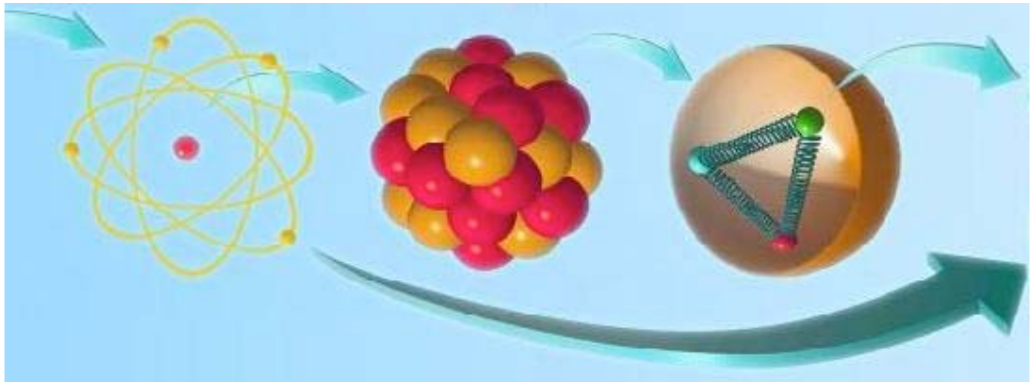
Is the Neutrino its own Antiparticle ?

Sulamith Goldhaber Memorial Lecture

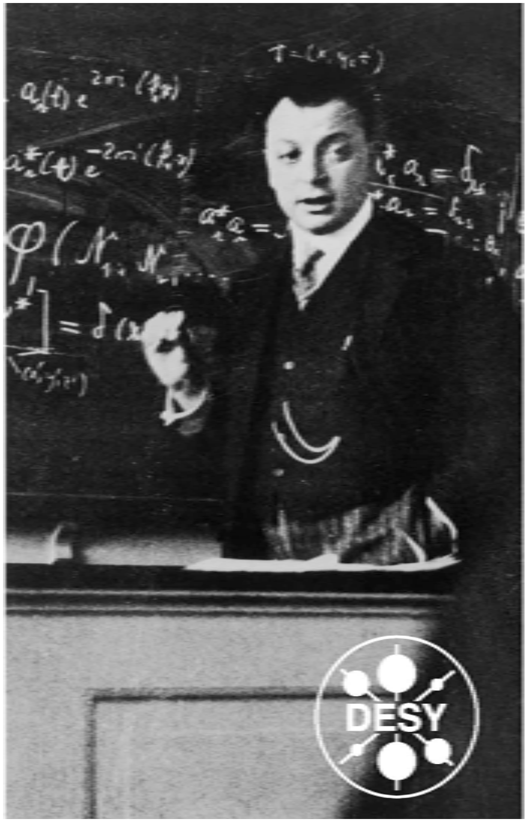


School of Physics
Tel Aviv University

Allen Caldwell
Max-Planck-Institut für Physik

History

1930 Pauli predicts neutrino

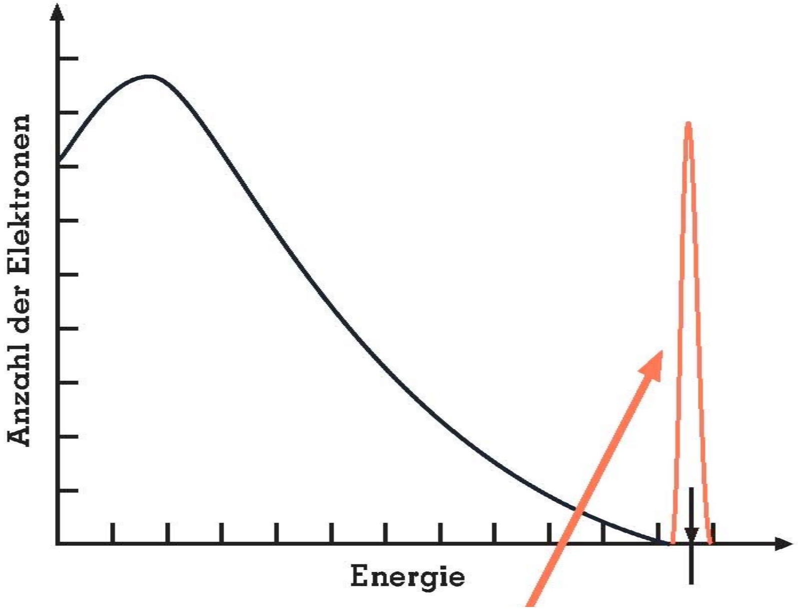


Physikalisches Institut der
Eidgenössische Technische Hochschule
Zürich

Offener Brief an die Gruppe der Radioaktiven bei der
Gauvereins-Tagung zu Tübingen
Zürich, 4. Dezember 1930

Liebe Radioaktive Damen und Herren,

Write reaction



Expectation for 2-body decay

History

1934 Fermi theory of Beta Decay

1956 Lee & Yang propose Parity non-conservation in Weak Decays

1957 Parity non-conservation observed

1950's V-A theory of weak decays established

1958 Reines & Cowan observe electron (anti) neutrino

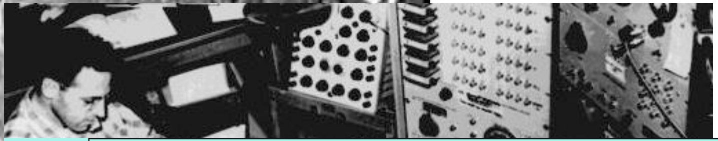
1962 Schwartz, Lederman Steinberger observe muon neutrino

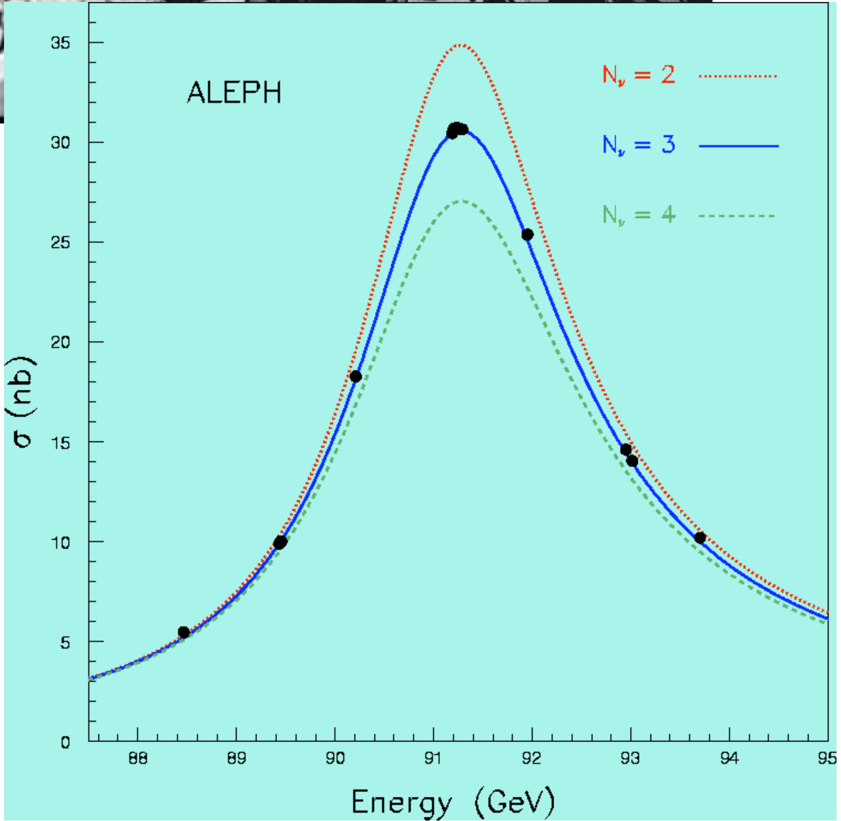
1973 Observation of weak neutral currents

1983 Observation of W boson

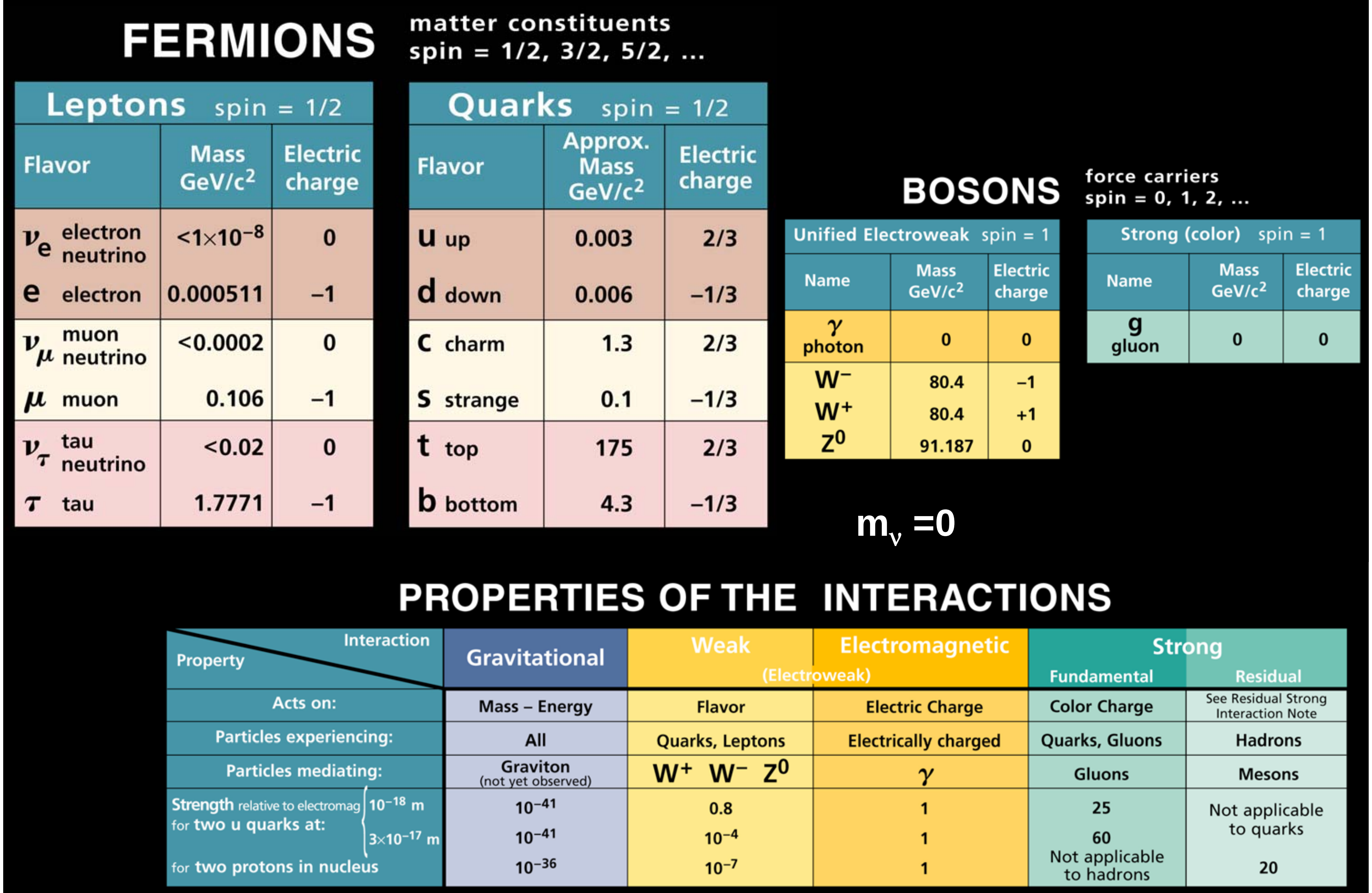
1990's LEP only 3 light neutrinos

2000 Tau neutrino observed at FNAL





Standard Model



FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2		
Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

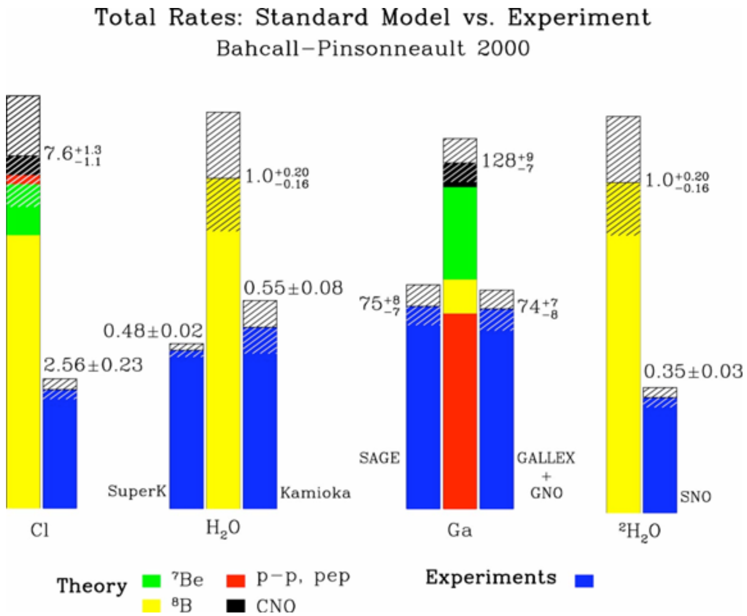
$m_\nu = 0$

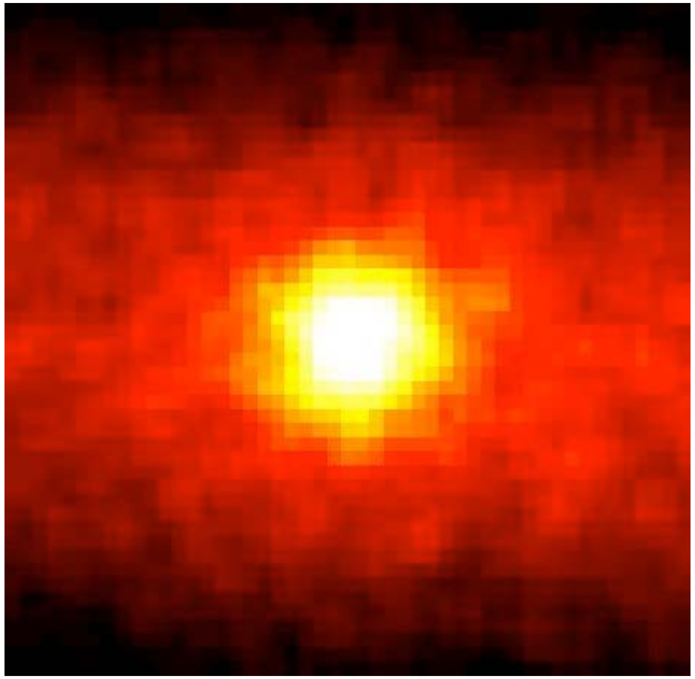
PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong Fundamental	Strong Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Non-SM History

1960's Davis discovers solar deficit

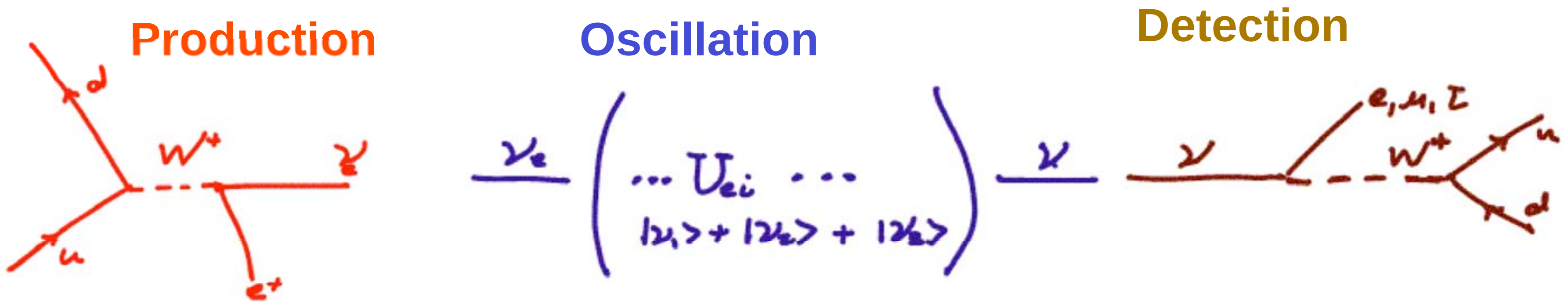




1990's Gallex, Kamiokande, SAGE confirms solar deficit, Super-K observes atmospheric neutrino oscillations

2002 SNO shows solar oscillations to active flavors, Kamland confirms solar oscillations, K2K confirms atmospheric oscillations

Neutrino Oscillations



Production **Oscillation** **Detection**

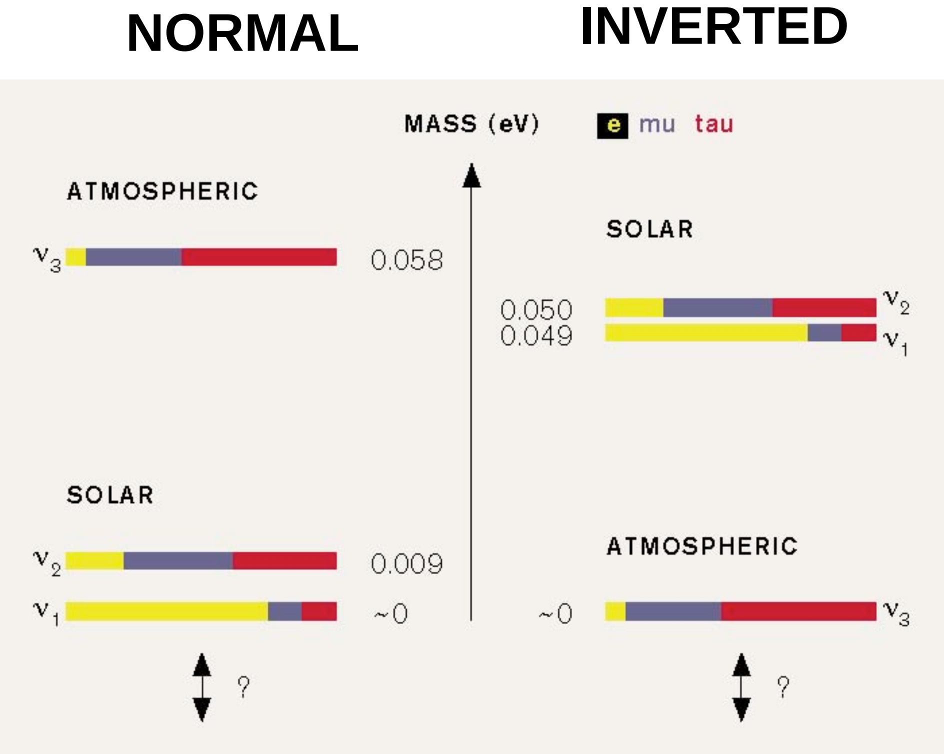
Mass eigenstates: ν_1, ν_2, ν_3 **Weak eigenstates:** ν_e, ν_μ, ν_τ

Oscillation experiment tell us about mixing and mass differences

Prob (oscillation) $\propto \sin^2 2\theta \cdot \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$ **2 flavors**

What we know

Mass Scale



Δm_{12}^2 known

$|\Delta m_{13}^2|$ known

Mixing Matrix

U_{ij} can be characterized by three mixing angles, Θ_{12}, Θ_{23}, Θ_{13},
one Dirac CP phase, δ,
and two Majorana phases Φ_2, Φ_3

Θ_{12}, Θ_{23} measured, upper limit on Θ_{13}

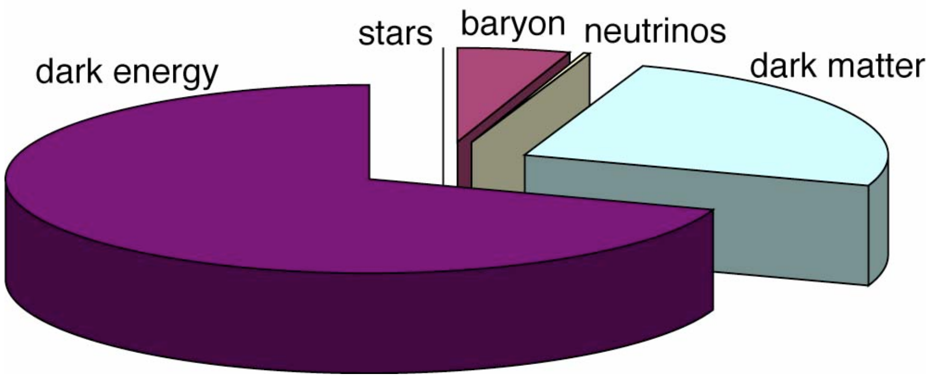
Current (lack of) Understanding

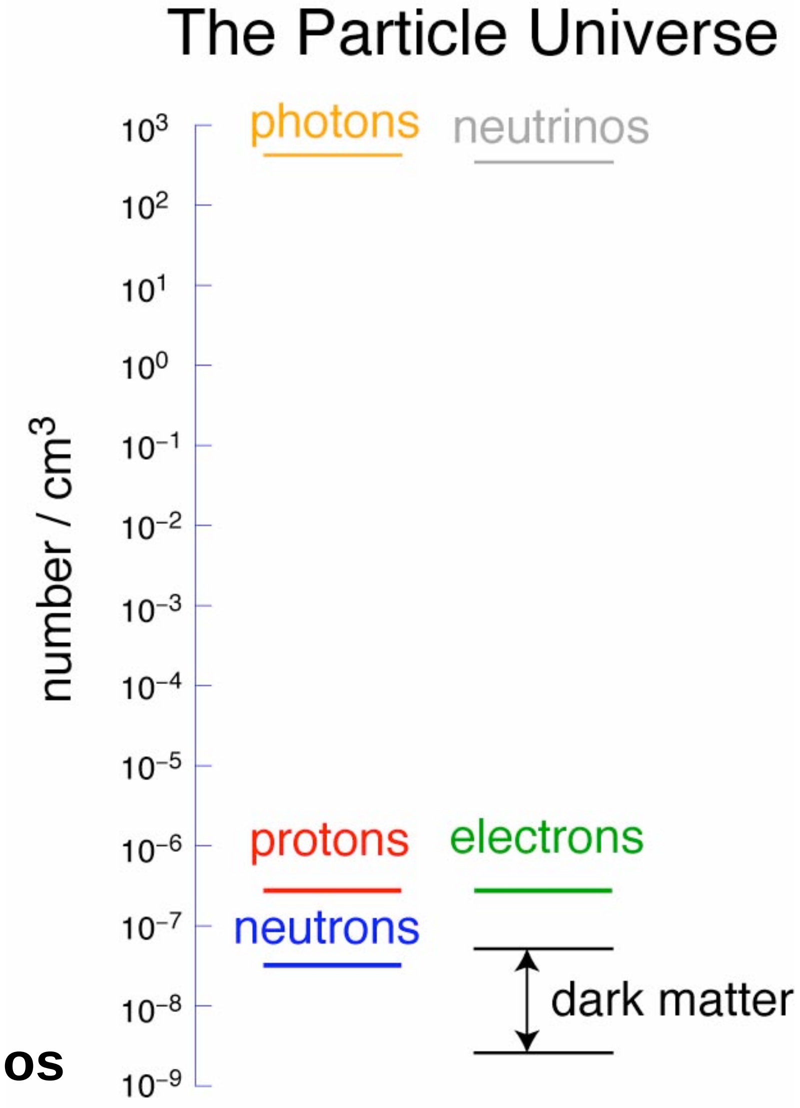
What we do not know about neutrinos:

1. **absolute mass scale (offset)**
2. **mass hierarchy (1,2,3 or 3,1,2)**
3. **nature of neutrino (Majorana, Dirac particle)**
4. **value of third mixing angle (Θ_{13})**
5. **CP phases (δ, Φ_2, Φ_3)**

Double beta decay experiment can address 3, and, if neutrinos are Majorana particles, then also a combination of 1,2,5

Neutrinos everywhere





There are a lot of neutrinos, but presumably they do not make up a large part of the Dark Matter

When a supernova happens - 99% of the energy is carried away by neutrinos

Reasons to Care

When Dirac postulated anti-matter, people thought it a crazy idea. Today, we wonder where all the antimatter went …

If neutrinos are their own anti-particles (Majorana), then Lepton Number is not a good Quantum Number

⇒ Baryon number may not conserved (conservation of B-L no longer valid)

i.e., could have an explanation for the observed matter-antimatter asymmetry in the universe (Leptogenesis)

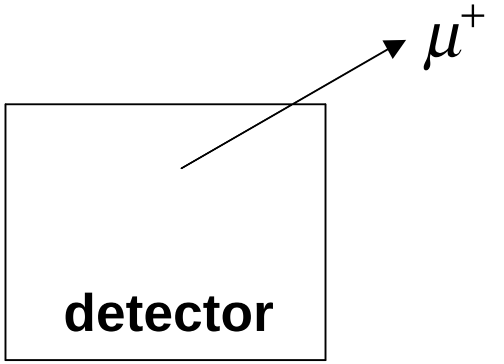
Most fundamental reason to care: neutrinos have been full of surprises. Neutrino experiments are difficult, but the payoff of a successful experiment could be very high !

Majorana vs Dirac Nature

Usual matter particles have electric charge (electron, quarks, …), and cannot be their own antiparticles. What about neutrinos ?

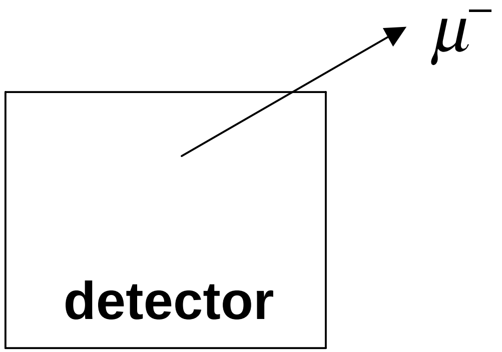
Review: how do we distinguish a neutrino from an anti-neutrino ?

$$\mu^- \leftarrow \pi^- \rightarrow \bar{\nu}_\mu \qquad \cdots$$



Neutral particle from π^- decay produces μ^+

$$\mu^+ \leftarrow \pi^+ \rightarrow \nu_\mu \qquad \cdots$$



Neutral particle from π^+ decay produces μ^-

Majorana vs Dirac

Usual explanation:

1. **The neutral particles in the two cases are distinct**
2. **There is a conserved quantum number (Lepton Number) with the following assignments**

$$\nu_\mu, \mu^- \rightarrow +1$$

$$\bar{\nu}_\mu, \mu^+ \rightarrow -1$$

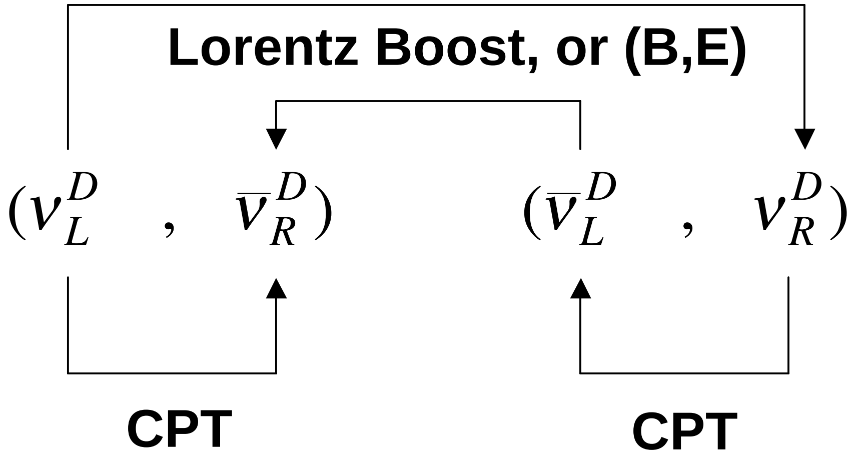
But

The existence of Lepton Number is not necessary. The neutral particle produced in π^+ decay is left-handed (V-A), and left-handed ν_μ only produce μ^-, then we could just have the left-handed and right-handed states of the same particle.

The existing data is neutral on the question of Majorana vs Dirac nature.

Majorana vs Dirac

Dirac: four states of the same mass



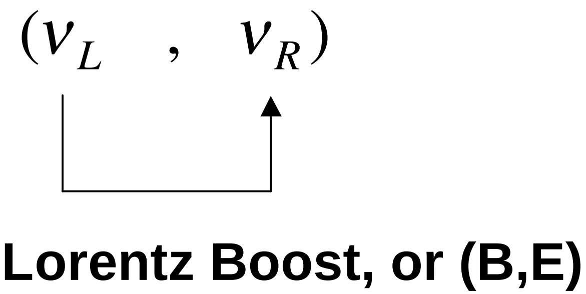
Lorentz Boost, or (B,E)

$$(\nu_L^D \quad , \quad \bar{\nu}_R^D) \qquad (\bar{\nu}_L^D \quad , \quad \nu_R^D)$$

CPT

CPT

Majorana: two states of the same mass



$$(\nu_L \quad , \quad \nu_R)$$

CPT, Lorentz Boost, or (B,E)

From B. Kayser

Majorana vs Dirac

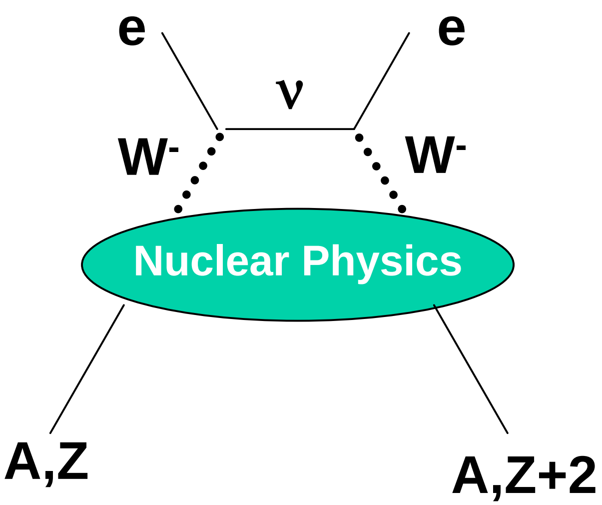
How can we test if neutrinos are Dirac or Majorana particles ?

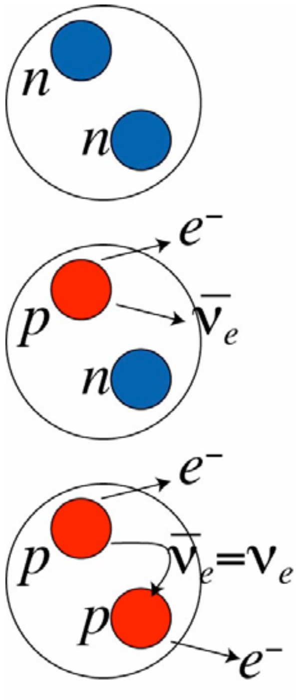
Experimental Problem:

$$P(\nu_L \to \nu_R) \propto \left(\frac{m_\nu}{E_\nu}\right)^2$$

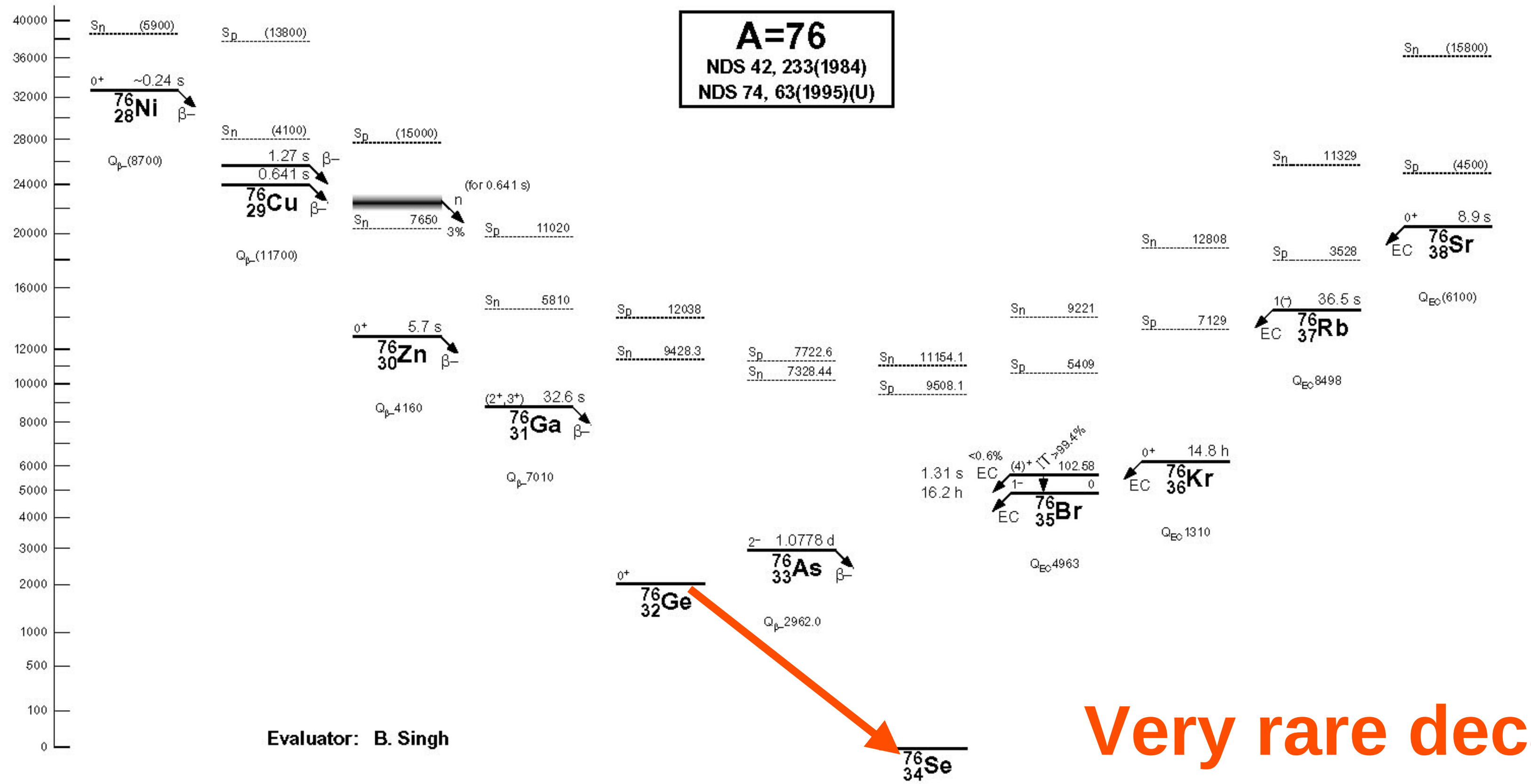
m ≤ eV, E MeV or more

Only known technique is neutrinoless double beta decay:





Double Beta Decay

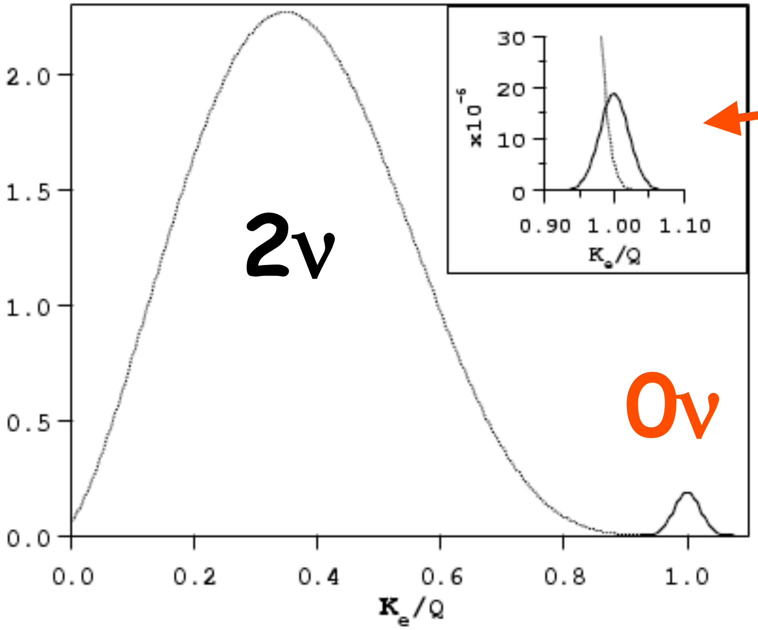


Very rare decay lifetimes >10^{20} years !

(A,Z) → (A,Z+1)+e+ν energetically forbidden
(A,Z) → (A,Z+2)+2e+2ν is allowed.
Then, for Majorana particle (A,Z) →(A,Z+2)+2e possible

Decay Rate & Spectrum

Normalized energy spectrum



If resolution poor

If resolution good

0ν-DBD rate

Phase space $\propto Q^5$

Nuclear matrix element

Effective Majorana mass

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

Decay Rate

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

Some numbers:

$G(Q,Z) \sim 10^{-25}\,(\mathrm{yr\ ev}^2)^{-1}$ **$M_{nucl} \sim 2\text{-}3$**

So $\tau \sim 1\ 10^{25}$ yrs for $\langle m_{ee}\rangle = 100$ meV

i.e., <1 % atoms decay per mole of material per year !!! Or, the chance for an atom to have decayed via neutrinoless double beta decay since the Big-Bang is 10^{-16}. This is a RARE decay.

Conclusion: need 1000's of mole-years of exposure for sensitivity at 100 meV level. I.e., many kg of material watched over many years.

And, the backgrounds must be extremely low !!!

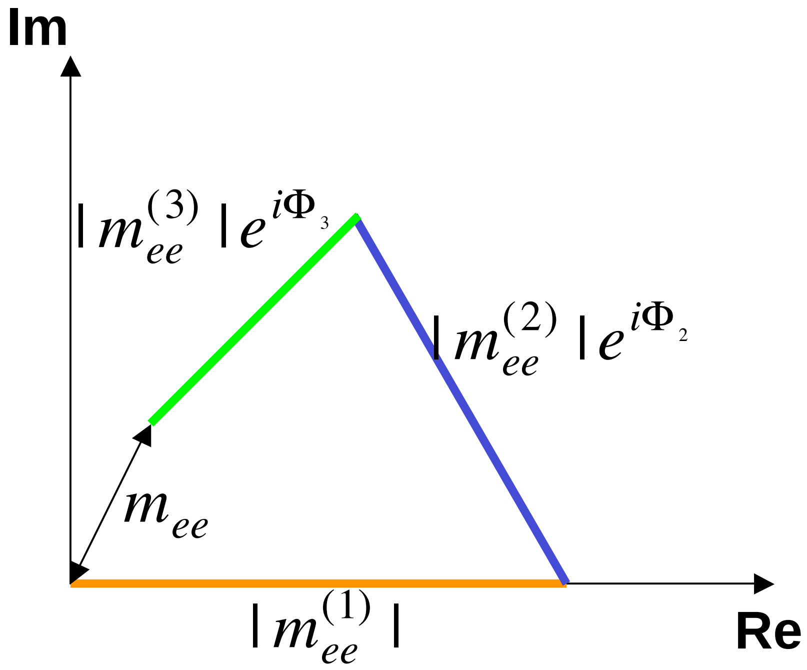
Effective Neutrino Mass

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

$$|m_{ee}^{(1)}| = |U_{e1}|^2 m_1$$

$$|m_{ee}^{(2)}| = |U_{e2}|^2 \sqrt{m_1 + \Delta m_{21}^2}$$

$$|m_{ee}^{(3)}| = |U_{e3}|^2 \sqrt{m_1 + \Delta m_{31}^2}$$



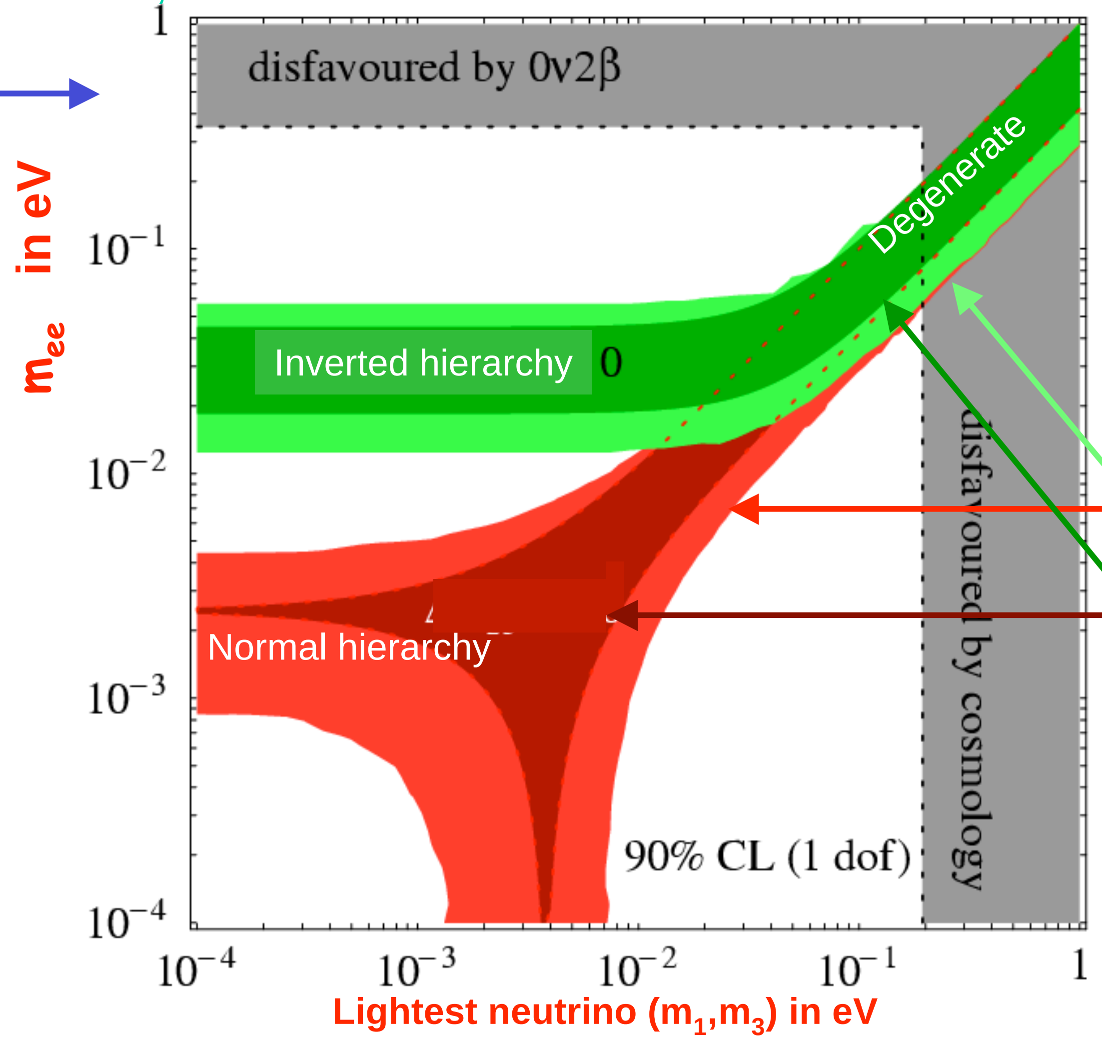
Complicated relationship between effective mass in neutrinoless double beta decay and neutrino masses, mixing angles and phases

Cancellation possible: m_{ee} could be vanishingly small

Effective Neutrino Mass

H.V. Klapdor-Kleingrothaus, I.V. Krivosheina, A. Dietz, O. Chkvorets
Phys.Lett.B586:198-212,2004

best value →



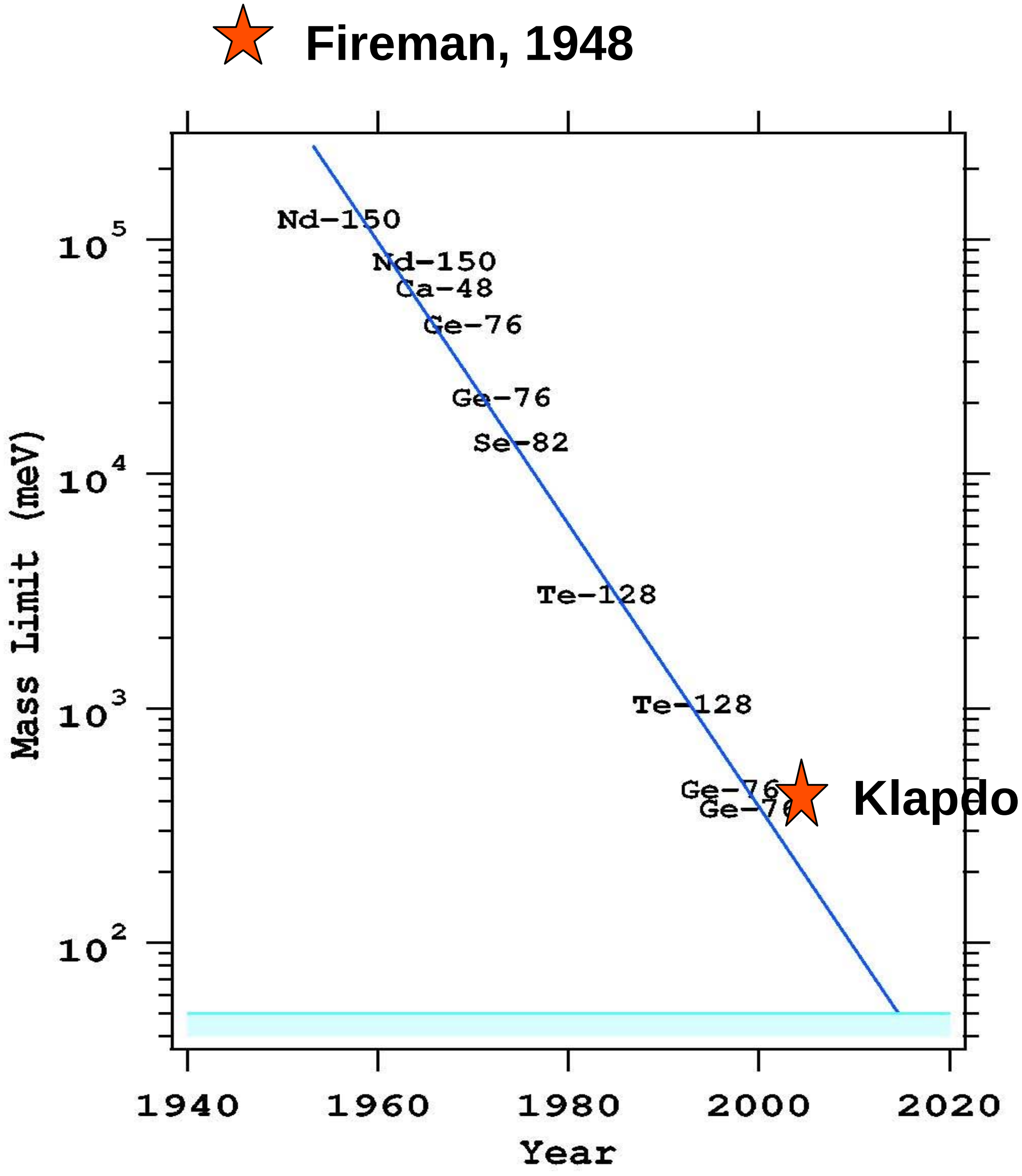
F.Feruglio,
A. Strumia,
F. Vissani,
NPB 637

90% CL

Negligible errors from oscillations; width due to CP phases

History of Searches for 0ν DBD

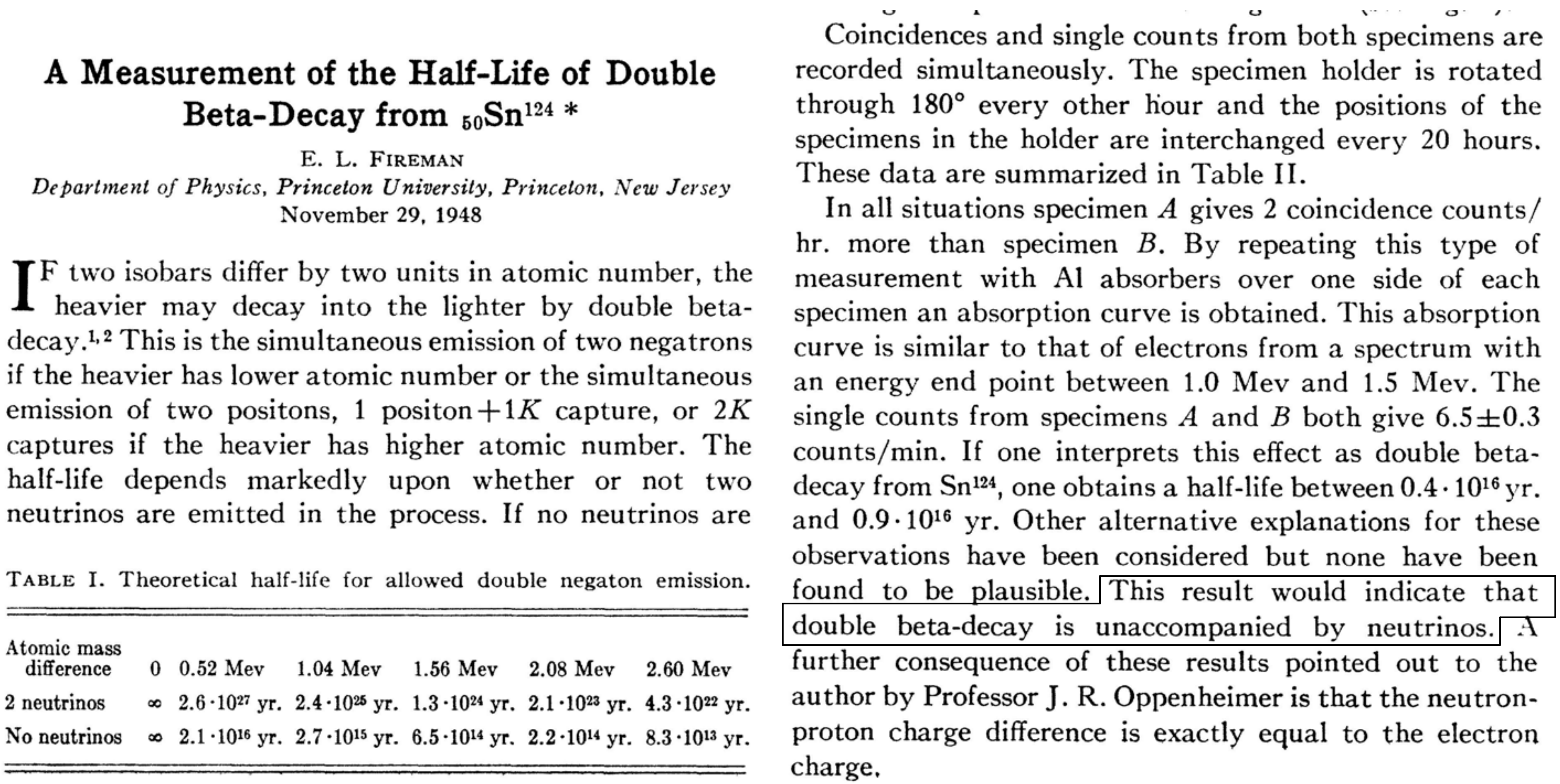
Fireman, 1948



Klapdor-Kleingrothaus et al.

There is a long history to the search for neutrinoless double beta decay, including claims of positive results.

0ν DBD Claims



A Measurement of the Half-Life of Double Beta-Decay from $_{50}\mathrm{Sn}^{124}$ *

E. L. Fireman
Department of Physics, Princeton University, Princeton, New Jersey
November 29, 1948

If two isobars differ by two units in atomic number, the heavier may decay into the lighter by double beta-decay.[1,2] This is the simultaneous emission of two negatrons if the heavier has lower atomic number or the simultaneous emission of two positons, 1 positon + 1K capture, or 2K captures if the heavier has higher atomic number. The half-life depends markedly upon whether or not two neutrinos are emitted in the process. If no neutrinos are

Table I. Theoretical half-life for allowed double negaton emission.

Atomic mass difference	0	0.52 Mev	1.04 Mev	1.56 Mev	2.08 Mev	2.60 Mev
2 neutrinos	∞	$2.6\cdot10^{27}$ yr.	$2.4\cdot10^{25}$ yr.	$1.3\cdot10^{24}$ yr.	$2.1\cdot10^{23}$ yr.	$4.3\cdot10^{22}$ yr.
No neutrinos	∞	$2.1\cdot10^{16}$ yr.	$2.7\cdot10^{15}$ yr.	$6.5\cdot10^{14}$ yr.	$2.2\cdot10^{14}$ yr.	$8.3\cdot10^{13}$ yr.

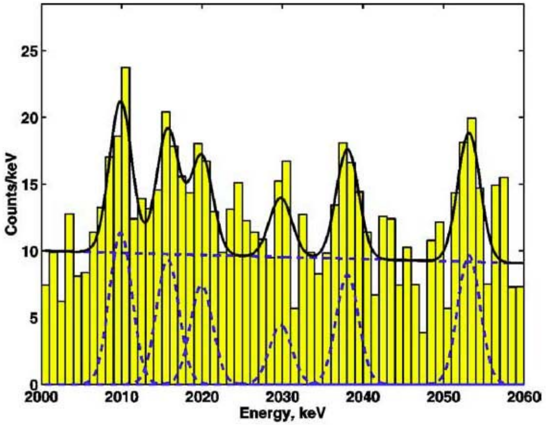
Coincidences and single counts from both specimens are recorded simultaneously. The specimen holder is rotated through 180° every other hour and the positions of the specimens in the holder are interchanged every 20 hours. These data are summarized in Table II.

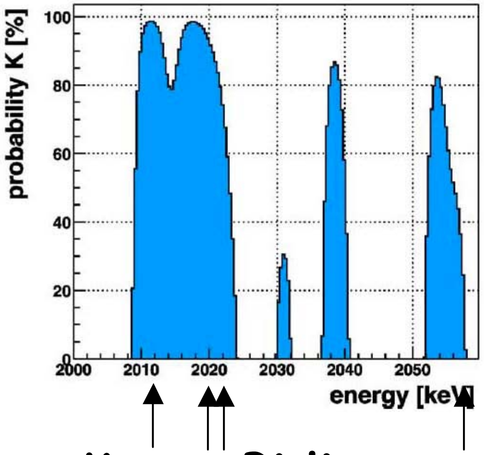
In all situations specimen A gives 2 coincidence counts/hr. more than specimen B. By repeating this type of measurement with Al absorbers over one side of each specimen an absorption curve is obtained. This absorption curve is similar to that of electrons from a spectrum with an energy end point between 1.0 Mev and 1.5 Mev. The single counts from specimens A and B both give 6.5 ± 0.3 counts/min. If one interprets this effect as double beta-decay from Sn^{124}, one obtains a half-life between $0.4\cdot10^{16}$ yr. and $0.9\cdot10^{16}$ yr. Other alternative explanations for these observations have been considered but none have been found to be plausible. This result would indicate that double beta-decay is unaccompanied by neutrinos. A further consequence of these results pointed out to the author by Professor J. R. Oppenheimer is that the neutron-proton charge difference is exactly equal to the electron charge.

Note: 0ν predicted to have shorter lifetime from phase space arguments

Positive result corresponds to $\langle m_{ee}\rangle \approx 30\ \mathrm{keV}$ **(my estimate)**

Heidelberg-Moscow Experiment





Known Bi lines

H.V. Klapdor-Kleingrothaus, I.V. Krivosheina, A. Dietz, O. Chkvorets

Phys.Lett.B586:198-212,2004

- **Experiment with Ge detectors enriched in ^{76}Ge**
- **Exposure 71.7 kg-yr**
- **Experiment carried out in Gran Sasso lab**
- **Background: 0.11/(keV kg yr)**

Claim: 4.2σ signal

$T_{1/2}$=0.69-4.18 10^{25} yr

m_{ee}=440 meV (best fit)

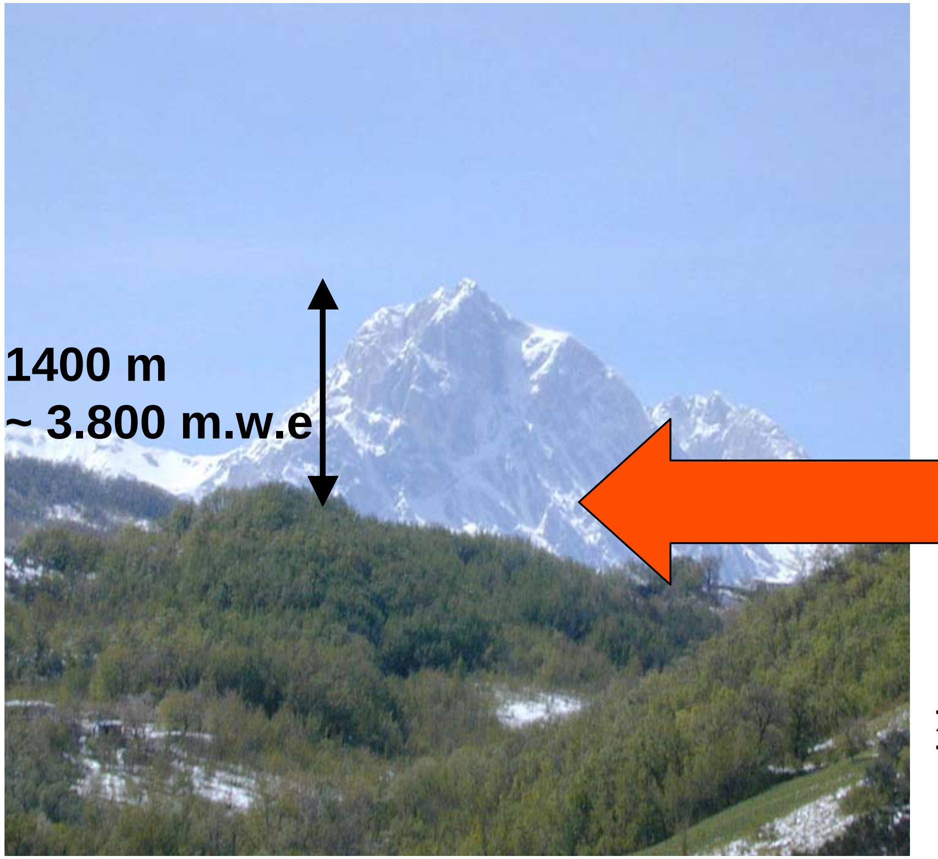
Proposed & Ongoing Experiments

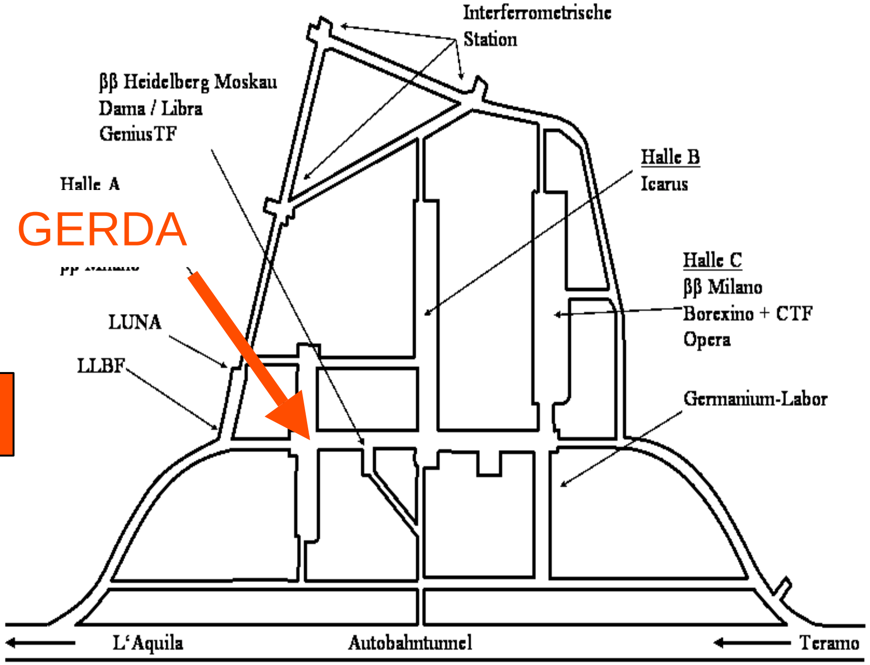
Some of the possible isotopes

Decay	Q(keV)	Nat. Abundance	Experiments
$^{48}Ca \rightarrow {}^{48}Ti$	4271	0.2%	CANDLES
$^{76}Ge \rightarrow {}^{76}Se$	2039	7.4%	**GERDA,Majorana**
$^{82}Se \rightarrow {}^{82}Kr$	2995	8.4%	**NEMO**
$^{96}Zr \rightarrow {}^{96}Mo$	3350	2.8%	
$^{100}Mo \rightarrow {}^{100}Ru$	3034	9.6%	**NEMO,**MOON
$^{116}Cd \rightarrow {}^{116}Sn$	2802	7.5%	
$^{128}Te \rightarrow {}^{128}Xe$	867	32%	
$^{130}Te \rightarrow {}^{130}Xe$	2529	34%	COBRA,**CUORE**
$^{136}Xe \rightarrow {}^{136}Ba$	2479	8.9%	**EXO,**XMASS
$^{150}Nd \rightarrow {}^{150}Sm$	3367	5.6%	

GERDA

GERDA (GERmanium Detector Array) is a collaboration of 12 institutes, ca. 80 physicists, from Germany, Italy, Russia, Poland, Belgium.
The experiment has been approved by the LNGS (Gran Sasso)

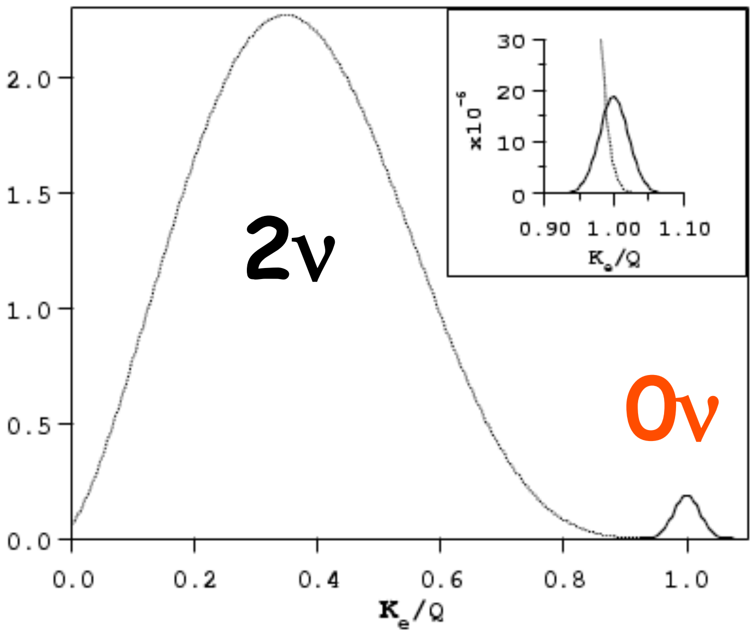




GERDA

We like Germanium because:

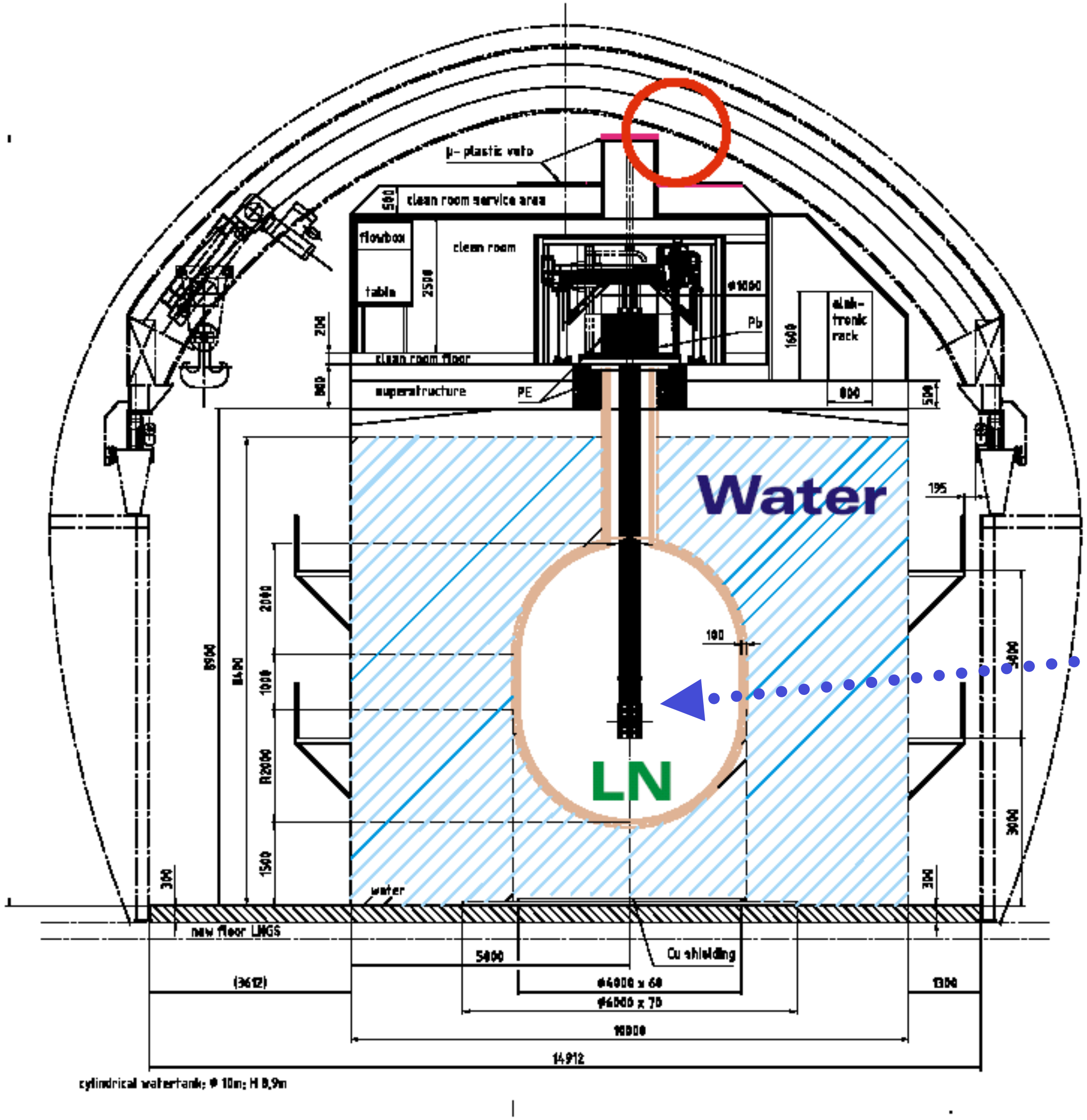
- excellent energy resolution (3 keV @ 2 MeV)
- considerable experience built up over the years - best background levels !
- still improvements possible



There are also some downsides:

- Q=2039 keV in region of γ backgrounds
- Q=2039 keV not among the higher Q values (recall $\tau \propto 1/Q^5$)
- enrichment possible, but expensive !

GERDA



Goal:

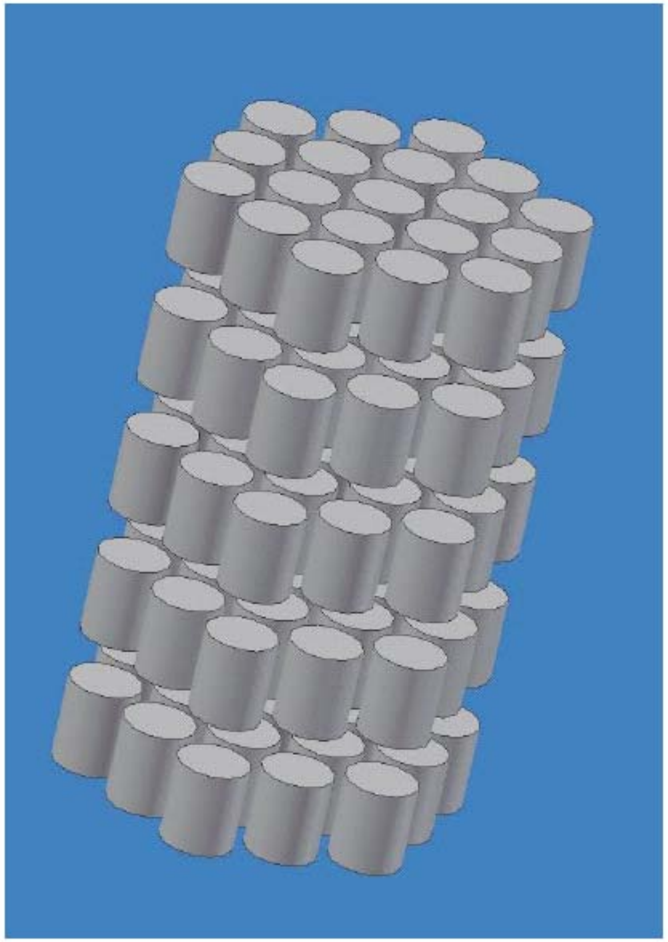
Reduce external backgrounds to 10^{-3}/(keV kg yr) with LN, factor 10 less with LAr

Germanium detectors

Ø 10 m water vessel
Ø 4 m Cu cryostat

45 m^3 of LN (LAr)
650 m^3 of water

Detector Setup

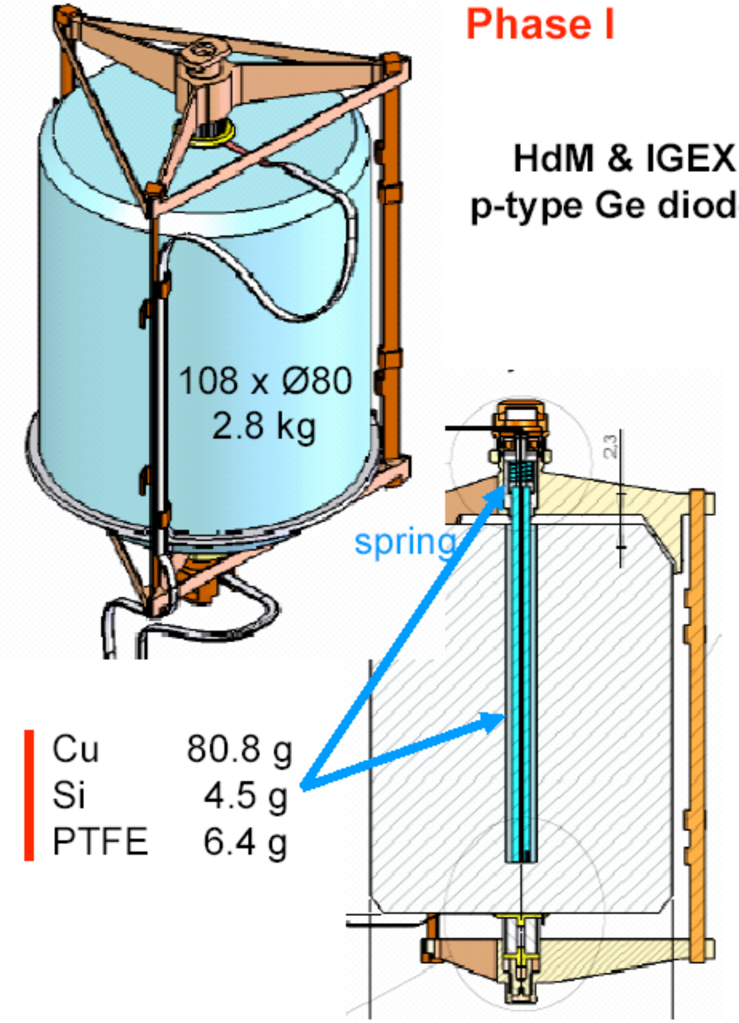


Maximum charge

Organized in strings

Phase I

HdM & IGEX
p-type Ge diodes



Cu	80.8 g
Si	4.5 g
PTFE	6.4 g

Start with existing detectors

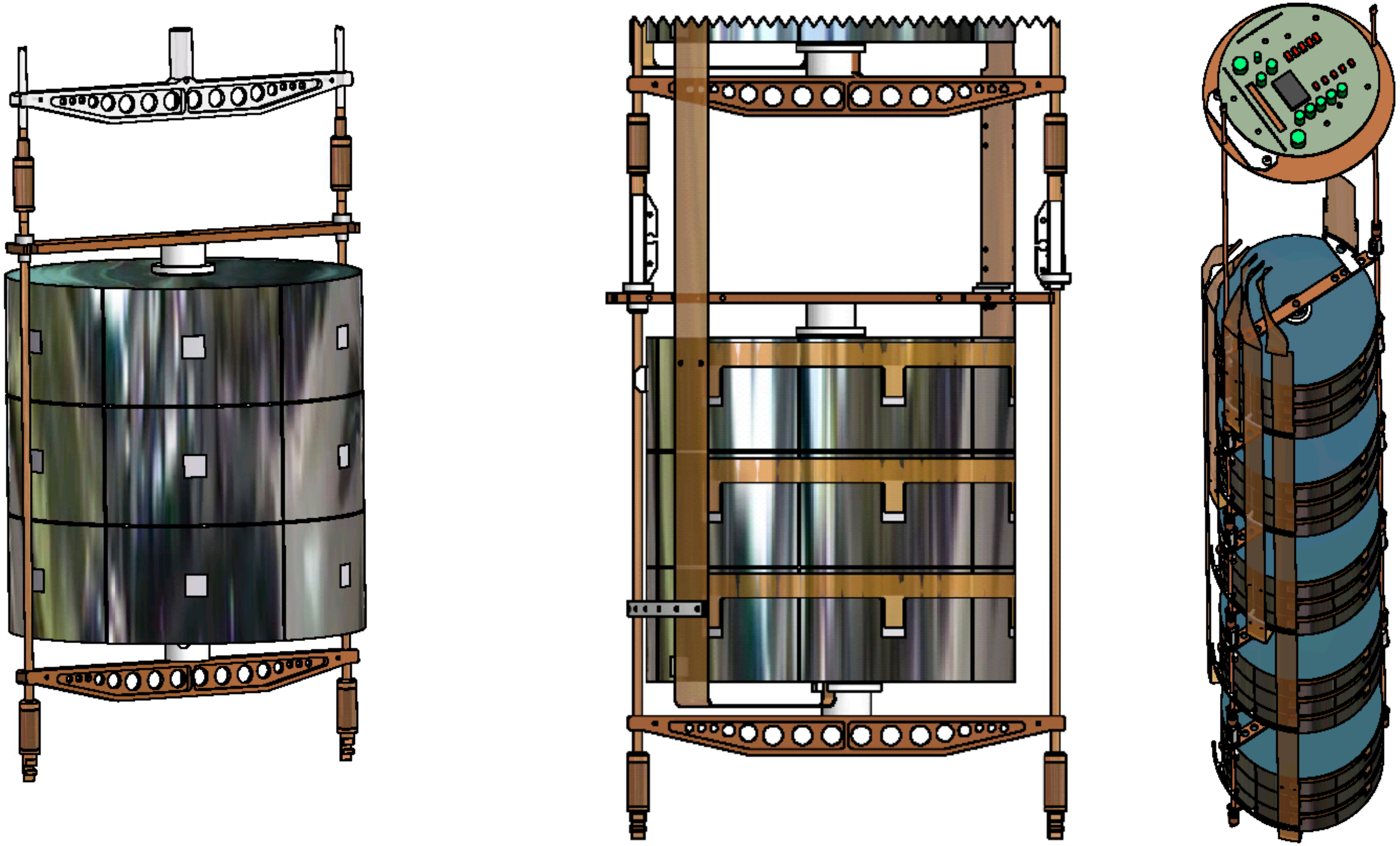
Existing Detectors

Heidelberg-Moscow detectors for Phase I of GERDA

In addition, three detectors from IGEX experiment. Total mass approx 18 kg

New Detectors

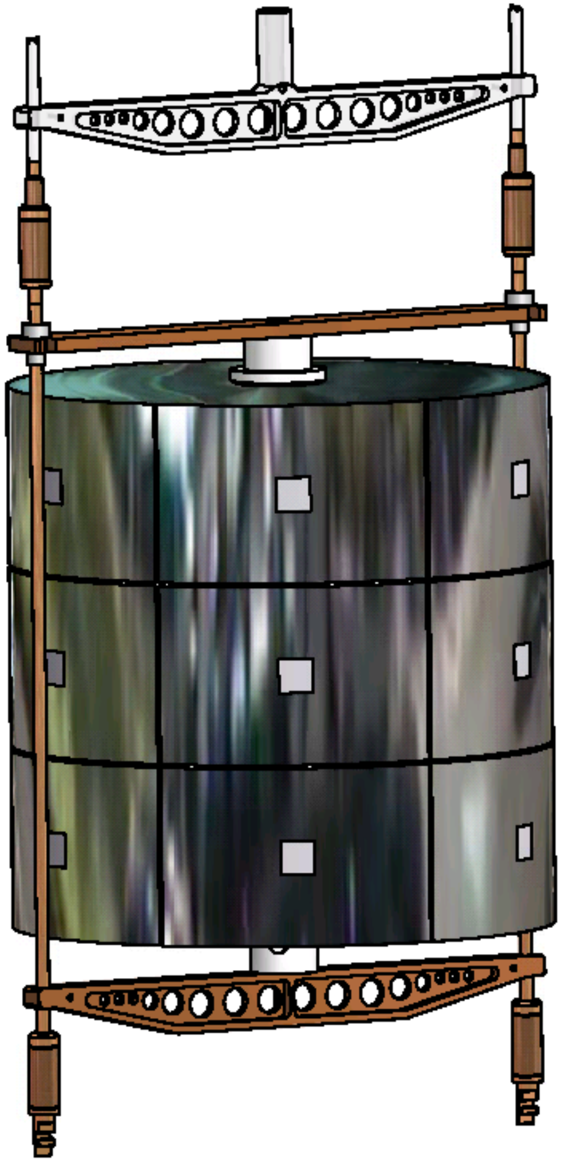
Phase II detectors 18-fold segmented detectors (true-coaxial, 3x6, n-type)



Phase II Detectors

Steps:

1. Enrich in ^{76}Ge (>86%)
    - Suppression of int
    - Cost
    - Signal/background
2. Chemically purify the e … 99.9999% pure Ge)
3. Zone refining (purity 9
4. Crystal pulling (purity … me of the purest material in the world - … 10^{-12}/atom
5. Detector manufacture
6. In parallel - developme … ng system



Khan river - Zhelenogorsk

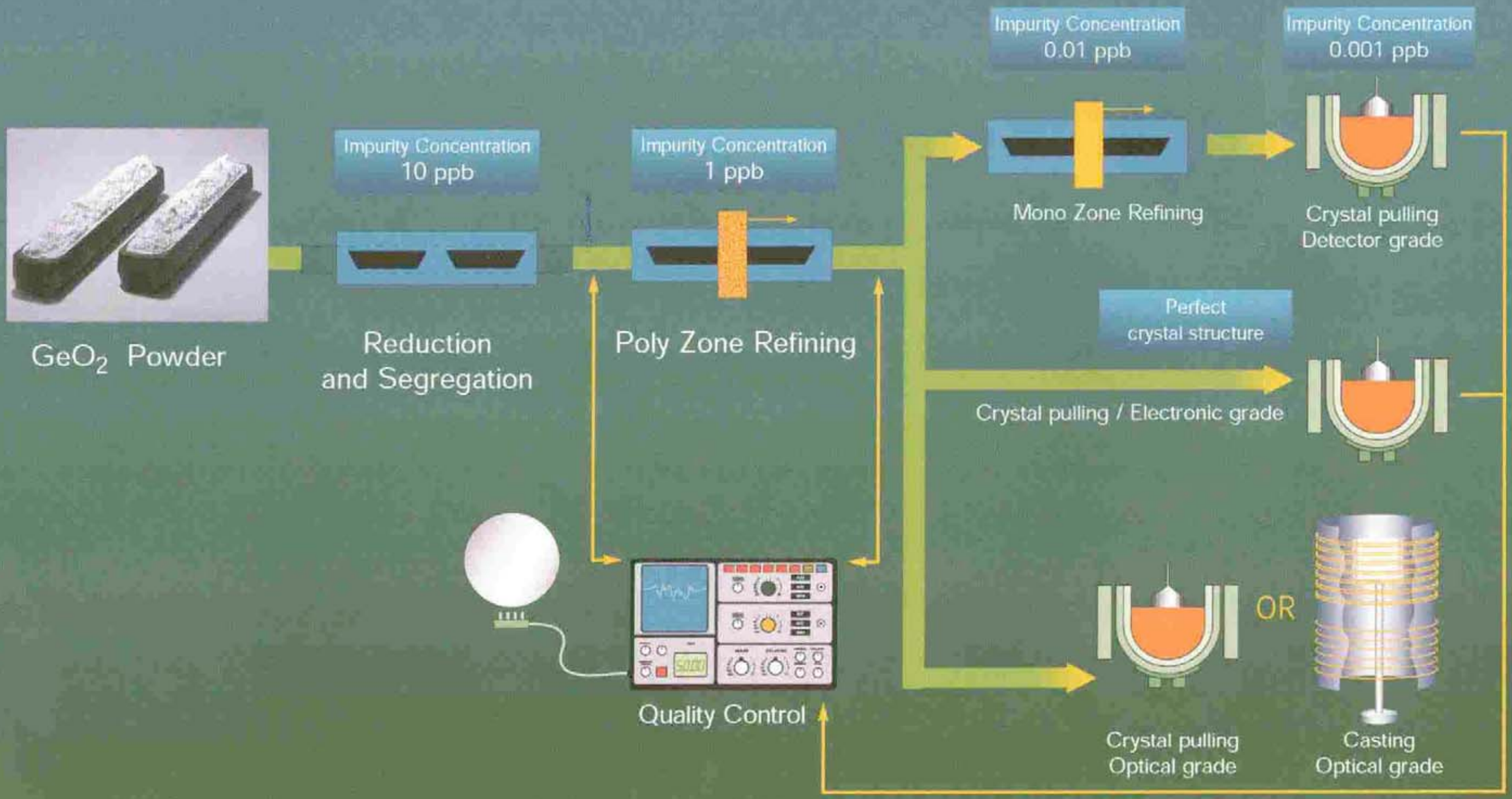
ECP plant (official photo)

Centrifuge hall

Sample Storage

Refining & crystal growth

umicore



GeO_2 Powder

Impurity Concentration
10 ppb

Reduction
and Segregation

Impurity Concentration
1 ppb

Poly Zone Refining

Quality Control

Impurity Concentration
0.01 ppb

Mono Zone Refining

Impurity Concentration
0.001 ppb

Crystal pulling
Detector grade

Perfect
crystal structure

Crystal pulling / Electronic grade

OR

Crystal pulling
Optical grade

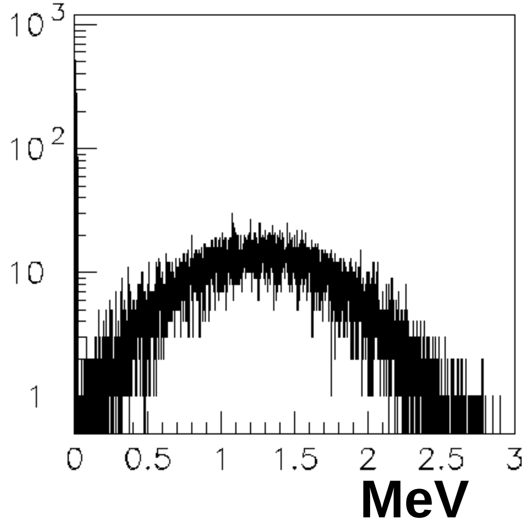
Casting
Optical grade

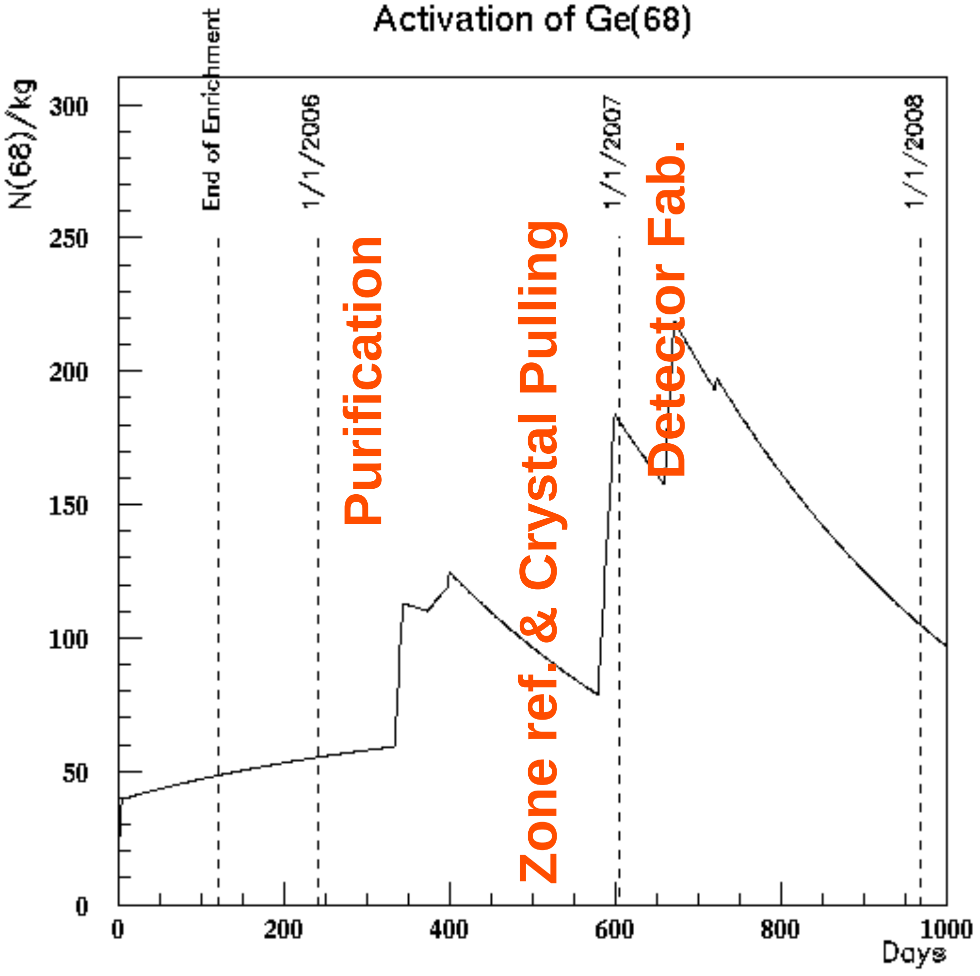
Backgrounds

The types of things we worry about:
e.g., cosmogenic activation of ^{68}Ge (about 6/(day kg) in enriched Ge)

^{68}Ge → ^{68}Ga via EC (10.6 KeV X-ray)
τ=271 days

^{68}Ga → ^{68}Zn via β^+ (90%, 1.9 MeV)
+ γ (0.511 MeV)
+ γ (0.511 MeV)
τ=68 minutes





Practice run - 20 day trip from Siberia in special transport container

Success !

Active Background Suppression

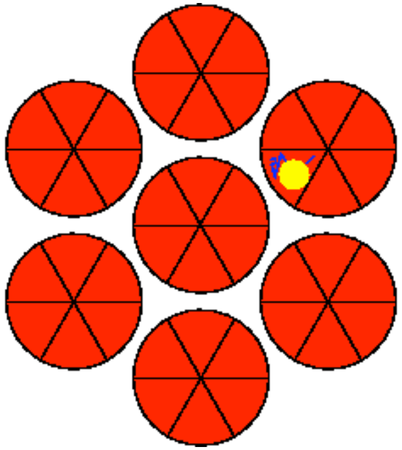
Background sources:

Cosmogenically produced ^{68}Ge and ^{60}Co

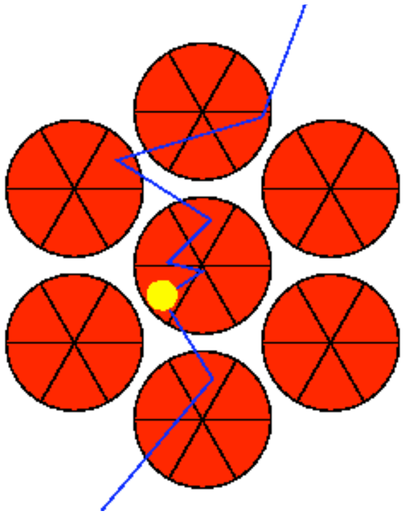
U/Th contamination, ^{210}Pb on surface

External gammas

Signal:



Background (^{60}Co):



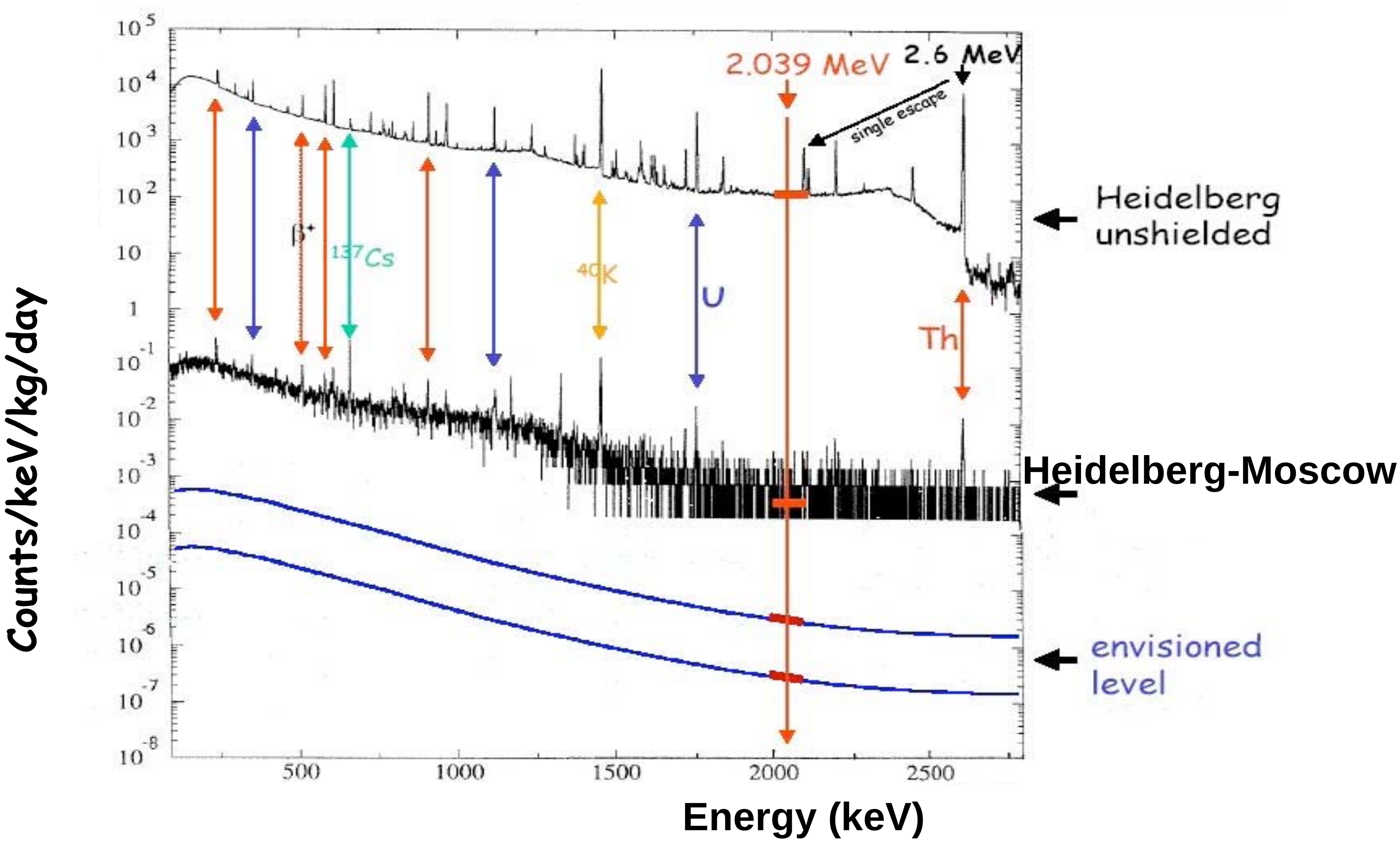
Signatures:

Signal has two electrons in final state → range ~mm

Background sources mostly γ with E_γ>2 MeV

Compton scattering dominant interaction, range ~few cm

Background Suppression

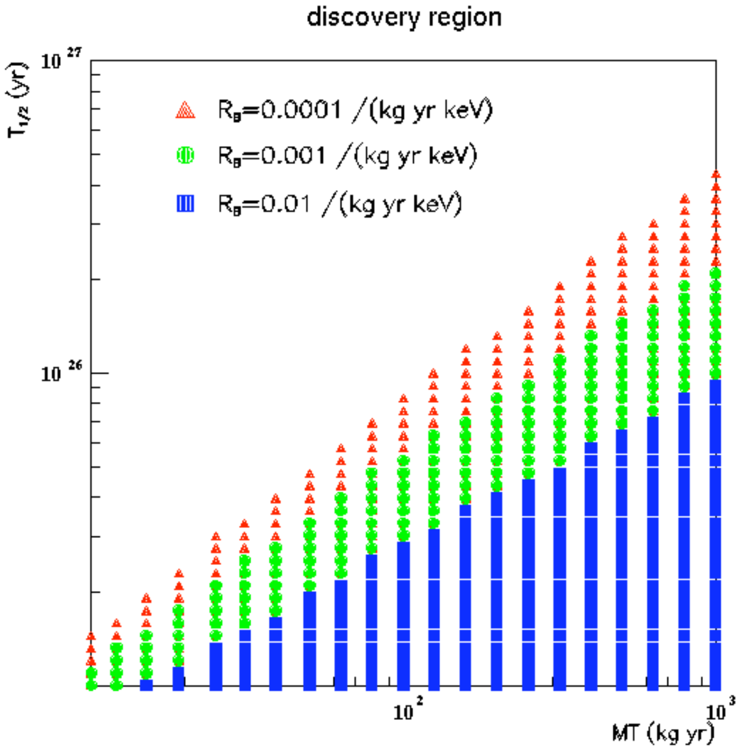


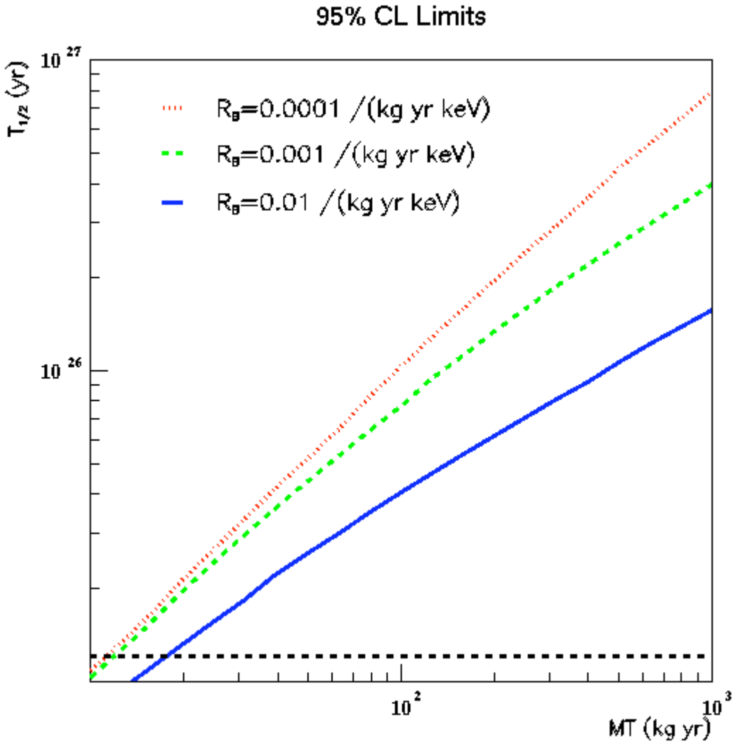
GERDA Sensitivity

Phase I: ca. 20 kg in 8 detectors, background level 10^{-2}/(kg yr keV)

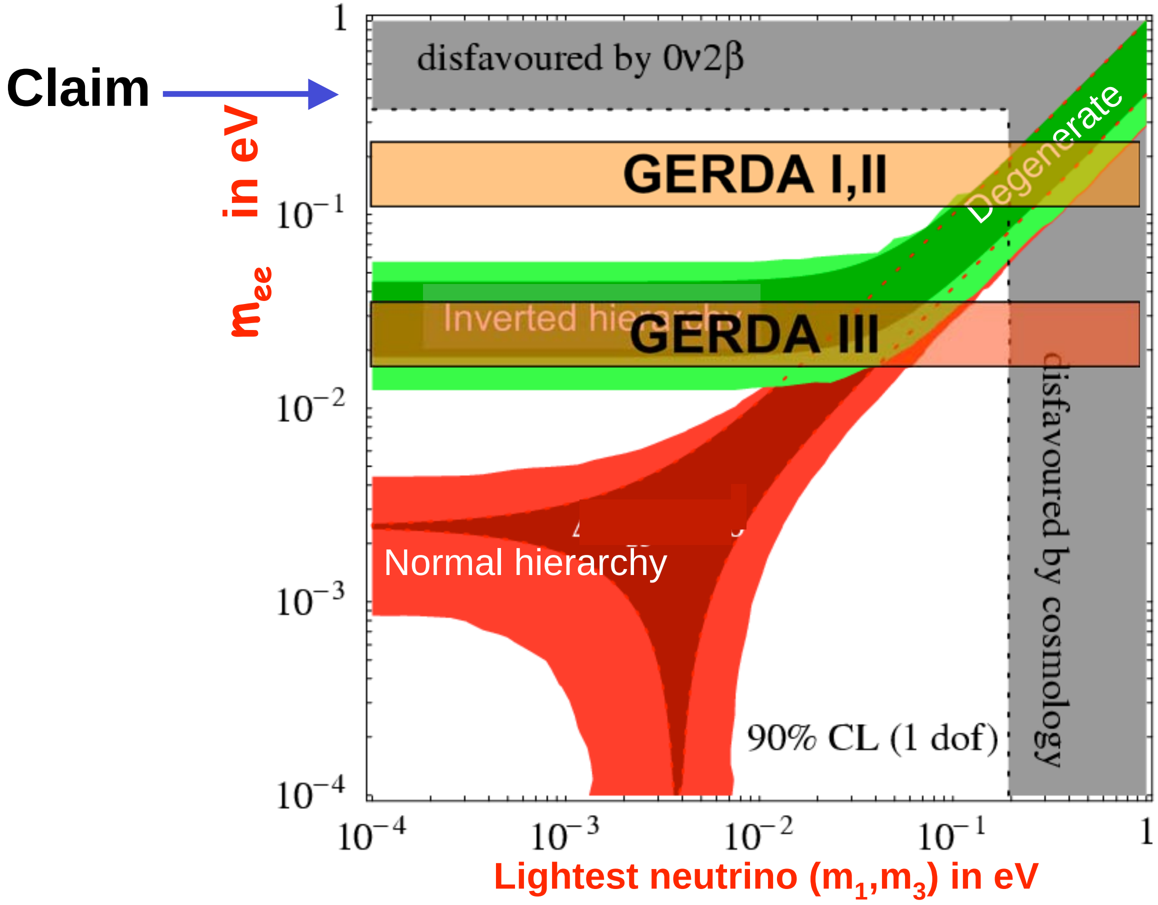
Phase II: addition 20 kg in 10 detectors, background level 10^{-3}/(kg yr keV)

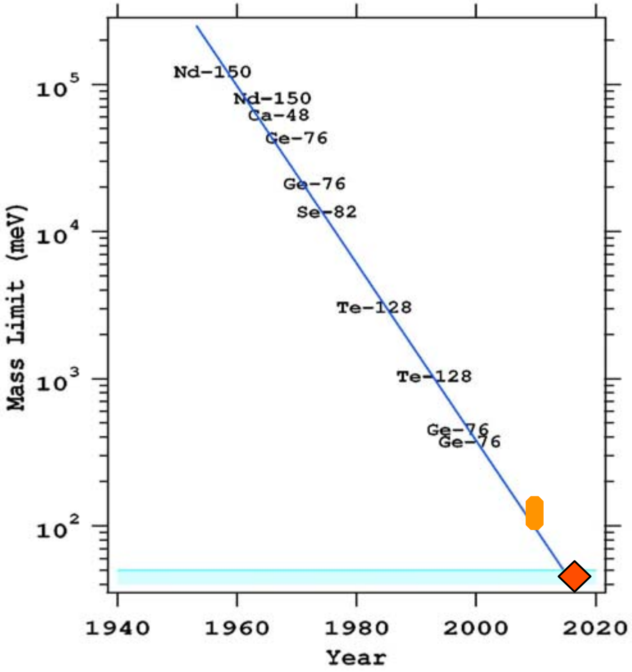
Sensitivity analysis:





Summary





1. **We will confirm or rule out the Klapdor-Kleingrothaus et al. claim**
2. **If not verified and background reduction to the level 10^{-3}/(kg yr keV) demonstrated, go for Phase III (ca. 1 ton, 20 meV level)**
3. **We want to get started with data taking within 2 years - stay tuned !**