Neutrinos: an open window for the next discoveries.
The DUNE experiment as a cornerstone.

Luca Stanco,
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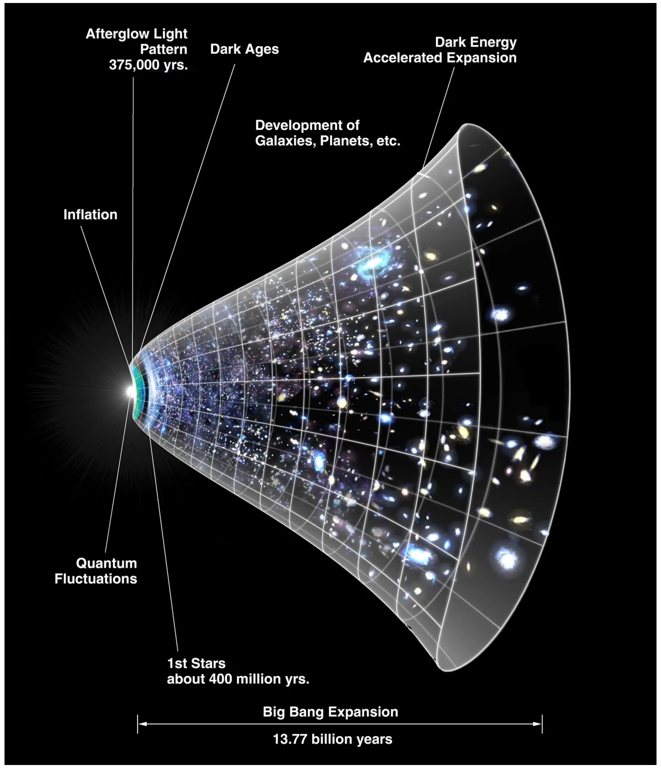
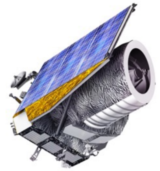
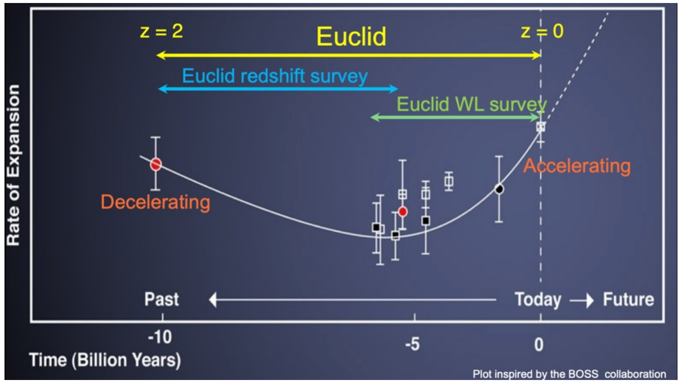
The three big questions/issues in HEP

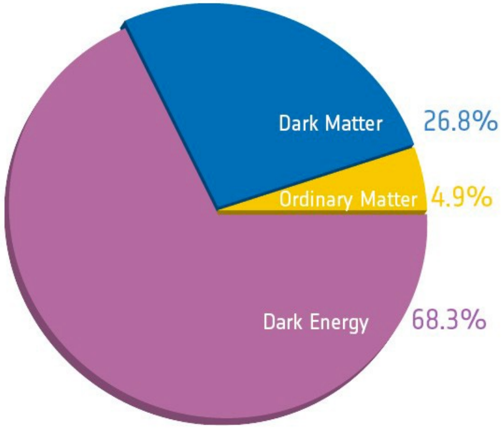
1. **The DARK Universe**: what is it? How does it shape the Universe? How does it interact with standard matter?





ΛCDM

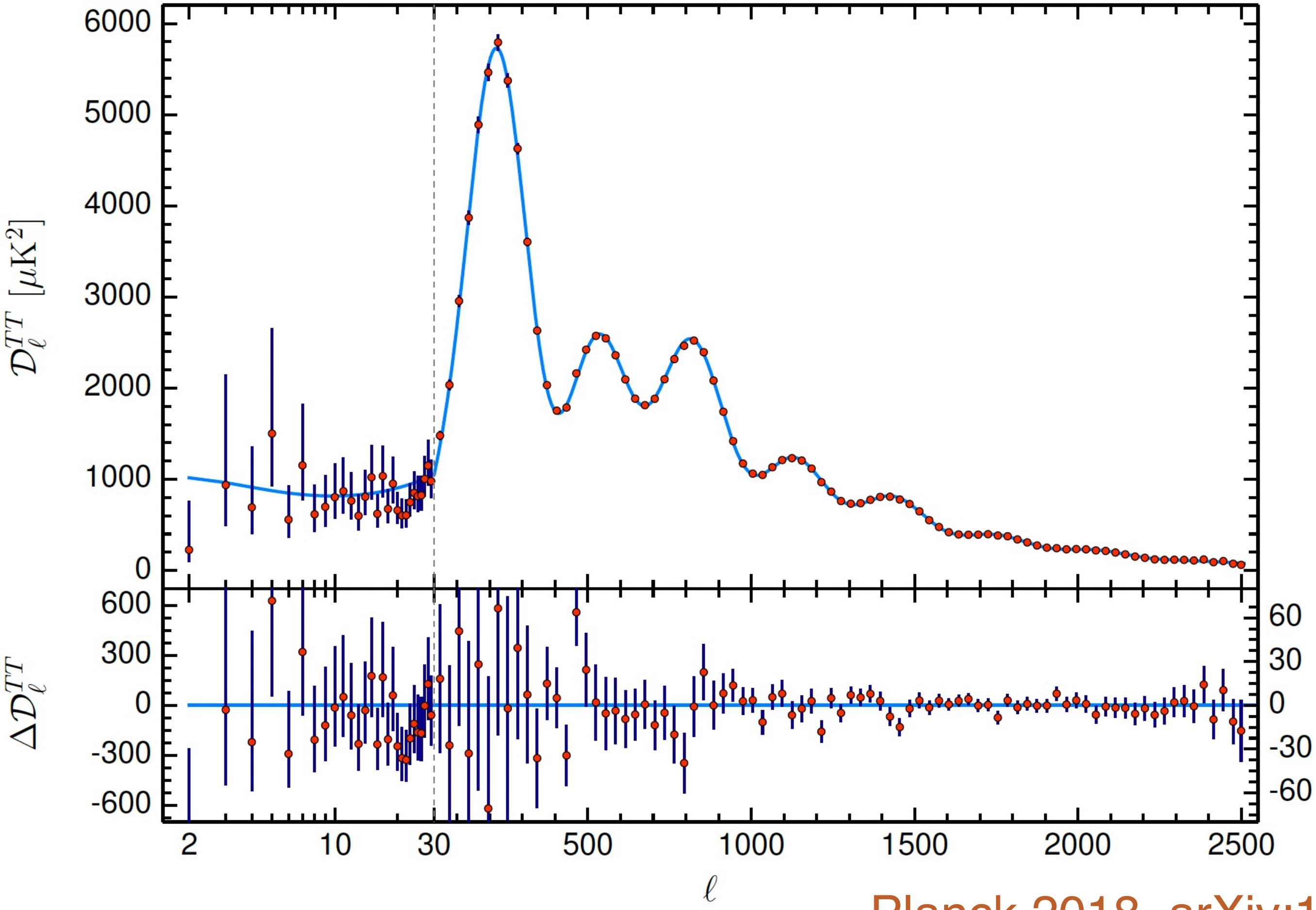




We do not know the 95% of content of the Universe

The DARK Universe - II

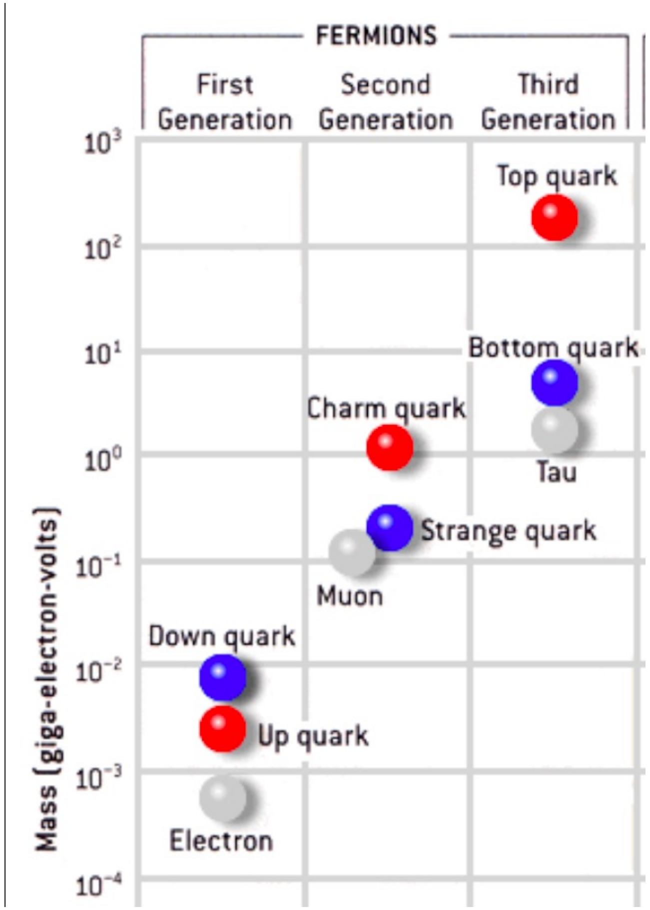
How it works the Cosmological Standard Model, ΛCDM (6 parameters)

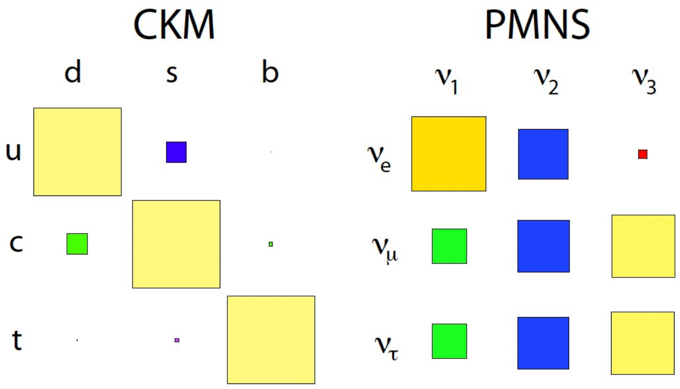


Planck 2018, arXiv:1807.06209

The three big questions/issues in HEP

2. **The Flavour problem**: why quarks and leptons look so uneven?
MIXING of FLAVOR STATES against MASS STATES





	θ_{23}	θ_{13}	θ_{12}	δ
Leptons	$\sim 45°$	8.5°	34°	?
Quarks	2.4°	0.20°	13°	69°

Is the θ_{23} mixing maximal?
$\theta_{23} = 45° \rightarrow |U_{\mu 3}| = |U_{\tau 3}|$

CKM: Cabibbo-Kobayashi-Maskawa

PMNS: Pontecorvo Maki-Nagawava-Sakata

In other words: why > 26 parameters in the SM?

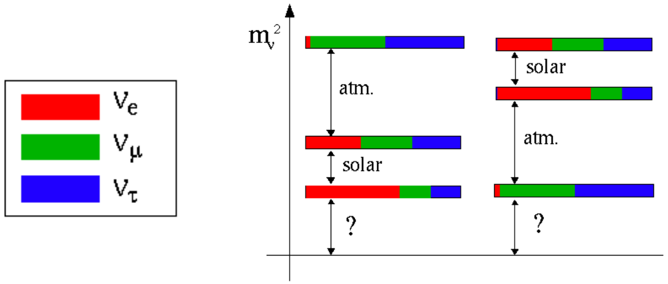
The Flavour problem - II

- Strong hierarchical pattern of quark and charged-lepton masses
- Almost diagonal CKM (quark-mixing) matrix

$$V_{CKM} \sim \begin{pmatrix} 0.9744 & 0.2250 & 0.0037 \\ 0.2248 & 0.9735 & 0.0418 \\ 0.0086 & 0.0411 & 0.99912 \end{pmatrix}$$

@PDG2022

- **LARGE** mixing angles in the neutrino sector, and not so precisely known
- Neutrino spectrum not fully known yet, but certainly not very hierarchical



Mass Ordering ?

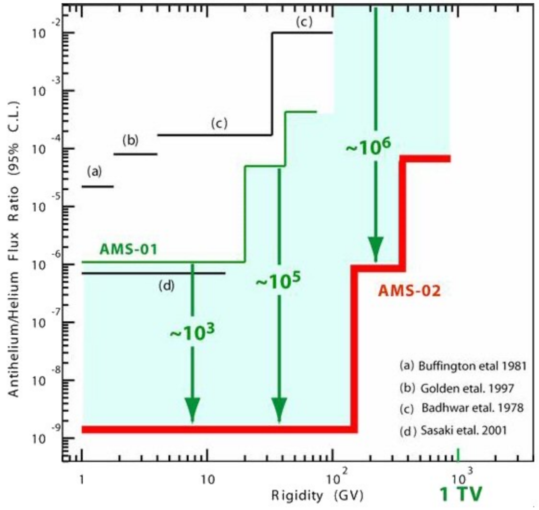
?

m_ν<0.8 eV @90%

It span ~ 12 orders of magnitude in mass with t

The three big questions/issues in HEP

3. **The Antimatter**: where is it? It mystifies us due to its apparent absence in the Universe



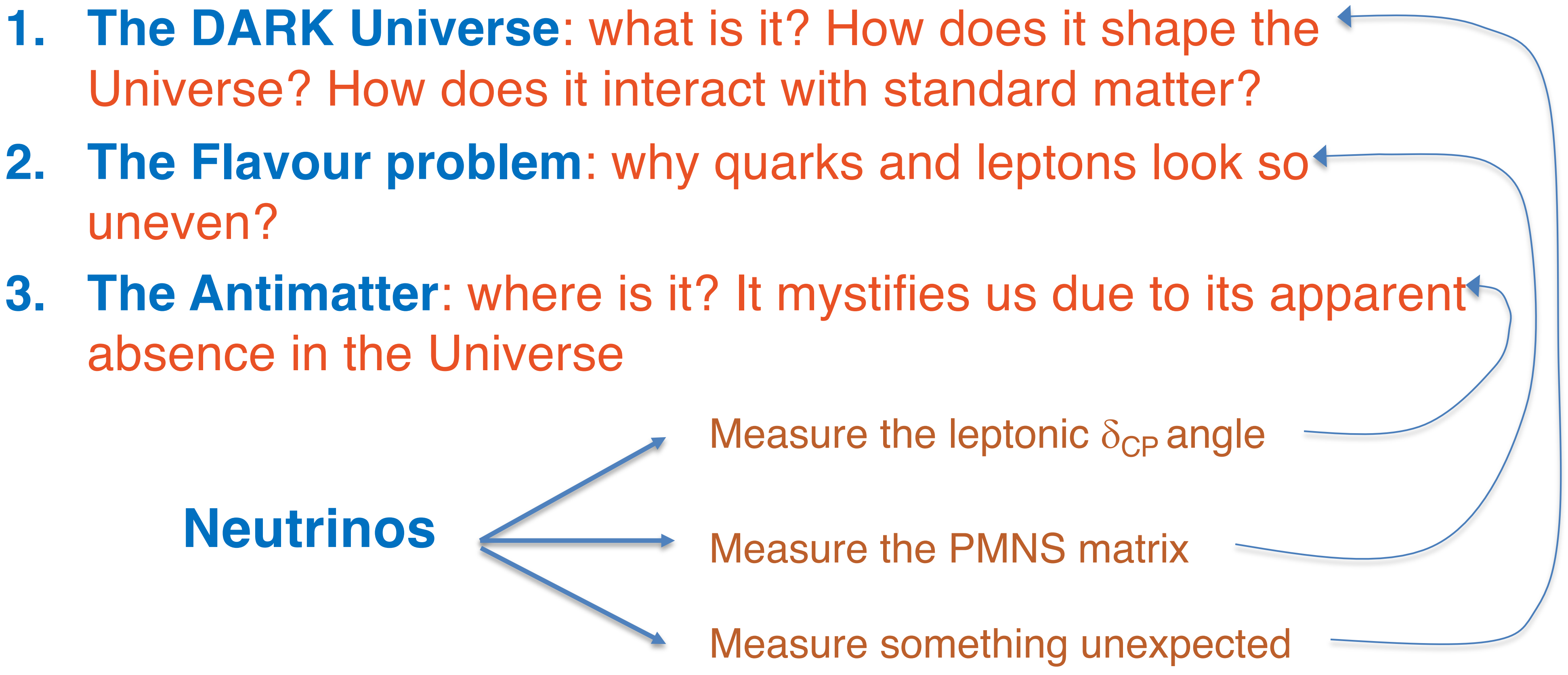
We observe an overwhelming abundance of matter in the Universe

- A tiny imbalance in the M and AM of the early Universe

- The Charge-Parity violation implies an asymmetry among MATTER and ANTIMATTER
  Established in 1964 for neutral Kaons, in 2001 for B and in 2019 for D decays
  A single independent phase δ_{CP} comes out from the Quark Sector
  CP_{quark} violation is too small to justify the missing antimatter in the Universe

- What about the Lepton Sector?

The three big questions/issues in HEP



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3. **The Antimatter**: where is it? It mystifies us due to its apparent absence in the Universe

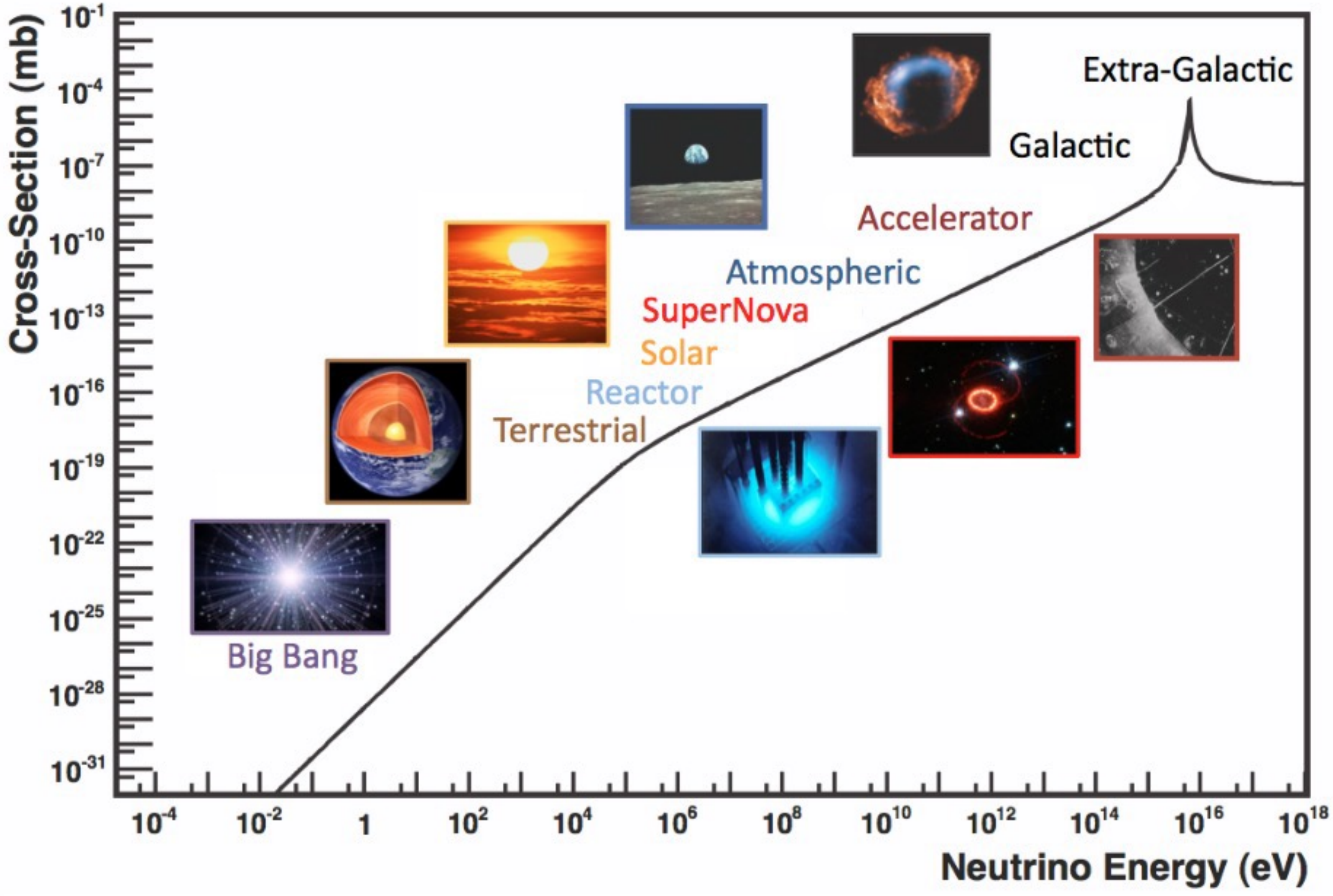
Neutrinos

Measure the leptonic δ_{CP} angle

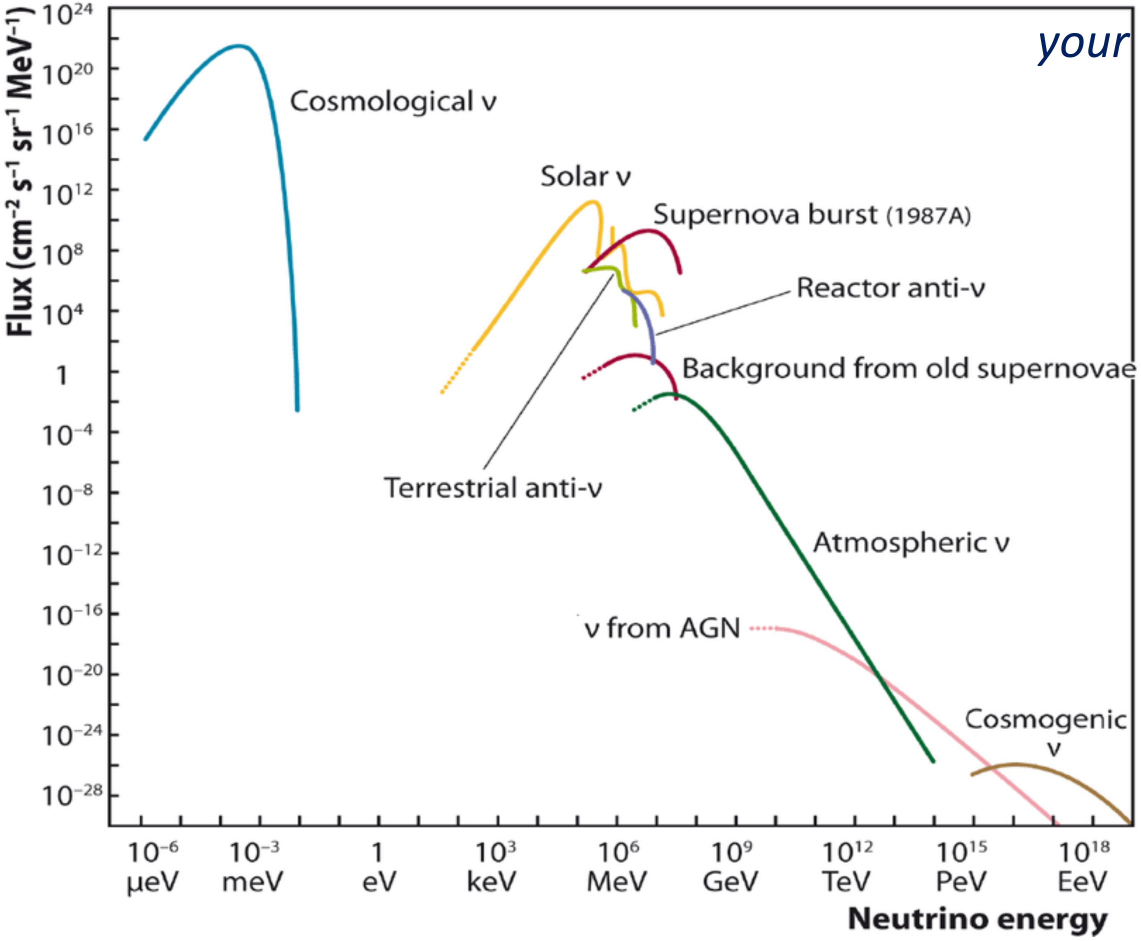
Measure the PMNS matrix

Measure something unexpected

Neutrino sources



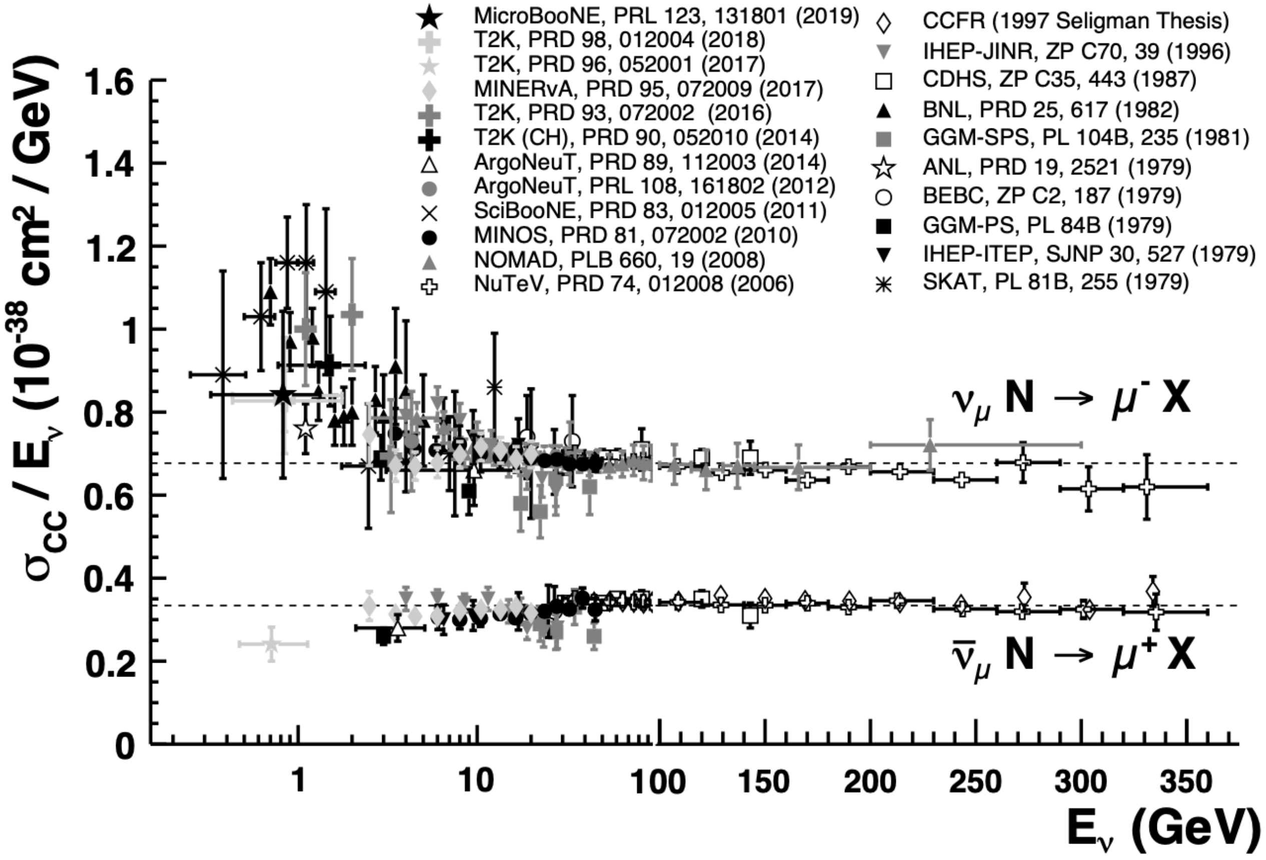
Neutrino fluxes

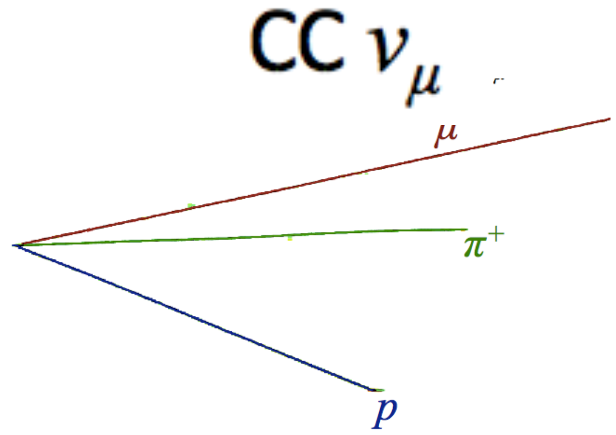


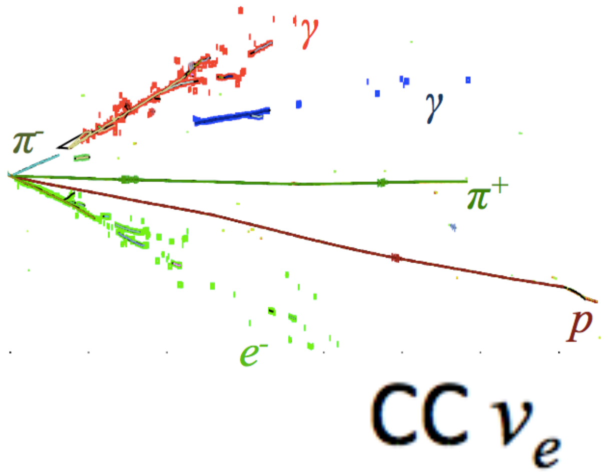
Billions of neutrinos through your thumb in one second

Neutrino cross-sections

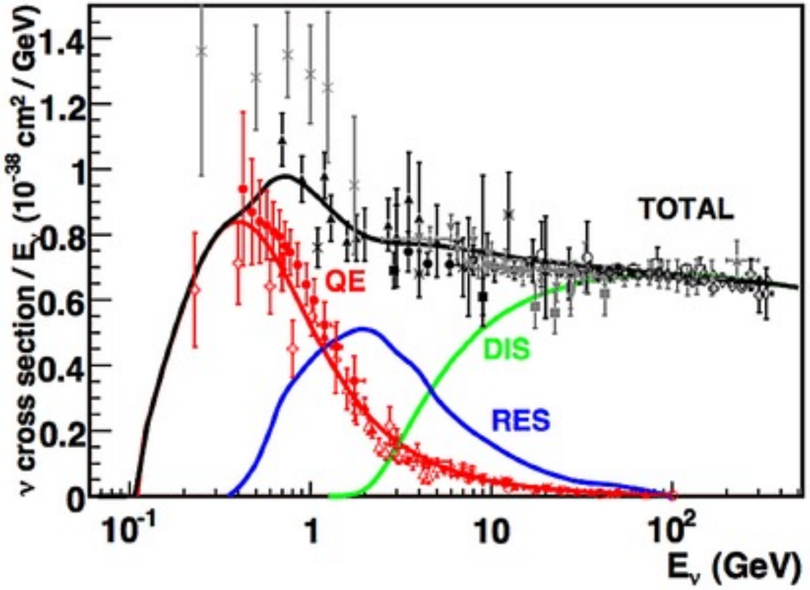
(un)fortunately its cross-section is quite small







ν cross-sections - II



There are concurrent interactions:
- Quasi-Elastic
- Resonant
- Deep-Inelastic-Scattering

Mean free path

$$\boxed{\sigma \approx 10^{-44}\ cm^2 \quad \text{for} \quad E(\bar{\nu}) = 2\ MeV} \Rightarrow \lambda = {}^{1}/_{n\sigma} \Rightarrow$$ 1000 light-years in H_2O

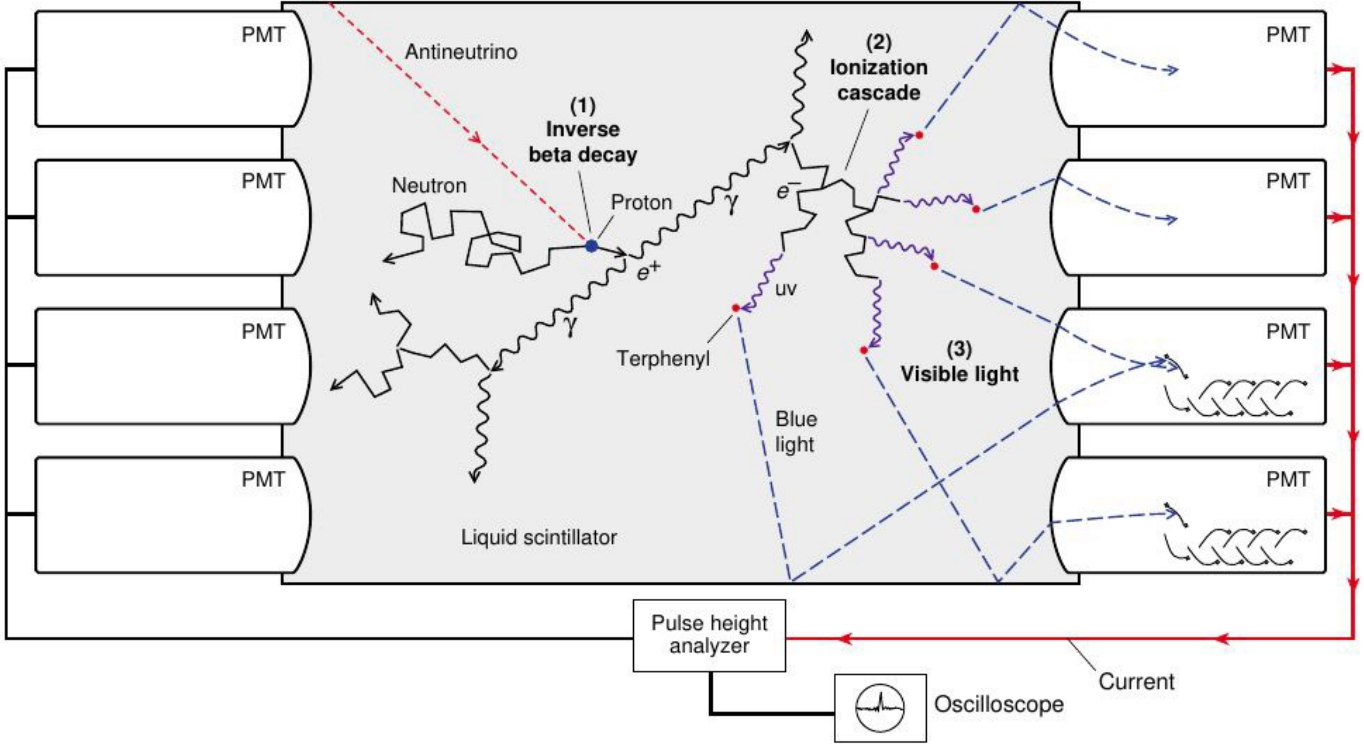
n: number of molecules per unit of volume

Compute probability of 1 neutrino interaction in 1 human body in 1 year

Neutrino detection

Reines & Cowan, 1956,
reactor of Savannah-River

$$\bar{\nu} + p = n + e^+$$



200 kg H_2O+
20 Kg $CdCl_2$

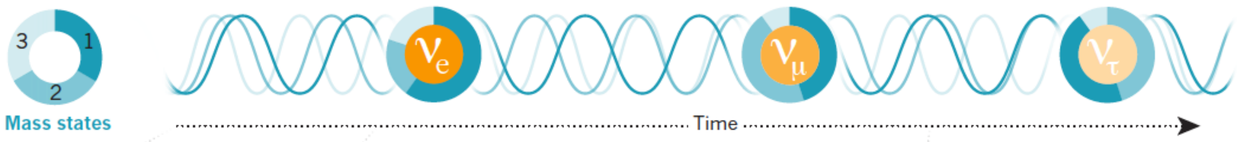
Coincidence of the prompt positron and the delayed (5 μs) of the neutron, captured by the cadmio and its further release of a photon

History was not so simple…

Although neutrinos are very abundant:

- Until 1998 nobody knew that neutrinos have masses and they could oscillate among them
- How do they oscillate?
- Mass states and Flavour states

LS, Rev. in Phys. 1 (2016) 90



A neutrino with flavor α can be expressed as a combination of mass states:

$$|\nu_\alpha >= \sum_{I=1}^{3} U_{\alpha i}|\nu_i >$$

Бруно Понтекорво

Pontecorvo, 1957

Standard Neutrino Oscillations

The recent Neutrino History

1998

1rst Annus Mirabilis

Oscillations :
- Observation by *SuperK* atm
- Reactor exclusion by *Chooz*

2002

2nd A. M.

3 x 3 matrix :
- Solar by *SNO*
- Reactor by *KAMLAND*

2012

3rd A. M.

θ_{13}:
- Reactor by *Daya Bay, RENO, Double Chooz,*
- *T2K* beam

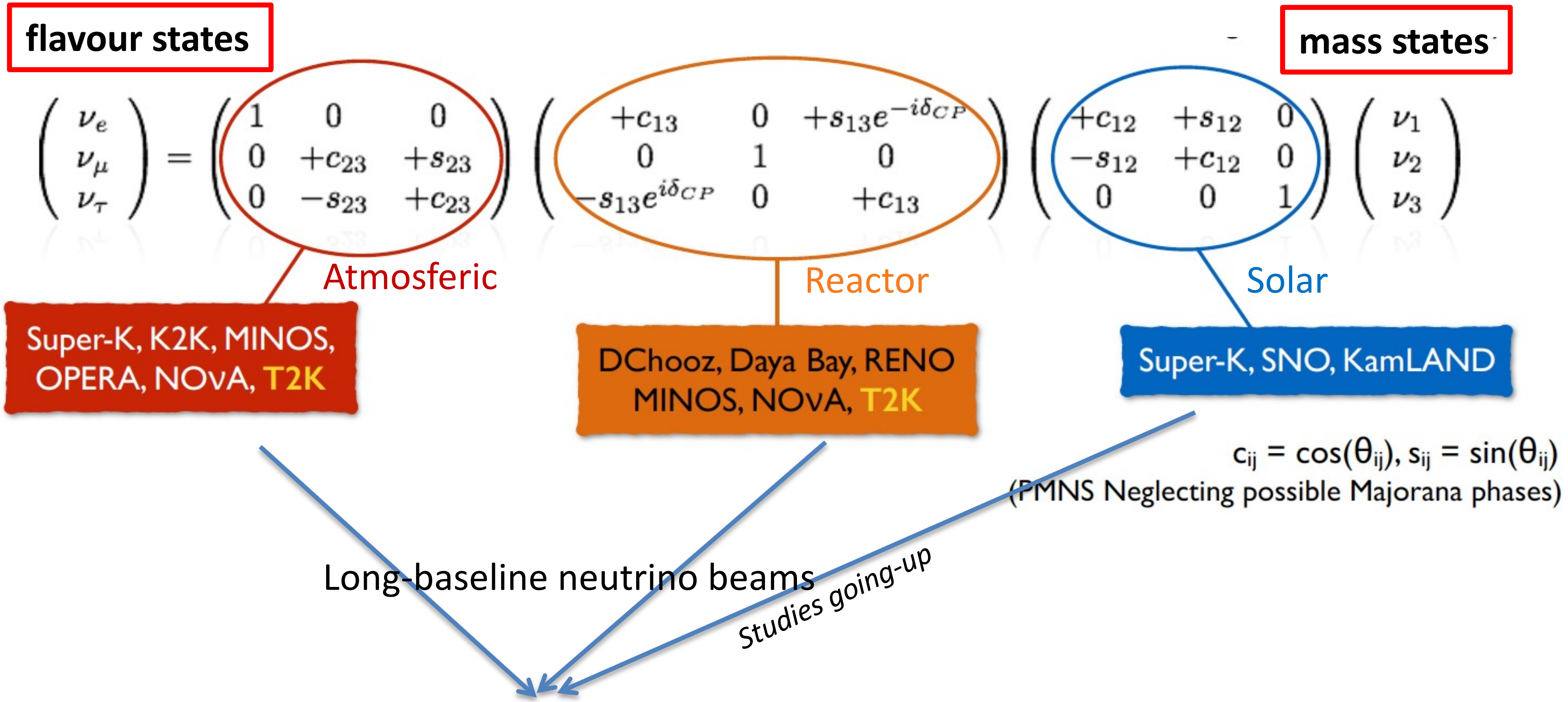
20- ?

4th A. M. ?

- Hints for Mass Hierachy by *NOvA/T2K*
- CPV by *T2K*

≥ 20- ? → δ_{CP} ?

Panorama



flavour states

mass states

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

Atmosferic

Super-K, K2K, MINOS, OPERA, NOvA, T2K

Reactor

DChooz, Daya Bay, RENO MINOS, NOvA, T2K

Solar

Super-K, SNO, KamLAND

$c_{ij} = \cos(\theta_{ij})$, $s_{ij} = \sin(\theta_{ij})$

(PMNS Neglecting possible Majorana phases)

Long-baseline neutrino beams

Studies going-up

DUNE and, partially, HK

Neutrino oscillations in the 3-neutrino framework

From the PMNS Matrix

$\Delta m^2_{ij} = m^2_i - m^2_j$

$$P_{\nu_\mu \to \nu_e, (\bar{\nu}_\mu \to \bar{\nu}_e)} \approx 4 \sin^2\theta_{13} \sin^2\theta_{23} \frac{\sin^2 \Delta}{(1-A)^2} + \alpha^2 \sin^2 2\theta_{12} \cos^2\theta_{23} \frac{\sin^2 A\Delta}{A^2} + 8\,\alpha\, J_{\mathrm{CP}}^{\max} \boxed{\cos(\Delta \pm \delta_{\mathrm{CP}})} \frac{\sin \Delta A}{A} \frac{\sin \Delta(1-A)}{1-A}$$

$$\Delta \equiv \frac{\Delta m^2_{31} L}{4E_\nu} \qquad A \equiv \frac{2E_\nu V}{\Delta m^2_{31}} \qquad \alpha \equiv \Delta m^2_{21}/\Delta m^2_{31} \qquad V_C = \sqrt{2} G_F n_e\,.$$

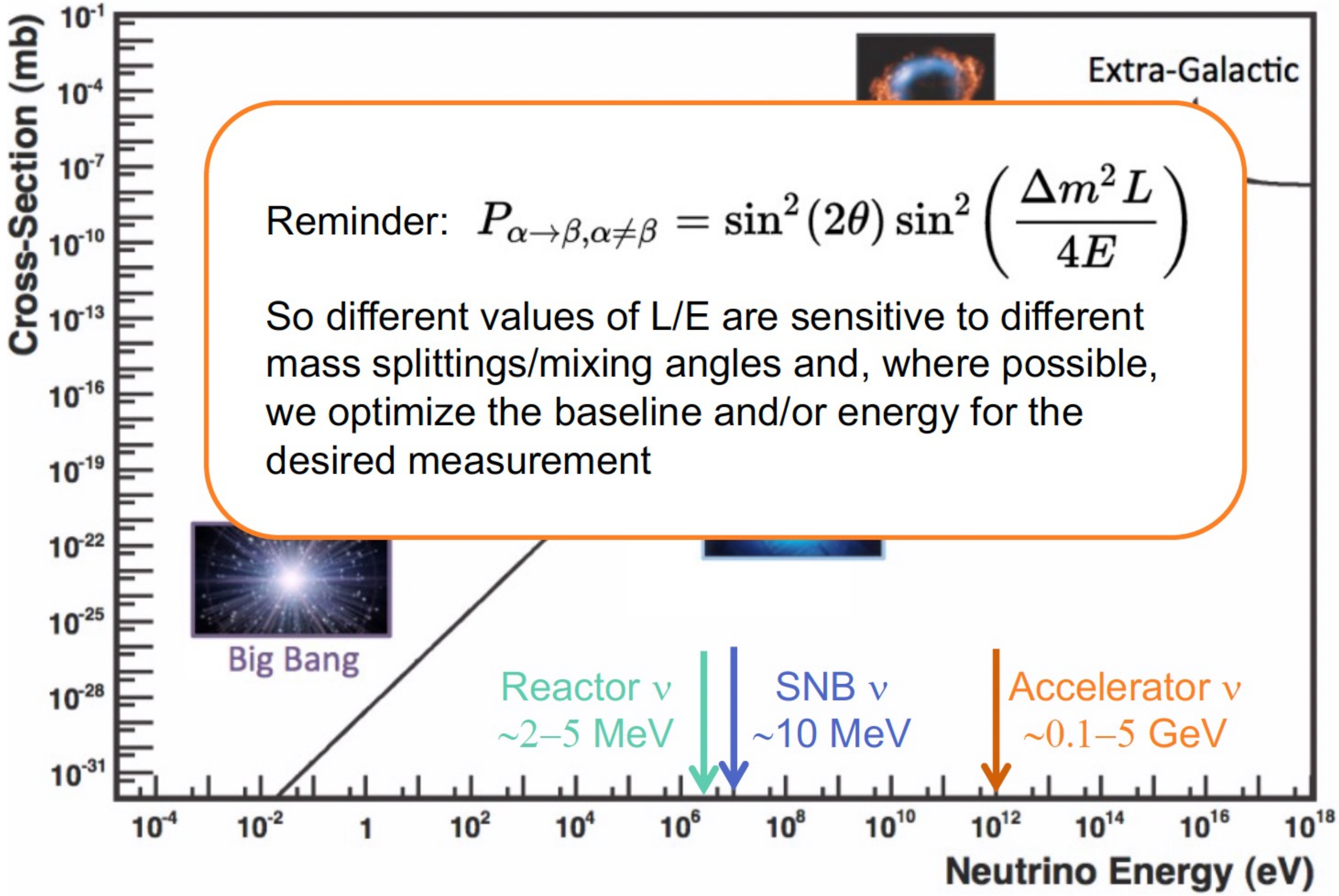
ν_e appearance :
mass ordering,
δ_{CP} , octant of θ_{23}

ν_μ disappearance:
$|\Delta m^2_{32}|, \sin \vartheta^2_{23}$,
constrain octant

for $\bar{\nu}$
- «minus» sign
- V→ -V

α, Δ , A are sensitive to the sign of Δm^2_{31}

Thus…

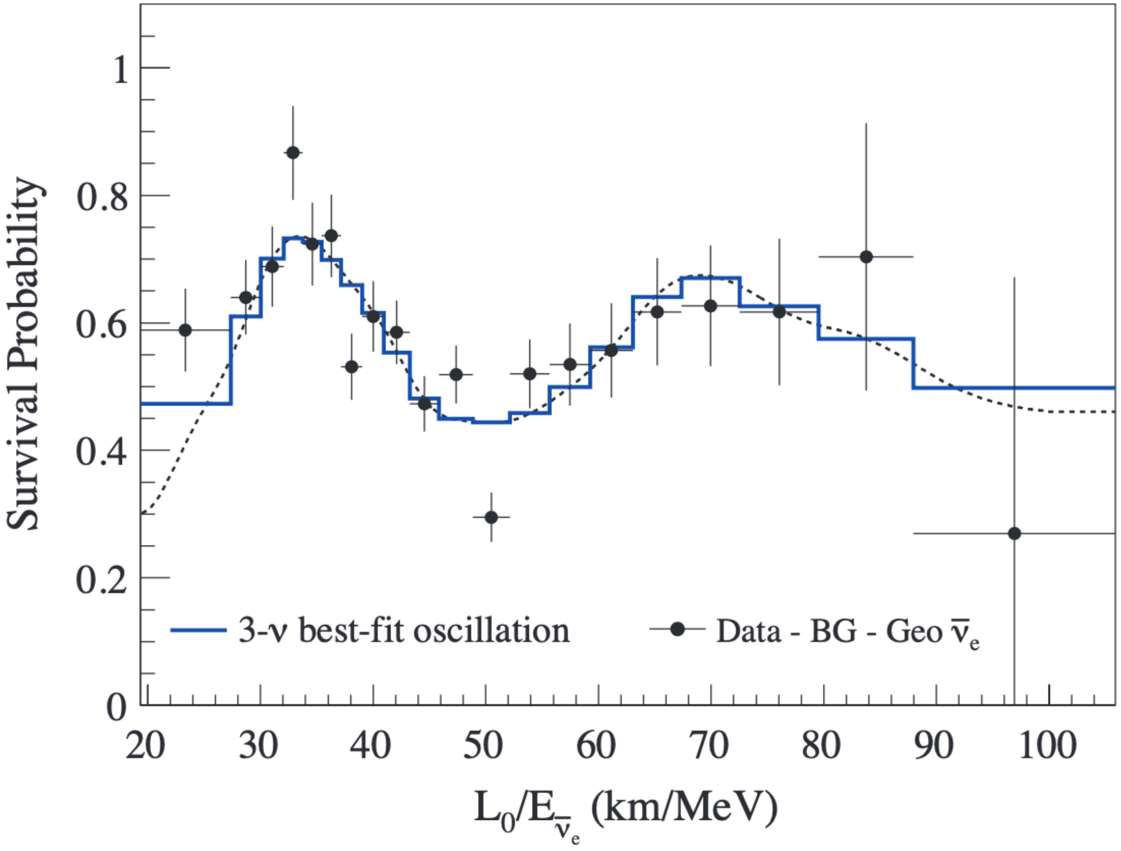


Reminder: $P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$

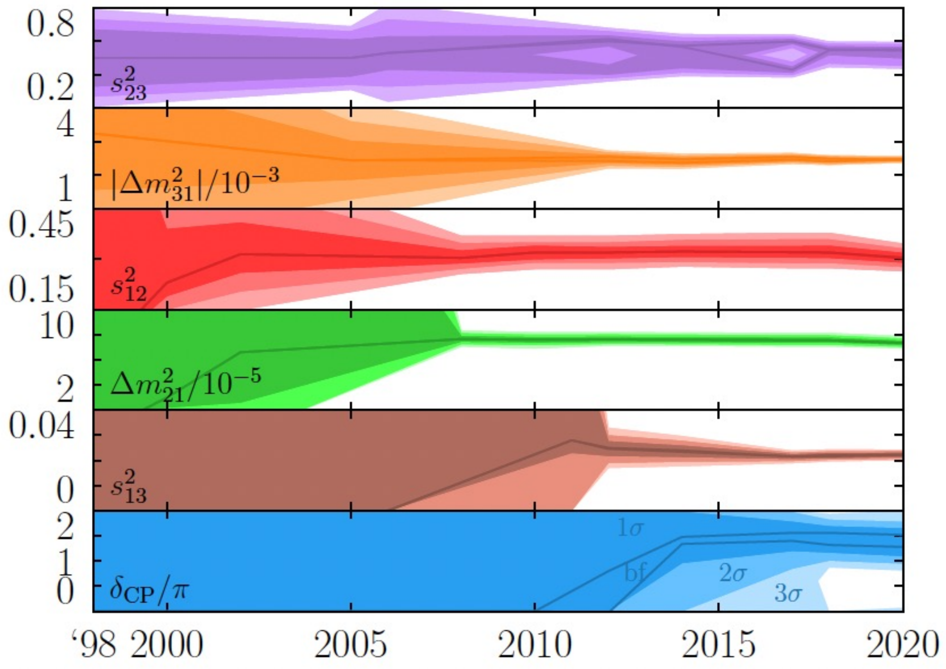
So different values of L/E are sensitive to different mass splittings/mixing angles and, where possible, we optimize the baseline and/or energy for the desired measurement

Is it really true? Yes! They oscillate

Survival probability of reactor antineutrino-electron (KAMLAND exp. 2013)



Impressive progress since 1998



arXiv:2212.00809

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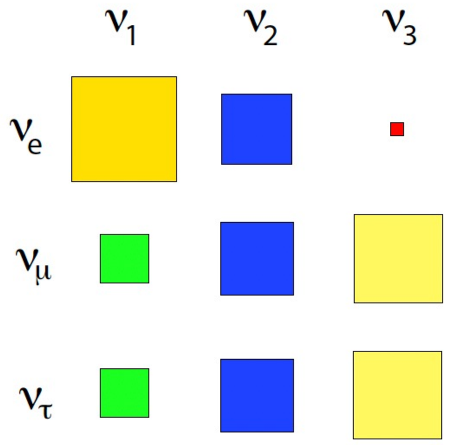
PMNS



arXiv:1212.6374v2

The source of all joys and torments
comes from this matrix (together with the smallness of the cross-section)

Neutrinos: What we do & do not know

- Neutral leptons with 3 active flavors
- Tiny small masses
    - Existing limits on sum of neutrino masses are order few hundred meV/c^2
- Flavor eigenstates (ν_e,ν_μ,ν_τ) ≠ mass eigenstates (ν_1,ν_2,ν_3)
    - Mixing described by PMNS matrix
    - All mixing angles and mass splittings have been measured
- Neutrinos detected via their interaction products
    - Neutrino interaction cross sections are small, $\mathcal{O}(10^{-38}$ cm^2/nucleon) at 1 GeV
- May be Majorana or Dirac

- Other kind of ”Sterile” neutrinos?
- Direct measurement limits currently $\lesssim$ 1 eV/c^2
- *More precise measurements of mixing angles needed

- *CP violation in PMNS?
- *Unitarity?

**Very large detectors are needed*

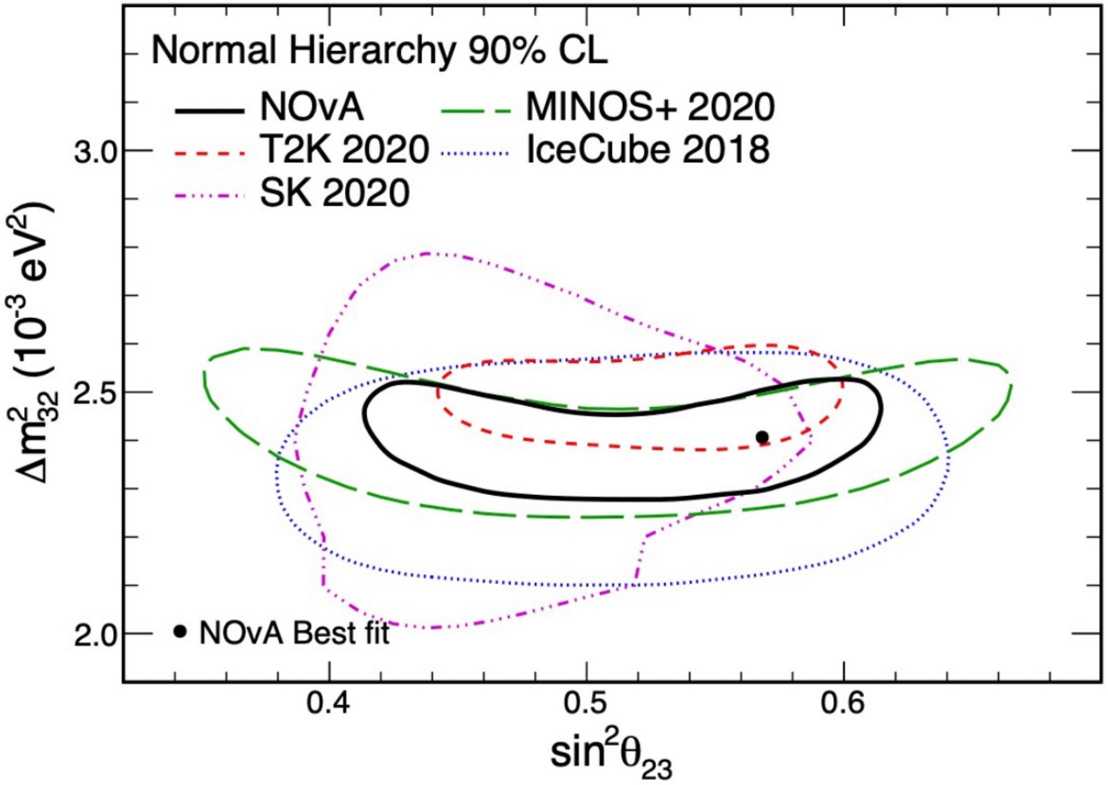
- Neutrino-nucleus interaction model has large uncertainties

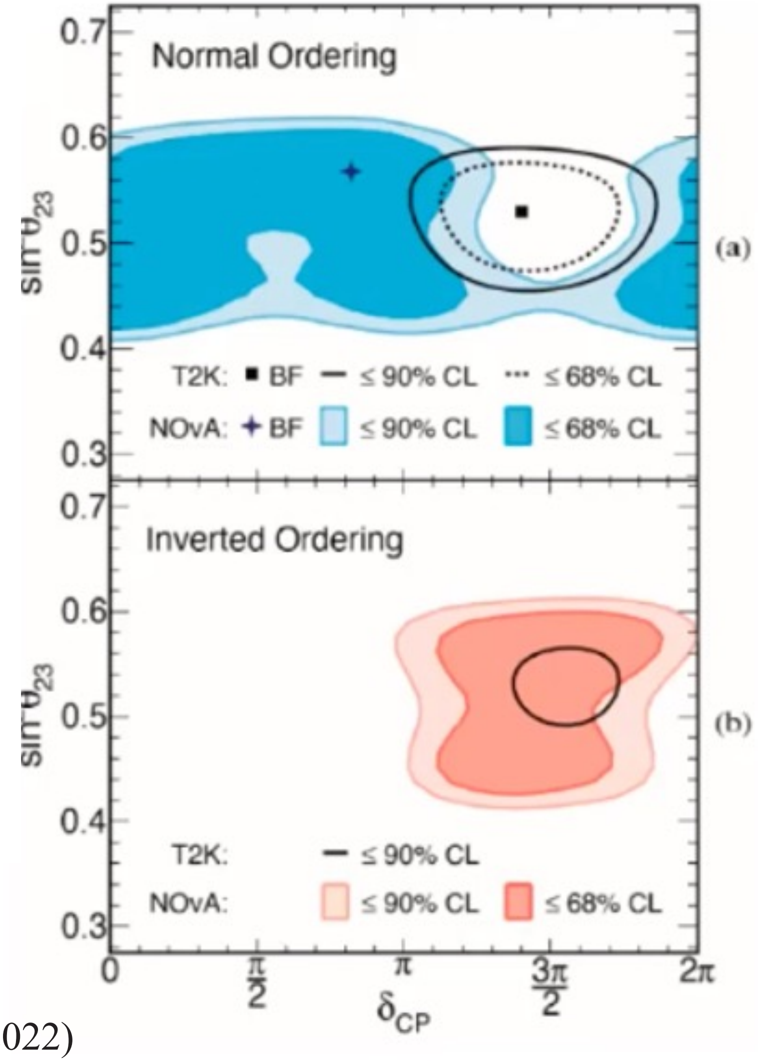
- Majorana phases?

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 59 years ago, but this violation does not help very much in understanding what happened soon after the Big Bang ($J_{CKM} \approx 3 \times 10^{-5}$)
- *Through leptogenesis, theory links the ν–mass generation to the generation of baryon asymmetry of the Universe (Fukugita and Yanagida, 1986).*
- *The Dirac phase δ_{CP} can be one of the ingredients of these mechanisms (and $J_{PMNS} \approx 0.033 \sin\delta_{CP}$)*
- It is mandatory to measure its value… also because it is one of the few unknowns of the Standard Model (together with neutrino masses)

… not a complete clear picture yet

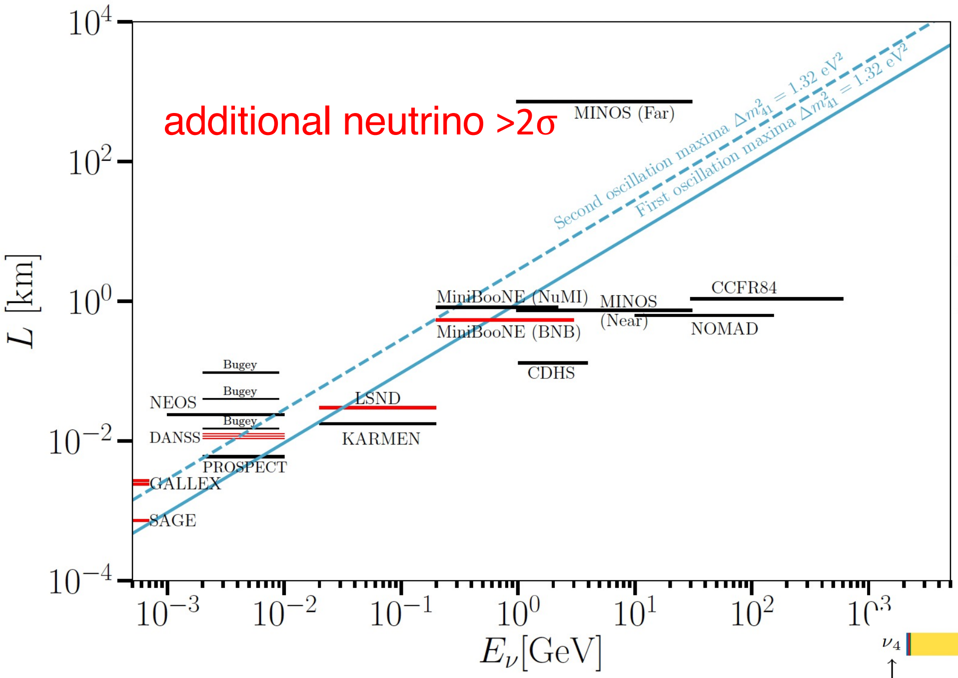




Phys Rev D 106, 032004 (2022)

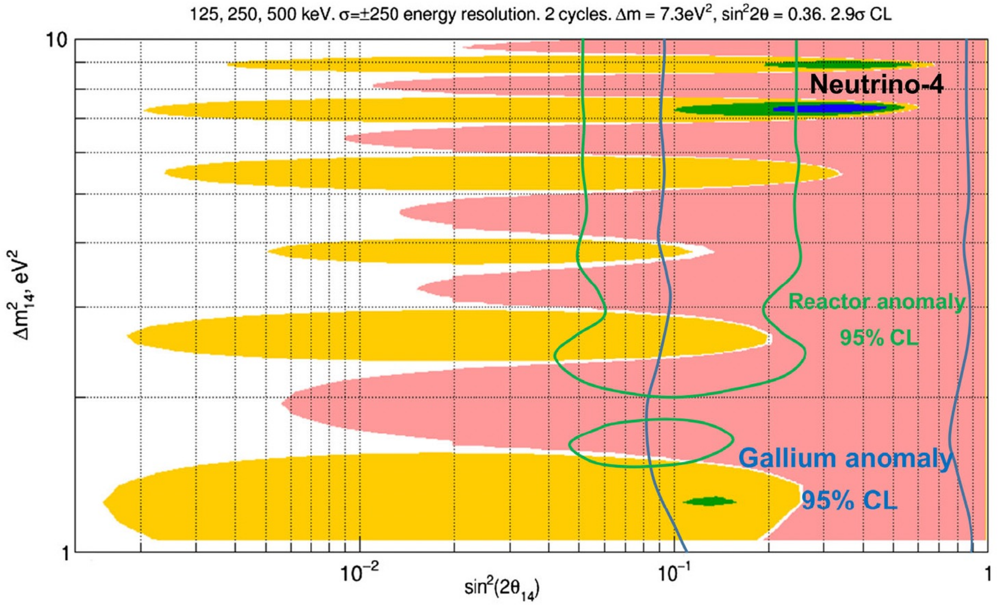
The «anomalies»

ref. ICARUS at FNAL



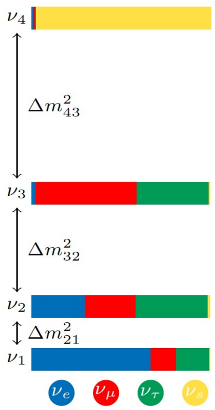
additional neutrino >2σ

arXiv:1906.00045



Phys.Rev.D 104, 032003 (2021)

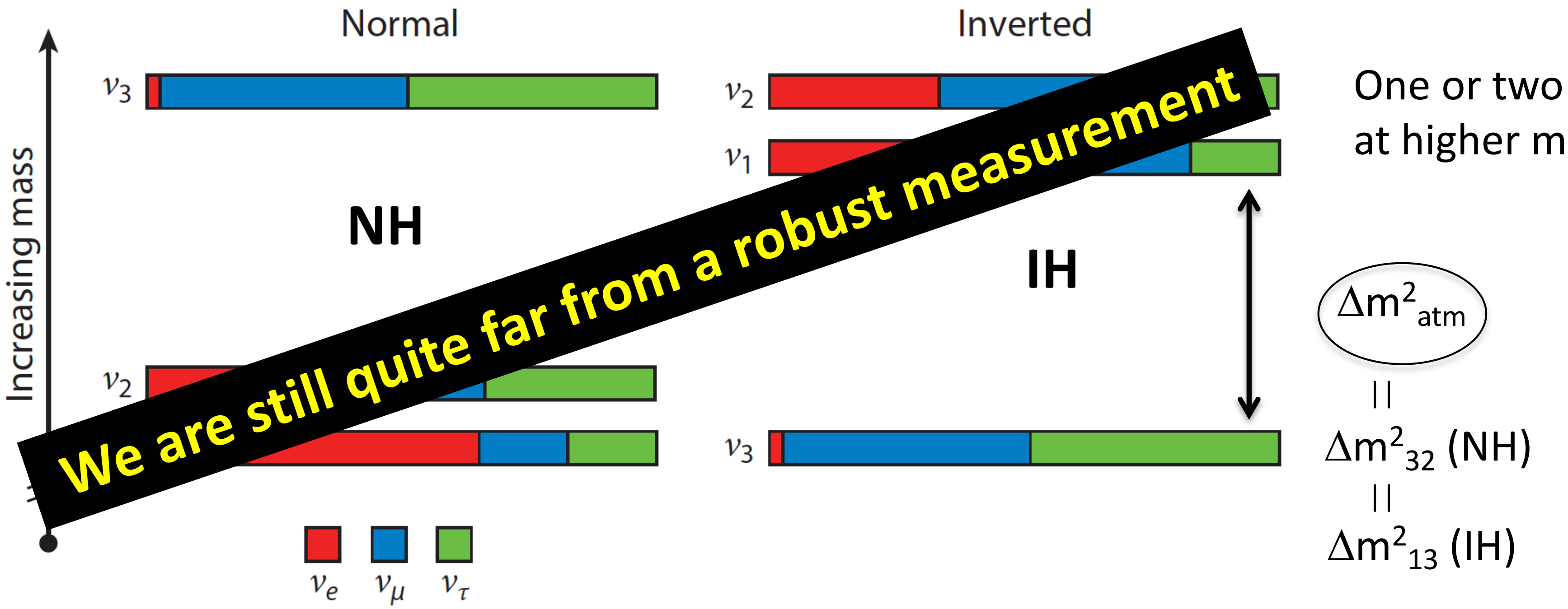
?



The present scenario

We are entering in the precision era, but there are still 4 results to be obtained, at least at first order :

1) Leptonic CP violation (phase δ_{CP})
2) Mass ordering (MO)
3) (θ_{23} octant)
4) Presence or not of more (sterile ?) neutrinos states



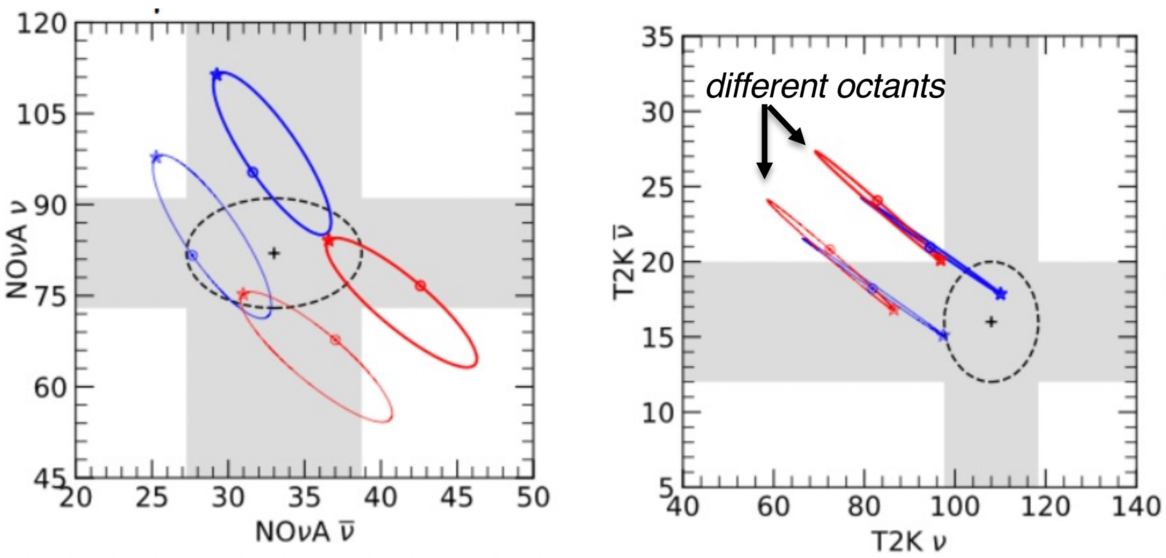
One or two states at higher mass ?

We are still quite far from a robust measurement

Measuring MH AND δ_{CP}

- In the last couple of years oscillation analysis is showing up rather controversial effects, due to correlations and degeneracies

Current experiments: NOνA(US)   T2K (Japan)



ν_e prediction as function of δ_{CP}

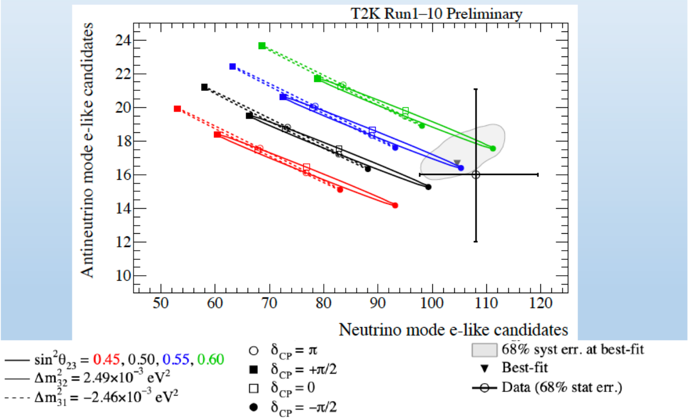
from A. Marrone, NeuTel, Feb. 2021

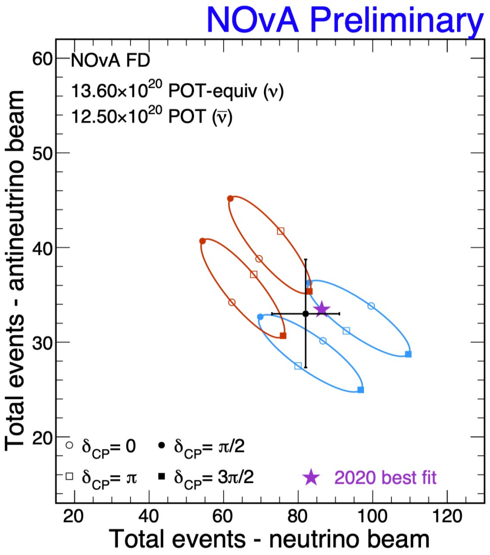
electron-ν appearance events,
in several years of data taking

- It seems mandatory to measure both MH and δ_{CP} in the same experiment

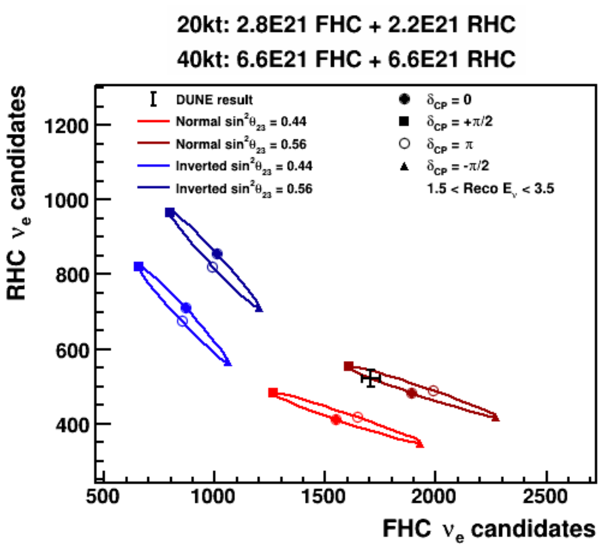
Comparing scenarios

T2K





DUNE simulation



In Hyper-K only the error bars will shrink

With 2 or 4 dects, 100 kt-MW-y, shared between FHC and RHC, in 3 y ramp-up

T2K -> Hyper-K:

Same baseline
Same beam spectrum
Same detector technology

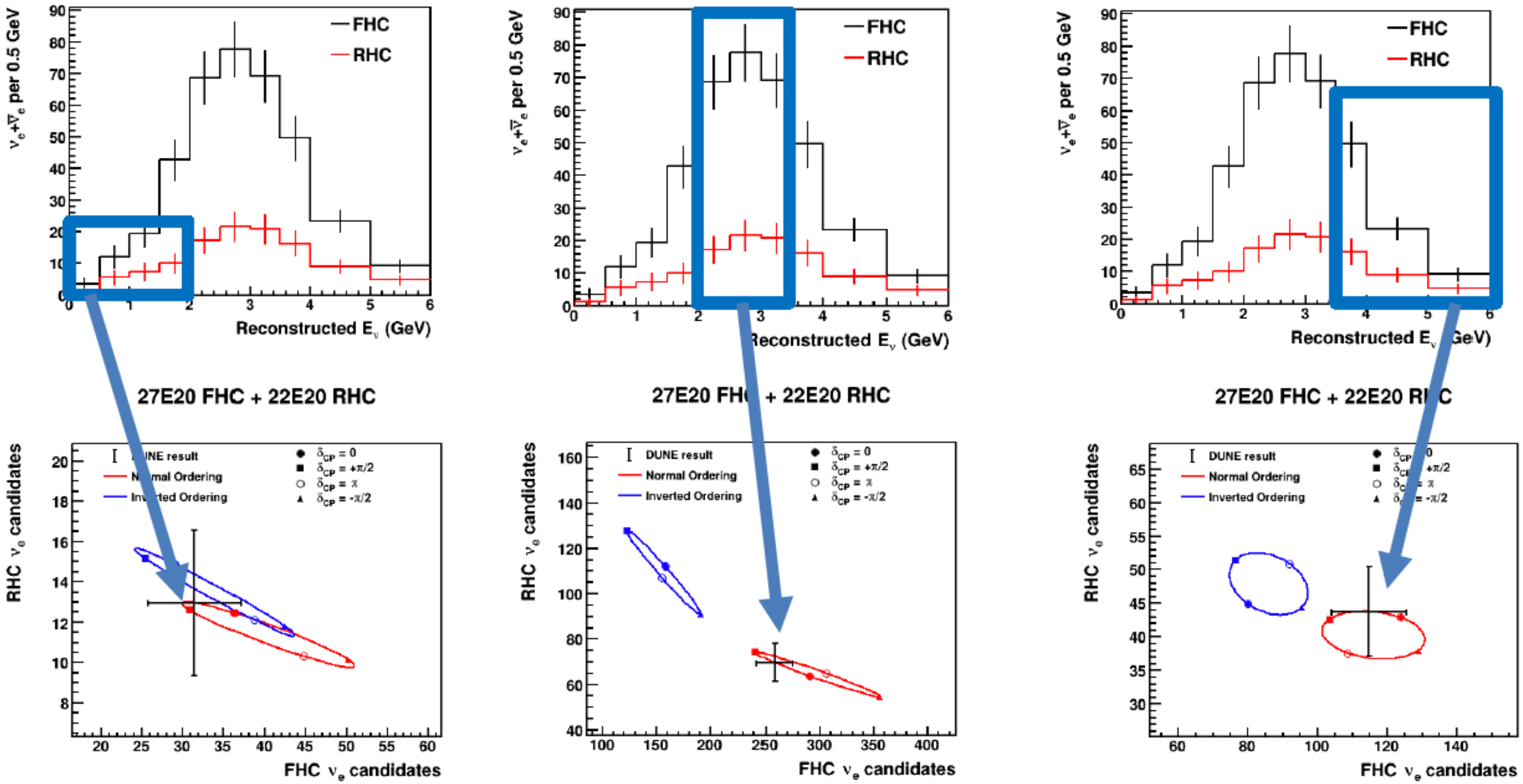
NoVA -> DUNE:

Longer baseline
Wideband beam
Better event reconstruction

FHC: Forward Horn Current
RHC: Reverse Horn Current

DUNE : enhanced by the wide-band beam

→ spectrum shape carries information (need proper energy reconstruction)



100 kt-MW-y,
shared between FHCand RHC,
in 3 y ramp-up

DUNE: What, How, When?

What to measure?
How to measure it?
When be available?

➡

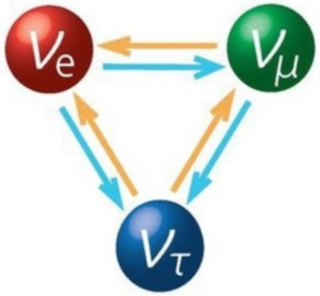
DUNE/LBNF, a multi-B$ project, to measure missing parameters of the 3 ν picture, with high precision the others, and sensitivity to SNB and BSM

With artificial beam from 1.2 to 2.4 MW proton beam and multi-kton Liquid-Argon detectors

Starting data taking for oscillations in 8 years from now (or less)

DUNE: Key Features and Physics Program

- Long- baseline wide-band neutrino beam
  - Measurement of CP violation phase and determination of the neutrino mass ordering in a single experiment with spectral information
- Underground location → access to astrophysical neutrinos
  - Supernova neutrino burst detection – sensitive to the ν_e component
  - Atmospheric neutrino – capability of ν_τ identification
  - Solar neutrinos – potential for detection of hep flux



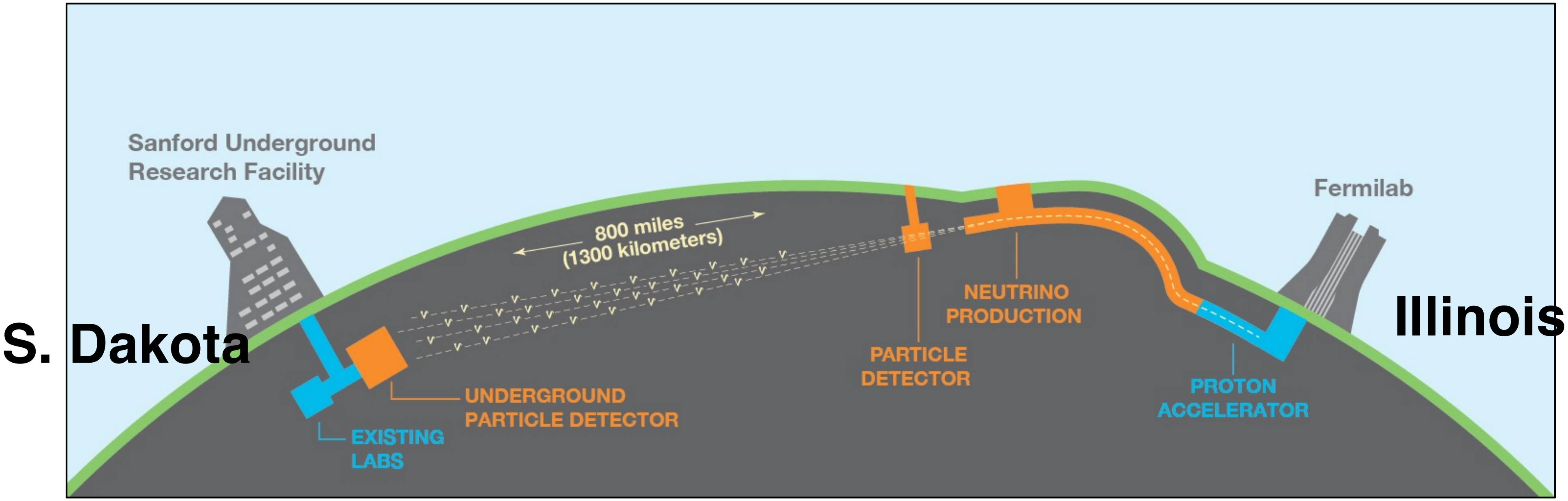
- Massive detectors with excellent tracking and calorimetric information
  - Search for baryon number violating processes – p → ν K+, $n\,\bar{n}$
- Long baseline + higher energy neutrino beam
  - ν_τ appearance, NSI searches
- Capable Near Detector Complex
  - Precise neutrino physics
  - BSM searches

The LBNF/DUNE project

LBNF → Facility

DUNE → Experiment

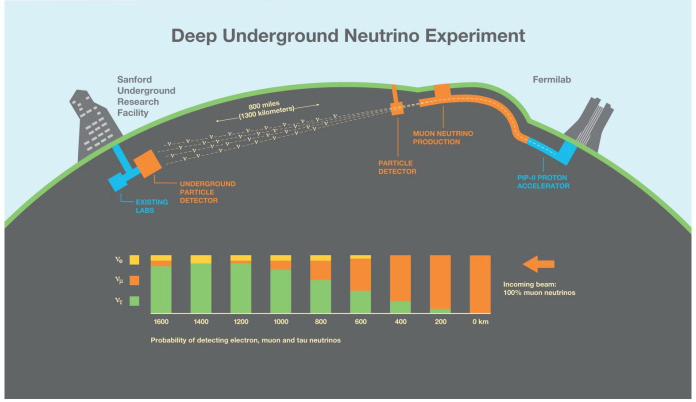
Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE)

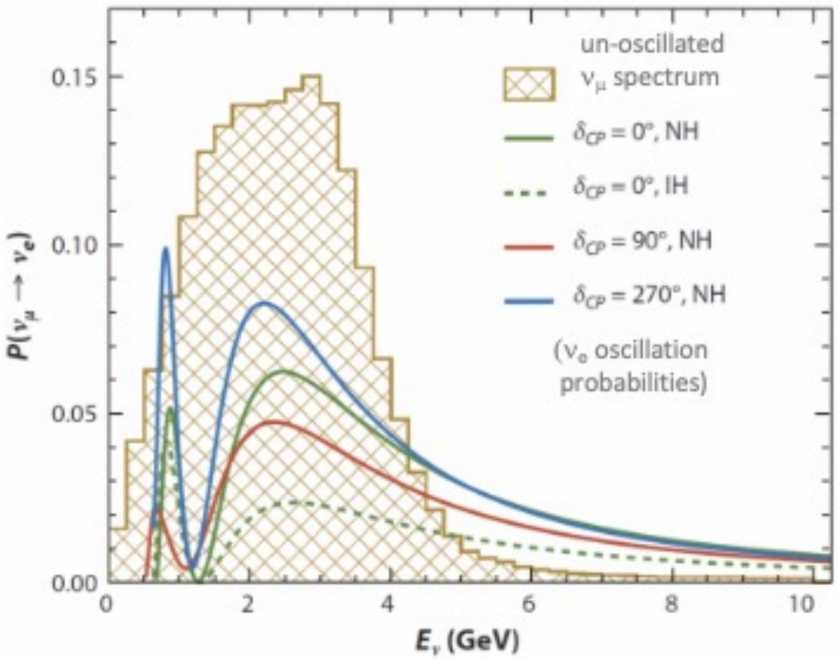


The DUNE Experimental Design

- DUNE TDR (Vol I,III,IV https://iopscience.iop.org/journal/1748-0221/page/extraproc95, Vol II arxiv:2002.03005 for Physics)
- ND CDR (arXiv:2103.13910, Instrument 5 (2021) 4, 31)

Neutrino Oscillations in DUNE





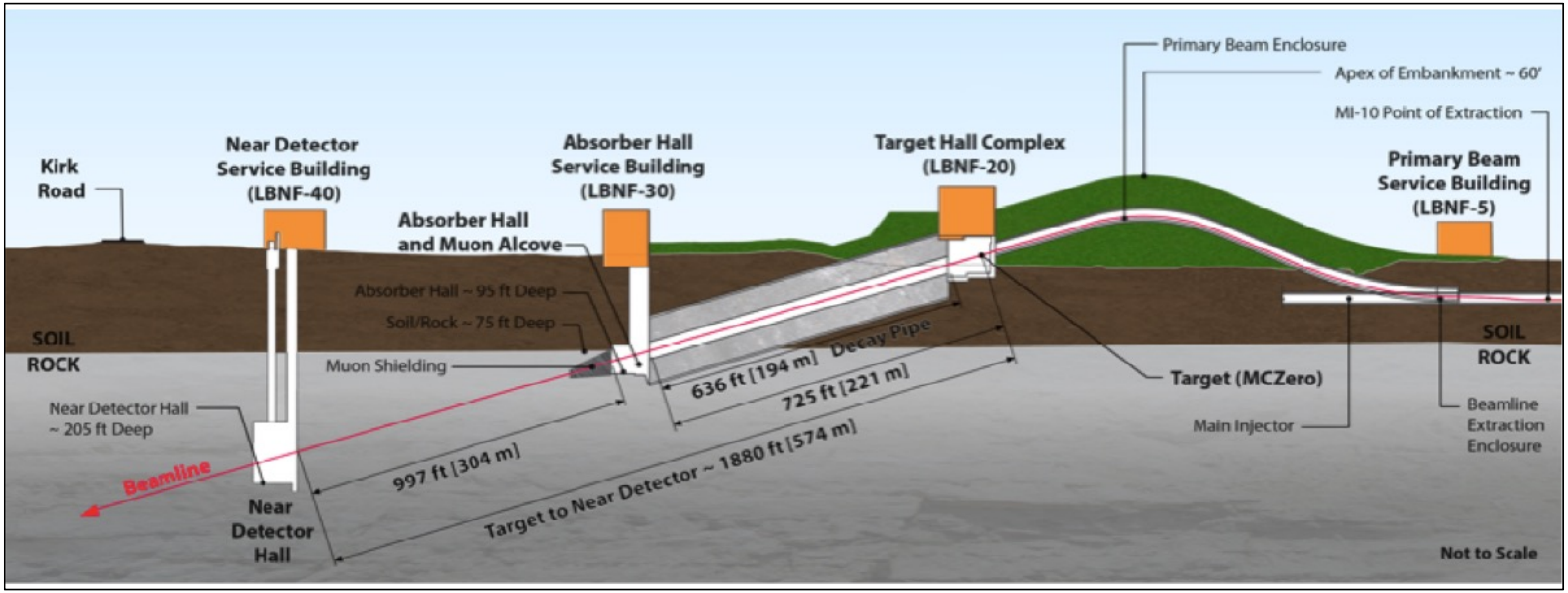
beam spectrum covers the full neutrino oscillation curve

not simply a counting experiment

The LBNF beamline at FNAL

- LBNF will use protons from the Main Injector
  - MI will start at 1.2 MW and be upgradeable to 2.4 MW
- Proton Improvement Plan (PIP II): upgrade of LINAC to reach 1.2 MW

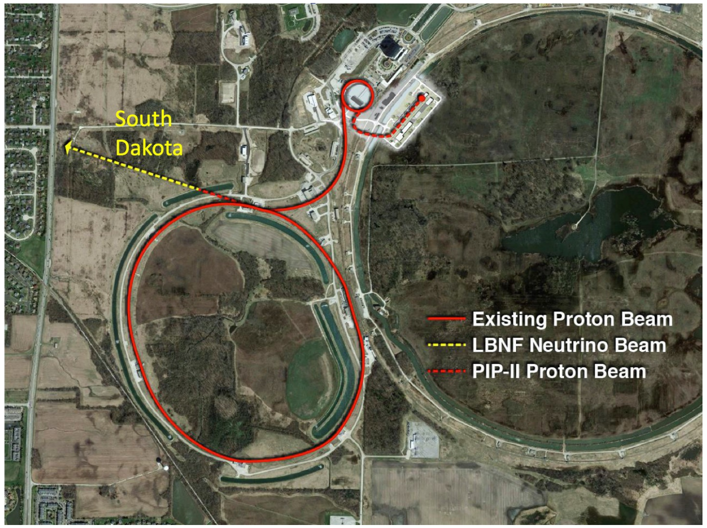
Long-Baseline Neutrino Facility (LBNF) Neutrino Beam

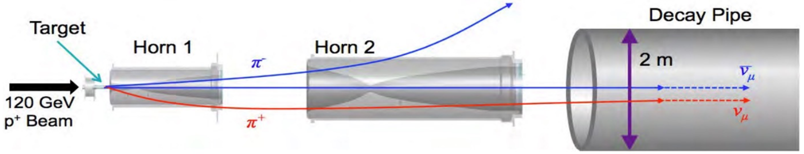


- ✓ LBNF will house and deliver beam to detectors built by DUNE Collaboration
- ✓ 60-120 GeV protons from Fermilab's Main Injector
- ✓ Initial power: 1.2 MW (@120 GeV); plan to upgrade to 2.4 MW
- ✓ 200 m decay pipe, angled at South Dakota (Sanford Underground Research Facility- SURF)
- ✓ Separate ν and ν-bar and running modes

LBNF wide-band beam

At FNAL, Fermi NAtional Lab



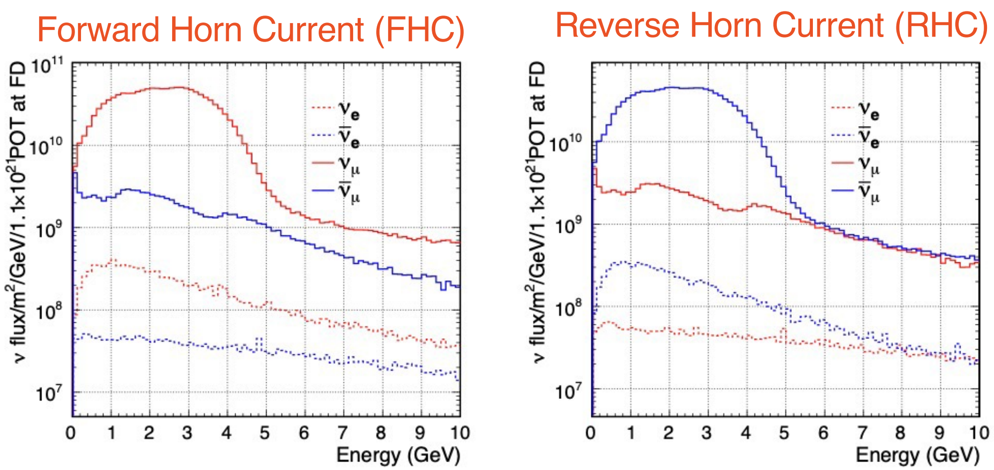


Horn-focused neutrino beam line optimized for CP violation sensitivity using genetic algorithm

1.2MW @ 100% efficiency=2x10^{21} pot/year
The 3-year ramp-up is equivalent to
one year of operation at 1.2MW from Day 1

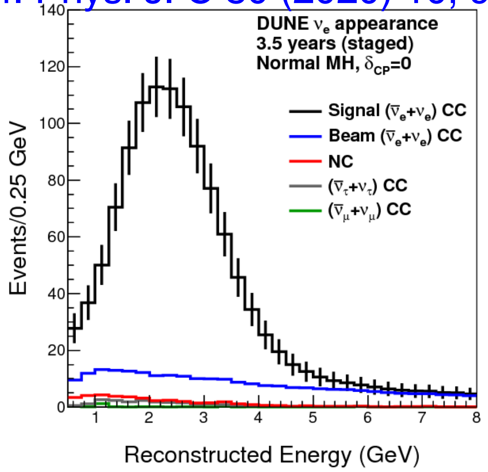
The LBNF neutrino beam will provide neutrinos and antineutrinos with energies from 0 to 8 GeV

Neutrino Flux at SURF, 1300 km away

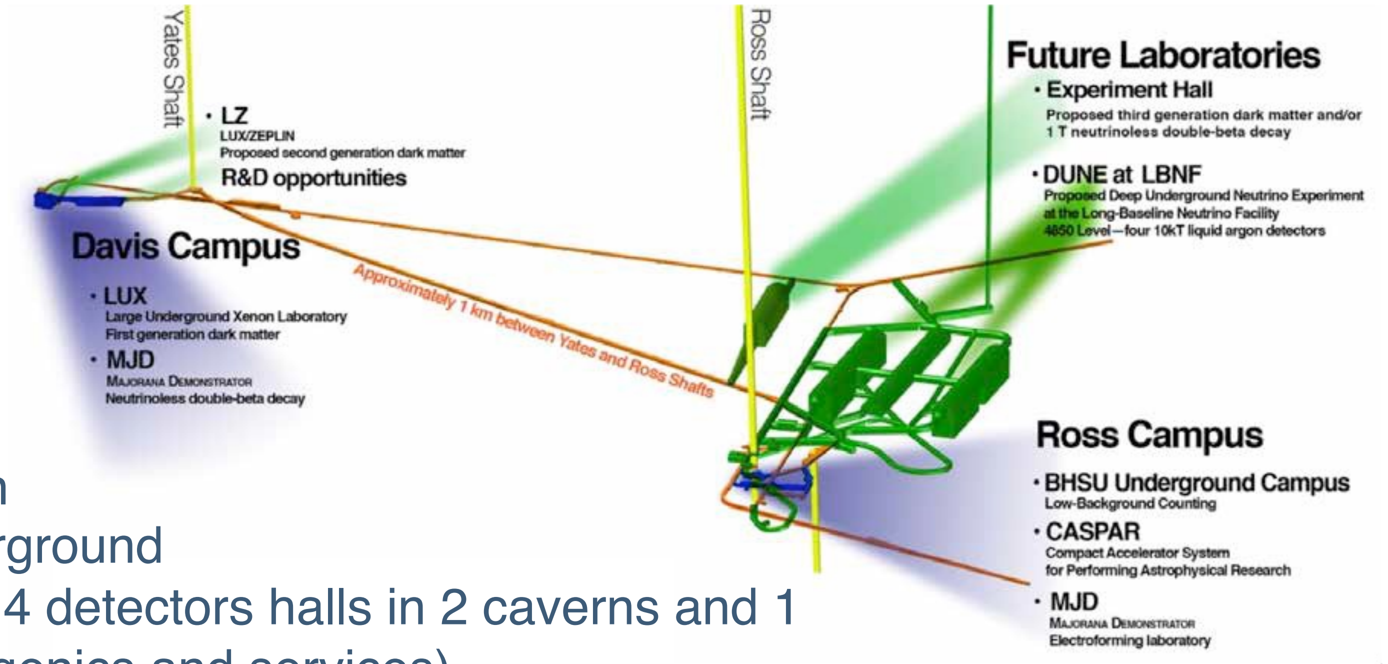


[Eur. Phys. J. C 80 (2020) 10, 978]

(DUNE CDR)



SURF



Future Laboratories
- **Experiment Hall**
  Proposed third generation dark matter and/or 1 T neutrinoless double-beta decay
- **DUNE at LBNF**
  Proposed Deep Underground Neutrino Experiment at the Long-Baseline Neutrino Facility
  4850 Level—four 10kT liquid argon detectors

- **LZ**
  LUX/ZEPLIN
  Proposed second generation dark matter

R&D opportunities

Davis Campus
- **LUX**
  Large Underground Xenon Laboratory
  First generation dark matter
- **MJD**
  Majorana Demonstrator
  Neutrinoless double-beta decay

Ross Campus
- **BHSU Underground Campus**
  Low-Background Counting
- **CASPAR**
  Compact Accelerator System for Performing Astrophysical Research
- **MJD**
  Majorana Demonstrator
  Electroforming laboratory

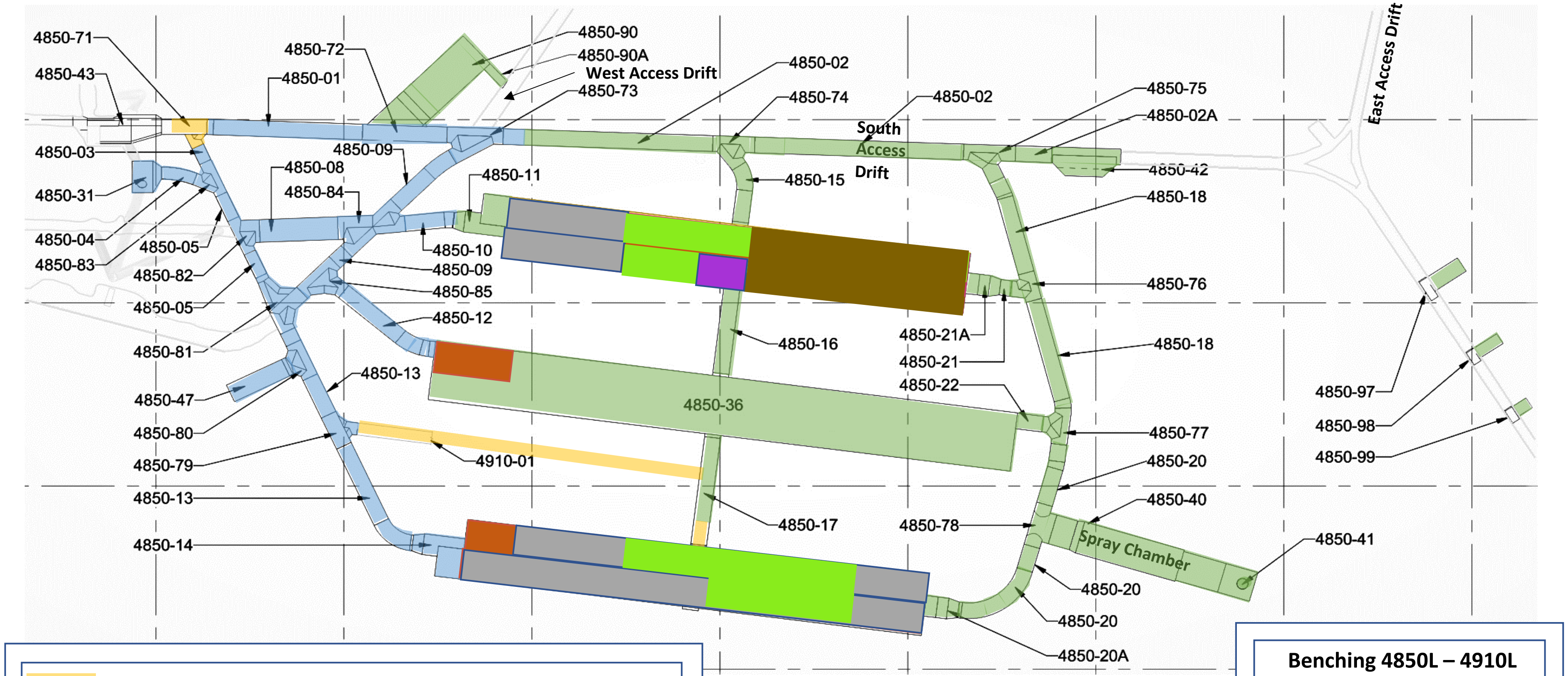
- Deepest laboratory in the US: 1.5 km underground
- Three main caverns: 4 detectors halls in 2 caverns and 1 support cavern (cryogenics and services)
- Excavation is ongoing *(875,000 tons of rock to be excavated)*
- FD first module installation second half of 2020’s

Previously known as Homestake (gold) Mine close to Lead,
in the Black Hills (South Dakota),
50 miles from Mount Rushmore and Crazy Horse statues

Excavation at SURF is ongoing

Sanford Underground Research Facility (SURF)

Excavation Progress –Reached 80% on 25 September 2023



🟨	4850L Excavation Completed
🟦	Excavation and Ground Support Complete and Accepted
🟩	Concrete Complete

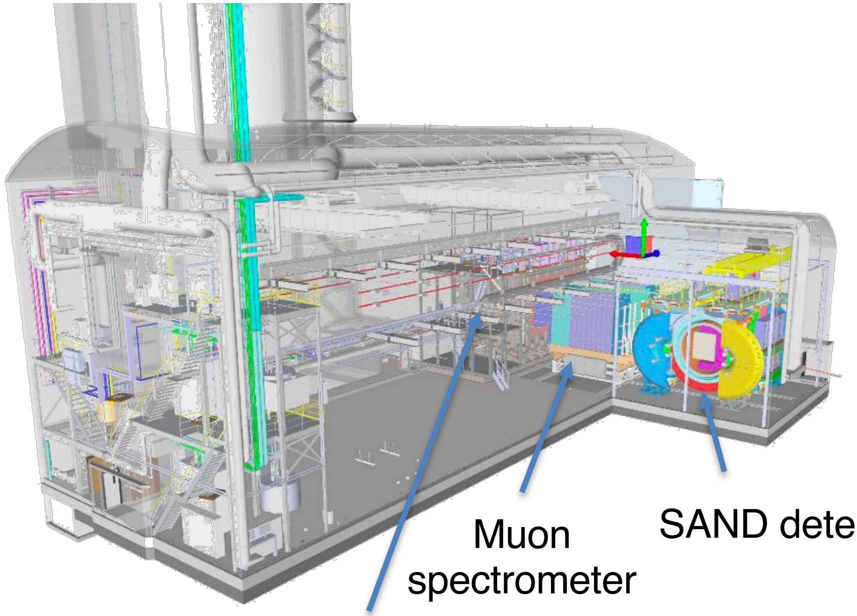
Benching 4850L – 4910L

Bench C	🟧
Bench D	⬜
Bench E	🟩
Bench F	🟫
Bench G	🟪

Near Site Conventional Facilities

Status:

- 100% final *design* completed on 28 Sep 2021 for the Beamline Complex and Near Detector Complex
- NSCF will start construction upon funding availability *(possibly better sooner than later)*

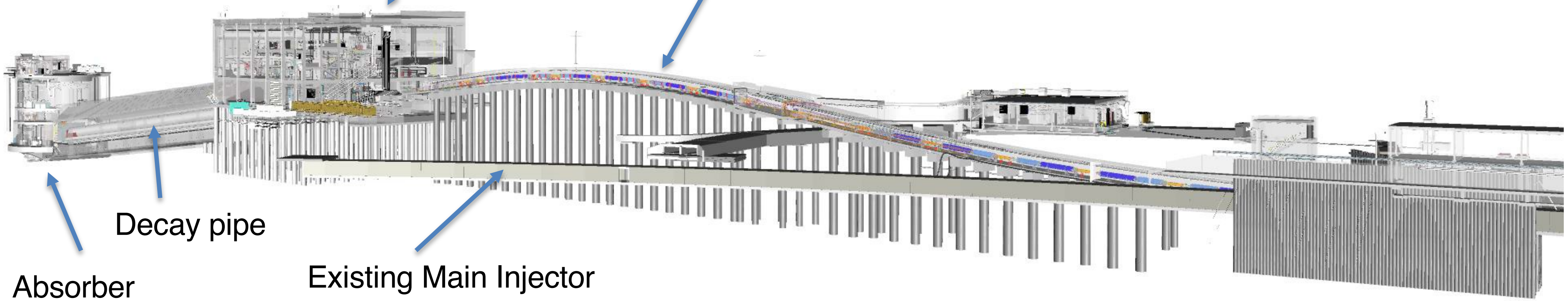


Muon spectrometer

SAND detector

ND Lar detector

ND complex



Target hall

Primary beam line

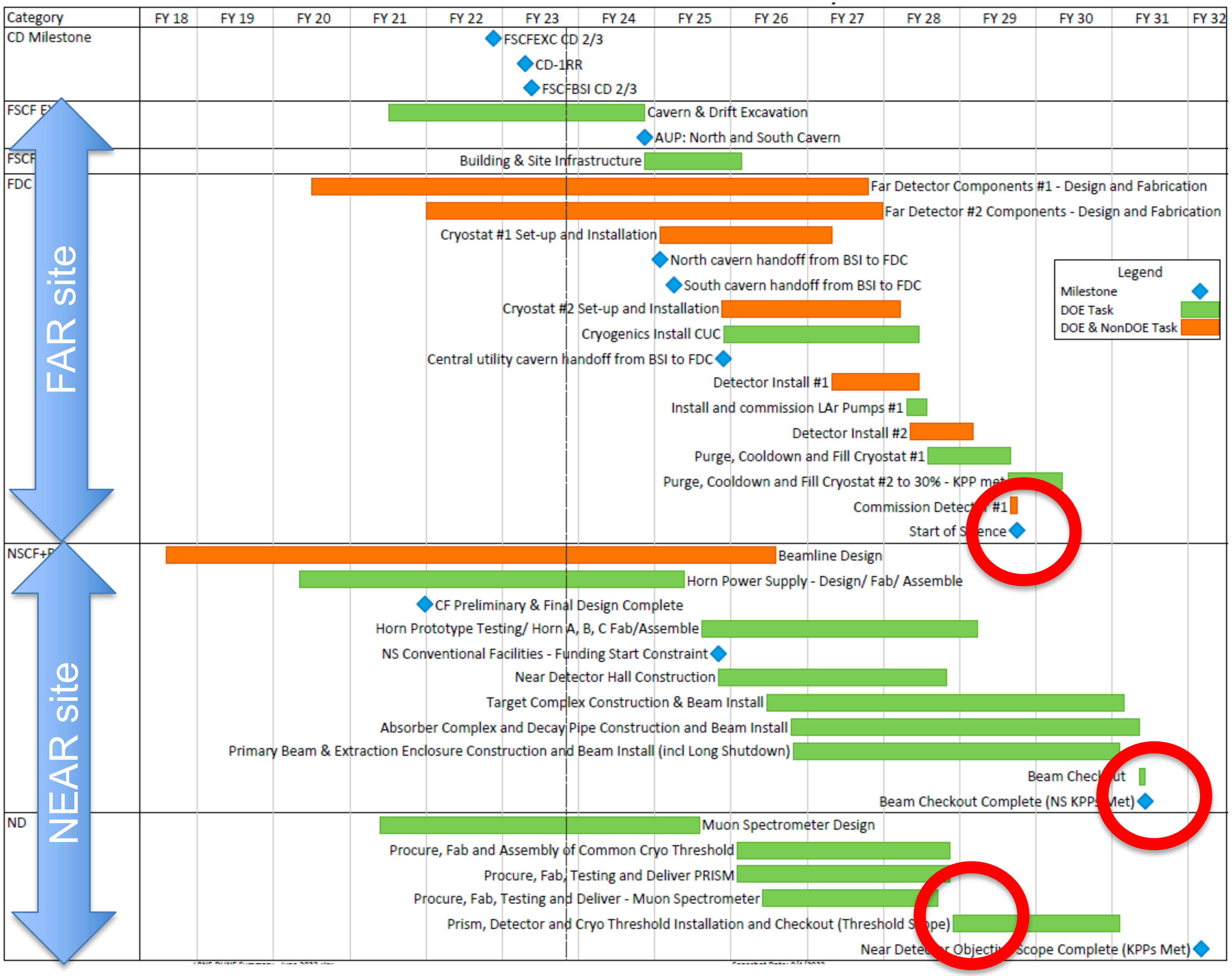
Decay pipe

Absorber

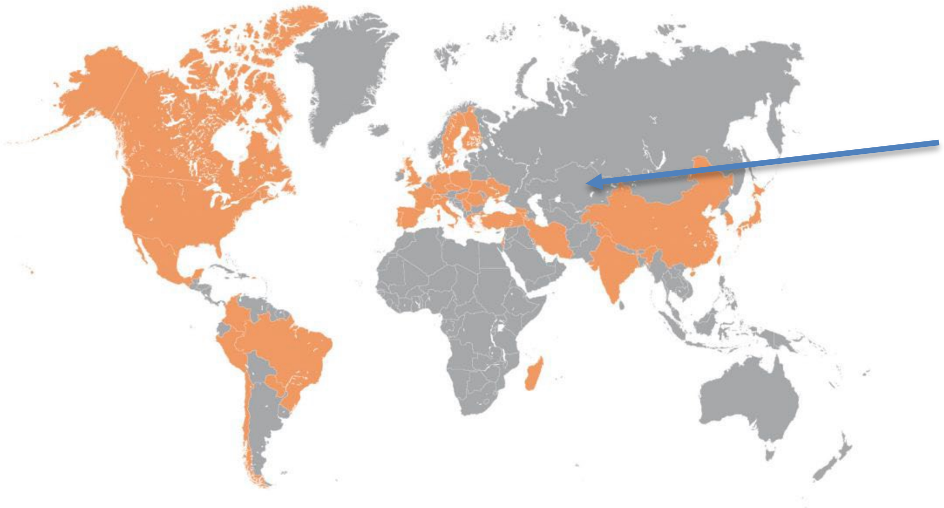
Existing Main Injector

Schedule summary: LBNF/DUNE

2028 2031



DUNE collaboration



New Institutions:

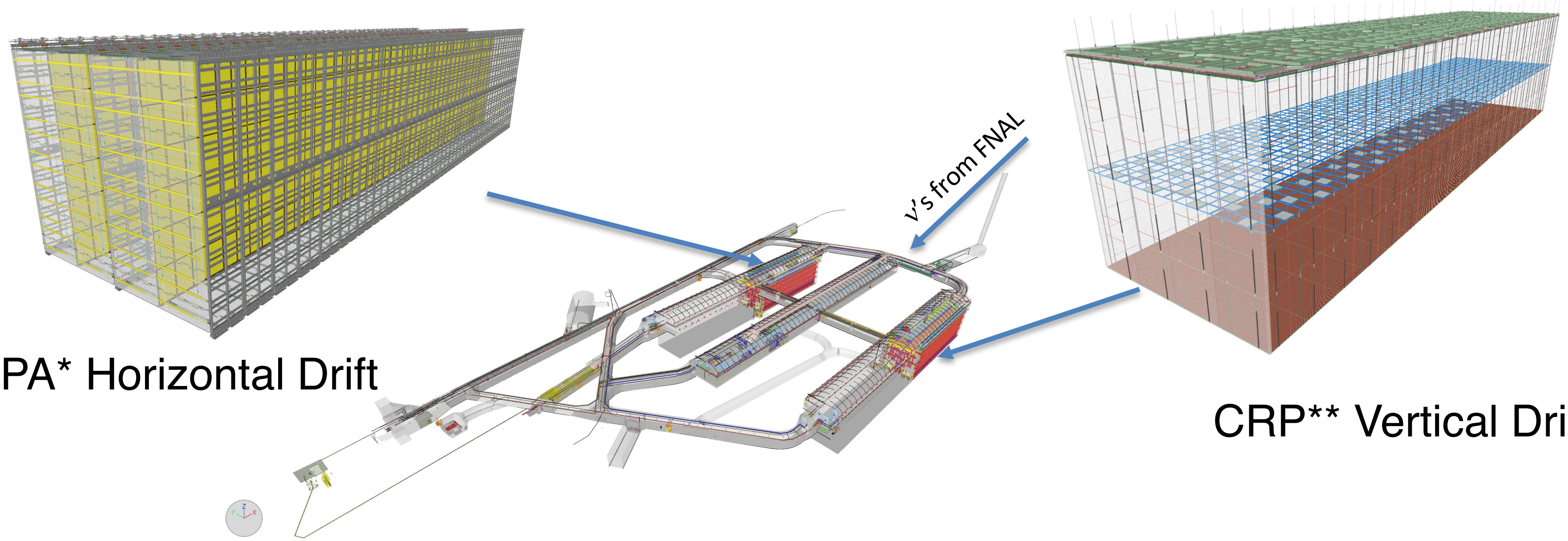
- Institute of Nuclear Physics, Almaty, Kazakhastan
- Hong Kong University of Science and Technology, China

Over 1,701 scientists, from more than 209 Institutions, 38 countries plus CERN

DUNE coll. Meet at FNAL, May. 2023

DUNE – Phase I

- LBNF will provide caverns for 4 detector modules at SURF
  - 1st detector to be installed in NE cavern has horizontal drift (like ICARUS and MicroBooNE)
  - 2nd detector will go into SE cavern and has vertical drift (capitalizing on elements of the dual phase development)



APA* Horizontal Drift

CRP** Vertical Drift

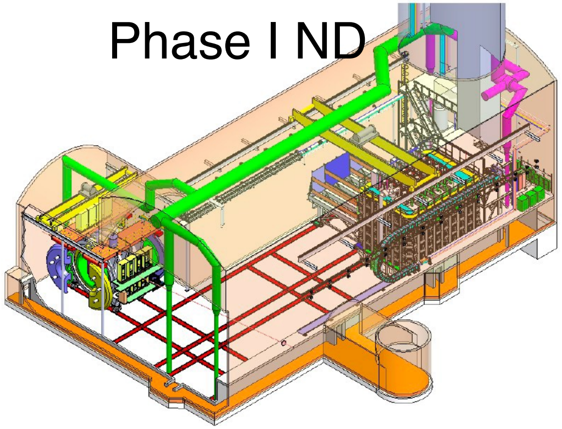
Note : DUNE Science begins when FD1 is filled and turned on and recording tracks

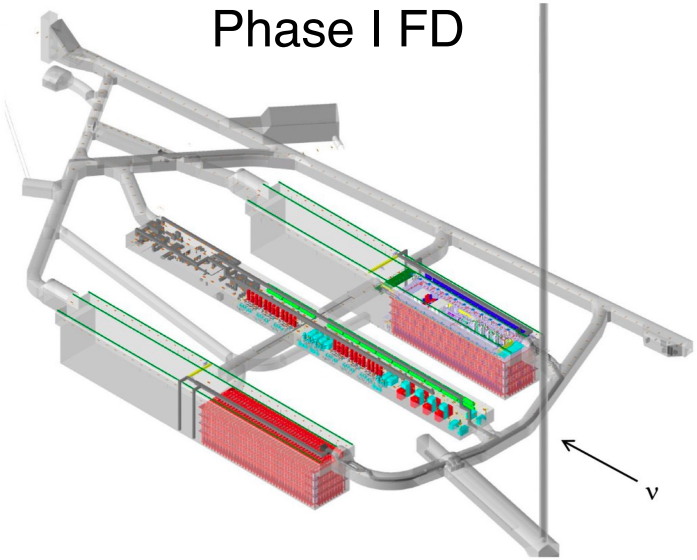
*Anode Plane Assemblies
**Charge Readout Planes

DUNE– Phase I (cont.)

DUNE Phase I:

- Neutrino beam with 1.2 MW intensity
- Two 17kt LAr TPC FD modules
- Underground facilities and cryogenic infrastructure to support four modules
- Near detector: ND-LAr + TMS (movable) + SAND
- The US DOE scope of Phase I was approved in July 2022 (CD1-RR)



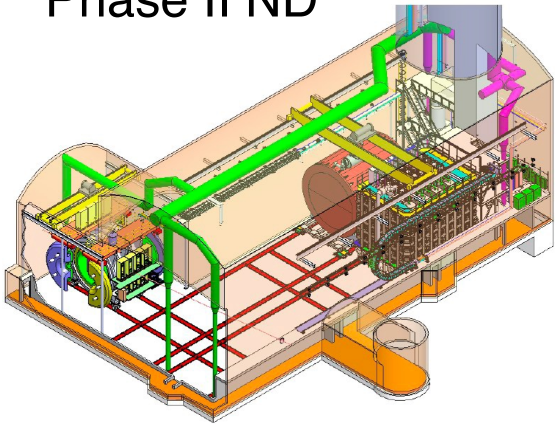


DUNE – Phase II (cont.)

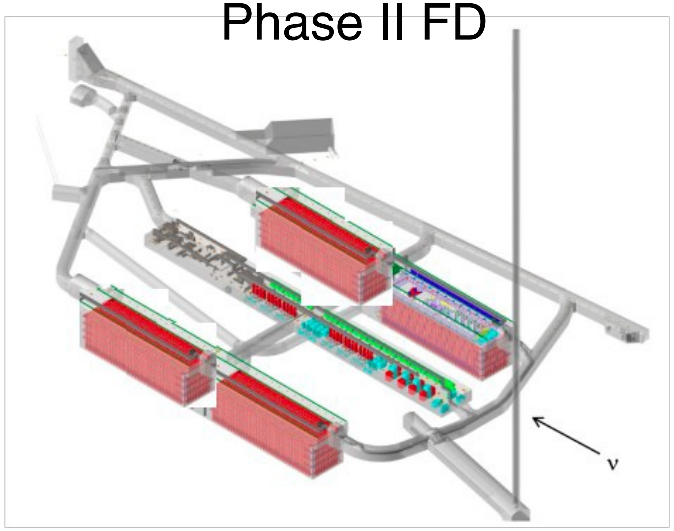
DUNE Phase II:

- Fermilab proton beam upgrade to 2.4 MW
- Two additional 17kt FD modules
- Near detector: ND-LAr + MCND (movable) + SAND
- ND upgrade is driven by improved performance at reducing systematics, not driven by increased beam intensity
- DUNE Phase II will collect twice as many neutrinos

Phase II ND



Phase II FD

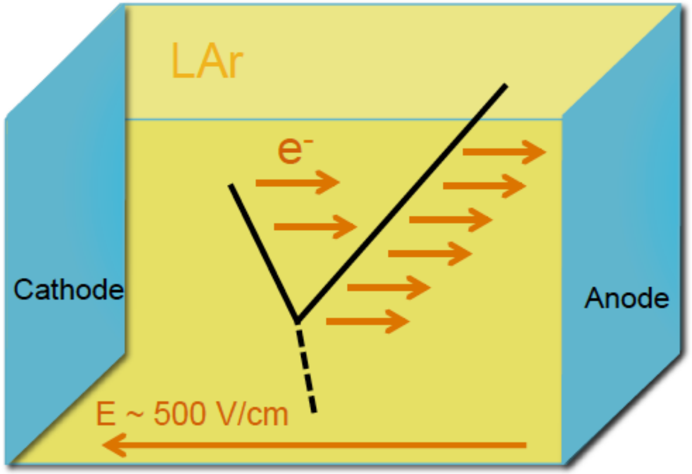


DUNE Far Detector (FD)

DUNE Far Detector Technical Design Reports in arXiv:2002.02967, 2002.03005, 2002.03008, 2002.03010 (1483 pages)

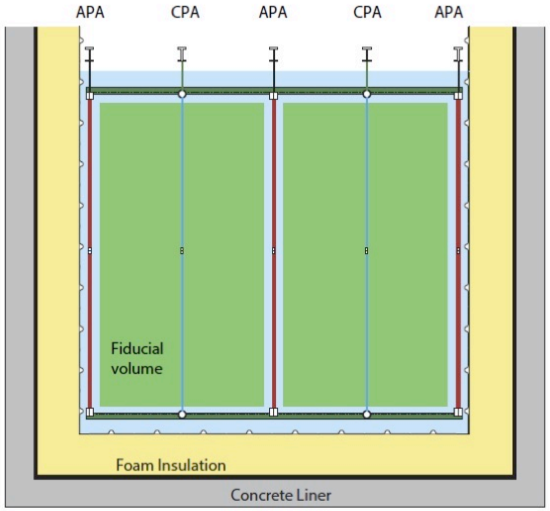
Four 17-kt liquid argon TPC modules
- **Horizontal** and **Vertical**-drift detector for the first 2 modules
- Integrated photon detection
- Modules will not be identical

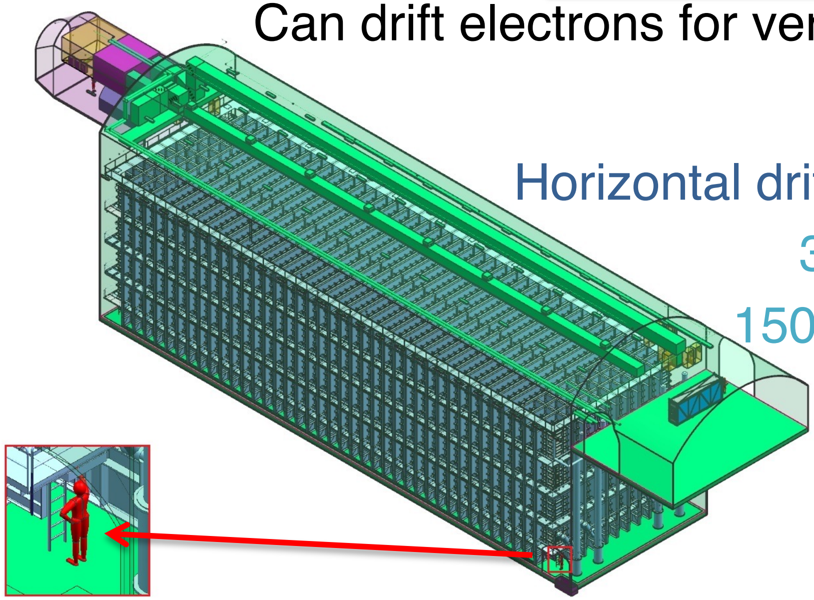
TPC Critical features:
- LAr ultra-high purity
- E Field: *uniformity* and *stability*



Can drift electrons for very large distances

Horizontal drift: modular wire-plane readout





Horizontal drift: 17 kt module

384,000 readout wires

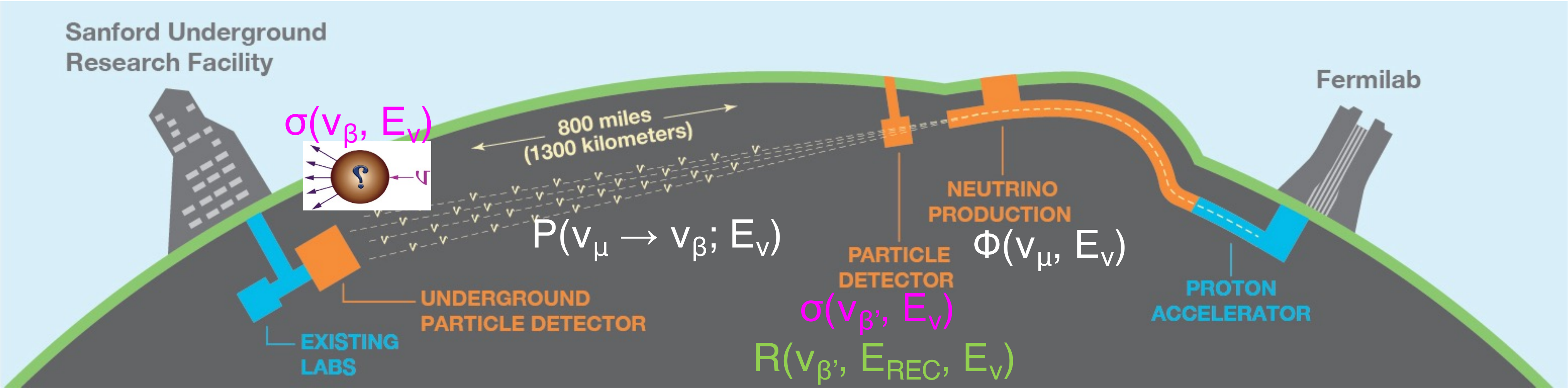
150 "APAs" (2.3 m x 6 m)

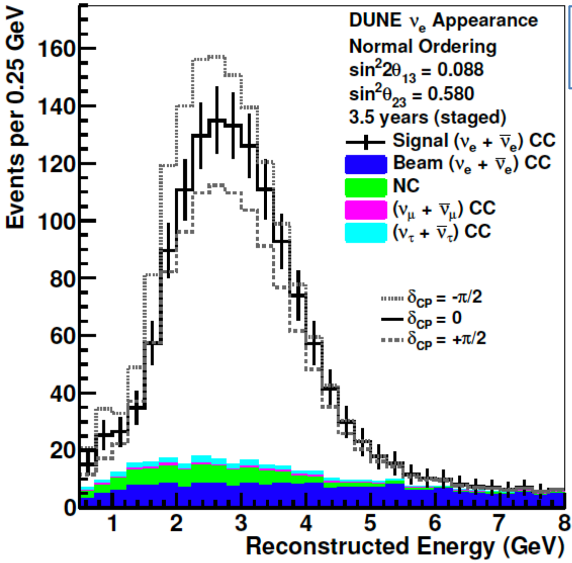
12 m high

15.5 m wide

58 m long

Dune at work





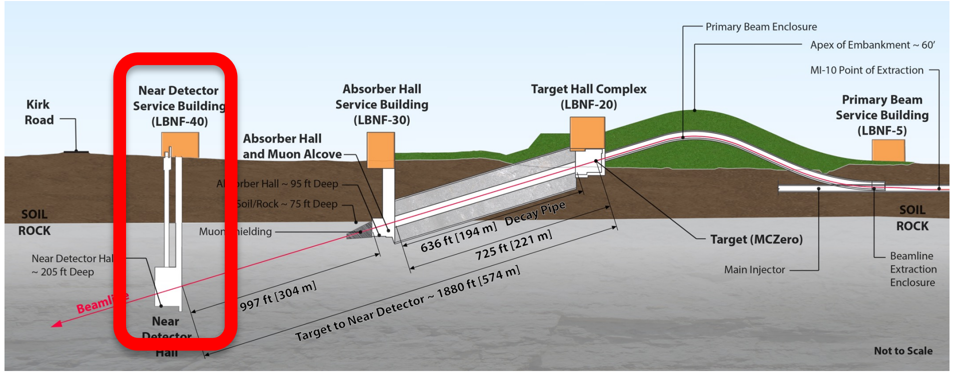
ν_e appearance from ν_μ beam after 3.5 years (staged)

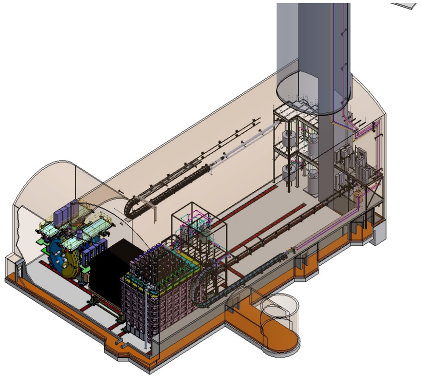
Need maximal control of prediction under PMNS parameters:
fluxes, cross-sections, detector responses

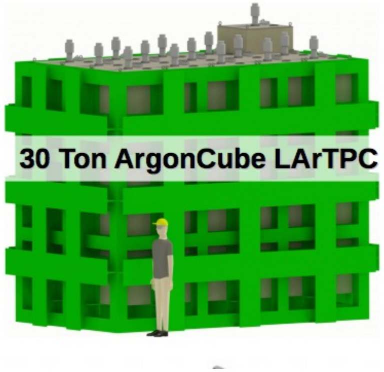
To maximize deconvolution of intrinsic degeneracies perform single measurements for as many as possible sources of systematics effects ☞ Near Detector complex

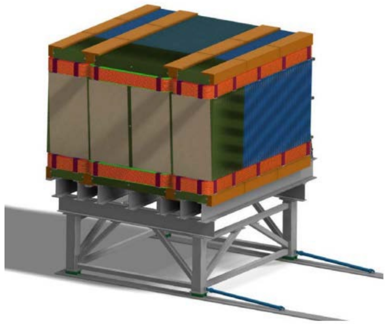
Near Detector (ND) – Phase I

- Role: constrain systematic uncertainties needed to oscillation analyses
  - Measure unoscillated beam flux
  - Measure multiple interaction cross-section channels
- Hall location
  - 574 m from LBNF target
  - ~60 m underground
- Multi-component Near detector
  - Highly segmented LArTPC
  - Magnetized tracker
  - Electromagnetic calorimeter
- Move (part of) ND detectors for off-axis measurements (PRISM concept)









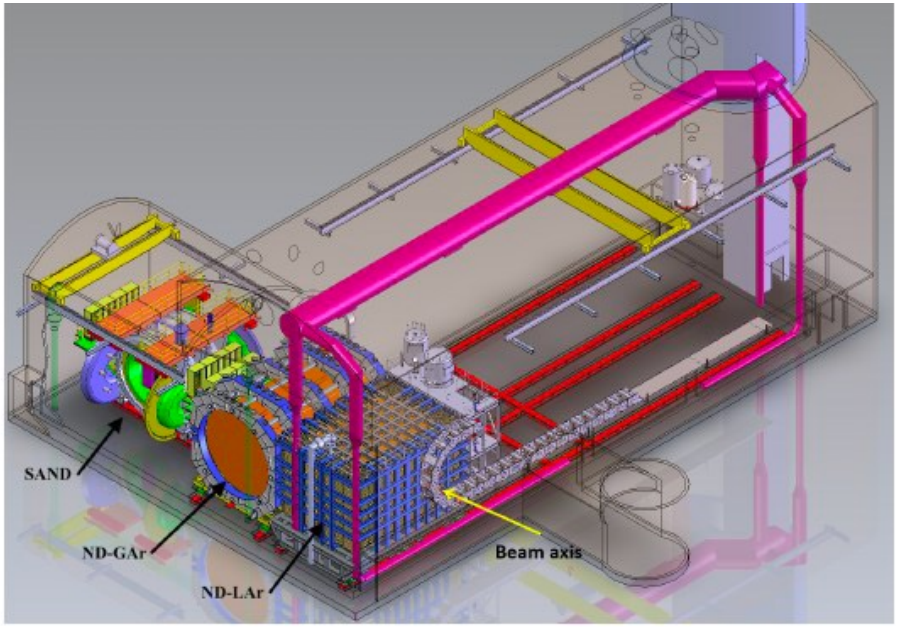
ND continues

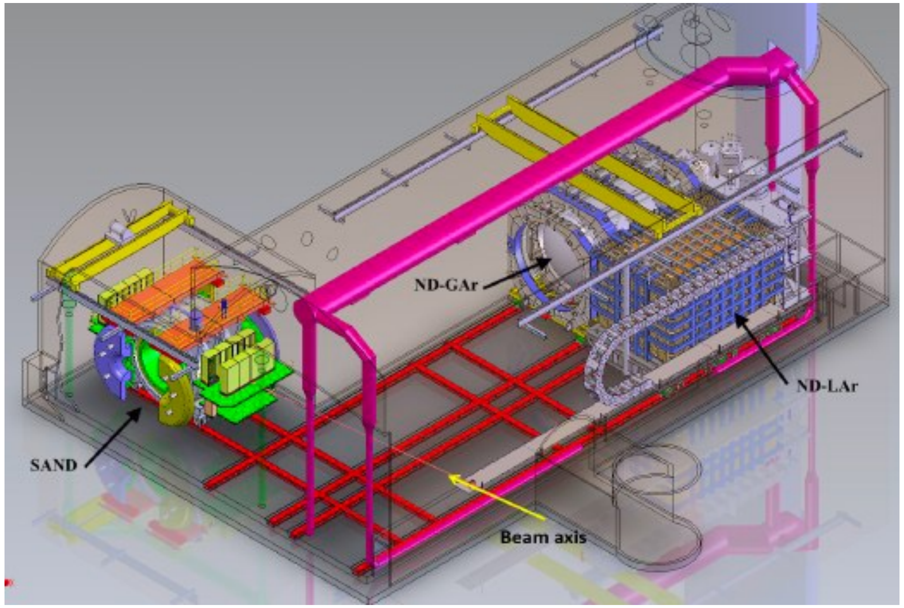
Multi-component near detector will ensure excellent control of systematics

- ND-LAr: Modular TPC construction, pixel readout
- ND-GAr: HP GAr TPC + magnet
- System for on-Axis Neutrino Detection (SAND), tracker and ECAL in magnetic field

DUNE-PRISM: ND-LAr and ND-GAr can move sideways to constrain flux and interaction uncertainties.

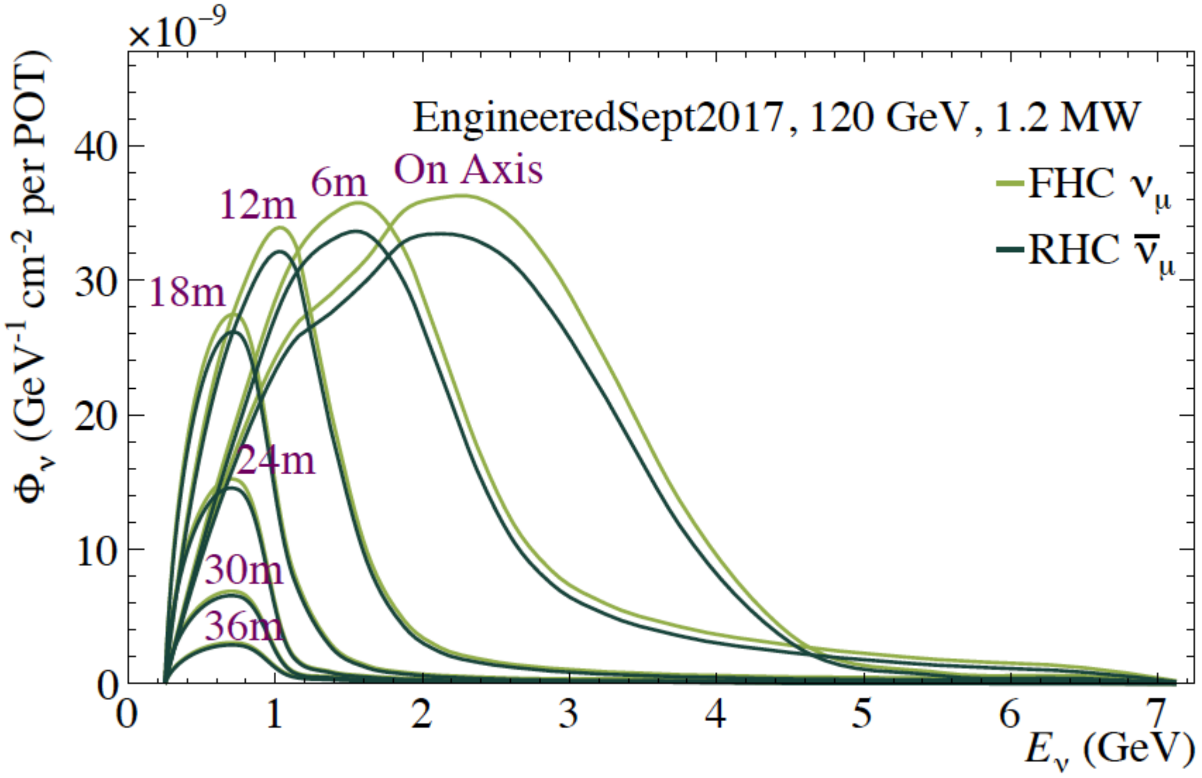
DUNE-SAND: event-by-event allows exclusive channels control





DUNE ND capabilities

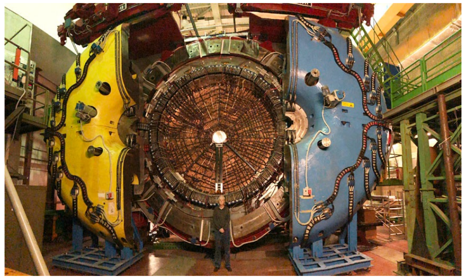
>100 million interactions will enable a rich non-oscillation physics program



Capability to move ND (LAr+TMS) for off-axis measurements (DUNE-Prism)

SAND

System on Axis for Neutrino Detection

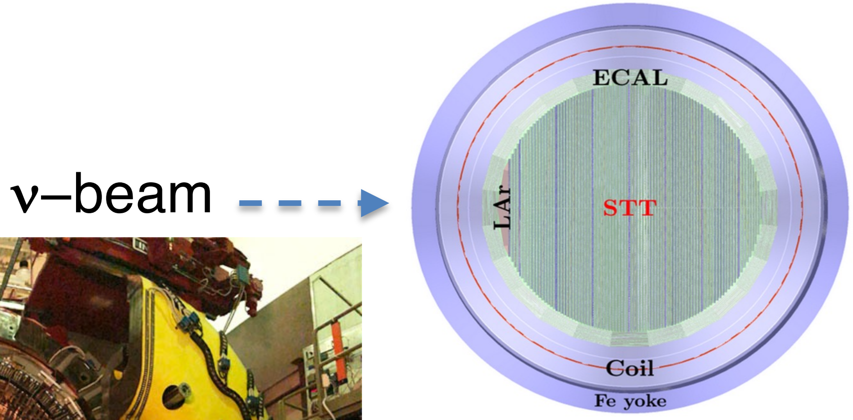


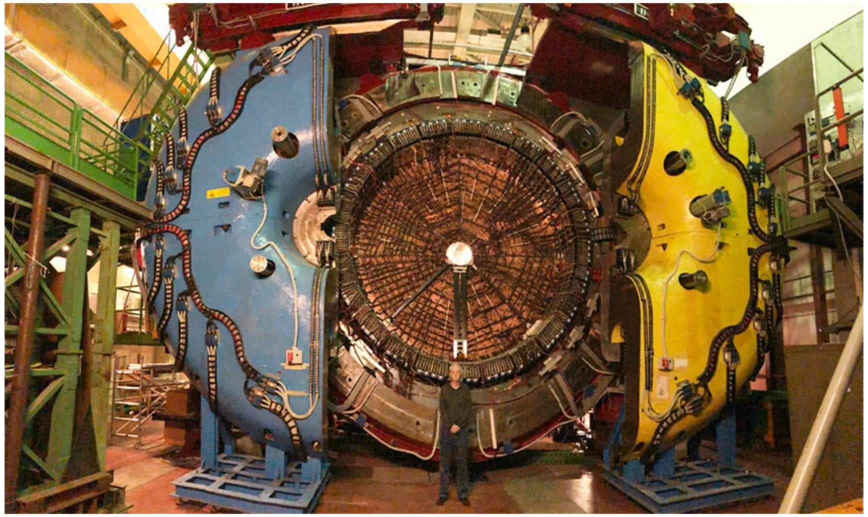
1. It **should** monitor the (relevant) beam changes on a **weekly basis** with sufficient sensitivity
2. It **should** contribute to remove **degeneracies** when the other components are off-axis (50% of the time)
3. It **should** provide an independent measurement of the **flux** and measure the **flavor** content of the neutrino beam on event-by-event basis.
4. It **would** add robustness to the ND complex to keep **systematics** and **background** under control
5. While delivering all of the above, it **would** contribute to **oscillation analysis** and enjoy the high statistics to perform a plethora of **other physics** measurements.

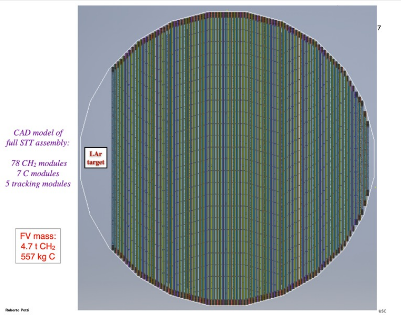
As a matter of fact SAND will be a multipurpose detector

(with innovative compromises between mass, ID and tracking)

KLOE → SAND







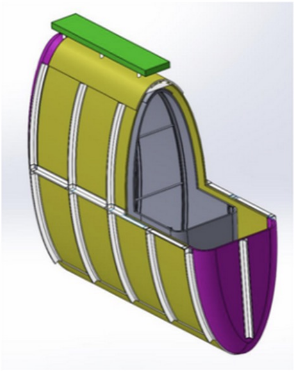
~200K Straw Tubes

KLOE experiment run at Laboratori Nazionali di Frascati(Rome) Italy from 1999 until 2018, at DAΦNE e^+e^- collider, for physics of K and Φ mesons.

Electromagnetic calorimeter
- Lead/scintillating fibers
- 4880 PMT's

Superconducting coil (5 m bore)
B = 0.6 T ($\int B\,dl = 2.2$ T.m)

- Energy resolution $\sigma/E=5.7\%/\sqrt{E(\mathrm{GeV})}$
- Time resolution $\sigma=54\ \mathrm{ps}/\sqrt{E(\mathrm{GeV})} \oplus 50\mathrm{ps}$



Liquid Argon target

Proto-DUNE detectors R&D and goals

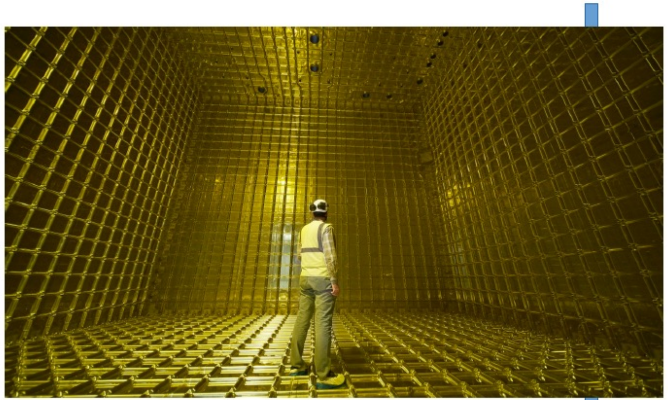
- Prototyping production and installation procedures for DUNE Far Detector Design

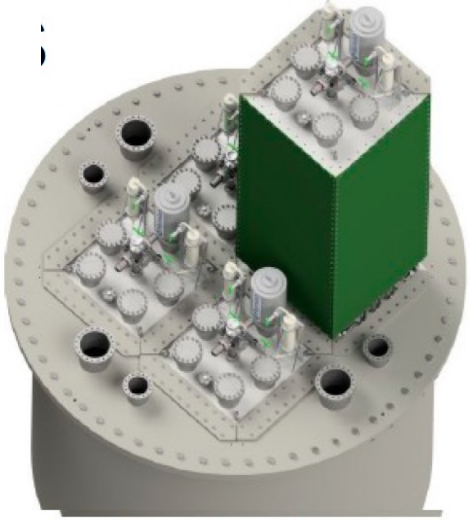
  many of the components for the far detector prototyping at 1:1 scale
- Validating design from perspective of basic detector performance
- **Accumulating test-beam data to understand/calibrate response of detector to different particle species**
- Demonstrating long term operational stability of the detector

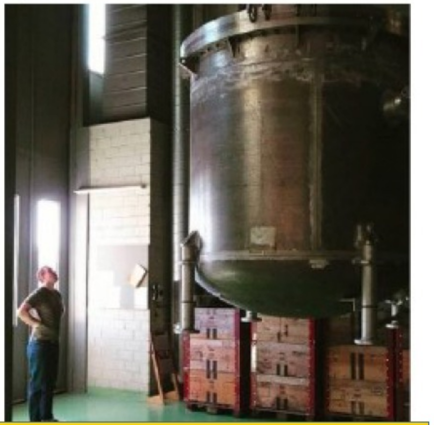
1 kton massive Liquid Argon detectors

DUNE prototypes

- ProtoDUNEs at CERN with charged particle beam
- 2x1kton cryostats used to validate FD components at full scale.
- Successful run from 2018-2020
- Next phase starting in spring 2023







ArgonCube 2x2 ND-LAr Demonstrator.

4 independent modules, test In NuMI beam scheduled in 2022

First R&D and physics results published [JINST 15 (2020) 12, P12004]
(see backup for full list)

Perspectives

Perspectives…

“Experiments” in running:

- NOvA
- T2K
- Cosmology
- SuperNovae

Future:

- JUNO → *Reactor neutrinos*

- ORCA (KM3Net)
- PINGU (IceCube)
- INO
- HK

→ *Atmospheric neutrinos*

- NOvA+T2KII
- **DUNE**
- HK (T2KK)

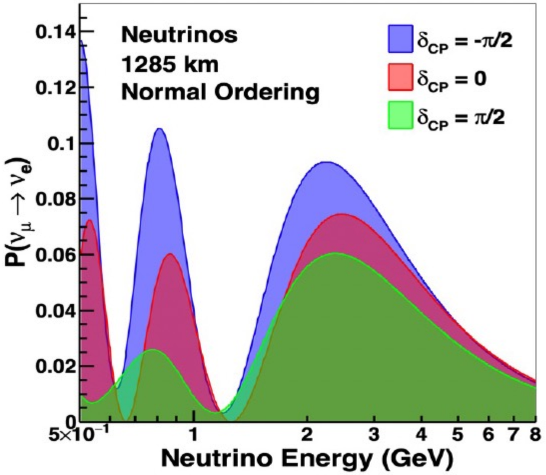
→ *Long baseline*

DUNE Physics Program—Neutrino Oscillation

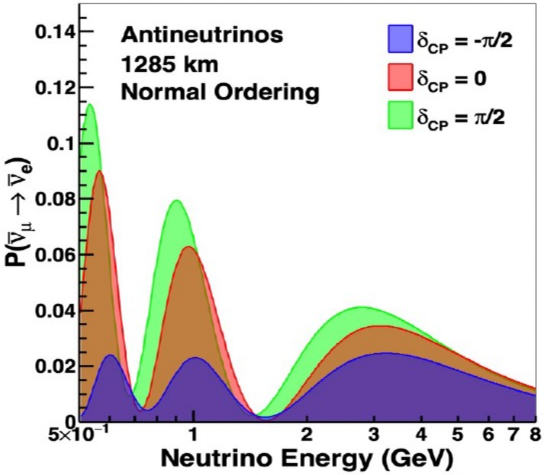
Three-neutrino oscillations: ν_μ / $\bar{\nu}_\mu$ disappearance, $\nu_e/\bar{\nu}_e$ appearance

- Charge-Parity symmetry violation (CPV): δ_{CP}
- Neutrino mass ordering: normal or inverted
- Neutrino mixing parameters

[Eur. Phys. J. C 80 (2020) 10, 978]



$$\nu_\mu \to \nu_e \overset{?}{\Leftrightarrow} \bar{\nu}_\mu \to \bar{\nu}_e$$



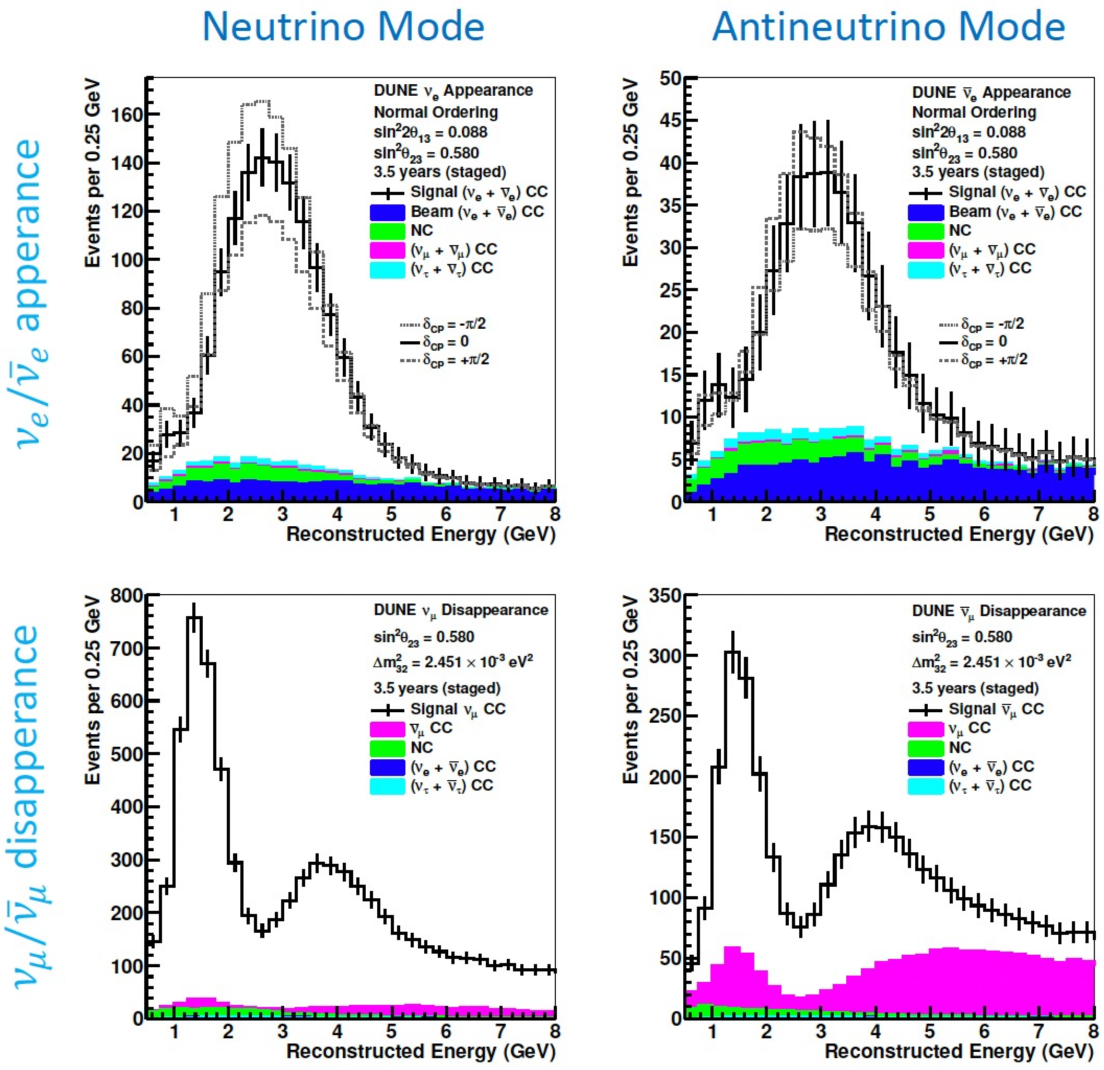
Mass ordering and CP violation induce different shapes in ν_e , $\bar{\nu}_e$ oscillation probabilities

DUNE's unique capability: with a wide band beam measures these shapes over more than a full period, resolving degeneracies and measure Mass Ordering, CP-Violation and θ_{23} **with a single experiment**

Oscillation Sensitivity for DUNE

[Eur. Phys. J. C 80 (2020) 10, 978]

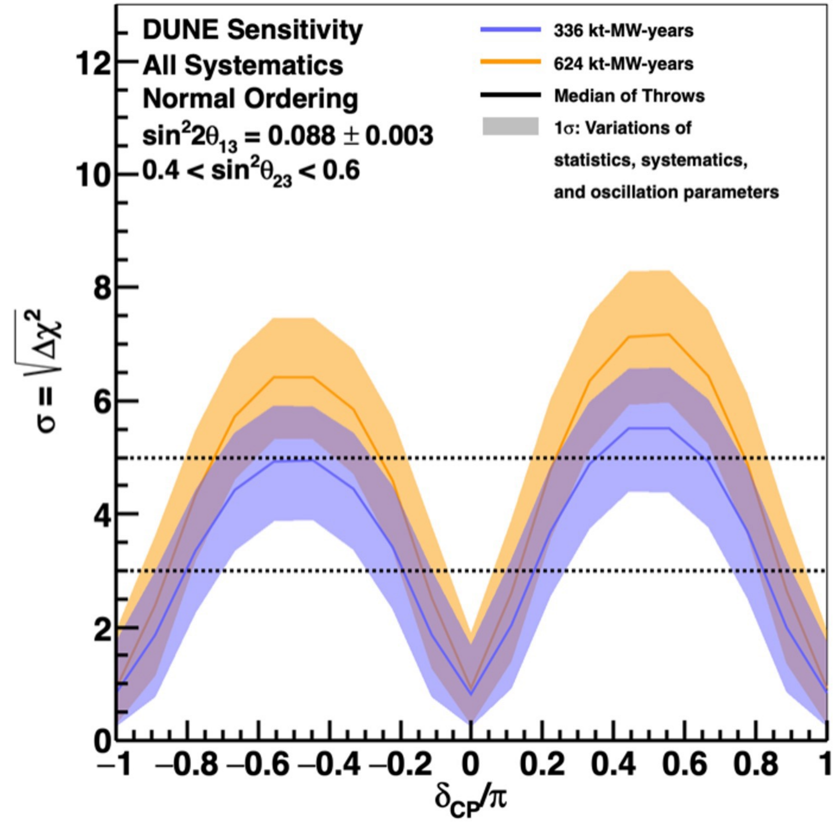
- Reconstructed spectra of selected CC-like events
- Sensitivity assessment includes full FD systematics treatment
- 3.5 years neutrino beam mode
- 3.5 years anti-neutrino beam mode
- ~1000 ν_e/ν_e–bar events in 7years
- ~10,000 ν_μ/ν_μ-bar events in 7years

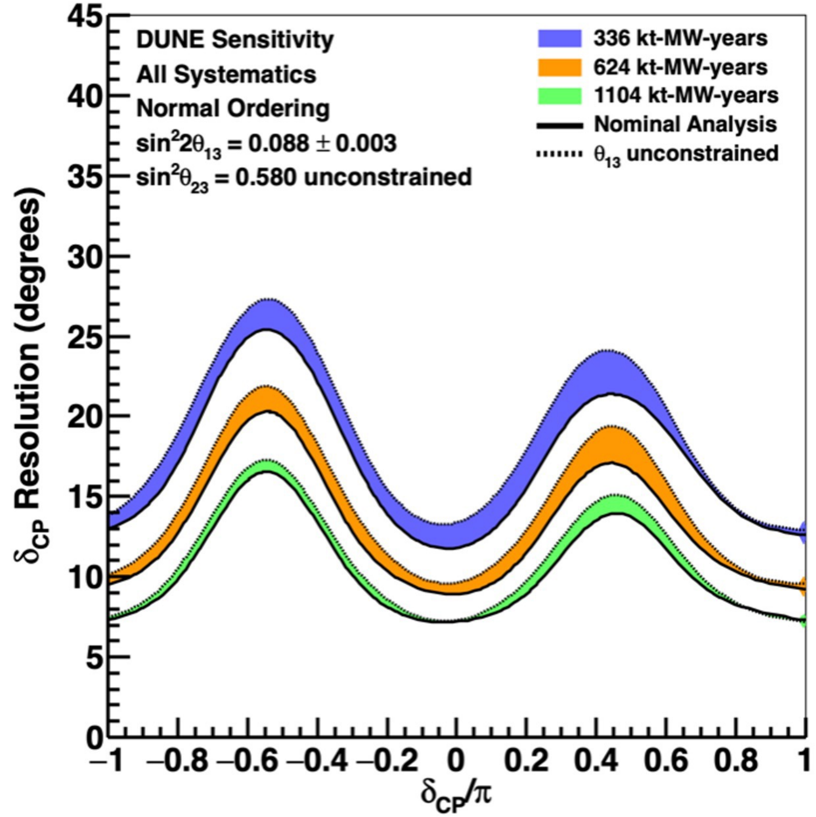


Simultaneous fit to four spectra to extract oscillation parameters

Sensitivity to CPV for DUNE

- 5σ discovery potential for CP violation over >50% of δ_{CP} values
- 7-16° resolution to δ_{CP}, with external input for only solar parameters.





- Simultaneous measurement of neutrino mixing angles and δ_{CP}
- Width of band indicates variation in possible central values of θ_{23}

Perspectives for MH

Many different ways to define "sensitivity"

Only above 5 σ
we are "unsensitive"
to methodology

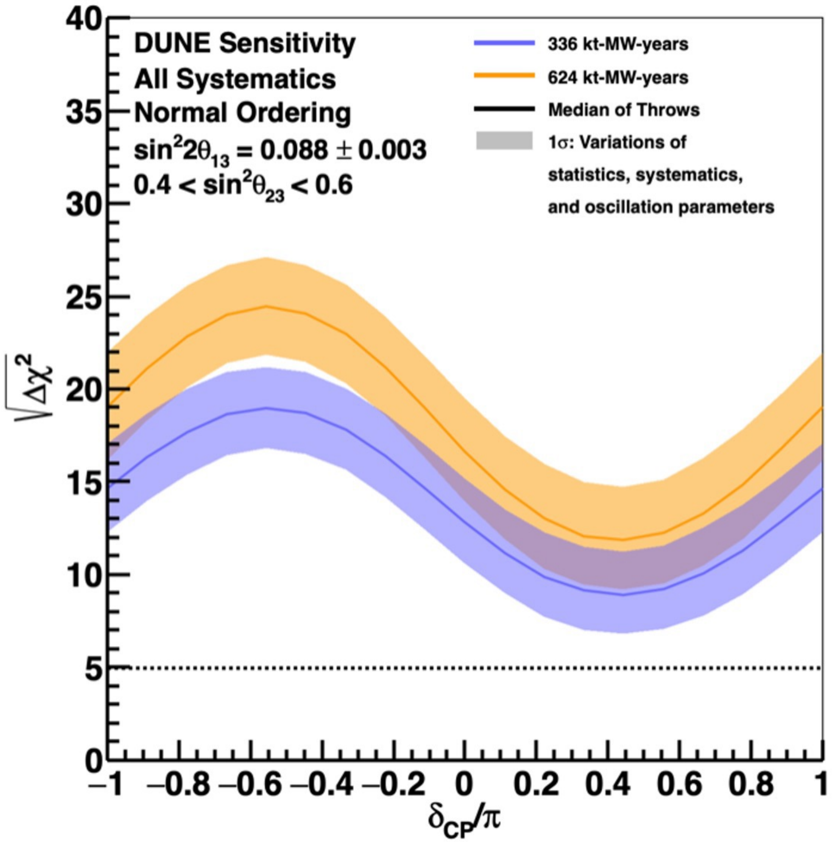
- NOvA: Degeneracy with δ_{CP} ?
- PINGU/ORCA: funded ? systematics ?
  Degeneracy with δ_{CP} and θ_{23} ?
- INO: really ?
- JUNO: technical challenge on energy resolution ?
  Degeneracy with Δm^2_{atm} ?

DUNE: ok, it will get it

MH and θ_{23} Oscillation Physics

Mass Ordering

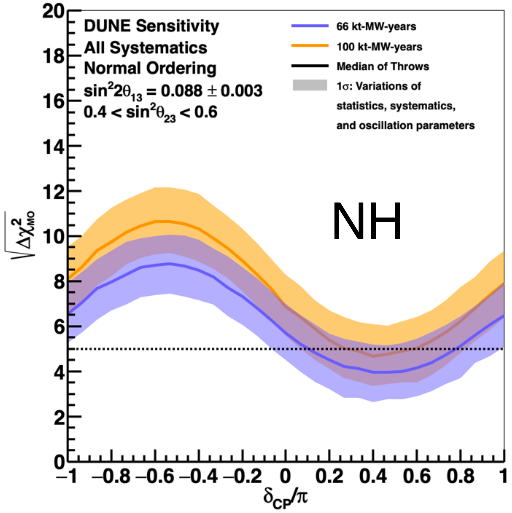
DUNE low exposure, PRD (2022) 105, 7, 072006
arXiv:2109.01304

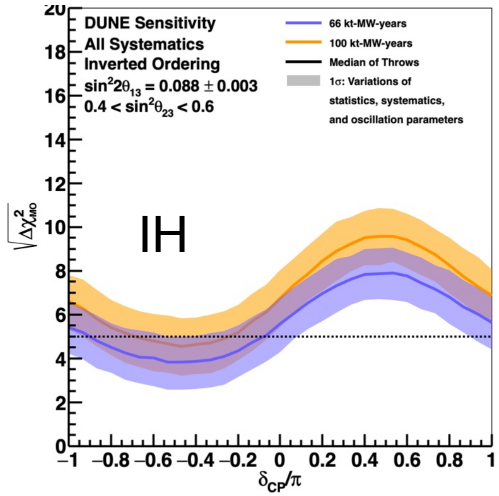


EPJC 80 (2020) 978

100 kt

66 kt

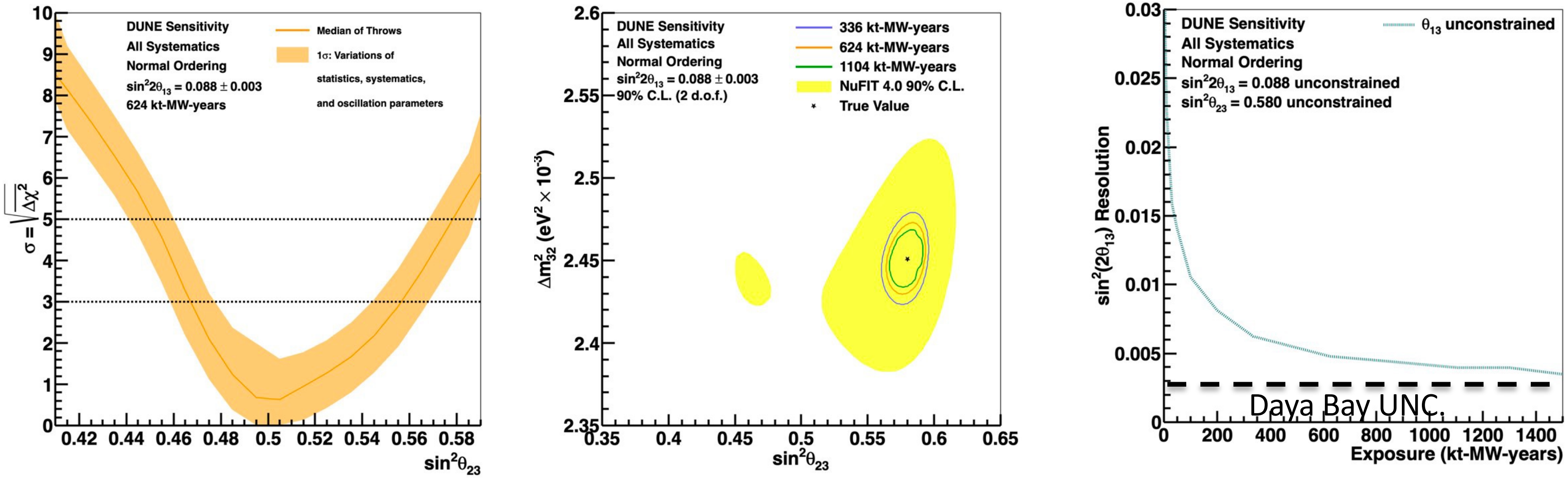




- Width of band indicates variation in possible central values of θ_{23}
- Width of band indicates variation in possible true value of δ_{CP}

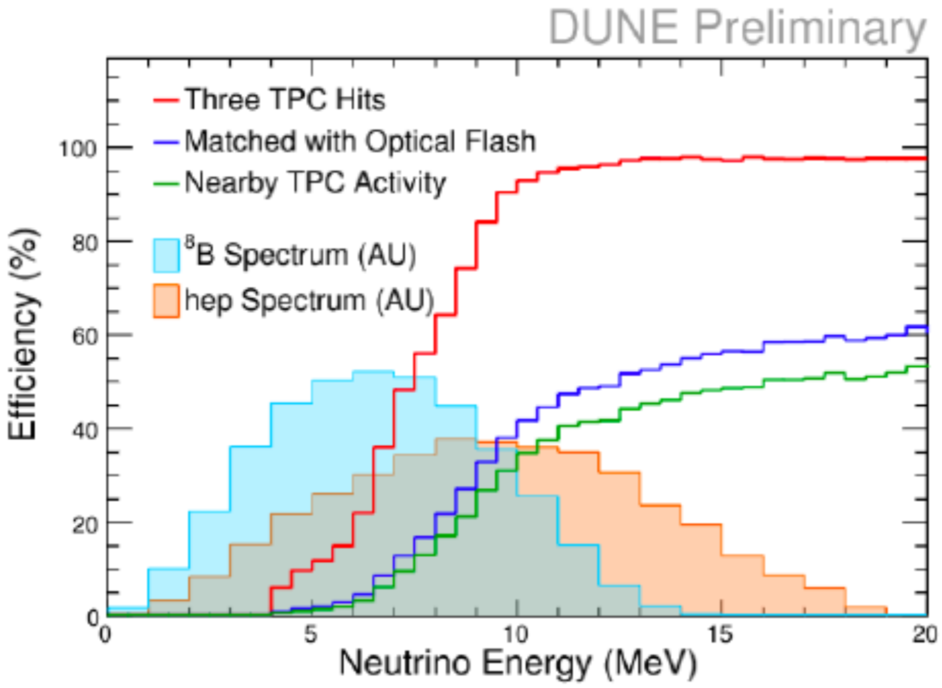
By exposure of 66 kt-MW-yr, probability to extract wrong ordering < 0.01

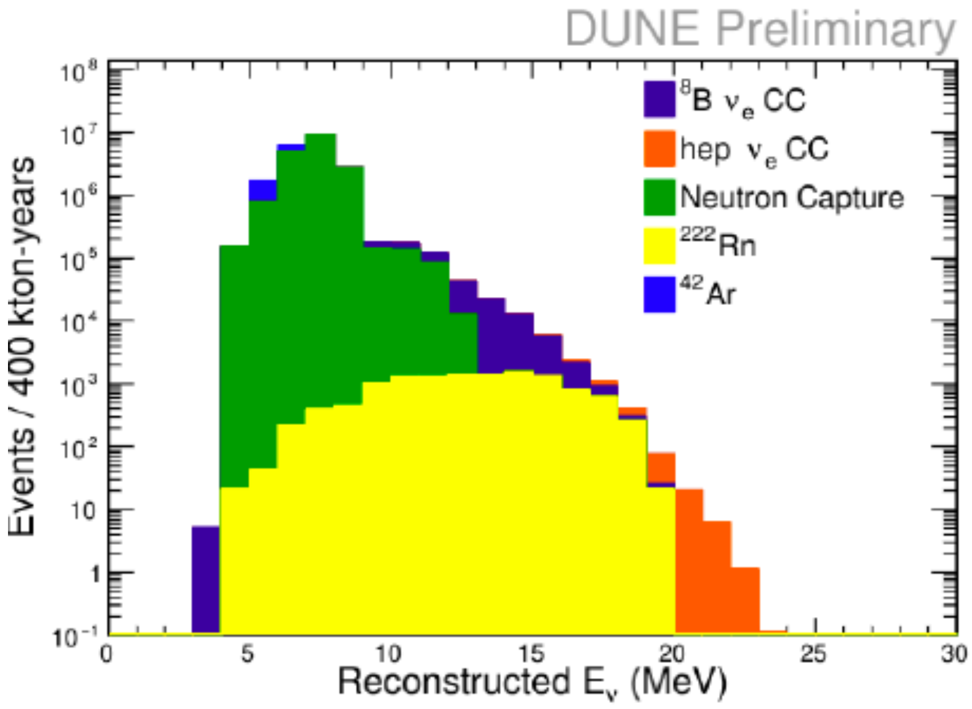
Oscillation Parameter Sensitivity



- Excellent on Δm^2_{32} and θ_{23}, including octant, and unique PRISM measurement technique that is less sensitive to systematic effects
- Ultimate reach does not depend on external θ_{13} measurements, and comparison with reactor data directly tests PMNS unitarity

Solar neutrinos



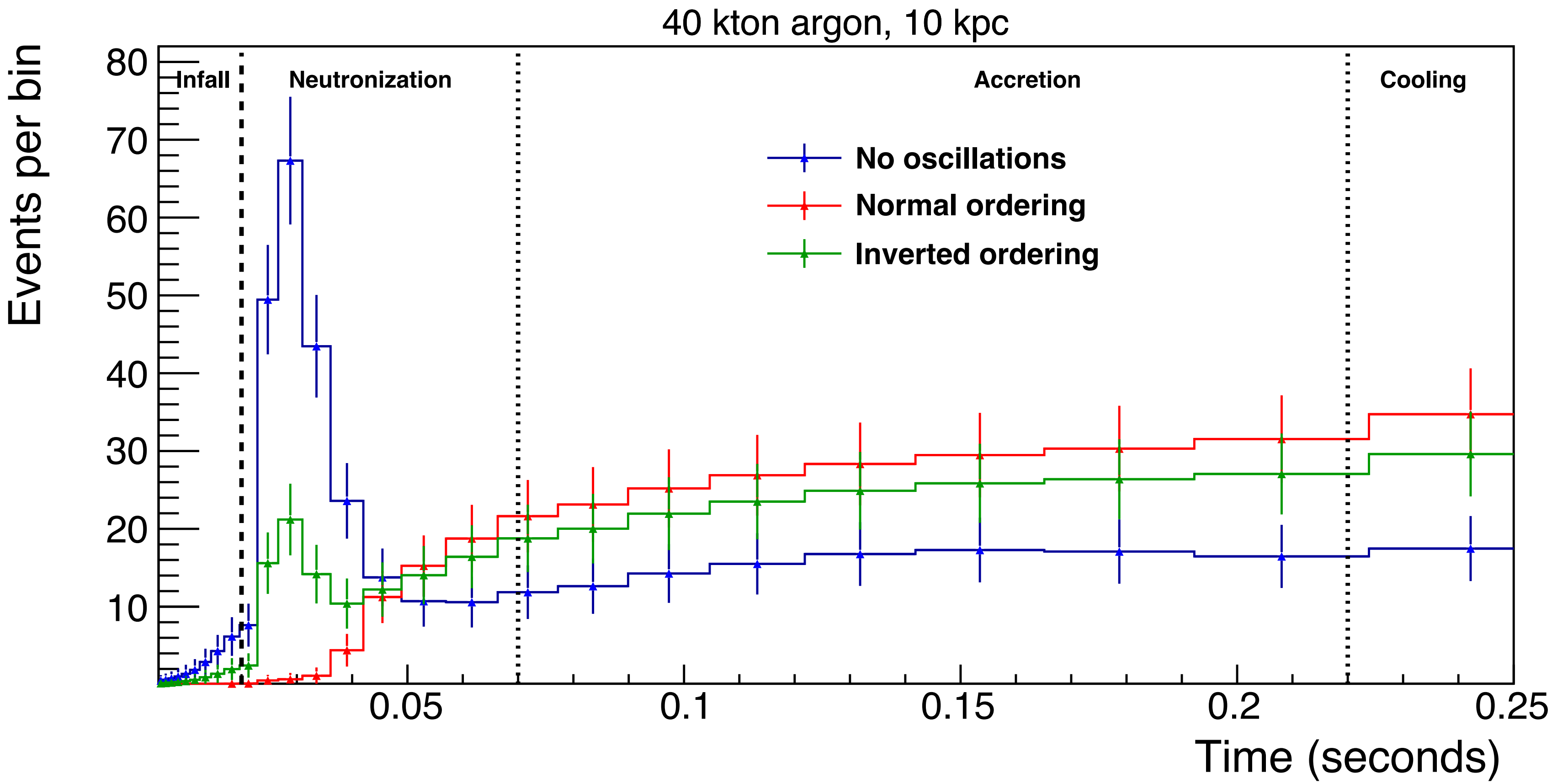


- DUNE should be sensitive to solar neutrinos, with a potential to observe hep neutrinos
- Main backgrounds: neutrons and Rn-induced alpha-gamma interactions

SNB neutrinos

Eur.Phys.J. C81 (2021) 5, 423

In LArTPC, SNB signal dominated by electron neutrinos: $\nu_e + {}^{40}\text{Ar} \rightarrow e^- + {}^{40}\text{K}^*$

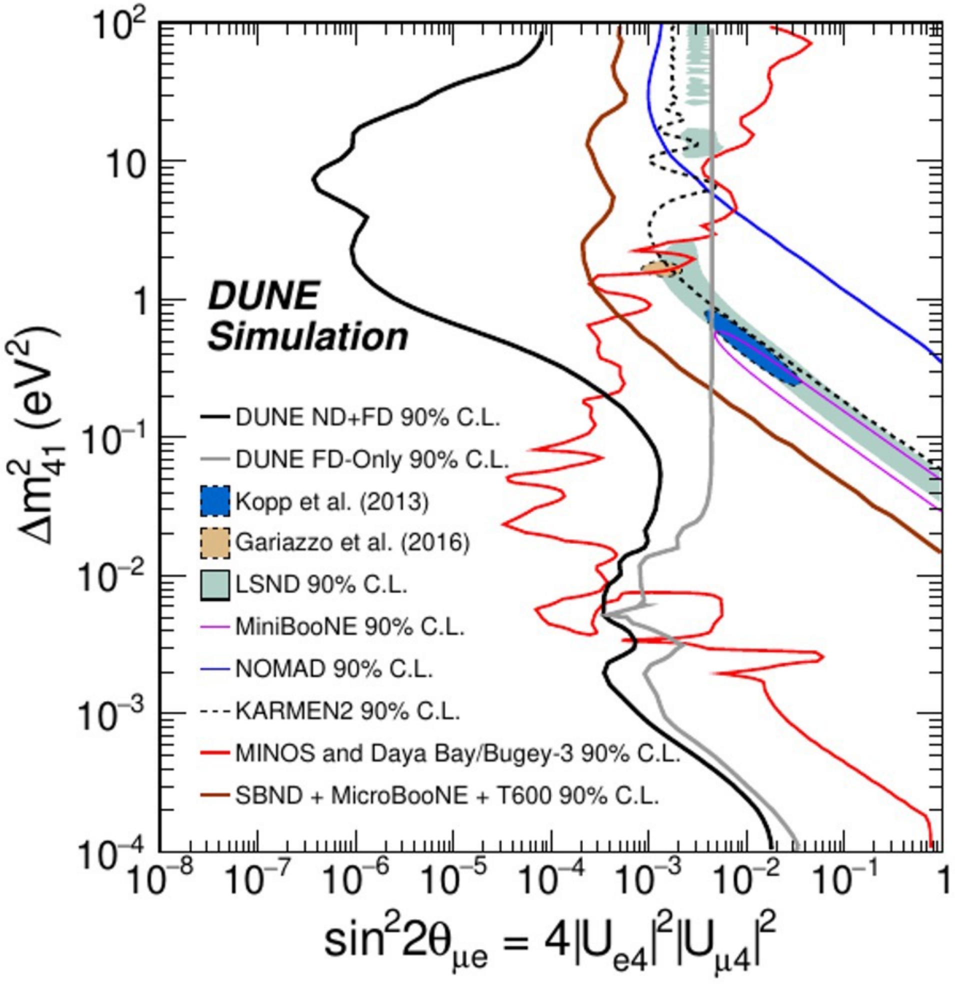


Observation of early time development yields sensitivity to neutrino mass ordering and details of SNB model.

BSM searches

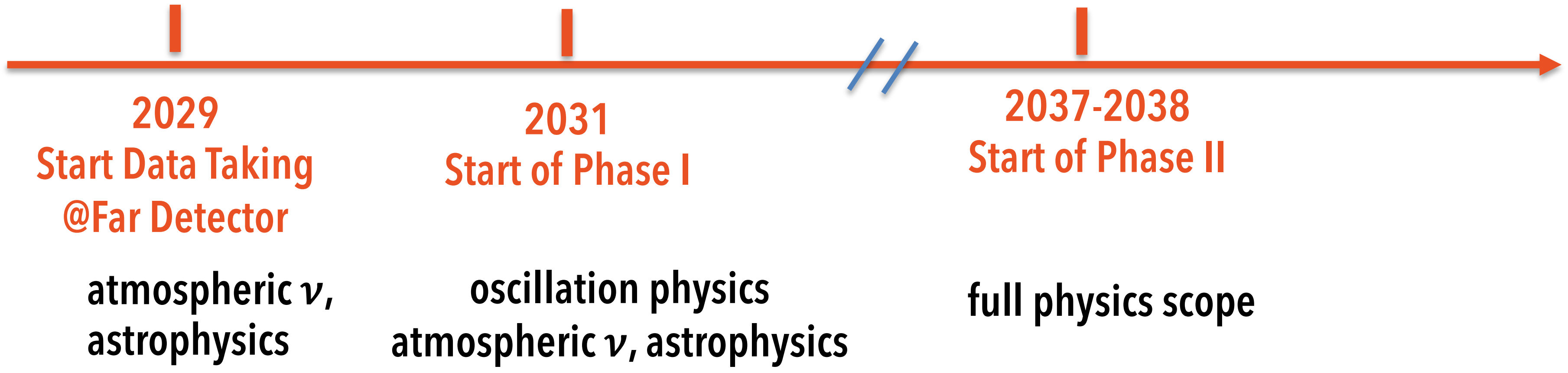
- DUNE sensitive to many BSM particles and processes
  - *Light dark matter*
  - *Boosted dark matter*
  - *Sterile neutrinos*
  - *Non-standard interactions, non-unitary mixing, CPT violation*
  - *Neutrino trident searches*
  - *Large extra dimensions*
  - *Neutrinos from dark matter annihilation in sun*
- Active area of research within phenomenology community as well as the DUNE collaboration
- GLoBES configurations arXiv:1606.09550

Sterile Neutrino Sensitivity (ν_e CC appearance at ND)



Summary for DUNE

- LBNF/DUNE: the ultimate neutrino facility/observatory
- DUNE will enable very rich physics program in the next decades (LifeCycle 20 years):
  - Neutrino oscillations
  - Studies of MeV-scale neutrinos
  - Many BSM searches
- LBNF and DUNE making rapid progress on facility construction, detector design, and physics analysis
- Expect first DUNE FD data in 2029, oscillation physics starts end of this decade



2029
Start Data Taking
@Far Detector

atmospheric ν,
astrophysics

2031
Start of Phase I

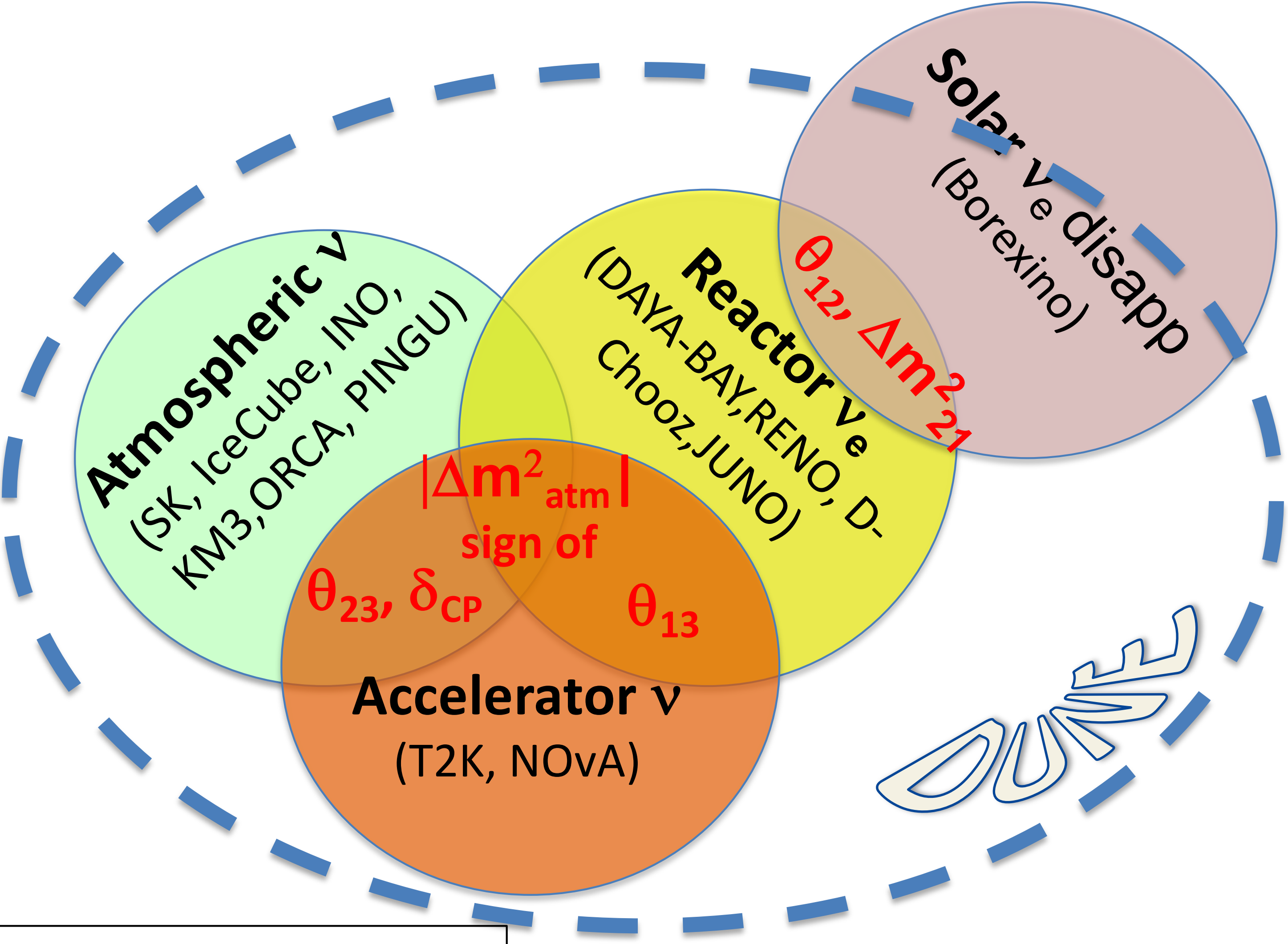
oscillation physics
atmospheric ν, astrophysics

2037-2038
Start of Phase II

full physics scope

Neutrino Oscillation industry

(in the 3 neutrino framework)



Atmospheric ν
(SK, IceCube, INO, KM3,ORCA, PINGU)

Reactor ν_e
(DAYA-BAY,RENO, D-Chooz,JUNO)

Solar ν_e disapp
(Borexino)

Accelerator ν
(T2K, NOvA)

θ_{12}, Δm^2_{21}

$|\Delta m^2_{atm}|$
sign of

θ_{23}, δ_{CP}

θ_{13}

From a Maxim Gonchar (DLNP) picture

disclaimer: major actors only, not a full list…

Thank you for your attention