Neutrinos in DUNE: long-baseline oscillations and non-beam physics

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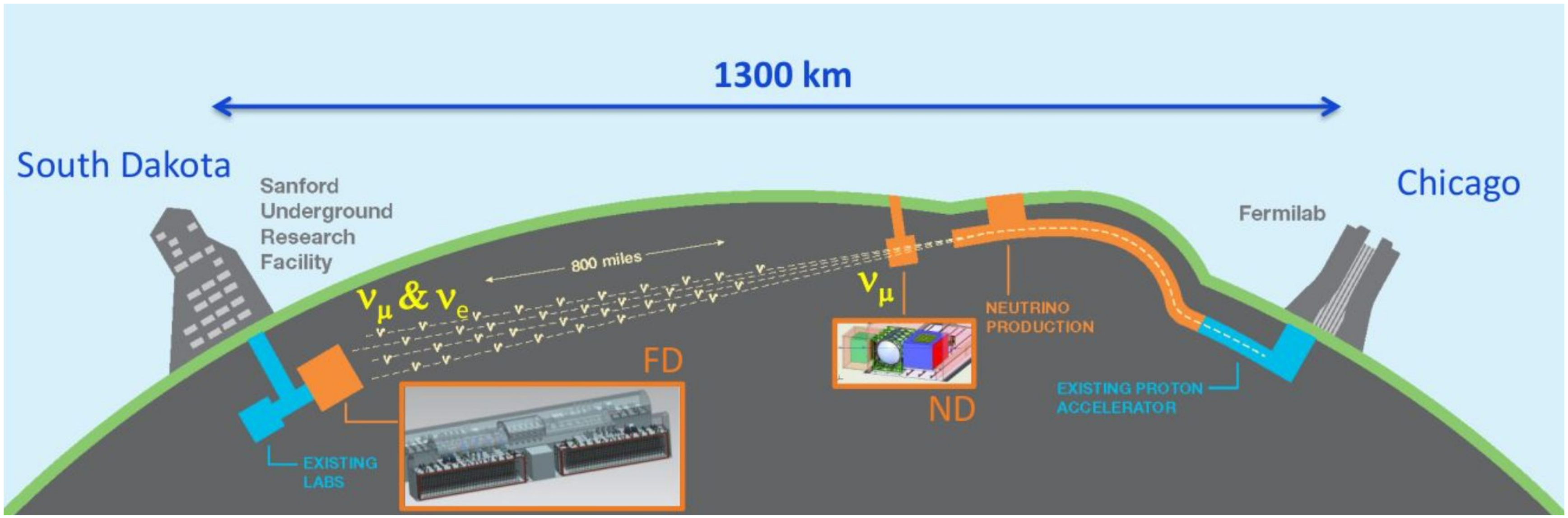
Outline

- Why neutrinos?
- DUNE: the concept
- Neutrino oscillations: the baseline
- DUNE's capabilities for neutrino oscillations physics
- Supernovae (SN): the baseline
- DUNE's capabilities for SN neutrinos physics
- Conclusions

DUNE mission and concept

- What is the origin of the matter-antimatter asymmetry in the universe?
- What are the fundamental underlying symmetries of the universe?
- Is there a Grand Unified Theory of the universe?
- How do supernovae explode? New physics from a neutrino burst?



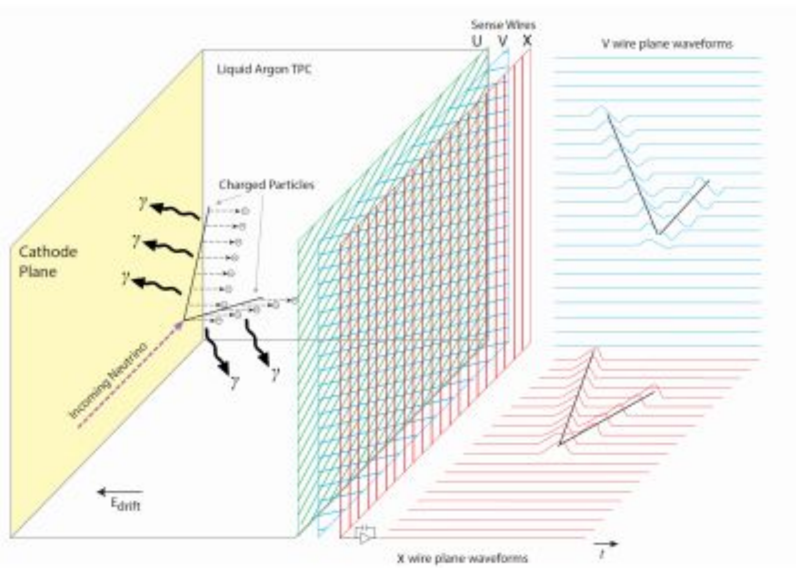
- ✔ New and very bright neutrino beam from Fermilab (LBNF)
- ✔ A highly capable Near Detector at Fermilab to measure the unoscillated neutrino (spectrum, flux and cross-sections constraints)
- ✔ A large LArTPC deep underground at SURF (Lead (SD) 1300 km baseline) to measure oscillations and non-beam physics
- ✔ Exposure of ~7 years to ν / $\bar{\nu}$ modes (50% / 50%)

DEEP UNDERGROUND NEUTRINO EXPERIMENT

1129 collaborators from 188 institutions in 34 countries

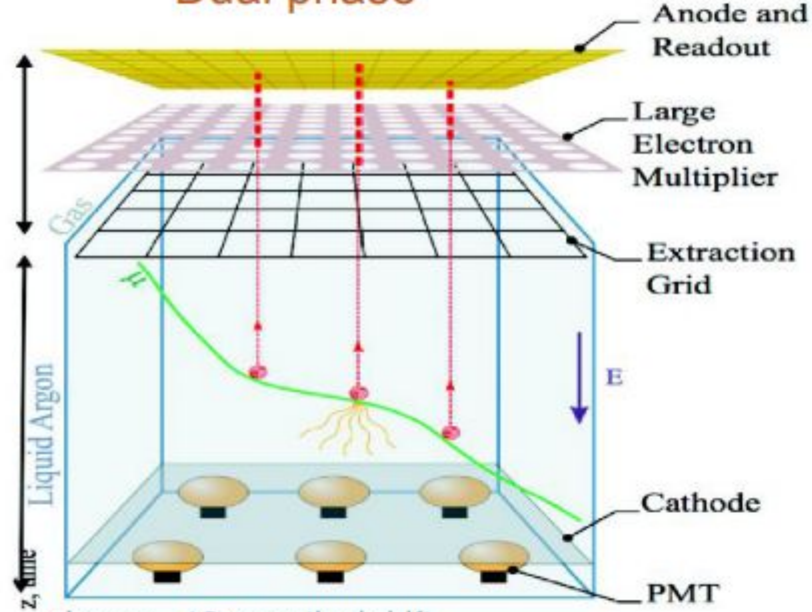
Far Detectors technologies

Single phase



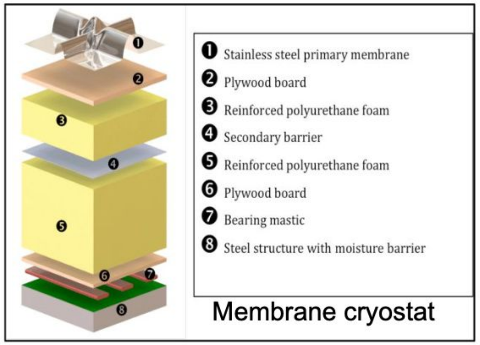
- Horizontal drift, 3.6 m drift distance
- Anode wires immersed in LAr
- Vertical Anode and Cathode Planes Assembles (APA, CPA)
- 1 collection + induction planes, rotated at ~37 degrees + 5 mm wire pitch
- Photon detectors: light guides + SiPMs in APAs → fast triggering light + calibration

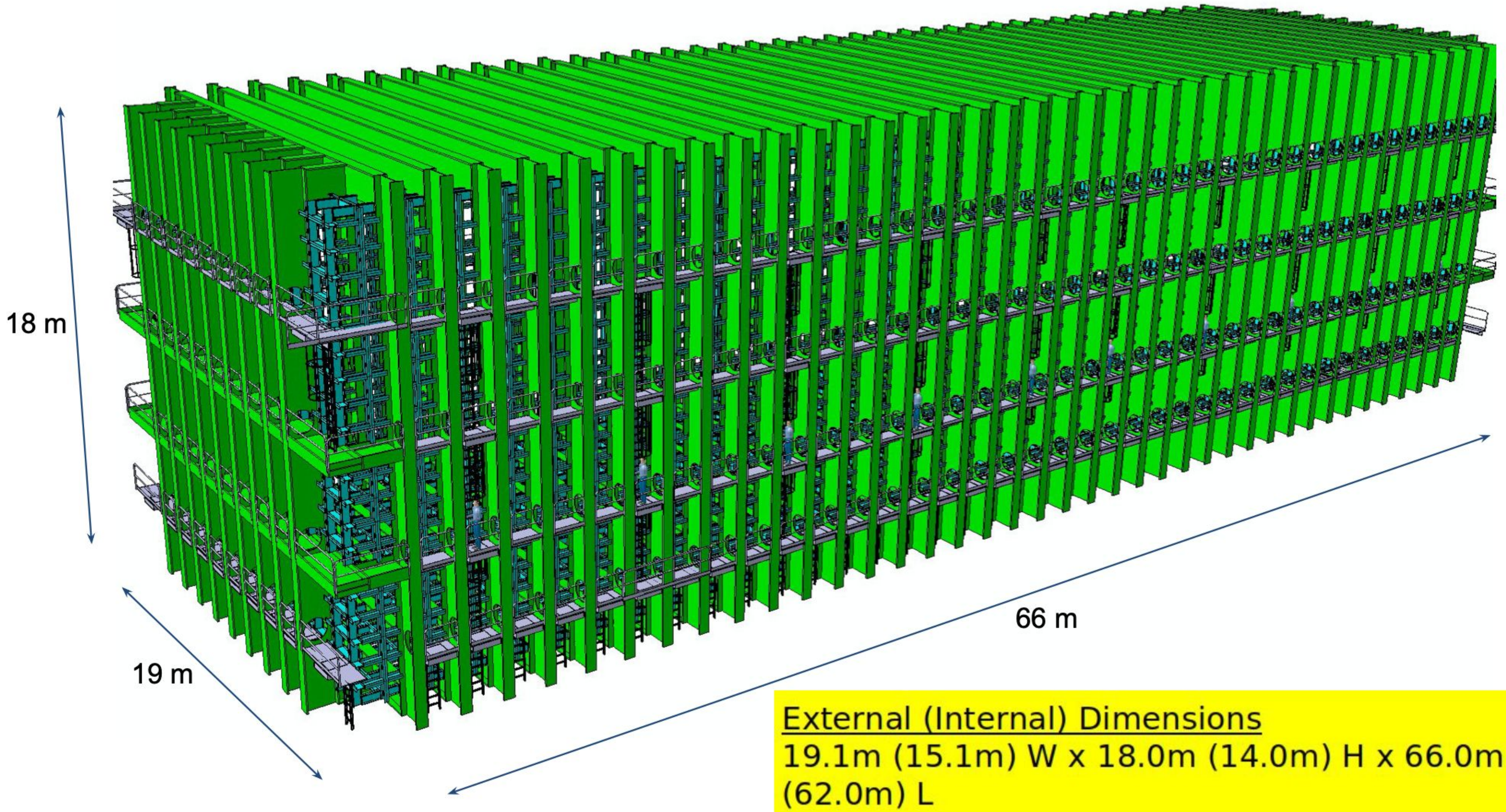
Dual phase



- Large ~12m vertical drift
- Ionisation extracted and further amplified in Gas
- LEM electron amplifier
- 1 collection + induction planes, rotated at calibration
- Possible better resolution but more detector off challenges
- Bottom PMTs for prompt light collection

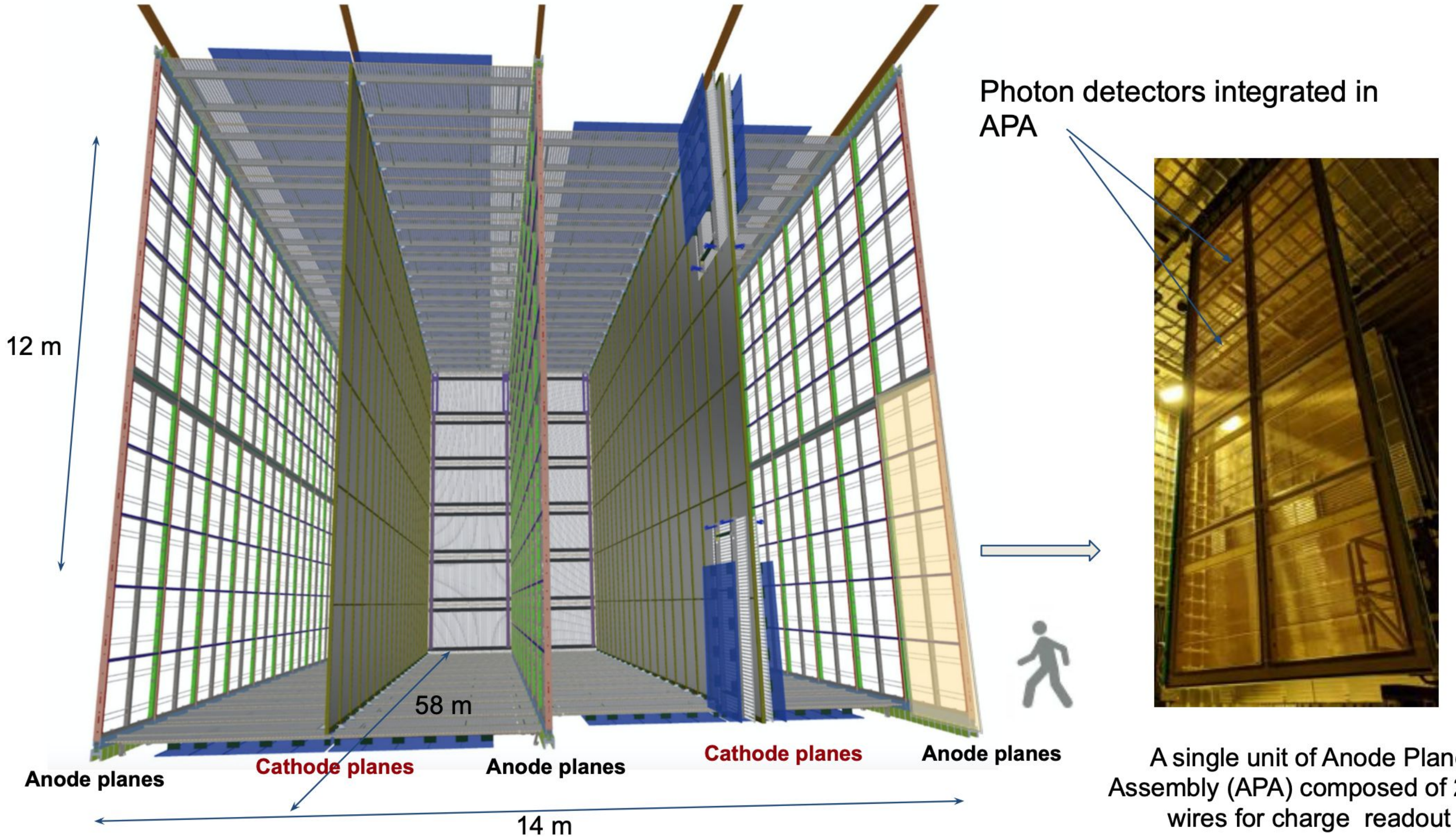
Free-Standing Steel Cryostat Design





External (Internal) Dimensions
19.1m (15.1m) W x 18.0m (14.0m) H x 66.0m (62.0m) L

DUNE: Far Detector - Single phase LArTPC

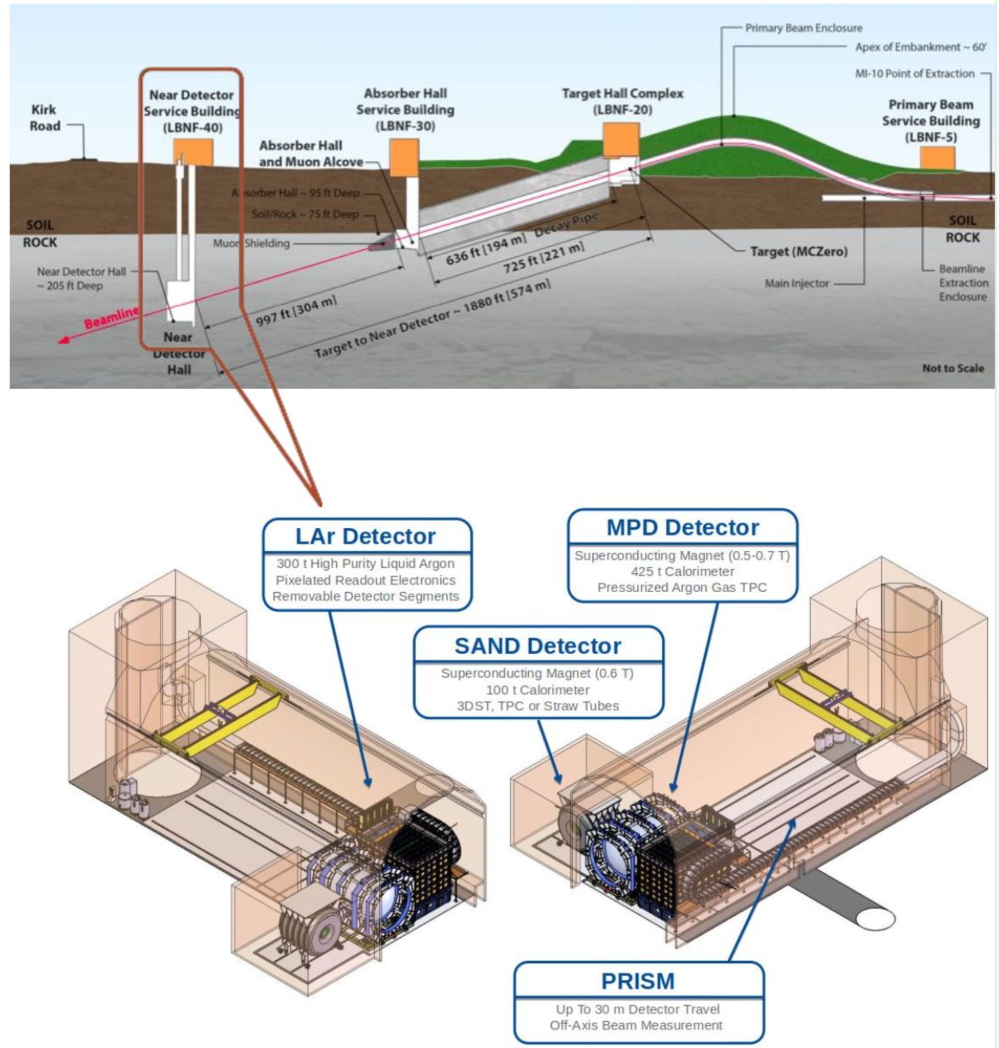


A single unit of Anode Plane Assembly (APA) composed of 2560 wires for charge readout

DUNE: ND at Fermilab

- DUNE ND design concept is an integrated system composed of four main components working together:

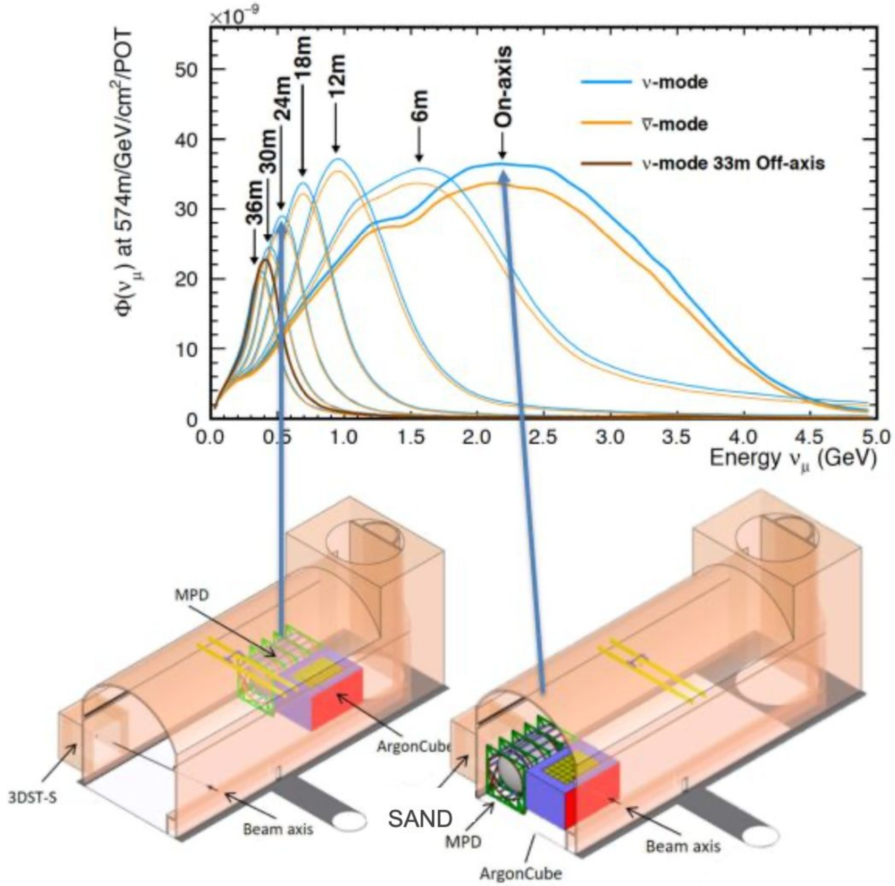
1) ArgonCube (LArTPC)
2) MPD (Multi Purpose Detector)
3) SAND (Beam Monitor)
4) DUNE-Prism (ArgonCube+MPD off-axis)



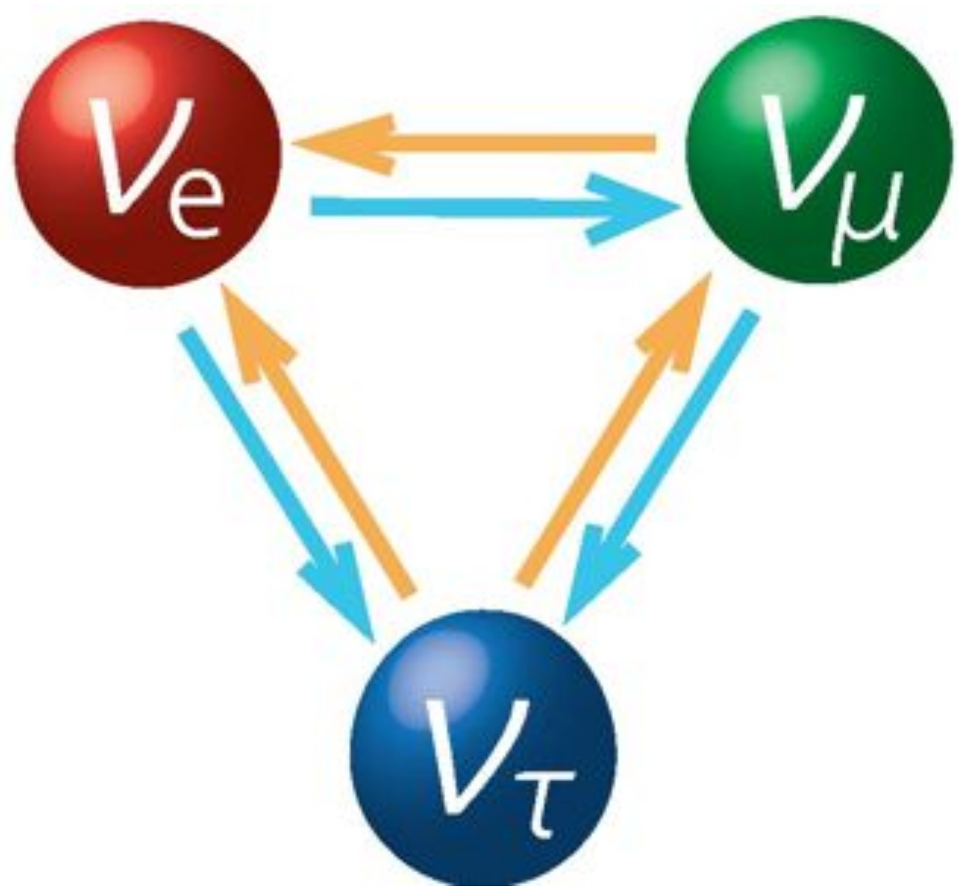
- Primary purpose is to constrain systematic uncertainty for long-baseline oscillation analysis
  - Constrain flux, cross-section, and detector uncertainties

DUNE: ND at Fermilab

- DUNE-PRISM:
  - ArgonCube and MPD move of axis to sample flux
    - 30m off axis proposed motion
    - Allows to deconvolve flux and cross section
- SAND does not move
  - Beam monitor for stability



DUNE: ν oscillation physics



ν's oscillations

Neutrino mixing:
Flavor eingenstates (interaction) don't coincide with mass eigenstates (propagation)

flavor (α = e, μ, τ) ⇔ linear combinations ⇔ mass (i = 1, 2, 3)

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle \quad \Longleftrightarrow \quad |\nu_i\rangle = \sum_\alpha U_{\alpha i} |\nu_\alpha\rangle$$

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \underbrace{\begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}}_{\text{Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix}} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}.$$

ν's oscillations

Mixing angles = (θ_{12}, θ_{23}, θ_{13}) , δ_{CP} is the CP-violation phase

$$U_{\mathrm{PMNS}} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\mathrm{I}} \underbrace{\begin{pmatrix} c_{13} & 0 & e^{i\delta_{\mathrm{CP}}} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{\mathrm{CP}}} s_{13} & 0 & c_{13} \end{pmatrix}}_{\mathrm{II}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\mathrm{III}}$$

atmospheric reactor solar

where: $c_{\alpha\beta} = \cos\theta_{\alpha\beta}$; $s_{\alpha\beta} = \sin\theta_{\alpha\beta}$

Nonzero δ_{CP} ⟹ neutrinos and antineutrinos oscillate different

ν's oscillations

- Standard Model:
  - allows CP-violation in weak interactions.
  - CPT are invariant.
- Under CPT: neutrino and antineutrino oscillations are equivalent
  - $P(\nu_l \rightarrow \nu_l) = P(\text{anti-}\nu_l \rightarrow \text{anti-}\nu_l)$ where $l = e, \mu, \tau$.
- CPT invariance was tested:
  - measurements of $\nu_\mu \rightarrow \nu_\mu$ and anti-$\nu_\mu \rightarrow$ anti-ν_μ survival probabilities,
    no evidence for CPT violation was found.
    MINOS Collaboration , Phys.Rev. D84 (2011) 071103
- Asymmetries in neutrino versus antineutrino oscillations arising from CP violation:
  - can only be accessed in appearance experiments!

ν's oscillations: δCP via disappearance

$$P(\nu_\mu \to \nu_e) \cong P(\nu_e \to \nu_\mu) \cong P_0 + \underbrace{P_{\sin\delta}}_{\text{CP violating}} + P_{\cos\delta} + P_3$$

$$P_0 = \sin^2\theta_{23}\frac{\sin^2 2\theta_{13}}{(A-1)^2}\sin^2[(A-1)\Delta],$$

$$P_3 = \alpha^2\cos^2\theta_{23}\frac{\sin^2 2\theta_{12}}{A^2}\sin^2(A\Delta),$$

changes sign: nu (-), anti-nu (+)

$$P_{\sin\delta} = \alpha\frac{8J_{cp}}{A(1-A)}\sin\Delta\sin(A\Delta)\sin[(1-A)\Delta],$$

CP conserving

$$P_{\cos\delta} = \alpha\frac{8J_{cp}\cot\delta_{\mathrm{CP}}}{A(1-A)}\cos\Delta\sin(A\Delta)\sin[(1-A)\Delta],$$

where:

$J_{CP}^{\mathrm{PMNS}} \equiv \frac{1}{8}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\cos\theta_{13}\sin\delta_{\mathrm{CP}}$; $\Delta = \Delta m^2_{31}L/4E$; $A = \sqrt{3}G_F N_e 2E/\Delta m^2_{31}$;

$\alpha \equiv |\Delta m^2_{21}|/|\Delta m^2_{31}|$

ν's oscillations

What we do know:

$$\left[|U_{e1}|^2 > |U_{e2}|^2 > |U_{e3}|^2\right]$$

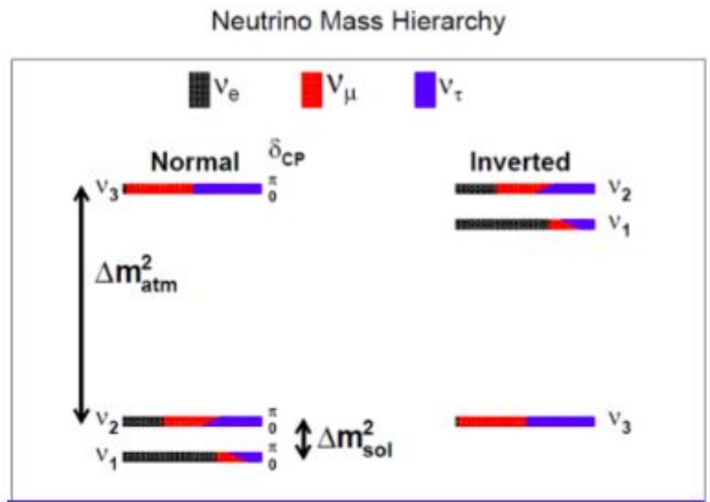
$$\Delta m^2_{\rm sol} \equiv \Delta m^2_{21} \simeq 7.5 \times 10^{-5}\ {\rm eV}^2$$
$$\Delta m^2_{\rm atm} \equiv |\Delta m^2_{32}| \simeq 2.5 \times 10^{-3}\ {\rm eV}^2$$

$$\sin^2\theta_{21} \simeq 0.31$$
$$\sin^2\theta_{23} \simeq 0.45\text{–}0.55$$
$$\sin^2\theta_{13} \simeq 0.02$$

ν's oscillations

What needs to be determined:

- Mass hierarchy / splitting:
  - sign of Δm_{32}^2
    - $\Delta m_{32} > \Delta m_{21}$ (NH) ?
    - $\Delta m_{32} < \Delta m_{21}$ (IH) ?



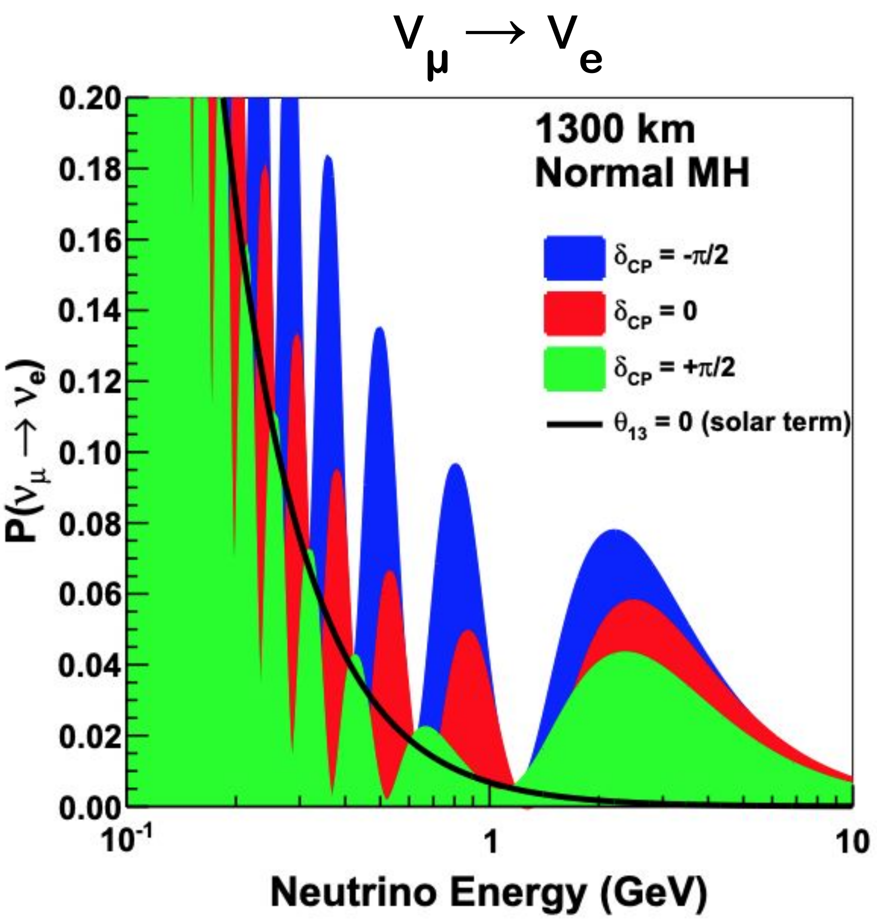
X. Qian & P. Vogel, arXiv:1505.01891

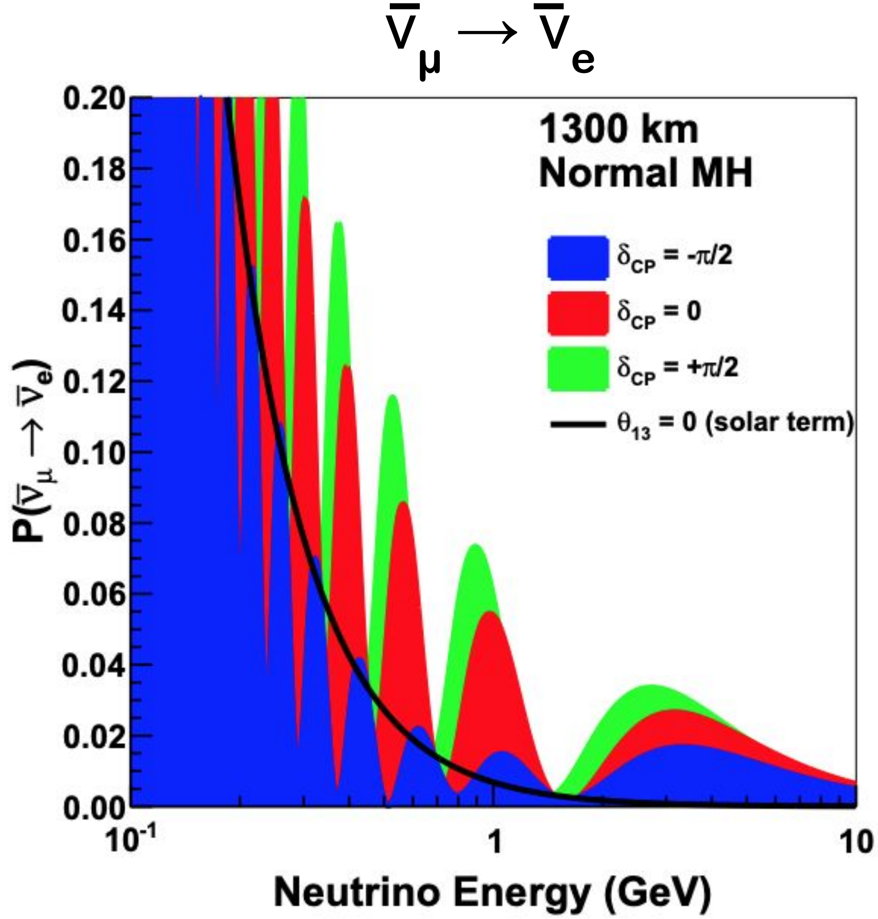
- θ_{23} octant:
  - dominant flavor in ν_3?

  if $\theta_{23} = 45^o \rightarrow$ symmetry,
  which constrains quark-lepton universality
- CP-violation?
  - Baryon Asymmetry @GUT scale can be related to low energy CP-violation in leptons.

    →observable in ν oscillations

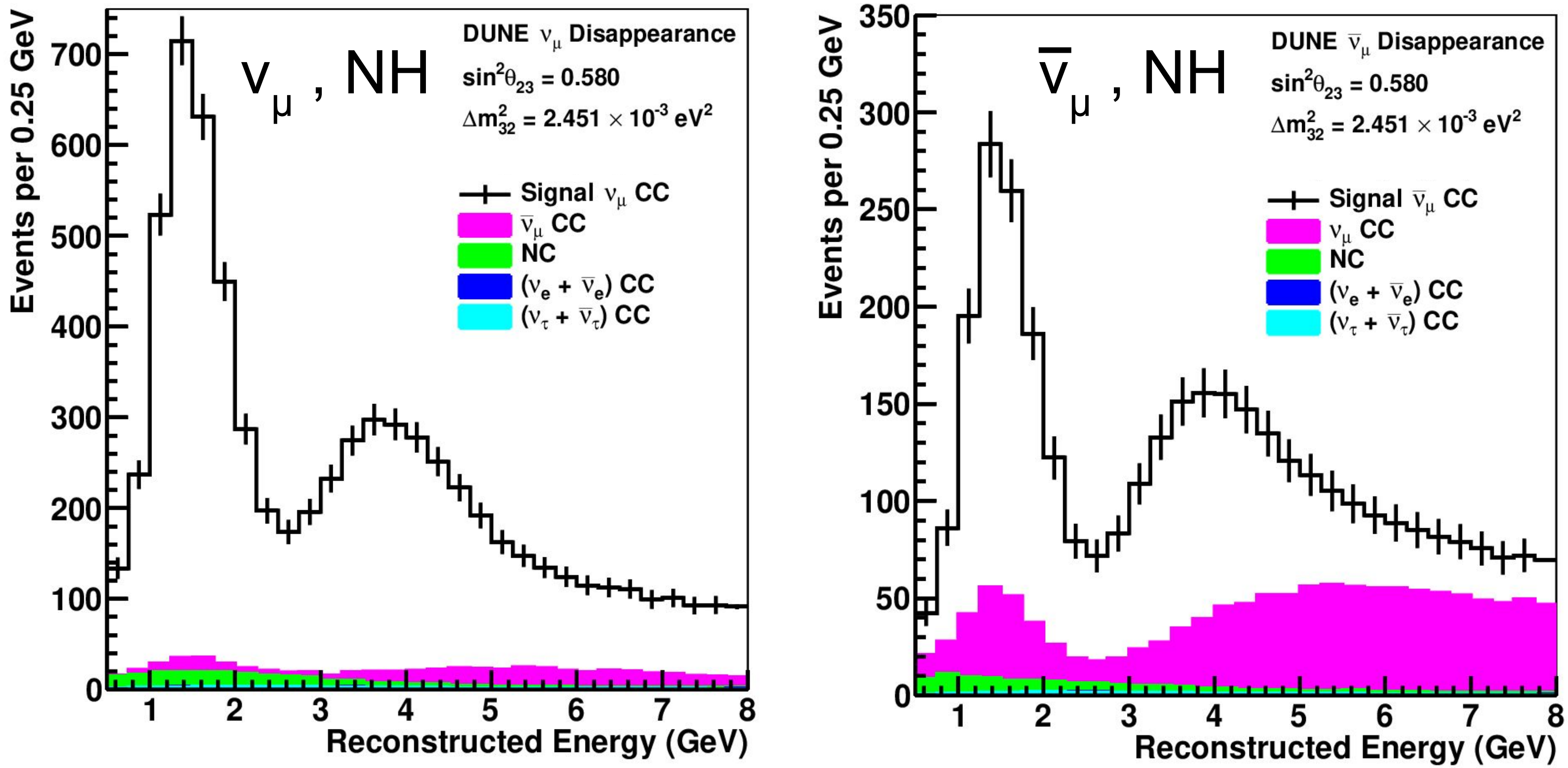
DUNE oscillation physics





DUNE sensitivity: *disappearance* spectra

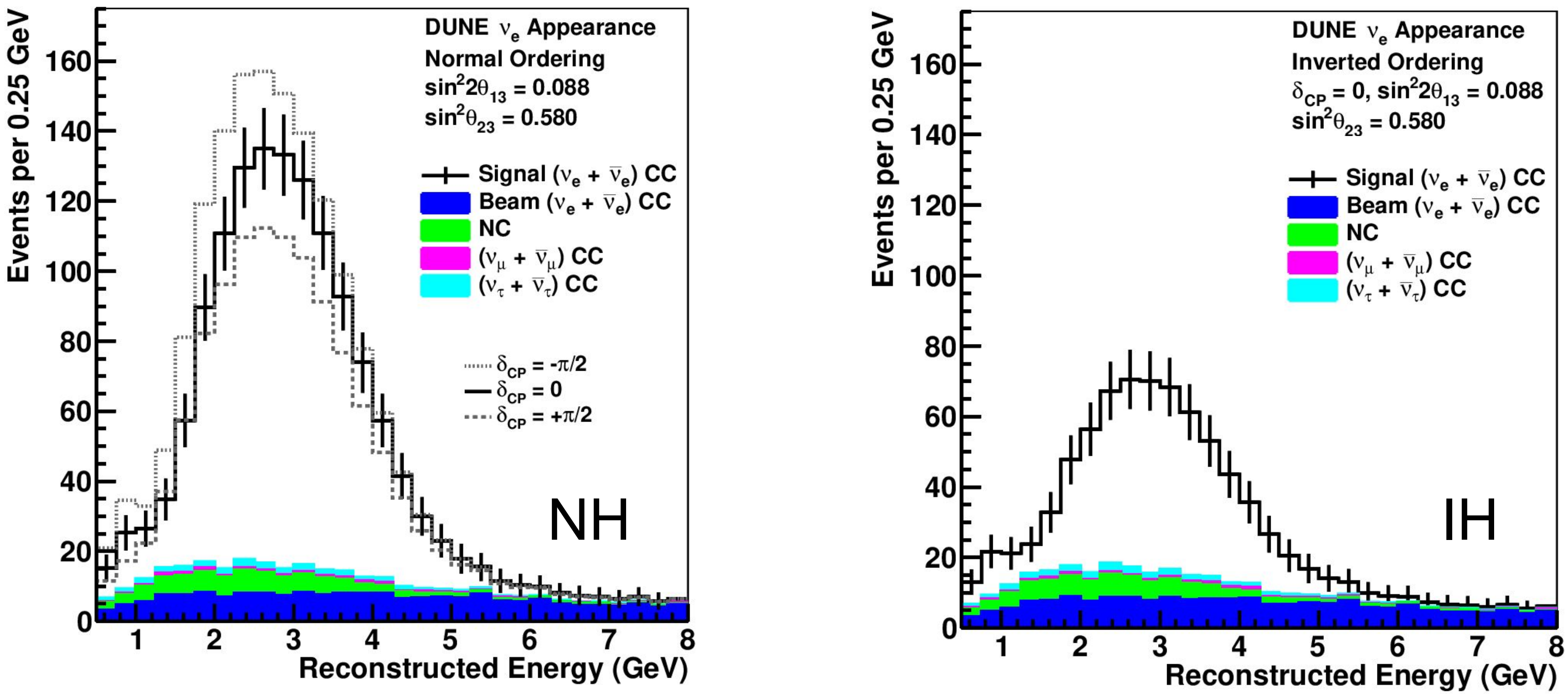
Reconstructed $\overset{(-)}{\nu}_\mu$ energy (CC-like events)



- DUNE Monte Carlo sim & reco chain
- exposure: 3.5 year

DUNE sensitivity: <u>*appearance*</u> spectra

Reconstructed ν_e energy (CC-like events)



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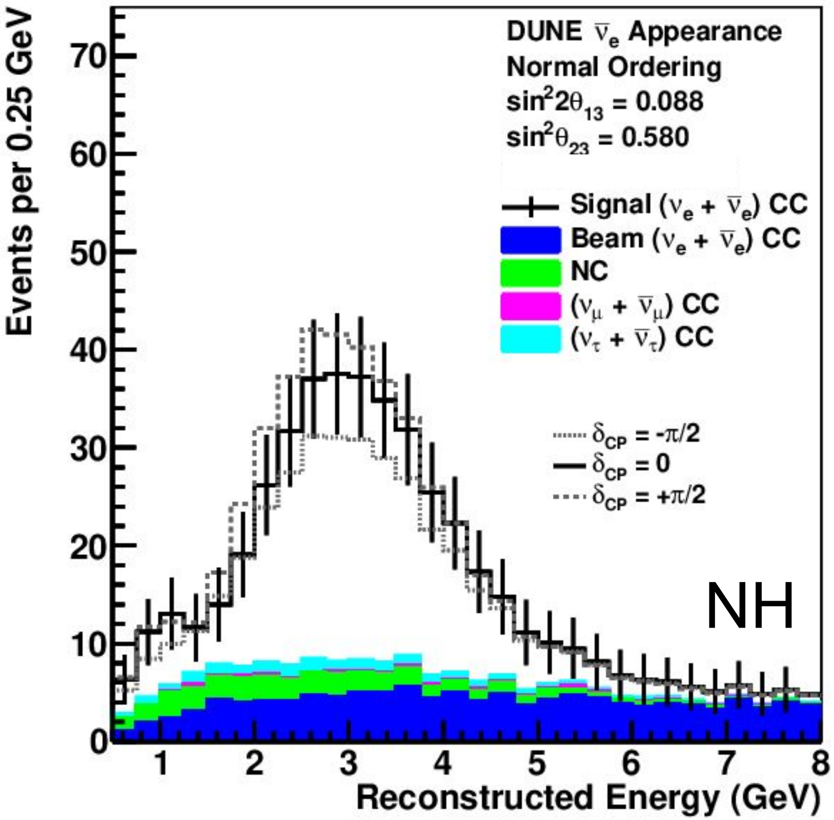
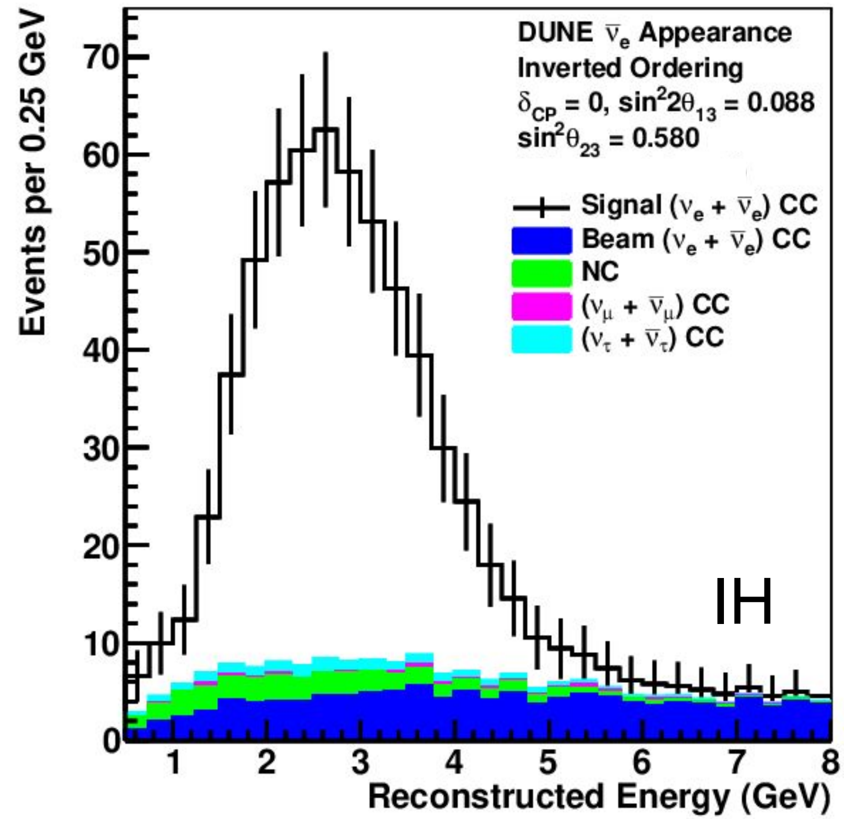
DUNE sensitivity: *appearance* spectra

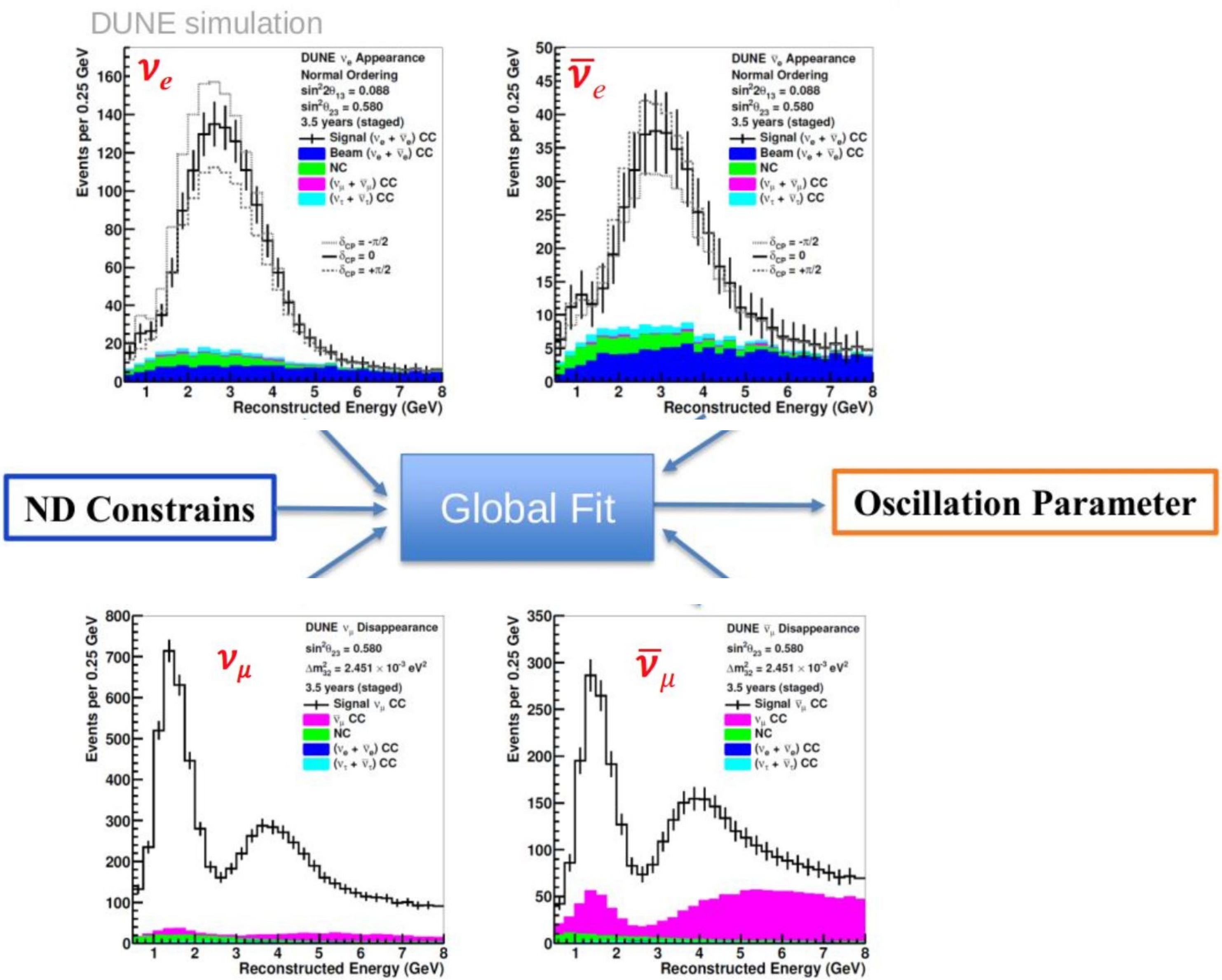
Reconstructed $\bar{\nu}_e$ energy (CC-like events)



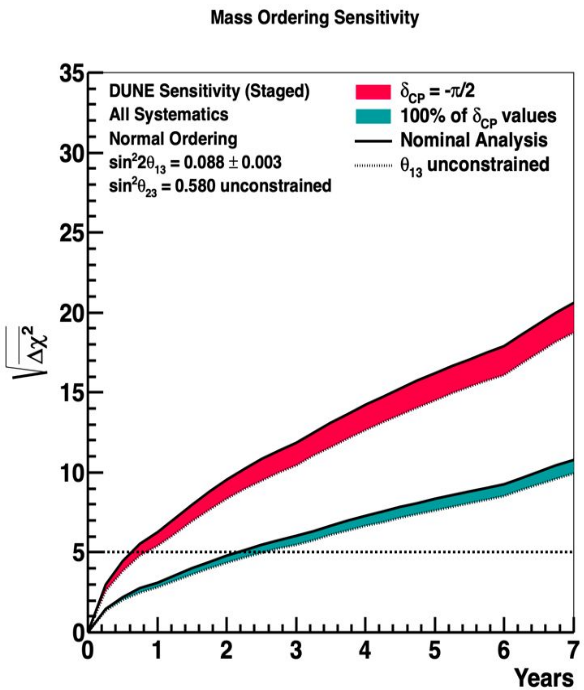


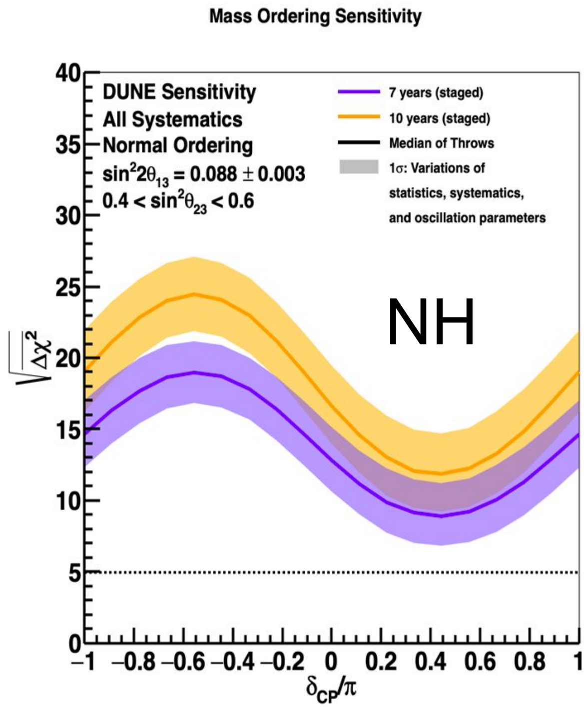
- **DUNE Monte Carlo sim & reco chain**
- **exposure: 3.5 year**

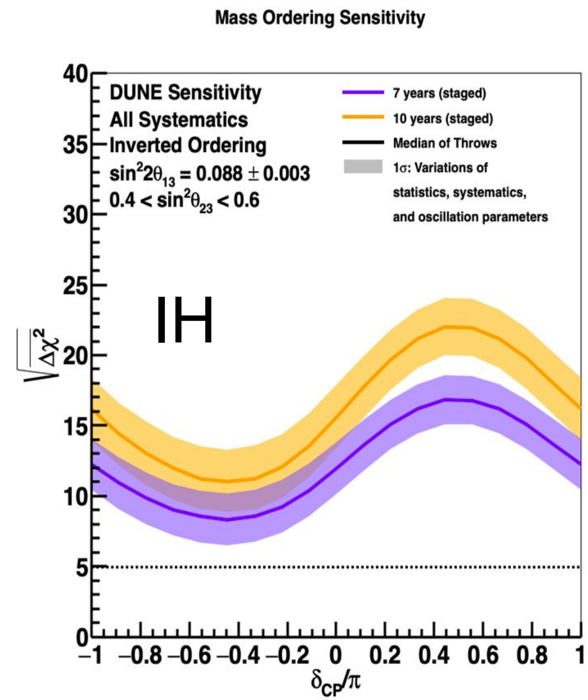
DUNE sensitivity: analysis strategy



DUNE sensitivity: Mass Hierarchy

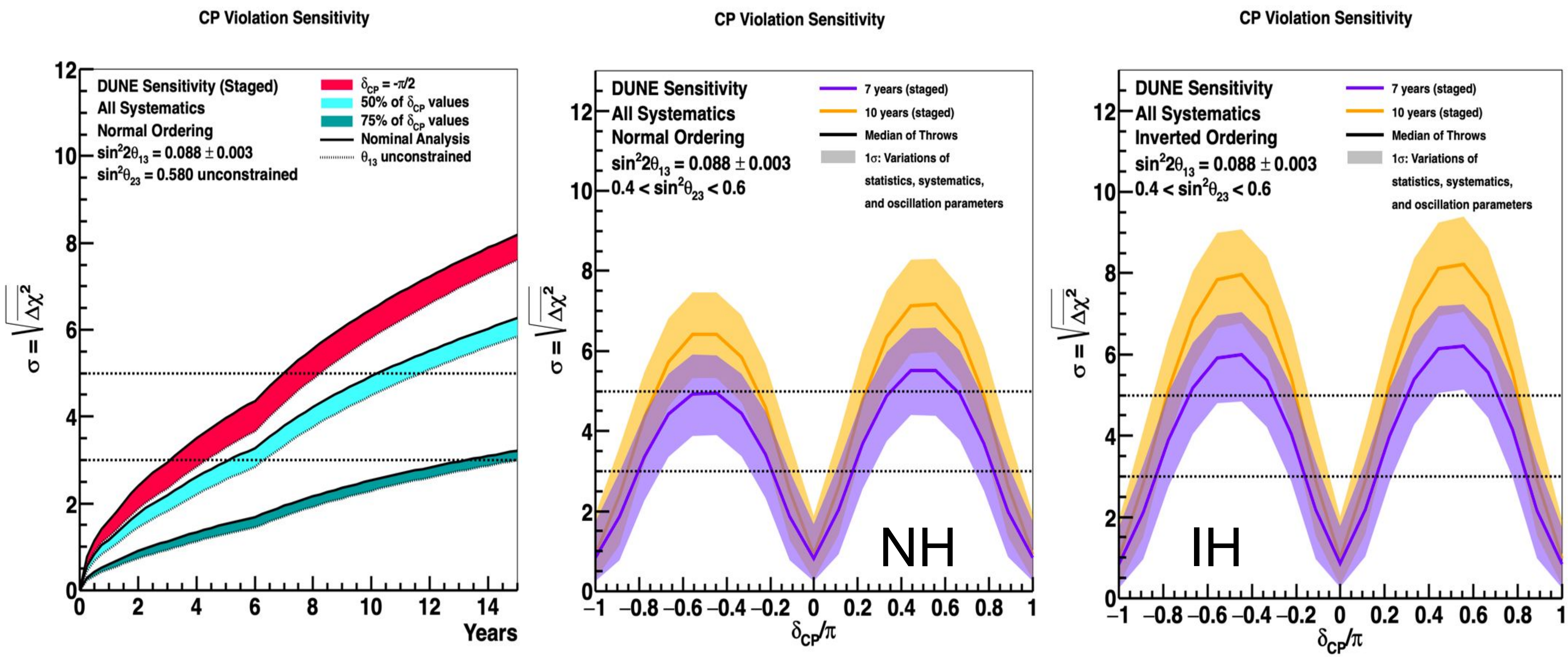






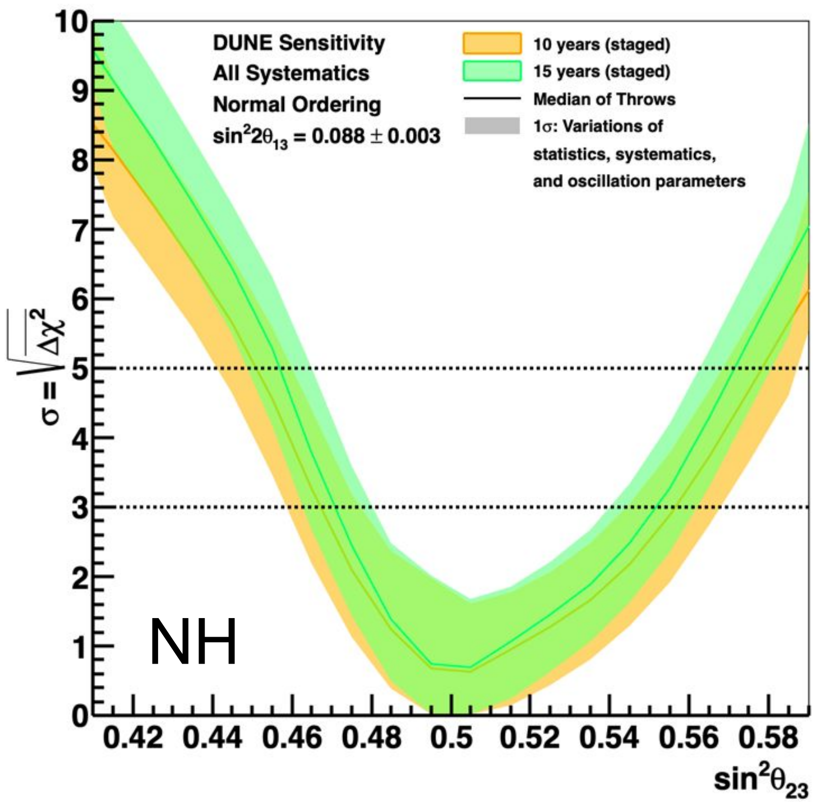
- DUNE will be able to establish the neutrino mass ordering in 2-3 year on 100% δ_{CP} values from the start of the data-taking

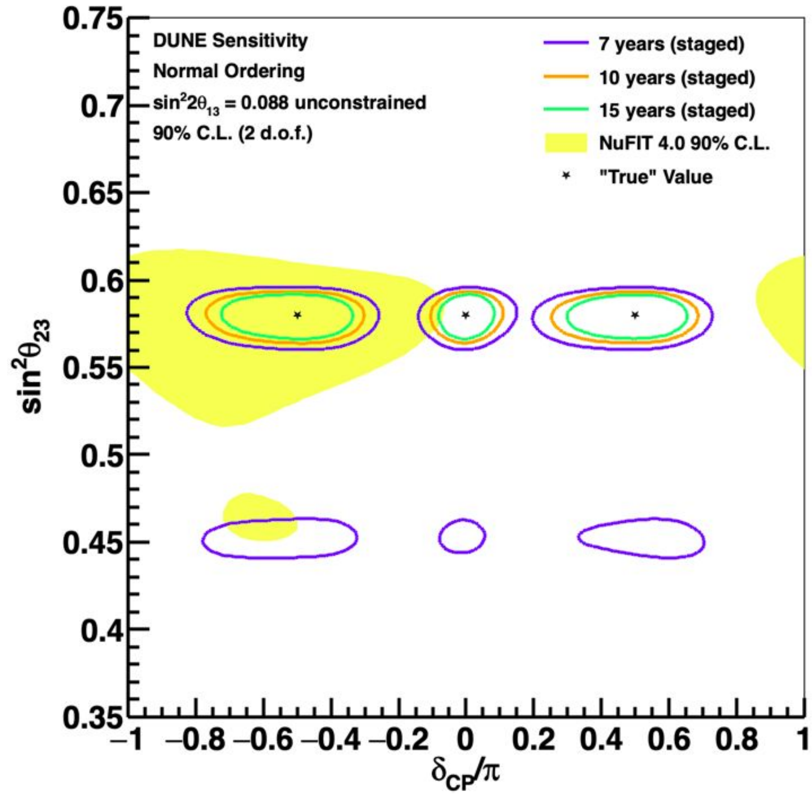
DUNE sensitivity: CP violation



- 5 sigma sensitivity is an ultimate goal for definitive discovery
- FD + ND detectors systematics

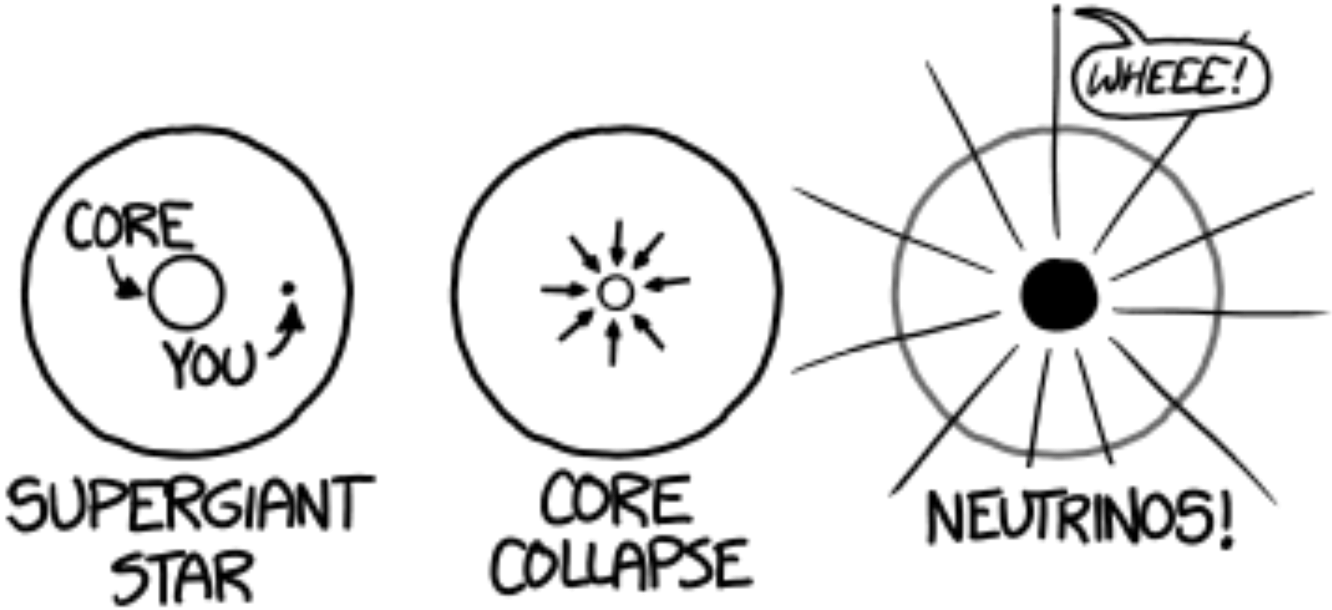
DUNE sensitivity: θ_{23} octant





- Non maximal mixing → Larger significance
- Longer exposure → degeneracy removal

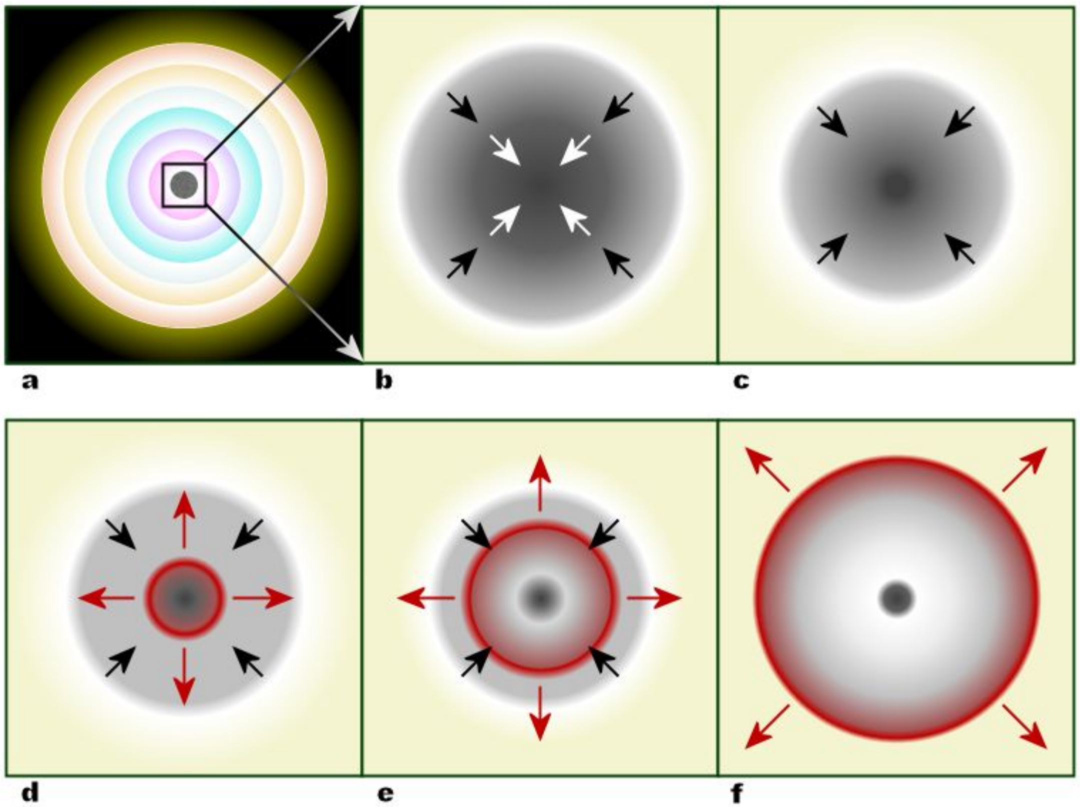
DUNE: SN vs detection



SN explosion* in one slide

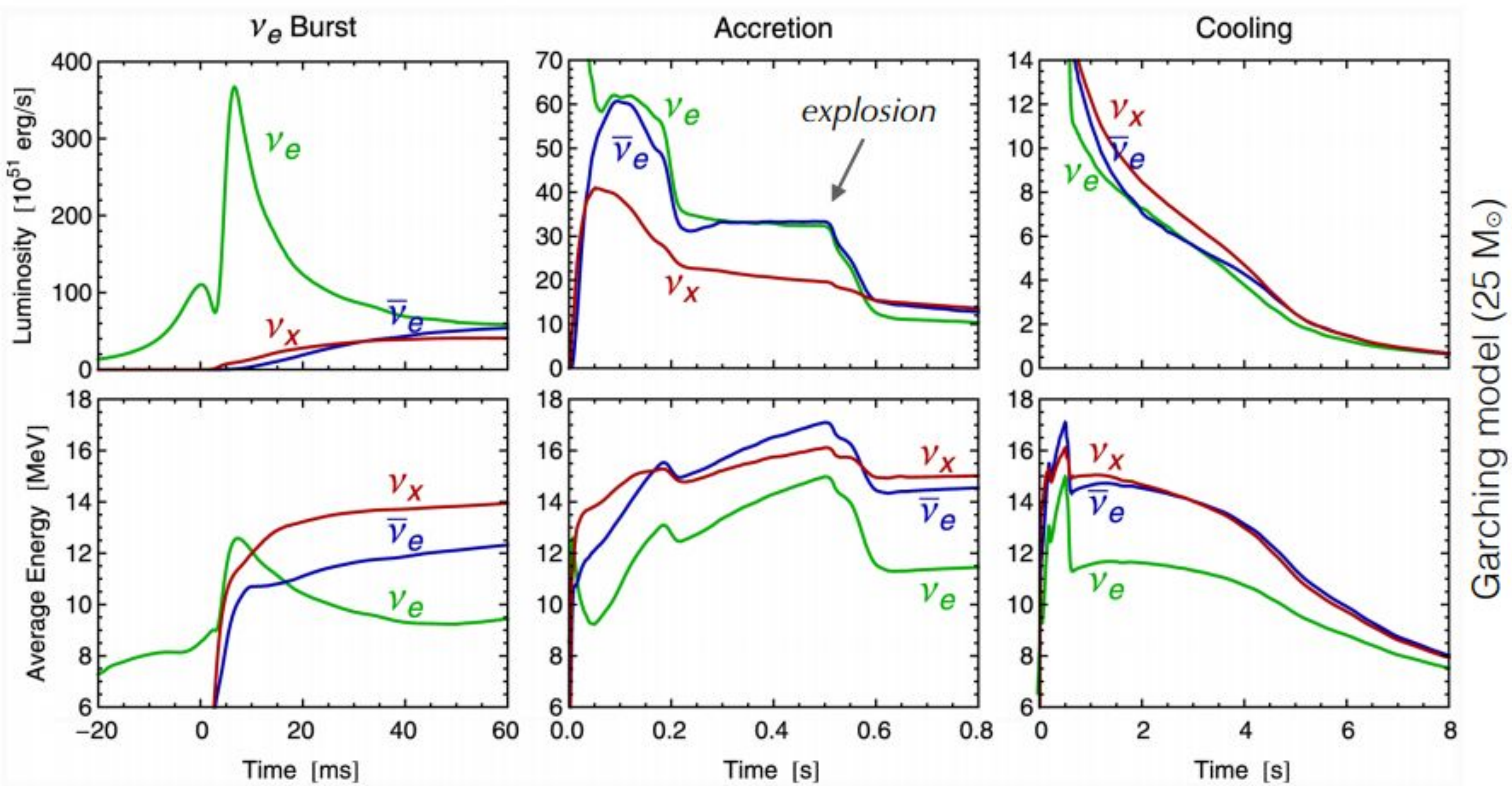
Within a massive, evolved star
(a) the onion-layered shells of elements undergo fusion, forming an iron core
(b) that reaches Chandrasekhar mass and starts to collapse.
(c) The inner part of the core is compressed into neutrons
(d) causing infalling material to bounce
(e) and form an outward propagating shock front (red). The shock starts to stall,
(f) but it is re-invigorated by neutrino interaction. The surrounding material is blasted away leaving only a degenerate remnant.

* Type-II from gravitational collapse



3 phases of SN ν emmission

slide from
Amanda Weinstein



Neutronization burst

- Shock breakout
- De-leptonization of outer core layers

Accretion phase

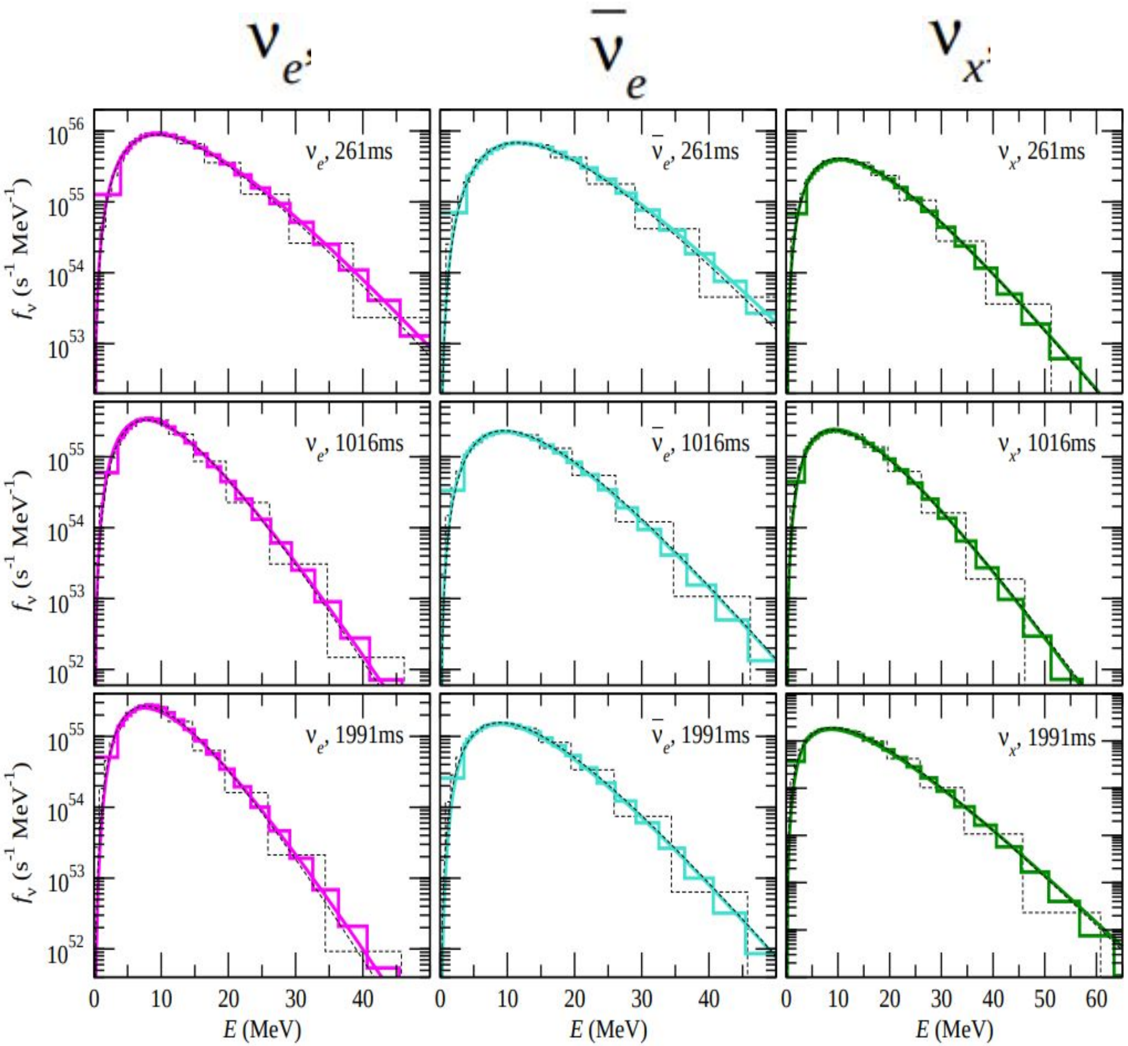
- Shock stalls ~150 km
- Neutrinos powered by infalling matter

Cooling phase

- Cooling on neutrino diffusion time scale

SN ν spectral features

I. Tamborra et al., arXiv:1211.3920v2



quasi-thermal distribution

$$f_\nu(E) \propto E^\alpha \, e^{-(\alpha+1)E/E_{\rm av}} \,.$$

E_{av}: average energy

$$\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_x} \rangle$$

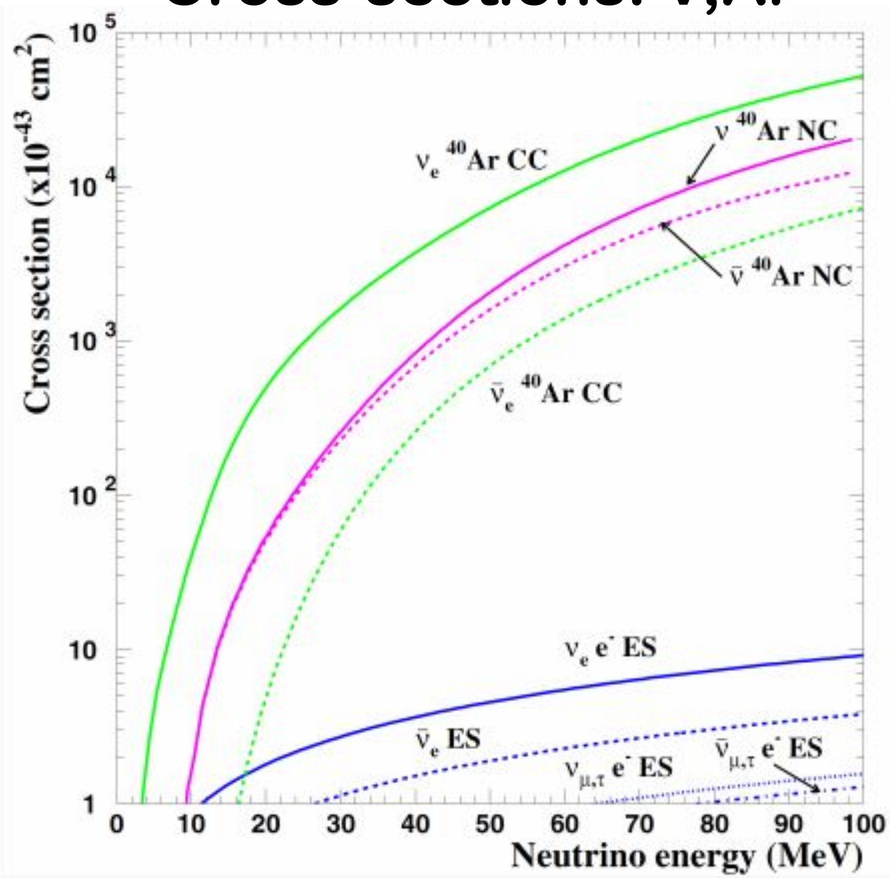
$E_{av} \propto T_\nu$
(ν-sphere temperature)

α : pinching parameter (deviations from thermal spectrum)

DUNE: SN ν signal

slide from
Ines Gil-Botella

Cross-sections: ν,Ar



- Elastic scattering (ES) on electrons

$$\boxed{\nu + e^- \rightarrow \nu + e^-}$$

- Charged-current (CC) interactions on Ar

$$\nu_e + {}^{40}Ar \rightarrow {}^{40}K^* + e^- \qquad E\nu_e > 4.0\text{ MeV}$$

$$\bar{\nu}_e + {}^{40}Ar \rightarrow {}^{40}Cl^* + e^+ \qquad E\bar{\nu}_e > 7.48\text{ MeV}$$

- Neutral current (NC) interactions on Ar

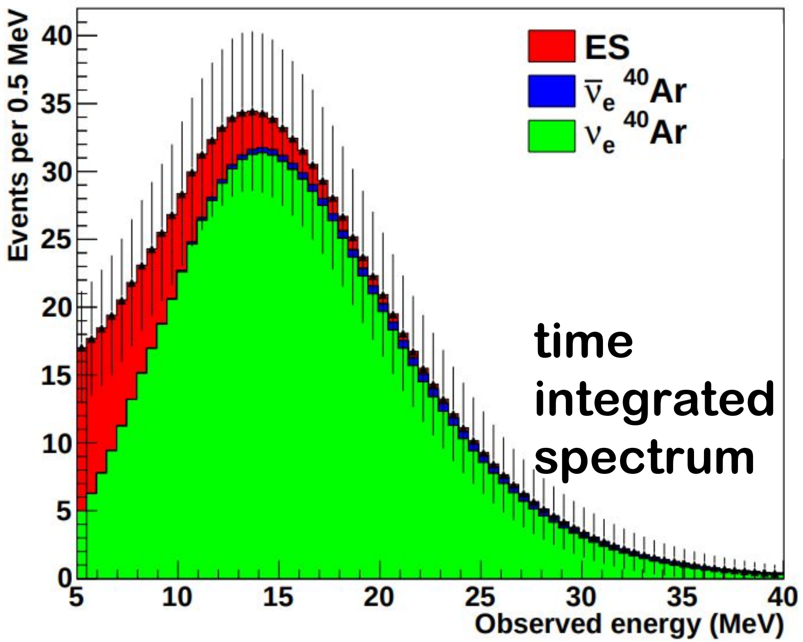
$$\nu + {}^{40}Ar \rightarrow \nu + {}^{40}Ar^* \qquad E\nu > 1.46\text{ MeV}$$

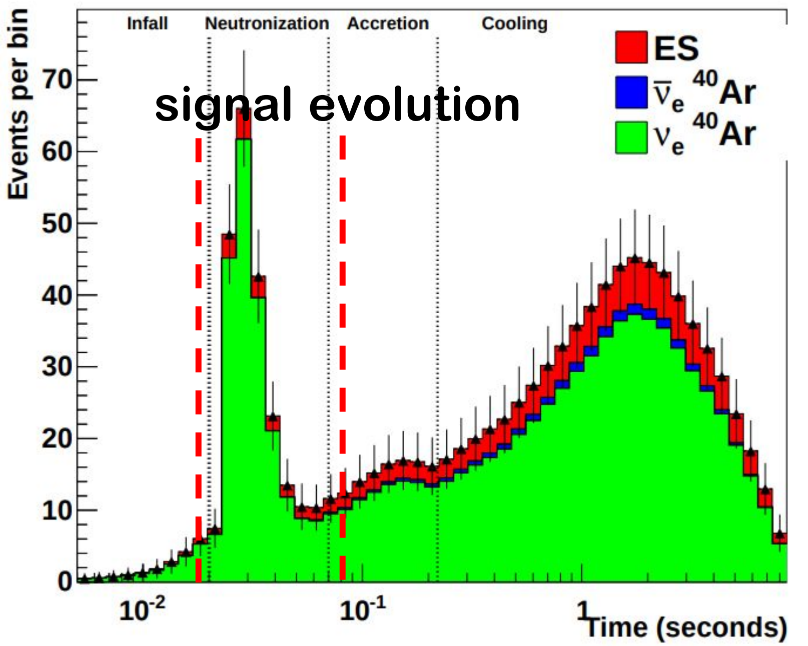
Possibility to separate the different channels by a classification of the associated photons from the K, Cl or Ar de-excitation (specific spectral lines for CC and NC) or by the absence of photons (ES)

UNICAMP

DUNE:
SN ν rates and spectrum

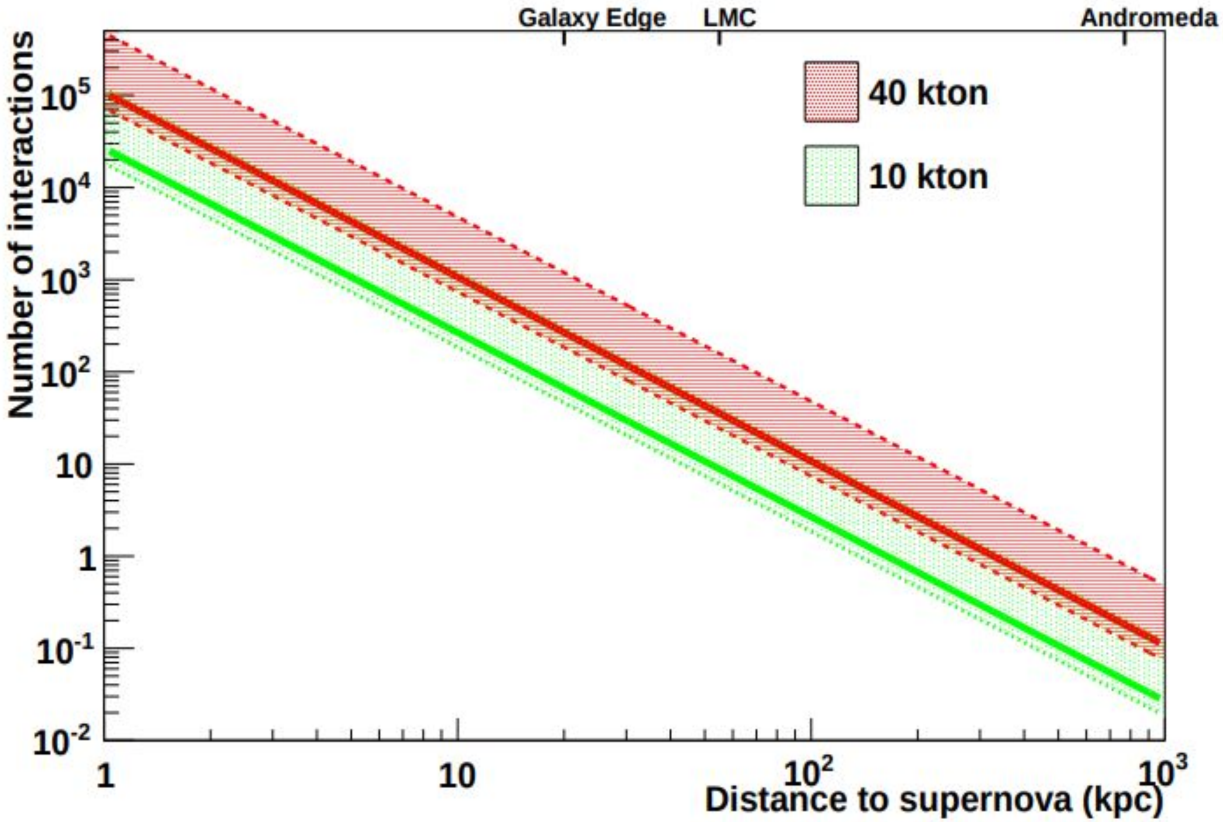
- Other experiments rely on $\bar{\nu}_e$ capture via inverse β-decay
    - complementarity
- DUNE will be able to observe the ν_e flux through capture on Ar40
- Unique sensitivity to the electron flavor component of the flux
- Provides information on time, energy and flavor structure





DUNE: Supernova Detection

- Requires an efficient non-beam trigger
- Rates depend on core collapse model, ν oscillation models, and distance.
- Expect > 3000 events from a supernova at 10 kpc



Supernova ν oscillation effects

- Different oscillation physics in neutrinos propagation from the stellar core to Earth

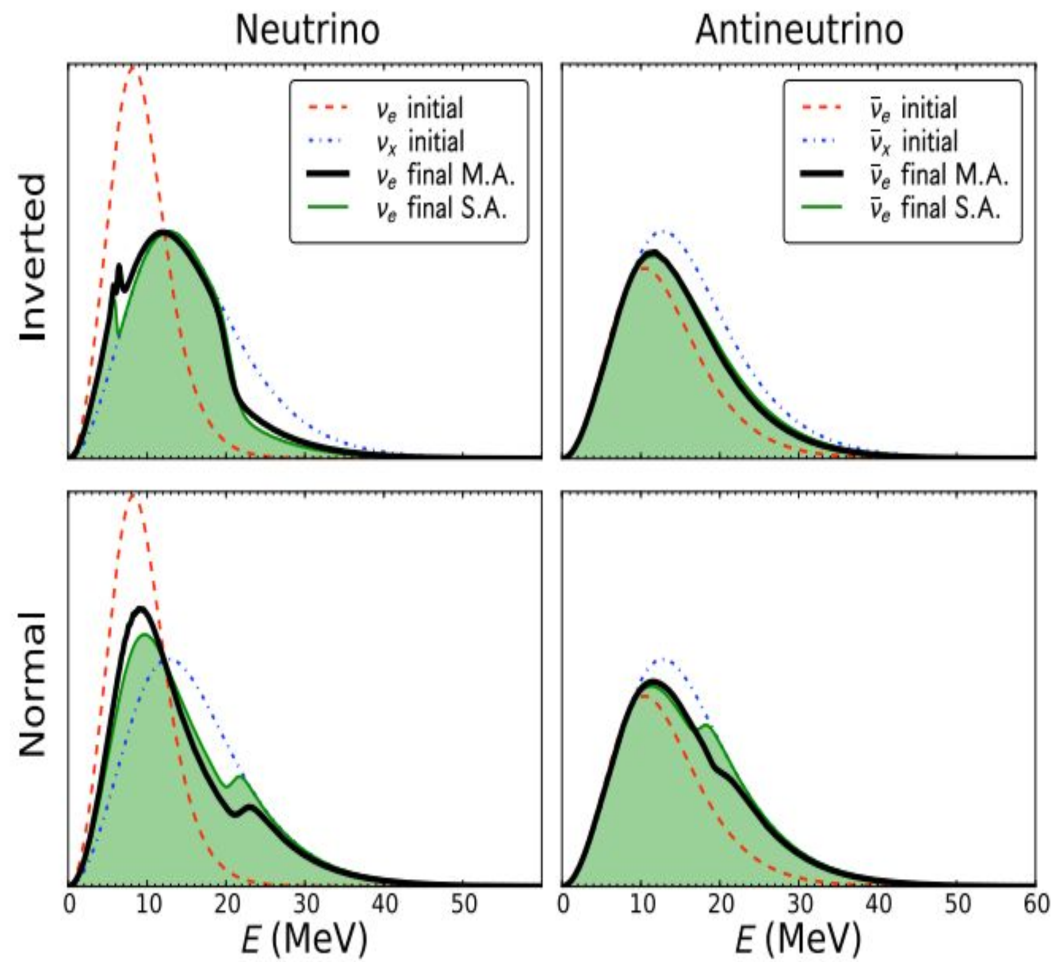
- Collective effects:
  r < 200 km
- MSW effects :
  r > 200 km

A. Dighe, A. Smirnov
Phys.Rev. D62 (2000) 033007

- Vacuum oscillations:
  from SN to Earth labs

- Flavor-specific burst evolution carries information about mass ordering and SN processes

- Key requirements:
  - Energy resolution <10%
  - Energy threshold ~ 5 MeV



Duan & Friedland, Phys. Rev. Lett. 106 (2011) 091101

Collective effects imprints

DUNE: Baryon Number violation

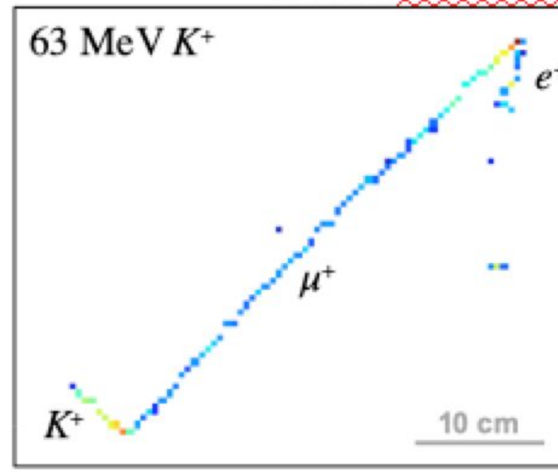
slide from
Ryan Patterson

Many avenues for searches

- **Baryon number violation**
  General feature of GUTs. Rich model space.
  Many search modes being explored in DUNE.

Updated simulation/reconstruction/analysis:
More details and more channels in TDR

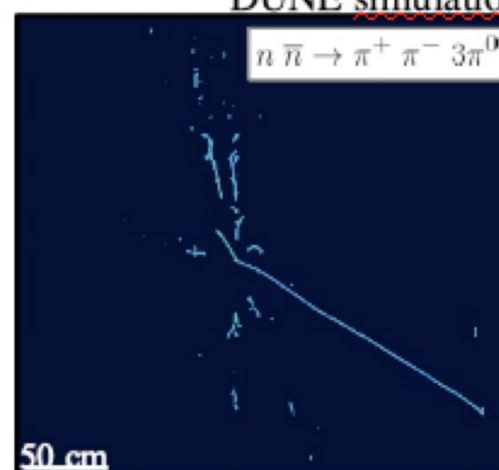
DUNE simulation



$p \to K^+ \nu$ Tracking and dE/dx for rejection of ν_μ CC background ($p + \mu$ final state)

~0.5 bkgnd at 400 kt-yr, 30% signal efficiency
If no signal: $\tau/B > 1.3\ 10^{34}$ yr (90% C.L.)

DUNE simulation



n-$\bar{n}$ osc. Spherical spray of hadrons with $E \approx 2M_n$ and net momentum □ $p_F \sim 300$ MeV

Free-neutron-equivalent sensitivity:
$\tau_{free,osc} > 5.5\ 10^8$ s (90% C.L.)

DUNE: multi-topic physics list

Intense and wide beam + complex detectors + different baselines (off-axis) + large exposure + deep underground lab

⇩

Rich physics program, including non-beam physics

- Baryon number violation
  - Nucleon decay
  - $n\bar{n}$ oscillations
- Light dark-matter
- Sterile neutrinos
- Non-standard interactions, non-unitary mixing
- CPT violation (?) in oscillations

DUNE: timeline

2018
ProtoDUNEs at CERN

2019
Technical Design Report

2019
Far Site Primary Excavation Begins

2022
First Module Installation Begins

2026
Neutrino Beam Available

June-2018
ProtoDUNE-SP installation completed

Aug-2018
ProtoDUNE-SP LAr filling

Sep-Nov 2018
ProtoDUNE-SP test beam

Fall 2019
ProtoDUNE-DP installation completed

Physics data as soon 1st module complete

Atmospherics,SNB and solar neutrinos, Baryon number violation, Detector calibration

Conclusions

- DUNE will have: MW neutrino beam, 40kt LArTPC deep underground, flux and beam contamination uncertainties under control (highly-capable fine-grained ND).
- Aim to solve neutrino mass hierarchy and CP-violating phase via oscillation measurement.
- High capability for neutrino physics and SN astrophysics studies
- Rich non-beam physics topics: supernova astrophysics, ν interactions physics, baryon number violation, and more

Future is promising !!

Thank you!

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The End

Special credits for DUNE colleagues (comments and slides inspiration):
Bob Svoboda, Alessandra Tonazzo, Diego Gratiere, Inés Gil-Botella, Amanda Weinstein, Serhan Tufanli, Ryan Patterson

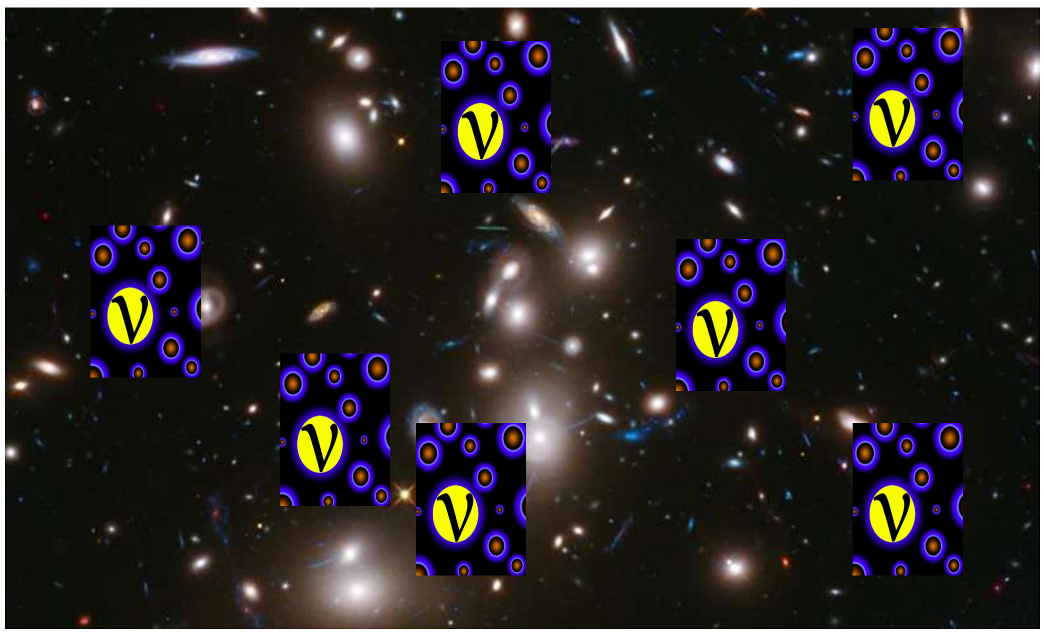
Main Content:
Deep Underground Neutrino Experiment (DUNE), Far Detector Technical Design Report, Volume II DUNE Physics. arXiv:2002.03005

BACKUP

Why Neutrinos? ... some interesting facts

- **Neutrinos are super abundant.**
  - Neutrinos are the second most abundant particle in the universe.
    - THE MOST ABUNDANT FERMION.
  - If we were to take a snapshot, we'd see that every cubic centimeter has approximately 1,000 photons and 300 neutrinos.
  - The nuclear fusion reactions in the Sun sends 65 billion neutrinos per second per square centimeter to Earth, they are crossing us all the time.

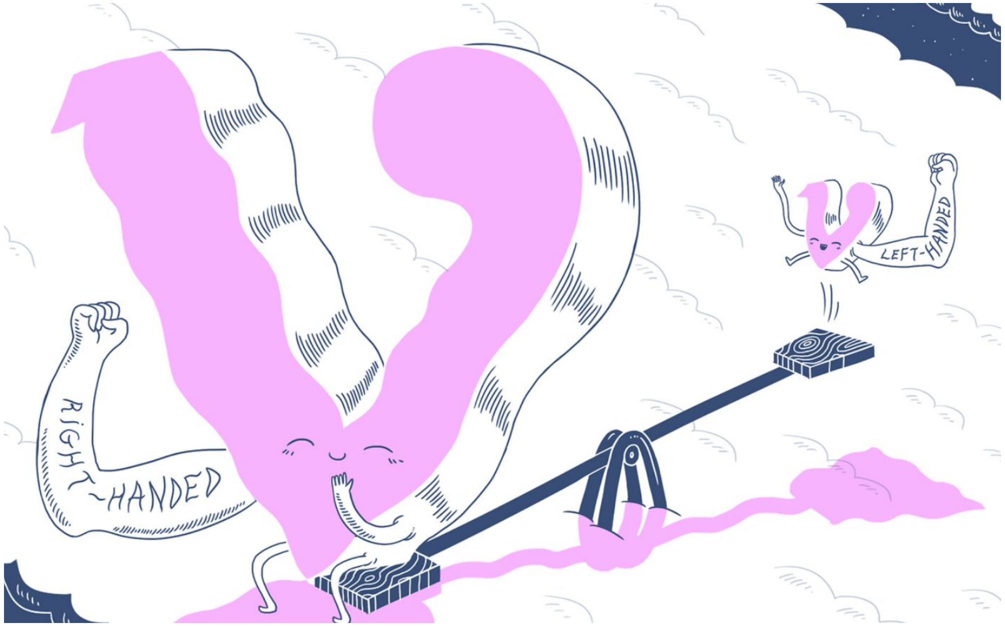
THEY ARE NUMEROUS AND UBIQUITOUS



Why Neutrinos? ... some interesting facts

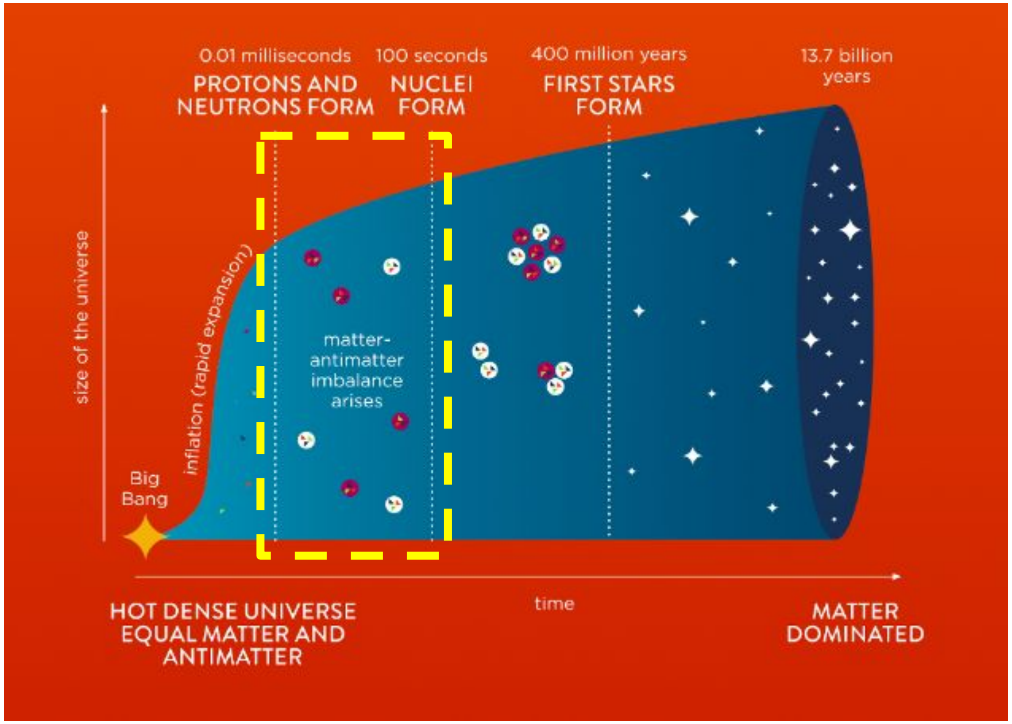
- **Neutrinos are almost massless.**
  - The three types of neutrinos in the standard model are the lightest particles with a non-zero mass ever discovered.
    The upper limit on the mass of the heaviest neutrino is still more than 4 million times lighter than the electron, the next lightest particle.

    Neutrinos x Quarks mass scale: new symmetries ??



Why Neutrinos? ... some interesting facts

- Neutrinos may have altered the course of the universe. Why we have predominance of matter over antimatter?
  - Cosmologists think that at the start of the universe there were equal parts of matter and antimatter.
    Neutrino interactions may have tipped this delicate balance, enabling the formation of galaxies, stars and planets like our own Earth.



Why Neutrinos? ... some interesting facts

- **Neutrinos are the key particle in the heavy-element forges of the universe.**
  - **Neutrinos dissipate more than 99 percent of a supernova's energy. Supernovae eject heavy elements to the cosmos in a recycling matter mechanism.**
  - **"Core collapse" supernovae end as either a black hole or a neutron star. Neutrinos are key particles to understand how supernovae explode and tell us more about other astronomical objects like active galactic nuclei.**

ν's oscillations

Mixing angles = (θ_{12}, θ_{23}, θ_{13}) , δ_{CP} is the CP-violation phase

$$U_{\rm PMNS} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\rm I} \underbrace{\begin{pmatrix} c_{13} & 0 & e^{i\delta_{\rm CP}} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{\rm CP}} s_{13} & 0 & c_{13} \end{pmatrix}}_{\rm II} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\rm III}$$

atmospheric reactor solar

where: $c_{\alpha\beta} = \cos\theta_{\alpha\beta}$; $s_{\alpha\beta} = \sin\theta_{\alpha\beta}$

The relationship between the three mixing angles θ_{12}, θ_{23}, and θ_{13} and the mixing between the neutrino flavor and mass states can be described as follows :

$$\tan^2\theta_{12} : \frac{\text{fraction of } \nu_e \text{ in } \nu_2}{\text{fraction of } \nu_e \text{ in } \nu_1}$$

$$\tan^2\theta_{23} : \text{ratio of } \nu_\mu \text{ to } \nu_\tau \text{ in } \nu_3$$

$$\sin^2\theta_{13} : \text{fraction of } \nu_e \text{ in } \nu_3$$

Nonzero δ_{CP} ⟹ neutrinos and antineutrinos oscillate different

DUNE oscillation physics

slide from
Alexander Izmaylov

- Neutrino and antineutrino appearance and disappearance studies

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - (\cos^4\theta_{13}\sin^2 2\theta_{23})\sin^2\left(\Delta m^2_{31}\frac{L}{4E}\right)$$

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

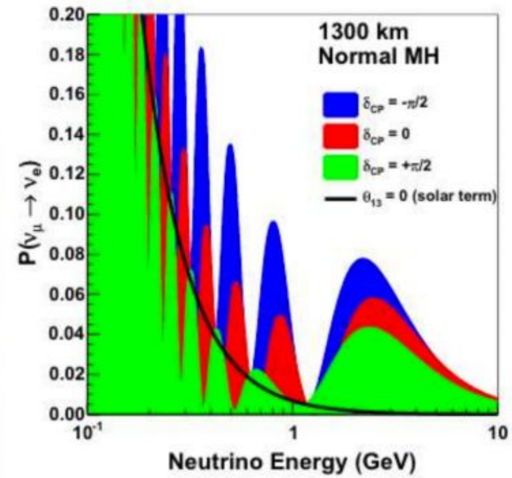
CP-violating $\alpha\sin\delta_{CP}\times\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\times\sin\Delta\,\frac{\sin[x\Delta]}{x}\,\frac{\sin[(1-x)\Delta]}{(1-x)}$

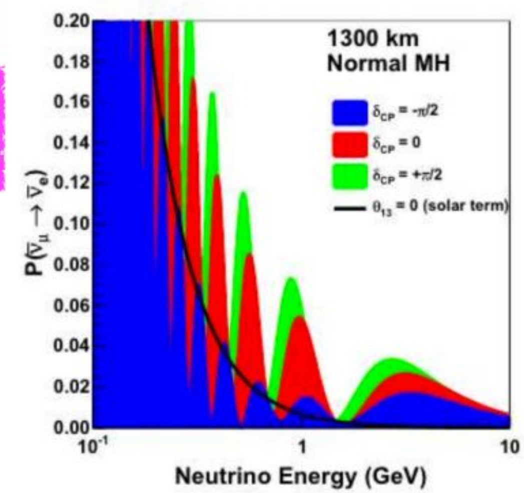
"+" sign for anti-ν

CP-conserving $+\alpha\cos\delta_{CP}\times\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\times\cos\Delta\,\frac{\sin[x\Delta]}{x}\,\frac{\sin[(1-x)\Delta]}{(1-x)}$

$+O(\alpha^2)$ $\quad \alpha = \left|\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\right| \sim \frac{1}{30} \quad \Delta = \frac{\Delta m^2_{31}L}{4E} \quad x = \frac{2\sqrt{2}G_F N_e E}{\Delta m^2_{31}}$

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar\nu_\mu \to \bar\nu_e)}{P(\nu_\mu \to \nu_e) + P(\bar\nu_\mu \to \bar\nu_e)} \sim \frac{\cos\theta_{23}\sin 2\theta_{12}\sin\delta_{CP}}{\sin\theta_{23}\sin\theta_{13}}\left(\frac{\Delta m^2_{21}L}{4E_\nu}\right) + \text{matter effects}$$



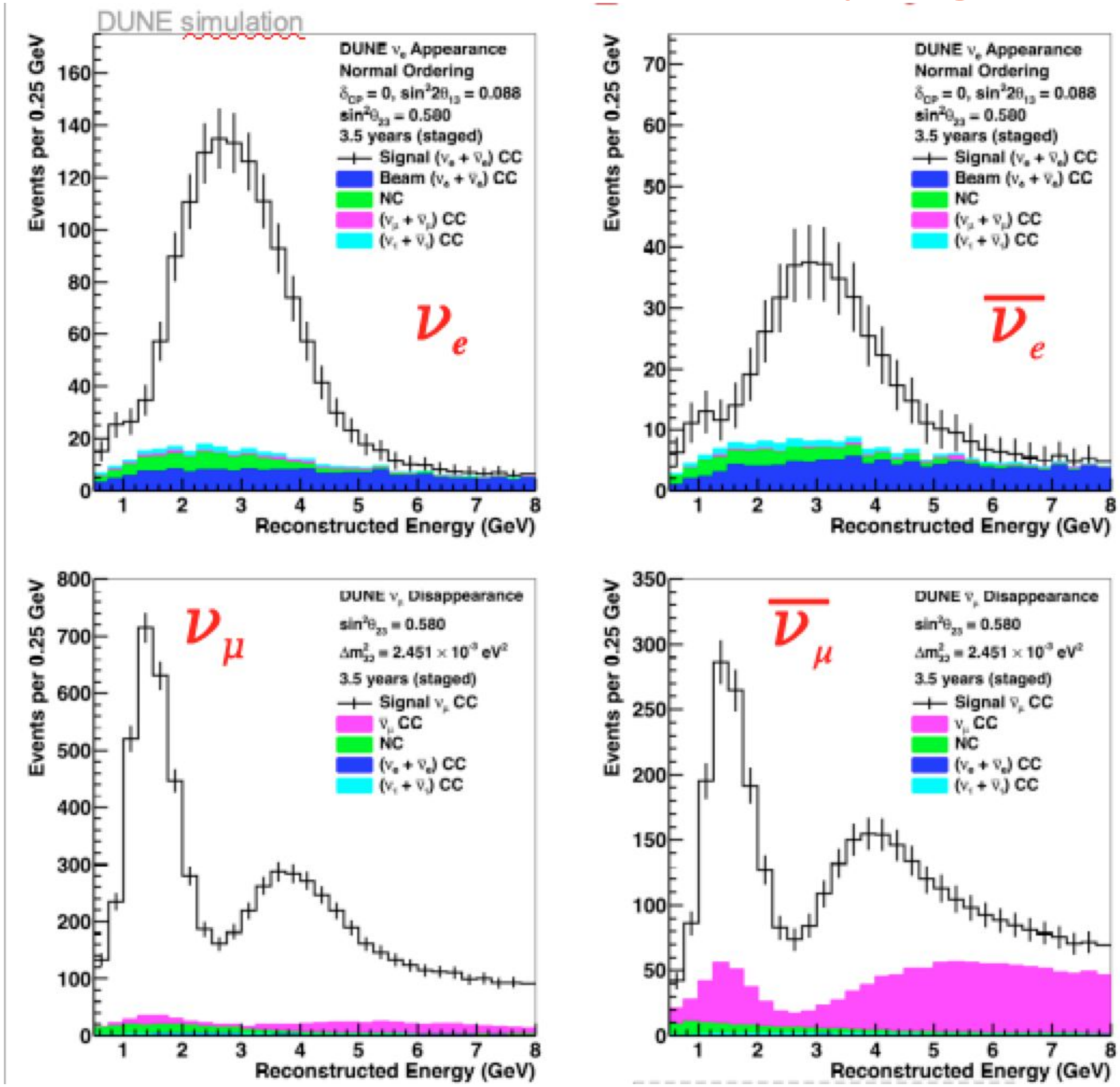


- More E and baseline → more sensitivity to mass ordering
- 1285 km baseline for DUNE: optimised for ordering and δCP

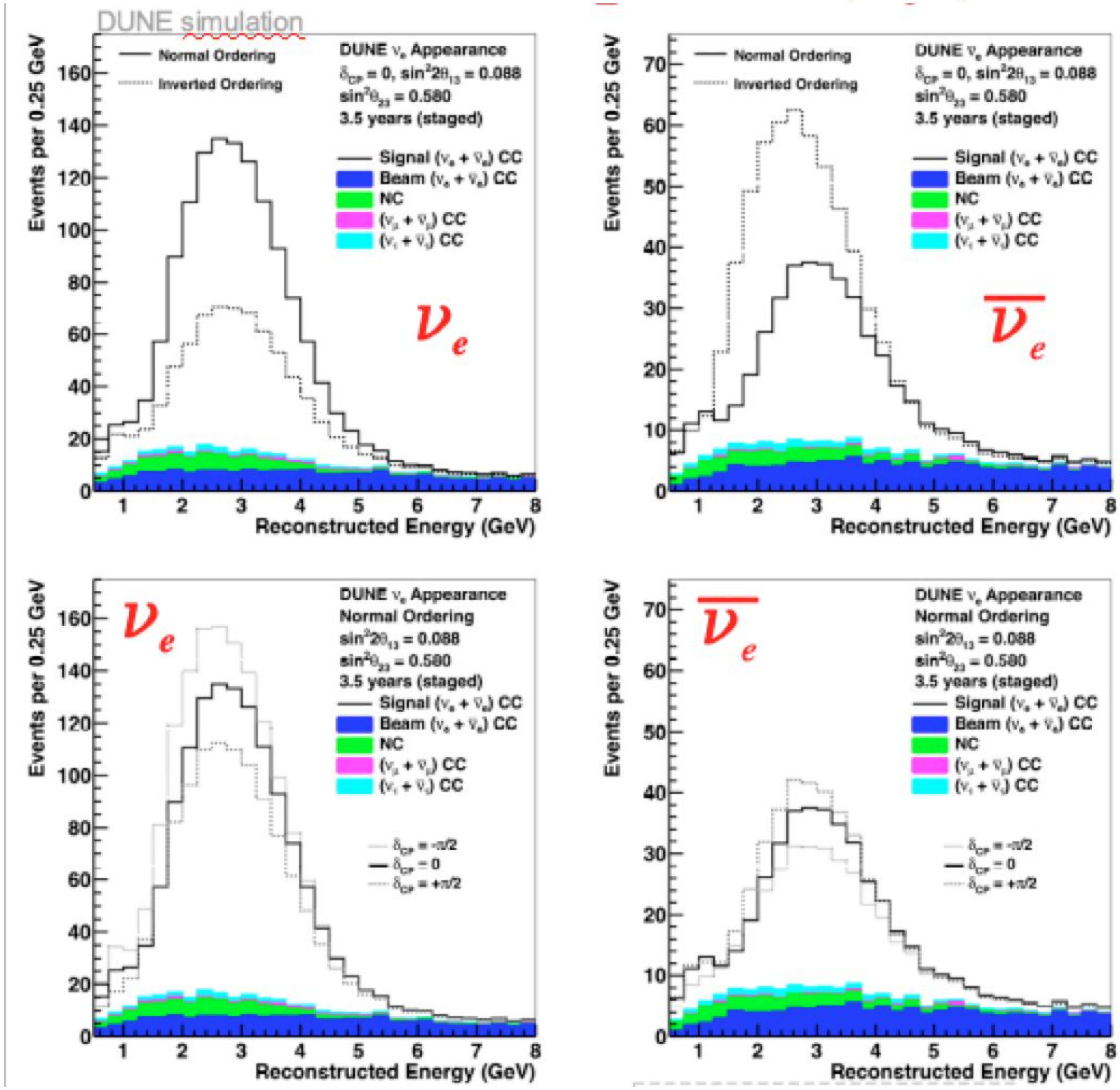
DUNE sensitivity: metrics

$$
\begin{aligned}
\Delta\chi^2_{MH} &= \chi^2_{IH} - \chi^2_{NH} \text{ (true normal hierarchy)},\\
\Delta\chi^2_{MH} &= \chi^2_{NH} - \chi^2_{IH} \text{ (true inverted hierarchy)},\\
\Delta\chi^2_{CPV} &= Min[\Delta\chi^2_{CP}(\delta^{test}_{\mathrm{CP}} = 0), \Delta\chi^2_{CP}(\delta^{test}_{\mathrm{CP}} = \pi)], \text{ where}\\
\Delta\chi^2_{CP} &= \chi^2_{\delta^{test}_{\mathrm{CP}}} - \chi^2_{\delta^{true}_{\mathrm{CP}}}.
\end{aligned}
$$

DUNE oscillation physics



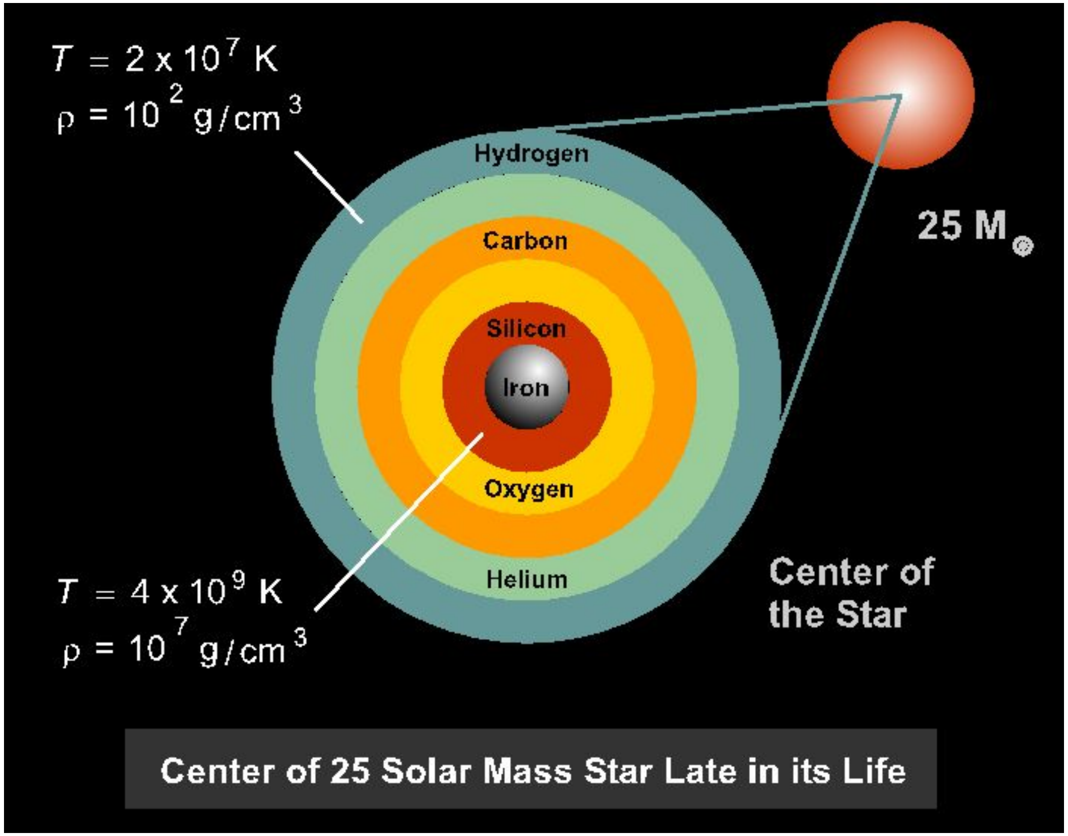
DUNE oscillation physics



SN: the end point of stellar evolution

- **Thermonuclear Evolution:**
  Sequential fuel burning producing heavier elements

$$\mathrm{H} \rightarrow \mathrm{He} \rightarrow \mathrm{C} \rightarrow \mathrm{O\ (Ne)} \rightarrow \mathrm{Si} \rightarrow \mathrm{Fe}$$



DUNE sensitivity: disappearance spectra

	Expected Events (3.5 years staged)
ν mode	
ν_μ Signal	6200
$\bar{\nu}_\mu$ CC background	389
NC background	200
$\nu_\tau + \bar{\nu}_\tau$ CC background	46
$\nu_e + \bar{\nu}_e$ CC background	8
$\bar{\nu}$ mode	
$\bar{\nu}_\mu$ Signal	2303
ν_μ CC background	1129
NC background	101
$\nu_\tau + \bar{\nu}_\tau$ CC background	27
$\nu_e + \bar{\nu}_e$ CC background	2

DUNE sensitivity: appearance spectra

	Expected Events (3.5 years staged)
ν mode	
ν_e Signal NO (IO)	1092 (497)
$\bar{\nu}_e$ Signal NO (IO)	18 (31)
Total Signal NO (IO)	1110 (528)
Beam $\nu_e + \bar{\nu}_e$ CC background	190
neutral current (NC) background	81
$\nu_\tau + \bar{\nu}_\tau$ CC background	32
$\nu_\mu + \bar{\nu}_\mu$ CC background	14
Total background	317
$\bar{\nu}$ mode	
ν_e Signal NO (IO)	76 (36)
$\bar{\nu}_e$ Signal NO (IO)	224 (470)
Total Signal NO (IO)	300 (506)
Beam $\nu_e + \bar{\nu}_e$ CC background	117
NC background	38
$\nu_\tau + \bar{\nu}_\tau$ CC background	20
$\nu_\mu + \bar{\nu}_\mu$ CC background	5
Total background	180

DUNE: SN ν event rates