Attualita’ e prospettive delle ricerche sperimentali in fisica del neutrino

Focus alle energie dei MeV

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Pisa

Struttura del mio intervento:

Una selezione delle attivita’ in fisica del neutrino da gli anni ’80 ad oggi

Principali risultati nel settore delle oscillazioni dei neutrini.
- Neutrini solari
- Neutrini da reattore
- Neutrini da acceleratori
- Stato dell’arte della determinazione dei parametri della matrice di mixing dei neutrini

Le questioni rimaste aperte nel settore di Yukawa leptonico

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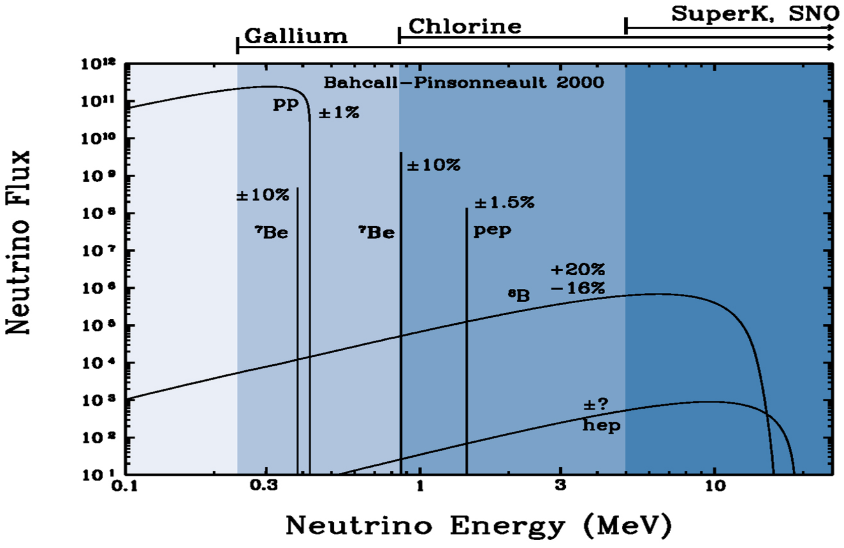
Stato dell’arte ed attivita’ future della ricerca del Decadimento Doppio Beta senza emissione di neutrini ($0\nu\beta\beta$ o 0nDBD)

La fisica di precisione nei futuri esperimenti

- Reattore
- Acceleratore

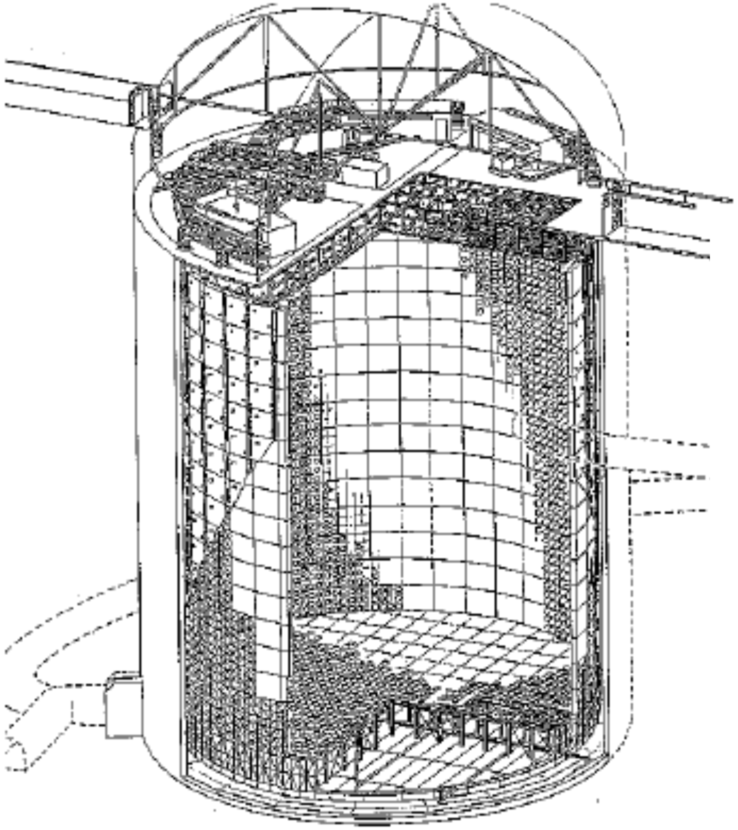
Dal 1967 al ~ 2000: Gli esperimenti sui neutrini solari e atmosferici danno evidenza del fenomeno di oscillazione fra gli autostati di massa dei neutrini



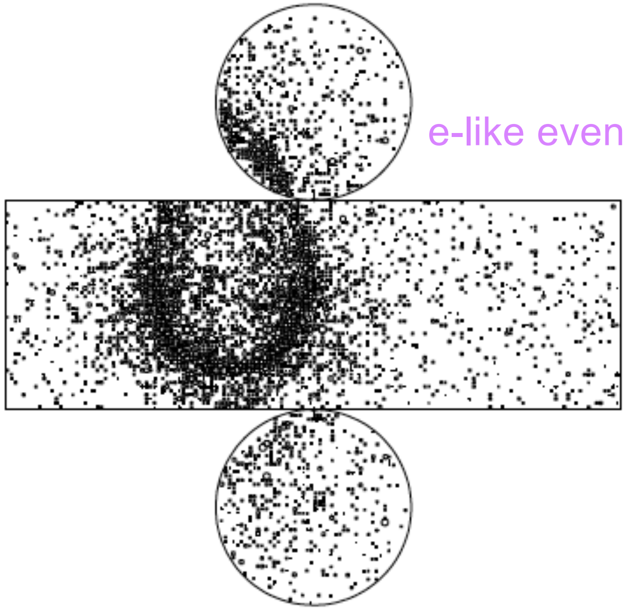
	Measured	Expected
Cl experiment	2.56 $\pm$ 0.23 SNU	8.2 SNU
Ga exp. (GALLEX,GNO,SAGE)	68.1 $\pm$ 3.75 SNU	129^{+9}_{-7} SNU
Kamiokande (1 kton, water Cerenkov, electron Scattering)	(2.8 ± 0.19 ± 0.33) x 10^{+6} cm^{-2} s^{-1}	(5.82 ± 1.34) × 10^{+6} cm^{-2} s^{-1}
SuperKamiokande (12 kton water Cerenkov, electron scattering $\nu_x + e^- \rightarrow \nu_x + e^-$ (ES))	(2.32 ± 0.03 ± 0.08) x 10^{+6} cm^{-2} s^{-1}	

The ν_{atm} sector: Kamiokande and Super-K find the deficit

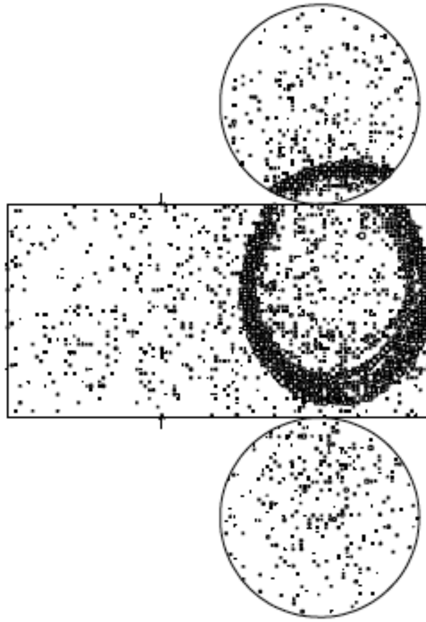
12 kton water Cerenkov
Located at Kamioka mine



- (quasi-)elastic scattering, $\nu\, N \rightarrow l\, N'$,
- single meson production, $\nu\, N \rightarrow l\, N'\, m$,
- coherent π production, $\nu\ {}^{16}\mathrm{O} \rightarrow l\, \pi\ {}^{16}\mathrm{O}$,
- deep inelastic scattering, $\nu N \rightarrow l\, N'$ *hadrons*.

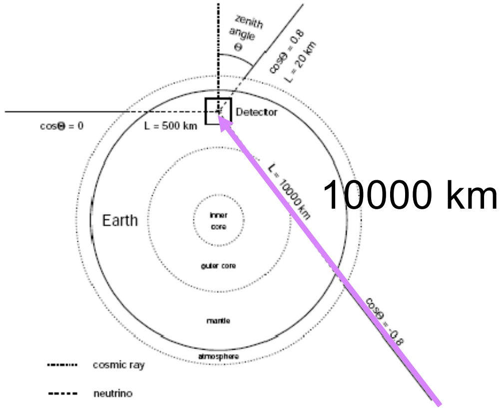


e-like event



μ-like event

Kamiokande and Super-K find the ν_{atm} deficit



Atmospheric neutrino experiments measure two quantities :

1. the ratio of ν_μ to ν_e observed in the flux
2. zenith angle distribution of the neutrinos (that is, the path length distribution).

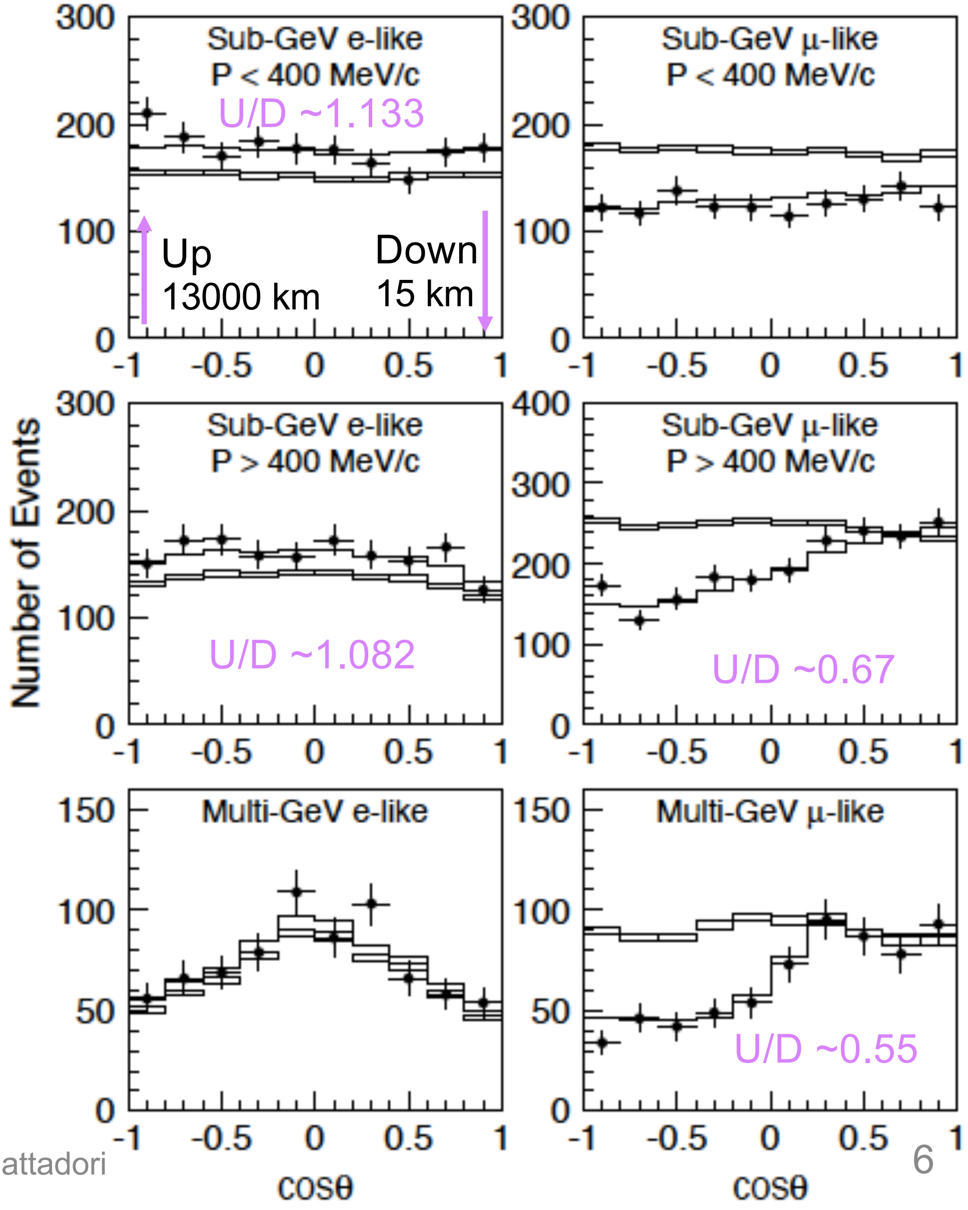
To help interpret the results and to cancel systematic uncertainties most experiments report a double ratio

$$R = \frac{(N_\mu/N_e)_{DATA}}{(N_\mu/N_e)_{SIM}}$$

Found Significant U/D asym

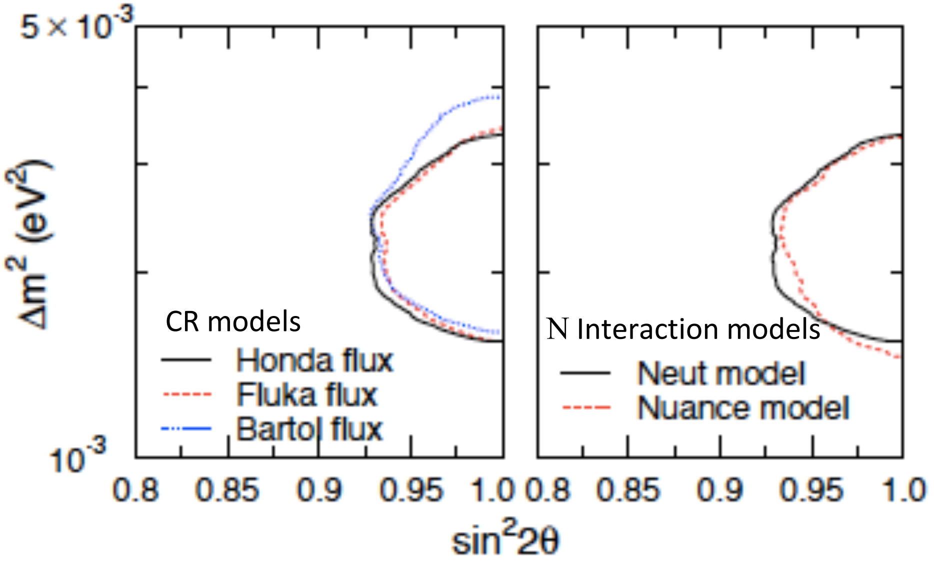
R was found < 1

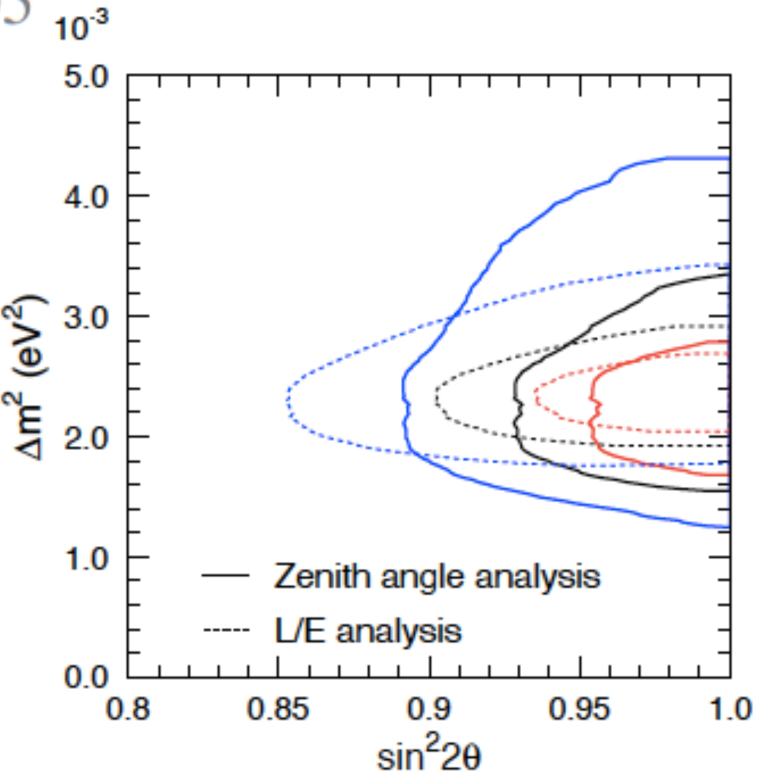
- Too many ν_e ?
- Too few ν_μ ?
- Both?



Super- Kamiokande results (2005)

arXiv:hep-ex/0501064v2 15 Jun 2005





Results well explained in the framework of $\nu_\mu -> \nu_\tau$ oscillations

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2 \left(\frac{1.27 \Delta m^2 (\mathrm{eV}^2) L(\mathrm{km})}{E_\nu (\mathrm{GeV})} \right)$$

Δm^2_{12}=6.5 $\times 10^{-5}$ eV^2

1.5×10^{-3} < $sin^2 2\theta$ < 3.4×10^{-3} eV^2 at 90% C.L.

Fino al 2011: sorgenti artificiali confermano risultati dei ν_{atm}

Tra il 1998 e il 2005, le evidenze di oscillazioni di neutrino diventano davvero molto solide (SuperKamiokande, SNO, MACRO, K2K…) e appare chiaro che **esiste almeno un'oscillazione visible sulla terra con sorgenti artificiali**. Quella tra la seconda e la terza famiglia di neutrino ("scala degli atmosferici"):

$$\frac{\Delta m^2_{32} L}{4E}$$

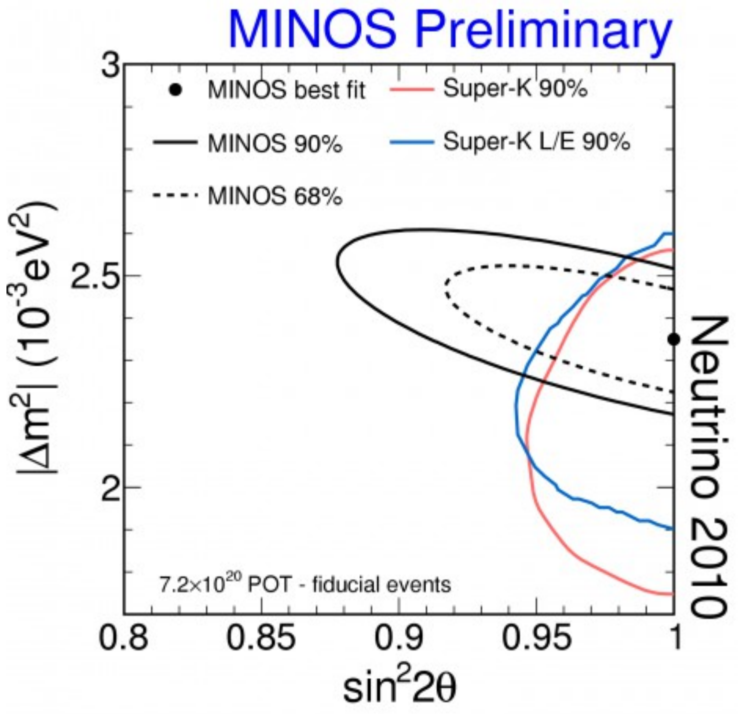
Year 2005

«**oscillation phase**» It is O(1) for
E= O(1 GeV) and L= O(100 km)
Cool, we can build experiment on Earth ☺

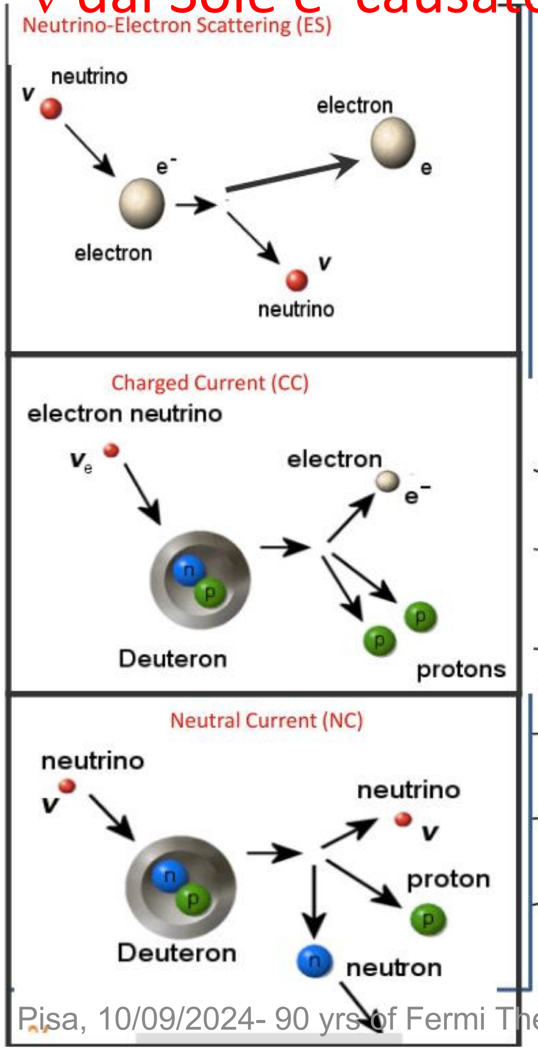
$$P(\nu_\mu \to \nu_\tau) \simeq \underbrace{\cos^4\theta_{13}}_{\approx 1}\,\underbrace{\sin^2 2\theta_{23}}_{\approx 1}\,\sin^2\frac{\Delta m^2_{32} L}{4E}$$

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) = \sin^2 2\theta_{13}\,\sin^2\theta_{23}\,\sin^2\frac{\Delta m^2_{32} L}{4E}$$

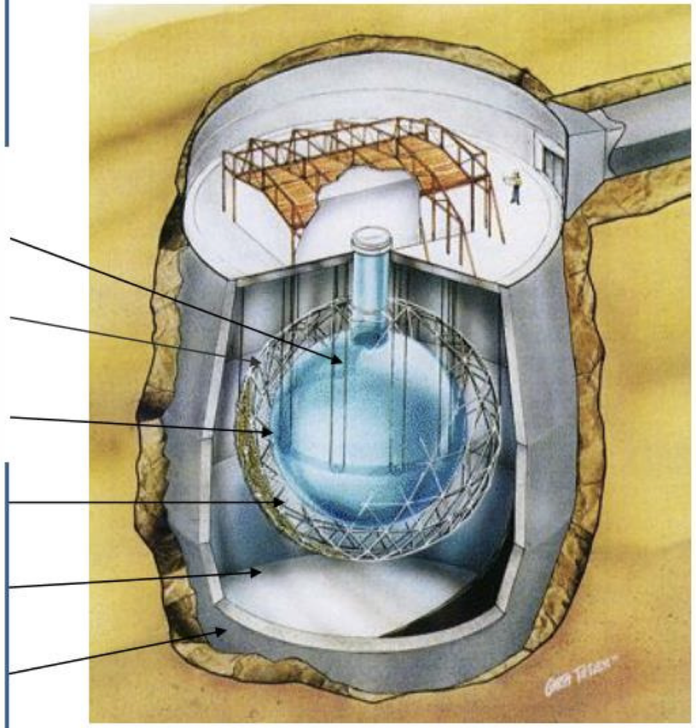
<0.1 (ma quanto piccolo??)



Dalla fine anni ’90 entra in funzione SNO: dal 2001 indica che il deficit di ν dal Sole e’ causato dalle fenomeno delle oscillazioni



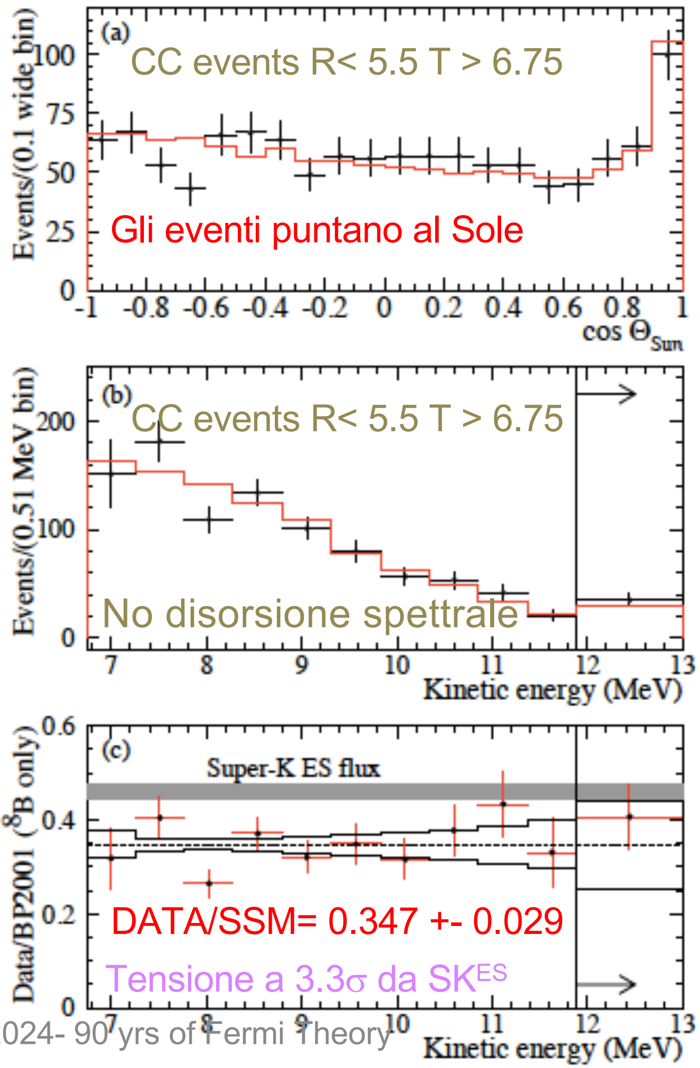
Sudbury Neutrino Observatory



1kton D_2O Cerenkov in a water shielding buffer

SNO first (2001) scientific results

Phys. Rev. Lett. 87, 071301 – Published 25 July 2001



CC events R< 5.5 T > 6.75

Gli eventi puntano al Sole

CC events R< 5.5 T > 6.75

No disorsione spettrale

DATA/SSM= 0.347 +- 0.029

Tensione a 3.3σ da SK^{ES}

Using the integrated rates above the kinetic energy threshold $T_{\text{eff}} = 6.75$ MeV, the measured ^{8}B neutrino fluxes assuming no oscillations are:

$$\phi^{CC}_{SNO}(\nu_e) = 1.75 \pm 0.07\ (\text{stat.})^{+0.12}_{-0.11}\ (\text{sys.}) \pm 0.05\ (\text{theor.}) \times 10^6\ \text{cm}^{-2}\text{s}^{-1}$$

$$\phi^{ES}_{SNO}(\nu_x) = 2.39 \pm 0.34 (\text{stat.})^{+0.16}_{-0.14}\ (\text{sys.}) \times 10^6\ \text{cm}^{-2}\text{s}^{-1}$$

$$\phi^{ES}_{SK}(\nu_x) = 2.32 \pm 0.03\ (\text{stat.})^{+0.08}_{-0.07}\ (\text{sys.}) \times 10^6\ \text{cm}^{-2}\text{s}^{-1}.$$

The difference between the flux $\phi^{ES}(\nu_x)$ measured by Super-Kamiokande via the ES reaction and the $\phi^{CC}(\nu_e)$ flux measured by SNO via the CC reaction is $0.57 \pm 0.17 \times 10^6$ cm^{-2}s^{-1}, or 3.3σ [8]. The probability that the SNO measurement is not a downward fluctuation from the Super-Kamiokande measurement is 99.96%. For reference, the ratio of the SNO CC ^{8}B flux to that of the BP2001 solar model [7] is 0.347±0.029, where all uncertainties are added in quadrature.

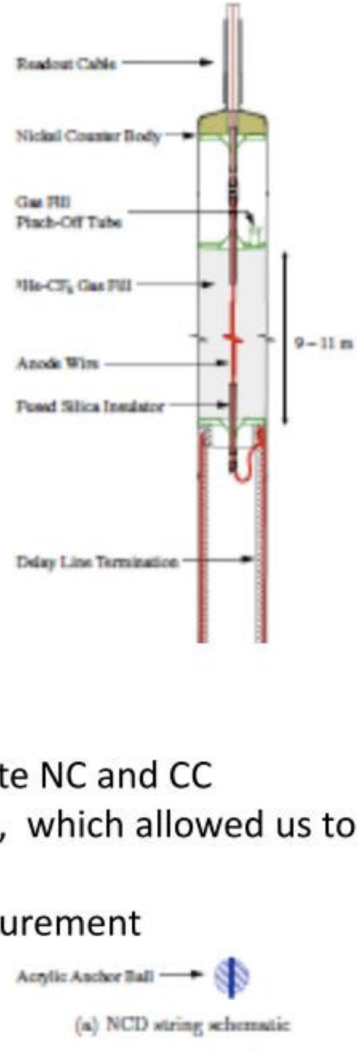
In summary, the results presented here are the first direct indication of a non-electron flavor component in the solar neutrino flux, and enable the first determination of the total flux of ^{8}B neutrinos generated by the Sun.

Three Phases of SNO: 3 NC reactions

✓ **Phase I: Just D_2O: neutron capture on deuteriu**
- Simple detector configuration, clean me
- Low neutron sensitivity
- Poor discrimination between neutrons a

✓ **Phase II: D_2O + NaCl: neutron capture on Chlorine**
- Very good neutron sensitivity
- Better neutron electron separation

● **Phase III: D_2O + ^{3}He Proportional Counters**
- Good neutron sensitivity
- Great neutron/electron separation



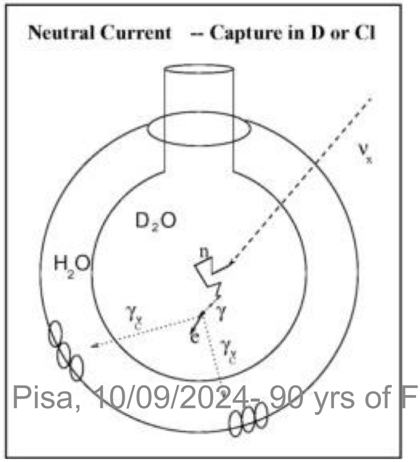
(a) NCD string schematic

2001: First scientific results

2002: Neutral current & day/nigt results

2003: Salt Phase Results

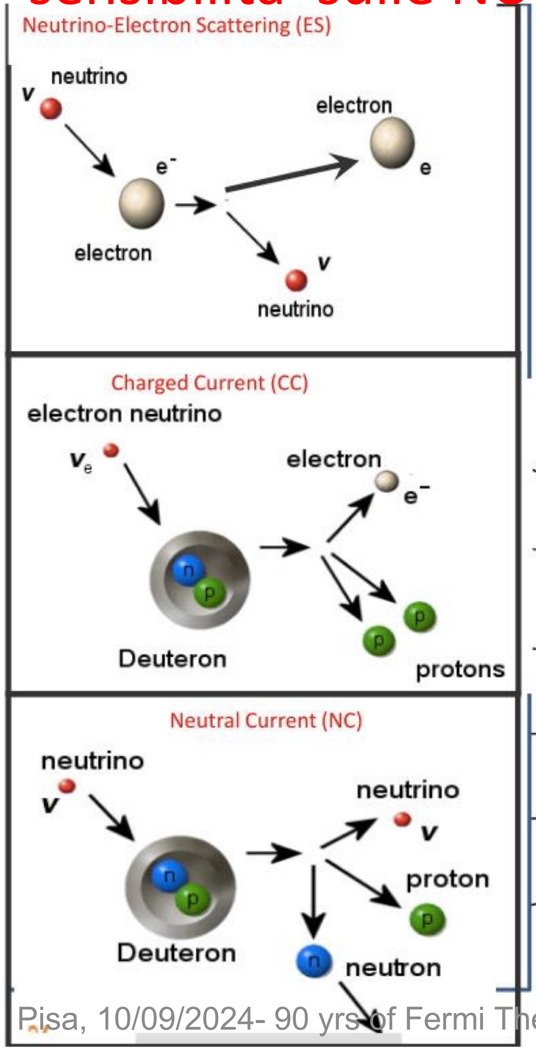
2015: Art Mc Donald shares the Noble Prize with M. Koshiba



Why three phases?

1. Additional information to separate NC and CC
2. Completely different systematics, which allowed us to check for consistency.
3. Allowed us to “repeat” the measurement

Risultato di SNO – diluizione di NaCl per catturare il n e cosi'migliorare sensibilita' sulle NC



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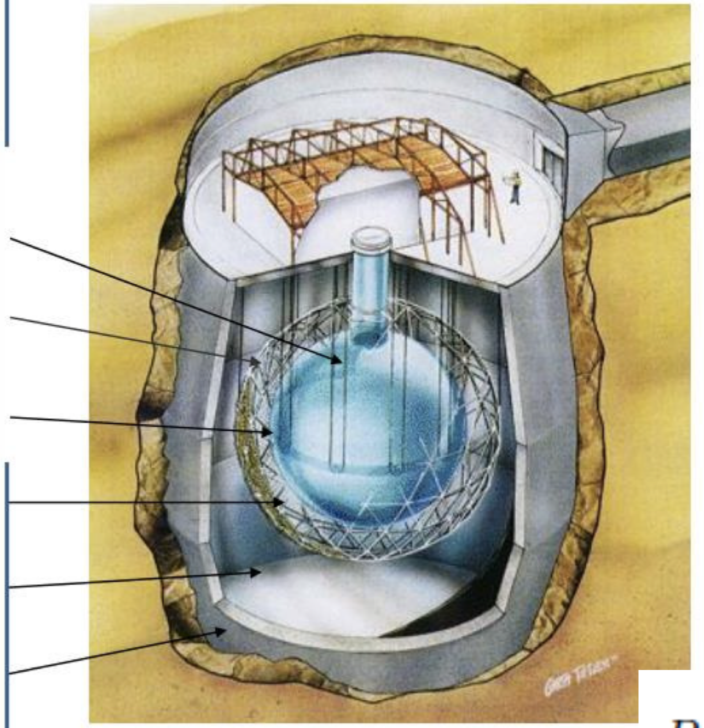


$$\Phi_{CC} = 1.59^{+0.08}_{-0.07}(\text{statistical})^{+0.06}_{-0.08}(\text{systematic})$$

$$\Phi_{NC} = 5.21 \pm 0.27(\text{stat}) \pm 0.38(\text{syst})$$

$$\Phi_{ES} = 2.21^{+0.31}_{-0.26}(\text{stat}) \pm 0.10(\text{syst})$$

1. about 2/3 of the ν_e have changed their flavor to other active neutrino types.

2. the observed total flux of active ν is in excellent agreement with the flux of ^{8}B ν obtained from solar models:

$\Phi^B{}_{SSM} = 5.82 \times (1 \pm 0.23) \times 10^{-6}\,\text{cm}^{-2}\text{s}^{-1}$

→ Null hypothesis of no flavor change for ν_e rejected at 7σ

$$P_m(\nu_e \to \nu_\mu) = sin^2(2\theta_m) sin^2(1.27\Delta m_m^2 \frac{L}{E})$$

Neutrino oscillation

The primary candidate to explain the observed solar and atmospheric neutrino deficit, was neutrino oscillation.

Such oscillation can occur if flavor eigenstates for the three active neutrino types (*l* = *e*, *μ*, *τ*) are related to mass eigenstates (*i*) via the PMNS (Pontecorvo-Maka-Nakagawi-Sakata) mixing matrix U_{li}:

$$|\nu_l\rangle = \Sigma U_{li}|\nu_i\rangle$$

For non-degenerate mass eigenstates, and for small θ_{13},

- Oscillations of solar neutrinos are dominated by the first sub-matrix involving θ_{12}.
- The second sub-matrix dominates the oscillation of atmospheric neutrinos,
- The third sub-matrix involves the CP violating angle δ and
- the fourth sub-matrix is tested by reactor and accelerator neutrino measurements
- The fifth sub-matrix determines the existance of DBD

$$U_{li} = \overset{\text{Solar Osc}}{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}} \cdot \overset{\text{Atm Osc.}}{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}} \cdot \overset{\text{CP violating}}{\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix}} \cdot \overset{\text{Reactor \& Accel}}{\begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix}} \cdot \overset{\substack{\text{Majorana Phases} \\ \text{Double } \beta \text{ decay only}}}{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha_2/2} & 0 \\ 0 & 0 & e^{-i\alpha_3/2+i\delta} \end{pmatrix}}$$

where $c_{ij} = \cos\theta_{ij}$, and $s_{ij} = \sin\theta_{ij}$

The atmosferic and solar and neutrino deficit can be explained by ν oscillation

Two neutrino oscillation case:

- θ = mixing angle: it defines how much one flavour state differs from each mass state.
- θ = 0 they coincide → no mixing.
- θ =p/4 maximal mixing→ at some point of the travel ν_α will be fully converted in ν_β

- $\Delta m^2 = m_1^2 - m_2^2$ = difference between two mass eigenstates → for oscillation to happen at least one of the them must be non 0!!! Δm^2 allows the two states to get out of phase!

For terrestrial experiment we can choose L/E

If L/E is fixed for us by Nature as in solar or atmospheric experiments, we can only probe limited range of (Δm^2 , θ)

Oscillation amplitude

Oscillation phase

Source detector dist

$$P(\nu_\alpha \rightarrow \nu_\beta) = sin^2(2\theta) sin^2(1.27\Delta m^2 \frac{L(km)}{E(GeV)})$$

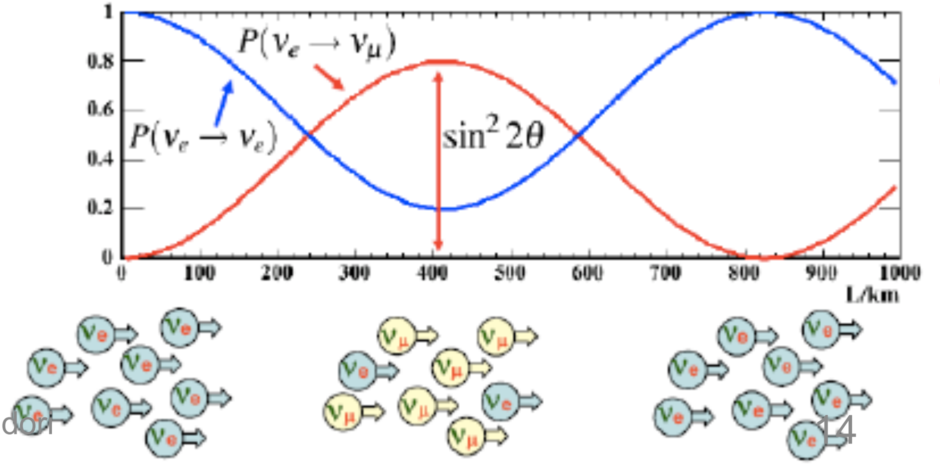
Neutrino Energy

To observe maximal Oscillation we must have

$$1.27\Delta m^2 \frac{L}{E} = \frac{\pi}{2}$$

$$\frac{L}{E} = \frac{\pi}{2.54\Delta m^2}$$

•e.g. $\Delta m^2 = 0.003\,\mathrm{eV}^2, \qquad \sin^2 2\theta = 0.8, \qquad E_\nu = 1\,\mathrm{GeV}$



The Matter Enhanced Flavour Oscillation: the MSW effect

- Electron neutrinos can forward scatter on electrons by charged current interactions, and other neutrino flavors cannot.
- Under favorable circumstances a resonance enhancement of the oscillation amplitude, the so-called Mikheyev-Smirnov-Wolfenstein (MSW) effect (Wolfenstein 1979, 1980) and (Mikheyev and Smirnov 1986a, 1986b), can take place

$$P_m(\nu_e \rightarrow \nu_\mu) = sin^2(2\theta_m) sin^2(1.27 \Delta m_m^2 \frac{L}{E})$$

$$sin2\theta_m = \frac{sin2\theta}{\sqrt{(\Delta V / \Delta m^2 - cos2\theta)^2 + sin^2 2\theta}}$$

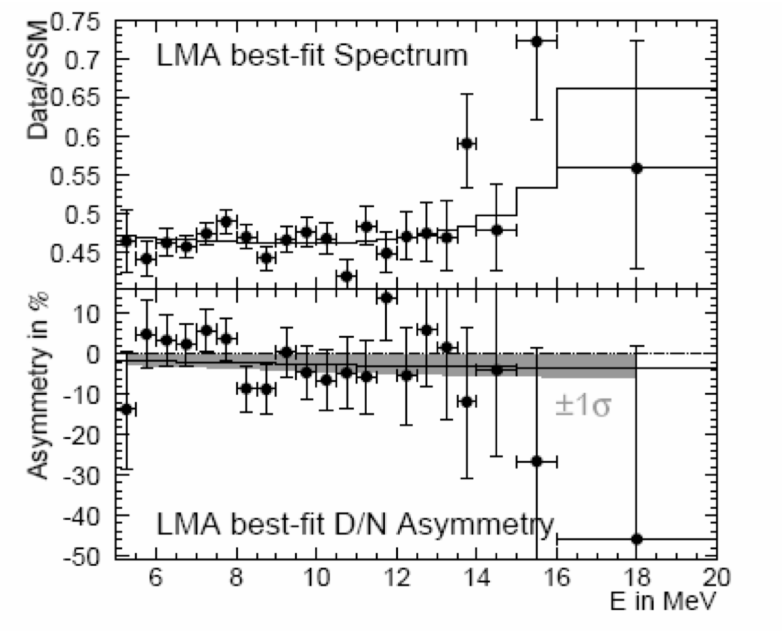
$$\Delta m_m^2 = m_{1m}^2 - m_{2m}^2 = \Delta m^2 \sqrt{(\Delta V / \Delta m^2 - cos2\theta)^2 + sin^2 2\theta}$$

$$V_\alpha - V_\beta = 2\sqrt{2} G_F E N_e$$

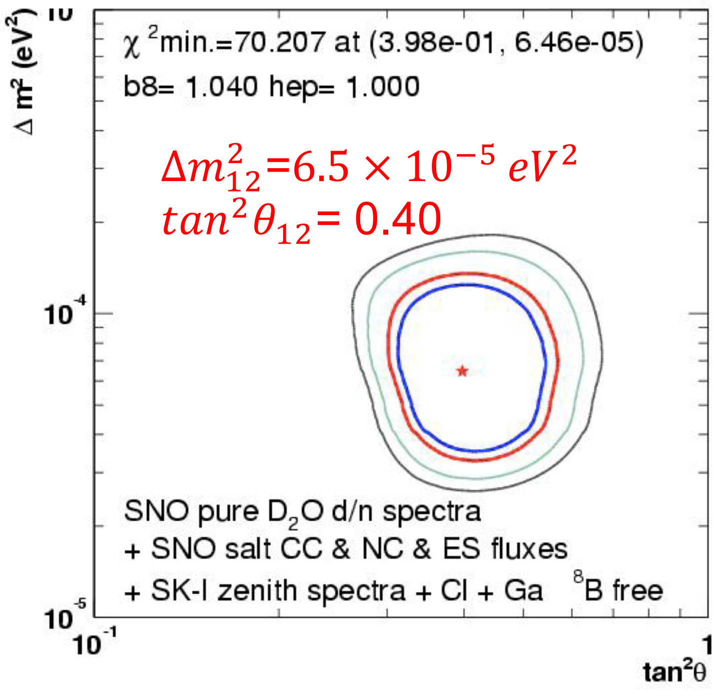
2004: L'analisi globale dei dati sperimentali (Cl, Ga, SK, SNO) individua i parametri di mixing che li descrivono nell'ipotesi di oscillazione

Under CPT Invariance and for small θ_{13} →

$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\theta_{12} \sin^2 (1.27 \frac{\Delta m_{12}{}^2 L}{E})$$



No significant distortion for MSW observed in SK data, as expected for Large Mixing Angle oscillation solution of the Solar Neutrino Puzzle

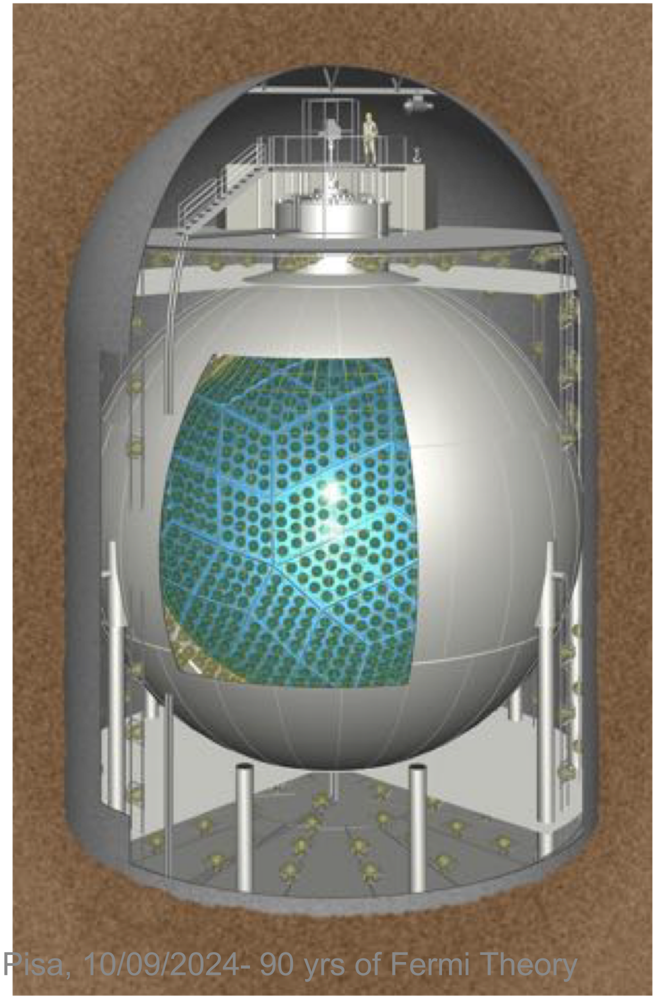


Δm_{12}^2=$6.5 \times 10^{-5}\ eV^2$

$tan^2\theta_{12}$= 0.40

Large Mixing Angle (LMA) solution for a 2 neutrino fit

2002 KamLAND determines reactor $\overline{\nu_e}$ oscillations that fully explain the missing solar ν_e: the first oscillation evidence with man made ν



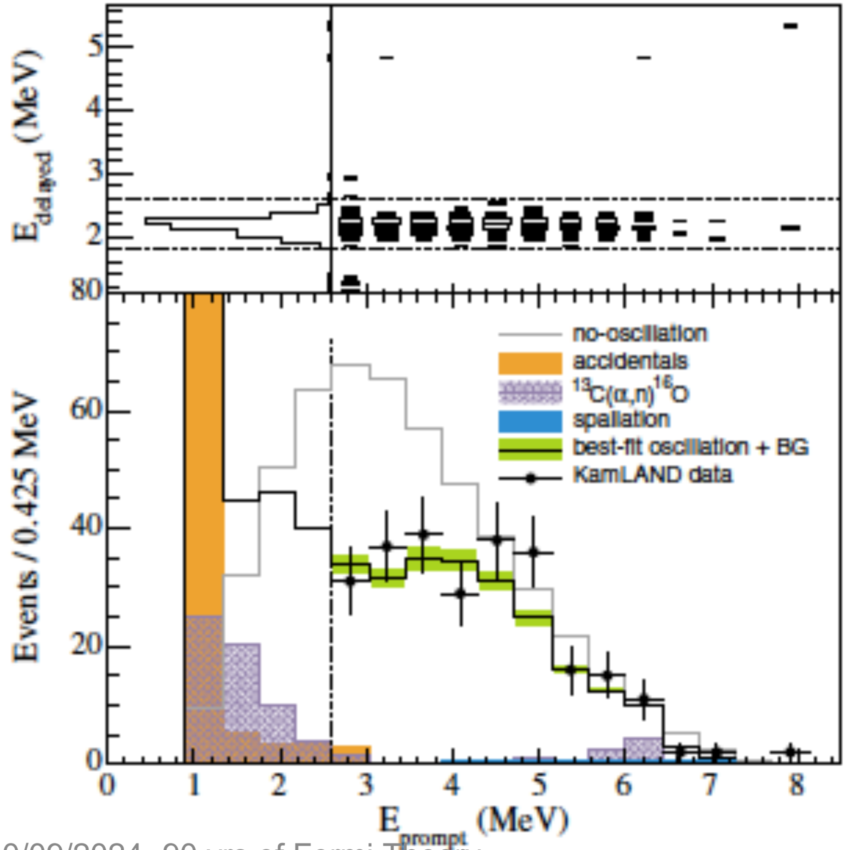
- 1 kton of ultrapure liquid scintillator (LS) in a 13 m-diameter transparent nylon-based balloon suspended in nonscintillating oil. At Kamioka Mine close to SK
- 50 power reactor reactors; average distance L_{ave} ~ 180 km
- The balloon is surrounded by 1879 photomultiplier tubes (PMTs) mounted on the inner surface of an 18-m-diameter steel vessel
- Electron antineutrinos (E_{ave}~5 MeV) are detected via inverse decay (IBD)

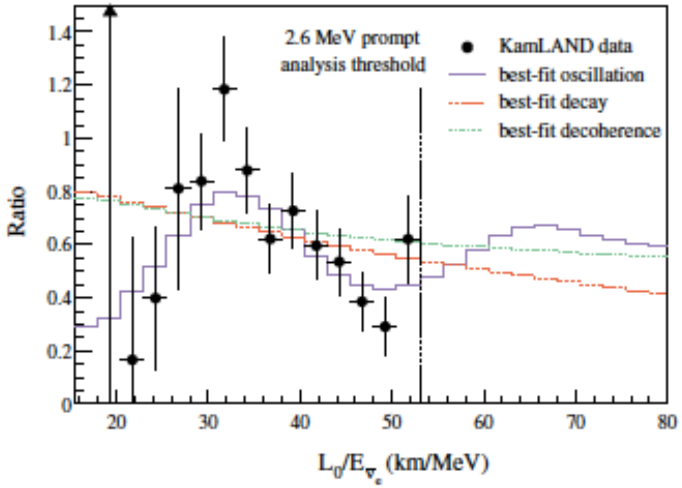
$$\bar{\nu}_e + p \rightarrow e^+ + n; \qquad E_{thrs} = 1.8\, MeV$$

- The prompt scintillation light from the e^+ gives an estimate of the incident energy,
- $E_{\bar{\nu}_e} = E_{prompt} + E_n + 0.8\, MeV$;
- $n + H \rightarrow D + \gamma$ ($E_\gamma = 2.2$ MeV delayed (~200μsec))
- E_{prompt} is the prompt event energy including the positron kinetic energy and the annihilation energy
- E_n is the average neutron recoil energy, which is small

2005: KamLAND results

The solar ν_e flavor oscillation through the Mikheyev-Smirnov-Wolfenstein matter effect has a direct correspondance with $\bar{\nu}_e$ oscillation in vacuum



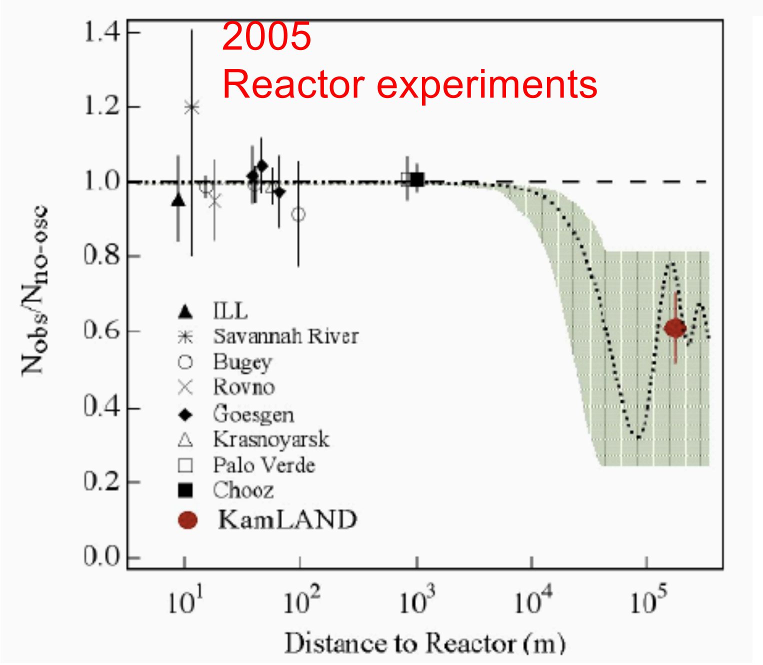


In 2015 M. Koshiba shares the Noble Prize with A. Mc Donald for discovery of neutrino oscillations

La milestone di Kamland:

- Find positive evidence of ν_e disappearance for a set of parameters very close to the LMA

→ θ_{13} very small! The ν_e survival probability observed by KL is almost driven by $sin^2\theta_{12}$ as for solar neutrinos
→ KL allows important restriction of LMA parameter space

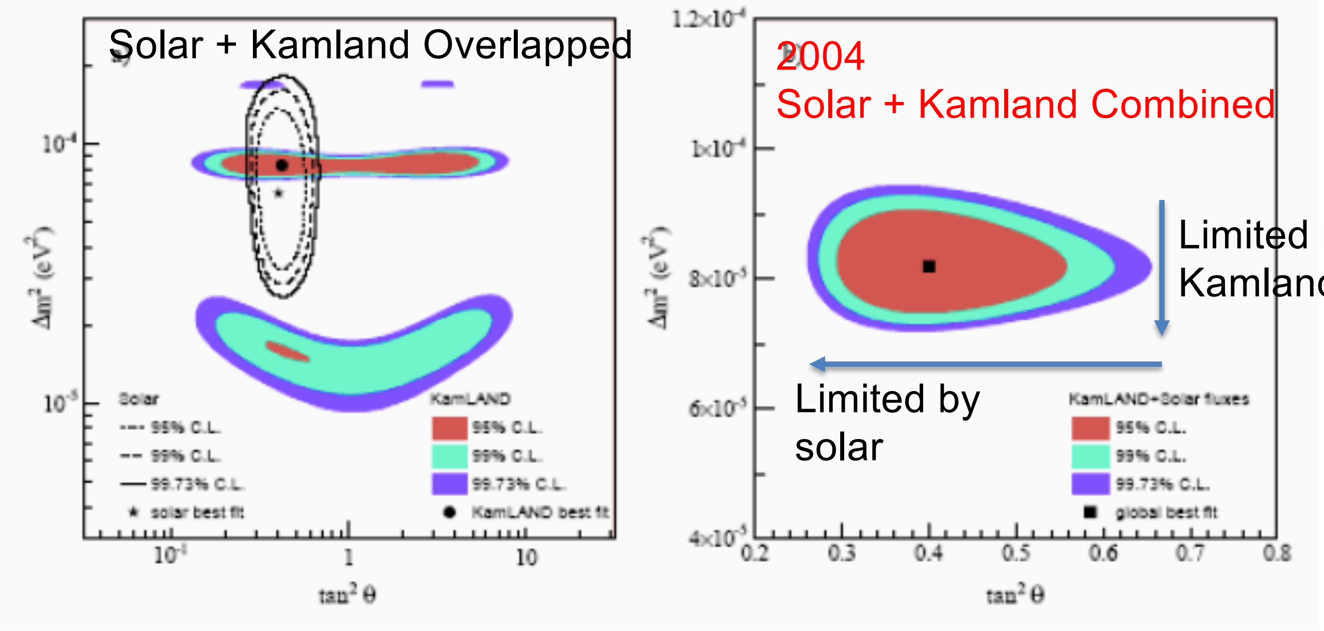


2005
Reactor experiments

E. Eguchi et al. Phys. Rev. Lett. 90 (2003) 021802.

Under the assumption of CPT Invariance

$$\Delta m^2_{12}=8.2^{+0.6}_{-0.5}\times 10^{-5}\ eV^2$$
$$tan^2\vartheta_{12}=0.40^{+0.09}_{-0.07}0.40$$



Solar + Kamland Overlapped

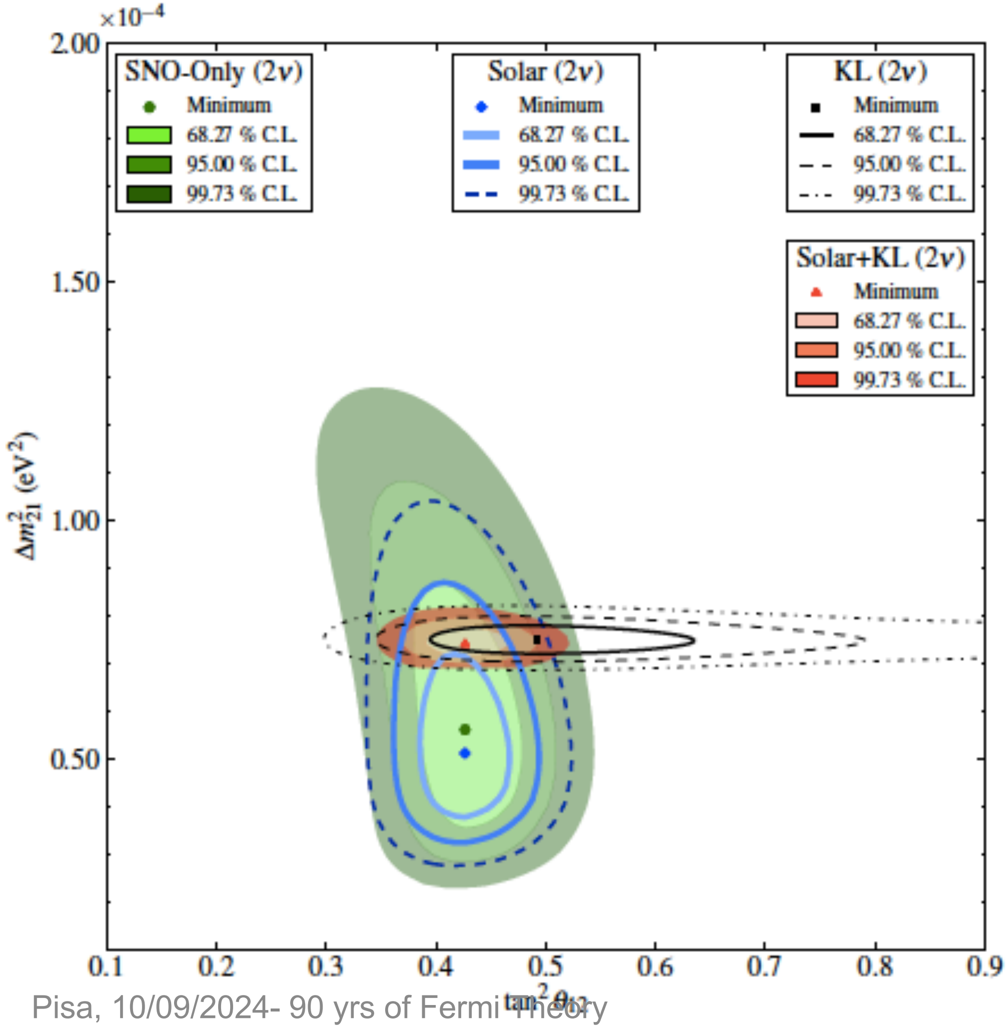
2004
Solar + Kamland Combined

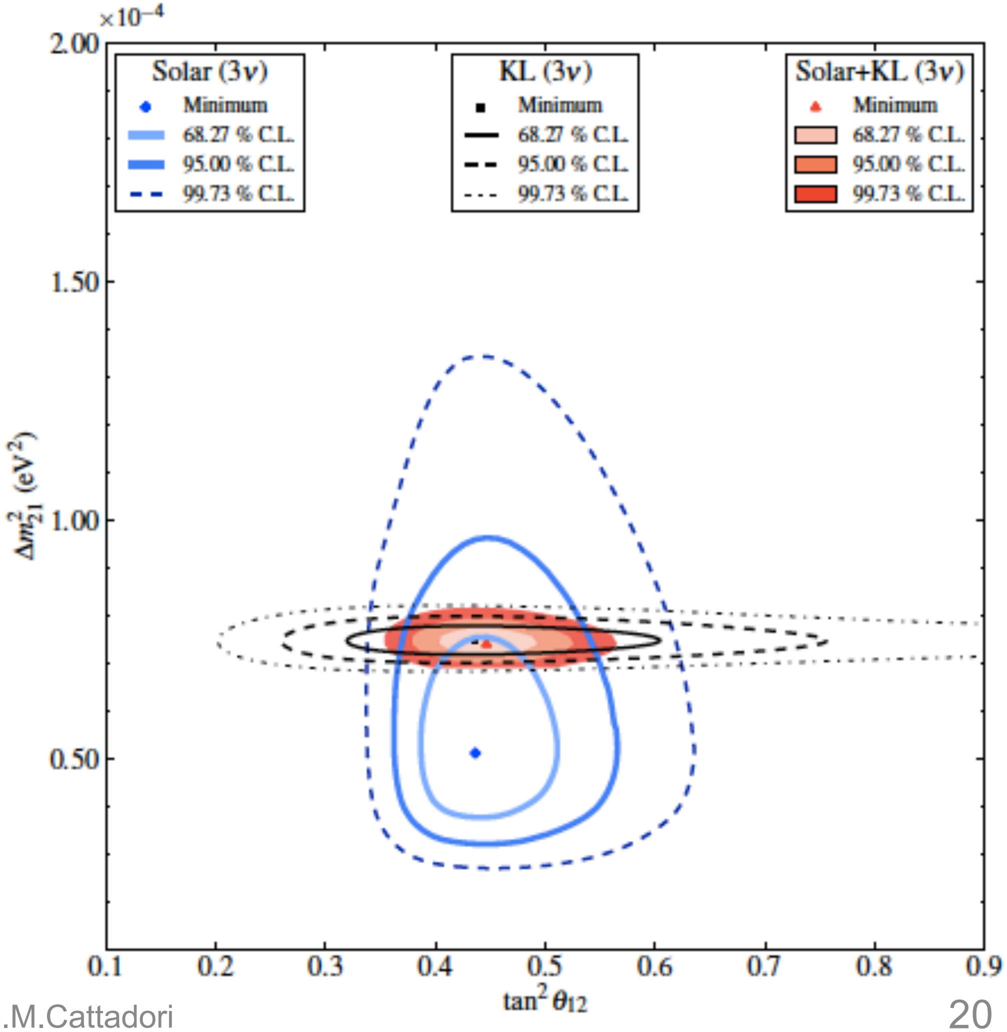
Limited by Kamland

Limited by solar

T. Araki et. al. Phys. Rev. Lett., (2004) to be published, hep-ex/0406035.

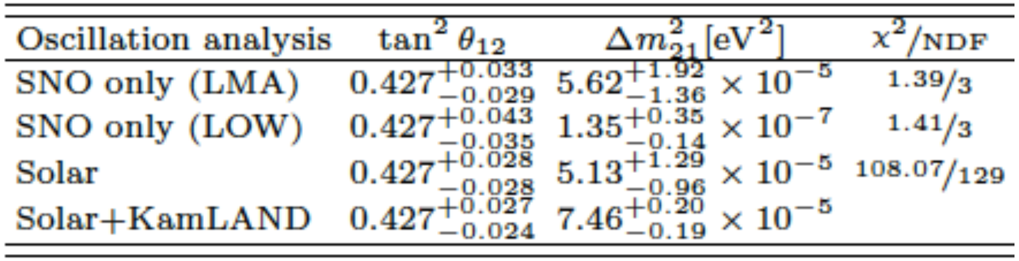
2 ν solar + KL analysis (SNO final paper 2020)





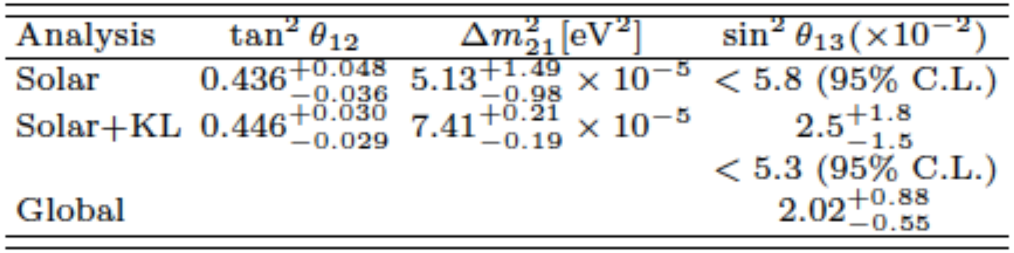
3 ν solar + global analysis (SNO final paper 2020)

Best fit of SNO,Solar,KL data: two flavor oscillations

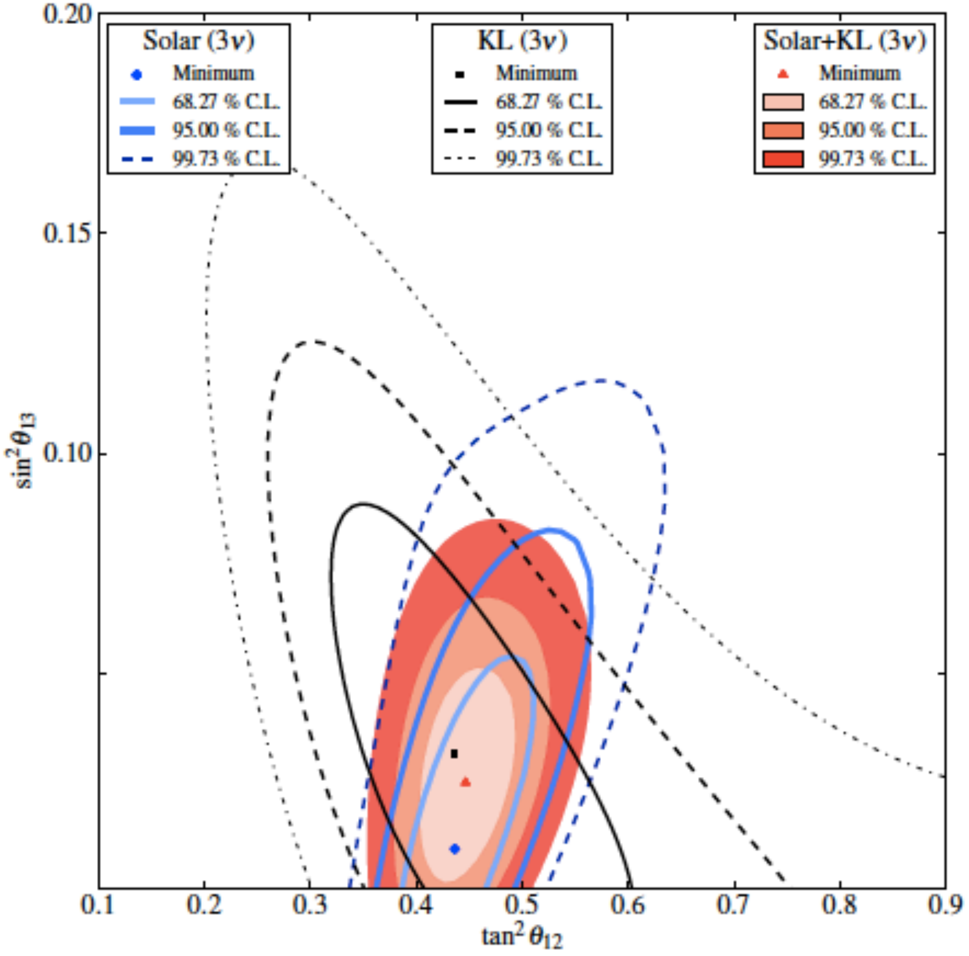


Oscillation analysis	$\tan^2\theta_{12}$	$\Delta m^2_{21}[\mathrm{eV}^2]$	χ^2/NDF
SNO only (LMA)	$0.427^{+0.033}_{-0.029}$	$5.62^{+1.92}_{-1.36}\times 10^{-5}$	1.39/3
SNO only (LOW)	$0.427^{+0.043}_{-0.035}$	$1.35^{+0.35}_{-0.14}\times 10^{-7}$	1.41/3
Solar	$0.427^{+0.028}_{-0.028}$	$5.13^{+1.29}_{-0.96}\times 10^{-5}$	108.07/129
Solar+KamLAND	$0.427^{+0.027}_{-0.024}$	$7.46^{+0.20}_{-0.19}\times 10^{-5}$	

Best fit of global data (LBL, atm, KL, All Solar, Chooz): three flavor oscillations



Analysis	$\tan^2\theta_{12}$	$\Delta m^2_{21}[\mathrm{eV}^2]$	$\sin^2\theta_{13}(\times 10^{-2})$
Solar	$0.436^{+0.048}_{-0.036}$	$5.13^{+1.49}_{-0.98}\times 10^{-5}$	< 5.8 (95% C.L.)
Solar+KL	$0.446^{+0.030}_{-0.029}$	$7.41^{+0.21}_{-0.19}\times 10^{-5}$	$2.5^{+1.8}_{-1.5}$
			< 5.3 (95% C.L.)
Global			$2.02^{+0.88}_{-0.55}$



Borexino (May- 2007- July 2021)

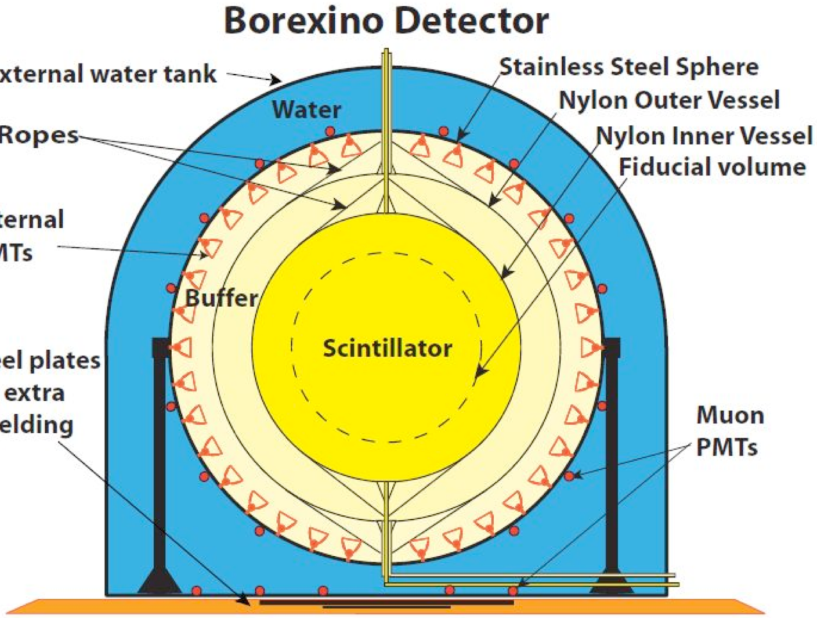
- 278 ton of organic liquid scintillator contained within a sphere of 4.25 m diameter, viewed by 2200 photomultipliers and shielded against the external radioactivity

- Neutrino detected by ES on electron :

$$\nu_e + e \rightarrow \nu_e + e$$

- Unprecedented low levels of background achieved after several years of research and efforts.
- Phase I:
- Phase II: From 2010→6 cycles of closed-loop water extraction allowed to achieve
  - ^{238}U < 9.4 10^{-20} g/g (95% C.L.),
  - ^{232}Th < 5.7 10^{-19} g/g (95% C.L.),
  - ^{85}Kr and ^{210}Bi reduced of factors 4.6 and 2.3 w.r.t. Phase I

Nature **562**, 505–510 (2018).
https://doi.org/10.1038/s41586-018-0624-y



Sun luminosity (L) measured with ν

$$L = \left(3.89^{+0.35}_{-042}\right) x\ 10^{33} erg\ s^{-1}$$

in agreement with the luminosity calculated using the well measured photon output

$$L = (3.846 \pm 0.015)\ x\ 10^{33}\ erg\ s^{-1}.$$

2018 Borexino: Comprehensive measurement of pp-chain solar

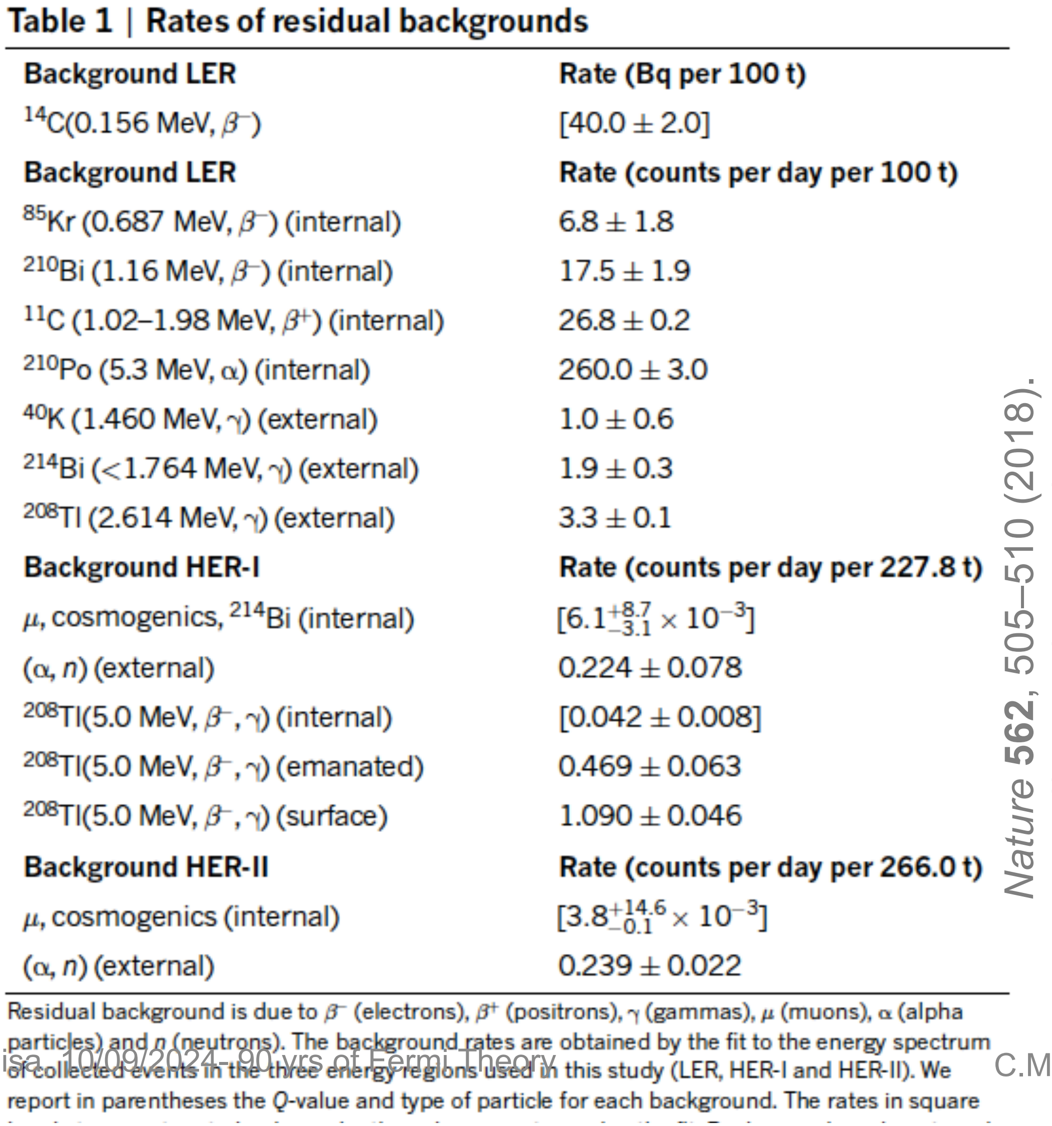


Table 1 | Rates of residual backgrounds

Background LER	**Rate (Bq per 100 t)**
^{14}C(0.156 MeV, β^-)	[40.0 ± 2.0]
Background LER	**Rate (counts per day per 100 t)**
^{85}Kr (0.687 MeV, β^-) (internal)	6.8 ± 1.8
^{210}Bi (1.16 MeV, β^-) (internal)	17.5 ± 1.9
^{11}C (1.02–1.98 MeV, β^+) (internal)	26.8 ± 0.2
^{210}Po (5.3 MeV, α) (internal)	260.0 ± 3.0
^{40}K (1.460 MeV, γ) (external)	1.0 ± 0.6
^{214}Bi (<1.764 MeV, γ) (external)	1.9 ± 0.3
^{208}Tl (2.614 MeV, γ) (external)	3.3 ± 0.1
Background HER-I	**Rate (counts per day per 227.8 t)**
μ, cosmogenics, ^{214}Bi (internal)	$[6.1^{+8.7}_{-3.1} \times 10^{-3}]$
(α, n) (external)	0.224 ± 0.078
^{208}Tl(5.0 MeV, β^-, γ) (internal)	[0.042 ± 0.008]
^{208}Tl(5.0 MeV, β^-, γ) (emanated)	0.469 ± 0.063
^{208}Tl(5.0 MeV, β^-, γ) (surface)	1.090 ± 0.046
Background HER-II	**Rate (counts per day per 266.0 t)**
μ, cosmogenics (internal)	$[3.8^{+14.6}_{-0.1} \times 10^{-3}]$
(α, n) (external)	0.239 ± 0.022

Residual background is due to β^- (electrons), β^+ (positrons), γ (gammas), μ (muons), α (alpha particles) and n (neutrons). The background rates are obtained by the fit to the energy spectrum of collected events in the three energy regions used in this study (LER, HER-I and HER-II). We report in parentheses the Q-value and type of particle for each background. The rates in square

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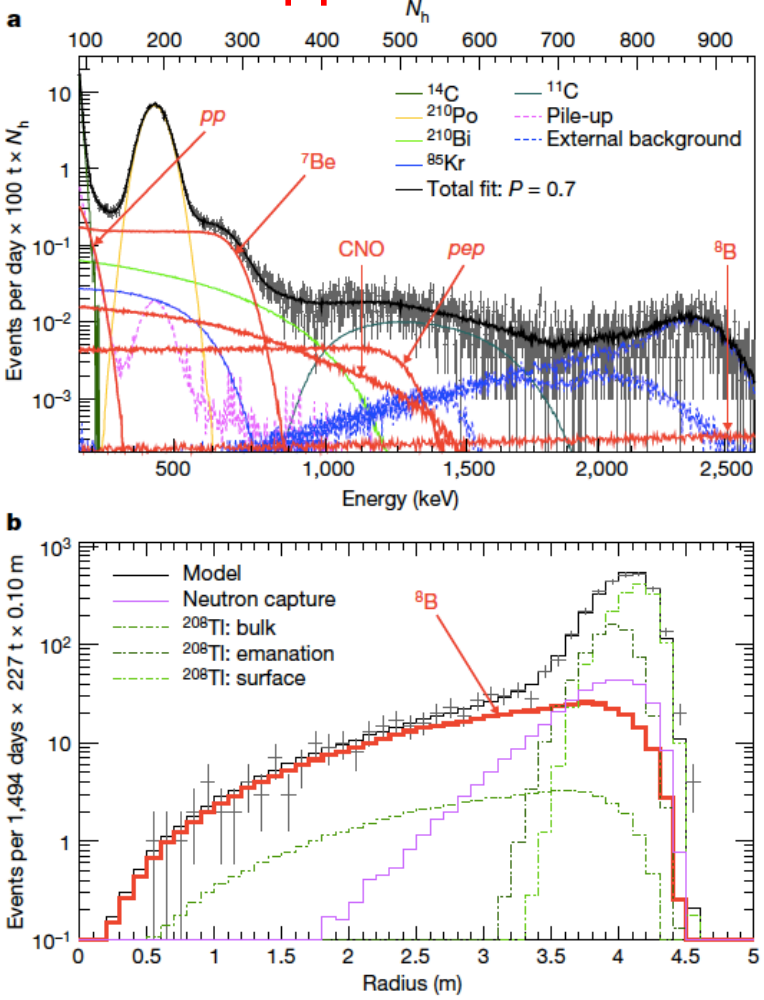

Fig. 2 | Results of the fit used to extract the neutrino signal. Distributions of events after selection cuts and corresponding fits with neutrino and background components. **a**, TFC-subtracted energy spectrum with suppressed ^{11}C background in LER. The horizontal upper scale is in units of N_h, that is, the total number of photons collected for

2018 Borexino: Comprehensive measurement of pp-chain solar

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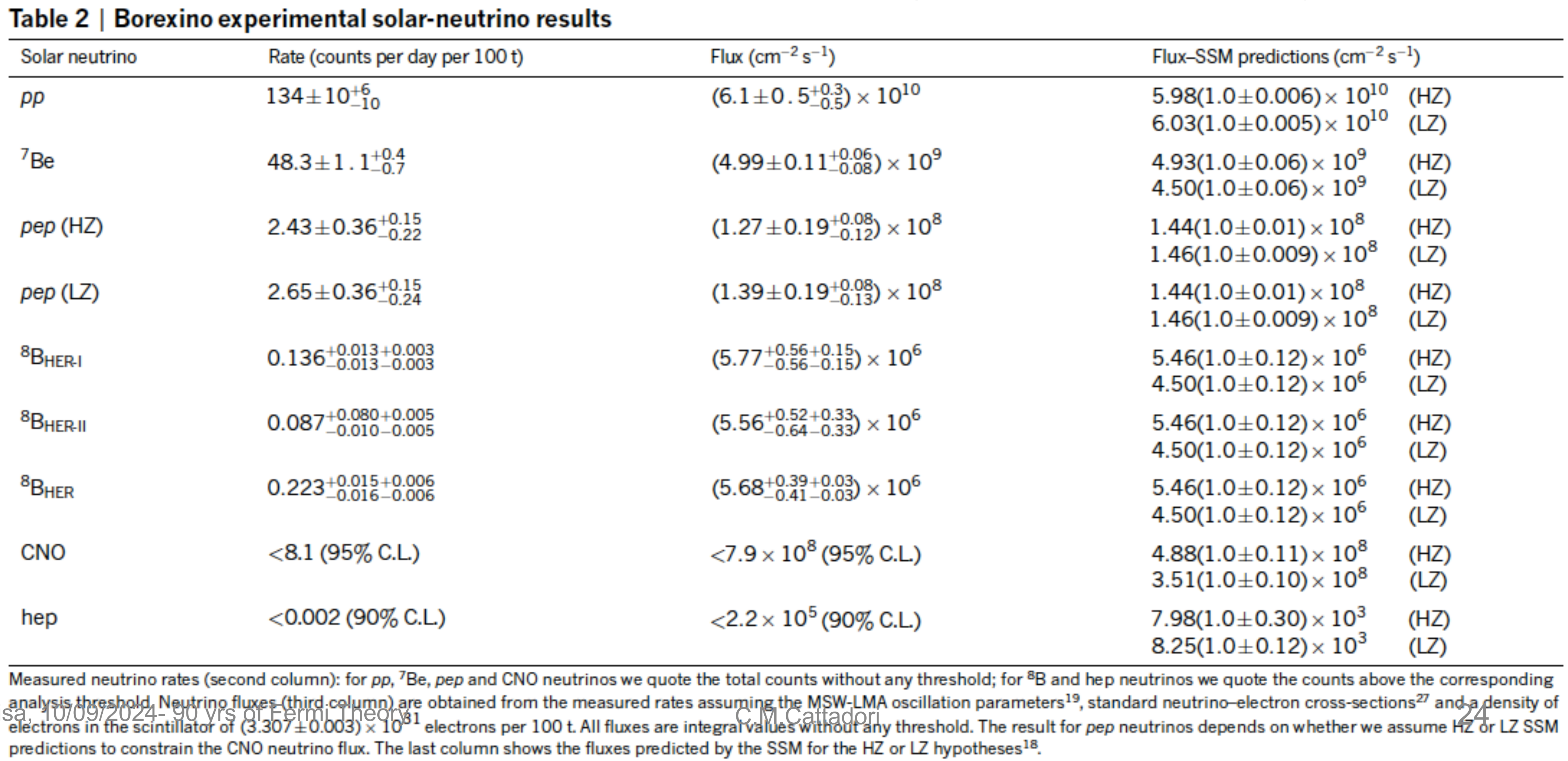

Table 2 | Borexino experimental solar-neutrino results

Solar neutrino	Rate (counts per day per 100 t)	Flux ($cm^{-2}\,s^{-1}$)	Flux–SSM predictions ($cm^{-2}\,s^{-1}$)
pp	$134 \pm 10^{+6}_{-10}$	$(6.1 \pm 0.5^{+0.3}_{-0.5}) \times 10^{10}$	$5.98(1.0 \pm 0.006) \times 10^{10}$ (HZ) $6.03(1.0 \pm 0.005) \times 10^{10}$ (LZ)
^{7}Be	$48.3 \pm 1.1^{+0.4}_{-0.7}$	$(4.99 \pm 0.11^{+0.06}_{-0.08}) \times 10^{9}$	$4.93(1.0 \pm 0.06) \times 10^{9}$ (HZ) $4.50(1.0 \pm 0.06) \times 10^{9}$ (LZ)
pep (HZ)	$2.43 \pm 0.36^{+0.15}_{-0.22}$	$(1.27 \pm 0.19^{+0.08}_{-0.12}) \times 10^{8}$	$1.44(1.0 \pm 0.01) \times 10^{8}$ (HZ) $1.46(1.0 \pm 0.009) \times 10^{8}$ (LZ)
pep (LZ)	$2.65 \pm 0.36^{+0.15}_{-0.24}$	$(1.39 \pm 0.19^{+0.08}_{-0.13}) \times 10^{8}$	$1.44(1.0 \pm 0.01) \times 10^{8}$ (HZ) $1.46(1.0 \pm 0.009) \times 10^{8}$ (LZ)
$^{8}B_{HER\text{-}I}$	$0.136^{+0.013+0.003}_{-0.013-0.003}$	$(5.77^{+0.56+0.15}_{-0.56-0.15}) \times 10^{6}$	$5.46(1.0 \pm 0.12) \times 10^{6}$ (HZ) $4.50(1.0 \pm 0.12) \times 10^{6}$ (LZ)
$^{8}B_{HER\text{-}II}$	$0.087^{+0.080+0.005}_{-0.010-0.005}$	$(5.56^{+0.52+0.33}_{-0.64-0.33}) \times 10^{6}$	$5.46(1.0 \pm 0.12) \times 10^{6}$ (HZ) $4.50(1.0 \pm 0.12) \times 10^{6}$ (LZ)
$^{8}B_{HER}$	$0.223^{+0.015+0.006}_{-0.016-0.006}$	$(5.68^{+0.39+0.03}_{-0.41-0.03}) \times 10^{6}$	$5.46(1.0 \pm 0.12) \times 10^{6}$ (HZ) $4.50(1.0 \pm 0.12) \times 10^{6}$ (LZ)
CNO	<8.1 (95% C.L.)	$<7.9 \times 10^{8}$ (95% C.L.)	$4.88(1.0 \pm 0.11) \times 10^{8}$ (HZ) $3.51(1.0 \pm 0.10) \times 10^{8}$ (LZ)
hep	<0.002 (90% C.L.)	$<2.2 \times 10^{5}$ (90% C.L.)	$7.98(1.0 \pm 0.30) \times 10^{3}$ (HZ) $8.25(1.0 \pm 0.12) \times 10^{3}$ (LZ)

Measured neutrino rates (second column): for *pp*, ^{7}Be, *pep* and CNO neutrinos we quote the total counts without any threshold; for ^{8}B and hep neutrinos we quote the counts above the corresponding analysis threshold. Neutrino fluxes (third column) are obtained from the measured rates assuming the MSW-LMA oscillation parameters[19], standard neutrino–electron cross-sections[27] and a density of electrons in the scintillator of $(3.307 \pm 0.003) \times 10^{31}$ electrons per 100 t. All fluxes are integral values without any threshold. The result for *pep* neutrinos depends on whether we assume HZ or LZ SSM predictions to constrain the CNO neutrino flux. The last column shows the fluxes predicted by the SSM for the HZ or LZ hypotheses[18].

2018: Borexino results

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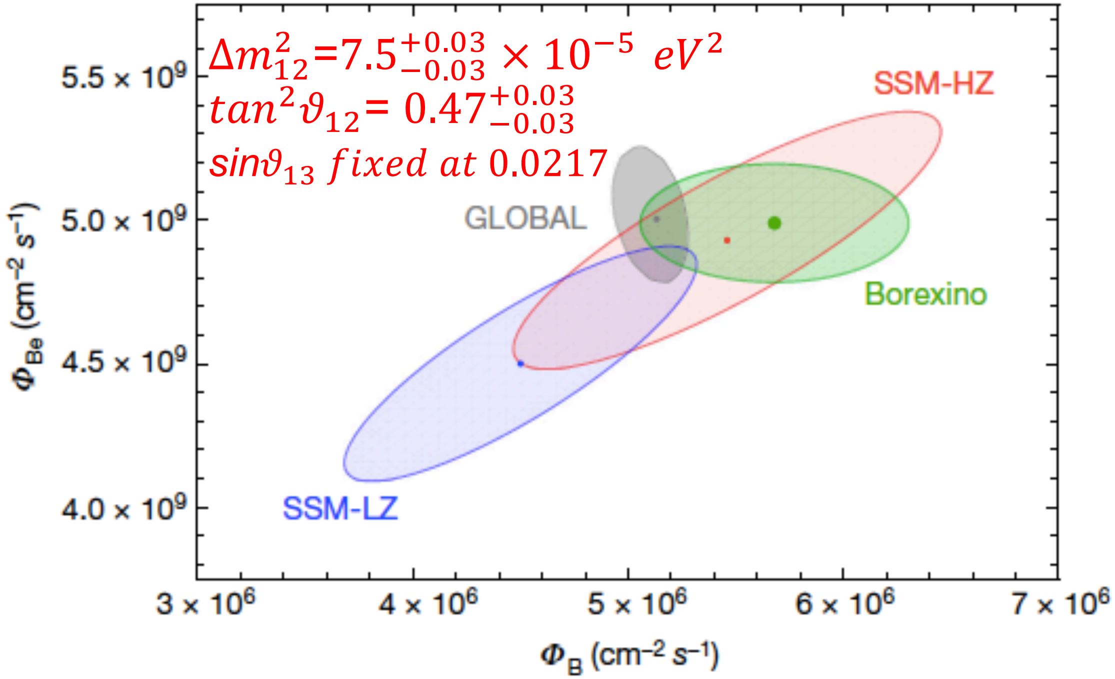
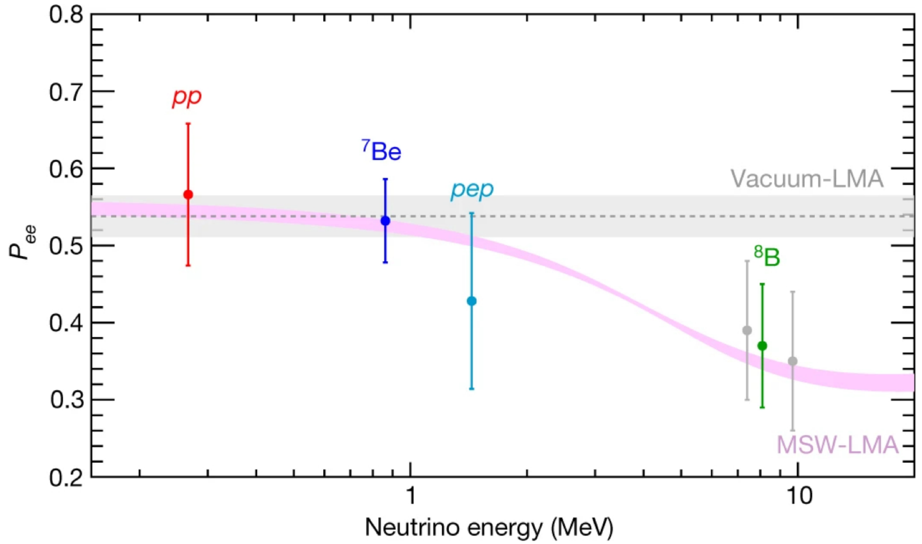


$\Delta m^2_{12}=7.5^{+0.03}_{-0.03} \times 10^{-5}\ eV^2$

$tan^2\vartheta_{12}= 0.47^{+0.03}_{-0.03}$

$sin\vartheta_{13}\ fixed\ at\ 0.0217$



Allowed contours in the Φ_{Be}- Φ_B space:

- Borexino alone: ^{7}Be and ^{8}B fluxes.
- Global analysis (all solar+Kamland)
- High Metallicity Standard Solar model (theo)
- Low Metallicity Standard Solar model (theo)

Ratio of the ratio of the measured/expected fluxes of the ν solar flux for each subcomponent as measured by Borexino:

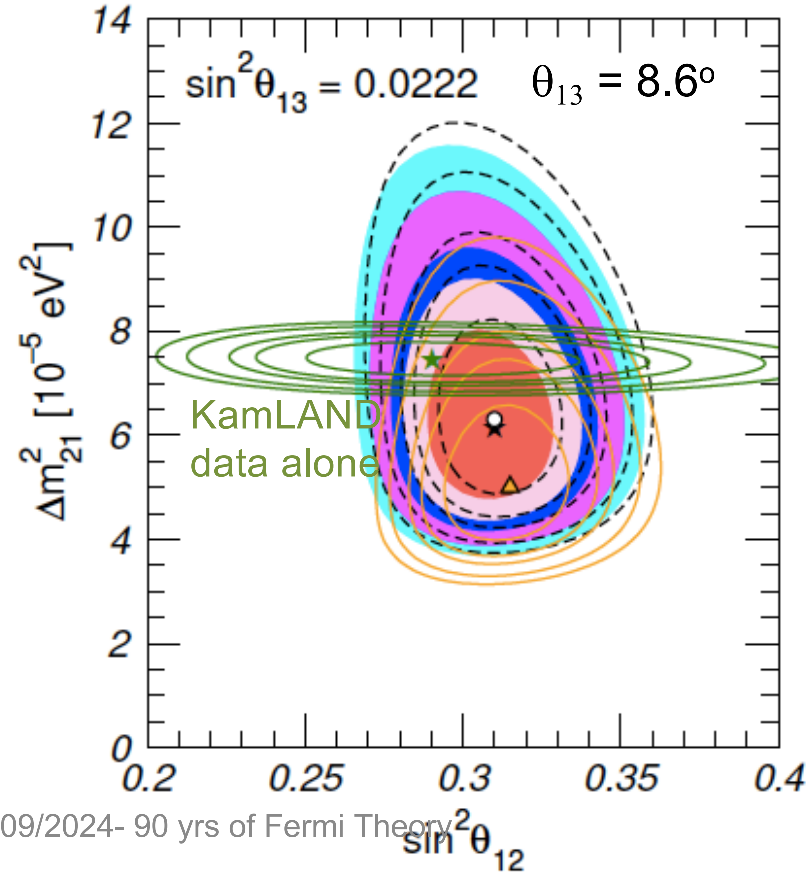
- Expected P_{ee} energy dependence for Vacuum – LMA oscillation
- Expected P_{ee} energy dependence for MSW-LMA (matter effects)

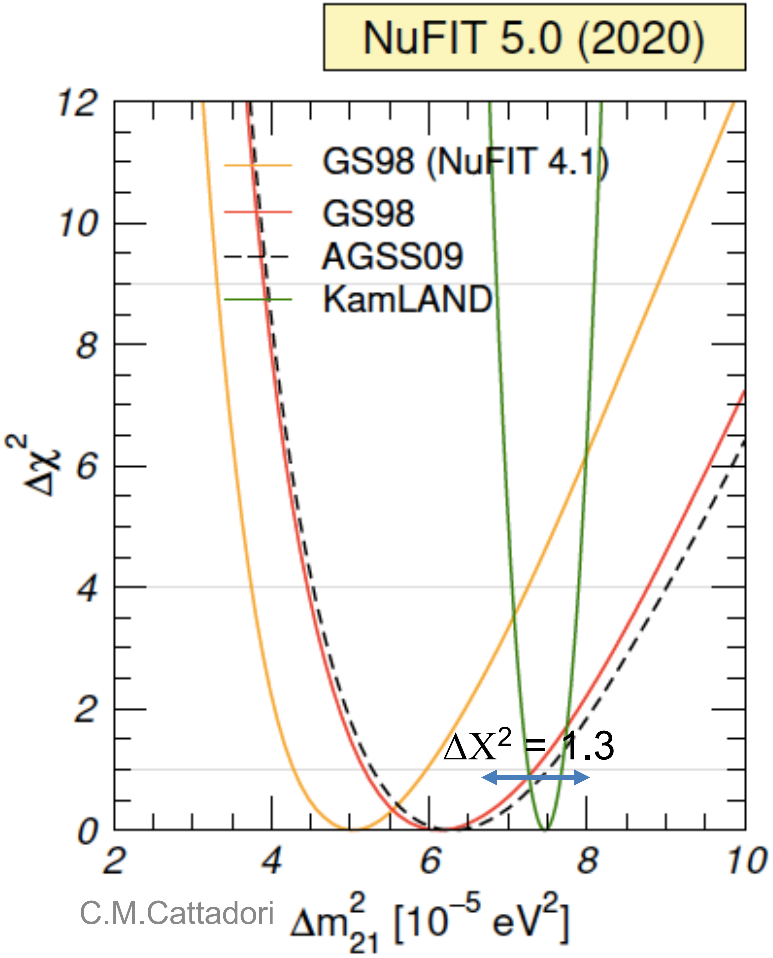
Comparison of Oscillation analysis of All Solars & KamLAND

Combined Solar for GS98
(full regions), and AGSS09
(dashed contours) models

Tension between KL & Solar reduced thanks to reduced SK D/N asymmetry of the full SK4 data set

$A_{D/N}$,SK4 (2970 days) = (-2:1 +/- 1:1)%



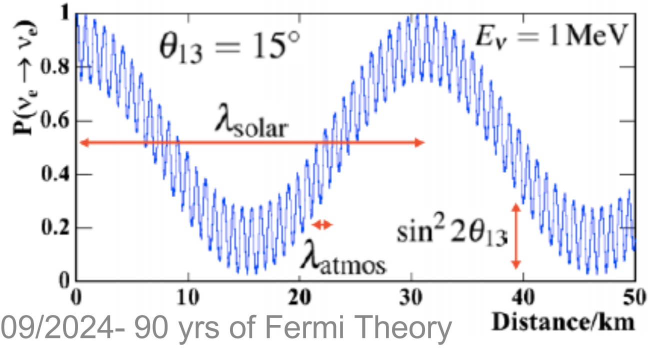


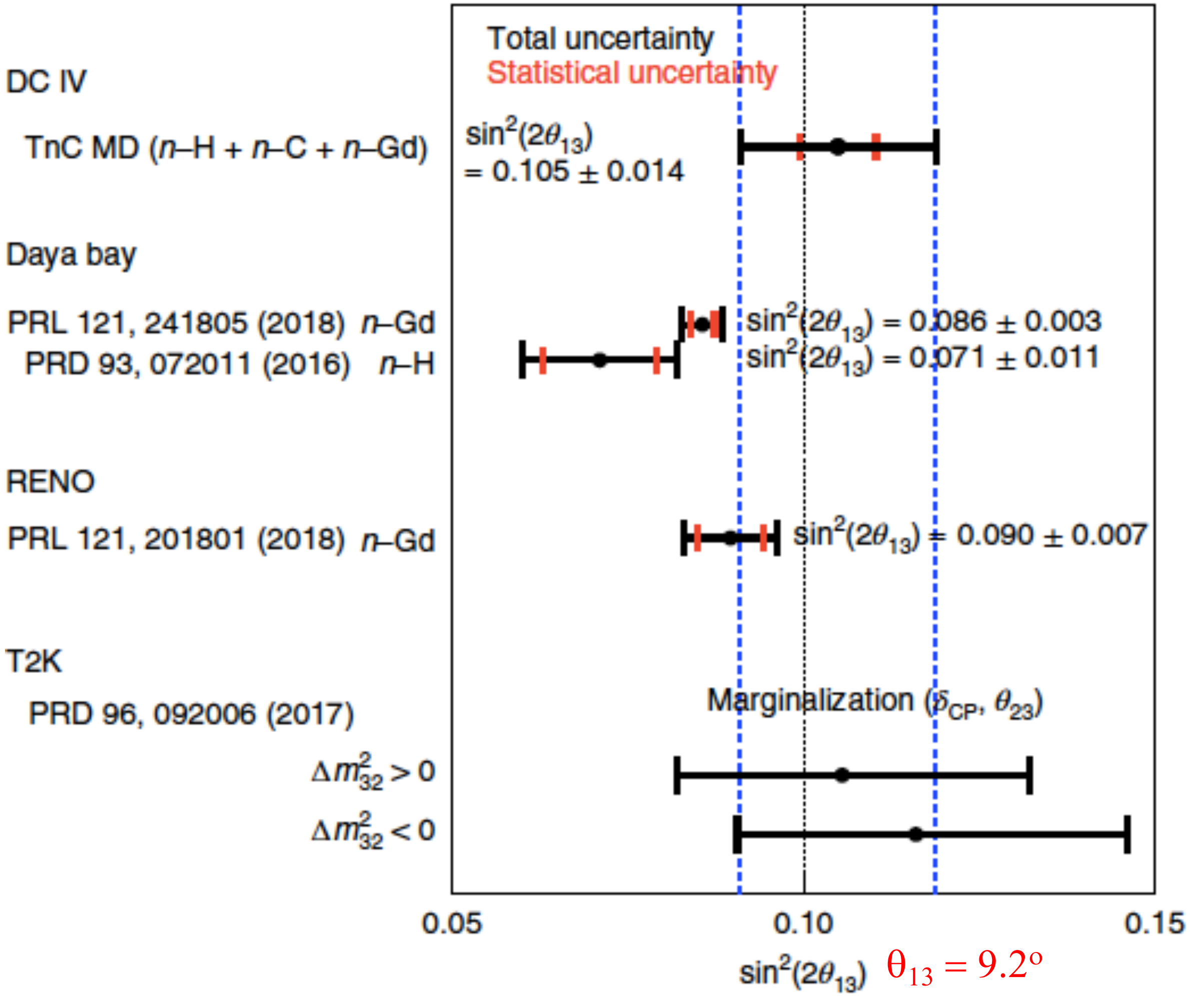
Third genertion of Reactor Experiments : assessing θ_{13}

Before 2001: CHOOZ & Palo Verde (second generation) set limit for $\theta_{13} < 0.15$

After 2011:

- third generation experiments measure $positive\ value\ of\ \theta_{13}$
- Far Detector & Near Detector to cancel the systematics related to the reactor flux uncertainties
- Multidetector approach to reduce systematics
- Double Chooz (France), Daya Bay (Brazil), Reno (US), T2K (Japan)
- Baseline too short to observe the first oscillation dip, observed by Kamland





$\theta_{13} = 9.2^{\circ}$

Nature Physics | VOL 16 | May 2020 | 558–564

Finoal 2011: sorgenti artificiali confermano risultati dei ν_{atm}

Tra il 1998 e il 2005, le evidenze di oscillazioni di neutrino diventano davvero molto solide (SuperKamiokande, SNO, MACRO, K2K…) e appare chiaro che **esiste almeno un'oscillazione visible sulla terra con sorgenti artificiali**. Quella tra la seconda e la terza famiglia di neutrino ("scala degli atmosferici"):

$$\frac{\Delta m^2_{32} L}{4E}$$

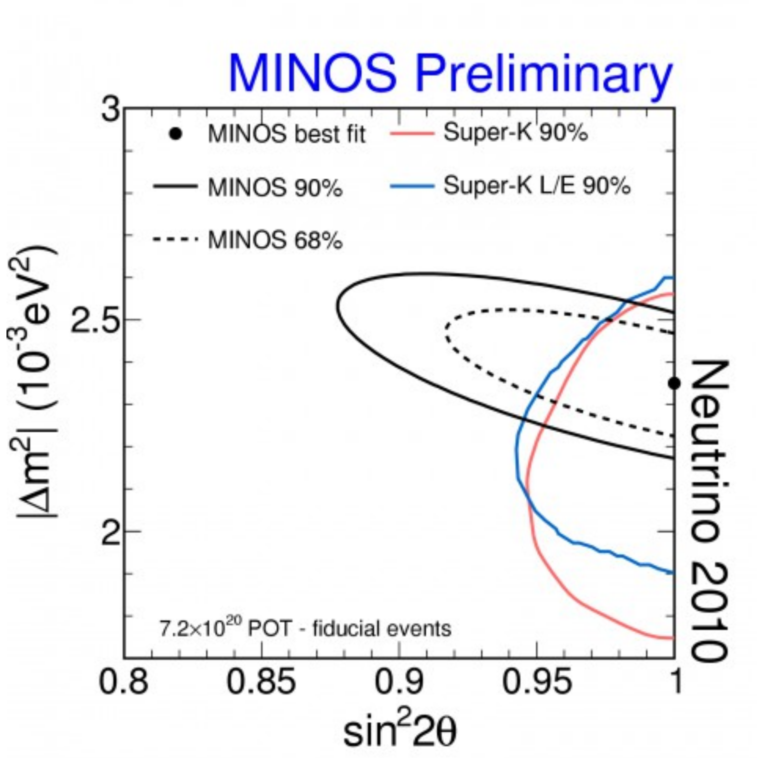
Year 2005

«**oscillation phase**» It is O(1) for
E= O(1 GeV) and L= O(100 km)
Cool, we can build experiment on Earth ☺

$$P(\nu_\mu \to \nu_\tau) \simeq \underbrace{\cos^4\theta_{13}}_{\approx 1}\,\underbrace{\sin^2 2\theta_{23}}_{\approx 1}\,\sin^2\frac{\Delta m^2_{32} L}{4E}$$

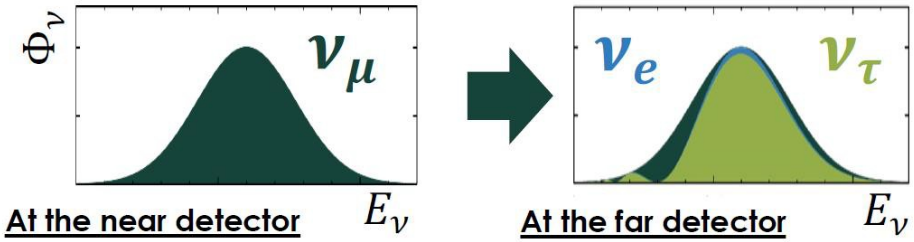
$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) = \sin^2 2\theta_{13}\,\sin^2\theta_{23}\,\sin^2\frac{\Delta m^2_{32} L}{4E}$$

<0.1 (ma quanto piccolo??)



Le oscillazioni di neutrino avevano mostrato la "prima evidenza di fisica oltre il modello standard" (neutrino massivi) senza però realmente scardinare il modello standard stesso

Esperimenti long-baseline



At the near detector

$$N_\mu^{ND}(E_\nu) = \sigma(E_\nu)\Phi_\nu(E_\nu)\epsilon(E_\nu)$$

Interaction cross section

Neutrino flux

ND Detector effects

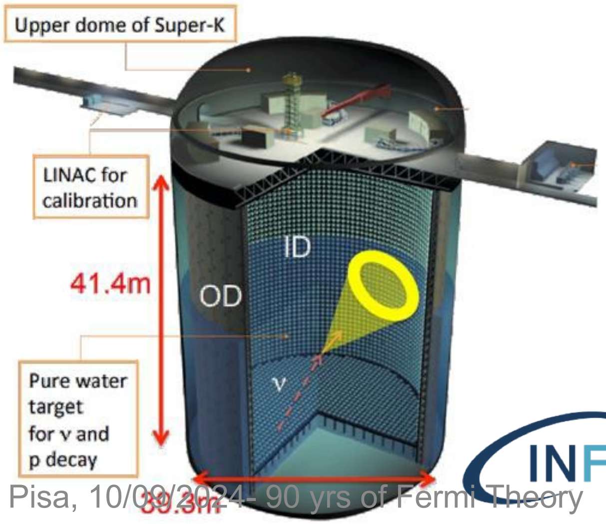
At the far detector

$$N_\mu^{FD}(E_\nu) = P(\nu_\mu \to \nu_\mu)\sigma(E_\nu)\Phi_\nu(E_\nu)\epsilon(E_\nu)$$

$$N_e^{FD}(E_\nu) = P(\nu_\mu \to \nu_e)\sigma(E_\nu)\Phi_\nu(E_\nu)\epsilon(E_\nu)$$

Oscillation probability

FD Detector effects

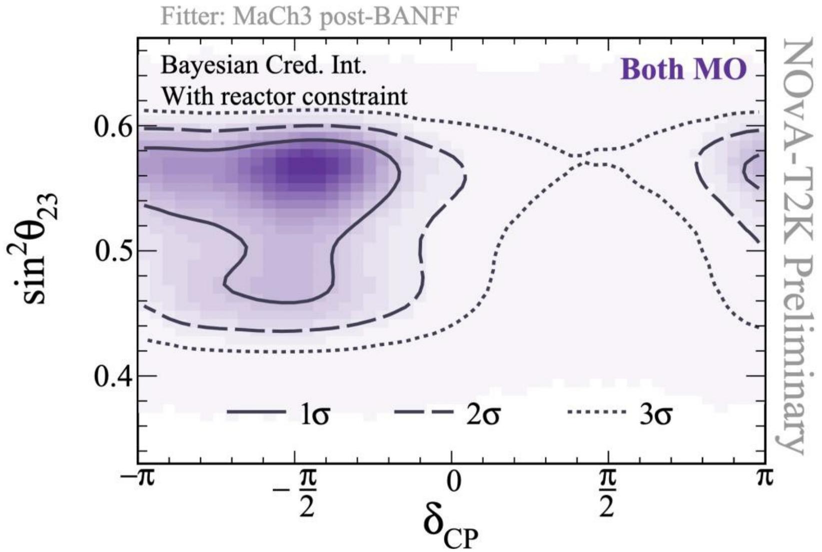


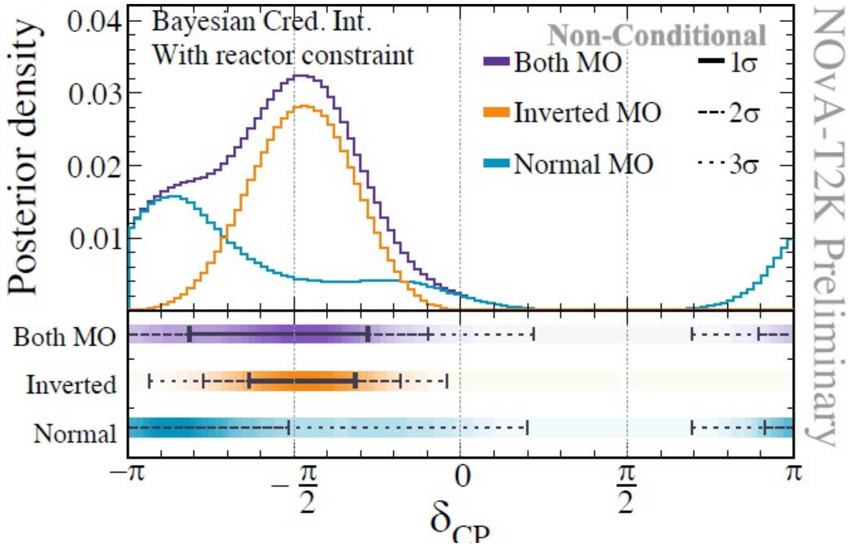
T2K: neutrini da JPARC a SuperKamiokande (296 km)

Ideale per θ_{13} e violazione di CP

Nova: neutrini dal Fermilab ad Ash River (810 km). Ideale per la gerarchia di massa

Il primo fit combinato “stile LHC” (Febbraio 2024)



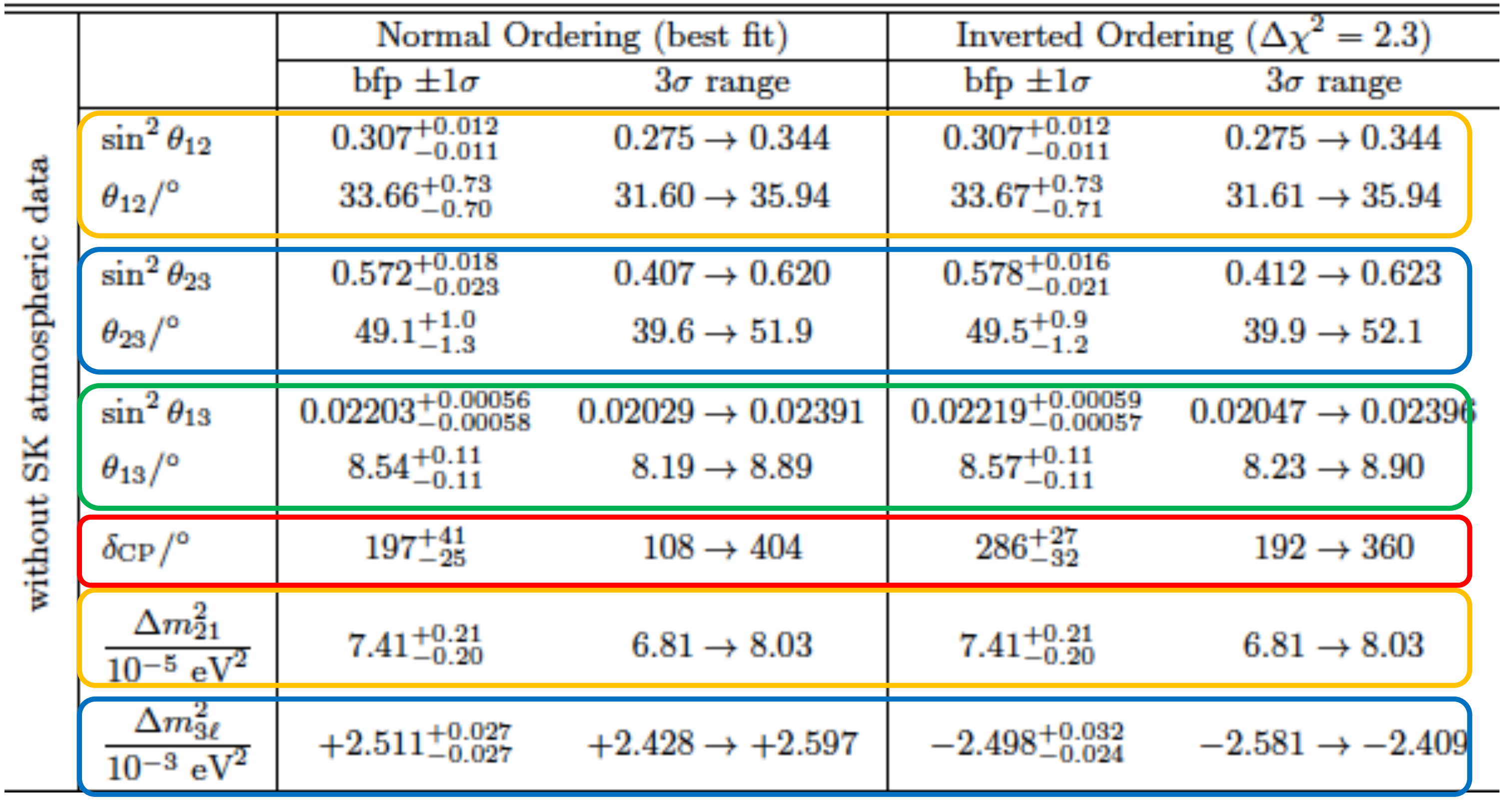


Zoya Vallari, Fermilab Seminar, Feb 16, 2024

- Mass Ordering preference remains inconclusive.
  - Small preference for the Inverted Ordering in the joint fit whereas individual experiments prefer Normal Ordering.
  - Reverts to a weak preference for Normal ordering on adding simultaneous constraint on $|\Delta m^2_{32}|$ and $\sin^2 2\theta_{13}$ from Daya Bay.
- $\delta_{CP} = \pi/2$ lies outside 3-sigma credible interval for both mass ordering.
- Normal ordering permits a wide range of permissible δ_{CP} ,while CP conserving values for the Inverted Ordering fall outside the 3-sigma range.

Neutrino Oscillations: results from global fit (2024)

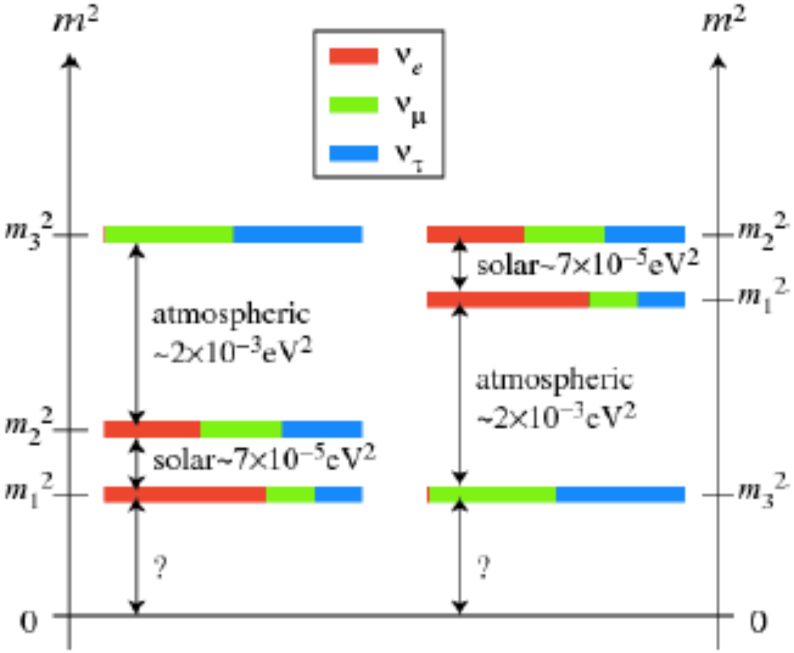
NuFIT 5.3 (2024)



		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.3$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
without SK atmospheric data	$\sin^2\theta_{12}$	$0.307^{+0.012}_{-0.011}$	$0.275 \to 0.344$	$0.307^{+0.012}_{-0.011}$	$0.275 \to 0.344$
	$\theta_{12}/^\circ$	$33.66^{+0.73}_{-0.70}$	$31.60 \to 35.94$	$33.67^{+0.73}_{-0.71}$	$31.61 \to 35.94$
	$\sin^2\theta_{23}$	$0.572^{+0.018}_{-0.023}$	$0.407 \to 0.620$	$0.578^{+0.016}_{-0.021}$	$0.412 \to 0.623$
	$\theta_{23}/^\circ$	$49.1^{+1.0}_{-1.3}$	$39.6 \to 51.9$	$49.5^{+0.9}_{-1.2}$	$39.9 \to 52.1$
	$\sin^2\theta_{13}$	$0.02203^{+0.00056}_{-0.00058}$	$0.02029 \to 0.02391$	$0.02219^{+0.00059}_{-0.00057}$	$0.02047 \to 0.02396$
	$\theta_{13}/^\circ$	$8.54^{+0.11}_{-0.11}$	$8.19 \to 8.89$	$8.57^{+0.11}_{-0.11}$	$8.23 \to 8.90$
	$\delta_{\mathrm{CP}}/^\circ$	197^{+41}_{-25}	$108 \to 404$	286^{+27}_{-32}	$192 \to 360$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.41^{+0.21}_{-0.20}$	$6.81 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.81 \to 8.03$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.511^{+0.027}_{-0.027}$	$+2.428 \to +2.597$	$-2.498^{+0.032}_{-0.024}$	$-2.581 \to -2.409$

Alcune domande rimaste aperte:

- **Gerarchia di massa dei neutrino**
- **Violazione di CP**
- **Violazione del numero leptonico**
- **Quale possibilità ha la fisica del neutrino di produrre un profondo cambiamento nel paradigma della fisica delle particelle elementari (il Modello Standard) e della cosmologia (il paradigma ΛCDM)?**



Sono i punti aperti che impattano sulla strategia INFN nel settore, sui programmi di fisica dei laboratori tradizionalmente legati ai collider - CERN, Fermilab e KEK – e quelli underground (il Gran Sasso).

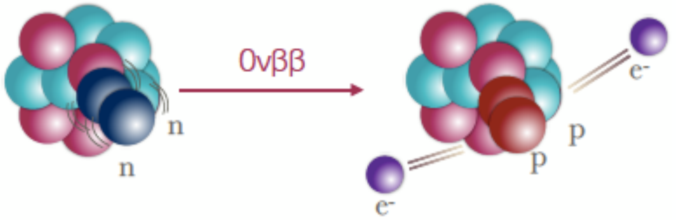
The birth of 0νββ decay

- in 1897 J.J. Thomson discovers the electron, later (1911-1919) E. Rutherford discovers the atom and the proton.
- this model goes into crisis (among mass inconsistencies) with the observation of the continuous spectrum of beta decay;
- in 1930 Pauli to overcome this problem proposes the a new particle the **neutron**, but it is E. Fermi that in 1932 after the discovery of neutron by J. Chadwick calls the Pauli particle neutrino;
- in 1937 E. Majorana propose a description of neutral ½ spin particles (e.g neutrinos) where particle and anti-particle are identical.
- as a consequence in 1939 H. Furry suggests that 0νββ decay can be observed

$$U_{li} = \overset{\text{Solar Osc}}{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}} \cdot \overset{\text{Atm Osc.}}{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}} \cdot \overset{\text{CP violating}}{\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix}} \cdot \overset{\text{Reactor \& Accel}}{\begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix}} \cdot \overset{\substack{\text{Majorana Phases} \\ \text{Double } \beta \text{ decay only}}}{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha_2/2} & 0 \\ 0 & 0 & e^{-i\alpha_3/2+i\delta} \end{pmatrix}}$$

where $c_{ij} = \cos\theta_{ij}$, and $s_{ij} = \sin\theta_{ij}$

0νββ decay and the ν mass

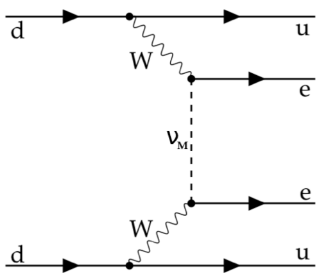


It allows to assess the yet unknown neutrino properties: hierarchy, the $m_{\beta\beta}$ absolute mass and the two Majorana phases α and β not measurable in the oscillation experiments

Observation of 0νββ decay will assess:

1. neutrino has Majorana nature
2. lepton number is violated (ΔL = 2)
3. determination of ν absolute mass (nuclear model dependent)

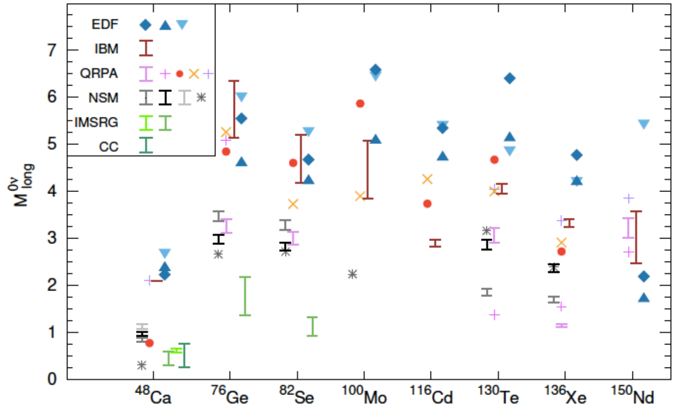
$$\langle m_{\beta\beta}\rangle = \left|\sum |U_{ei}|^2 e^{i\phi_i} m_i\right|$$
$$= \left|c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 m_2 e^{i\alpha} + s_{13}^2 m_3 e^{i\beta}\right|$$



The half life of 0νββ in case of light Majorana neutrino exchange:

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G_{0\nu} \times |M_{0\nu}|^2 \times \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

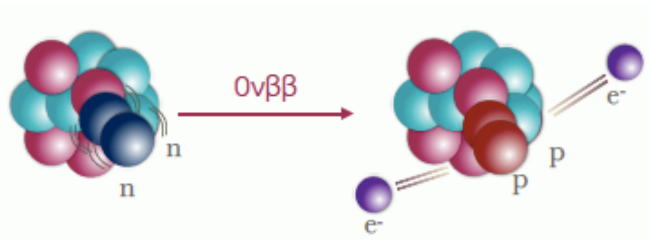
- **Phase Space Integral:** well known quantity
- **Nuclear Matrix Element:** most critical ingredient, produces uncertainty in the determination of $m_{\beta\beta}$ (quenching problem)
- **Neutrino Effective Mass:** estimated by measuring $T_{1/2}$



Agostini, Benato, Detwiler, JM, Vissani, Rev. Mod. Phys. 95, 025002 (2023)

Experimental aspects

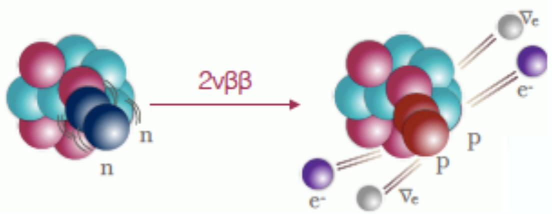
(A,Z) → (A,Z+2) + 2e⁻



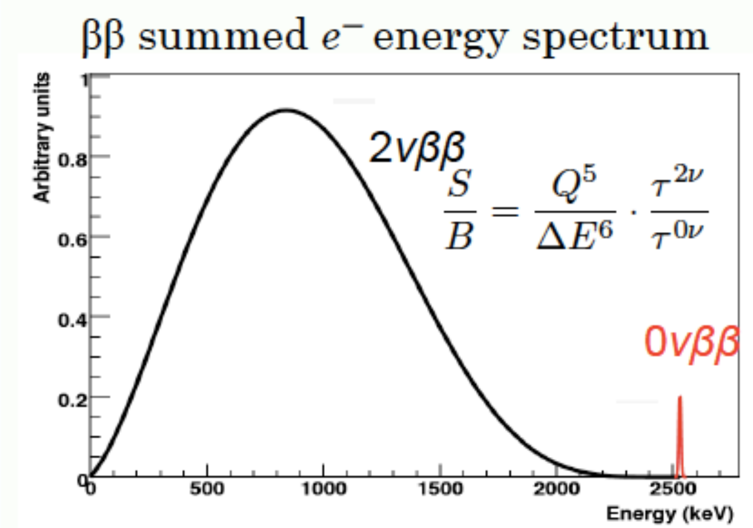
- Experimental signature
  - One daughter ionized isotope + 2 e⁻
  - e⁻ summed kinetic energy = monochromatic line at $Q_{\beta\beta}$ (~2-3 MeV)

Irreducible background

(A,Z) → (A,Z+2) + 2e⁻+ 2$\overline{\nu}$



- 2nd order weak process in SM
- measured at a few % precision
- $T^{2\nu}_{1/2} > 10^{18}$ yr



$$\frac{S}{B} = \frac{Q^5}{\Delta E^6} \cdot \frac{\tau^{2\nu}}{\tau^{0\nu}}$$

$$S \propto \underset{\text{abundance}}{a}\,\overset{\text{efficiency}}{\varepsilon}\sqrt{\frac{\overset{\text{exposure}}{M\cdot t}}{\underset{\text{energy resolution}}{\Delta E}\cdot\underset{\text{background index}}{BI}}}$$

Experimental aspects

- Experiment Sensitivity (S): it is a computed value
- Half-life ($T^{0\nu}_{1/2}$) of the $0\nu\beta\beta$ → $m_{\beta\beta}$ is derived
- Half-life ($T^{2\nu}_{1/2}$) of the $2\nu\beta\beta$
- Beyond SM/exotic physics

$$(T^{0\nu}_{1/2})^{-1} = \underset{\text{phase space integral}}{G_{0\nu}}\,\underset{\text{nuclear matrix element}}{|M_{0\nu}|^2}\left(\frac{\overset{\text{effective neutrino mass}}{m_{\beta\beta}}}{m_e}\right)^2$$

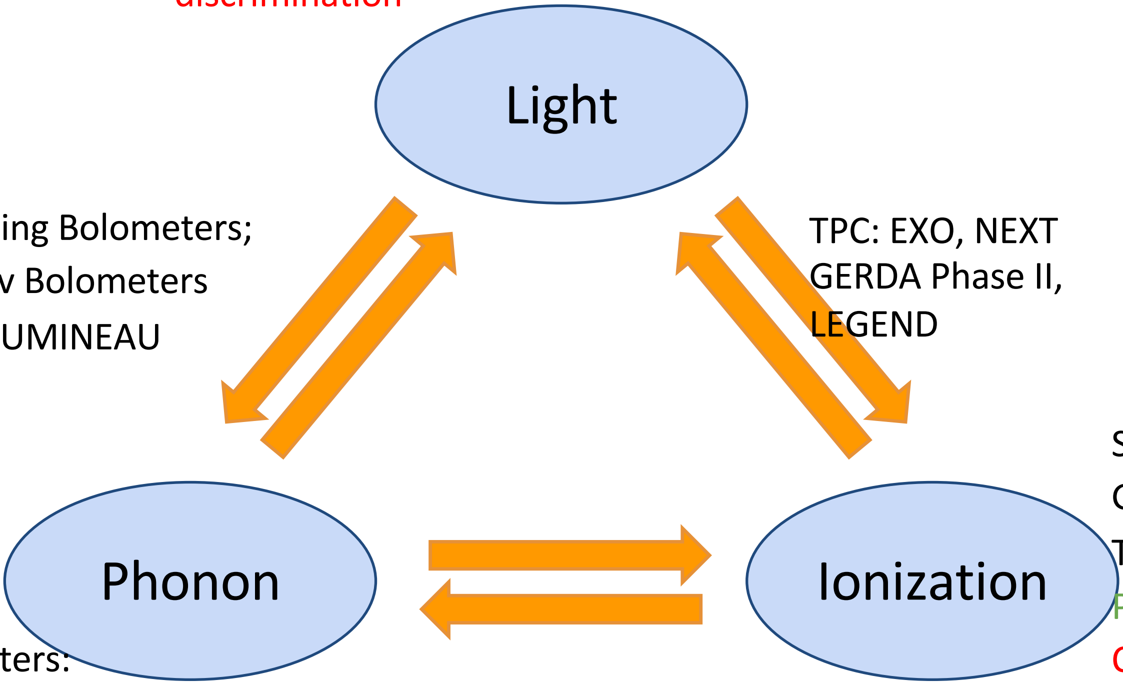
$$S \propto a\varepsilon \cdot M \cdot t$$

Results depend on achieved performances:

- **Exposure (M·T)** units [kg·yr]: it expresses the "observed" (mass of isotope) x the "observation time"
- **Background Index (B or BI)** in units of [cts/(keV·kg·y)] i.e. intensity of the residual background in the ROI
- **Energy resolution (ΔE)** [keV]: how well the system can resolve peaks in the energy spectra over the exposure time

$$S \propto \underset{\text{abundance}}{a}\,\overset{\text{efficiency}}{\varepsilon}\sqrt{\frac{\overset{\text{exposure}}{M \cdot t}}{\underset{\text{energy resolution}}{\Delta E} \cdot \underset{\text{background index}}{BI}}}$$

0νββ: Experimental techniques (over the last 70 years)



Liquid Scintillators: Kamland-Zen, SNO+
Scintillating Crystals: Candles
PRO: High Masses possible
CONS: Limited En. Res. Limited Bkg discrimination

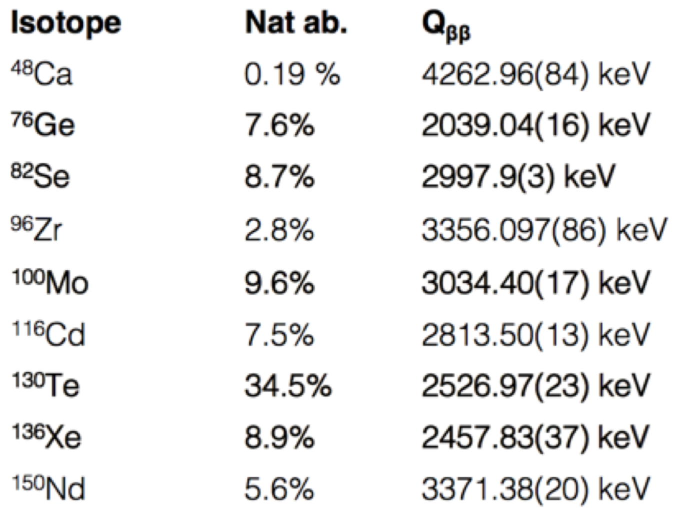
Scintillating Bolometers;
Cerenkov Bolometers
CUPID, LUMINEAU

TPC: EXO, NEXT
GERDA Phase II,
LEGEND

Bolometers:
CUORE

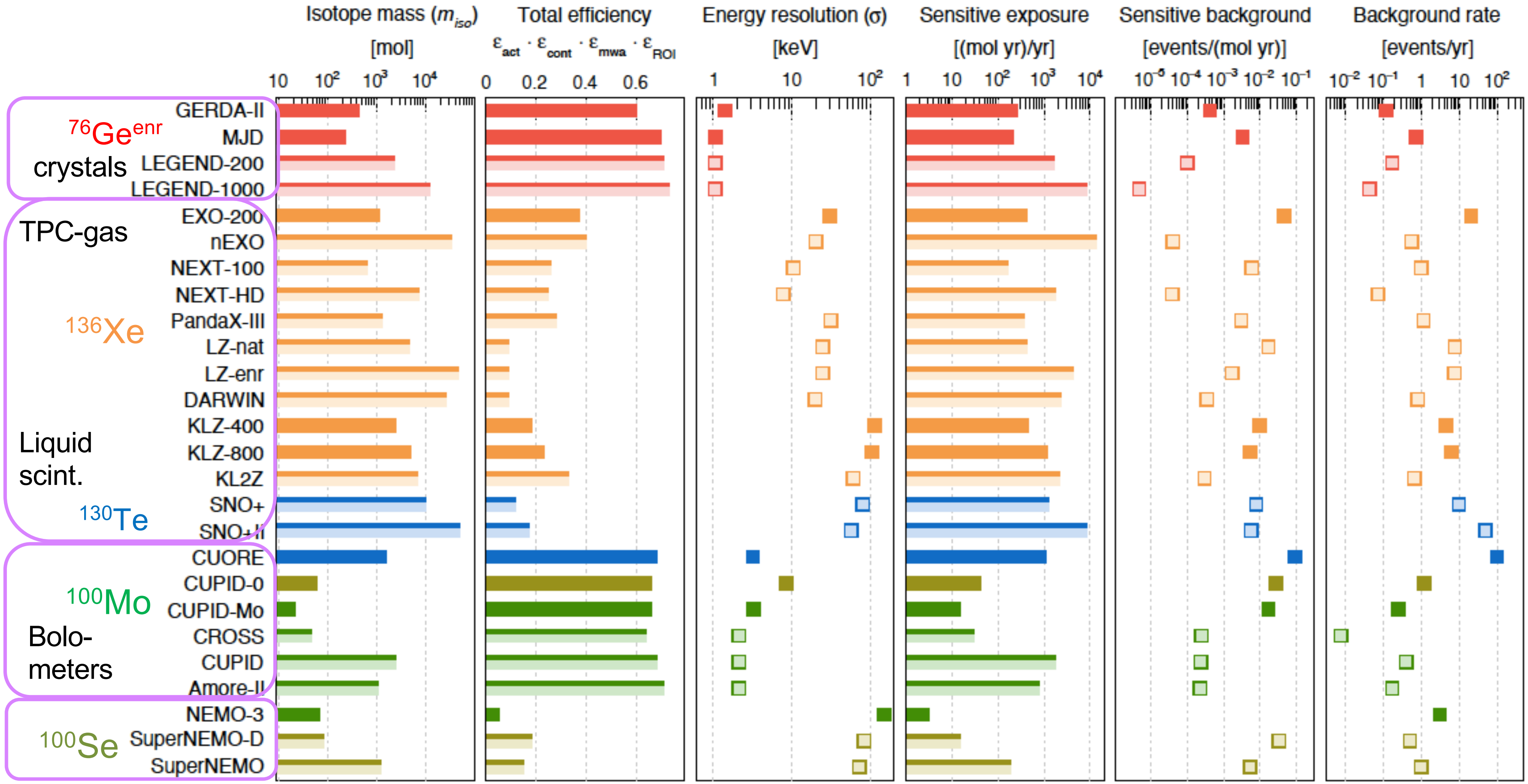
Semiconductor Calorimeters:
GERDA; MAJORANA, LEGEND
Tracking Calorimeters: SuperNEMO; DCBA
PRO: Good En. Res. Good Bkg discrimination
CONS: Difficult/Costly to scale up Masses

Energy of 0νββ for different isotopes



Isotope	**Nat ab.**	**$Q_{\beta\beta}$**
^{48}Ca	0.19 %	4262.96(84) keV
^{76}Ge	7.6%	2039.04(16) keV
^{82}Se	8.7%	2997.9(3) keV
^{96}Zr	2.8%	3356.097(86) keV
^{100}Mo	9.6%	3034.40(17) keV
^{116}Cd	7.5%	2813.50(13) keV
^{130}Te	34.5%	2526.97(23) keV
^{136}Xe	8.9%	2457.83(37) keV
^{150}Nd	5.6%	3371.38(20) keV

Present and future $0\nu\beta\beta$ experiments: relevant parameters

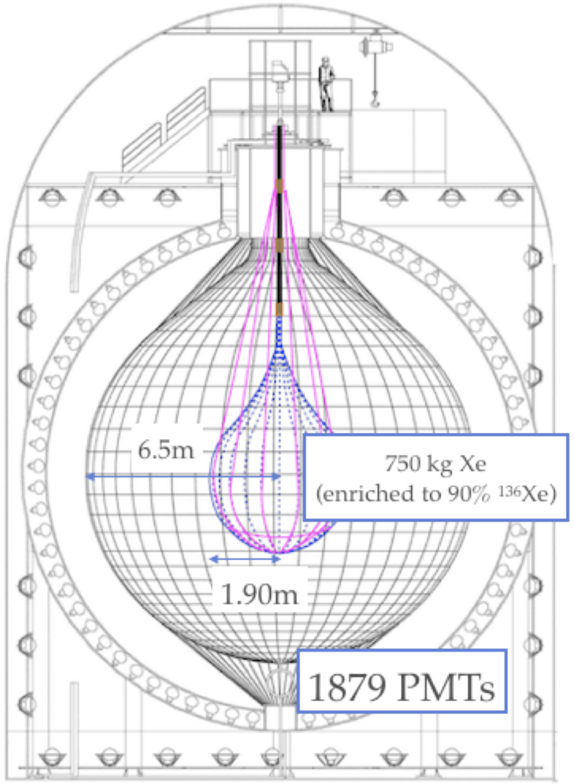


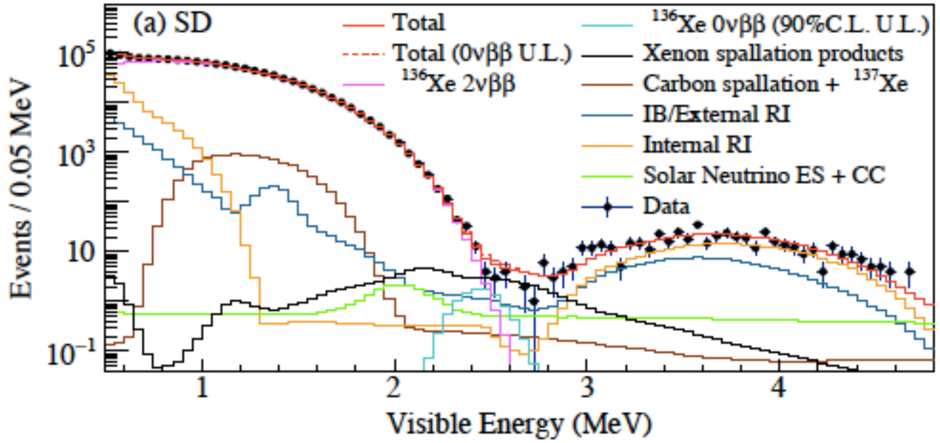
Agostini, Benato, Detwiler, Menendez, Vissani- Rev. Modern Phys., 95, 025002 (2023)

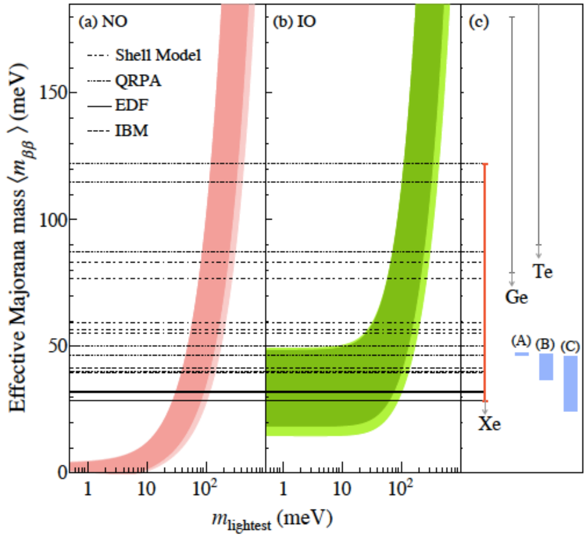
KamLAND-ZEN

754 kg 90% enr. 136Xe diluted in liquid scintillator deployed in in KamLAND detector

ΔE @ $Q_{\beta\beta}$ (2457 keV) ~ 250 keV (10%)







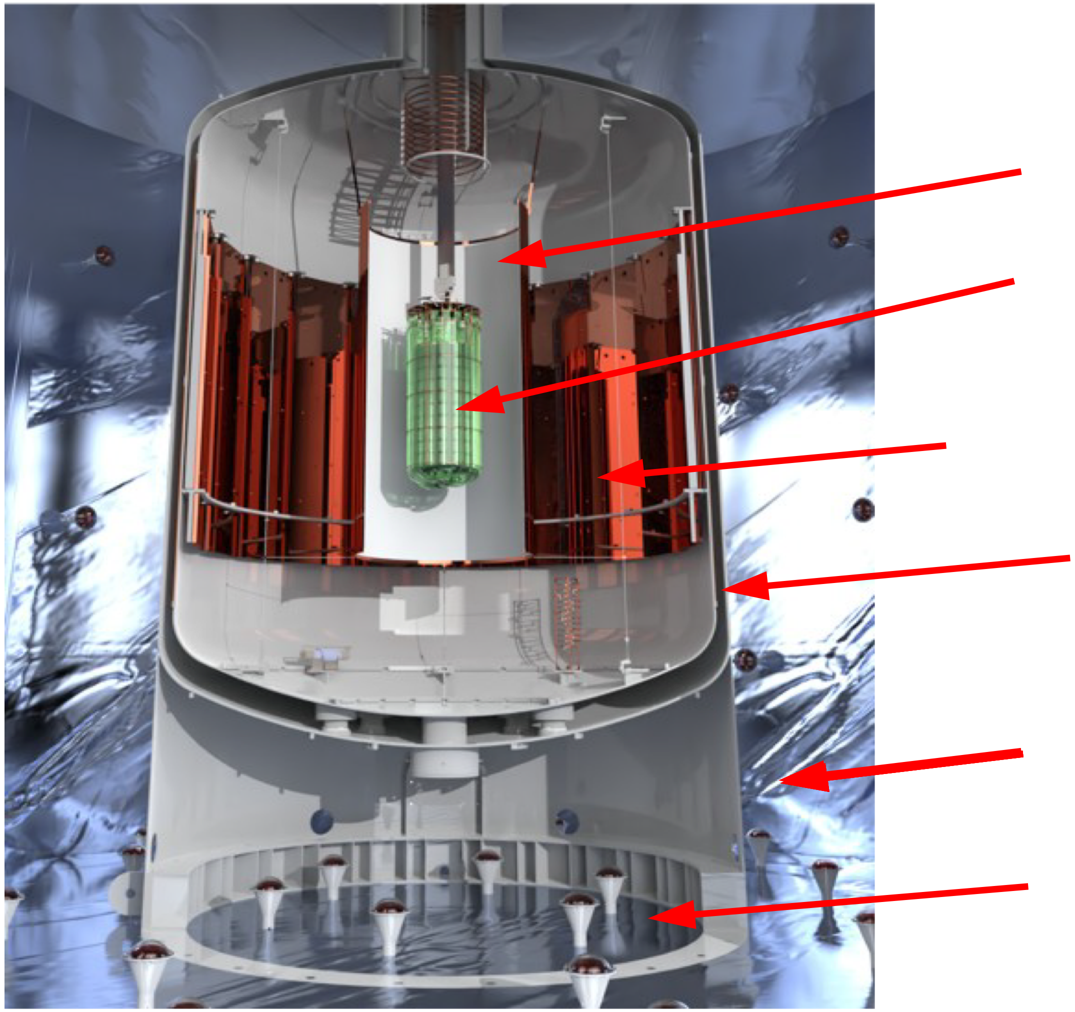
Combined with KL-ZEN 400

Total exposure: ~2.5 Ton yr

$T^{0\nu}_{\beta\beta}$ > 3.8 10^{26} 90%C.L.

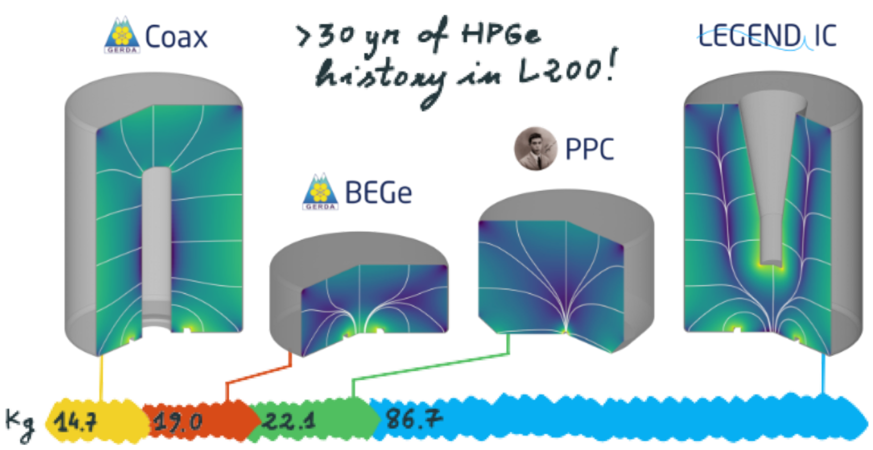
$m_{\beta\beta}$ < 28- 122 meV

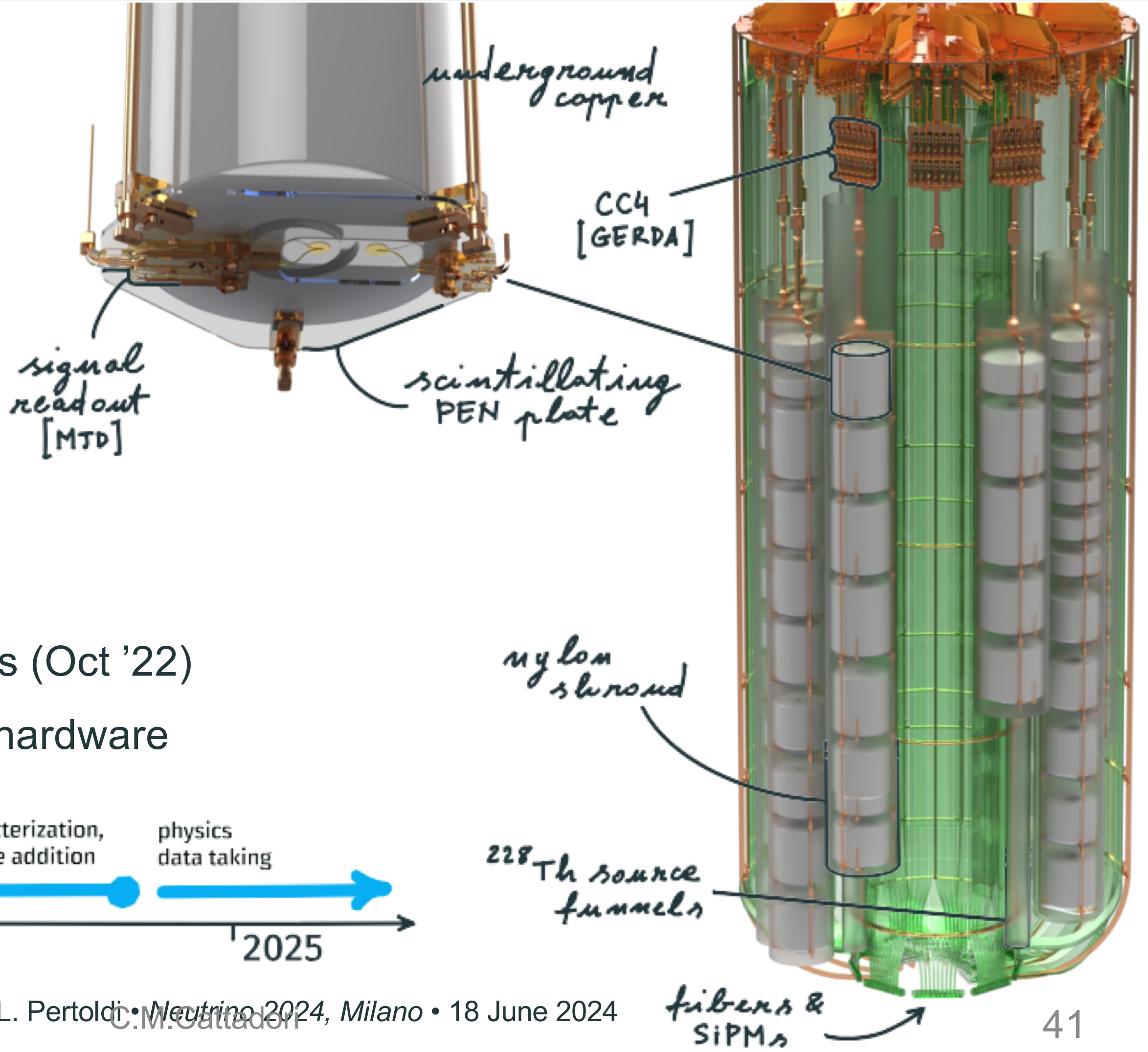
LEGEND-200: apparato



- wavelength shifting reflector
- rivelatori Ge e Liquid Argon Veto
- schermo in Cu
- criostato
- water tank
- PMT per µ-veto Cerenkov ad acqua

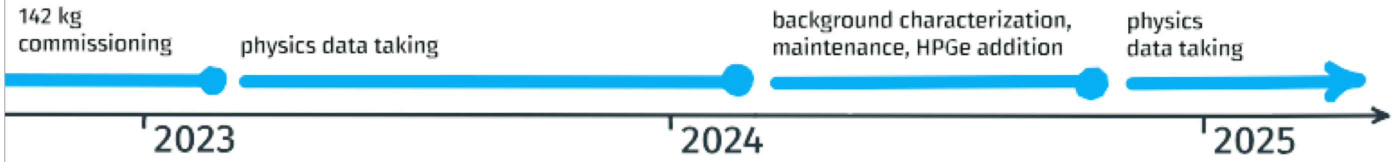
THE LEGEND -200 EXPERIMENT AT LNGS



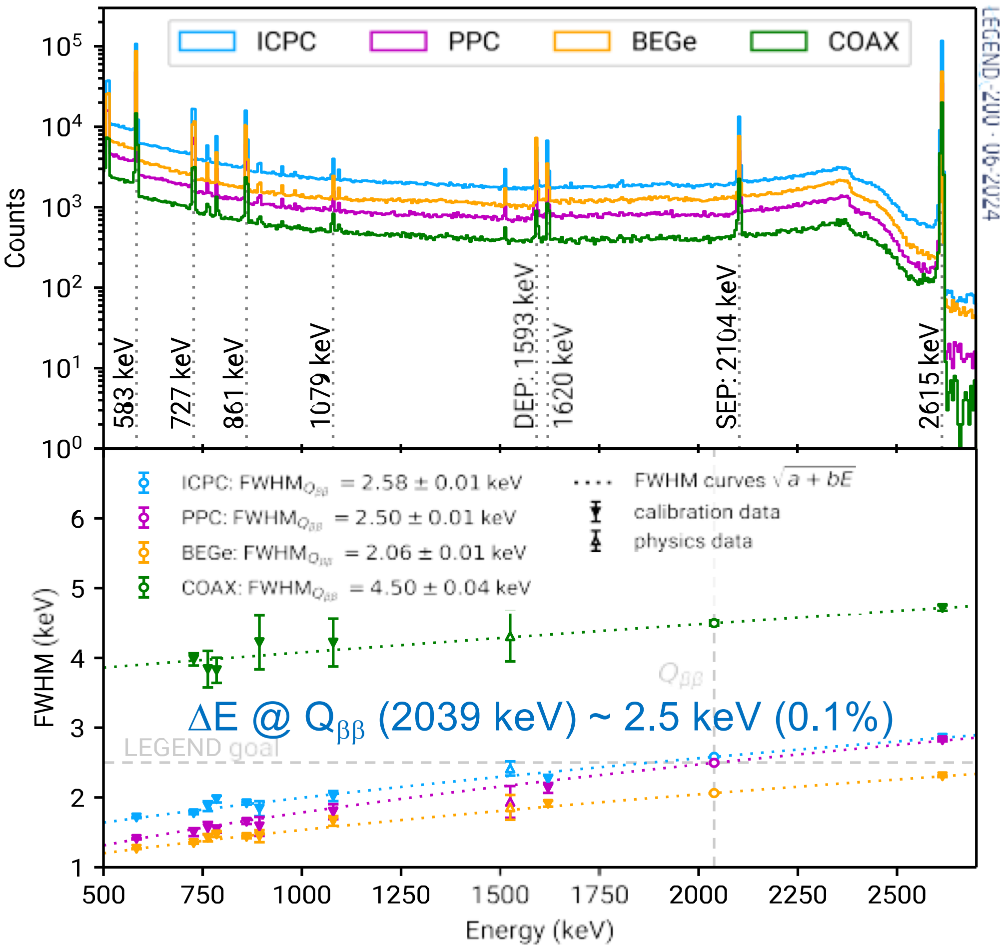


Hardware status — more at [TAUP23]

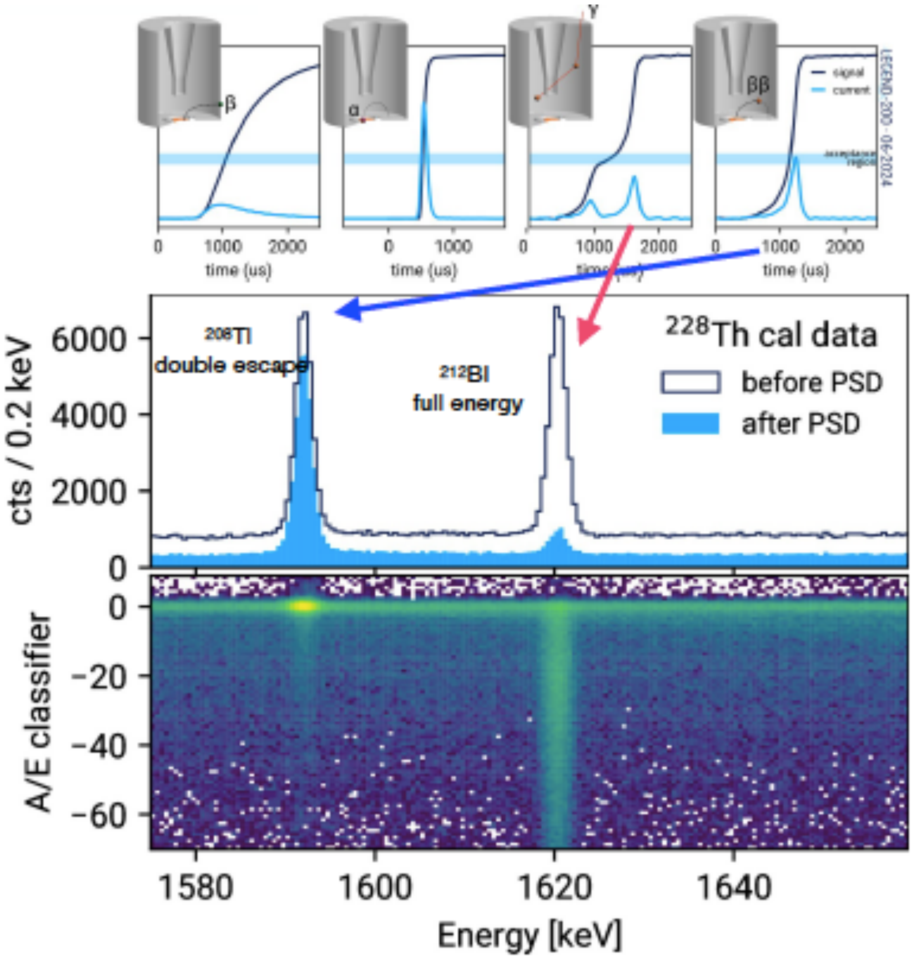
- Installed first **142 kg** of HPGe detectors (Oct ’22)
- 130 kg operational (12 kg OFF due to hardware failure)



THE LEGEND-200: Performances



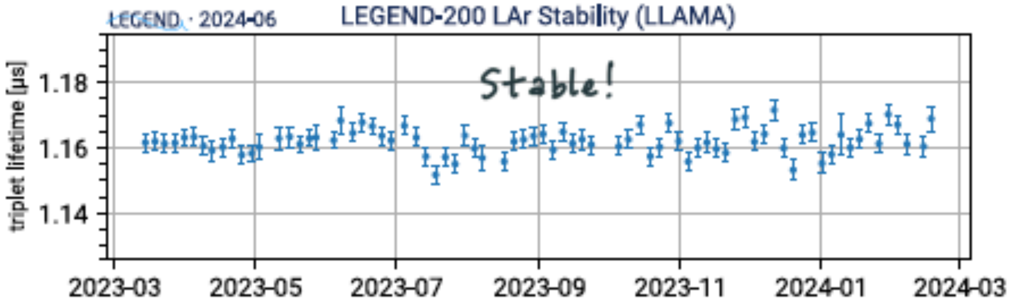
ΔE @ $Q_{\beta\beta}$ (2039 keV) ~ 2.5 keV (0.1%)

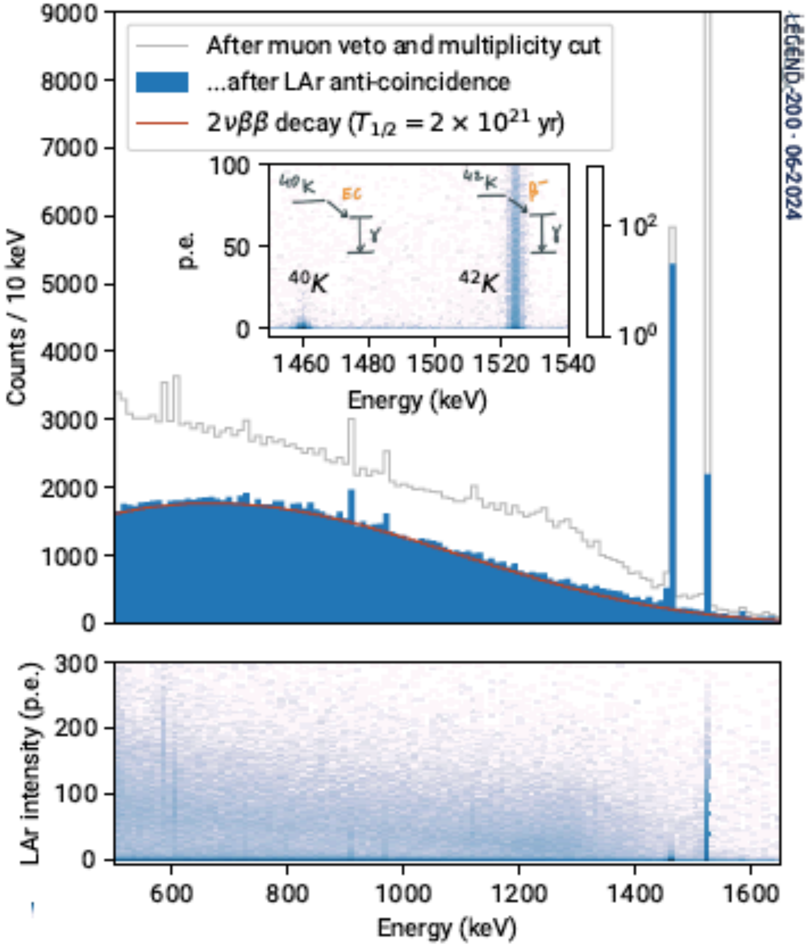


The first year of LEGEND-200 physics data in the quest for 0νββ • L. Pertoldi • *Neutrino 2024, Milano* • 18 June 2024

THE LEGEND-200: Performances

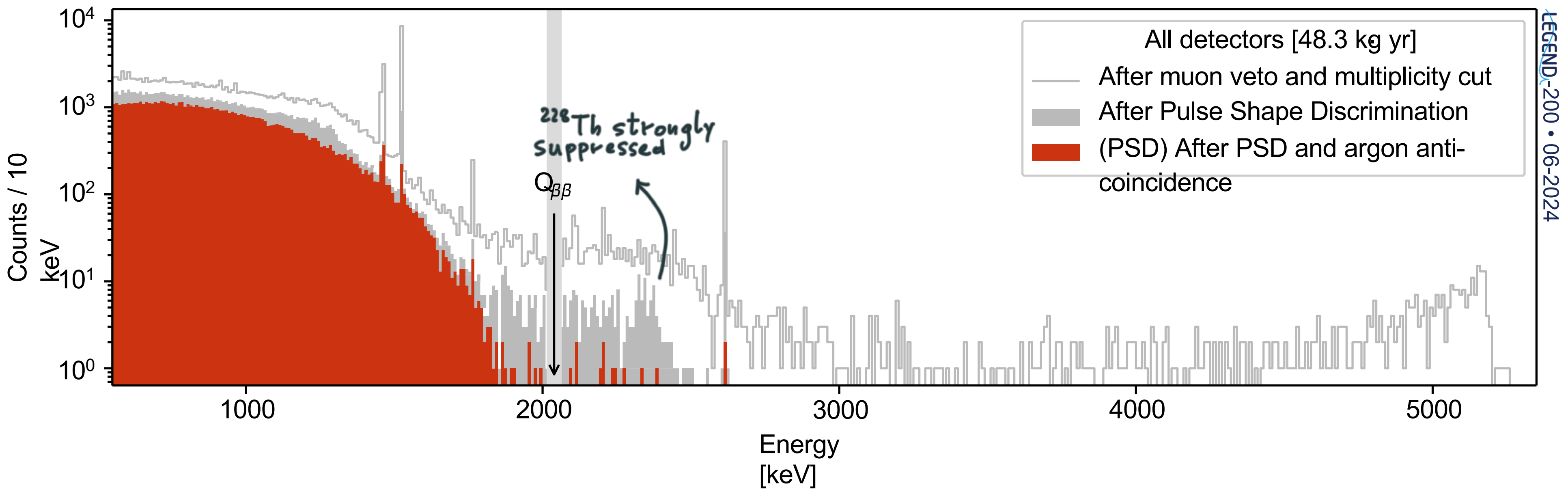
- Improved light yield compared to GERDA (×3)
- **Stable** argon properties
    - *Monitoring through LLAMA instrumentation*
- **Characterized** with special calibration runs
    - *~1 photoelectron per 10 keV deposited in argon*
- **Strong suppression** of background above 2νββ
    - *ββ decay signal acceptance of ~93%*





The first year of LEGEND-200 physics data in the quest for 0νββ • L. Pertoldi • *Neutrino 2024, Milano* • 18 June 2024

DATA AFTER PULSE SHAPE DISCRIMINATION AND ARGON ANTI-COINCIDENC



- Strong anti-correlation of argon and PSD cuts
- Overall 0νββ survival fraction of ~60%
- “Pure” 2νββ distribution, few events surviving at $Q_{\beta\beta}$

LEGEND200- DATA IN THE REGION OF INTEREST — AFTER UNBLINDING

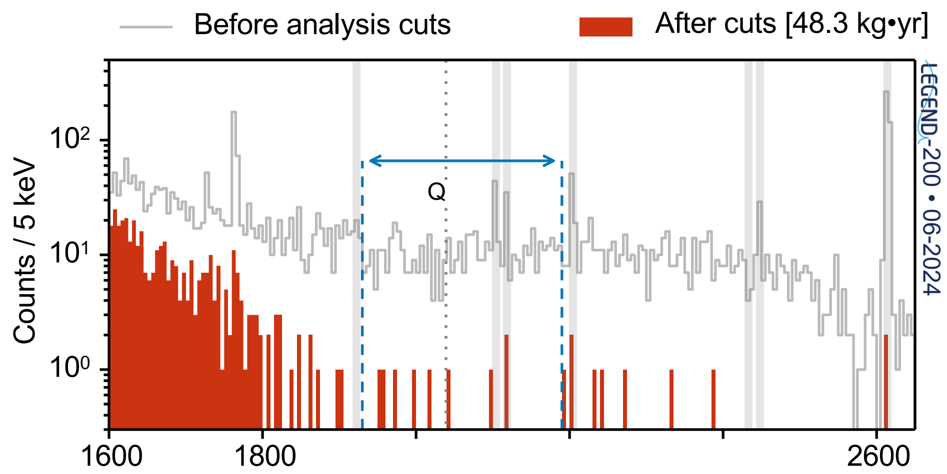
- 7 events surviving = 5.3 ± 2.2· 10^{-4} cts / (keV kg yr)
- *p-value* of background only = 26%
- $T^{0\nu}_{1/2}$ lower limits (90% frequentist C.L.)

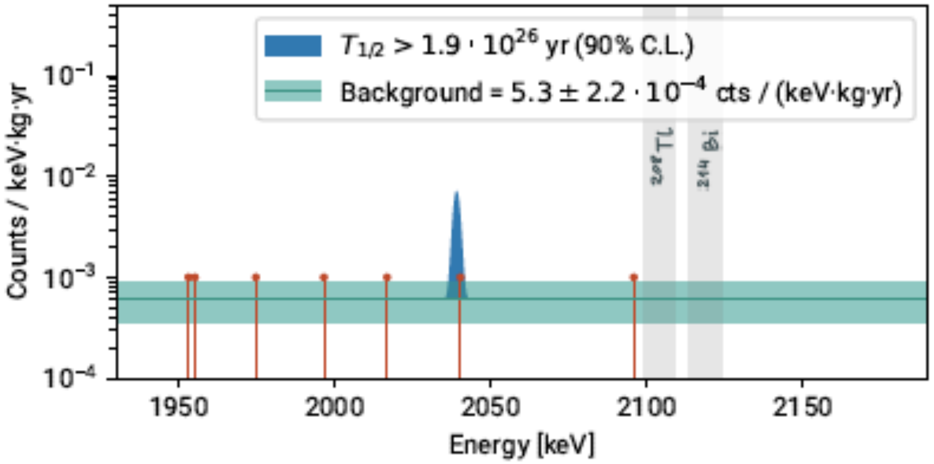
	Sensitivity	Observed
L200	$> 0.8 \cdot 10^{26}$ yr	$> 0.5 \cdot 10^{26}$ yr
^{76}Ge†	$> 3.1 \cdot 10^{26}$ yr	$> 1.9 \cdot 10^{26}$ yr

†) GERDA, MAJORANA and LEGEND combined

- Combined $m_{\beta\beta}$ limit: $m_{\beta\beta} < 75$–178 meV

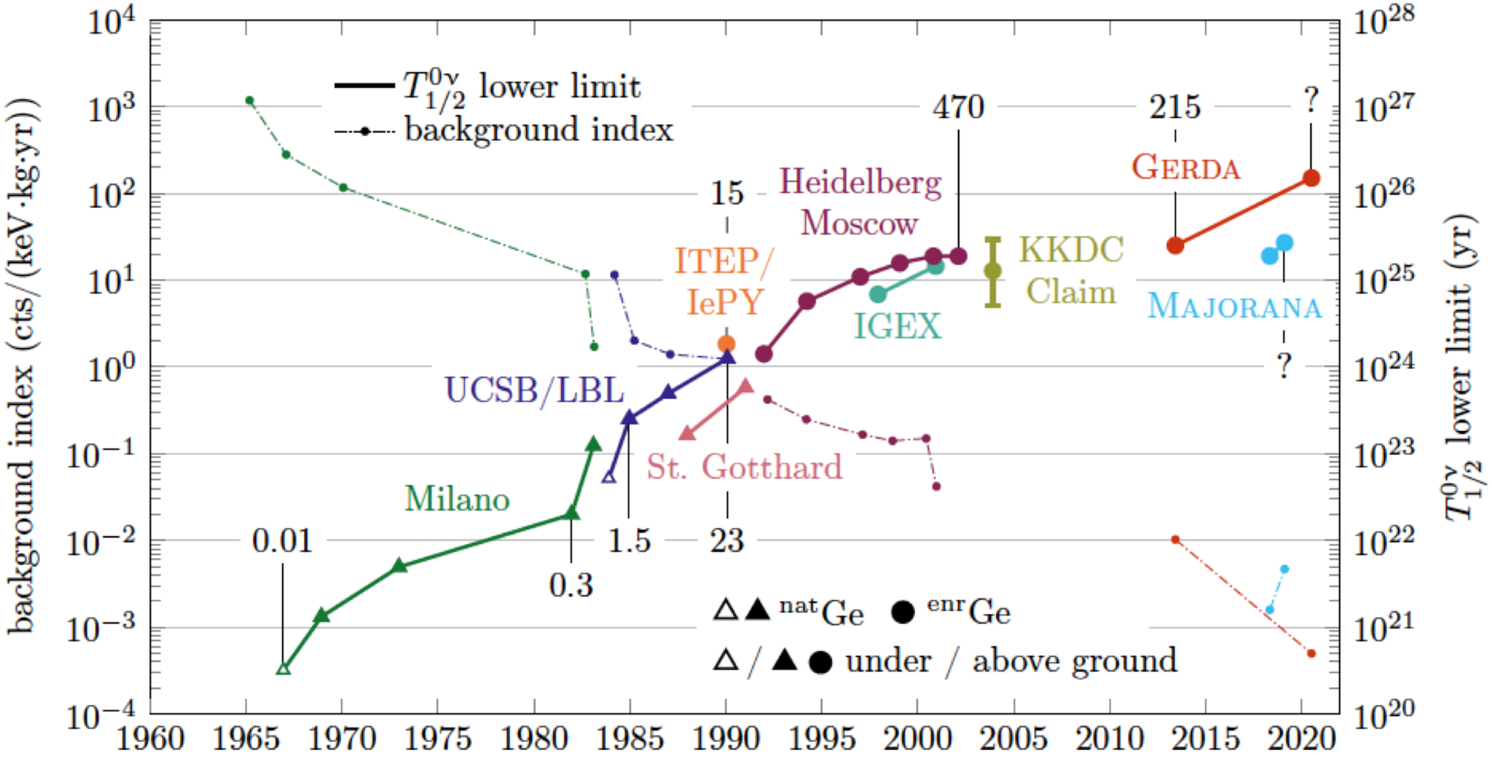
- L200 Contribution
- +30% limit of median expectation
- The event at 2040 keV (+1.4σ from $Q_{\beta\beta}$) weakens the combined limit





The first year of LEGEND-200 physics data in the quest for 0νββ • L. Pertoldi • *Neutrino 2024, Milano* • 18 June 2024

History of ^{76}Ge experiments: lessons learned

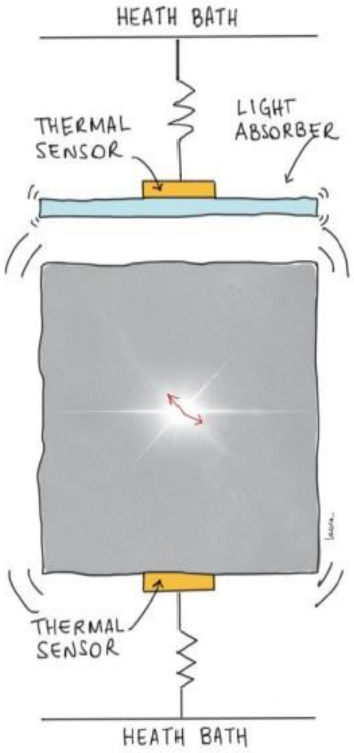


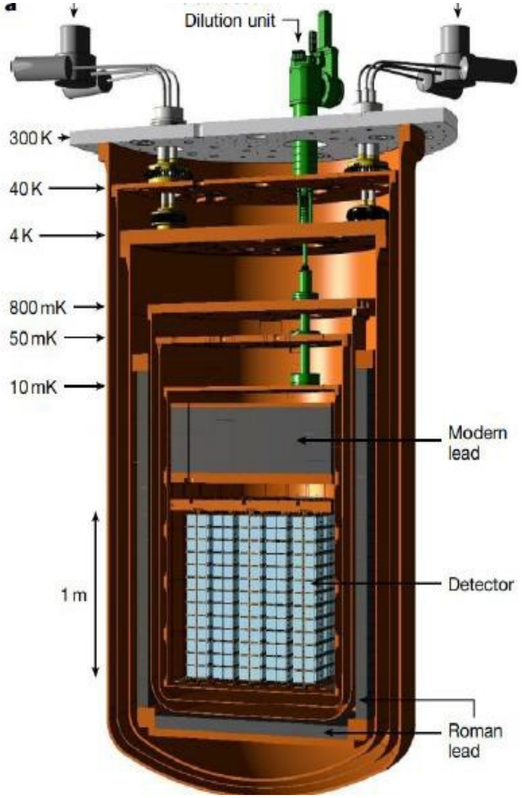
Lessons learned

- Increase the mass
- Increase radiopurity
- Decrease Z of shielding materials surrounding the Ge detectors (GERDA technology)
- Improve PSD

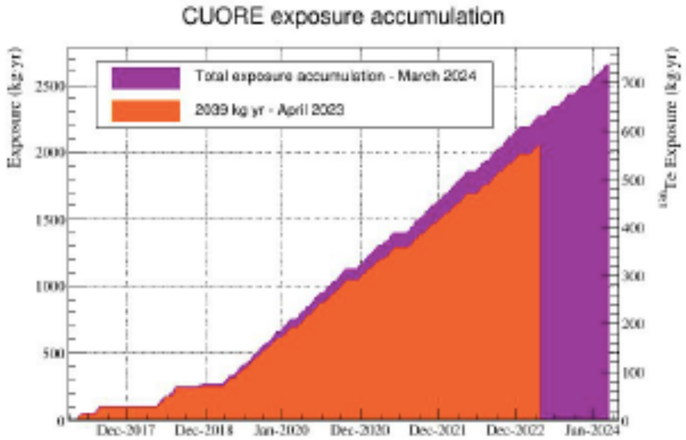
CUORE

- Larger bolometric detector ever built
- 988 $^{nat}TeO_2$ crystals operated at 10 mk
- 742 kg of TeO_2, 206 kg ^{130}Te



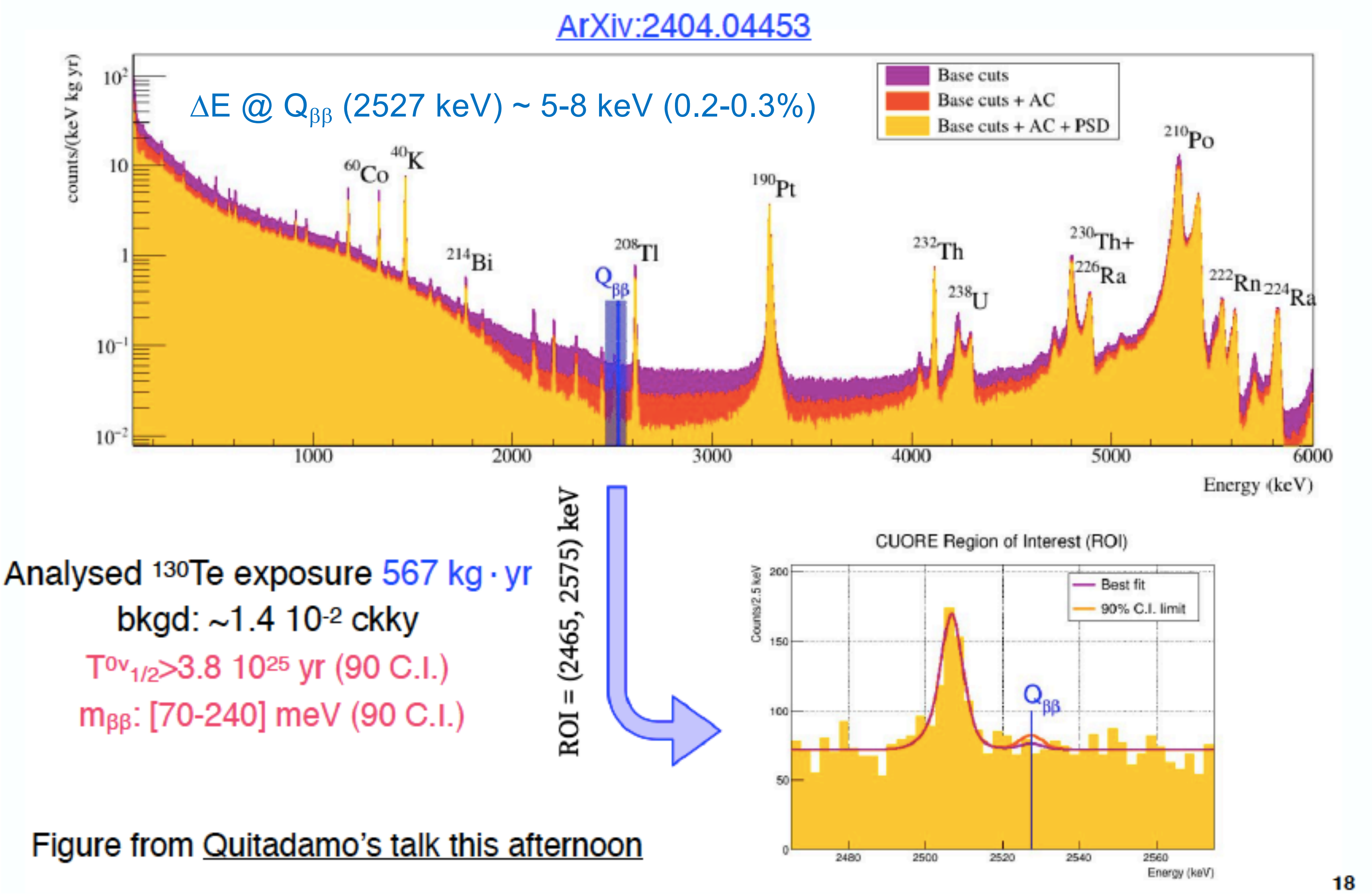


- Continuous physics data taking with high duty cycle and stable performances since 2019



- Collected ^{130}Te exposure ~750 kg · yr

CUORE



ArXiv:2404.04453

ΔE @ $Q_{\beta\beta}$ (2527 keV) ~ 5-8 keV (0.2-0.3%)

ROI = (2465, 2575) keV

Analysed ^{130}Te exposure 567 kg · yr

bkgd: ~1.4 10^{-2} ckky

$T^{0\nu}_{1/2}$>3.8 10^{25} yr (90 C.I.)

$m_{\beta\beta}$: [70-240] meV (90 C.I.)

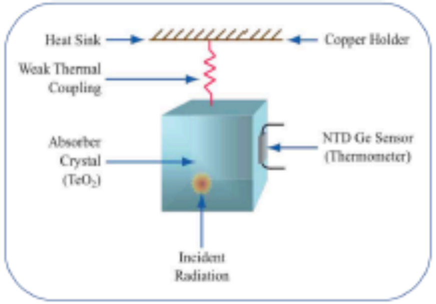
Figure from Quitadamo's talk this afternoon

Future $0\nu\beta\beta$ decay experiments: CUPID

- Builds on CUORE and CUPID0/CUPID-Mo success
- Re-use CUORE infrastructure + 1600 $Li_2{}^{100}MoO_4$ (240 kg ^{100}Mo)

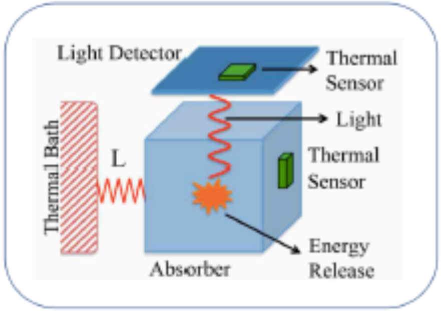
arXiv:1907.09376

CUORE ^{130}Te
pure thermal detector
(**bolometer**)



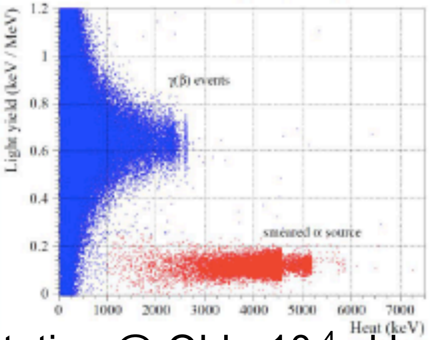
No PID
Q = 2527 keV **< 2615 keV**

CUPID ^{100}Mo
heat + light
(**scintillating bolometer**)



PID

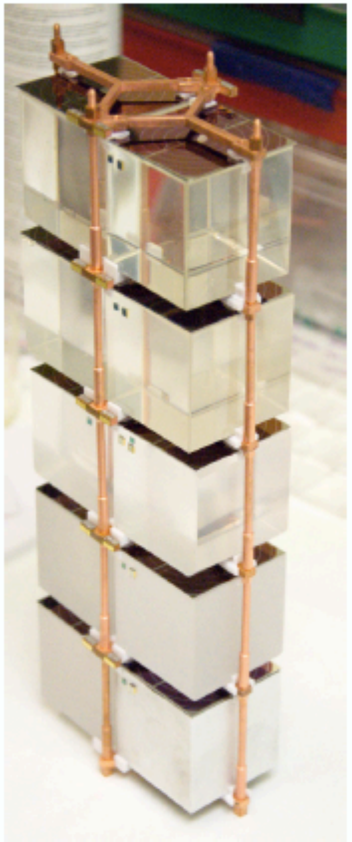
LMOenr, Th (125 h)



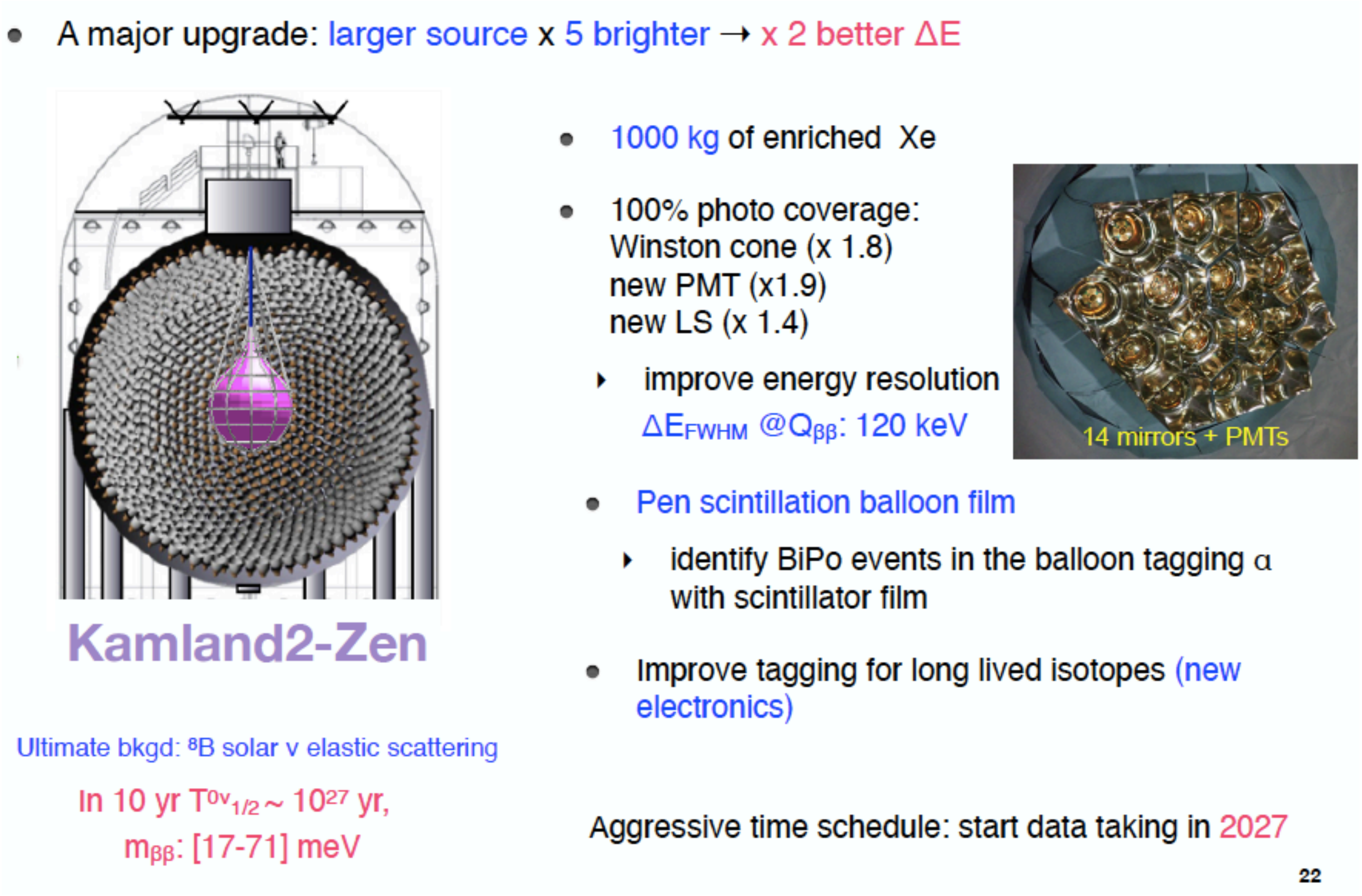
~~α background~~
~~γ background~~

Q = 3034 keV **> 2615 keV**

Data driven Background expectation @ Qbb: 10^{-4} ckky



Future $0\nu\beta\beta$ decay experiments: KamLAND2-ZEN



- A major upgrade: larger source x 5 brighter → x 2 better ΔE

Kamland2-Zen

- 1000 kg of enriched Xe
- 100% photo coverage:
  Winston cone (x 1.8)
  new PMT (x1.9)
  new LS (x 1.4)
  - improve energy resolution
    ΔE_{FWHM} @$Q_{\beta\beta}$: 120 keV

14 mirrors + PMTs

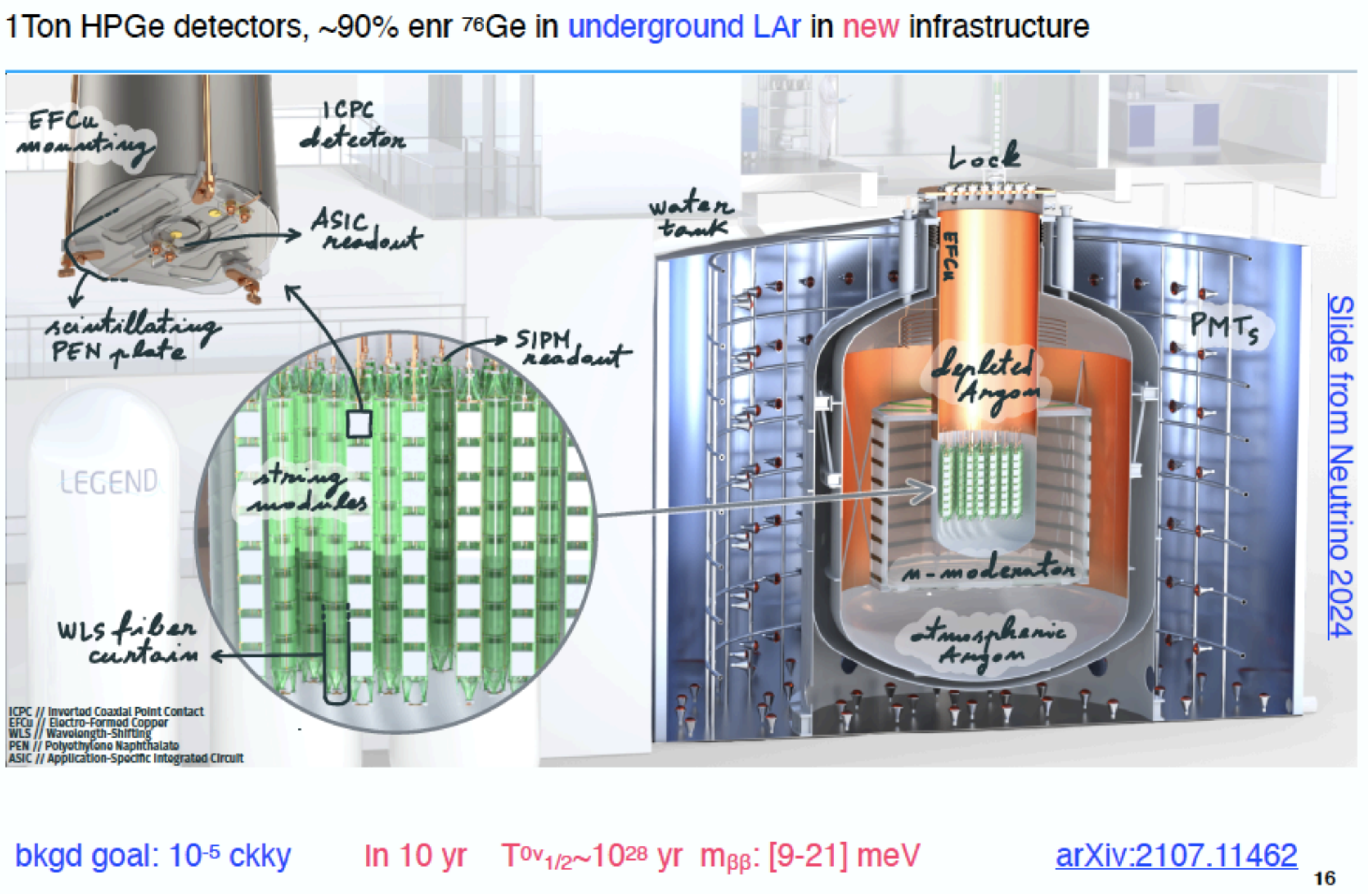
- Pen scintillation balloon film
  - identify BiPo events in the balloon tagging α with scintillator film
- Improve tagging for long lived isotopes (new electronics)

Ultimate bkgd: ^{8}B solar ν elastic scattering

In 10 yr $T^{0\nu}_{1/2} \sim 10^{27}$ yr,
$m_{\beta\beta}$: [17-71] meV

Aggressive time schedule: start data taking in 2027

Future $0\nu\beta\beta$ decay experiments: LEGEND1000



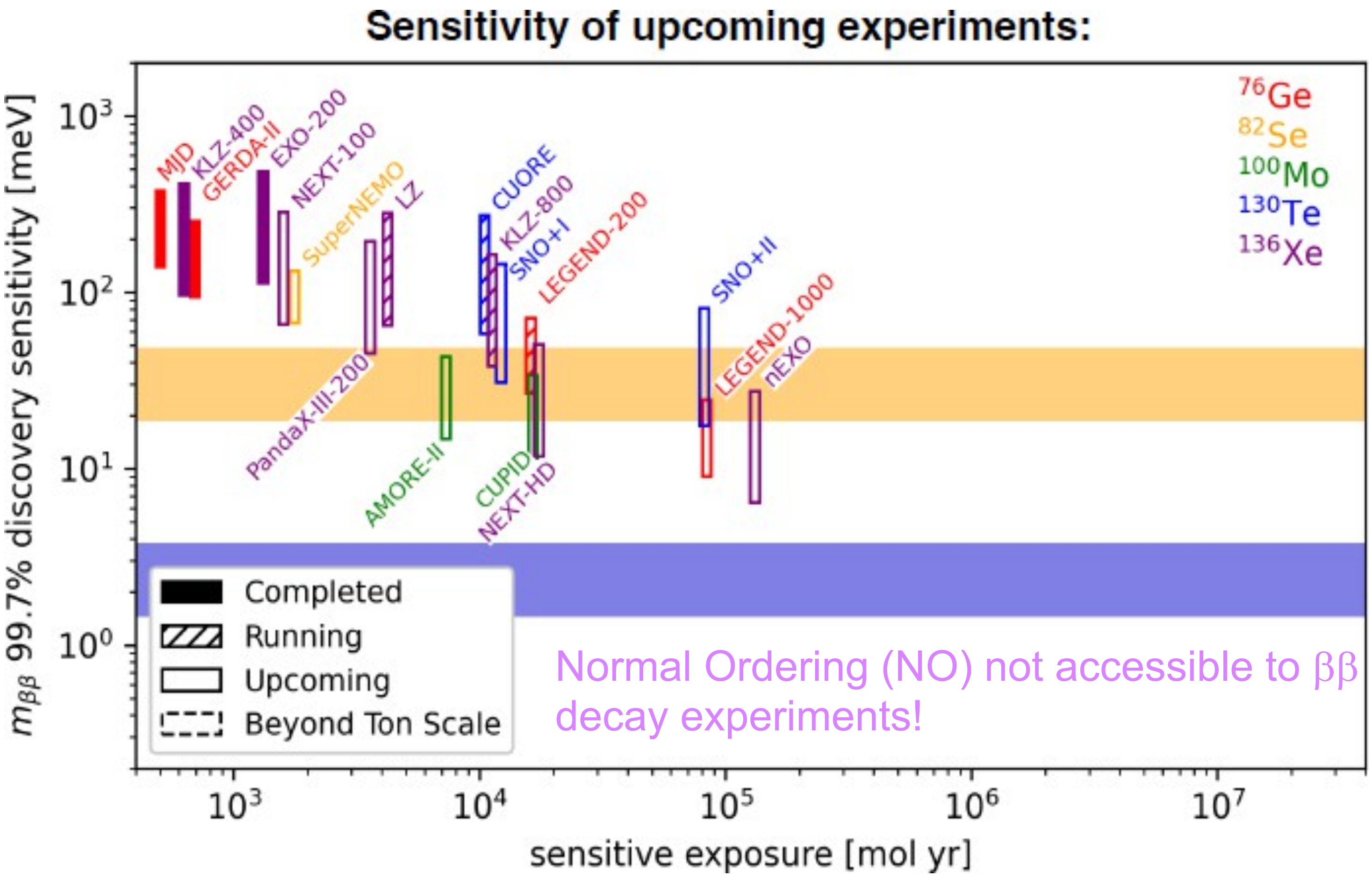
1Ton HPGe detectors, ~90% enr ^{76}Ge in underground LAr in new infrastructure

ICPC // Inverted Coaxial Point Contact
EFCu // Electro-Formed Copper
WLS // Wavelength-Shifting
PEN // Polyethylene Naphthalate
ASIC // Application-Specific Integrated Circuit

Slide from Neutrino 2024

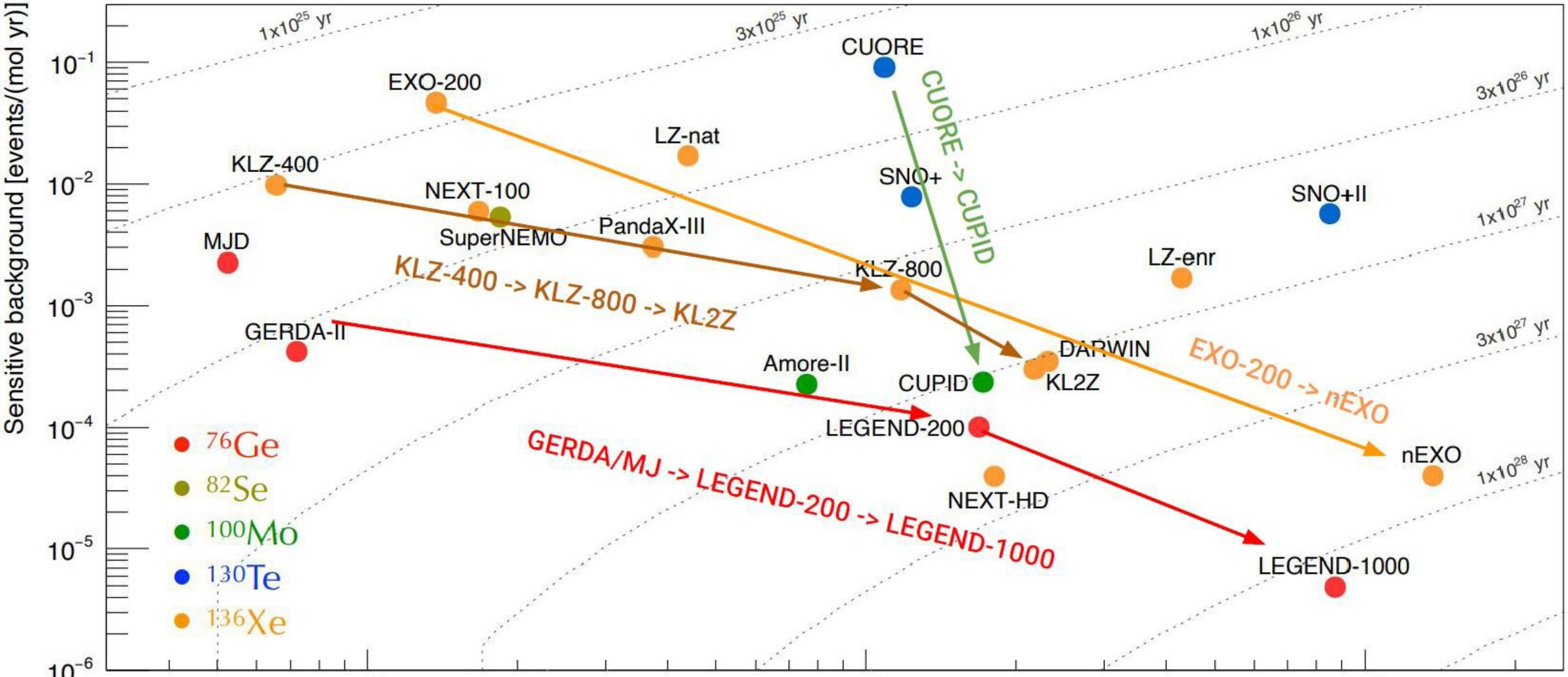
bkgd goal: 10^{-5} ckky In 10 yr $T^{0\nu}_{1/2}$~10^{28} yr $m_{\beta\beta}$: [9-21] meV arXiv:2107.11462

Sensitivita’ della presente/prossima generazione di $0\nu\beta\beta$ experiments



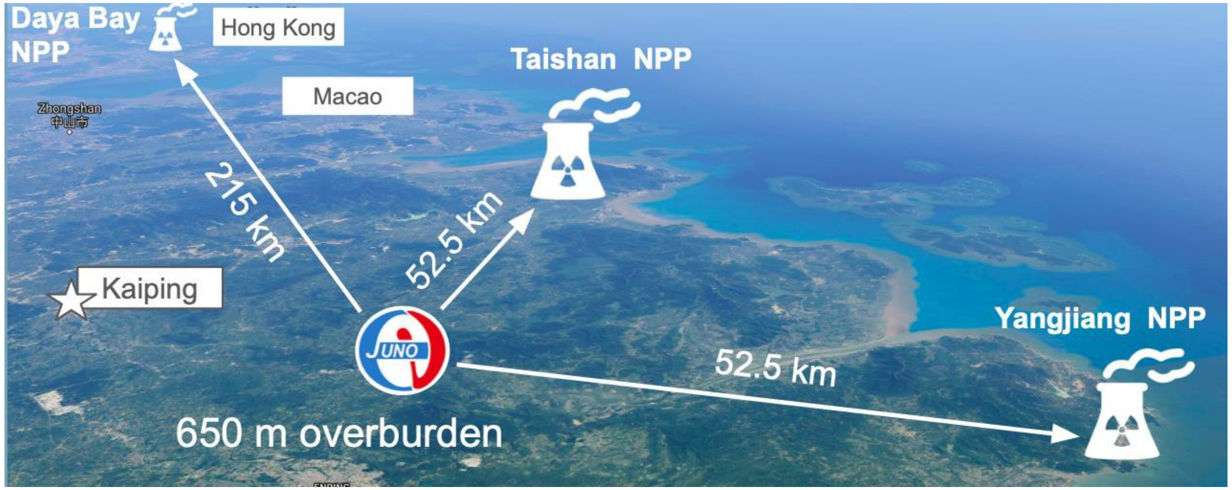
Normal Ordering (NO) not accessible to $\beta\beta$ decay experiments!

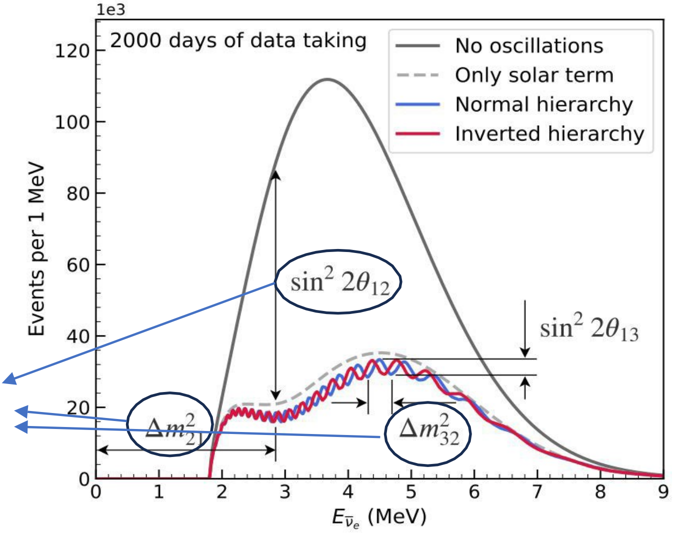
Future $0\nu\beta\beta$ decay experiments: Sensitive BI vs Exposure



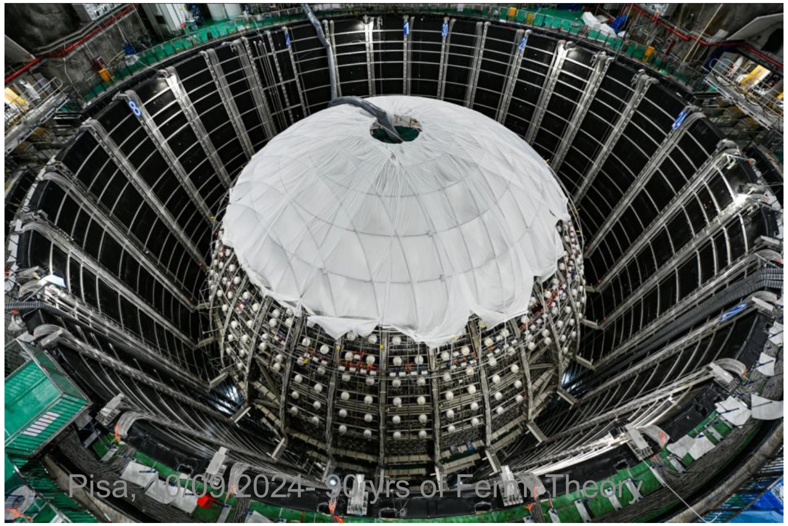
MA, Benato, Detwiler, Menéndez, Vissani, Rev. Mod. Phys. 95, 025002 (2023)

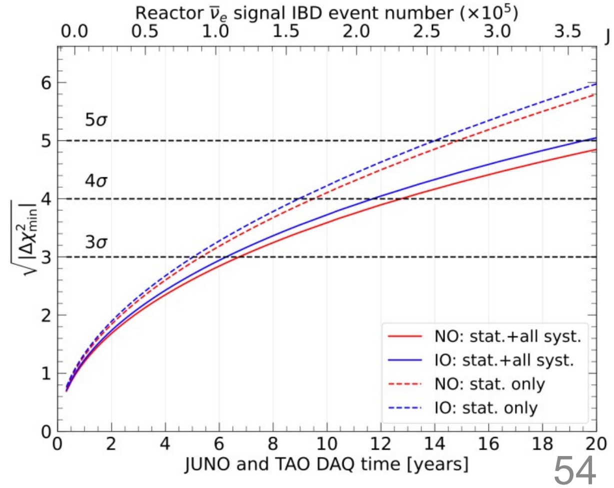
Verso la risoluzione del puzzle della gerarchia di massa: JUNO



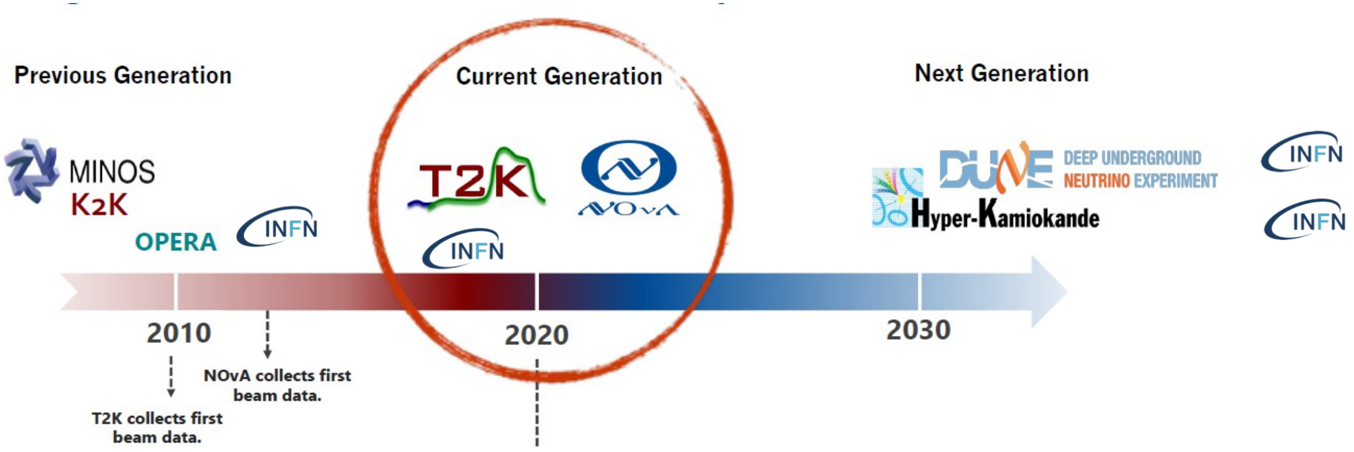


Misurabili da JUNO a <0.5%





Gli esperimenti long-baseline di nuova generazione



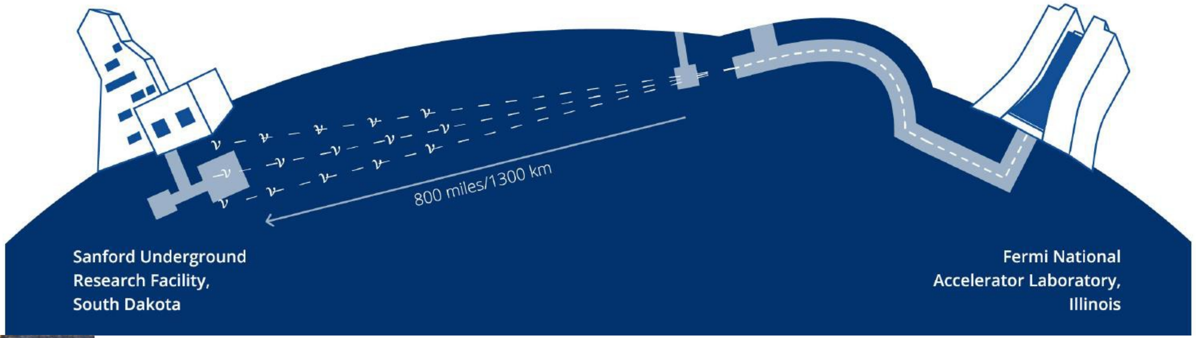
Sono progetti globali di durata multi-decennale con ampie collaborazioni internazionali. Uno standard insolito per la fisica del neutrino ma comune nella fisica dei collider.

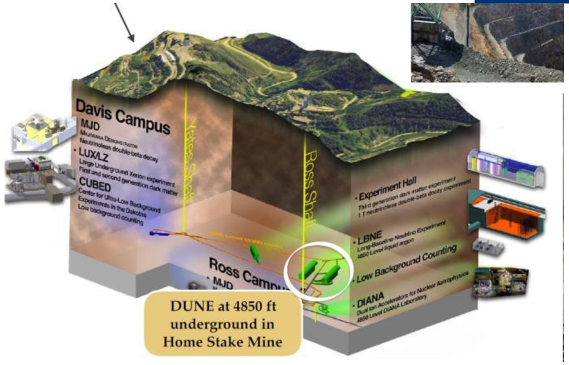
Obiettivi generali:

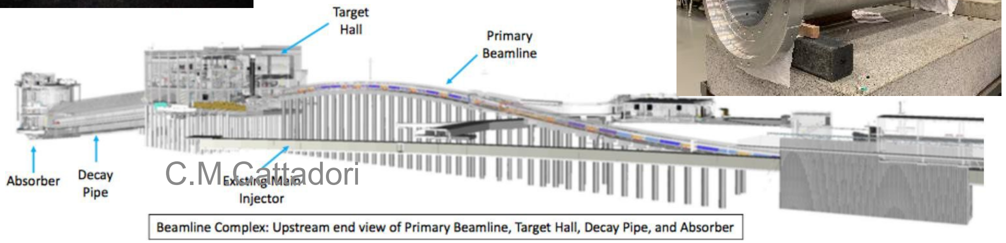
- Stabilire in modo certo la violazione di CP nel settore leptonico
- Determinare la gerarchia di massa dei neutrino e la massimalità del mixing 2-3
- Effettuare misure di precision su tutti gli angoli di mixing e la fase di Dirac a livello di 5-10^{o}
- Studiare sorgenti astrofisiche come i neutrini da supernova, neutrino solari e atmosferici
- Investigare deviazioni dal Modello Standard dovuti a neutrino sterili, decadimento del protone, candidati dark matter (boosted dark matter di orgine cosmica o dark sector prodotto dal fascio di neutrino)

La Long Baseline Neutrino Facility e SURF

A differenza di HyperK, DUNE utilizza due nuove facilities pensate per sostenere il programma di fisica delle particelle americano per i prossimi decenni: un fascio broad band da 1.2 → 2.4 MW power e il laboratorio SURF in South Dakota. E', perciò, il progetto flagship del Fermilab e della fisica underground USA.
L'INFN è fortemente coinvolta sia per gli stretti legami col Fermilab sia perché la tecnologia del Far Detector è basata su una tecnologia INFN: le TPC ad Argon Liquido proposta da C. Rubbia e sviluppata da ICARUS.







Beamline Complex: Upstream end view of Primary Beamline, Target Hall, Decay Pipe, and Absorber

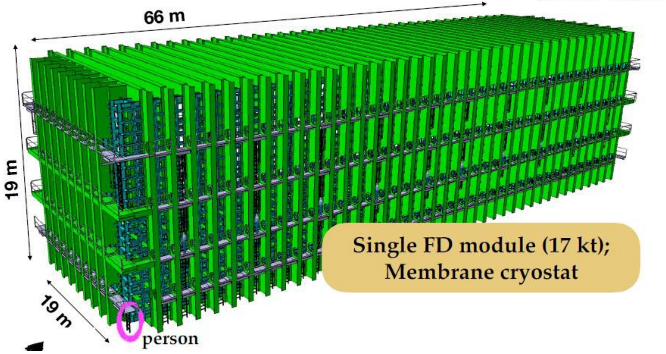
Scavi completati nel Feb 2024

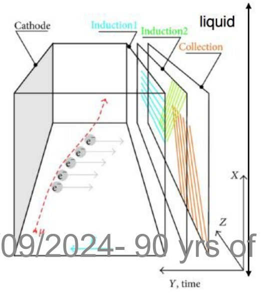
DUNE in a nutshell

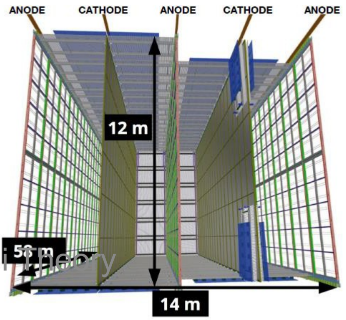
Massa: il Far Detector di DUNE è composto da 4 moduli di liquid argon per una **mass fiduciale totale di 40 kton** (full mass **70 kton**).

Risoluzione: DUNE è basata sulla migliore tecnica di **particle imaging** disponibile alla scala del kton: la Liquid Argon TPC (C. Rubbia, 1977)

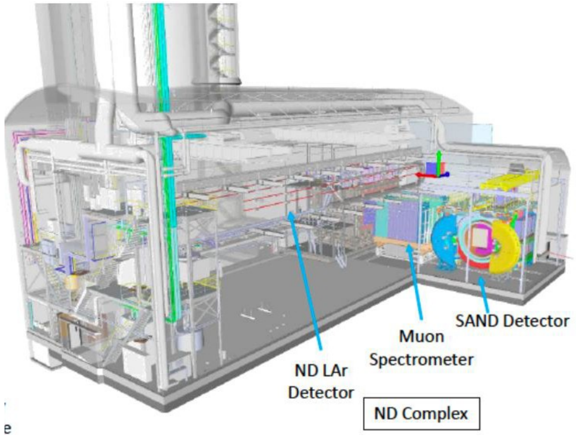
JINST 15 T08010

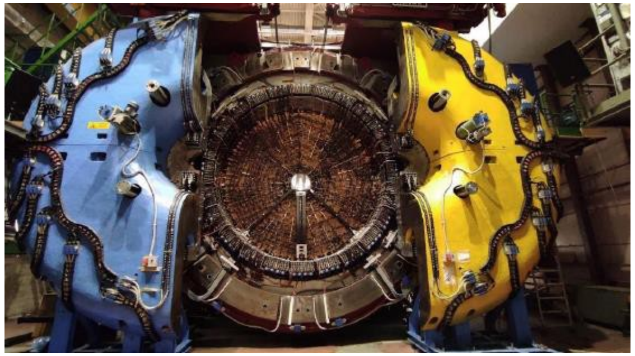


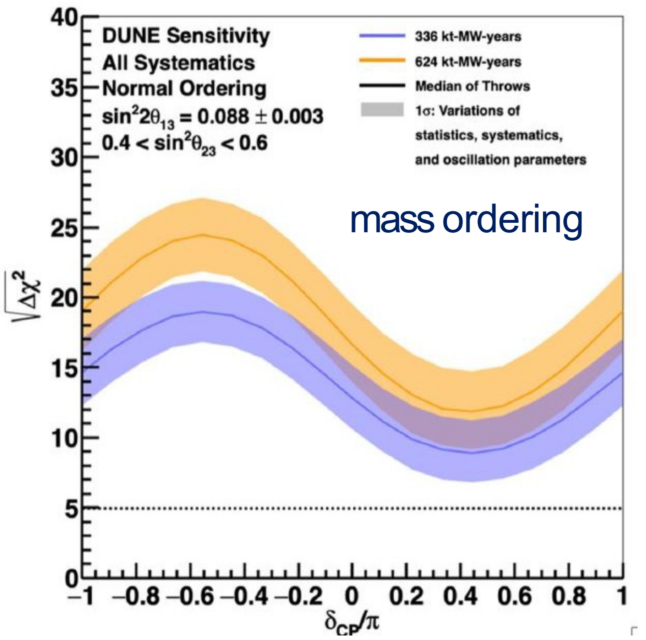




Precisione: DUNE utilizza un **near detector complex** per la caratterizzazione dle fascio basato su un sistema movibile (NDLAr, TMS/NDGar) + un rivelatore on-axis (SAND+GRAIN) detector.



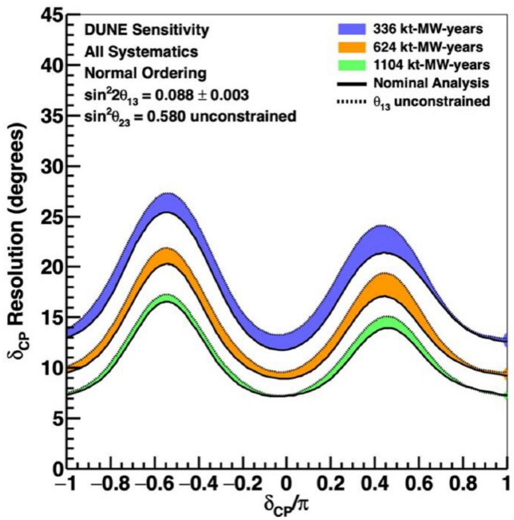


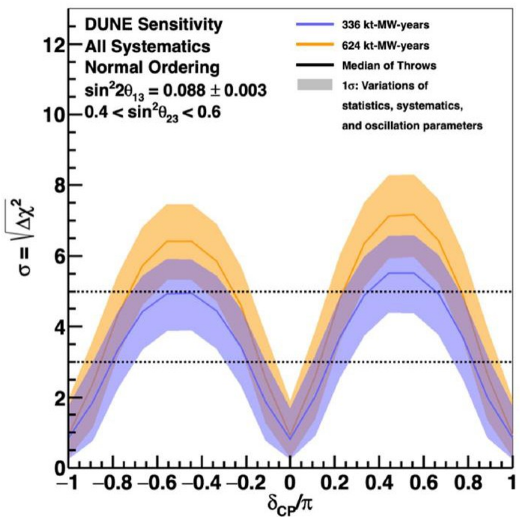


mass ordering

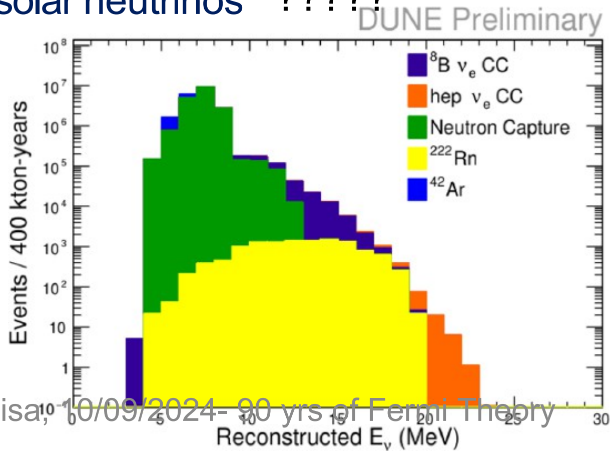
- 5σ discovery potential for CP violation over >50% of δ_{CP} values
- 7-16° resolution to δ_{CP}, *with external input for only solar parameters.*

M. Bishai, Talk at Neutrino2022

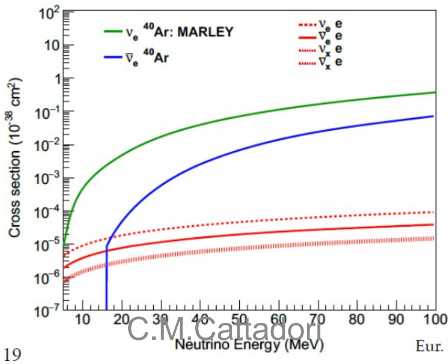




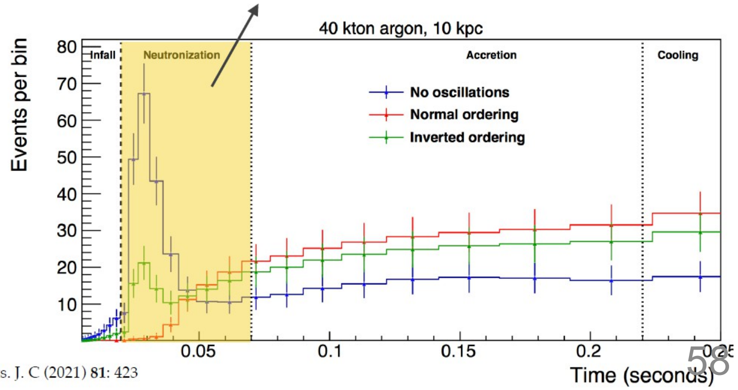
solar neutrinos ?????



supernova neutrinos



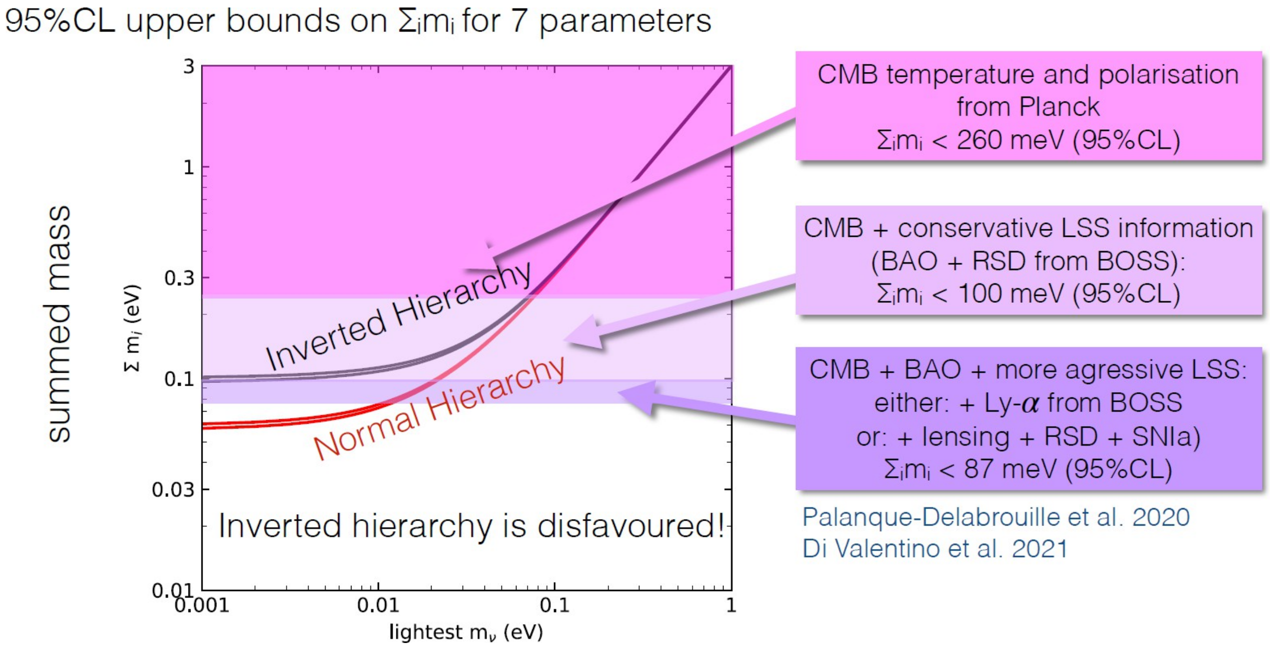
19



Eur. Phys. J. C (2021) 81: 423

L’anello mancante: “the lightest mass eigenstate”

Le oscillazioni ricostruiscono il settore di Yukawa eccetto che per l’autostato più leggero. Ma la cosmologia osservativa dipende dalla somma di tutti gli autostati **$m_1+m_2+m_3$** Per la prima volta, i fisici del neutrino hanno necessità di credere nel ΛCDM. O di testarlo....



CMB temperature and polarisation from Planck
$\Sigma_i m_i < 260$ meV (95%CL)

CMB + conservative LSS information (BAO + RSD from BOSS):
$\Sigma_i m_i < 100$ meV (95%CL)

CMB + BAO + more agressive LSS:
either: + Ly-α from BOSS
or: + lensing + RSD + SNIa)
$\Sigma_i m_i < 87$ meV (95%CL)

Palanque-Delabrouille et al. 2020
Di Valentino et al. 2021

Nei prossimi 10-20 anni, le nostre misure impatteranno direttamente sulle osservabili e le misure di laboratori dovranno confrntarsi con la cosmologia osservativa.

Visto che il Modello Standard e il ΛCDM sono disconnessi andra’ tutto liscio?

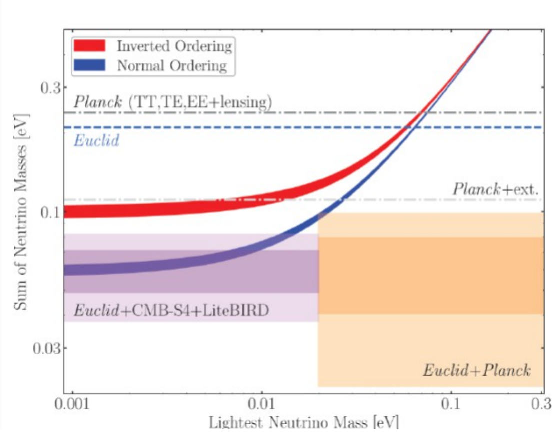
Conclusioni

Cosa possiamo aspettarci nel lungo termine dalla fisica del neutrino?

Una descrizione completa e precisa del settore di Yukawa leptonico del Modello Standard

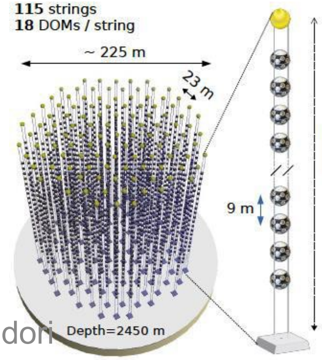
Fa eccezione l’autostato più leggero di massa che potrà essere accessibile solo a mezzo di avanzamenti sostanziali nelle misure assolute di massa o grazie alla scoperta del doppio beta

Un link diretto tra il Modello Standard e il ΛCDM della cosmologia



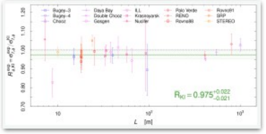
Un potente strumento di caratterizzazione delle sorgenti astronomiche

Un tema che non coperto in questa review dove protagonist sono I progetti **KM3NET e IceCUBE**



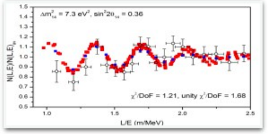
Un salto di qualità

Affinchè questi progetti abbiano successo, la fisica del neutrino deve liberarsi di una sua debolezza storica: **la conoscenza delle sorgenti e dei processi SM deve essere portata agli standard della fisica dei collider**. Abbiamo già pagato a sufficienza lo scotto per questo tipo di «dimenticanze»



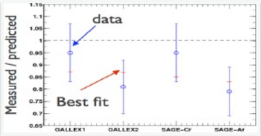
reactor flux anomaly
resolved with new input data
to flux calculation

✓



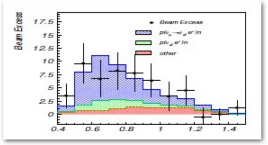
reactor spectra
is there really an anomaly?

?



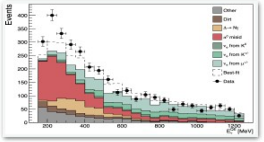
gallium anomaly
unresolved, recently reinforced

?



LSND
unresolved

?

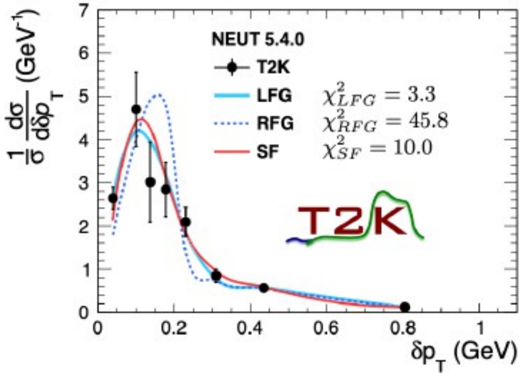


MiniBooNE
unresolved

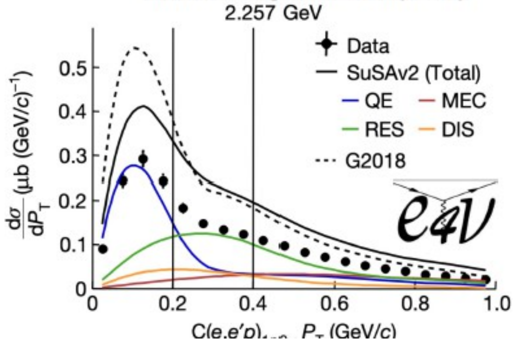
?

No model is able to describe global neutrino scattering measurements

arXiv:1810.06043
Phys. Rev. D 98, 032003 (2018)



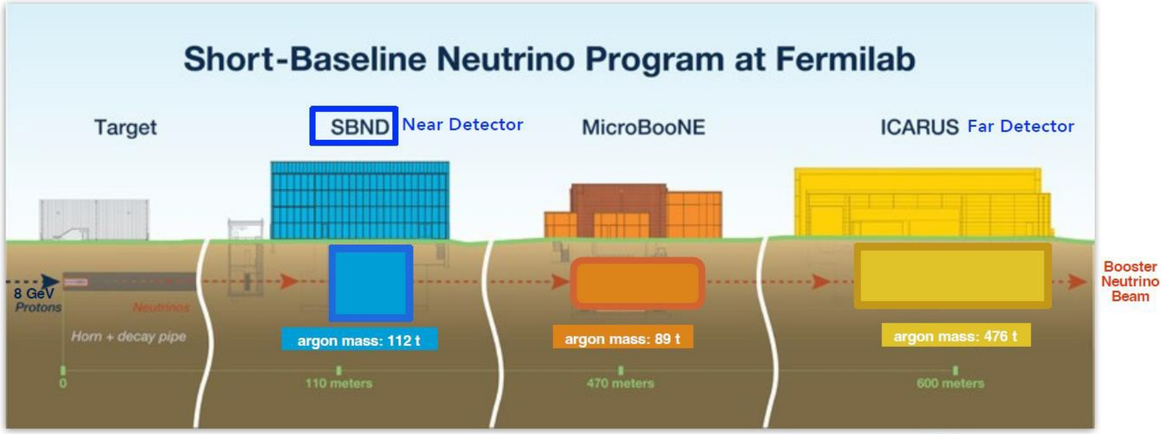
Nature 599, p. 565–570 (2021)



L. Munteanu, Talk at Nuphys 2023 (Dec 2023, London)

Due casi esemplari: (I) ICARUS e il programma SBN al Fermilab

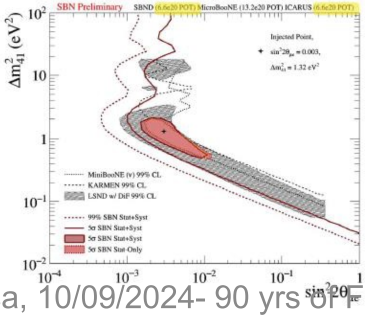
Grazie alla tecnologia delle TPC ad argon liquido, il Fermilab ha realizzato un programma completo di verifica delle anomalie di LSND e MiniBoone e questo sforzo sta dando i suoi frutti



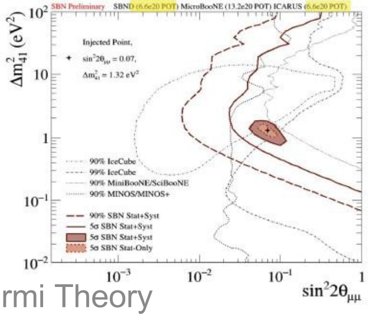
2015–2021
Large production of
scientific results

2022–
Collecting data in final
configuration

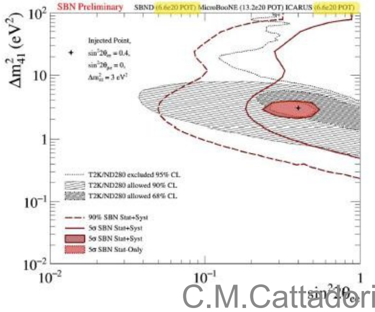
ν_e Appearance



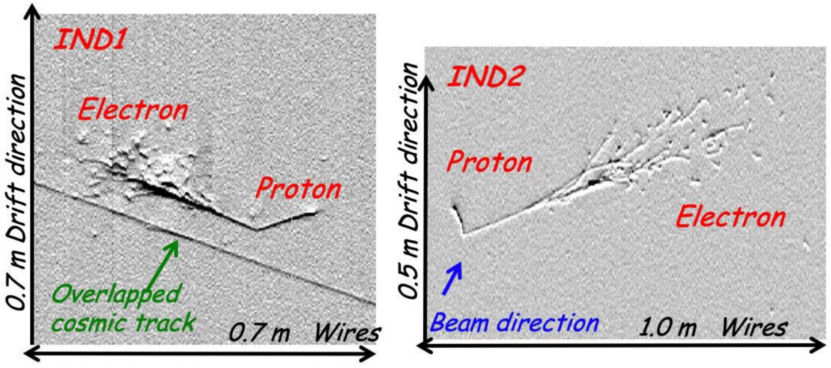
ν_μ Disappearance



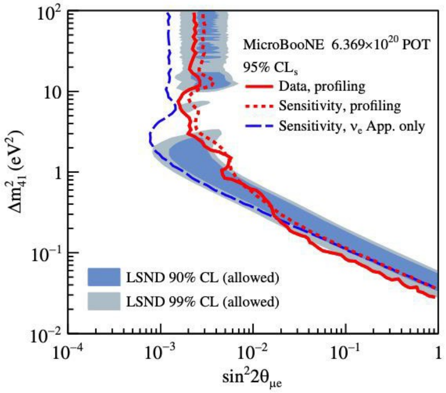
ν_e Disappearance



ICARUS al Fermilab 2022-in corso

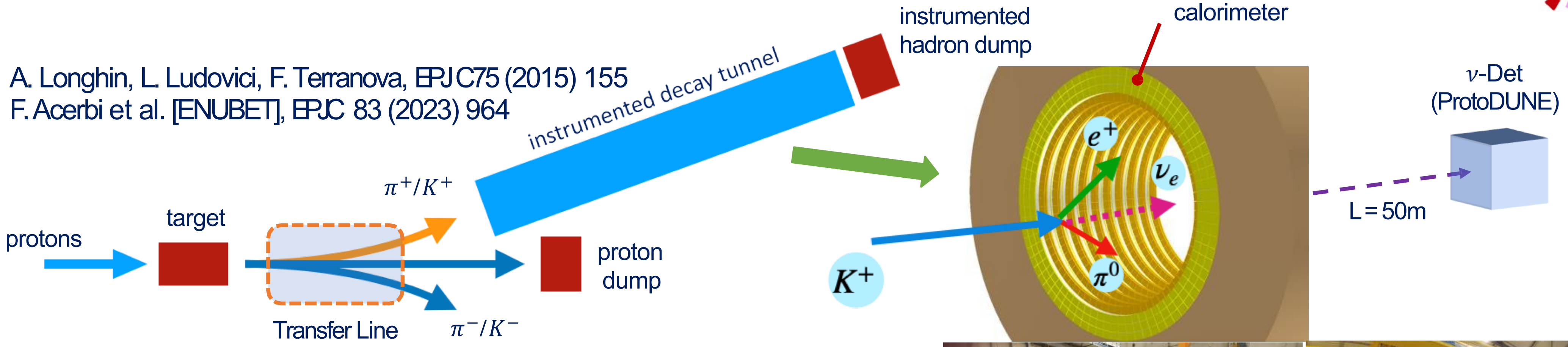


MicroBooNE 2016-23

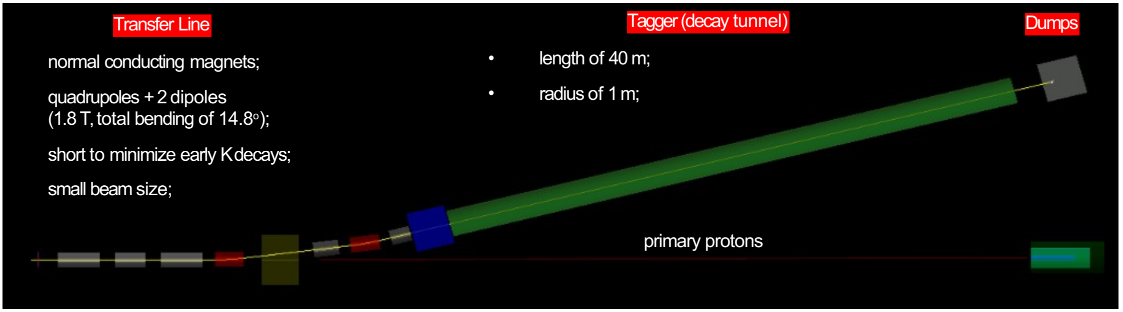


Due casi esemplari: (II) NP06/ENUBET e i fasci monitorati

A. Longhin, L. Ludovici, F. Terranova, EPJ C75 (2015) 155
F. Acerbi et al. [ENUBET], EPJC 83 (2023) 964



CERN SPS



Transfer Line

normal conducting magnets;

quadrupoles + 2 dipoles
(1.8 T, total bending of 14.8°);

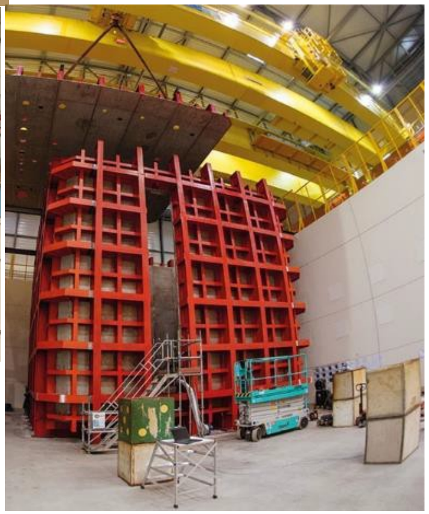
short to minimize early K decays;

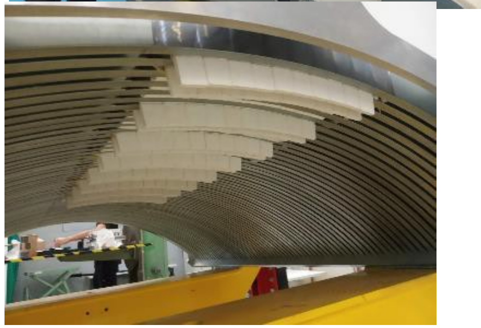
small beam size;

Tagger (decay tunnel)

- length of 40 m;
- radius of 1 m;

Dumps





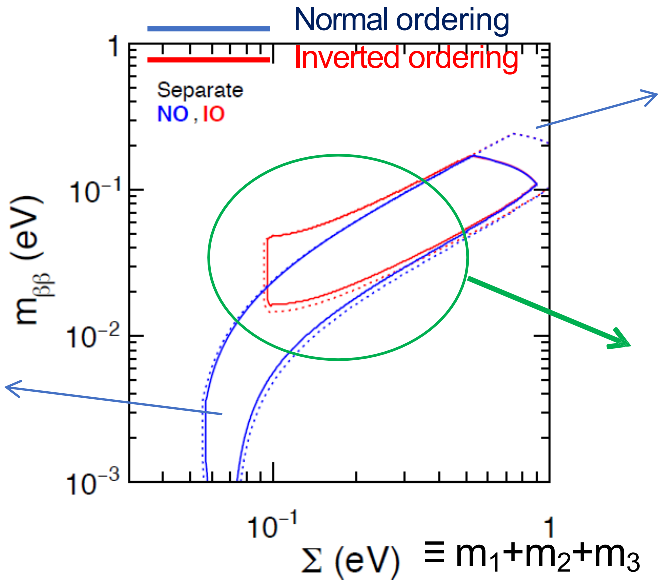
https://www.pd.infn.it/eng/enubet/


Welcome to the ENUBET webpage
Enhanced NeUtrino BEams from kaon Tagging

ENUBET
Enhanced NeUtrino BEams from kaon Tagging

Oscillazioni, cosmologia e neutrini di Majorana

Dal 2012, $m_{\beta\beta}$ è ben costretto dalle oscillazioni e dalla cosmologia osservativa.
Sappiamo finalmente dove dobbiamo guardare



Masse quasi degeneri.
Best case scenario:
possible ma improbabile
(cosmologia)

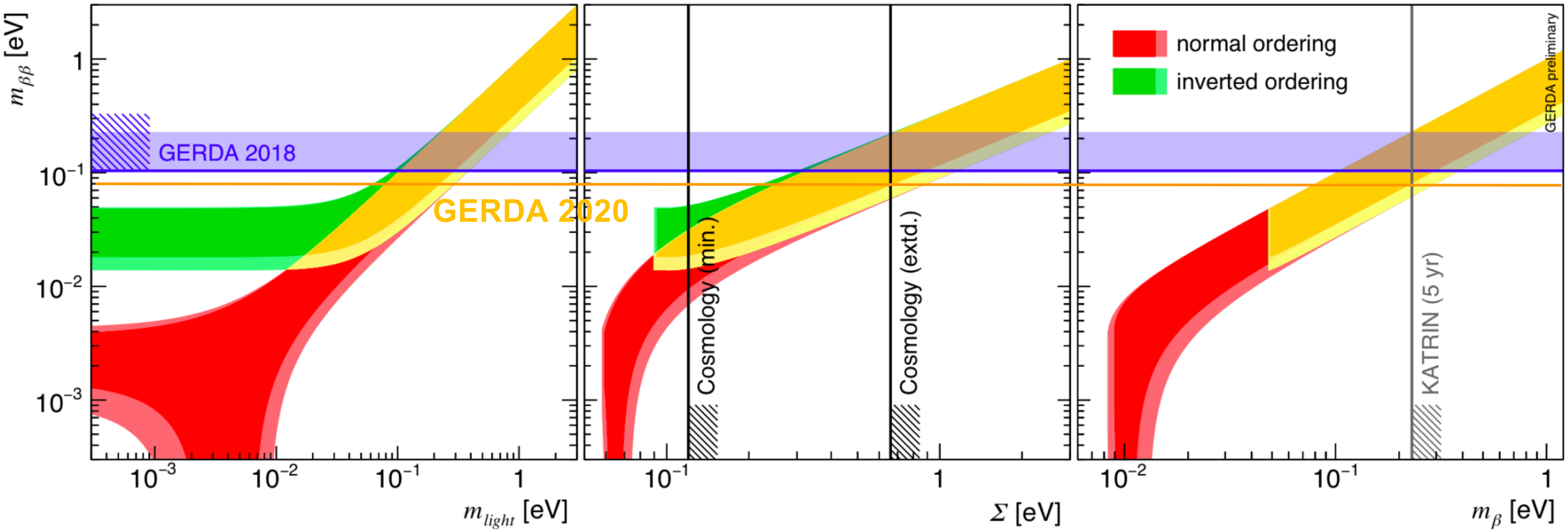
Cancellazioni accidentali delle fasi di CP. E' il caso peggiore: possibile ma improbabile

Ecco dove cercare:
possible e probabile

Stiamo sviluppando tecnologie che testano vite-medie al livello di 10^{26} y e che sono scalabili a livello di 10^{28} y.

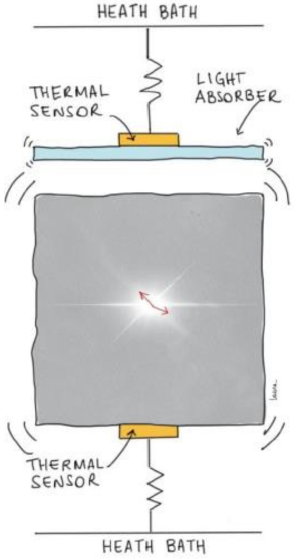
L'INFN e i Laboratori del Gran Sasso hanno un ruolo centrale e hanno scelto come tecnica di elezione i rivelatori ad alta risoluzione energetica

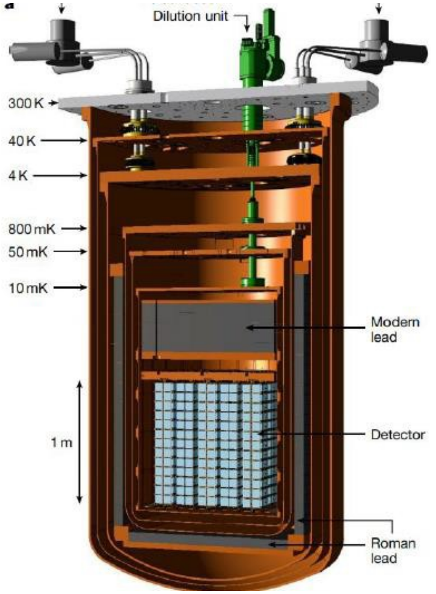
Neutrino Mass Observable



Assuming g_A = 1.27 and NME ranging ~ 2.8 ÷6.0

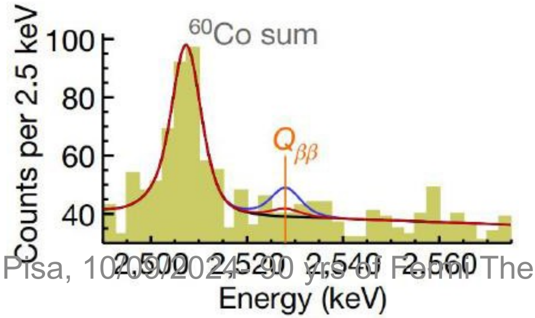
CUORE → CUPID





CUORE, Nature 604 (2022)

$$\boxed{T^{0\nu}_{1/2} > 2.2 \cdot 10^{25}\ \text{yr}}$$

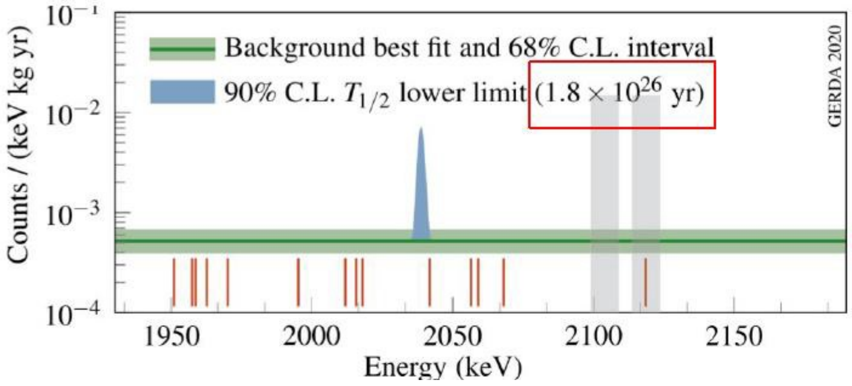


GERDA → LEGEND

GERDA/MAJORANA (40 kg), lowest background

LEGEND-200 (200 kg) in data taking since 2023, good performance and background released at TAUP

LEGEND-1000 (1 t) preparing for DOE reviews this and next year, baseline design at LNGS



GERDA PRL 125 (2020)

Perché “rivoluzione”?

A partire dal 2012, la fisica del neutrino ha potuto tracciare **quantitativamente** la sua strada per rispondere a domande estremamente ambiziose:

Come è fatto il settore di Yukawa del Modello Standard?

Qual’è la natura del neutrino?

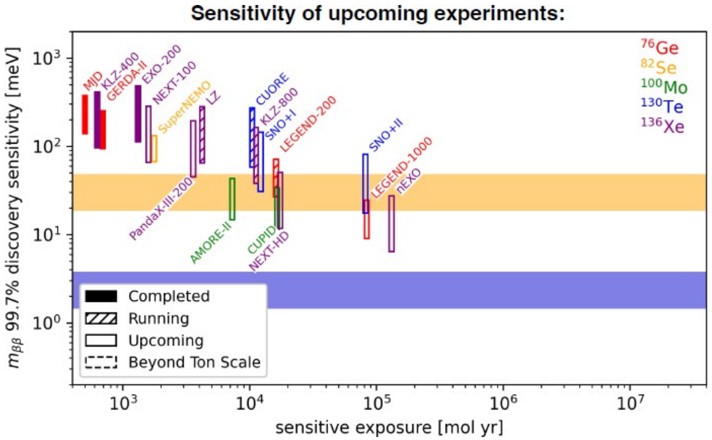
I neutrini nell’universo si comportano come previsto dal paradigma LCDM?

I neutrini violano la simmetria di CP?

Qual’è il pattern di massa dei neutrini? (mass ordering)

Il mixing massimale (θ_{23}) è davvero massimale?

La matrice di mixing è unitaria?



Sono in grado di originare l’asimmetria materia-antimateria?

Danno origine alle perturbazioni primordiali effettivamente osservate?

Quali sono le sorgenti astrofisiche dei neutrini energetici?

After Fermi’s V-A theory neutrinos theory developed

- The success of Fermi’s theory (1934) in describing the observed β-decay rates and spectra convinced the scientific community of the existence of the ν and triggered its experimental search.

- Wick (1934) exploited Fermi’s theory to explain β+ decay and electron capture, Wang (1942) proposed to measure the e^- capture nuclear recoil to indirectly detect the neutrino.

- Between the late ’30s and the early ‘50s, several measurements demonstrated that β decay and e^- capture are subject not only to missing energy, but also to an apparent momentum non-conservation, thus pointing to the existence of the neutrino.

- The final confirmation arrived in 1956, with the detection of neutrinos in “appearance mode” through inverse β+ decay $\bar{\nu}_e + p \rightarrow e^+ + n$; $E_{thrs} = 1.8\ MeV$ (Cowan et al., 1956; Reines and Cowan,1953), another process predicted by Fermi’s theory.

- Wu et al. (1957) observed parity-violation in β decays. Soon after, Landau (1957), Lee and Yang (1957), and Salam (1957) independently came to the conclusion that, if the neutrino produced by weak interactions was massless, it would have a fixed and opposite helicity compared to the antineutrino, and parity violation in weak interactions would be maxima.

- (Goldhaber et al., 1958) Experimental evidence in favour of the neutrino’s fixed helicity

La rivoluzione del 2012. Un incredibile colpo di fortuna ☺

$$\begin{aligned} P_{\nu_e\to\nu_\mu} \simeq\ & \sin^2 2\theta_{13}\, \sin^2\theta_{23} \frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2} \\ & + \alpha \sin 2\theta_{13}\, \xi \sin\delta \sin(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\ & + \alpha \sin 2\theta_{13}\, \xi \cos\delta \cos(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\ & + \alpha^2 \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}. \end{aligned}$$

$\Delta \equiv \Delta m^2_{31} L/(4E)$ Year 2005 → **«oscillation phase»** It is O(1) for E= O(1 GeV) and L= O(100 km)
Cool, we can build experiment on Earth ☺

$\alpha \equiv \Delta m^2_{21}/|\Delta m^2_{31}|$ Year 2003 → Must be <1. The larger the better.
We know now that is 0.028

$\xi \equiv \cos\theta_{13}\, \sin 2\theta_{12}\, \sin 2\theta_{23}$

$\sin^2 2\theta_{13}$ **Year 2012** → The larger the better! It is O(1) in neutrinos! (it is tiny in quarks..)

Nel settore di Yukawa leptonico del modello standard:

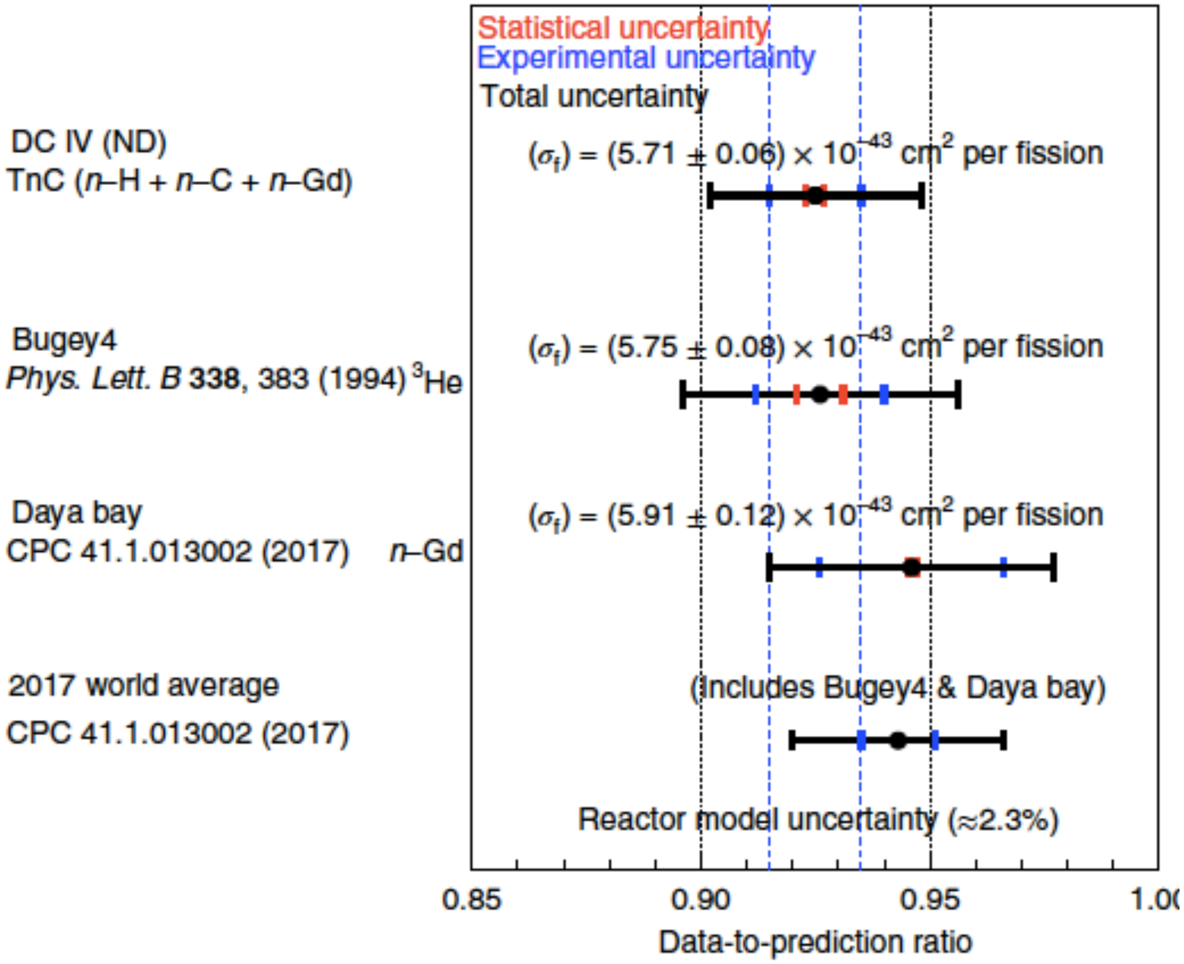
- Tutti gli angoli di mixing sono grandi. Il più piccolo (θ_{13}) è circa grande quanto l'angolo di Cabibbo!!
- Il valore assoluto degli autostati di massa non è attualmente noto ma sappiamo che è piccolo mentre le differenze di massa sono abbastanza grandi da permettere oscillazioni di neutrini "da acceleratori" (1 GeV) per distanze di alcune centinaia di chilometri

In linea di principio, un esperimento di neutrino agli acceleratori "sufficientemente potente" sarebbe in grado di ricostruire tutto il settore di Yukawa del Modello Standard per i leptoni

Third genertion of Reactor Experiments : assessing the IBD cross section

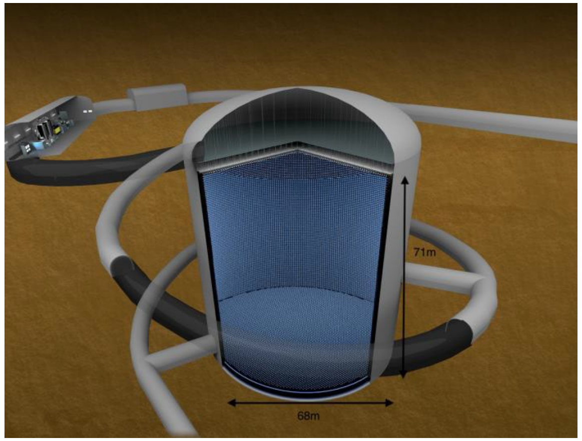
After 2011:

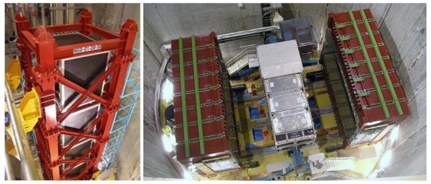
- third generation experiments measure $positive\ value\ of\ \theta_{13}$
- Far Detector & Near Detector to cancel the systematics related to the reactor flux uncertainties
- Multidetector approach to cancel
- Double Chooz (France), Daya Bay (Brazil), Reno (US), T2K (Japan)
- Evidence of reactor neutrino anomaly (now much reduced)



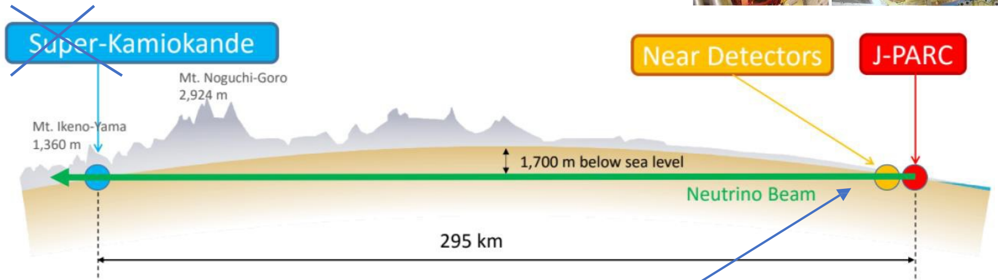
Nature Physics | VOL 16 | May 2020 | 558–564

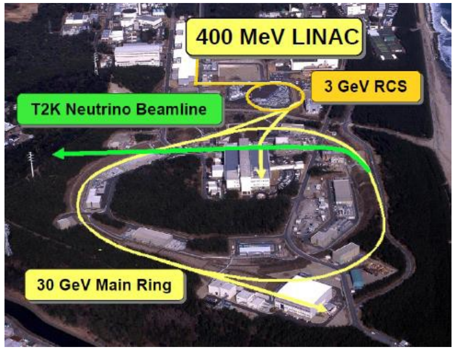
HyperKamiokande



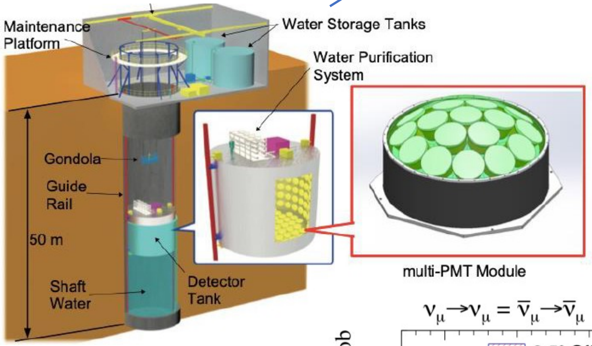


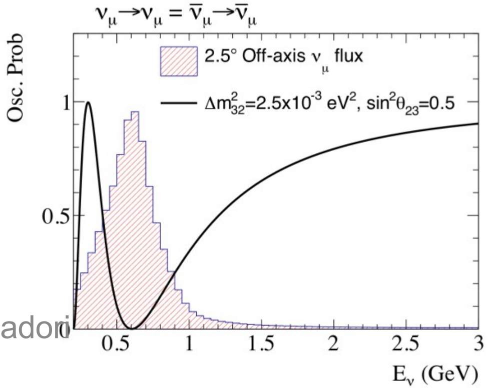
Hyper!!

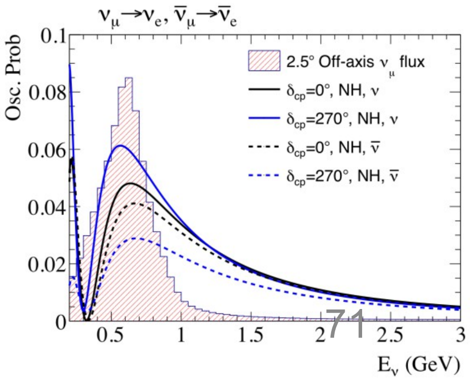


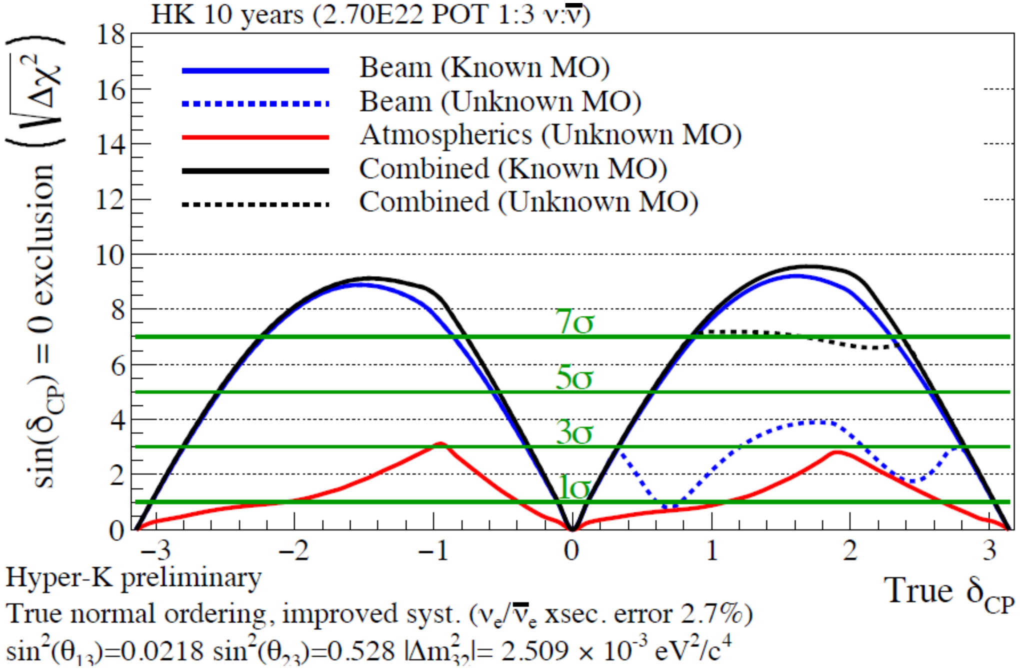


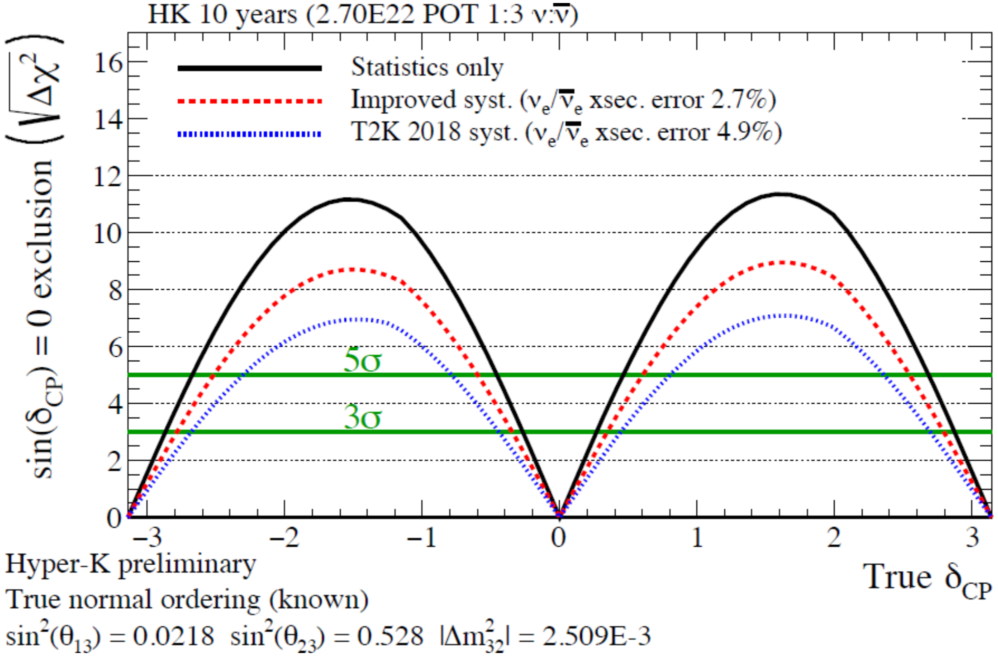
Intermediate detector





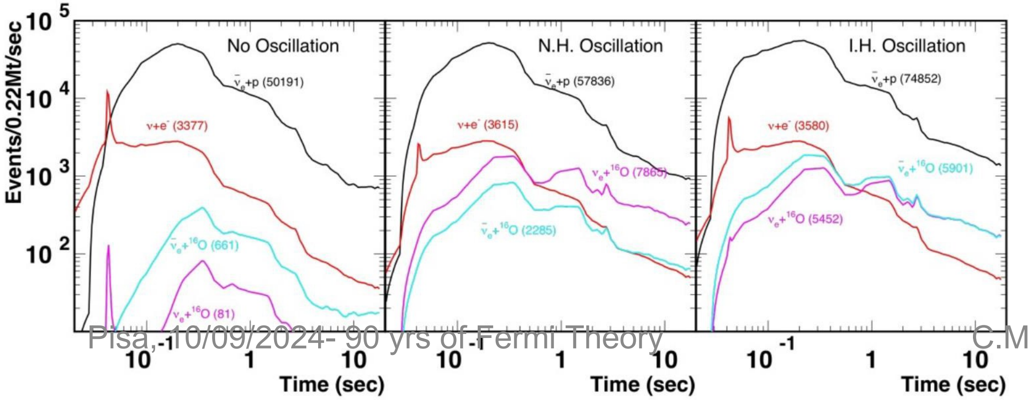


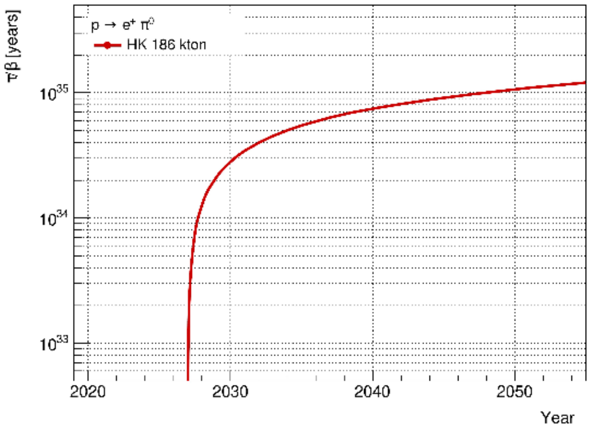




supernova burst

J. Wilson, Talk at Neutrino2022





Proton decay