ASPERA WP 2: Neutrino Mass

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Physics motivations

Experiments and projects

Project summaries & ressources

Physics case

- Absolute neutrino mass and neutrino mass hierarchy (SDB, DBD)

- Nature of neutrino : Dirac ($\nu \neq \bar{\nu}$) or Majorana ($\nu = \bar{\nu}$) (DBD)

-Leptonic number violation (DBD)

- Right-handed current interaction (DBD)

- CP violation in leptonic sector (DBD)

- Search of Supersymmetry and new particles (DBD)

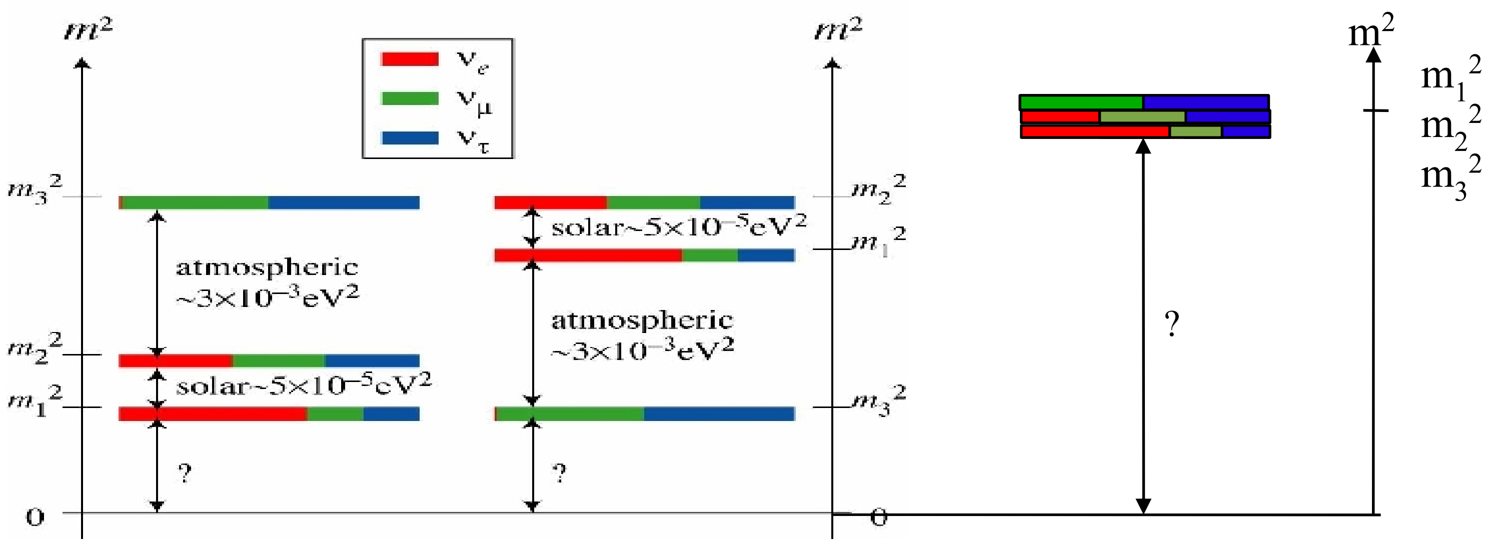
SDB: Single Beta Decay

DBD: Double Beta Decay

Absolute Neutrino mass

Process	Measured mass	Present limit	Futur
Beta decay	$m_\nu = \left[\Sigma \lvert U_{ei} \rvert^2 m_i^2 \right]^{1/2}$	**<2.3 eV**	**< 0.2 eV**
Double beta decay	$\lvert \langle m_\nu \rangle \rvert = \lvert \Sigma U_{ei}^2 m_i \rvert$	**< 0.2 - 0.8 eV**	**< ~0.05 ev**
Cosmology	$\Sigma m_i = m_1 + m_2 + m_3$	**<~1 eV**	**< ~0.1 eV**

Mass Hierarchy

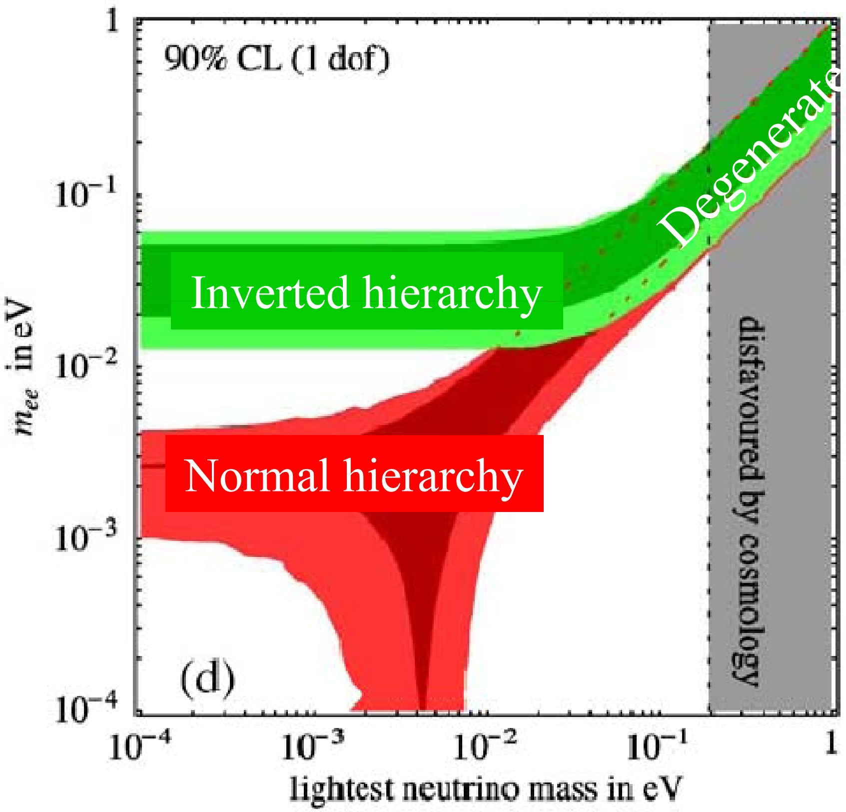


Normal hierarchy
$m_3 >> m_2 \sim m_1$

Inverted hierarchy
$m_2 \sim m_1 >> m_3$

Degenerate
$m_1 \approx m_2 \approx m_3 \gg |m_i - m_j|$

Mass Hierarchy



Degenerate: can be tested by SDB and DBD

Inverted hierarchy: tested by the next generation of ββ experiment

Normal hierarchy: seems inaccessible within 10 years

Nature of neutrino

Dirac neutrino **particle ≠ antiparticle** **4 states $\nu_L, \nu_R, \bar{\nu}_L, \bar{\nu}_R$**

Conservation of global leptonic number

Majorana neutrino **$\nu = \bar{\nu}$** **2 states ν_L and ν_R**

No conservation of global leptonic number

If $\nu_{Majorana}$ and CP violation in leptonic sector -> leptogenesis

WP2 roadmap

Currently Europe has leadership for both single and double beta decay experiments

To improve the sensitivity on neutrino mass by at least a factor 10 whithin 10 years

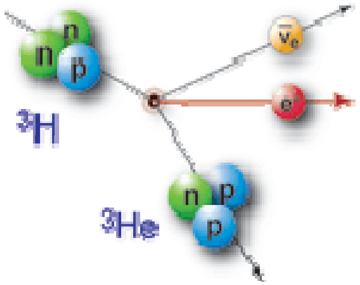
To select the most sensitive techniques for the next generation of experiments

To support R&D to develop new techniques

Neutrino mass

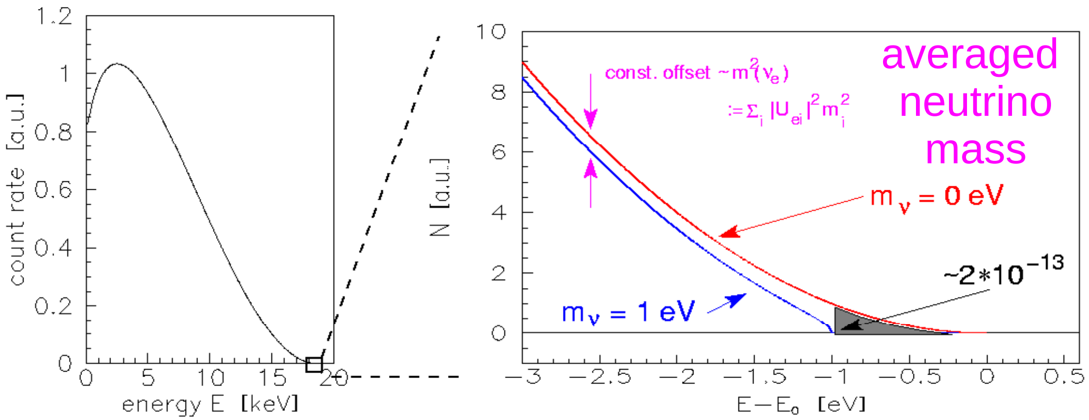
Single beta decay

$$(A,Z) \rightarrow (A,Z+1) + e^- + \nu_e$$



$dN/dE \sim [\ (E_0\text{-}E_e)^2 - m_{\nu i}^2\ ]^{1/2}$:

$$m_{\nu_e}^2 = \sum |U_{e_i}|^2 m_i^2$$

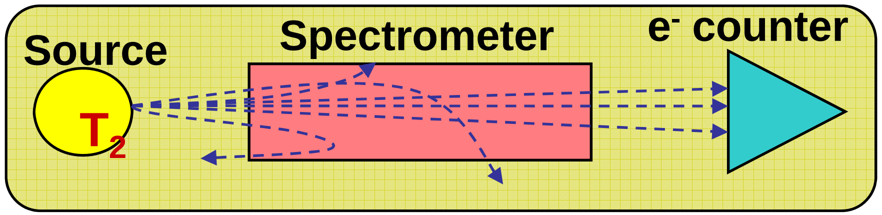


Extraction of m_ν is not model dependant

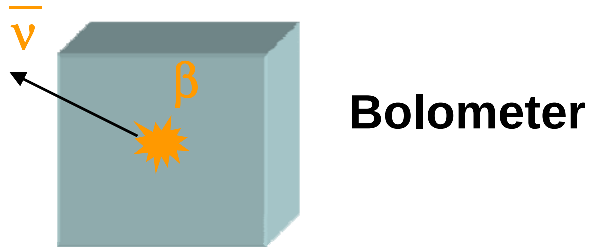
Neutrino mass

Two possible approaches

KATRIN
Spectrometer



MARE
Calorimeter



Source (^{3}He) ≠ detector

High activity source ~ 2Ci/s

Energy resolution: 0.92 eV

Integrated beta energy spectrum

Size limit

β-source (^{187}Re) = detector

Low activity source ~ 1 Bq/mg

Energy resolution: 5 eV

Measure differential spectrum DN/DE

Can be extended

Different systematics → complementary techniques

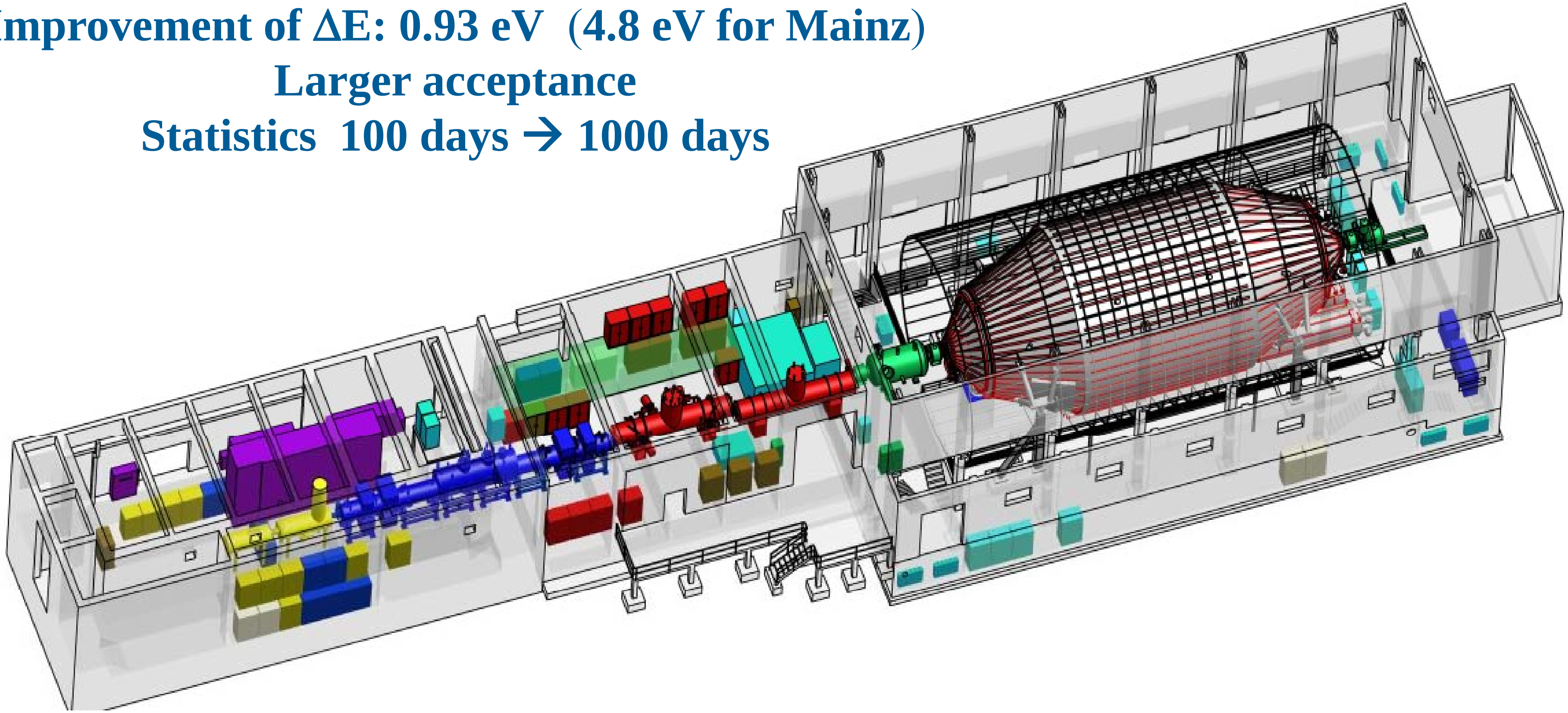
Neutrino mass

KATRIN

Czech Republic – Germany – Russian Federation – United Kingdom – United States

2007: 120 Collaborators from 16 institutions including 30 PhD and diploma students

Improvement of ΔE: 0.93 eV (4.8 eV for Mainz)
Larger acceptance
Statistics 100 days → 1000 days

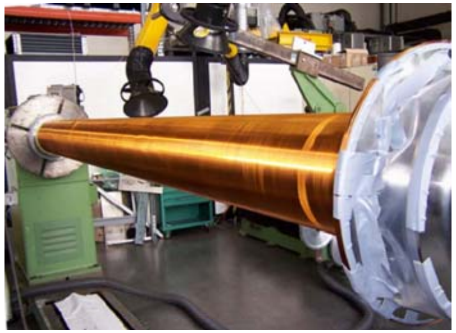


KATRIN

Tritium source

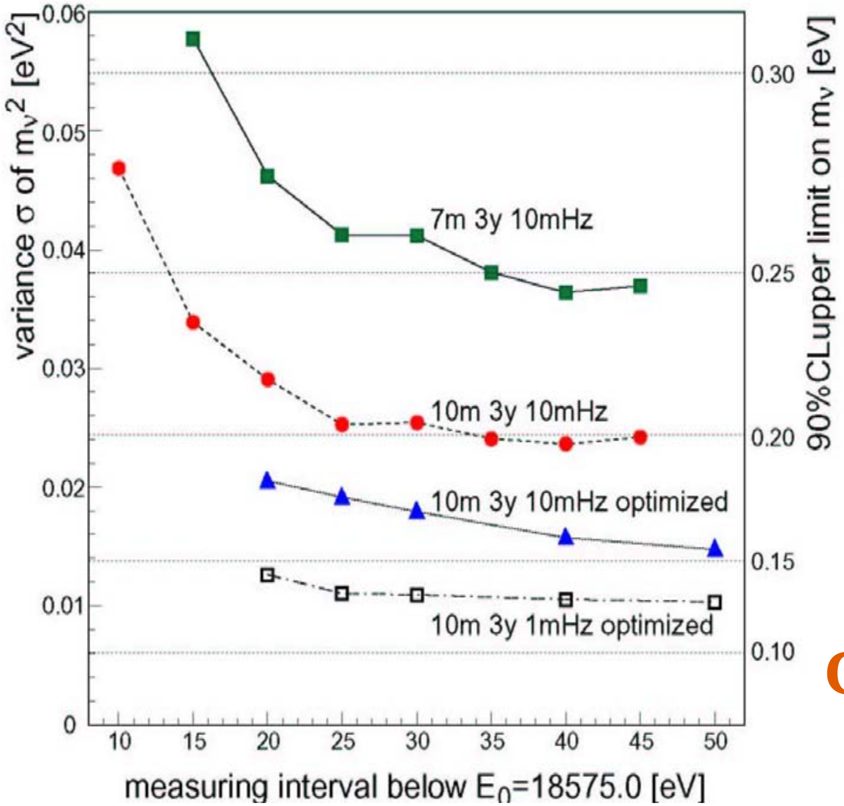
one of the most complex cryostats ever built:

- **42 sub-assemblies**
- **12 cryo circuits**
- **6 working fluids**
- **>500 sensors**
- **7 magnet modules**



Main spectrometer

KATRIN



Sensitivity (90% CL)
m(ν) < 0.2 eV

Discovery potential
m(ν) = 0.35 eV (5σ)

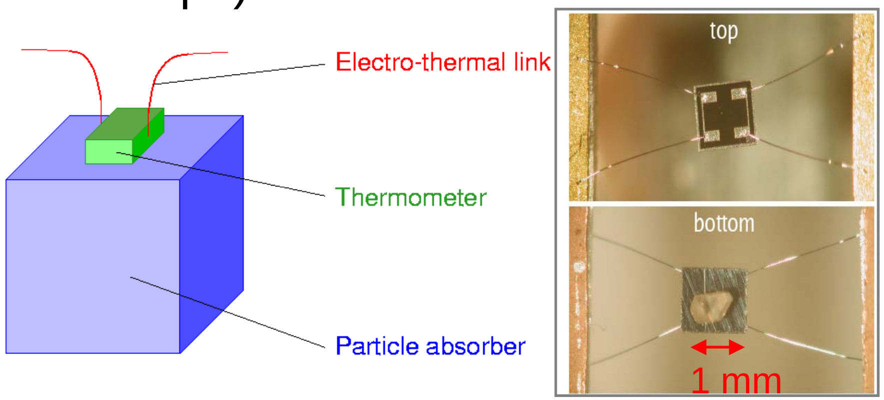
Commissioning and operation: 2010
Final results 2015-2016

MARE

Italy, USA, Germany (10 physicist in Europe)

MicroBolometers of ArReO4

^{187}Re Q_{β} = 2.47 keV



MARE-I: 300 detectors

Energy resolution ~20 eV

$\langle m_{\nu} \rangle <$ 2 –4 eV (2010)

MARE – II : 50000 detectors

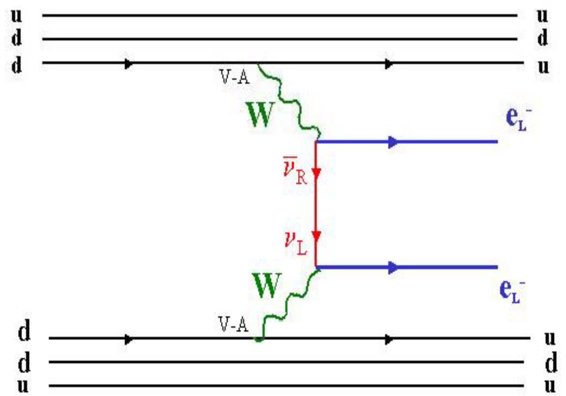
Energy resolution ~5 eV

Need new techniques

$\langle m_{\nu} \rangle <$ 0.2 eV (2015)

Neutrinoless double beta decay

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



Light neutrino exchange ⟶

$\Delta L = 2$

Lepton number violation

Majorana neutrino ($\nu = \bar{\nu}$)

Massive neutrino

Phase space factor

Nuclear matrix element

$$T_{1/2}^{-1} = F(Q_{\beta\beta}, Z)\, |M^{0\nu}|^2 \, \langle m_\nu \rangle^2$$

$$\langle m_\nu \rangle = m_1 |U_{e1}|^2 + m_2 |U_{e2}|^2 . e^{i\alpha} + m_3 |U_{e3}|^2 . e^{i\beta}$$

|Uei|: mixing matrix elements

α et β: Majorana phases

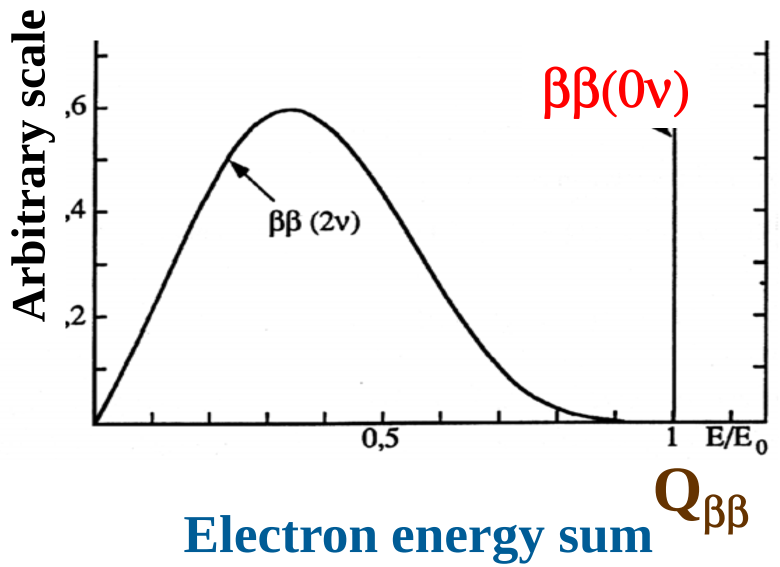
Other possible process :

V+A current : $\langle m_\nu \rangle, \langle \lambda \rangle, \langle \eta \rangle$

Majoron emission : $\langle g_M \rangle$

Supersymmetry : $\lambda'_{111}, \lambda'_{113}$

ββ(0ν) observables



Angular distribution

Individual electron energy

Allow to distinguish the mechanism

Background : natural radioactivity, radon,neutrons, muons, ββ(2ν)

Double beta decay

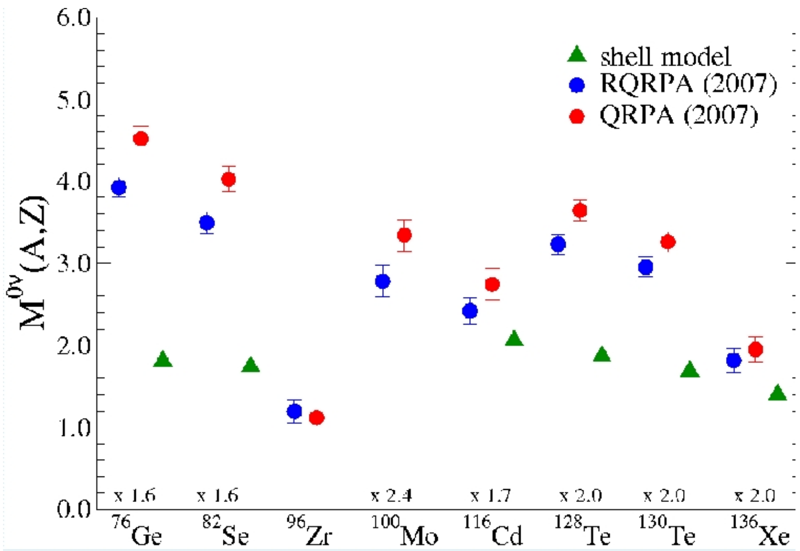
Why several nuclei and why several techniques are required ?

Isotope	$Q_{\beta\beta}$ (MeV)	Isotopic abundance (%)	$G_{0\nu}(yr^{-1}) \times 10^{25}$
^{48}Ca	4.271	0.187	2.44
^{76}Ge	2.040	7.8	0.24
^{82}Se	2.995	9.2	1.08
^{96}Zr	3.350	2.8	2.24
^{100}Mo	3.034	9.6	1.75
^{116}Cd	2.802	7.5	1.89
^{130}Te	2.528	33.8	1.70
^{136}Xe	2.479	8.9	1.81
^{150}Nd	3.367	5.6	8.00

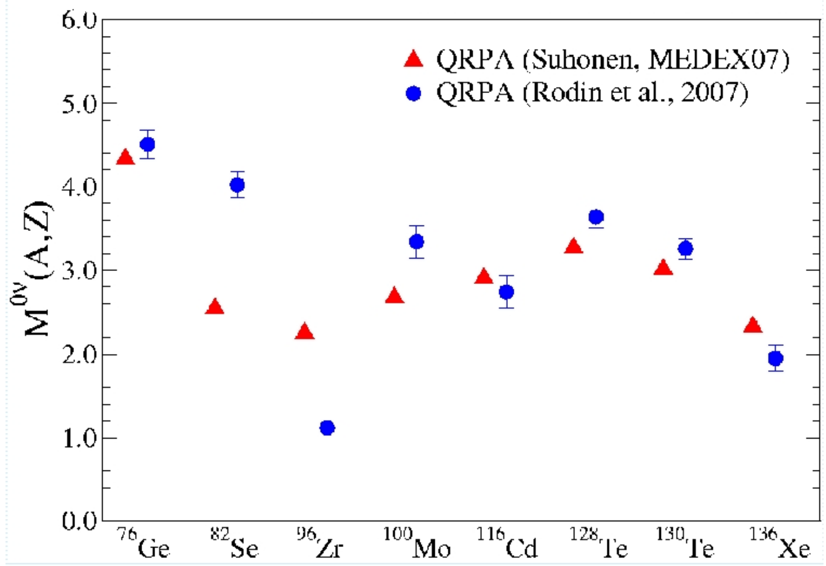
$$T_{1/2}^{-1} = F(Q_{\beta\beta}^{5}, Z)\ |M^{0\nu}|^2 <m_\nu>^2$$

$<m_\nu>$ is model dependant

Shell Model (Poves et al) - QRPA



Two different QRPA calculations



A lot of improvements have been done but still discrepancies
Uncertainties for extraction of $<m_\nu>$

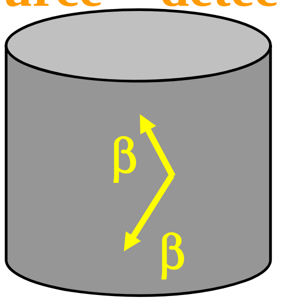
With background:

$$T^{0\nu}_{1/2}(y) > \frac{\ln 2 \,.\, \mathcal{N}}{k_{C.L.}} \,.\, \frac{\varepsilon}{A} \,.\, \sqrt{\frac{M \,.\, t}{N_{Bckg} \,.\, \Delta E}}$$

M: masse (g)
ε : efficiency
$K_{C.L.}$: Confidence level
$\mathcal{N}$: Avogadro number
t: time (y)
N_{Bckg}: Background events ($keV^{-1}.g^{-1}.y^{-1}$)
ΔE: energy resolution (keV)

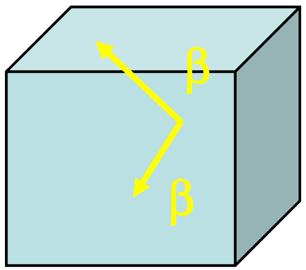
Today, no technique able to optimize all the parameters

Calorimeter
Semi-conductors
Bolometers
Source = detector



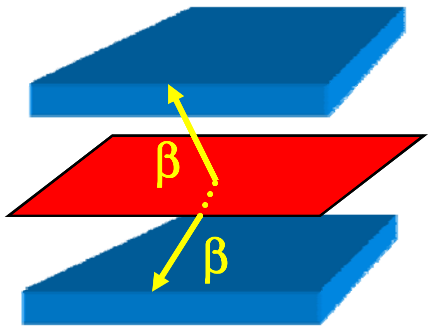
ε, ΔE

Calorimeter
(Loaded) Scintillator
Source = detector



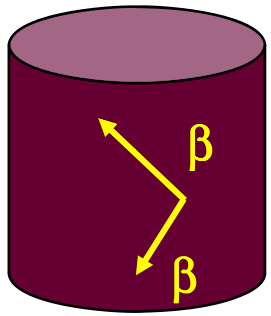
ε, M

Tracko-calo
Source ≠ detector



NBckg, isotope choice

Xe TPC
Source = detector

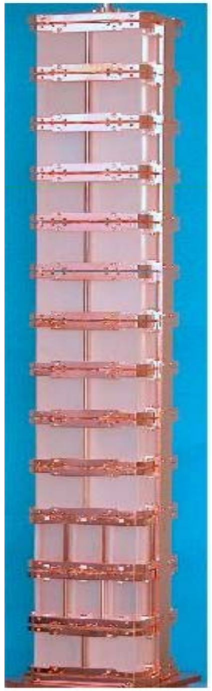


ε,M, (N_{Bckg})

Neutrino mass

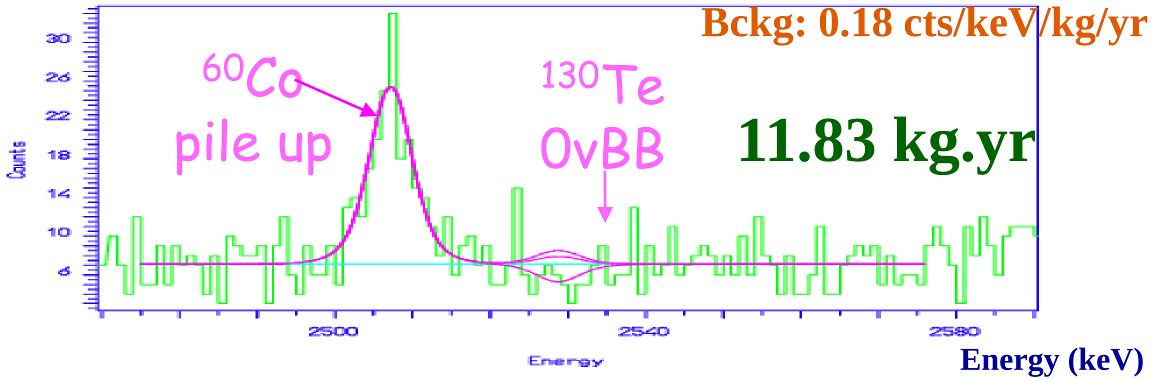
Name	Nucleus	Method	Location	European Members	Others
Running experiments					
CUORICINO	^{130}Te	bolometric	LNGS	IT, NL, ES	US
NEMO-3	^{82}Se	tracking	Frejus	FR, CZ, UK	US, RU, JP
Construction funding					
CUORE	^{130}Te	bolometric	LNGS	IT, NL, ES	US
GERDA	^{76}Ge	ionization	LNGS	DE,BE,IT,PO	RU
Substantial R&D funding					
COBRA	^{116}Cd, ^{130}Te	scintillation	LNGS	UK, DE	-
EXO	^{136}Xe	tracking	WIPP	CH	US, RU, CAN
MAJORANA	^{76}Ge	ionization	SNOLAB or DUSEL	-	US
SuperNEMO	^{82}Se	tracking	t.b.d.	FR,CZ,UK,SL	US,RU, JP
R&D and/or conceptual design, and other decay modes					
CANDLES	^{48}Ca	scintillation	Oto Lab	-	JP
CARVEL	^{48}Ca	scintillation	Solotvina		UKR, RU, US
DCBA	^{150}Nd	tracking	t.b.d.	-	JP
MOON	^{100}Mo	tracking	t.b.d.	-	JP
SNO++	^{150}Nd	scintillation	SNOLAB	-	CAN, US + …
TGV	^{106}Cd, ^{48}Ca	electron capture, R&D	Frejus	FR, CZ	RU

Cuoricino



Italy, USA,Spain (12 scientists in Europe)

Bolometer of TeO_2 (~10 kg of ^{130}Te)
Running at gran Sasso since 2003



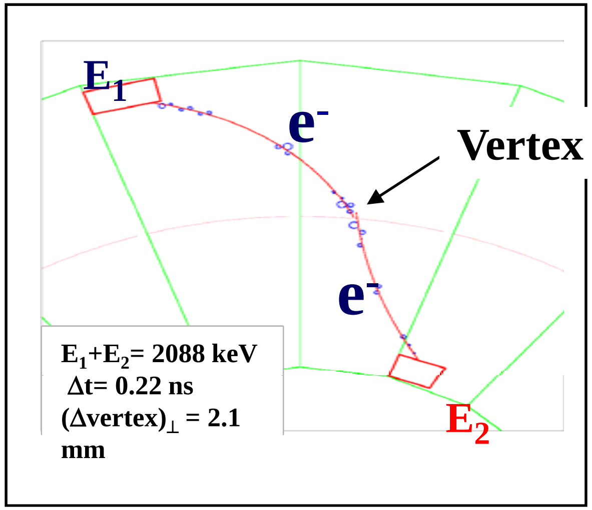
$T_{1/2} > 3.\ 10^{24}$ yr (90% CL) $<m_\nu> < 0.2 – 1$ eV (90% CL)

Expected final sensitivity ~2009: $T_{1/2} > 6.\ 10^{24}$ yr $<m_\nu> < 0.1 – 0.7$ eV

NEMO 3

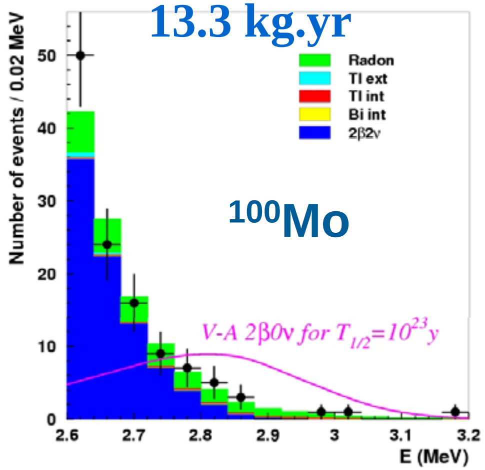
France, UK, Russia, Spain, USA, Czech Republic,Ukraine, Finland (30 scientists in Europe)

Tracko-calo running at Modane since 2003
Multi-isotopes 7 kg of ^{100}Mo and 1 kg ^{82}Se



ββ events

Phase I + II
13.3 kg.yr



$T_{1/2}(\beta\beta0\nu) > 5.8\ 10^{23}$ yr (90 % C.L.) **$<m_\nu> < 0.6 – 1.3$ eV**

Expected in 2009 **$T_{1/2}(\beta\beta0\nu) > 2.\ 10^{24}$ yr (90 % CL)** **$<m_\nu> < 0.3 –0.7$ eV**

Roadmap for double beta decay search

Current running experiment Cuoricino (bolometers 130Te) and NEMO 3 tracko-calo have ~10 kg of enriched isotopes sensitivities ~0.2 – 0.7 eV

Next generation with 100 – 200 kg enriched source, sensitivities ~30 – 100 meV validation of background for 1 ton detector

In Europe, 3 complementary techniques: Semi-conductors, bolometers and tracko-calo

Several nuclei can be studied: ^{76}Ge (check of HM claim), ^{130}Te, ^{82}Se (and ^{150}Nd ?)

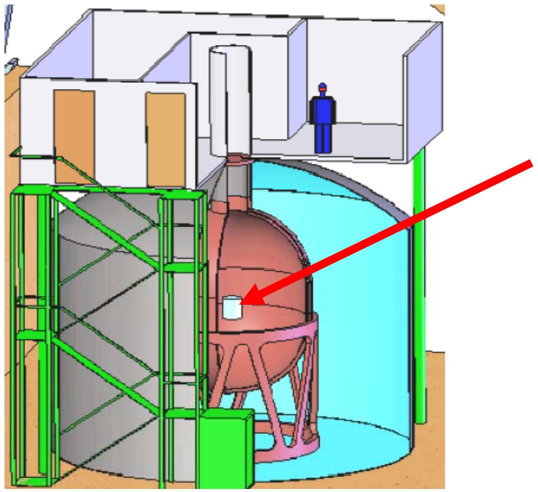
R&D to improve technique or to develop new techniques

In case of signal: must be check with other nucleus and techniques. Need of tracko-calo to determine the process

GERDA

Germany, Italy, Belgium, Russia (27 scientists in Europe)

Ge diodes in liquid nitrogen
Background supression bu removing matter and active veto



PHASE I: 17.9 kg of enriched ^{76}Ge

In 1 year of data if $B=10^{-2}$ cts/keV/kg/yr

Start 2009 at Gran Sasso, results 2010

$T_{1/2} > 3\ 10^{25}$ yr $\langle m_\nu \rangle < 250$ meV

PHASE II: 40 kg of enriched ^{76}Ge

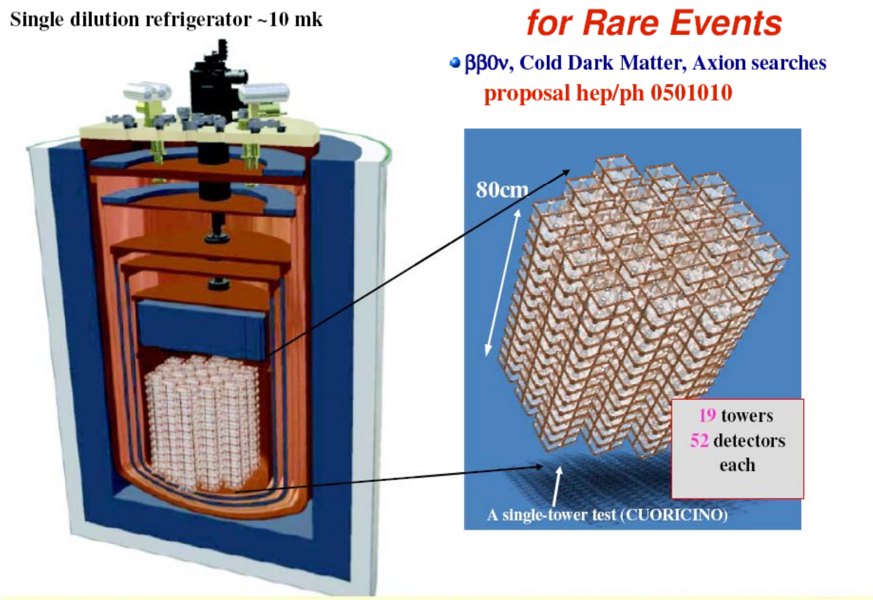
if $B=10^{-3}$ cts/keV/kg/an

$T_{1/2} > 2\ 10^{26}$ yr in 3 years of data $\langle m_\nu \rangle < 110$ meV

Phase I + II already funded

CUORE

Italy, USA,Spain (12 scientists in Europe)



Bolometer of TeO_2 (^{130}Te 203 kg)

Background rejection improvement

Five years of data

N_{bckg}**=0.01 cts.keV^{-1}.kg^{-1}.yr^{-1}**

$T_{1/2} > 2.1\ 10^{26}$ yr $\langle m_\nu \rangle < 30 - 170$ meV

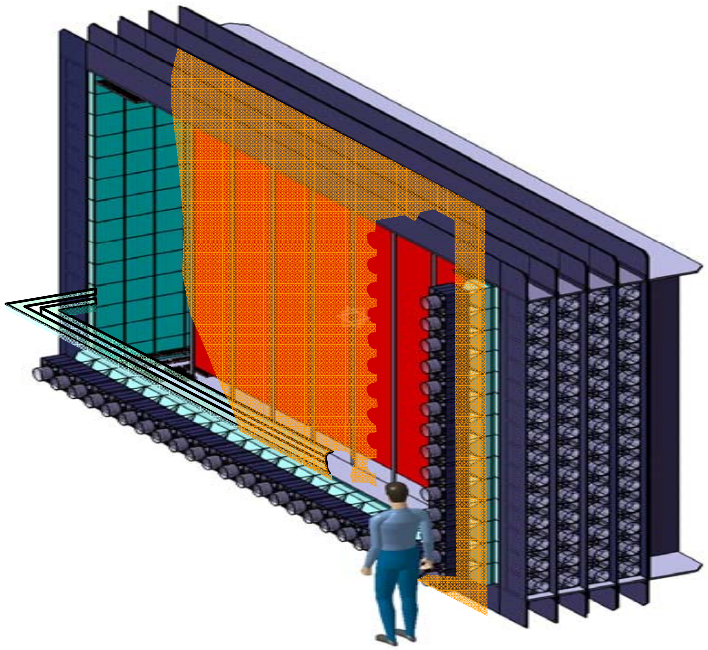
Detector is in construction in Gran Sasso

Commissioning: 2010

Operation: 2011

SuperNEMO

France, UK, Russia, Spain, USA, Japan, Czech Republic,Ukraine, Finland (30 scientists in Europe)



20 modules of a tracko-calo

100 kg of ^{82}Se or ^{150}Nd

3 years R&D program: improvement of energy resolution
Increase of efficiency
Background reduction
…….

5 years of data

$T_{½} > 2.\ 10^{26}$ yr $\langle m_\nu \rangle < 50 – 90$ meV

R&D → 2009

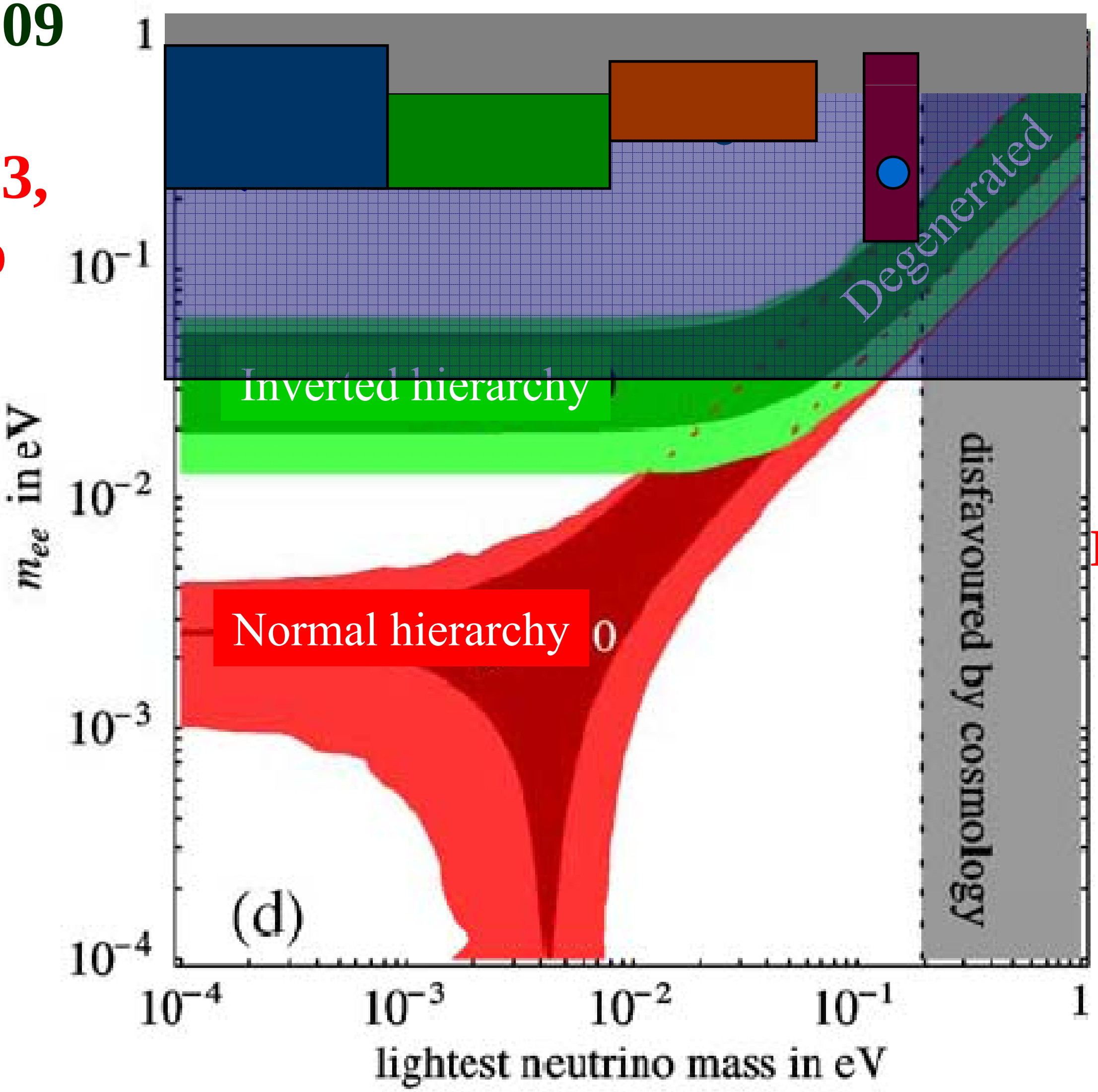
TDR : 2009

First modules in Canfranc in 2011

HM Cuoricino NEMO3 Klapdor claim

Limits in 2009

HM,NEMO3, Cuoricino



Expected limits 2009 – 2015

CUORE,GERDA, SuperNEMO, Majorana,EXO,….

Strategy for double beta decay search

To try to cover the inverted hierarchty → to go to 1 ton detectors

Which nuclei ?

Which techniques ?

R&D needed after 100 kg ? (it was the case to go from 1 kg to 10 kg and from 10 kg to 100 kg)

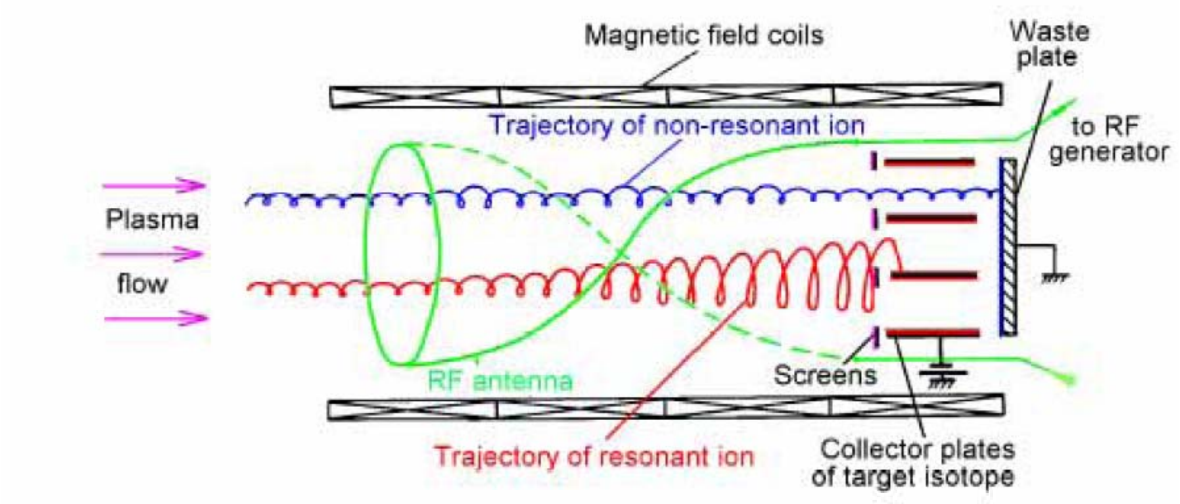
Difficult to produce today a calendar beyond 2015

Cost of the enriched product > 50 M€ for 1 ton

> 100 M€ per experiment

If Europe support at the level of 50 % 3 experiments → 150 – 200 M€

Ion cyclotron resonance

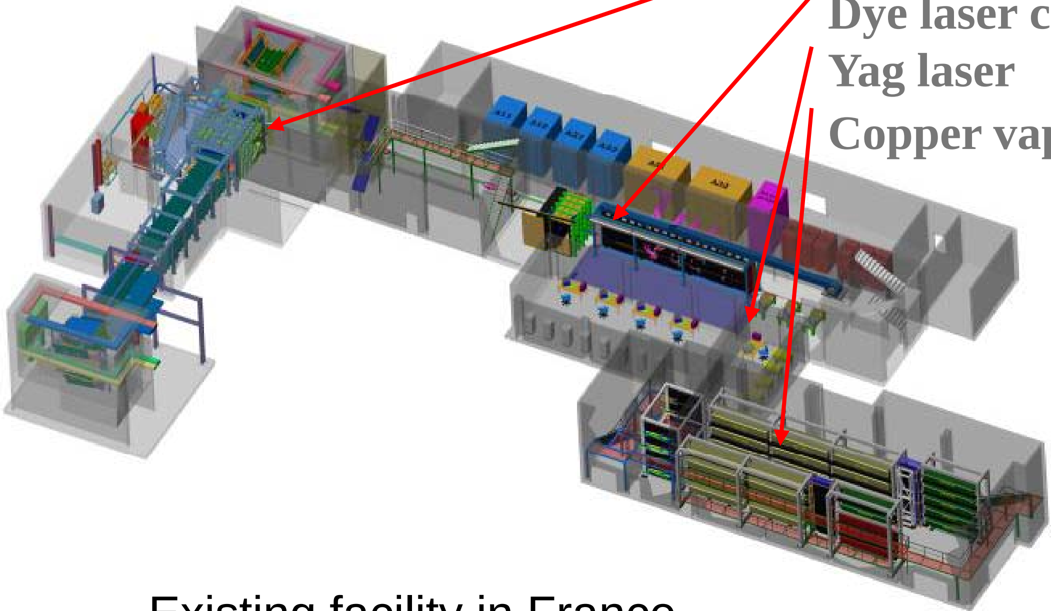


Allow production of ^{48}Ca, ^{76}Ge, ^{82}Se, ^{150}Nd, ^{100}Mo,…

Prototype built by CEA has worked for small quantities (mg)

Extrapolation possible in principle to produce 10 – 100 kg

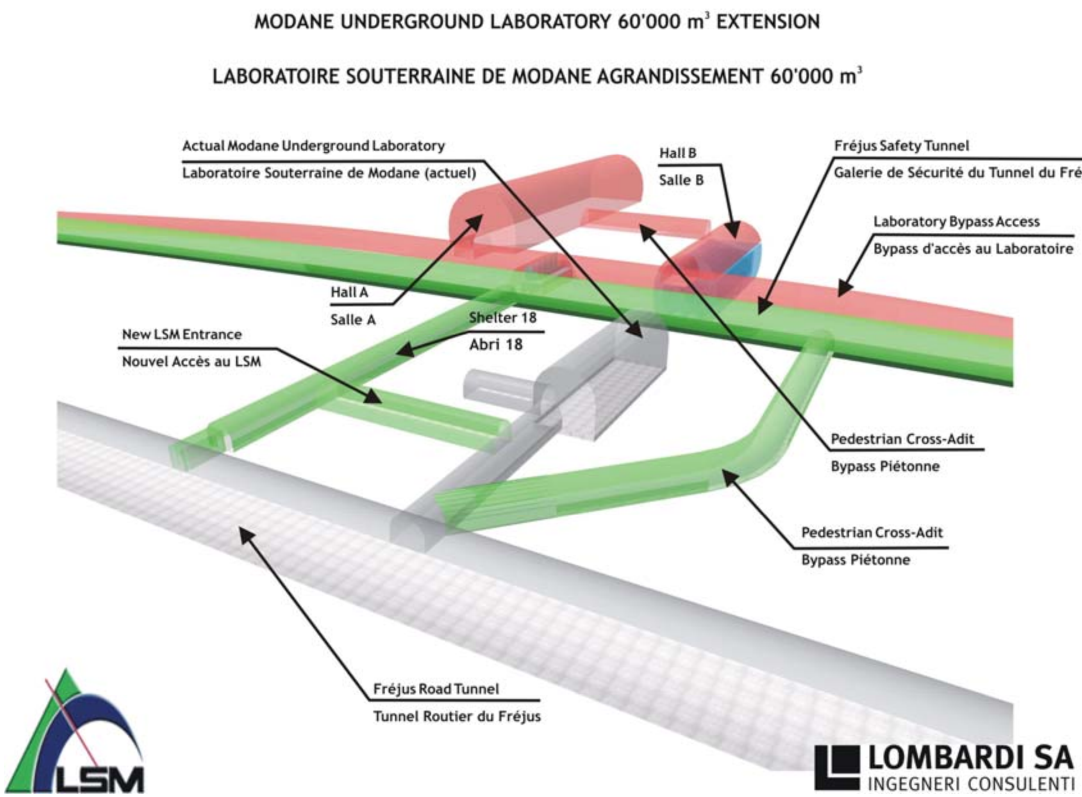
Laser isotopique separation



Existing facility in France

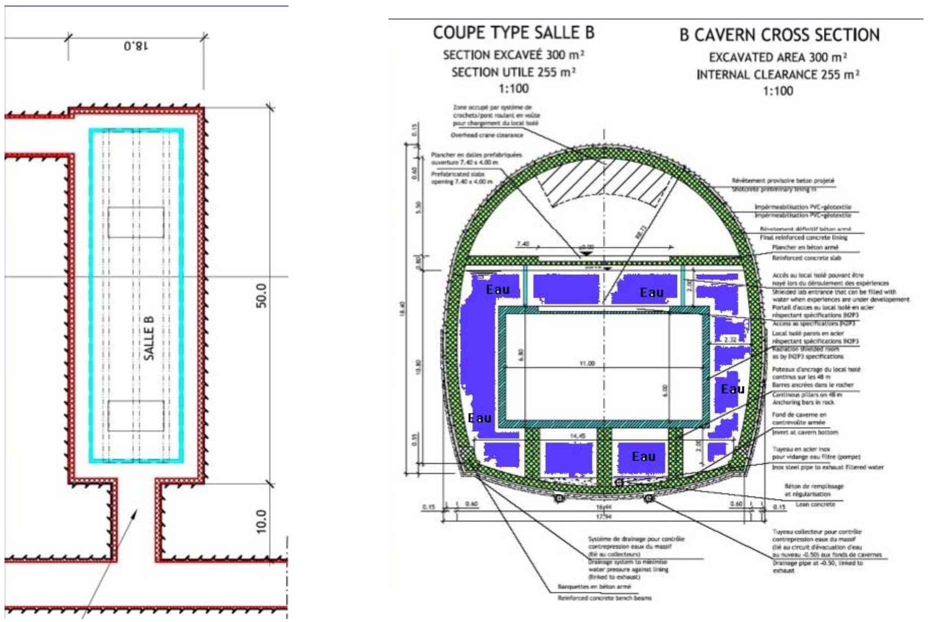
Could produced ^{150}Nd in large quantities

Modane underground laboratory extension

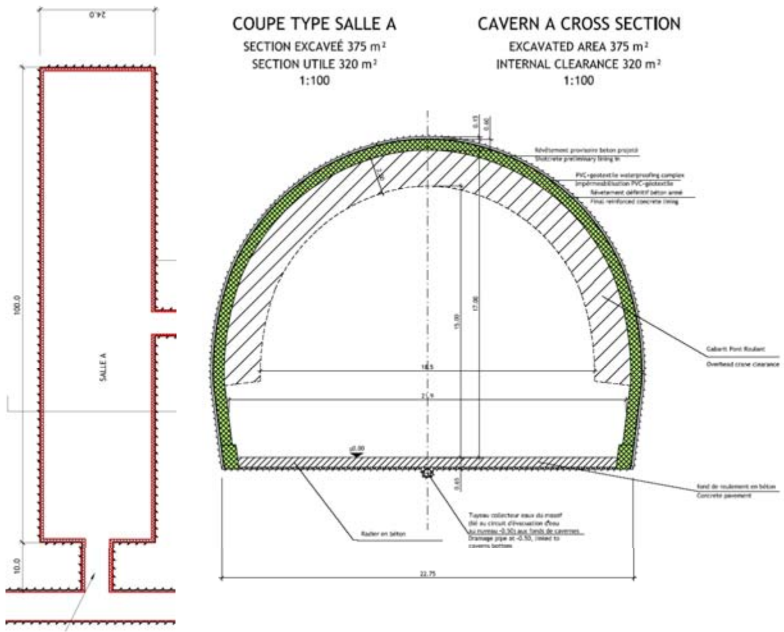


Excavation of safety gallery 2008 - 2011

Modane underground laboratory extension

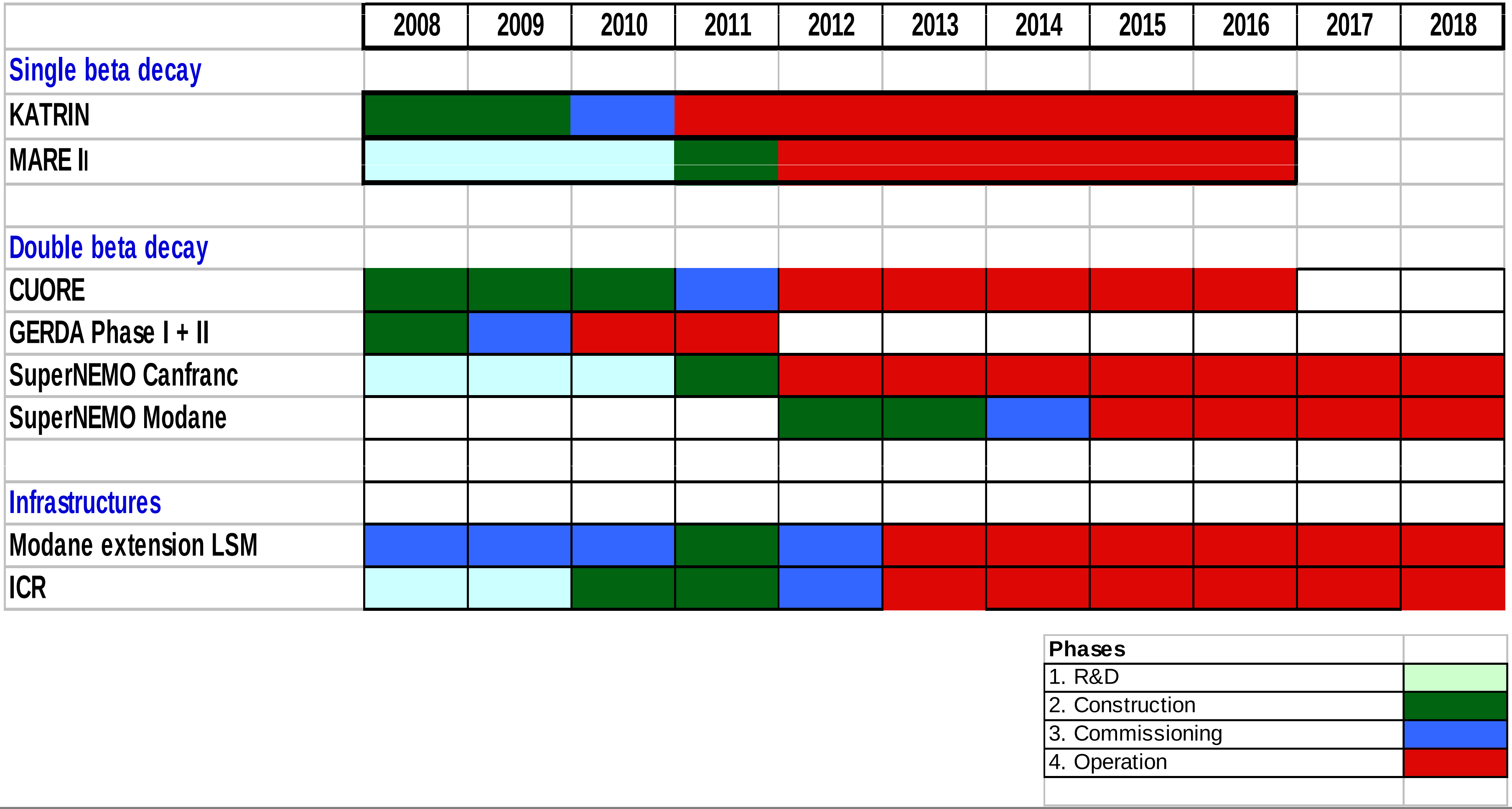


Ultra-low background 20 000 m^3 cavity



Classical 40 000 m^3 cavity

Neutrino mass

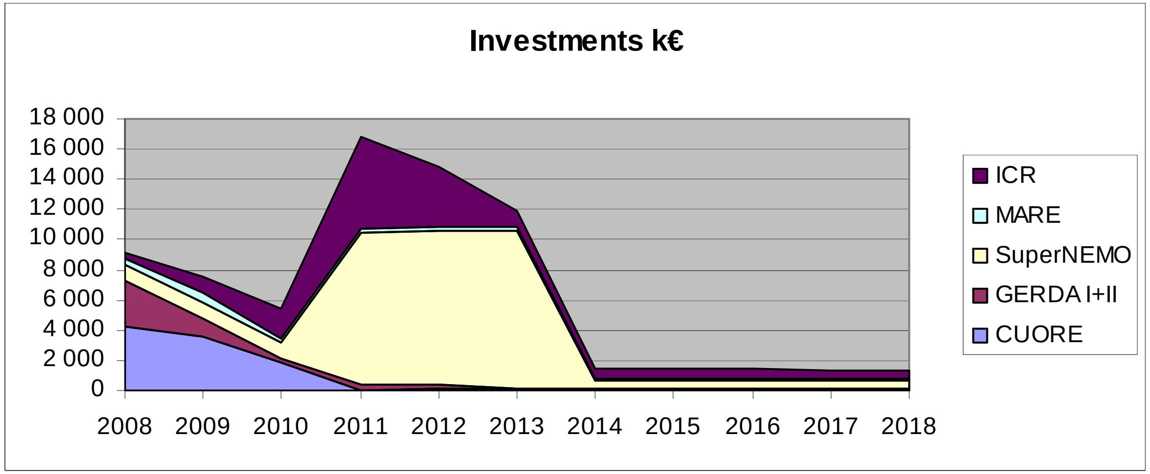


Neutrino mass

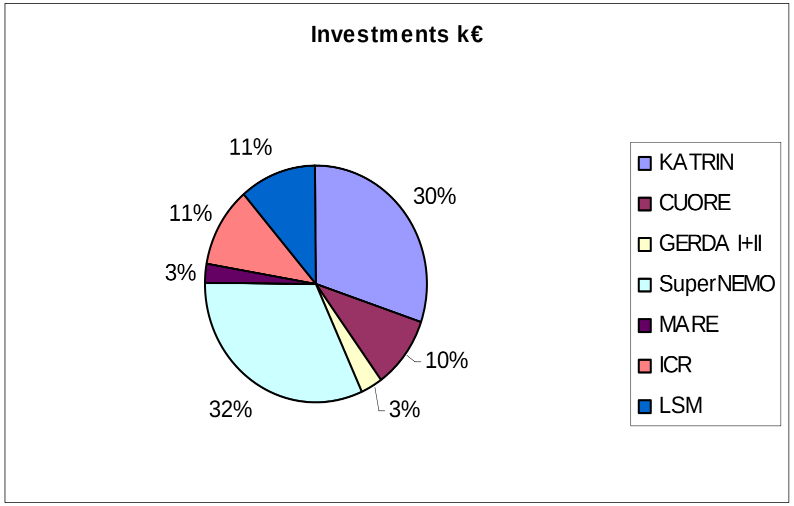
Experiment	k€	main source	milestones
KATRIN:	40.000 -	Astrop.Phys.	operation 2010
MARE I:	5.450	Astrop.Phys.	R&D<2011; construction=2011; operation 2016
CUORE:	13.900	Astrop. Phys	contruction + commissioning<2012; operation 2017
GERDA I+II:	5.250	Astrop. Phys	contruction + commissioning<2009; operation 2009
SuperNEMO:	46.000	Astrop. Phys	R&D <2009 construction <2013 Operation 2011

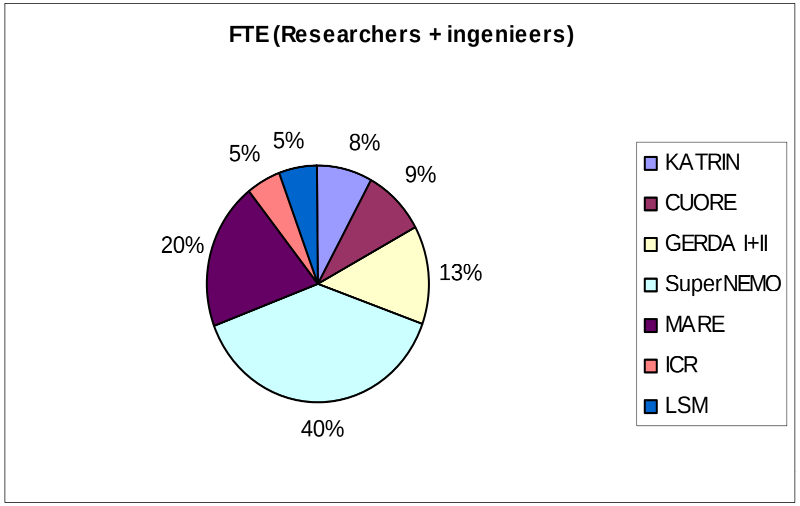
Investment

	total		*Europe*		*presently involved scientists*	
	Investmen	FTE	Investmen	FTE	total	ASPERA
KATRIN	40 000	5 000	35 000	5 000		
MARE	5 450	9 205	2 100	4 920	13	10
CUORE	13900	5240	9 500	3 680	16	12
GERDA I+II	5 250	9 840	5 250	7 980	35	27
SuperNEMO	45820	26775	33 000	21 300	36	30
ICR	17500	3200	14 500	3 200	4	4
	127 920	59 260	99 350	46 080	104	83

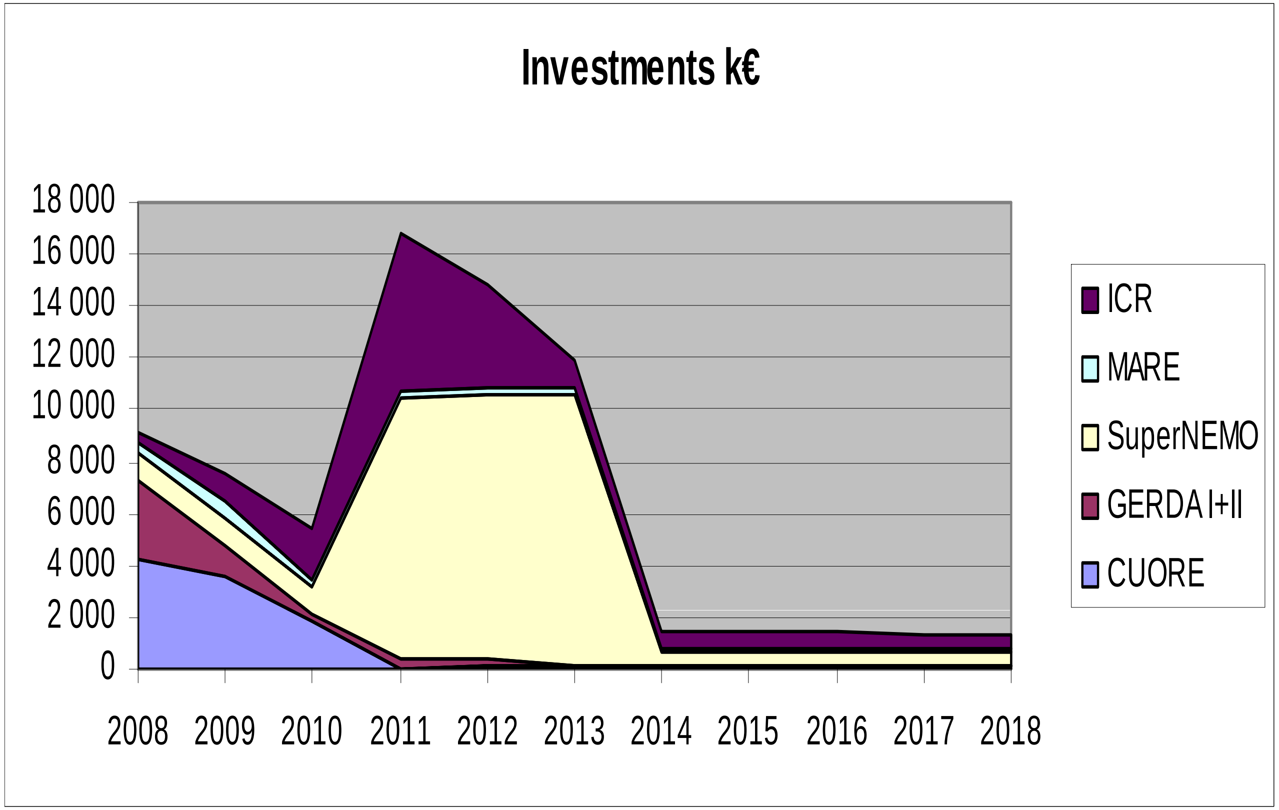


Neutrino mass



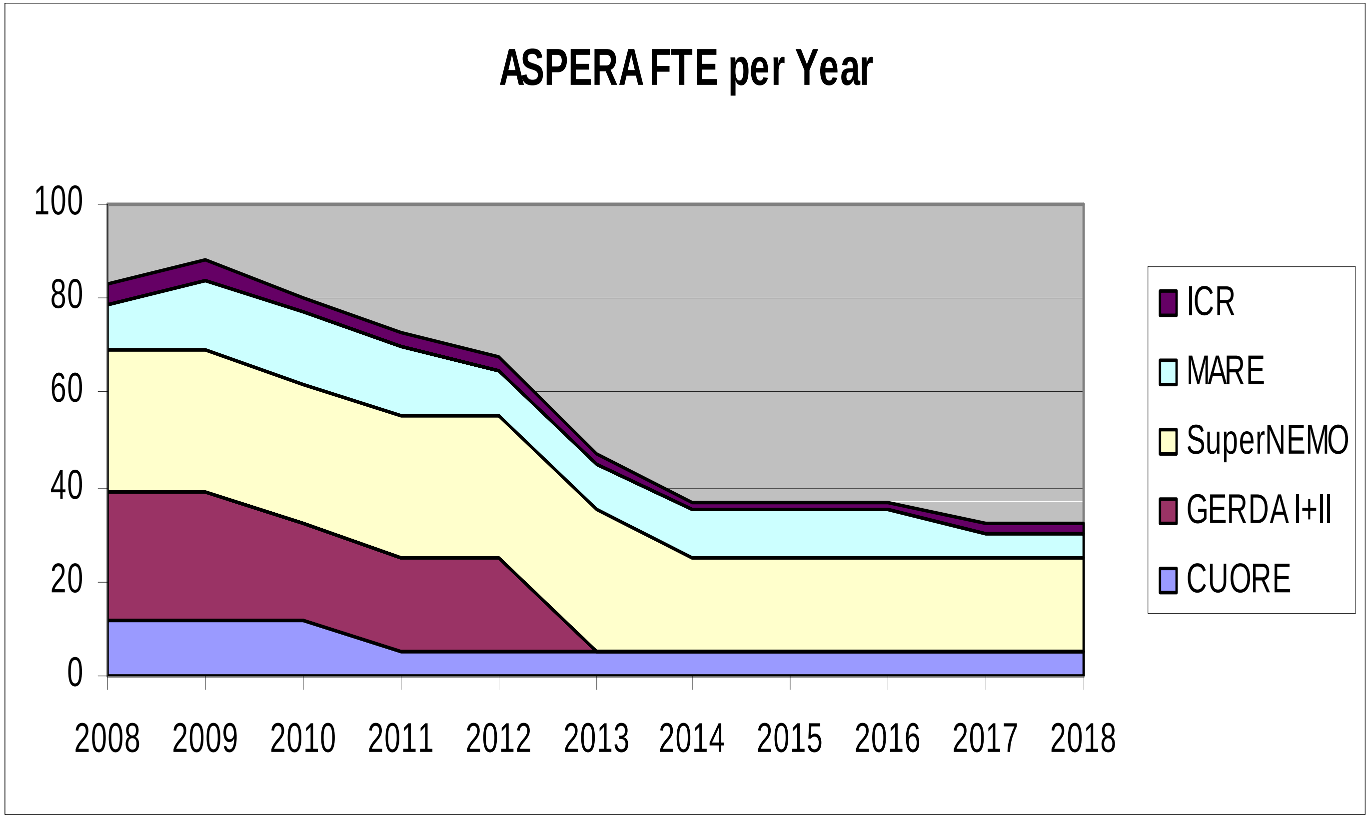


Neutrino mass



Need R&D investments beyond 2015 to improve and develop new techniques

Neutrino mass



Plans for 2008 - 2018

Plans up to 2015 are clear:

Single beta decay KATRIN (funded) and MARE (R&D)

Double beta decay: 2 experiments funded GERDA and CUORE (calorimeters)
1 R&D SuperNEMO (tracko-calo)

Results expected in 2013 - 2015

Need significant effort for R&D beyond this phase

Future plans beyond 2015 will depends on the results of 100 kg phase

Neutrino mass