Mauro Mezzetto,
Istituto Nazionale Fisica Nucleare, Padova

Future long baseline facilities at accelerators

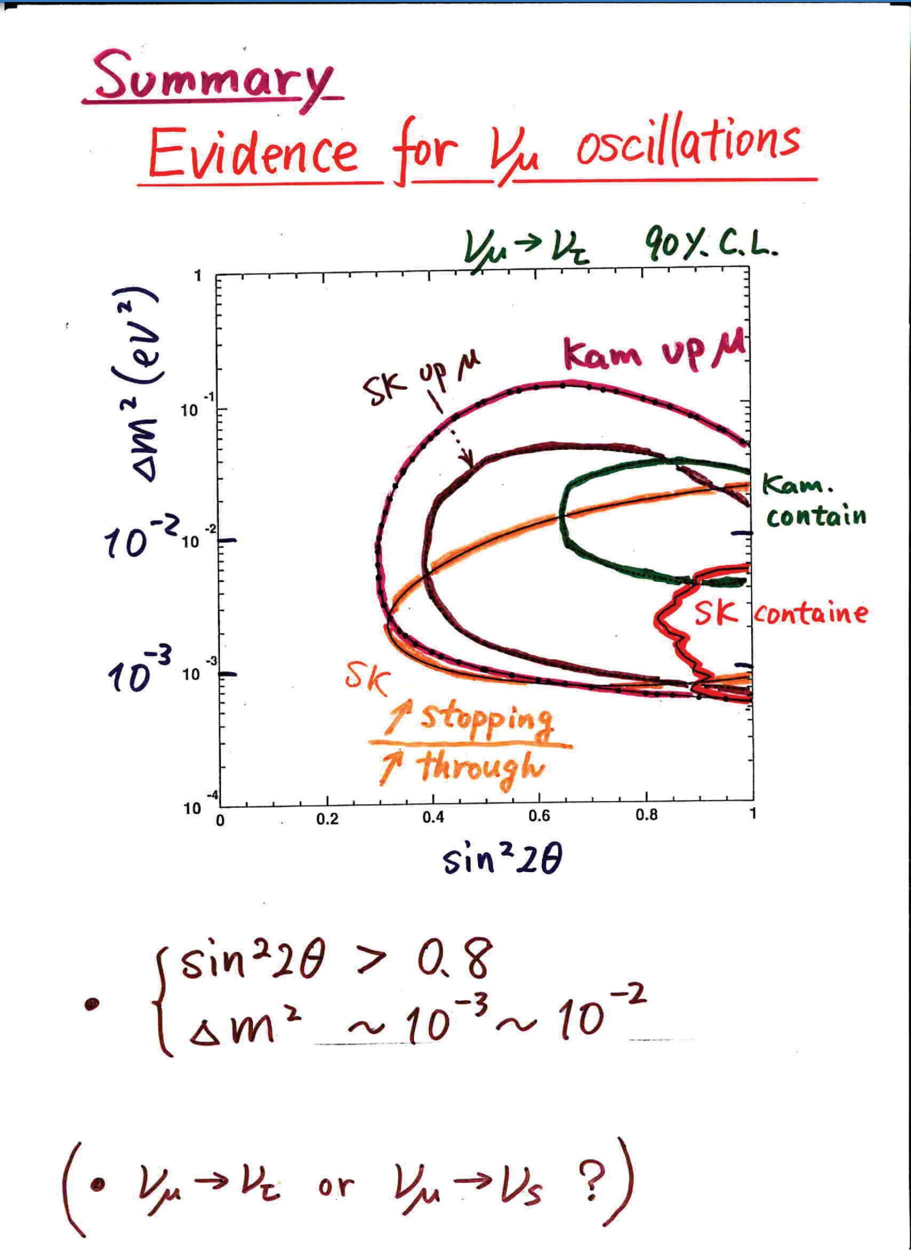
- A little bit of history
- Concepts, strategies, challenges
- The two players: Dune and Hyper-Kamiokande
- Conclusions

The history began in 1998

The discovery of neutrino oscillations by Super-Kamiokande made clear that progresses in this field would have required long baselines, $\mathcal{O}(10^2$-10^3 km).

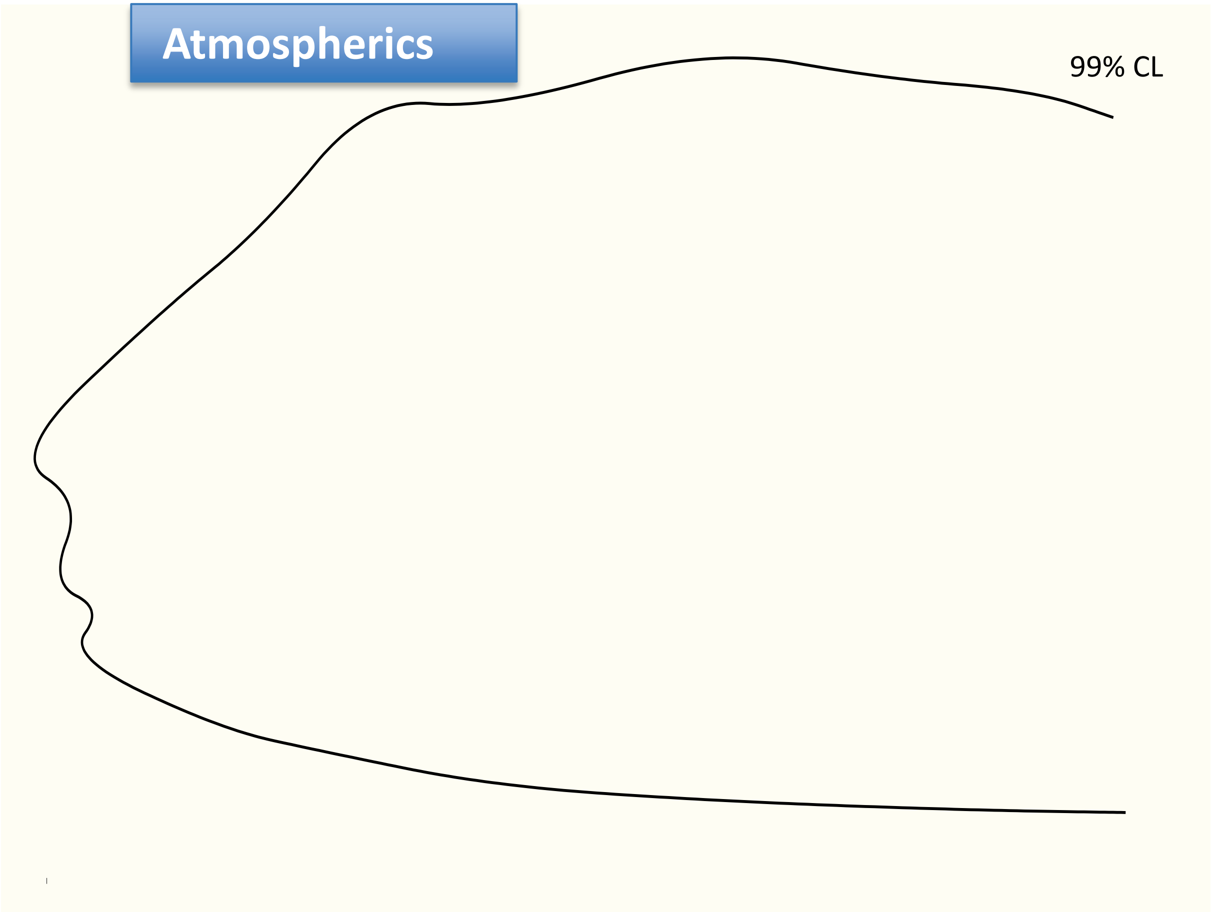
Requiring gigantic detectors deep underground (SK ↑, accelerator labs ↓)

Several people were looking for the same process at Δm^2 bigger than 4-6 orders of magnitude …

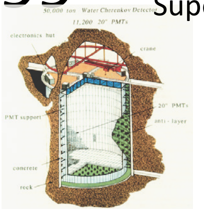


Since then a remarkable progress

1999



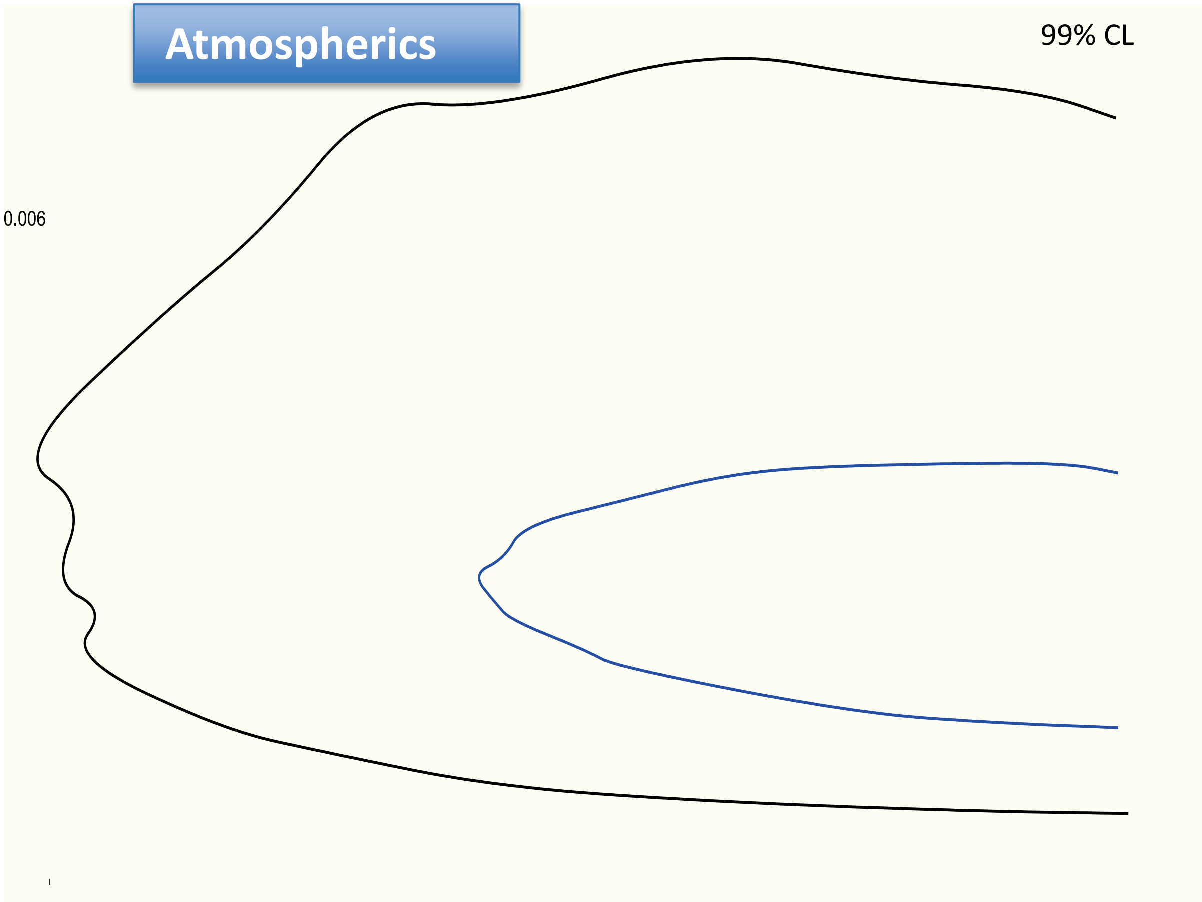
SuperK



MACRO at GRAN SASSO

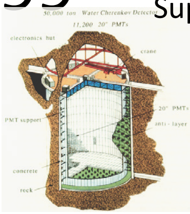
Monopole, Astrophysics, and Cosmic Ray Observatory

Since then a remarkable progress

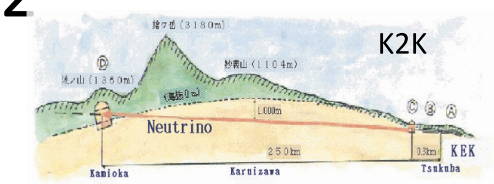


1999

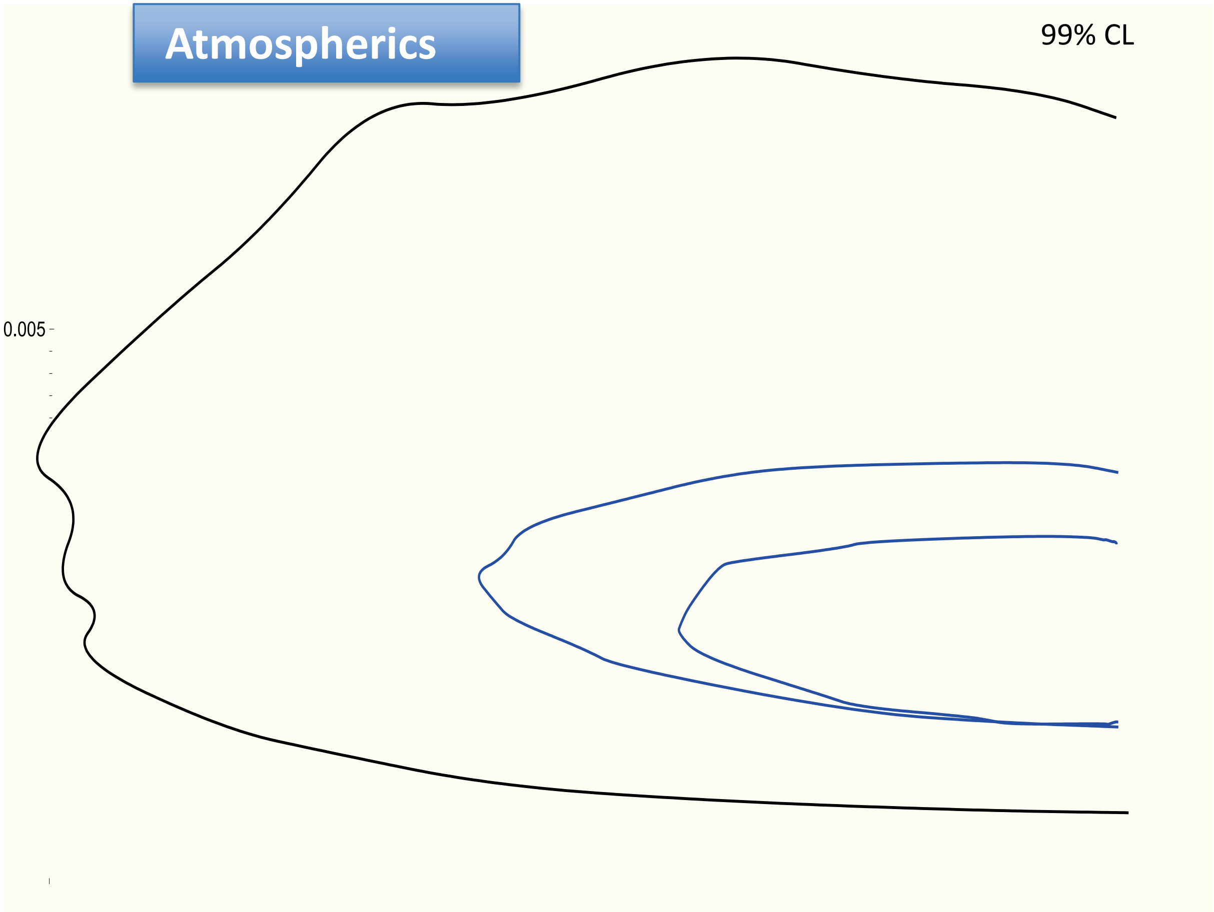
SuperK



2002



Since then a remarkable progress



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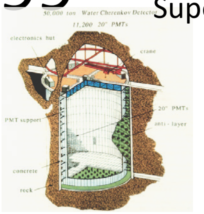

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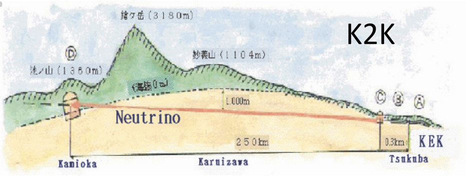

2005

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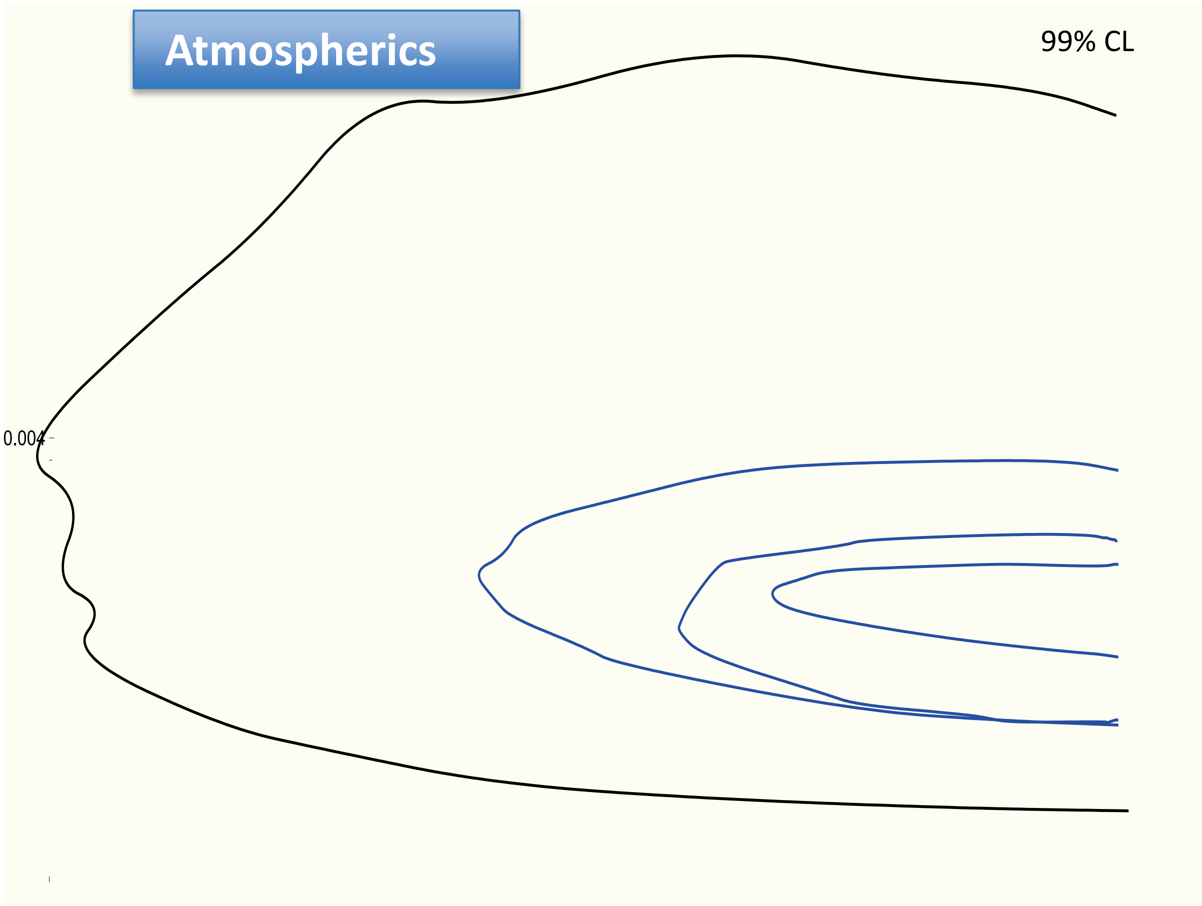


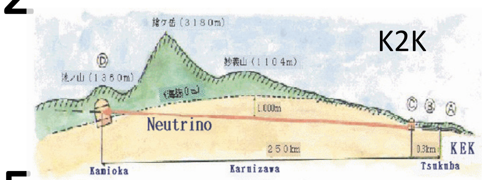
1999

SuperK

MACRO
at GRAN SASSO
Monopole, Astrophysics, and Cosmic Ray Observatory

2002

K2K

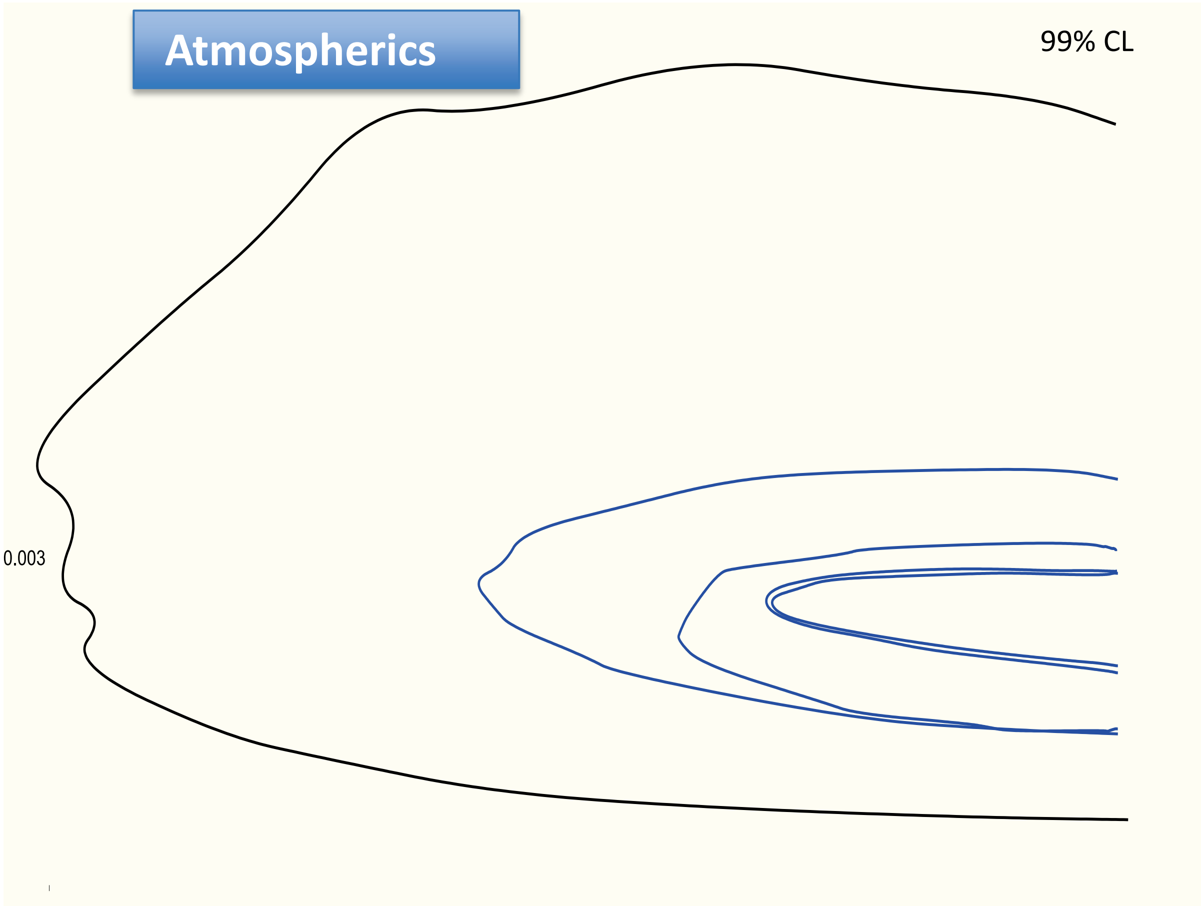


2005

2008

MINOS

Since then a remarkable progress



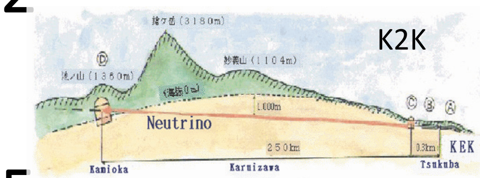
1999

SuperK

MACRO at GRAN SASSO
Monopole, Astrophysics, and Cosmic Ray Observatory

2002

K2K



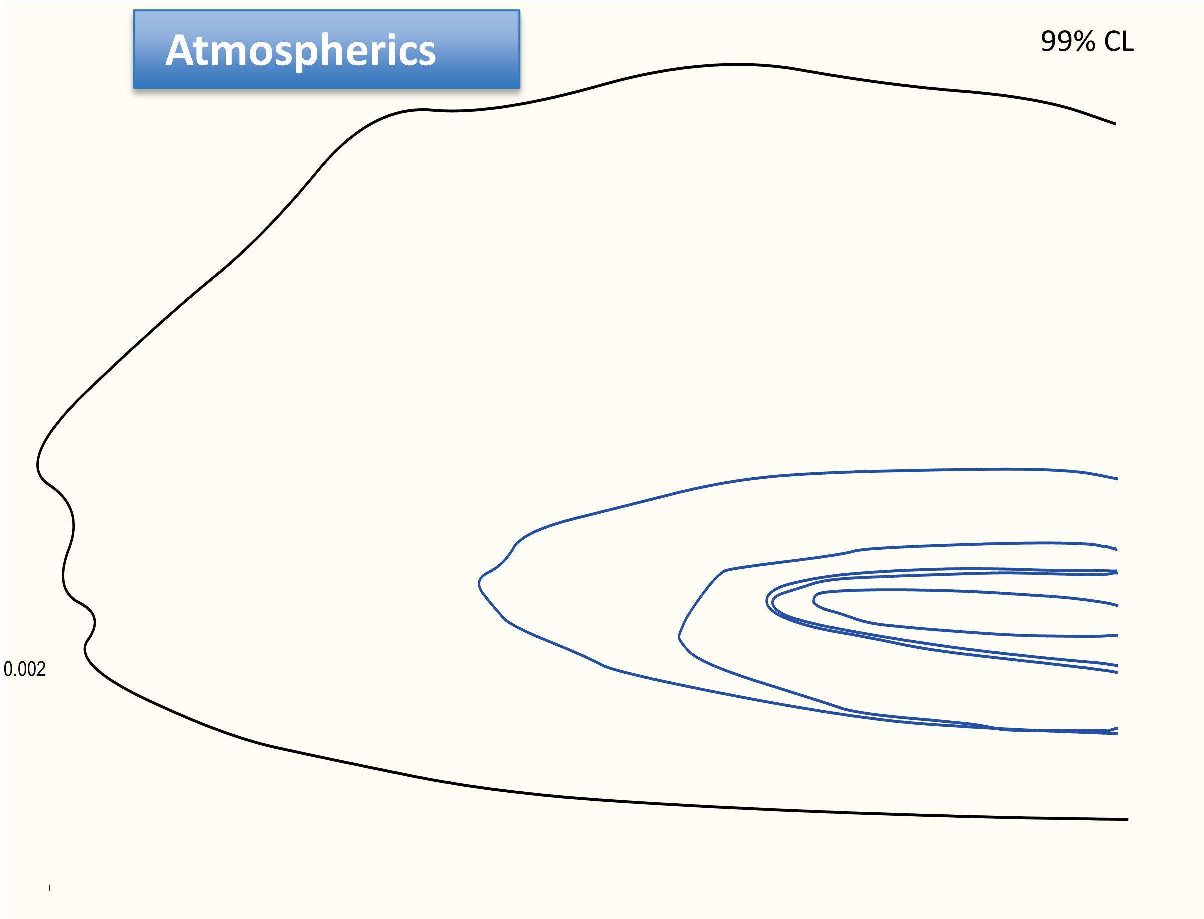
2005

2008

MINOS

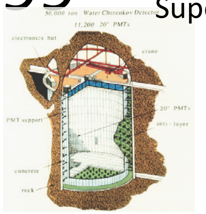
2010

Since then a remarkable progress



1999

SuperK

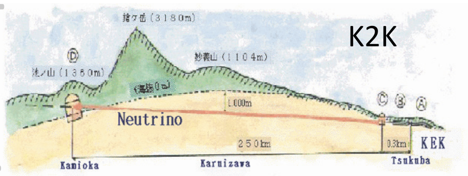


MACRO at GRAN SASSO

Monopole, Astrophysics, and Cosmic Ray Observatory

2002

K2K



2005

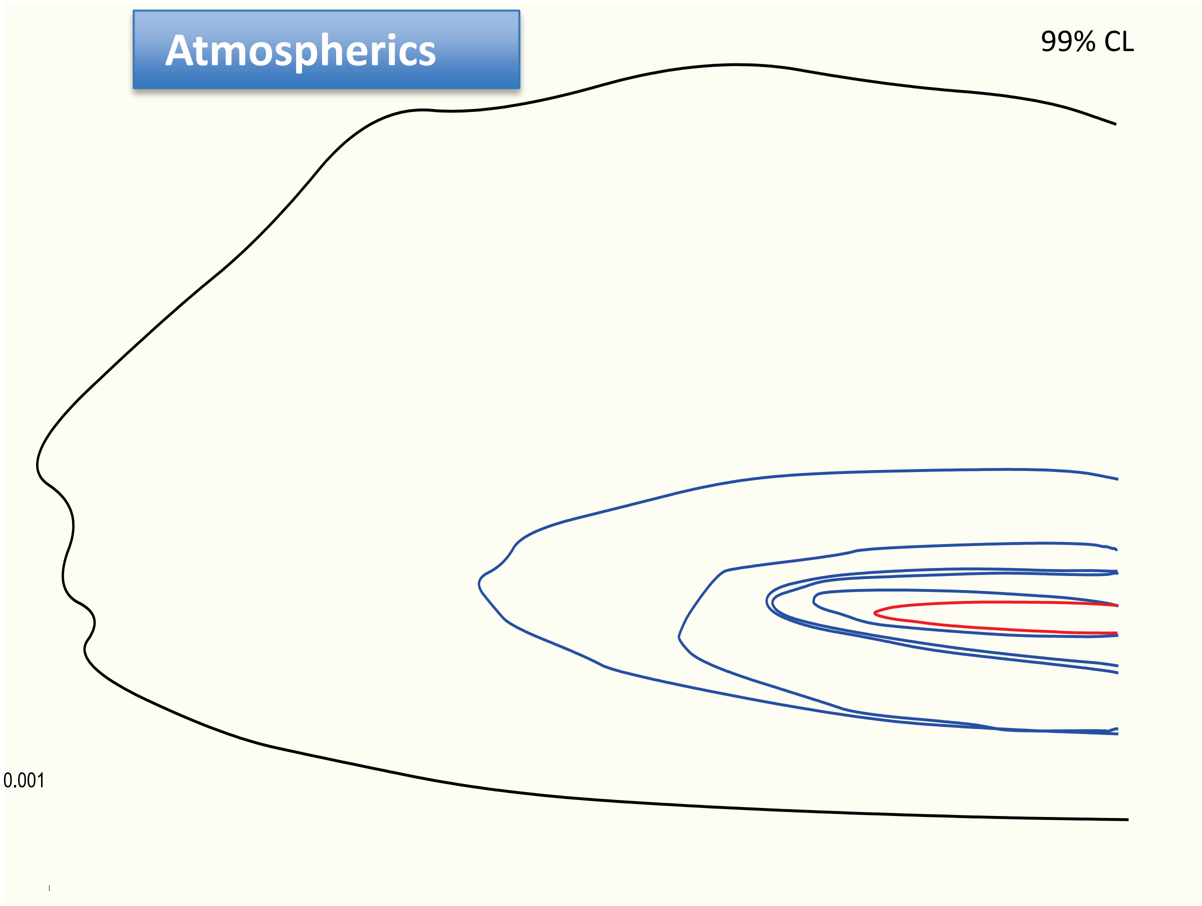
2008

MINOS

2010

2012

Since then a remarkable progress



Along time changed variables, fitting methods, conventions, assumptions ….

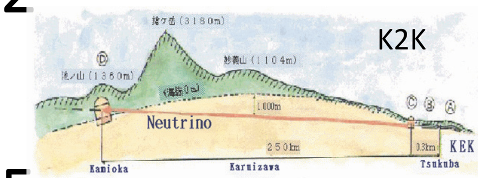
Results also from Opera, Antares, IceCube ….

1999

SuperK

MACRO at GRAN SASSO
Monopole, Astrophysics, and Cosmic Ray Observatory

2002



2005

2008

MINOS

2010

2012

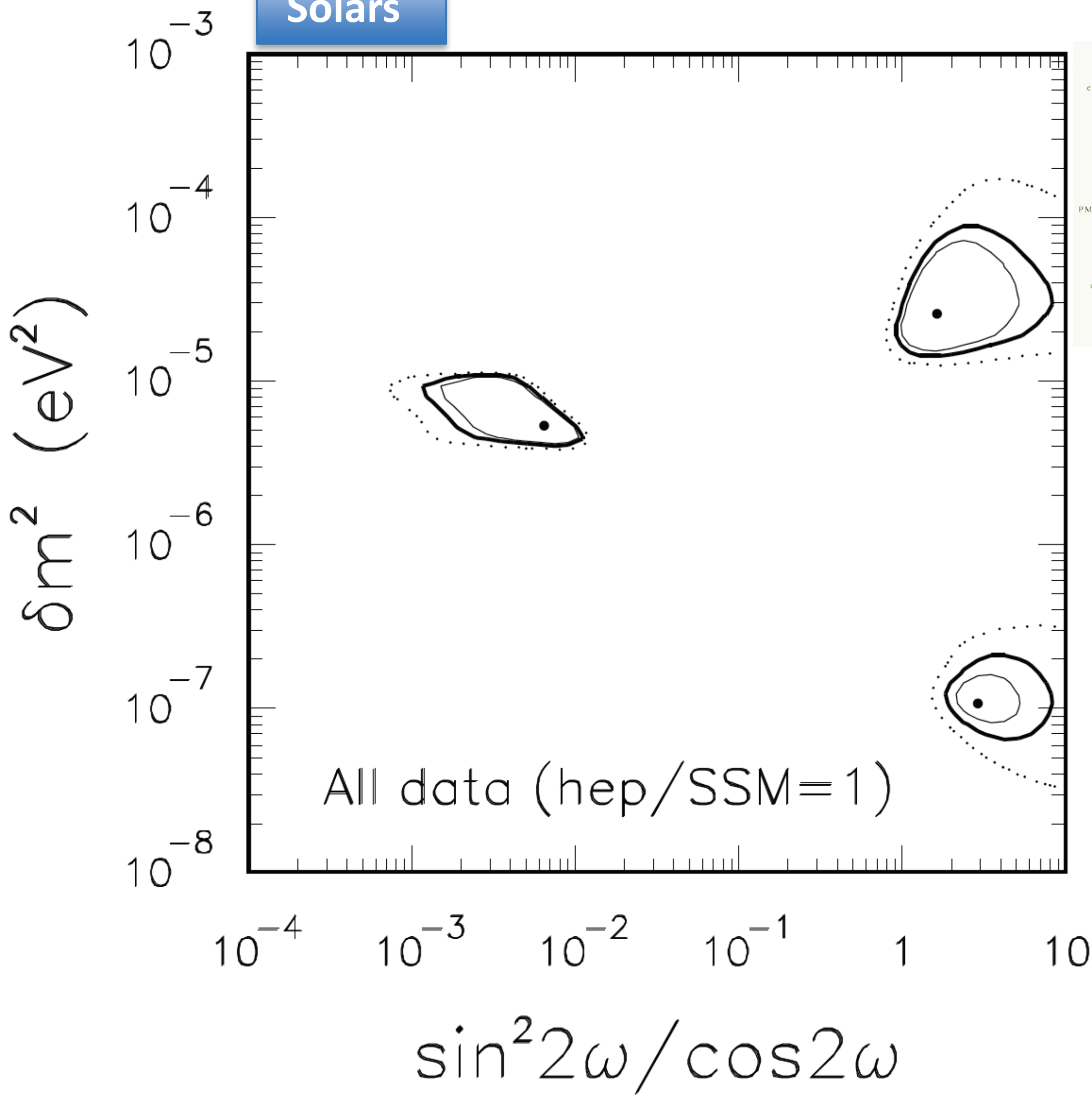
2014

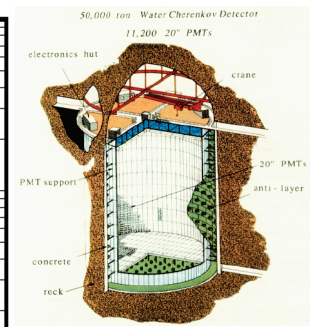
T2K

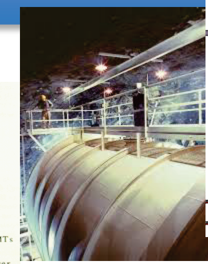
Since then a remarkable progress

Solars

1999

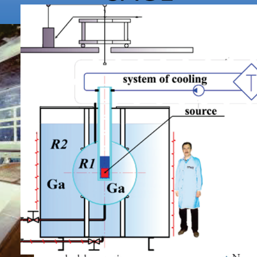


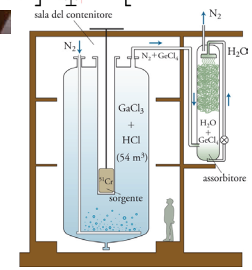




Homestake

SAGE

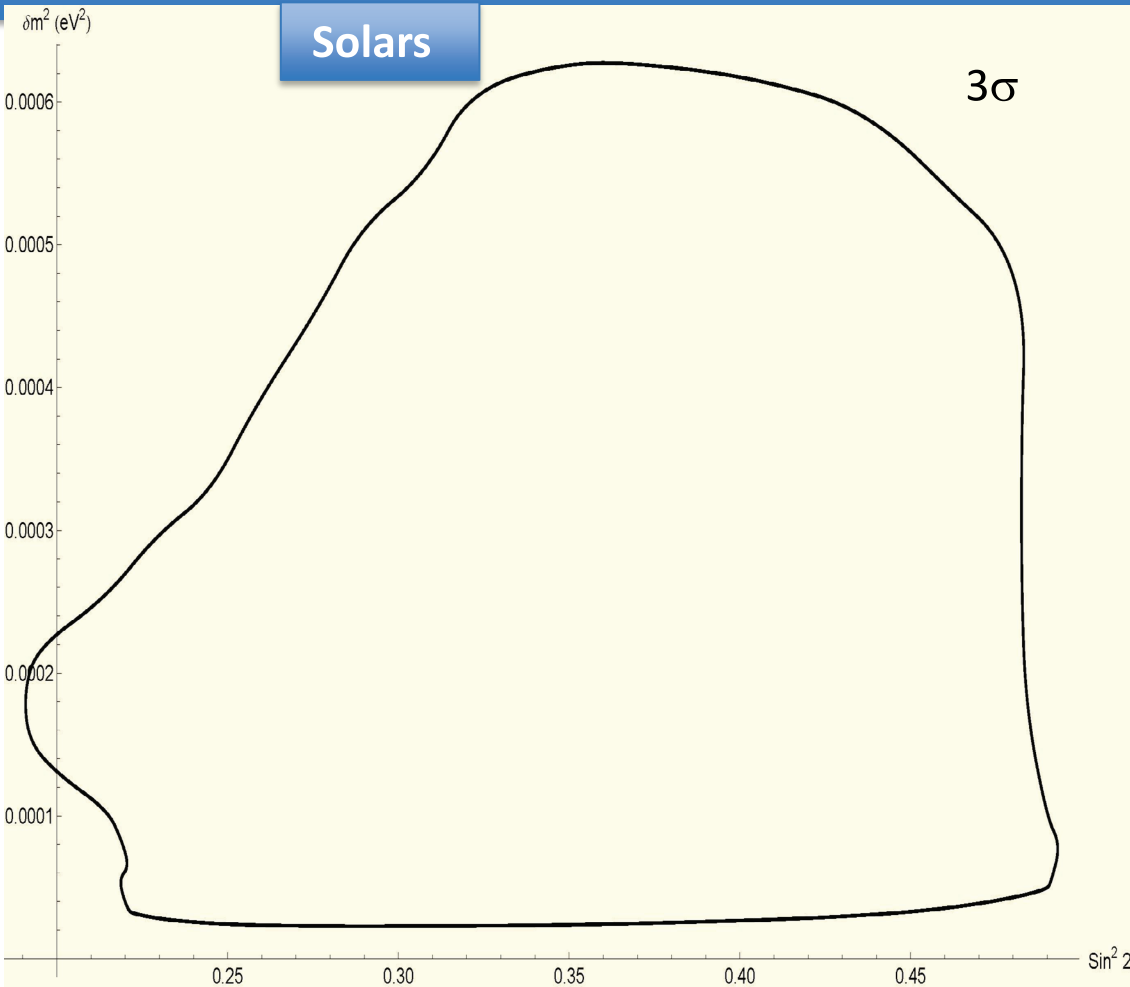




Gallex/GNO

Since then a remarkable progress

Solars



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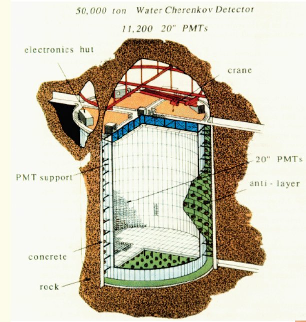

Homestake

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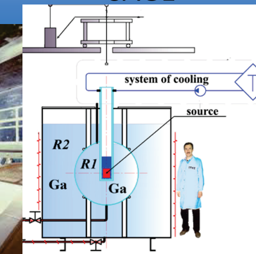
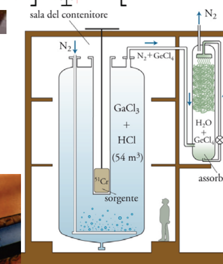
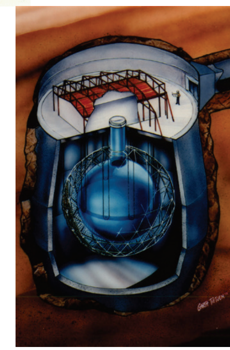




Gallex/GNO

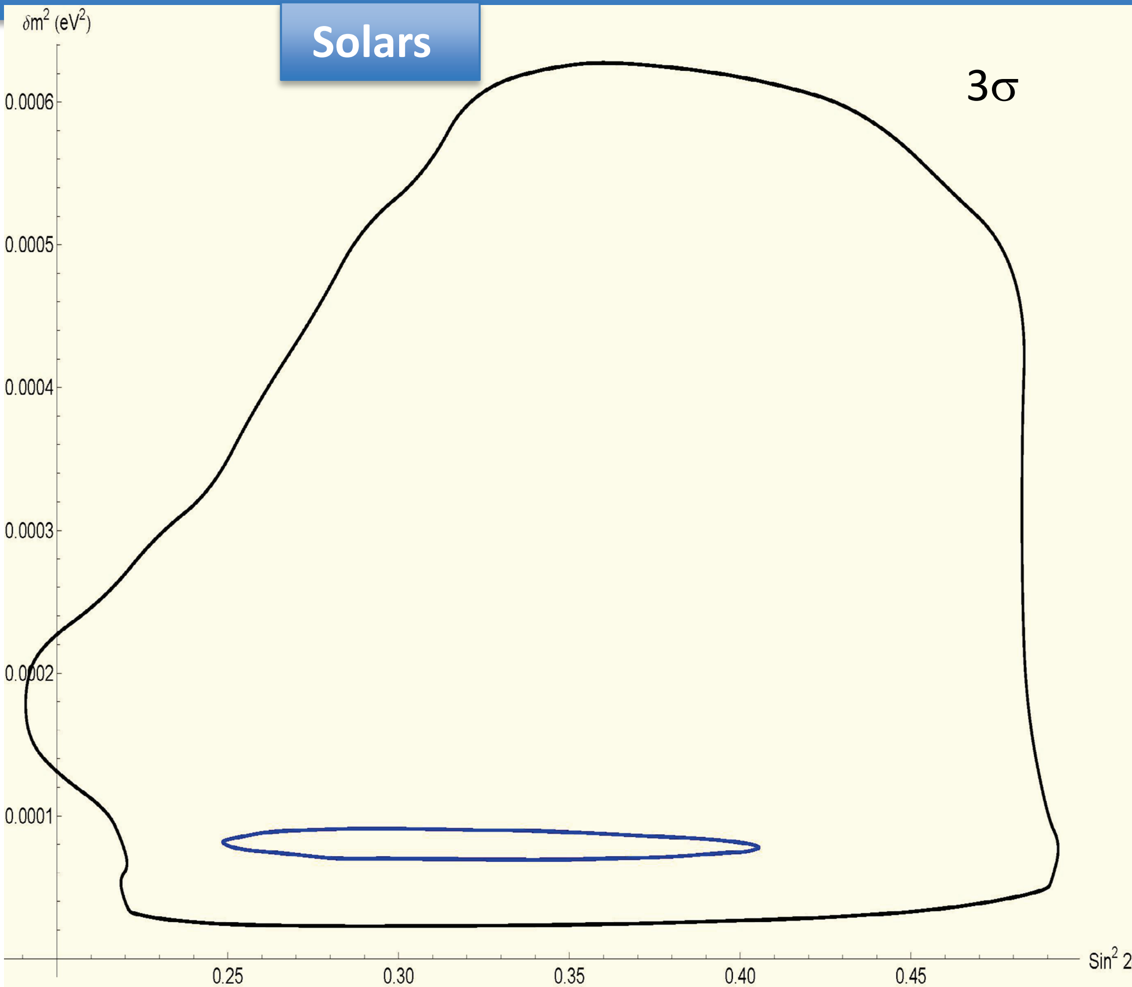
2002



SNO

Since then a remarkable progress

Solars



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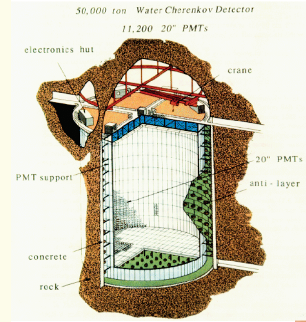

Homestake

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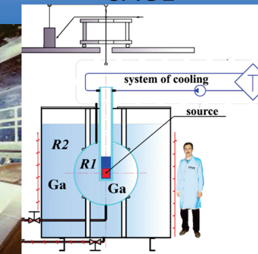
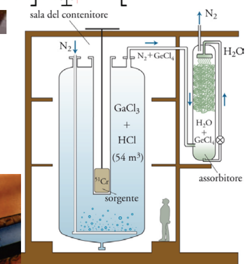


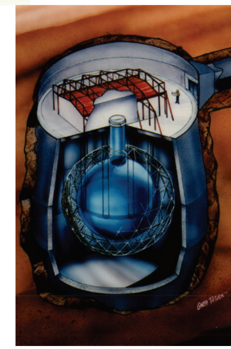


Gallex/GNO

2002

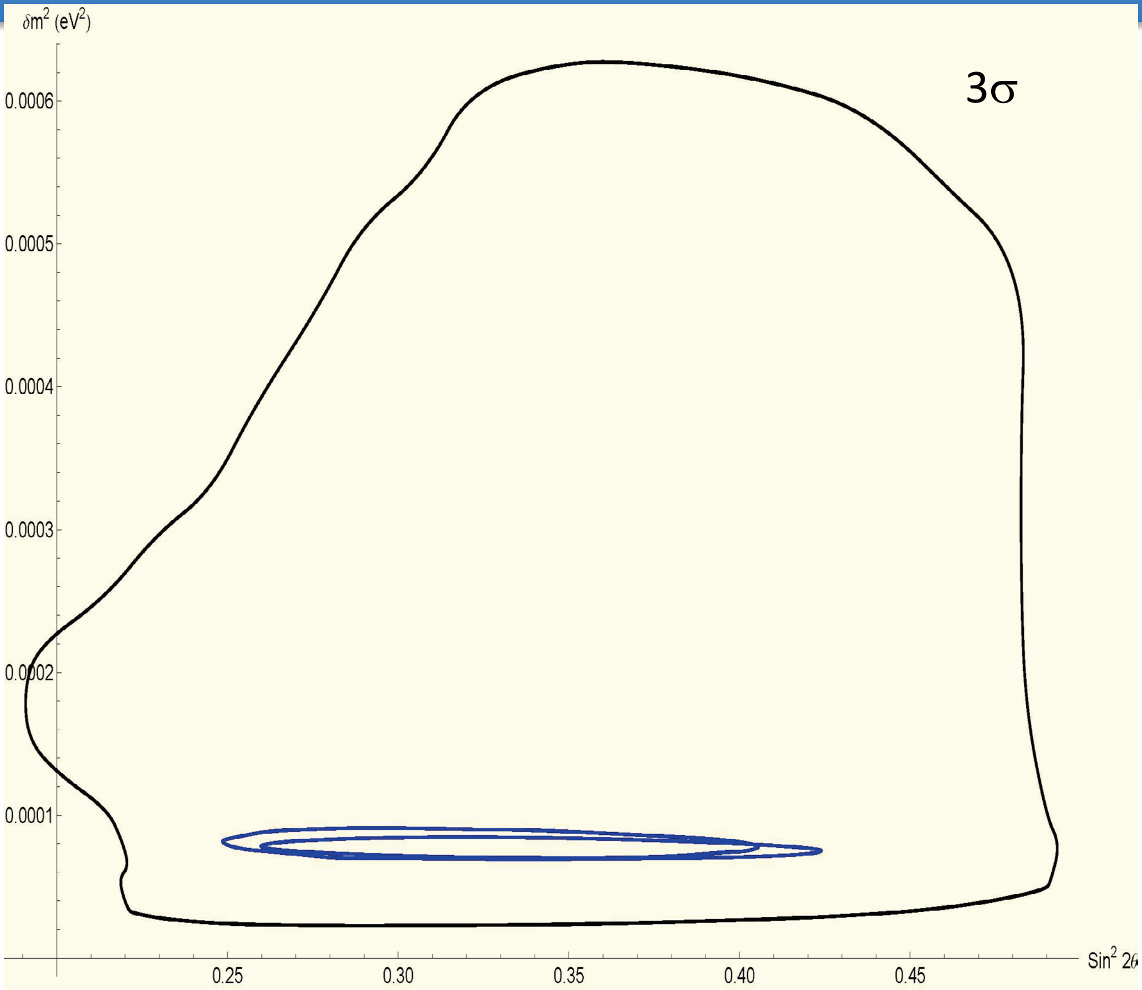
KamLAND

2005



SNO

Since then a remarkable progress



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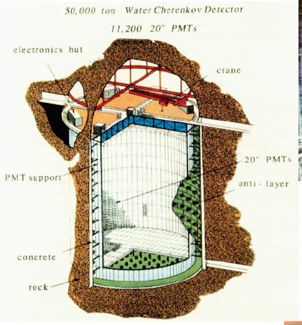

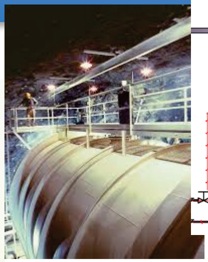

Homestake

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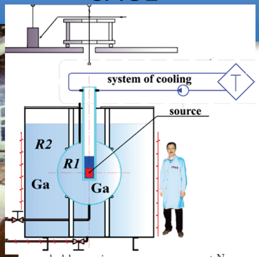
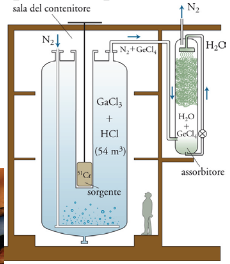
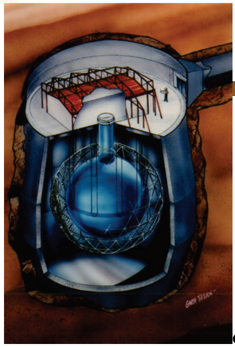




Gallex/GNO

2002

Kam
LAND
Kamioka Liquid scintillator Anti-Neutrino Detector

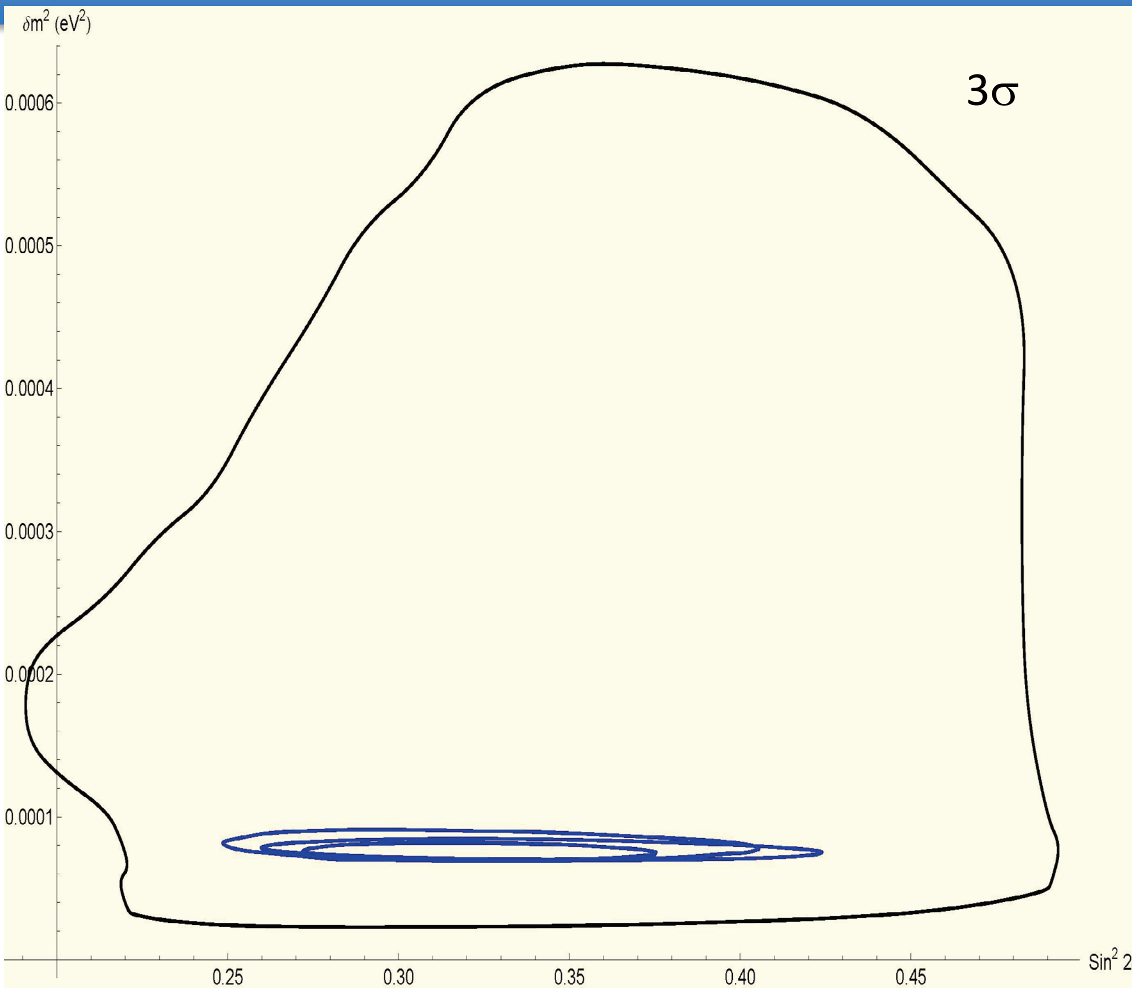


SNO

2005

2008

Since then a remarkable progress



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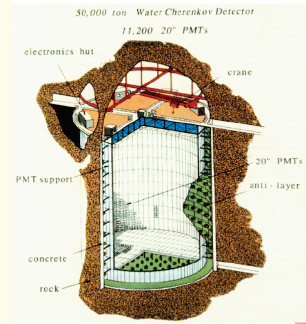
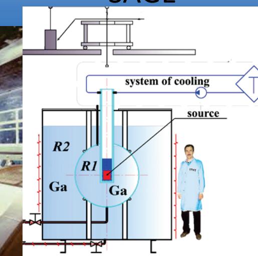
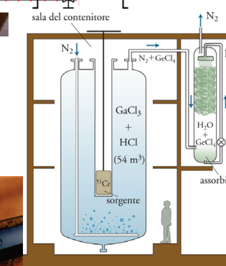


Homestake

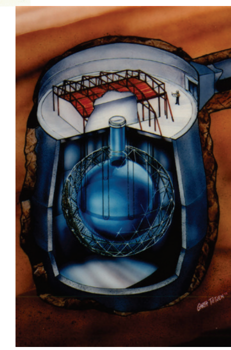
SAGE





Gallex/GNO

2002



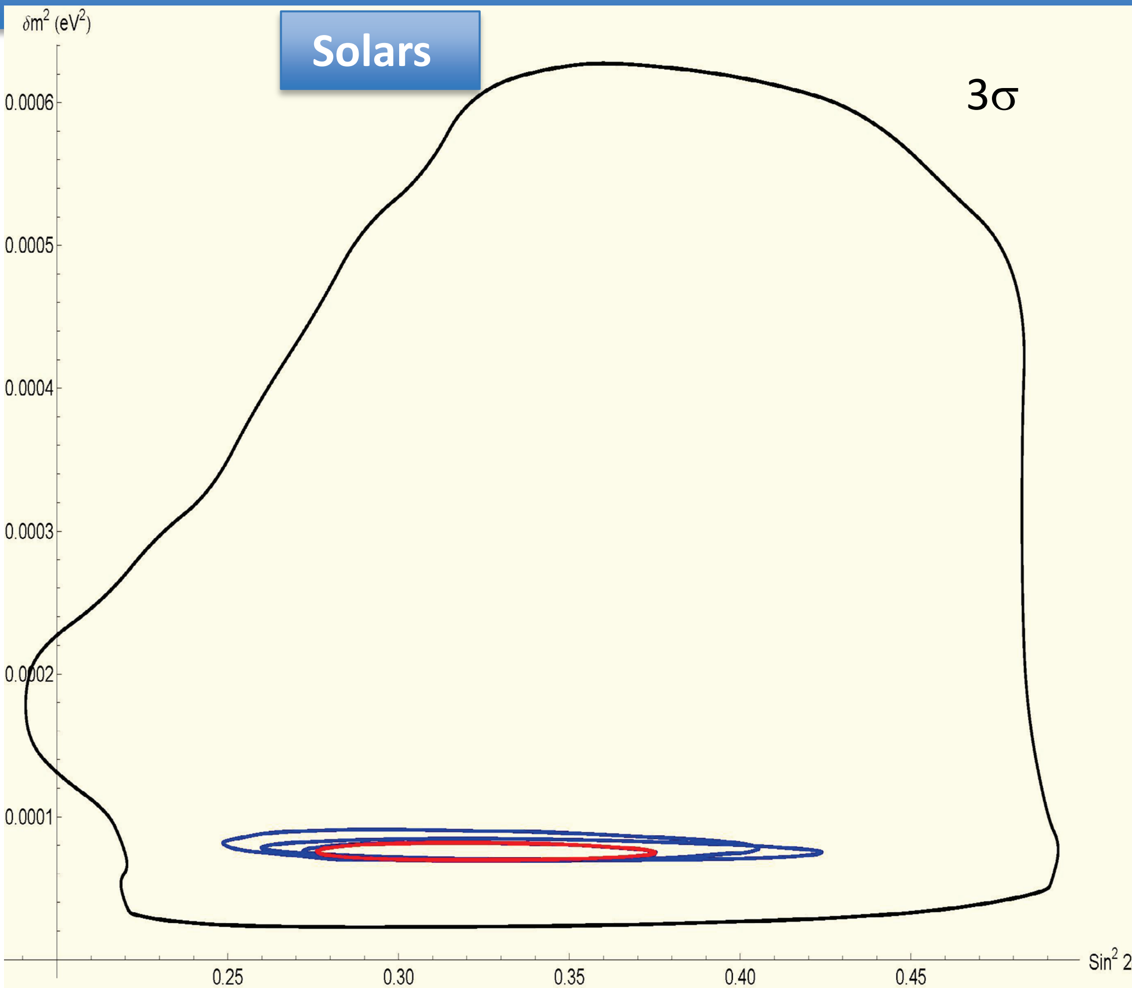
SNO

2005

2008

2010

Since then a remarkable progress



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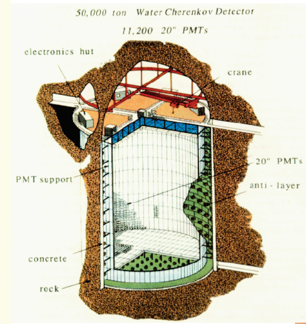

Homestake

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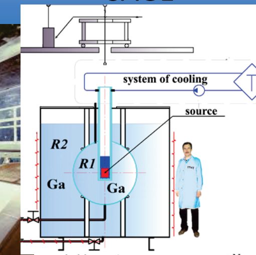
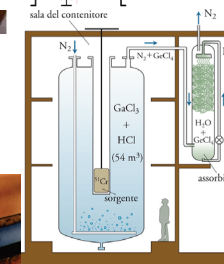


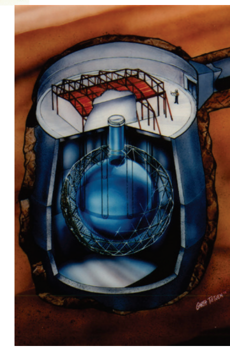


Gallex/GNO

2002

KamLAND

Kamioka Liquid scintillator Anti-Neutrino Detector



SNO

2005

2008

2010

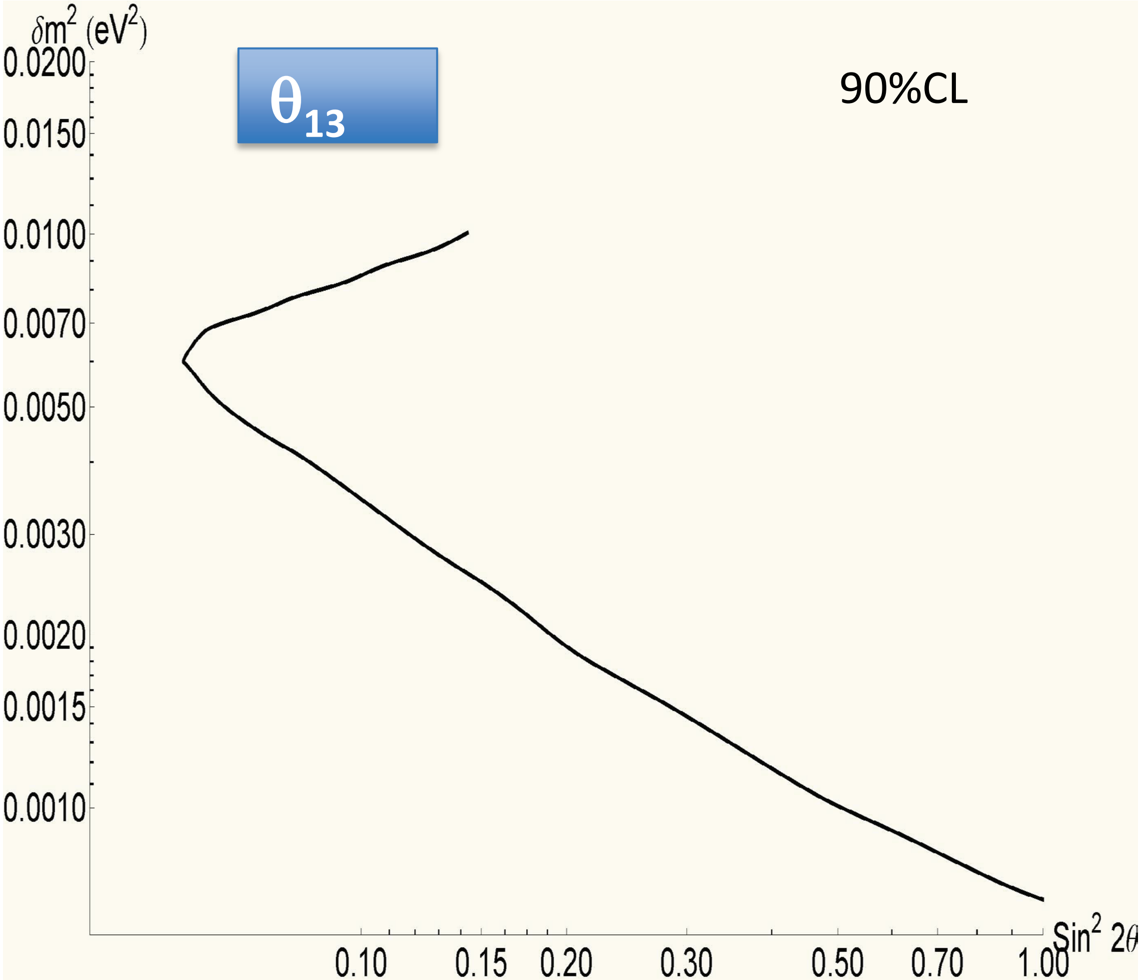
2012

2014

BOREXINO GRAN SASSO

Along time changed variables, fitting methods, conventions, assumptions …. And also some important cross section both at the source and the detector, not to mention the new evaluation of reactor antineutrino rates.

Since then a remarkable progress



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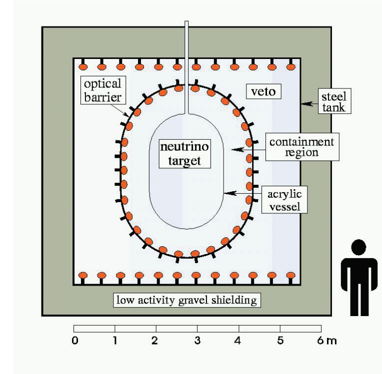

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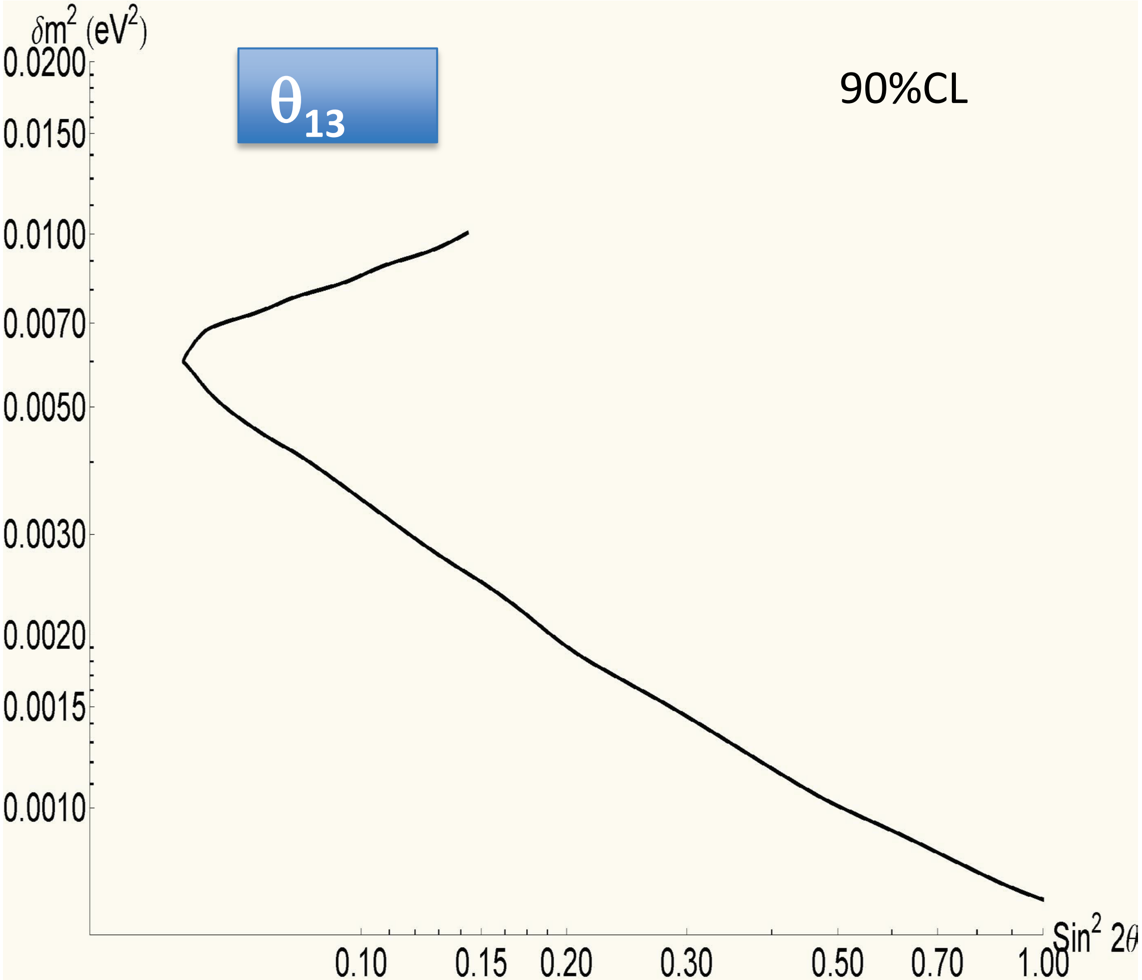

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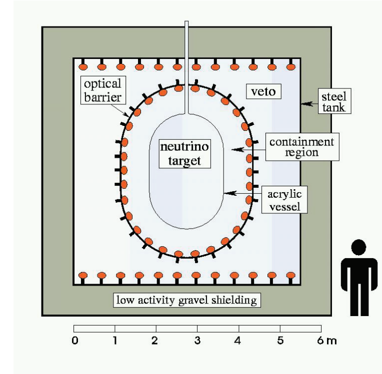

2002

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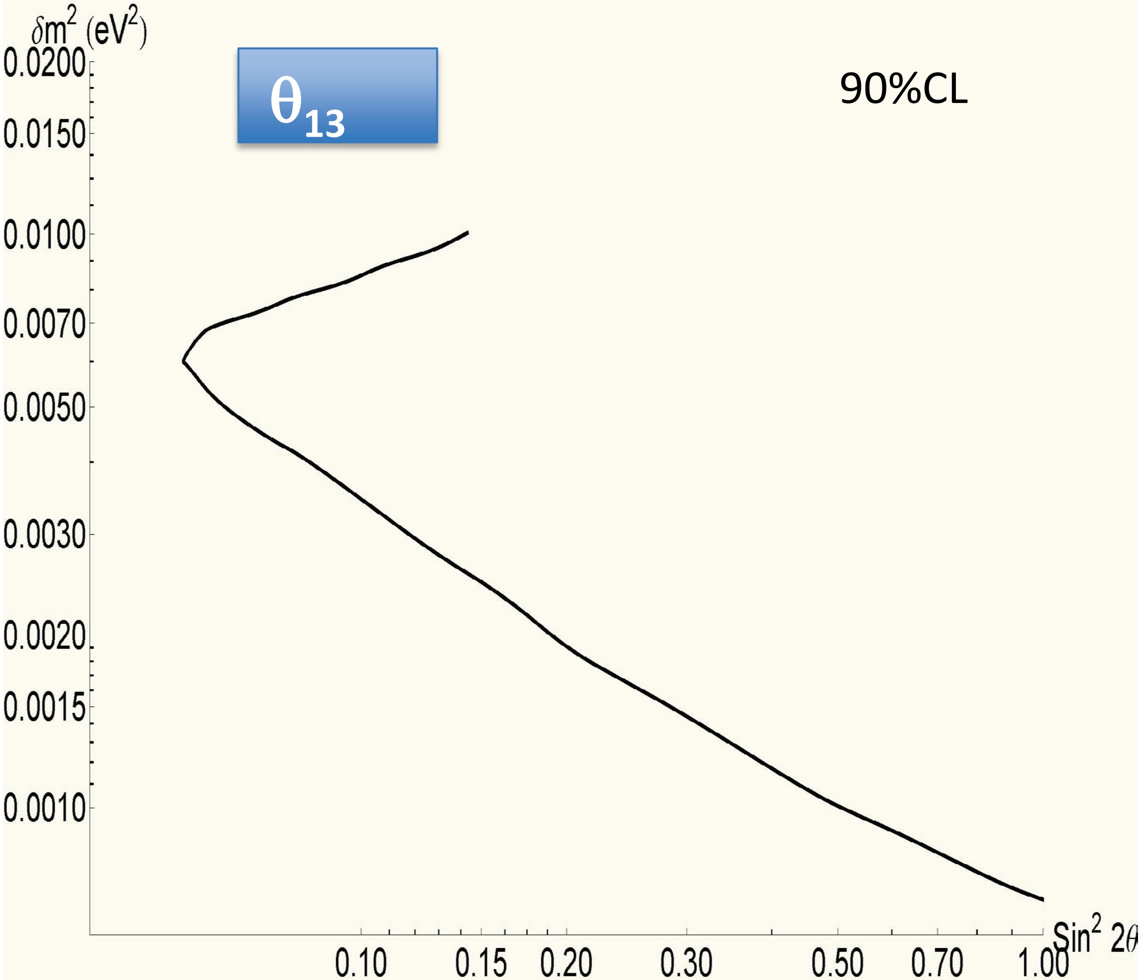

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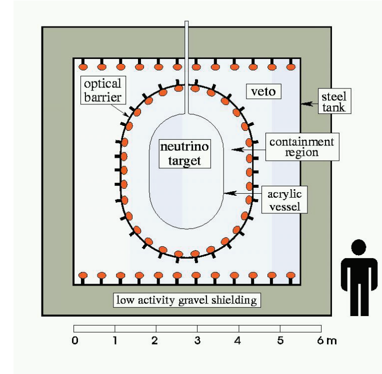

2002

2005

2008

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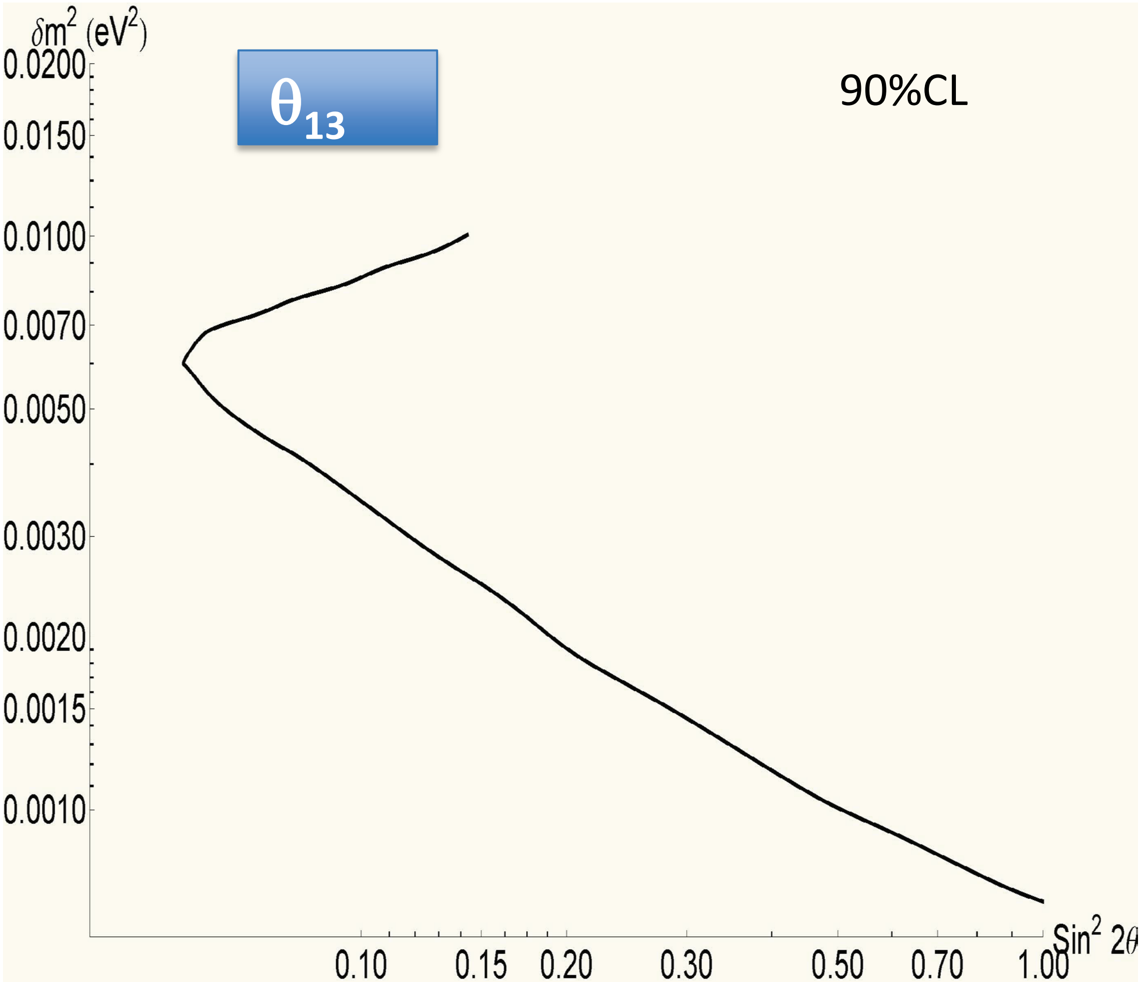

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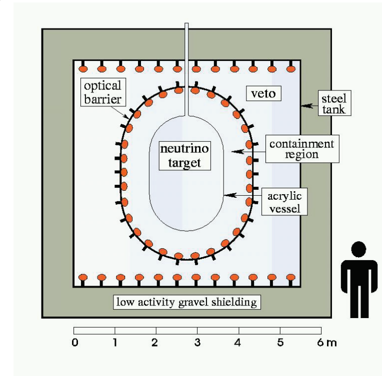


2002

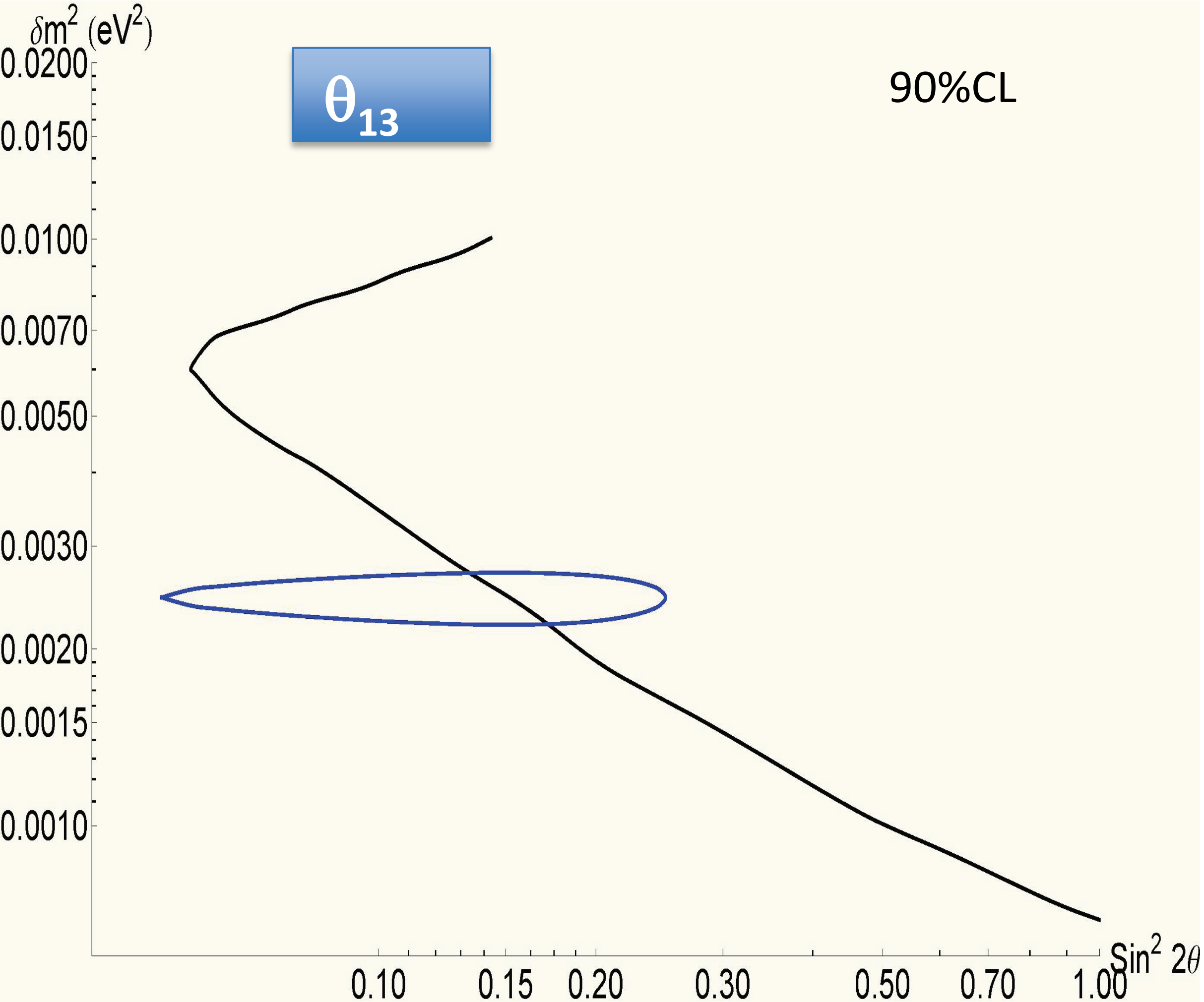
2005

2008

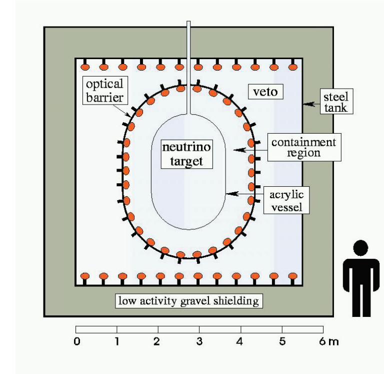
2009

At Neutel 2009 Fogli et al. start claiming that global fits favour $\sin^2 2\theta_{13}$=0.1 at 1.5σ

Since then a remarkable progress



1999



2002

2005

2008

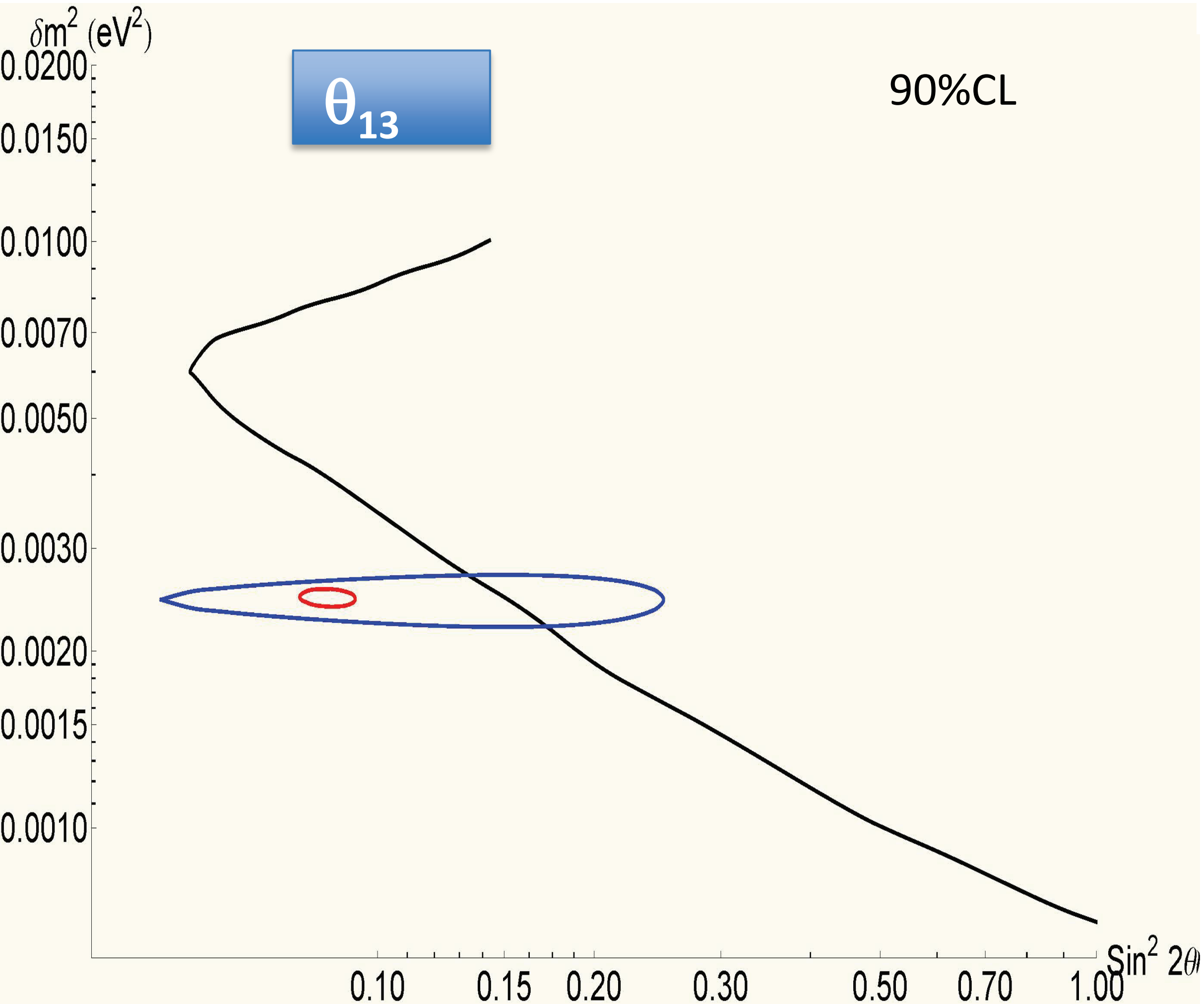
2010

At Neutel 2010 Fogli et al.
Start claiming that global fits
Favour $\sin^2 2\theta_{13}$=0.1 at 1.5σ

2011

T2K

Since then a remarkable progress



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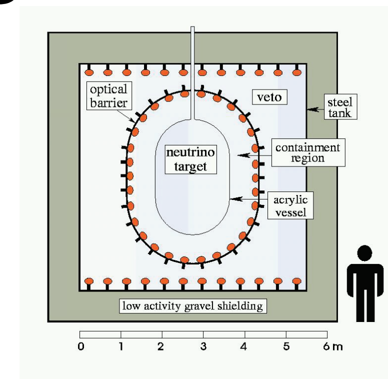


2002

2005

2008

2010 At Neutel 2010 Fogli et al. Start claiming that global fits Favour $\sin^2 2\theta_{13}=0.1$ at 1.5σ

2011

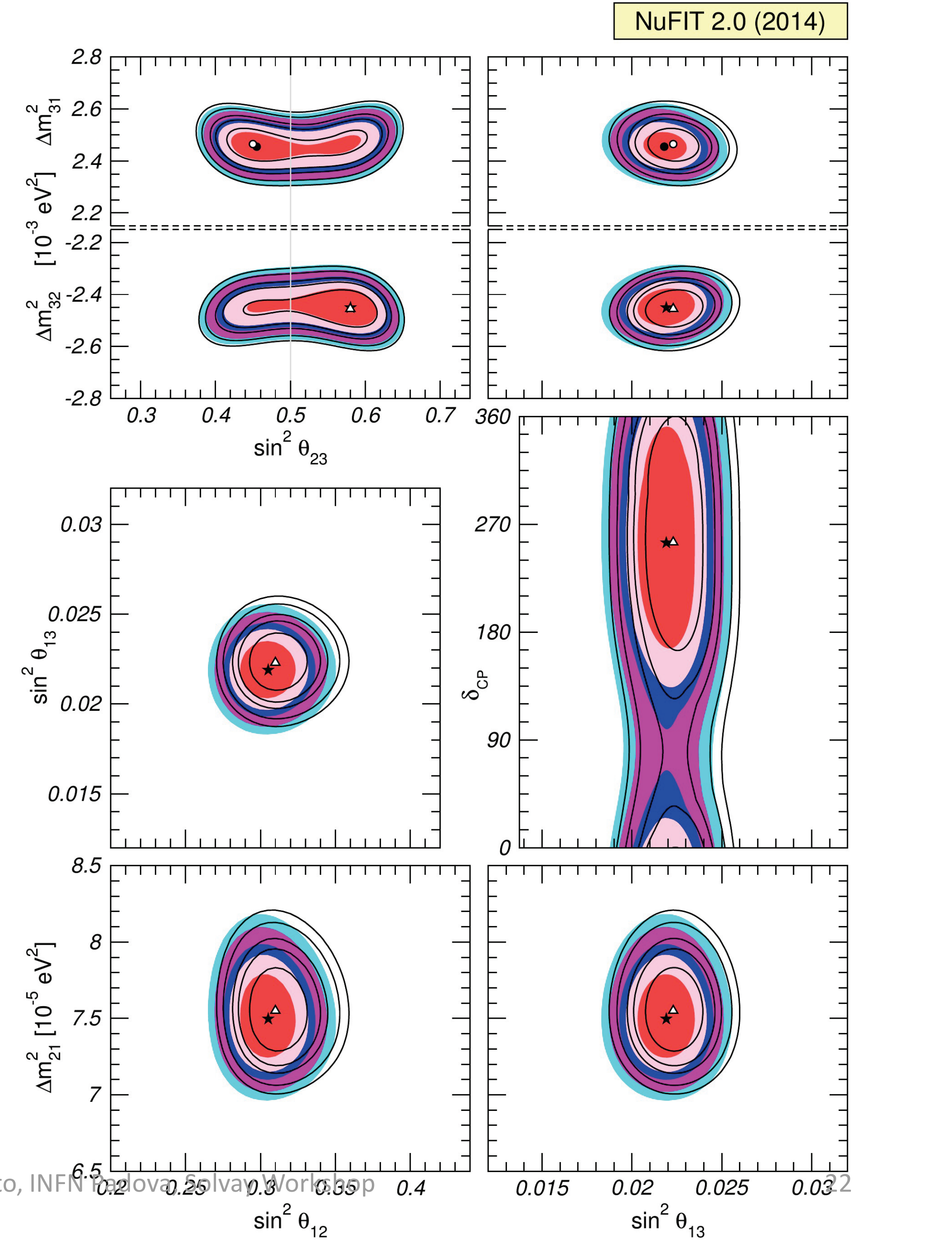
2012

Whats wrong with θ_{13} ?

Why 12 years to improve Chooz?

Present situation

- Precision era started
- Can precision constrain new physics?
- What about unitarity ? (It's assumed in all these plots)

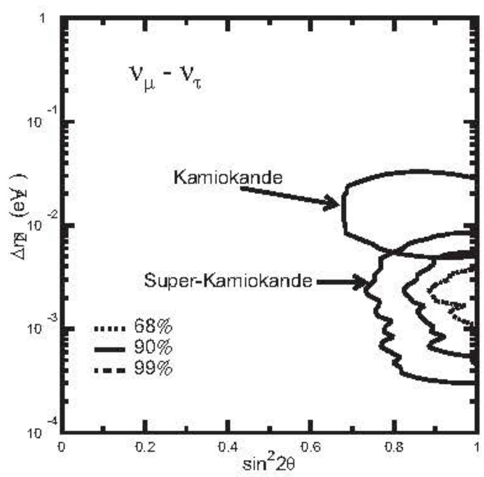


The values of oscillation parameters conspire to make CP violation detectable

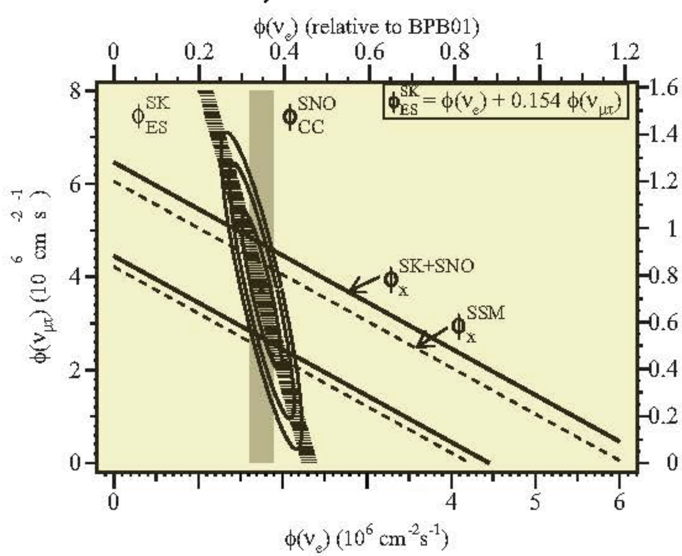
The CP odd term in oscillation formulas is

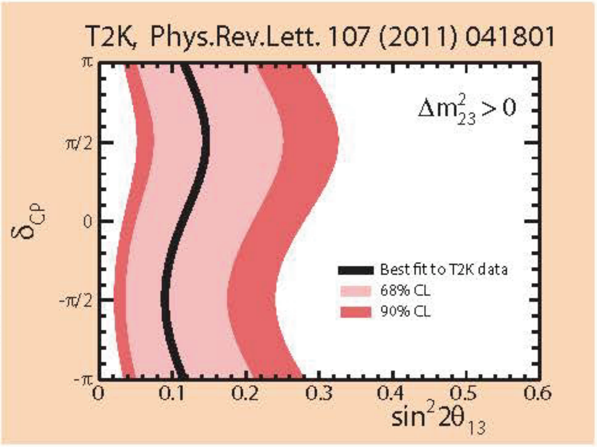
$$\propto \sin 2\theta_{23} \sin 2\theta_{12} \sin 2\theta_{13} \sin\delta \sin\frac{\Delta m^2_{13} L}{4E}$$

SuperKamiokande PRL 81(1998) 1562



SNO + SK, Phys.Rev.Lett. 87 (2001) 071301





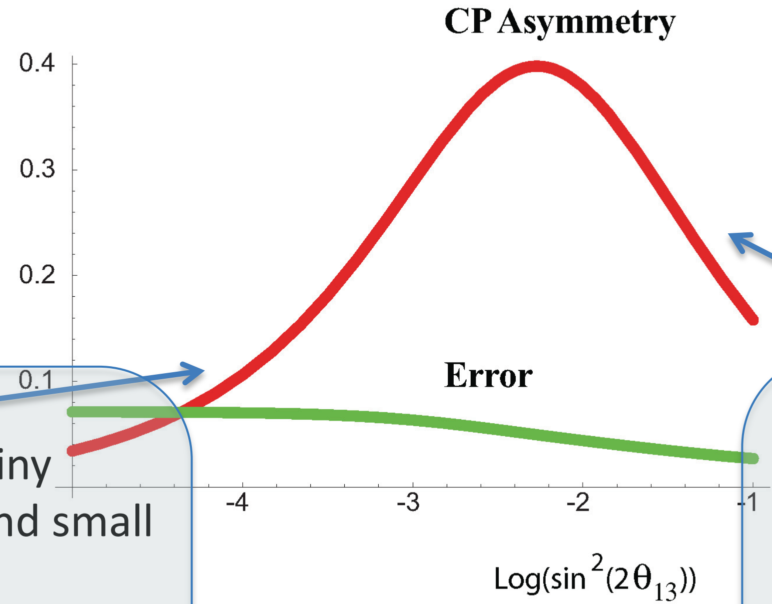
The value of θ_{13} decides the strategy

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\overline{\nu}_\mu \to \overline{\nu}_e)} \propto \frac{1}{\sin\theta_{13}}$$

Signal statistics is maximum BUT $\nu - \overline{\nu}$ asymmetry is minimum

In other terms systematic errors dominate

Blondel, Cervera, Donini, Huber, MM, Strolin, Acta Phys. Polon. B **37** (2006) 2077



SMALL VALUES:

$\nu_\mu - \nu_e$ transitions are tiny

Need large statistics and small background rates

Transition asymmetry is large

Little effect of systematic errors

Conventional neutrino beams are not enough

LARGE VALUES:

$\nu_\mu - \nu_e$ transitions are large

Relaxed constraints on statistics and background rates

Transition asymmetry is small

Large effects of systematic errors

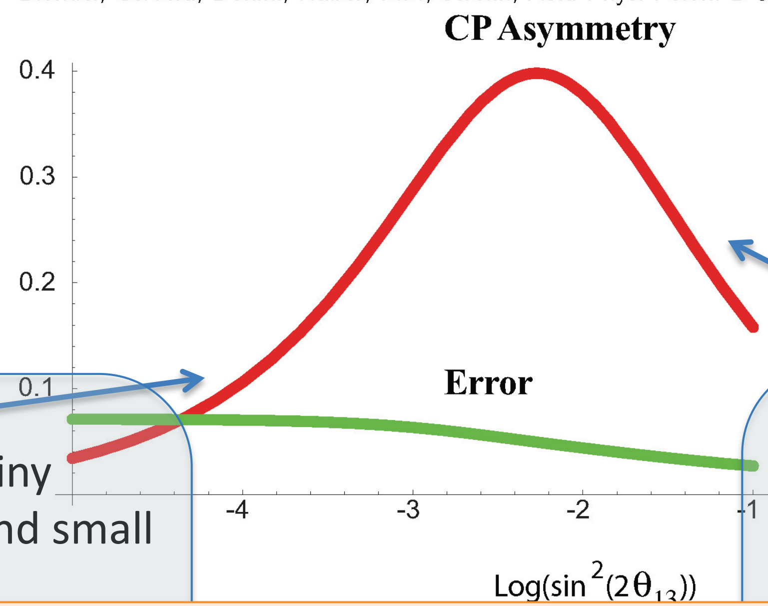
Conventional neutrino beams maybe enough

The value of θ_{13} decides the strategy

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\overline{\nu}_\mu \to \overline{\nu}_e)} \propto \frac{1}{\sin\theta_{13}}$$

Signal statistics is maximum BUT $\nu - \overline{\nu}$ asymmetry is minimum
In other terms systematic errors dominate

Blondel, Cervera, Donini, Huber, MM, Strolin, Acta Phys. Polon. B **37** (2006) 2077



SMALL VALUES:
$\nu_\mu - \nu_e$ transitions are tiny
Need large statistics and small background rates
Transition asymmetry
Little effect of systema

Conventional neutrino
are not enough

LARGE VALUES:
$\nu_\mu - \nu_e$ transitions are large
Relaxed constraints on statistics and background rates
ion asymmetry is small
ffects of systematic errors

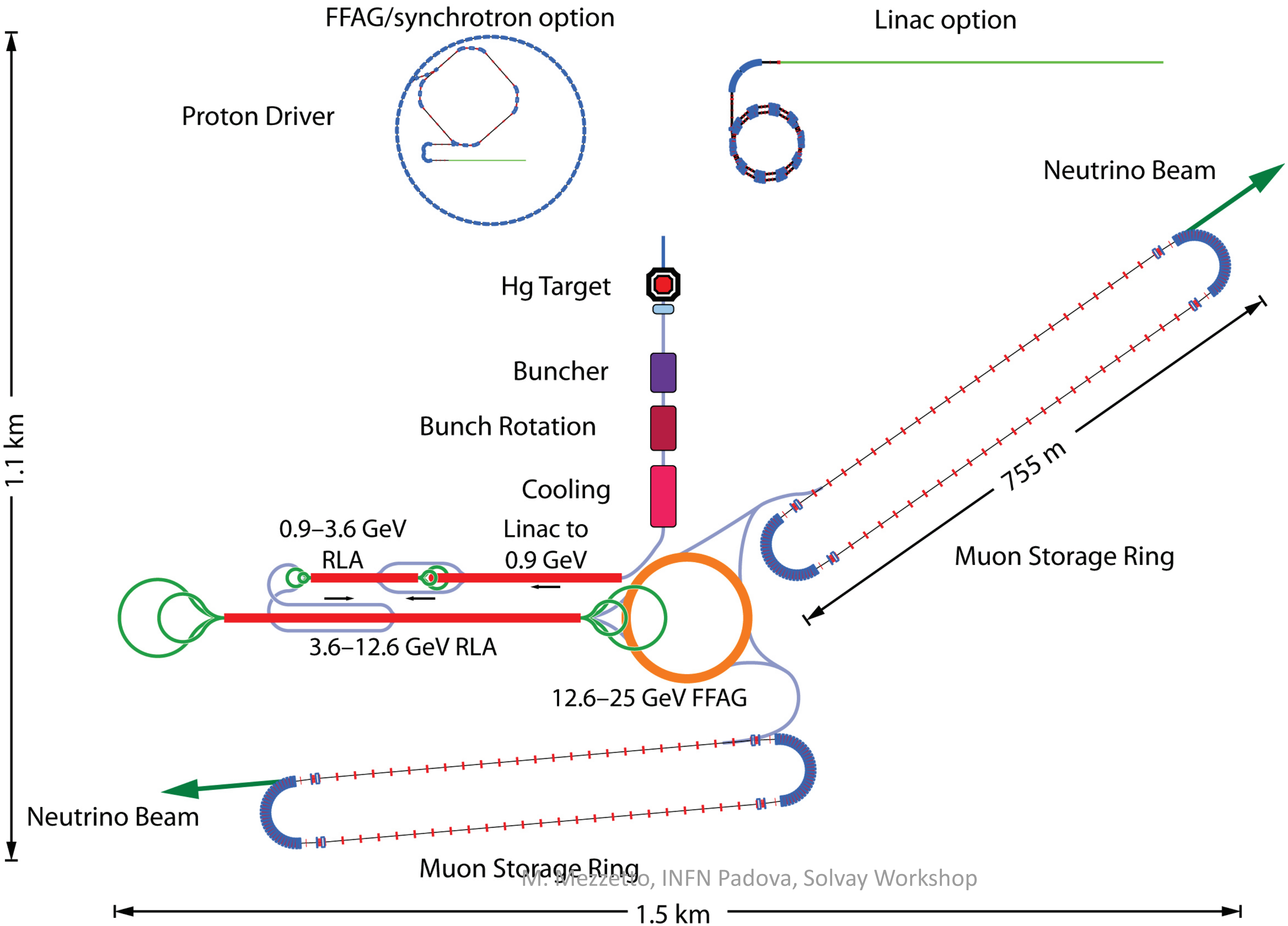
ntional neutrino beams
enough

New concepts for neutrino beams, for the moment, have been abandoned
CP violation searches are designed to use «brute force» upgrades on conventional neutrino beams

New concepts: Neutrino Factories

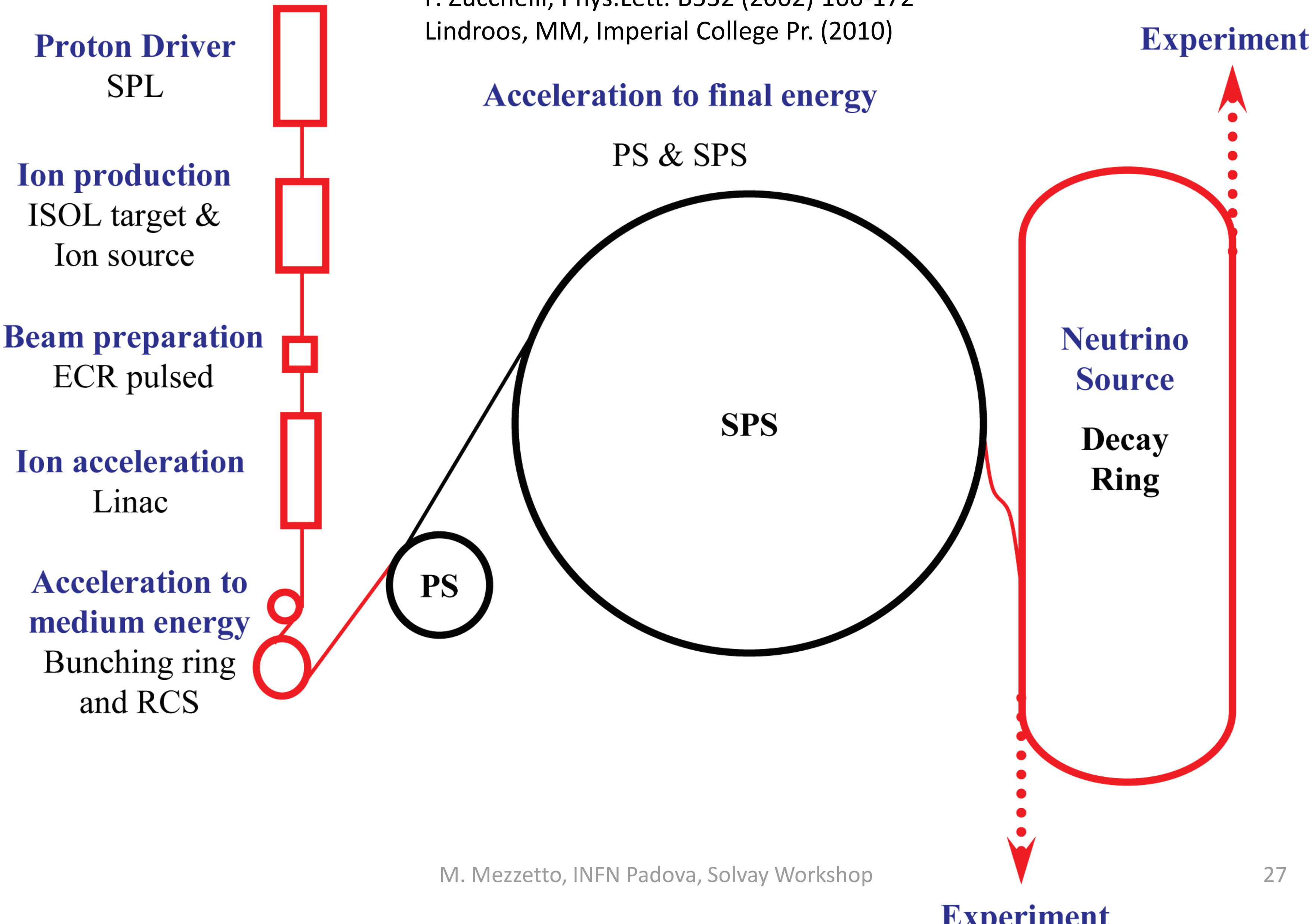
S. Geer, Phys. Rev. D57 (1998) 6989–6997

IDS-NF, arXiv:1112.2853



New concepts: Beta Beams

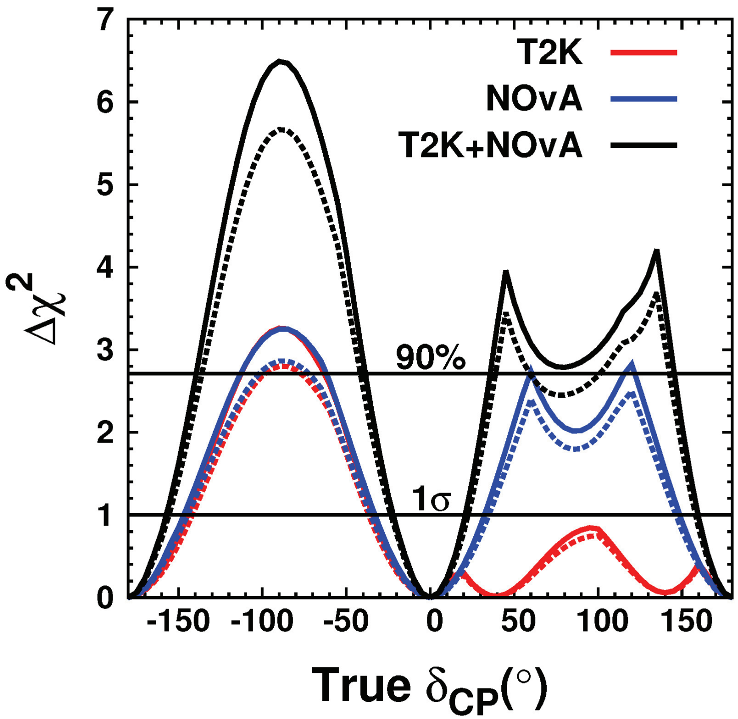
P. Zucchelli, Phys.Lett. B532 (2002) 166-172
Lindroos, MM, Imperial College Pr. (2010)



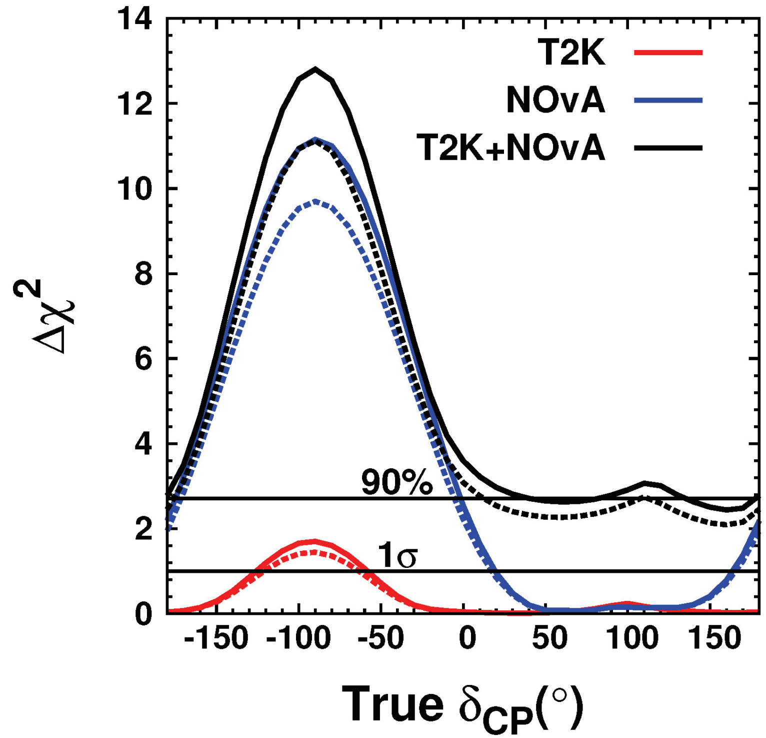
What about existing facilities?

From T2K collaboration: **PTEP 2015 (2015) 4, 043C01**

CP

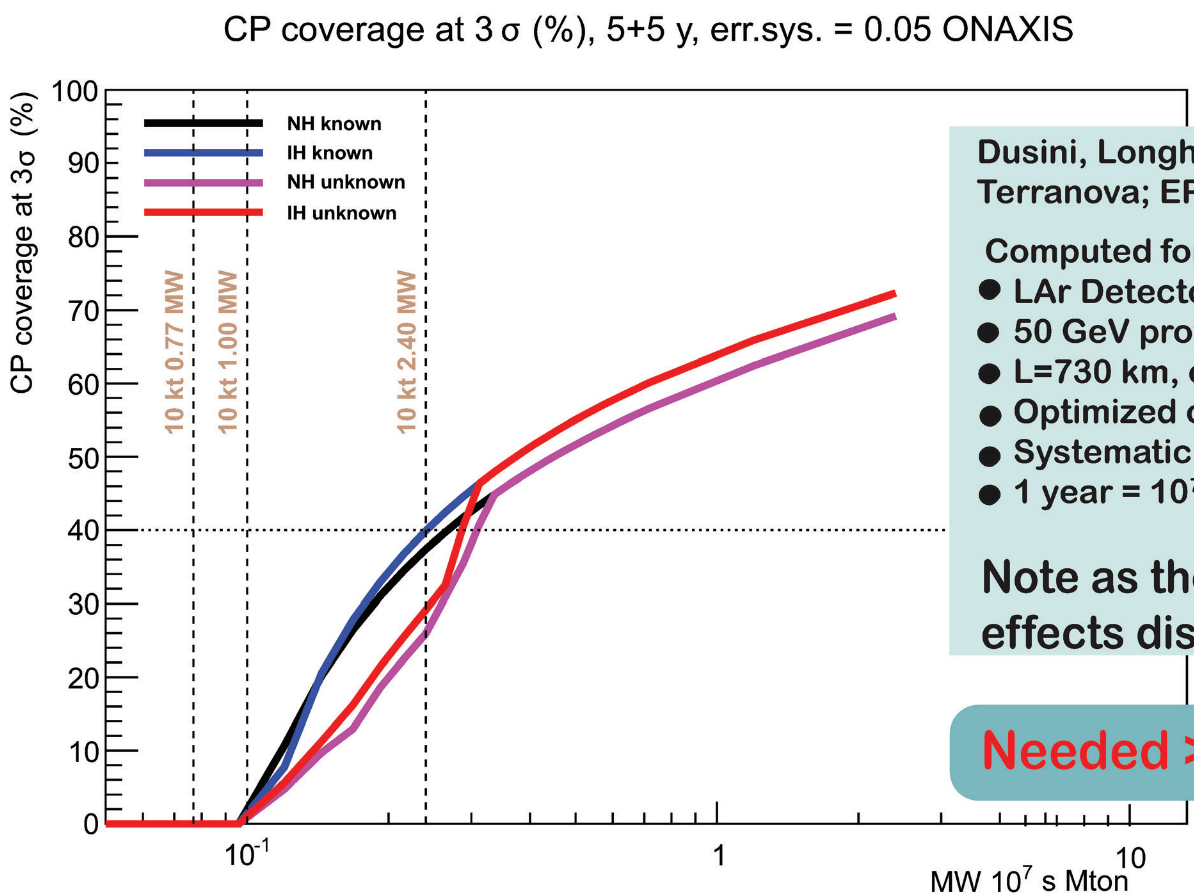


MH



Full statistics, equal ν and ν runs, dashed lines: including systematics

Good CP coverage requires order of 1 Mton *x* Mwatt *x* year



Dusini, Longhin, MM, Patrizii, Sioli, Sirri, Terranova; EPJ C73 (2013) 2392

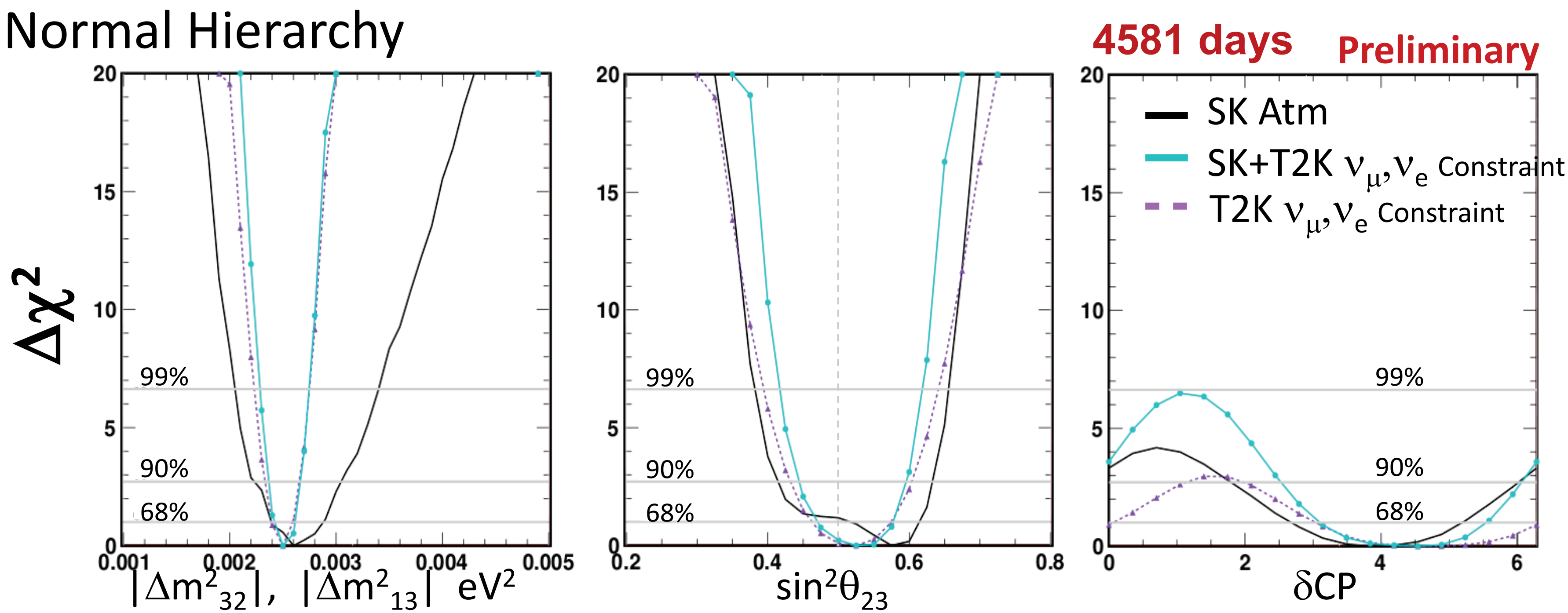
Computed for:

- LAr Detector
- 50 GeV proton beam
- L=730 km, on-axis
- Optimized optics
- Systematic errors: 5%
- 1 year = 10^7 s

Note as the MH degeneracy effects disappear with exposure

Needed >1 Mton x MW x year

θ13 Fixed SK + T2K (external constraint)



Fit (543 dof)	$\chi2$	$\sin^2\theta_{13}$	δ_{cp}	$\sin^2\theta_{23}$	Δm^2_{23} (eV^2)
SK + T2K (NH)	578.2	0.025	4.19	0.55	2.5×10^{-3}
SK + T2K (IH)	579.4	0.025	4.19	0.55	2.5×10^{-3}

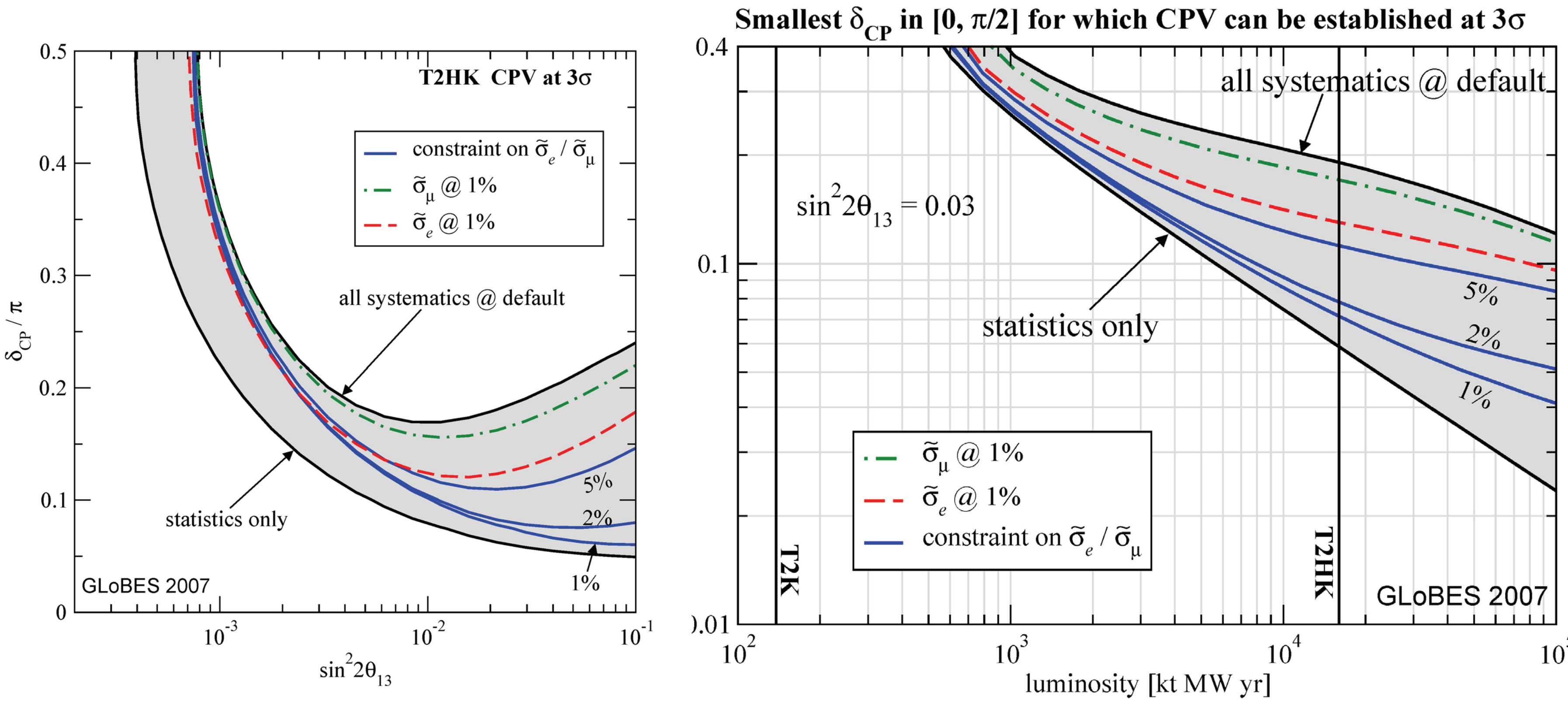
- **Normal** hierarchy favored at: $\chi^2_{IH} - \chi^2_{NH}$ = **1.2** (0.9 SK only)
- Some fraction of CP phase is excluded at 90% C.L.
- **CP** Conservation ($\sin\delta_{cp}$ = 0) allowed at (at least) 90% C.L. for both hierarchies

From Nakahata-san presentation at Neutel 2015: SK improves with external information

Systematic errors

Since a long time they are known to be the real bottleneck

Huber, Mezzetto, Schwetz, JHEP 0803 (2008) 021



Systematic errors

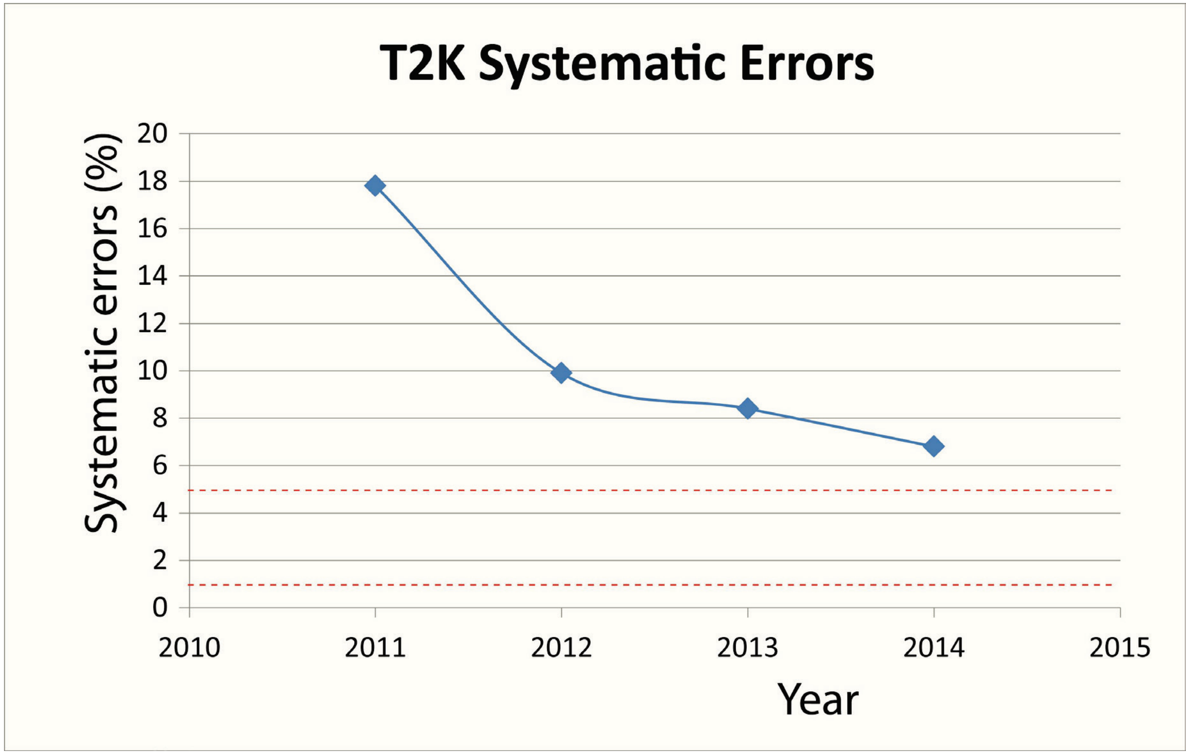
The experience of T2K

A sophisticated close detector station: ND280 + Ingrid

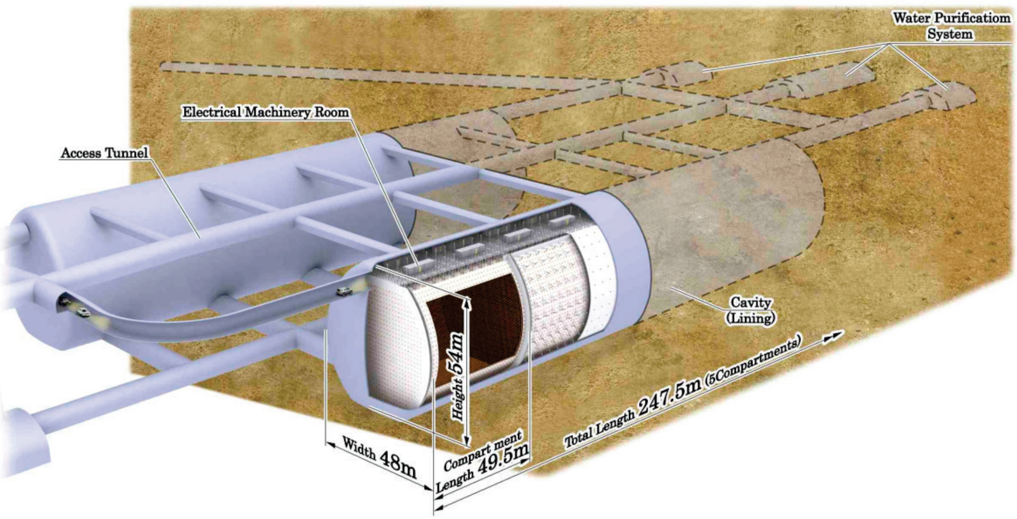
The best quality hadroproduction data ever produced (NA61) already included

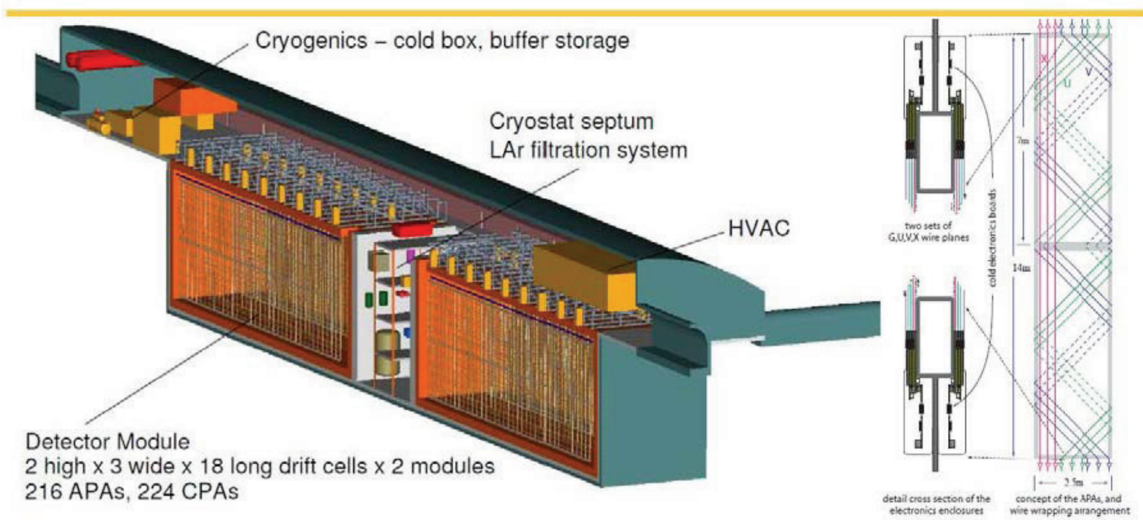
A huge, qualified, effort by the largest collaboration ever seen in neutrino physics

At present limited by statistics



Two players: Dune and HK





Hyper-Kamiokande Detector

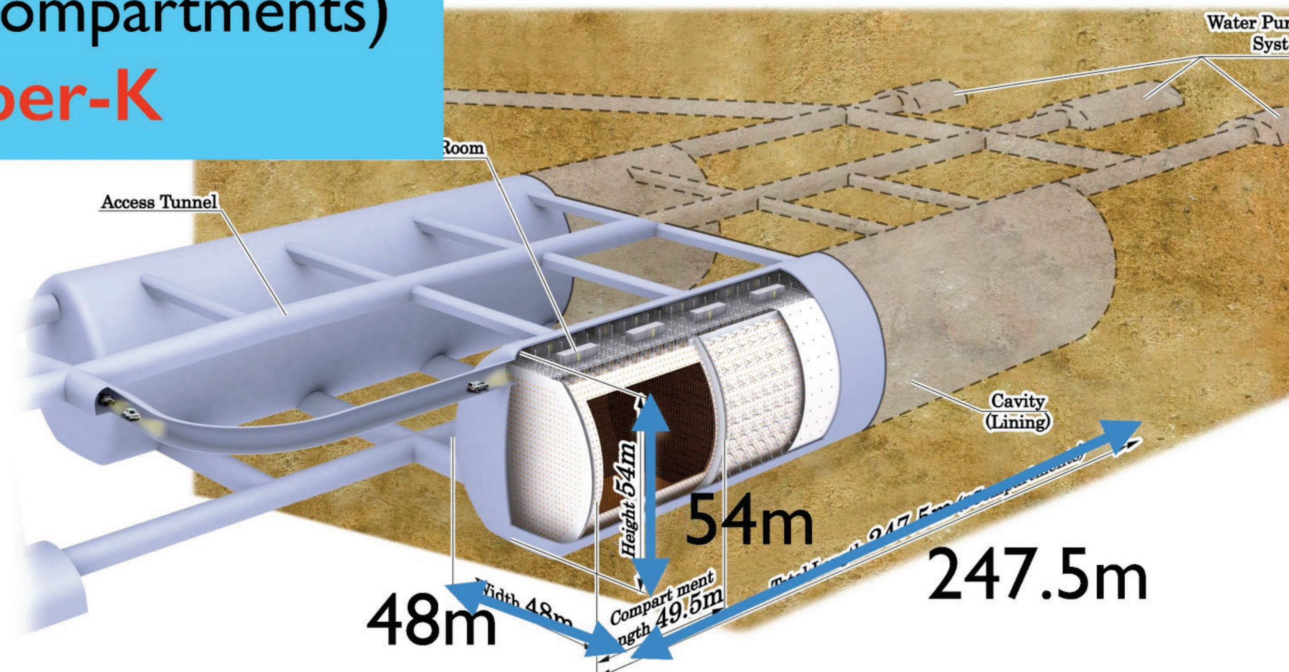
Total volume:	0.99 Mton
Inner volume:	0.74 Mton
Outer volume:	0.2 Mton
Fiducial volume:	0.56 Mton

(0.056Mton × 10 compartments)

x25 of Super-K

Hyper-K WG,
arXiv:1109.3262
arXiv:1309.0184
arXiv:1502.05199
(to appear in PTEP)

- 99,000 20” PMT for inner-det. (20% coverage)
- 25,000 8” PMT for outer-det.



Multi-purpose detector for a wide range of science

M. Thomson, 2nd LNI

LBNF-DUNE: 1.2 MW beam from FNAL, 40 kt Lar TPC at SURF, 1st 10kt installation in 2021, CD-1 refresh out in June, CD2a-CD3a (cavern) this autumn

★ **Three main pillars**

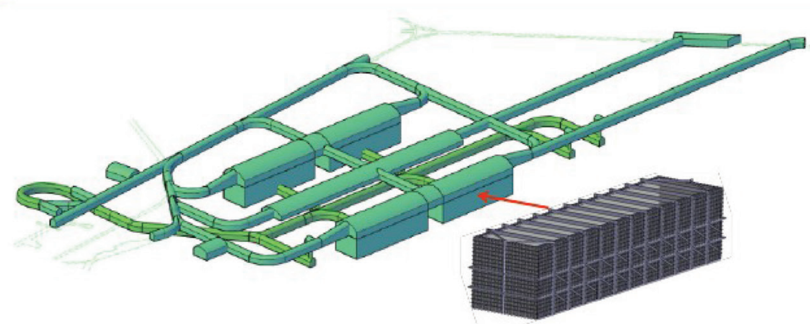
1) LBL Neutrino Physics
- CPV in the leptonic sector
- Mass Hierarchy
- Precision oscillation physics (θ_{23} octant, …)
- Testing 3-flavour paradigm

2) Nucleon Decay
- Targetting SUSY-favoured modes, e.g. $p \rightarrow K^{+}\nu$

3) Astro-particle Physics
- Core collapse super-nova, sensitivity to ν_e

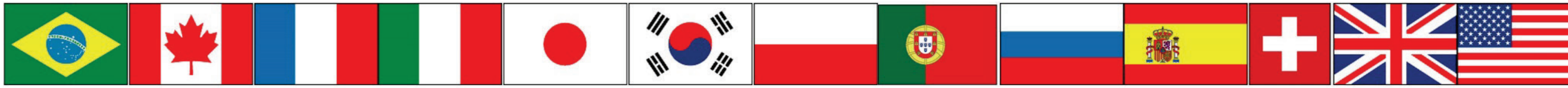
+ Precision neutrino physics in the near neutrino detector

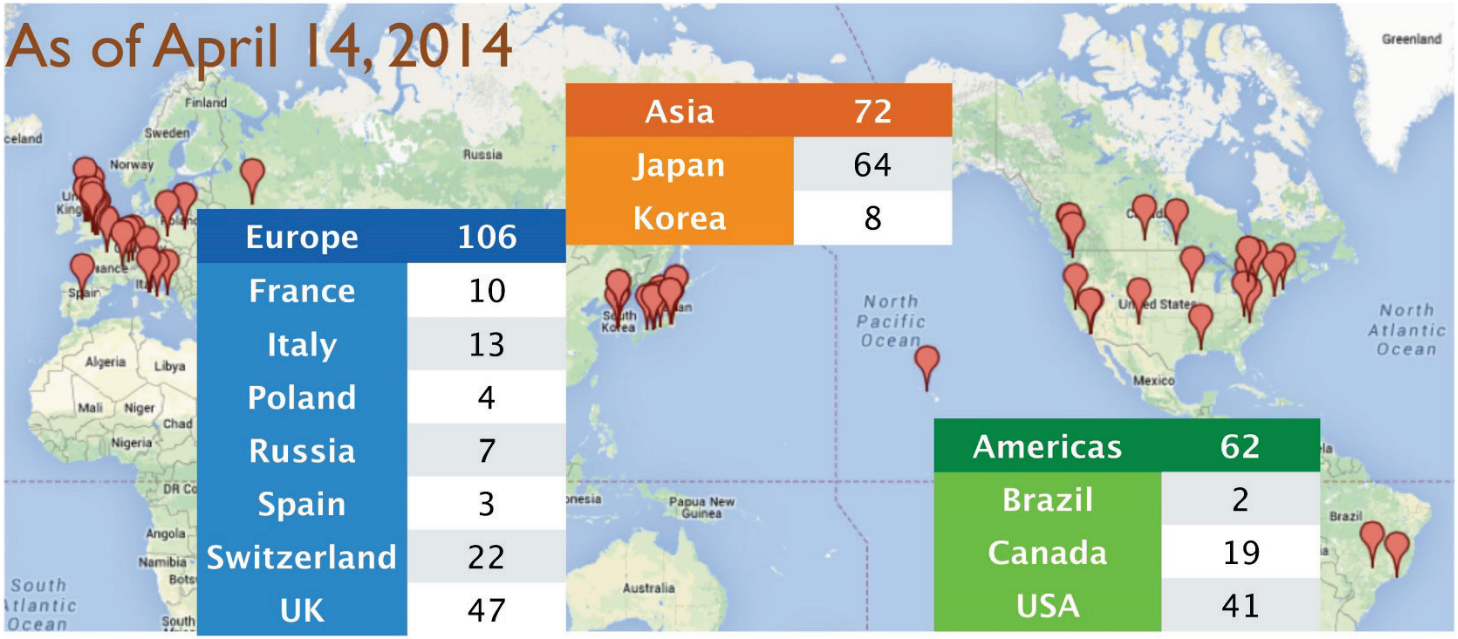
★ **LBNF will provide “homes” for the DUNE FD modules**
- Four caverns + four cryostats for four 10 kt FD LAr-TPCs



★ **Modular design provides flexibility w.r.t. FD design and funding**

Hyper-Kamiokande International Group





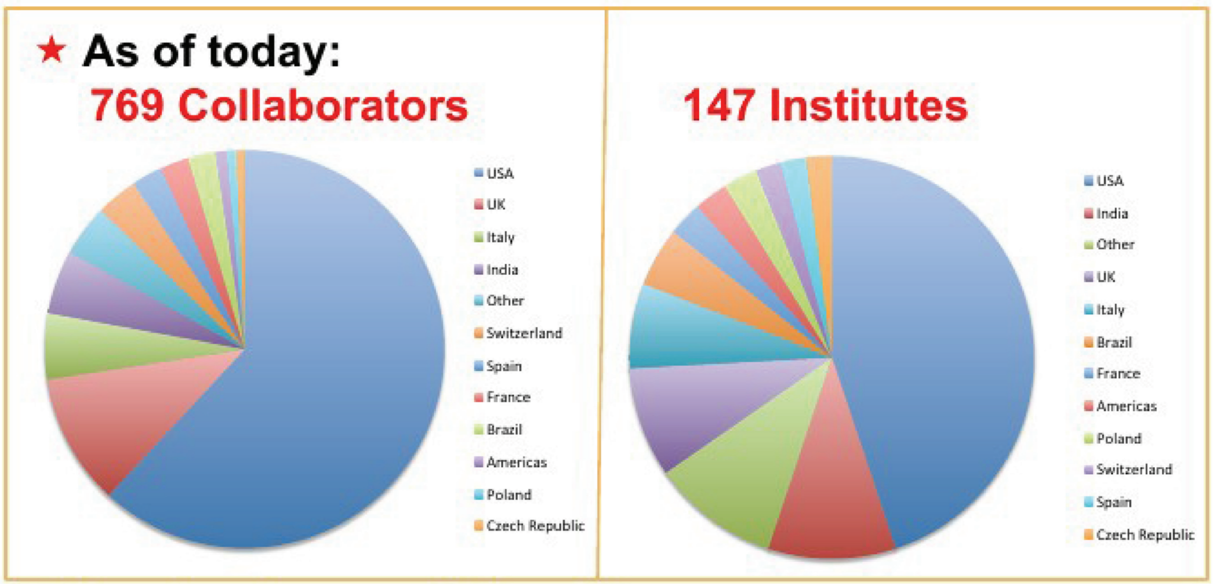
Europe	106
France	10
Italy	13
Poland	4
Russia	7
Spain	3
Switzerland	22
UK	47

Asia	72
Japan	64
Korea	8

Americas	62
Brazil	2
Canada	19
USA	41

- 240 people and growing!
- Hyper-K Governance Structure has been defined
  - Steering Committee, International Board Representatives, and Convener Board
- R&D fund and travel budget already secured in some countries, and more in securing processes.

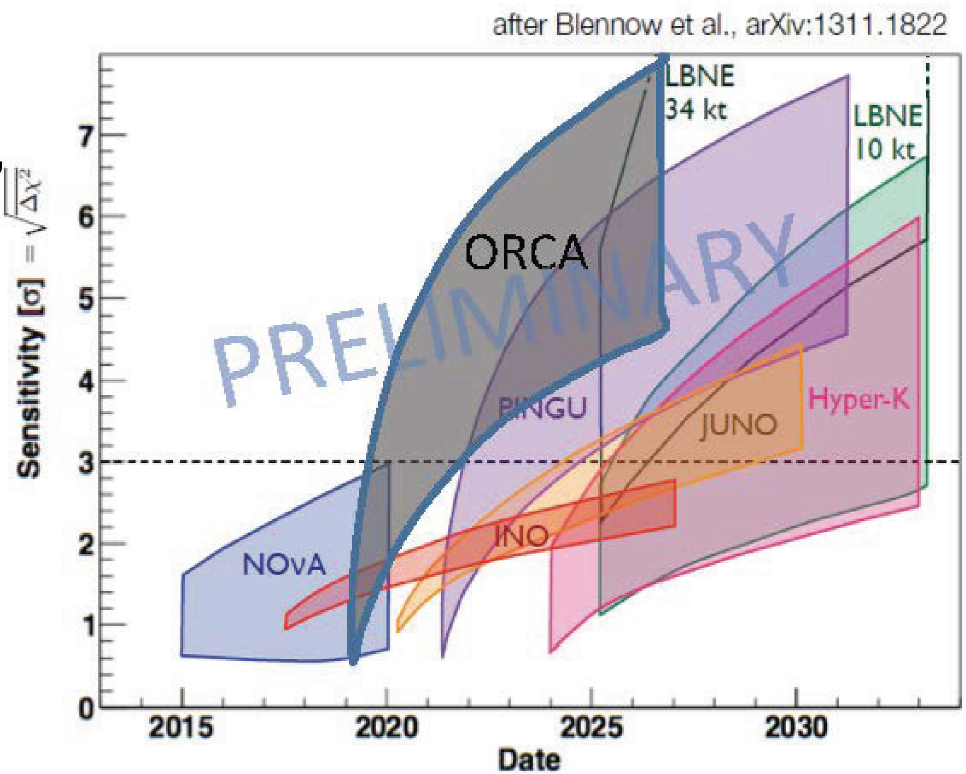
DUNE Collaboration



★ **Already a large collaboration**

Mass Hierarchy

- Pure oscillation effects in ν_e disappearance: **Juno**
- Matter effects in ν_μ disappearance and/or ν_e appearance : **NOνA, INO**, Pingu, Orca, Dune, HK



- The Dune baseline is a clear premium
- HK sensitivity on CP does not relies on external knowledge on MH

CP violation: general considerations

- **HK**:
  - short baseline →no matter effects: pure CP but reduced MH
  - Off axis → reduced intrinsic ν_e contamination, reduced NC backgrounds

- **DUNE**:
  - Long baseline → sensitive to matter effects: excellent performances in MH
  - On axis: second oscillation maximum and sensitive to ν_τ appearance (tiny effects at 1300 km)
  - On axis: Extended lever of arm for measurement of oscillation parameters

CP violation: just event numbers

HYPERK , δ_{CP}=0, and NH

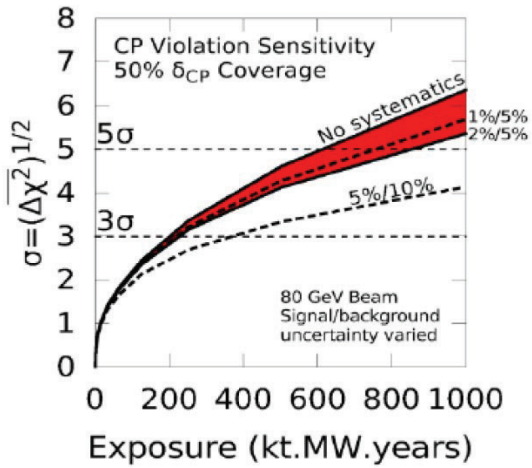
10 years

	Signal ($\nu\mu \to \nu e$ CC)	Wrong sign appearance	$\nu\mu/\bar{\nu}\mu$ CC	beam $\nu e/\bar{\nu}e$ contamination	NC
ν	3,016	28	11	523	172
$\bar{\nu}$	2,110	396	9	618	265

ELBNF 40KT

6 years

Run Mode	Signal Events δ_{CP}			Background Events			
	$-\pi/2$	0	$\pi/2$	ν_μ NC	ν_μ CC	ν_e Beam	ν_τ CC
Neutrino	1068	864	649	72	83	182	55
Antineutrino	166	213	231	41	42	107	33



CP violation: systematic errors

HK estimation assuming identical close detector as T2K

Uncertainty on the expected number of events at Hyper-K (%)

	ν mode		anti-ν mode		(T2K 2014)	
	νe	νμ	$\bar{\nu}$e	$\bar{\nu}$μ	νe	νμ
Flux&ND	3.0	2.8	5.6	4.2	3.1	2.7
XSEC model	1.2	1.5	2.0	1.4	4.7	5.0
Far Det. +FSI	0.7	1.0	1.7	1.1	3.7	5.0
Total	3.3	3.3	6.2	4.5	6.8	7.6

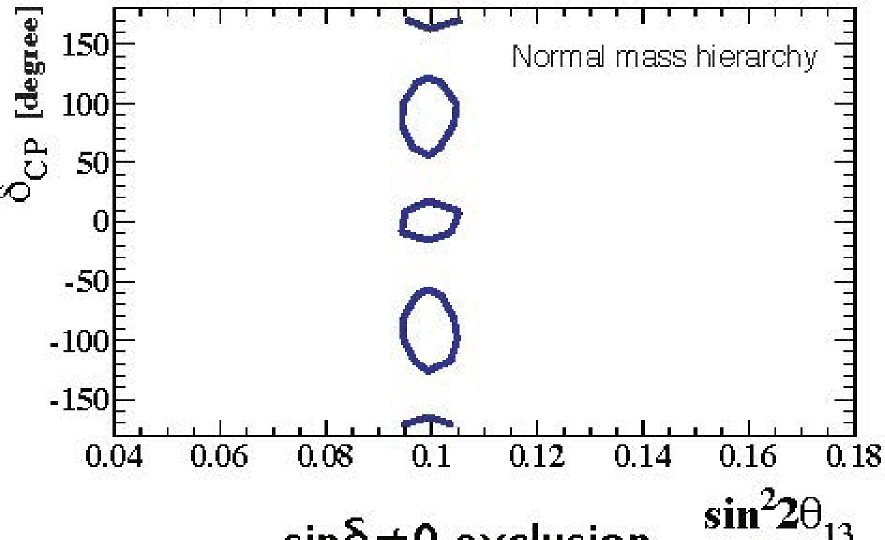
Source of Uncertainty	MINOS ν_e	T2K ν_e	ELBNF ν_e	Comments
Beam Flux after N/F extrapolation	0.3%	2.9%	2%	MINOS is normalization only. ELBNF normalization and shape highly correlated between ν_μ/ν_e.
Neutrino interaction modeling				
Simulation includes: Hadronization Cross sections Nuclear models	2.7%	7.5%	~2%	Hadronization models are better constrained in the ELBNF LArTPC. N/F cancellation is larger in MINOS/ELBNF. Cross-section uncertainties are larger at T2K energies. Spectral analysis in ELBNF provides extra constraint.
Detector effects				
Energy scale (ν_μ)	3.5%	included above	(2%)	Included in ELBNF ν_μ sample uncertainty only in 3-flavor fit. MINOS dominated by hadronic scale.
Energy scale (ν_e)	2.7%	3.4% Includes all FD effects	2%	Totally active LArTPC with calibration and test beam data lowers uncertainty.
Fiducial volume	2.4%	1%	1%	Larger detectors = smaller uncertainty.
Total	5.7%	8.8%	3.6 %	Uncorrelated ν_e uncertainty in full ELBNF 3-flavor fit = 1-2%.

Dune estimation extrapolating from Minos (no LAr close detector data so far) arXiv:1502.05199 (to appear in PTEP)

Expected sensitivity to CP asymmetry

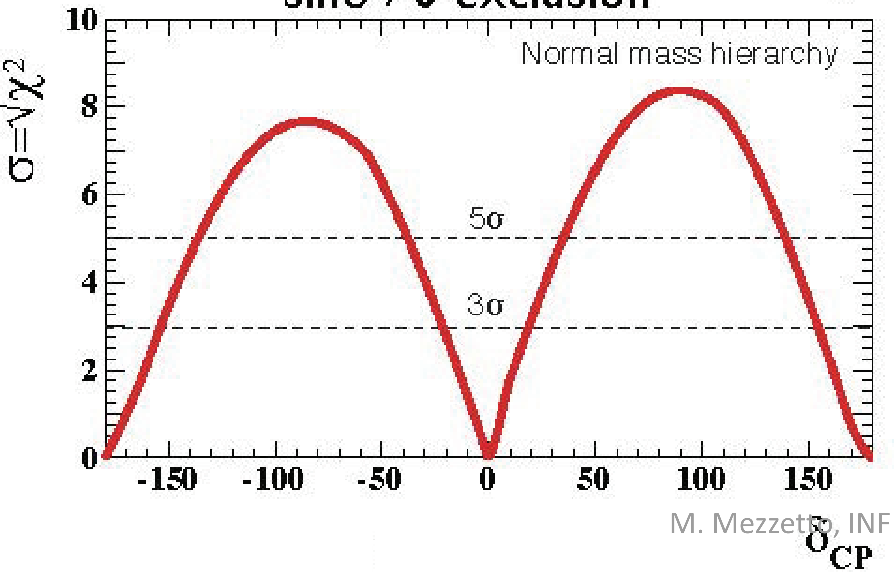
Mass hierarchy assumed to be known

90% CL contour on $\sin^2 2\theta_{13}$-δ plane
(δ=0°, 90°, 180°, -90° overlaid)

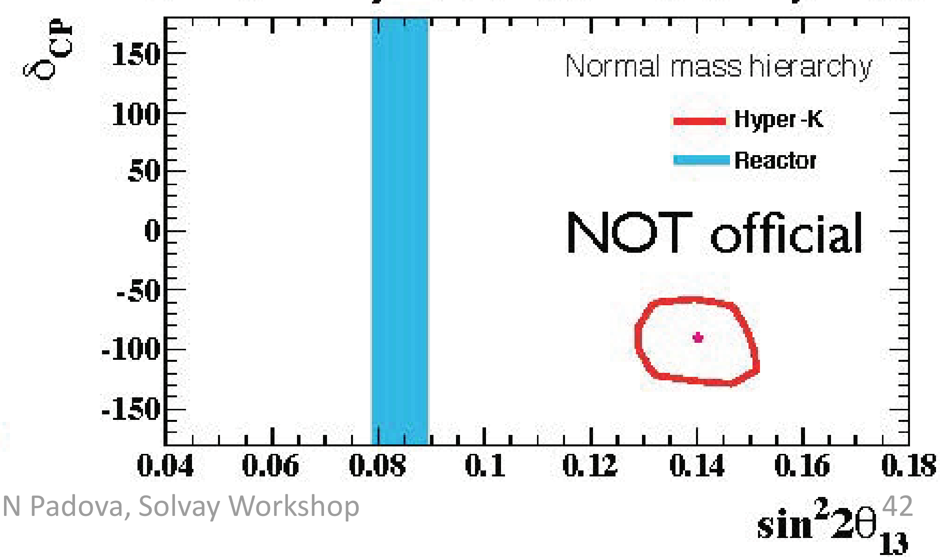


- Exclusion of $\sin\delta$=0
  - >3σ for 76% of δ
  - >5σ for 58% of δ
- Possible to establish CP violation in the lepton sector!

sinδ≠0 exclusion



Or, we may see some surprise

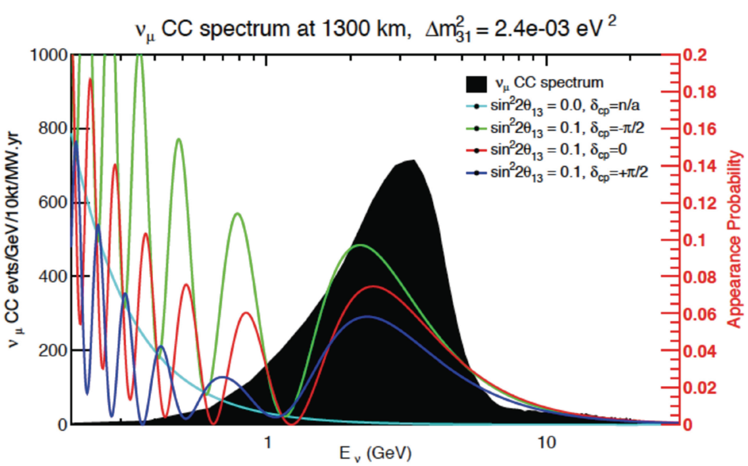


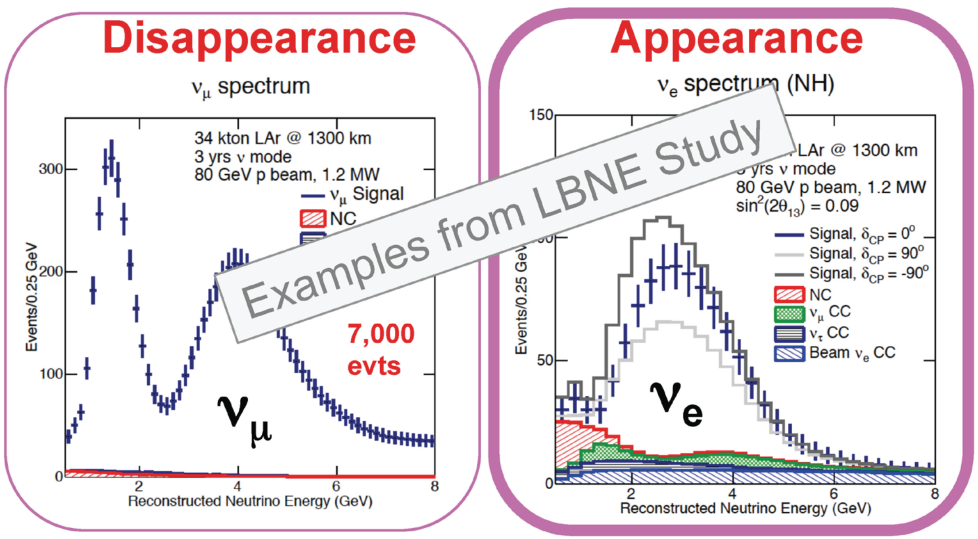
LBL Scientific Strategy

★ **Measure oscillated spectra at 1300 km in a wide-band beam**

★ **Determine MH and θ_{23} octant, probe CPV and search for ν non-standard-interactions (NSIs) in a single experiment**

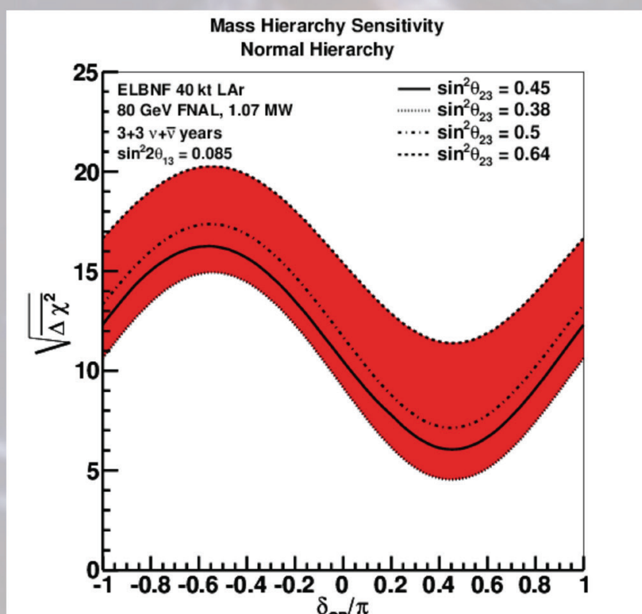
- **Long baseline:**
  - Matter effects are large (~40 %)
  - MH and CPV effects are separable: removes ambiguities
- **Wide-band ν_μ beam:**
  - Measure ν_e and ν_μ spectra over wide range of energies

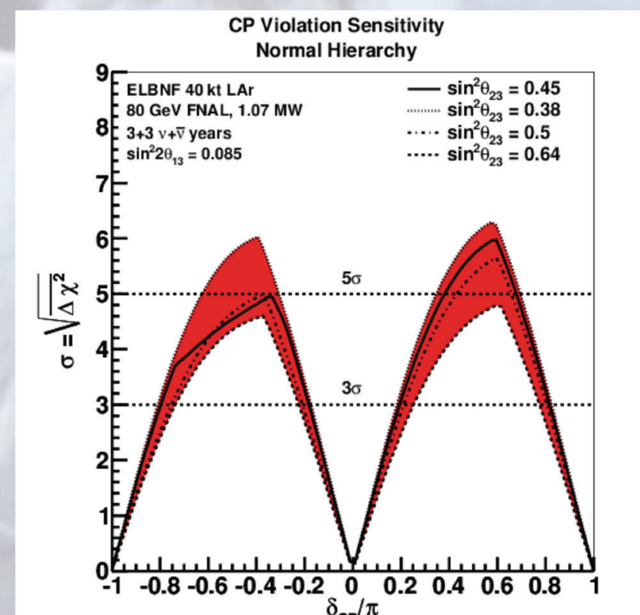




e.g. CPV & MH

- **Ultimate sensitivity depends:**
  - Beam power – need νs
  - Detector mass – detect the νs
  - Experiment/Facility design – optimize for CPV
  - Beam efficiency
- **Sensitivities (as presented in "ELBNF" LoI)**





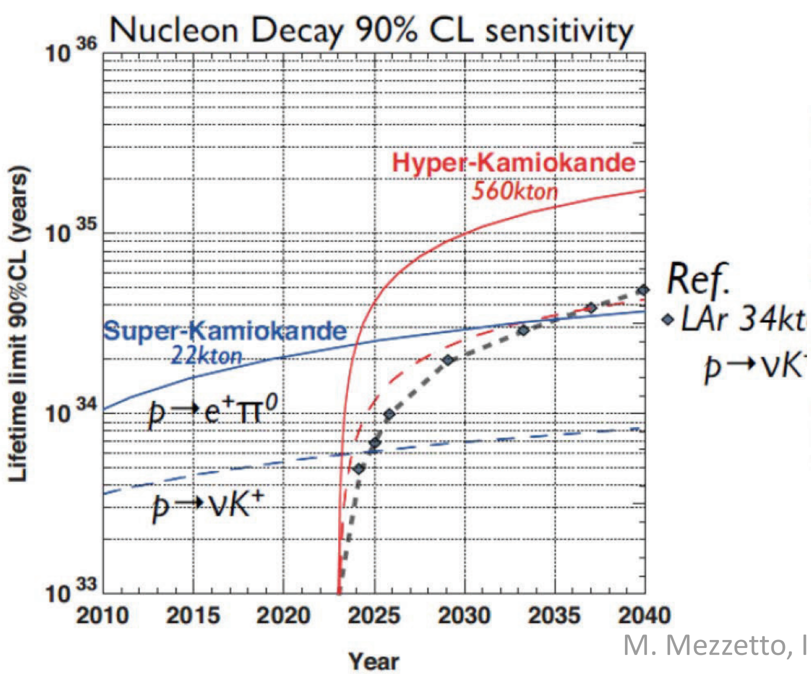
Proton Decay

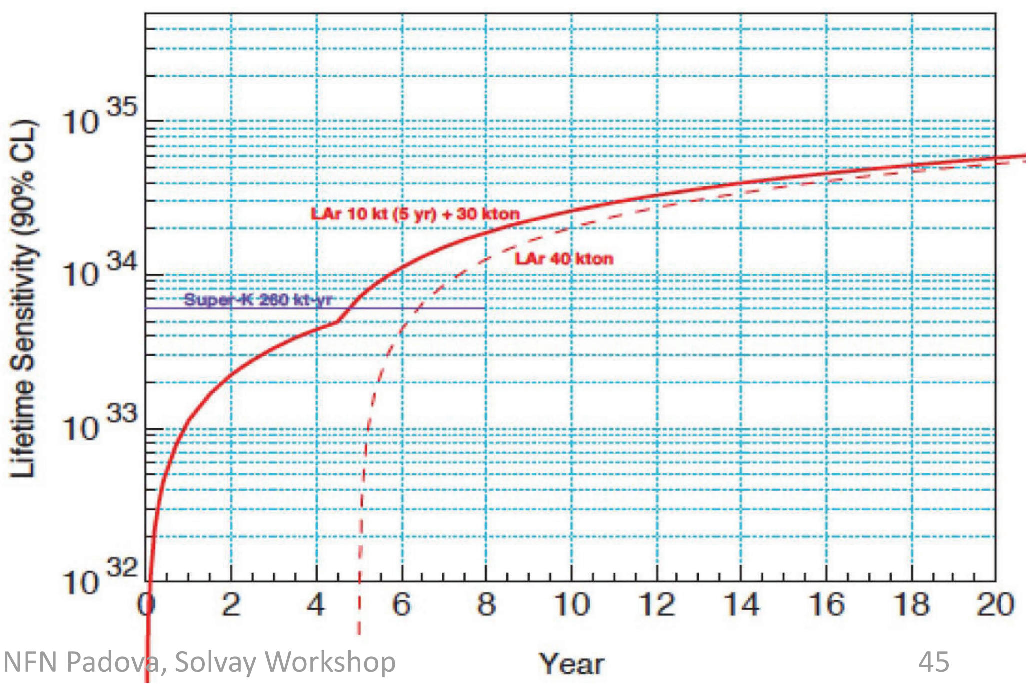
HK

DUNE

- $p \to e^+ + \pi^0$ — 1.3×10^{35} yrs (90% CL UL); 5.7×10^{34} yrs (3σ discovery)
- $p \to \bar{\nu} + K^+$ — 3.2×10^{34} yrs (90% CL UL); 1.2×10^{34} yrs (3σ discovery)

- Will improve Super-Kamiokande limits in very few channels, notably in the $p \to K^+\nu$ channel





Supernova Neutrinos

HK

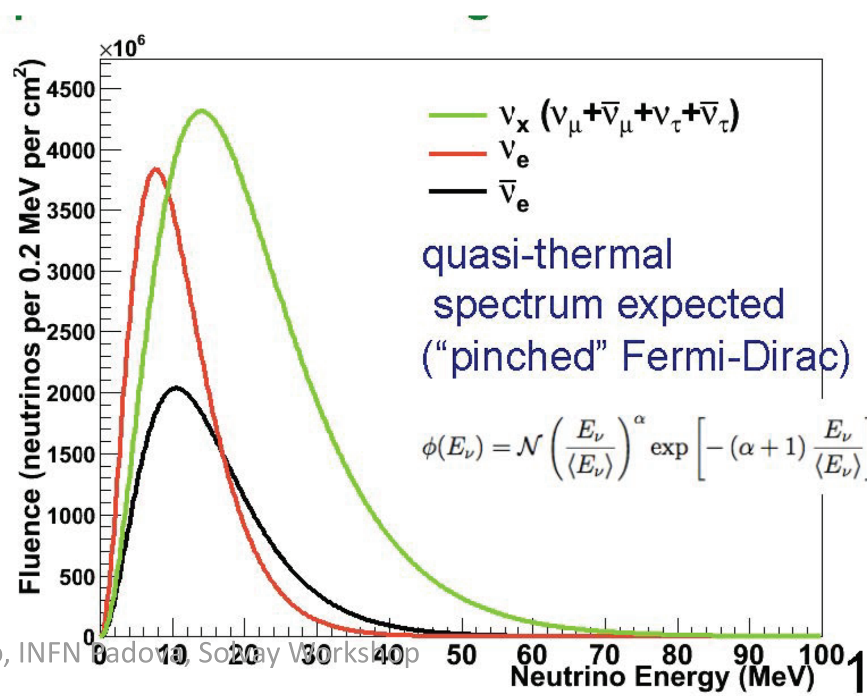
Mainly $\bar{\nu}_e$ from $\bar{\nu}_e\, p \rightarrow e^+\, p$

- Burst from galactic center (10 kpc)
  170,000 – 260,000 ν's
- Burst from Andromeda Galaxy
  30 – 50 ν's
- Supernova relic ν
  200 in 10 years

DUNE

Mainly ne from $\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$

- Burst from galactic center (10 kpc)
  ~ 900 ν's in 10 kton detector



Solar Neutrinos

HK

- ^{8}B ν from Sun
  200 ν's/day @ 7 MeV threshold

Allows detailed day/night studies

DUNE

In principle sensitive both to

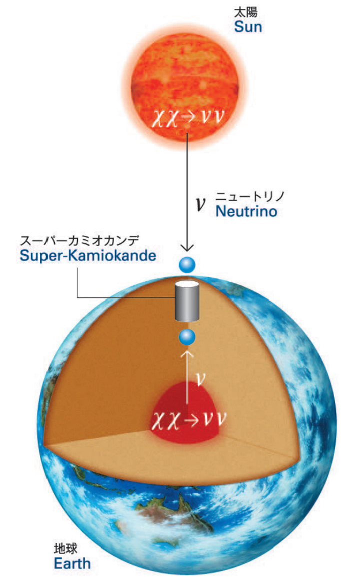
- CC events

  $\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$
- ES events

  $\nu_e + e^- \rightarrow \nu_e + e^-$

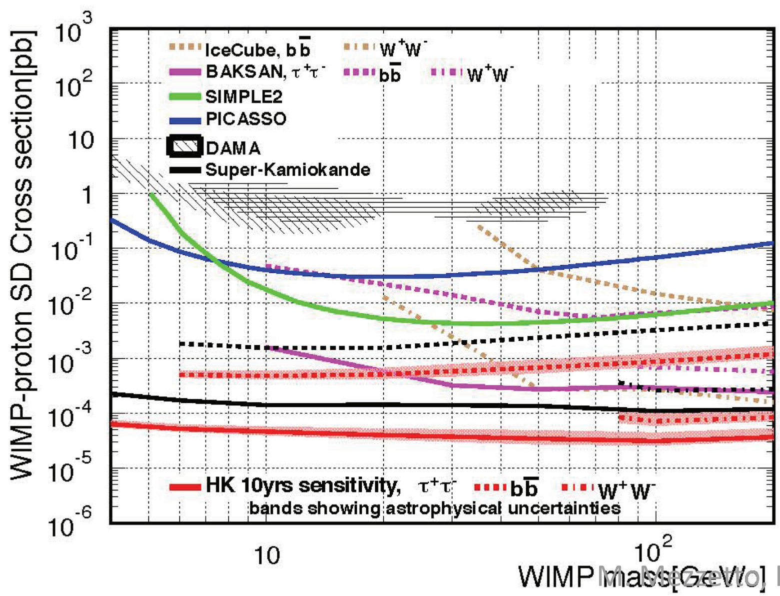
Not clear to which value the e^- detection threshold can be set

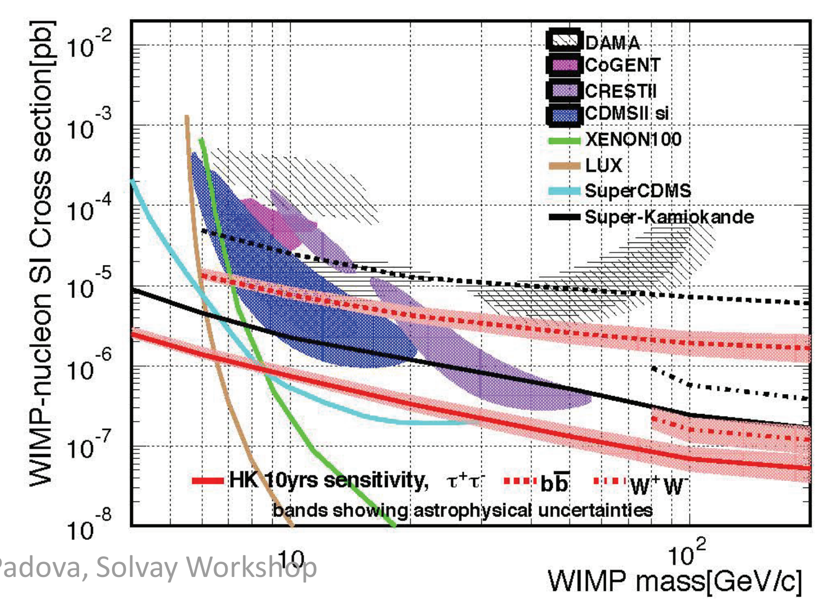
WIMP annihilation at Sun



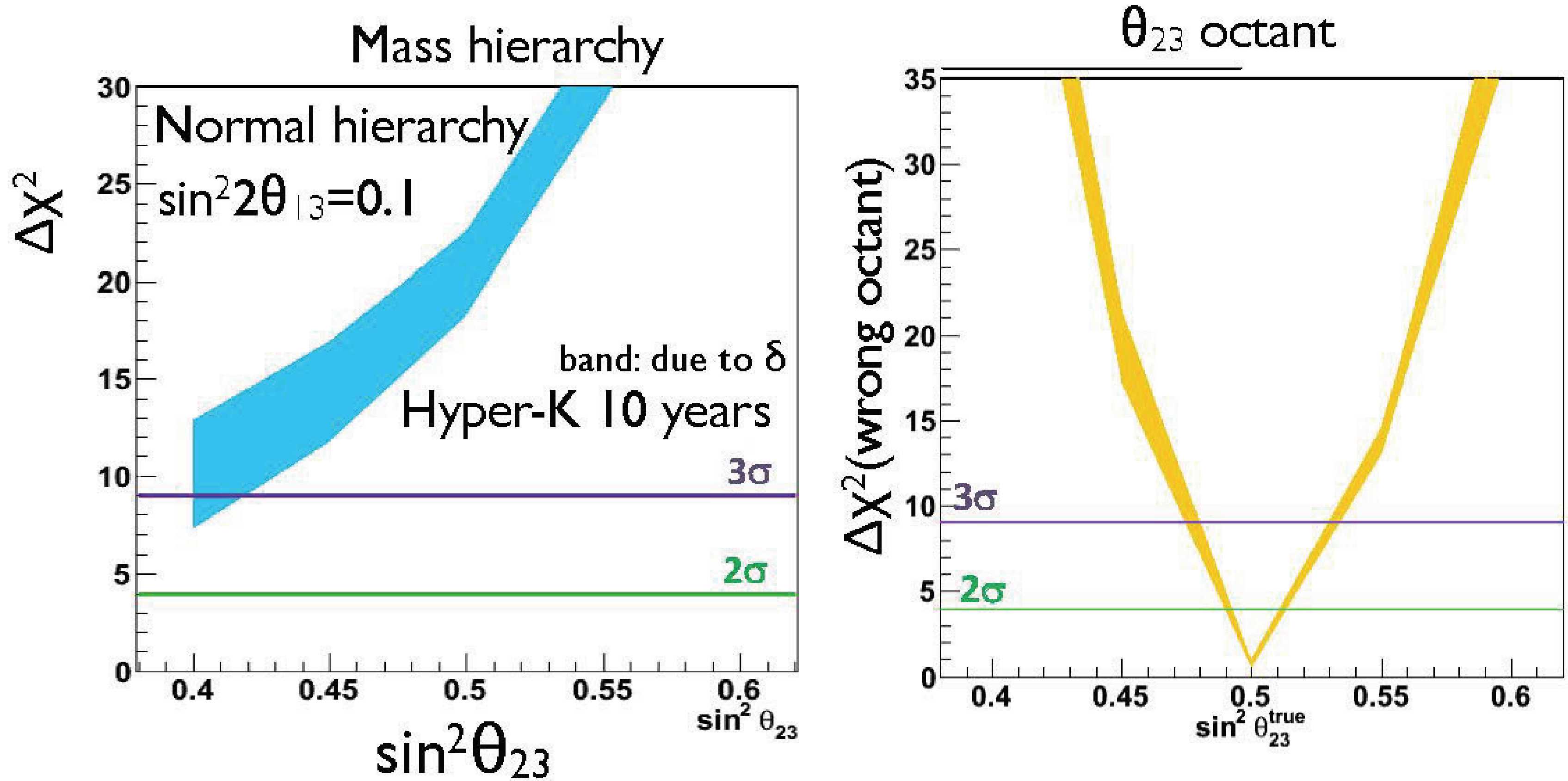
SK updated results recently presented by Nakahata-san at Neutel 2015

HK sensitivity by far the best Spin Dependent (SD) and very competitive in the SI low WIMP mass region



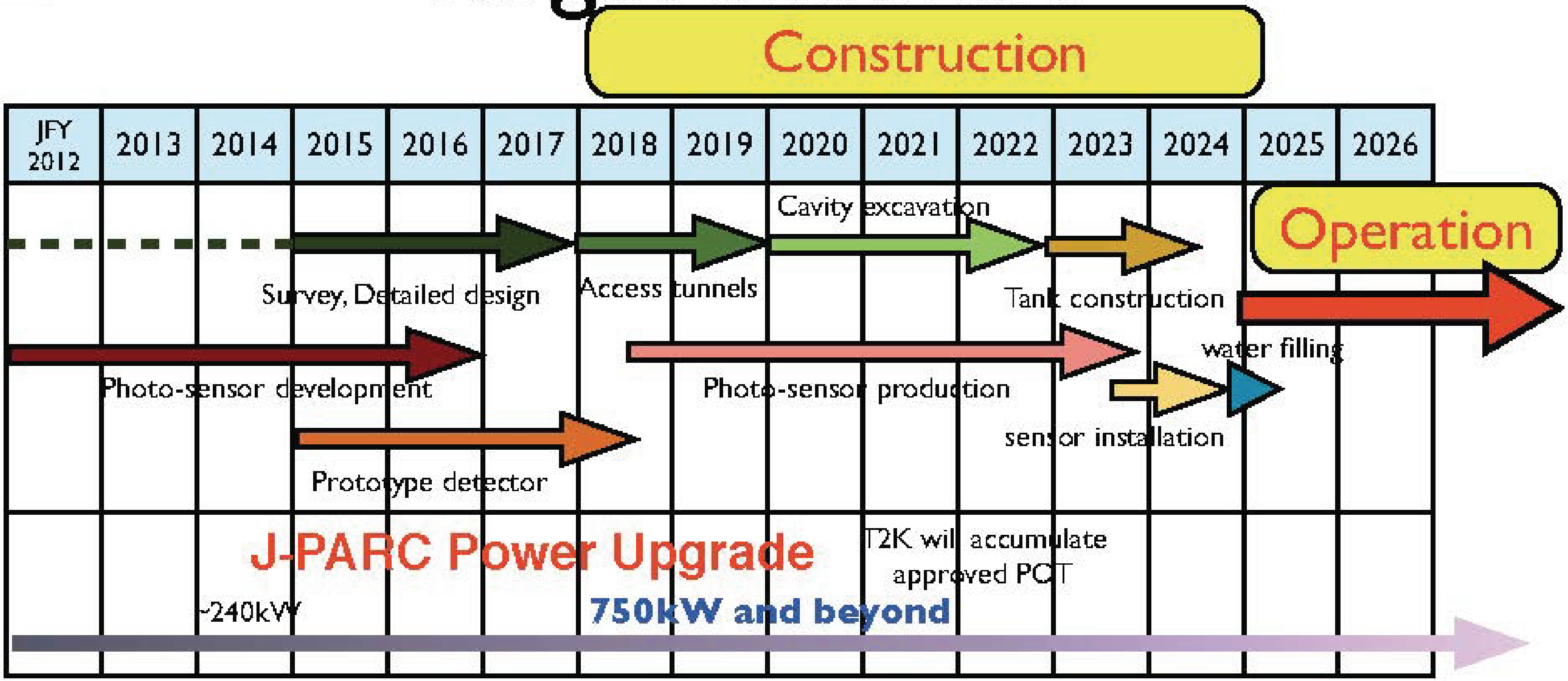


Atmospheric ν



Complementary measurements to accelerator ν
Combined analysis of acc + atm ν will enhance capability

Target schedule



-2018 Construction starts

-2025 Data taking start

-2028 Discovery of Neutrino CP violation ?

-2030 Discovery of Proton Decay ?

-20xx Detection of supernova neutrinos

-20xx Discovery of new phenomena

Towards Construction

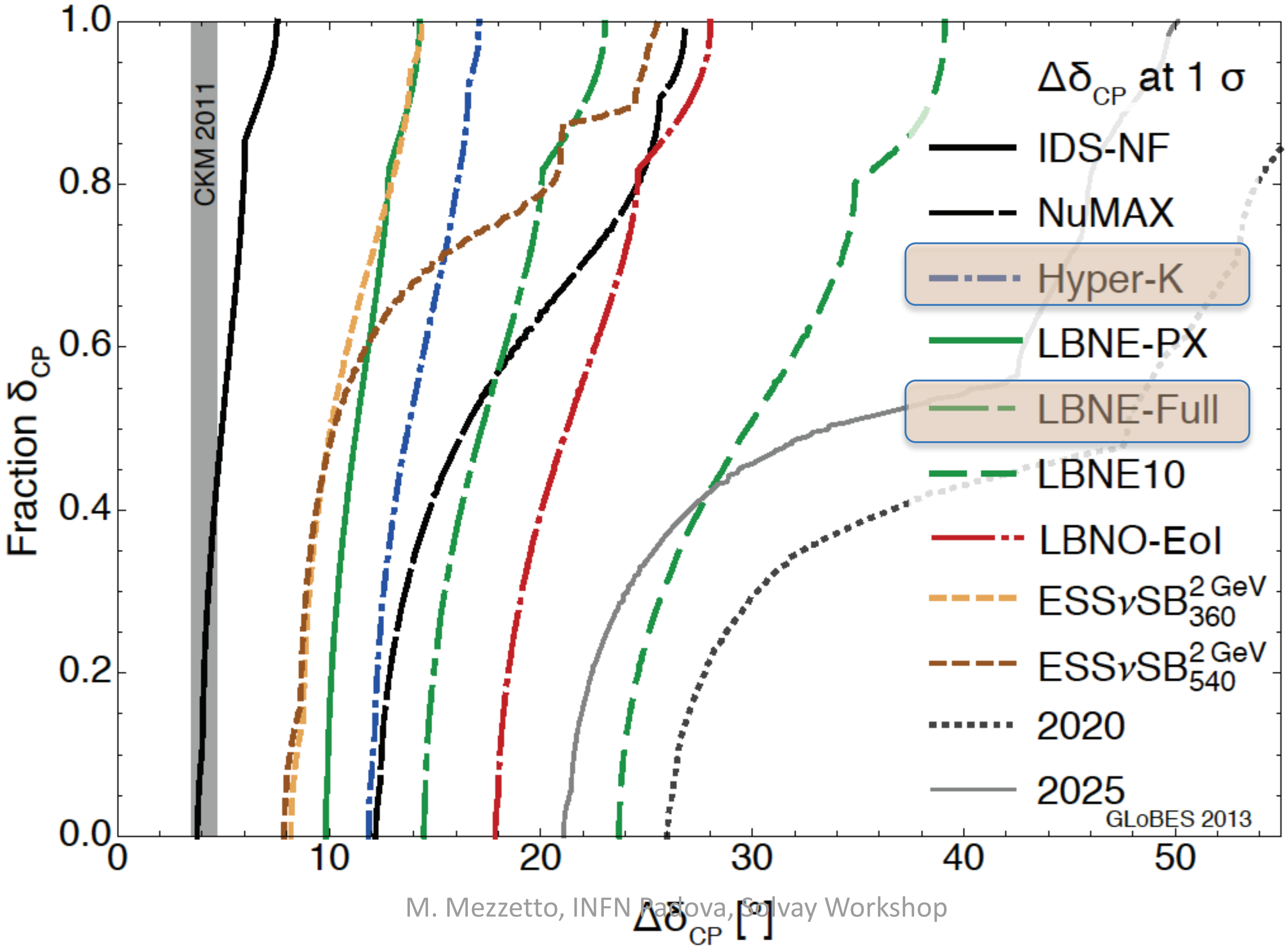
★ **DUNE-LBNF design builds on strength**
- i.e. the in-depth work from LBNE, LBNO and others
- Design at or beyond "conceptual design level"
- Realistic resource-loaded schedule being assembled
- DOE CD-1-Refresh in July 2015
  - "CDR level" review – defining cost range

★ **Things are progressing very rapidly**
- DOE CD-2a/CD-3a for **Far Site CF** in Nov 2015
  - Would allow early start to far site excavation
  - **A major milestone**

★ **Aiming (realistically) for**
- Far site excavation starting ~2018
- Far detector installation starting **2021/2022**

CP violation: performances

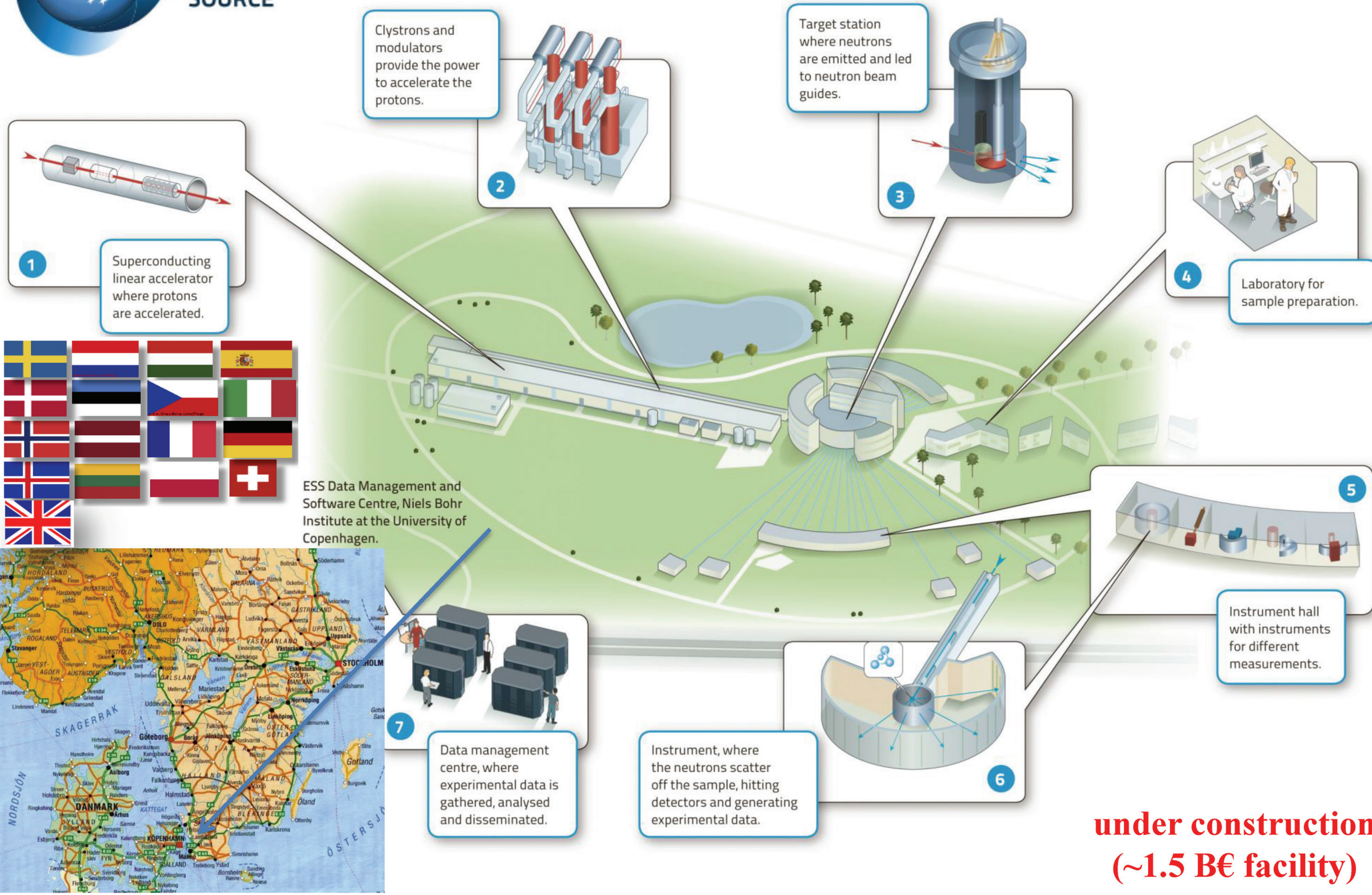
(USA snowmass process, P. Coloma)



Based on arXiv:1501.03918 by ICFA Neutrino Panel

«… given the challenging nature of the measurement and the importance of the discovery (CP violation), independent confirmation by a qualitatively different experiment is likely to be essential»

European Spallation Source

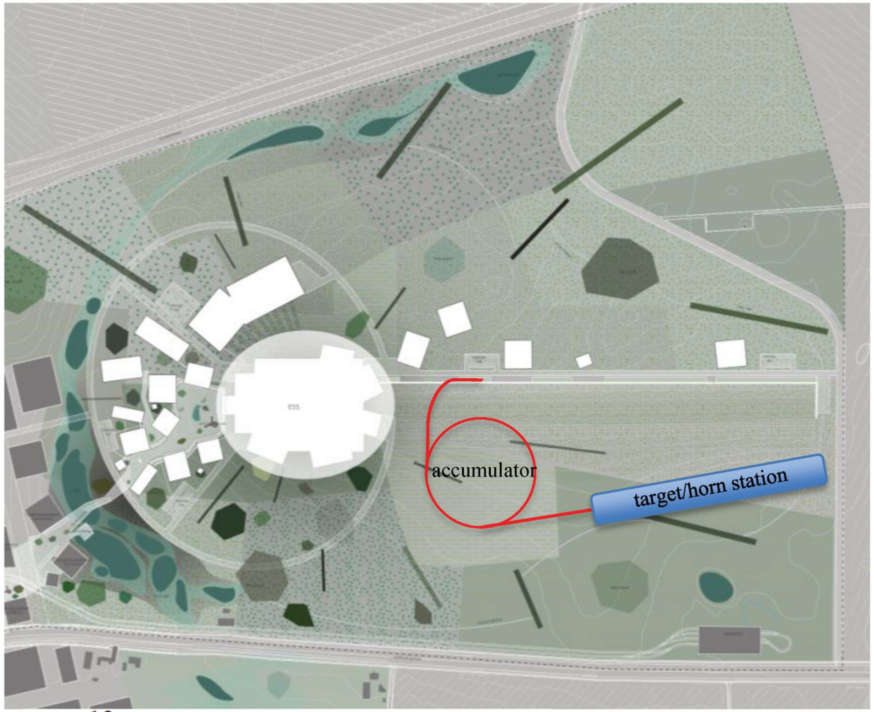


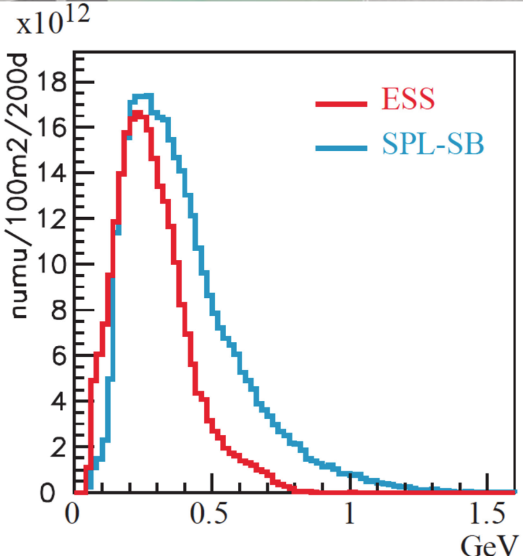
under construction
(~1.5 B€ facility)

How to add a neutrino facility?

- We must not affect the neutron program and if possible be synergetic
- Linac modifications: double the rate (14 Hz → 28 Hz)
- Accumulator (ø 143 m) needed to compress to few μs the 2.86 ms proton pulses, affordable by the magnetic horn (350 kA, power consumption, Joule effect)
    - H^- source (instead of protons)
    - space charge problems to be solved
- Target station (studied in EUROnu)
- Underground detector (studied in LAGUNA)
- ~300 MeV neutrinos
- Linac and accumulator could be the first step towards the Neutrino Factory

(http://lanl.arxiv.org/abs/1212.5048)





flux at 100 km

The MEMPHYS Detector (Water Cherenkov) (LAGUNA)

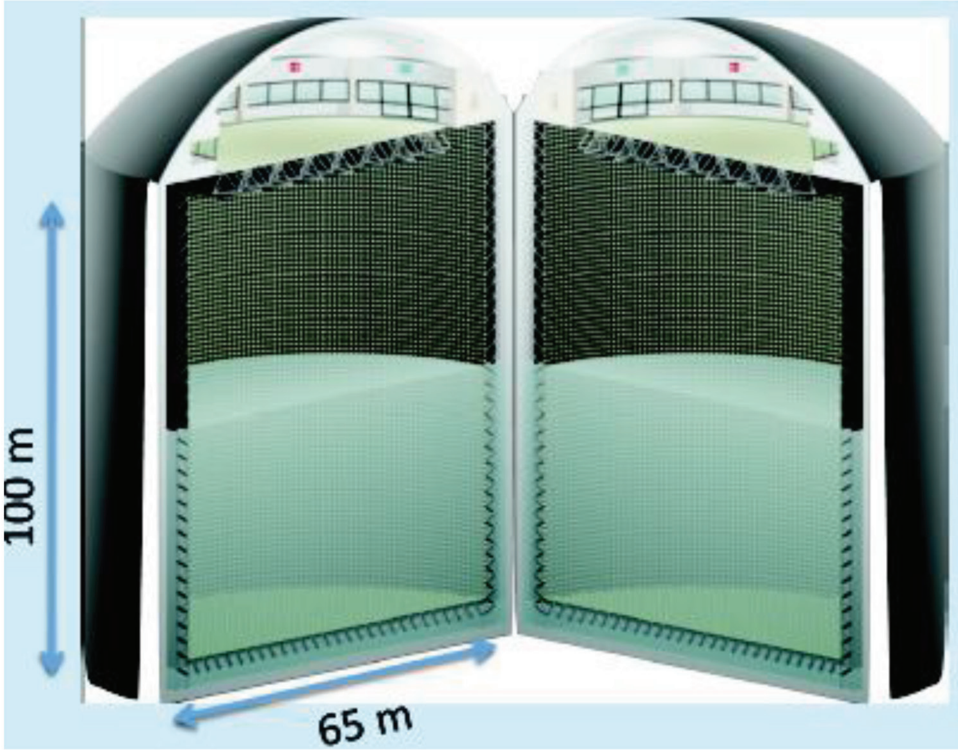
Mainly to study:

•Proton Decay (GUT)

- up to ~10^{35} years lifetime

•Neutrino properties and Astrophysics

- Supernovae (burst + "relics")
- Solar neutrinos
- Atmospheric neutrinos
- Geoneutrinos
- neutrinos from accelerators (Super Beam, Beta Beam)



Water Cerenkov Detector with total fiducial mass: 500 kt:
• 2 Cylindrical modules 100x65 m
• Readout: 22.2k 8" PMTs, 30% geom. cover.

(arXiv: hep-ex/0607026)

Conclusions

- Bright future for accelerator neutrino physics, unfortunately not in Europe.
- Main goal: CP violation in the leptonic sector
- But also unitarity tests of the 3ν mixing matrix
- The gigantic far detectors have an excellent non-accelerator physics program in their own
- The sophisticated close detectors will have their hard job in measuring neutrino cross sections in all their tricky manifestations