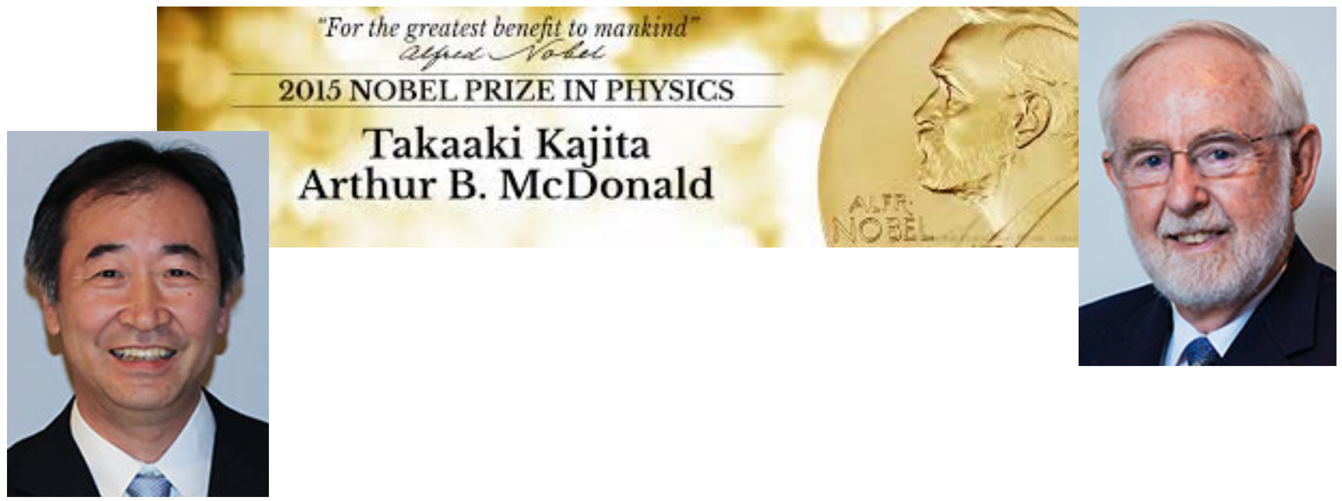
Problemi aperti nella fisica dei neutrini


#NobelPrize
WSJ
Nobelprize.org

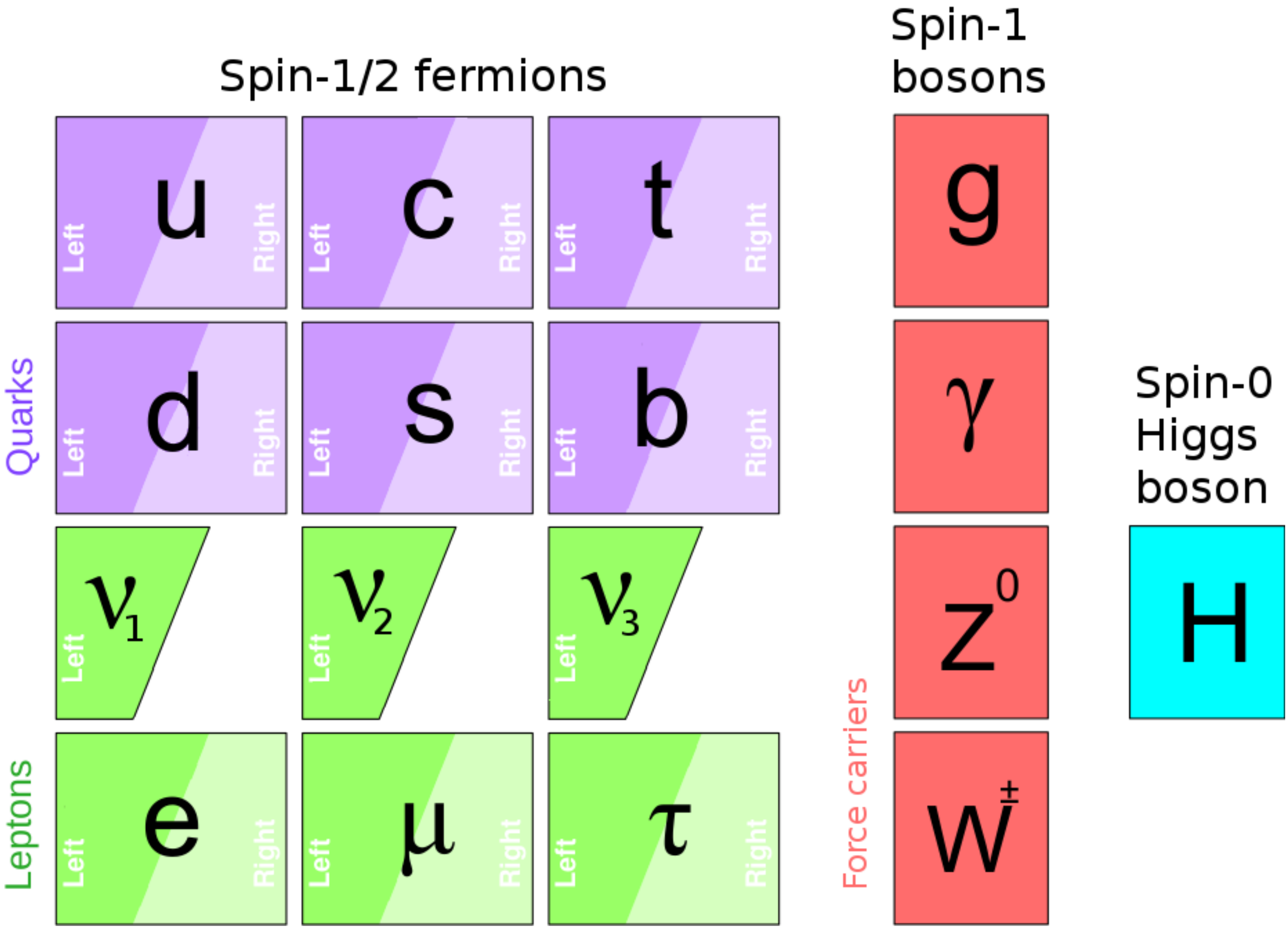
"For the discovery of neutrino oscillations,
which shows that neutrinos have mass"



Tuttavia questo Nobel a mio parere ha delle conseguenze: abbiamo il <u>dovere</u> di studiare in dettaglio le caratteristiche di queste oscillazioni, misurare le masse e la gerarchia E spiegare PERCHE' i neutrini hanno massa e molti altri PERCHE'

Oscillazioni a 3 neutrini

NB: Fisica BSM!


Spin-1/2 fermions
Spin-1
bosons
Spin-0
Higgs
boson
Quarks
Leptons
Force carriers
u
c
t
d
s
b
ν1
ν2
ν3
e
μ
τ
Left
Right
g
γ
Z0
W±
H

$$|\nu_i(t)\rangle = e^{-i(E_i t - \vec{p}_i \cdot \vec{x})} \mid \nu_i(0)\rangle$$

$$E_i = \sqrt{p_i^2 + m_i^2} \simeq p_i + \frac{m_i^2}{2p_i} \approx E + \frac{m_i^2}{2E}$$

$$|\nu_i(L)\rangle = e^{-im_i^2 L/2E} |\nu_i(0)\rangle$$

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}^* \, |\nu_i\rangle$$

$$|\nu_i\rangle = \sum_\alpha U_{\alpha i} \, |\nu_\alpha\rangle$$

$$P_{\alpha\to\beta} = |\langle \nu_\beta(t)|\nu_\alpha\rangle|^2 = \left| \sum_i U_{\alpha i}^* U_{\beta i} e^{-im_i^2 L/2E} \right|^2$$

$$P_{\alpha\to\beta} = \delta_{\alpha\beta} - 4\sum_{i>j}\mathrm{Re}(U_{\alpha i}^{*}U_{\beta i}U_{\alpha j}U_{\beta j}^{*})\sin^2\left(\frac{\Delta m_{ij}^2 L}{4E}\right)$$
$$+ 2\sum_{i>j}\mathrm{Im}(U_{\alpha i}^{*}U_{\beta i}U_{\alpha j}U_{\beta j}^{*})\sin\left(\frac{\Delta m_{ij}^2 L}{2E}\right),$$

$$A_{\mathrm{CP}}^{(\alpha\beta)} = P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) = 4\sum_{i>j}\mathrm{Im}\left(U_{\alpha i}^{*}U_{\beta i}U_{\alpha j}U_{\beta j}^{*}\right)\sin\left(\frac{\Delta m_{ij}^2 L}{2E}\right)$$

$$\mathrm{Im}\left(U_{\alpha i}U_{\beta i}^{*}U_{\alpha j}^{*}U_{\beta j}\right) = J\sum_{\gamma,k}\varepsilon_{\alpha\beta\gamma}\varepsilon_{ijk}$$

$$A_{\mathrm{CP}}^{(\alpha\beta)} = 16J\sum_{\gamma}\varepsilon_{\alpha\beta\gamma}\sin\left(\frac{\Delta m_{21}^2 L}{4E}\right)\sin\left(\frac{\Delta m_{32}^2 L}{4E}\right)\sin\left(\frac{\Delta m_{31}^2 L}{4E}\right)$$

I neutrini, molte domande aperte…

Neutrino oscillation status

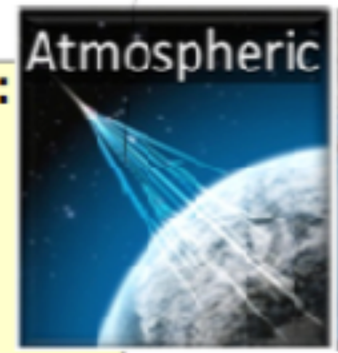
lavour eigenstates Mass eigenstates

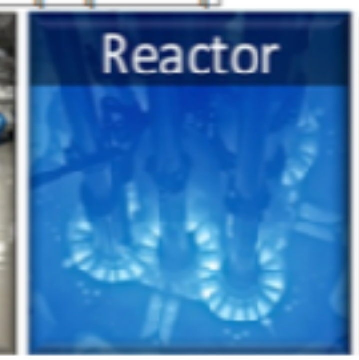
$$\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix} = U_{PMNS}\begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix}$$

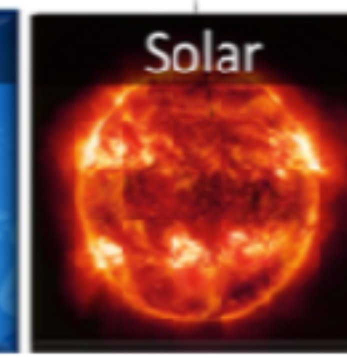
\+ Majorana phases

$$U_{PMNS} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}$$

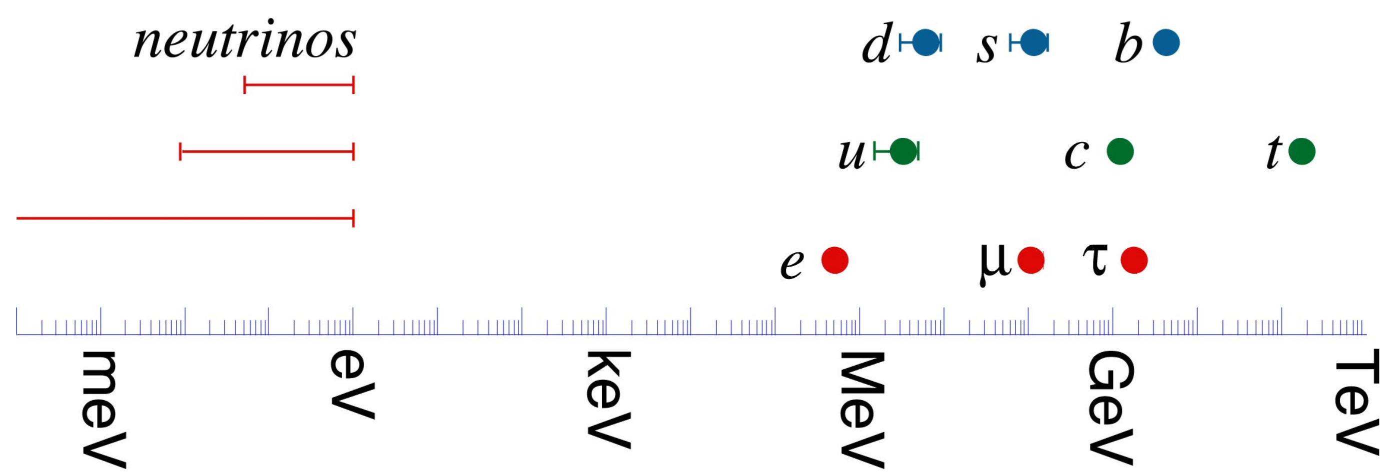
where $c_i = \cos\theta_i$, $s_i = \sin\theta_i$



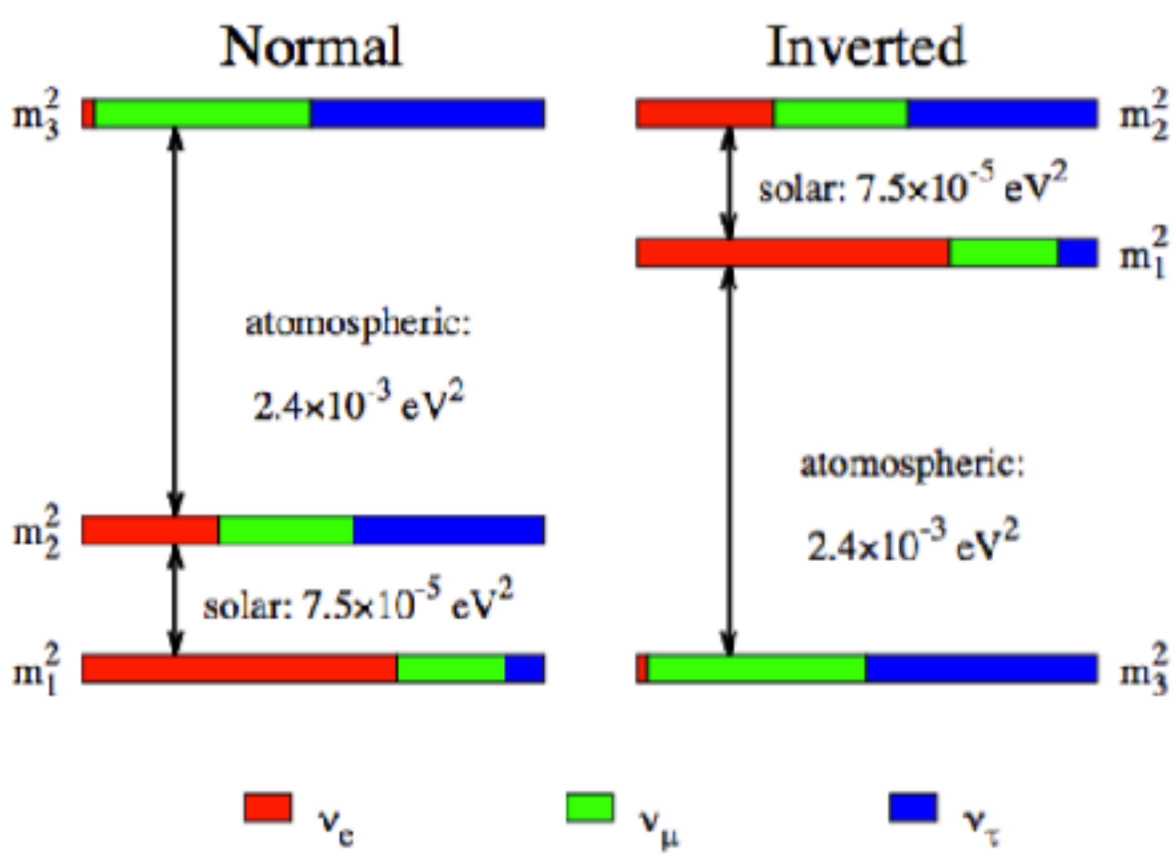




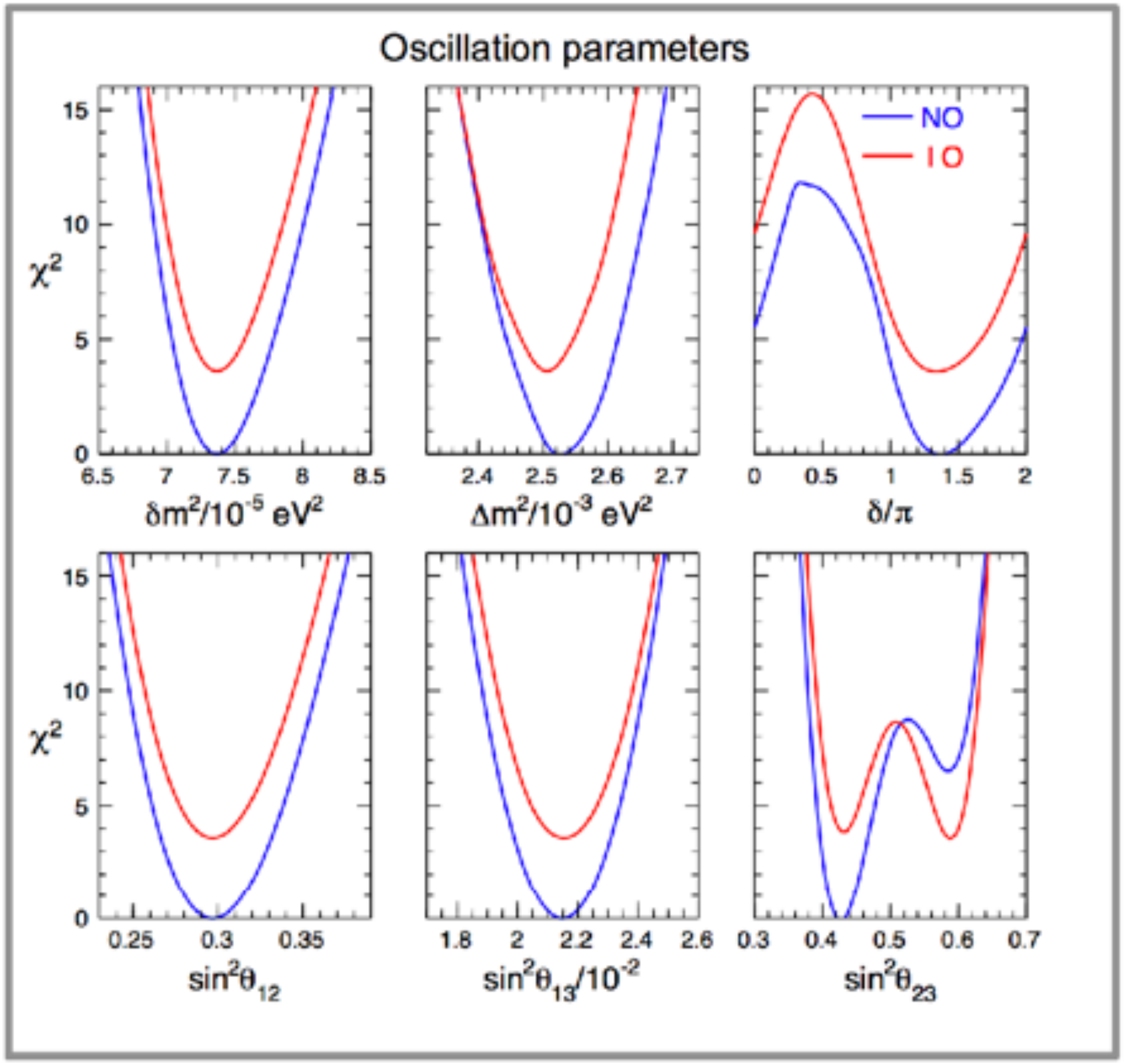
- **Oscillation probabilities $P(\nu_\alpha \to \nu_\beta)$ depend on:**
  - **3 mixing angles:**
  - $\Theta_{12} = (33.4 \pm 0.85)°$
  - $\Theta_{23} = (45.8 \pm 3.2)°$
  - $\Theta_{13} = (8.88 \pm 0.39)°$
  - **2 independent mass splittings:**
  - $|\Delta m^2_{32}| = (2.44 \pm 0.06) \,.\, 10^{-3}$ eV^2
  - $\Delta m^2_{12} = (7.53 \pm 0.18) \,.\, 10^{-5}$ eV^2
  - **1 complex CP phase:**
  - δ_{CP} around $-\pi/2$
  - Source-detector distance (L), neutrino energy (E)



quali masse (e quale ordinamento delle masse)?
perche' c'e il deserto tra neutrini e leptoni carichi?
perche' hanno massa?Dirac o Majorana?



Current status of 3-flavor parameters



Capozzi, Di Valentino, Lisi, Marrone, Melchiorri, A.P.
arXiv: 1703.04471

~ 2σ preference for normal mass ordering

~ 2σ indication of CPV
$\delta \in [\pi, 2\pi]$ ($\sin\delta < 0$)

Hint of non-maximal θ_{23}

Palazzo, NUTEL2017

Why do they mix so differently ?

CKM

$$|V|_{\rm CKM} = \begin{pmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.0065 & (3.51 \pm 0.15) \times 10^{-3} \\ 0.2252 \pm 0.00065 & 0.97344 \pm 0.00016 & (41.2^{+1.1}_{-5}) \times 10^{-3} \\ (8.67^{+0.29}_{-0.31}) \times 10^{-3} & (40.4^{+1.1}_{-0.5}) \times 10^{-3} & 0.999146^{+0.000021}_{-0.000046} \end{pmatrix}$$

PMNS

3σ

NuFIT 3.0 (2016)

$$|U|_{3\sigma} = \begin{pmatrix} 0.800 \to 0.844 & 0.515 \to 0.581 & 0.139 \to 0.155 \\ 0.229 \to 0.516 & 0.438 \to 0.699 & 0.614 \to 0.790 \\ 0.249 \to 0.528 & 0.462 \to 0.715 & 0.595 \to 0.776 \end{pmatrix}$$

+ ha la PMNS una fase di Dirac CPV come CKM?

con quale precisione serve conoscere i coefficienti?

perche' i Giapponesi si ostinano a chiamarla MNS?

What about mixing ?

- Anarchy for leptons ?
  Murayama, Naba, De Gouvea

- Discrete symmetries: e.g. tri-bimaximal mixing Harrison, Perkings, Scott
  not so much motivated with large θ_{13} -> understanding corrections
  -> + GUTs

- Minimal flavour violation and dynamical origin of Yukawas

The measurement of the Dirac phase in the PMNS mixing matrix, together with an improvement of the precision on the mixing angles θ_{12}, θ_{13} and θ_{23}, can provide unique information about the possible existence of new fundamental symmetry in the lepton sector.

S.T. Petcov, Neutrino Telescopes, Venice, 14/03/2017

Esperimenti INFN

Esperimento	Tipologia	Obiettivi	Stato
BOREXINO	Scintillatore liquido	neutrini solari, geoneutrini, neutrini da supernova…	in presa dati
ENUBET2	Tagger instrumentato	flusso νe per sezioni d'urto	R&D/prototyping
ICARUS	LAr-TPC	neutrino sterile	in costruzione
JUNO	Scintillatore liquido	gerarchia, solari, geoneutrini, neutrini da supernova…	in costruzione
KM3	Water Cherenkov	gerarchia, neutrini cosmici	in costruzione/presa dati
LVD	Scintillatore liquido	neutrini da supernova	in presa dati
NU@FNAL (DUNE)	LAr-TPC	ΔCP, gerarchia, neutrini solari e atmosferici, neutrini da supernova…	R&D/prototyping
T2K/SK	Water Cherenkov	$\theta 13$, $\theta 23$, gerarchia, ΔCP	in presa dati

Misura della gerarchia di massa e della fase di Dirac di CP

The future possible landscape for <u>new</u>
Neutrino Accelerator Infrastructure
(as far we understand today!)

3 facilities

- ✓ *no beams at CERN !*
- ✓ *ν beams in the US and in Japan*

IL PATTO…(post CNGS)

Prospettive sulla misura della gerarchia di massa

tre metodi con sistematiche e statistiche differenti

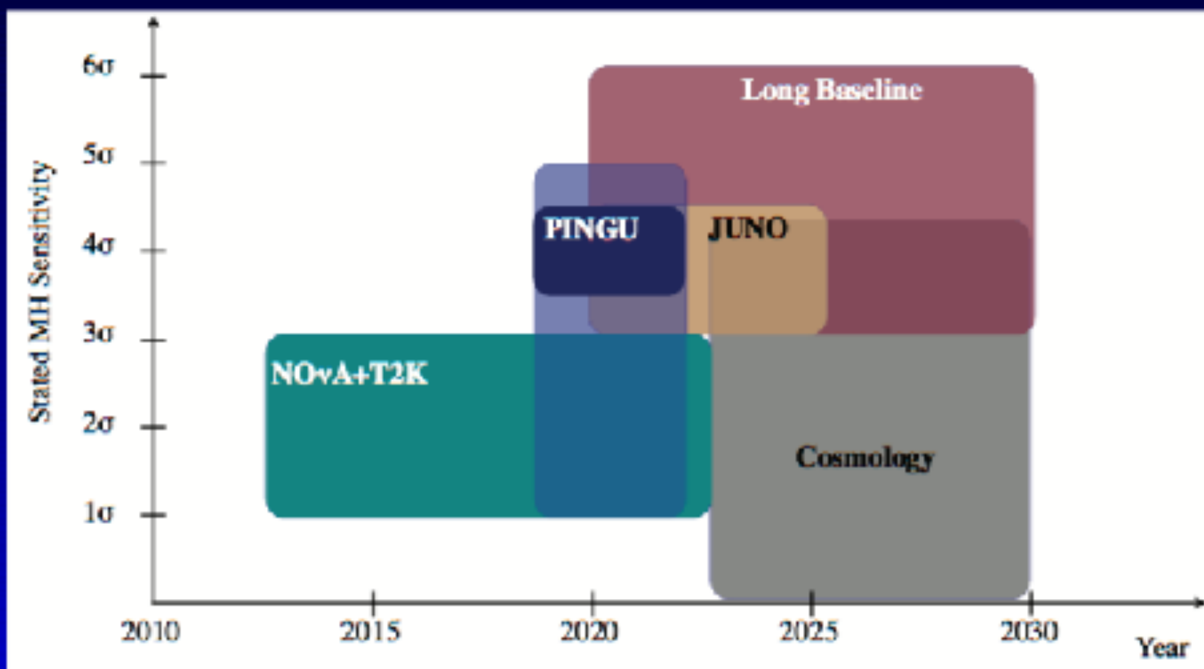
— anti-νe disappearance con neutrini dei reattori (LScint, JUNO-RENO50)

— oscillazioni LNBL (NOνA, DUNE LAr,T2K-T2HK-Cerenkov)

— νμ disappearance di neutrini atmosferici (ORCA,PINGU, HK Cerenkov)

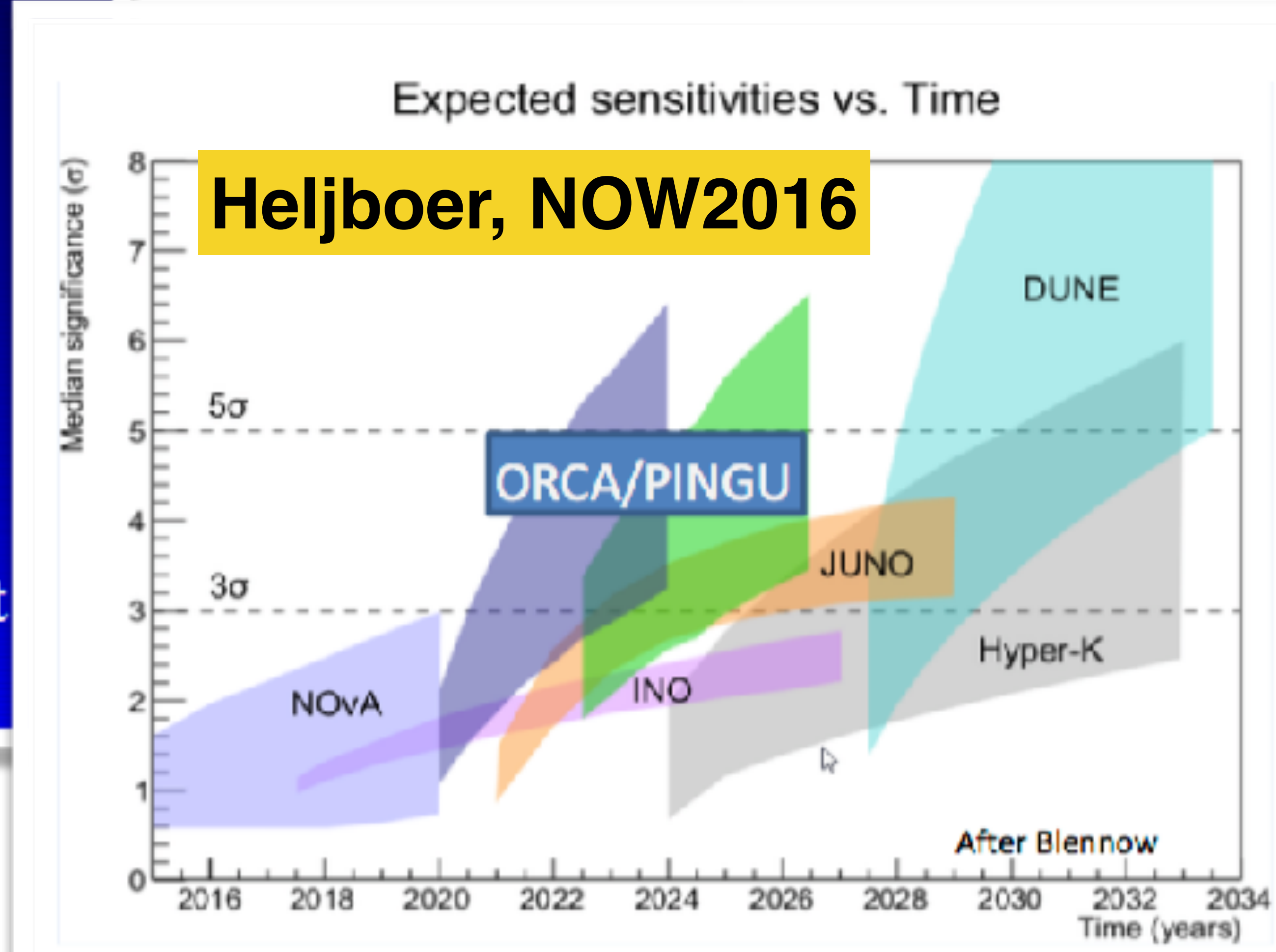
Mass hierarchy

Literature survey arXiv:1307.5487



Many experiments are expected to have a result at above 3 σ within a decade from now.

Huber, NUFACT2016



GERARCHIA: JUNO

(Original idea by Choubey, Petcov, Piai (PRD68 (2003) 113006))

Mass hierarchy and reactor antineutrinos

- $\bar{\nu}_e$ survival probability: $\Delta m_{ij}^2 = m_i^2 - m_j^2$

$$P_{ee} = 1 - \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right) - \sin^2(2\theta_{13})\left(\cos^2\theta_{12}\sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + \sin^2\theta_{12}\left(\frac{\Delta m^2_{32} L}{4E}\right)\right)$$

- **The last term (sensitive to the mass hierarchy)**, can be written as:

$$\frac{1}{2}\sin^2(2\theta_{13})\left\{1 - \left[1 - \sin^2(2\theta_{12})\sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)\right]^{1/2}\cos\left(2\left|\frac{\Delta m^2_{ee} L}{4E}\right| \pm \varphi\right)\right\},$$

$\Delta m^2_{ee} = (\cos^2(\theta_{12})\,\Delta m^2_{31} + \sin^2(\theta_{12})\,\Delta m^2_{32})$ and

$\sin\varphi$ and $\cos\varphi$ denote combinations of mass and mixing parameters of the 1-2 sector.

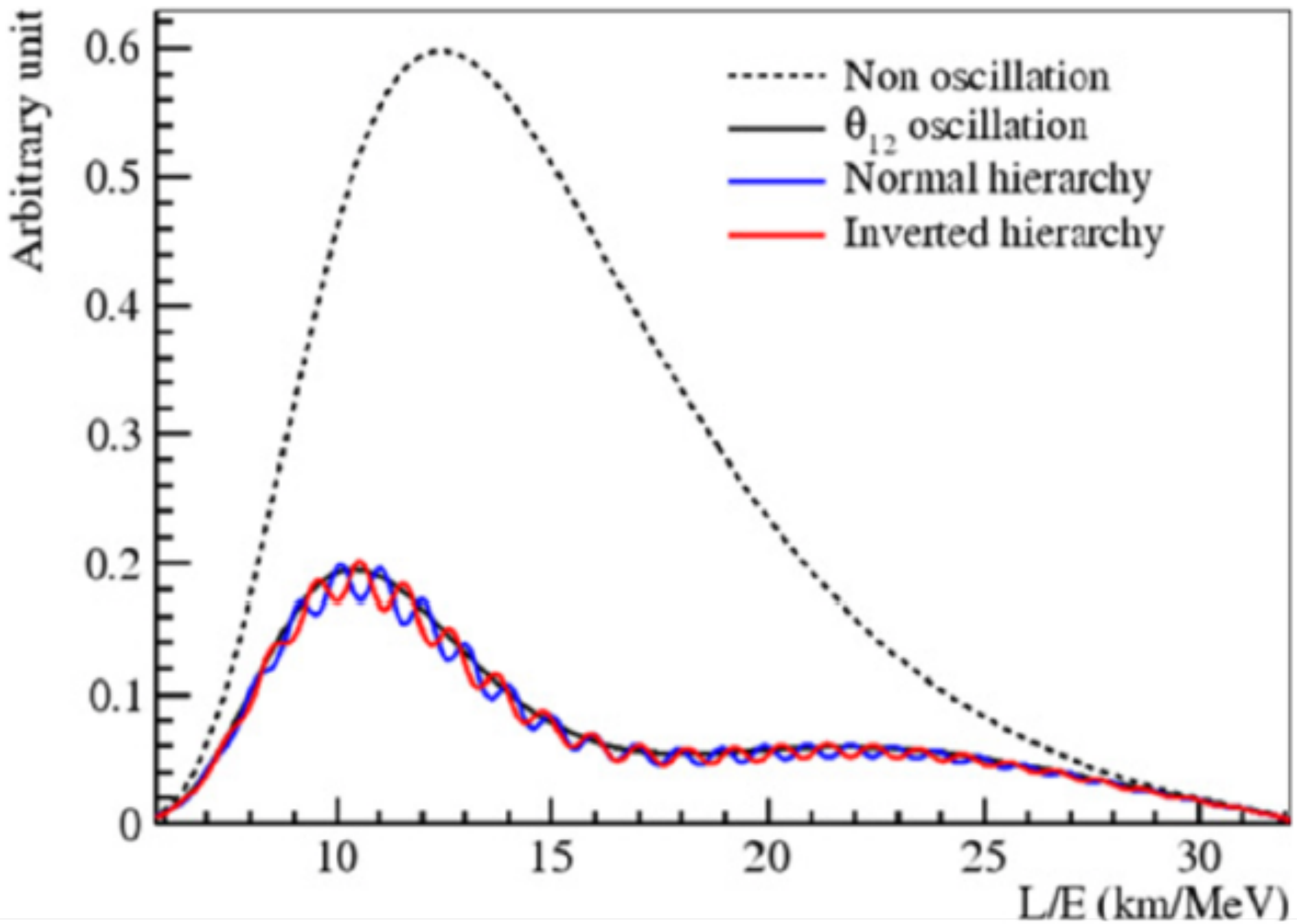
- The sign of **φ term** is **positive for NH** and **negative for IH** →

Fastly oscillating term, opposite for the 2 hierarchies, superimposed to the **general oscillation pattern**

4

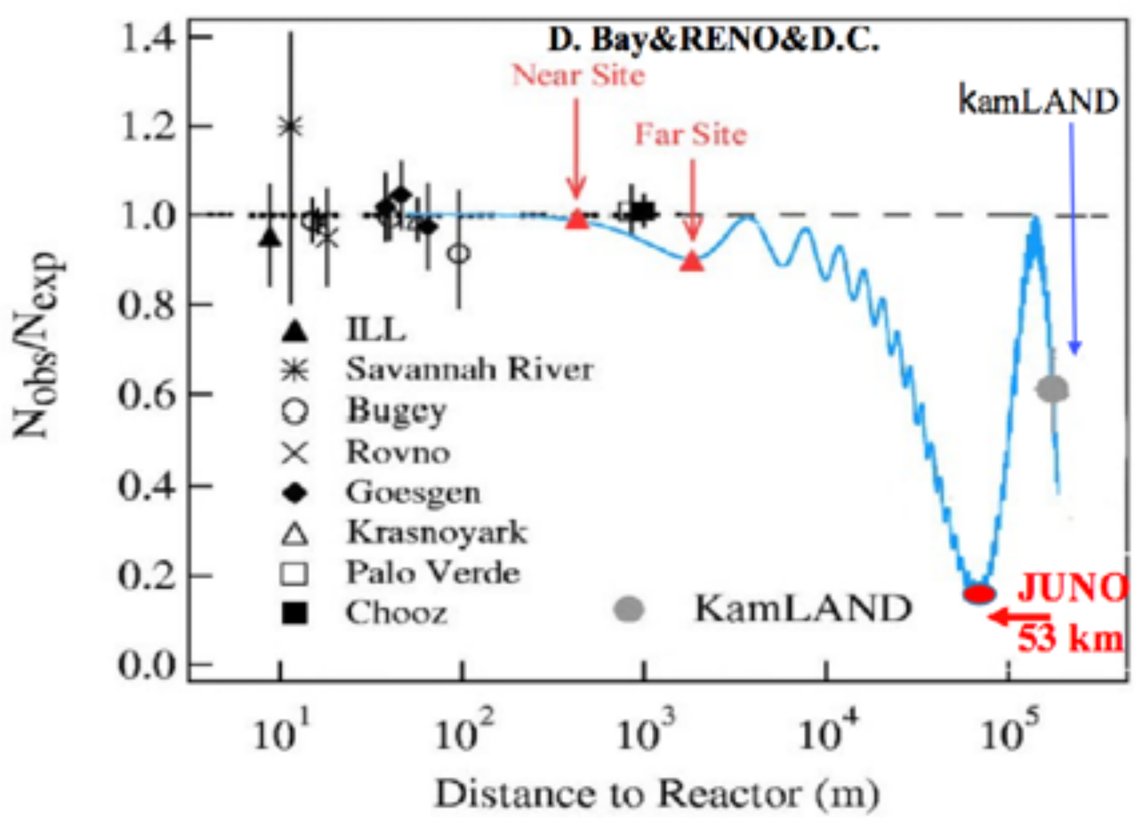
Spectrum dependence upon the Mass Hierarchy

Observed energy spectrum has a small dependence on the hierarchy
(in addition to other oscillation parameters).



The JUNO option

- **JUNO** (Jiangmen Underground Neutrino Observatory): **"multipurpose"** reactor $\bar{\nu}_e$ **experiment,** under construction near Kaiping (South China).
- **Baseline** from reactors (10 nuclear cores) to detector about 53 km: **optimized in the region of the maximum 1-2 oscillation**



6

JUNO main features

❖ Medium baseline (53 km); high statistics required

⇊

Large detector mass and proximity to several reactors

❖ Signature: position of the spectral wiggles in the spectrum

⇊

Very good E resolution $\left(\frac{\sigma(E)}{\sqrt{E}} \cong 3\%\right)$

Liquid scintillator (LAB+PPO+bis-MSB)

High photon yield

❖ Reduction of the cosmogenic background

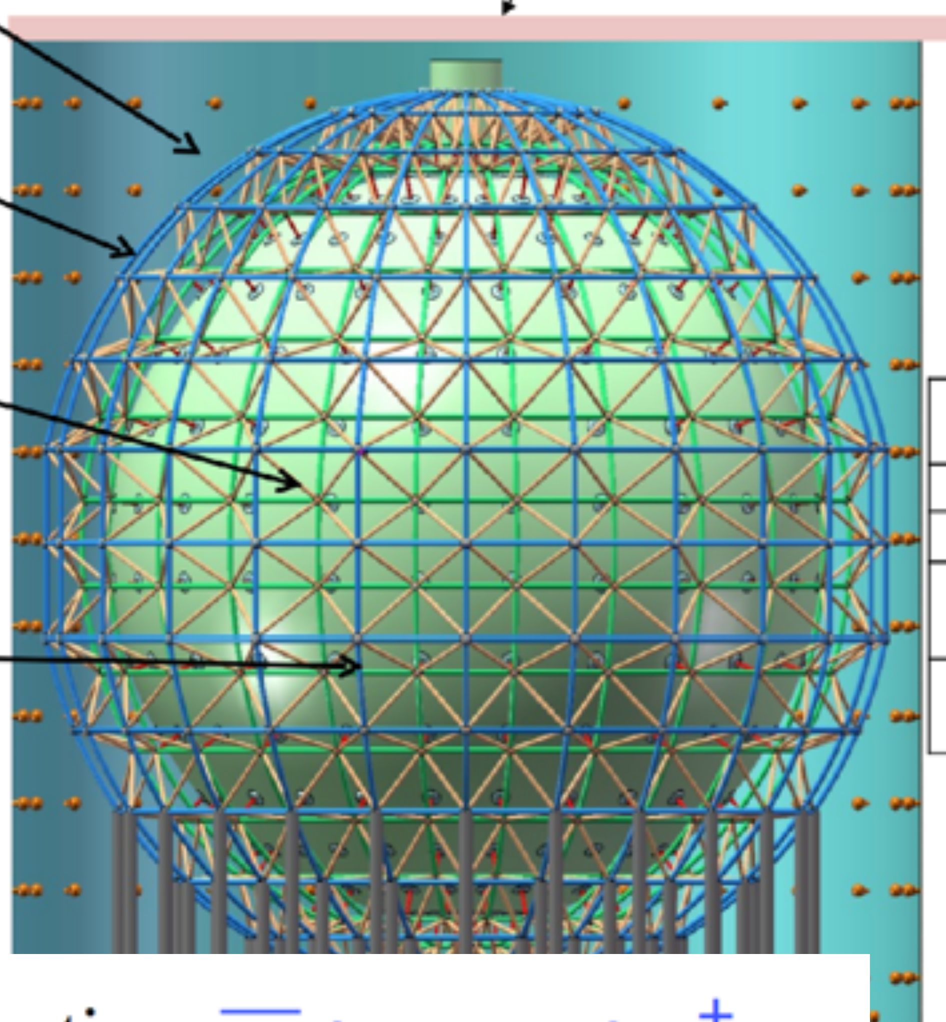
⇊

Rock overburden about 720 m and a muon veto system

10

Antonelli, NUTEL2017

The JUNO detector



Underground detector: more than 700 m of rock overburden

Experiment	Daya Bay	BOREXINO	KamLAND	JUNO
LS mass	20 ton	~ 300 ton	~ 1kton	20 kton
Coverage	~ 12%	~ 34%	~ 34%	~ 80%
Energy resolution	$7.5\%/\sqrt{E}$	$\sim 5\%/\sqrt{E}$	$\sim 6\%/\sqrt{E}$	$\sim 3\%/\sqrt{E}$
Light yield	~ 160 p.e./MeV	~ 500 p.e./MeV	~ 250 p.e./MeV	~ 1200 p.e./MeV

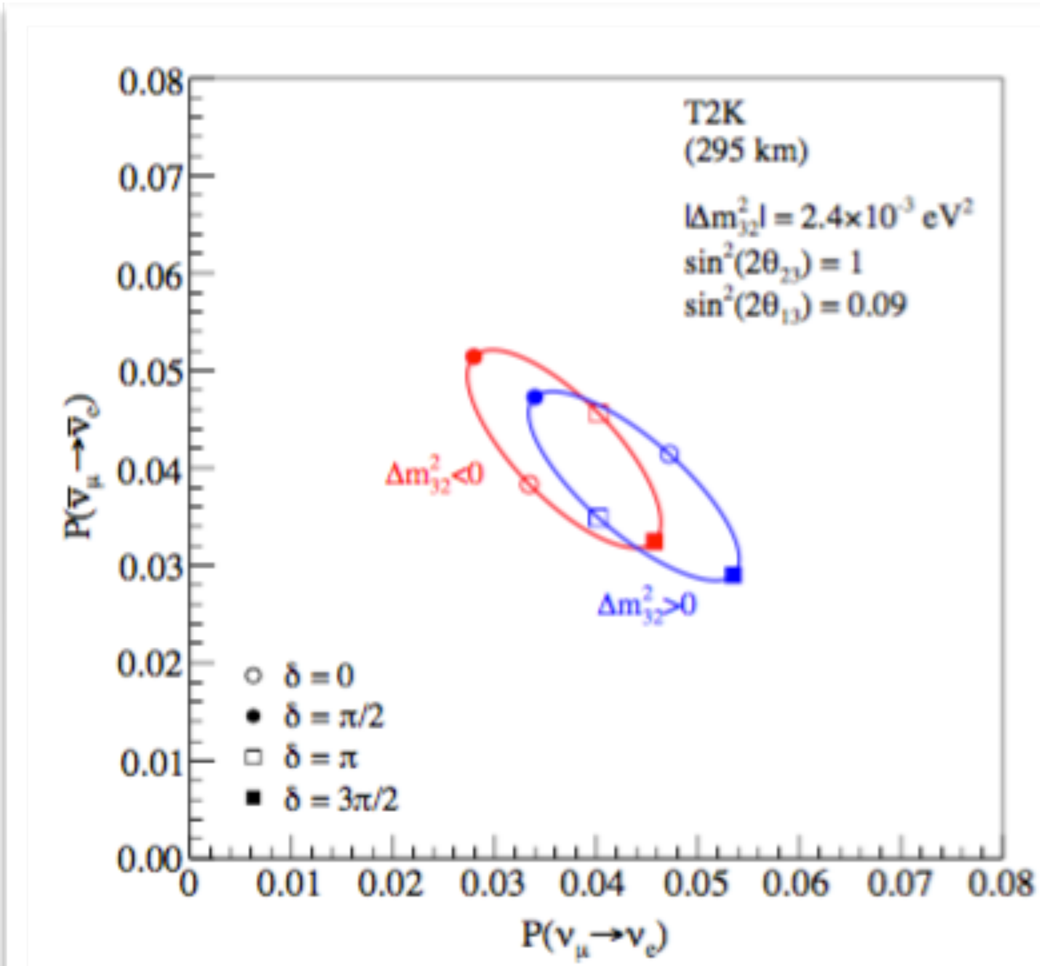
8

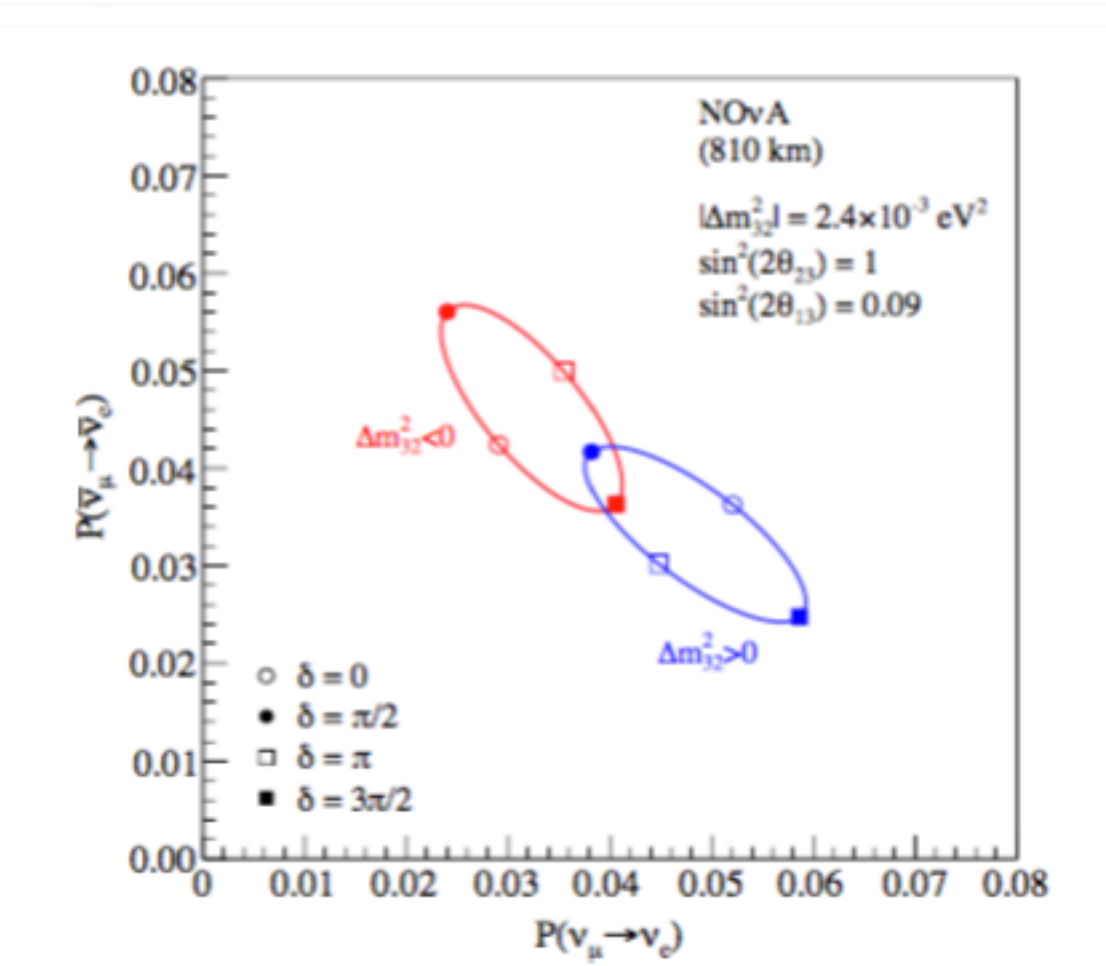
- Main reaction: $\overline{\nu_e} + p \rightarrow n + e^+$

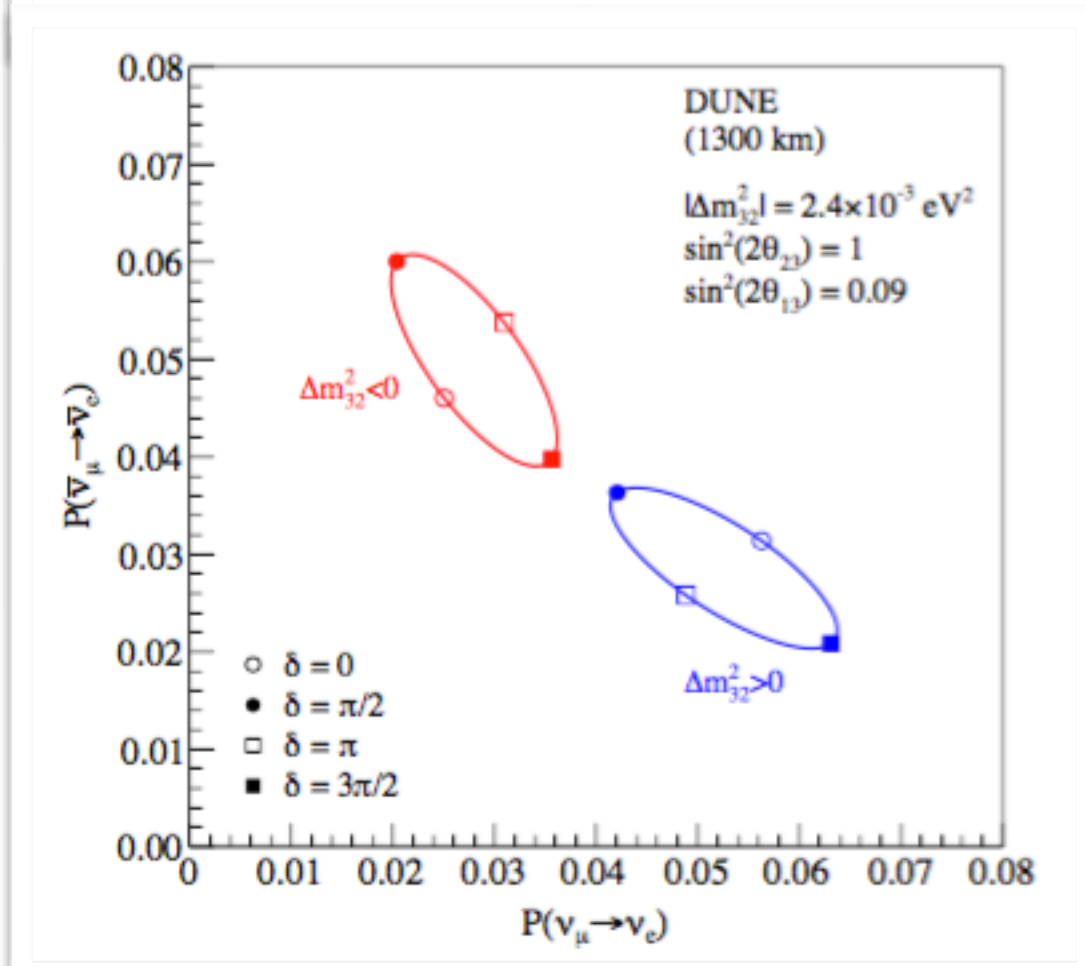
$$E_{\overline{\nu}} \geq 1.8 \text{ MeV}$$

Time coincidence between e^+ and 2.2 MeV γ from nuclear capture

GERARCHIA: LONG BASELINE







$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta(1-x))}{(1-x)^2} + \alpha J\cos(\Delta\pm\delta)\frac{\sin(\Delta x)\sin(\Delta(1-x))}{x(1-x)} + \alpha^2\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(\Delta x)}{x^2},$$

$$, x \equiv \pm 2\sqrt{2}G_F n_e E/\Delta m^2_{32},$$

$$\Delta = \frac{\Delta m^2_{31}L}{4E}$$

x cambia segno a seconda della gerarchia; effetto aumenta con E quindi con L!

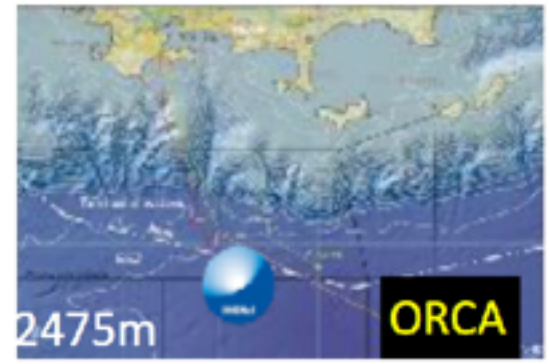
GERARCHIA: atmosferici

KM3NeT

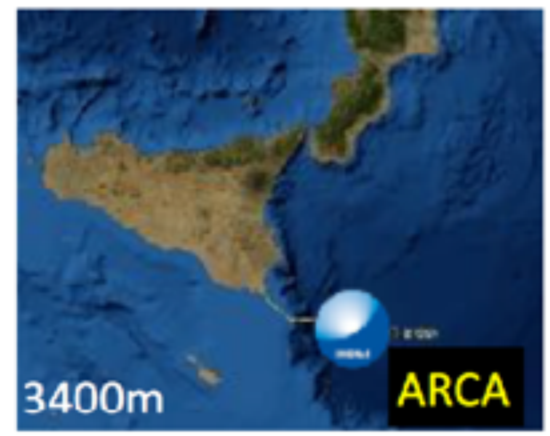
Multi-site, deep-sea infrastructure

Single collaboration, Single technology

+Nantes, Johannesburg, Marrakech, Tbilisi



Oscillation **R**esearch with **C**osmics In the **A**byss



Astroparticle **R**esearch with **C**osmics In the **A**byss

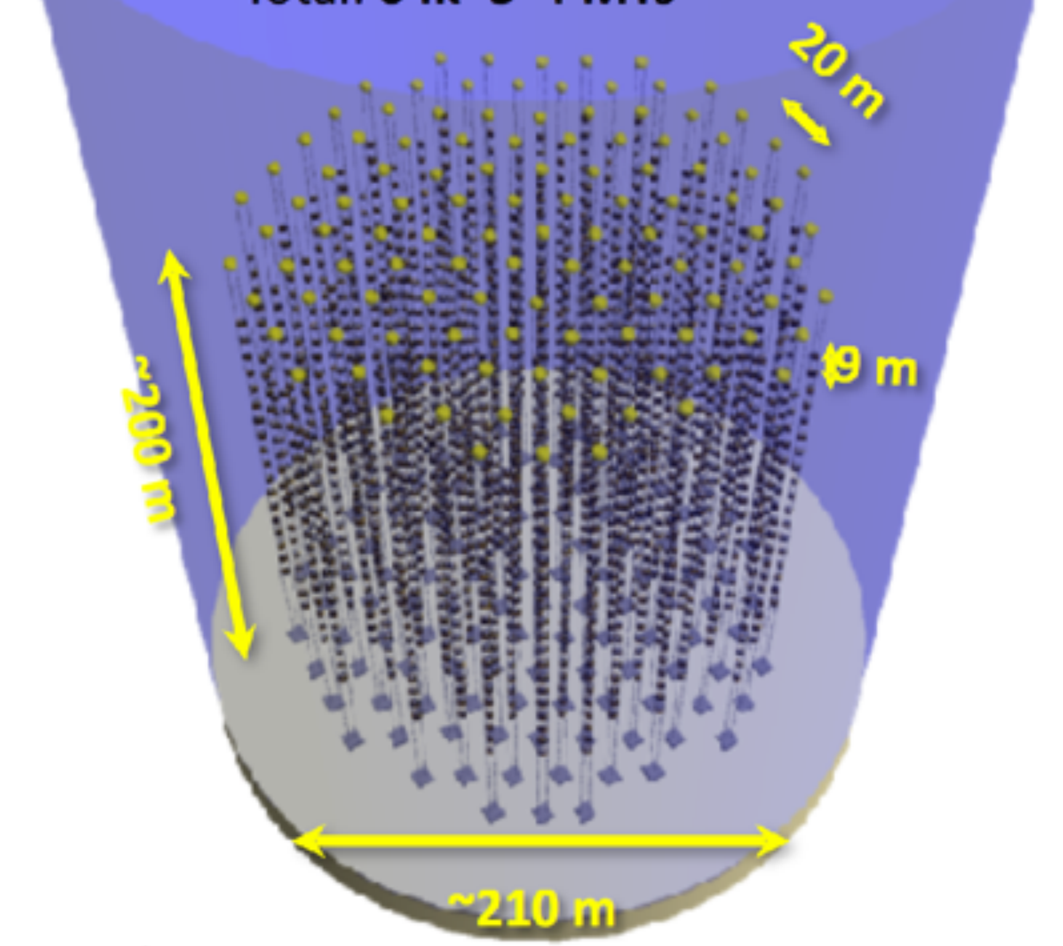
Connection nodes of emso (european multidisciplinary seafloor & water column observatory)

3

Brunner, NUTEL2017

The ORCA Detector

- ~5.7 Mt instrumented
- **115** strings
- **18** DOMs / string (~50 kt ~ 2 × SK)
- **31** PMTs / DOM (~3 kt ~ MINOS)
- Total: **64k*3¨ PMTs**



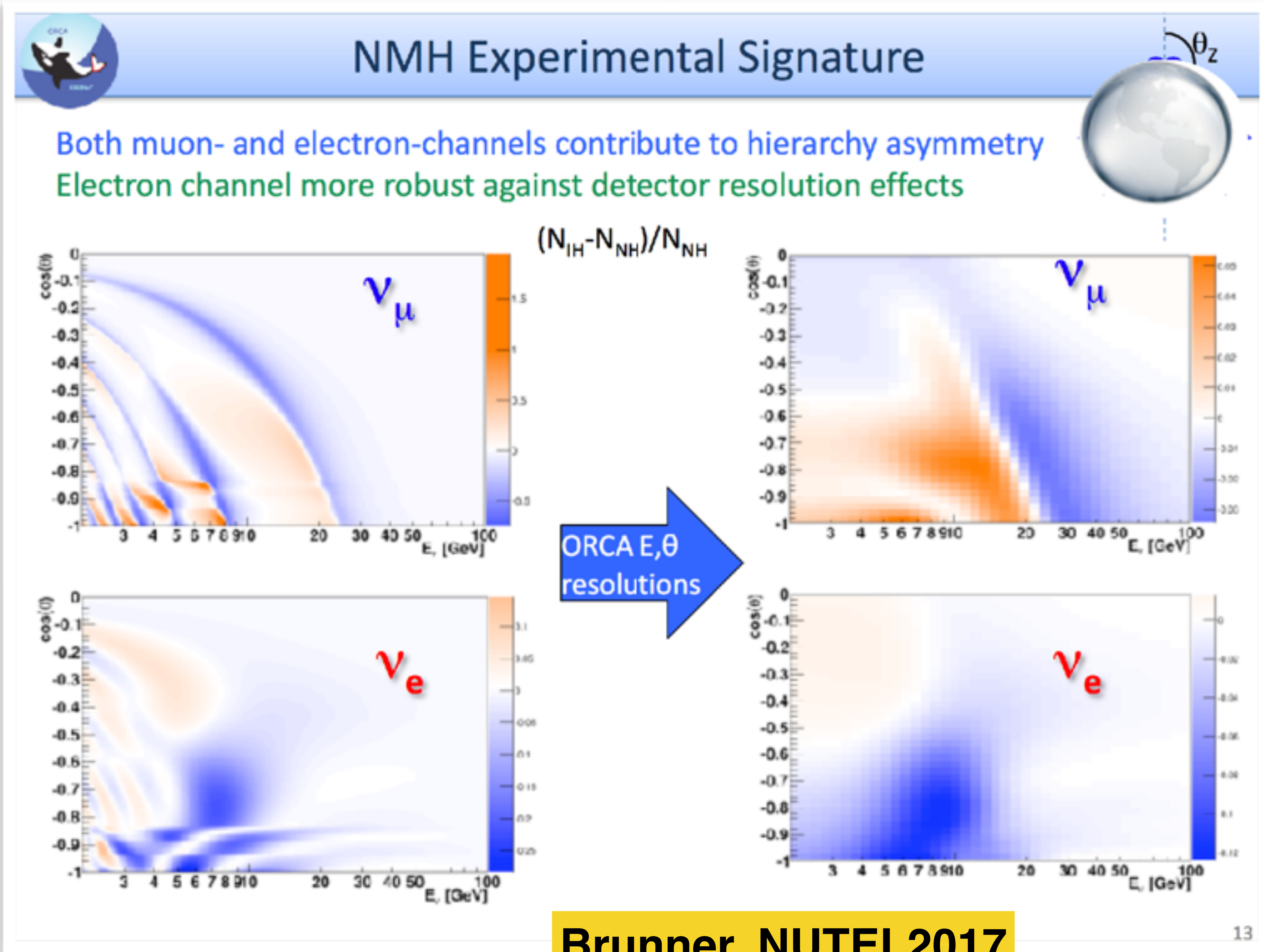
Depth=2475m

Digital Optical Module

- 31 x 3” PMTs
- Uniform angular coverage
- Directional information
- Digital photon counting
- Background rejection
- All data to shore

Brunner, NUTEL2017

7



Brunner, NUTEL2017

effetto risonante di interazione con la materia dei neutrini

CPV: misura della fase di Dirac della PMNS

LONG BASELINE

NEUTRINO OSCILLATIONS IN T2K

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - (\cos^4\theta_{13}\sin^2 2\theta_{23})\sin^2\left(\Delta m^2_{31}\frac{L}{4E}\right)$$

- Precise measurement of $\sin^2 2\theta_{23}$ and CPT test via ν vs anti-ν disappearance analysis

From Phys. Rev. D64 (2001) 053003

$$P(\nu_\mu \to \nu_e) \simeq \sin^2 2\theta_{13}\sin^2\theta_{23} \times \frac{\sin^2[(1-x)\Delta]}{(1-x)^2}$$

Leading term

CP-violating, "+" sign for anti-ν:

$$-\alpha \sin\delta_{CP} \times \sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23} \times \sin\Delta \frac{\sin[x\Delta]}{x}\frac{\sin[(1-x)\Delta]}{(1-x)}$$

CP-conserving:

$$+\alpha \cos\delta_{CP} \times \sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23} \times \cos\Delta \frac{\sin[x\Delta]}{x}\frac{\sin[(1-x)\Delta]}{(1-x)}$$

$$+O(\alpha^2) \qquad \alpha = \left|\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\right| \sim \frac{1}{30} \qquad \Delta = \frac{\Delta m^2_{31}L}{4E} \qquad x = \frac{2\sqrt{2}G_F N_e E}{\Delta m^2_{31}}$$

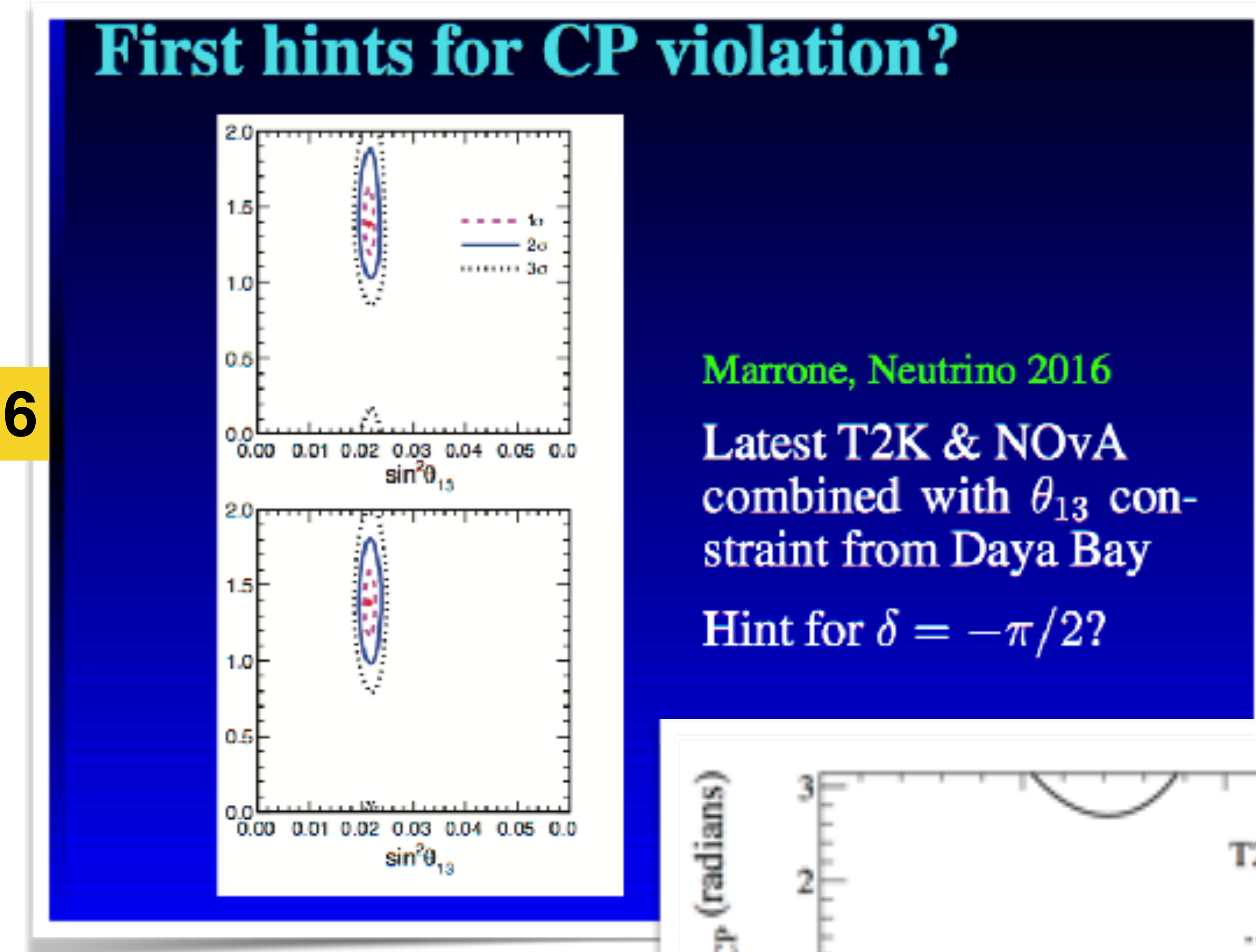
- Leading term defines the octant of θ_{23}: <, > or = 45°
- Sub-leading term accounts for CPV: enhanced effect when comparing neutrino and antineutrino data

CP PHASE/ CHANNEL	$P(\nu_\mu \to \nu_e)$	$P(\bar{\nu}_\mu \to \bar{\nu}_e)$
$\delta_{CP}=-\pi/2$	Enhance	Suppress
$\delta_{CP}=\pi/2$	Suppress	Enhance

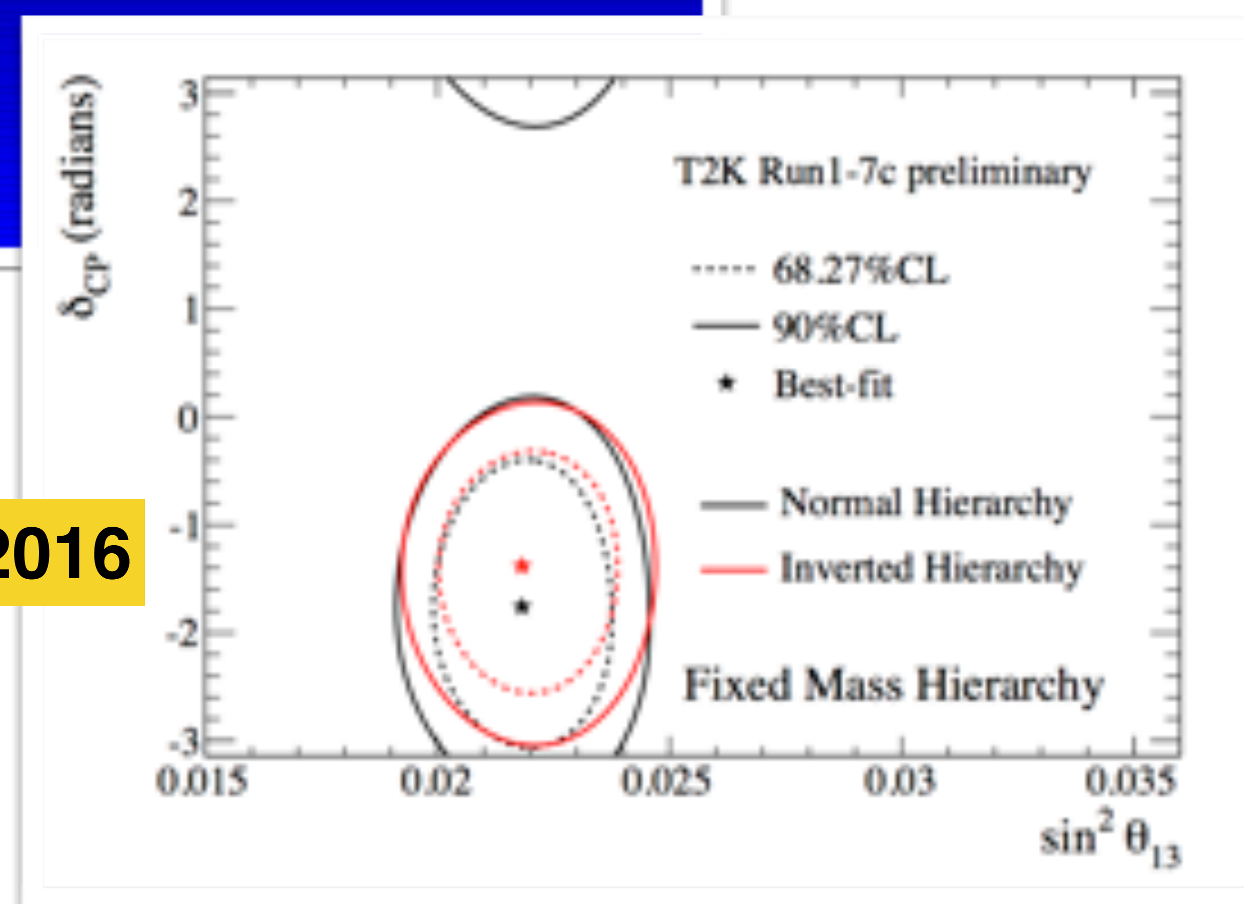
Izmailov, NUTEL2017

Stato misura di violazione di CP

Huber, NUFACT2016

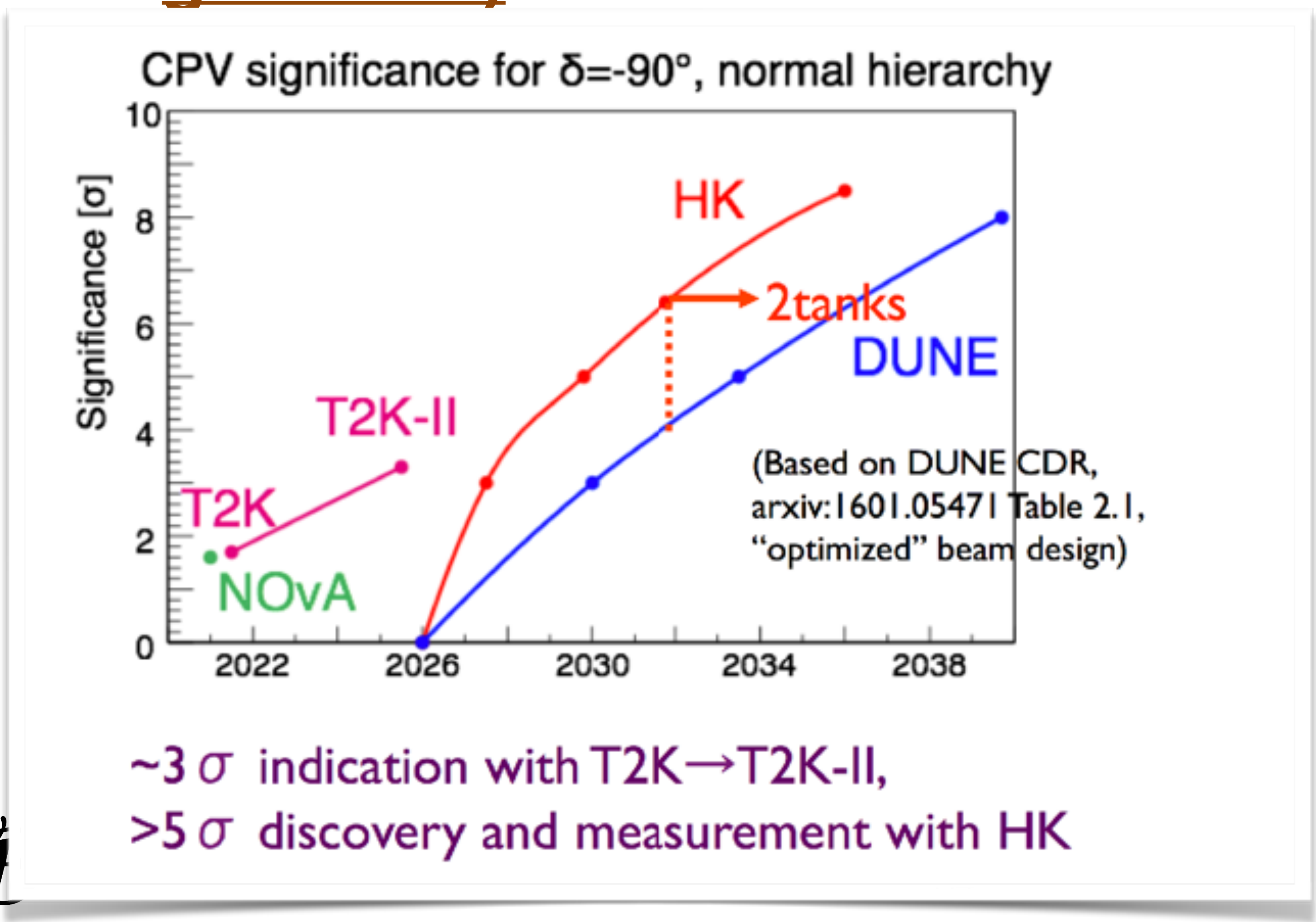


Mezzetto, NEUTRINO2016



Prospettive sulla misura di violazione di CP

La misura di precisone della fase di PNMS (almeno 10 gradi, necessaria per distinguere tra flavor models) richiede fasci intensi (2-3volte gli attuali) e rivelatori molto grandi (almeno 10 volte gli attuali)



Catanesi, NUTEL2017

sensibilita' simile a HK se entrambi normalizzati a 10anni

DUNE

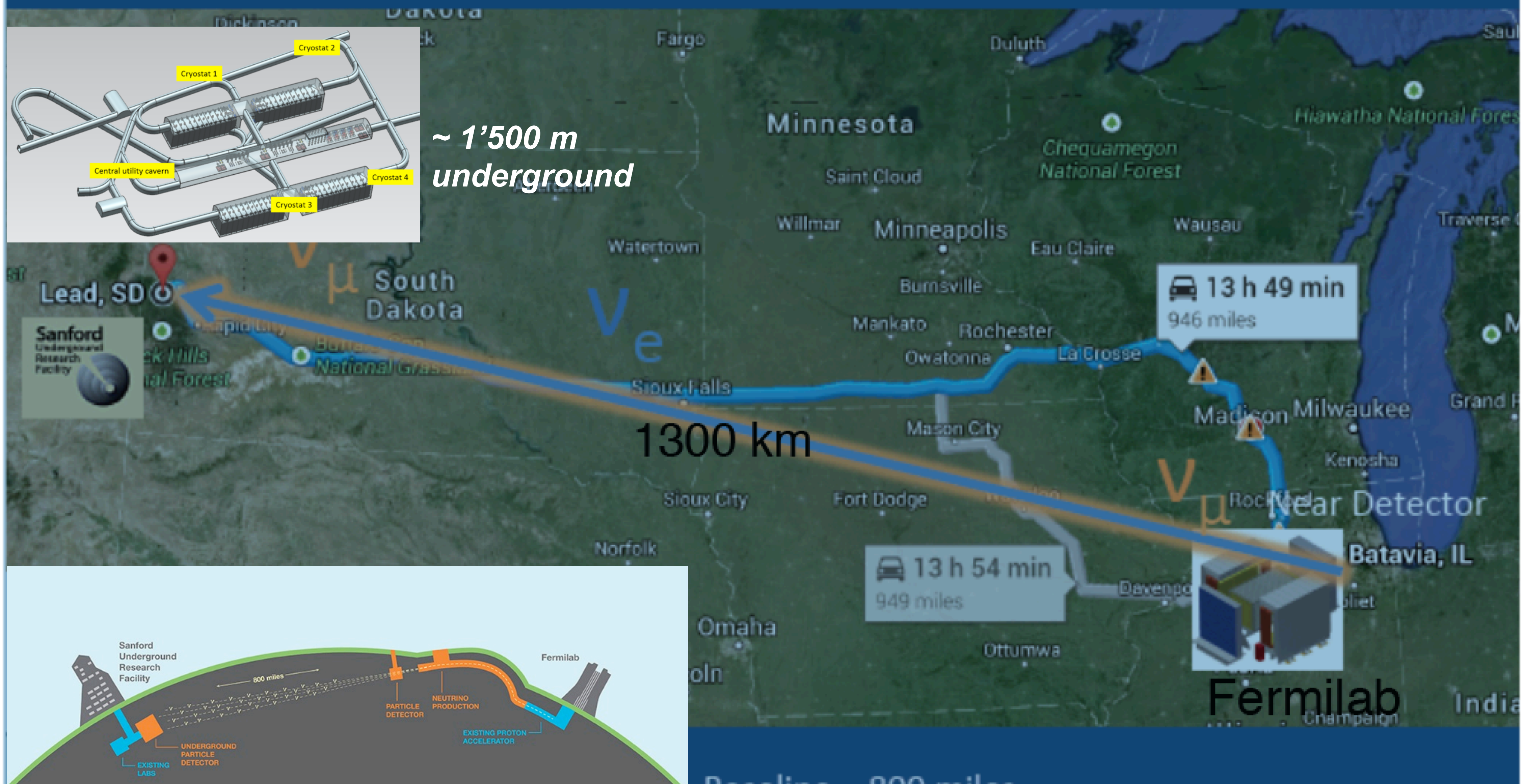
DUNE

A merger of all previous efforts and any other interested parties to build, operate, exploit

- a (staged) 40 Kt LAr detector, at the SURF site, 1300 Km from FNAL
- An high granularity/high precision near detector

exposed to a 1.2 MW, tunable ν beam produced by the PIP-II upgrade at FNAL by 2024, evolving to a power of 2.3 MW by ~ 2030.

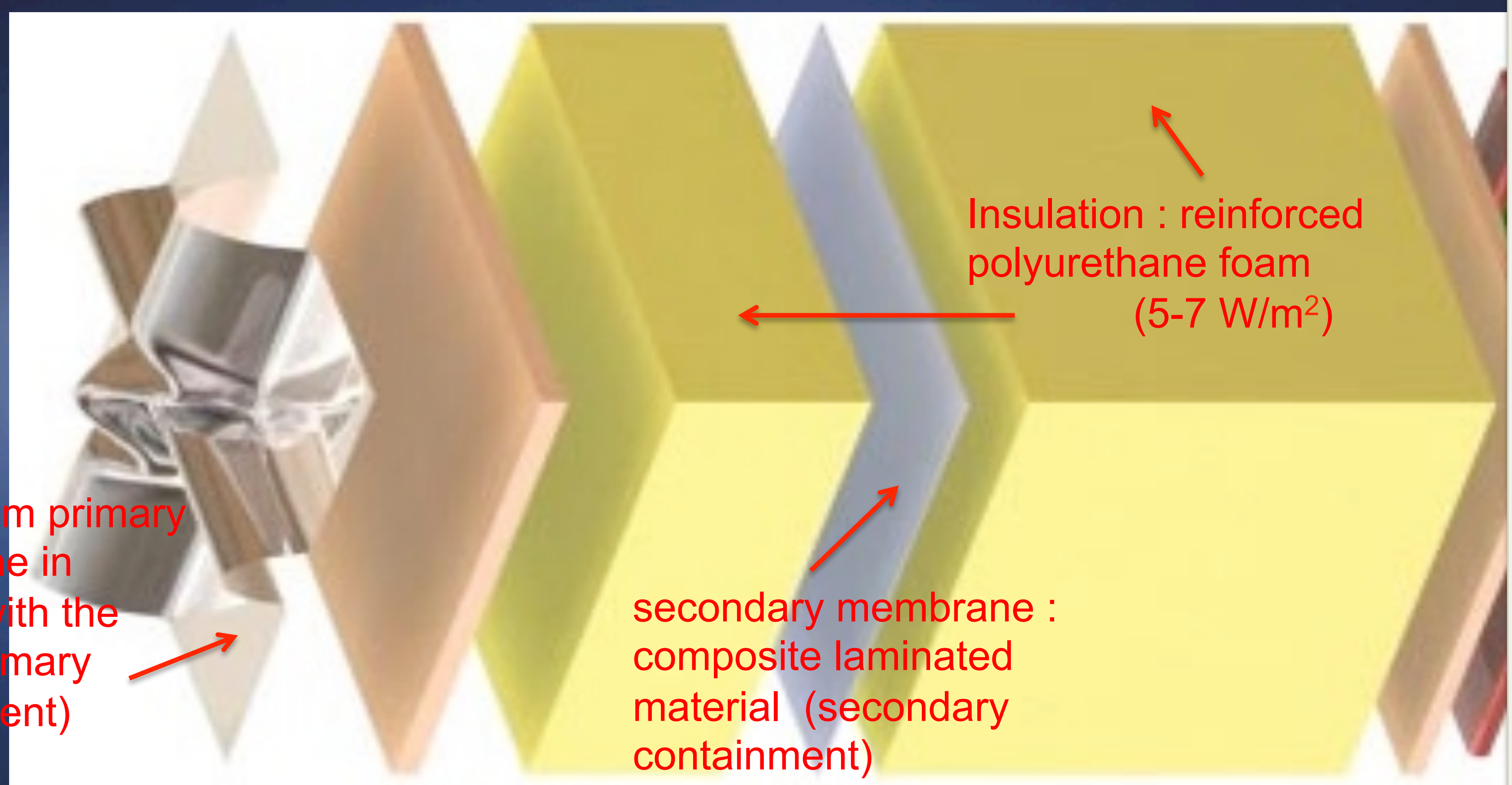
The Long Baseline Facility in the US (LBNF)



Baseline = 800 miles

New cryostat paradigm

- Cold cryostats technology based on LNG transport techniques



Warm structure : support structure

NEUTRINO CERN PLATFORM (LAr TPCs)

- …. the large scale is a big and new challenge

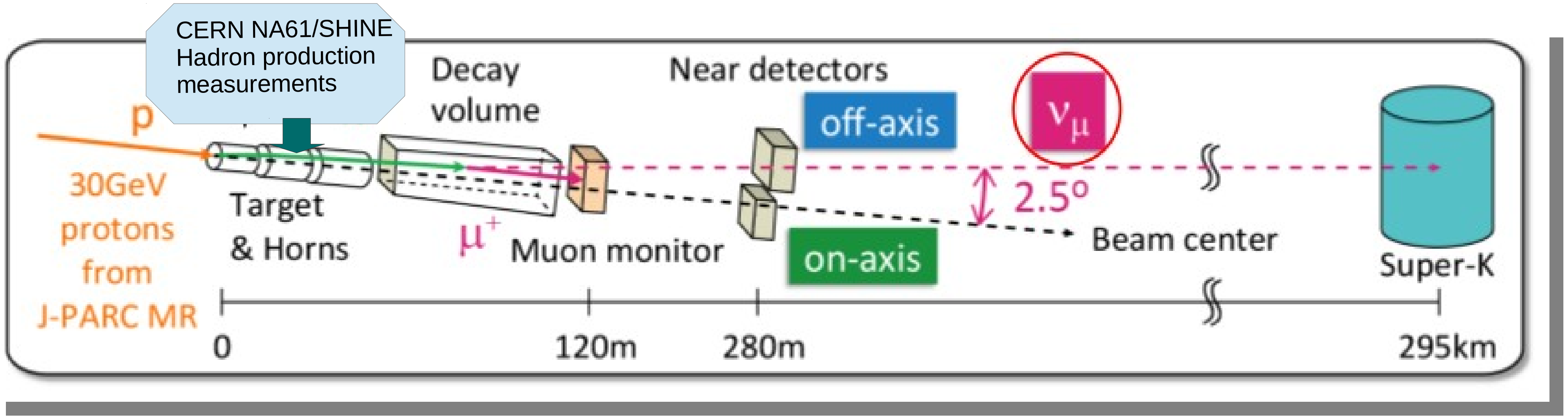
T2K-T2HK

The T2K experiment

Tokai-to-Kamioka

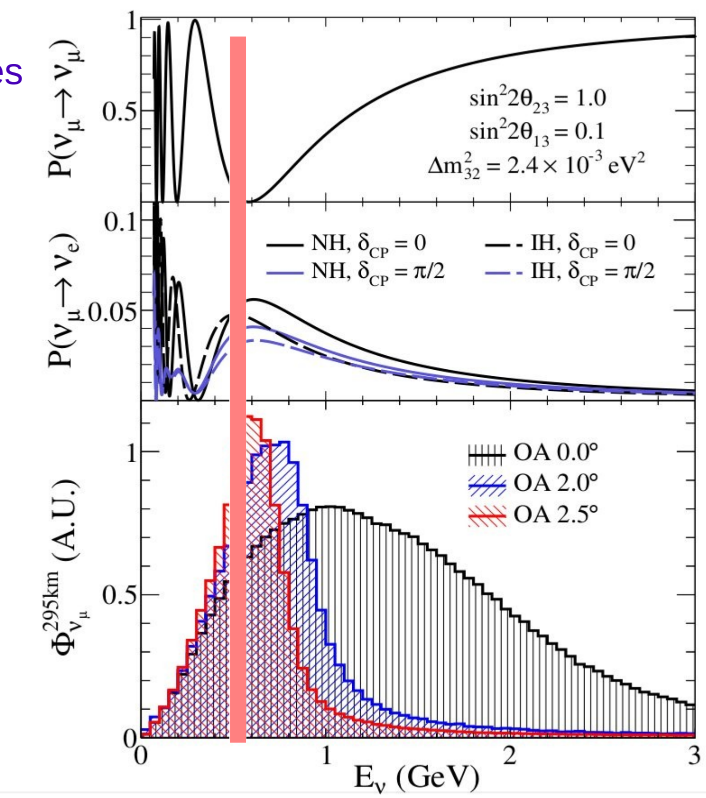
- 11 countries,
- 63 institutions
- ~500 people

T2K beam

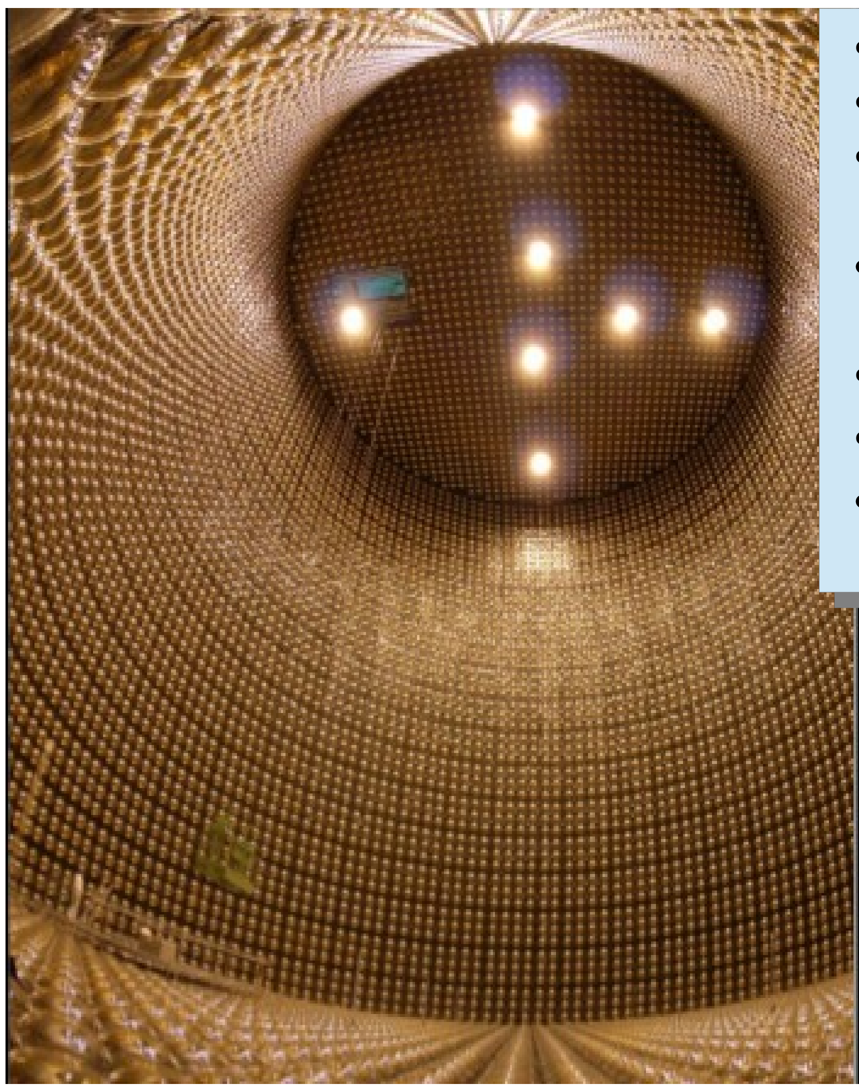


First use of off-axis ν_μ beam (moving away from beam axis changes ν energy spectrum) **:**

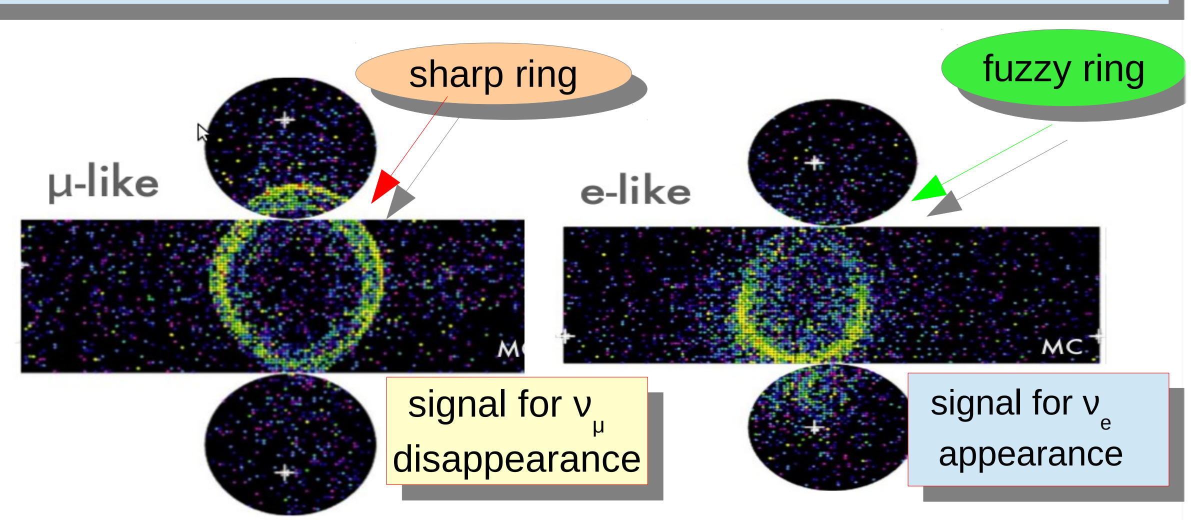
- E_ν peak around oscillation maximum (~0.6GeV).
- Small high energy tail → reduces feed-down background events.
- Intense & high quality beam - beam direction stability < 1mrad (~1 mrad shift corresponds to ~2% energy shift at peak).
- π,K production at target is measured using CERN NA61/SHINE exp.
- $\bar{\nu}$ beam production is obtained by reversing current in magnetic horns.



T2K Far Detector - Super-K



- 50 kton water Cherenkov Detector 1 km underground
- More than 11000 PMTs in the inner detector
- Efficient for CCQE-like interactions; select single ring - only leptons above threshold
- Neutrino flavour identification based on ring topology from charged particle
- Excellent muon-electron separation
- (<1% ν_μ misidentified as ν_e)
- No magnetic field (no separation between ν and $\bar{\nu}$)



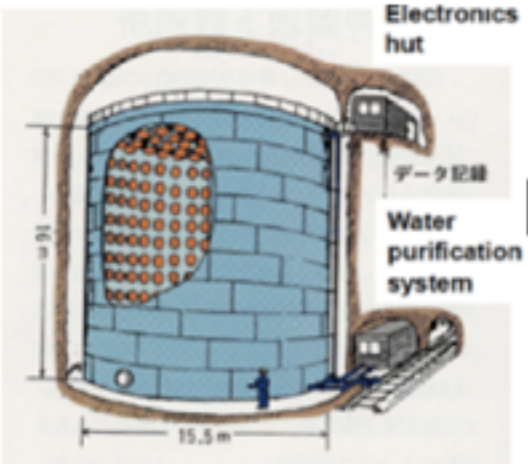
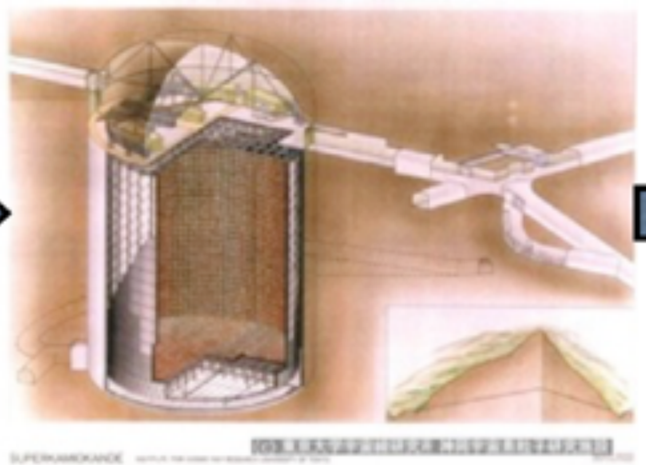
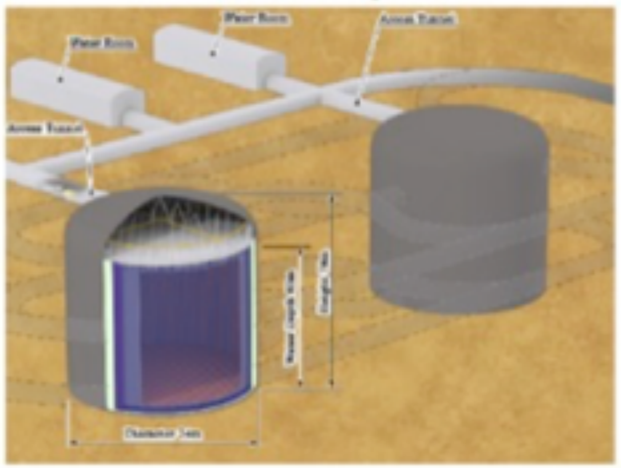
Tokai to Hyper-K (T2HK)

13

- Long baseline oscillation using the J-PARC neutrino beam-line (as T2K)
- Same off-axis angle (2.5°) as Super-K
- Improved Neutrino Beam (1.3 MW)

3 generations of Kamiokande family

2

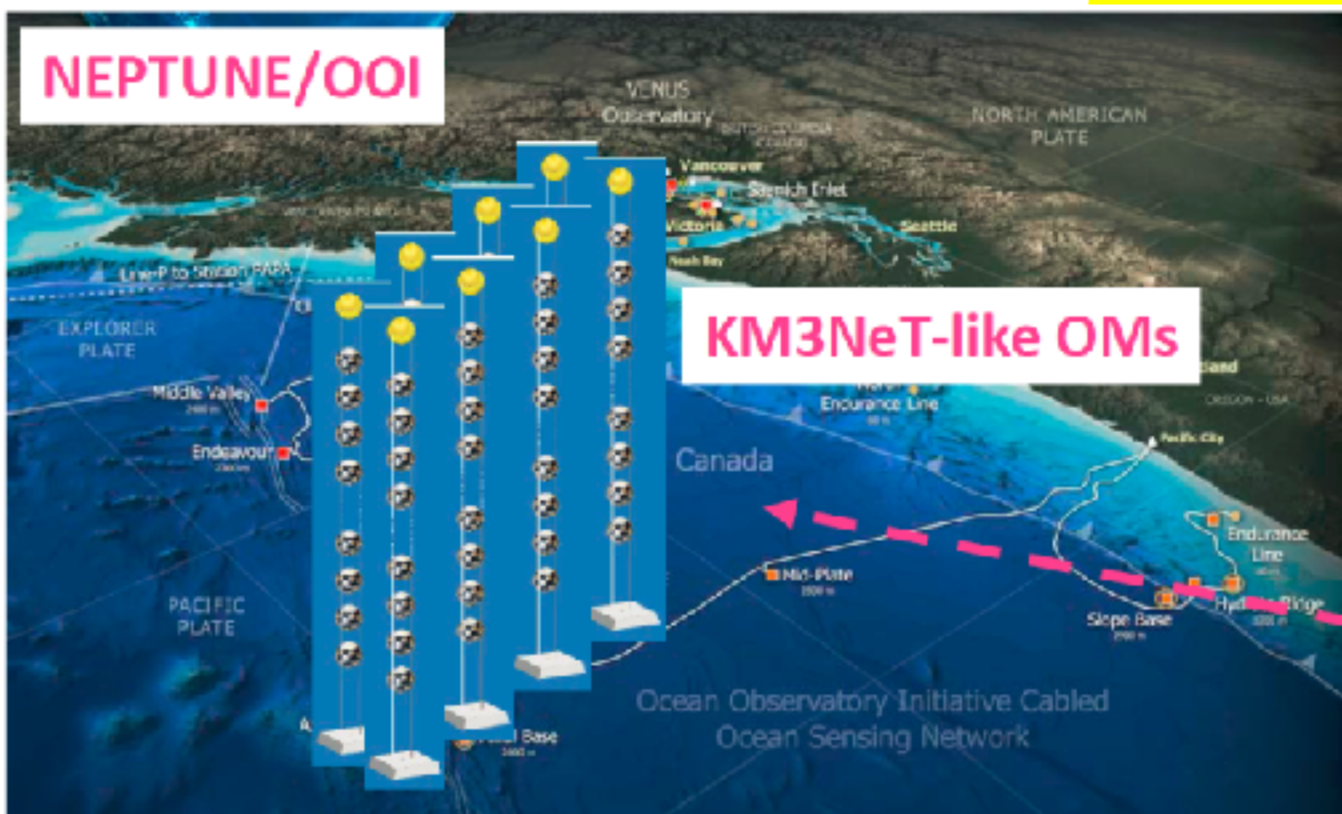
Kamiokande (1983-1996)	Super-Kamiokande (1996-)	Hyper-Kamiokande (~2026-)
		
3kton	50kton	260kton×2
20% coverage with 50cm PMT	40% coverage with 50cm PMT	40% coverage with high-QE 50cm PMT

- Larger mass for more statistics
- Better sensitivity by more photons with improved sensors

New long baseline ideas:

T2HKK

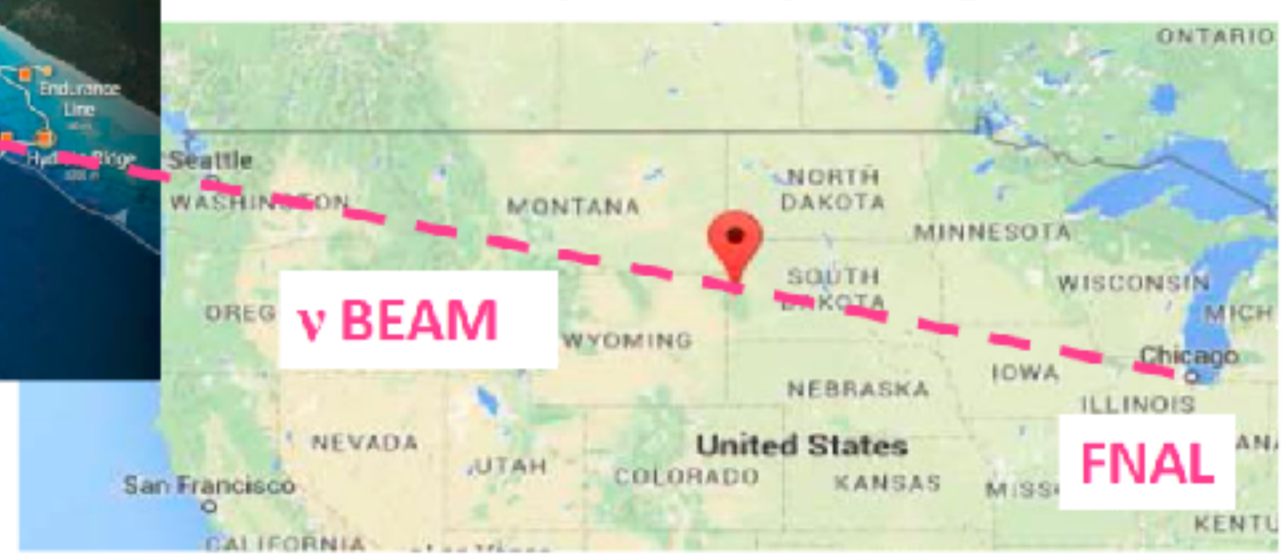
PACIFIC NEUTRINOS



1 OM/kton water (~ORCA granularity)

→ instrumentation of 10 Mton water for a cost of ~ 100 M€

NB: Detector volume only limited by sensor funding



Mechanical layout may/can be adapted to optimize the detector topology

A caccia del IV neutrino

E' un esempio di ricerca stimolata da una anomalia sperimentale, che, se si dimostrasse vera, potrebbe avere una conseguenza molto interessante

—> peraltro ce n'e' un altra adesso (il bump a 5MeV)…

Il campo e' complesso, nemmeno gli esperti del ramo son concordi nel dire ciò che e' escluso e ciò che non lo e'

Molta competizione internazionale! Escludere il gia' escluso non molto entusiasmante…quindi chi primo arriva…situazione in RAPIDISSIMA evoluzione

Tipicamente il framework utilizzato e' il 3+1; ma naturalmente bisogna ragionare in termini più generali di 3+n

Anomalie sperimentali:

LSND + MiniBoone: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ signal (3.8σ): $U_{e\mu}=U_{\mu 4}U_{e4}$

Gallex/SAGE ν_e disappearance (51Cr e 37Ar sources) (3.8σ): U_{e4}

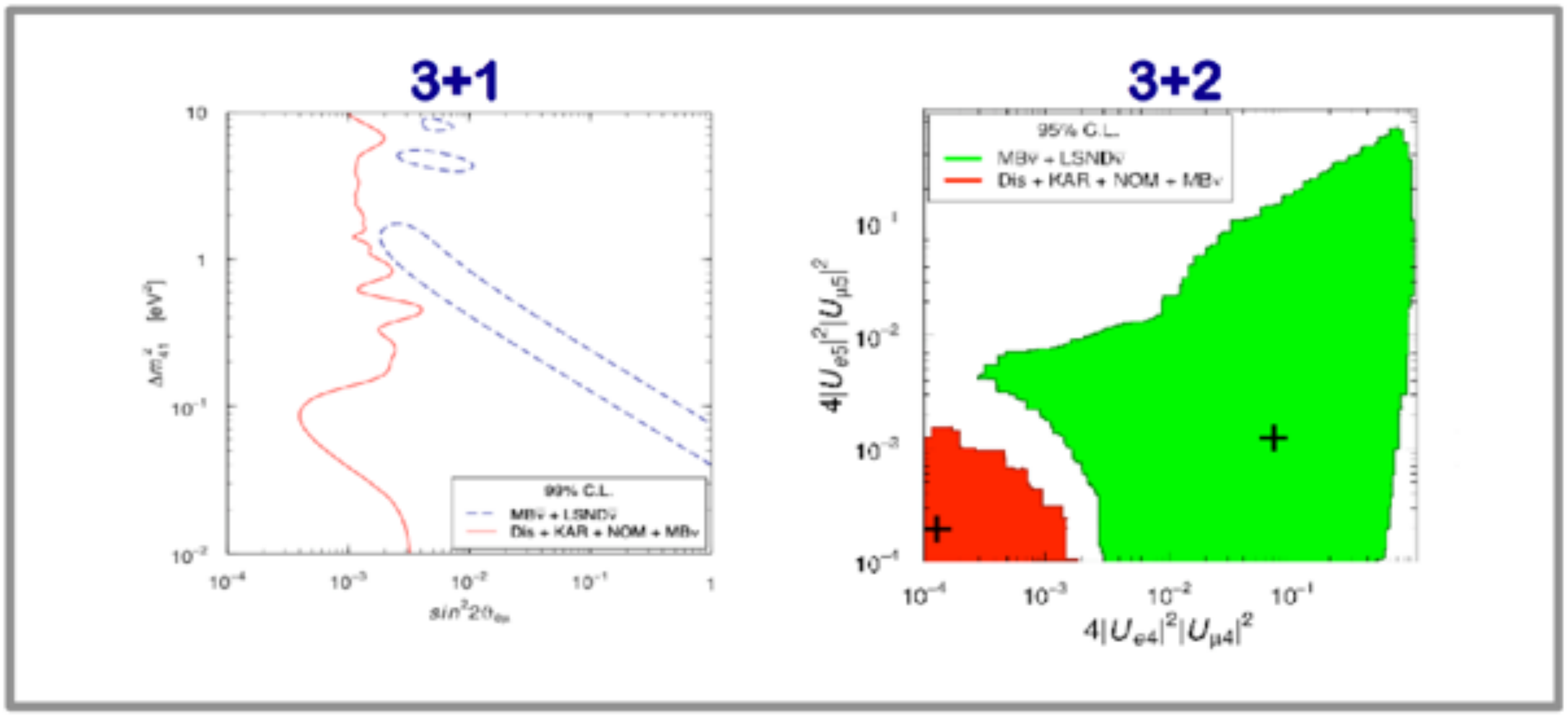
Reactor $\bar{\nu}_e$ disappearance (2.5σ): U_{e4}

Vigorous experimental program to check conclusively in a few years:

L/E≈1 (m/MeV)

ν_e and $\bar{\nu}_e$ disappearance (or oscillatory behaviour) with reactors and radioactive sources: U_{e4}
$\nu_\mu \rightarrow \nu_e$ transitions with accelerator neutrinos: $U_{e\mu}=U_{e4}*U_{\mu 4}$
ν_μ disappearance with accelerator e atmospheric neutrinos: $U_{\mu 4}$

Tension in all ν_s models

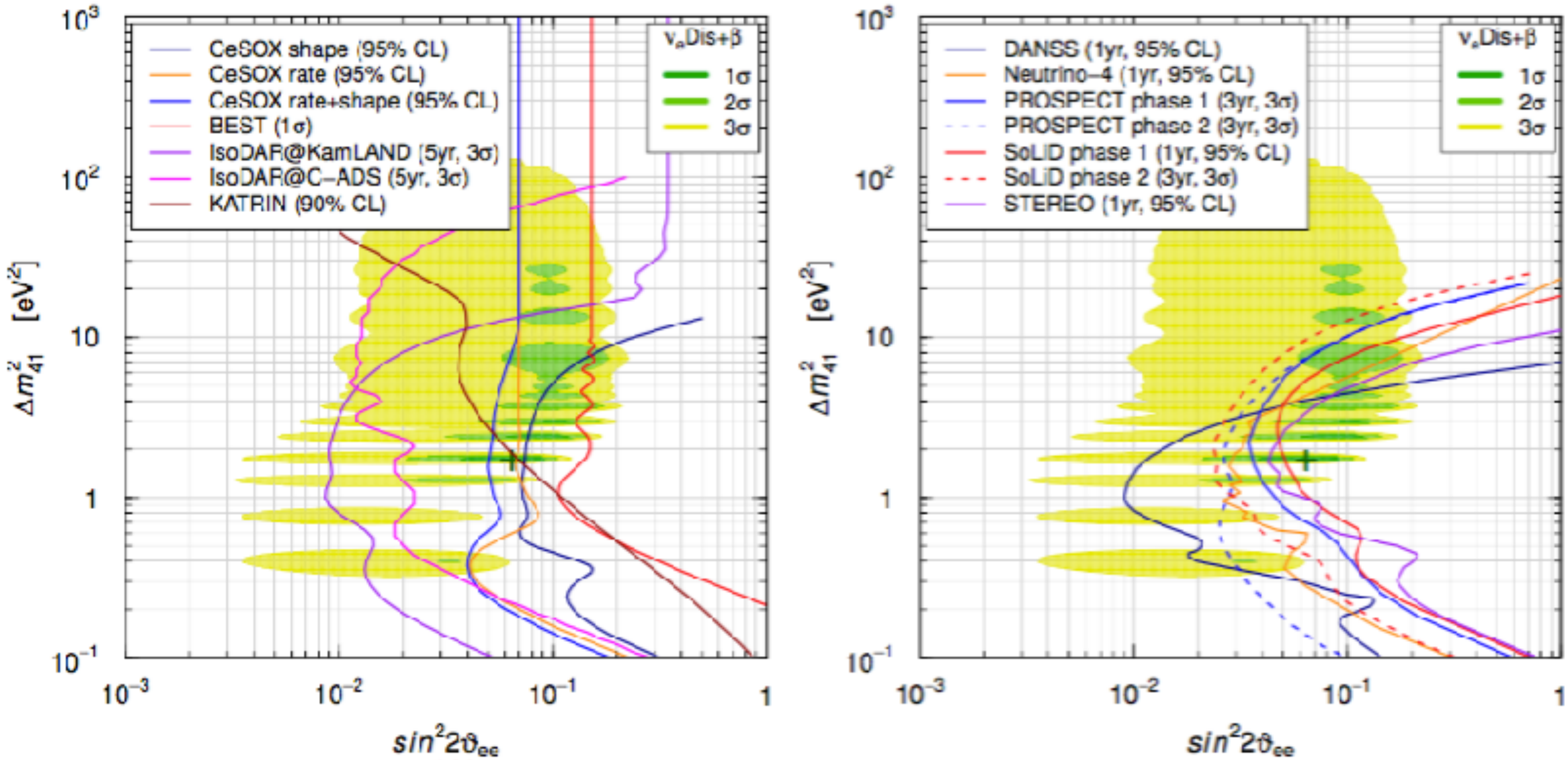


Giunti
&
Laveder

arXiv:1107.1452

combinazione degli esperimenti con qualche problema…

The Race for ν_e and $\bar{\nu}_e$ Disappearance



CeSOX (Gran Sasso, Italy) $^{144}Ce \to \bar{\nu}_e$
BOREXINO: $L \simeq$ 5-12m [Vivier@TAUP2015]

BEST (Baksan, Russia) $^{51}Cr \to \nu_e$
$L \simeq$ 5-12m [PRD 93 (2016) 073002]

IsoDAR@KamLAND (Kamioka, Japan)
$^{8}Li \to \bar{\nu}_e$ $L \simeq$ 16m [arXiv:1511.05130]

IsoDAR@C-ADS (Guangdong, China)
$^{8}Li \to \bar{\nu}_e$ $L \simeq$ 15m [JHEP 1601 (2016) 004]

DANSS (Kalinin, Russia) $L \simeq$ 10-12m [arXiv:1606.02896]

Neutrino-4 (RIAR, Russia) $L \simeq$ 6-11m [JETP 121 (2015) 578]

PROSPECT (ORNL, USA) $L \simeq$ 7-12m [arXiv:1512.02202]

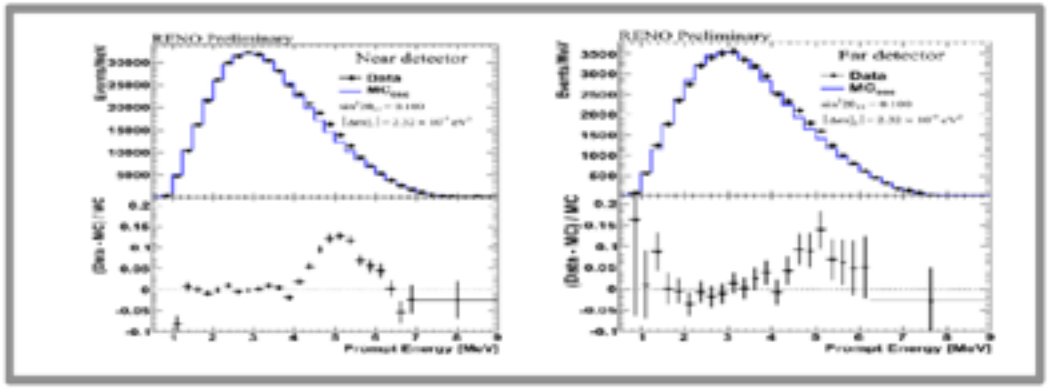
SoLid (SCK-CEN, Belgium) $L \simeq$ 5-8m [arXiv:1510.07835]

STEREO (ILL, France) $L \simeq$ 8-12m [arXiv:1602.00568]

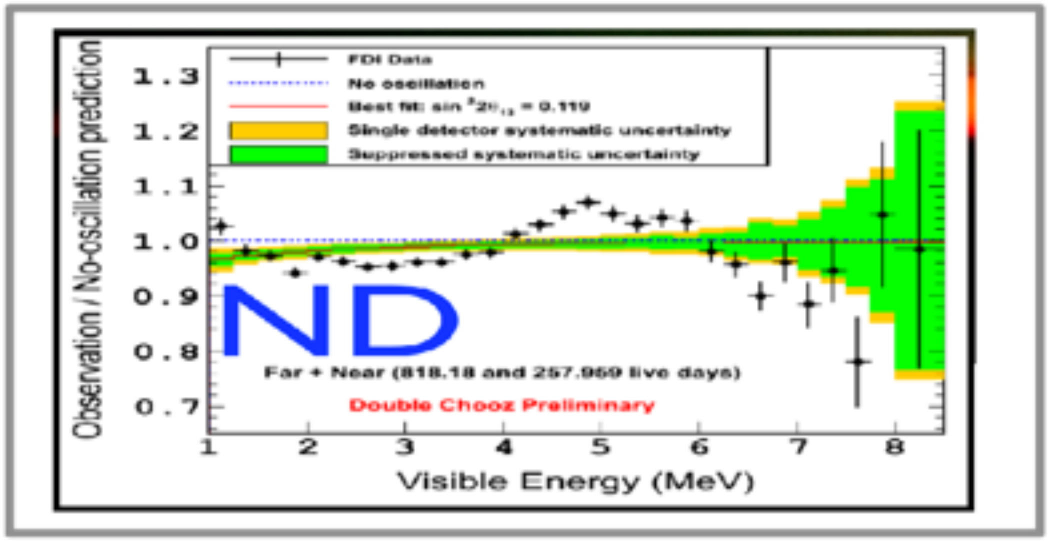
KATRIN (Karlsruhe, Germany) $^{3}H \to \bar{\nu}_e$ [Drexlin@NOW2016]

Understanding of reactor spectrum is incomplete

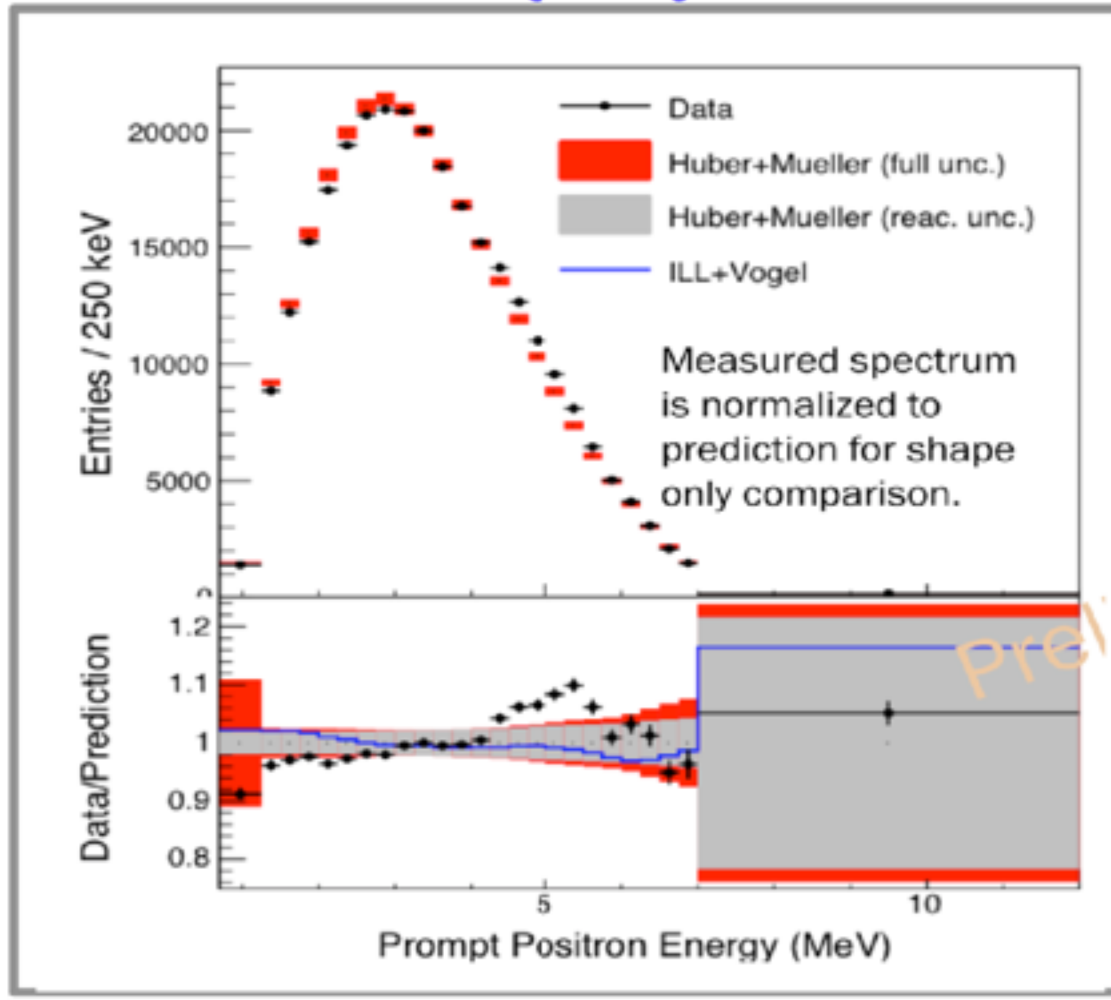
RENO



Double-CHOOZ



Daya Bay



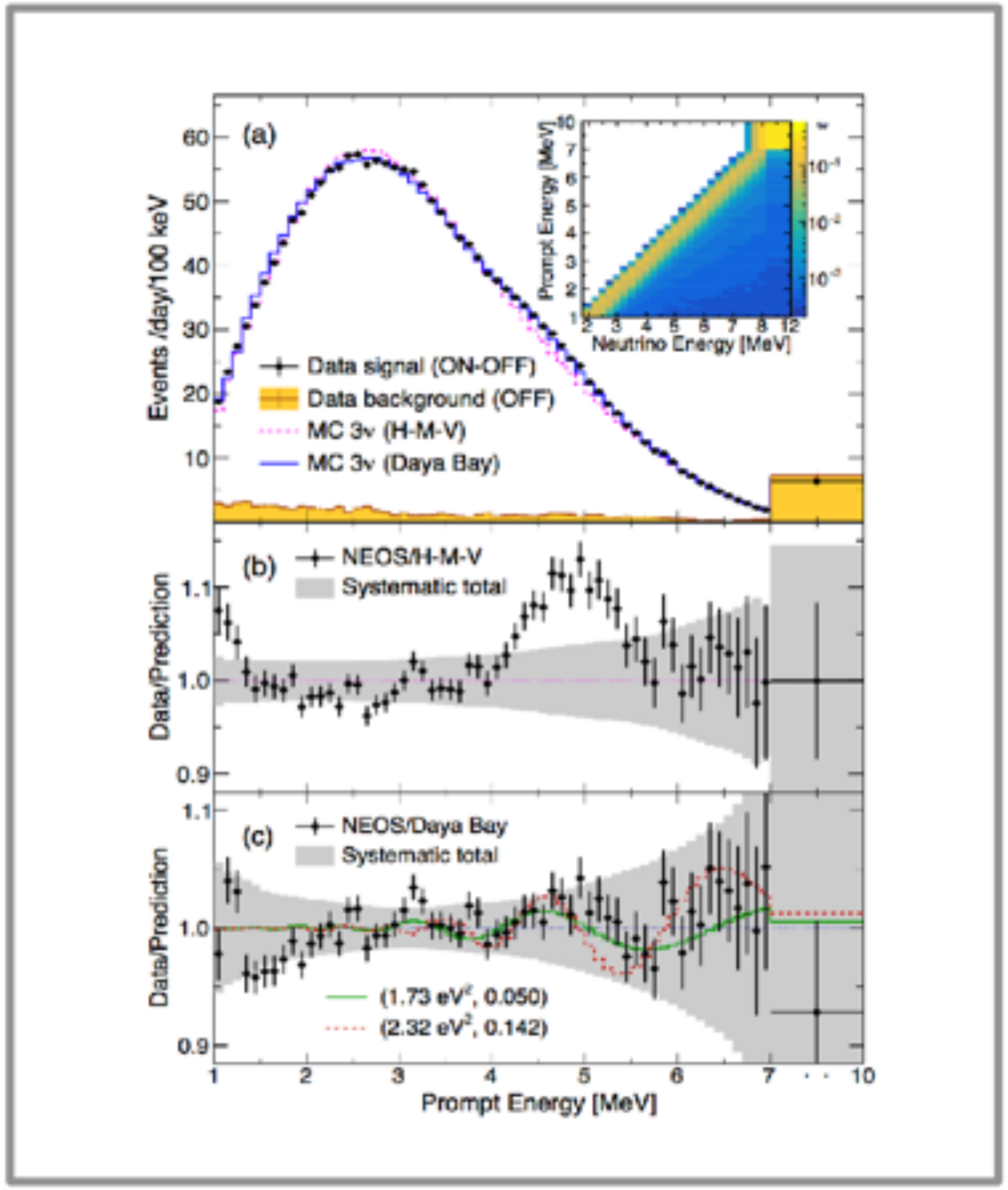
Bump/shoulder at 5 MeV observed in all the three experiments

Found both a near & far sites: not imputable to new osc. physics

θ_{13} extraction is unaffected (based on near/far comparison)

Palazzo, NUTEL2017

3) NEOS: scent of sterile neutrinos!



NEOS arXiv:1610:05134

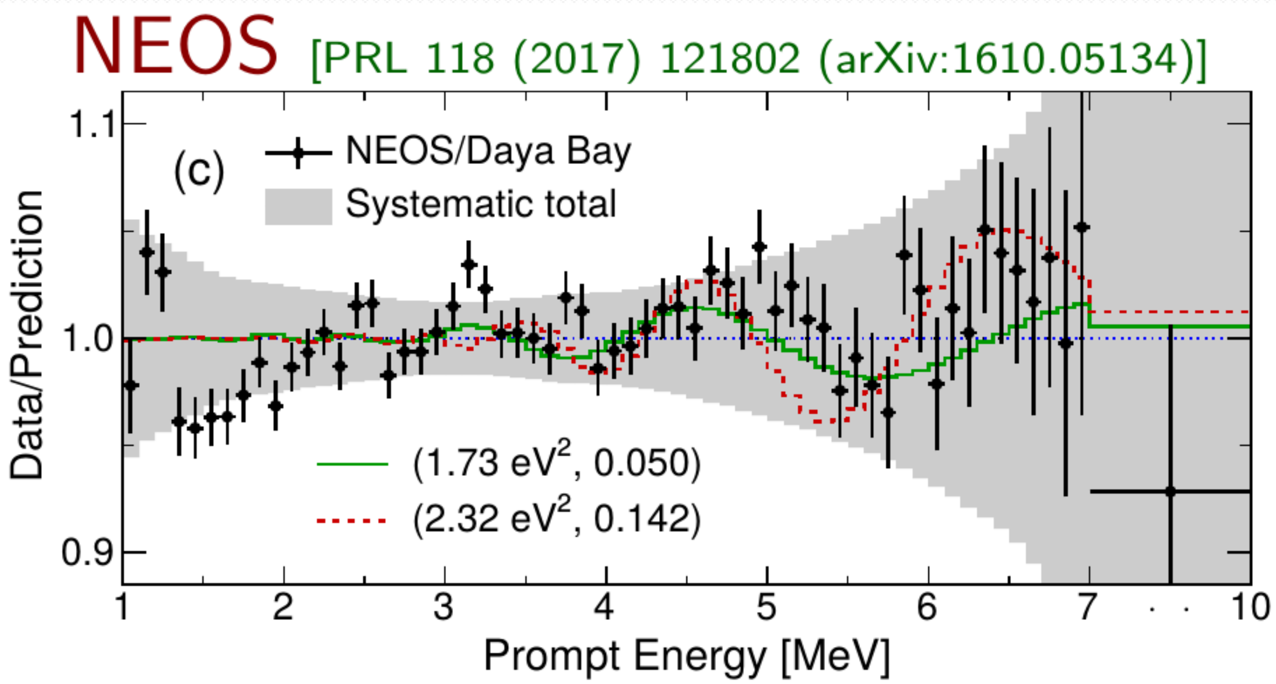
Hanbit Nuclear Power Complex, Korea

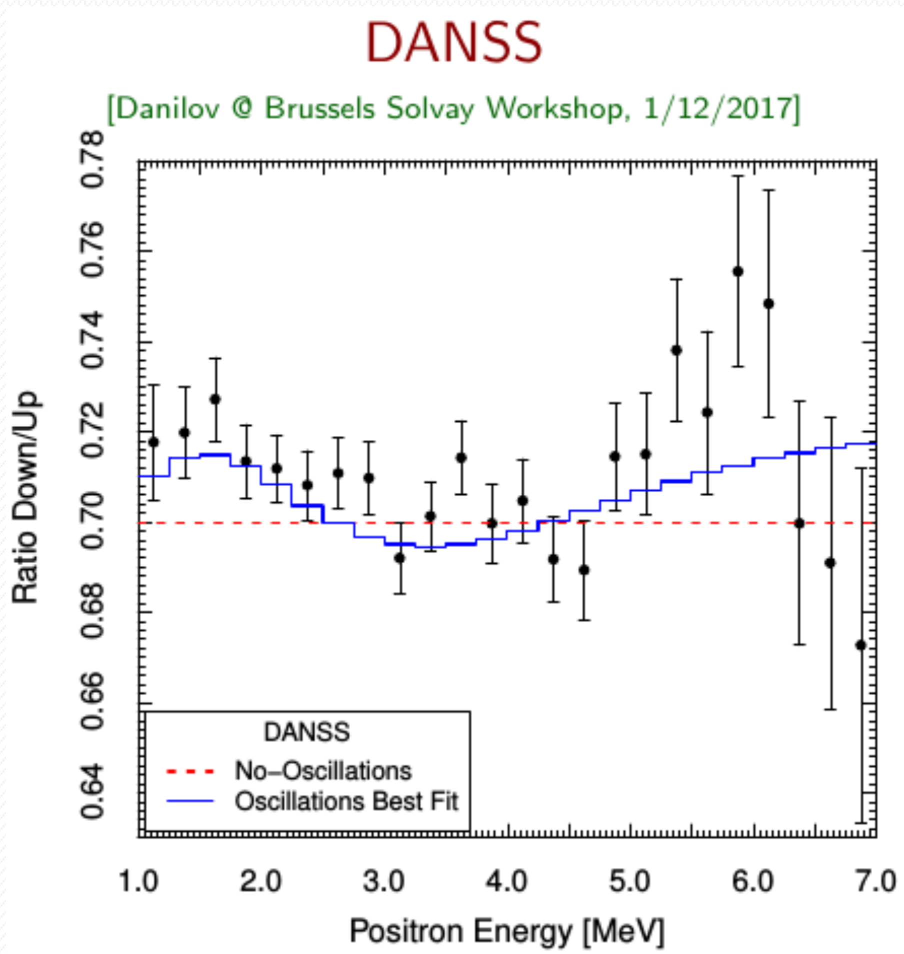
Detector: 1 ton Gd-loaded liquid scintillator 24 m from the reactor core

Daya-Bay absolute spectrum used as a normalization

Oscillating pattern visible after normalization

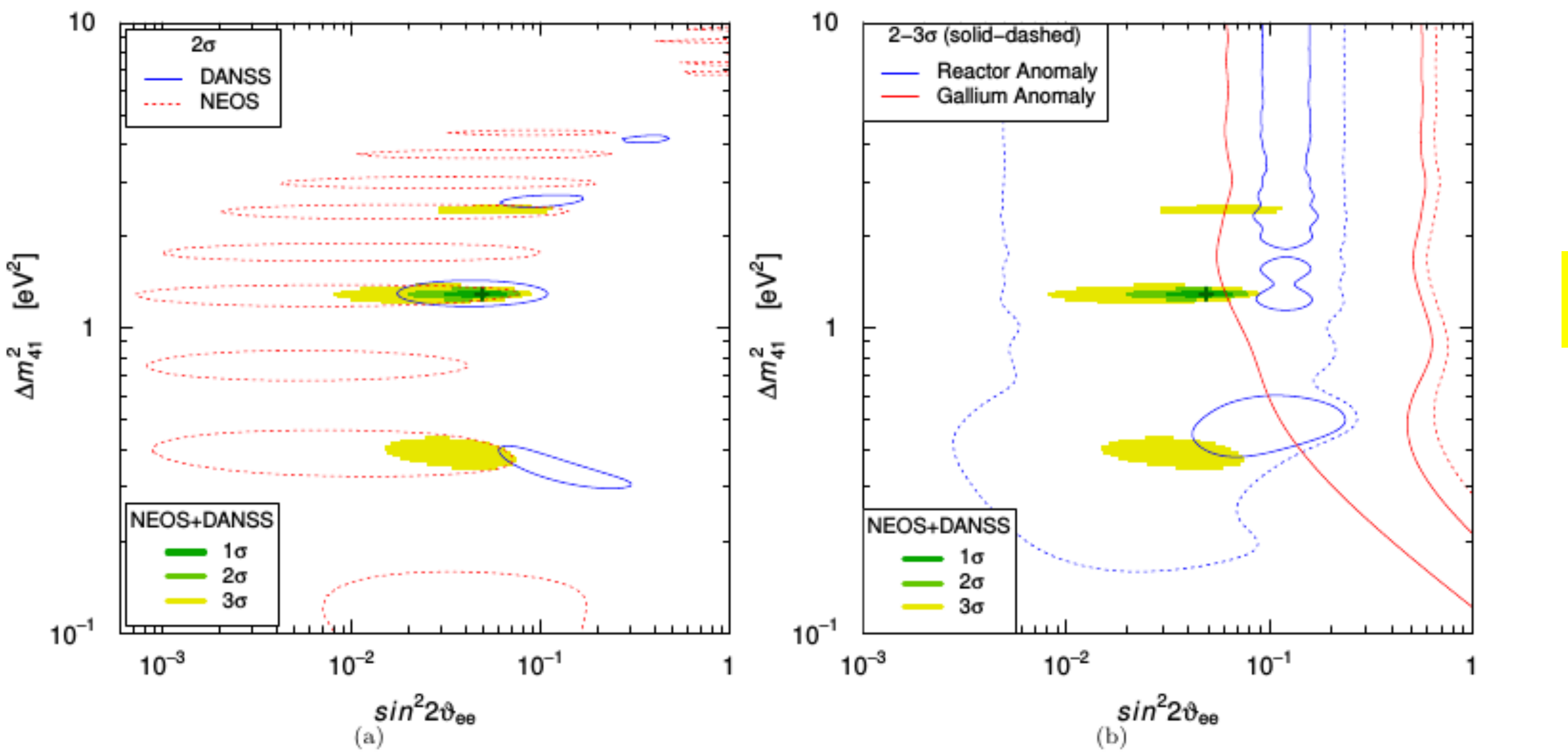
Palazzo, NUTEL2017





- … e ora abbiamo DANSS che pare confermare!

- Ci si può sbizzarrire nei fit globali:



S. Gariazzo et al., ArXiv 1801.06467

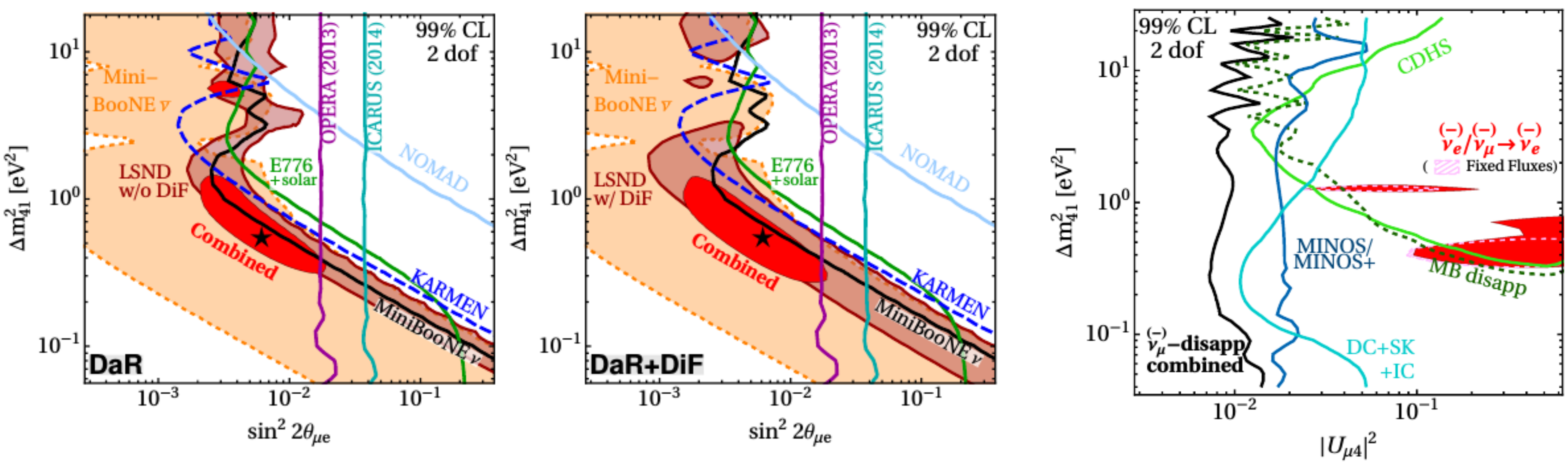
$$\Delta m^2_{41} \simeq 1.3\,\mathrm{eV}^2$$

Compatibile con l'anomalia GALLEX + SAGE!

MODEL INDEPENDENT!

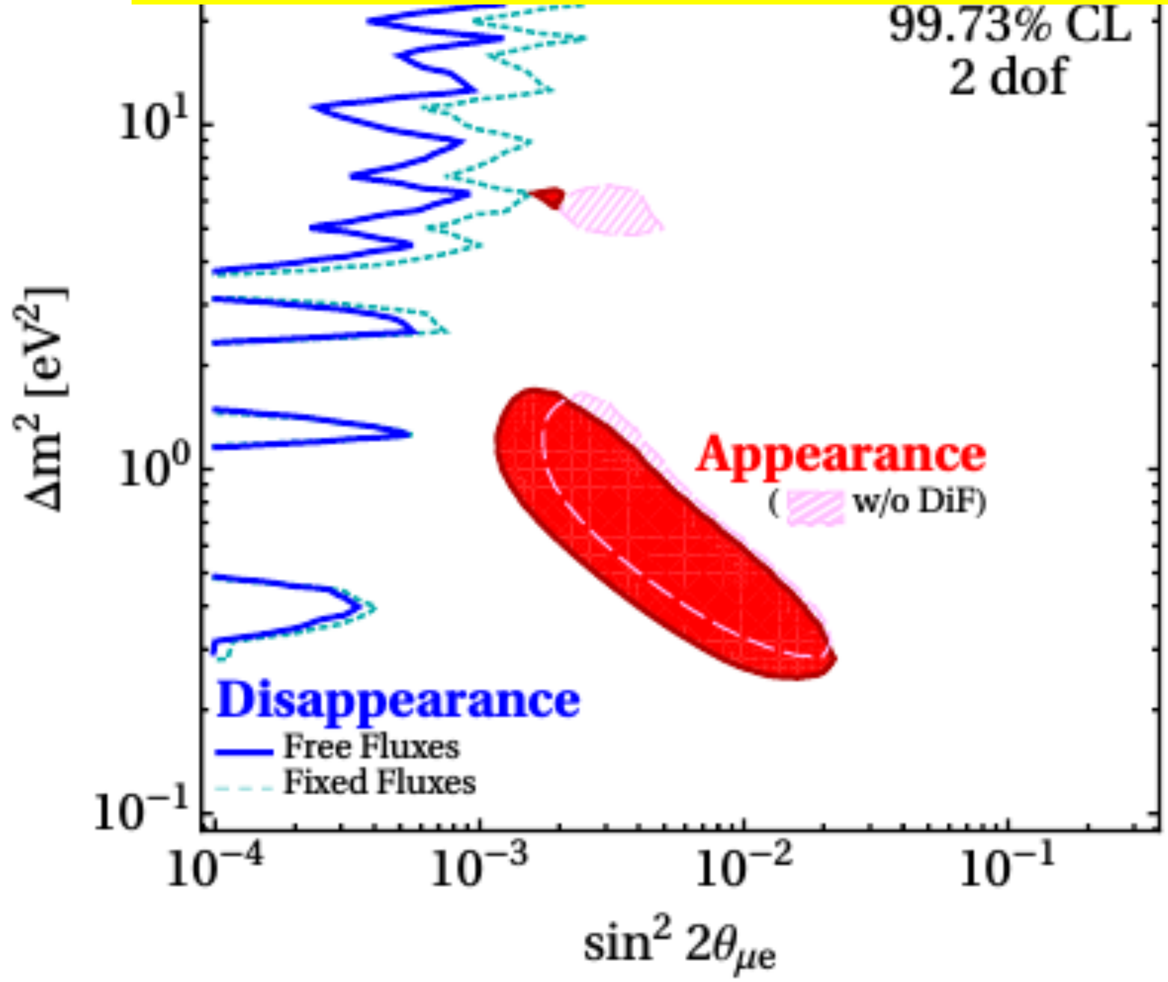
$\sim 3.5\sigma$

- Si può poi tenere conto di $\nu\mu \rightarrow \nu e$ e $\nu\mu$ disappearance e la situazione inizia a sfuggire di mano…



- … si mescola il tutto e…

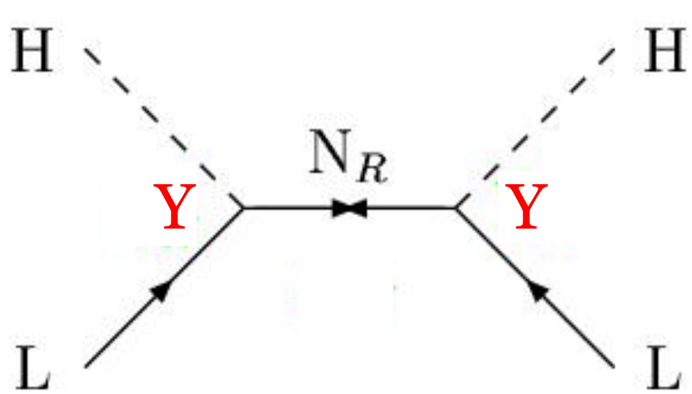
M. Dentler et al., ArXiv 1803.10661



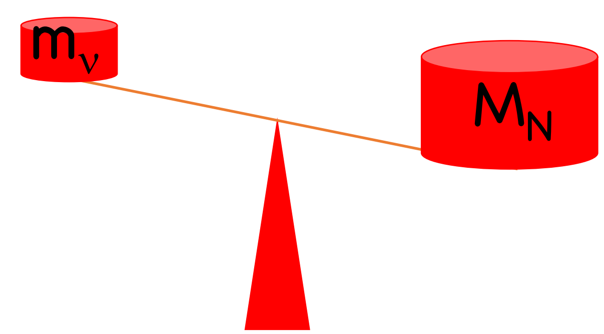
Qui MiniBooNE è incluso e c'è DANSS: tensione tra appearance e disappearance

Minimal model of neutrino masses: SM+right-handed neutrinos

$$\mathcal{L}_\nu = -\bar{l} Y \tilde{\Phi} N_R - \frac{1}{2} \bar{N}_R M N_R + h.c.$$

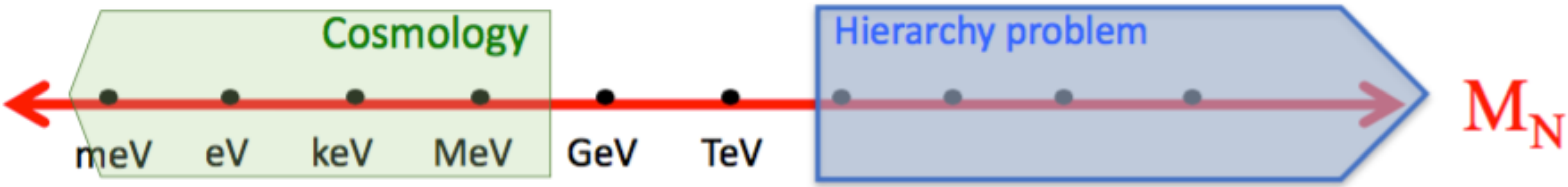


$$n_R \geq 2$$



$$m_\nu = \lambda \frac{v^2}{\Lambda} \equiv Y^T \frac{v^2}{M} Y$$

Minkowski; Yanagida; Glashow; Gell-Mann, Ramond Slansky; Mohapatra, Senjanovic...



Sterile neutrinos below 100MeV can strongly modify

Big-Bang Nucleosynthesis
Cosmic Microwave background
Large Scale structure

Notzold, Raffelt; Barbieri&Dolgov; Kainulainen....;
Dolgov, Hansen, Raffelt,Semikoz;
Ruchayskiy, Ivashko;Vincent et al;
PH, Kekic, Lopez-Pavon

Either they contribute too much radiation or too much matter, modifying in unacceptable ways the expansion history and/or growth of perturbations

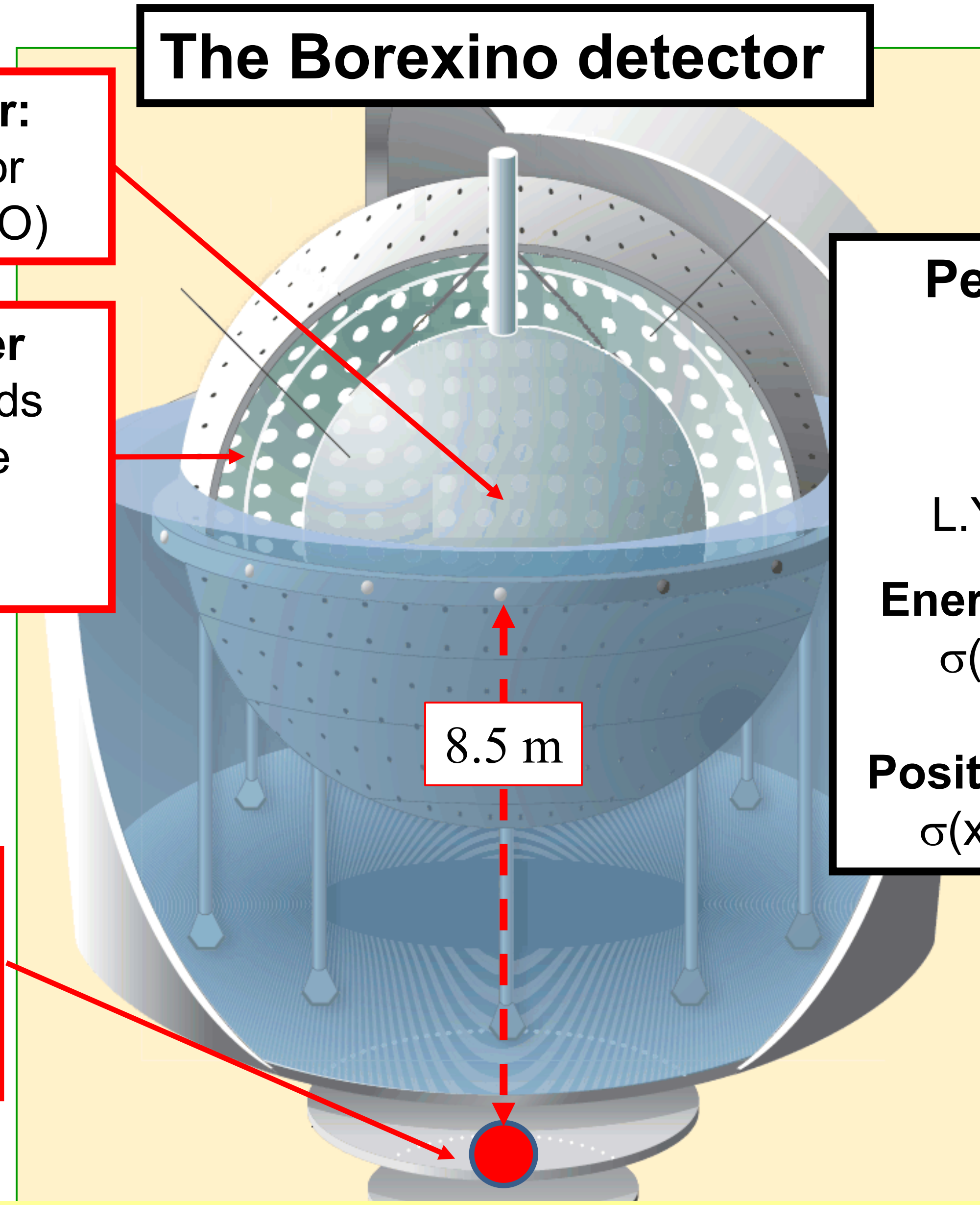
SOX

SOX: Short distance ν_e Oscillations with boreXino

Core of the detector:
300 tons of scintillator
(pseudocumene+PPO)

2212 photomultiplier tubes pointing towards the center to view the light emitted by the scintillator;

PIT under the detector where the source will be located.



Performances of Borexino

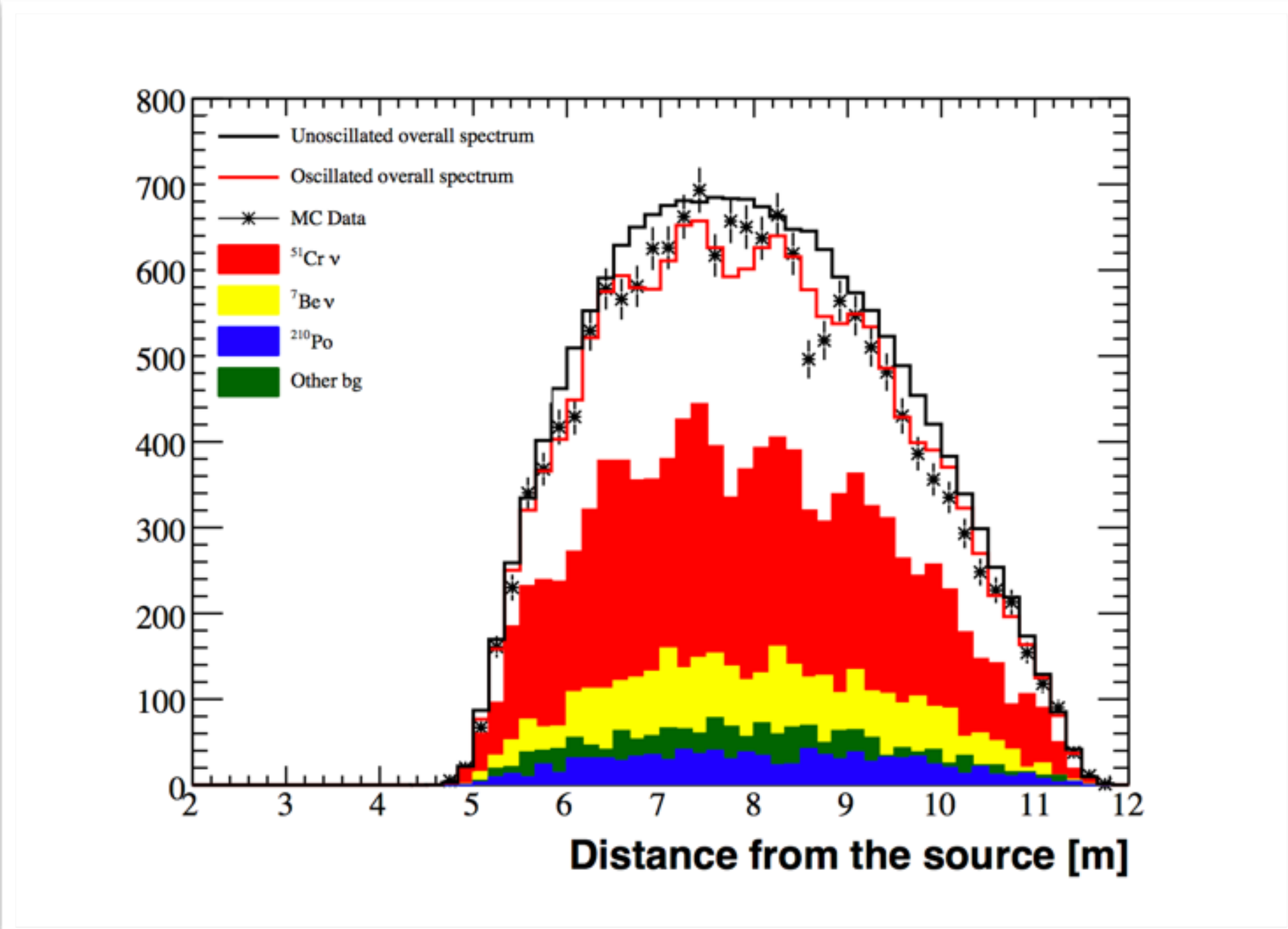
Light Yield
L.Y.~ 500 p.e./MeV

Energy reco capability
$\sigma(E)$= 5% @1MeV

Position reco capability
$\sigma(x)$=10 cm @1MeV

Short distance neutrino oscillations with Borexino - Barbara Caccianiga (INFN-Milano)

^{144}Ce; Time~1.5 years, activity=100 kCi; R<4.25m



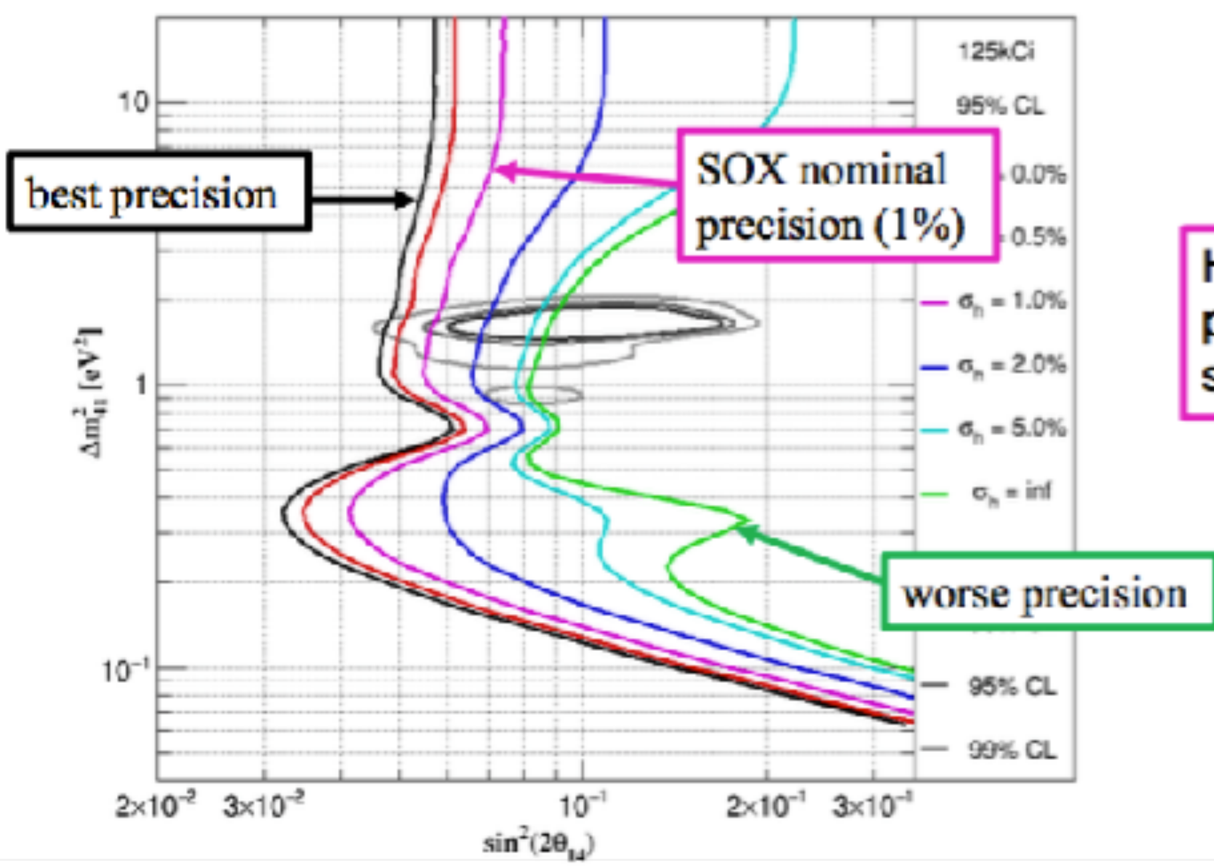
a spectacular signature!

rivelazione di IBD

sorgente di 100 kCi (3.7 x 10^{15} ν/sec) ^{144}Ce-^{144}Pr

SOX: the importance of knowing the source activity

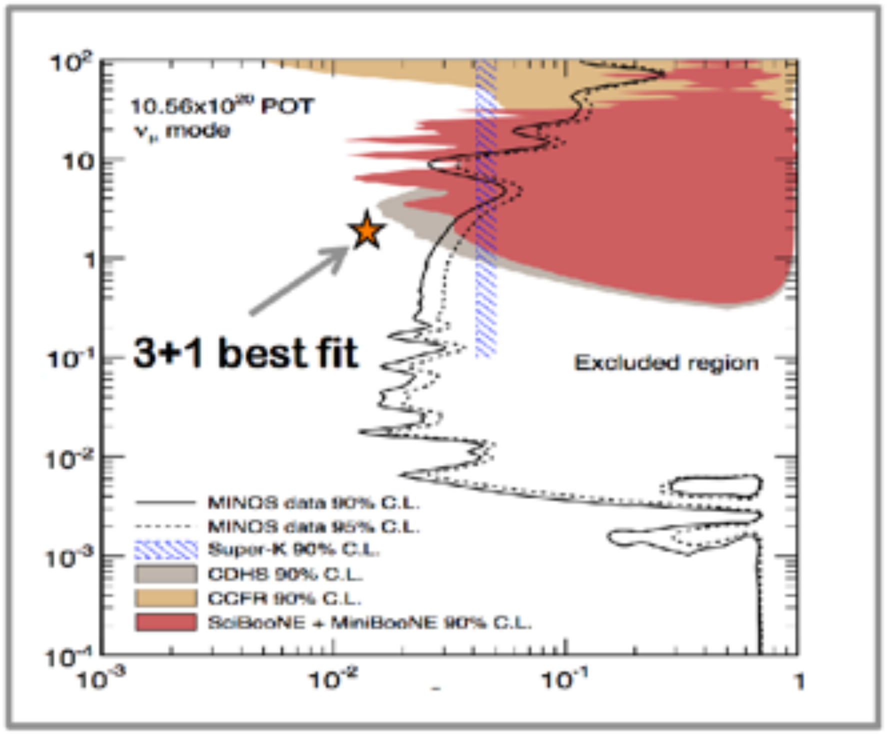
- Knowing precisely the source activity is crucial for the "rate-only" analysis;
- **The source activity will be measured with a calorimetric method: the precision of the measurent will be 1% or better;**



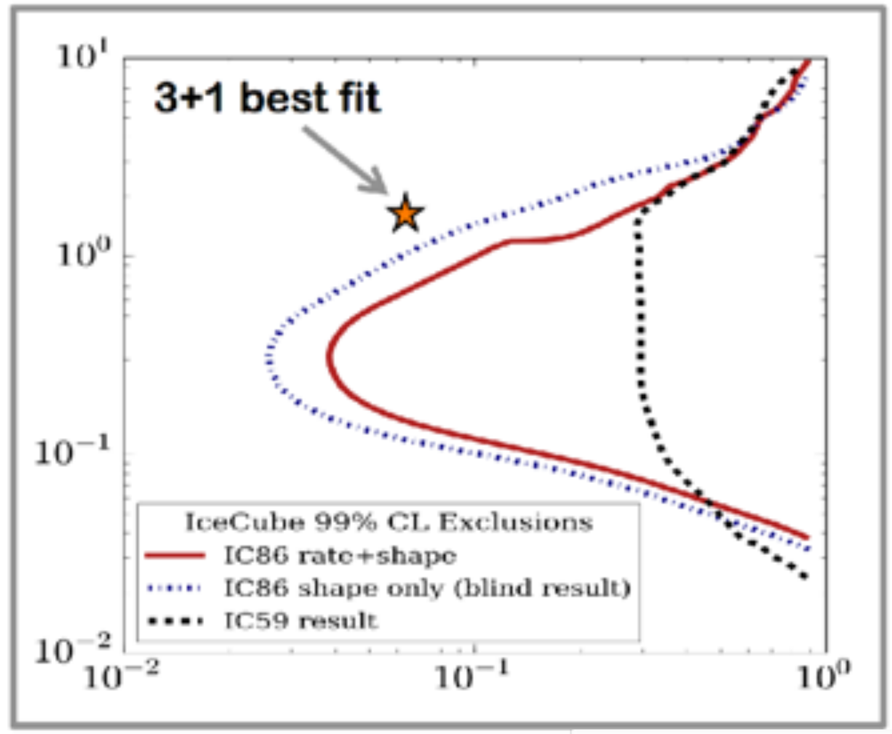
How can SOX reach a precision of 1% on the source activity?

No anomaly in ν_μ disappearance

SBL & MINOS (NC)



IceCube



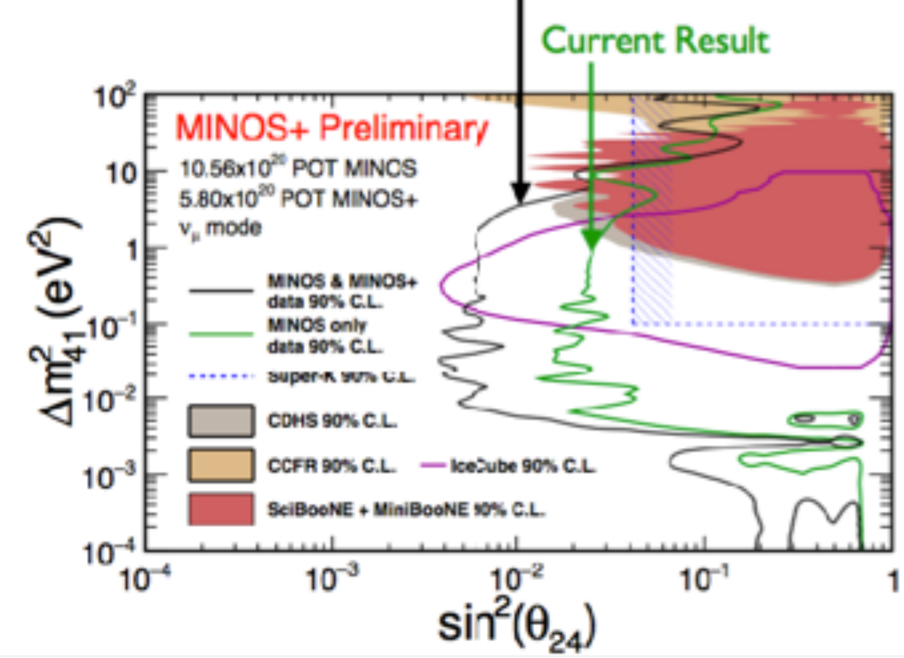
Δm^2

$\sin^2\theta_{\mu\mu}$ $\sin^2 2\theta_{\mu\mu}$

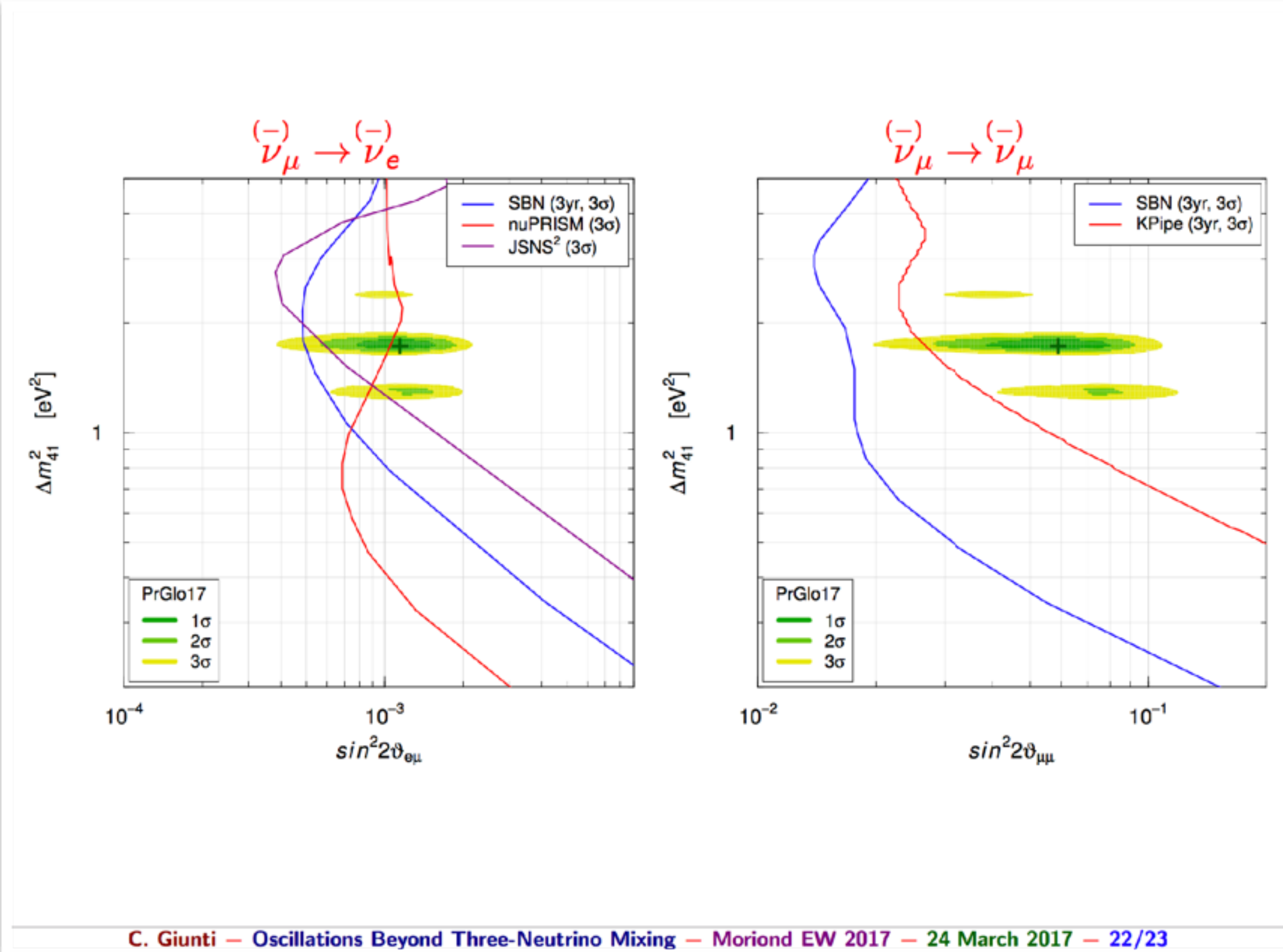
A thorn in the side of sterile neutrin

MINOS and MINOS+

Preliminary analysis adding the first two years of MINOS+ data

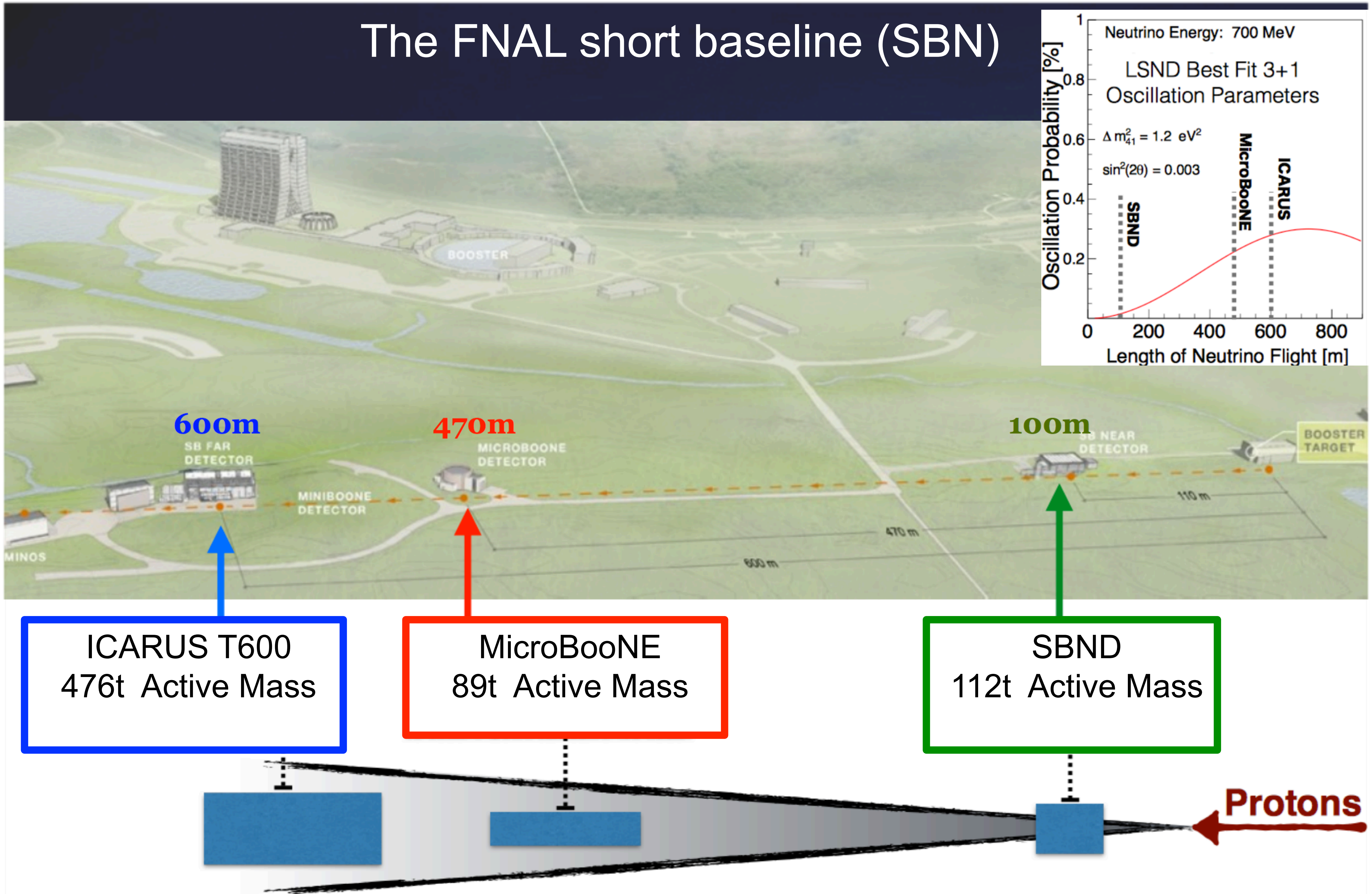


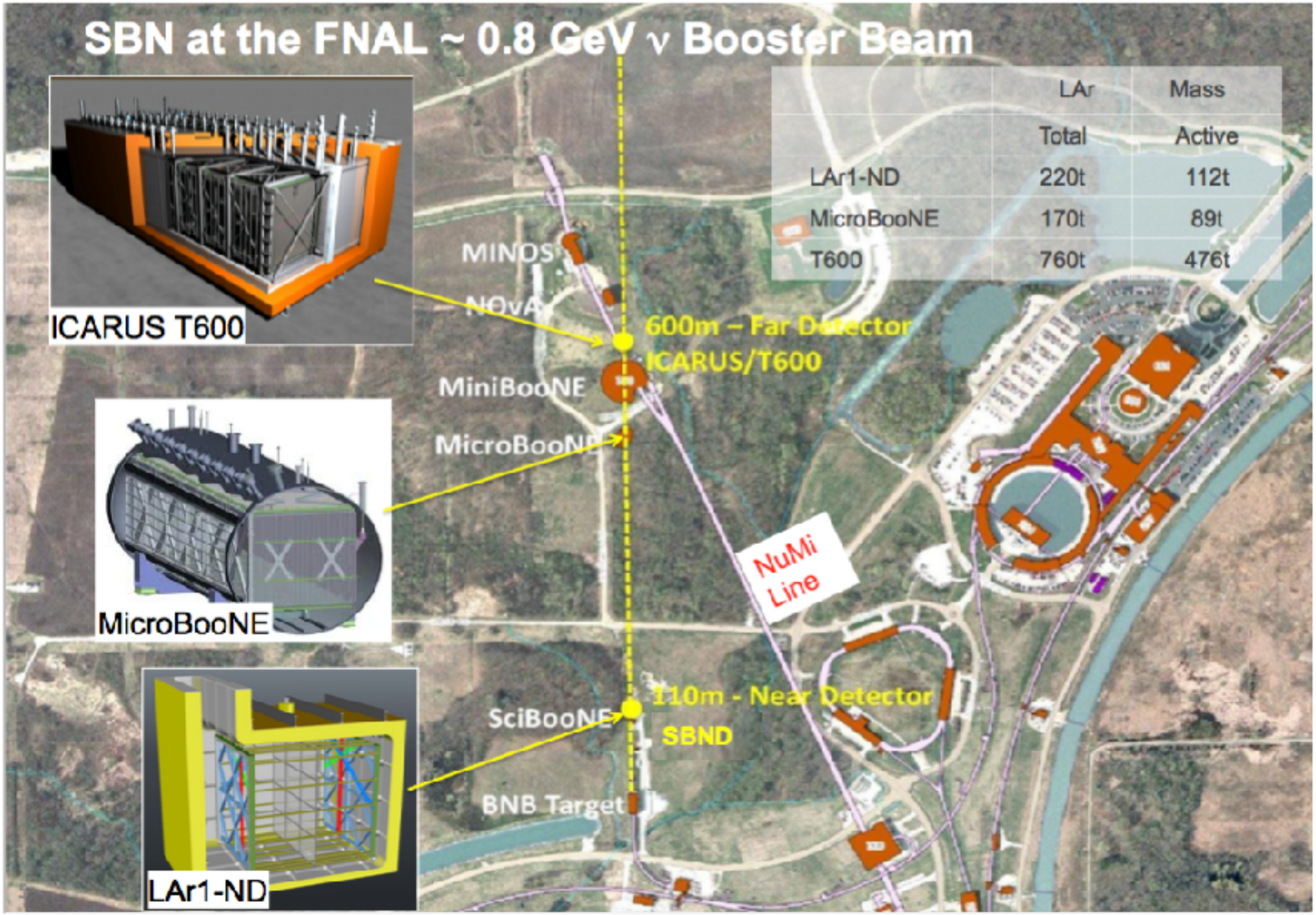
Palazzo, NUTEL2017


$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$
SBN (3yr, 3σ)
nuPRISM (3σ)
JSNS² (3σ)
PrGlo17
1σ
2σ
3σ
Δm^2_{41} [eV²]
1
10^{-4}
10^{-3}
$sin^2 2\vartheta_{e\mu}$
$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu$
SBN (3yr, 3σ)
KPipe (3yr, 3σ)
10^{-2}
10^{-1}
$sin^2 2\vartheta_{\mu\mu}$
C. Giunti — Oscillations Beyond Three-Neutrino Mixing — Moriond EW 2017 — 24 March 2017 — 22/23

SBN

The FNAL short baseline (SBN)





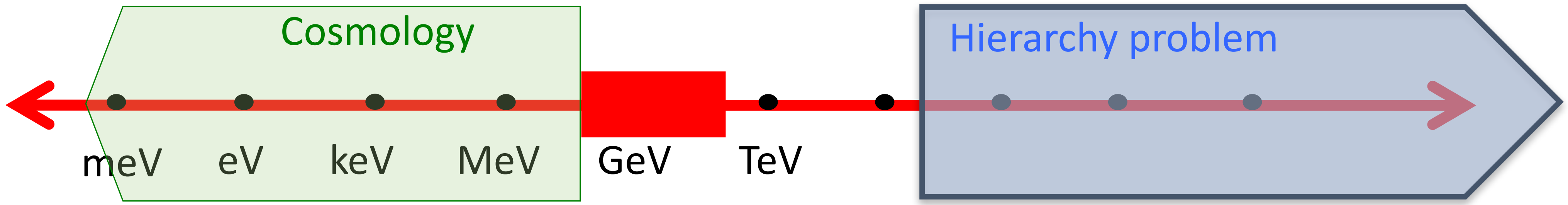
	LAr	Mass
	Total	Active
LAr1-ND	220t	112t
MicroBooNE	170t	89t
T600	760t	476t

A caccia del IV e del V neutrino massivo in altri modi —> DUNE + telescopi X + riunioni della CNS1! (ATLAS,CMS, LHCb, Belle2, NA62, SHiP, FCCee)

e.g. produzione da decadimenti di D e B; rivelazione con decadimenti (—>$\nu\gamma$ se m~keV or $\mu\pi$ se m~GeV)

—-> non solo le masse dei neutrini leggeri ma anche bariogenesi via low-scale leptogenesi

—> forte correlazione con $\beta\beta0\nu$



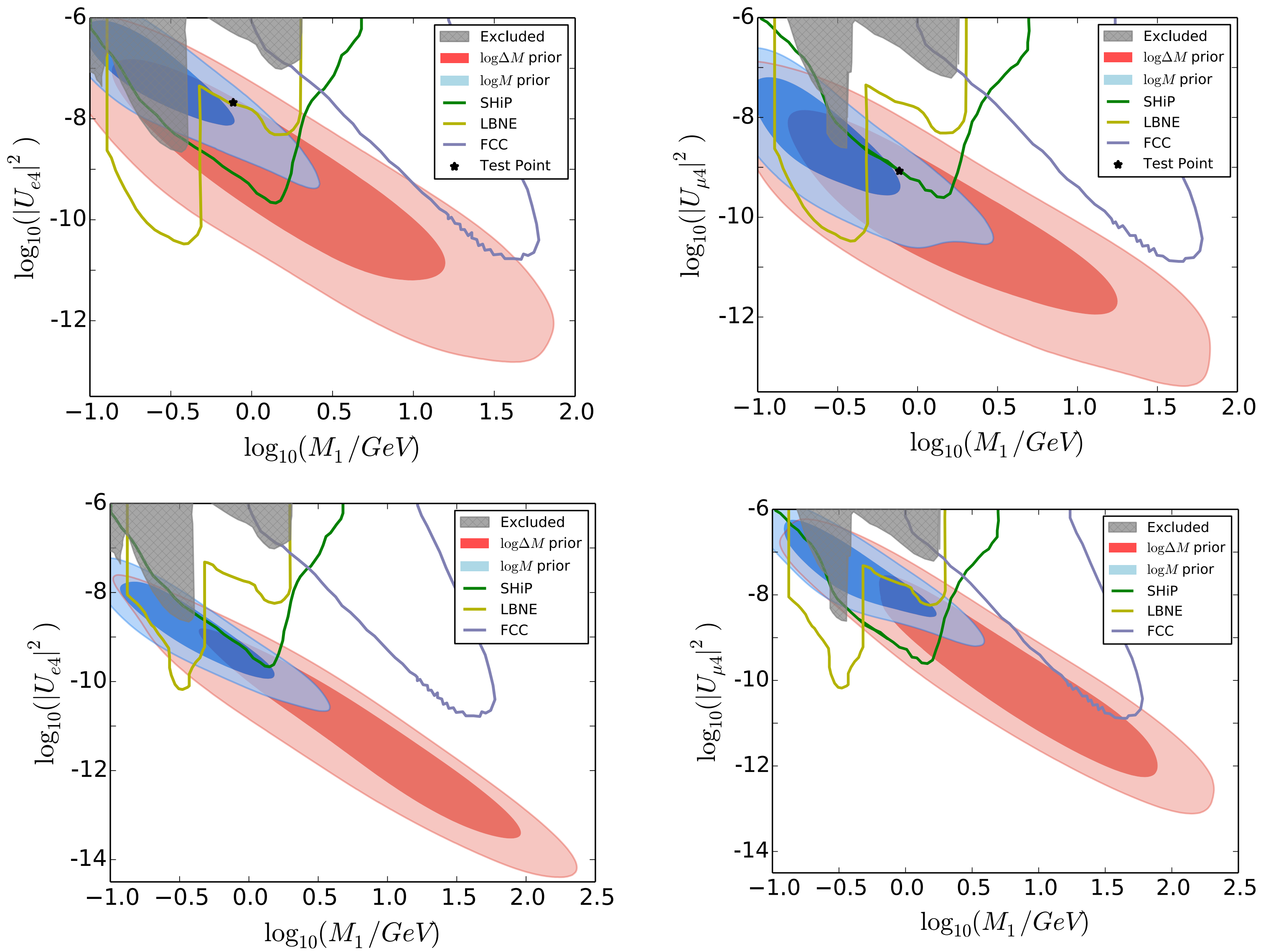
Leptogenesis from neutrino oscillations   0.1GeV <M < 100GeV

Akhmedov, Rubakov, Smirnov

Asaka, Shaposhnikov;Shaposhnikov;Asaka, Eijima, Ishida;Canetti, Drewes, Frossard, Shaposhnikov; Drewes, Garbrecht;Shuve, Yavin;Abada, Arcadi, Domcke, Lucente; PH, Kekic, Lopez-Pavón,Racker, Rius, Salvado...

low scale lepto-genesi

Full exploration of the minimal model N=2



IH

NH

Less fine-tunned region prefers the range of SHIP & DUNE!

Salvado Neutrinos,CERN2017

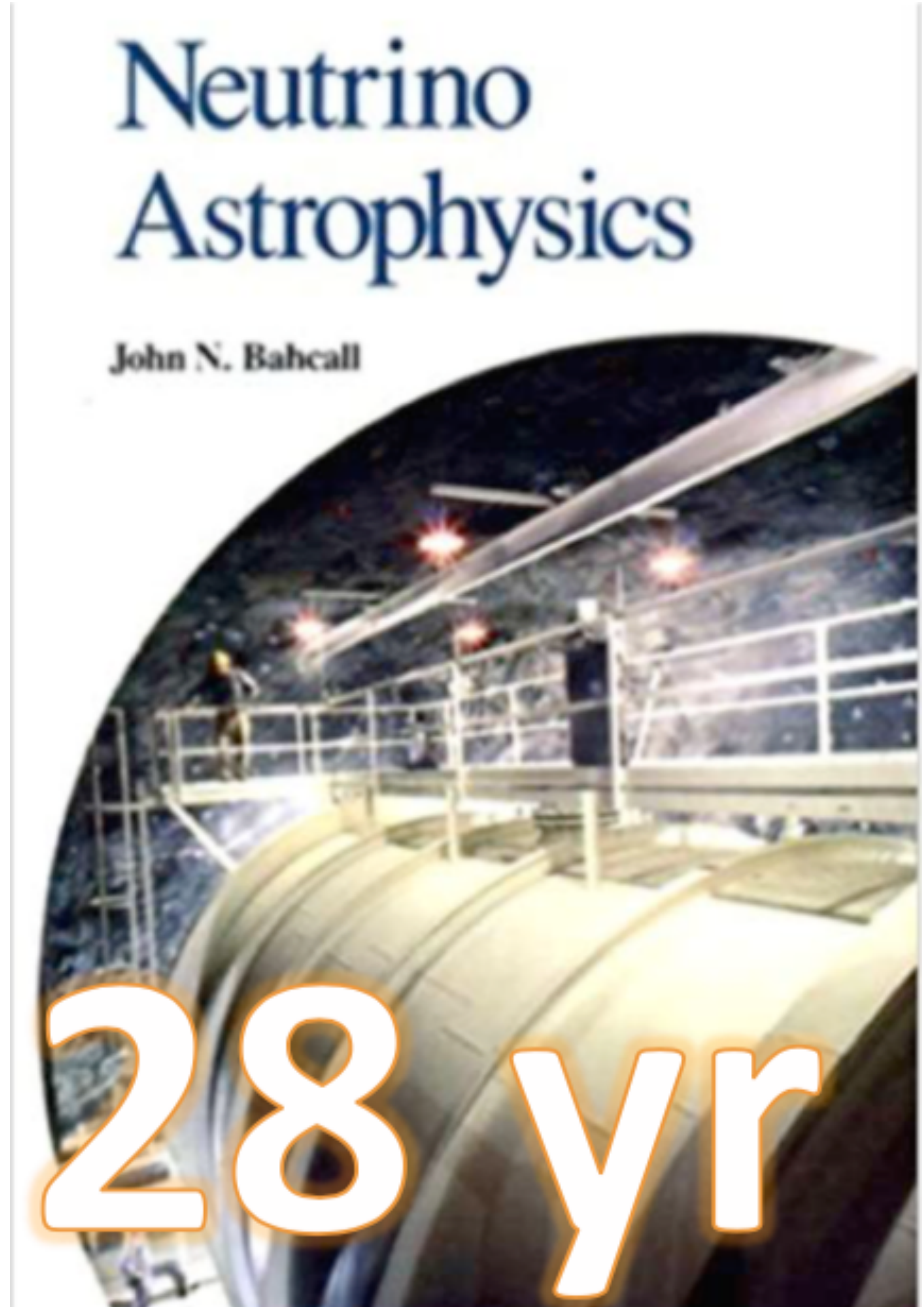
usando il ND di DUNE (con molte assunzioni semplificate sul fondo)

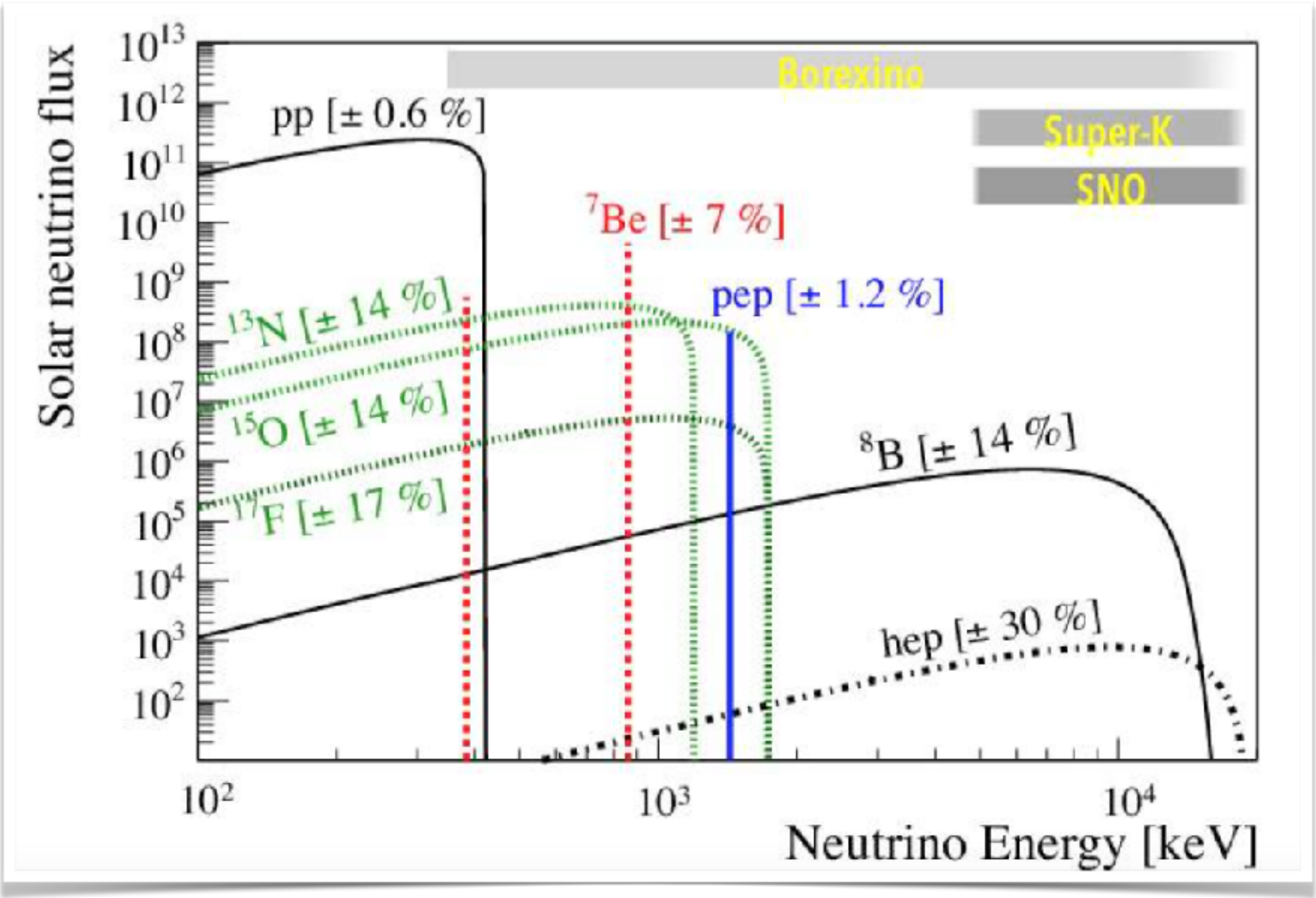
Neutrini solari

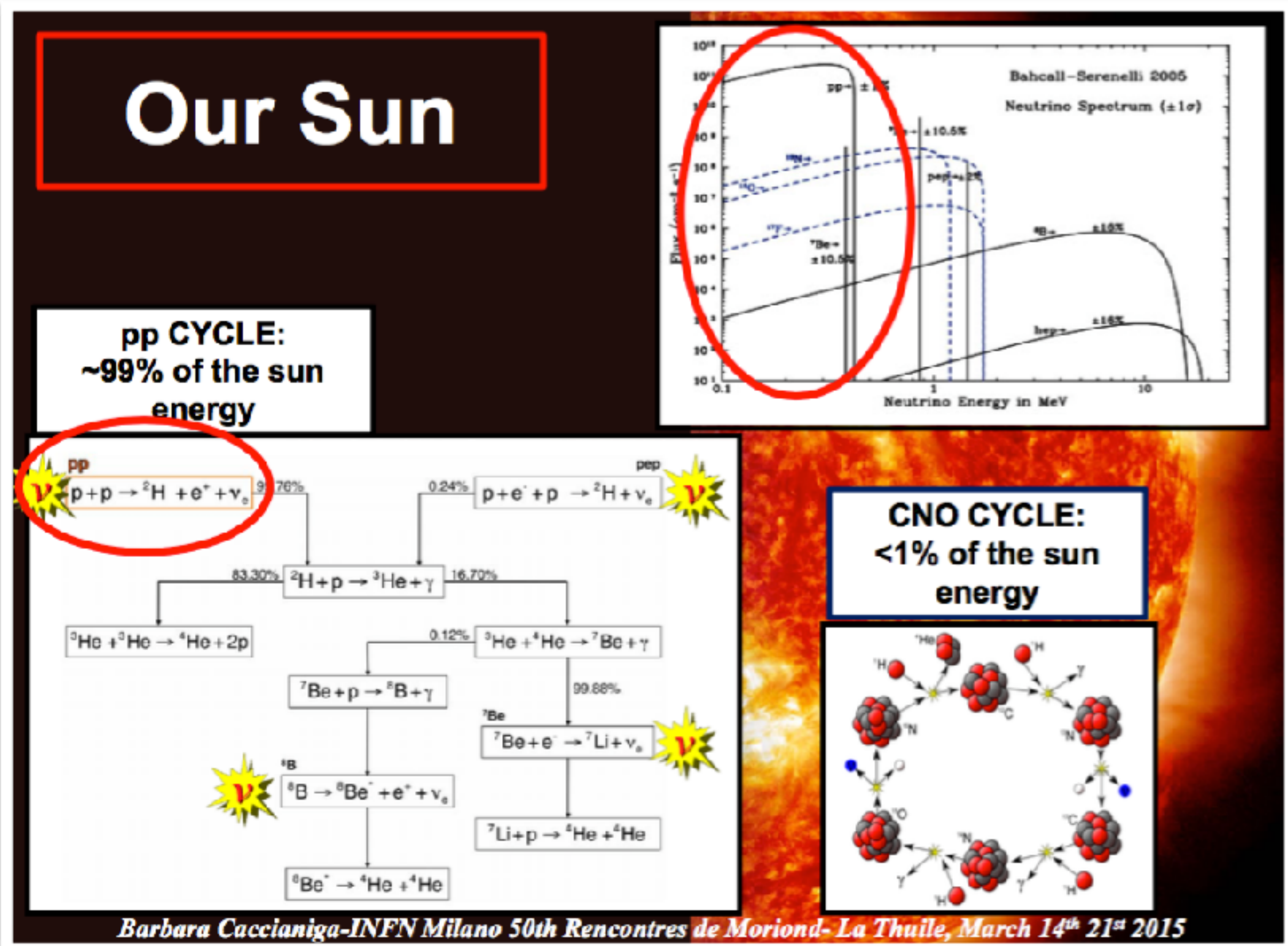
- Cherenkov

- Scintillatori

- LAr (futuro)




Solar neutrino flux
Borexino
Super-K
SNO
pp [± 0.6 %]
7Be [± 7 %]
pep [± 1.2 %]
13N [± 14 %]
15O [± 14 %]
17F [± 17 %]
8B [± 14 %]
hep [± 30 %]
Neutrino Energy [keV]


Our Sun
pp CYCLE:
~99% of the sun energy
CNO CYCLE:
<1% of the sun energy
Bahcall-Serenelli 2005
Neutrino Spectrum (±1σ)
Neutrino Energy in MeV
pp
p+p → ²H + e⁺ + νₑ
pep
p+e⁻+p → ²H + νₑ
0.24%
²H+p → ³He+γ
83.30%
16.70%
³He + ³He → ⁴He + 2p
³He + ⁴He → ⁷Be + γ
0.12%
⁷Be + p → ⁸B + γ
99.88%
⁷Be
⁷Be + e⁻ → ⁷Li + νₑ
⁸B
⁸B → ⁸Be* + e⁺ + νₑ
⁷Li + p → ⁴He + ⁴He
⁸Be* → ⁴He + ⁴He
Barbara Caccianiga-INFN Milano 50th Rencontres de Moriond- La Thuile, March 14th 21st 2015

Our Sun

Why studying solar neutrinos?

- The standard Solar Model predicts the neutrino fluxes and their spectrum;
- Studying solar neutrinos is interesting both for ASTROPHYSICS (comparison with predictions of the SSM) and for PARTICLE PHYSICS (neutrinos oscillations);

ASTROPHYSICS

Sources	$\Phi(\nu\ sec^{-1}\ cm^{2})$ *high-metallicity*	$\Phi(\nu\ sec^{-1}\ cm^{2})$ *low-metallicity*	Difference %
pp	$5.98(1 \pm 0.006) \times 10^{10}$	$6.03(1 \pm 0.006) \times 10^{10}$	0.8
pep	$1.44(1 \pm 0.012) \times 10^{8}$	$1.47(1 \pm 0.012) \times 10^{8}$	2.1
hep	$8.04(1 \pm 0.300) \times 10^{3}$	$8.31(1 \pm 0.300) \times 10^{3}$	3.3
^{7}Be	$5.00(1 \pm 0.070) \times 10^{9}$	$4.56(1 \pm 0.070) \times 10^{9}$	8.8
^{8}B	$5.58(1 \pm 0.140) \times 10^{6}$	$4.59(1 \pm 0.140) \times 10^{6}$	17.7
^{13}N	$2.96(1 \pm 0.140) \times 10^{8}$	$2.17(1 \pm 0.140) \times 10^{8}$	26.7
^{15}O	$2.23(1 \pm 0.150) \times 10^{8}$	$1.56(1 \pm 0.150) \times 10^{8}$	30.0
^{17}F	$5.52(1 \pm 0.170) \times 10^{6}$	$3.40(1 \pm 0.160) \times 10^{6}$	38.4

- **Solar Model:** Serenelli, Haxton and Pena-Garay arXiV:1104.1639
- **High metallicity GS98** = Grevesse et al.*S. Sci. Rev. 85,161 ('98);*
- ***Low metallicity AGS09** = Asplund, et al,* A.R.A.&A. 47(2009)481

Open Issues: solar metallicity

- Metallicity is input in the Standard Solar Model;
- Differences as large as 30-40% (for CNO);
- Differences of ~9% for $^{7}Be\ \nu$

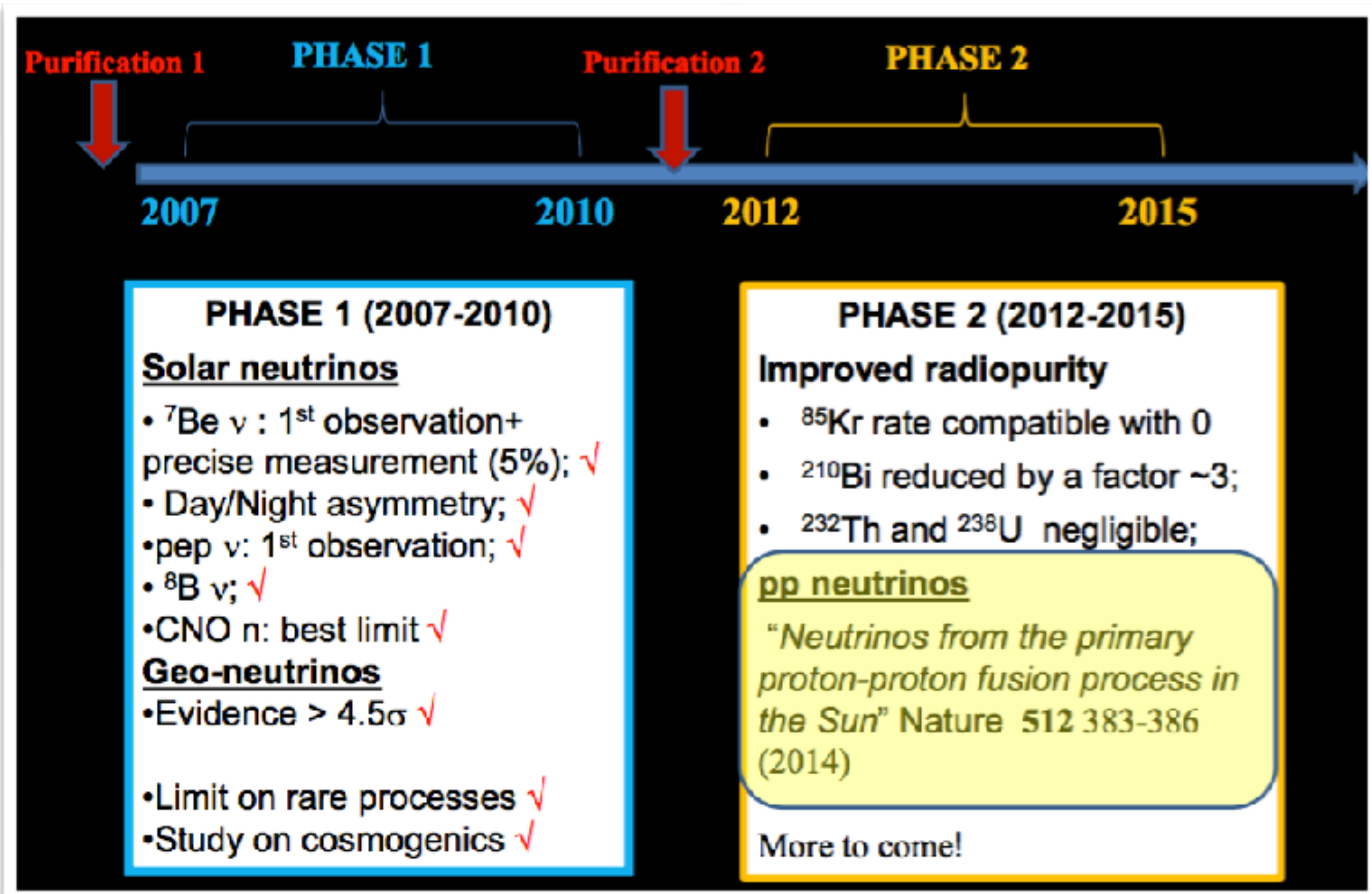
BOREXINO

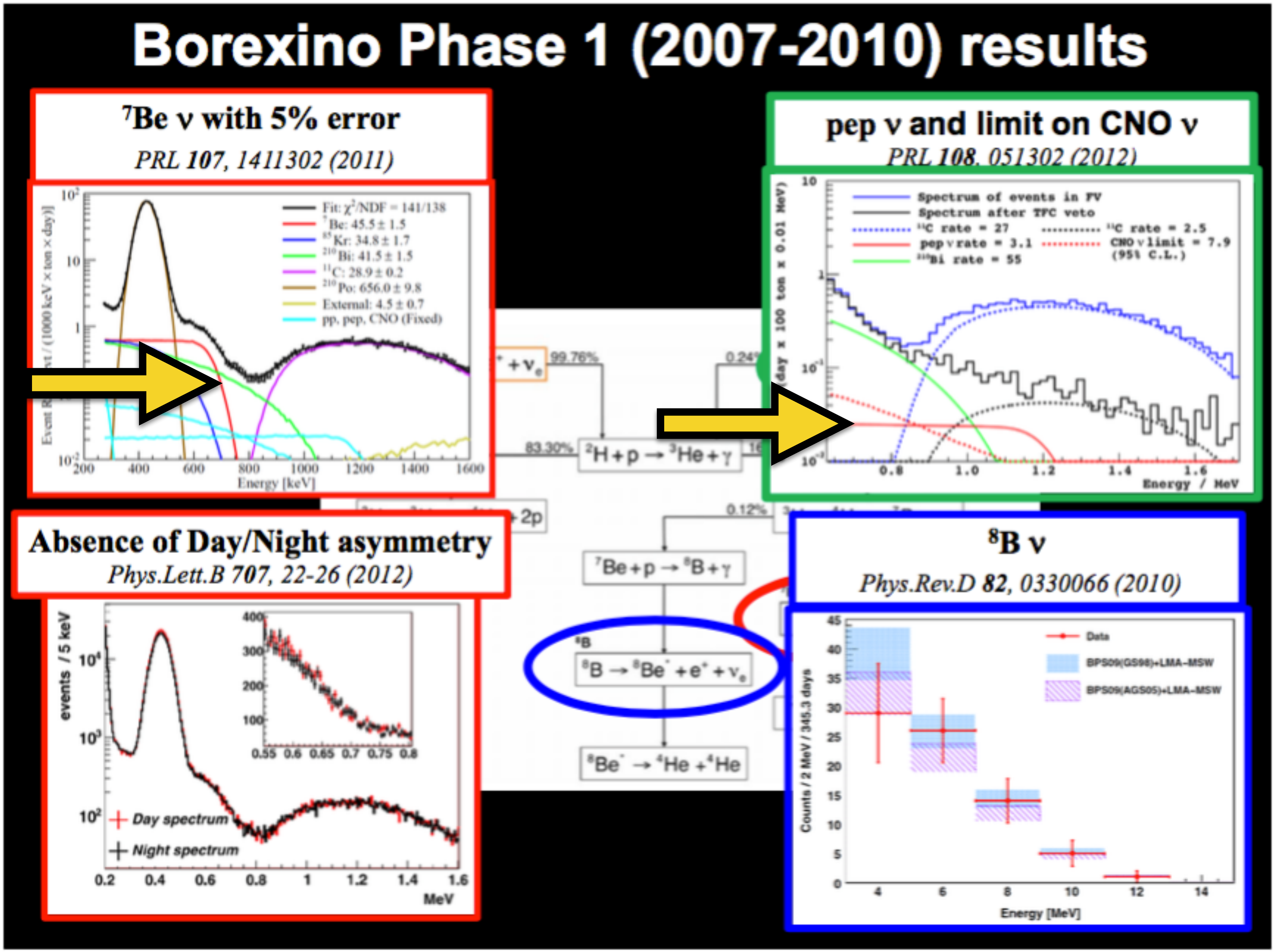
Detection principle: scattering of neutrinos on electrons
Detection technique: large mass of organic liquid scintillator; e^- above 150 keV are visible with few % energy resolution
Technique advantages: high light-yield (higher than Cerenkov)
•Technique disadvantages: no directional information (unlike Cerenkov);
Signal is indistinguishable from background: high radiopurity is a MUST!

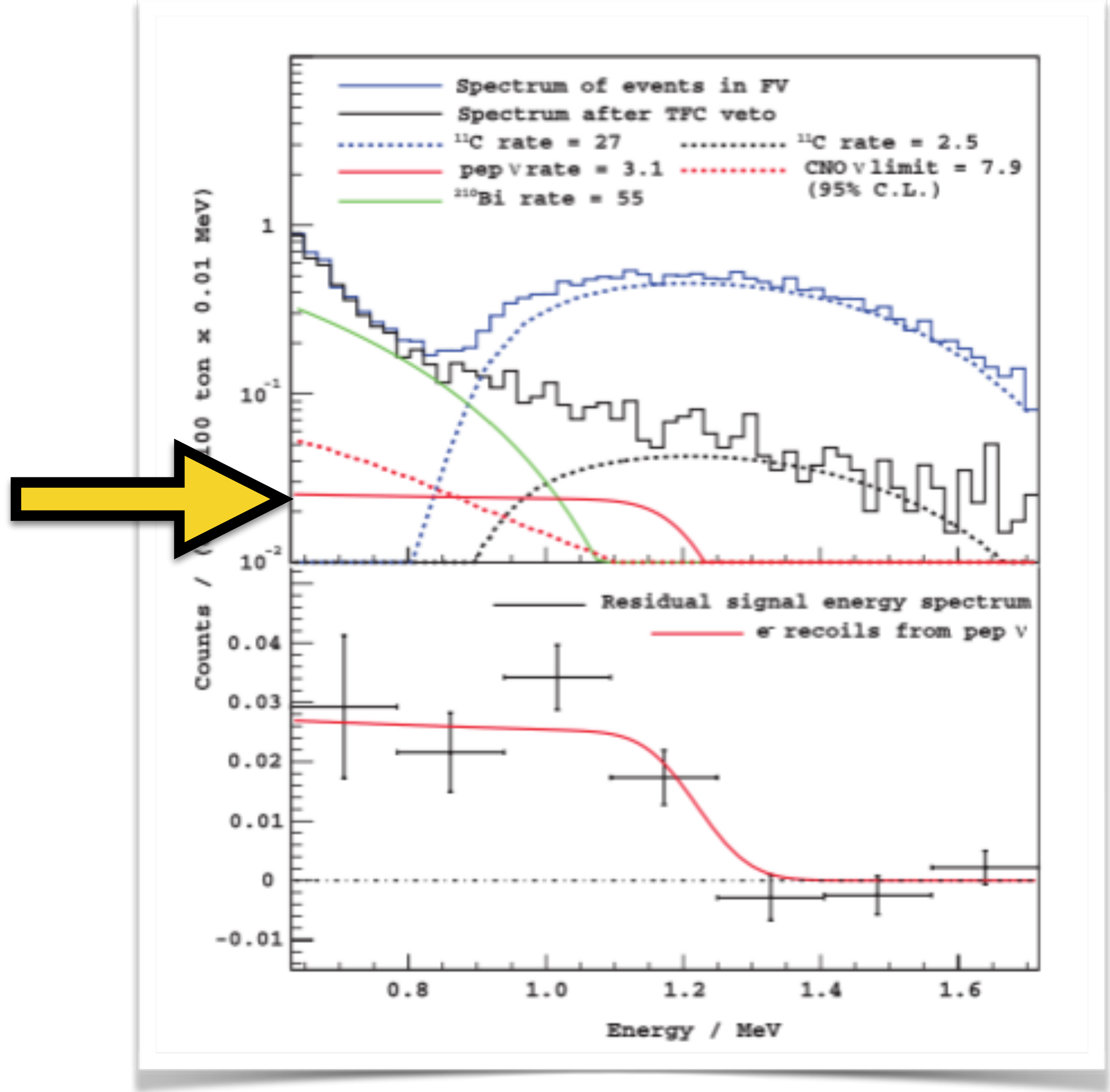
- The expected rate of solar neutrinos in 100tons of BX scintillator is ~50 counts/day which corresponds to ~ 5 10^{-9} Bq/Kg;
- Just for comparison:
  - Natural water is ~ 10 Bq/Kg in ^{238}U, ^{232}Th and ^{40}K
  - Air is ~ 10 Bq/m^3 in ^{39}Ar, ^{85}Kr and ^{222}Rn
  - Typical rock is ~ 100-1000 Bq/m^3 in ^{238}U, ^{232}Th and ^{40}K

•Contamination from ^{238}U and ^{232}Th chain are found to be in the range of $\sim 10^{-17}$ g/g and $\sim 5x \times 10^{-18}$ g/g respectively;

•**More than one order of magnitude better than specifications!** •Three backgrounds out of specifications: ^{210}Po, ^{210}Bi and ^{85}Kr.

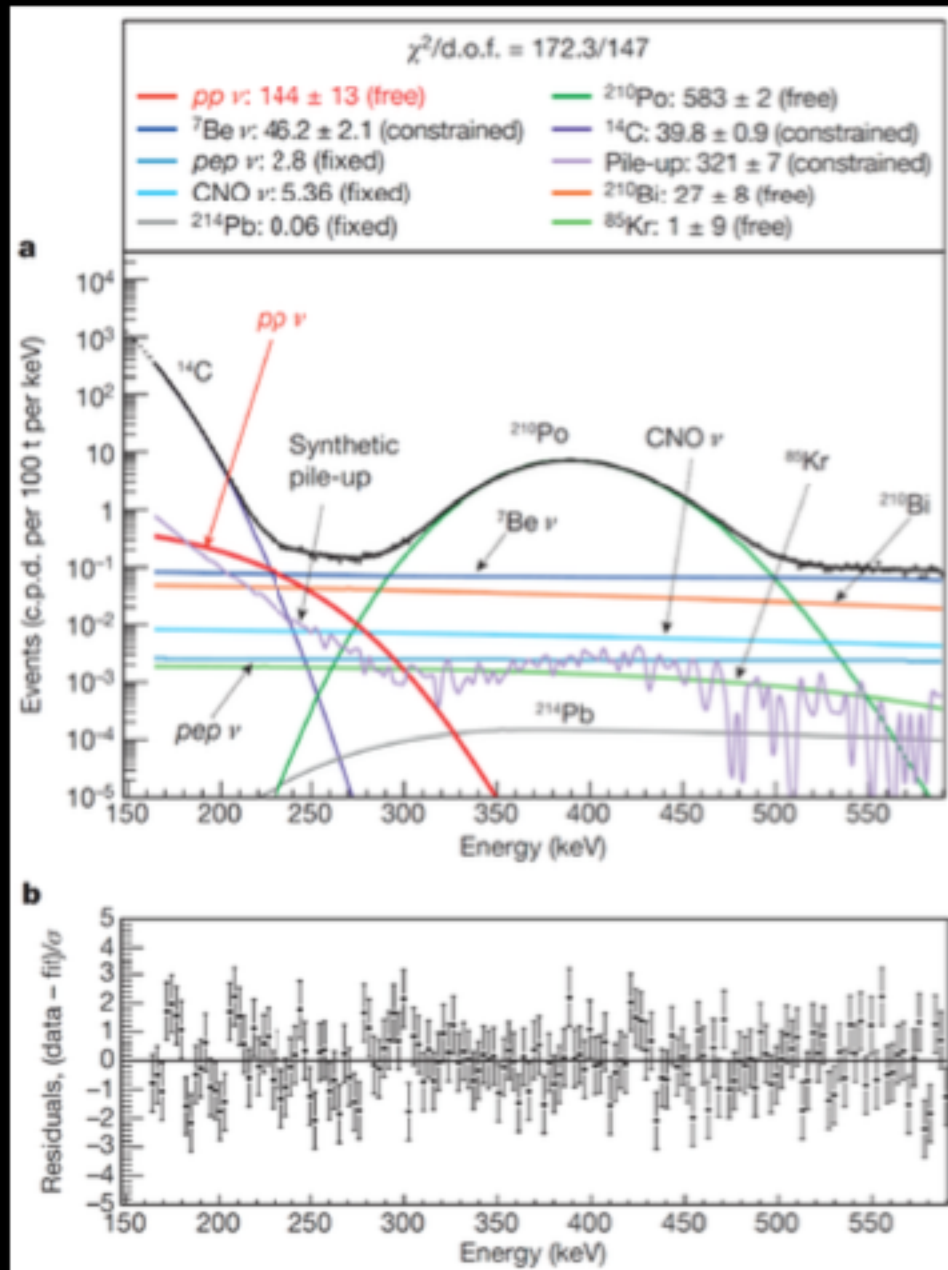



Borexino Phase 1 (2007-2010) results
⁷Be ν with 5% error
PRL 107, 1411302 (2011)
Fit: χ²/NDF = 141/138
⁷Be: 45.5 ± 1.5
⁸⁵Kr: 34.8 ± 1.7
²¹⁰Bi: 41.5 ± 1.5
¹¹C: 28.9 ± 0.2
²¹⁰Po: 656.0 ± 9.8
External: 4.5 ± 0.7
pp, pep, CNO (Fixed)
Energy [keV]
pep ν and limit on CNO ν
PRL 108, 051302 (2012)
Spectrum of events in FV
Spectrum after TFC veto
¹¹C rate = 27
¹¹C rate = 2.5
pep ν rate = 3.1
CNO ν limit = 7.9 (95% C.L.)
²¹⁰Bi rate = 55
Energy / MeV
Absence of Day/Night asymmetry
Phys.Lett.B 707, 22-26 (2012)
events / 5 keV
Day spectrum
Night spectrum
MeV
⁸B ν
Phys.Rev.D 82, 0330066 (2010)
Data
BPS09(GS98)+LMA-MSW
BPS09(AGS05)+LMA-MSW
Counts / 2 MeV / 345.3 days
Energy [MeV]
²H + p → ³He + γ
⁷Be + p → ⁸B + γ
⁸B → ⁸Be* + e⁺ + νₑ
⁸Be* → ⁴He + ⁴He
99.76%
83.30%
0.12%

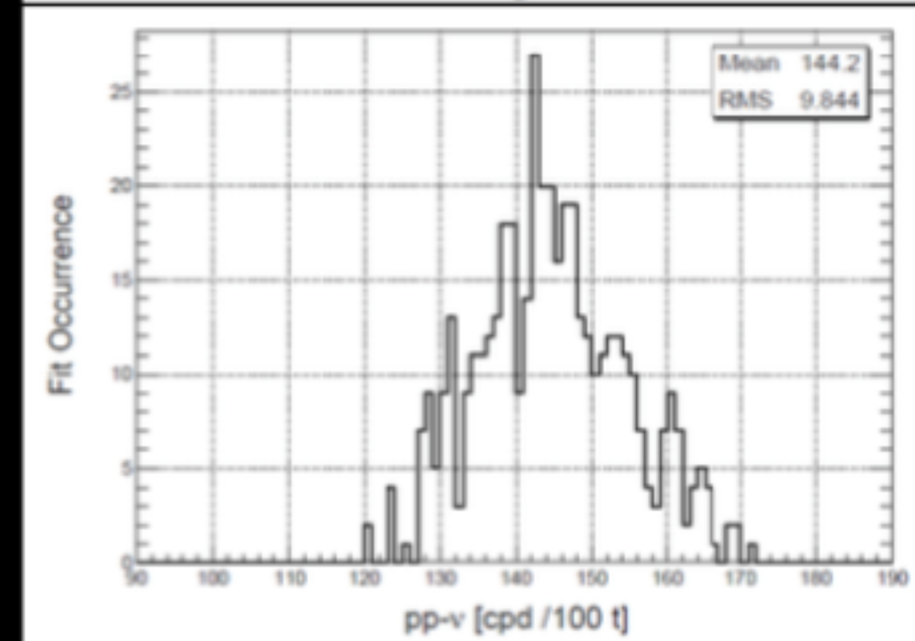


per gli increduli/e…

Search for pp-neutrinos: results



Evaluation of systematics



- Distribution of the best fit values for pp-rate obtained varying some of the fit conditions (fit range, energy estimator...)

pp-ν rate= 144 ±13(stat) ±10 (sys) cpd/100tons

Predicted rate for SSM (High Metallicity) + MSW-LMA = 131 ± 2 cpd/100tons

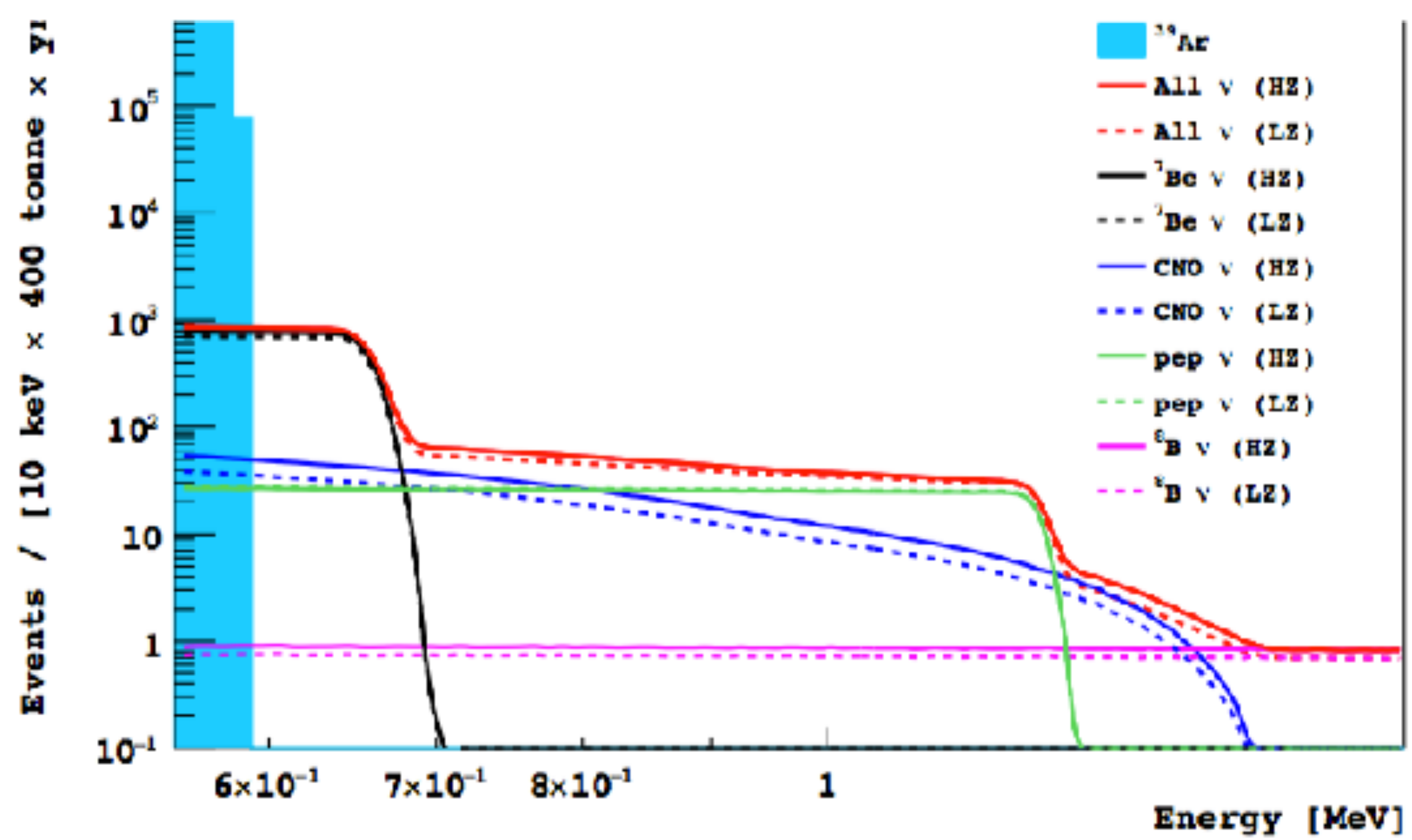
Sensibilta' di ARGO (LAr-400t)

fondi diversi da LScint: ^{39}Ar ha end point doppio del ^{14}C —>non sensibile al pp; no Bi no Po nel LAr

4 x luce: circa 20 eventi al giorno E> 500KeV

Neutrino Source	Low Metallicity		High Metallicity	
	All	[0.6-1.3] MeV	All	[0.6-1.3] MeV
pp	107.9 ± 2.0	0	107.0 ± 2.0	0
pep	2.28 ± 0.05	1.10 ± 0.02	2.23 ± 0.05	1.07 ± 0.02
^{7}Be	36.10 ± 2.60	2.85 ± 0.21	39.58 ± 2.85	3.13 ± 0.23
CNO	3.06 ± 0.30	0.64 ± 0.06	4.28 ± 0.44	0.90 ± 0.09
^{8}B	0.30 ± 0.04	0.035 ± 0.005	0.36 ± 0.06	0.042 ± 0.007
Total		4.63 ± 0.22		5.14 ± 0.25

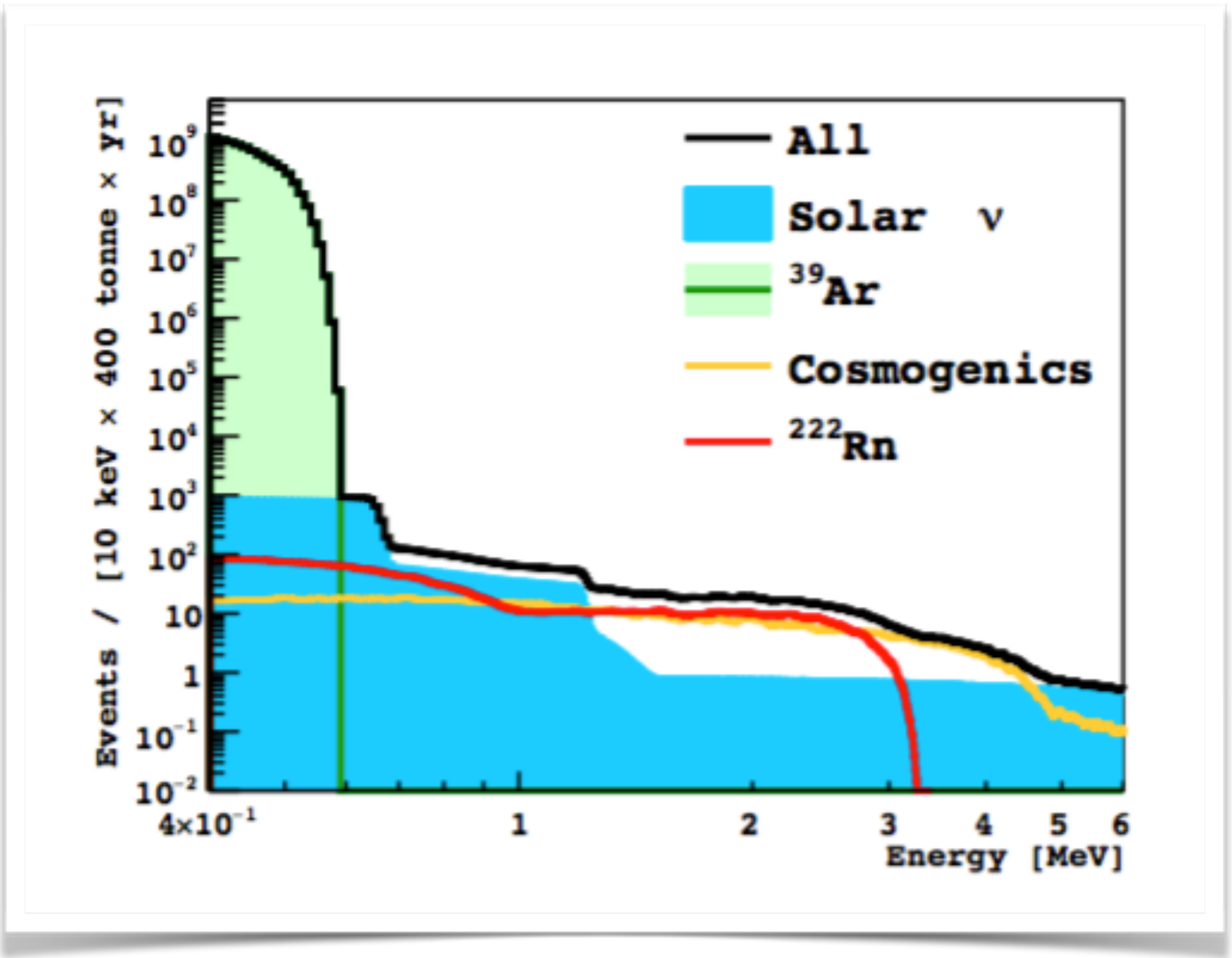
cpd / 100 ton

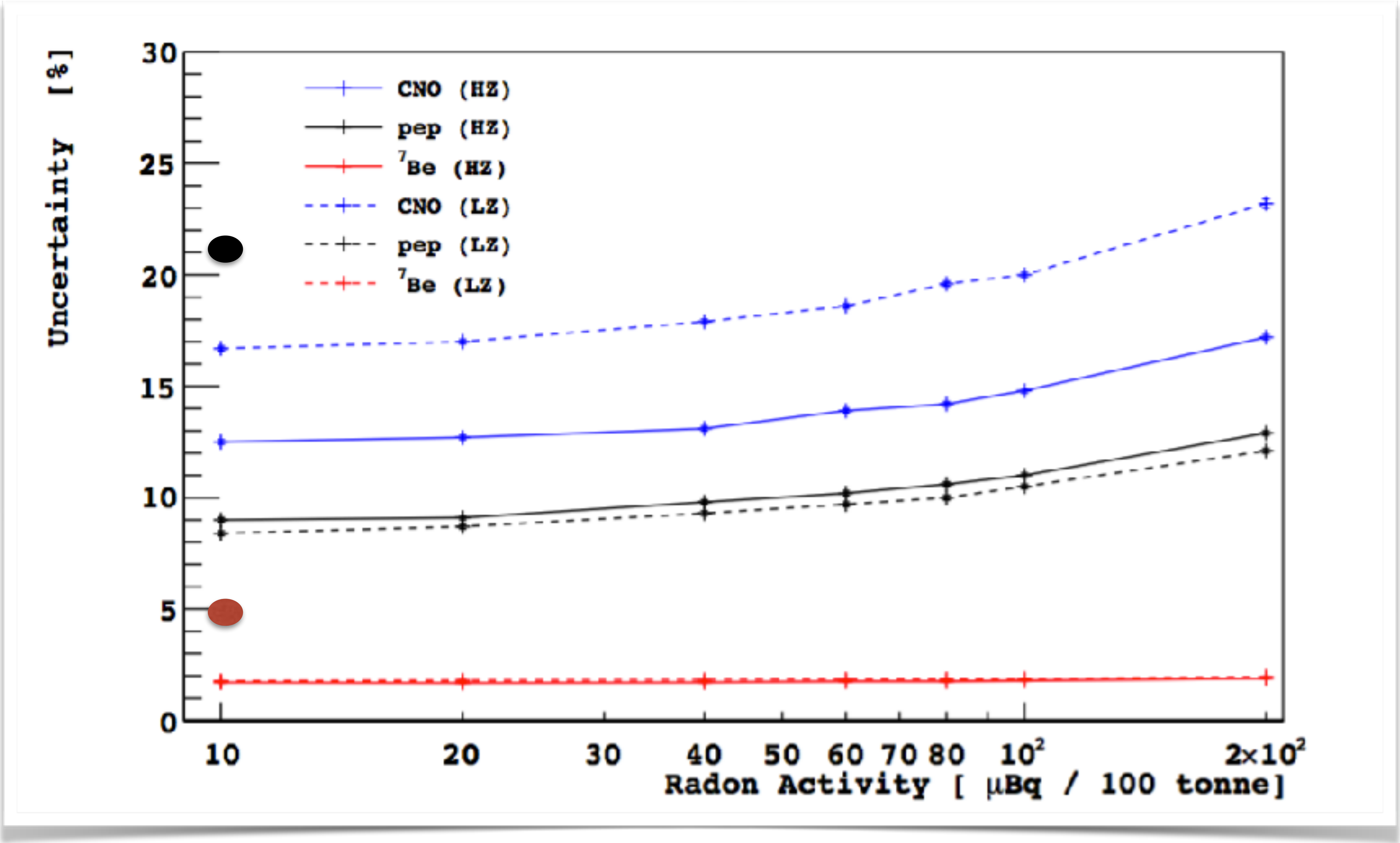


Fondi gamma soppressi dall'identificazione di ionizzazioni multiple

Fondi residui rilevanti:

^{222}Rn : può essere misurato in situ; serve <200uBq/100t





30
25
20
15
10
5
0
Uncertainty [%]
CNO (HZ)
pep (HZ)
7Be (HZ)
CNO (LZ)
pep (LZ)
7Be (LZ)
10
20
30
40
50
60
70
80
10^2
2×10^2
Radon Activity [μBq / 100 tonne]

Neutrini da supernovae

Ruolo dei neutrini nello studio delle SN molto importante nello studio della dinamica dell'esplosione (Gamow, Zeldovich ecc.)

+ di 99% dell'energia emessa sotto forma di neutrini con E O(10MeV)

SN1987A rivelo' 24 neutrini (Kamiokande-II, IMB e Baksan)—> troppo pochi per studiare le proprieta' in dettaglio

— distanza 50kpc, LMC , 20 masse solari

— rivelatori piccoli

La probabilita' di una SN nella via lattea e' 1/10-1/100 anni

—> rivelatori grandi, con soglie basse e con lunghe osservazioni e tempi morti ridottissimi

Inoltre la luce di core-collapse SN potrebbe essere assorbita dalla polvere galattica (o nascosta se in asse con la VL) e ci sono anche le "failed" SN che diventano buchi neri

Tecnologie per la rivelazione:

- telescopi Cherenkov: AMANDA, IceCube (10^6 events), Ice-Cube-Gen2, Super-Kamiokande, HyperKamiokande (10^5 events), SNO

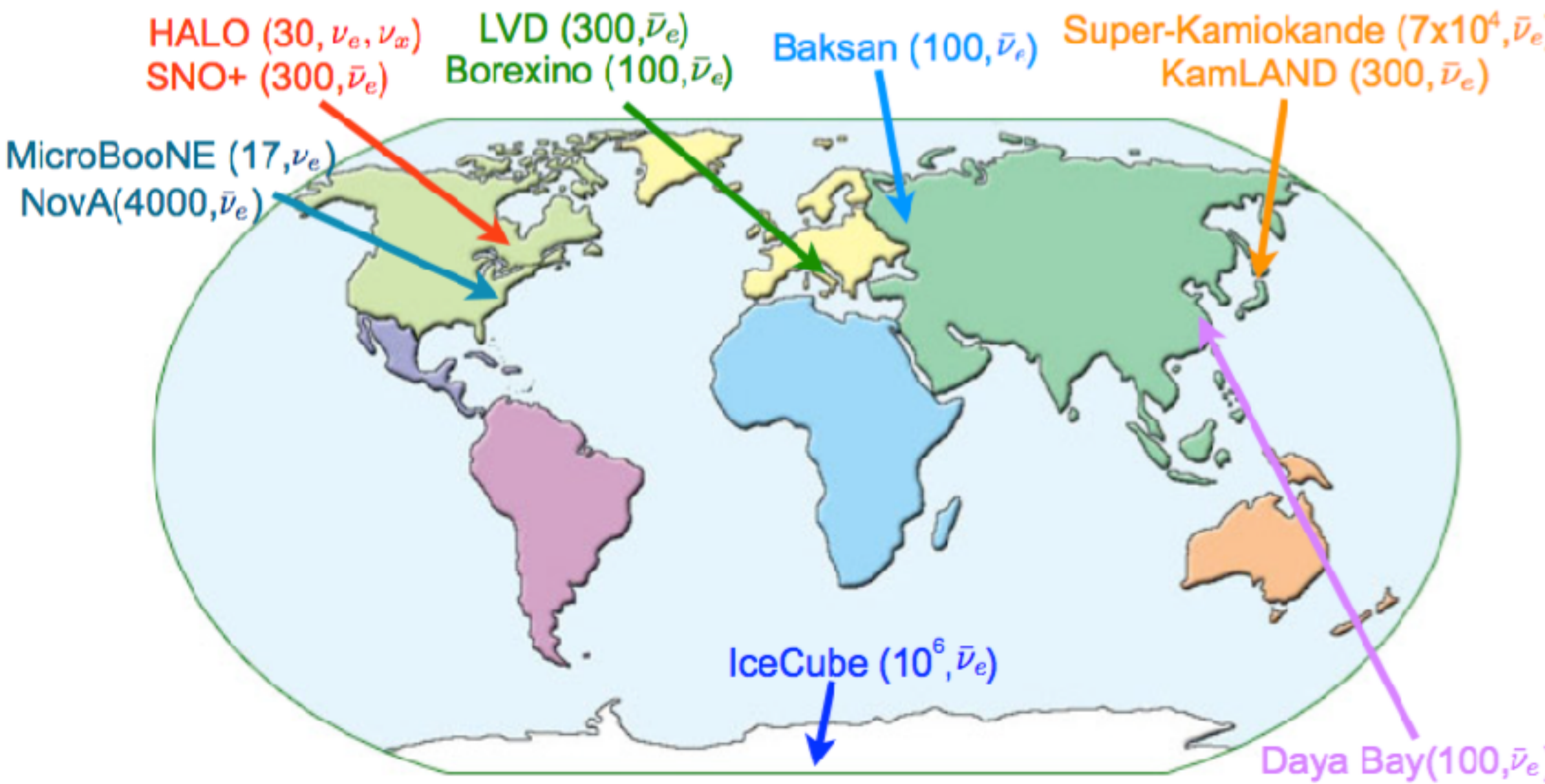
- Scintillatori liquidi: LVD, JUNO (6000 events), Borelxino, Kamland, RENO-50

- altre tecnologie: MACRO

- neutrini e- in CC

- Liquidi nobili: Xenon, LZ, DARWIN (700 eventi); correnti neutre CNNS

Are We Ready For SN 20XXa?



Expected number of events for a SN at 10 kpc and dominant flavor sensitivity in parenthesis.

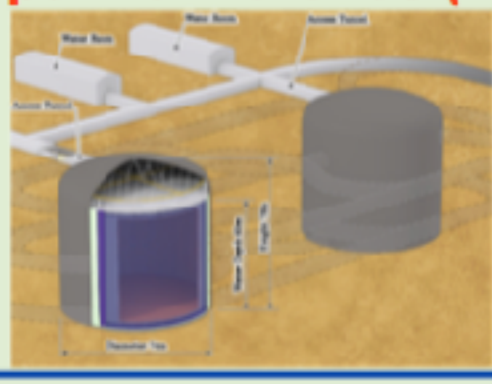
Fundamental to combine the SN signal seen in detectors employing different technologies.

Recent review papers: Scholberg (2012). Mirizzi, Tamborra, Janka, Scholberg et al. (2016).

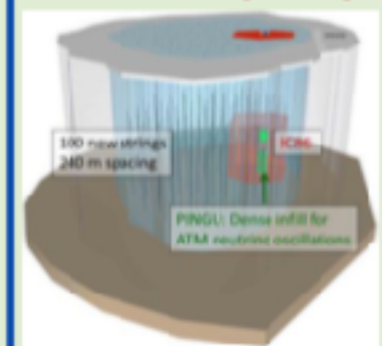
Next Generation Large Scale Detectors

Cherenkov telescopes ($\bar{\nu}_e$)

Hyper-Kamiokande (10^5)

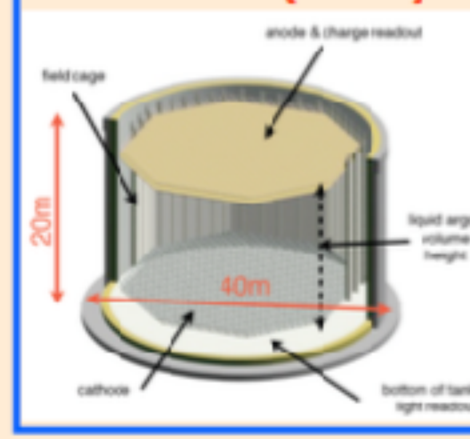


IceCube-Gen2 PINGU (10^6)



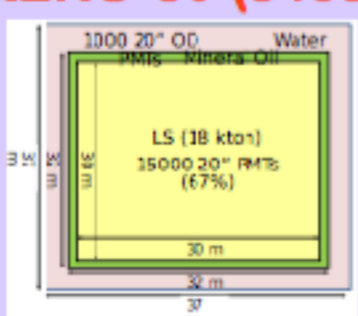
Liquid Argon detectors (ν_e)

DUNE (3000)

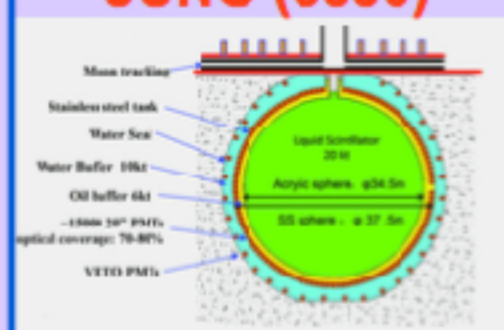


Scintillation detectors ($\bar{\nu}_e$)

RENO-50 (5400)



JUNO (6000)



Dark Matter Detectors ($\nu_{e,x}$, $\bar{\nu}_{e,x}$)

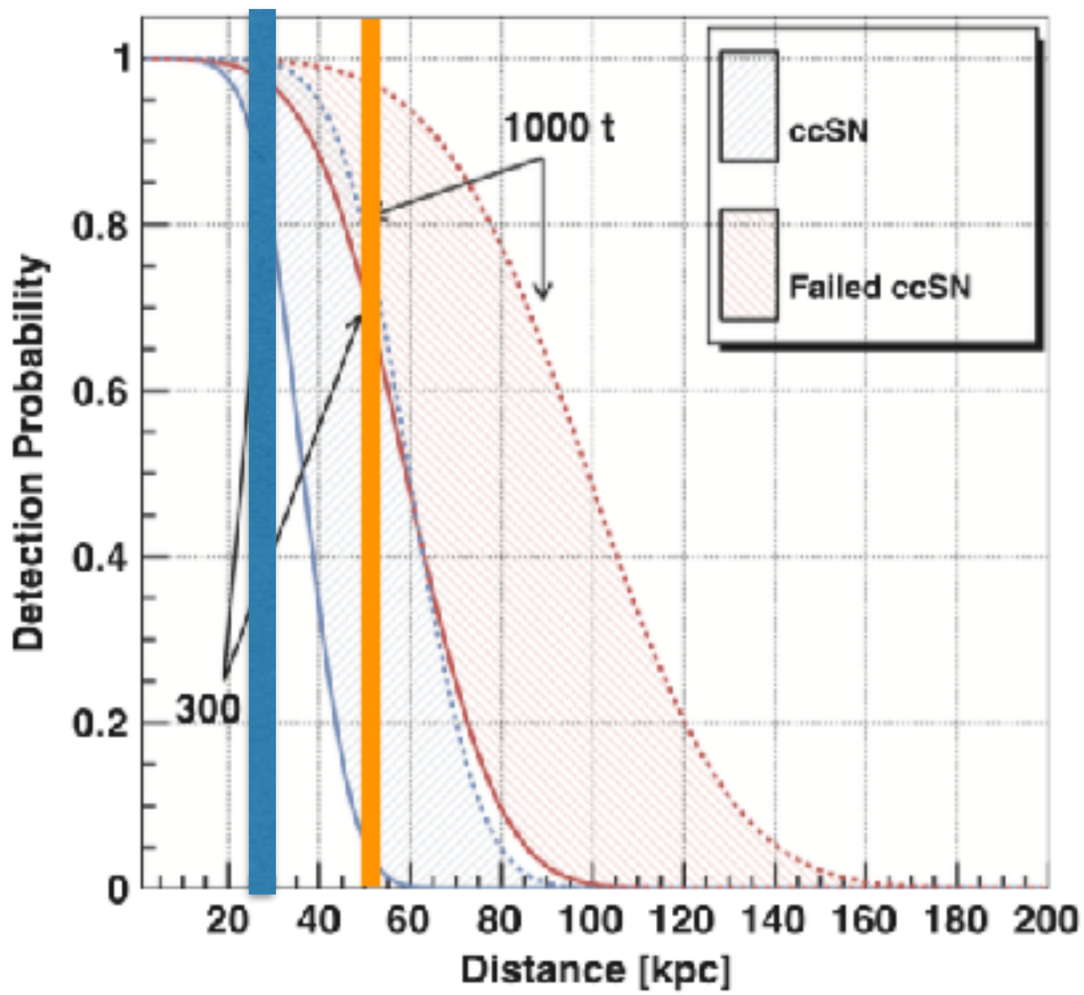
e.g., DARWIN (700)

- Do we have under control cross-sections, systematics?

LVD

Scintillatore liquido 1kton + struttura in Fe 0.85kton

Interazione dominante IBD



Blu=margine della via lattea; arancio=SN1987A nel LMG

The Astrophysical Journal, 802:47 (9pp), 2015 March 20

doi:10.1088/0004-637X/802/1/47

IMPLICATION FOR THE CORE-COLLAPSE SUPERNOVA RATE FROM 21 YEARS OF DATA OF THE LARGE VOLUME DETECTOR

N. Y. Agafonova[1], M. Aglietta[2], P. Antonioli[3], V. V. Ashikhmin[1], G. Badino[2,7], G. Bari[3], R. Bertoni[2], E. Bressan[4,5], G. Bruno[6], V. L. Dadykin[1], E. A. Dobrynina[1], R. I. Enikeev[1], W. Fulgione[2,6], P. Galeotti[2,7], M. Garbini[3], P. L. Ghia[8], P. Giusti[3], F. Gomez[2], E. Kemp[9], A. S. Malgin[1], A. Molinario[2,6], R. Persiani[3], I. A. Pless[10], A. Porta[2], V. G. Ryasny[1], O. G. Ryazhskaya[1], O. Saavedra[2,7], G. Sartorelli[3,4], I. R. Shakiryanova[1], M. Selvi[3], G. C. Trinchero[2], C. Vigorito[2,7], V. F. Yakushev[1], A. Zichichi[3,4,5,11]
(The LVD Collaboration)
[1] Institute for Nuclear Research, Russian Academy of Sciences, Moscow, Russia
[2] INFN-Torino, OATo-Torino, I-10100 Torino, Italy; vigorito@to.infn.it, fulgione@to.infn.it
[3] INFN-Bologna, 40126 Bologna, Italy
[4] University of Bologna, I-40126 Bologna, Italy
[5] Centro Enrico Fermi, I-00184 Roma, Italy
[6] INFN-Laboratori Nazionali del Gran Sasso and Gran Sasso Science Institute, I-67100 LAquila, Italy
[7] Dep. of Physics, University of Torino, I-10125 Torino, Italy
[8] CNRS-IN2P3, Paris, Laboratoire de Physique Nucléaire et de Hautes Energies (LPNHE), Universités Paris 6 et Paris 7, France
[9] University of Campinas, 13083-859 Campinas, SP, Brazil
[10] Massachusetts Institute of Technology, Cambridge, MA 02139-4307, USA
[11] CERN, Geneva, Switzerland
Received 2014 October 30; accepted 2015 January 12; published 2015 March 20

ABSTRACT

The Large Volume Detector (LVD) has been continuously taking data since 1992 at the INFN Gran Sasso National Laboratory. The LVD is sensitive to neutrino bursts from gravitational stellar collapses with full detection probability over the Galaxy. We have searched for neutrino bursts in LVD data taken over 7,335 days of operation. No evidence of neutrino signals has been found between 1992 June and 2013 December. The 90% C.L. upper limit on the rate of core collapse and failed supernova explosions out to distances of 25 kpc is found to be 0.114 yr^{-1}.

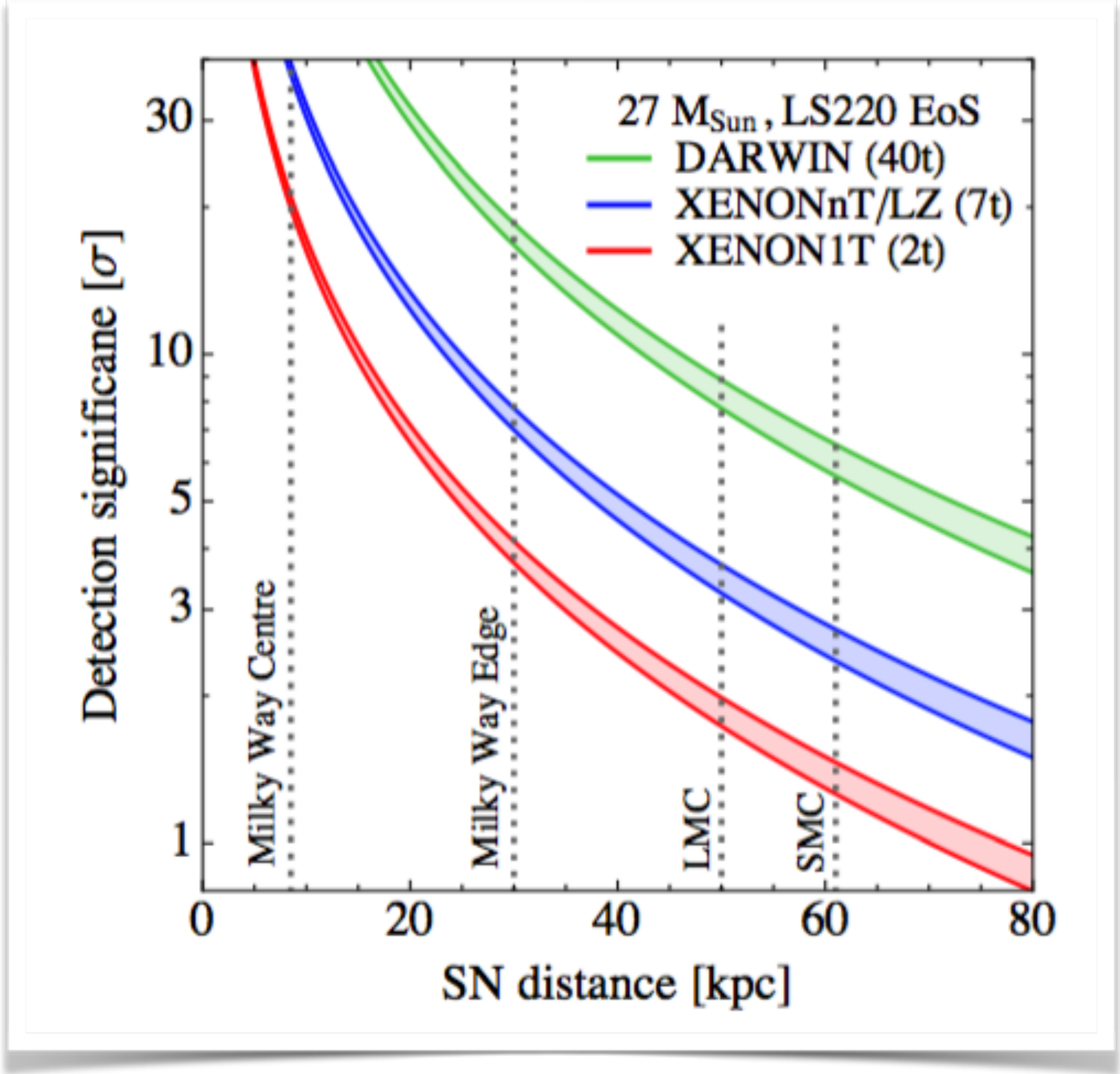
Key words: methods: observational – neutrinos – supernovae: general

Partecipazione a SNEWS

Allerta per astronomi

—> studi dello shock breakout

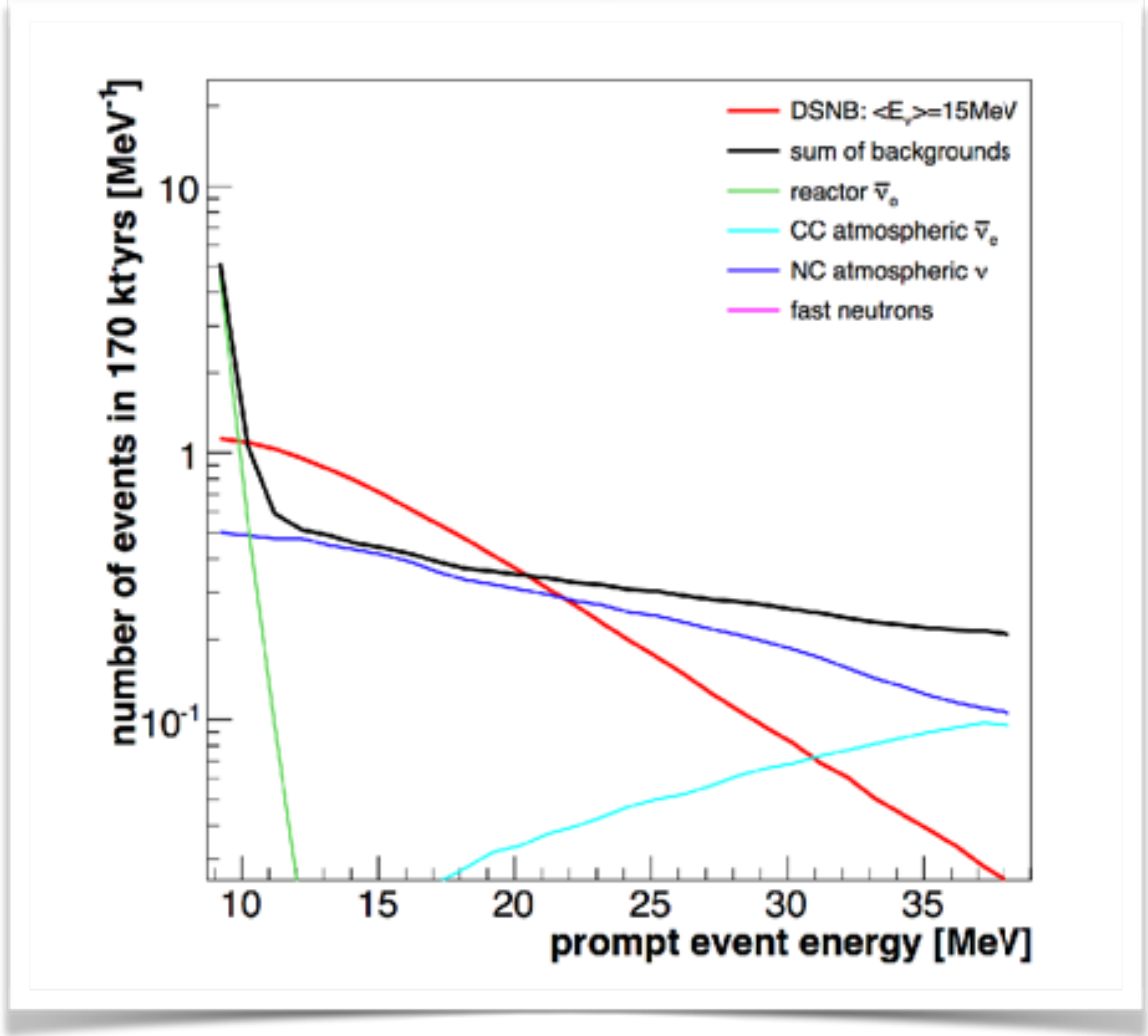
—> allerta onde gravitazionali



rivelatori a Xe: CNNS —> più informazioni sulla SN!

osservazioni di tutte le specie, misura dell'energia totale, indipendente da oscillazioni

da considerare che CNNS non e' mai stat osservato —> un esperimento (COHERENT) in corso alla neutron spallation source a Oak Ridge

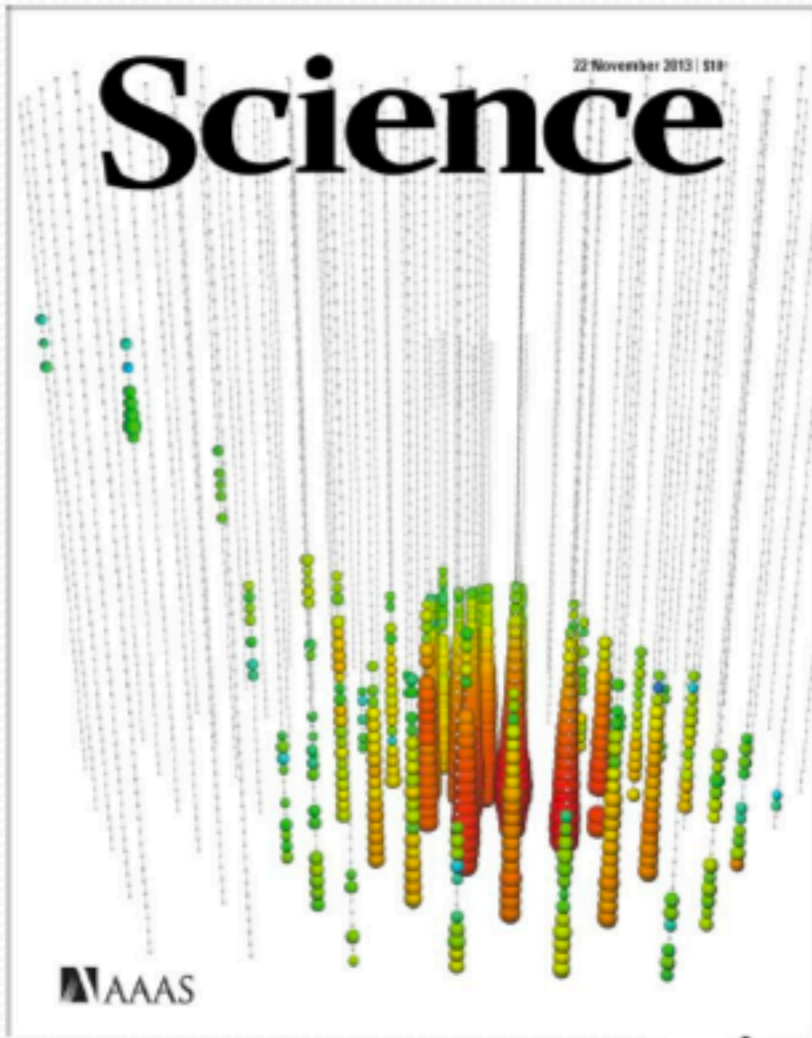


SNDB (diffuse background): densità di energia confrontabile con i fotoni emessi da tutte le stelle!

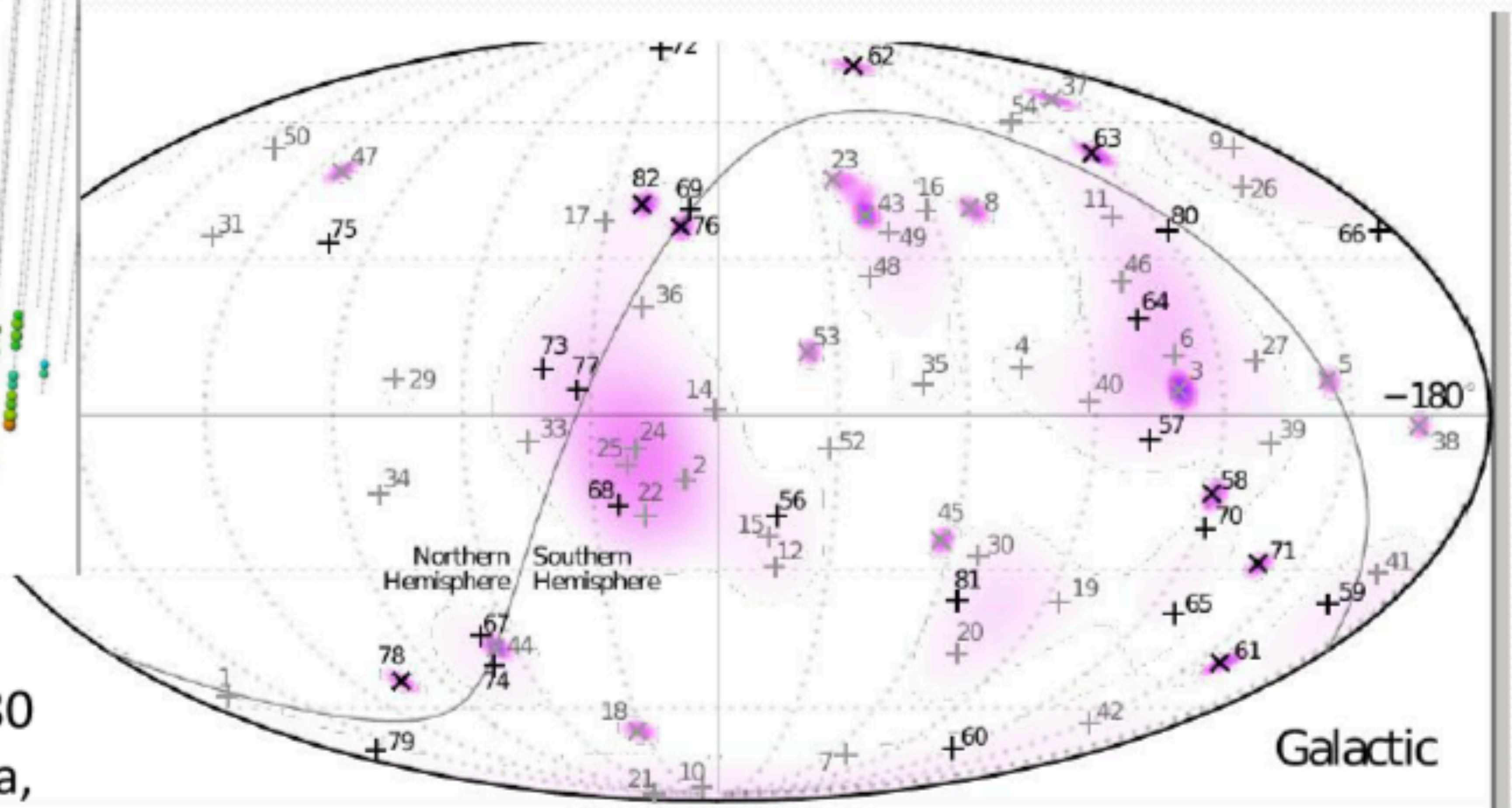
Rivelazione in JUNO: IBD con 15 ev in 10anni

Possibile concorrenza di SK con opzione Gd

Neutrini Cosmici

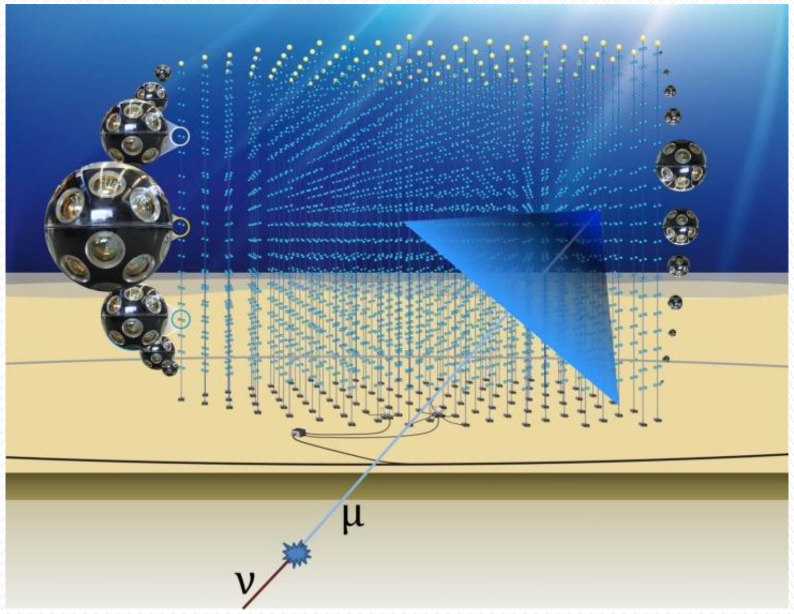


ICECUBE nel 2013 apre le porte all'astronomia a neutrini cosmici → 28 neutrini da 30 TeV a 1200 TeV!



In totale isolati più di 80 neutrini di alta energia, tra 100 TeV e 10 PeV

KM3NET

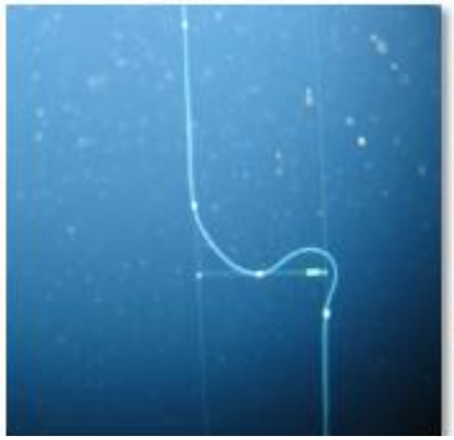


Very hostile enviroment due to huge pression (350 bar), corrosion, difficult access (installation, maintainance) …

- Exploit optical Cherenkov radiation
  - all flavour detection in the TeV-PeV region
  - 1 km^3 of sea water equipped with a 3D array of optical sensors
  - two building blocks of 115 Detection Units (DU)
    - each DU hosts 18 multi-PMT Digital Optical Modules (DOM) with 36 m spacing
    - a backbone cable with breakouts at DOMs distributes power and data
  - Sea network of submarine cables and Junction Boxes provide power and data transmission to shore via a main electro-optical cable
- All data to shore

KM3NET: ARCA (Capo Passero)

- - String (700 m) with 18 optical modules (DOM)
- - 36 m DOM spacing, 90 m DU spacing
- - Mechanical structure made of two Dyneema ropes, anchor and buoys
- - Backbone (VEOC) made of a 6mm oil filled tube hosting two conductors and 18 fibres with breakouts at each DOM
- - Base module with optoelectronics for data transmission
  - DWDM, White Rabbit, All-data-to-shore
- - Interlink cable for connection to the sea-floor network
  - connection operated by a ROV (Remote Operable Vehicle)

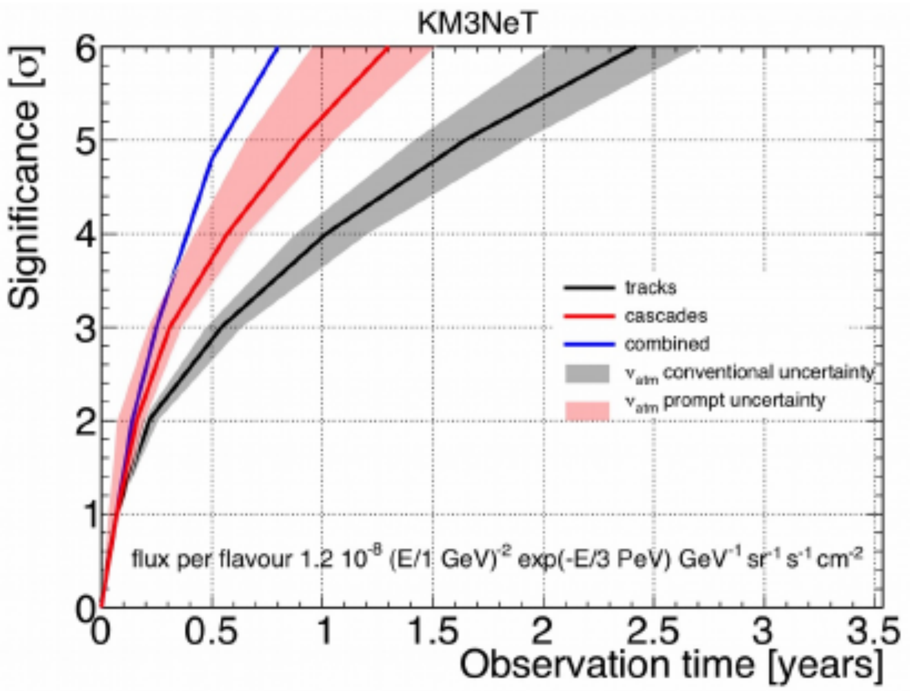


KM3NET: ARCA

PHASE	BLOCKS	PRIMARY DELIVERABLES
ARCA phase 1	0.2 0.1 km3	Proof of feasibility and first science results
ARCA phase 2	2 1 km3	Study of neutrino signal reported by IceCube All flavor ν astronomy

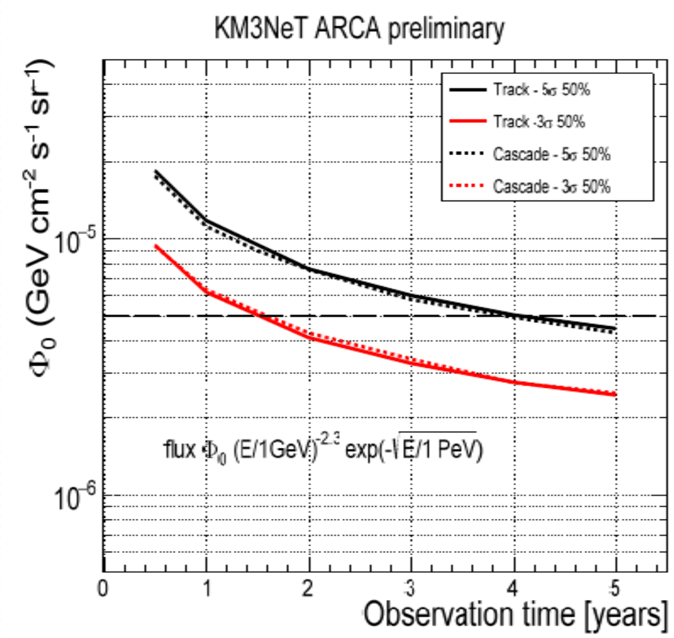
- 2 DU installate alla posizione nominale a 3500 metri di profondità
- Più di un anno di dati raccolti
- Analisi dati in corso
- Sistema off causa corto circuito
- Prevista campagna marina per ripristino DU

Scoperta con significatività di 5σ (probabilità 50%) sul flusso di neutrini di ICECUBE in meno di un anno con analisi combinata.

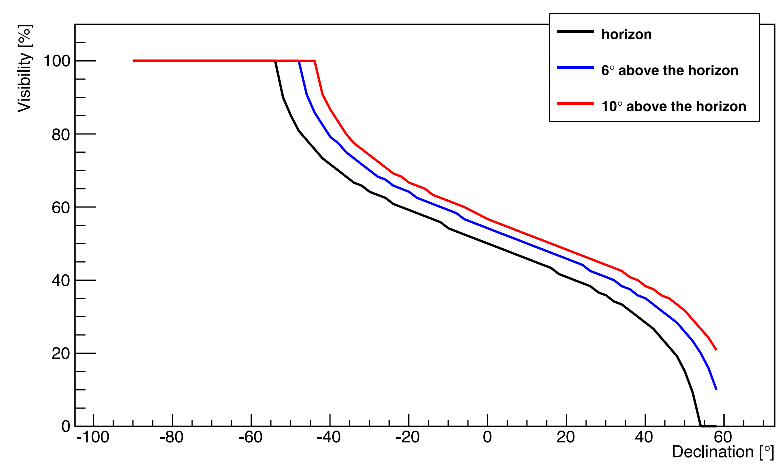


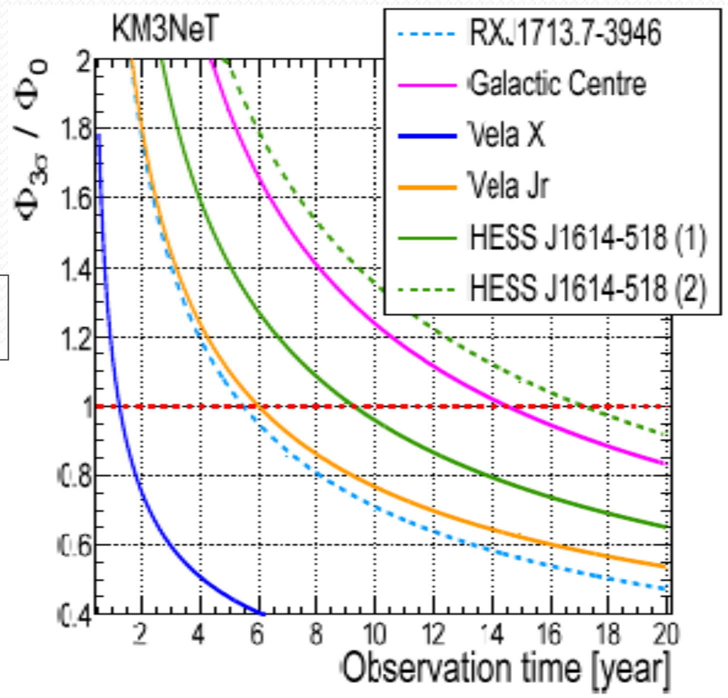
KM3NET: ARCA

- 87% del cielo coperto, inclusa la maggior parte della Galassia e il centro galattico.
- Ricerca di flussi di neutrini correlati alle emissioni gamma vicine al centro galattico (FERMI, HESS).
- Ricerca di sorgenti galattiche: i muoni sono il golden channel per l'astronomia a neutrini.



ARCA visibility for up going muons





P. Sapienza, FERMI Coll. Meeting March 2018

Fisica dei neutrini: un campo di ricerca ancora molto attivo con molte risposte ancora da dare (e soldi per l'INFN da investire)…