Neutrinoless Double Beta Decay Overview

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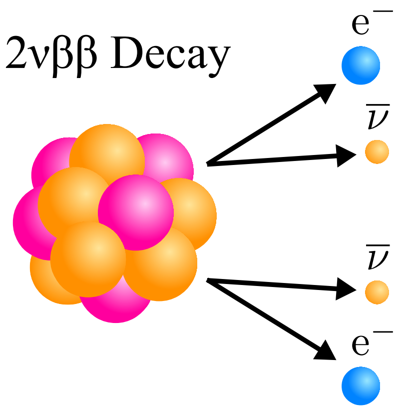
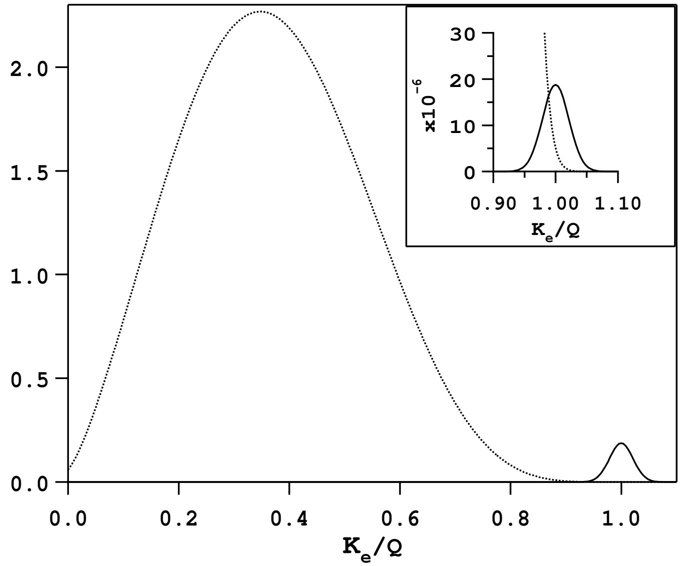
Double Beta Decay



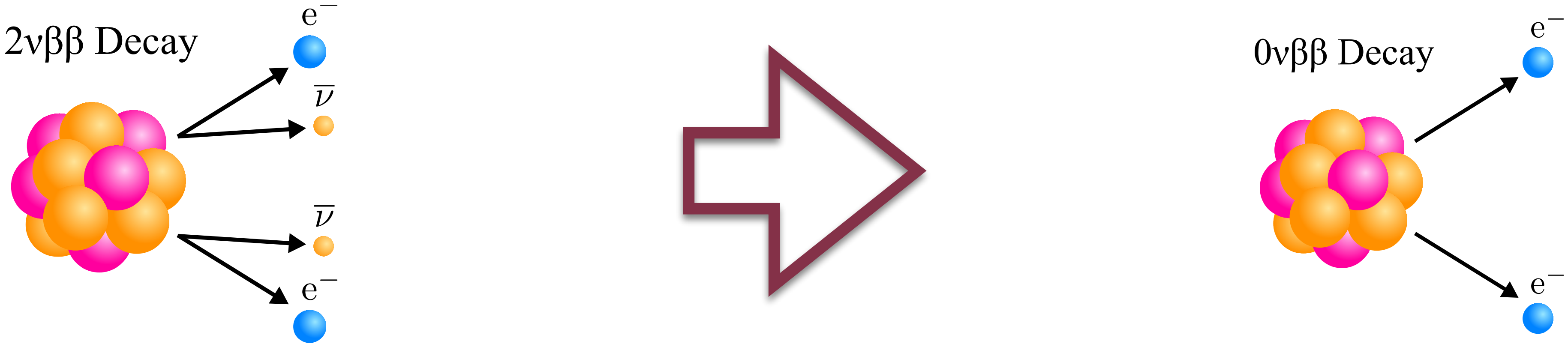
- Nuclear Process: simultaneous decay of 2 neutrons
- Predicted by Standard Model, observable for 35 nuclei
- Signature: continuous spectrum up to the Q-value [for most of the nuclei 2-3 MeV]

- Observed for 11 nuclei
- Half-life: 10^{18}-10^{24} years



Neutrinoless Double Beta Decay

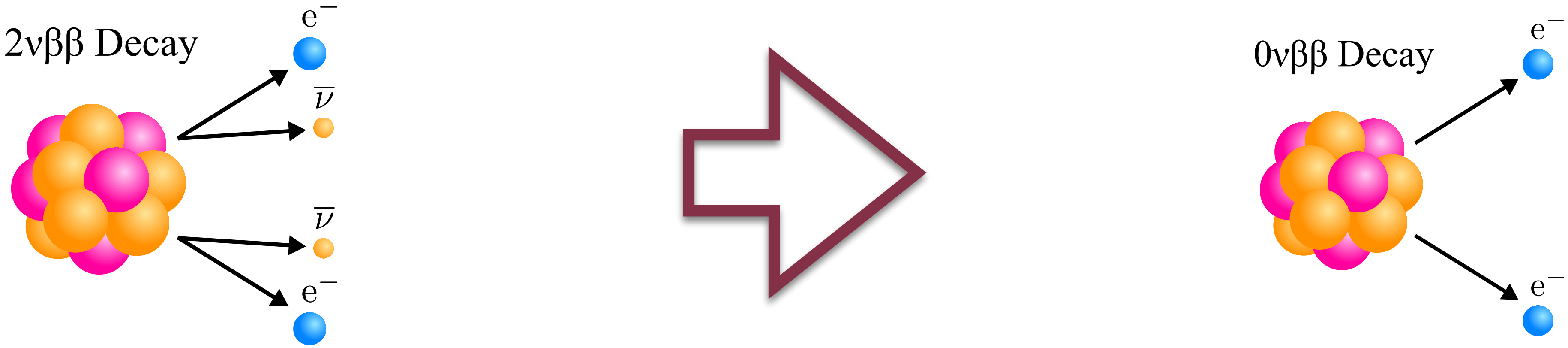
Hypothesised (NEVER observed) nuclear transition



What is the importance of this process?

Neutrinoless Double Beta Decay

Hypothesised (NEVER observed) nuclear transition



- (Only process that) can establish Majorana nature of ν
- Violates lepton number conservation (actually also B-L)
- Other sources of CP violation
- Insight in neutrino absolute mass

What do we measure

The observable of this decay, the half-life, scales as:

$$(T^{0\nu}_{1/2})^{-1} = \underbrace{G^{0\nu}(Q,Z)}_{\text{Phase Space Factor}} \underbrace{\left|M^{0\nu}\right|^2}_{\text{Nuclear Matrix Element}} \left(\frac{\langle m_{\beta\beta}\rangle}{m_e}\right)^2$$

$$m_{\beta\beta} = |m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{i\alpha_{21}} + m_3 s_{13}^2 e^{i(\alpha_{31}-\delta)}|$$

- **m_1, m_2, m_3** particle neutrino **mass eigenstates**
- **c_{12}, c_{13}… mixing angles** parametrising the PMNS matrix (transform mass to flavor bases)
- **α_{21}, α_{31}: Majorana phases**

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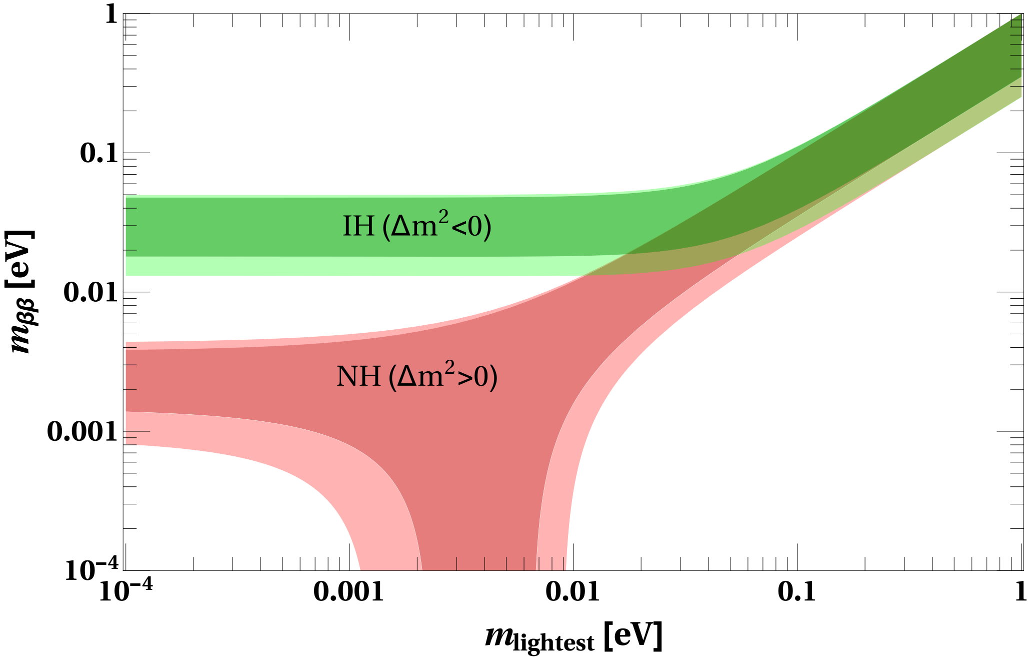
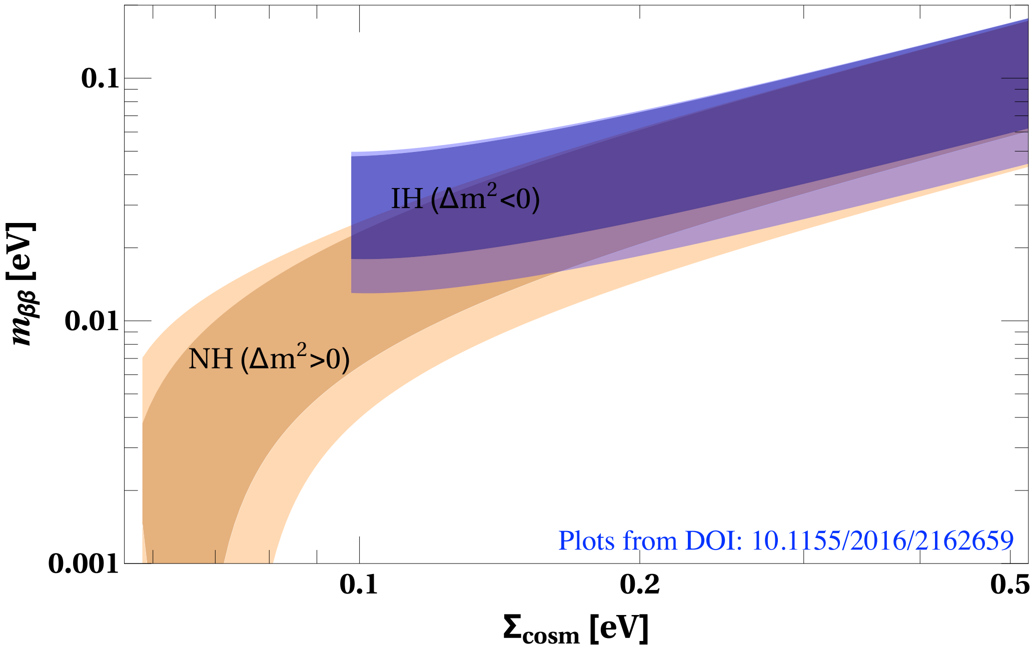
- **m_1, m_2, m_3** particle neutrino **mass eigenstates** absolute values not known
- **c_{12}, c_{13}… mixing angles** parametrising the PMNS matrix (transform mass to flavor bases) investigated by oscillations experiments
- **α_{21}, α_{31}: Majorana phases** no idea

Possible values of $m_{\beta\beta}$

In this field, exclusion plots refers to the variable $m_{\beta\beta}$





Plots from DOI: 10.1155/2016/2162659

Inverted Hierarchy: 15-50 meV

Normal Hierarchy < 5meV

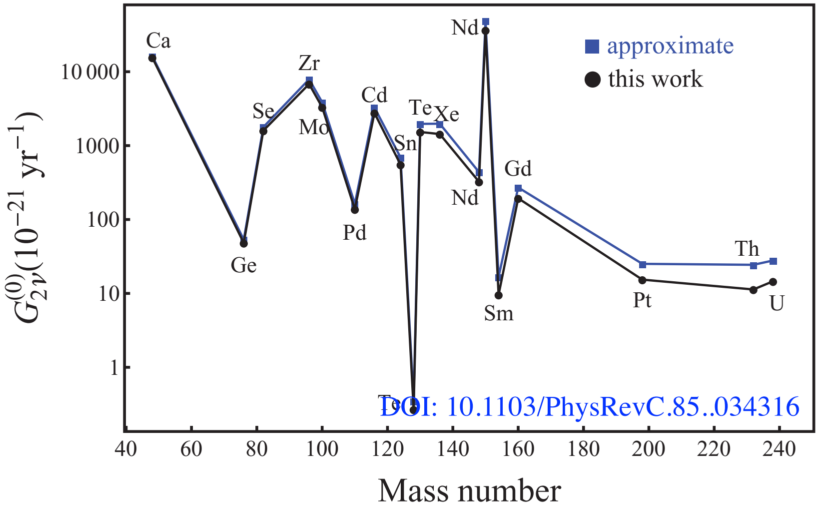
Impact on $T_{1/2}$

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\,\left|M^{0\nu}\right|^2 \left(\frac{\langle m_{\beta\beta}\rangle}{m_e}\right)^2$$

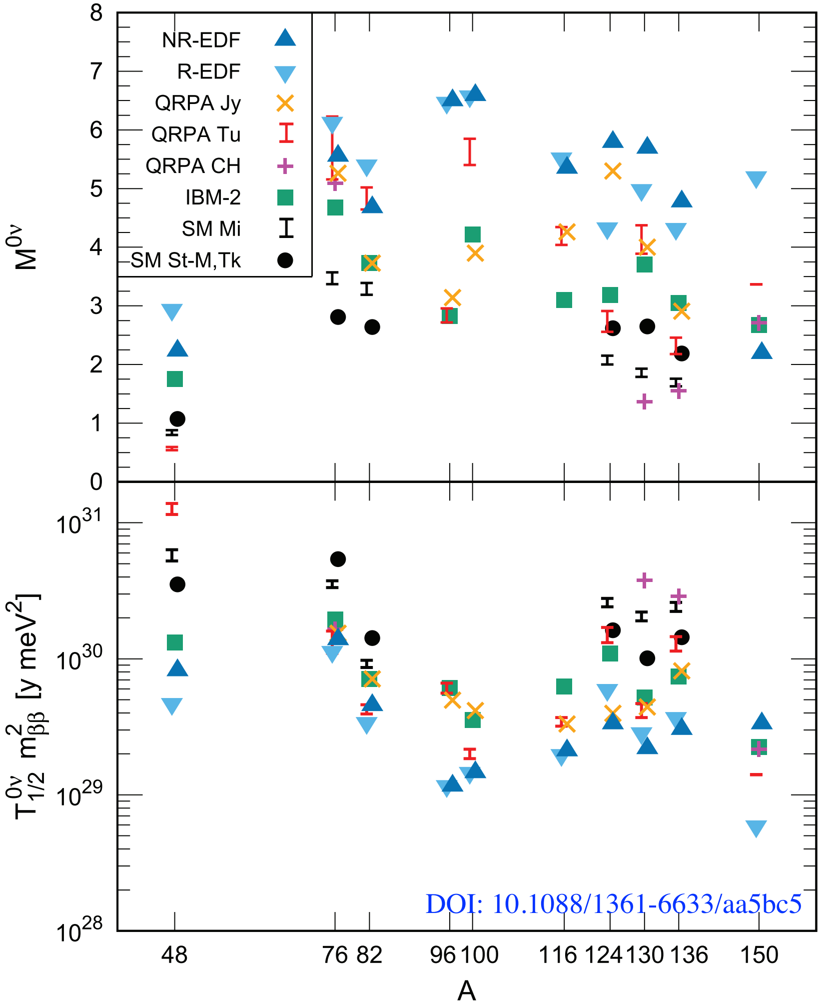
Phase Space Factor

Nuclear Matrix Element

Computed with high precision



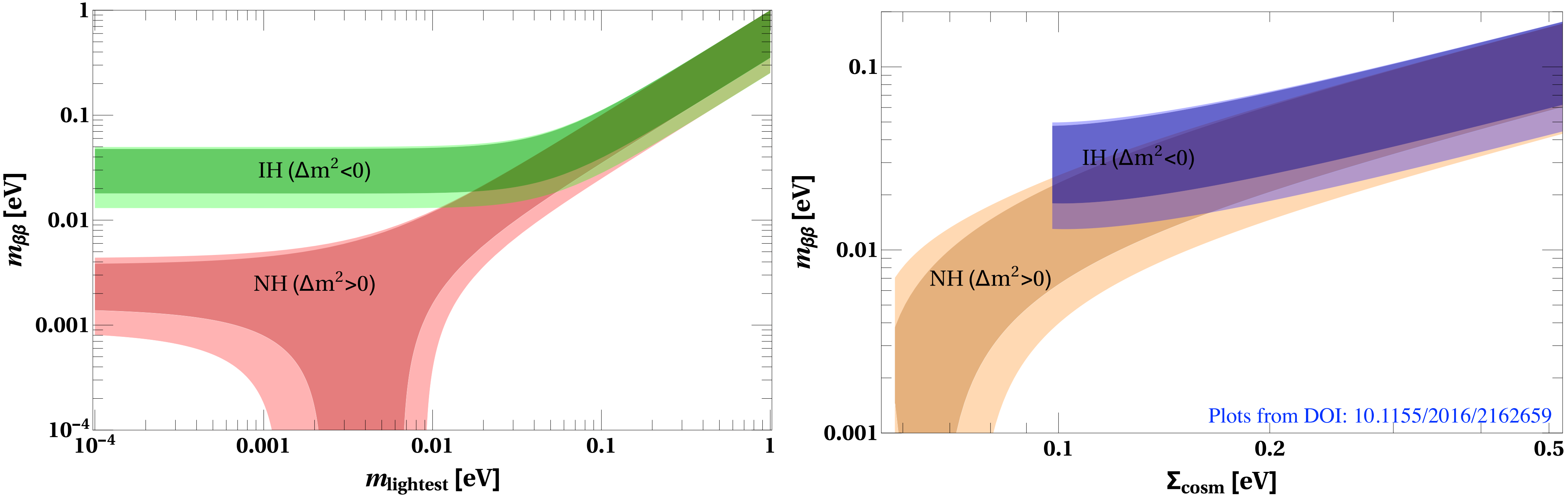
DOI: 10.1103/PhysRevC.85..034316



DOI: 10.1088/1361-6633/aa5bc5

Experimental Challenge

The allowed regions of $m_{\beta\beta}$ correspond to very long half-lives —> few signals

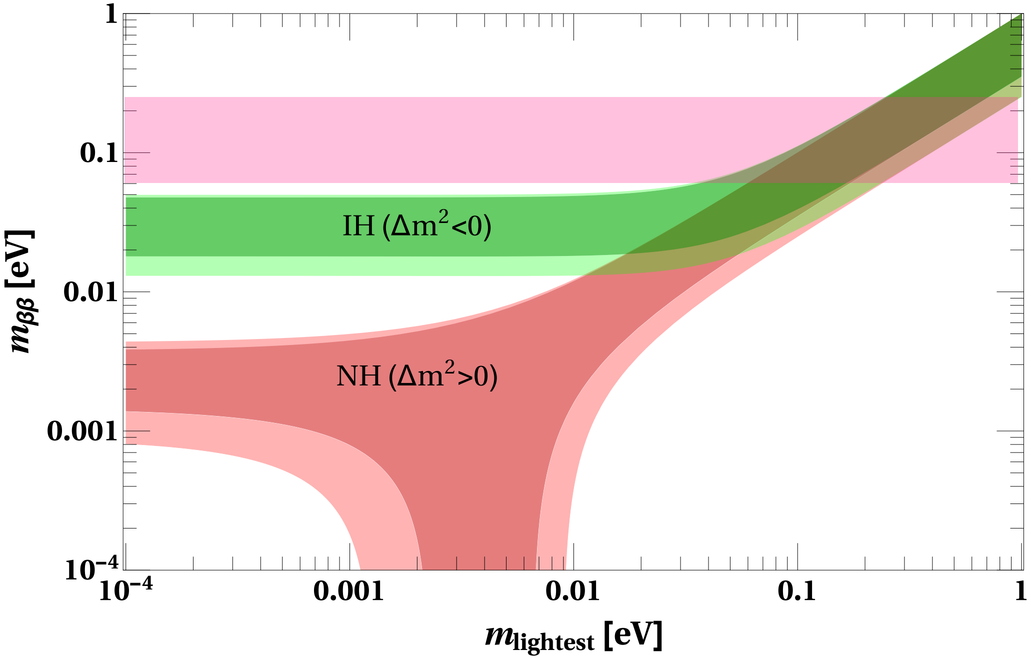


Plots from DOI: 10.1155/2016/2162659

	$m_{\beta\beta}$	$T_{1/2}$	Signal Events
Inverted Hierarchy	15-50 meV	10^{26} - 10^{28} yr	0.5 - 40 (ton y)$^{-1}$
Normal Hierarchy	<5 meV	>10^{28}	<0.5 (ton y)$^{-1}$

Where are we now

Current experiments are measuring $T_{1/2} > 10^{25}$ -10^{26} yr, or $m_{\beta\beta}$ (<61-165 meV)



$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\left|M^{0\nu}\right|^2\left(\frac{\langle m_{\beta\beta}\rangle}{m_e}\right)^2$$

Next goal:

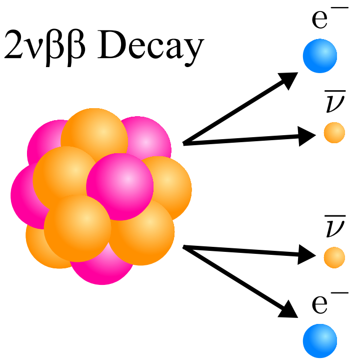
Complete exploration of IH!

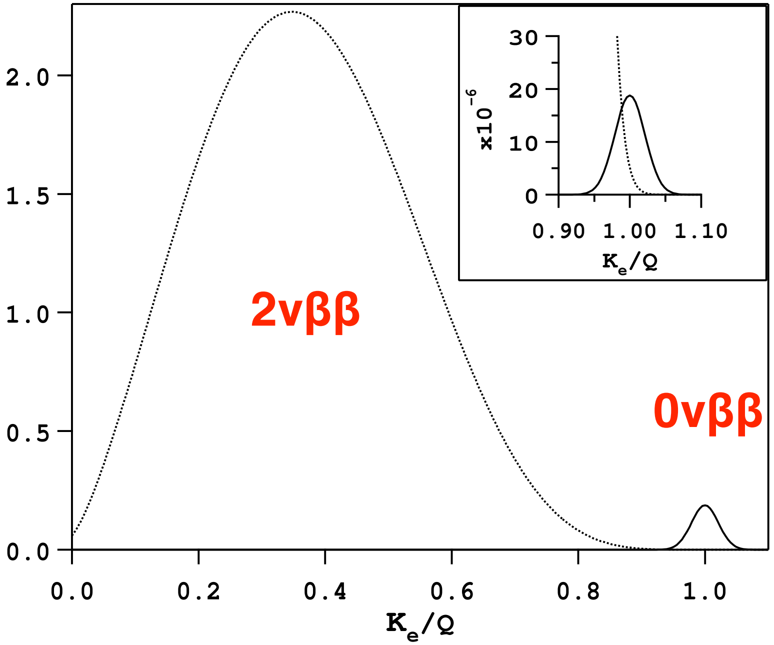
Technical challenge:

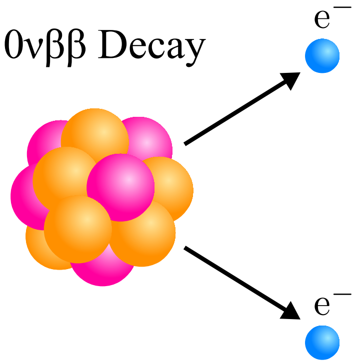
Improving sensitivity on $m_{\beta\beta}$ by 10, requires an improvement on $T_{1/2}$ by 100!

Signature

For a given isotope, we expect the following spectrum.





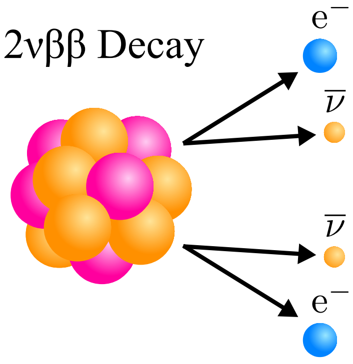


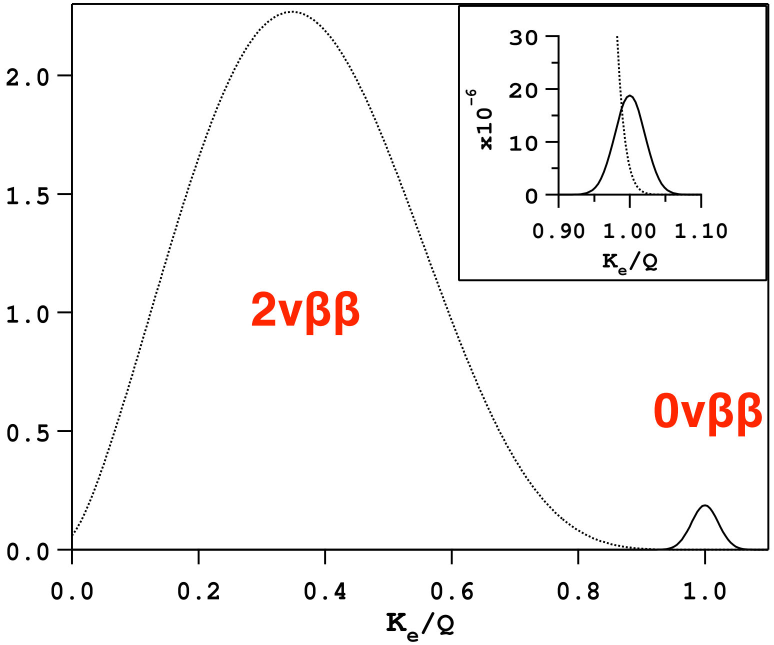
Clear Signature:

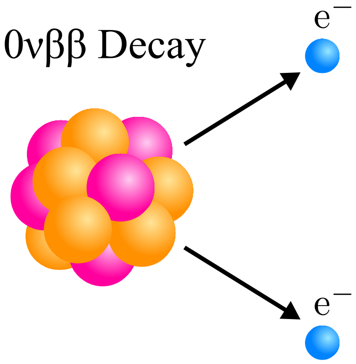
Peak at the Q-value of the emitter (2-3 MeV)

Ideal Requirements

For a given isotope, we expect the following spectrum.







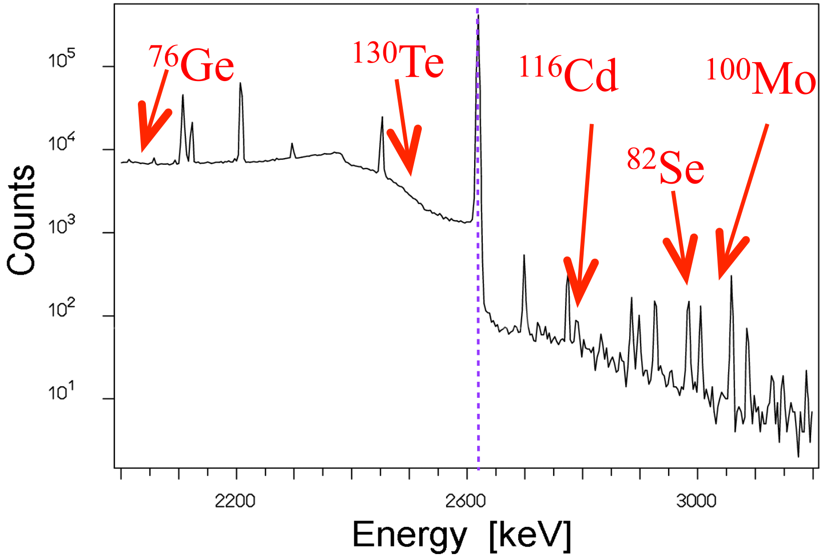
- Many emitters: $T_{1/2}$ larger than 10^{26}, means 10^{27} isotopes (hundreds of kg)
- Zero background
- Energy resolution (also to suppress unavoidable 2νββ decays)

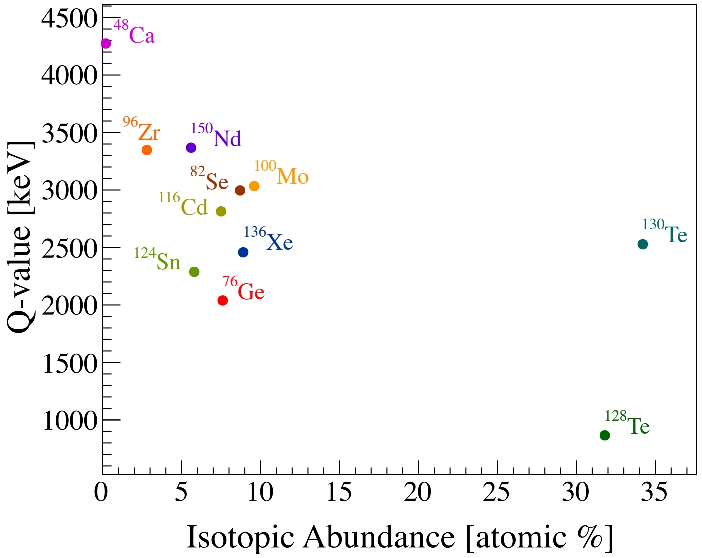
Let’s build the detector

Few isotopes for 0νββ: ^{136}Xe, ^{82}Se, ^{130}Te, ^{100}Mo, ^{76}Ge…

From the theoretical point of view, no strong preference

Experimentally, a high Q-value is beneficial for background suppression, but comes at the cost of a low isotopic abundance





No ideal answer, many technologies and many interesting R&Ds

Three Main Families

Today, ~all detectors coinciding with source to enhance efficiency

Fluids

Non-homogeneous

Solid State

Three Main Families

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Fluids

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^{136}Xe

KamLAND-Zen

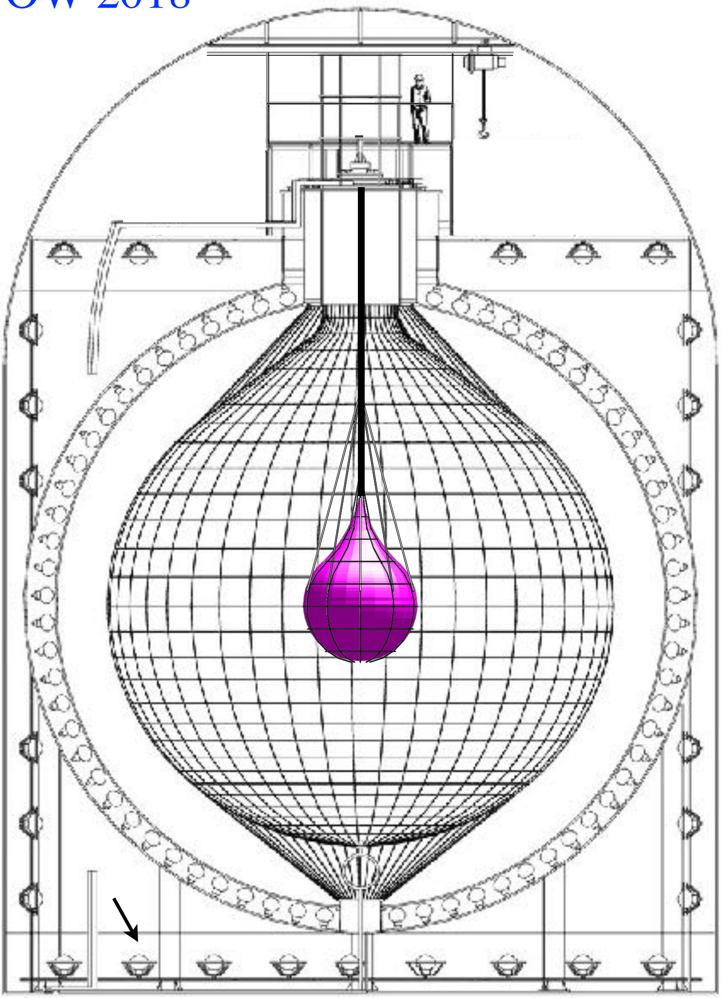
IH:

10^{26} - 10^{28} yr

Dissolve hundreds of kg of source in liquid scintillator

Y. Gando's talk

NOW 2018



- Poor resolution $\sigma = (6.6 - 7.3)\,\% \sqrt{(E[MeV])}$
- No particle ID
- But large mass:
  - (320 kg phase-I) + (383 kg phase-II)
  - $T_{1/2}>1.07\mathrm{x}10^{26}$ yr, $m_{\beta\beta}<45$-160 meV
  - This winter: 750 kg and new balloon, aiming at $4.6\mathrm{x}10^{26}$ yr
  - Future: 1-ton, with better ΔE (280 —> 170 keV) and scintillating crystals

^{136}Xe

EXO-200 and nEXO

IH:

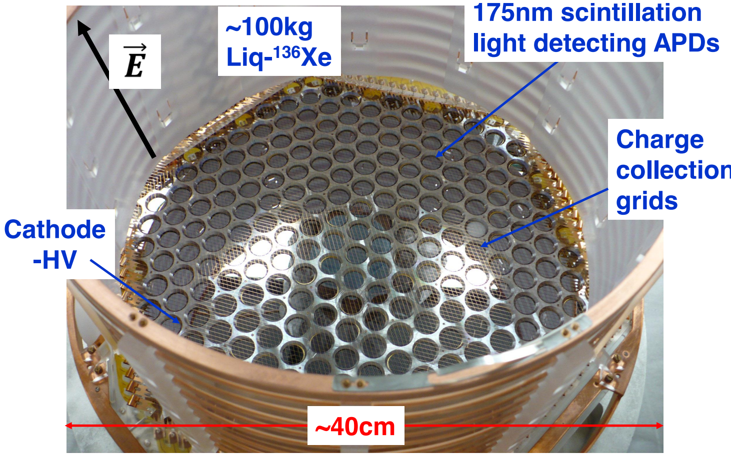
10^{26} - 10^{28} yr

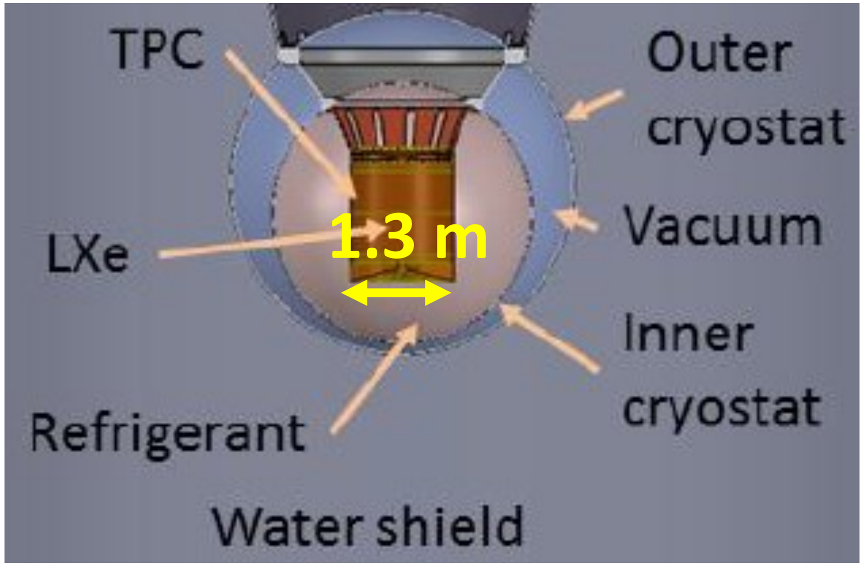
Hundreds of kg of source used as liquid TPC

G. Gratta’s talk, Neutrino 2018

Today: EXO-200

- ^{136}Xe in liquid phase, resolution: $\sigma = 1.23\,\%\,E$
- ~75 kg Xe in fiducial volume
- $T_{1/2} > 1.8\text{x}10^{25}$ yr (still ongoing)





Future: nEXO

- Increase LXe from 150 to 5000 kg
- Improve energy resolution
- Exceed sensitivity 10^{27} yr

^{136}Xe

NEXT

IH:

10^{26} - 10^{28} yr

High pressure (10-15 bar) TPC based on enriched Xe

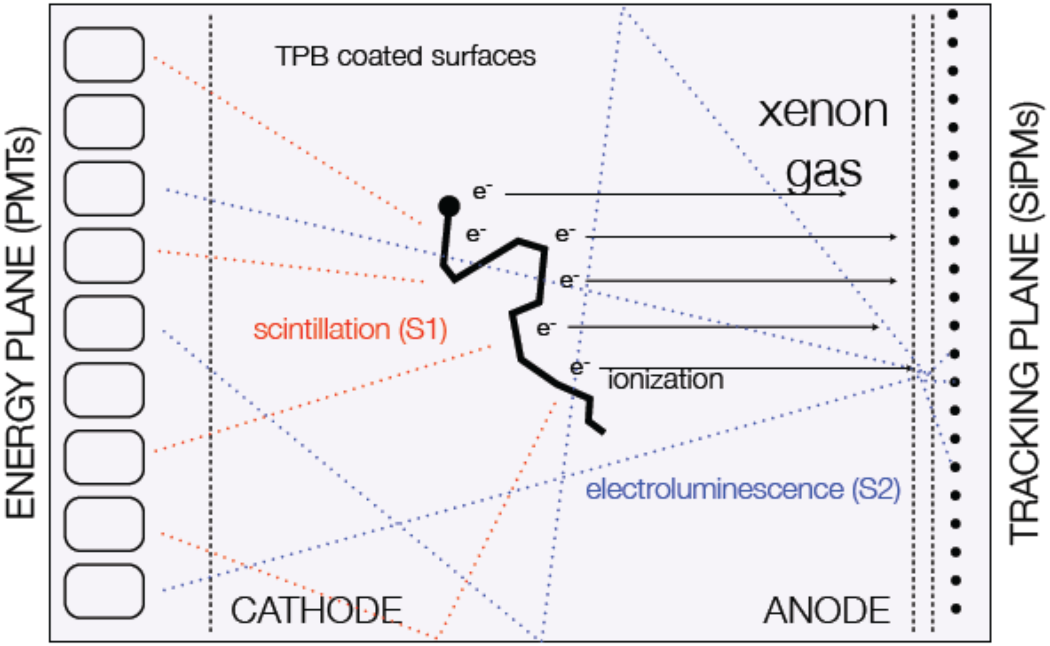
JJ Gomez-Cadenas's talk, Neutel 2017

Today: 10 kg prototype

- Proved ΔE < 1%

NETX-100 in 2019

- Aiming at 9.8×10^{25} yr



Future

- Ton-scale
- Lower background (SiPM vs PM)
- Ba tagging (?)
- Aiming at 1.5×10^{27} yr

^{130}Te

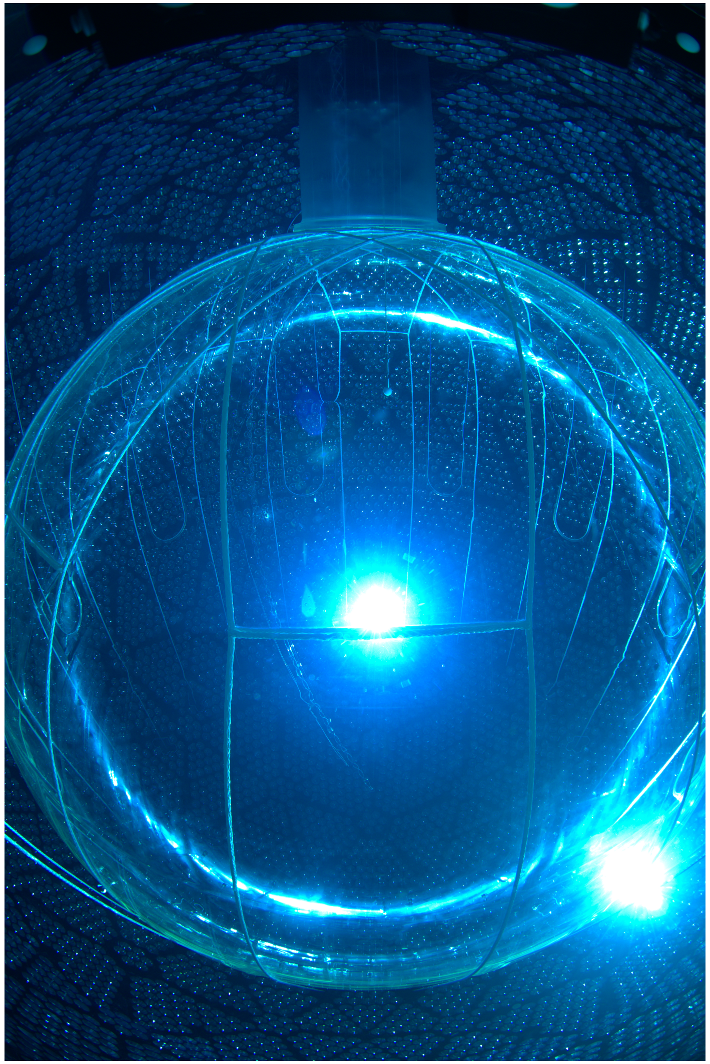
SNO+

IH:

10^{26} - 10^{28} yr

Fill the acrylic vessel with hundreds of kg of source dissolved in LS

G.D.Orebi Gann's talk, Neutrino 2018



- Multipurpose (nucleon decay, supernovae, geo-, solar and reactor ν)
- Autumn 2019: load LAB scintillator with 0.5% ^{nat}Te aiming at T>10^{26} yr in 1 yr
- Future:
  - Increase Te concentration, LY, transparency to surpass 10^{27} yr
  - THEIA project with a 50 kton water-based liquid scintillator detector, aiming at surpassing 10^{28} yr without enriching

Three Main Families

Today, ~all detectors coinciding with source to enhance efficiency

Fluids

Non-homogeneous

Solid State

- Typical energy resolution worse with respect to solid state detector
- At the moment, and likely in the future, experiments with largest source mass
- Clear path for mid-term and future

PANDA-X-III, AXEL, LiquidO
Not covered in this talk :(

Three Main Families

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Fluids

Non-homogeneous

Solid State

^{76}Ge

LEGEND

IH:

10^{26} - 10^{28} yr

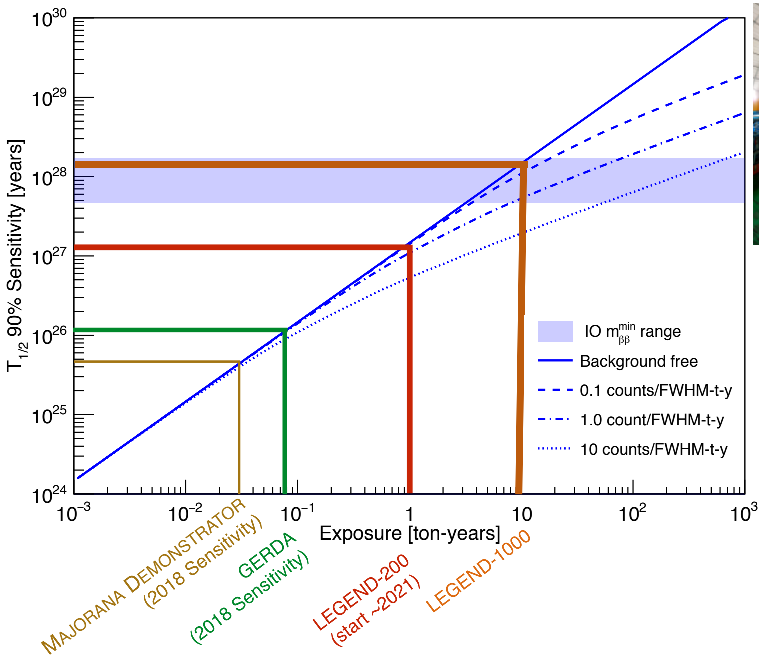
^{76}Ge embedded in HPGe crystals, to be operated as diodes: today detectors scale: tens of kg

- GERDA: excellent resolution (3-4 keV FWHM) and best background in this field: $T_{1/2}>9x10^{25}$ yr
- Majorana even better resolution (2.5 keV FWHM), slightly worse background and lower exposure: $T_{1/2}>2.7x10^{25}$ yr

A.J. Zsigmond and V. Guiseppe's talks, Neutrino 2018

Now forming LEGEND collaboration

- First phase (2021) with ~200 kg ^{76}Ge (GERDA + Majorana + 135 kg new detectors), background x3 lower.
- Long-term plan: 1000 kg to exceed 10^{28} yr

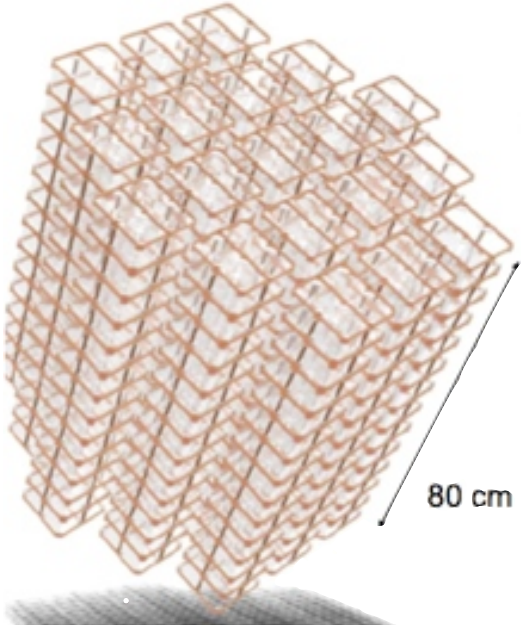


^{130}Te

CUORE

IH:

10^{26} - 10^{28} yr

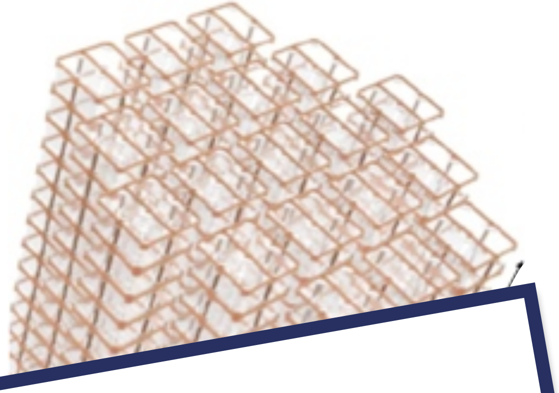


- CUORE: Tonne-scale experiment operating 206 kg of ^{130}Te (988 TeO_2 crystals, 15 tons of Pb, Cu, TeO_2 at <4K)

- Excellent resolution 7.4 keV FWHM, now optimising cryostat to reach 5 keV

- Combined with its ancestors, $T_{1/2}>1.5\times10^{25}$ yr, aiming at 10^{26} yr in 5 yr

CUORE —> CUPID

CUPID

(Cuore Upgrade with Particle IDentification)

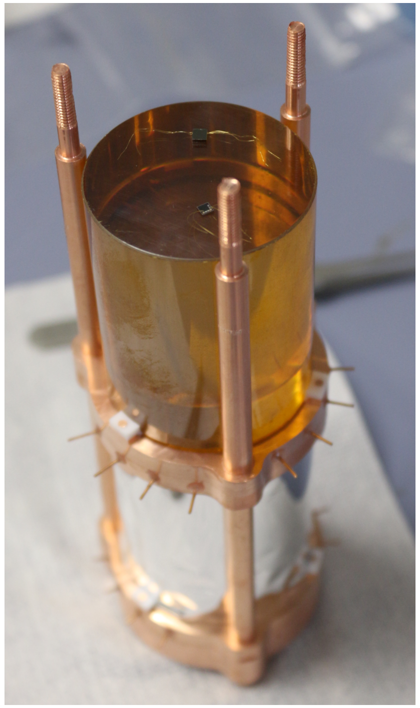
technology for a next-generation project

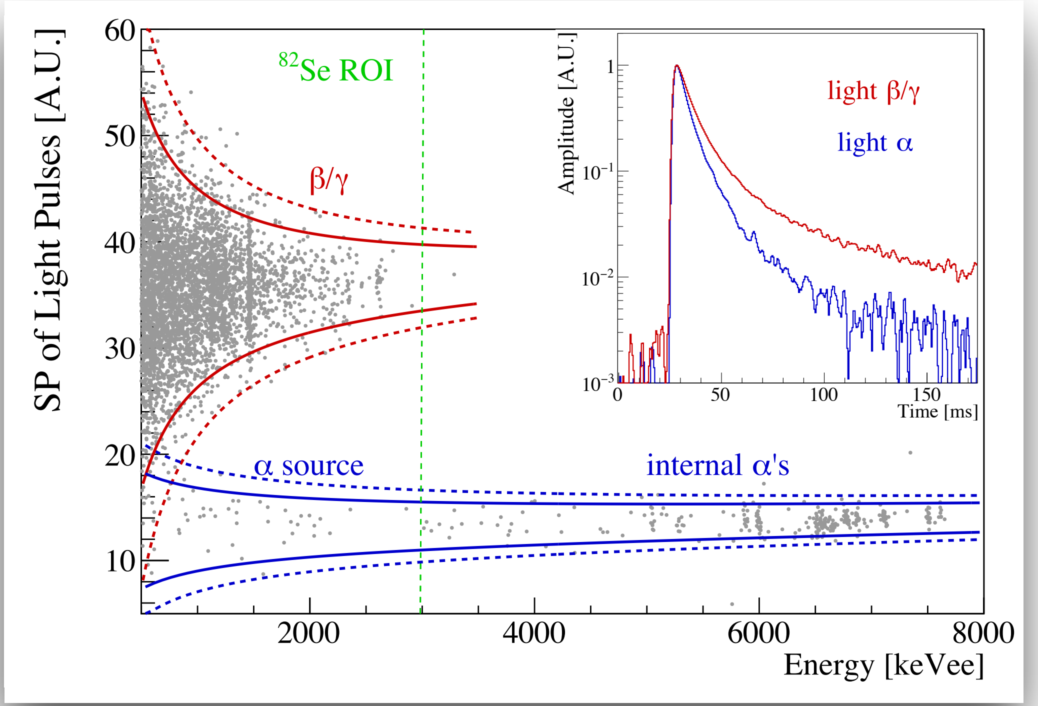
Tonne-scale, excellent energy resolution, background free!

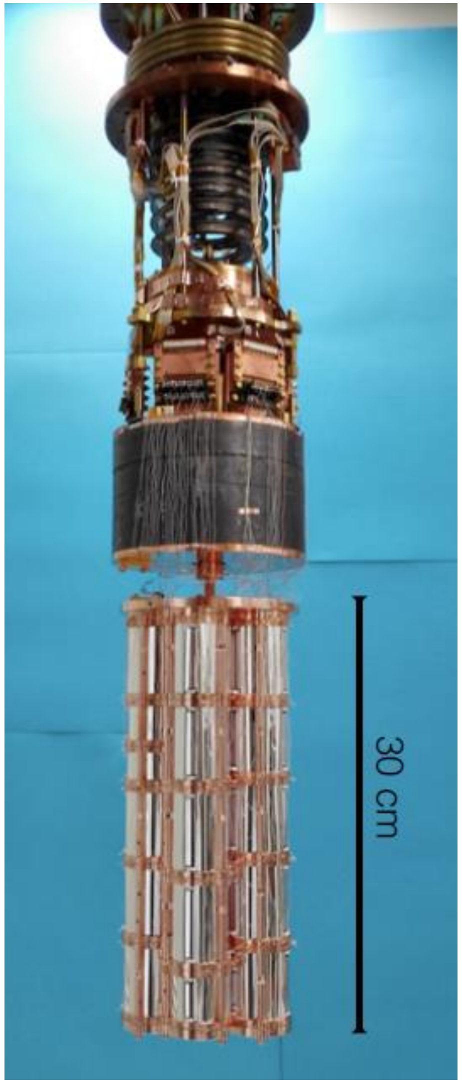
-
- yr, aiming at 10^{26} yr in next 5 yr

CUORE —> CUPID

- First medium-scale prototype: CUPID-0 proved rejection of α bkg
- Limit on ^{82}Se half-life > 4x10^{24} yr with 5.46 kg x y
- Results from CUPID-Mo coming soon







L. Cardani, INFN Roma

Three Main Families

Today, ~all detectors coinciding with source to enhance efficiency

Fluids

Non-homogeneous

Solid State

- Excellent energy resolution (crucial for discovery)
- At the moment, small masses (with the exception of CUORE)
- Clear path for mid-term and future for ^{76}Ge, several mature and viable options for the CUORE upgrade

AMoRE, CROSS
Not covered in this talk :(

Three Main Families

IH:

10^{26} - 10^{28} yr

Today, ~all detectors coinciding with source to enhance efficiency

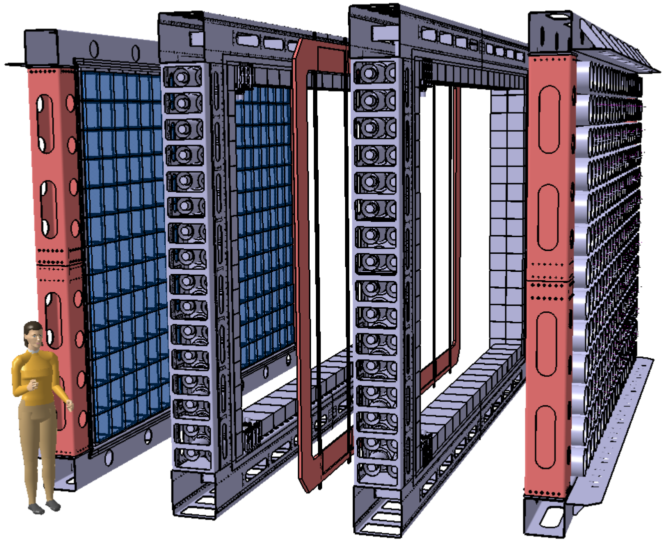
Fluids

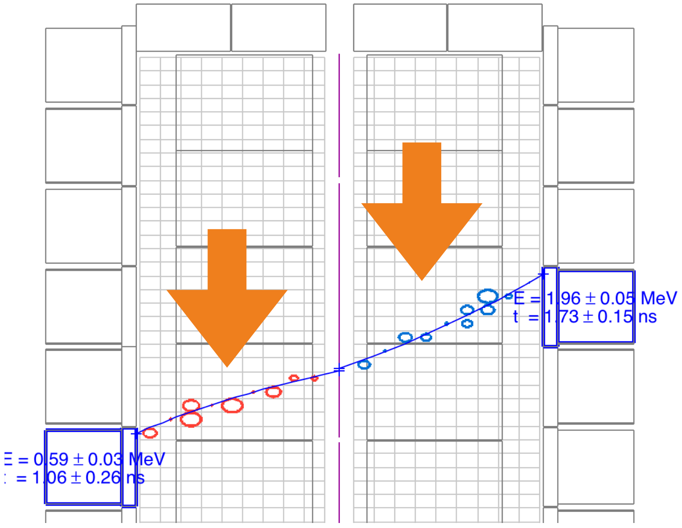
Non-homogeneous

Solid State

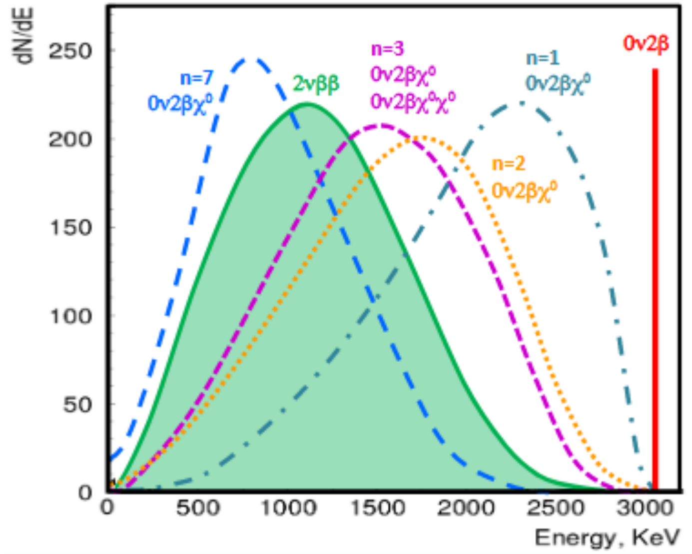
SuperNEMO: with full topological reconstruction of the 2 emitted electrons,

7 kg of ^{82}Se aiming at 6x10^{24} yr, plans with ^{150}Nd



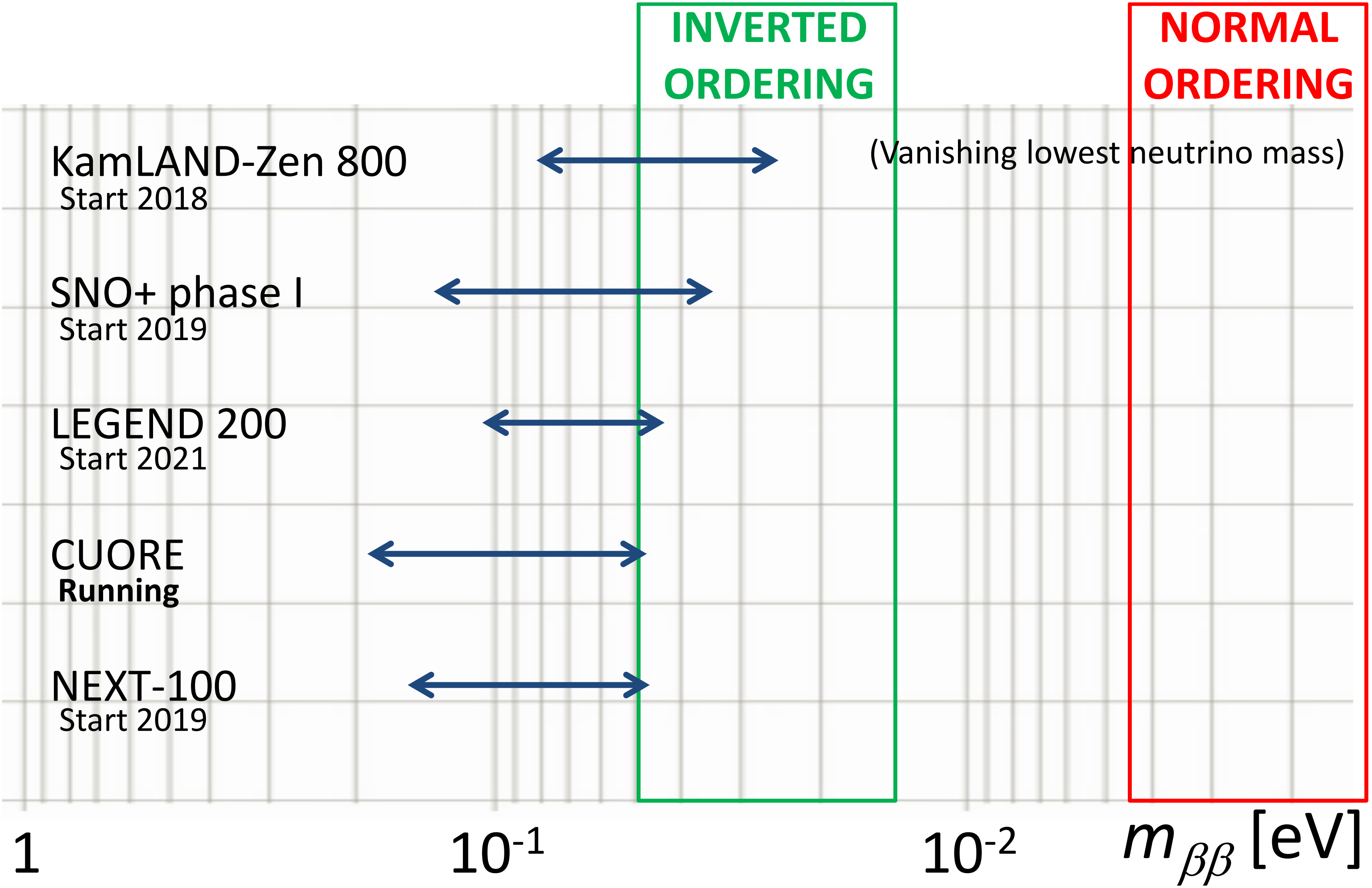


C. Patrick’s talk, IOP APP/HEPP Conference 2018

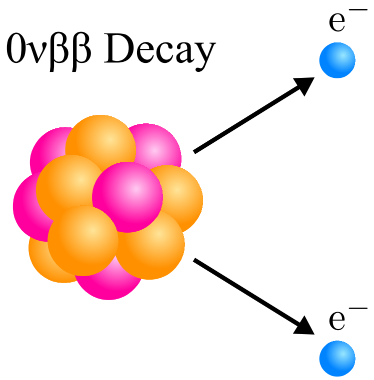


Prospects for the near future

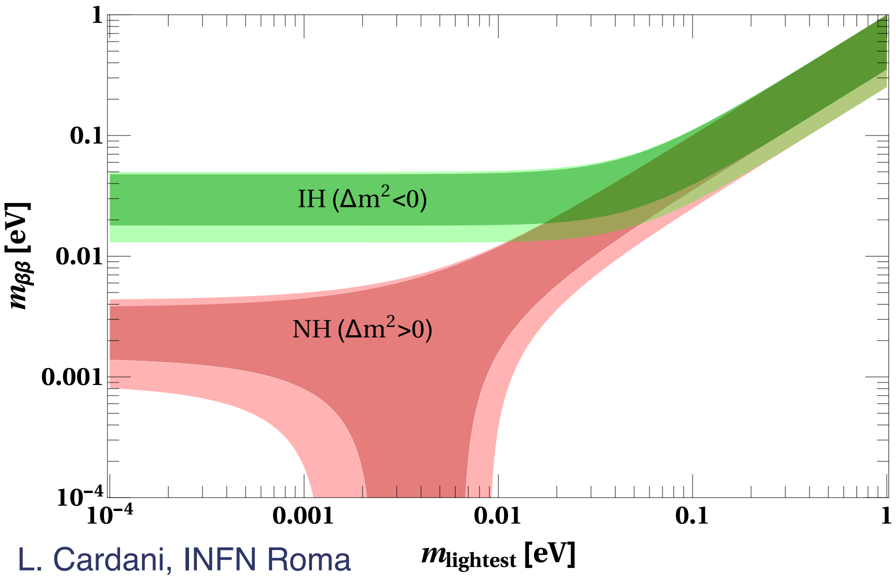
(I stole this slide from A.Giuliani's talk at Neutrino2018, thanks!)



Conclusions

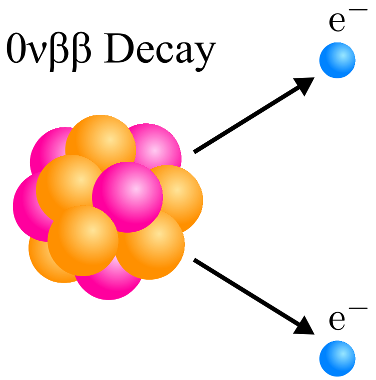


- Double Beta Decay is a unique probe for New Physics
    - Lepton Number Violation
    - Neutrino Nature
- Nuclear Matrix Elements, g_a are challenging theorists
- The rarity of this process is a challenge for experimentalists



- Active field, with projects <hundreds M$
- Down-selection of 2-3 technologies for the long-term future

Conclusions



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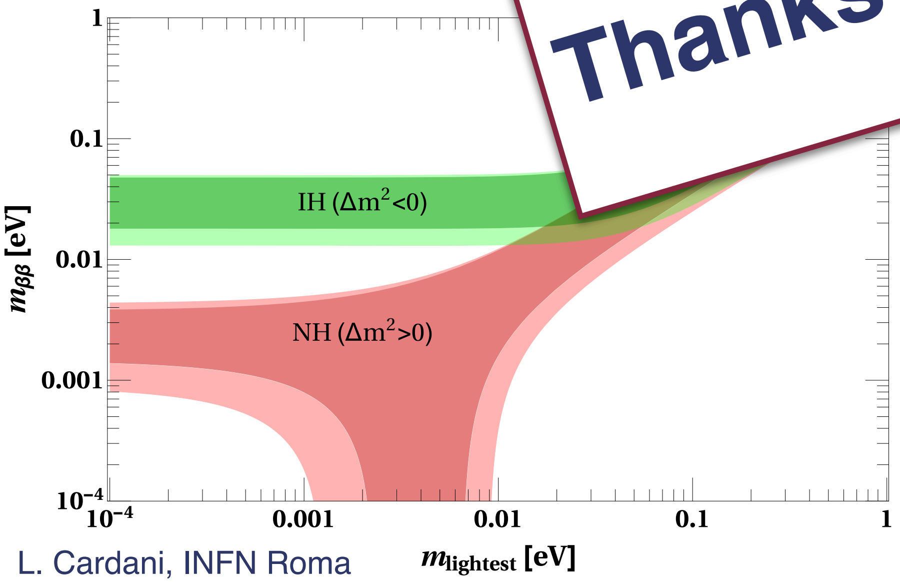
- Nuclear Matrix Elements, g_a are challenging th
- The rarity of this process is

Thanks for the attention!



- Active field, with projects <hundreds M$
- Down-selection of 2-3 technologies for the long-term future

Background Suppression

$$S^{bkg} \propto \varepsilon \, \frac{i.a.}{A} \sqrt{\frac{MT}{B\Delta E}} \quad [y] \quad \Rightarrow \quad S^{0bkg} \propto \varepsilon \, \frac{i.a.}{A} MT \quad [y]$$

the detection technique:

- ε = detector efficiency
- M = detector mass [kg]
- T = measurement time [y]
- ΔE = energy resolution [keV]
- B = background [counts/keV/kg/y]

the 0νββ emitter:

- i.a. = isotopic abundance
- A = mass number
- B = background [counts/keV/kg/y]

S increases **linearly** with MT

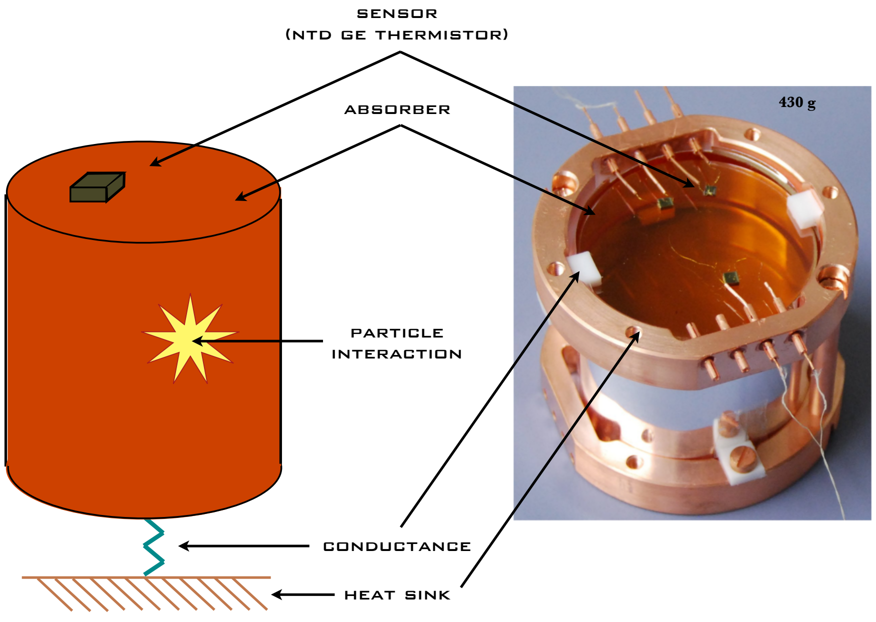
Majorana Theory

- Evidences for massive neutrinos: how to incorporate ν mass in SM?
- Being completely neutral, neutrinos could be the only fermion equal to its own anti-particle

Neutrinos could be **Majorana particles** (as opposed to all the other fermions)

- Implies **violation of lepton number** conservation
- Crucial for theories explaining the **dominance of matter over antimatter** in the Universe

Cryogenic Calorimeters



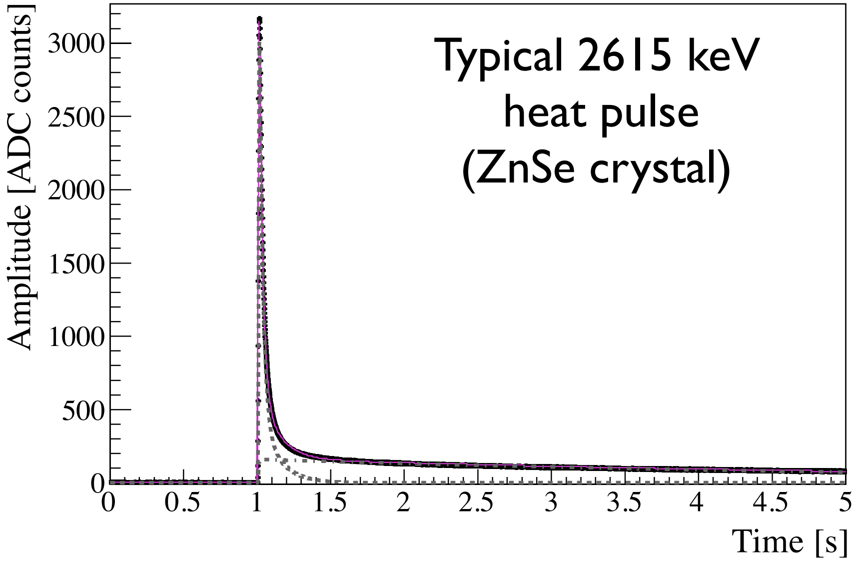
Wednesday, September 4, 13

Crystal operated as calorimeter at ~10 mK

Particle interaction ➪ E deposit ➪ T increase

Dedicated sensor to convert ΔT in a voltage pulse

- Grown from 0νββ emitter ➪ ε > 80%
- Test different 0νββ emitters
- Excellent resolution (5-20 keV FWHM at 2615 keV)
- Scalability ➪ large source mass

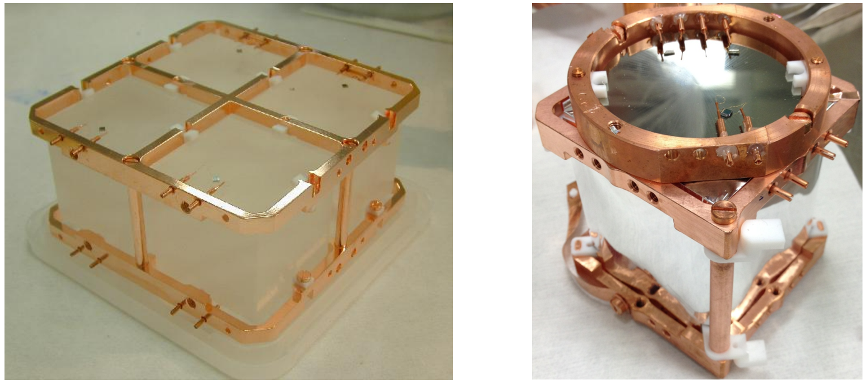


CUPID

Natural evolution of CUORE, with background suppression via Particle ID

Cherenkov light in TeO_2 (CUORE)

CALDER, *SINGLE*, and others



Rejection of α background proved

Reproducibility and Scalability of light detection under investigation

CUPID

Natural evolution of CUORE, with background suppression via Particle ID

Cherenkov light in TeO_2 (CUORE)

Scintillation Light in other crystals

CALDER, *SINGLE*, and others

CUPID

Natural evolution of CUORE, with background suppression via Particle ID

CUPID-0

Zn^{82}Se

Lowest bkg, best limit on ^{82}Se: 4.0x10^{24} yr

Crystals resolutions to be improved

CUPID-Mo

Li$_2$^{100}MoO$_4$

Excellent energy resolution proved

Medium scale prototype results in the next months

Scintillation Light in other crystals