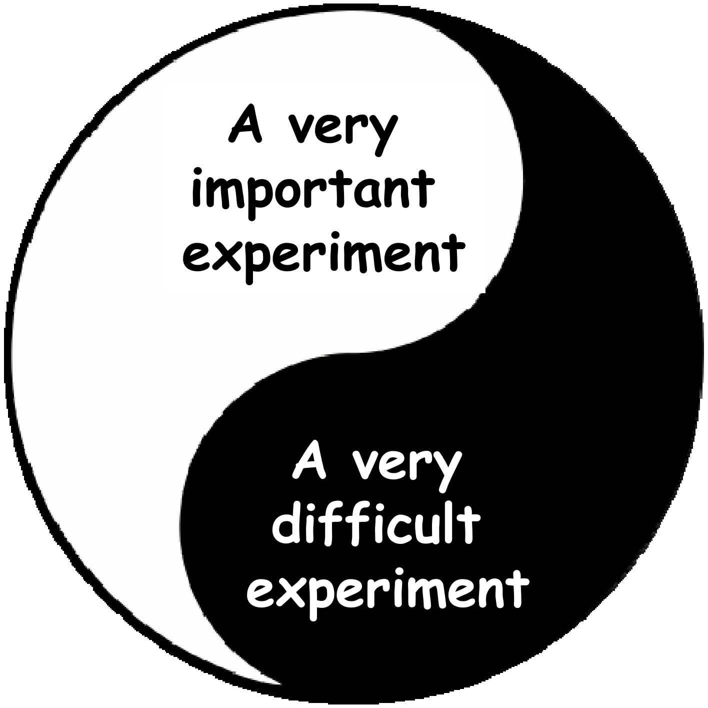
Double-beta decay:

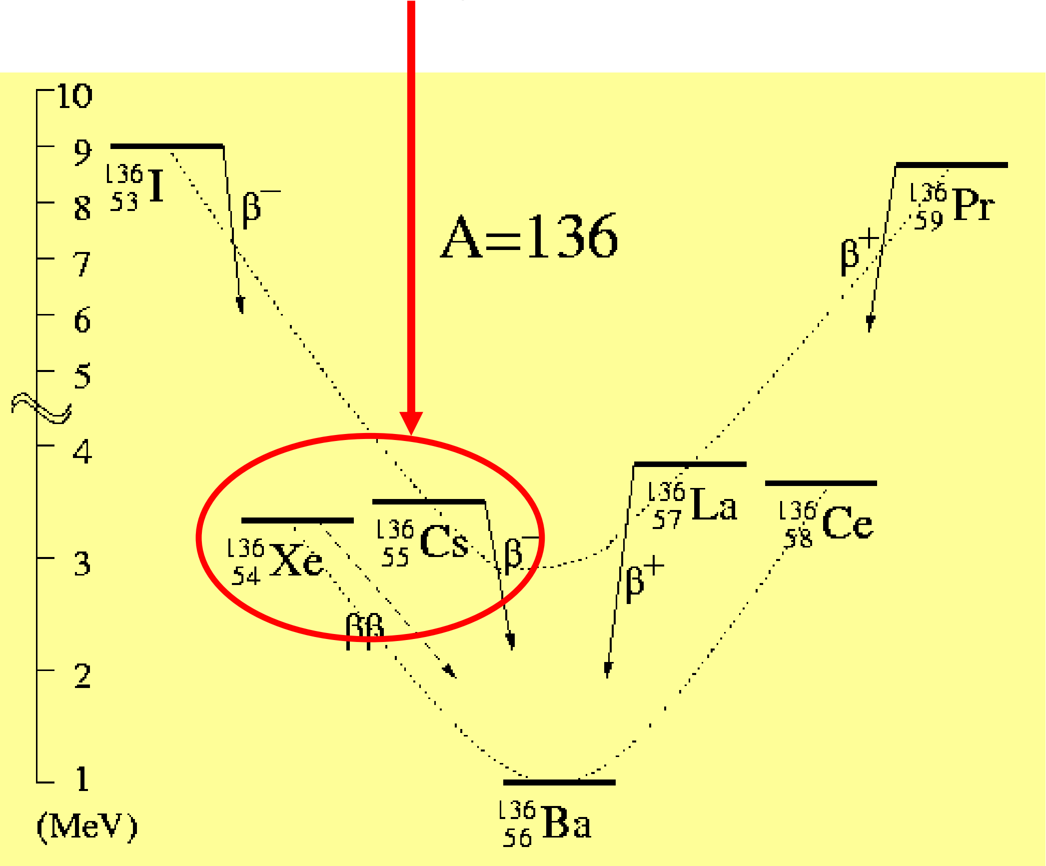


G.Gratta. Physics Dept. Stanford University

ICECUBE PARTICLE ASTROPHYSICS SYMPOSIUM
May 13-15, 2013, Madison Wisconsin

Double-beta decay:

a second-order process only detectable if first order beta decay is energetically forbidden



Candidate nuclei with Q>2 MeV

Candidate	Q (MeV)	Abund. (%)
^{48}Ca→^{48}Ti	4.271	0.187
^{76}Ge→^{76}Se	2.040	7.8
^{82}Se→^{82}Kr	2.995	9.2
^{96}Zr→^{96}Mo	3.350	2.8
^{100}Mo→^{100}Ru	3.034	9.6
^{110}Pd→^{110}Cd	2.013	11.8
^{116}Cd→^{116}Sn	2.802	7.5
^{124}Sn→^{124}Te	2.228	5.64
^{130}Te→^{130}Xe	2.533	34.5
^{136}Xe→^{136}Ba	2.458	8.9
^{150}Nd→^{150}Sm	3.367	5.6

There are two varieties of ββ decay

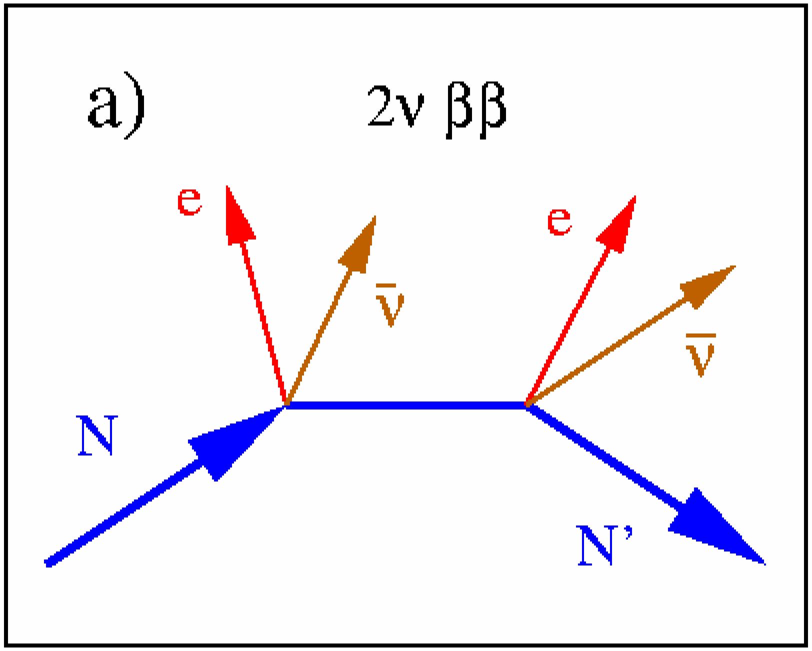
0ν mode: a hypothetical
process can happen
only if: $M_\nu \neq 0$

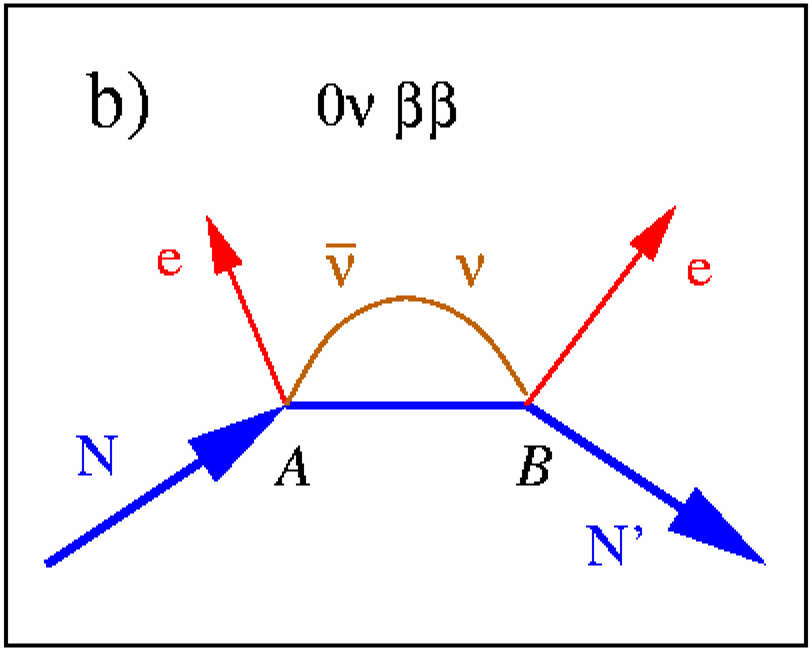
$\nu = \bar{\nu}$

$|\Delta L| = 2$

$|\Delta(B-L)| = 2$

2ν mode:
a conventional
2nd order process
in nuclear physics





“Dirac” neutrinos

(some “redundant” information but the “good feeling” of things we know…)

$$\nu^D = \begin{pmatrix} \nu_L \\ \overline{\nu}_L \\ \nu_R \\ \overline{\nu}_R \end{pmatrix}$$

“Majorana” neutrinos

(more efficient description, no lepton number conservation, new paradigm…)

$$\nu^M = \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$$

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Which way Nature chose to proceed is an experimental question

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“Majorana” neutrinos

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Which way Nature chose to proceed is an experimental question

Strangely enough Majorana-type excitations are today thought to possibly exist in p-wave superconductors
(see e.g. F.Wilczek Nature Physics vol 5, Sept 2009)

The idea of double-beta decay is almost as old as neutrinos themselves

The possibility of neutrinos-less decay was first discussed in 1937:

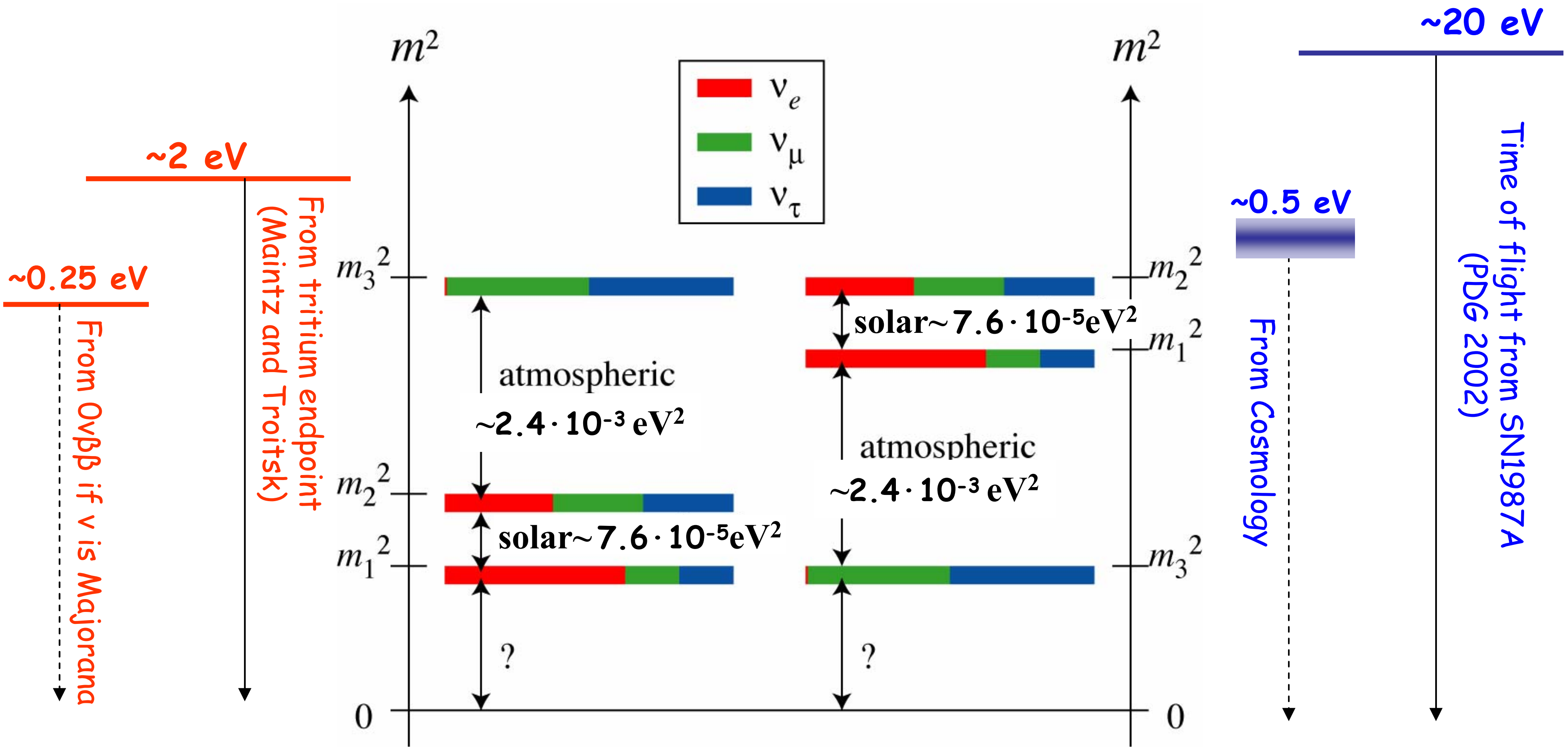
E. Majorana, Nuovo Cimento 14 (1937) 171

G. Racah, Nuovo Cimento 14 (1937) 322

Even earlier the study of nuclear structure led to the conclusion that the 2 neutrino mode would have half lives in excess of 10^{20} years

M.Goeppert-Mayer, Phys. Rev. 48 (1935) 512

Our knowledge of the ν mass pattern



The comparison with ν masses from cosmology measurements is particularly interesting: see Sarah Church / Yvonne Wong.

We need both, the connection between the two is the interesting part!

In the last 10 years there has been a transition

1) From a few kg detectors to 100s or 1000s kg detectors
→ Think big: qualitative transition from cottage industry to large experiments

2) From "random shooting" to the knowledge that at least the inverted hierarchy will be tested

Discovering 0νββ decay:

→ Discovery of the neutrino mass scale
→ Discovery of Majorana particles
→ Doscovery of Majorana masses
→ Discovery of lepton number violation

Note that along with the double β^- decay

$$ {}_{Z}^{A}N \rightarrow {}_{Z+2}^{\;\;A}N' + e^- + e^- $$

there is also a β^+ mode that in practice would appear as a single or double electron capture

$$ {}_{Z}^{A}N \rightarrow {}_{Z-2}^{\;\;A}N' + e^+ + e^+ $$

$$ {}_{Z}^{A}N + e^- \rightarrow {}_{Z-2}^{\;\;A}N' + e^+ $$

$$ {}_{Z}^{A}N + e^- + e^- \rightarrow {}_{Z-2}^{\;\;A}N' $$

All these processes are phase-space suppressed respect to the β^- case and isotope fractions low in natural mix: usually not considered

If $0\nu\beta\beta$ is due to light ν Majorana masses

$$\langle m_\nu \rangle^2 = \left(T_{1/2}^{0\nu\beta\beta} \; G^{0\nu\beta\beta}(E_0, Z) \; \left| M_{GT}^{0\nu\beta\beta} - \frac{g_V^2}{g_A^2} M_F^{0\nu\beta\beta} \right|^2 \right)^{-1}$$

$M_F^{0\nu\beta\beta}$ and $M_{GT}^{0\nu\beta\beta}$ can be calculated within particular nuclear models

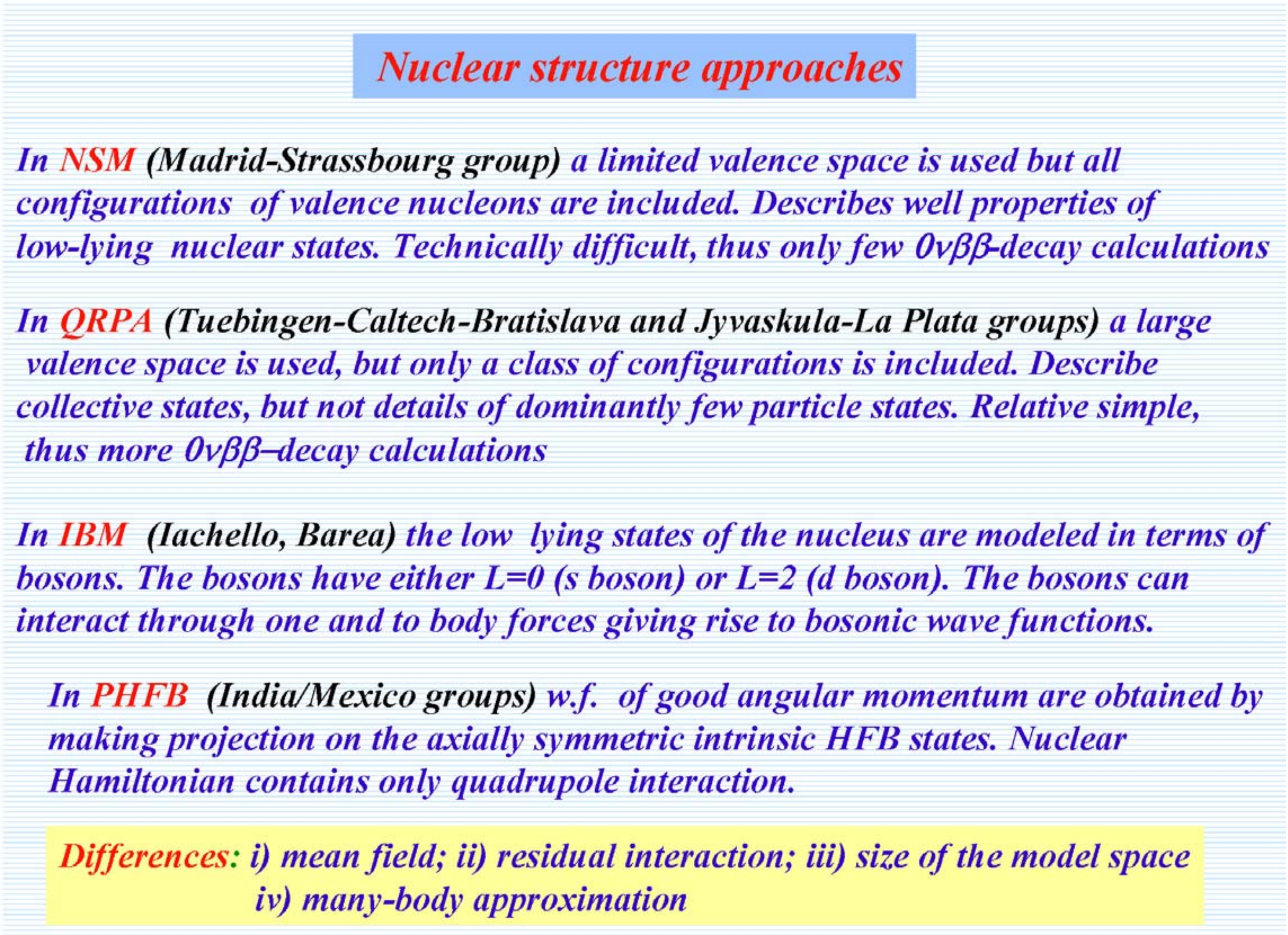
$G^{0\nu\beta\beta}$ a known phasespace factor

$T_{1/2}^{0\nu\beta\beta}$ is the quantity to be measured

$$\langle m_\nu \rangle = \sum_{i=1}^{3} \left| U_{e,i} \right|^2 m_i \; \varepsilon_i$$

effective Majorana ν mass

($\varepsilon_i = \pm 1$ if CP is conserved)



Nuclear structure approaches

In NSM (Madrid-Strassbourg group) a limited valence space is used but all configurations of valence nucleons are included. Describes well properties of low-lying nuclear states. Technically difficult, thus only few $0\nu\beta\beta$-decay calculations

In QRPA (Tuebingen-Caltech-Bratislava and Jyvaskula-La Plata groups) a large valence space is used, but only a class of configurations is included. Describe collective states, but not details of dominantly few particle states. Relative simple, thus more $0\nu\beta\beta$–decay calculations

In IBM (Iachello, Barea) the low lying states of the nucleus are modeled in terms of bosons. The bosons have either L=0 (s boson) or L=2 (d boson). The bosons can interact through one and to body forces giving rise to bosonic wave functions.

In PHFB (India/Mexico groups) w.f. of good angular momentum are obtained by making projection on the axially symmetric intrinsic HFB states. Nuclear Hamiltonian contains only quadrupole interaction.

Differences: i) mean field; ii) residual interaction; iii) size of the model space iv) many-body approximation

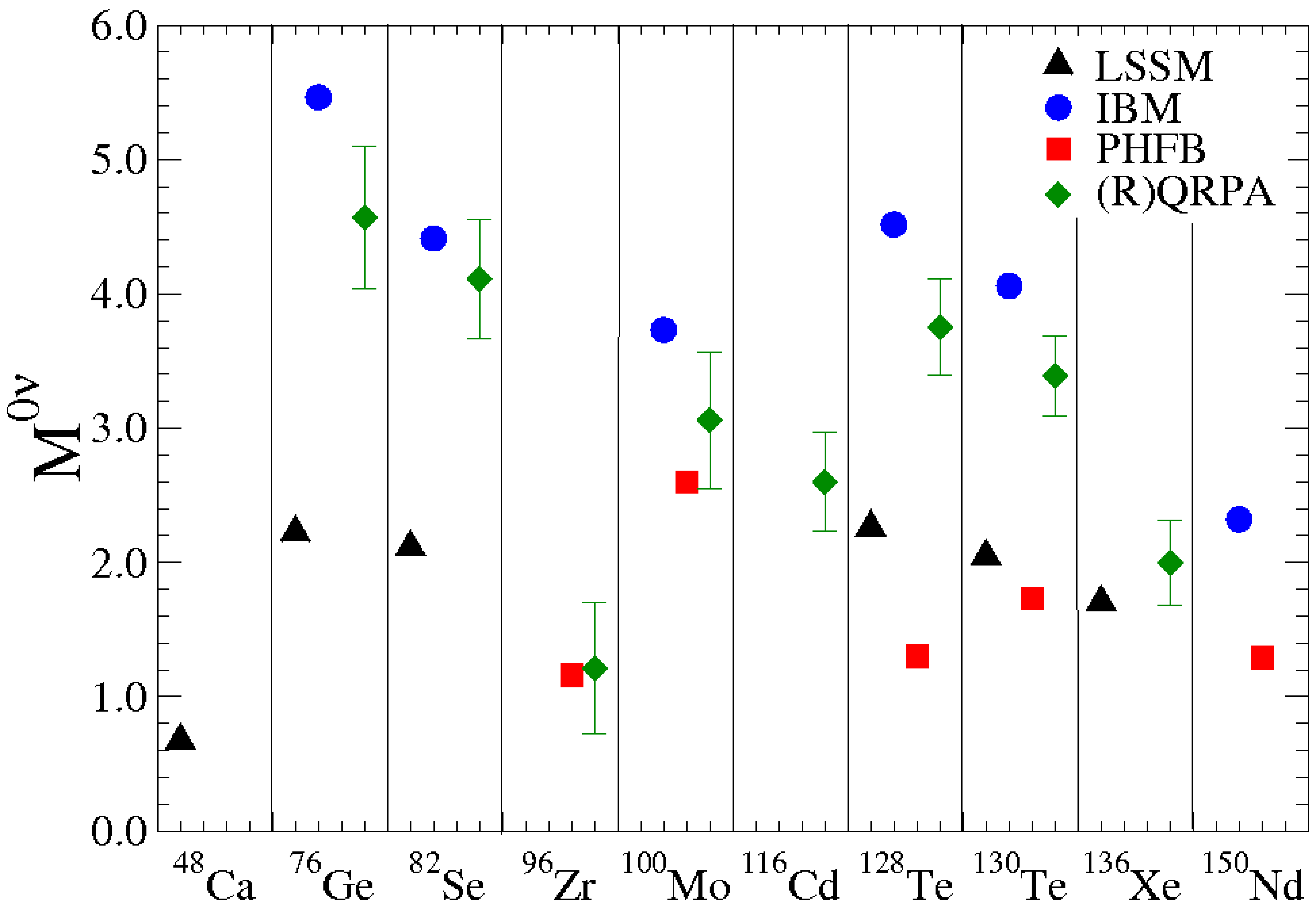
F. Simkovic, Neutrino 2010

Good news: Lots of activity!

A number of new groups and ideas are entering the game!

Calculations differ by about a factor of two

(but care is necessary in treating some of them generally regarded as obsolete)



F. Simkovic, Neutrino 2010

Note, however, that to discover Majorana neutrinos and lepton number violation the value of the nuclear matrix element is inessential!

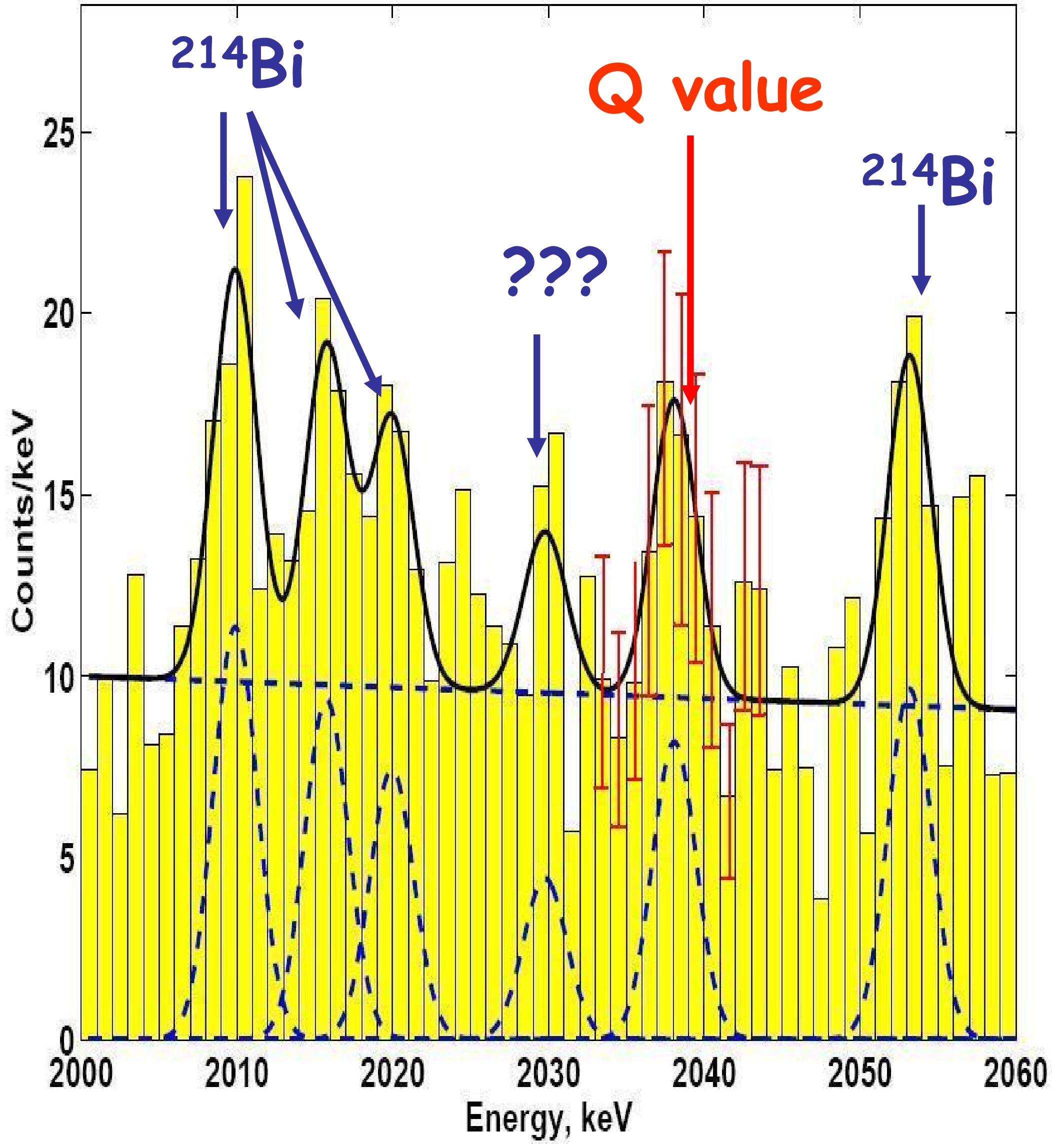
→ $0\nu\beta\beta$ decay always implies new physics

This is comforting for the one of us spending their time building experiments!

Simplified List of Limits for $\beta\beta 0\nu$ decay

Nucleus	Detector type	(kg yr)	Present $T_{1/2}^{0\nu\beta\beta}$ (yr)	<m> (meV)
^{48}Ca			$>5.8*10^{22}$ (90%CL)	
^{76}Ge	Ge diode	~47.7	$>1.9*10^{25}$ (90%CL)	<350
^{82}Se			$>2.1*10^{23}$ (90%CL)	
^{96}Zr			$>9.2*10^{21}$ (90%CL)	
^{100}Mo	Foil/tracking		$>1*10^{24}$ (90%CL)	<500 - 1000
^{116}Cd			$>1.7*10^{23}$ (90%CL)	
^{128}Te			$>1.1*10^{23}$ (90%CL)	
^{130}Te	TeO_2 cryo	~12	$>3*10^{24}$ (90%CL)	<190 – 680
^{136}Xe	Xe TPC/scint	~90	$>1.9*10^{24}$ (90%CL)	<120 – 250
^{150}Nd			$>1.8*10^{22}$ (90%CL)	
^{160}Gd			$>1.3*10^{21}$ (90%CL)	

ββ0ν discovery claim



Fit model:
6 gaussians + linear bknd.

Fitted excess @ $Q_{\beta\beta}$
28.75 ± 6.86.

Claimed significance: 4.2 σ

$$T_{1/2} = 2.23^{+0.44}_{-0.31} \cdot 10^{24}\, yr$$

$$\langle m_\nu \rangle = 0.32 \pm 0.03\, eV$$

[H.V.Klapdor-Kleingrothaus and I.Krivosheina, Mod.Phys.Lett. A21 (2006) 1547]

However, this is a very controversial matter

See e.g. Strumia+Vissani Nucl Phys B726 (2005) 294

Measured 2νββ decay half lives, now observed for all interesting isotopes

Isotope	Experimental $T_{1/2}^{2\nu}$ (yr)
^{48}Ca	$(4.3\pm2.2)\cdot10^{19}$
^{76}Ge	$(1.77\pm0.12)\cdot10^{21}$
^{82}Se	$(9.6\pm1)\cdot10^{19}$
^{96}Zr	$(9.4\pm3.2)\cdot10^{18}$ § $(2.1\pm0.6)\cdot10^{19}$
^{100}Mo	$(5.7\pm1.2)\cdot10^{20}$
^{116}Cd	$(2.9\pm0.4)\cdot10^{19}$
^{128}Te	$(7.2\pm0.4)\cdot10^{24}$ §
^{130}Te	$(7\pm0.9\pm1.1)\cdot10^{20}$
^{136}Xe	$(2.11\pm0.21)\cdot10^{21}$
^{150}Nd	$(1.4\pm0.7)\cdot10^{20}$
^{238}U	$(2.0\pm0.6)\cdot10^{21}$ *

Arbitrarily simplified from PDG

Slowest processes ever measured in nature!

…a good explanation for my title!

§Geochemical experiment
*Radiochemical experiment

Need very large fiducial mass (tons) of isotopically separated material (except for ^{130}Te)

[using natural material typically means that 90% of the source produced background but not signal]

This is expensive and provides encouragement to use the material in the best possible way:

Candidate	Q (MeV)	Abund. (%)
$^{48}Ca\rightarrow^{48}Ti$	4.271	0.187
$^{76}Ge\rightarrow^{76}Se$	2.040	7.8
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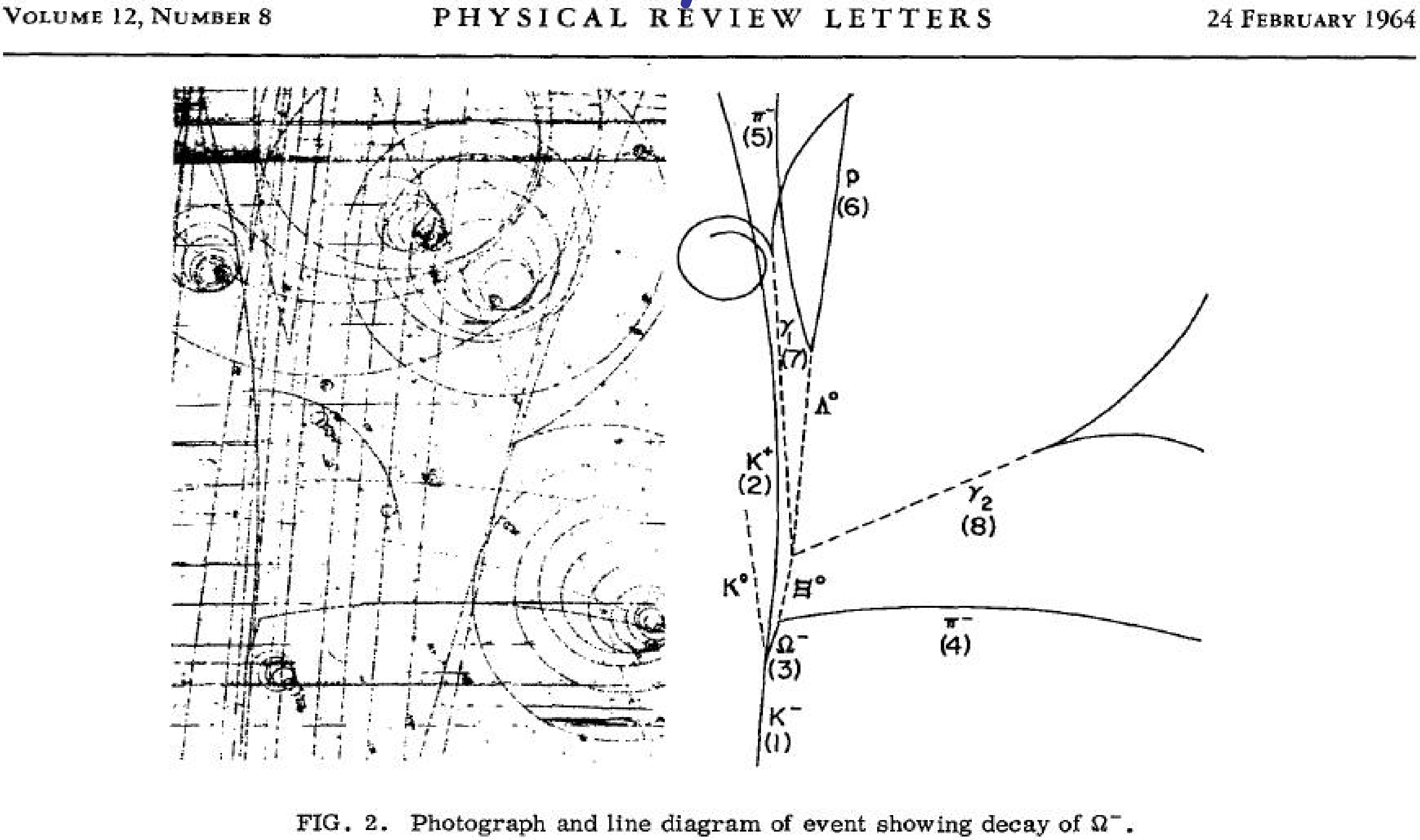
For no bkgnd $\langle m_\nu \rangle \propto 1/\sqrt{T_{1/2}^{0\nu\beta\beta}} \propto 1/\sqrt{Nt}$

For statistical bkgnd subtraction $\langle m_\nu \rangle \propto 1/\sqrt{T_{1/2}^{0\nu\beta\beta}} \propto 1/(Nt)^{1/4}$

Discovery of the Ω^-



VOLUME 12, NUMBER 8 PHYSICAL REVIEW LETTERS 24 FEBRUARY 1964

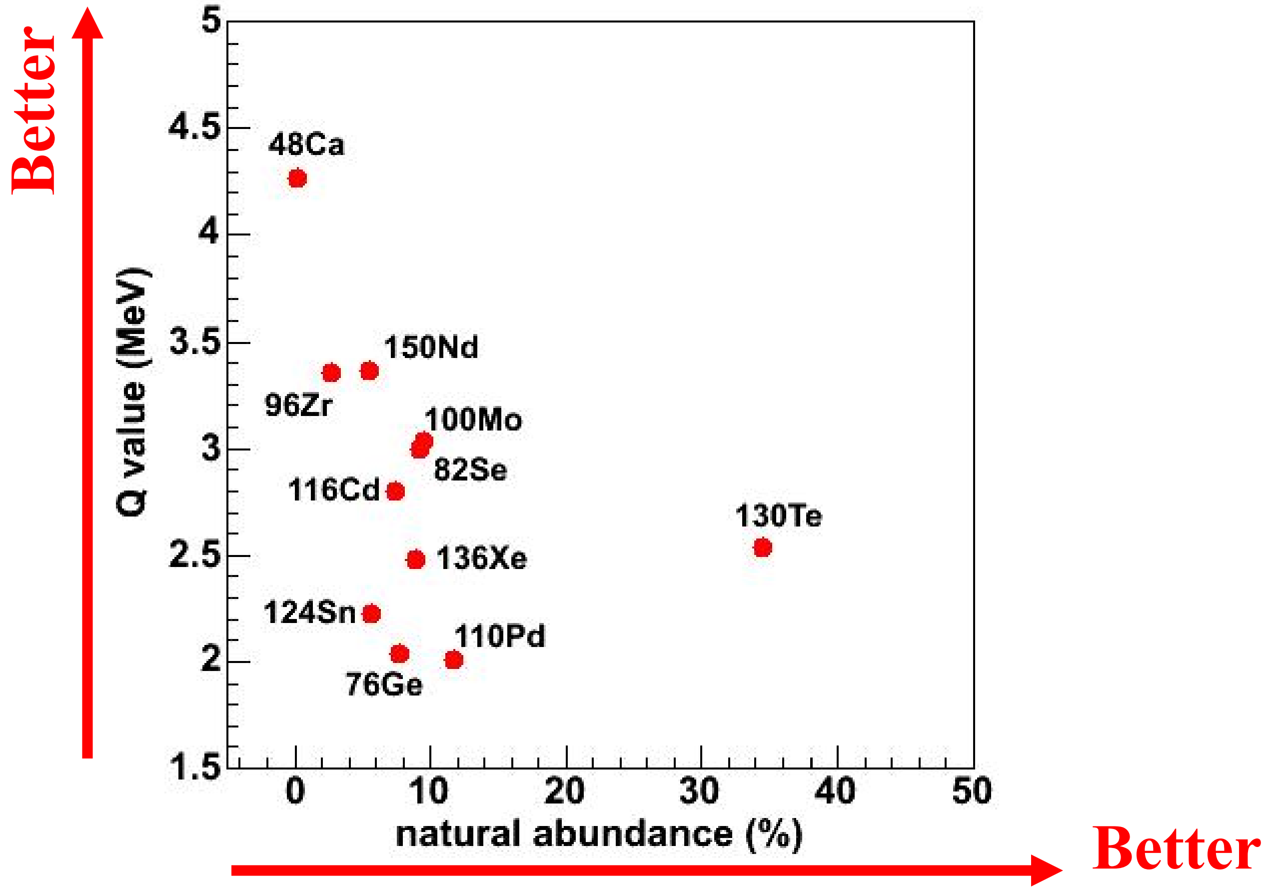
FIG. 2. Photograph and line diagram of event showing decay of Ω^-.

The statistical significance of a signal is determined by how strongly you can reject the null hypothesis.

The importance of clean, multi-parameter measurements grows as the size of detectors grows, making cross-checks painfully slow and expensive

“Background” runs with un-enriched or depleted material do not seem to be a panacea as isotopic separation alters, sometimes drastically, the background in the source

How to "organize" an experiment: the source



C.Hall SLAC Summer Institute 2010

- High Q value reduces backgrounds and increases the phase space & decay rate,
- Large abundance makes the experiment cheaper

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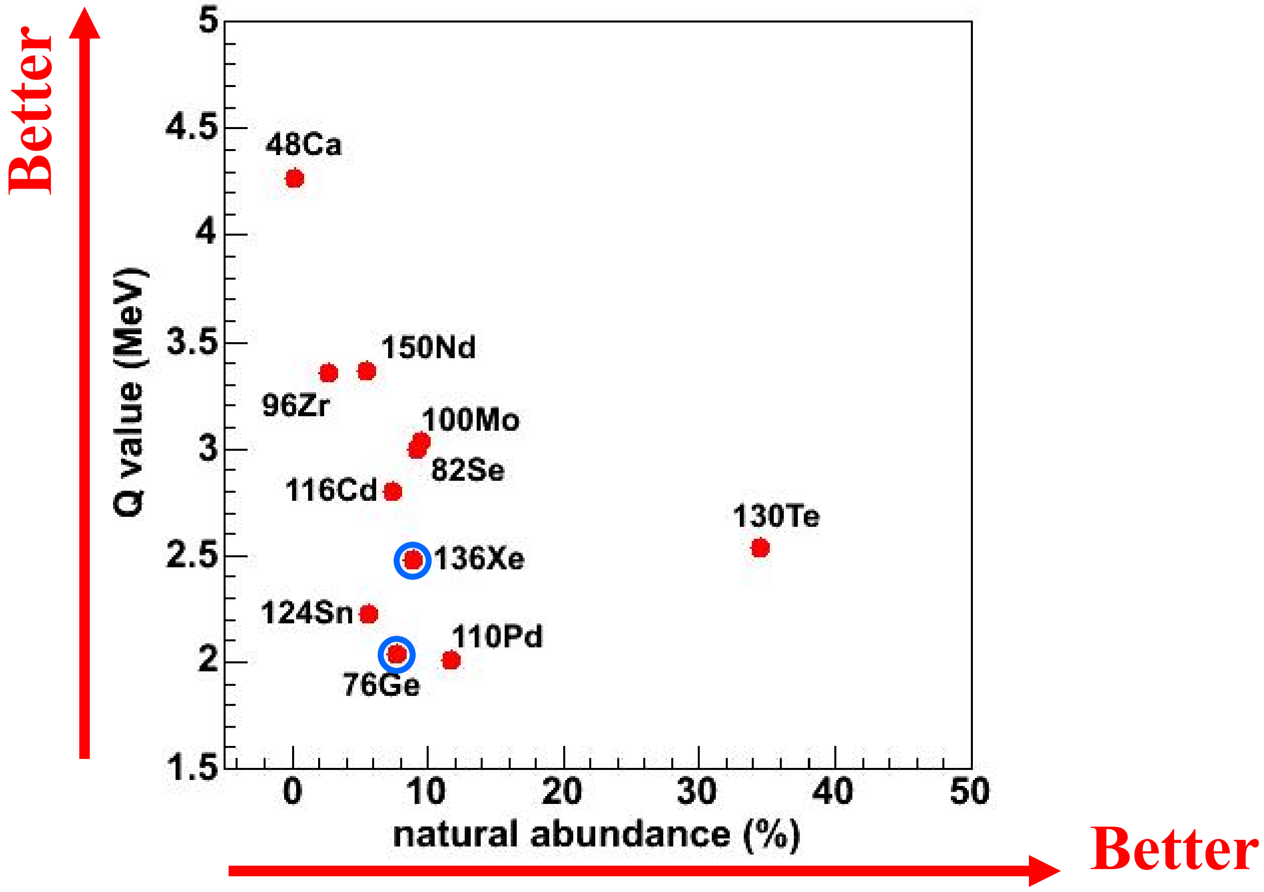


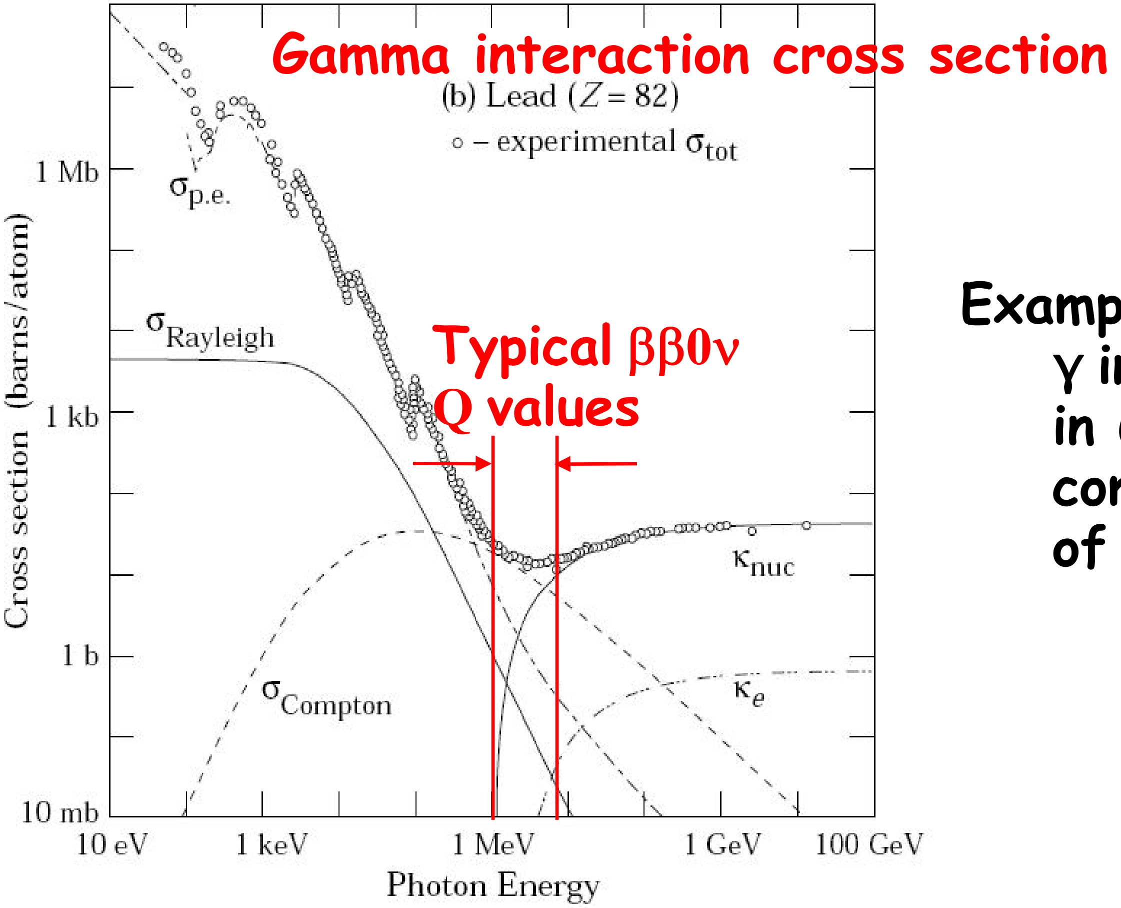
C.Hall SLAC Summer Institute 2010

- High Q value reduces backgrounds and
  increases the phase space & decay rate,
- Large abundance makes the experiment cheaper
- A number of isotopes have similar matrix element performance

How to "organize" an experiment: the technique

- Final state ID: 1) "Geochemical": search for an abnormal abundance of (A,Z+2) in a material containing (A,Z)
  - 2) "Radiochemical": store in a mine some material (A,Z) and after some time try to find (A,Z+2) in it
    - \+ Very specific signature
    - \+ Large live times (particularly for 1)
    - \+ Large masses
    - \- Possible only for a few isotopes (in the case of 1)
    - \- No distinction between 0ν, 2ν or other modes
- "Real time": ionization or scintillation is detected in the decay
  - a) "Homogeneous": source=detector
  - b) "Heterogeneous": source≠detector
    - \+ Energy/some tracking available (can distinguish modes)
    - \+ In principle universal (b)
    - \- Many γ backgrounds can fake signature
    - \- Exposure is limited by human patience

Shielding a detector from gammas is difficult because the absorption cross section is small.

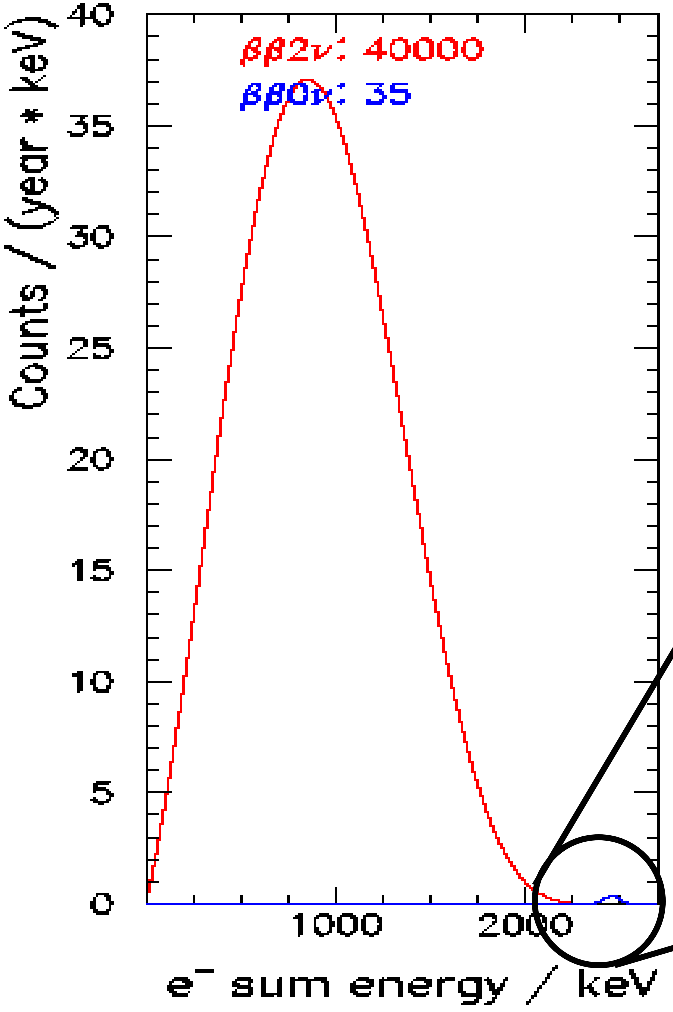


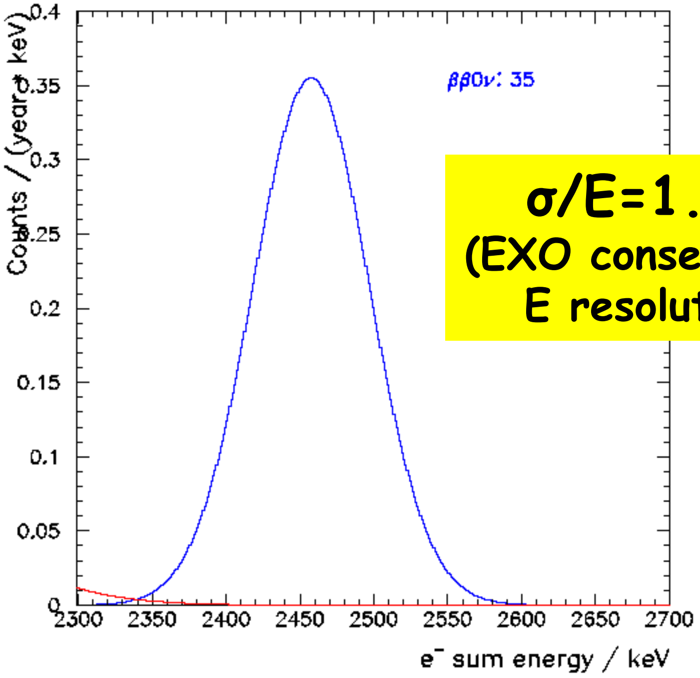
Example:

γ interaction length in Ge is 4.6 cm, comparable to the size of a germanium detector.

Shielding double-beta decay detectors is much harder than shielding Dark Matter ones

Background due to the Standard Model $2\nu\beta\beta$ decay



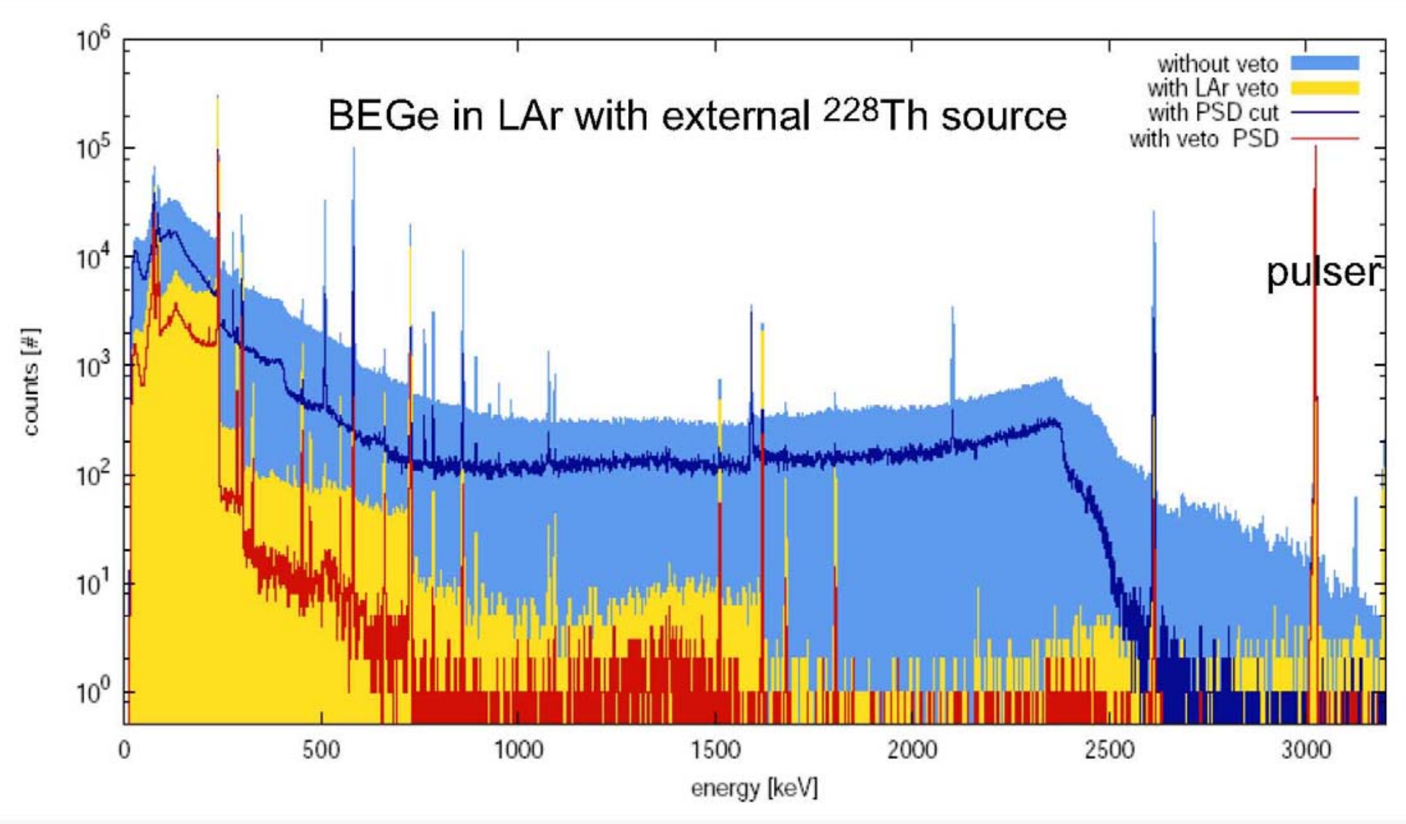


$\sigma/E=1.6\%$
(EXO conservative E resolution)

The two can be separated in a detector with sufficiently good energy resolution

Topology and particle ID are also important to recognize backgrounds

About energy resolution



Superior energy resolution:

^{76}Ge (diode): 0.2% FWHM

^{130}Te (bolometer): 0.4% FWHM

Intermediate energy resolution:

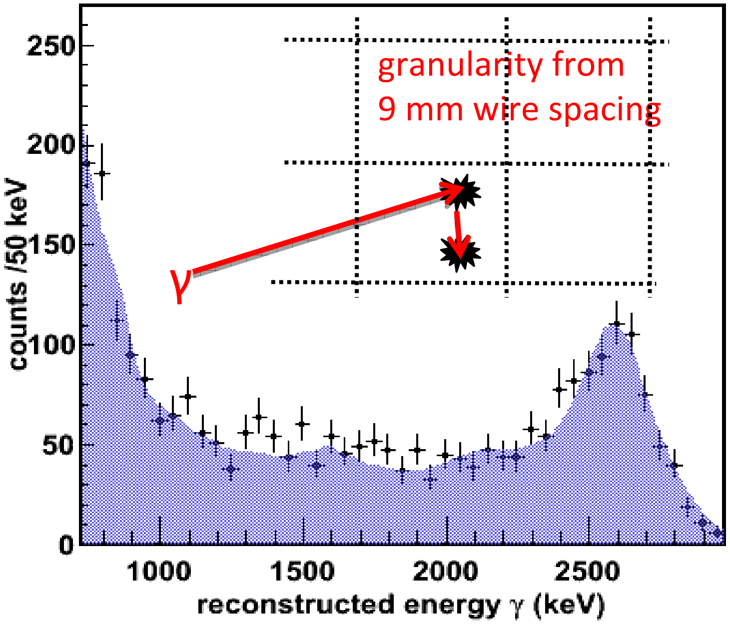
^{136}Xe (liquid TPC): 3.3% FWHM

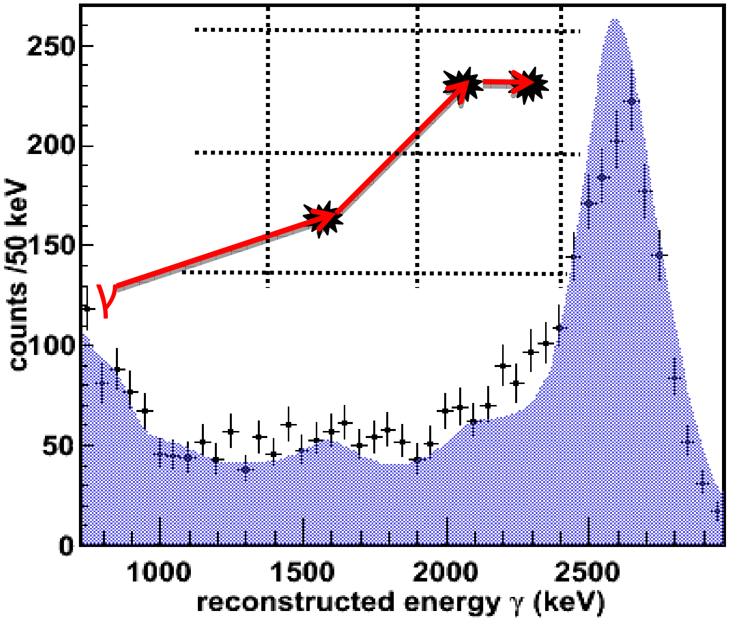
Modest energy resolution:

^{100}Mo, ^{136}Xe, ^{130}Te ^{150}Nd (scintillators): 10%-15% FWHM

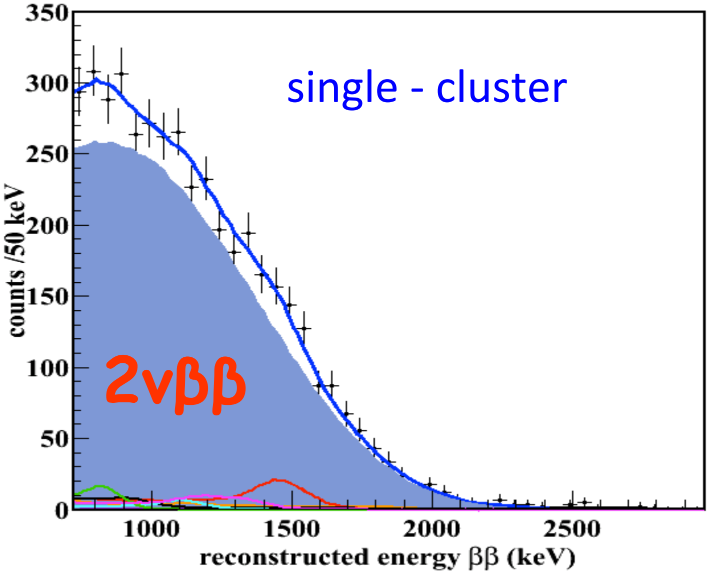
Pattern recognition can be a very powerful tool against background (example from 2νββ in EXO-200)

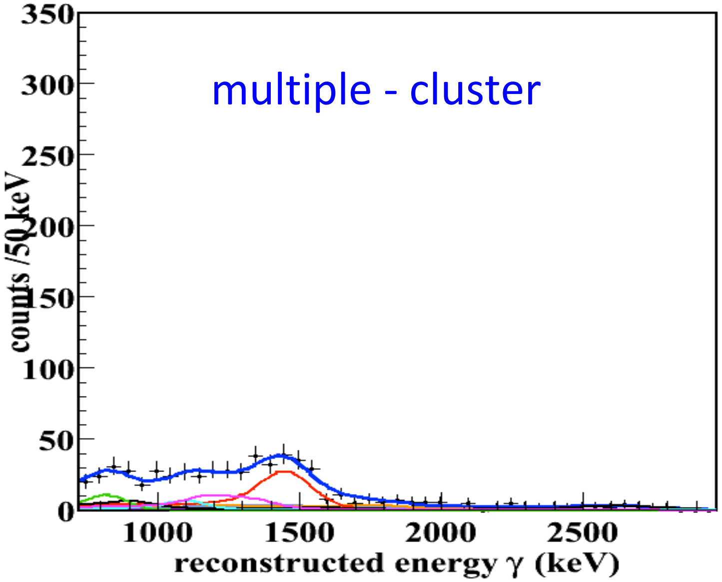
^{228}Th calibration source





Low background data





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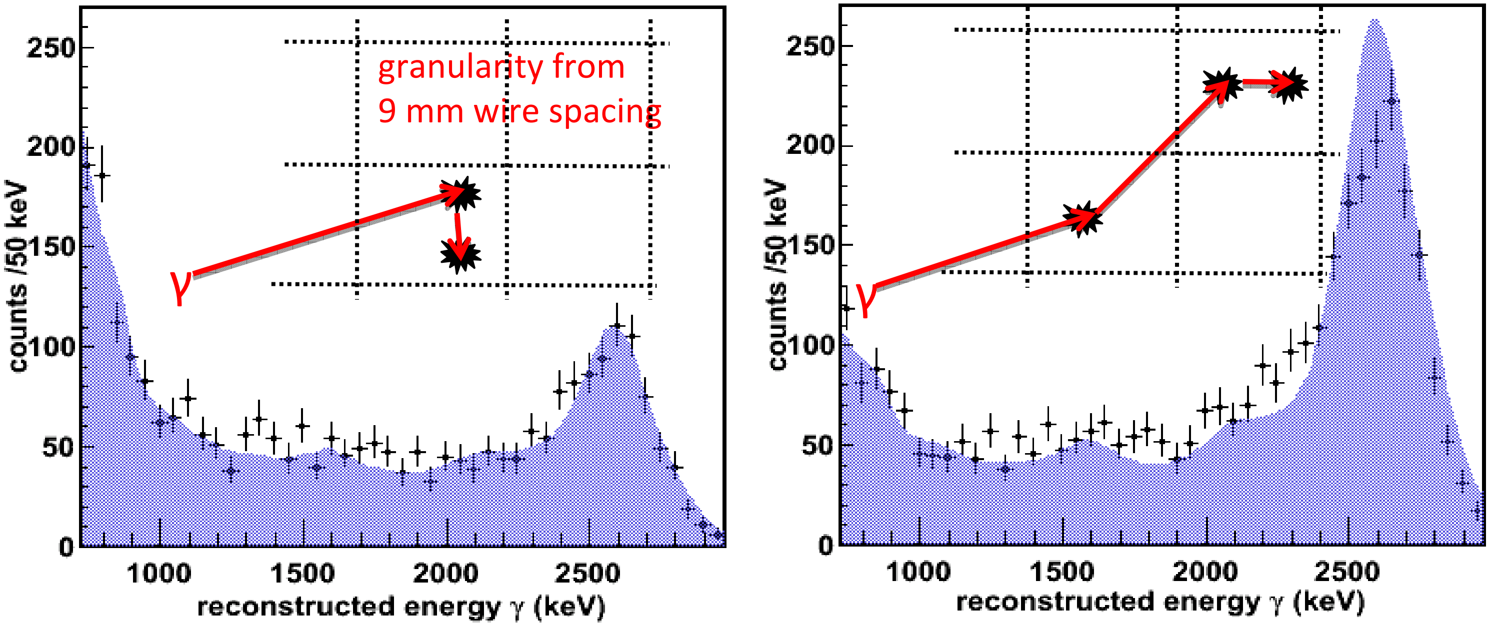
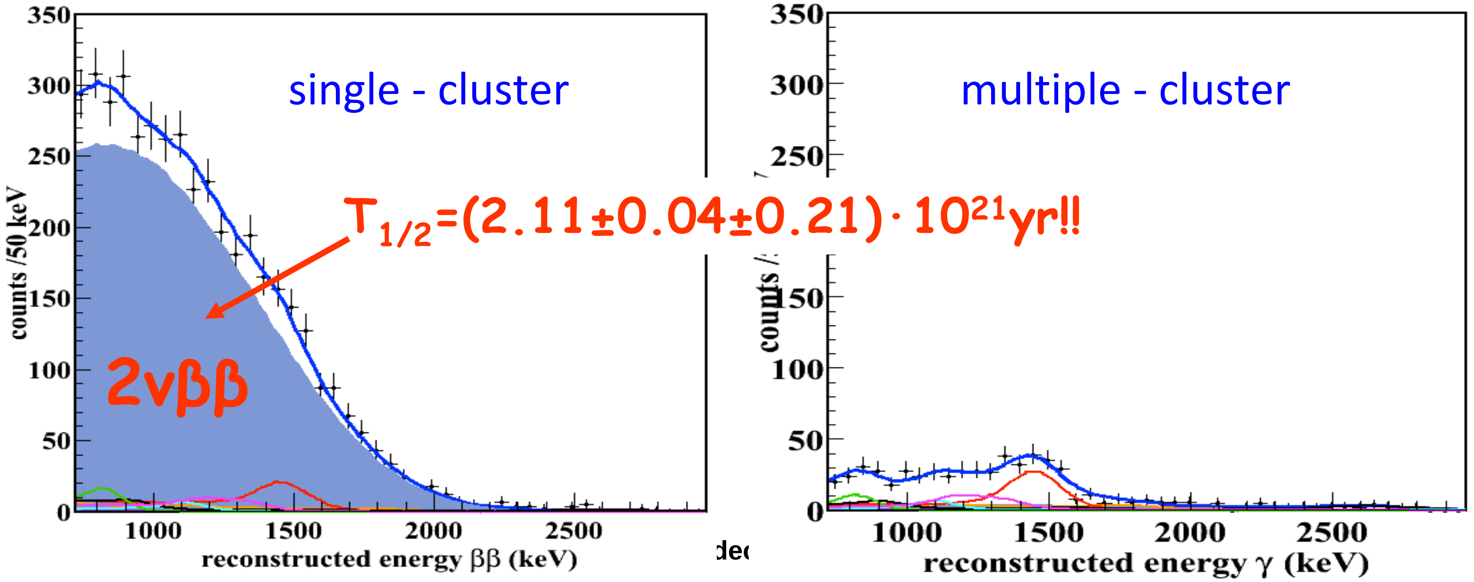
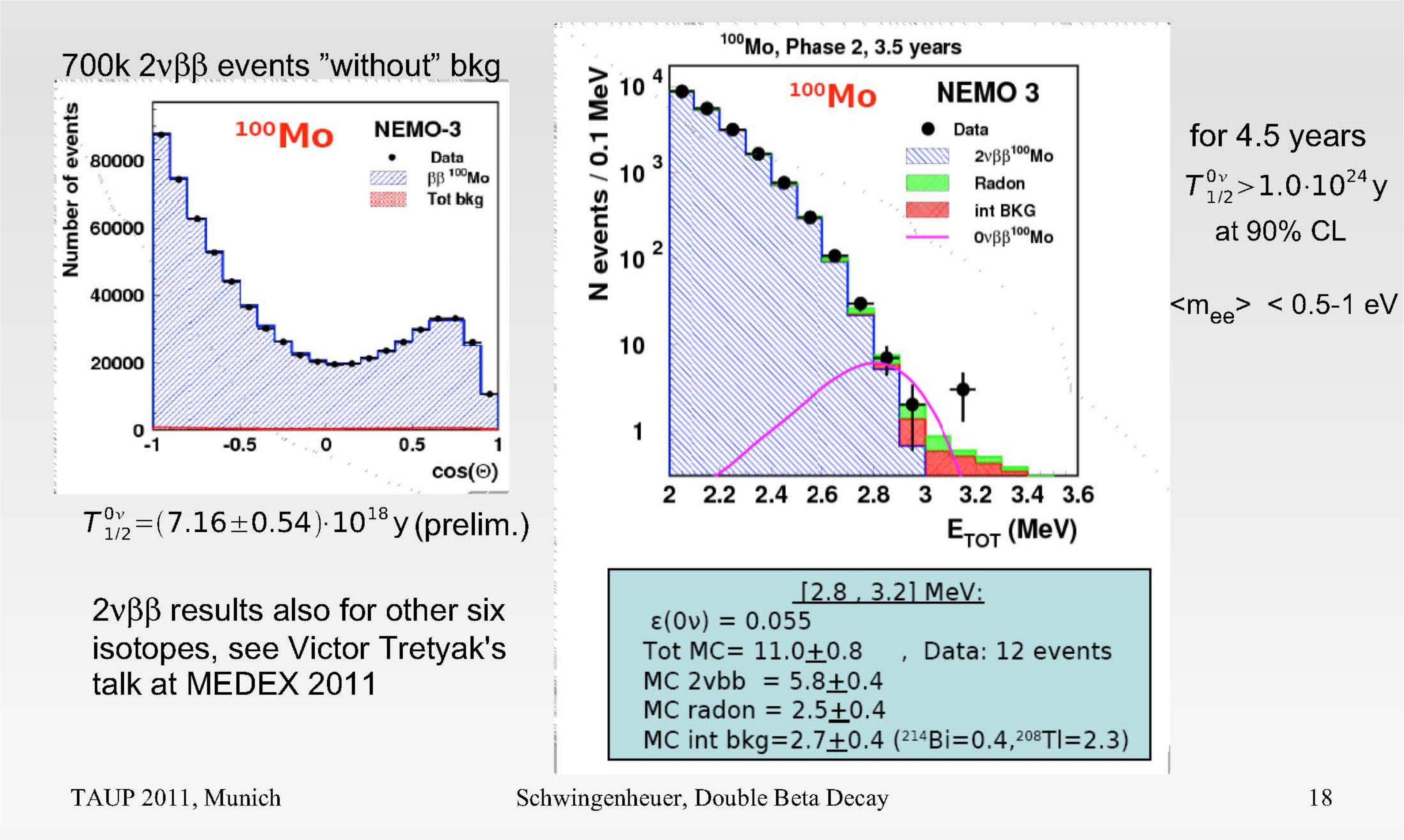


Low background data



$T_{1/2}=(2.11\pm0.04\pm0.21)\cdot10^{21}$yr!!

“Extreme” pattern recognition (at the expense of fiducial mass)



700k 2νββ events ”without” bkg

$T^{0\nu}_{1/2} = (7.16 \pm 0.54) \cdot 10^{18}$ y (prelim.)

2νββ results also for other six isotopes, see Victor Tretyak's talk at MEDEX 2011

for 4.5 years

$T^{0\nu}_{1/2} > 1.0 \cdot 10^{24}$ y

at 90% CL

$\langle m_{ee} \rangle$ < 0.5-1 eV

[2.8 , 3.2] MeV:

ε(0ν) = 0.055

Tot MC= 11.0±0.8 , Data: 12 events

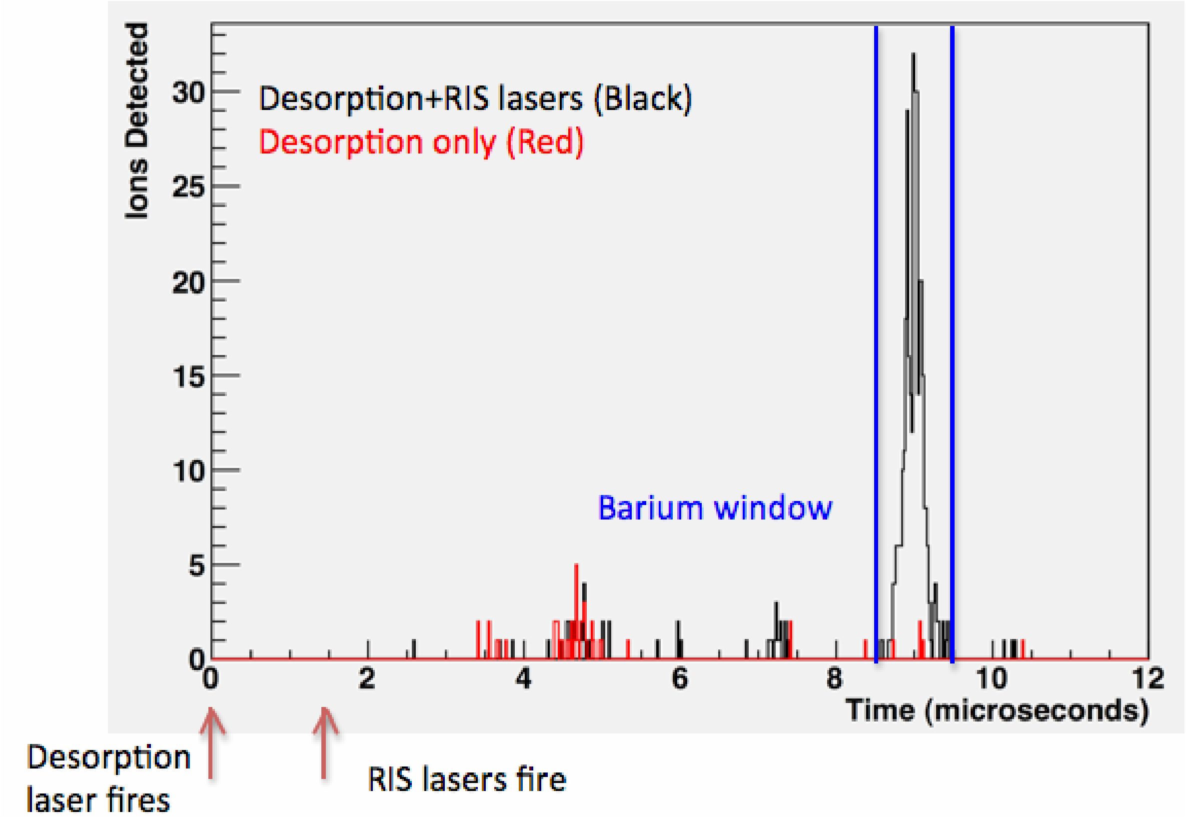
MC 2vbb = 5.8±0.4

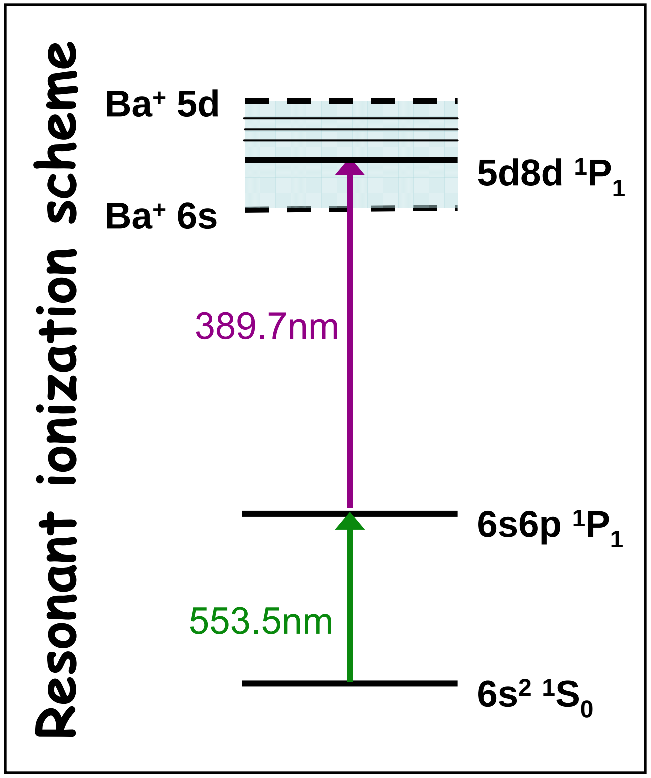
MC radon = 2.5±0.4

MC int bkg=2.7±0.4 (^{214}Bi=0.4,^{208}Tl=2.3)

TAUP 2011, Munich Schwingenheuer, Double Beta Decay 18

Xe possibly offers an extra tool against background: $^{136}Xe \rightarrow {}^{136}Ba^{++}\, e^-\, e^-$ final state can be identified using optical spectroscopy (M.Moe PRC44 (1991) 931)





~2% Ba tagging efficiency obtained in the lab.

Plenty of R&D still left to do to demonstrated
if the technique is viable

It is very important to understand that a healthy neutrinoless double-beta decay program requires more than one isotope. This is because:

- ***There could be unknown gamma transitions and a line observed at the "end point" in one isotope does not necessarily imply that 0νββ decay was discovered***
- ***Nuclear matrix elements are not very well known and any given isotope could come with unknown liabilities***
- ***Different isotopes correspond to vastly different experimental techniques***
- ***2 neutrino background is different for various isotopes***
- ***The elucidation of the mechanism producing the decay requires the analysis of more than one isotope***

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- *The elucidation of the mechanism producing the decay requires the analysis of more than one isotope*

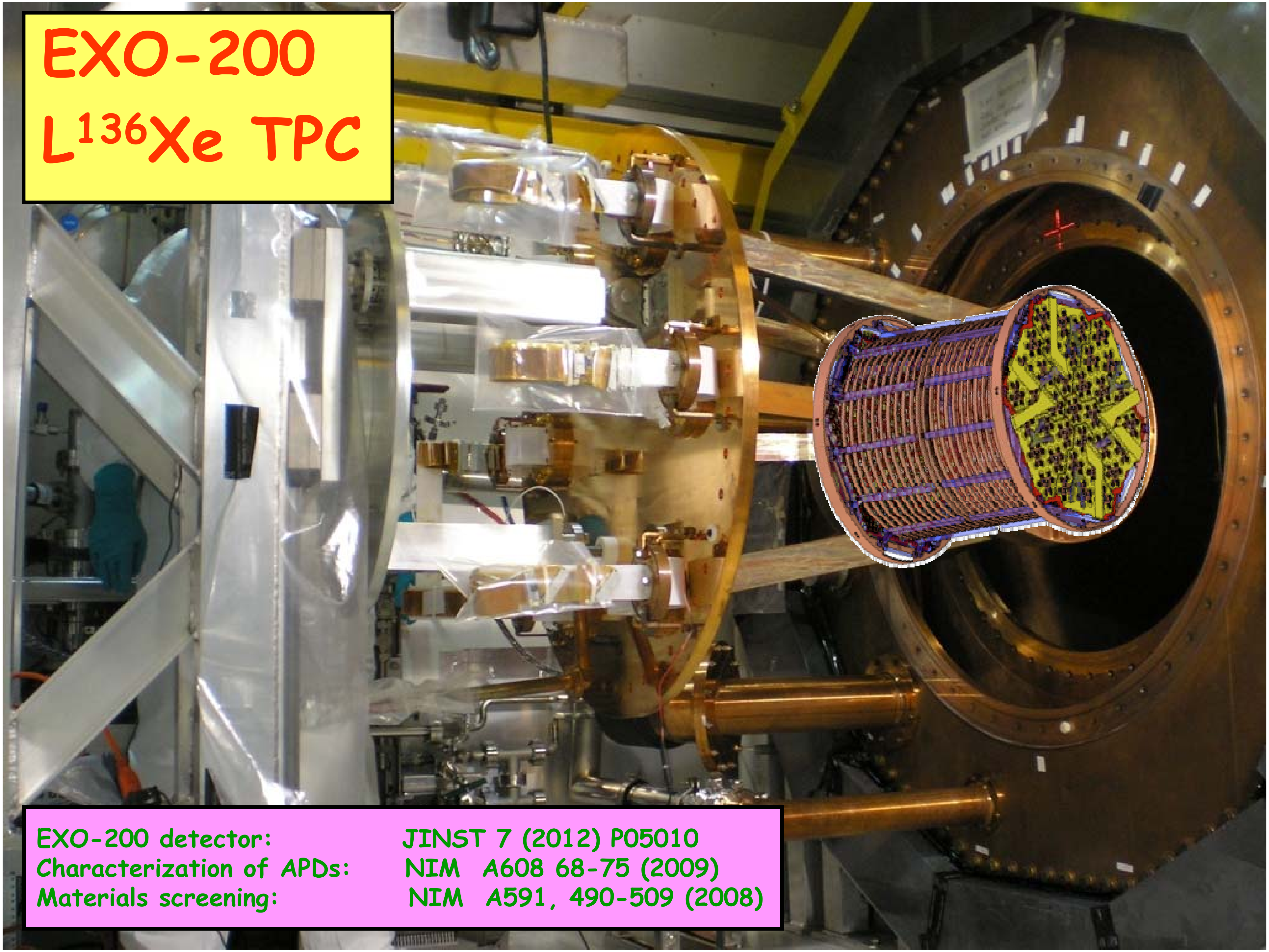
Experiments taking data or under advanced construction

Isotope	Experiment	Main principle	Fid mass	Lab	Status
^{76}Ge	Majorana	Eres,2site tag, Cu shield	30 kg	SUSEL	Building
	Gerda	Eres,2site tag, LAr shield	15-35 kg	G Sasso	Data taking
^{130}Te*	SNO+	Size/shielding	800 kg†	SNOlab	Commissioning
^{130}Te*	CUORE	E Res.	204 kg	G Sasso	Building
^{136}Xe	KamLAND-Zen	Size/shielding	400 kg	Kamioka	Re-commissioning
	EXO-200	Tracking/Eres	150 kg	WIPP	Data taking

* No isotopic enrichment

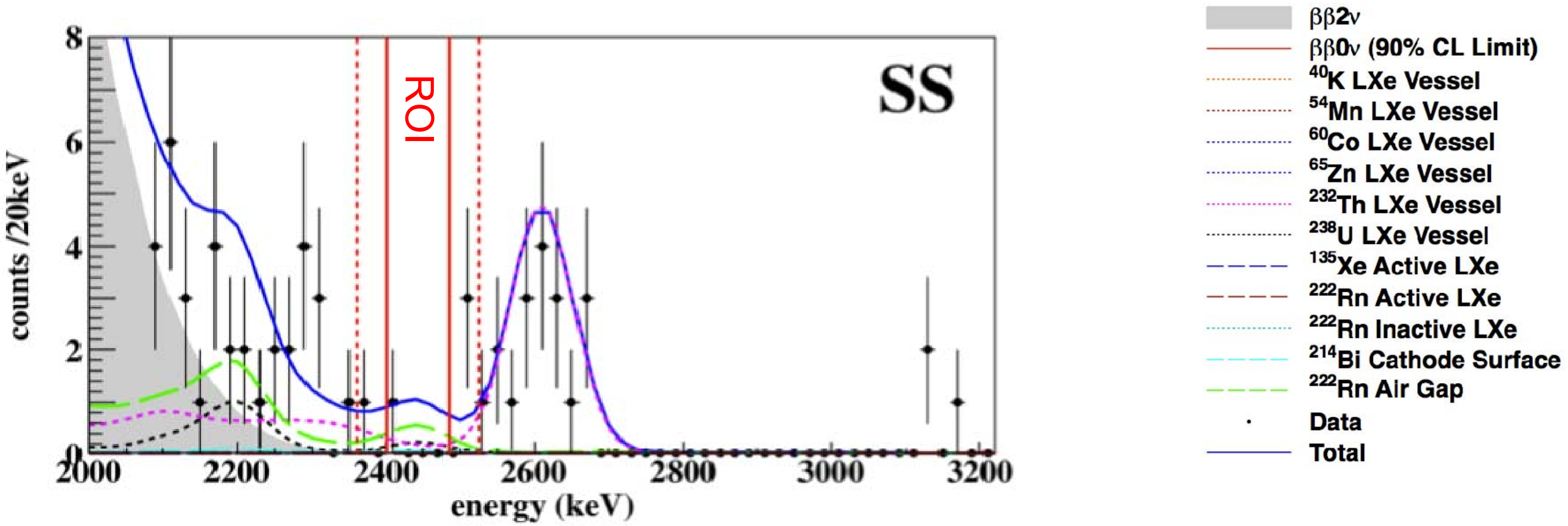
† But needs fiducial cut

EXO-200
L^{136}Xe TPC



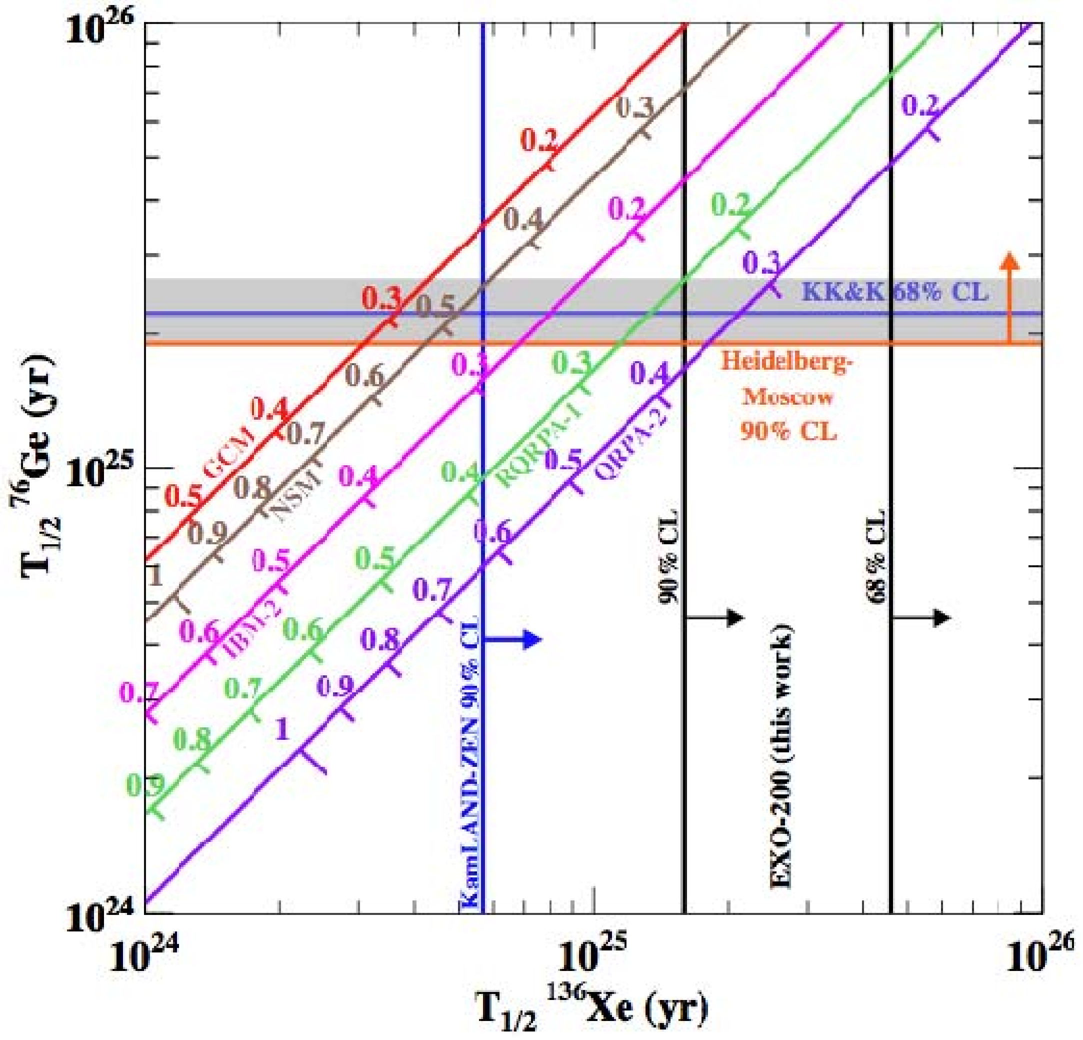
EXO-200 detector:	JINST 7 (2012) P05010
Characterization of APDs:	NIM A608 68-75 (2009)
Materials screening:	NIM A591, 490-509 (2008)

Background counts in ±1,2 σ   ROI



	Expected events from fit			
	±1 σ		±2 σ	
^{222}Rn in cryostat air-gap	1.9	±0.2	2.9	±0.3
^{238}U in LXe Vessel	0.9	±0.2	1.3	±0.3
^{232}Th in LXe Vessel	0.9	±0.1	2.9	±0.3
^{214}Bi on Cathode	0.2	±0.01	0.3	±0.02
All Others	~0.2		~0.2	
Total	4.1	±0.3	7.5	±0.5
Observed	1		5	
Background index b (kg^{-1}yr^{-1}keV^{-1})	$1.5 \cdot 10^{-3} \pm 0.1$		$1.4 \cdot 10^{-3} \pm 0.1$	

Limits on $T_{1/2}^{0\nu\beta\beta}$ and $\langle m_{\beta\beta}\rangle$



From profile likelihood:

$T_{1/2}^{0\nu\beta\beta} > 1.6 \cdot 10^{25}$ yr

$\langle m_{\beta\beta}\rangle < 140\text{–}380$ meV

(90% C.L.)

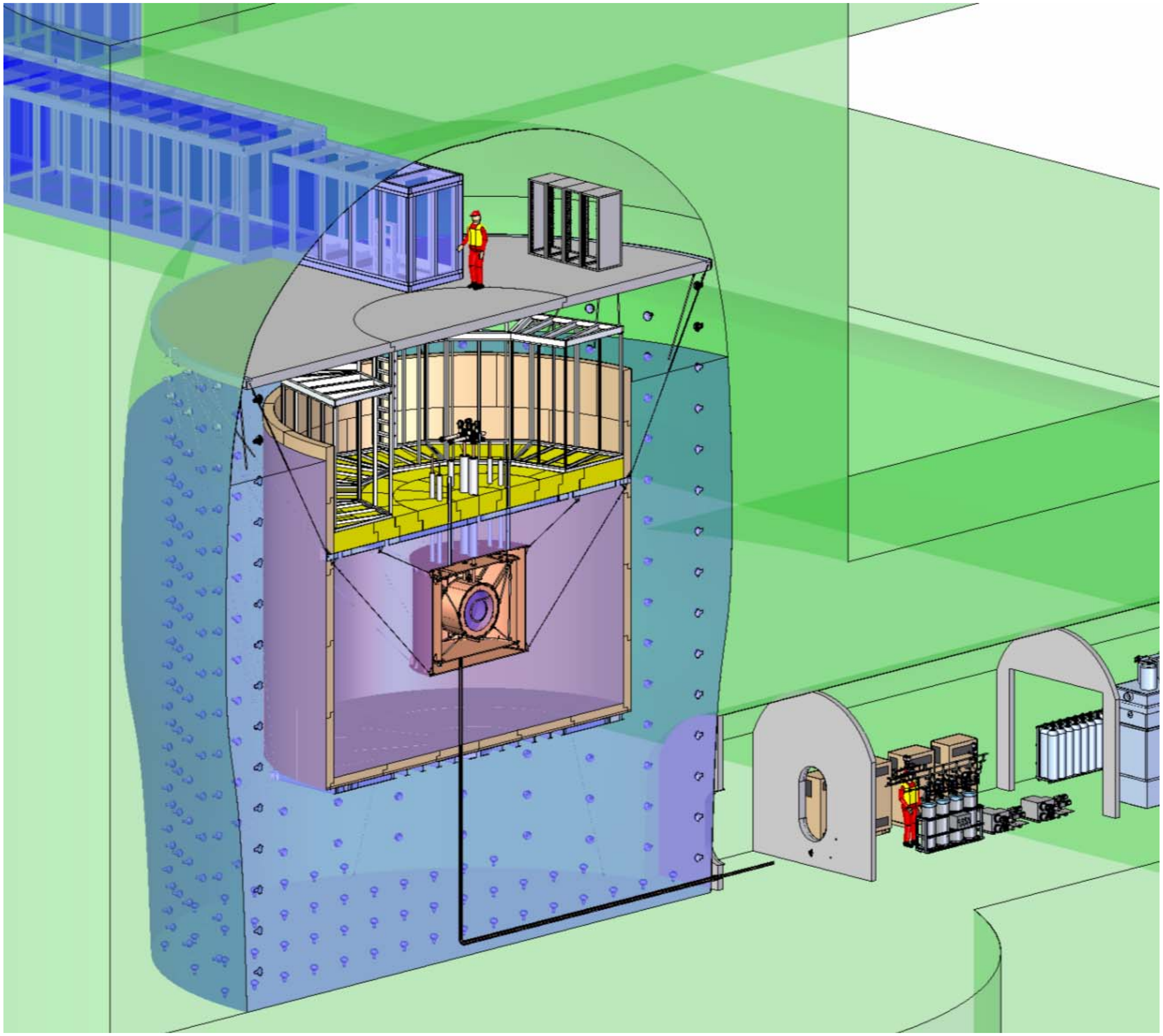
Phys Rev Lett 109 (2012) 032505

➔ A.Pocar talk in parallel session

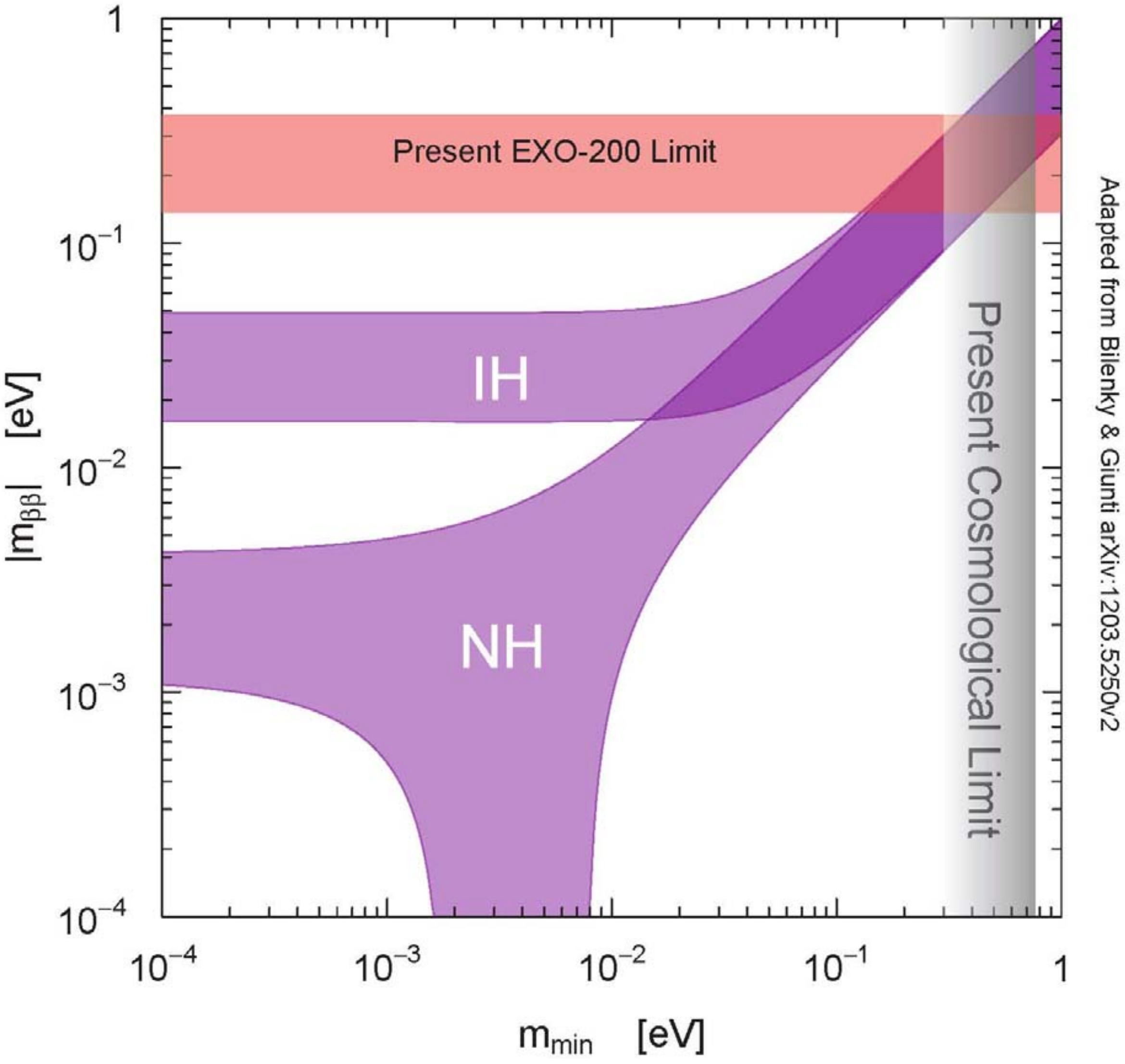
More ideas for the future *(not a complete list!)*

Isotope	Experiment	Main principle	Fid mass	Lab
^{76}Ge	MaGe/GeMa	Best from GERDA and Majorana	~1ton	
^{116}Cd	Cobra	Eres/tracking		Gran Sasso
^{48}Ca	CandlesIII	Size/shielding	0.35 kg	Oto-Cosmo
^{150}Nd	DCBA	Tracking	32 kg	
^{150}Nd ^{82}Se	MOON	Tracking		
^{82}Se	SuperNEMO	Tracking	~100 kg	Modane
	Lucifer	Eres + particle ID		
^{136}Xe	NEXT	Tracking/Eres	100 kg	Canfranc
	nEXO	Ba tag, Tracking/Eres	5 ton	SNOlab

The 5 tonne nEXO detector at SNOlab



EXO-200 and nEXO projected sensitivities



Adapted from Bilenky & Giunti arXiv:1203.5250v2

Blue bands are 68%CL from oscillation experiments for "Inverted" and "Normal" Hierarchy

The EXO-200 "Present limit" is the 90%CL envelope of Limits (for different NMEs) from PRL 109 (2012) 032505

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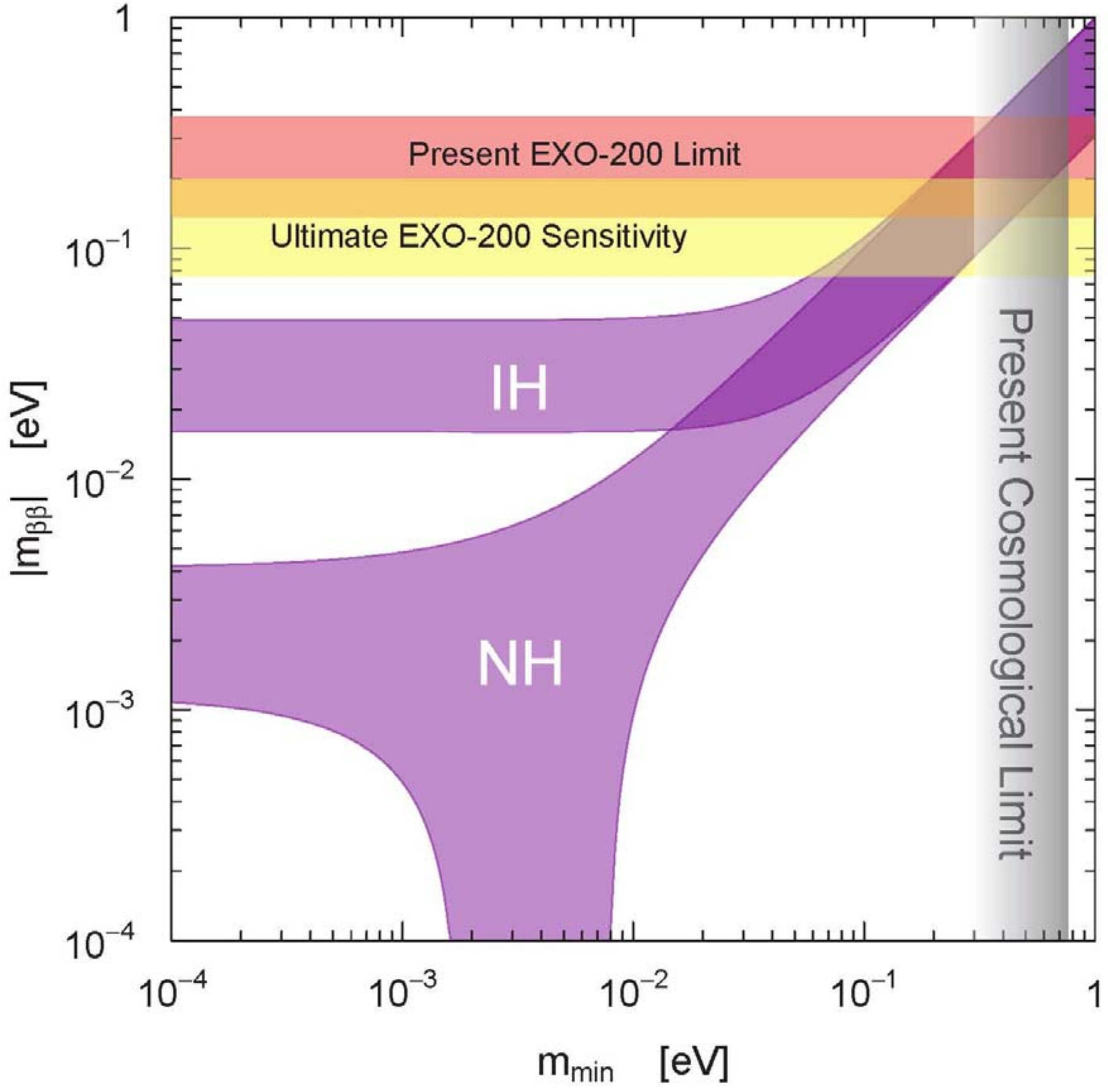

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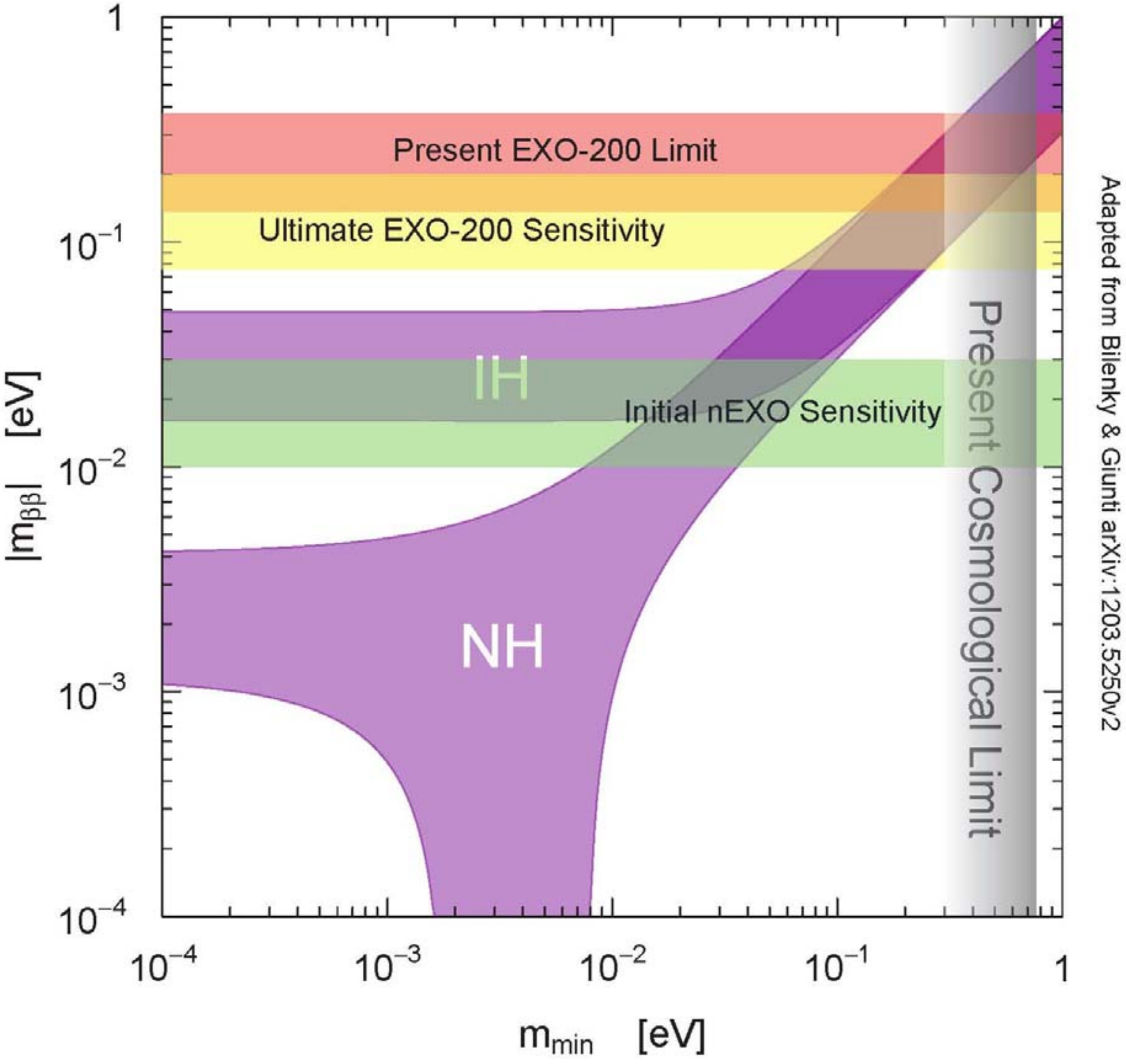

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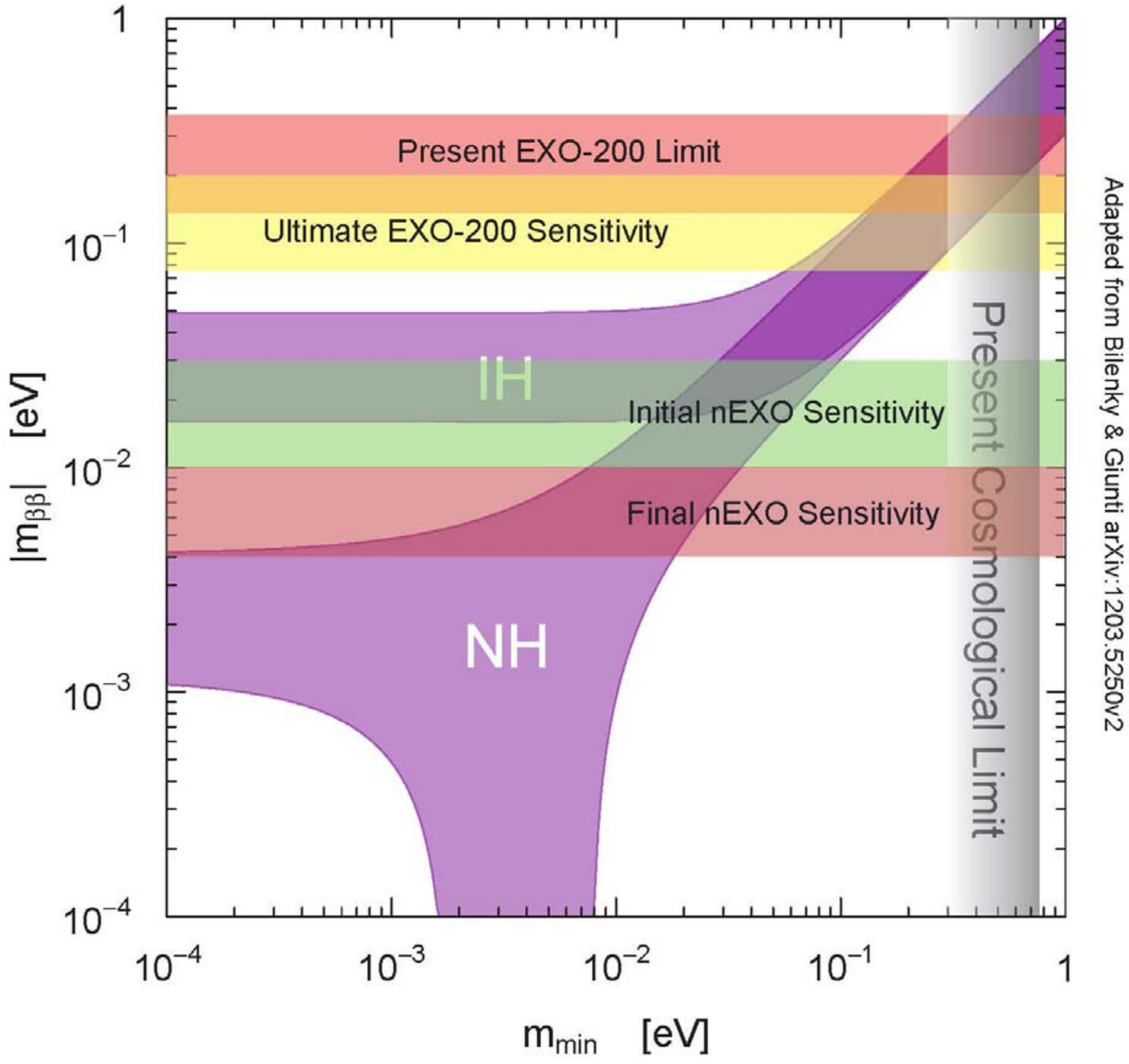
EXO-200 and nEXO projected sensitivities



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The EXO-200 "Ultimate" sensitivity: 90%CL for no signal in 4 yrs livetime with new analysis & Rn removal

The "Initial nEXO" band refers to a detector directly scaled from EXO-200, including its measured background and 10yr livetime.

The "Final nEXO" band refers to the same detector and no background other than 2ν

Conclusions

> *Two nus is good news,*
> *even better will be no nus!*
>
> **R.Blandford (inspired by the EXO-200 2ν measurement)**

Conclusions

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R.Blandford (inspired by the EXO-200 2v measurement)

Exciting time for neutrino physics:

- Neutrino-less double-beta decay
- θ_{13} from reactors
- Hierarchy/CP violation parameters
- Mass measurements from cosmology
- Sterile neutrinos
- Supernova neutrinos

…could all be accessible in the next ~10 years

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Over the years neutrino physics has provided plenty of surprises and required forays in many different areas of science and technology

The search for neutrinoless double beta decay really belongs to this tradition!

- **Isotope enrichment on a large scale is a reality**
- **100kg-class experiments have started data taking**
- **ton-class experiments are being planned for the near future using exquisite techniques**

Conclusions

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R.Blandford (inspired by the
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As in the past, neutrinos may surprise us again