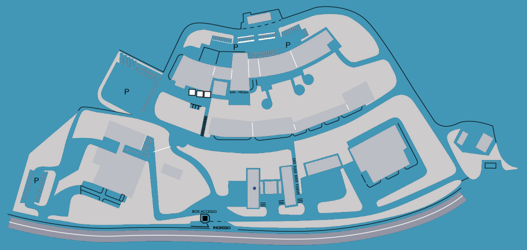
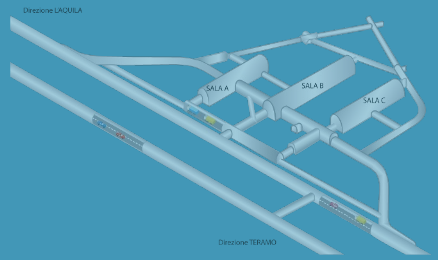
ETTORE MAJORANA FOUNDATION AND CENTRE FOR SCIENTIFIC CULTURE

TO PAY A PERMANENT TRIBUTE TO ARCHIMEDES AND GALILEO GALILEI, FOUNDERS OF MODERN SCIENCE AND TO ENRICO FERMI, THE "ITALIAN NAVIGATOR", FATHER OF THE WEAK FORCES

INFN LNGS



Highlights from Gran Sasso



Erice, 17 Giugno 2024

Prof. Antonio Zoccoli

Istituto Nazionale di Fisica Nucleare

Università degli Studi di Bologna

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External Buildings

Undergound Site

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Why can't we see the stars by day?

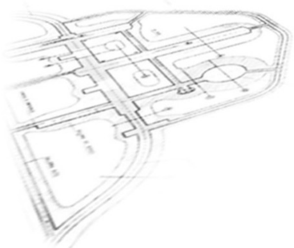
If we want to see a very small signal (e.g. starlight) we need to get rid of the strongest light sources (the sun)

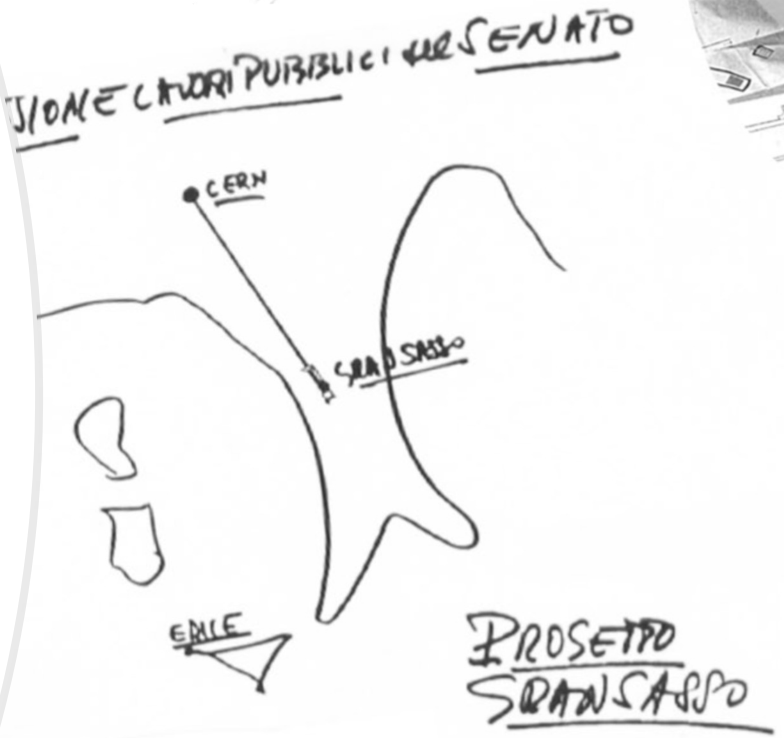
Why underground?

Underground laboratories are shielded by layers of rock and offer the unique possibility of studying rare physics phenomena in an environment which is almost free from cosmic ray background

A brief history of Gran Sasso National Laboratory

- 1979: **submission** of the proposal to **Italian Parliament** (by **A. Zichichi**)
- 1982: **approval** of the proposal
- 1987: the underground Laboratory is **completed**
- 1989: the **first experimental apparatus**, MACRO, begins the data taking





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Features of the underground laboratory

- 1400 m of rock overhead
- Cosmic ray flux reduction: 1.000.000
- The largest in the world actually running

Underground Surface: 17800 m^2
Underground Volume: 180000 m^3

International Community of Gran Sasso National Laboratory

Since the beginning of 2023
Registered LNGS users

Total:	538 (981*)
Italian:	282 (417*)
Foreign:	256 (564*)

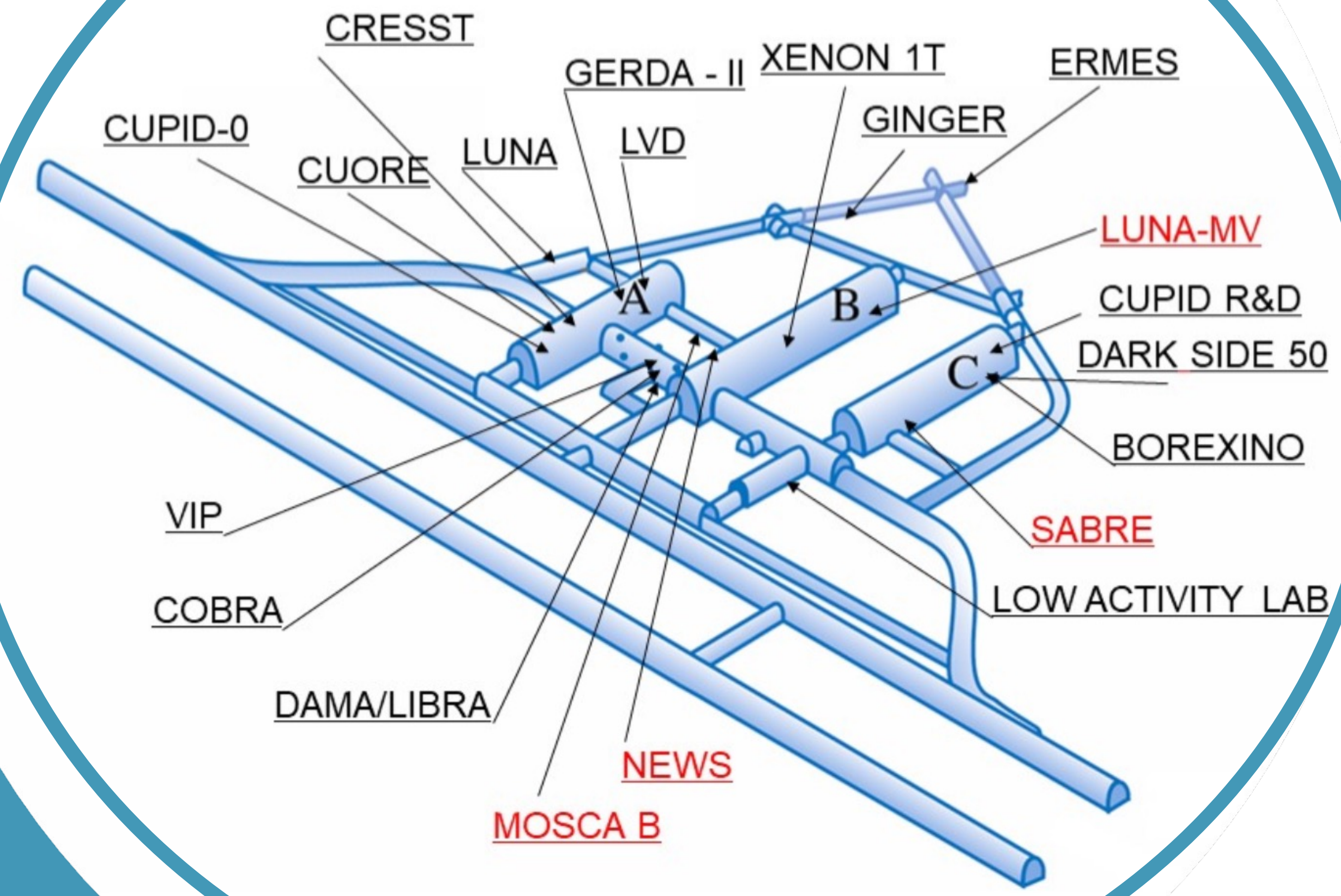
*** 2019, before pandemic period**

3 main experimental halls 100 m long, 20 m width and 18 m hight

Many small tunnels for lab facilities and small experiments

Actually there are 22 experiments in data taking or under construction

The most sensitive laboratory for very low radioactivity measurements



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LNGS experiments

Fundamental physics

- **Neutrino astrophysics**
  - Solar neutrinos
  - Geo-neutrinos
  - Supernova neutrinos
- **Nuclear astrophysics**
  - Astrophysical nuclear processes
- **Neutrino properties**
  - Neutrinoless Double Beta Decay
  - Search for relic neutrinos
- **Dark Matter**
  - Direct interaction of WIMPs with Nuclei

…… but also

- **Test on quantum mechanics**
  - Quantum Coherence
  - Electron decay
- **Radiobiology**
  - Biological effects of low radioactive environment
- **Geophysics**
  - Earthquacke monitoring and study
  - Analysis of water resources
- **Ultra Trace elemental analysis**
  - Low radioactivity tests and measurements
  - Cultural Heritage analysis
  - Advanced additive manufacturing

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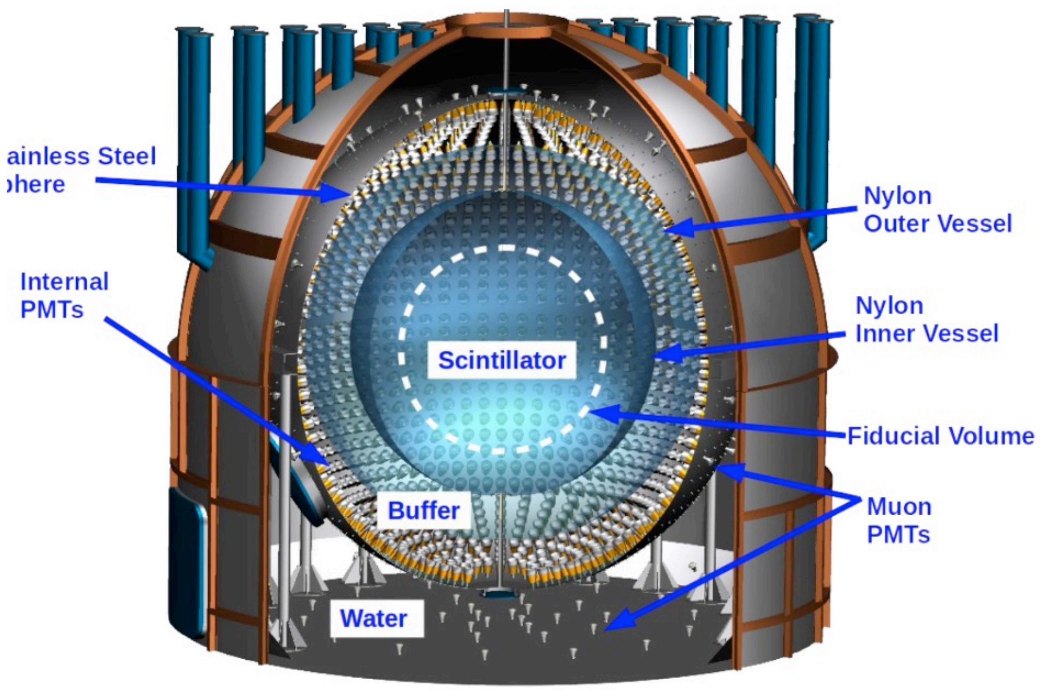
KEY words

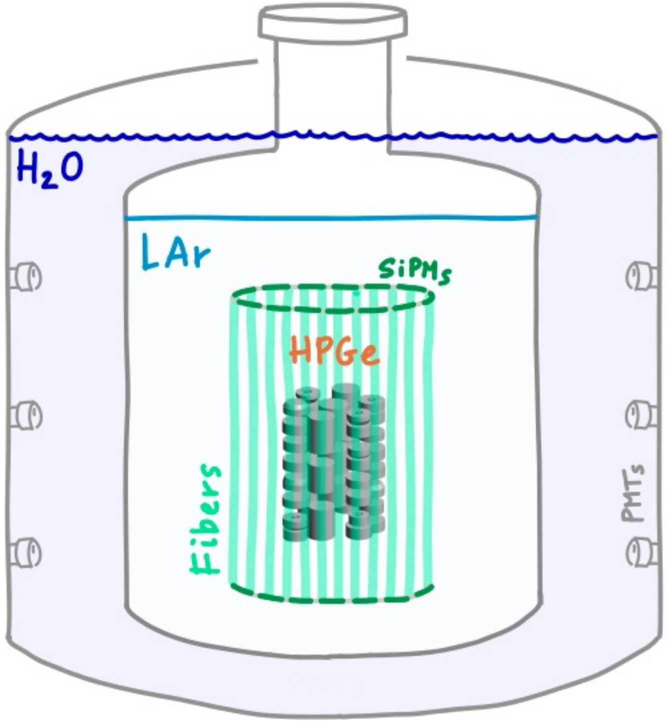
- Rare events
- Low Background
- Radiopurity
- Screening

Background & Screening

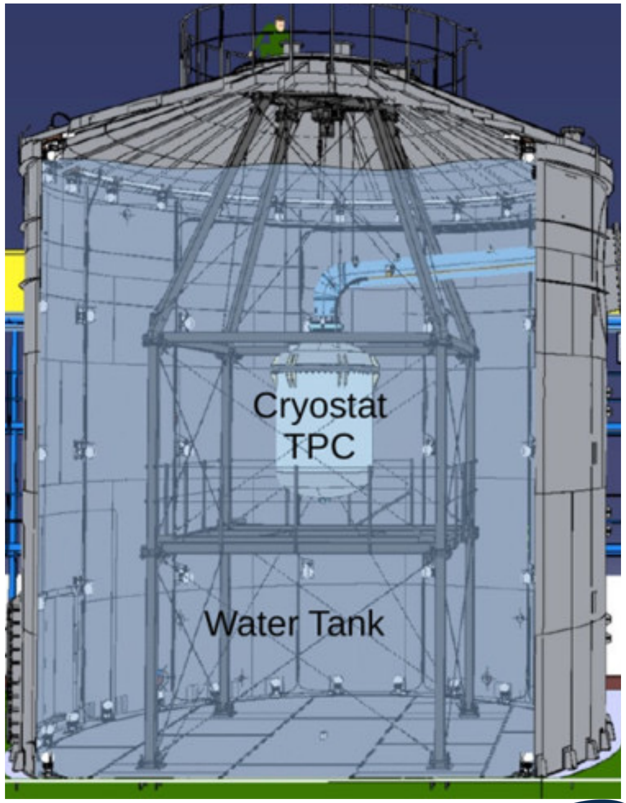
Solar Neutrinos



Double beta decay

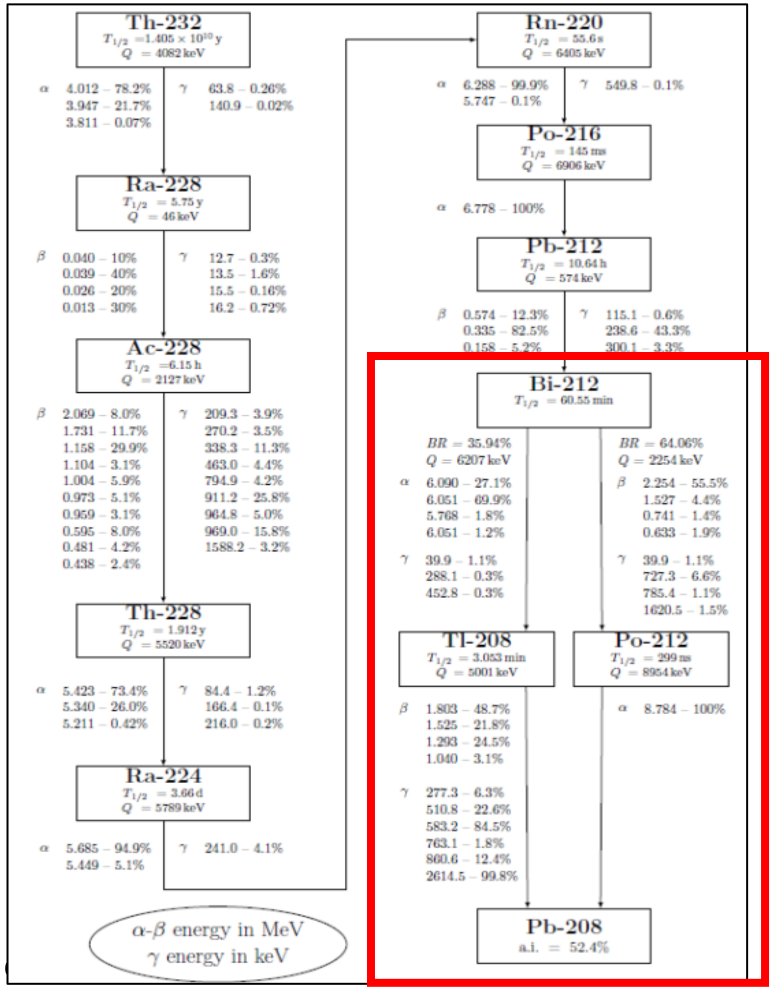


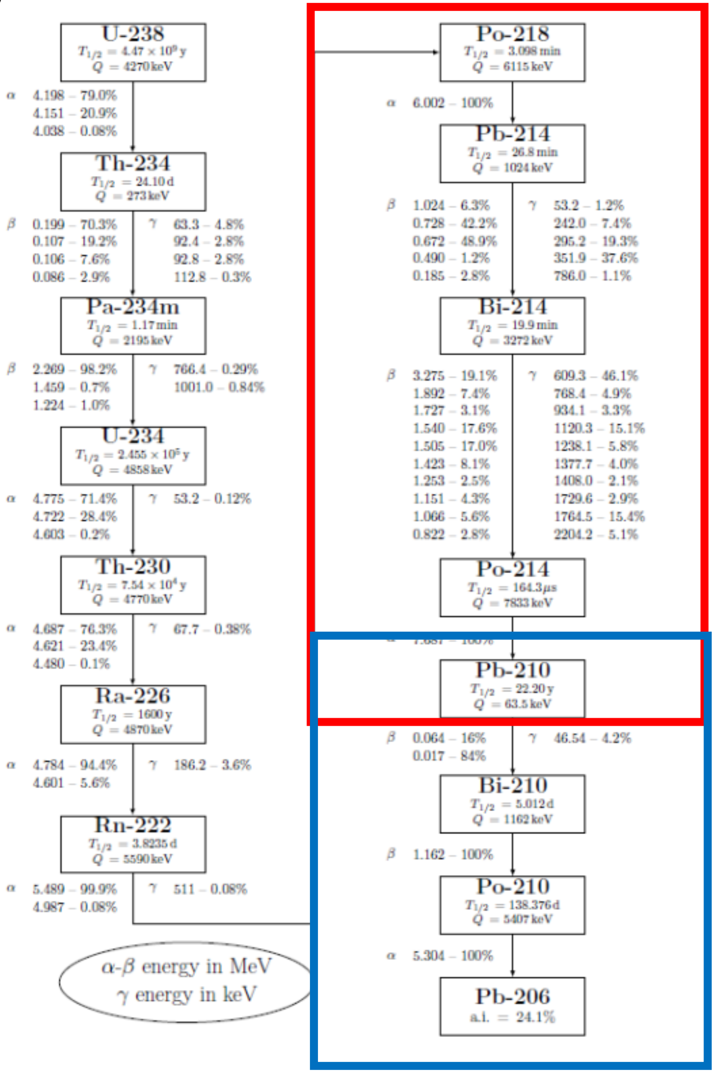
Dark Matter



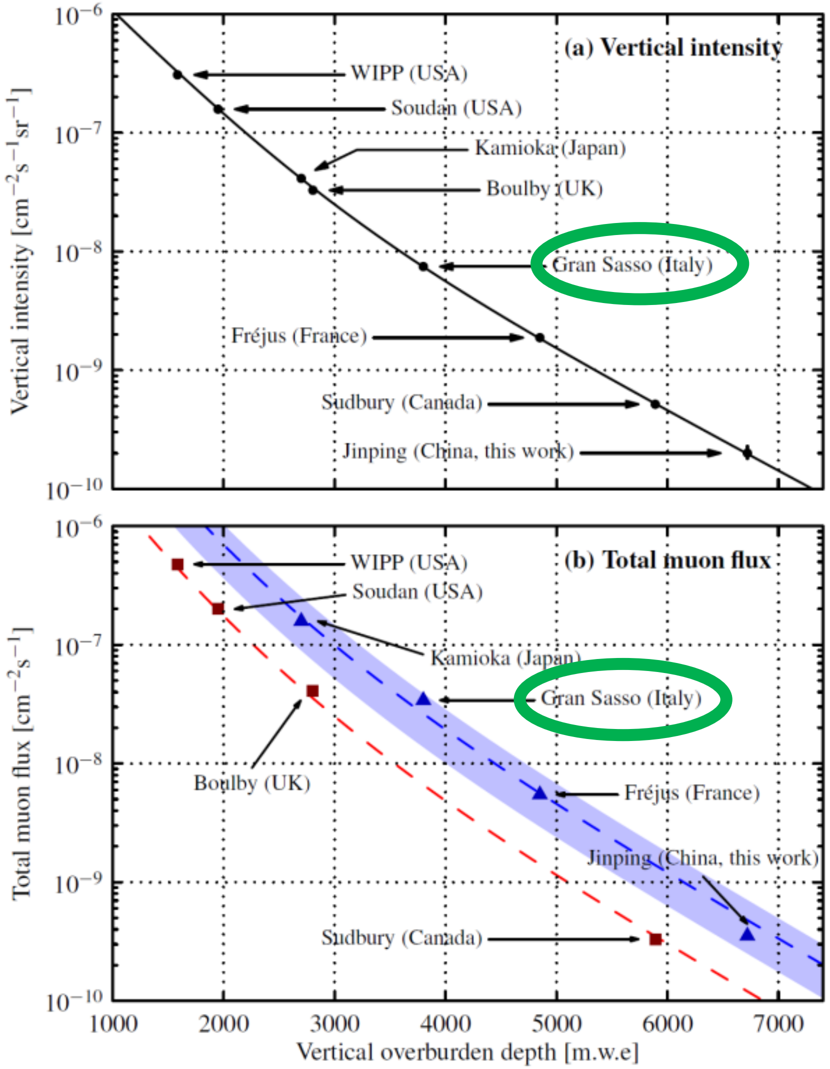
Background & Screening

Reduce Radioactivity

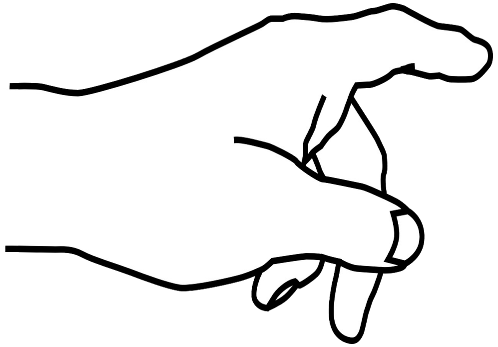




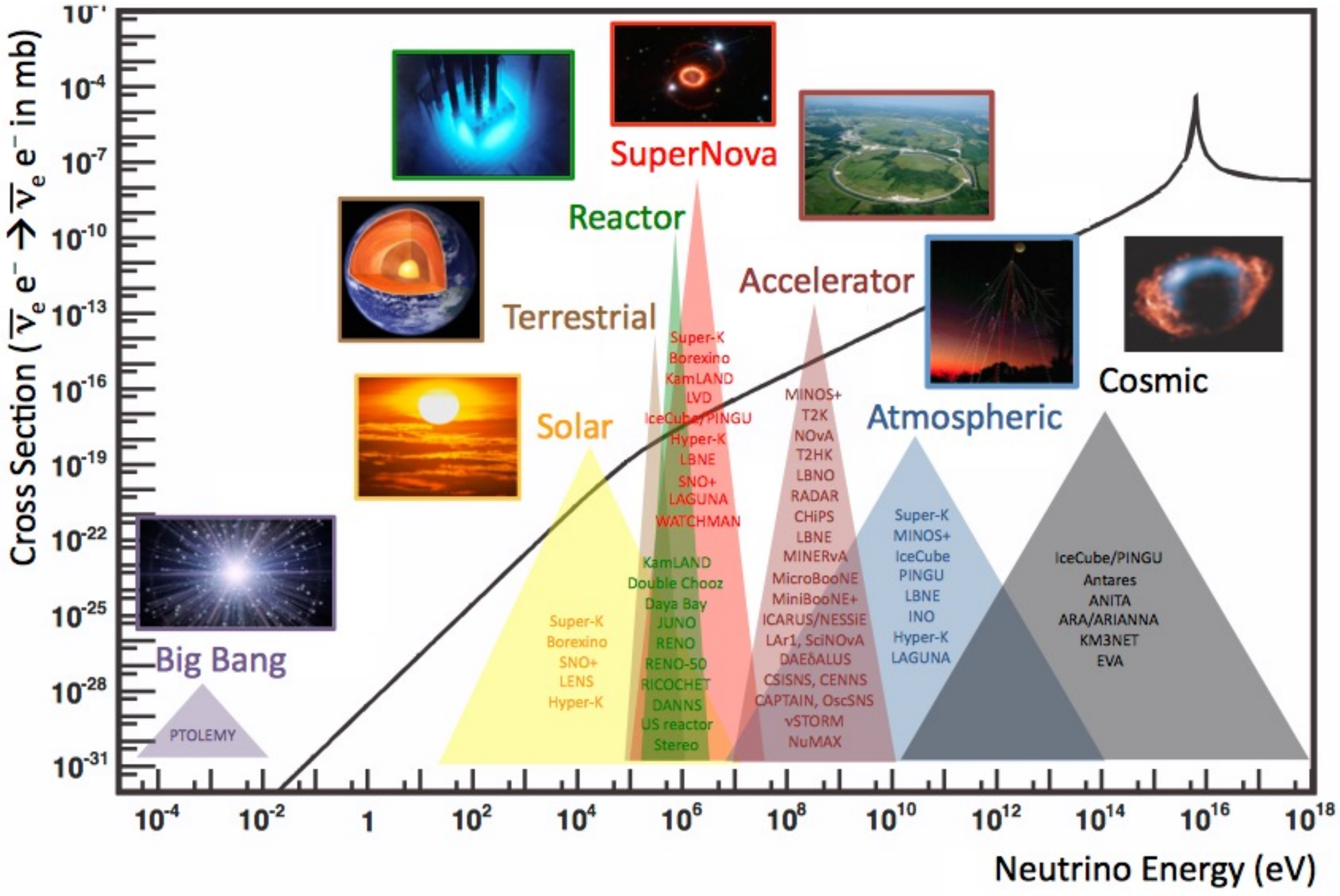
Reduce Cosmic rays



Neutrino AstroPhysics



Every second our fingers are crossed by around **60 Billions** of neutrinos
Produced by many different sources



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Neutrino Astrophysics Experiments

- **LVD**

  SN neutrinos

- **OPERA**

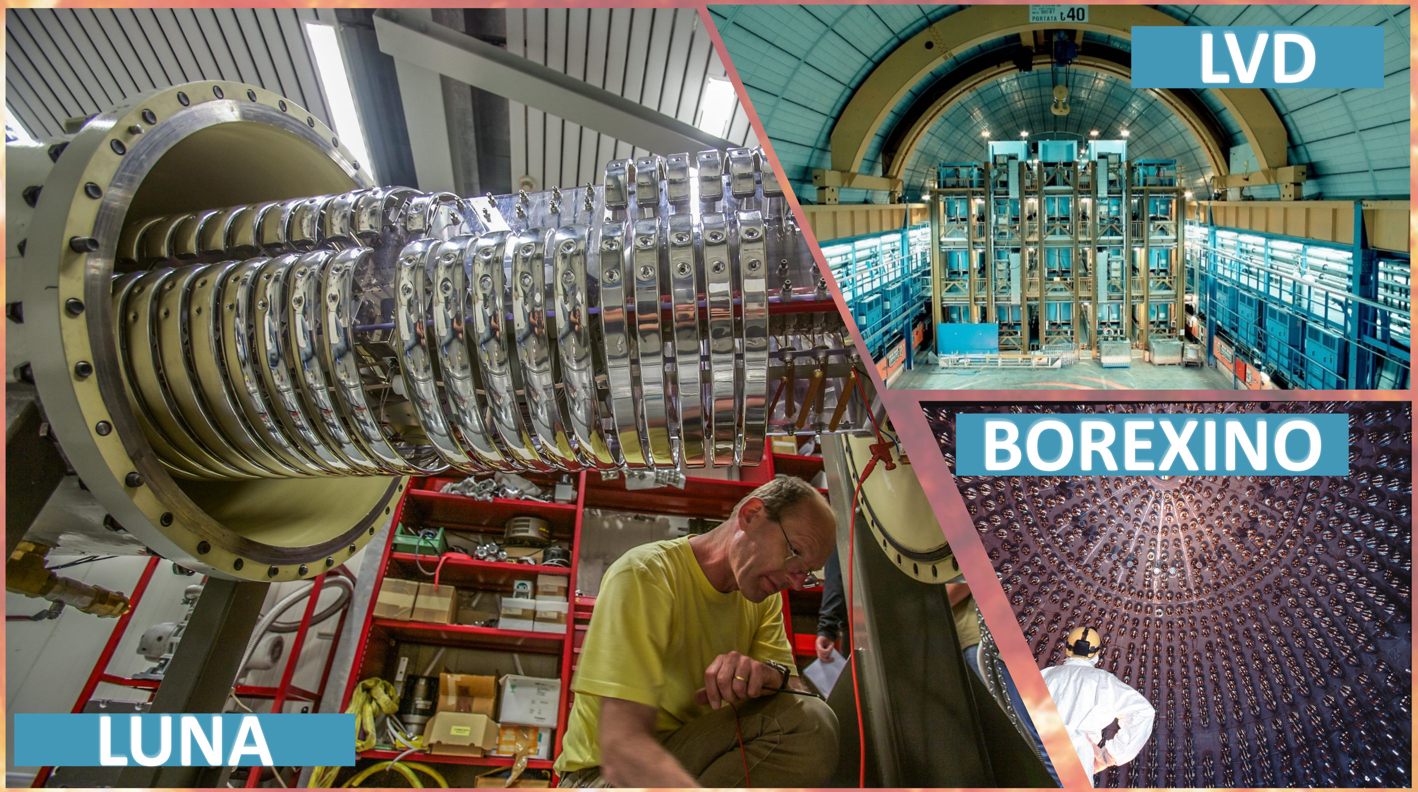
  neutrino oscillation

- **BOREXINO**

  solar neutrinos
  geo-neutrinos
  SN neutrinos

- **LUNA**

  Nuclear Astophysics



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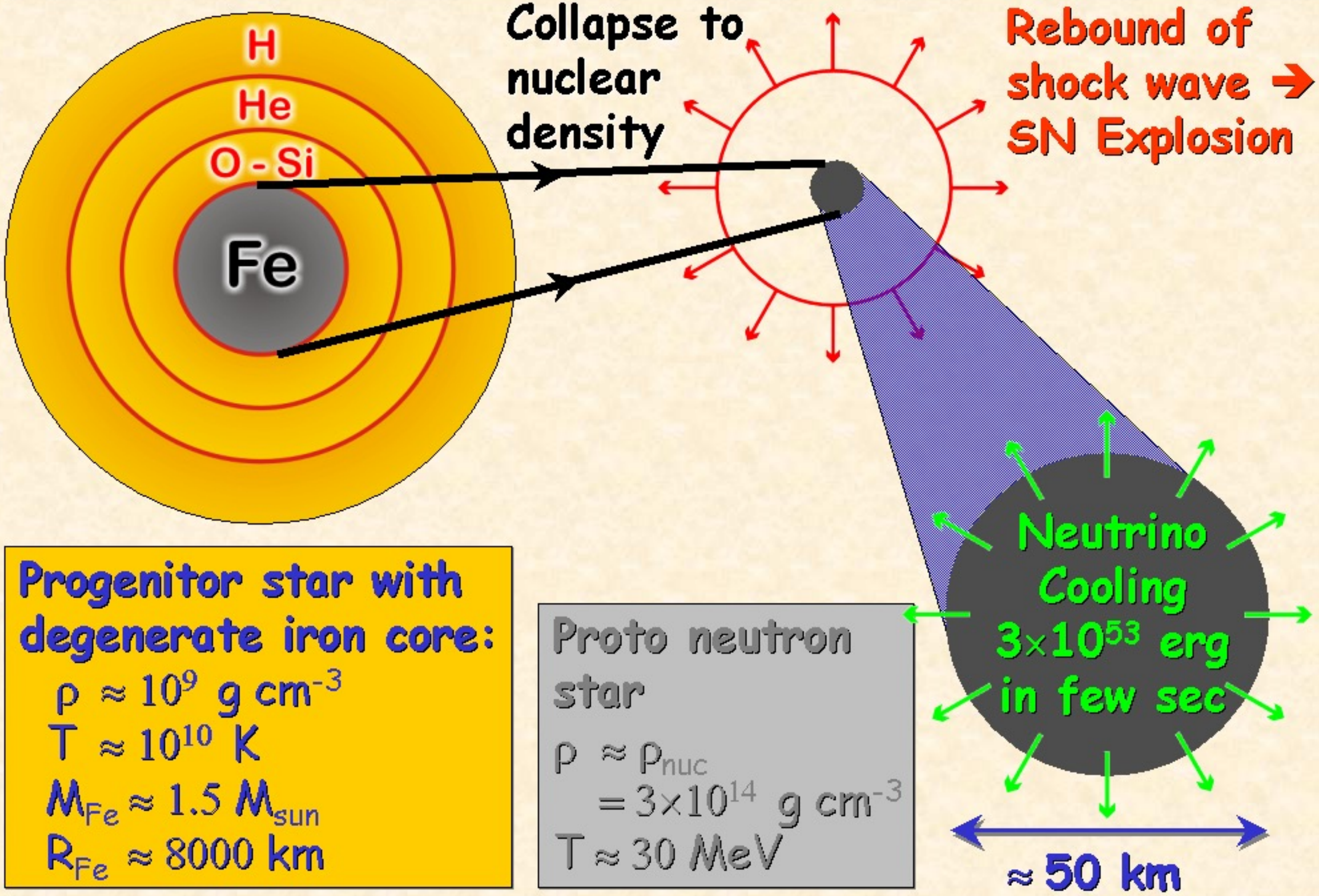
Stellar Collapse and Supernova Explosion



Progenitor star with degenerate iron core:

$\rho \approx 10^9$ g cm^{-3}

$T \approx 10^{10}$ K

$M_{Fe} \approx 1.5\ M_{sun}$

$R_{Fe} \approx 8000$ km

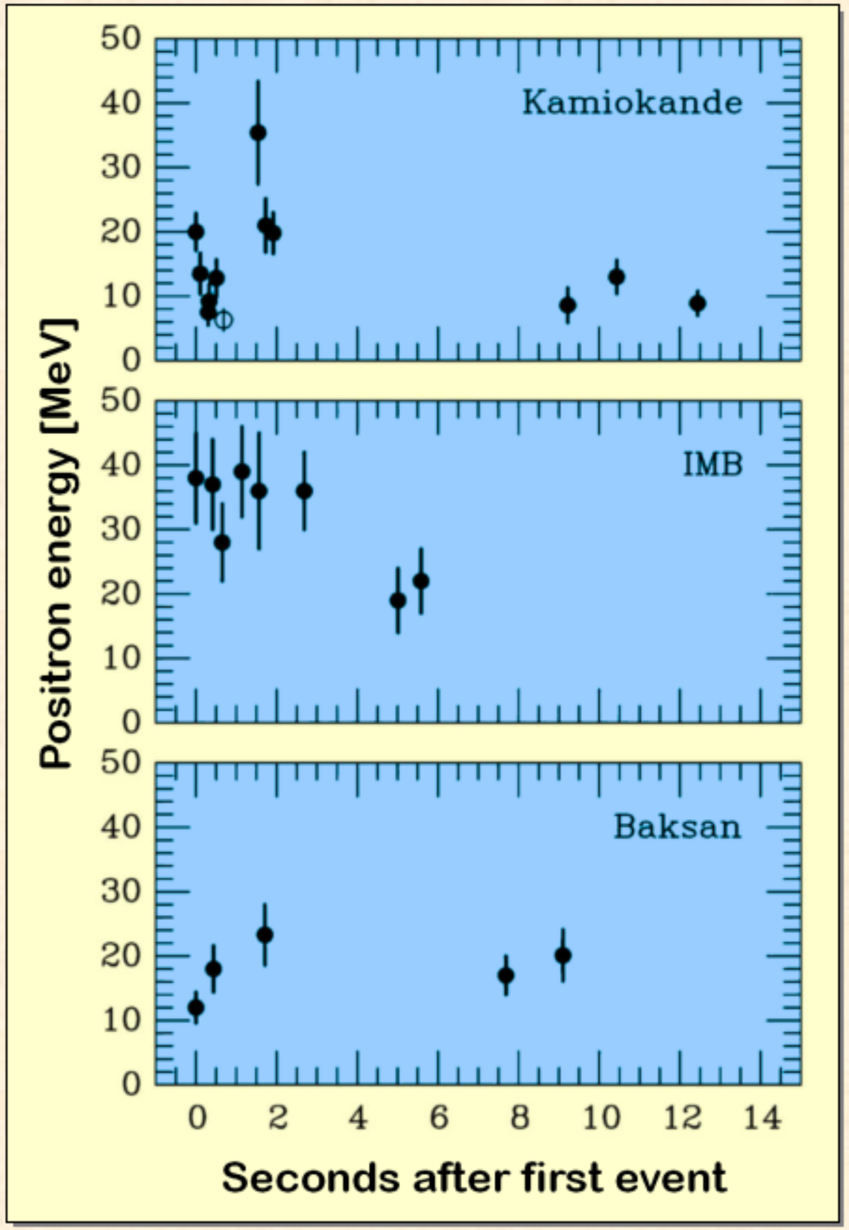
Proto neutron star

$\rho \approx \rho_{nuc} = 3\times10^{14}$ g cm^{-3}

$T \approx 30$ MeV

Georg Raffelt, Max-Planck-Institut für Physik (München)

Neutrino Signal of Supernova 1987A



Kamiokande (Japan)
Water Cherenkov detector
Clock uncertainty ±1 min

Irvine-Michigan-Brookhaven (USA)
Water Cherenkov detector
Clock uncertainty ±50 ms

Baksan Scintillator Telescope (Soviet Union)
Clock uncertainty +2/-54 s

Within clock uncertainties, signals are contemporaneous

Georg Raffelt, Max-Planck-Institut für Physik (München)

The beginning: Supernovae neutrinos

LVD

The most powerful scintillator telescope

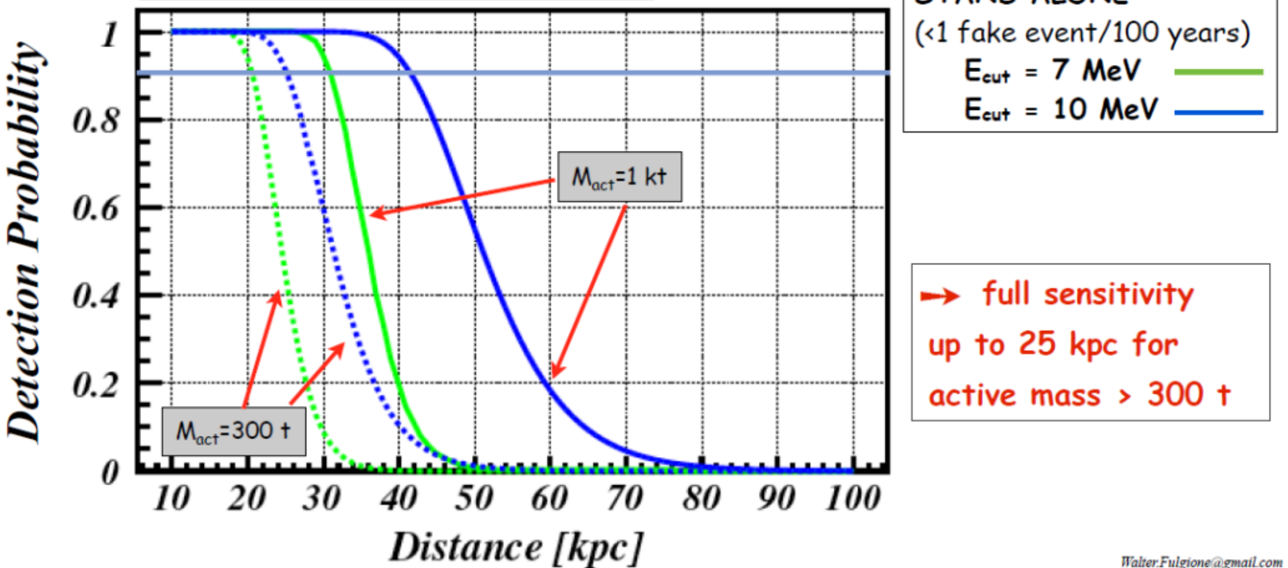
Main features:

Liquid Scintillator: C_nH_{2n+2} <n>=9.6 + 1g/l PPO + 0.03g/l POPOP, ρ=0.8 g/cm^3 **total 1 kt**

840 stainless steel, 1.5 m^3, counters **total 0.85 kt**

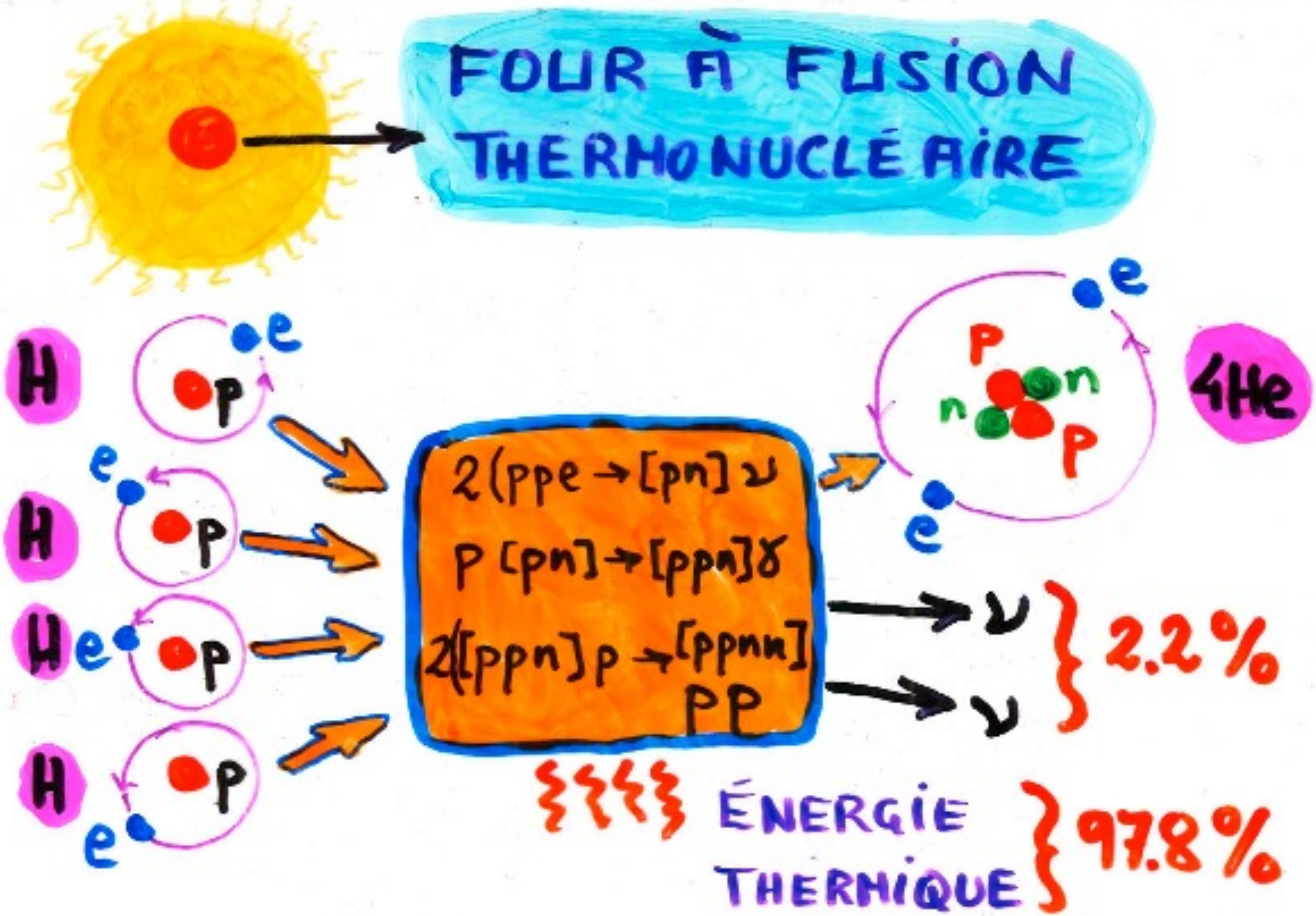
(FEU49b or FEU125) 15 cm diameter **2520 PMTs**

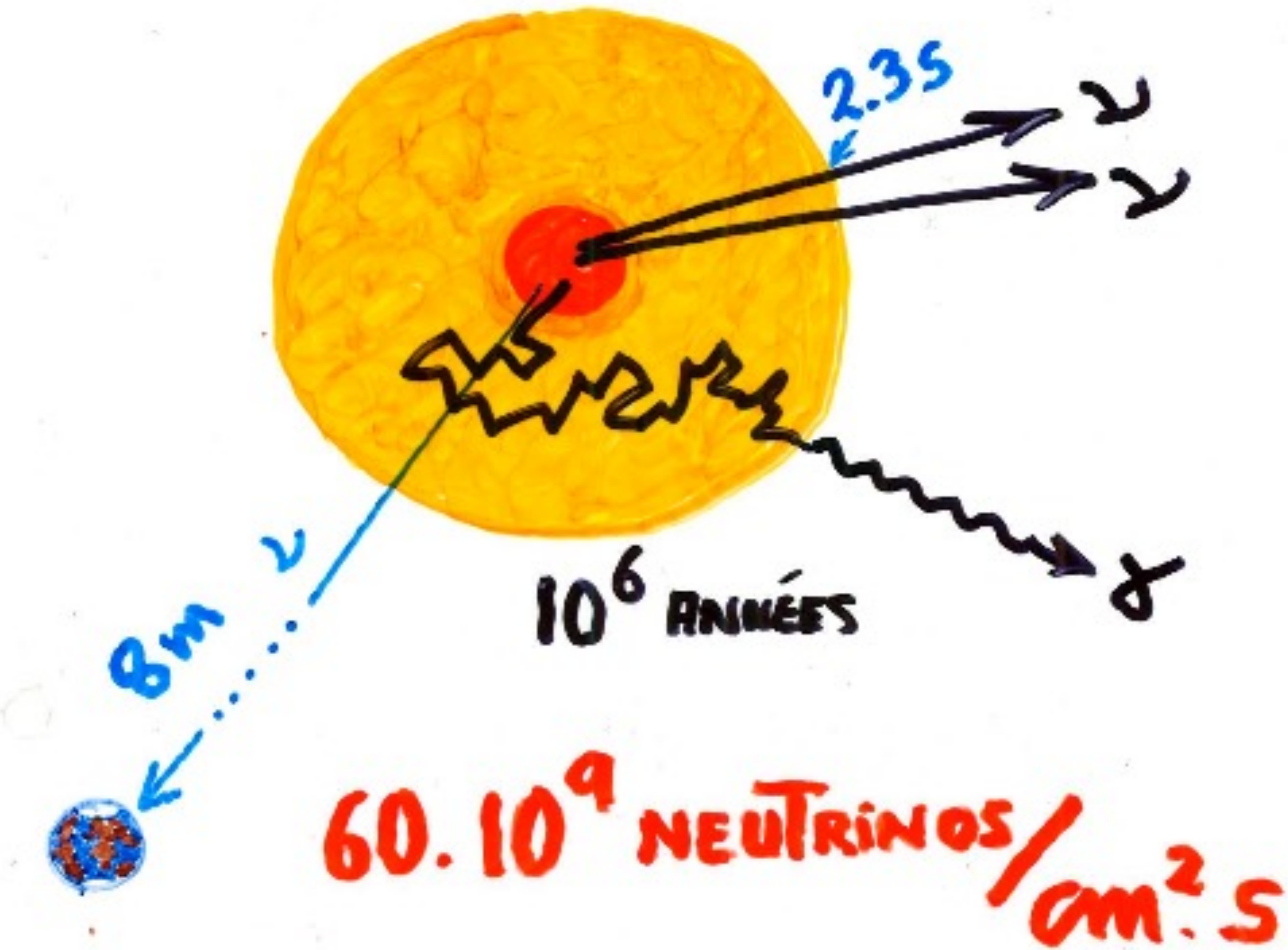
LVD Collaboration, "On-line recognition of supernova neutrino bursts in the LVD detector", Astropart. Phys. 28, 516-522 (2008) [arXiv:0710.0259].



→ full sensitivity up to 25 kpc for active mass > 300 t

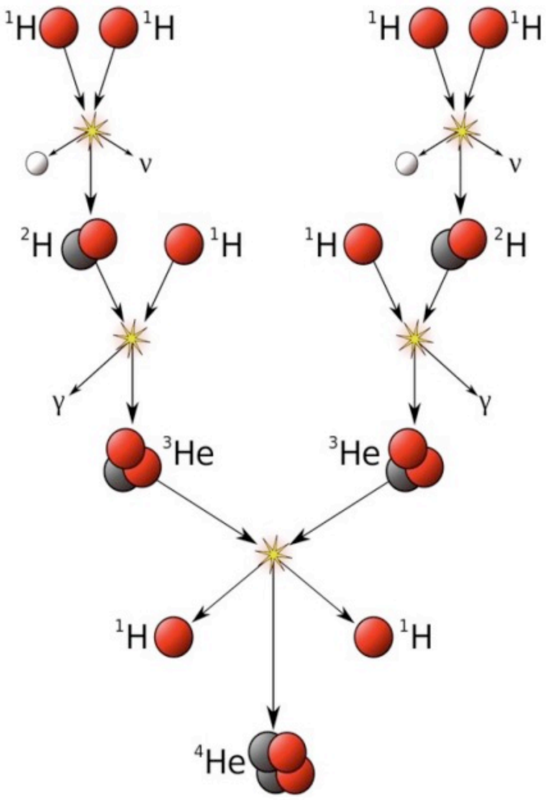
Walter.Fulgione@gmail.com


FOUR À FUSION
THERMONUCLÉAIRE
H
H
H
H
e
e
e
e
p
p
p
p
2(ppe → [pn] ν
p [pn] → [ppn] γ
2([ppn] p → [ppnn]
pp
p
n
n
p
e
e
4He
ν
ν
2.2%
ÉNERGIE
THERMIQUE
97.8%

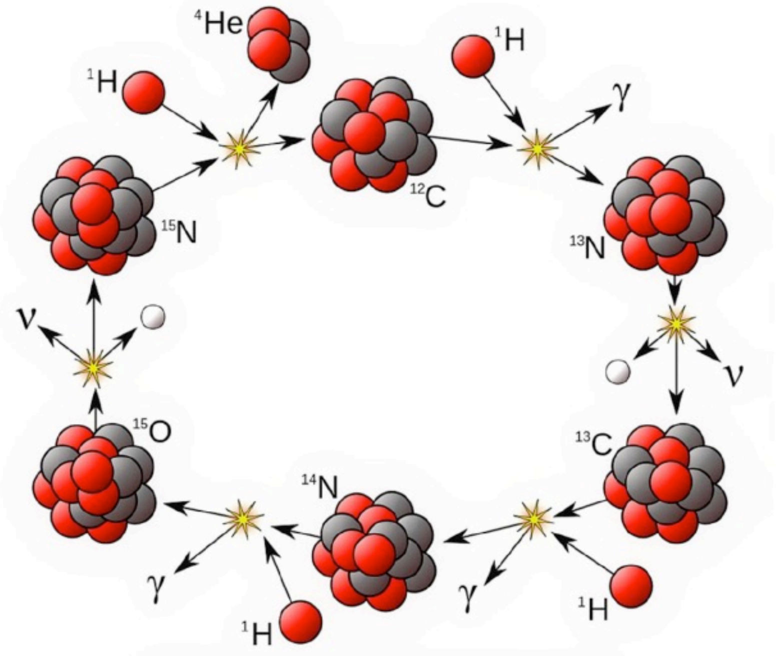

2.3s
ν
ν
γ
10^6 ANNÉES
8m ν
60.10^9 NEUTRINOS/$cm^2.s$

Borexino detector

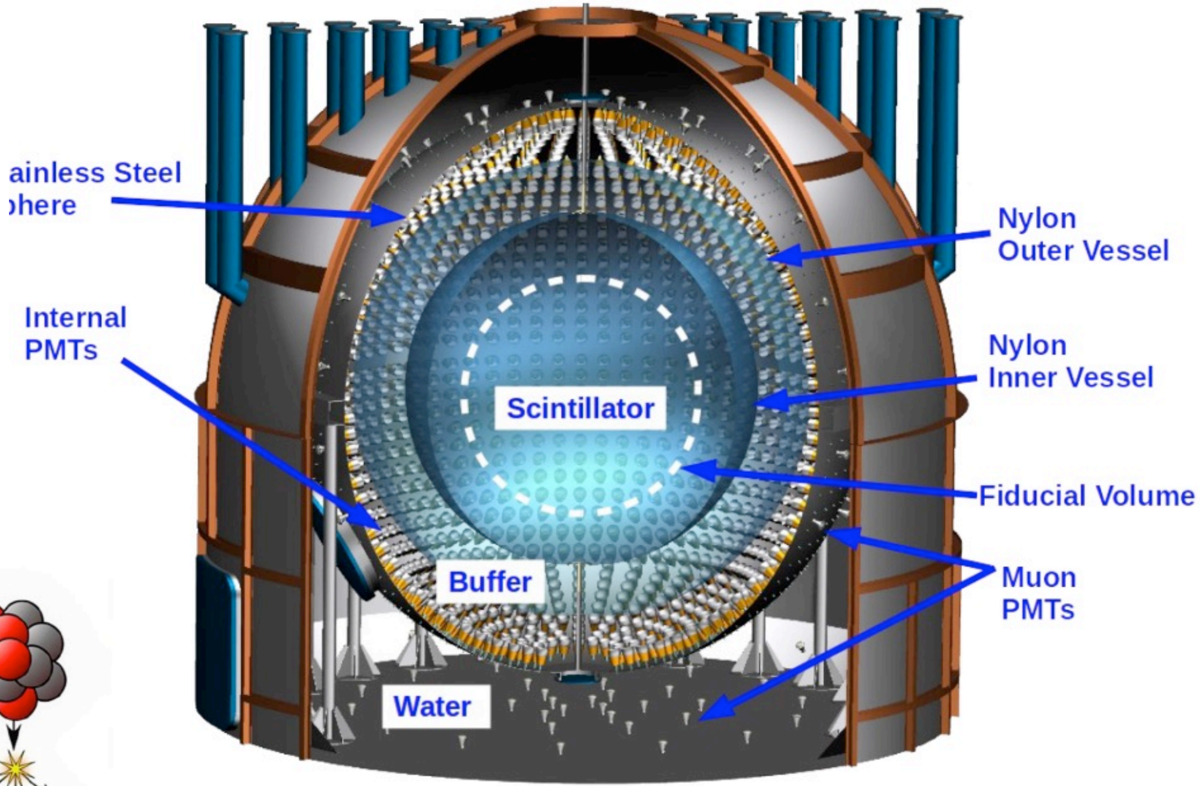
Nuclear Fusion Processes in the Sun

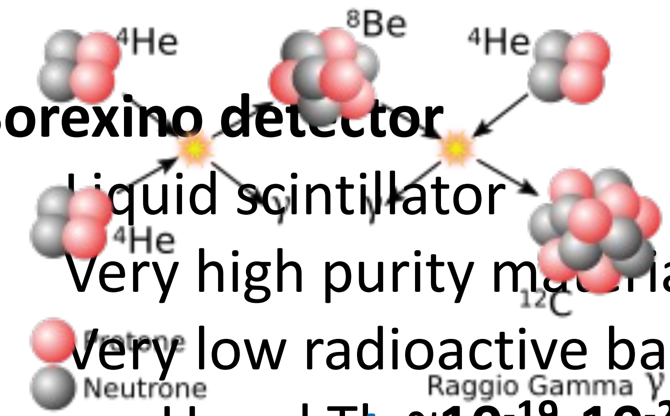


pp chain (99%)



CNO cycle (1%)





Borexino detector

- Liquid scintillator
- Very high purity materials
- Very low radioactive background
  - U and Th **~10^{-19}-10^{-20} g/g**

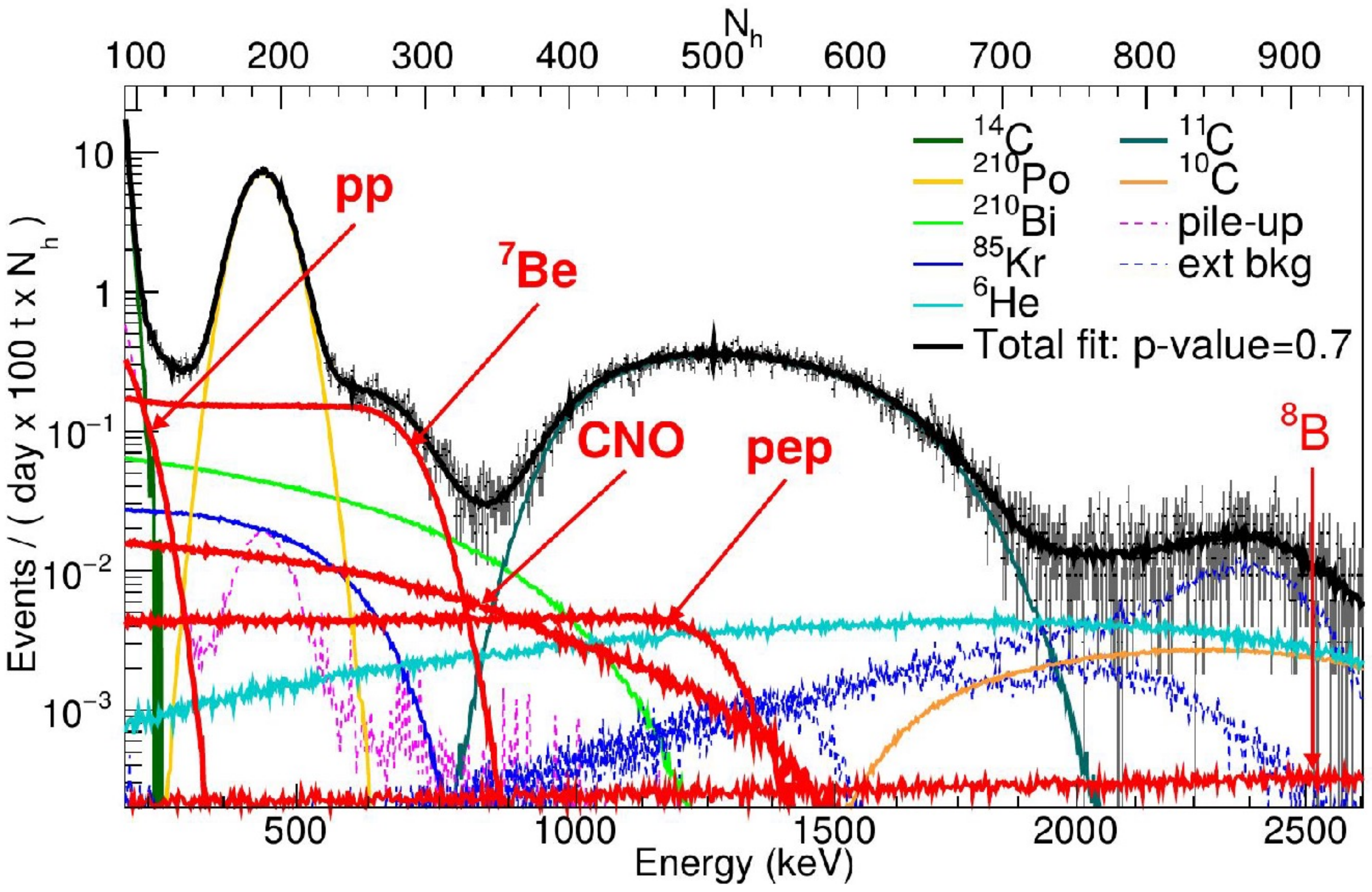
Hoyle Resonance

Borexino results

Solar fusion processes

Neutrino emissions of all the solar fusion processes.

Awarded with the EPS-HEP Cocconi price, 2021



physicsworld
TOP 10
BREAKTHROUGH
2020

EPS
Cocconi
Prize 2021

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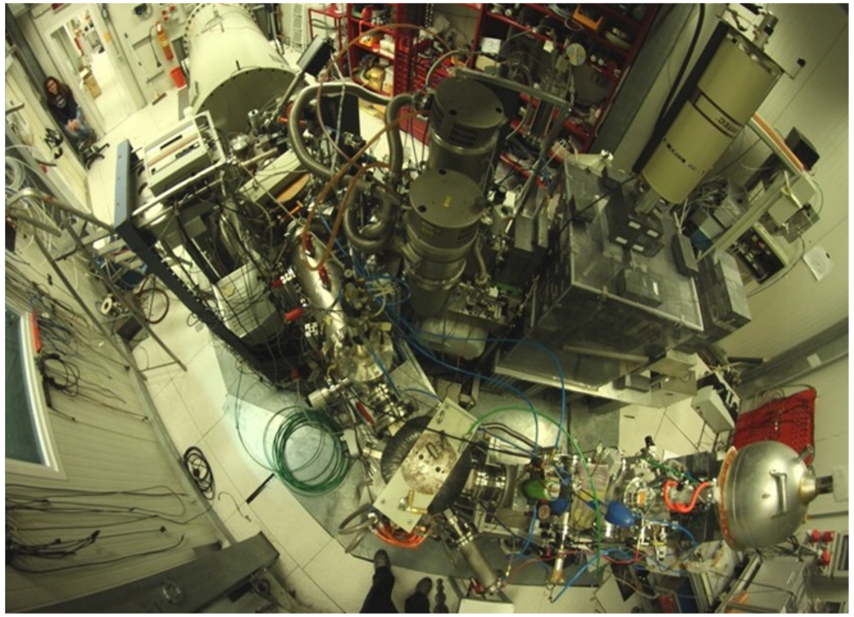
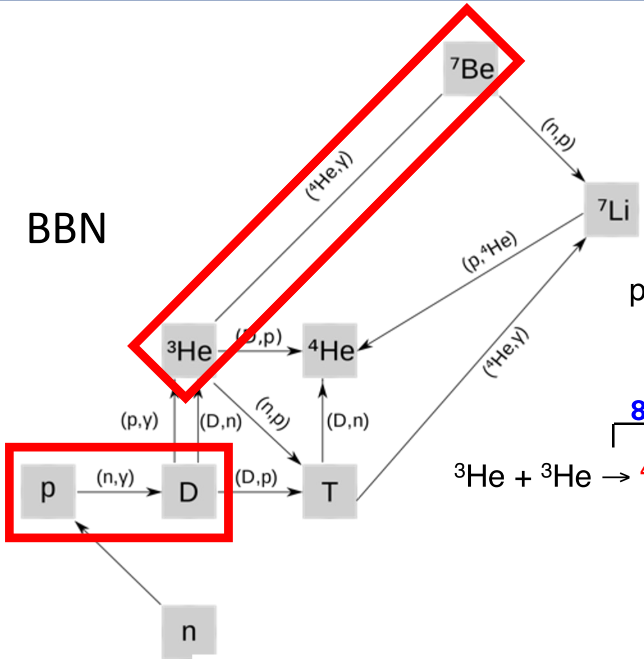
Nuclear Astrophysics - LUNA400





pp chain

$p + p \rightarrow {}^2H + e^+ + \nu$ 99.75%

$p + e^- + p \rightarrow {}^2H + e^+ + \nu$ 0.25%

${}^2H + p \rightarrow {}^3He + \gamma$

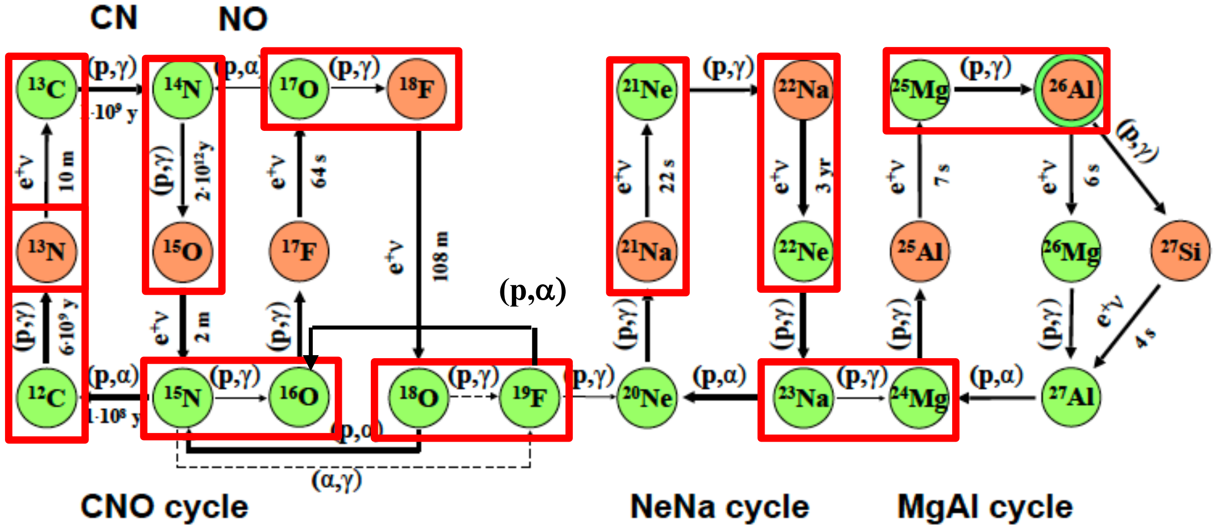
86%: ${}^3He + {}^3He \rightarrow {}^4He + 2p$

14%: ${}^3He + {}^4He \rightarrow {}^7Be + \gamma$

$2\cdot10^{-5}$%: ${}^3He + p \rightarrow {}^4He + e^+ + \nu$

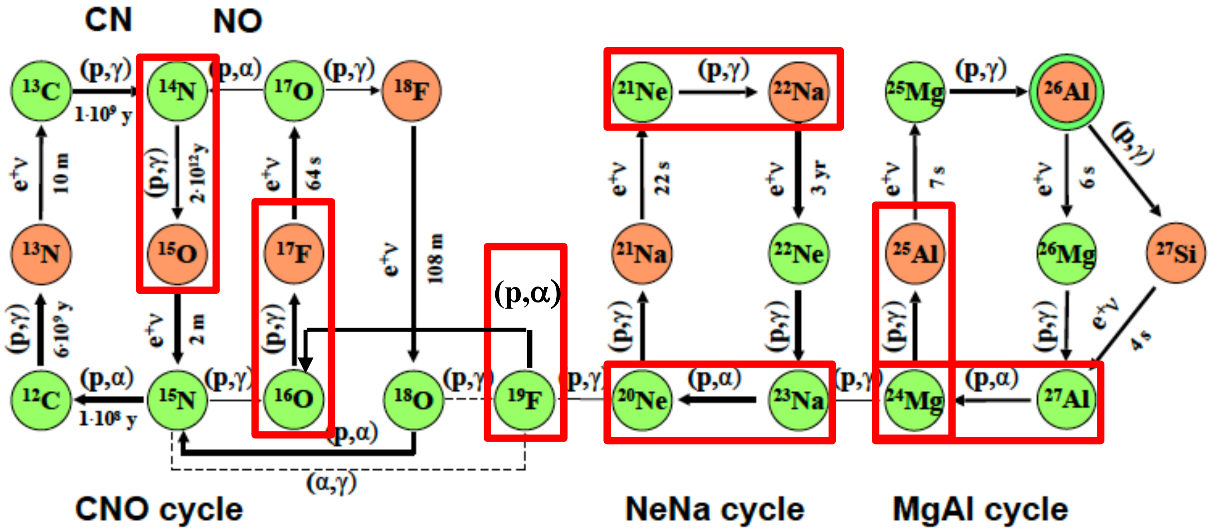
99.89%:
${}^7Be + e^- \rightarrow {}^7Li + \nu$
${}^7Li + p \rightarrow {}^8Be$
${}^8Be \rightarrow 2\,{}^4He$

0.11%:
${}^7Be + p \rightarrow {}^8B + \gamma$
${}^8B \rightarrow {}^8Be + e^+ + \nu$
${}^8Be \rightarrow 2\,{}^4He$

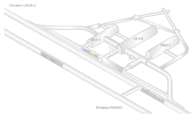


LUNA400: what can still be done

- $^{14}N(p,\gamma)^{15}O$ to decrease the uncertainty at solar temperature;
- $^{16}O(p,\gamma)^{17}F$ to determine the $^{16}O/^{17}O$ abundance ratio in red giant stars;
- $^{19}F(p,\alpha)^{16}O$ to constrain AGB star nucleosynthesis and to investigate spectroscopy of self-conjugate ^{20}Ne nucleus;
- $^{21}Ne(p,\gamma)^{22}Na$ to determine the production of ^{22}Na in Novae and Supernovae
- $^{23}Na(p,\alpha)^{20}Ne$ to understand the ^{23}Na production during H-burning both in stellar cores and shells;
- $^{24}Mg(p,\gamma)^{25}Al$ which is crucial to understand MgAl anticorrelation;
- $^{27}Al(p,\alpha)^{24}Mg$ which significantly affects the Mg and Al production;
- ......



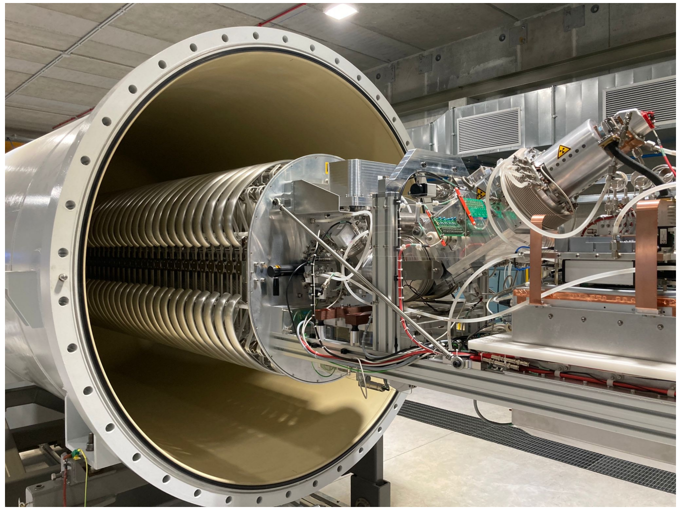
LNGS “Enrico Bellotti” IBF



The new MV accelerator is taking data in Hall B
A PAC organized the research program
Physics program is almost fixed for two years

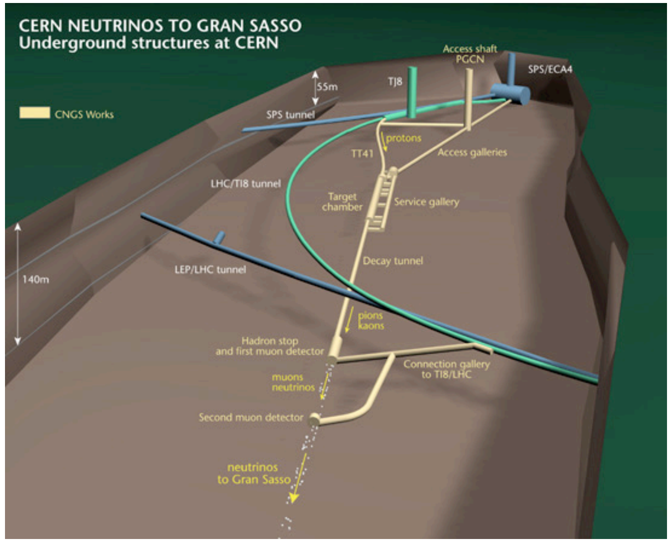
A redesign of the underground area will be done to accommodate 400 kV accelerator in Hall B

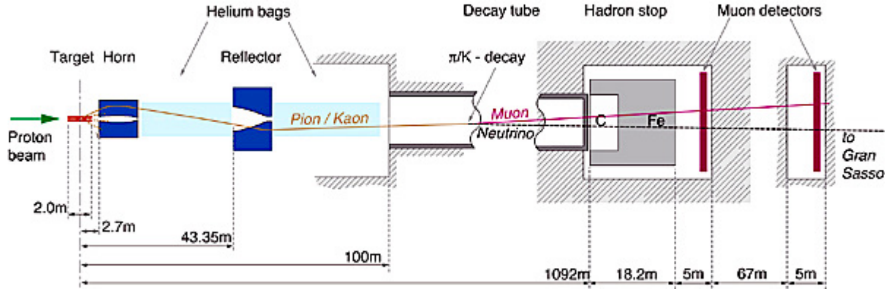
This will be the only facility of this type in the world

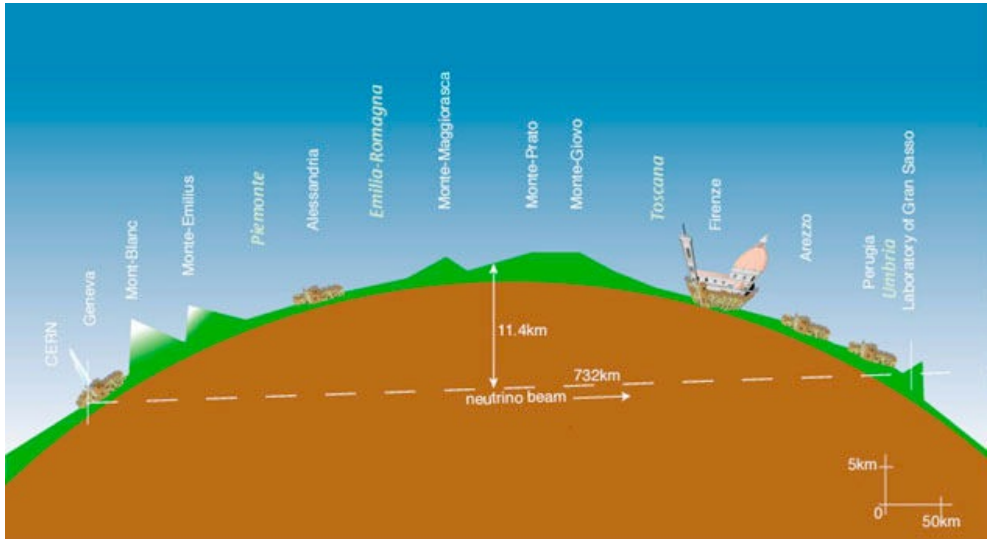


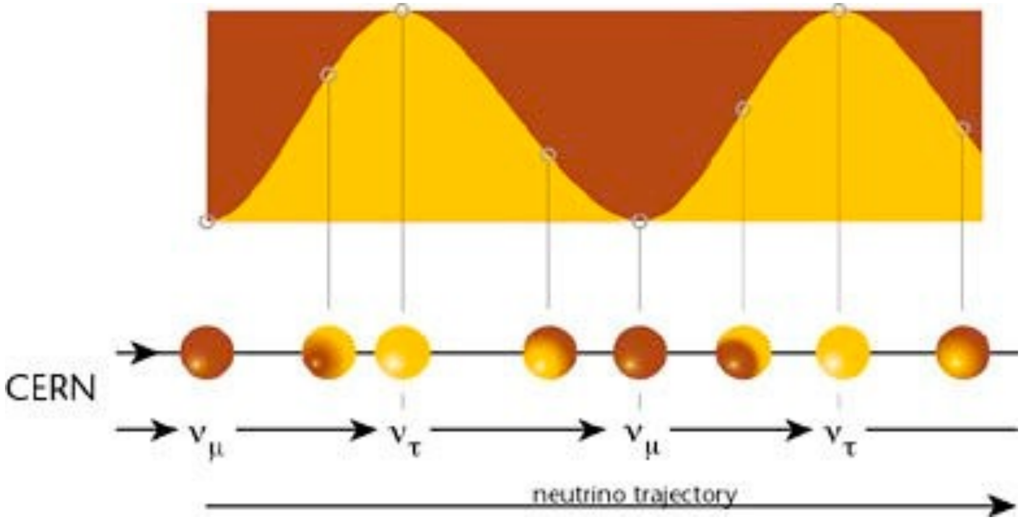
Neutrino Oscillation - Opera

Detection of the $\nu_\mu \rightarrow \nu_\tau$ oscillation



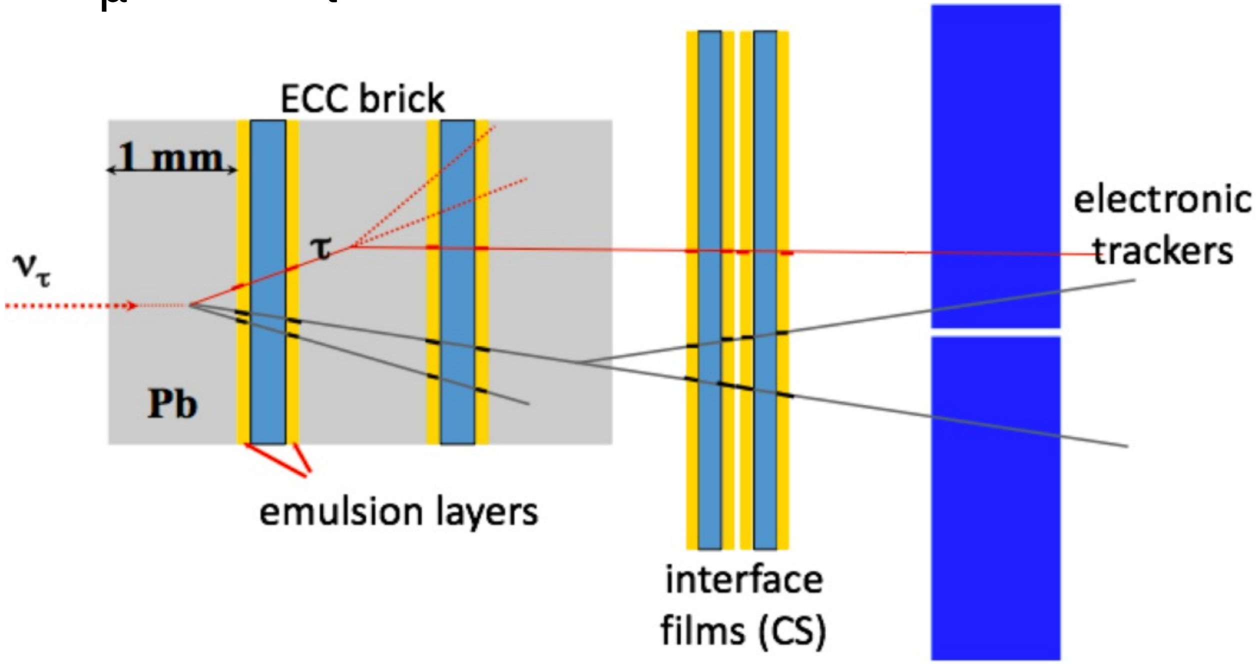






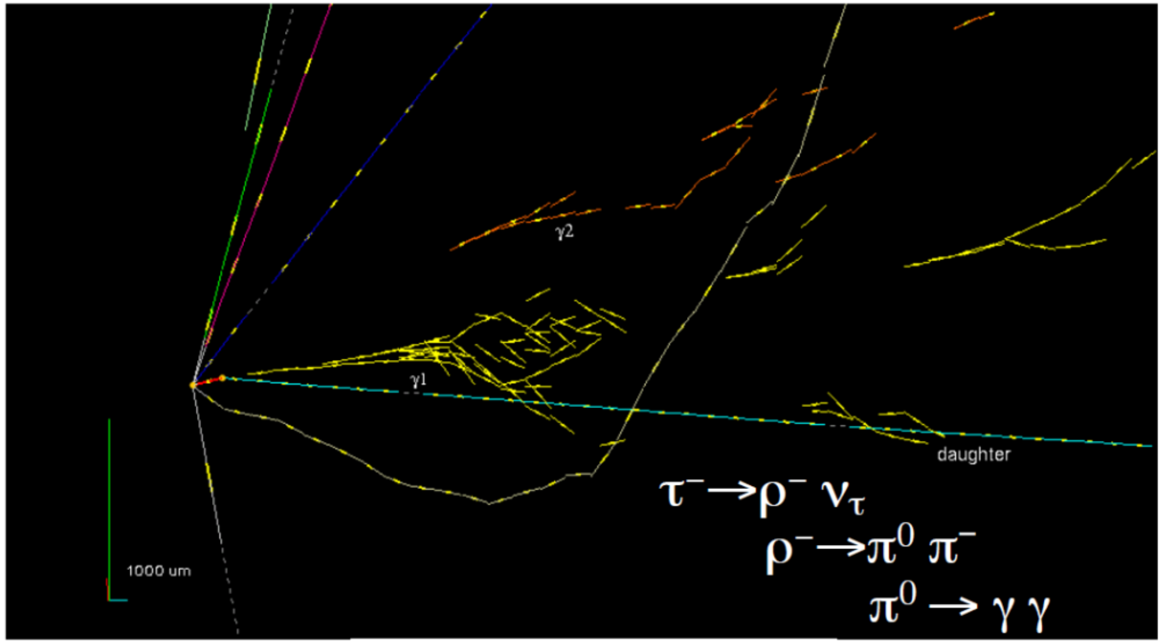
Neutrino Oscillation

$\nu_\mu \rightarrow \nu_\tau + N \rightarrow \tau^- + X$



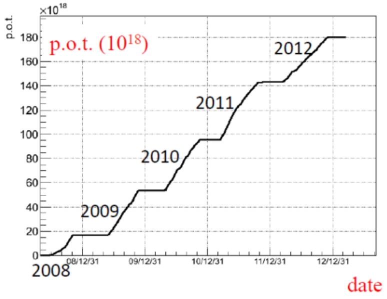
THE FIRST ν_τ CANDIDATE

in the brick



The CNGS beam along its five years of operation 2008 ÷ 2012

Year	Beam days	P.O.T. (10^{19})
2008	123	1.74
2009	155	3.53
2010	187	4.09
2011	243	4.75
2012	257	3.86
Total	**965**	**17.97**

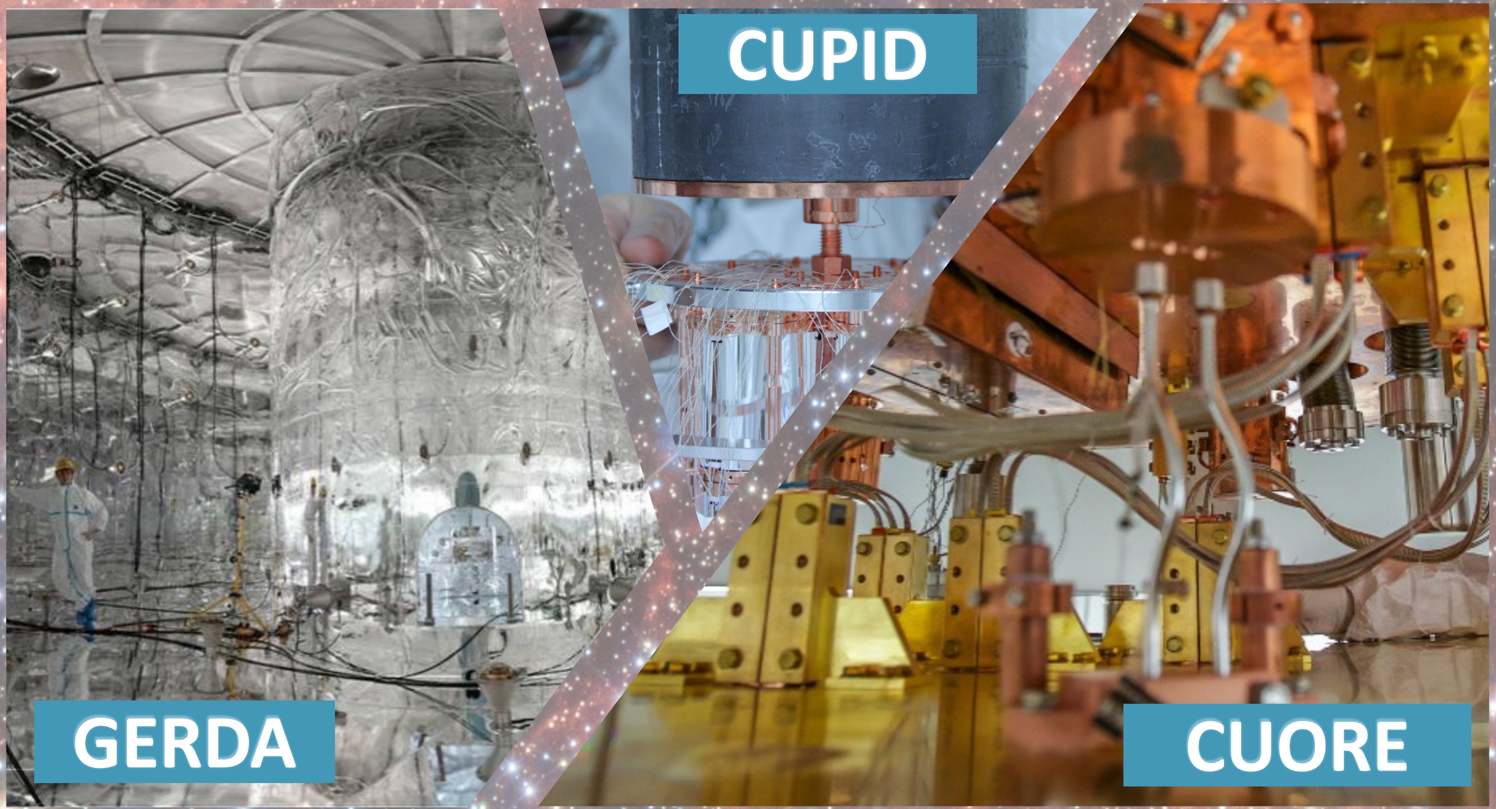


1.8×10^{20} Protons on target, 5603 ν interactions

10 events $\nu_\mu \rightarrow \nu_\tau$ reconstructed (2 bkg)

$$|\Delta m^2_{32}| = (2.7^{+0.7}_{-0.6}) \times 10^{-3}\ \mathrm{eV}^2$$

Neutrinoless Double Beta Decay

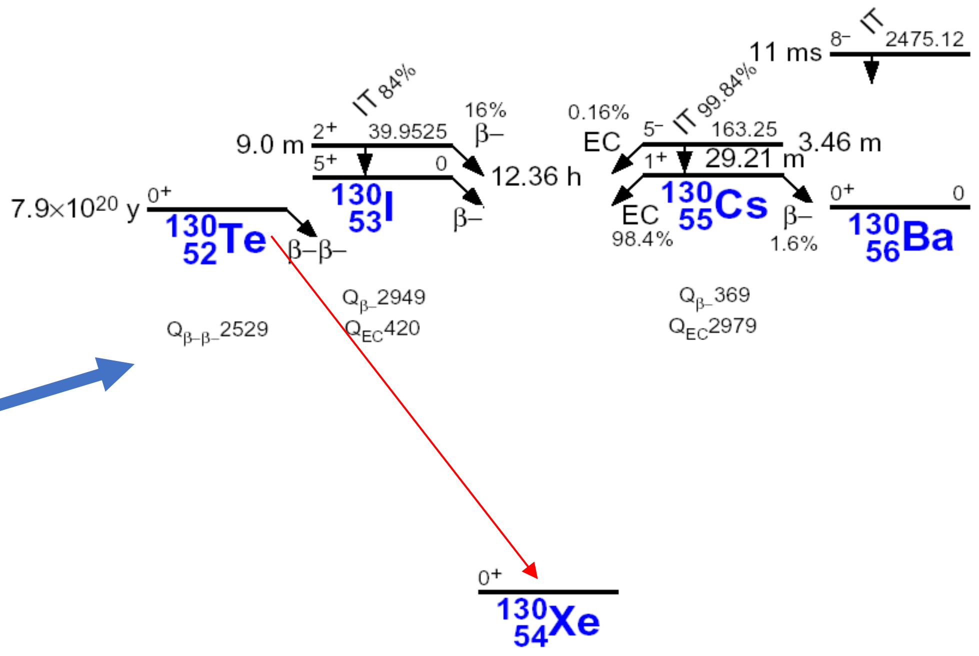


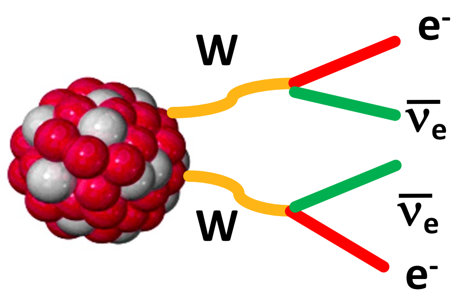
Double Beta Decay

Rare Nuclear Decay

(A,Z) → (A,Z+2) + 2e^- + [...]

occurs in a number of even-even nuclei in *A* even multiplets

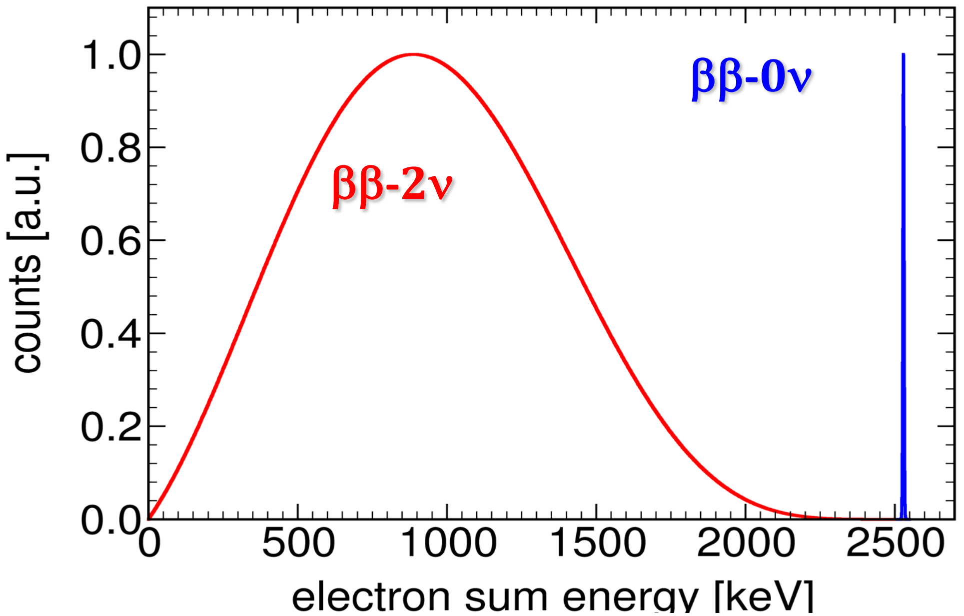




ββ-2ν: two neutrino mode

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

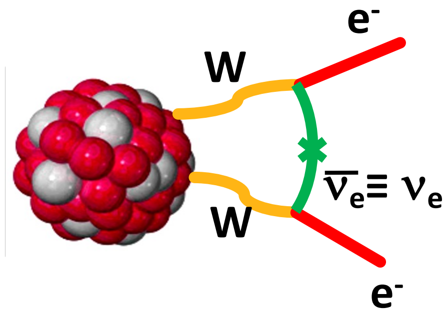
- allowed in Standard Model
- *second order weak transition*



ββ-0ν: neutrinoless mode

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

- not allowed in Standard Model (ΔL=2)
- neutrino is a massive Majorana particle
- lepton number violation
- matter/antimatter asymmetry in universe



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Experimental Sensitivity

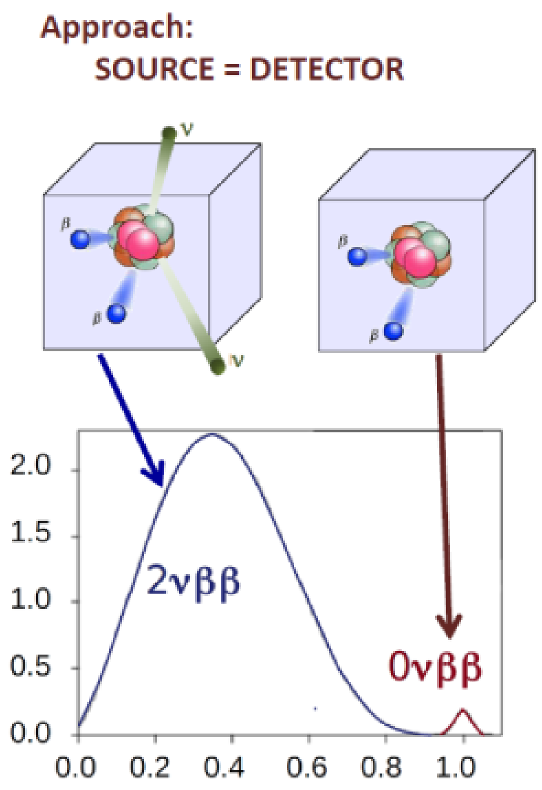
Phase space factor

Nuclear Matrix Element

$$\tau^{-1} = G_{0\nu} \cdot |M^{0\nu}|^2 \cdot |\langle m_\nu \rangle|^2 = F_N \cdot \frac{|\langle m_\nu \rangle|^2}{m_e^2}$$

Effective Neutrino Mass

Nuclear Factor of Merit



detector mass [kg]

measuring time [y]

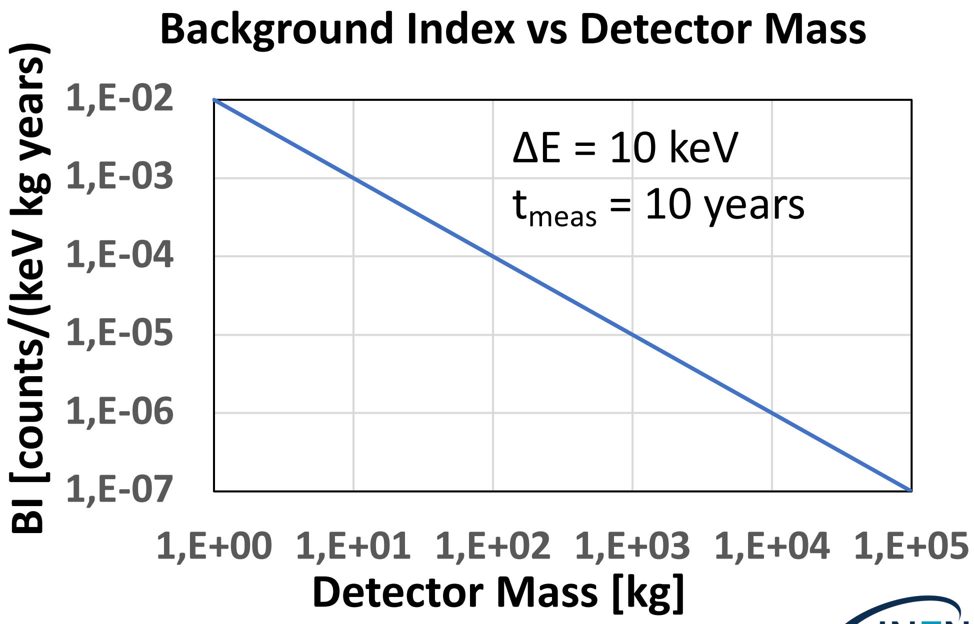
detector efficiency

$$S(\tau^{0\nu}_{1/2}) \propto \epsilon \cdot \frac{a.i.}{A} \sqrt{\frac{M\, t_{meas}}{\Delta E \cdot BI}}$$

isotopic abundance
atomic number

energy resolution [keV]

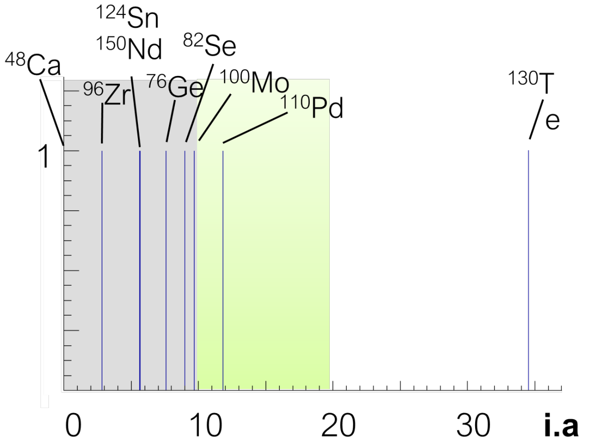
background [c/keV/y/kg]

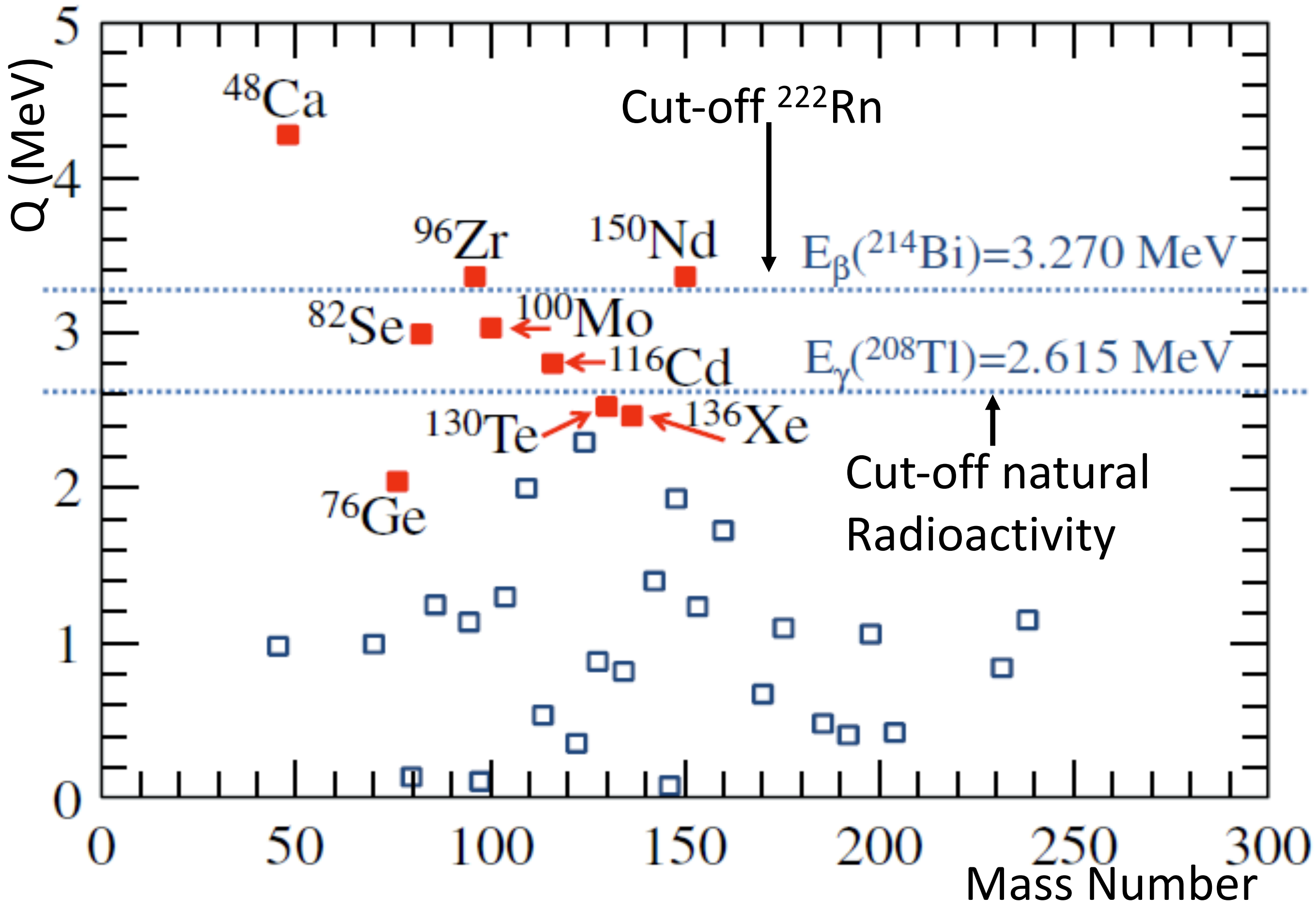


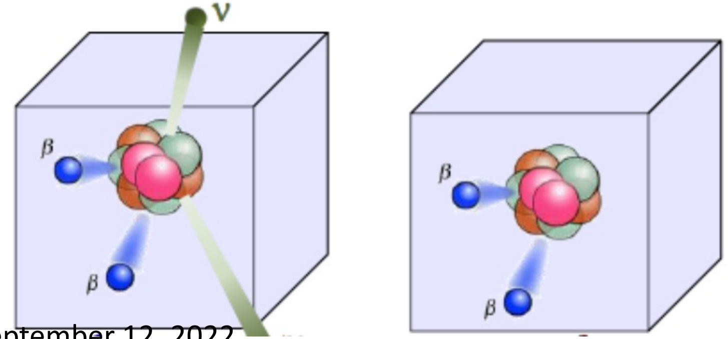
Isotope selection

From the Table of Isotopes

- 35 isotopes with double beta decay transitions
- 9 promising for sensitive measurements
- most promising candidates: $Q_{\beta\beta}$ > 2-3 MeV
- isotope enrichments are needed







Considering a calorimetric approach (**Source == Detector**)

- **isotope enrichments** are needed
- **very clean materials** have to be identified

Possible Calorimetric Approaches

Fluid or diluted in a fluid	← **Source** →	Integral part of a crystal
• Container size • Concentration of the source	← **Scalability** →	• Size of a single crystal • Number of crystals

Large volumes of fluid

- Diluted source in liquid scintillator →
  - Without balloon (SNO+)
  - With balloon (**KamLAND-Zen**)
  - With balloon+Cherenkov (Theia)
  - Opaque scintillator (LiquidO)
- TPC
  - High-pressure gas →
    - Cylindrical(Xe: Next, PandaX, Axel; SeF6:N\nuDEx)
    - Spherical(R2D2)
  - Liquid →
    - Single phase (Xe: EXO-200, **nEXO**)
    - Double phase (Xe: Darwin, LZ)

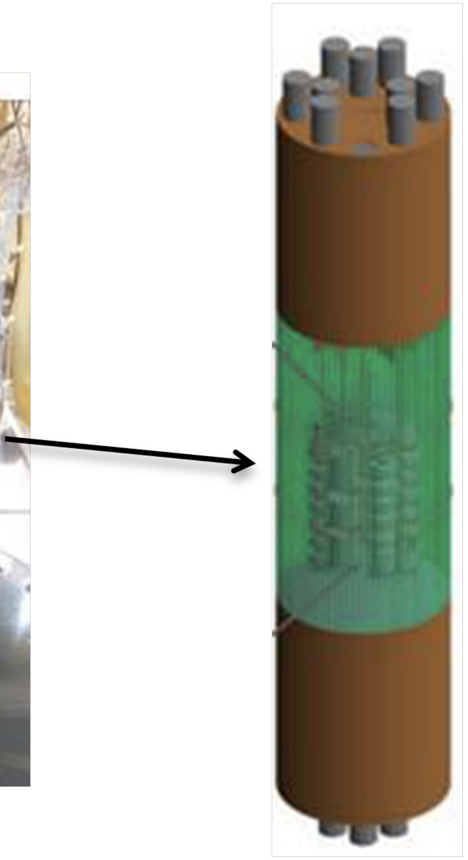
Crystal arrays

- Inorganic Scintillators (Candles)
- Semiconductor detectors
  - Germanium diodes →
    - Immersed in LAr (**GERDA, LEGEND**)
    - Conventional cryostats (MJD)
  - CCD to Se (SELENA)
  - CdZnTe (COBRA)
- Bolometers →
  - Pure bolometers (**CUORE**)
  - Scintillating bolometers (**CUPID, AMORE**)
  - PSD (CROSS)

Gerda Experiment

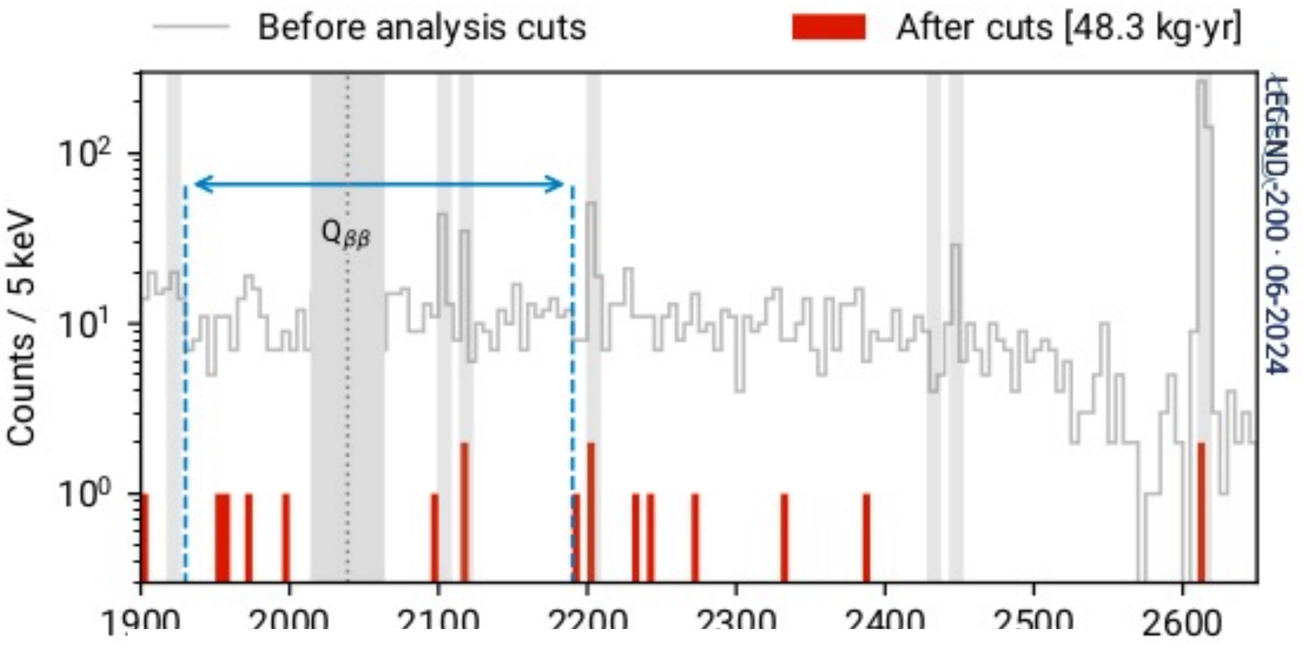
High purity germanium diodes immersed in LAr

- ΔE < 3 Kev FWHM @ Qββ
- Pulse shape analysis: multi/single site vs.
- anticoincidence with LAr
  - scintillating fibers (WLS) coupled to SIPMS
  - PMT above and below the detector



blind analysis:

events close to Qββ are hidden
fix all procedures & cuts
open the box and apply analysis



Sensitivity for 90% C.L. $T_{1/2}$ limit

L200 alone	0.8×10^{26} yr
combined w. GERDA + Majorana Dem.	3.1×10^{26} yr

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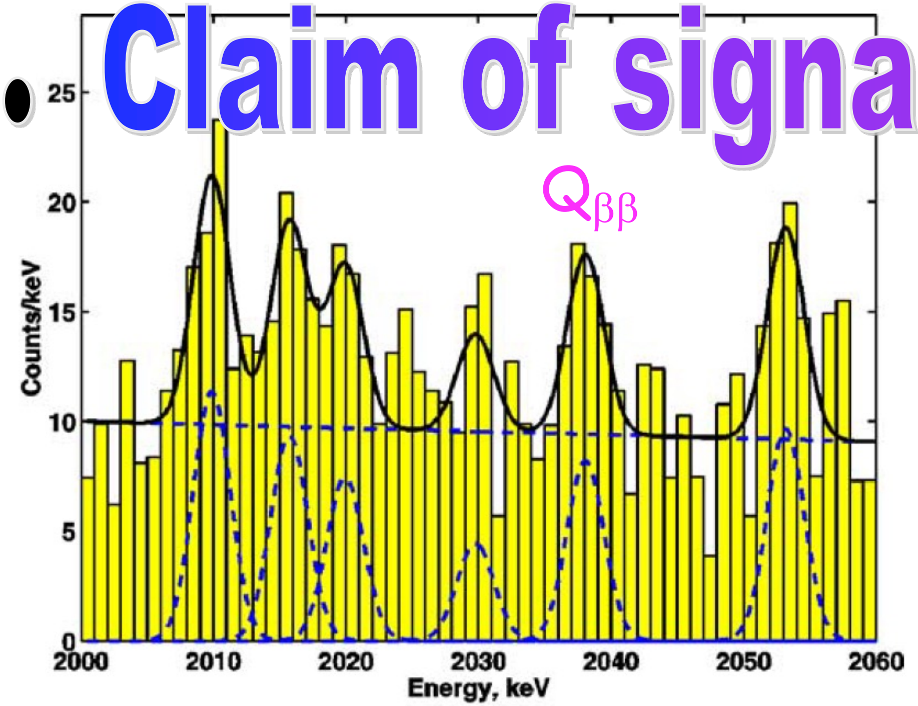
Klapdor-Kleingrothaus et al, Phys.Lett. B586 (2004)198

Claim of signal

5 det. 10.9 kg, total exposure 71.7 kg y

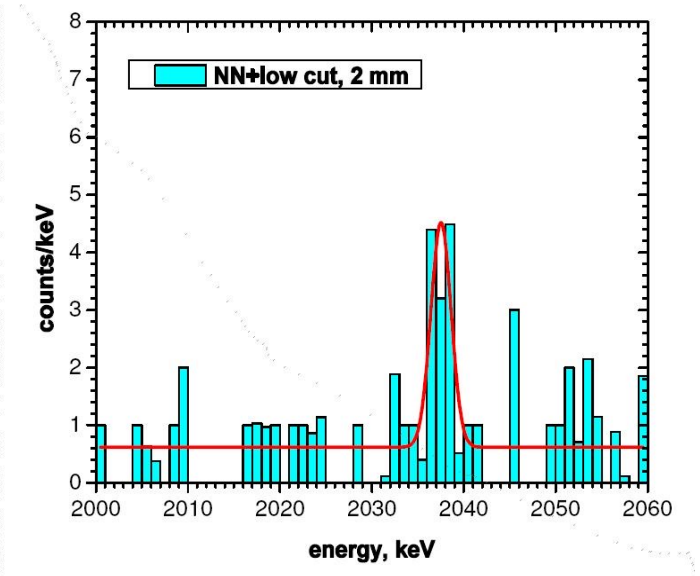
$$T_{1/2}^{0\nu} = (0.69 - 4.2) \cdot 10^{25} \text{y } (3\sigma \text{ interval})$$

$\langle m_{ee} \rangle \sim 0.4$ eV



- claimed signfcance of 4.2 s disputed in literature, see e.g. Strumia+Vissani Nucl Phys B726 (2005)

NOT the first claim, see talk of Tretyak at MEDEX 2011



Mod Phys Lett A21 (2006) 1547:
after Pulse Shape Analysis 11±1.6 events

$$T_{1/2}^{0\nu} = \left(2.23^{+0.44}_{-0.31}\right) \cdot 10^{25} y$$

The errors are clearly wrong &
the numbers can not be used for $\langle m_{ee} \rangle$

not a blind analysis

Lessons to be learned

- No blind analysis → unconscious Bias ?
- Experiment repeated with the same detectors
- Results not confirmed also by different experiments

→ Importance of the independent verification of the results (experimental method) before claiming a discovery

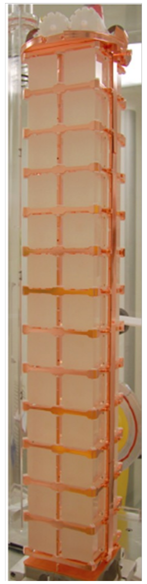
→ different experiments and technologies

CUORE

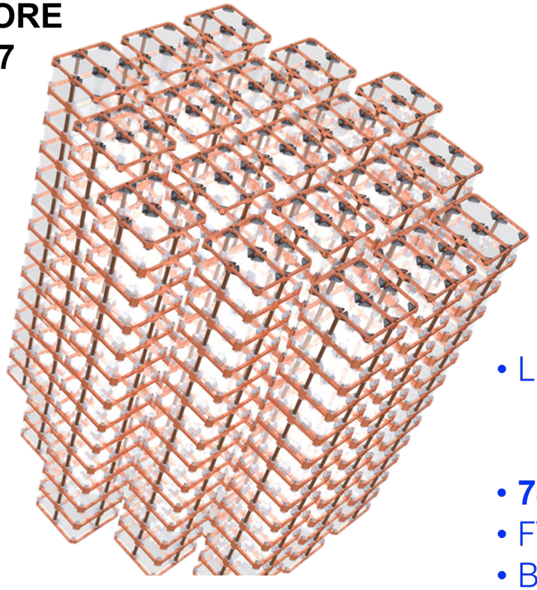
Largest cryogenic particle detector ever realized

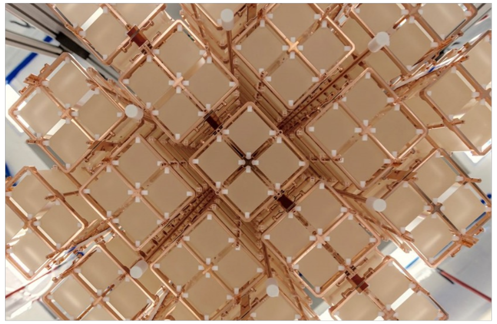
Cuoricino 2003

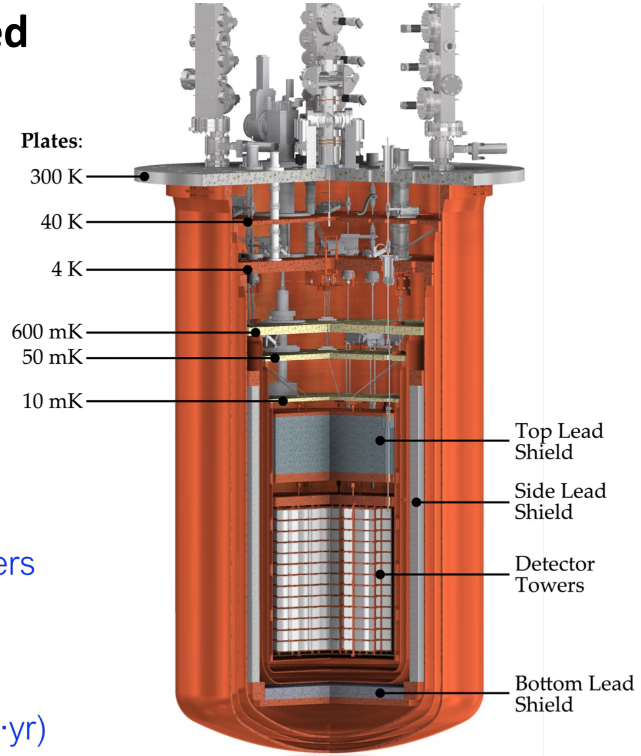
CUORE-0 2012



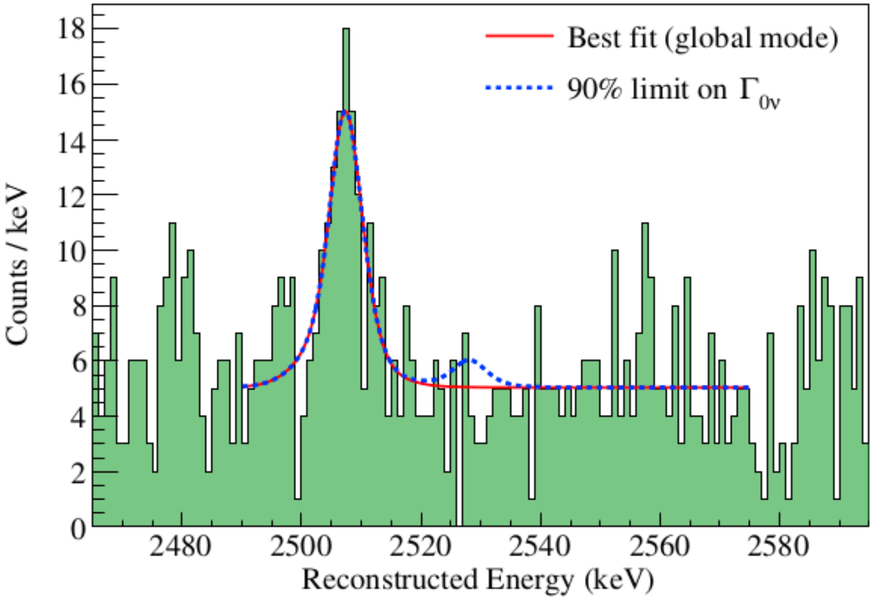
CUORE 2017







- LNGS
  - 988 TeO_2 crystals arranged on 19 towers
  - dedicated "dry" cryostat
- **742 kg** di $^{natural}TeO_2$ (206 kg of ^{130}Te)
- FWHM: **7.7 keV** FWHM (ROI)
- Background: **(1.4 ± 0.2)·10^{-2}** cnts/(keV·kg·yr)
- Total exposure: 1.8 tonne (TeO_2)·yr

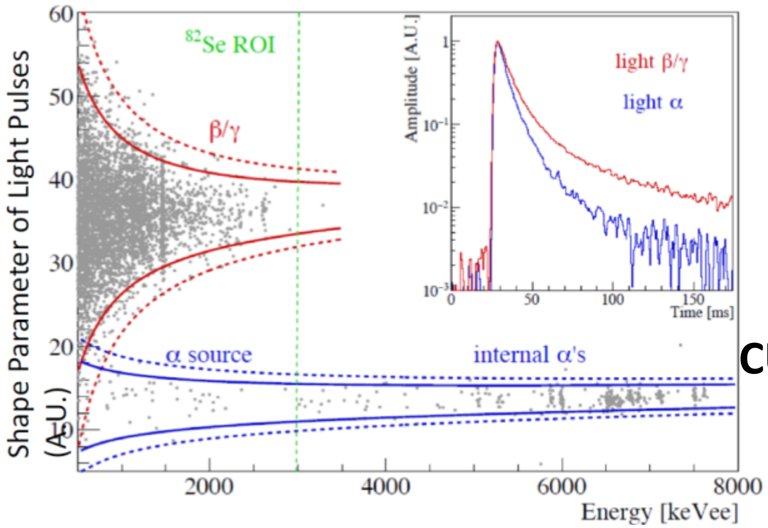


data taking since 2017
FWHM ~0.28% at $Q_{\beta\beta}$ bkg ~ 0.01 cnt/(keV kg yr)
$T_{1/2}$ > 3.2 10^{25} yr (90% C.I.)

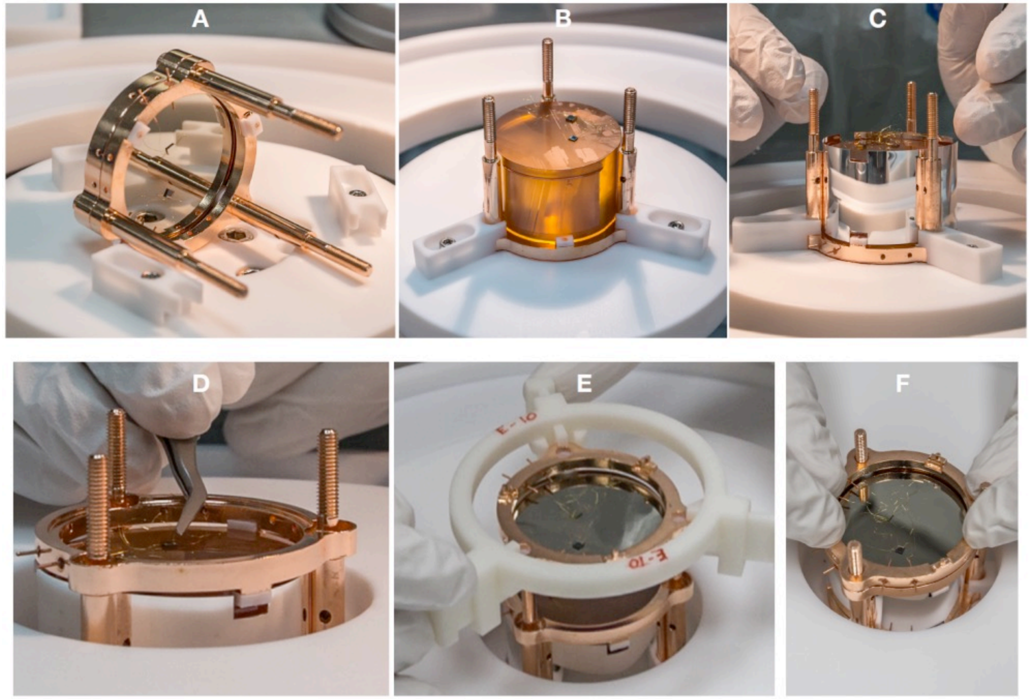
INFN

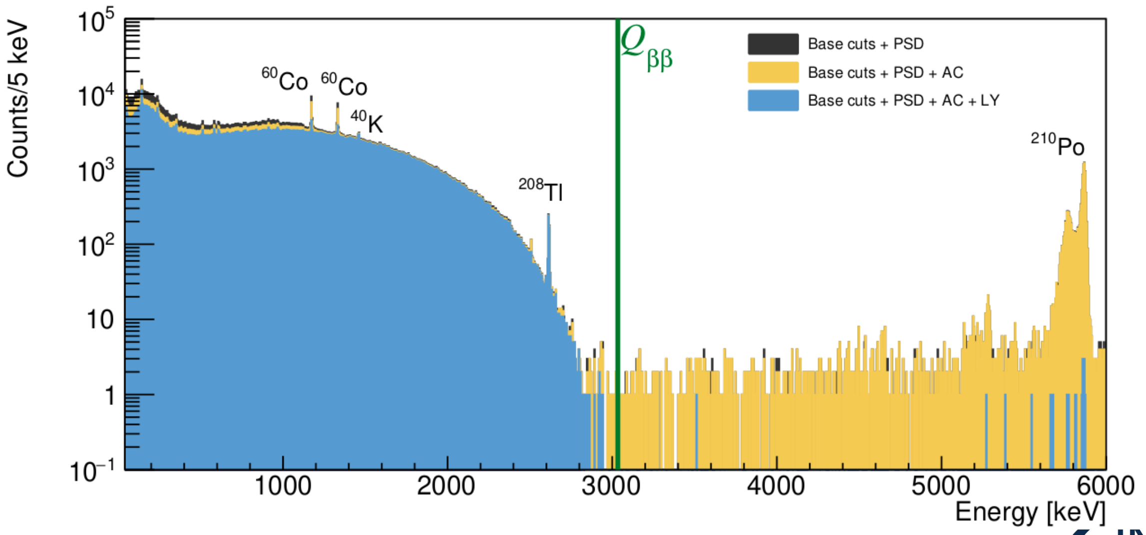
CUPID

- Scintillating crystals and light detectors operated @ 10 mK
- Grown from **various ββ emitters** (**multi-isotope approach**)
- **Excellent energy resolution** @$Q_{\beta\beta}$ (<1%)
- Possibility to high $Q_{\beta\beta}$ (3 MeV) for **^{82}Se and ^{100}Mo**
- **$LY_{\alpha} \neq LY_{\beta/\gamma}$** → Particle ID
- **$LShape_{\alpha} \neq LShape_{\beta/\gamma}$** → Particle ID
- **$HShape_{\alpha} \neq HShape_{\beta/\gamma}$** → Particle ID



CUPID-0 Data

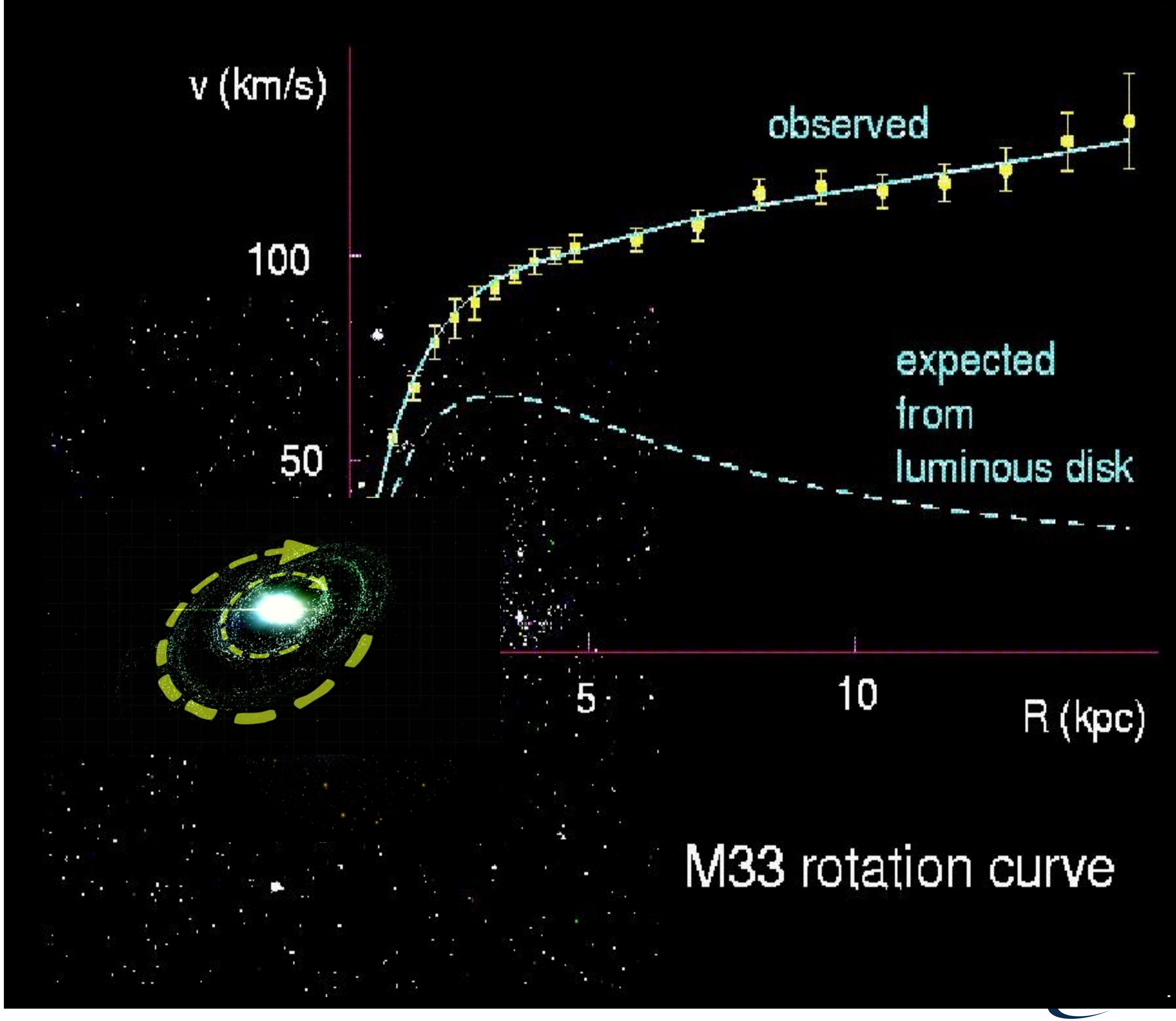




Cosmological studies @ LNGS

Dark Matter Searches

...large part of our Universe is completely unknown...



Dark Matter Search Experiments@ LNGS

Cryogenic Liquids

XENON

Dark Side

Bolometers

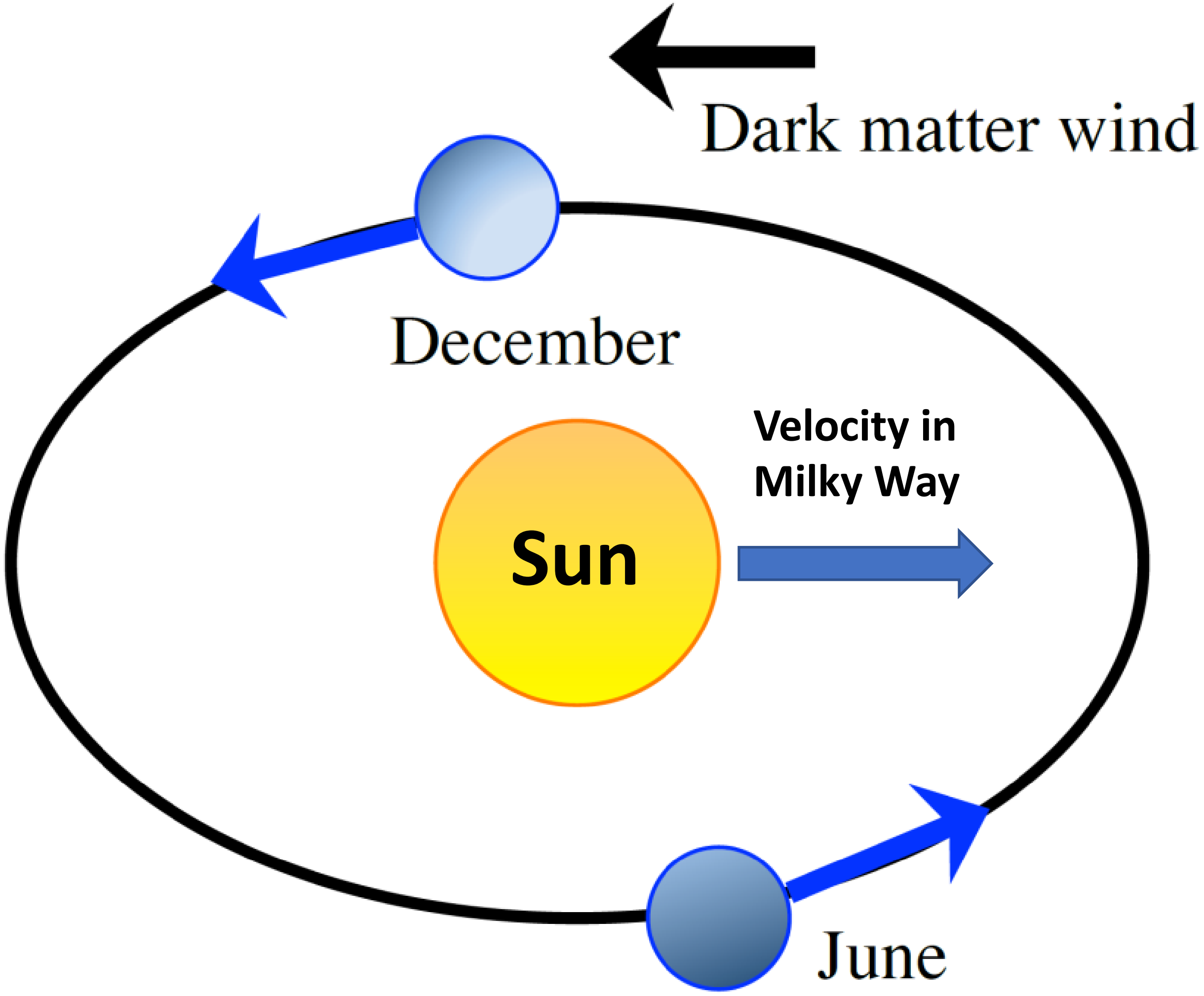
CRESST

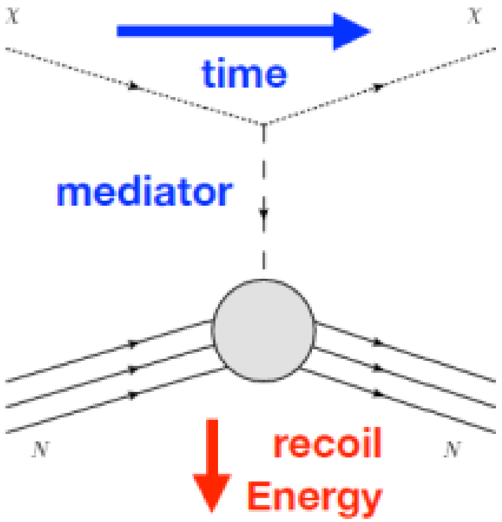
Ultrapure Scintillator

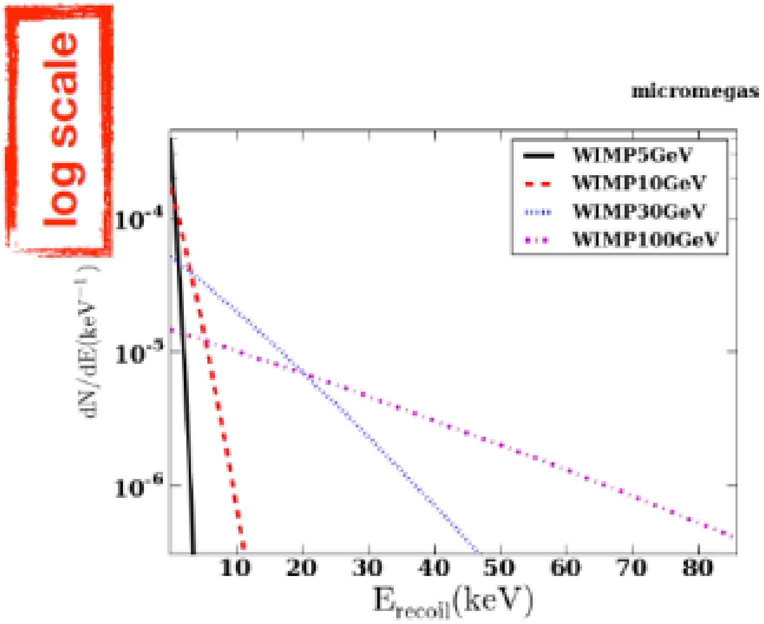
DAMA/LIBRA

SABRE

Dark Matter Searches

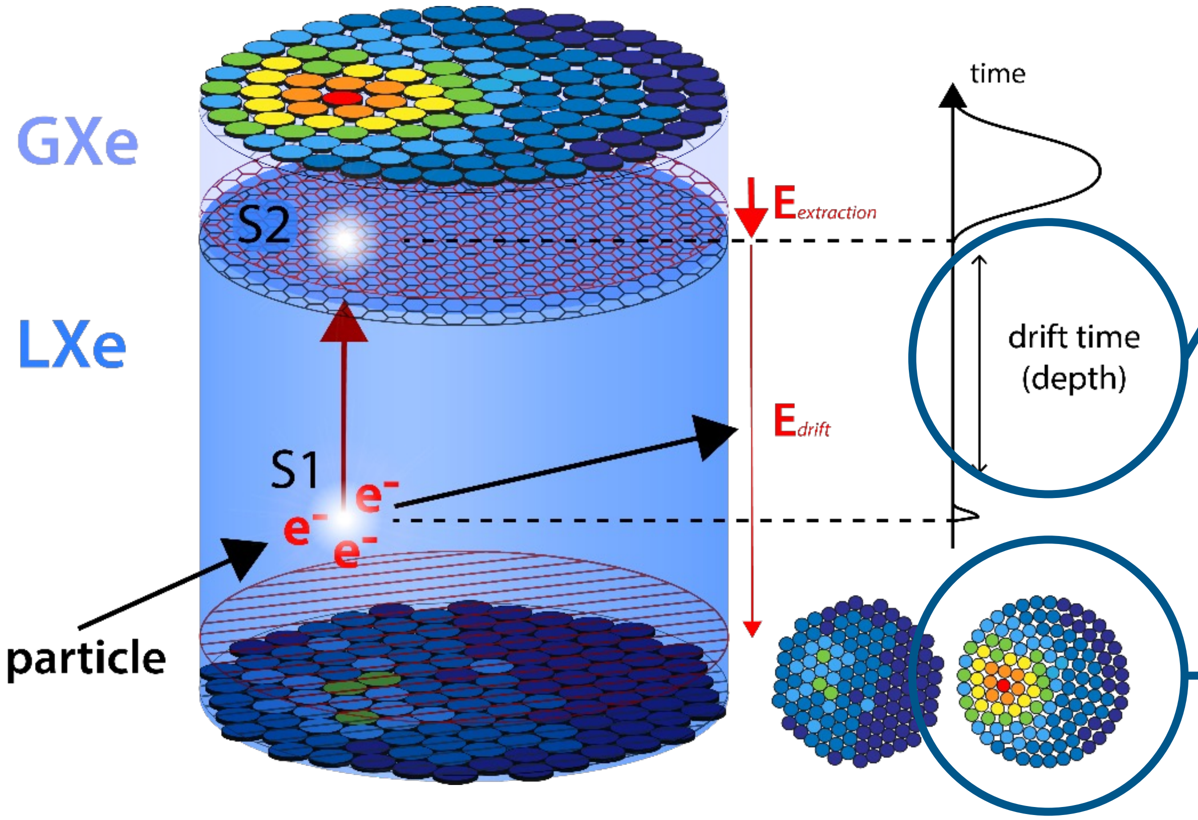






WIMP - ^{78}Ge nucleon scattering

Dual Phase TPC



Thanks C. Weinheimer

Drift time:

$$\Delta t = t_{S2} - t_{S1}$$

Drift velocity:

$$v \approx 2\ {}^{mm}/_{\mu s} \approx 7200\ {}^{km}/_{h}$$

Depth (z - position):

$$z = v \cdot \Delta t$$

+

Concentric PMT array on top
→ S2 signal local
→ **x - and y - position**

=

→ **3D position reconstruction**
→ **Self - shielding**
→ **Inner + radio-pure volume**

Dual Phase TPC

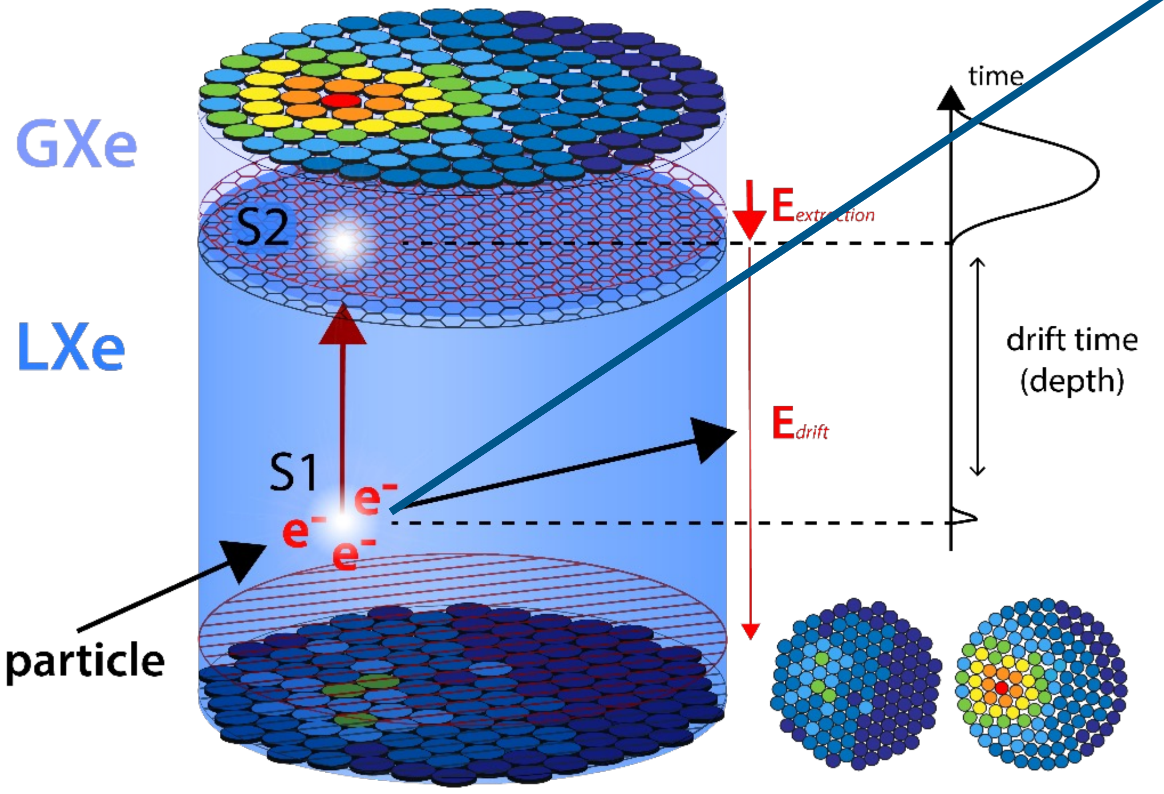
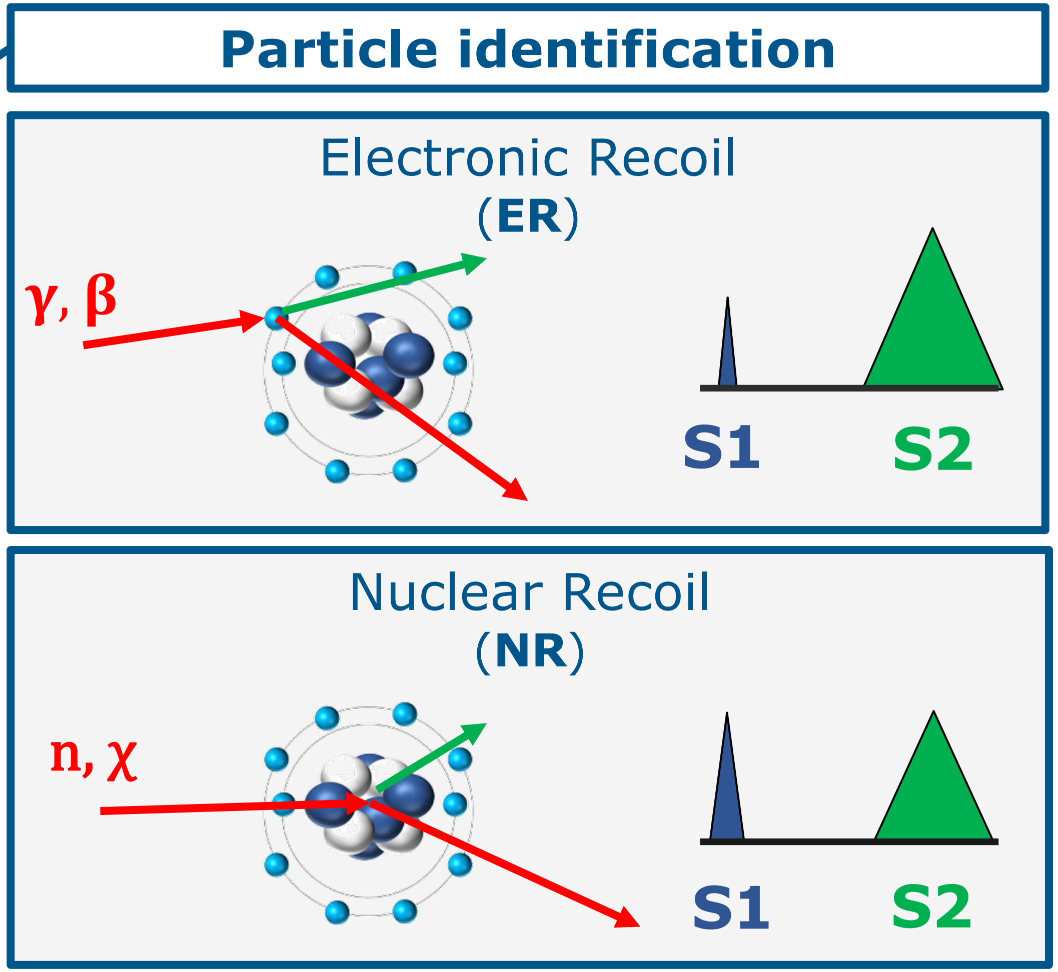


Figure in courtesy: L. Althüser



Thanks C. Weinheimer

Xenon TPC

Particle identification

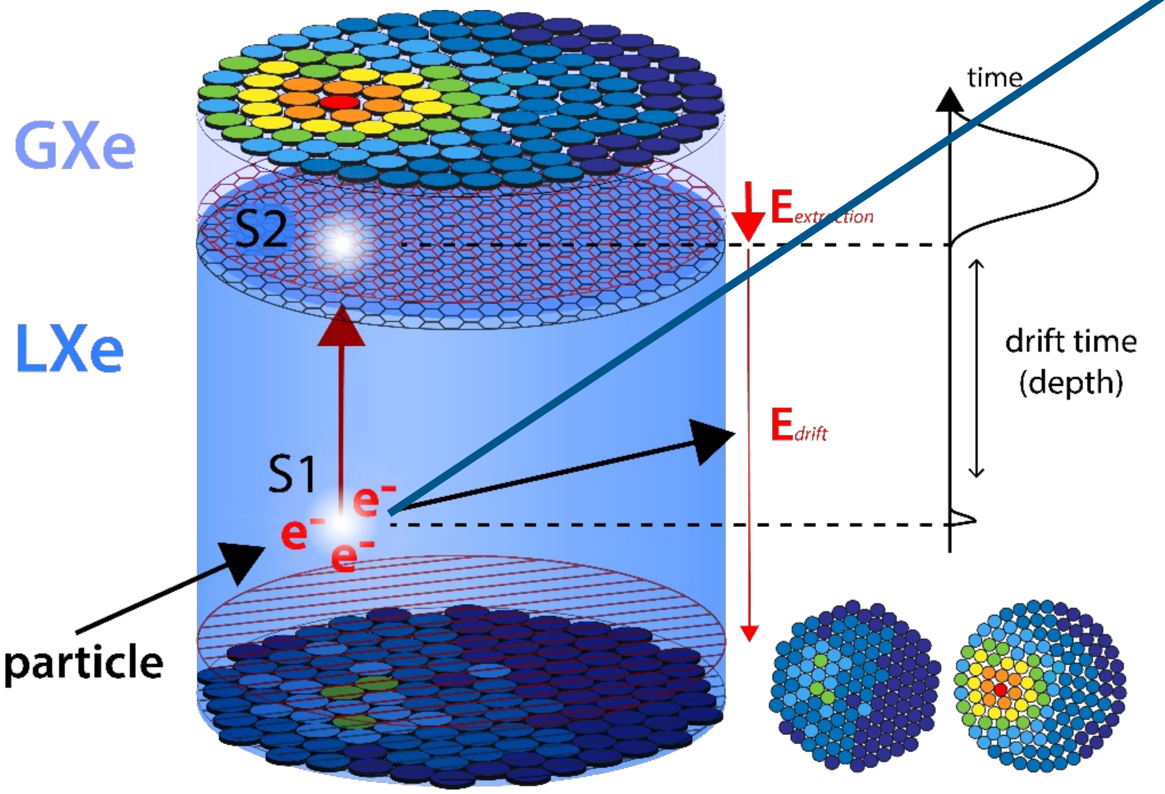
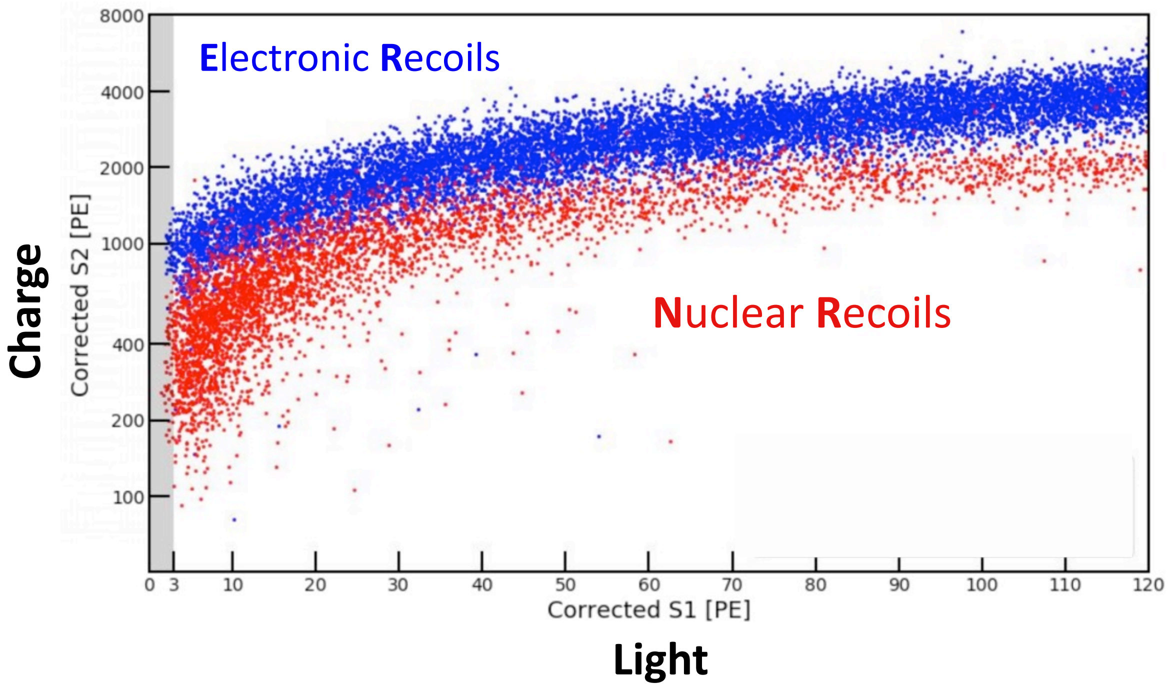


Figure in courtesy: L. Althüser



Reduction of ER-induced background up to 99.75% at 50% NR acceptance

Thanks C. Weinheimer

Xenon @ LNGS

Dark Matter results

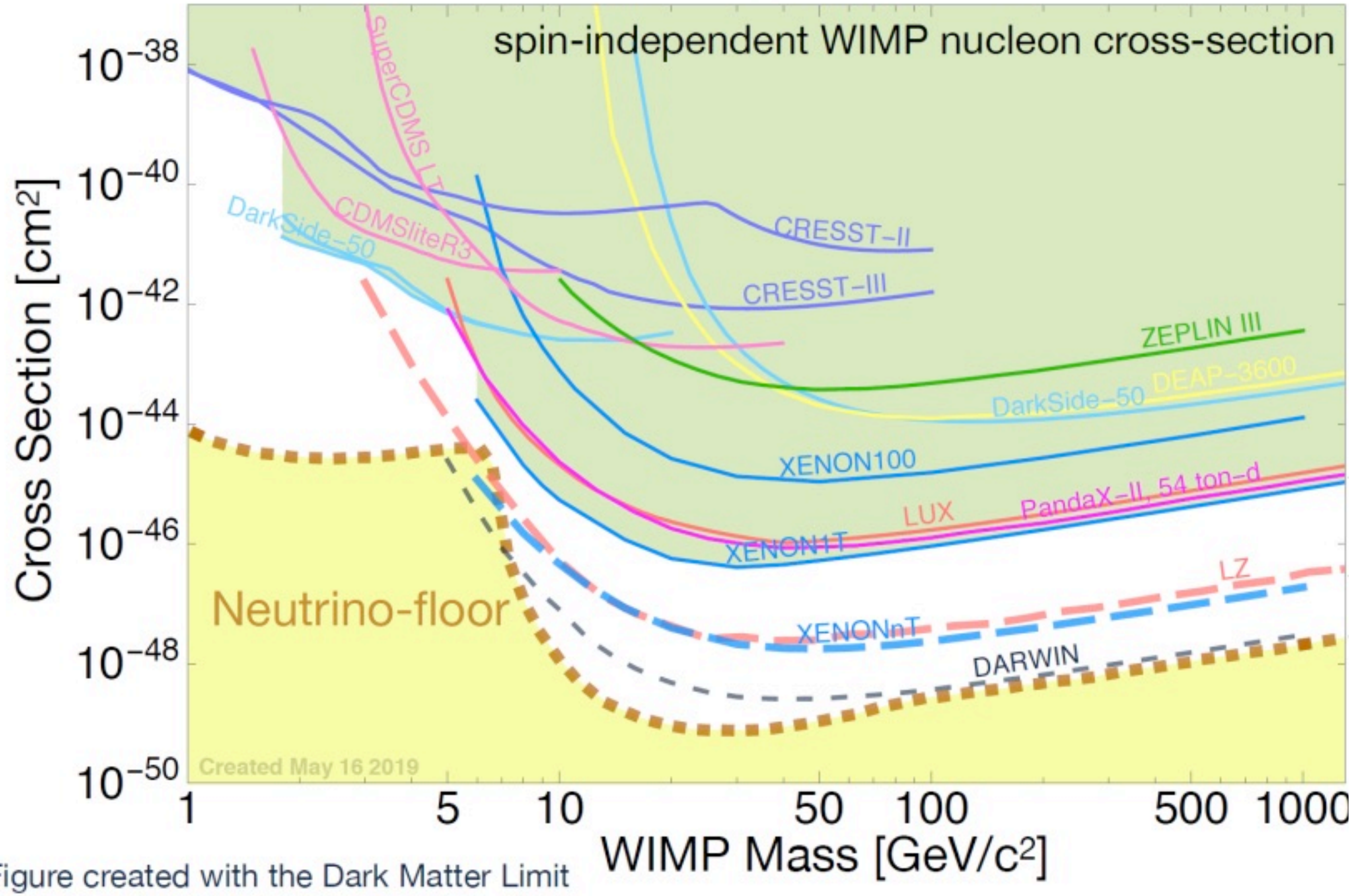
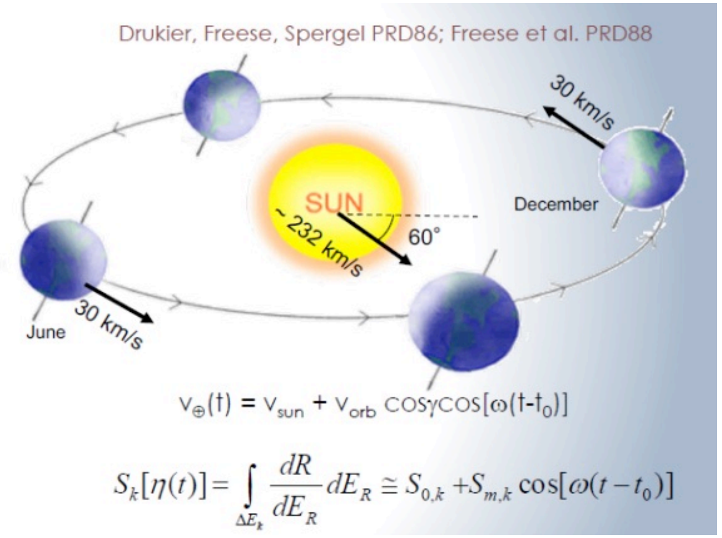


Figure created with the Dark Matter Limit Plotter by T. Saab and E. Figueroa

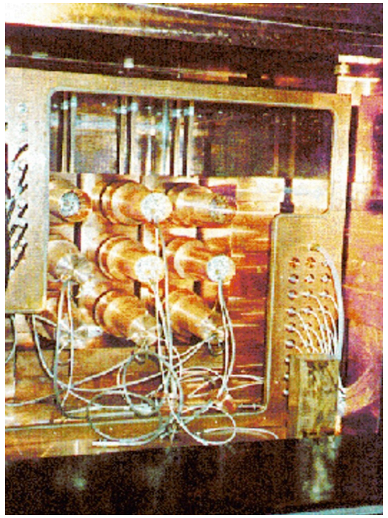
The Dama Libra result for Dark Matter search

Dama is looking for annual modulation signal of Dark Matter using High Purity NaI crystals.
This approach could guaranty a model independent analysis of Dark Matter in the solar system.



To perform the measurement the requirements are

1) Cosine-like modulation of the rate
2) In low energy range
3) Period of 1 year
4) Phase at about June 2nd
5) For single-hit events in a multidetector set-up
6) With modulation amplitude in the region of maximal sensitivity must be <7% for usually adopted halo distributions, but it can be larger in case of some possible scenarios



DAMA/NaI

Concluded on July 2002; 7 annual cycles collected; exposure 0.29 ton×yr

Model independent evidence of a particle DM component in the galactic halo at 6.3σ C.L.

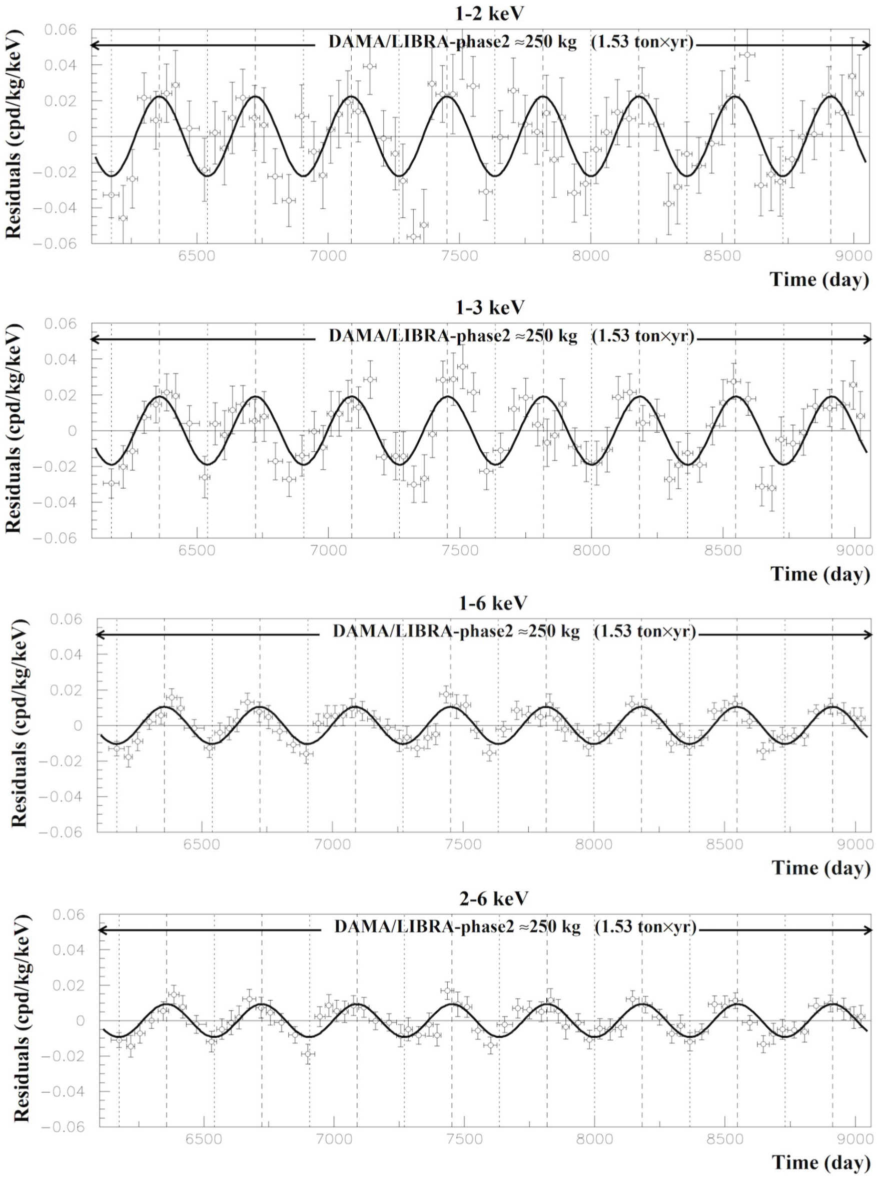
DAMA/LIBRA

New NaI(Tl) detectors with better radiopurity features

Phase 1: 7 annual cycles, 1.04 ton×yr

Phase2: 8 annual cycles released so far (1.53 ton×yr)

Dama Libra results for Dark Matter search



Fit on DAMA/LIBRA-phase2

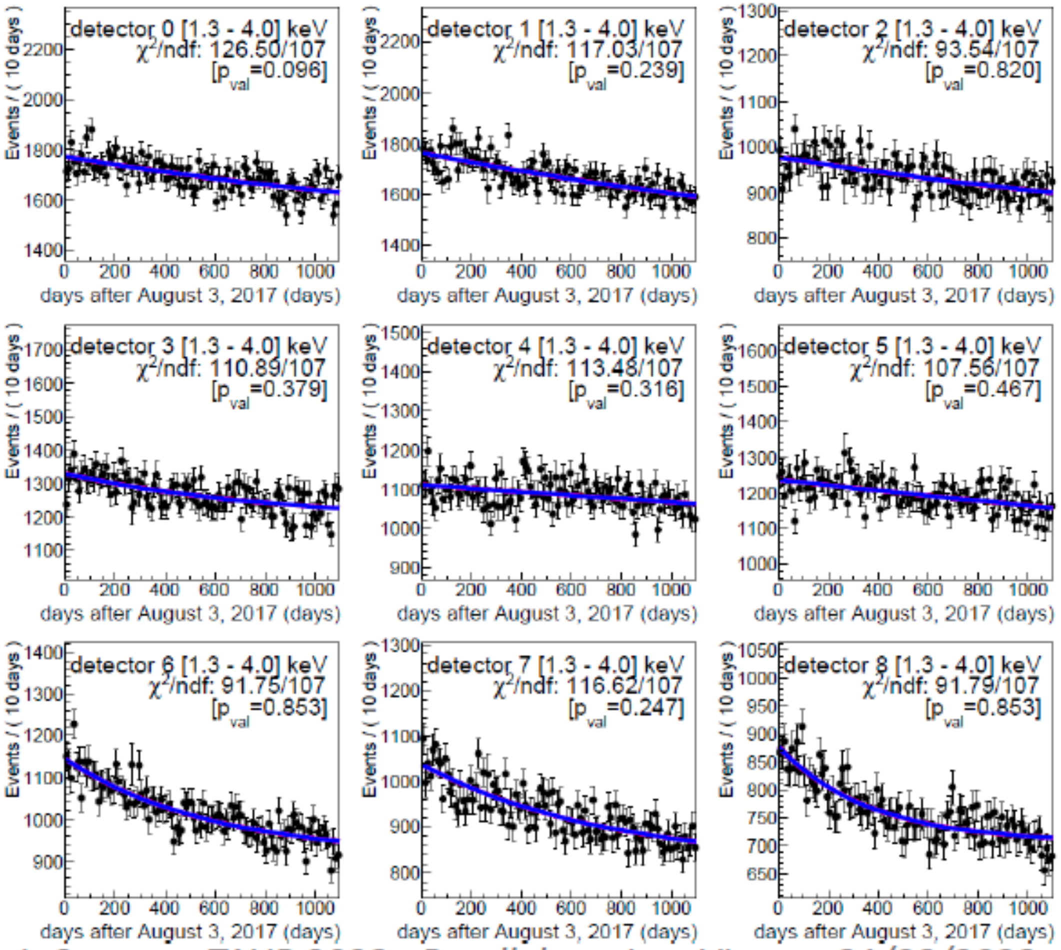
$A\cos[\omega(t-t_0)]$; t_0 = 152.5 d, T = 1.00 y

1 – 2 keV	A=(0.0224±0.0030) cpd/kg/keV	7.4 σ C.L.
1 – 3 keV	A=(0.0191±0.0020) cpd/kg/keV	9.7 σ C.L.
1 – 6 keV	A=(0.01048±0.00090) cpd/kg/keV	11.6 σ C.L.
2 – 6 keV	A=(0.00933±0.00093) cpd/kg/keV	9.9 σ C.L.

The data of DAMA/LIBRA-phase2 favor the presence of a modulated behavior with proper features at 11.6σ C.L.

Independent checks: Anais-112/Cosine-100

ANAIS-112

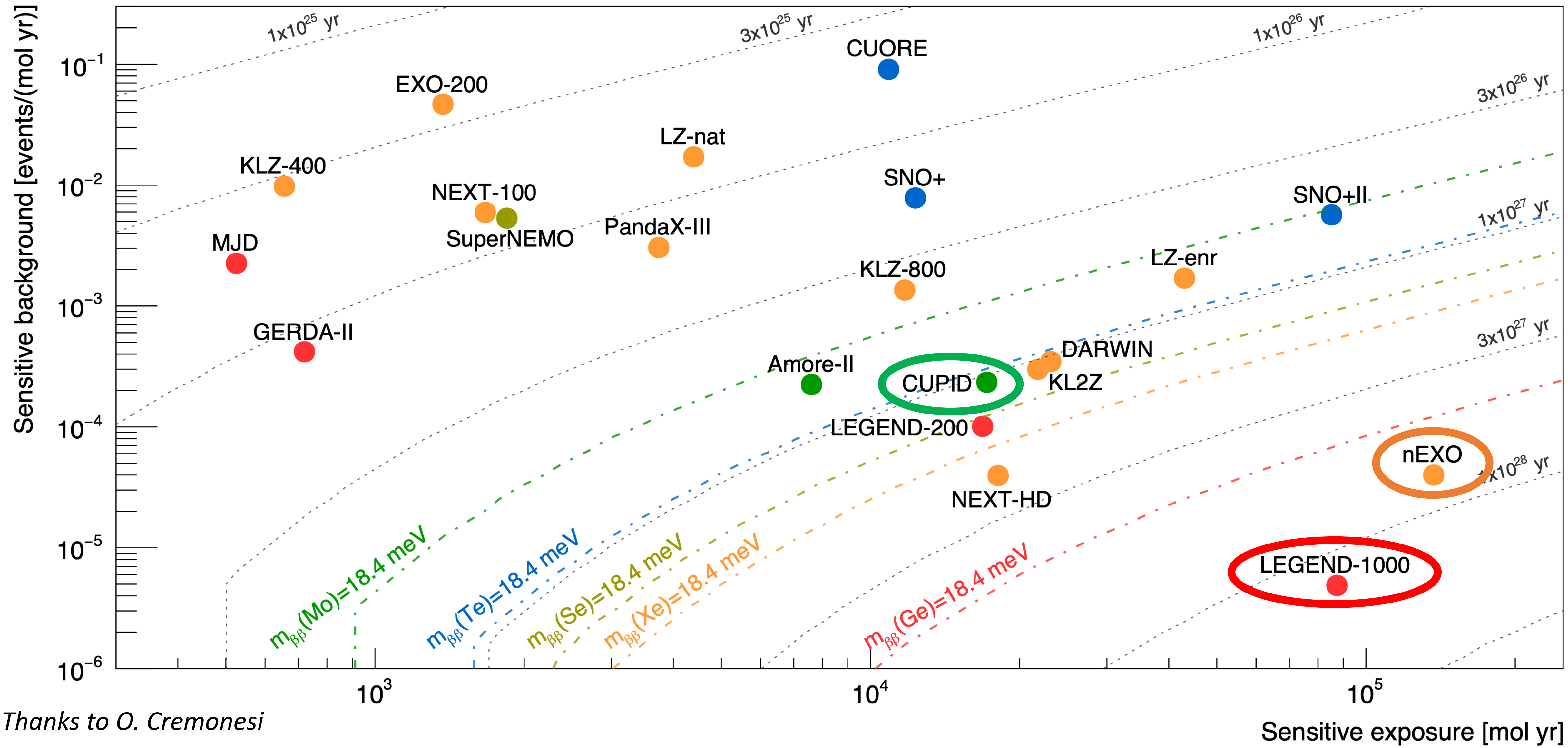


I. Coarasa, TAUP 2023 - Parallel session, Vienna, 31/08/2023

- Difficult to evaluate and cross check the DAMA results
- Not possible to use the same detector
- Difficult to produce NaI Crystal with the same purity → Larger bkg
- Up to now result not confirmed by two experiments:
  - ANAIS-112@Camfranc (incompatible 2-3 sigma level=
  - Cosine-100 in Korea

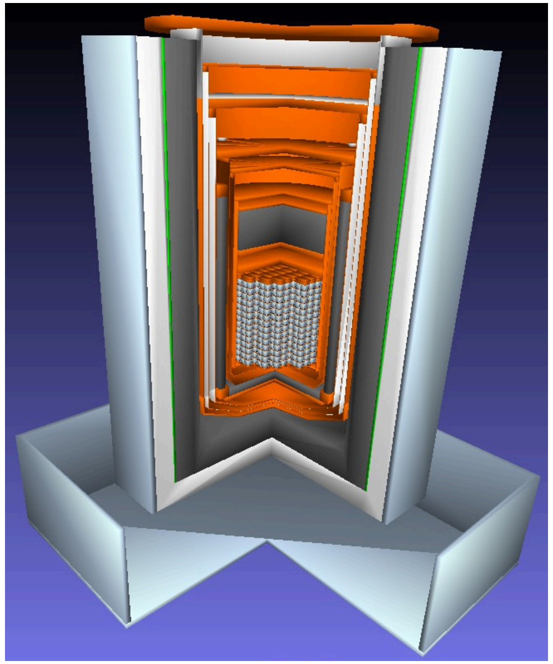
Future experiments @ LNGS

Double Beta Decay : Next Generation Experiments



Thanks to O. Cremonesi

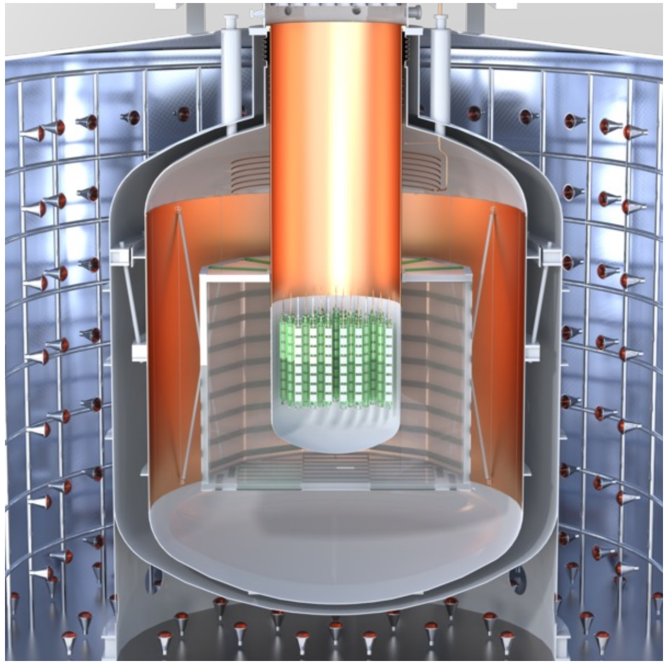
CUPID



250 kg ^{100}Mo

$T_{1/2}$ sens. 2.2×10^{27}yr

Legend-1000

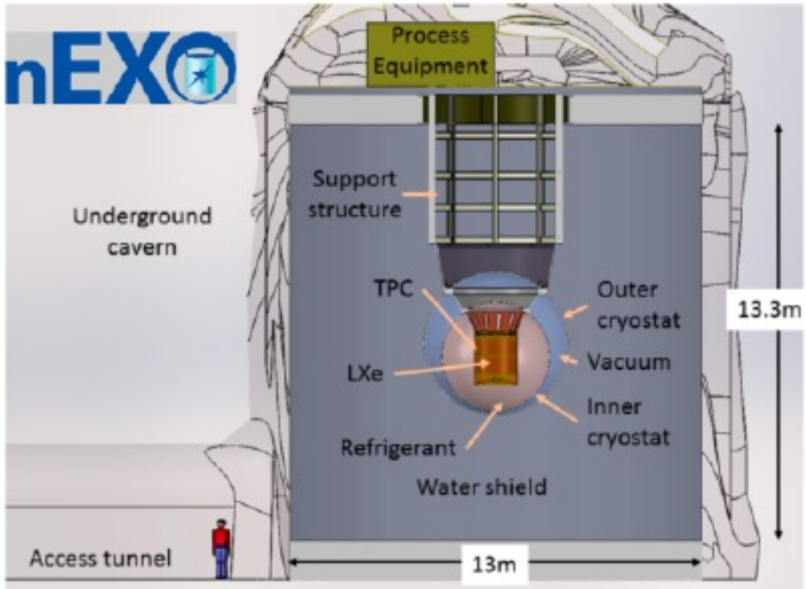


910 kg ^{76}Ge

FWHM 0.12% at $Q_{\beta\beta}$

$T_{1/2}$ sens. 1.2×10^{28}yr

nEXO



5100 kg Xe

FWHM 2.3% at $Q_{\beta\beta}$

$T_{1/2}$ sens. 6×10^{27} yr

Open questions

Is it possible to fund and support all the 3 experiments?
Which is the optimal location of the experiments ?
Which is a reasonable timeline ?

	$T_{1/2}$ (10^{28} years)		$m_{\beta\beta}$ (meV) 3σ Discovery		COST	Laboratory
	Excl. Sens.	3σ Discovery	Median	Range		
CUPID	0.14	0.10	15	12 to 20	50-60 M€	LNGS
LEGEND-1k	1.60	1.30	12	9 to 21	150-200 M€	LMGS ?
nEXO	1.35	0.74	11	7 to 32	150-200 M€	SNOLAB?

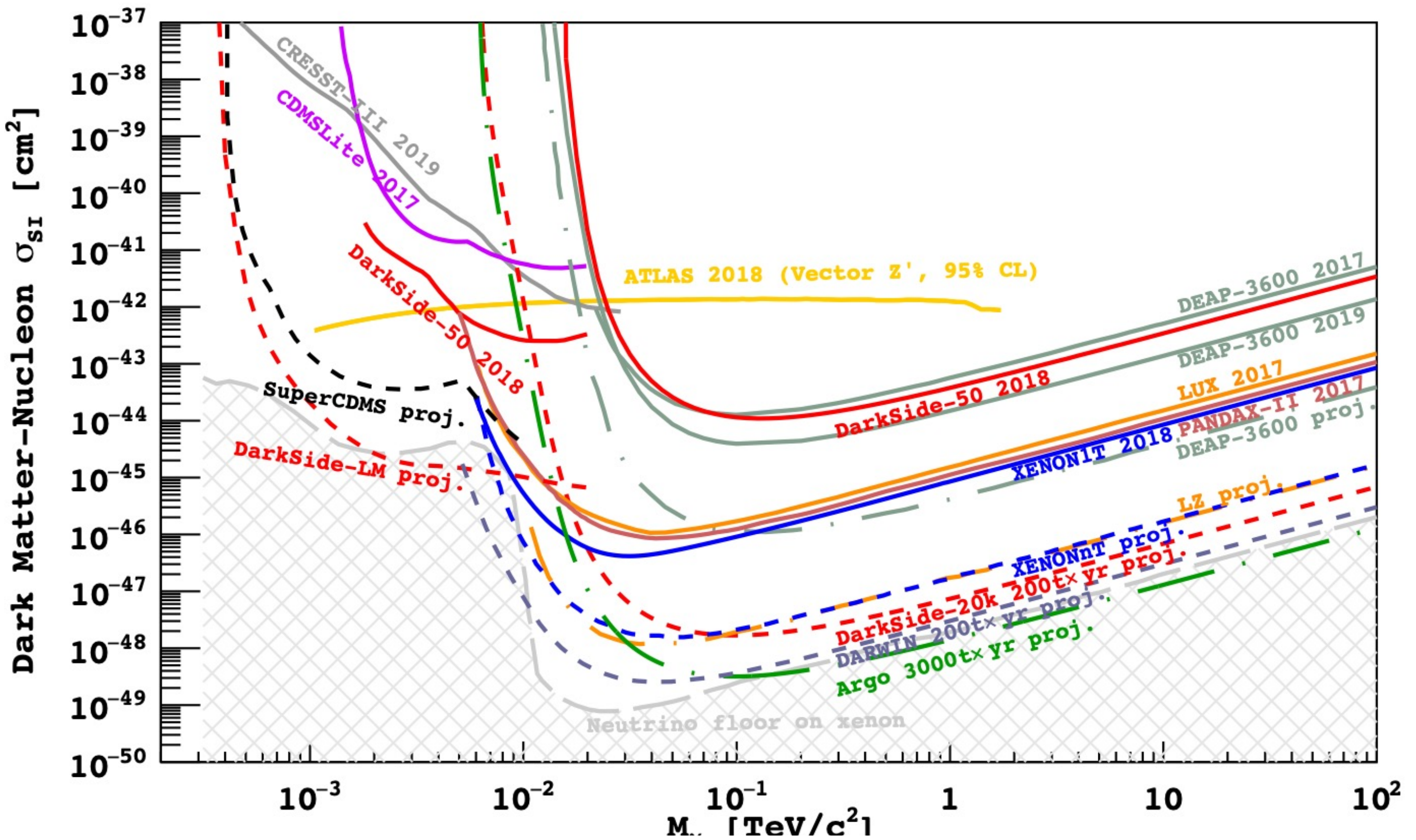
Possible solution:

- CUPID/LEGEND LNGS
- nEXO @SNOLAB

Dark Matter search experiments

A rich experimental program is actually in preparation:

- XENONnT
- Dark Side 20k
- COSINUS
- SABRE
- LIME/CYGNO
- ……



Specific LNGS facilities are under preparation

- NOA Clean Room for detector assembly
- New cryogenic plant for large LN production
- Screening facility for material selection
- ……

Medium/Long term activities on Dark Matter experiments are ongoing

Some LoIs for future experiments (Darwin, …) were received by LNGS

A 5/10 years plan on Dark Matter experiments is practically well established

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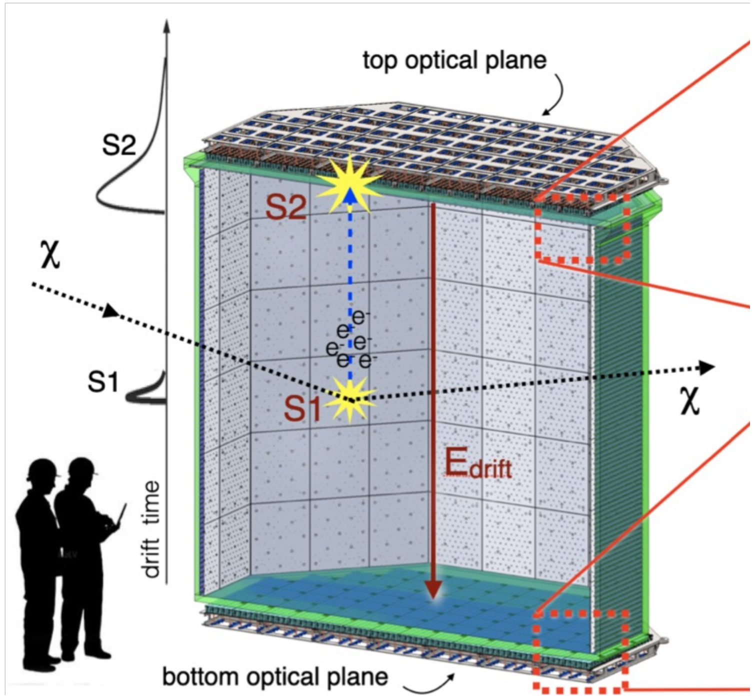
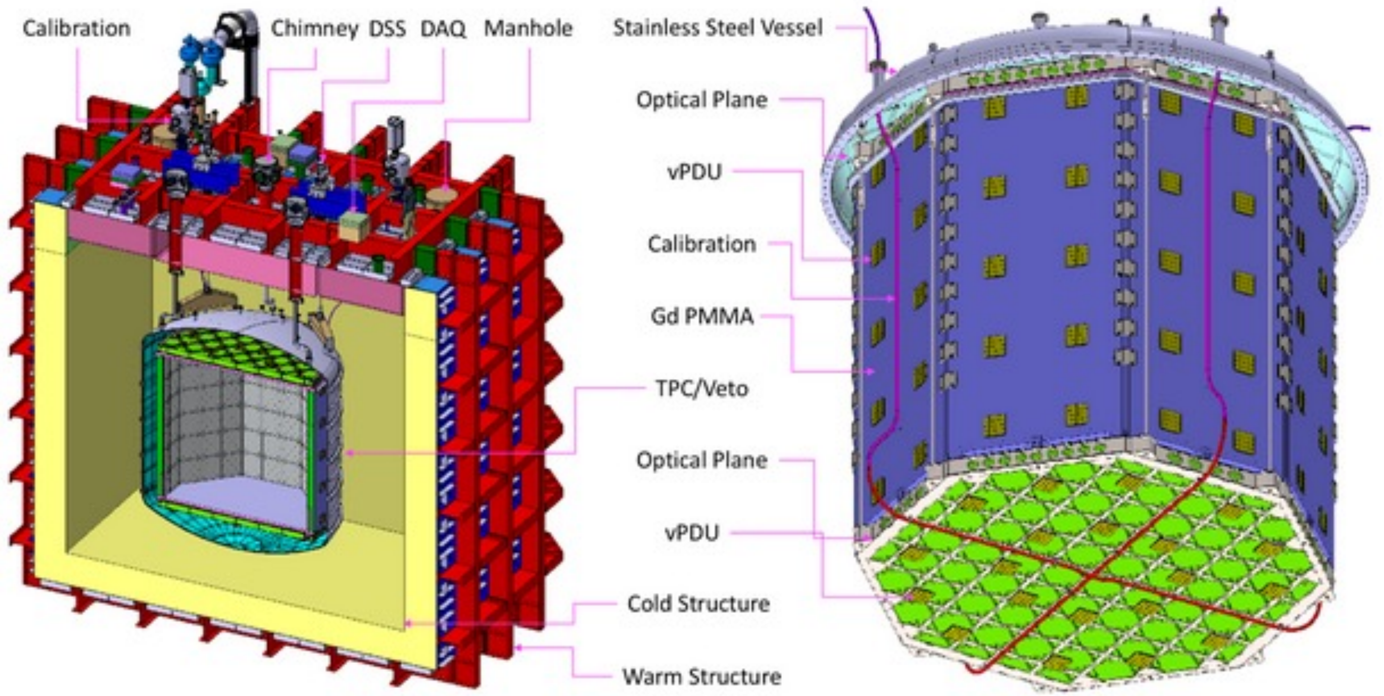
Dark Matter search – Darkside 20k

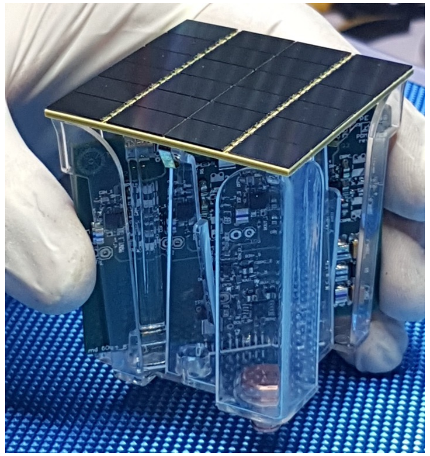




A 20-tonnes fiducial argon detector filled with underground argon

TPC acrylic vessel surrounded by AAr + Gd-loaded acrylic shell as a neutron veto

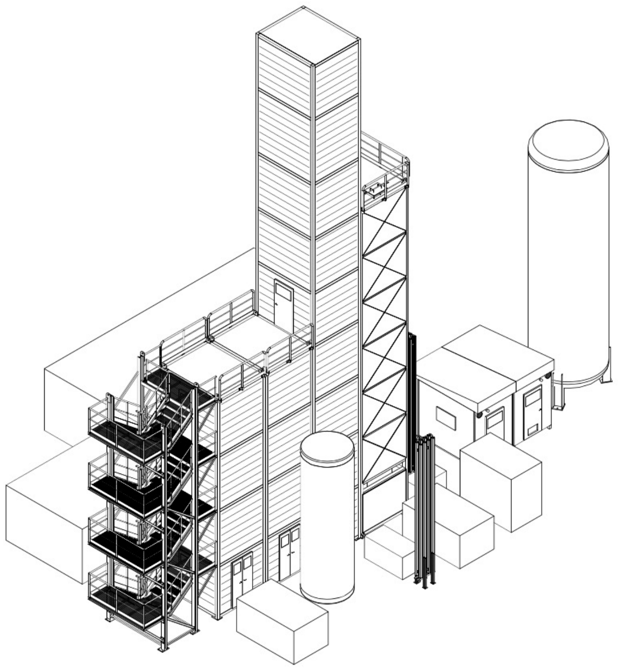
21 m2 of Cryogenic Silicon based Photo-Multipliers

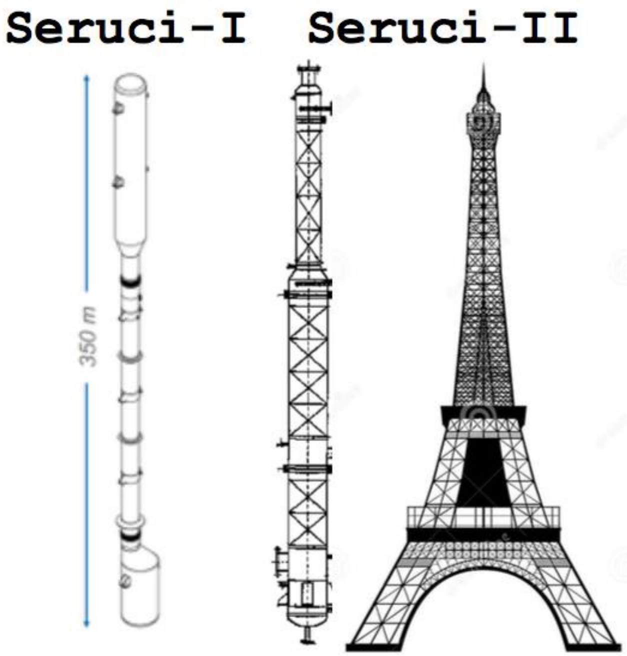


Darkside cryostat installation @LNGS

URANIA

- Procurement of 50 tonnes of UAr from same Colorado source as for DS-50
- Extraction of 250 kg/day, with 99.9% purity
- UAr transported to Sardinia for final chemical purification at Aria





ARIA

- Big cryogenic distillation column in Seruci, Sardinia
- Final chemical purification of the UAr
- Can process O(1 tonne/day) with 10^3 reduction of all chemical impurities
- Ultimate goal is to isotopically separate ^{39}Ar from ^{40}Ar (at the rate of 10 kg/day in Seruci-I)

Cutting Edge Technologies

Advanced Additive Manufacturing

Copper 3D printing

Ultra-Trace elemental and isotopical analysis

Cultural Heritage
Environmetal Studies
High Purity Material
.....

Quantum Technology

Quantum Computing
Quantum Communication

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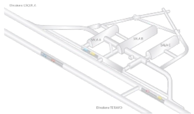
NOA - Nuova Officina Assergi



NOA funded with national/local funds

- **450 m² Clean Room**/Radon Free
- Detector instrumentation for

  Bonding,

  Dicing,

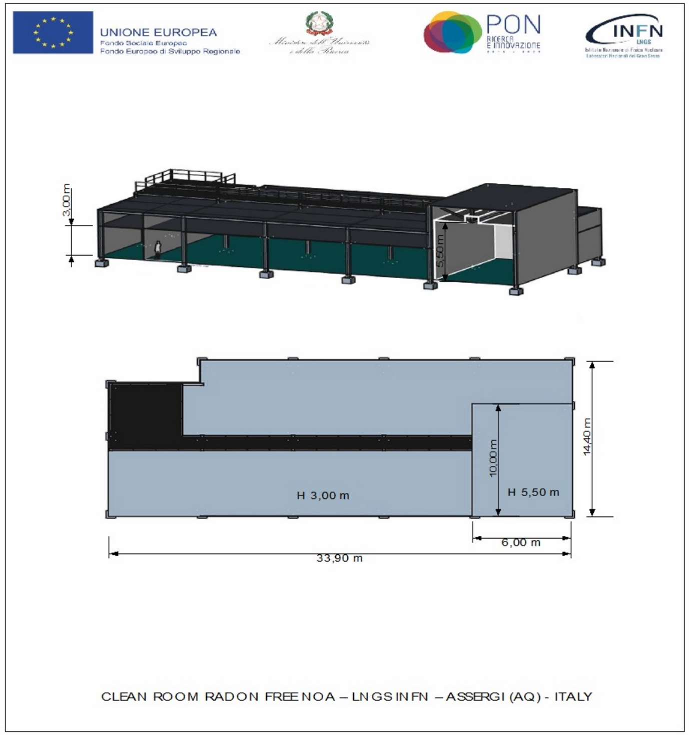
  Thermo-compression/epoxy bonding,

  Wire bonding
- PCB preparation

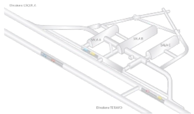
  Advanced and radio-clean reflow system
- Testing capabilities

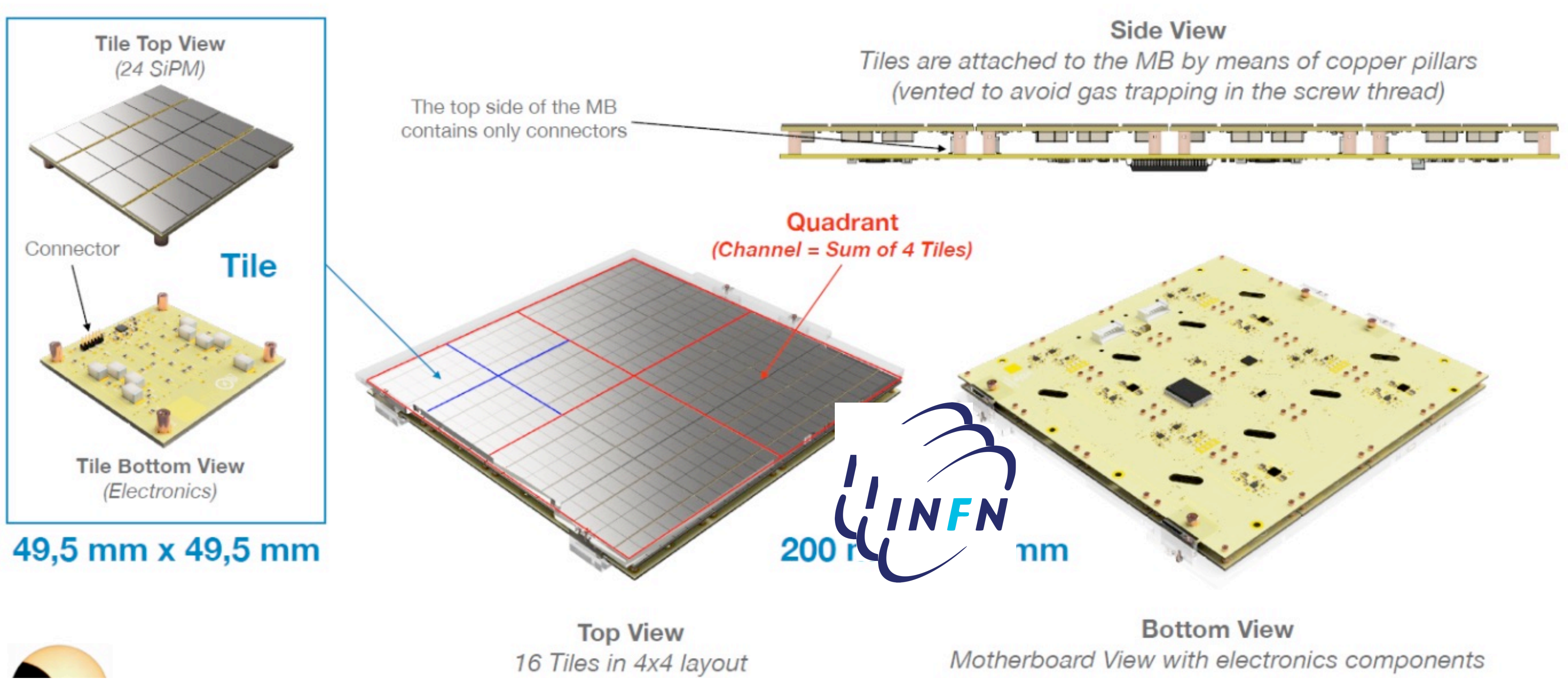
  Characterization at cryogenic temperature
- Production

  1st production for DS20k: ~ **20 m² SiPM**



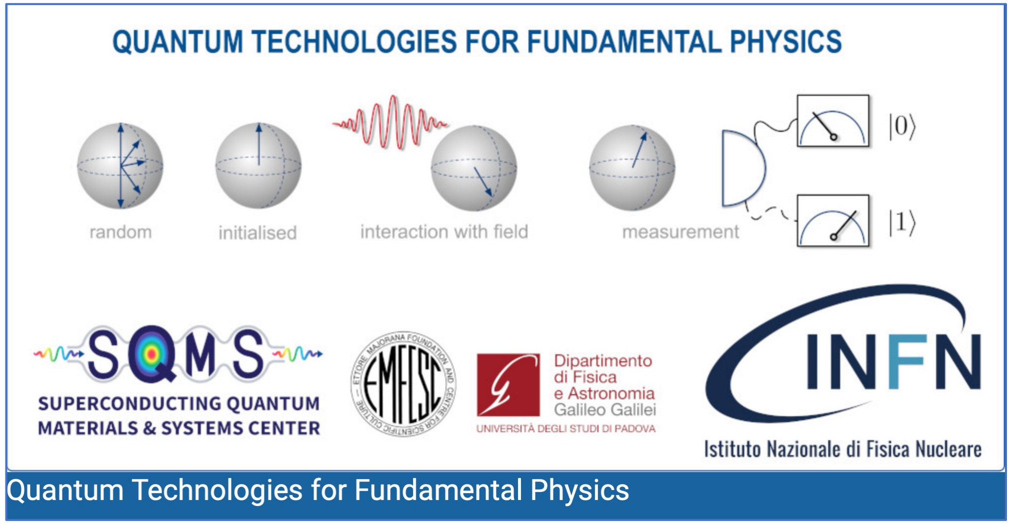
SiPM for DS20k @ NOA

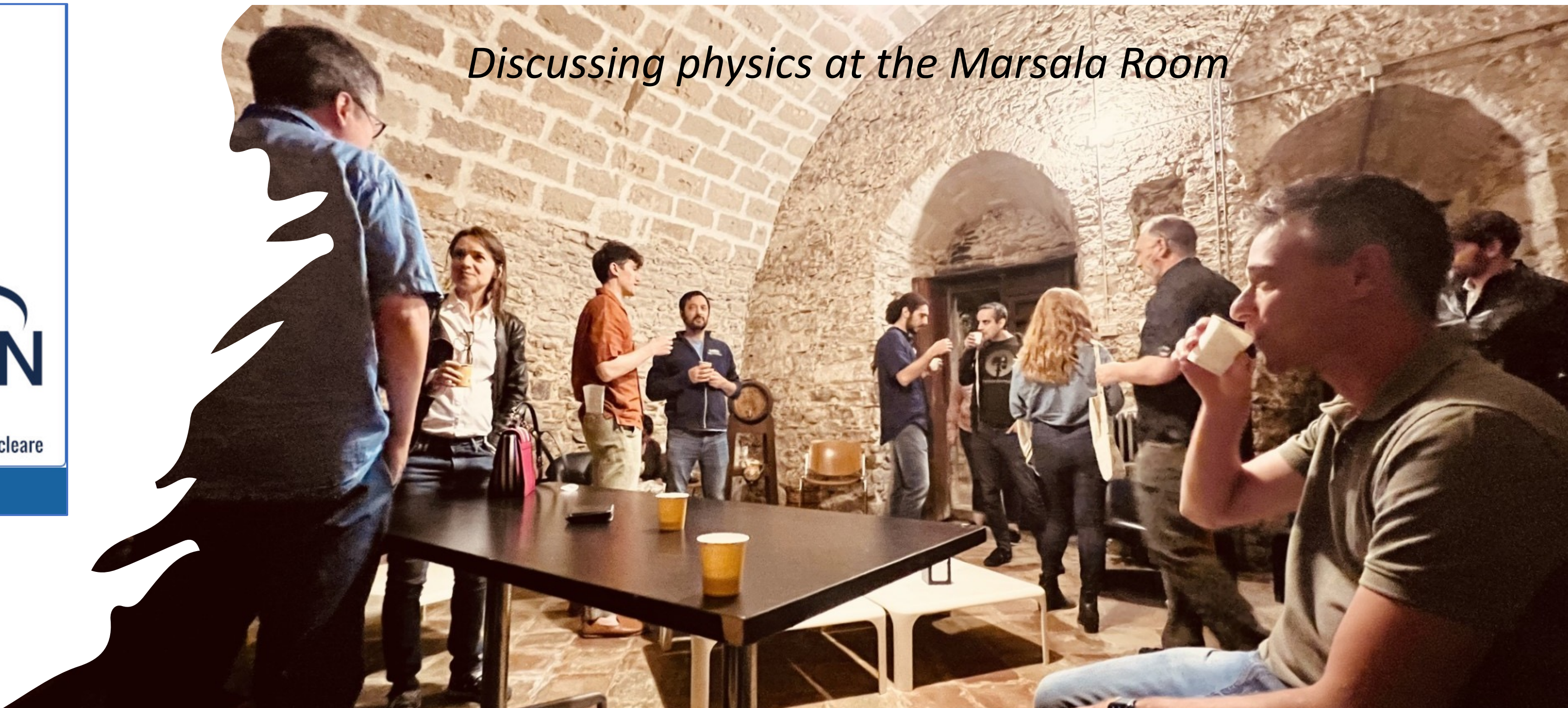




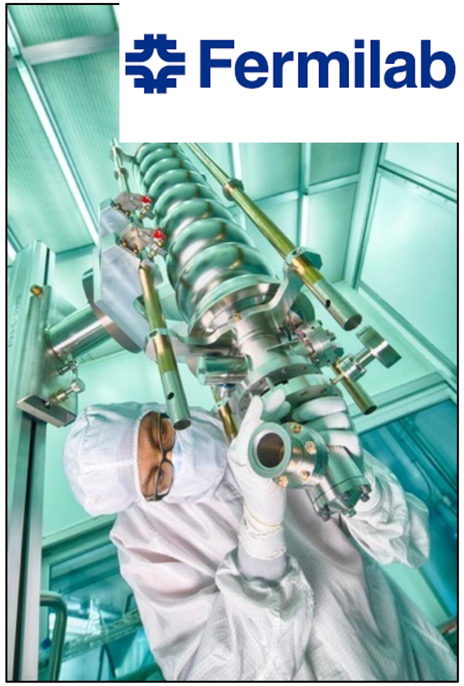
Quantum Technologies for Fundamental Physics

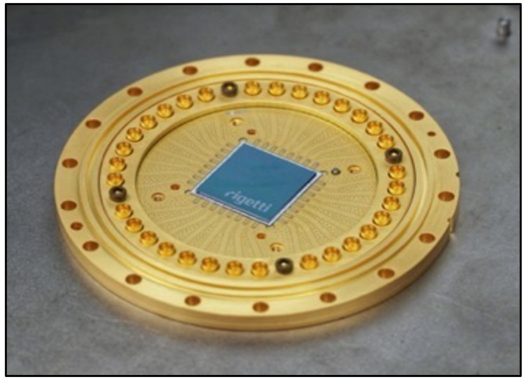
SQMS Project

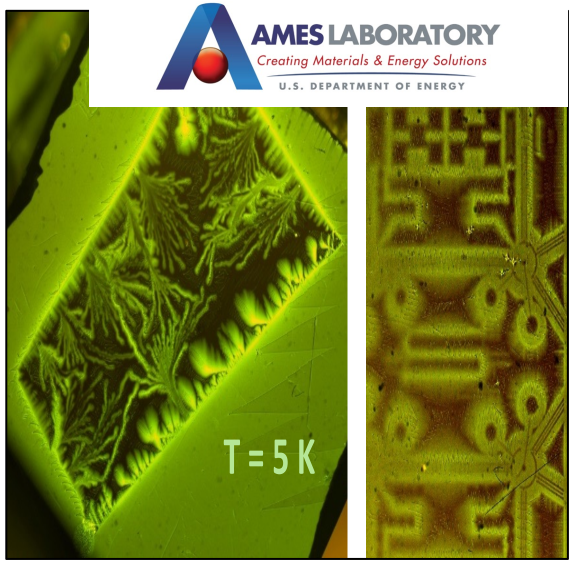



Discussing physics at the Marsala Room

Mission: Attacking the Decoherence Cross-Cutting Challenge





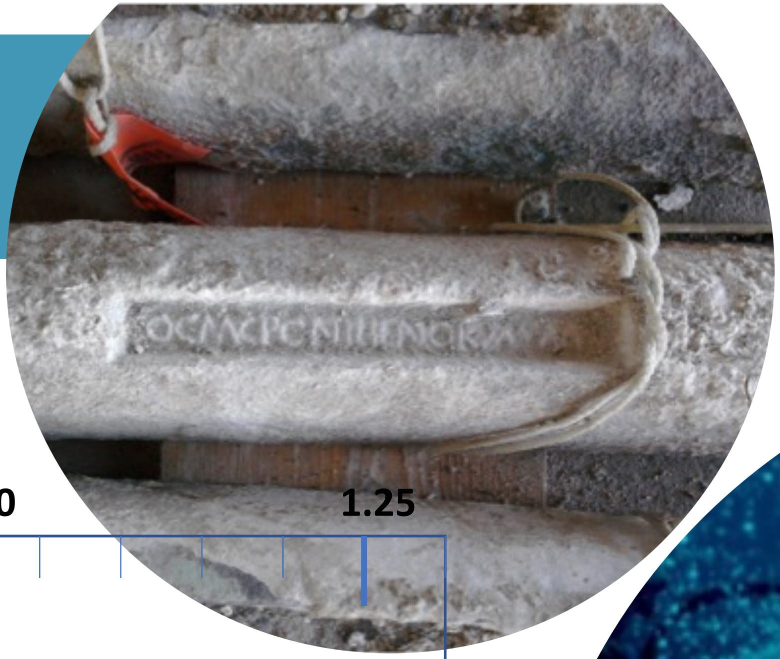


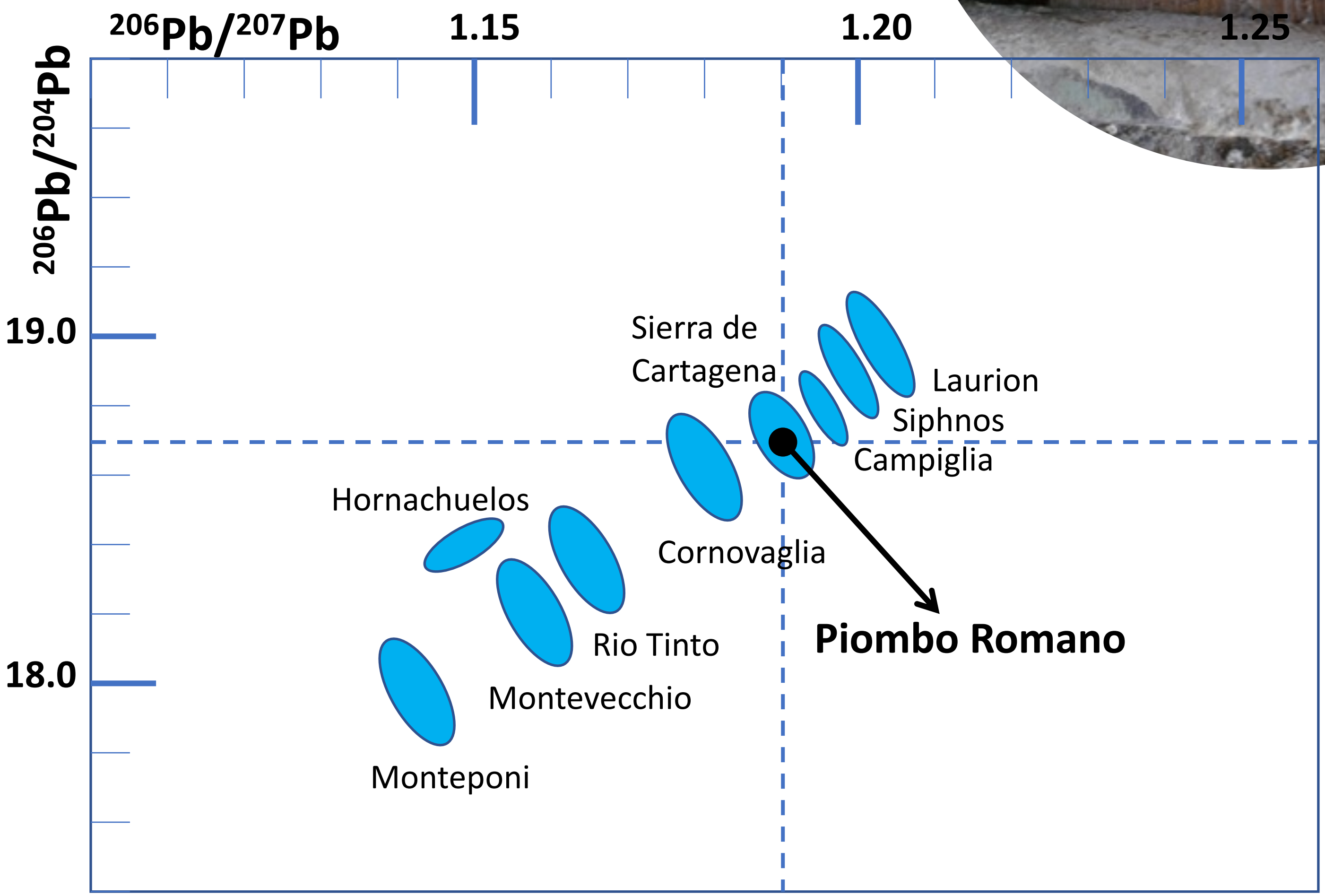
SQMS Mission
“bring together the power of national labs, industry and academia to achieve transformational advances in the QIS **major cross-cutting challenge** of **understanding** and **eliminating** the **decoherence** mechanisms in superconducting 2D and 3D devices, with the goal of enabling construction and deployment of superior quantum systems for computing and sensing."

Multidisciplinarity

Archeological Study

Ancient Roman Lead recovered from a Ship sunked in Sardegna **(I century b. C.)**





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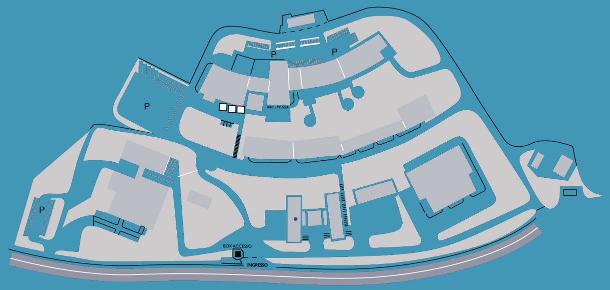
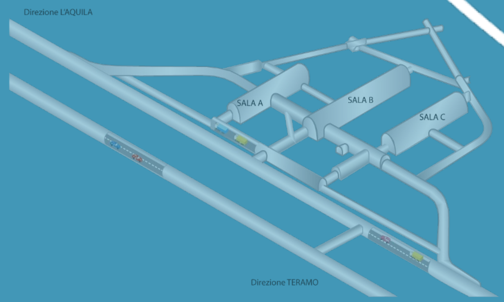
Conclusions

- @LNGS a large number of experiments are actually taking data or are under construction
- LNGS international community involve many country around the world and large number of researchers
- LNGS play a leading role in many different field of researches (DBD, DM, NA …)
- Future scientific programs are under discussion at international level:



Thank you



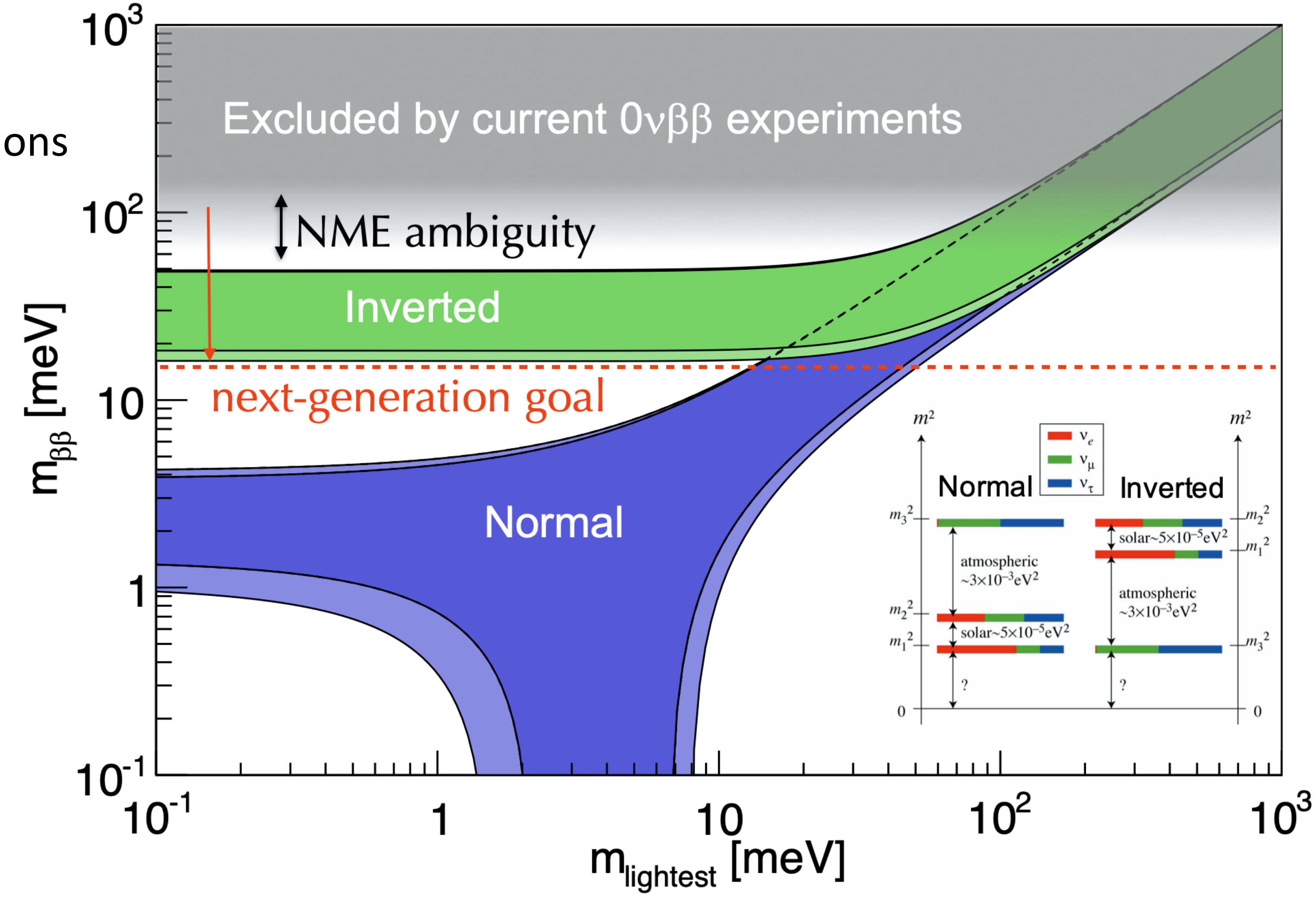
Light Majorana Neutrinos Mechanism

ββ0ν mediated by exchange of light Majorana neutrinos other mechanisms give no contributions

$$\eta_x = <m_{ee}> = \sum_k U_{ek}^2 m_k$$
$$= c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 e^{i\alpha} m_2 + s_{13}^2 e^{i\beta} m_3$$

m_{ee} depends on three masses and two Majorana phases

- Transition amplitude is proportional to the coherent sum of neutrino masses
- Majorana phases play a crucial role: possible cancellations
- Oscillation experiments could identify only neutrino mass differences



E. Previtali

Experimental Sensitivity

$$\tau_{1/2}^{0\nu} = ln2 \frac{\epsilon N_{nuclei} t_{meas}}{N_{\beta\beta}}$$

$$N_{\beta\beta} \leq \sqrt{bkg \cdot \Delta E \cdot M \cdot t_{meas}}$$

$N_{bkg} >> 1$
$$S_{1/2}^{0\nu} \propto \epsilon \frac{i.a.}{A} \sqrt{\frac{M \cdot t_{meas}}{bkg \cdot \Delta E}}$$

$N_{bkg} \sim 1$
$$S_{1/2}^{0\nu} \propto \epsilon \frac{i.a.}{A} M \cdot t_{meas}$$

Many important Parameters

$\mathbf{N_{nuclei}}$	number of active nuclei
$\mathbf{t_{meas}}$	measurement time [y]
M	mass of the detector [kg]
ε	detection efficiency
i.a.	isotopic abundance
A	atomic number
ΔE	energetic resolution [keV]
bkg	background index [c/keV/y/kg]

- isotope choice/enrichment
- experimental approach
- scalability
- stability
- cost

Urania

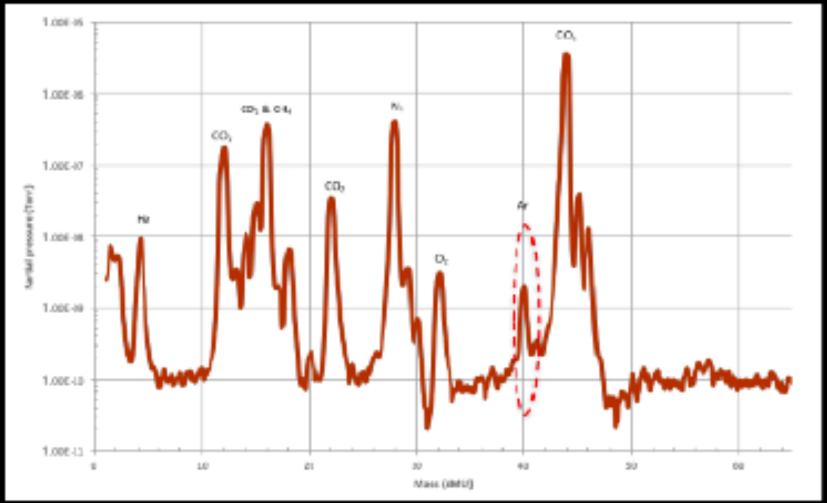
Isotope	Abundance	Specific activity (Bq/kg_{Ar})
^{40}Ar	0.9960	Stable
^{36}Ar	0.0033	Stable
^{38}Ar	0.0006	Stable
^{39}Ar	8.2×10^{-16}	1.0 [7,8]
^{37}Ar	$\approx 1.3 \times 10^{-20}$	$\approx 4.5 \times 10^{-2}$ [9]
^{42}Ar	6.8×10^{-21}	6.8×10^{-5} [10,11]

PHYSICAL REVIEW C 100, 024608 (2019)

- ^{39}Ar: Q=565keV and $T_{1/2}$=269y;
- 8×10^{-16} g/g in the AAr; β emitter with specific activity 1Bq/Kg
- Produced in the atmosphere mainly by neutron-induced reactions of cosmic rays on ^{40}Ar
- Very low production going underground (UAr). Production from natural radioactivity reactions (α, n)-induced on ^{39}K

Urania extrction site

- DOE canyon, Dolores County, Colorado
- The company Kinder-Morgan (KM), extracts gas from the subsoil, which is later used for oil mining purposes, with composition: CO_2 95%, UAr 430ppm; DarkSide "takes" the argon and returns the rest to KM
- The gas comes from the mantle ('magmatic CO_2'); the concentration of uranium and thorium in the mantle is typically at the level of ppb, 1/1000 relative to the crust (Well depth 3 KM) —>low probability of production of ^{39}Ar

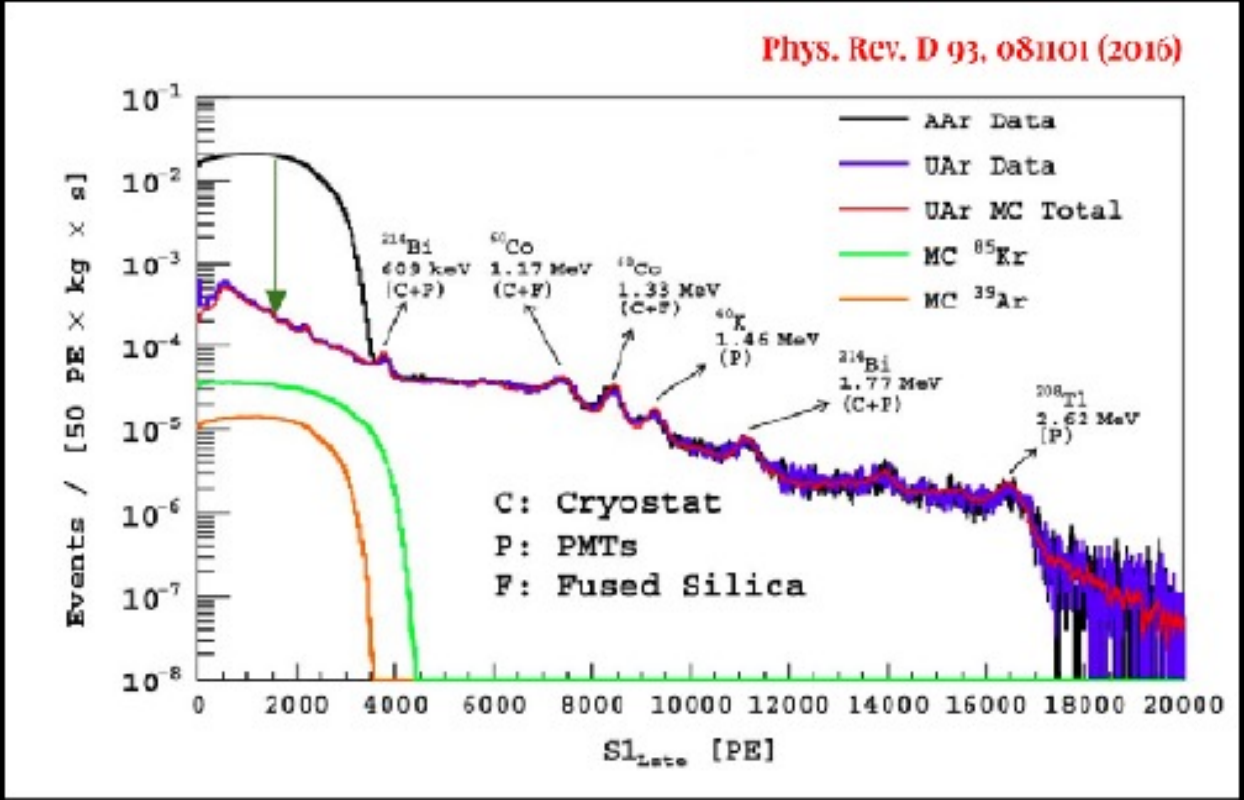


Composition	# of atoms (neutrons) yr^{-1} kg^{-1}			
	^{4}He	neutrons	^{21}Ne	^{39}Ar
Upper Continental Crust	1.64×10^{10}	10,680	753	28.7
Middle Continental Crust	8.98×10^{9}	6114	416	13.9
Lower Continental Crust	1.53×10^{9}	1129	70.2	0.749
Bulk Continental Crust	9.43×10^{9}	6253	433	15.3
Bulk Oceanic Crust	3.79×10^{9}	260	15.8	0.0235
Depleted Upper Mantle	2.51×10^{7}	22.4	1.06	0.000257

(O. Šrámek et al., Geochimica et Cosmochimica Acta 196 (2017) 370)

Urania

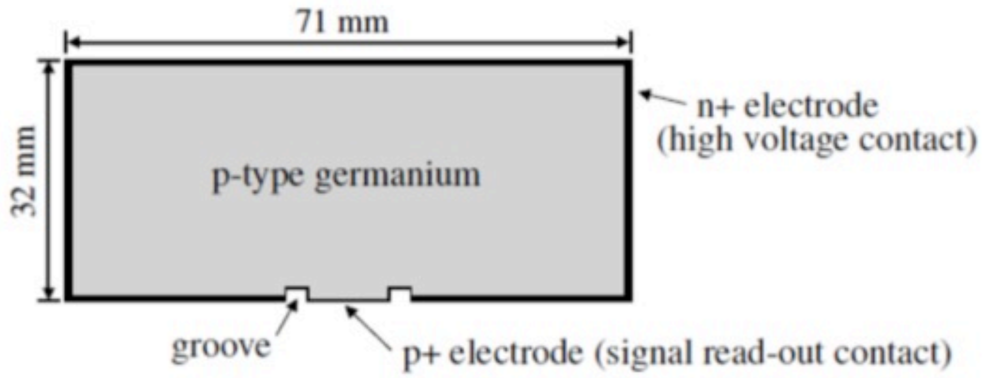
- ^{85}Kr : 1.8 ± 0.1 mBq/kg
- ^{39}Ar : 0.7 ± 0.1 mBq/kg

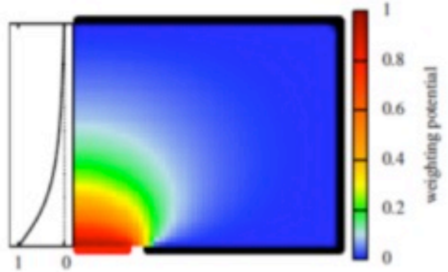


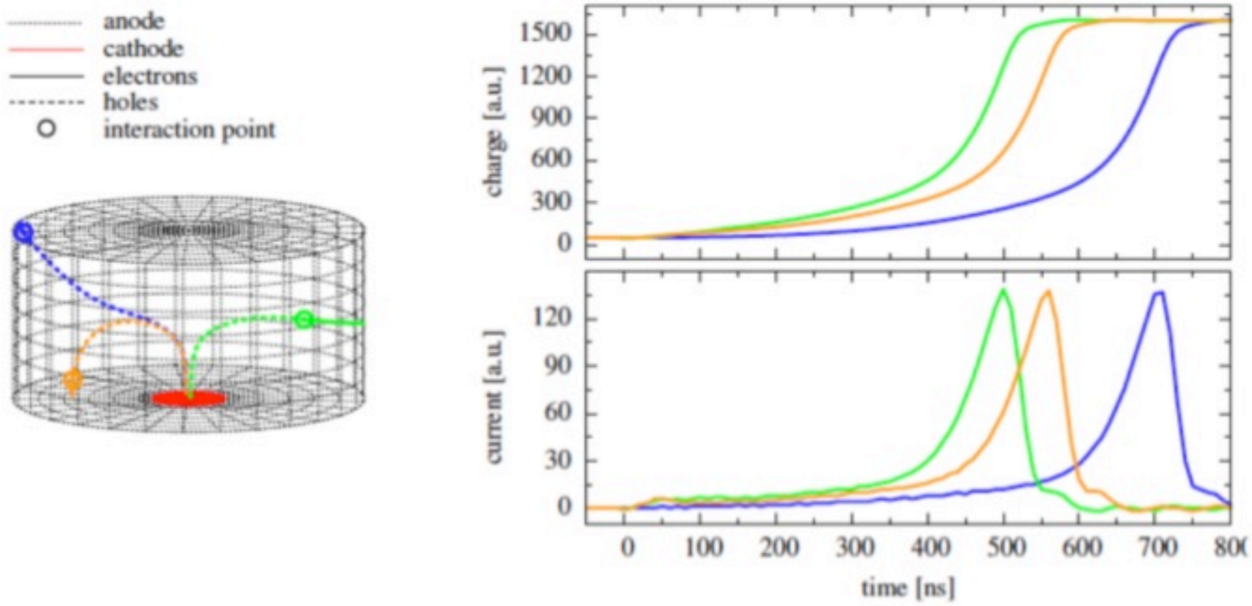
For DS50 results please see the talk of T.Hugues Aug 29th 4.45PM Dark Matter session

Gerda/Legend

Novel HPGe detectors allow for efficient PID







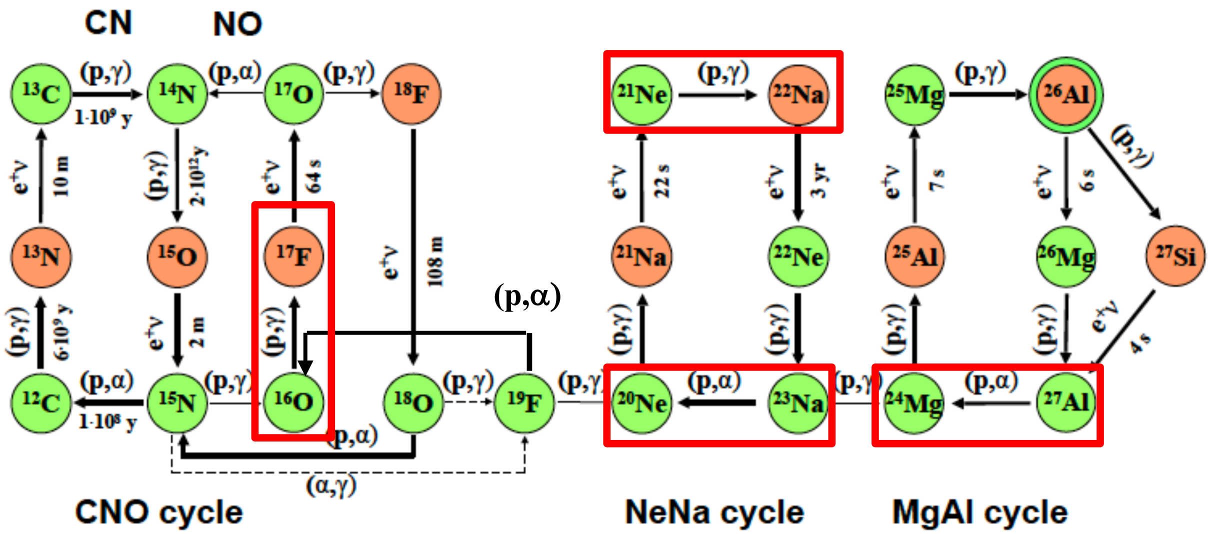
(a) Trajectories

(b) Charge and current pulses

Thanks Prof. S. Shoenert

LUNA400 2022-2024 new program

- $^{16}O(p,\gamma)^{17}F$ will be done using the solid target beam line setup together with the γ detectors available, only minimal modifications are foreseen;
- $^{21}Ne(p,\gamma)^{22}Na$ will be done using the gas target beam line setup together with the γ detectors available, only gas enriched in ^{21}Ne is needed;
- $^{23}Na(p,\alpha)^{20}Ne$ & $^{27}Al(p,\alpha)^{24}Mg$ Edinburgh group will develop the α particle detection setup.



Completed
Data taking

Current situation

$T_{1/2} > 10^{24}$ y 90% C.I. restricted club

GERDA $T_{1/2} > 1.8 \times 10^{26}$ y
Phys. Rev. Lett. 125, 252502 (2020)

KamLAND-Zen 400 $T_{1/2} > 1.07 \times 10^{26}$ y
Phys. Rev. Lett. 117, 082503 (2016)

EXO-200 $T_{1/2} > 3.5 \times 10^{25}$ y
Phys. Rev. Lett. 123, 161802 (2019)

MAJORANA dem. $T_{1/2} > 2.7 \times 10^{25}$ y
Phys. Rev. C 100, 025501

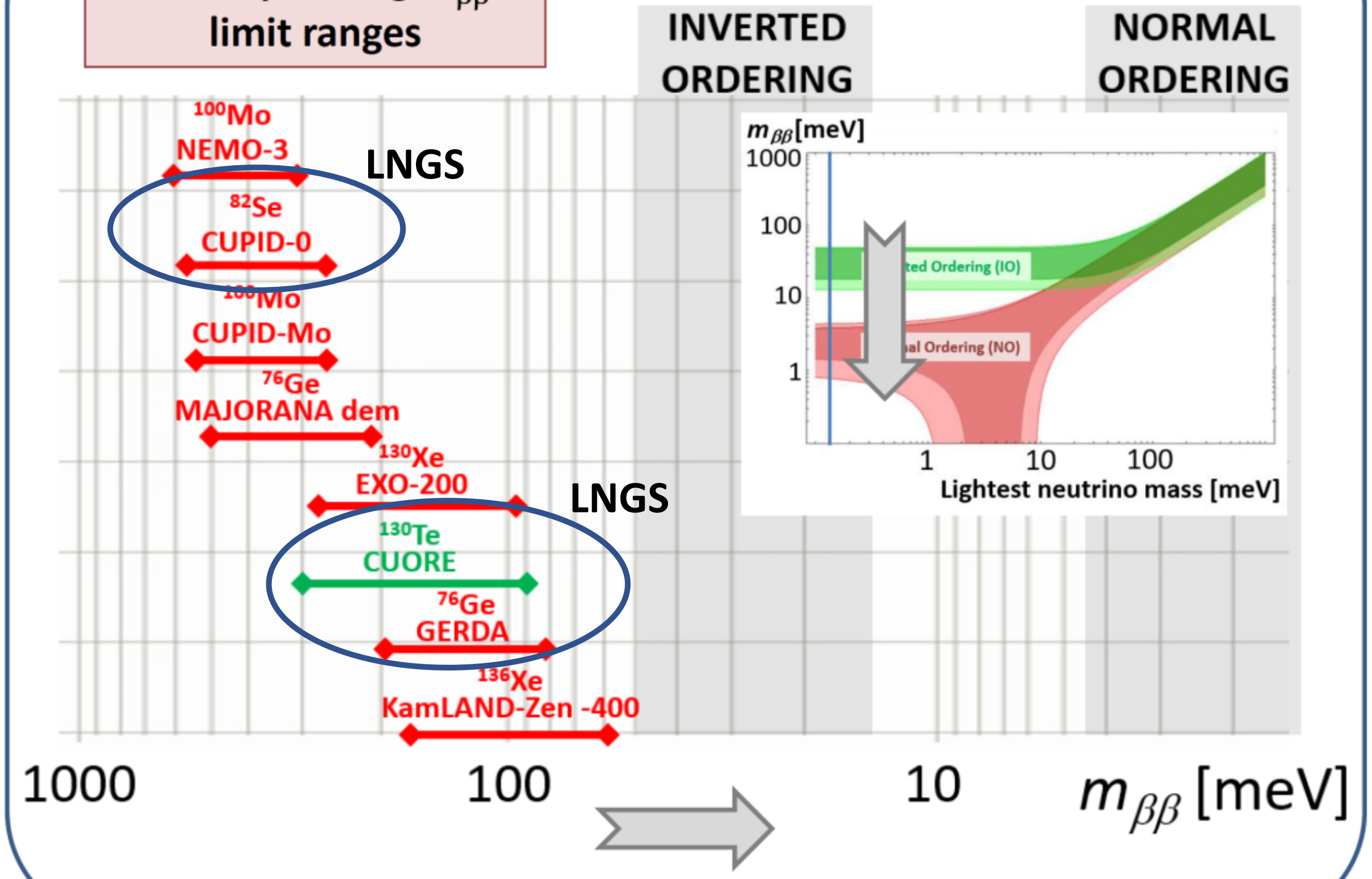
CUORE $T_{1/2} > 2.2 \times 10^{25}$ y
arXiv:1907.09376

CUPID-0 $T_{1/2} > 4.7 \times 10^{24}$ y
L. Pagnanini, TAUP 2021

CUPID-Mo $T_{1/2} > 1.8 \times 10^{24}$ y
B. Welliver, TAUP 2021

NEMO-3 $T_{1/2} > 1.1 \times 10^{24}$ y
Phys. Rev. D 92, 072011 (2015)

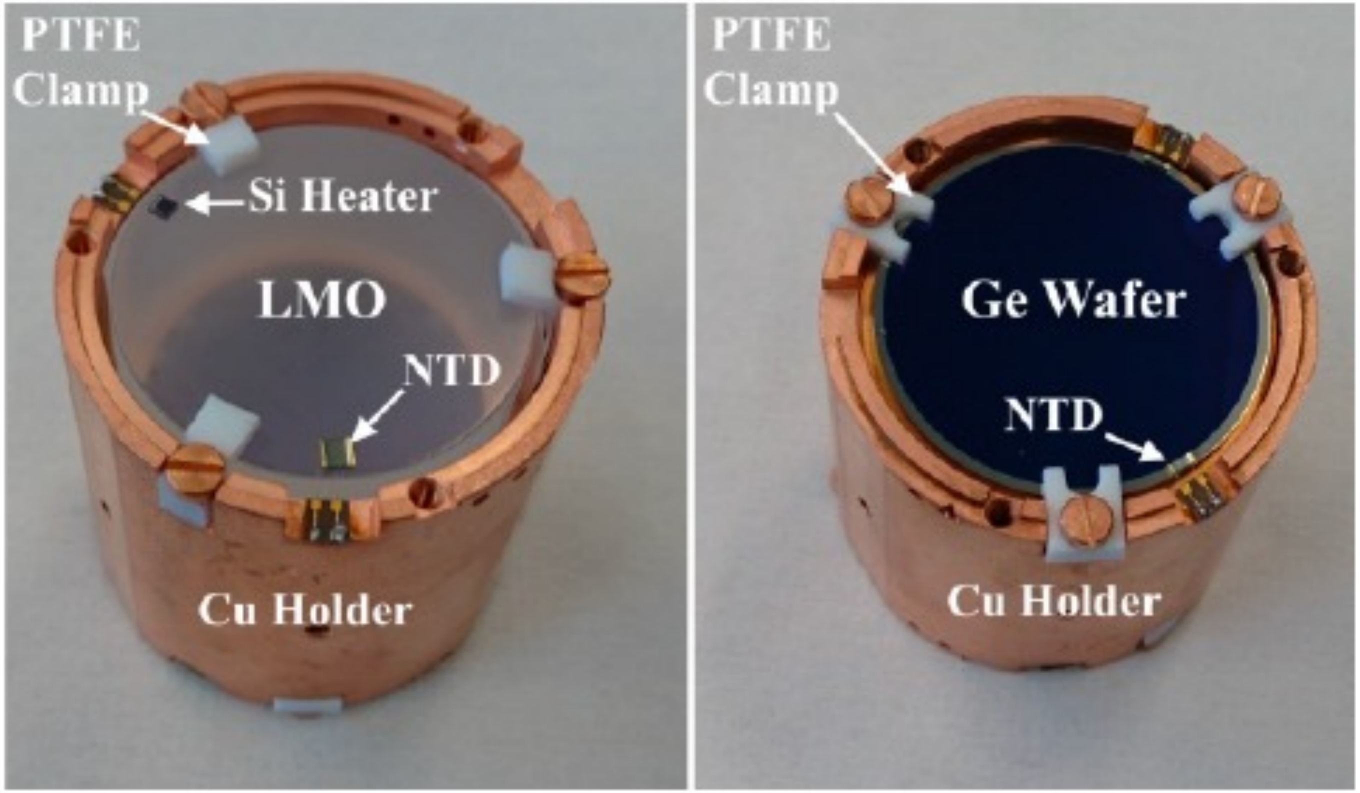
Corresponding $m_{\beta\beta}$ limit ranges



Present and Future experiments

	Experiment	Isotope	Status	Laboratory	Moles of isotope	Isotopic abundance	B (events/kg$_{iso}$/keV/yr)	Fiducial isotope mass (kg)	Active fraction (%)	Eficiency	FWHM (keV)
High-purity Ge detectors	GERDA-II	^{76}Ge	completed	LNGS	450	0.87	6.00E-04	30	88	0.7189	3.29
	MJD	^{76}Ge	completed	SURF	240	0.88	4.74E-03	16	90	0.8099	2.585
	LEGEND-200	^{76}Ge	construction		2400	0.9	2.10E-04	166	91	0.819	2.585
	LEGEND-1000	^{76}Ge	proposed		12000	0.91	1.00E-05	839	92	0.828	2.585
Xenon TPC's	EXO-200	^{136}Xe	completed	WIPP	1200	0.81	1.99E-03	75	46	0.84	72.85
	nEXO	^{136}Xe	proposed	SNOLAB	34000	0.9	2.10E-06	2959	64	0.66	47
	NEXT-100	^{136}Xe	construction	LSC	640	0.9	4.90E-04	77	88	0.3724	23.5
	NEXT-HD	^{136}Xe	proposed		7400	0.9	5.80E-06	956	95	0.3916	18.095
	PandaX-III-200	^{136}Xe	construction	CJPL	1300	0.9	1.20E-04	136	77	0.481	72.85
	LZ-nat	^{136}Xe	construction	SURF	4700	0.09	1.22E-03	90	14	0.8	58.75
	LZ-enr	^{136}Xe	proposed	SURF	46000	0.9	1.20E-04	876	14	0.8	58.75
	Darwin	^{136}Xe	proposed		27000	0.09	4.10E-05	477	13	0.9	47
Large liquid scintillators	KLZ-400	^{136}Xe	completed	Kamioka	2500	0.91	3.80E-04	150	44	0.97	267.9
	KLZ-800	^{136}Xe	data taking	Kamioka	5000	0.91	5.30E-05	394	58	0.97	267.9
	KL2Z	^{136}Xe	proposed	Kamioka	6700	0.91	2.20E-05	729	80	0.97	141
	SNO+I	^{130}Te	construction	SNOLAB	10000	0.348	3.00E-04	272	20	0.97	188
	SNO+II	^{130}Te	proposed	SNOLAB	51000	0.348	3.00E-04	1873	27	0.97	133.95
Cryogenic calorimeters	CUORE	^{130}Te	data taking	LNGS	1585	0.348	5.38E-02	206	100	0.8096	7.52
	CUPID-0	^{82}Se	completed	LNGS	62	0.96	5.95E-03	5	100	0.6966	19.975
	CUPID-Mo	^{100}Mo	completed	LSM	23	0.97	7.82E-03	2.3	100	0.6916	7.52
	CROSS	^{100}Mo	construction	LSC	48	0.96	1.71E-02	5	100	0.675	4.935
	CUPID	^{100}Mo	proposed	LNGS	2500	0.96	1.70E-04	250	100	0.711	4.935
	AMORE	^{100}Mo	proposed	Yemilab	1100	0.96	1.70E-04	110	100	0.7462	4.935
Tracking calorimeters	NEMO-3	^{100}Mo	completed	LSM	690	0.9	2.18E-03	69	100	0.11	347.8
	SuperNEMO-D	^{82}Se	construction	LSM	850	0.9	1.10E-04	70	100	0.28	195.05
	SuperNEMO	^{82}Se	proposed	LSM	1200	0.9	3.20E-05	98	100	0.28	169.2

CUORE → CUPID



1534 Li_2MoO_4 crystals with
Ge wafer as light detectors

253 kg ^{100}Mo (472 kg crystals)
background 10^{-4} cnt/(keV kg yr)
FWHM ~ 0.2% at $Q_{\beta\beta}$

sensitivity $T_{1/2}$ ~ 1.5 10^{27} yr (limit)
1.1 10^{27} yr (discov)