Neutrino experiments: recent results and plans

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Conseil Scientifique de l'IRFU
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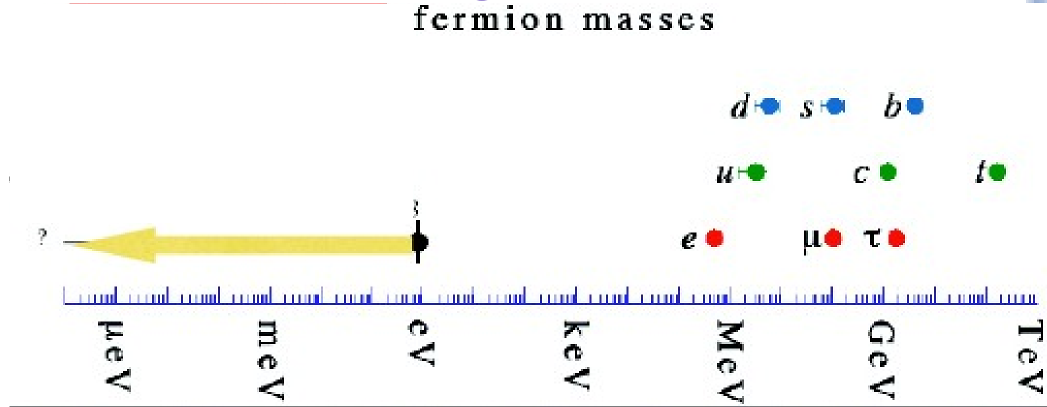
Neutrino physics: surprising results

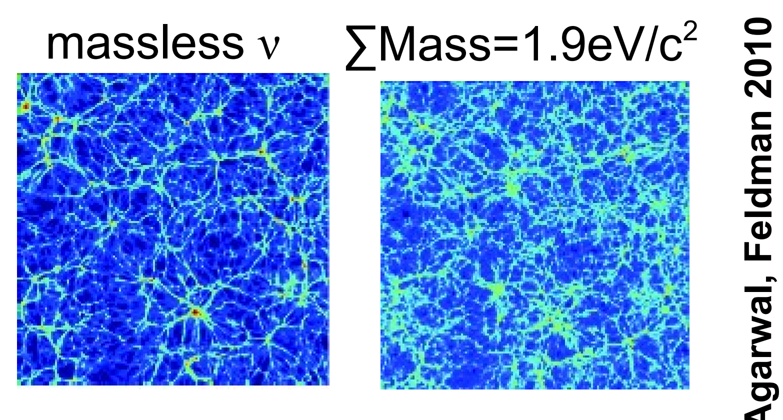
- The unbearable lightness of neutrino masses begs a compelling explanation



- The neutrino mixing angles are large, at variance with the quark mixing angles: large CP violation effects are allowed

$$V_{PMNS} = \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \quad V_{CKM} = \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

- Neutrinos play a fundamental role in the evolution of the Universe. Can they explain matter-antimatter asymmetry ?



Baryon density

Neutrino oscillations

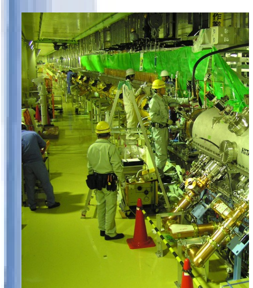
$$\begin{pmatrix}\nu_e \\ \nu_\mu\end{pmatrix} = \begin{pmatrix}\cos\theta & \sin\theta \\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\nu_1 \\ \nu_2\end{pmatrix}$$

If neutrino flavor eigenstates are different from mass eigenstates, propagation induces a phase shift with the appearance of a new flavor

$\nu_\mu = -\sin\theta\, \nu_1 + \cos\theta\, \nu_2$

Propagation

Source



W

ν_μ

μ

$\nu_1 \rightarrow \exp(-ip_1x)\, \nu_1$

$\nu_2 \rightarrow \exp(-ip_2x)\, \nu_2$

$\Delta\varphi = \Delta m^2 L/(4E)$

ν_e

e

Detector

L

$\text{Prob}(\nu_\mu \rightarrow \nu_e) = \sin^2(2\theta)\, \sin^2(\Delta m^2 L/4E)$

This is a simplified two neutrino scenario

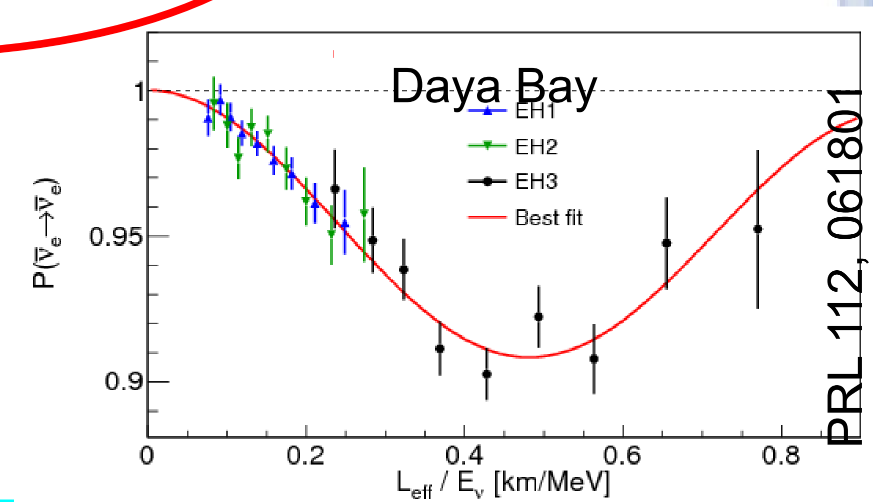
The Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix

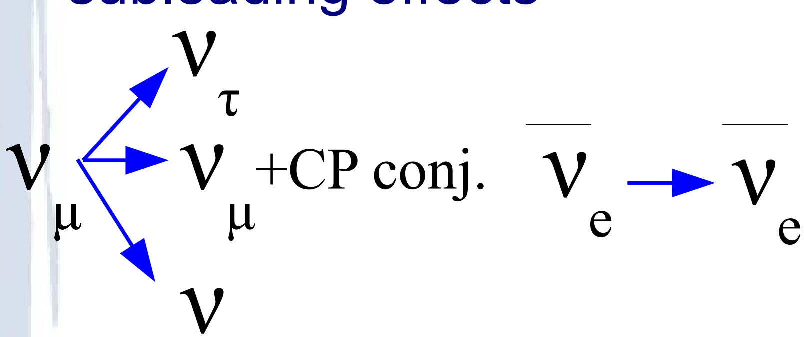
$s_{ij}=\sin\theta_{ij}$

This talk

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}U_{e1}&U_{e2}&U_{e3}\\ U_{\mu1}&U_{\mu2}&U_{\mu3}\\ U_{\tau1}&U_{\tau2}&U_{\tau3}\end{pmatrix} = \begin{pmatrix}1&0&0\\ 0&c_{23}&s_{23}\\ 0&-s_{23}&c_{23}\end{pmatrix}\begin{pmatrix}c_{13}&0&s_{13}e^{-i\delta}\\ 0&1&0\\ -s_{13}e^{i\delta}&0&c_{13}\end{pmatrix}\begin{pmatrix}c_{12}&s_{12}&0\\ -s_{12}&c_{12}&0\\ 0&0&0\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

- The oscillation phenomena have been convincingly observed using solar, atmospheric, reactor and accelerator neutrinos, establishing the three neutrino SM paradigm
- Currently unveiling three-neutrino subleading effects





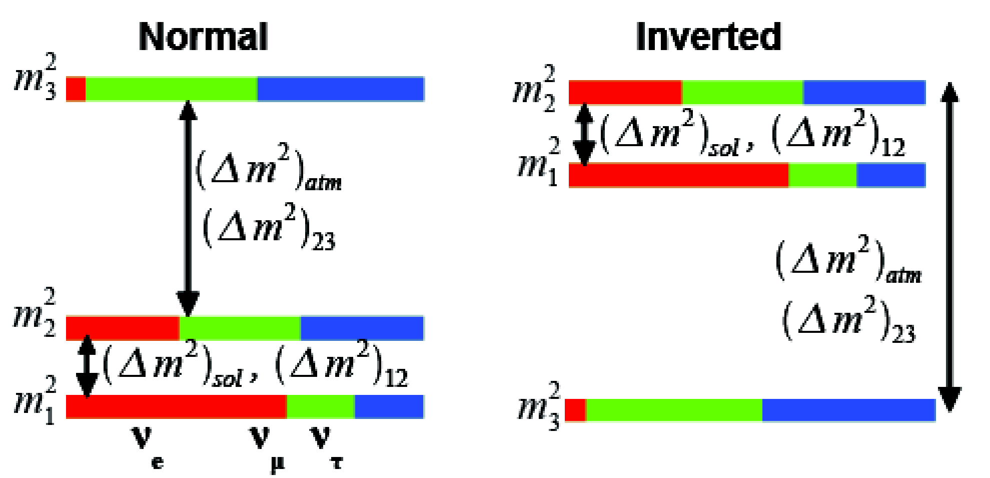
Parameter	Value	Precision (%)
Δm^2_{21}	7.5 10^{-5} eV^2	2.6
θ_{12}	34°	5.4
Δm^2_{32}	2.4 10^{-3} eV^2	2.6
θ_{23}	42°	~10
θ_{13}	9°	8.5

Capozzi et al.
ArXiv:1312.2878
Talk by M. Tortola

Next steps in neutrino oscillation studies

1) Is θ_{23} =45°? which octant ?
2) Determine the mass hierarchy
3) Measure the CP violation parameter δ
4) Precision tests of the PMNS paradigm (ideally at the % level, as for the CKM matrix)
5) Confirm/disprove the short baseline anomalies

1) Is there a symmetry between ν_μ and ν_τ ?
2) Help model builders. Impact on cosmology.
3) Link with leptogenesis. Are we born out of (heavy) neutrinos ?
4) How different are neutrinos ?
5) Possible existence of new neutrino states at the eV scale



Neutrino oscillations : observables

Reactor experiments

$$\bar{\nu}_e \longrightarrow \bar{\nu}_e$$

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

$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \left(\cos^2\theta_{12} \sin^2 \frac{\Delta m^2_{31} L}{4E} + \sin^2\theta_{12} \sin^2 \frac{\Delta m^2_{32} L}{4E}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2 \frac{\Delta m^2_{21} L}{4E}$$

Accelerator experiments

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

$$P(\nu_\mu \to \nu_\mu) = 1 - (\cos^4\theta_{13} \sin^2 2\theta_{23} - \sin^2 2\theta_{13} \sin^2\theta_{23}) \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$

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

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) - \frac{\sin 2\theta_{12} \sin 2\theta_{23}}{2 \sin\theta_{13}} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right) \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) \sin\delta_{CP}$$

Disappearance channel : sensitivity to θ_{23} and (subleading) to the octant

Appearance channel : sensitivity to θ_{13} and (subleading) to the CP phase

THE DOUBLE CHOOZ EXPERIMENT

Near detector site
Distance: <L>=410m
~10 t of Gd-doped LS
~300 ν/day
Start end of 2014

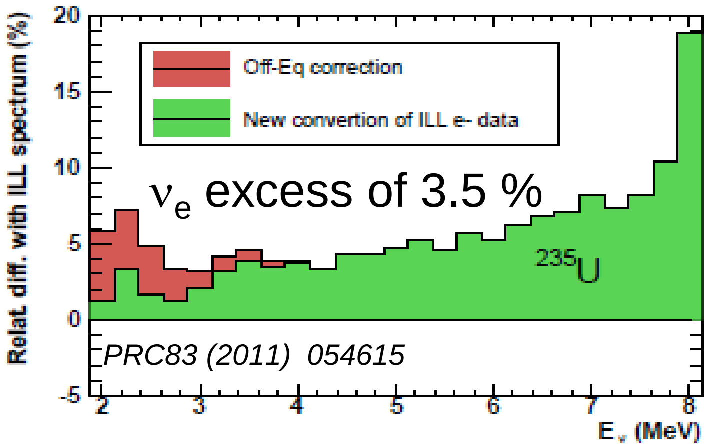
Far detector site
Distance: <L>=1067m
~10 t of Gd-doped LS
~40 ν/day
Start in 2011

Two identical detectors based on $\bar{\nu}_e + p \rightarrow e^+ + n$ detection in Gd-doped LS

Θ13 RESULT IN « SINGLE-DETECTOR » PHASE

First evidence for $\theta_{13} \neq 0$ (95%C.L.)

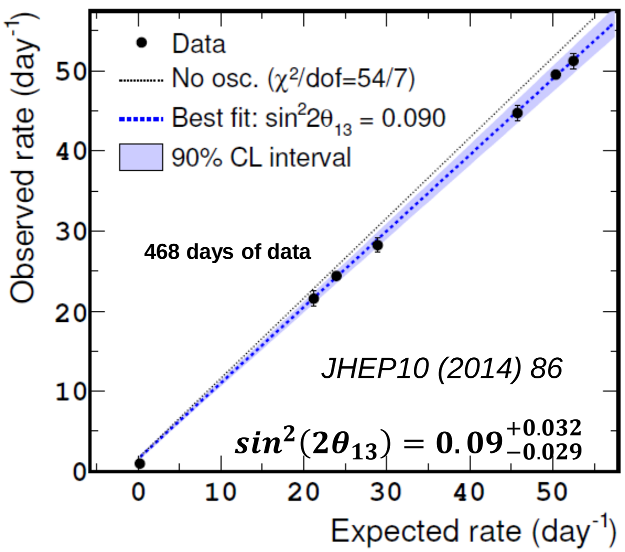
Phys. Rev. Letter 108 (2012) 131801

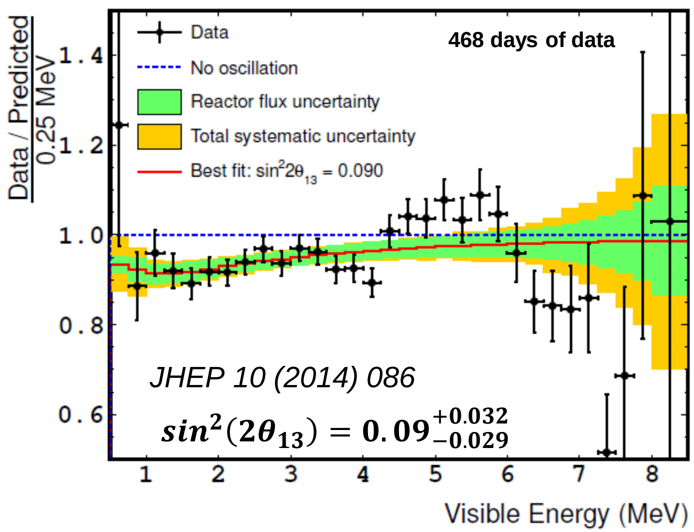


Main Irfu contributions to the analysis

- Reactor simulations: from β-decay to detection
  - ▸ reference rate and energy spectra
- Energy scale, efficiency, background studies

Rate + Shape analysis





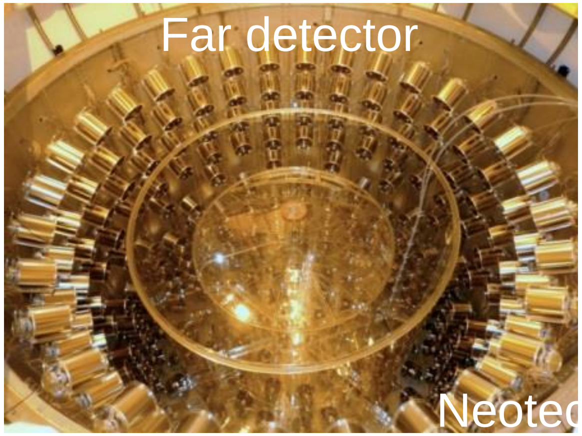
➢ Burning question: origin of the bump above 5 MeV ?

INVOLVMENT OF IRFU IN DOUBLE CHOOZ

Irfu initiated the project in 2002

Global responsabilities in the project
(SPP-SPhN-SIS-SEDI)

- **Project Management (co-project owner for near lab)**
- **On-site integration**
- Coordination of mechanic, liquid analysis
- Responsabilities on acrylic vessels, radiopurities, target mass measurement, safety files
- Analysis coordination for the first data release
- Coordination of the reading comitee



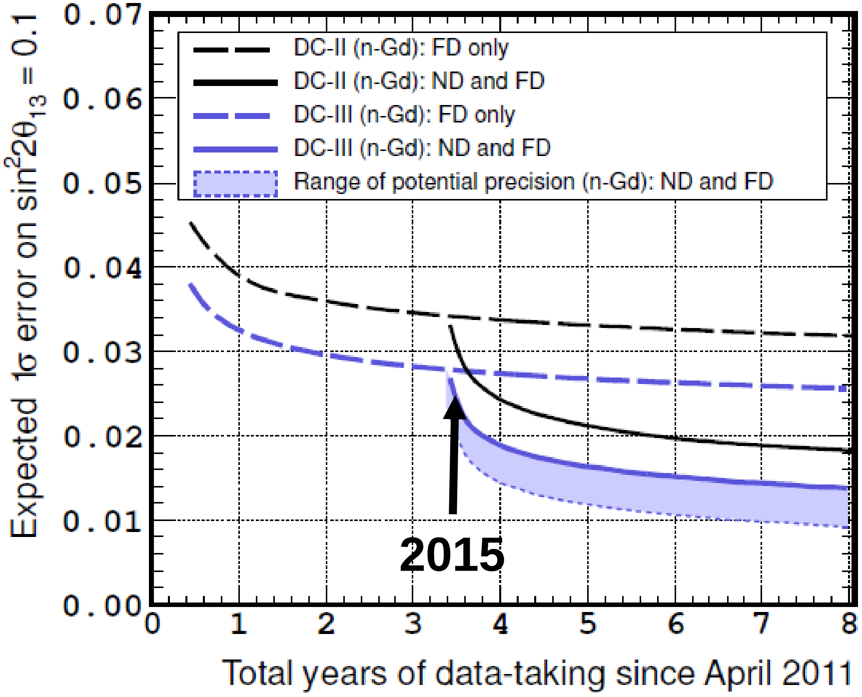
NEAR FUTURE: 2015-2019

- Near detector in operation since christmas 2014

- Analysis in rate and shape
  PRD86 (2012) 052008
  PRD87 (2013) 011102(R)
  PLB735 (2014) 51
  JHEP10 (2014) 86
  ▸ control of systematics

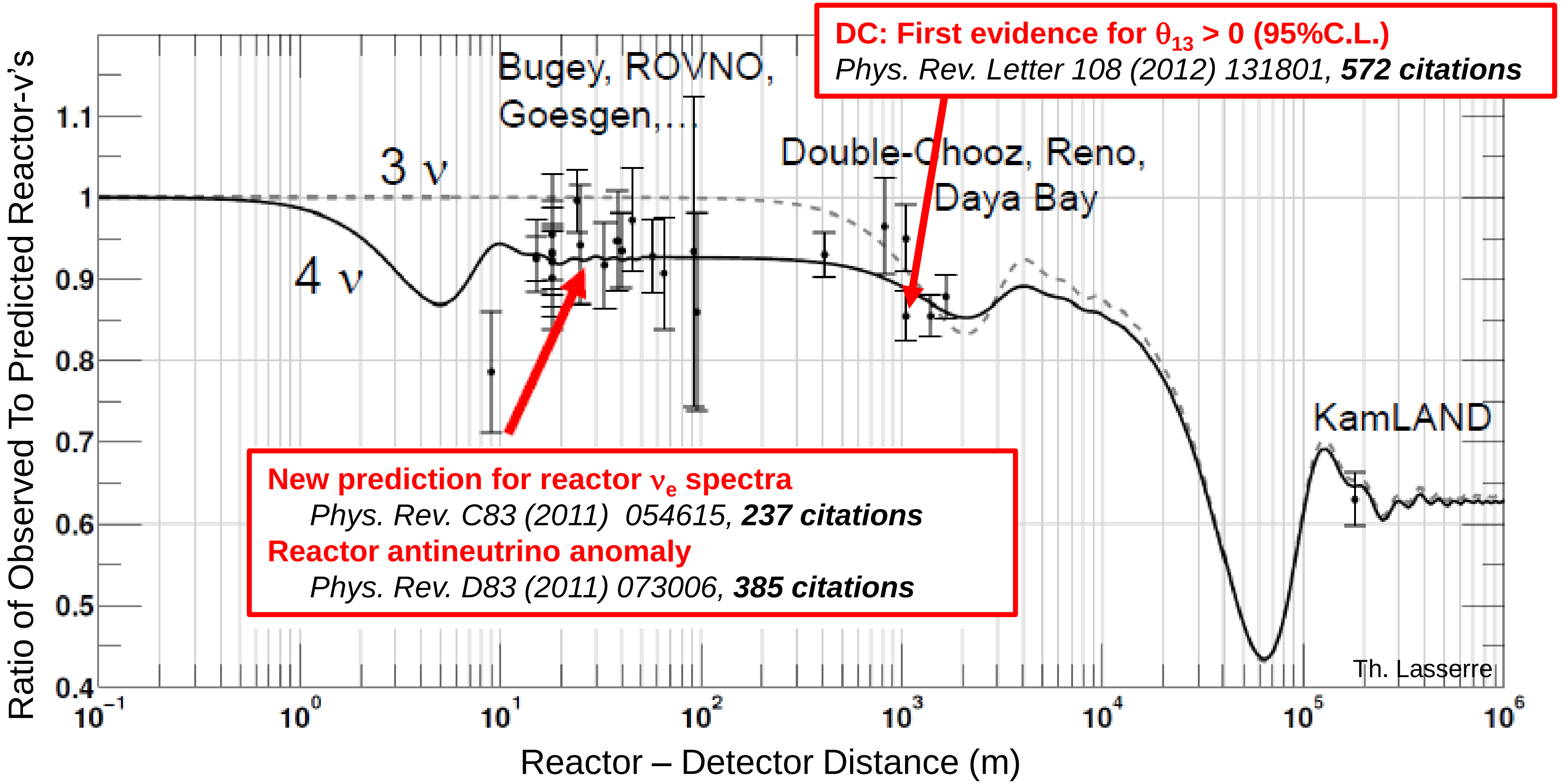
- OFF-reactors measurement
  ▸ unique background measure
  PRD87 (2013) 011102(R)

- Analysis with capture on H
  PLB723 (2013) 66
  ▸ increase the fiducial volume
  ▸ independent data sample



➢ $\sin^2(2\theta_{13})$ measured at the 10% level or even better (dominated by statistic)
➢ constraining data for nuclear β-decay modelling

STATE OF THE ART



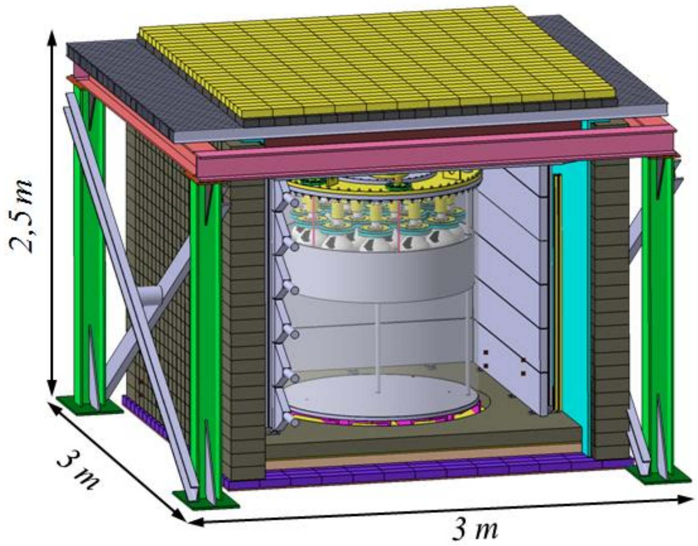
- Best measurement from Daya Bay: $\sin^2(2\theta_{13})=0.09^{+0.008}_{-0.009}$
  - ➢ era of high precision measurement
- Burning question: origin of the deficit at low range ?
  - ➢ new short-range oscillation ?

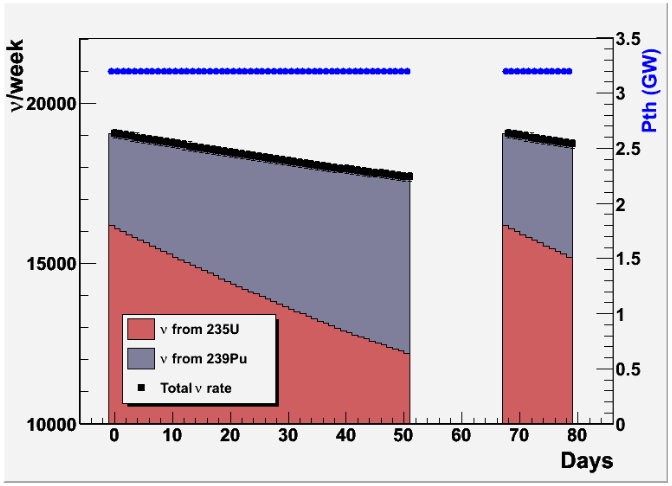
NUCIFER @ OSIRIS 2006-2015

Nucifer detector (coll. Irfu, CEA/DAM, Subatech)

Demonstrate the ability of LS technology for safeguard applications

- 1 m^3 detector based on commercial components
- 7m from a $70MW_{th}$ "pool type" OSIRIS reactor.
- Major challenge: the high level of background
  ► heavy external shielding (Pb + polyethylen)





Simulation of a 1m^3 neutrino detector at 25 m distance from a 3 GW reactor core

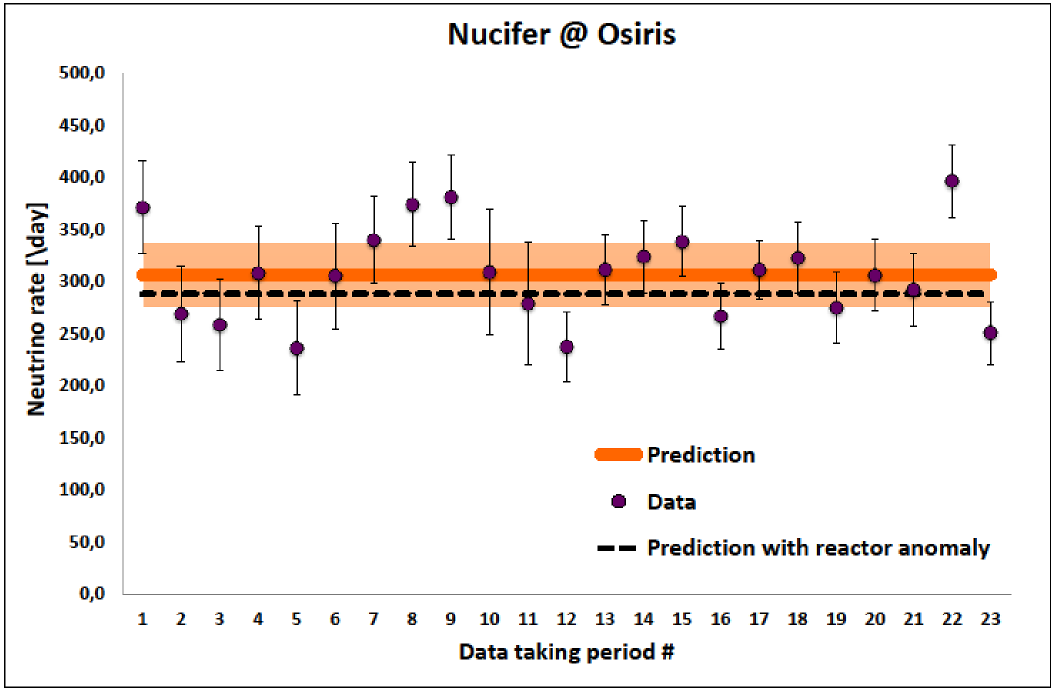
Develop detection technology for reactor monitoring

IAEA interest → working group at IAEA

- Very strong tamper resistance
- Real-time information on isotopic fission rates:
  - ON/OFF periods
  - power monitoring ?
  - fuel composition evolutions ?
- Can be operated remotely
- Non-intrusive and continuous acquisition

NEUTRINO-METRY (PRELIMINARY)

105 days of data taking from May 2013 to December 2014



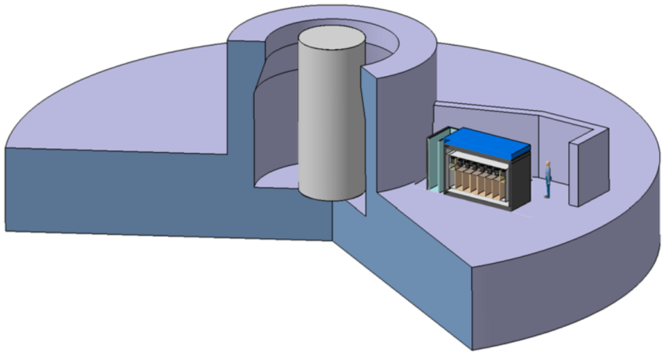
Observed rate:
306 ± 9 ν/day (only stat)

Expected rate:
307 ± 32 ν/day (with syst)

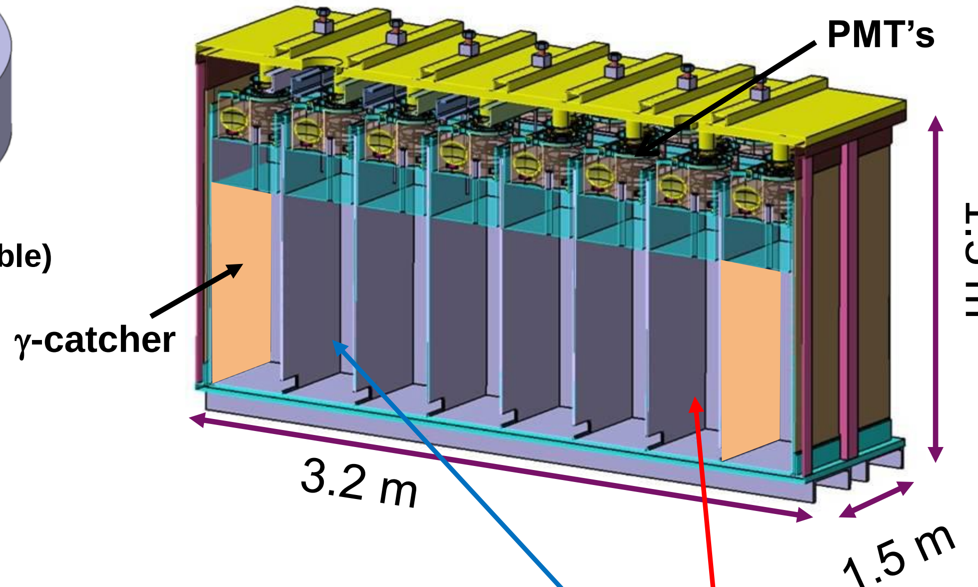
- Nucifer shows a very good reliability and measure 300 ν_e/day despite the high level of background at the OSIRIS site
- After one year of data taking should confirm (or not) the reactor neutrino anomaly
  ► ongoing effort to reduce the systematics

STEREO @ ILL 2013-2018

Collab.: Irfu, LPSC, LAPP, MPIK, Univ. Rabat

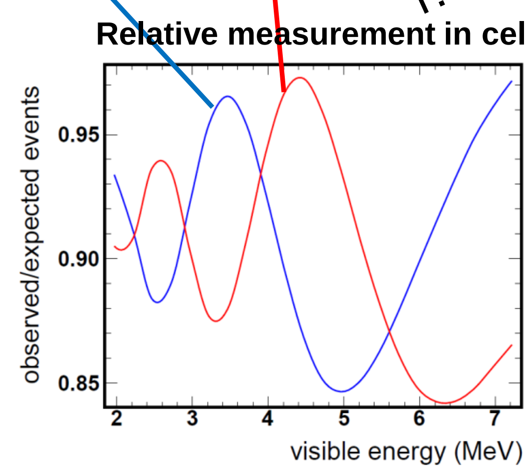


[8.5-11] m from the core of the HFR ILL (Grenoble)



Irfu responsabilities
(SPhN-SEDI-SIS)

- Spokesperson
- Project management
- Detector development
- Reactor simulation



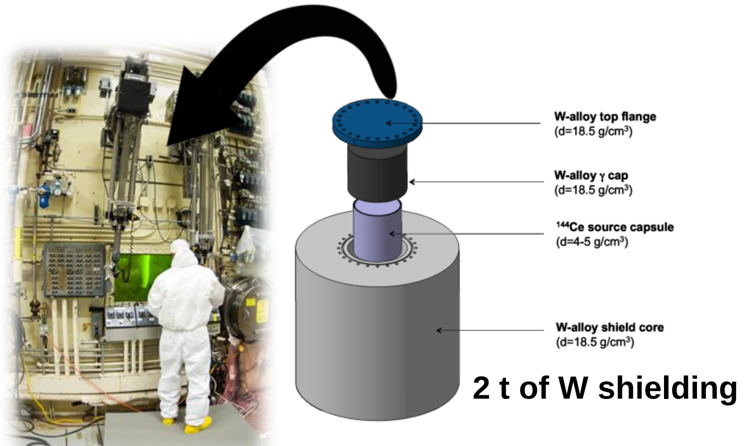
- ➢ Test of a cell prototype in progress
- ➢ Construction of the detector in 2015
- ➢ Data taking in 2016 for 2 years

CE-SOX EXPERIMENT 2013-2018

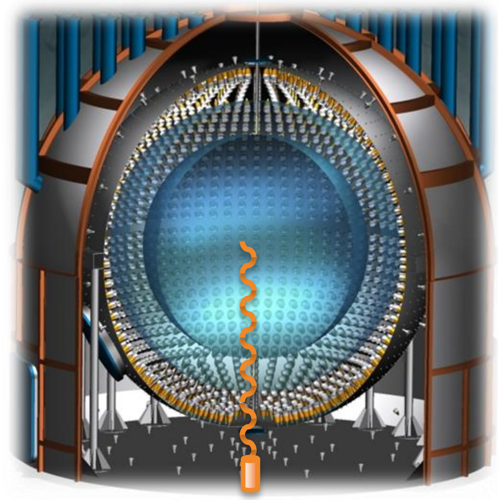
Collab.: Irfu/DEN/SPR/LNHB
Borexino collaboration + Hawaii Univ

- 4 PBq of ^{144}Ce-^{144}Pr (CeO) source
- Production at Mayak Facility:
  - Standard reprocessing of spent fuel
  - Ce extraction through displacement chromatography
- Project management of the source (SPP-SEDI-SIS)
  fabrication, transport, characterisation

➢ Characterisation of Ce samples in progress
➢ Fabrication of the source and transport in 2015
➢ Data taking in 2016 for 1.5 year

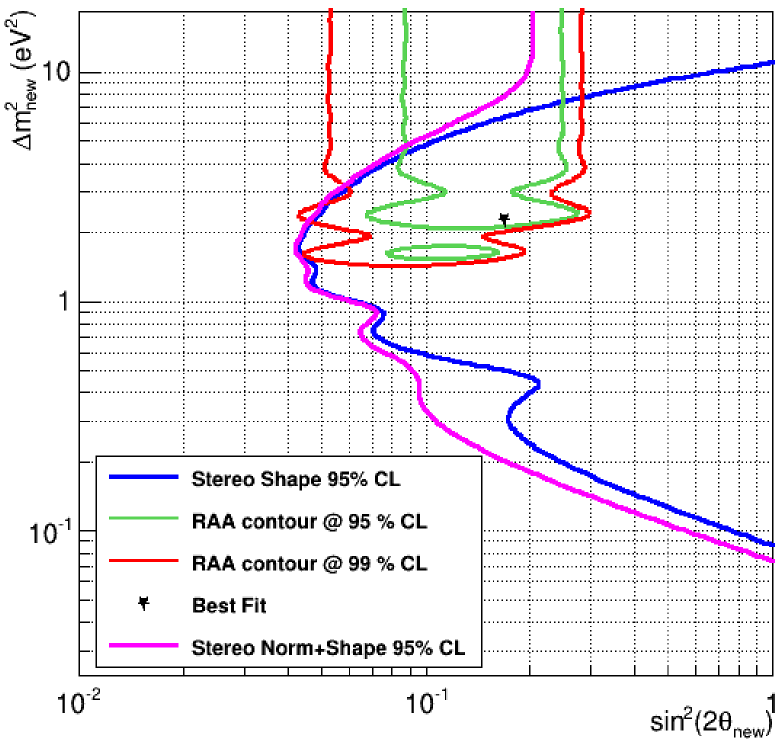


Handling inside hot cell at Mayak (Russia)

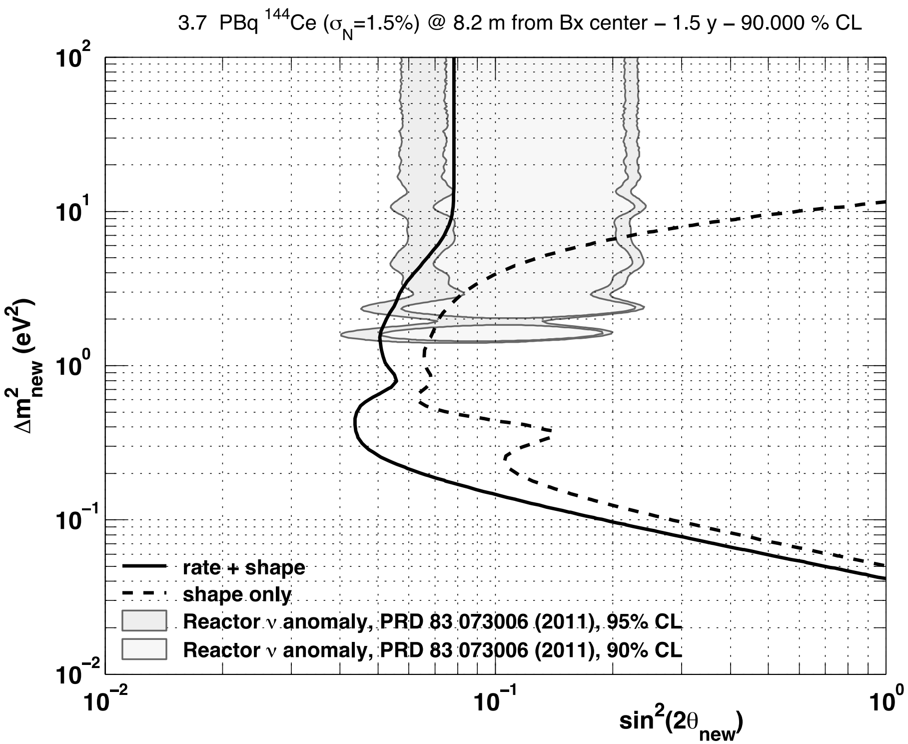

8.25 m from the Borexino center

EXPECTED SENSITIVITIES

Stereo

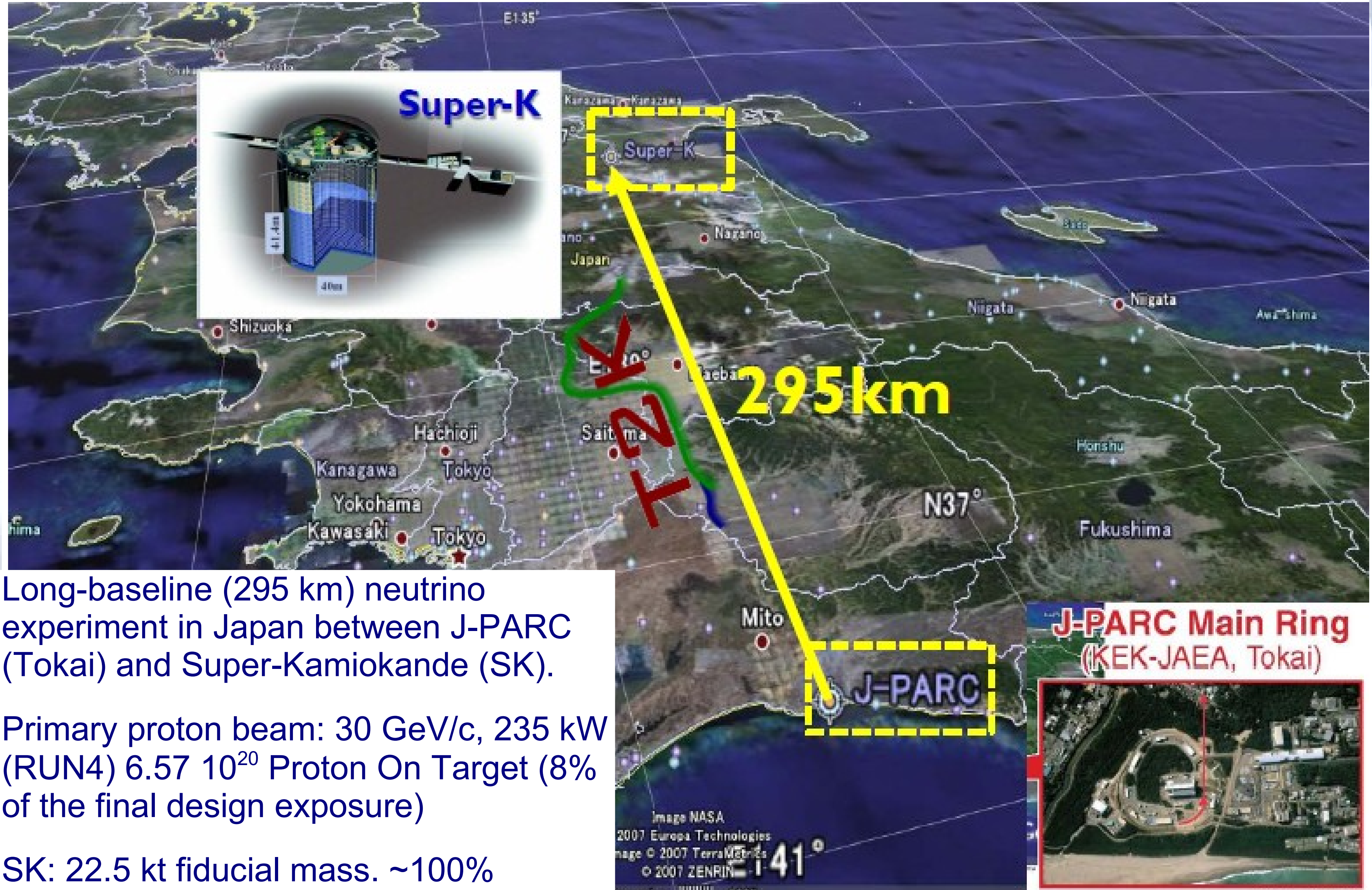


Ce-Sox



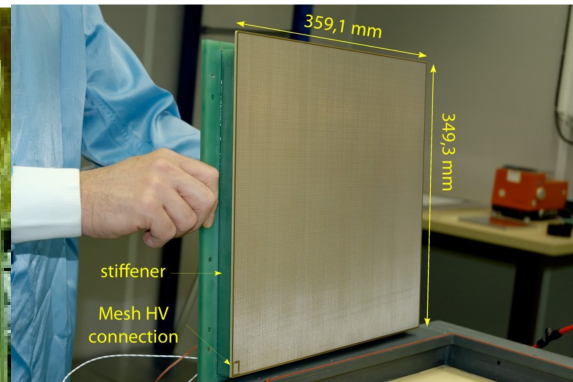
All the proposed projects cover the anomaly region with $\Delta m^2 \geq 0.5$ eV^2, $\sin^2(2\theta) \geq 0.1$

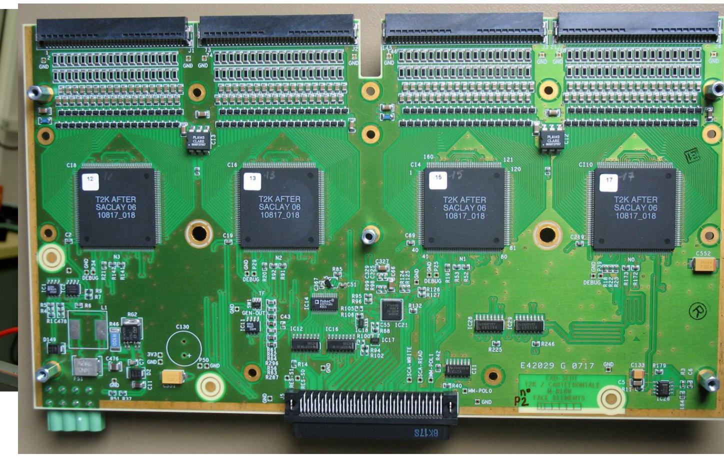
The Tokai to Kamioka (T2K) experiment



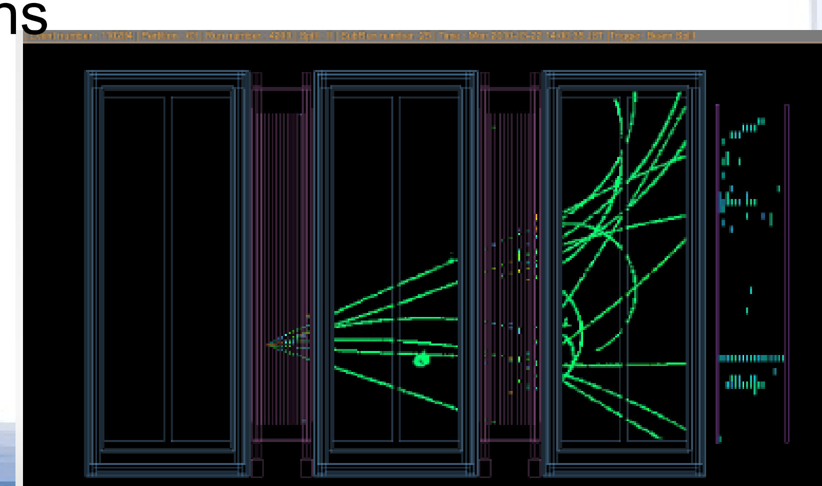
- Long-baseline (295 km) neutrino experiment in Japan between J-PARC (Tokai) and Super-Kamiokande (SK).
- Primary proton beam: 30 GeV/c, 235 kW (RUN4) 6.57 10^{20} Proton On Target (8% of the final design exposure)
- SK: 22.5 kt fiducial mass. ~100% livetime

The first large Micromegas TPC



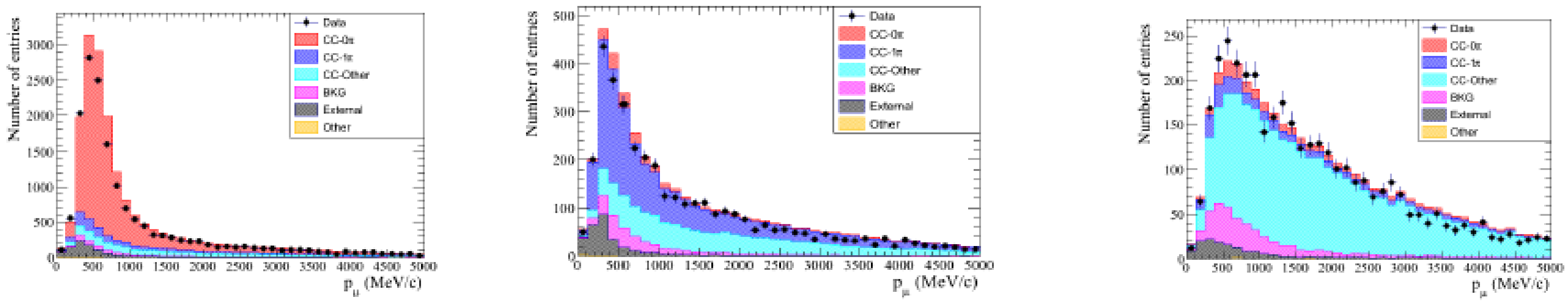


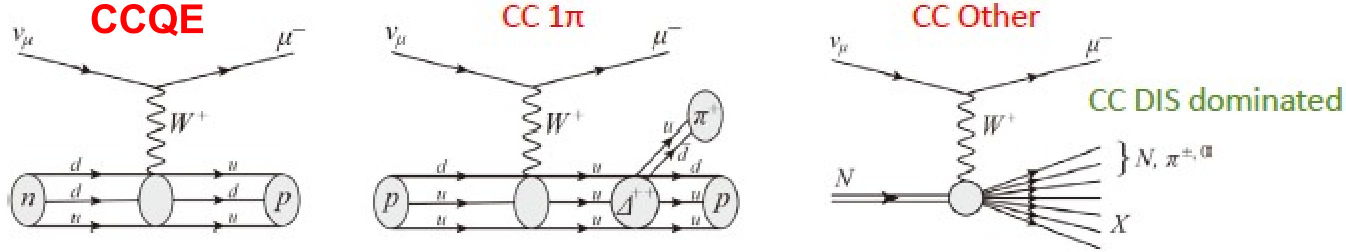
- Three large TPC for T2K near detector
- The first large TPC using MPGD
- ~9 m**2 equipped with bulk Micromegas detectors, large effort by IRFU/SEDI-SPP
- Playing a key role in the study of the neutrino flux and interactions



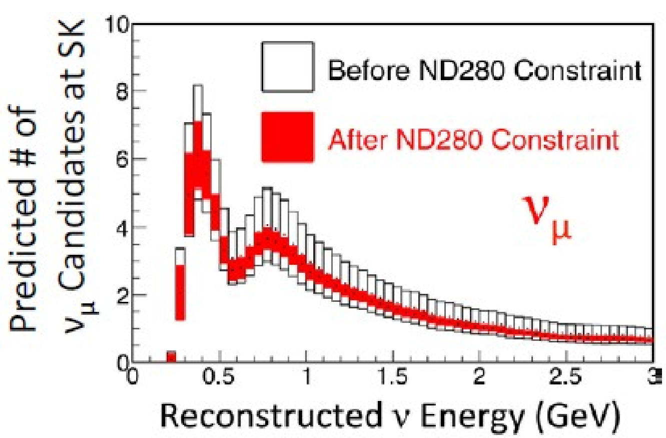
72 Micromegas and 120k channels functioning flawlessly since 2009

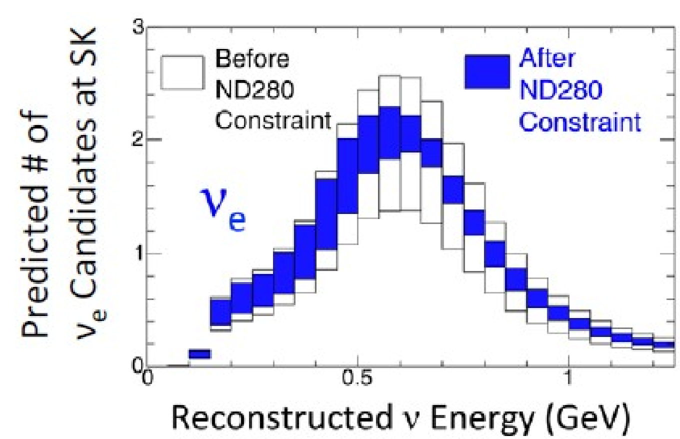
T2K Near detector constraint





Flux and cross-section systematic uncertainty on N_{SK} significantly reduced to ~7%



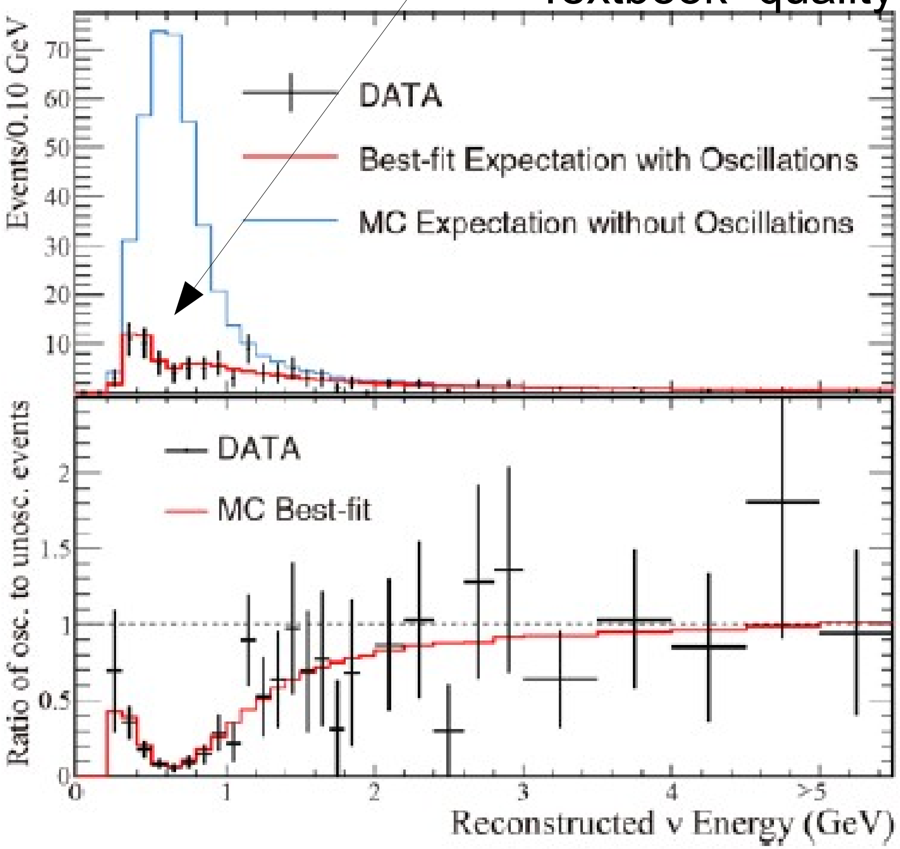


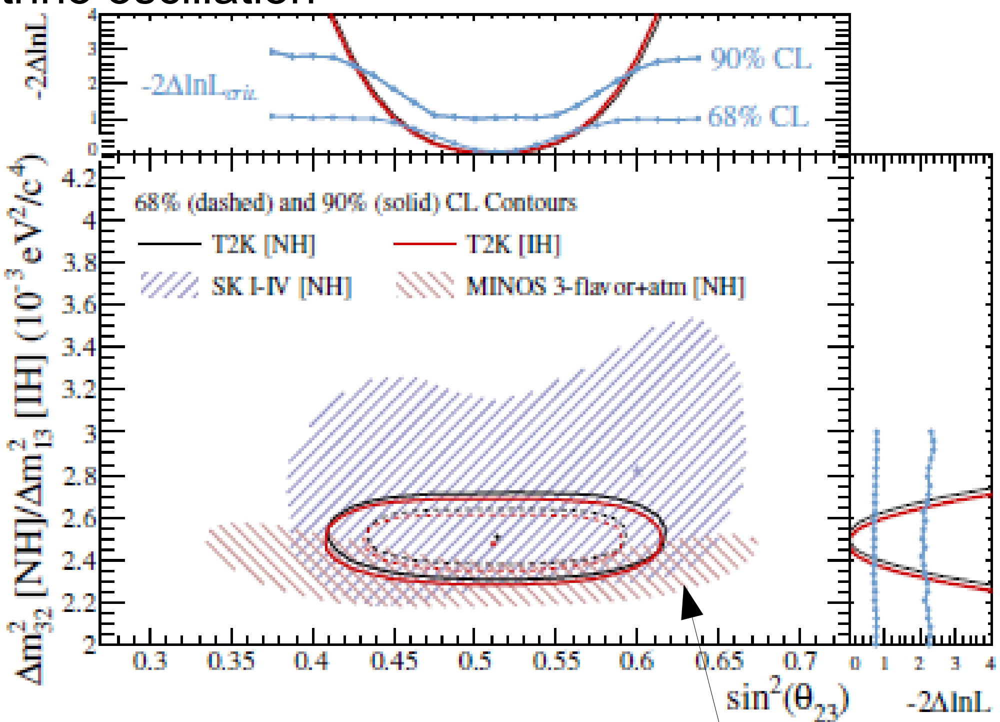
$\nu_\mu \longrightarrow \nu_\mu$

Phys. Rev. Lett. 112, 181801 (2014)

T2K ν_μ disappearance measurement

"Textbook" quality neutrino oscillation





Notice recent MINOS 3-flavor result

Oscillation parameters		Best-fit value
NH	$\sin^2(\theta_{23})$	$0.514^{+0.055}_{-0.056}$
	Δm^2_{32} (10^{-3} eV^2)	2.51 ± 0.10
IH	$\sin^2(\theta_{23})$	0.511 ± 0.055
	Δm^2_{13} (10^{-3} eV^2)	2.48 ± 0.10

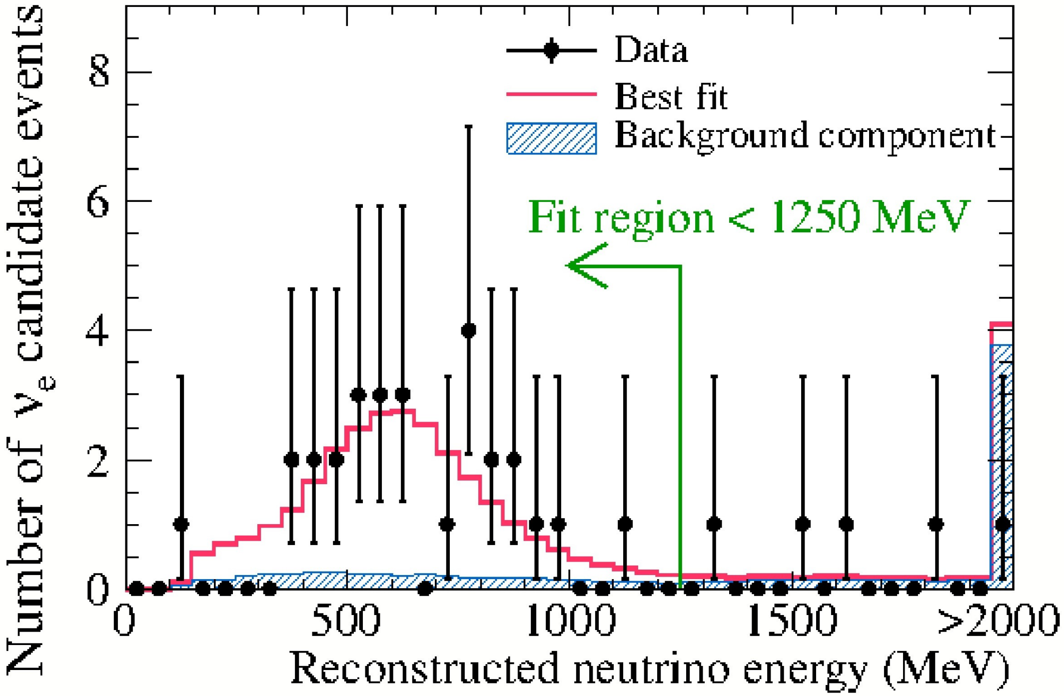
N_{obs} = 120

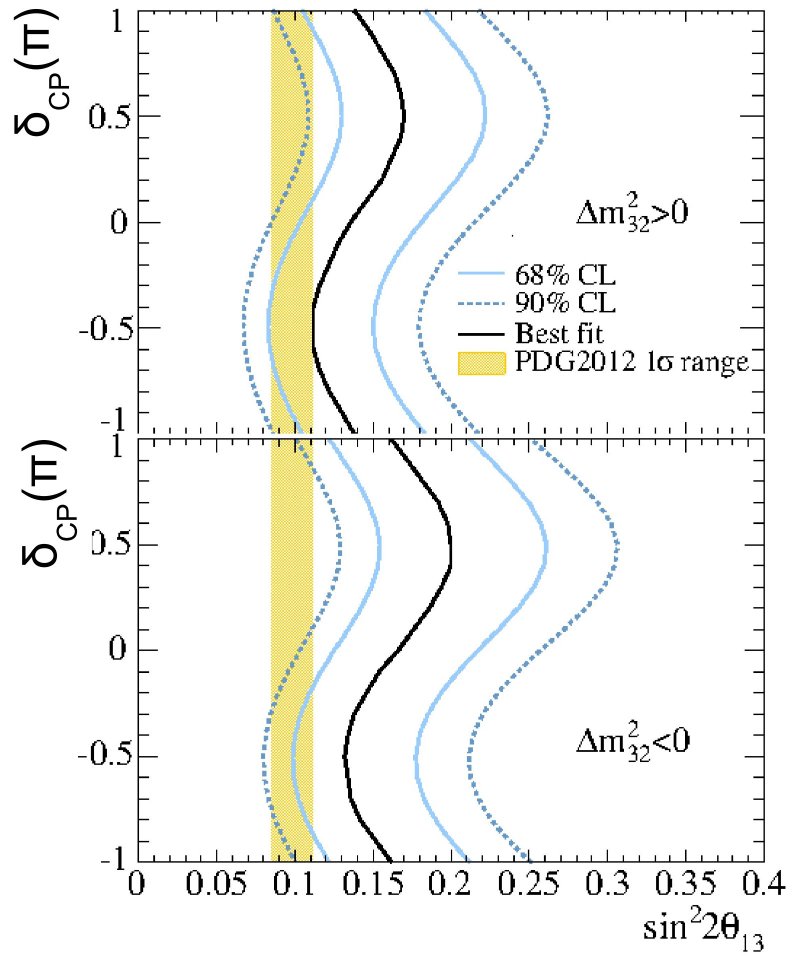
N_{exp} (no osc) = 446±23(syst.)

Data favor maximum disappearance.

Phys. Rev. Lett. 112, 061802 (2014)

T2K observation of $\nu_\mu \rightarrow \nu_e$ appearance

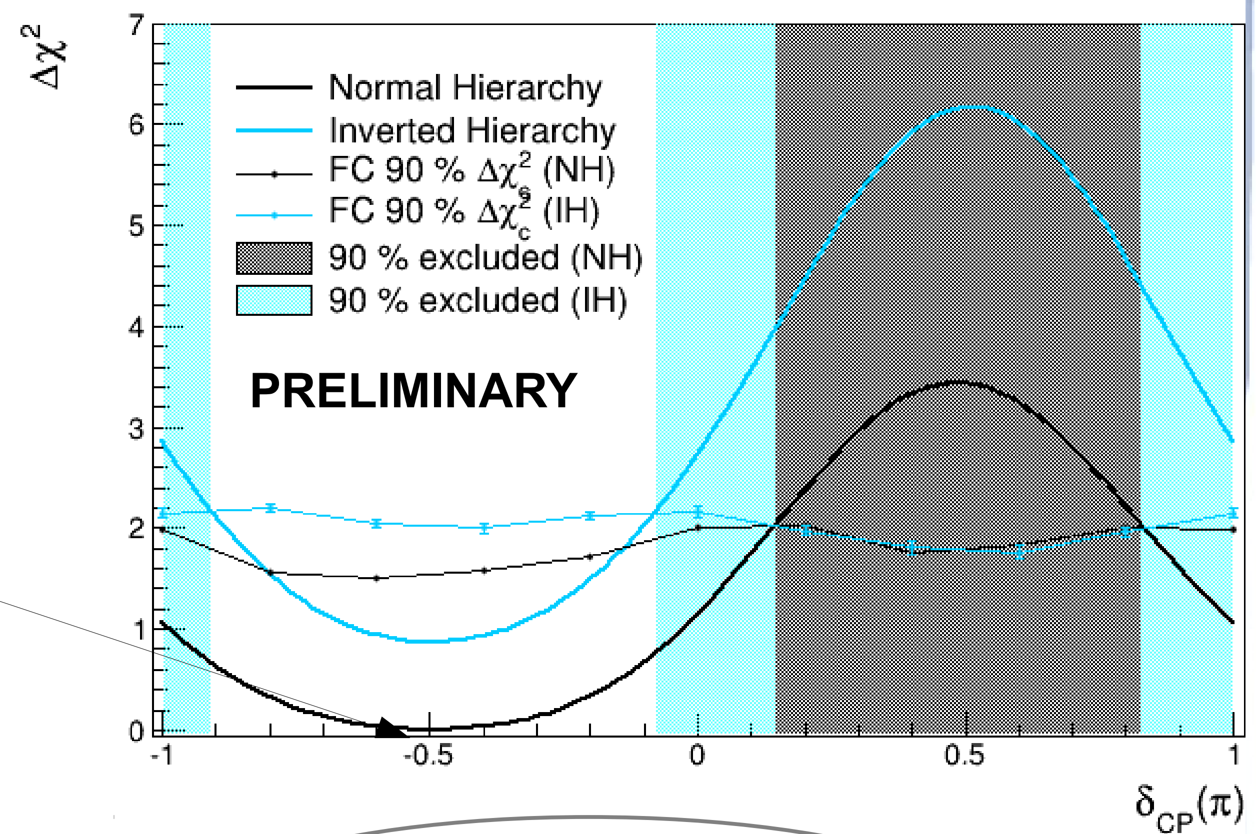




- N_{obs} = 28
- N_{exp} (bck. only) = 4.9±0.6(syst.)
- N_{exp} ($\sin^2 2\theta_{13}$=0.1) = 21.6
- 7.3 σ evidence of non-zero θ_{13}
- First direct observation of a new flavor appearance
- Opens the way to the determination of the CP violation parameter δ

T2K combined fit to appearance and disappearance data

- Combined fit to the ν_μ and ν_e samples
- Using PDG 2013 θ_{13} T2K obtains an indication favoring $\delta = -\pi/2$
- If nature has chosen this happy spot: a) a generous help to experiments b) a solution that satisfies the leptogenesis bound with no additional CP violation



Leptogenesis bound

$$|\sin\theta_{13}\sin\delta| \geq 0.11$$

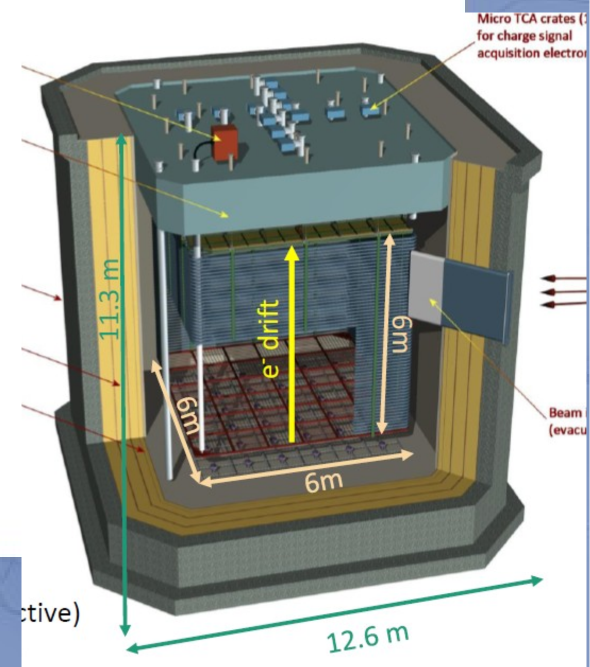
Pascoli Petcov Riotto 2007

Next long baseline experiments

- General consensus : we need a new facility beyond T2K and NovA to complete the PMNS study
- The IRFU SPP group has been very active in the LAGUNA design studies
- We are currently exploring the LBNF proposal in USA and the HK proposal in Japan
- And in the demonstration of the double phase Liquid Argon technology, where we are developing the MPGD-based charge readout

LBNO-DEMO/WA105

- A large 300 ton 6x6x6 m^3 demonstrator of the double phase liquid Argon TPC
- It is an approved experiment at CERN and will be located in the North Area EHN1 extension
- Timeline: smaller 3x1x1 m**3 prototype in 2015, commissioning of WA105 in 2017, beam test (charged particles) in 2018
- First collaboration meeting in October 2014
- TDR: Arxiv: 1409.4405

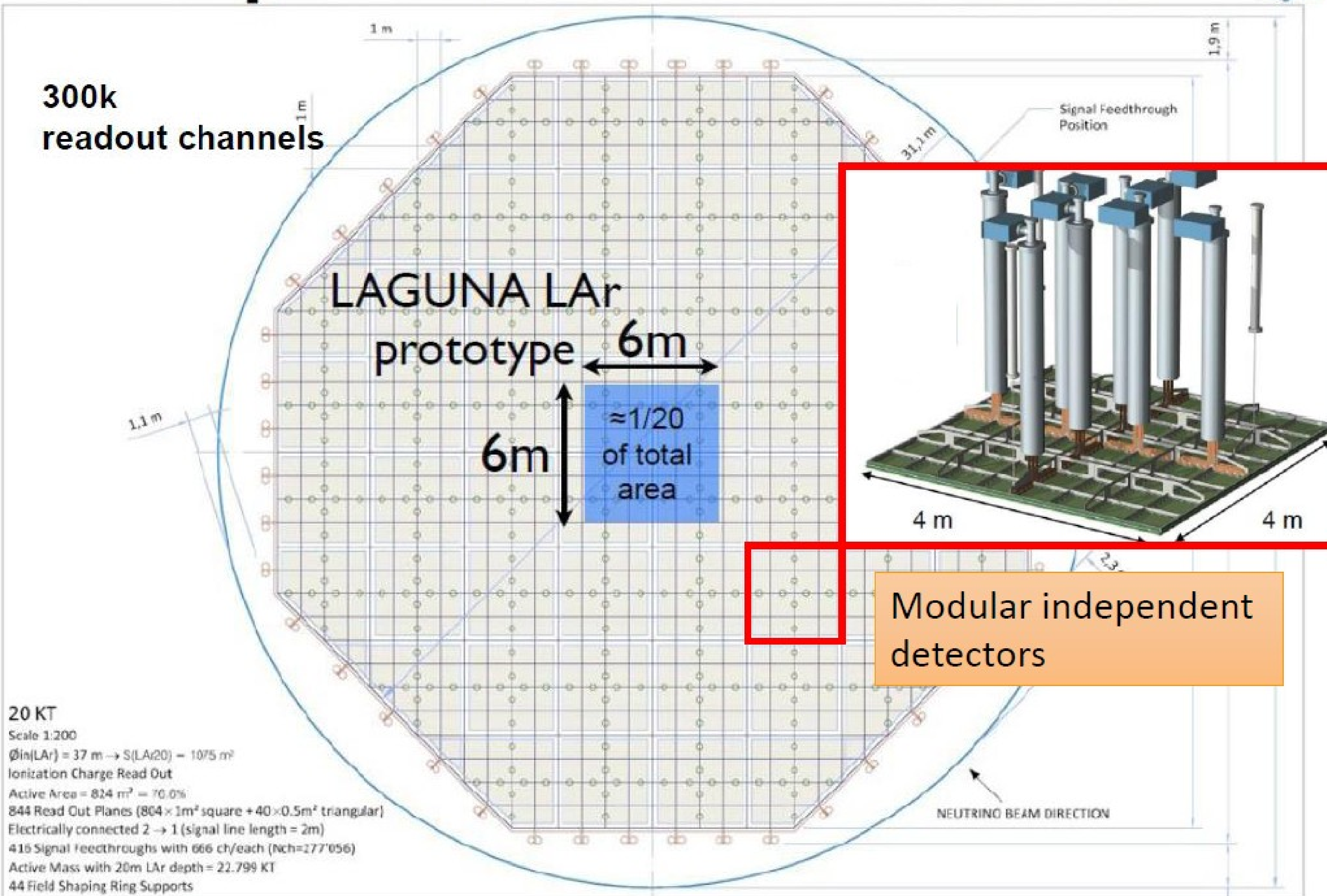


LBNO-DEMO: aims

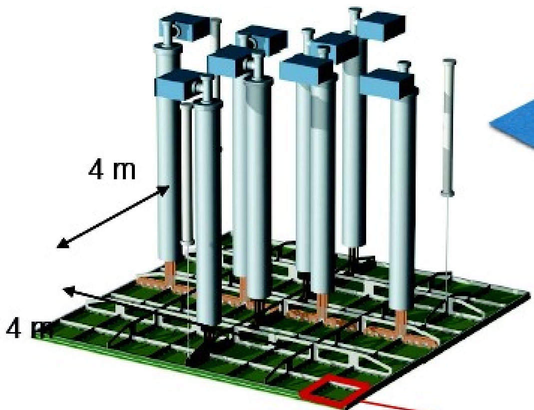
The aim is to demonstrate scalable solutions towards large scale LAr TPC's:

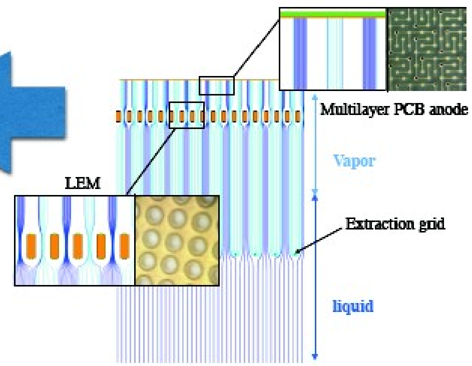
- Purity in a non-evacuated tank
- Large hanging cathode and field cage
- Very high voltage generation
- Charge readout using LEM for amplification
- Accessible cold front-end electronics

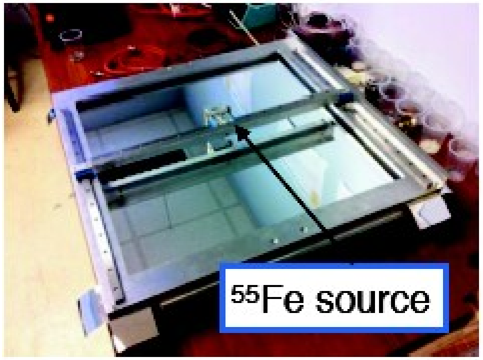
Compared to LAGUNA/LBNO 20 kton DLAr



Charge readout plane

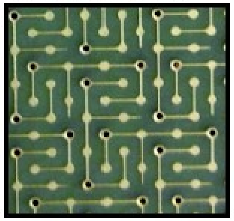




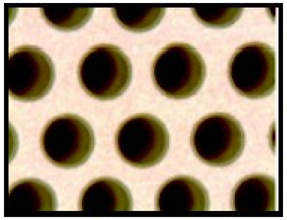


Modules of 50x50 cm^2

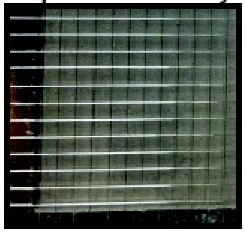
multilayer PCB anode
- 3.125 mm readout pitch
- 3.4 mm thick



LEM
- 500 µm holes, 800 µm pitch
- 1 mm thick FR4



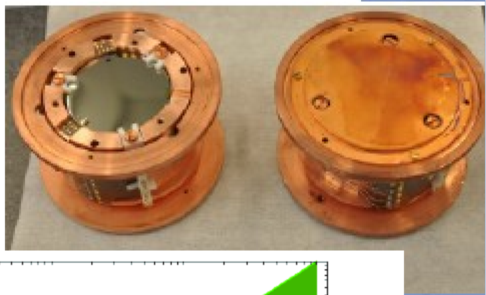
Extraction grid
- 100 µm stainless wires
- 3mm pitch in x and y



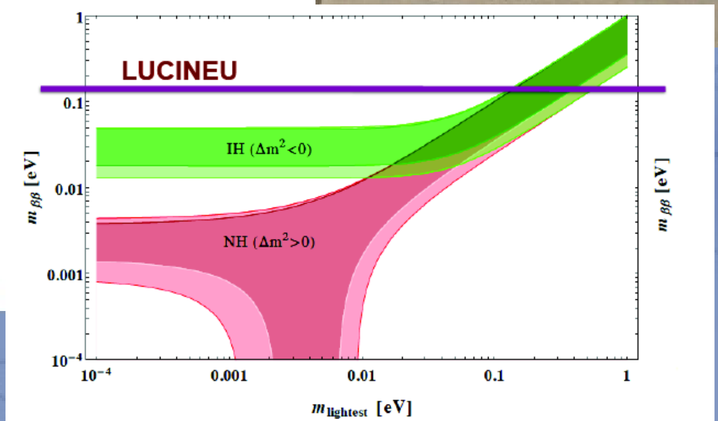
36 m**2 to be equipped
Currently envisaging a solution based on LEM
Saclay contribution:
- R&D based on Micromegas
- Calibration test bench
- Validation of a MPGD based solution (experience from T2K TPC)

Neutrinoless double beta decay

- Aim: determine Dirac or Majorana nature of neutrino
- R&D activity starting in IRFU/SPP in the LUMINEU (ANR) framework
- For the development of a scintillating bolometer (heat+scintillation signals) using enriched $Zn^{100}MoO_4$
- Prototype test in the Edelweiss cryostat in Modane
- Timescale: 0.68 kg in 2015, proposal for a 10 kg demonstrator



Option	Number of ≈ 400 g crystals	Total isotope mass [kg]	Half-life sensitivity [10^{25} y]	$M_{\beta\beta}$ sensitivity [meV]
(1) – LUMINEU	4	0.676	0.53	167 – 476
(2) – LUCINEU	40	6.76	4.95	55 – 156
(3)	2000	338	92.5	13 – 36



Conclusions

- The three neutrino mixing paradigm has been confirmed by the reactor (Double Chooz, RENO, Daya Bay) and accelerator experiments (T2K) → the θ_{13} angle is large and will be measured with high precision by reactor experiments
- We are exploring the CP violation phase
- Data taking by Stereo and CeSox should start beginning of 2016 → confirm or reject the existence of short-baseline oscillations
- Nucifer is running for one year (reactor monitoring, reactor anomaly)
- Preparing the next generation long baseline experiments (LBNF, HK): WA105 at CERN

The WA105 collaboration

- LAPP, Université de Savoie, CNRS/IN2P3, Annecy-le-Vieux
- OMEGA Ecole Polytechnique/CNRS-IN2P3
- UPMC, Université Paris Diderot, CNRS/IN2P3, Laboratoire de Physique Nucléaire et de Hautes Energies (LPNHE)
- APC, AstroParticule et Cosmologie, Université Paris Diderot, CNRS/IN2P3, CEA/Irfu, Observatoire de Paris, Sorbonne Paris Cité
- IRFU, CEA Saclay, Gif-sur-Yvette
- Université Claude Bernard Lyon 1, IPN Lyon

- University of Glasgow
- University College London

- University of Jyväskylä
- University of Oulu
- Rockplan Ltd

- Horia Hulubei National Institute (IFIN-HH)
- University of Bucharest

10 countries
22 institutes
>100 physicists

- University of Geneva, Section de Physique,
- ETH Zürich

- INFN-Sezione di Pisa

- CERN

- Institut de Fisica d'Altes Energies (IFAE), Bellaterra (Barcelona)

- Faculty of Physics, St.Kliment Ohridski University of Sofia

- Institute for Nuclear Research of the Russian Academy of Sciences, Moscow

- High Energy Accelerator Research Organization (KEK)

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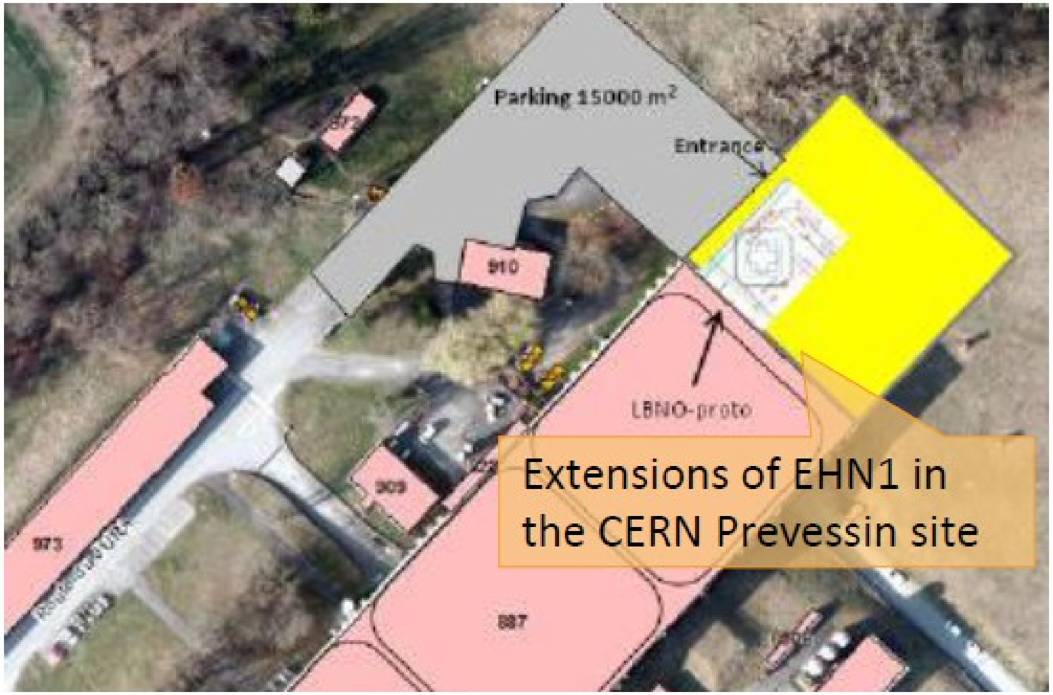
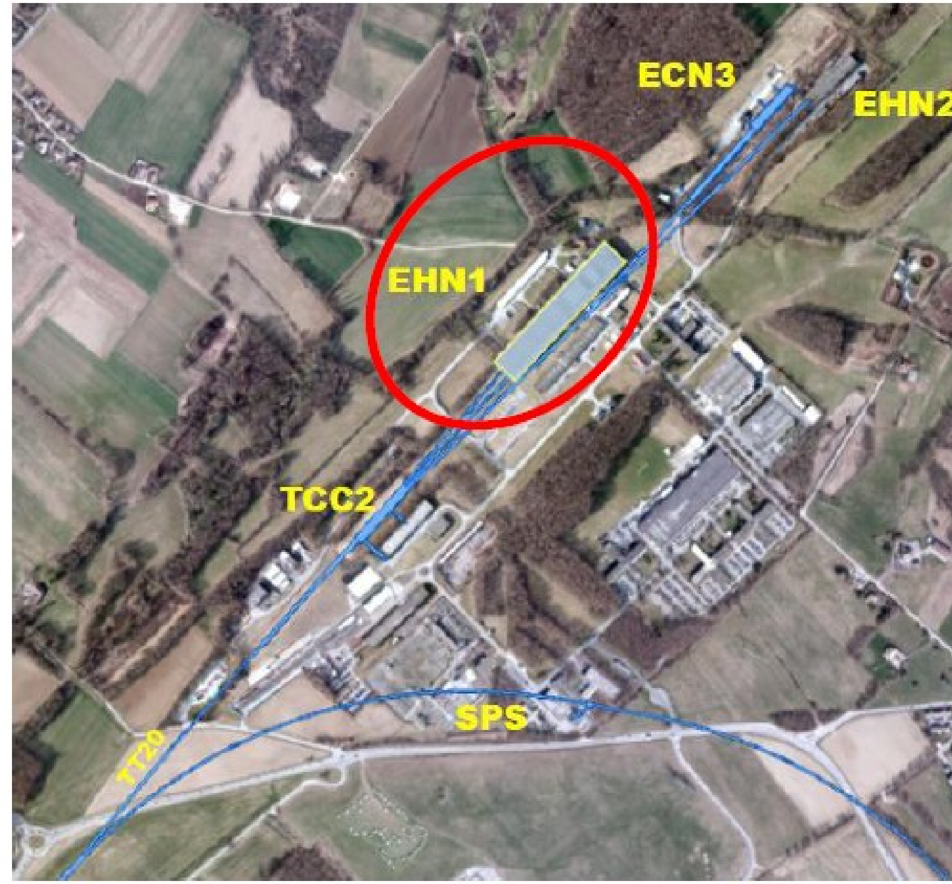
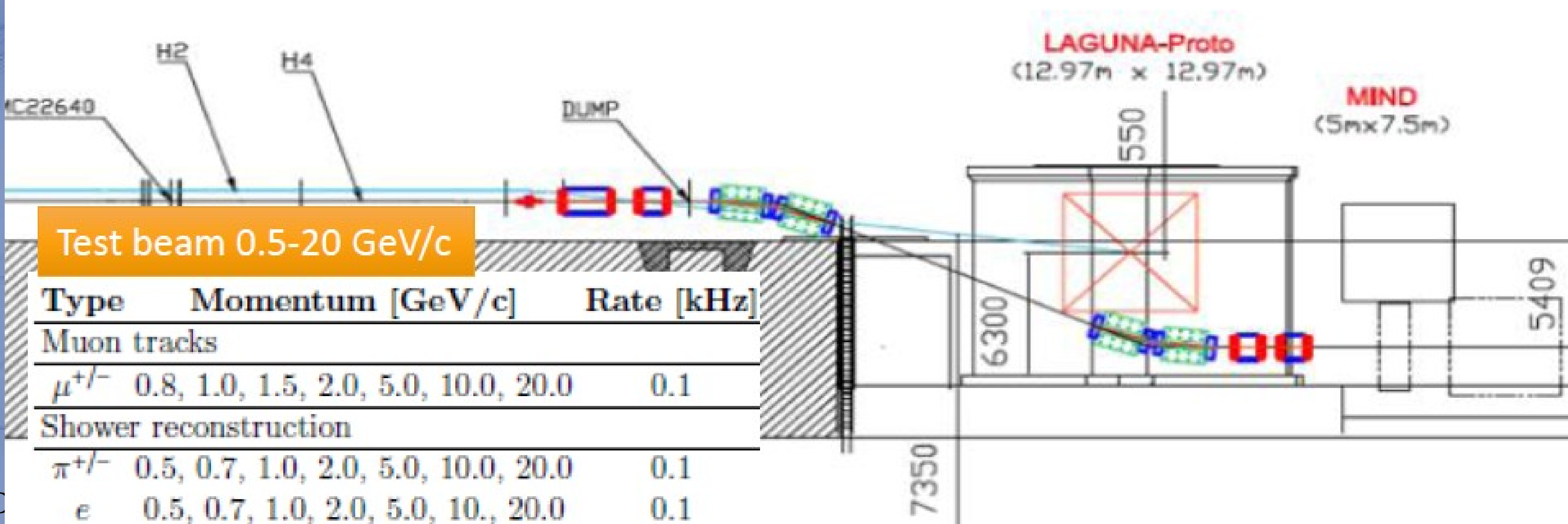
WA105 at CERN





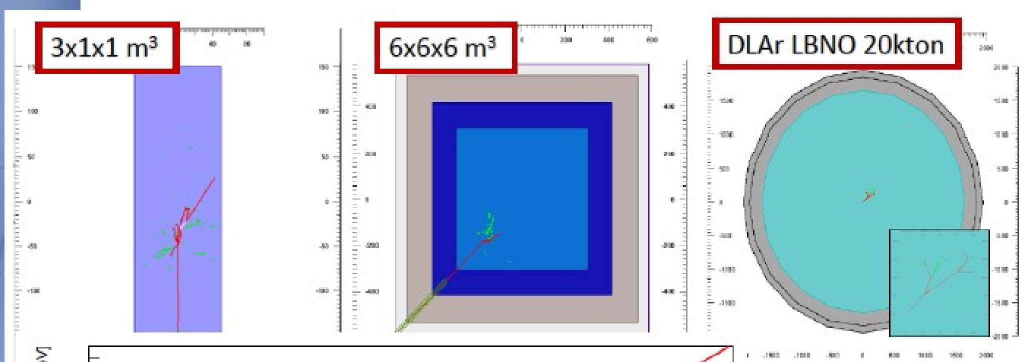


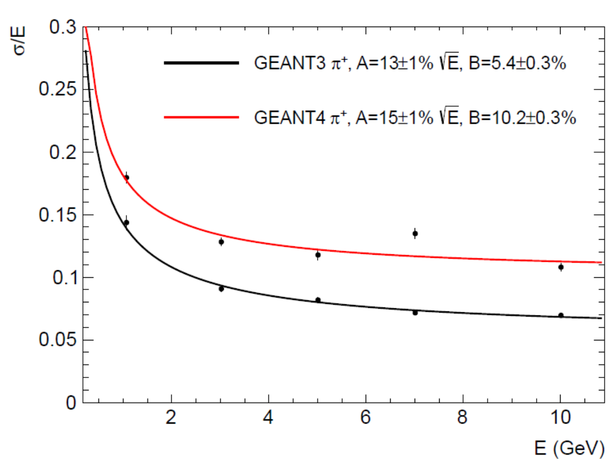
Test beam 0.5-20 GeV/c

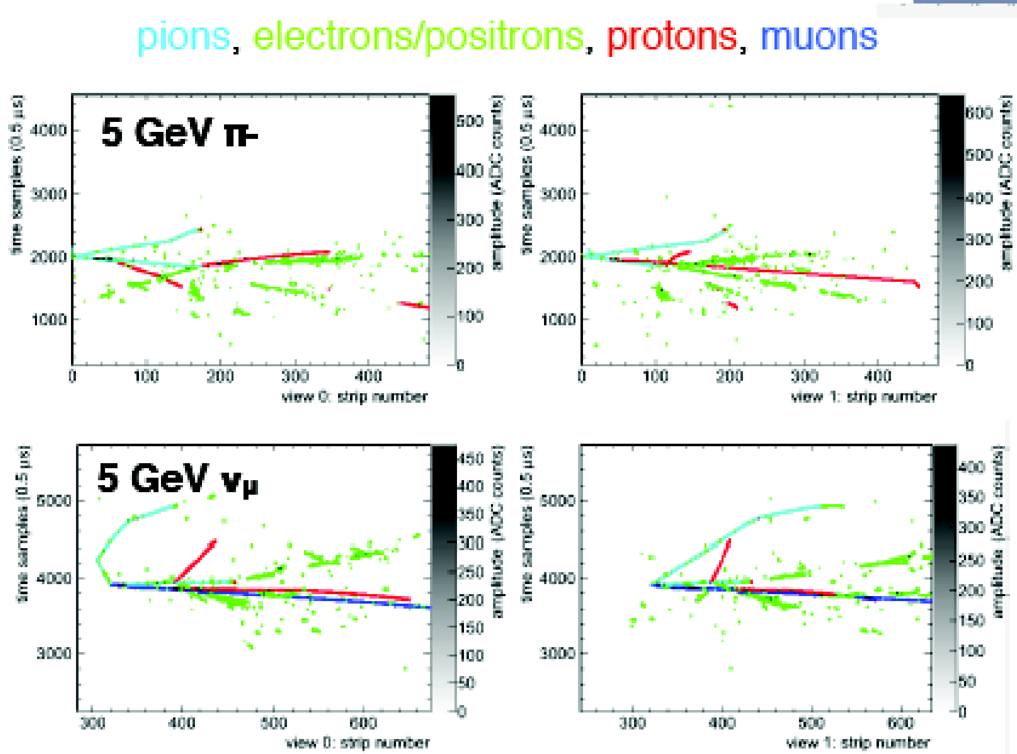
Type	Momentum [GeV/c]	Rate [kHz]
Muon tracks		
$\mu^{+/-}$	0.8, 1.0, 1.5, 2.0, 5.0, 10.0, 20.0	0.1
Shower reconstruction		
$\pi^{+/-}$	0.5, 0.7, 1.0, 2.0, 5.0, 10.0, 20.0	0.1
e	0.5, 0.7, 1.0, 2.0, 5.0, 10., 20.0	0.1

Hadron calorimetry studies

- The containment of the hadron shower within a totally active medium with high granularity readout (3x3mm^2) allows hadron calorimetry studies and calibration
- Large event samples as test-bench for automatic reconstruction

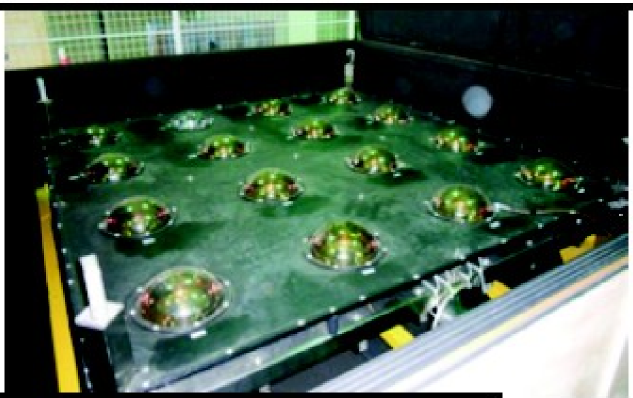




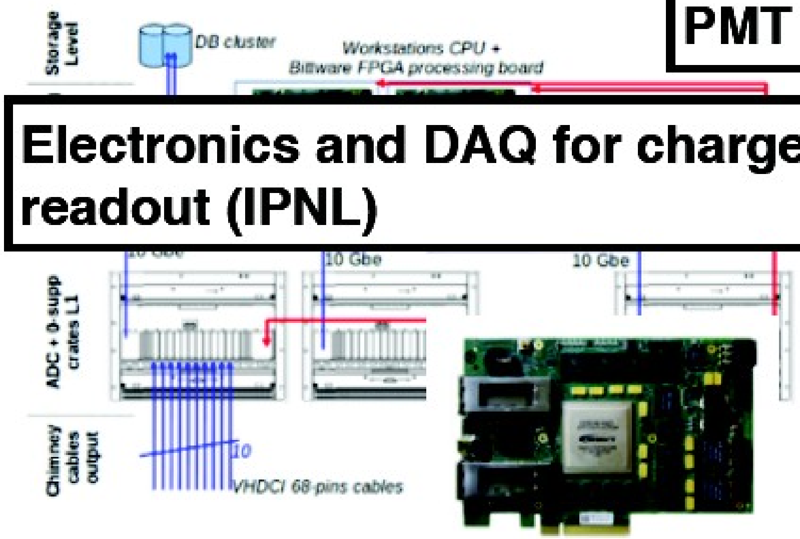


LBNO-DEMO: DLAr design work in progress WA105

PMT light readout (APC, Barcelona, CIEMAT, KEK,LAPP)



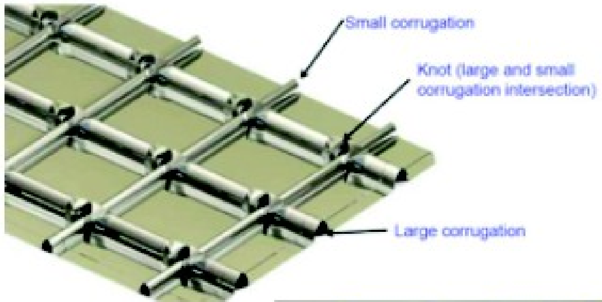
Electronics and DAQ for charge readout (IPNL)



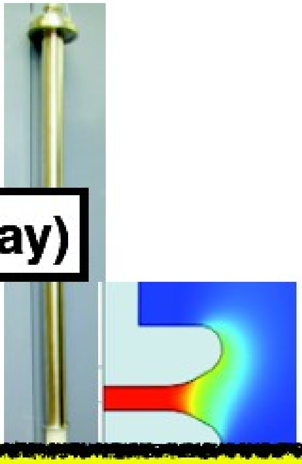
SiPM light readout (INR+Genève)

Field cage (CEA, Romania)

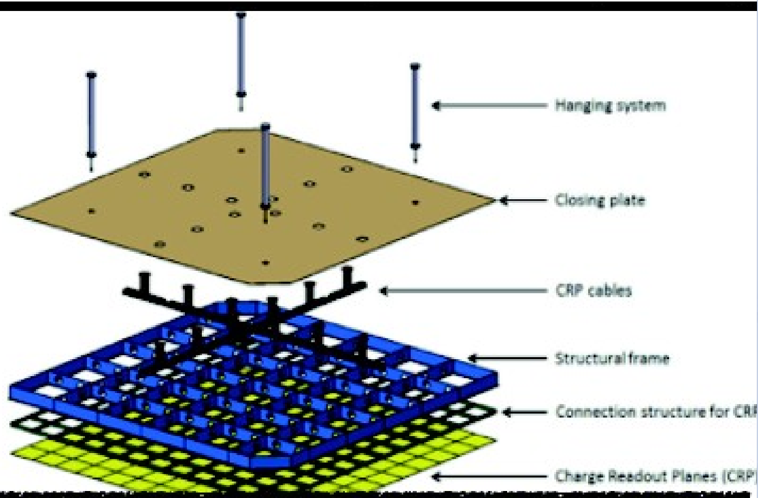
membrane tank (ETHZ, CERN)



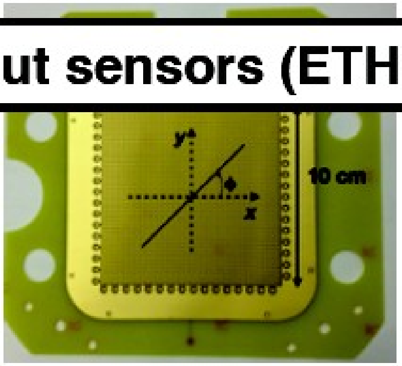
HV (LPNHE, ETHZ)



Anode deck suspension (LAPP)

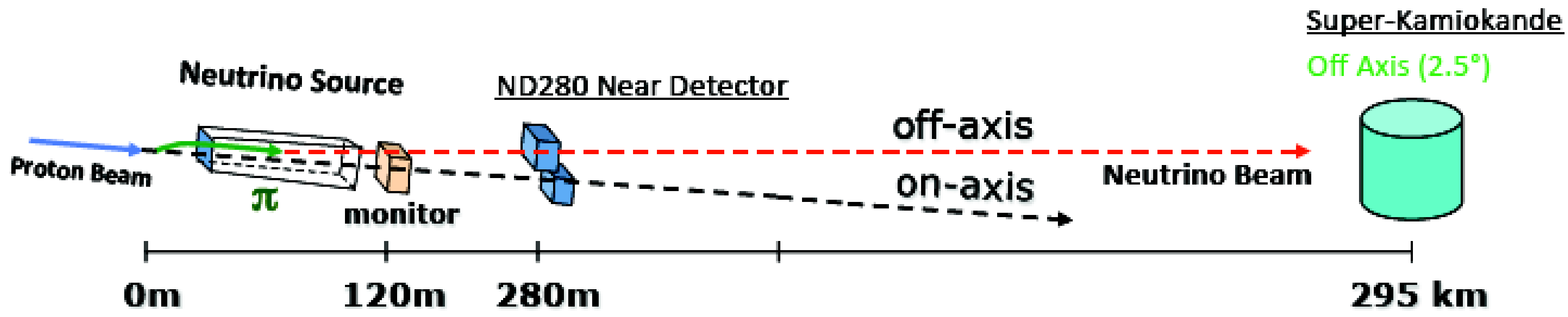


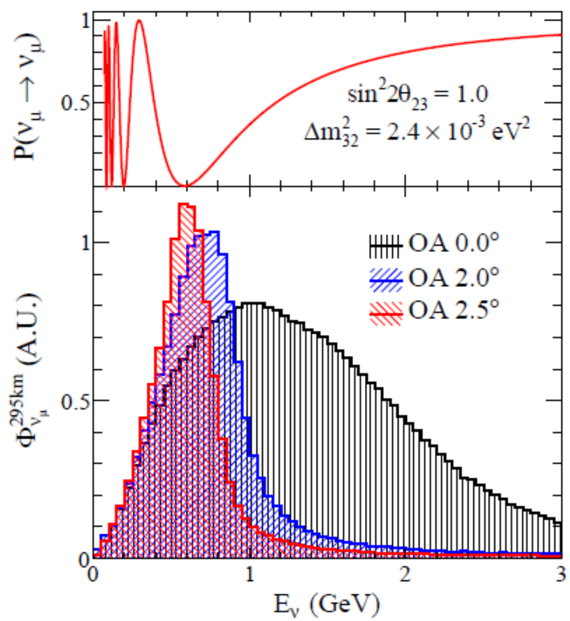
charge readout sensors (ETHZ, Saclay)



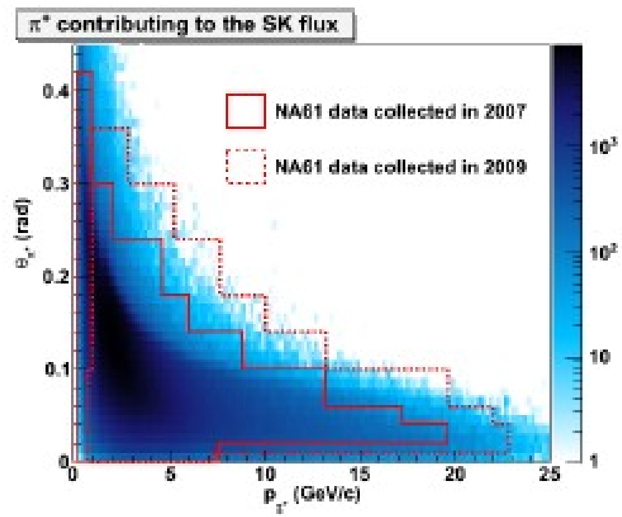
all groups involved in software and data analysis

T2K: Main Experimental Features

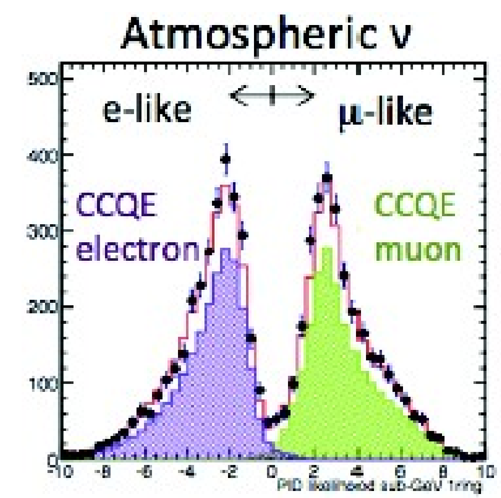




Off-axis beam.
Flux has a narrow peak tuned for the first oscillation maximum

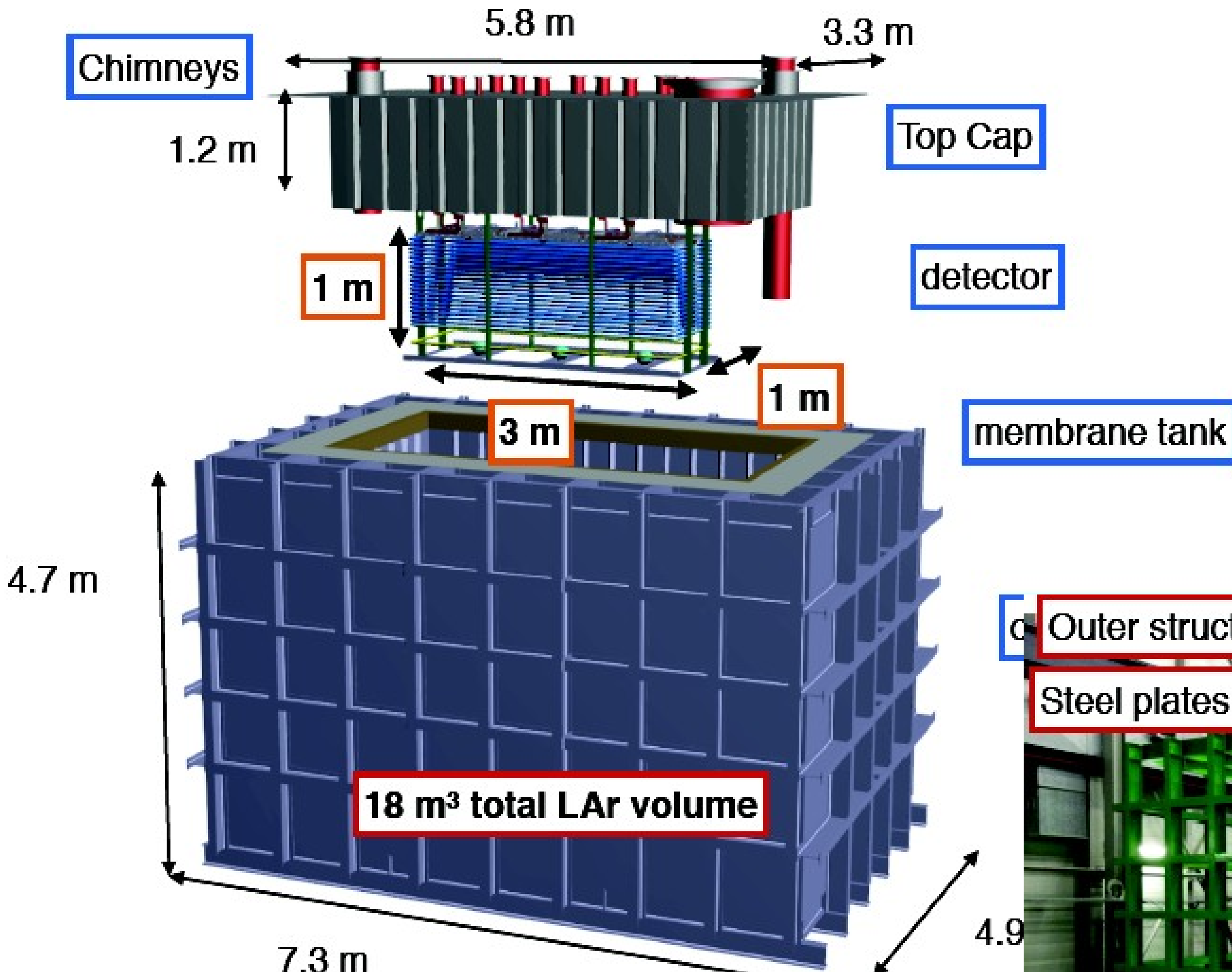


Pion and kaon production measured by the NA61 exp. at CERN



Excellent particle identification capabilities in SK (misid <1%)

WA105 3x1x1 m^3



At CERN bdg 182