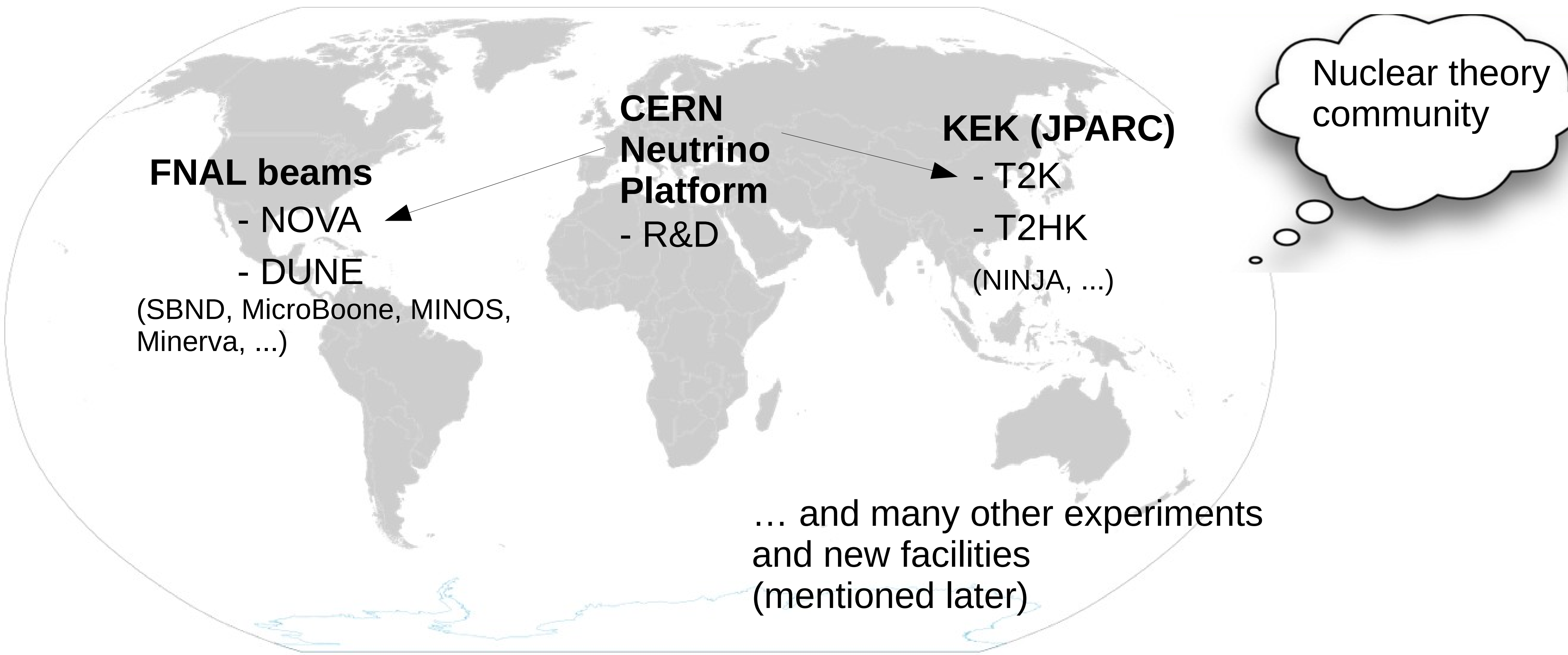
Scientific Council of IN2P3 – 26 October 2021

Introduction to next-generation (long baseline) experiments

S.Bolognesi (IRFU, CEA Saclay)

Neutrinos with beams around the world

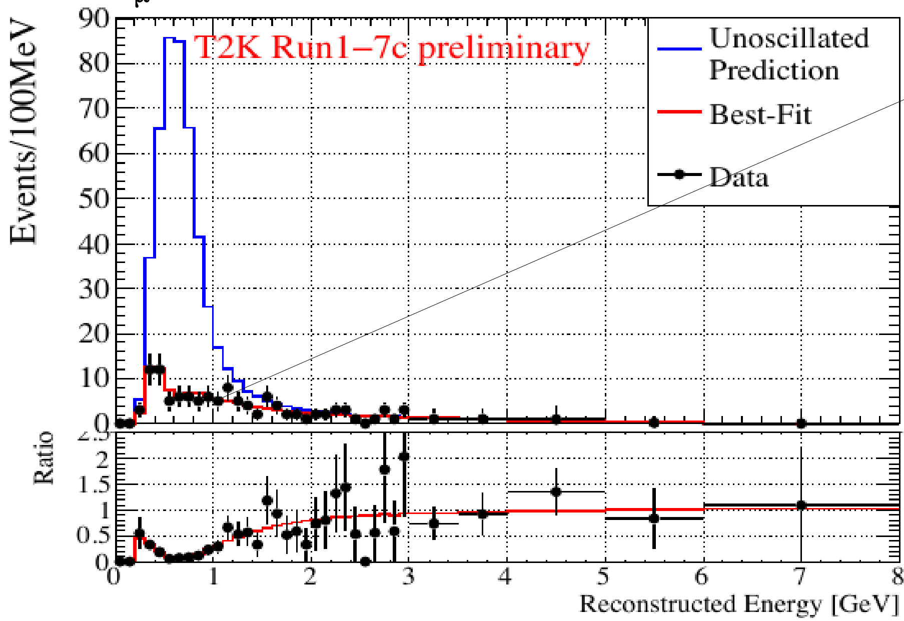
Neutrino oscillation physics with accelerators entered the precision era with NOVA and T2K → next generation experiments will be worldwide efforts comparable to collider experiments

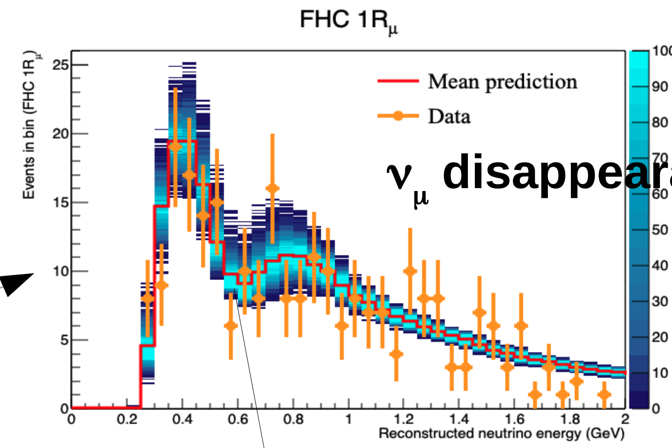


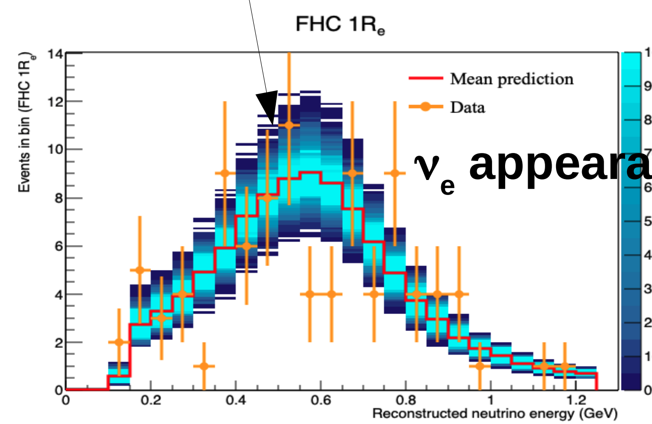
Neutrino physics has a rich present and a bright future!

Neutrino oscillations

ν_μ spectrum at the far detector







T2K preliminary Run1-10

$$P(\nu_\alpha \rightarrow \nu_\beta) = \underbrace{\sin^2(2\theta)}_{\textbf{amplitude}} \sin^2\left(\underbrace{1.27\frac{\Delta m^2_{ji}[\mathrm{eV}^2]L[\mathrm{km}]}{E_\nu[\mathrm{GeV}]}}_{\textbf{frequency}}\right)$$

(simplified 2-flavors approximation)

Atmospheric angle (θ_{23}) is mostly about measuring the size of the ν_μ deep → requires **rate (ie cross-section+flux)** of muon neutrinos under control at the oscillation maximum)

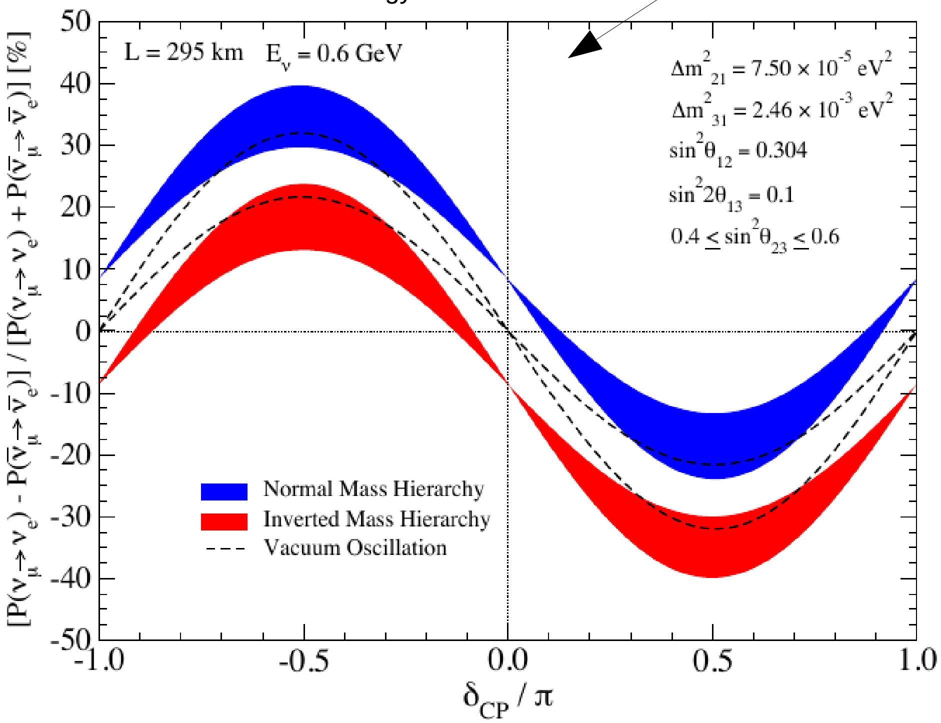
Atmospheric mass difference (Δm^2_{32}) is mostly about measuring the position of the minimum → requires good control of **neutrino energy reconstruction**

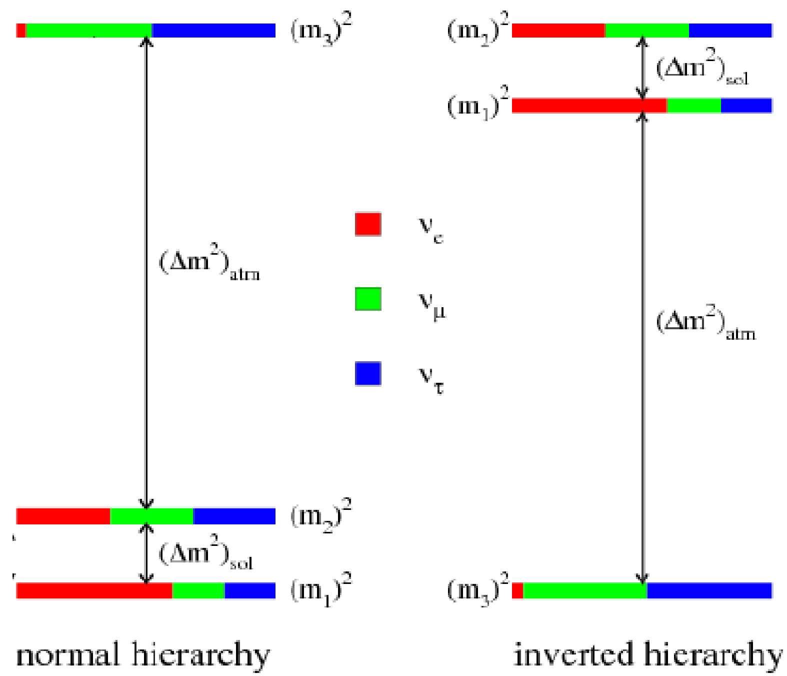
$\nu_e/\overline{\nu}_e$ appearance: δ_{CP} and MH

$$\mathcal{A}_{CP} \equiv \frac{P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\overline{\nu}_\mu \to \overline{\nu}_e)} \simeq - \frac{\sin 2\theta_{12} \sin\delta}{\sin\theta_{13} \tan\theta_{23}} \Delta_{21} + \text{matter effects},$$

longer the baseline → larger MH sensitivity

T2K baseline and energy



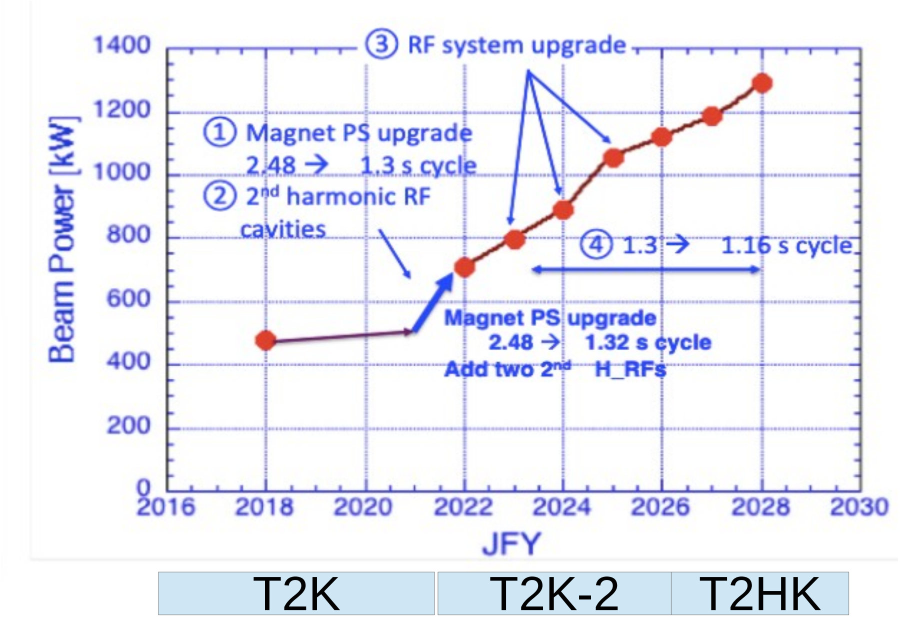


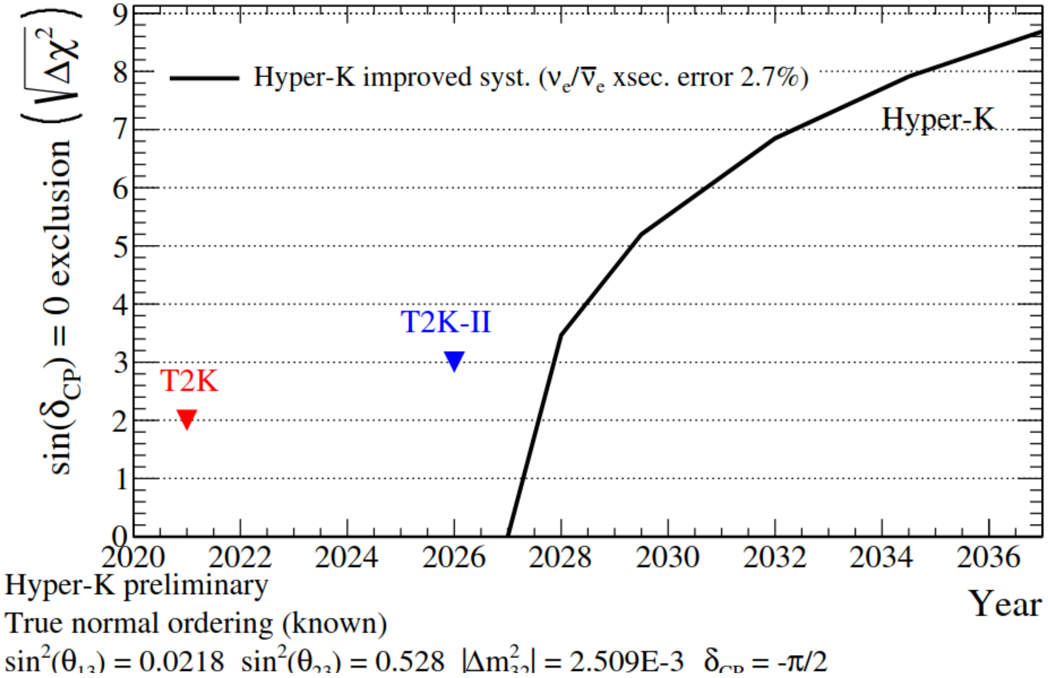
δ_{CP} parametrizes different oscillations for ν and $\overline{\nu}$ → **new fundamental source of CP violation (and first in leptonic sector!)**

Mass Hierachy : is the mass ordering the same for charged and neutral leptons?

T2K → T2K-"2"→ T2HK

- **Beam upgrade from 500kW to 750kW in 2022 for T2K → 1.3MW in HyperKamiokande era**





- **Seamless program of neutrino beam**

- T2K-"2" will push further the study of systematics at % level with upgrade of near detector ND280.

- ND280 upgrade will be ported from T2K to HK: robust path to understand of systematic from day 1 of HK

- **Hyperkamiokande: huge water cherenkov detector on JPARC upgraded beam**

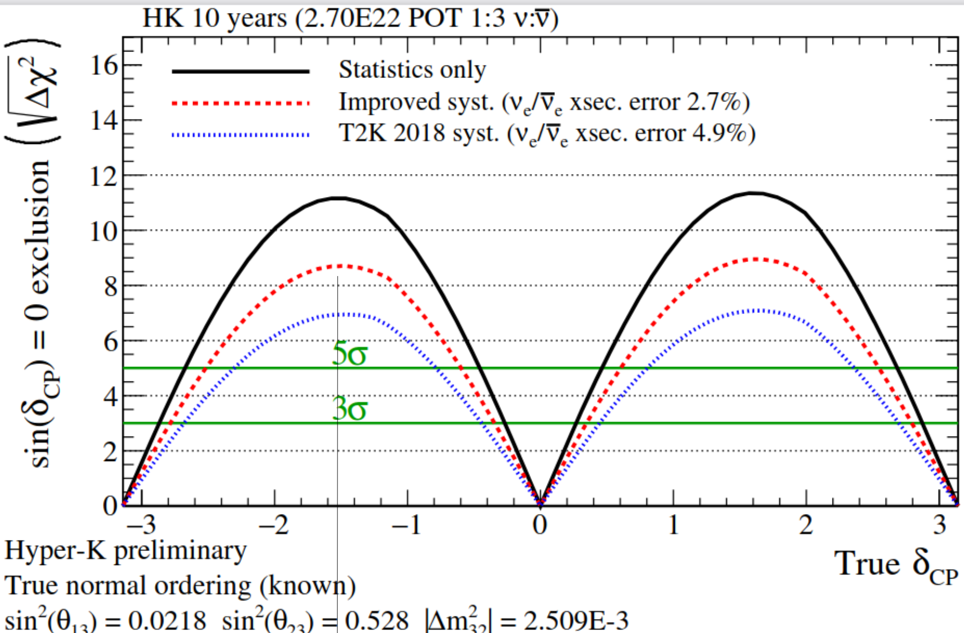
- 190kTon fiducial mass (x8.4 SuperKamiokande)

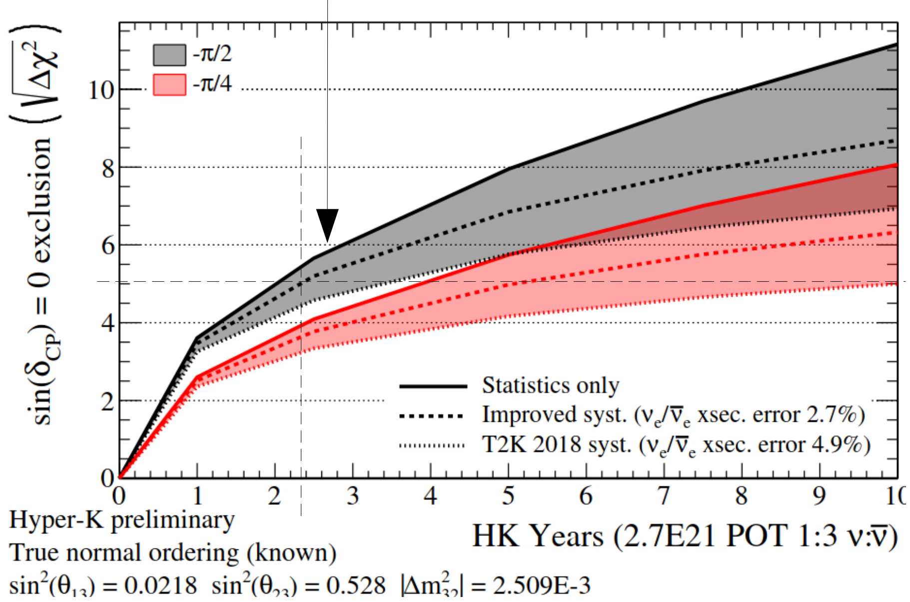
→ more than x20 SuperKamiokande beam instantaneous neutrino rate

→ **enabling very fast CP-violation discovery**

HyperKamiokande sensitivity

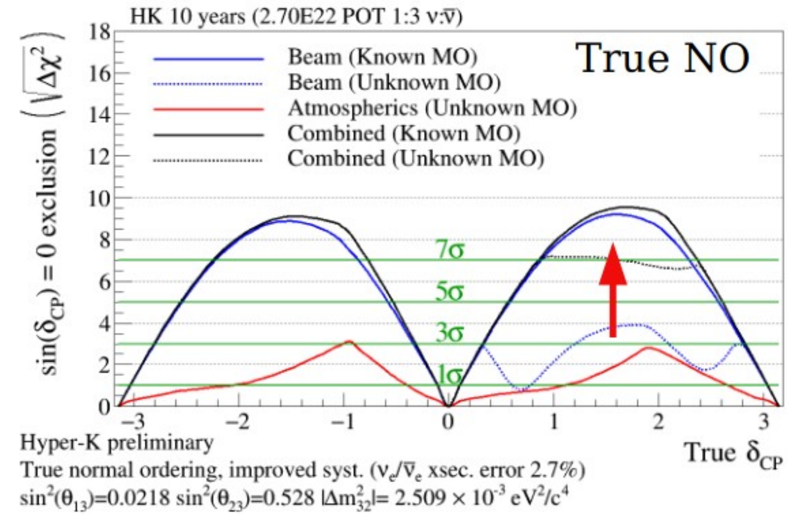
CP-violation sensitivity with known mass hierarchy: →

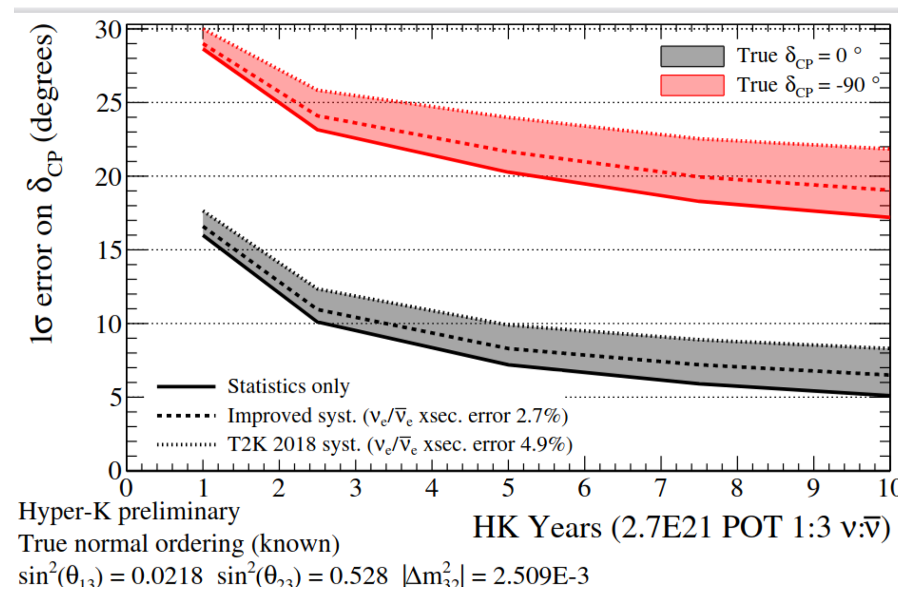




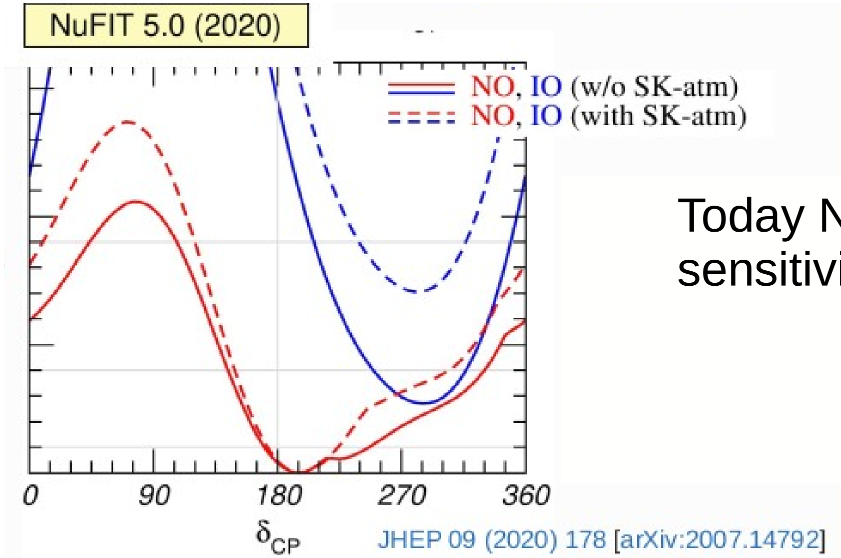
Unknown MH: combination of atm and beam neutrinos to measure δCP and MH

→ x8 SuperKamiokande natural neutrino rate





Mass Hierarchy

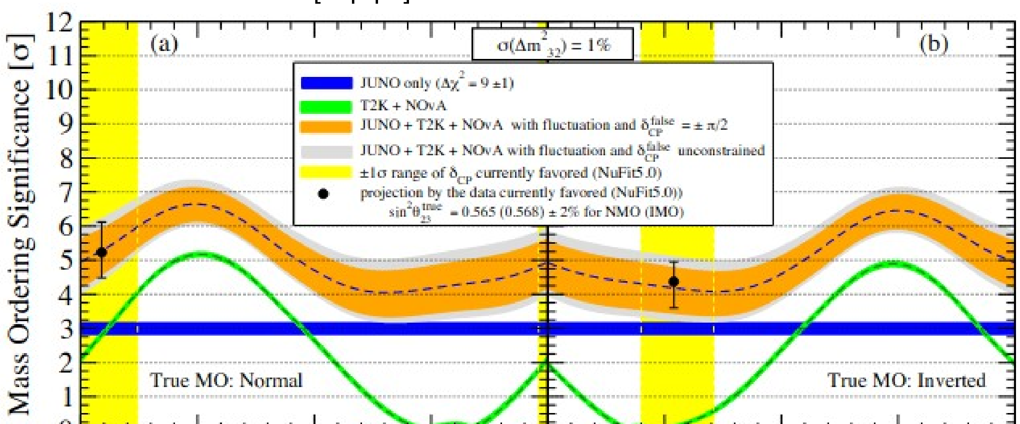


JHEP 09 (2020) 178 [arXiv:2007.14792]

Today NO favoured at 2.7σ: dominated by SuperKamiokande sensitivity + NOVA entangled measurement MH - δ_{CP}

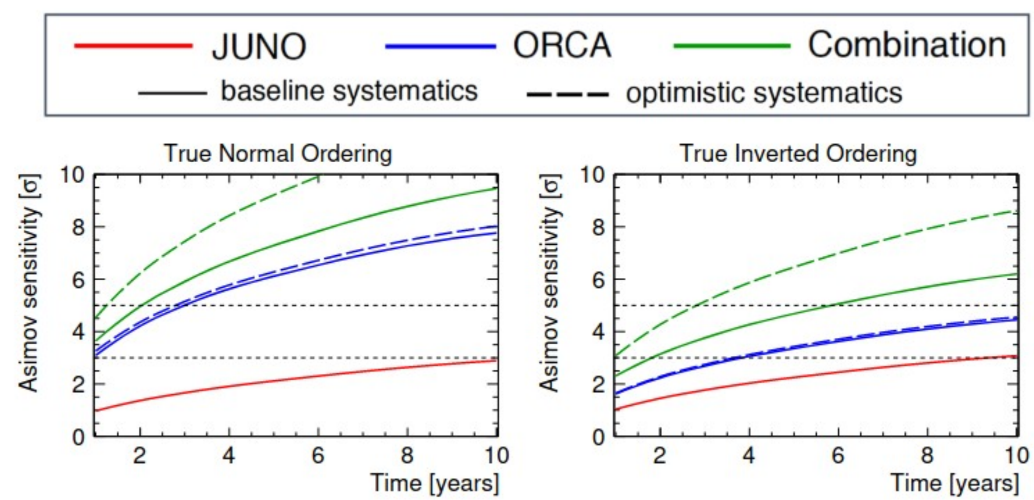
Combinations with JUNO and ORCA show sensitivities up to 5σ (SuperKamiokande not included)

arXiv:2008.11280 [hep-ph]



JUNO+T2K+NOVA

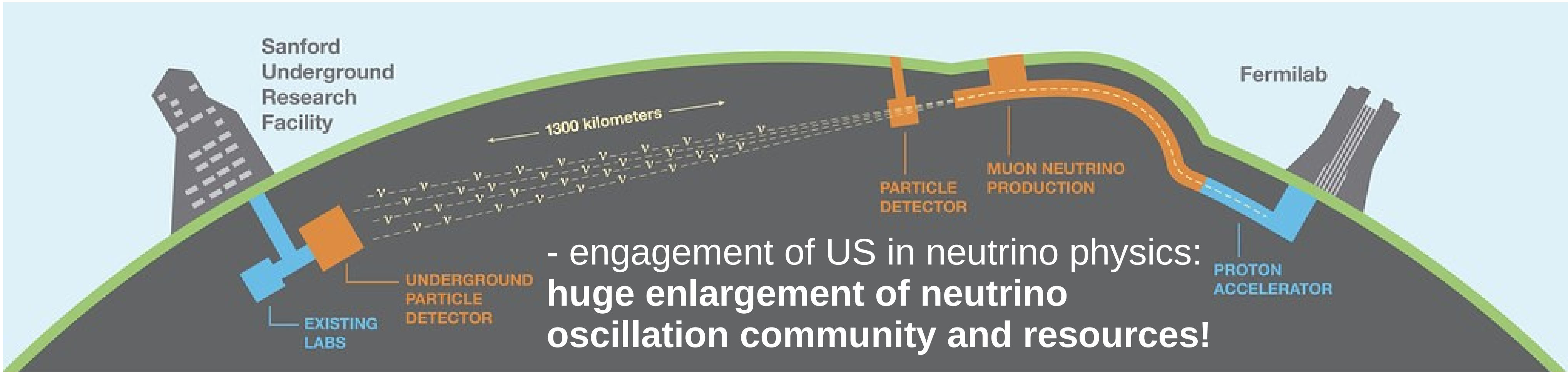
arXiv:2108.06293 [hep-ex]



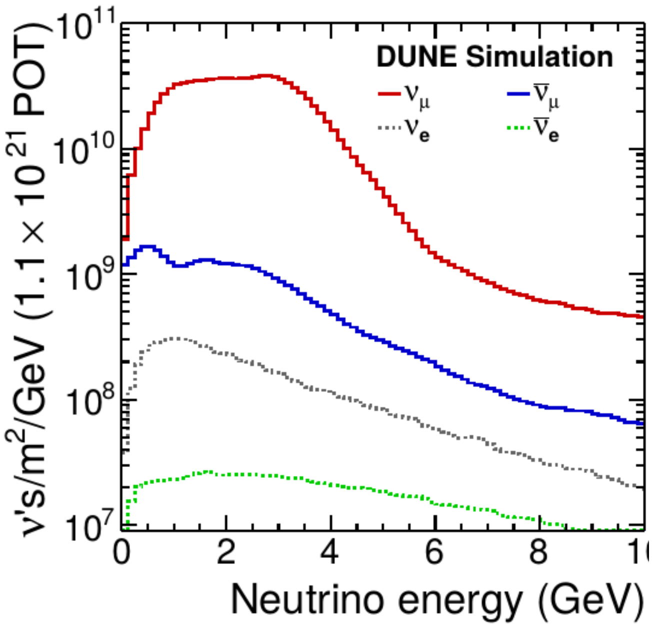
JUNO+ORCA

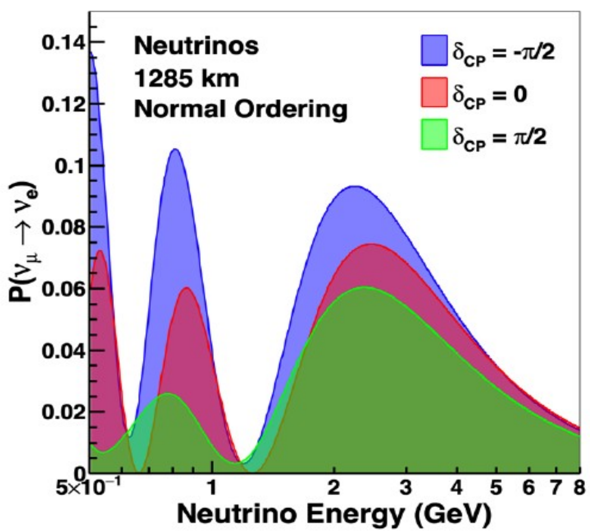
DUNE

New wide-band neutrino beam at Fermilab: 1.2MW → 2.4MW with a 1300km baseline



- engagement of US in neutrino physics: **huge enlargement of neutrino oscillation community and resources!**



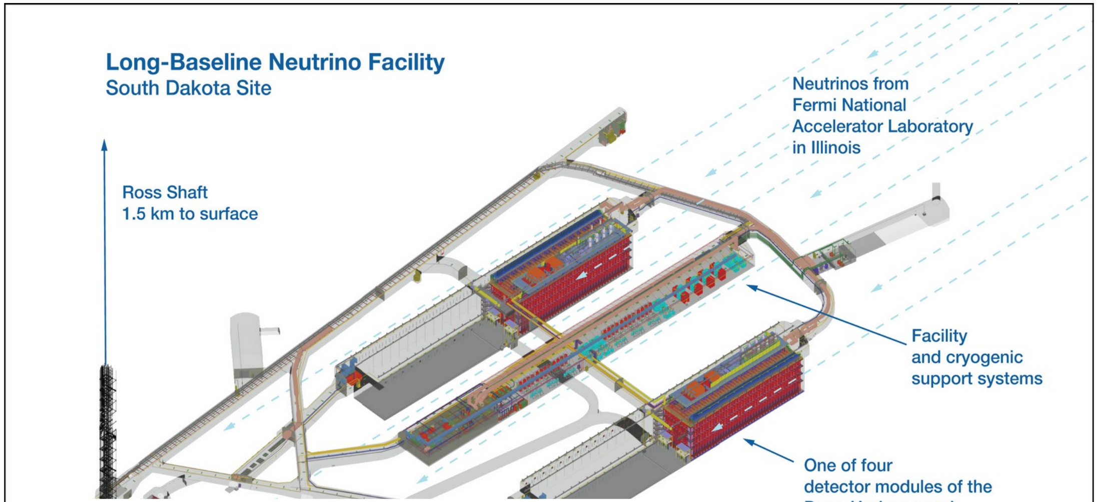


- Cover two oscillation maxima → a lot of shape information to exploit for precision physics on PMNS paradigm

- To exploit full sensitivity a shape analysis is needed
→ need extremely good resolution on neutrino energy reconstruction

DUNE: far detectors

(Relatively) new technology to be deployed to unprecedented scale: huge LAr TPCs with charge readout

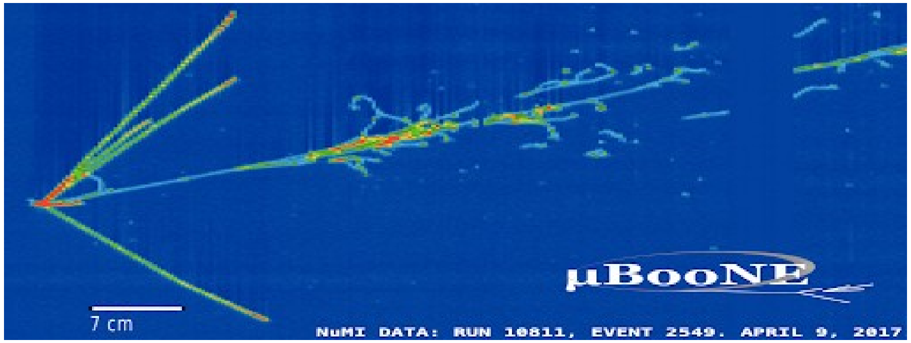


Wonderful opportunity for very interesting R&D

- **4 LAr TPC:** 4 x 10kTon fiducial mass. Staged approach (from 2029 to 2035)

- Full reconstruction of final state particles **→ prospects for extremely good resolution on neutrino energy**

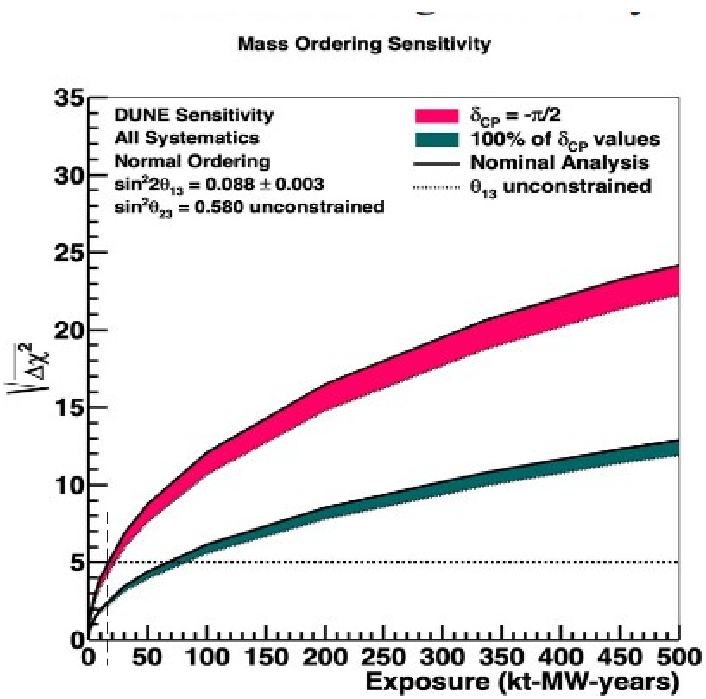
(except neutrons)

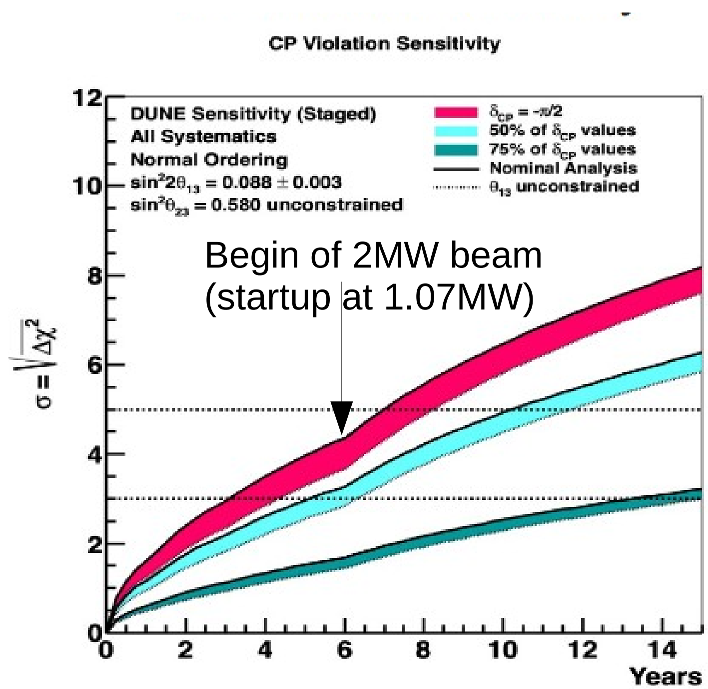


- **Argon target**: 'heavy' target with complex nuclear effects (eg nuclear transparency to protons 50%)

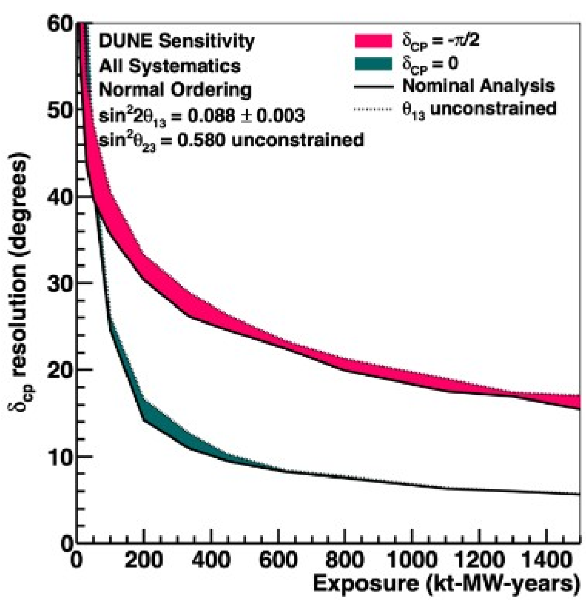
- Big challenge: new detectors, new beam, new energy, new nucleus → challenge of characterizing all these novelties would strongly profit of **'anchoring' points** (eg: ProtoDUNE, MicroBoone Argon studies, neutrons in ν interactions from ND280 upgrade, ...)

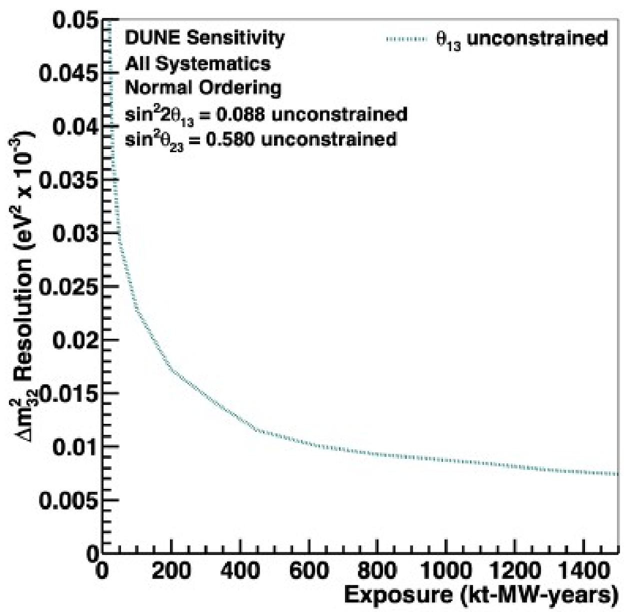
DUNE sensitivity





- **Very fast MH determination at 5σ**
  due to very large baseline
  → large matter effects





- **Precision physics: prospects for δ_{CP}, Δm^2 resolution**

HK & DUNE

- HyperKamiokande has prospects of very fast CP violation discovery and precise measurements of $\sin\theta$ and Δm^2.

- It is a **“safe”** technology based on existing beam (being upgraded) and with **robust** sensitivity studies based on T2K experience.
- The timeline is **realistic**

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- **JUNO+ORCA(+SK+NOVA)** has prospects of 5σ establishement of Mass Hierachy

- **DUNE** will have very fast sensitivity to MH and prospects of precise measurements of sinθ and Δm^2 ("in a different way")

    "open a new window" "measurement of MH and δ_{CP} in the same experiment"

What does it means? **Why both HK and DUNE?**

The question is: do we expect the study of neutrino oscillations to have a future beyond the low-hanging fruits of CPV and MH?
If so, we should look at the topic from a **wider prospective** (beyond the present "simplistic" paradigm of the measurement of PMNS parameters)

What we want to do is to characterize **precisely** the oscillation as a function of the fundamental variable **L/E**

→ **different baselines** → characterizing oscillations beyond PMNS

→ study oscillations at **different neutrino energies**

→ reconstruct neutrino energy with **different technologies**

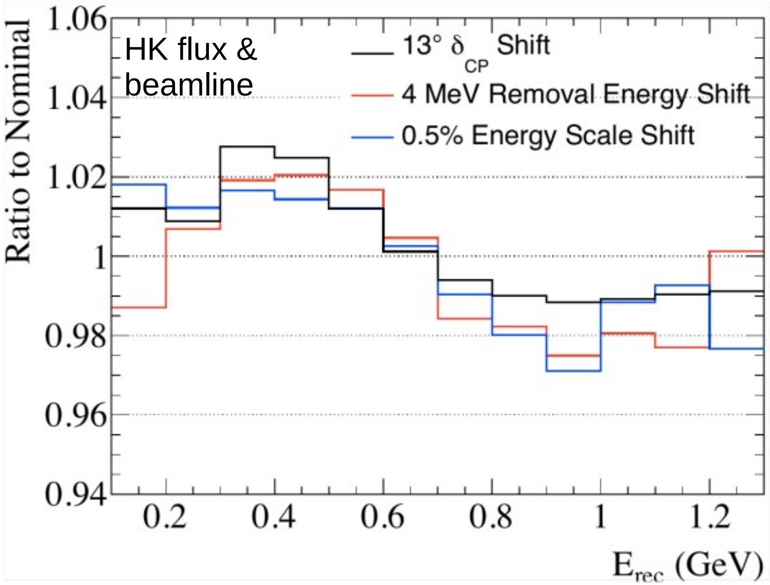
I will make few examples of **complementarity and importance of combination: PMNS precision, beyond PMNS**

Precision measurements of PMNS parameters

- Precision physics will be dominated by systematics

  - ~2000 of ν_e ($\bar{\nu}_e$) and ~10000 events ν_μ ($\bar{\nu}_\mu$)

  → precision measurements require very good control of **neutrino energy spectrum shape**



Both HK and DUNE aim to same precision targets:

measurement of δ_{CP} <15deg and of Δm^2 ~ 1% require control of energy scale (calibration + nuclear effects) <1%

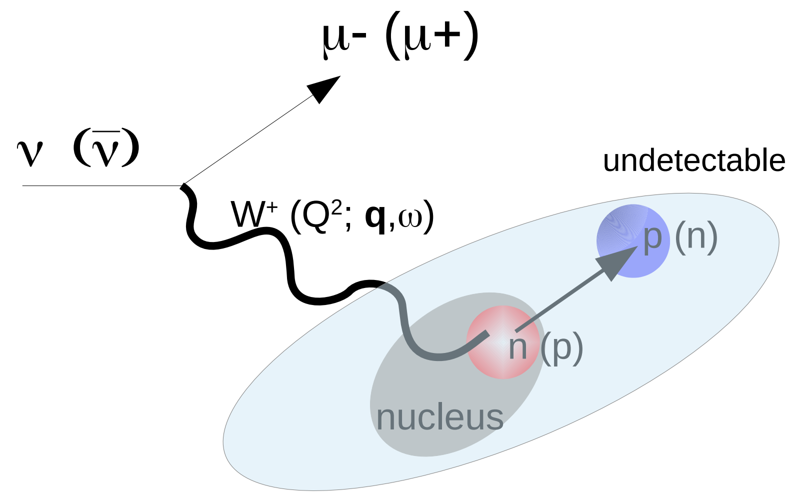
- Crucial role of **present experiments (T2K – NOVA) to open the road to % systematics** and indicating analysis strategies and detector design enabling such precision

- Crucial role of **near detectors**

Neutrino energy reconstruction

HyperKamiokande: can measure neutrino energy with lepton only

- protons below Cherenkov threshold
- neutrons can be tagged with Gd-doping but not measured

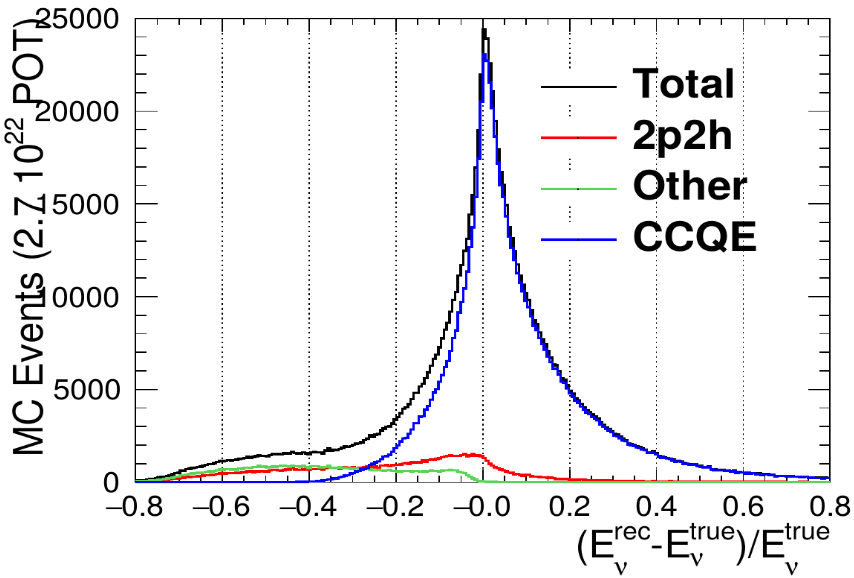


The resolution is intrinsically limited by nuclear effects

→ width from Fermi momentum

→ bias from nuclear removal energy

→ tail from nucleon-nucleon correlations and pion absorption in nucleus



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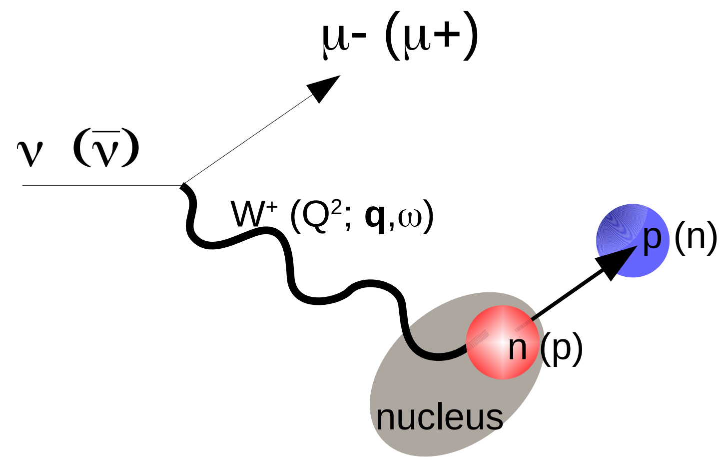

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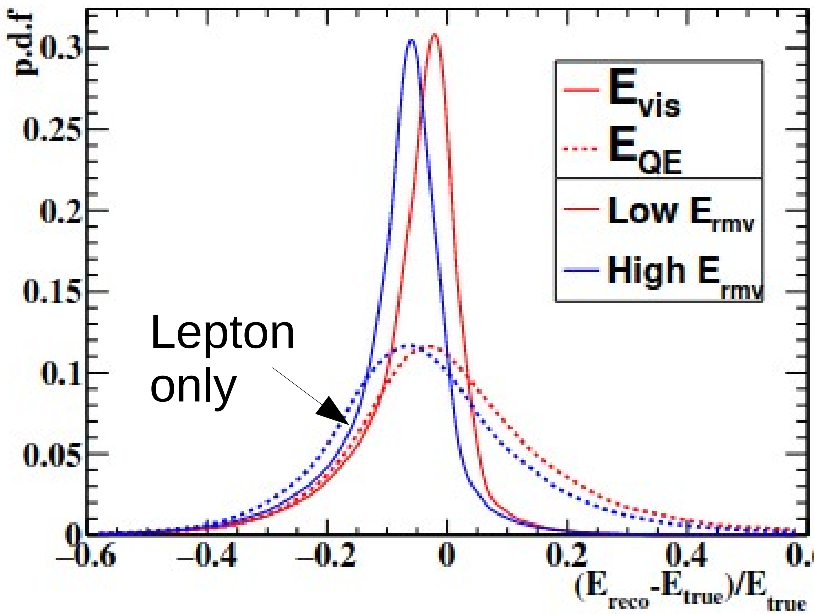
ND280 upgrade will be able for the first time to measure protons (at low momentum) and neutrons.
Exclusive reconstruction of final state is crucial to keep nuclear effects under control

With ND280-upgrade detector efficiency and resolution



Neutrino energy reconstruction

DUNE prospects to measure precisely Eν also at FD, thanks to exclusive reconstruction of leptons + hadrons with LAr

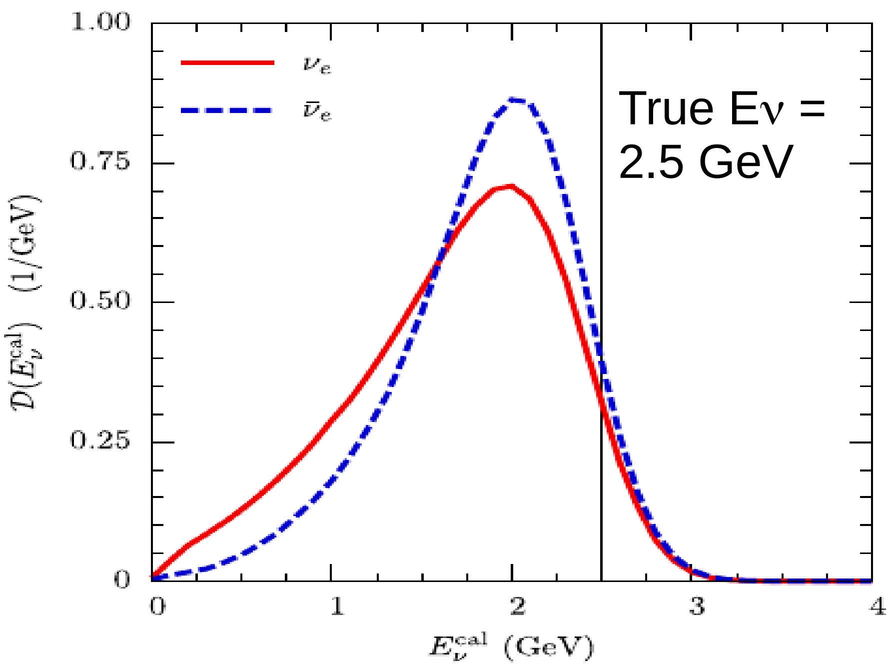
Nuclear effects are still important

→ energy removal (especially in a complex and 'new' nucleus as Argon)

→ correction for protons, pions stuck in the nucleus below tracking threshold (eg MicroBoone)

→ large uncertainty is coming from energy going into neutrons

J. Phys. G: Nucl. Part. Phys. **44** (2017) 054001



Complementarity HK and DUNE:

- different impact of nuclear effects
- importance of cross-check and combination of near detector measurements
  - especially for **DUNE**, which has to disentangle uncertainties due to **new beam, new detector technology, new nucleus**
  (neutron measurement at ND280 upgrade is the only anchoring point for neutron production in neutrino interactions)
  - **comparison of C,O and Ar interactions** provides useful handle for tuning and understanding of nuclear effects

Beyond PMNS

- **The ‘standard’ oscillation paradigm (PMNS-based) is very strict and not motivated by fundamental symmetries** (mixing angles and neutrino masses are ‘accidental’ numbers).
In particular it assumes
  - minimal 3-flavour scenario
  - standard neutrino interactions for production and detection
  - standard matter effects along propagation

Beyond PMNS

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In particular it assumes
  - minimal 3-flavour scenario
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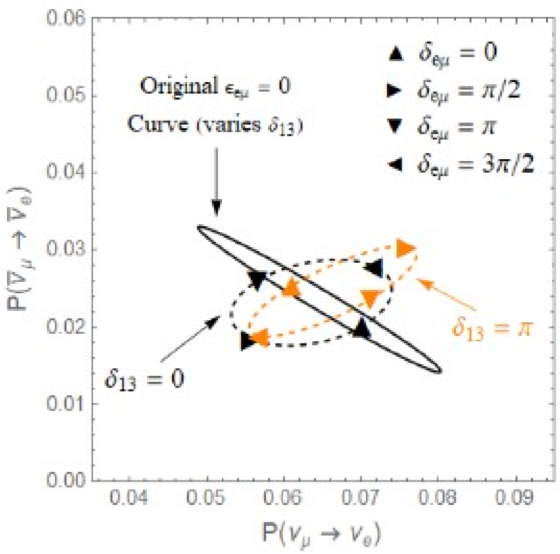
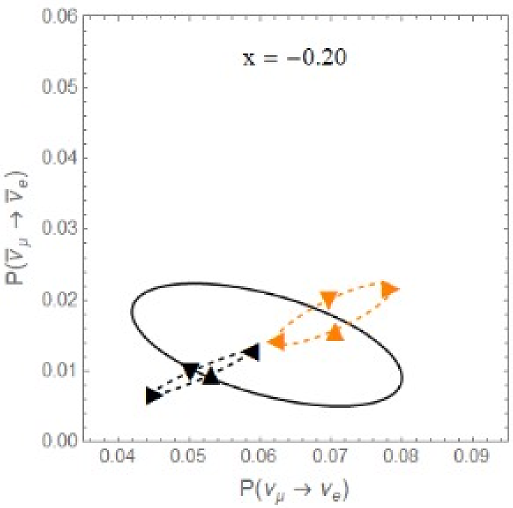
- **Combination of HK and DUNE beyond the PMNS paradigm useful for**
  - bounds on New Physics in specific models (eg, Non Standard Interactions)
  - more than the sum of sensitivities: effects of New Physics can offuscate 'standard' PMNS interpretation and induce degeneracies: comparison between experiments at different L/E solve them

Eg: new sources of **CP-violation in Non Standard Interactions** from non-diagonal terms in matter potential



moving to different (L/)E



CIPANP 2018, Print:1809.11128 [hep-ph]

Study of L

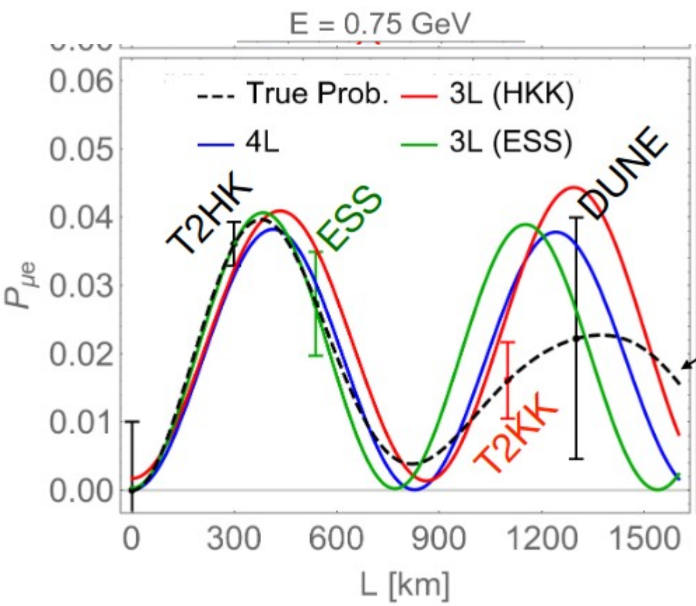
- Expand the oscillation study with a **more general paradigm: with next generation of experiments we will look at oscillations with a much more open-mind approach:** we want to characterize the L/E dependency of flavour mixing

Eg: can we search for **fundamental CP violation in a more model-independent way?**

- allow for arbitrary (non-standard) matter effect -
- allow for arbitrary (non-unitary) mixing between flavour and energy eigenstates (even different for production and detection)

→ search for T-violation → look for L dependency of oscillations at fixed energy

arXiv:2106.16099 [hep-ph]



No good fit with L-even terms only → T-Violation !

3nu probability with $\delta_{CP} = 90^{\circ}$

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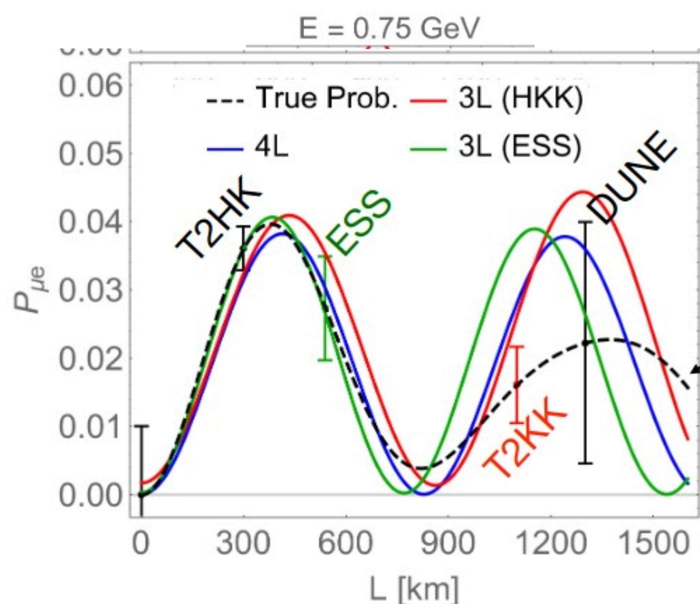

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3nu probability with $\delta_{CP} = 90°$

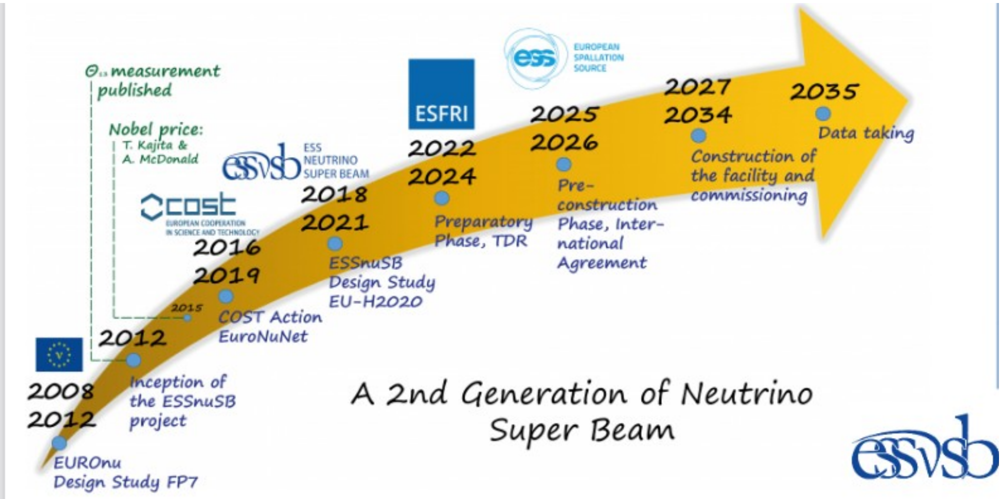
- Combination of experiments will be crucial for a **comprehensive, precise and open-minded** characterization of ν oscillations
Crucial to have a coherent program of Near Detectors + establish a common language in terms of nuclear models, ...
A reharsal: T2K+NOVA combination (really though!!)
It is difficult! → Start to plan for it well in advance!
Eg: BSMNu project financed by the P2IO labex → **French community covering multiple experiments is an ideal position to lead this effort**

Looking further into the future

- **T2KK:** second HK tank in Korea

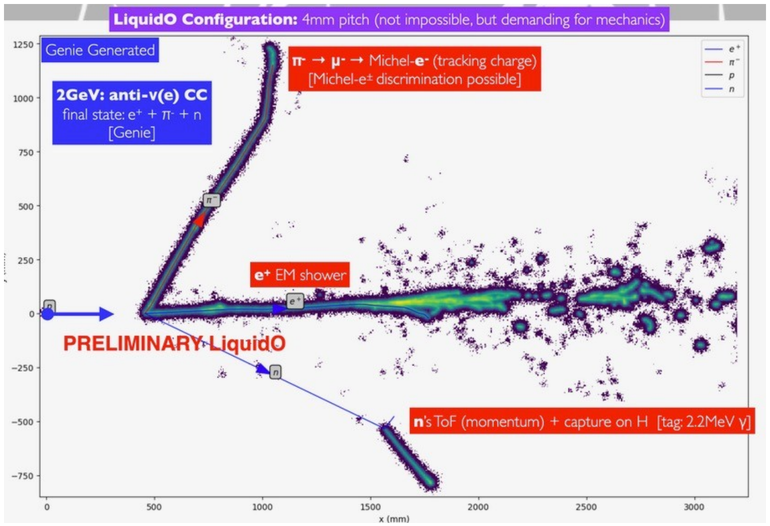
- **ESSνSuperBeam:**
covering 2nd oscillation peak
+ HIFI
(demonstrator for low energy νSTORM)

https://arxiv.org/abs/2107.07585

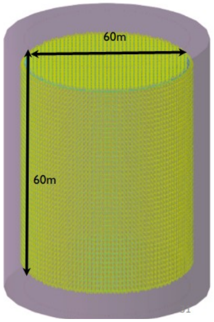


- **νSTORM:** muon storage ring giving very well known ν_e and ν_μ fluxes
(R&D toward Neutrino Factories)

- **LiquidO:** studies for even improved S/B and resolution
→ θ_{13}, non-unitarity, solar neutrinos...
Opaque target readout by many fibers
→ SuperCHOOZ



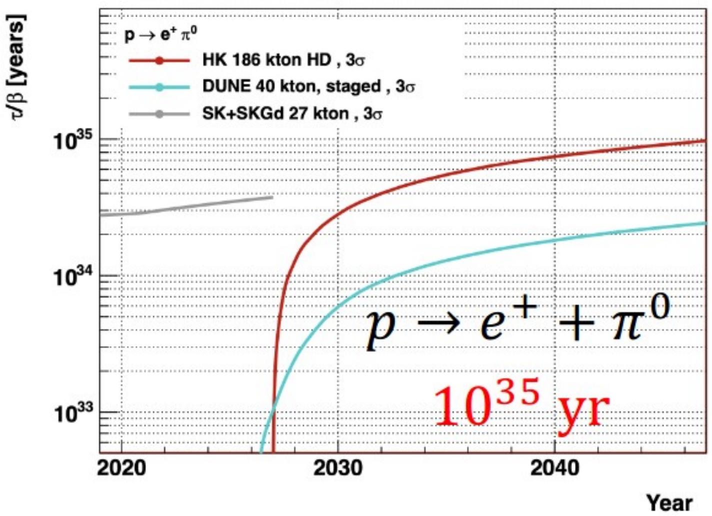
- **THEIA:** water based (doped) optical detector for comprehensive neutrino program (scintillation + Cherenkov)

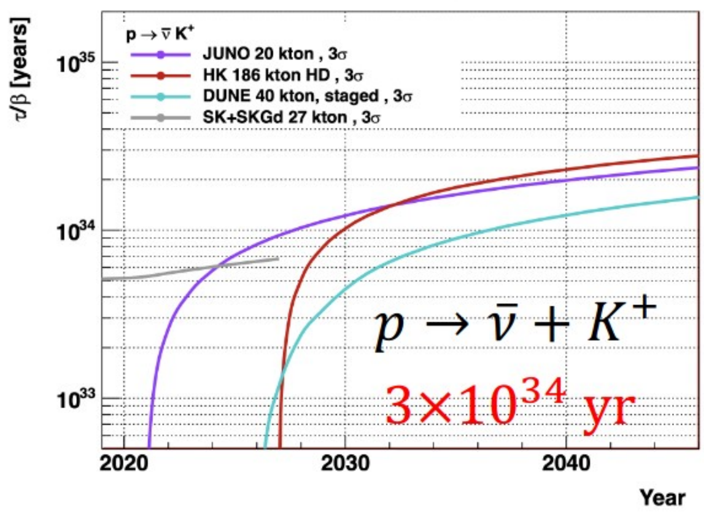


Proton decay + SN + DBSN

Last but not least, HK and DUNE will have an unprecedented reach for proton decays and SuperNova neutrinos

JUNO: J. Phys. G 43 (2016) 030401 (arXiv:1507.05613)
DUNE: FERMILAB-PUB-20-025-ND (arXiv:2002.03005)

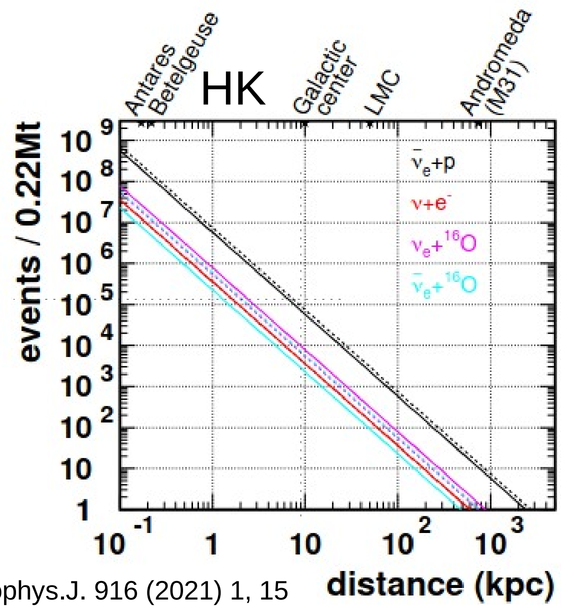




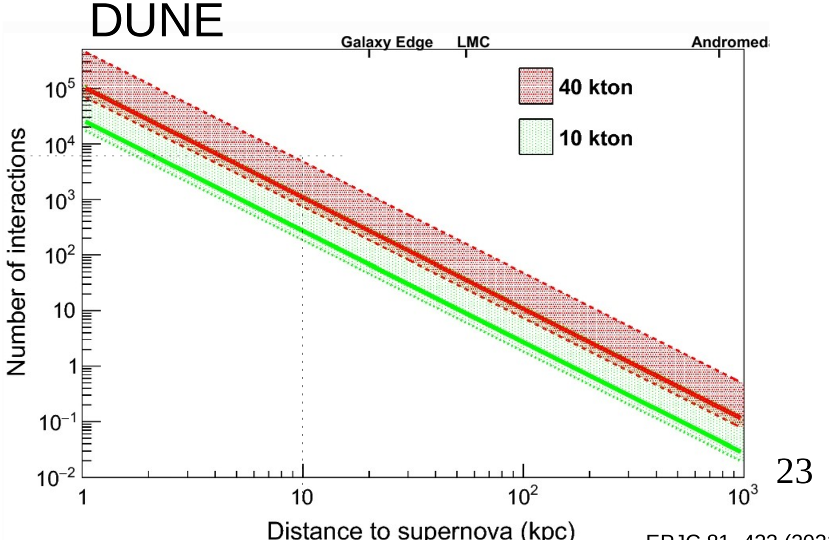
Proton lifetime sensitivity (at 3σ)

Number of observed event for Core-Collapse SuperNOVA

- different neutrino channels → sensitivity to time dependence of energy release



Astrophys.J. 916 (2021) 1, 15



EPJC 81, 423 (2021)

Summary

The study of neutrino oscillation has a vibrant present and sparkling future

The next generation of experiments will feature unprecedented sensitivity and precision

- **HyperKamiokande** will enable in fast and robust way large statistics samples, at the core of CPV discovery
→ the results of a seamless program of the highest quality for neutrinos in Japan

- **DUNE** is an opportunity for the neutrino community:

    - huge opportunity for interesting R&D and enlarging of neutrino community (Fermilab strong involvement!)

    - prospects to unprecedented neutrino energy resolution and to explore new L/E region

The cross-check and eventually combination of them will allow a **complete (open-minded) and precise (%-level systematics)** characterization of neutrino oscillations