Neutrinos

Oscillations, CP violation, mass hierarchy (ordering)

Prospectives scientifiques du DPhP - Ferme du Manet, October 16th 2017

- Introduction & motivations
- Measurements of oscillation parameters (including **T2K**)
- **T2K phase 2**, **Cross-section systematics**
- **Future long baseline oscillation experiments (DUNE, HyperK)**
    - main goals : CP violation, mass ordering, PMNS precision measurements, ν astrophysics
- **WA105, double phase Liquid Argon TPC**
- Future measurements : mass ordering & other oscillation parameters
- Time schedule
- Other physics studies

Sara Bolognesi, Sandrine Emery-Schrenk, Edoardo Mazzucato, Georges Vasseur, **Marco Zito**
Philippe Cotte, Mathieu Lamoureux (PhD students), [Francesco Gizzarelli]
New comers: Stephen Dolan, Serguei Suvorov
Paul Colas (upgrade ND280)

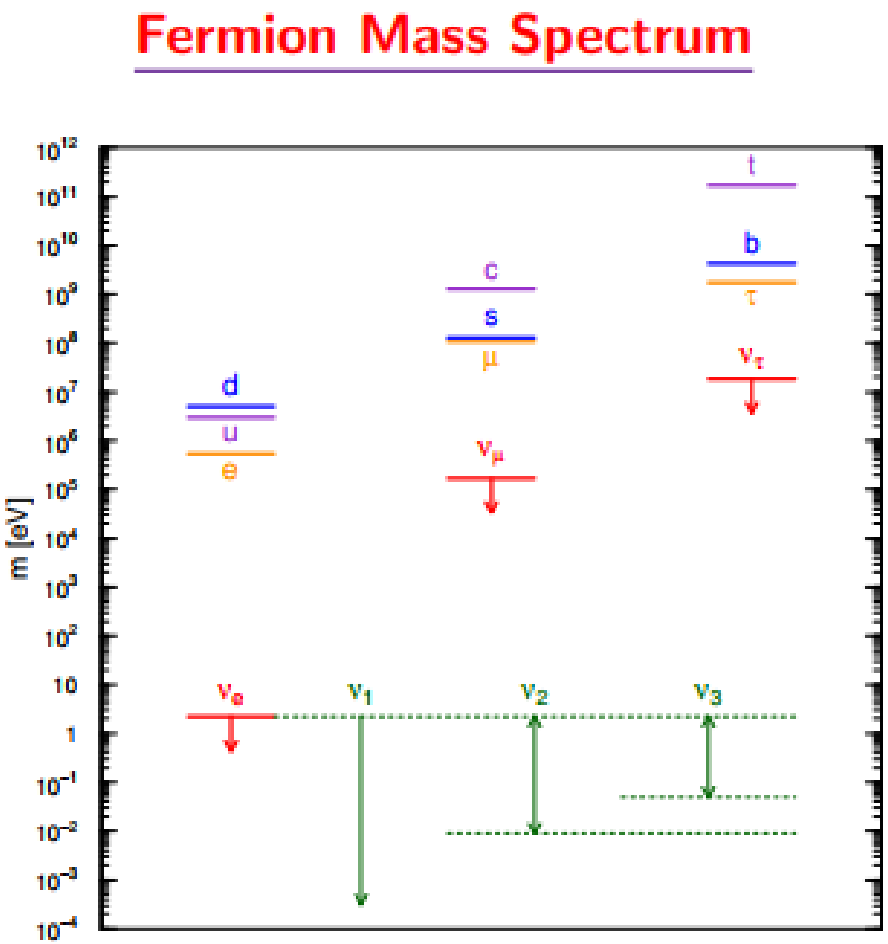
Neutrino oscillations as a window for physics beyond the standard model

- In the standard 3 neutrinos model, neutrino oscillations depend on :
  - PMNS parameters (three mixing angles and a CP violation phase δ)
  - 2 Δm^2 – squared ν masses differences –
    - one sign is unknown (mass ordering)

- Neutrinos have mass → Standard Model is incomplete
  - Neutrino mass < 1eV → a new mass scale (might be related to physics at very high mass scale ~M_GUT)

- Values of PMNS matrix elements very different from CKM
  - unknown flavor symmetry ?

- Study of CP violation in the leptonic sector
  - clue for matter-anti-matter asymetry?
  - Main Goal for coming experiments: observe and measure CP violation


Fermion Mass Spectrum

3-Neutrino Model: PMNS Matrix

$$|\nu_i\rangle = \sum_\alpha U_{\alpha i}|\nu_\alpha\rangle \Rightarrow U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

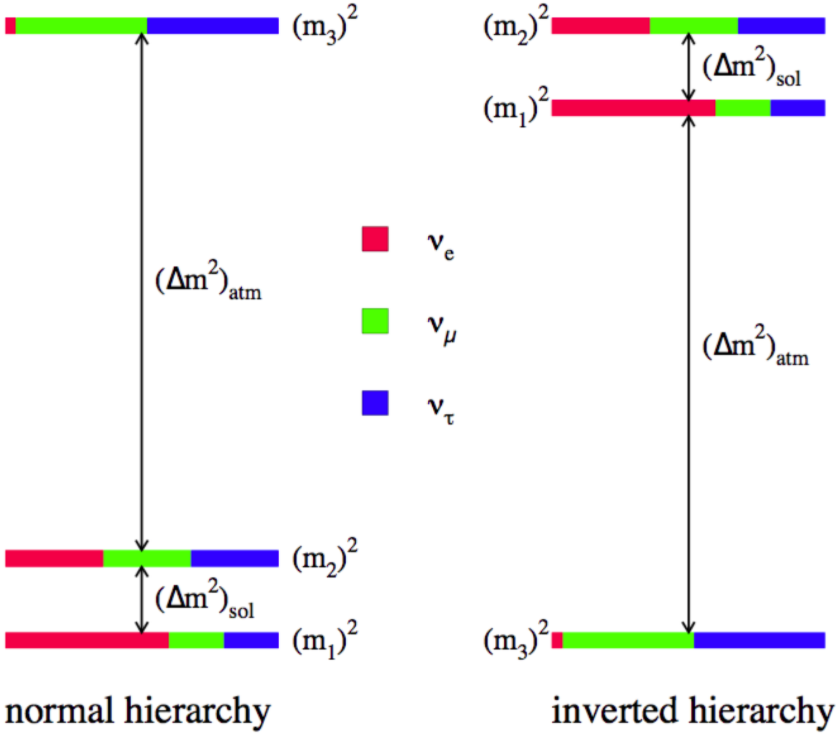
- **$\theta_{23} \approx 45°$**
- Atmospheric, Accelerator
- Octant unknown

(θ_{23} <45° or θ_{23} >45°)

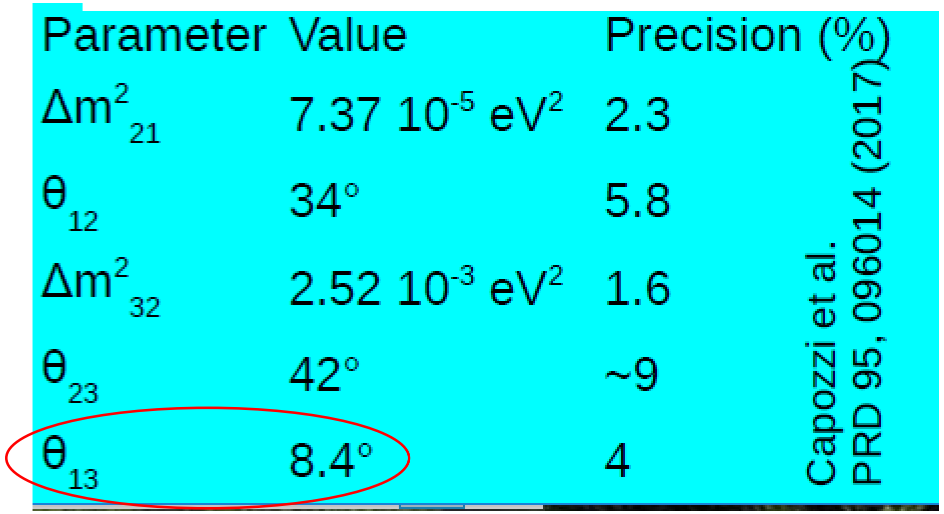
- $\theta_{13} \approx 10°$
- Short-Baseline Reactor, Accelerator
- **δ_{CP} UNKNOWN**

- **$\theta_{12} \approx 35°$**
- Solar, Long-Baseline Reactor

Mass ordering



$(\Delta m^2)_{atm/23}$ sign unknown



Parameter	Value	Precision (%)
Δm^2_{21}	$7.37\ 10^{-5}\ \mathrm{eV}^2$	2.3
θ_{12}	34°	5.8
Δm^2_{32}	$2.52\ 10^{-3}\ \mathrm{eV}^2$	1.6
θ_{23}	42°	~9
θ_{13}	8.4°	4

Capozzi et al.
PRD 95, 096014 (2017)

Relatively large

KNOWN

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

UNKNOWN : δ_{CP} , $(\Delta m^2)_{23/13}$ sign, θ_{23} octant

- Subleading effects : need high precision measurements
- Degeneracy in oscillation probability

ν_e Appearance

$$a = G_F N_e / \sqrt{2}$$

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

$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23} \sin^2 2\theta_{13} \frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2} \Delta_{31}^2 + \sin 2\theta_{23} \sin 2\theta_{13} \sin 2\theta_{12} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \Delta_{31} \frac{\sin(aL)}{(aL)} \Delta_{21} \cos(\Delta_{31} + \delta_{CP}) + \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(aL)}{(aL)^2} \Delta_{21}^2,$$

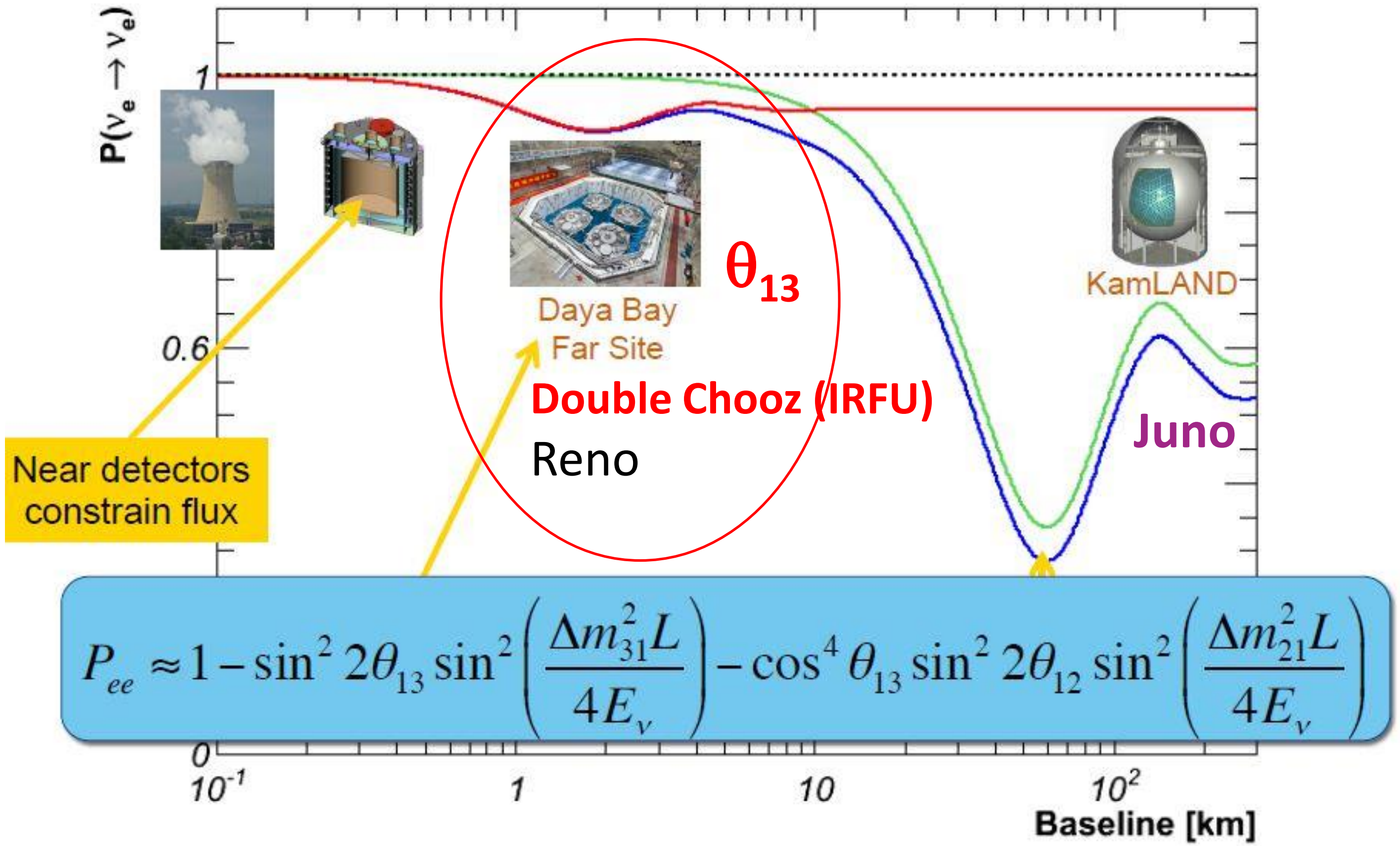
ν_e appearance amplitude depends on θ_{13}, θ_{23}, δ_{CP}, and matter effects.
Some signs change when we use anti-neutrinos

$\overline{\nu_e}$ disappearance

Reactor Antineutrinos

Measurement of θ_{13}:
systematics becomes important

- **Double Chooz** (data taking ending soon)
- **Reno** may still run for ~3 years
- **Daya Bay** will still take data ; precise energy spectrum measurement for JUNO



Near detectors constrain flux

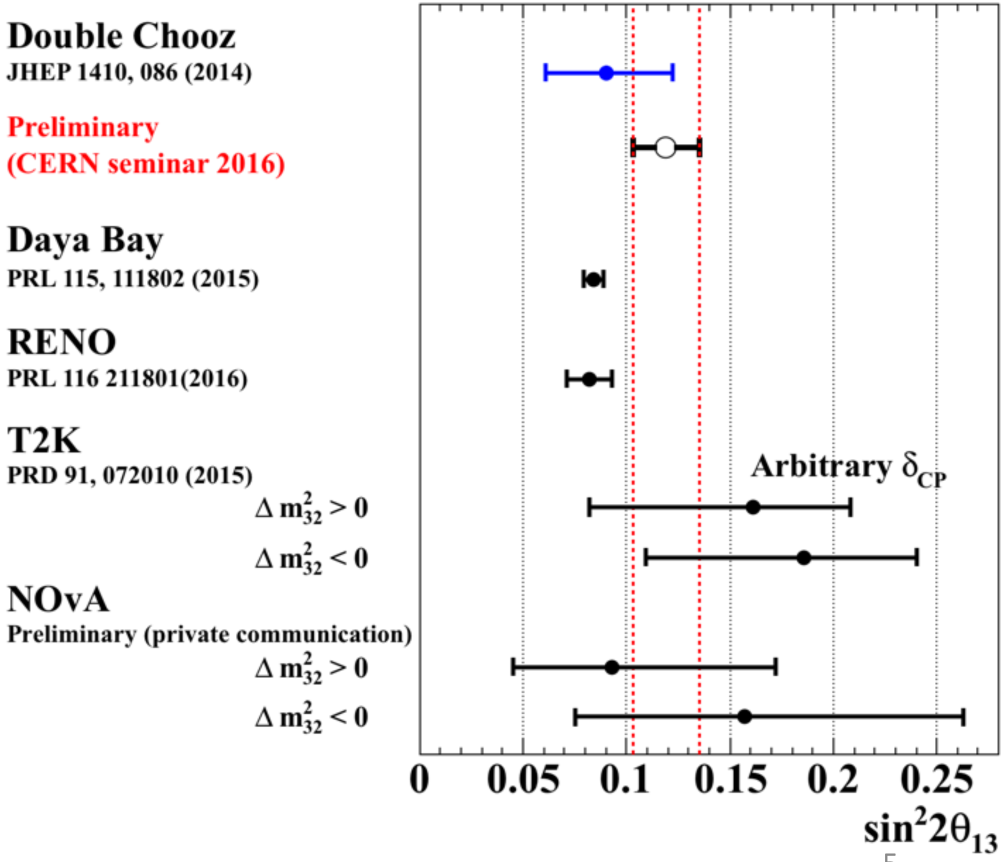
θ_{13}

Double Chooz (IRFU)

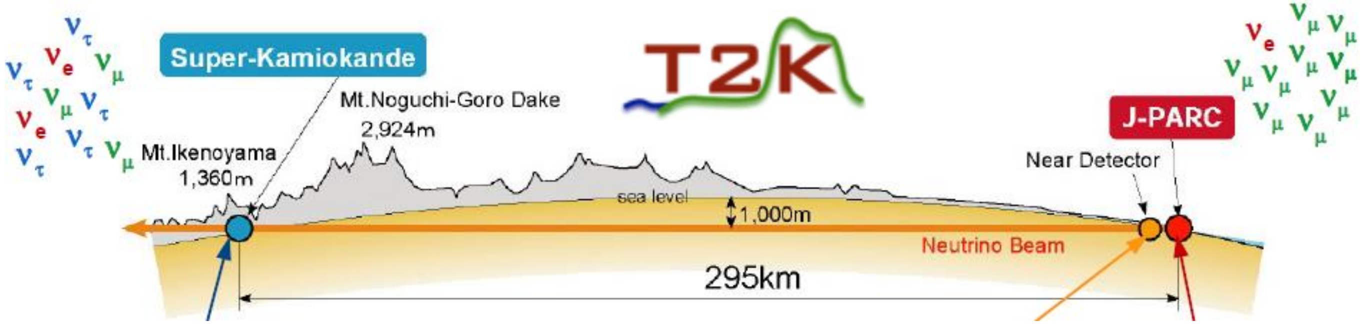
Reno

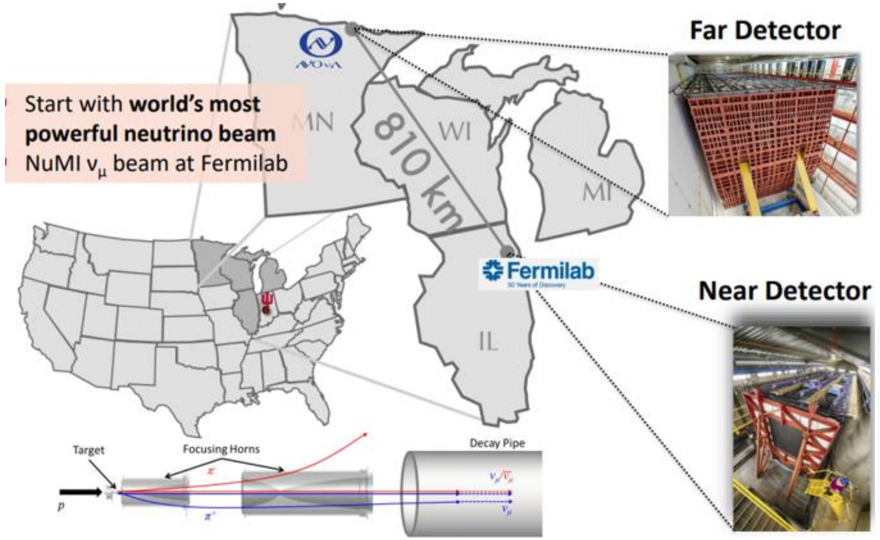
Juno

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E_\nu}\right)$$



T2K = **T**okai-to-**K**amioka long baseline neutrino oscillations experiment



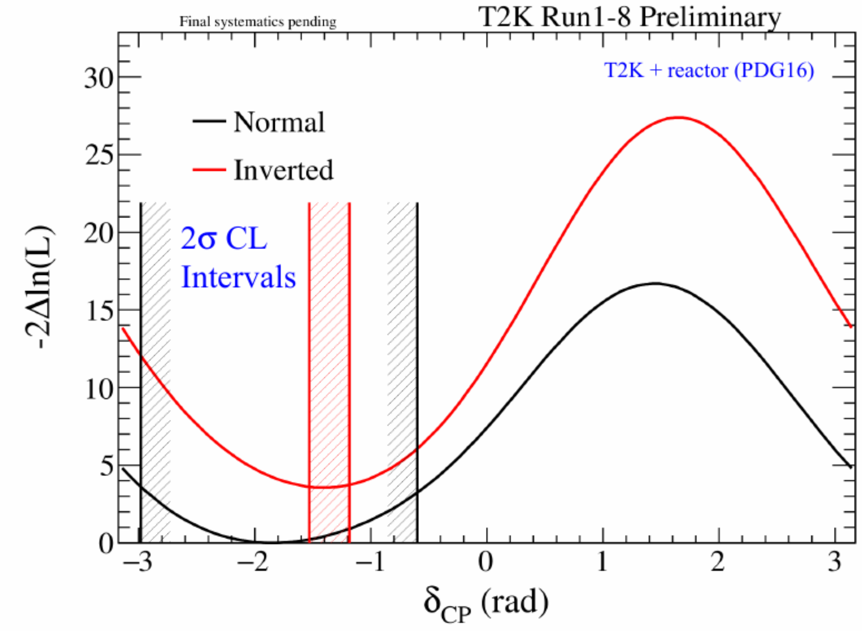

Start with world's most powerful neutrino beam
NuMI ν_μ beam at Fermilab

No CP violation excluded at 2σ

Includes constraint on θ_{13} from reactors!

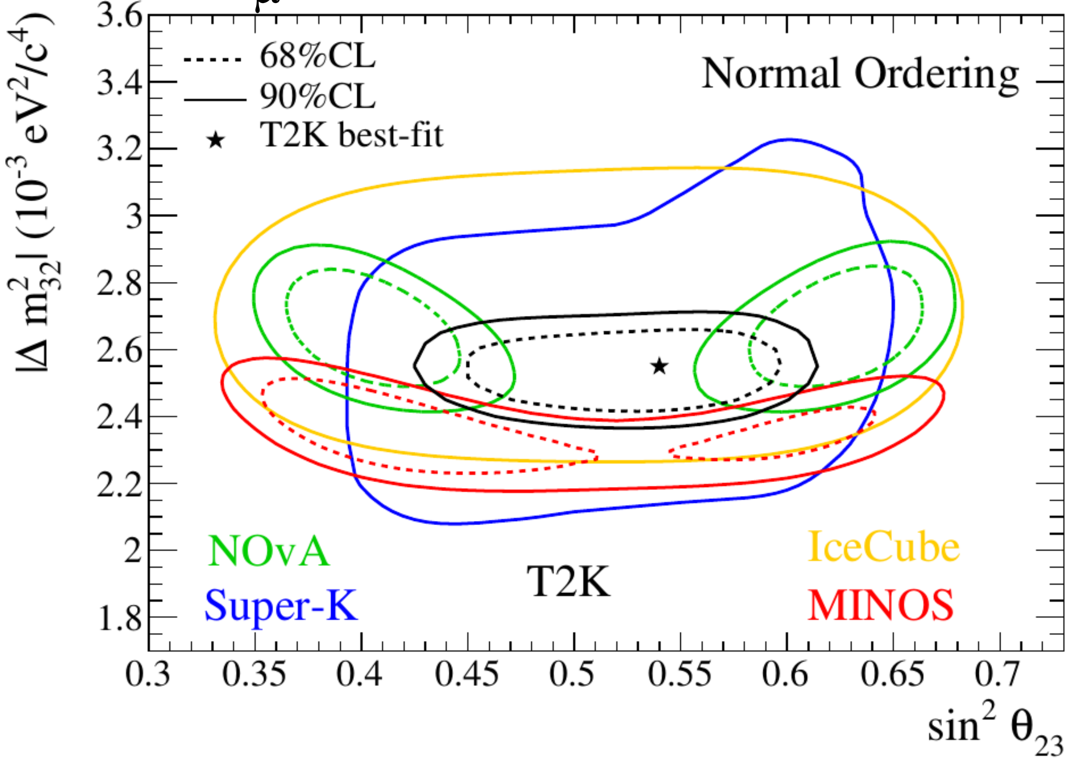
Uses neutrinos and antineutrinos data

$\overset{(-)}{\nu}_e$ appearance from $\overset{(-)}{\nu}_\mu$ beam



Favored value : $\delta_{CP} \sim -\frac{\pi}{2}$

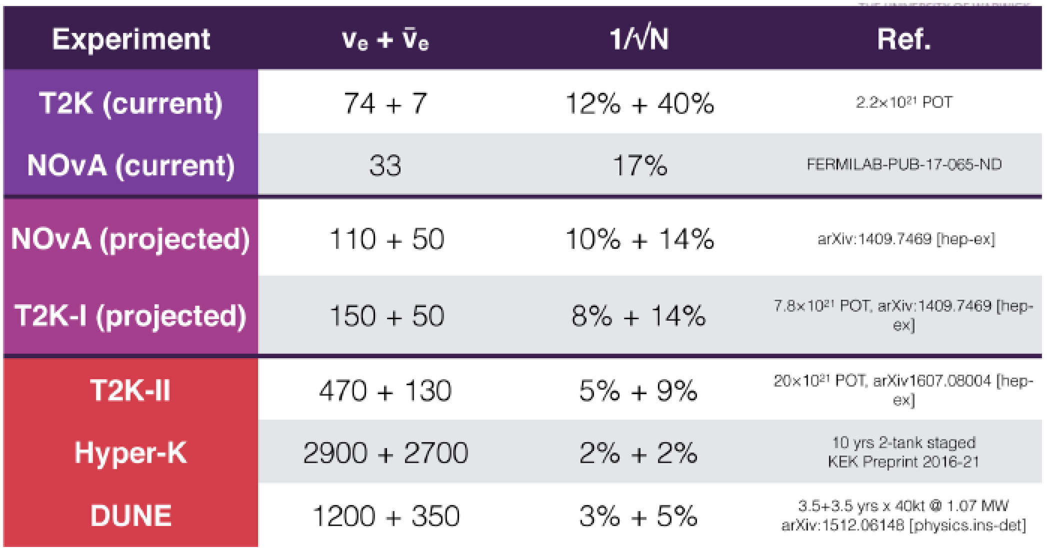
$\overset{(-)}{\nu}_\mu$ disappearance result



Towards CP violation at 3σ : controlling nuclear effects

- The ultimate (optimistic) goal of HK and Dune is 3% systematics
- It's the value where statistical error equal systematics

NUFACT2017 Talk on systematics by D. Hadley

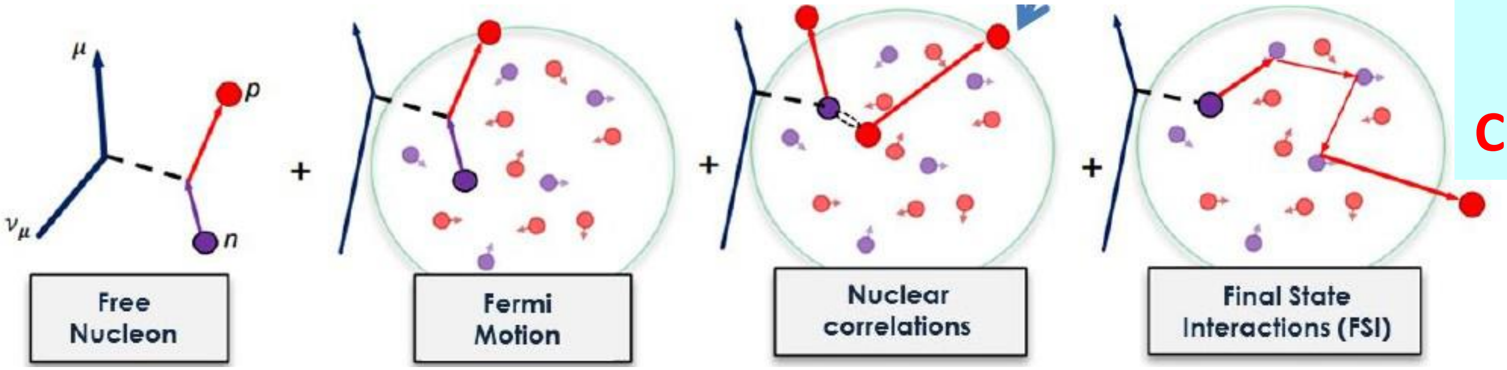


Experiment	$\nu_e + \bar{\nu}_e$	$1/\sqrt{N}$	Ref.
T2K (current)	74 + 7	12% + 40%	2.2×10^{21} POT
NOvA (current)	33	17%	FERMILAB-PUB-17-065-ND
NOvA (projected)	110 + 50	10% + 14%	arXiv:1409.7469 [hep-ex]
T2K-I (projected)	150 + 50	8% + 14%	7.8×10^{21} POT, arXiv:1409.7469 [hep-ex]
T2K-II	470 + 130	5% + 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]

Systematics : important contribution from uncertainty on ν cross-sections.

- Theoretical models have large uncertainties.
- Measurements at near detectors and other dedicated experiments

Neutrino interaction on nuclei, not on free nucleons! Possible biases on the neutrino energy reconstruction and oscillation parameters



DPhP in T2K :

- **In charge of the ν cross-section analyses and models parametrisation**
- **Involved in ν cross section analyses.**

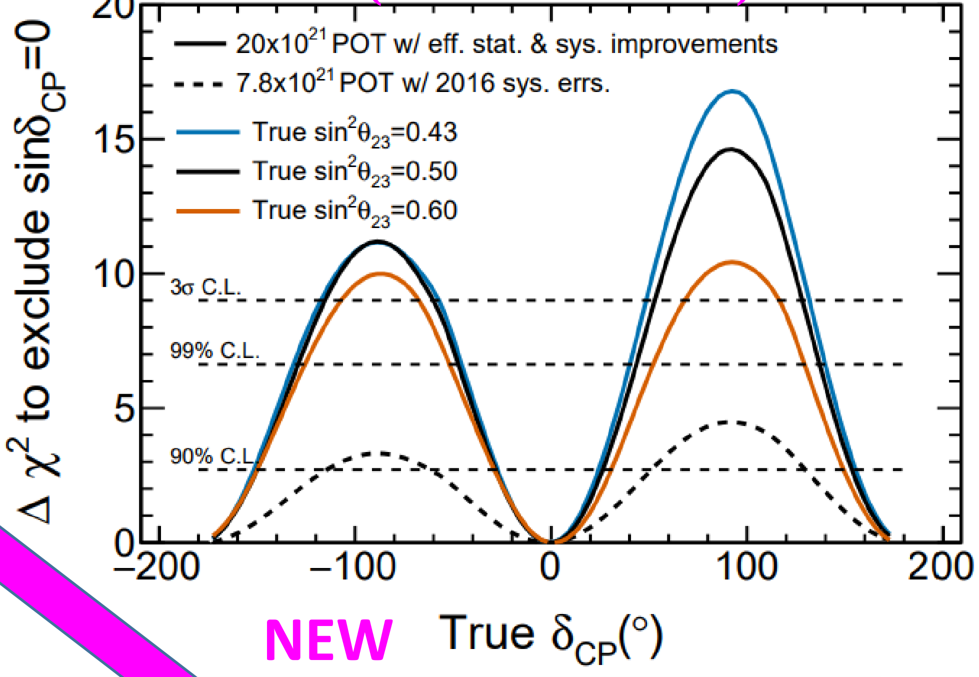
Collaboration with DPhN

T2K- phase II – 2021 to 2026

- With 3x full T2K phase 1 statistics ~ 10x T2K current statistics : Rule out CP conservation at 3 sigma for 36% of δ_{CP} values (49% if mass ordering is known)

- **Upgraded near detector** : better acceptance and more target.
  - Two new horizontal TPCs and a horizontal scintillator detector (R&D for high granularity SuperFGD)
  - Install time of flight around the new tracker
  - See Mathieu Lamoureux’s talk at NUFACT 2017

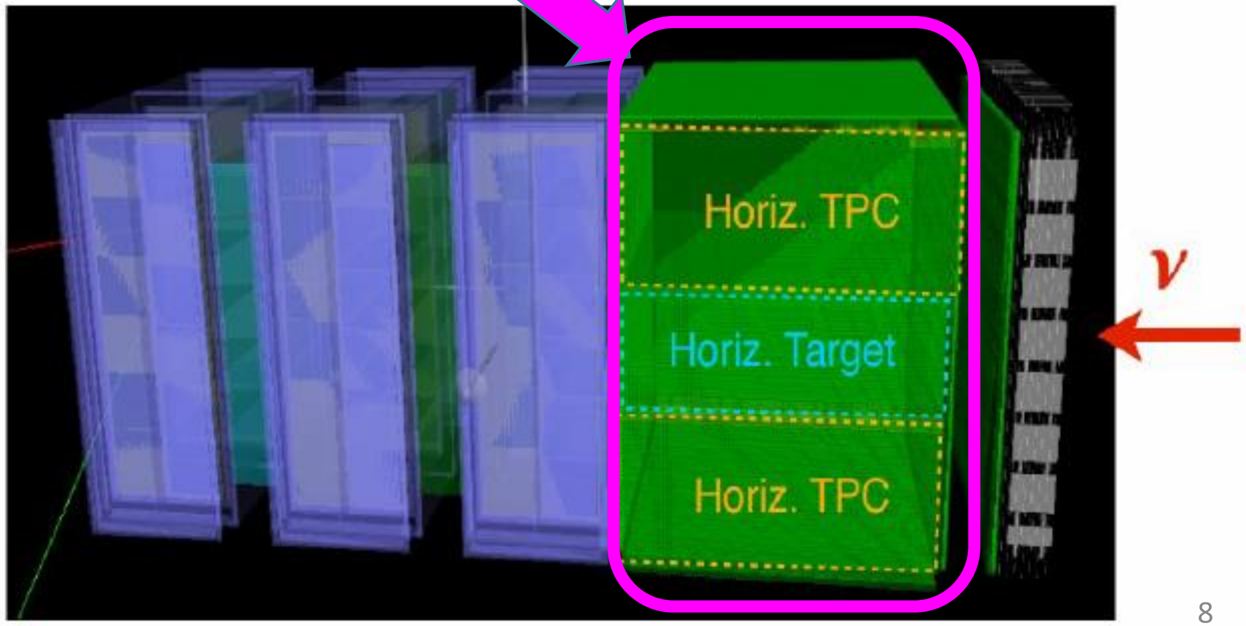
(arXiv:1710.00715)



NEW

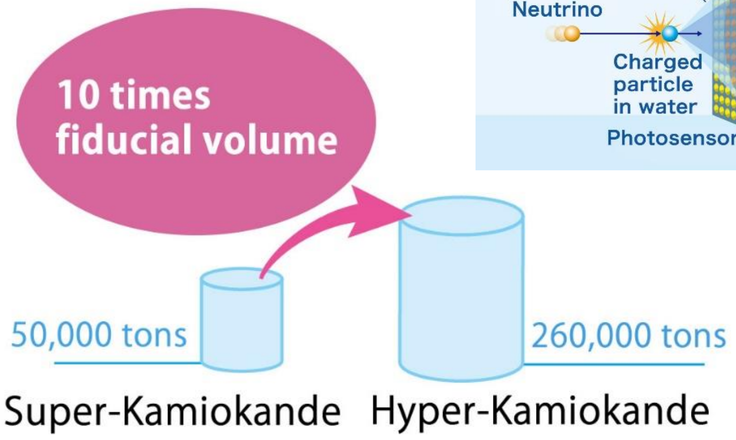
IRFU in upgraded near detector :

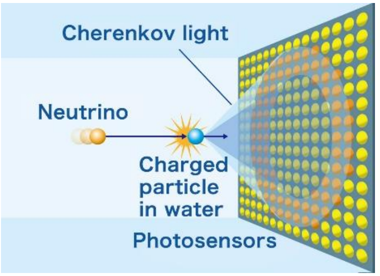
- Coordination, workshops
- Physics analyses, simulations
- Hardware (2 new horizontal TPCs)
  - Resistive micromegas (ILC-TPC R&D)
  - Electronics

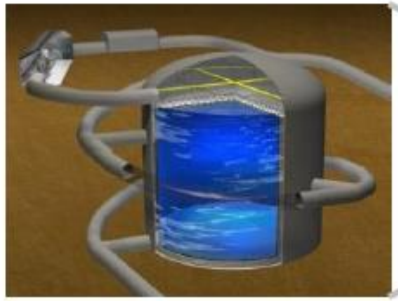


Possible second detector in Korea : improve accuracy on δ_{CP}

Hyper-Kamiokande







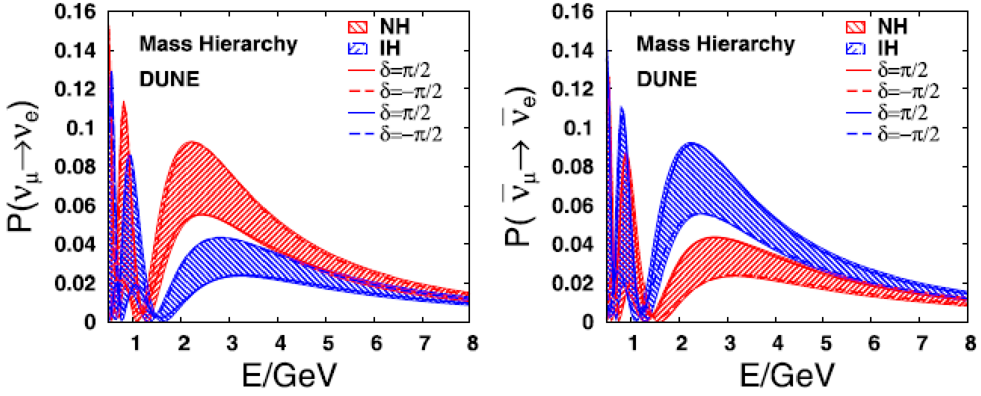
Hyper-K

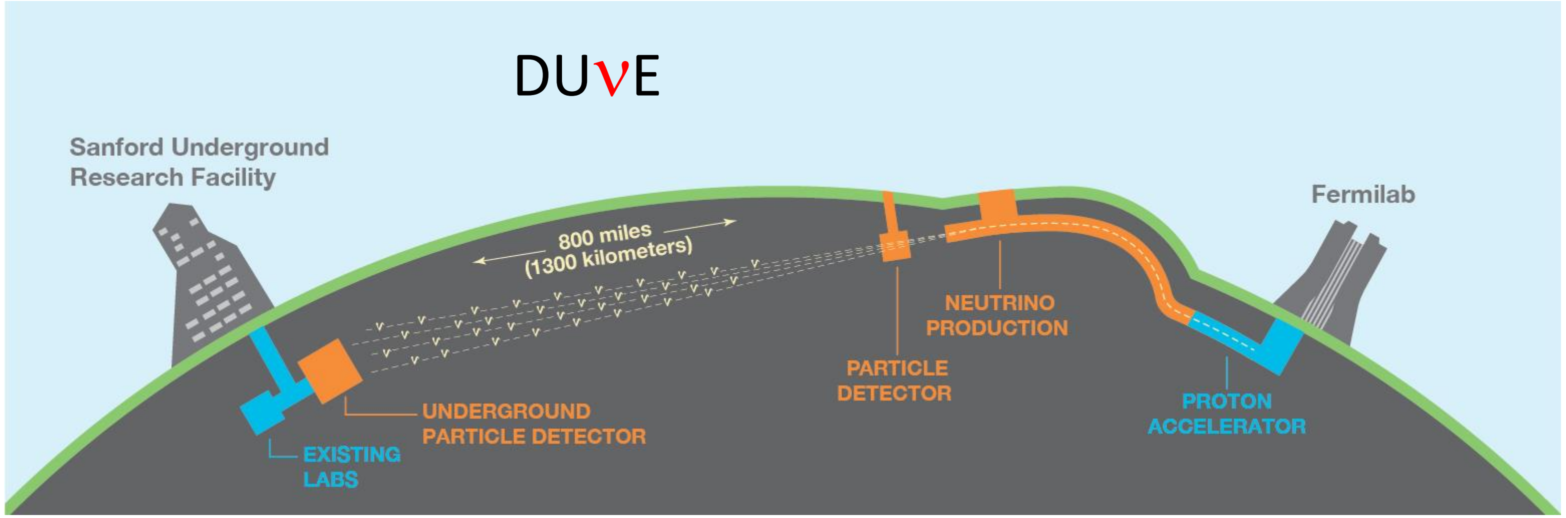
J-PARC

Accelerator Complex

Off-axis neutrino beam : Peaked beam energy range. CCQE dominant.

No final approval but in MEXT large project raodmap since summer 2017





4 Liquid Argon TPCs

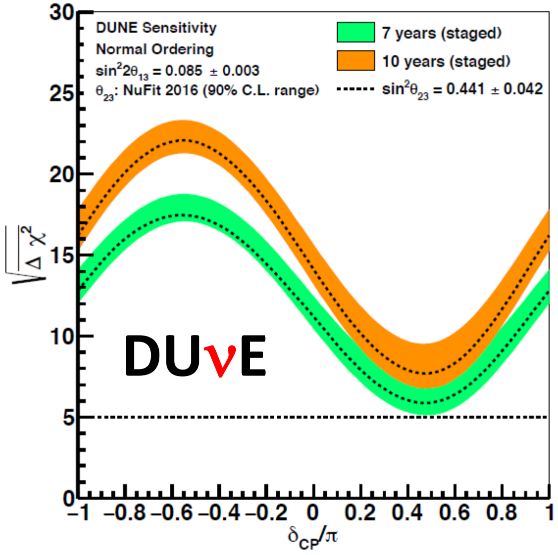
Single and Double phase

Broad beam energy range – Measure two oscillation peaks

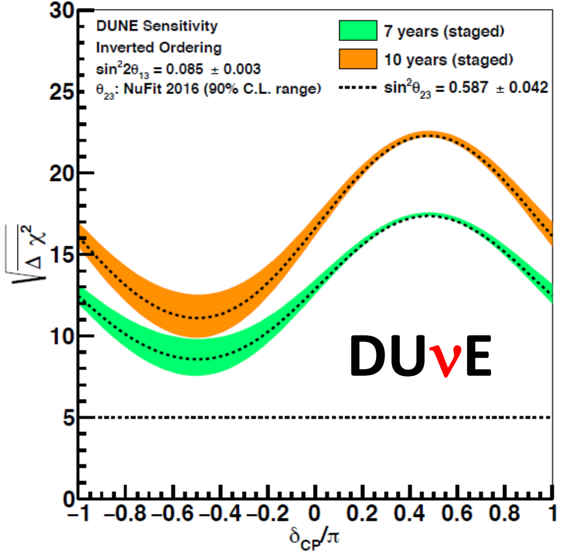
Sensitivities

Mass ordering

Normal MH

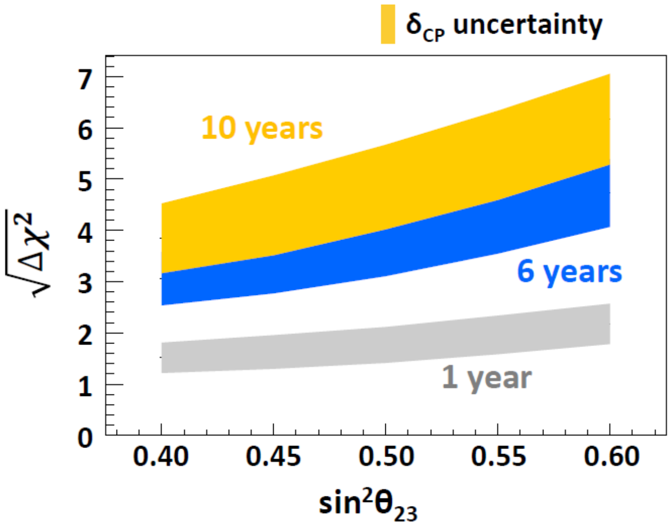


Inverted MH

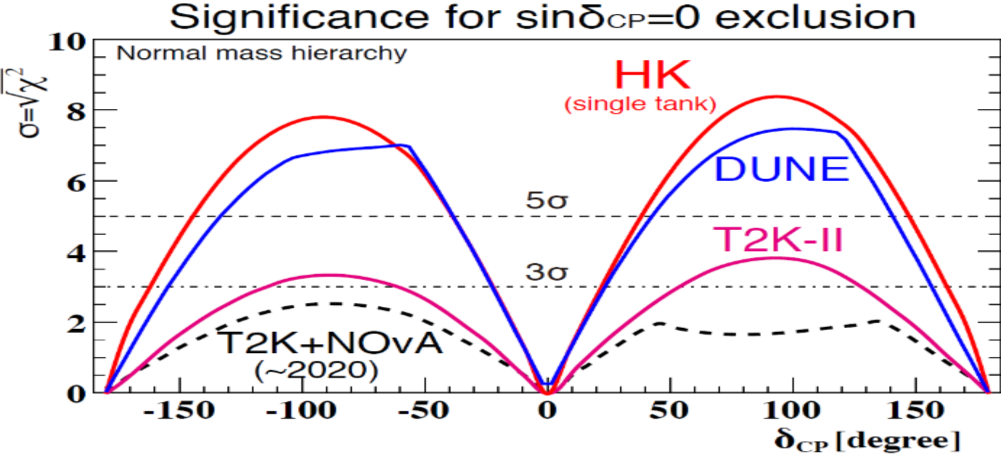


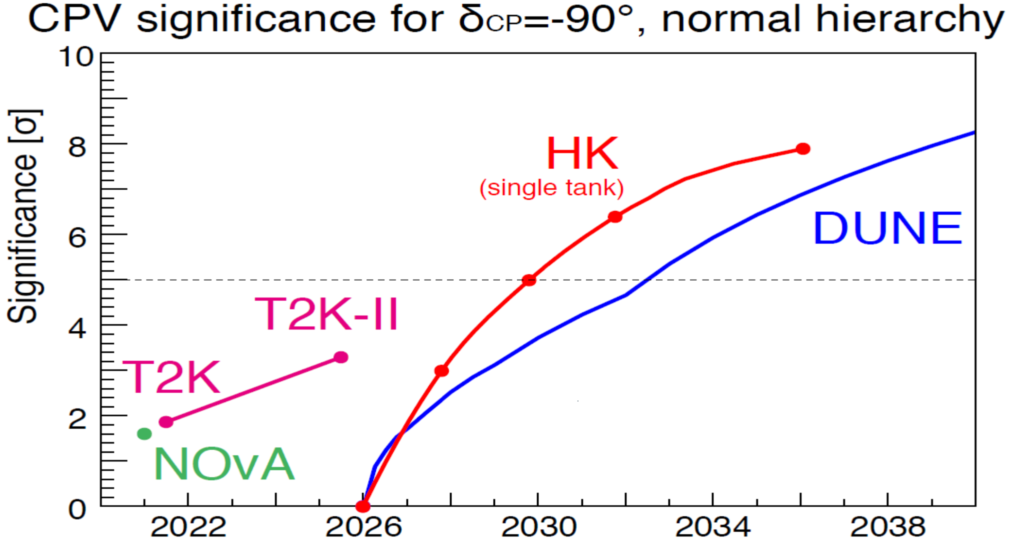
Hyper-Kamiokande

wrong hierarchy rejection



CP violation (normal mass ordering)

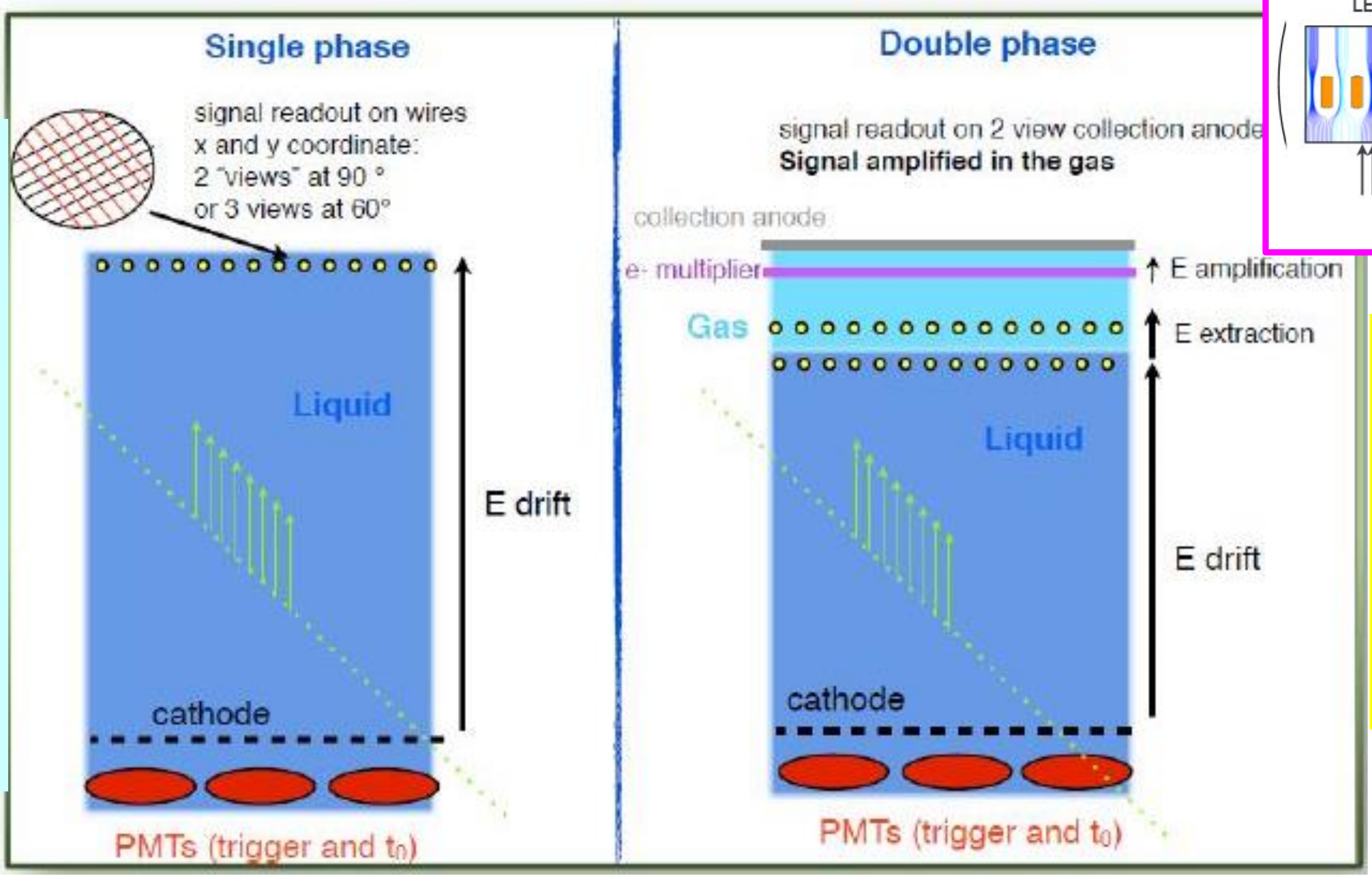




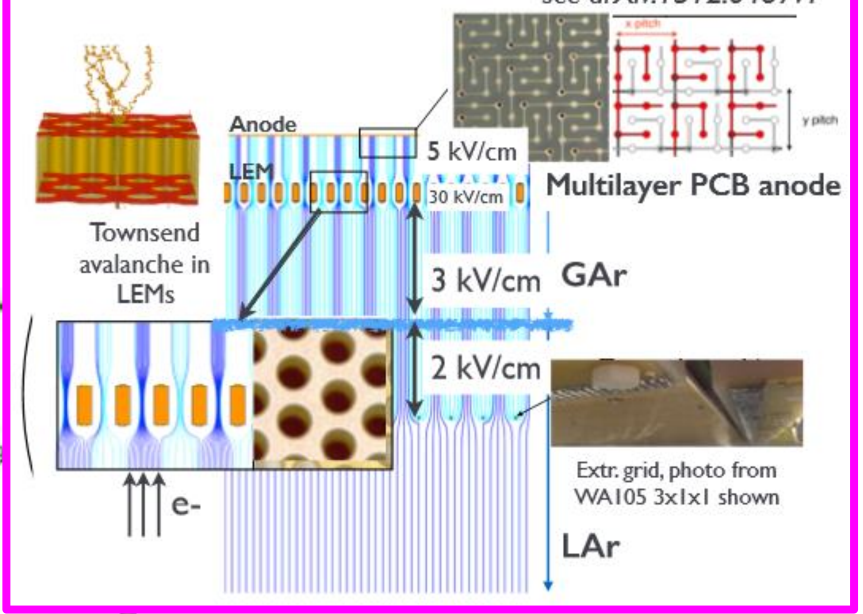
DUNE: Liquid Argon TPCs

In Saclay, conception, test & characterization of LEMs (~GEMs)

Already used : Icarus, MiniBooNE, …



see arXiv:1312.6487v1



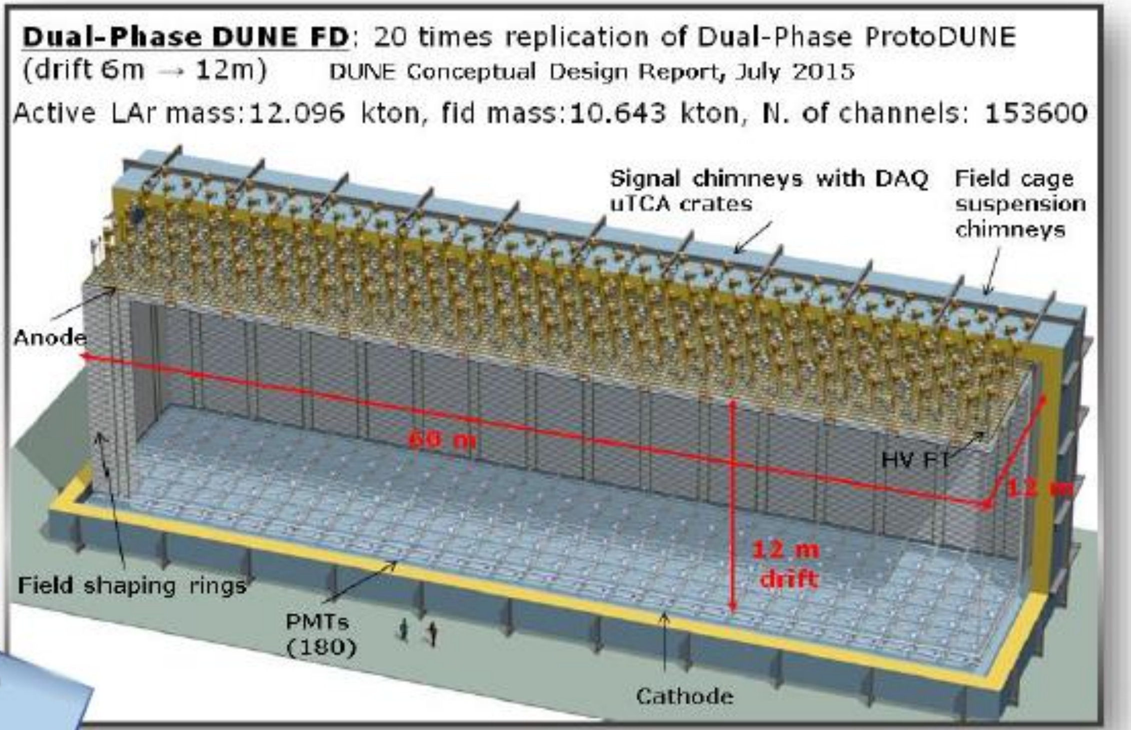
NEW CONCEPT!

EC-FP7-LAGUNA-LBNO

Towards the 10kton dual-phase TPC

Advantages of double-phase design:

- Tunable gain in gas phase
- High Signal/Noise ratio
- Reduced number of readout channels
- No materials in the active volume



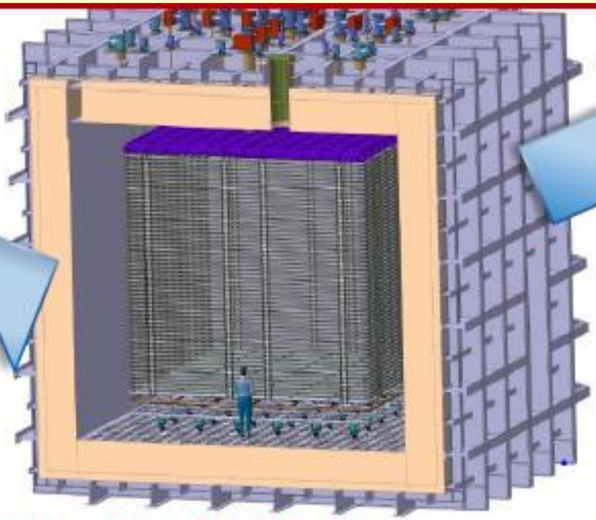
Dual-Phase DUNE FD: 20 times replication of Dual-Phase ProtoDUNE (drift 6m → 12m) DUNE Conceptual Design Report, July 2015

Active LAr mass: 12.096 kton, fid mass: 10.643 kton, N. of channels: 153600

LArProto 3x1x1m^3 25ton DP LAr TPC at CERN

Cosmics

2017



WA105/ProtoDUNE DP 6x6x6m^3 300ton DP LAr TPC LAr TPC at CERN

Test beam

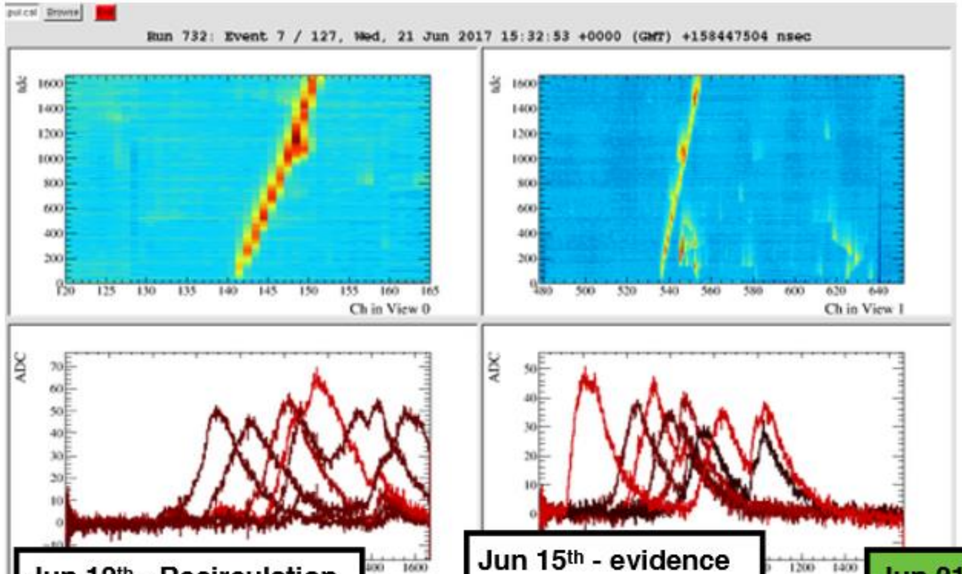
2018

DUNE DP 60x12x12m^3 10kton DP LAr TPC Underground at Sanford

2026

Summer 2017: First cosmic track in LArProto 3x1x1 m^3

We can use double phase Liquid Argon TPCs with large detection surfaces.



Jun 12th - Recirculation started → **Jun 15th - evidence of extraction from LAr to GAr** → **Jun 21st 2017 - First track seen!**

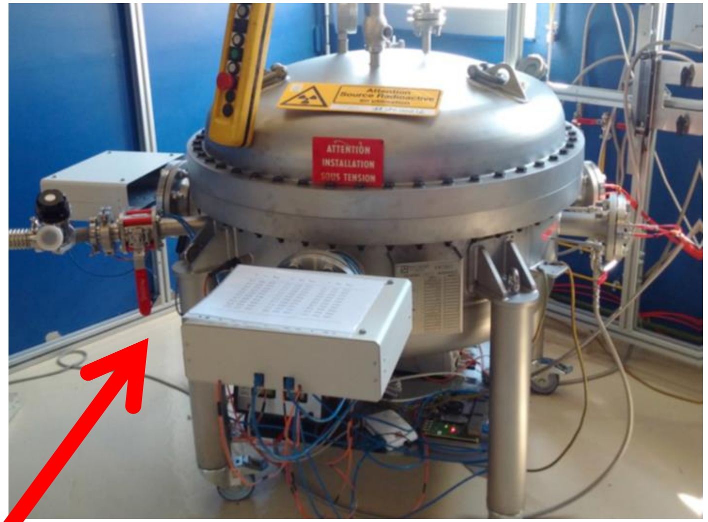
IRFU and WA105 : LEMs

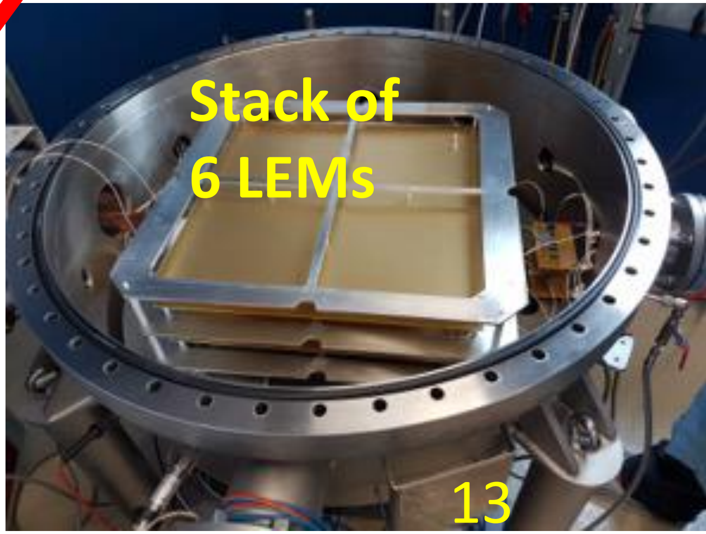
LEM : 450k holes of 0.5mm diameter. At 3kV in Argon gas at 87°K : electrons multiplication with a gain > 10.

2015-2016 : LEM current design and study of functioning under high voltage.

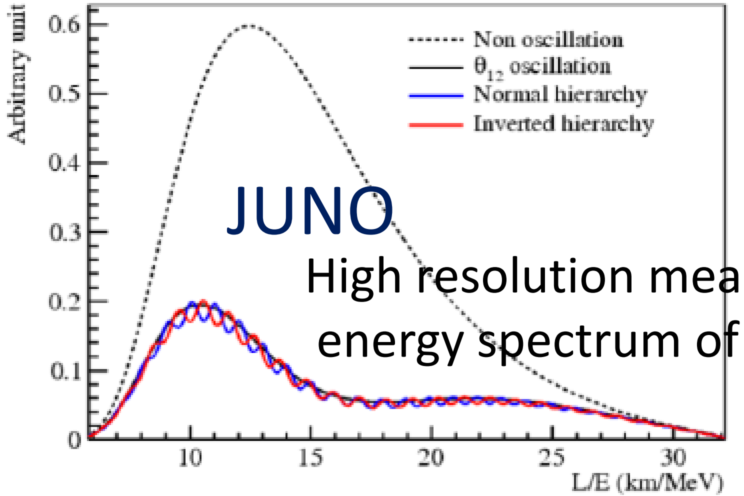
IRFU : supply and test half of the 144 - 50×50cm^2 - LEMs for WA105.

- Construction : partnership with industry
- Tests in Saclay : high pressure (as in double phase LAr TPC) Argon Gas chamber.
- Production of all LEMs and anodes for WA105 started in summer 2017.
- To be installed into WA105 in 2017-2018.





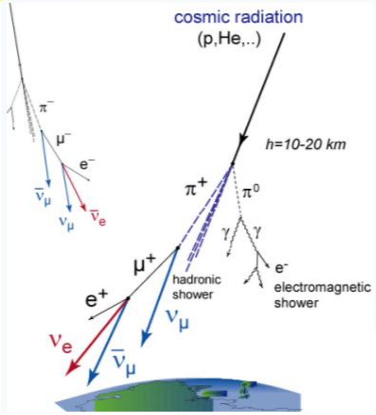
Other future projects to measure mass ordering

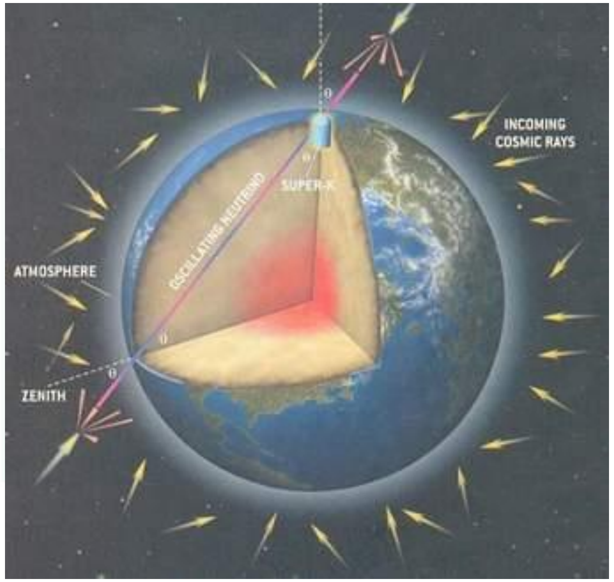


JUNO

High resolution measurement of the energy spectrum of reactor $\overline{\nu_e}$ (~ 50km away)

Use atmospheric ν.

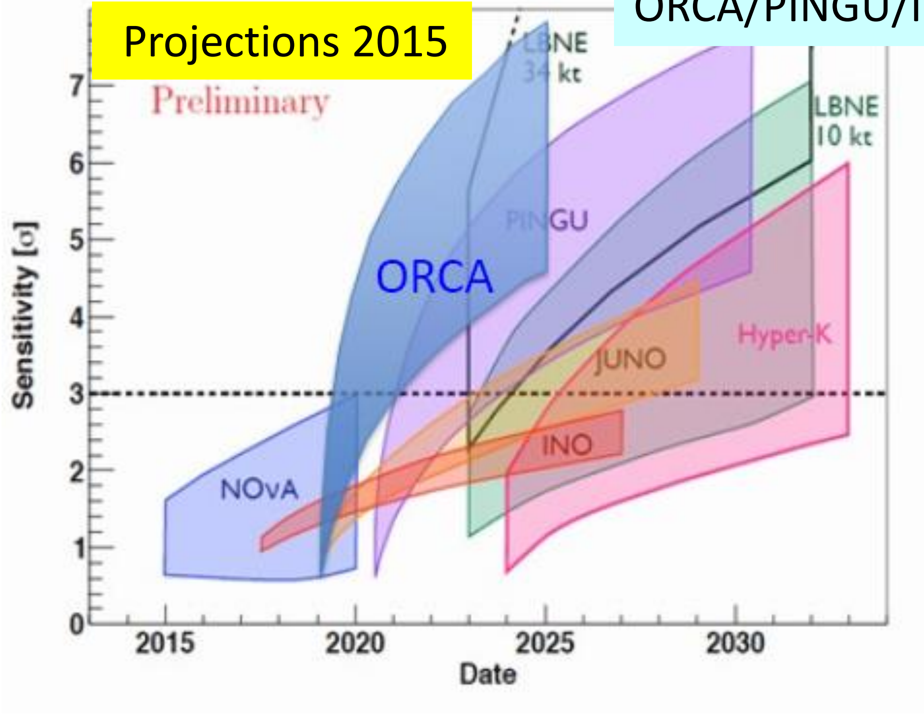




LBNE/NOVA : δ_{CP}
JUNO : σ_E (3.0-3.5%)
ORCA/PINGU/INO: θ_{23}

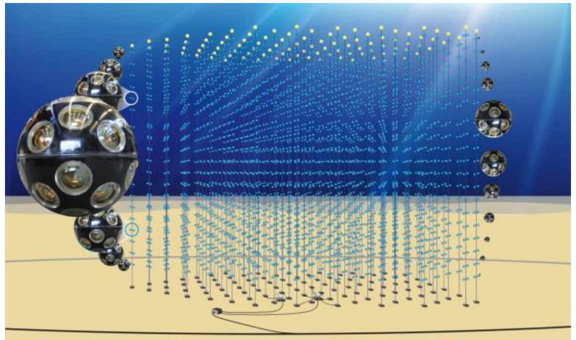
Widths : main uncertainties

Projections 2015

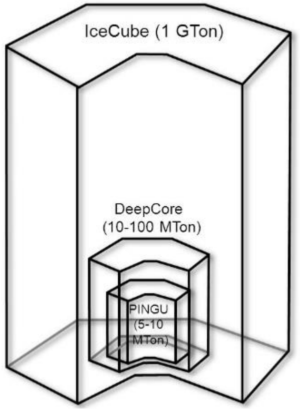


ORCA

KM3NeT Collaboration



Dense Cherenkov light detectors



Precision IceCube Next Generation Upgrade

ν energy range : 1-20 GeV

Future measurements of other oscillation parameters

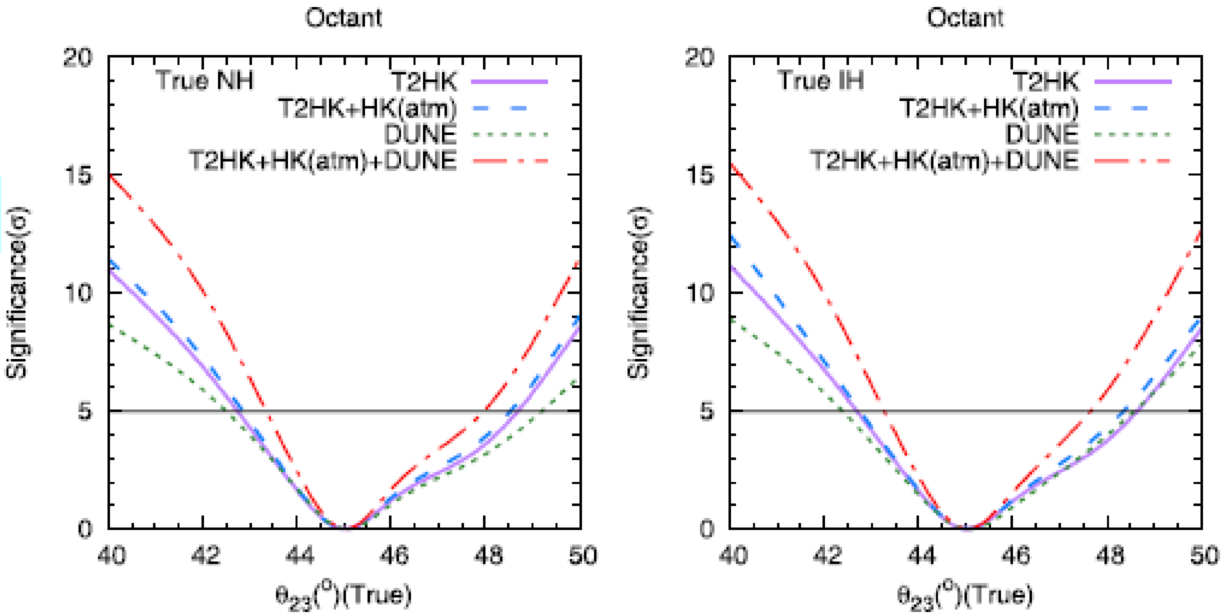
- JUNO will measure precisely the solar sector oscillation parameters

- θ_{23} octant - **(arXiv:1501.03918)**

S. Fukasawa et al., Nucl. Phys. B918 (2017), 337-357

For T2HK +HK (DUNE), **octant resolved at 5σ C.L. except for 43.5°<θ_{23}<48°** for both hierarchies and irrespective of the value of δ_{CP}.

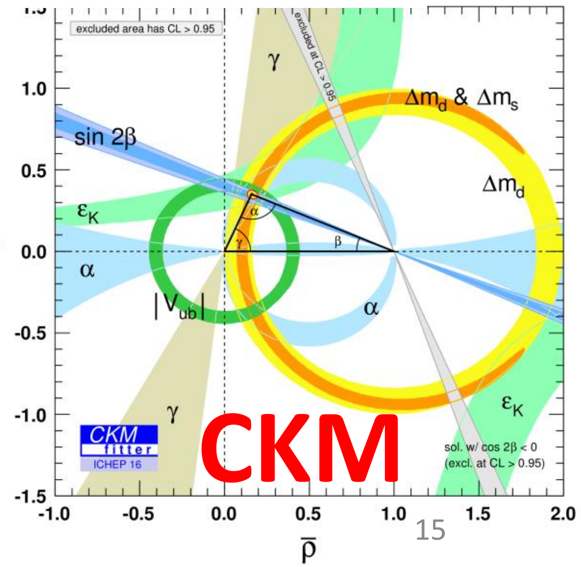
Orca & Pingu can also constrain the octant and the atmospheric parameters



Mauro Mezzetto NUFACT 2017 : « Complementarity »

- 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, …

Not just measure parameters but test the formalism (over-constrain the parameters space)



CKM

Summary and calendar

In red: DPhP group involved – May be involved

Long baseline accelerator experiments

- **Until 2021** : **T2K**, Nova
- **2021- 2026** : **T2K phase II**
- **WA 105** : 6x6x6 m^3 to take beam data before the LHC shut down in **2018**.
- **~2026** : DUNE, HyperK

Other mass hierarchy : under construction and will start around **2020**:

- ORCA - PINGU (atmospheric neutrinos, matter effects)
- JUNO (reactor antineutrinos, oscillation in vacuum)

Optimize leading edge physics output with high profile participation of IRFU/DPhP to one future long baseline experiment

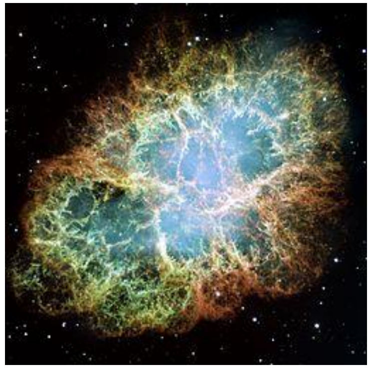
→ decision expected in 2018-2019

New physics horizons of large neutrino detectors

Future very large detectors with different liquids (Water/ice, Liquid Argon, scintillator)
Complementary (neutrino energy range, reconstruction, etc.)

Neutrinos astrophysics :

- Supernovae neutrinos (explosions and old supernovae background)
- Solar neutrinos



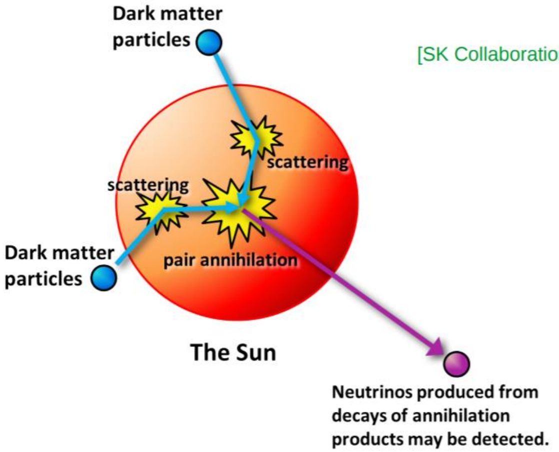
Example : In HyperKamiokande
Synergy with DAP Supernovae explosion studies

Search for proton decay

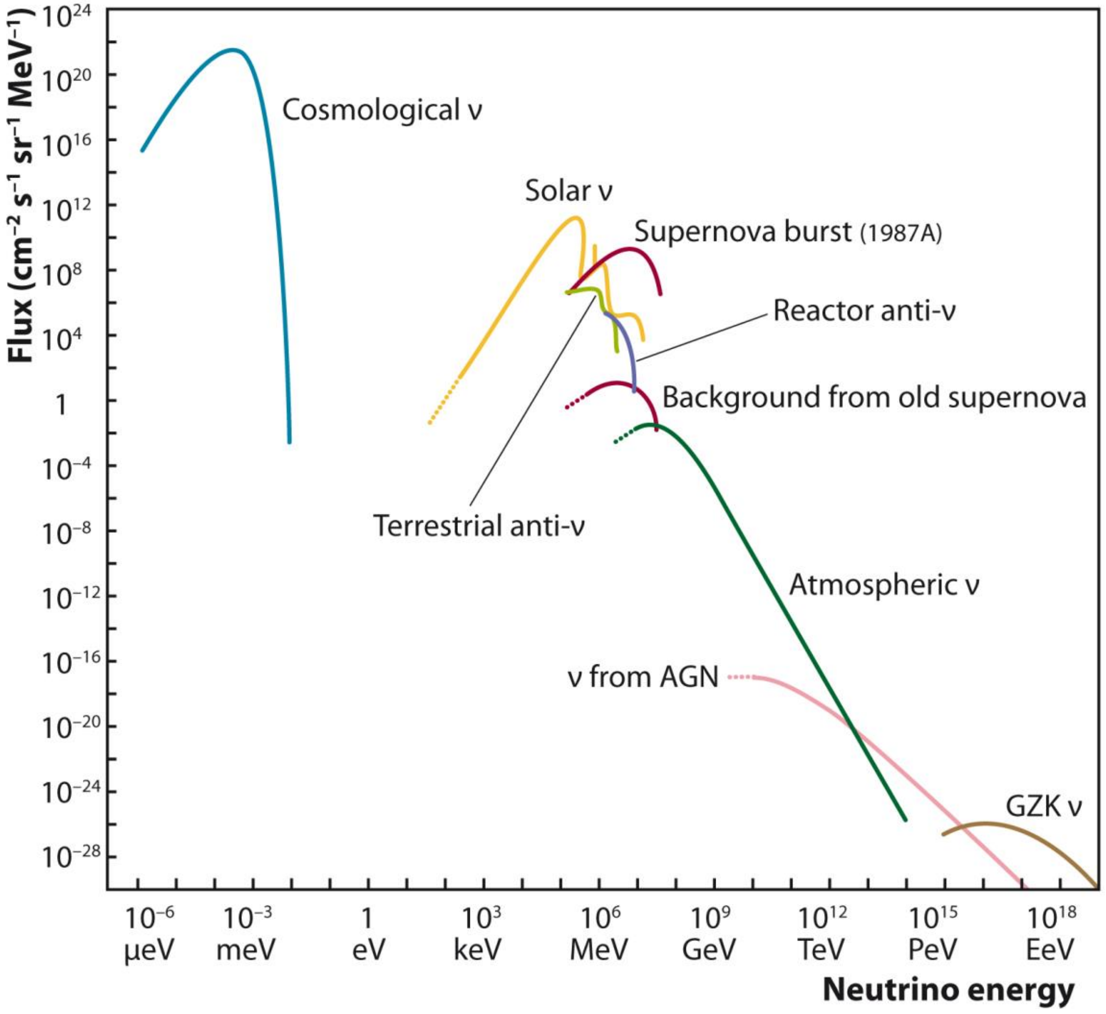
Example: $\mathrm{p} \rightarrow K^{+}\overline{\nu}$

Search for Dark Matter

Neutrinos from the Sun



[SK Collaboration]



BACK-UP

From PDG

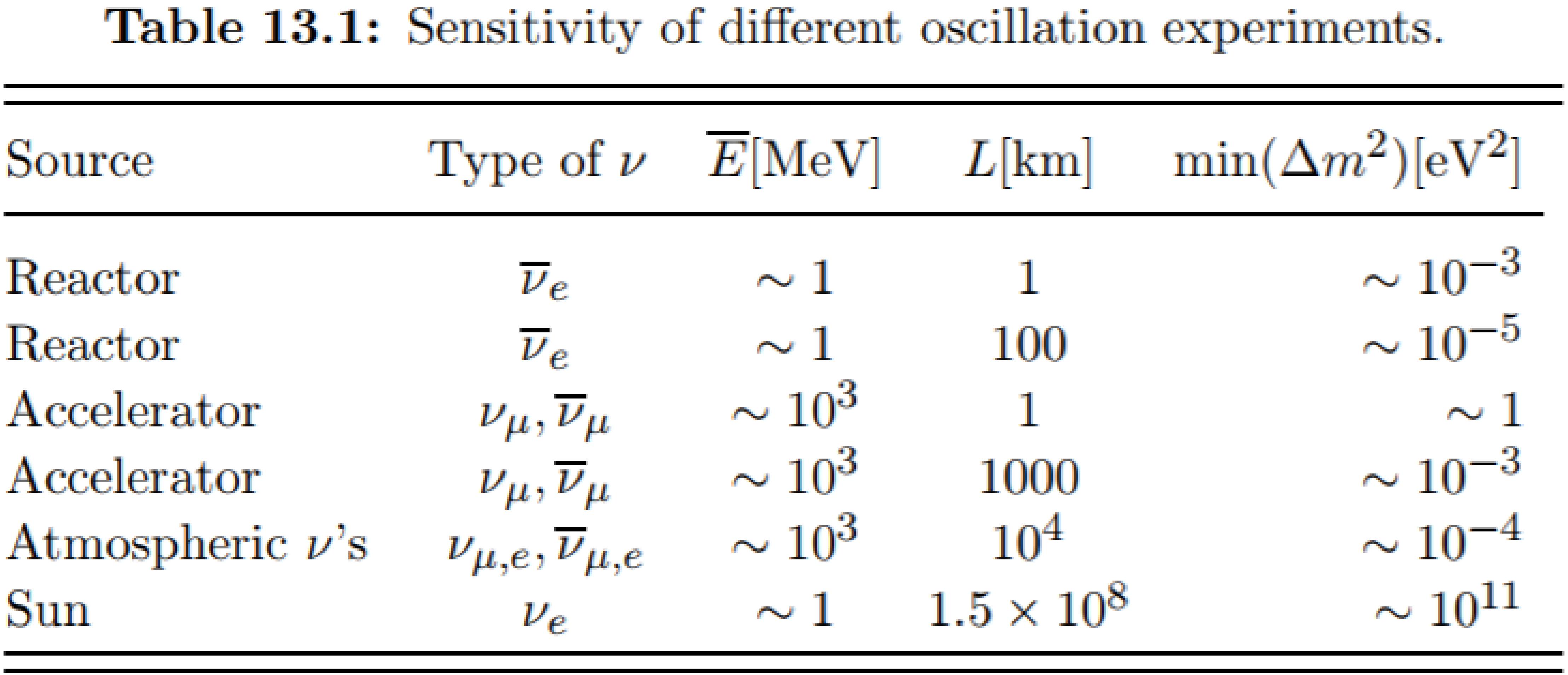
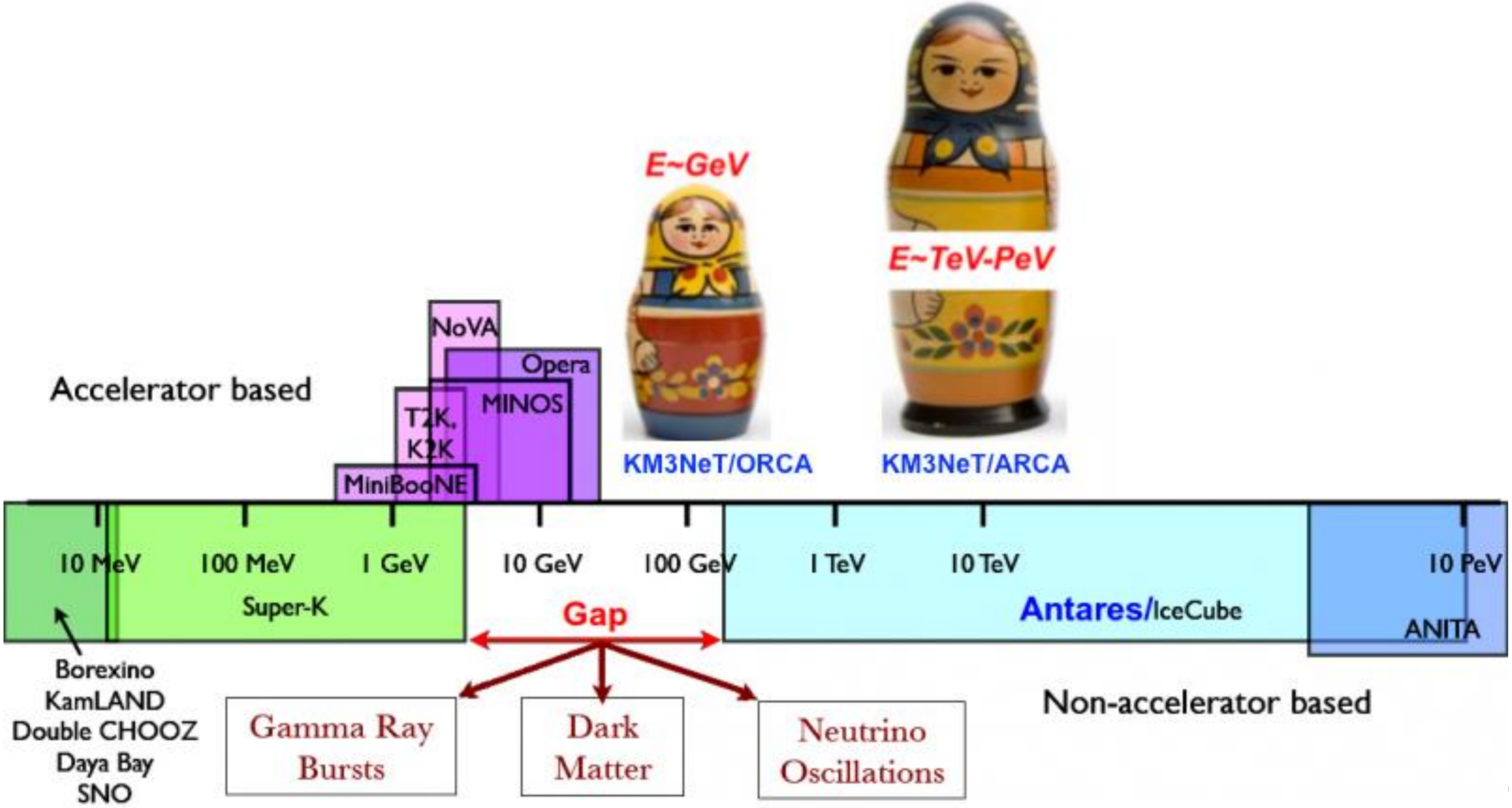


Table 13.1: Sensitivity of different oscillation experiments.

Source	Type of ν	$\overline{E}$[MeV]	L[km]	$\min(\Delta m^2)[\mathrm{eV}^2]$
Reactor	$\overline{\nu}_e$	~ 1	1	$\sim 10^{-3}$
Reactor	$\overline{\nu}_e$	~ 1	100	$\sim 10^{-5}$
Accelerator	$\nu_\mu, \overline{\nu}_\mu$	$\sim 10^3$	1	~ 1
Accelerator	$\nu_\mu, \overline{\nu}_\mu$	$\sim 10^3$	1000	$\sim 10^{-3}$
Atmospheric ν's	$\nu_{\mu,e}, \overline{\nu}_{\mu,e}$	$\sim 10^3$	10^4	$\sim 10^{-4}$
Sun	ν_e	~ 1	1.5×10^8	$\sim 10^{11}$



Accelerator based

Gamma Ray Bursts

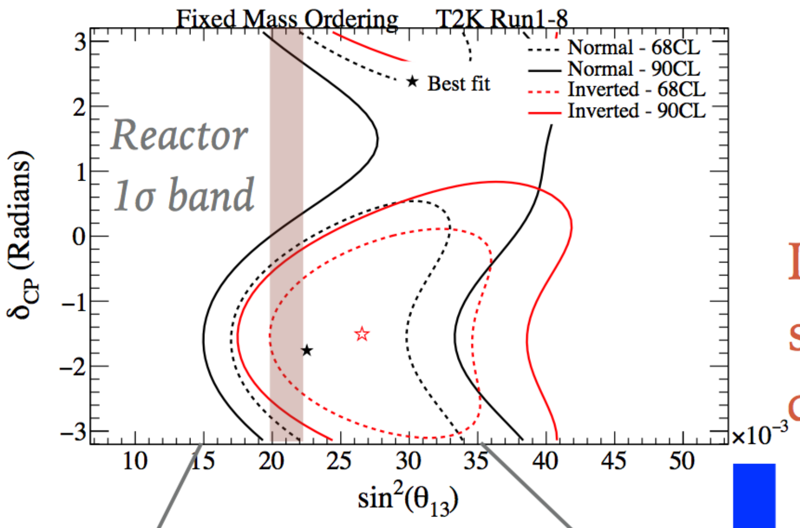
Dark Matter

Neutrino Oscillations

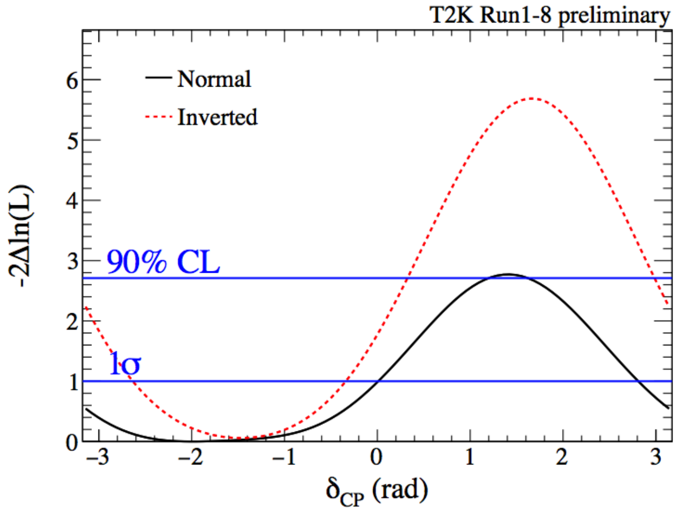
Non-accelerator based

OSCILLATION PARAMETER SENSITIVITIES (2017)

Without the reactor experiment constraint on $\sin^2 2\theta_{13}$

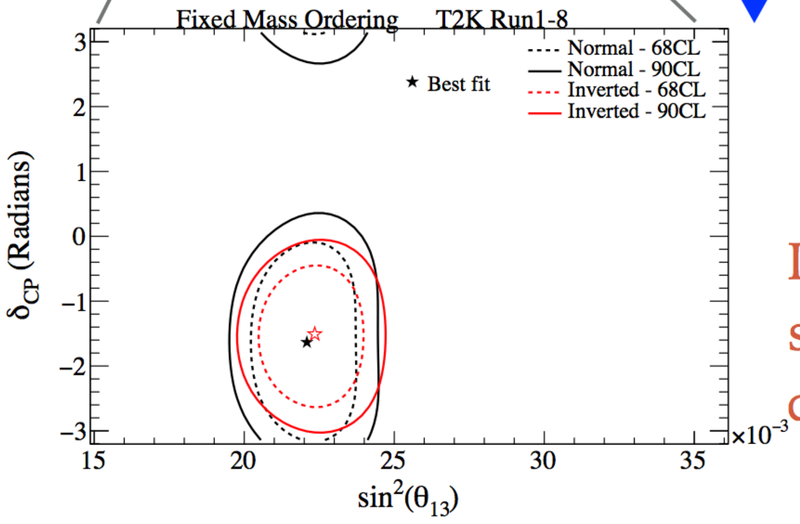


Integrate out $\sin^2\theta_{13}$ dependence

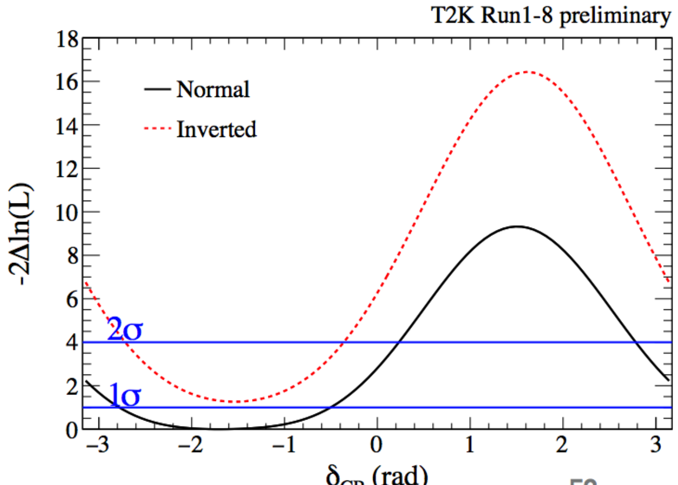


Mark HARTZ
KEK colloquium

Reactor constraint on $\sin^2(2\theta)_{13}$ (PDG2016)



Integrate out $\sin^2\theta_{13}$ dependence

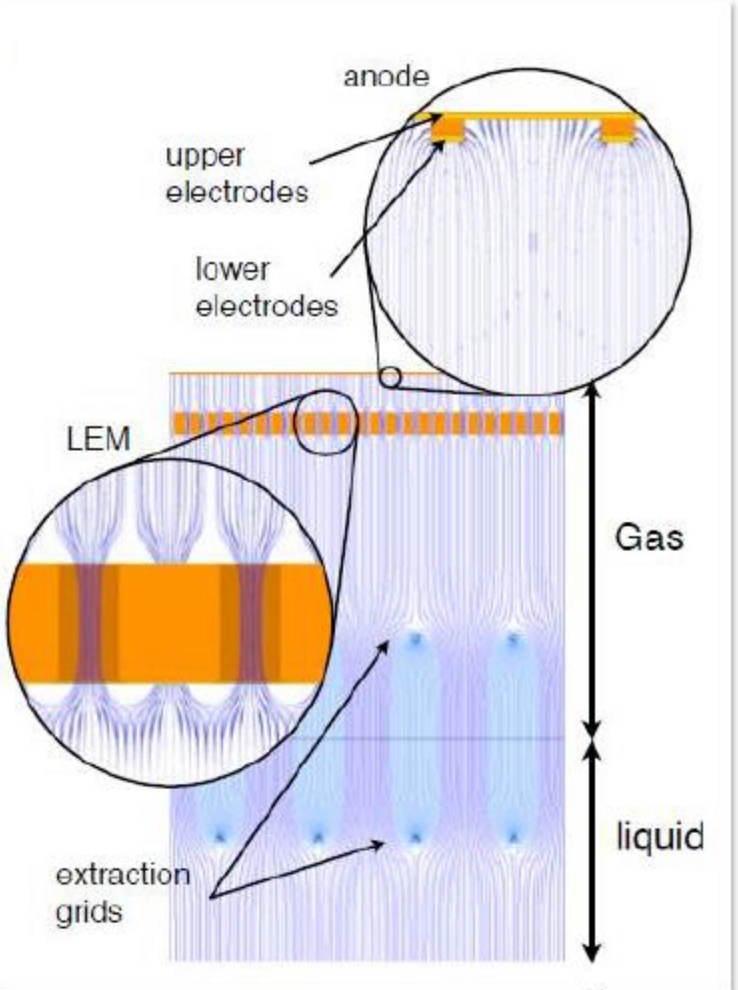


THE DUAL-PHASE CONCEPT

Lar TPC: Basic technique established → Technical Challenges towards very long drifts and very massive detectors

- **Long drifts requires ultra high purity → charge attenuation along the drift path**
- **No charge amplification in single phase**

→ Compensate the effect with charge multiplication at the anode



Charge Collection on anode readout (2 orthogonal views) **(no induction plane)**

↑

Charge multiplication: LEM – Large Electron Multipliers

↑

Electrons extraction from liquid to gas phase through a grid

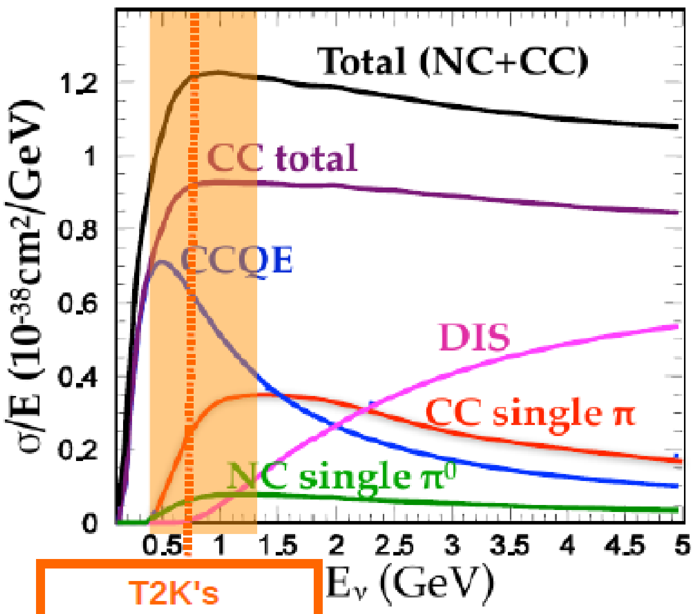
↑

Ionization electrons drift towards the liquid argon surface

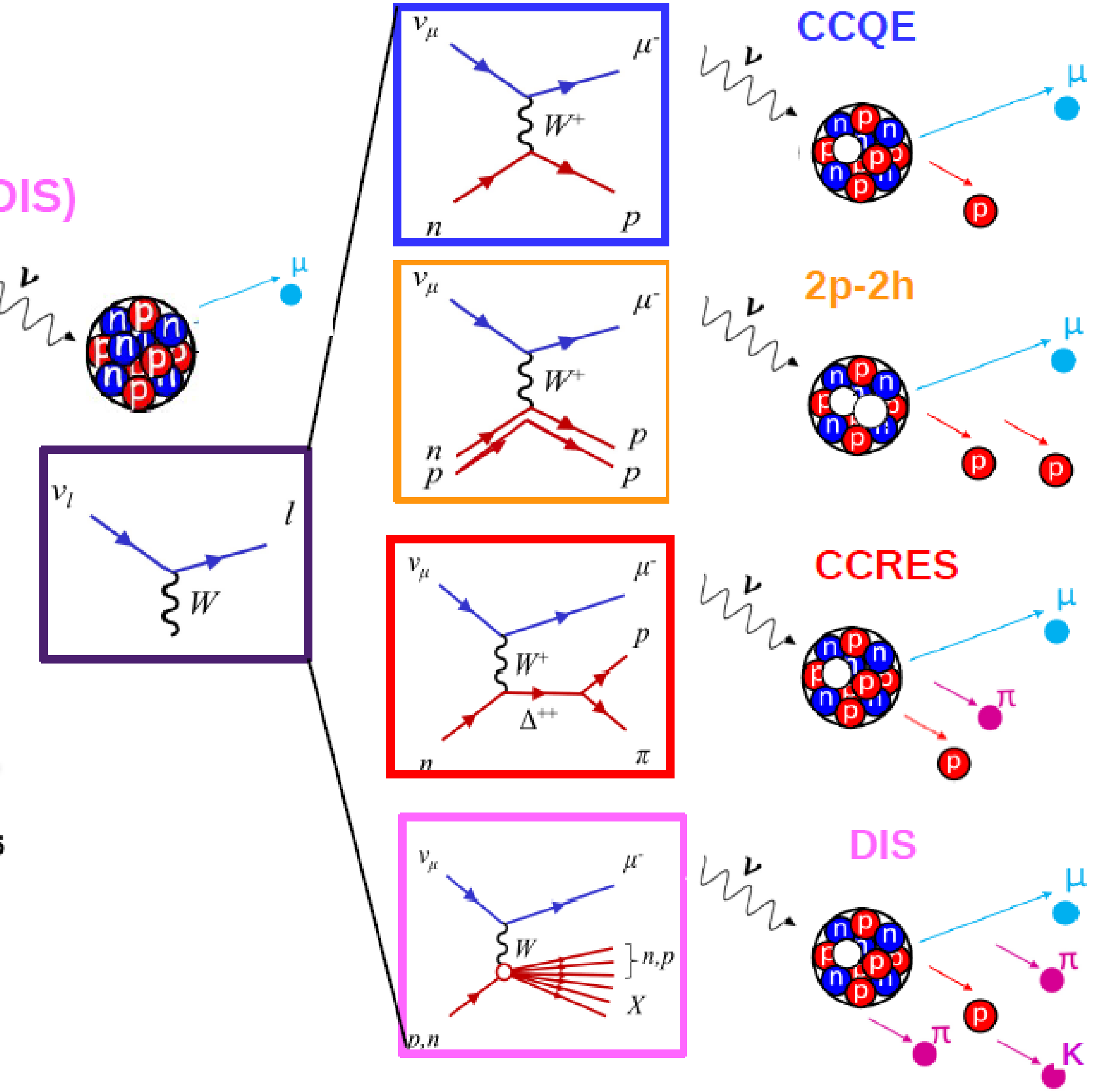
Neutrino interactions at T2K (I)

Charge Current (CC):

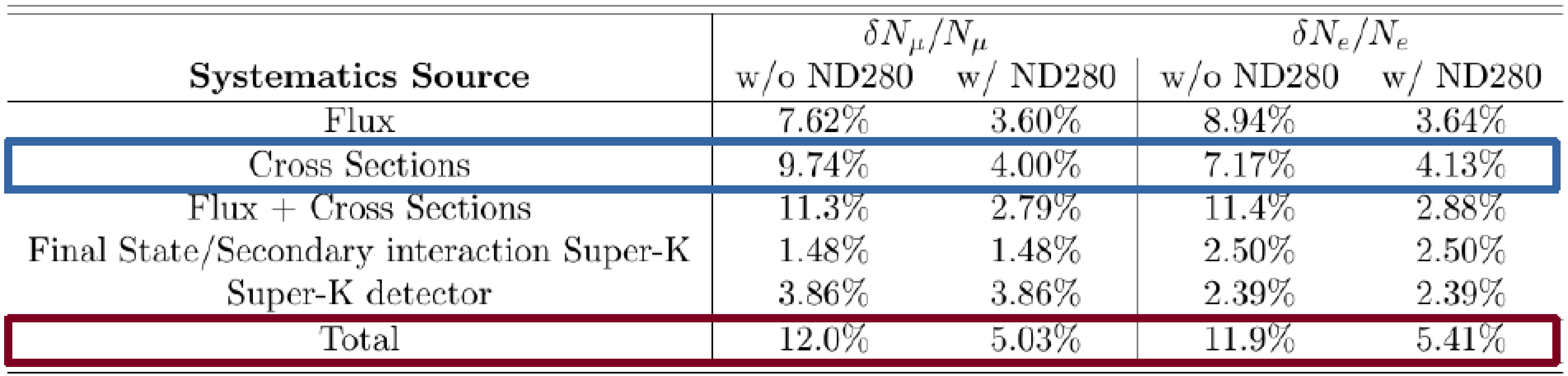
- CC Quasi Elastic (CCQE)
- 2particle – 2hole (2p2h)
- CC RESonance (CCRES)
- Deep Inelastic Scattering (DIS)



T2K's Energy Peak



Systematics



Systematics Source	$\delta N_\mu/N_\mu$ w/o ND280	$\delta N_\mu/N_\mu$ w/ ND280	$\delta N_e/N_e$ w/o ND280	$\delta N_e/N_e$ w/ ND280
Flux	7.62%	3.60%	8.94%	3.64%
Cross Sections	9.74%	4.00%	7.17%	4.13%
Flux + Cross Sections	11.3%	2.79%	11.4%	2.88%
Final State/Secondary interaction Super-K	1.48%	1.48%	2.50%	2.50%
Super-K detector	3.86%	3.86%	2.39%	2.39%
Total	12.0%	5.03%	11.9%	5.41%

- **ND280 constraints** are crucial for T2K oscillation analyses precision
- One of the largest uncertainty comes from **neutrino interaction**
- Smaller uncertainties are needed to precisely measure θ_{13} ,θ_{23} and δ_{CP}

Oscillations at T2K

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - \sin^2 2\theta_{23} \sin^2 \Delta_{32}$$

$$P(\overline{\nu}_\mu \to \overline{\nu}_\mu) \simeq 1 - \sin^2 2\theta_{23} \sin^2 \Delta_{32}$$

→ **Same**

$$P(\nu_\mu \to \nu_e) \simeq \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2[(1 - x)\Delta_{31}]}{(1 - x)^2}$$

$$+ \left|\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\right| \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin(x\Delta_{31})}{x} \frac{\sin[(1 - x)\Delta_{31}]}{(1 - x)} \left(- \sin \delta_{CP} \sin \Delta_{31} + \cos \delta_{CP} \cos \Delta_{31} \right)$$

$$P(\overline{\nu}_\mu \to \overline{\nu}_e) \simeq \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2[(1 + x)\Delta_{31}]}{(1 + x)^2}$$

$$+ \left|\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\right| \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin(x\Delta_{31})}{x} \frac{\sin[(1 + x)\Delta_{31}]}{(1 + x)} \left(+ \sin \delta_{CP} \sin \Delta_{31} + \cos \delta_{CP} \cos \Delta_{31} \right)$$

→ **Opposite signs for the matter effects terms and CP phase!**

$$*\Delta_{ij} = \frac{\Delta m^2_{ij} L}{4E_\nu}, \quad x = \frac{2\sqrt{2} G_F N_e E_\nu}{\Delta m^2_{31}}$$

Neutrino/anti-neutrino oscillation probabilities with matter effects.

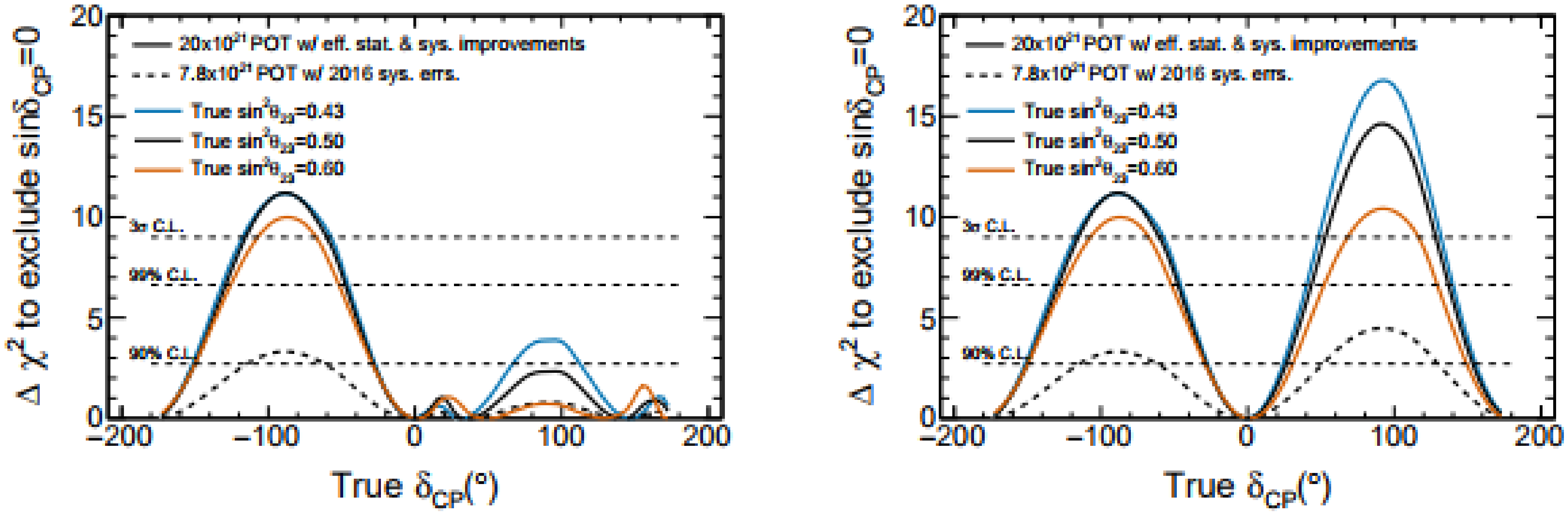
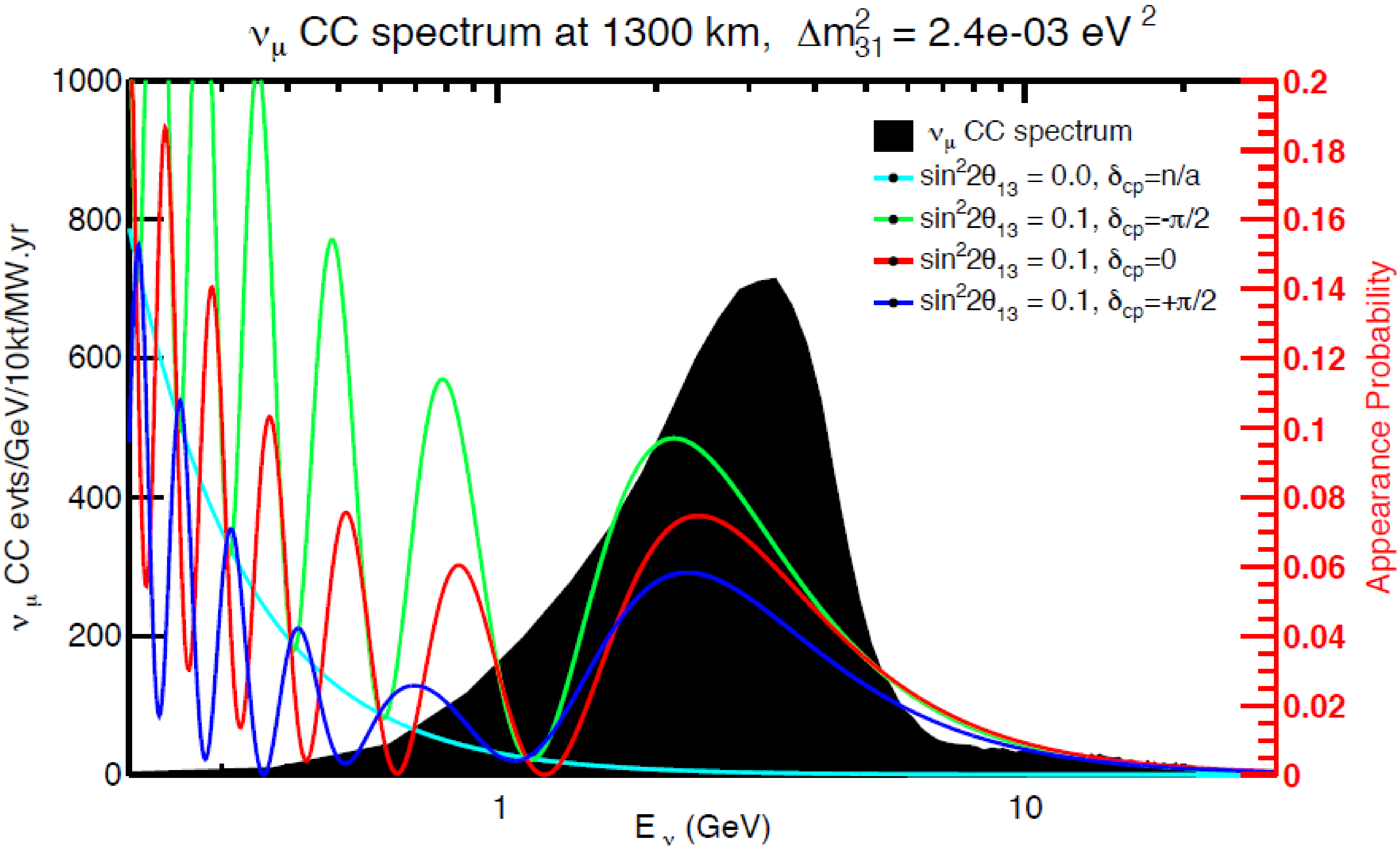


Figure 24: Sensitivity to CP violation as a function of the true δ_{CP} for three values of $\sin^2\theta_{23}$ (0.43, 0.50, 0.60) and normal hierarchy, for the full T2K-II exposure of 20×10^{21} POT and a reduction of the systematic error to 2/3 of the 2016 T2K uncertainties. On the left plot the mass ordering is considered unknown, while on the right plot it is considered known [244]. Courtesy of the T2K collaboration.



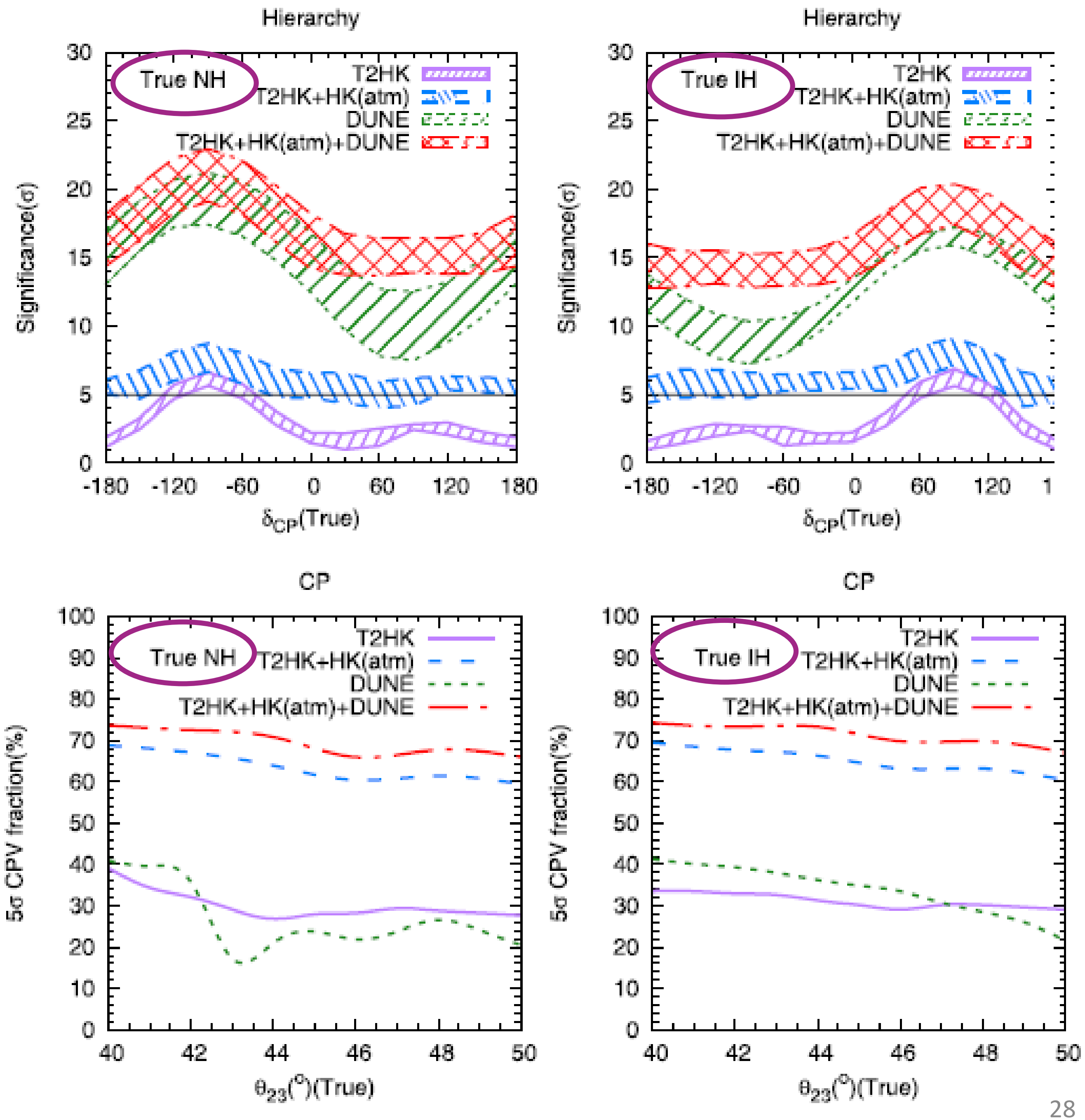
DUNE, spectra at 1300 km

Sensitivities

S. Fukasawa et al., Nucl. Phys. B918 (2017), 337-357

Mass ordering :

- Hierarchy sensitivity of both T2HK & HK limited due parameter degeneracy, removed when T2HK and HK combined.
- **T2HK +HK (DUNE):** hierarchy determined at > **5σ (8σ)** C.L. for any value of true δ_{CP}.

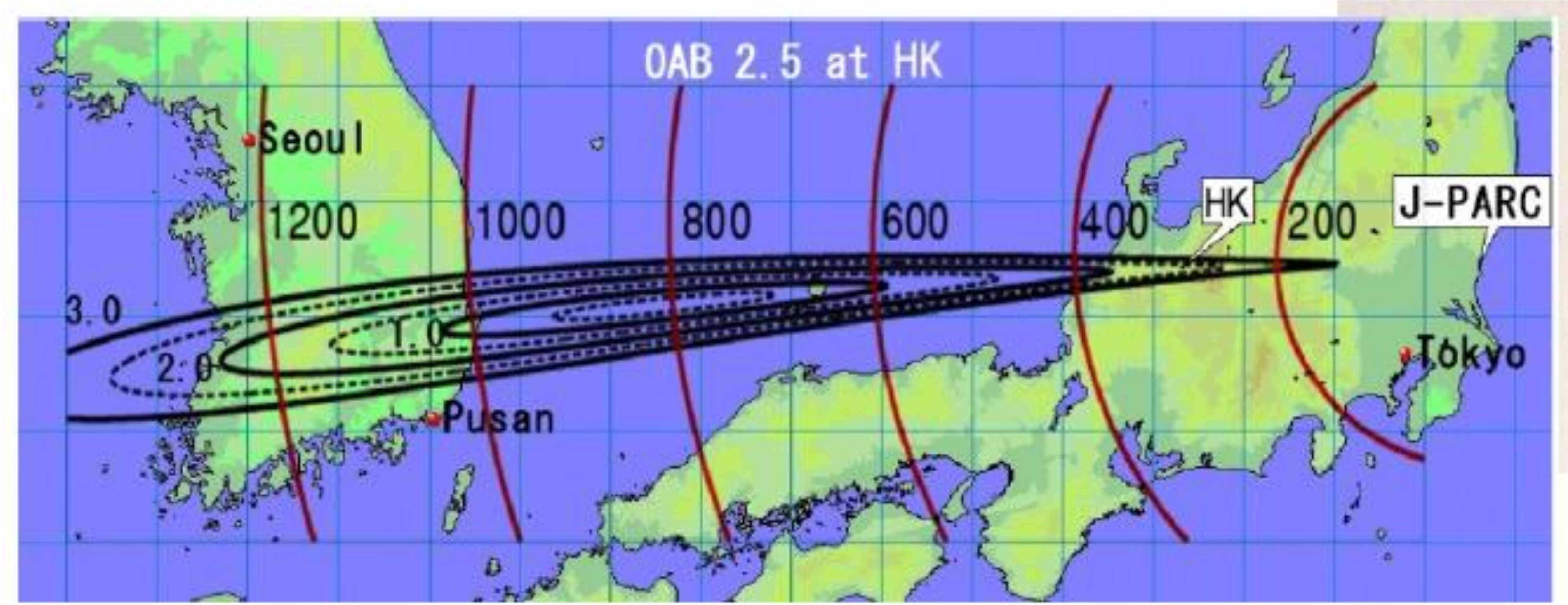


CP violation:

T2HK +HK + DUNE:

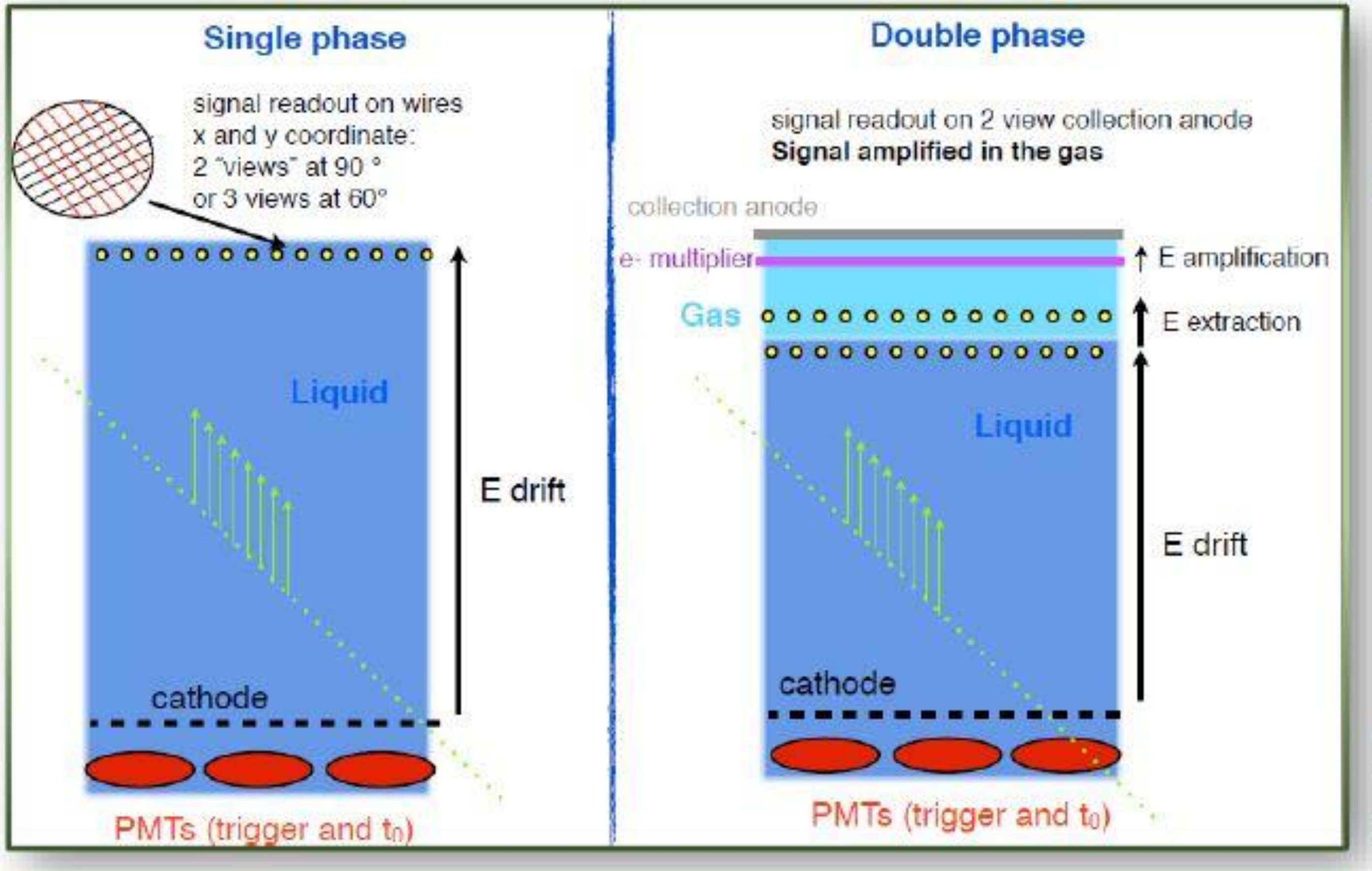
- significance of CP violation ~ 10σ C.L. for δ_{CP}~±90°.
- Capability to discover CP violation for at least 68% fraction of the true δ_{CP} values at 5σ for any value of true θ_{23}.

HyperK : Possible second Korean detector



Traditional liquid argon TPC readout scheme

- e- drift in the liquid phase in a uniform electric field
- read out by a system of wires: one collection view and one or more induction views.
- No amplification of the initial ionization signal: collection at the anode after losses due to the presence of impurities along the drift path.



The dual-phase scheme

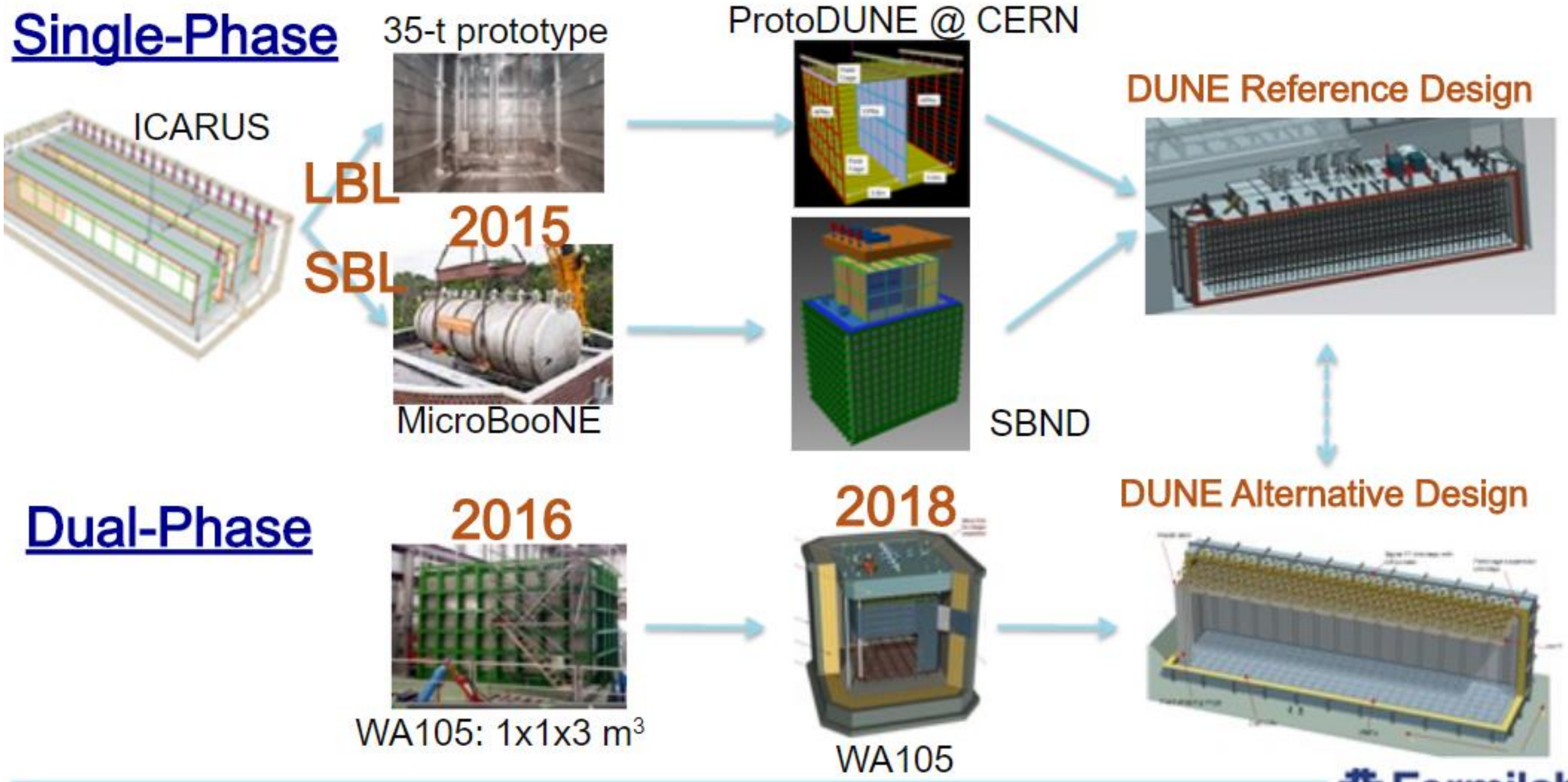
vertical drift up a region with a stronger electric field

→ *extraction of the electrons to the gas phase above the liquid level.*

→ *avalanche multiplication of the electrons in the pure argon gas in confined regions with very strong electric fields*

(Micro-pattern detectors like the Large Electron Multipliers **(LEM)**, located just above the liquid level)

- Fermilab SBN and CERN neutrino platform provide a strong LArTPC hardware, electronics and software development and prototyping program



Single-Phase

ICARUS

LBL

SBL

35-t prototype

2015

MicroBooNE

ProtoDUNE @ CERN

SBND

DUNE Reference Design

Dual-Phase

2016

WA105: 1x1x3 m^3

2018

WA105

DUNE Alternative Design

M. Dracos EPS 2017

The ESS NUSB Project

Based on the European Spallation Source 5 MW beam (Lund, Sweden)
Design study (H2020) approved by EU
Developing results obtained by the EURONU SB WG
Synergies with the T2K and HK program

The neutrino target

NUFACT 2017

Marco Zito