Neutrinoless Double Beta Decay and new Physics

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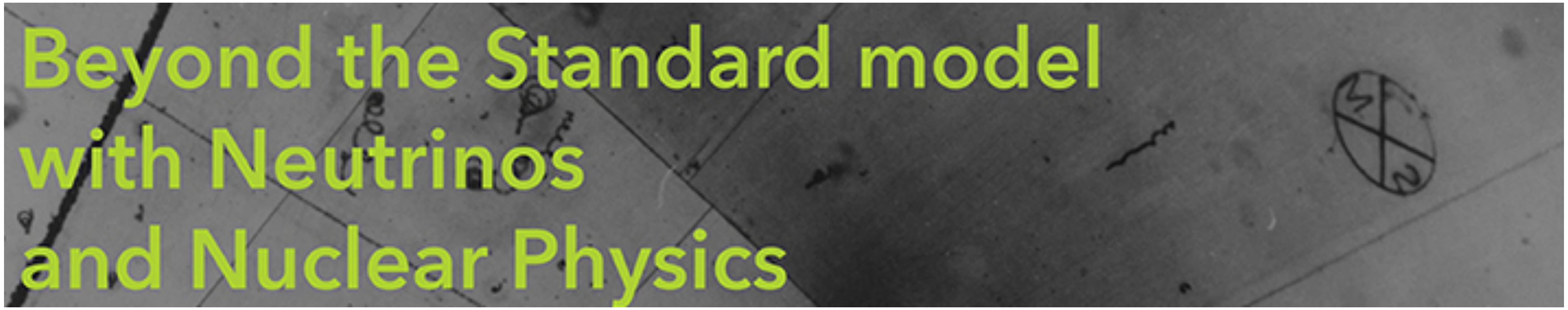
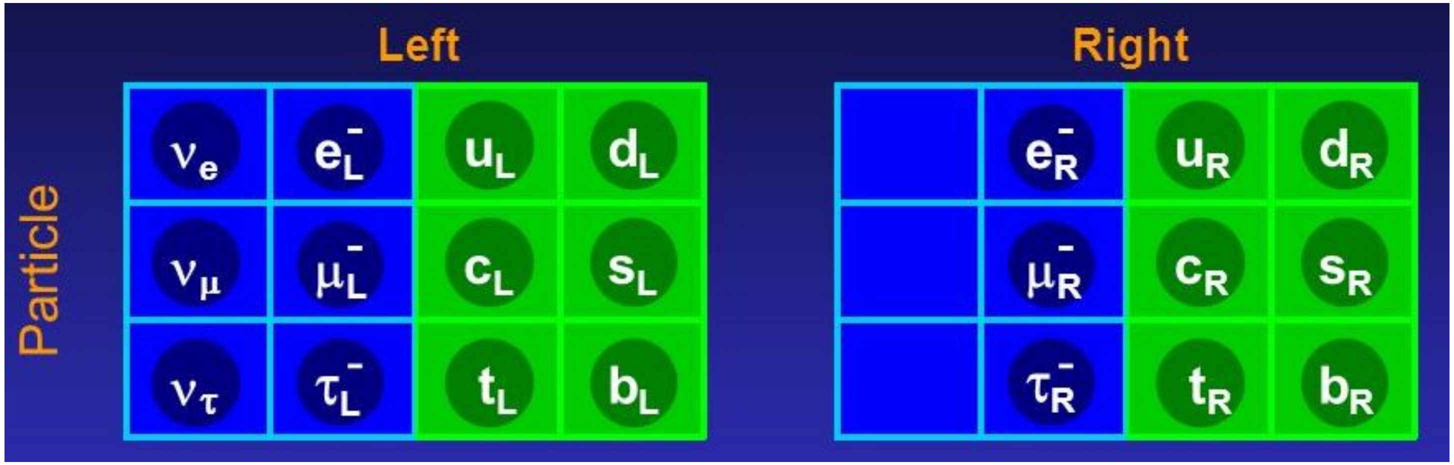


Beyond the Standard model
with Neutrinos
and Nuclear Physics

A Solvay workshop in Brussels, November 29th - December 1st 2017

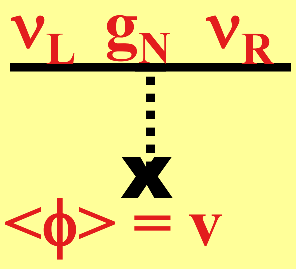
ULB, Campus Plaine - Solvay Room

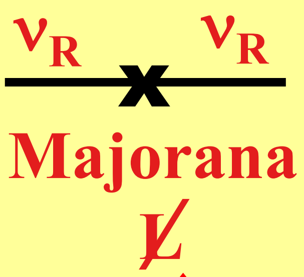
Adding Neutrino Masses to the SM



Particle	Left				Right			
	ν_e	e^-_L	u_L	d_L		e^-_R	u_R	d_R
	ν_μ	μ^-_L	c_L	s_L		μ^-_R	c_R	s_R
	ν_τ	τ^-_L	t_L	b_L		τ^-_R	t_R	b_R

Simplest and suggestive possibility: add 3 right handed singlets (1_L)





$$\rightarrow \begin{pmatrix}\overline{\nu}_L & \overline{\nu}^c_R\end{pmatrix}\begin{pmatrix}0 & m_D\\ m_D & M_R\end{pmatrix}\begin{pmatrix}\nu^c_L\\ \nu_R\end{pmatrix}$$

like quarks and charged leptons → Dirac mass terms (including NMS mixing)

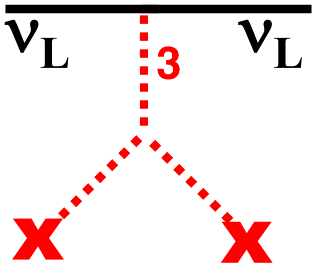
+9 param. & new ingredients:
1) Majorana mass = scales
2) lepton number viol. → SM+

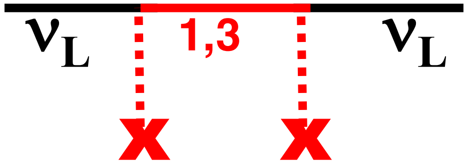
6x6 block mass matrix block diagonalization M_R heavy → 3 light ν's

Other Possibilities

Add scalar triplets (3_L) or add fermionic (1_L) or (3_L)

➔left-handed Majorana mass term: $M_L LL^c$



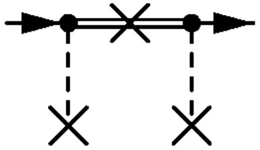


Both ν_R and new singlets / triplets:

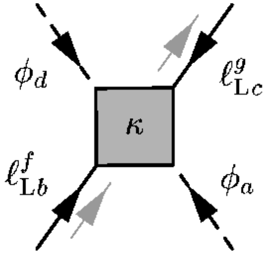
➔ see-saw type II, III

$$m_\nu = M_L - m_D M_R^{-1} m_D^T$$

Higher dimensional operators: d=5, …



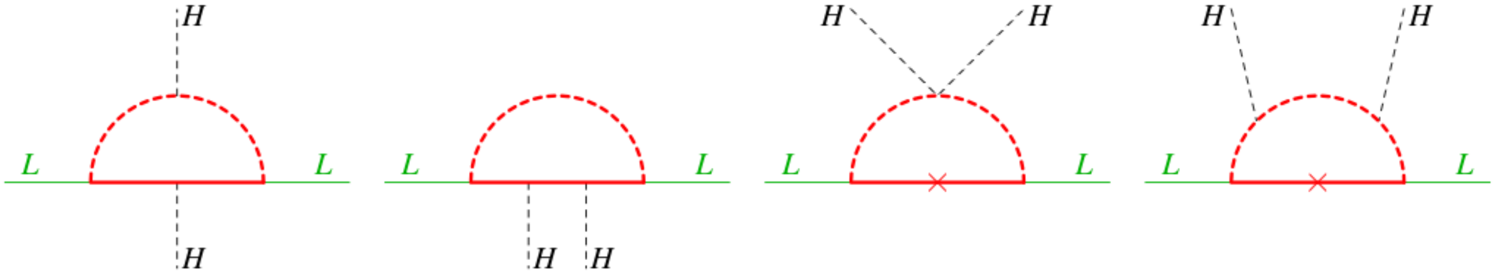
$\Rightarrow$



$\Leftrightarrow$ $\mathcal{L}_{mass} = \kappa \cdot \overline{\nu}^C_L \nu_L \Phi^T \Phi$

➔ $M_L L\overline{L}^c$

Radiative neutrino mass generation



Add: more neutrinos, SUSY, extra dimensions, …

➔ huge number of papers on neutrino masses...
... but we know only two Δm^2... (plus mass & unitarity bounds)

➔ neutrino masses can/may solve two of the SM problems:
- leptogenesis as explanation of BAU (both Majorana and Dirac)
- keV sterile neutrinos as excellent warm dark matter candidate

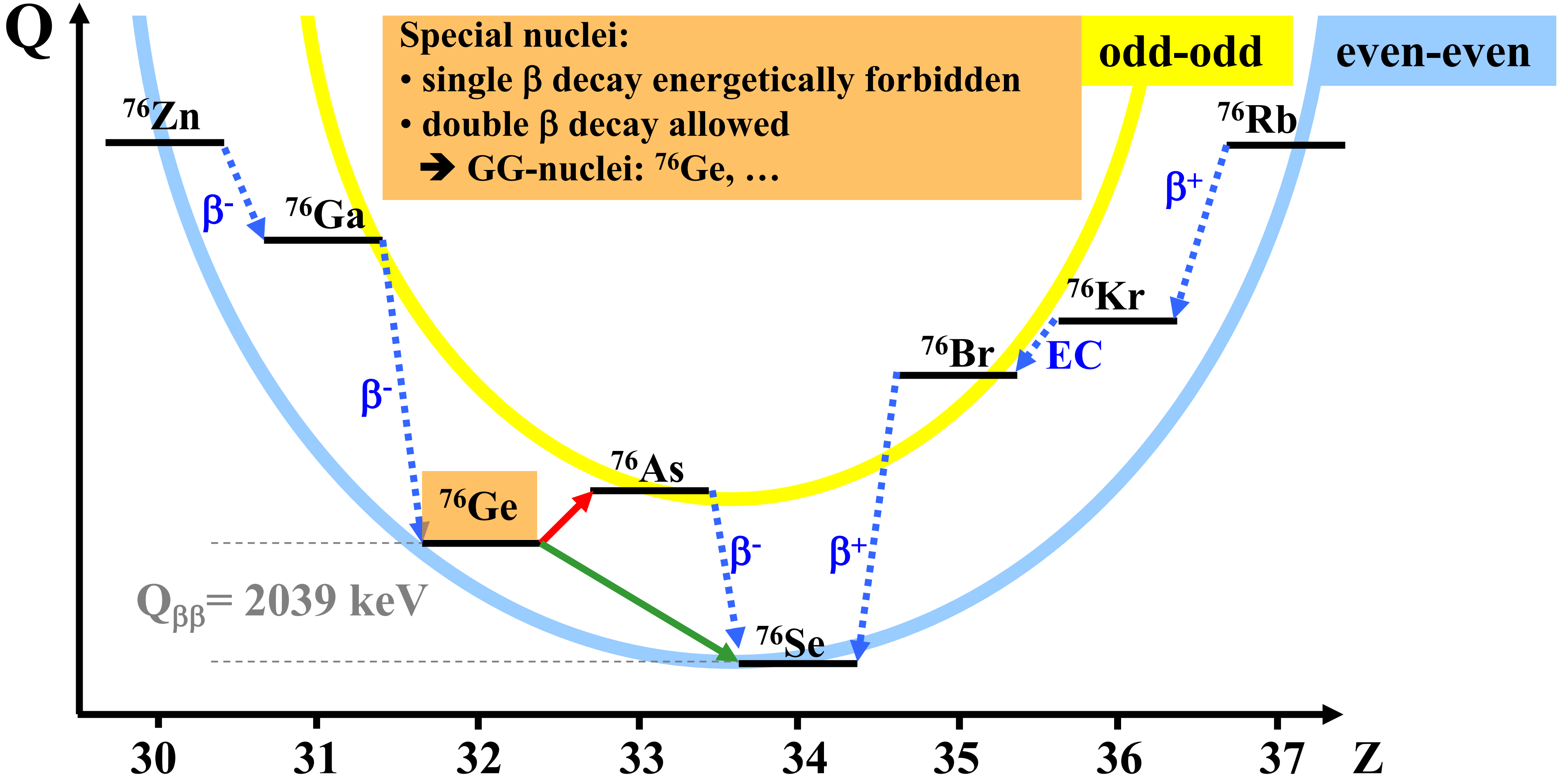
even for ν_R only ➔ BSM physics
in many cases connections to LFV, LHC, DM

Double Beta Decay

If neutrinos have Majorana masses
➔ Lepton Number Violation
➔ Neutrinoless Double Beta Decay

BUT: Be careful about the inverted reasoning!

Double β-Decay & Mass Parabolas



^{76}Ge: Only double β decay ➔ SM: 2ν+2e$^-$ *OR* BSM: 0ν+2e$^-$

Further 0νββ isotopes…

In addition: isotopic composition, backgrounds, costs, NMEs, ...

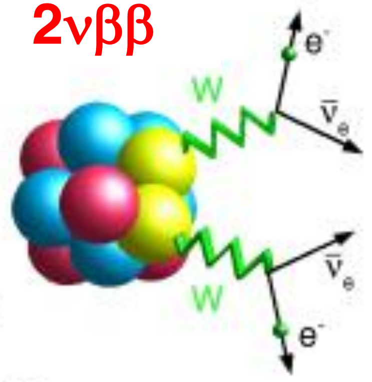
The Standard Picture of Double Beta Decay

2νββ decay seen for diff. isotopes (Kirsten,…)

$T^{1/2} = O(10^{18} - 10^{21}$ years) ➔ up to $10^{11} \otimes T_{Universe}$

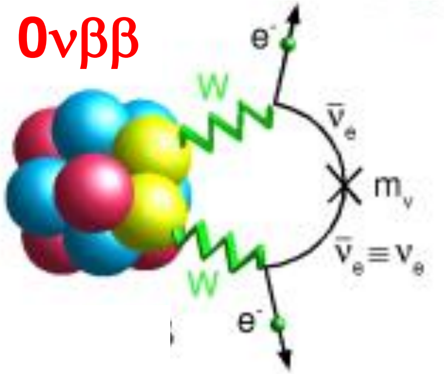
2νββ

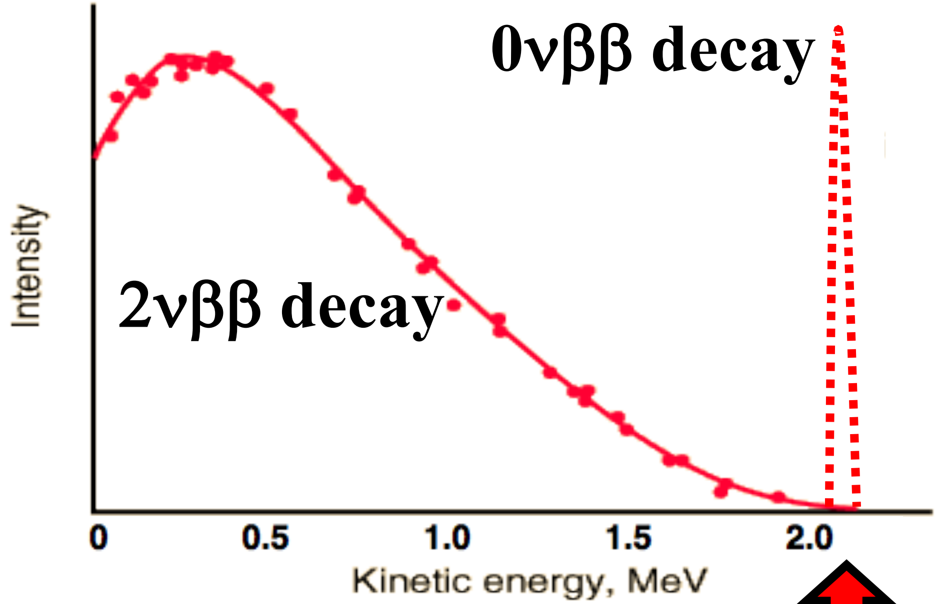
SM



0νββ

Majorana mass





$T^{1/2} > O(10^{25}y)$

$$1/\tau = G(Q,Z)\ |M_{nucl}|^2 <m_{ee}>^2$$

important: NMEs and their uncertainties…

- observe 2νββ
- look for 0νββ signal at $Q_{\beta\beta}$

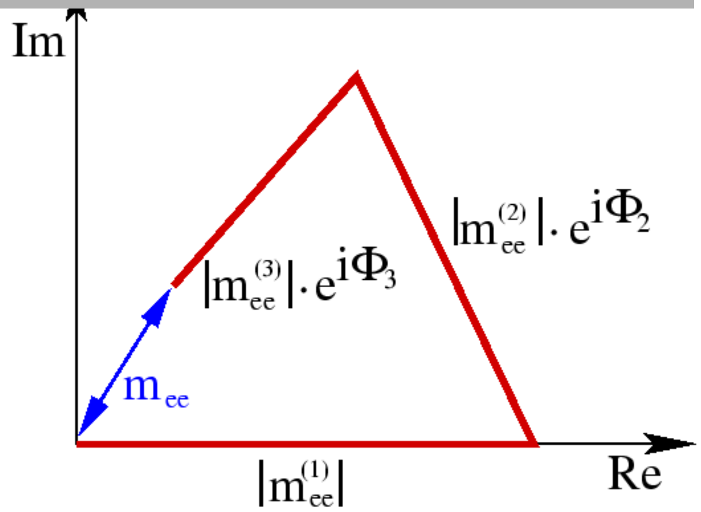
➔ big amount of 0νββ nuclei

- extreme low backgrounds!

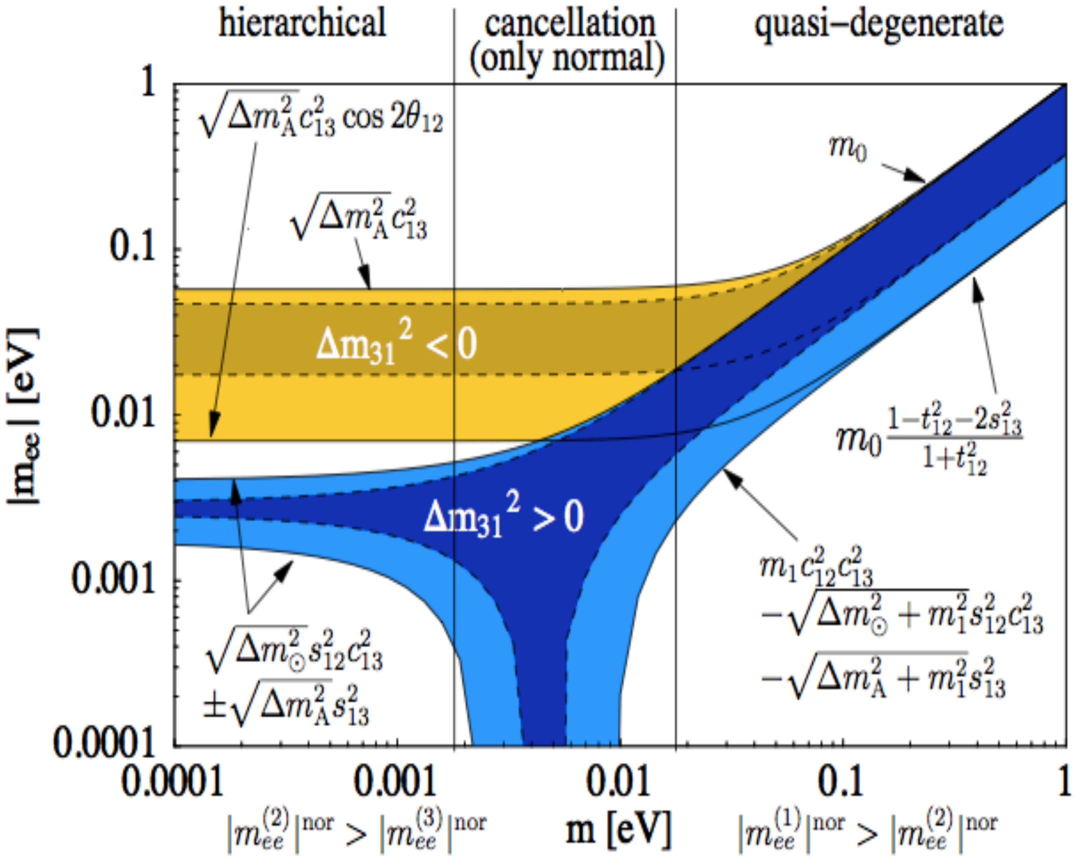
➔ signal = Majorana mass

m_{ee}: The Effective Neutrino Mass

$$m_{ee} = |m_{ee}^{(1)}| + |m_{ee}^{(2)}| \cdot e^{i\Phi_2} + |m_{ee}^{(3)}| \cdot e^{i\Phi_3}$$



$$\begin{aligned} |m_{ee}^{(1)}| &= |U_{e1}|^2 m_1 \\ |m_{ee}^{(2)}| &= |U_{e2}|^2 \sqrt{m_1^2 + \Delta m_{21}^2} \\ |m_{ee}^{(3)}| &= |U_{e3}|^2 \sqrt{m_1^2 + \Delta m_{31}^2} \end{aligned}$$



Comments:

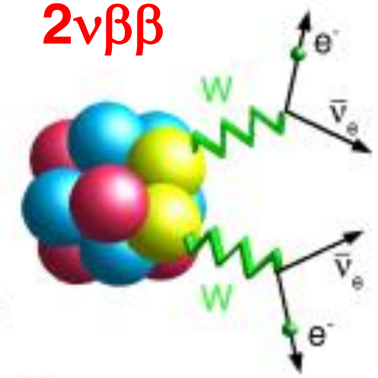
- **cosmology: m < 0.2-0.3 eV**
- **0νββ: m_{ee} < 0.1-0.3 eV**
- **NMEs➔ unavoidable theory errors**
- **known Δm^2 from oscillations**
  - **➔ yellow/blue areas**
  - **➔ improved sensitivity is very promising!**

- **warnings:**
  - **assumes no *other* ΔL=2 physics**
  - **assumes no sterile neutrinos, ...**

More general: L Violating Processes

SM

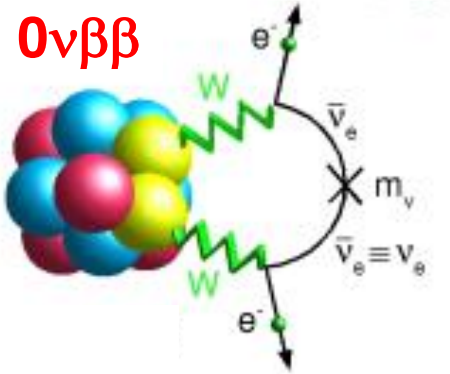
2νββ



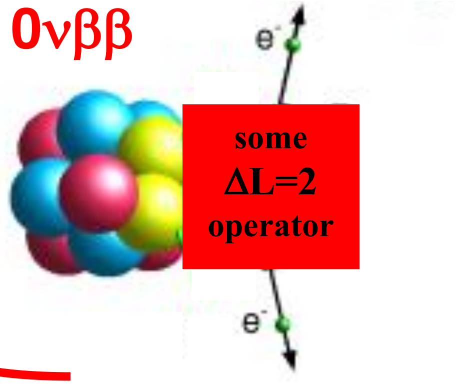
BSM

$T^{1/2} > O(10^{25} y)$

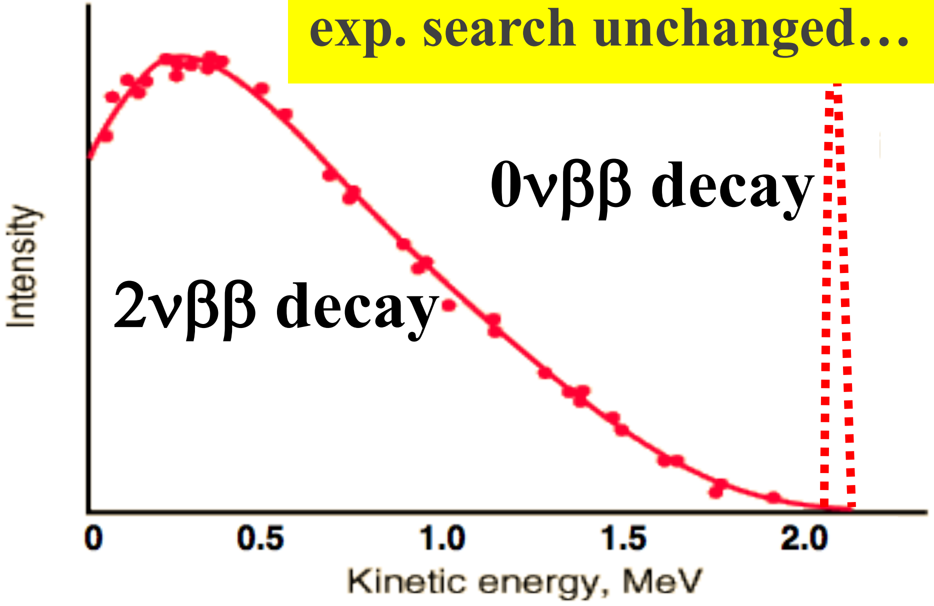
0νββ



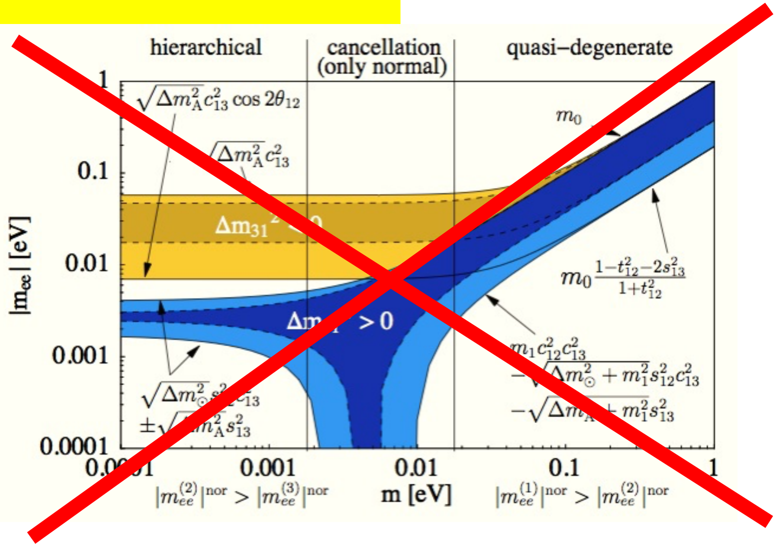
0νββ



exp. search unchanged…

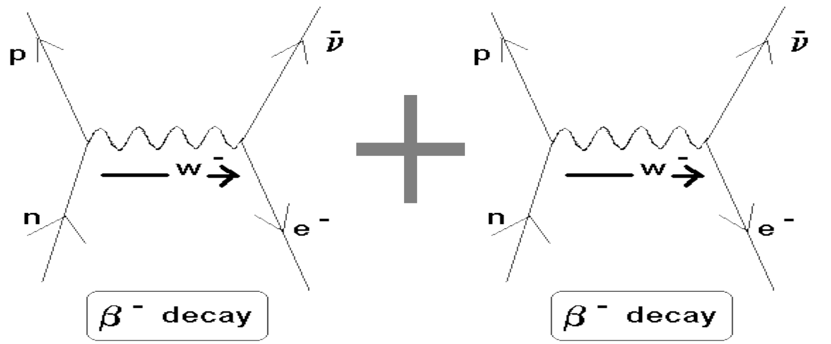


…interpretation changes:



Other Double Beta Decay Processes

Standard Model:

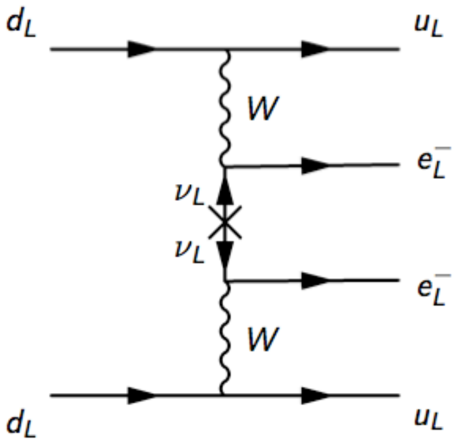


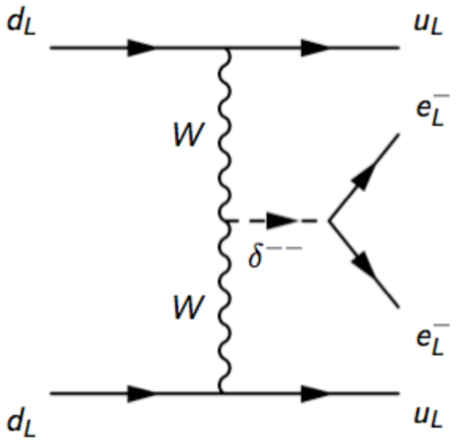
➔ 2 electrons + 2 neutrinos

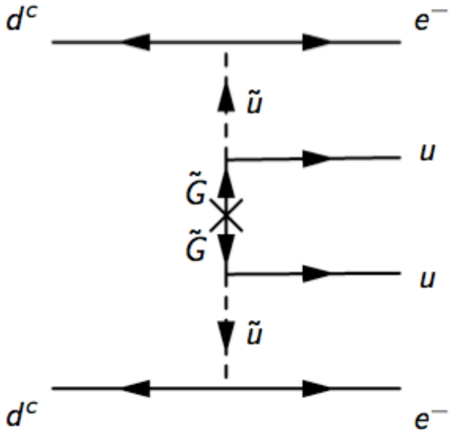
2νββ

Majorana ν-masses or other ΔL=2 physics: ➔ 2 electrons

0νββ







…

Majorana
neutrino masses
←→ Dirac?

SM + Higgs triplet

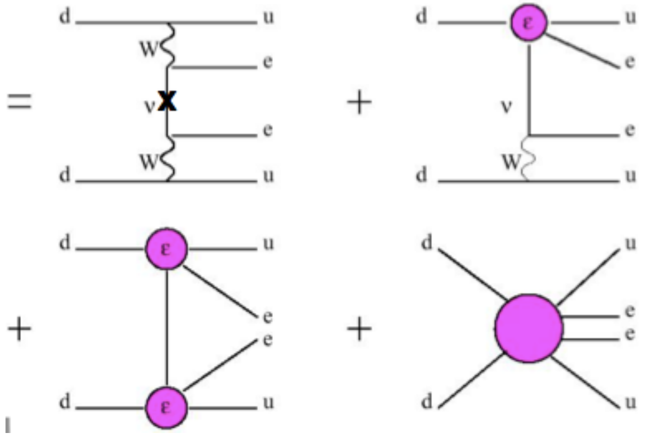
SUSY

important connections to LHC and LFV …
sub eV Majorana mass ←→ TeV scale physics

Interference of ΔL=2 Operators

Usually $$\left(T_{1/2}^{0\nu}\right)^{-1} = \left(\frac{|m_{0\nu\beta\beta}|}{m_e}\right)^2 |\mathcal{M}^{0\nu}|^2 G^{0\nu}.$$

with interferences



$$\begin{aligned}\left(T_{1/2}^{0\nu}\right)^{-1} &= |m_{0\nu\beta\beta}\mathcal{M}^{0\nu} + \epsilon m_e \mathcal{M}^{\epsilon}|^2 \frac{G^{\rm int}}{m_e^2} \\ &= |(m_{0\nu\beta\beta} + \epsilon m_e \mathcal{M}^{\epsilon}(\mathcal{M}^{0\nu})^{-1})\mathcal{M}^{0\nu}|^2 \frac{G^{\rm int}}{m_e^2} \\ &= |m_{0\nu\beta\beta}^{\rm int}|^2 |\mathcal{M}^{0\nu}|^2 \frac{G^{\rm int}}{m_e^2},\end{aligned}$$

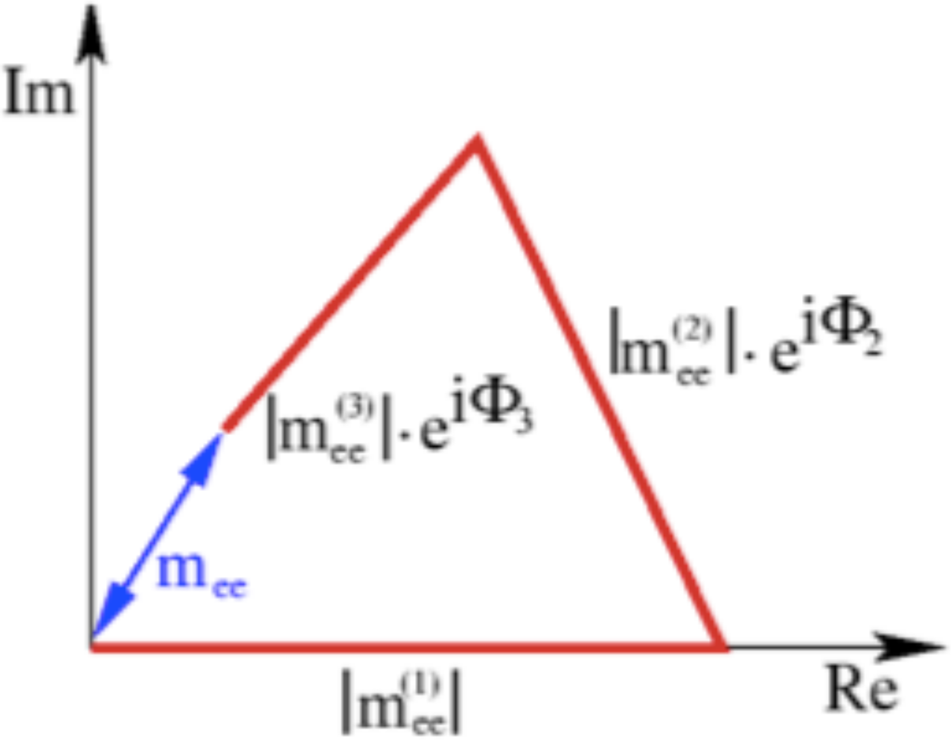
$G^{\rm int}$ = overall phase space factor

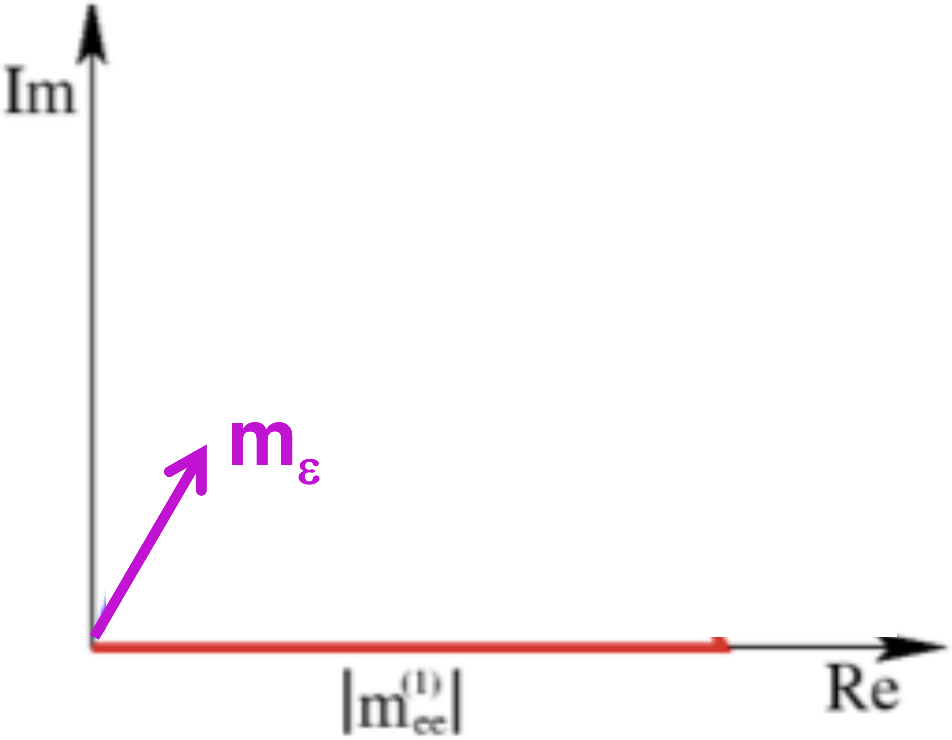
$\epsilon m_e \mathcal{M}^{\epsilon}$ ←→ determined by parameters of new physics

$$m_{0\nu\beta\beta}^{\rm int} \equiv m_{0\nu\beta\beta} + \epsilon m_e \mathcal{M}^{\epsilon}(\mathcal{M}^{0\nu})^{-1} \boxed{\equiv m_{0\nu\beta\beta} + m_{\epsilon}.}$$

$m_\varepsilon \simeq (\Lambda_{\rm new})^{-5}$ $\boxed{m_{0\nu\beta\beta} = 1\ \text{eV} \leftrightarrow \Lambda_{\rm new} \simeq \text{TeV}}$

Extreme Cases

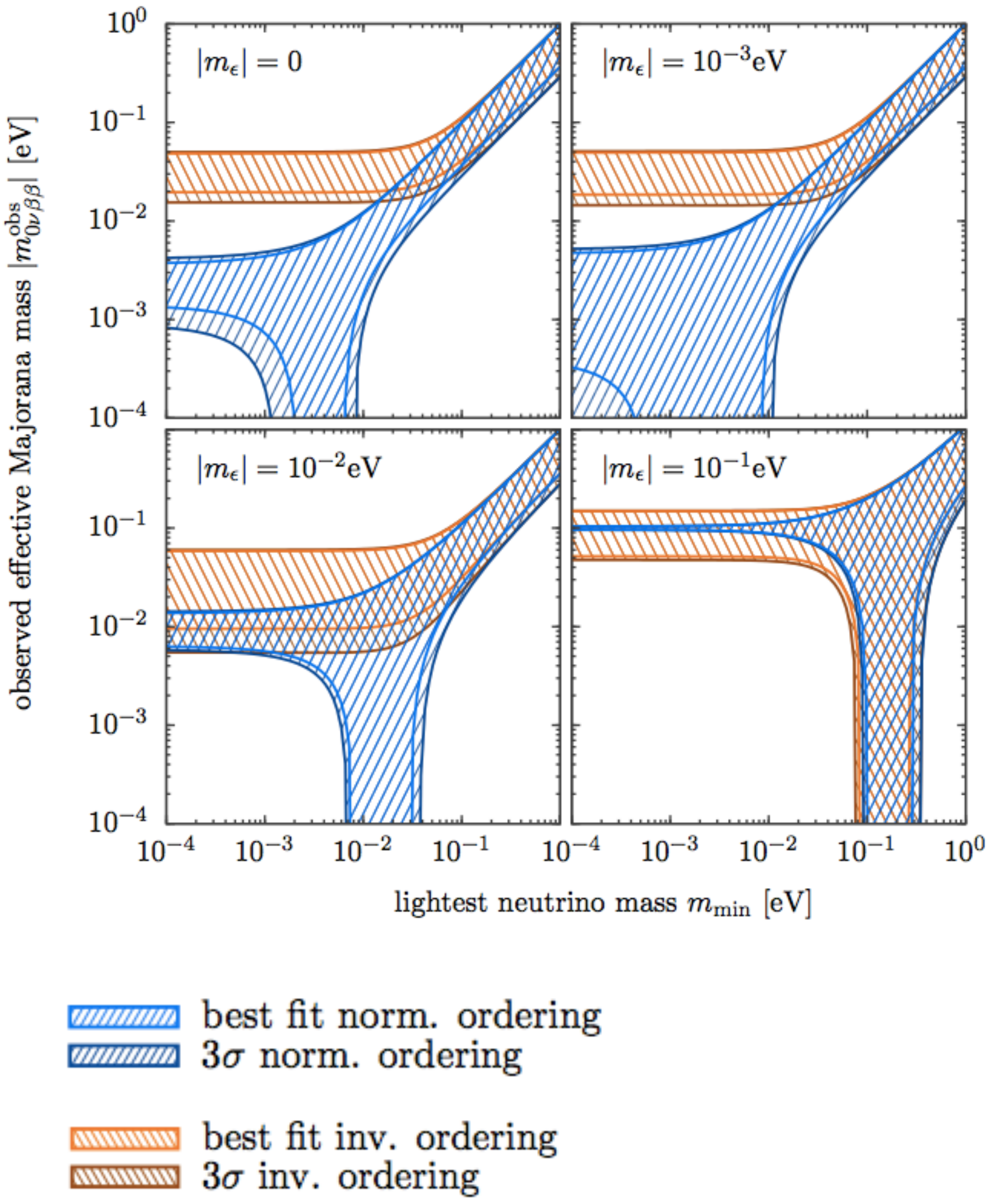


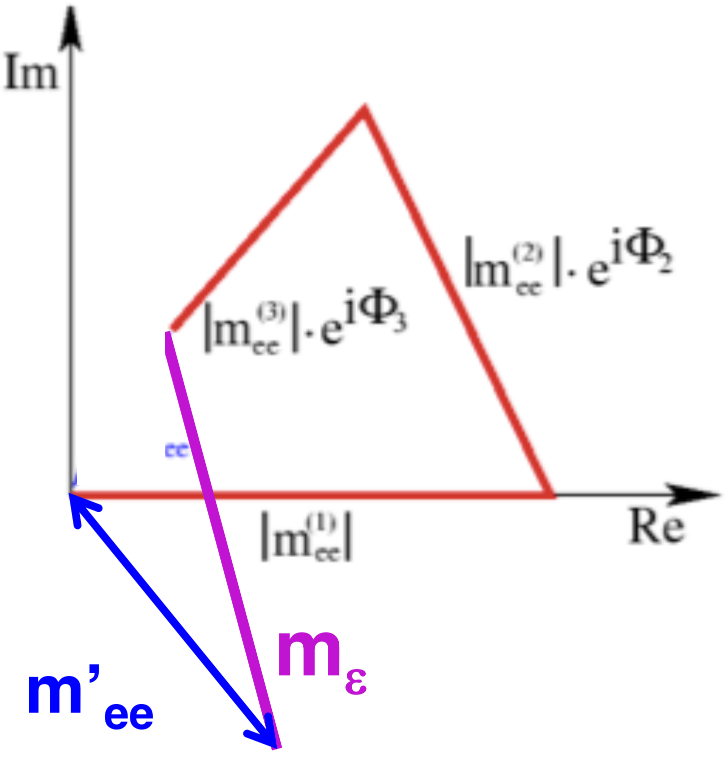


m_{ee} from Majorana neutrinos only
and no other $\Delta L=2$ physics

m_ε from other $\Delta L=2$ physics
with Dirac neutrino masses

and anything in-between





interferences

growing m_ε for fixed $0\nu\beta\beta$

→ shifts of masses, mixings and CP phases

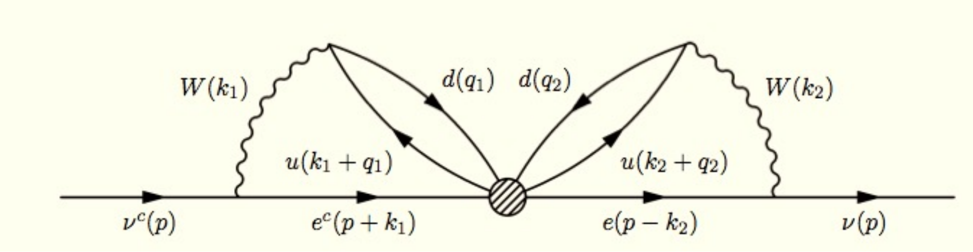
→ destroys ability to extract Majorana phases

→ sensitivity to TeV

Does 0νββ Decay imply Majorana Masses?

- <u>Schechter-Valle Theorem</u> ➔ is misleading
  Any ΔL=2 operator which mediates the decay induces via loops Majorana mass terms ➔ unavoidable: Majorana neutrinos…!?

0νββ➔ some ΔL=2 operator



Dürr, ML, Merle

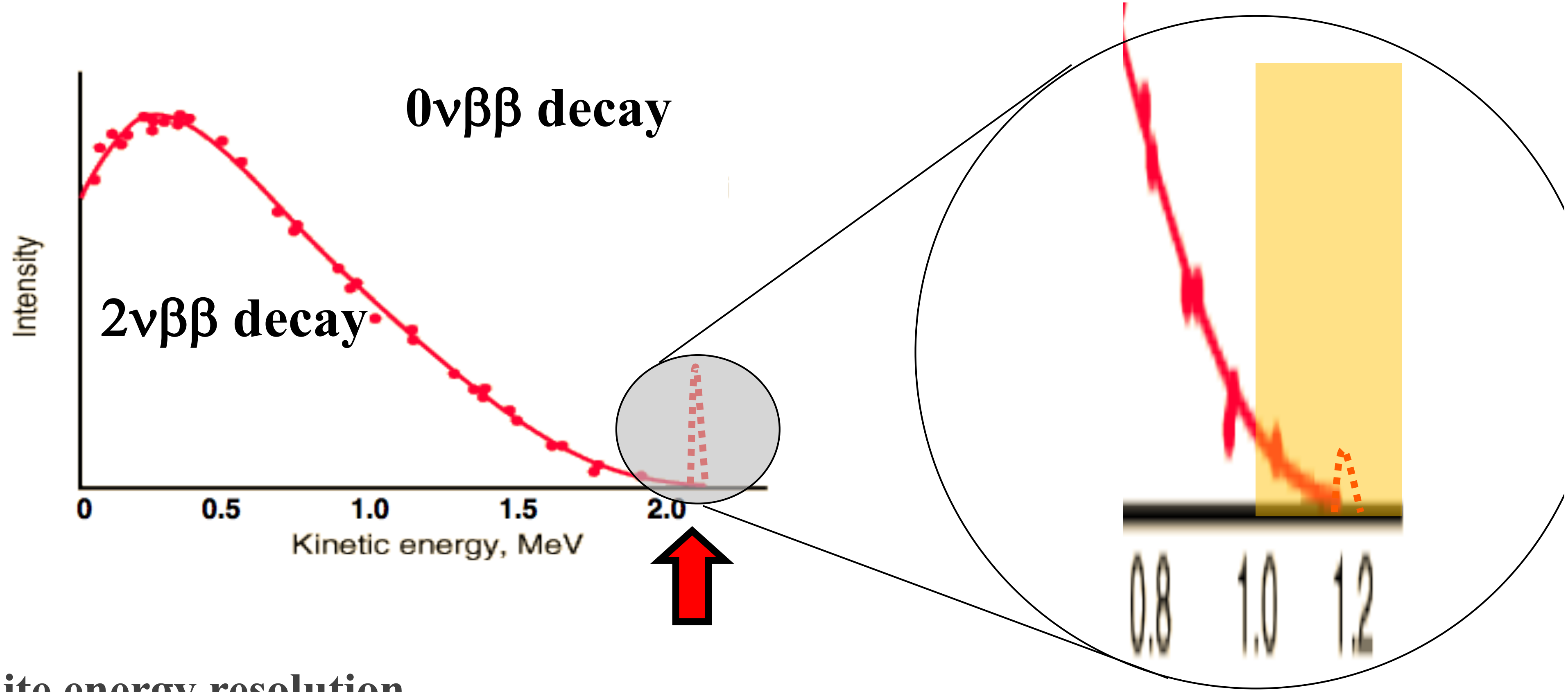
4 loops ➔ enforce $\delta m_\nu = 10^{-25}$ eV ➔ very tiny (academic interest)

➔ cannot explain observed ν masses and splitting's

Extreme possibility:

- 0νββ = L violation = other BSM physics
- neutrino masses = Dirac (plus very tiny Majorana corrections)
+ Dirac leptogenesis, + ...

The experimental Task

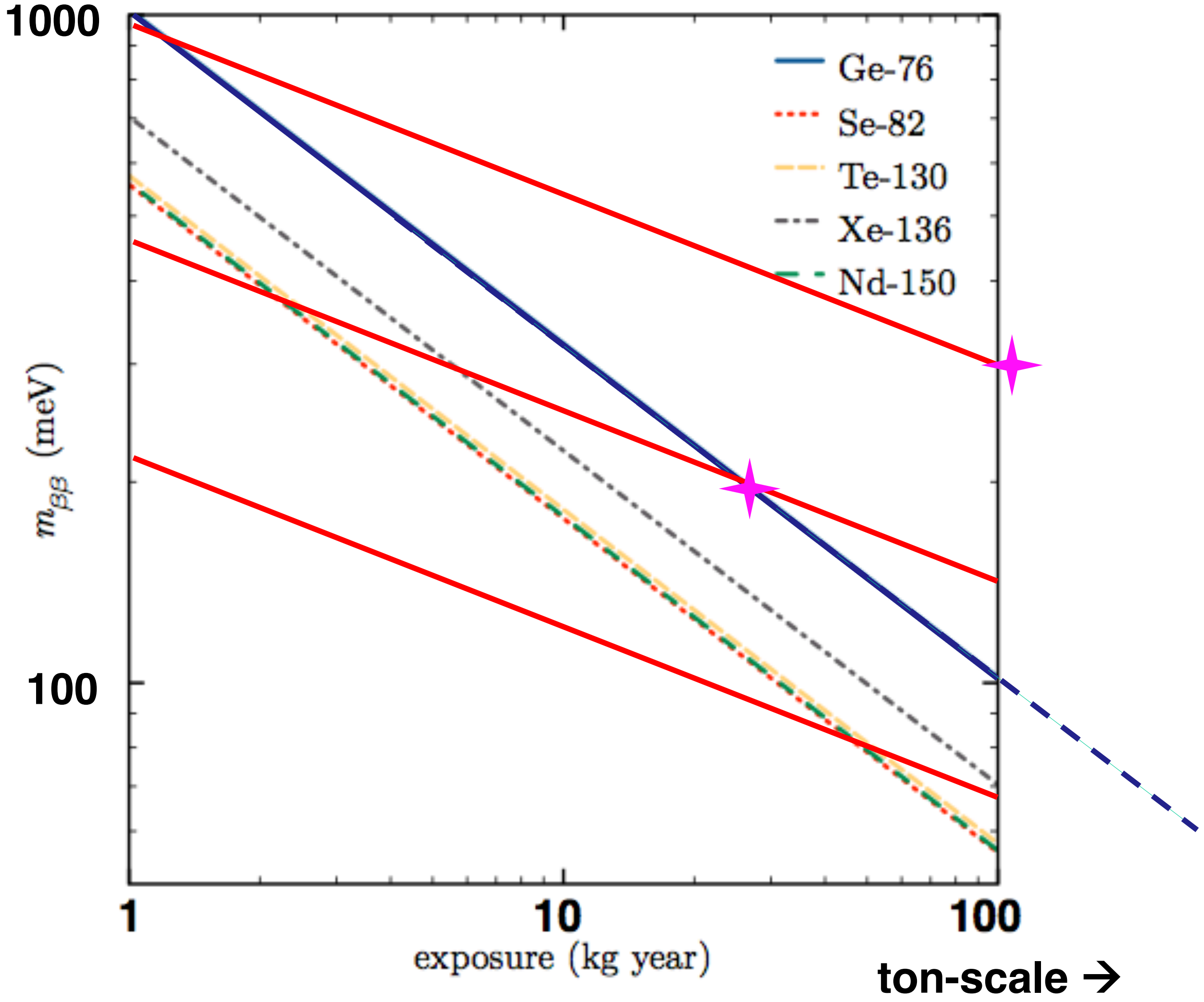


- finite energy resolution
  ➔ background from the tail of 2νββ
- extreme low background ➔ does not mean no background ➔ **lines…**
  ➔ need a method to ensure that it is 0νββ and not some background
  1) two different isotopes
  2) isotopic fingerprint

Sensitivity & Background (for a Majorana Mass)

$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z) \left|M_{0\nu}\right|^2 m^2_{\beta\beta}$$

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



ton-scale →

without background

$$N = \log 2 \cdot \frac{N_A}{W} \cdot \varepsilon \cdot \frac{M \cdot t}{T^{0\nu}_{1/2}}$$

N_A = Avogadro's number
W = atomic weight of isotope
ε = signal detection efficiency
M = isotope mass
t = data taking time

→ $$\boxed{m_{\beta\beta} = K_1 \sqrt{\frac{N}{\varepsilon M t}}}$$

with background

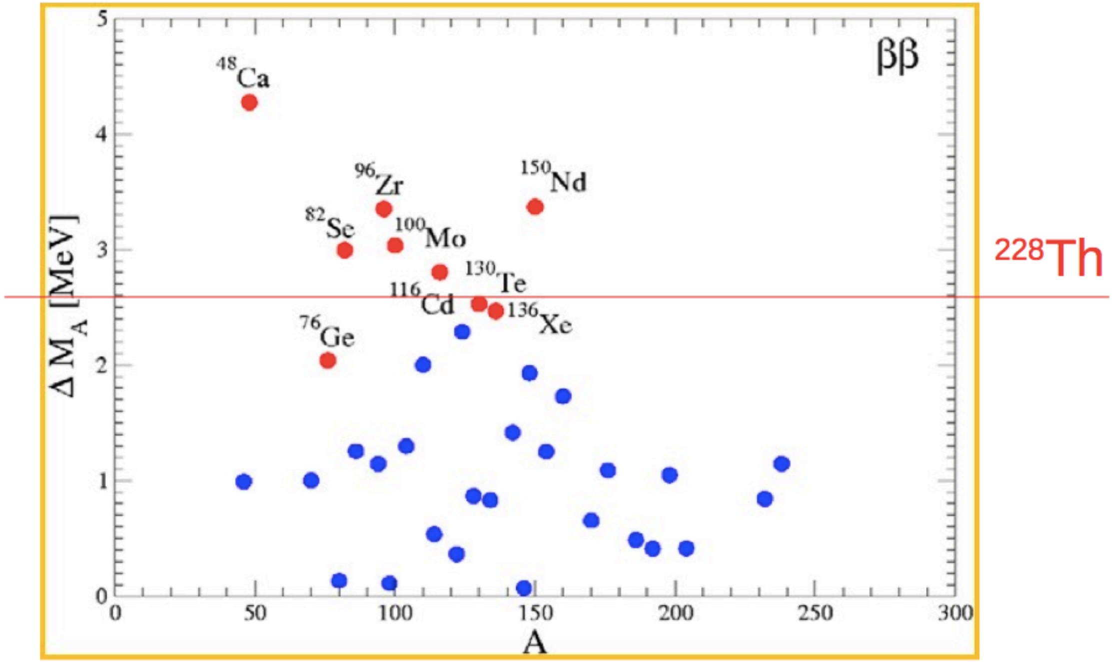
$N' = N + N_{background}$

→ $$\boxed{m_{\beta\beta} = K_2\, \sqrt{1/\varepsilon} \left(\frac{c\, \Delta E}{Mt}\right)^{1/4}}$$

c = cts/keV/kg/yr ; ΔE = ROI

Which Isotope?

- **Large detector mass**
  - ←→ natural abundance
    or enrichment (cost, time)
  - ←→ detection technology
  - ←→ costs, feasibility, …

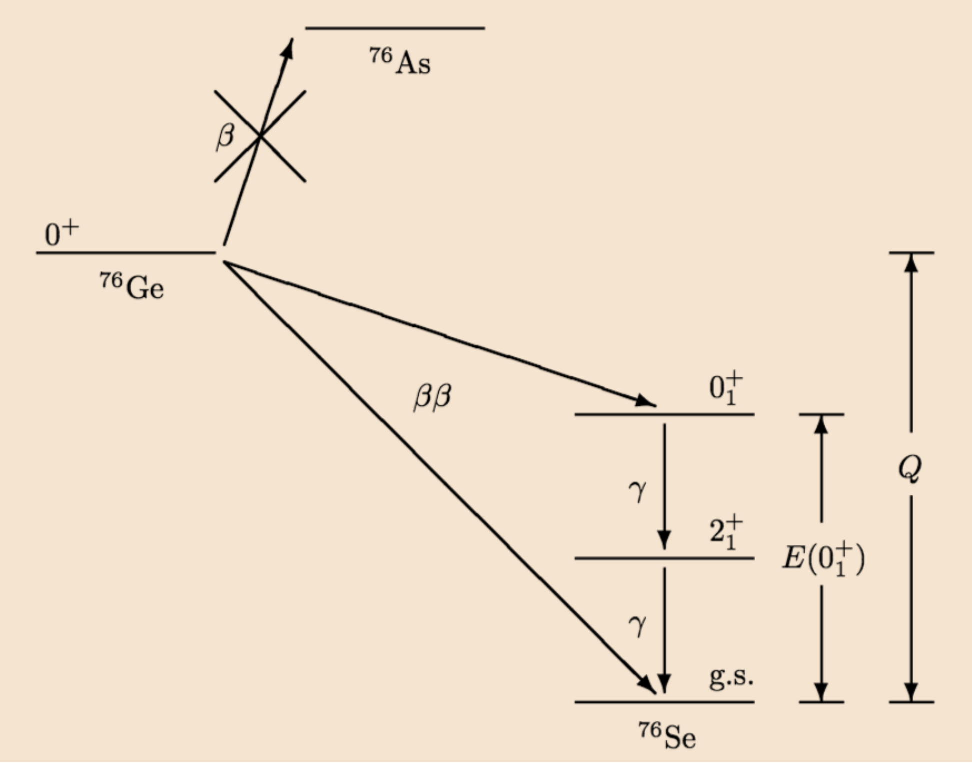


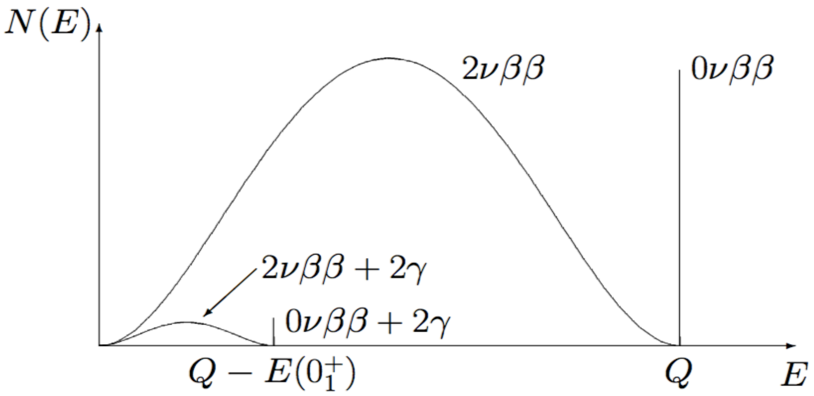
- **Radio-purity**
  - ←→ ultra clean $0\nu\beta\beta$ source
    and instrumentation
  - ←→ high $Q_{\beta\beta}$ ←→ less bgd.

- **Good energy resolution**
  - ←→ avoid known and unknown backgrounds in ROI: $Q_{\beta\beta} \pm \Delta E$

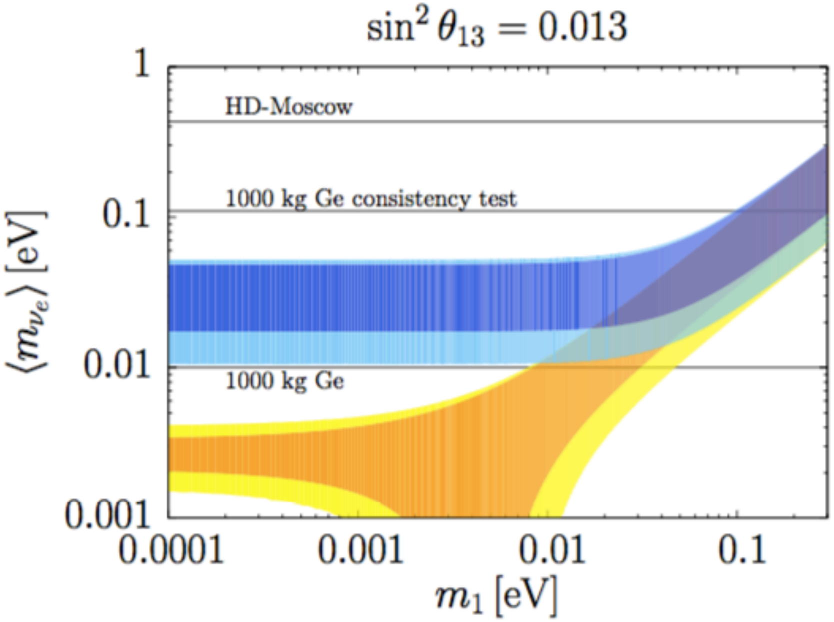
- **Uncertainties in nuclear matrix elements + energy resolution**
  - ➔ Germanium is a very good choice
  - ➔ use two different isotopes to confirm a signal …

Consistency Test with one Isotope





$$\frac{\Gamma_{0_1^+}}{\Gamma_{\text{g.s.}}} = \frac{(Q - E(0_1^+))^n}{Q^n} \times \left(\frac{\mathcal{M}^{0_1^+}}{\mathcal{M}^{\text{g.s.}}}\right)^2$$



ratio is set by nuclear spectra
- independent of backgrounds!

Duerr, ML, Zuber

The Fight against Background

Extreme rare reaction (T>10^{25} years >> age of Universe)

Magnitude 1 decay/kg/year

Environment $\simeq$ 30Bq/kg = 10^9 /kg/year ➔ 3000/person/second

➔ avoid single β decay ⇐⇒ suitable isotopes

➔ avoiding / suppression of environmental radioactivity

- in the 0νββ detector material
  - → ultra clean (production, handling)
  - → puls form analysis (identify & reject background)
- in the detector parts (e.g. holders, signal amplifiers)
  - → lowest amount of material
  - → ultra pure materials (selection; environmnt = O(100Bq/kg) ⇐⇒ μBq/kg)
  - → extremely helpful: ^{76}Ge source = detector (a big Ge diode)
- in the environment
  - → ultra clean room (clean room, …)
  - → avoid Radon (decay of U, Th in the environment → ^{222}Rn-gas)
  - → avoid cosmogenic activation (new isotopes → go underground)
  - → avoid cosmogenic myons, neutrons → go underground

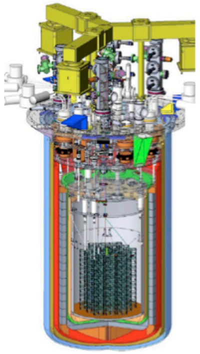
Experimental Realizations

0νββ decay is important!

➔low background expertise!
➔long history and diverse
plans for the future

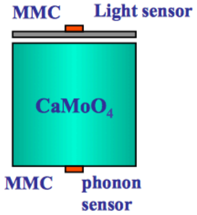
Important mile stone:
Heidelberg-Moskau-Experiment
(H.V. Klador-Kleingrothaus MPIK)
- for many years best limts
- signal?

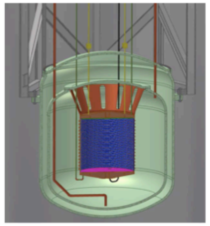
➔GERDA
➔important result



CUORE
bolometer
with cc

AMoRE

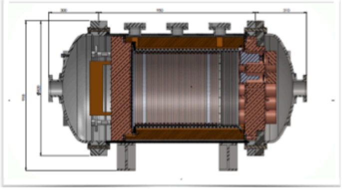




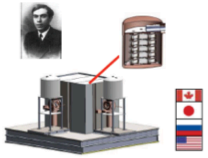
nEXO
5ton of Xe

NEXT
5ton of Xe

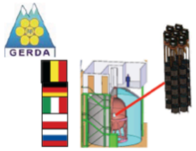
MAGIX
5ton of Xe

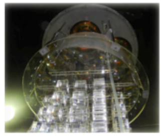


Majorana
uses Ge



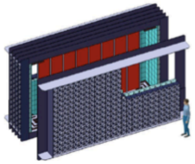
GERDA
uses Ge





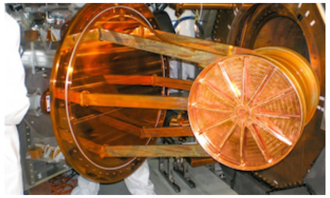
CANDLES
uses Ca

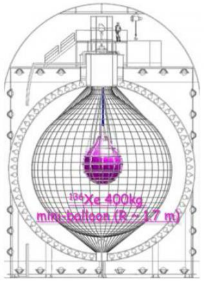
SNO+



SuperNEMO
and **DCBA**

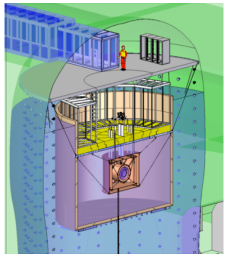
EXO





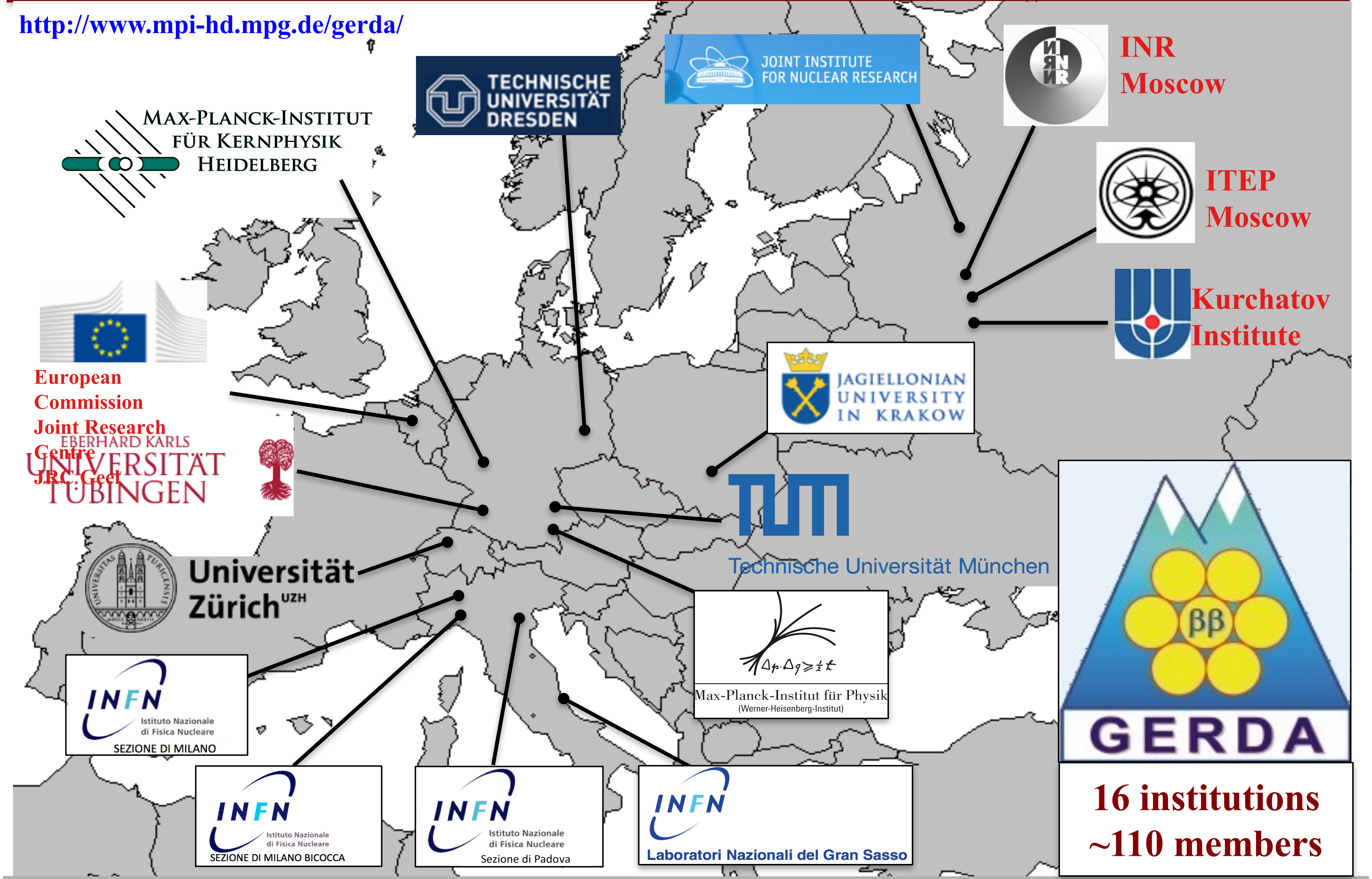
KamLAND-Zen

nEXO



The GERDA Collaboration

http://www.mpi-hd.mpg.de/gerda/



Max-Planck-Institut für Kernphysik Heidelberg

Technische Universität Dresden

Joint Institute for Nuclear Research

INR Moscow

ITEP Moscow

Kurchatov Institute

European Commission Joint Research Centre JRC Geel

Eberhard Karls Universität Tübingen

Universität Zürich UZH

Jagiellonian University in Krakow

Technische Universität München

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

INFN Istituto Nazionale di Fisica Nucleare
SEZIONE DI MILANO

INFN Istituto Nazionale di Fisica Nucleare
SEZIONE DI MILANO BICOCCA

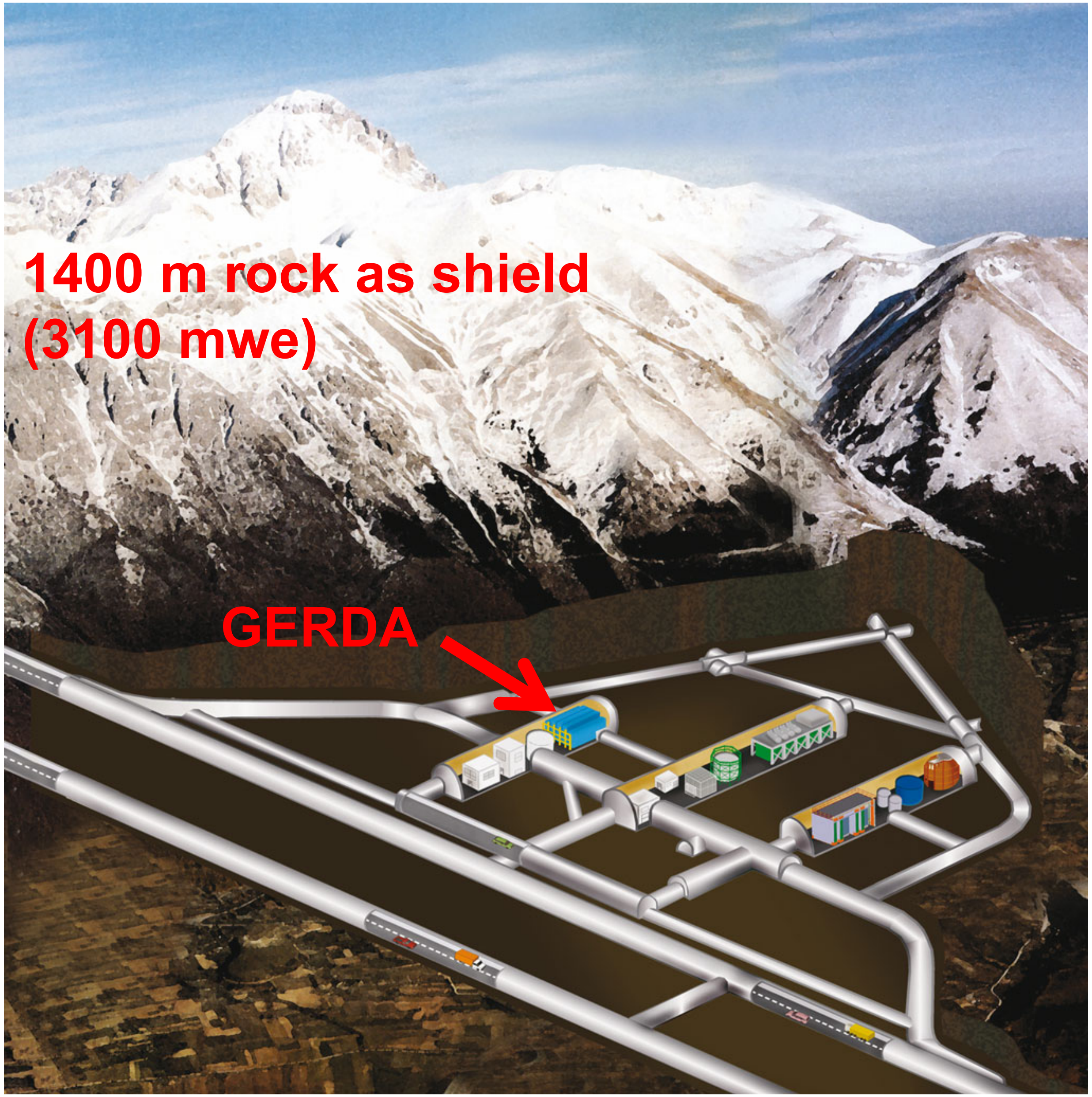
INFN Istituto Nazionale di Fisica Nucleare
Sezione di Padova

INFN
Laboratori Nazionali del Gran Sasso

GERDA

16 institutions
~110 members

Protection against Cosmogenic Radiation

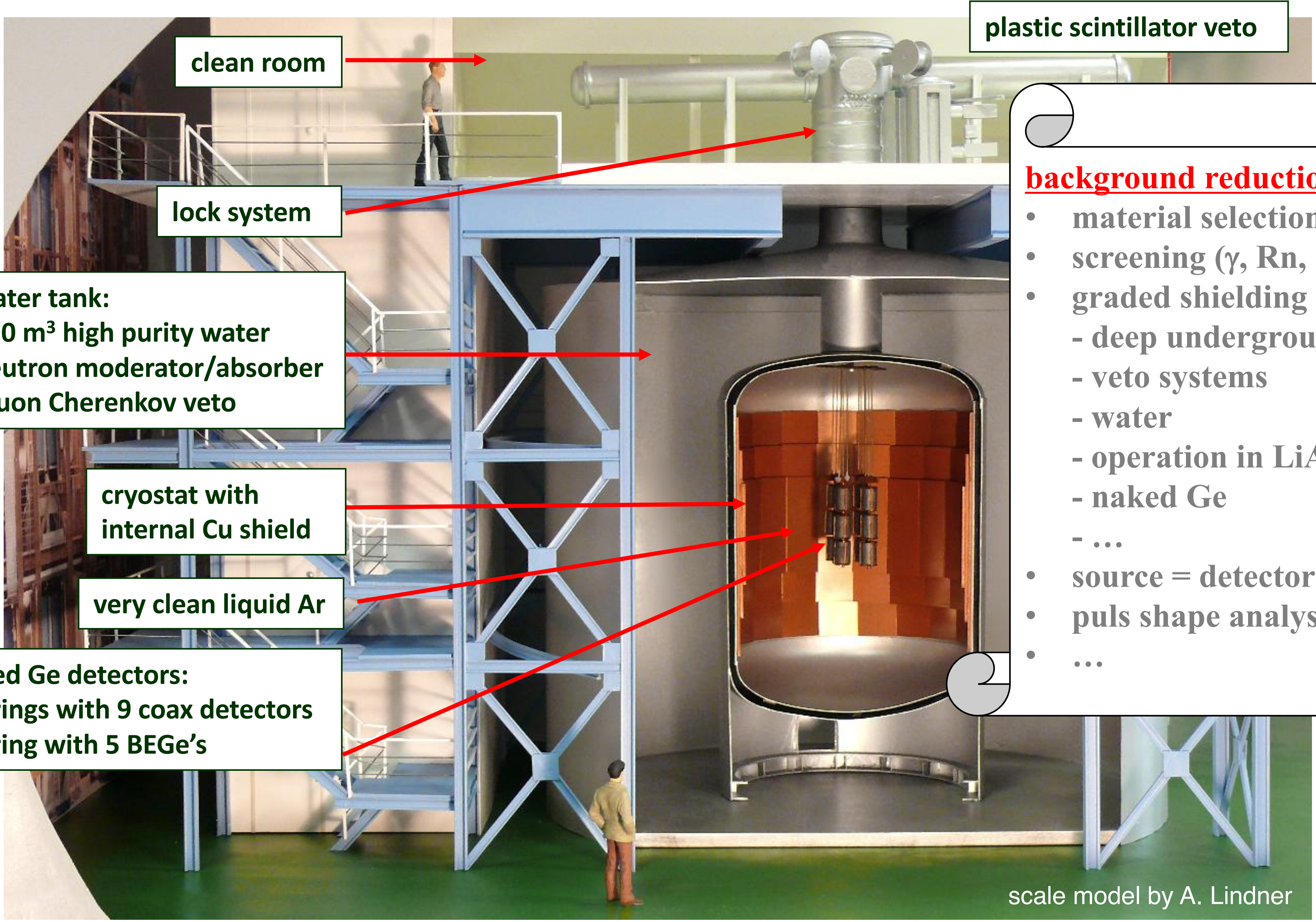


1400 m rock as shield
(3100 mwe)

Untergground laboratory
➔ Gran Sasso (Italy)

A very special place
to work…

The GERDA Detector (original idea by G. Heusser, MPIK)



plastic scintillator veto

clean room

lock system

water tank:
590 m^3 high purity water
neutron moderator/absorber
muon Cherenkov veto

cryostat with
internal Cu shield

very clean liquid Ar

naked Ge detectors:
3 strings with 9 coax detectors
1 string with 5 BEGe's

scale model by A. Lindner

background reduction:

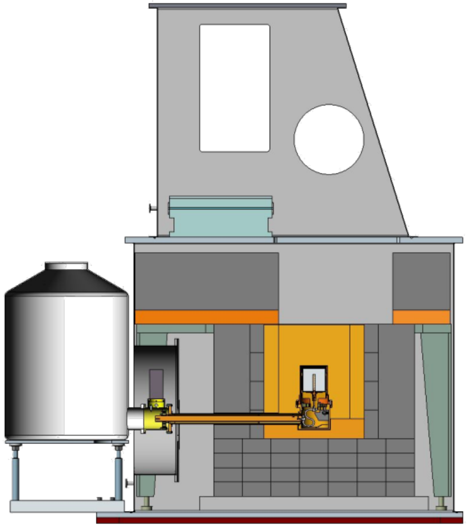
- material selection
- screening (γ, Rn, …)
- graded shielding
  - - deep underground
  - - veto systems
  - - water
  - - operation in LiAr
  - - naked Ge
  - - …
- source = detector
- puls shape analysis
- …

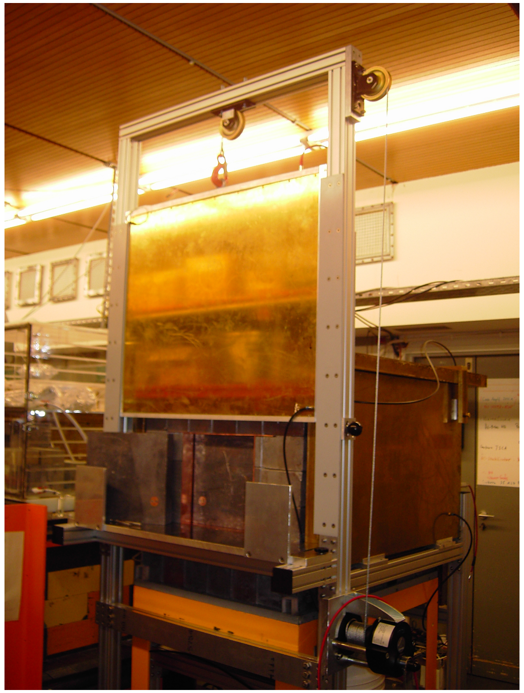
MPIK Material γ-Screening Facilities

- Different screening stations@MPIK underground lab: BRUNO, CORRADO, … (1mBq/kg)

- 4 GEMPIs @LNGS (10μBq/kg)

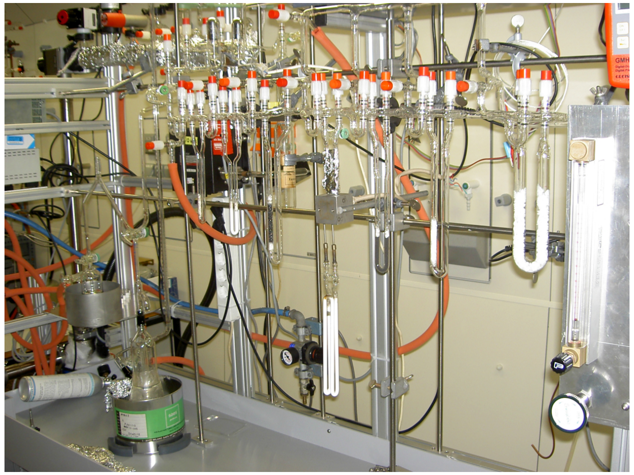
- New: GIOVE @MPIK (50μBq/kg)





➔ extensive task for GERDA and other experiments (XENON, …)

Rn Screening Facilities



Gas counting systems
@LNGS and @MPIK

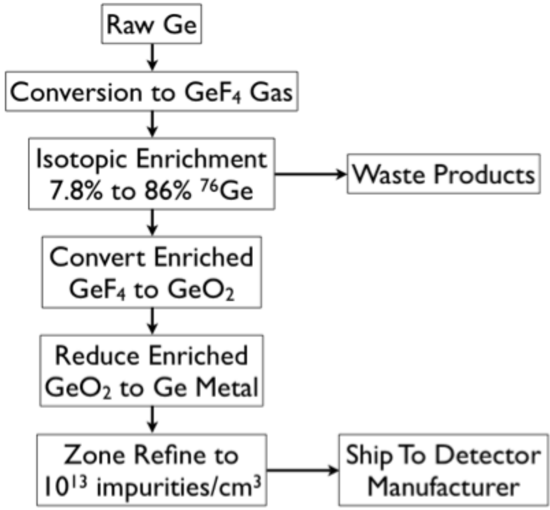
^{222}Rn emanation technique

- sensitivity = few atoms/probe
- large samples ←→ absolute sensitivity
- non-trivial; not commonly available; routine @MPIK
- established numbers:

Nylon (Borexino) < 1μBq/m^2
Copper (Gerda): 2μBq/m^2
Stainless steel (Borexino): 5μBq/m^2
Titanium: (100 ± 30) μBq/m^2

New: Auto-Ema - automatized Rn screening facility @MPIK → many samples

BEGe Detector production



Raw Ge

Conversion to GeF₄ Gas

Isotopic Enrichment 7.8% to 86% ^{76}Ge

Waste Products

Convert Enriched GeF_4 to GeO_2

Reduce Enriched GeO_2 to Ge Metal

Zone Refine to 10^{13} impurities/cm^3

Ship To Detector Manufacturer

3) Crystal pulling at Oak Ridge (USA)

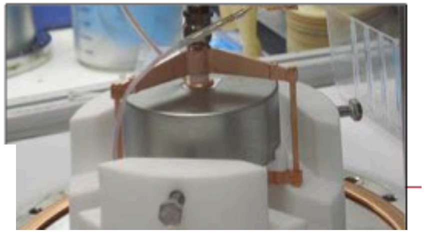
4) Detector production at Olen (Be)

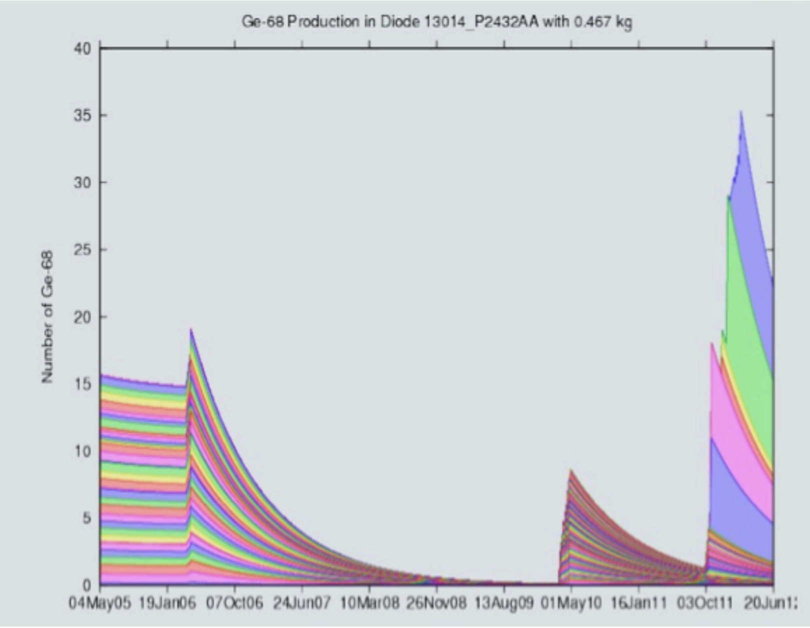
2) Reduction and zone refinment at Goettingen (Germany)

1) Isotope enrichement at ECP, Svetlana (Ru)

To minimize activation by cosmic ray:

- Transportation by truck or ship in shielded containers
- deep underground storage



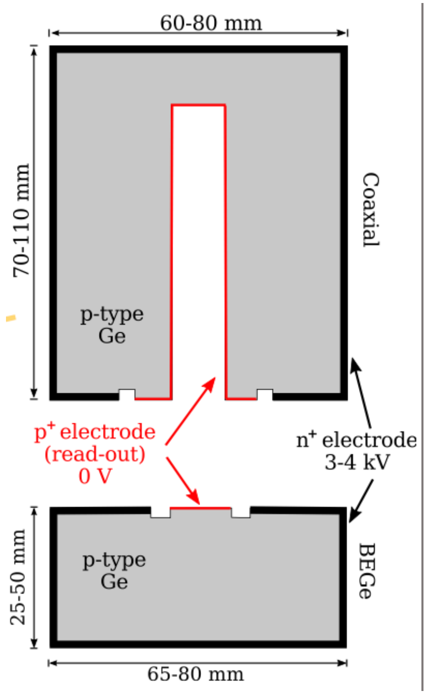


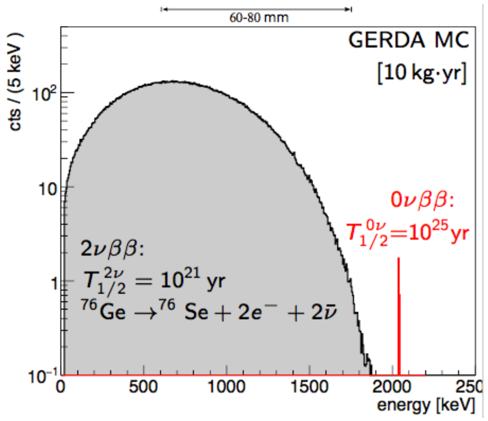
← accumulated activity and its decay
beware of long-lived isotopes…!

GERDA Detector Types

1) Big Ge-diodes ➔ HV ➔ electrical signal
2) re-processed HdM, IGEX and GTF detectors p-type semi-coaxial
3) new p-type BEGe (Broad Energy Ge) detectors

- n^+ conductive Li layer, separated by a grove from the boron implanted p^+ contact
- operated as ``diode”: events ➔ pulses
- SSE/MSE (single/multi site event) discrimination

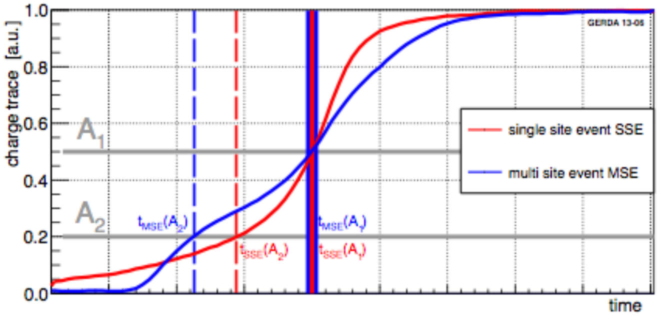




0νββ signature:

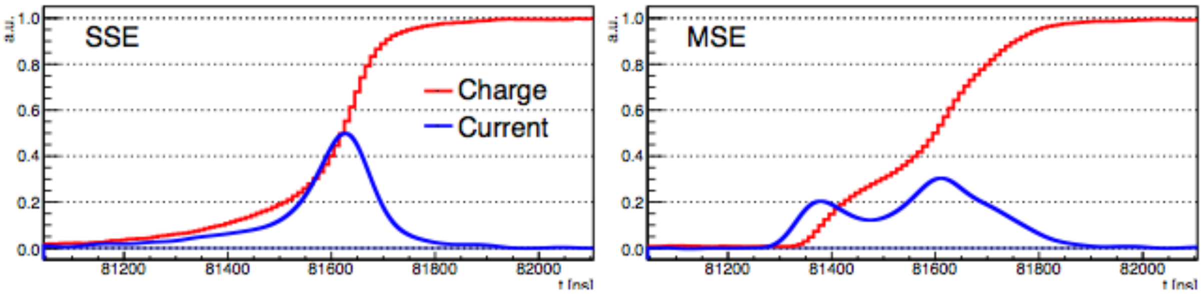
◦ point-like energy deposition in detector bulk volume

◦ sharp energy peak at 2039 keV (FWHM = 3-4 keV)

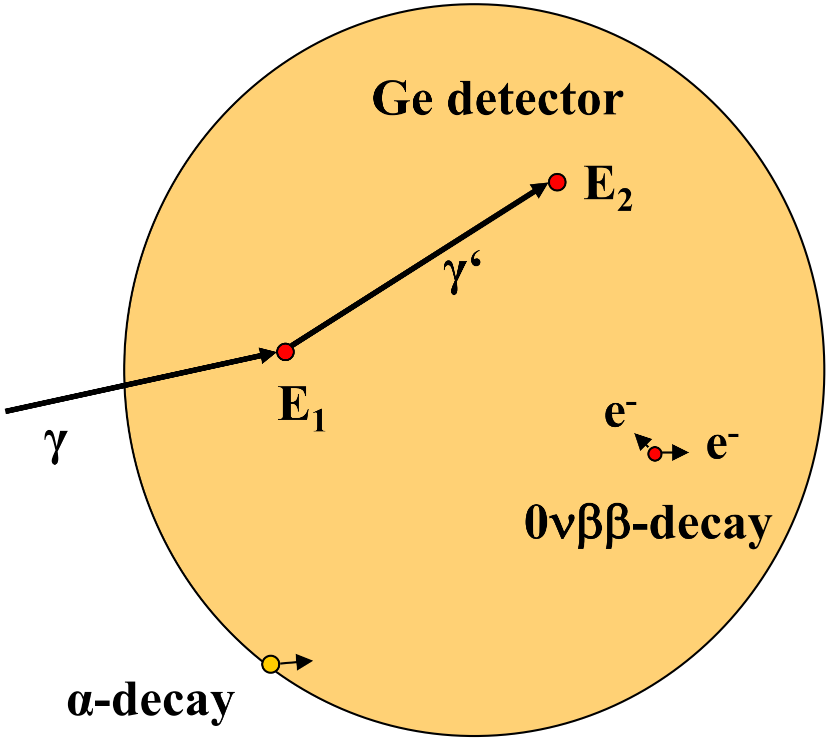


← coaxial

BEGe ⬇

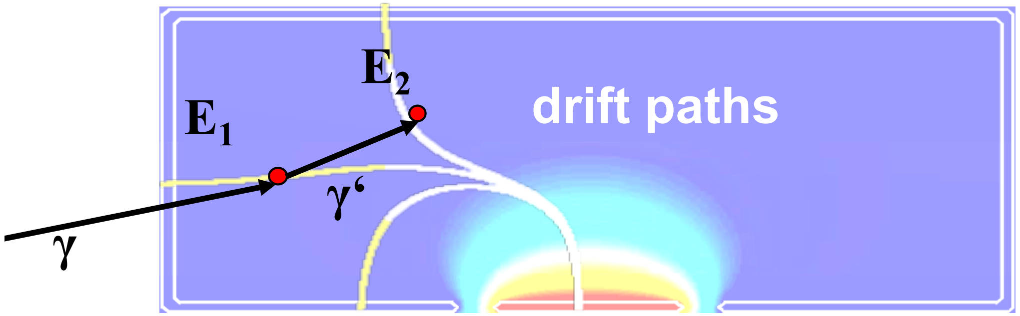


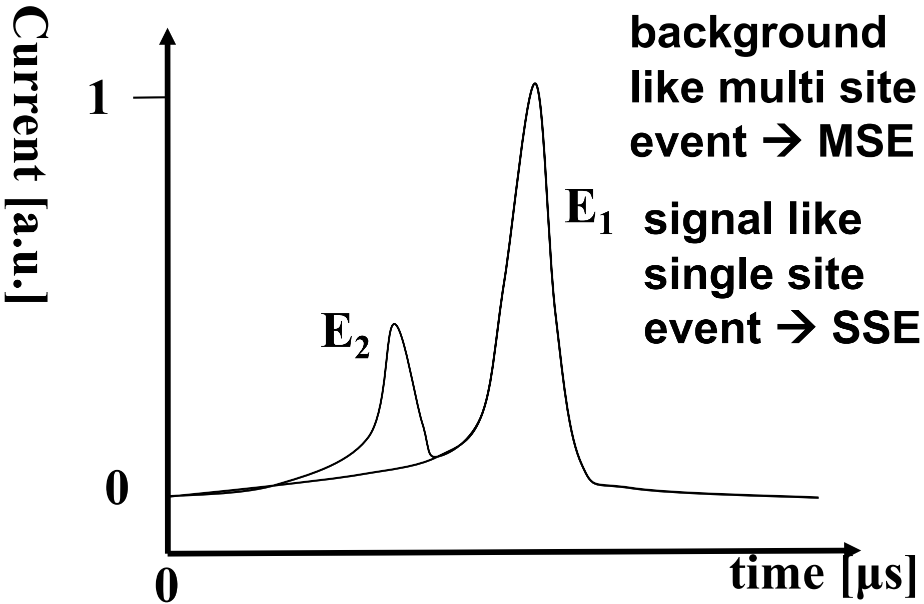
Pulse Shape Discrimination



- **Single Site Events (SSE)**
- **Multi Site Events (MSE)**

- 0νββ-decays → localized energy deposition → SSE
- Compton scattering evt. → background like MSE
- surface events → SSE @ surface
- SSE by γ's look like events (cannot be rejected)
- β particles enter via n^+ surface → slow pulses
- α's @ p^+ contact → comparatively high signal





background like multi site event → MSE

signal like single site event → SSE

Backgrounds

Background sources:

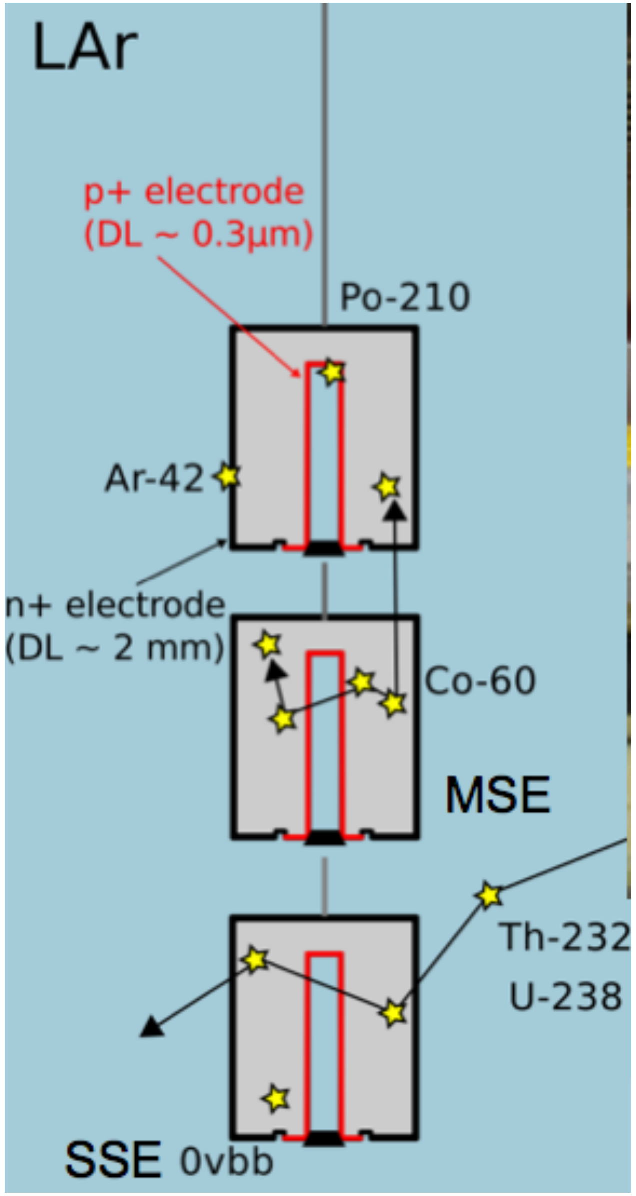
- α decays on the p^+ surface
- β decay of ^{42}K on the surface or close to the detector from ^{42}Ar (10x more than expected)
- β decay of ^{60}Co inside detectors
- γ from ^{208}Tl, ^{214}Bi and from various set-up components

Generic phase I background reduction

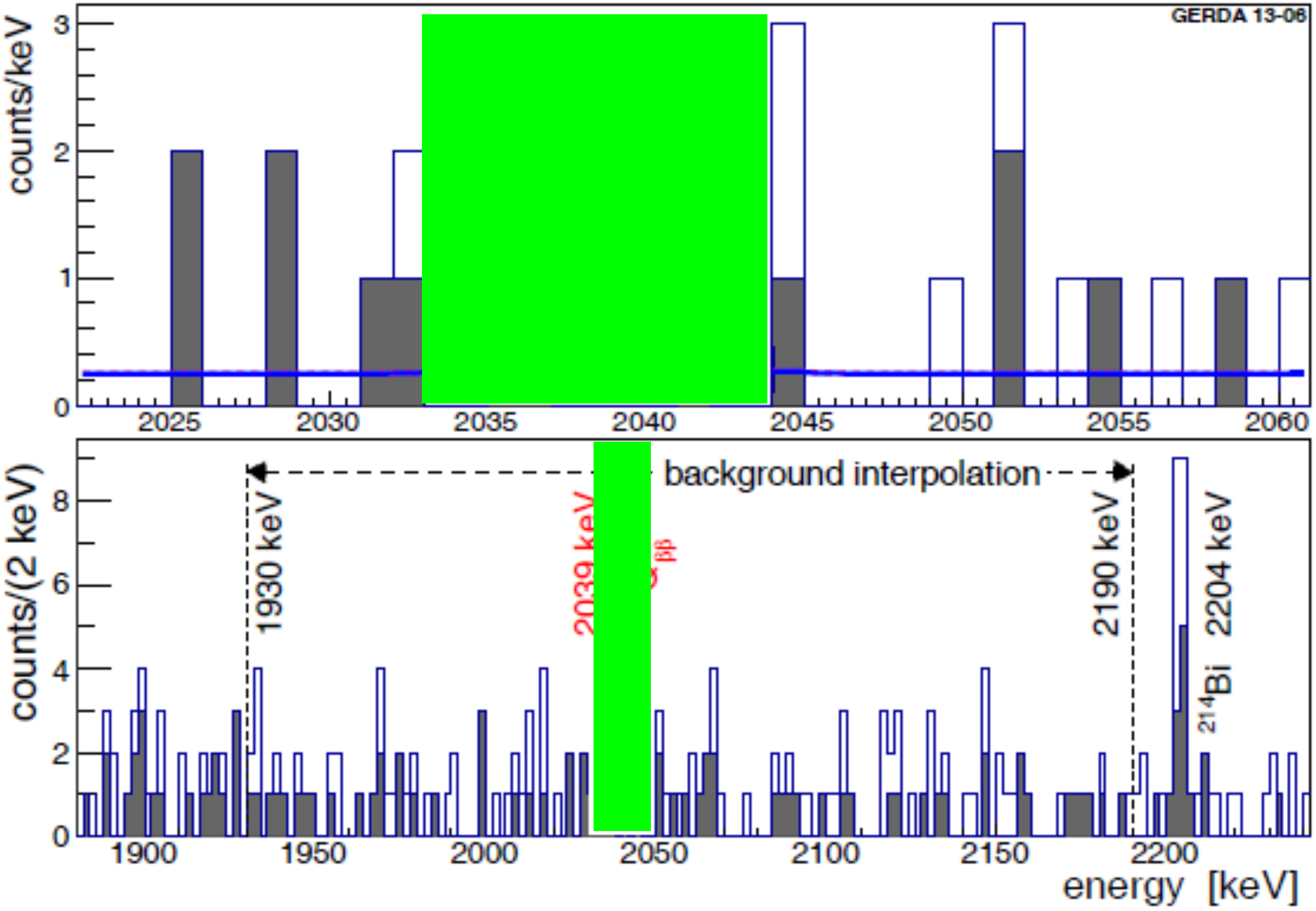
- use cleanest possible material
- prevent ^{42}K ions from drifting to detectors using minishrouds
- cut detector coincidences
- pulse shape analysis

➔ Background model ←→ from screening

➔ Measured background away from $Q_{\beta\beta}$ consistent with expectation from measurement ➔ **flat**



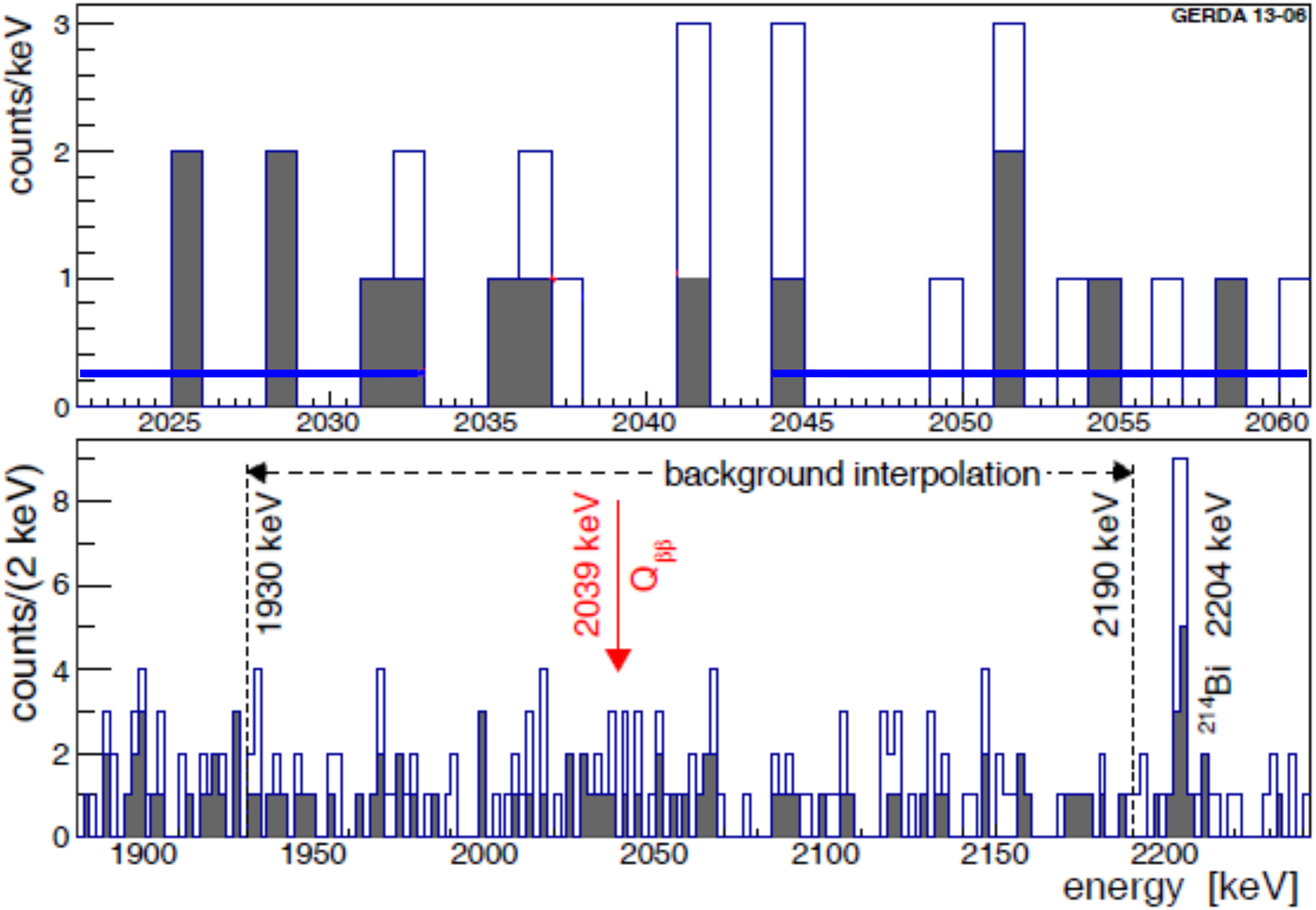
Phase I: The Region of Interest



expected bg from interpolation: **5.1 events w/o PSD**

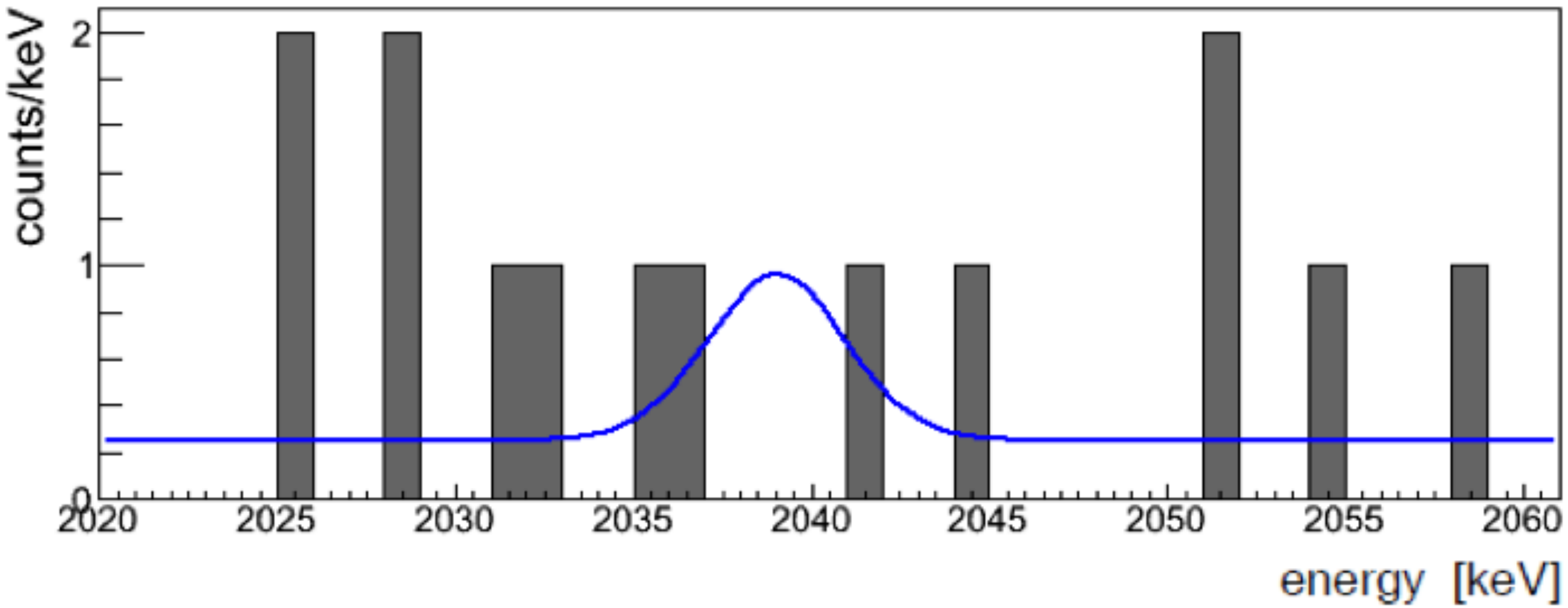
2.5 events with PSD

Phase I: The Region of Interest



expected bg from interpolation:	**5.1 events w/o PSD** **2.5 events with PSD**	**observed**	**➔ 7 events w/o PSD** **➔ 3 events with PSD**

Profile Likelihood Fit to PSD Spectrum



profile likelihood fit = hypothesis test: is there a line at Qββ

signal = a*flat background + b*line ➔ extract coefficients

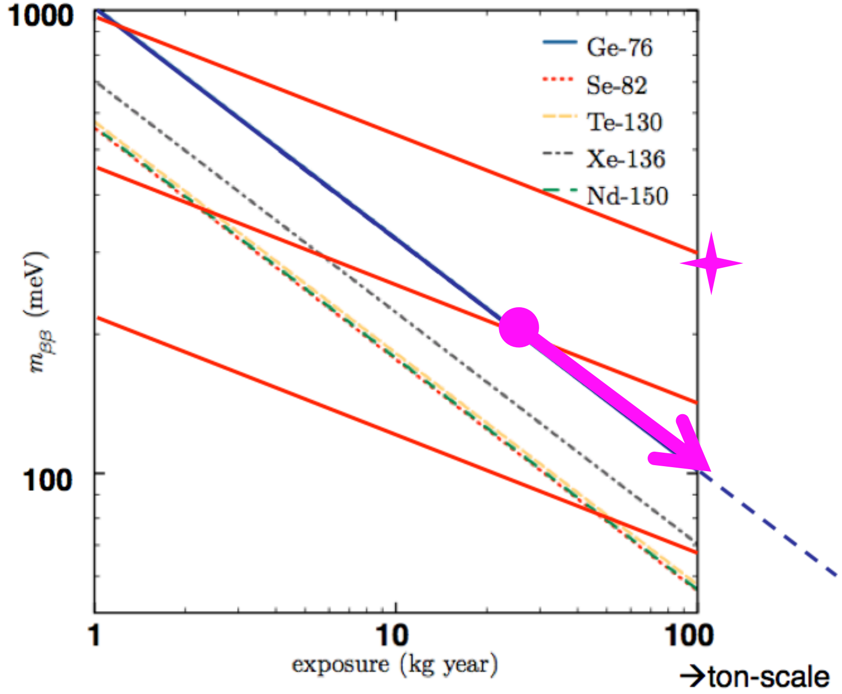
➔ best fit: $N^{0\nu} = 0$; upper limit: $N^{0\nu} < 3.5$ (90%CL)

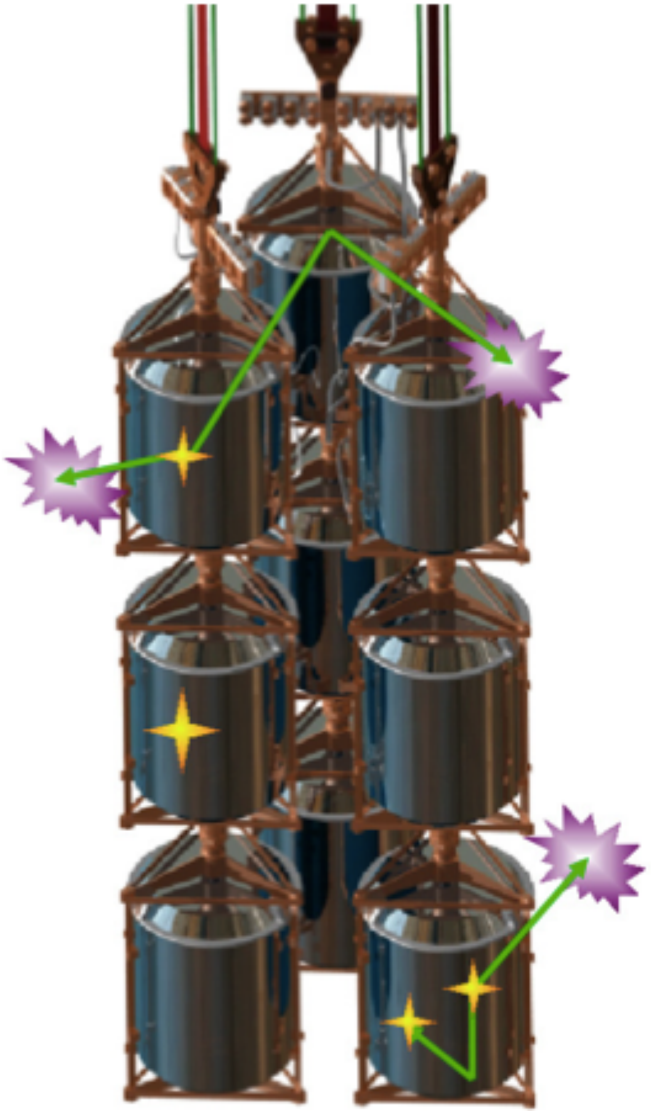
➔ half life limit $T_{1/2}(0\nu\beta\beta) > 2.1 * 10^{25}$ yr (90% C.L.)

GERDA Phase II

Improvement for Phase II:

- more new BEGe detectors
  ➔ ~factor 2 in ^{76}Ge mass
- active veto (light instrumentation)
  ➔ even more background suppresion





upgrade ➔ data taking

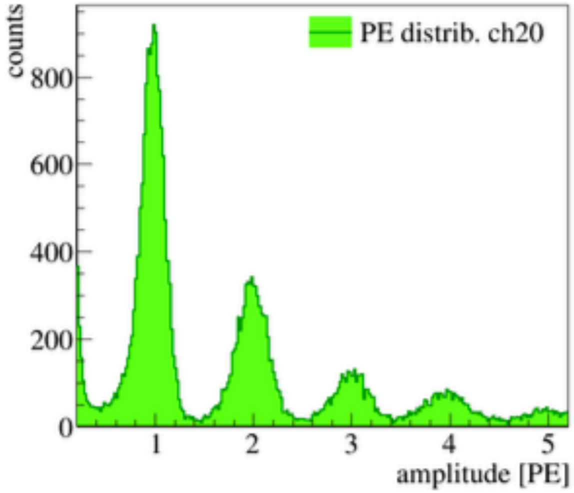
LAr Scintillation light Veto

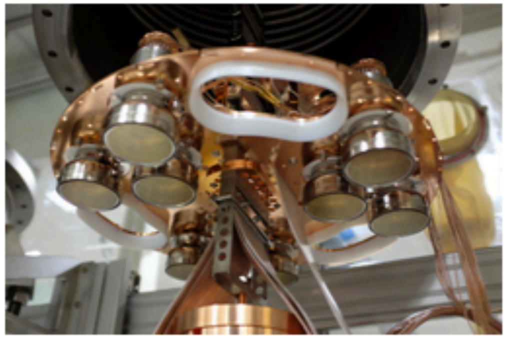
Hybrid veto instrumentation:

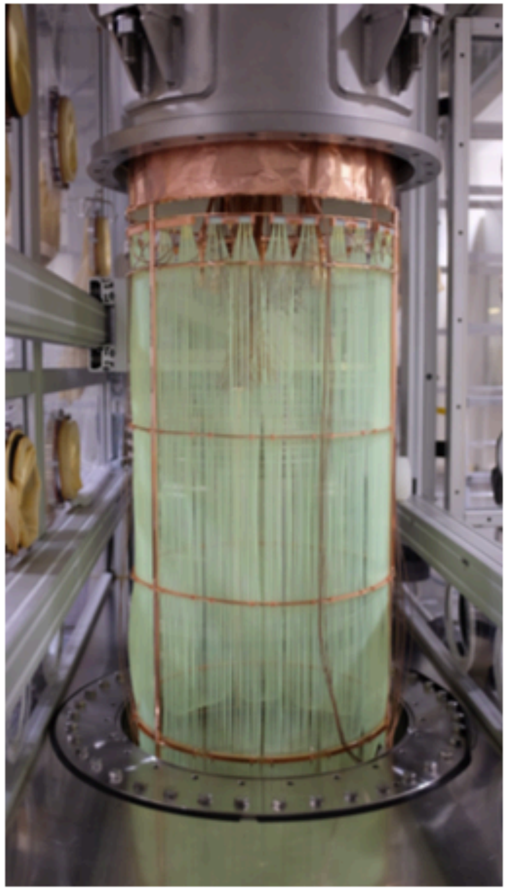
- 16 PMTs (9 top / 7 btm)
- 800 m fibers coated with WLS + 90 SiPMs
- nylon mini-shroud around each string coated with WLS

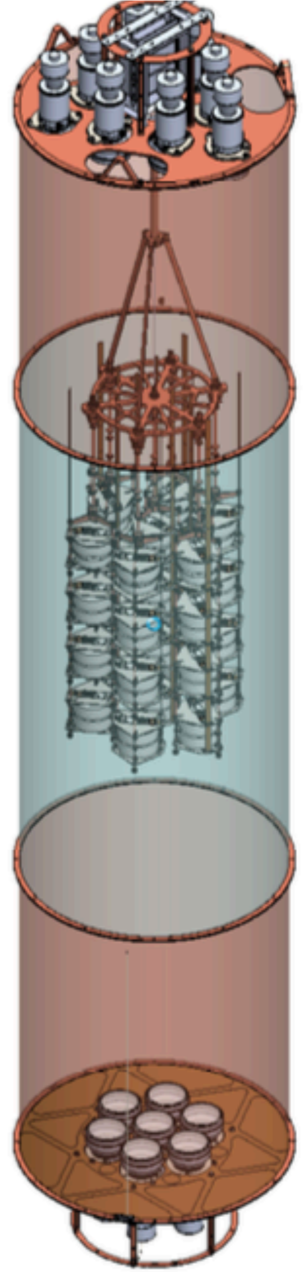
Parameters optimized for each channel:

- ~0.5 PE threshold
- $\sim 5-6\,\mu s$ anticoincidence window







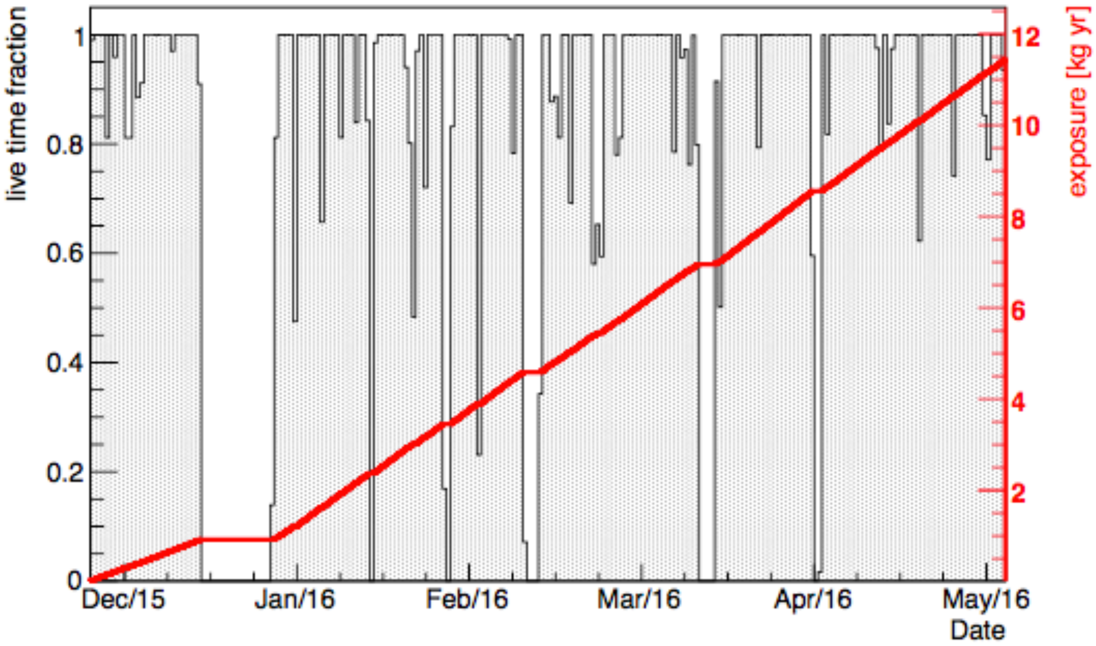


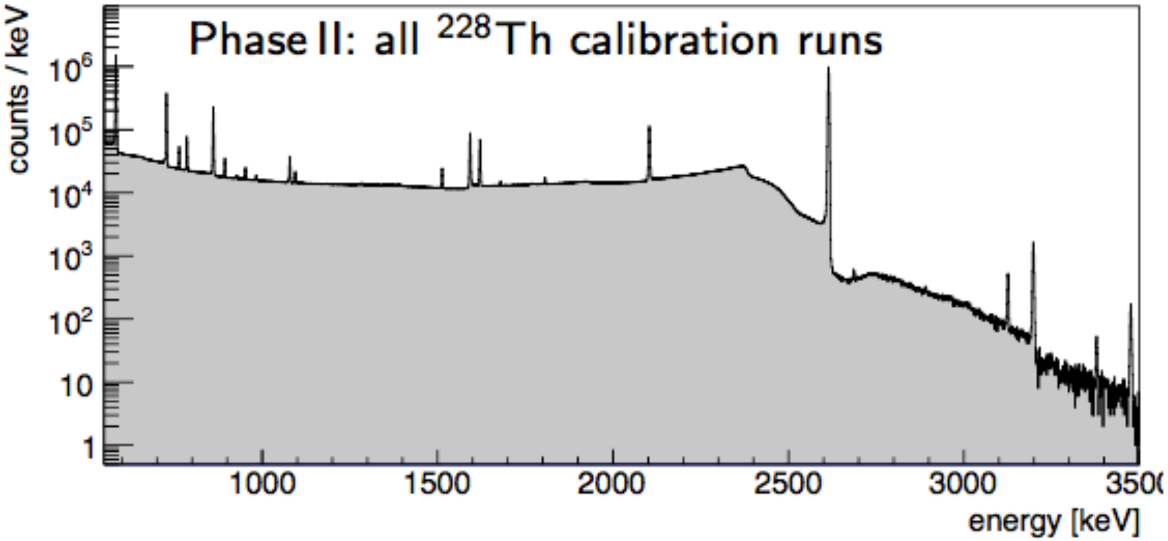
Data Taking 2015-2016

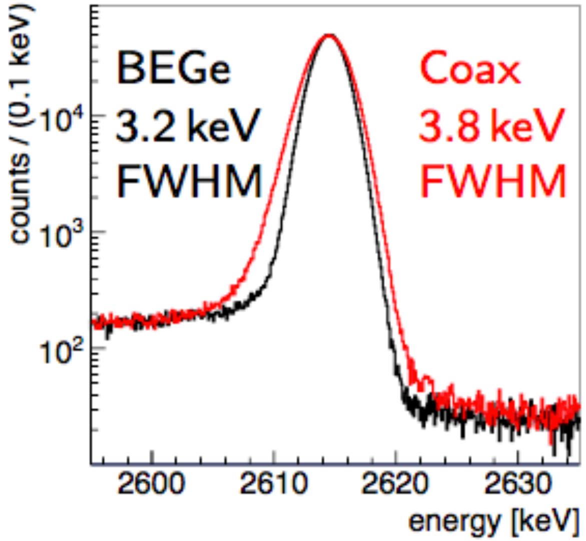
- Dec 2015 - May 2016
- 82% average duty cycle
- exposure used for analysis:

  5.8 kg·yr for enriched BEGe:

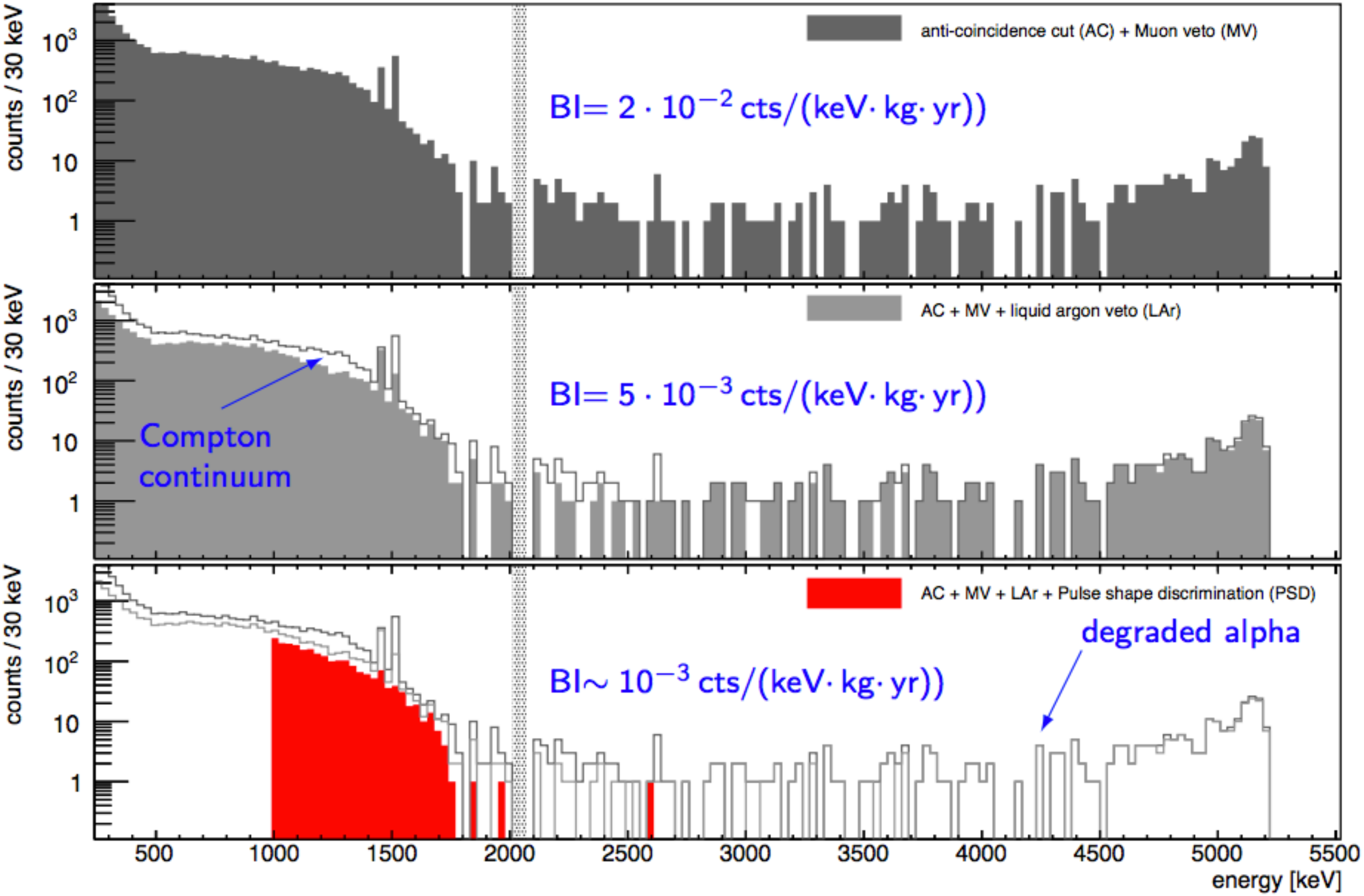
  5.0 kg·yr for enriched coax:
- weekly calibration runs with ^{228}Th
- blinding window $Q_{\beta\beta} \pm 25$ keV




Phase II: all ^{228}Th calibration runs



Background Suppression @ BEGe



Results

- GERDA Phase II is running stable
- 3-4 keV energy resolution at $Q_{\beta\beta}$
- lowest background in ROI ever achieved:

$35^{+21}_{-15} \cdot 10^{-4}$ cts/(keV· kg· yr) for Coax

$7^{+11}_{-5} \cdot 10^{-4}$ cts/(keV· kg· yr) for BEGe

- combined Phase I+II sensitivity:

$T^{0\nu}_{1/2} > 4.0 \cdot 10^{25}$ yr (90% C.L.)*

- blind analysis, no $0\nu\beta\beta$ signal:

$T^{0\nu}_{1/2} > 5.2 \cdot 10^{25}$ yr (90% C.L.)*

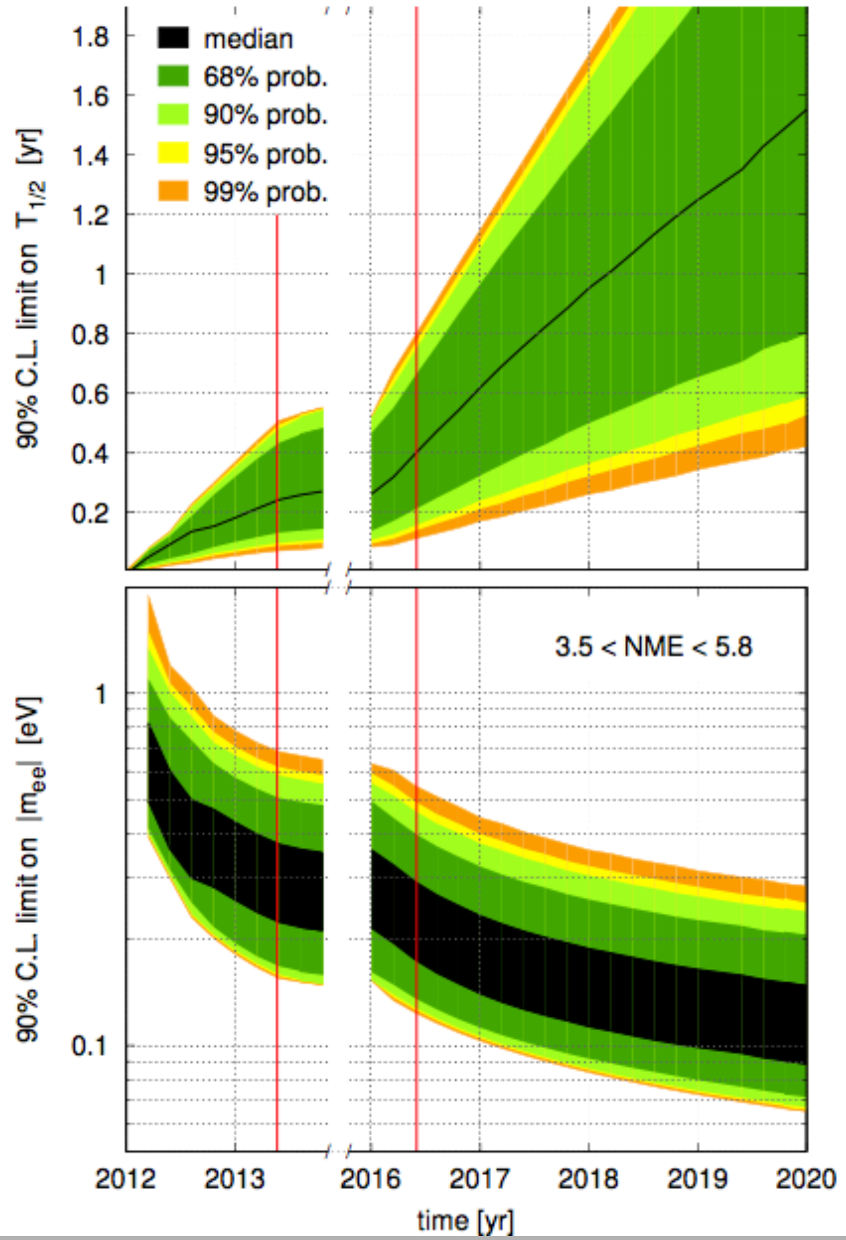
$|m_{ee}| < [160,260]$ meV (90% C.L.)*

(* preliminary, ϵ^{PSD}_{coax} to be finalized)

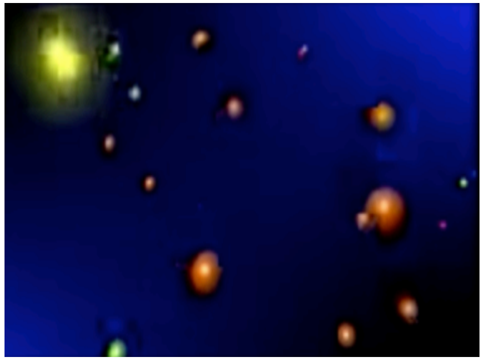
GERDA Phase II is the high-resolution and background-free experiment!

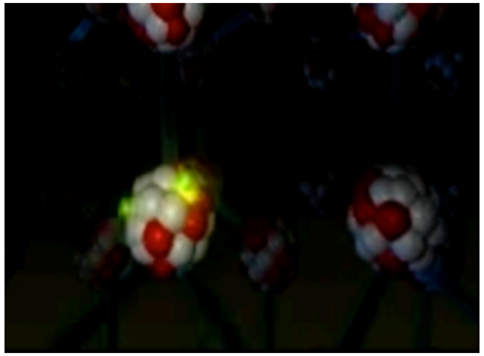
[see poster on next gen ^{76}Ge exp: P4.057]

Based on current BI and duty cycle:



Conclusion / Outlook / Discussion





- The Majorana nature of neutrinos is a very important question
- Now: GERDA, EXO, KamLAND-Zen, CUORE
- Other projects ...
- Upscaling:
  - 200kg in GERDA → LEGEND200
  - LEGEND → 1t
  - nEXO → 5t enriched Xe136
  - DARWIN →50t natural Xe (DM+0νββ search)
- Expectations:
  - global fits tend towards NH
  - cosmology tends towards NH

  → we need new ideas to reach the NH