Prospect of physics with large neutrino detectors

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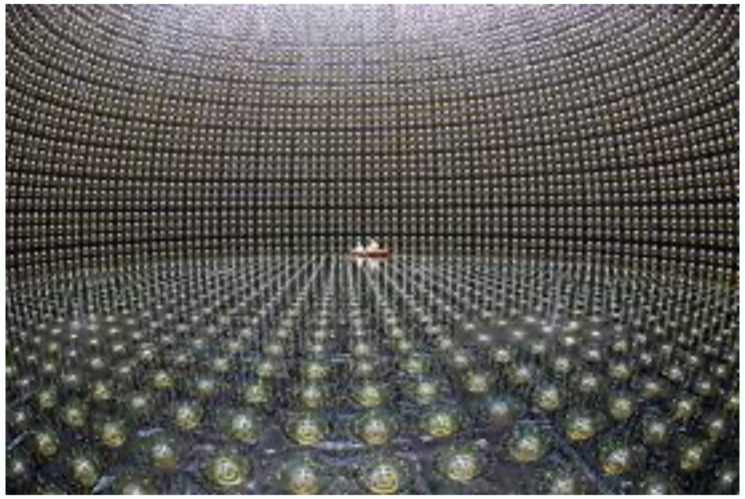
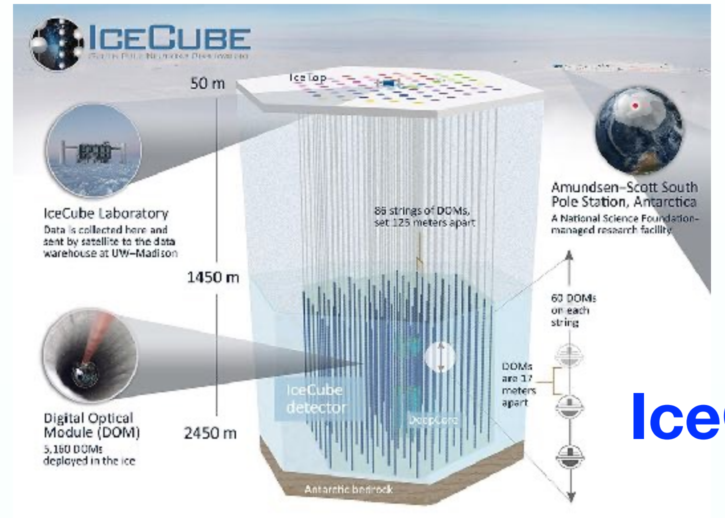
Physics in LHC and Beyond, May 12-15 2022, Matsue

Large (>10kt) neutrino detectors

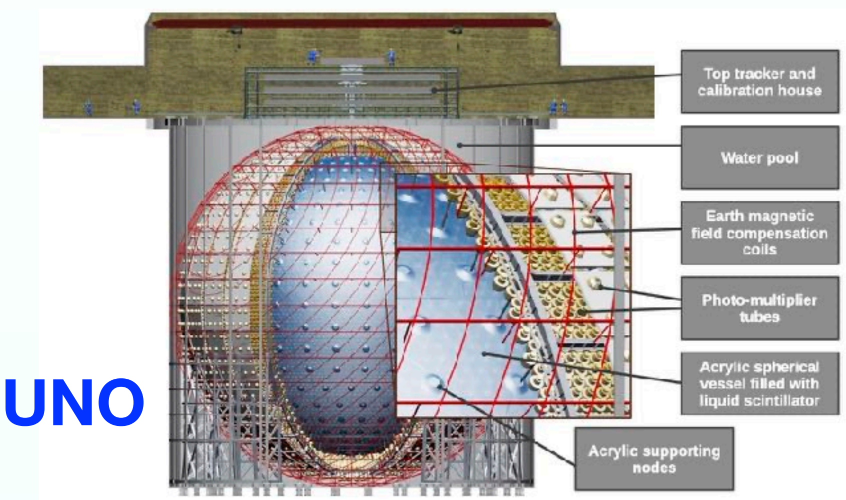


Super-Kamiokande, SK-Gd

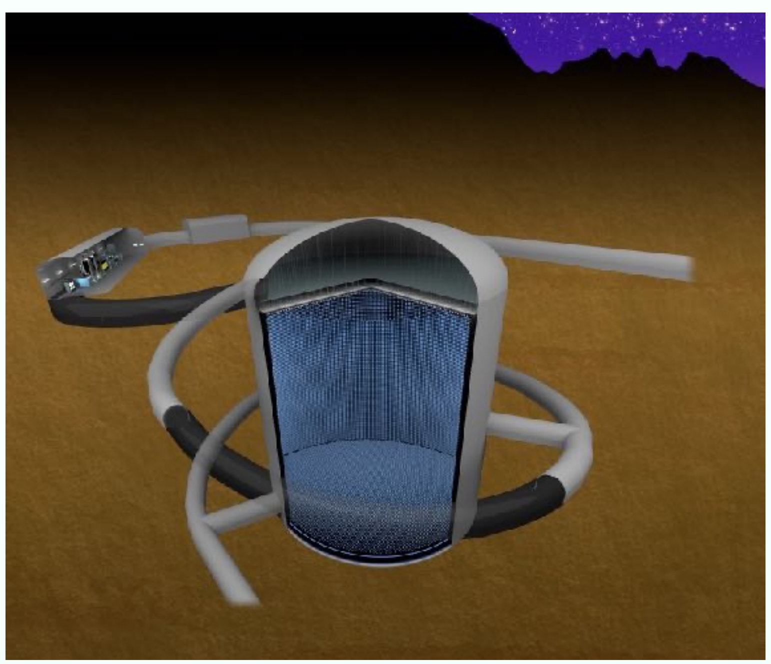


IceCube

NOvA

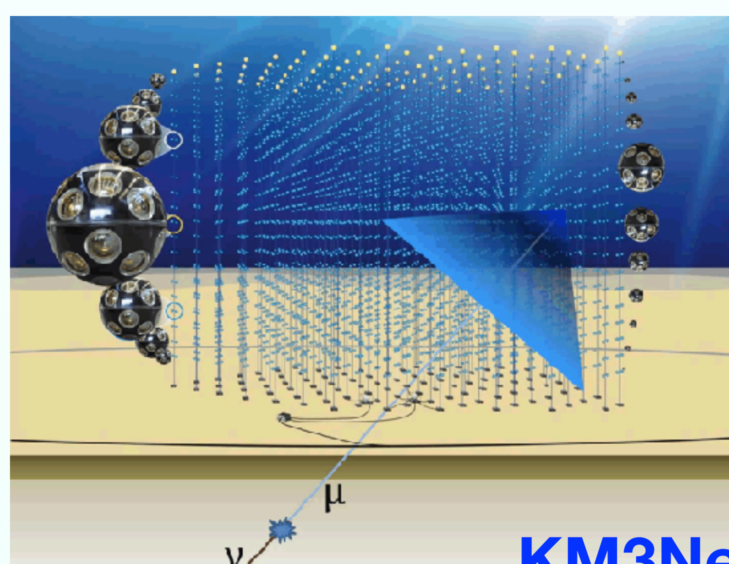


JUNO

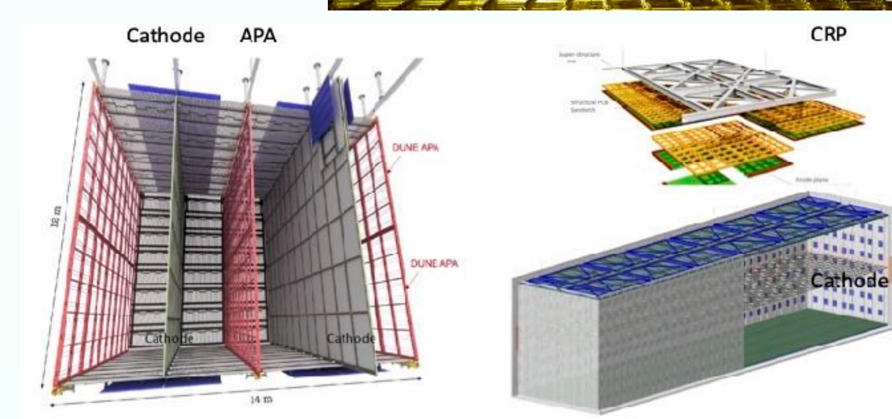


Hyper-Kamiokande

DUNE



KM3Net

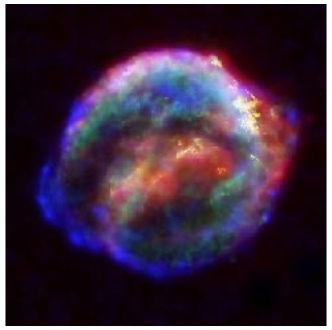


Physics with large neutrino detectors

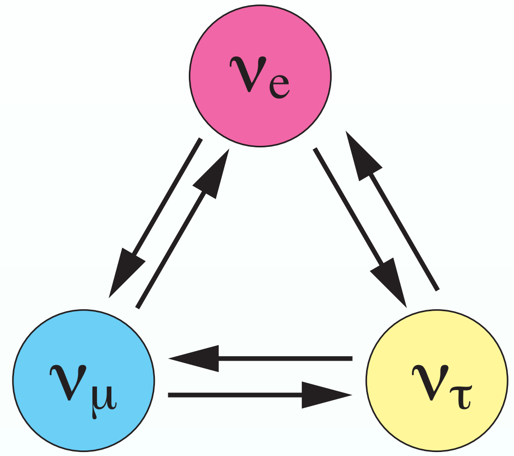
(MeV)

(>PeV)

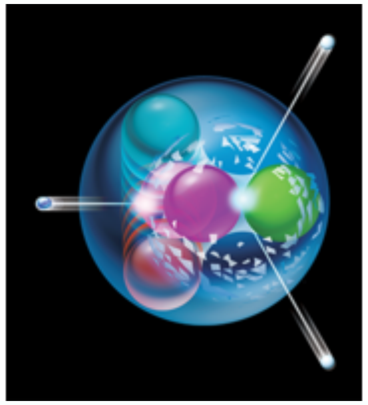
Supernova

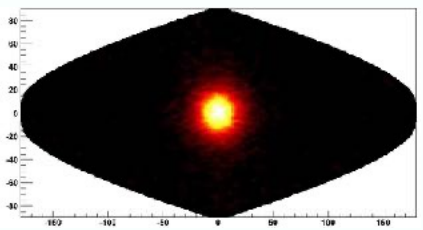


Neutrino oscillations



Nucleon decay

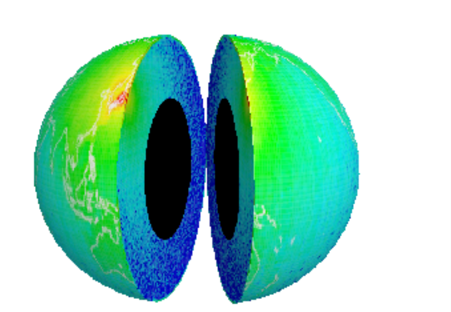




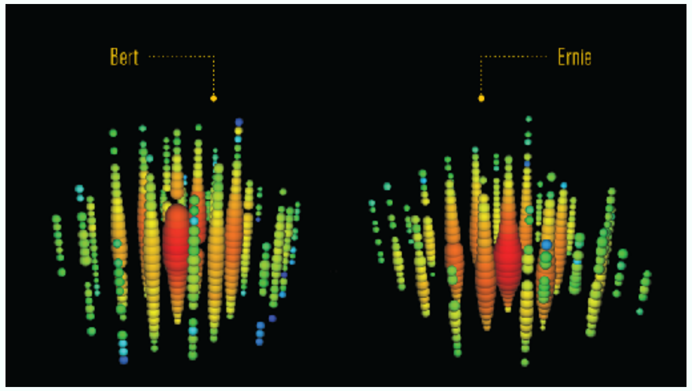
Solar physics

High energy neutrino astrophysics

Geophysics



http://kamland.stanford.edu/GeoNeutrinos/geoNeutrinos.html



IceCube collaboration

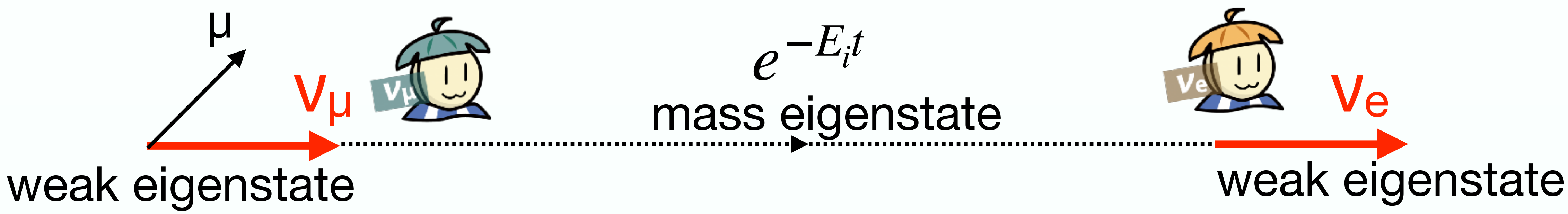
- Although they have very broad science coverage, this talk will focus on two topics related to particle physics
  1. **Neutrino oscillation**
  2. **Nucleon decays**

Neutrino oscillations

$$|\nu_\alpha\rangle = \sum U^*_{\alpha i} |\nu_i\rangle$$

Weak eigenstates Mass eigenstates

Higgstan.com



Production Propagation Detection

Flavors change during flight

$$P = \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E}$$ (for 2 flavor case)

θ: mixing angle

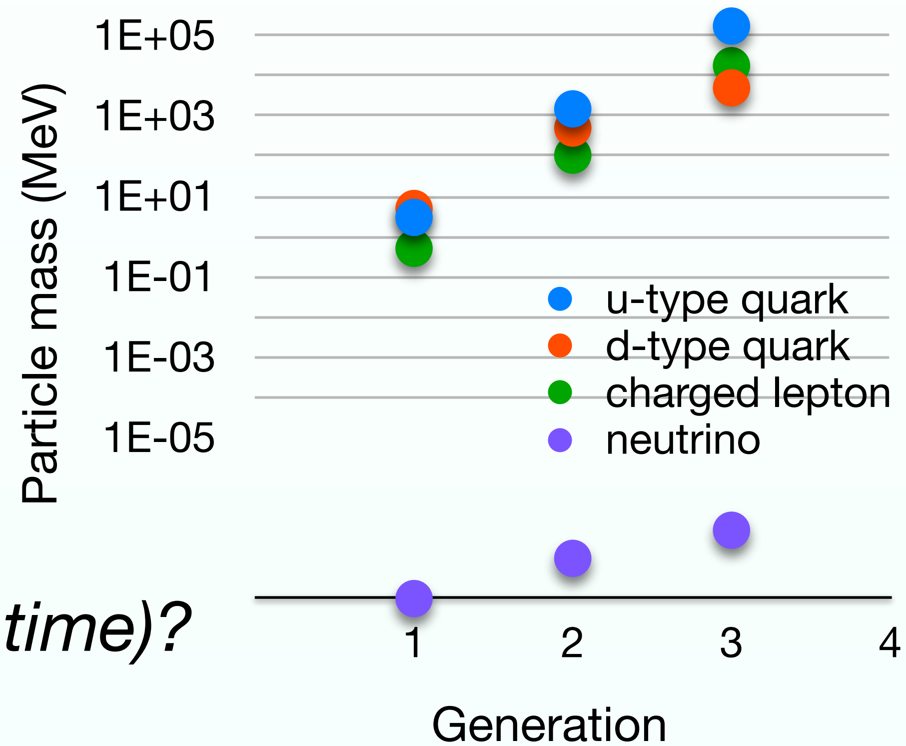
Δm²: mass-squared difference

Quantum effect over very macroscopic (>100km) length!

Neutrino oscillations

We learned a lot about neutrinos through **neutrino oscillation**, but many questions emerged and remain

- Origin of **tiny mass**
  - *Why the mass is much smaller than other fermions?*
- **Large mixing** parameters
  - *Why so different from quarks?*
  - *Symmetry behind the pattern?*
- **Mass ordering**
  - *Which is the heaviest?*
- **CP** violation
  - *Is this fundamental symmetry violated (for 2nd time)?*
- Extra neutrino **families**?



Properties of neutrino are considered to be connected with fundamental questions

- Source of baryon asymmetry of Universe?
- Very high scale physics? (seesaw?)
- Origin of generations?

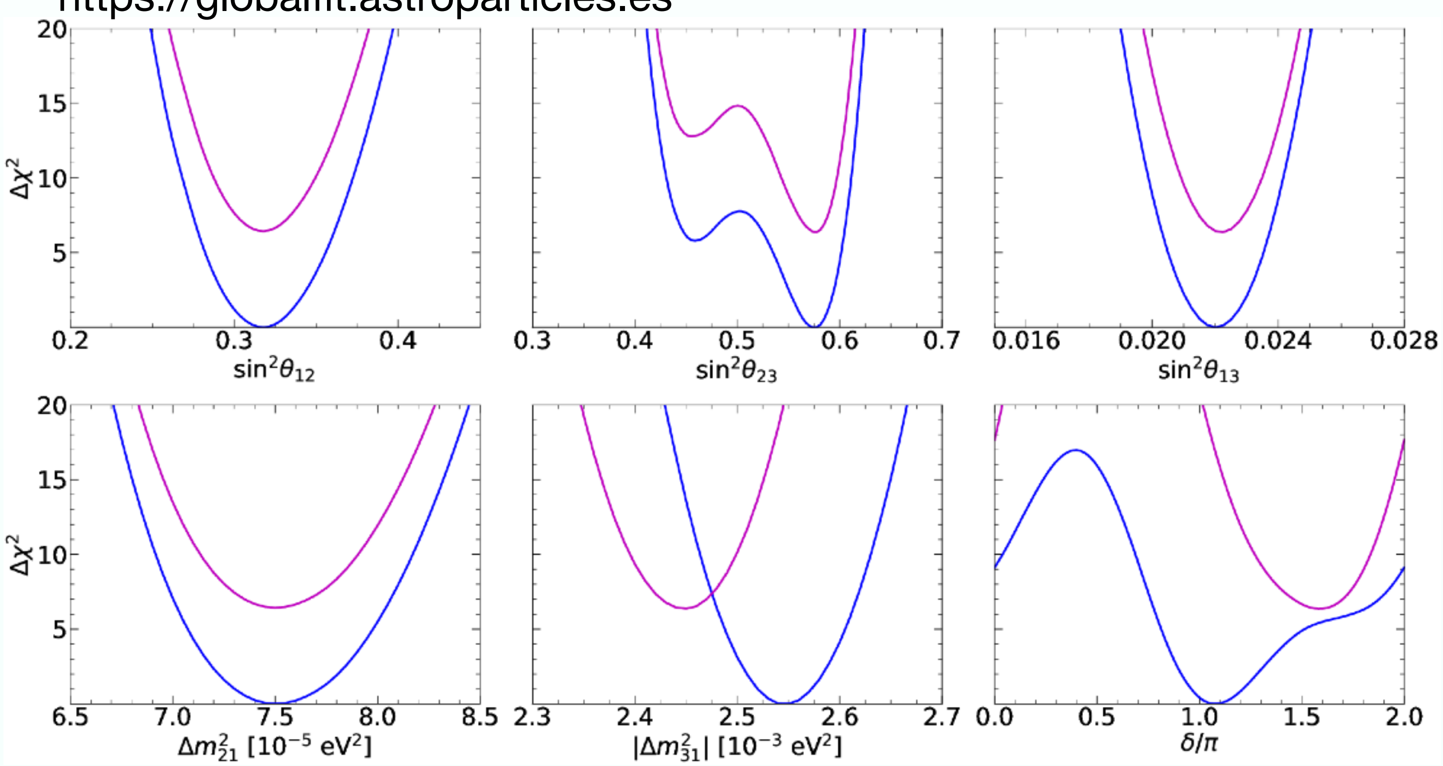
Oscillation measurement status

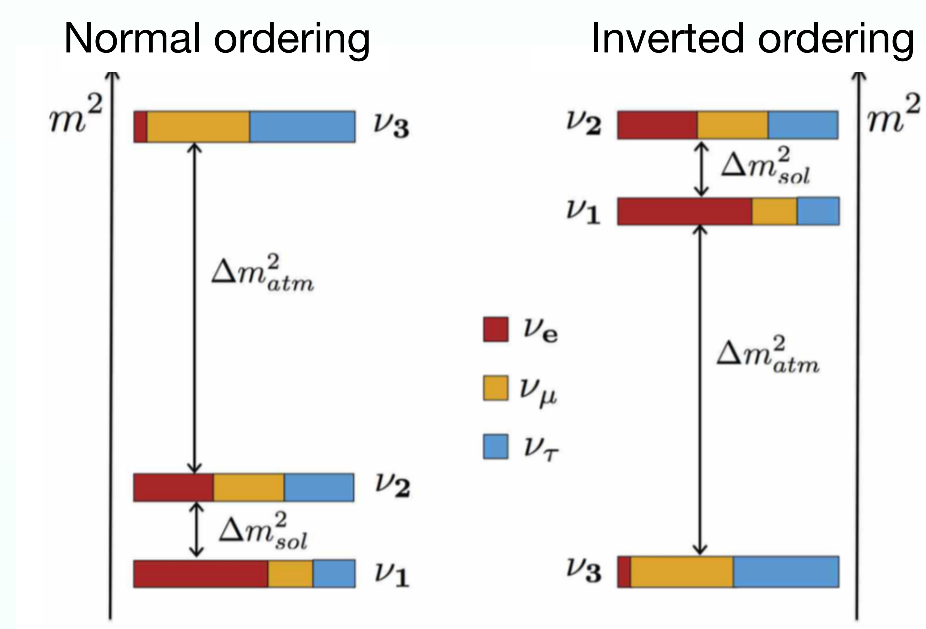
3-flavor mixing matrix

θ_{12}, θ_{23}, θ_{13}, δ_{CP}

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

https://globalfit.astroparticles.es





$|\Delta m^2|$, θ measured to ~3-5%

J_{CP} ~ 0.03 $\sin\delta_{CP}$

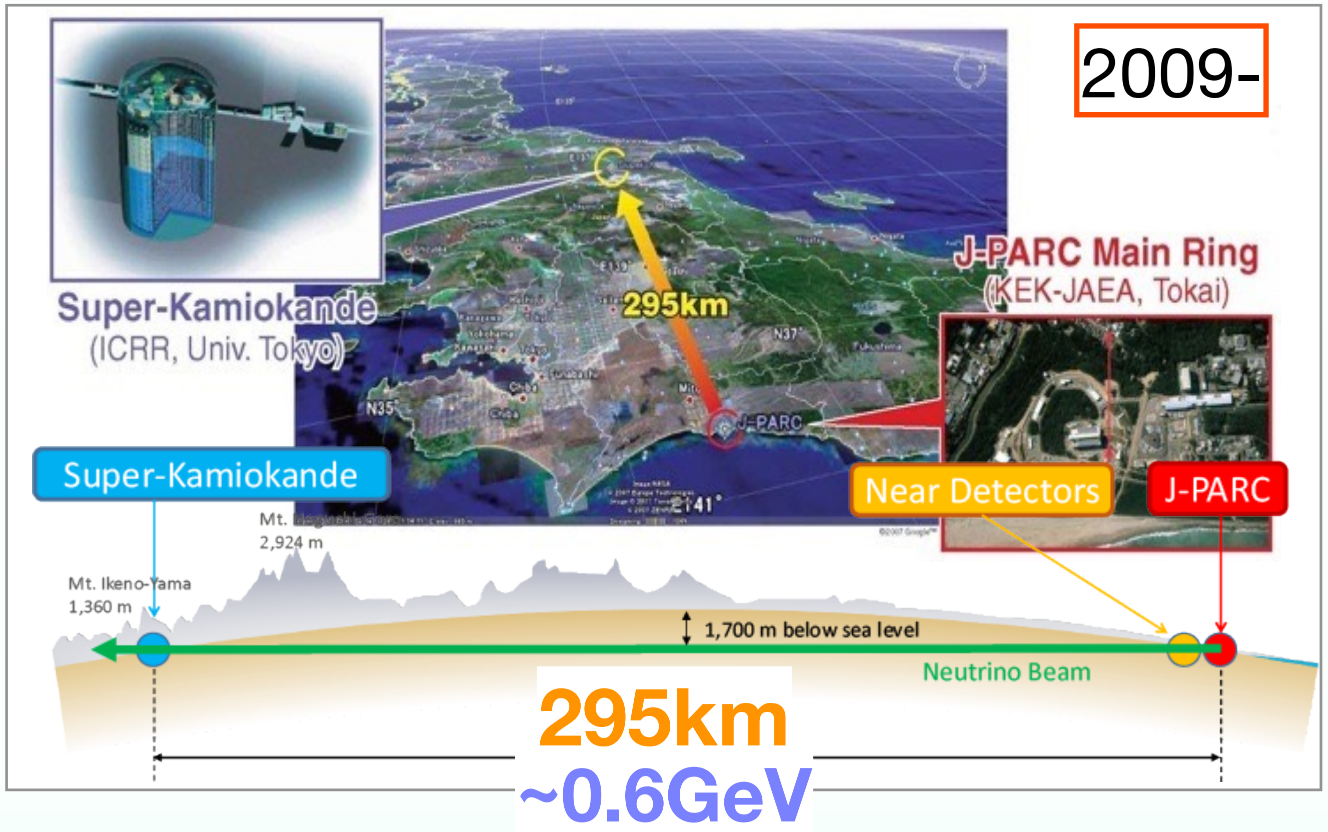
(⇔~3×10^{-5} for CKM)

Current major targets

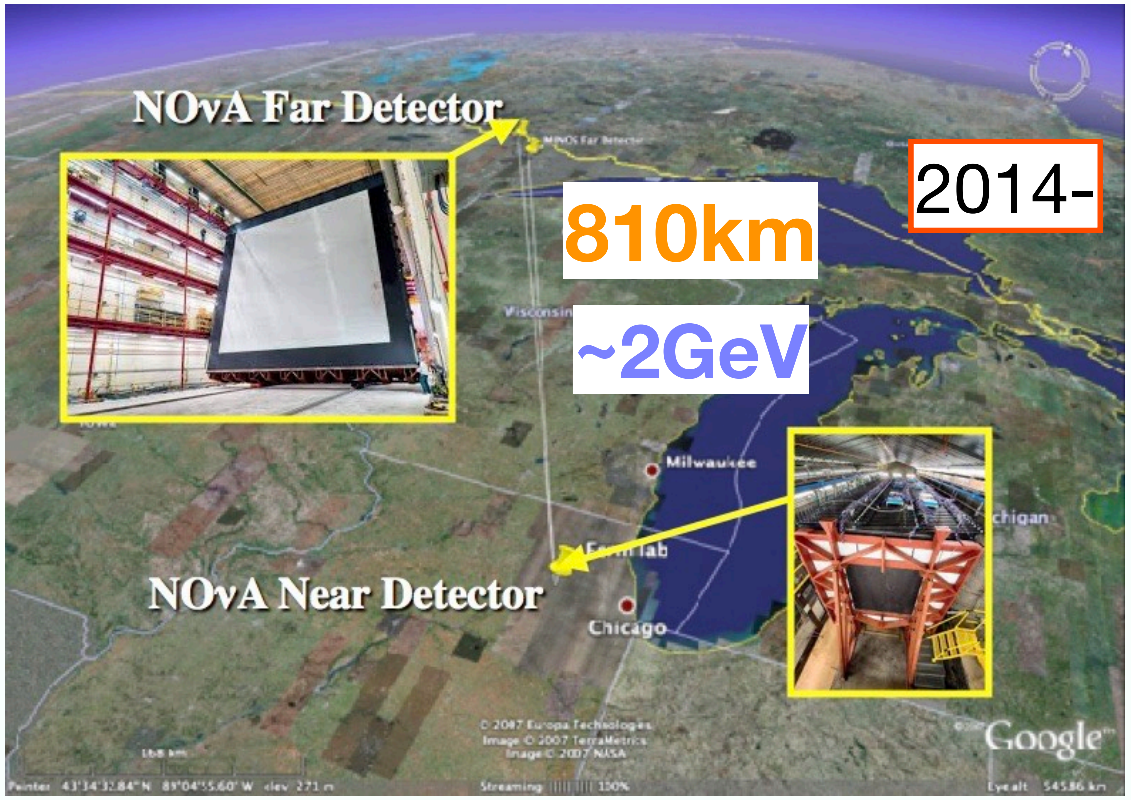
More precision measurements
θ_{23} octant (<=>45°?)
Mass ordering
CP violation
Consistency check of 3ν framework

Long baseline experiments

T2K



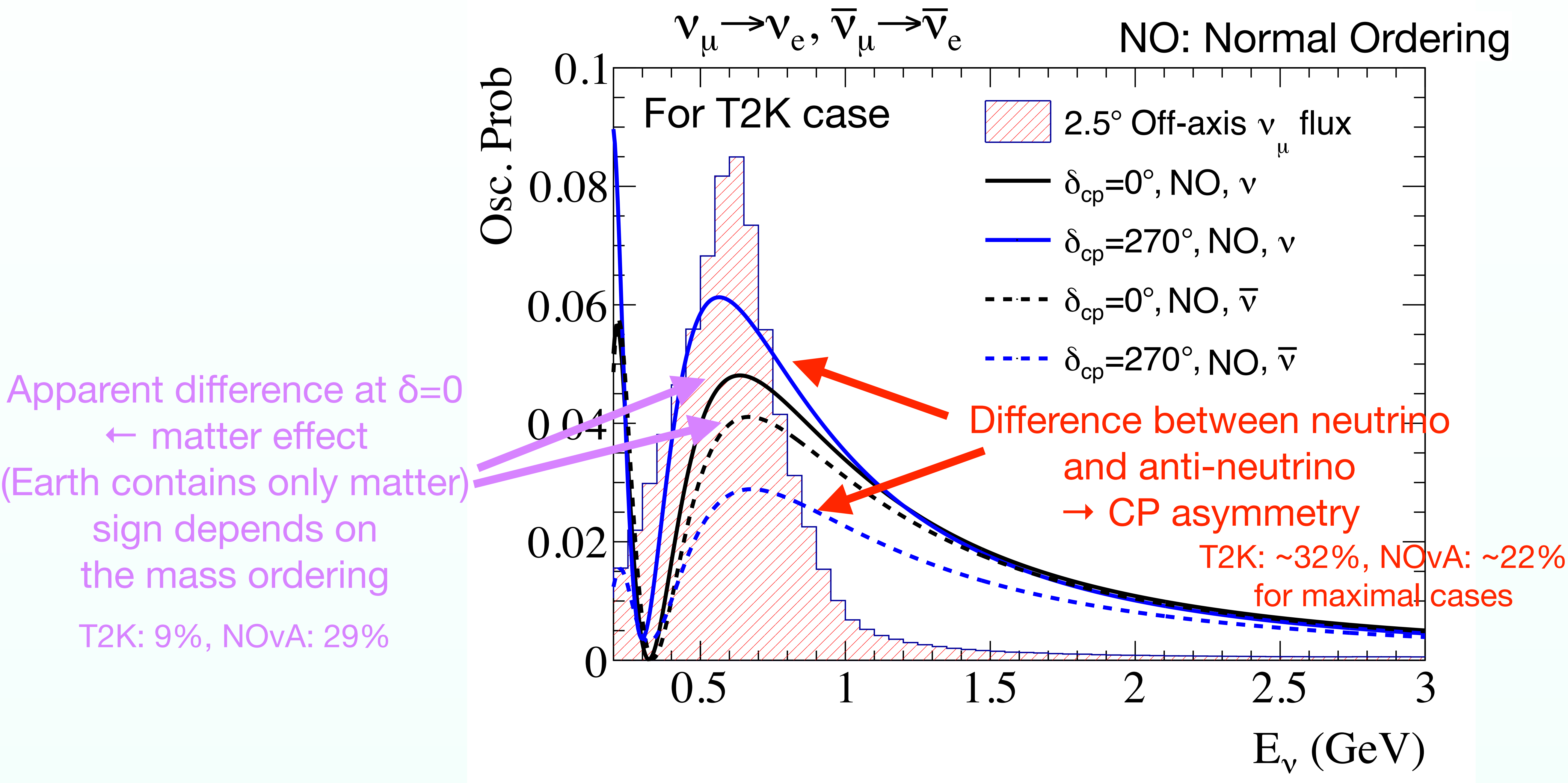
NOvA



- Different baselines — different effects from matter effect (and possibly others not dependent on L/E)
  - T2K has a shorter baseline, purer effect of CPV
  - NOvA has a longer baseline, more matter effect and sensitivity to the mass ordering
- Different detector technology, different systematics

Measuring CP asymmetry

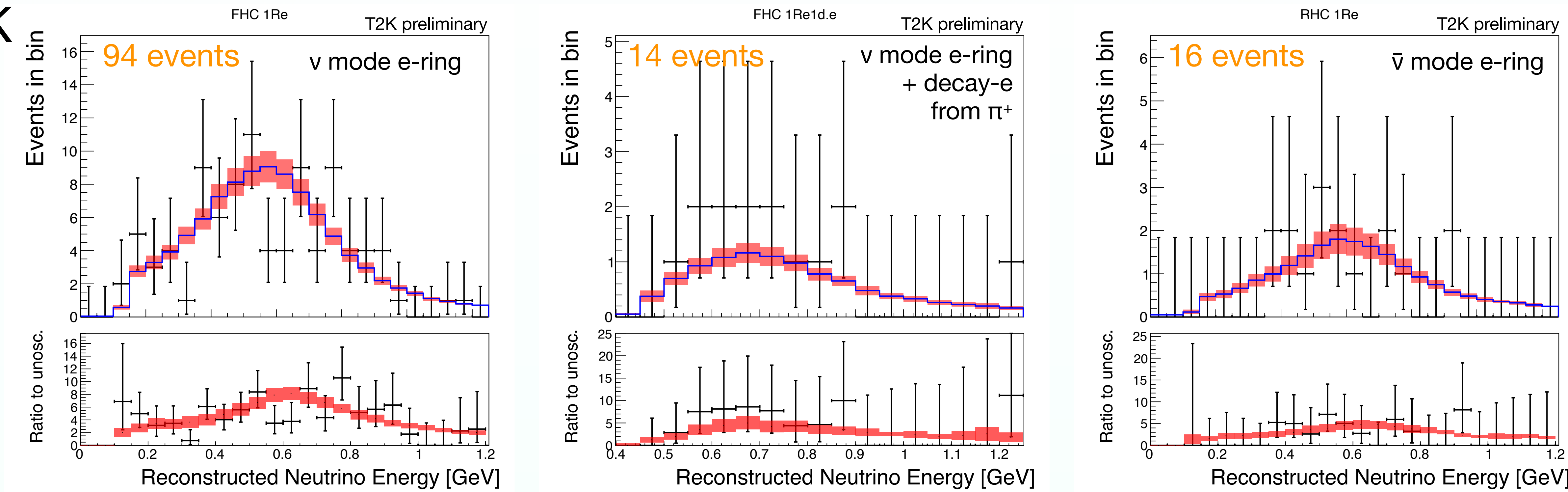
Comparison of appearance probabilities



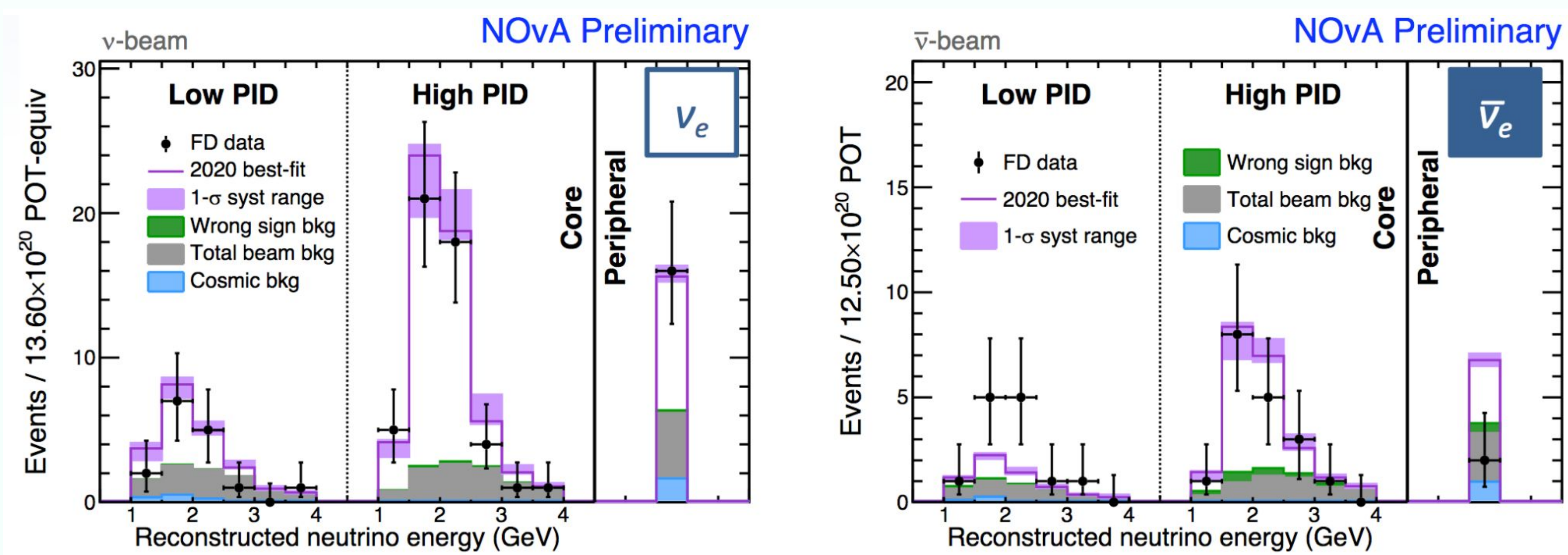
Small effects: need large statistics + control of systematics

Observed events (electron like)

T2K



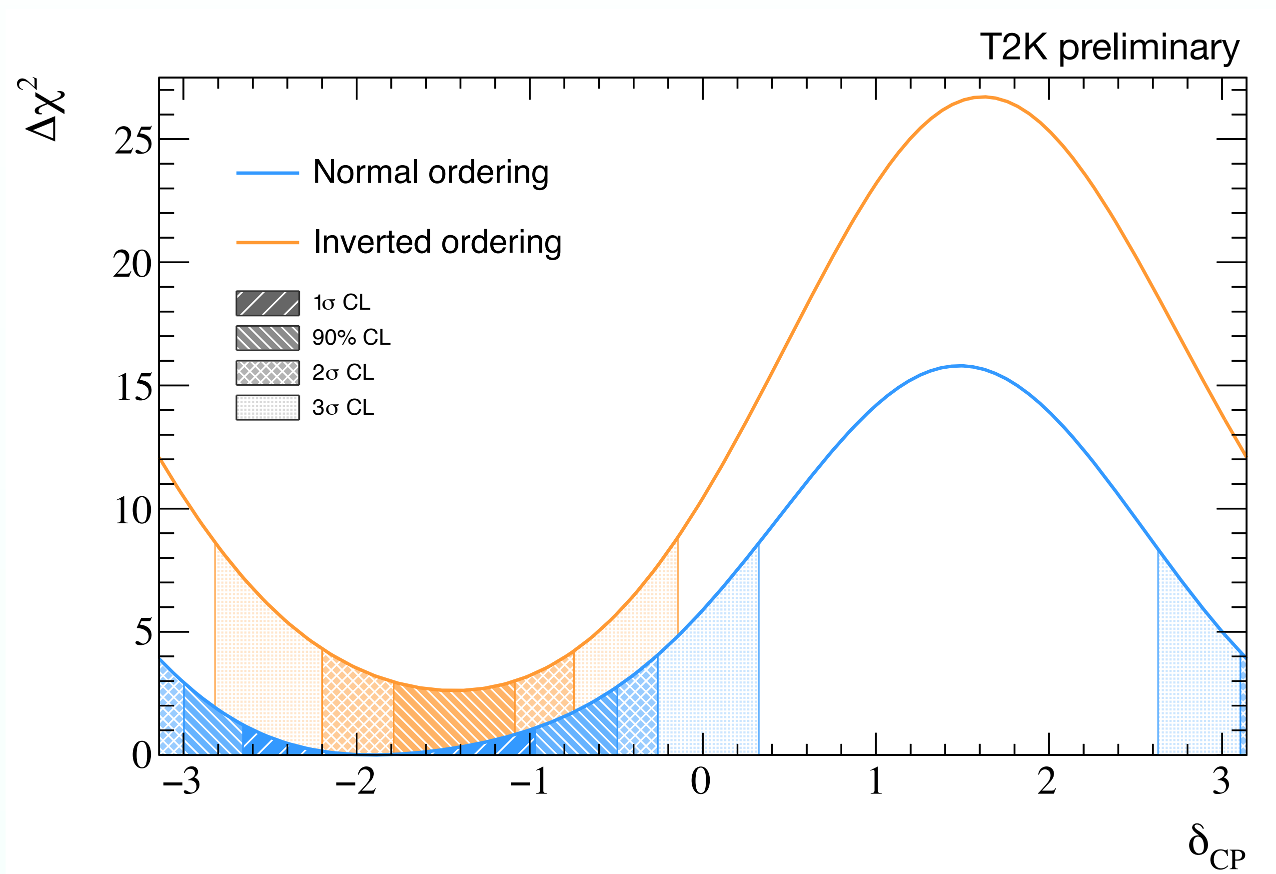
NOvA



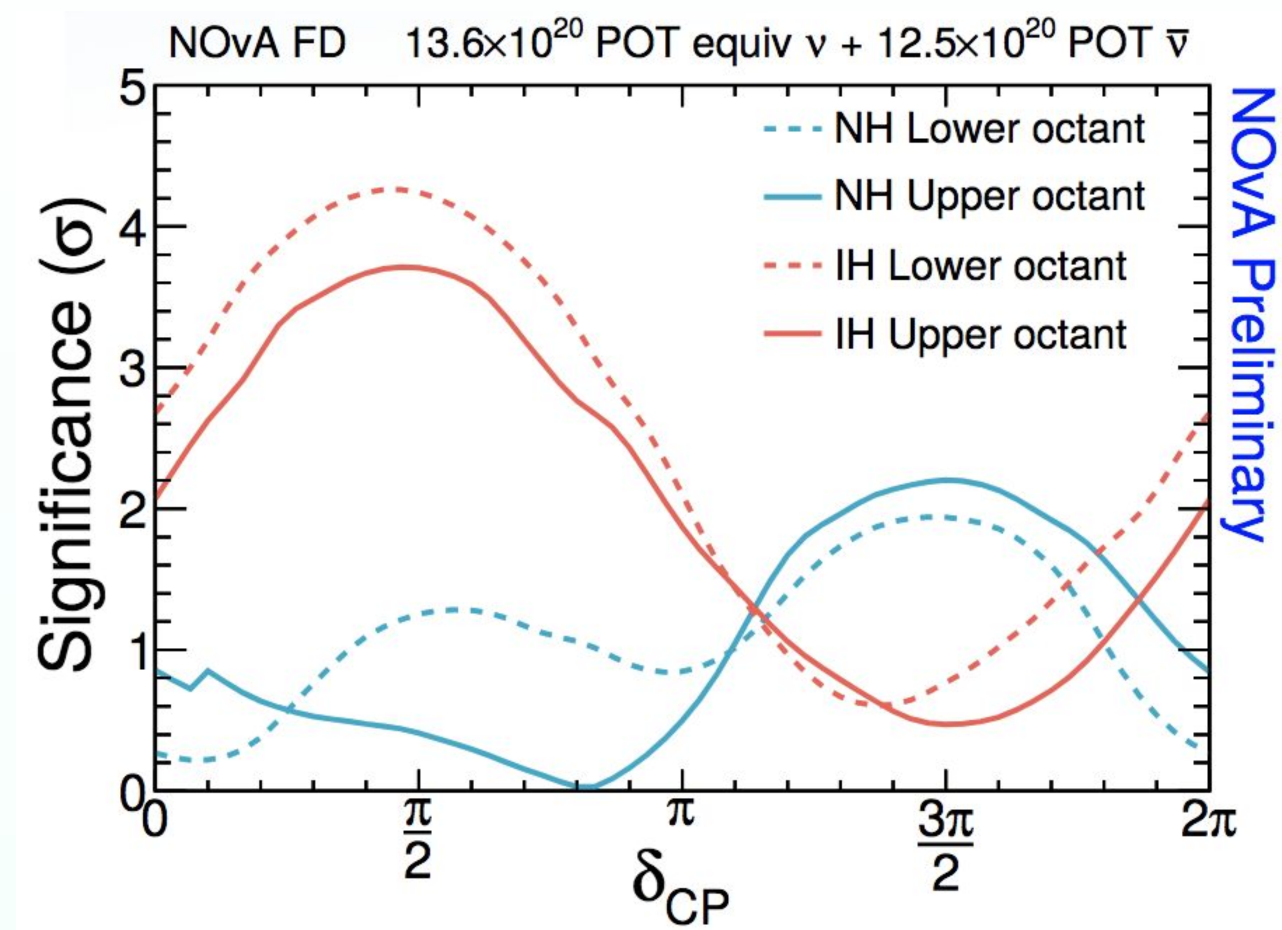
In the analysis, both fit e-like and μ-like samples simultaneously with full oscillation formula

Constraints on δ_{CP}

T2K



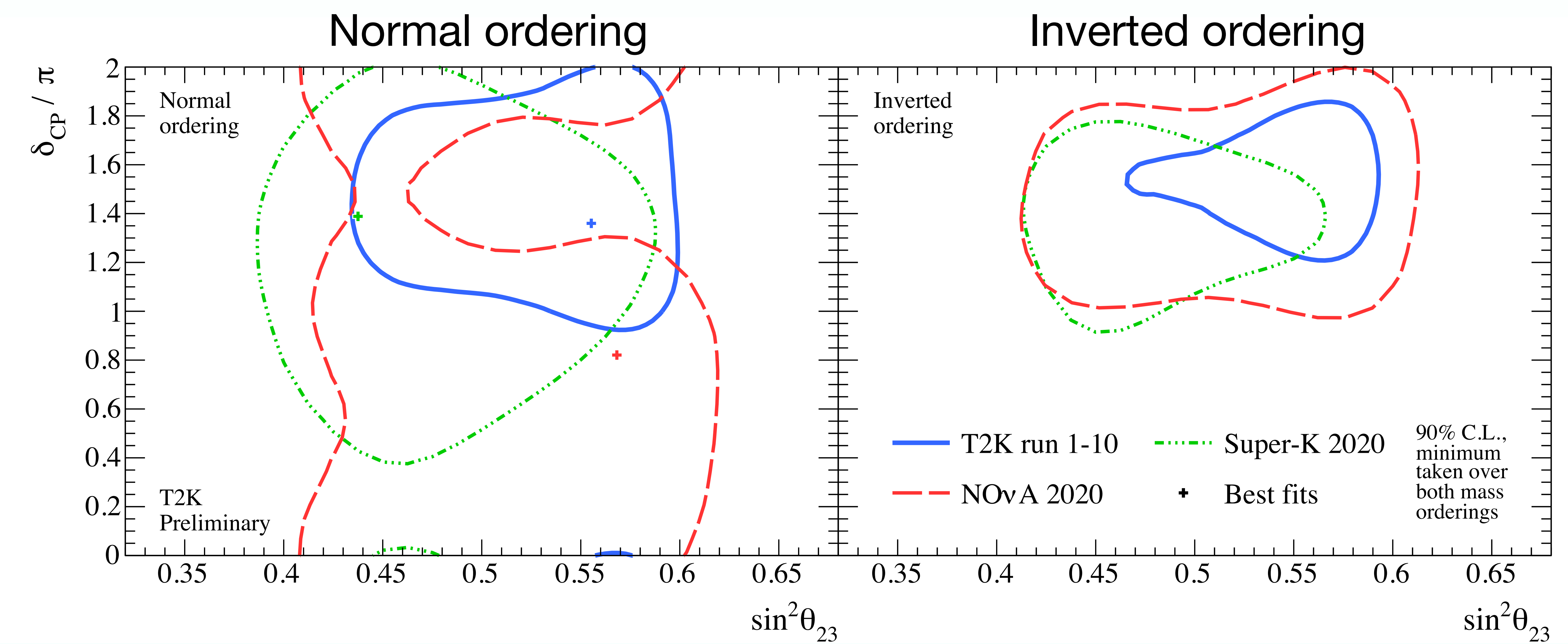
NOvA



Note: different convention of δ_{CP} range

- T2K favors maximal CPV, exclude ~35% of δ_{CP} values at 3σ (marginalized over both mass ordering)
- NOvA best fit in normal ordering and upper θ_{23} octant (θ_{23}>4/π), disfavors large asymmetry in ν_e and $\bar{\nu}_e$ appearance

A comparison

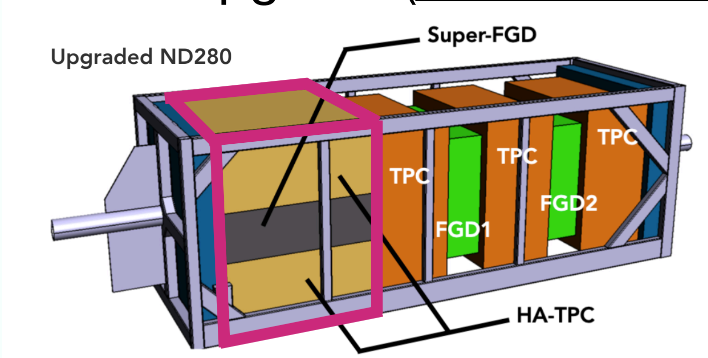


- Allowed regions overlap
- Interesting to see future results, including combined analysis!

Future prospects: T2K

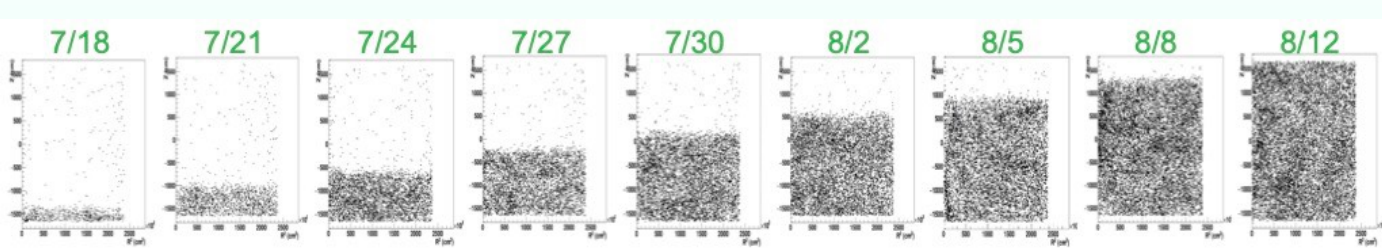
- Improve sensitivity with upgrading all components
  - Beam power upgrade 500kW → 750kW → **1.3MW**
  - Major upgrade of near detectors (**ND280**) in early 2023
  - Super-K with **Gd loading** (0.01% Gd in 2020→ 0.03% in 2022)
  - + analysis improvements, better neutrino interaction models, …
- Aiming for ~3σ for the maximal CPV case

T2K ND280 upgrade (CERN NP07)

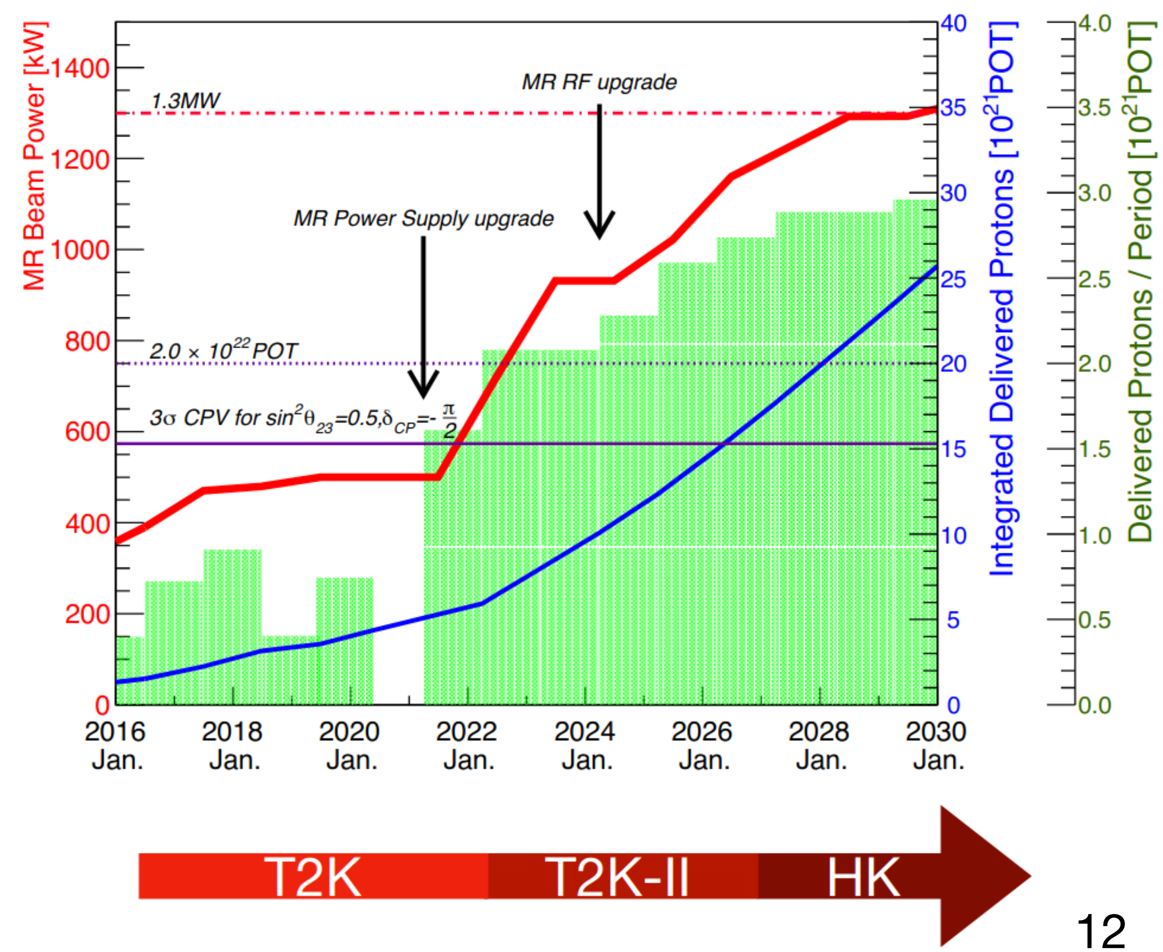


2 million scintillator cubes assembled

Vertex distribution of spallation neutron Gd(n, γ) candidates in SK during Gd loading in 2020



T2K-II Target POT (Protons-On-Target)



Future prospects: NOvA and combination

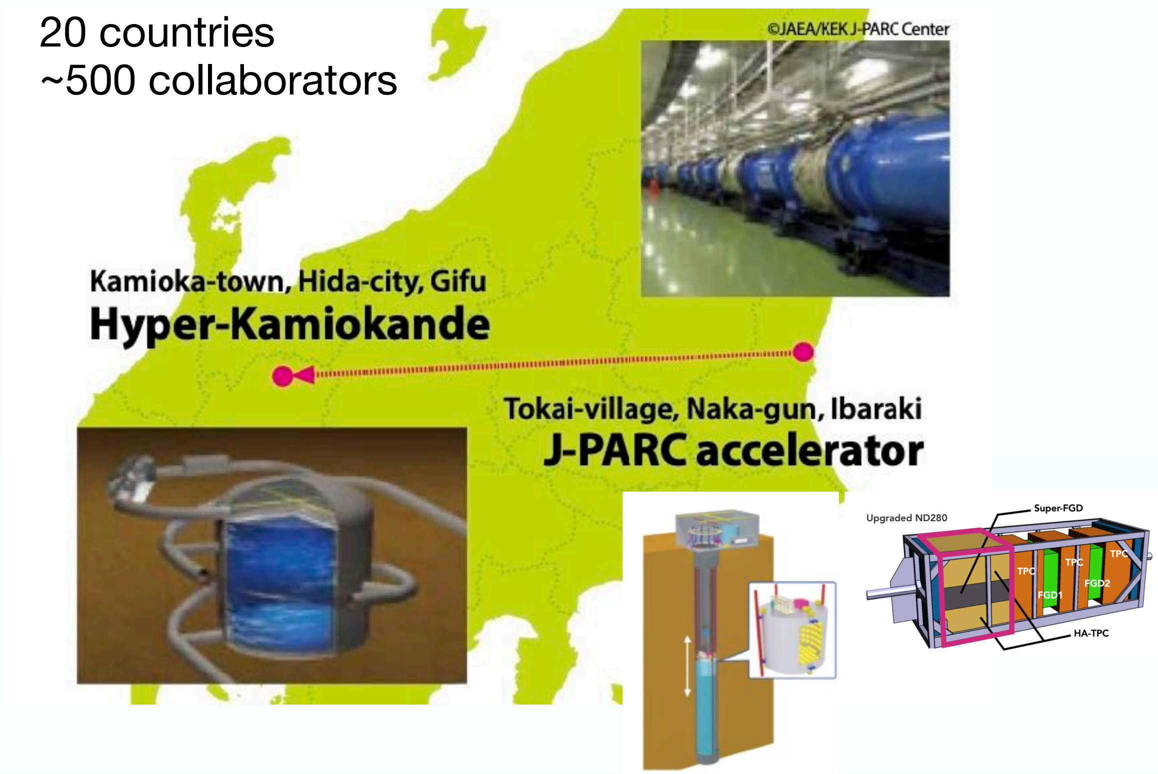
- NOvA is also expected to take data through 2026 with **various improvements**
  - Beam power upgrade to 900+kW
  - Reduction of the largest systematics with a test beam program

NOvA test beam detector

- **Combined analysis** between experiments ongoing
  - T2K-NOvA and T2K-SK
    - Different baselines/energies, increased sensitivities
    - Understanding of potential systematic correlations is important
- Various **associated/supporting program** for systematics reduction
  - Hadron production: NA61/SHINE, EMPHATIC, ..
  - Neutrino interaction: joint effort of particle/nuclear experiment/theory
- Foundation for the next generation experiments

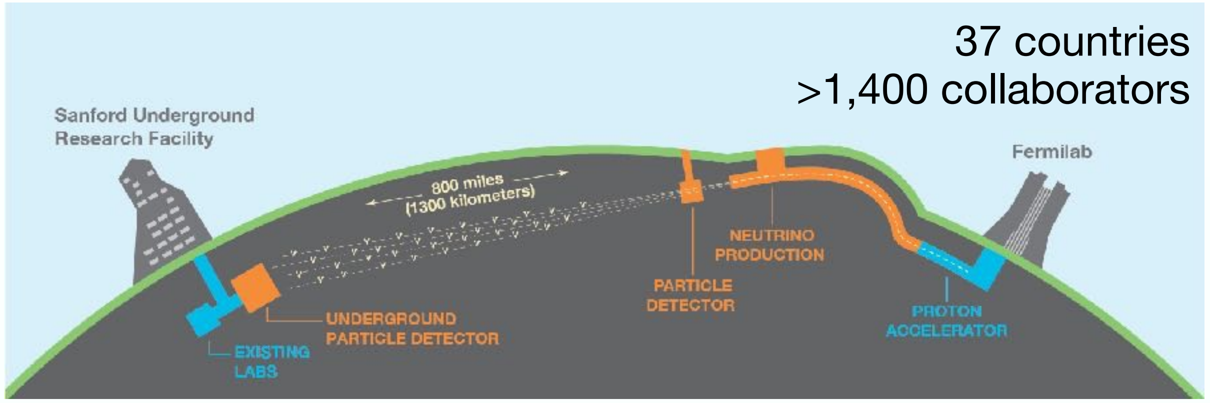
Next generation long baseline experiments

Hyper-Kamiokande in Japan



- 295km baseline
- ~0.6GeV off-axis neutrino beam
  - 1.3MW beam power
- 190kton water Cherenkov detector
- Upgraded/new near detectors

DUNE @LBNF in US



- 1300km baseline
- 0.5-4GeV wide-band beam
  - 1.2MW, upgradable to 2.4MW
- >40kton(4×10) liquid argon TPCs
- Highly capable near detector system
- Expected to start “Phase I” with 2 far detectors, 1.2MW beam, and a limited near detector

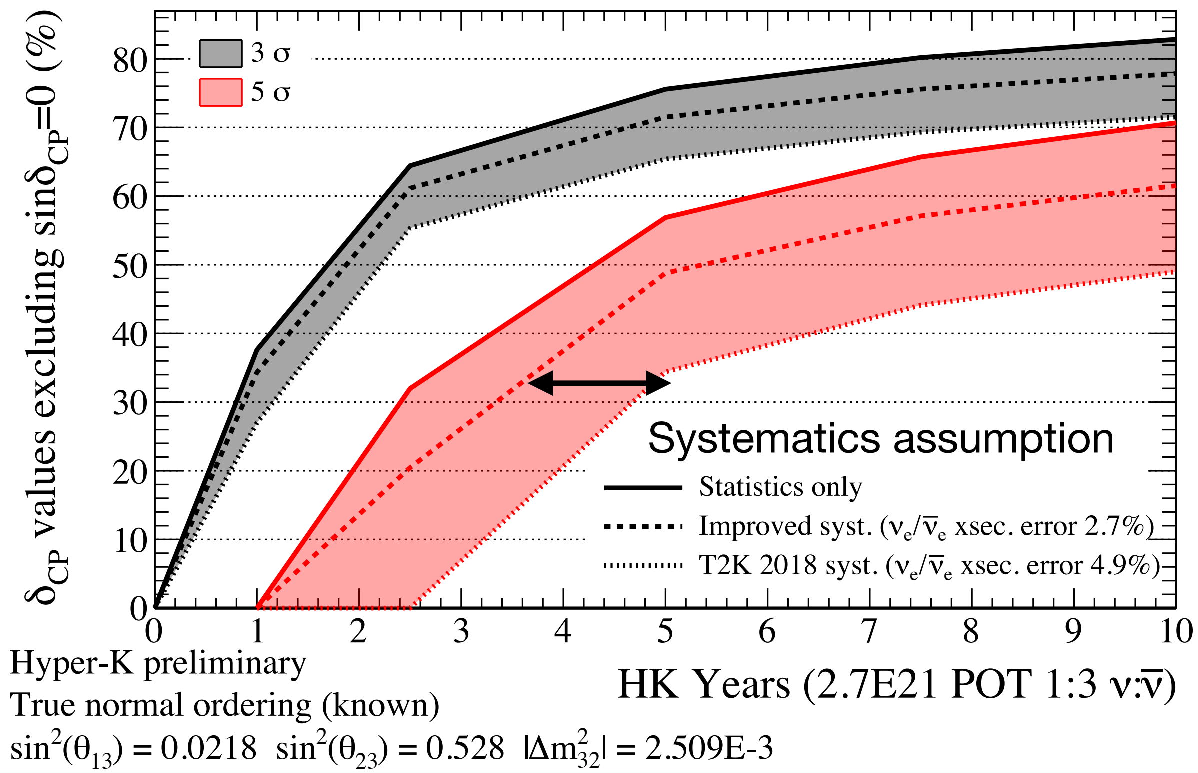
arXiv:2203.06100 DUNE Physics Summary (Snowmass white paper)

Different baseline, energy, technology, systematics → complementary

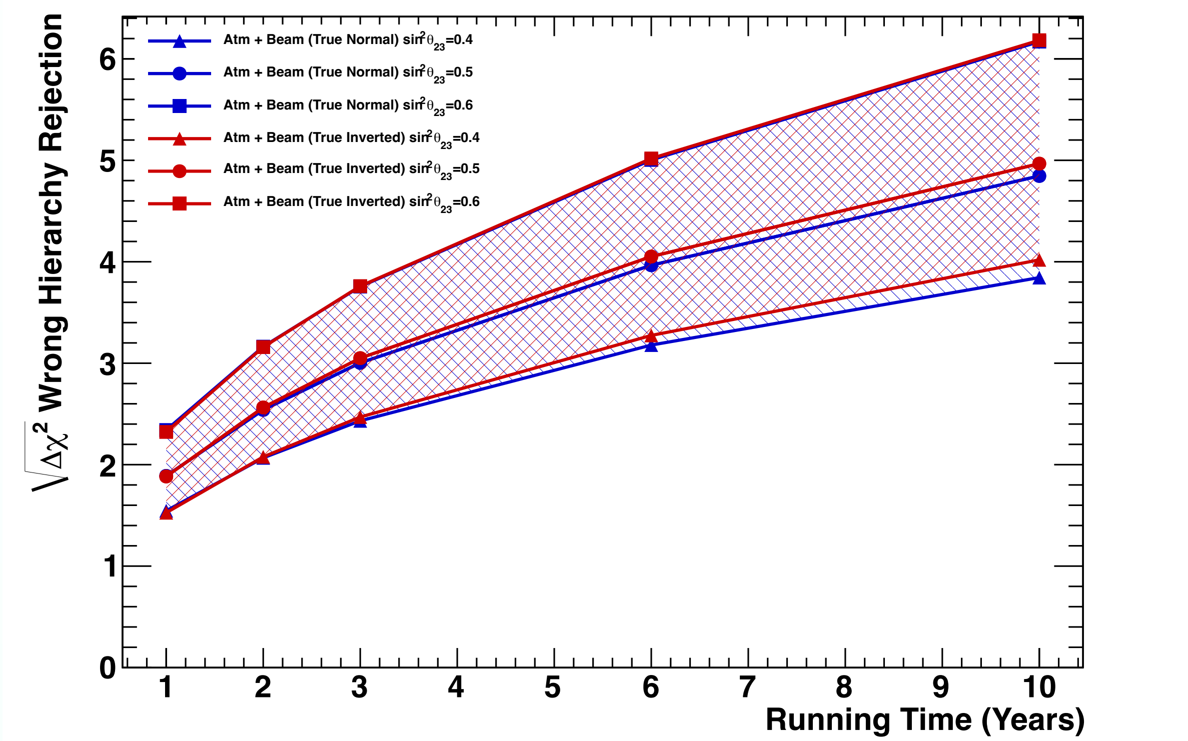
Both have rich non-beam physics programs

Hyper-K sensitivity

CP violation



Mass ordering

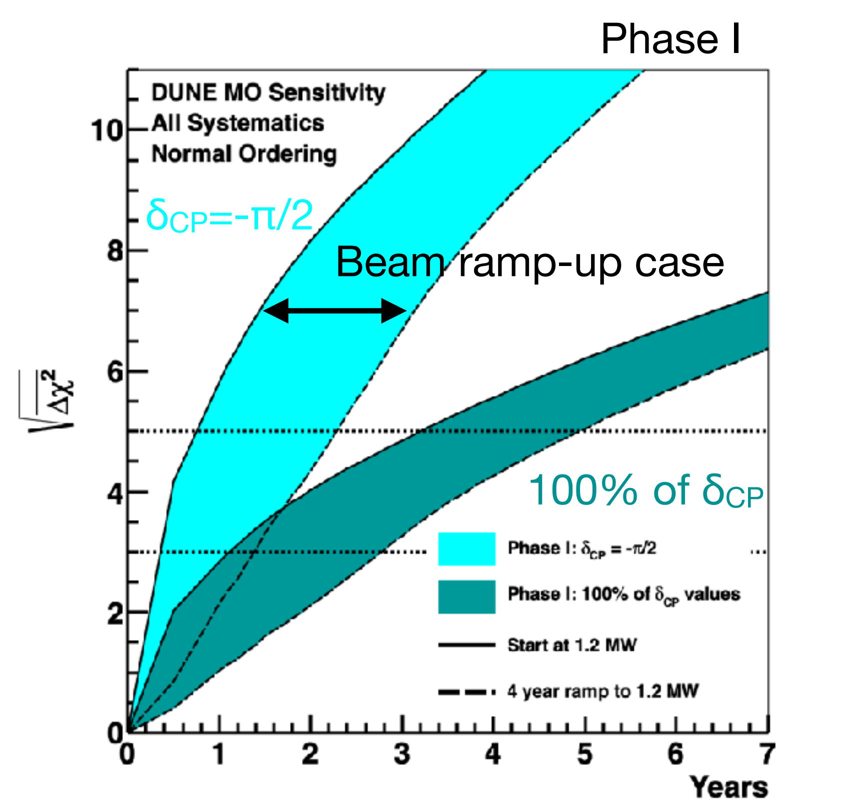


- **5σ CPV** sensitivity for **>50%** of δ_{CP} with ~5years of data taking
  - Control of systematic uncertainties is critical
  - Near and intermediate detectors to reduce uncertainties
  - Maximal use of experience from T2K
- Mass ordering sensitivity by combining atmospheric and beam neutrinos

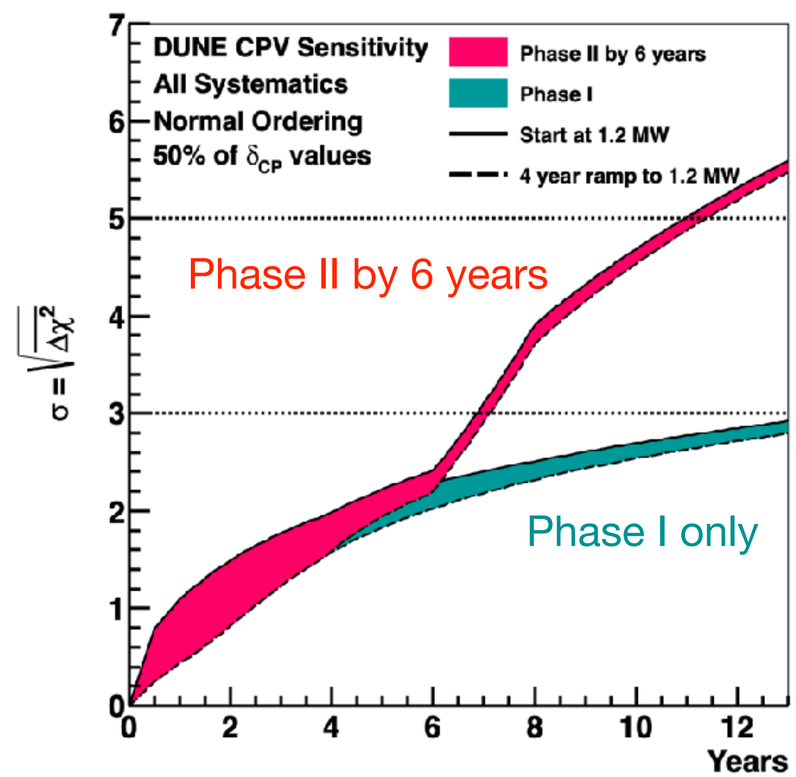
DUNE sensitivity

arXiv:2203.06100 DUNE Physics Summary (Snowmass white paper)

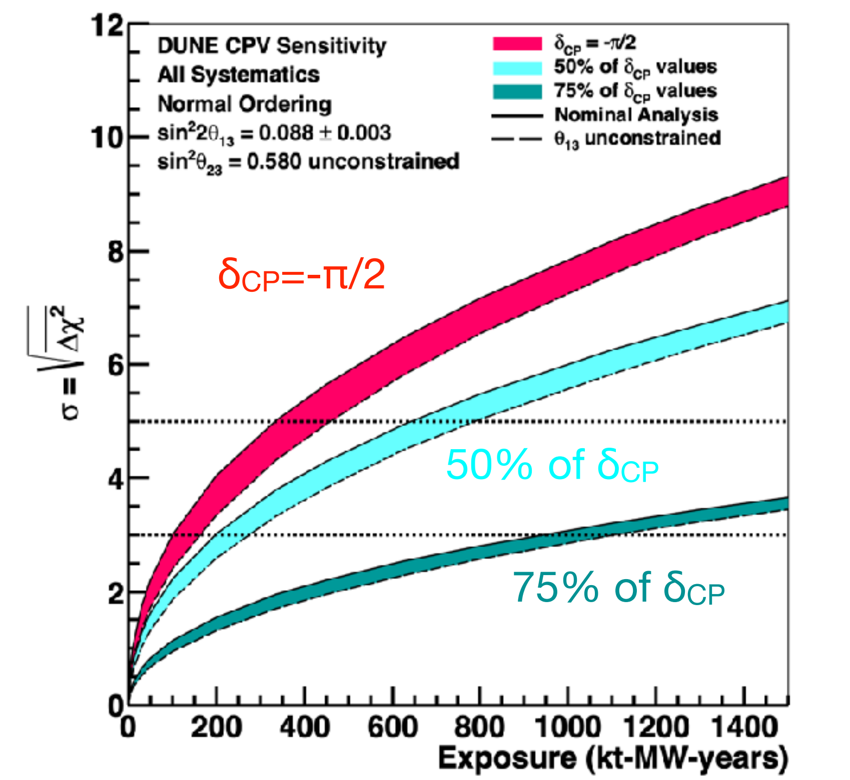
Mass ordering



CP violation



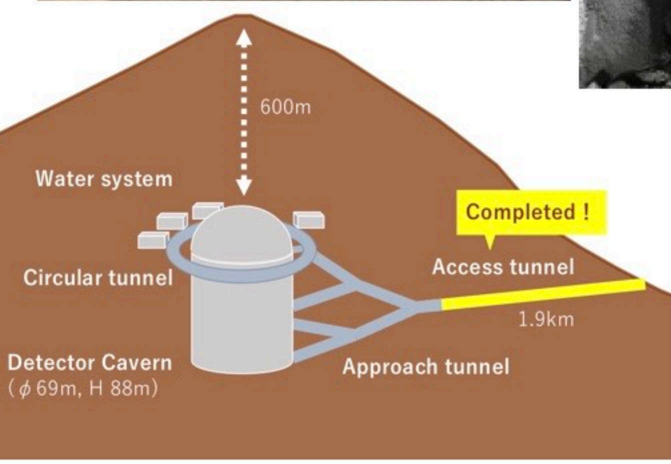
CPV vs. exposure



- Unambiguous determination of **mass ordering** in Phase I
- **3σ CPV** at maximal δ_{CP} with Phase I, **>5σ for 50%** of δ_{CP} with Phase II
- Various BSM physics also possible with near and far detectors, as well as other broad physics topics

HK&DUNE: project status

Hyper-Kamiokande



- ~2km access tunnel completed
- PMT production/testing ongoing
- J-PARC upgrade in progress
- Aim to start experiment in 2027

DUNE/LBNF

Depositing rock in Open Cut

NP-02 and NP-04 ProtoDUNE 8m x 8m x 8m detector prototypes at CERN.

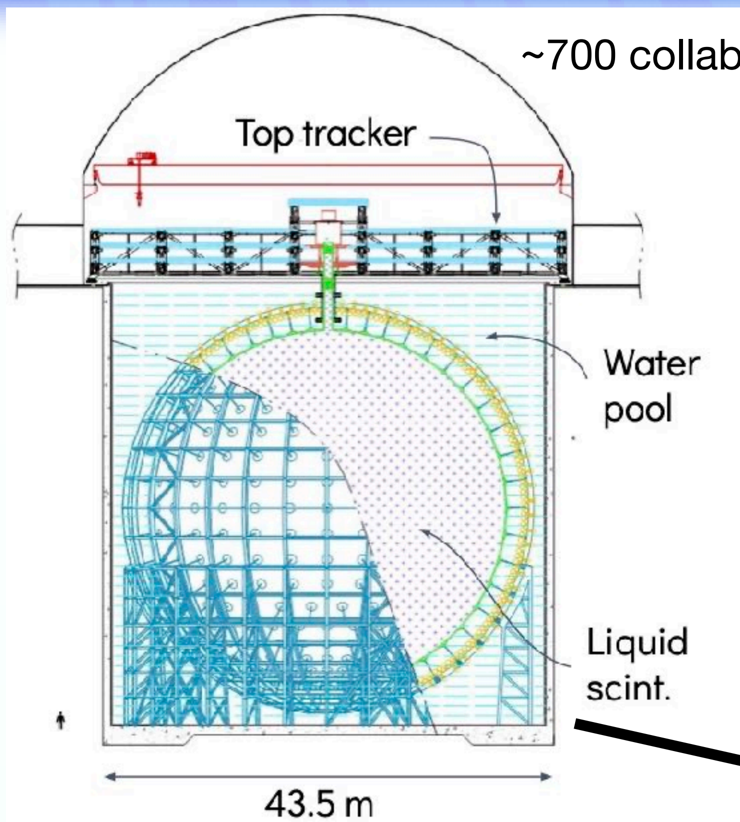
APAs for Module 0 ProtoDUNE being tested at Daresbury Laboratory, UK. One 2.3m x 6.3m APA is shown; UK to provide 130 APAs.

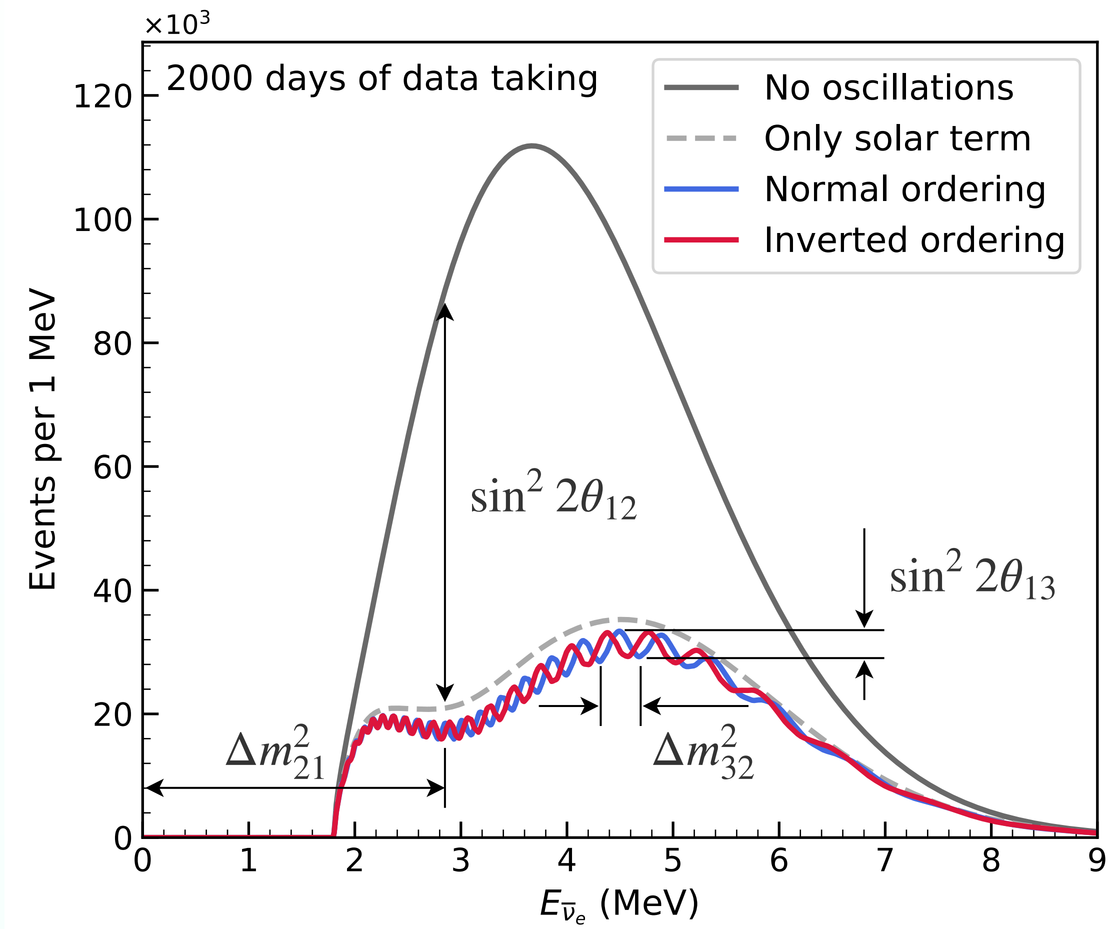
- Excavation of underground halls ongoing
- Technology development well in progress with ProtoDUNE @ CERN-NP
- Production of detector component started
- Far detectors expected to begin data taking in the late 2020s
- Phase II strategy to be discussed in Snowmass/P5

Jiangmen Underground Neutrino Observatory (JUNO)

~700 collaborators

arXiv:2104.02565

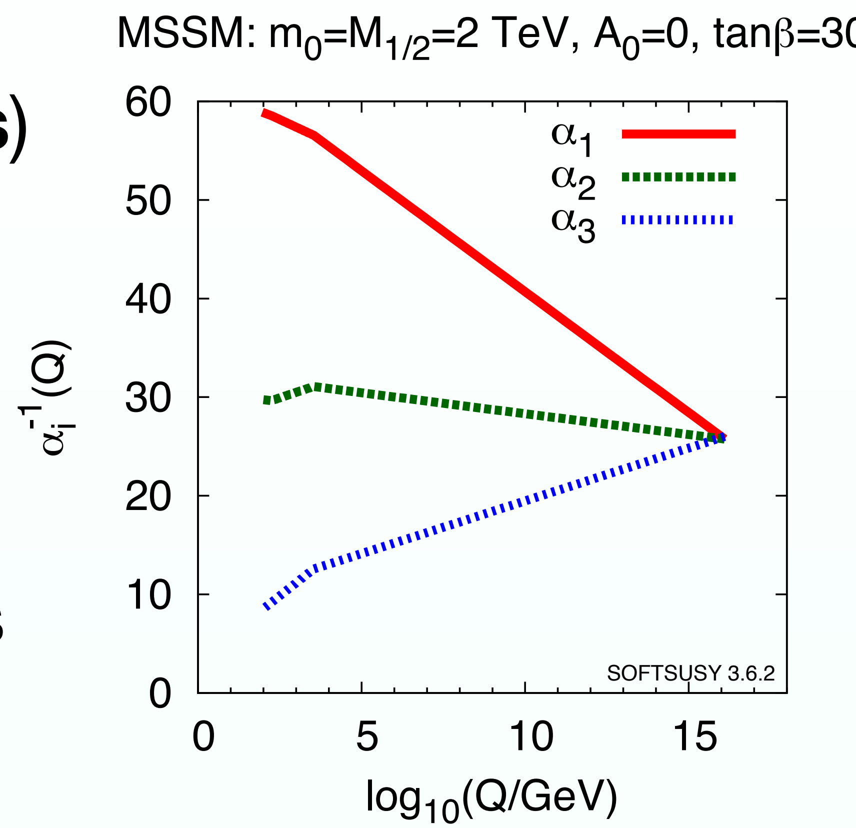




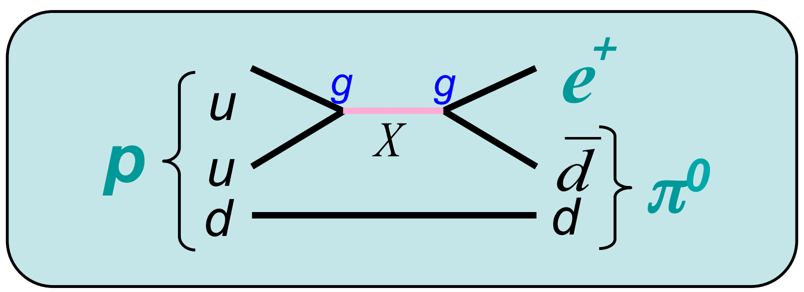
- **20kton liquid scintillator** detector in China
- Reactor $\bar{\nu}_e$ with ~53km baseline
- Determination of **mass ordering** with precise spectrum measurement utilizing interference of Δm^2_{21} and Δm^2_{31}
  - Unprecedented energy resolution (3%/$\sqrt{E(\text{MeV})}$) and large mass
- **Precision (<0.6%) measurements** of θ_{12}, Δm^2_{21}, and $|\Delta m^2_{32}|$
- Many other physics targets: solar, supernova, geo, atmospheric neutrinos
- Detector construction expected to complete within 2022

Nucleon decays

- Search for nucleon decays is the most direct experimental probe for Grand Unified Theories (**GUTs**)
  - Physics at at an extremely high energy scale (~$\mathbf{10^{16}}$**GeV**)!
  - Original motivation of large underground detectors (e.g. KamiokaNDE = Nucleon Decay Experiment)
- Two "benchmark" modes, predicted by many models



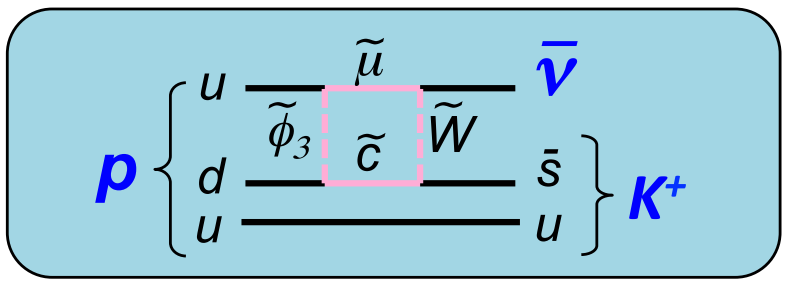
Mediated by gauge bosons



$p \to e^+\pi^0$

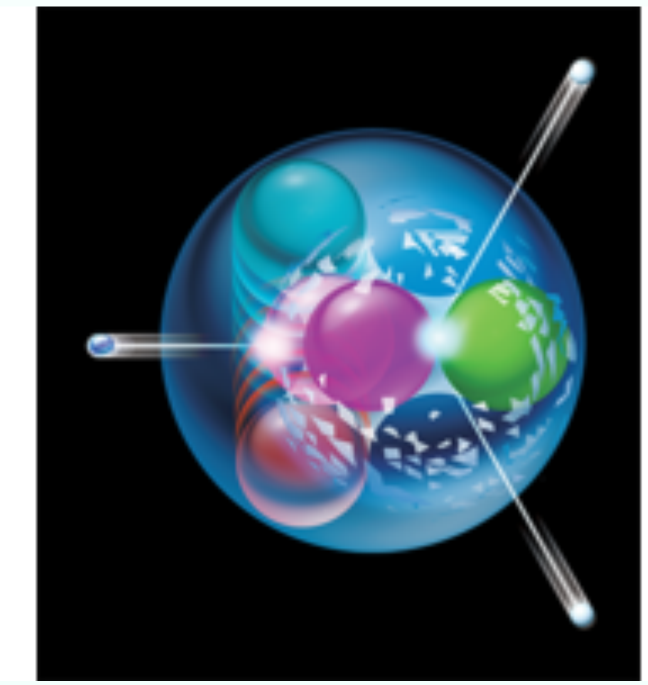
$$\Gamma(p \to e^+\pi^0) \sim \frac{g^4 m_p^5}{M_X^4}$$

SUSY mediated



$p \to \bar{\nu}K^+$

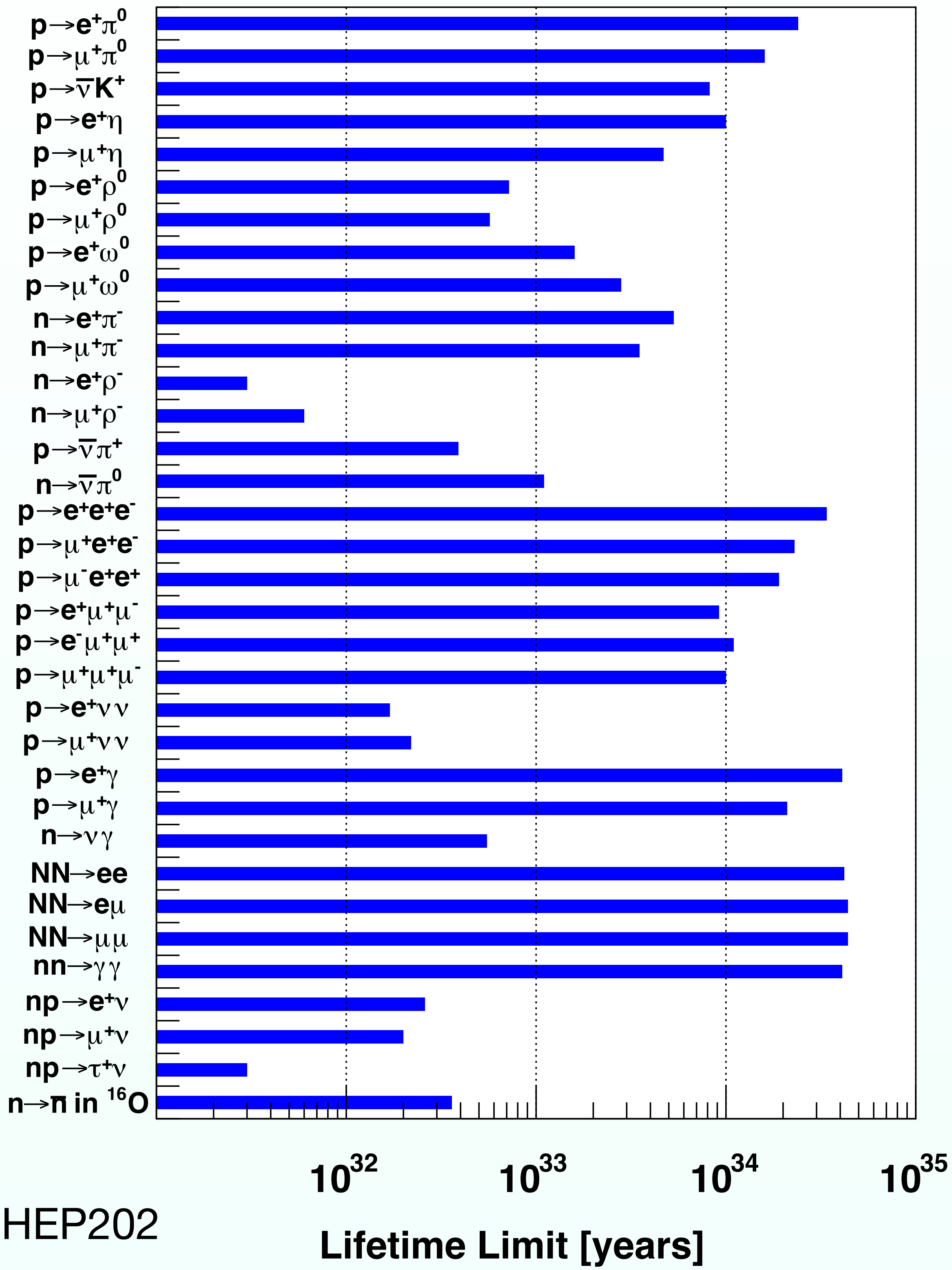
$$\Gamma(p \to \bar{\nu}K^+) \sim \frac{\tan^2\beta \times m_p^5}{M_{\tilde{q}}^2 \times M_3^2}$$



- Broad searches including other possible modes are important: prediction varies depending on GUT models

Nucleon decay search status

Baryon Number Violation search results from SK

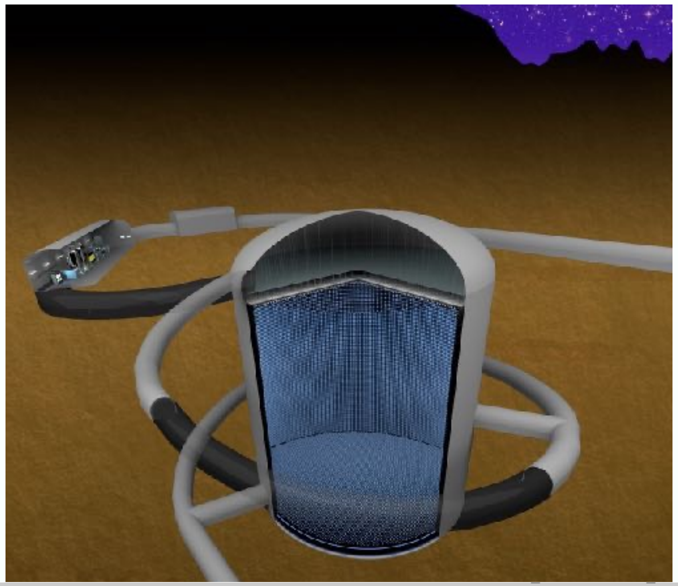
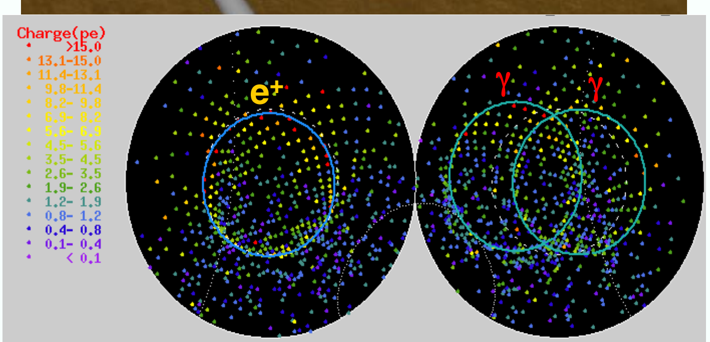


ICHEP202

- For past >20 years, mostly dominated by **Super-Kamiokande**
- Lower limits (90% CL)
  - **$p \to e^+\pi^0$ > 2.4×10^{34} years**
  - **$p \to \bar{\nu}K^+$ > 0.66×10^{34} years**
- Updating with broader search
  - $p \to 3$ leptons, dinucleon decay, n-$\bar{n}$ oscillation, ..
- Still **improving sensitivities**
  - Atmospheric BG rejection by neutron tagging
    - First with hydrogen capture, now enhanced with Gd
  - Expanding fiducial volume, new reconstruction, …

Next generation nucleon decay experiments

Hyper-Kamiokande

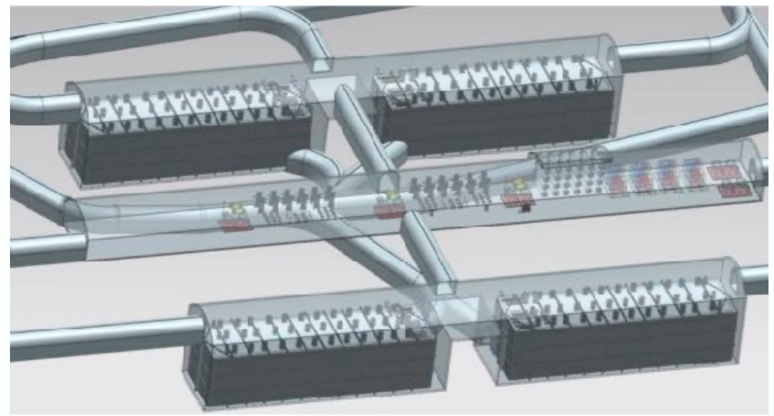
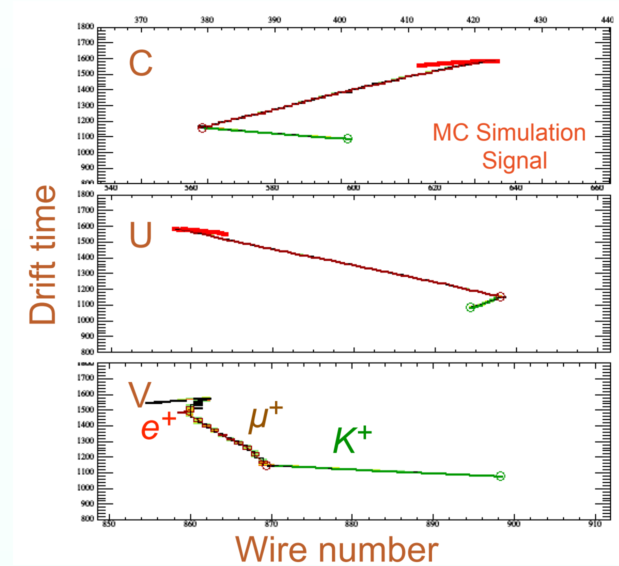
190kton water Cherenkov

broad search capabilities as demonstrated by SK

free proton available
(no nuclear effects)

kaon below threshold
(detect decay products)

DUNE

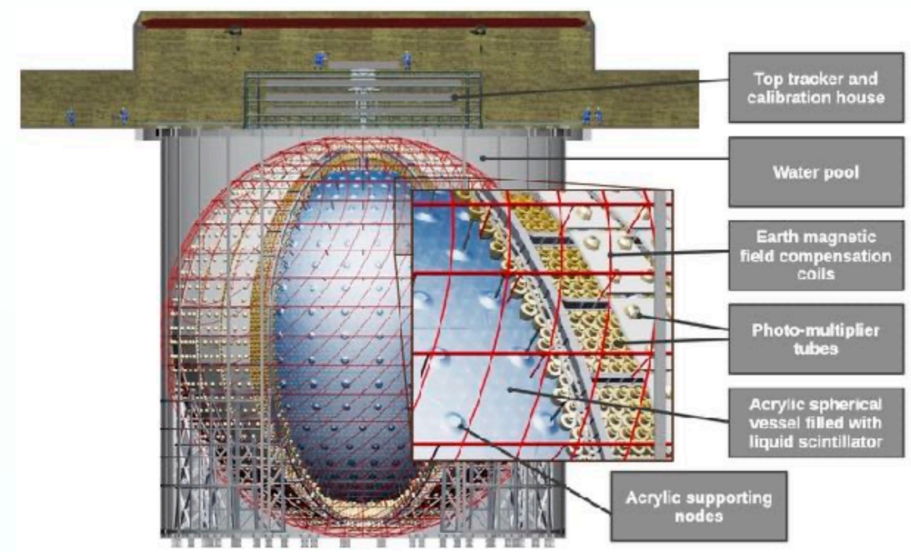



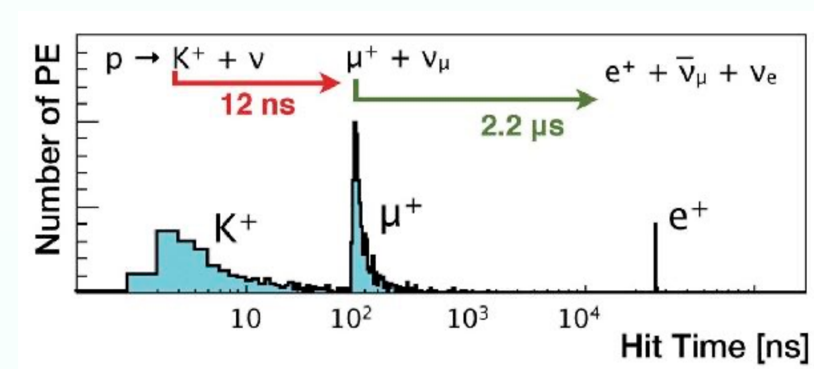
4x10kton liquid Ar TPCs

detail information with fine-grained tracking and calorimetry

kaon track visible

JUNO





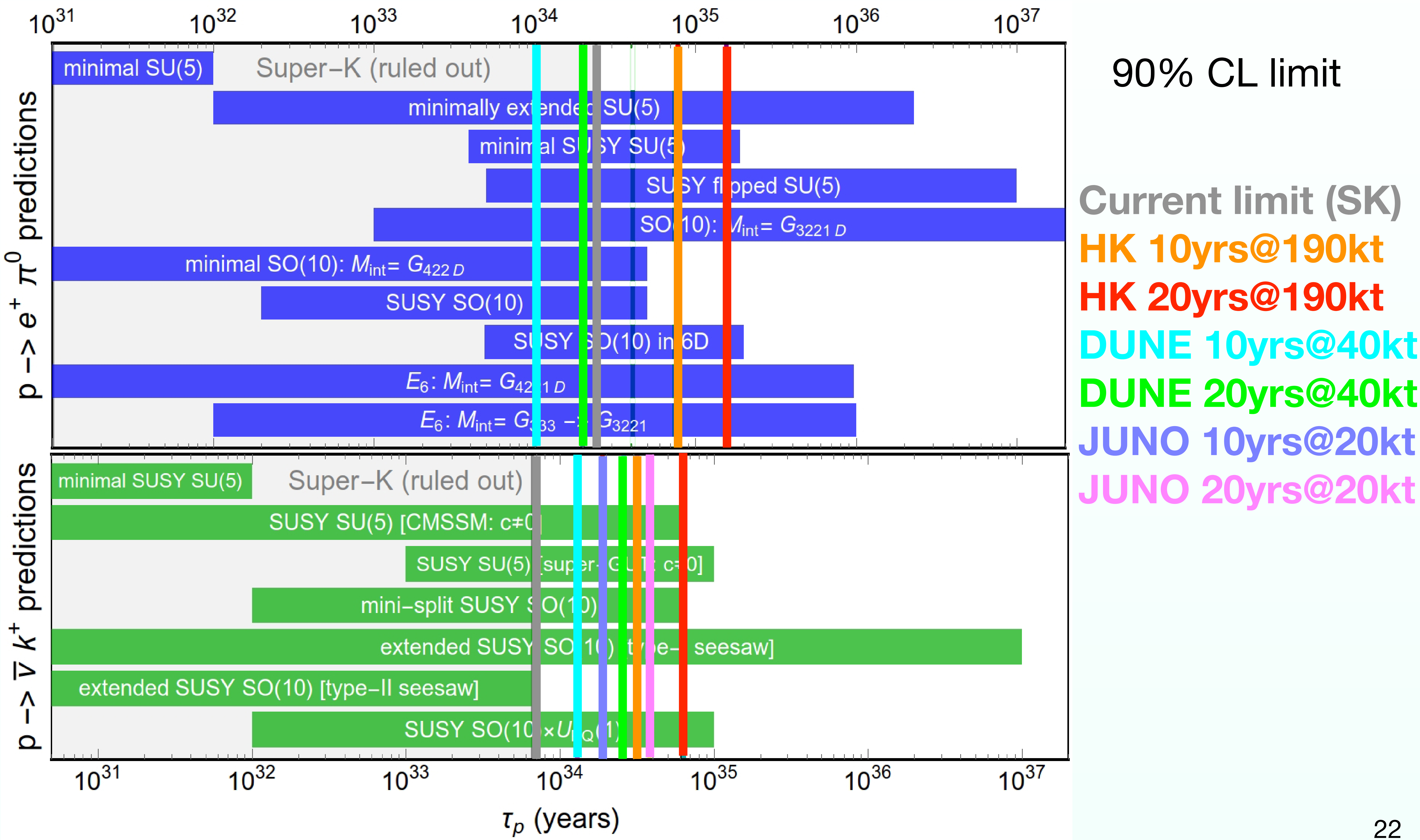
20kton liquid scintillator

clean timing signature

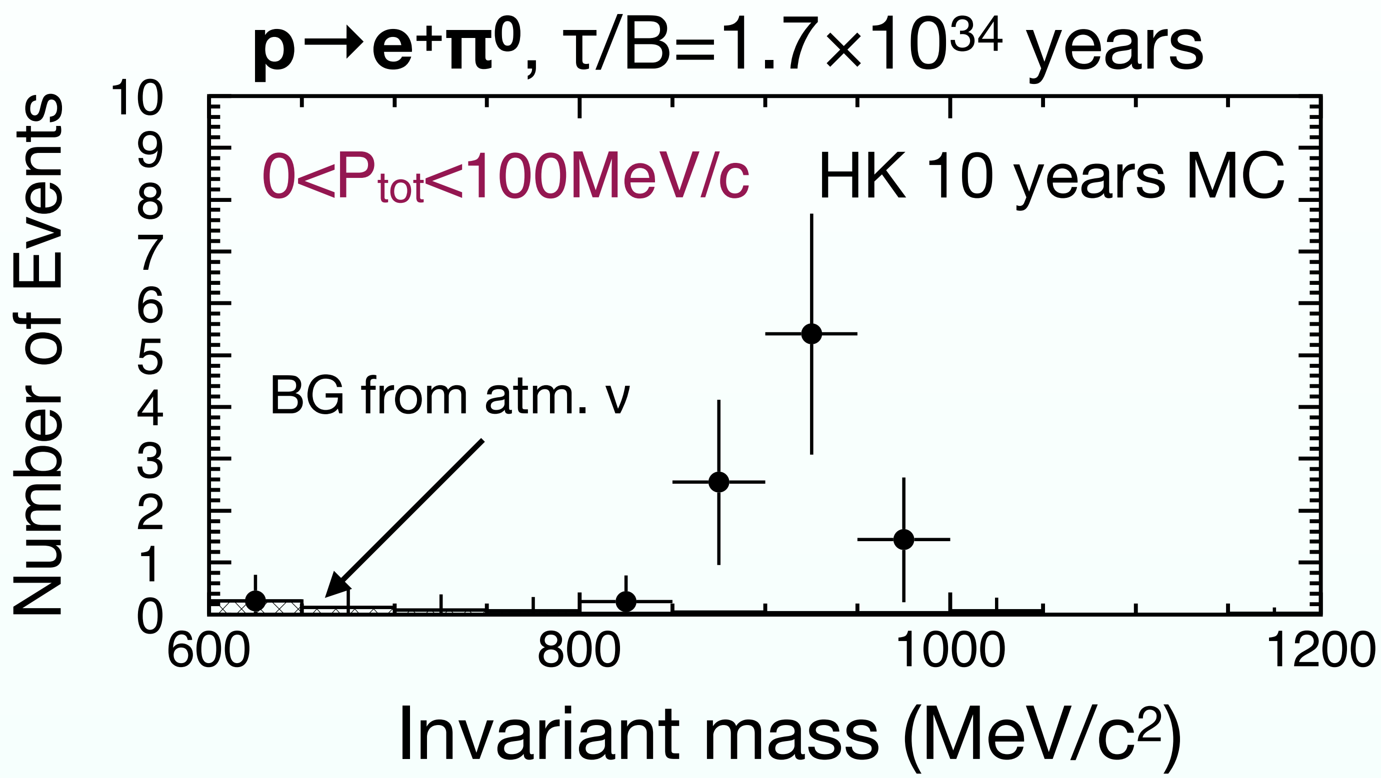
high sensitivity in
kaon mode
& **invisible** decay

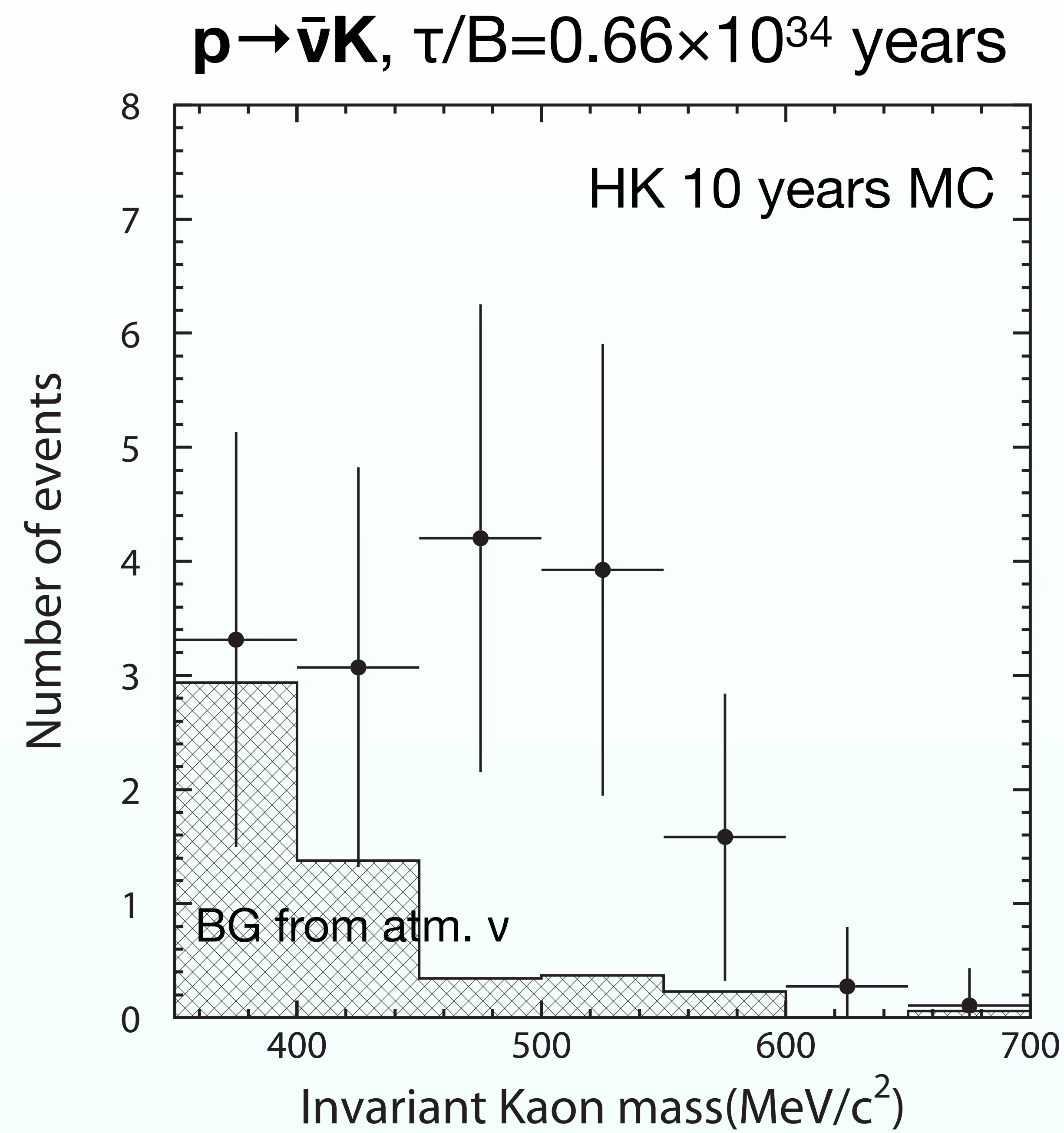
Expected sensitivities

Adopted from arXiv:2203.08771 (Snowmass Whitepaper)



Expected sensitivities





We may find a clear evidence of GUT.

Nucleon decay: prospects

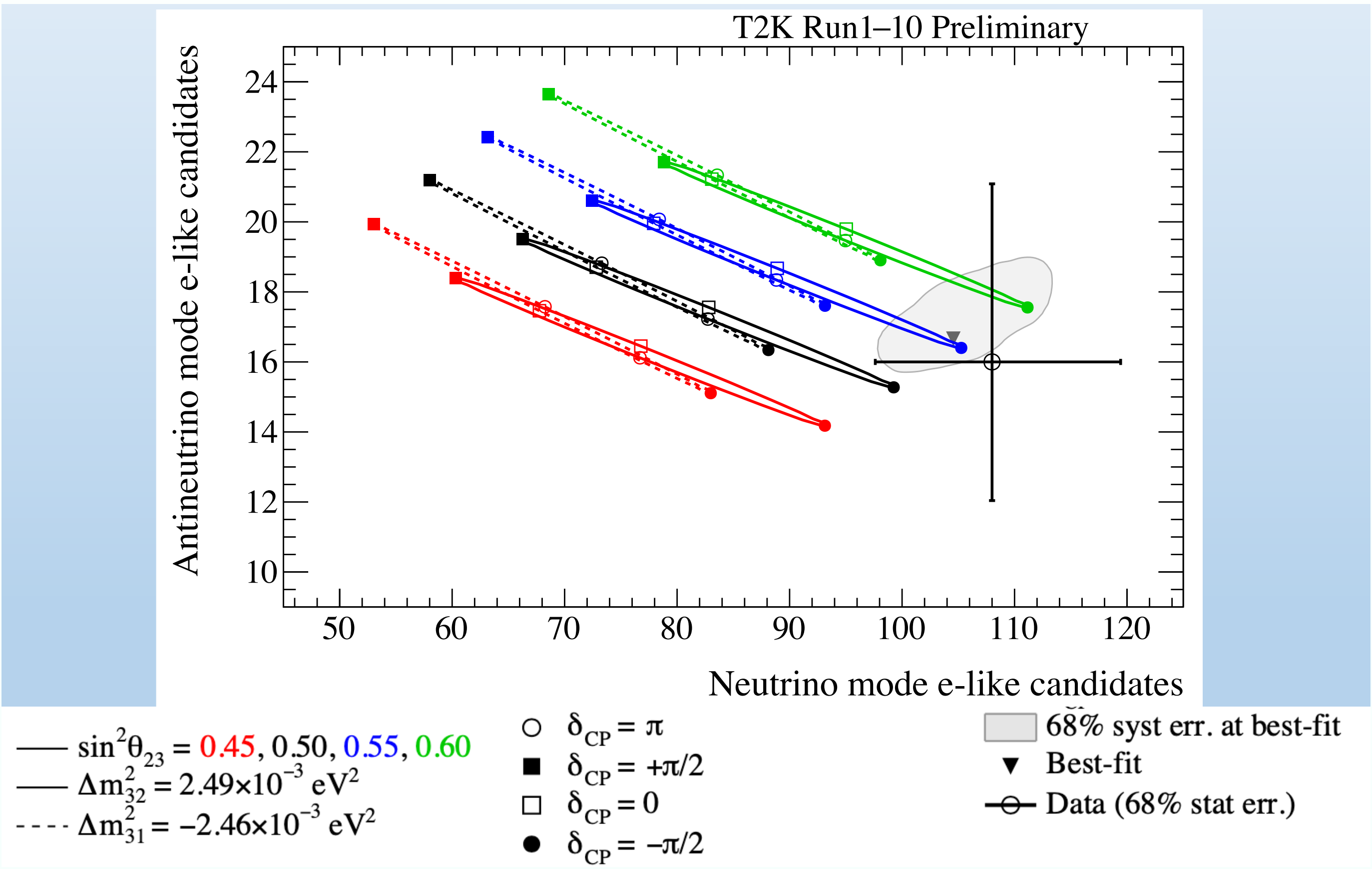
- **Multiple experiments** with sensitivities beyond current limits
  - $>10^{35}$ years for some modes
  - Test predictions by various GUT models
  - **Different strengths** with different technologies
    - Searches in as many modes as possible
    - Study of GUT models in case of discovery!
- Other baryon number violating processes also considered
  - e.g. n-n̄ oscillation in DUNE: 5.5×10^{8}sec @400kt·yr
    (current limit by SK: 4.7×10^{8}sec)

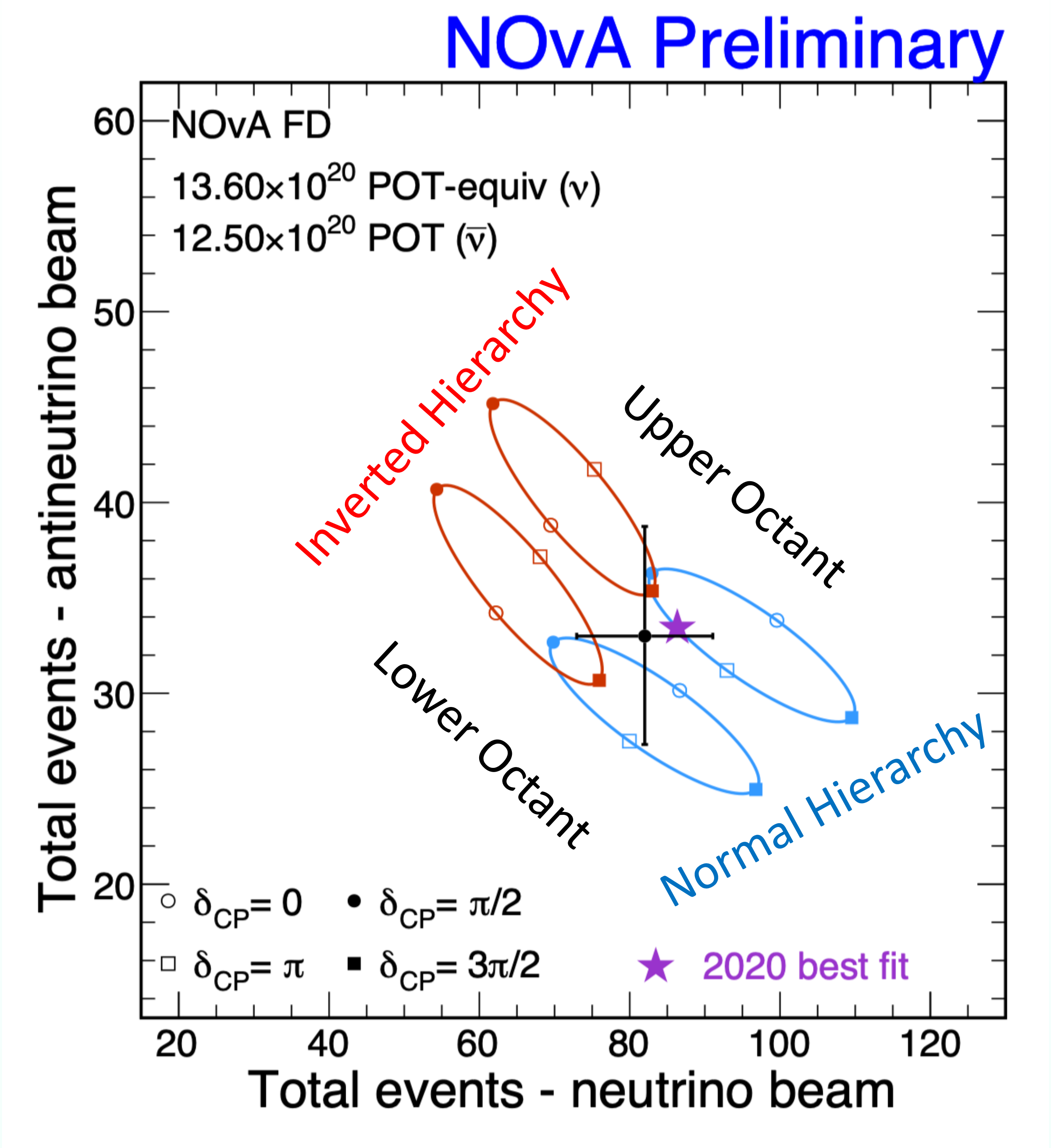
- Time to think about the next step,
  e.g. what comes after discovery? or technology for $\tau>10^{36}$ yr?

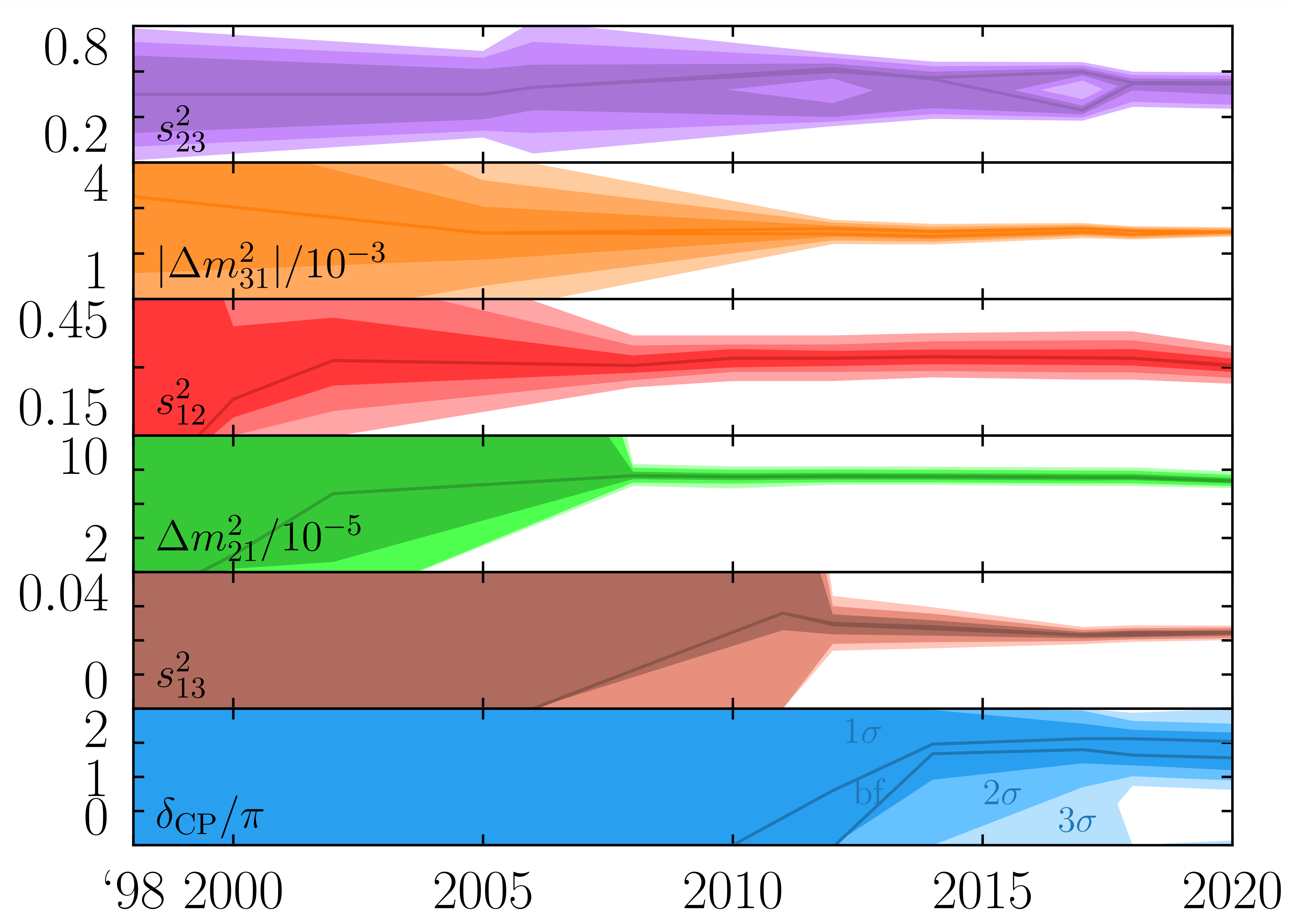
Conclusions

- **Large neutrino detectors** provide a broad science program
  - Study of **neutrino oscillation** is one of major focus areas
    - Start to explore CP asymmetry and mass ordering
    - Precision measurements, BSM searches, ..
  - Search for **proton decay** signal continues
  - Astrophysics, geophysics, .. (not covered in this talk)
- Expect interesting results from **current experiments** with improved sensitivities
- **Next generation** experiments are under construction
  - Multiple experiments with complementarity
  - Expect exciting results for a few decades

Backup


T2K Run1–10 Preliminary
Antineutrino mode e-like candidates
Neutrino mode e-like candidates
$\sin^2\theta_{23}$ = 0.45, 0.50, 0.55, 0.60
$\Delta m^2_{32} = 2.49\times10^{-3}$ eV^2
$\Delta m^2_{31} = -2.46\times10^{-3}$ eV^2
$\delta_{CP} = \pi$
$\delta_{CP} = +\pi/2$
$\delta_{CP} = 0$
$\delta_{CP} = -\pi/2$
68% syst err. at best-fit
Best-fit
Data (68% stat err.)


NOvA Preliminary
NOvA FD
13.60×10^{20} POT-equiv (ν)
12.50×10^{20} POT ($\bar{\nu}$)
Inverted Hierarchy
Upper Octant
Lower Octant
Normal Hierarchy
Total events - antineutrino beam
Total events - neutrino beam
δ_{CP}= 0
δ_{CP}= $\pi/2$
δ_{CP}= π
δ_{CP}= $3\pi/2$
2020 best fit



From Snowmass Neutrino Frontier: NF01 Topical Group Report