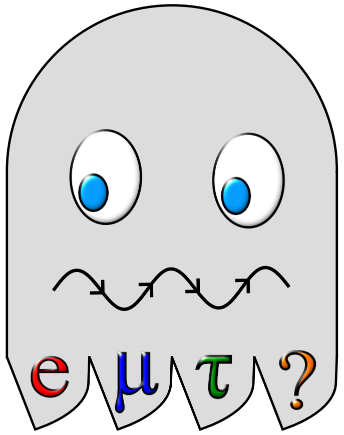
Highlights and prospectives in neutrino physics

Alberto Remoto
remoto@in2p3.fr

Laboratoire d’Annecy-le-vieux de Physique des Particules

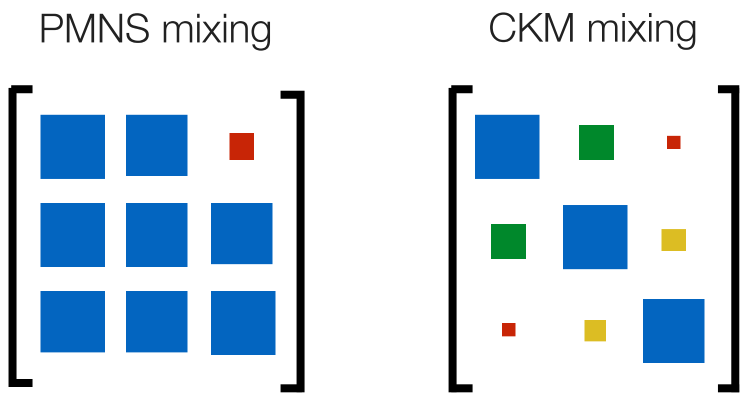


What do we know so far?

Massive neutrino, mixing, oscillations…

Pontecorvo–Maki–Nakagawa–Sakata matrix

3 flavour mixing in analogy to quark sector (CKM)



$c_{ij} = \cos\theta_{ij}$

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

$P(\nu_\mu \to \nu_\mu)$ & $P(\nu_\mu \to \nu_\tau)$ $\quad$ $P(\nu_\mu \to \nu_e)$ & $P(\bar{\nu}_e \to \bar{\nu}_e)$ $\quad$ $P(\nu_e \to \nu_{\mu,\tau})$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{+i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

atmospheric, accelerator $\quad$ **accelerator, reactor** $\quad$ **solar, reactor**

3 Flavour states

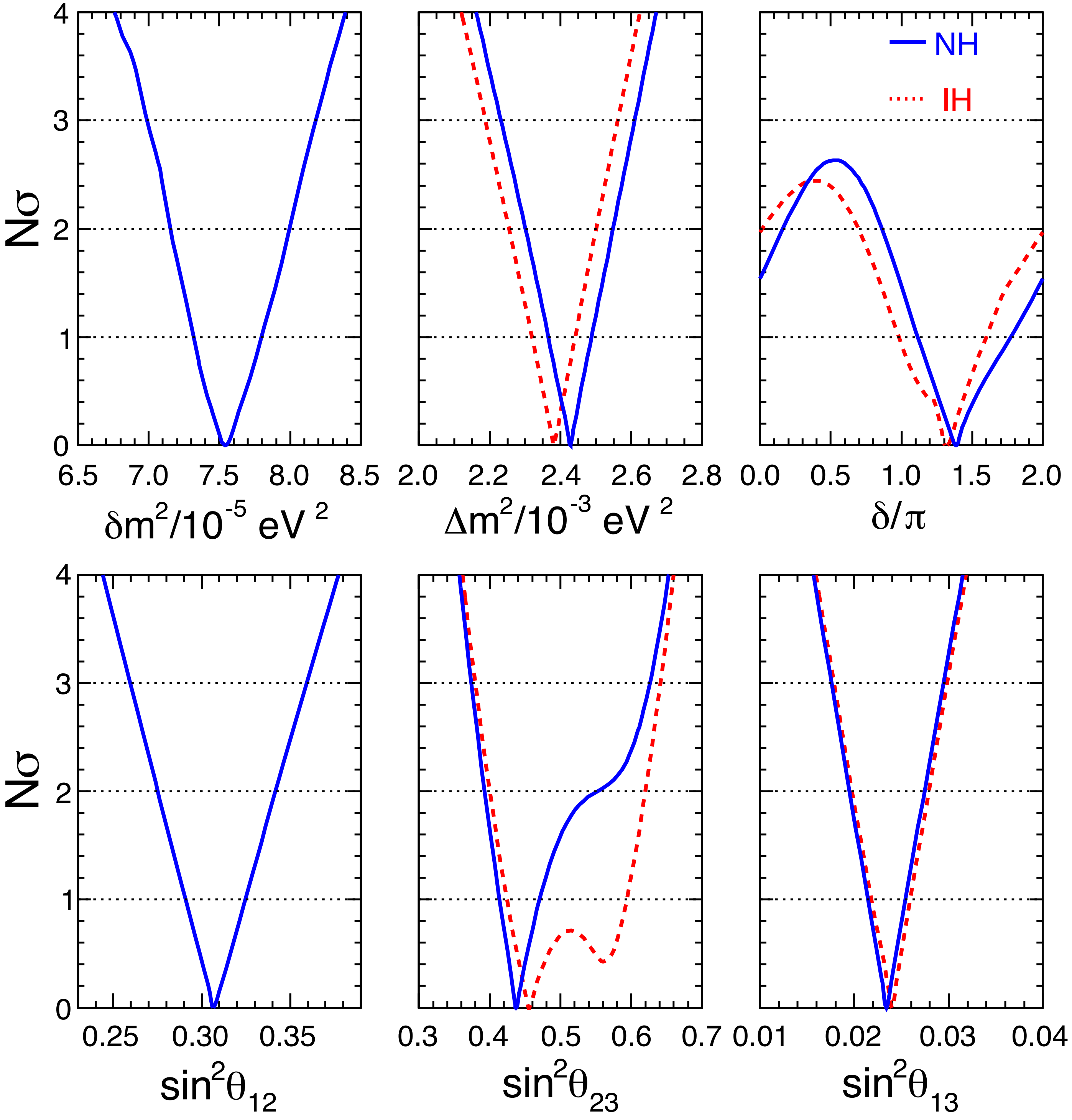
3 mixing angles, 2 squared mass differences, 1 complex phase (δ_{CP}), 2 Majorana phase

3 Mass states
$m_1 \neq m_2 \neq m_3$

15 years of experimental efforts

Oscillation: a comprehensive summary

LBL Acc + Solar + KL + SBL Reactors + SK Atm



- ☑ θ_{12} , θ_{23}, θ_{13}
- ☑ Δm^2_{13}, Δm^2_{23}
- ☐ Sign of Δm^2_{23}
- ☐ θ_{23} octant
- ☐ δ_{CP}

Parameter	Best fit	1σ range
$\delta m^2/10^{-5}$ eV^2 (NH or IH)	7.54	7.32 – 7.80
$\sin^2\theta_{12}/10^{-1}$ (NH or IH)	3.08	2.91 – 3.25
$\Delta m^2/10^{-3}$ eV^2 (NH)	2.43	2.37 – 2.49
$\Delta m^2/10^{-3}$ eV^2 (IH)	2.38	2.32 – 2.44
$\sin^2\theta_{13}/10^{-2}$ (NH)	2.34	2.15 – 2.54
$\sin^2\theta_{13}/10^{-2}$ (IH)	2.40	2.18 – 2.59
$\sin^2\theta_{23}/10^{-1}$ (NH)	4.37	4.14 – 4.70
$\sin^2\theta_{23}/10^{-1}$ (IH)	4.55	4.24 – 5.94
δ/π (NH)	1.39	1.12 – 1.77
δ/π (IH)	1.31	0.98 – 1.60

[PRD 89, 093018 (2014)]

Mass hierarchy?

Mass scale?

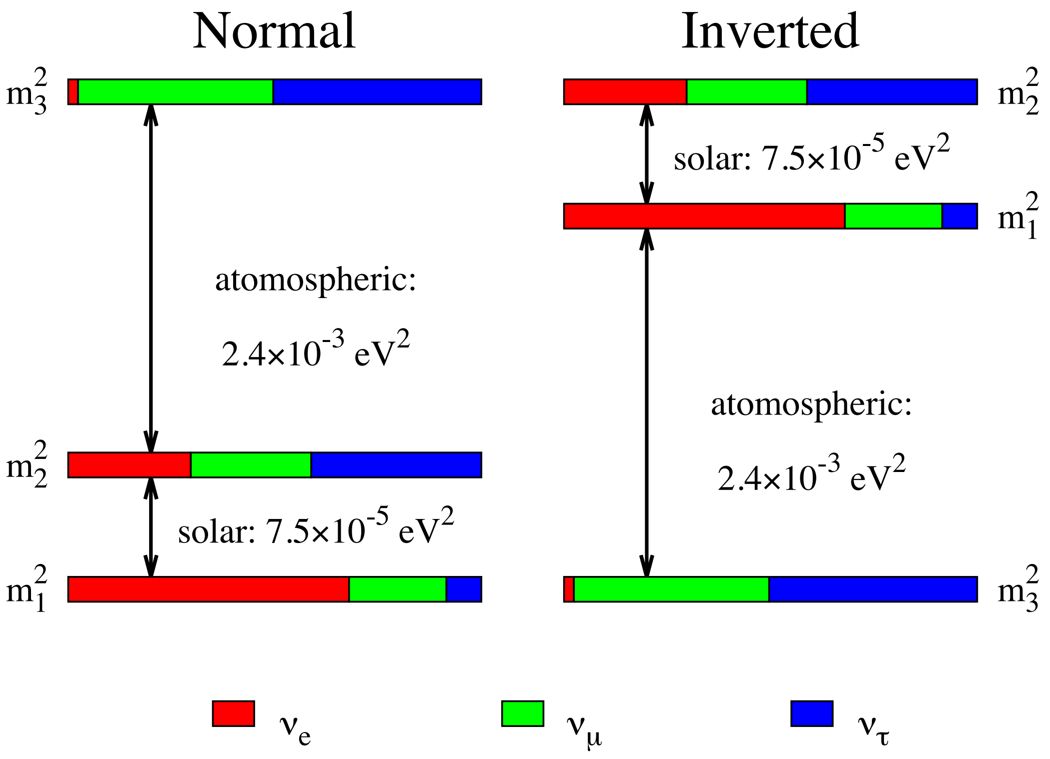
Dirac/Majorana?

CP Violation?

Sterile neutrinos?

Mass hierarchy

- Oscillations provides the **amplitude** of the mass splittings but **not the sign**
- The sign of Δm^2_{21} has been fixed studying solar oscillation
- Two possibility for Δm^2_{31}: **Normal or Inverted**



It **impacts many important processes** in particle physics, astrophysics and cosmology:

1. Crucial factor to determine δ_{CP} : degenerate solution depending from MH
2. Define target sensitivity for neutrino-less double beta decay
3. Neutrino astronomy, Cosmology
4. Critical parameter to understand origin of neutrino masses and flavour mixing

Mass hierarchy via matter effects

- Electron v/anti-v propagation through dense medium gets significantly modified by coherent forward scattering
- **Oscillation probability** gets modified and **becomes sensitive to the MH** (MSW)

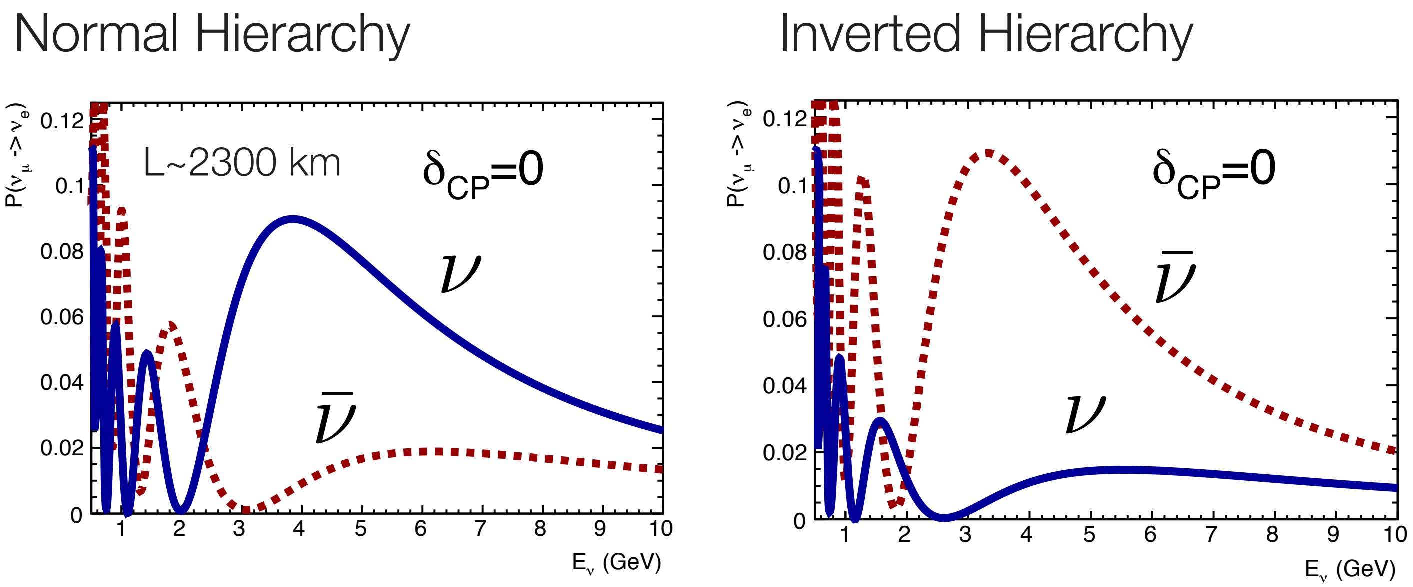
$$A = \pm\frac{2\sqrt{2}G_F N_e E}{\Delta m^2}$$

+ for v

- for anti-v

Enhancing of the oscillation happen under resonant condition for A > 0

	NH **Δm**	**IH** **Δm**
v	✓	✗
$\bar{\text{v}}$	✗	✓


Normal Hierarchy

Inverted Hierarchy

Mass hierarchy via matter effects — the present

T2K [PRL 112, 061802] — 295 km

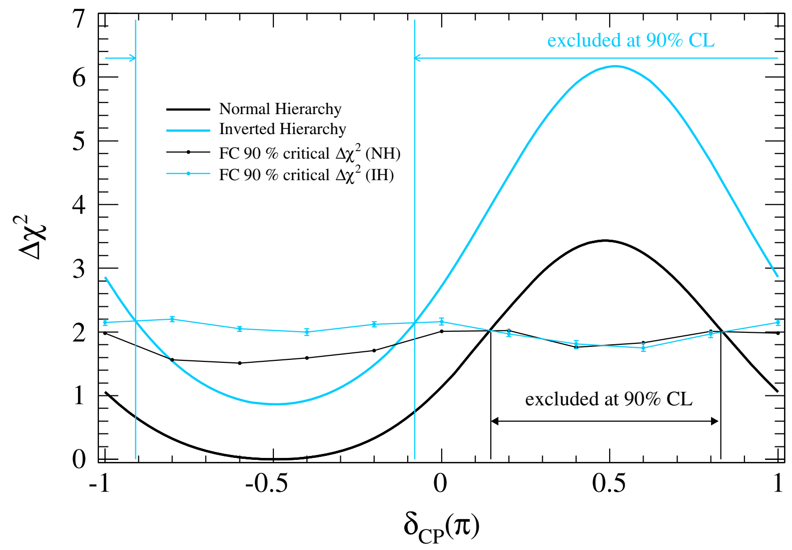
- IH disfavoured @ 2σ for δ_{CP} ~[0.9; 1]
- NH disfavoured @ 2σ for δ_{CP} ~[0.1; 0.8]

NOvA (preliminary) — 830 km

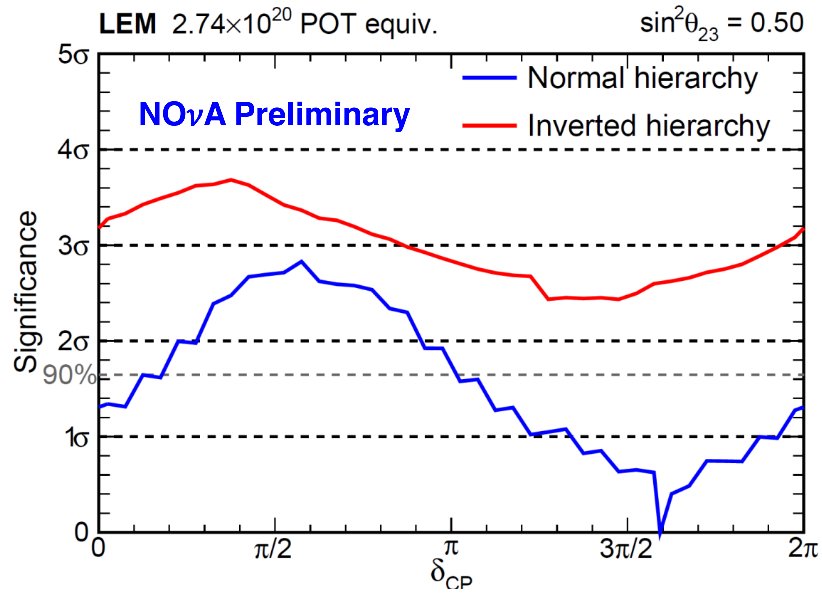
- IH disfavoured @ 2σ for every value of δ_{CP} and $\sin^2\theta_{13}$ in [0.4; 0.6] range

T2K + NOvA potential:

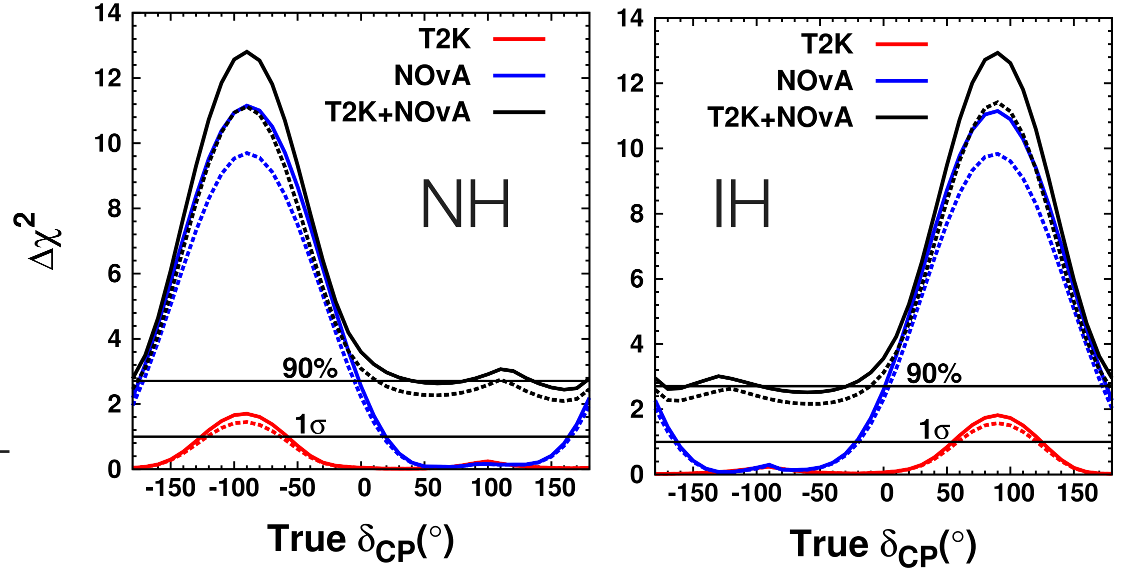
- **3σ sensitivity** combining 6 year NOvA running + T2K pot projection
- ~50 % phase—space unreachable



[PRL 112, 061802]



[NuFact2015]



[arxiv:1409.7469v1]

Mass hierarchy via matter effects — the future

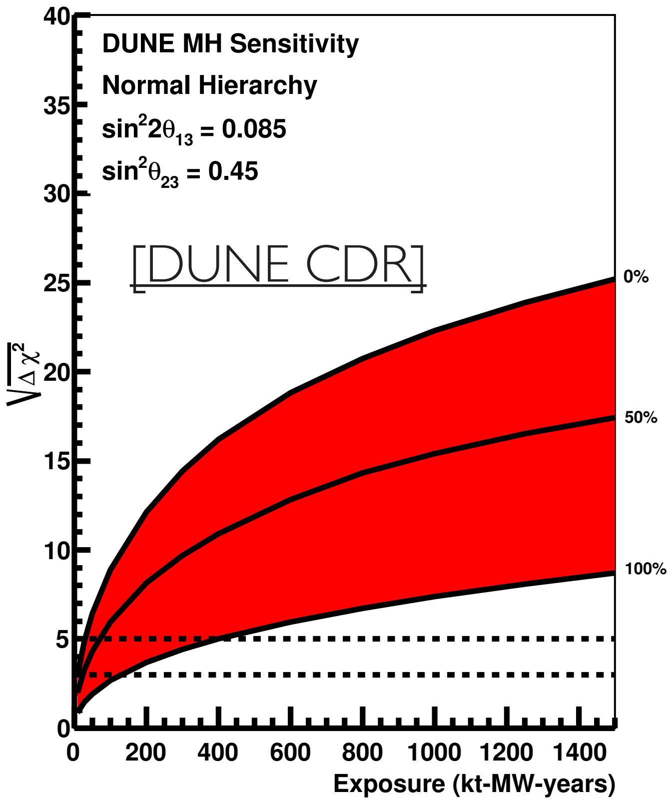
DUNE: 40 kT LAr TPC @ Sanford, 1.2 MW beam from Fermilab (~1300 km) + Atm.

- 5σ MH for all values of δ_{CP} for ~ 400 kt x MW x y (~ 4.5 y ν_μ + 4.5 y anti-ν_μ)

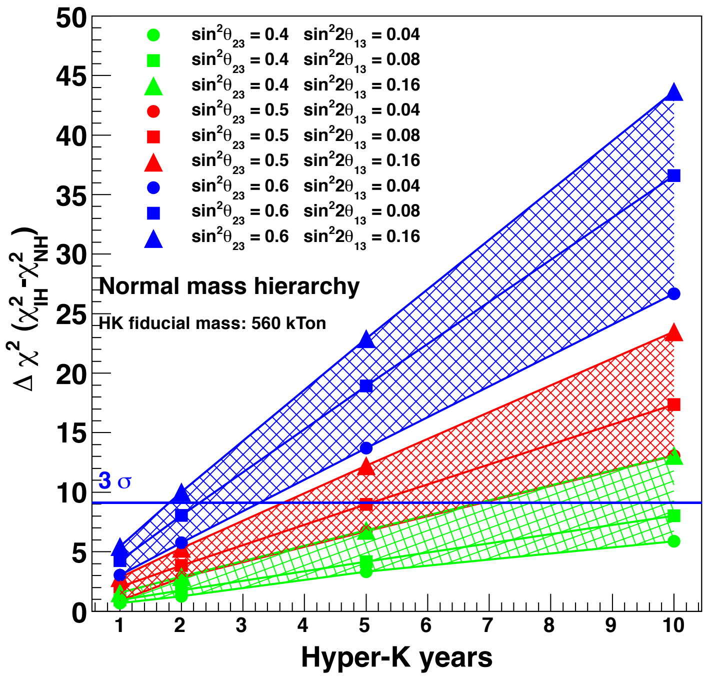
Hyper K: 1 MT W. Cherenkov @ Kamioka, Atm. + 1.66 MW beam from JPARC (~300 km)

- 3σ MH for $\sin^2\theta_{13} > 0.42$ (0.43) for NH (IH) in 10 years.

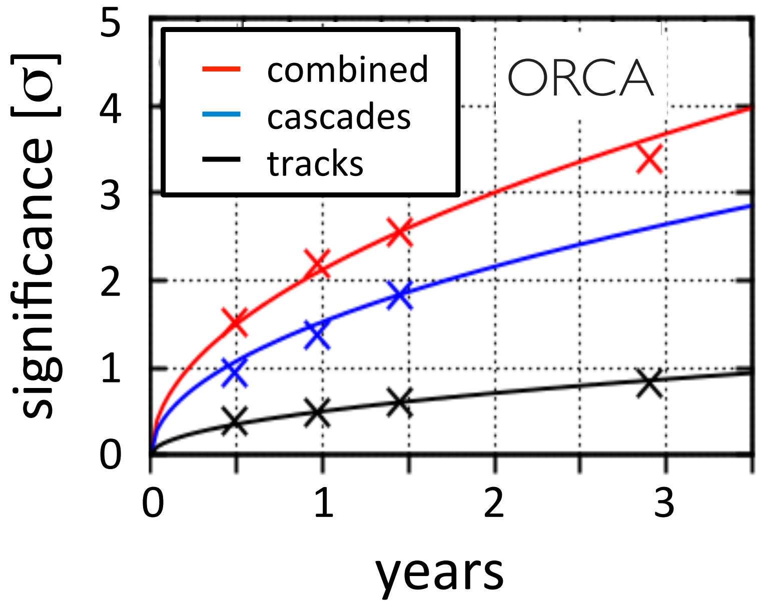
PINGU, ORCA: ν—observatory in Antarctica & Mediterranean sea, high energy atm.



[DUNE CDR]



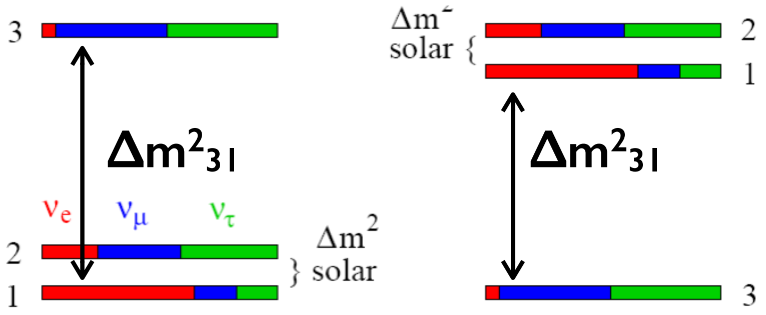
[arxiv:1109.3262v1]



[Neutrino 2014]

Mass hierarchy via oscillation interference

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}\left(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}\right)$$

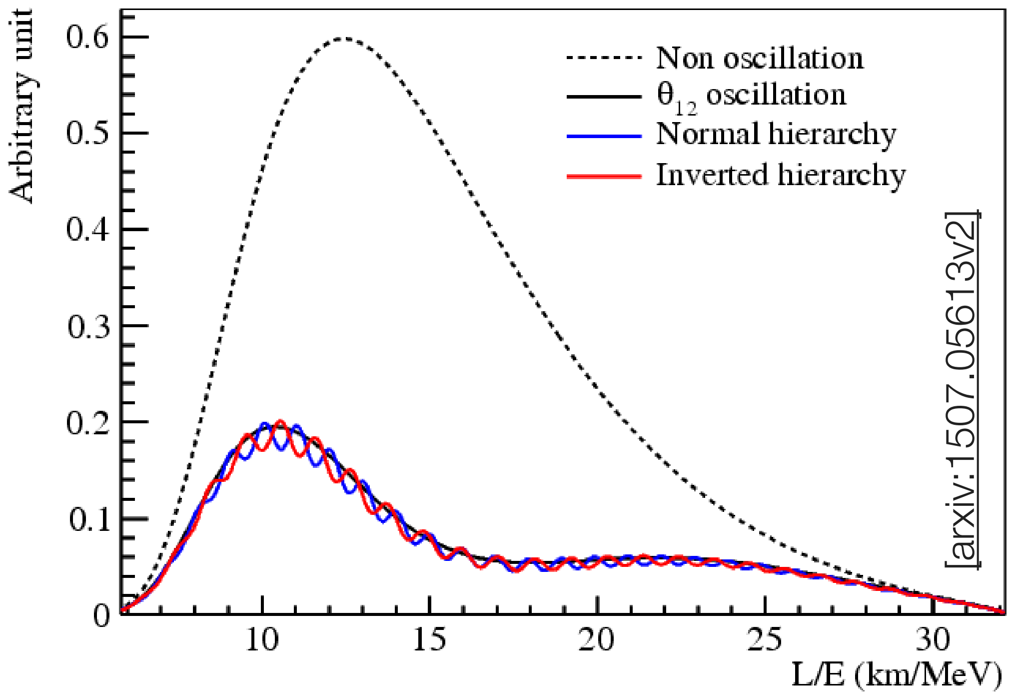


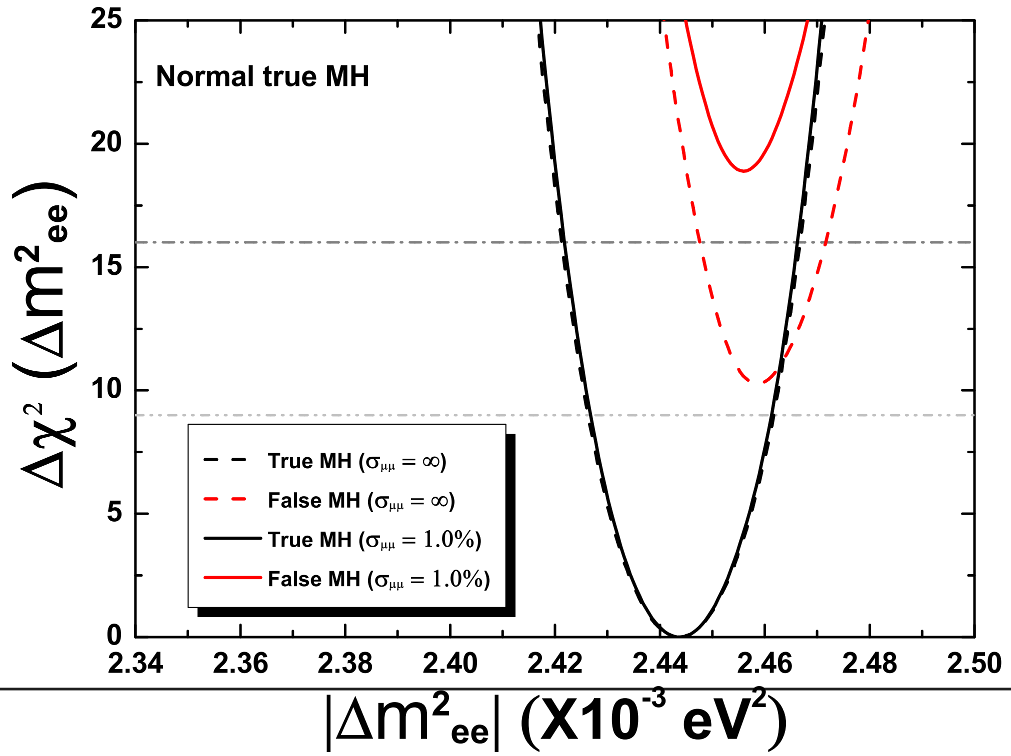
$$\Delta_{ij} = \Delta m^2_{ij}\frac{L}{4E}$$

There is a 3% difference in Δm^2_{31} depending from the MH

Spectral distortion on medium (~50 km) baseline reactor neutrino experiment contain information on the MH: distinctive features in the frequency (Δm^2) domain

JUNO — 20 kt Liquid Scintillator with 50 km baseline, require 3% energy resolution





Dirac vs Majorana

Mass limits inferred by direct measurement (^{3}H β-decay — **$m_\nu \lesssim 1$ eV**)
and Indirect observation (Plank 2015 — **$\Sigma m \lesssim 0.2$ eV**)

- The Higgs coupling is **unnatural**
- **See-saw** as possible explanation but **requires Majorana** neutrinos

$$m_D = \frac{v}{\sqrt{2}} Y_\nu \longleftarrow Y_\nu \simeq 10^{-12}$$

$$(Y_e \sim 0.3 \times 10^{-5})$$

$$m = \frac{m_D^2}{m_R}$$

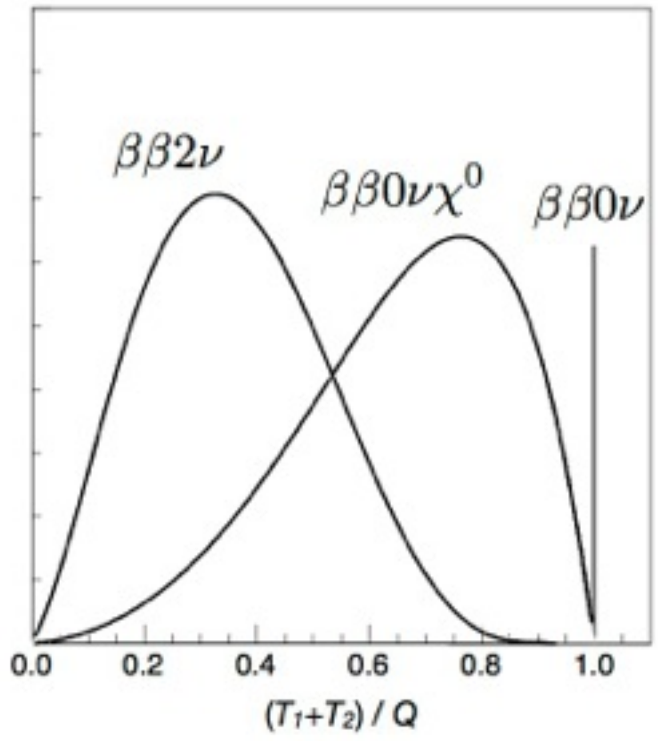
← Higgs-coupled

← Arbitrary big

The only practical way to test Majorana/Dirac nature:

- 2vββ decay: $(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e$
- 0vββ decay: $(A, Z) \rightarrow (A, Z+2) + 2e^-$

$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)|M_{0\nu}|^2\eta^2$$



Neutrino-less double beta decay

$$\langle m_{\beta\beta} \rangle = \left| \sum_i U_{ei}^2 m_i \right|$$

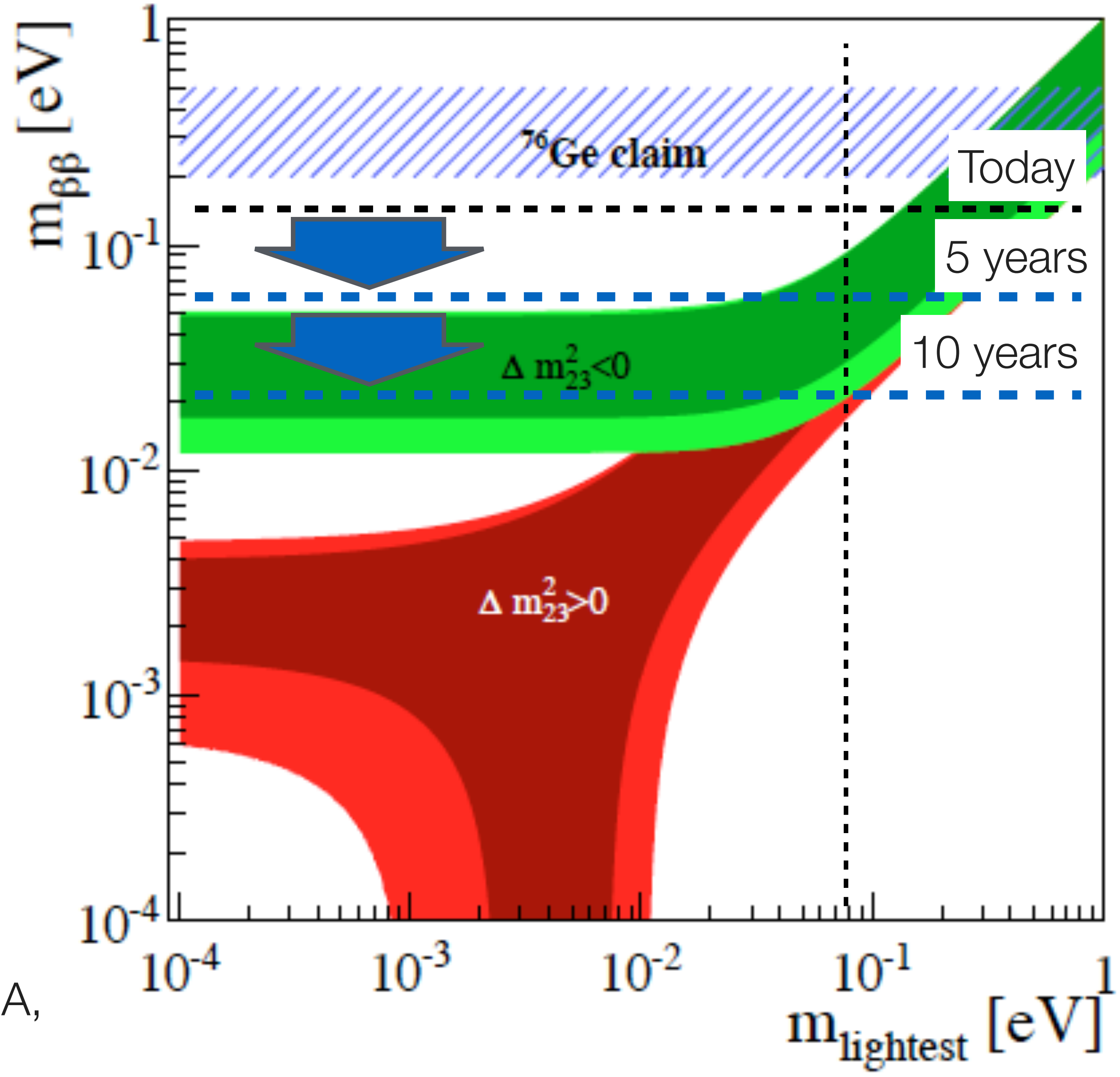
Related to oscillation parameters and **mass hierarchy**

5 years time scale:

- M ~ 10 - 50 kg of ββ isotope
- Background level 10^{-3} cts. /(keV kg y)
- Explore quasi-degenerate region

10 years time scale:

- M ~ 100 kg - 1t of ββ isotope
- Background level 10^{-4} cts. /(keV kg y)
- Approach Inverse Hierarchy region

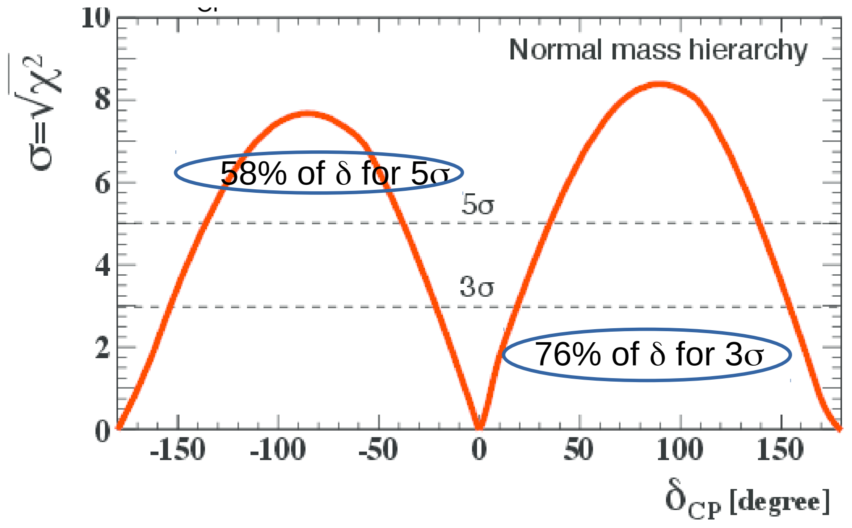


CUORE, Gerda, Majorana, Lucifer, AMORE, NEXT, COBRA, EXO, SNO+, KamLAND-Zen, CANDLES, SuperNEMO, ...

CP violation in the lepton sector

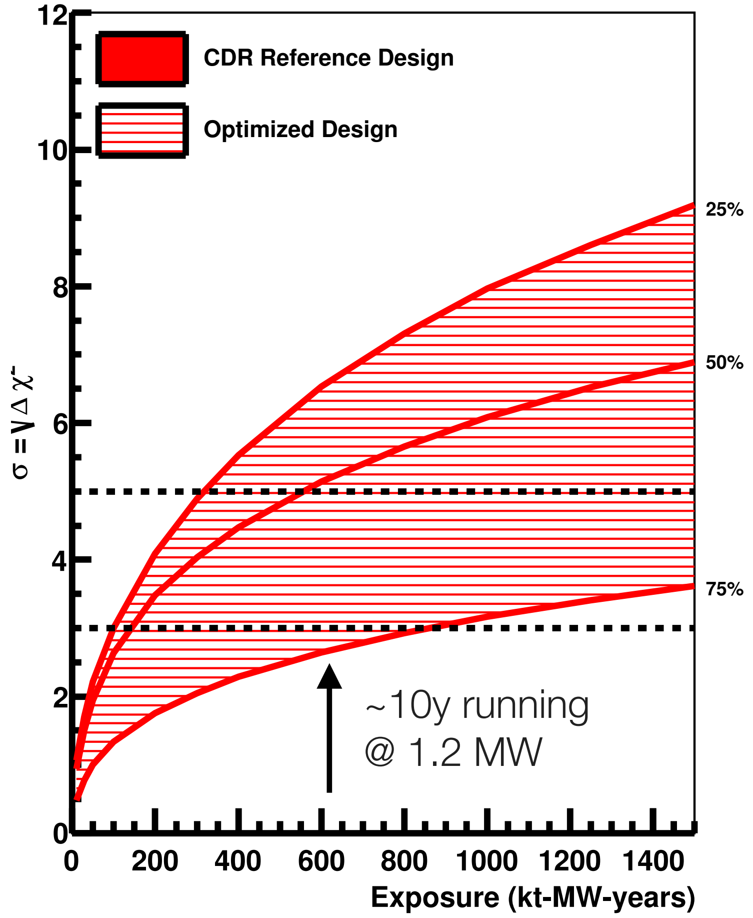
- Big-bang: symmetry between matter and antimatter
- Matter is dominant in the universe right now → asymmetry
- **CP violation in baryon sector** is not enough
- **CP violation in the lepton sector + leptogenesis** → might explain current asymmetry
- DUNE/HyperK experiments aim to measure δ_{CP} with long baseline
  - Cover > 50% δ_{CP} values @ 5σ in ~10 y
  - Cover > 75% δ_{CP} values @ 3σ in ~10 y

H-K ~10 y running at 750 kW



58% of δ for 5σ

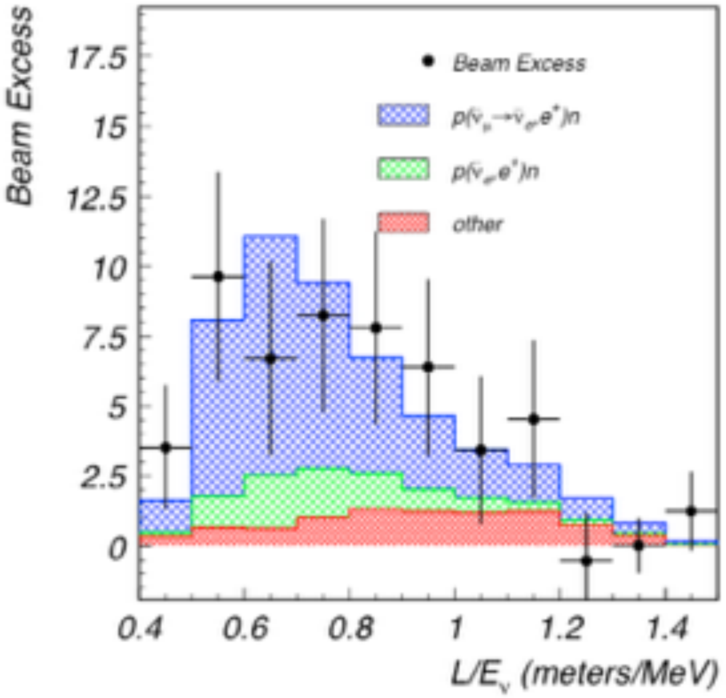
76% of δ for 3σ

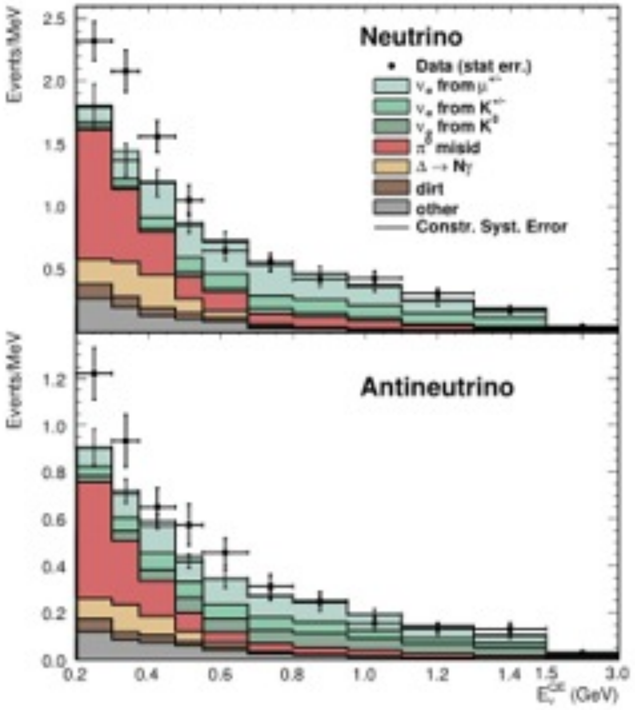


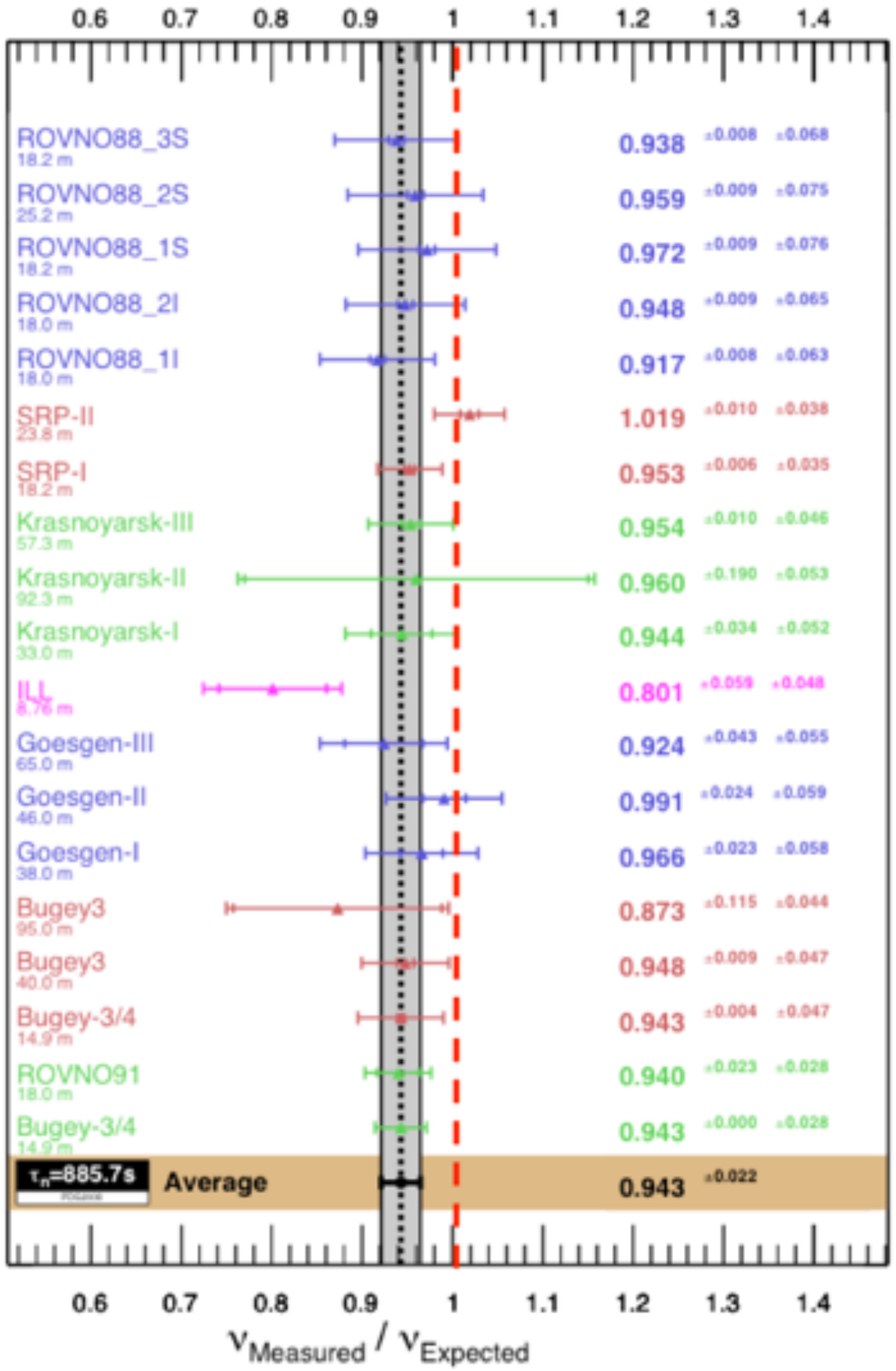
~10y running @ 1.2 MW

Sterile neutrino

- Reactor anti-ν_e disappearance at very-short baseline
- LSND & MiniBooNE: ν_e appearance at high Δm^2 (not covered in this talk) — SBN program @ FNAL
- **Additional neutrinos** may explain the anomalies
- LEP data constrain number of active neutrino: the additional neutrinos **must be sterile**





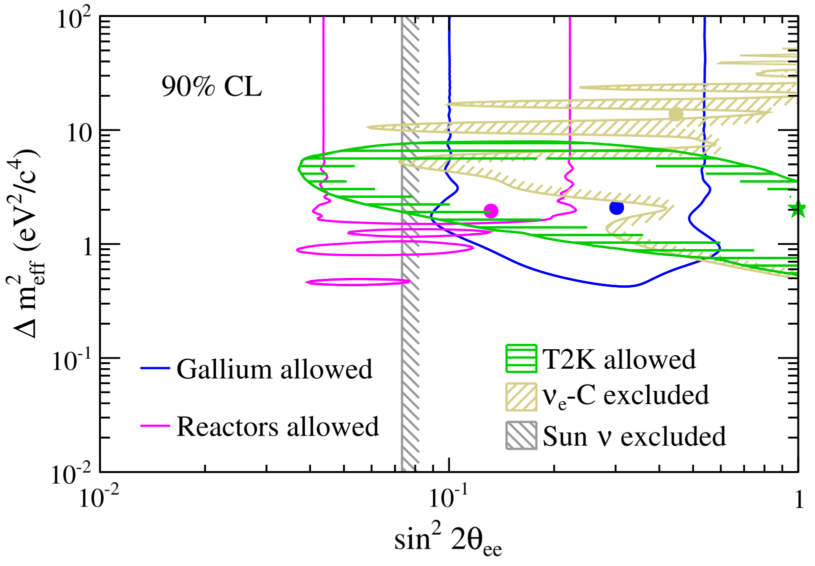


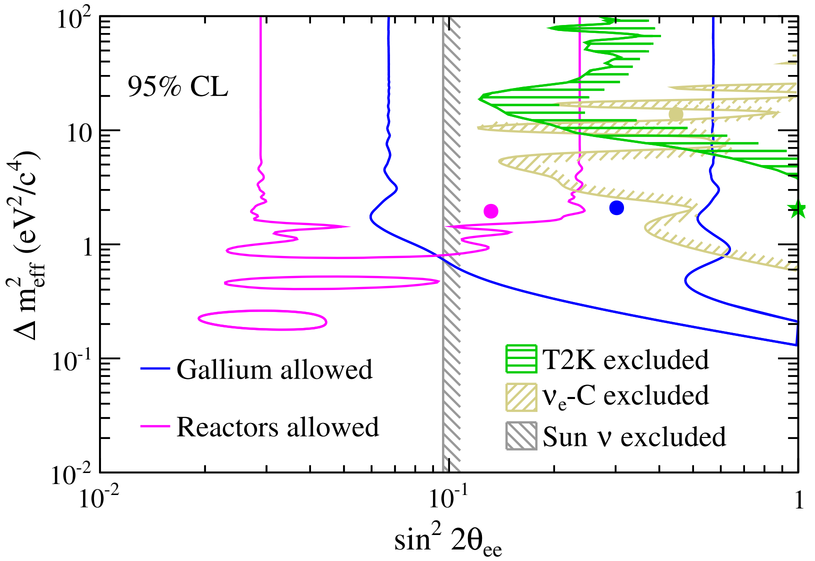
Sterile neutrino — what's going on? (ν_e disappearance)

@ accelerator

Search for ν_e disappearance at very-short baseline with ND280 @ T2K

Analysis still statistical dominated.





[Phys. Rev. D 91, 051102(R)]

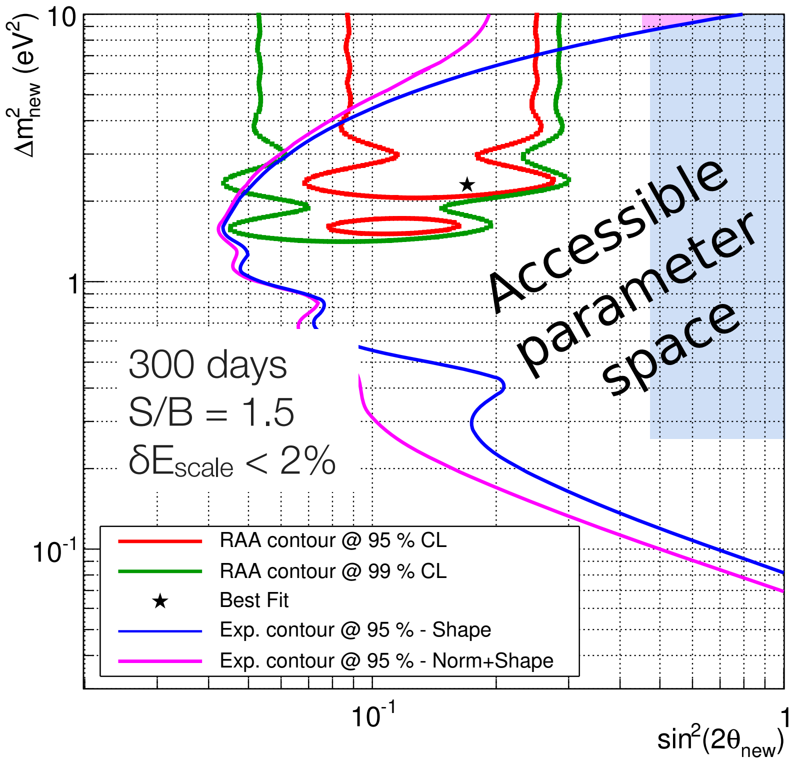
@ very short baseline rector neutrino experiment

STEREO,

Segmented Gd-doped LS

Good energy resolution, low S/B ratio

Data expected from summer 2016



300 days
S/B = 1.5
$\delta E_{scale} < 2\%$

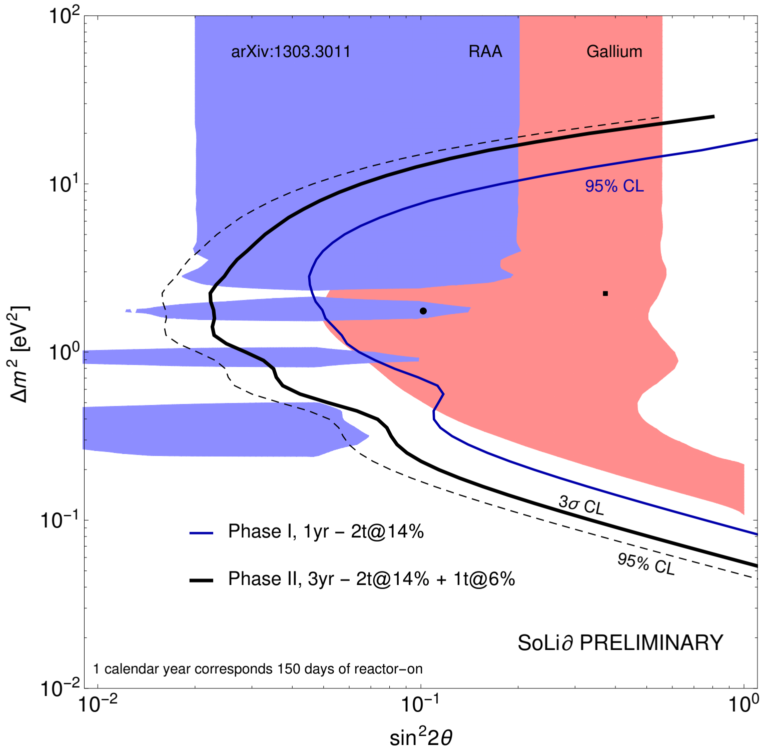
Accessible parameter space

SoLid,

Highly segmented plastic scintillator + ^{6}LiF:ZnS(Ag)

Low energy resolution, good S/B ratio, high n/γ discrimination

Deployment of a 2t detector from summer 2016



Projection of sensitivity dominated by background assumption

Conclusions

Mass Hierarchy is at hand:

- If we're lucky (i.e. NH and $\delta_{CP} = \pi/2$) NOvA + T2K will provide an answer at 3σ in the next ~5 years
- If we're unlucky we have to wait ~10 years for a 3-4σ from JUNO, DUNE, HyperK. 15-20 year for a definitive 5σ.

MH will help boost (or discourage) future generation $0\nu\beta\beta$ experiments:

- IH region in the next 10 years
- NH no sensitivity (for the moment)

δ_{CP} will follow after MH measurement:

- Long term effort with DUNE & HyperK, 20-30 year time scale

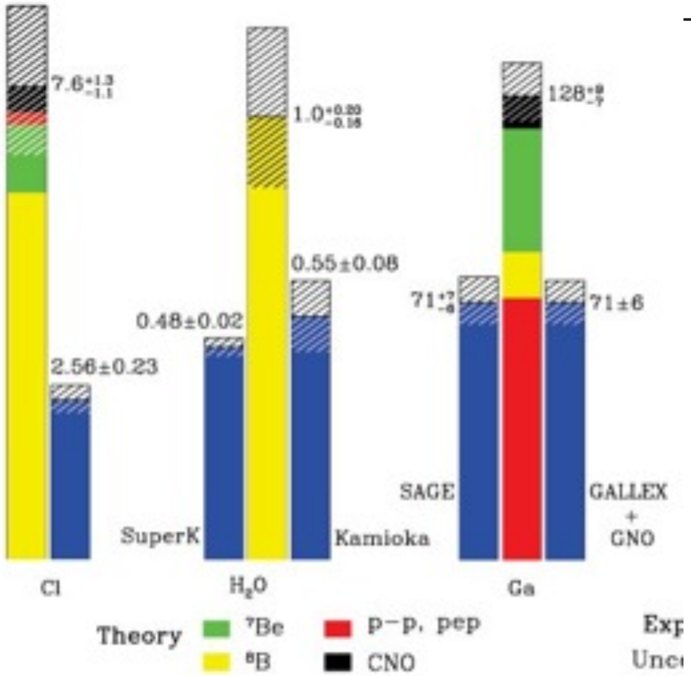
Search for sterile neutrinos will clarify current (anti-)neutrino anomalies

- Next 2-3 years with STEREO, SoLid, T2K and SBN program @ FNAL

Backup

Solar/Atmospheric anomalies

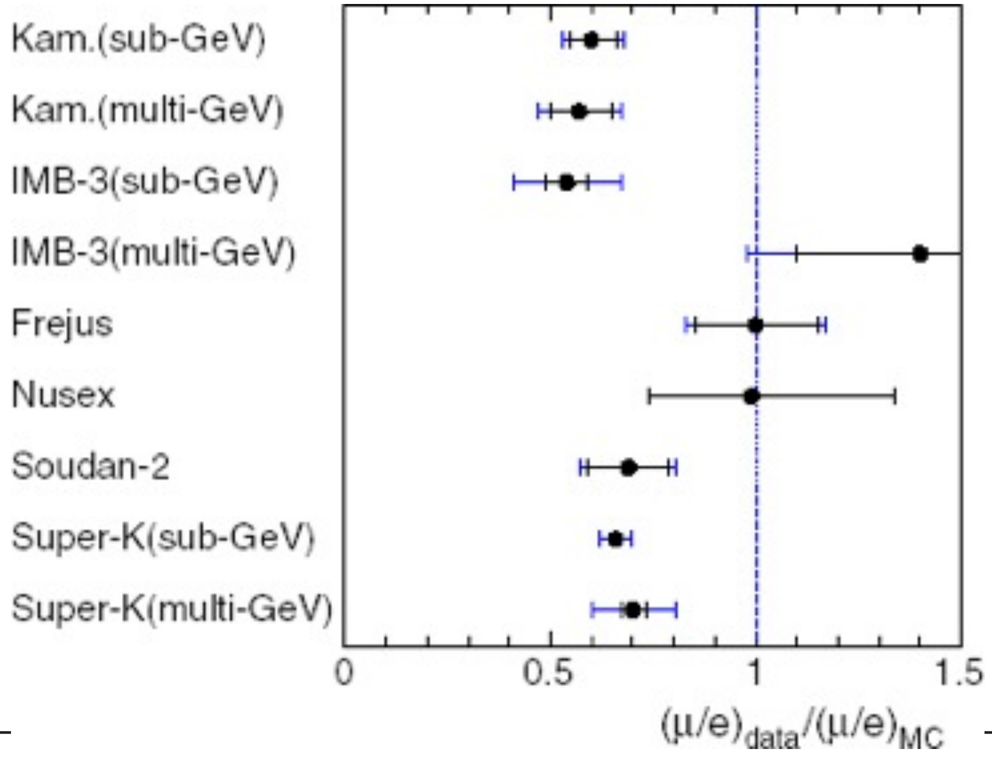
- The Sun is a fusion reactor which emits **ν_e in great quantity**
- 1968 - R. Davies first detection of solar neutrinos ($\nu_e + {}^{38}Cl \to {}^{37}Ar + e^-$)
- **2/3 of expected ν_e are missing**



- The ratio of muon and electron neutrino produced in atmosphere ~ 2

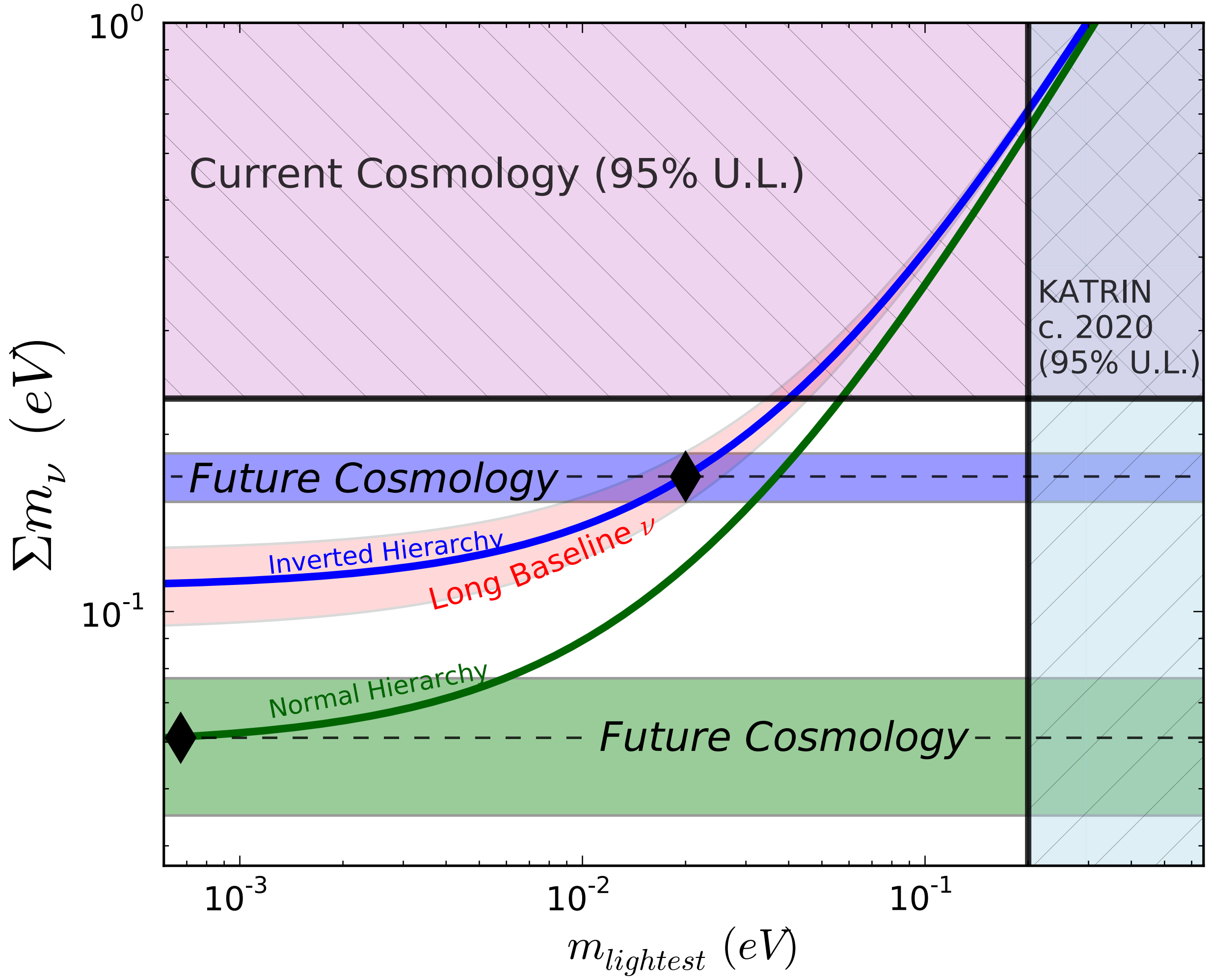
$$\begin{array}{l} \pi^+ \to \mu^+ + \nu_\mu \\ \qquad\ \ \downarrow \\ \qquad\ \ e^+ + \nu_e + \bar{\nu}_\mu \end{array}$$

- The ratio is observed to be ~1
- **1/2 of expected ν_μ are missing**



Additional handle — future cosmology

- Cosmological observations related to mass hierarchy and the mass scale
- Future cosmological probes could unambiguously measure neutrino mass



[arXiv:1309.5383]