Ghostly Heat

Understanding neutrinos Through Calorimetry

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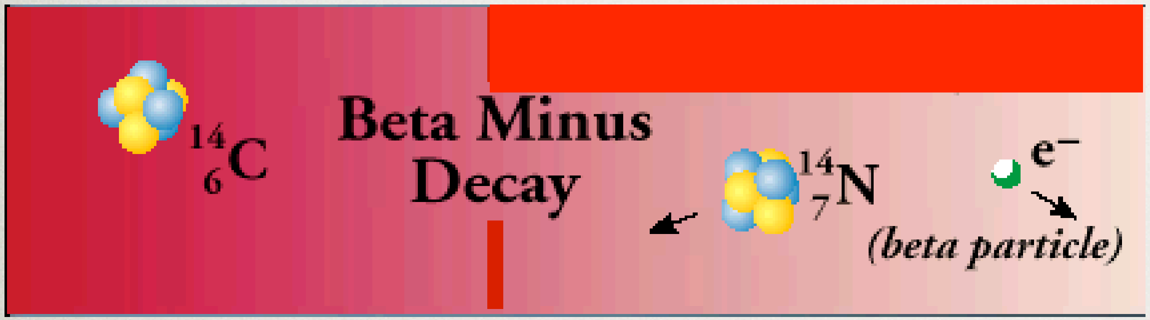
Cal Poly Physics Colloquium, Feb 2006

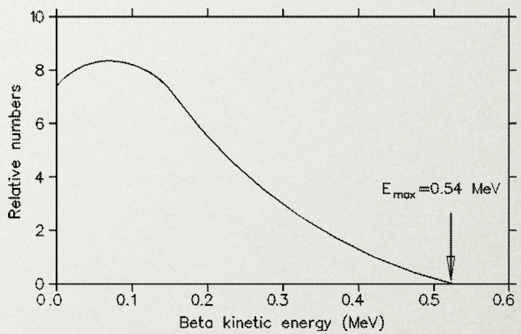
Overview

- What are neutrinos?
- How do we know neutrinos have mass? What is that mass?
- Are neutrinos their own antiparticle?
- Why are these questions important?
- How can measuring an exotic nuclear decay help us?
- How do you use calorimetry to measure this decay?
- What experiment uses this method?
- How students can get involved and at what level?

Beta Decay

Beta decay seems to violate energy-momentum conservation



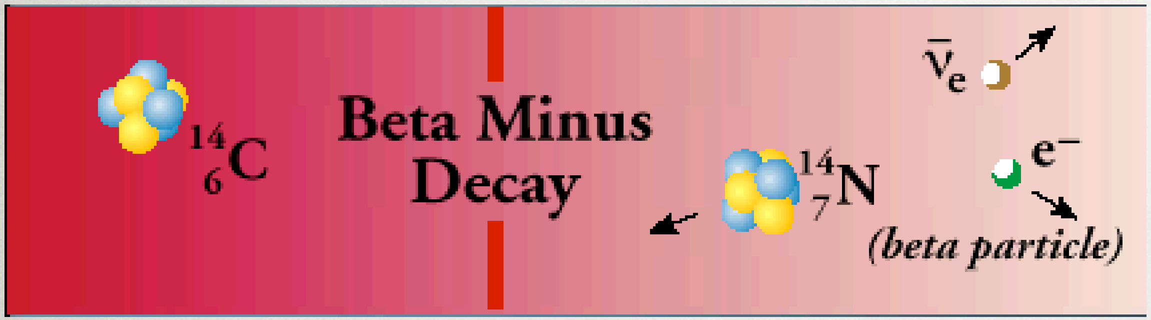


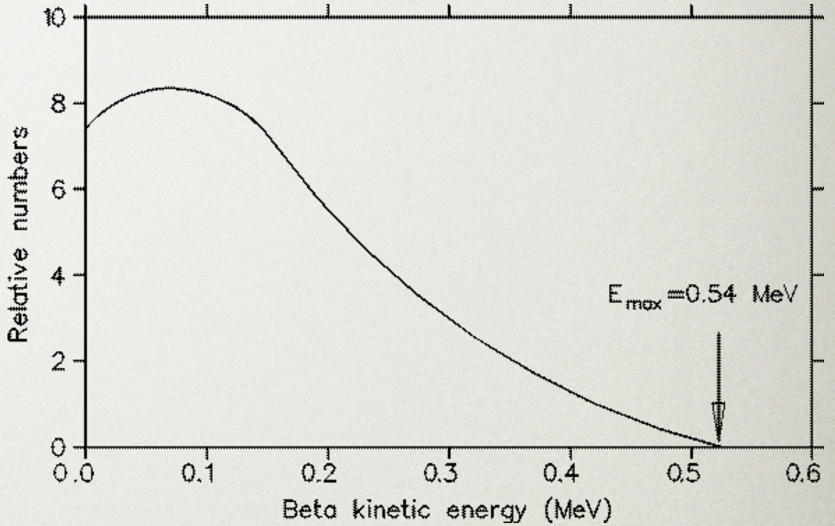
Liebe Radioaktive
Damen und Herren

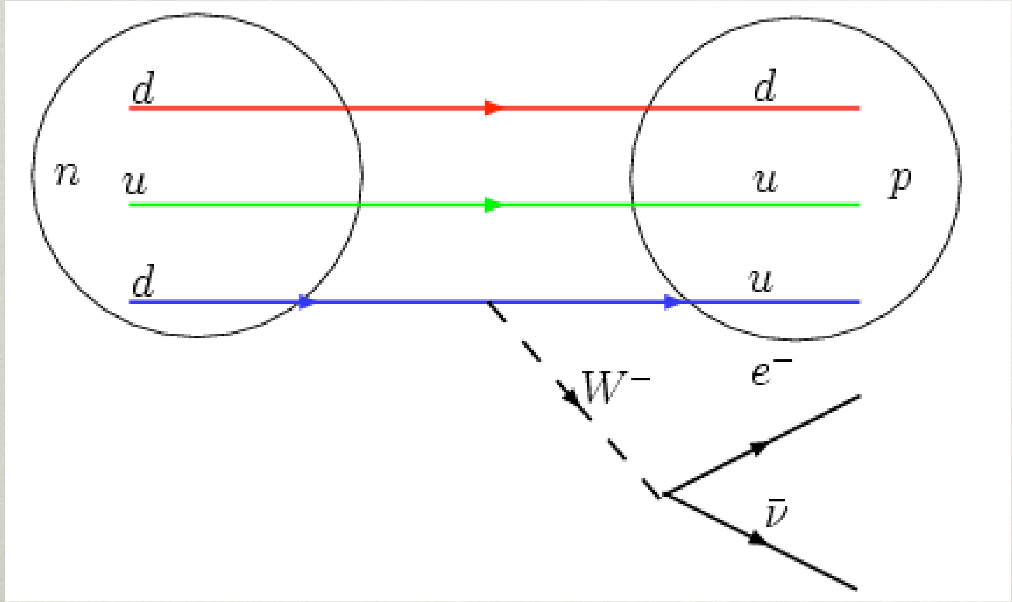
1930

The New Beta Decay

A neutron is converted to a proton via a weak force interaction







A three body final state that includes a massless fermion naturally explains the continuum of electron energies

1933

Lo chiamo il neutrino

Neutrinos Interact Weakly

They are often called "ghost particles" because they only interact weakly; they are notoriously difficult to measure

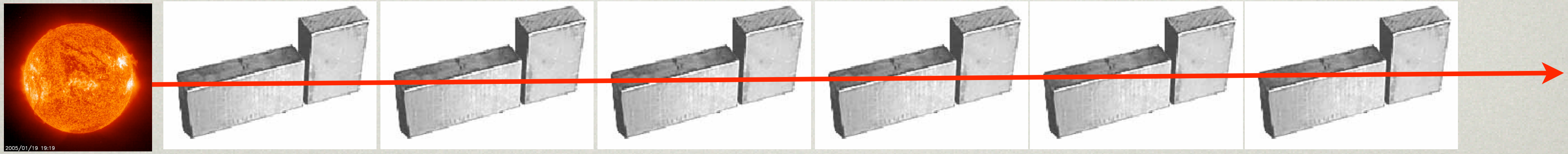
The sun produces copious electron neutrinos

~10^{11} solar neutrinos per second pass through your thumb

Despite being difficult to measure, it was eventually discovered in 1956

1 light year of solid lead

1/2 neutrinos from the sun still get through

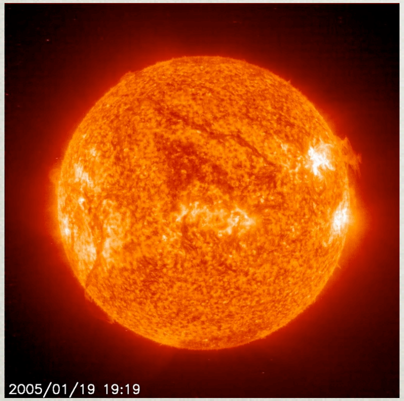


The Solar Neutrino Problem

Careful measurements of electron neutrinos from the sun showed a substantial deficit compared to otherwise established solar models

Only ~1/3 of the electron neutrinos predicted by Bahcall's model were measured by Davis

1964: Davis and Bahcall at Homestake



ν_e $\longrightarrow$ ν_e

$\nu_e + {}^{37}Cl \mapsto {}^{37}Ar + e^-$

The Standard Model

In the Standard Model, the neutrino is a massless neutral fermion with several important properties

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

Comes in 3 different flavors

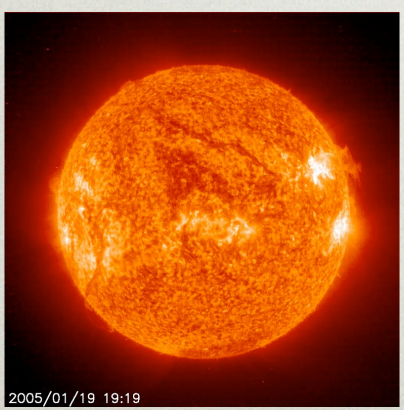
The flavors (“electron”, “muon”, “tau”) are regarded as fundamental quantum numbers in their own right

+Antiparticles

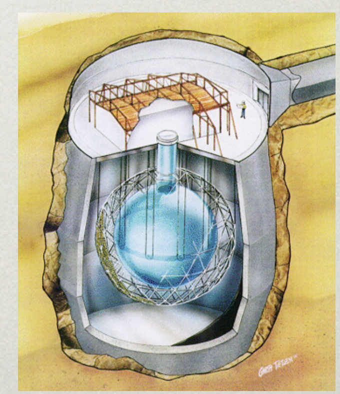
Problem Solved

When all flavors are accounted for (~35 years later!), the number of total neutrinos from the sun matches Bahcall's model

The SNO experiment accounted for all neutrino flavors; electron neutrinos must be transforming into other kinds of neutrinos mid-flight



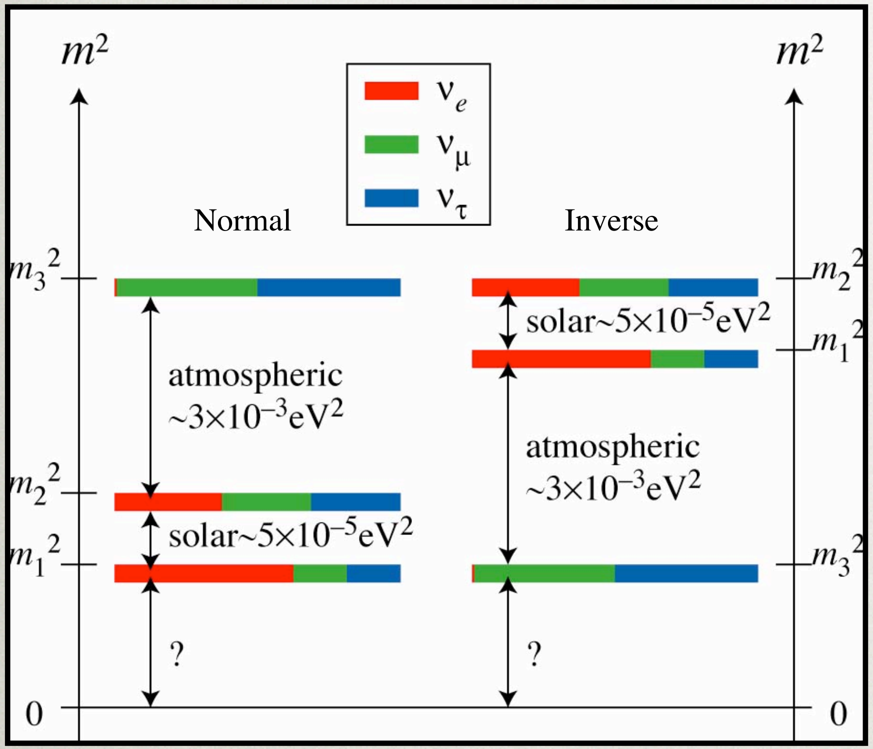
$$\nu_e \longrightarrow \nu_\mu + \nu_e + \nu_\tau$$



How can this be?

Flavor Oscillations

The neutrinos we measure in reactions are not energy eigenstates



Neutrinos of definite mass (energy) don't change in time

We measure neutrinos of definite FLAVOR in the lab

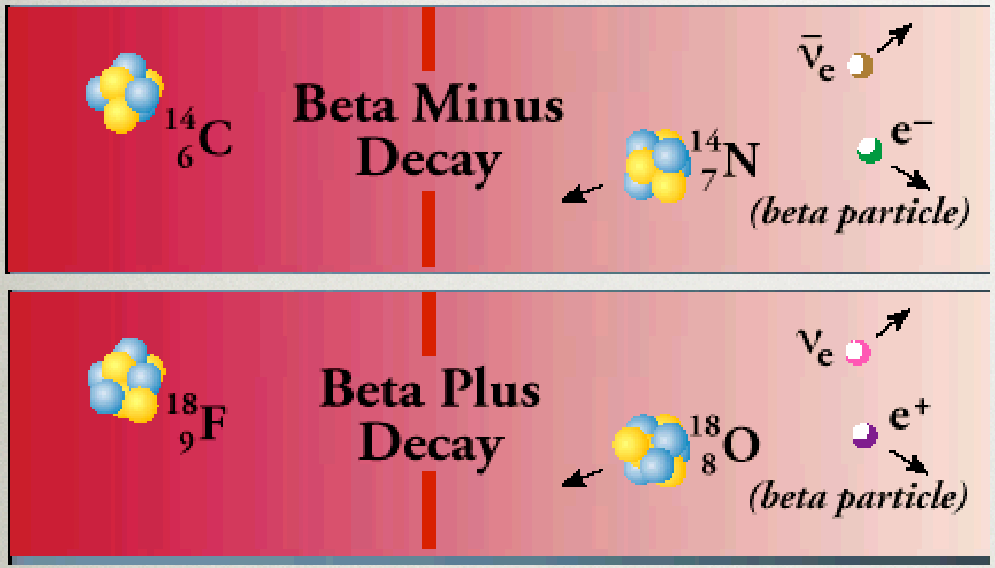
Flavors are made of different mass states so <u>do</u> change in time

The absolute mass scale and ordering is unknown

☑ Neutrinos have mass but we don't know what it is

The Antineutrino

Can we really tell neutrinos apart from their antiparticles?



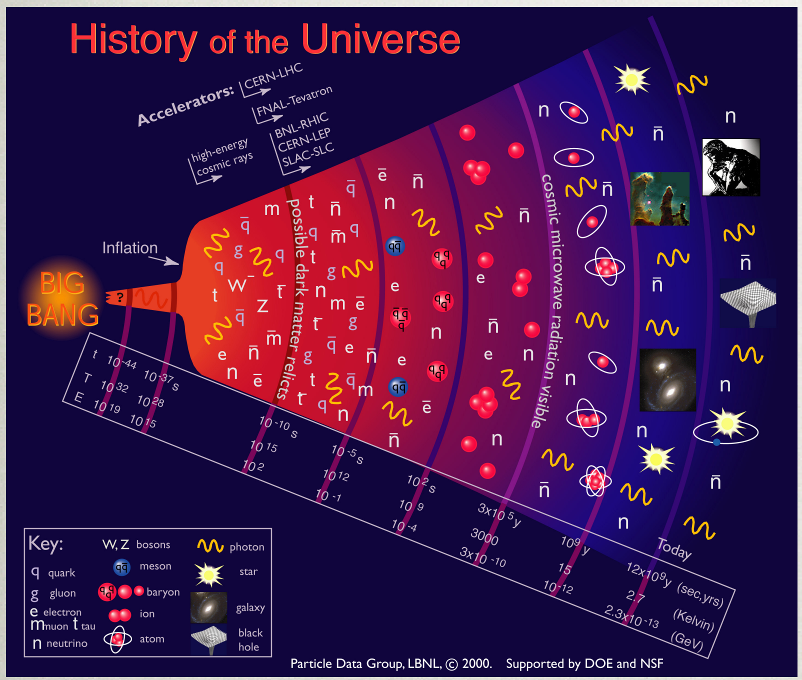
In contrast to other fermions, the neutrino has no electric charge or internal structure, so the distinction between a "particle" and "antiparticle" is subtle

The classification is by the type of reactions observed and then by following a convention

☑ The neutrino could be it's own antiparticle

Why is it important?

Knowing the neutrino's mass and if it is distinct from its antiparticle may have profound implications for cosmology



Knowing the neutrino mass will provide the neutrino contribution to dark matter

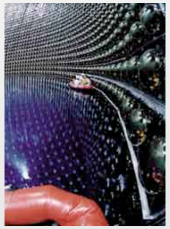
Knowing the nature will help understand the matter/antimatter asymmetry in the universe

May provide footholds into other Beyond Standard Model physics

Review and Onward

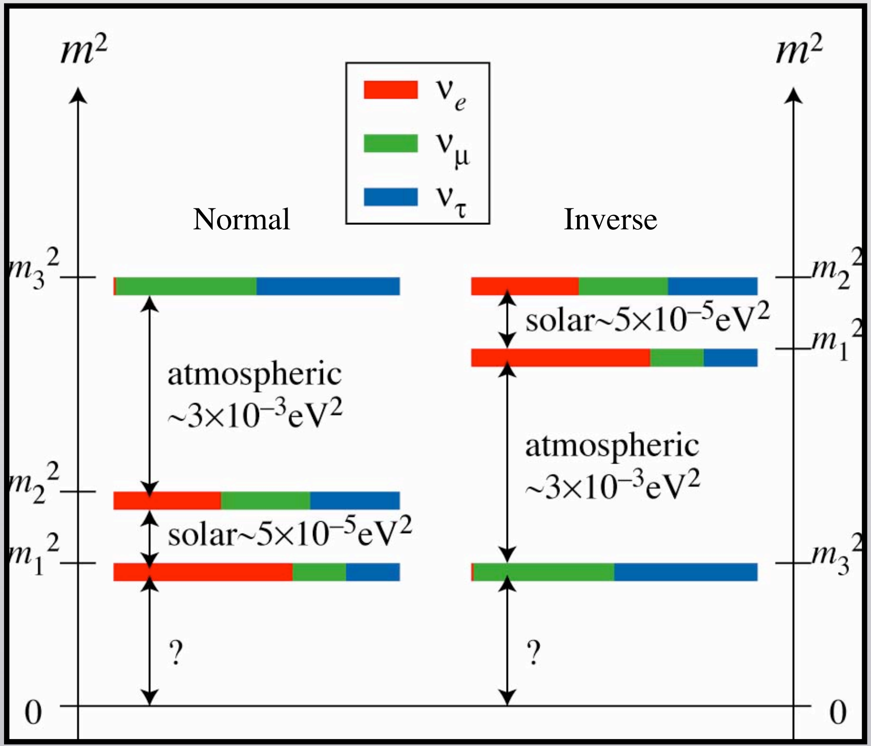
Experiments have shown:

- Neutrinos undergo flavor-changing oscillations
  - This implies neutrinos have finite masses
  - Only sensitive to mass difference squared



Important open questions in ν physics

- What is absolute mass?
- What is correct mass ordering?
- Are they their own antiparticles?



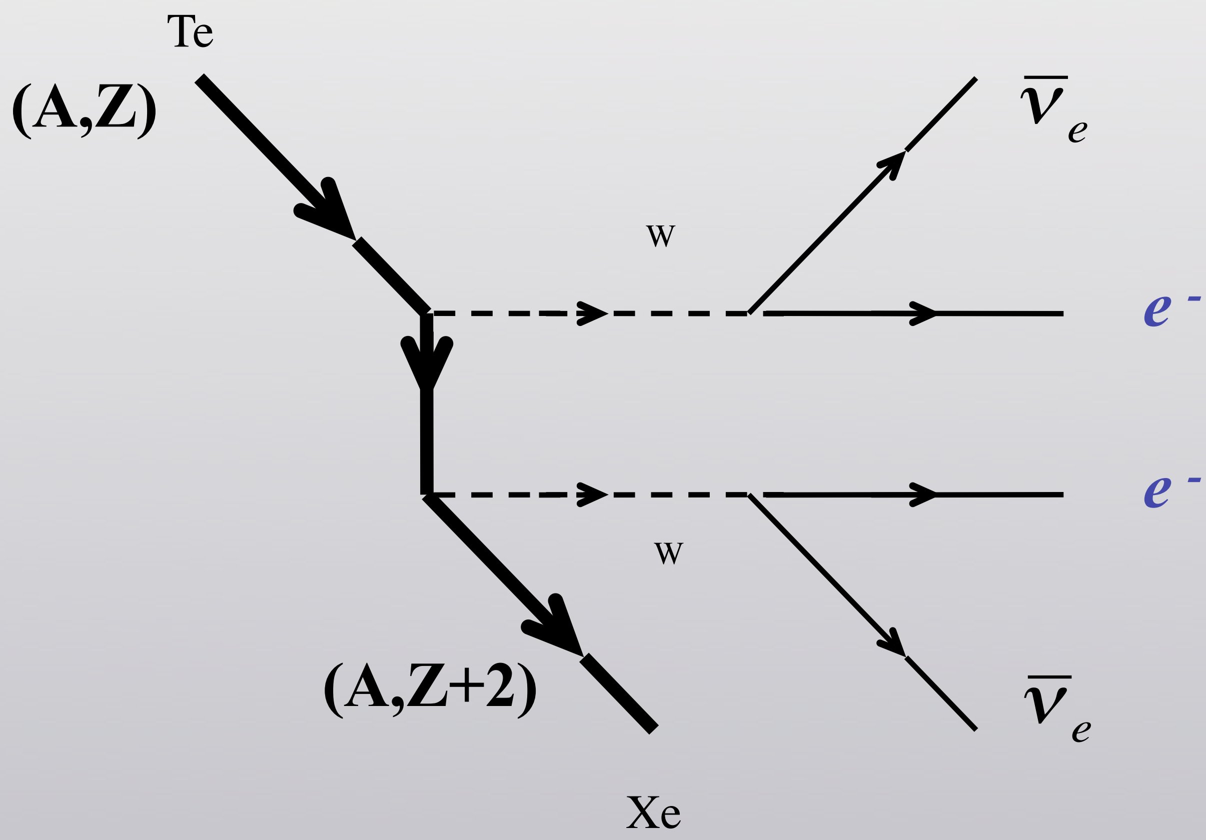
Amazingly, there is a single measurement that can address these

$\beta\beta2\nu$: Double Beta Decay

$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$

Really is just two simultaneous beta decays: very unlikely

Allowed by the Standard Model
$\tau \geq 10^{18}$ y
Measured in real systems
(NEMO, geochemical, etc.)



Time scale reminder:
NASA's WMAP mission
(2003) sets the age of the
universe at
$13.7 \pm 0.2 \times 10^9$ years

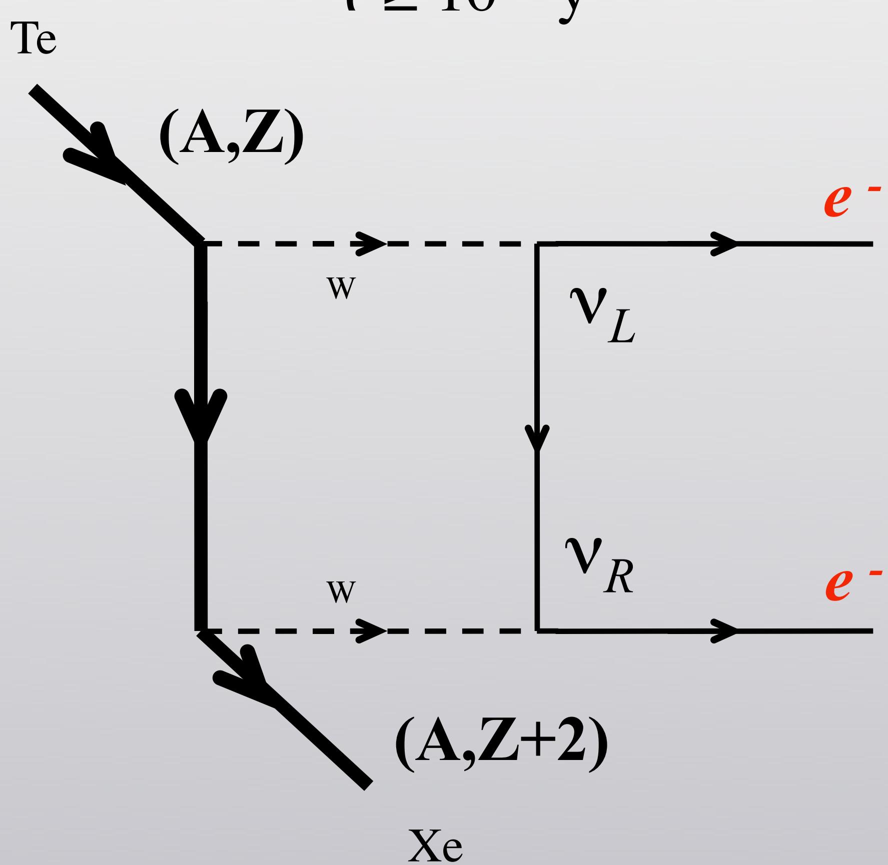
ββ0ν: Neutrinoless Double Beta Decay

$(A,Z) \rightarrow (A,Z+2) + 2e^-$

open discussion on its observation

$\tau \geq 10^{25}$ y

Observation of ββ0ν implies Physics beyond the Standard Model

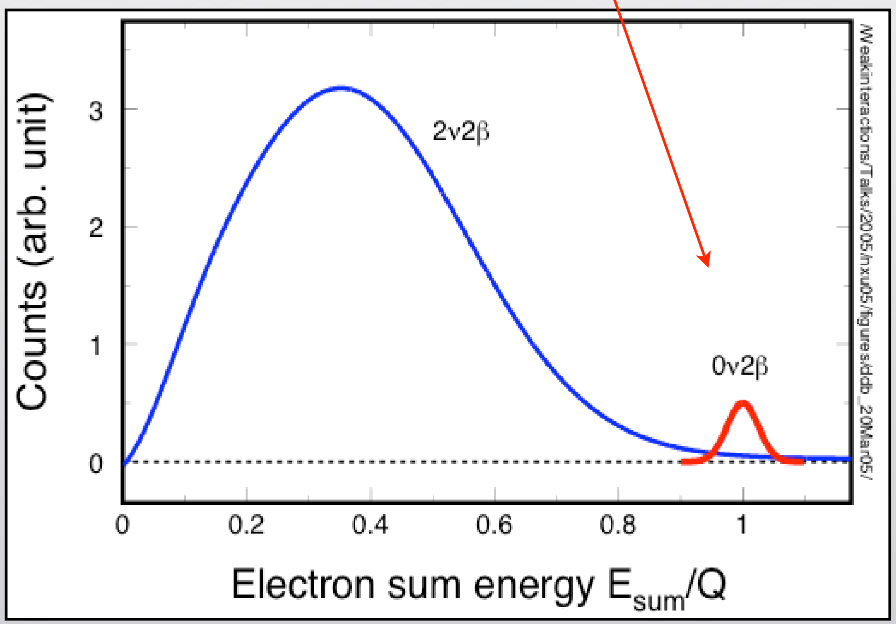


- Rate of decay sets ν mass scale and reveals hierarchy
- Process only occurs if neutrinos are their own anti-particles

A long lifetime means you need more moles (thus mass) of source material to measure the decay in a reasonable time

ββ0ν: The measurement

Smearing from
energy resolution;
introduces background



$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$

$(A,Z) \rightarrow (A,Z+2) + 2e^-$

Each candidate isotope has a predicted Q value for the reaction

This is the maximum kinetic energy available to the electron pair

Measure the two electron sum energy:
The two neutrino mode will be a continuum
The zero neutrino mode will be a peak

ββ0ν Rate and Neutrino Mass

Calculated

Phase space ∝ Q^5

Calculated

Nuclear matrix element

0ν-DBD rate

Measured

Effective neutrino mass

Extracted

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

high Q candidates preferred

large phase space

Many possible candidates with various Q values

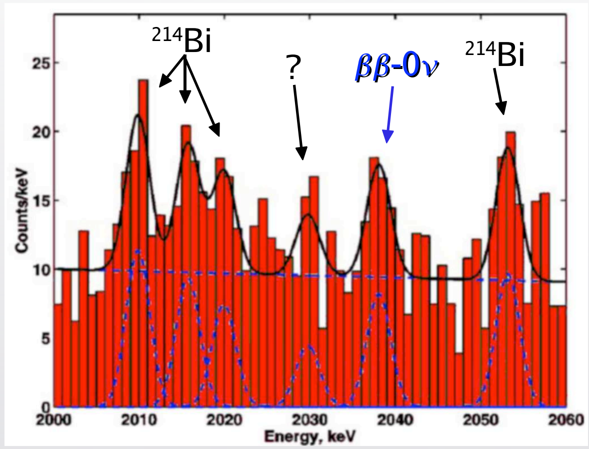
low background

^{238}U γ end at 2400 keV

^{232}Th γ end at 2600 keV

[2039 keV (^{76}Ge) ⇔ 4271 keV (^{48}Ca)]

ββ0ν Scientific Context

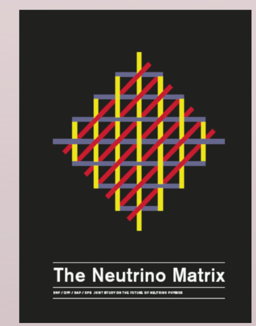


The gauntlet is down:
There is an existing
ββ0ν claim in ^{76}Ge
"KKDC"

Klapdor et al., Phys. Lett B 586 (2004) 198

APS Neutrino Study (2004)

We recommend, as a high priority, a phased program of sensitive searches for neutrinoless nuclear double beta decay. *In this rare process, one atomic nucleus turns into another by emitting two electrons. Searching for it is very challenging, but the question of whether the neutrino is its own antiparticle can only be addressed via this technique. The answer to this question is of central importance, not only to our understanding of neutrinos, but also to our understanding of the origin of mass.*

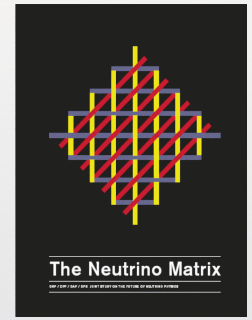


Recommendation: The Neutrino Scientific Assessment Group recommends that the highest priority for the first phase of a neutrino-less double beta decay program is to support research in two or more neutrino-less double beta decay experiments to explore the region of degenerate neutrino masses ($\langle m_{\beta\beta} \rangle > 100$ meV). The knowledge gained and the technology developed in the first phase should then be used in a second phase to extend the exploration into the inverted hierarchy region of neutrino masses ($\langle m_{\beta\beta} \rangle > 10 - 20$ meV) with a single experiment.

NuSAG report to Nuclear Science Advisory Committee (2005)

Strategies and Tactics

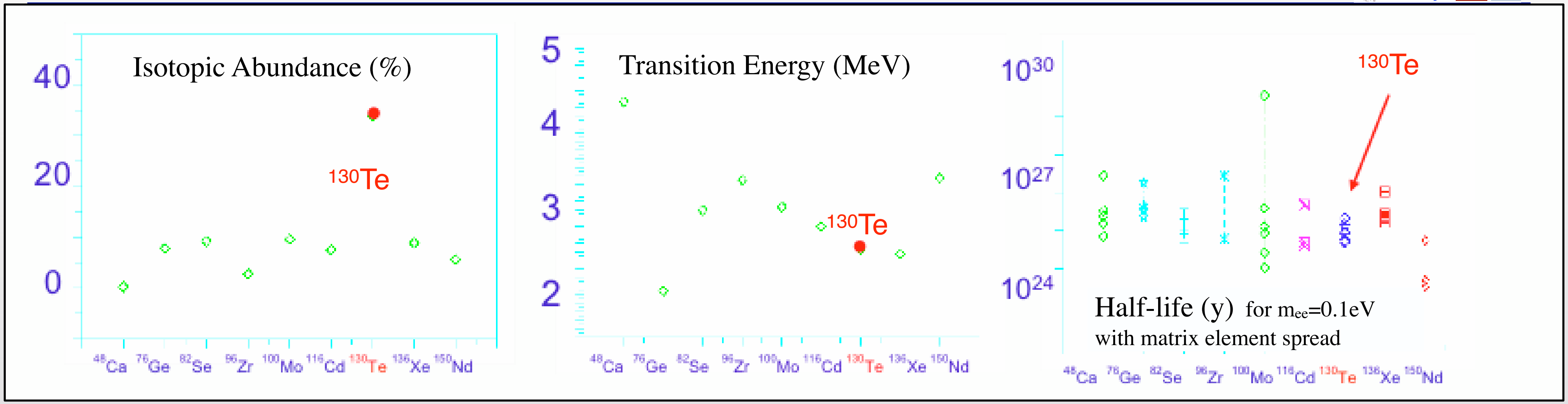
$\beta\beta0\nu$



- $\beta\beta0\nu$ is one of the top priorities in neutrino physics
- Near term:
  - KKDC claim must be addressed
    - Different isotopes
    - Different methods
  - If necessary:
    - Build bigger experiments to gain more sensitivity
      - more mass means more decays in a fixed amount of time

The massive tellurium cryogenic bolometers Cuoricino and CUORE are prepared to play their role this grand neutrino adventure

Why Tellurium?

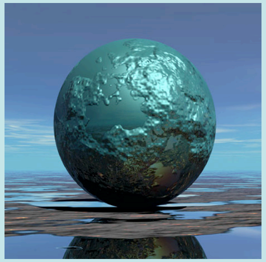


- Cost effective: Enrichment <u>not</u> *required*
  - Natural abundance 33.87%
- Reasonable Q = 2528.8 keV
  - Large phase space
  - Low gamma background: Q sits between the Compton edge (2360 keV) and full ^{208}Tl energy (2615 keV)
- $\beta\beta2\nu$ observed with geochemical techniques = potential neutrinoless double beta decay candidate

Discovered : by Baron Franz Muller von Reichenstein in 1783
Isolated in Sibiu, Romania
Origin : The name is derived from the Latin 'tellus', meaning Earth.

"Its compounds are to be avoided because not only are they poisonous but contact with even the tiniest amounts leads to unpleasant body odors!"

^{130}Te

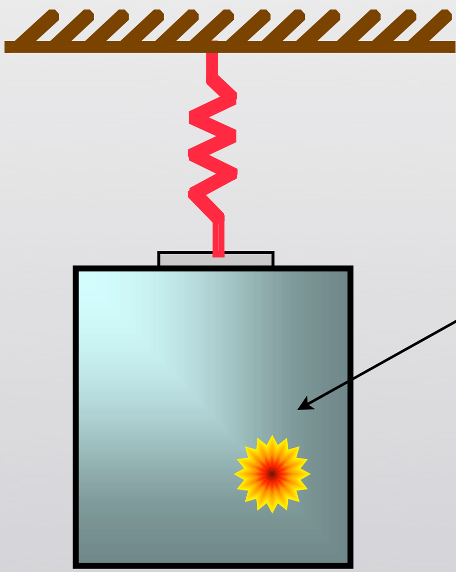


TeO_2 crystals used today in very high end opto-acoustic laser printers for lithography

http://www.chemsoc.org/viselements/

Did someone say Bolometer?

- What is a Bolometer?
  - A detector that measures the energy of a particle through calorimetry



$$Q = mc\Delta T$$

Treat a particle's deposited kinetic energy as a heat exchange between the particle and some material

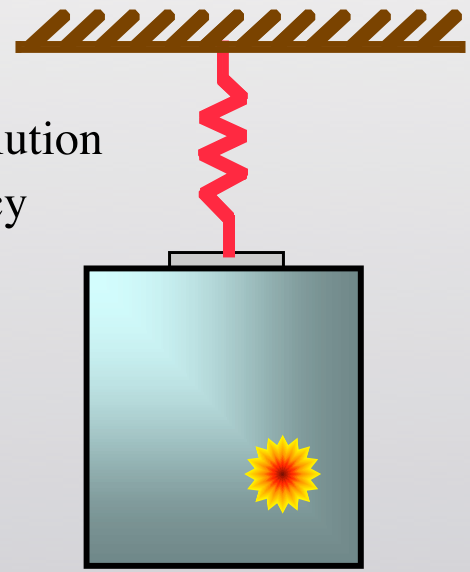
To get any measurable temperature rise, the specific heat capacity will have to be insanely small: this means you have to cool things down

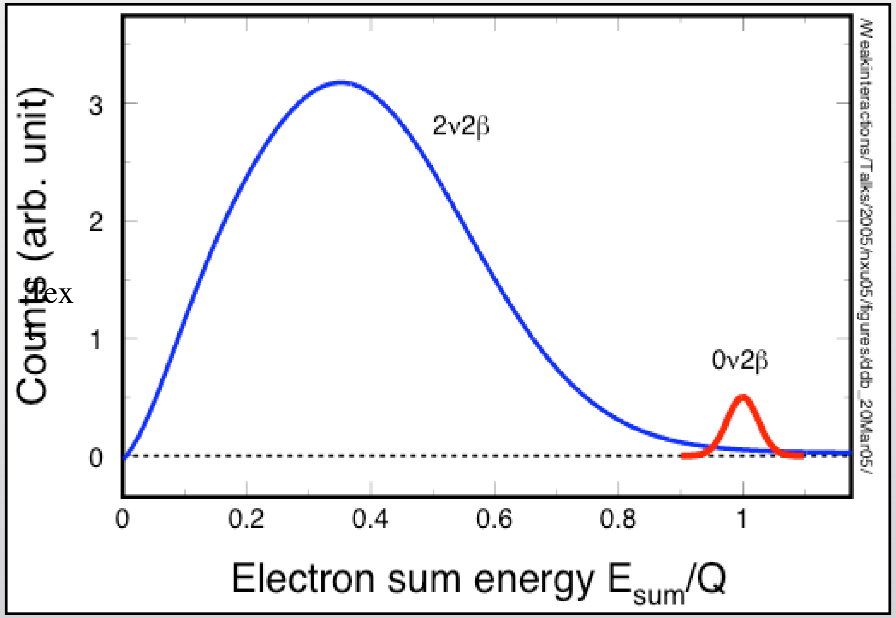
Measure the temperature change of the material

Source = Detector Bolometry

We want to measure the total electron energy of some material undergoing neutrinoless double beta decay: why not build the entire bolometer out of the material that is decaying?

Great energy resolution
Amazing efficiency

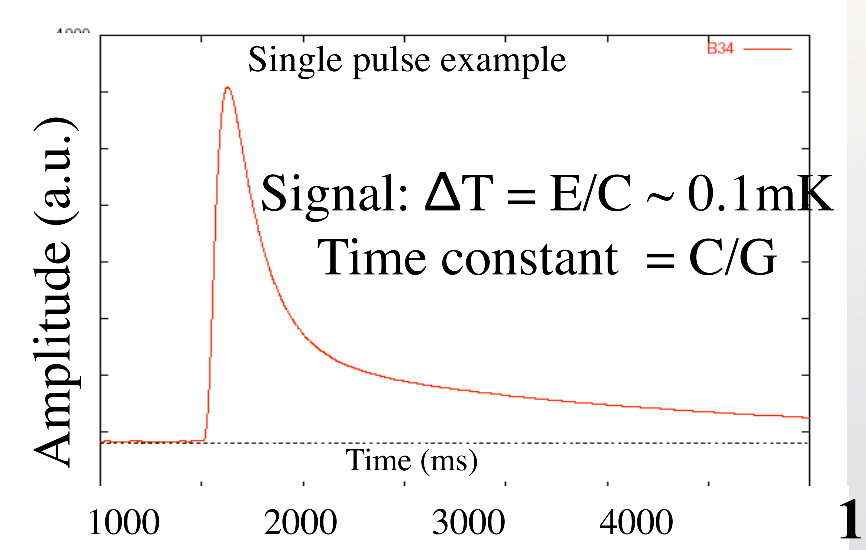




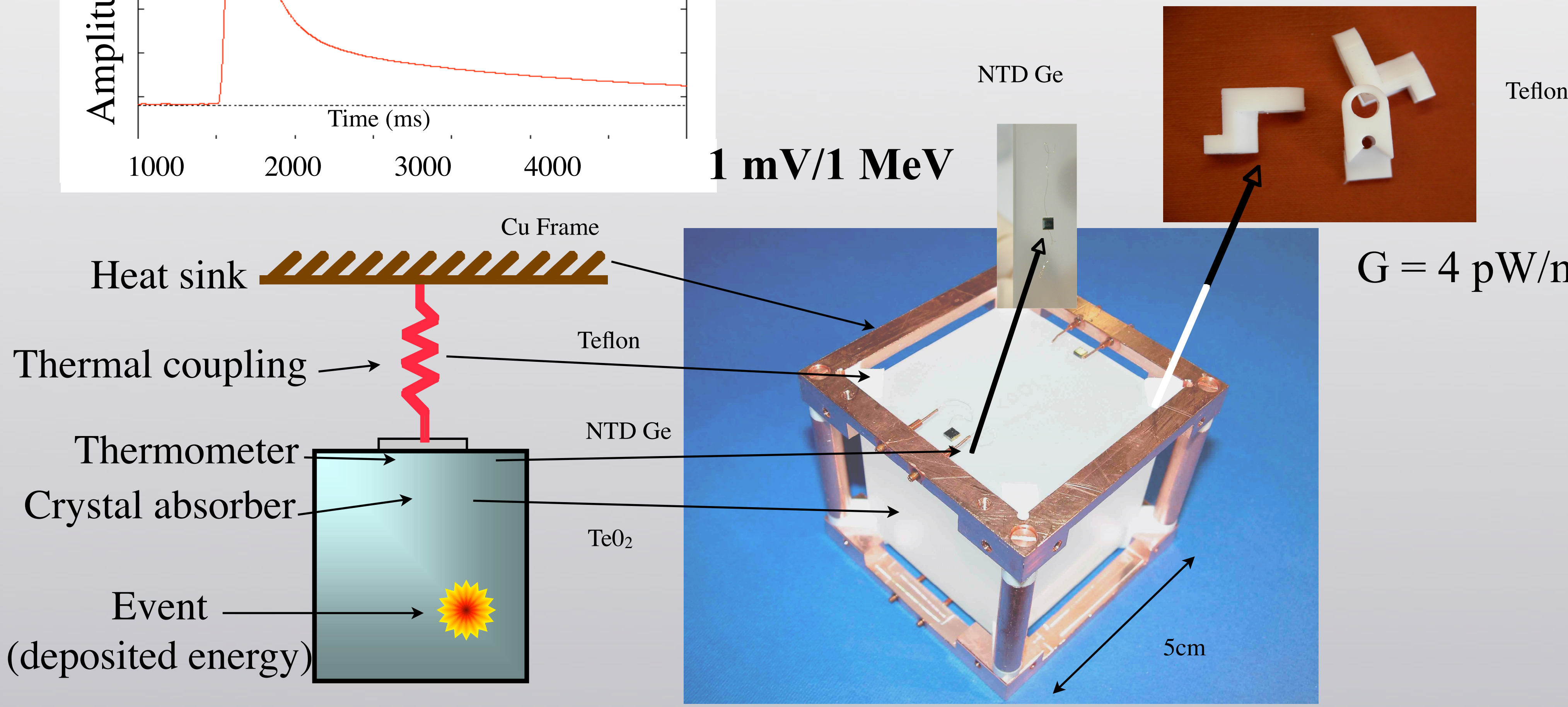
This is exactly what we have done using Tellurium as the source and the detector

Massive Cryogenic Bolometers

- Dielectric diamagnetic materials
- Low temperatures (~10mK)
- Low heat capacity ~T^3
  - C~2 nJ/K = 1 MeV / 0.1 mK

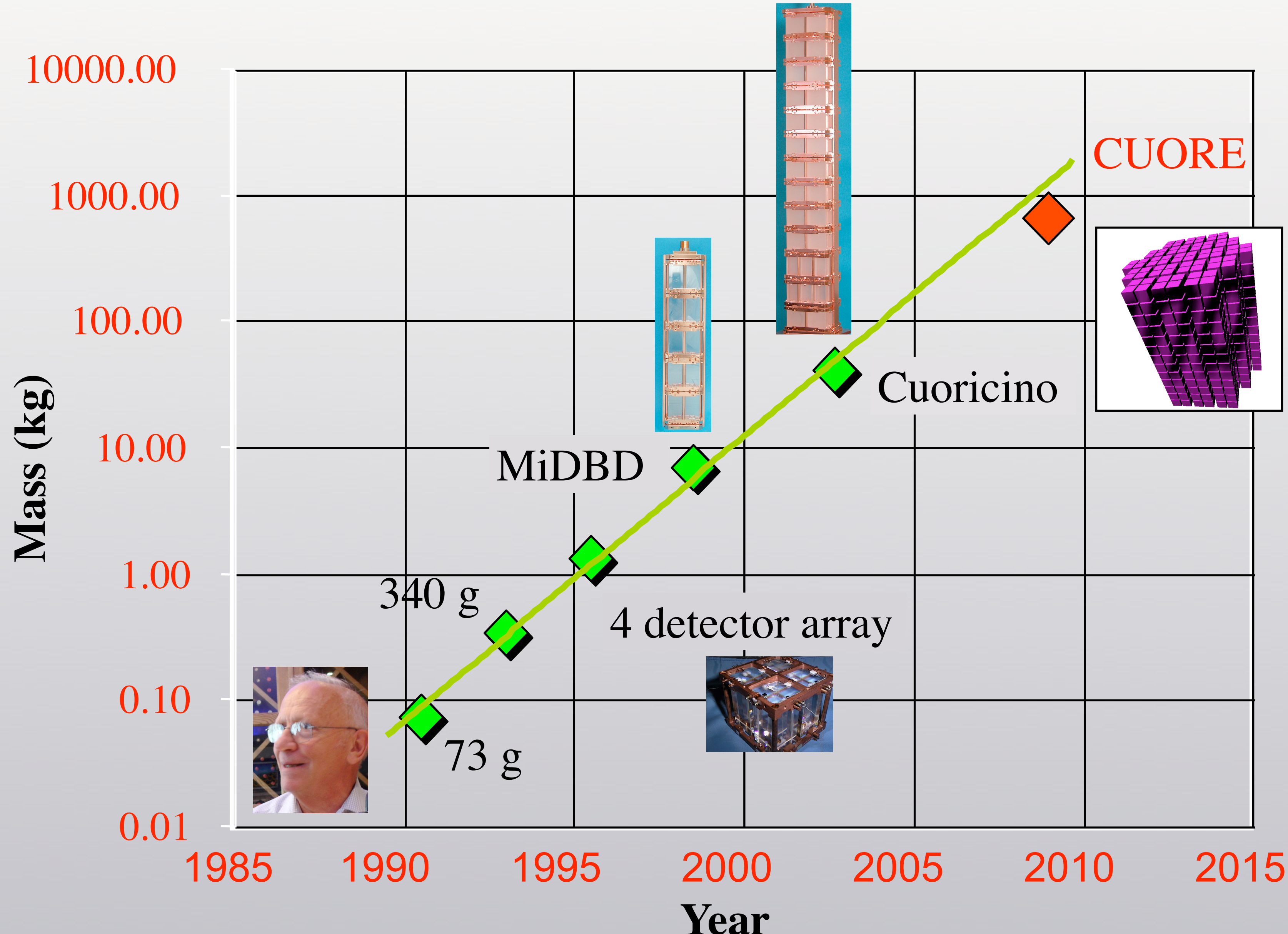


1 mV/1 MeV



G = 4 pW/mK

"Moore's Law" Scaling of TeO_2 Bolometry Experiments

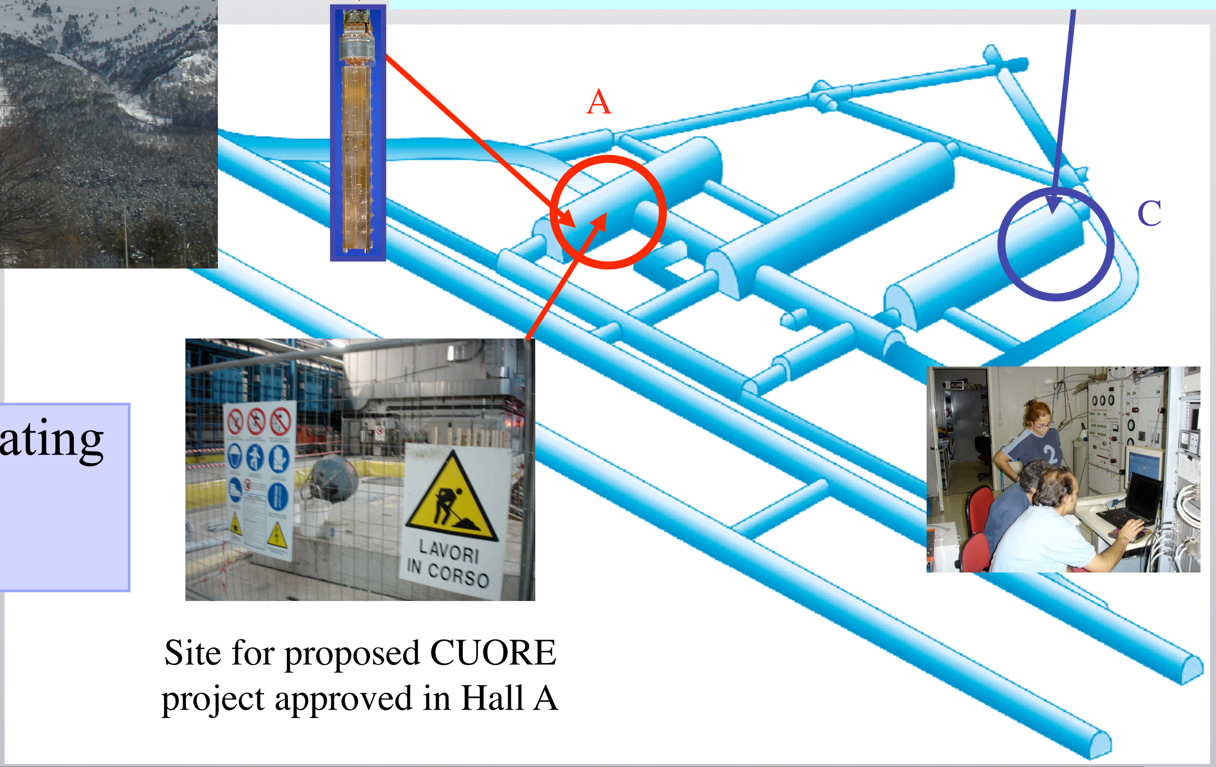


Gran Sasso National Laboratory (LNGS)

Underground to reduce cosmic rays

Two dilution refrigerators
1. Hall A (Cuoricino) ⇒ Running!

2. Hall C (R&D final tests for CUORE)



Site for proposed CUORE project approved in Hall A

Cuoricino is currently the largest operating bolometer and double beta decay experiment in the world

Life at the LNGS: External Lab





World Class Research Facility

Beautiful Italian countrysides

2 hours East of Rome in the Gran Sasso Range

LNGS: Into the Underground

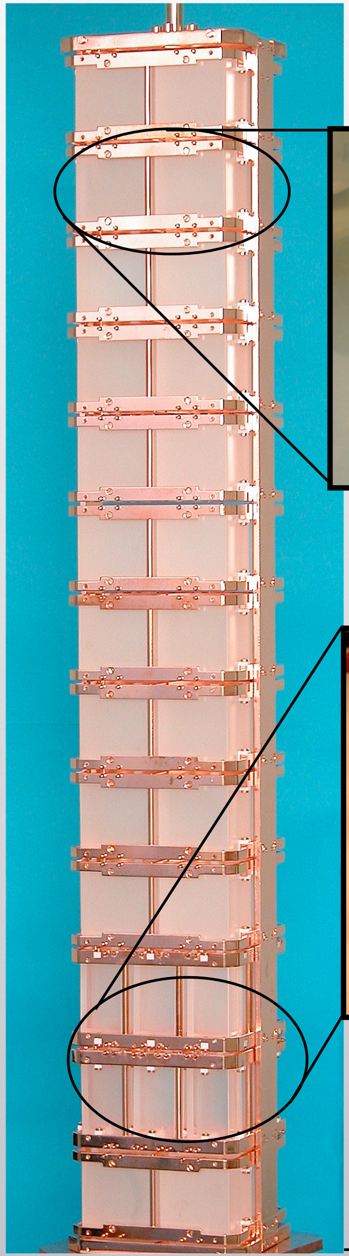
LNGS: Underground

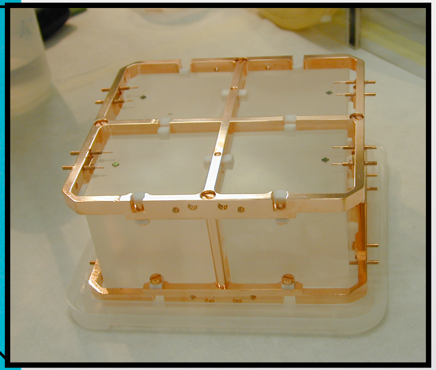
Many experiments running and/or preparing to run

JAMES BOND
007

Cuoricino, the "little heart" of Gran Sasso

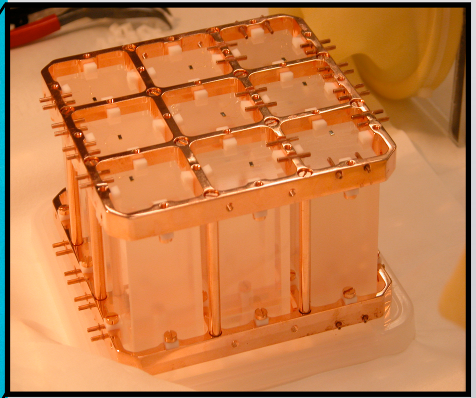
Cooled to 10mK with a powerful dilution refrigerator





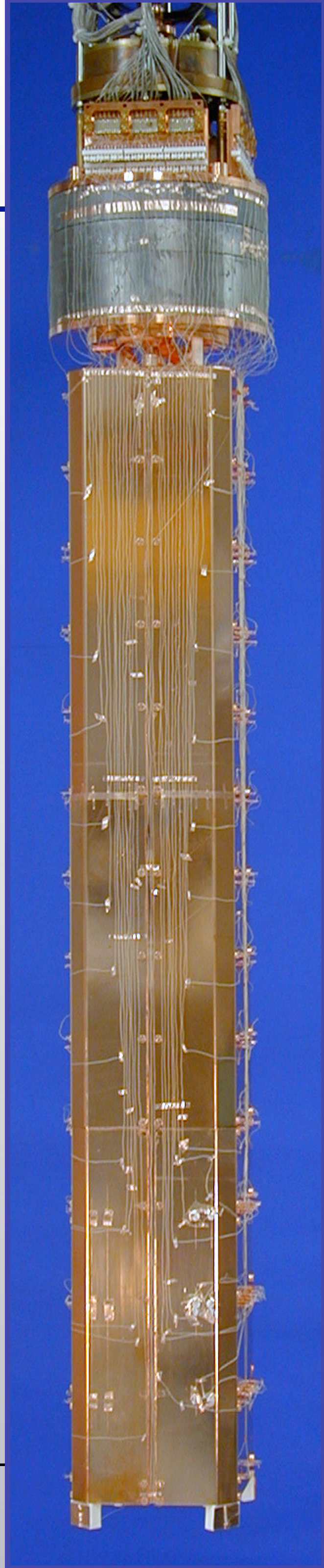
11 modules, 4 detector each,
crystal dimension: 5x5x5 cm^3
crystal mass: 790 g
44 x 0.79 = 34.76 kg of TeO_2

Encased in a cryostat, lead shield, nitrogen box, neutron shield, and Faraday cage



2 modules x 9 crystals each
crystal dimension: 3x3x6 cm^3
crystal mass: 330 g
18 x 0.33 = 5.94 kg of TeO_2

Total detector mass: 40.7 kg $TeO_2 \Rightarrow$ **11.34 kg ^{130}Te**

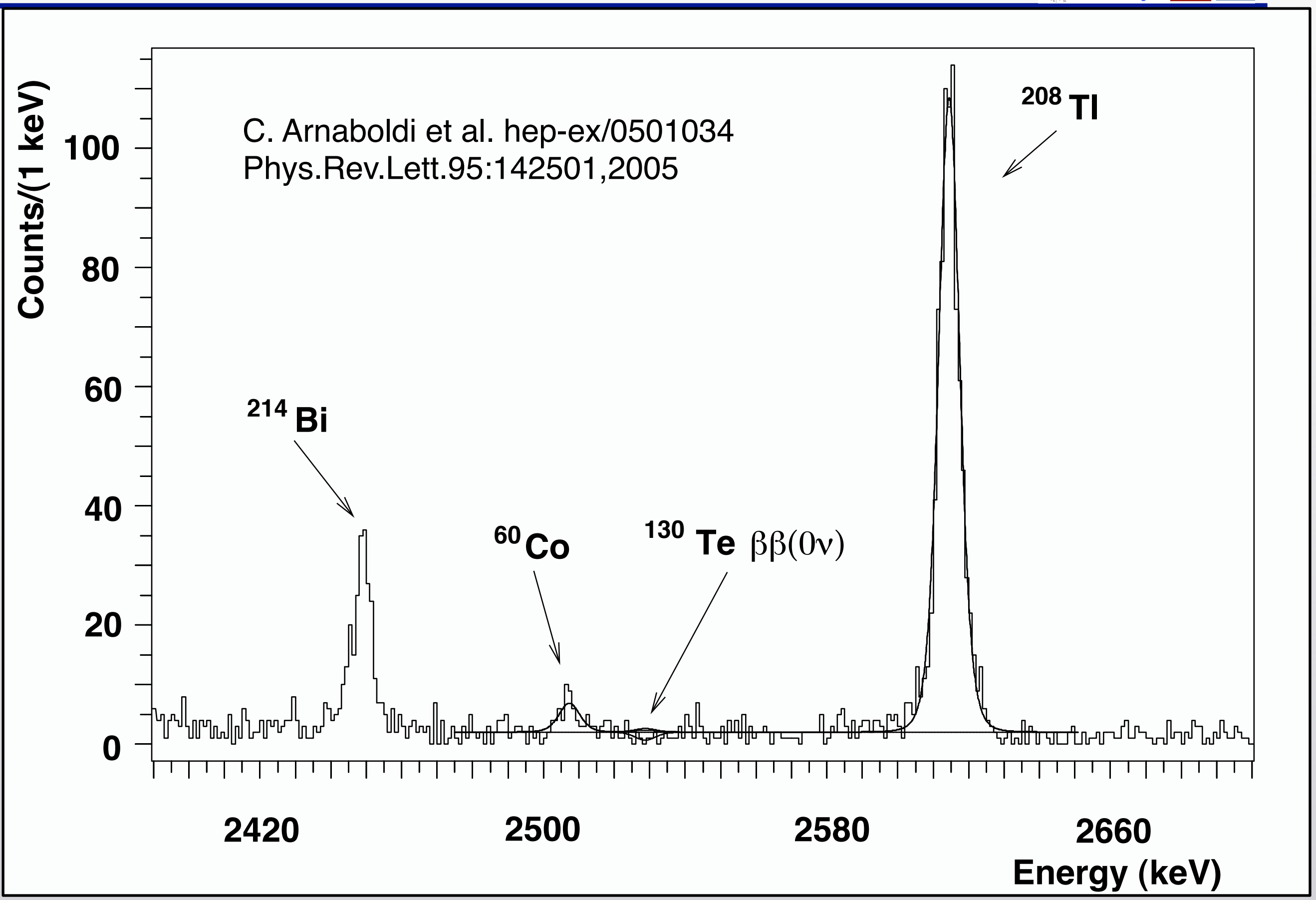


Cuoricino Results from Runs 1&2: No Peak

Exposure
= 10.85 kg y

Resolution:
FWHM at 2615 keV
= 9.2 ± 0.5 keV

Background:
In the ββ0ν region
= 0.18 ± 0.01 counts /(keV kg y)



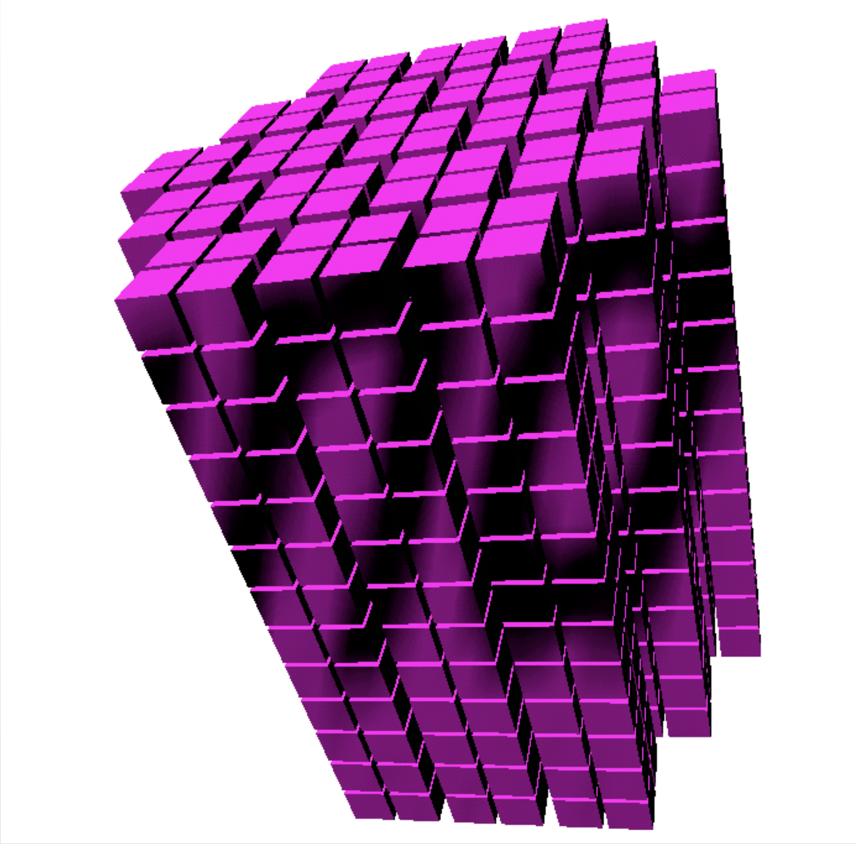
- Anticoincidence spectrum
- ϵ~85%
- Maximum Likelihood + Flat + ^{60}Co (2505 keV)
  - energy region: 2480-2650 keV
- ~5% systematic error upon parameter variation
- N-Gaussian response function with individual FWHM detector resolution @ 2615 keV

No peak found
$\tau^{0\nu}_{1/2} > 1.8 \times 10^{24}$ y at 90% C.L.
$m_\nu < 0.2 - 1.1$ eV

Spread is due to a range of published matrix elements

CUORE: Cryogenic Underground Observatory for Rare Events

- Array of 988 TeO_2 crystals
- 19 Cuoricino-like towers suspended in a cylindrical structure
- 13 levels of 4 5x5x5 cm^3 crystals (750g each)
- ^{130}Te: 33.8% isotope abundance
- Time of construction: 4 years
- Total cost: 14-17M USD (depends on Euro…)
- 1st Data target: Jan 1, 2010



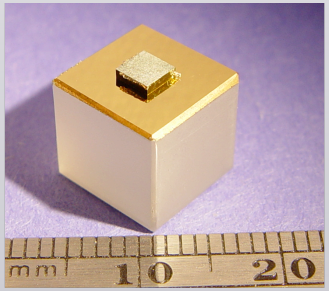
Acts as a single, highly segmented, detector

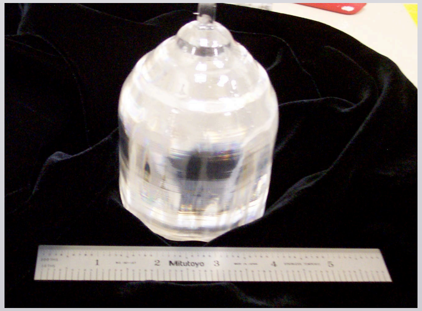
750 kg TeO_2 => 200 kg ^{130}Te

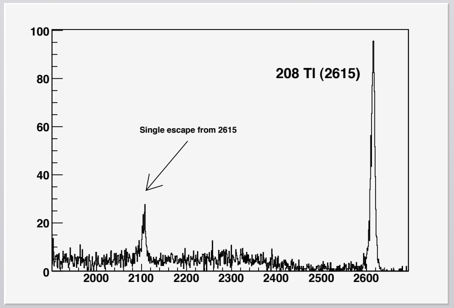
Approved by the Science Counsel of Gran Sasso Laboratory and by INFN

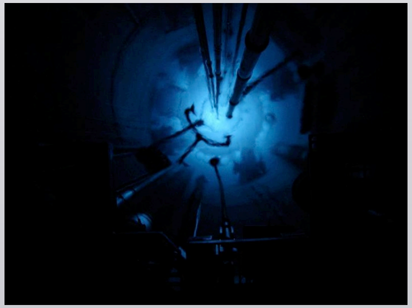
LBNL and LLNL Efforts in CUORE and Cuoricino

- Thermisor Production
- Crystals
- Data Analysis
- Background Studies
- Construction





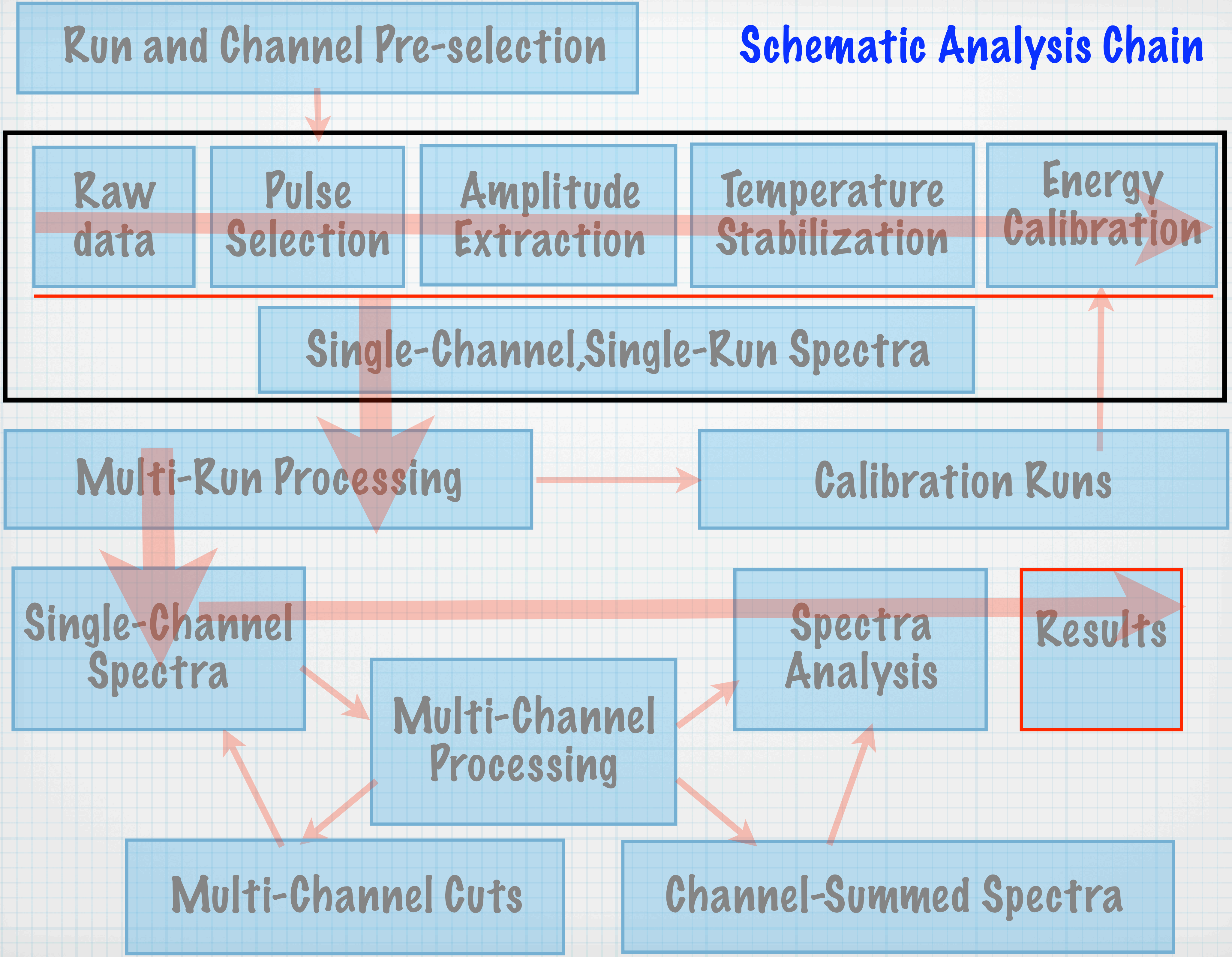




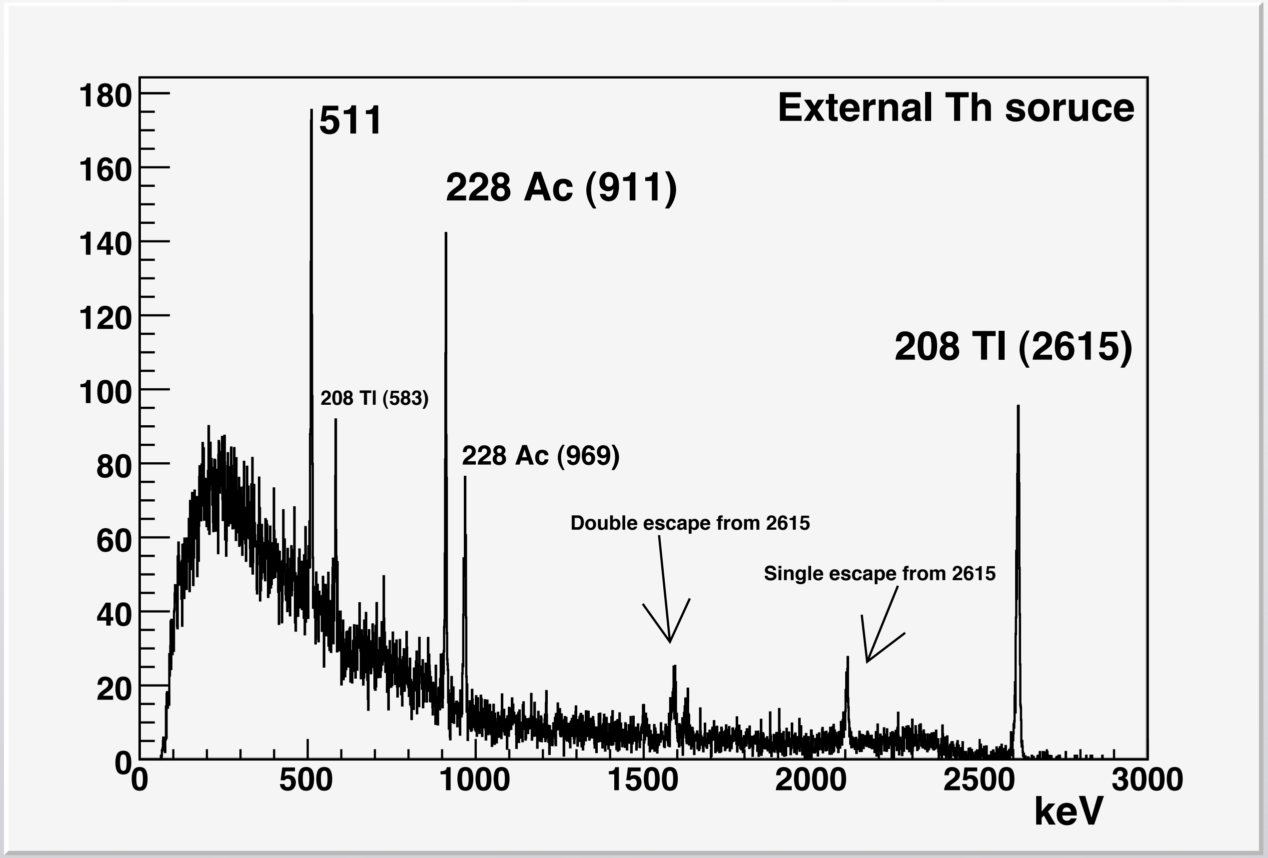
My Analysis Efforts at LBL

- Independently understand and examine current Cuoricino analysis chain starting from the raw data
- Develop an analysis framework that facilitates local research projects
- Contribute collaboratively to ongoing CUORE data analysis development and standards

Schematic Analysis Chain



Berkeley Analysis Output

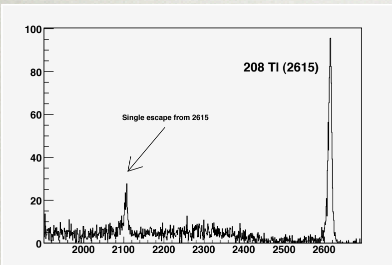


- Calibration Data
- Independent “first principles” spectra from raw data

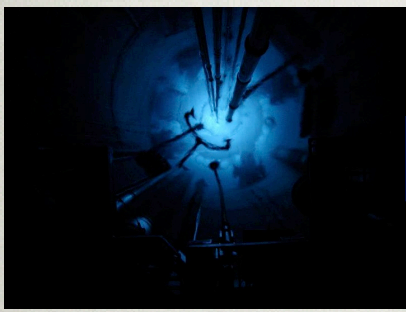
- Work with the raw data
- Understand nuclear process and backgrounds
- Understand the detector
- Lots of fun programming (C++ etc.)

Many possible fun senior projects

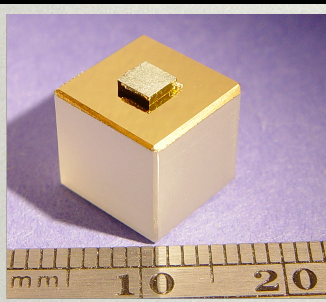
Potential Local Student Projects



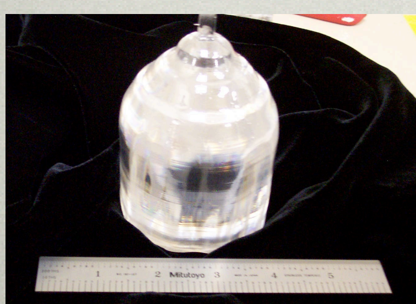
Cuoricino and CUORE
Data Analysis (my focus)
Perhaps eventually set up a small dilution refrigerator?



Background analysis



Thermistor and Misc R&D



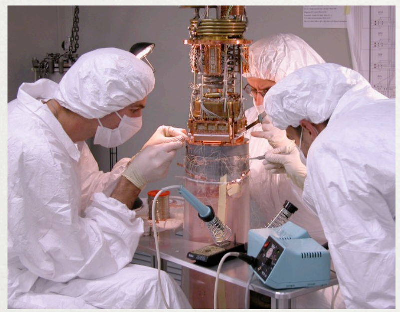
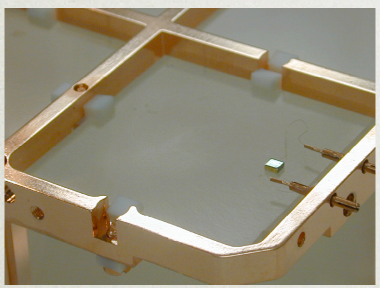
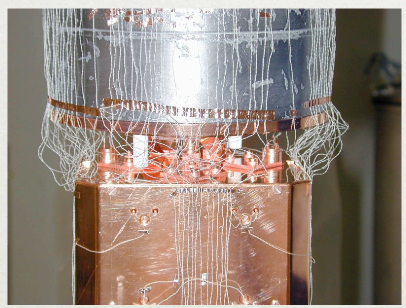
Crystals

Shifts at Gran Sasso for Cuoricino

Spend several weeks in Gran Sasso during the summer working on Cuoricino

The work will be "on the job training" for physics students at all levels

Remote Student Projects

In the coming years there will be plenty of exciting work at Gran Sasso to be done in preparing for CUORE

The work will be hands-on "on the job training" for physics students at all levels

Many potential fun hands-on senior projects

Summary

- Neutrinoless Double Beta Decay can help determine neutrino's mass and nature
- CUORE and Cuoricino are cutting edge calorimetry experiments poised to measure this process
- Plenty of room for student involvement on many levels
- Exciting time for neutrino physics!

The CUORE Collaboration

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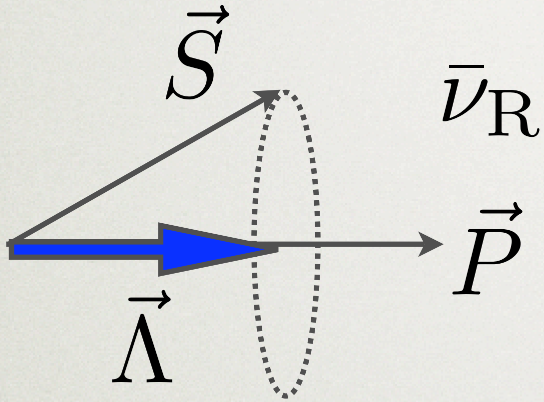
Further Reading and Viewing

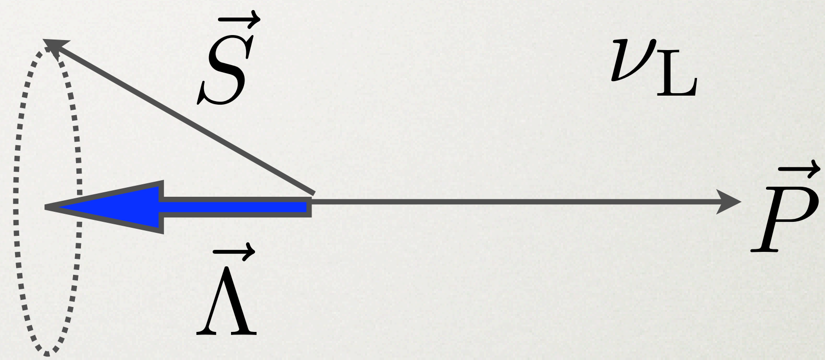
- The Neutrino Matrix physics/0411216
- CUORE proposal hep-ex/0501010
- CUORE website http://crio.mi.infn.it/wig/, http://cuore.lbl.gov/
- The Ghost Particle (NOVA) http://www.pbs.org/wgbh/nova/neutrino/
- Particle data group http://pdg.lbl.gov/

Backup

The Antineutrino

Can we really tell neutrinos apart from their antiparticles?





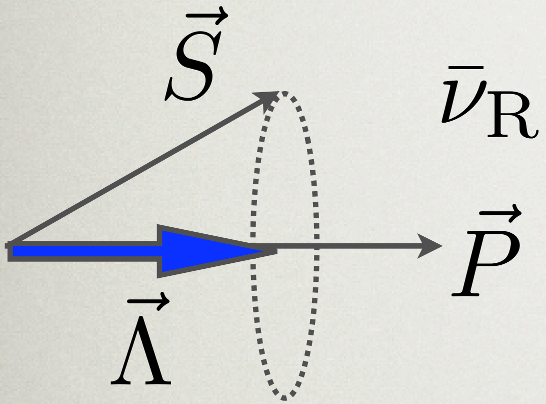
The weak force, when interacting with neutrinos, only seems to interact with particles we call "left-handed neutrinos" or "right-handed antineutrinos"

"Handedness" is then regarded as the projection of the spin along the momentum vector

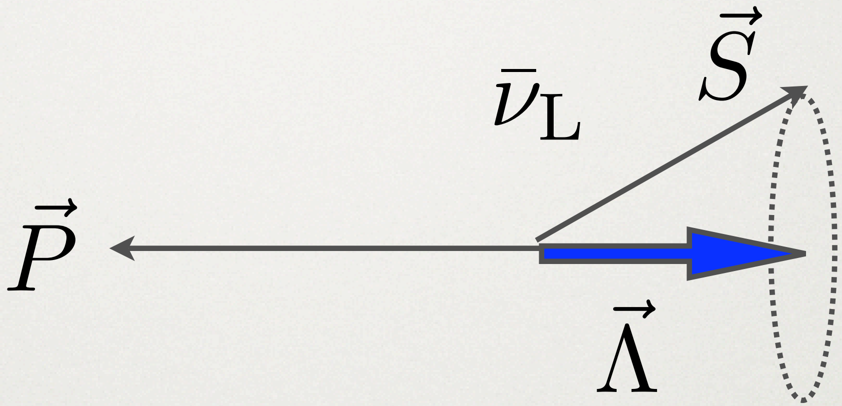
If the neutrino is massless it is moving at the speed of light; this categorization works well because the handedness is fixed; we simply accept that "other" particles don't exist for some reason

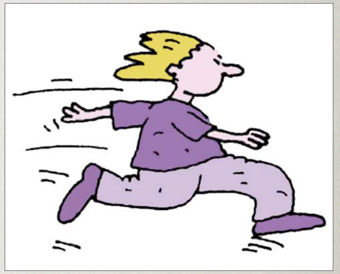
The Antineutrino

Can we really tell neutrinos apart from their antiparticles?



In our frame:
moving slower than the
antineutrino





Same particle in the frame of the little purple running dude:
moving faster than the antineutrino

If the neutrino has mass we should be able to convert it into particles <u>we thought didn't exist</u> just by changing reference frames!

What if the objects we called the "neutrino" and "antineutrino" were just different spin projections of the <u>same</u> kind of particle all along?

The Antineutrino

Can we really tell neutrinos apart from their antiparticles?

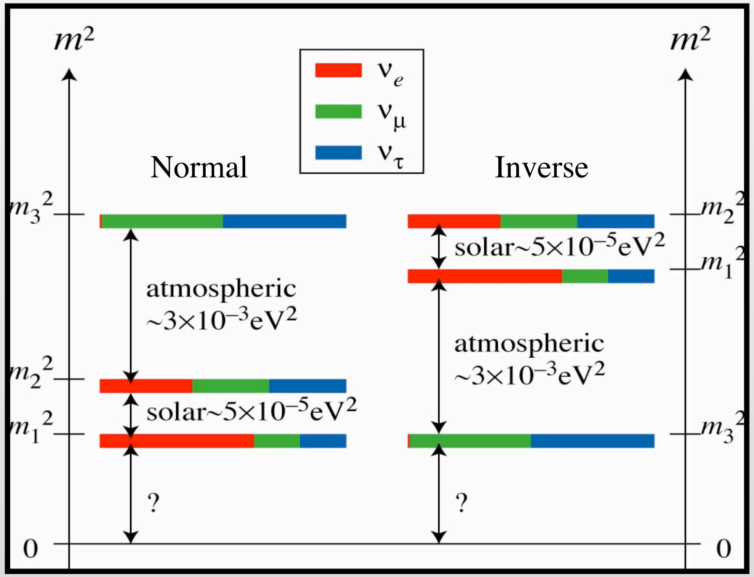
Dirac		Majorana
$\bar{\nu}_{\rm R}$	$\nu_{\rm L}$	$\nu_{\rm L}$
$\bar{\nu}_{\rm L}$	$\nu_{\rm R}$	$\nu_{\rm R}$

Four particles only two are observed

Two particles, both are observed; regarded as "more natural" for massive neutrinos

I will now refer to this issue as a question of the neutrino's "nature"

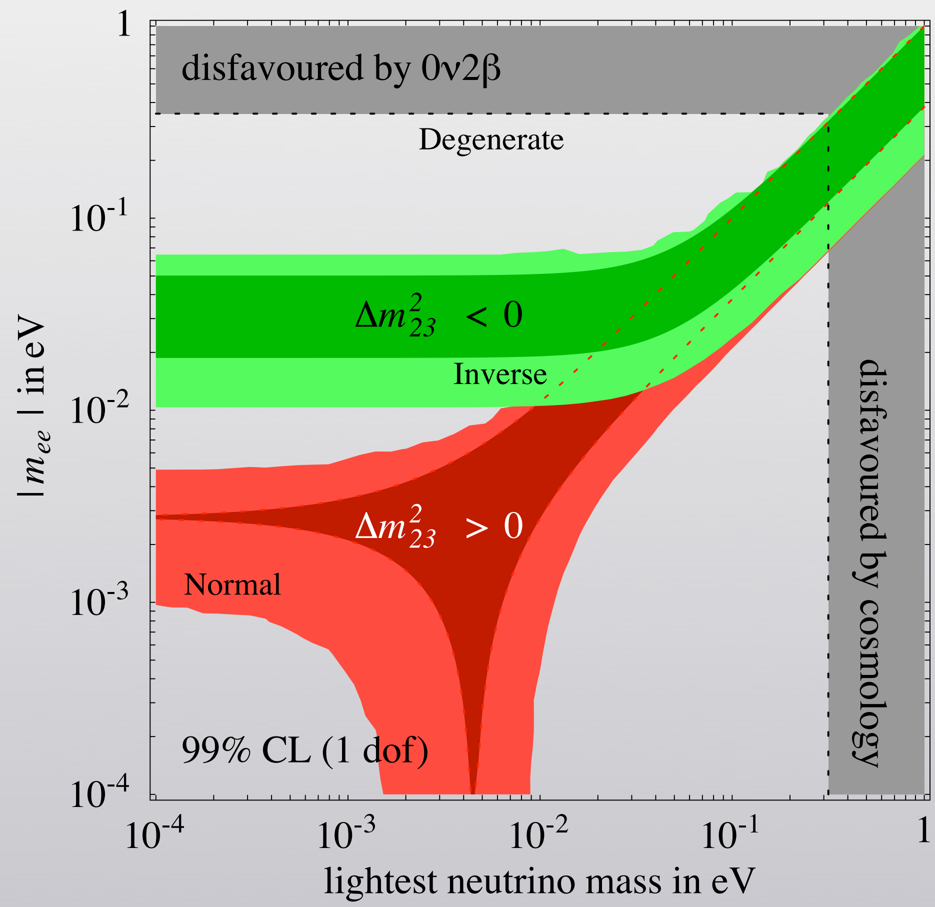
ββ0ν: a powerful observational tool



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

The rate depends on the number of moles of active material available

A. Strumia and F. Vissani, hep-ph/0503246



CUORE Sensitivity

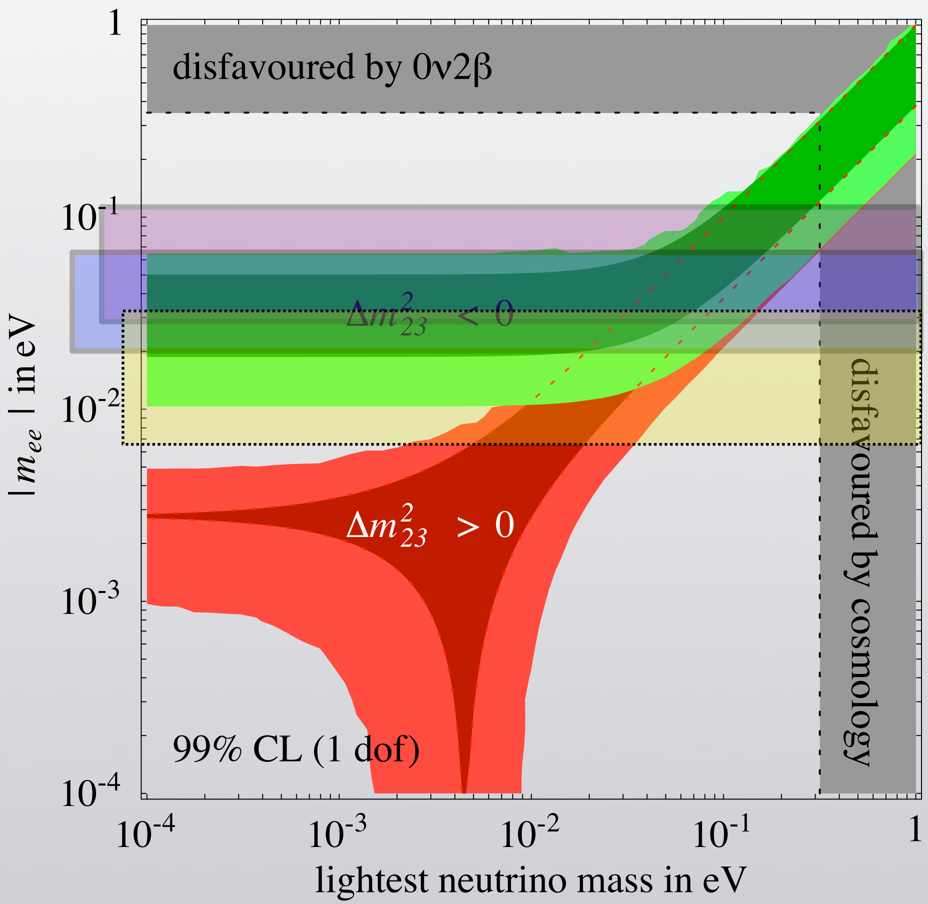
Five year sensitivity based on detector resolution, background, and matrix element spread

B(counts/keV/kg/y)	Δ(keV)	$T_{1/2}$(y)	$\lvert\langle m_\nu\rangle\rvert$ (meV)
0.01	10	1.5×10^{26}	23–118
0.01	5	2.1×10^{26}	19–100
0.001	10	4.6×10^{26}	13–67
0.001	5	6.5×10^{26}	11-57

More optimistic but plausible case: eliminate degenerate hierarchy and continue excavation deeper into inverse hierarchy

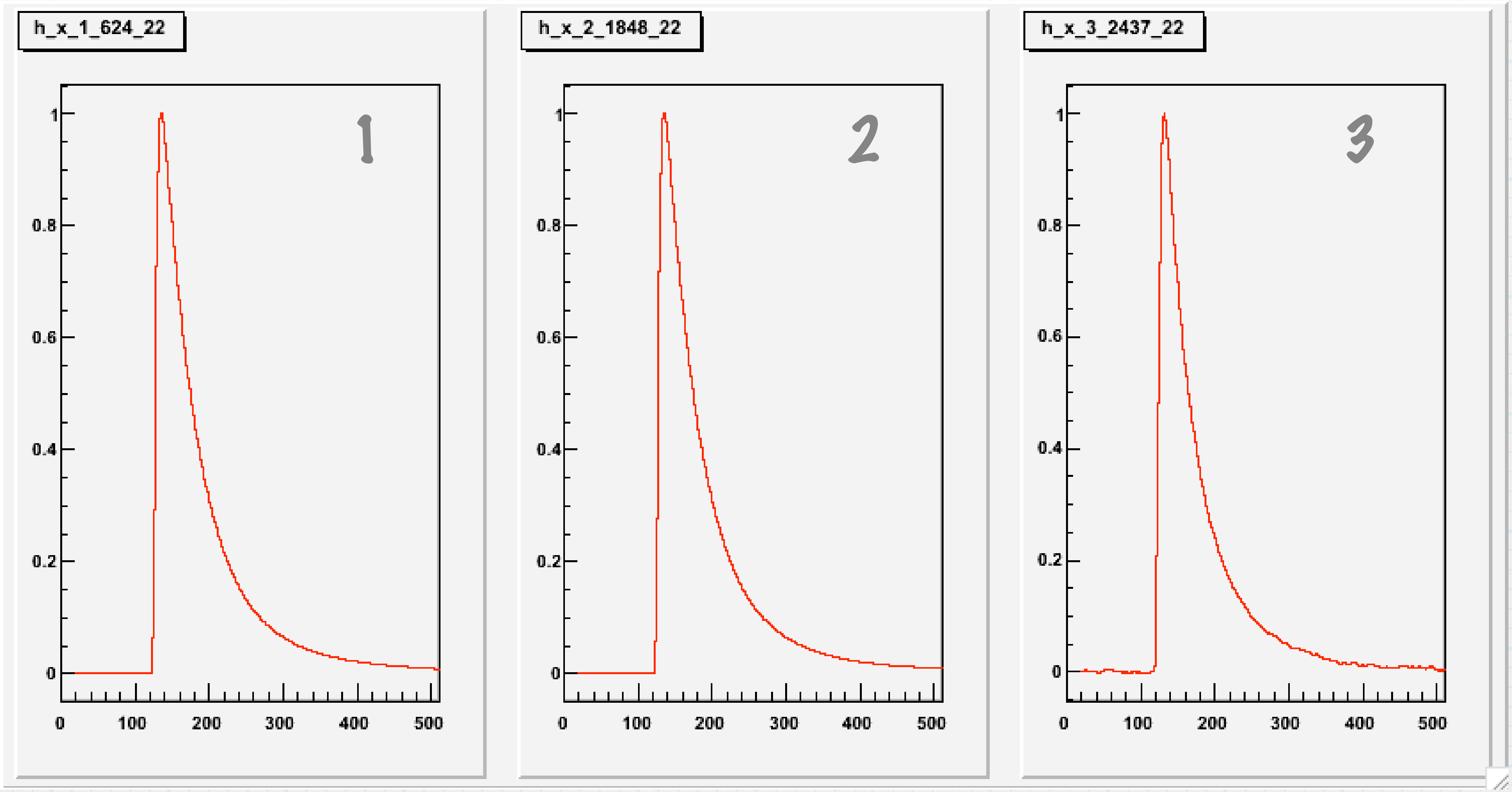
Fantasy: 99% enriched CUORE after 10 years with 5 keV resolution and 0.001 c/keV/kg/y

A. Strumia and F. Vissani, hep-ph/0503246



10 years from now, with input from different isotopes, the theoretical mass spread will hopefully be smaller

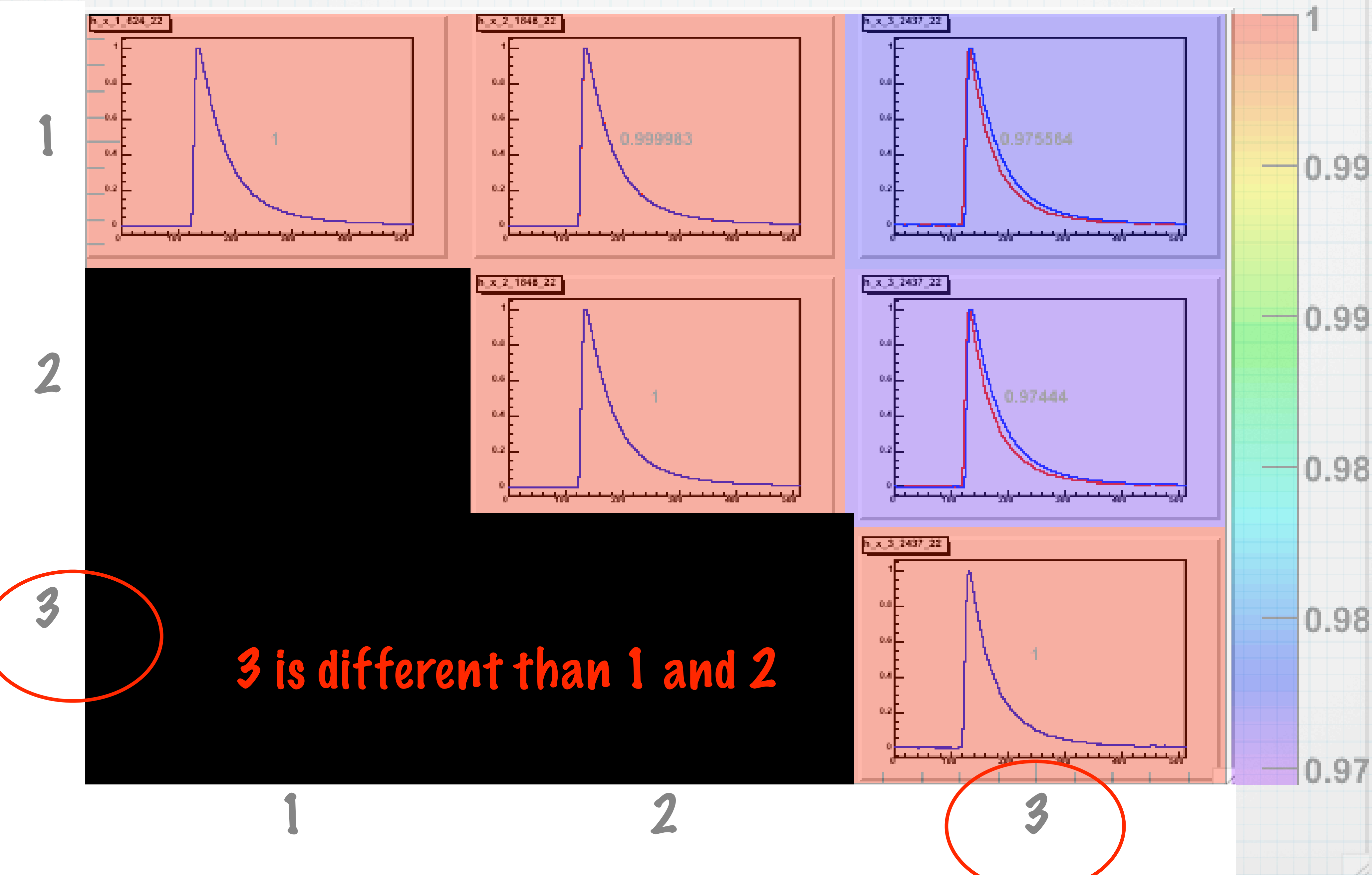
Pulse Selection and pattern recognition software: Simple Example

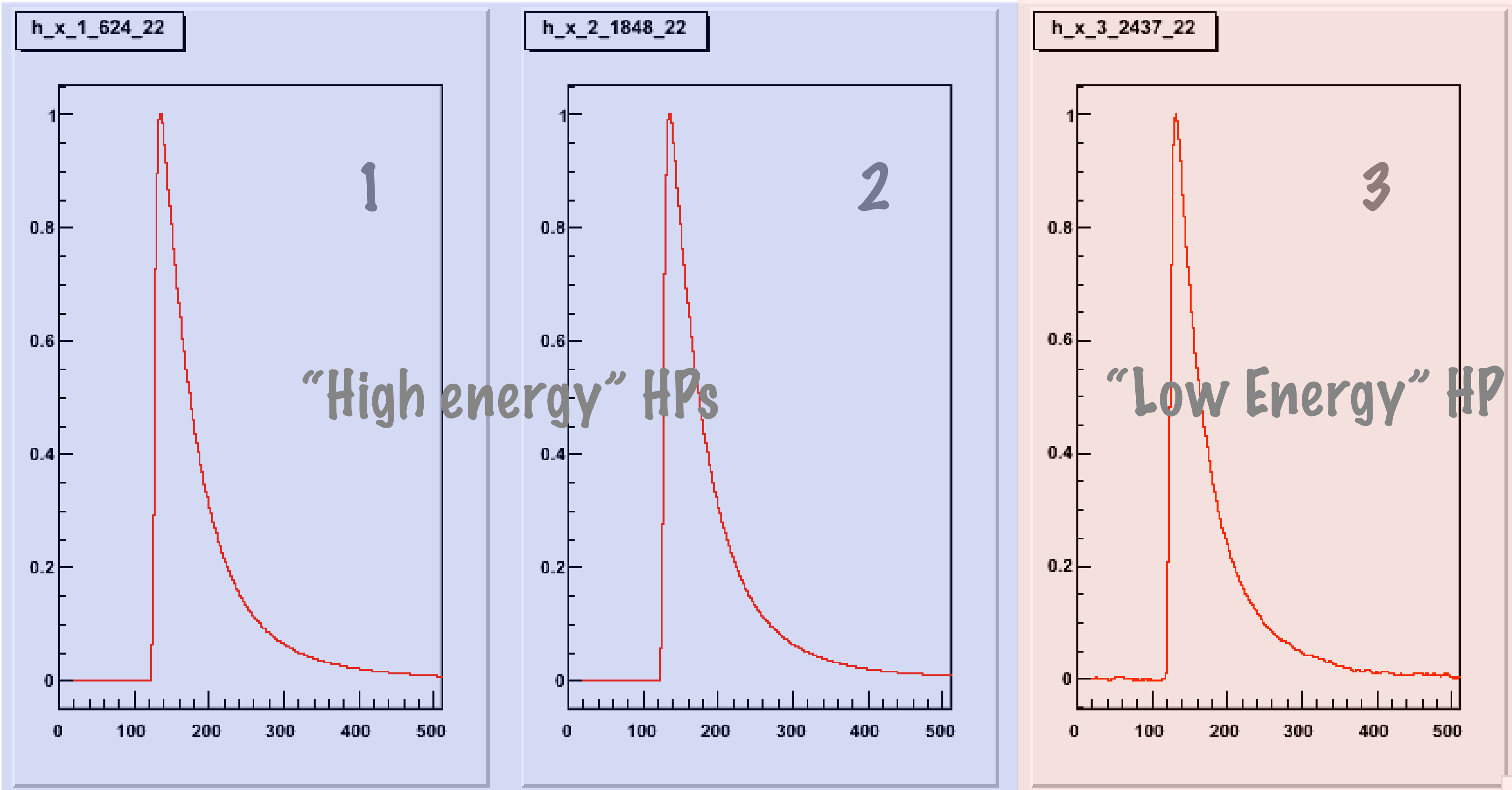


3 pulses scaled to unit height to highlight shape

$$C_{ij} = \hat{P}_i \cdot \hat{P}_j$$

[(1,1)=1.000000] [(1,2)=0.999983] [(1,3)=0.975564]
[redacted] [(2,2)=1.000000] [(2,3)=0.974440]
[redacted] [(3,3)=1.000000]





******************	
Entry	1
Entry in TTree (1st=0)	624
Channel (tower)	22
Pulse Time (s)	166.434
Rise time t-to-m (s)	0.112
Decay const (~1/s)	0.615127
Max Loc (ch,s)	135.5 , 1.084

******************	
Entry	2
Entry in TTree (1st=0)	1848
Channel (tower)	22
Pulse Time (s)	471.954
Rise time t-to-m (s)	0.112
Decay const (~1/s)	0.615184
Max Loc (ch,s)	135.5 , 1.084

******************	
Entry	3
Entry in TTree (1st=0)	2437
Channel (tower)	22
Pulse Time (s)	624.53
Rise time t-to-m (s)	0.096
Decay const (~1/s)	2.33407
Max Loc (ch,s)	131.5 , 1.052

[redacted]