Ettore Majorana meets his shadow

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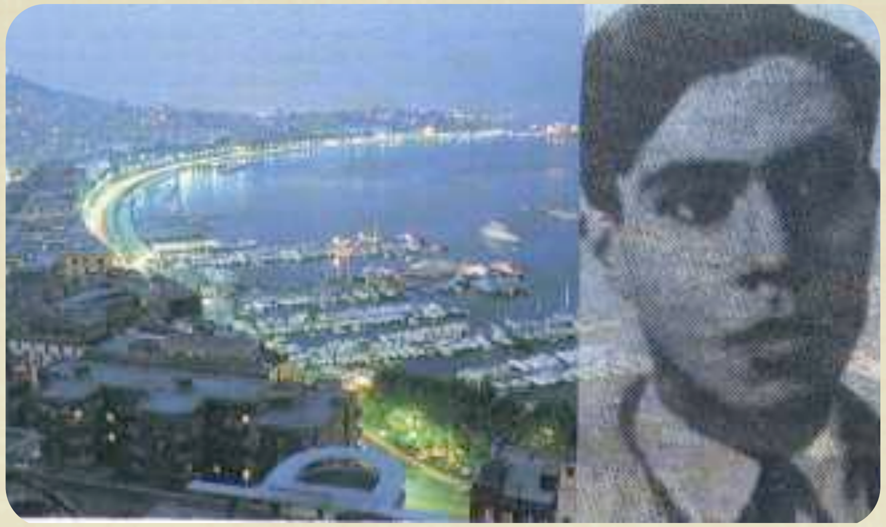
Meet the genius

"Because, you see, in the world there are various categories of scientists: people of a secondary or tertiary standing, who do their best but do not go very far. There are also those of high standing, who come to discoveries of great importance, fundamental for the development of science.

But then there are geniuses like Galileo and Newton. Well, Ettore was one of them. Majorana had what no one else in the world had".

E. Fermi

La scomparsa



Nel marzo del 1938, prima di dissolversi e nel nulla, lo scienziato catanese Ettore Majorana, trentaduenne, fisico teorico di altissima, internazionale levatura, docente all'Università di Napoli, molto vicino al gruppo dei «ragazzi di via Panisperna», cioè i giovani ricercatori atomici guidati a Roma da Fermi, scrive due lettere, una ai familiari, una a un amico, nelle quali esprime il proposito di suicidarsi. Nella seconda annunzia addirittura il giorno, l'ora e il luogo del suicidio. Ma non vi tiene fede: non e solo il suo corpo non sarà ritrovato nel luogo indicato, e nemmeno in nessun altro luogo, ma le ricerche, attivate da Mussolini, approderanno a una mezza certezza e cioè che Majorana era ancora vivo qualche giorno dopo

La scienza, come la poesia, si sa che sta ad un passo dalla follia

Original - Photocopie of PLC 0393

Abschrift/15.12.56 PW

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

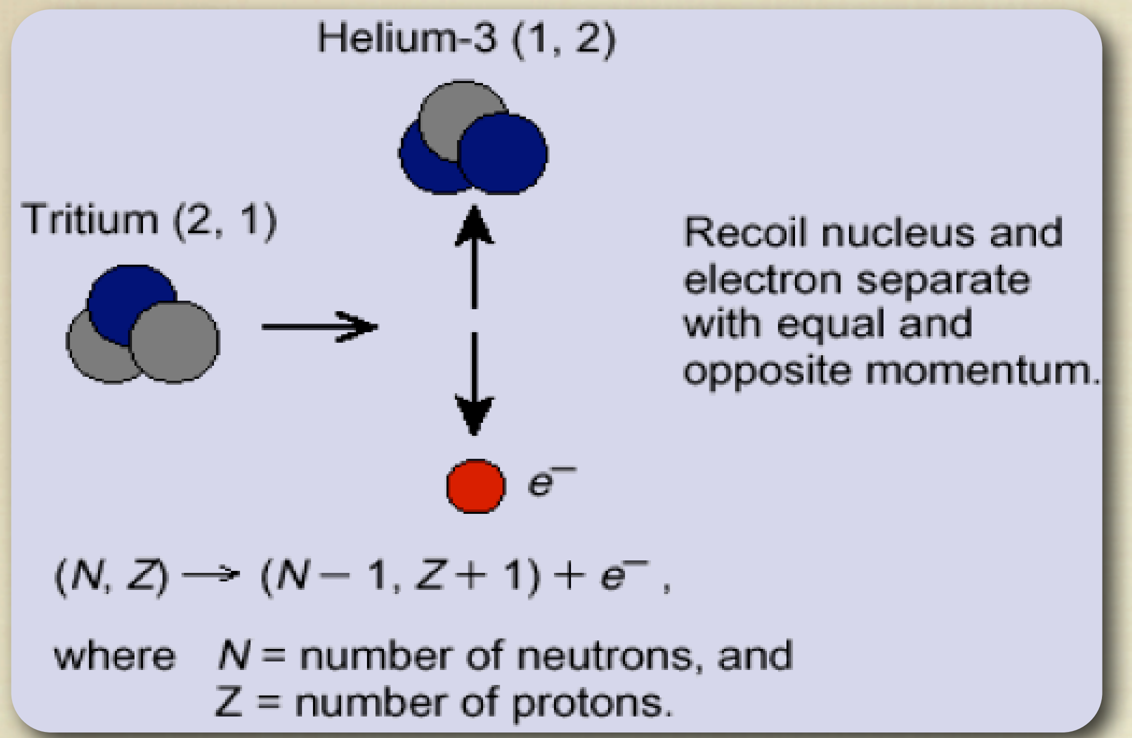
Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grössenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

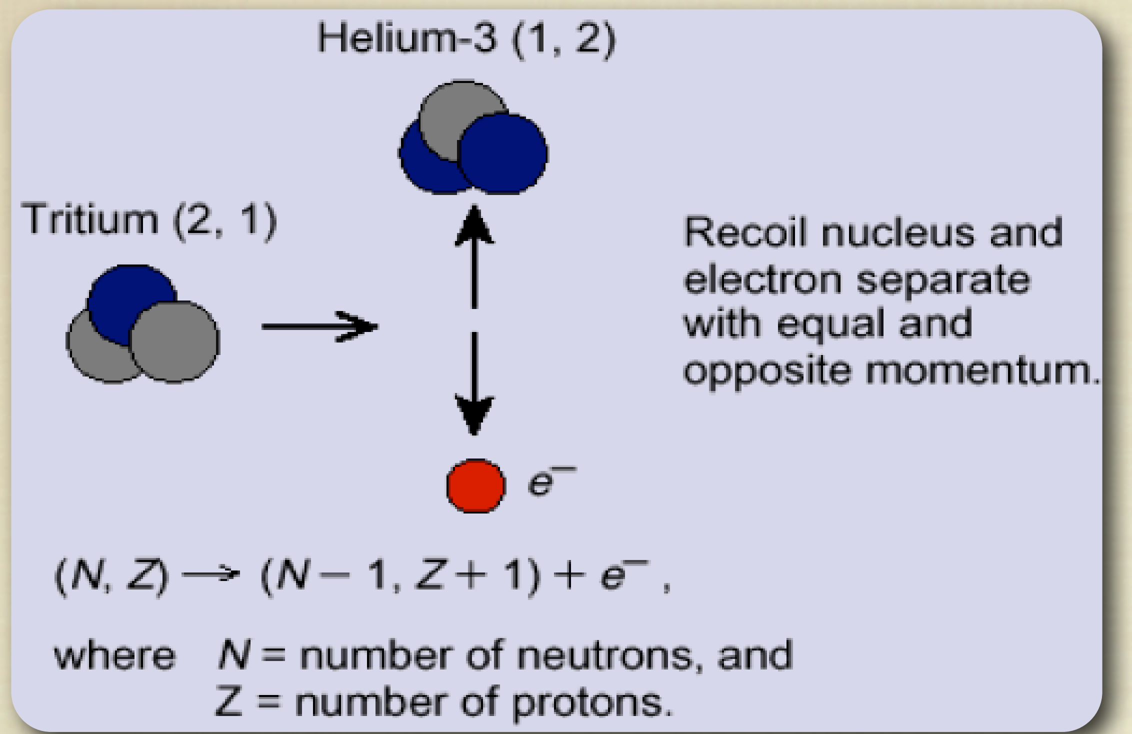
DEAR RADIACTIVE LADIES AND GENTLEMEN
... TO EXPLAIN THE CONTINUOUS SPECTRUM IN THE BETA DECAY OF SOME NUCLEI.. I HAVE FOUND A DESESPARATE REMEDY TO SAVE THE LAW OF ENERGY CONSERVATION...

Beta decay

Beta decay


Helium-3 (1, 2)
Tritium (2, 1)
Recoil nucleus and electron separate with equal and opposite momentum.
e^-
$(N, Z) \longrightarrow (N-1, Z+1) + e^-$,
where N = number of neutrons, and
Z = number of protons.

Beta decay



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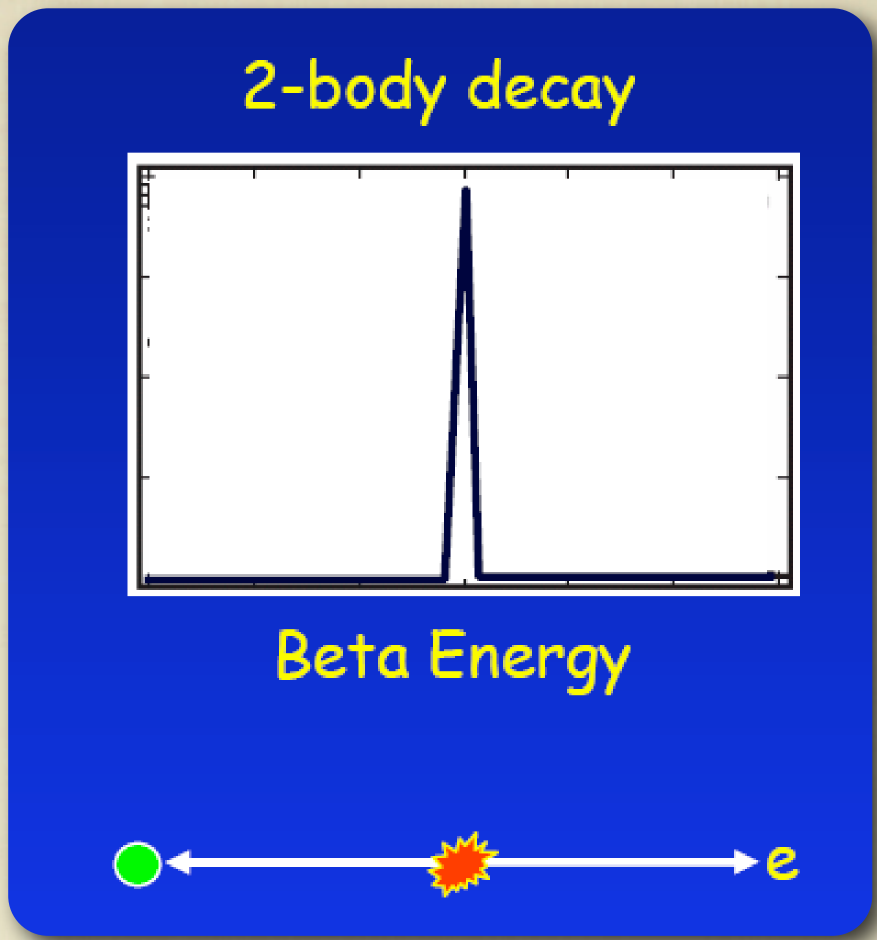
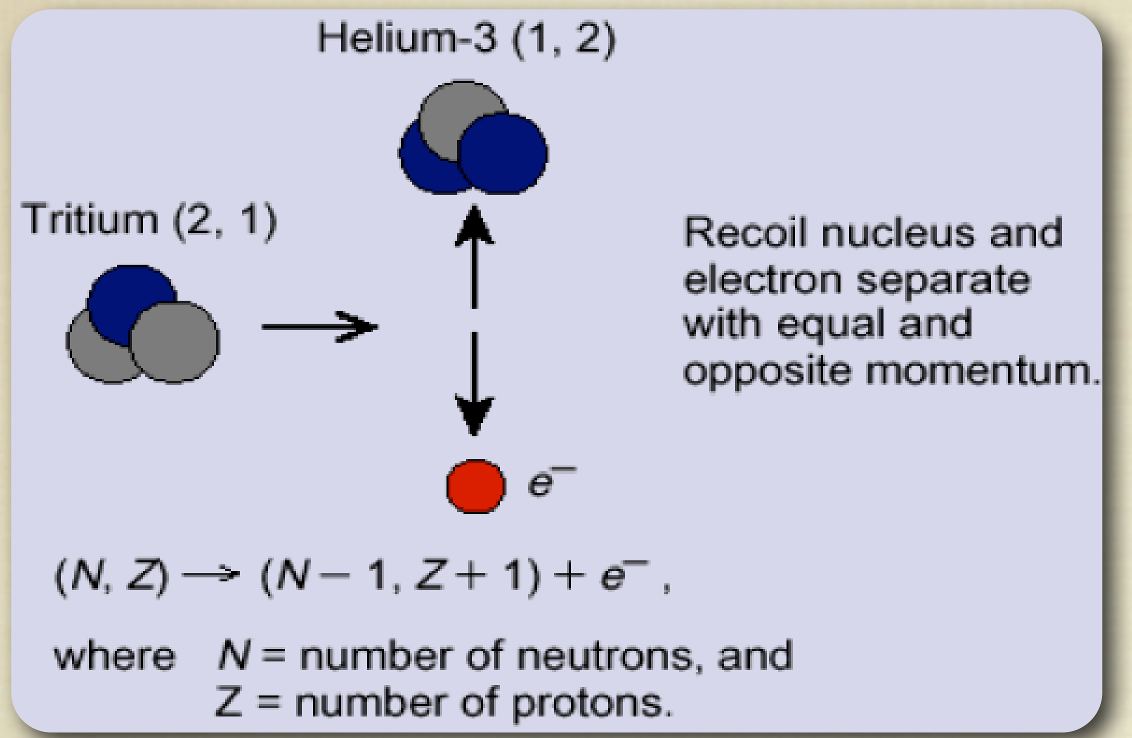
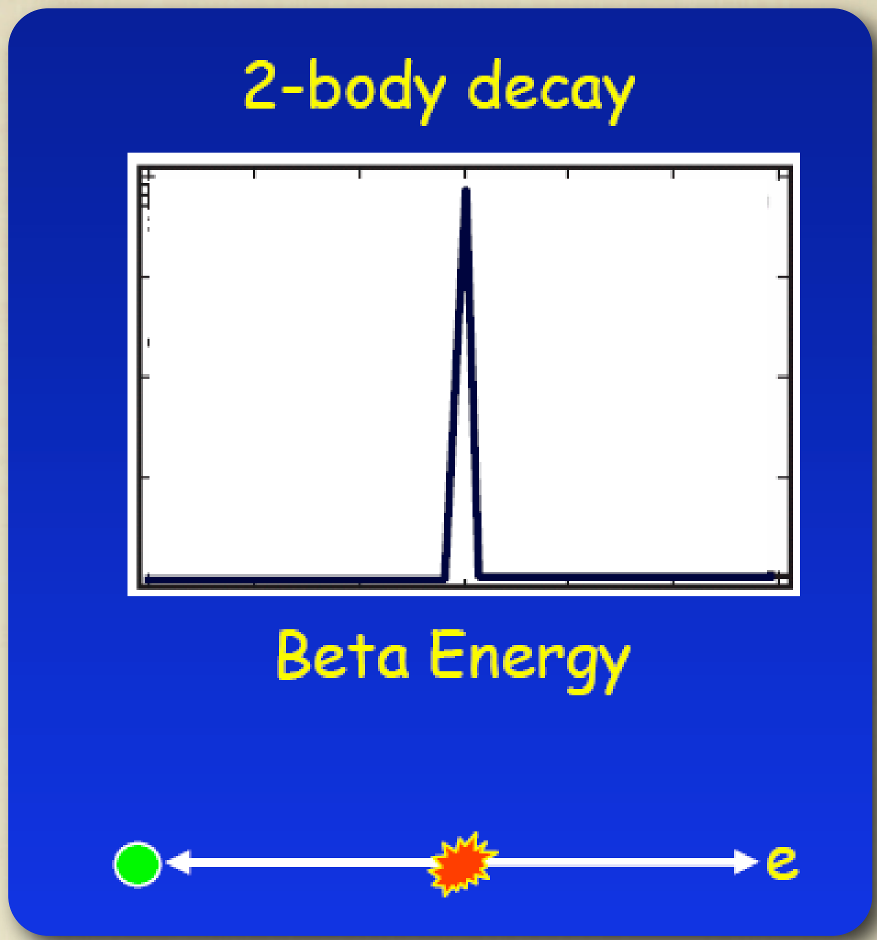


2-body decay
Beta Energy
e

Beta decay



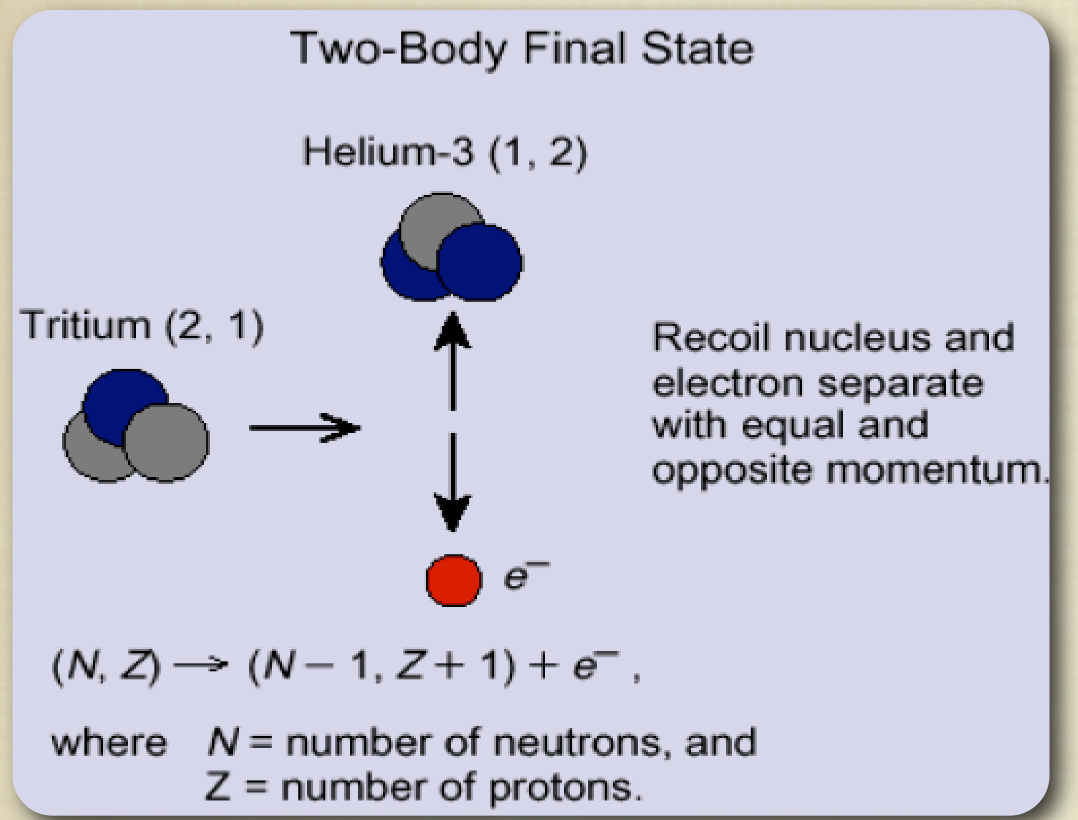


Only one electron observed, carrying the available energy in the reaction

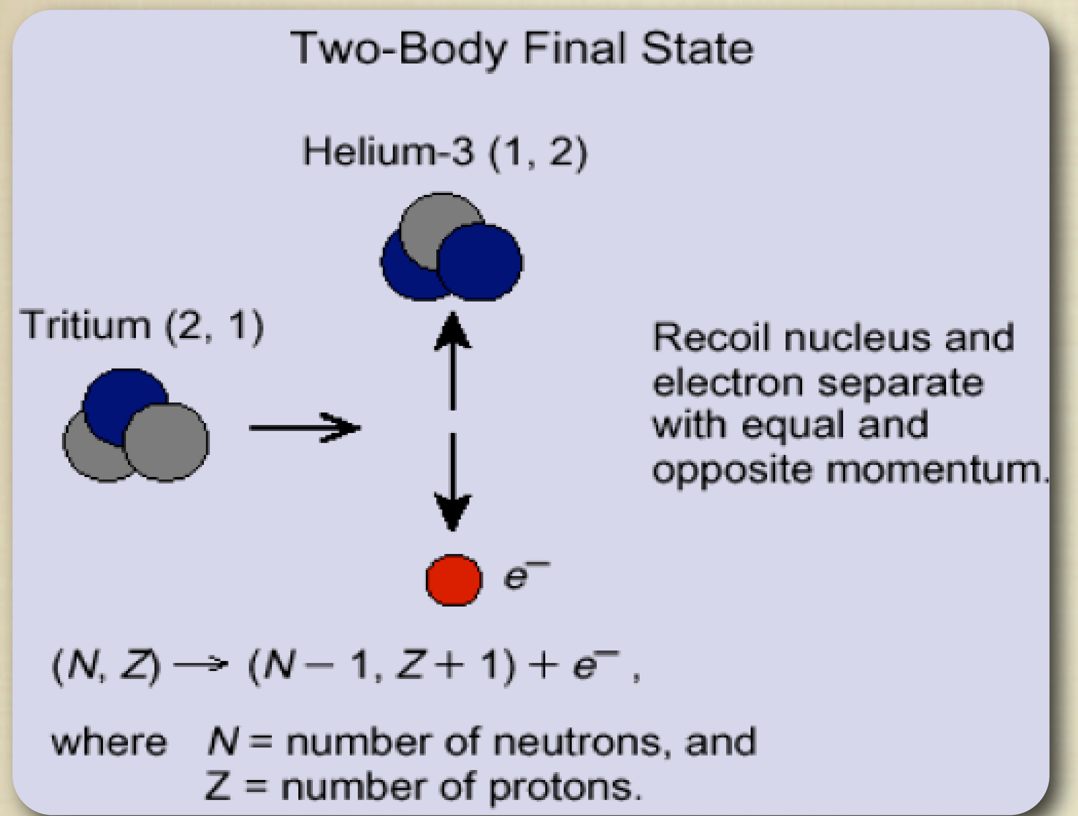
Therefore, all the emitted electrons should carry the same energy

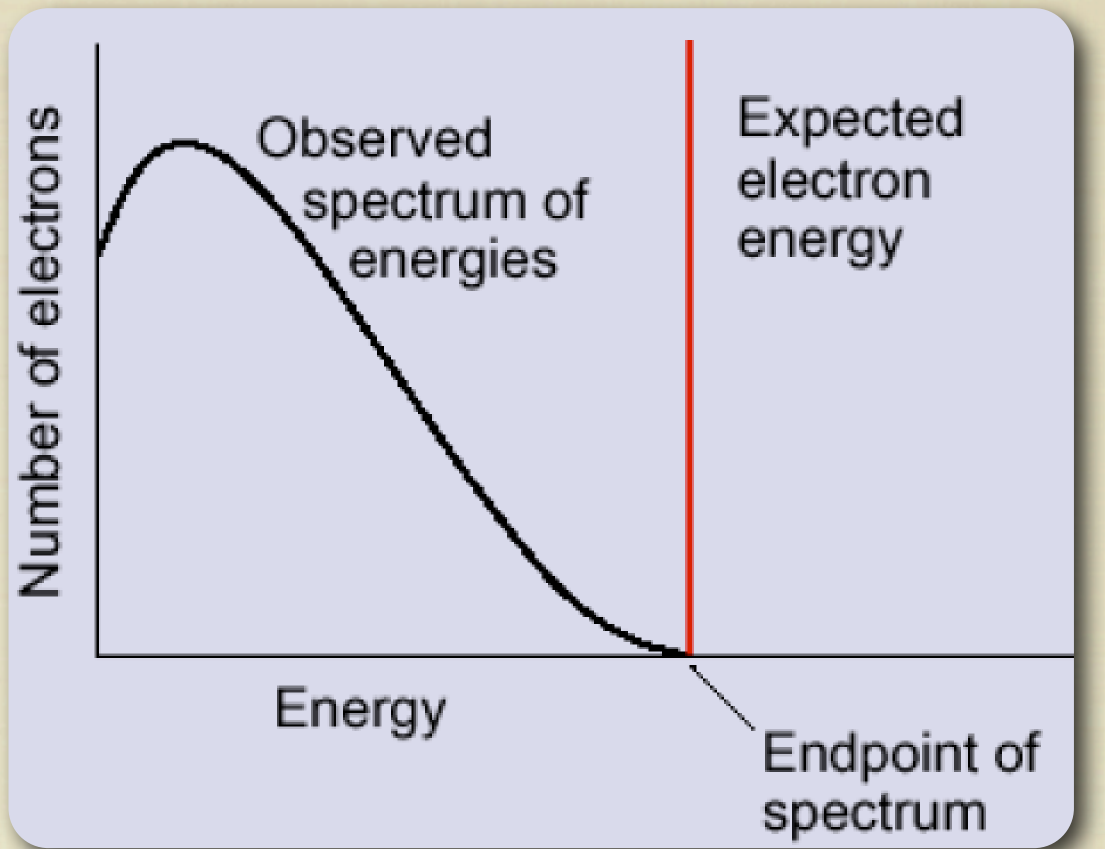
Energy conservation?

Energy conservation?

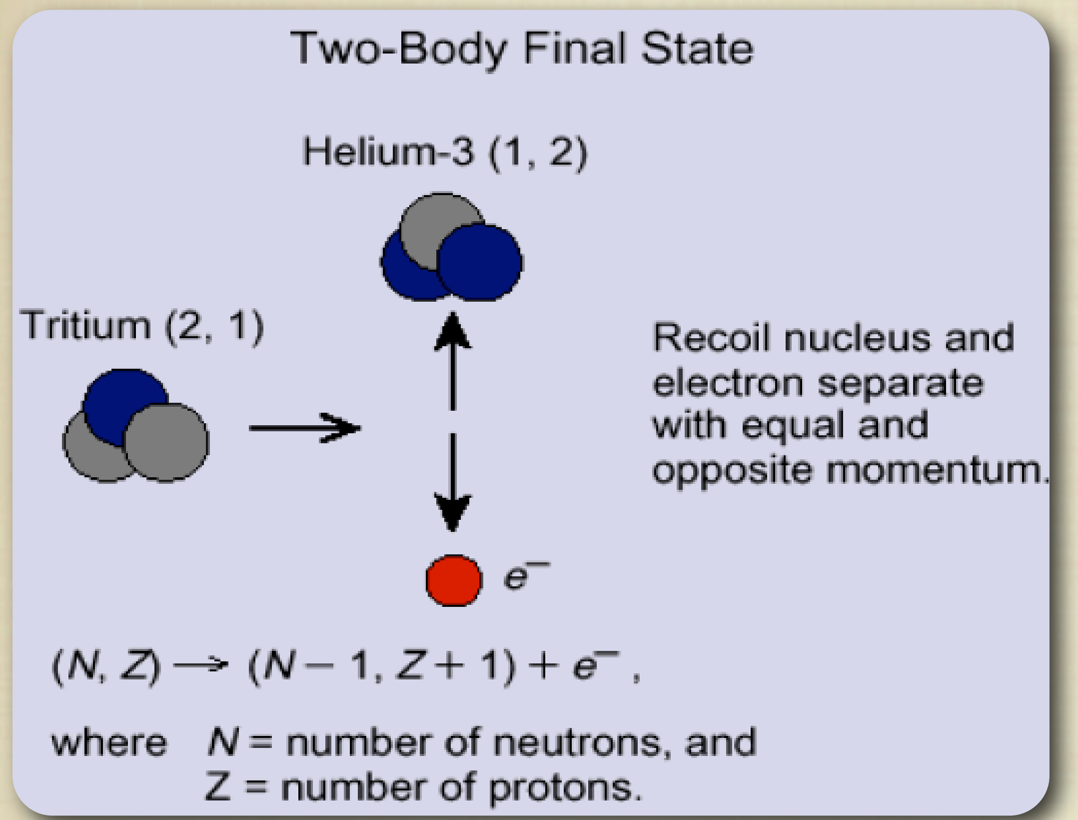


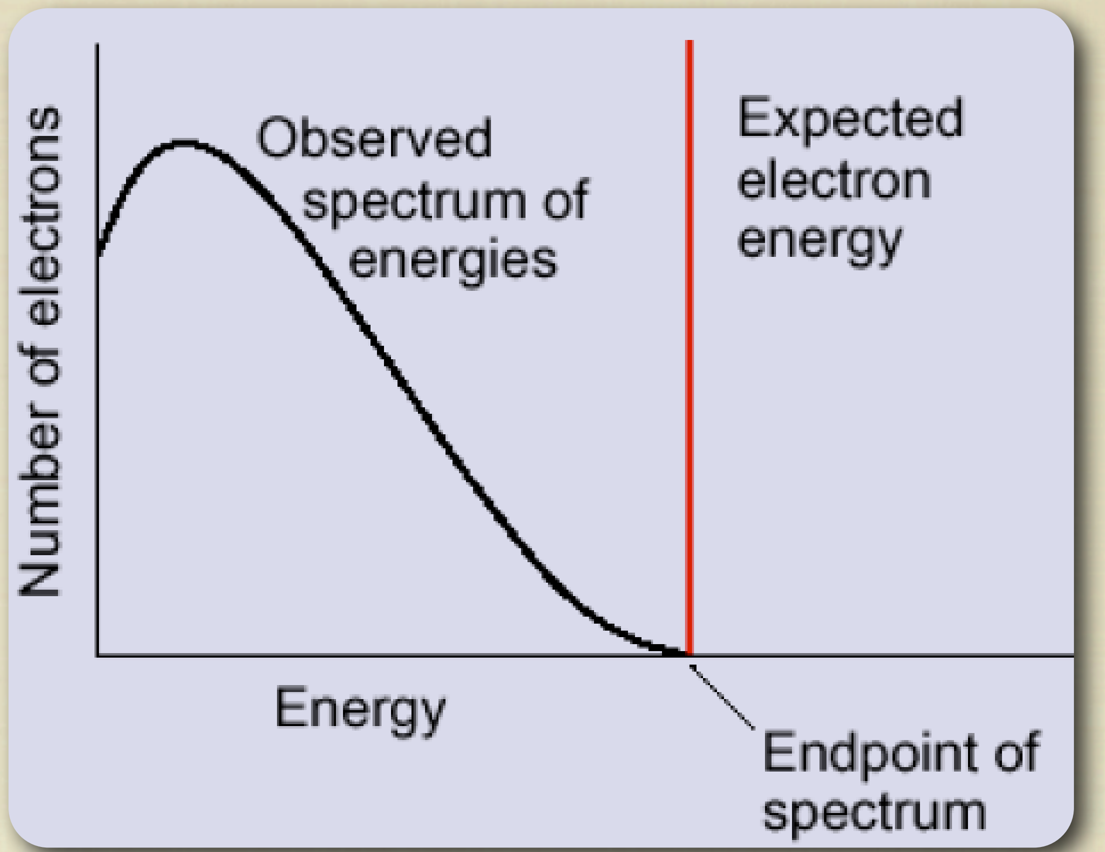
Energy conservation?





Energy conservation?



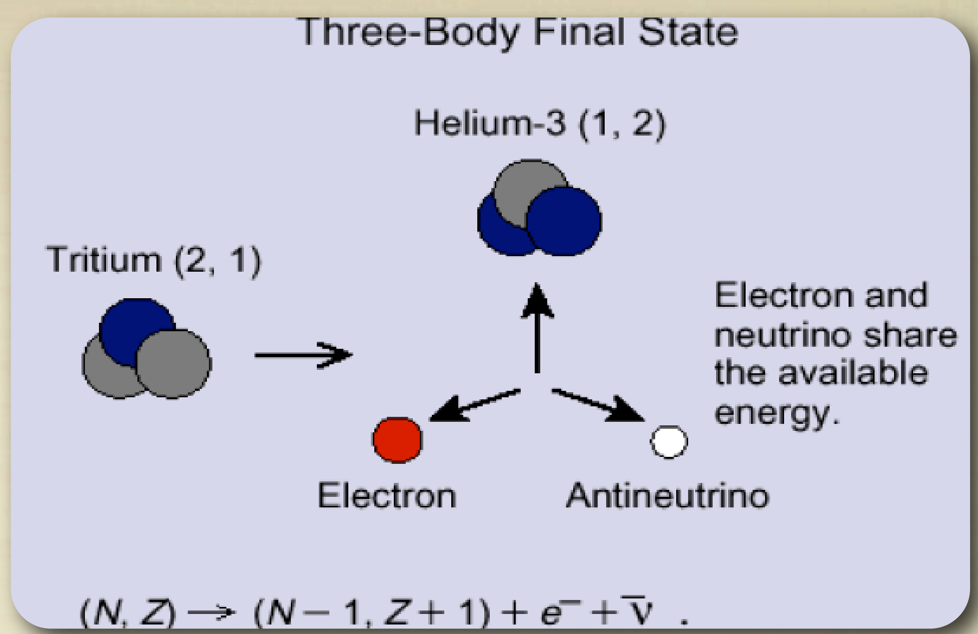


Experimentally one observes all possible energies between 0 and the maximum enegy available rather than a monochromatic peak

Where is the missing energy going?

I HAV MADE A TERRIBLE THING...
I HAVE POSTULATED A PARTICLE
THAT CANNOT BE DETECTED

THIS IS SOMETHING THAT
NO THEORIST SHOULD EVER DO...



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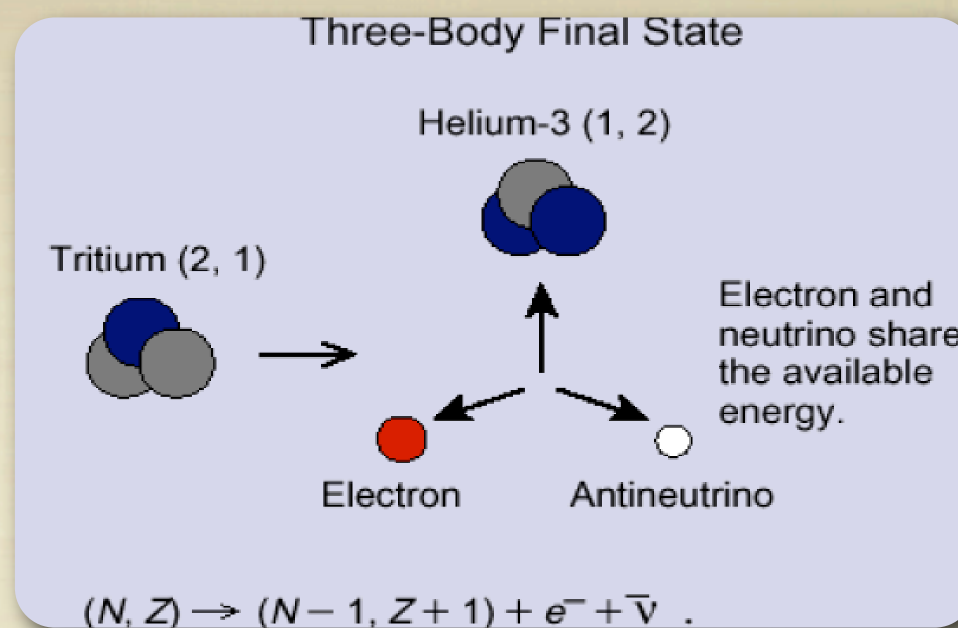

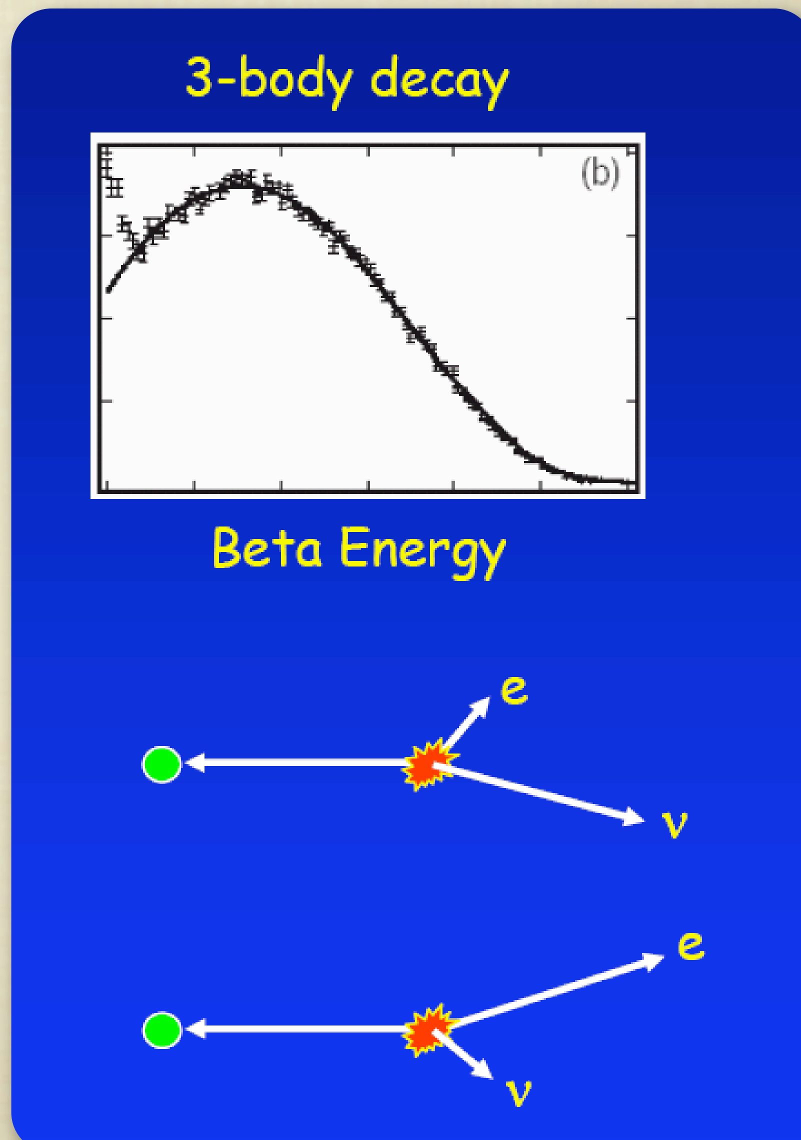

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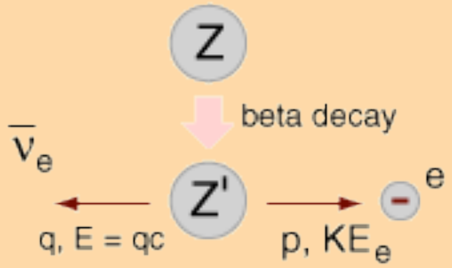
FERMI'S NEUTRINO



Fermi function to account for the nuclear coulomb interaction with the emitted particle.

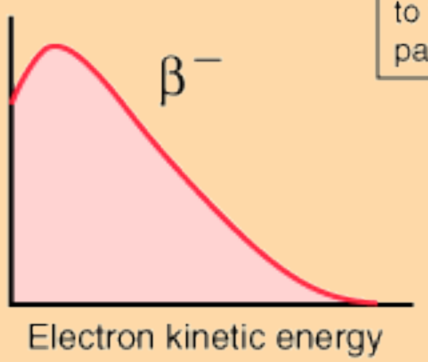
Shape factor to correct the matrix element for various types of "forbidden" decay paths.

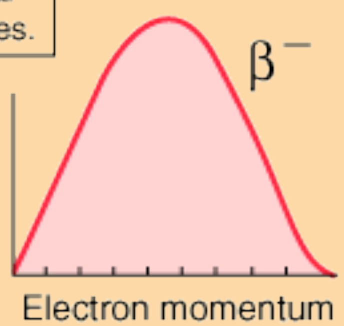
$$N(p) = \underbrace{Cp^2(Q - KE_e)^2}_{} F(Z', p) \left| M_{fi} \right|^2 S(p,q)$$

Distribution of electron momentum

Statistical factor derived from the density of final states available to the emitted particles.

Matrix element for allowed transitions gives the strength of the interaction between initial and final states.





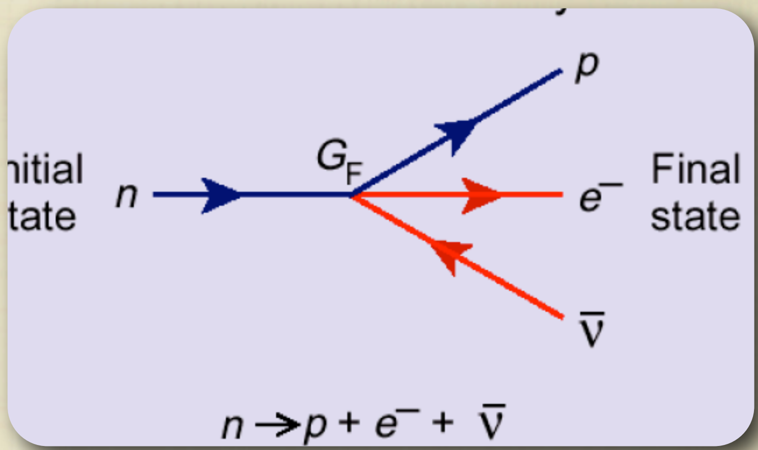
$$\lambda_{if} = \frac{2\pi}{\hbar} \left| M_{if} \right|^2 \rho_f$$

Fermi's Golden Rule

Transition probability

Matrix element for the interaction

Density of final states

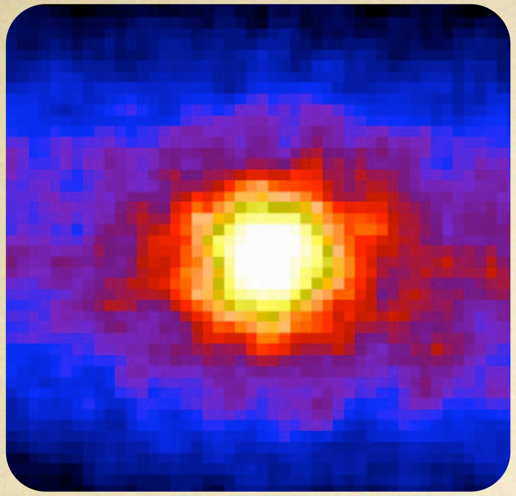


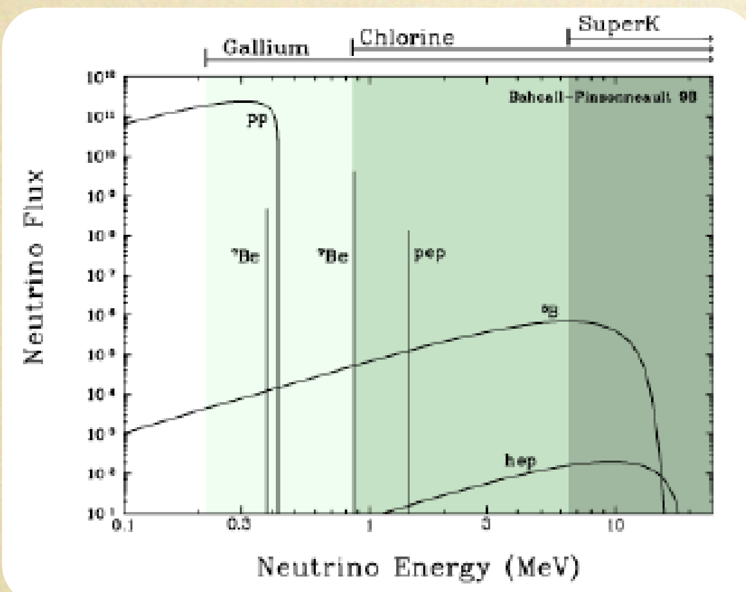
IN 1936 FERMI DEVELOPS THE FORMALLY THE BETA DECAY THEORY

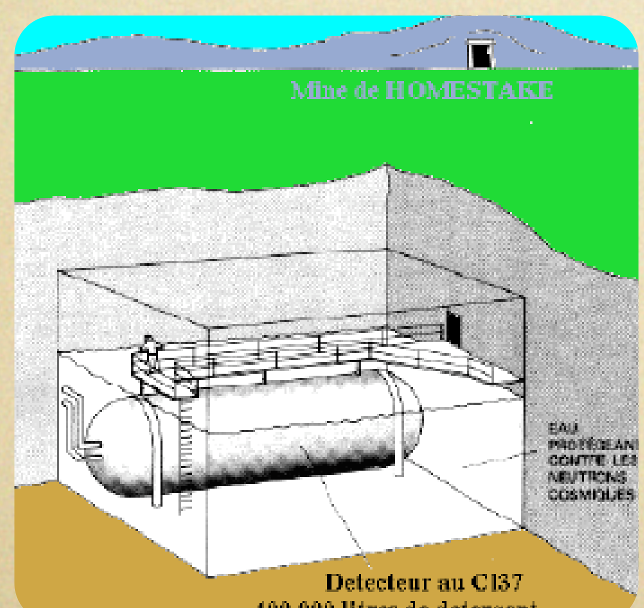
HE REALIZES THAT THE NEUTRINO HAS A MASS WHICH IS EITHER VERY LIGHT OR ZERO

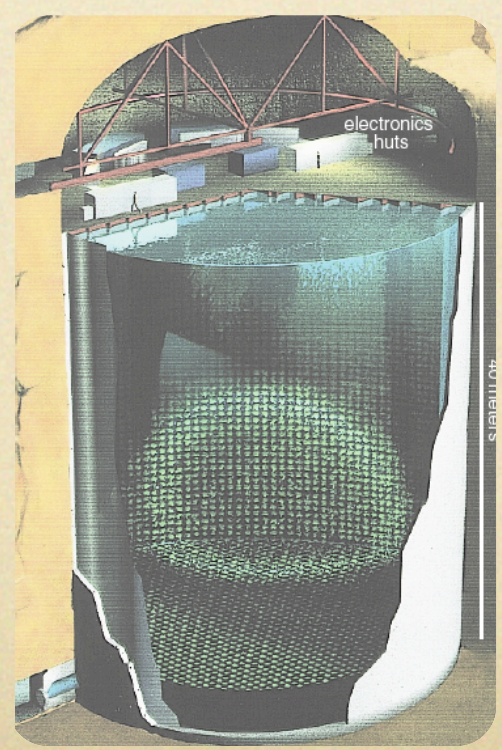
HIS GREAT ARTICLE IS FAMOUSLY REJECTED BY NATURE

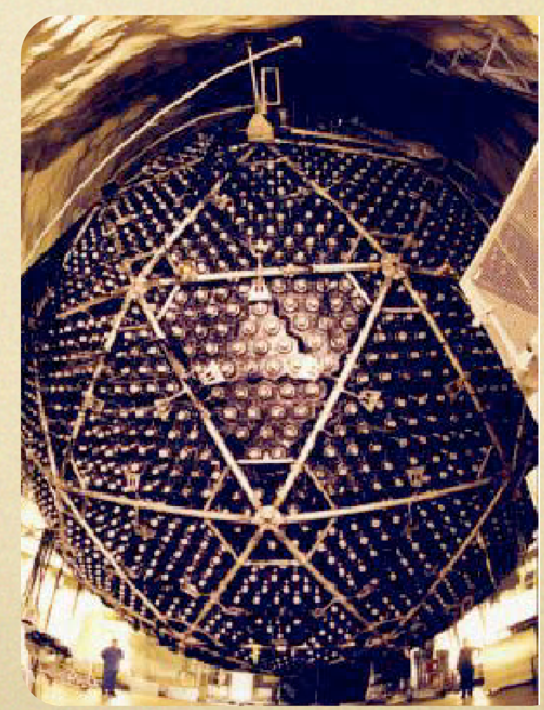
1968-1995-2002: Solar anomaly



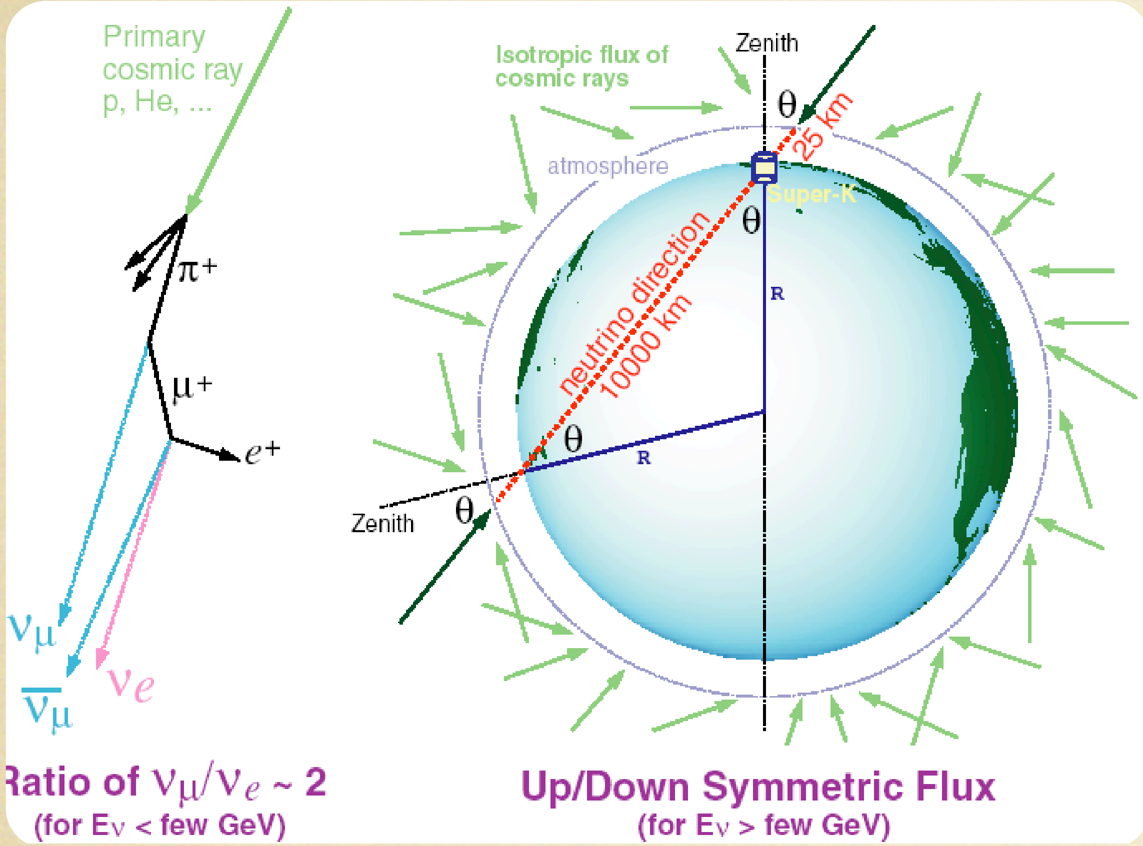








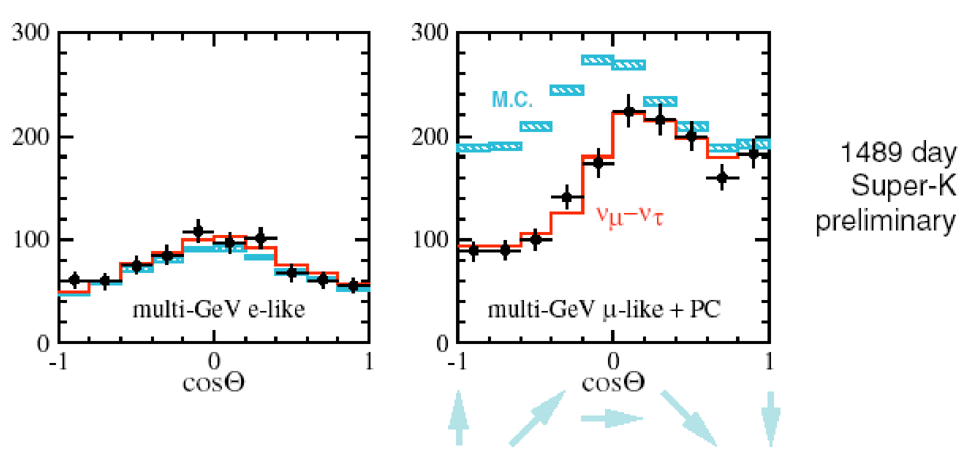
1988-1998:
Atmospheric Anomaly

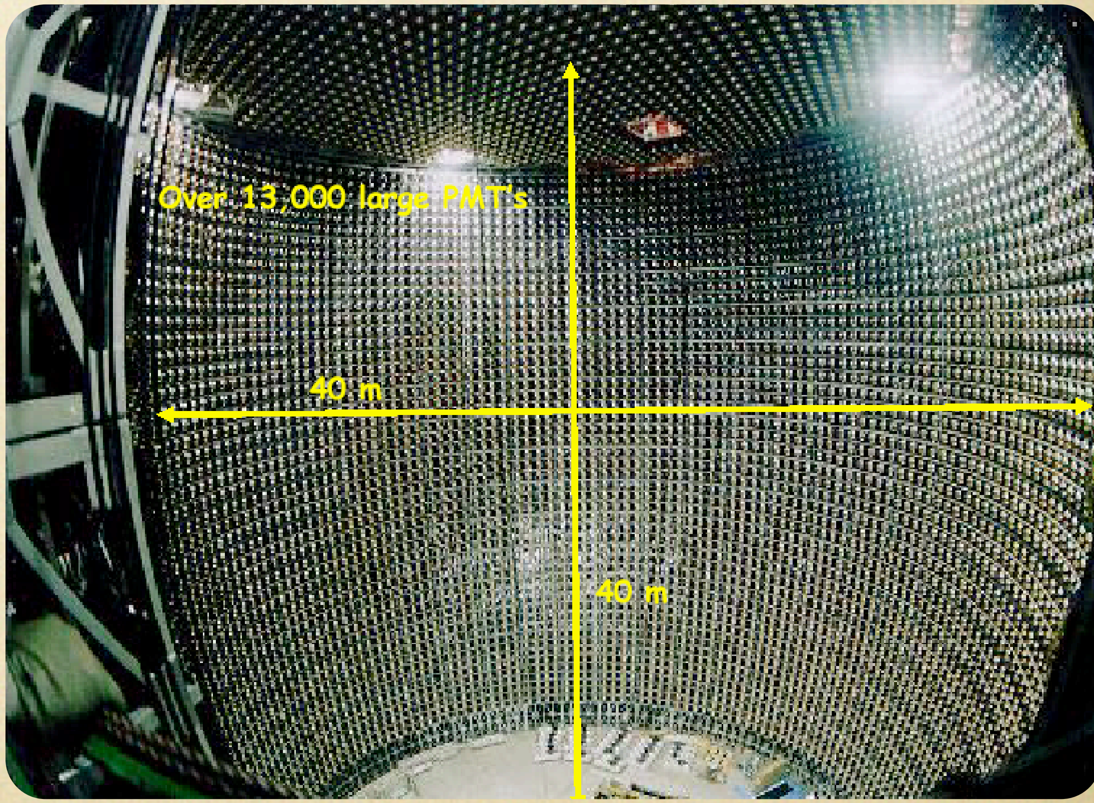


sub-GeV: $$\frac{(N_\mu/N_e)_{DATA}}{(N_\mu/N_e)_{M.C.}} = 0.688 \pm 0.016_{\text{stat.}} \pm 0.050_{\text{sys.}}$$

multi-GeV: $$\left(\frac{N_{UP} - N_{DOWN}}{N_{UP} + N_{DOWN}}\right)_{\mu\text{-like}} = -0.303 \pm 0.030_{\text{stat.}} \pm 0.004_{\text{sys.}}$$

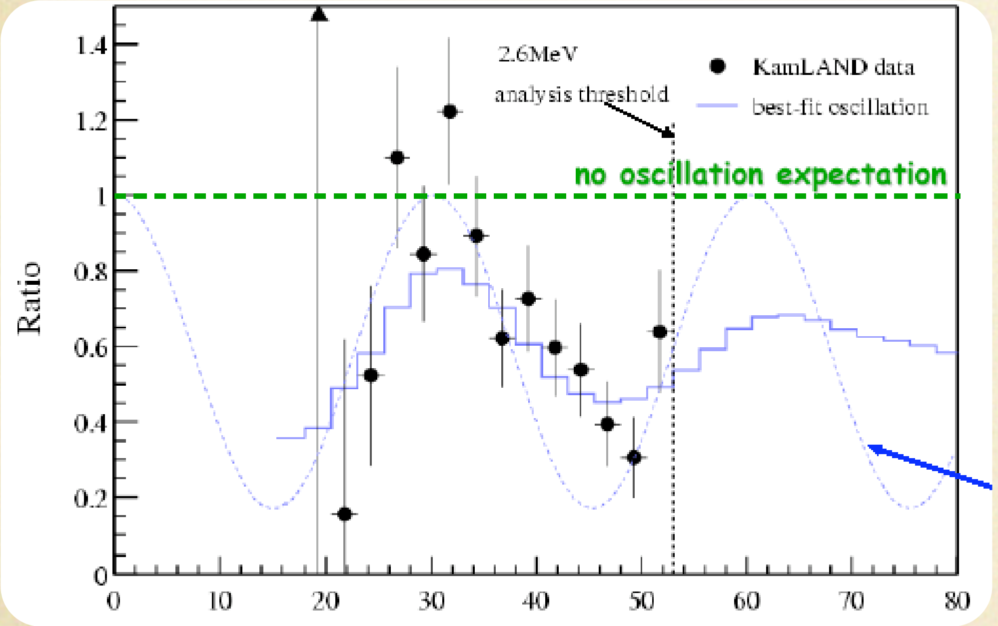
> 10σ deviation!



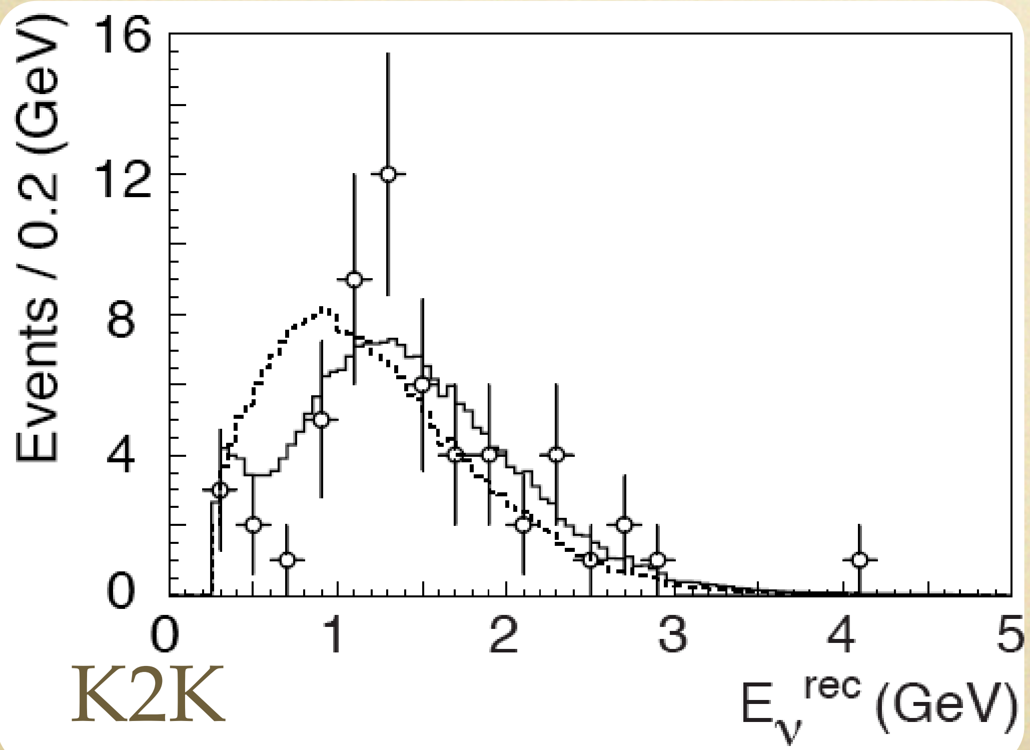


1998-2002-2004: Neutrino Oscillations

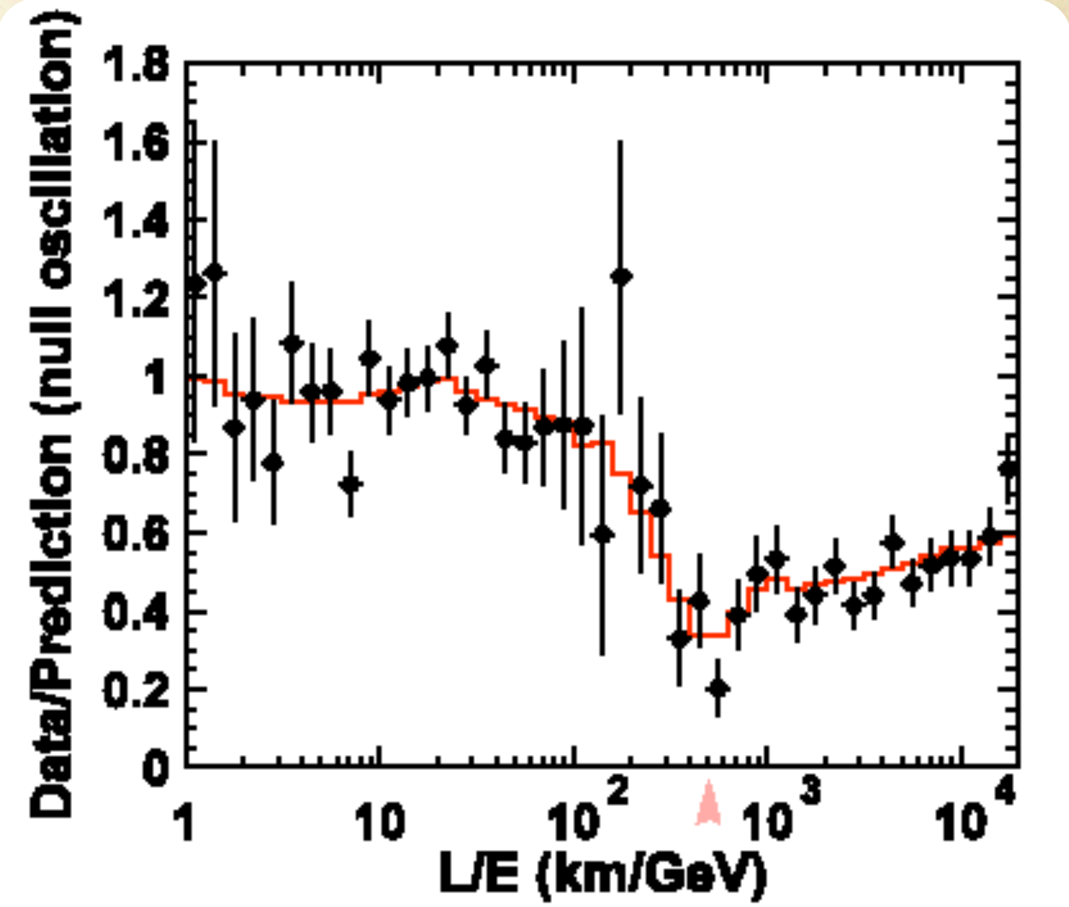
Kamland



L/E (km/MeV)



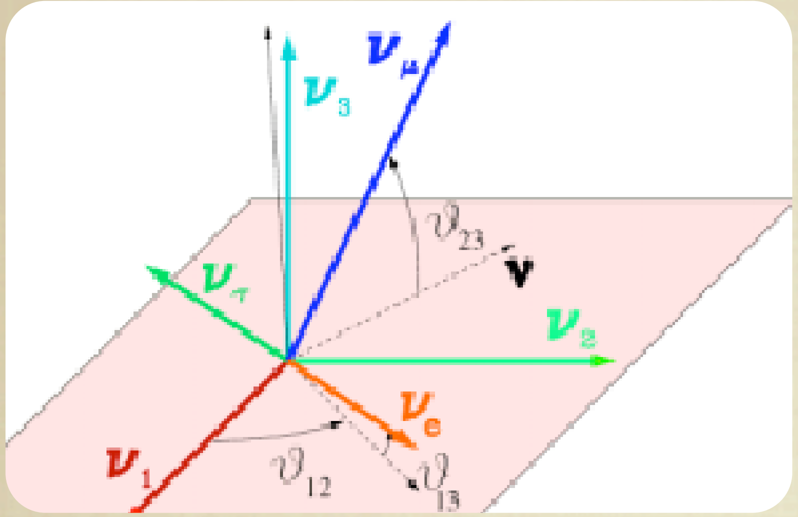
K2K

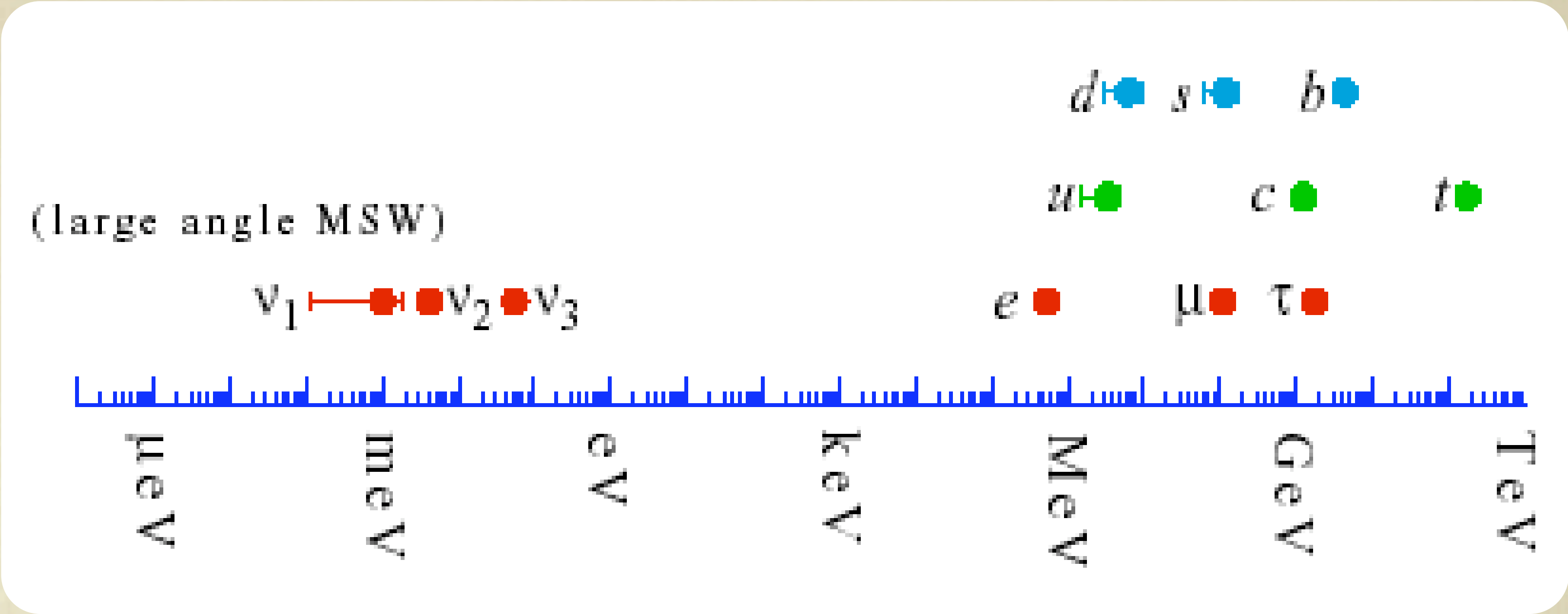


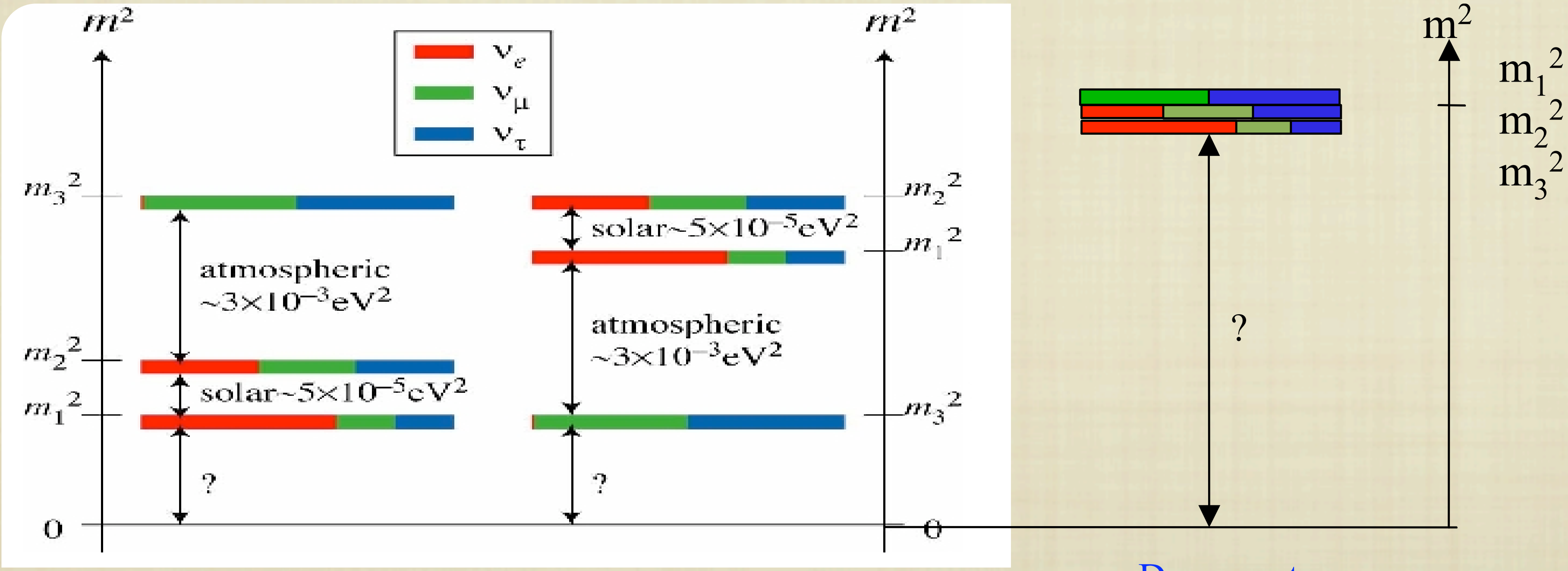
Super-K

oscillation dip seen at ~500 km/GeV

The neutrino picture





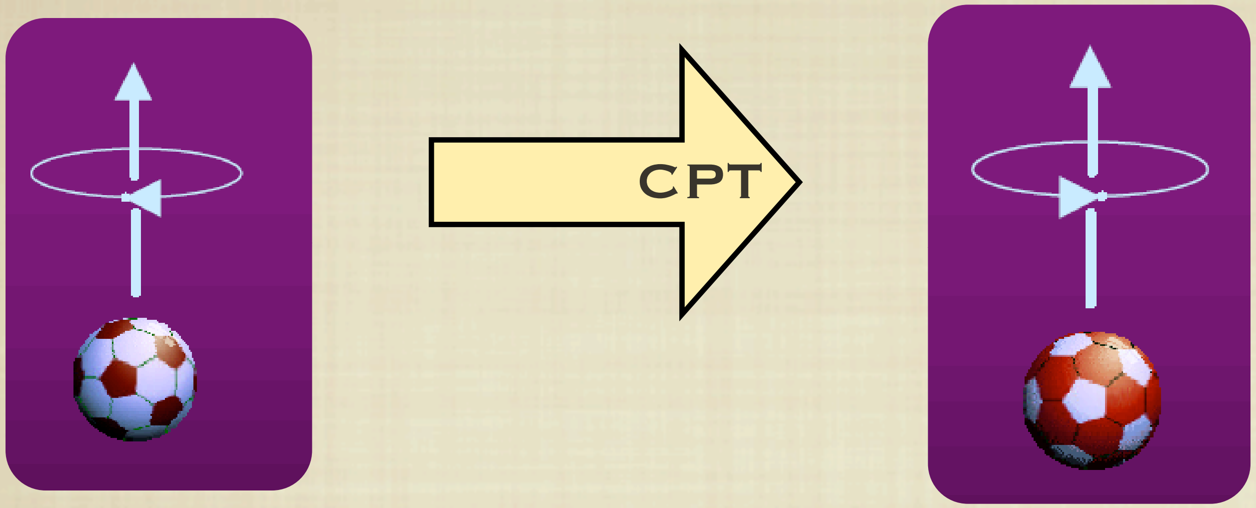


Normal hierarchy

Inverted hierarchy

Degenerate

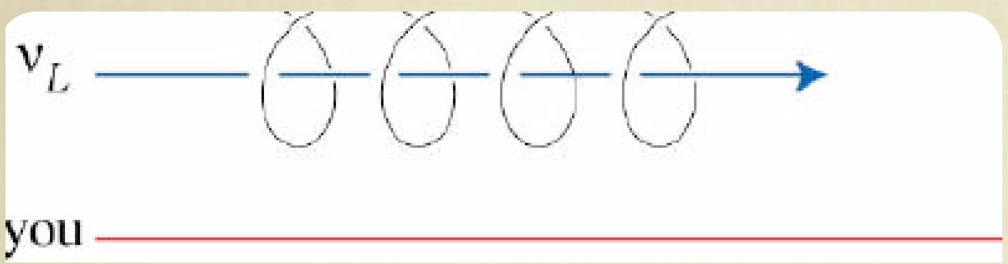
Particles & antiparticles

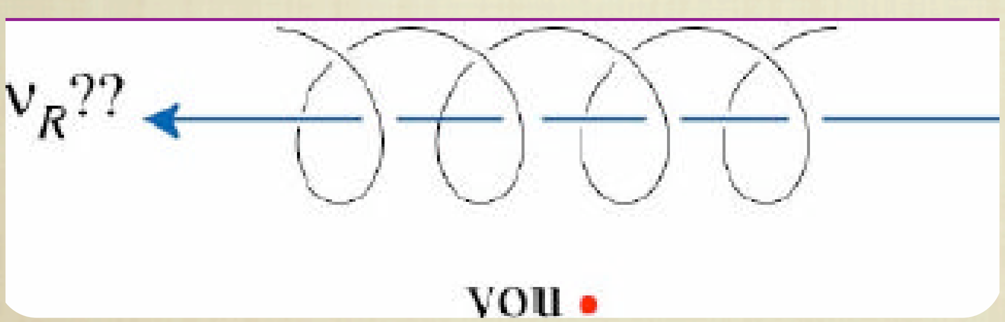


Same mass

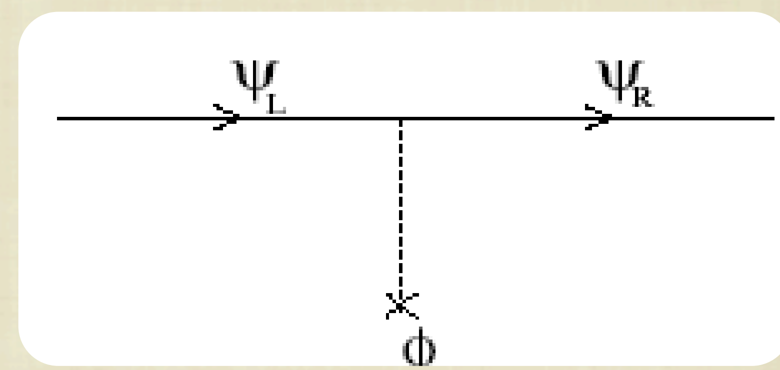
Opposite electric charge

Opposite helicity





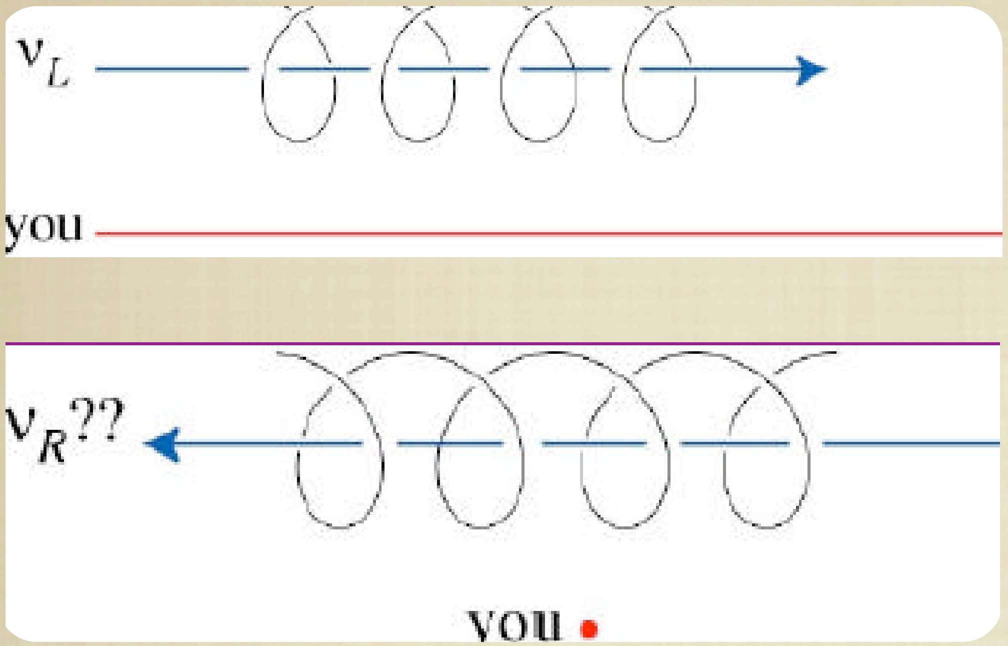
If a particle is massive left and right states must exist

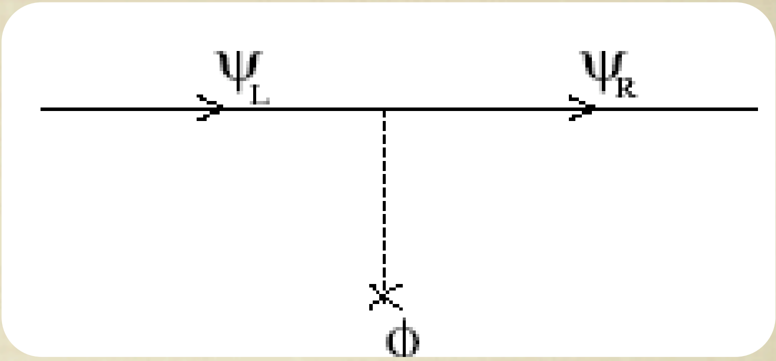


A (electrically) charged fermion such as the electron as left and right states for particle and antirparticle (which are distintc by electric charge)

Charged fermions couple left-right states to a scalar (the Higgs) to generate masses

Majorana's neutrino



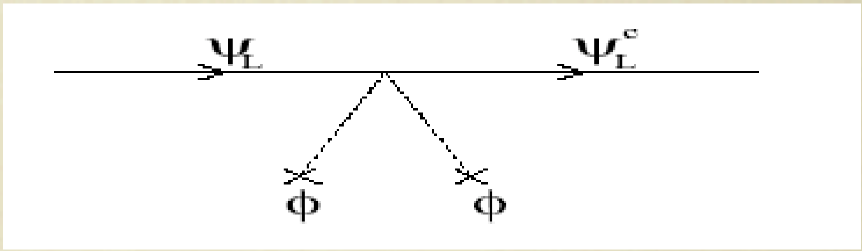


$$m_\nu = \lambda v$$

If neutrinos are massive then there exists a right-handed state (as for electrons)

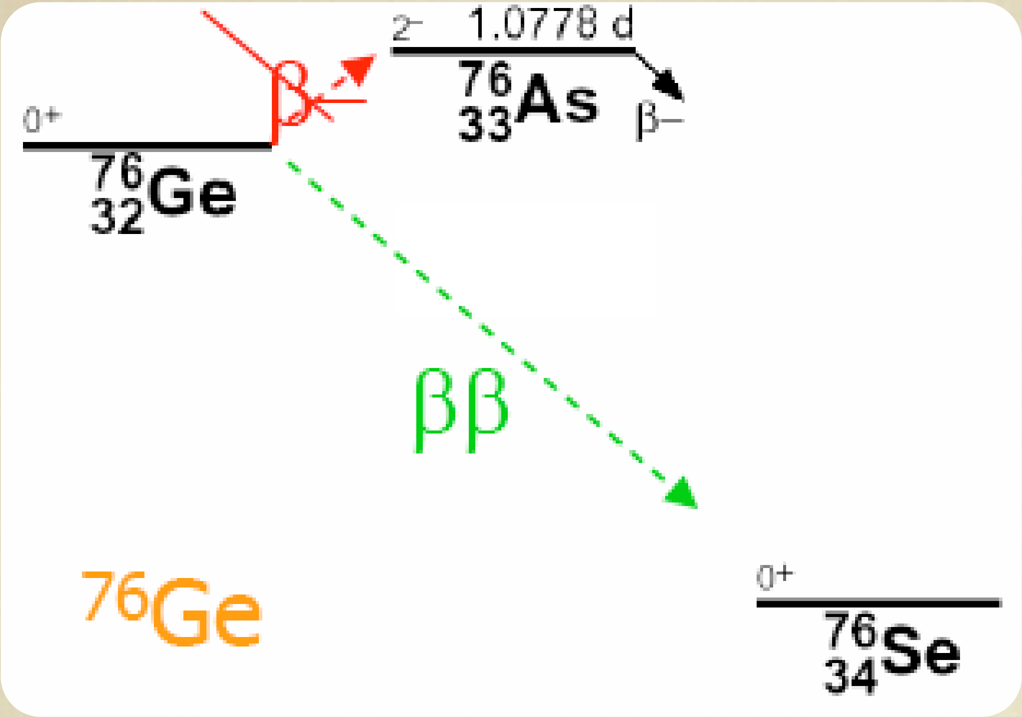
But unlike electrons, neutrinos do not have (electric) charge

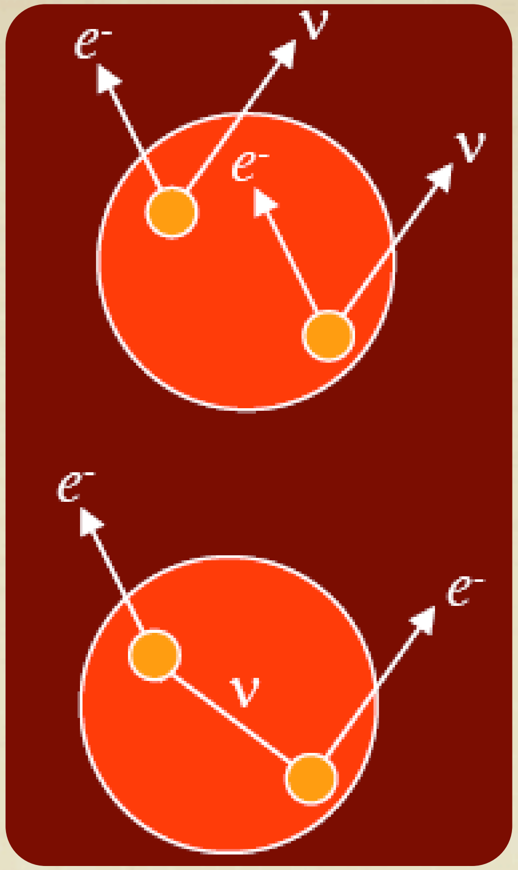
Then one could associate the right handed state to the antineutrino

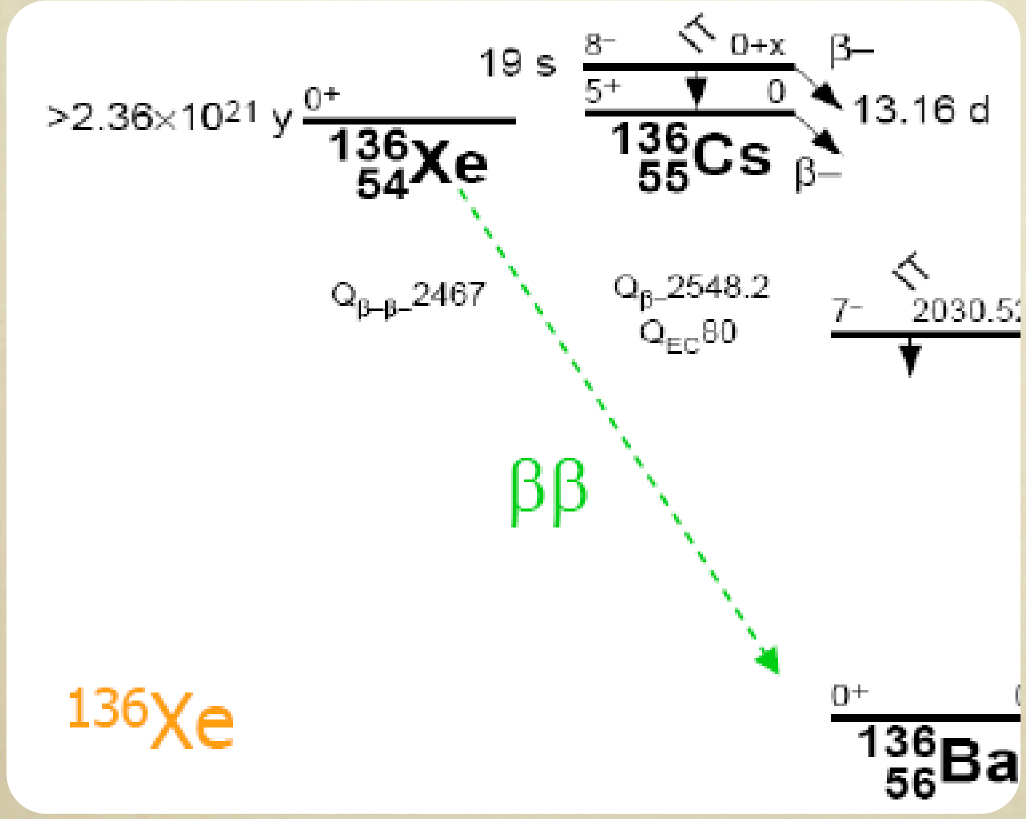


$$m_\nu = \lambda \frac{v^2}{\Lambda}$$

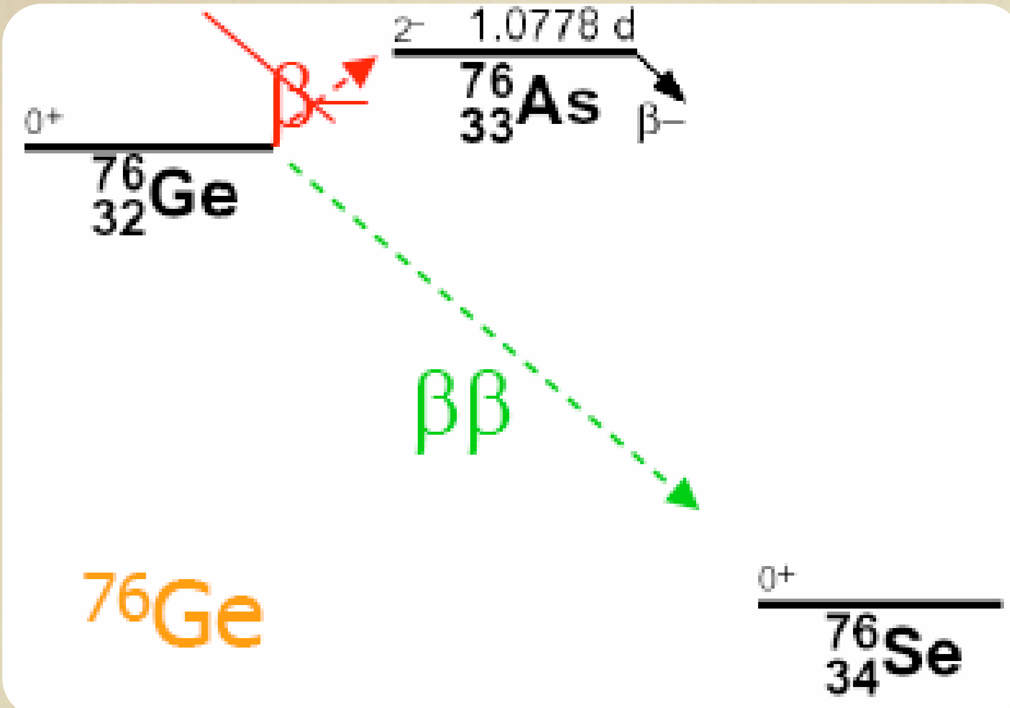
Neutrino double-beta decay

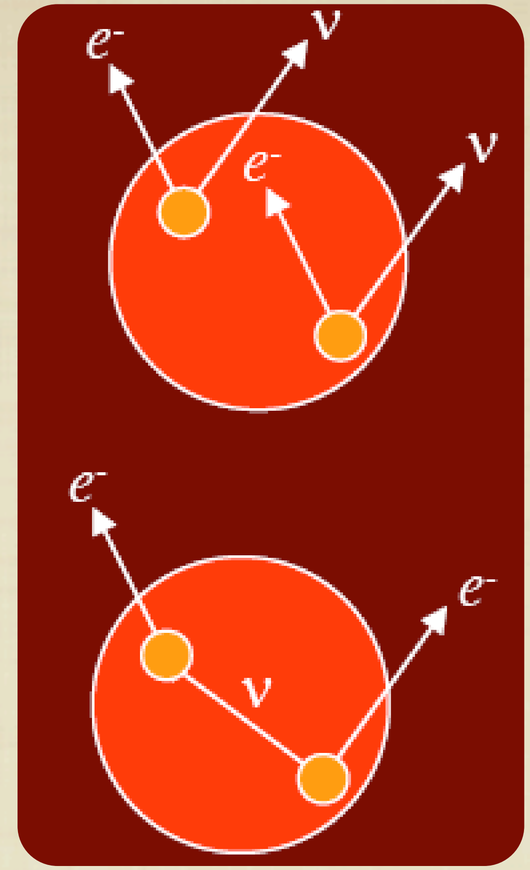


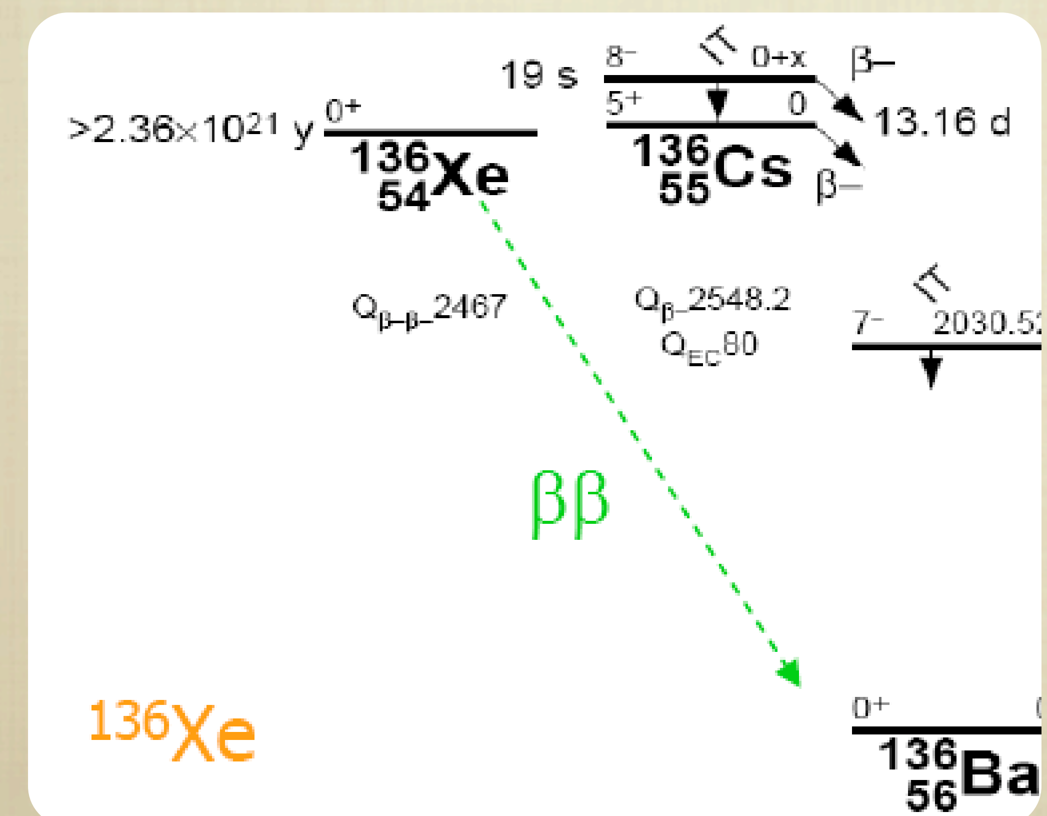


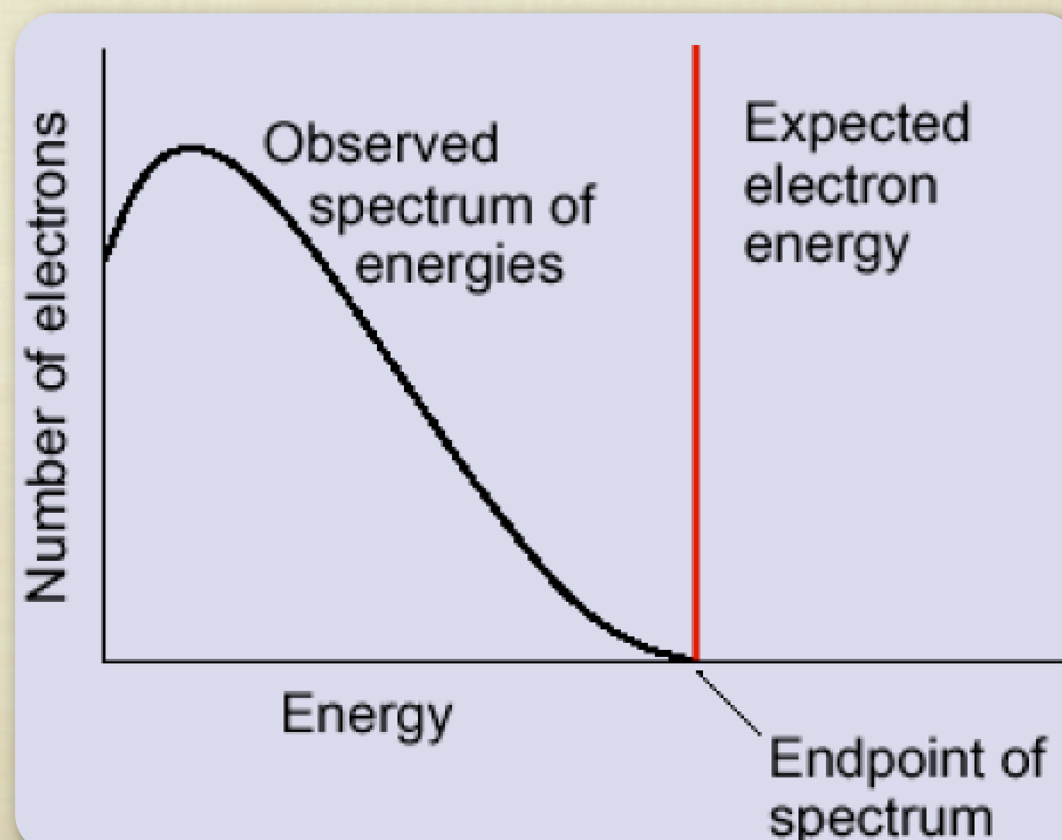


Neutrino double-beta decay









Neutrino double-beta decay

ββ2ν: two simultaneous β decays

$$(Z,A) \to (Z+2,A) + e_1^- + e_2^- + \overline{\nu}_{e_1} + \overline{\nu}_{e_2}$$

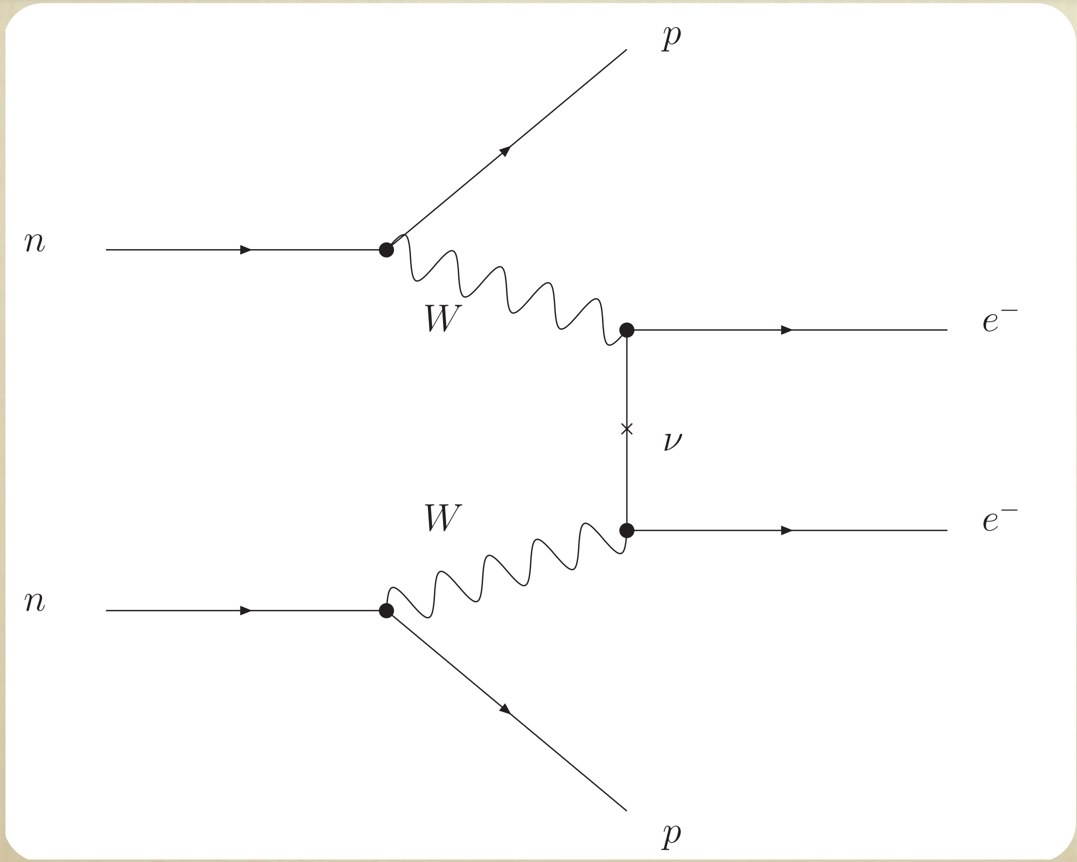
$$\frac{1}{T_{1/2}^{2\nu}} = G^{2\nu}(Q,Z)|M^{2\nu}|^2$$

ββ0ν: requires massive Majorana neutrinos. Non-SM process.

$$(Z,A) \to (Z+2,A) + e_1^- + e_2^- + \cancel{\overline{\nu}_{e_1} + \overline{\nu}_{e_2}}$$

$$(\Delta L = 2)$$

$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}(Q,Z)|M^{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$

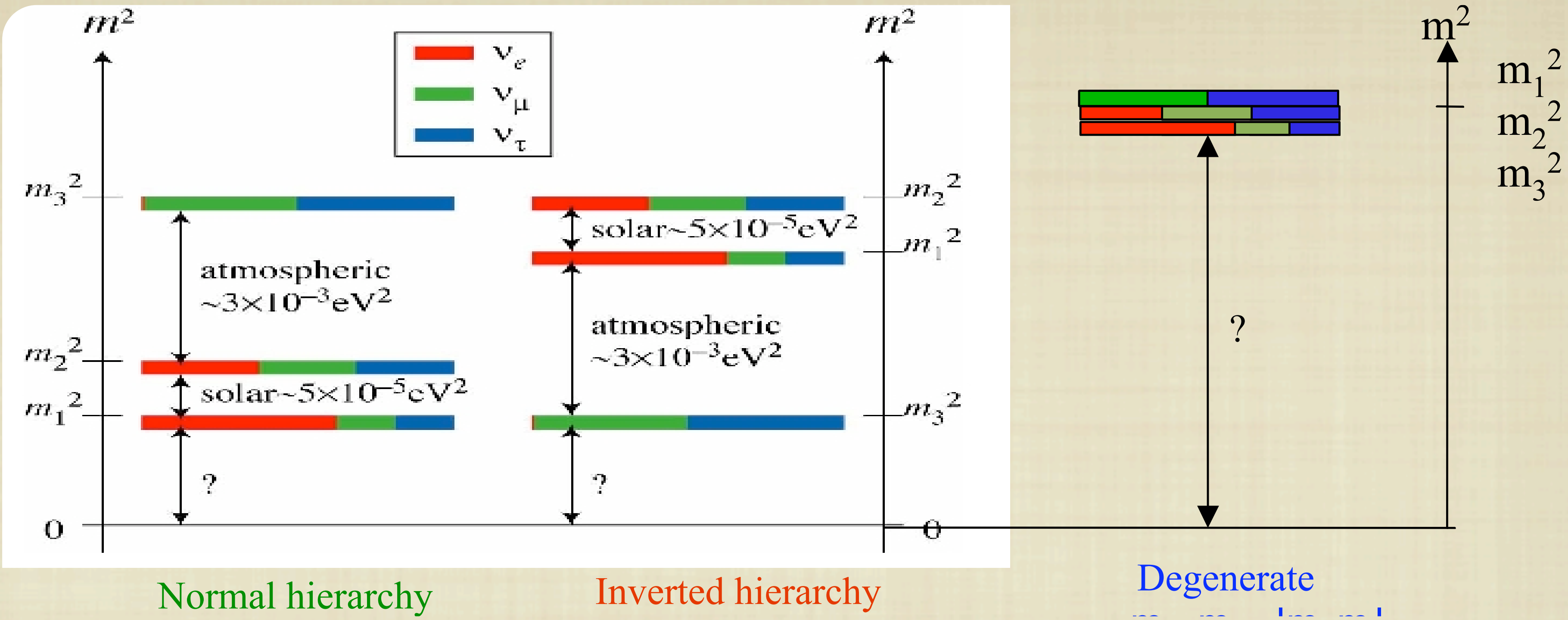


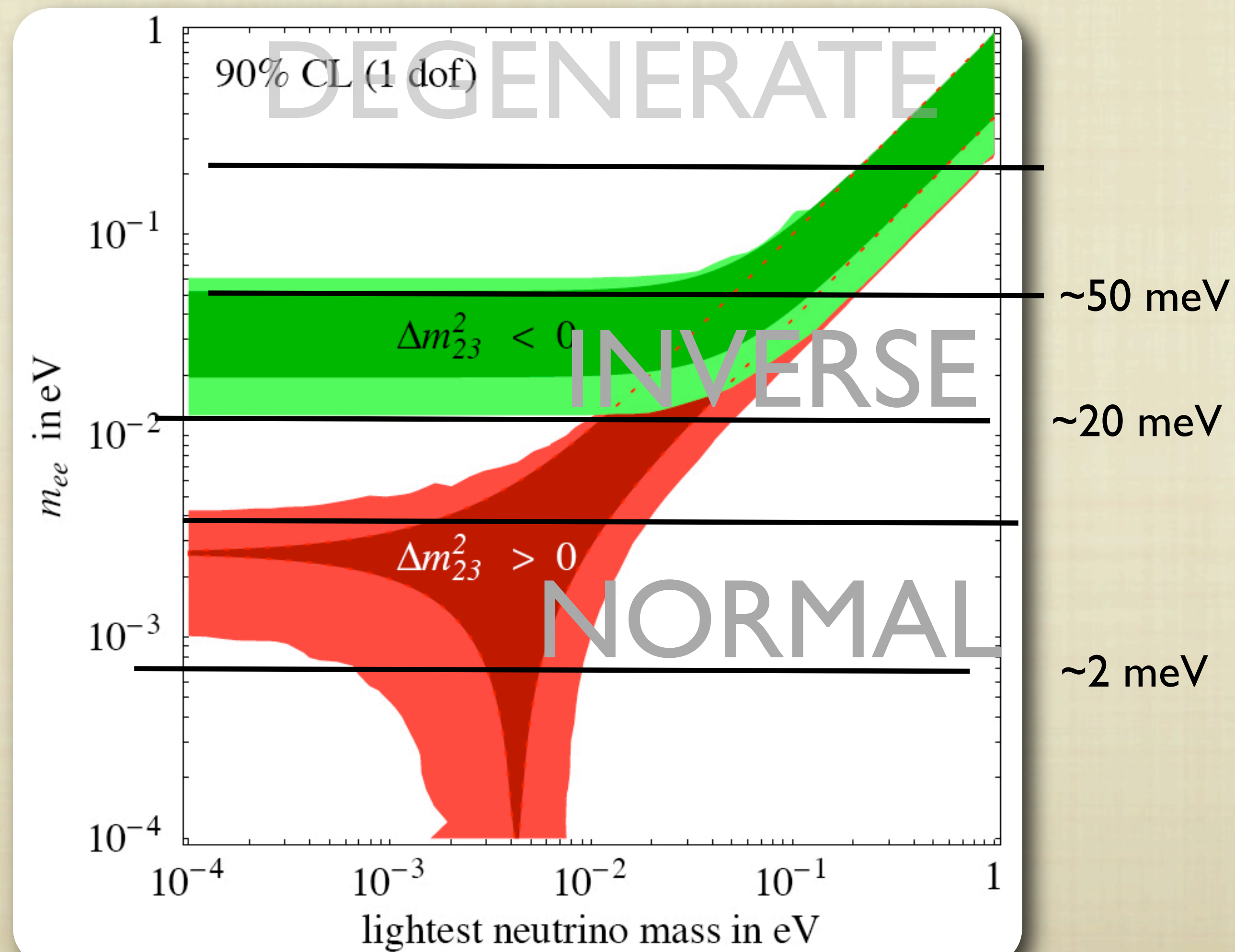
Neutrino double beta decay (standard but rare decay. Lifetime of the order of 10^{18} y for most nuclei

Neutrinoless double beta decay can only happen if neutrino is a Majorana particle

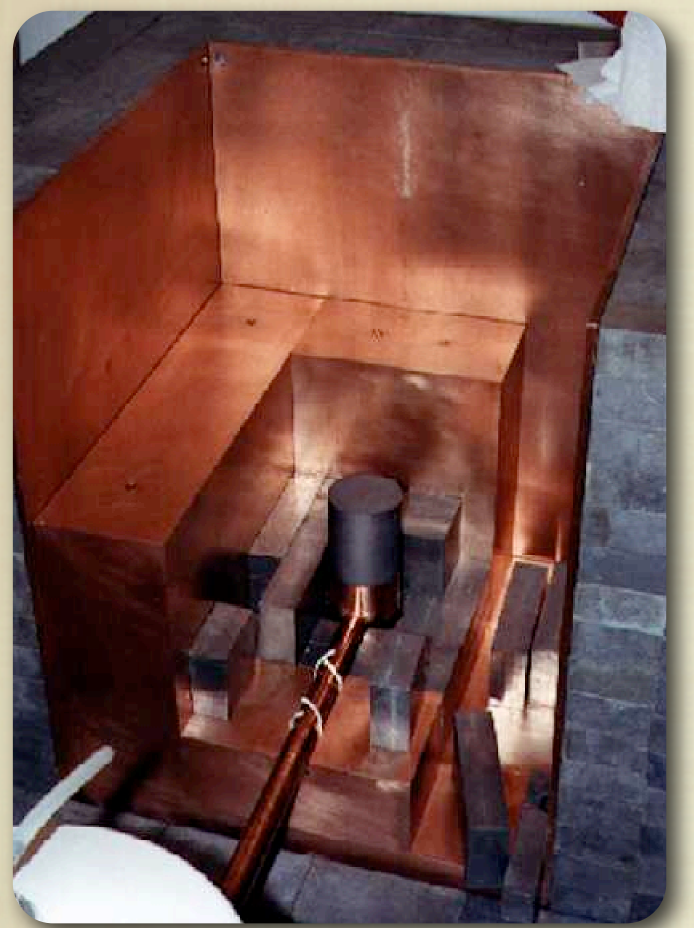
If neutrino mass too small difference vanishes

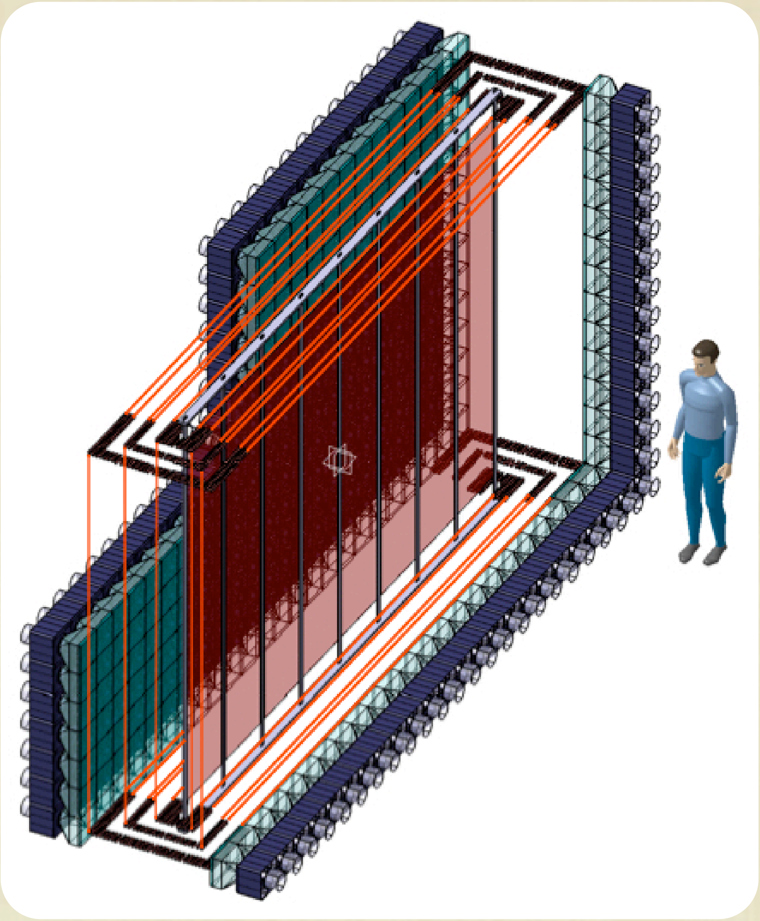
BB0nu & mass hierarchies

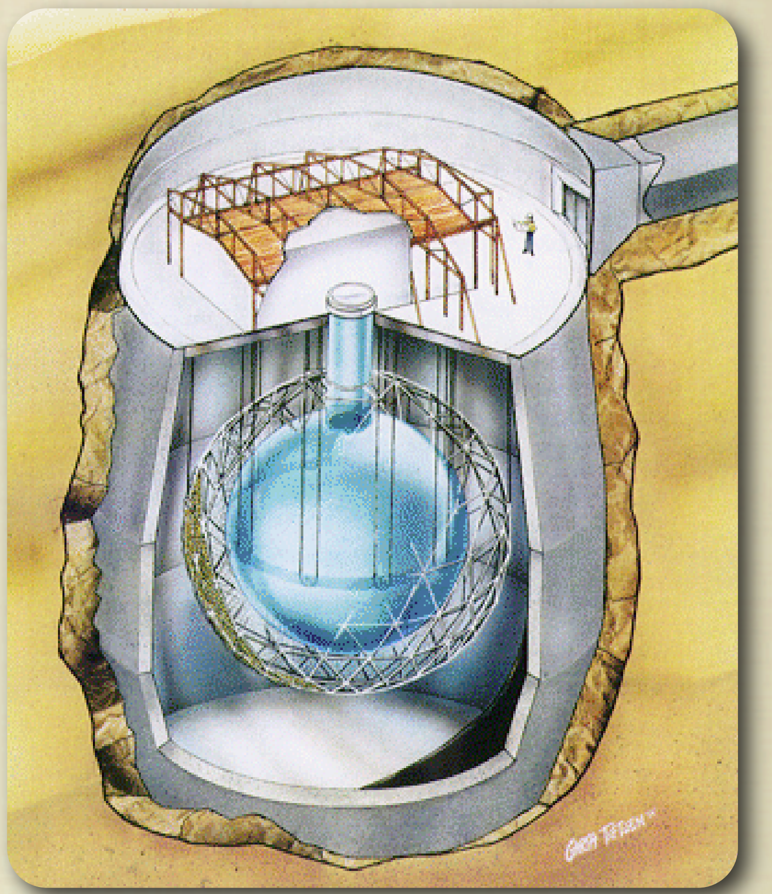




Experimental techniques







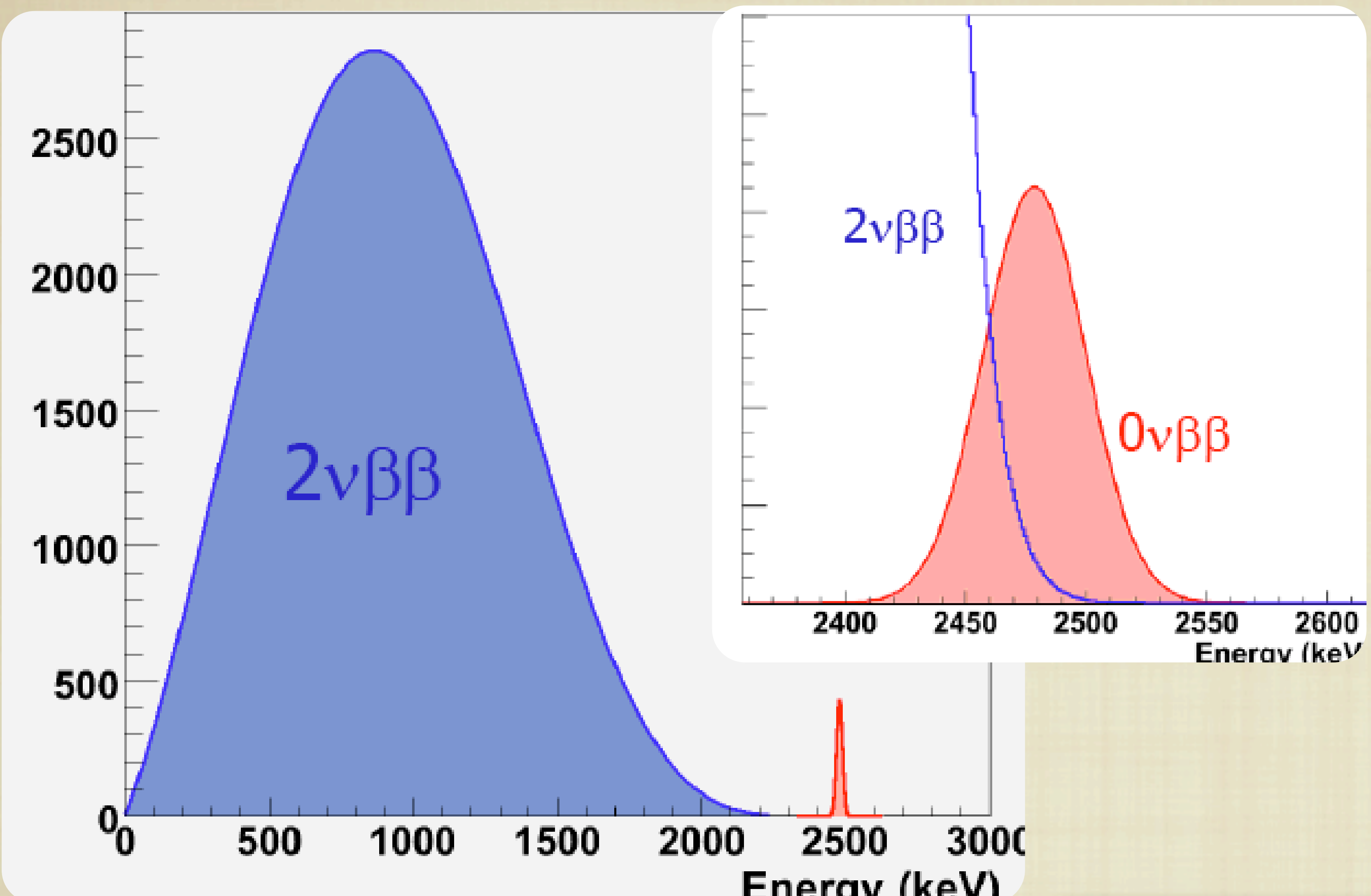
Diodes & Bolometers
GERDA
Majorana
Cuore
COBRA

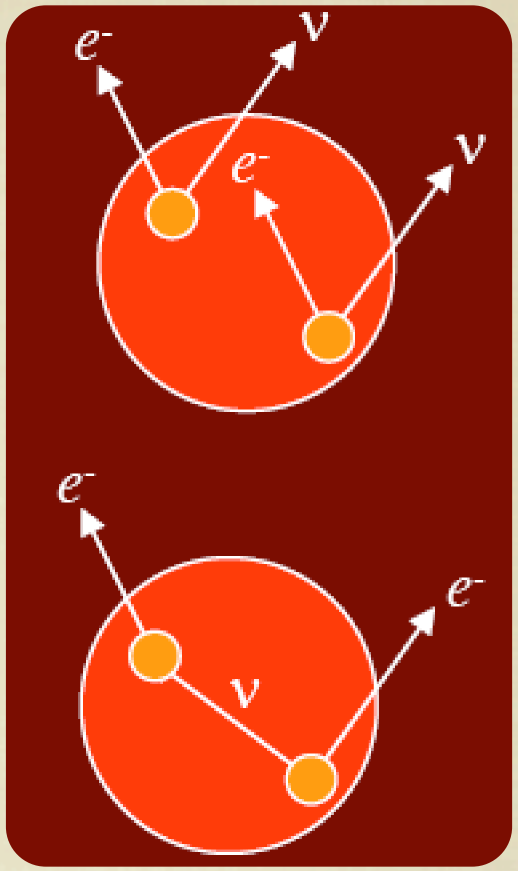
Calo+Tracko
SuperNEMO

Xenon TPCs
EXO

Liquid Scintillator
CANDLES, CAMEO, SNO+

The energy signature

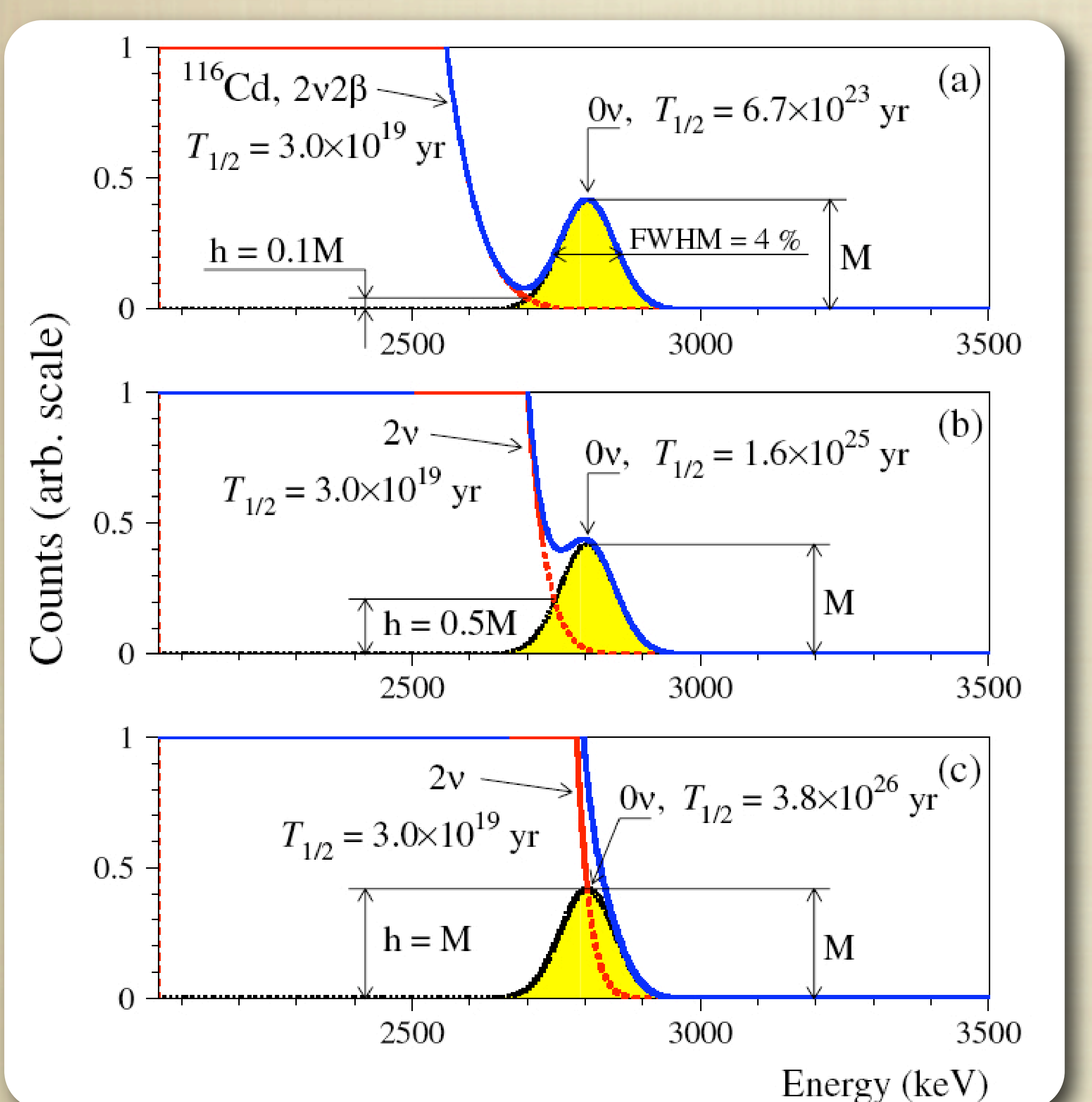




Energy resolution is a MUST
One is tipically aiming to separate 5-7 orders of magnitude

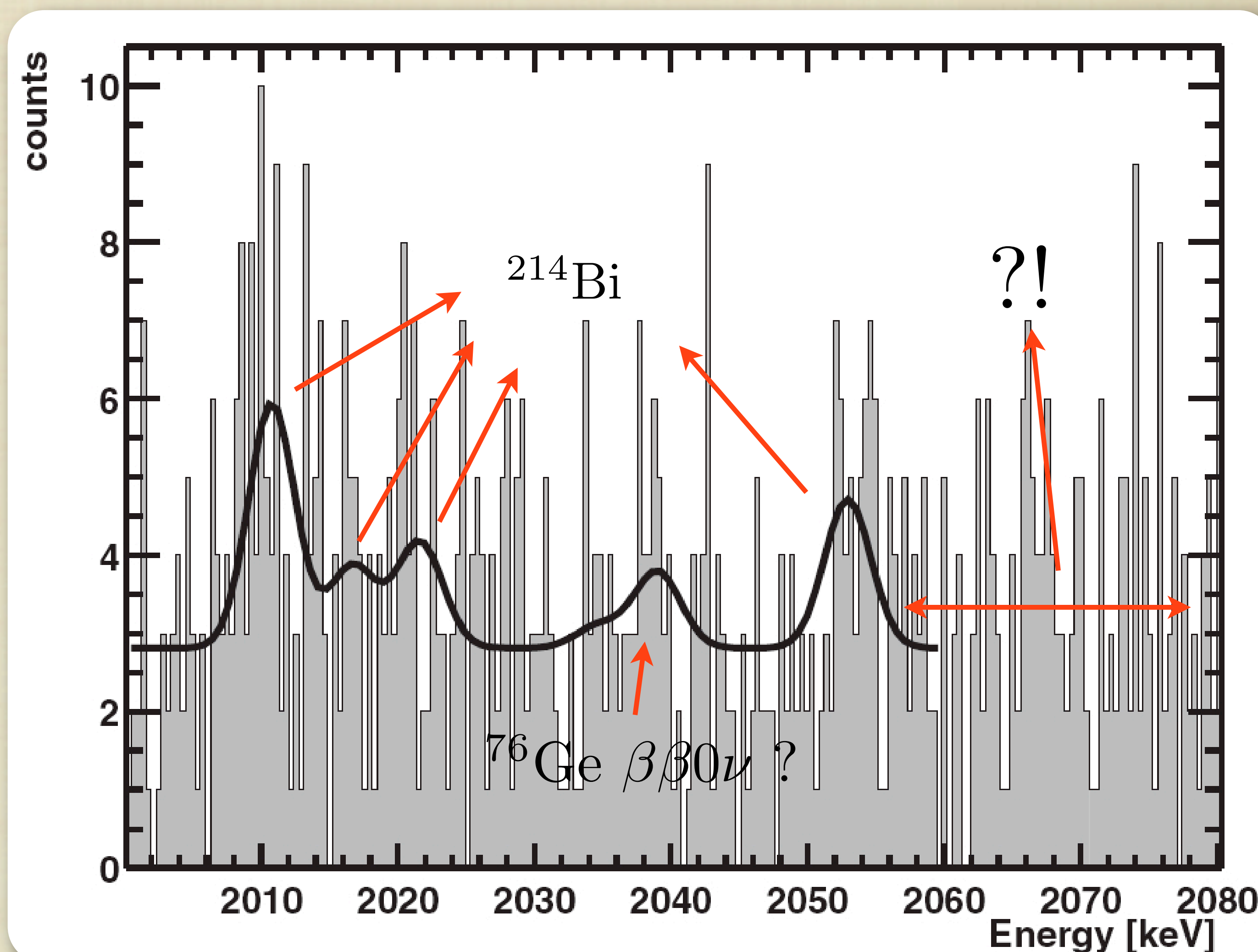
Resolution only may not be enough

Y. G. Zdesenko *et al.*, J. Phys. G **30** (2004) 971-981



ββ2ν background can only be separated from ββ0ν signal using energy resolution.

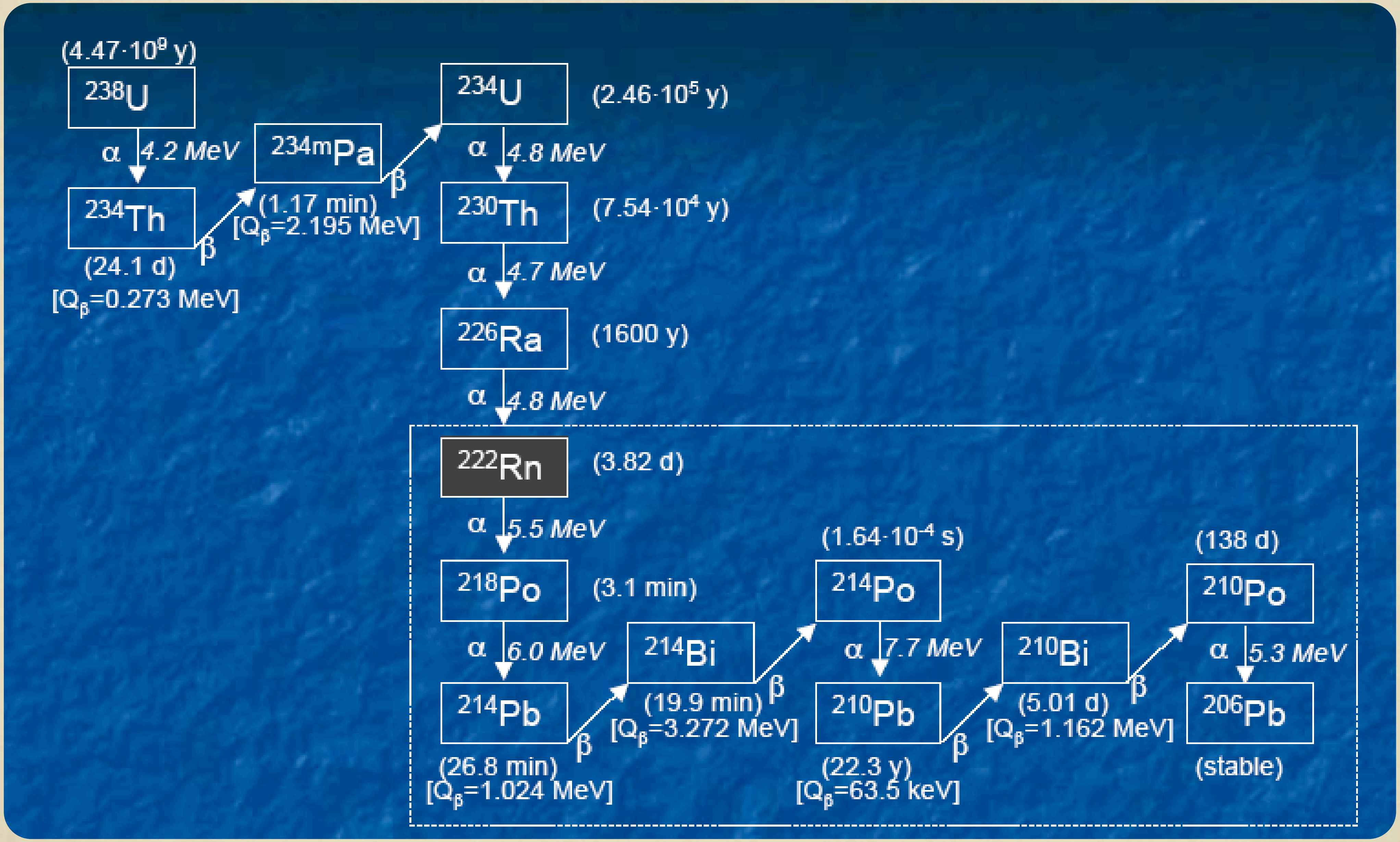
Klapdor-Kleingrothaus *et al.*, [arXiv: hep-ph/0302248].



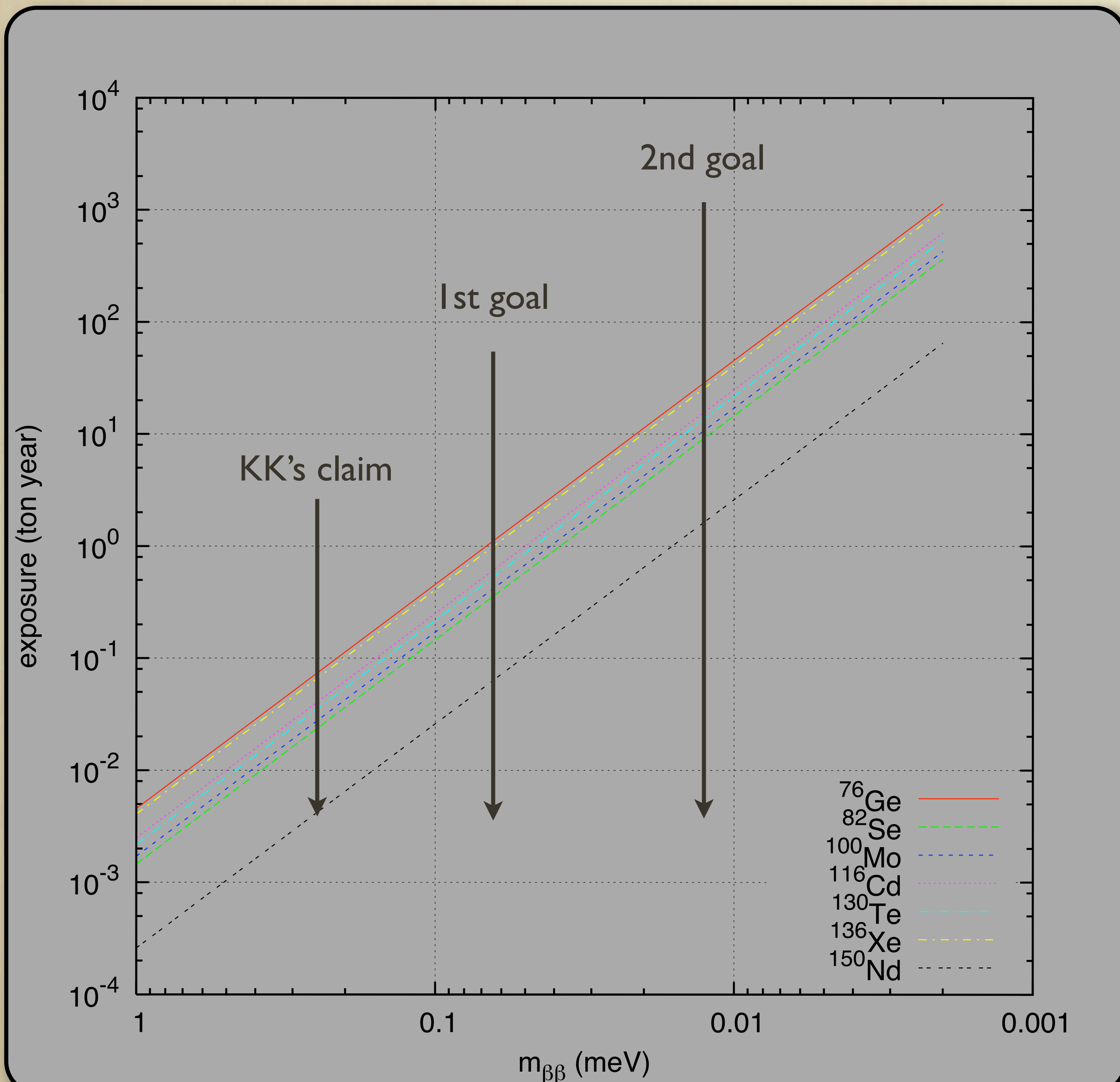
Example: KK's claim in Heidelberg-Moscow experiment.

Backgrounds other ββ2ν than become dominant if only total energy available: any energy deposition under signal peak fakes the signal. Need extra handles!!

The natural radioactiviy chains (or, the experimentalist nightmare)



Detector mass critical for small mbb



$$T_{1/2} = \ln 2 \ \frac{N_A \times 10^3}{A \ N_{\beta\beta}} \ Mt$$

zero-background

$$\langle m_{\beta\beta} \rangle \propto (Mt)^{-1/2}$$

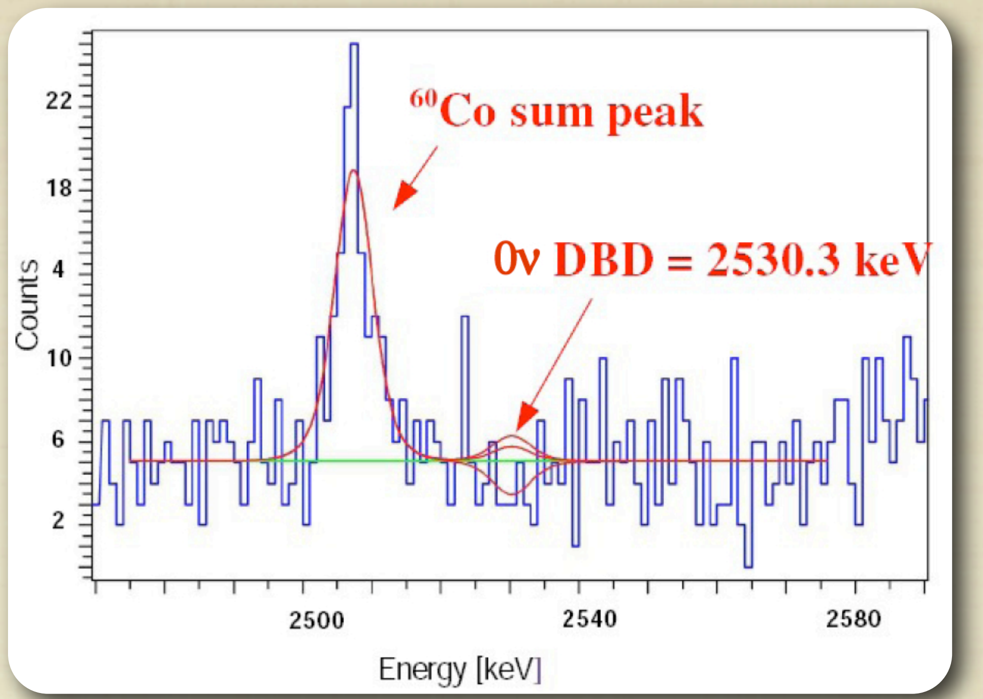
background-limited

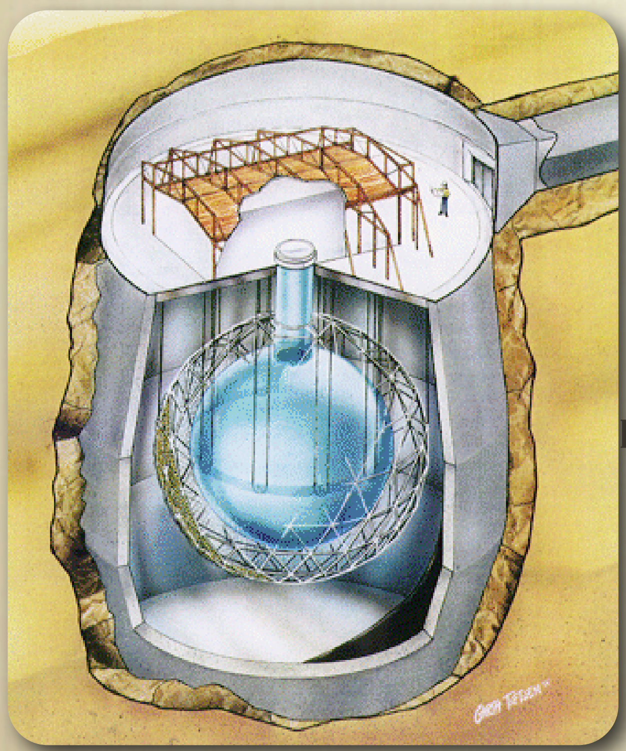
$$\langle m_{\beta\beta} \rangle \propto (Mt)^{-1/4}$$

To explore inverse hierarchy (20 meV) one needs O(10) ton y if background free experiment! (impossible otherwise)

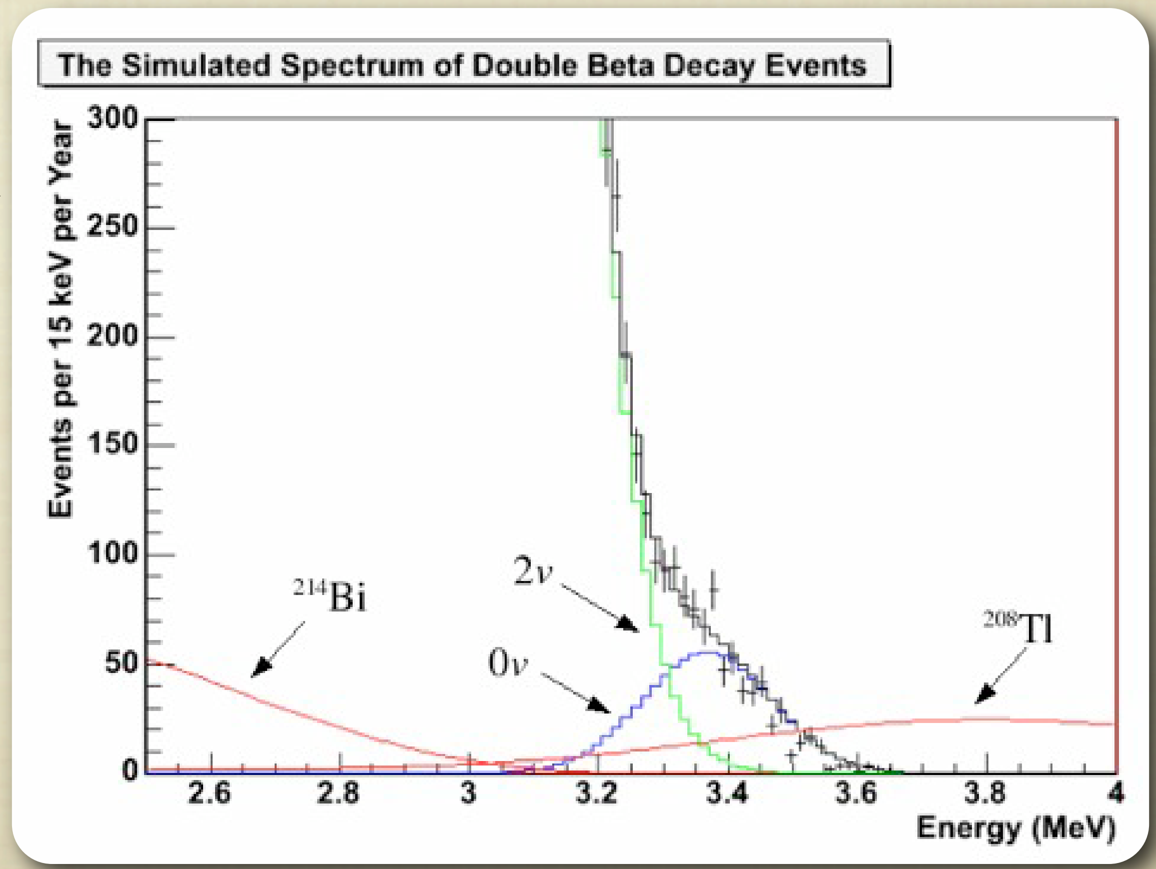
Current generation limited by backgrounds

backgrounds (natural radioactivity chain)





backgrounds (bb2n)



An example: Super Nemo

Planar and **modular** design: ~ 100 kg of isotope (~20 modules × 5-7 kg)

1 module:

Source (~40 mg/cm²) 4 (length) x 3(height) m²

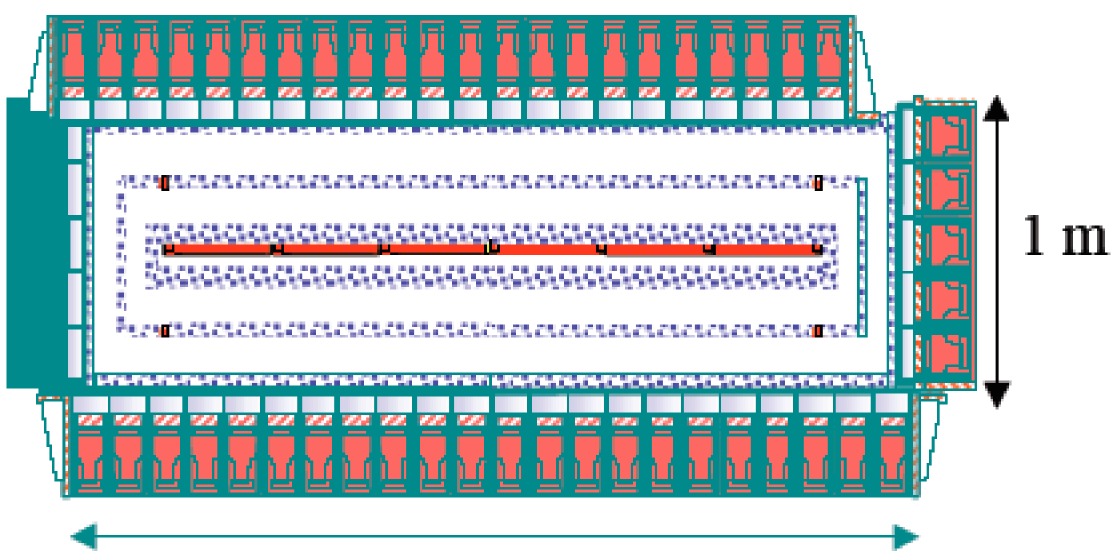
Tracking : drift chamber ~3000 cells in Geiger mode

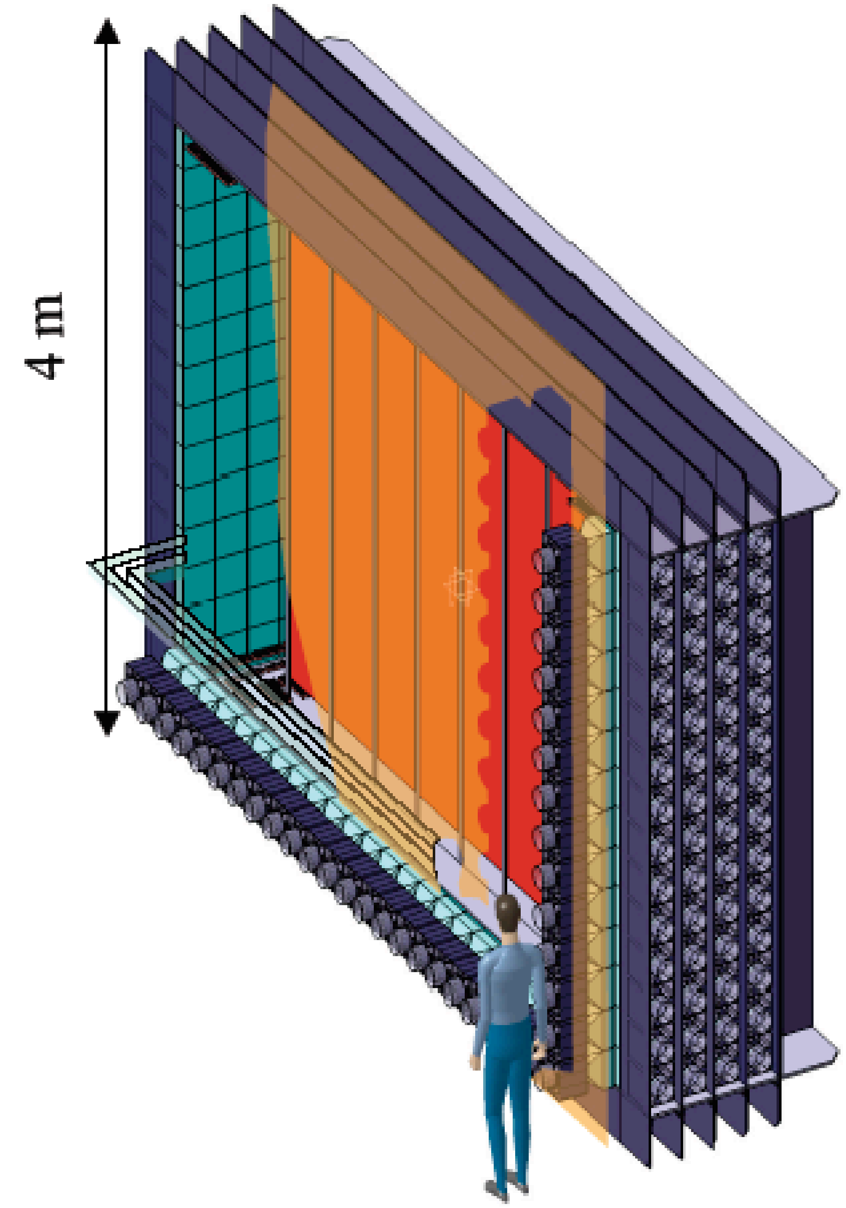
Calorimeter: scintillators + PM

~1 000 PM if scint. blocks

~ 100 PM if scint. bars

Top view

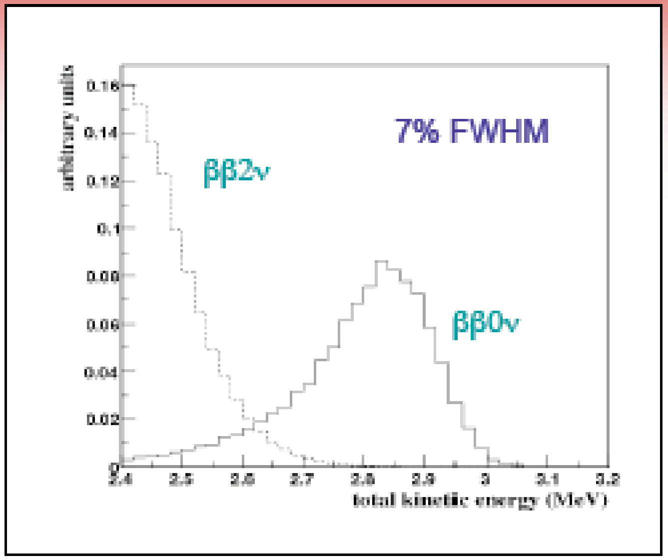


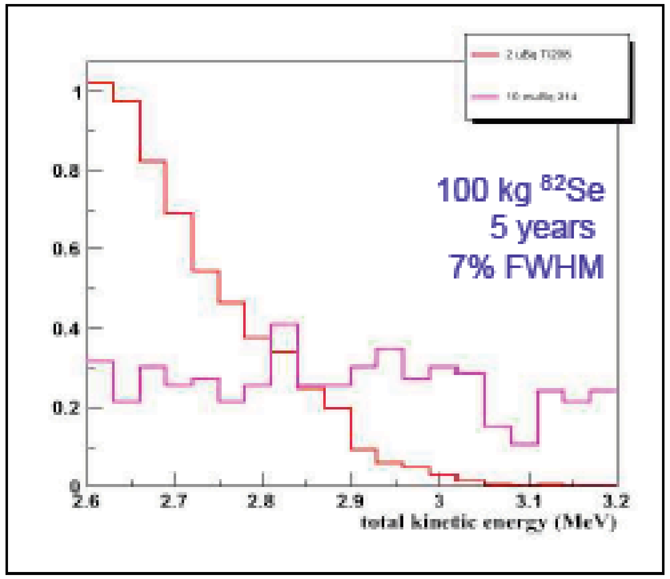


A very difficult experiment

SuperNEMO backgrounds

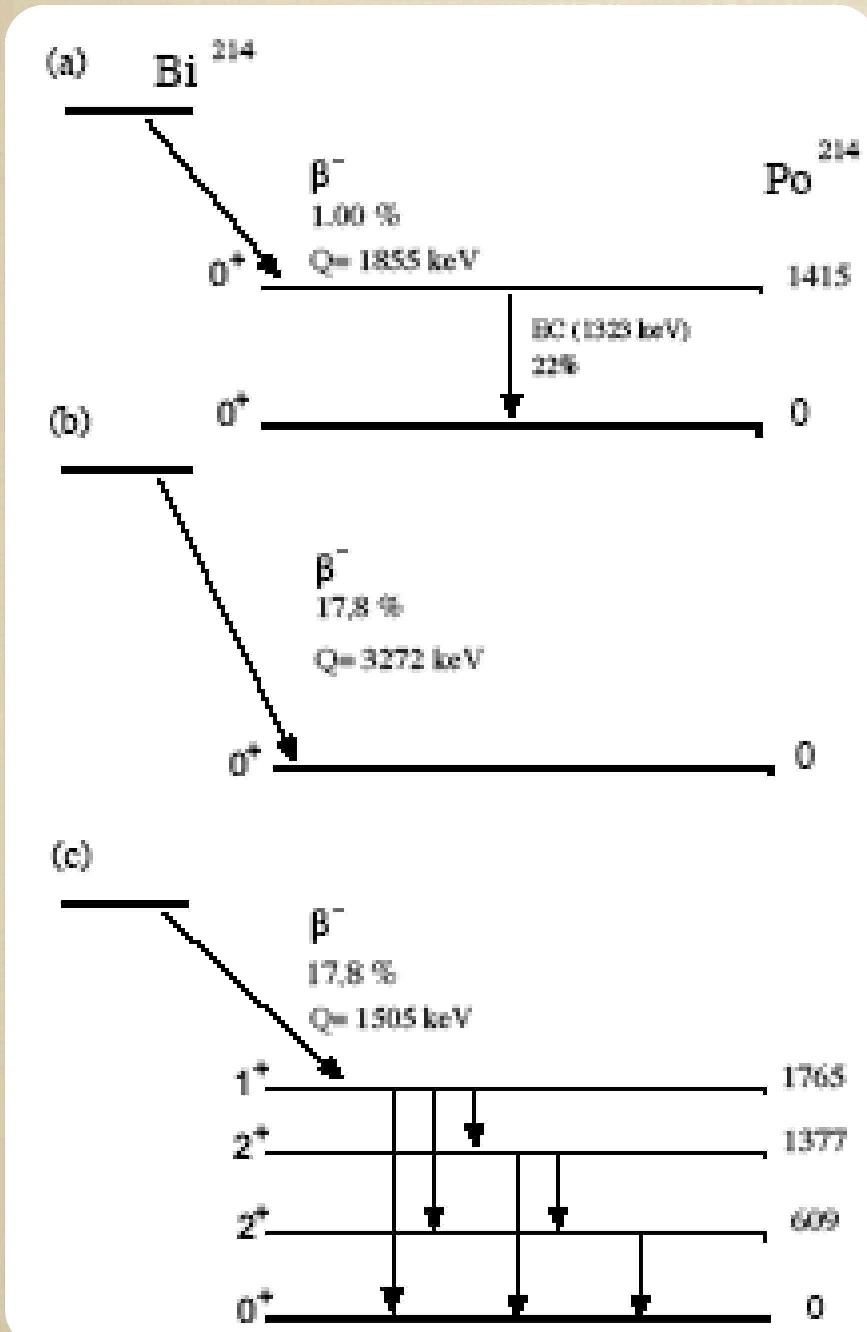
- Tail of bb2nu spectra
  - depens on energy resolution
- Internal backgrounds: ^{214}Bi, ^{208}Tl
  - fake ββ event when decaying
  - measured with BiPo detector
- External backgrounds: ^{214}Bi, ^{208}Tl, neutrons and γ
  - expected to be negligible (from NEMO experience)
  - measured by BiPo

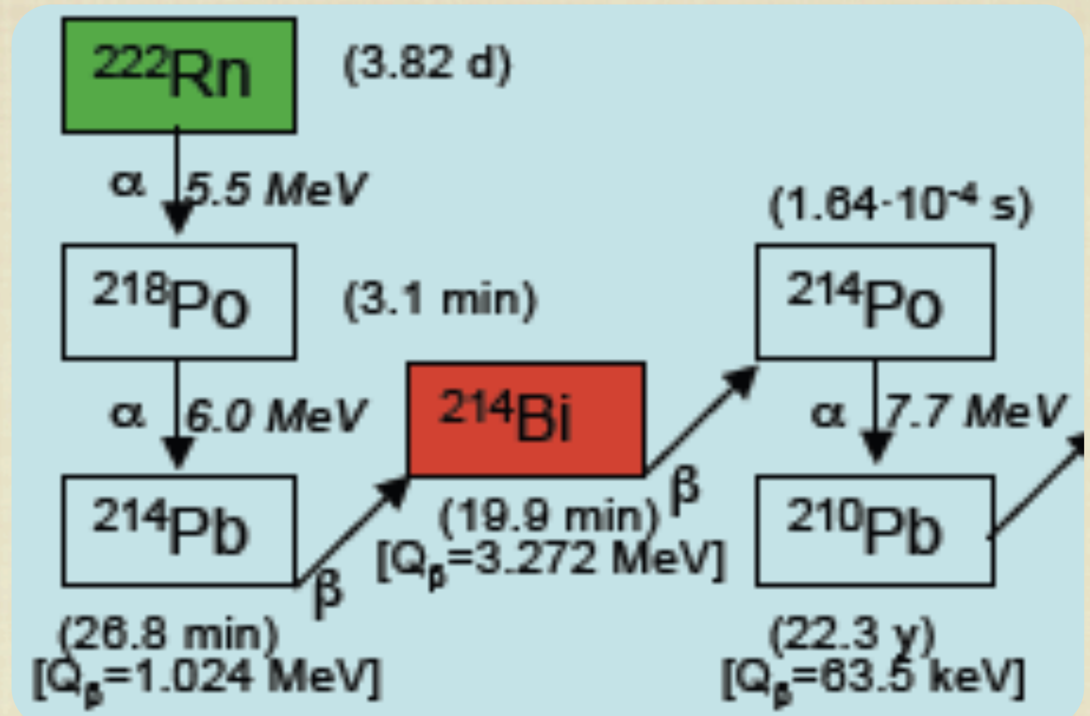


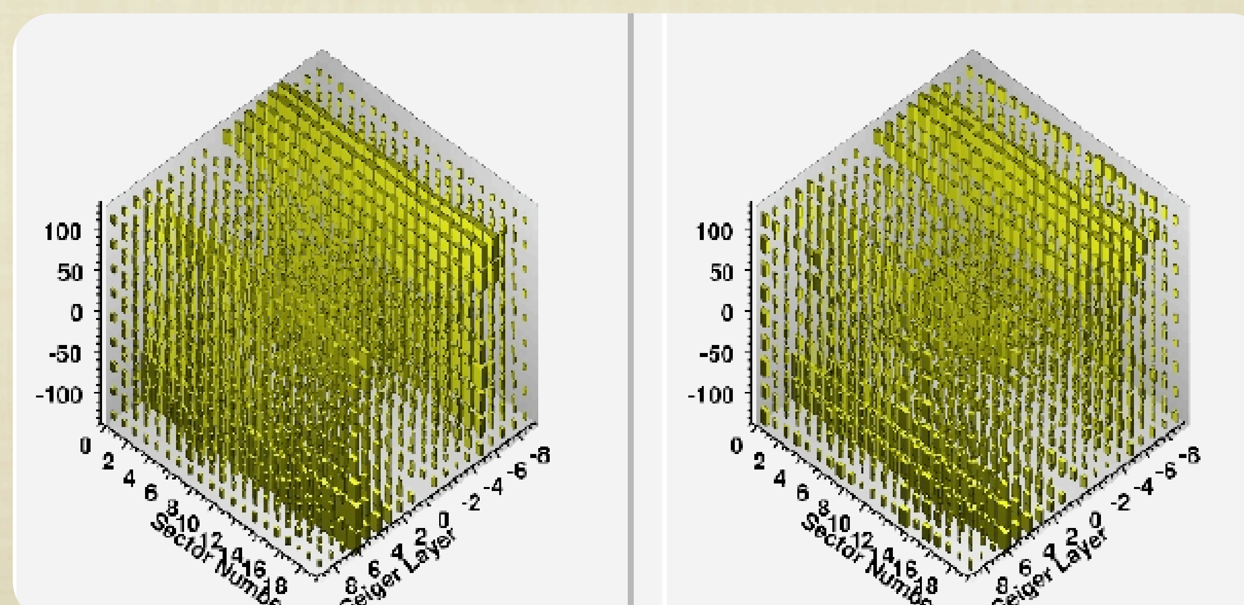


- ^{222}Rn inside tracking chamber: ^{214}Bi sticks to foil and wires
  - dominant background in NEMO (5 mBq/cm3)

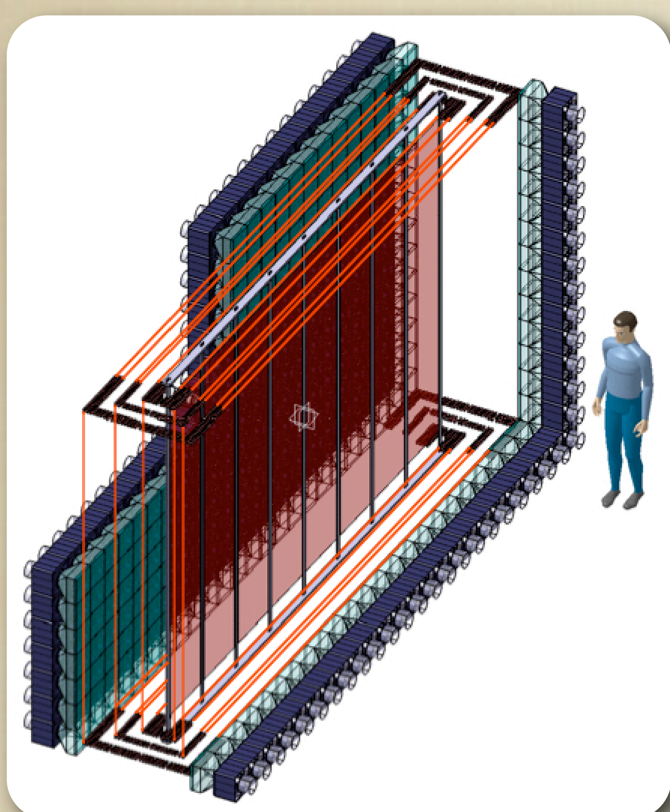
The ^{222}Rn nightmare

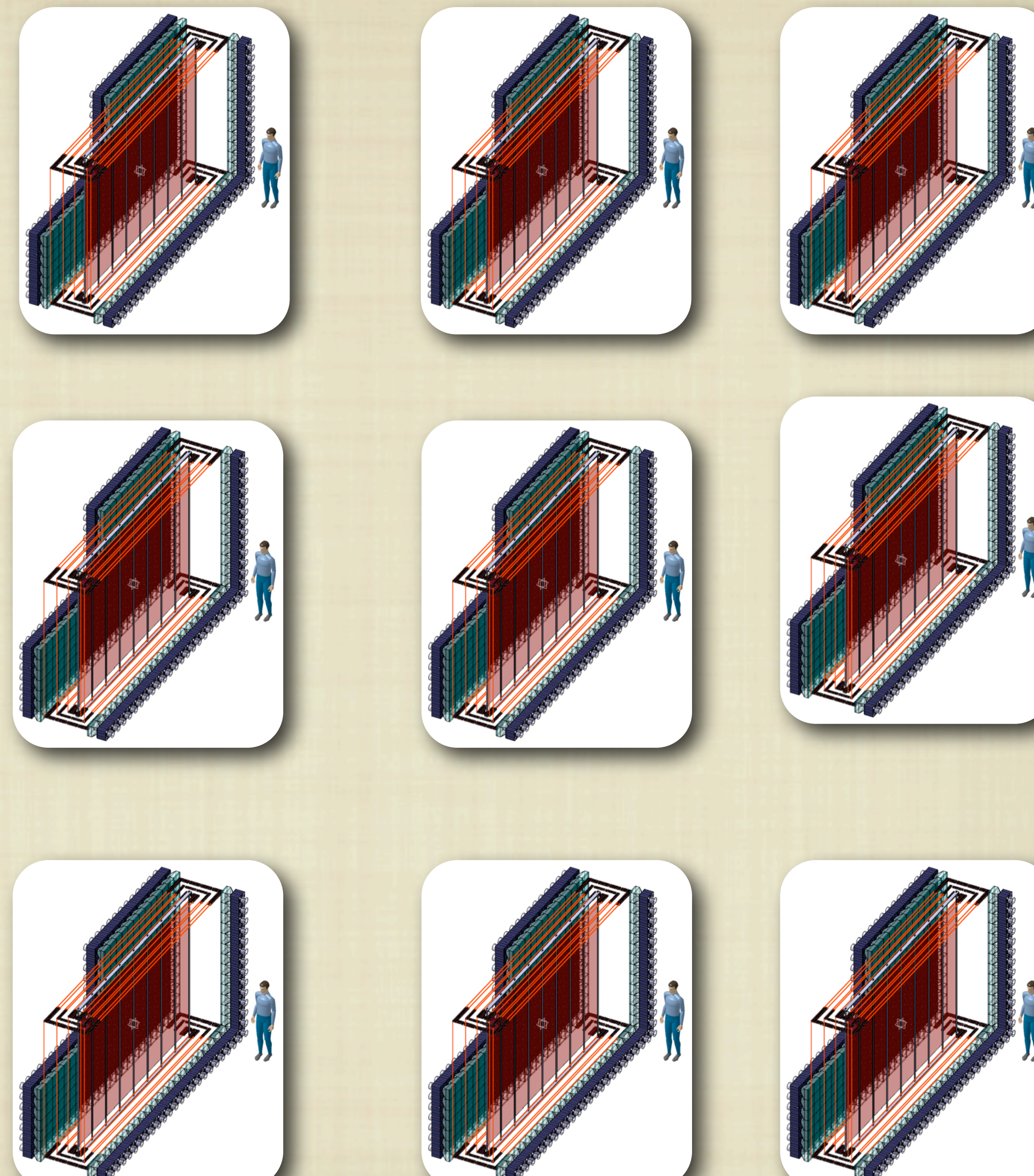






The problem of scaling





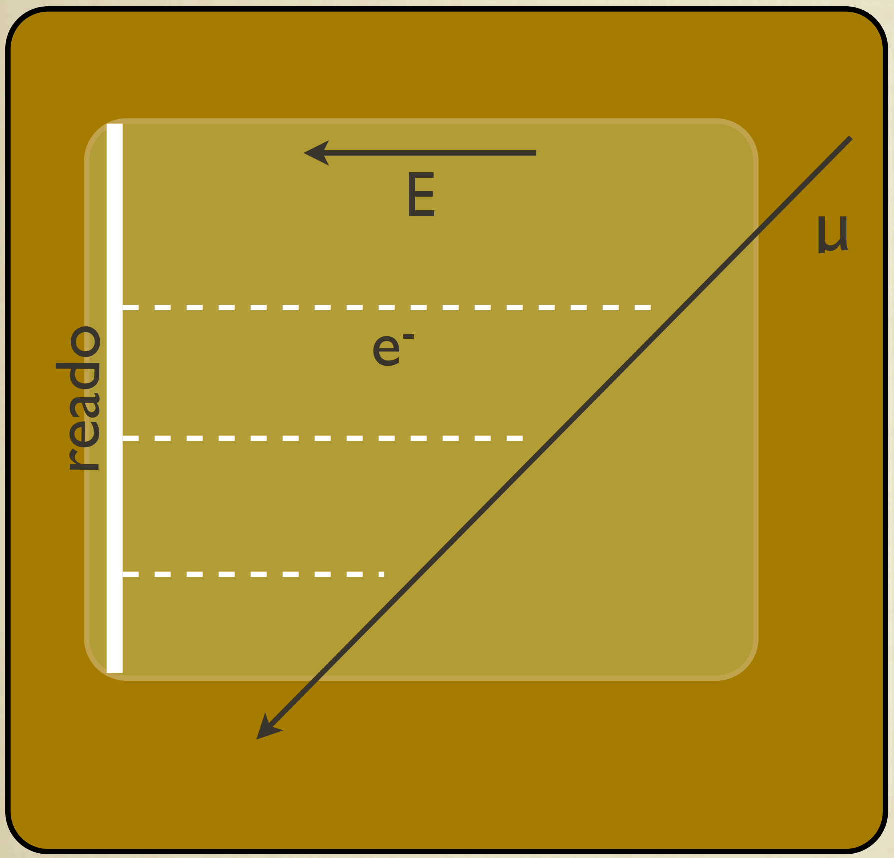
Modular detectors must be duplicated

Price & effort scales linearly

Backgrounds (proportional to surfaces) scale linearly

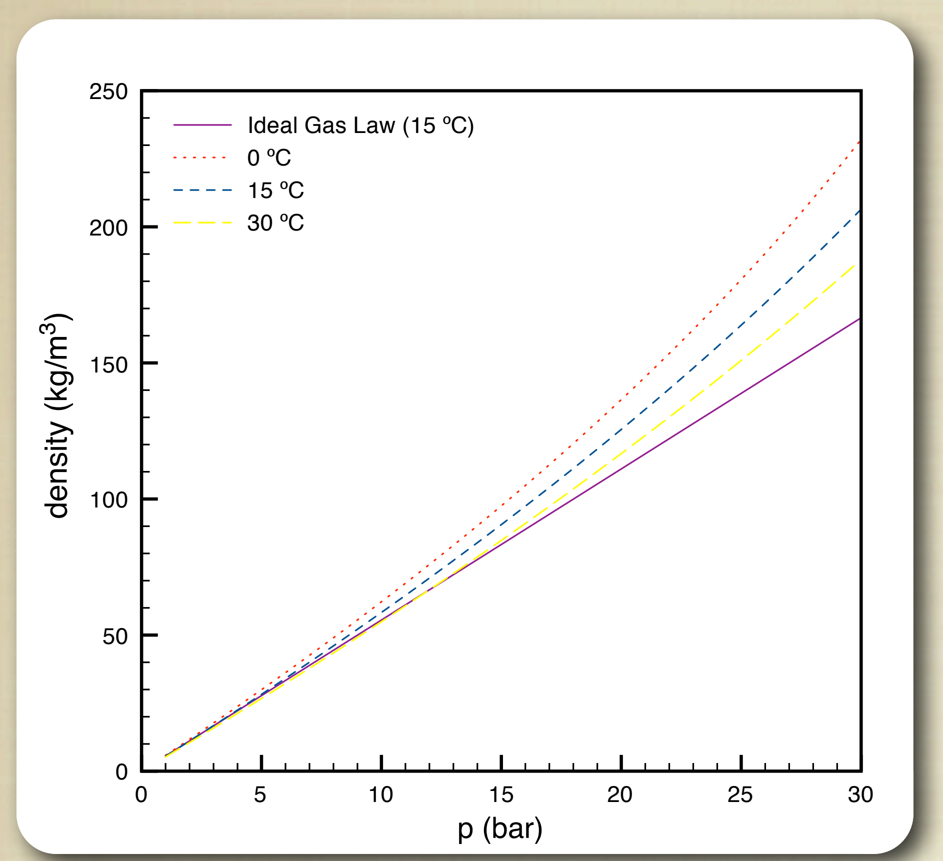
The TPC detector

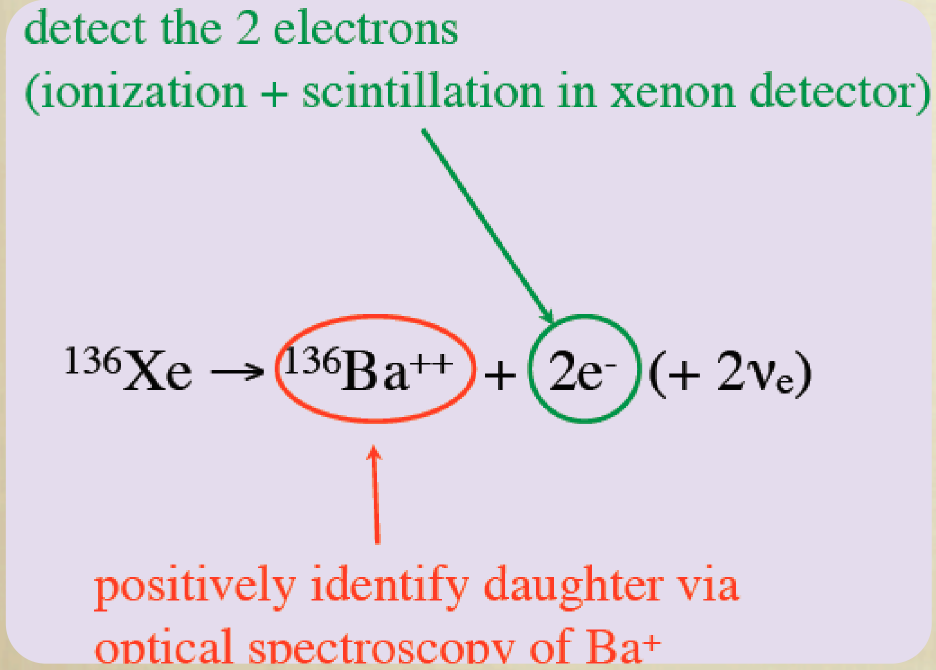
Time Projection Chamber: invented by D. Nygren in the 1970's.
Can be seen as an electronic bubble chamber.



- Requires a noble gas to operate
- Charged particles traversing TPC ionize gas leaving a track
- If track stops inside TPC then its energy is calorimetrically measured (with good resolution)
- Large volume possible (thus large mass)
- No surfaces in fiducial volume for background ions to attach to

Why a Xe TPC





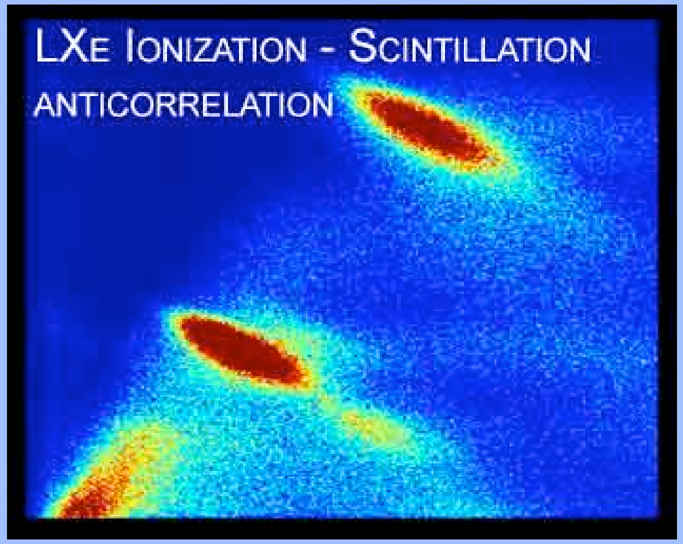
- Good ionization detecting medium. Provides also scintillation light. Can be large (scalability).
- Xenon is a noble gas: easy to enrich, purify and manipulate.
- No long-lived isotopes that can be activated.
- Xe-136 has a slow $\beta\beta2\nu$ mode.
- No surfaces/wires for ^{214}Bi to attach to.
- Kinematical signature (Observe two electrons)
- Ba^{++} tagging using optical spectroscopy.

Xe TPC

Liquid Xenon: EXO

- Mass scalability (compact detector).
- Ba+ tagging.

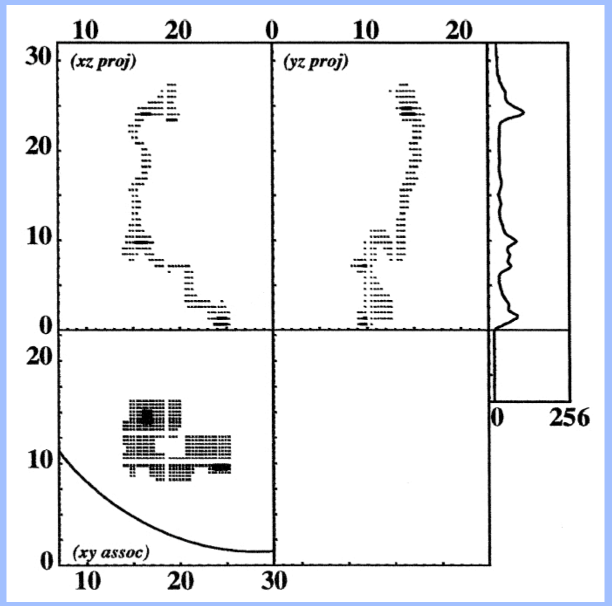
- Energy resolution.
- Lost of tracking capabilities.

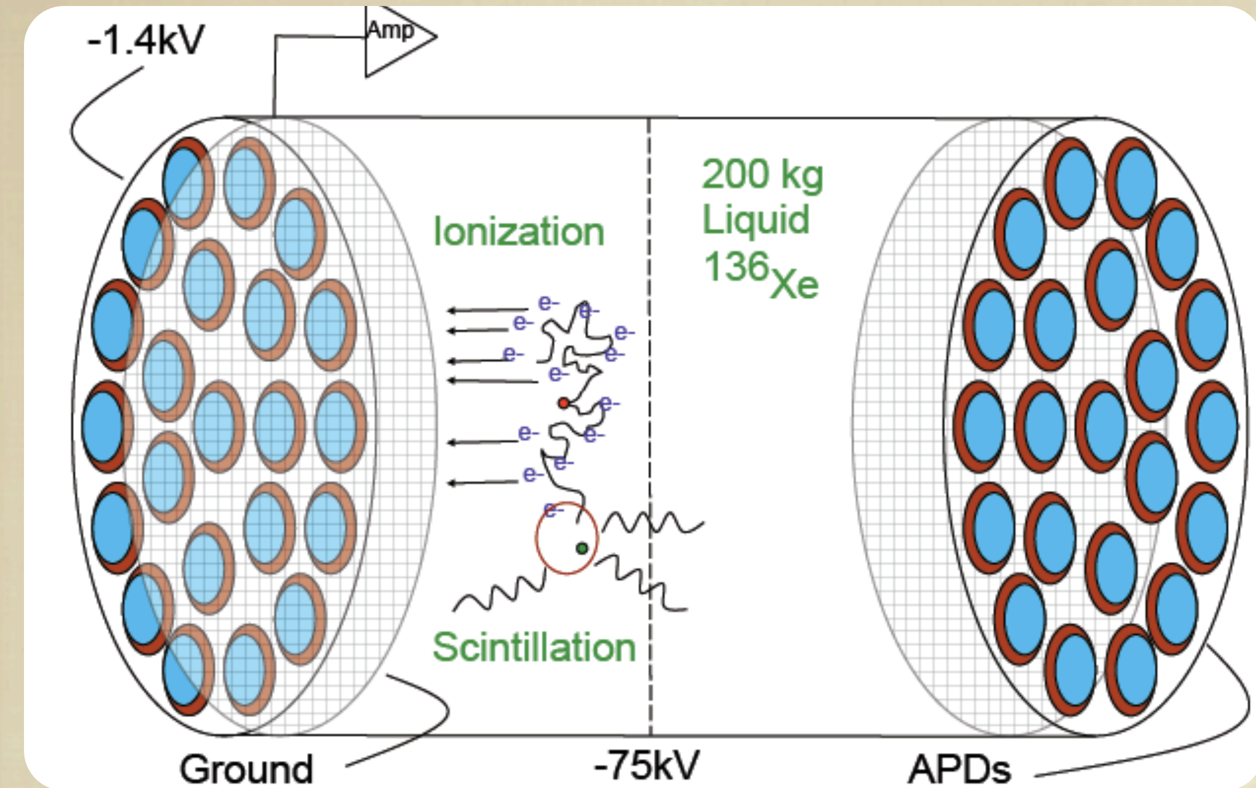


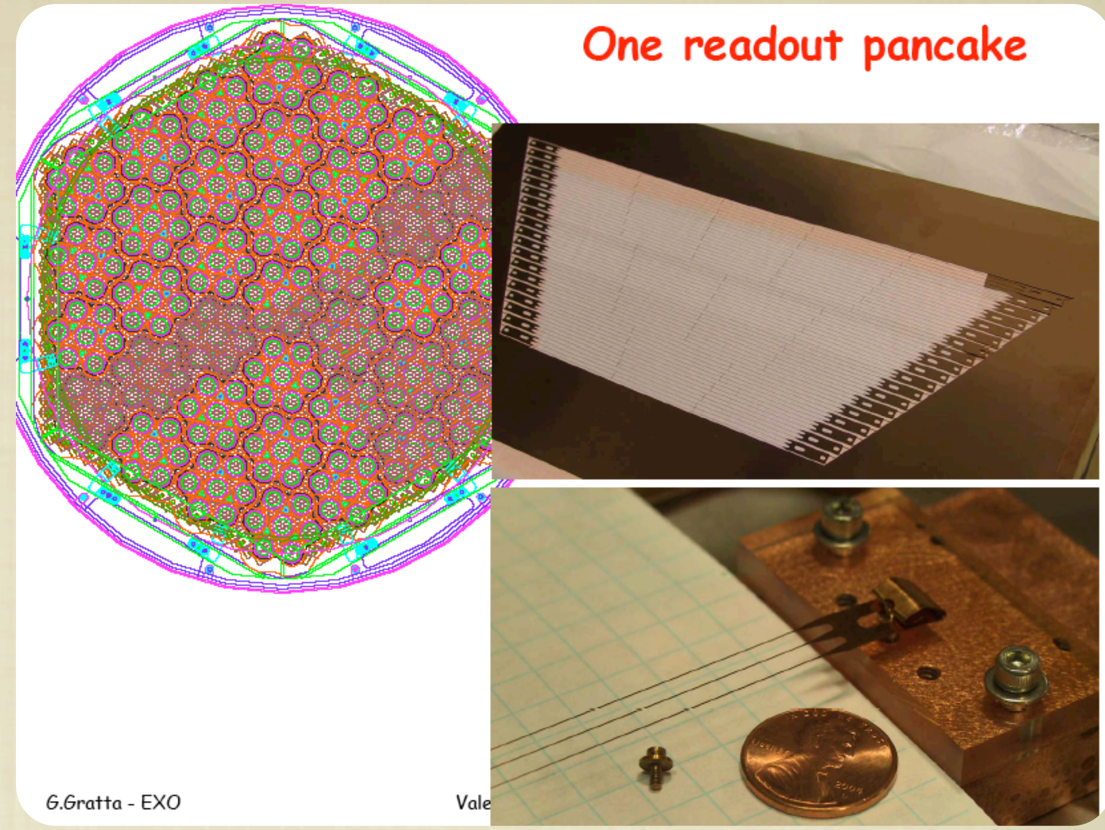
Gas Xenon: Gotthard

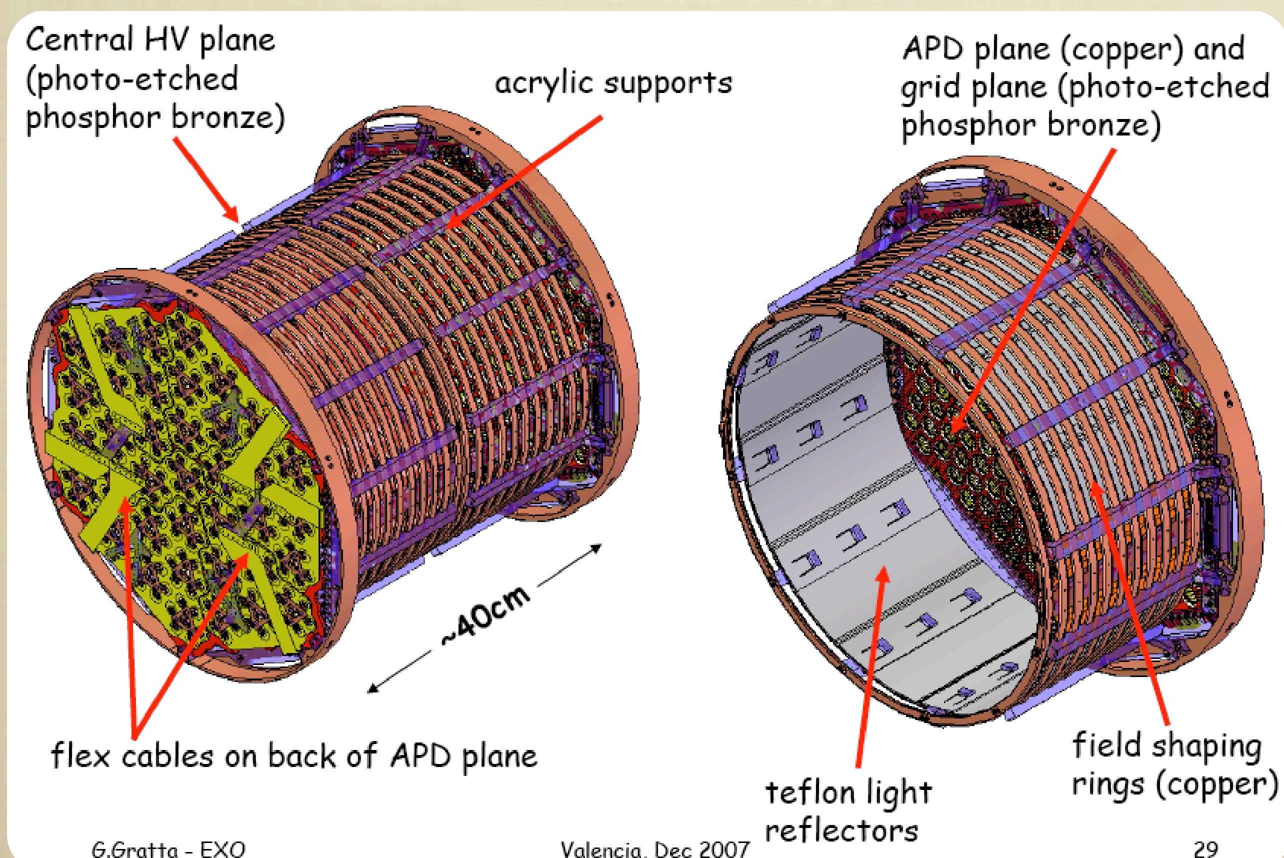
- Good energy resolution.
- Mass scalability.
- Ba+ tagging and event kinematics.

- Equalization & calibration
- Mechanics




-1.4kV
Amp
Ionization
200 kg
Liquid
136Xe
Scintillation
Ground
-75kV
APDs


One readout pancake
G.Gratta - EXO


Central HV plane
(photo-etched
phosphor bronze)
acrylic supports
APD plane (copper) and
grid plane (photo-etched
phosphor bronze)
~40cm
flex cables on back of APD plane
teflon light
reflectors
field shaping
rings (copper)
G.Gratta - EXO
Valencia, Dec 2007
29

Backgrounds for EXO

- γ (2449 keV) from ^{214}Bi decay (from ^{238}U and ^{222}Rn decay chains)
- γ (2615 keV) from ^{208}Tl decay (from ^{232}Th decay chain)
- γ (1.4 MeV) from ^{40}K (a concern for the $2\nu\beta\beta$)
- ^{60}Co: 1173 + 1333 keV simultaneous γ's (from ^{63}Cu(α,n)^{60}Co)
- other γ's in ^{238}U and ^{232}Th chains
- other cosmogenics of Cu (a concern for the $2\nu\beta\beta$)
- ^{222}Rn anywhere (Xe, HFE, air gaps inside lead shield)
- in situ cosmogenics in Xe, neutron capture de-excitations, ...

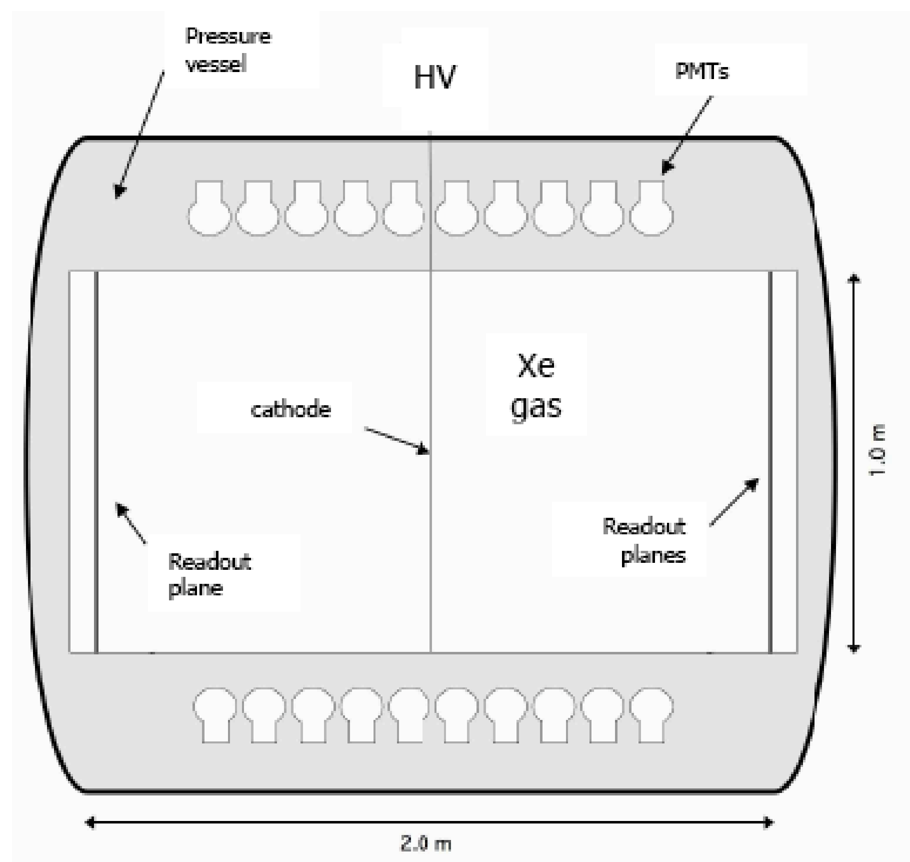
EXO does not discriminate gammas from two electrons!

A Xe detector for the NEXT generation

NEXT

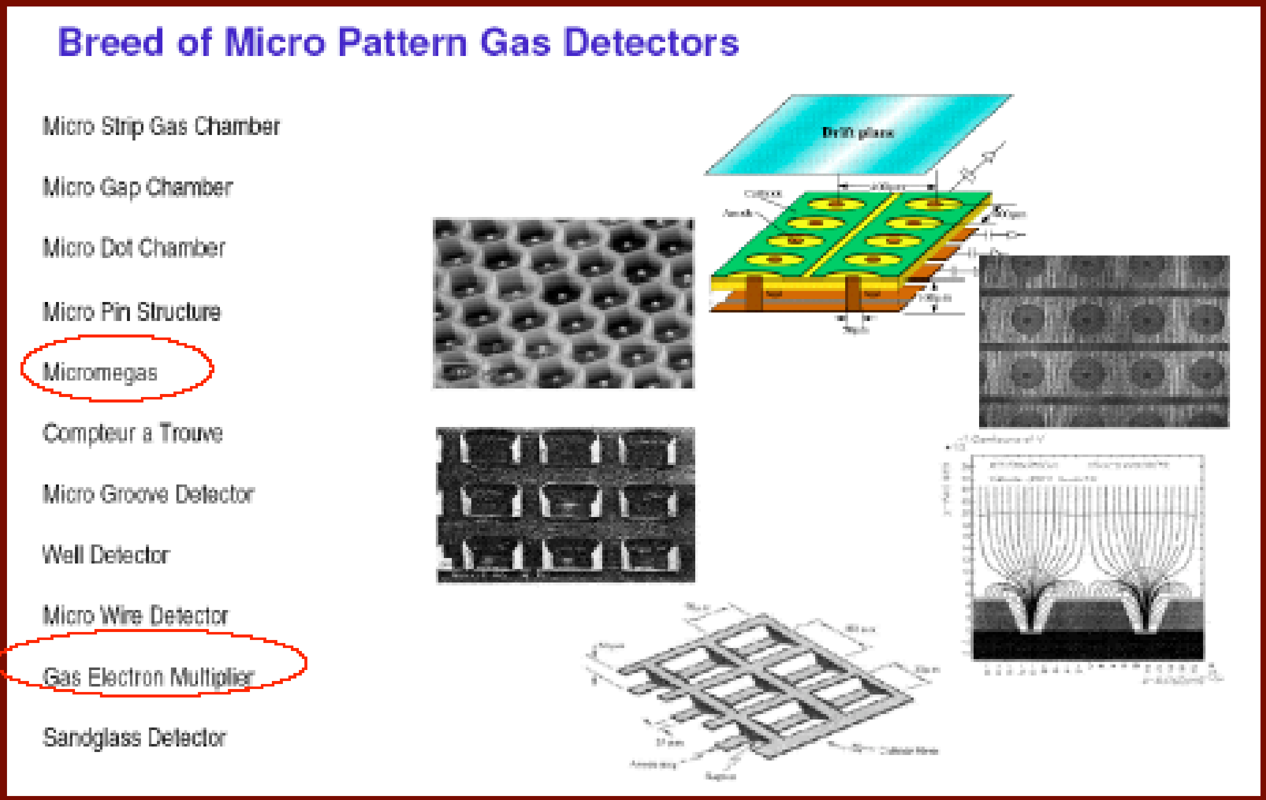
- A **N**eutrino **E**xperiment with a gas **X**e **T**PC may:

1. Have all advantages of a Xe monolithic detector (like EXO)
2. Outdo Liquid Xe by getting topological info
3. Override tradicional limitation of gas TPCs (Gothard) by applying the latest developments on TPC readouts
4. Be a competitive option for the next (ton scale) generation of experiments

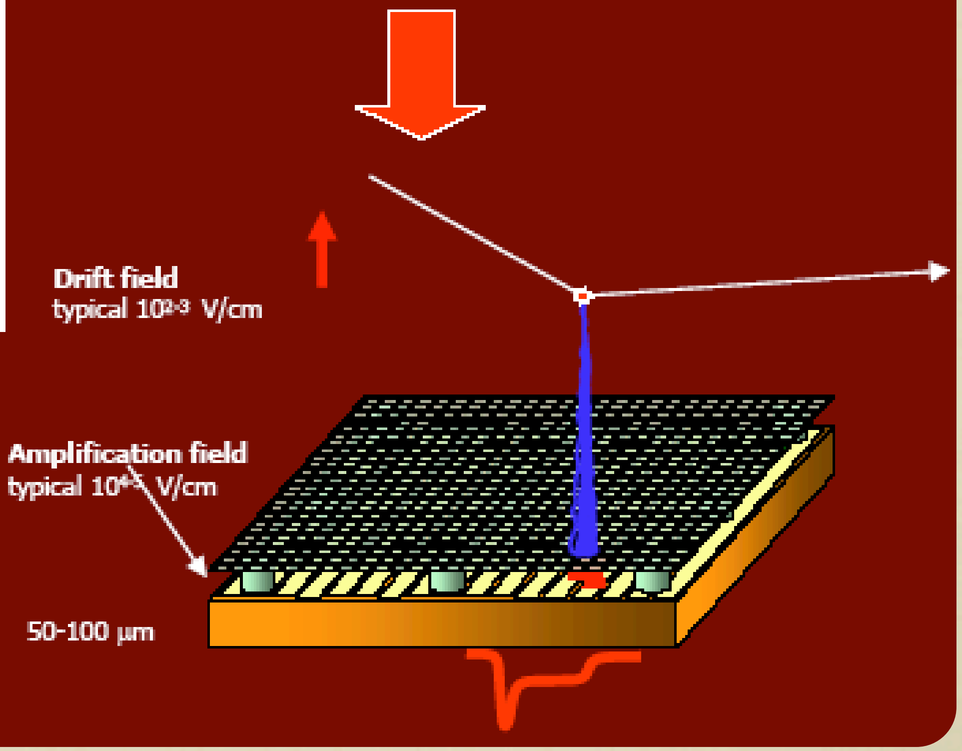


Micropattern detectors

seminal idea is atributed to Oed (88)

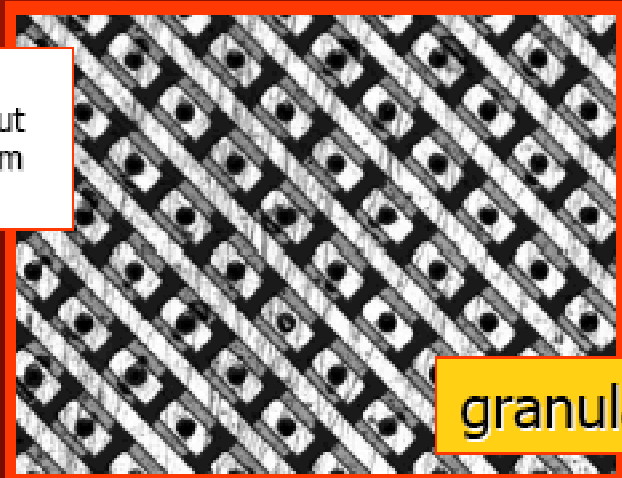


e.g. MICROMEGAS
Giomataris, Charpak (96)



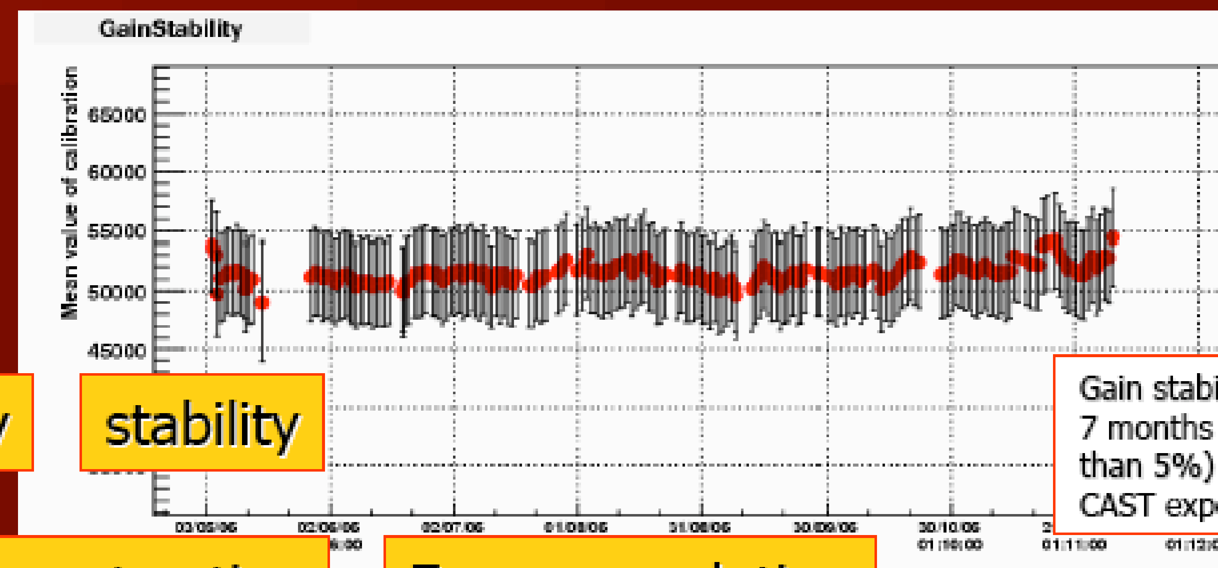
Micromegas: latest developments

CAST readout 300 μm pitch



granularity

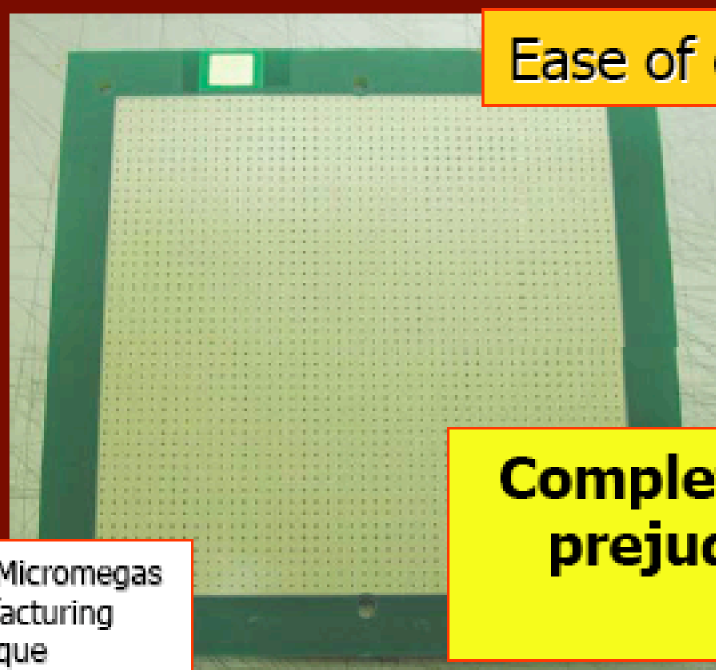
stability



Gain stability over 7 months (less than 5%) in the CAST experiment

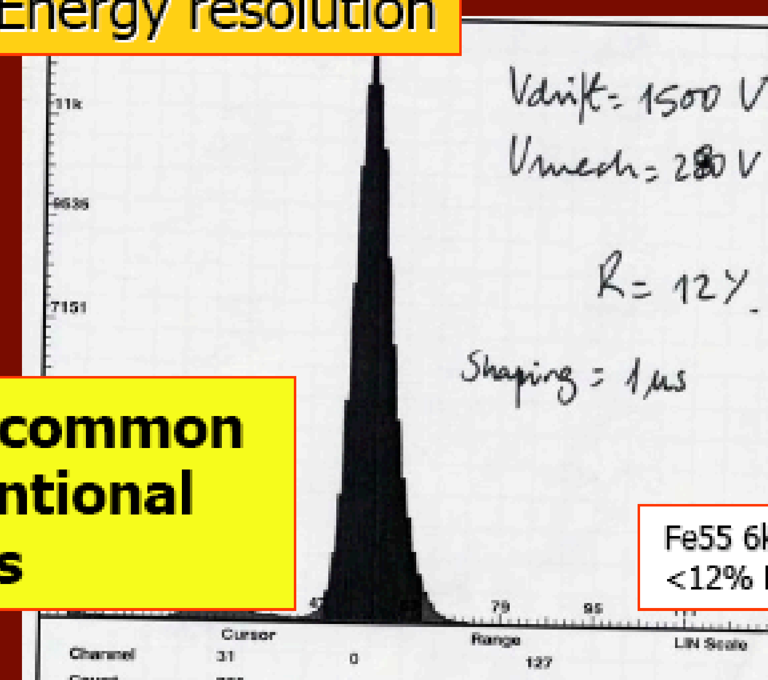
Ease of construction

Energy resolution



BULK Micromegas manufacturing technique

Completely overrides common prejudices on conventional multiwire TPCs

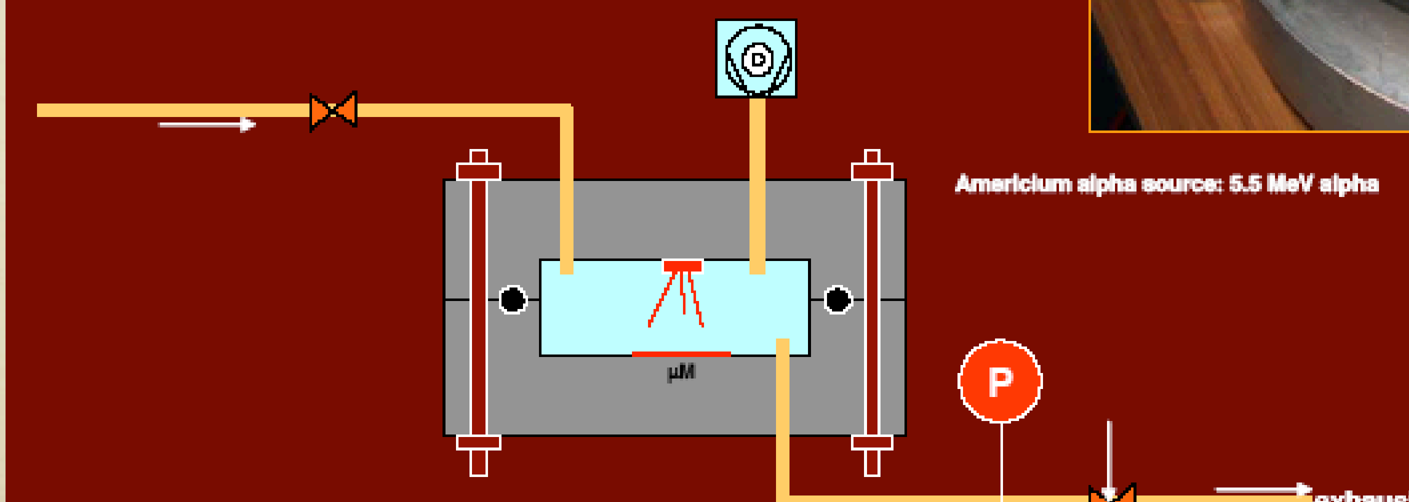


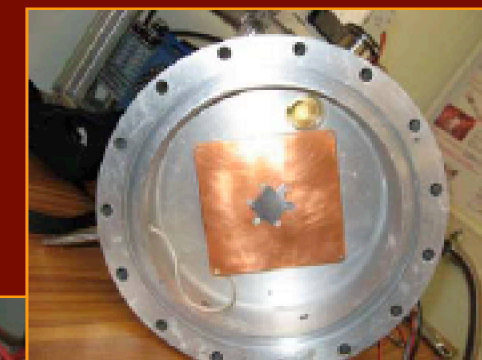
Fe55 6keV source <12% FWHM

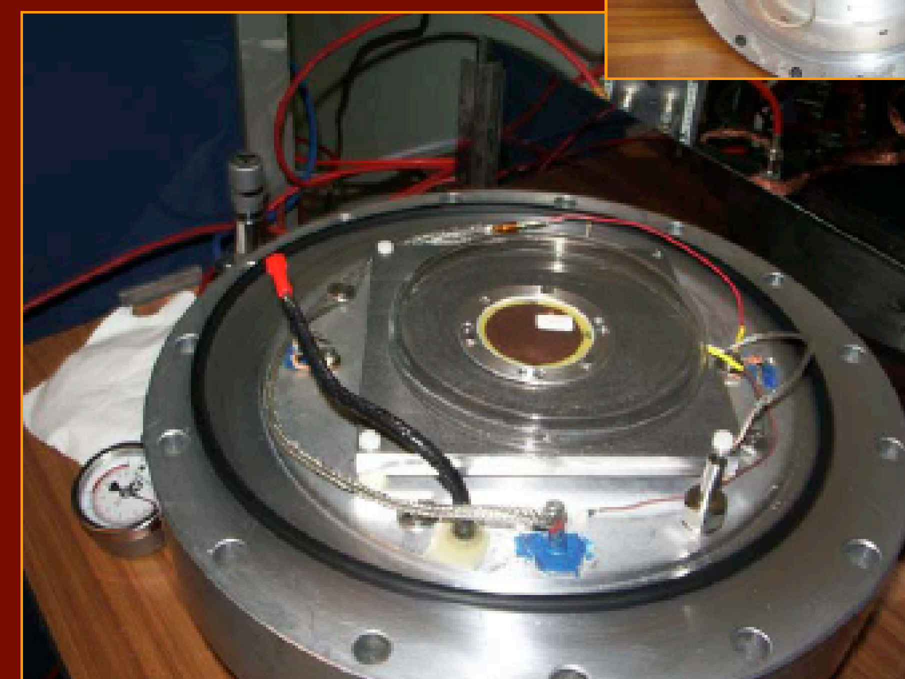
Energy resolution

- Measurement of E resolution at high energies:
  - High pressure Ar+Isob small setup, read by new generation Micromegas readout (*microbulk*) non-pixelized anode

- Mixtures testes: Ar + Iso 2%, Ar + Iso 5%
- Pressures tested: from 1 to 5 bar







Energy resolution

- Obtained resolutions

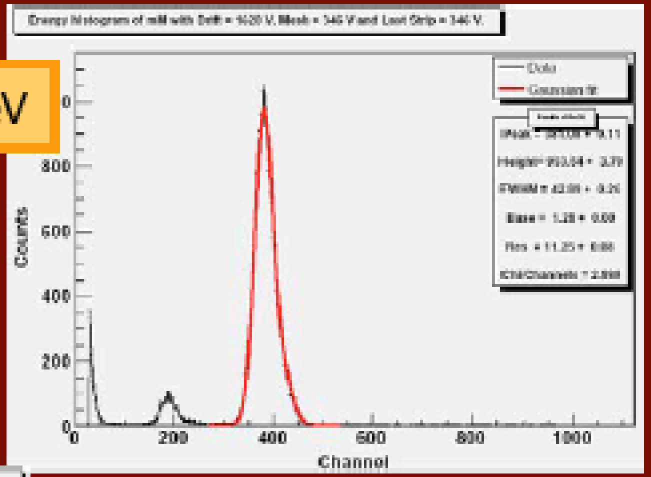
1.5 – 2 % (FWHM)

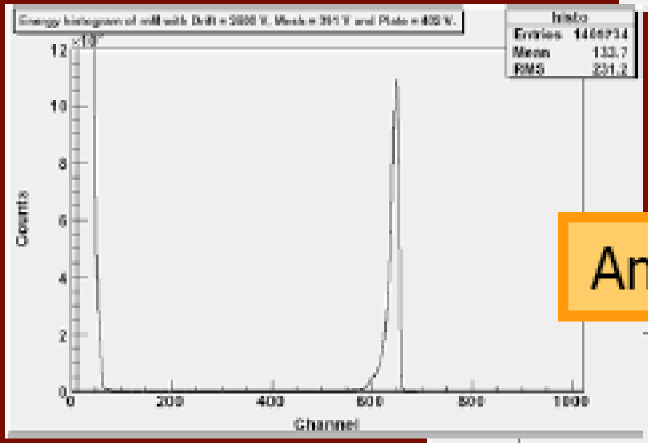
in a wide range of parameters (mesh and drift V, P, etc…)

- Landau deconvolution analysis indicate possible intrinsic Micromegas energy resolution of 0.7 % FWHM.

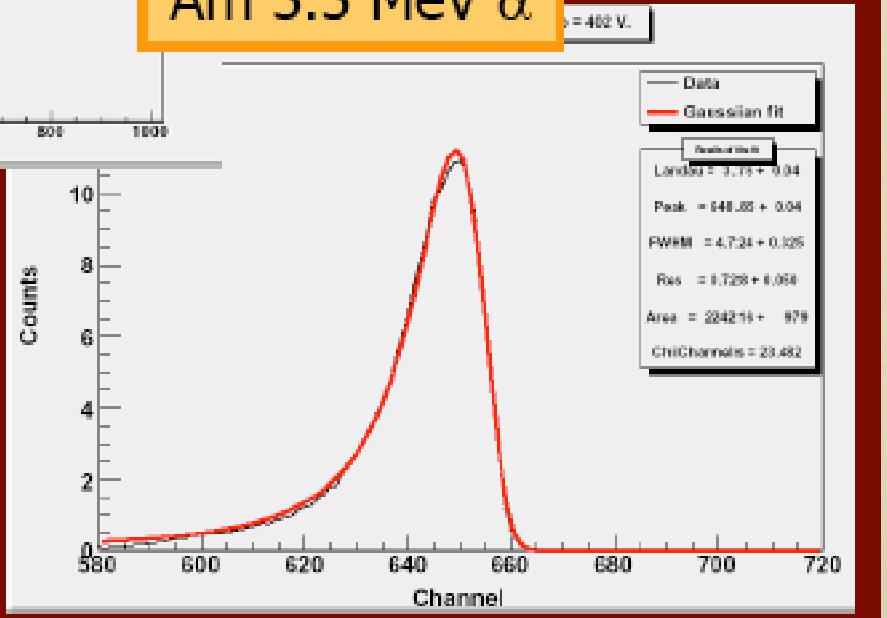
- **Same measurements in Xe and Xe mixtures in preparation**

^{55}Fe 6 keV



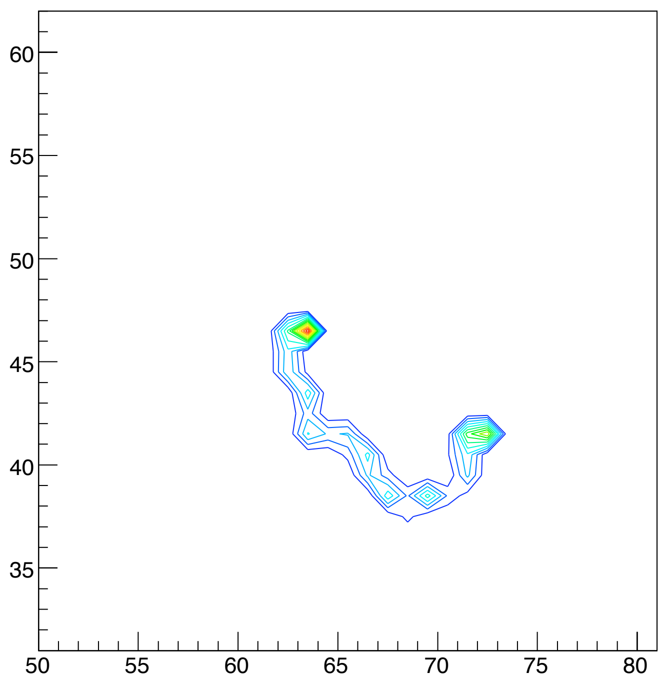


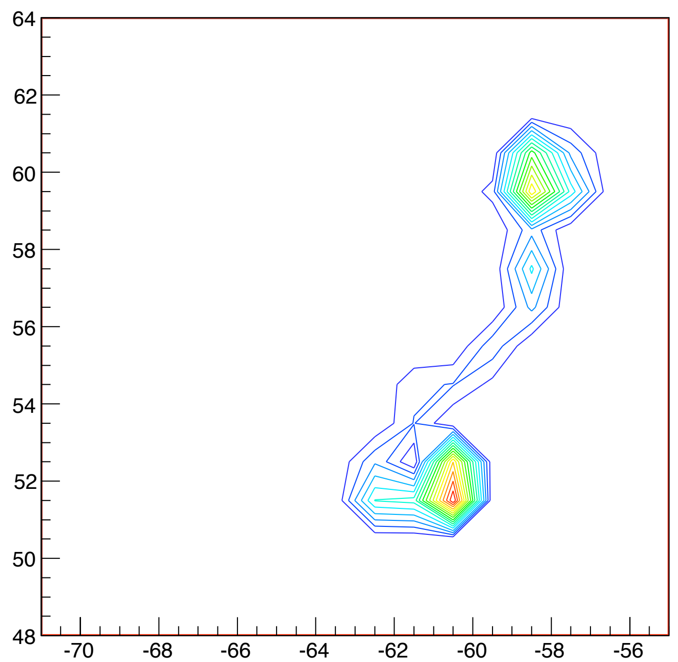
Am 5.5 MeV α



An spaguetti with two meat balls

PID





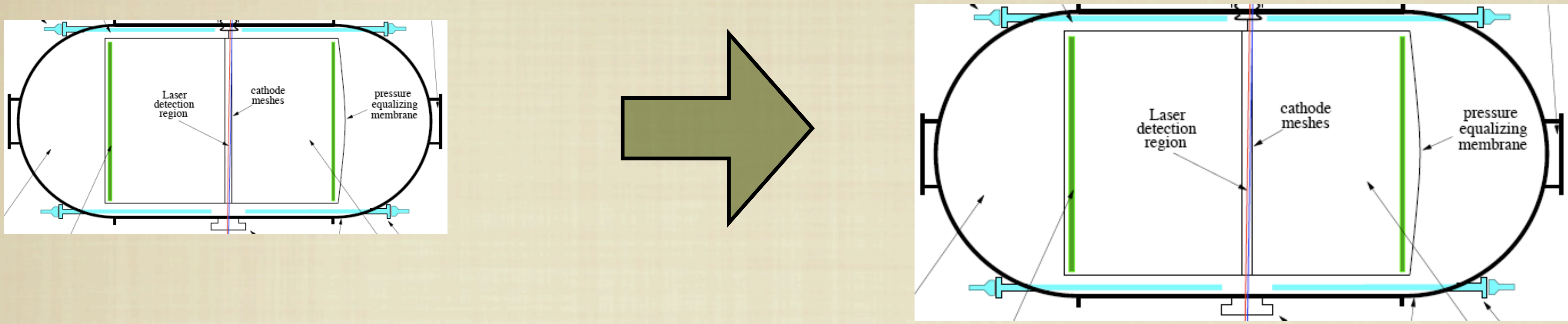
Kinematical signature allows to reject non bb backgrounds

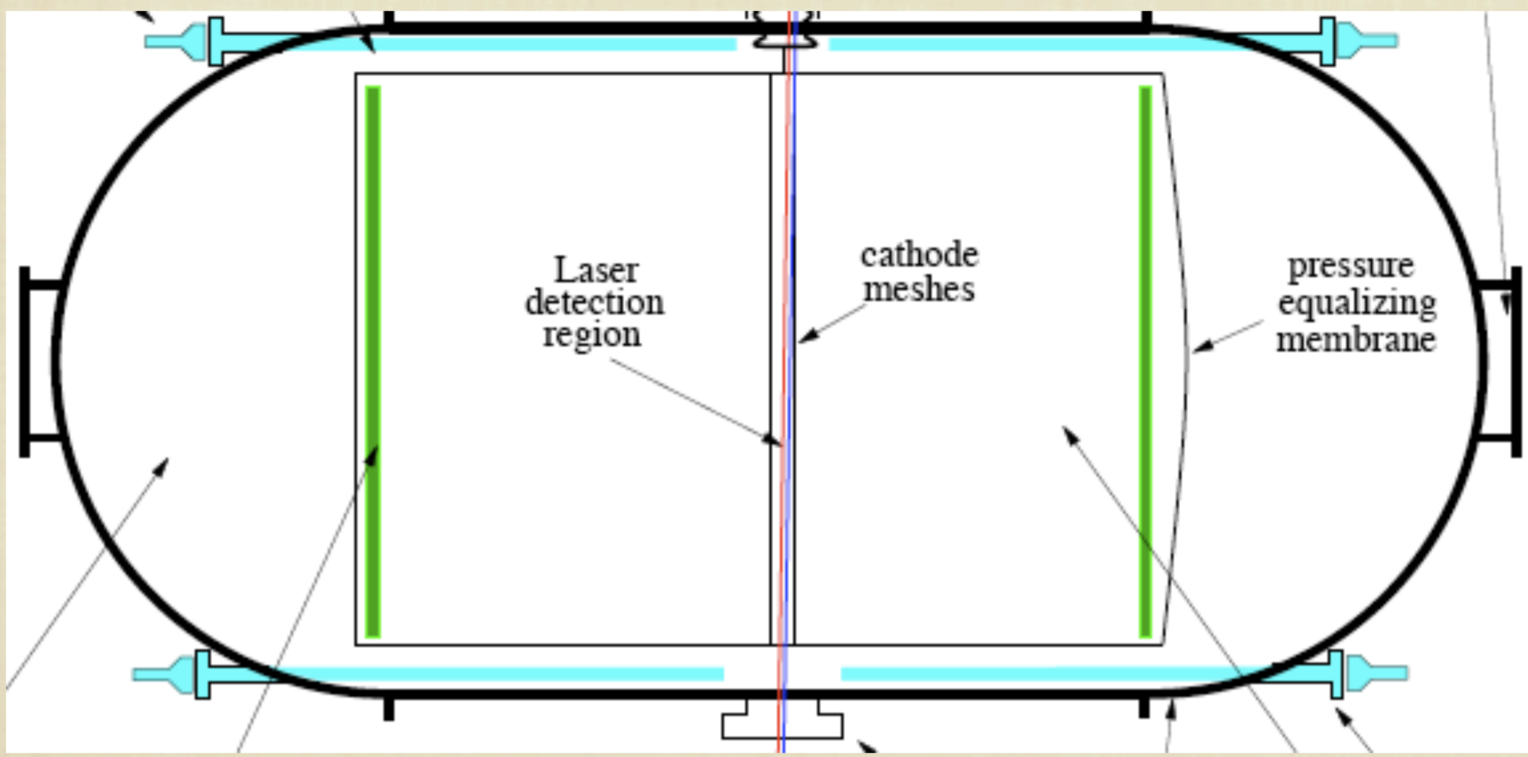
EXO: gammas will fake the signal

GXE: Tracks are seen, gamma need to convert in fiducial volume to be a background

Plus, signature of two electron different from single electron. Extra rejection

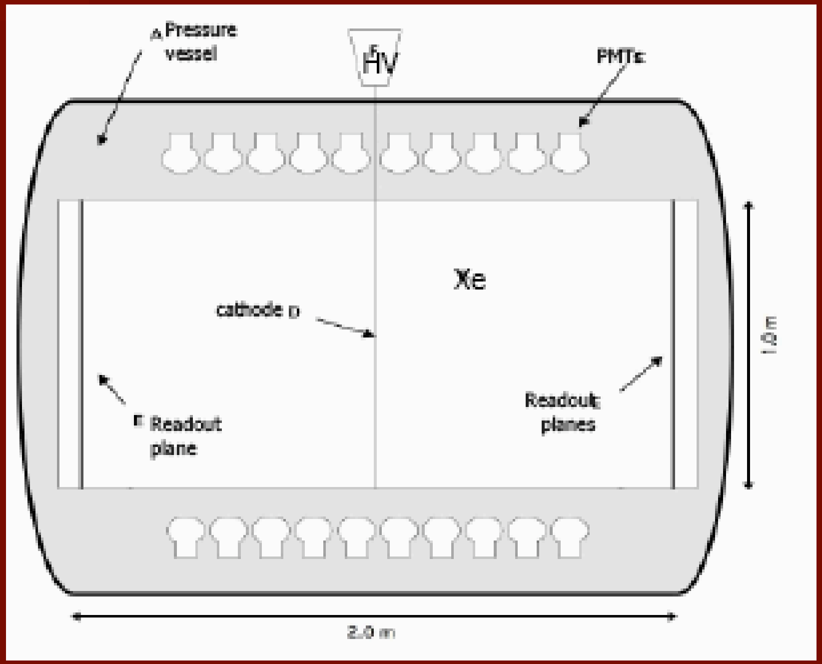
Scaling a TPC





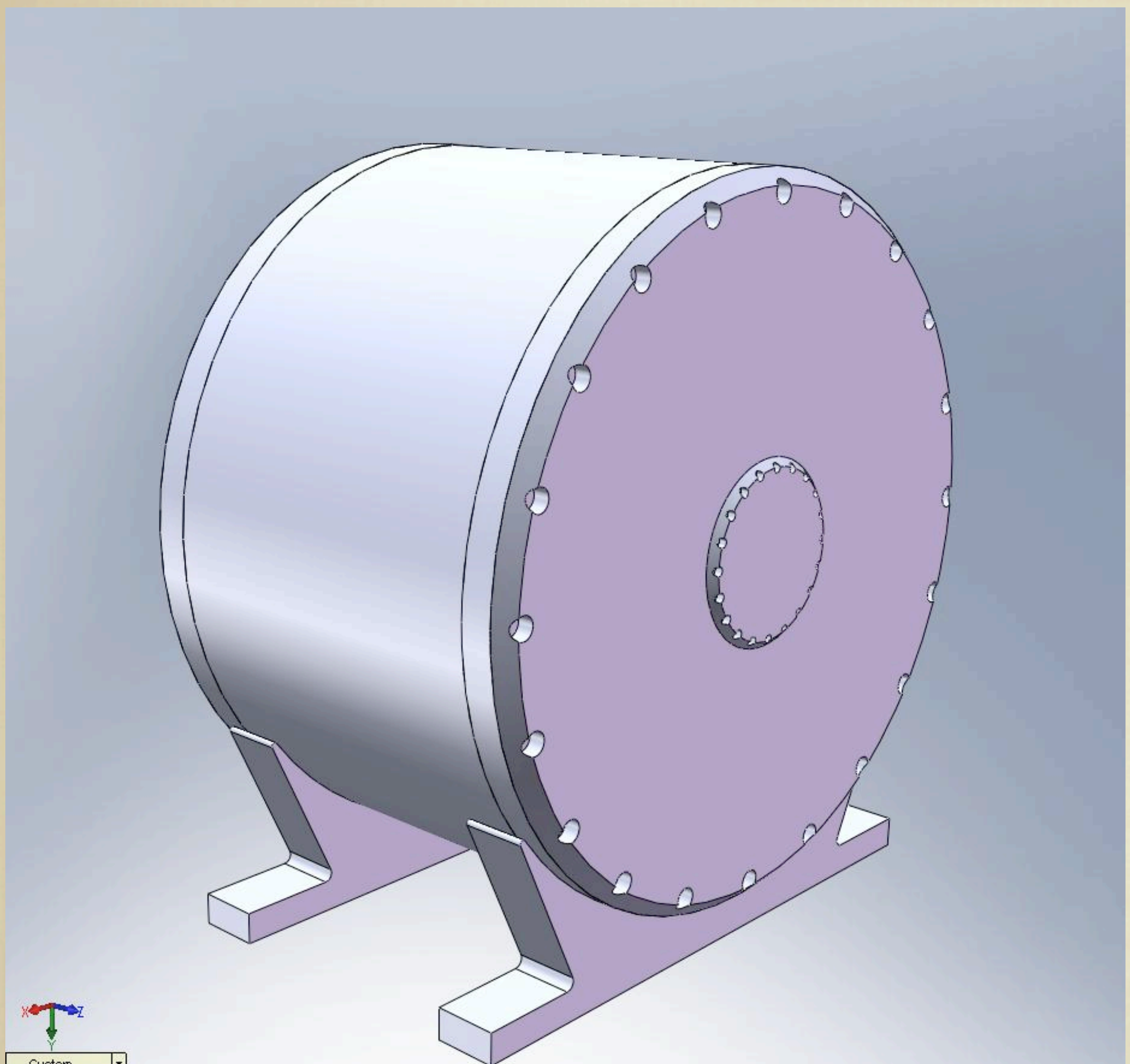
No modules! Win with L^3. Pay with L^2 (for electronics)

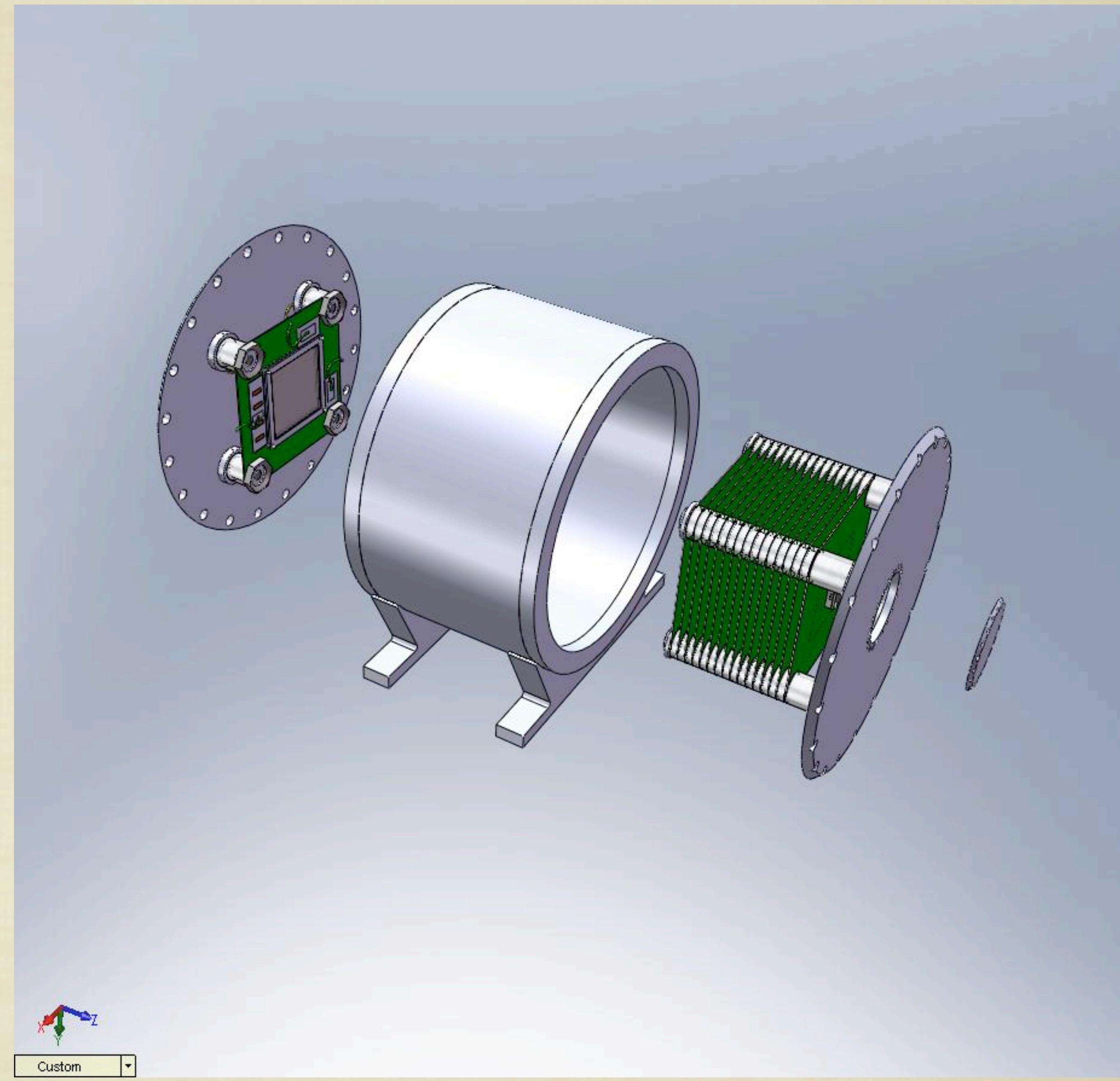
NEXT R&D



- Energy resolution and gas mixture
  - Demonstrate in Xe
  - Role of quencher. Compromise with scintillation signal.
- T0 measurement (UV light)
- Software: simulations
  - Best use of topology information
  - Backgrounds
- Mechanics (high P issues)
- Background
  - Needed radiopurity measurement program
  - Needed shielding? Active/pasive? Selfshielding?
- Readout type and design
  - Which is best for NEXT?
  - Implications to radiopurity

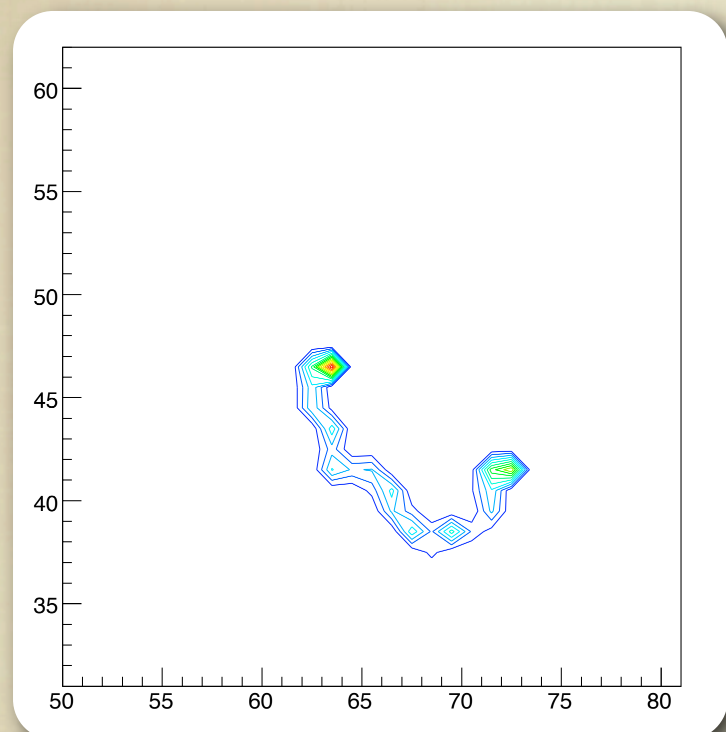
Gas Xe TPC Prototypes

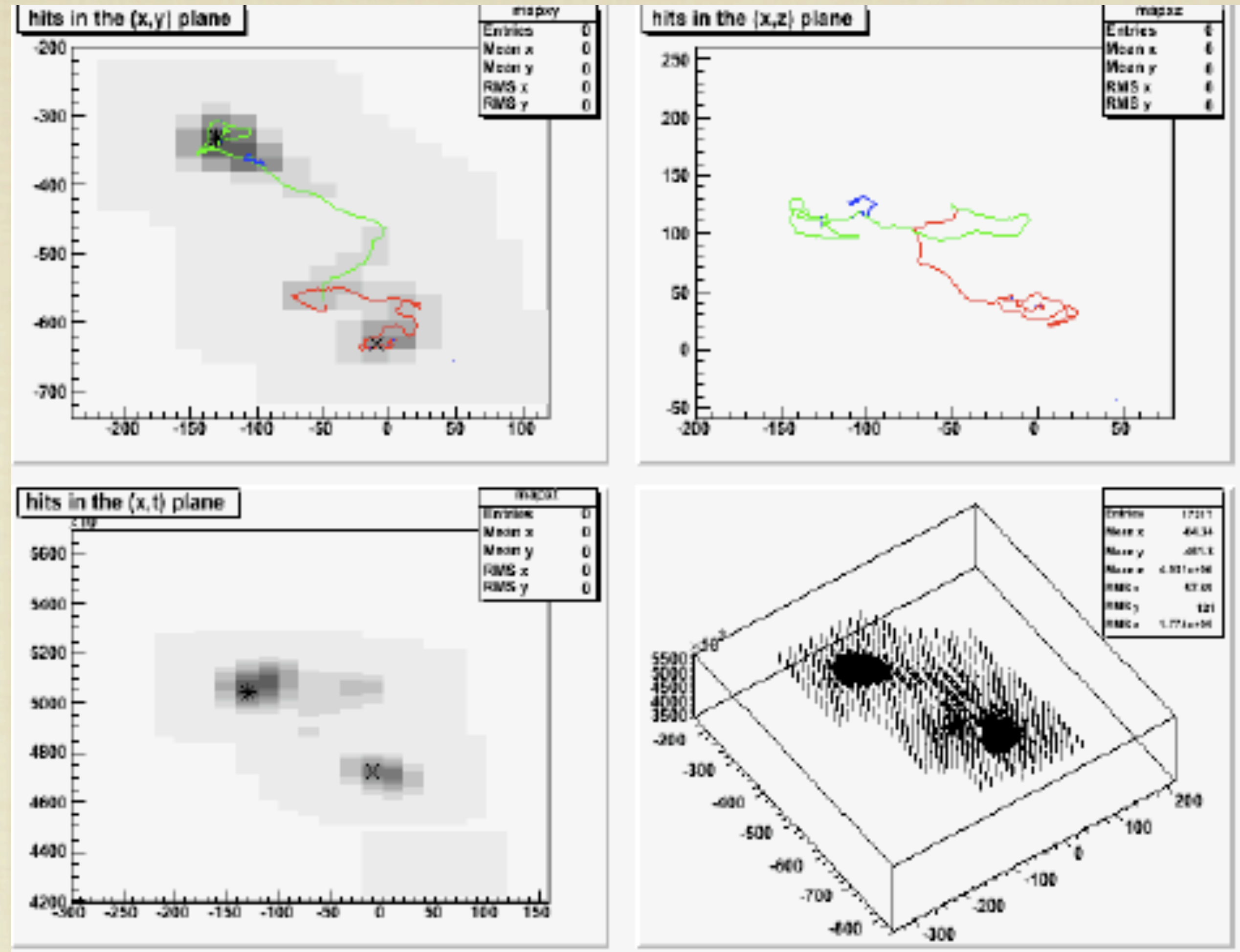


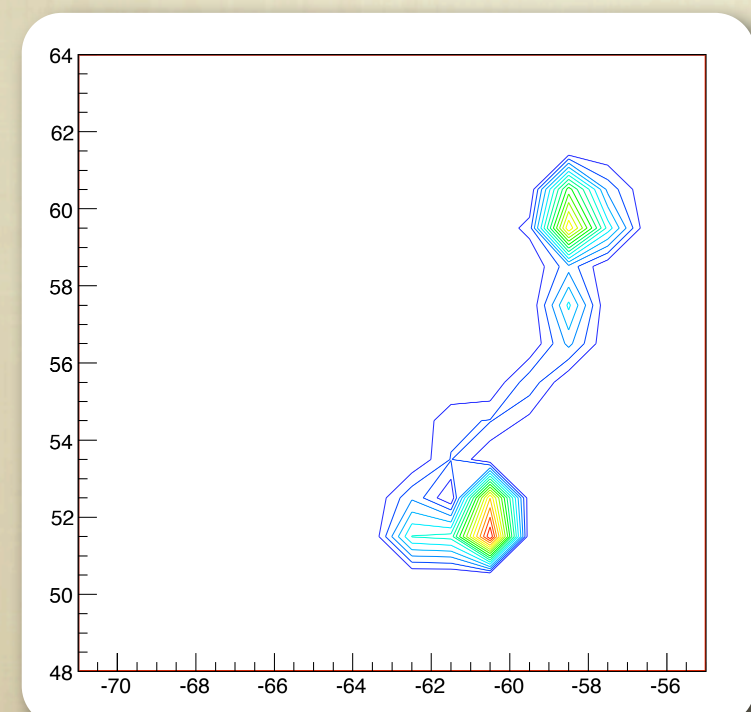


Prototype design at IFAE

Monte carlo simulations



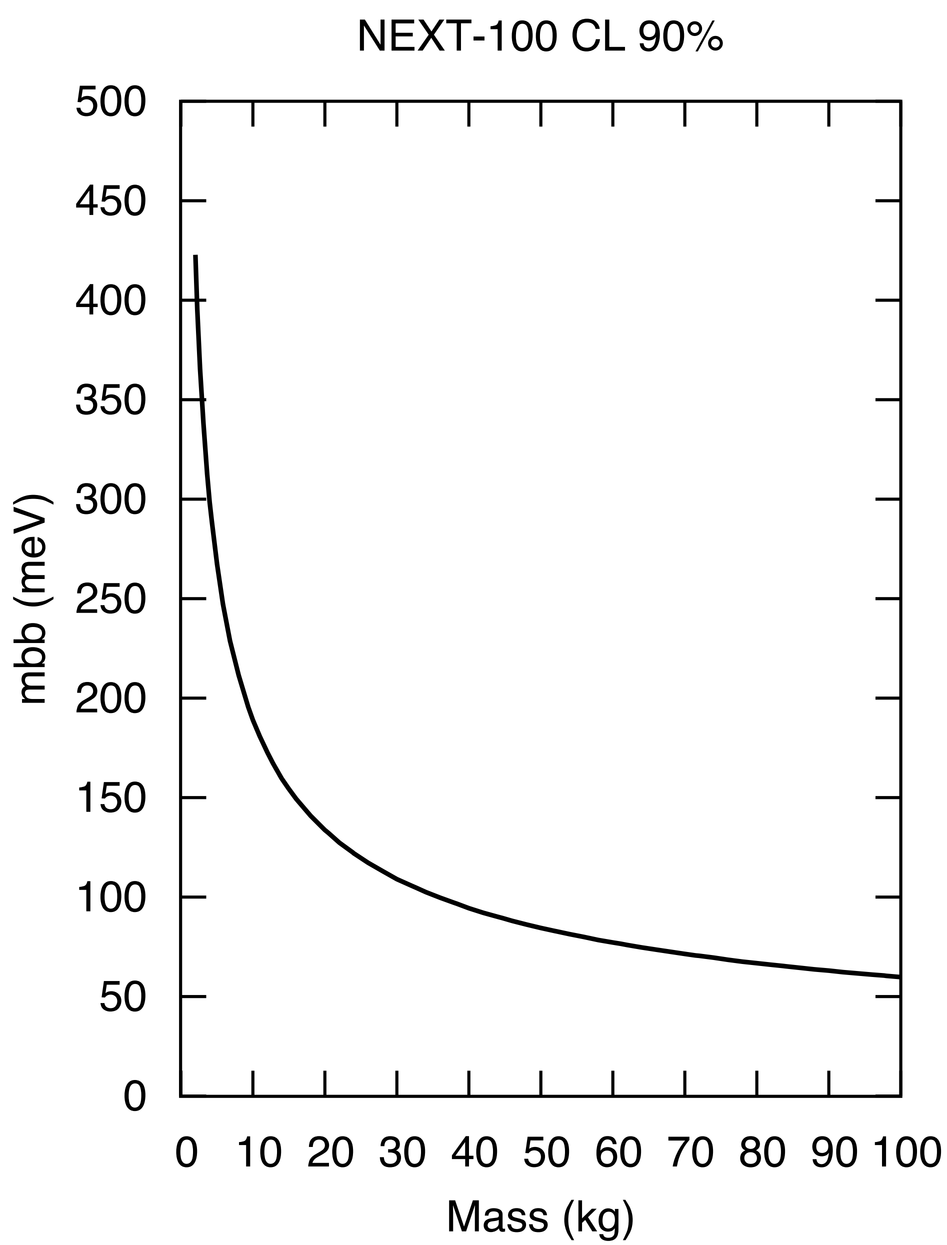


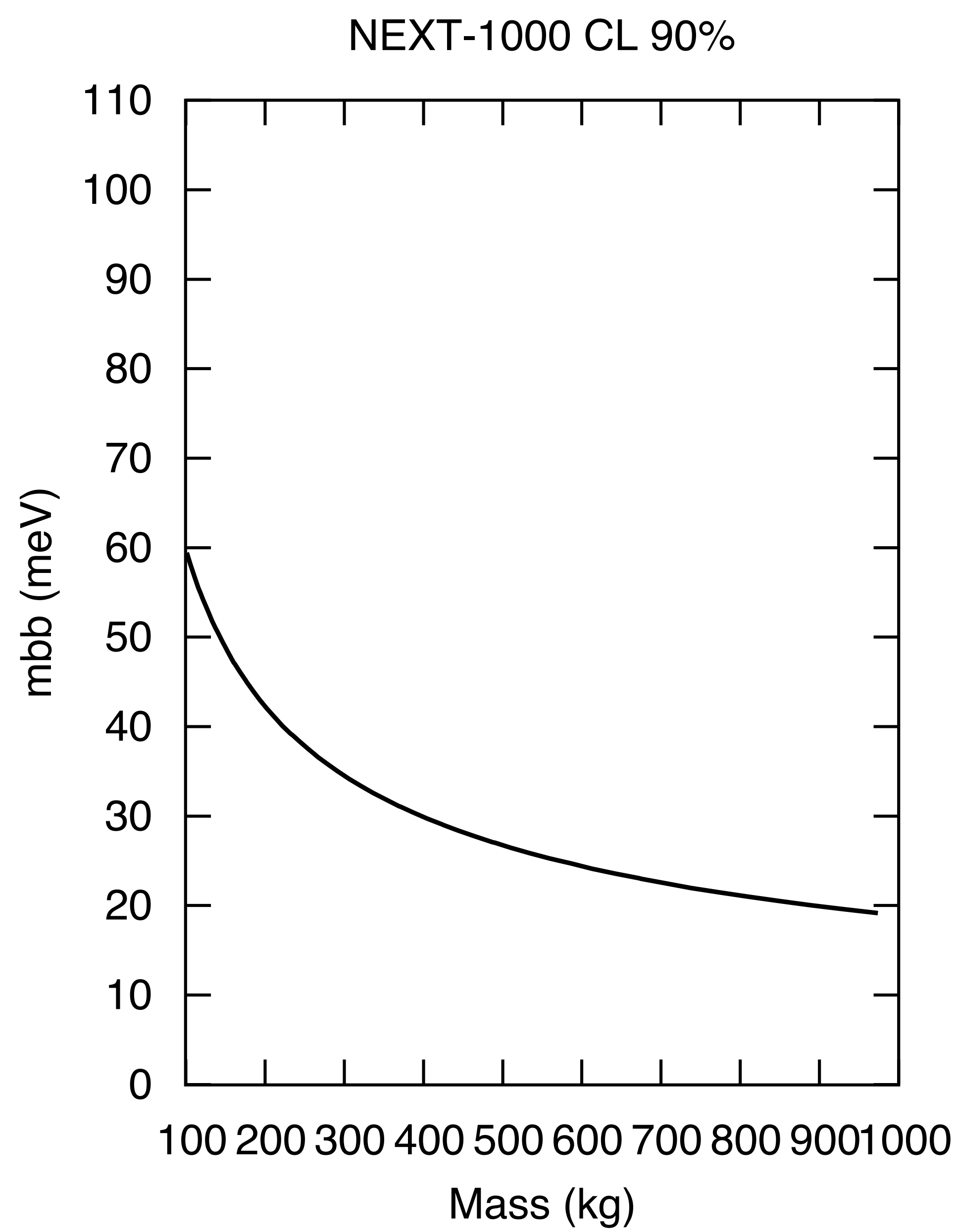


Study efficiency, event characterization & background rejection
(IFIC, IFAE)

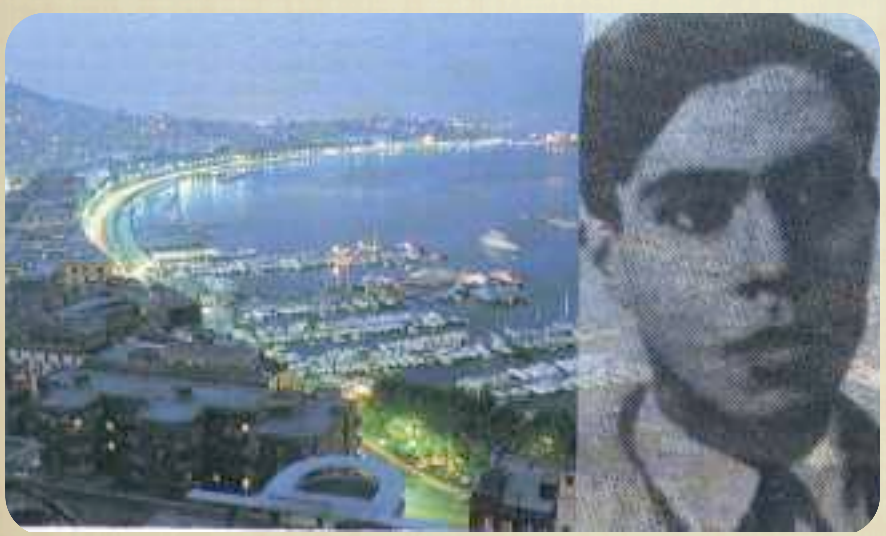
A GXe TPC can explore inverse hierarchy

10 y





Ettore Majorana meets his shadow



The neutrino, as Ettore Majorana himself is a misterious particle.

Why Did Majorana dissapear? Did he commit suicide? Did he choose to vanish, to retire from the world, to become a shadow?

If so, he could be still alive, 100+ years old and still wandering if the neutrino is its own antiparticle its own shadow

Maybe the answer can come soon. A 100 kg Xe TPC could find the signal for bb0nu in less than 10 years.

Can one explore the inverse hierarchy? This requires 1 ton TPC or more. Perhaps it can be done...

Perhaps WE can do it at Canfranc