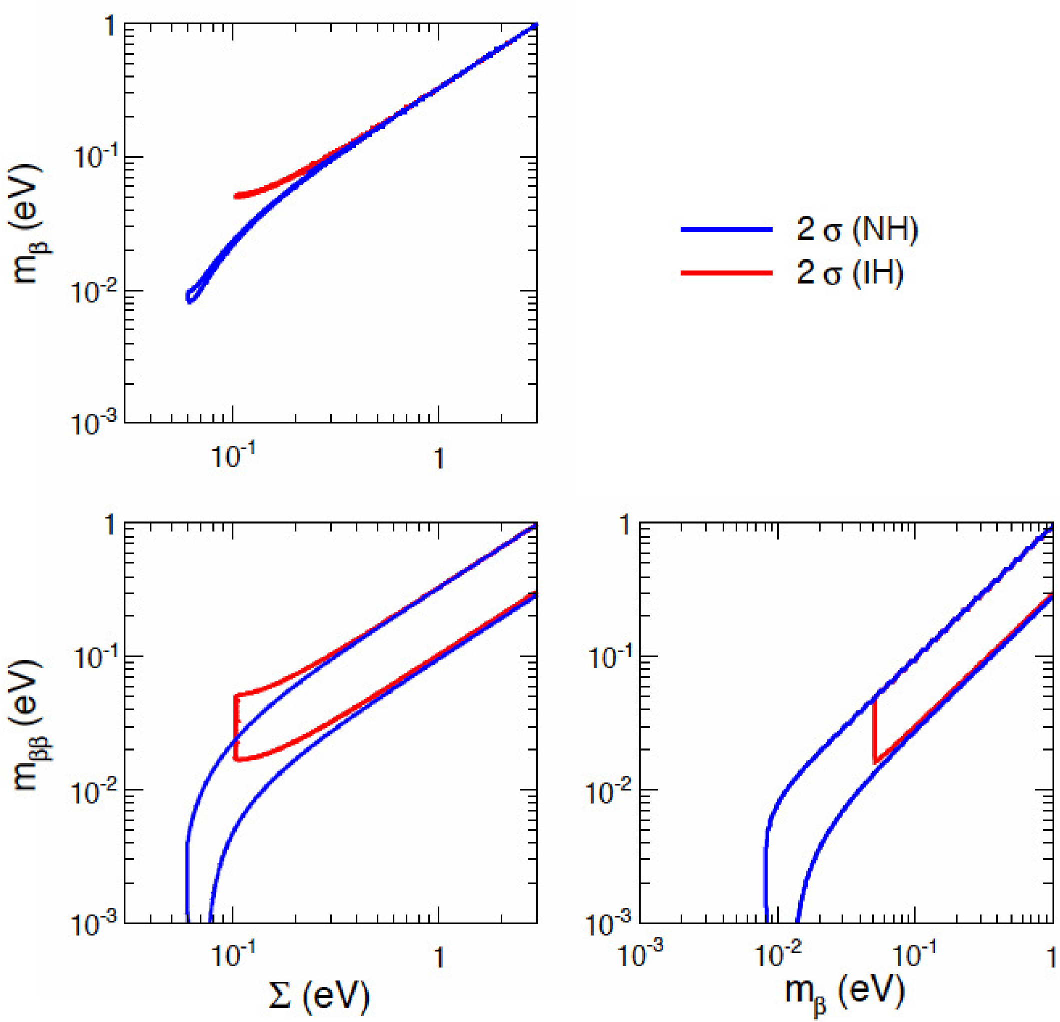
Cosmology



$$\sum_i m_i$$

Very recent: Hint for 0.4 eV sterile nu's from cosmological data? PRL 112 051303; 051302.

Predictions from oscillation experiments for mass observables



E. Lisi et al.

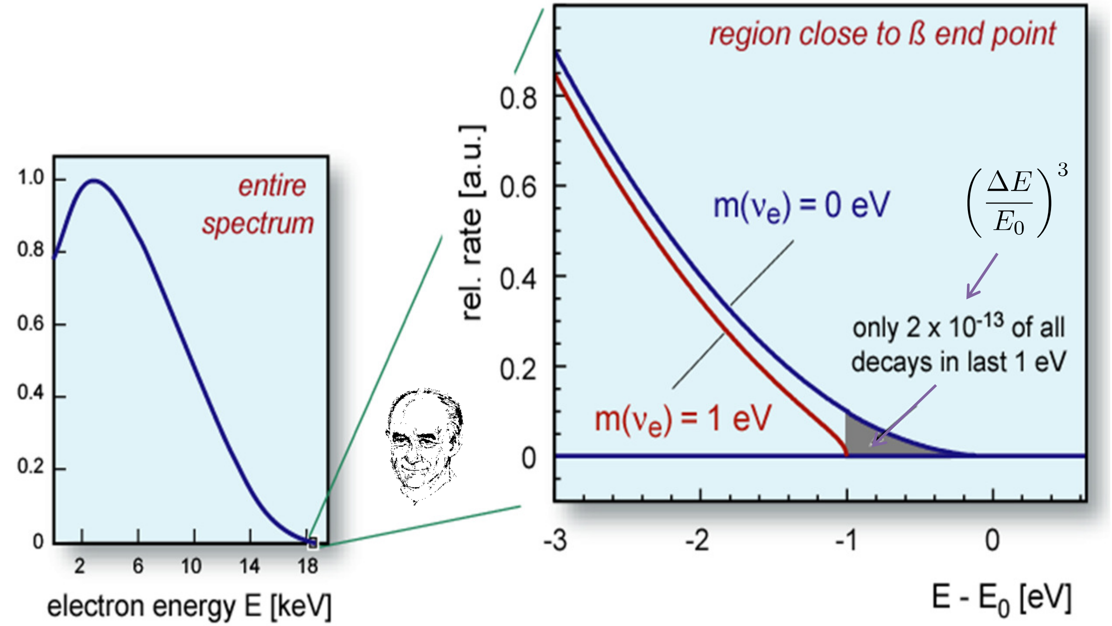
ß-decay – Fermi theory & ν-mass

ß-decay kinematics close to endpoint E_0: model independent measurement of $m(\nu_e)$, based solely on **kinematic parameters & energy conservation**

$$\frac{d\Gamma_i}{dE} = C \cdot p \cdot (E + m_e) \cdot (E_0 - E) \cdot \sqrt{(E_0 - E)^2 - m_i^2} \cdot F(E,Z) \cdot \theta(E_0 - E - m_i)$$

observable $m^2(\nu_e)$:
effective electron-ν-mass

$$m(\nu_e) = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 \cdot m_i^2}$$



key requirements:

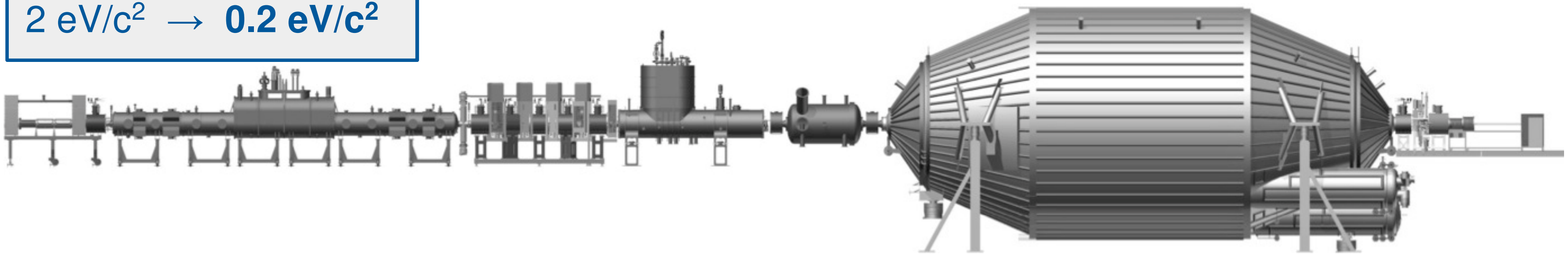
- low endpoint β source
- high count rate
- high energy resolution
- extremely low background

- small modifications by final states, radiative & recoil corrections

Courtesy T. Thümmler (Katrin)

The Karlsruhe Tritium Neutrino Experiment

Sensitivity on $m(\nu_e)$:
$2\ eV/c^2 \rightarrow$ **$0.2\ eV/c^2$**

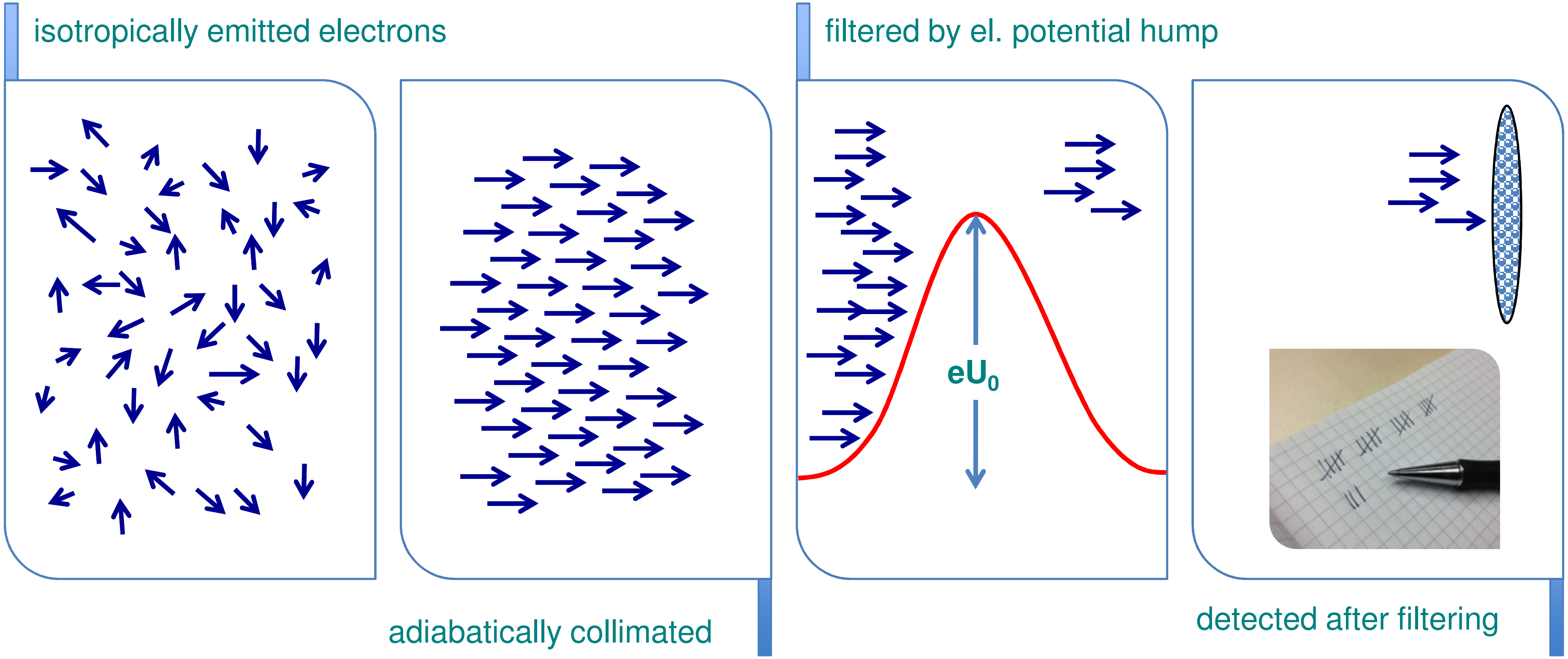


- The KATRIN collaboration is based on strong international (US, CZ, RUS, UK) & national partners with unique expertise in many key technological areas
- Uniting the world-wide expertise in tritium β-decay

Courtesy T. Thümmler (Katrin)

The MAC-E filter

Magnetic Adiabatic Collimation with Electrostatic Filter A. Picard et al., NIM B 63 (1992)



- collimation: adiabatic transport: $\mu = E_{\perp} / B = \textit{const}$, thus $E_{\perp} \rightarrow E_{||}$ from B_{max} to B_{min}
- energy analysis: transmission condition: $E_{||} > eU_0$ (retarding potential)
  → **high-pass energy filter** with a sharp transmission function, no tails!
- energy resolution: $\Delta E = E \cdot B_{min} / B_{max} = 18.6\ \text{keV} \cdot 0.3\ \text{mT} / 6\ \text{T} = 0.93\ \text{eV}$

Courtesy T. Thümmler (Katrin)

The MAC-E filter

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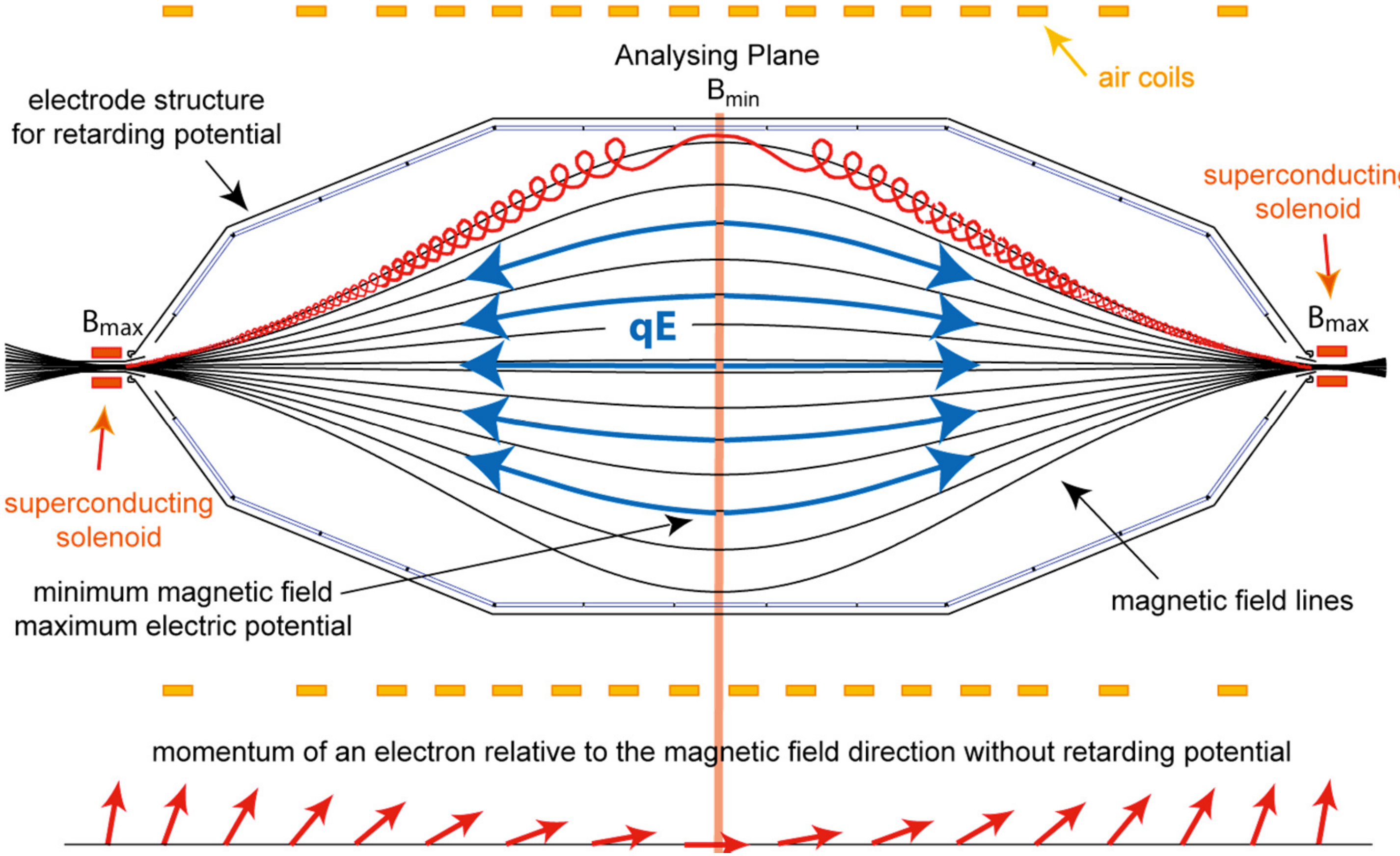

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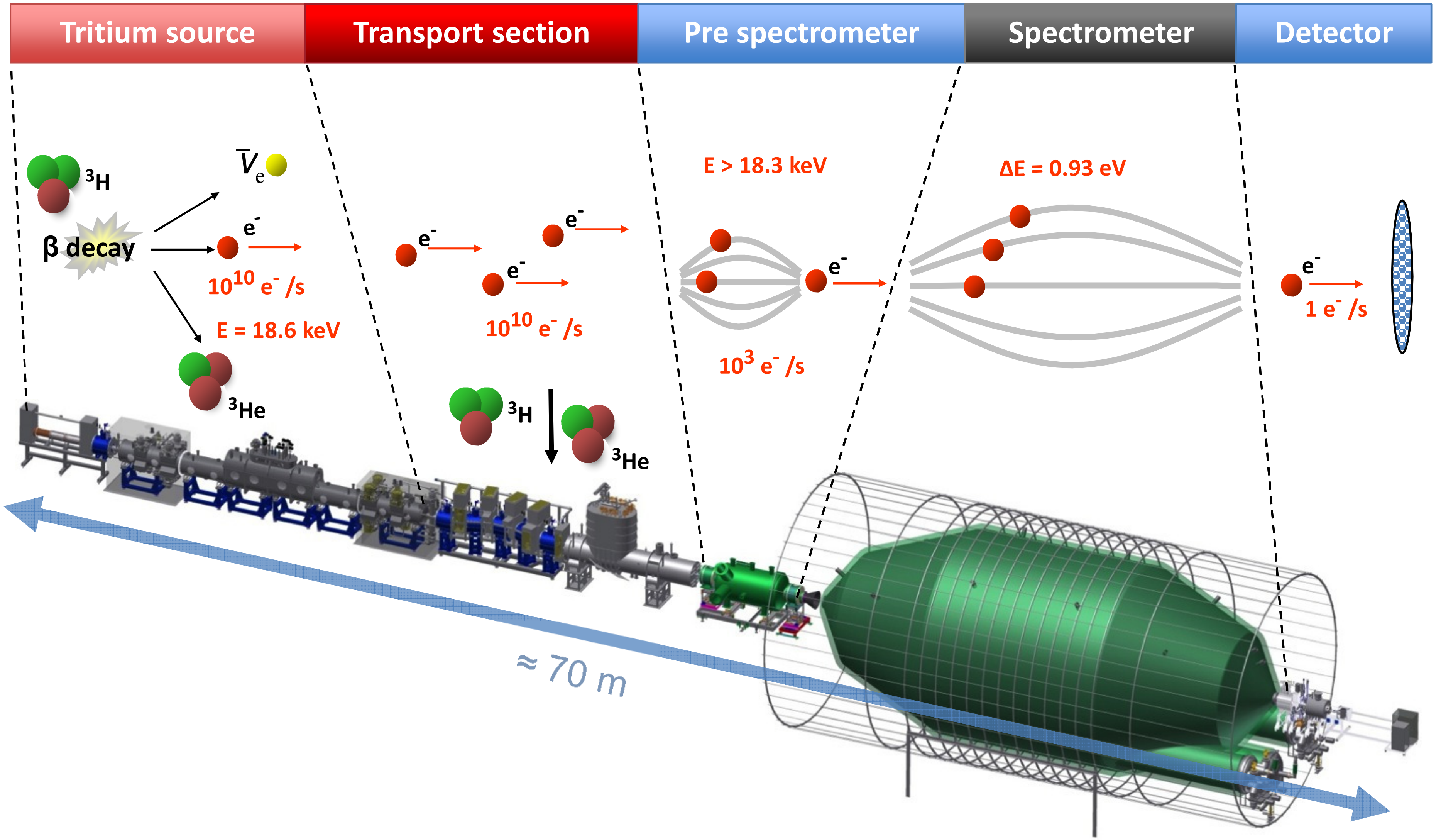
Courtesy T. Thümmler (Katrin)

The KATRIN Setup - Overview



Courtesy T. Thümmler (Katrin)

Windowless Gaseous Tritium Source WGTS

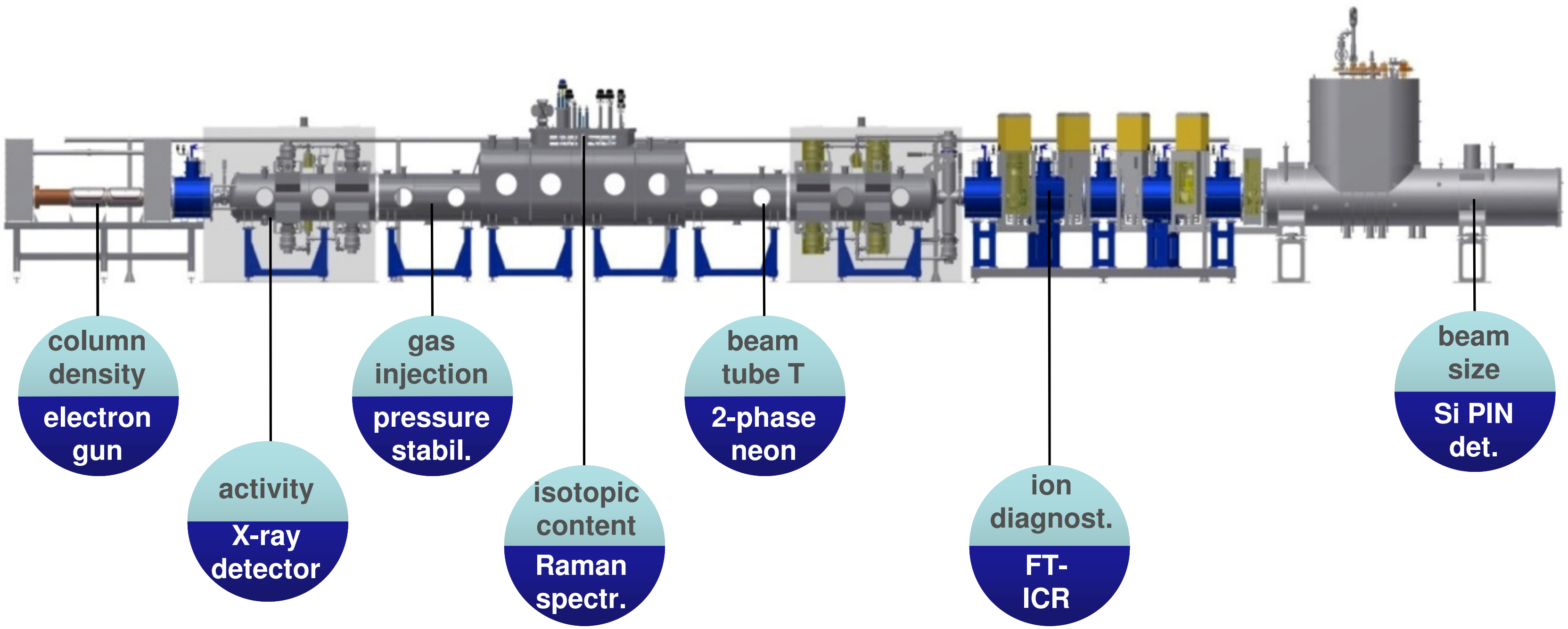
Source systematics

challenge

reduce source systematics by > **factor 10** compared to previous experiments

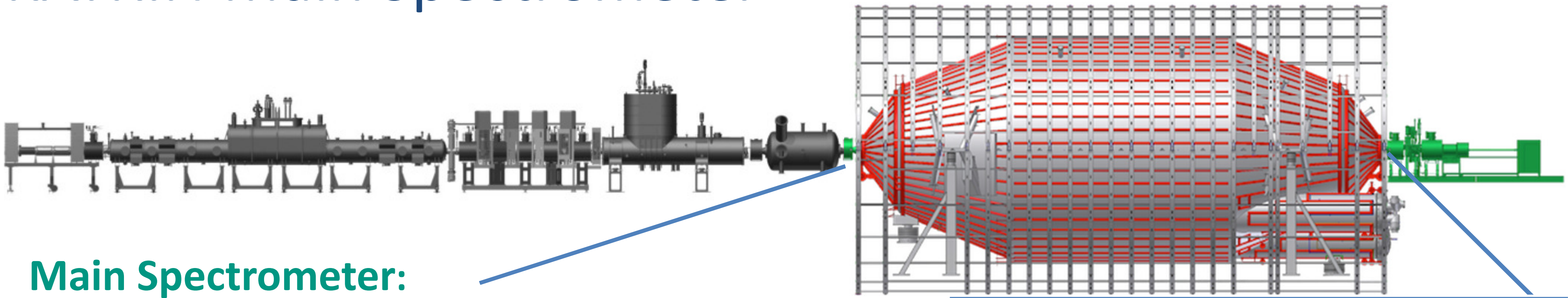
technological development

monitoring & control of all relevant parameters with unprecedented precision & accuracy



Courtesy T. Thümmler (Katrin)

KATRIN Main Spectrometer



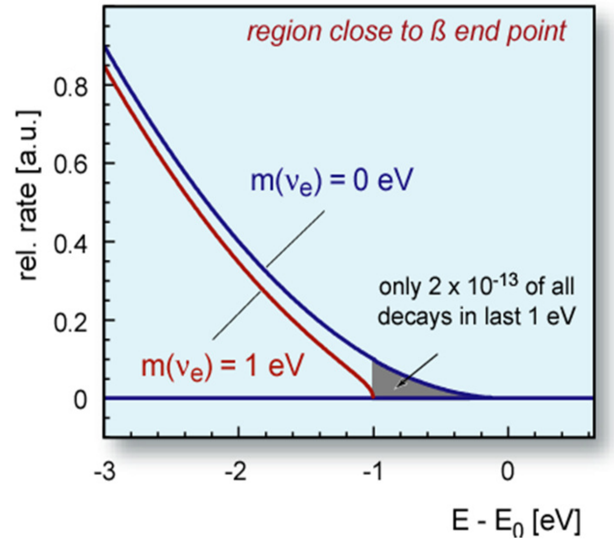
Main Spectrometer:

- MAC-E Filter principle → precise energy analysis
- Vacuum vessel on retarding potential
- high resolution: **ΔE = 0.93 eV**

$$\Delta E / E_0 = B_{min} / B_{max} = 1/20000$$

- □ 10 m, length 23 m
  - volume: 1240 m³ , inner surface: 690 m²
- **Background Reduction:**
  - **ultra high vacuum (UHV): $p < 10^{-11}$ mbar**
  - **cosmic ray induced background → counter measure: wire electrode**
  - **Radon decay induced background → counter measure: LN2 baffle**
  - **active methods to prevent particle storage**

precision filter - scanning
variable retarding potential
U_0 = - 18.4 … -18.6 kV
ΔE ~ 0.93 eV (100% transmission)

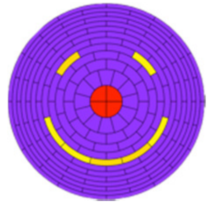


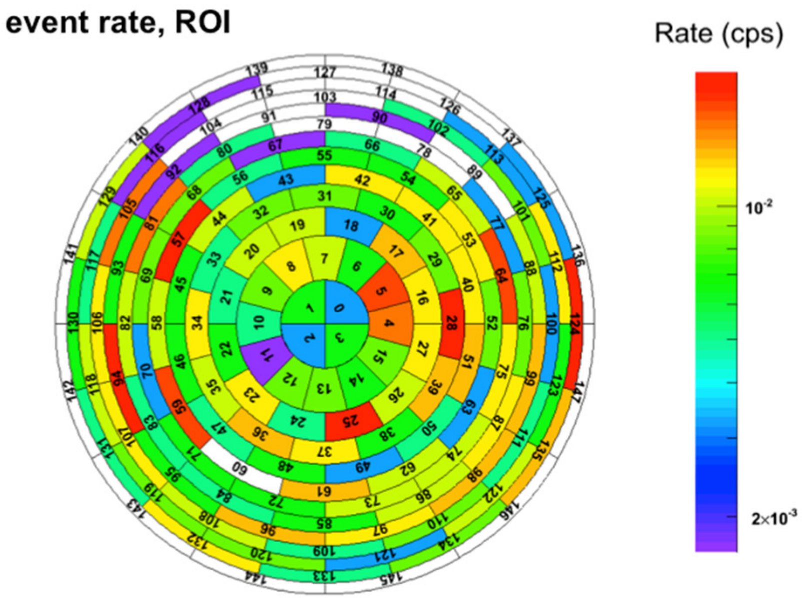
Courtesy T. Thümmler (Katrin)

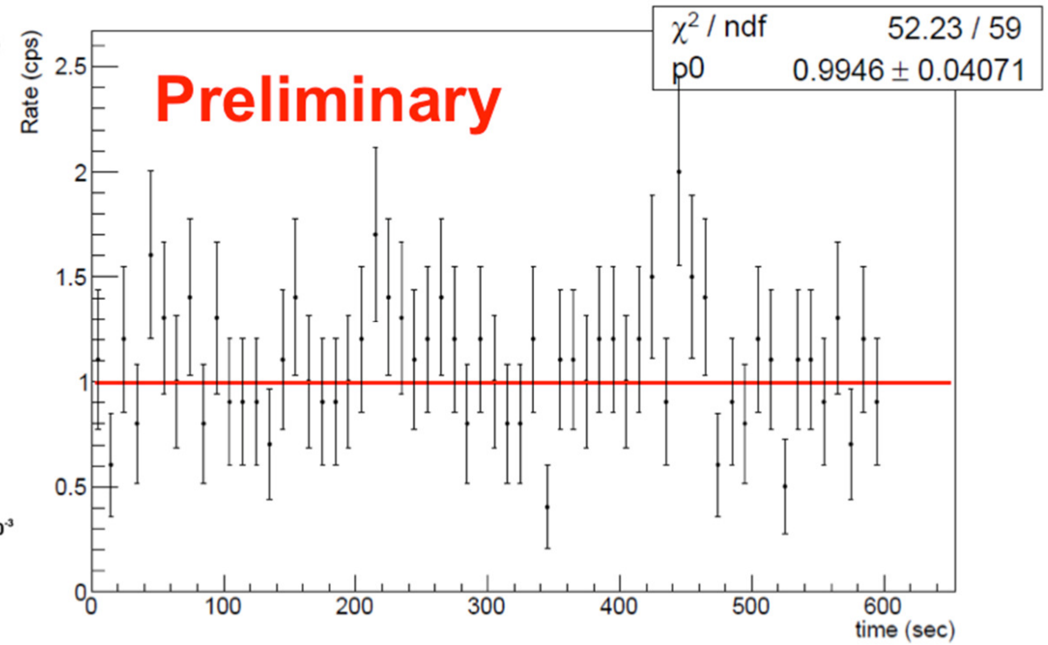
KATRIN Main Spectrometer Measurements

first data – first 10 minutes after applying high voltage

- no Penning traps
- background reduction by magnetic shielding: > factor 10^4





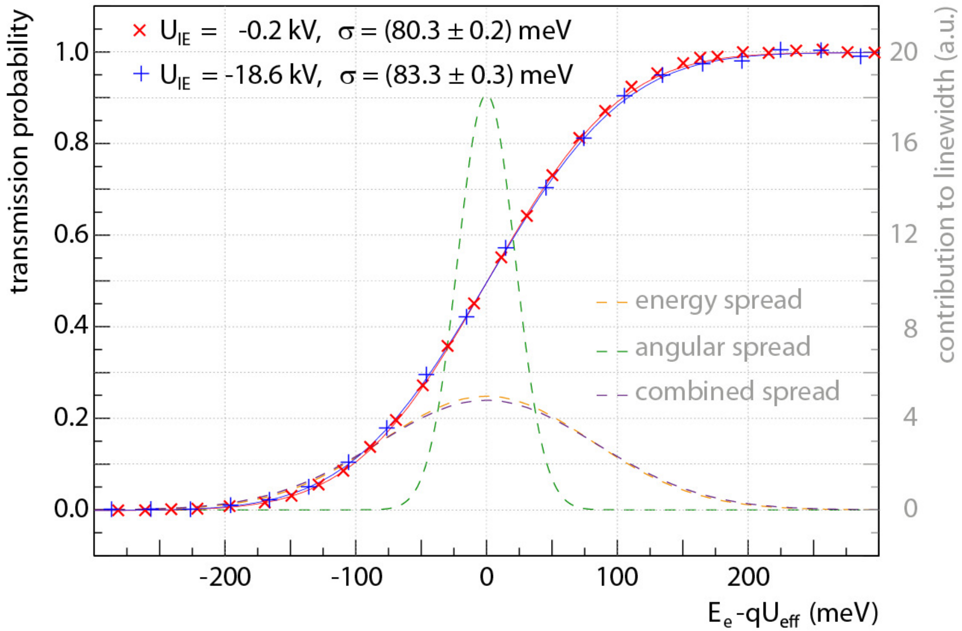


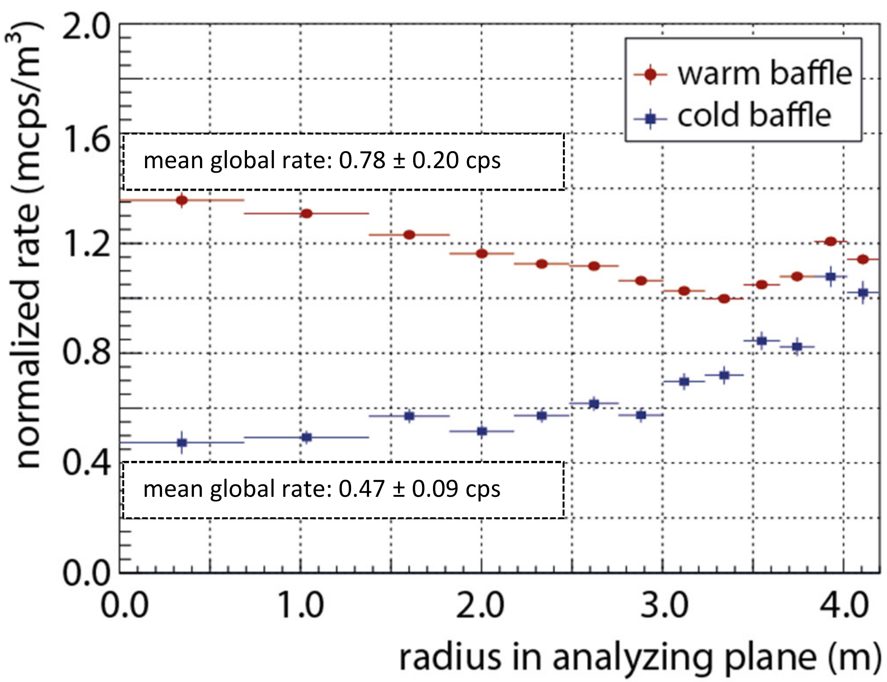
Courtesy T. Thümmler (Katrin)

KATRIN Main Spectrometer Measurements

detailed transmission and background studies

- sharpest transmission function ever measured with MAC-E filter
- background from $^{219}Rn/^{220}Rn$ emanation eliminated

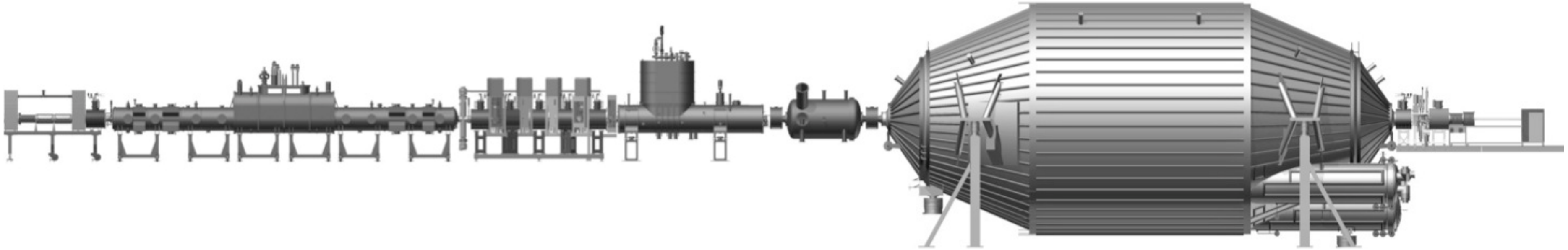




- will be improved during 2014 commissioning runs

Courtesy T. Thümmler (Katrin)

KATRIN Schedule



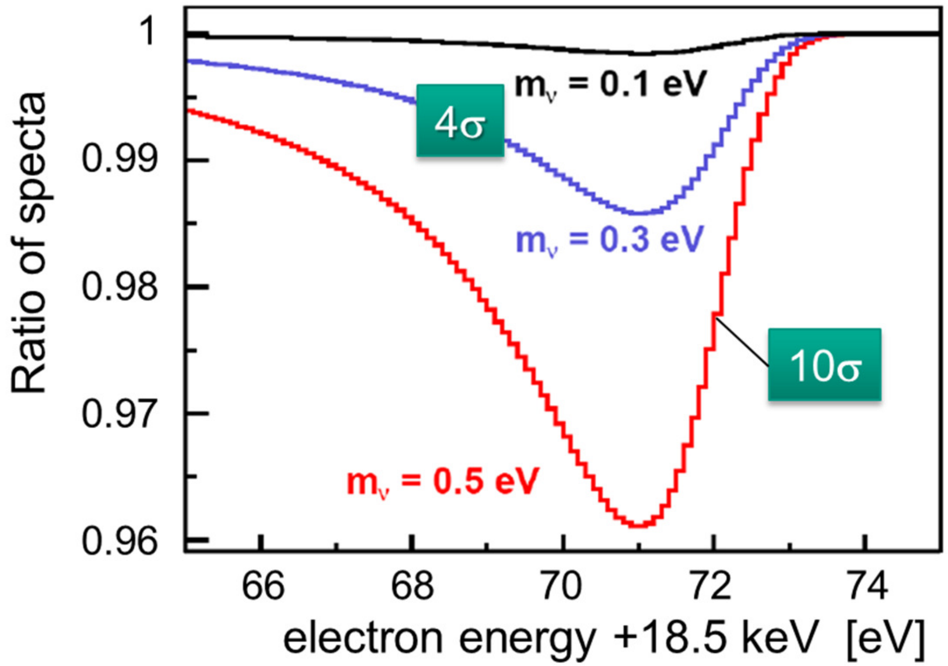
- spectrometer upgrade for 0.01 cps	Q1/2015
- tritium retention units DPS and CPS functional	Q2/2015
- tritium source WGTS final mounting completed	mid-2015
- spectrometer upgrade completed	Q3/2015
- all source elements & tritium loops integrated	Q4/2015
- first tritium in source, ramp up to nominal ρd	Q1-Q2/2016
- **first tritium data with entire beam line**	**mid-2016**

Courtesy T. Thümmler (Katrin)

KATRIN Neutrino Mass Analysis

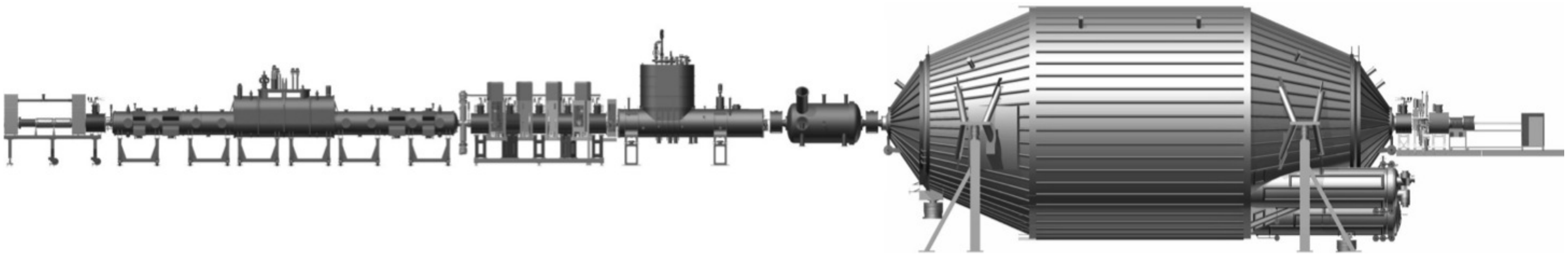
continuous data taking 2016-2021

- study of source sytematics, 3D model of source
- publish sub-eV sensitivity results after first few months of data taking
- **publish high-sensitivity neutrino mass result based on 3 years of data taking (2019)**

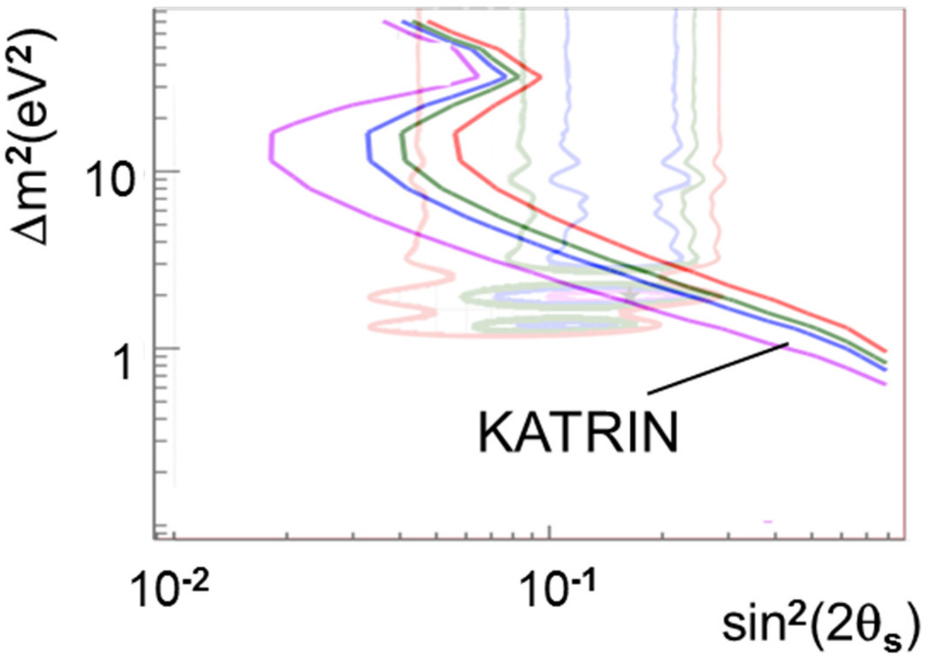


Courtesy T. Thümmler (Katrin)

KATRIN Search for New Physics



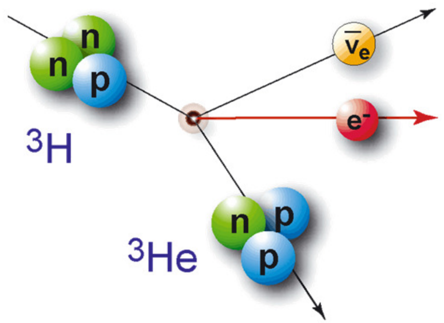
- search for light sterile ν´s (eV-scale, reactor anomaly)
- explore techniques for keV-mass sterile ν´s (WDM)
- RH currents
- violation of Lorentz symmetry



Courtesy T. Thümmler (Katrin)

ν-mass observables

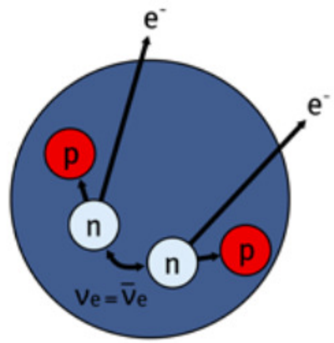
β-decay



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

(Dirac or Majorana)

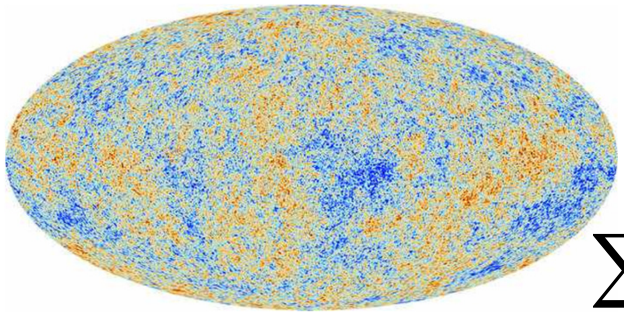
0νββ-decay



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

(Majorana)

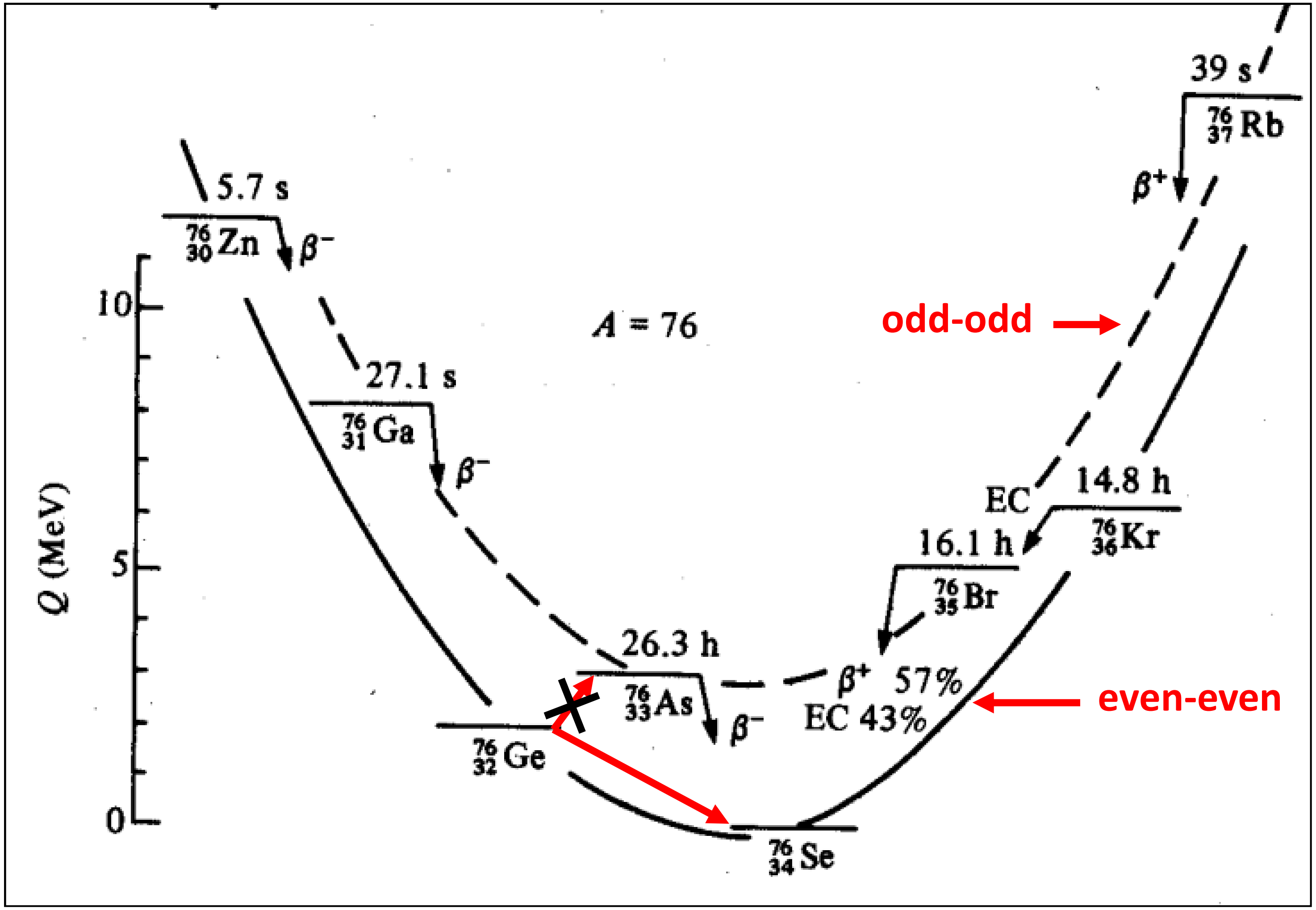
Cosmology



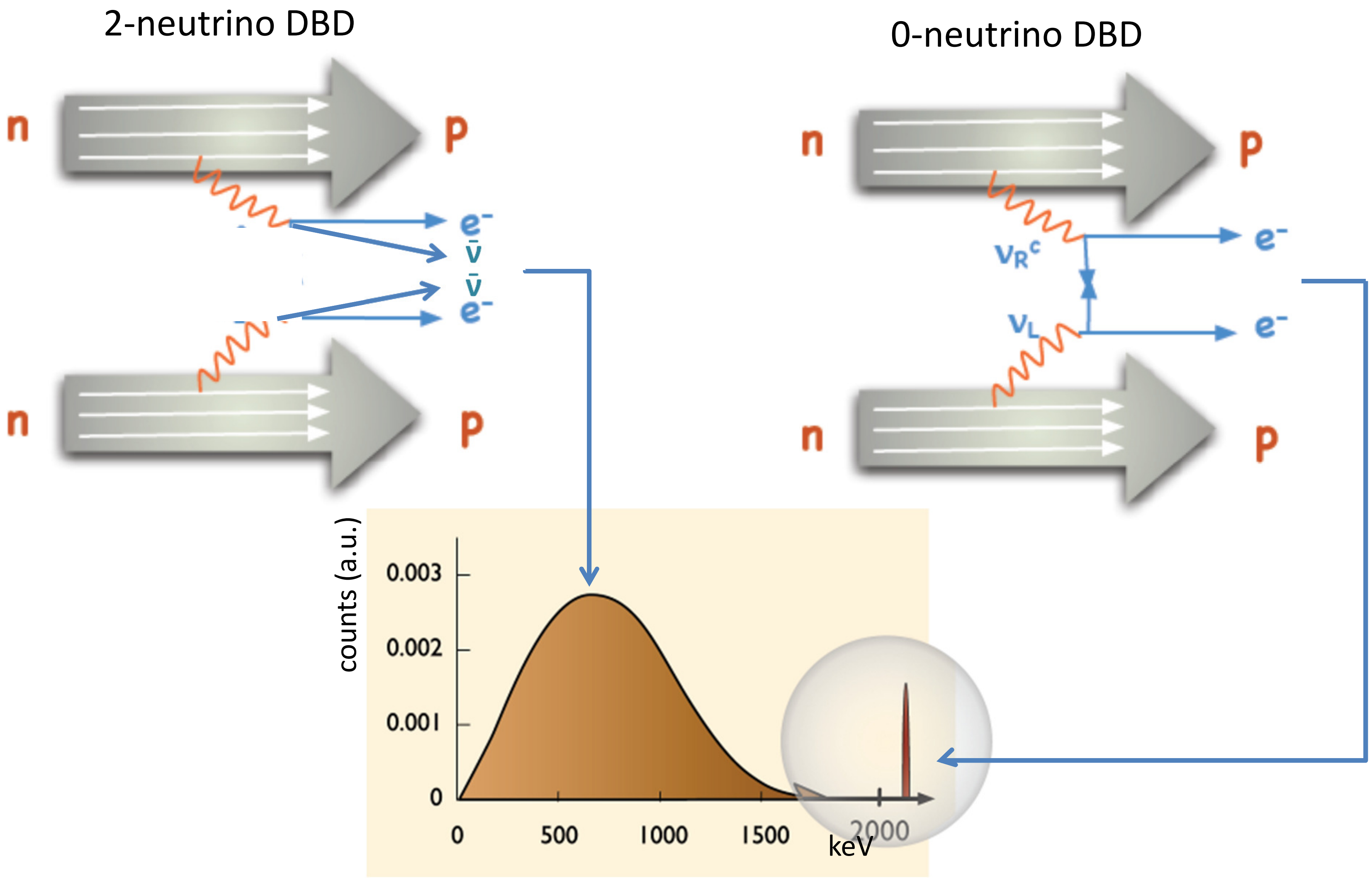
$$\sum_i m_i$$

Very recent: Hint for 0.4 eV sterile nu's from cosmological data? PRL 112 051303; 051302.

Double beta decay

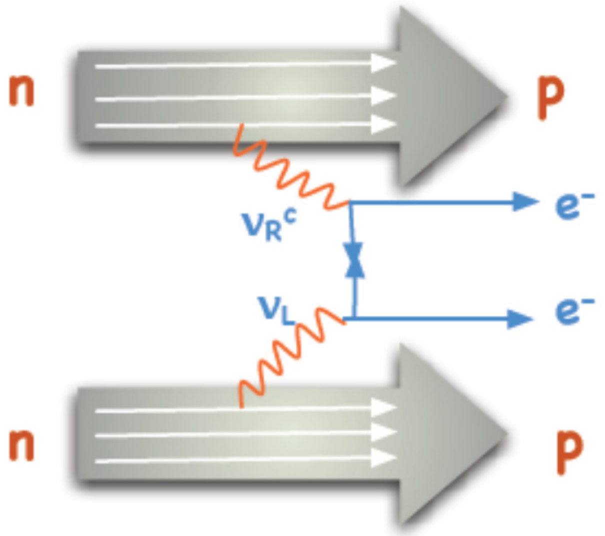


$Q_{\beta\beta}$ = (2039.061±0.007) keV B. J. Mount et al., Phys.Rev. 401 C81, 032501 (2010)



2-electron spectra

0νββ decay and neutrino mass



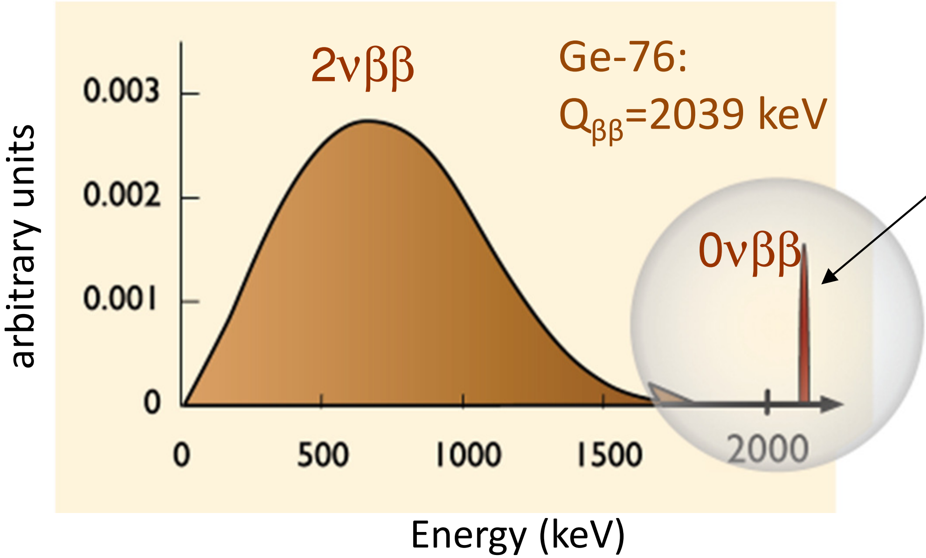
Expected decay rate:

$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu}(Q,Z)\,|M^{0\nu}|^2\,\langle m_{ee}\rangle^2$$

Phase space integral — Nuclear matrix element

$$\langle m_{ee}\rangle = \left|\sum_i U_{ei}^2\, m_i\right|$$ Effective neutrino mass

U_{ei} Elements of (complex) PMNS mixing matrix



Experimental signatures:

- peak at $Q_{\beta\beta}$ = m(A,Z)-m(A,Z+2)
- two electrons from vertex

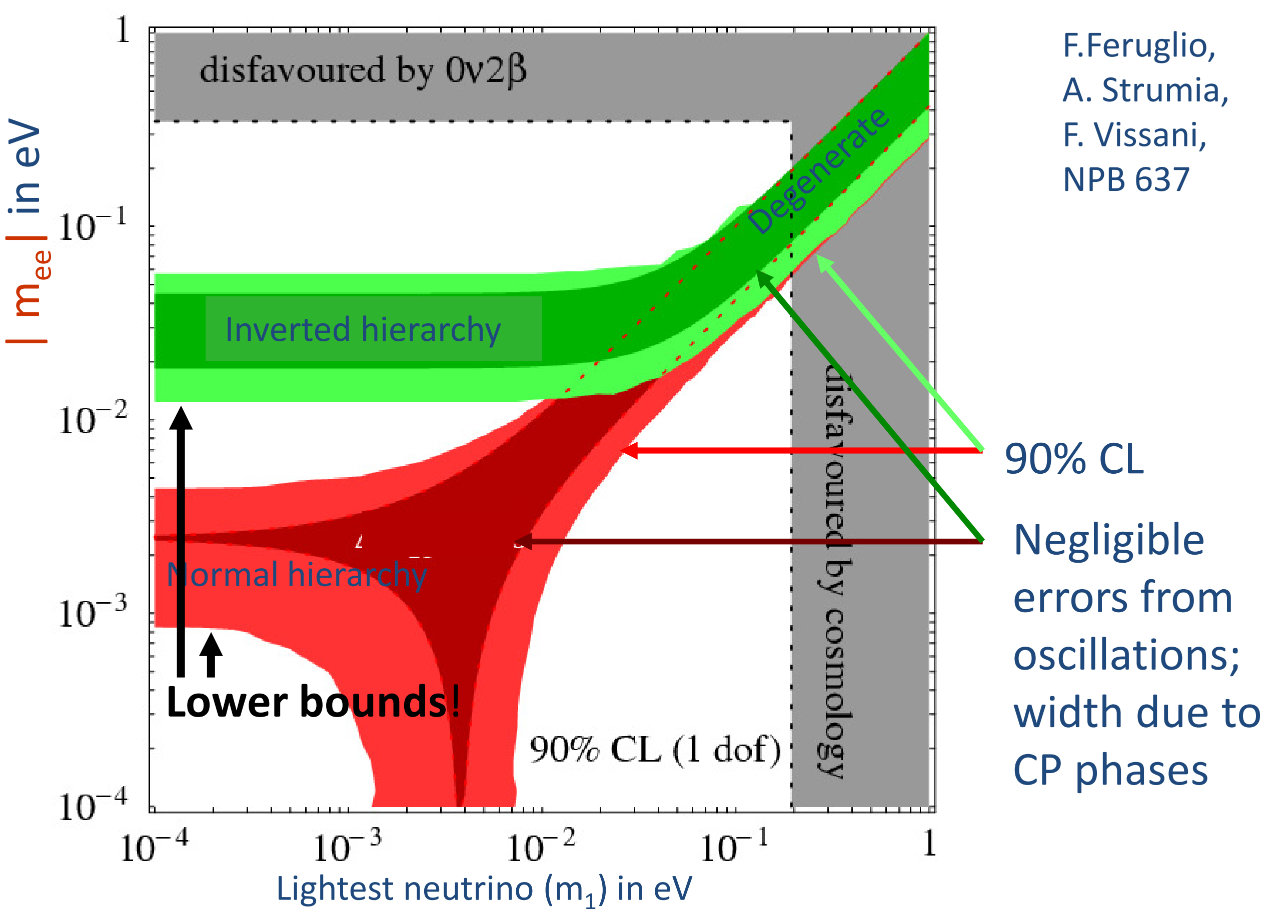
Discovery would imply:

- lepton number violation ΔL = 2
- ν's have Majorana character
- mass scale & hierarchy
- physics beyond the standard model

0νββ: Range of m_{ee} derived from solar and atmospheric oscillation experiments

$$m_{ee} = f(m_1, \underbrace{\delta m^2_{sol}, \Delta m^2_{atm}, \theta_{12}, \theta_{13}, \alpha\text{-}\beta}_{\text{from oscillation experiments}})$$

$$\langle m_{ee} \rangle = \left| \sum_i U_{ei}^2 m_i \right|$$



F.Feruglio, A. Strumia, F. Vissani, NPB 637

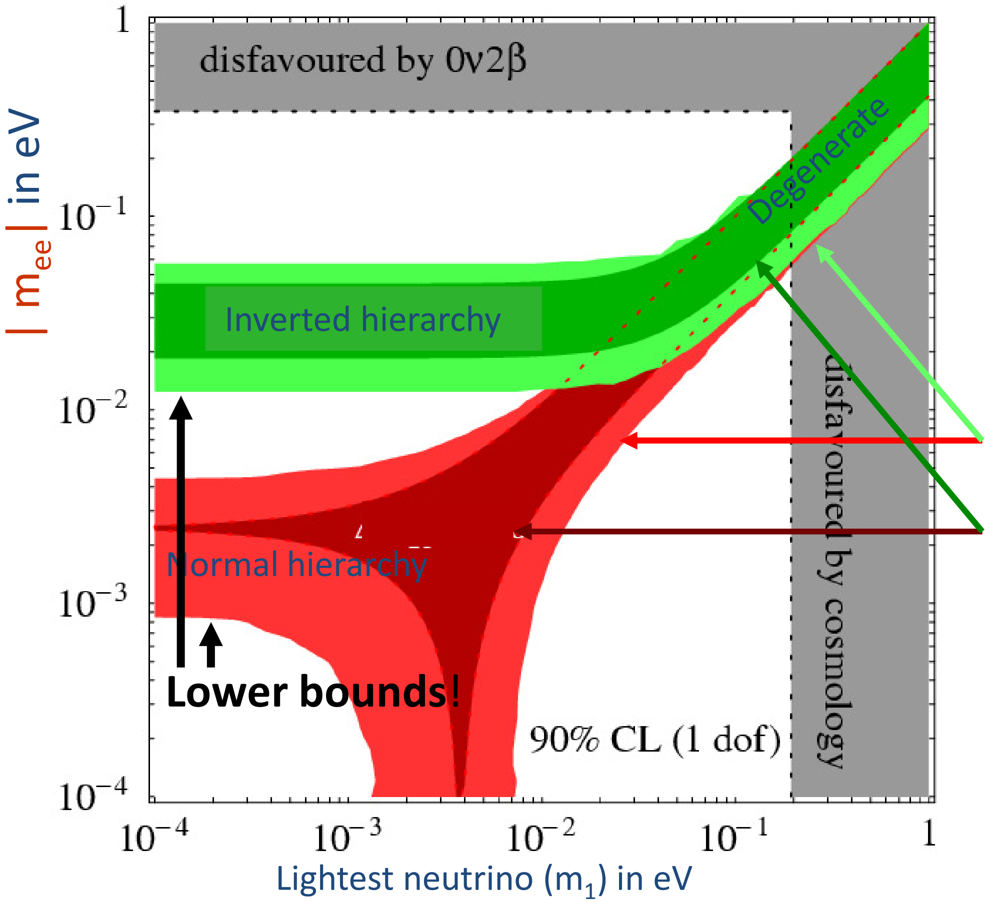
$0\nu\beta\beta$: Range of m_{ee} derived from solar and atmospheric oscillation experiments

$$m_{ee} = f(m_1, \delta m^2, \Delta m^2, \theta_{12}, \theta_{13}, \alpha-\beta)$$

from oscillation experiments

KDKC claim: 0.44 eV

Goal of next generation experiments: ~10 meV

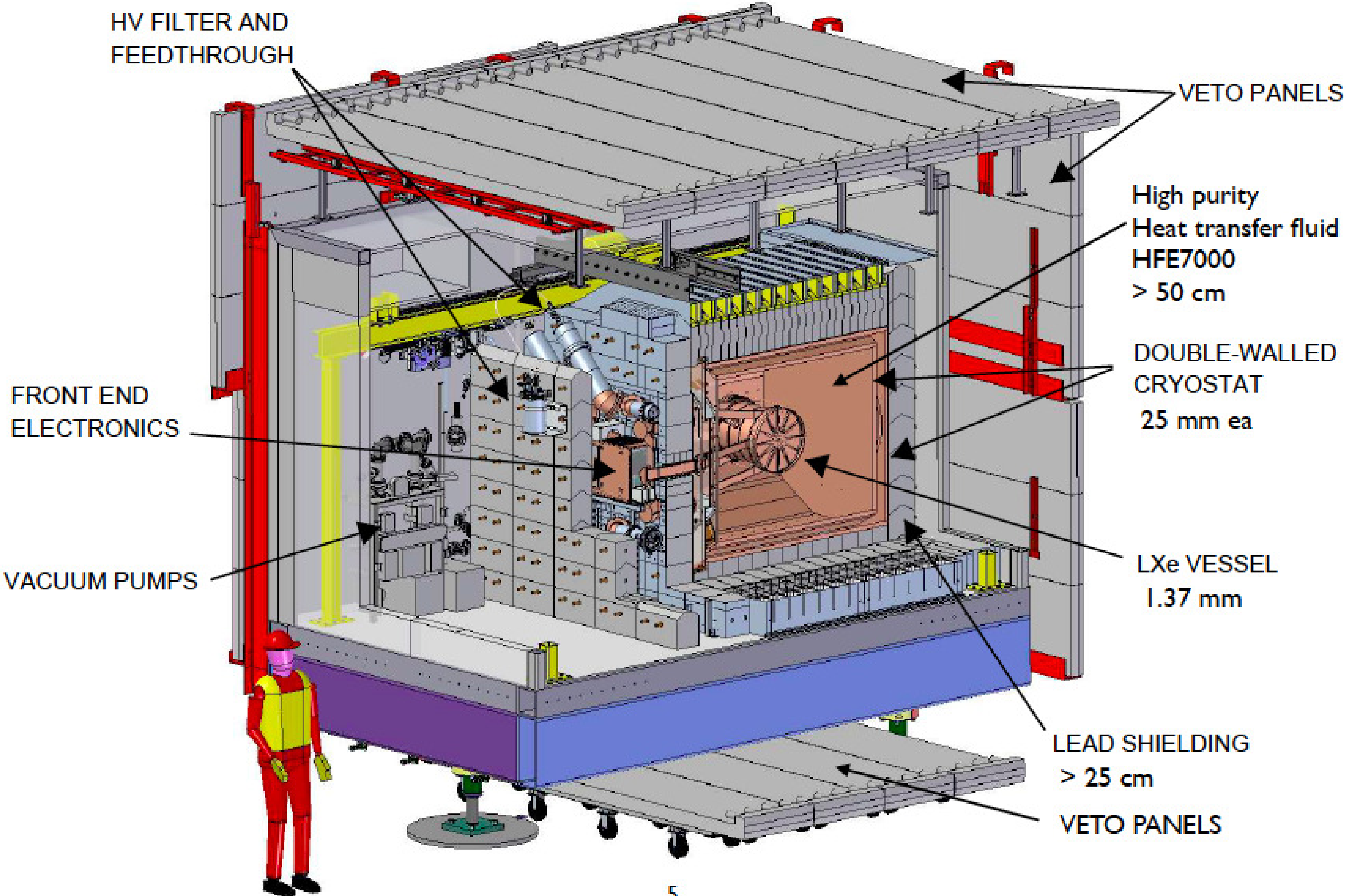


F.Feruglio, A. Strumia, F. Vissani, NPB 637

90% CL

Negligible errors from oscillations; width due to CP phases

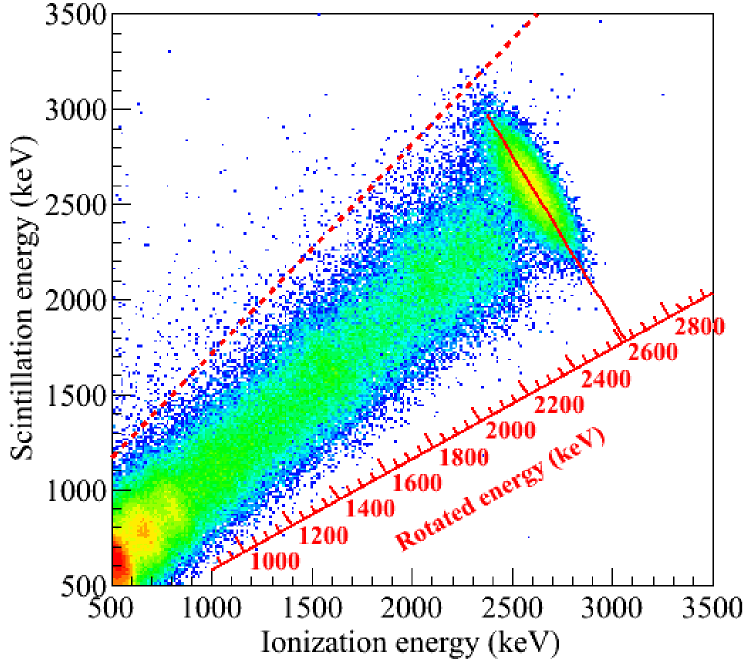
New results from EXO-200 (^{136}Xe)

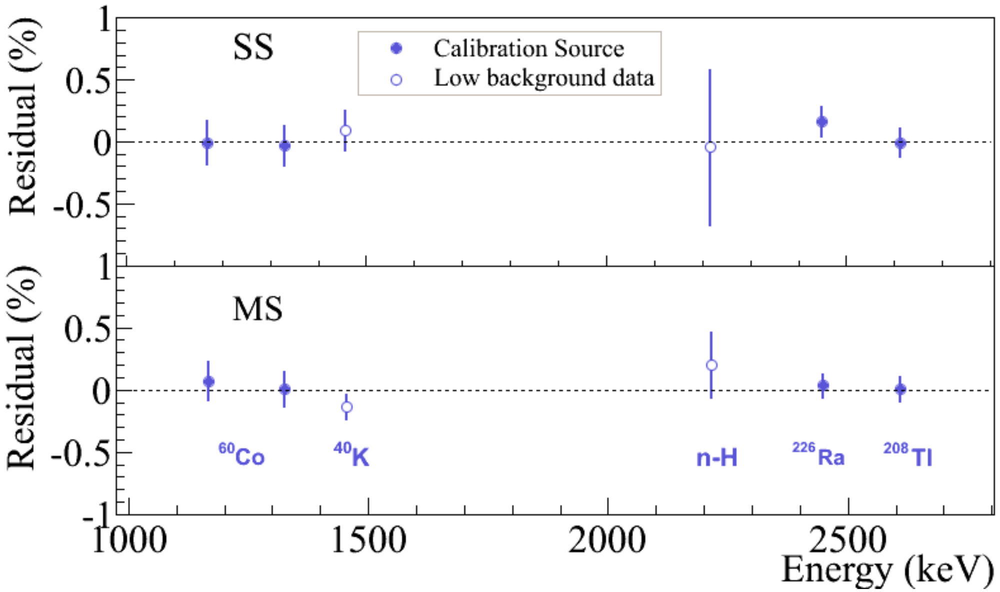


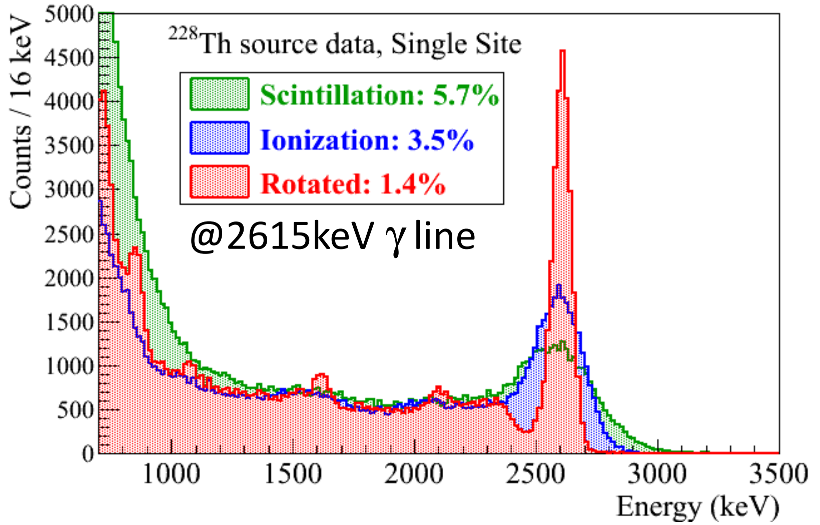
Courtesy M. Marino, TUM

New EXO-200 results: energy calibration

- Anti-correlation between scintillation and ionization in LXe is used improve energy resolution
- Rotation angle is chosen to optimize energy resolution at 2615keV, and is time-dependent taking into account the noise variation in scintillation
- Cross checks: γ's from ^{40}K and n-captures on H in HFE in low-background data

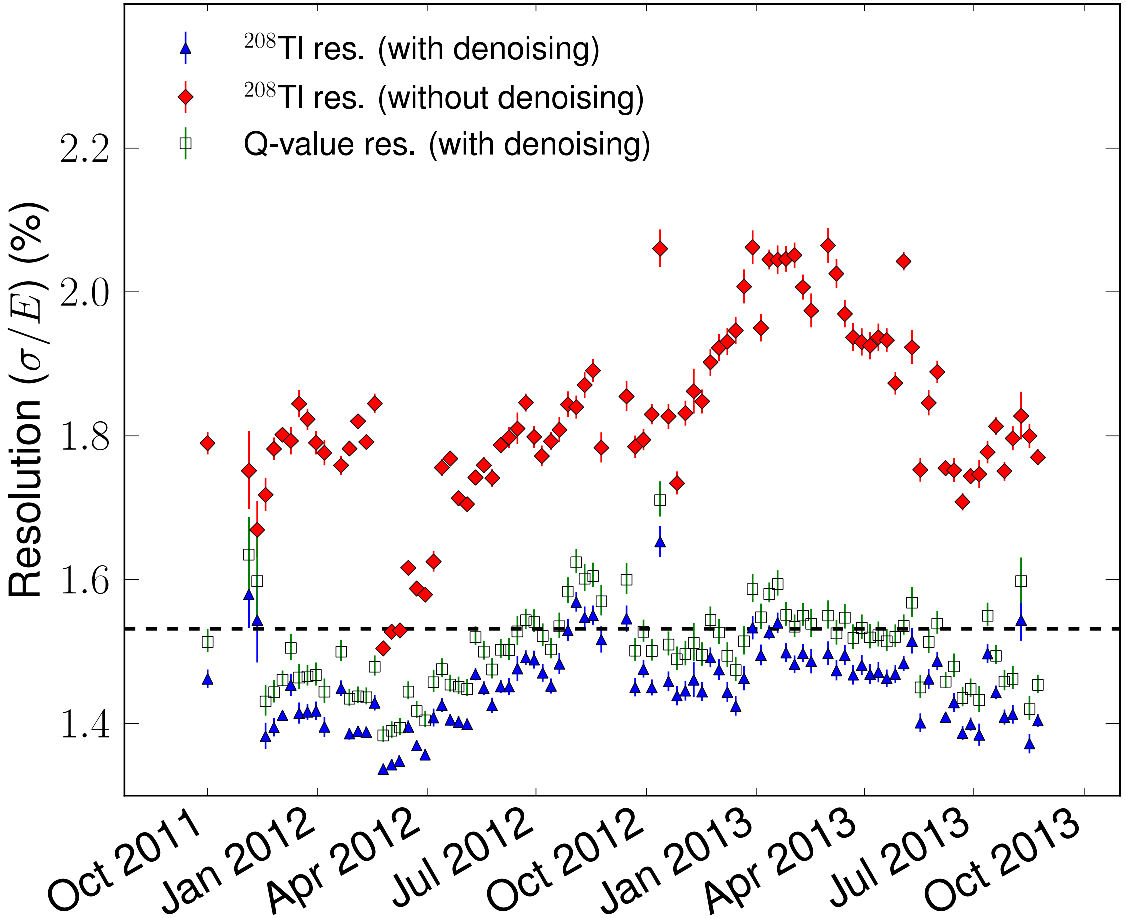






Courtesy M. Marino, TUM

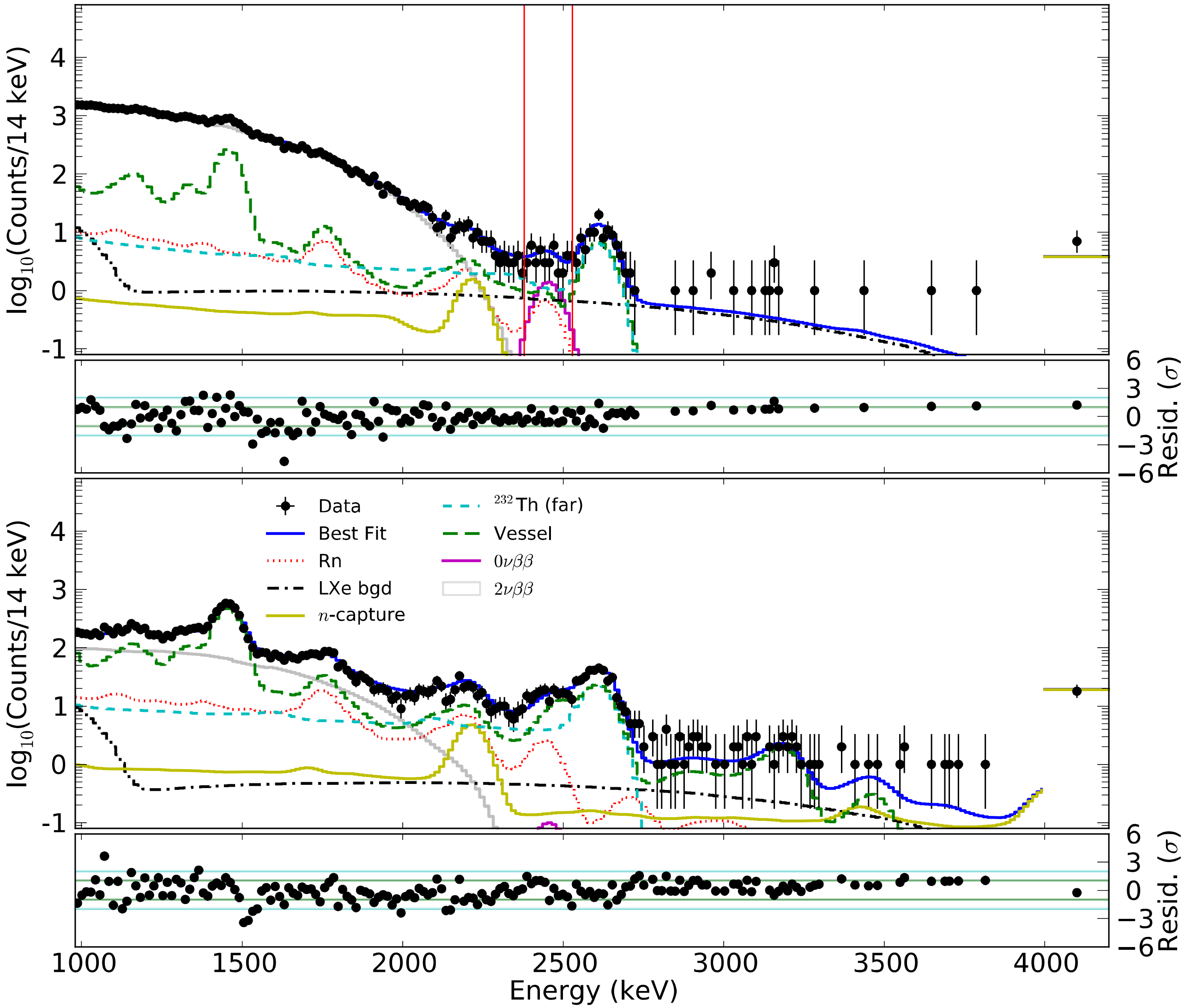
New EXO-200 results: Improvement of energy resolution



- Improvement of resolution over time for SS events (similar improvement seen in MS events) by using a denoising algorithm on the scintillation signals

Courtesy M. Marino, TUM

New EXO-200 results

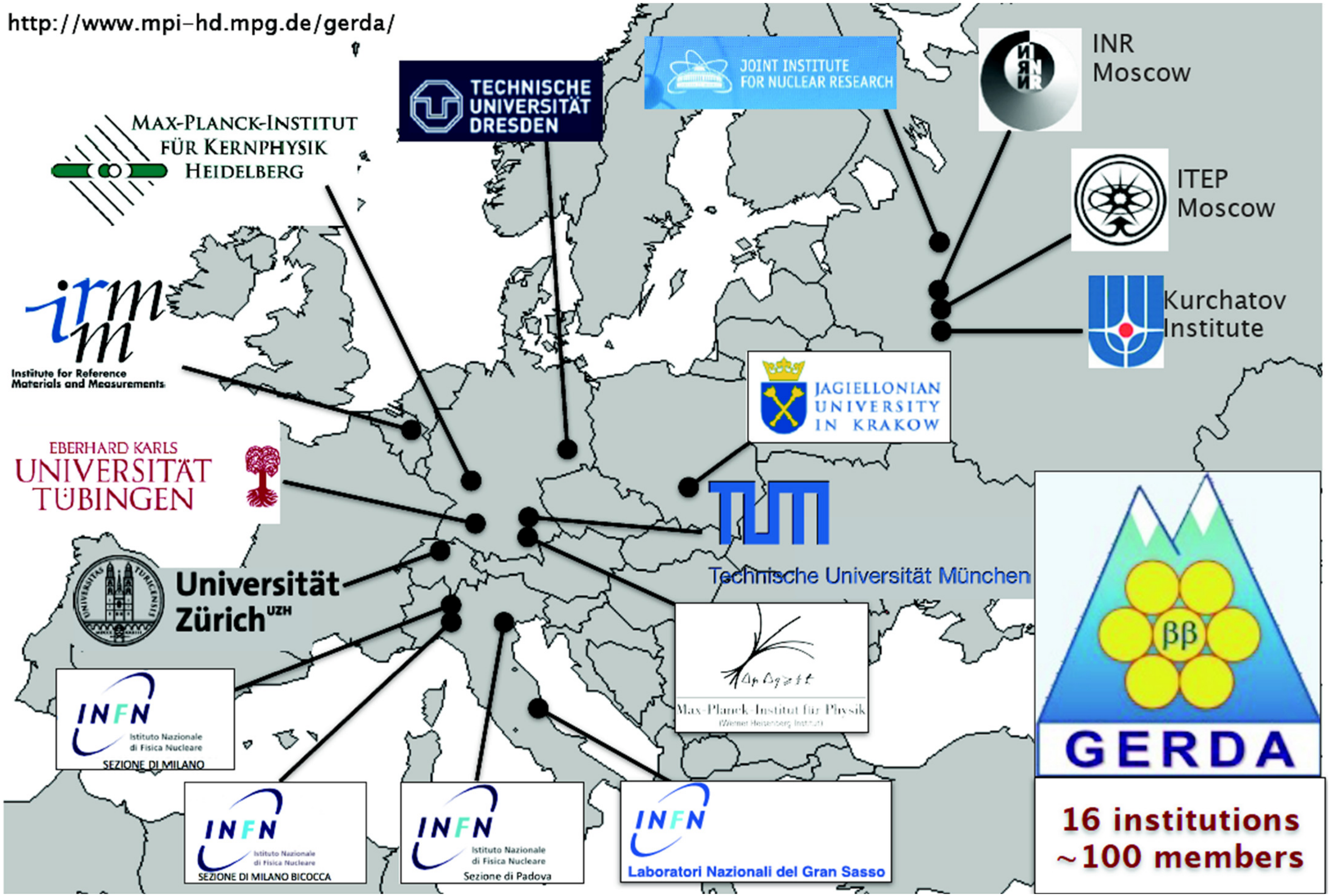


99.8 kg·yr ^{136}Xe exposure, $T_{1/2}$ > 1.1 x 10^{25} yr ($m_{\beta\beta}$ < 190 – 450 meV) 90 % CL.

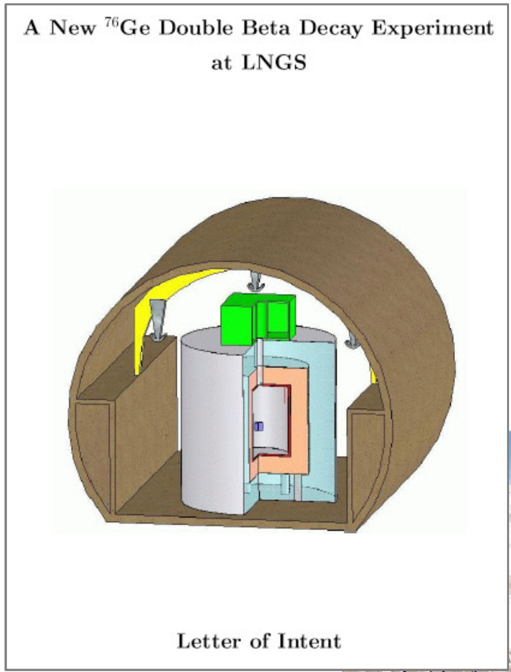
Sensitivity (90% CL) $T_{1/2}$ ~ 1.9 x 10^{25} yr, arXiv:1402.6956

Courtesy M. Marino, TUM

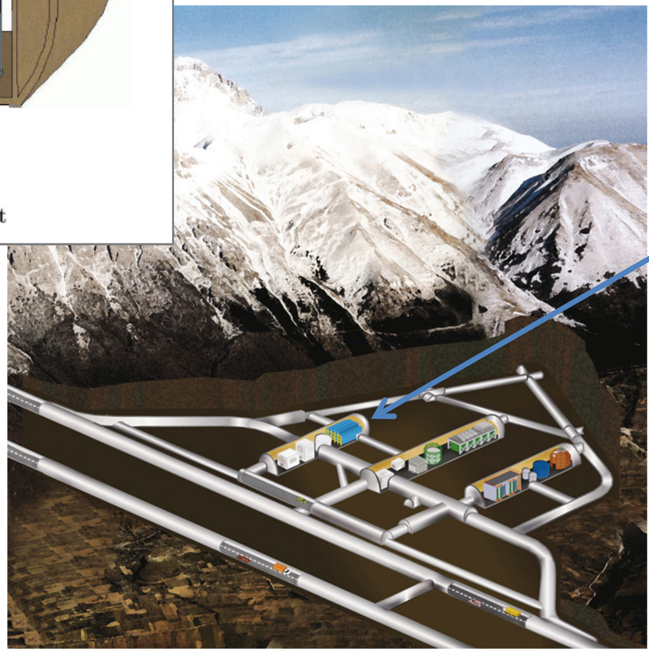
The GERDA collaboration

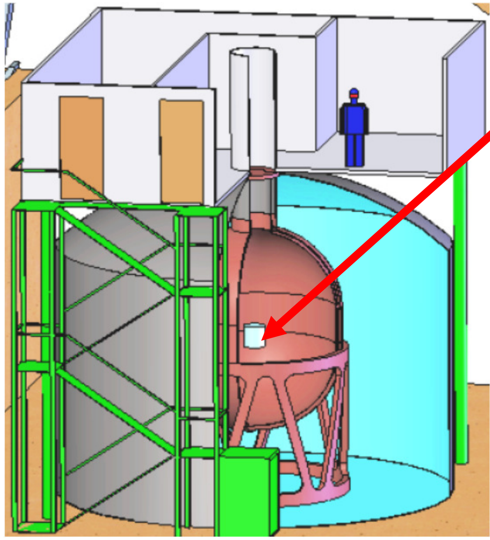


GERDA @ LNGS


A New ^{76}Ge Double Beta Decay Experiment at LNGS

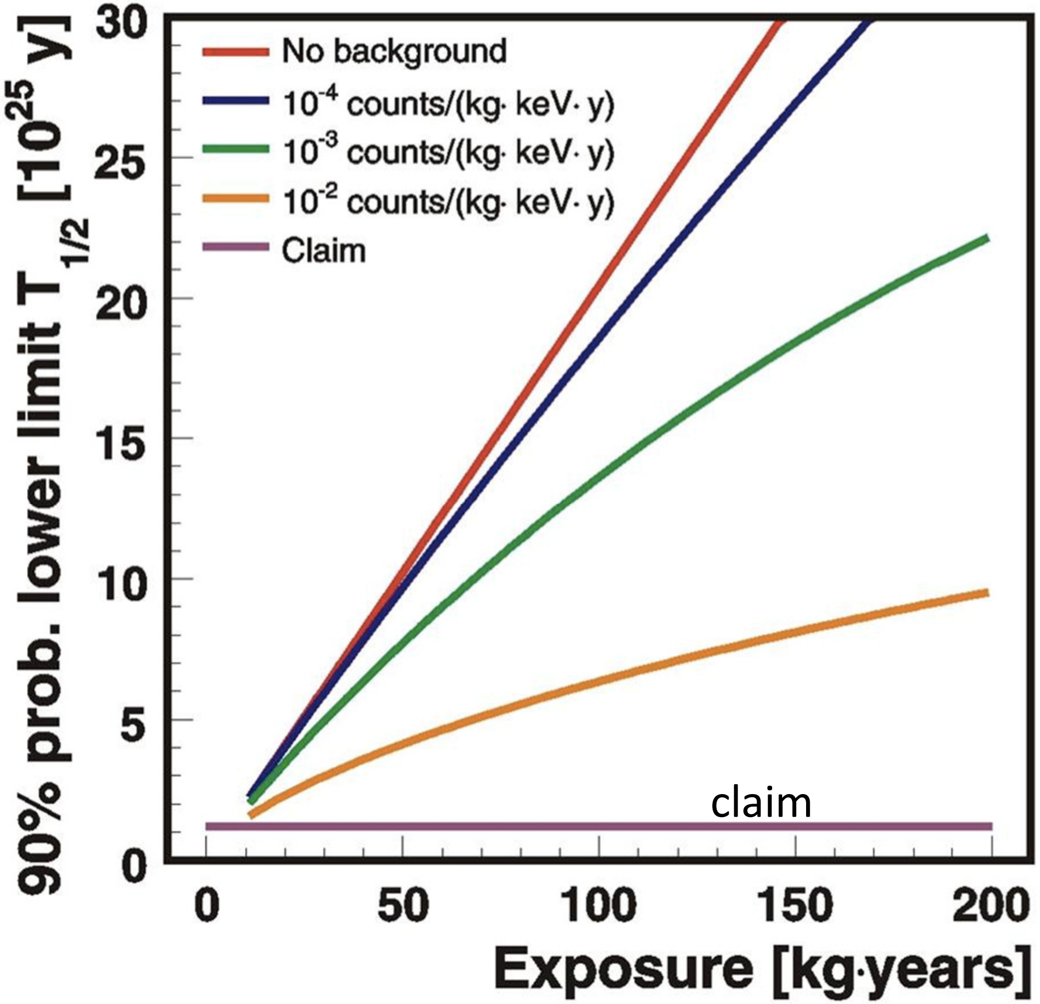
Letter of Intent



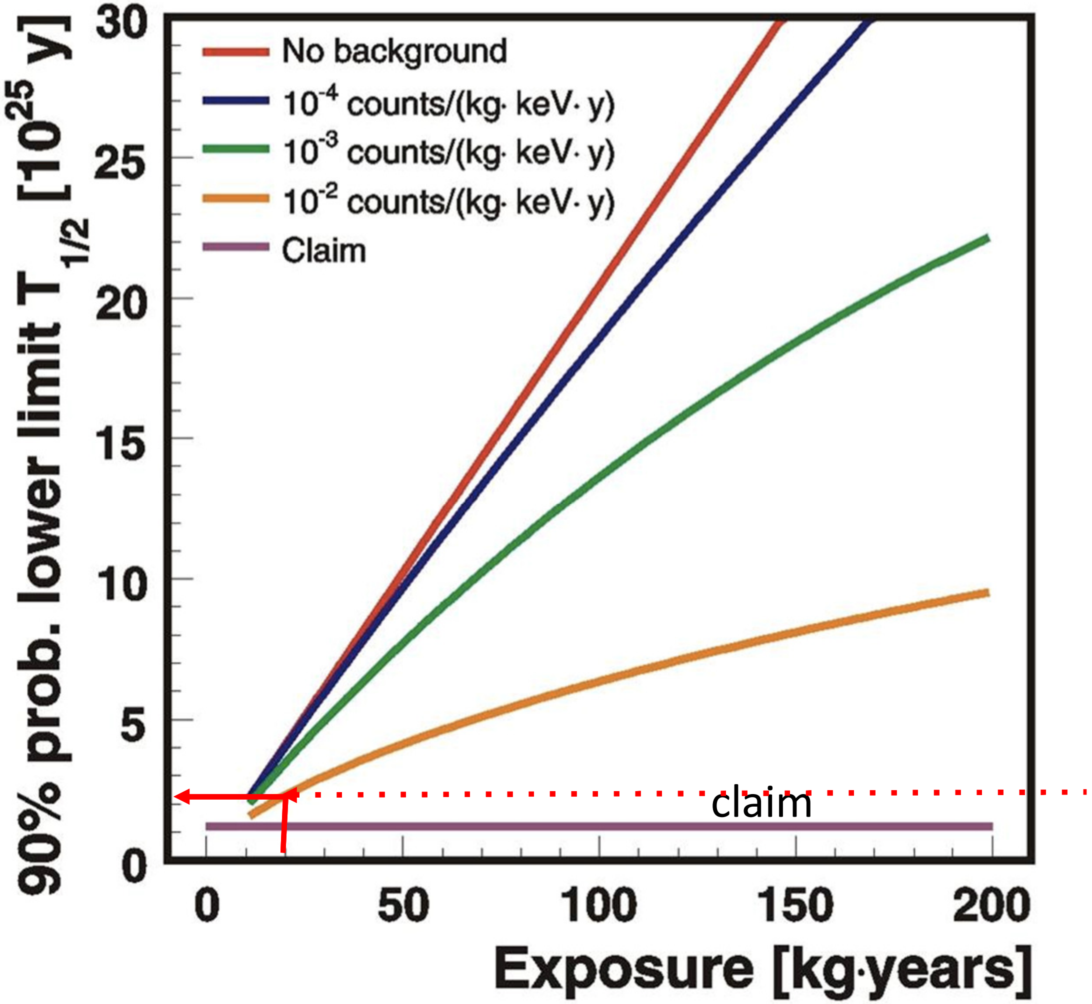


- 'Bare' ^{enr}Ge array in liquid argon
- Shield: high-purity liquid Argon / H_2O
- Phase I: 18 kg (HdM/IGEX)
- Phase II: add ~20 kg new enriched detectors

GERDA Phases



GERDA Phases

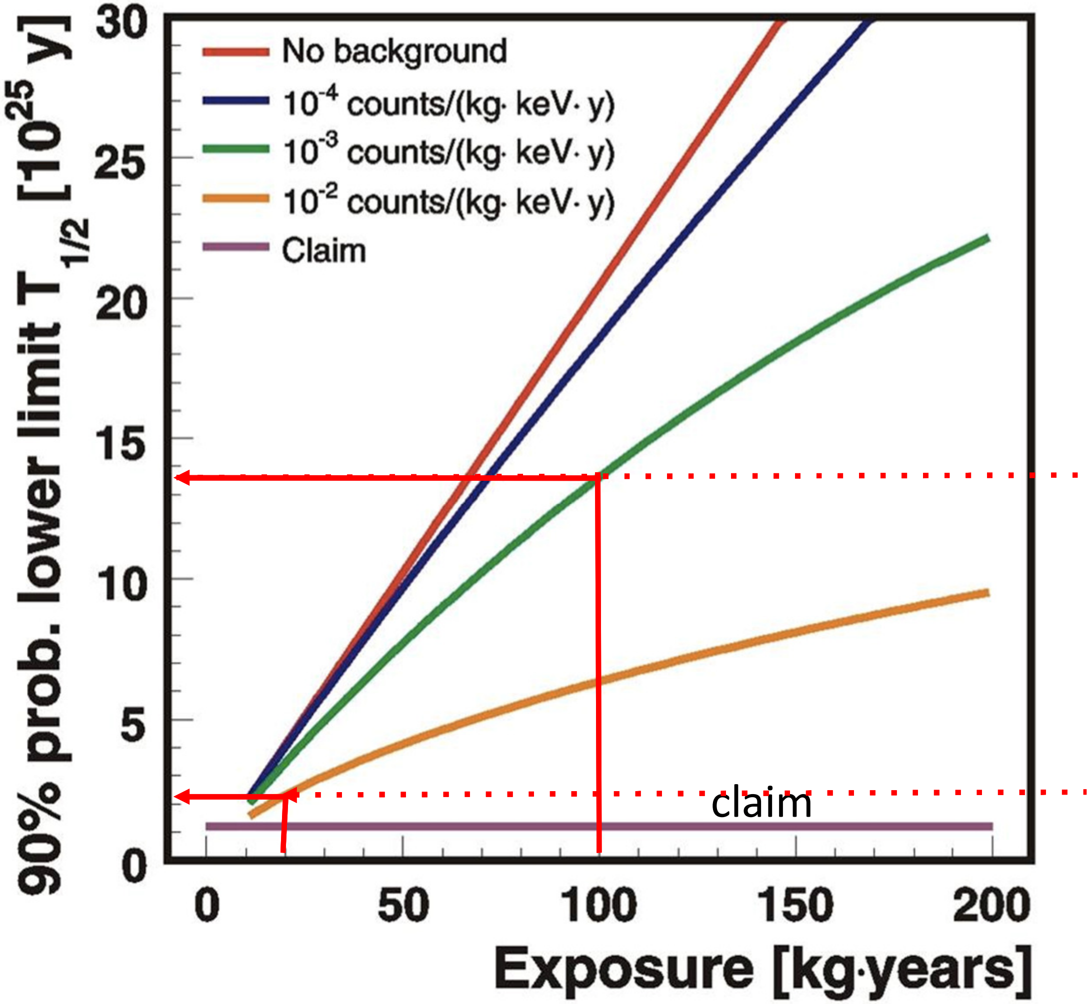


Phase I:

Use refurbished HdM & IGEX (18 kg)

BI ≈ 0.01 cts / (keV kg yr)

Sensitivity after 20 kg yr

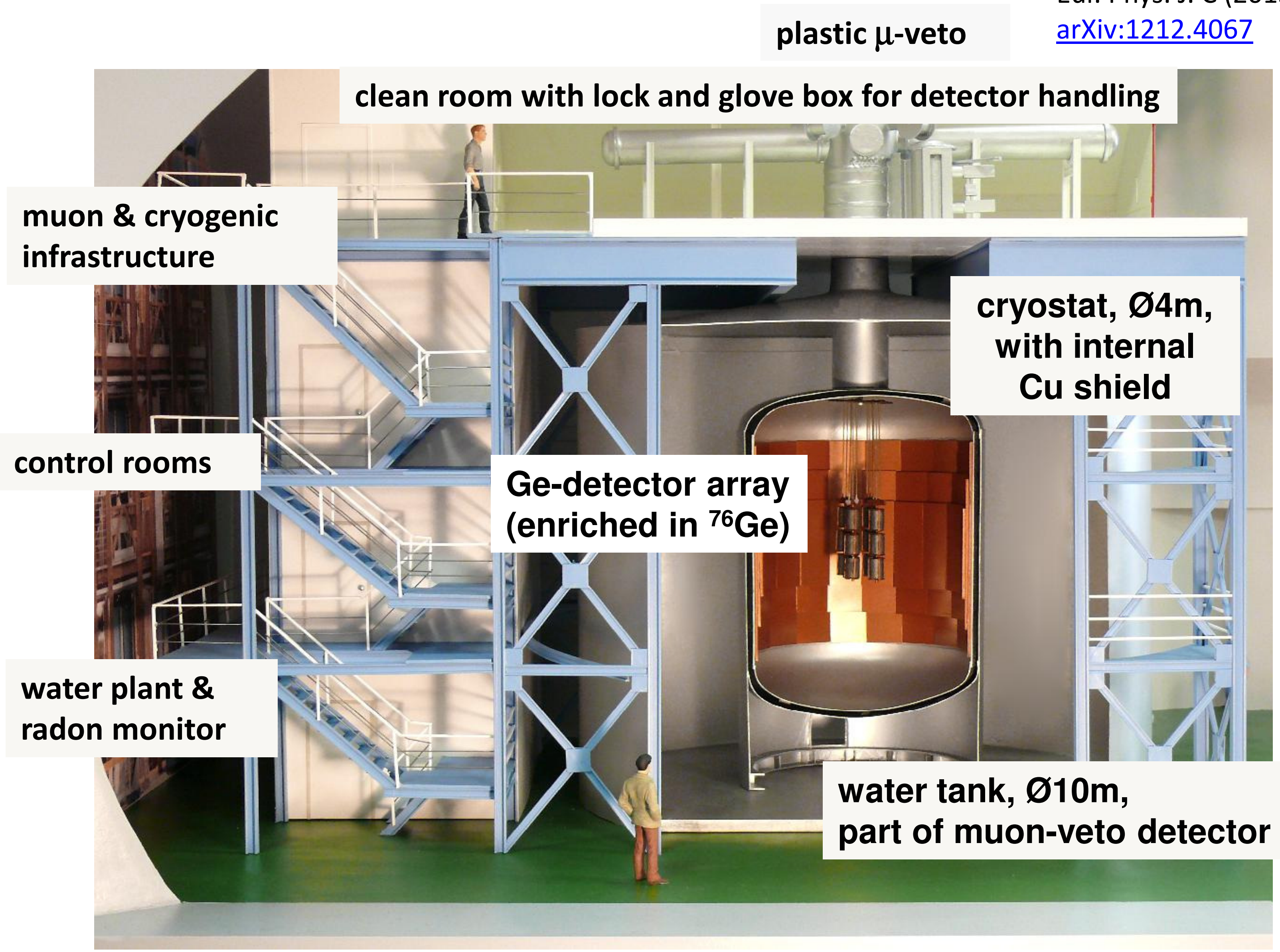


Phase II:
Add new enr. BEGe detectors (20 kg)
BI ≈ 0.001 cts / (keV kg yr)
Sensitivity after 100 kg yr

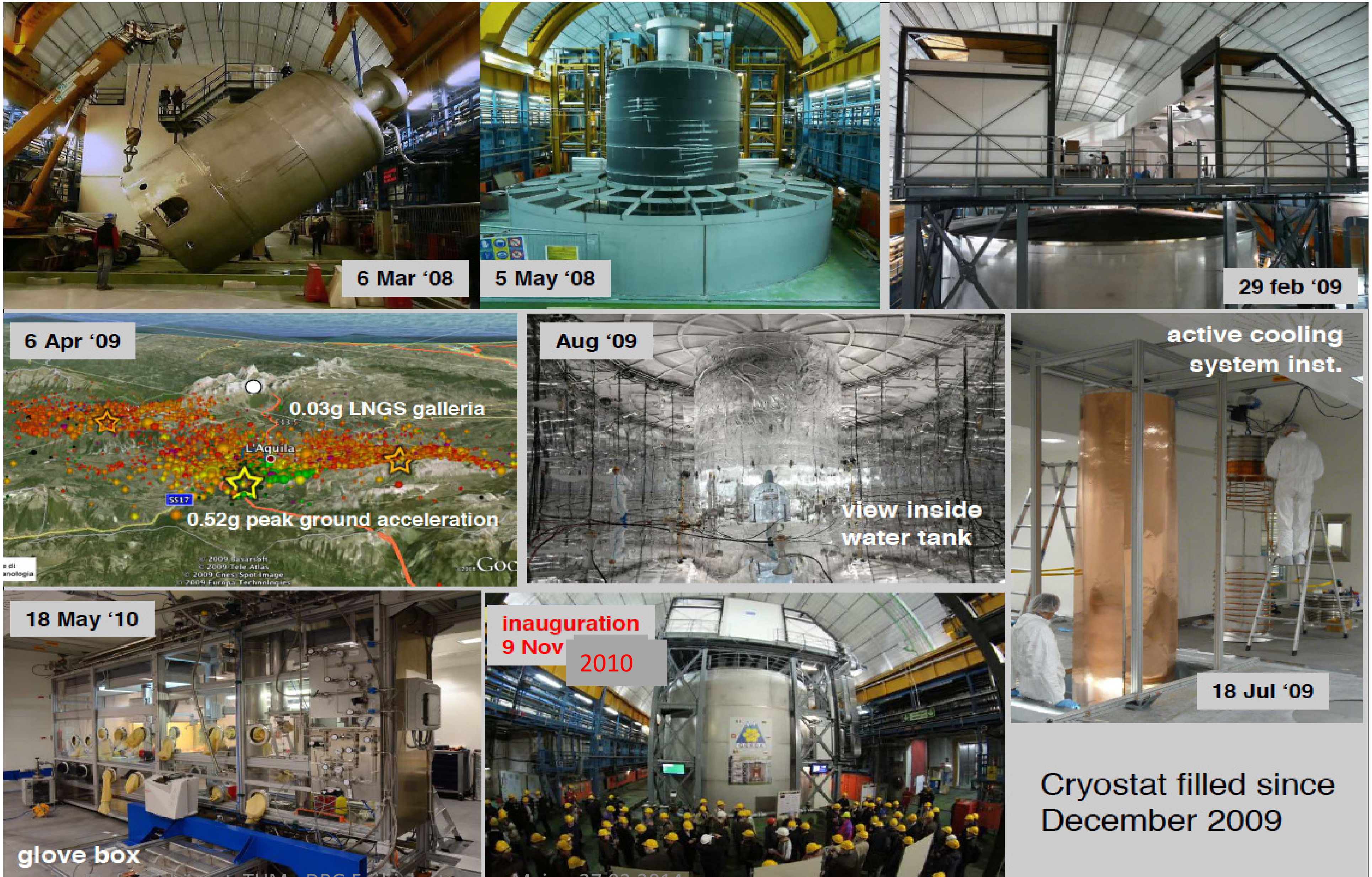
Phase I:
Use refurbished HdM & IGEX (18 kg)
BI ≈ 0.01 cts / (keV kg yr)
Sensitivity after 20 kg yr

The GERDA experiment

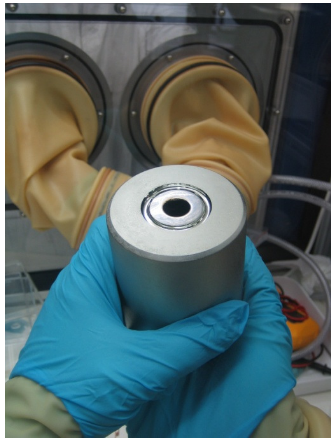
Eur. Phys. J. C (2013) 73:2330
arXiv:1212.4067



The GERDA construction 2008-2010



Nov 2011: deployment of 3-string & start of phase I physics runs

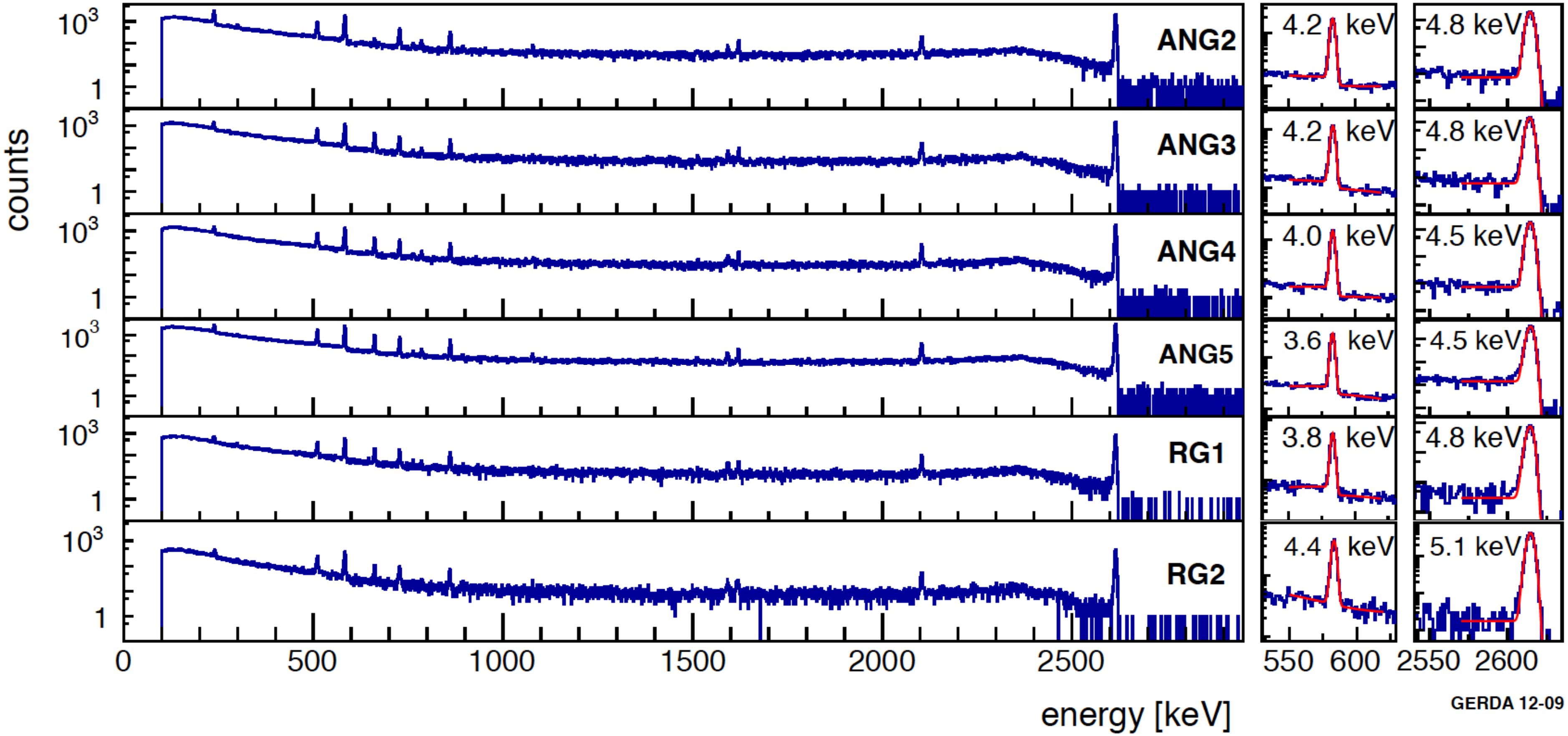


8 refurbished enriched diodes from HdM & IGEX
- 86% isotopically enriched in Ge-76
- 17.66 kg total mass
- plus 1 natural Ge diode from GTF

2 diodes shut off because leakage current high:
- total enriched enriched detector mass 14.6 kg

First calibration spectra

Eur. Phys. J. C (2013) 73:2330
arXiv:1212.4067



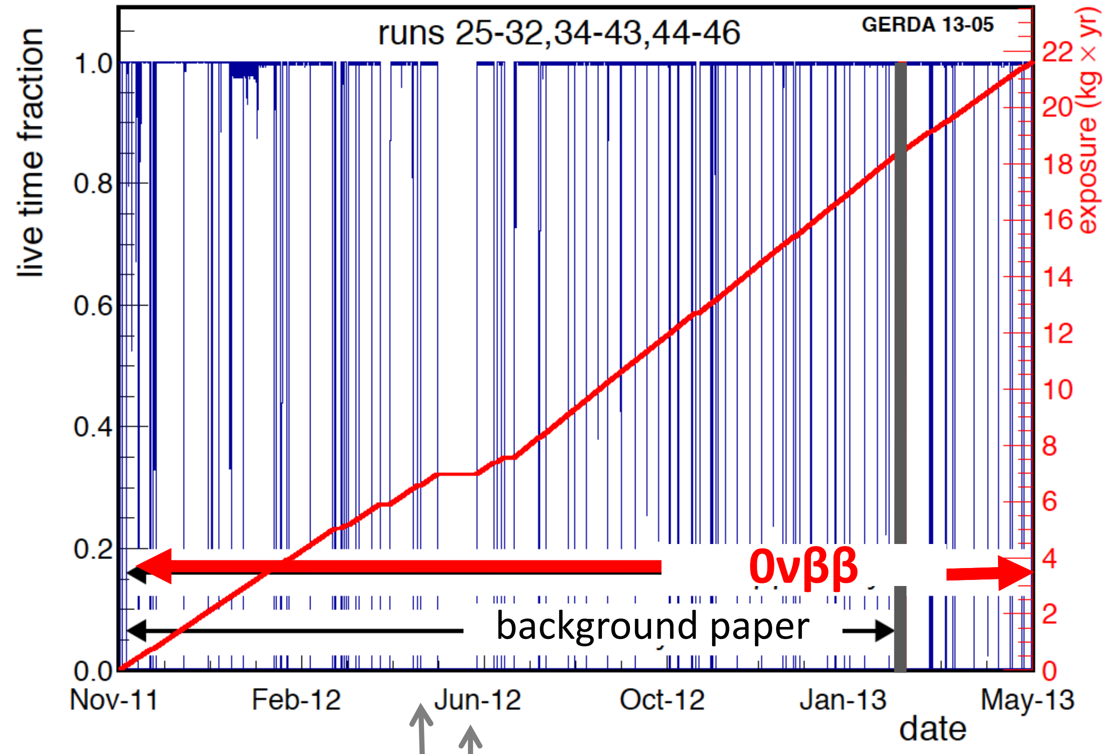
^{228}Th calibration once every one to two weeks; stability continuously monitored with pulser

Overview of data taking

Eur. Phys. J. C (2013) 73:2330
arXiv:1212.4067

Total exposure for 0νββ analysis: 21.6 kg yr

(bi-)weekly calibration runs ('spikes')



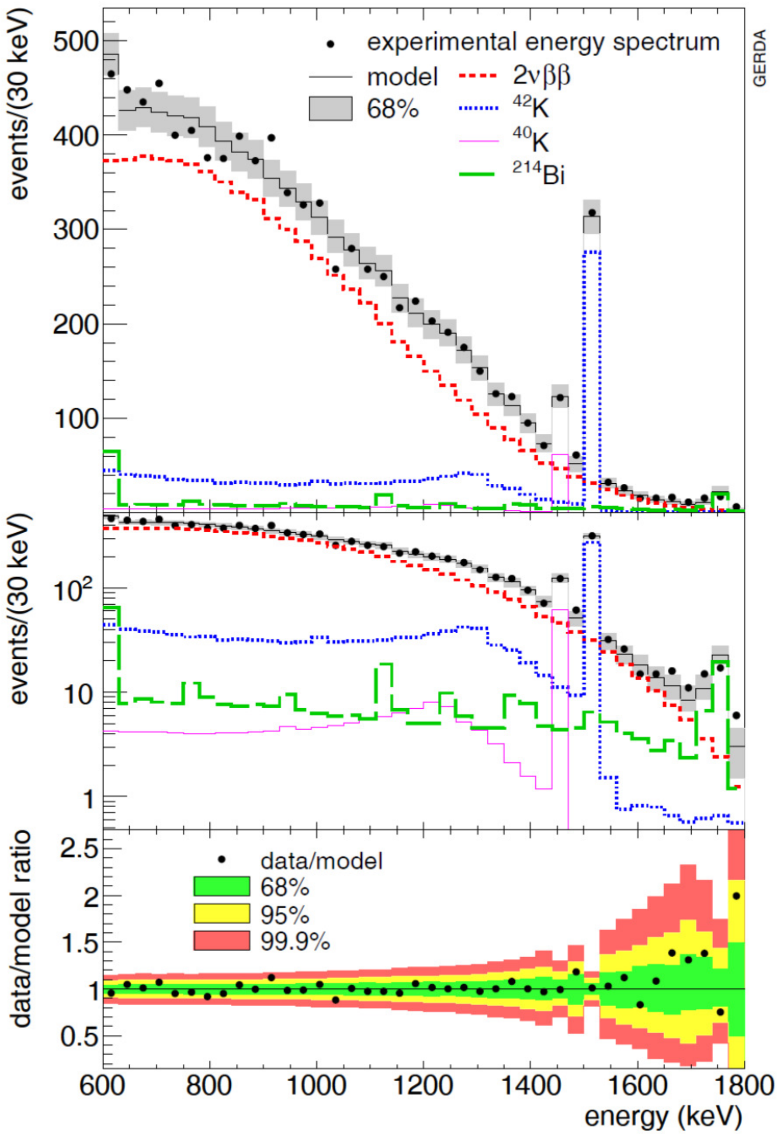
Insertion of 5 Phase II enrBEGe

1st physics: 2νββ analysis (5.04 kg yr)

Data blinding:

- All events in $Q_{\beta\beta}$±20 keV removed in Tier 1
- 2 copies of raw data kept for processing after unblinding

Measurement of $T^{2\nu}_{1/2}$ (^{76}Ge)

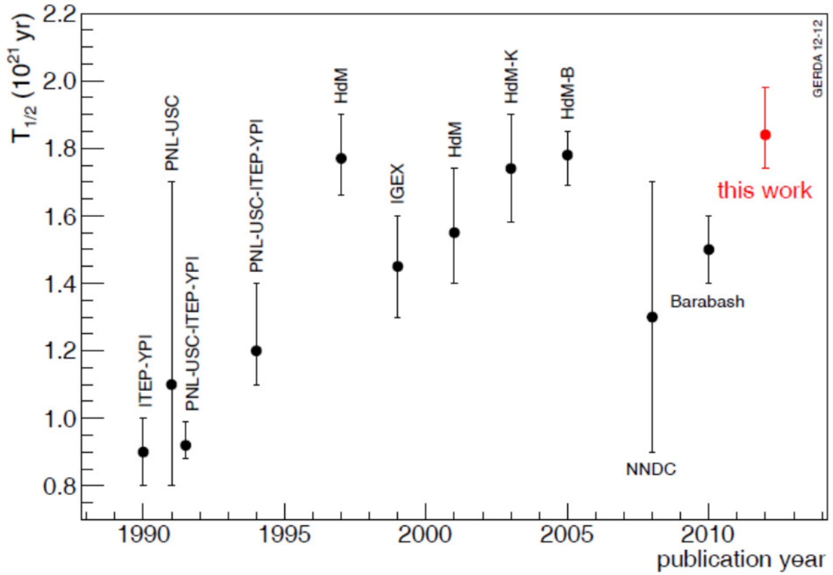


IOP PUBLISHING JOURNAL OF PHYSICS G: NUCLEAR AND PARTICLE PHYSICS

J. Phys. G: Nucl. Part. Phys. **40** (2013) 035110 (13pp) doi:10.1088/0954-3899/40/3/035110

Measurement of the half-life of the two-neutrino double beta decay of ^{76}Ge with the GERDA experiment (with 5.04 kg yr exposure)

$T^{2\nu}_{1/2}(^{76}Ge) = (1.84^{+0.14}_{-0.10}) \cdot 10^{21}$ yr

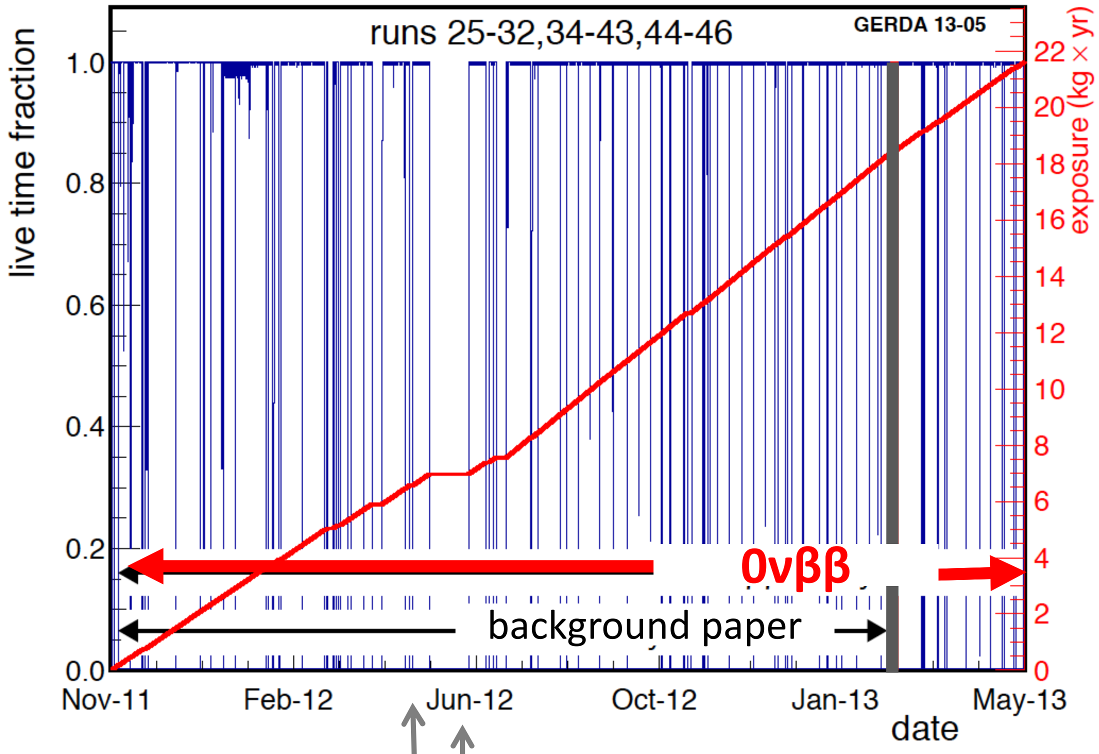


LAB Talk of J. Phys. G Feb. 2013 issue:
http://iopscience.iop.org/0954-3899/labtalk-article/52398

Overview of data taking

Eur. Phys. J. C (2013) 73:2330
arXiv:1212.4067

Total exposure for 0νββ analysis: 21.6 kg yr
(bi-)weekly calibration runs ('spikes')

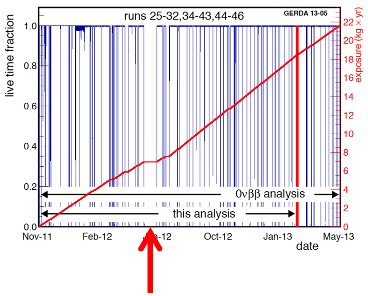


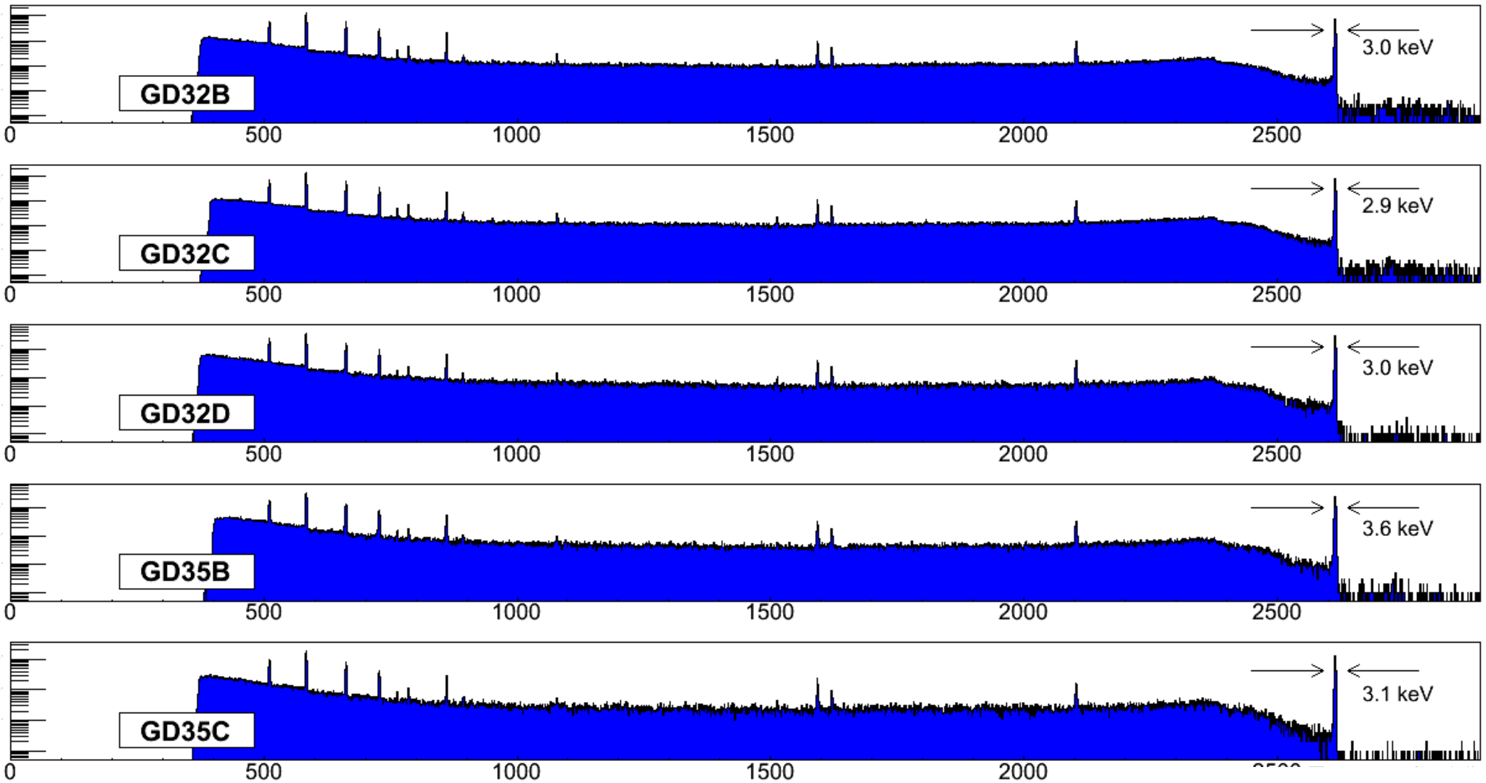
Insertion of 5 Phase II ^{enr}BEGe

1st physics: 2νββ analysis (5.04 kg yr)

Data blinding:
- All events in $Q_{\beta\beta}$±20 keV removed in Tier 1
- 2 copies of raw data kept for processing after unblinding

June 2012: 5 ^{enr}BEGe Phase II detectors deployed in GERDA



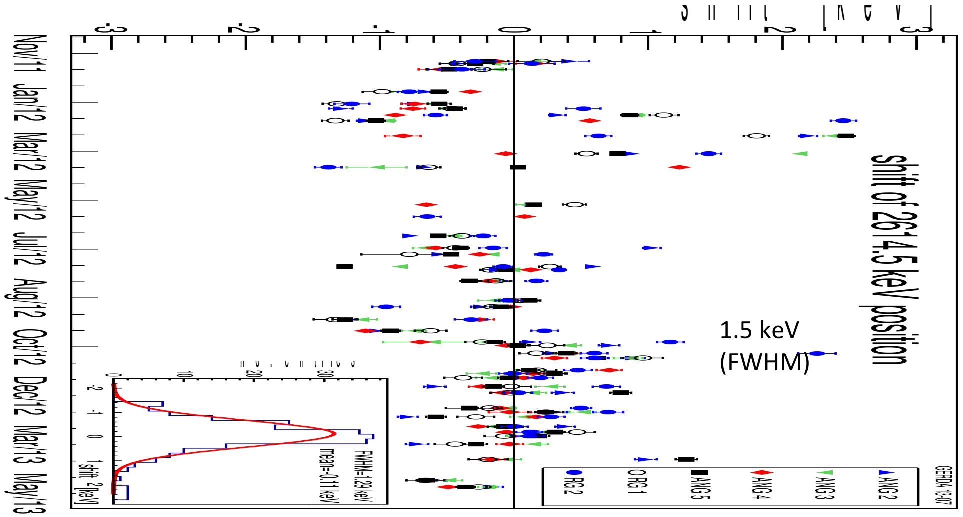


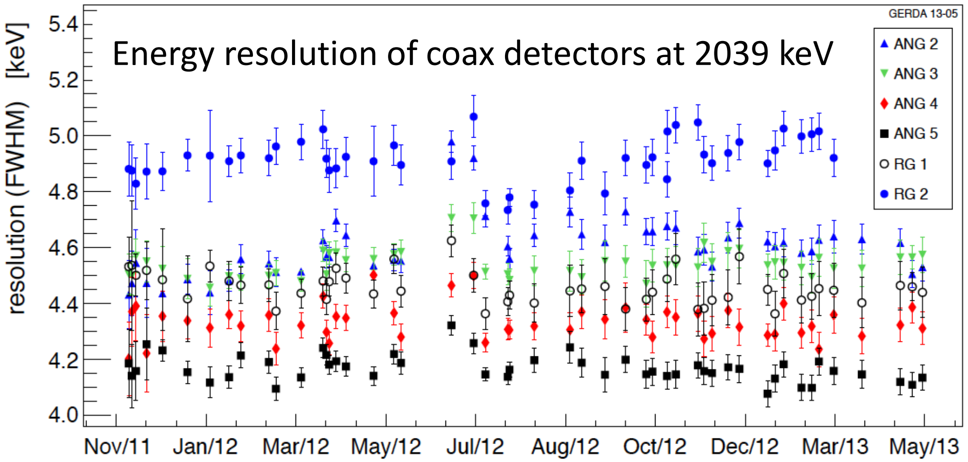
Energy (keV)

Calibration: stability of HPGe detectors

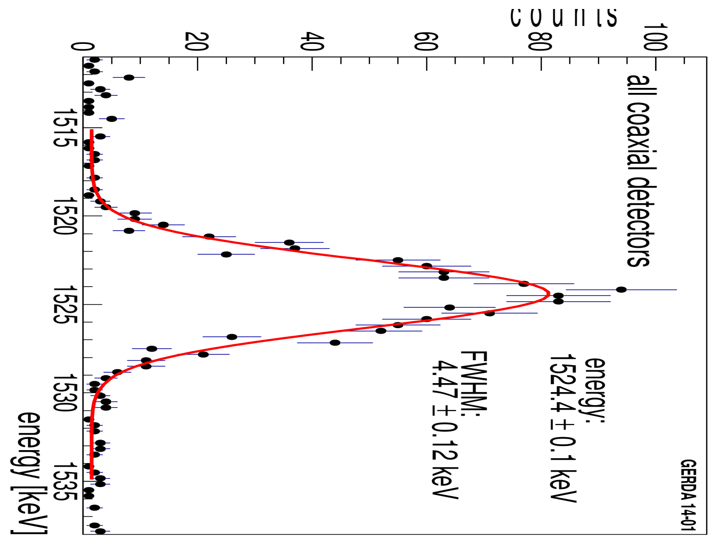
[arXiv:1306.5084](https://arxiv.org/abs/1306.5084)

Peak position stability of 2614.5 keV calibration line:
coax: 1.5 keV / BEGe: 1.0 keV (FWHM)





<u>Summing all runs:</u>



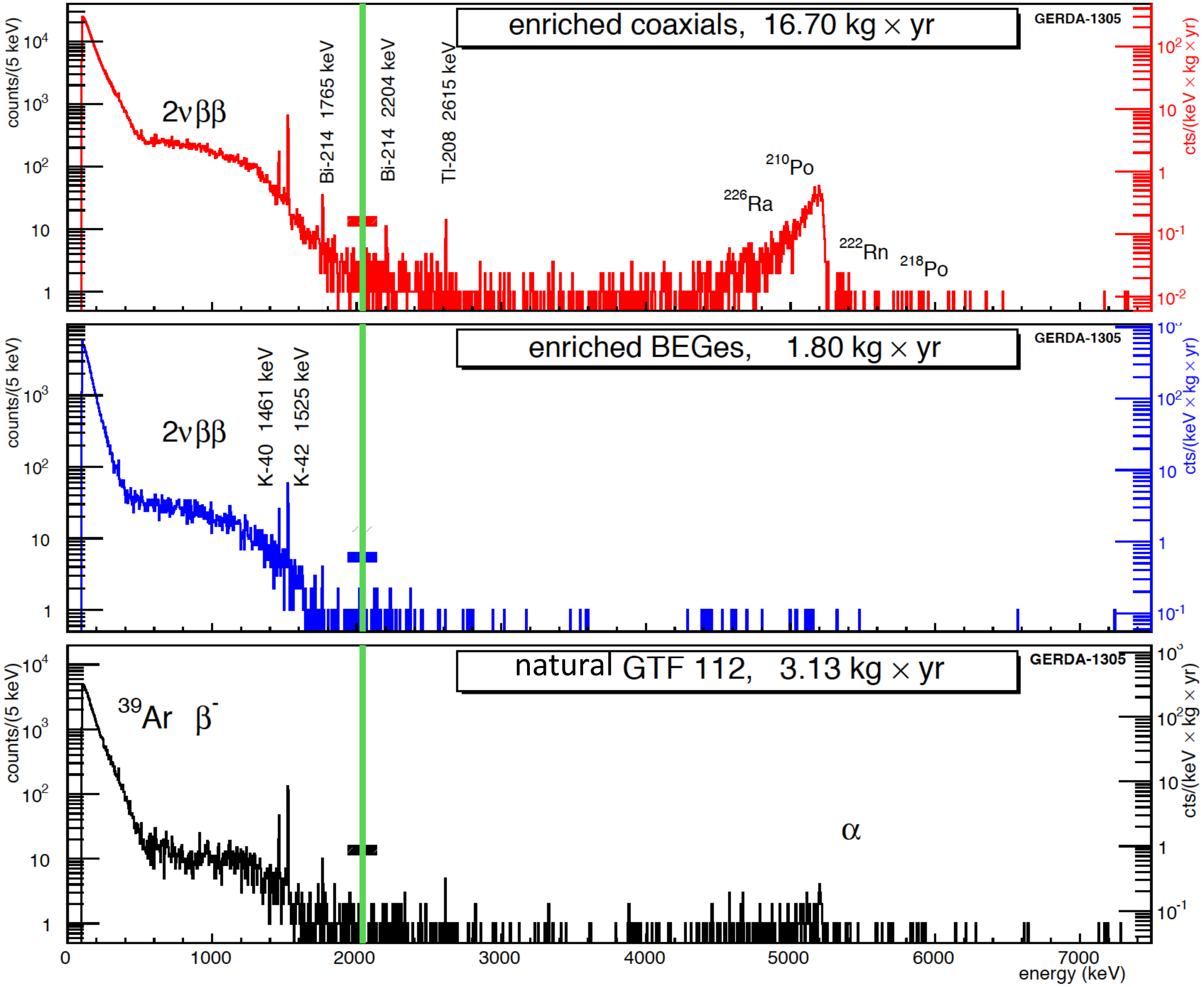
Mean energy resolution at $Q_{\beta\beta}$ =2039 keV:

- Coax: 4.8 keV (FHWM)
- BEGe: 3.2 keV (FWHM)

detector	FWHM [keV]	detector	FWHM [keV]
SUM-coax		*SUM-bege*	
ANG 2	5.8 (3)	GD32B	2.6 (1)
ANG 3	4.5 (1)	GD32C	2.6 (1)
ANG 4	4.9 (3)	GD32D	3.7 (5)
ANG 5	4.2 (1)	GD35B	4.0 (1)
RG 1	4.5 (3)		
RG 2	4.9 (3)		
mean coax	4.8 (2)	mean BEGe	3.2 (2)

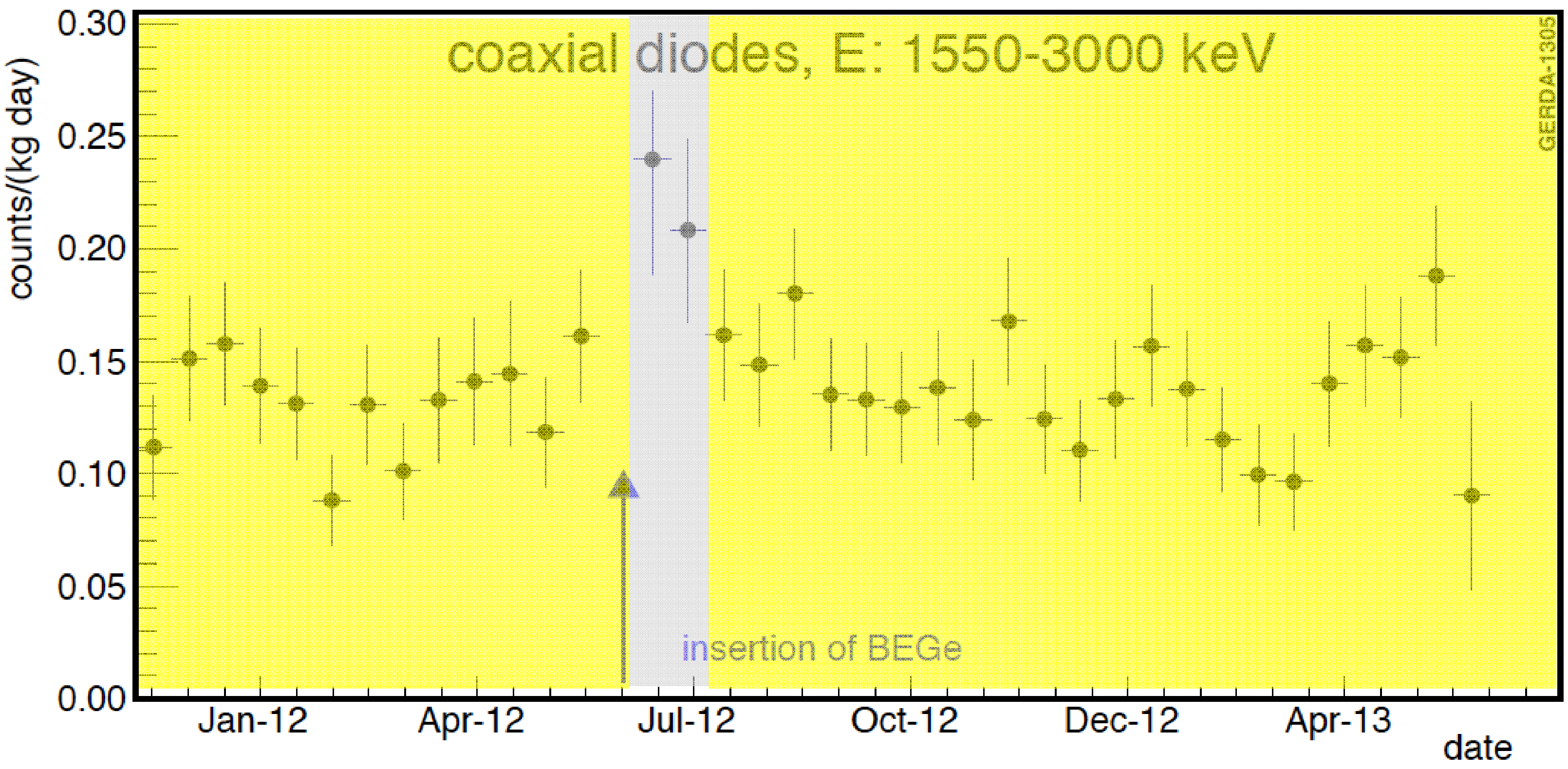
Physics run: energy spectra

arXiv:1306.5084
(In print EPJ)



Physics run: background rate as function of time

arXiv:1306.5084

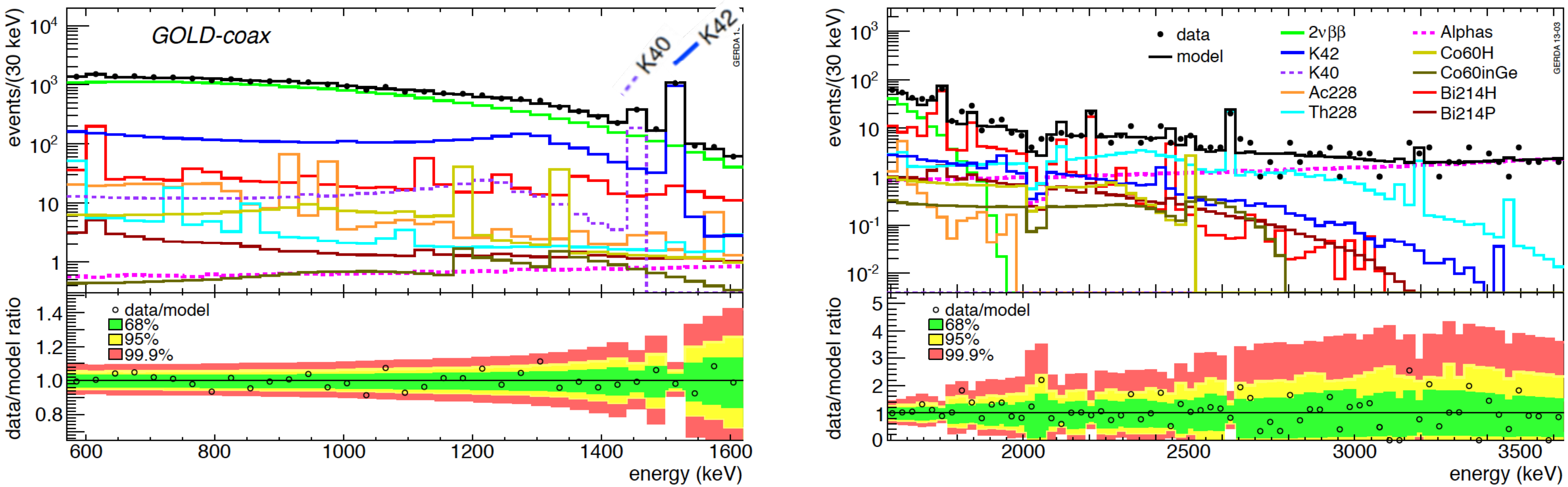


Coax-detector data set split in 'Gold' and 'Silver' (30 d)

Physics run: background decomposition

arXiv:1306.5084

Fit of minimal background model to complete energy spectrum

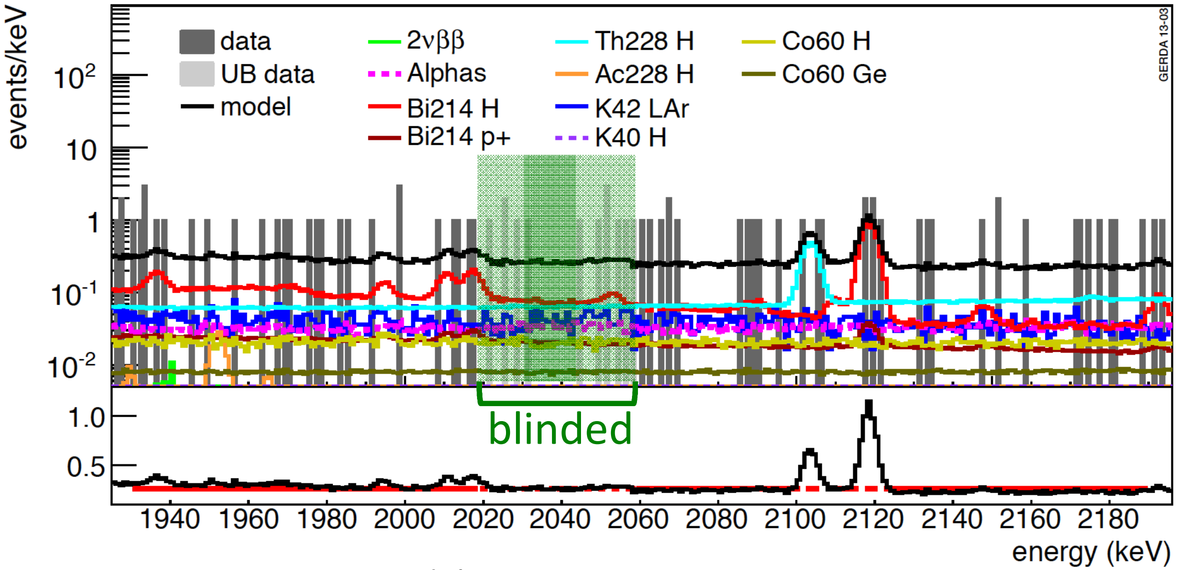


- “Minimal Model” is sufficient to describe data well
- “Maximum Model” includes ^{42}K on p+ and n+ contacts, ^{214}Bi in LAr & far sources

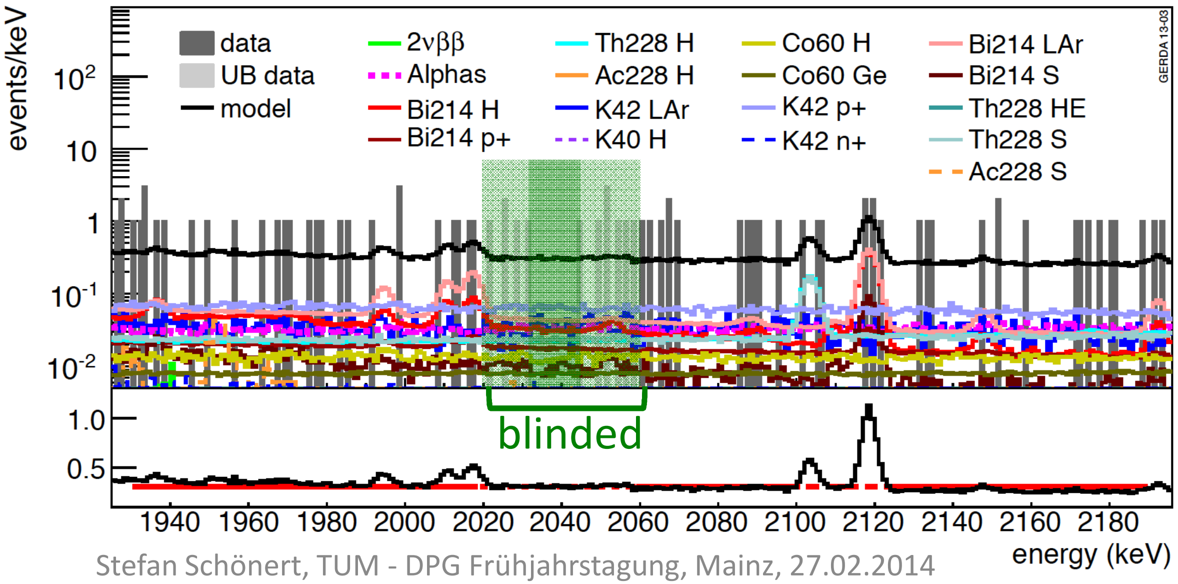
Physics run: background model and prediction of BI at $Q_{\beta\beta}$

arXiv:1306.5084

Minimal model



Maximum model



Background model:

- No background peak expected around $Q_{\beta\beta}$
- Spectrum can be modeled with flat background (red line) in 1930-2190 keV excluding known peaks at 2104 and 2119 keV
- Background index (BI) at $Q_{\beta\beta}$ (17.6-23.8) 10^{-3} cts/(keV kg yr) depending on assumptions for location of sources
- Statistical uncertainty of BI from interpolation coincides numerically with systematic uncertainty from model
- Prediction for 30 keV BW:
  Min./Max Mod: 8.2-9.1 / 9.7-11.1
  observed.: 13

➔ fit with constant background 1930-2190 keV excluding peaks

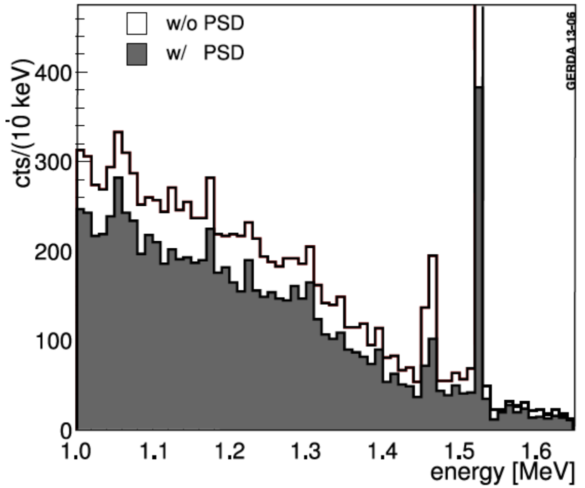
Pulse shape discrimination: method and cuts fixed prior unblinding

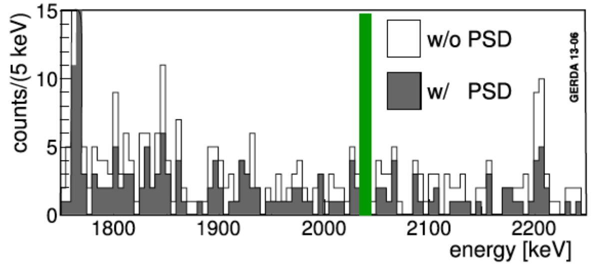
Coaxial detectors:

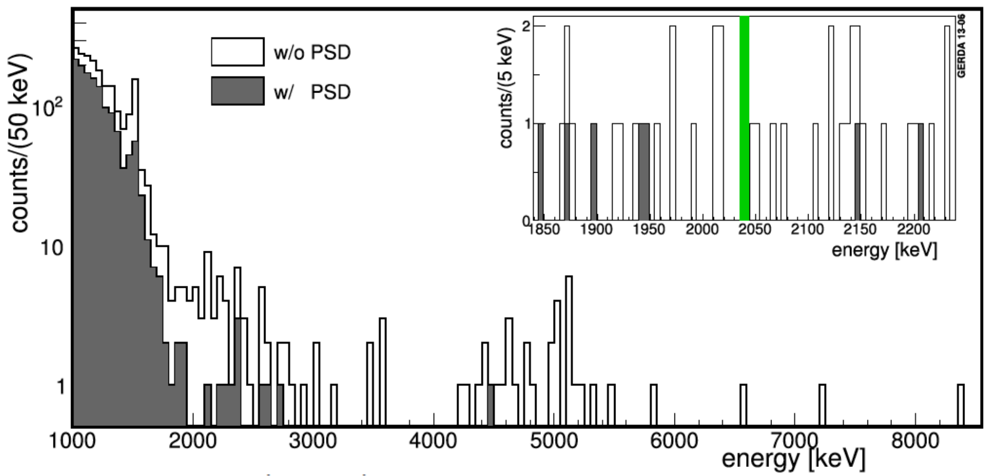
- artificial neural network TMIpANN
- cut defined using ^{228}Th calibration data
  cut fixed to 90% acceptance of 2.6 MeV DEP
- cross checks:
  - $2\nu\beta\beta$ acc. = (85±2)%
  - 2.6 MeV γ-line compton-edge acc. = 85-94%
  - Co-56 DEP (1576 & 2231 keV) acc. = 83-95%

$0\nu\beta\beta$ acceptance $= 90^{+5}_{-9}\%$

background acc at $Q_{\beta\beta} = \sim 45\%$







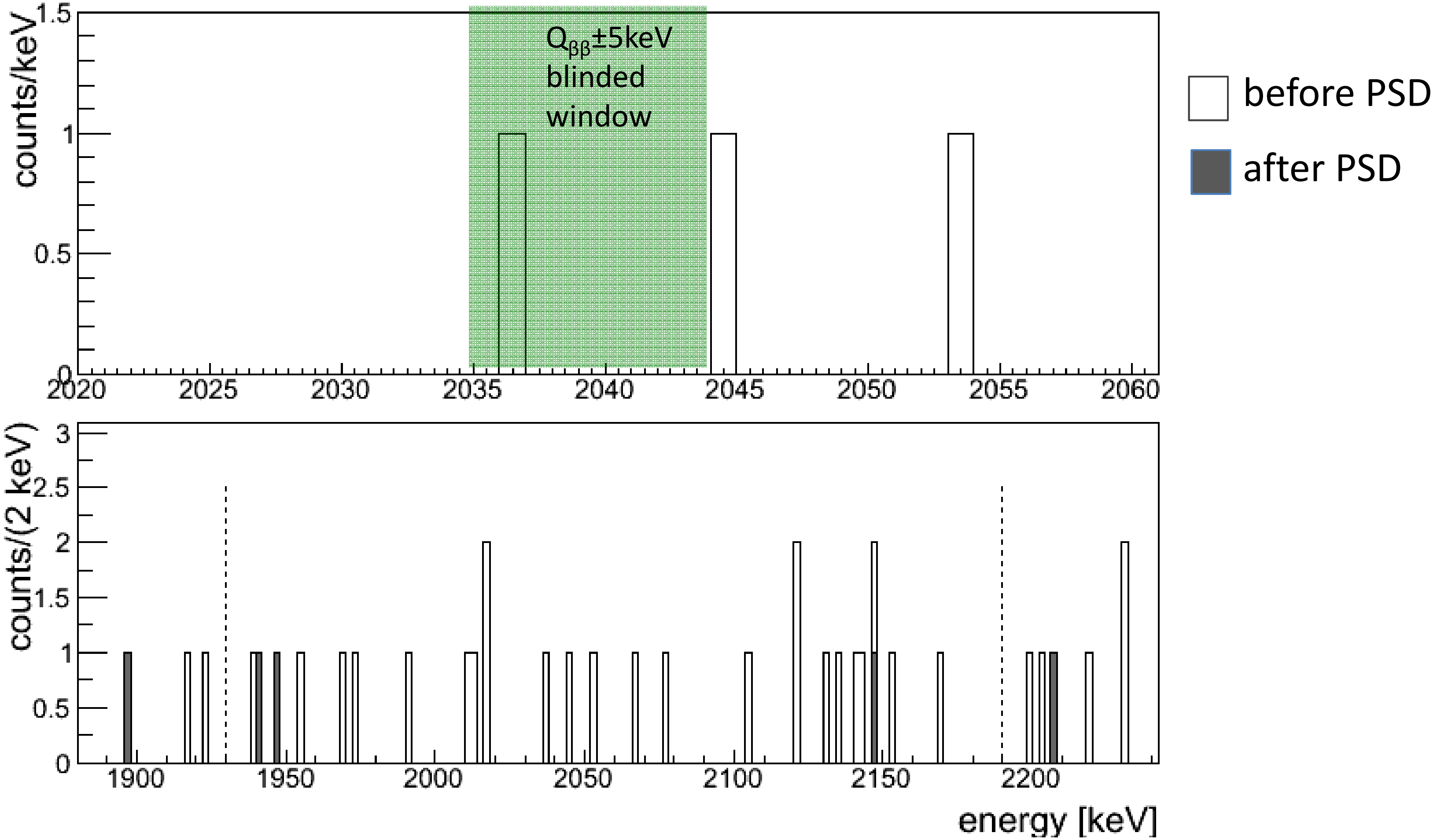
BEGe detectors:

- A/E method (mono-parametric PSD)
- $0\nu\beta\beta$ acc (DEP and simulations) (92±2)%
- $2\nu\beta\beta$ acc (91±5)%
- background acc at $Q_{\beta\beta} \leq 20\%$

more details in [Eur.Phys.J C73 (2013) 2583]

Unblinding: BEGe data set (2.4 kg yr)

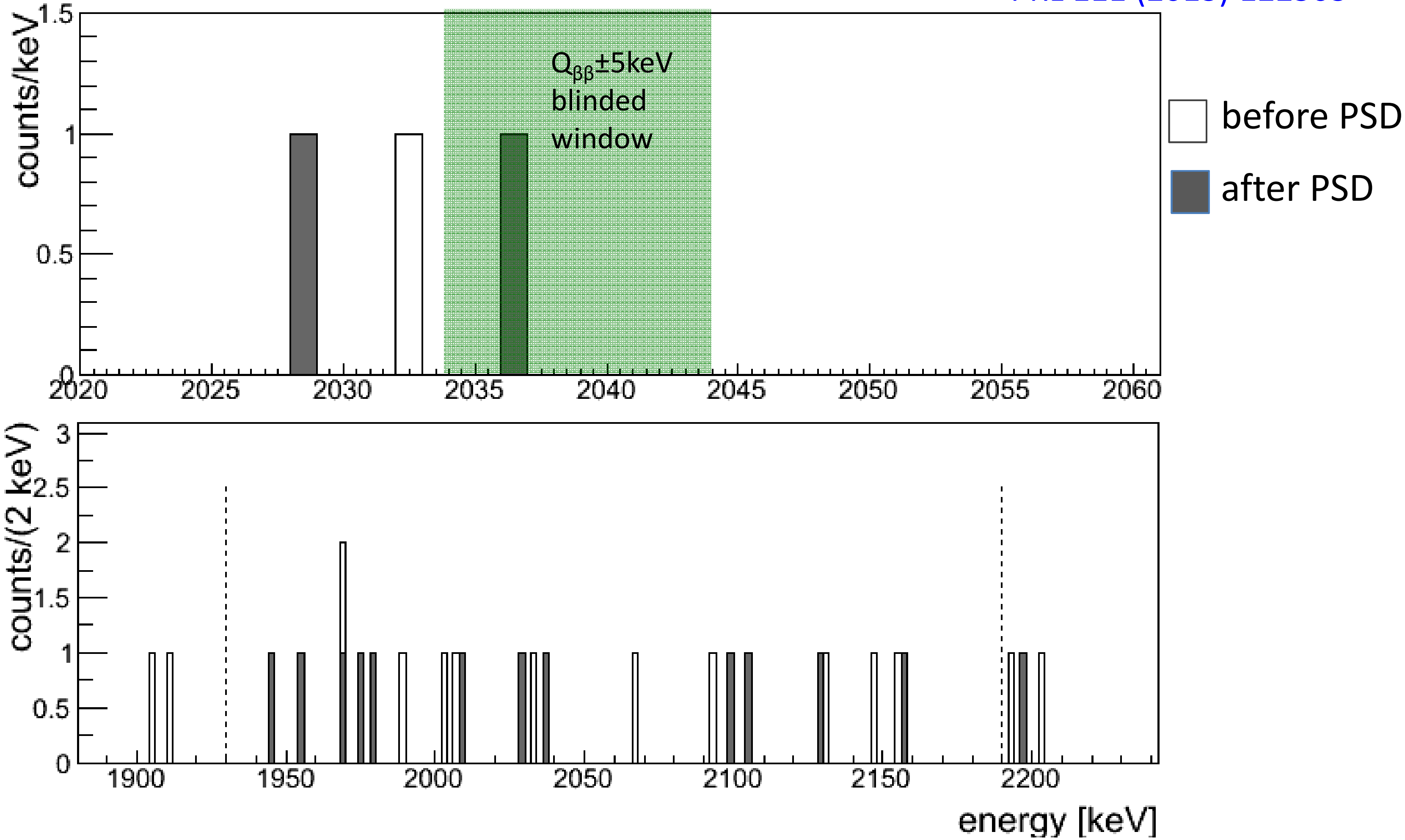
PRL 111 (2013) 122503



BEGe data set: 1 event in blinded window
0 event survive PSD cut

Unblinding: silver-coax data set (1.3 kg yr)

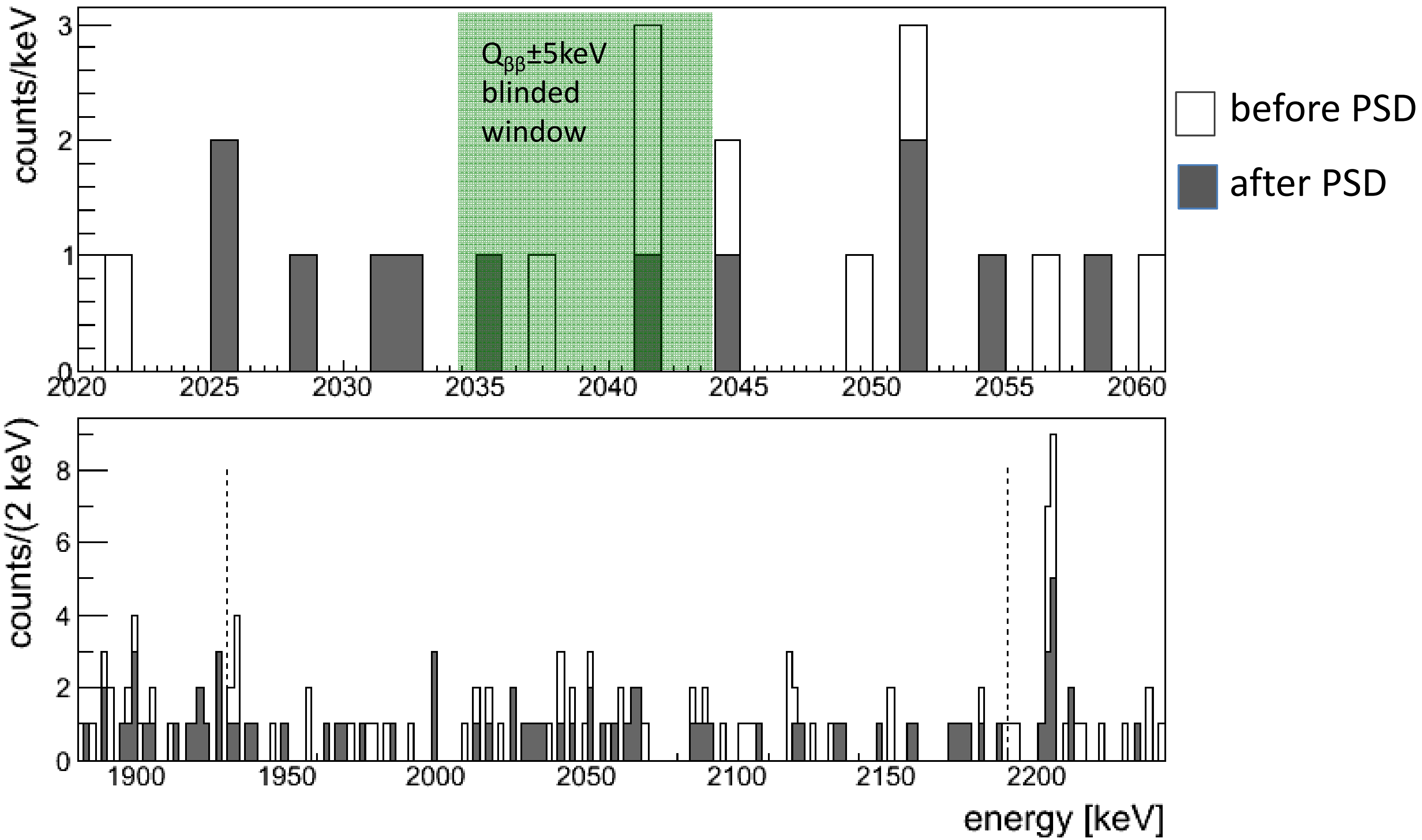
PRL 111 (2013) 122503



Silver data set:	1 event in blinded window
	1 event survives PSD cut

Unblinding: golden-coax data set (17.9 kg yr)

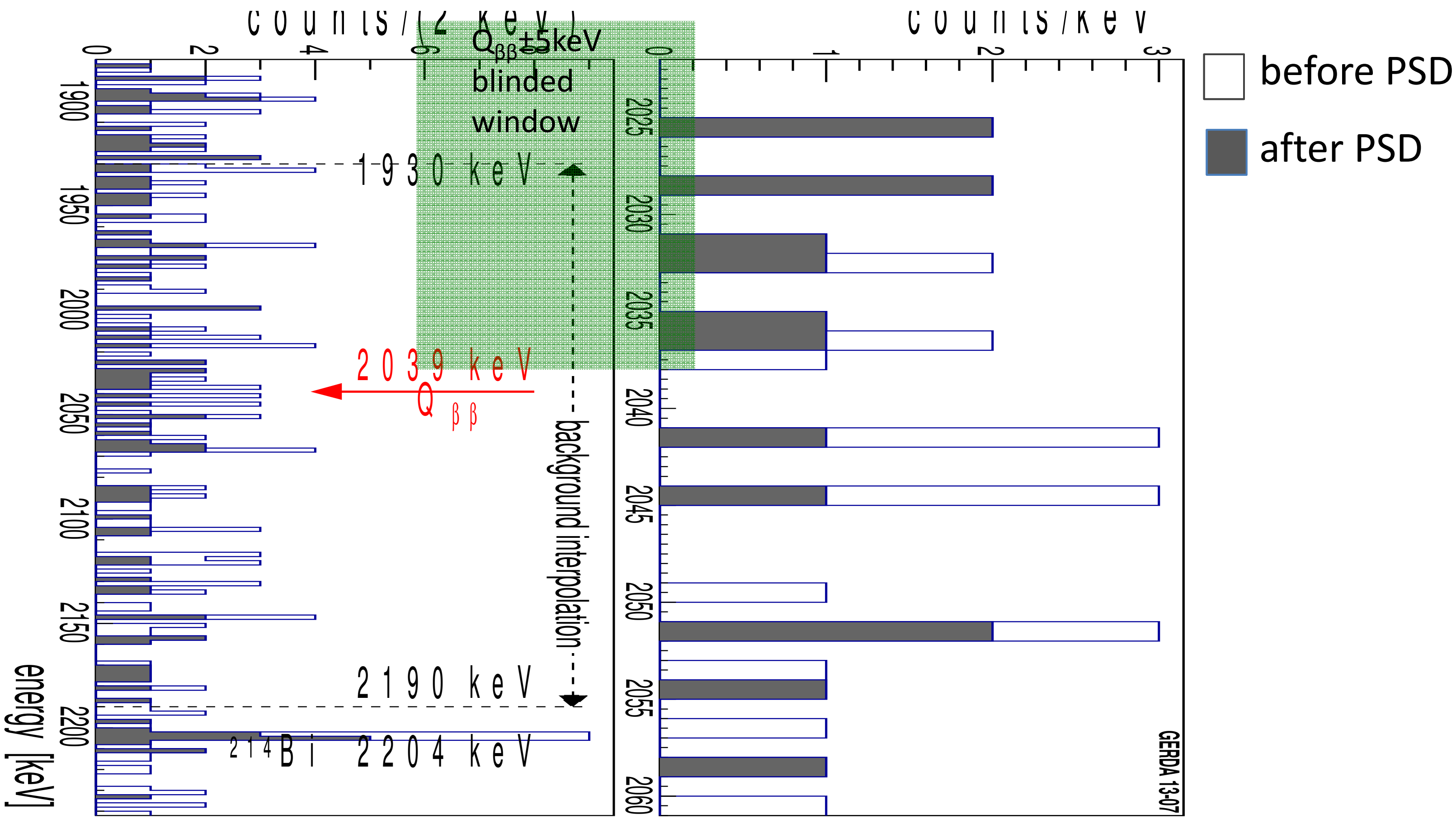
PRL 111 (2013) 122503



Golden data set: 5 event in blinded window
2 event survive PSD cut

Unbinding: full data set (21.6 kg yr)

PRL 111 (2013) 122503



Full data set: 7 event in blinded window
3 event survive PSD cut

Parameters of 3 data sets and counts in blinded window

PRL 111 (2013) 122503

data set	$\mathcal{E}$[kg·yr]	$\langle\epsilon\rangle$	bkg (in 230 keV)	BI †)	cts
without PSD					
golden	17.9	0.688 ± 0.031	76	18 ± 2	5
silver	1.3	0.688 ± 0.031	19	63^{+16}_{-14}	1
BEGe	2.4	0.720 ± 0.018	23	42^{+10}_{-8}	1
with PSD					
golden	17.9	$0.619^{+0.044}_{-0.070}$	45	11 ± 2	2
silver	1.3	$0.619^{+0.044}_{-0.070}$	9	30^{+11}_{-9}	1
BEGe	2.4	0.663 ± 0.022	3	5^{+4}_{-3}	0

†) in units of 10^{-3} cts/(keV·kg·yr).

Counts in blinded window (BW)

Total counts in BW	Expected (bgd only)	Observed
without PSD	5.1	7
with PSD	2.5	3

From counts to half-life

PRL 111 (2013) 122503

$$T^{0\nu}_{1/2} = \frac{\ln 2 \cdot N_A}{m_{enr} \cdot N^{0\nu}} \cdot \mathcal{E} \cdot \epsilon$$

$$\epsilon = f_{76} \cdot f_{av} \cdot \varepsilon_{fep} \cdot \varepsilon_{psd}$$

N_A: Avogadro number
E: exposure
ε: exposure averaged efficiency
m_{enr}: molar mass of enriched Ge
$N^{0\nu}$: signal counts / limit

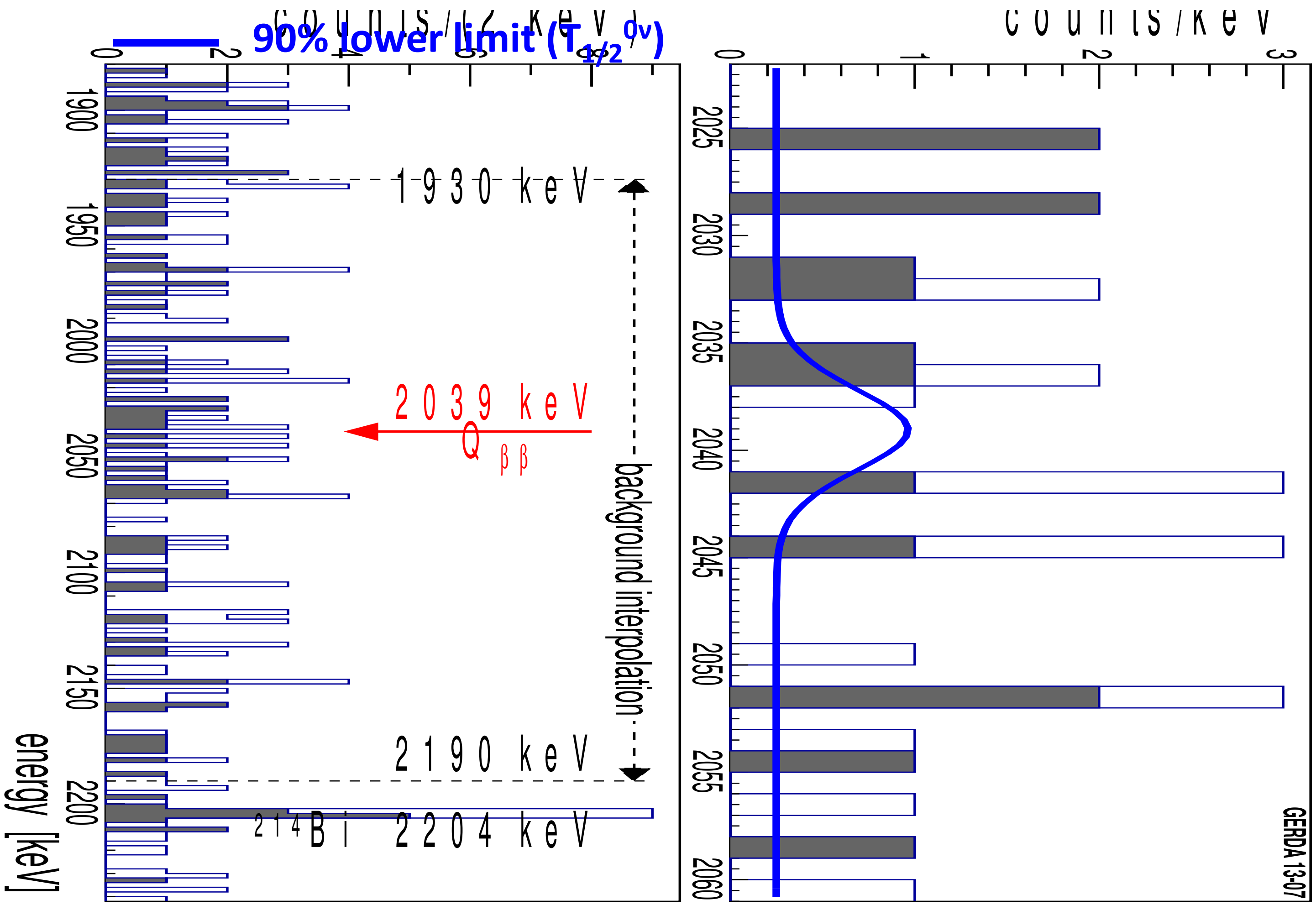
f_{76}: enrichment fraction
f_{av}: fraction of active detector volume
ε_{fep}: full energy peak efficieny for 0νββ
ε_{psd}: signal acceptance

Data set	**Exposure (kg yr)**
Golden-coax	17.9
Silver-coax	1.3
BEGe	2.4

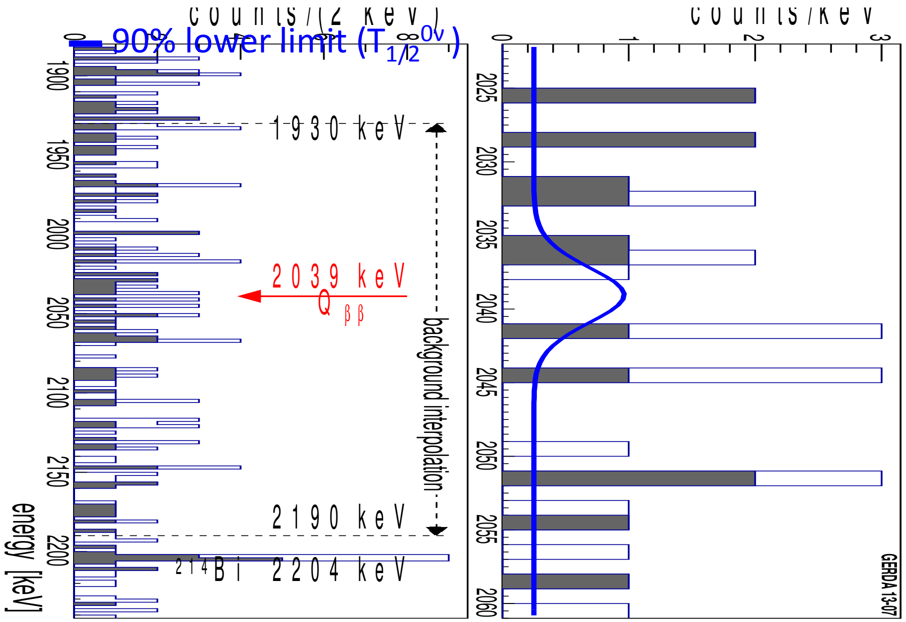
	$\langle f_{76}\rangle$	**$\langle f_{av}\rangle$**	**$\langle \varepsilon_{fep}\rangle$**	**$\langle \varepsilon_{psd}\rangle$**	**$\langle \varepsilon\rangle$**
Coax	0.86	0.87	0.92	0.90 +0.05/ -0.09	0.619 +0.044/-0.070
BEGe	0.88	0.92	0.90	0.92 ±0.02	0.663 ±0.022

Profile likelihood fit to 3 data set (21.6 kg yr)

PRL 111 (2013) 122503



Frequentist and Bayesian limits & median sensitivities



Systematics:

Parameter	Det./Set	Value	Uncertainty
<ε> w/o PSD	Coax	0.688	0.031
	BEGe	0.720	0.018
Energy res.	Golden	4.83 keV	0.19 keV
	Silver	4.63 keV	0.14 keV
	BEGe	3.24 keV	0.14 keV
Energy scale (keV)		N.A.	0.2 keV
ε_{PSD}	Coax	0.90	+0.05/-0.09
	BEGe	0.92	0.02

PRL 111 (2013) 122503

Frequentist limit:

- 90% lower limit derived from profile likelihood fit to 3 data sets (constraint to physical 1/T range; excluding known γ-lines from bgd model at 2104±5 and 2119±5 keV)
- Best fit: **$N^{0\nu}$=0**
- **No excess** of signal counts above the background
- 90% C.L. lower l[imit]: $T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}$ yr
- Limit on half-life corresponds to $N^{0\nu}$<3.5 cts
- Median sensitivity (90% C.L.): >2.4×10^{25} yr

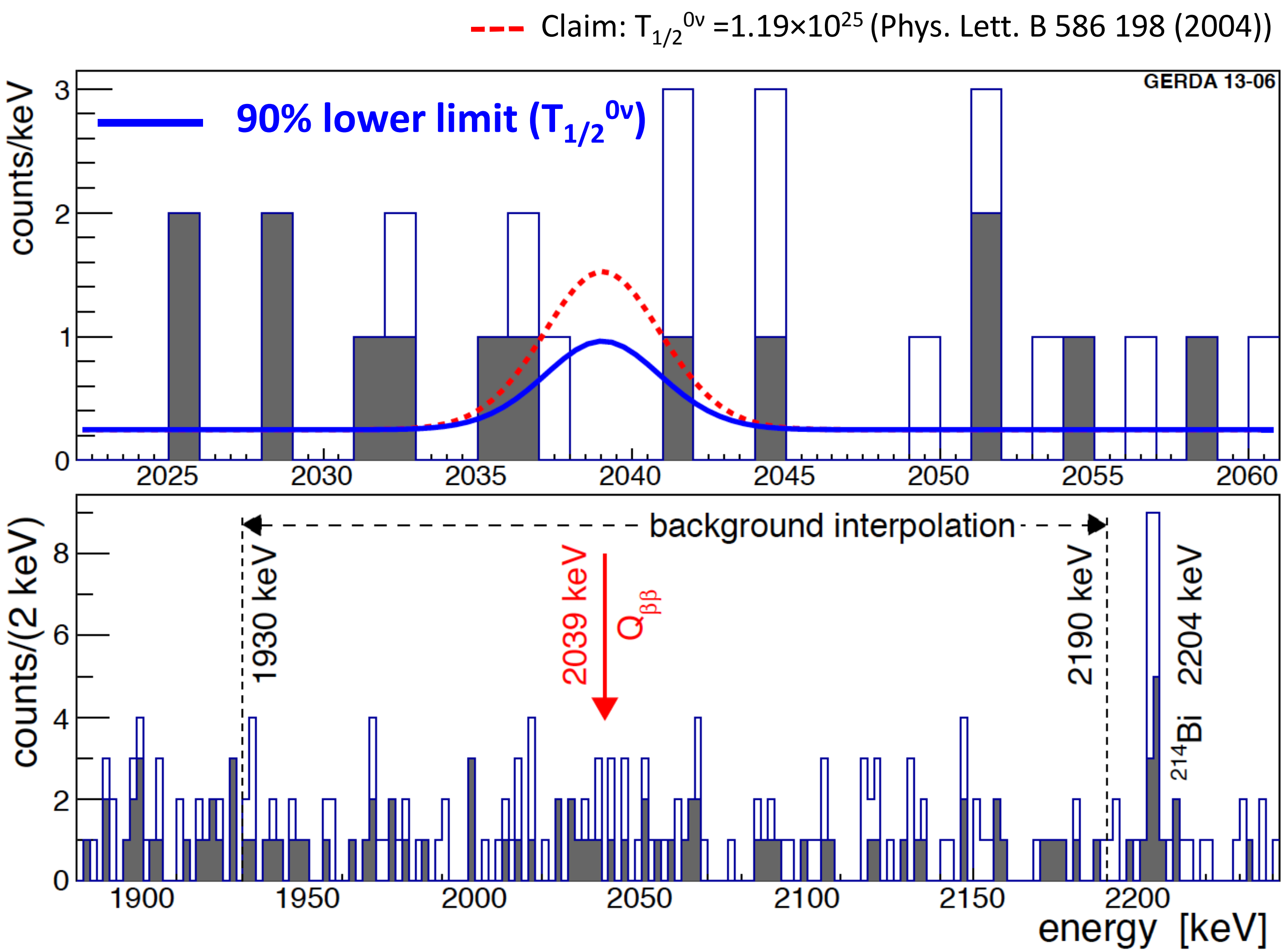
Bayesian:

- Flat prior for 1/T
- Posterior distribution for $T_{1/2}^{0\nu}$
- Best fit: **$N^{0\nu}$=0**
- 90% credibile interval: $T^{0\nu}_{1/2} > 1.9 \cdot 10^{25}$ yr
- Median sensitivity: (90% C.I.): >2.0×10^{25} yr

Systematics folded: limit weakened by 1.5%

Comparison with Phys. Lett. B 586 198 (2004) claim

PRL 111 (2013) 122503

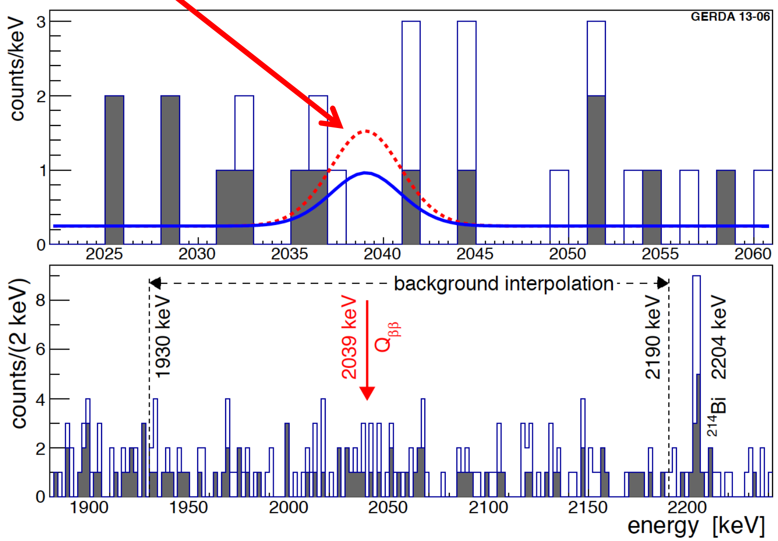


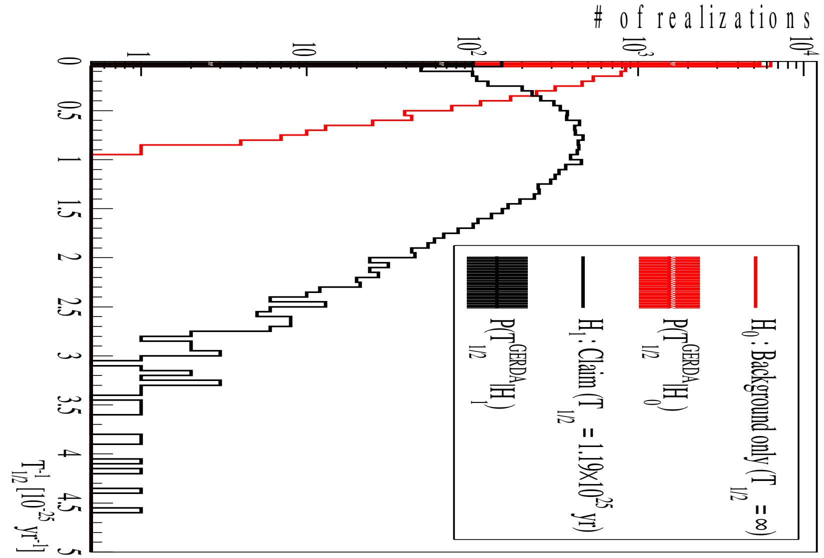
Comparison with Phys. Lett. B 586 198 (2004) claim

PRL 111 (2013) 122503

Expectation for claimed $T_{1/2}^{0\nu} = 1.19\times10^{25}$ yr (Phys. Lett. B 586 198 (2004)):

5.9±1.4 signal over 2.0±0.3 bgd in ±2σ energy window to be compared with 3 cts (0 in ±1σ)





H0: background only

H1: claimed signal plus background

Bayes factor: P(H1)/P(H0)=0. 024

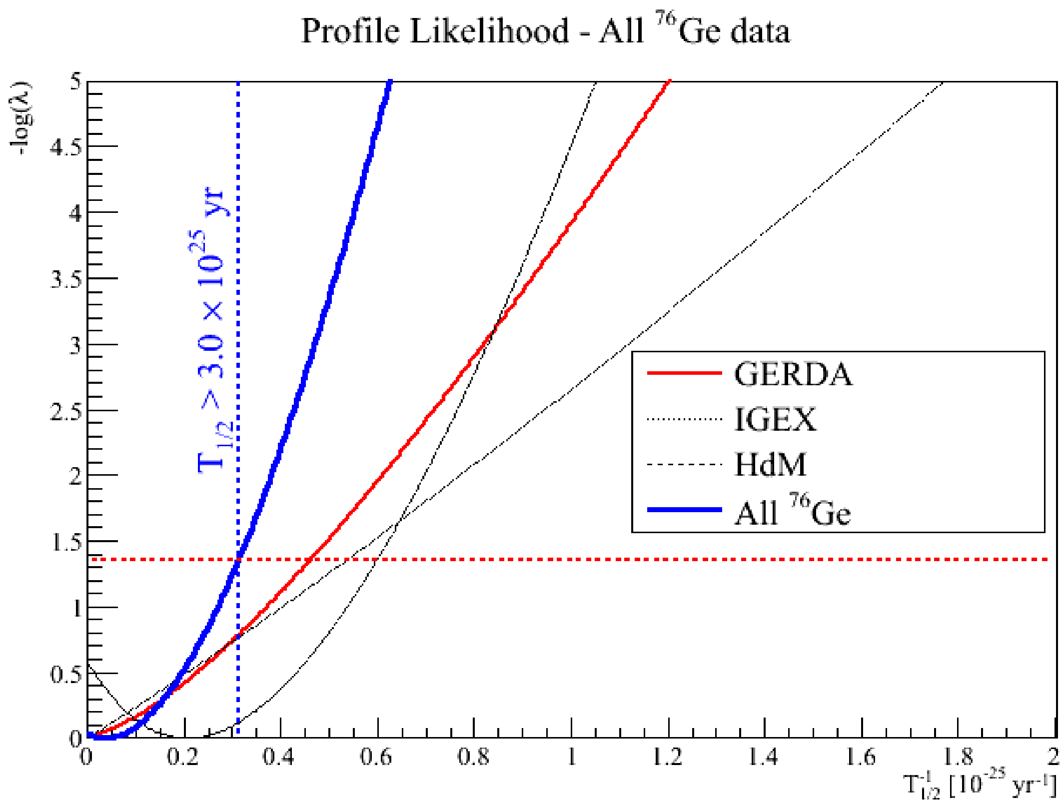
p-value from profile likelihood

P(N=0|H1) = 0. 01 (0.006 if 1/T unconstrained)

➔Claim refuted with high probability

Combined analysis with HdM and IGEX experiments

PRL 111 (2013) 122503



HdM: Eur. Phys. J. A 12, 147 (2001)
IGEX: Phys. Rev. D 65, 092007 (2002), Phys. Rev. D 70 078302 (2004)

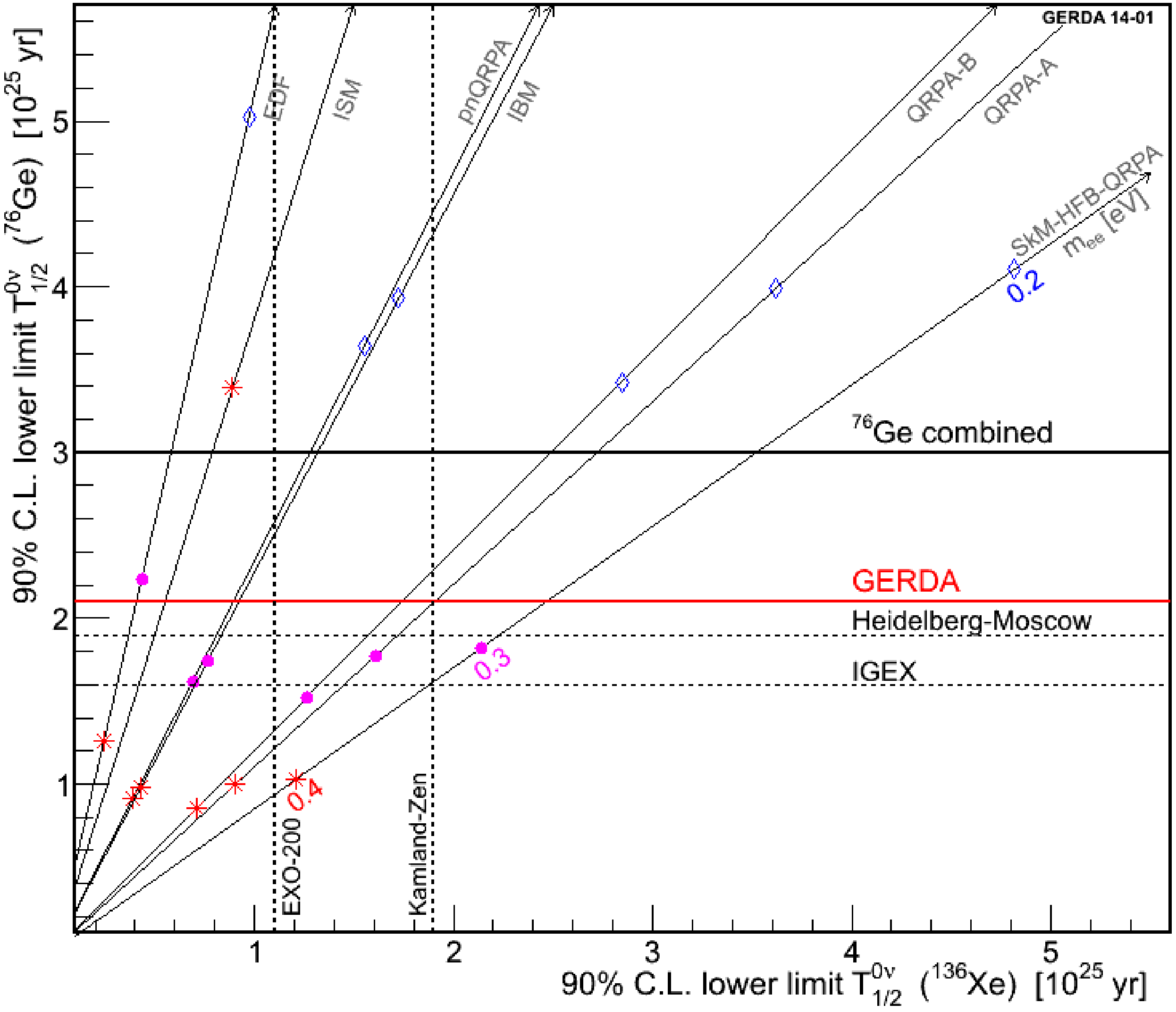
$$T^{0\nu}_{1/2} > 3.0 \cdot 10^{25}\ \mathrm{yr} \quad (90\,\%\ \ \mathrm{C.L.})$$

- Coverage verified with toy MC
- Identical limits with Frequentists & Bayesian analysis

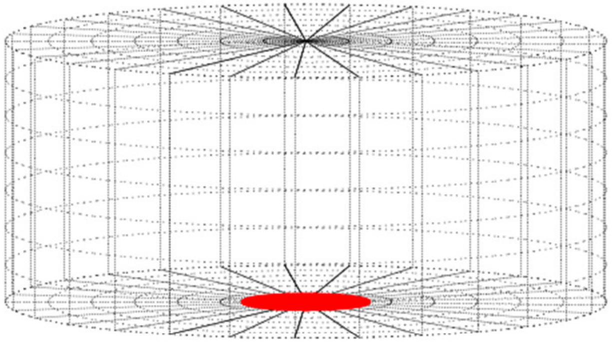
Bayes Factor: P(H1)/P(H0)=2×10^{-4} strongly disfavors claim

Comparison is independent of NME and of physical mechanism which generates 0νββ

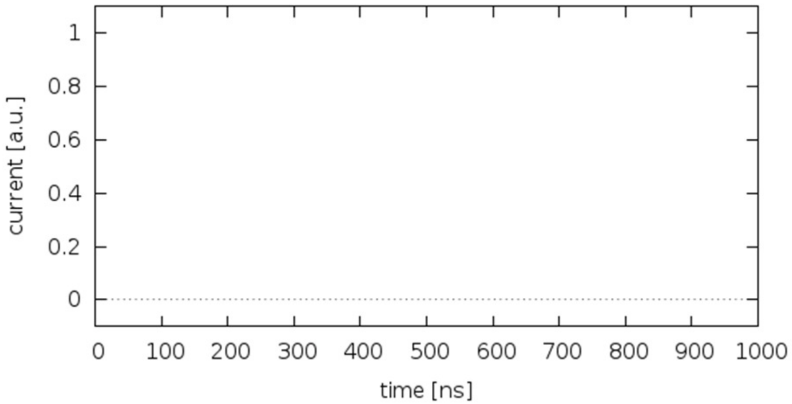
Comparison with the Xenon DBD experiments

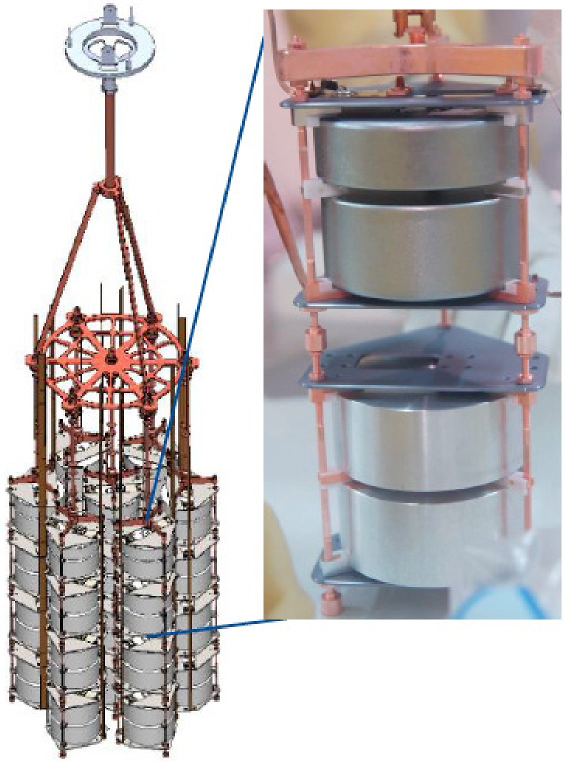


Phase II BEGe detectors: enhanced pulse shape discrimination

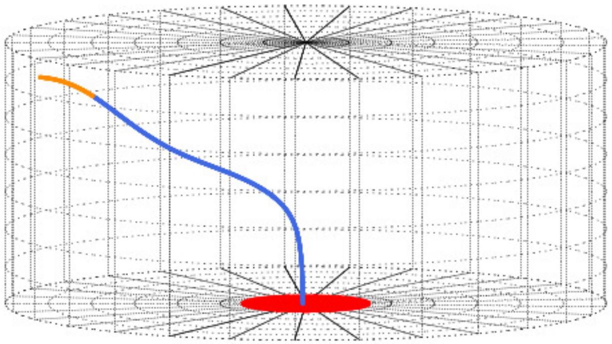


M. Agostini et al.
JINST 6 (2011) P03005





Phase II BEGe detectors: enhanced pulse shape discrimination



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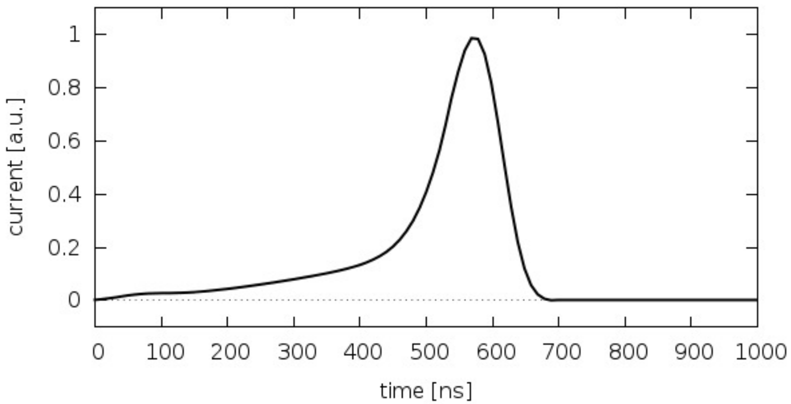
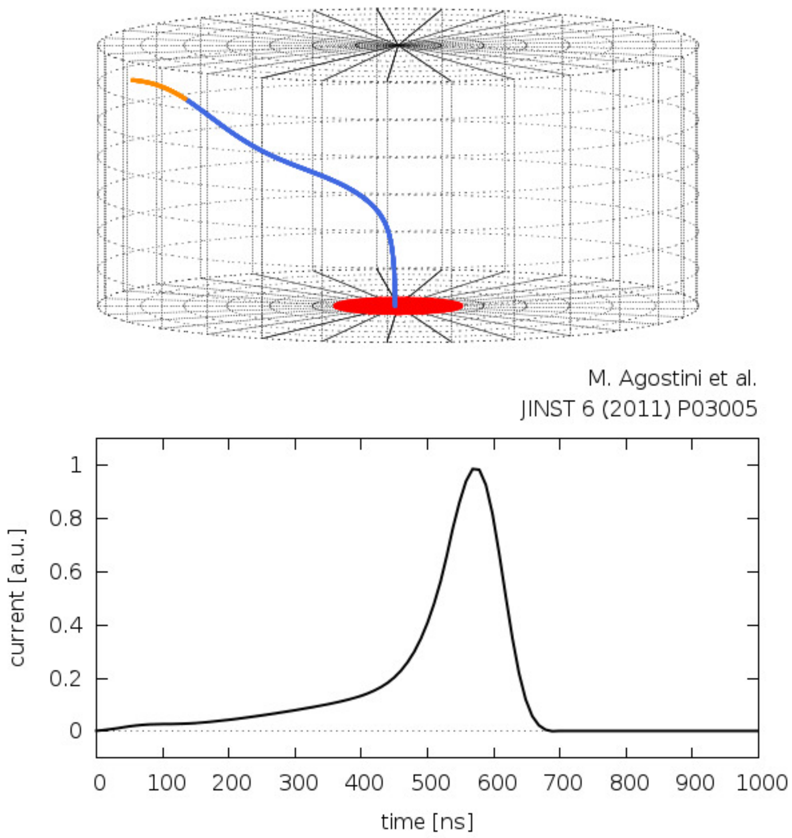
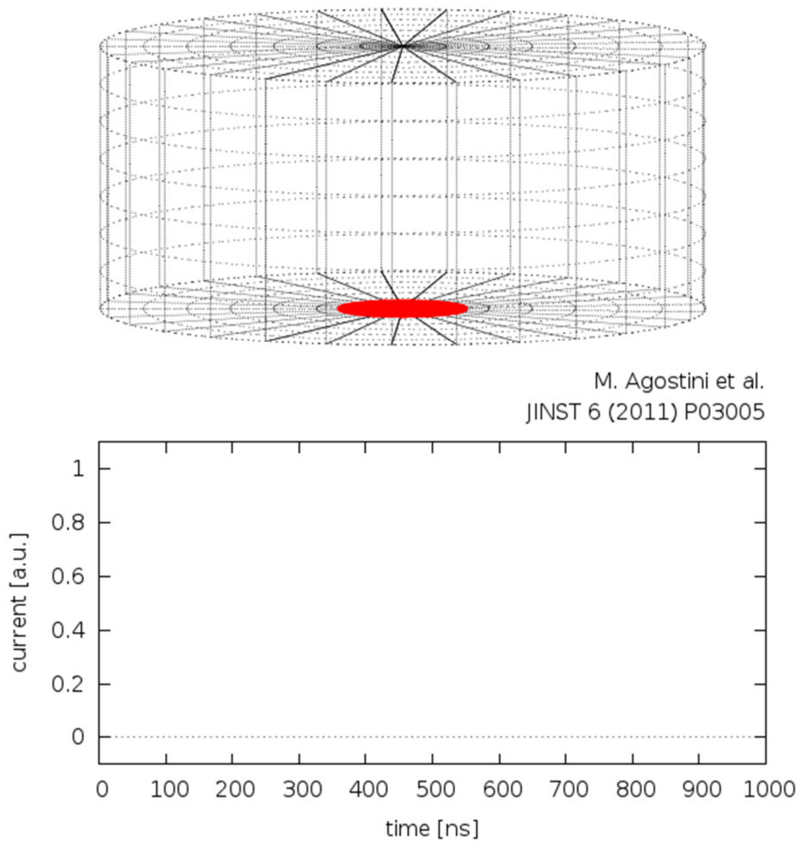
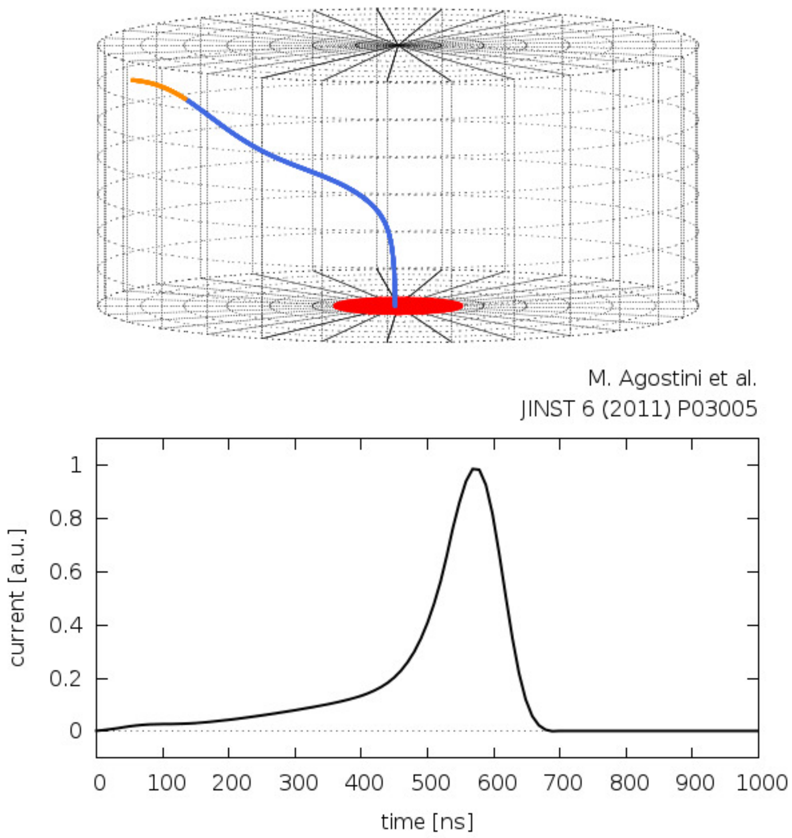


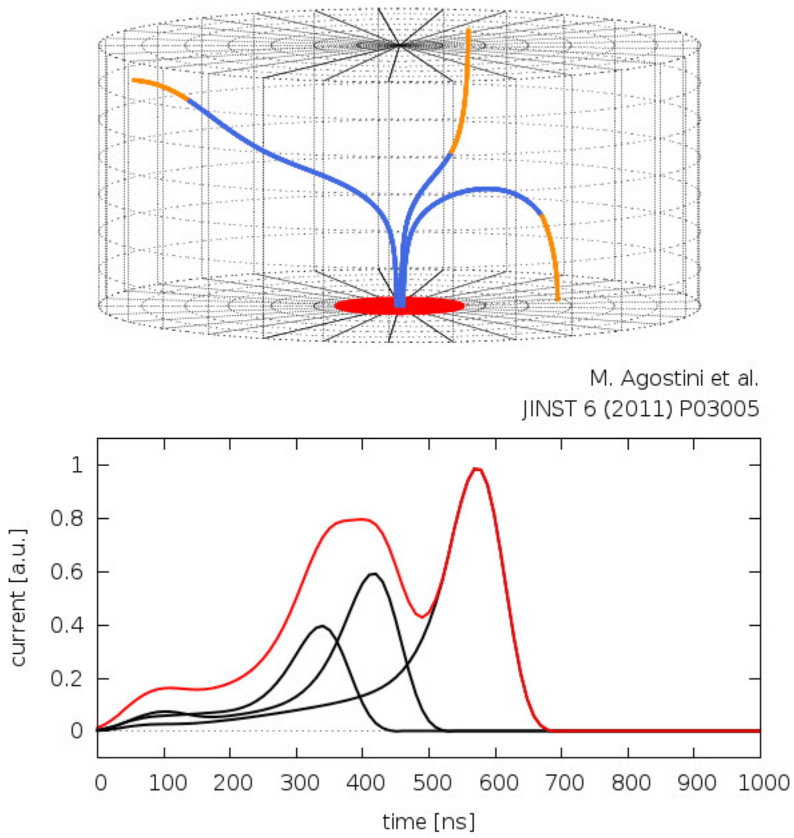
Phase II BEGe detectors: enhanced pulse shape discrimination



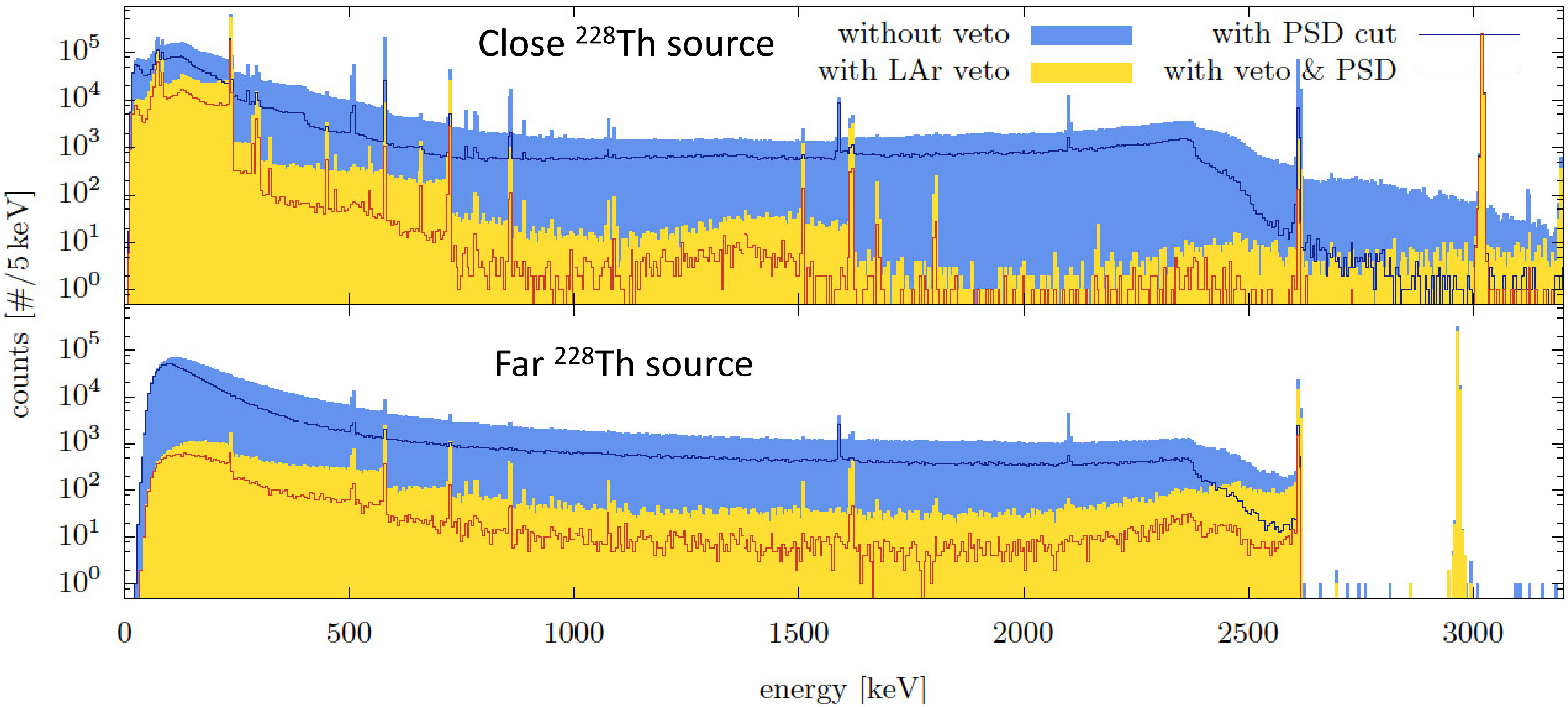


Phase II BEGe detectors: enhanced pulse shape discrimination





Phase II: Liquid argon instrumentation & BEGe PSD



Suppression factors up to 10^3 at $Q_{\beta\beta}$ achieved in LArGe setup!

- **GERDA Phase I design goals reached:**
  - Background index after PSD: 0.01 cts / (keV kg yr)
  - Exposure 21.6 kg yr

- **No $0\nu\beta\beta$-signal observed at $Q_{\beta\beta}$ = 2039 keV; best fit: $N^{0\nu}$=0**
  - Background-only hypothesis H_0 strongly favored
  - Claim strongly disfavored (independent of NME and of leading term)

- **Bayes Factor / p-value:**

  GERDA: 2.4×10^{-2} / 1.0×10^{-2}

  GERDA+IGEX+HdM: 2×10^{-4} / -

- **Limit on half-life:**

  GERDA: $T_{1/2}^{0\nu} > 2.1\times10^{25}$ yr (90% C.L.)

  GERDA+IGEX+HdM: $T_{1/2}^{0\nu} > 3.0\times10^{25}$ yr (90% C.L.) ($\langle m_{ee}\rangle < 0.2$-$0.4$ eV)

- Results reached after only 21.6 kg yr exposure because of **unprecedented low background:** bgd expectations after analysis cuts and correcting for efficiencies:

  0.006 cts /(mol yr FWHM) (cf. EXO: 0.044, KL: 0.19)

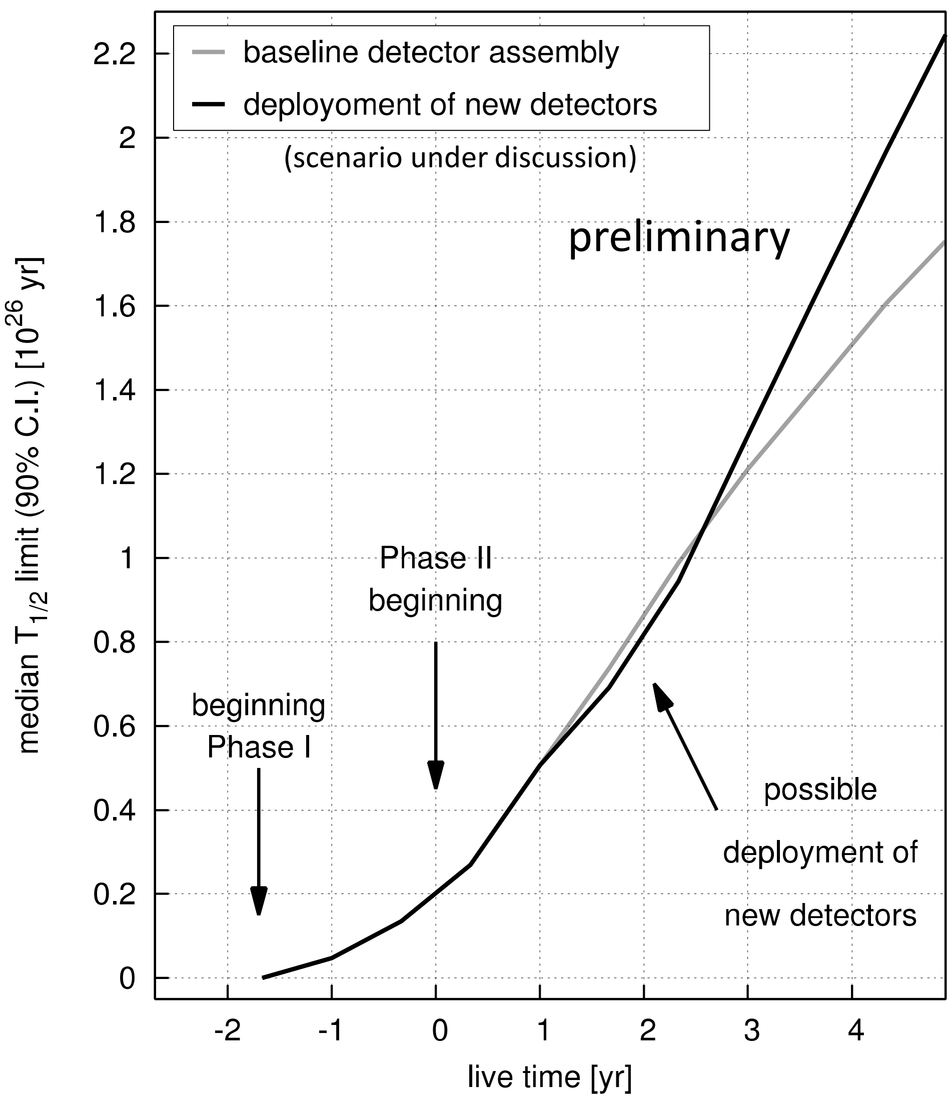
Outlook

<u>Transition to Phase II ongoing:</u>

- Increase of target mass (+20 kg; total ≈40 kg of Ge detectors)
- New custom made BEGe detectors with enhance pulse shape discrimination
- Liquid argon instrumentation (anti-coincidence veto)
- Background ≤ 10^{-3} cts /(keV kg yr)
- Explore $T_{1/2}(0\nu)$ values in the 10^{26} yr range

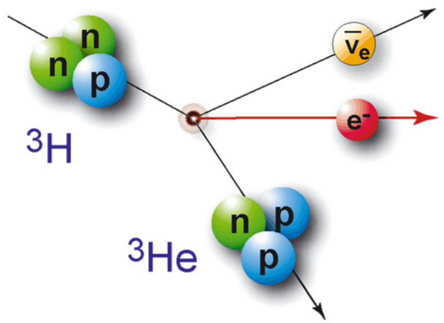
<u>Beyond Phase II:</u>

- Common 1t experiment with Majorana to cover 'inverse mass hierarchy' mass range conceived



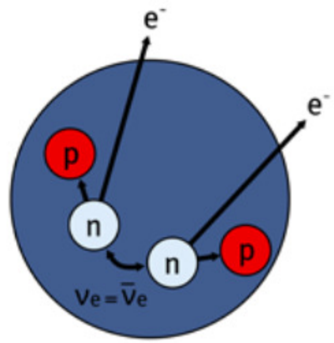
New generation of experiments will provide high sensitive results on ν-mass observables

<u>β-decay</u>



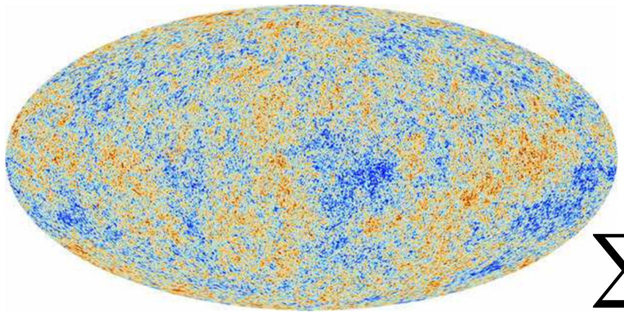
$$m_\beta = \sqrt{\sum_i |U_{ei}|^2 \cdot m_i^2}$$

<u>0νββ-decay</u>



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

<u>Cosmology</u>



$$\sum_i m_i$$

See next talk (Simon White)