
# Neutrinos at Gran Sasso: the beginning

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Dedicated to:
***Nicola Cabibbo, Puccio Bellotti and Ettore Fiorini***

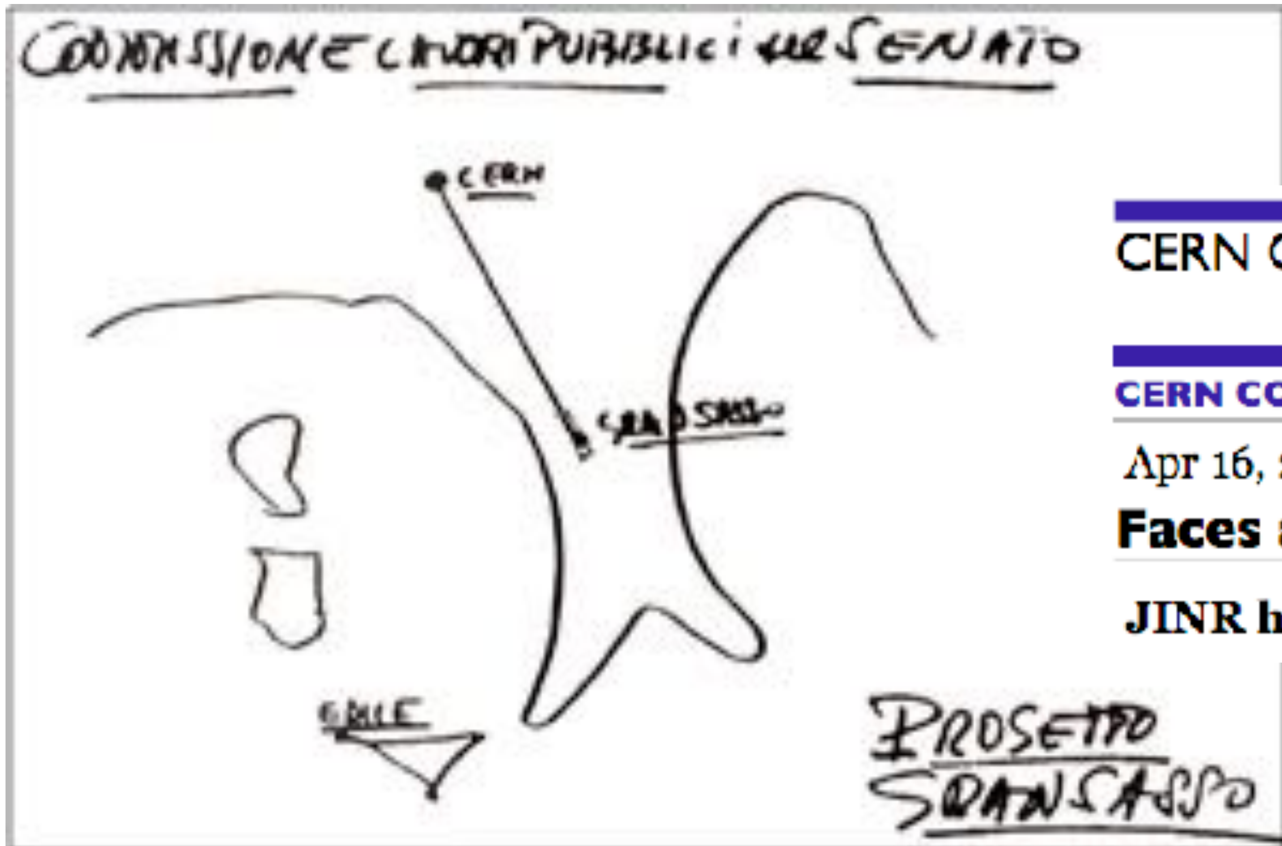
# 1. Underground Laboratories

- In 1974, after pioneering works by Abdus Salam, a theory of Grand Unification of all particle interactions at very high energy was advanced by Howard Georgi and Sheldon Glashow.
- Superheavy bosons were predicted to mediate baryon number non-conservation. Proton could decay, e.g. $P \to e^+\pi^0$, with an extremely long lifetime, compatible with the limits on the stability of matter known at the time.
- The observation of proton decay required to monitor large quantities of matter, e.g. water, in environments well protected from the noise produced by cosmic ray interactions. The race to realize big underground laboratories started in Japan and US.
- In Italy, Carlo Castagnoli, to study the penetrating component of very high energy cosmic rays, had obtained the use of a service room (Garage 27) accessible from the tunnel under the Mont Blanc, which connects Italy to France.
- Ettore Fiorini and his group installed in Garage 27 one of the first proton decay experiment: NUSEX (Nuclear Stability EXperiment) that produced significant results, in the late 1970’s, in parallel with the first stages of the large underground installations, Kamioka in Japan and IMB in the US.

# The birth of Gran Sasso National Laboratory

- In 1979 Antonino Zichichi, then INFN President, submitted to the Senate of the Italian Republic a project for the realization of a large underground laboratory to be accessed from the tunnel of the highway L'Aquila-Teramo, then in construction. The tunnel runs under the highest peak of Central Italy, the Gran Sasso mountain, that would provide the needed protection from cosmic rays.
- " Progetto Gran Sasso" was approved by the Italian Parliament and included in the financial laws of 1982 and 1983. Works lasted from 1982 to 1985. The Laboratory became effective in 1987, with a first experiment, MACRO, to detect cosmic monopoles.
- It was clear from the outset that Grand Sasso was not ideal to search for proton's decay (too small and not extendable). However, several interesting lines of research emerged soon:
  - Search for cosmic magnetic monopoles
  - Solar and perhaps long baseline neutrinos (the halls of LNGS had been oriented toward CERN!!) (for *solar neutrinos: see Kirsten's and Bellini's talks*)
  - Double $\beta$-decay ($2\nu$ or $0\nu$)
  - search for Dark Matter. (*only few remarks*)

# 1979. A. Zichichi's sketch of a ν beam from CERN




CERN Courier

**CERN COURIER**

Apr 16, 2008

**Faces and Places**

**JINR honours Zichichi with the 2007 Bruno Pontecorvo prize**

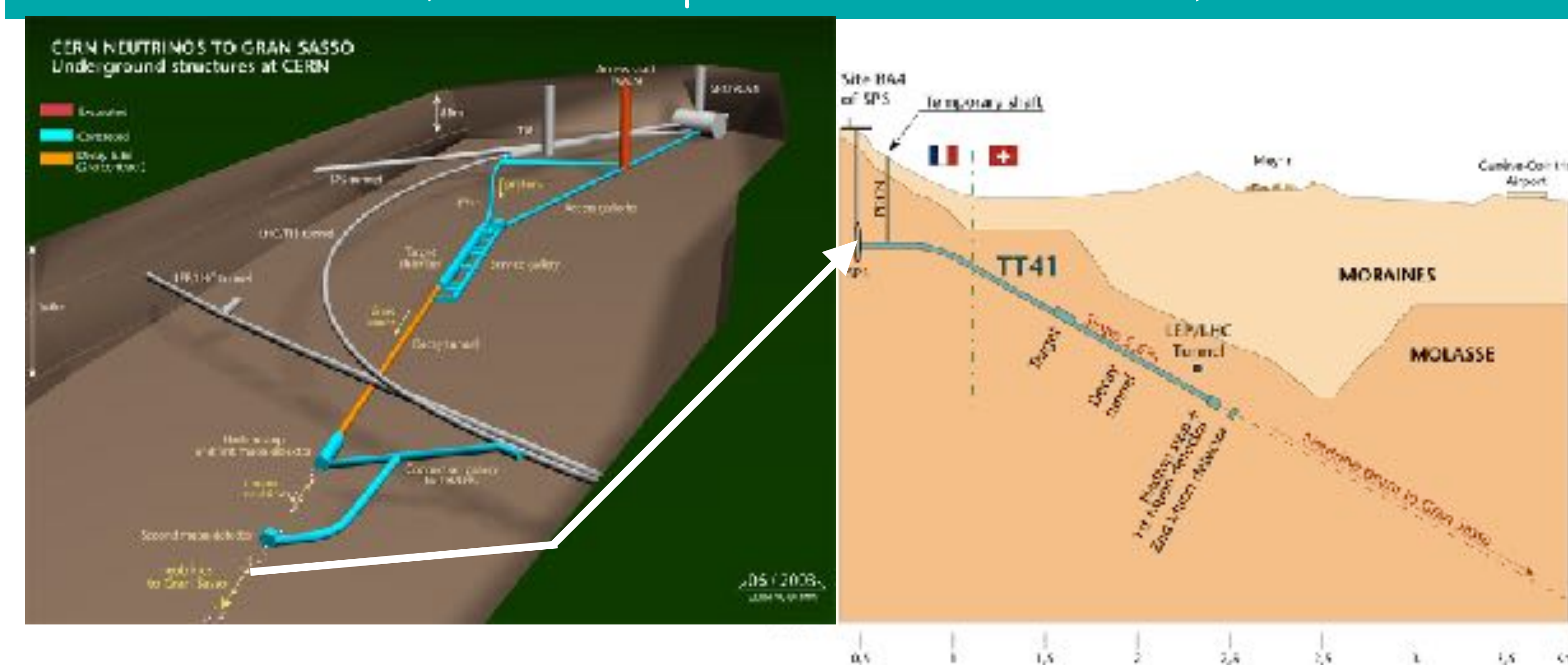
Ground-Breaking Ceremony, October 12, 2000

October 12, 2000

*Madame Marie-Paule BARDECHE, Sous-Préfet de Gex;*
*Prof. Alessandro BETTINI, Direttore, Laboratori nazionali del Gran Sasso, I*
*Prof. Luciano MAIANI, Director General, CERN.*

CNGS, 11/09/2006 L. Maiani. Neutrini al Gran Sasso

## The Long Baseline Neutrino Beam from CERN to Gran Sasso, to test $\nu_\mu \rightarrow \nu_\tau$ oscillations, 2000-2006



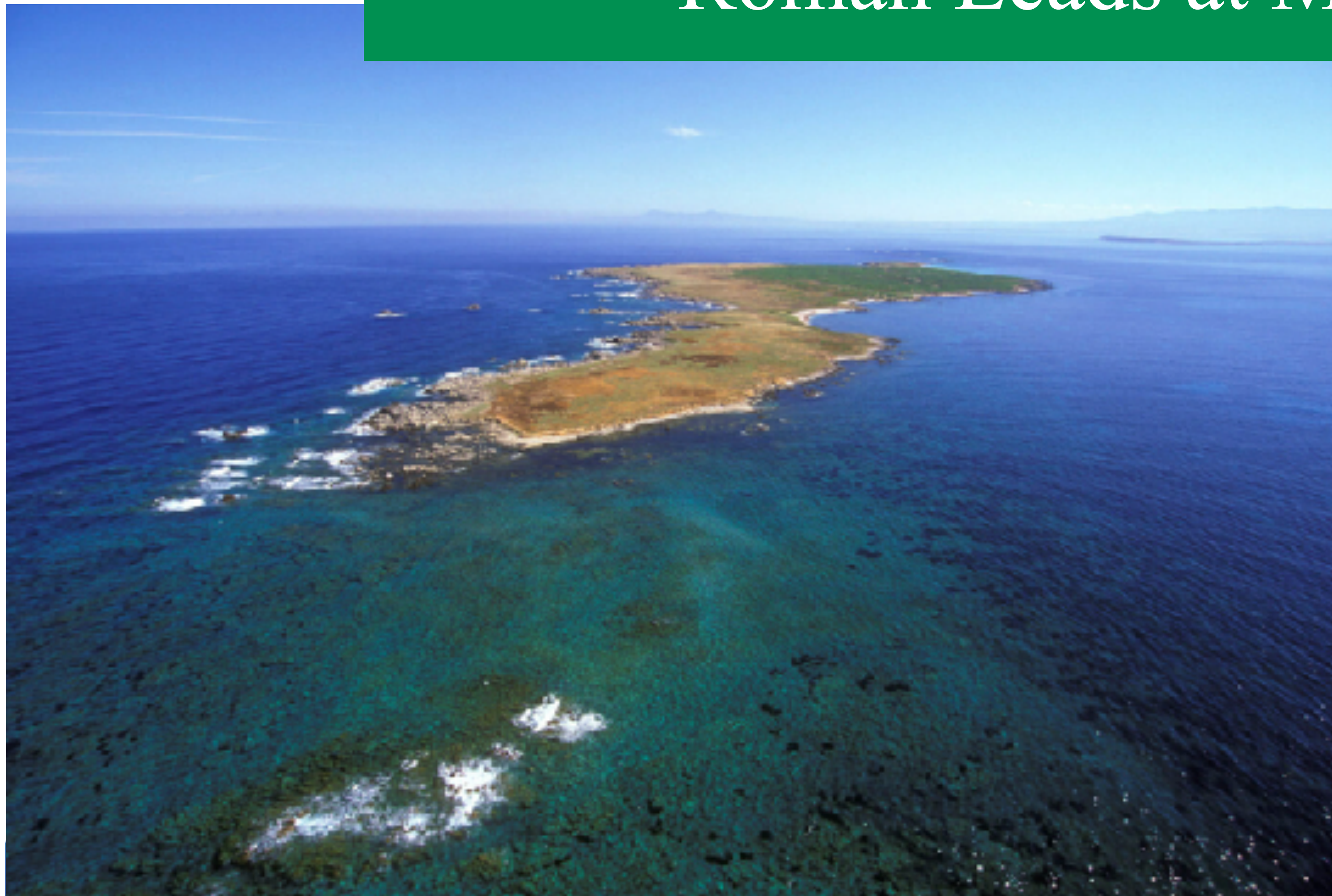
# Nicola Cabibbo and LNGS

- In 1985, Nicola Cabibbo succeeded to Zichichi as President of INFN.
- An eminent scientist and a regular speaker at the Erice School, the other successful initiative of Zichichi, Nicola continued Nino's support to LNGS and promoted new initatives in the field of solar neutrino physics:
- approval and execution of Gallex and the start of the R&D phase of a new, ambitious project, Borexino.
- Under Nicola's Presidency, LNGS became a first class international laboratory, open to collaborations from Europe, USA and Russia.
- I will conclude the introduction with the spectacular initiative of the Roman Leads, started in 1990 and realised with Nicola and Ettore Fiorini as protagonists.

# Roman Leads at Isola di Mal di Ventre

- Around 1990, in the coast of *Isola di Mal di Ventre* (on the West side of Sardegna) an amateur sub discovered a sunk roman ship, a large vessel 36 m long, with a charge of about 2000 lead ingots.
- Modern lead has a significant contamination of $Pb^{210}$, which is formed in the lead ore by successive decays along the Uranium-Radium decay chain. With a $Pb^{210}$ lifetime of 22 years, the roman lead, extracted 2000 years ago from the ore, is essentially free from this contamination and is therefore a very precious material to build protective screens in a radiaoctivity-free laboratory, such as LNGS.
- For this reason, immediately after the discovery Ettore Fiorini asked Cabibbo to promote an agreement with Regione Sardegna to:
  - contribute with INFN funds to the recuperation of the vessel and its charge and
  - to assign the ingots to LNGS to screen low background detectors.
- Nicola reacted promptly and provided the support that made the agreement possible.
- *The use of roman lead ingots is an exemplary case of collaboration between Institutions, finalized to valorize the national archaeological heritage and, at the same time, the frontier research in the fundamenta field of neutrino physics.* (Fernando Ferroni, President of INFN, on the occasion of the delivery of the last 30 roman lead ingots to LNGC, January 2016).

# Roman Leads at Mal di Ventre

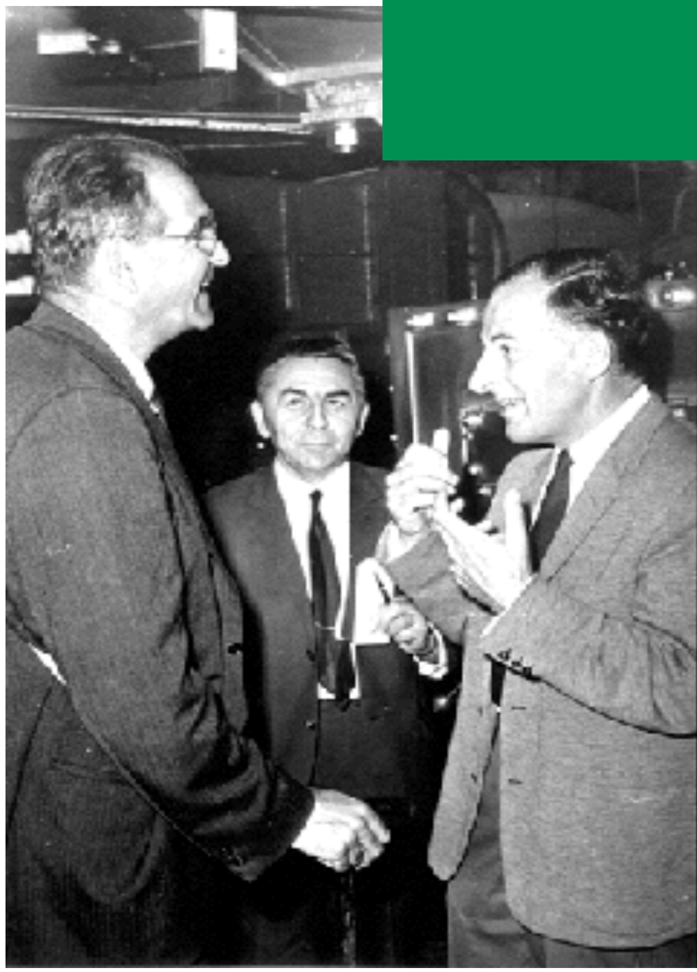


Posizione del lingotti di piombo nello scavo del relitto di Mal di Ventre (fonte: Area marina Sinis)

Gran

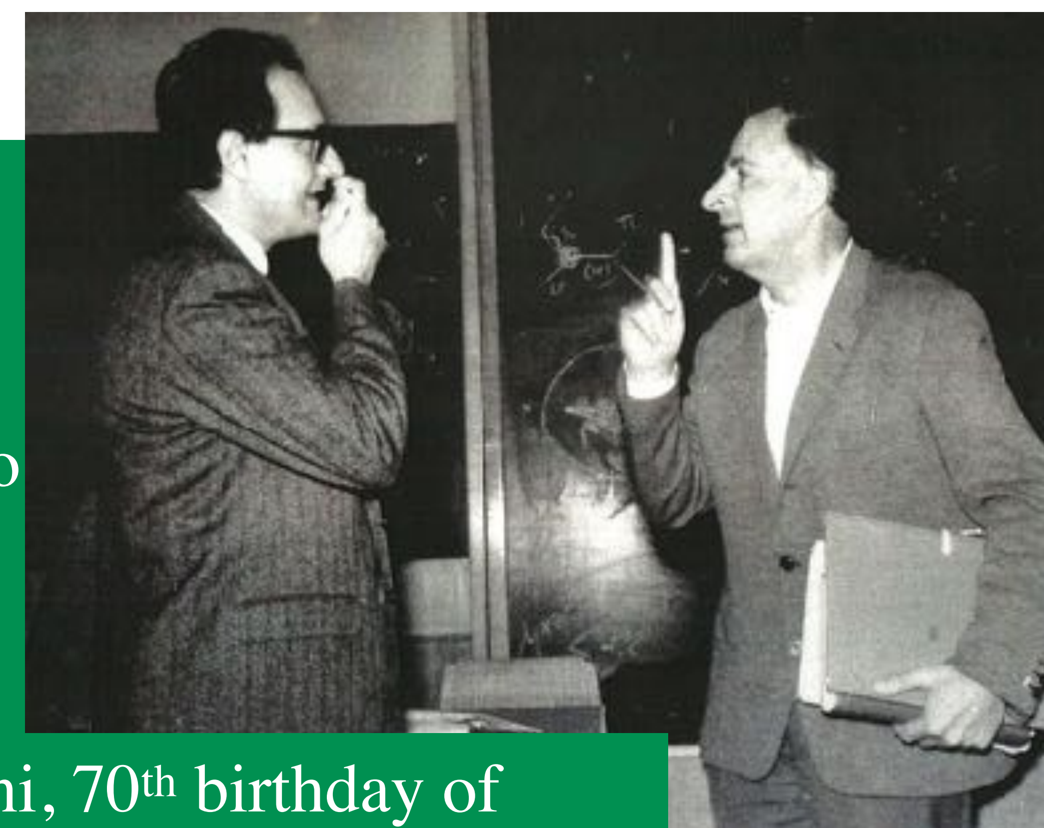
# 2. Neutrino Oscillations

- Neutrino Oscillations between two neutrino flavors have been introduced by Bruno Pontecorvo in 1967 and suggested to be the explanation of a possible deficit of the solar neutrino flux that was emerging, in 1969, from the deep underground experiment conducted by Raymond Davis and John Bahcall in the Kolar Gold mines.
- In modern terms, Pontecorvo's suggestion corresponds to the *just so* solution: the Earth just happens to be at the minimum of the oscillation.



Bruno Pontecorvo meets Viki Weisskopf, then CERN DG, in the Laboratory of Nuclear Problems, JINR, Dubna, 1963.


with Carlo Franzinetti, discussing about neutrino neutral currents



with Ettore Fiorini, 70th birthday of Edoardo Amaldi, Roma 1978

# Neutrino oscillations (cont'd)

- A more natural solution was found by Mikheyev, Smirnov and Wolfenstein (MKW): the oscillation occurs in the solar atmosphere (for Boron neutrinos).
- Alternatively, the neutrino deficit is just an average over the Earth position (vacuum oscillations, p-p neutrinos).
- Neutrino oscillations with 3 flavours, with CP and CPT violation was worked out for the first time by Nicola Cabibbo at Erice in 1976.
- Today, data are fully consistent with the oscillations of three neutrinos mixed with real angles, the *just so* solution is excluded.
- *Yet to be seen*: one possible complex (CP violating) phase and the sign of the 2-3 mass difference (mass hierarchy).

Nicola Cabibbo, as President of INFN, gave a decisive support to GALLEX at Gran Sasso Lab, then directed by Puccio Bellotti.

* G. L. Fogli, E. Lisi, A. Marrone, A. Palazzo, and A. M. Rotunno, Phys. Rev. D **84**},(2011) 053007, arXiv:1106.6028.
** T. Schwetz, M. Tortola, and J. W. F. Valle, New J. Phys. **13**, (2011) 109401; arXiv:1108.1376

| parameter | Fogli *et al.* * | Schwetz *et al.* ** |
|---|---|---|
| $\Delta m^2_{12}(10^{-5}\ \mathrm{eV}^2)$ | $7.58^{+0.22}_{-0.26}$ | $7.59^{+0.20}_{-0.18}$ |
| $\lvert\Delta m^2_{23}\rvert(10^{-3}\ \mathrm{eV}^2)$ | $2.35^{+0.12}_{-0.09}$ | $2.50^{+0.09}_{-0.16}$ |
| $\sin^2\theta_{12}$ | $0.312^{+0.017}_{-0.016}$ | $0.312^{+0.017}_{-0.015}$ |
| $\sin^2\theta_{23}$ | $0.42^{+0.08}_{-0.03}$ | $0.52^{+0.06}_{-0.07}$ |
| $\sin^2\theta_{13}$ | $0.025\pm0.007$ | $0.013^{+0.007}_{-0.005}$ |

solar: $\nu_e \to \nu_{\mu,\tau}$

atmospheric: $\nu_\mu \to \nu_\tau$

$\nu_\mu \to \nu_e$ (Minos, USA)
$\nu_e$ disappearence (Daya Bay, China)

# good to know

- The master formula for neutrino oscillations

$$P(\nu_e \to \nu_e) = 1 - \sin^2(2\theta)\ \sin^2(\frac{\Delta m^2 L}{4E_\nu}) = 1 - \sin^2(2\theta)\ \sin^2(\phi)$$

$$\phi \simeq 1.27\ \frac{\Delta m^2(\mathrm{eV}^2) L(\mathrm{m})}{E_\nu(\mathrm{MeV})}$$

$$E_{\bar{\nu}}(1-2) = 4\ \mathrm{MeV}, \phi = \pi/2\ \text{at}\ L(1-2) \simeq 90\ \mathrm{km}\ \text{(Kamland)}$$

$$E_\nu(2-3) = 1\ \mathrm{GeV}, \phi = \pi/2\ \text{at}\ L(2-3) \simeq 530\ \mathrm{km}\ \text{(Kamioka)}$$

# $\nu_\mu$ oscillations

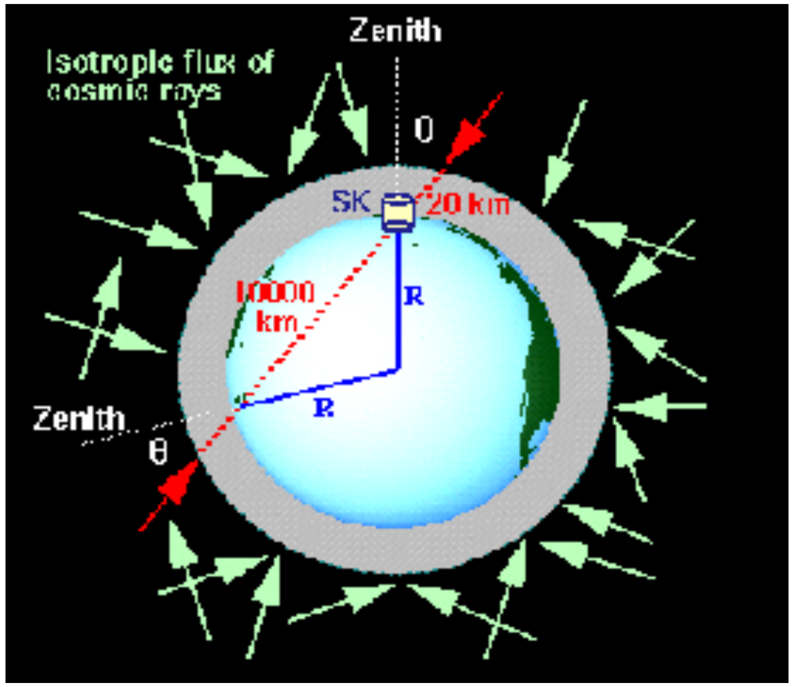
- I got interested in neutrino oscillations in 1980, studying the anomalous behaviour of the interactions of neutrinos produced in a "Beam dump" experiment at the CERN SPS.
- Protons of momentum 400 GeV/c from the CERN SPS were focused onto the copper dump target. Pions and other long lived hadrons produced in the collisions are absorbed by the dense material of the dump, but charmed particles with some $10^{-12}$ sec lifetime have time to decay and produce an equal number of $\nu_\mu$ and $\nu_e$ which interact in BEBC, CHARM and CDS detectors at about 1 km from the beam dump.
- We tried to interpret the alleged difference in the number of $\nu_\mu$ and $\nu_e$ interactions observed by the exernal detectors in terms of neutrino oscillations

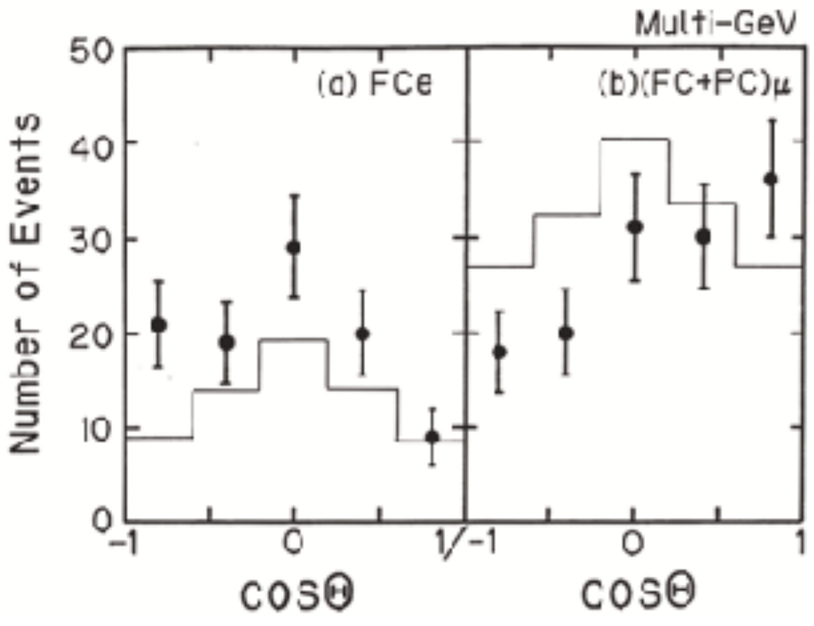
A. De Rujula, M. Lusignoli, L. Maiani, S. T. Petcov Nucl. Phys. B **168** (1980), 54

- $\nu$ oscillations were a rather unorthodox concept at CERN (everybody believed in massless neutrinos) and our analysis did not go very far.
- In 1983, while visiting ITEP in Moscow, I heard about a suppression of atmospheric $\nu_\mu$ versus $\nu_e$ in Kamioka, but was not very much impressed
- …but in 1993, in a conversation with Bellotti, the argument came out and he told me to be definitely convinced that the data had to be taken seriously.

# Atmospheric neutrino oscillations

- Cosmic rays in the upper atmosphere produce pions that have time to decay forming the cascade $\pi^+ \to \mu^+ + \nu_\mu \to e^+ + \nu_e + 2\nu_\mu$
- thus, when neutrinos interact in with matter with charged current interactions, we expect to see muon and electron events with very similar energy distributions and in the ratio 2:1. This is what Kamioka found for *downward going neutrino events*, i.e. $\nu$s coming from the upper atmosphere.
- However, neutrinos produced by cosmic rays entering in the athmospere on the other side of the Earth, that is *upward going $\nu$ s,* showed a completely different behaviour, as function of the zenith angle.



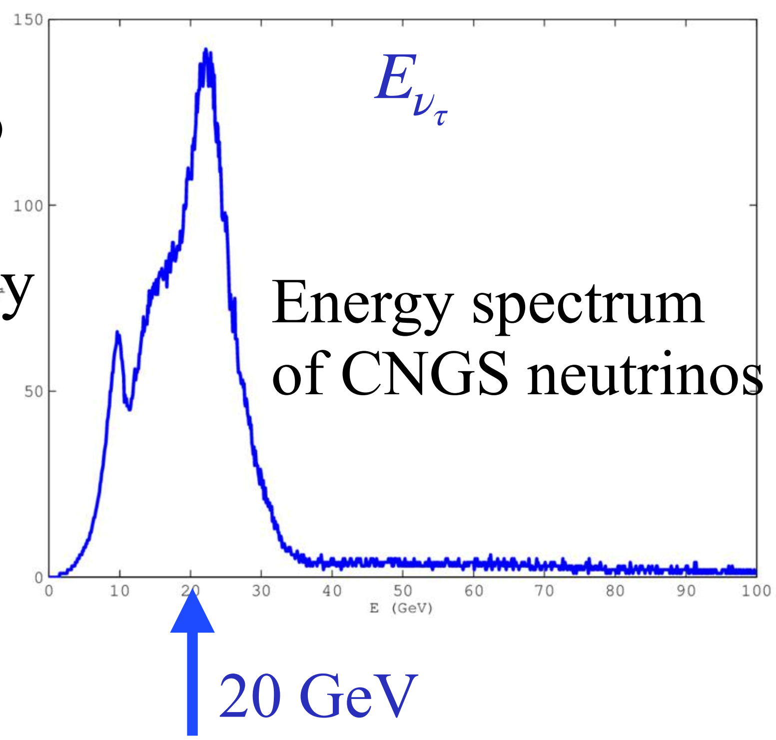

Zenith angle distributions for multi-GeV (a) *e*-like and (b) μ-like events observed in Kamiokande [7]. Solid histogram shows the predicted distributions without oscillations. Absolute normalization had an uncertainty of 20 to 30%.

Y. Fukuda, et al., Phys. Lett. B 335 (1994) 237, see T. Kajita, Nobel Lecture, December 8, 2015

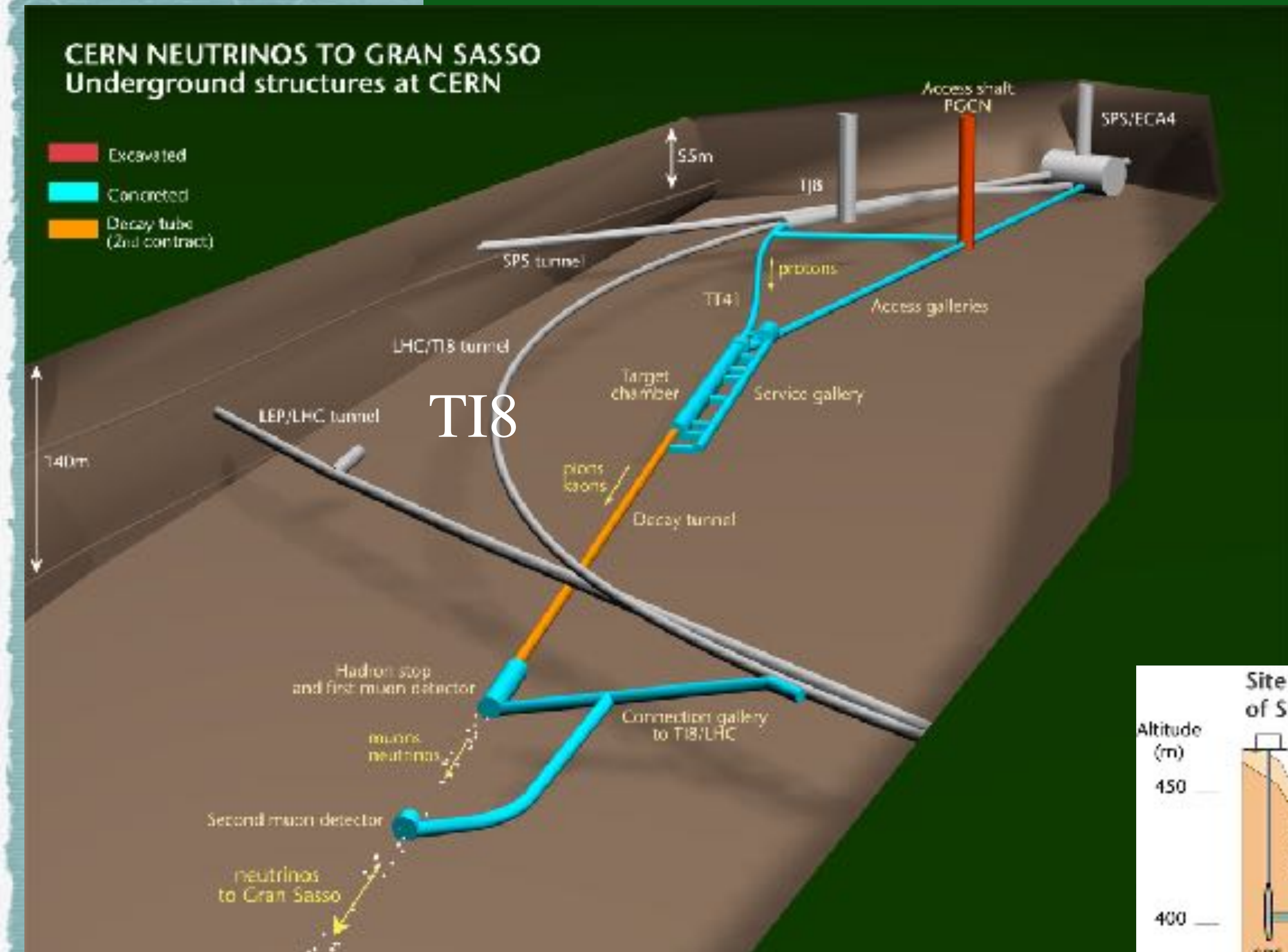
# 3. The search for $\nu_\mu \to \nu_\tau$ at Gran Sasso with OPERA

- By 1998, the Kamioka the paradigm of $\nu_\mu$ disappearing into "something" (not $\nu_e$) was universally accepted.
- At that time the existence of a third lepton family was also established and the most likely oscillation to bet on was $\nu_\mu \to \nu_\tau$
- However, atmospheric neutrino spectrum does not go high enough in energy as to allow real $\tau$ production in the interactions of the hypothetical $\nu_\tau$
- Thus the idea came to observe $\nu_\mu \to \nu_\tau$ oscillations with $\nu_\mu$ produced at a particle accelerator with sufficient energy togive rise to $\nu_\mu \to \nu_\tau$ followed by $\nu_\tau + \text{matter} \to \tau + \ldots$
- CERN SPS was an ideal source, and Gran Sasso, with its halls oriented versus Geneva, the ideal landing place of a neutrino beam 700 km long, to allow the positive detection of $\tau$ leptons.

- The short life of  leptons required an emulsion experiment. By summer 1999, discussing with Paolo Strolin (Napoli) and Kimio Niwa (Nagoya) I was convinced that an International Collaboration promoted by Napoli and Nagoya could realistically realize an emulsion detector, thereby justifying the CERN, 700 km long, neutrino beam to Gran Sasso.
- In Dec. 1999, the CERN Council approved the construction of the CERN to Gran Sasso long-baseline beam, CNGS, with a substantial contribution of Italy, via INFN.

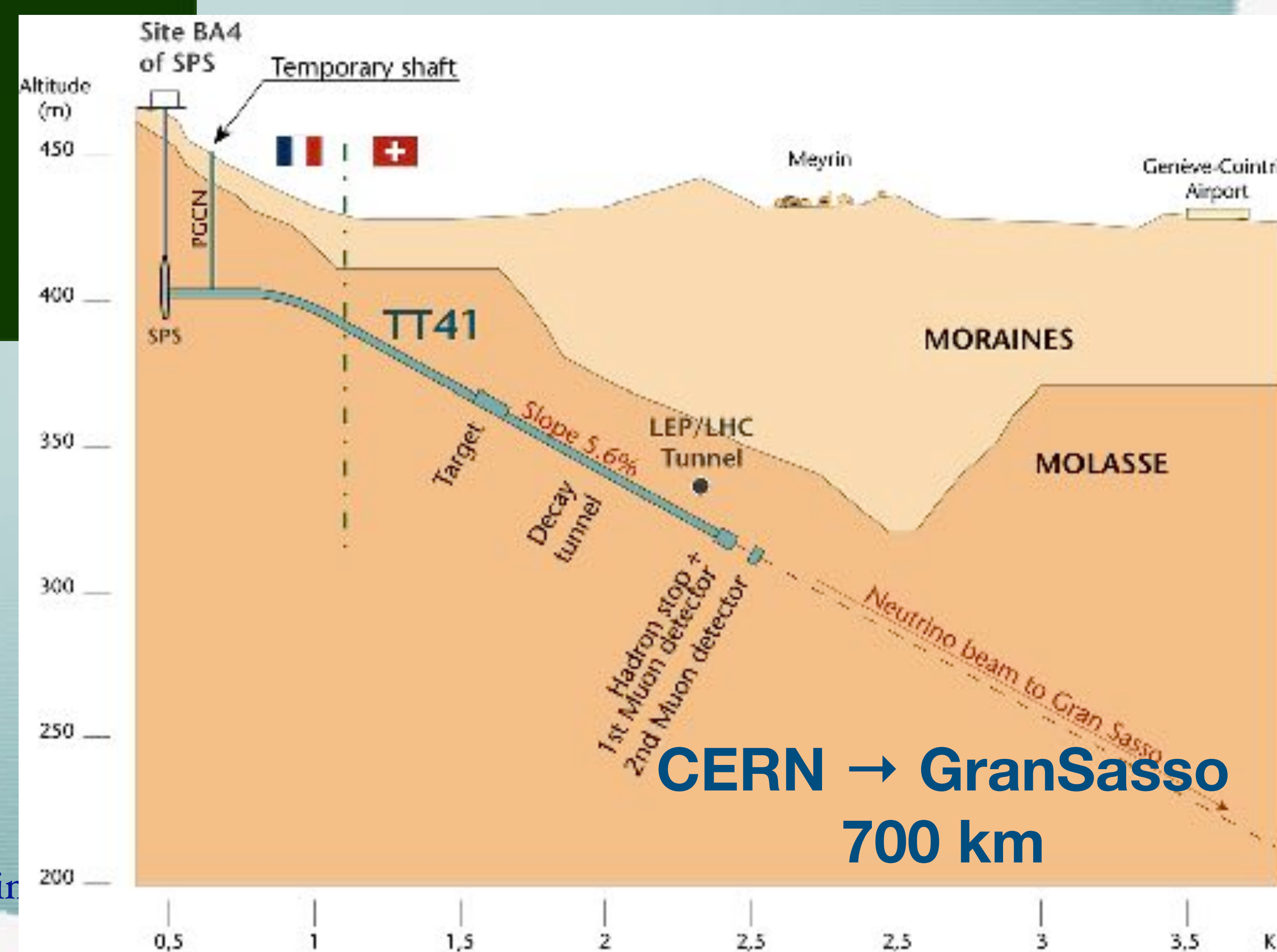


# Neutrinos from CERN to GranSasso (CNGS)

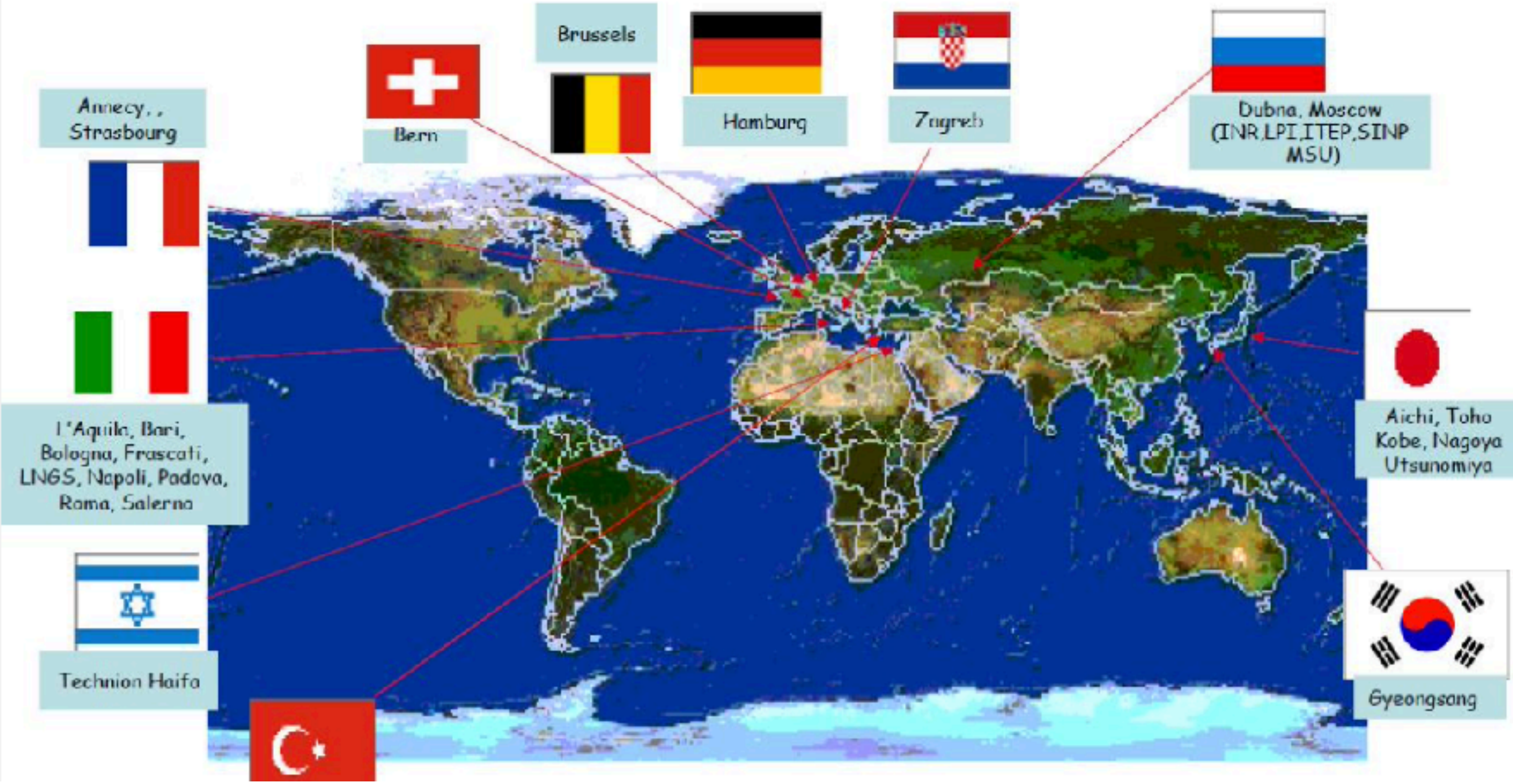



In orange, the decay tunnel where $\pi$ and K from the CERN PS produce a neutrino beam towards Laboratori del Gran-Sasso (2006)

From 2012 to 2018 the OPERA experiment at Gran Sasso has observed 10 events of $\tau$ production and decay the from the interaction of CNGS beam in the emulsion



# The OPERA collaboration



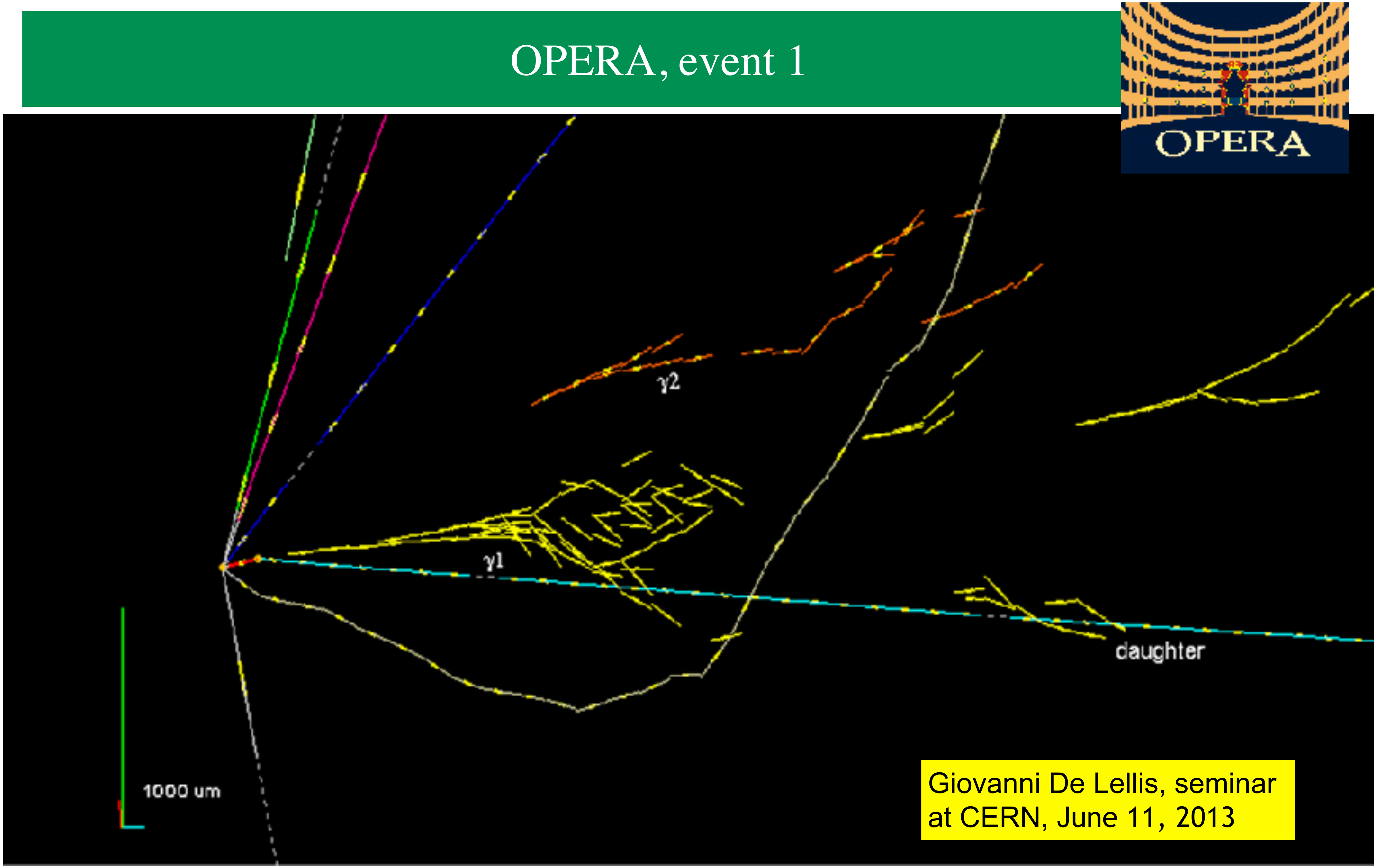

Few persons who have been crucial for the success of CNGS/OPERA:

- E. Iarocci, INFN, President, 1998-2004, A. Bettini, LNGS Director, 1999-2012;
- P. Strolin, Y. Declais, K. Niwa, A. Ereditato, G. De Lellis, OPERA SpokePersons;
- K. Hübner, C. Wyss, Directors of Accelerators and C. Detraz, Director for Fixed Target Programs, CERN;
- K. Elsener, Head of CNGS program, CERN;
- R. Aymar, Chair of the CERN External Review Committee (2001-2002) and CERN DG (2004-2008).

# OPERA: results

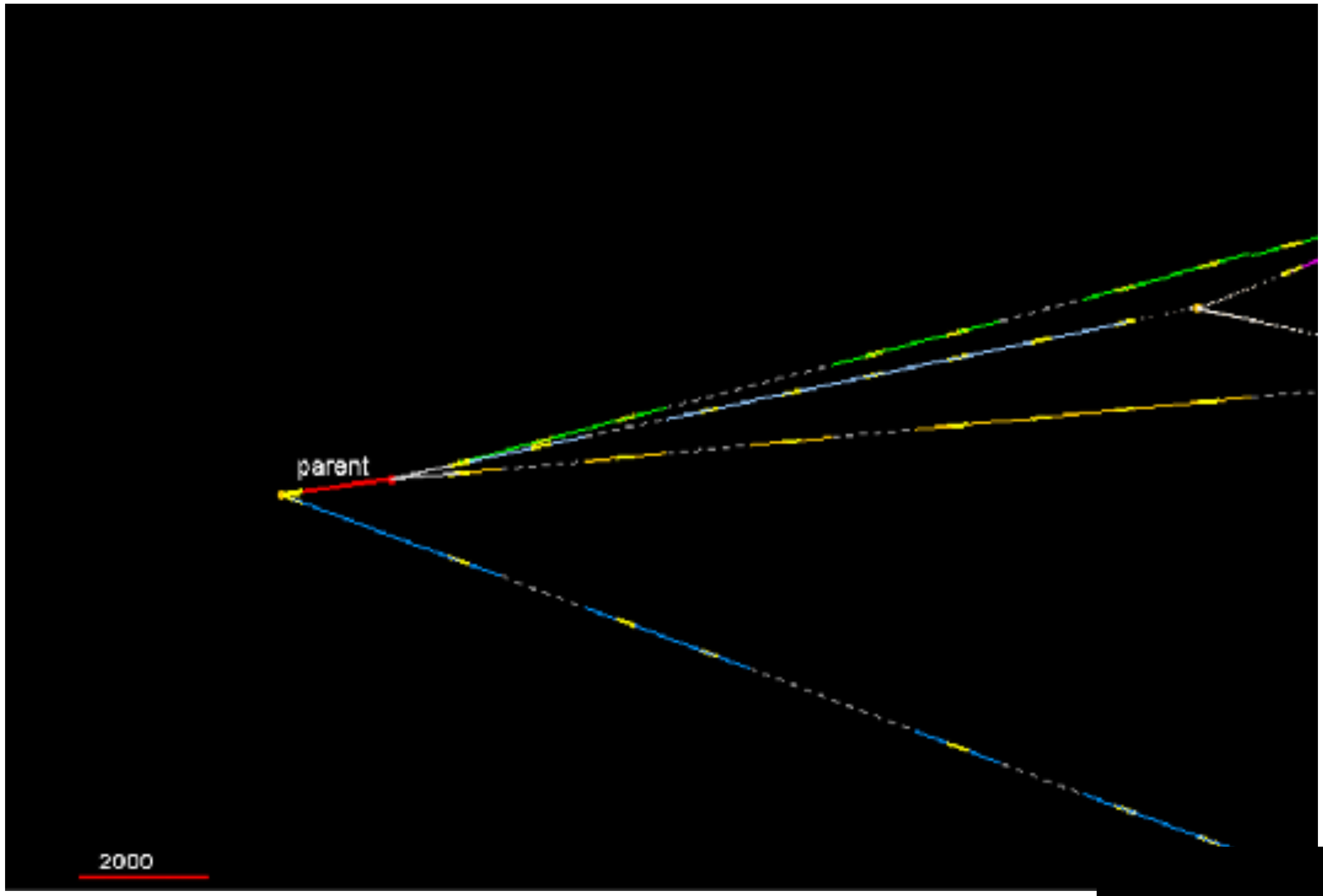
- OPERA was designed to discover the $\tau$ appearance in a $\nu_\mu$ beam, due to neutrino oscillations.
- The detector, located in the Gran Sasso Laboratory, consisted of a nuclear photographic emulsion/lead target with a mass of about 1.25 kt, complemented by electronic detectors.
- It was exposed from 2008 to 2012 to the CNGS beam: an almost pure $\nu_\mu$ beam at CERN, with a baseline of 730 km, collecting a total of $1.8\ 10^{20}$ protons on target.
- The OPERA Collaboration eventually assessed the discovery of $\nu_\mu \rightarrow \nu_\tau$ oscillations with a statistical significance of 6.1 $\sigma$, with the observation of *10* $\nu_\tau$ ***CC interaction candidates***.

# OPERA, event 1

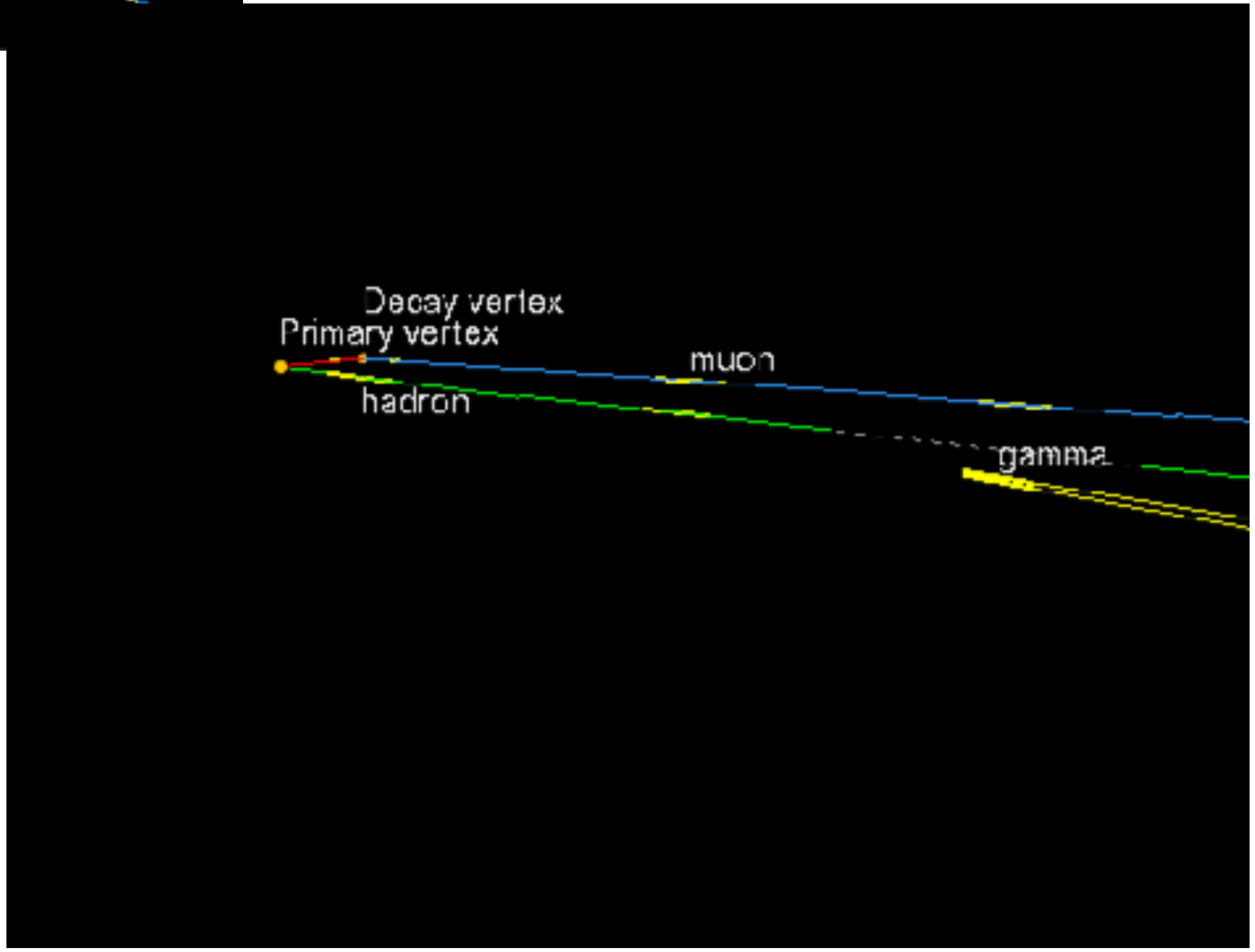



Display of the first $\tau$ candidate event. The event topology and kinematics is consistent with a $\tau \to \rho + \nu_\tau$ and the subsequent $\rho \to \pi^0 + \pi$ and $\pi^0 \to \gamma + \gamma$ decays.

In total OPERA has observed 10 tau production events with:
$\tau \rightarrow$ 3 hadrons, $\tau \rightarrow \mu$




Display of the second $\tau$ candidate event. The event topology and kinematics is consistent with a $\tau \rightarrow 3$ charged hadrons.



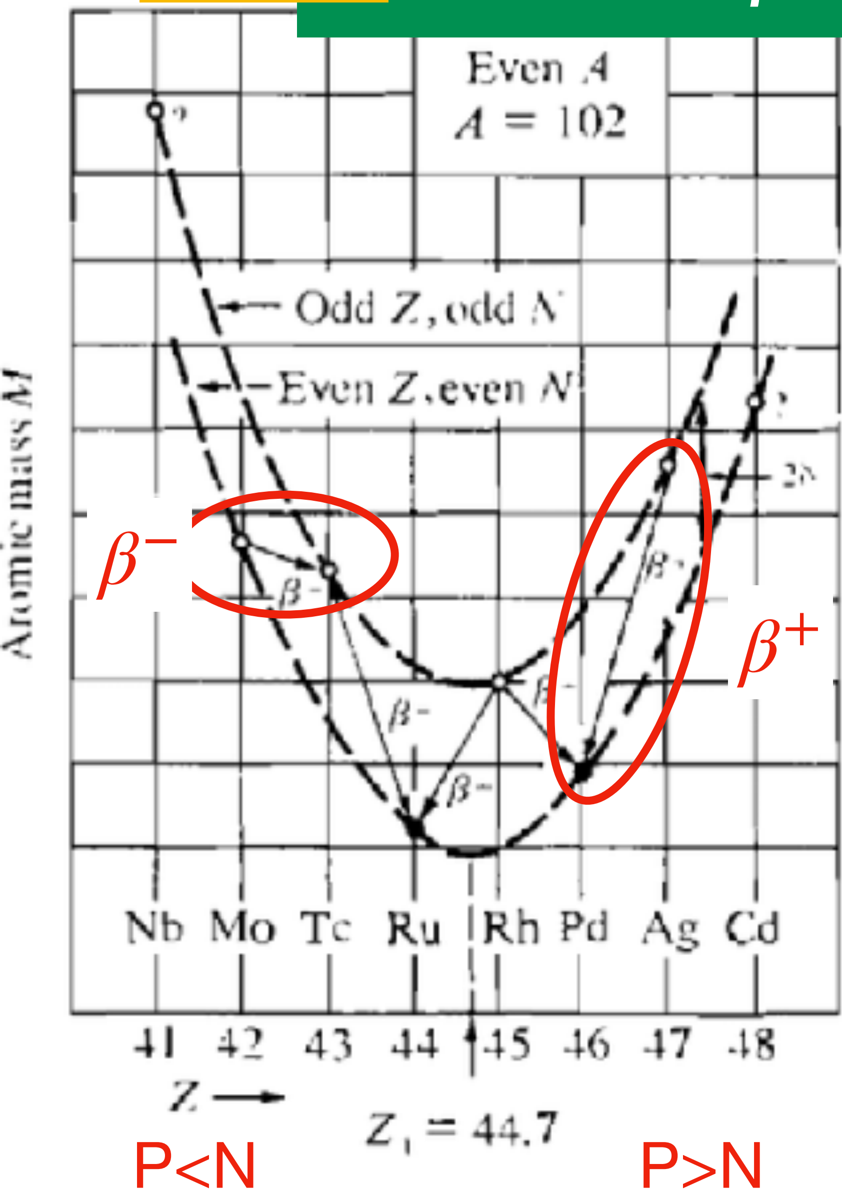

Display of the third $\tau$ candidate event. The event topology and kinematics is consistent with a $\tau^- \rightarrow \bar{\nu}_\tau + \mu^-$decay.

# 4. Electron neutrinos: are they Majorana fermions ? The search of $0\nu 2\beta$ decays at Gran Sasso

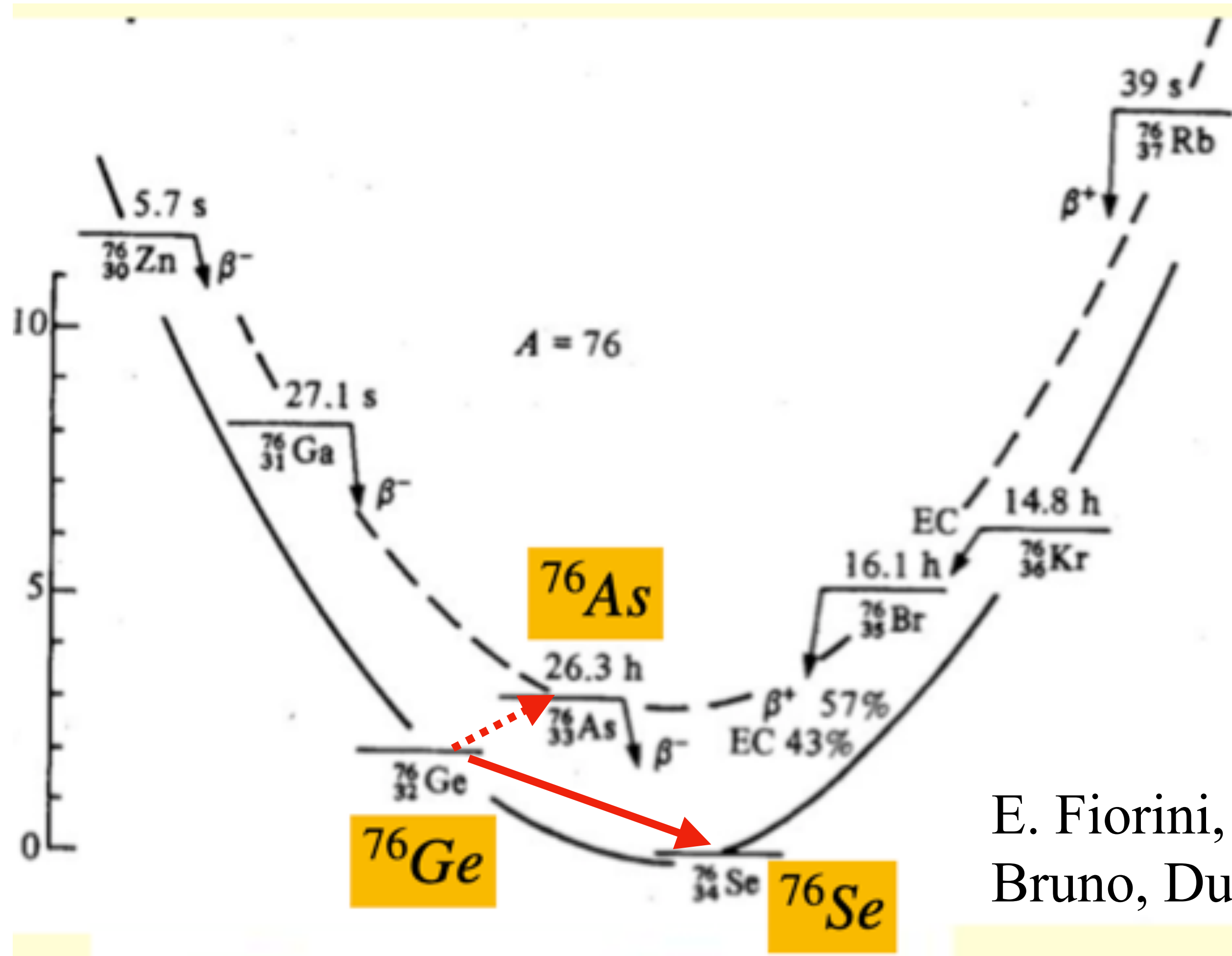
- There is only one process where we can decide between Majorana and Dirac-Weyl neutrinos: ***double-beta decay without neutrinos*** ($0\nu\ 2\beta$)
- for long, the search for $0\nu\ 2\beta$ decay has been a superspecialized matter, restricted to a club of happy fews (among them, Ettore Fiorini)
- today it is one of the most thriving lines of particle physics, in particular experiments are running or in preparation in Gran Sasso (GERDA, XENON1T, CUORE) and other underground laboratories around the world.

$\beta$ decays

# β-decay, 2β-decay, 0ν-2β-decay



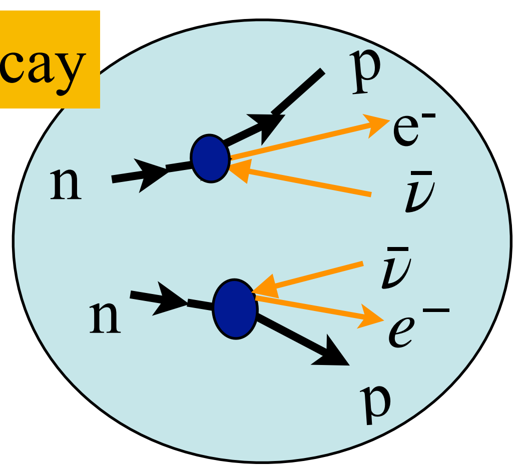

If the Z+1 isobar is heavier than the Z isobar, the latter may decay directly into the Z+2 isobar, to 2nd order in the Fermi interaction.



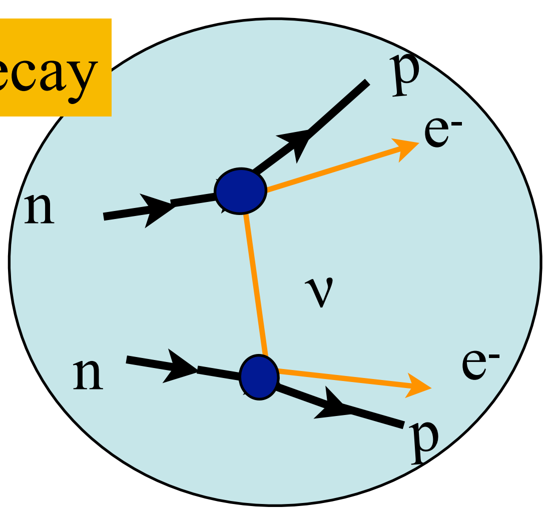

E. Fiorini, My debts to Bruno, Dubna, 2013.

This is the double beta decay, predicted by Maria Goeppert Mayer in 1935.

$2\nu2\beta$ decay




$0\nu2\beta$ decay



# in formulae

$$J^\mu = \bar{\psi}_e \gamma_\mu \frac{1}{2}(1-\gamma_5)U$$

All Reps: $\gamma^0 \gamma^{\mu\dagger} \gamma^0 = \gamma^\mu$
Majorana Rep: $\gamma^0 \gamma^{\mu T} \gamma^0 = -\gamma^\mu$

that is:

$$J^\mu = -U^T \frac{1}{2}(1+\gamma_5)\gamma^{\mu T}\gamma^0 \psi_e^C =$$

$$= U^T \gamma^0 \frac{1}{2}(1-\gamma_5)\gamma^\mu \psi_e^C$$

Leptonic part of $H_{0\nu 2\beta} = J^\mu(x) J^\nu(0) =$

$$= \bar{\psi}_e \gamma_\mu \frac{1}{2}(1-\gamma_5) < 0|U(x)\ U^T(0)\gamma^0|0 > \frac{1}{2}(1-\gamma_5)\gamma^\nu \psi_e^C$$

$$< 0|U(x)\ U^T(0)\gamma^0|0 > \to \frac{\hat{k}+m}{k^2+m^2}$$

⇒ $\hat{k}$ is eliminated by the $(1-\gamma_5)$ projectors

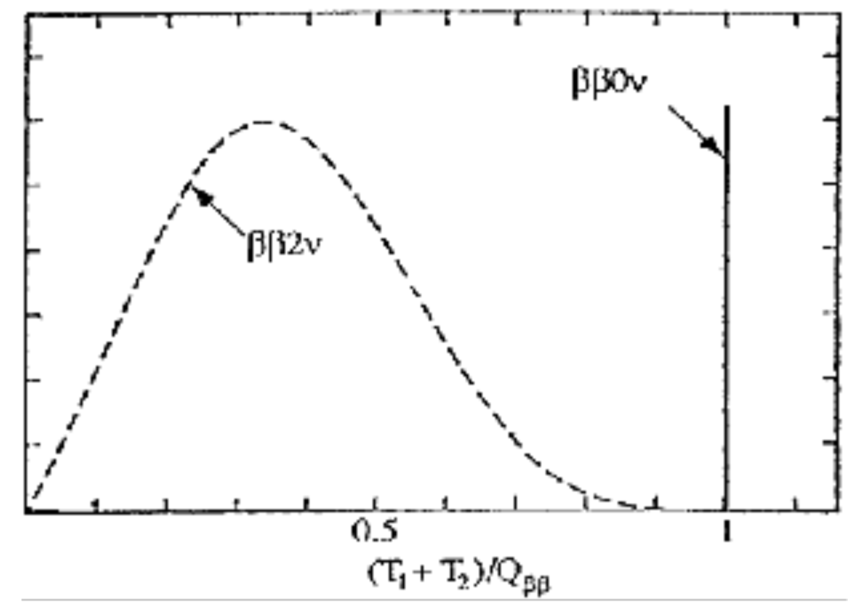
**$0\nu 2\beta$ decay amplitudes are proportional to $m_\nu$**

# Double beta decay isotopes

| Nuclide | Half-life, $10^{21}$ years | Mode | Transition | Method | Experiment |
|---|---|---|---|---|---|
| $^{48}$Ca | $0.064^{+0.007}_{-0.006} \pm ^{+0.012}_{-0.009}$ | $\beta^-\beta^-$ | | direct | NEMO-3[11] |
| $^{76}$Ge | $1.926 \pm 0.094$ | $\beta^-\beta^-$ | | direct | GERDA[10] |
| $^{78}$Kr | $9.2^{+5.5}_{-2.6} \pm 1.3$ | $\varepsilon\varepsilon$ | | direct | BAKSAN[10] |
| $^{82}$Se | $0.096 \pm 0.003 \pm 0.010$ | $\beta^-\beta^-$ | | direct | NEMO-3[10] |
| $^{96}$Zr | $0.0235 \pm 0.0014 \pm 0.0016$ | $\beta^-\beta^-$ | | direct | NEMO-3[10] |
| $^{100}$Mo | $0.00693 \pm 0.00004$ | $\beta^-\beta^-$ | | direct | NEMO-3[10] |
| | $0.69^{+0.10}_{-0.08} \pm 0.07$ | $\beta^-\beta^-$ | $0^+ \to 0^+_1$ | | Ge coincidence[10] |
| $^{116}$Cd | $0.028 \pm 0.001 \pm 0.003$<br>$0.026^{+0.009}_{-0.005}$ | $\beta^-\beta^-$ | | direct | NEMO-3[10]<br>ELEGANT IV[10] |
| $^{128}$Te | $7200 \pm 400$<br>$1800 \pm 700$ | $\beta^-\beta^-$ | | geochemical | [10] |
| $^{130}$Te | $0.82 \pm 0.02 \pm 0.06$ | $\beta^-\beta^-$ | | direct | CUORE-0[12] |
| $^{124}$Xe | $18 \pm 5 \pm 1$ | $\varepsilon\varepsilon$ | | direct | XENON1T[13] |
| $^{136}$Xe | $2.165 \pm 0.016 \pm 0.059$ | $\beta^-\beta^-$ | | direct | EXO-200[10] |
| $^{130}$Ba | $(0.5 - 2.7)$ | $\varepsilon\varepsilon$ | | geochemical | [14][15] |
| $^{150}$Nd | $0.00911^{+0.00025}_{-0.00022} \pm 0.00063$ | $\beta^-\beta^-$ | | direct | NEMO-3[10] |
| | $0.107^{+0.046}_{-0.026}$ | $\beta^-\beta^-$ | $0^+ \to 0^+_1$ | | Ge coincidence[10] |
| $^{238}$U | $2.0 \pm 0.6$ | $\beta^-\beta^-$ | | radiochemical | [10] |

Frejus
LNGS
RUSSIA
Frejus
Japan
LNGS
LNGS
USA

Note: $\epsilon\epsilon$= double electron capture




when no neutrinos are emitted, the sum of the energies of the two β rays is fixed and equal to the difference of the energy of the initial and final nuclei.
Germanium may be source and detector at the same time (E. Fiorini)

# GERDA Installations

https://www.mpi-hd.mpg.de/gerda/

Located in Hall A
@ LNGS

8/09/2014

## GERDA (all data sets) vs 0νββ observation claim

PLB 586(2004)

For $T_{1/2}^{0\nu} = 1.19 \times 10^{25}$ yr

Expected Signal (after PSD): 5.9 ± 1.4 cts in ±2σ

Expected Bckgd (after PSD): 2.0 ± 0.3 cts in ±2σ

Observed: 3.0 (0 in ±1σ)

# Closing in on neutrino Majorana mass

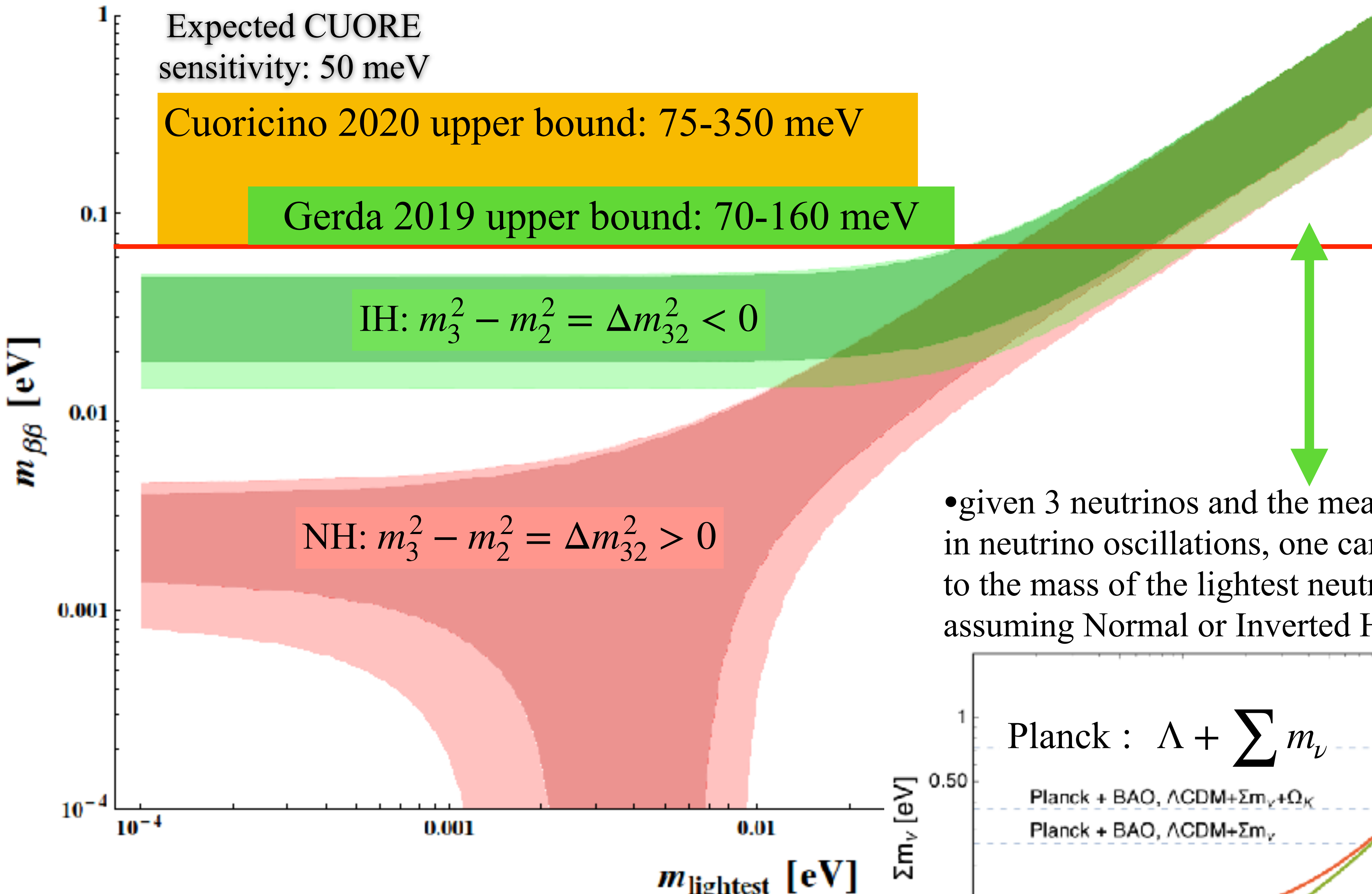
***GERDA, Max Planck Institute communication***
***09/06/2019***
Latest GERDA limits
If the new lower limit for the half-life determined with GERDA is combined with that of other experiments on neutrinoless double beta decay, the mass of the neutrinos must be below a value of 0.07 to 0.16 eV.

***D. Q. Adams et al. (CUORE Collaboration)***
***Phys. Rev. Lett. 124, 122501*** – Published 26 March 2020

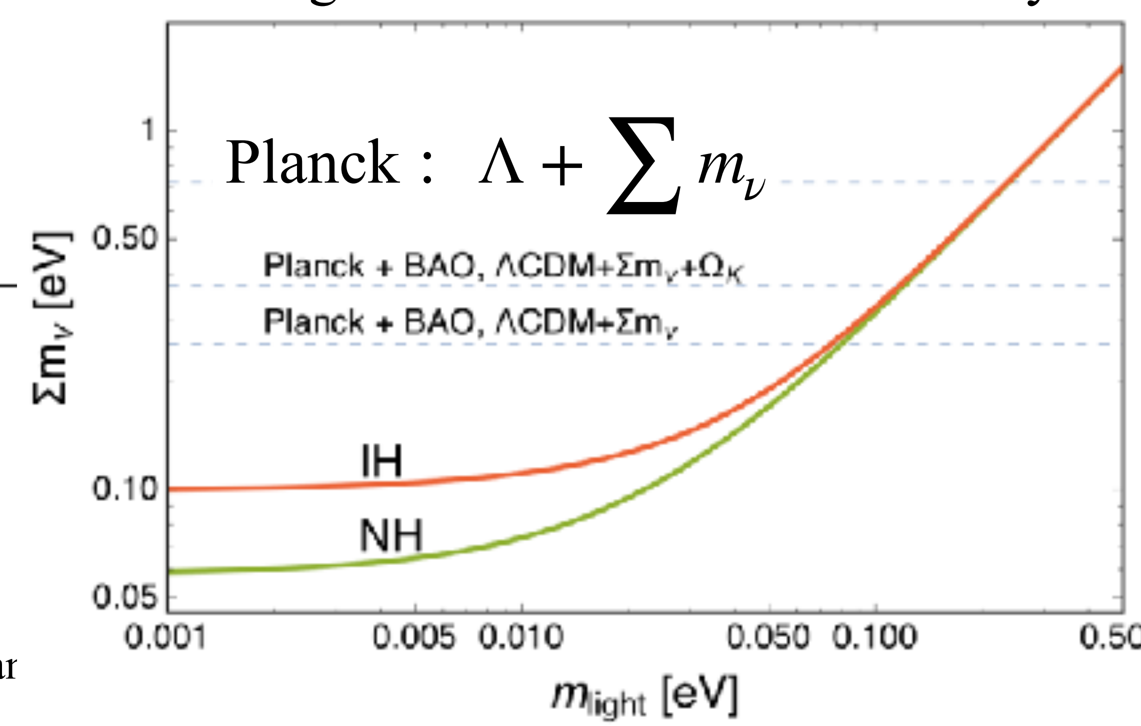
…..In the hypothesis that $0\nu\beta\beta$ decay is mediated by light Majorana neutrinos, this results in an upper limit on the effective Majorana mass of 75–350 meV, depending on the nuclear matrix elements used.

For other experimental results, see pdglive.lbl.gov

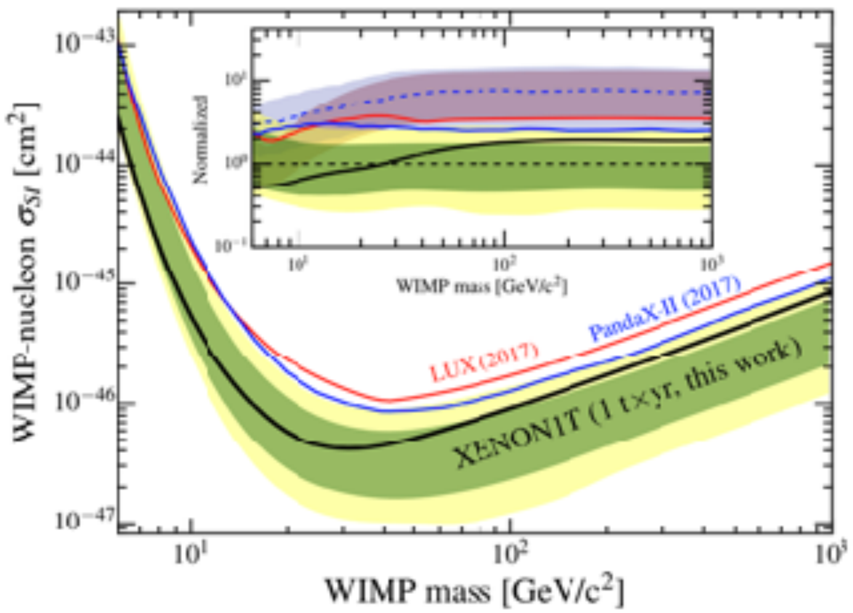
# we may be not so far

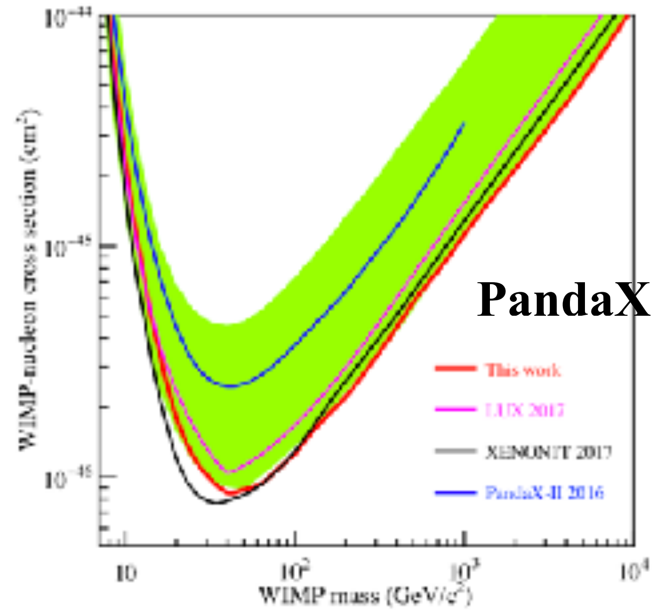



•given 3 neutrinos and the measured $\Delta m^2$ in neutrino oscillations, one can relate $\Sigma m_\nu$ to the mass of the lightest neutrino $m_{light}$ assuming Normal or Inverted Hierarchy



# 5. Dark Matter-WIMP-searches



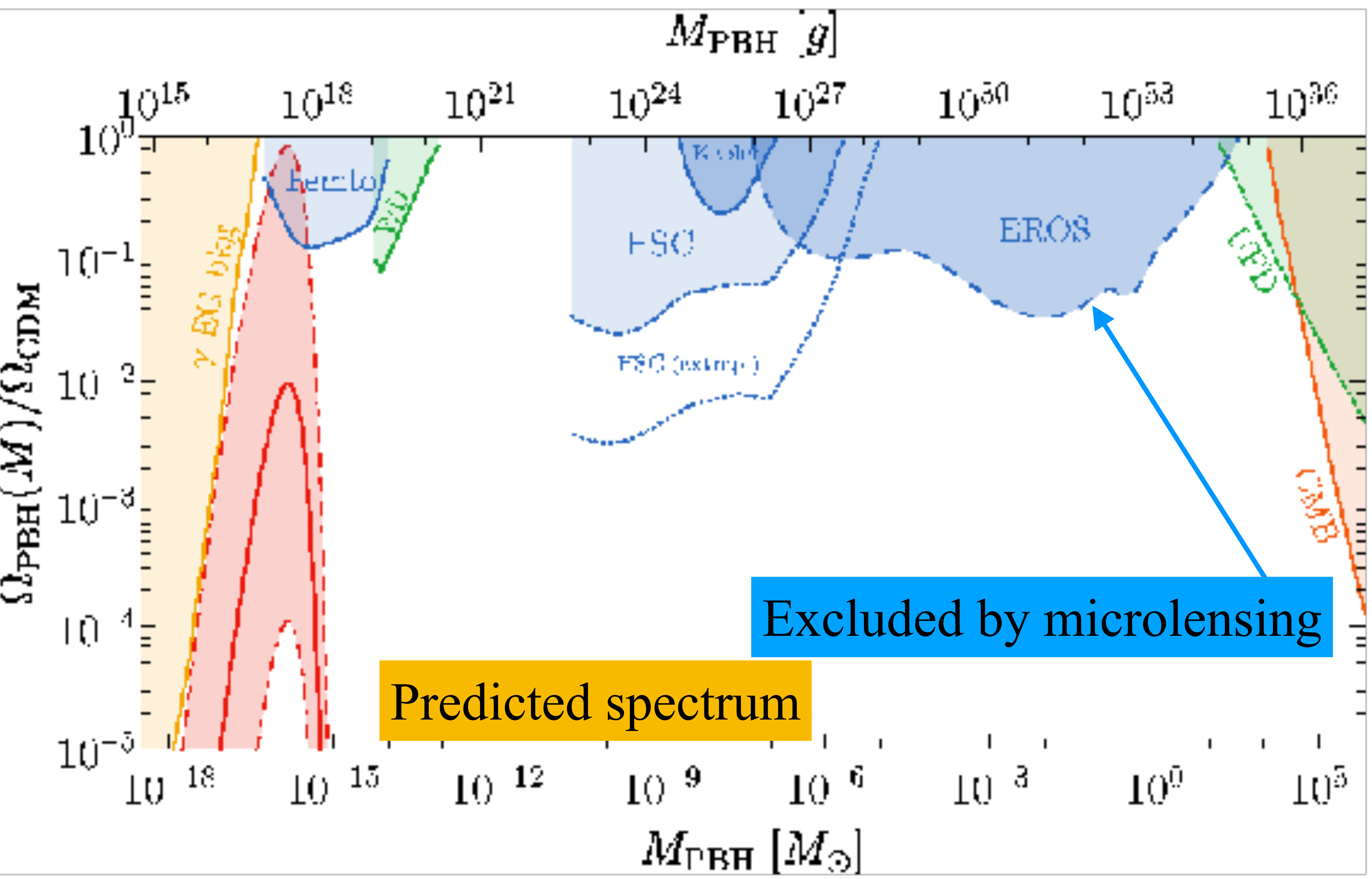




**Xenon1T, PandaX**

https://xenonexperiment.org/infrastructure/
https://pandax.sjtu.edu.cn/pandax

- neutrino background is getting close
- efforts to detect directionality

## Primordial Black Holes from Higgs instability??




J. R. Espinosa, D. Racco and A. Riotto, *Primordial BHs*; arXiv:1804.07731 [hep-ph].

- Created from the gravitational collapse of the fluctuations of the inflaton (Higgs) field
- coupled to normal baryon matter only by gravitation
- could be seen by microlensing while passing infront of normal stars
- There are already important limits set e.g. by the old searches for Massive Compact Halo Obiects (MACHOs).

**Other possibilities: Axions ?? XXXX ???**

Thank You !!!