Status of 0νββ decay experiments

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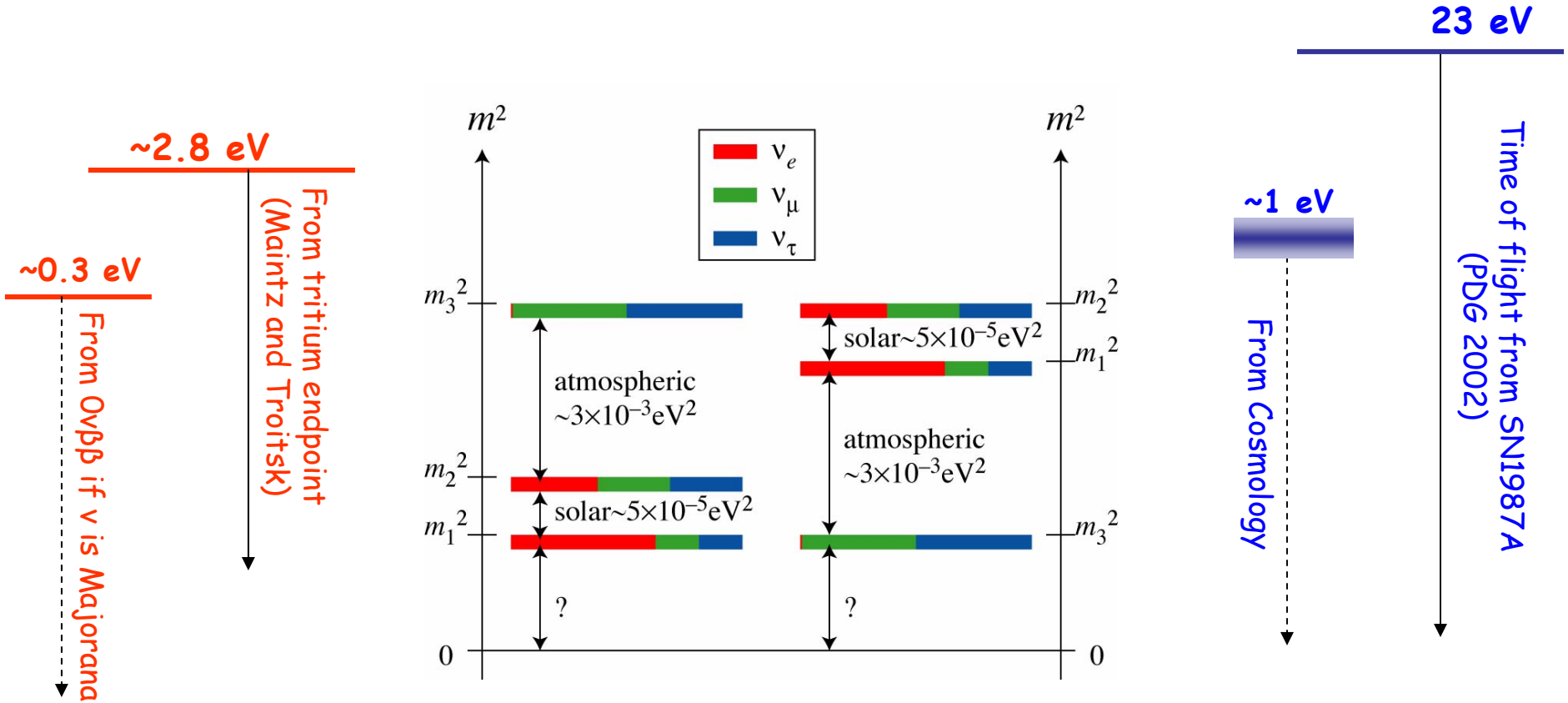
P5, SLAC Feb 21, 2008

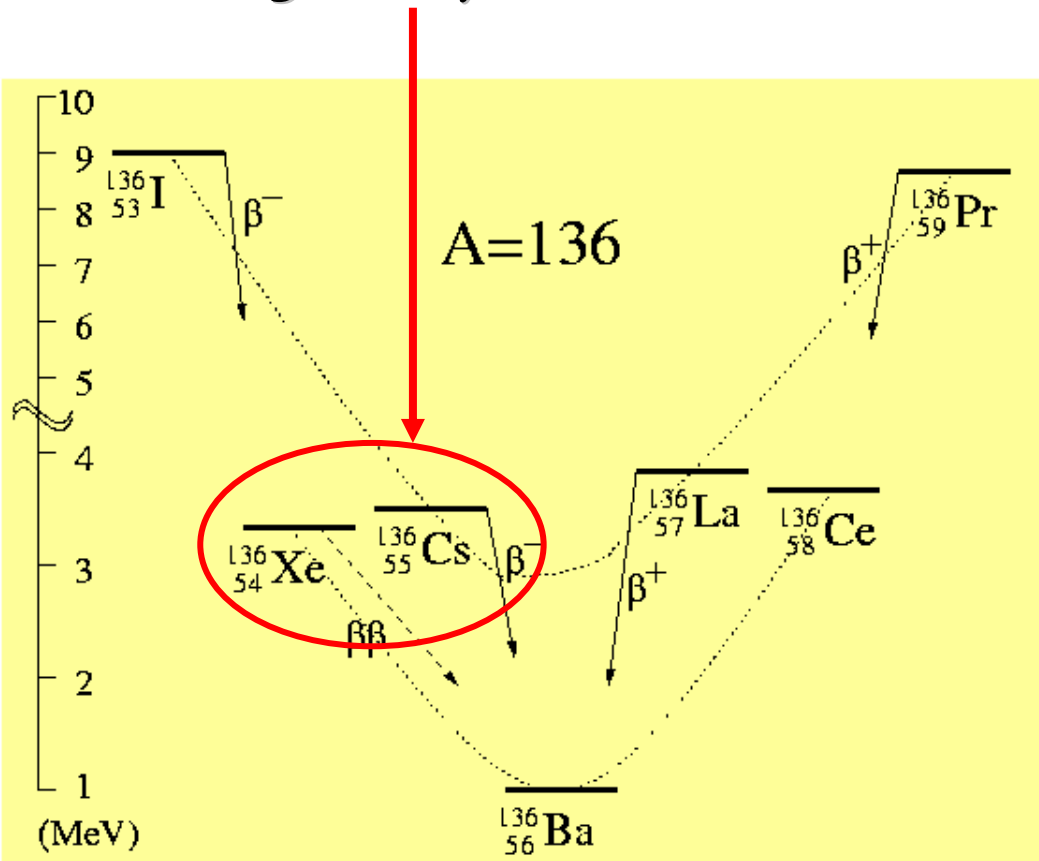
The next crucial measurement in neutrino physics:

Discovery of the neutrino mass scale



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. (%)
$^{48}Ca \rightarrow ^{48}Ti$	4.271	0.187
$^{76}Ge \rightarrow ^{76}Se$	2.040	7.8
$^{82}Se \rightarrow ^{82}Kr$	2.995	9.2
$^{96}Zr \rightarrow ^{96}Mo$	3.350	2.8
$^{100}Mo \rightarrow ^{100}Ru$	3.034	9.6
$^{110}Pd \rightarrow ^{110}Cd$	2.013	11.8
$^{116}Cd \rightarrow ^{116}Sn$	2.802	7.5
$^{124}Sn \rightarrow ^{124}Te$	2.228	5.64
$^{130}Te \rightarrow ^{130}Xe$	2.533	34.5
$^{136}Xe \rightarrow ^{136}Ba$	2.479	8.9
$^{150}Nd \rightarrow ^{150}Sm$	3.367	5.6

There are two varieties of ββ decay

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

0ν mode: a hypothetical process can happen only if:

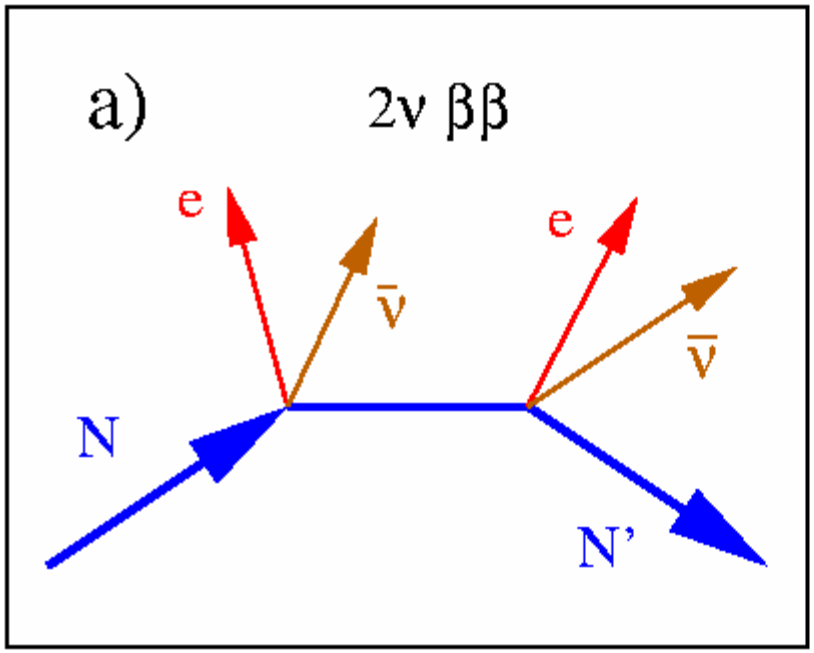
$M_\nu \neq 0$

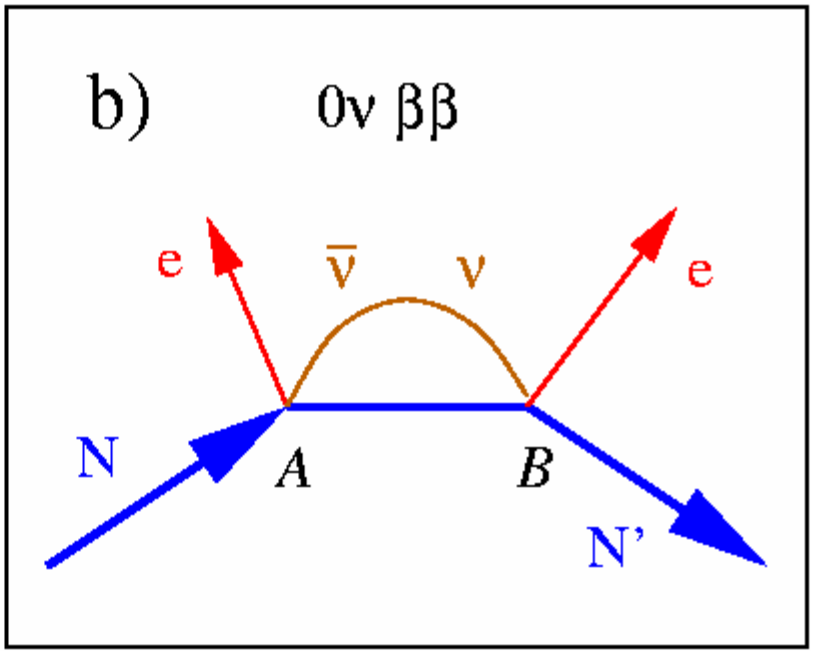
$\nu = \bar{\nu}$

$|\Delta L| = 2$

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

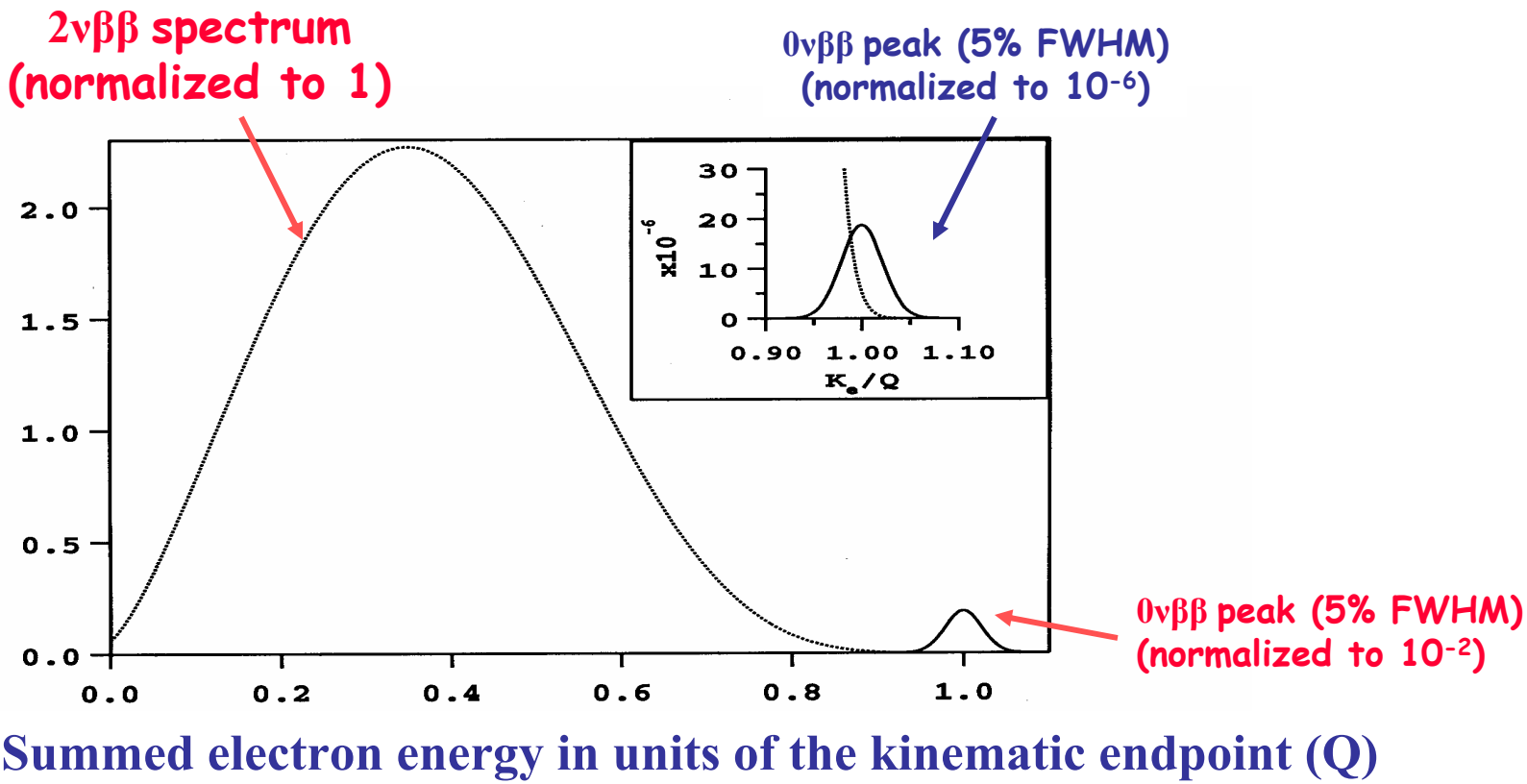
Since helicity has to "flip"





Background due to the Standard Model 2νββ decay

from S.R. Elliott and P. Vogel, Ann.Rev.Nucl.Part.Sci. **52** (2002) 115.



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

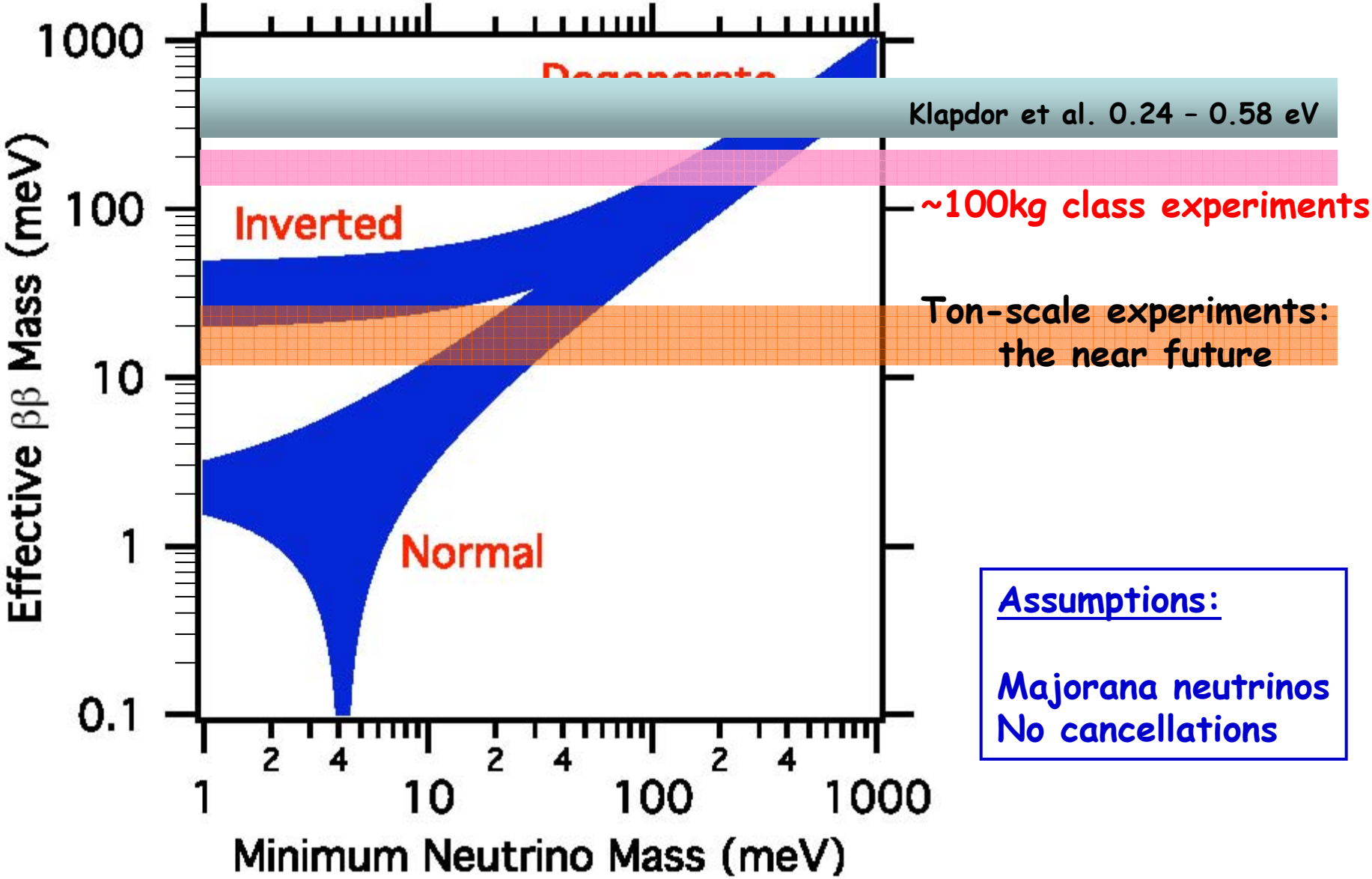
In the last 10 years there has been a transition

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*
→ *Discovery of lepton number violation*

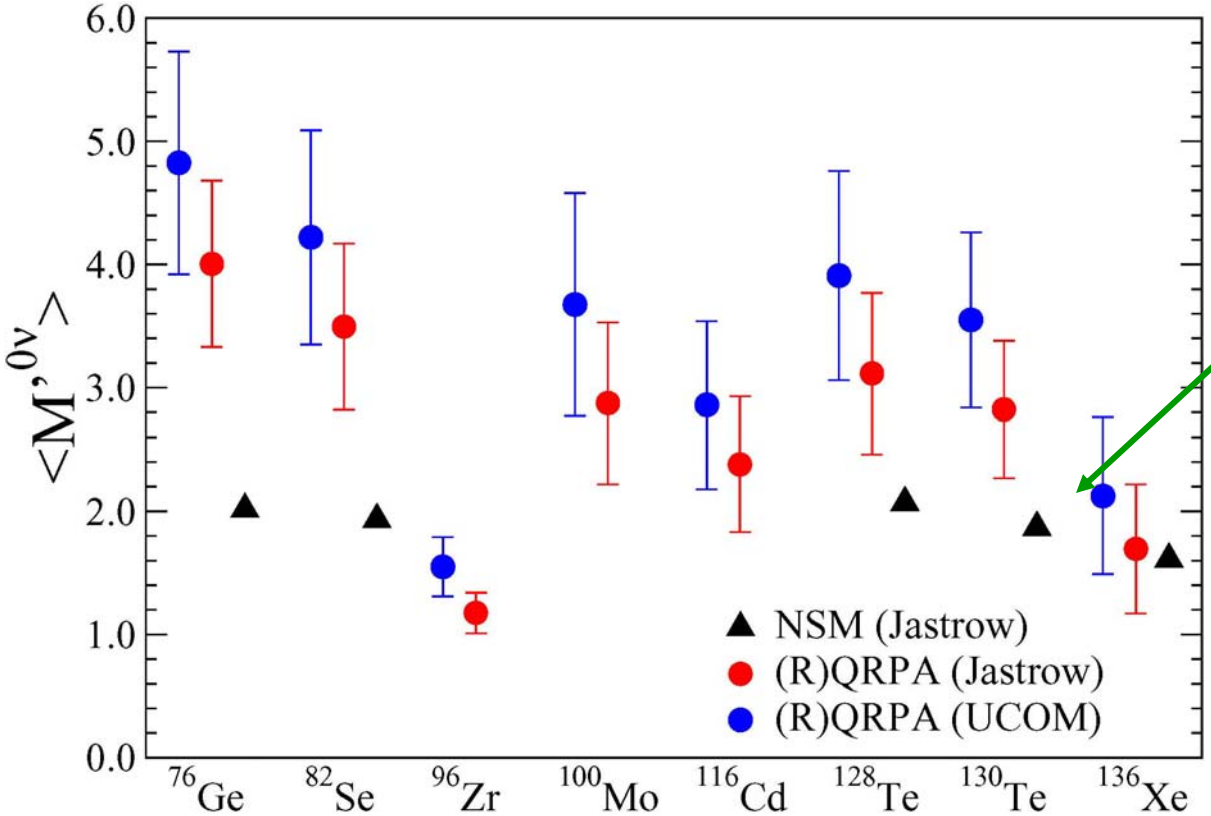


Assumptions:

Majorana neutrinos
No cancellations

Plot from Avignone, Elliott, Engel arXiv:0708.1033 (2007)

Much progress made recently in accuracy of nuclear matrix elements.
(e.g. was found that main uncertainly in (R)QRPA calculations comes from the single particle space around the Fermi surface.
→ Can *use the measured 2νββ $T_{1/2}$ to make a correction.*)



Lower bound on $T_{1/2}$ used for ^{136}Xe

F.Simkovic et al. arXiv:0710.2055

Still, if/once 0νββ decay is discovered, the $T_{1/2}$ in more than one nucleus will be needed to pin down neutrino masses

$\beta\beta$ decay experiments are at the leading edge of "low background" techniques

- 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$\neq$detector
  - + Energy/some tracking available (can distinguish modes)
  - + In principle universal (b)
  - - Many γ backgrounds can fake signature
  - - Exposure is limited by human patience

To reach $\langle m_\nu \rangle$ ~ 10 meV very large fiducial mass (*tons*)

(except for Te) need massive isotopic enrichment

Background suppression requirements exceedingly difficult to meet

these are the lowest background experiment ever built

For no bkgnd $\langle m_\nu \rangle \propto 1/\sqrt{T_{1/2}^{0\nu\beta\beta}} \propto 1/\sqrt{Nt}$

Scaling with bkgd goes like *Nt* $\langle m_\nu \rangle \propto 1/\sqrt{T_{1/2}^{0\nu\beta\beta}} \propto 1/(Nt)^{1/4}$

All this drives the choice for modern experiments to high density and homogeneous detectors

→ *This means tracking ability is limited (but not irrelevant)*

Future experiments (a very broad brush, personal view)

Isotope	Experiment	Main principle	Fid mass	Lab	Main US funding	Lead continent
^{76}Ge	Majorana†	Eres,2site tag, Cu shield	30-60kg	SUSEL	DoE-NP NSF	N America
	Gerda†	Eres,2site tag, LAr shield	34.3 kg	G Sasso		Europe
	MaGe/GeMa	See above	~1ton	DUSEL? GS?	DoE-NP NSF	EU? NAm?
^{150}Nd	SNO+	Size/shielding	56 kg	SNOlab		N America
^{150}Nd or ^{82}Se	SuperNEMO‡	Tracking	100 kg	Canfranc Frejus		Europe
^{130}Te*	CUORE	E Res.	204 kg	G Sasso	DoE-NP NSF	Europe
^{136}Xe	EXO	Tracking	150 kg	WIPP	DoE-HEP	N America
		Ba tag, Track	1-10ton	DUSEL?	DoE-HEP NSF	

Each exp above has a US component and some US funding. Funding source listed only if "major".
Experiments in red are US led.
* No isotopic enrichment in baseline design
† Plan to merge efforts for ton-scale experiment ‡ Non-homogeneous detector

R&D projects

A number of R&D programs towards new detector types and ideas is also an important component of the program (and, until detectors are designed, costs little money:

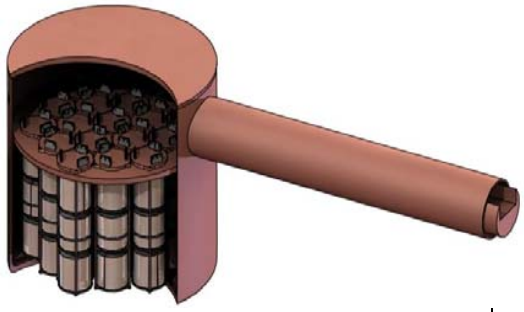
Moon (^{100}Mo)
Cobra (mainly ^{130}Te)
Candles (^{48}Ca)
……

Continuing support to improve the calculations of Matrix Elements is very important

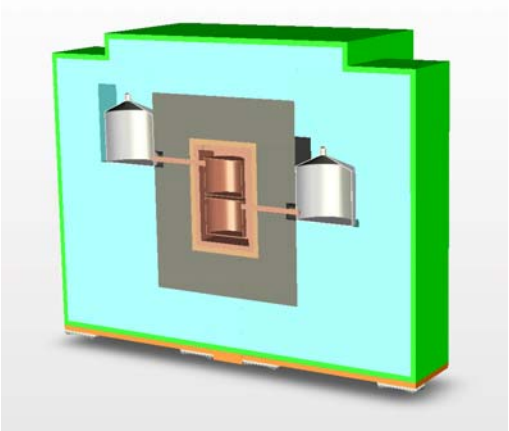
The MAJORANA Demonstrator Module

^{76}Ge offers an excellent combination of capabilities & sensitivities

Excellent energy resolution, intrinsically clean detectors, commercial technologies, best 0νββ sensitivity to date



- **60-kg of Ge detectors**
  - 30-kg of 86% enriched ^{76}Ge crystals required for science goal; 60-kg for background sensitivity
  - Examine detector technology options p- and n-type, segmentation, point-contact.
- **Low-background Cryostats & Shield**
  - ultra-clean, electroformed Cu
  - naturally scalable
  - Compact low-background passive Cu and Pb shield with active muon veto

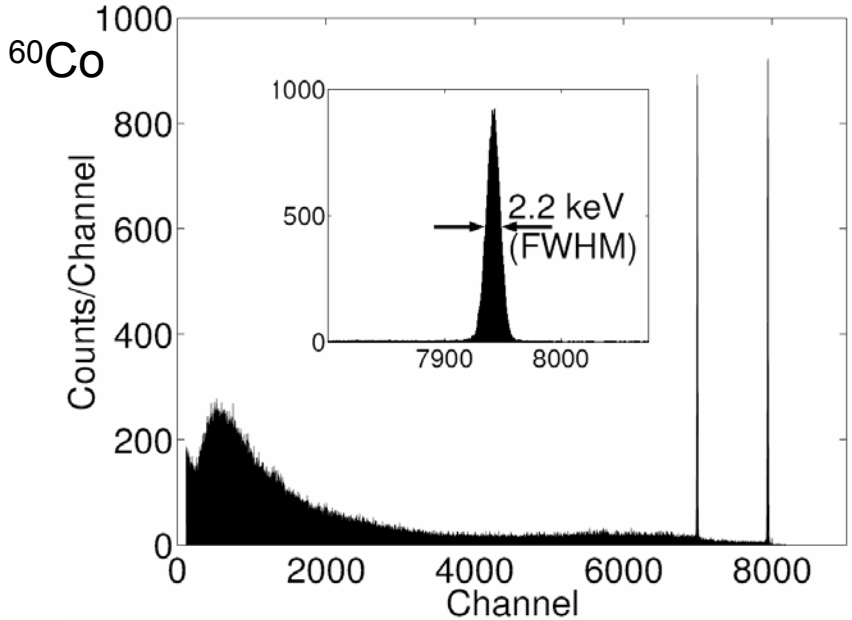


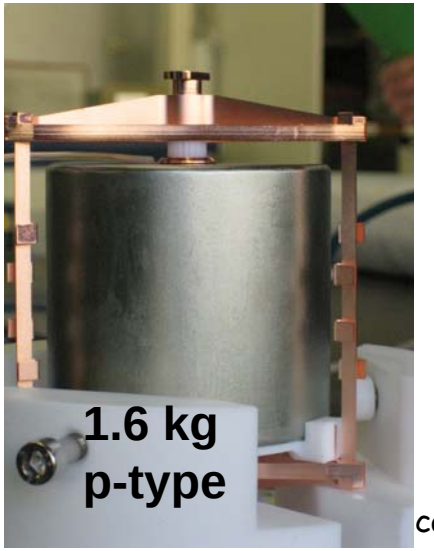
- **Located underground 4850' level at SUSEL/DUSEL**
- **Background Goal** in the 0νββ peak region of interest (4 keV at 2039 keV) ~ 1 count/ROI/t-y (after analysis cuts)

MAJORANA technical progress - past year

- *Materials & Assay* - Samples of low-activity plastics and cables have been obtained for radiometric counting and neutron activation analysis. Additional improvements have been gained in producing pure Cu through electroforming at PNNL and we have established an operating pilot program demonstrating electroforming underground at WIPP.
- *Ge Enrichment* - Options available for germanium oxide reduction, Ge refinement, and efficient material recycling are being considered, including developing this capability located near detector fabrication facilities.
- *Detectors* - Additional p-type point contact (PPC) detectors have been ordered, using FY07 DUSEL R&D funds as well as LDRD or institutional funds. Initial data is extremely encouraging. Progress has been made in E-M modeling. A PPC detector has been successfully fabricated at the LBNL Instrument Support Laboratory. Efforts to deploy a prototype low-background N-type segmented contact (NSC) detector using our enriched SEGA crystal are underway. This will allow us to test low-mass deployment hardware and readout concepts while working in conjunction with a detector manufacturer.
- *Cryostat Modules* - A realistic prototype deployment system has been constructed at LANL. First measurements, with one string and a single P-type HPGe detector have been completed.
- *DAQ & Electronics* - Modeling of preamps to optimize noise are being compared to measurements. ORCA support for a TCP-IP based VME crate controller has been completed.
- *Facilities* - Designs for an underground electroforming facility and a detector laboratory located on the 4850' level in the Homestake Mine have been developed in conjunction with SUSEL engineers.
- *Simulations* - Several papers describing background studies have been published and our simulation framework has been submitted for publication.

Bare Ge crystals in LAr





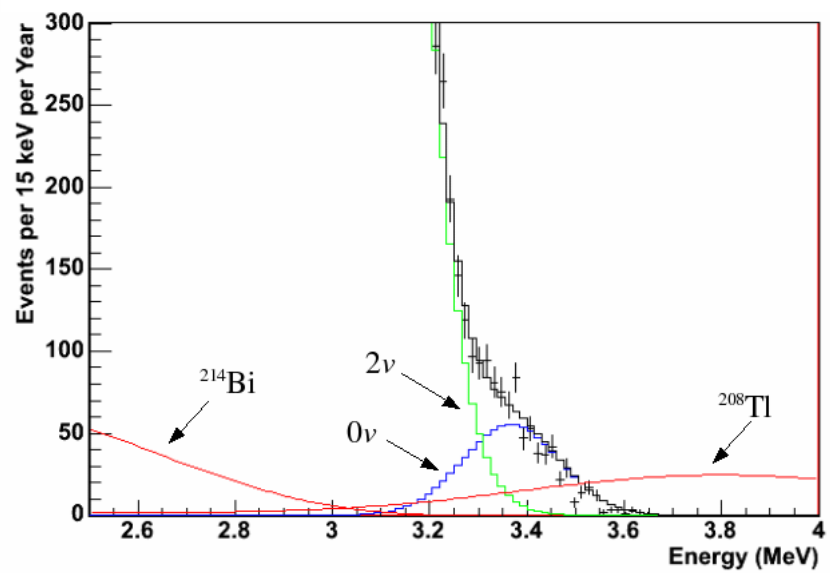
- More than 1 year of operation at low leakage current (LC) in LAr with prototype detector Detector; parameters are not deteriorated (LC: 10 pA→ 10 pA)
- Processing of enriched (HdM&IGEX) / non-enriched Phase I completed until summer '08

- **^{150}Nd double beta decays with an endpoint of 3.37 MeV (above most backgrounds).**
- **Poor energy resolution compensated by**
  - **little material near fiducial volume**
  - **meters of self-shielding**
  - **source in–source out capability**

Simulations with 500kg of ^{150}Nd in SNO+ assuming background levels similar to KamLAND

- **show a 3σ statistical sensitivity of $\langle m_\nu \rangle$ = 30 meV.**
- **preserve sensitivity down to $\langle m_\nu \rangle$ = 50 meV including preliminary studies of energy resolution systematics**

simulation of one year of data testing $\langle m_\nu \rangle$ = *150 meV*



Conceptual SuperNEMO design

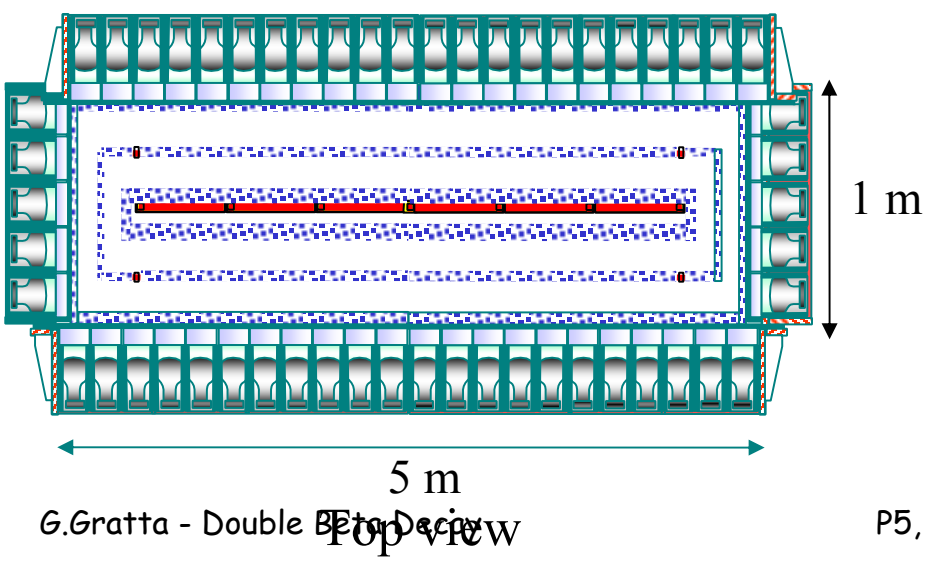
Planar and modular design: ~ 100 kg of enriched isotopes (20 modules × 5 kg)

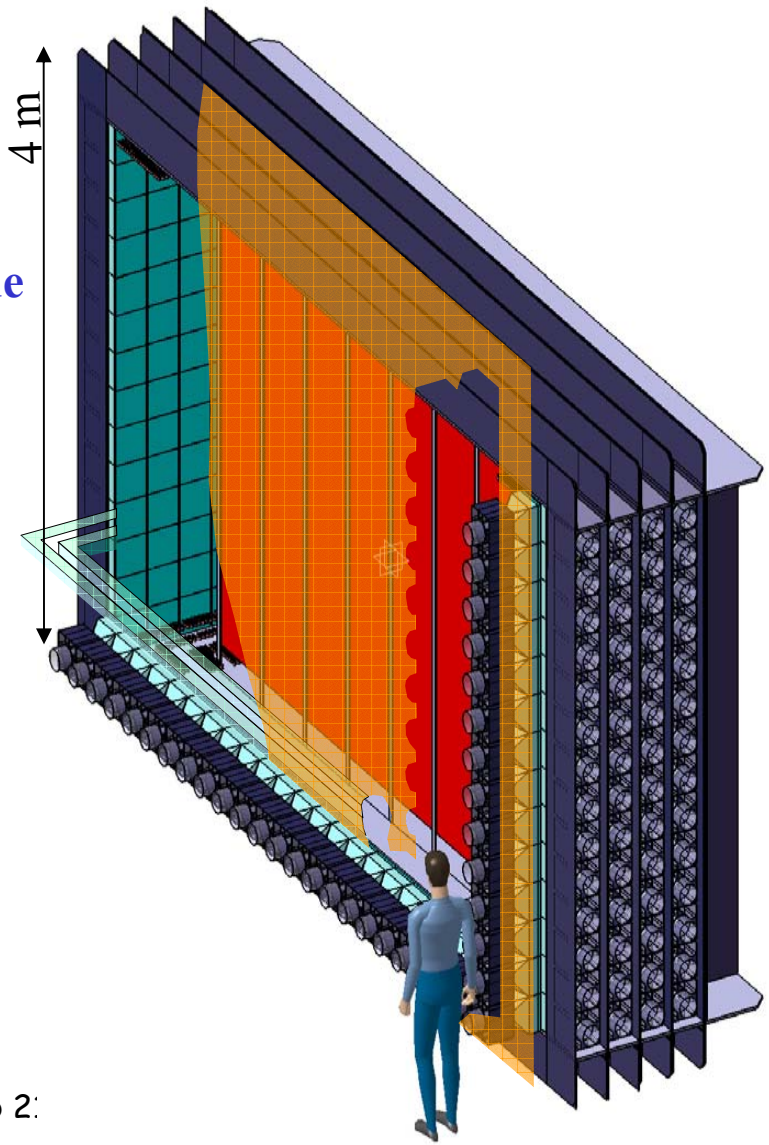
1 module:

Source (40 mg/cm^2) 4 x 3 m^2

Tracking : drift chamber ~3000 cells in Geiger mode

Calorimeter: scintillators + PM
~1 000 PM if scint. blocks
~ 100 PM if scint. bars





The CUORE Experiment

TeO crystals

- The small temperature rise induced by the energy deposited by a single particle in a crystal is measured by neutron transmutation doped thermistors.
- The background level in the region of interest is expected to be about 0.01 counts/keV/kg/year.

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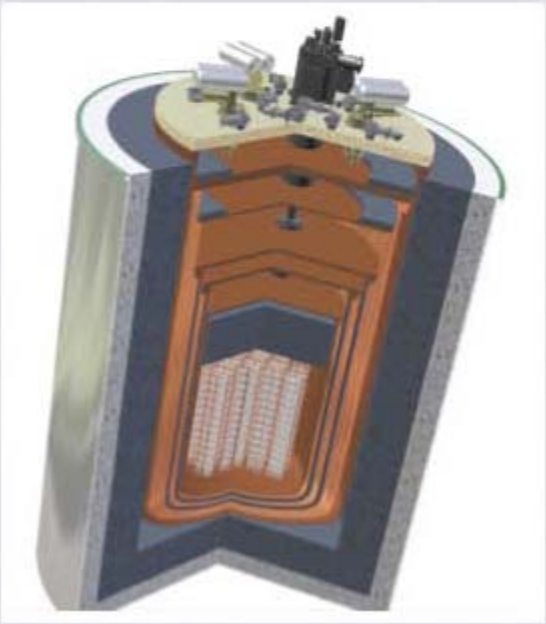
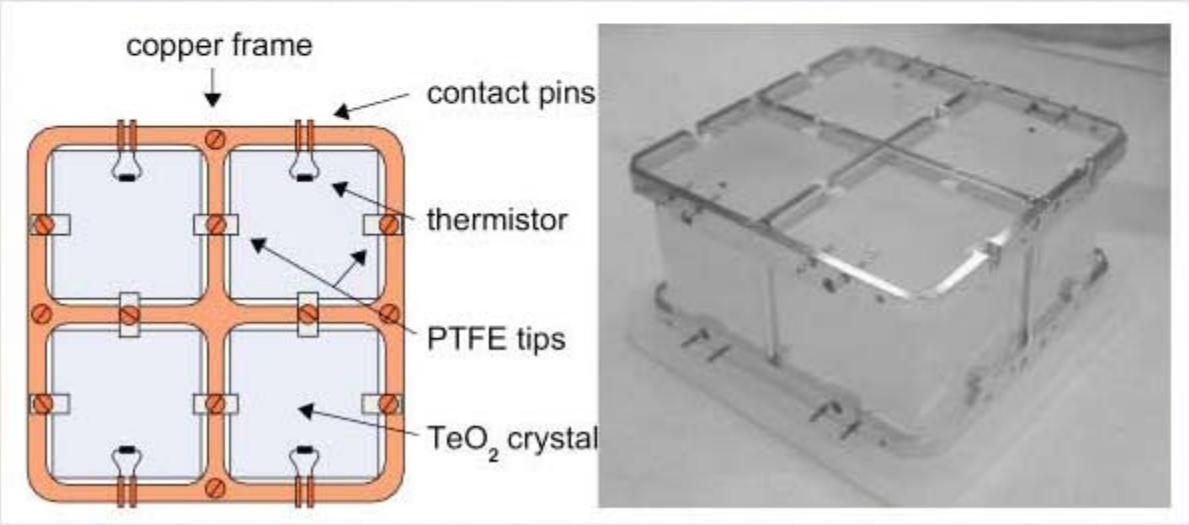




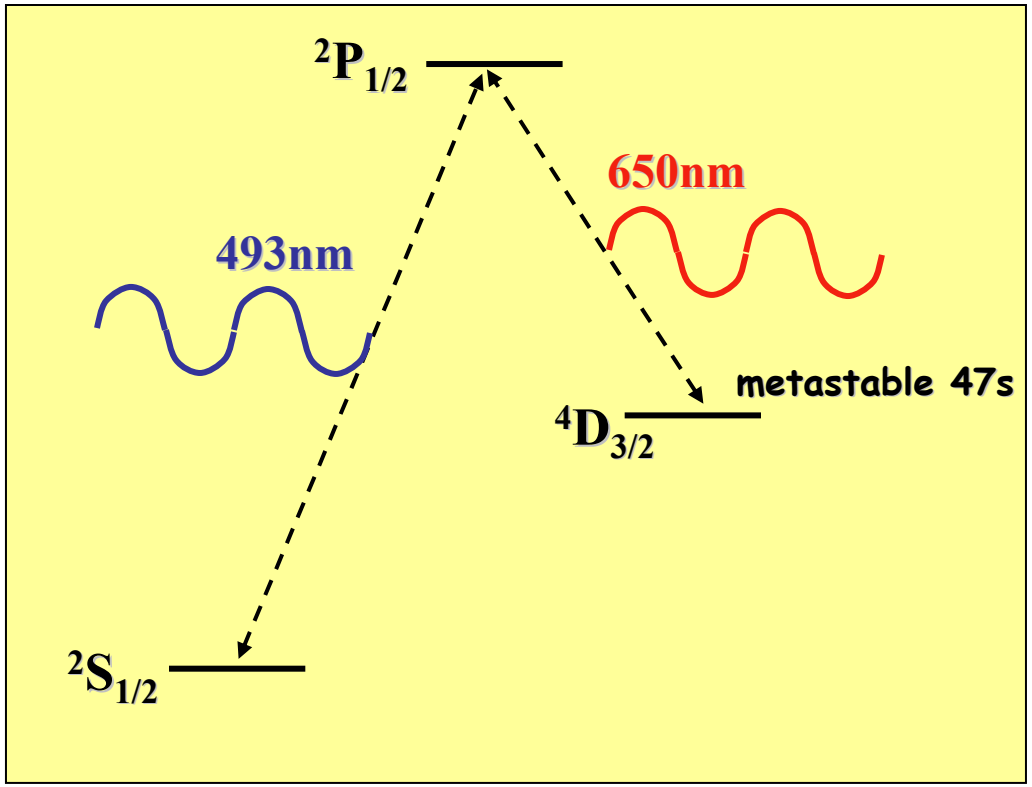
Xe is ideal for a large experiment

- No need to grow crystals
- Can be re-purified during the experiment
- No long lived Xe isotopes to activate
- Can be easily transferred from one detector to another if new technologies become available
- Noble gas: easy(er) to purify
- ^{136}Xe enrichment easier and safer:
  - noble gas (no chemistry involved)
  - centrifuge feed rate in gram/s, all mass useful
  - centrifuge efficiency ~ Δm. For Xe 4.7 amu
- ^{129}Xe is a hyperpolarizable nucleus, under study for NMR tomography… a joint enrichment program ?

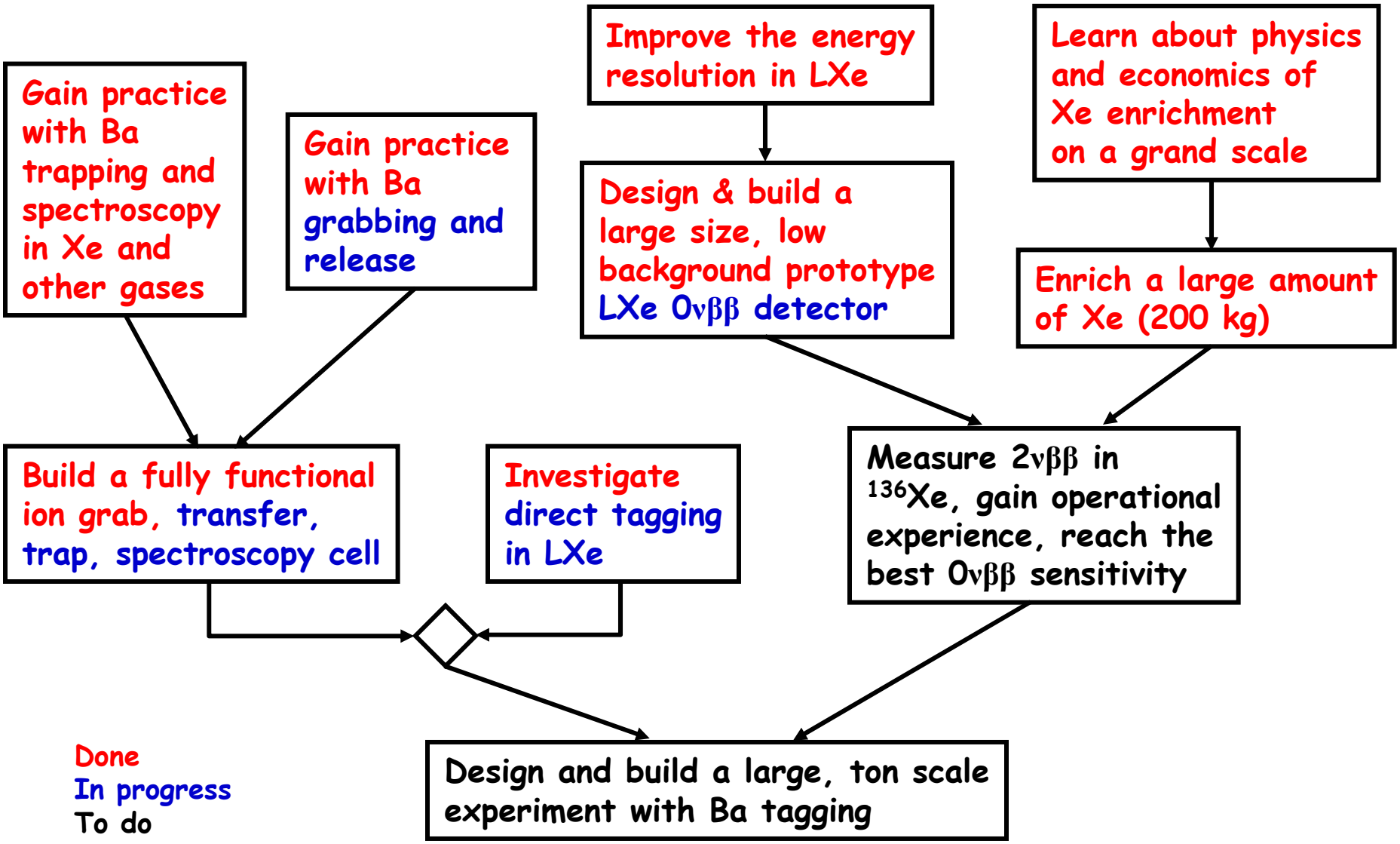
Xe offers a qualitatively new tool against background: $^{136}Xe \rightarrow {}^{136}Ba^{++}\, e^-\, e^-$ final state can be identified using optical spectroscopy (M.Moe PRC44 (1991) 931)

Ba^+ system best studied (Neuhauser, Hohenstatt, Toshek, Dehmelt 1980)
Very specific signature "shelving"
Single ions can be detected from a photon rate of 10^7/s

- **Important additional constraint**
- **Drastic background reduction**

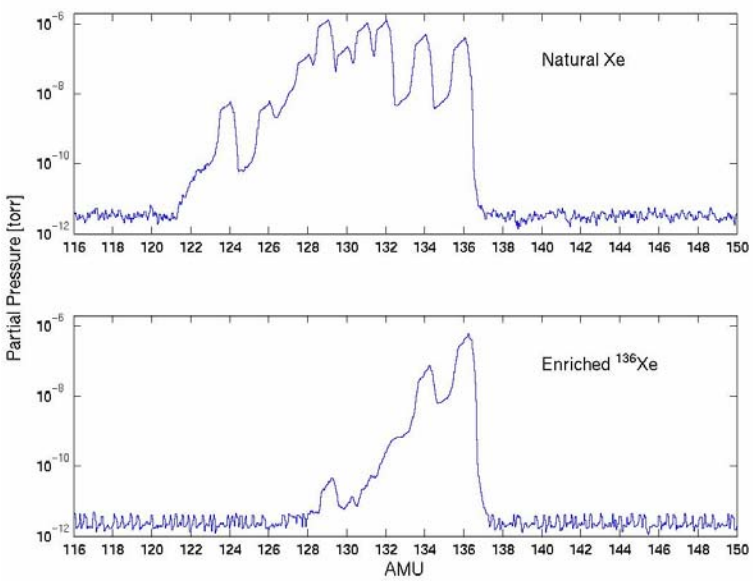


EXO tree of tasks



Done
In progress
To do

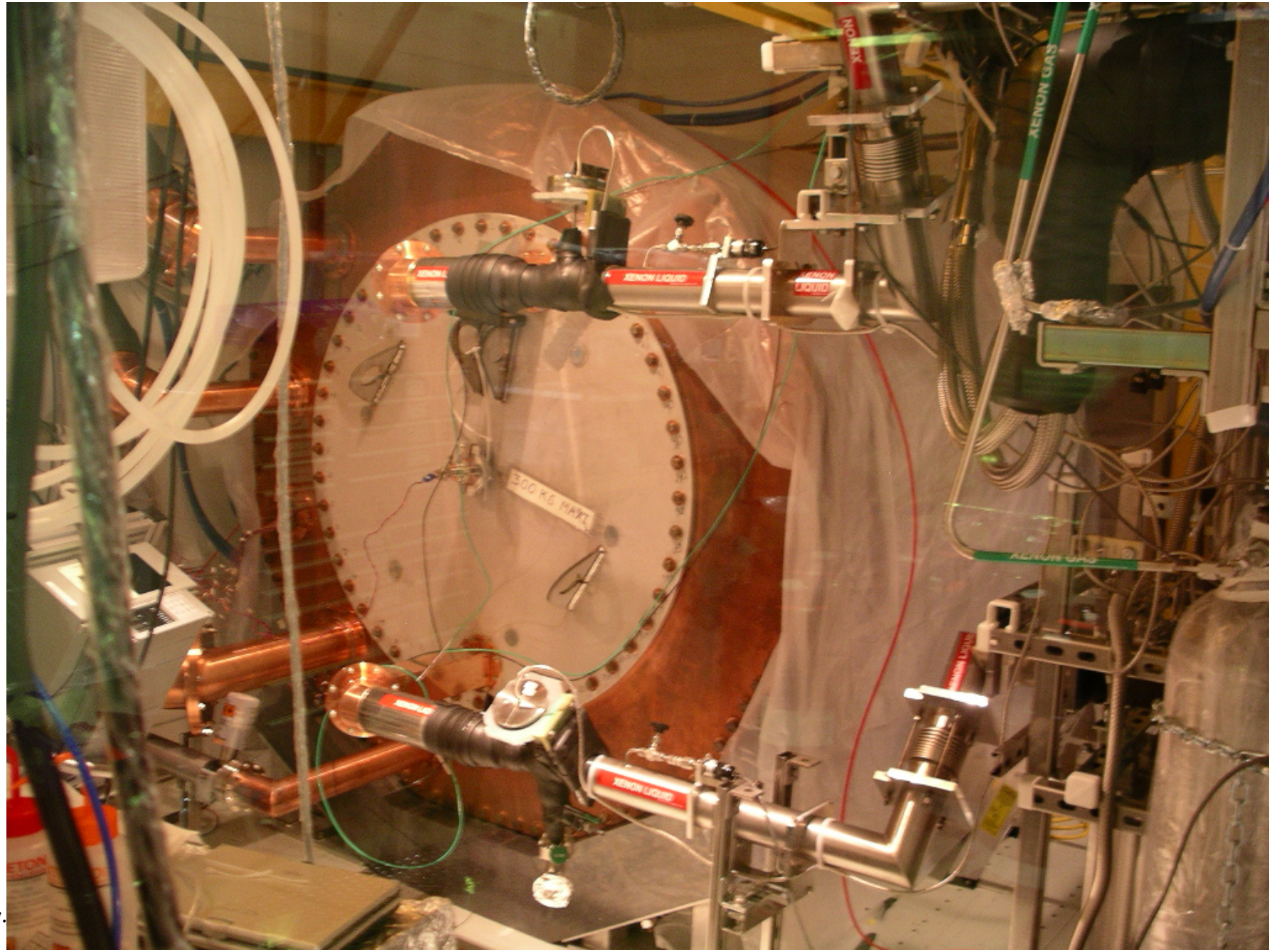
200 kg ^{136}Xe test production completed in spring '03 (80% enrichment)



- Largest highly enriched stockpile not related to nuclear industry
- Largest sample of separated ββ isotope (by ~factor of 10)

Commissioning LXe cryogenics and pressure control at Stanford

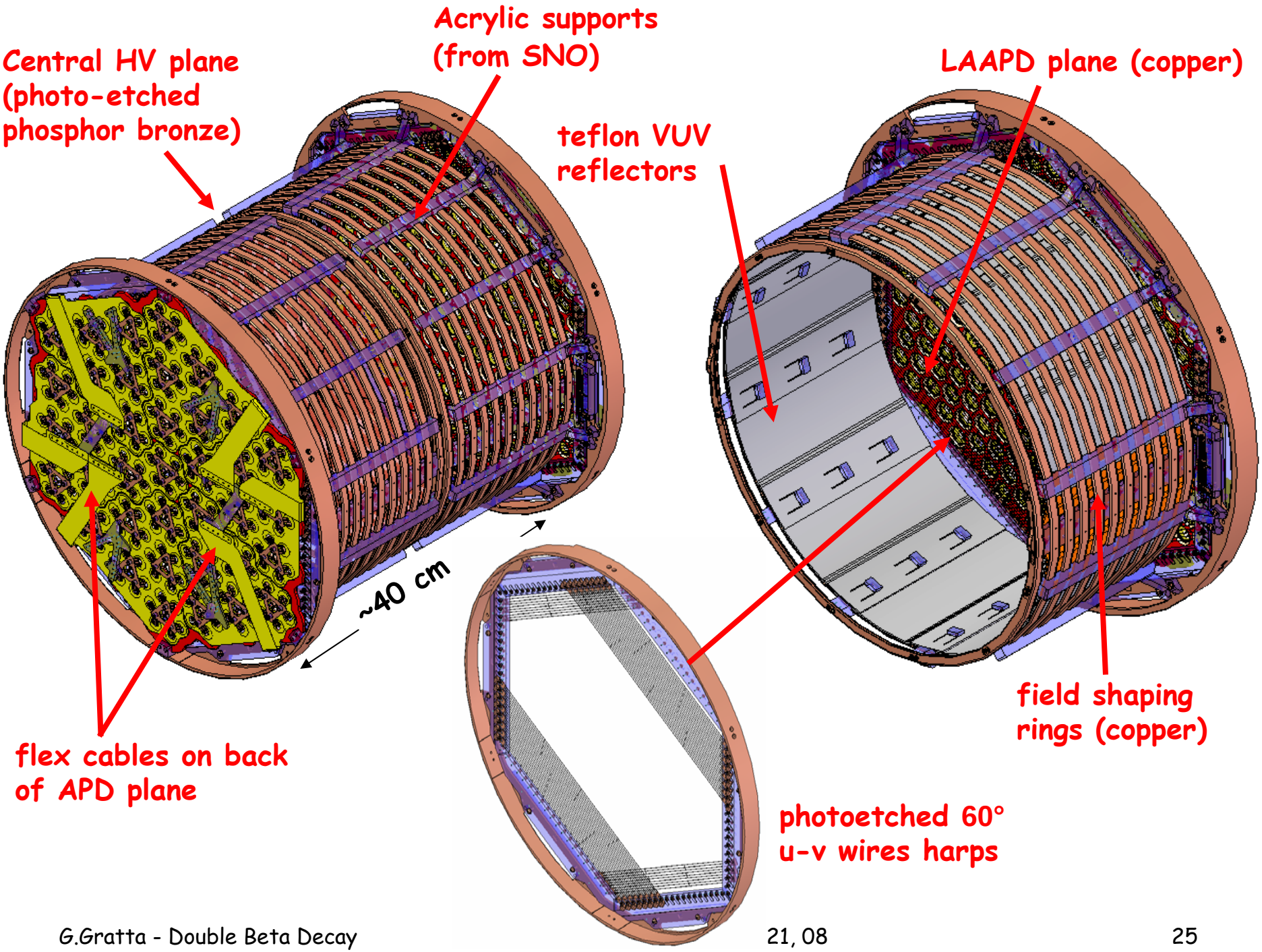
April 2007, ~30kg natural Xe

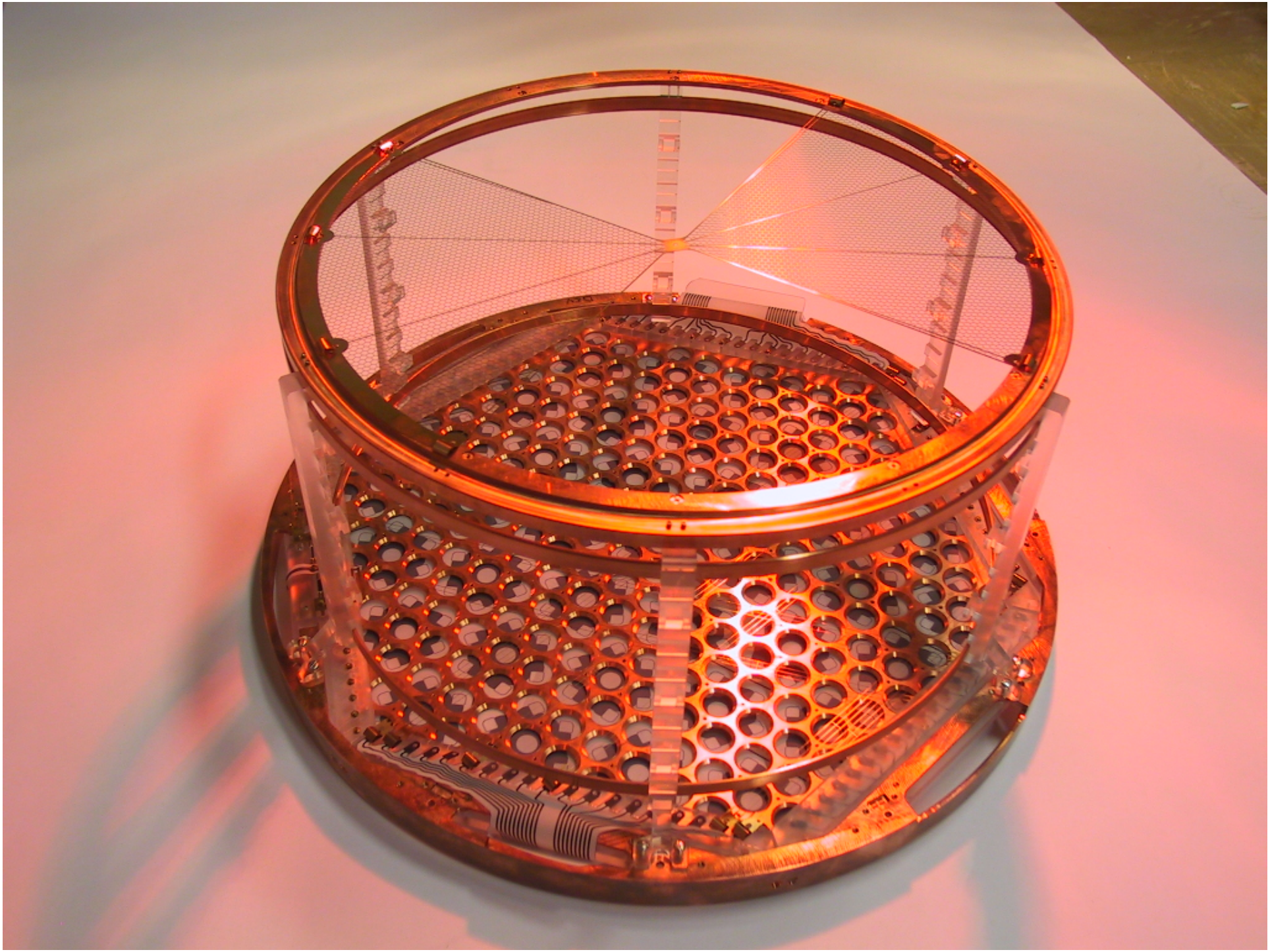


G.

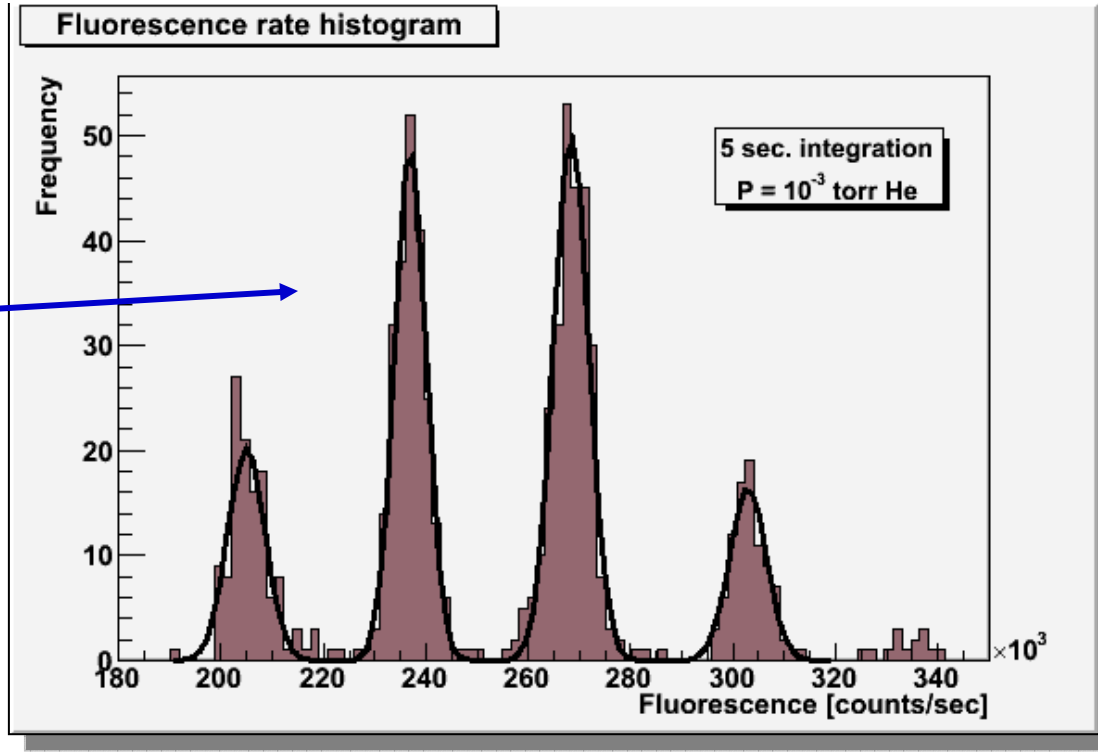
Jul 5, 07, the first EXO200 modules leave Stanford…

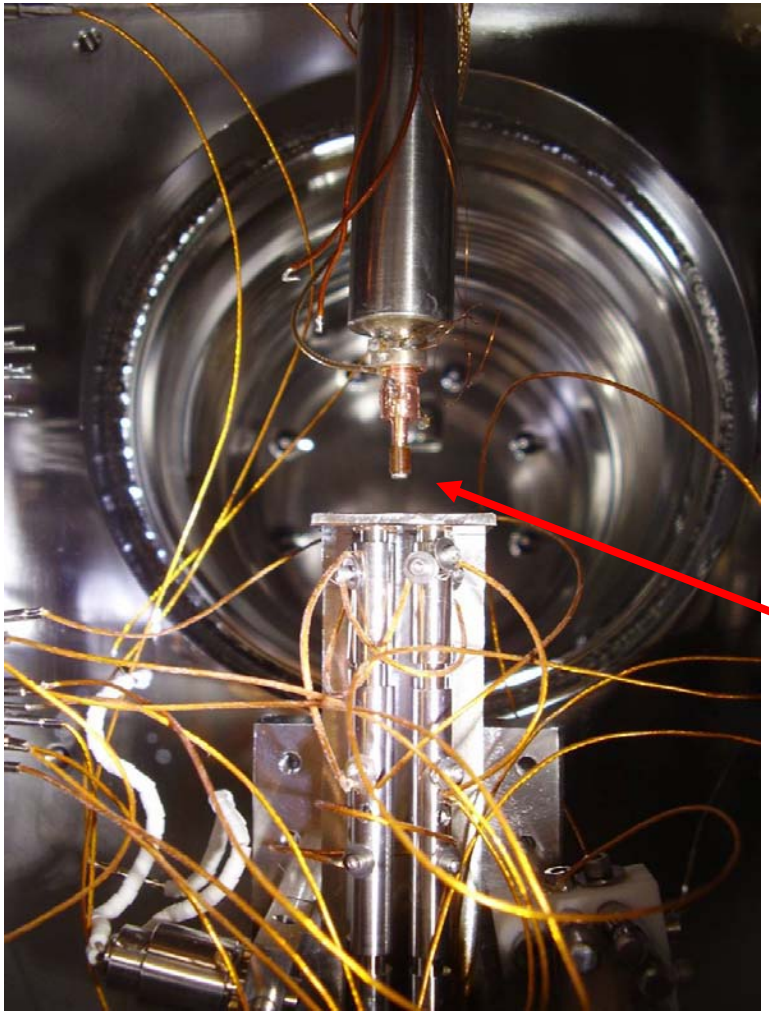
…and are reinstalled in the WIPP underground


Central HV plane
(photo-etched
phosphor bronze)
Acrylic supports
(from SNO)
teflon VUV
reflectors
LAAPD plane (copper)
~40 cm
flex cables on back
of APD plane
field shaping
rings (copper)
photoetched 60°
u-v wires harps



EXO linear trap can see single Ba ions in gas with large S/N ratio





Learning how to transfer single Ba ions from Xe to the ion trap

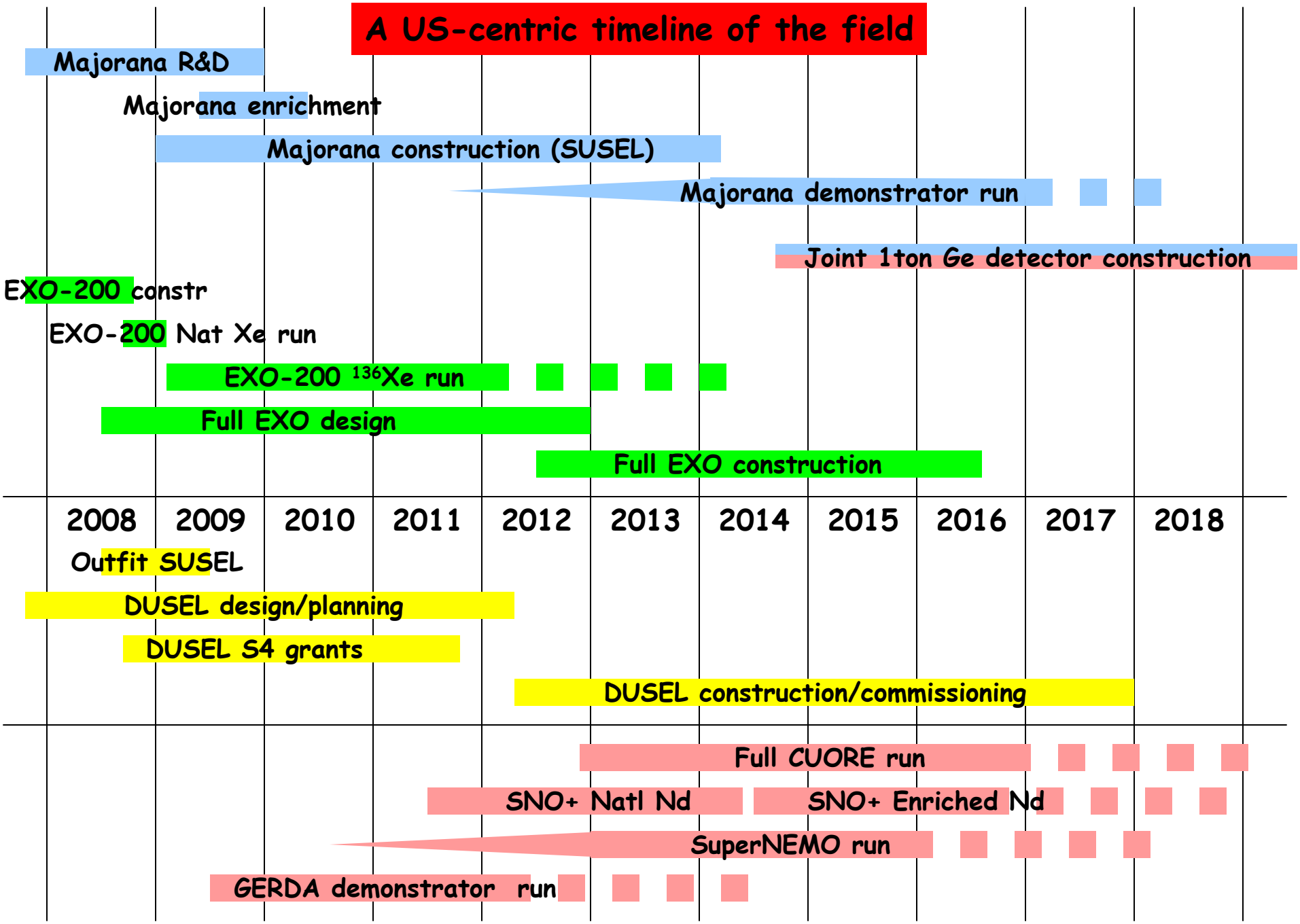
Exceedingly crude budgets

Assume that S4 grants running for 3 years from Fall 08 will support design and costing of first suite of ββ decay experiments at DUSEL

	Scale	M&S (2007 M$)	Enrichment (2007 M$)	Manpower (FTE yrs)
Majorana demonstrator	30+30kg‡	17		65
1ton ^{76}Ge	860kg	165M$†		
Cuore	204kg	9M$ (US contribution)		
EXO*	8000kg	50†	85†	100†

* Running expenses for EXO-200 not included
† Total cost, to be shared with non-US institutions
‡ 30kg enriched + 30kg natural

A US-centric timeline of the field



Conclusions

Very exciting and active field

Results will come in from several experiments in the near and far future

Big potential for a major discovery

ββ-decay in the Nuclear Physics LRP

NSAC Finalized Dec. 2007 http://www.sc.doe.gov/np/nsac/nsac.html

Recommendation III (of four)

We recommend a targeted program of experiments to investigate neutrino properties and fundamental symmetries. These experiments aim to discover the nature of the neutrino, yet unseen violations of time-reversal symmetry, and other key ingredients of the new standard model of fundamental interactions. Construction of a Deep Underground Science and Engineering Laboratory is vital to US leadership in core aspects of this initiative.

A "New Standard Model Initiative" that represents one of the major thrusts in nuclear science for the next decade.

... Two experimental programs having outstanding discovery potential anchor the initiative: ***the search for neutrinoless double beta decay of atomic nuclei*** *and the search for a permanent electric dipole moment of the neutron, neutral atoms, and the electron...*

... In the immediate term, two of the three U.S. 0νββ experiments CUORE, EXO, and MAJORANA, have major nuclear physics involvement.