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Neutrino physics results

Goals
Results
Perspectives

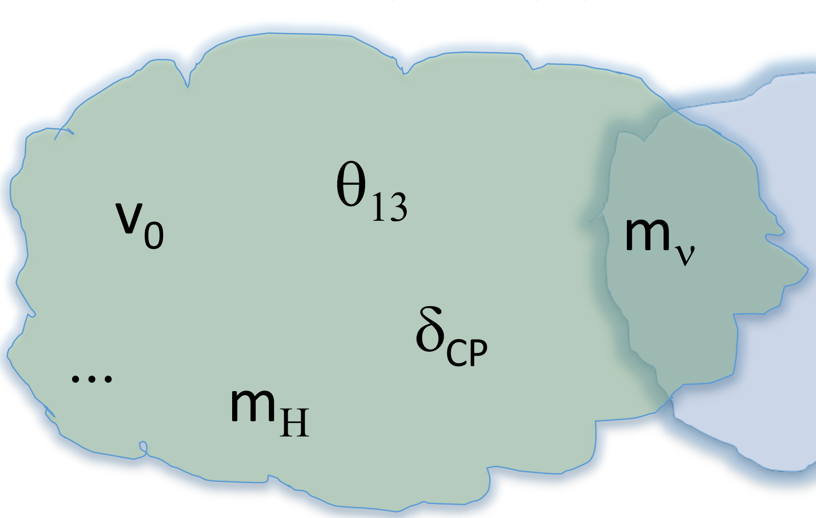
(mainly) Neutrino oscillations
Sterile neutrinos
Double Beta Decays
Direct mass measurements

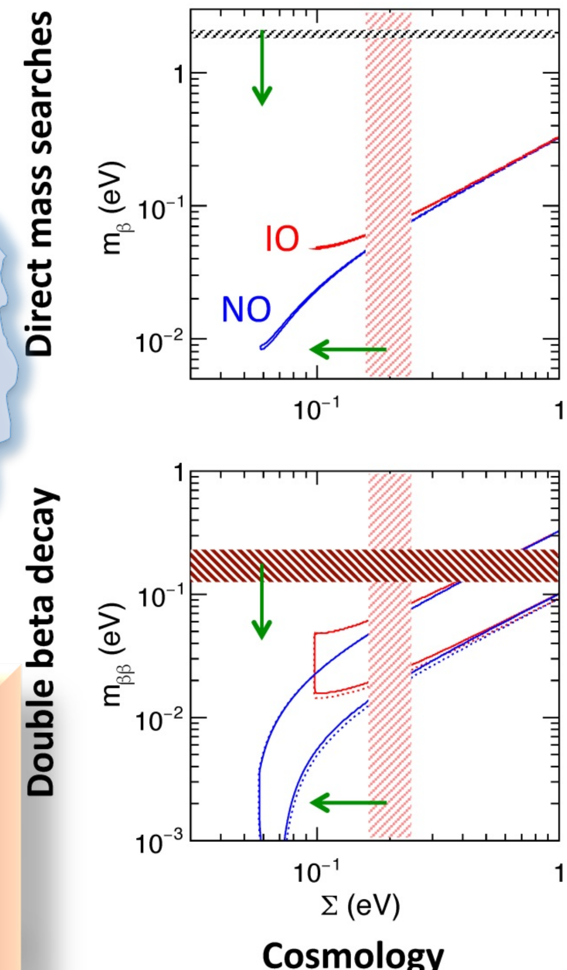
SUSY 2018, Barcelona, 23-27 June 2018

The importance of measuring m_ν

- The only parameter measurable both by hep and cosmology
- **A crucial test of consistency**

Standard model of particle physics **Standard model of cosmology**





Cosmology measures $\sum_i m_i$

Double beta decay measures $\left|\sum_i U_{ei}^2\, m_i\right|$

Direct searches measure $\left(\sum_i |U_{ei}^2|\, m_i^2\right)^{1/2}$

To compare hep with cosmology, neutrino oscillations parameters must be known, in particular mass ordering (MO)

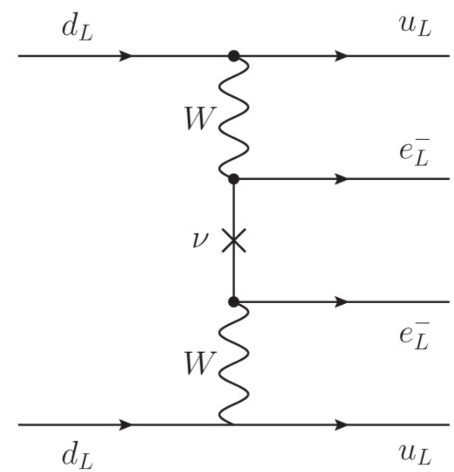
The importance of measuring δ_{CP}

- Matter/antimatter asymmetry in the Universe requires CP violation
- CP violation in the quark sector has been measured the first time 54 years ago, but this violation doesn't help very much in understanding what happened soon after the big-bang
- Through leptogenesis, theory link the ν −mass generation to the generation of baryon asymmetry of the Universe as suggested by Fukugita and Yanagida already in 1986.
- The Dirac phase δ_{CP} can be one of the ingredients of these mechanisms
- So it's mandatory to measure its value
- … also because it's one of the few unknowns of the Standard Model (together with neutrino masses)

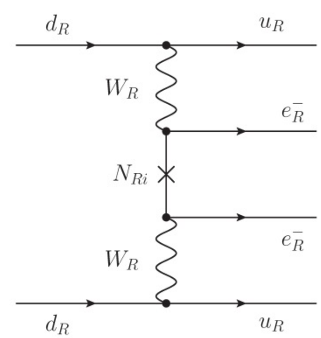
Sterile neutrinos

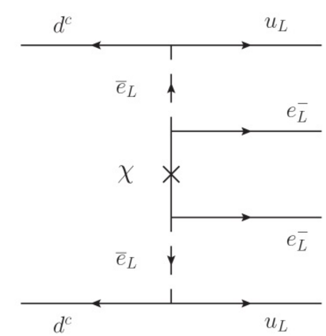
- Several experimental anomalies in neutrino experiments could be explained (not in a very consistent way) with eV sterile neutrinos
- Heavy sterile neutrinos (heavy neutral leptons) are good candidates as particles beyond the standard models. Not covered in this talk.

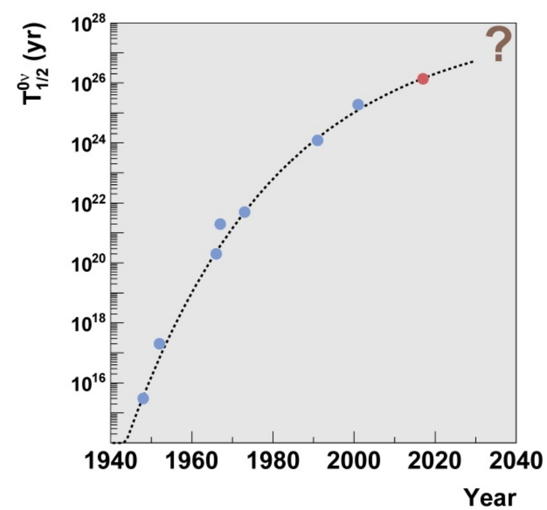
Neutrinoless Double Beta Decays



- The only experimental way to decide if neutrinos are Majorana particles
- A way to measure neutrino masses
- A way to observe leptonic number violation(ΔL=2)
- Additional CP violating phases
- A portal to new physics
- … and a very challenging experimental effort







Not discussed in this talk

Metallicity of the sun

- A critical parameter to compute star luminosity and lifetime
- Estimates from sunlight spectroscopy and helioseismology disagree: 1.3% vs 1.8%
- Could be fixed by precisely measuring solar neutrinos, in particular the CNO cycle

Neutrinos and Multimessenger Physics

- In spite of the spectacular TXS 0506+056 event measured by IceCube and gamma ray telescopes one week ago
- … the INFN effort in Km3Net
- … and the “Neutrino Telescopes” conference cycle we run at Venice since 1988

Recap: neutrino oscillations

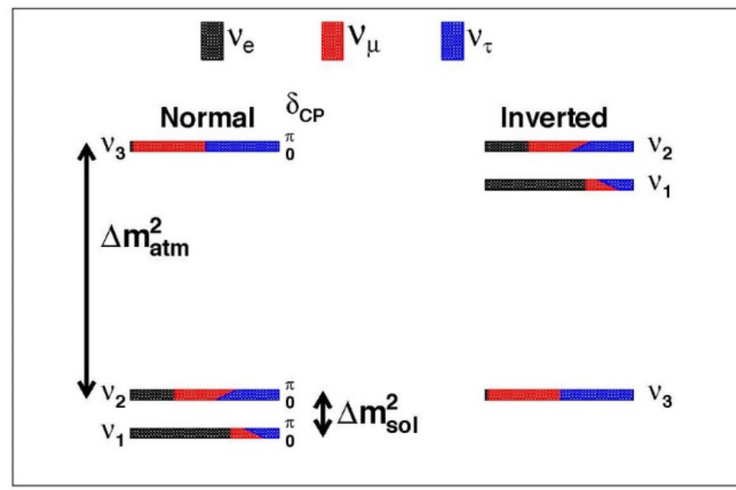
$$U_{3\times3} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

https://globalfit.astroparticles.es/

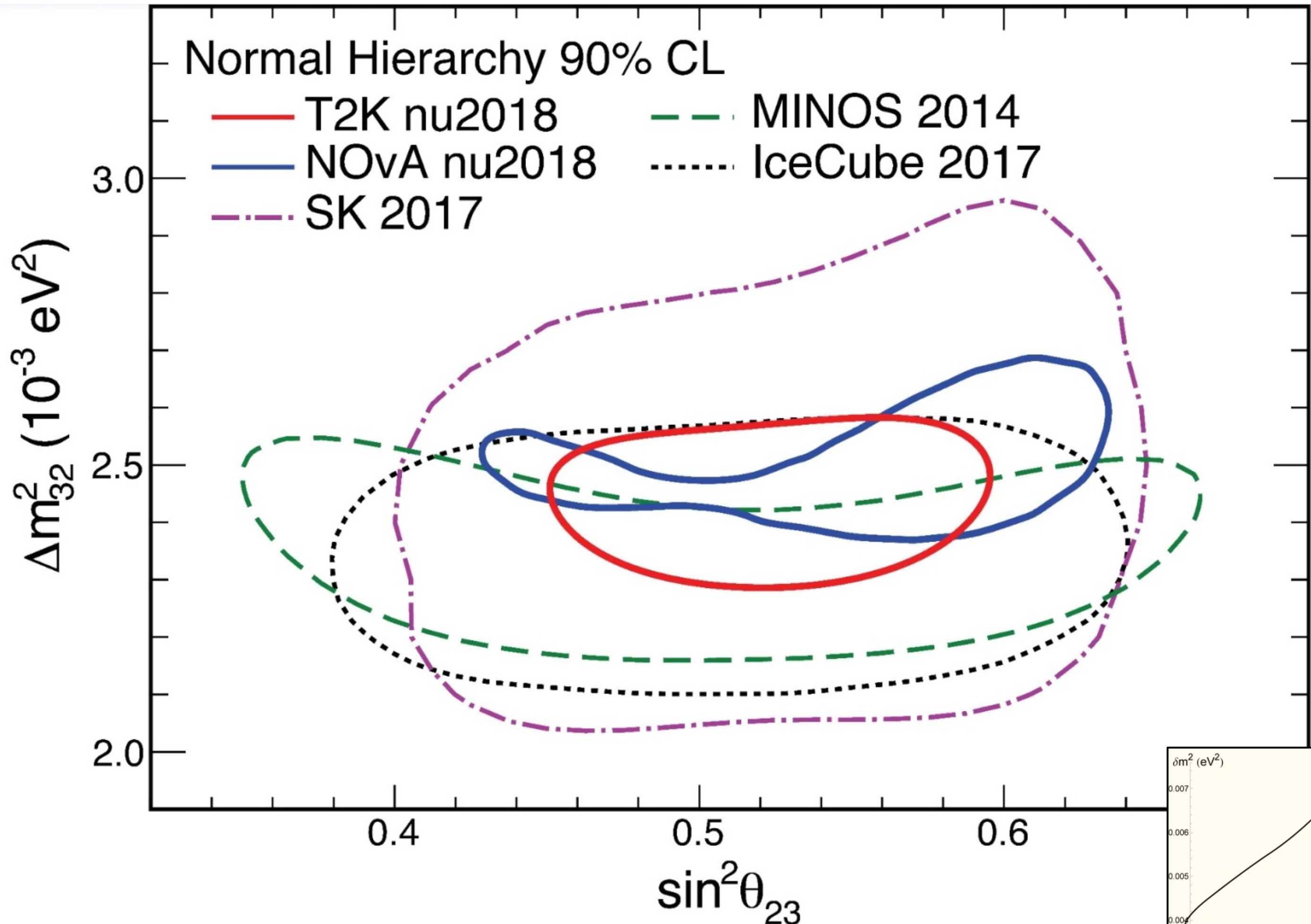
parameter	best fit $\pm 1\sigma$	3σ range	relative 1σ uncertainty
Δm^2_{21} [10^{-5}eV^2]	$7.55^{+0.20}_{-0.16}$	7.05–8.14	2.4%
$\|\Delta m^2_{31}\|$ [10^{-3}eV^2] (NO)	2.50 ± 0.03	2.41–2.60	1.3%
$\|\Delta m^2_{31}\|$ [10^{-3}eV^2] (IO)	$2.42^{+0.03}_{-0.04}$	2.31-2.51	
$\sin^2\theta_{12}/10^{-1}$	$3.20^{+0.20}_{-0.16}$	2.73–3.79	5.5%
$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.47^{+0.20}_{-0.30}$	4.45–5.99	4.7%
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.51^{+0.18}_{-0.30}$	4.53–5.98	4.4%
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.160^{+0.083}_{-0.069}$	1.96–2.41	3.5%
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.220^{+0.074}_{-0.076}$	1.99–2.44	
δ/π (NO)	$1.32^{+0.21}_{-0.15}$	0.87–1.94	10%
δ/π (IO)	$1.56^{+0.13}_{-0.15}$	1.12–1.94	9%

deSalas et al, 1708.01186 (May 2018)

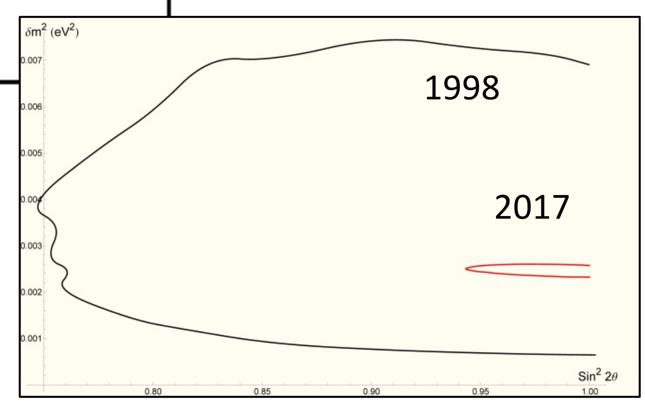
Neutrino Mass Ordering



Atmospheric Parameters



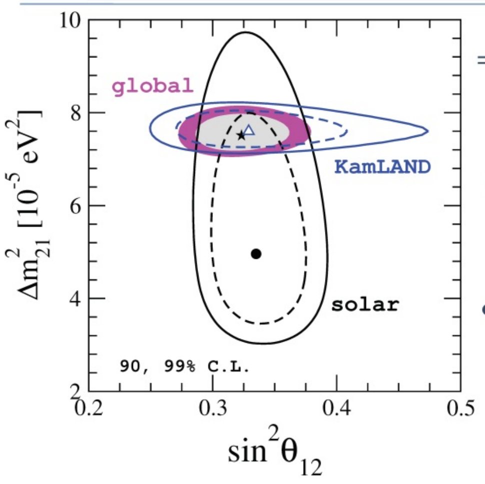
Progress since the discovery



Solar Parameters

From M. Tortola talk at Neutrino 2018

Tension between solar and KamLAND



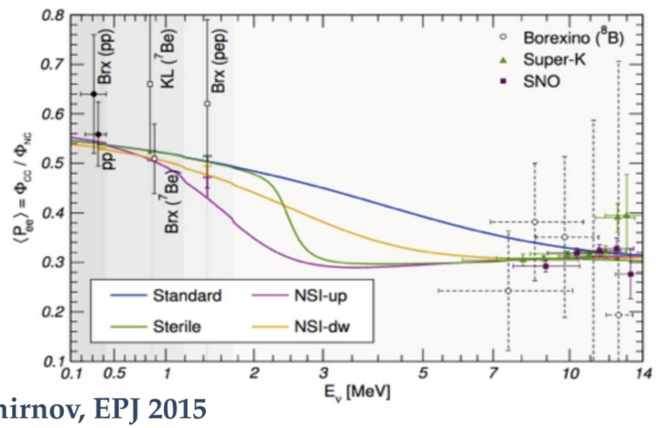
⇒ 2σ tension between preferred value of Δm^2_{21} from KamLAND and solar data

- Δm^2_{21} preferred by KamLAND predicts steep upturn at solar spectrum and smaller D/N asymmetry
- More precise measurements of Δm^2_{21} by reactor (JUNO,RENO-50) and solar experiments may help.

- NSI (ε ~0.3) can reconcile solar and KL data

⇒ flatter spectrum at intermediate E-region

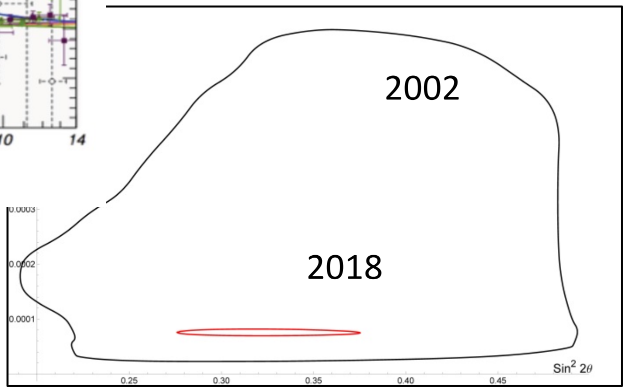
⇒ larger D/N asymmetries can be expected



Escrihuela et al, PRD80 (2009)

Coloma et al, PRD96 (2017)

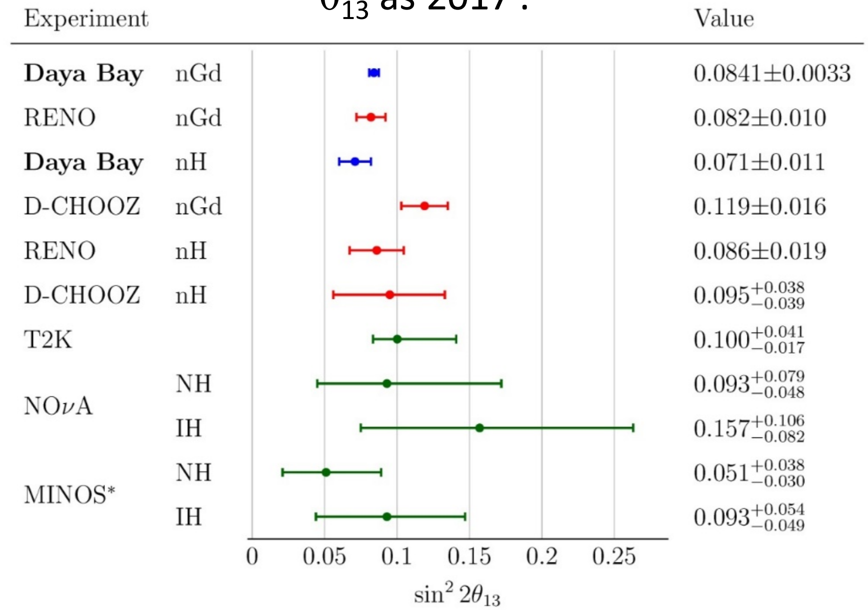
Maltoni & Smirnov, EPJ 2015



The large value of θ_{13} changed the worldwide strategy on neutrino oscillations

- Reactors could precisely measure θ_{13} (better than accelerators)
- The precise value of θ_{13} as measured by reactors improved significantly the sensitivity of accelerator experiments in measuring CP violation
- Several different methods for measuring neutrino mass ordering became possible (Juno, Orca, IceCube)
- High sensitivity (5σ) next generation experiments to measure CP violation could start without any R&D on new concepts for neutrino beams (Dune, Hyper-Kamiokande)
- Since they were no more necessary, R&D activities on new concepts for neutrino beams had been suddenly stopped.

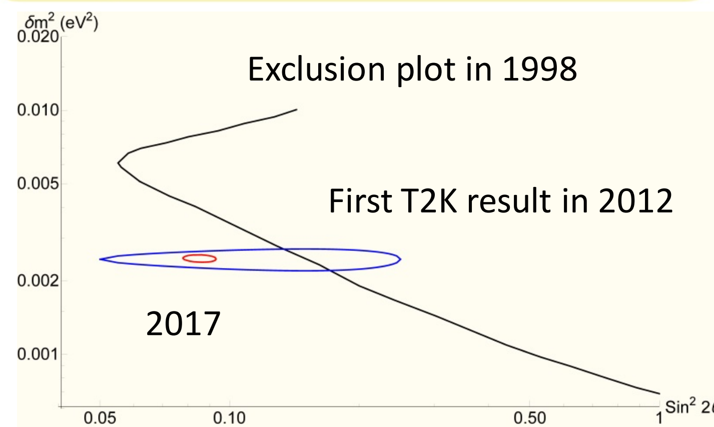
θ_{13} as 2017 .



Latest result by Daya Bay at Neutrino 2018

$$\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$$

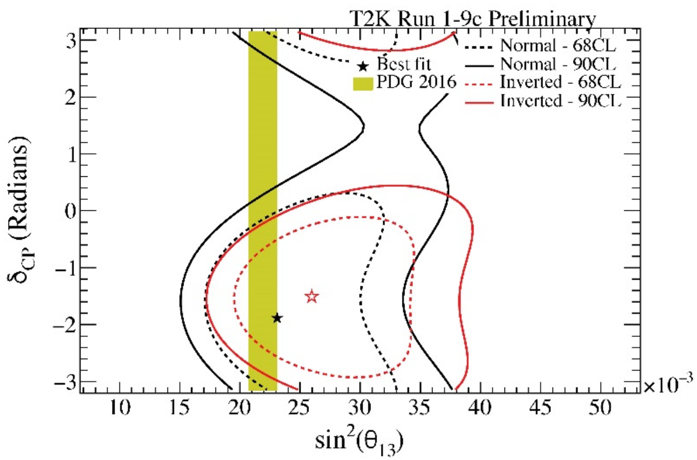
$$|\Delta m^2_{ee}| = (2.52 \pm 0.07) \times 10^{-3}\ \mathrm{eV}^2$$



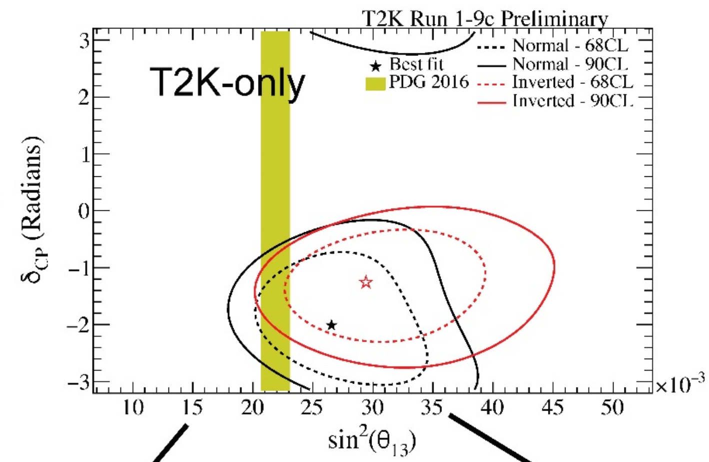
Latest T2K results: arXiv:1807.07891

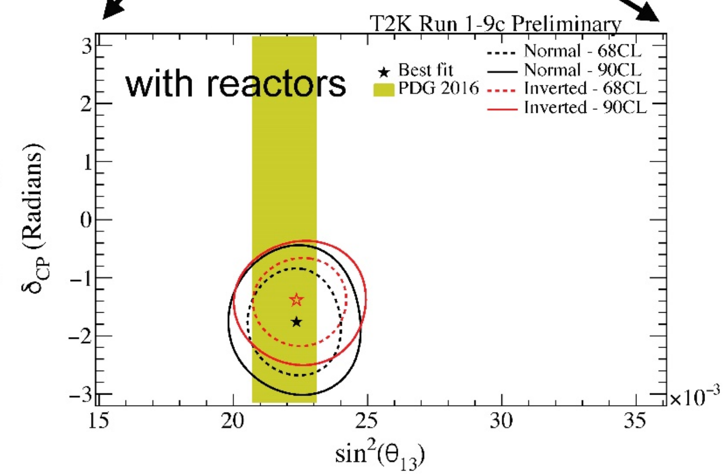
δ_{CP} vs. $\sin^2\theta_{13}$

SENSITIVITY



DATA FIT

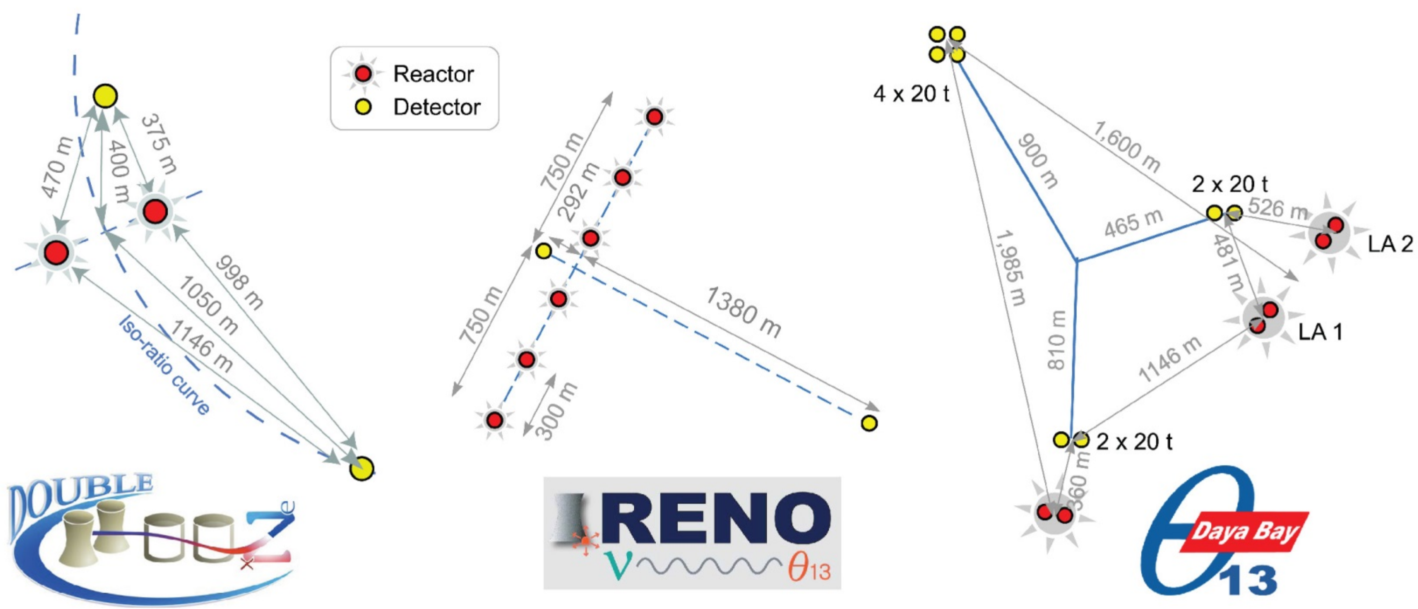




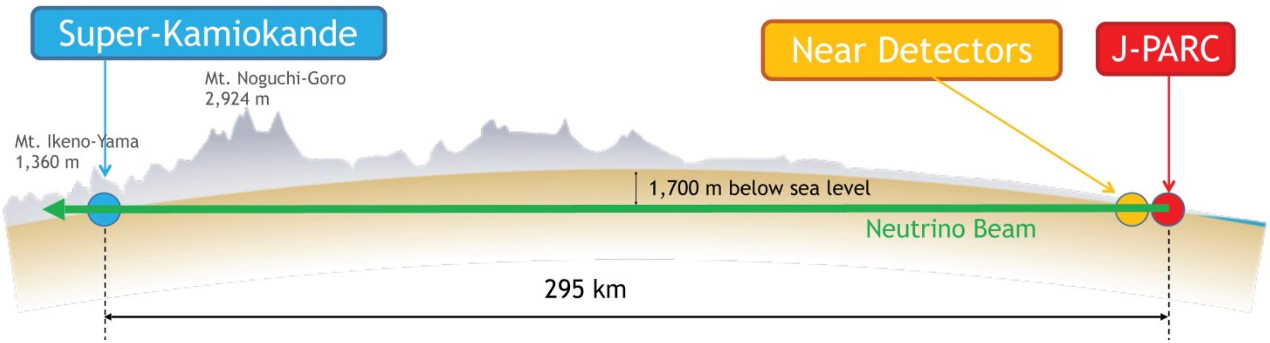
- sensitivity assumptions:
  - $\sin^2\theta_{13}$= 0.0219 (2016 PDG)
  - $\sin^2\theta_{23}$ = 0.528
  - NH, δ_{CP} = -1.601

Reactor experiments

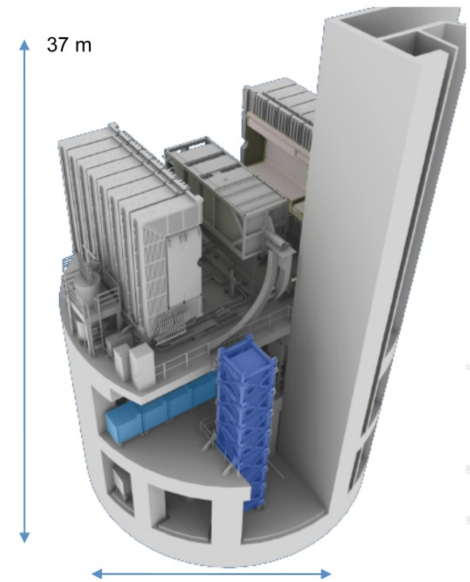
Setup	$P_{\rm Th}$ [GW]	L [m]	$m_{\rm Det}$ [t]	Events/year	Backgrounds/day
Daya Bay	17.4	1700	80	$10 \cdot 10^4$	0.4
Double Chooz	8.6	1050	8.3	$1.5 \cdot 10^4$	3.6
RENO	16.4	1400	15.4	$3 \cdot 10^4$	2.6



The T2K project



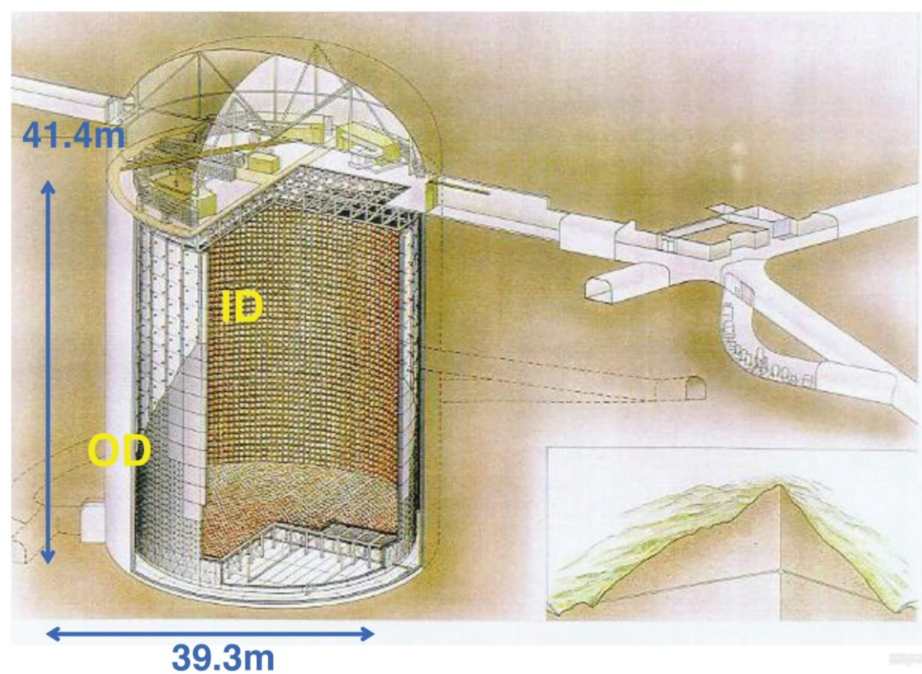
Powerful (0.5 MW at today) neutrino beam from J-Parc 30 GeV/c proton synchrotron



A set of close detectors both on and off-axis. In particular ND280 at 280 m from the target, off-axis.

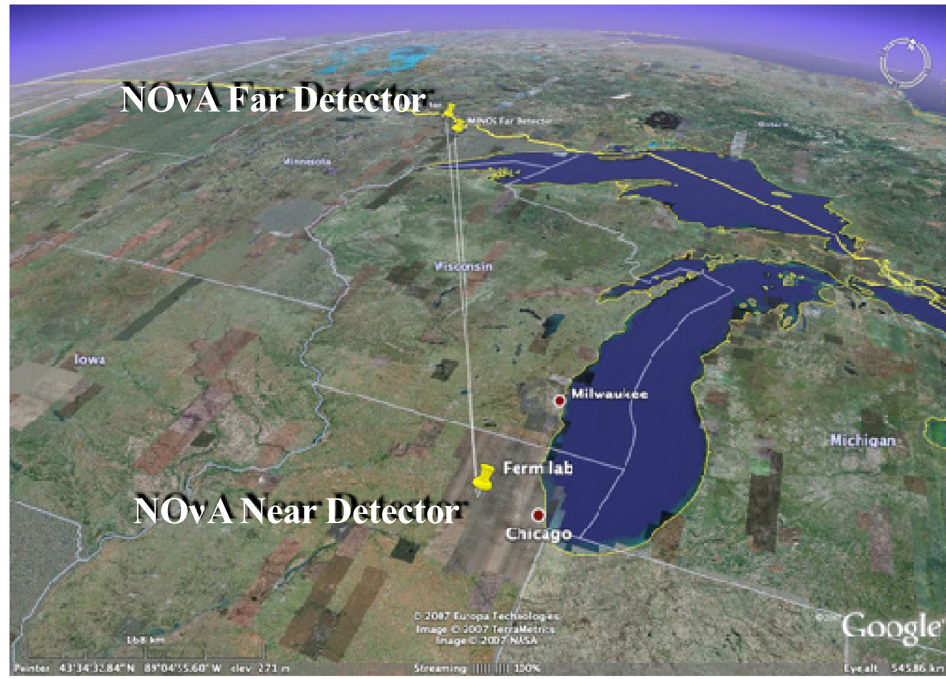
SK as far detector, 295 km off-axis

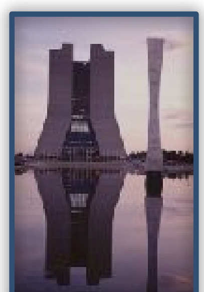
Data taking started in 2009.



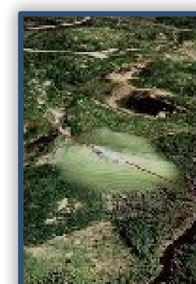
The Nova experiment

- Upgraded NuMI **beam of muon neutrinos or antineutrinos** at Fermilab running at 700kW.
- Highly active liquid scintillator **14- kton detector** off the main axis of the beam.
- Functionally identical detectors: Near Detector (ND) site at Fermilab and Far Detector (FD) 810 km away at Ash River,
- NOvA observes **disappearance of muon neutrinos and antineutrinos, appearance of electron neutrinos and antineutrinos** and potential suppression of neutral current interactions.
- 4σ evidence of $\overline{\nu}_e$ appearance presented at Neutrino 2018



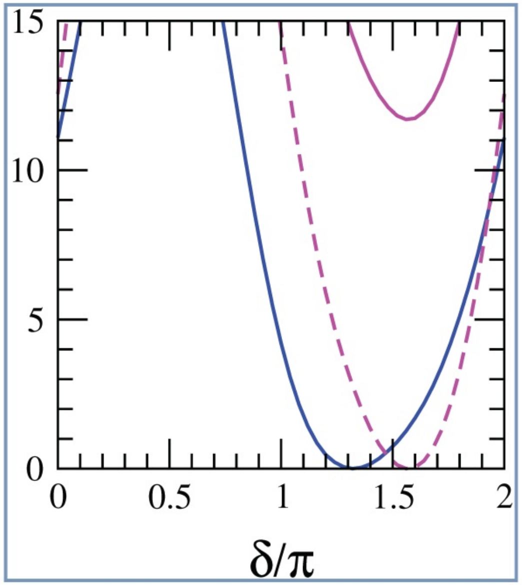


← longest baseline →

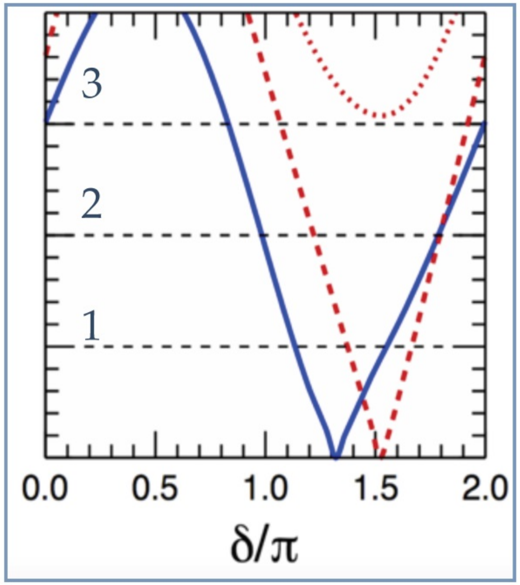


Status of CP and MO

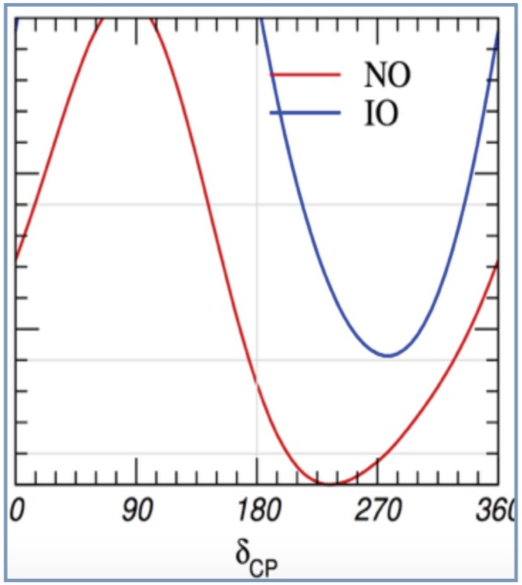
Δχ², Valencia [1708.01186]



Nσ, Bari [1804.09678]



Δχ², NuFit v3.2

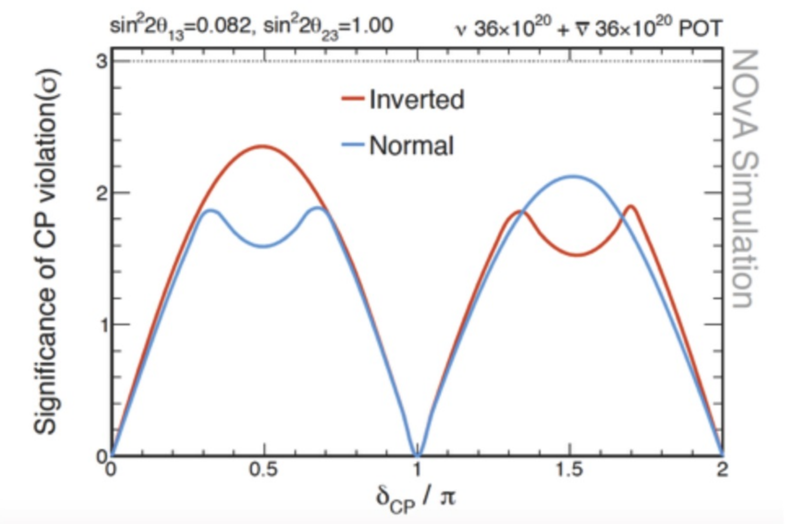


SK-atm not included

- Global fits exclude CP conservation at 2σ
- SK, T2K and Nova favor NO at 2σ
- **Global fits favor NO at 3σ**

Running experiments CP sensitivity projection

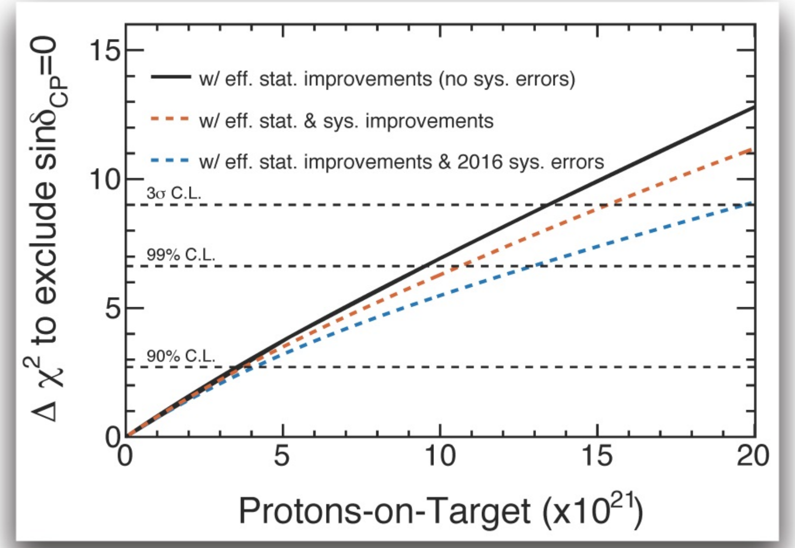
NOvA



• by 2024:
 > 2σ sensitivity on CP violation at max CP violation (π/2 & 3π/2)

T2K-II

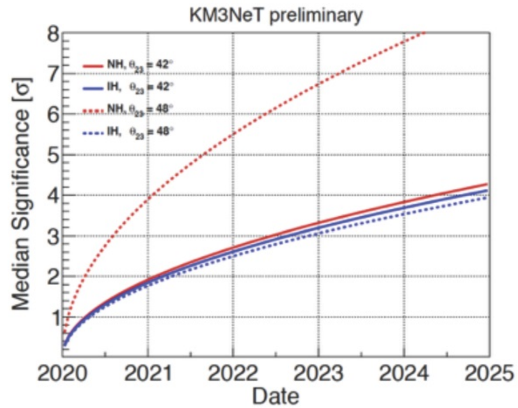
Abe et al, 1609.04111



• by 2026 (20×10^{21} POT):
 > 3σ sensitivity on CP violation

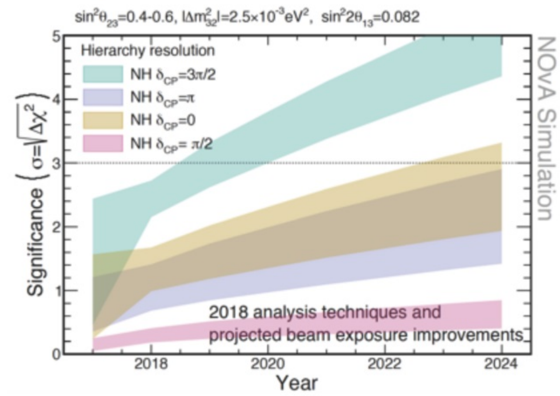
"Short term" sensitivities in MO

ORCA **Adrian-Martinez et al, 1601.07459**



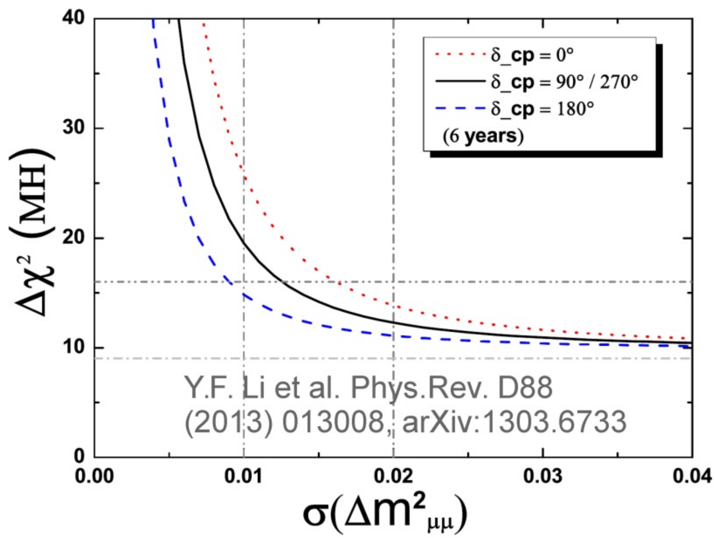
- by 2023: 3σ determination of MO
  (similar results for PINGU)

NOνA **Neutrino 2018**



- by 2020: 3σ sensitivity (NO and δ=3π/2)
- by 2024: 3σ sensitivity for 30/50% of δ

JUNO ⇒ 3σ sensitivity on mass ordering after 6 years



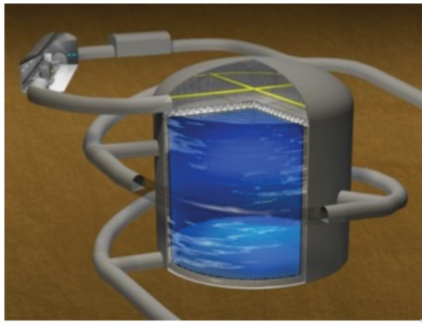
Third generation Long Baseline Experiments

Gigantic detectors with three liquids are under way:

- Liquid scintillator: **Juno** and **SNO+** are in construction
- Water**: Hyper-Kamiokande** selected as top project by Mext. And also **IceCube Gen 2 , Km3net/Orca**
- Liquid Argon: **Dune** is approved and partially funded

Great complementarity in many astrophysics measurements (SN, relic SN, solar and atmospheric neutrinos, indirect DM searches etc.) and **proton decay**

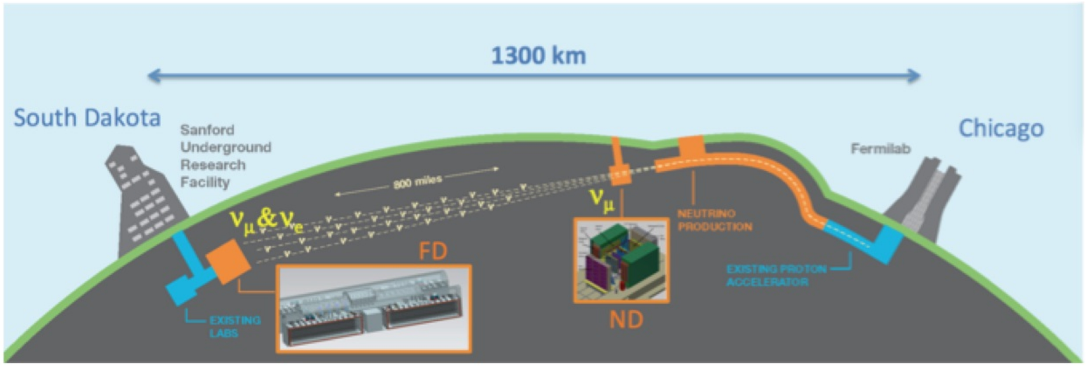
Hyper-Kamiokande

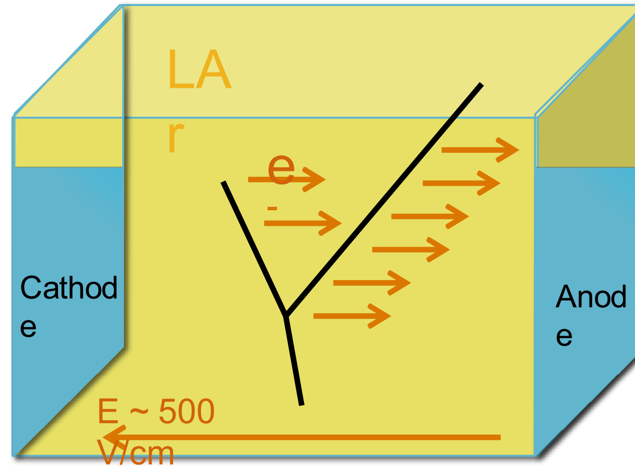


Hyper-K

J-PARC
Accelerator Complex

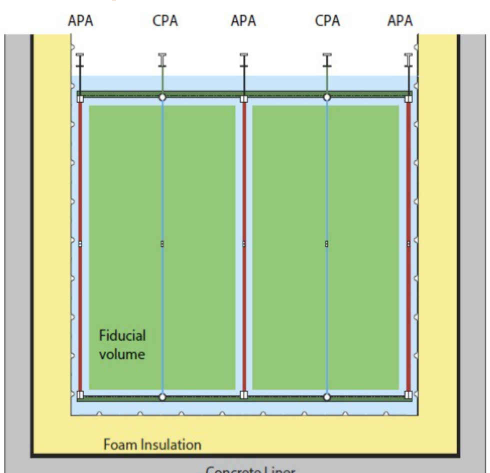
- ✓Gigantic neutrino and nucleon decay detector
  - ✓186 kton fiducial mass : ~10 × Super-K
  - ✓× 2 higher photon sensitivity than Super-K
  - ✓Superb detector capability, technology still evolving
  - ✓2nd oscillation maximum by 2nd tank in Korea under study
- ✓MW-class world-leading ν-beam by upgraded J-PARC
- ✓Project now is a priority project by MEXT's Roadmap
  - ✓Aiming to start construction in FY2019, operation in FY2026

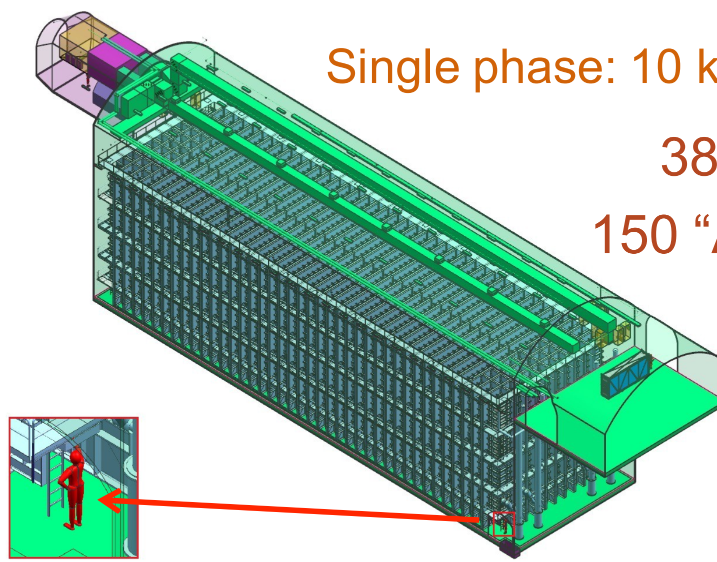




- 4 10-kt (fiducial) liquid argon TPC modules
- **Single-** and dual-phase detector designs (1st module will be single phase)
- Integrated photon detection
- Modules will not be identical

Single phase: modular wire-plane readout





Single phase: 10 kt module

384,000 readout wires

150 “APAs” (2.3 m x 6 m)

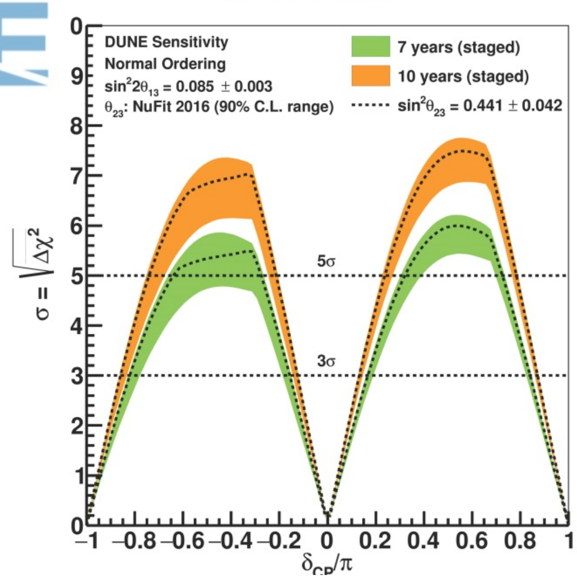
12 m high

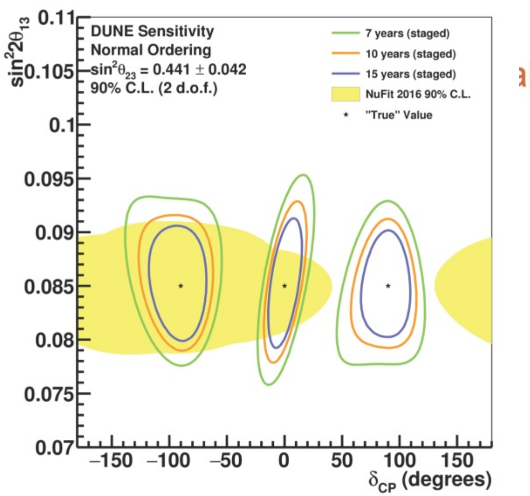
15.5 m wide

58 m long

Dune and HK CP Sensitivity

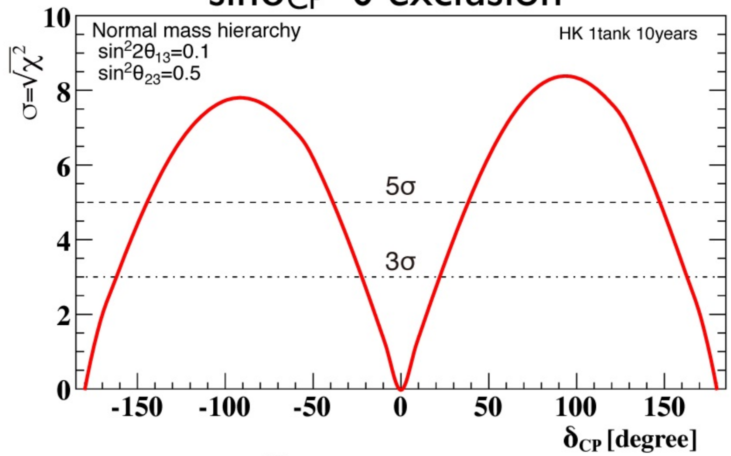
CP Violation



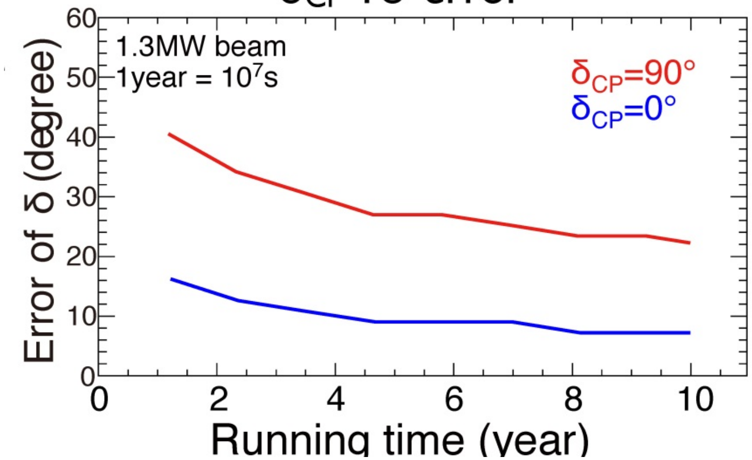


Simultaneous measurement of neutrino mixing angles and δ_{CP}

$\sin\delta_{CP}=0$ exclusion

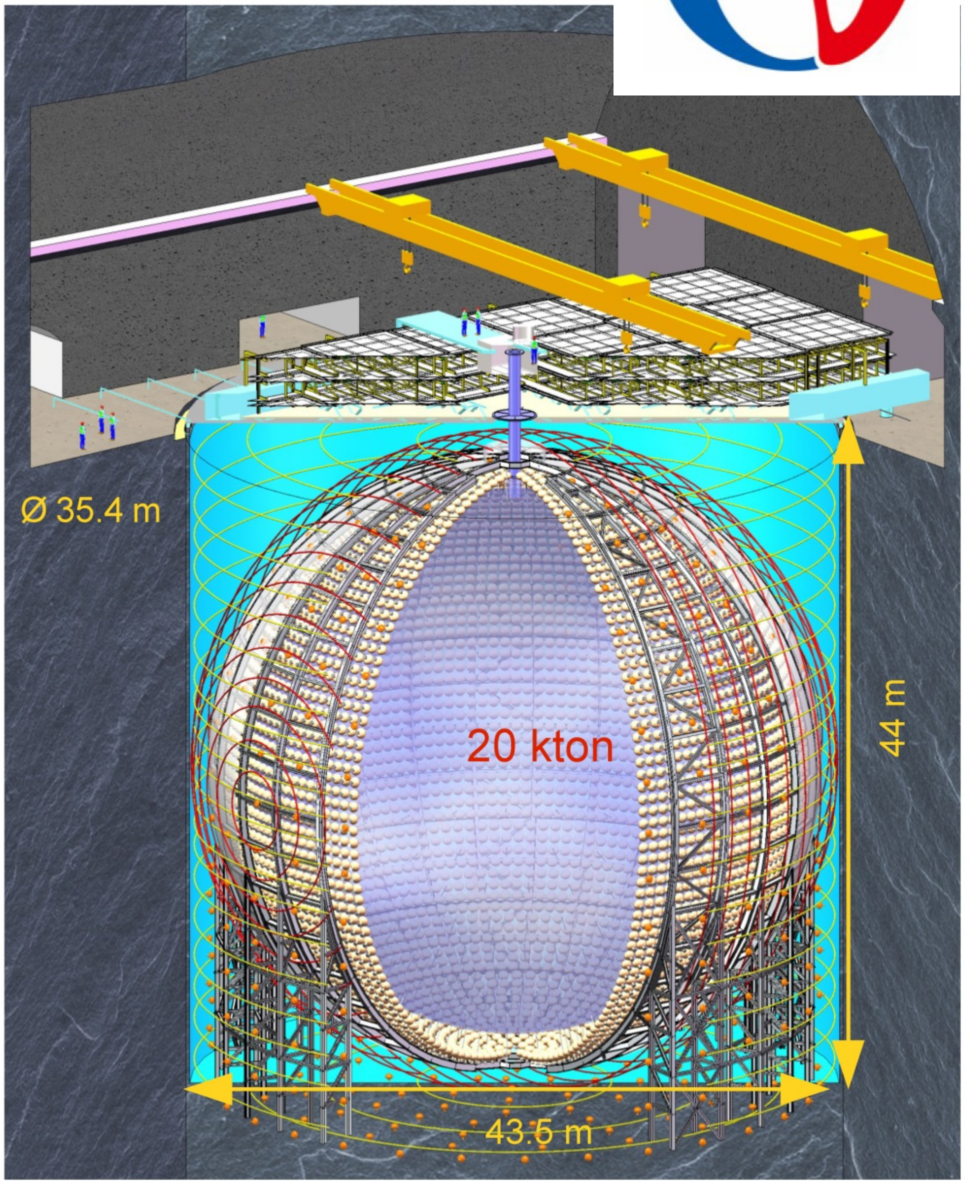


δ_{CP} 1σ error



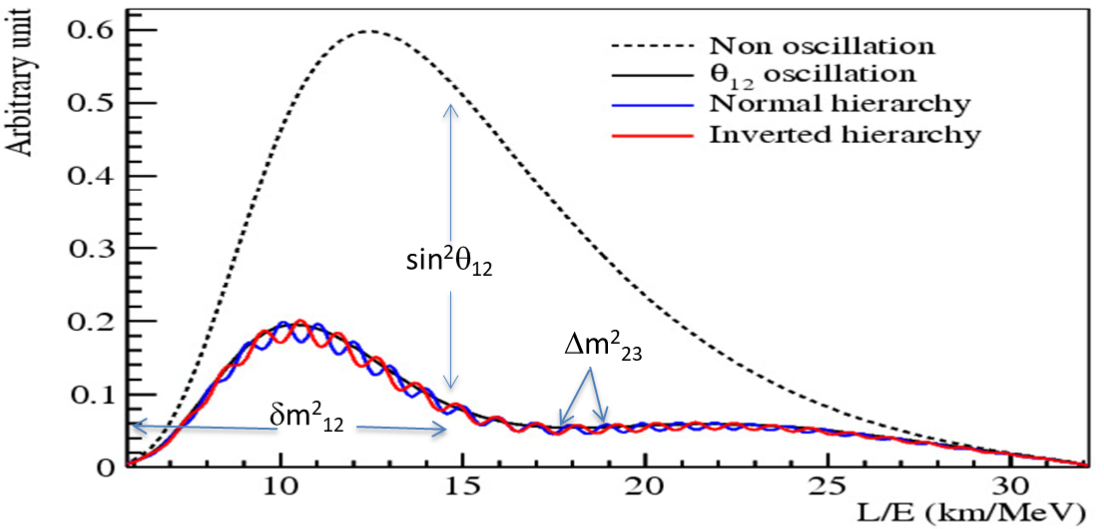
Juno

- **Central detector**
  - Acrylic sphere with liquid scintillator
  - PMTs in water buffer
  - 78% PMT coverage
- **Water Cherenkov muon veto**
  - 2000 20” PMTs
  - 35 ktons ultra-pure water
  - Efficiency > 95%
  - Radon control → less than 0.2 Bq/m^3
- **Compensation coils**
  - Earth magnetic field <10%
  - Necessary for 20” PMTs
- **Top tracker**
  - Precision muon tracking
  - 3 plastic scintillator layers
  - Covering half of the top area



Juno

- 3σ MO
- Provided that energy res. <3%
- 4σ with an external input of Δm_{ee}<1%
- Precision measurement of other 3 neutrino osc. parameters



	Δm^2_{21}	$\sin^2\theta_{12}$	$\lvert\Delta m^2_{31}\rvert$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$
Dominant experiment	KamLAND	SNO	T2K & NOvA /Daya Bay	Daya Bay	T2K
Individual 1σ	2.4%	6.7%	3.2%/3.5%	4.0%	9.8%
Global 1σ *	2.2%	3.9%	1.2%	3.4%	5%
JUNO expected 1σ	0.6%	0.7%	0.4%	~15%	-

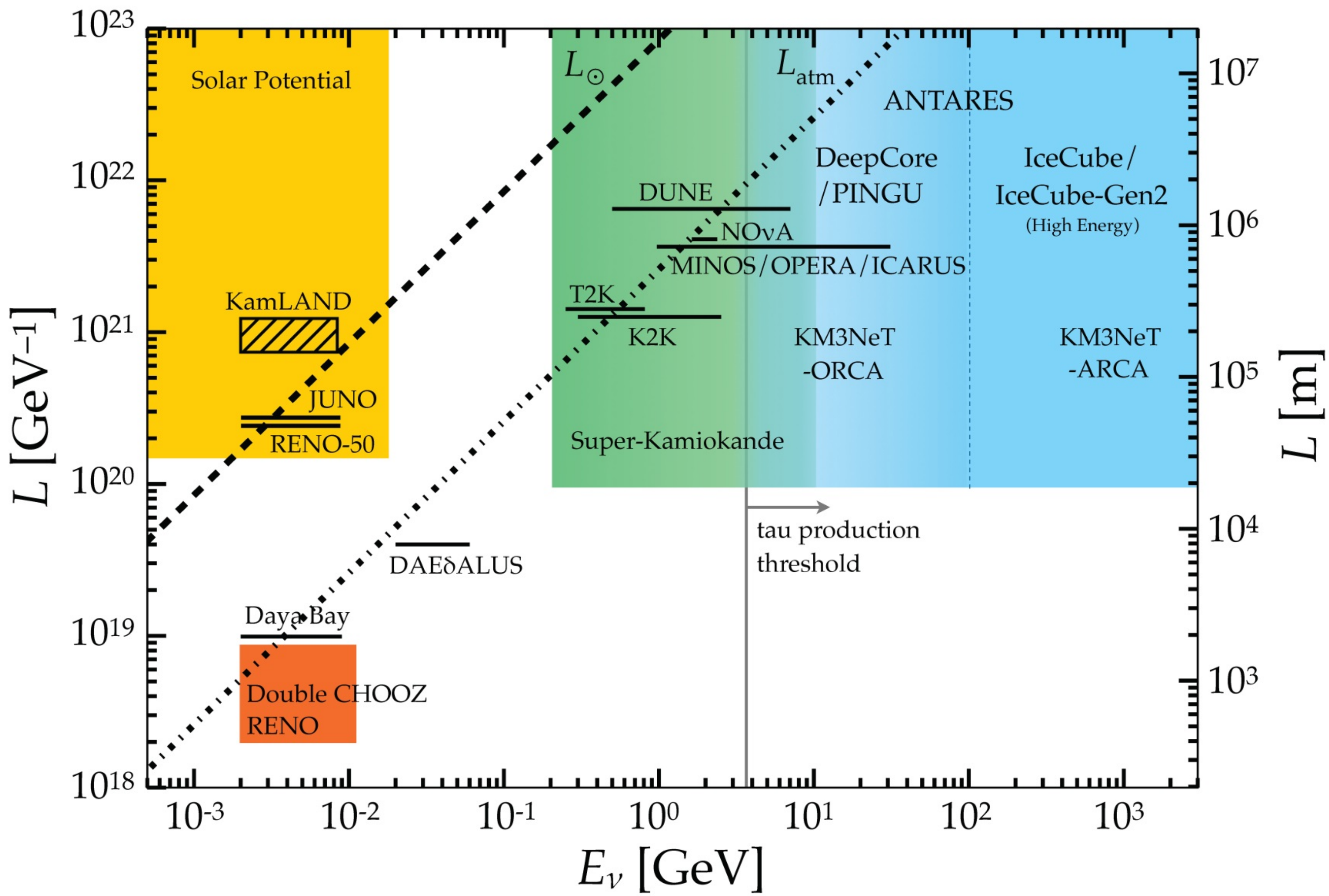
Complementarity

> *"There are two possible outcomes: if the result confirms the hypothesis then you've made a **measurement**. If the result is contrary to the hypothesis then you've made a **discovery**", **Enrico Fermi**.*

- Without complementarity and redundancy HK and Dune risk to produce "boring" yet powerful measurements.
- With they increase their discovery potential
- HK and Dune nicely complement their physics reach in neutrino oscillations (see f.i. arXiv:1501.03918)
- Juno can improve their sensitivity in precisely measuring solar parameters while HK and Dune can measure Δm_{ee}^2 for Juno
- The three liquids really complement each other in detecting SN neutrinos, proton decays, solar neutrinos, indirect DM searches, …

Complementarity: same L/E but different E

Any subleading non-oscillatory effect would violate L/E scaling

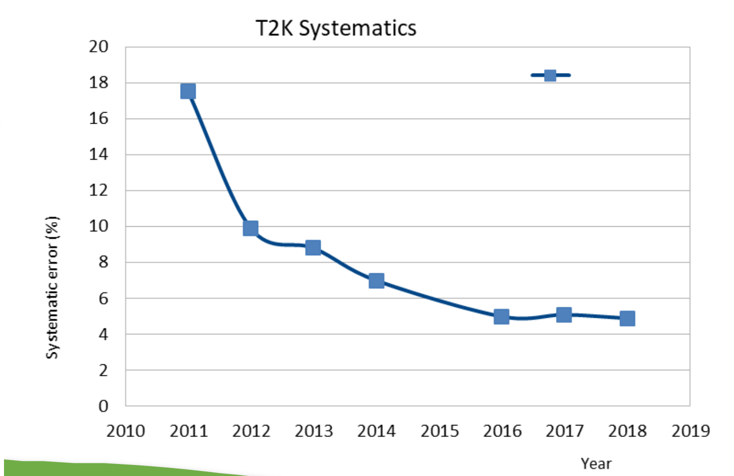


What Next

At full statistics Dune and HK, will be dominated by systematic errors. Detectors can't be improved very much and any significant progress of sensitivities can only be achieved through neutrino beams

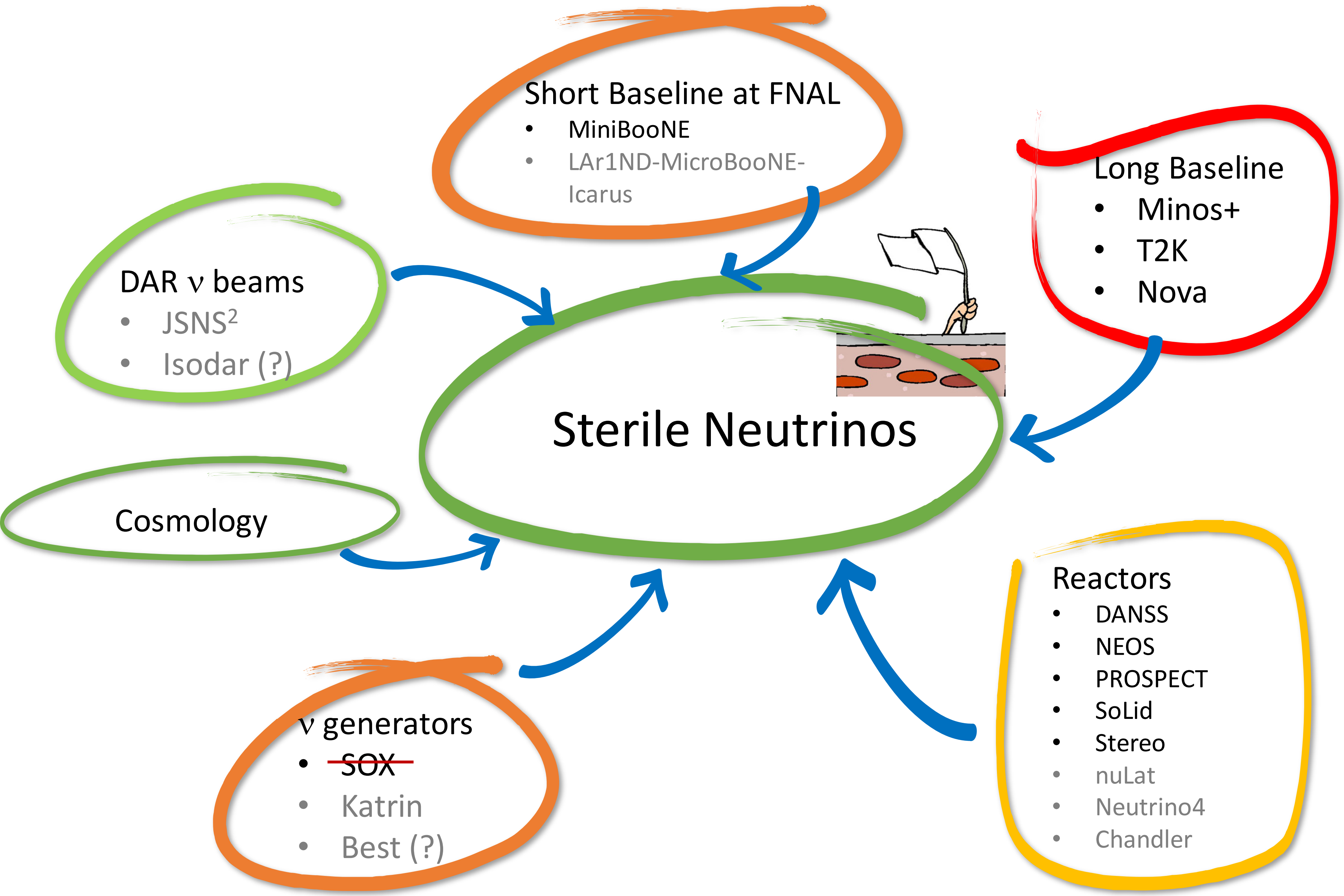
D. Hadley, Nufact '17

Experiment	$\nu_e + \bar{\nu}_e$	$1/\sqrt{N}$	Ref.
T2K (current)	74 + 7	12% + 40%	2.2×10^{21} POT
NOvA (current)	33	17%	FERMILAB-PUB-17-065-ND
NOvA (projected)	110 + 50	10% + 14%	arXiv:1409.7469 [hep-ex]
T2K-I (projected)	150 + 50	8% + 14%	7.8×10^{21} POT, arXiv:1409.7469 [hep-ex]
T2K-II	470 + 130	5% + 9%	20×10^{21} POT, arXiv1607.08004 [hep-ex]
Hyper-K	2900 + 2700	2% + 2%	10 yrs 2-tank staged KEK Preprint 2016-21
DUNE	1200 + 350	3% + 5%	3.5+3.5 yrs x 40kt @ 1.07 MW arXiv:1512.06148 [physics.ins-det]



The focus of next to next generation of Long Baseline experiments are new concepts in neutrino beams.

eV Sterile Neutrinos

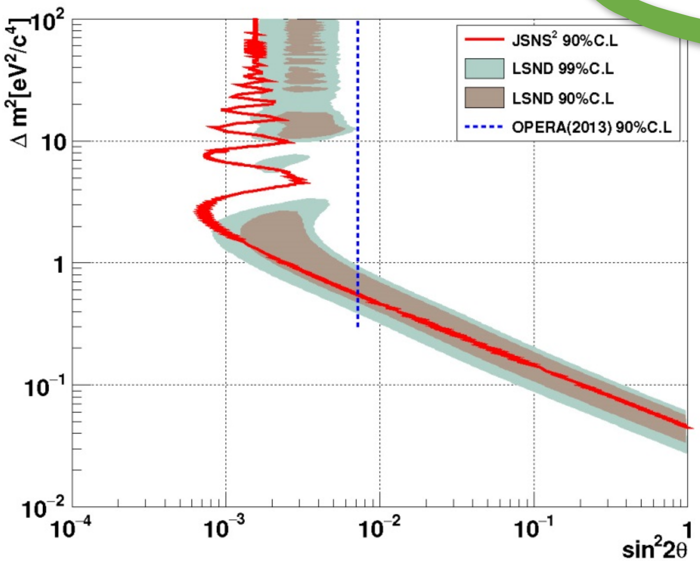


Check of LSND

π DAR

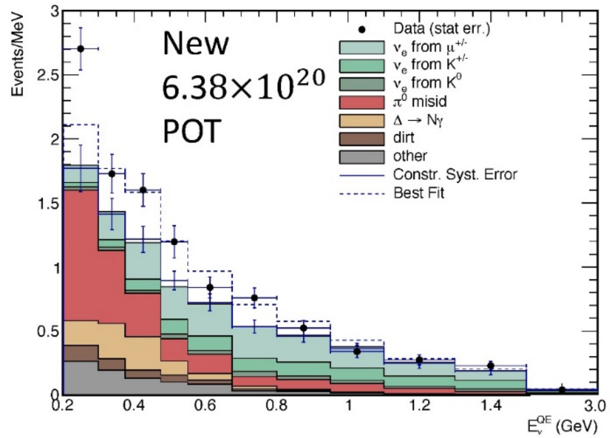
- JSNS^2

Excess of $\overline{\nu}_e$-like events in a ν beam from π decays at rest

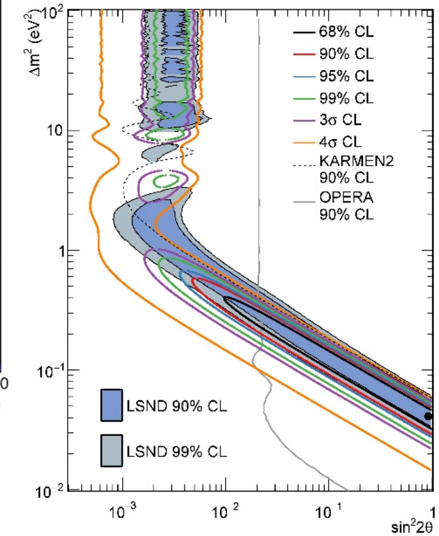


JSNS^2 TDR: arXiv:1705.08629
90%CL sensitivity for 1MW x 3 years x 1 detector

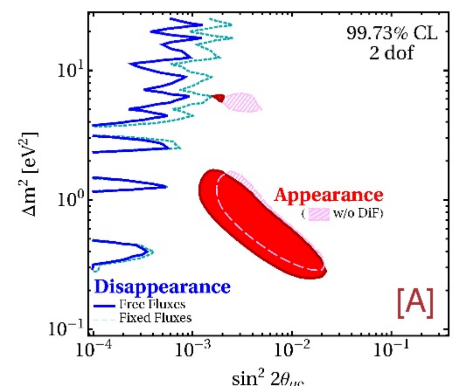
MiniBoone



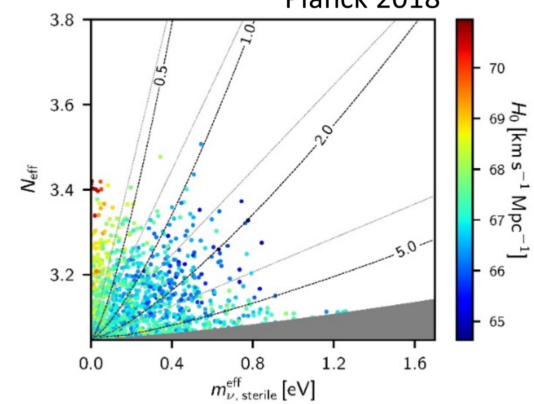
MiniBooNE vs LSND



Appearance vs Disappearance



Planck 2018



- Half data published already in 2012
- Excess of neutrinos at low energy, where, according to the proposal, backgrounds are not well normalized
- Fermilab approved MicroBooNE to measure the nature of the low energy excess (data not yet published)
- 2018 data doubles the statistics but doesn't clarify too much the background normalization
- If interpreted as sterile neutrino oscillations data is consistent with the LSND anomaly …
- … but it is in strong disagreement with the rest of phenomenology of sterile neutrino oscillations, mainly with the several null results on ν_μ disappearance both at short and long baselines (χ^2_{PG}/dof = 29.6/2, arXiv:1803.10661)
- Furthermore cosmology disfavors a fourth neutrino state with 1 eV mass

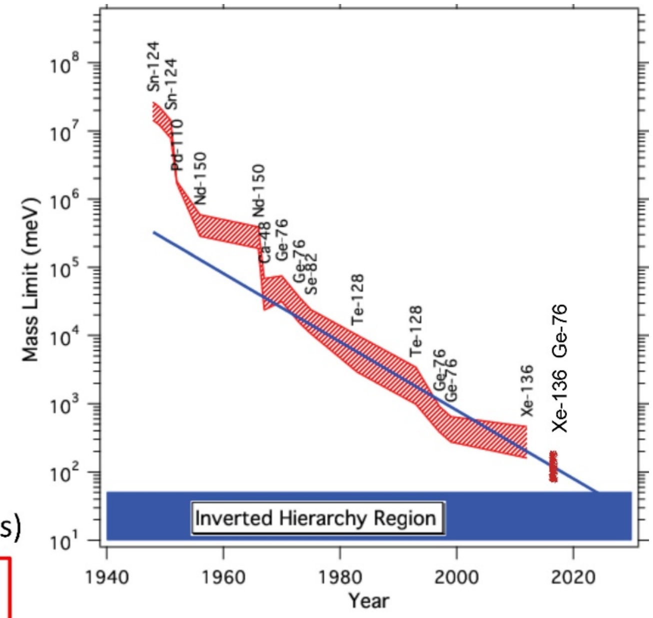
Neutrinoless double beta decay experiments

Several important new results by new generation experiments

Experiment	Isotope	Mass (isotope/tot) (kg)	$T_{1/2}$ (10^{26} yr)	$m_{\beta\beta}$ (meV)	Zero bck exposure (kg.yr)
Kamland-Zen	Xe^{136}	380/3900	1.07	45 - 160	45
Exo	Xe^{136}	100	0.18	150-400	10
Gerda	Ge^{76}	35	0.90	110-260	500
Cuore	Te^{130}	206/741	0.15	140-400	20

- Sensitivity scales as $(Mt)^{1/2}$ with null backgrounds, $(Mt)^{1/4}$ otherwise
- Critical parameter: backgrounds in the “region of interest”
- Here expressed as its inverse: expected exposure (kg yr) with zero backgrounds (kg are computed for the mass of the emitter isotope)
- **Goal for a next gen experiment**: zero bacgkround exposure of order of **10000 kg x yr** (1 ton x 10 years)

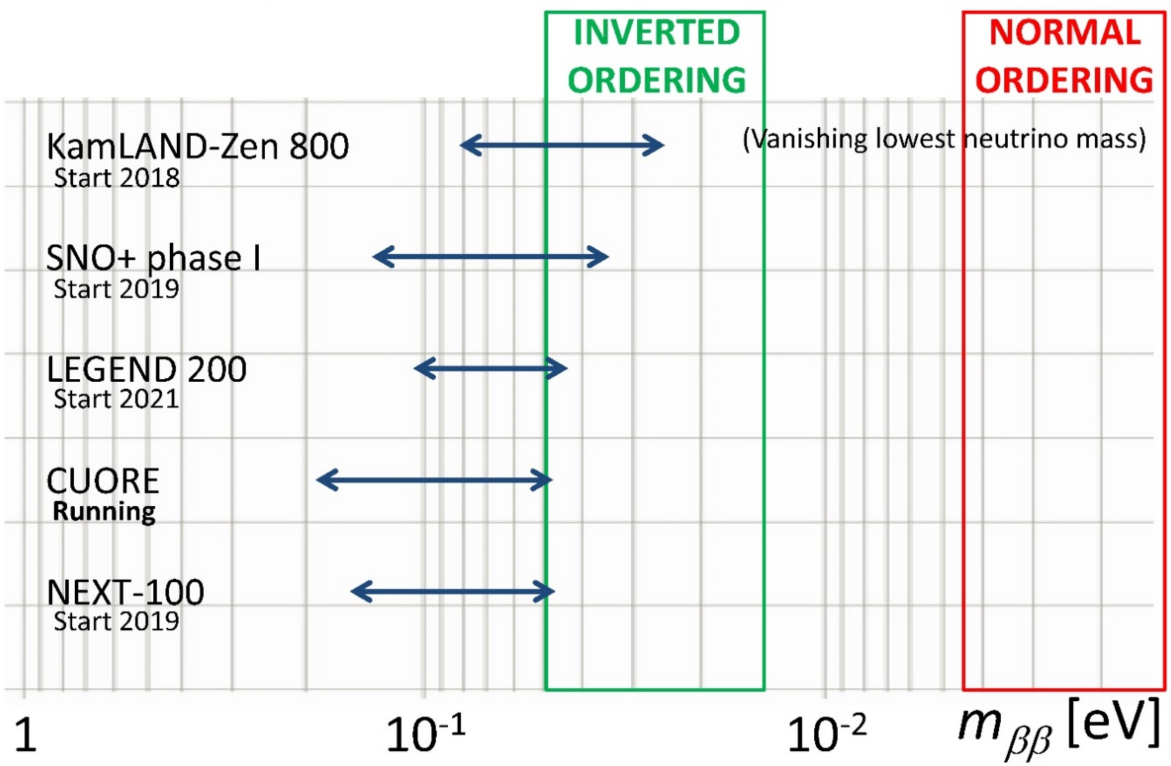
0ββν perspectives



From the summary talk of A. Giuliani at Neutrino 2018

Possible scenario in 2024

Considering running or well advanced projects (for results, funding and infrastructures)



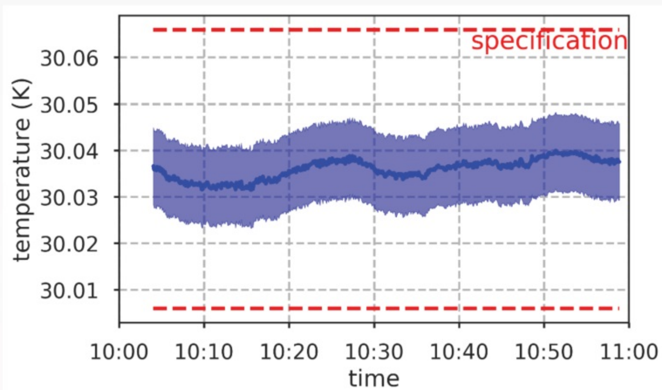
- 90%CL and not 5σ sensitivities
- Computed for the most favorable value of the quenching parameter g_A

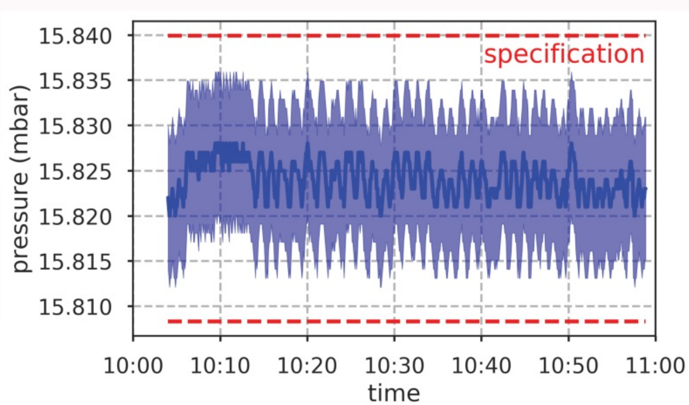
APPEC strongly supports the present range of direct neutrino-mass measurements and searches for neutrinoless double-beta decay. Guided by the results of experiments currently in operation and in consultation with its global partners, APPEC intends to converge on a roadmap for the next generation of experiments into neutrino mass and nature by 2020.

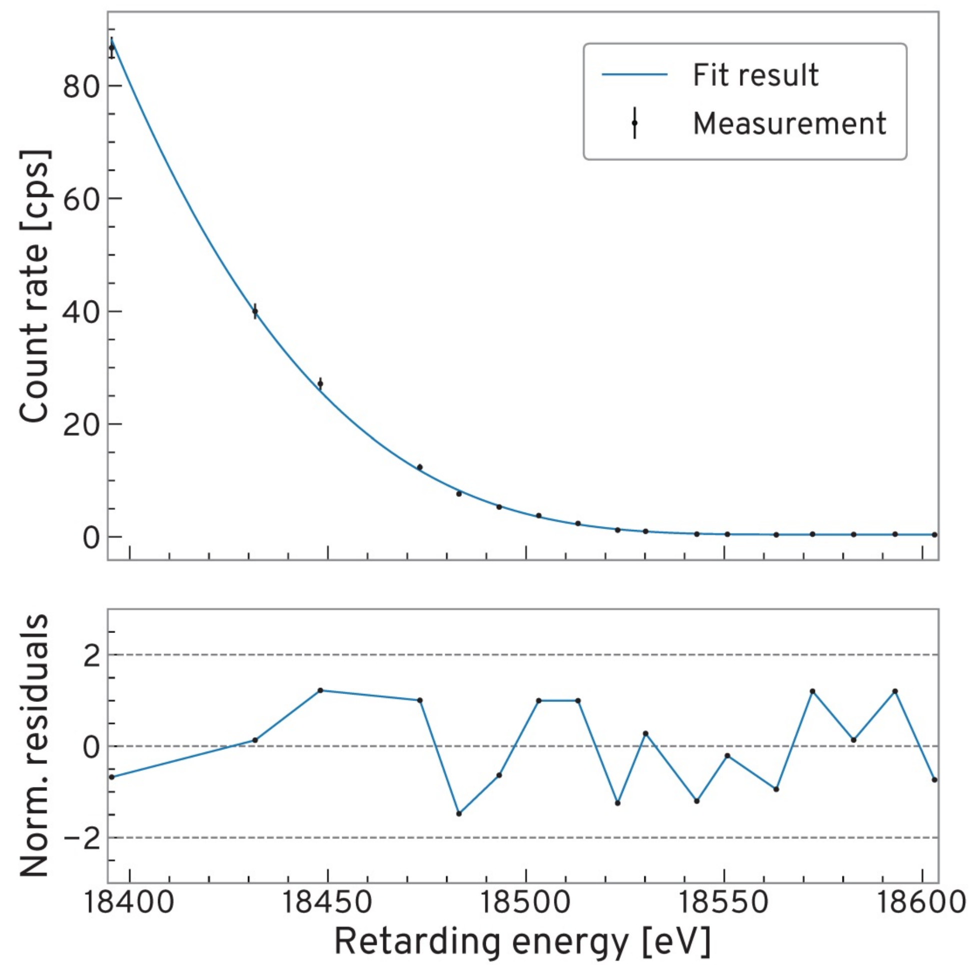
Direct neutrino mass measurement: Katrin

Commissioning started 4 months ago

- 1% of nominal tritium activity
- Tritium loop operation from 5 June - 18 June (no interruption)
- Source parameters are stable and within specifications







Goal of the experiment: 0.25 eV sensitivity on m_β

Conclusions

- Neutrino physics had an enormous progress since the discovery of neutrino oscillations in 1998
- New fundamental measurements are at hand in the next years and in the long term
- This convinced a growing community of physicists and funding agencies to invest in future experiments
- Complementarity and redundancy are necessary to strengthen the foreseen measurements and allow unexpected discoveries.
- As a "byproduct" new experiments will provide powerful BSM searches like proton decays ($\tau_p > 10^{35}$ yr) and neutron-antineutron oscillations.
- In the long term new technologies will be needed, particularly to develop neutrino beams of new concept