E15 Chair for Experimental Physics
and Astroparticle Physics

Excellence Cluster Universe

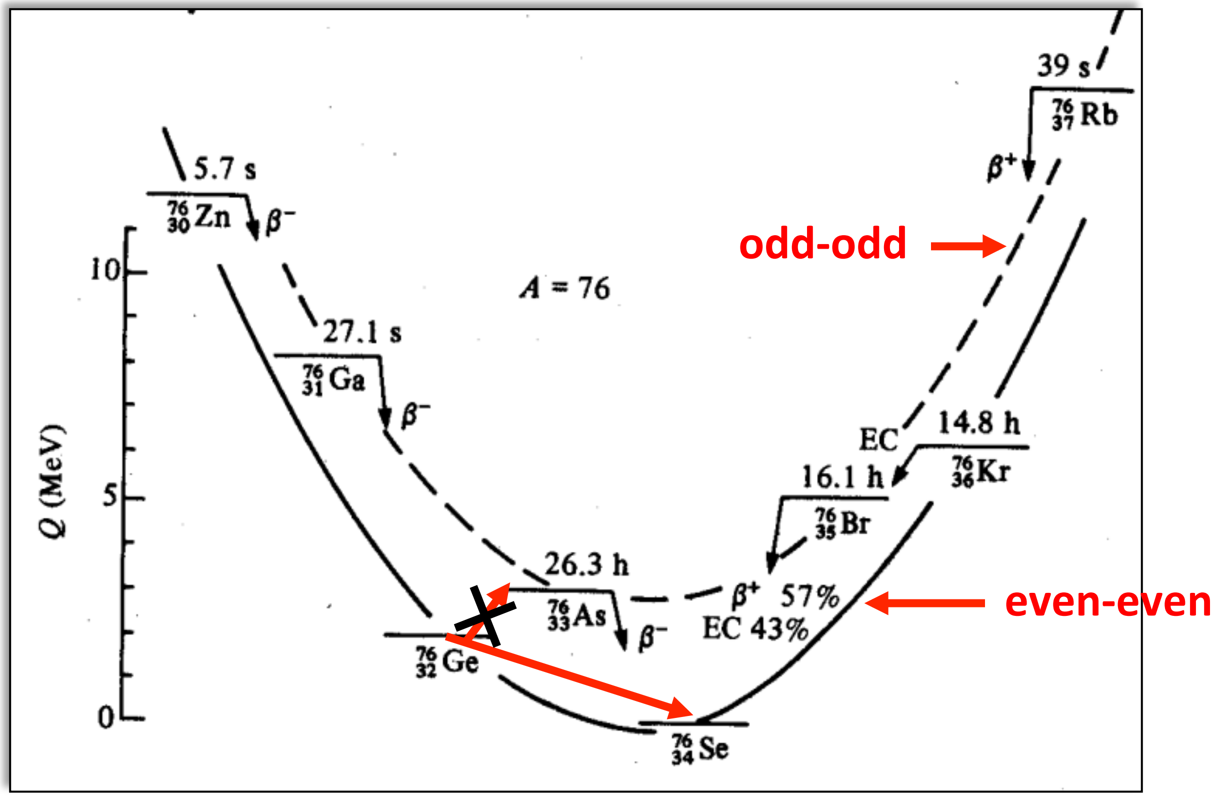
Cryogenic detectors for neutrinoless double beta decay search

Workshop on future Dark Matter Experiments
Wien, October 15-16, 2013

Stefan Schönert
Physik-Department TU München
schoenert@ph.tum.de

Figures from Lumineu and Lucifer R&D provided by Andrea Guiliani, CSNSM Orsay
All credits to the Lumineu & Lucifer teams!!

Double beta decay (DBD)

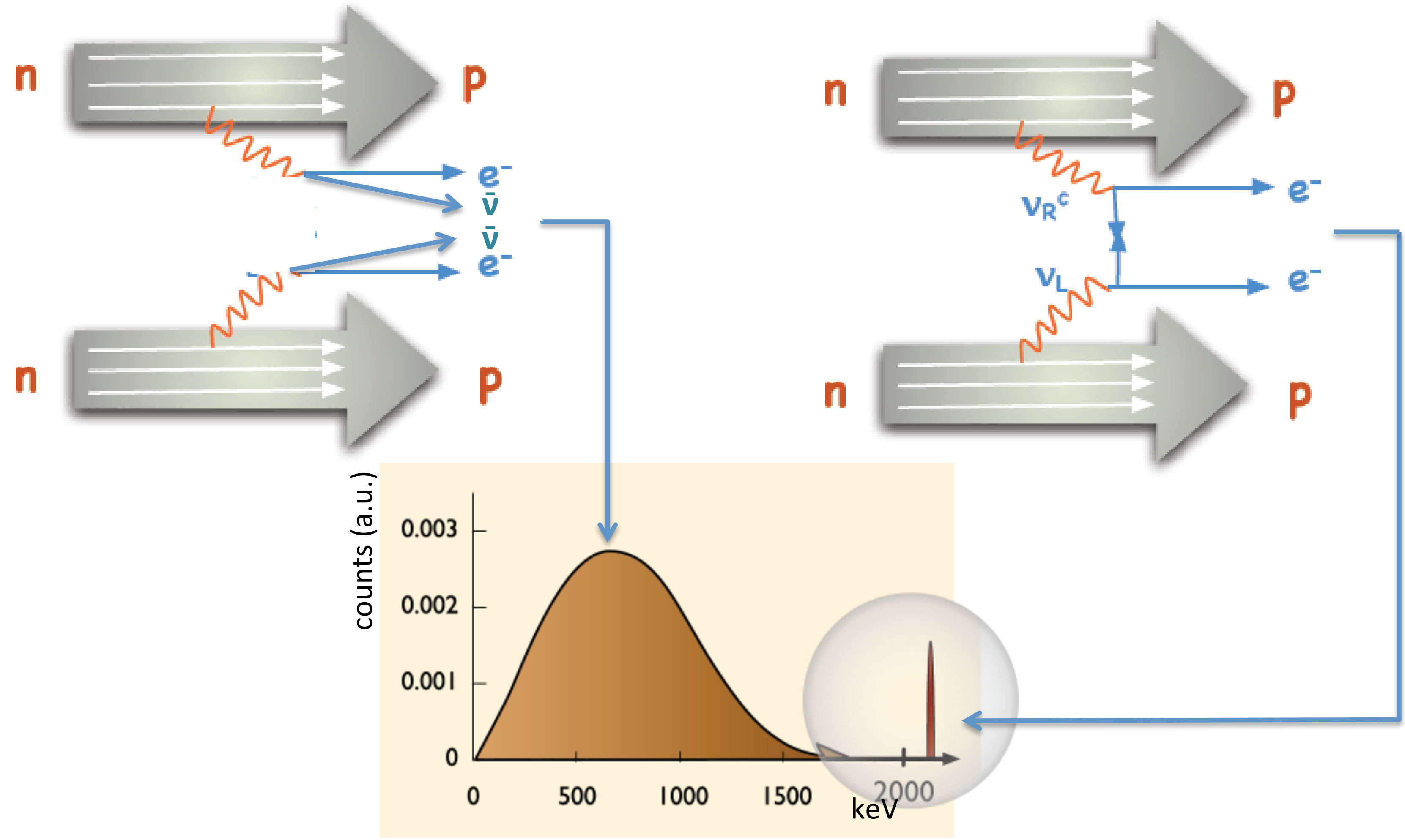


$Q_{\beta\beta}$ = 2039.01(5) keV

2νββ vs. 0νββ decay

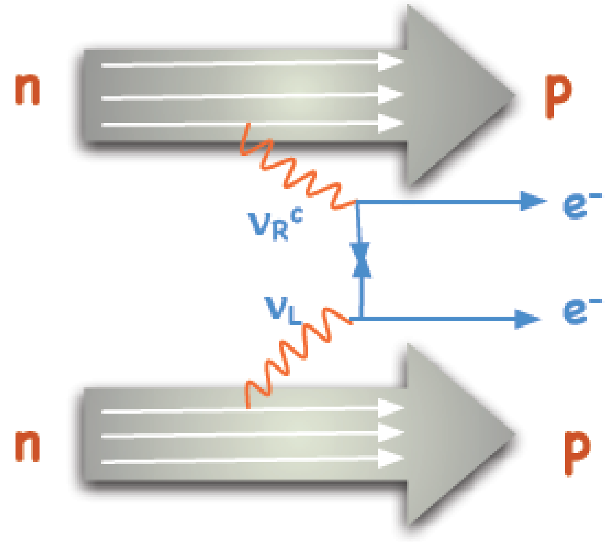
2-neutrino DBD

0-neutrino DBD



2-electron spectra

0νββ decay and neutrino mass



Expected decay rate:

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

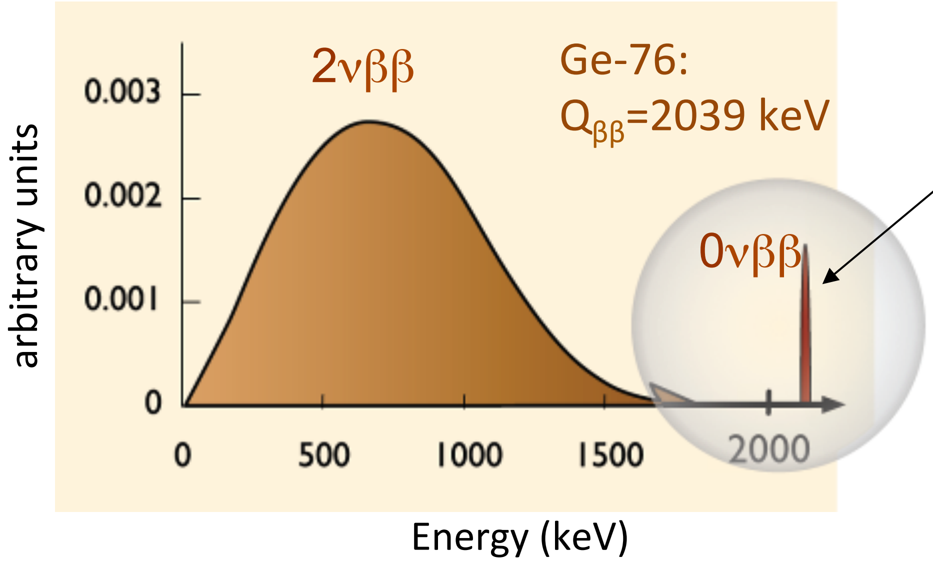
Phase space integral

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

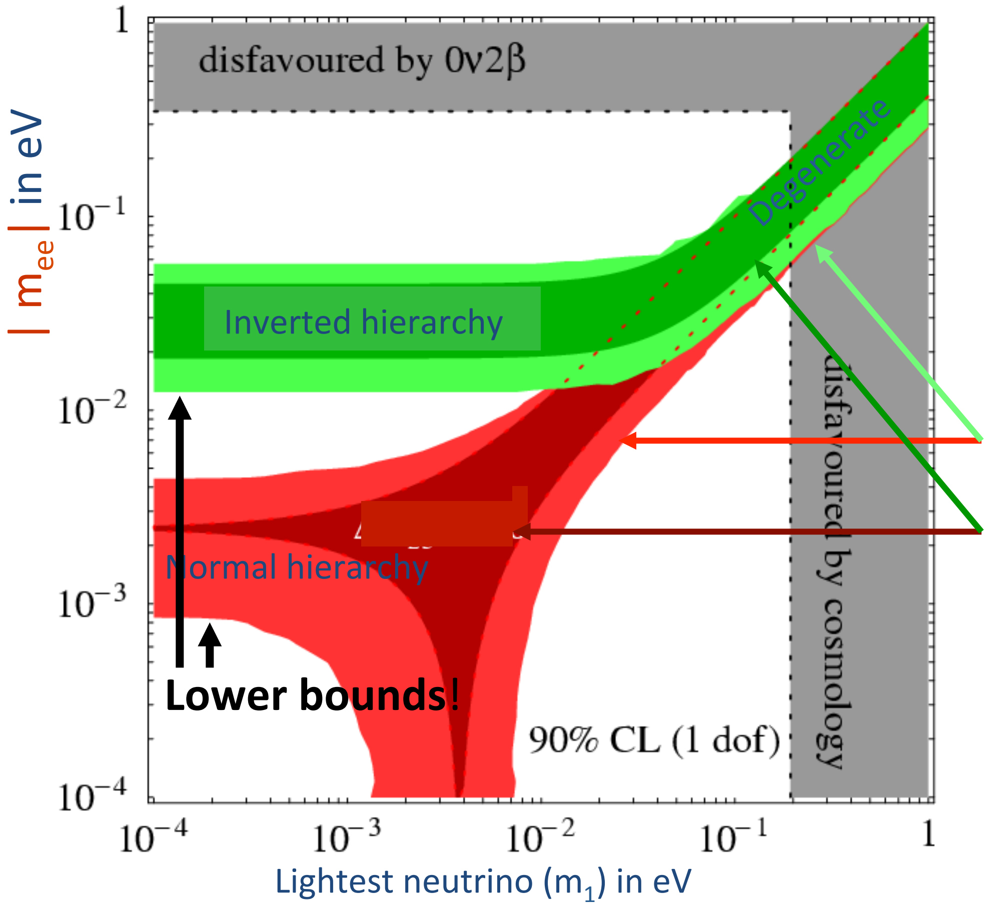
Discovery would imply:

- 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

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

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



90% CL

Negligible errors from oscillations; width due to CP phases

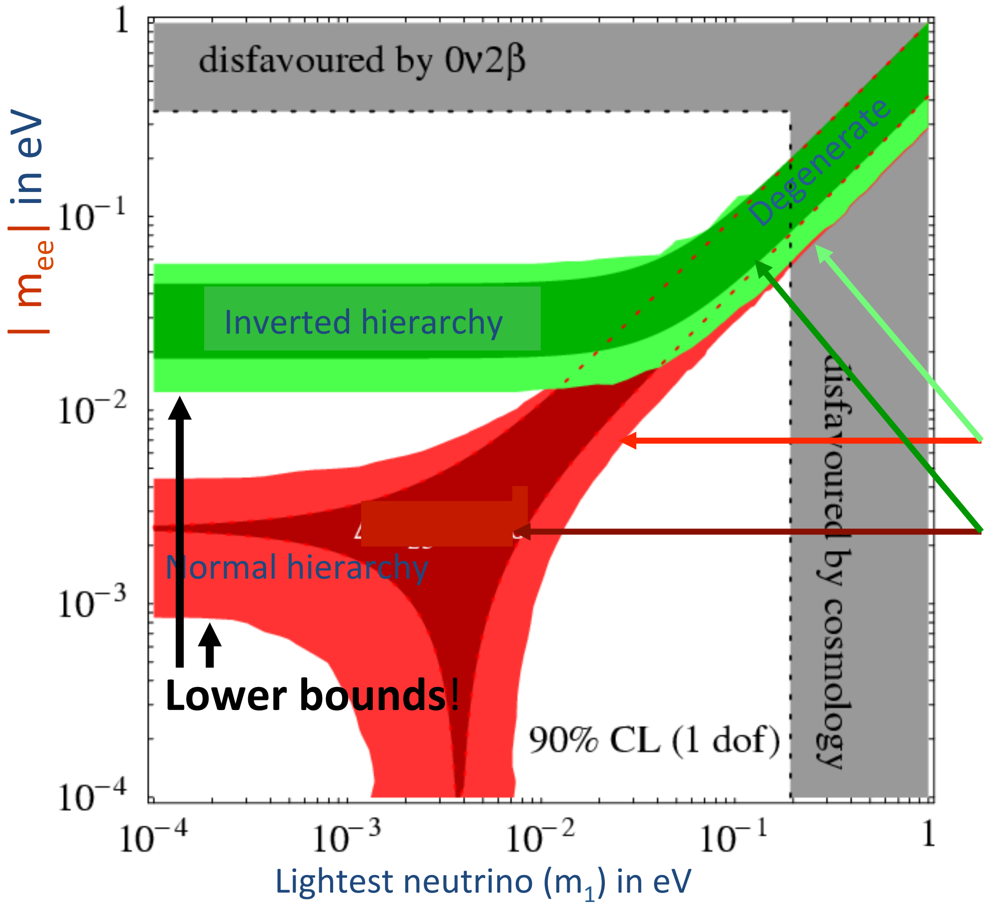
F.Feruglio,
A. Strumia,
F. Vissani,
NPB 637

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

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

KDKC claim:

Goal of next generation experiments: ~10 meV

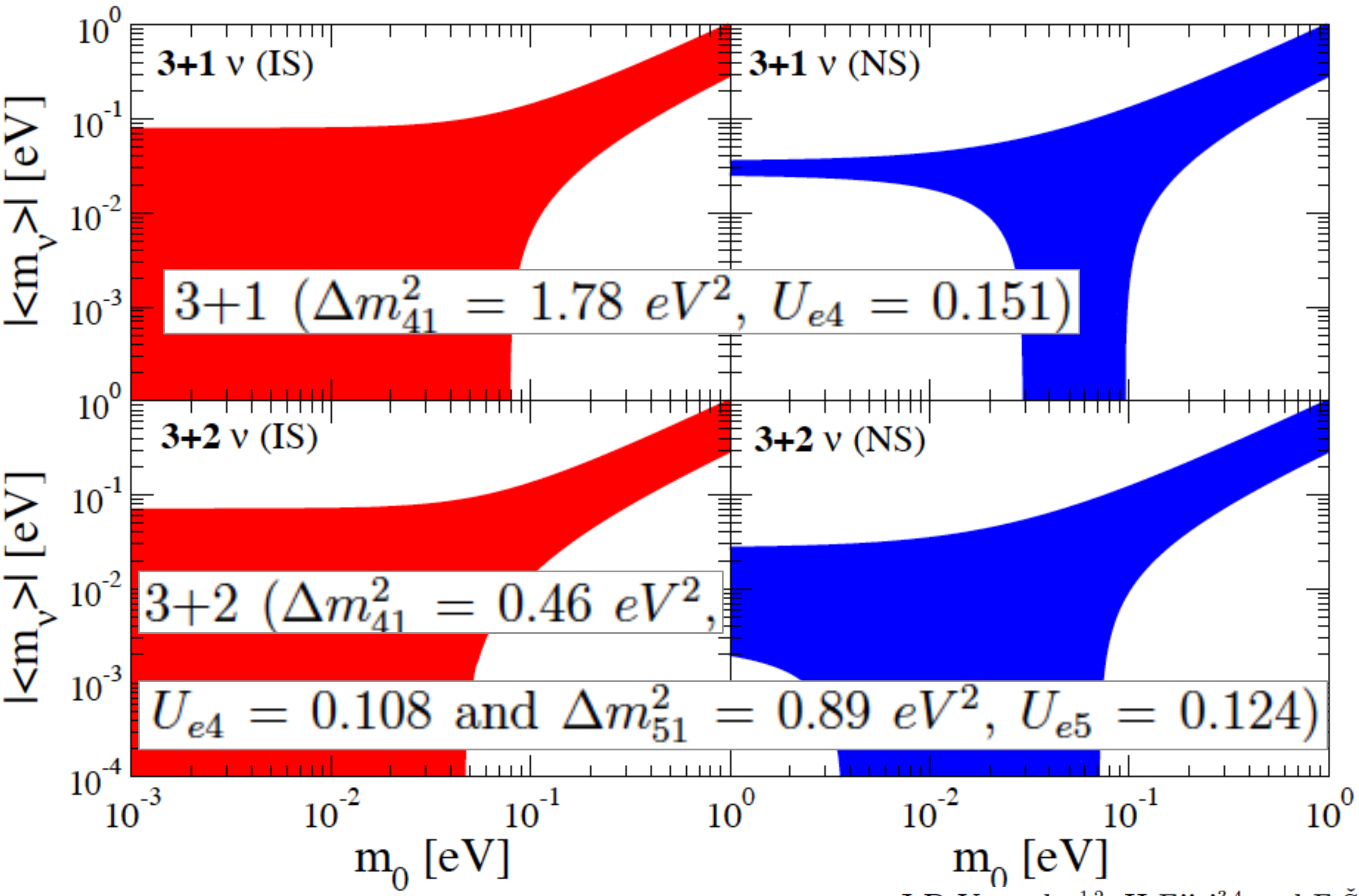


F.Feruglio,
A. Strumia,
F. Vissani,
NPB 637

90% CL

Negligible errors from oscillations; width due to CP phases

$0\nu\beta\beta$ including sterile neutrinos: range of m_{ee} derived from solar/atm experiments & reactor/Ga anomalies



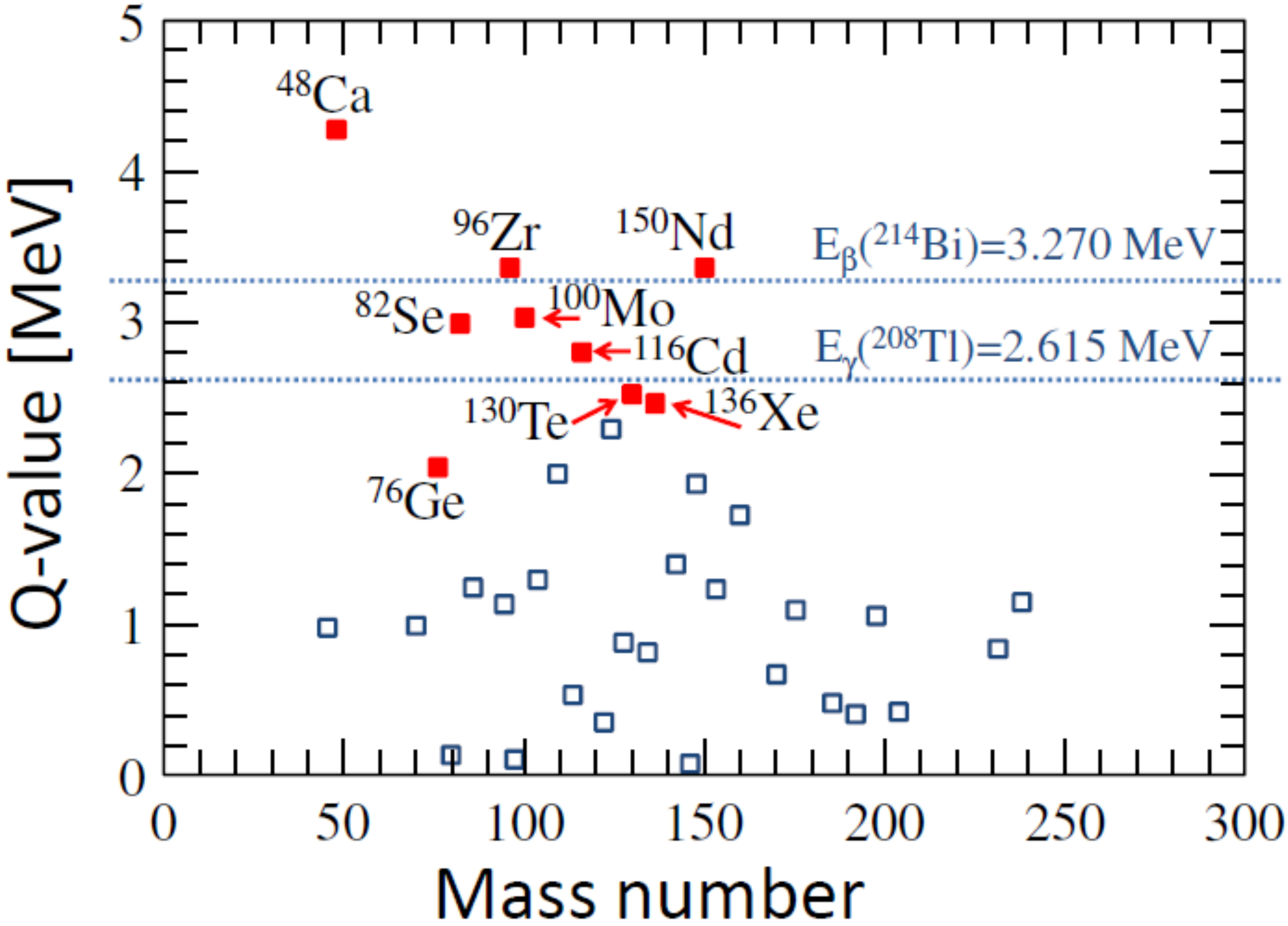
$3{+}1\ (\Delta m^2_{41} = 1.78\ eV^2,\ U_{e4} = 0.151)$

$3{+}2\ (\Delta m^2_{41} = 0.46\ eV^2,$

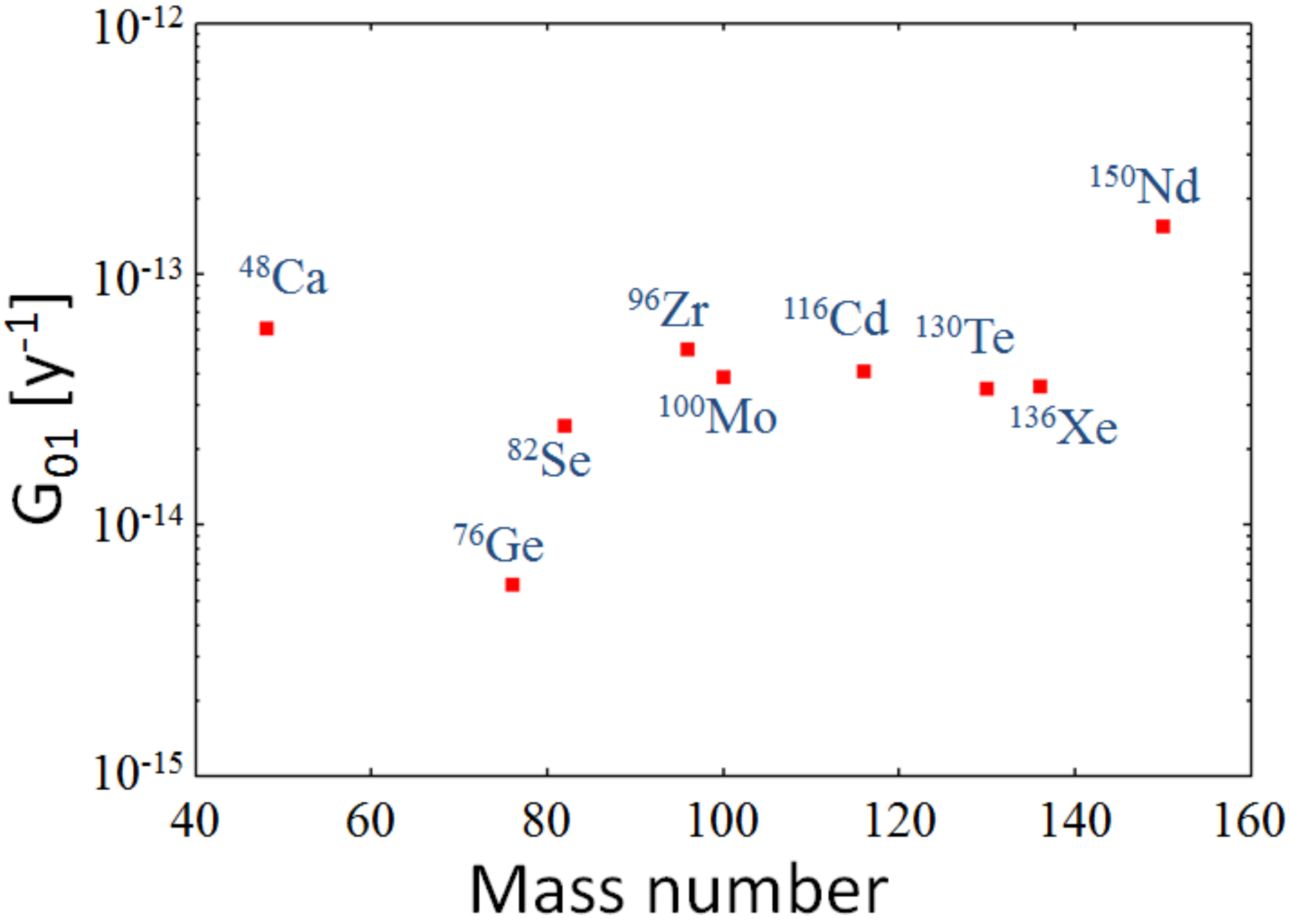
$U_{e4} = 0.108$ and $\Delta m^2_{51} = 0.89\ eV^2,\ U_{e5} = 0.124)$

J D Vergados[1,2], H Ejiri[3,4] and F Šimkovic[5,6]

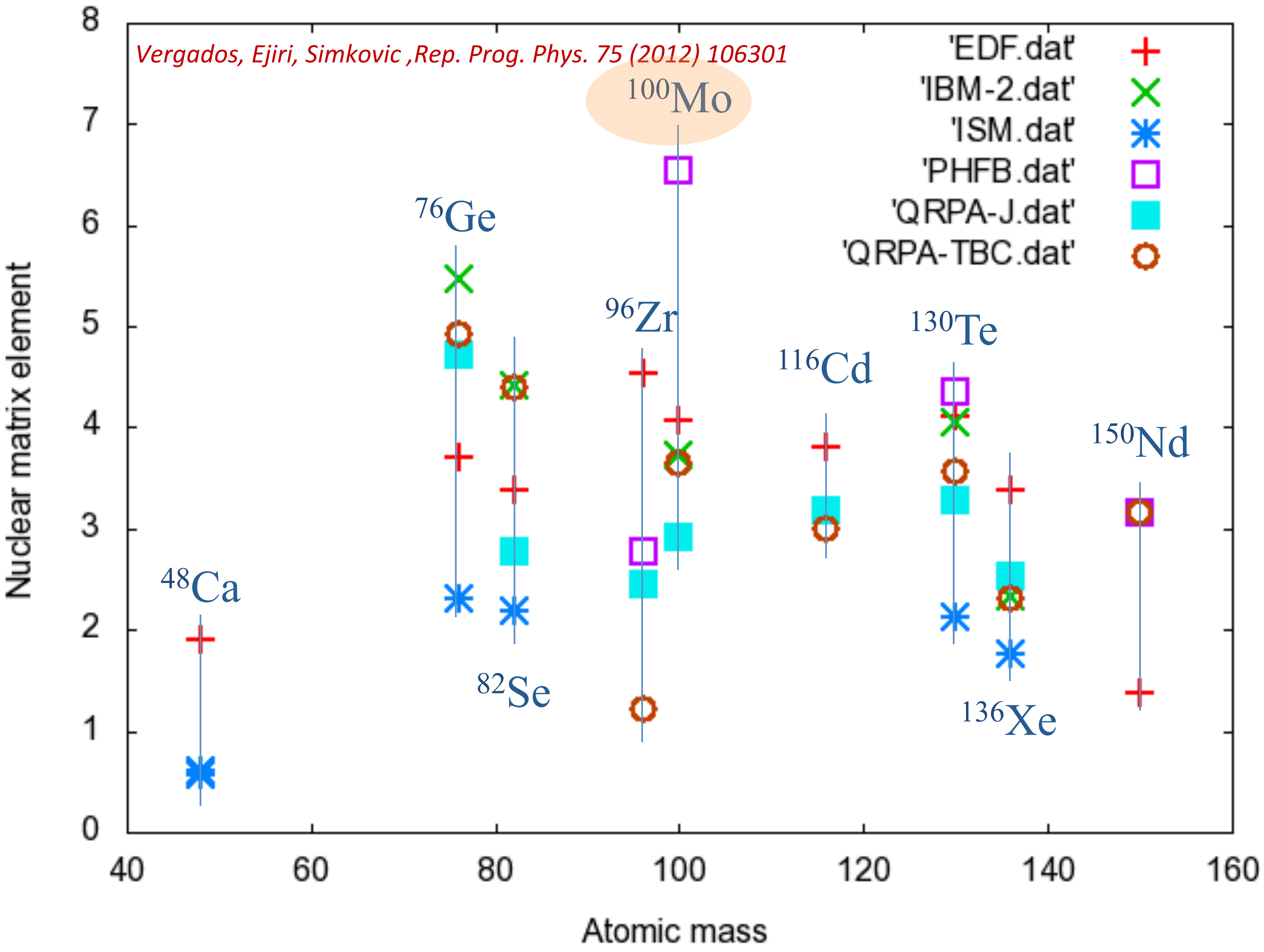
$$1/\tau = G(Q,Z)\, g_A^4\, |M_{nucl}|^2 \langle M_{\beta\beta}\rangle^2$$



$1/\tau = G(Q,Z)\, g_A^{\,4}\, |M_{nucl}|^2 \langle M_{\beta\beta}\rangle^2$

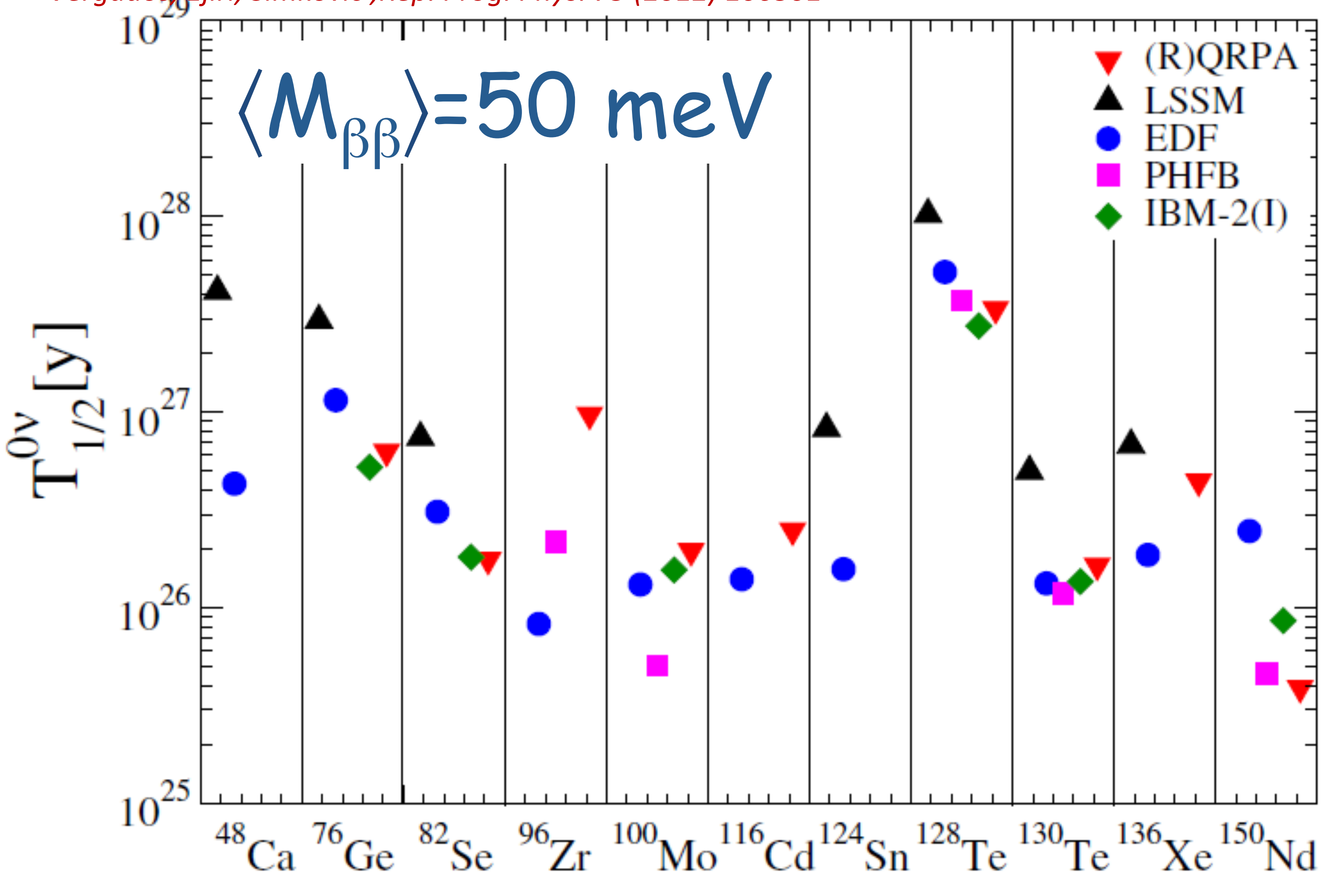


$$1/\tau = G(Q,Z)\, g_A^{\,4}\, |M_{nucl}|^2 \langle M_{\beta\beta}\rangle^2$$



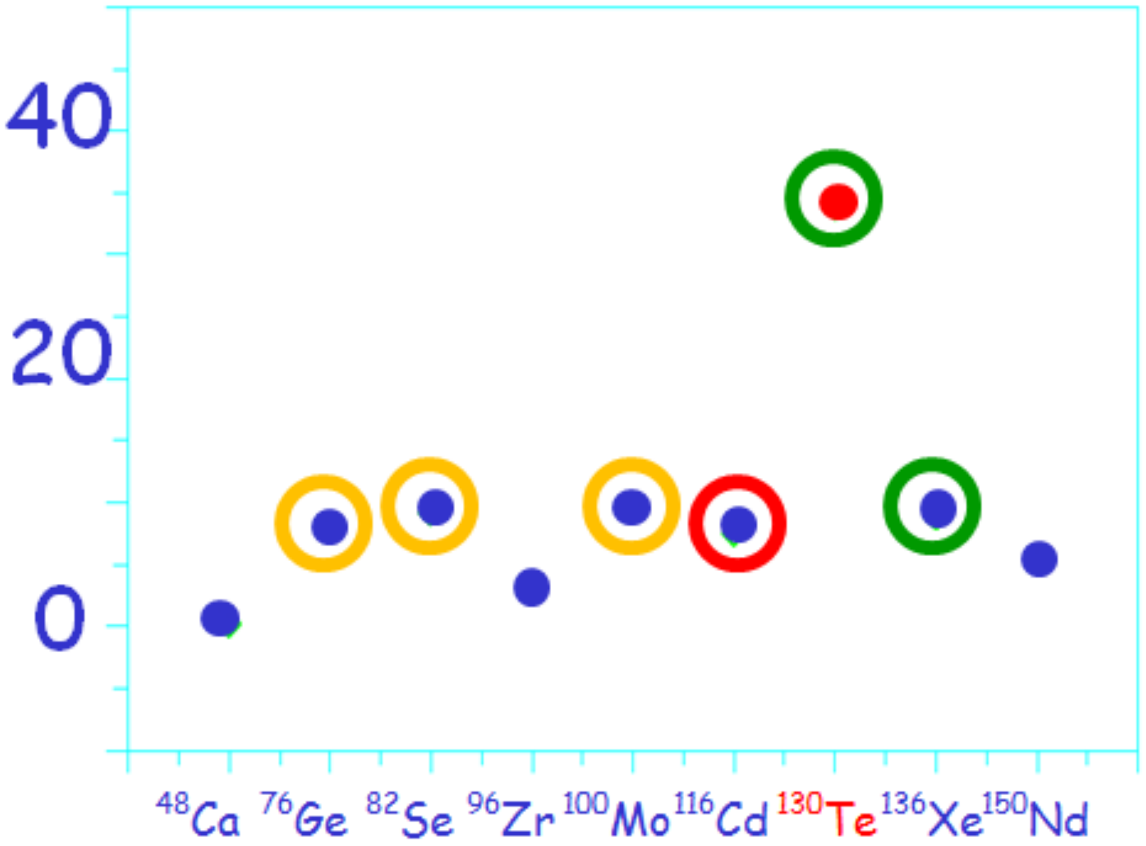
Rates

Vergados, Ejiri, Simkovic ,Rep. Prog. Phys. 75 (2012) 106301



$\langle M_{\beta\beta}\rangle$=50 meV

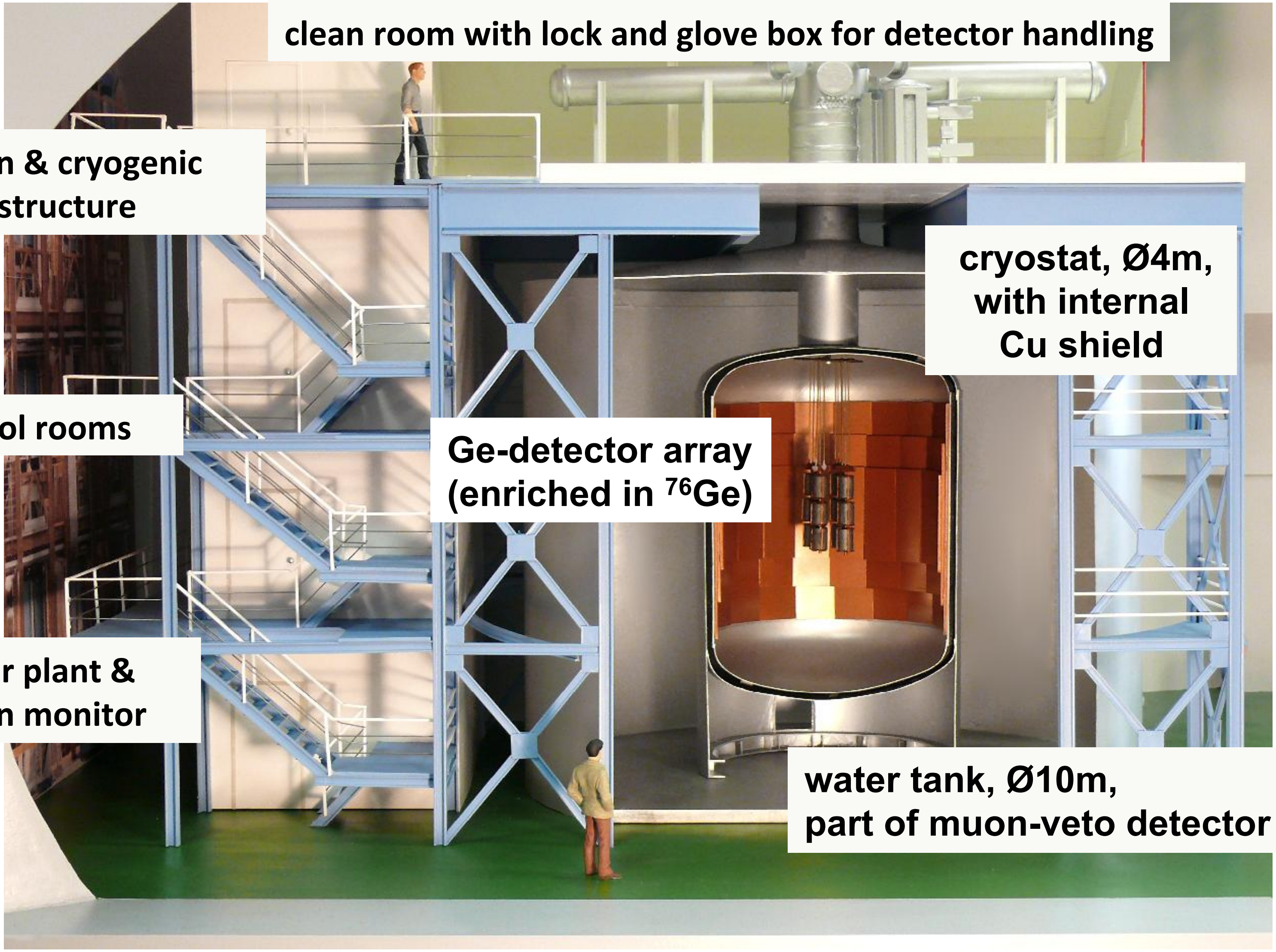
Isotopic abundance (%)



The GERDA experiment

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

plastic μ-veto



clean room with lock and glove box for detector handling

muon & cryogenic infrastructure

control rooms

water plant & radon monitor

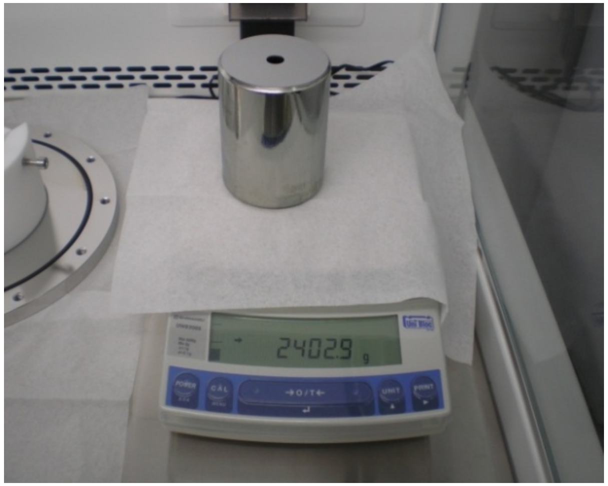
Ge-detector array (enriched in ^{76}Ge)

cryostat, Ø4m, with internal Cu shield

water tank, Ø10m, part of muon-veto detector

Phase I detectors: semi-coaxial detectors

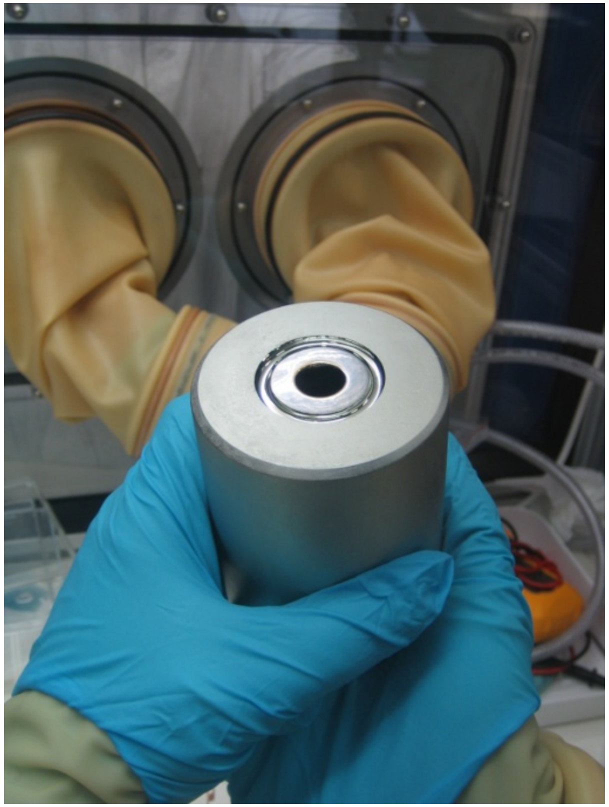
Eur. Phys. J. C (2013) 73:2330
arXiv:1212.4067

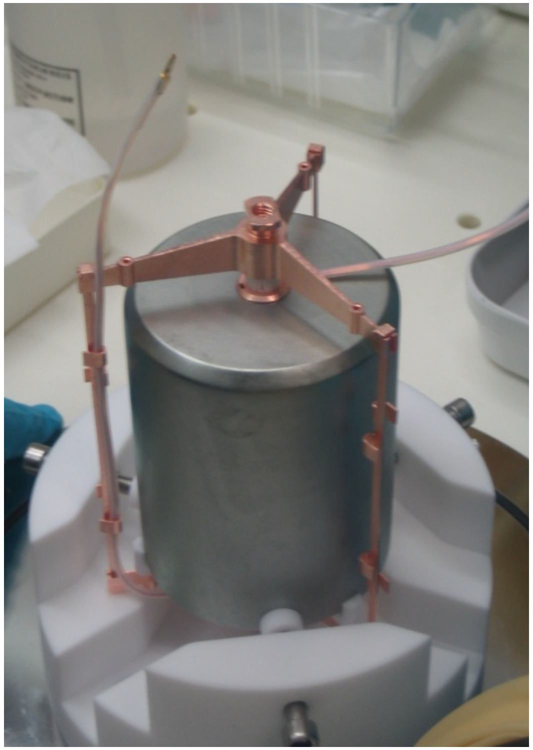


- HdM & IGEX diodes reprocessed at Canberra, Olen
- Long term stability in LAr w/o passivation layer
- Energy resolution in LAr: ~2.5 keV (FWHM) @1.3 MeV

8 diodes (from HdM, IGEX):

- Enriched 86% in ^{76}Ge
- Total mass 17.66 kg



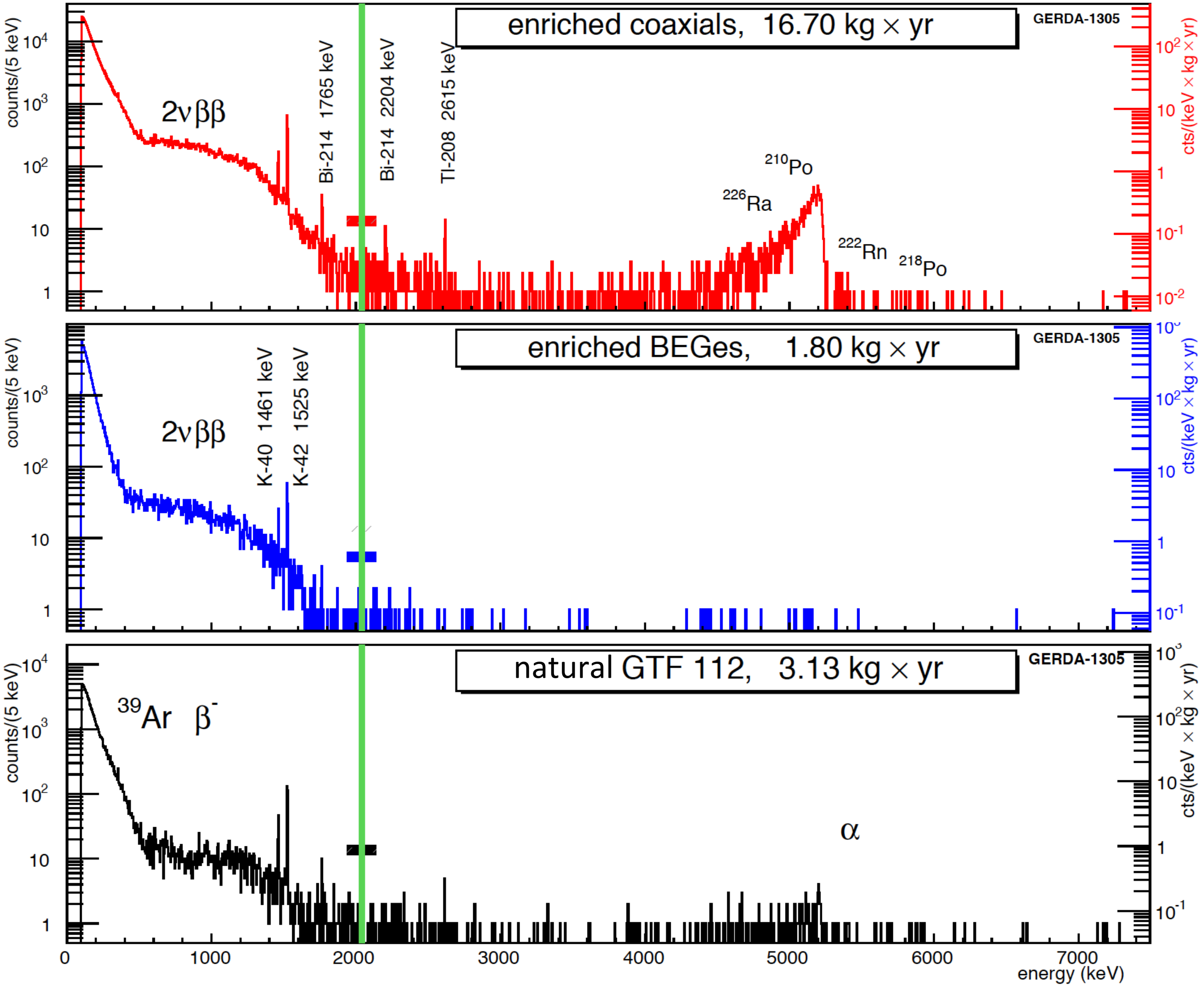


6 diodes from Genius-TF:

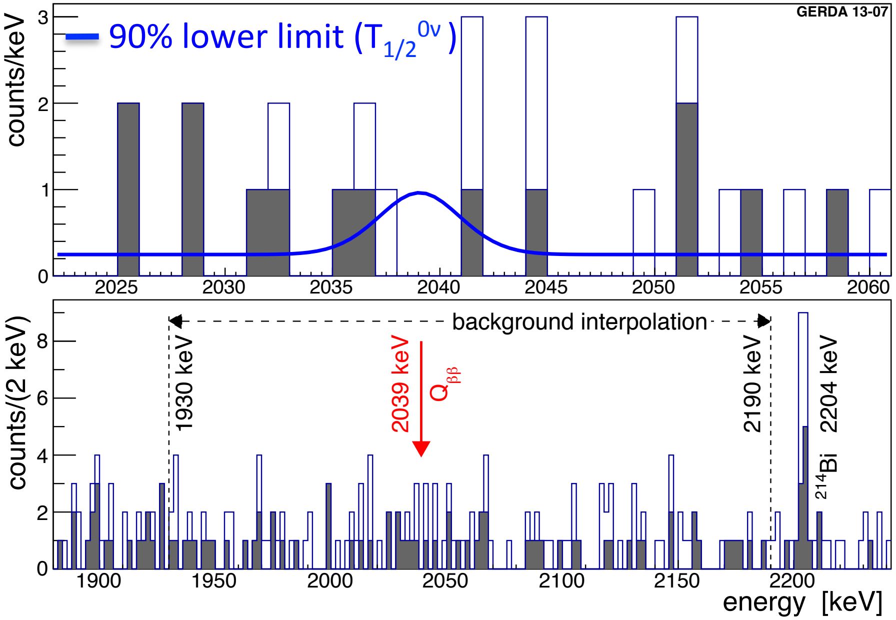
- ^{nat}Ge
- Total mass: 15.60 kg

Physics run: energy spectra

arXiv:1306.5084



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	0.10
	BEGe	0.92	0.02

arXiv:1307.4720

PRL. **111**, 122503 (2013)

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 $T_{1/2}^{0\nu} > 2.1 \cdot 10^{25}$ yr
- Limit on half-life corresponds to $N^{0\nu}<3.5$ cts
- Median sensitivity (90% C.L.): $>2.4\times10^{25}$ yr

Bayesian:

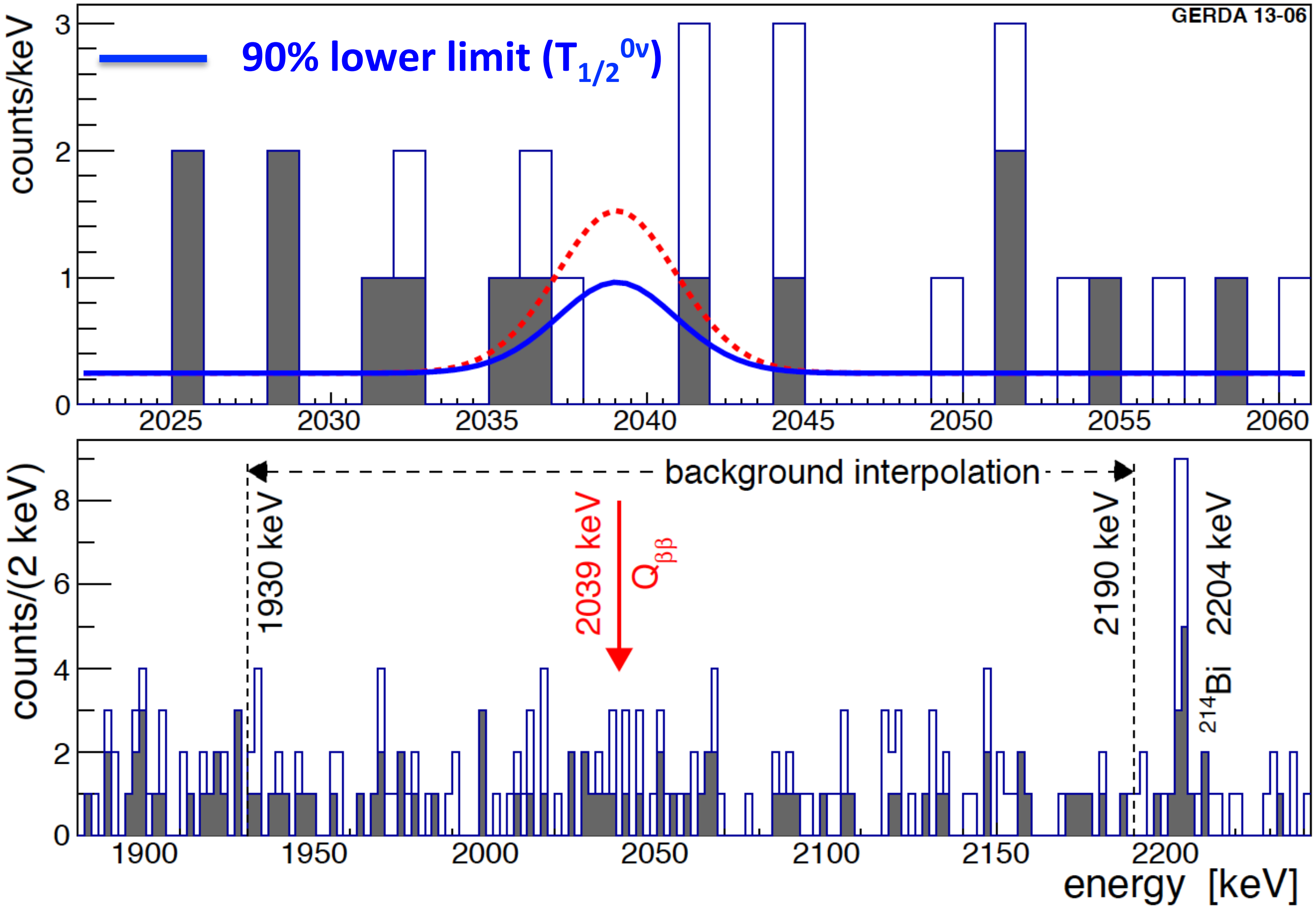
- Flat prior for 1/T
- Posterior distribution for $T_{1/2}^{0\nu}$
- Best fit: **$N^{0\nu}=0$**
- 90% credibile interval: $T_{1/2}^{0\nu} > 1.9 \cdot 10^{25}$ yr
- Median sensitivity: (90% C.I.): $>2.0\times10^{25}$ yr

Systematics folded: limit weakened by 1.5%

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

arXiv:1307.4720
PRL. **111**, 122503 (2013)

Claim: $T_{1/2}^{0\nu} = 1.19 \times 10^{25}$ (Phys. Lett. B 586 198 (2004))

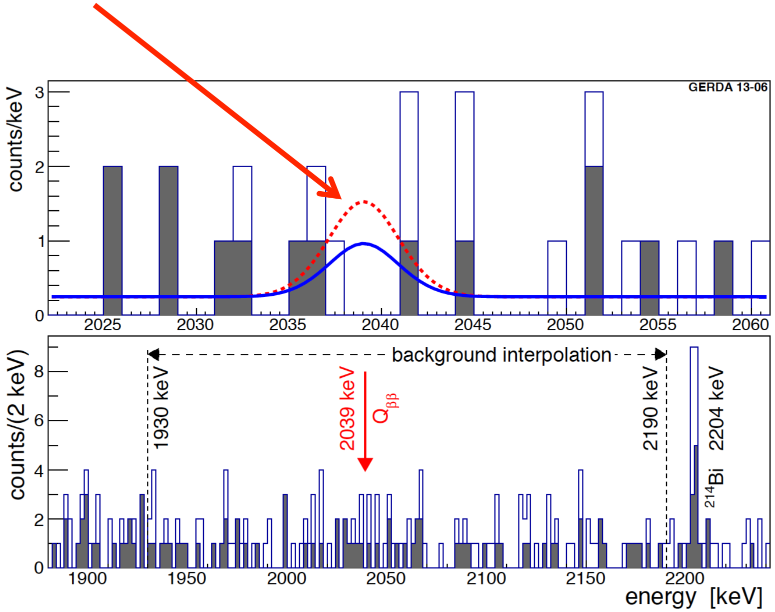


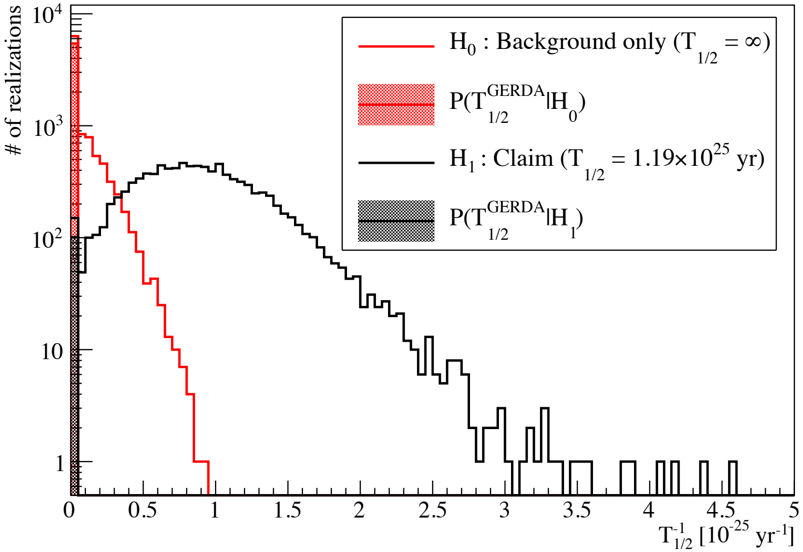
Comparison with Phys. Lett. B 586 198 (2004) claim

arXiv:1307.4720
PRL. **111**, 122503 (2013)

Expectation for claimed $T_{1/2}^{0\nu} = 1.19 \times 10^{25}$ 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)





H1: claimed signal: 5.9±1.4
H0: background only

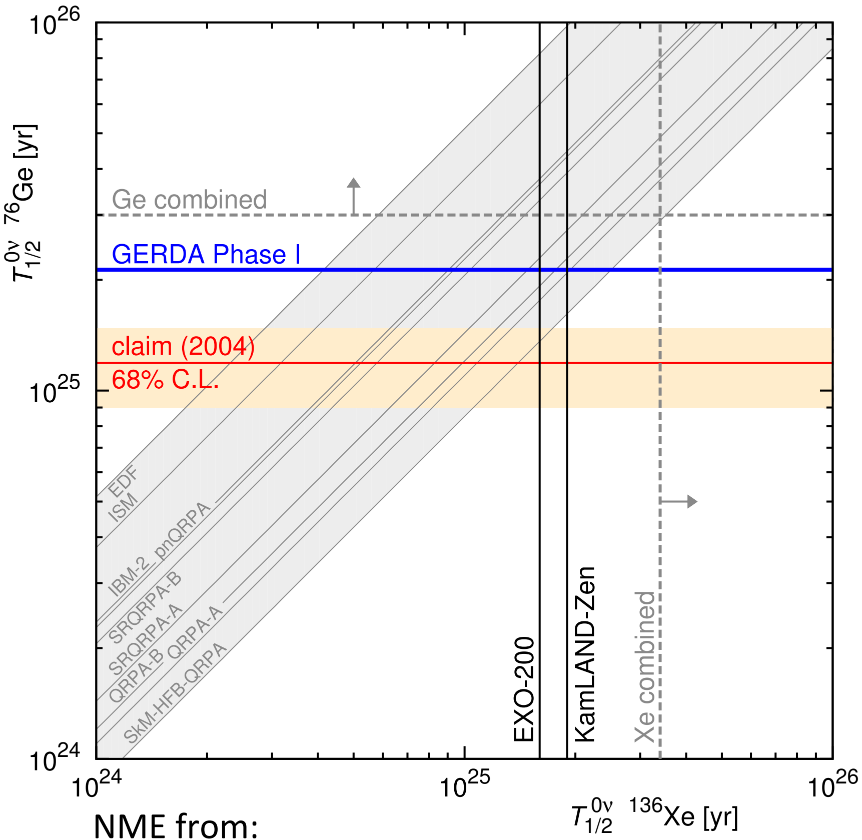
Bayes factor: P(H1)/P(H0)=0. 024

p-value from profile likelihood
P(N=0 = 0|H1) = 0. 01 (0.006 if 1/T unconstrained)

➔Claim refuted with high probability

The claim: global picture

arXiv:1307.4720
PRL. **111**, 122503 (2013)



NME from:
P. S. Bhupal Dev *et al.*, (2013), arXiv:1305.0056

H1: signal with $T_{1/2}^{0\nu} = 1.19 \times 10^{25}$ yr
H0: background only

	Isotope	**$P(H_1)/P(H_0)$**	**Comment**
GERDA	^{76}Ge	0.024	Model independent
GERDA +HdM+IGEX	^{76}Ge	0.0002	Model independent
KamLAND-Zen*	^{136}Xe	0.40	Model dependent: NME, leading term
EXO-200*	^{136}Xe	0.23	Model dependent: NME, leading term
GERDA+KLZ* +EXO*	^{76}Ge + ^{136}Xe	0.002	Model dependent: NME, leading term

*:with conservative NME ratio $M_{0\nu}(^{136}Xe)/M_{0\nu}(^{76}Ge) \approx 0.4$ from:

F. Simkovic, V. Rodin, A. Faessler, and P. Vogel, Phys. Rev. C. **87**, 045501 (2013).
M. T. Mustonen and J. Engel, (2013), arXiv:1301.6997 [nucl-th].
P. S. Bhupal Dev *et al.*, (2013), arXiv:1305.0056 [hep-ph].

Phases and physics reach

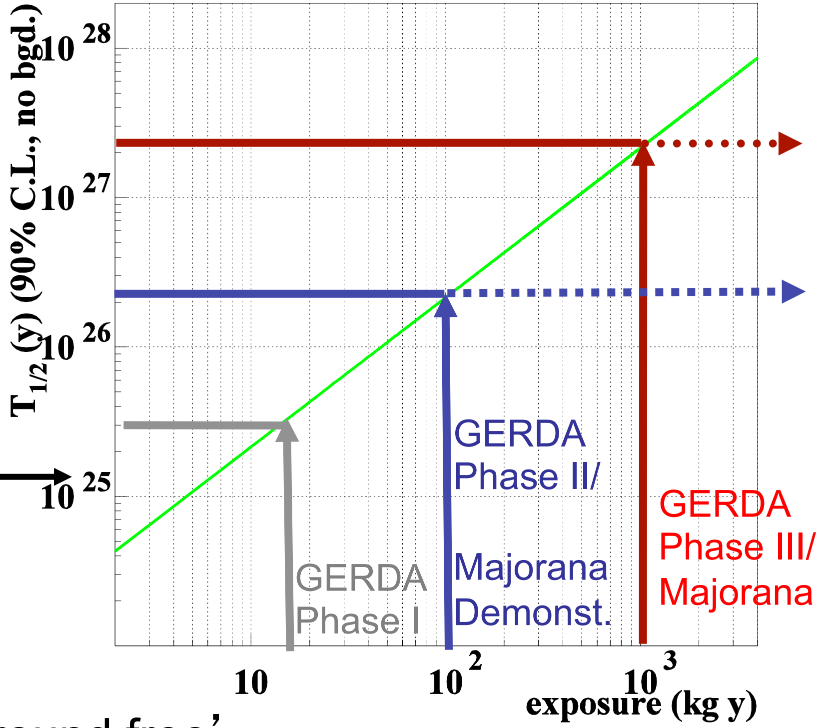
2·10^{27} (90 % CL) *

2·10^{26} (90 % CL) *

2·10^{25} (90 % CL)*

KK →

***: no event in ROI**



<24 - 41 meV

<75 - 129 meV

assuming
|M$^{0\nu}$|=2.99-8.99
[Smol&Grab PRC' 10]
and 86% enrichment

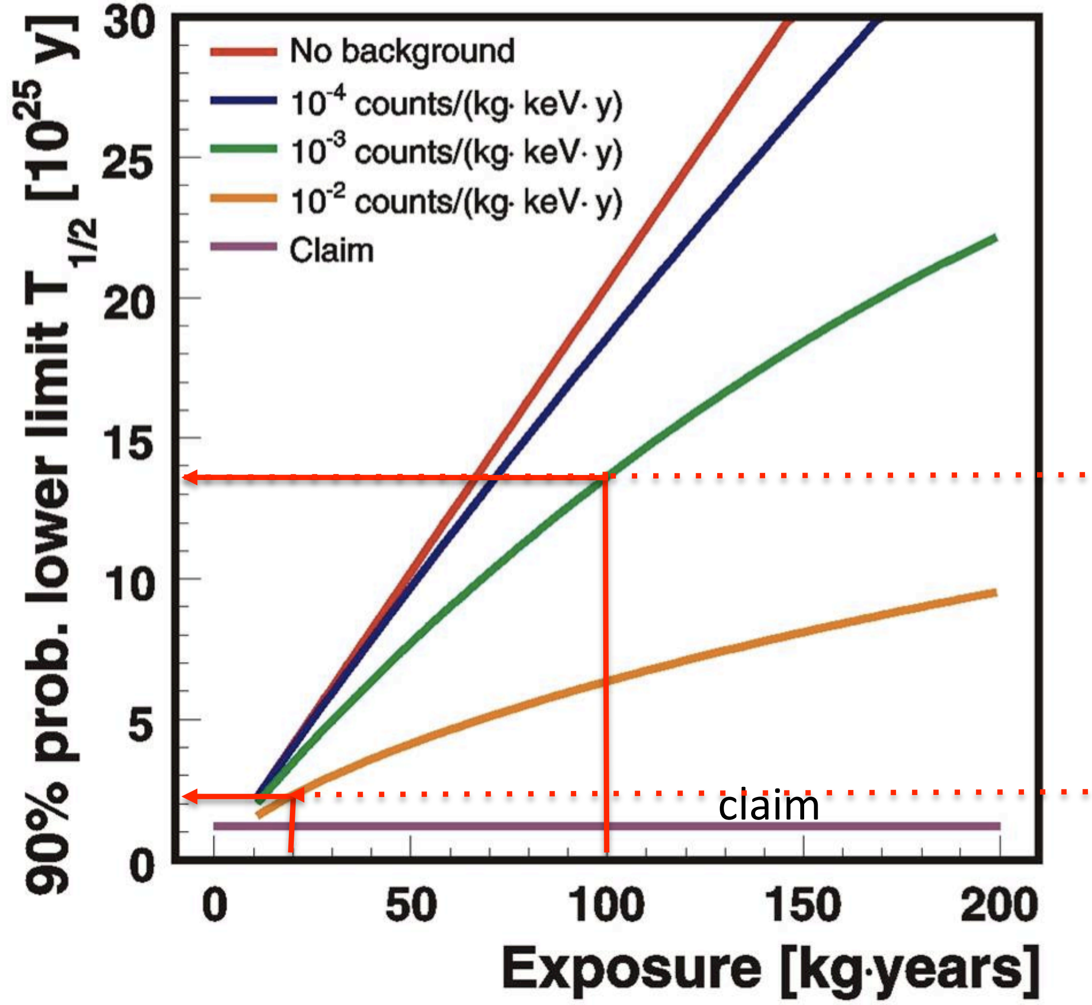
required for 'background free'
exp. with ΔE~3.3 keV (FWHM): **O(10^{-3})** **O(10^{-4})** counts/(kg·y·keV)

Background requirement for GERDA/Majorana:

⇒Background reduction by factor **10^2** **- 10^3** required w.r. to precursor exps.

⇒Degenerate mass scale **O(10^2 kg·y)** ⇒ Inverted mass scale **O(10^3 kg·y)**

GERDA Phases



Phase III:

contingent on results of Phase II:

1 ton (GERDA & Majorana & new group

BI ≈ 0.0001 cts / (keV kg yr)

Probe full inverse mass hierarchy with ~10 ton yr

Phase II:

Add new enr. BEGe detectors (20 kg)

BI ≈ 0.001 cts / (keV kg yr)

Sensitivity after 100 kg yr

Phase I:

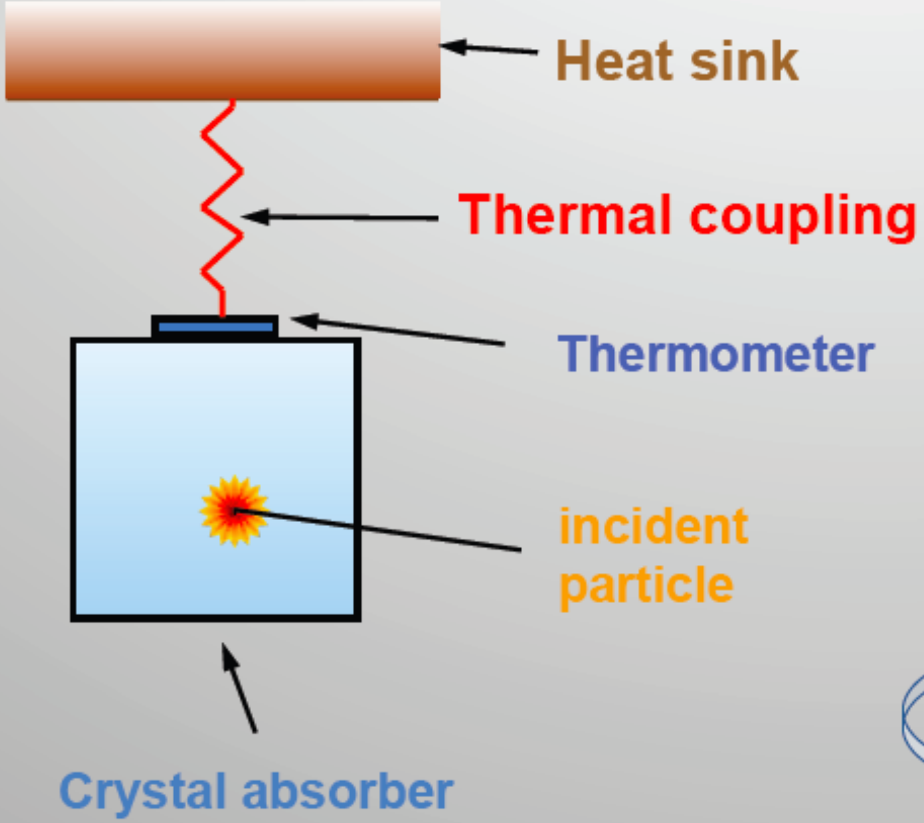
Use refurbished HdM & IGEX (18 kg)

BI ≈ 0.01 cts / (keV kg yr)

Sensitivity after 20 kg yr

Bolometric technique

The working principle is very simple:



Heat sink

Thermal coupling

Thermometer

incident particle

Crystal absorber

This technique measures **all** the energy deposited by a particle in form of increase of temperature in the absorber

↓

Absorber ≡ DBD source

Signal: $\Delta T = E/C$

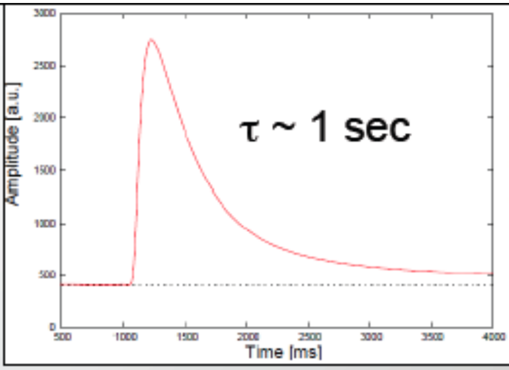
Time constant $= C/G$

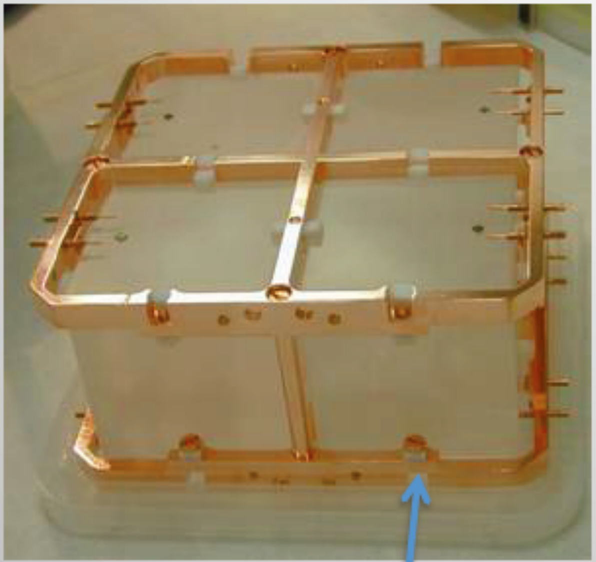
Low heat capacity

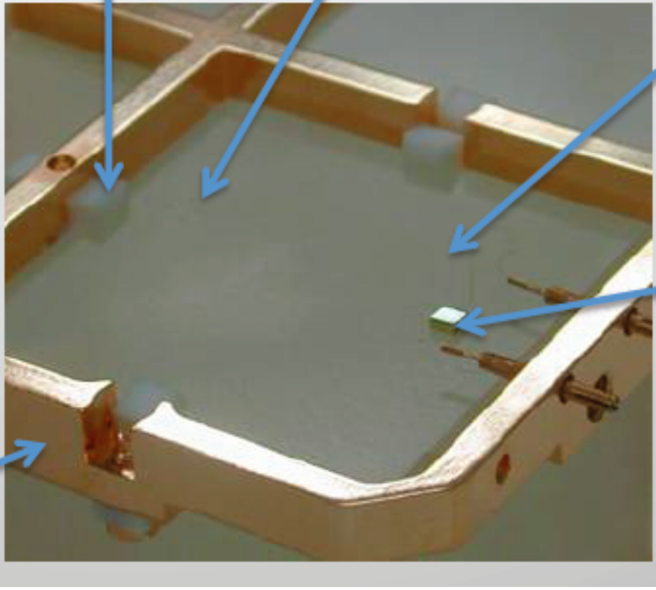
- Low temperatures (~10mK)
- Dielectric diamagnetic materials

From M. Pedretti, Neutrino 2012

TeO_2 Bolometers







PTFE pieces

TeO_2 crystal

25 μm gold wire connection

Neutron Transmutation Doped Ge sensor

Copper holder

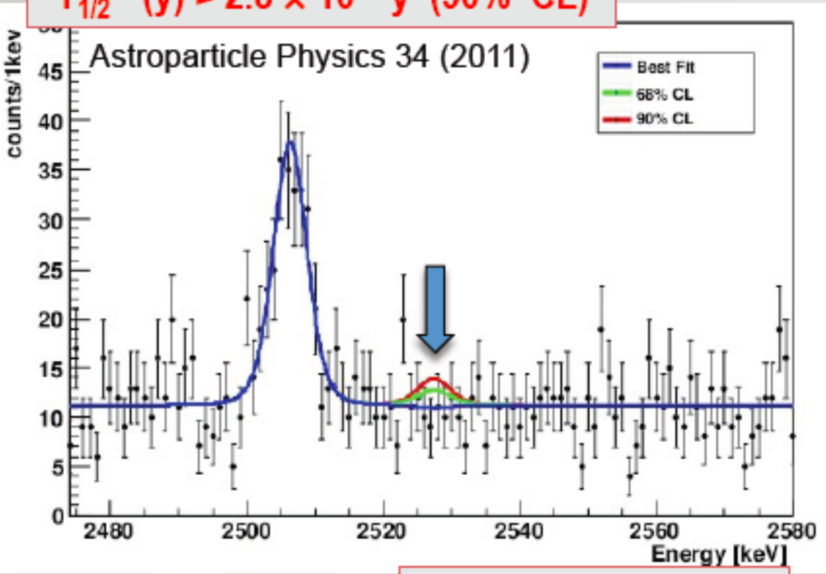
From M. Pedretti, Neutrino 2012

Bolometric 0νDBD experiment evolution

$\Delta E = 6.2 \pm 2.5$ keV (~0.3% FWHM)

Bkg = 0.169±0.006 c/keV/kg/y

$T_{1/2}^{0\nu}$ (y) > 2.8×10^{24} y (90% CL)

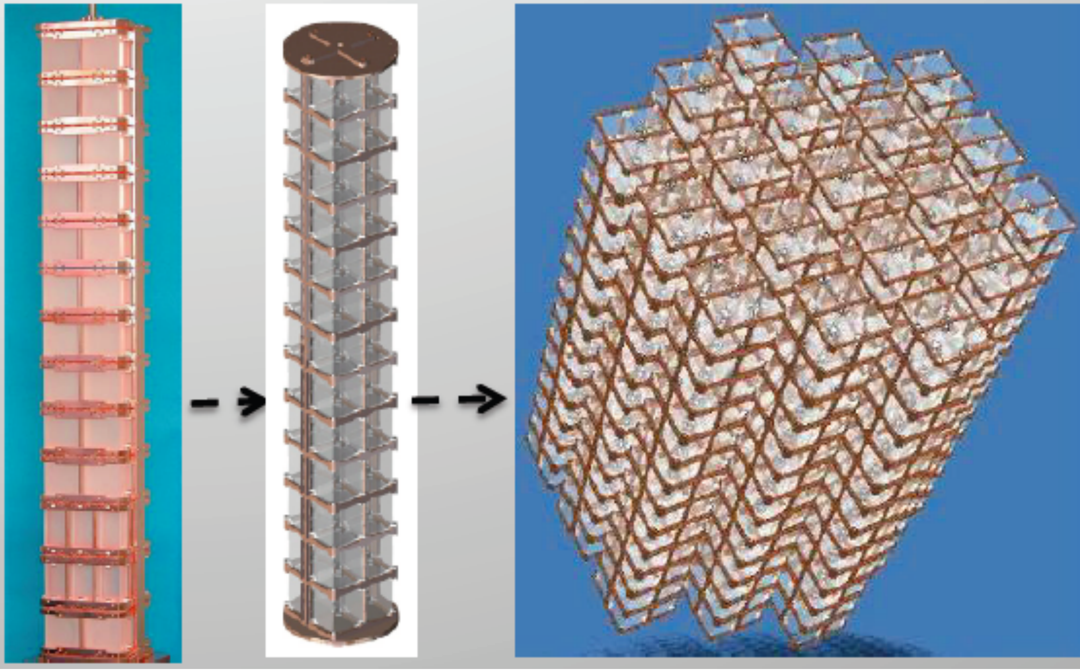

Astroparticle Physics 34 (2011)

$\langle M_{bb} \rangle < 0.3 - 0.7$ eV

CUORICINO
40 kg
(2003-2008)

CUORE-0
(2012)

CUORE
1 ton
(~2014)

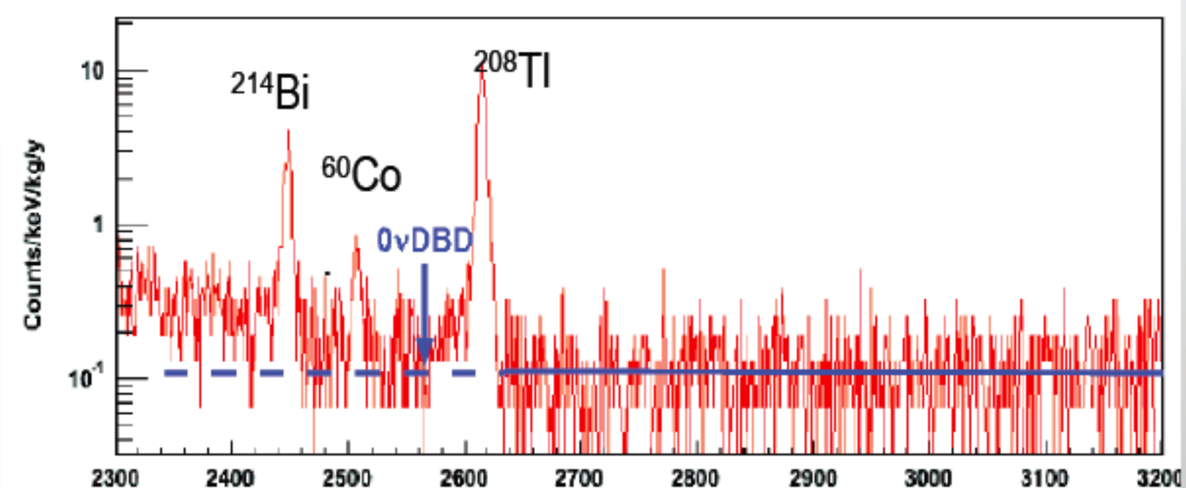


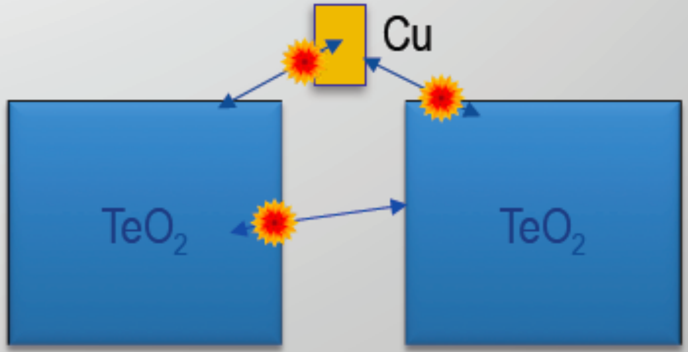
From M. Pedretti, Neutrino 2012

CUORICINO lesson: background

Sensitivity of current generation bolometric DBD experiment is limited by bkg.

MC: the background in CUORICINO is due to degraded alpha particles which release only part of their energy in the detector (surface contamination)





b

$b_{CUORICINO}$ = 0.169 c/keV/kg/y due to:

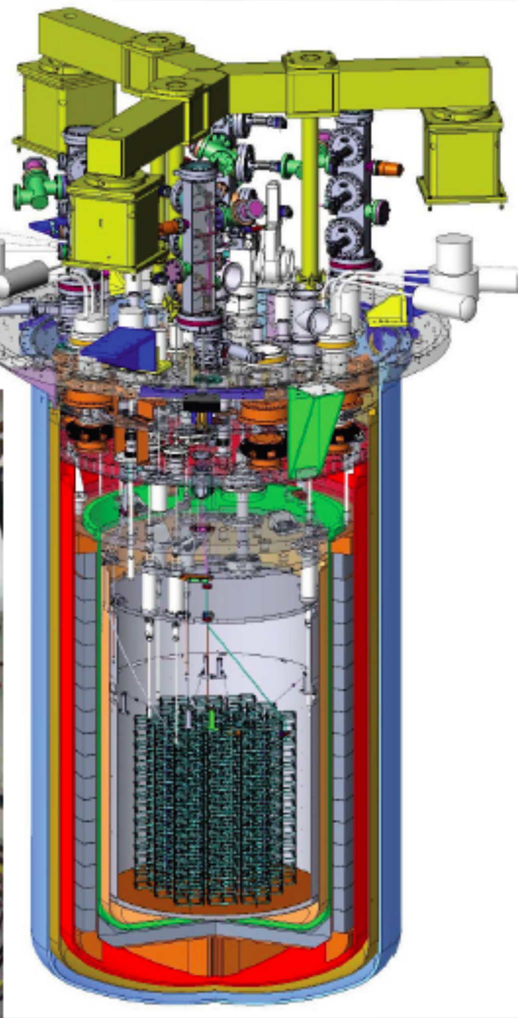
- ^{232}Th in cryostat (30 ± 10%) → γ
- TeO_2 surfaces (10 ± 5%)
- Surfaces facing detectors (50 ± 20%)

} degraded α particles

From M. Pedretti, Neutrino 2012

CUORE status

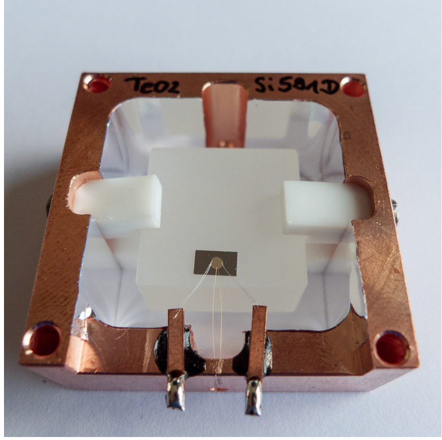
- Crystals, almost all arrived (all at LNGS by the end of 2012)
- Copper parts are being machined and cleaned
- Dilution unit delivered to LNGS (though some repairs needed)
- CUORE Hut, and most of all the infrastructures, ready
- Detector assembly line, ready (small modifications)
- Radon abatement system installed
- 3 (of 6) cryostat vessels delivered soon at LNGS
- Commissioning of the cryostat second half of 2012

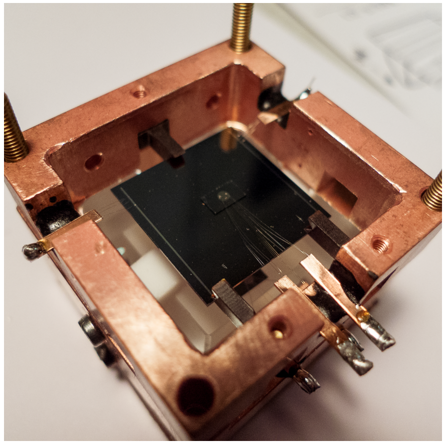


Crystals	12/12
Thermistors	13/03
Cleaned Cu parts	13/12
Cryogenic	13/12
Tower Assembly	14/04
Detector insertion	14/07
Cool Down	14/11

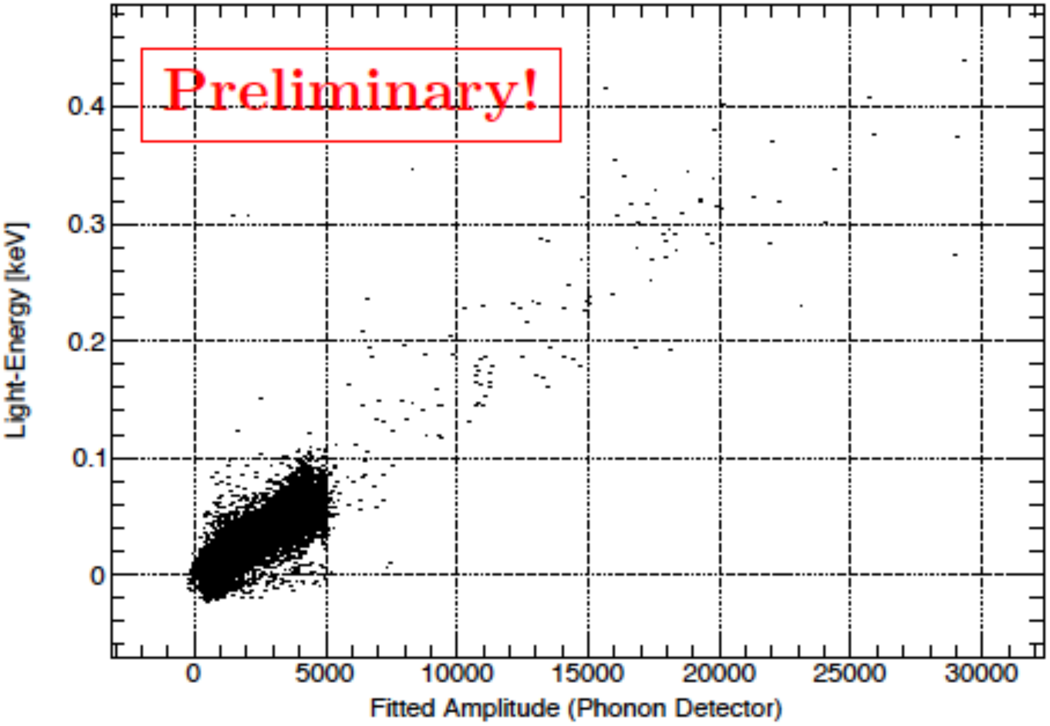
From M. Pedretti, Neutrino 2012

Detection of Cherenkov Photons with Neganov-Luke Light-Detectors: discrimination between alphas & betas



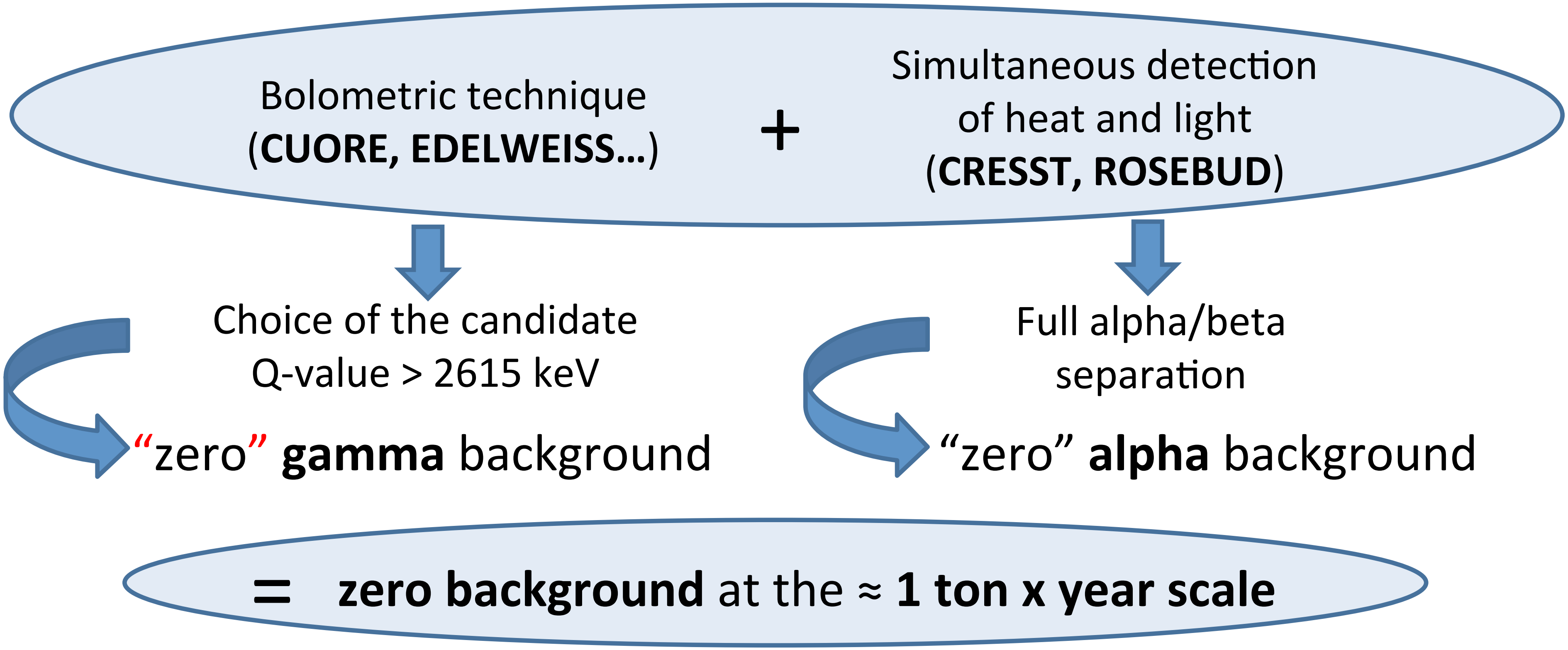


Detector module with Phonon- & NL Light Detector.



PhD thesis: M. Willers, TUM

Scintillating bolometers and DBD



Bolometric technique
(**CUORE, EDELWEISS…**)

+

Simultaneous detection
of heat and light
(**CRESST, ROSEBUD**)

Choice of the candidate
Q-value > 2615 keV

"zero" **gamma** background

Full alpha/beta
separation

"zero" **alpha** background

= **zero background** at the ≈ **1 ton x year scale**

Two very promising options:

1. isotope ^{82}**Se** (Q=2996 keV, i.a.=8.7%) embedded in **ZnSe** crystals

(**LUCIFER** **ERC advanced grant project**)

At CSNSM the research activity is focusing also on:

2. isotope ^{100}**Mo** (Q=3035 keV, i.a.=9.7%) embedded in **ZnMoO$_4$** crystals

⟹ **LUMINEU**

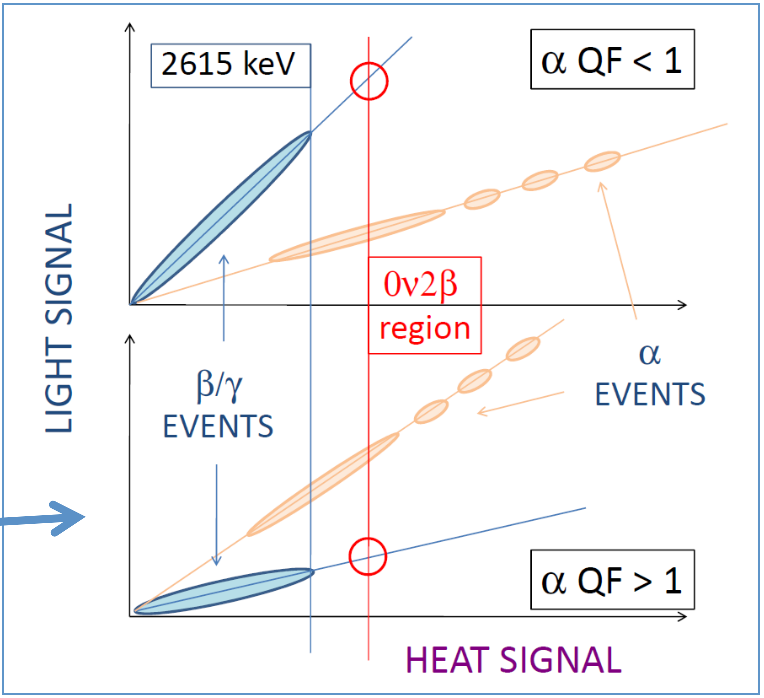
^{100}Mo – excellent candidate as scintillating bolometer

Candidate Nucleus	Isotopic Abundance [%]	Q-value [keV]	Some materials successfully tested as bolometers (good scintillators are underlined)
^{76}Ge	7.6	2039	Ge
^{136}Xe	8.9	2458	-
^{130}Te	34.2	2528	TeO_2
^{116}Cd	7.5	2809	<u>$CdWO_4$</u>
^{82}Se	8.7	2996	<u>ZnSe</u>
^{100}Mo	9.7	3034	<u>$ZnMoO_4$</u>, <u>$PbMoO_4$</u>, <u>$CaMoO_4$</u>, <u>$SrMoO_4$</u>
^{150}Nd	5.6	3368	-
^{48}Ca	0.2	4274	<u>CaF_2</u>, <u>$CaMoO_4$</u>

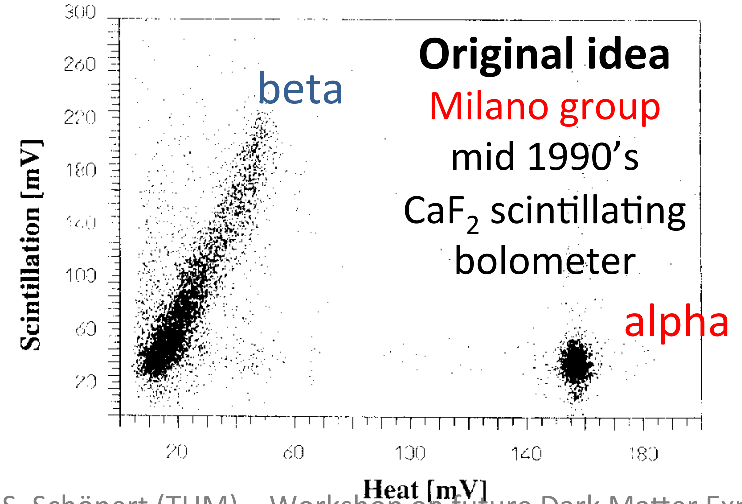
Scintillating bolometers and DBD

A device able to measure simultaneously the **phonon (heat)** excitations and the **photon (scintillation)** excitations generated in a crystal by the same nuclear event can efficiently discriminate **alphas from betas / gammas**.

Alphas emit a different amount of light with respect to beta/gamma of the same energy (normally lower → **α QF < 1, but not in all cases**).



A **scatter plot light vs. heat** separates alphas from betas / gammas.

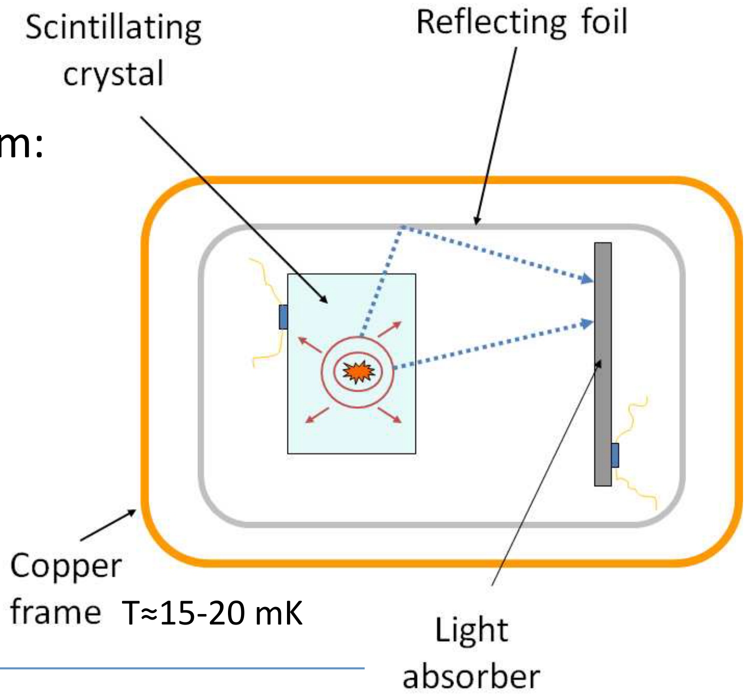


Original idea
Milano group
mid 1990's
CaF_2 scintillating bolometer

The **experimental premise** for **LUCIFER and LUMINEU** is the R&D activity lead by **Stefano Pirro** at LNGS , in the framework of the programs:

- **BOLUX**, funded by **INFN** – CSN5
- **ILIAS-IDEA** funded by the **European Commission** (WP2-P2)

Scintillating bolometers in LUMINEU



ZnMoO$_4$

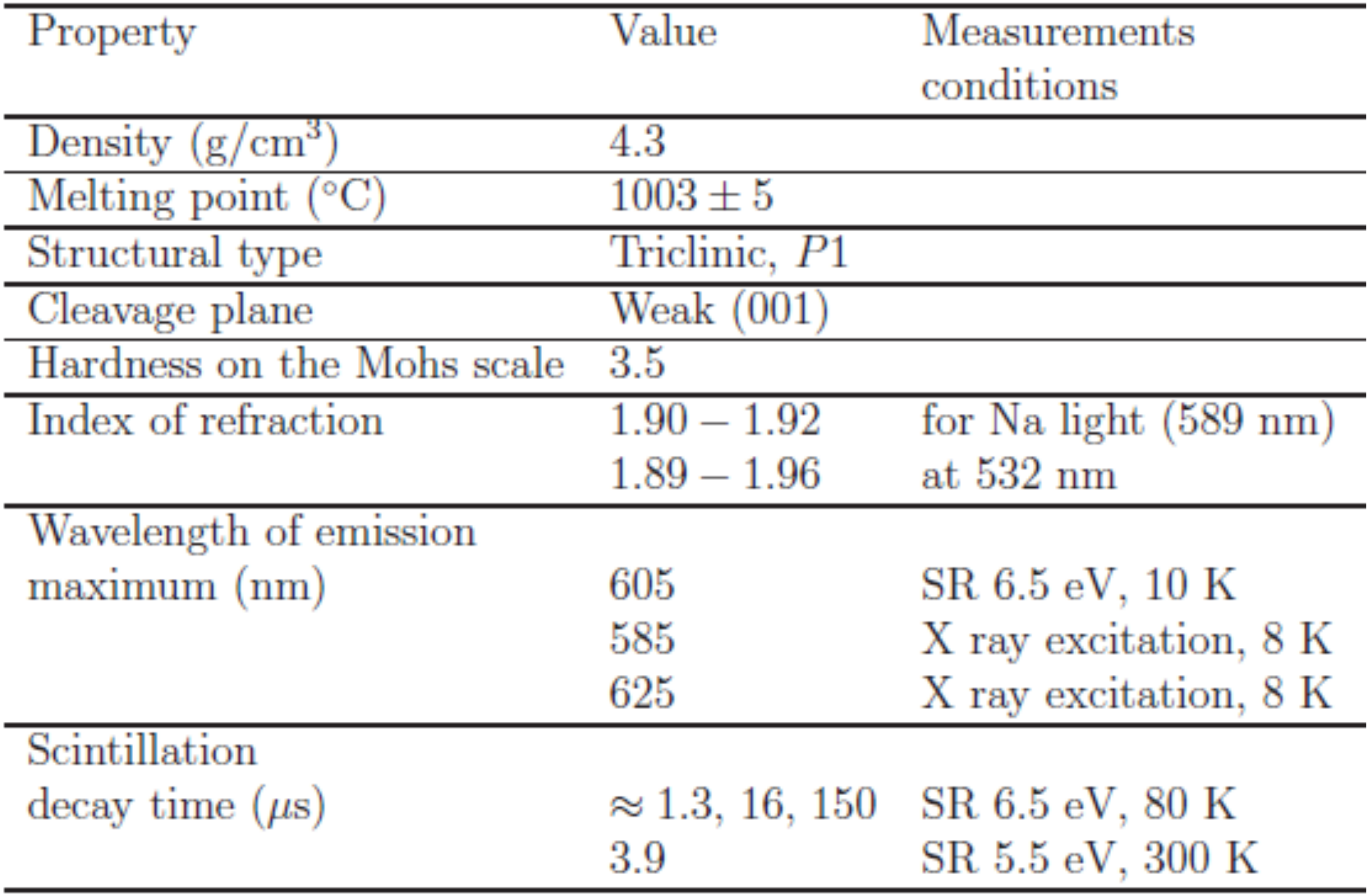
- ➢ Determination of the **growth conditions** for optimum:
  - Bolometric performance
  - Light Yield
  - Alpha/Beta rejection factor
- ➢ Scale up of crystal size up to **≈400-500 g**
- ➢ Crystal **radio-purity**
- ➢ Use of **enriched material**

HP Germanium wafer

- ➢ Development/Selection of the **temperature sensor**
- ➢ Minimization of **threshold** (not so critical as in DM)
- ➢ Standardized **assembly** and **coupling to scintillators**
- ➢ Achievement of a good **reproducibility**

Pilot experiments

ZnMoO$_4$ crystal features



Property	Value	Measurements conditions
Density (g/cm^3)	4.3	
Melting point (°C)	1003 ± 5	
Structural type	Triclinic, $P1$	
Cleavage plane	Weak (001)	
Hardness on the Mohs scale	3.5	
Index of refraction	1.90 – 1.92	for Na light (589 nm)
	1.89 – 1.96	at 532 nm
Wavelength of emission maximum (nm)	605	SR 6.5 eV, 10 K
	585	X ray excitation, 8 K
	625	X ray excitation, 8 K
Scintillation decay time (μs)	$\approx$ 1.3, 16, 150	SR 6.5 eV, 80 K
	3.9	SR 5.5 eV, 300 K

Nucl. Instr. Meth. A 729(2013)856

Production of $ZnMoO_4$ crystals

Large $ZnMoO_4$ single crystals were developed for the first time in 2008

Idea originated by a discussion btw S. Pirro and F. Danevich at NANP2005,Dubna, June 23

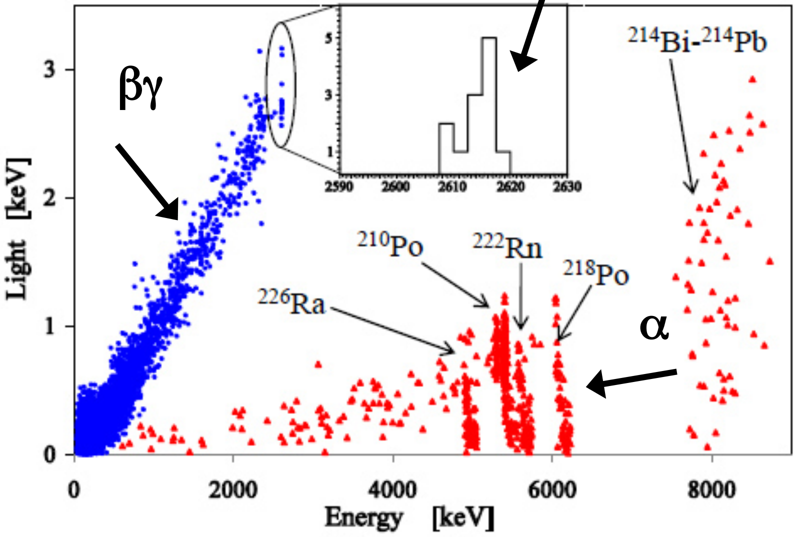
"Why nobody tries to grow $ZnMoO_4$?"

2008 (IGP, Moscow, Russia) [1]

2009 (ISMA, Kharkov, Ukraine) [2,3]

2010 Low-Thermal-Gradient Czochralski (NIIC, Novosibirsk, Russia) [4]

FWHM = 5.6 keV at 2615 keV



[3] L. Gironi *et al.*, JINST 5 (2010) 11007

A high sensitivity 2β experiment can be realized with enriched $Zn^{100}MoO_4$ [5,6]

[1] LI. Ivleva *et al.*, Crystallography Reports, 2008, Vol. 53, No. 6, pp. 1087
[2] L.L. Nagornaya, *et al.*, IEEE TNS 56 (2009) 2513
[4] J.W. Beeman *et al.*, J Low Temp Phys 167 (2012) 1021
[5] J.W. Beeman *et al.*, PLB 710 (2012) 318
[6] J.W. Beeman *et al.*, APP 35 (2012) 813

Courtesy of F.A. Danevich

Improved quality $ZnMoO_4$ crystals

- Transition metal impurities such as Fe, V, Cr, Co spoil crystal optical properties.

- Improvement obtained thanks to purification of initial charge (especially Mo) Wet chemistry using dissolution of MoO_3 in ammonia (2-3 stages)

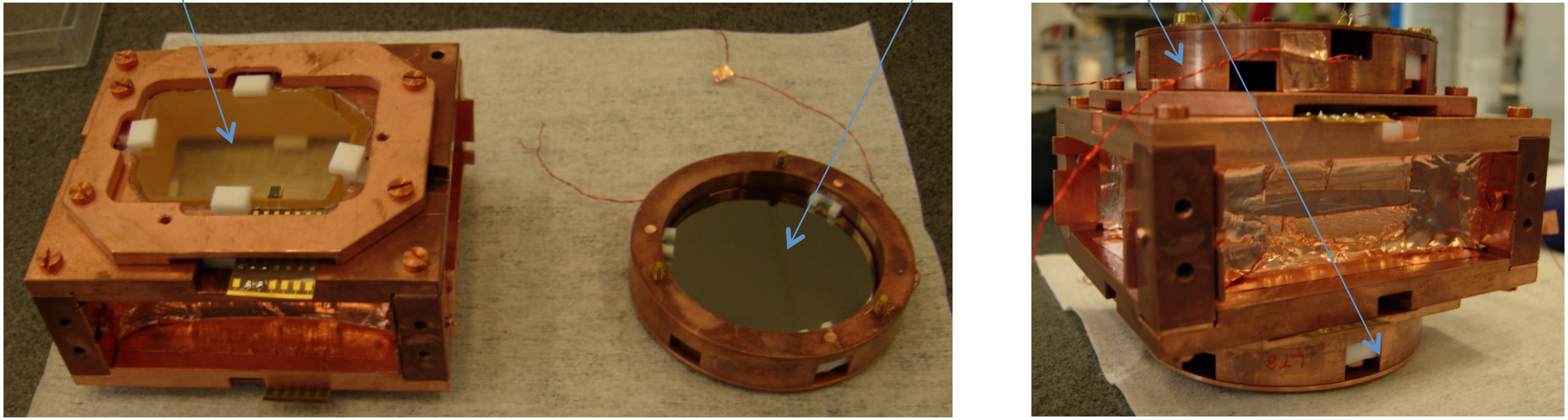
- Low-thermal-gradient Czochralski technique in Pt crucible ⌀40×100 mm The crystals were grown with a speed of 0.6-0.8 mm/h

Four working prototype detectors with masses up to 40 g were obtained using crystals from these boules

$ZnMoO_4$ - 313 g detector – version 1

M = 313 g
Irregular shape but two parallel sides with
H = 40 mm

LT1, LT2
Ge $\varnothing$=50 mm, Θ = 0.25 mm
m ~ 2.5 g



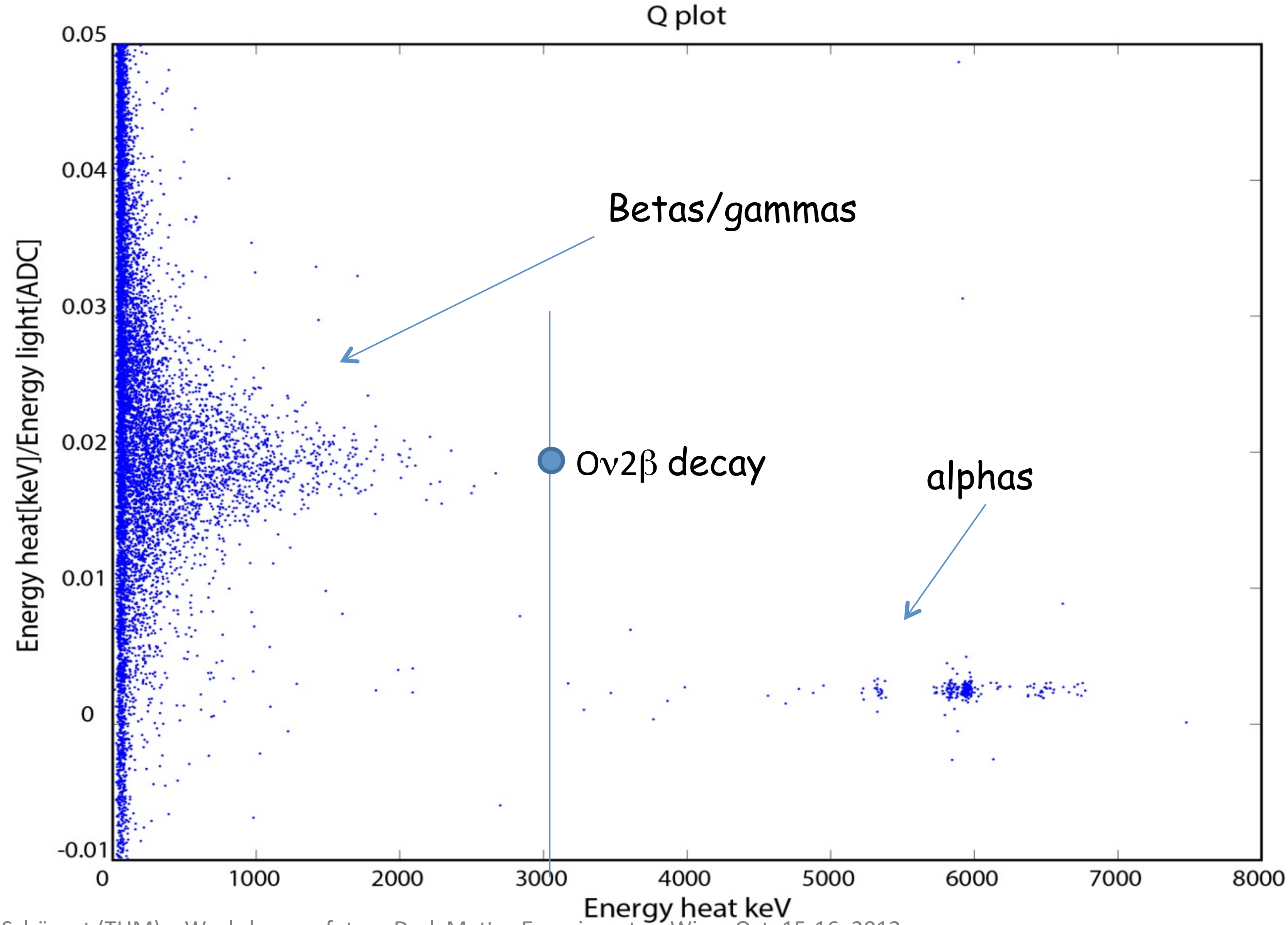
NTD thermistors for light detectors
$3 \times 2.2 \times 0.6$ mm^3 - M ~ 20 mg
Frontal contacts
R_0 = 0.75 Ohm
T_0 = 3.83 K

NTD thermistors for heat detector
$3 \times 3 \times 1$ mm^3 - M ~ 40 mg
Wrap around

(1) R_0 = 1.03 Ohm
T_0 = 3.83 K

(2) R_0 = 1.03 Ohm
T_0 = 4.23 K

$ZnMoO_4$ - 313 g detector – Q-plot



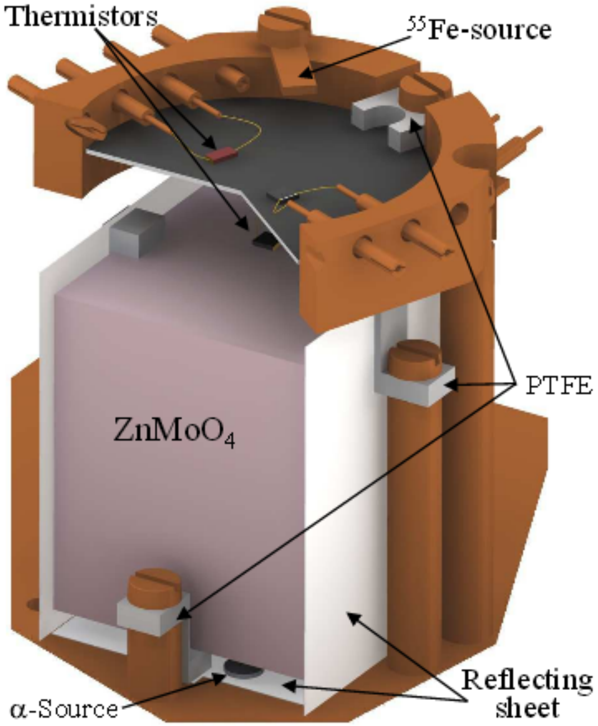
Betas/gammas

0ν2β decay

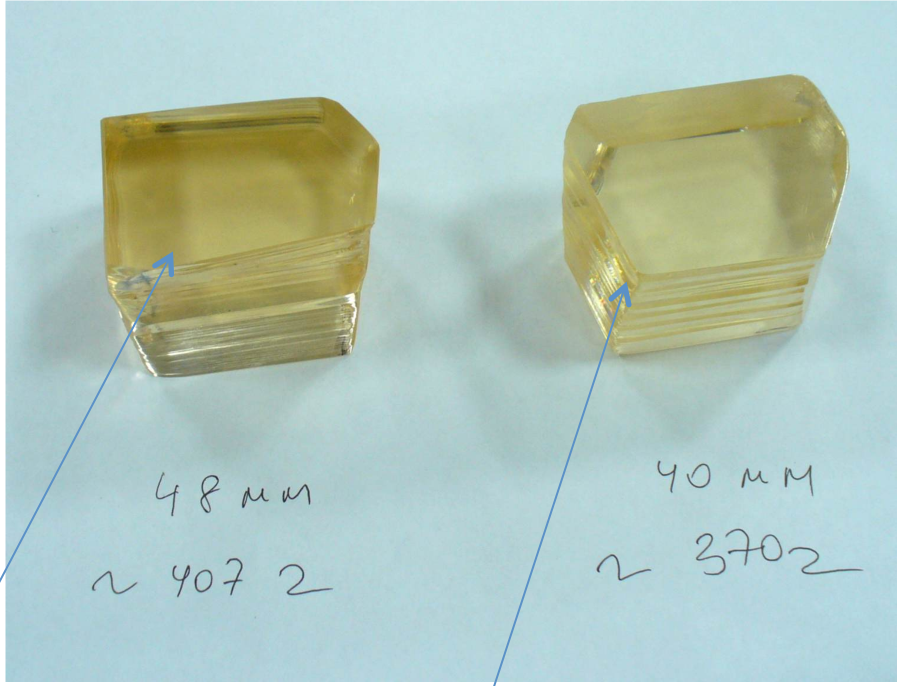
alphas

Large mass detectors operated at LNGS

A 330 g detector, from the same boule as the 313 g detector mentioned before, was successfully operated in LNGS, in the Hall-C facility also used for CUORE and LUCIFER R&D



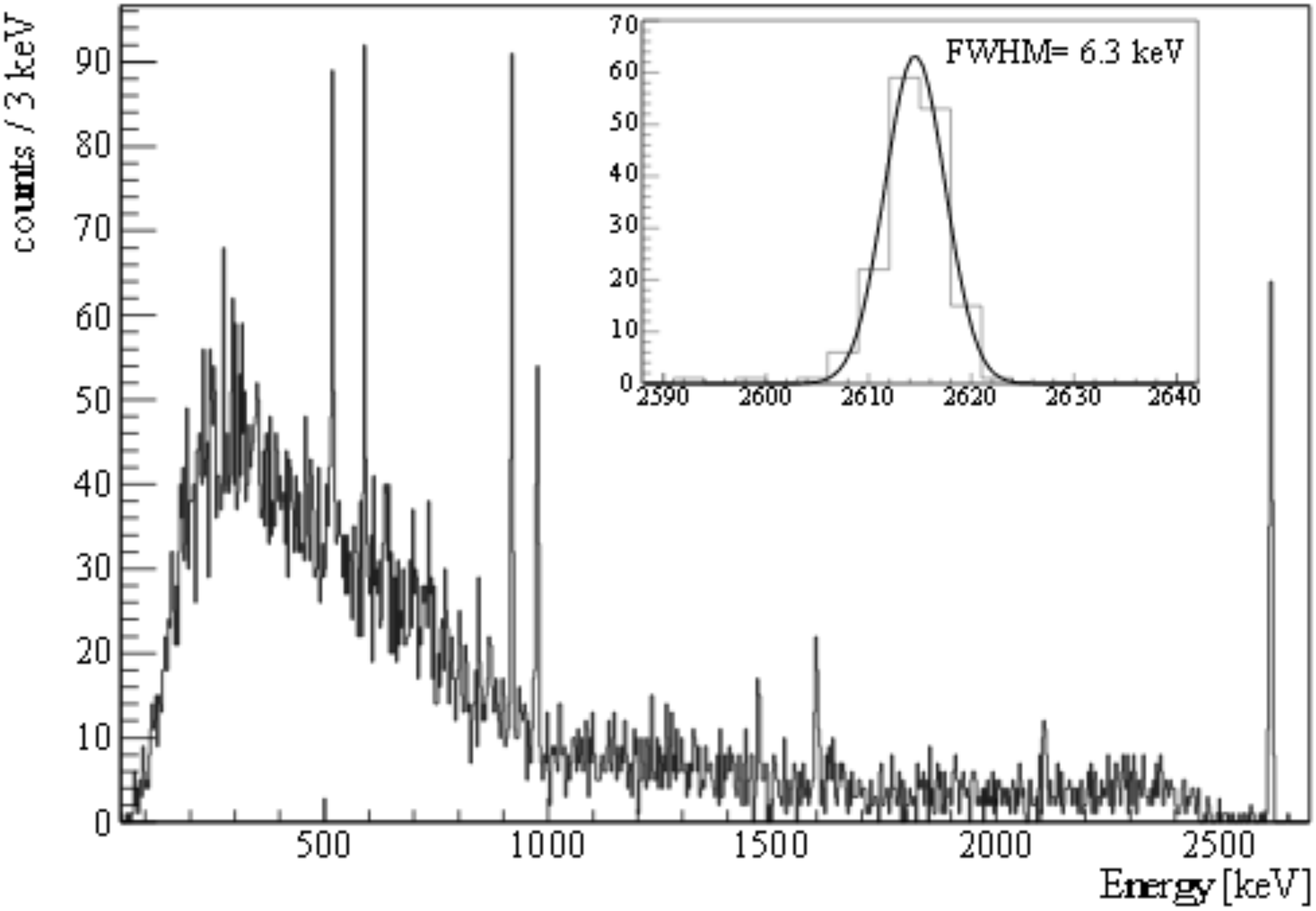
Schematic structure of LNGS detector



Used for Orsay/Modane 313 g detector

Used for LNGS 330 g detector

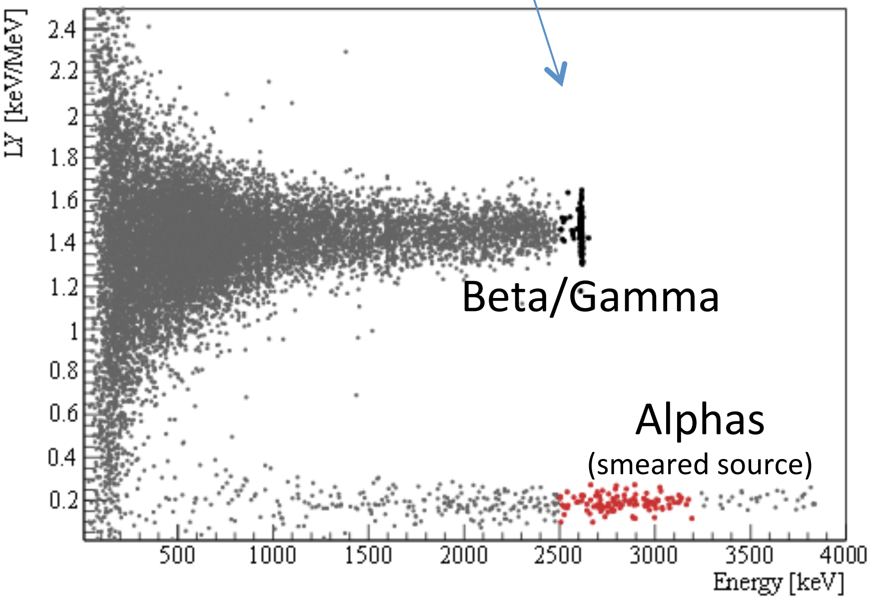
Excellent energy resolution at LNGS



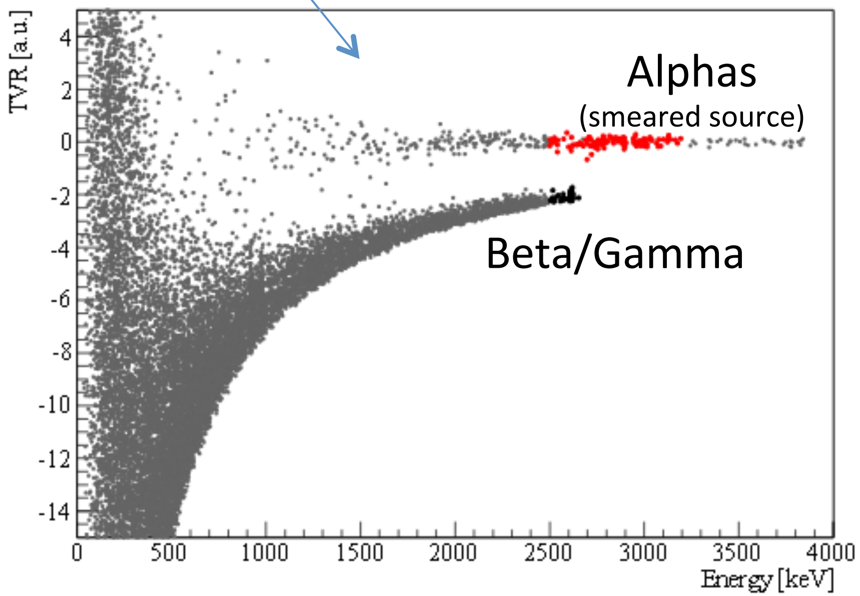
Excellent discrimination capability at LNGS

Alpha / Beta rejection can be made with similar efficiency using light signals or by pulse shape discrimination in the heat channel

Light Yield [keV/MeV]



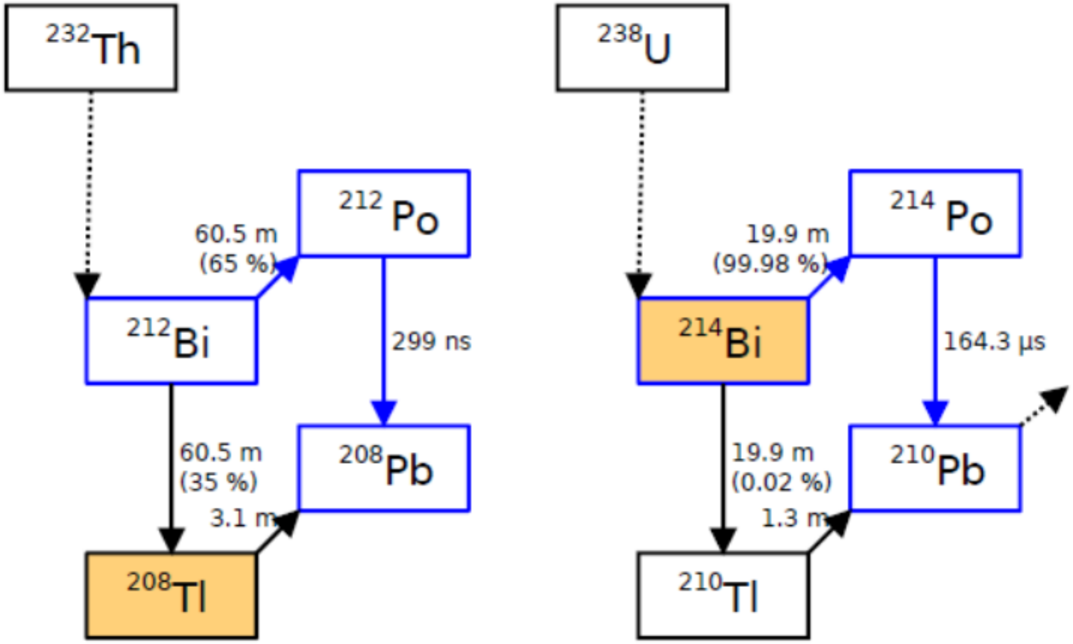
Pulse shape parameter



EPJC 72, 2142 (2012)

$ZnMoO_4$ - harmful contaminants

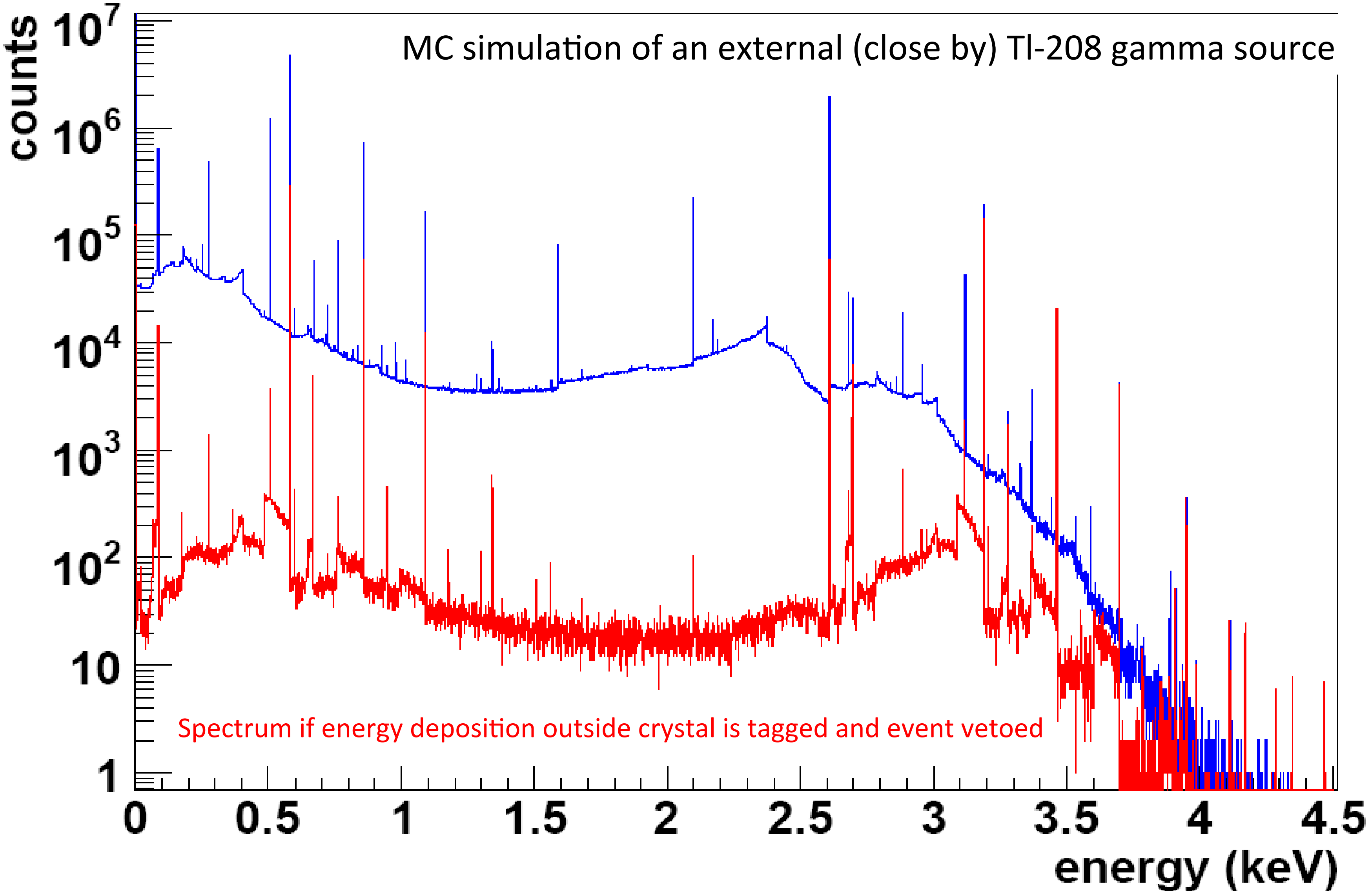
In the natural radioactivity chains, two beta active nuclides — ^{208}**Tl** and ^{214}**Bi** — have *Q* -values greater than 3 MeV (respectively, 3.270 MeV and 4.999 MeV)



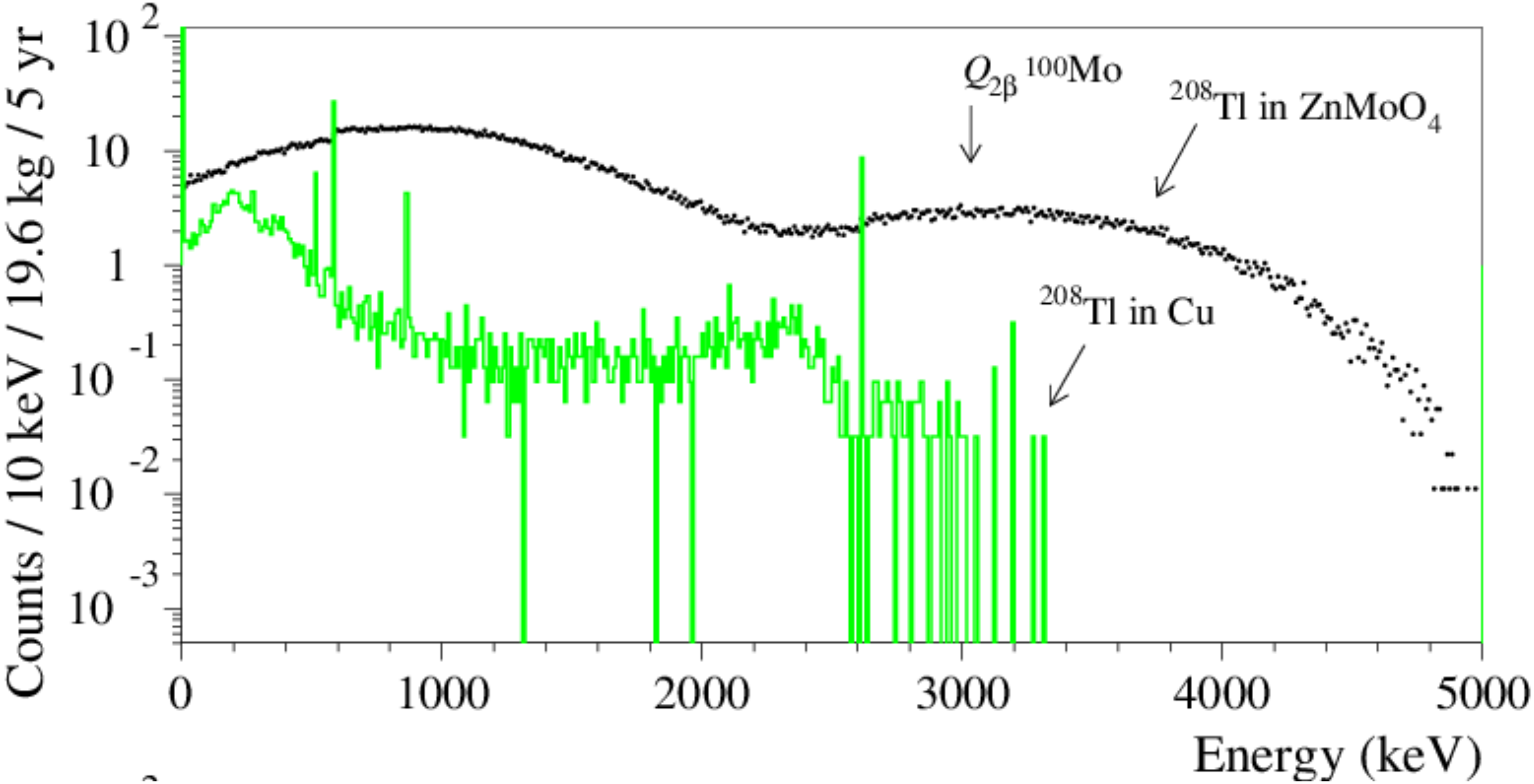
< 1-10 muBq/kg required!!

Background example: ^{232}Th (^{208}Tl) γ's

(Previous statement true only for distant sources)



In calorimetric measurement (β+γ) energies up to 5 MeV



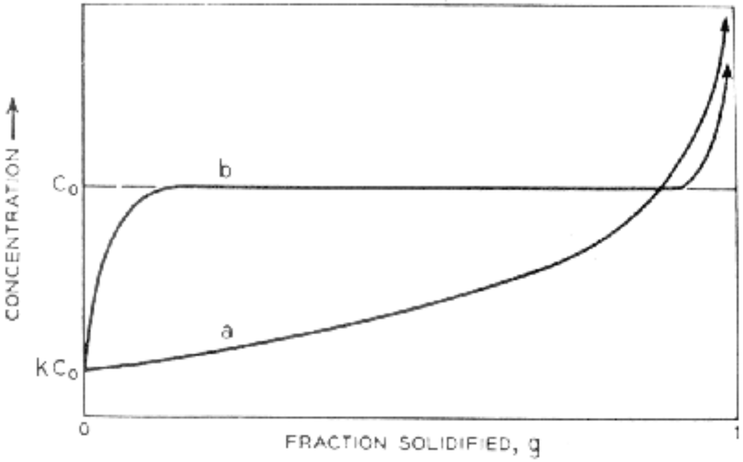
$ZnMoO_4$ crystal pulling R&D at TUM

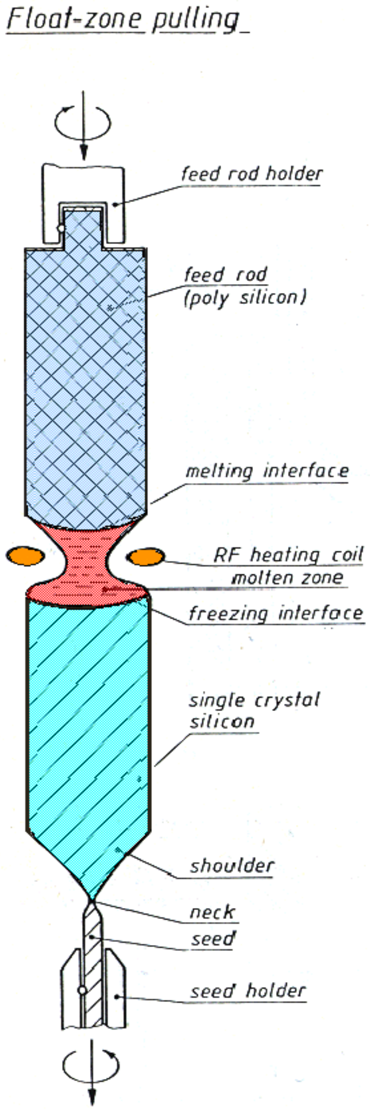
(Lanfranchi, Erb, Schönert with funding through Excellence Cluster)

- Goal:
  - Radio purity
  - High mass yield w.r. to starting material

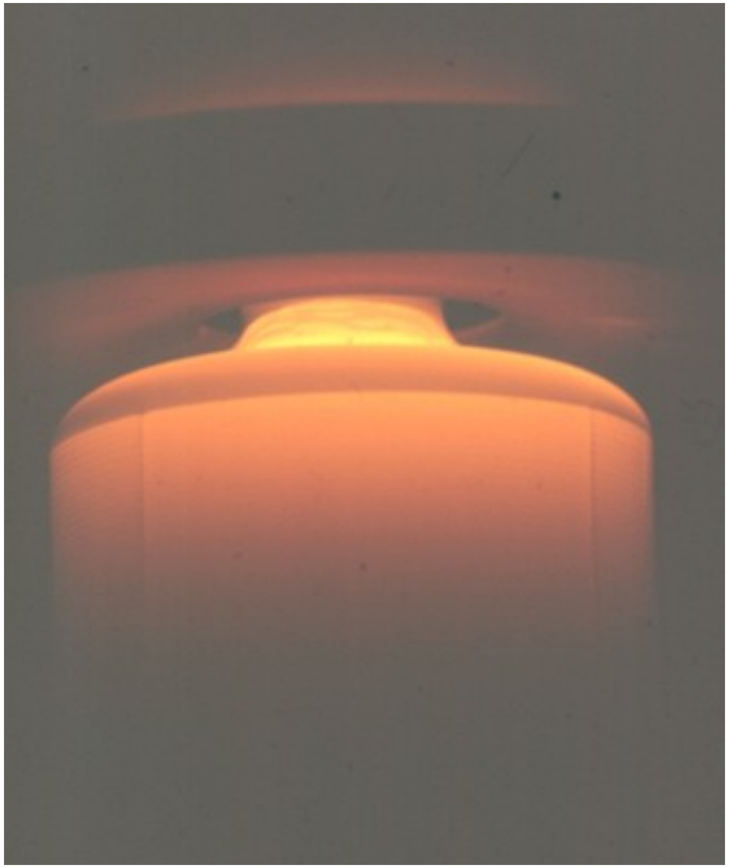
1) Czochralski: based on experience from $CaWO_4$ crystals

2) Floating Zone Technique: first tests

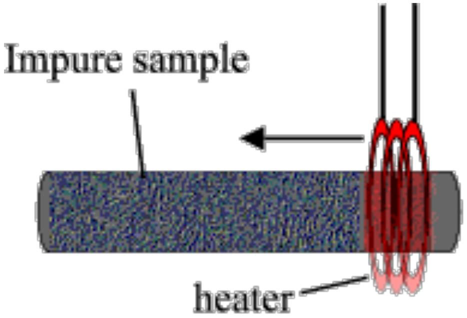




Floating Zone Technique



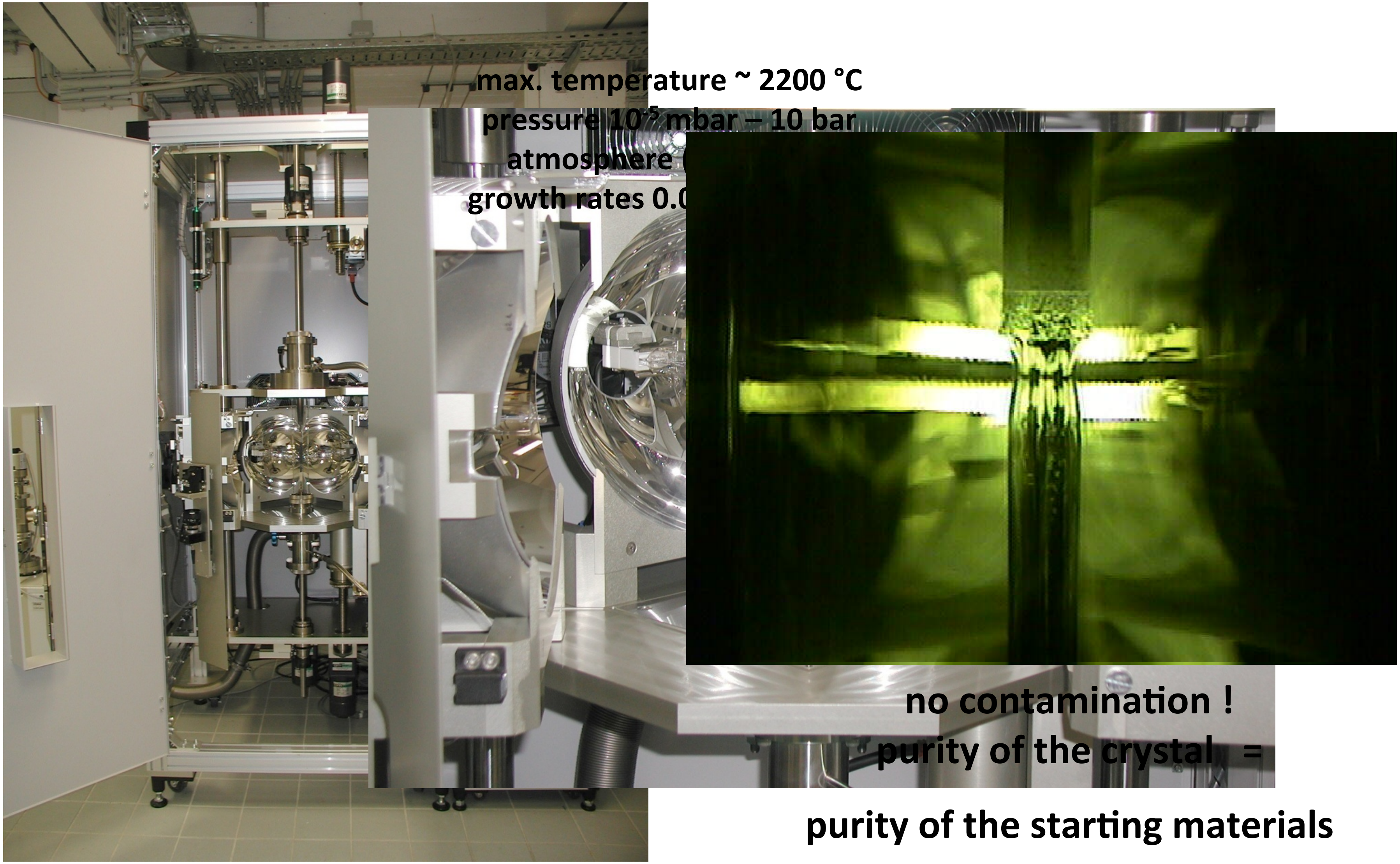
FZ-of Silicon



Effect of purification
by zone melting

No crucible !

Containerless crystal growth



max. temperature ~ 2200 °C

pressure 10^{-5} mbar – 10 bar

atmosphere (

growth rates 0.0

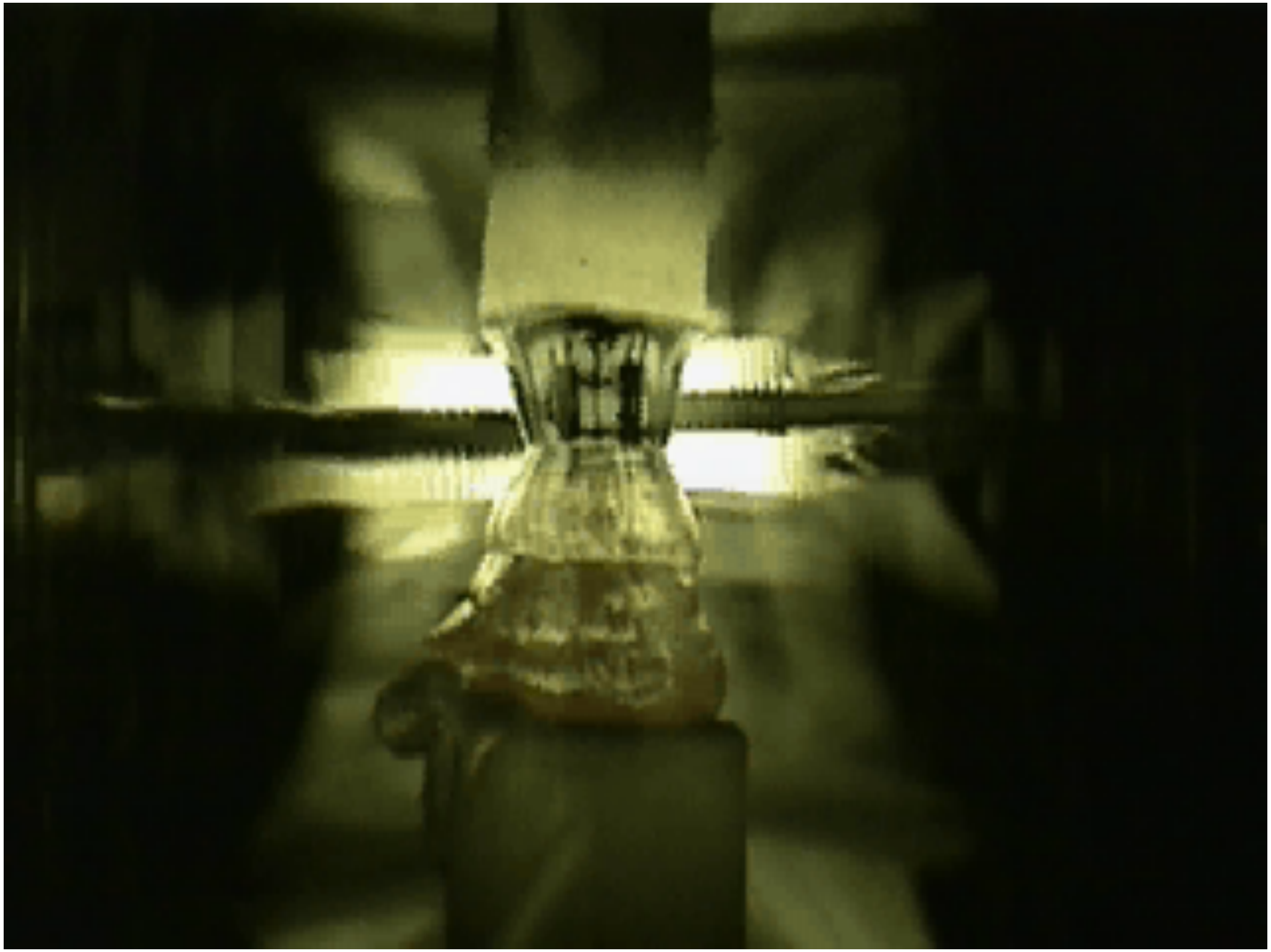
no contamination !

purity of the crystal =

purity of the starting materials

(+ contaminations by handling!)

First float zone growth tests of $ZnMoO_4$ at TUM



Summary & outlook

- Most important question in neutrino physics: Majorana vs. Dirac (Lepton-number violation); (together with establish / refute sterile neutrinos)
- Ge-diodes and bolometers only detectors with keV energy resolution
- Ge-detectors (GERDA) currently leading together with Xenon experiments
- Molibdate bolometers promising dbd-targets/detectors
- Italian & french colleagues (Lucifer & Lumineu) ground laying work (first Lumineu crystal running in Edelweiss setup)
- CRESST has most advanced technology for light detection
- Challenge: intrinsic radio-purity (Th, U) of molibdate crystals

- In-house production of molibdate crystals & detectors is very appealing and might be cost efficient
- R&D on molibdates crystal production started at TUM (in parallel to GERDA)
- If successful:
    - could be tested in CRESST
    - Long-term: cryogenic observatory for DM & DBD conceivable

Reconsider and adopt previous Eureca design concept: