DUNE: Physics program and status

Ryan Patterson
Caltech

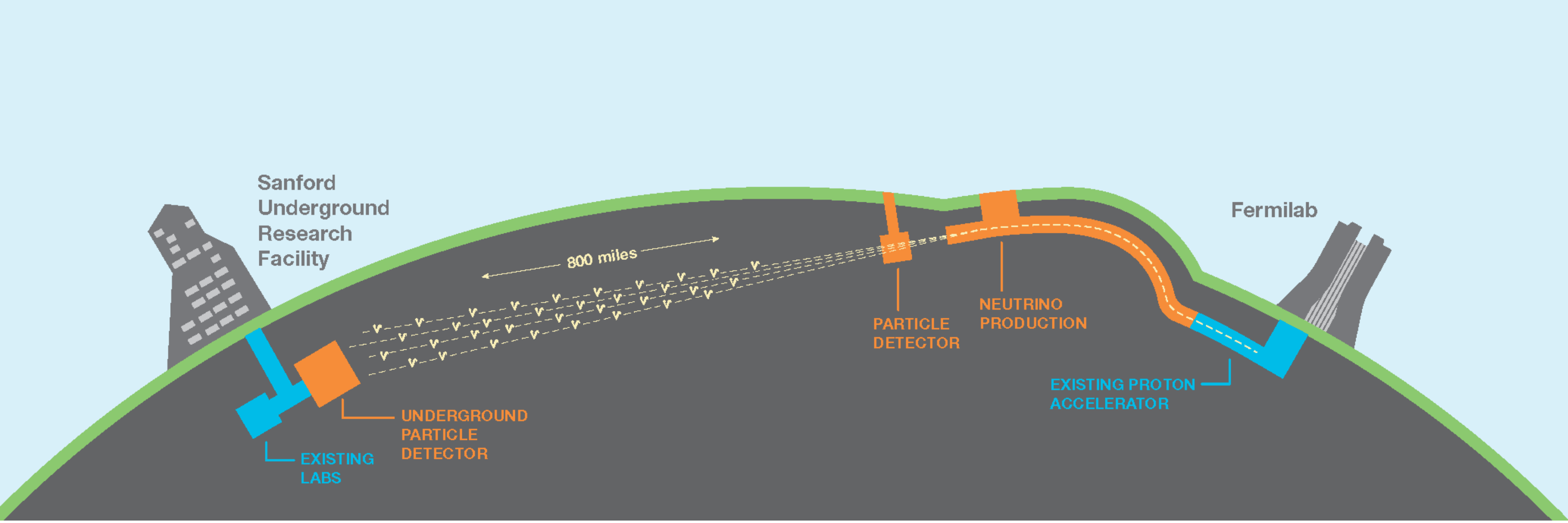
Aspen Winter Conference:
From the LHC to Dark Matter and Beyond

March 23, 2017

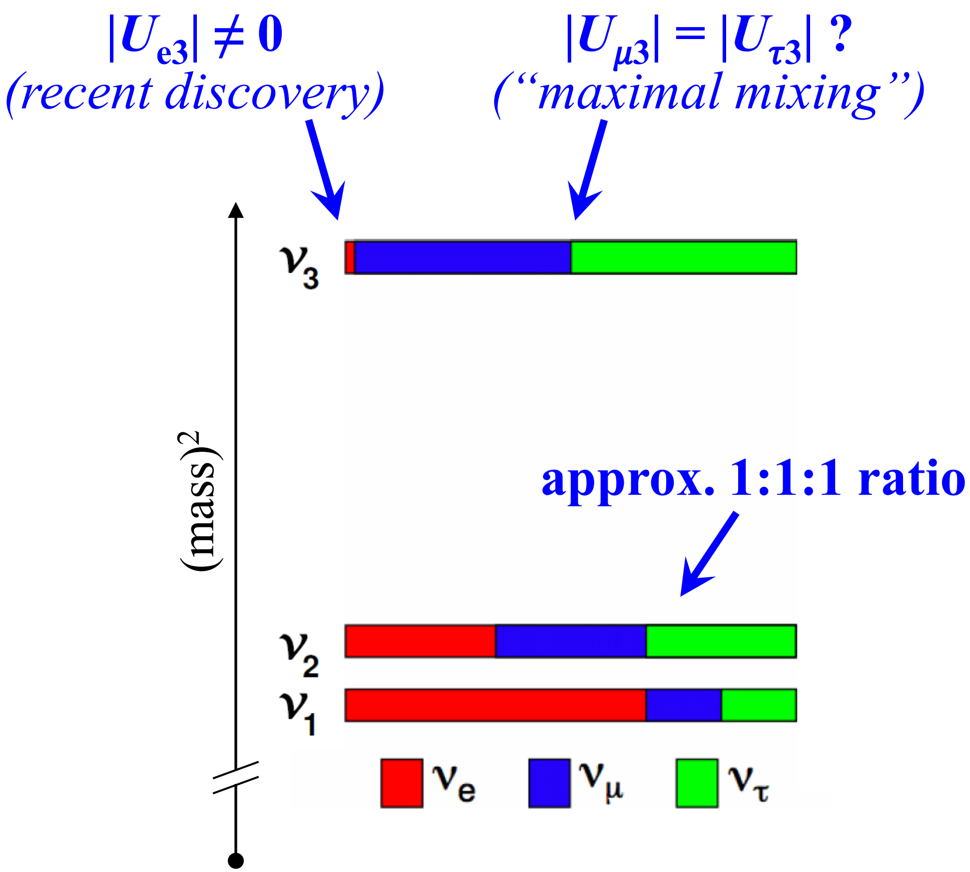
DUNE

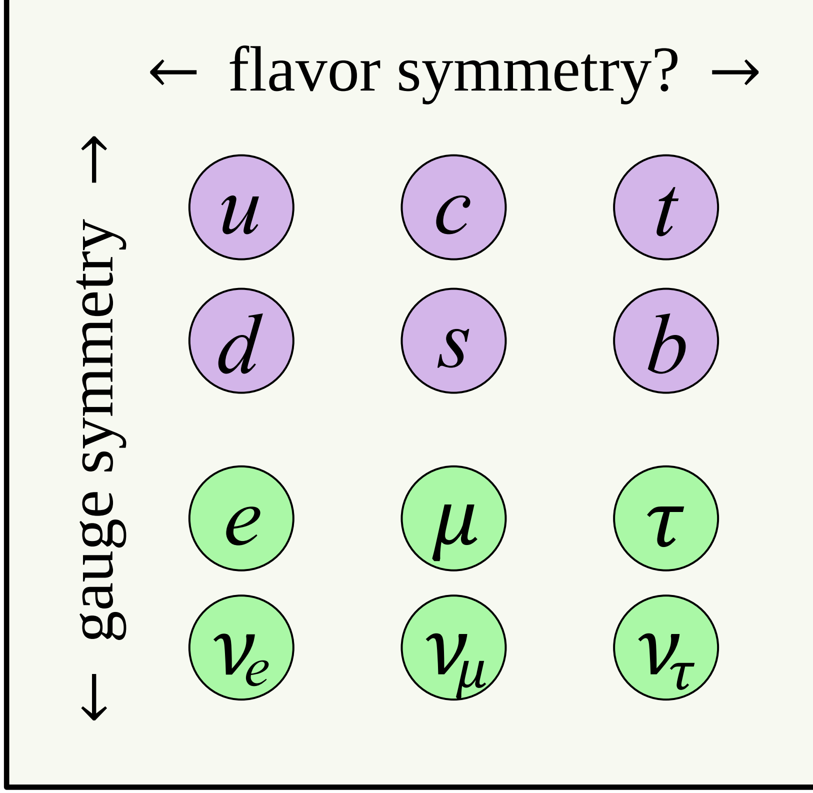
Deep Underground Neutrino Experiment

A next generation experiment for **neutrino science, nucleon decay,** and **supernova physics**

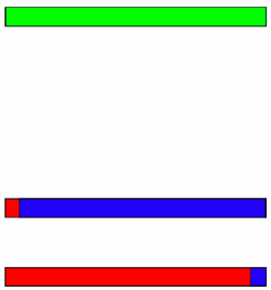


Neutrino mixing





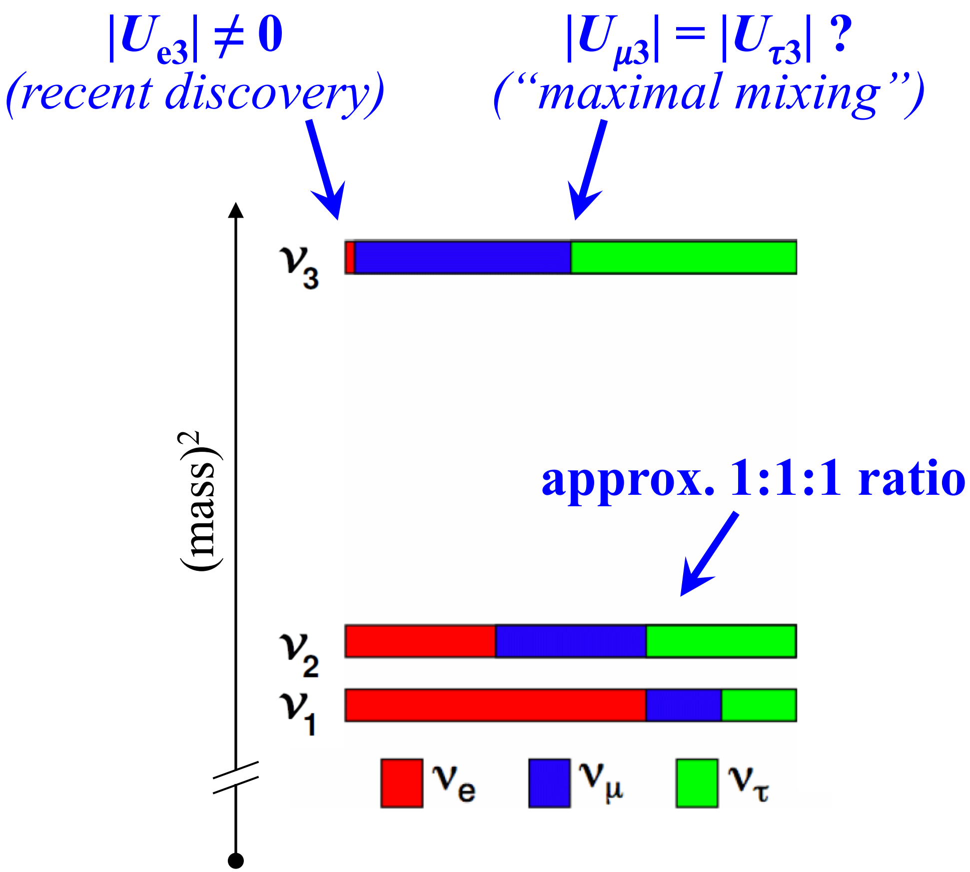
quark mixing:



What **flavor symmetry** can produce this pattern of mixings and masses, and how is that symmetry broken?

More broadly: what are the **dynamical origins** of fermion masses, mixings, and *CP* violation?

Neutrino mixing



Experimental question:

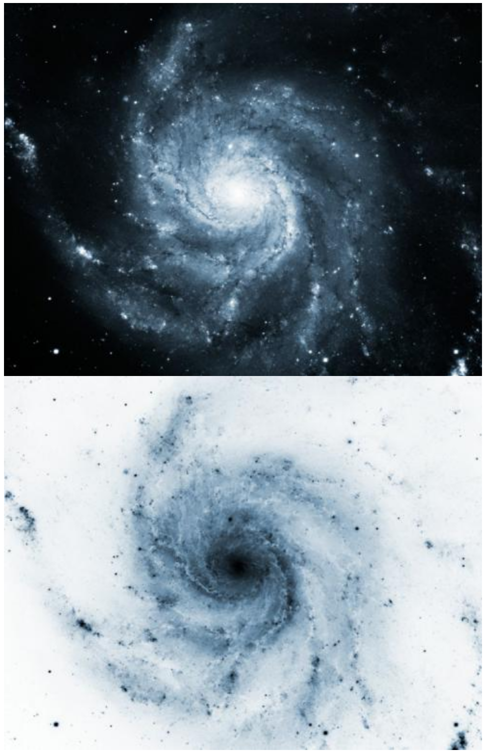
$\sin^2\theta_{23} \neq 0.5$?

Non-maximal mixing?
If so, which way does it break?

Standard parametrization of PMNS matrix:

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

CP violation



New source of *CP* violation required to explain baryon asymmetry of universe

part-per-billion level of matter/antimatter asymmetry in early universe

Neutrino *CP*v **allowed in νSM**, but not yet observed

…due so far to the experimental challenge, not physics!

Leptogenesis[1] is a workable solution for the baryon asymmetry, but need to first **find *any* leptonic (neutrino) *CP*v**

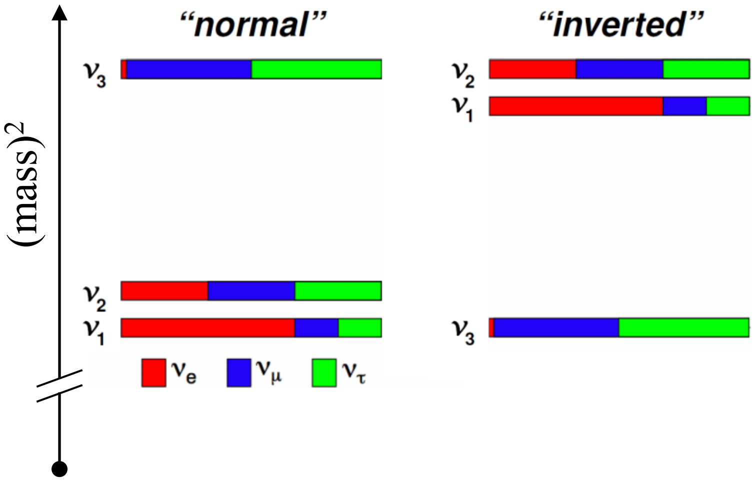
★ $\sin\delta \neq 0$?

Leptonic CP violation?

[1] M. Fukugita and T. Yanagida (1986); rich history since then.

ν mass hierarchy

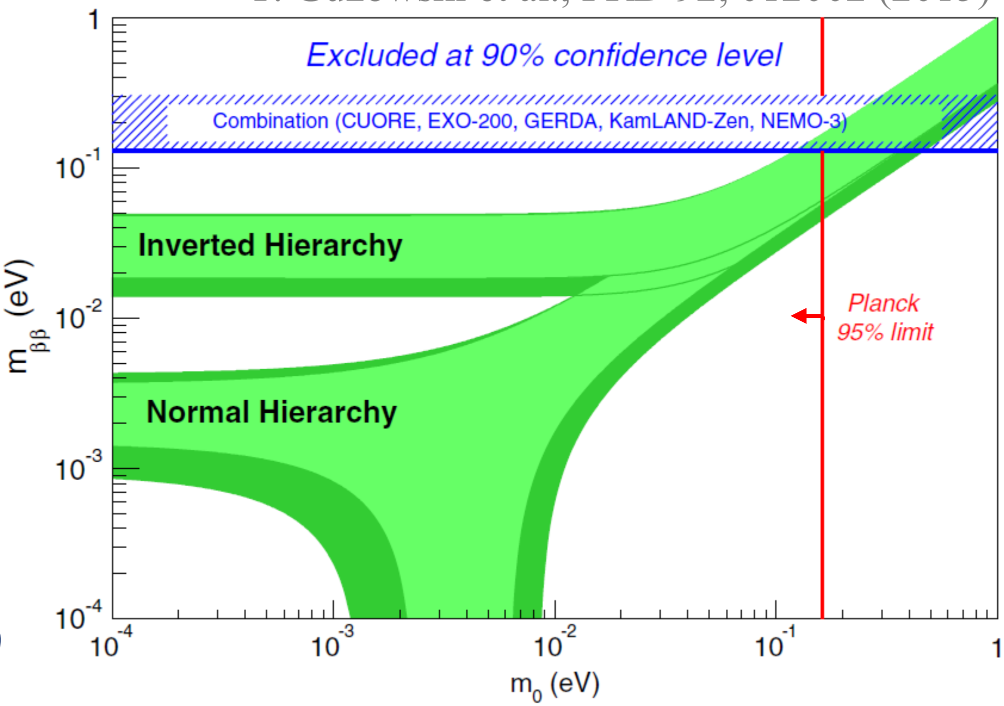
★ Are the electron-rich states ν_1 & ν_2 **heavier or lighter** than ν_3?



Far-reaching implications for such a simple question:

- **$0\nu\beta\beta$** and **Majorana nature of ν**
- Experimental approach to and interpretation of m_β
- **Cosmology** and **astrophysics**
- **Theoretical frameworks** for flavor and mass generation

P. Guzowski et al., PRD 92, 012002 (2015)



Notice:

An inverted hierarchy implies **<1.5% mass degeneracy**.

→ *Would hint at…??* *(cf.: π^+/π^0)*

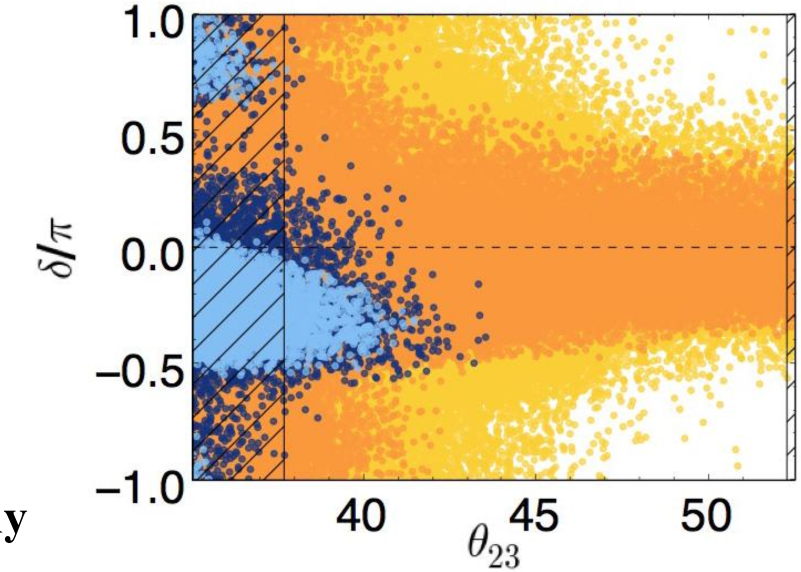
Flavor: A core problem for 21st century particle physics

Flurry of theoretical work.

Discrete flavor groups (A_4, S_4, $\Delta(3n^2)$, …) often combined with GUTs. Non-trivial flavor texture in heavy sector.

Emphasis on genuine predictive power. Explicit connections between low energy observables and leptogenesis.

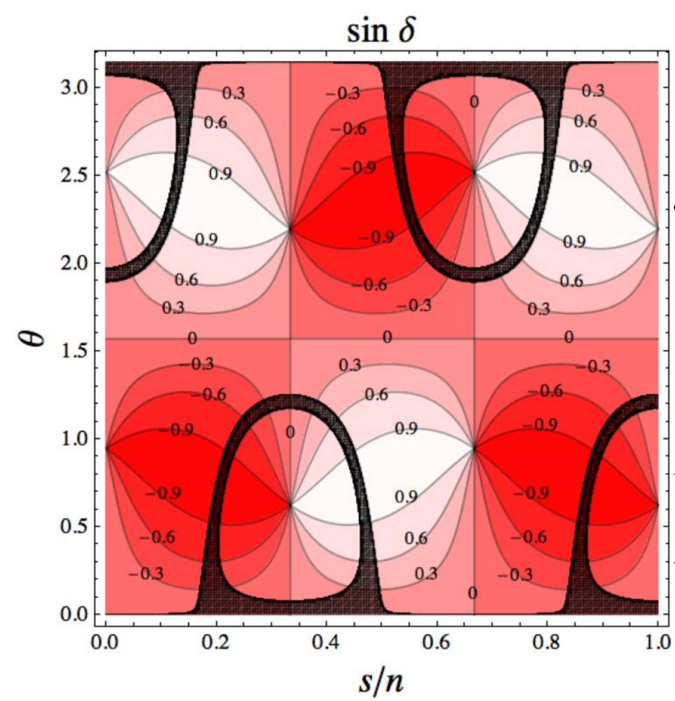
Often **immutable preferences** for **mass hierarchy** and **μ/τ asymmetry**



Di Bari, Marzola, Re Fiorentin
Nucl. Phys. B **893**, 122 (2015)

tan β	Output			
5	θ^q_{12}	13.027°	θ^l_{12}	34.3°
	θ^q_{13}	0.1802°	θ^l_{13}	8.67°
	θ^q_{23}	2.054°	θ^l_{23}	45.8°
	δ^q	69.18°	δ^l	-86.7°
	y_u	2.92×10^{-6}	Δm^2_{21}	7.38×10^{-5} eV^2
	y_c	1.43×10^{-3}	Δm^2_{31}	2.48×10^{-3} eV^2
	y_t	5.34×10^{-1}		
	y_d	4.30×10^{-6}	y_e	1.97×10^{-6}
	y_s	9.51×10^{-5}	y_μ	4.16×10^{-4}
	y_b	7.05×10^{-3}	y_τ	7.05×10^{-3}

Björkeroth, de Anda,
de Medeiros Varzielas, King
JHEP **06**, 141 (2015)



Hagedorn, Meroni, Molinaro
Nucl. Phys. B **891**, 499 (2015)

Flavor: A core question for 21st century particle physics

Flurry of theoretical work

Discrete flavor groups combined with GUTs. ... in heavy sector.

Emphasis on genuine p... connections between l... and leptogenesis.

Often **immutable pref... and μ/τ asymmetry**

$\tan\beta$				
5	θ^q_{12}	13.027°		
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	y_d	4.30×10^{-6}		
	y_s	9.51×10^{-5}	y_μ	[illegible]
	y_b	7.05×10^{-3}	y_τ	7.05×10^{-3}

Pascoli and Zhou, JHEP 06, 73 (2016)

Flavor symmetry $A_4 \times Z_2 \times Z_4$; flavon-induced connections between flavor mixing and CLFV, ***and…***

$$\sin\theta_{12} = \frac{1}{\sqrt{3}}\left(1 - 2|\epsilon_\varphi|\cos\theta_\varphi + 2\epsilon_\chi\right)$$

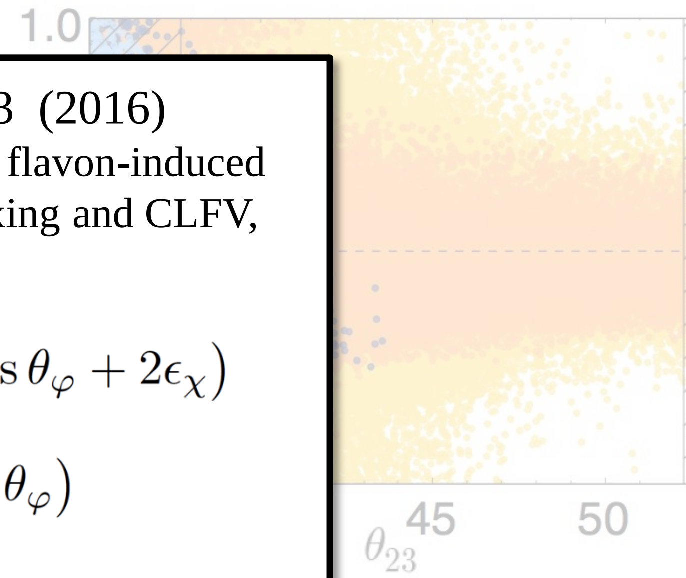
$$\sin\theta_{23} = \frac{1}{\sqrt{2}}\left(1 + |\epsilon_\varphi|\cos\theta_\varphi\right)$$

$$\sin\theta_{13} = \sqrt{2}|\epsilon_\varphi \sin\theta_\varphi|$$

$$\delta = \begin{cases} 270^\circ - 2|\epsilon_\varphi|\sin\theta_\varphi\,, & \theta_\varphi > 0\,, \\ 90^\circ - 2|\epsilon_\varphi|\sin\theta_\varphi\,, & \theta_\varphi < 0\,, \end{cases}$$

$$\epsilon_\varphi = |\epsilon_\varphi|e^{i\theta_\varphi}$$

$$\delta \approx \begin{cases} 270^\circ - \sqrt{2}\theta_{13}\,, & \theta_\varphi > 0\,, \\ 90^\circ + \sqrt{2}\theta_{13}\,, & \theta_\varphi < 0\,. \end{cases}$$



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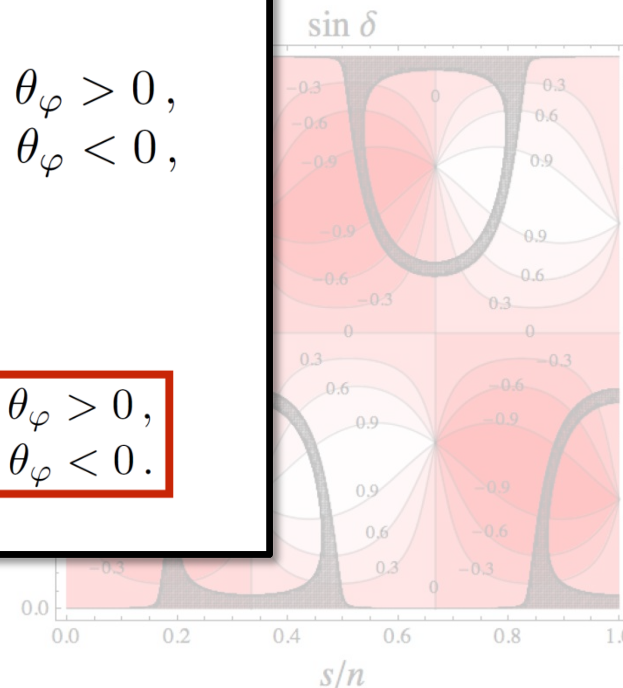
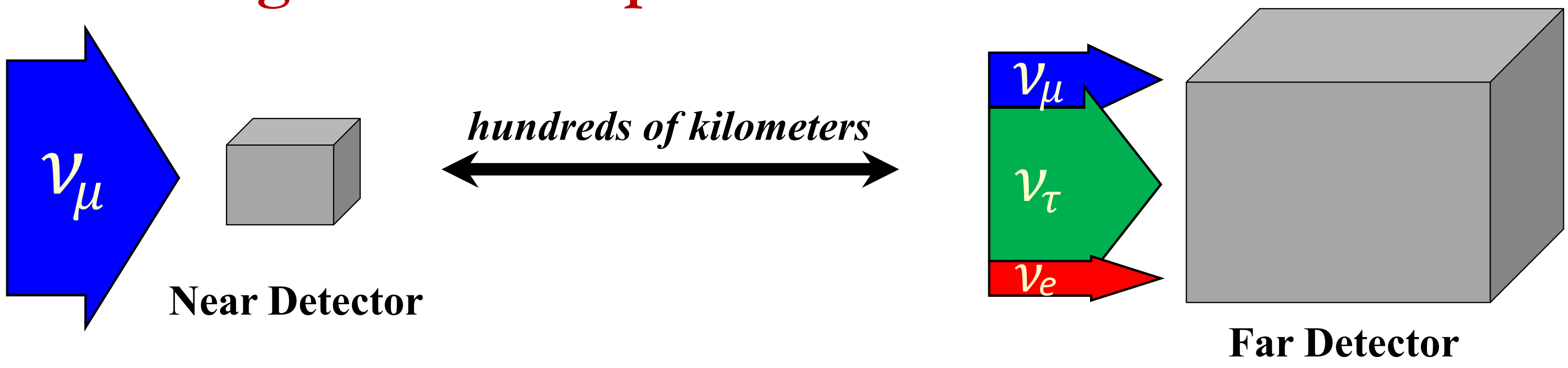


Hagedorn, Meroni, Molinaro
Nucl. Phys. B **891**, 499 (2015)

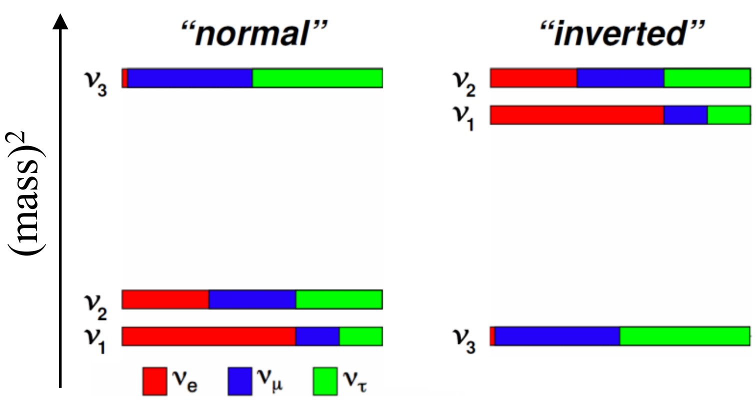
Generic long-baseline experiment



ν_e appearance:

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\,\sin^2 2\theta_{13}\,\sin^2(\Delta m^2_{32} L/4E)$$

...plus ***potentially large CPv*** *and* ***matter effect**** *modifications!*

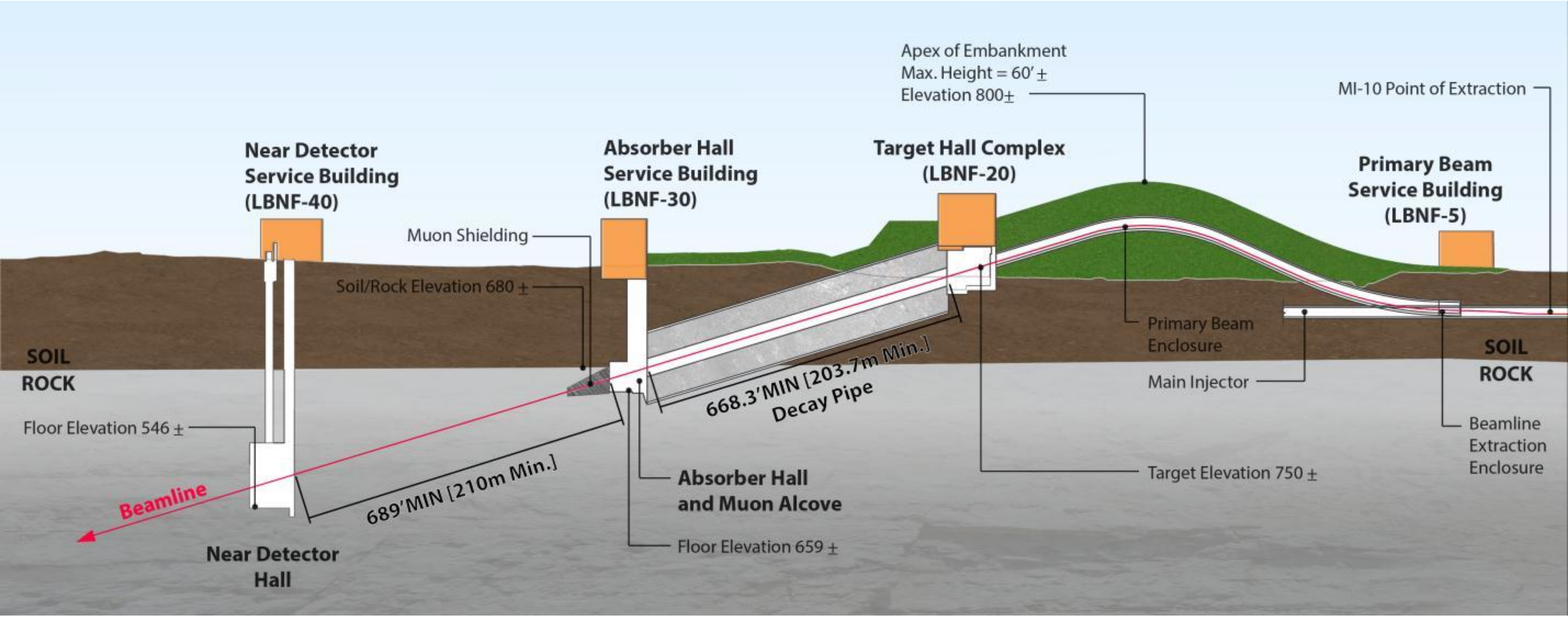


* ν_e see different potential than $\nu_{\mu,\tau}$ when propagating through matter (here, the earth)

⇒ a hierarchy-dependent effect

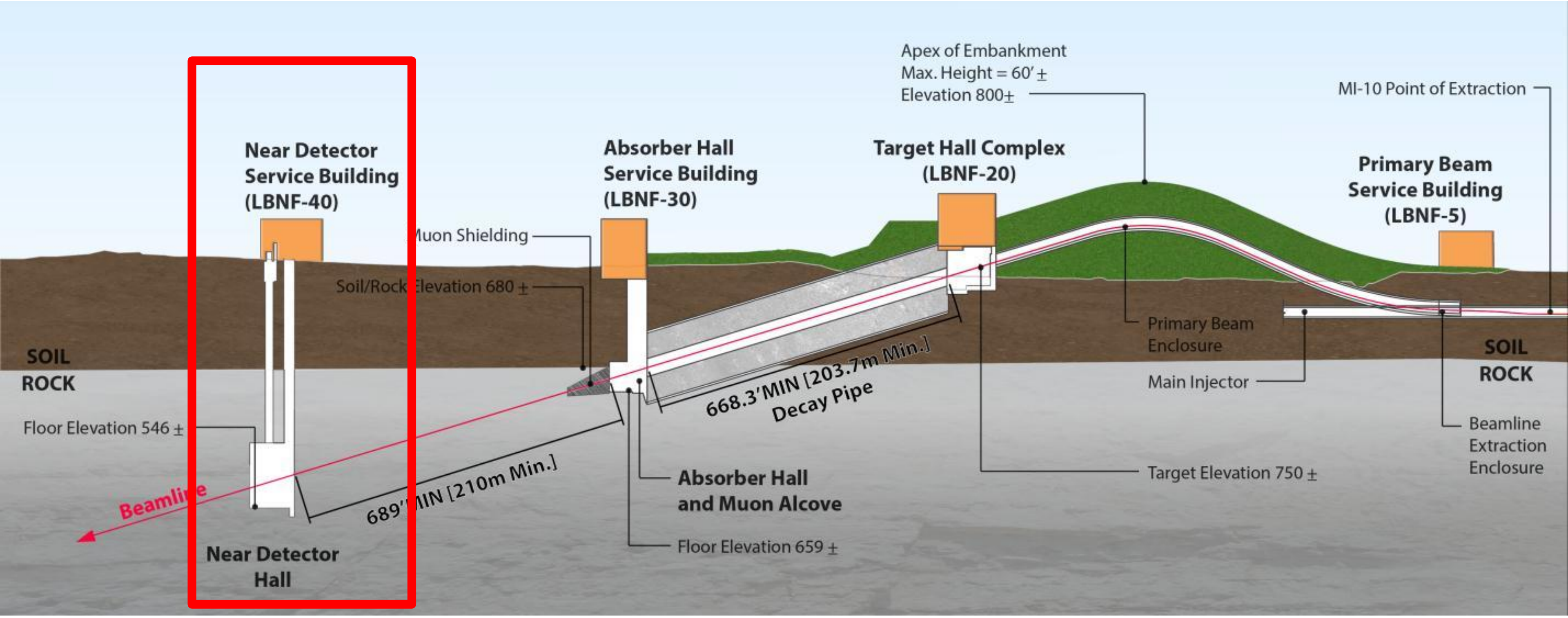
Long Baseline Neutrino Facility (LBNF)

- DOE/Fermilab hosted project with international participation
- **Horn-focused beamline** similar to NuMI beamline
  - 60 – 120 GeV protons from Fermilab's Main Injector
  - 200 m decay pipe at -5.8° pitch, angled at South Dakota (SURF)
  - Initial power 1.1 MW, upgradable to 2.4 MW



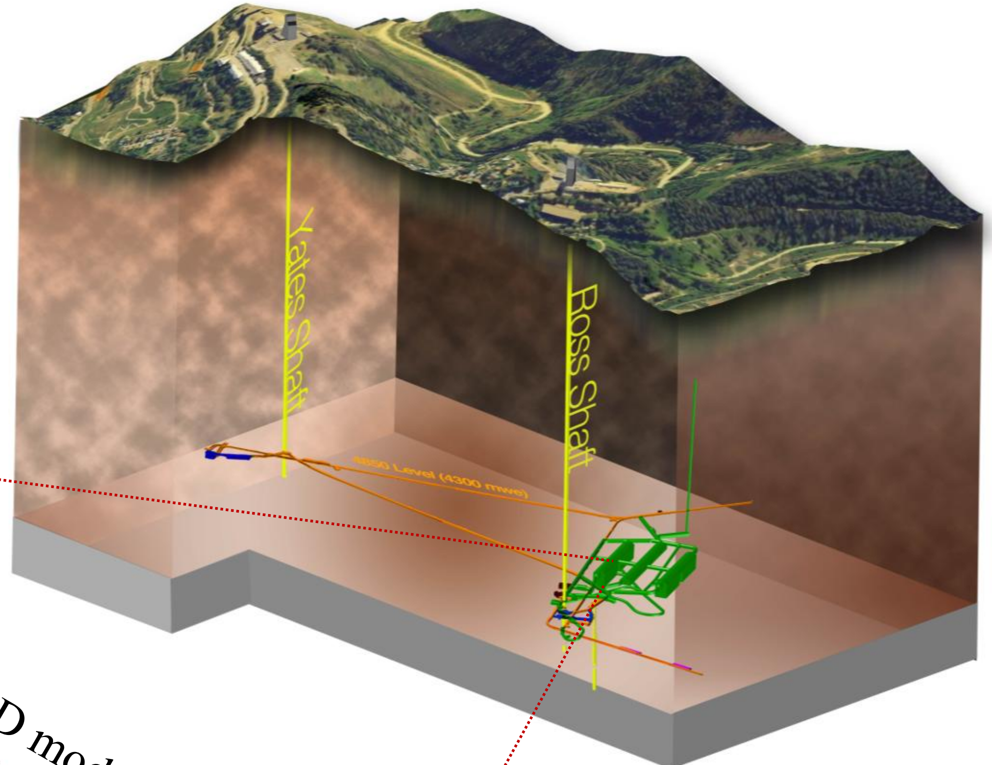
Near Detector

- DUNE will have a **Near Detector**
  - Constrain systematic uncertainties in oscillation measurements
  - Precisely measure initial fluxes of neutrinos in the beam
  - Measure numerous neutrino-nucleus scattering cross sections
- Multiple **designs** under consideration
  - LAr TPC, high-pressure GAr TPC, fine-grained tracker, hybrid designs

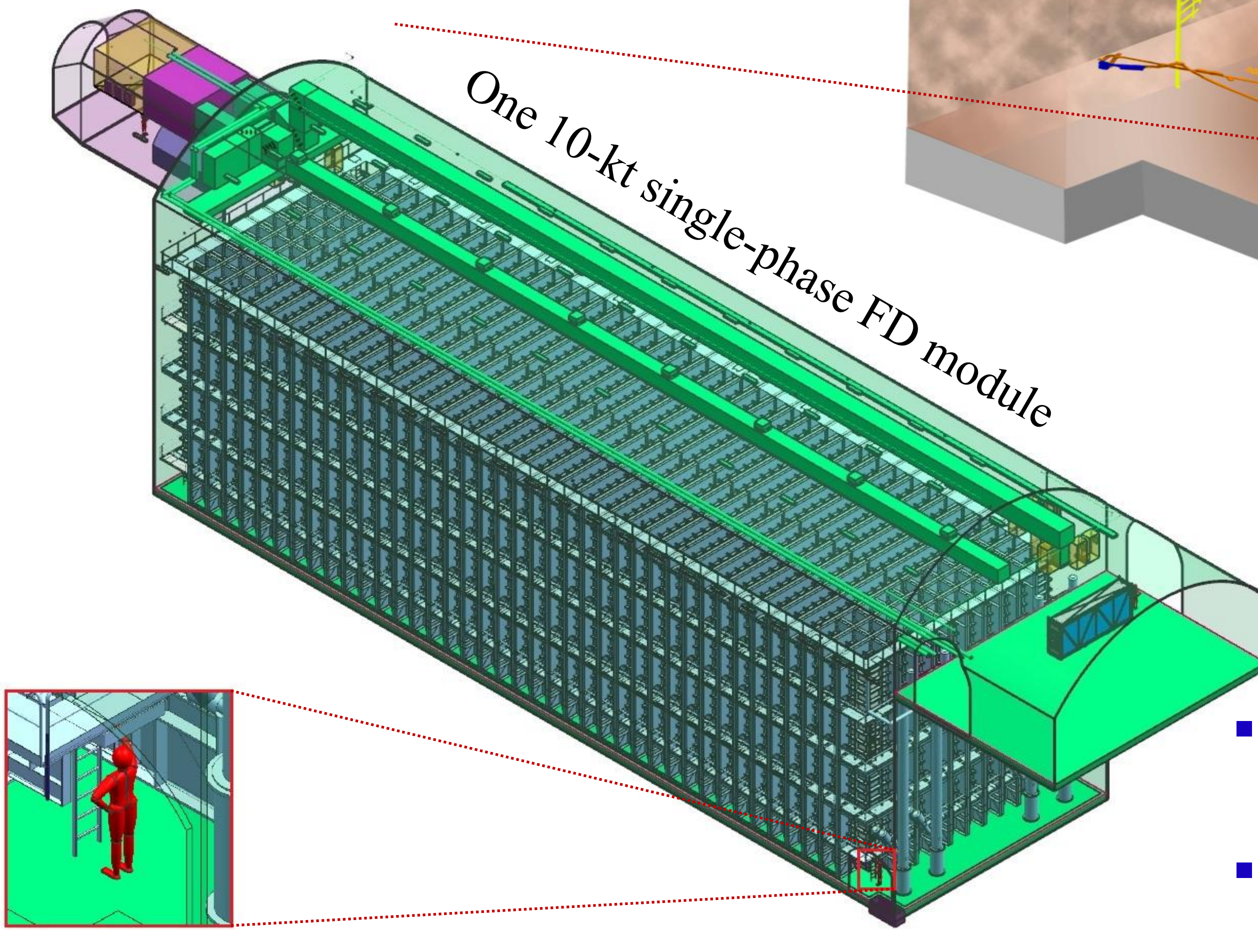


Far Detector

- **40-kt (fiducial)** LAr TPC
- Installed as four 10-kt modules at 4850' level of SURF



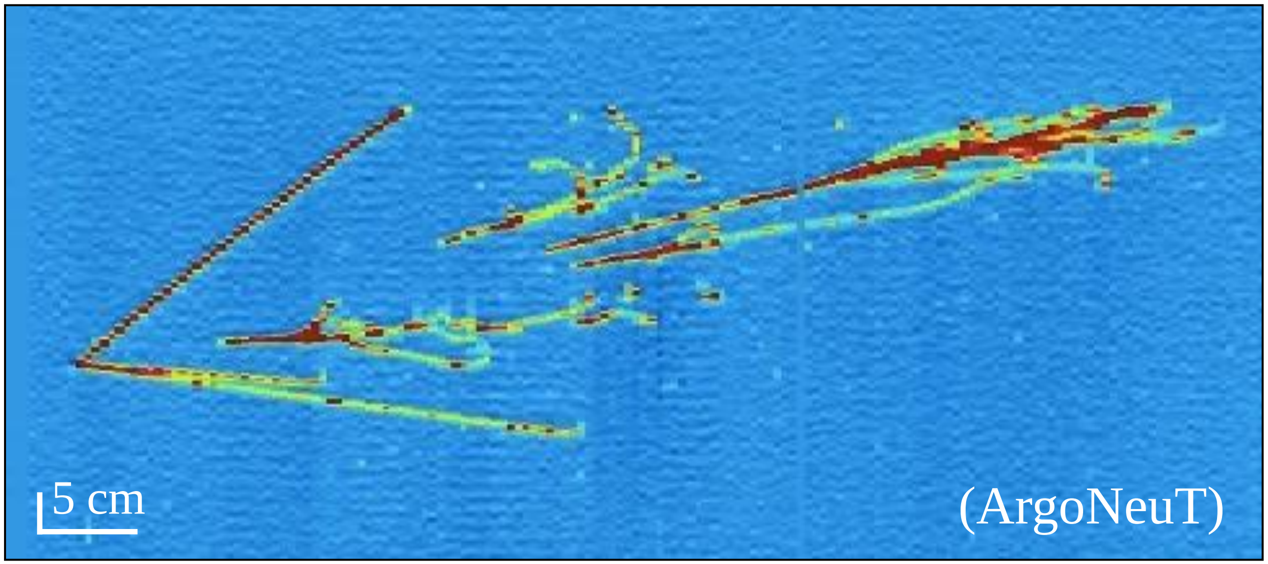
Sanford Underground Research Facility (SURF)

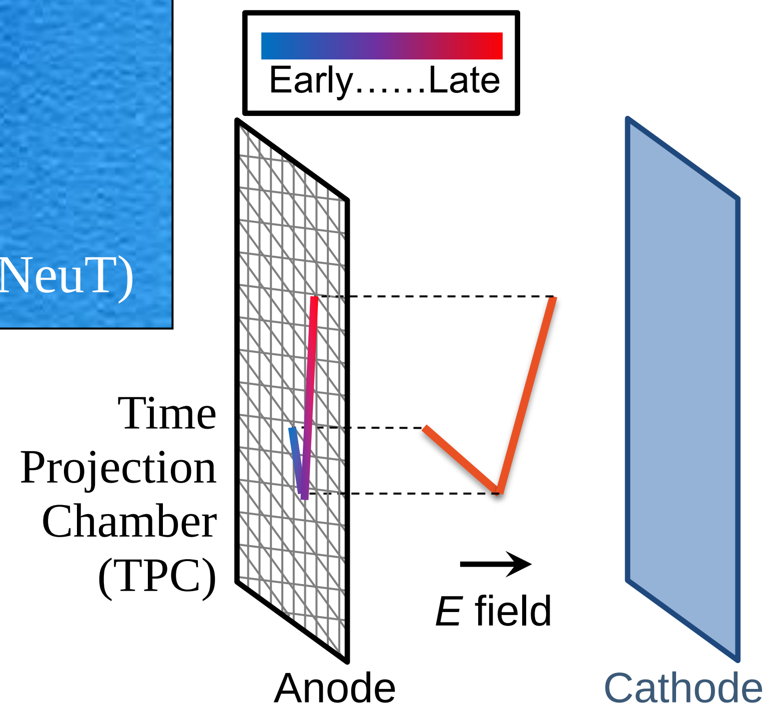


- First module will be a **single phase LAr TPC**
- Modules installed in stages. Not necessarily identical

Key design features:

Very long baseline → *no oscillation parameter ambiguities*
Large detector and powerful beam → *high event rate*
Highly capable LAr TPC → *excellent background rejection*
Low energy threshold → *rich underground physics program*



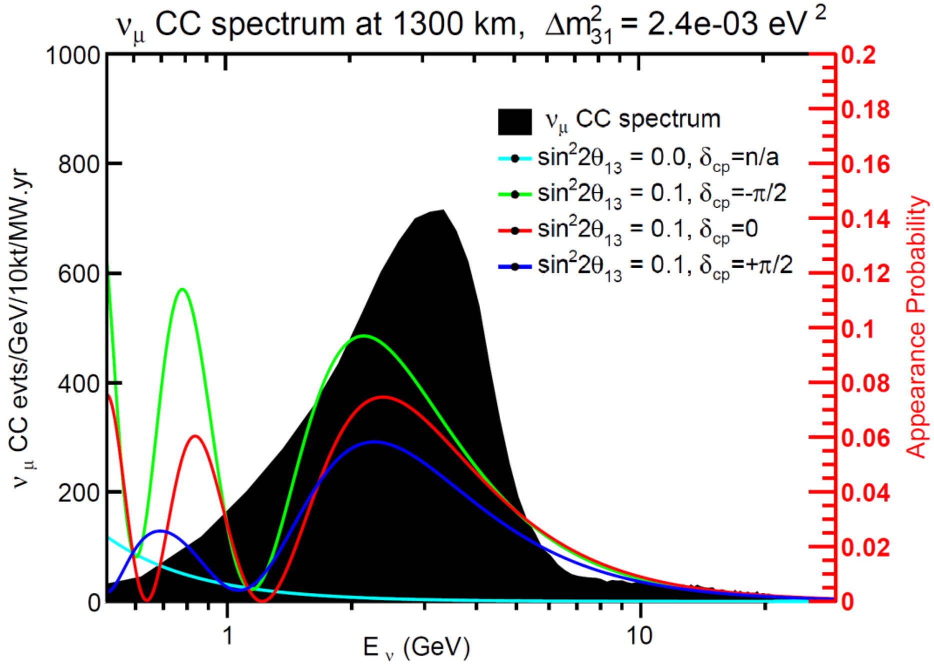


DUNE TPC:

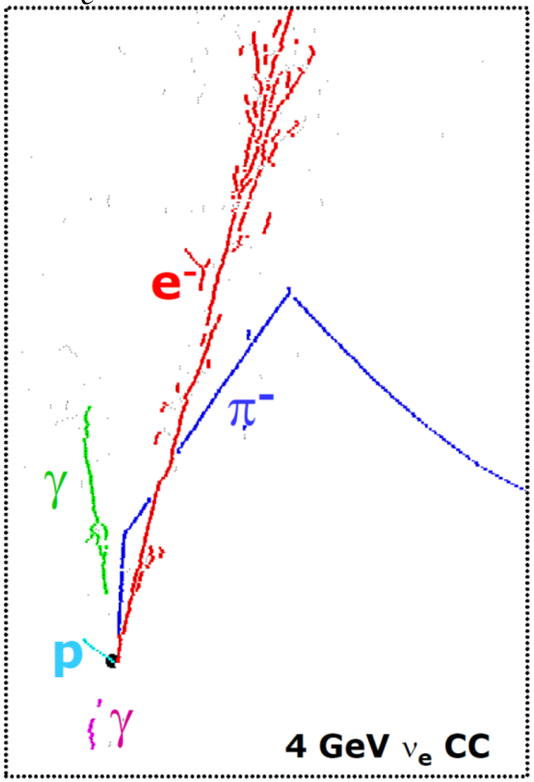
- **3.5 m drifts @ 175 kV** *(500 V/cm)*
- **3 ms** ***e***$^-$ **lifetime**
- **5 mm wire pitch**

High-resolution detector

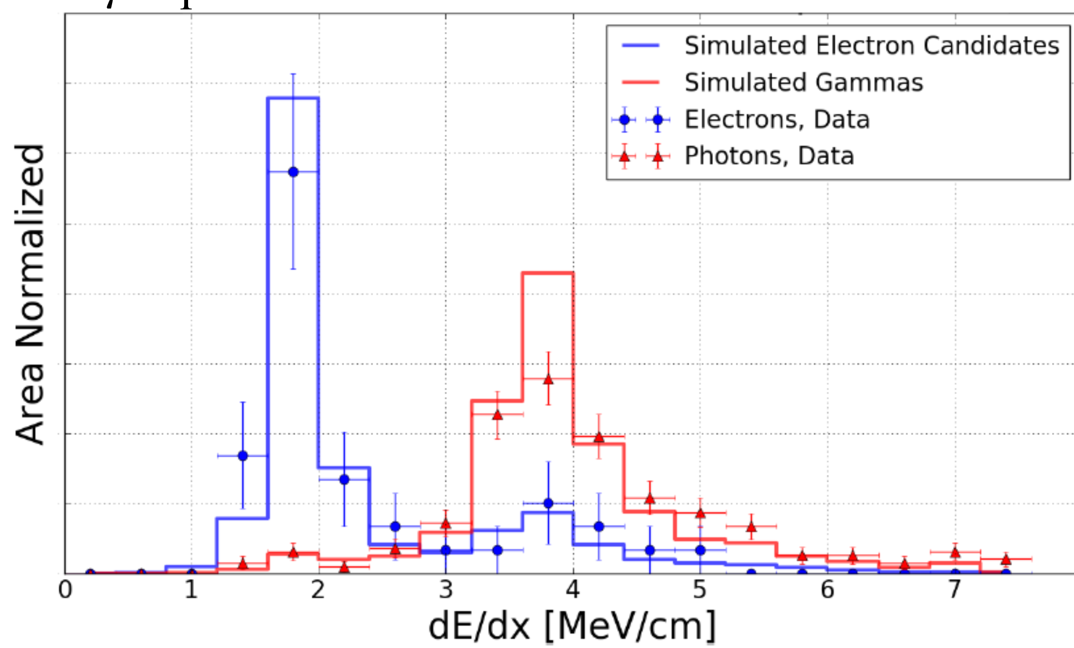
- permits broadband neutrino beam
- *e*-*γ* shower separation via both event topology and early *dE*/*dx*



Simulated and reconstructed ν_e CC event in DUNE



e/*γ* separation with R&D detector



ArgoNeuT, arXiv:1610.04102

(after 7 years, staged deployment)

Observation of leptonic *CP* violation

5σ near $\delta=\pi/2$

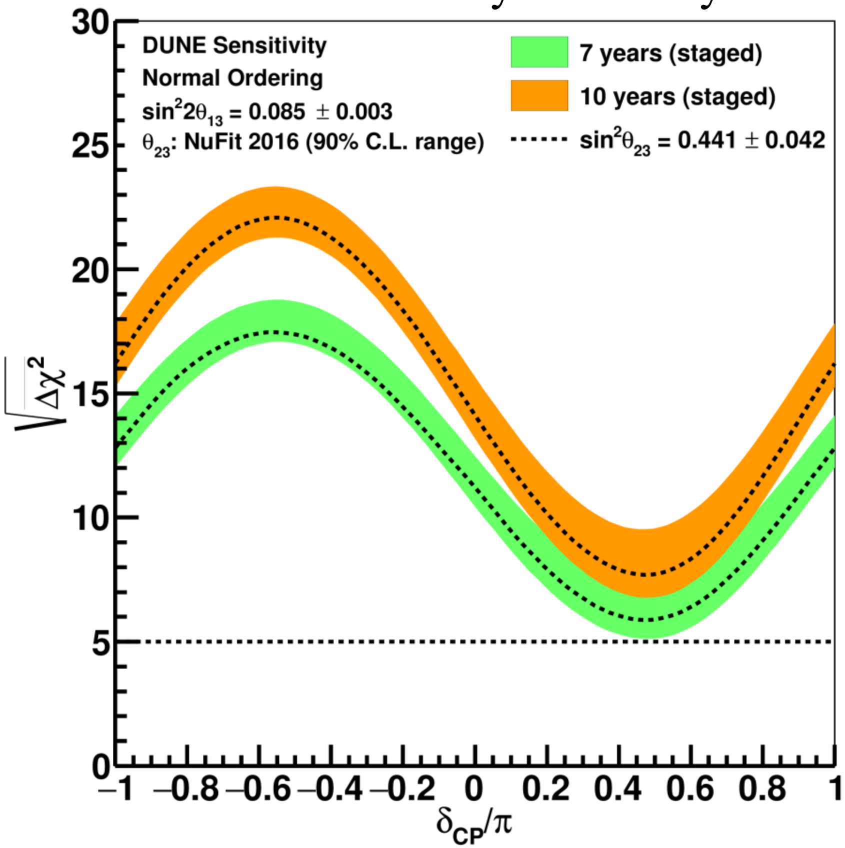
3σ for 65% of δ range

Definitive hierarchy determination

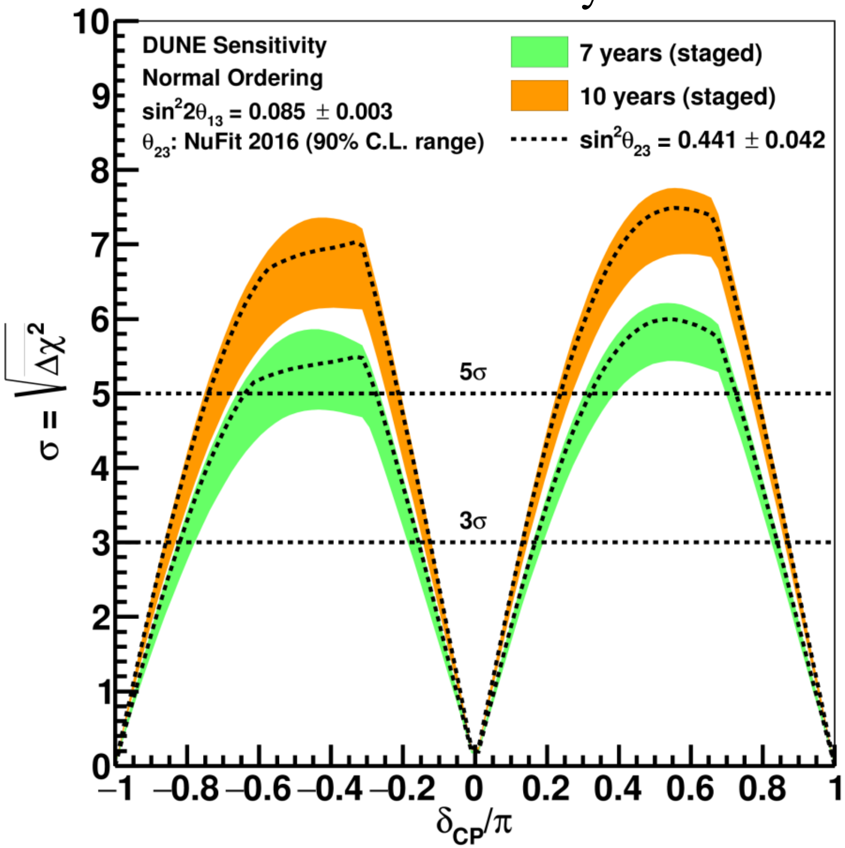
>5σ regardless of other parameter choices

Move quickly to **potential discovery**

Mass hierarchy sensitivity



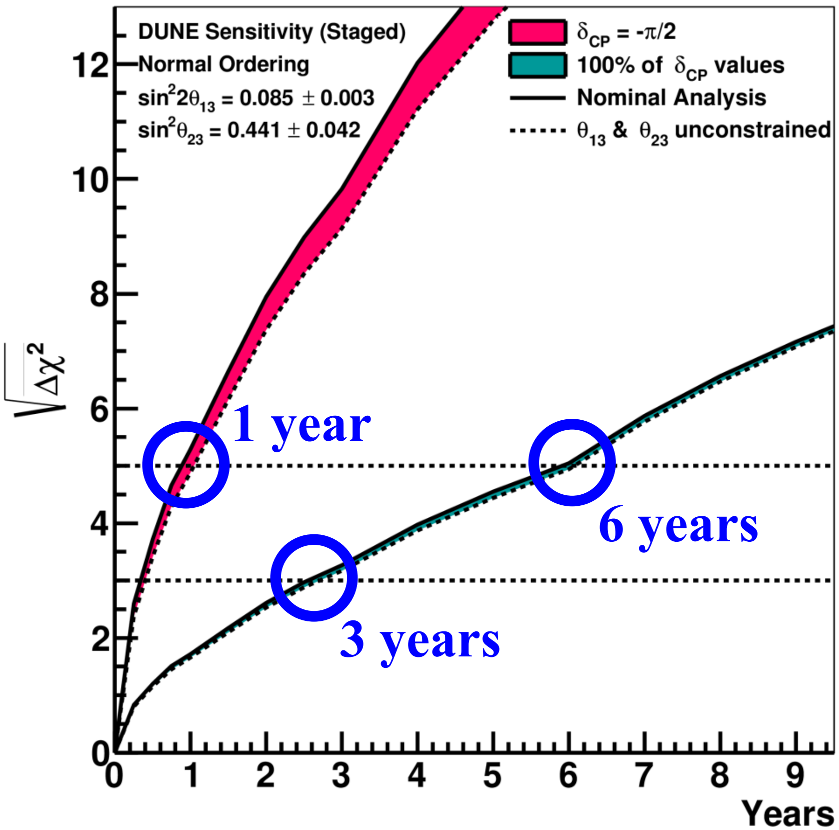
*CP*v sensitivity



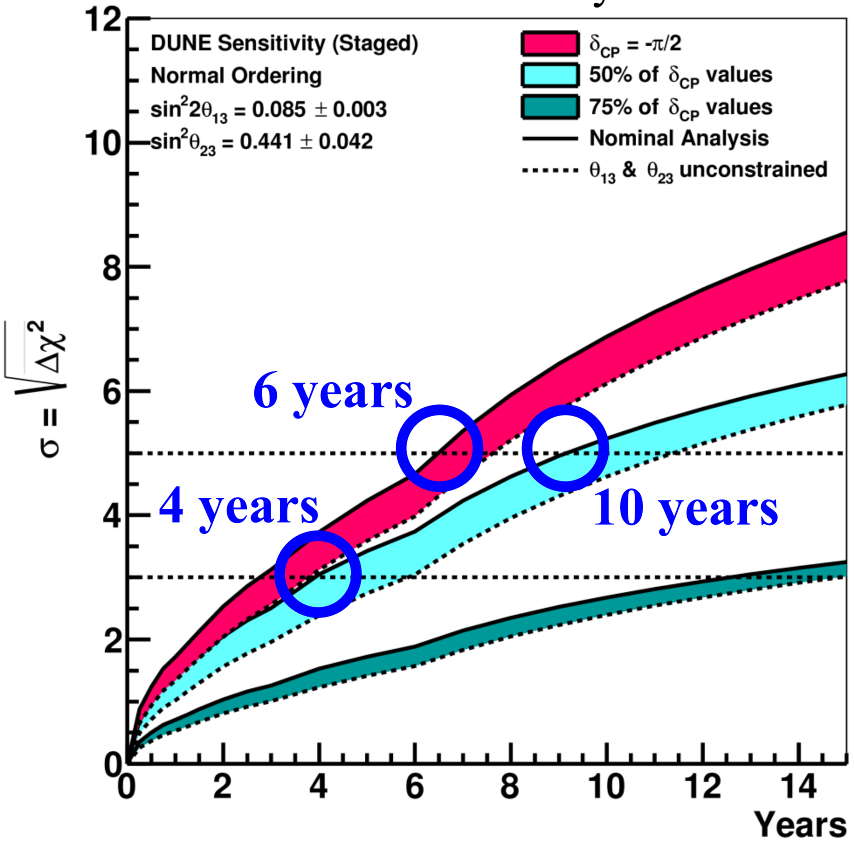
Sensitivity vs. time

- → **Significant milestones** throughout beam-physics program
- → **A few examples** below

Mass hierarchy sensitivity



*CP*v sensitivity



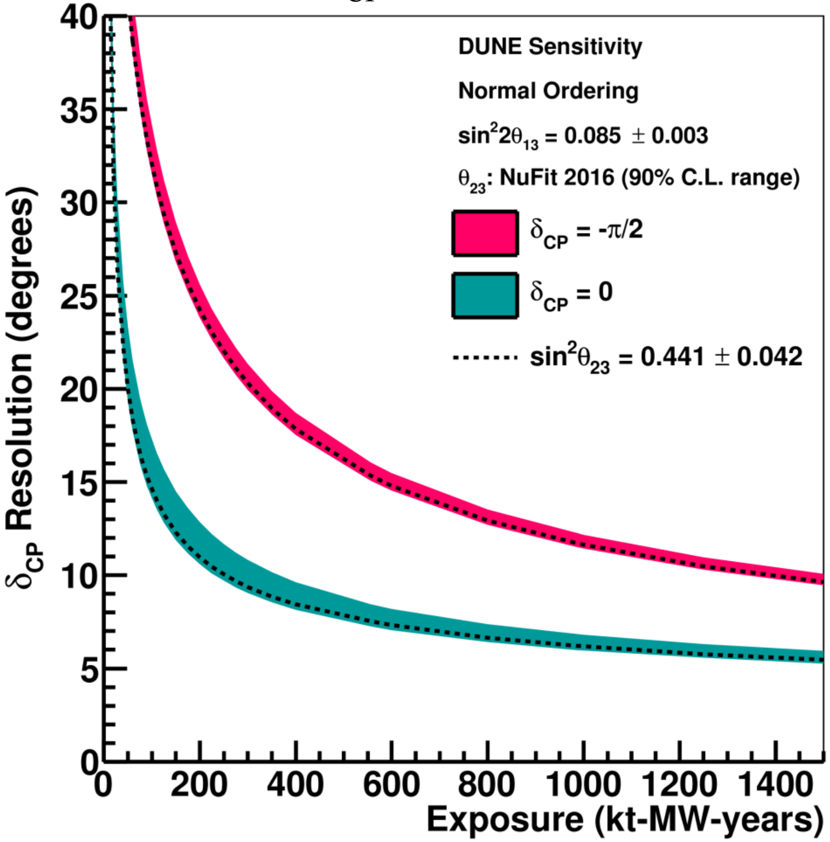
Precision PMNS

(ultimate precision depends on parameter values themselves)

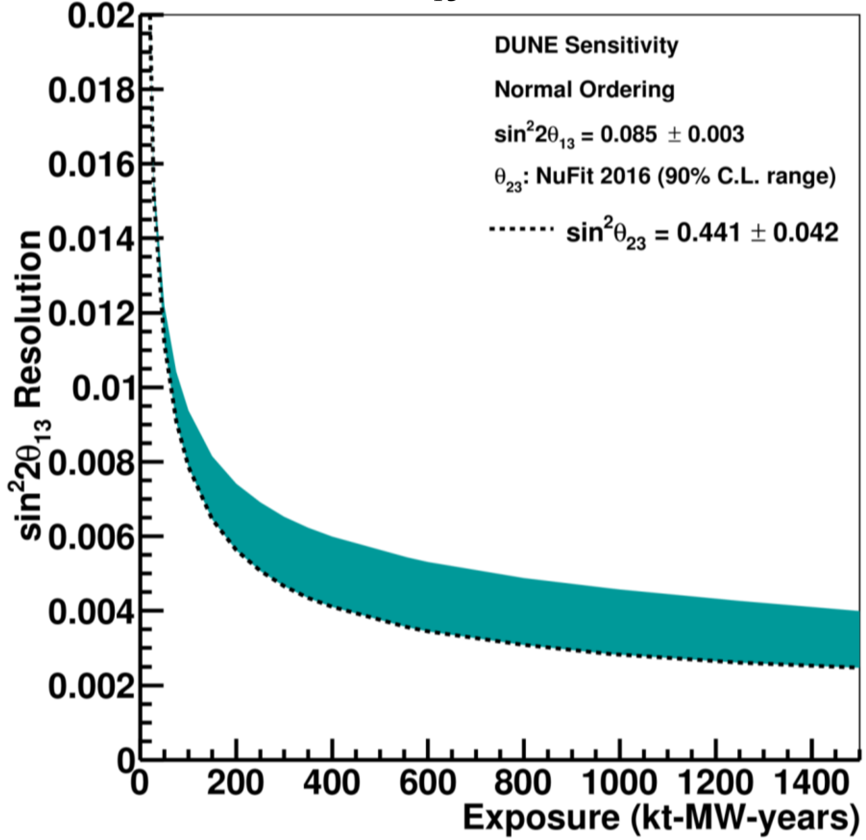
→ *E.g.:* δ_{CP} to ~10° ; θ_{13}, θ_{23} to ~0.2°

→ A suite of oscillation parameter measurements in a single experiment

δ_{CP} resolution

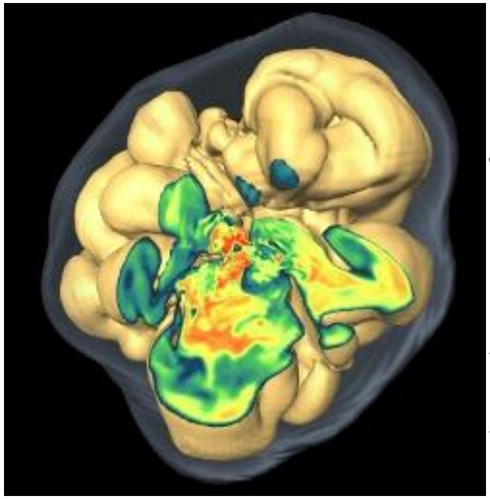


$\sin^2 2\theta_{13}$ resolution



Supernova neutrinos

- **99% of energy** released in a core-collapse supernova is **carried away by neutrinos** *(cf.: 0.01% carried away by light)*
- **Rich information** embedded in neutrino signal:
  - **Supernova physics:** core-collapse mechanism, black hole formation, shock stall/revival, nucleosynthesis, cooling, …
  - **Particle physics:** flavor transformations in core, collective effects, mass hierarchy, sterile neutrinos, extra dimensions, …

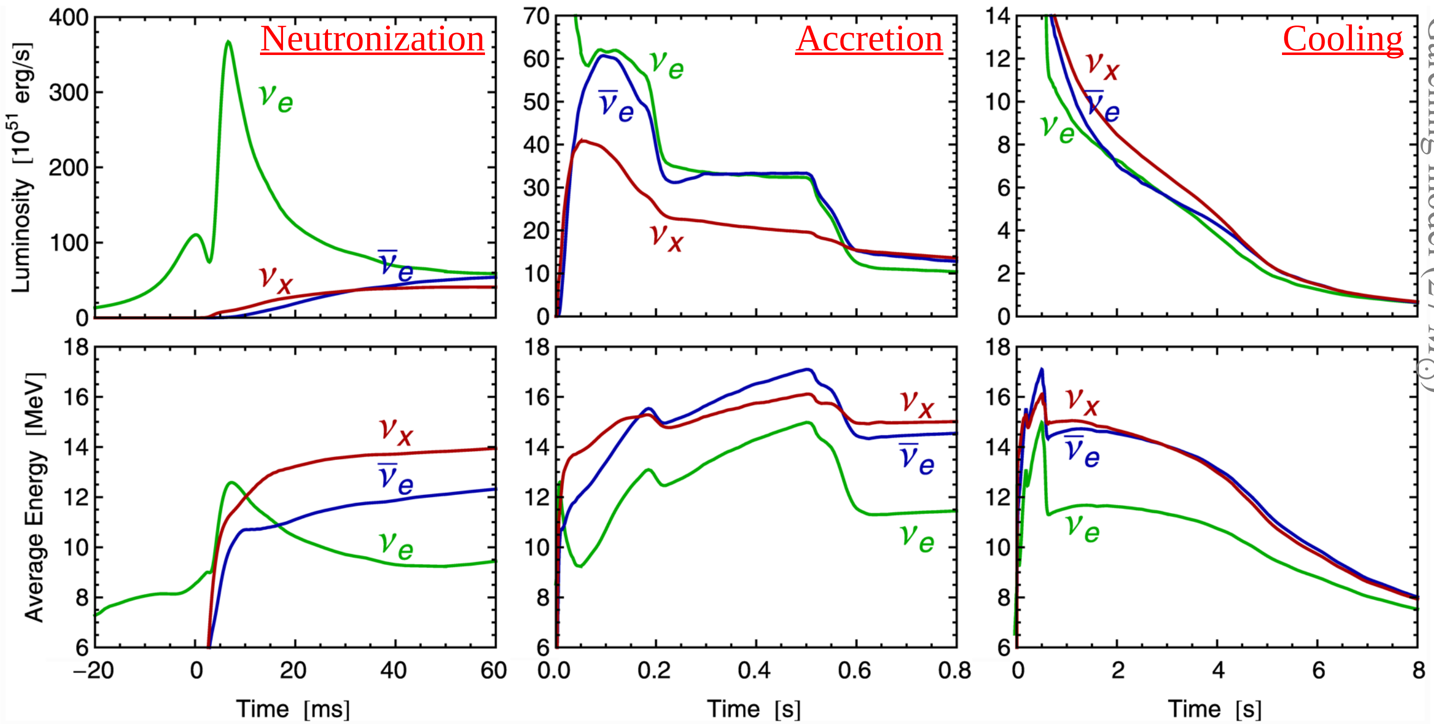


S. Woosley and T. Janka
Nature Physics **1**, 147 (2005)

Argon target:
Unique sensitivity to ν_e flux

DUNE at 10 kpc:
~3000 ν_e events over 10 seconds

with 5%–10% energy resolution & sub-μs time resolution



Garching model (27 $M_\odot$)

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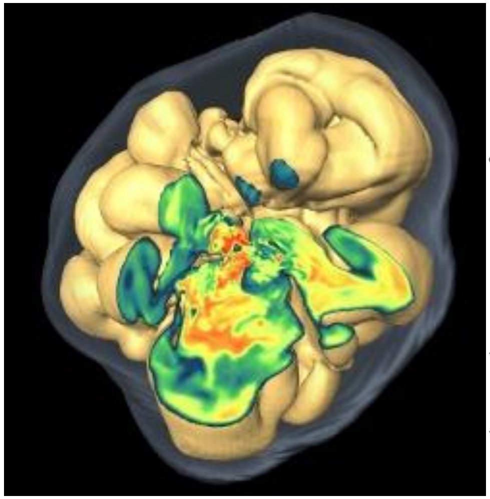


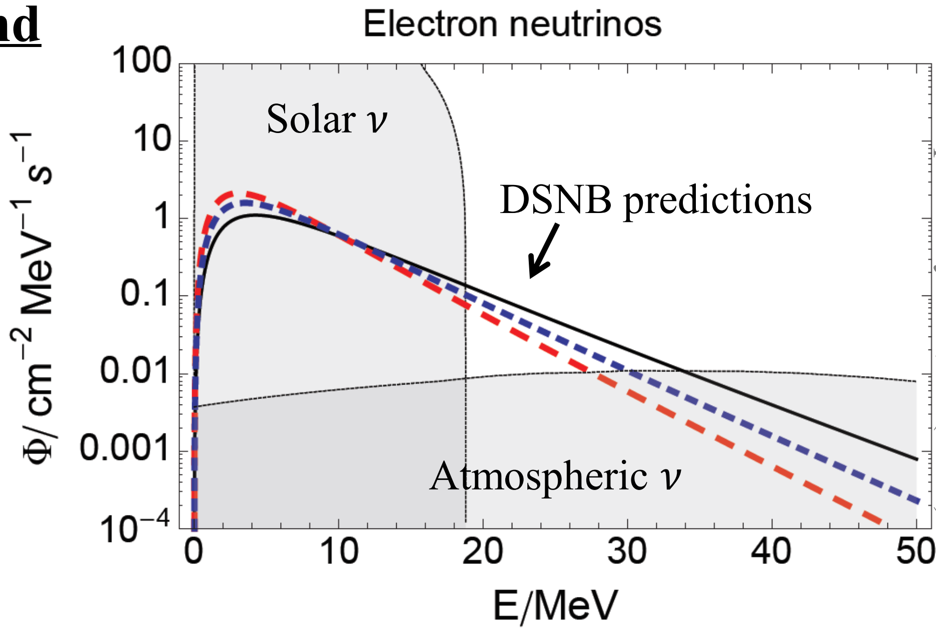
S. Woosley and T. Janka
Nature Physics **1**, 147 (2005)

Diffuse supernova neutrino background

Should be there. *Not yet observed.**

DUNE: Potential for DSNB discovery and ~20% rate measurement

(bkgnds still under study)



C. Lunardini,
Astropart. Phys. **79**, 49 (2016)

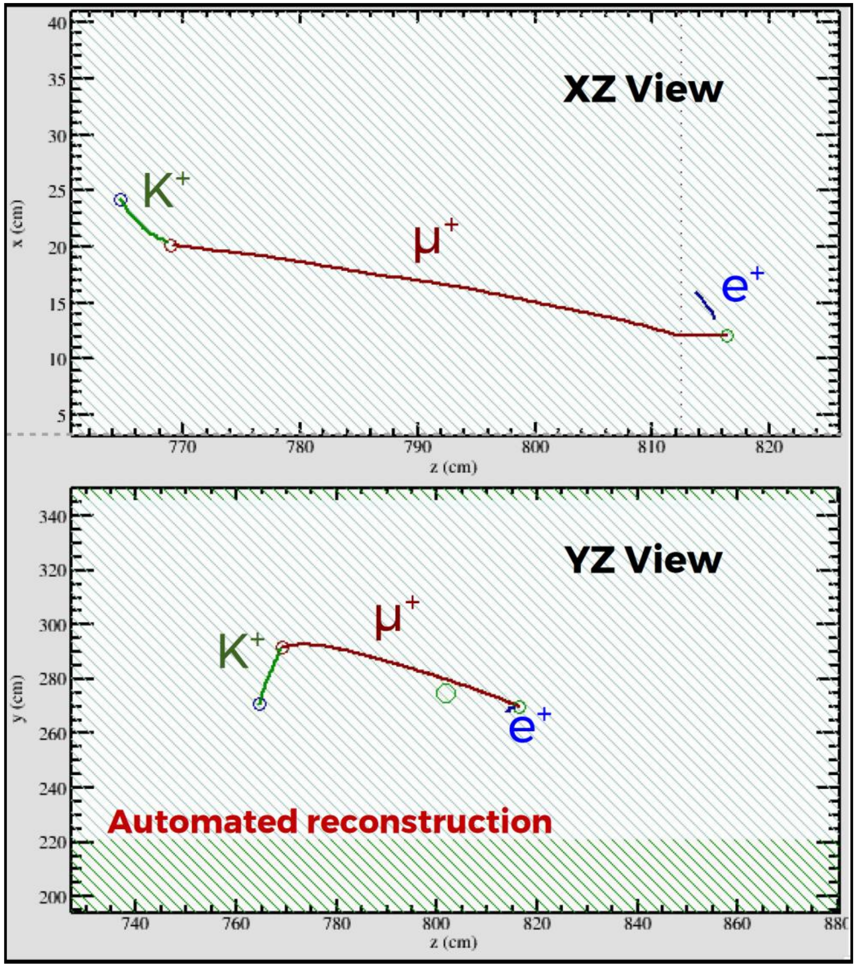
* Present limit from Super-K:
K. Bays *et al.*, Phys. Rev. D **85**, 052007 (2012)

Baryon number violation

Processes with $\Delta B \neq 0$, including **proton decay**, are a general prediction of **grand unified theories**

- An **effective proton decay search** requires (**and DUNE has**)
  - **Large exposure:** **40 kton, 20+ yr program**
  - **Low background rates:** **Deep underground location**
  - **High signal efficiency:** **Precision LAr TPC tracking**

LAr TPC technology **particularly shines** for complex *p* decay modes or modes with **final state kaons**, as **favored by SUSY GUTs**



At right:

***$K^{\pm}\to\mu\to e$* decay sequence**

Background-free signature in DUNE

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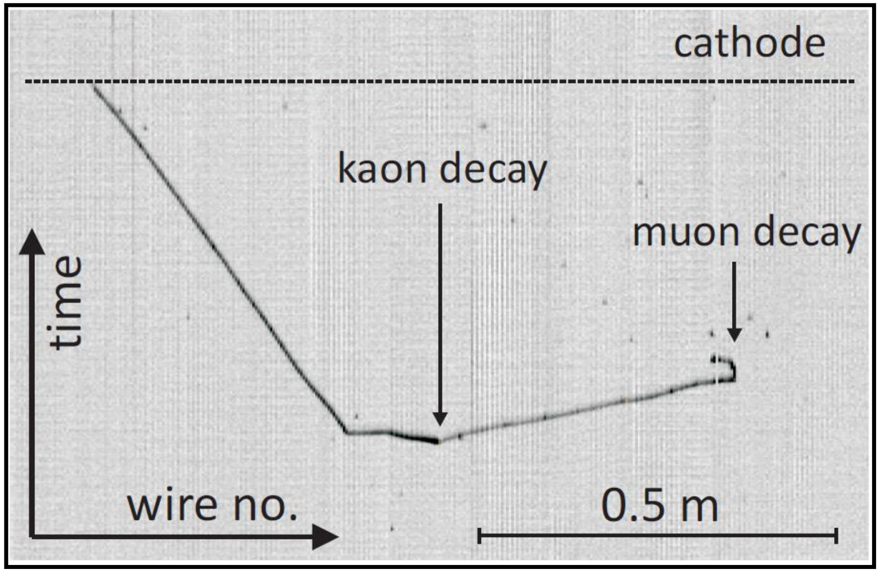
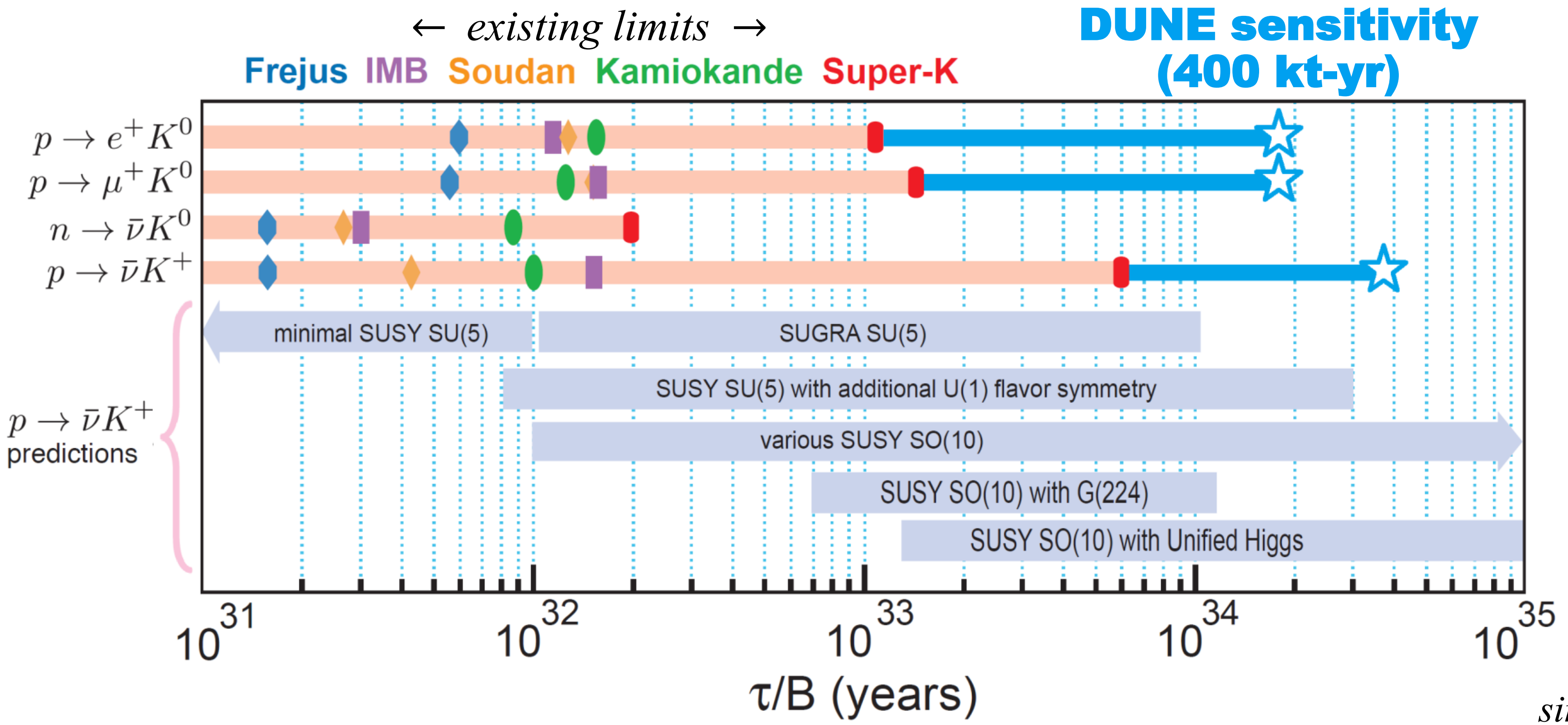
ICARUS collab., Adv. HEP, vol. 2013, 260820 (2013)



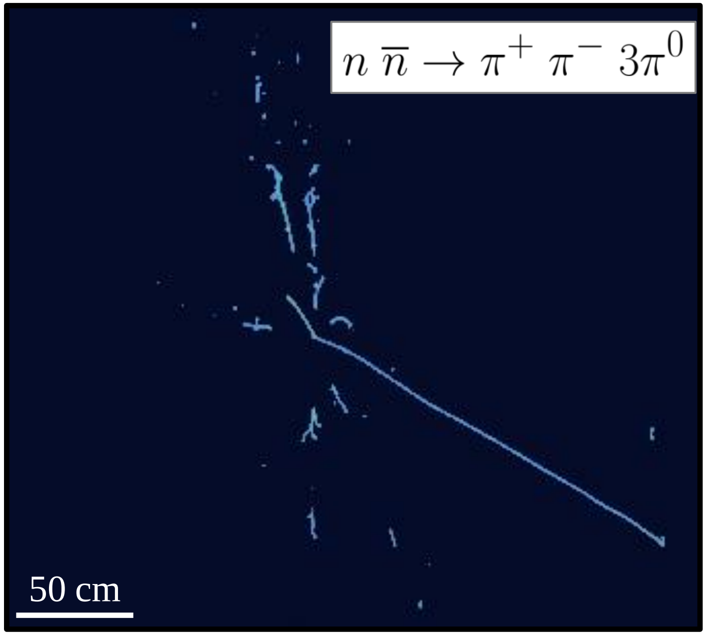
<u>At right:</u>

***$K^{\pm}\rightarrow\mu\rightarrow e$* decay sequence**

Background-free signature in DUNE



simulation



Order of magnitude step in lifetime

→ *Significant model discrimination*

At right:

n-$\bar{n}$ oscillation → intranuclear $n\bar{n}$ annihilation

Spherical spray of hadrons with $\boldsymbol{E \approx 2M_n}$ and **net momentum** $\lesssim p_F \sim 300$ MeV

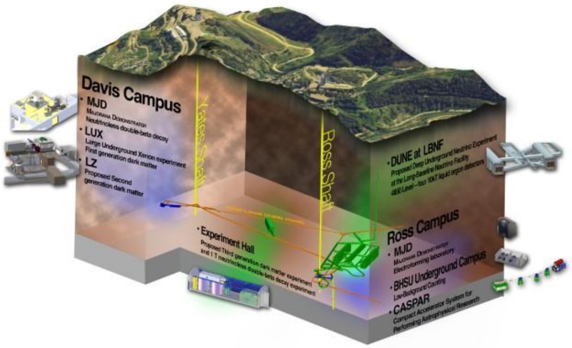
More of the physics program beyond "3ν"

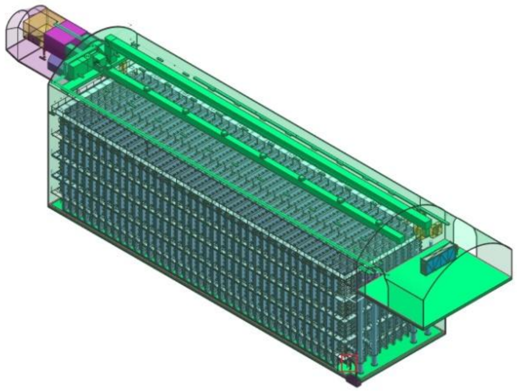
Some of the **new physics signatures** accessible with DUNE:

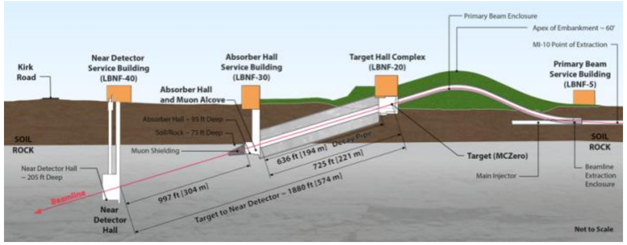
- **Light sterile neutrinos**
  Various experimental anomalies persist. Multiple channels for investigation in a LBL setup.
- **Non-standard interactions**
  Beam and atmospheric neutrinos passing through matter provide access to non-standard couplings. Unique search features: long baselines; appearance channel.
- **Dark matter**
  Astrophysical (*e.g.*, annihilation in the sun; at DUNE, look for up-going neutrinos) and beam-induced light dark matter (*e.g.*, $qq \rightarrow V^* \rightarrow \bar{\chi}\chi$ at target)
- **And more…**
  Lorentz violation, effective *CPT*v, large extra dimensions, non-unitarity, neutrino tridents (Z' and muon g–2)

Plus **millions of interactions** in the Near Detector for exploring ν-nucleus scattering: final state interactions, nuclear structure, MEC/2p2h channels, …

DUNE Timeline







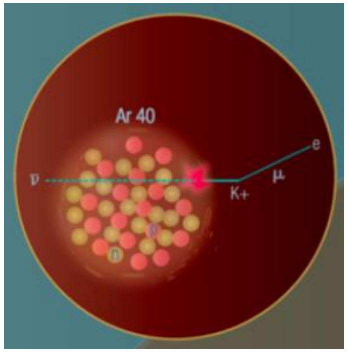
2017: Far Site Construction Begins

2018: ProtoDUNEs at CERN

2021: Far Detector Installation Begins

2024: Physics Data Begins (20 kt)

2026: Neutrino Beam Available



40 kton + 2 MW beam to follow in subsequent years

DEEP UNDERGROUND NEUTRINO EXPERIMENT

DUNE is a top priority of DOE and international HEP community

- A core part of US HEP's "P5" Strategic Plan for next two decades

Highly internationalized:

- 951 collaborators
- 164 institutions
- 30 countries

CD-3a approval in Sep. 2016

- Approval for $0.3B start of Far Site construction

Full-scale component prototypes will operate at CERN, 2018+

- Single- and dual-phase designs

ProtoDUNE cold box at CERN

Hoist/motion tests at Ash River

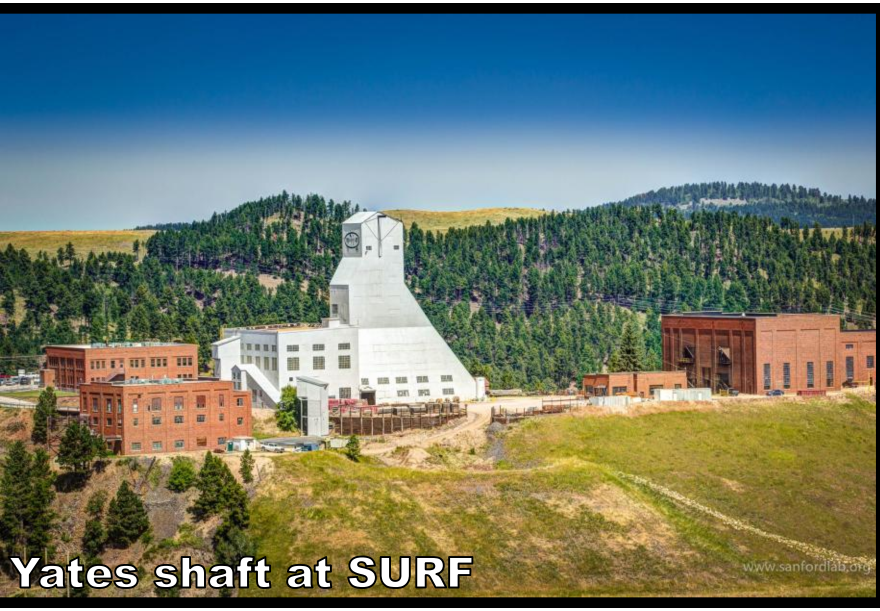
Conclusions

DUNE gearing up

- **ProtoDUNE** installation underway now at CERN
- **Far Detector** site prep work underway now at SURF

A broad physics program

- DUNE will determine the **νMH** and can measure **leptonic *CP*v** at 5σ
- Precision **PMNS**: a new era for flavor theory
- **Nucleon decay**
- **Supernova** neutrinos
- And a rich **BSM physics** program both inside and outside the neutrino sector



Extras

- **Cosmological observations** → sum of neutrino masses.

  Best limits: $\boldsymbol{\Sigma m_i}$ **< 0.23 eV** (95% C.L.) *Planck collaboration, arXiv:1502.01589*

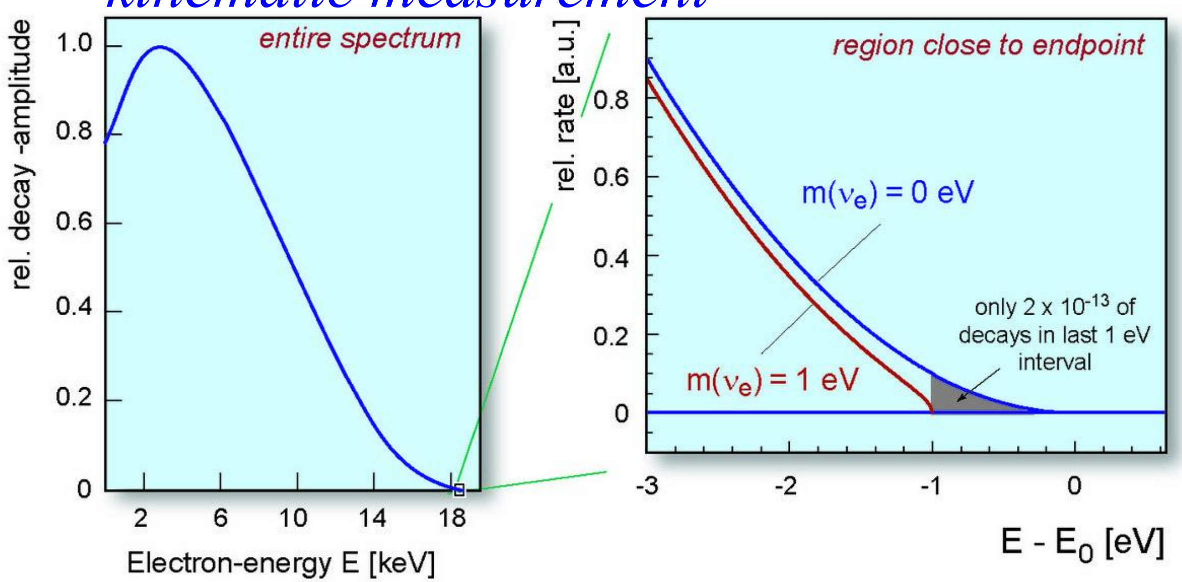
- ***β*-decay kinematic measurement** → effective ν_e mass, a.k.a. m_β:

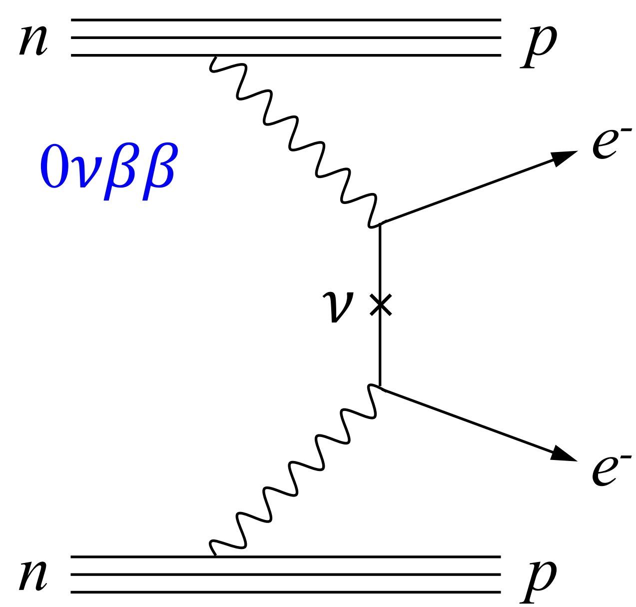
$$m_\beta^2 = \sum |U_{ei}|^2 m_i^2$$

- **0*νββ* decay process (if Majorana-*ν*-mediated)** → effective mass $m_{\beta\beta}$:

$$m_{\beta\beta}^2 = \left|\sum U_{ei}^2 m_i\right|^2$$

kinematic measurement





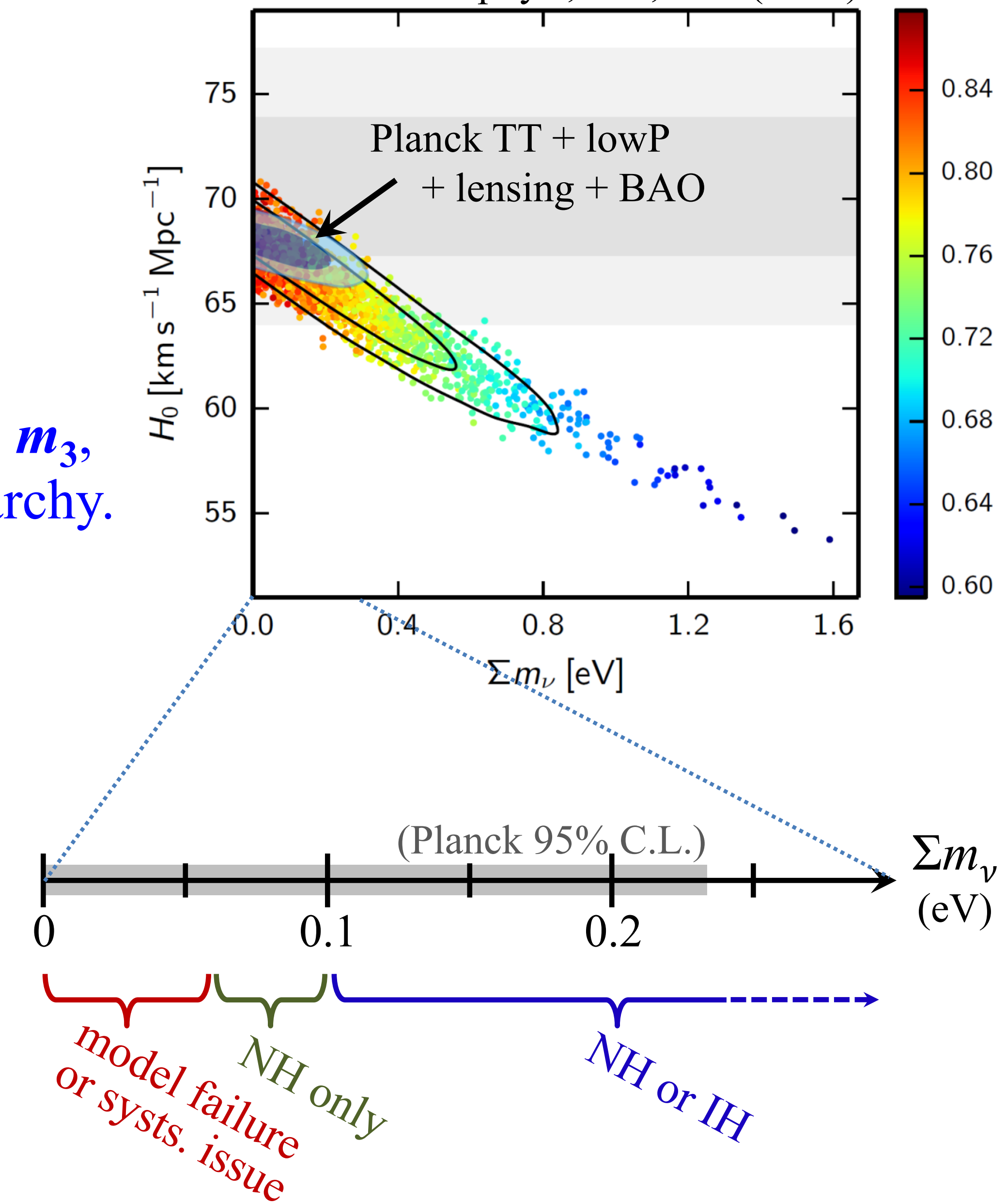
Mass hierarchy from cosmology?

Planck collaboration,
Astron. Astrophys., **594**, A13 (2016)

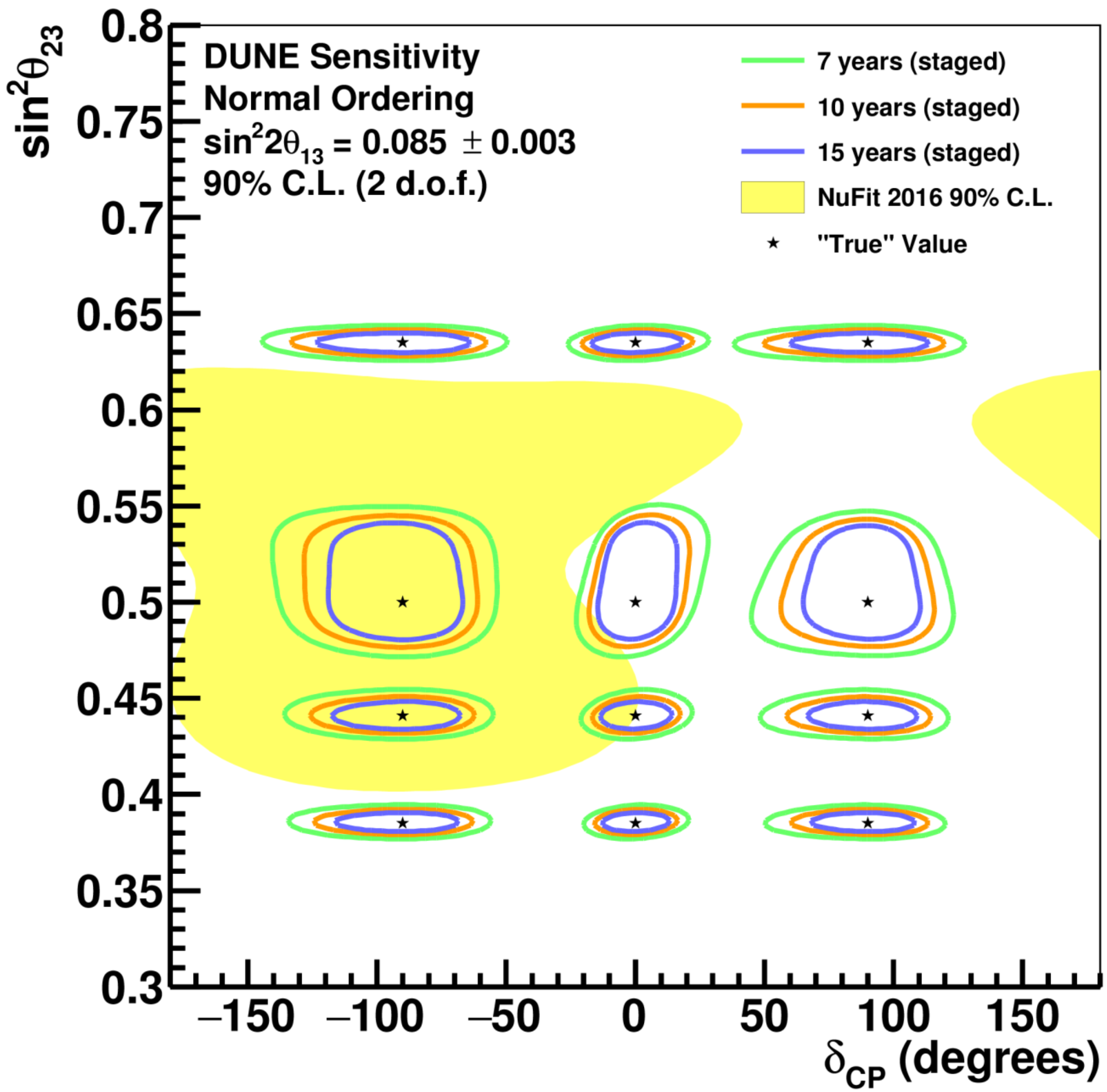
Multiple cosmological features (CMB, BAO, lensing, …) could carry imprints of **neutrino mass** **(Σm_ν)**

If nature has chosen **NH and $m_1 \ll m_3$**, then **Σm_ν** can reveal the mass hierarchy.

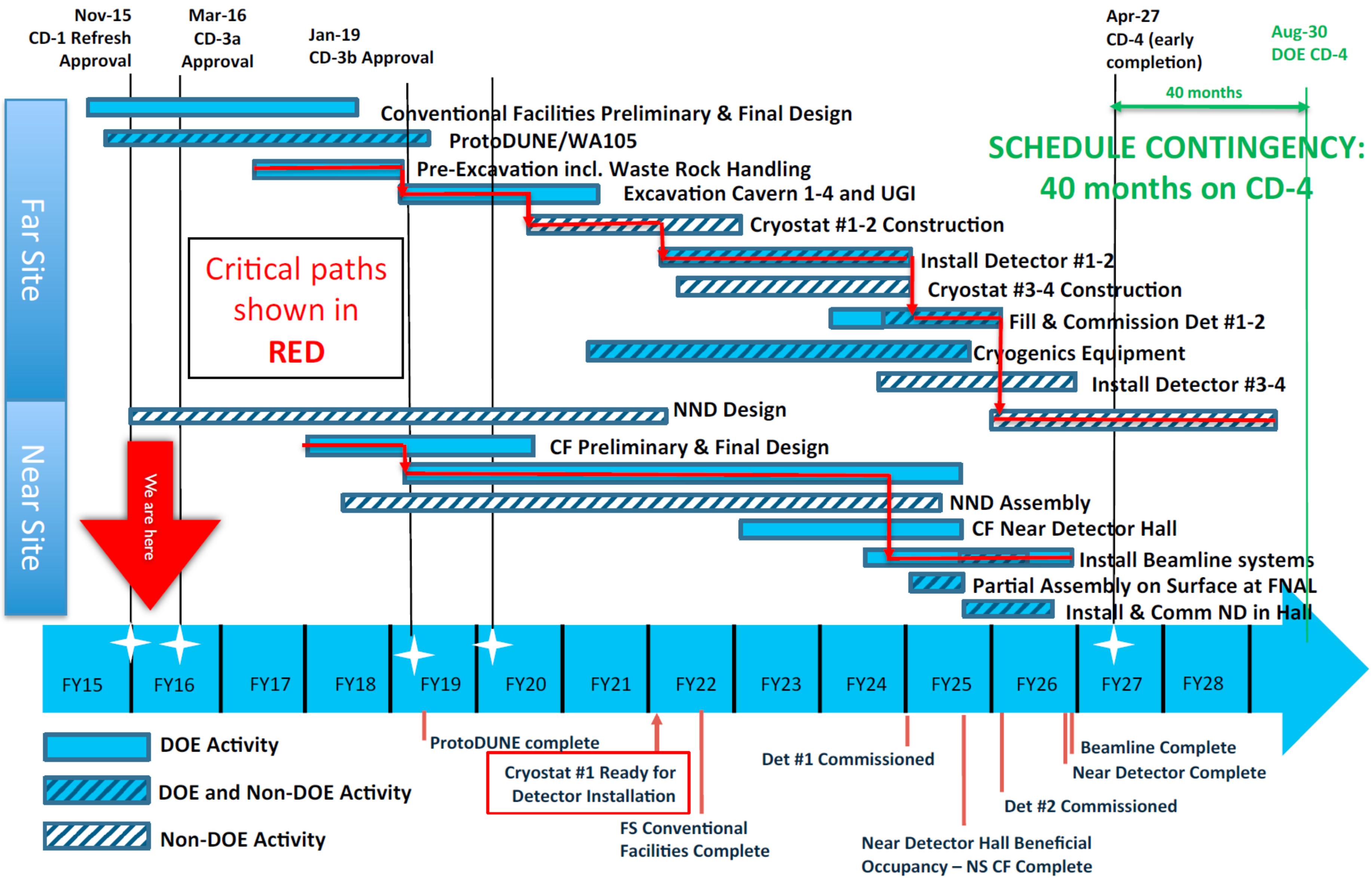
- *c.* 2025–2030 for 2–4σ



IH or $m_1 \gtrsim$ 20 meV precludes determining the mass hierarchy via Σm_ν.



DUNE Sensitivity
Normal Ordering
$\sin^2 2\theta_{13} = 0.085 \pm 0.003$
90% C.L. (2 d.o.f.)
7 years (staged)
10 years (staged)
15 years (staged)
NuFit 2016 90% C.L.
"True" Value
$\sin^2\theta_{23}$
0.8
0.75
0.7
0.65
0.6
0.55
0.5
0.45
0.4
0.35
0.3
−150
−100
−50
0
50
100
150
δ_{CP} (degrees)


Nov-15
CD-1 Refresh
Approval
Mar-16
CD-3a
Approval
Jan-19
CD-3b Approval
Apr-27
CD-4 (early
completion)
Aug-30
DOE CD-4
40 months
SCHEDULE CONTINGENCY:
40 months on CD-4
Far Site
Near Site
Critical paths
shown in
RED
We are here
Conventional Facilities Preliminary & Final Design
ProtoDUNE/WA105
Pre-Excavation incl. Waste Rock Handling
Excavation Cavern 1-4 and UGI
Cryostat #1-2 Construction
Install Detector #1-2
Cryostat #3-4 Construction
Fill & Commission Det #1-2
Cryogenics Equipment
Install Detector #3-4
NND Design
CF Preliminary & Final Design
NND Assembly
CF Near Detector Hall
Install Beamline systems
Partial Assembly on Surface at FNAL
Install & Comm ND in Hall
FY15
FY16
FY17
FY18
FY19
FY20
FY21
FY22
FY23
FY24
FY25
FY26
FY27
FY28
DOE Activity
DOE and Non-DOE Activity
Non-DOE Activity
ProtoDUNE complete
Cryostat #1 Ready for
Detector Installation
FS Conventional
Facilities Complete
Det #1 Commissioned
Near Detector Hall Beneficial
Occupancy – NS CF Complete
Det #2 Commissioned
Beamline Complete
Near Detector Complete

Staging Assumptions

Year 0 (2026): 20-kt FD with 1.07 MW (80-GeV) beam and initial ND constraints

Year 1 (2027): 30-kt FD

Year 3 (2029): 40-kt FD and improved ND constraints

Year 6 (2032): upgrade to 2.14 MW (80-GeV) beam (technically limited schedule)

Exposure (kt-MW-years)	Exposure (Years)
171	5
300	7
556	10
984	15