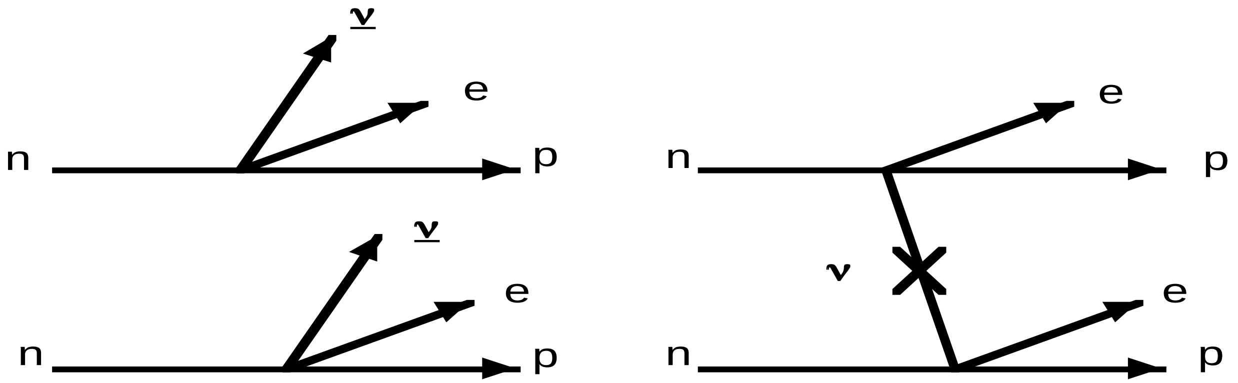
Neutrinoless Double-Beta Decay Experiments

Steve Elliott - Los Alamos Nat. Lab.
“Neutrinos and Implications for Physics
Beyond the Standard Model”
SUNY Stony Brook, Oct. 10-13, 2002

Outline

- What is ββ and why study it?
  - Assumes you heard previous talks.
- General Experimental Issues
- The New Proposals

ββ(2ν) vs. ββ(0ν)



ββ(2ν): Allowed and observed 2nd order weak process.

ββ(0ν): requires massive Majorana neutrinos even in presence of alternative mechanisms.

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ββ Decay Rates

$$\Gamma_{2\nu} = G_{2\nu}\left|M_{2\nu}\right|^2$$

$$\boxed{\Gamma_{0\nu} = G_{0\nu}\left|M_{0\nu}\right|^2 m_\nu^2}$$

G are calculable phase space factors.

$G_{0\nu} \sim Q^5$

|M| are nuclear physics matrix elements.

Hard to calculate.

Present estimate of uncertainty is not well founded.

m_ν is where the interesting physics lies.

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Neutrino Masses

Direct mass and ββ experiments set absolute mass scale.

$$<m_\beta> \quad < 3\ \mathrm{eV}$$

The results of oscillation experiments set the relative mass scale.

Sets m_ν scale > 50 meV

ββ also addresses Dirac/Majorana nature of ν.

3 Complementary Experimental Techniques

	Absolute Mass Scale	Relative Mass Scale	Mixing Matrix Elements	CP nature of ν
ββ	✓			✓
β	✓			
Oscil.		✓	✓	

Need all three types of experiments to fully understand the nature of the ν.

What about mixing, m_ν & ββ(0ν)?

No mixing:

$$\left\langle m_{\beta\beta} \right\rangle = m_{\nu_e} = m_1$$

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

virtual ν exchange

ε = ±1, CP cons.

Compare to β decay result: real ν emission

$$\left\langle m_{\beta} \right\rangle = \sqrt{\sum_{i=1}^{3} \left| U_{ei} \right|^2 m_i^2}$$

An exciting time for ββ!

For at least
one neutrino:

$$m_i > \sqrt{\delta m^2_{atmos}} \approx 50 meV$$

For the next experiments: $\langle m_{\beta\beta} \rangle \leq 50 meV$

**$< m_{\beta\beta} >$ in the range of
10 - 50 meV is very interesting.**

Classes of Background

ββ(2ν) tail

Need good energy resolution.

Natural U, Th in source and shielding

Pure materials, identify ββ daughter, pulse shape, timing, position.

Cosmic ray activation

Store and prepare materials underground.

An Ideal Experiment

Maximize Rate/Minimize Background

$$\left\langle m_{\beta\beta} \right\rangle \propto \left(\frac{b\Delta E}{Mt_{live}} \right)^{\frac{1}{4}}$$

Large Mass (~ 1 ton)

Good source radiopurity

Demonstrated technology

Natural isotope

Small volume, source = detector

Good energy resolution

Ease of operation

Large Q value, fast ββ(0ν)

Slow ββ(2ν) rate

Identify daughter

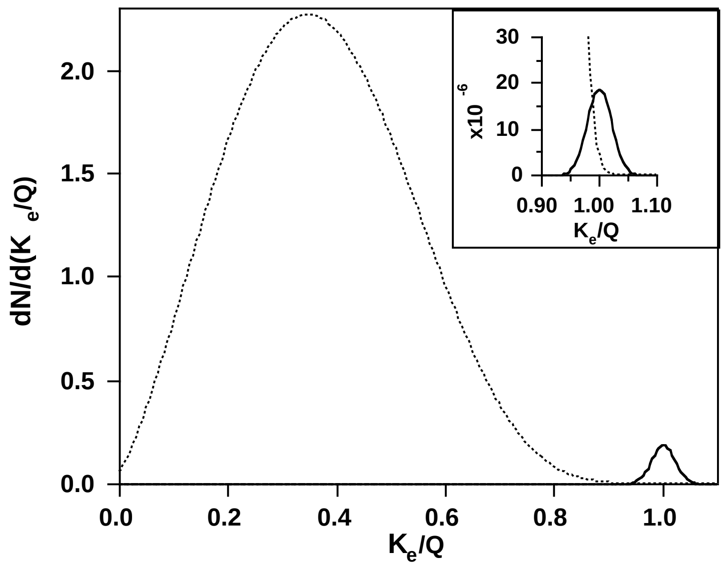
Event reconstruction

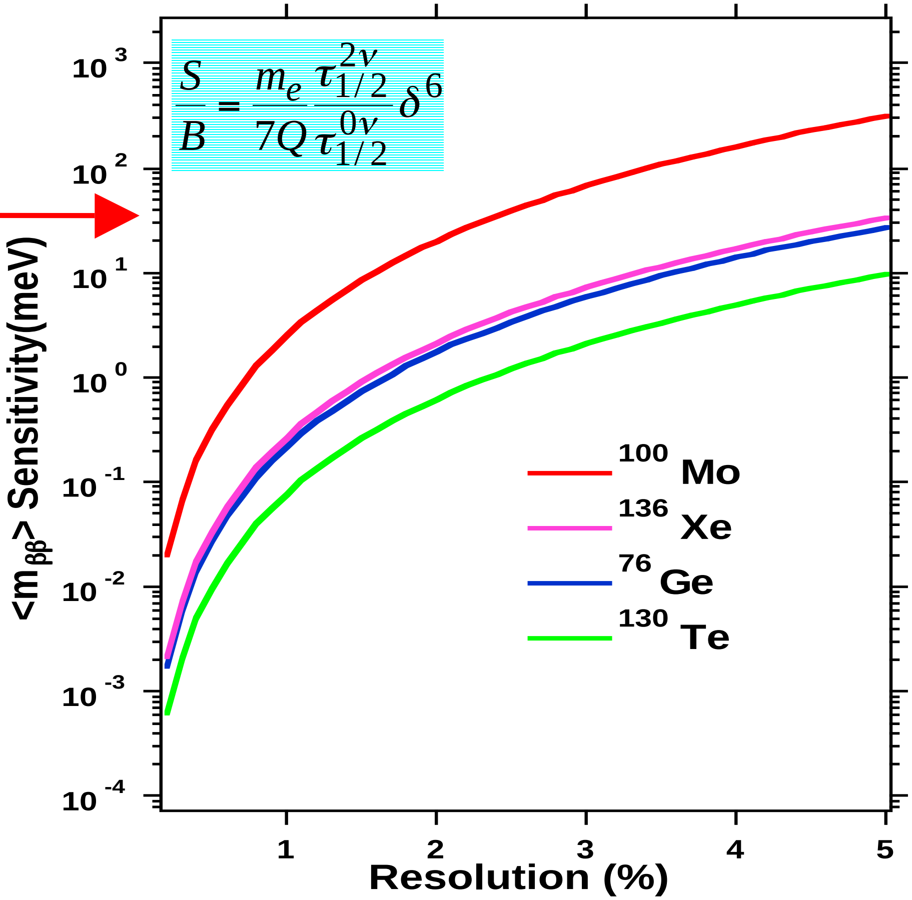
Nuclear theory

ββ(2ν) as a Background.

Sum Energy Cut Only

next generation
experimental
goal





$$\frac{S}{B} = \frac{m_e}{7Q}\frac{\tau_{1/2}^{2\nu}}{\tau_{1/2}^{0\nu}}\delta^6$$

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Natural Activity

The Problem:

τ(U, Th) ~ 10^9 years

Target: $\tau(\beta\beta(0\nu)$ ~ 10^{27} years

Detector

Shielding

Cryostat, or other experimental support

Front End Electronics

etc.

Cosmic Ray Induced Activity

Material dependent.

Need for depth to avoid activation.

Need for storage to allow activation to decay.

A Great Number of Proposed Experiments

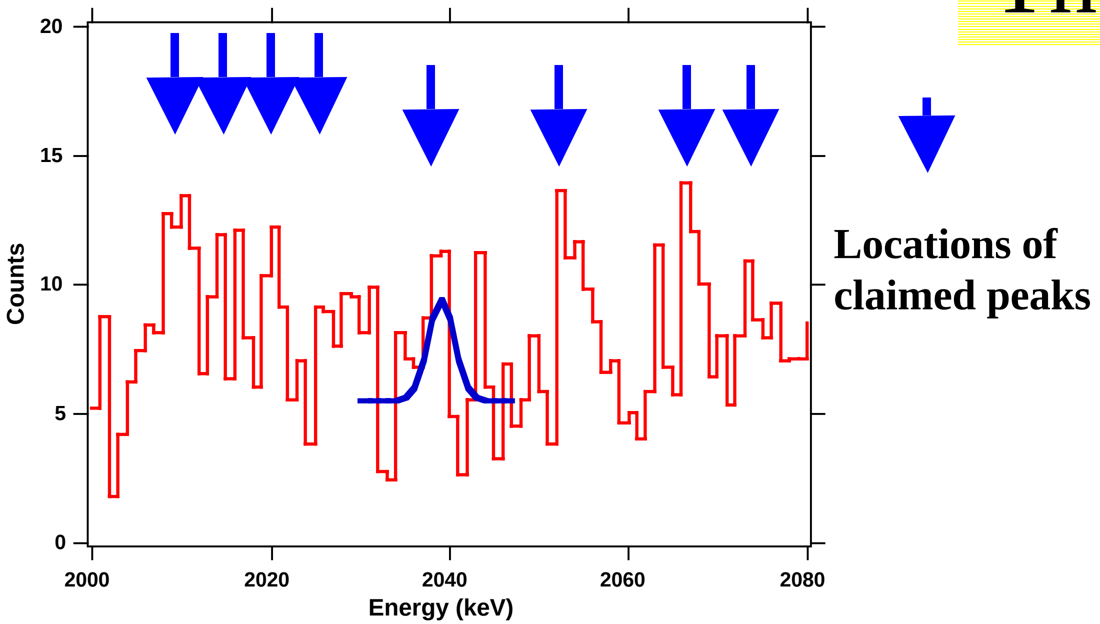
COBRA	Te-130	10 kg CdTe semiconductors
DCBA	Nd-150	20 kg Nd layers between tracking chambers
NEMO	Mo-100, Various	10 kg of ββ isotopes (7 kg of Mo)
CAMEO	Cd-114	1 t $CdWO_4$ crystals
CANDLES	Ca-48	Several tons CaF_2 crystals in liquid scint.
CUORE	Te-130	750 kg TeO_2 bolometers
EXO	Xe-136	1 ton Xe TPC (gas or liquid)
GEM	Ge-76	1 ton Ge diodes in liquid nitrogen
GENIUS	Ge-76	1 ton Ge diodes in liquid nitrogen
GSO	Gd-160	2 t Gd_2SiO_5:Ce crystal scint. in liquid scint.
Majorana	Ge-76	500 kg Ge diodes
MOON	Mo-100	Mo sheets between plastic scint., or liq. scint.
Xe	Xe-136	1.56 t of Xe in liq. Scint.
XMASS	Xe-136	10 t of liquid Xe

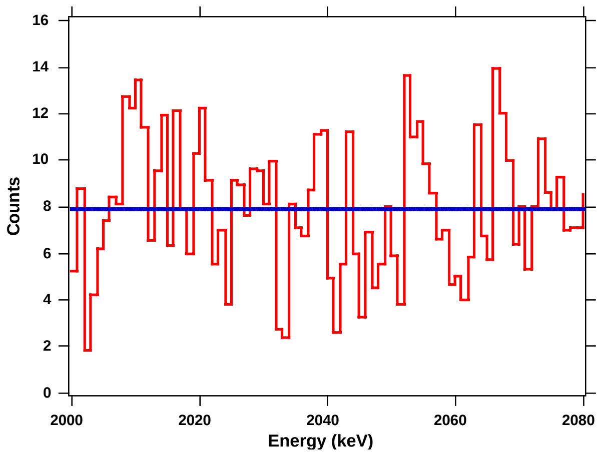
Present Experimental Limits

$$\langle m_{ee} \rangle \propto \left(\frac{1}{|M|\sqrt{G_{0\nu}\tau_{1/2}}} \right)$$

	Half Life	$<m_{ee}>$
Ge (IGEX) NP of RAS 63, 1299 (2000)	160 x 10^{23} y	~330 meV
Ge (Heid-Mosc) Dark Matter 2000	190 x 10^{23} y	~300 meV
Mo (ELEGANTS) NP A611, 85 (1996)	0.52 x 10^{23} y	~6600 meV
Te-130 (Cuoricino) PL B486, 13 (2000)	1.44 x 10^{23} y	~1700 meV
Te-128 (Geochem) PR C47, 806 (1993)	6.9 x 10^{24} y	~1100 meV
Xe (Gotthard) PL **B 434**, 407 (1998)	4.4 x 10^{23} y	~2500 meV

The Controversy.





Mod. Phys. Lett. A16, 2409 (2001)

If one had to summarize the controversy in a short statement:

Consider two extreme background models:

1. **Entirely flat in 2000-2080 keV region.**
2. **Many peaks in larger region, only ββ peak in small region.**

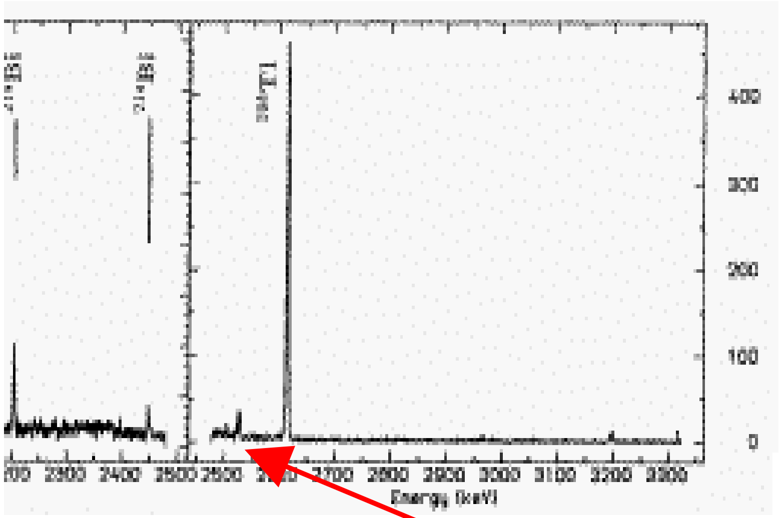
These 2 extremes give very different significances for peak at 2039 keV.

KDHK chose Model 2 but did not consider a systematic uncertainty associated with that choice.

“Found” Peaks:

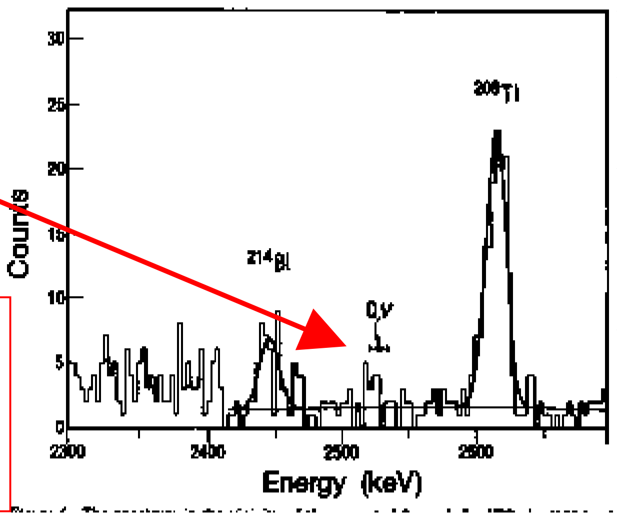
These experiments are hard

PR D45, 2548 (1992)



Need more than one experiment

A 2527-keV Ge-det. peak that was an electronic artifact.



NP B35 (Proc. Supp.), 366 (1994).

A ~2528-keV Te-det. peak that was a 2σ Statisticalflucuation.

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Potential Large-Mass Future Experiments

Experiments in Europe/Japan

CUORE, GENIUS, XMASS

NUSL Candidates

EXO, MAJORANA, MOON

Smaller Mass Experiments Cobra, DCBA, NEMO, CAMEO, CANDLES, GSO

Molybdenum Observatory Of Neutrinos - MOON

U. of Washington

U. of North Carolina

U. of Wisconsin

Research Center for Nuclear Physics, Osaka

Plus others as collaboration is forming.

Spokesperson
Hiro Ejiri
RCNP

MOON Overview

3.3 tons ^{100}Mo, 34 tons Mo

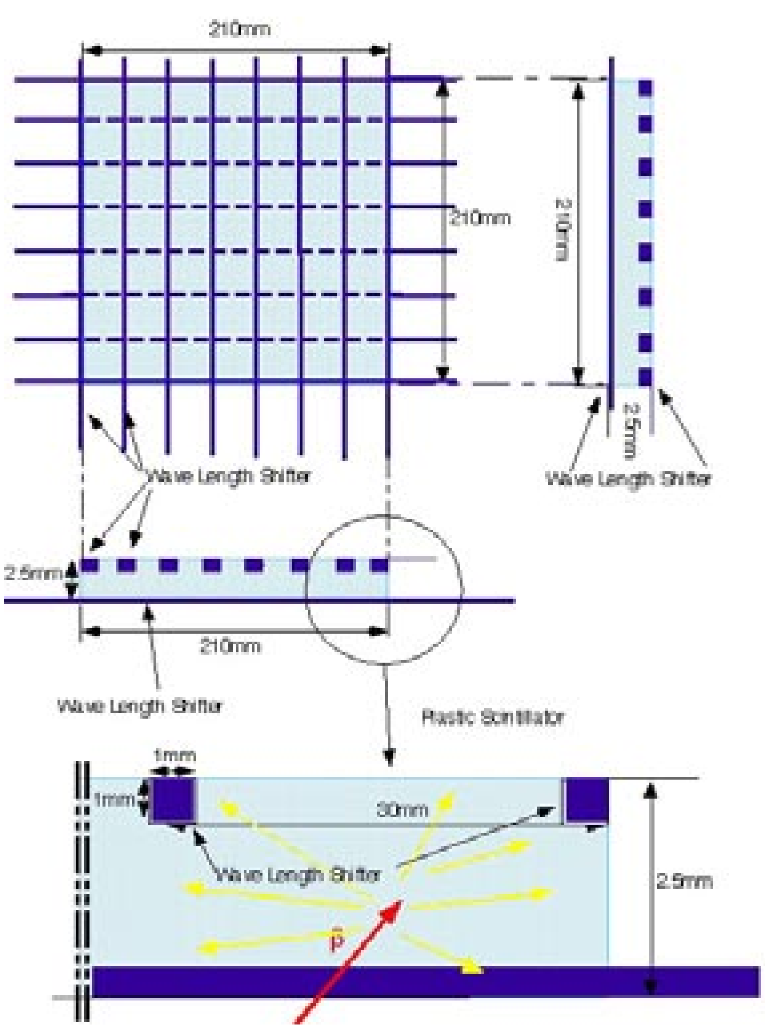
Doesn’t require enriched material (but would want it).

Scintillator/source sandwich

Position and single E_β data play big role in $\beta\beta(2\nu)$ and U, Th rejection.

14% efficiency

ELEGANTS is precursor.



MOON Scintillator

A liquid scintillator option is also being considered.

Cryogenic Underground Observatory for Rare Events - CUORE

Berkeley

Firenze

Gran Sasso

Insubria (COMO)

Leiden

Milano

Neuchatel

U. of South Carolina

Zaragoza

Spokesperson
Ettore Fiorini
Milano

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CUORE Overview

0.21 ton, 34% natural abund. ^{130}Te

TeO_2 bolometers, 750 g crystals

Doesn’t require enriched material.

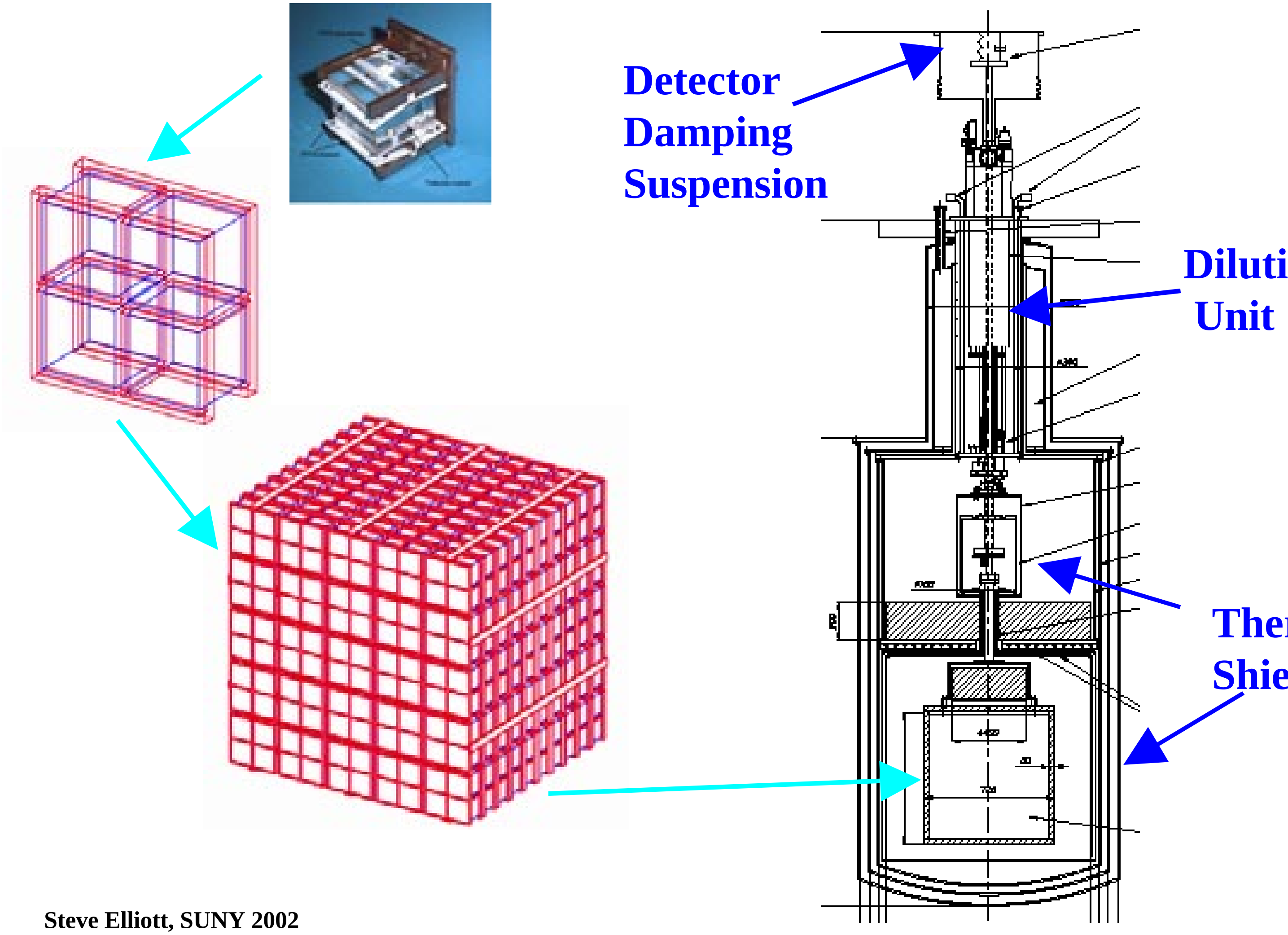
1020 5x5x5 cm^3 crystals

17 towers of 15 modules of 4 crystals

Gran Sasso Laboratory

CUORICINO begins operating this fall (45 kg).

CUORE Detector



Detector Damping Suspension

Dilution Unit

Thermal Shields

Enriched Xenon Observatory - EXO

U. of Alabama
Caltech
IBM Almaden
ITEP Moscow
U. of Neuchatel
INFN Padova
SLAC
Stanford U.
U. of Torino
U. of Trieste
WIPP Carlsbad

Spokesperson
Giorgio Gratta
Stanford

EXO Overview

10 ton, ~70% enriched ^{136}Xe

70% effic., ~10 atm gas TPC or LXe chamber

Optical identification of Ba ion.

 Drift ion in gas to laser path

 or extract on cold probe to trap.

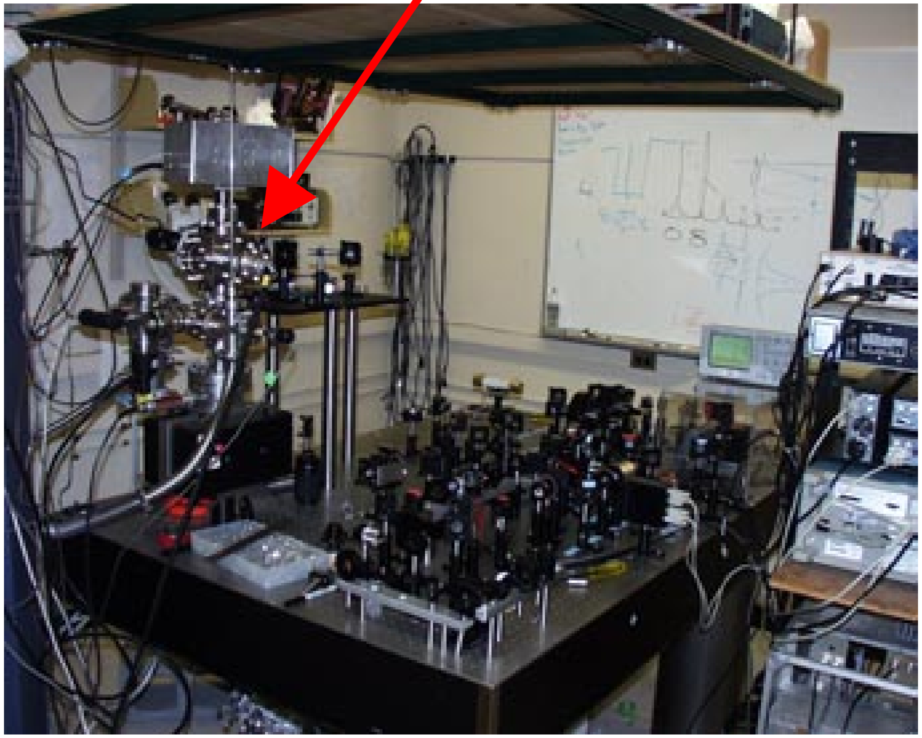
TPC performance similar to that at Gottard.

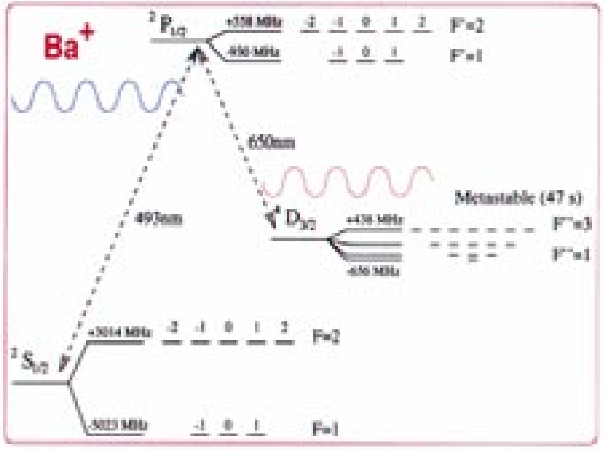
100-kg ^{enr}Xe prototype (no Ba ID)

 Isotope in hand

Stanford Optics Lab with Ba Trap

Ba Trap

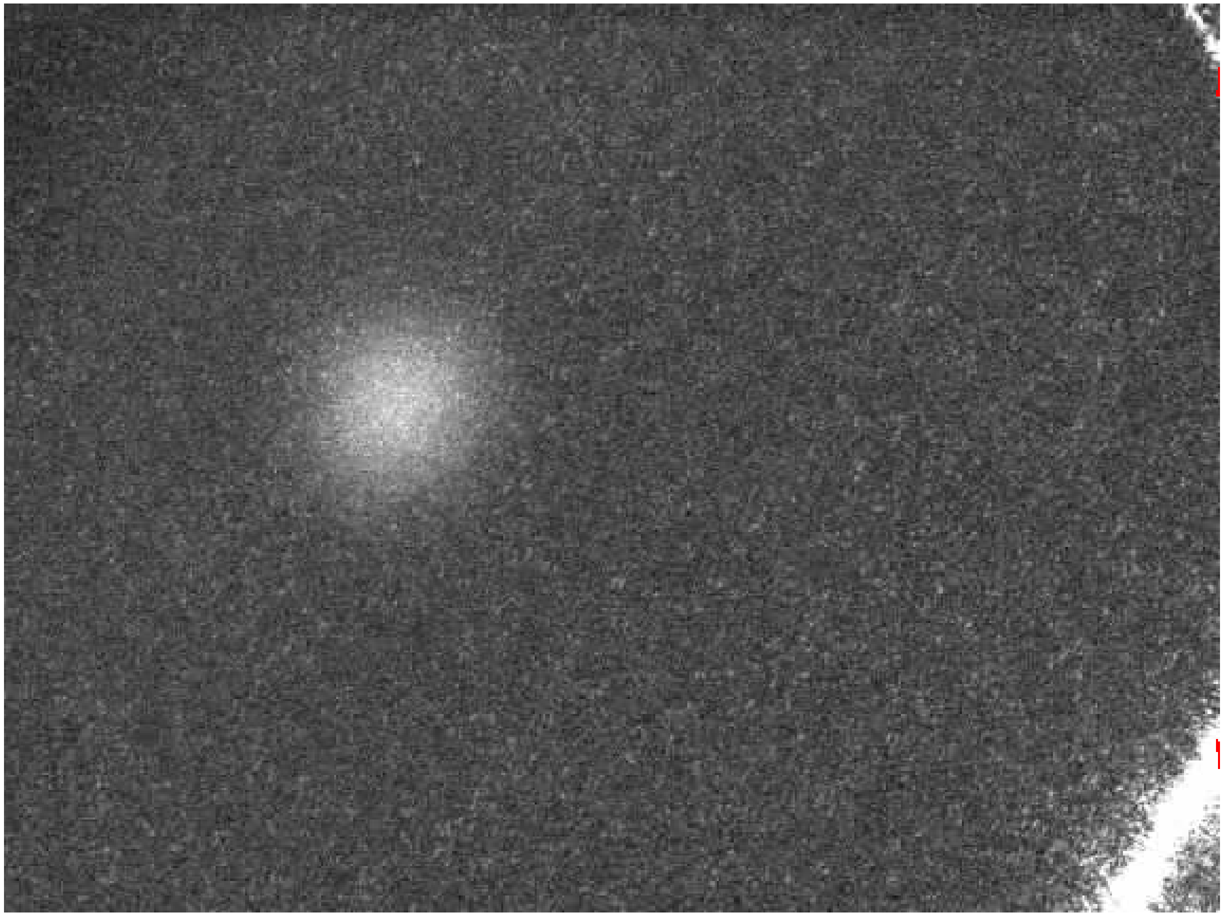




^{136}Xe -> ^{136}Ba^{++} e$^-$e$^-$ -> ^{136}Ba$^+$

Optically observe final state. (Moe, PRC44 (1991) 931

EXO Single Ion Observation



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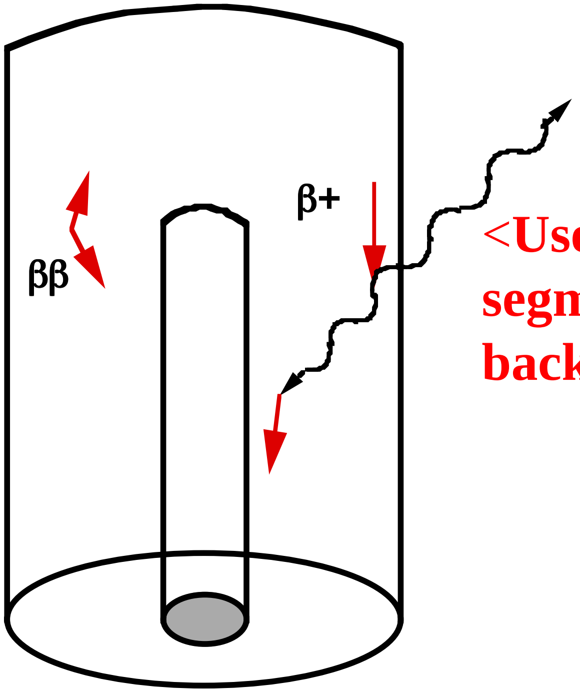
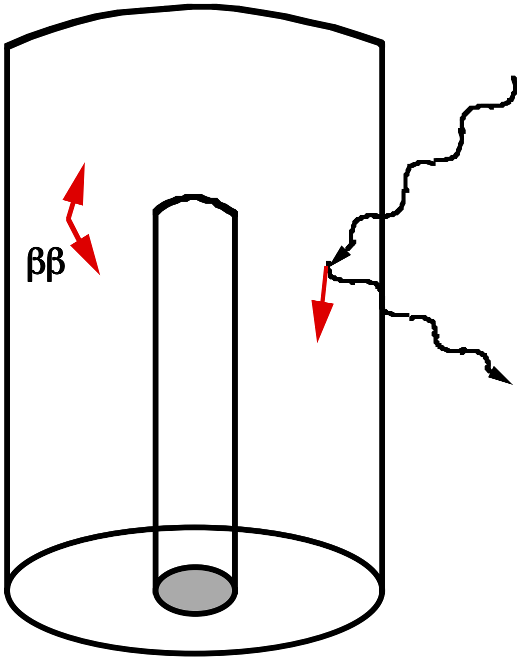
Two Ge Detector Background Philosophies

Internal Background



<Use pulse shape & segmentation to eliminate background.

External Background



>Minimize the materials near the crystal

Ge expts.: Different Approaches

Suppressing constants: $T_{1/2} = \frac{MT}{C} \Leftrightarrow \langle m_{\nu e} \rangle = \frac{1}{\sqrt{T_{1/2}}}$

“Majorana Approach”

If no signal seen:

$$T_{1/2} > \frac{MT}{\sqrt{B}}$$

If background, B~MT (i.e. within Ge mass), then:

$$T_{1/2} > \sqrt{MT}$$

Leads to emphasis on

- enrichment
- balanced mass and time
- ➢ background rejection

“GENIUS Approach”

If we assume background is in structural materials only, B=bT then:

$$T_{1/2} > M\sqrt{\frac{T}{b}}$$

Leads to emphasis on

- ➢ minimized structure
- increased natural mass
- decreased time

GErmanium NItrogen Underground Setup - GENIUS

MPI, Heidelberg

Kurchatov Inst., Moscow

Inst. Of Radiophysical Research, Nishnij Novgorod

Braunschweig und Technische Universität, Braunschweig

U. of L'Aquila, Italy

Int. Center for Theor. Physics, Trieste

JINR, Dubna

Northeastern U., Boston

U. of Maryland, USA

University of Valencia, Spain

Texas A & M U.

Spokesperson
Hans Klapdor-Kleingrothaus
MPI

GENIUS

GENIUS Overview

1 ton, ~86% enriched ^{76}Ge

Naked Ge crystals in LN

Very little material near Ge.

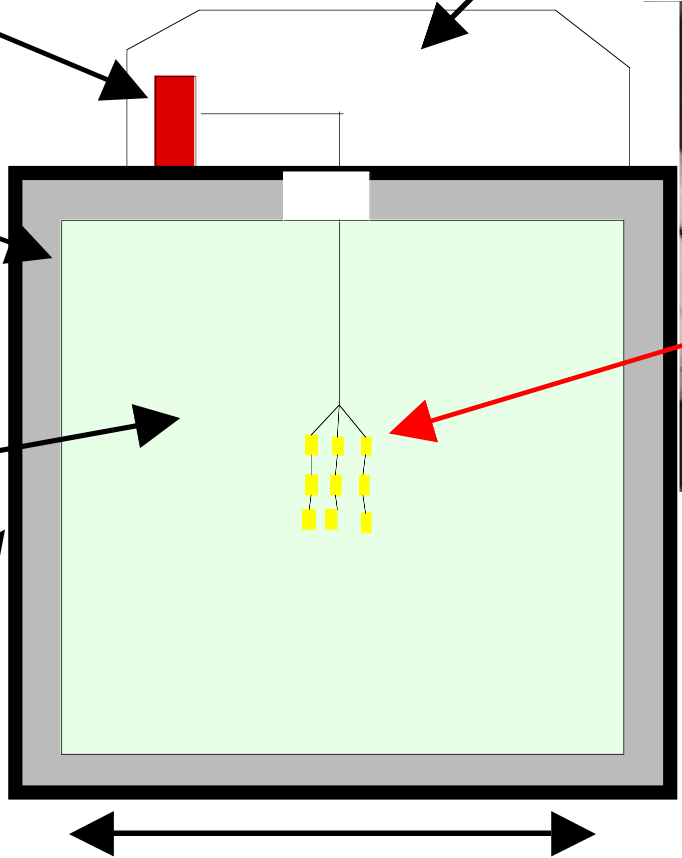
1.4x10^{6} liters LN

40 kg test facility is approved.

100% efficient

Heid.-Moscow experiment is precursor

GENIUS Layout



Data Acquisition

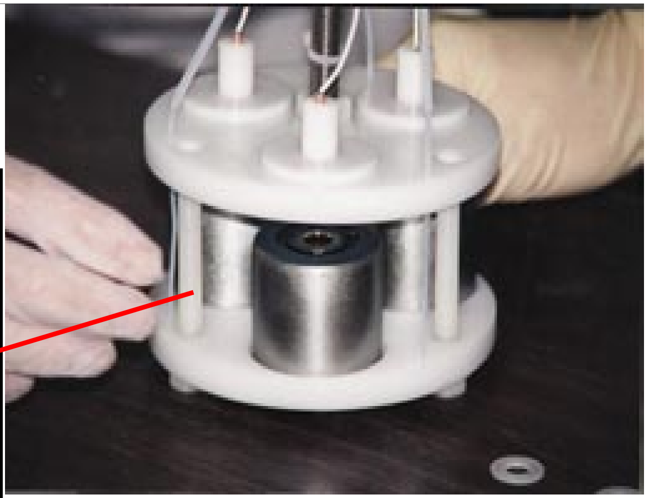
Clean Room

Insulation

Liquid Nitrogen

Steel Vessel

12 m



Setup for operation of three 'naked' Germanium detectors in liquid nitrogen.

GENIUS

The Majorana Project

- **Duke U.**
- **North Carolina State U.**
- **TUNL**
- **Argonne Nat. Lab.**
- **JINR, Dubna**
- **ITEP, Moscow**
- **New Mexico State U.**
- **Pacific Northwest Nat. Lab.**
- **U. of Washington**
- **LANL**
- **U. of South Carolina**
- **Brown**
- **Univ. of Chicago**
- **RCNP, Osaka Univ.**
- **Univ. of Tenn.**

Co-Spokespersons
Frank Avignone
Harry Miley

Majorana Overview

0.5 ton of 86% enriched ^{76}Ge

Segmented detectors using pulse shape discrimination to improve background rejection.

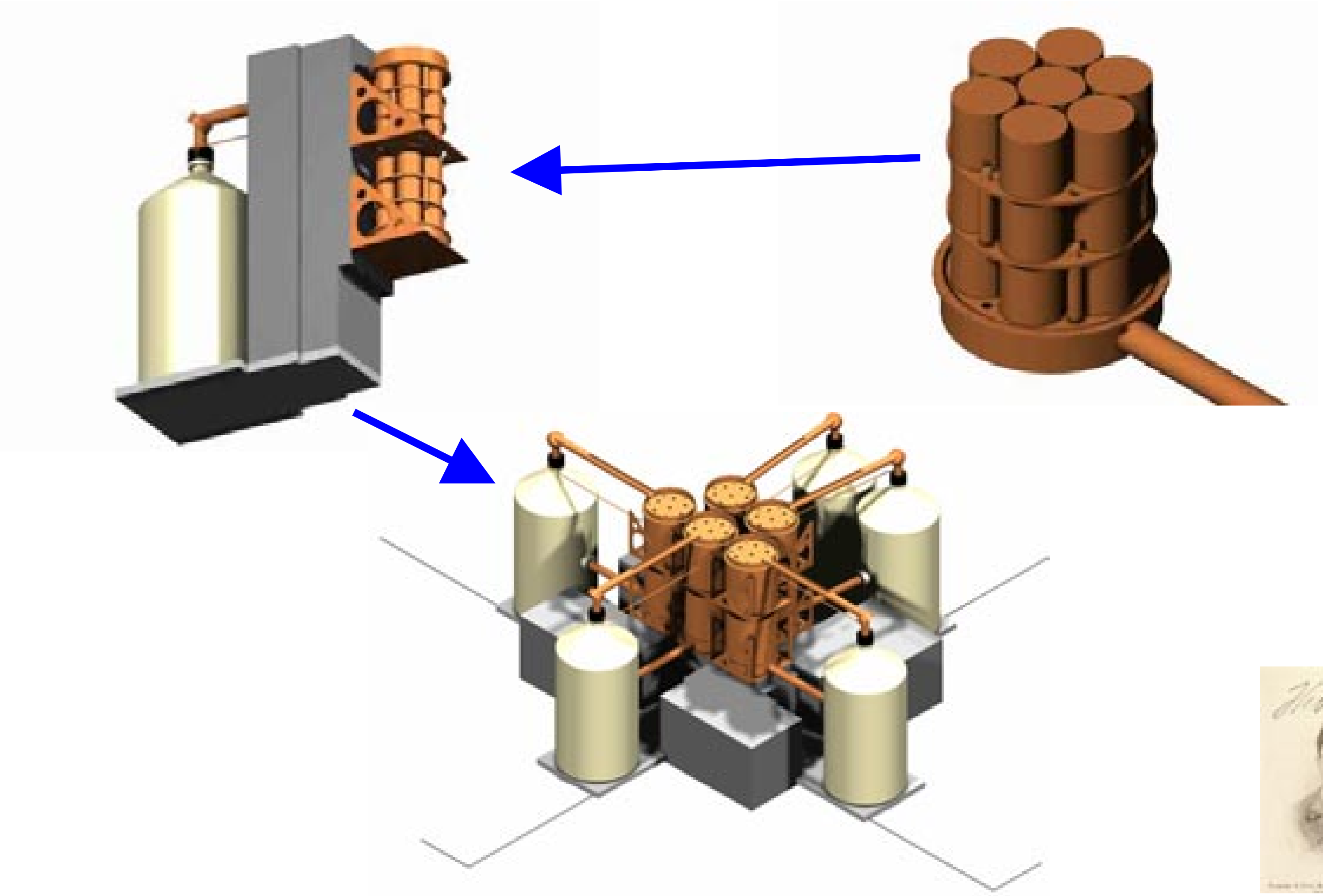
Prototypes being assembled. (18 crystals array, 1 enriched segmented detector)

100% efficient

Can do excited state decay.

IGEX is precursor

Majorana Layout



Recent Majorana pictures

Summary of Proposals

	Proposed ton-year = M * T * ε	Anticipated $<m_{ee}>$, (QRPA)
CUORE	0.21*5*1 = 1	60 meV
EXO	6.5*10*0.7 = 45	13 meV
GENIUS	1*2*1 = 2	20 meV
MAJORANA	0.5*10*1 = 5	25 meV
MOON	3.3*3*0.14 = 1.4	30 meV

The $<m_{\beta\beta}>$ limits depend on background assumptions and matrix elements which vary from proposal to proposal.

Conclusions

Research and Development are needed for all the future proposed detectors.

UG Lab space will be needed for some of that R&D.

The next generation ββ experiments have a good possibility of reaching an interesting $\langle m_{\beta\beta} \rangle$ region.