Rassegna Sperimentale sulla Fisica del Neutrino

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Neutrino Physics

- **How small is the Neutrino mass? (Fermi,Pauli ~1930)**
- **Which Neutrino: Dirac or Majorana? (Majorana 1937)**
- **Do Neutrinos oscillate? (Pontecorvo ~1960)**
- Astrophysical/Cosmological Neutrinos:

  relic neutrinos? Supernova neutrinos? high Energy neutrinos?
- Electromagnetic Neutrino Properties?
- Geo-neutrinos?
- Sterile neutrinos?
- ....

see Capone & De Bernardis' talk

Oscillations Results

Solar (row U_{e1}, U_{e2}, U_{e3}) — **Atmospheric** (column $U_{e3}, U_{\mu3}, U_{\tau3}$)

Atmospheric + accelerator | Mainly Chooz + Minos+solar+atmosferic | Solar+ Kamland

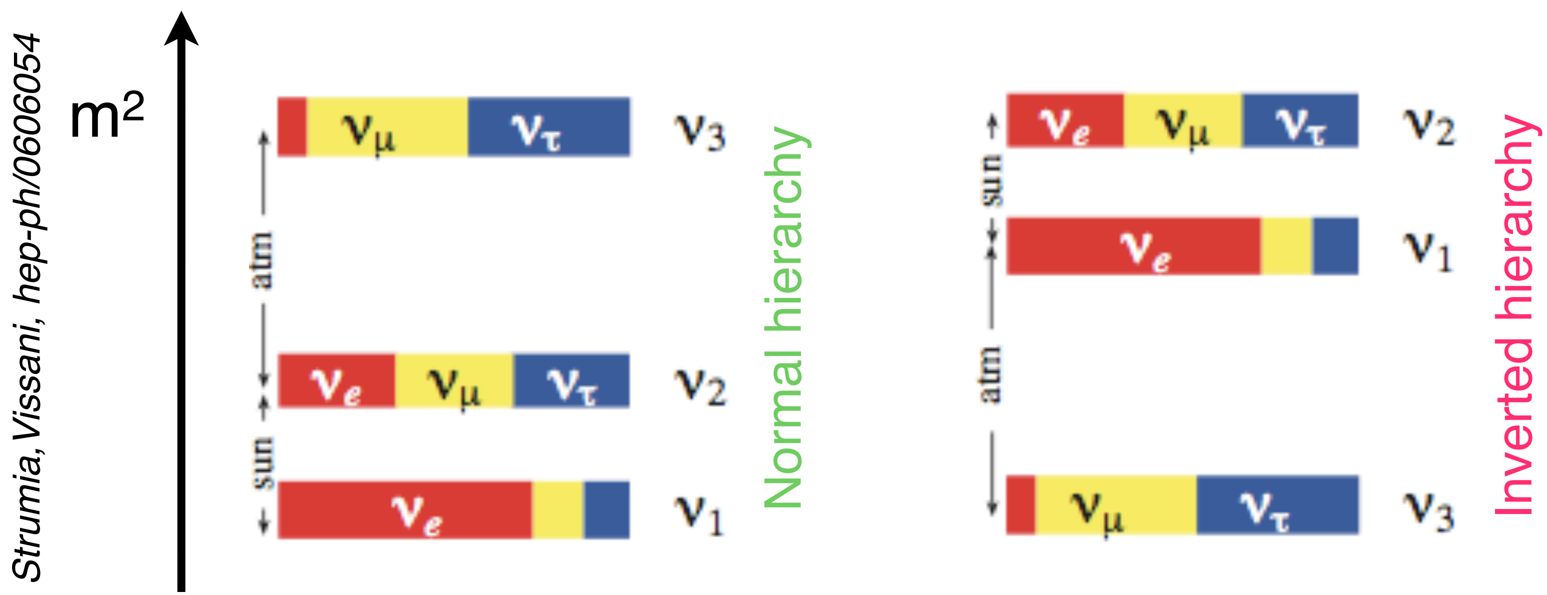
$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$\theta_{23} \cong \theta_{atm} = 45° \pm 8°$
$\sin^2(2\theta_{23}) = 1.02 \pm 0.04$

$\theta_{13} < 10°$
$\sin^2(2\theta_{13}) = 0.07 \pm 0.04$

$\theta_{12} \cong \theta_{sol} = 34° \pm 3°$
$\tan^2(\theta_{12}) = 0.484 \pm 0.048$

$$\Delta m^2_{21} \equiv \Delta m^2_{\rm sol} = (7.58 \pm 0.21) \cdot 10^{-5} {\rm eV}^2 \qquad |\Delta m^2_{32}| \equiv \Delta m^2_{\rm atm} = (2.40 \pm 0.15) \cdot 10^{-3} {\rm eV}^2$$



What's next

- Precision era: **Δm^2_{12}, θ_{12}, Δm^2_{23}, θ_{23}**
- Appearance paradox: *appearance of new flavors never observed unambiguously*

$$\nu_\mu \longrightarrow \nu_\tau$$

OPERA

$$\nu_\mu \longrightarrow \nu_e$$

T2K, NOvA, MINOS?

- Measure **θ_{13}**:
  - sub-leading transition $\nu_\mu \longrightarrow \nu_e$
  - $\bar{\nu}_e$ disappearance from reactors **DOUBLE CHOOZ, DAYA BAY**
- Depending on **θ_{13}:**
  - **Mass hierarchy** @ accelerators
  - **CP violation**: $P_{CP} \propto 0.23 \sin(\theta_{13}) \sin(\delta) \sin^2(\Delta m^2_{13} L/E) \sin(\Delta m^2_{12} L/E)$

$\nu_\mu \Rightarrow \nu_\tau$: OPERA

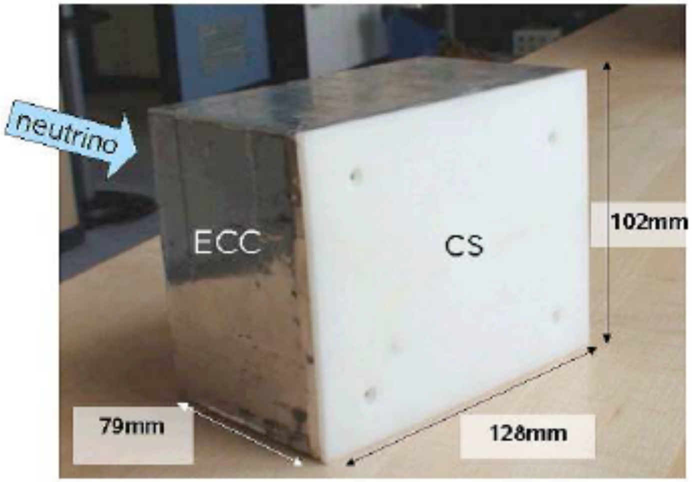
A. Buccheri, M.Capodiferro, P.Pecchi, A.Pelosi, G. Rosa, A. Ruggeri

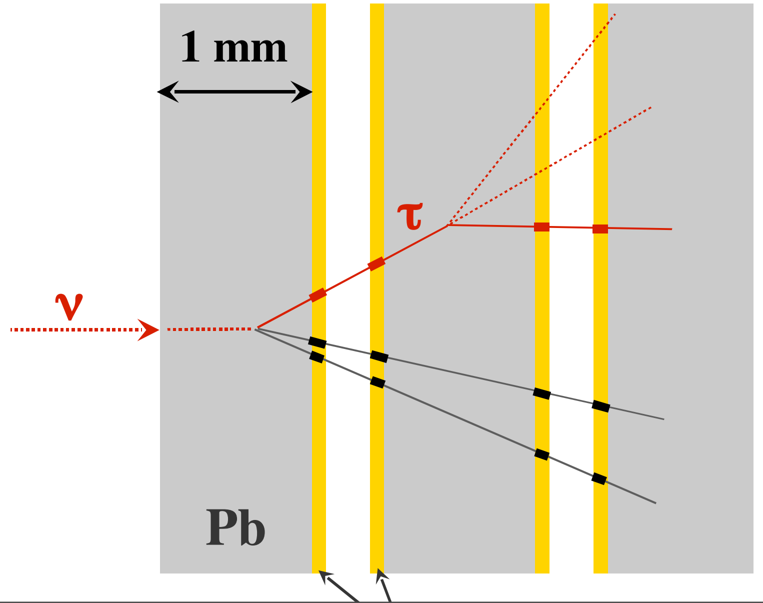
- Goal: identify ν_τ appearance through CC interaction

$$\nu_\mu \to \nu_\tau\,,\, \nu_\tau + N \to \tau^- + X$$

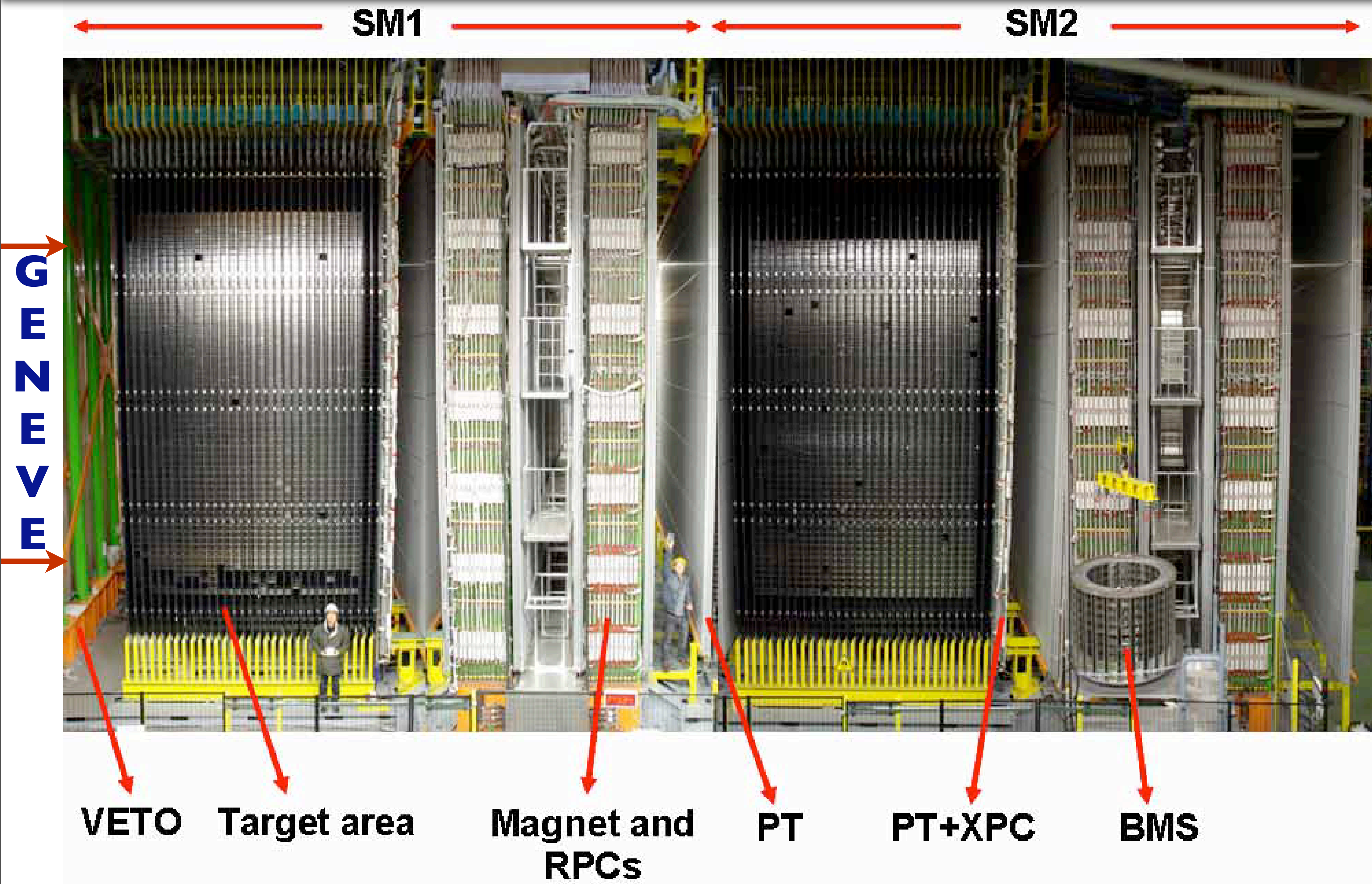
$\mu^- \ \nu_\tau \ \nu_\mu$	B. R. ~ 17%
$h^- \ \nu_\tau \ n(\pi^o)$	B. R. ~ 50%
$e^- \ \nu_\tau \ \nu_e$	B. R. ~ 18%
$\pi^+ \pi^- \pi^- \ \nu_\tau \ n(\pi^o)$	B. R. ~ 14%

- Need: O(kTon) target mass + high granularity detector (σ~μm) for τ detection ($c\tau$~87 μm) and bkgd rejection (mainly $\nu_\mu N \to c\mu X$)
  - Lead-nuclear emulsion target segmented into basics units(bricks): *57(330μm)emulsion films between 1 mm Pb sheets*





In Picture

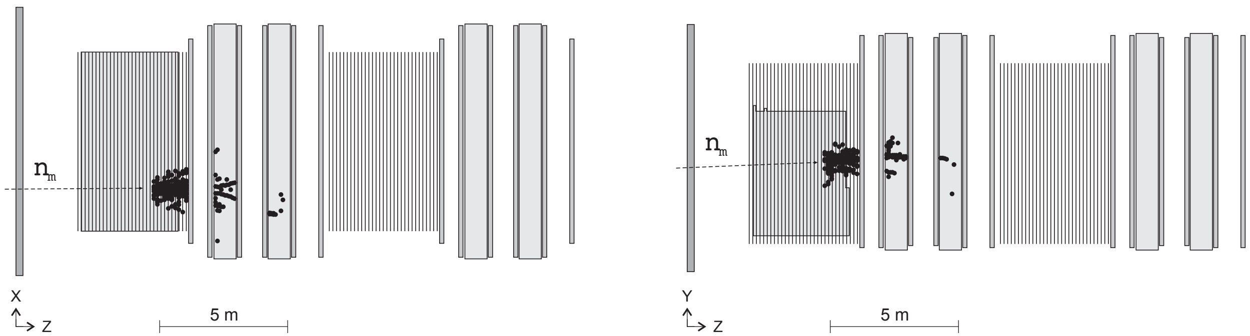


CNGS Run 2008

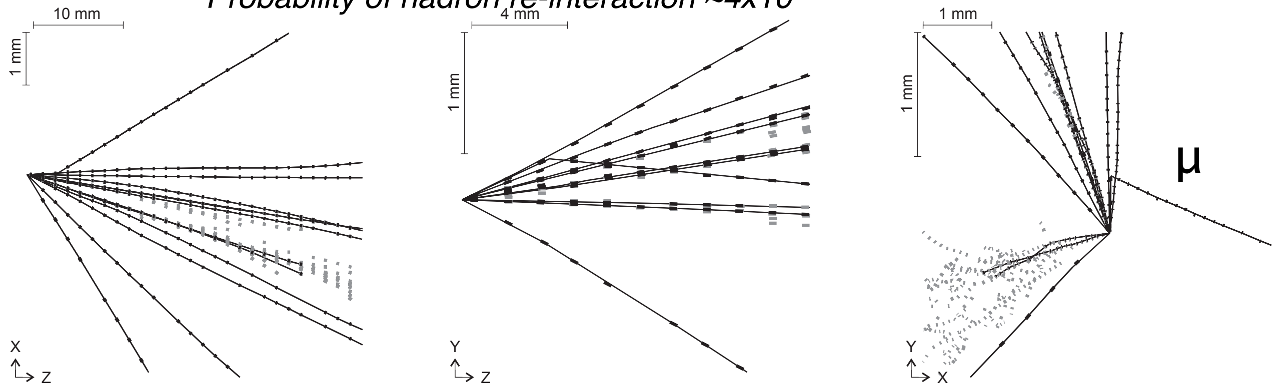
- Total beam intensity: **1.8 ·10^19 pot** (exp. 4.5·10^19 pot/y)
- **1663 ν candidate** interactions in the target
- 850 bricks scanned: 650 interactions (8 charm event)

<E (ν_μ)>	17 GeV
L	730 km
L/E	43 Km/GeV
$(\nu_e + \bar{\nu}_e)/\nu_\mu$	0.87%
$\bar{\nu}_\mu$ / ν_μ	4%
ν_τ prompt	negligible

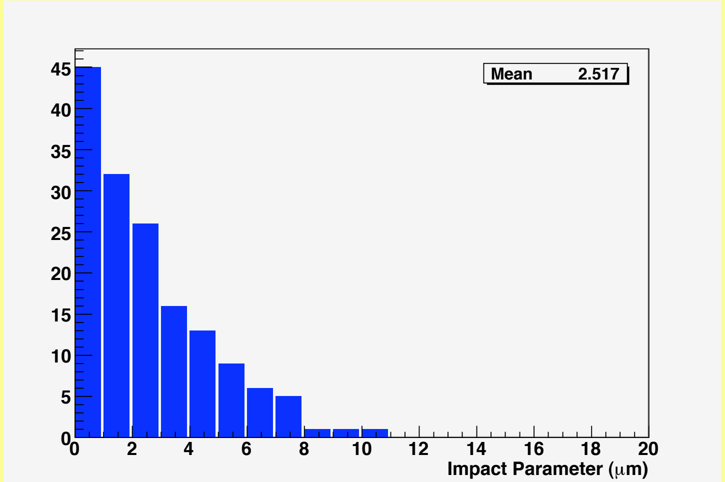
first charm event



Parent path length ~3247 μm, ΔΦ~165°
Daughter momentum p=3.9$^{+1.7}_{-0.9}$ GeV/c
Probability of hadron re-interaction ~4x10^{-4}



hep-ex 0903.2973v1:
live time >99%
first brick finding eff~70%
vertex location eff. ~80-90%



Opera perspectives

- Expectation for 2009: 3.6 $\cdot 10^{19}$ pot ⇒ 3500 ν events on detector
  - Looking forward to see the first τ event
- Total "Nominal" pot in 5 years: 22 $\cdot 10^{19}$ pot

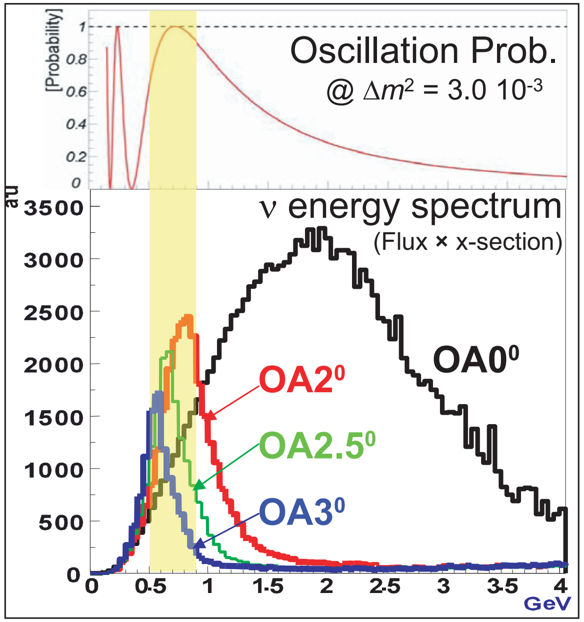
τ^- decay channels	ε(%)	BR (%)	Signal $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2	Background:
$\tau^- \to \mu^-$	17.5	17.7	2.9	0.17
$\tau^- \to e^-$	20.8	17.8	3.5	0.17
$\tau^- \to h^-$	5.8	49.5	3.1	0.24
$\tau^- \to 3h$	6.3	15	0.9	0.17
ALL	ε x BR =10.6%		10.4	0.75

- Activity in Rome: *emulsion scanning station for data analysis*

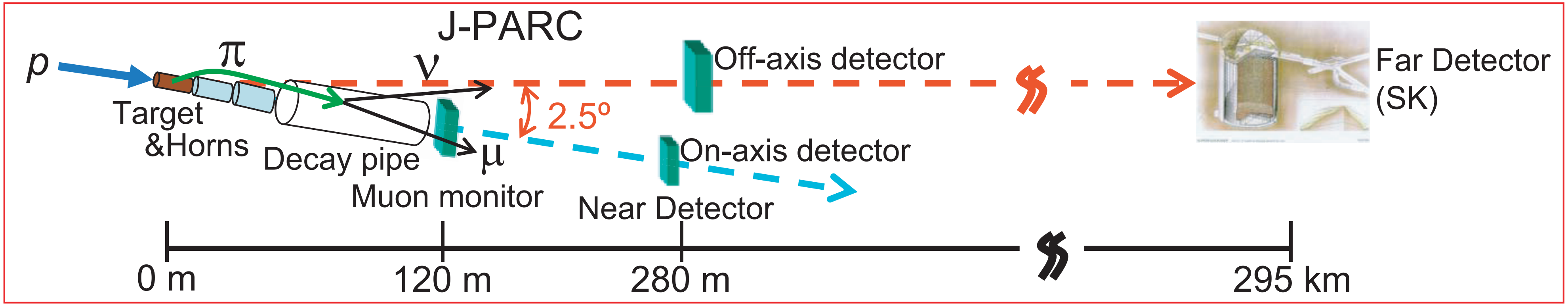
$\nu_\mu \Rightarrow \nu_\mu$, $\nu_\mu \Rightarrow \nu_e$: T2K

U.Dore, C. Gargiulo, P. Loverre, L.Ludovici, C.Mariani

- Precise measurement of Δm^2_{23}, θ_{23} from ν_μ disappearance
  - signal: $\nu_\mu n \rightarrow p \mu^-$ bkgd: CC-1π events
- Search for θ_{13}: $\nu_\mu \Rightarrow \nu_e$ appearance
  - signal: $\nu_e n \rightarrow p e^-$ bkgd: Intrinsic beam ν_e, NC-1π^0



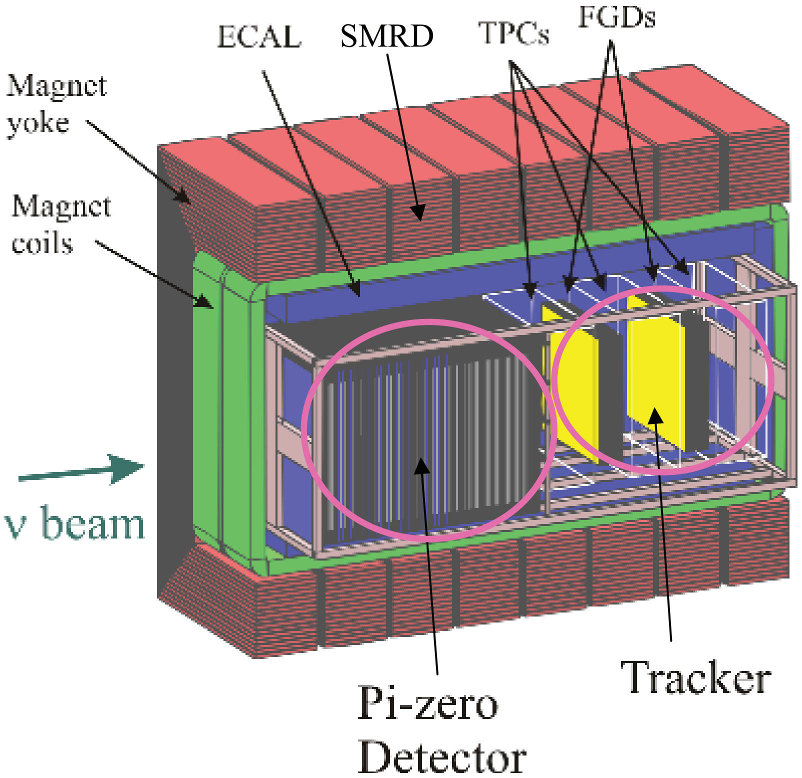
- **Off-axis** beam technique: ν_e contamination @ peak ~0.4%

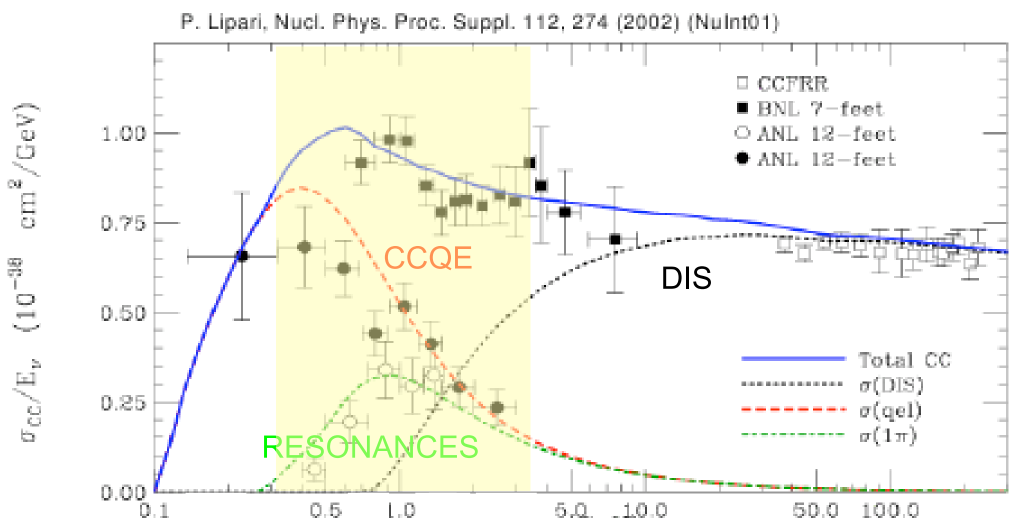


The Close detector

Key for good E_ν spectrum and background estimate

Installation foreseen in this summer





Rome activity:
-data taking/electron final state analysis(beam ν_e contamination)
-feasibility study for LAr near detector for T2K upgrade

- **April 23rd 2009:** ***first protons on target*** http://www.kek.jp/intra-e/press/2009/J-PARCT2K.html
- Start Data taking at December 2009 and accumulate **~10^{20} POT** by summer 2010

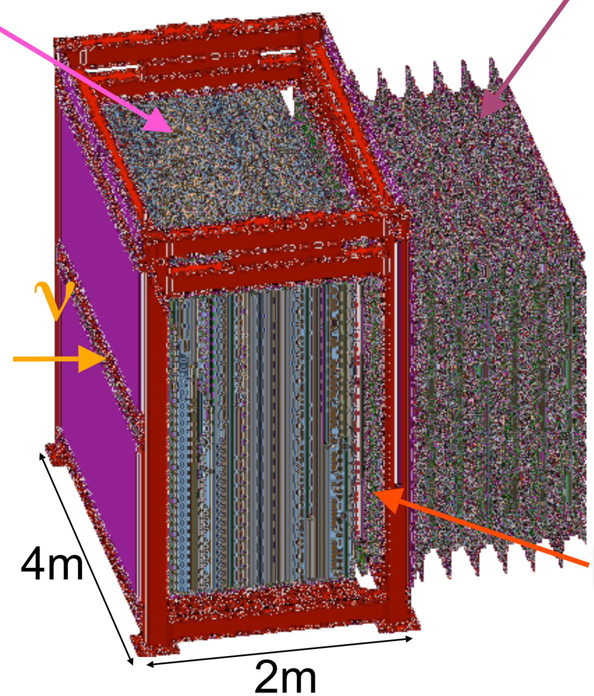
($\bar{\nu}$)ν cross section: SciBoone

- **K2K-SciBar detector at FNAL Booster Neutrino Beam**

SciBar

- Scintillator tracking detector
- 14,336 scintillator bars (15 tons)
- Neutrino target (CH)
- detect all charged particles
- p/π separation using dE/dx

Used in K2K experiment



Muon Range Detector (MRD)

- 12 2"-thick steel + scintillator planes
- measure muon momentum with range up to 1.2 GeV/c

Parts recycled from Past experiment

Electron Catcher (EC)

- spaghetti calorimeter
- 2 planes (11 X_0)

- Data taking is over. Collected statistics: 1(1.5) $\cdot 10^{20}$ POT di ν ($\bar{\nu}$)
- No evidence of CC coherent π production *Phys.Rev.D 78:112004, 2008*
- **CC-QE, CC1π, NC1π, NC-elastic** measurement cross section on going

θ_{13} Experiments

- **T2K: $\sin^2(2\theta_{13}) < 0.01$** in 5 years(no sensitivity for CP violation and matter effects)
- **Double Chooz:**
  - End of **2009**: start with only far detector: **$\sin^2(2\theta_{13}) < 0.06$ 90%CL in 1.5 y**
  - Far+Near from **2011**: **$\sin^2(2\theta_{13}) < 0.03$ 90%CL in 3 y**
- **Daya Bay**:
  - Start in **2012** **$\sin^2(2\theta_{13}) < 0.01$ 90%CL**
- **NOvA**:
  - 2nd generation LBL experiment

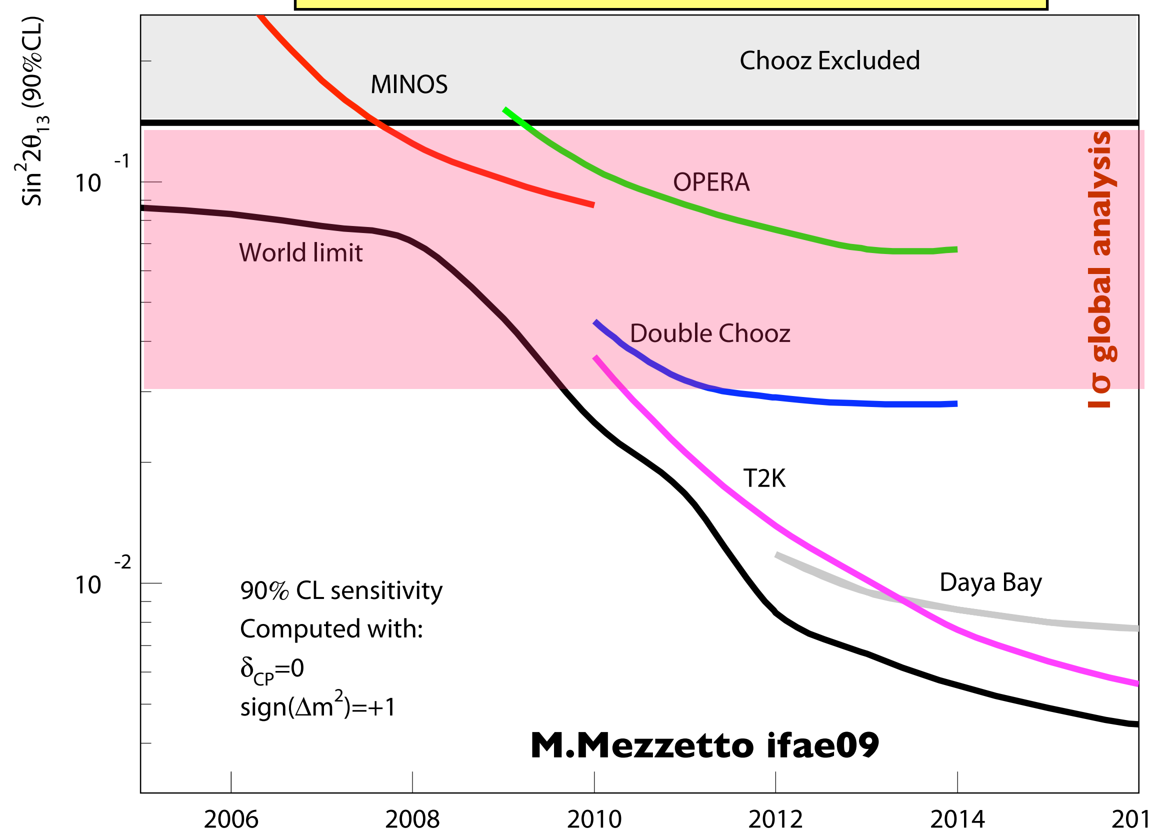
    (15kTon tracking liquid scintillator at

    810 km off-axis from NUMI(700kW))
  - Full detector start:**2013**

    Groundbreaking started May 1st 2009
  - **$\sin^2(2\theta_{13}) < 0.01$ + matter and CP effect**

Current limit

CHOOZ: $\sin^2(2\theta_{13}) < 0.15$ 90%CL



θ_{13} dilemma

- All mixing matrix and mass hierarchy could be explored with accelerator experiment
- If **$\sin^2(2\theta_{13})>0.01(\theta_{13}>3°)$**
  - **Superbeam** (2-4 MW) + **new detectors**

    Electronic final state→*low density detector*: MTon WC, 0.1Mton LAr, Liquid scintillator

    Systematic limited: flux composition and low energy nuclear cross section
- If **$\sin^2(2\theta_{13})<0.01$ $(\theta_{13}<3°)$**
  - **Neutrino factories:** initial beam $\nu_\mu+\bar{\nu}_e$ or $\bar{\nu}_\mu+\nu_e$

    Golden channel $\nu_e\Rightarrow\nu_\mu$ wrong sign muons: Minos like detector (*wrong charge rejection*$<10^{-3}$)

    Silver channel $\nu_e\Rightarrow\nu_\tau$: 4xOPERA or 10 kTon LAr detector

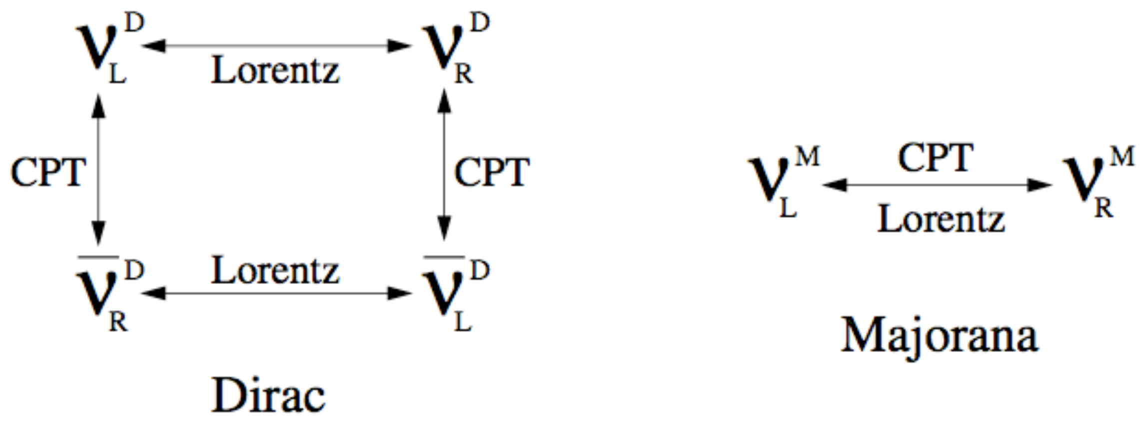
    High density detector: E>10GeV, L~3000 km, consistent matter effect

  - **Beta beams:** ν_μ appearance but only one flavor at t=0: ν_e or $\bar{\nu}_e$

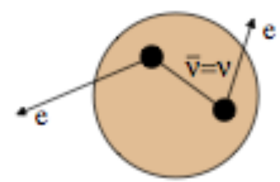
    Drawback low energy neutrinos sub GeV: single π NC production and e mis-id

Dirac or Majorana?

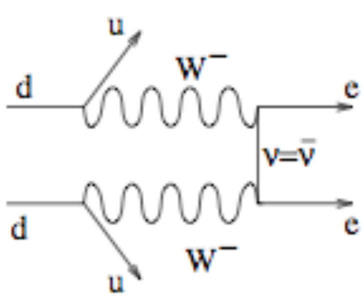
- Majorana conjecture (1937) $\nu=\nu^C$



- Massless neutrino DOES NOT allow testing of the Majorana nature
- Implication: Lepton number violation



- Neutrinoless Double Beta Decay: (A,Z) → (A,Z+2) + 2 e^-

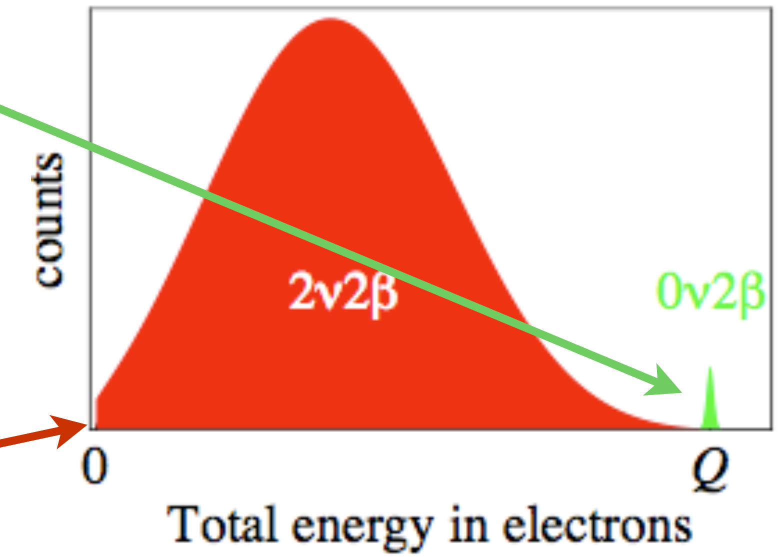


$$\Gamma^{0\nu}_{1/2} \propto Q^5 |M_{nucl}|^2 |m_{\beta\beta}|^2$$

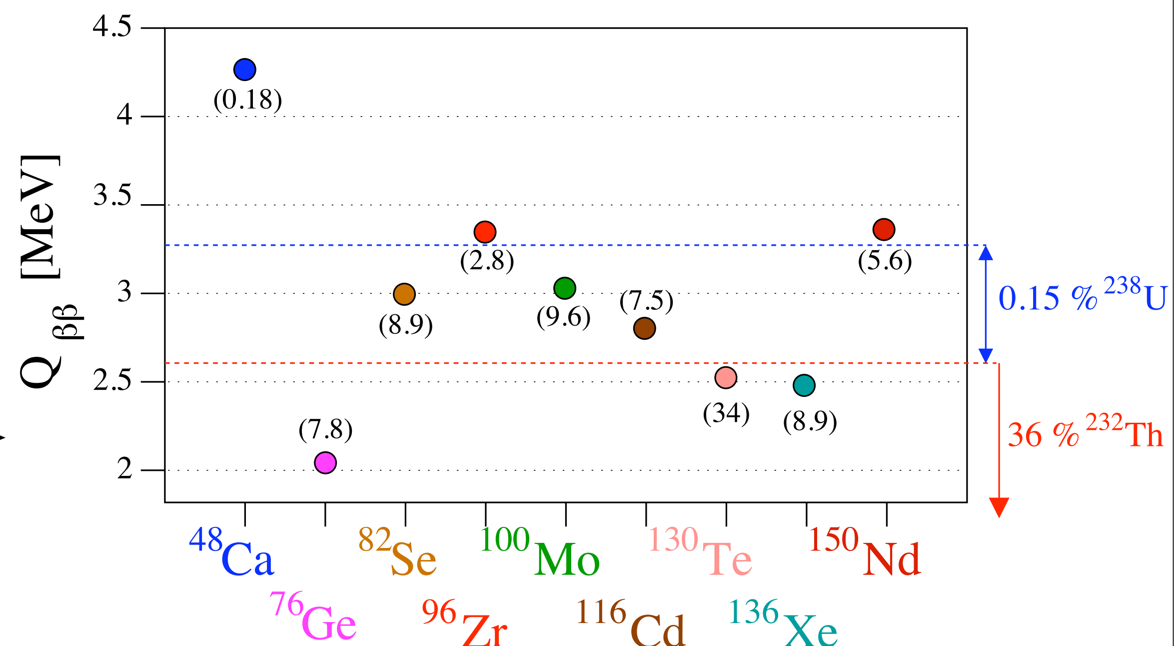
$$m_{\beta\beta} = \cos^2\theta_{13}(m_1\cos^2\theta_{12} + m_2 e^{2i\alpha}\sin^2\theta_{12}) + m_3 e^{2i\beta}\sin^2\theta_{13}$$

The challenge

- Signature: monochromatic line at the Q-value
- $\tau_{0\nu\beta\beta}$ ~$10^{25\sim26}$ y (m_ν^{light}~50 meV)
  - 1 event/year→10^3 moles~O(100kg)



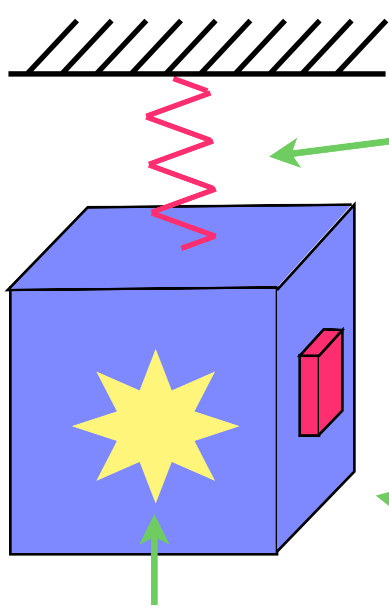
- Background:
  - $\tau_{2\nu\beta\beta}$ ~10^{20} y ($N_{2\nu\beta\beta}/N_{0\nu\beta\beta}$ ~$(\delta E/Q)^6$)
  - Primordials: **U, Th (τ~10^9y)**
  - neutrons & cosmic induced
  - β decay forbidden
  - ⇒ even-even nuclei



CUORICINO

F.Bellini, F.Orio. C.Tomei, M.Vignati

- Particle energy converted into phonons → temperature variation $\Delta T = E/C$
- Need very low heat capacity: crystals (dielectric, diamagnetic) @~10mK → TeO_2 detector = source



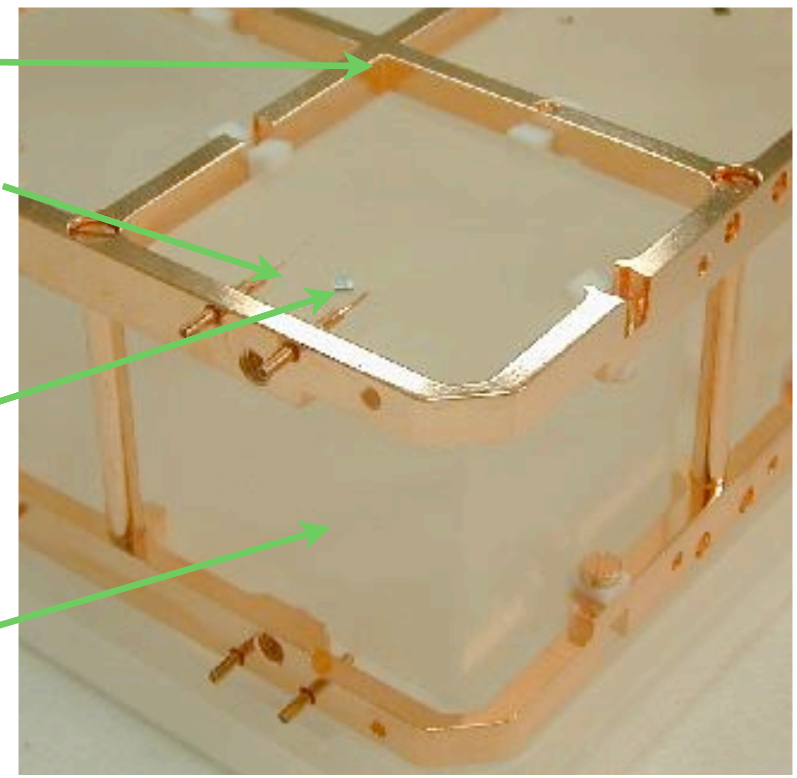
Heat bath

Weak thermal coupling

Thermometer:
NTD Ge thermistor
R ~ 100 MΩ

Absorber Crystal
TeO_2 $C \sim 10^{-9}$ J/K

Energy release



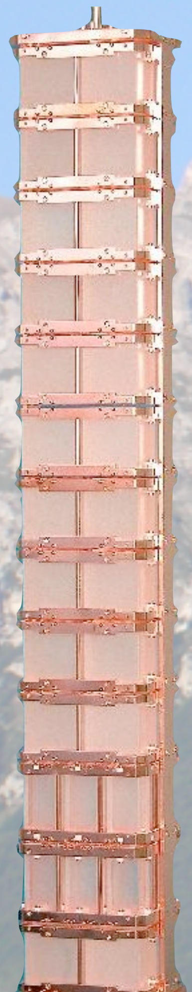
- Detector response in this configuration: ~ 0.2 mK / MeV~0.2 µV/MeV
- FWHM Resolution @0νDBD ~ 0.3%

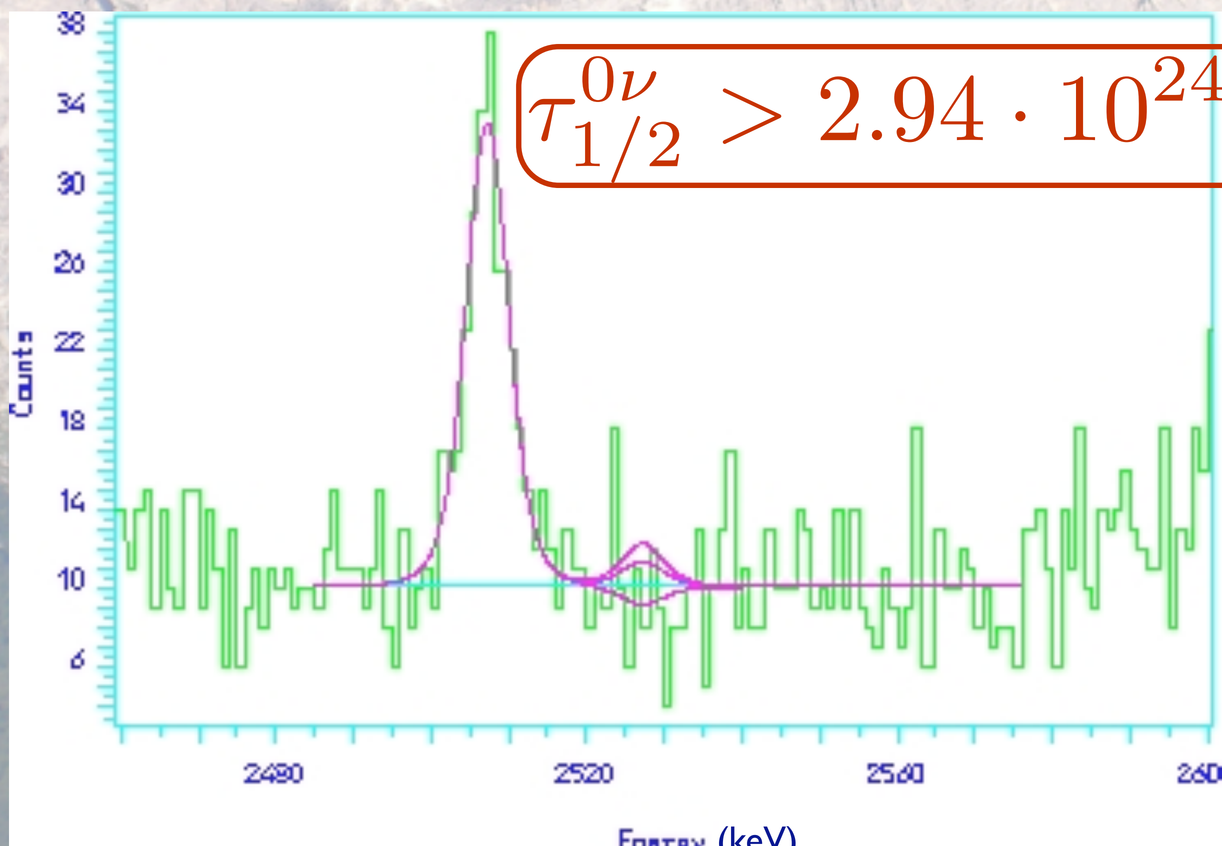
Final (preliminary) Results

Hosted @ Laboratori Nazionali del Gran Sasso, Italy.

Final statistics: $M \cdot t = 18 \text{ kg } ^{130}\text{Te} \cdot \text{y}$

Background level: $b = (0.18 \pm 0.01)\text{counts/keV/kg/y}$

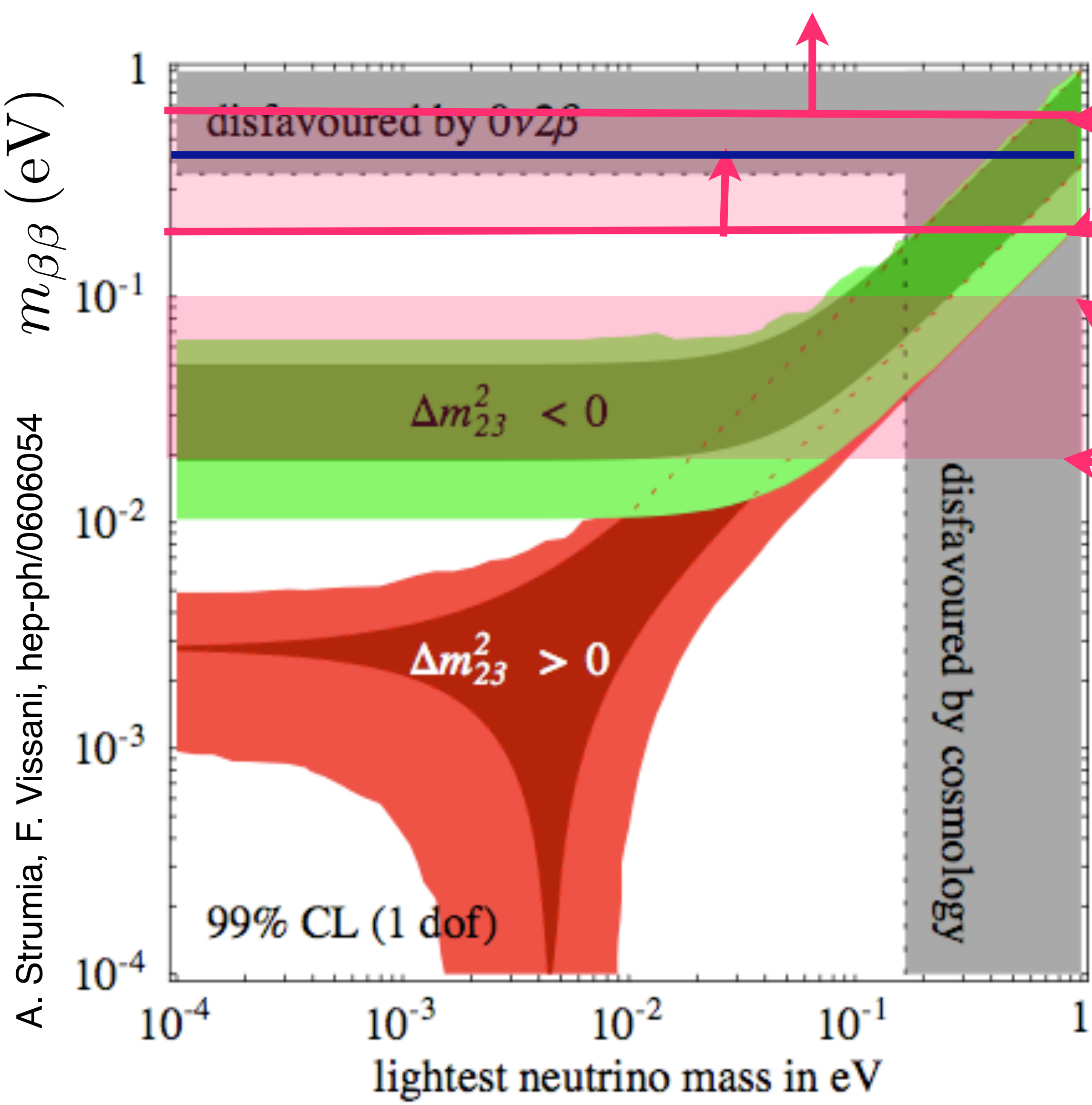




$$\tau^{0\nu}_{1/2} > 2.94 \cdot 10^{24} \text{ y @}90\%CL$$

$0\nu\beta\beta$: where we are & we will be

- Express $m_{\beta\beta}$ as function of measured oscillation parameters and the unknown lightest neutrino mass: $m_{\beta\beta} = f(U_{ek}, m_{lightest}, \Delta m_{12}, \Delta m_{13})$



A. Strumia, F. Vissani, hep-ph/0606054

CUORICINO

$m_{\beta\beta} < 0.20 \div 0.68\,\mathrm{eV}$

CUORE goal:
test inverted hierarchy

$\tau^{0\nu}_{1/2} > 2.1 \cdot 10^{26}\,\mathrm{y}\ @90\%CL$

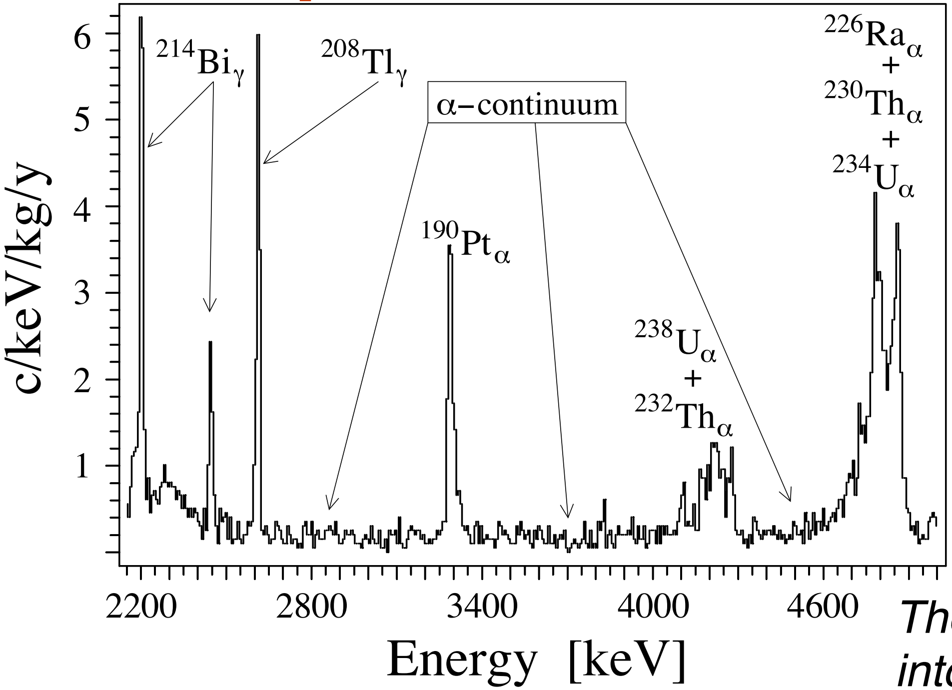
$m_{\beta\beta} < 20 \div 100\,\mathrm{meV}$

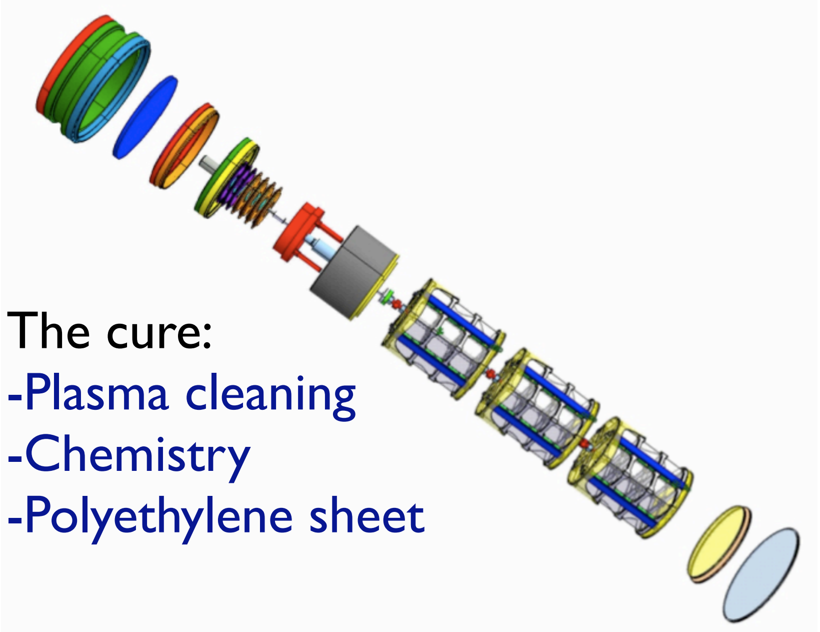
Scaling CUORICINO to CUORE
M = 20 x m
δE = 0.7 x δE
B = b / 20
⇒0.01 counts/keV/kg/y

The way to CUORE

F.Bellini, A.Buccheri, C.Cosmelli, I.Dafinei, R.Faccini, F.Ferroni,C.Gargiulo E.Longo, S.Morganti, F.Orio, V.Pettinacci, C.Tomei, M.Vignati

The problem: α





The cure:
- -Plasma cleaning
- -Chemistry
- -Polyethylene sheet

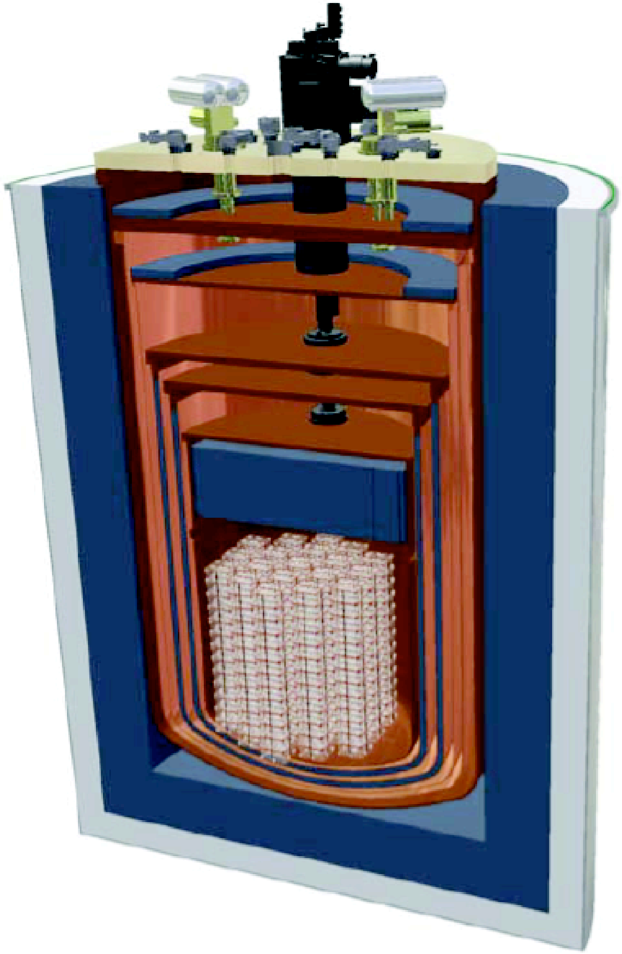
The chosen one will hold the new(56) CUORE crystals into the CUORICINO cryostat and CUORE-0 will start(2010)

Rome activities:
Engineering of CUORE(0) detector construction
Crystal production
Construction/installation/data taking/data analysis
Bolometer response function development
Alternative CUORE calibration system study
Dark matter studies

CUORE and competitors

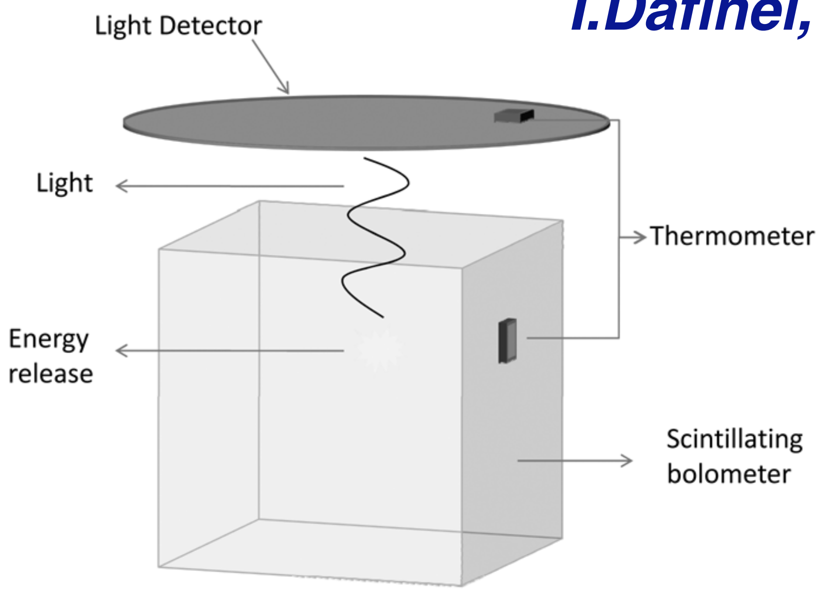
- **CUORE**: 200 kg ^{130}**Te** (2012)
  - **$\tau > 2.1 \cdot 10^{26}$ ⇔ $0.02 < m_\nu < 0.1$ eV**
- **GERDA @LNGS**: naked ^{76}**Ge** in high purified Ar
  - Phase I:15 kg **$\tau > 2 \cdot 10^{25}$ in 1 y** (end 2009)
  - Phase II(III): 40(1000) kg enriched

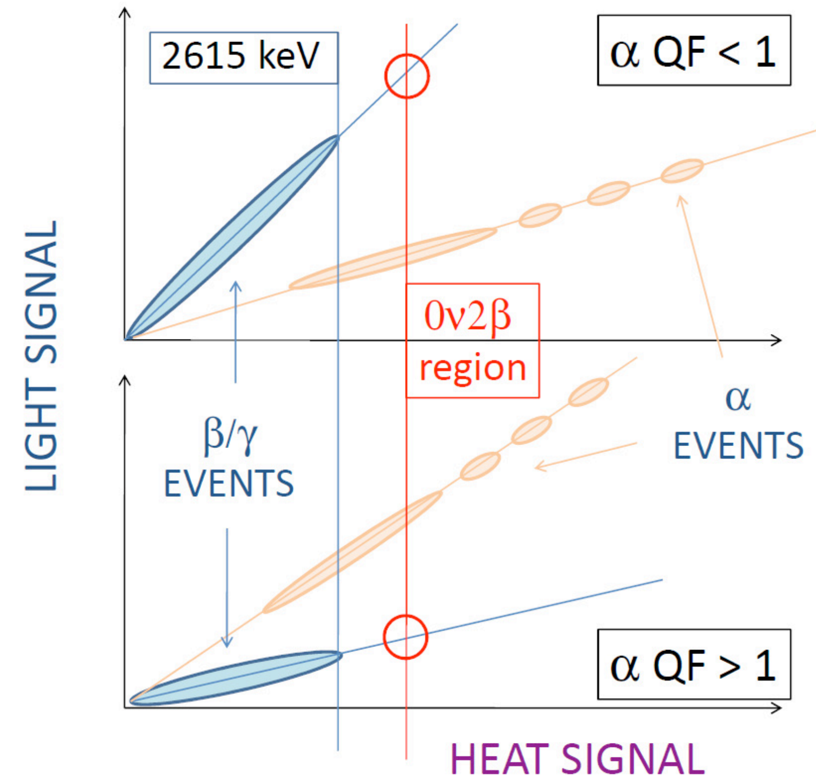
    $\tau > 2 \cdot 10^{26}$ ⇔ $0.07 < m_\nu < 0.3$ eV in 3 y
- **SUPERNEMO(**R&D):improved tracking detectors(2013)
  - 100-20 kg ^{82}**Se** **$\tau > 1\text{-}2 \cdot 10^{26}$ ⇔ $0.04 < m_\nu < 0.1$ eV**
- **EXO:** Liquid enriched ^{136}**Xe** TPC
  - phase I: 200 kg **$\tau > 2 \cdot 10^{25}$ ⇔ $0.1 < m_\nu < 0.2$ eV**
  - phase II: 1 Ton (Ba^{++} tag) **$\tau > 8 \cdot 10^{26}$ ⇔ $0.03 < m_\nu < 0.06$ eV**

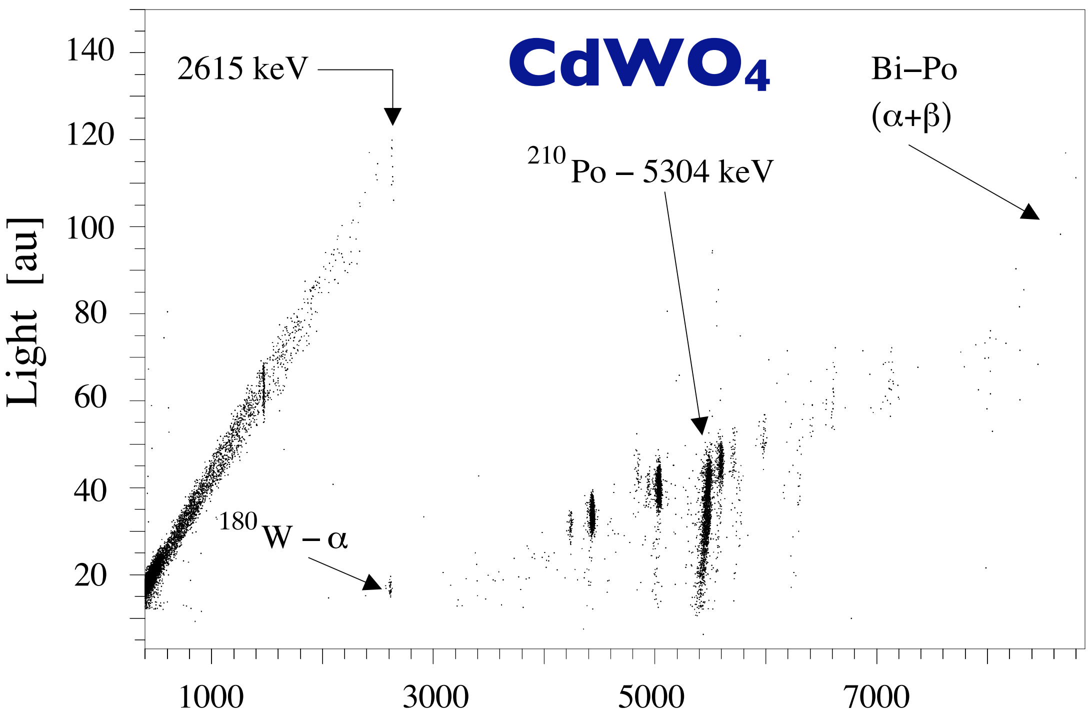


Bolux: double read-out

I.Dafinei, F.Ferroni, F.Orio





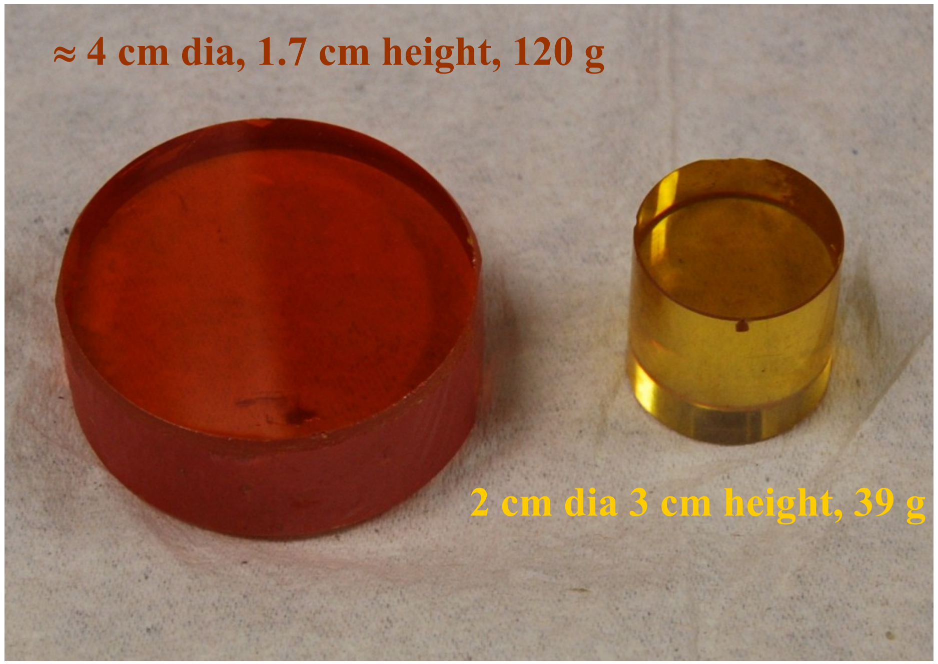


Bolux @ CSN5

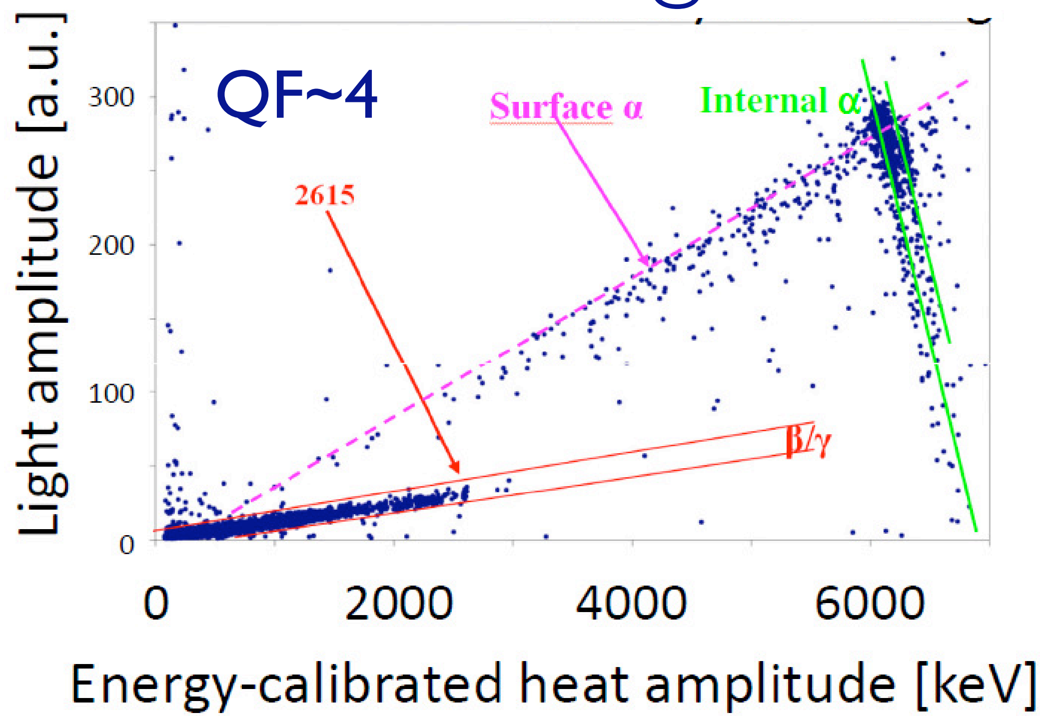
Stefano Pirro @ L.N.G.S.

δE(light detector)~250eV @ 6keV

A promising candidate: ZnSe



Stefano Pirro @ LNGS



Preliminary:
α rejection efficiency ~99%
exp. bkgd~$10^{-3/4}$ counts/keV/kg/y

Rome activities:
-developement and characterization of ZnSe scintillating crystals
-construction and data taking/analysis of scintillating bolometers @LNGS

Conclusions

- **Neutrino physics is one of the leading field in HEP today**

- **Oscillation**:
  - 2009: the generation of experiment optimize to detect θ_{13} is starting:

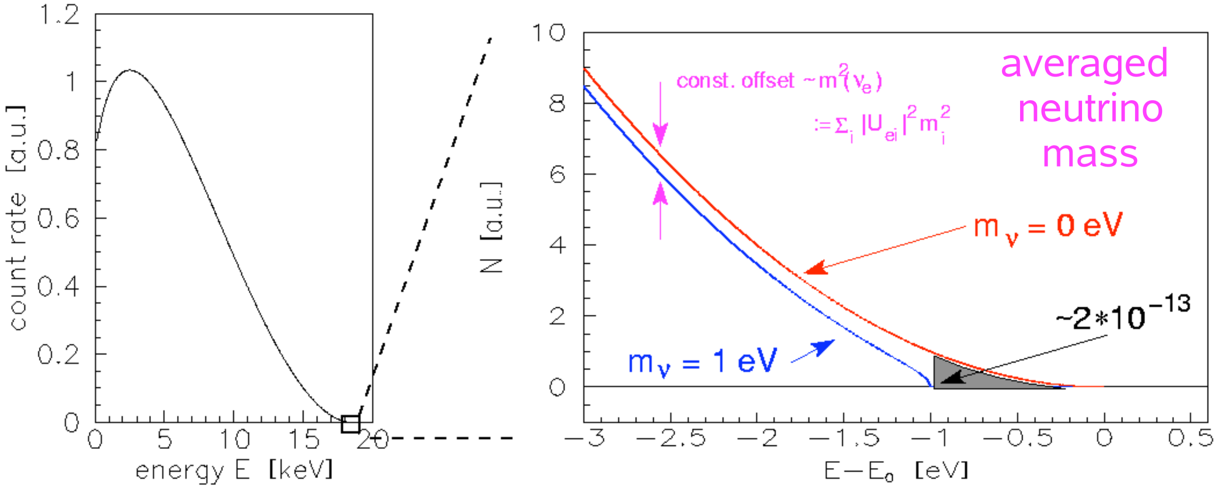
    Double Chooz, T2K, (soon after Daya Bay, then NOvA)
  - Neutrino oscillation future dictated by θ_{13} value
  - Accelerator neutrino beam might have a bright future

- **Dirac or Majorana** nature is a fundamental question that needs to be answered
  - The second generation experiment could win or might show the path to victory
  - It could represent the only chance to give a measure of the neutrino mass

Thanks to F.Ferroni, P.Loverre,L.Ludovici, S.Pirro, G.Rosa

m_ν from beta decay: MARE

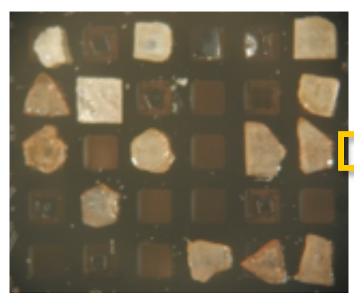
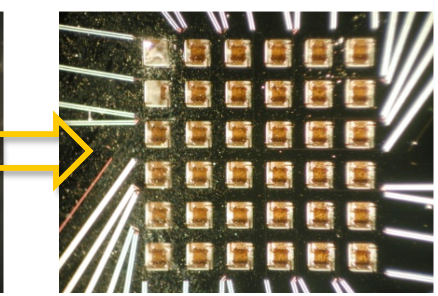
P. De Bernardis, M.Calvo, S.Masi



$$m(\nu_e) = \sqrt{\sum_i |U_{ei}^2| \cdot m_i^2}$$

Previous results: m_ν<15 eV

- **Rhenium Bolometer array:** $^{187}Re \rightarrow {}^{187}Os\ e^-\ \bar{\nu}$ (Q=2.47 keV, $\tau_{1/2}$~43.2 Gy)
- Phase I: ΔE~5eV, Δt~50μs ⇒ m_ν~0.2 eV

Rome R&D: Kinetic Inductance detector

- Phase II: magnetic micro-calorimeters R&D: ΔE~5eV Δt~1μs ⇒ m_ν~0.2 eV
- KATRIN: the ultimate spectrometer m_ν~0.2 eV