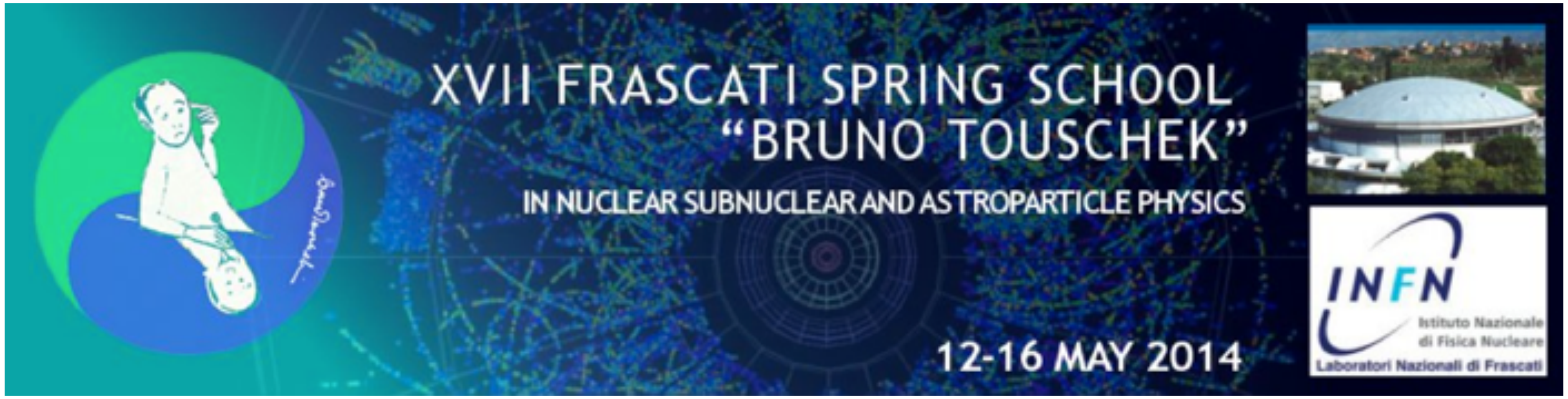
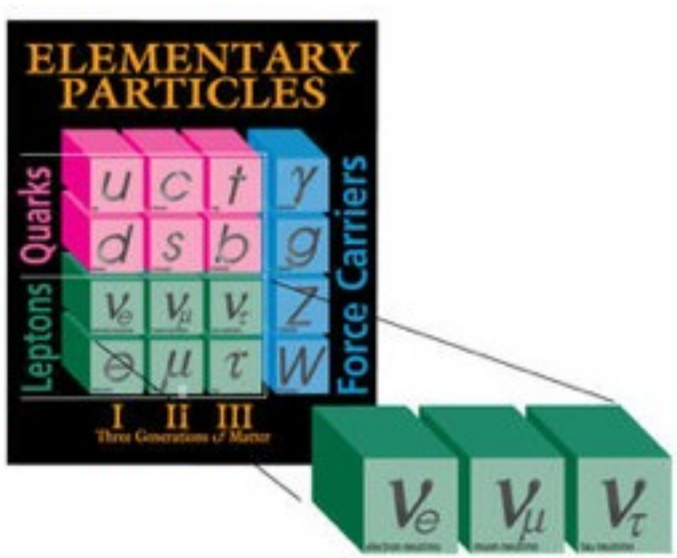
Neutrino Experiments

M. Sorel (IFIC - CSIC & U. de Valencia)



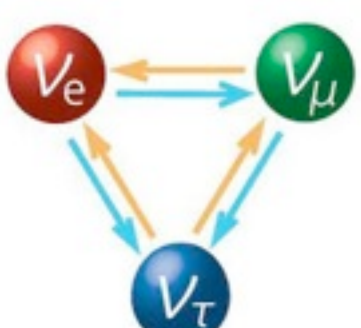
Neutrinos: what we know

(see E. Lisi's lectures)



- Interact only weakly
  - No color, no electric charge
- Three light ($<m_Z/2$) neutrino states
  - ν_e, ν_μ, ν_τ flavors

- Neutrino number density in Universe only outnumbered by photons
  - $n(\nu+\overline{\nu}) \approx 100\ \text{cm}^{-3}$ per flavor

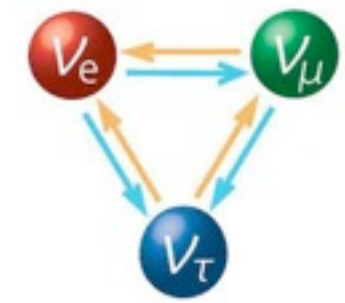


From neutrino oscillations:

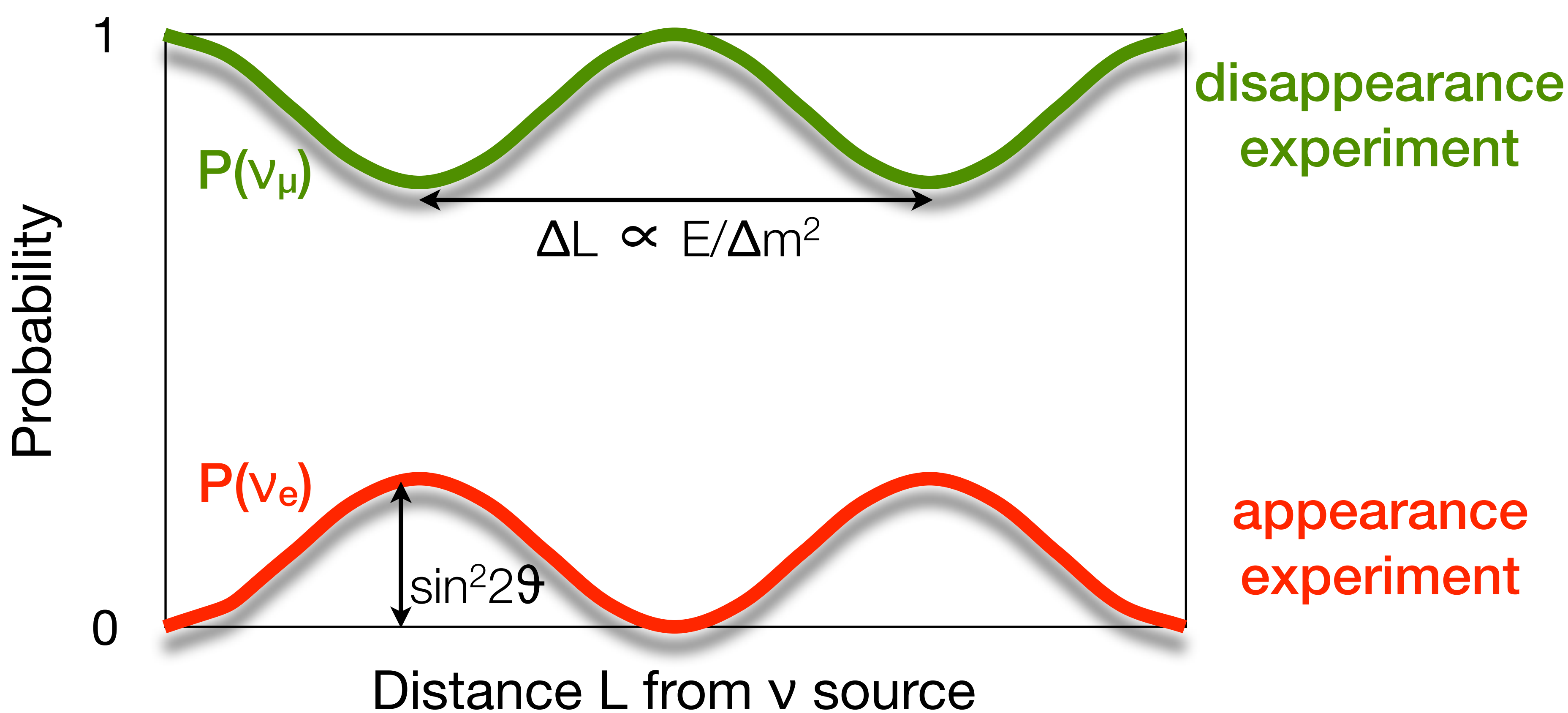
- Lightest known fermions, but massive
- Large flavor mixing

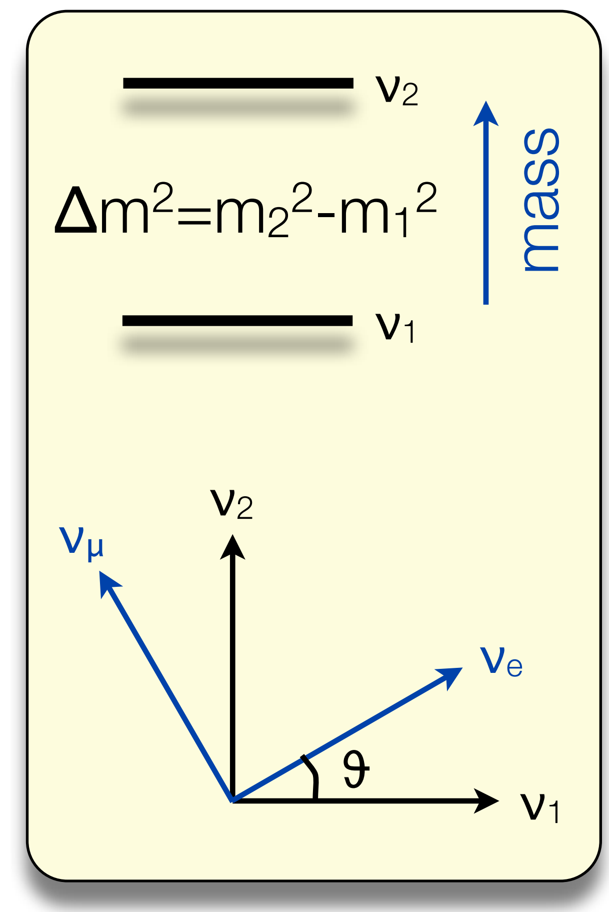
Neutrino flavor oscillations

(see E. Lisi's lectures)



- Neutrinos ***change flavor*** as they propagate through space!
- Flavor change follows *oscillatory pattern* depending on neutrino baseline *L* and energy *E*
- Neutrino oscillation implies *massive neutrinos ($\Delta m^2 \neq 0$)* and *neutrino mixing ($\vartheta \neq 0$)*
- 2-neutrino mixing example, for ν_μ beam with energy E:





Knowledge on 3-neutrino oscillation parameters

(see E. Lisi's lectures)

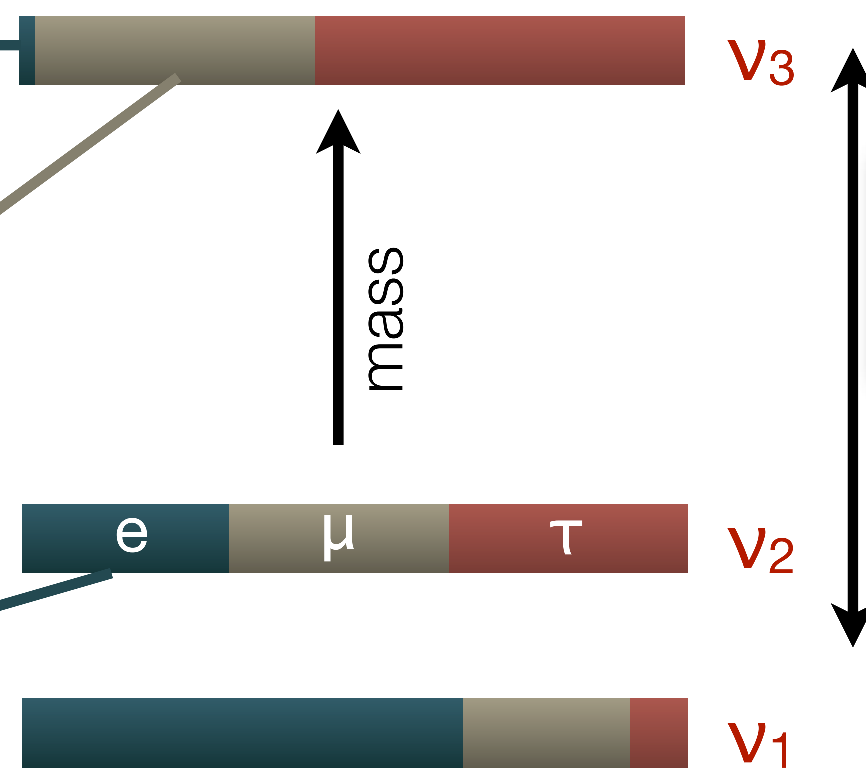
Mass splittings and mixing angles measured with 10% precision or better*

$\sin^2\vartheta_{13} = 0.024 \pm 0.002$

$\sin^2\vartheta_{23} = 0.386 \pm 0.024^{*}$

* $\sin^2\vartheta_{23} > 0.5$ allowed at 3σ (octant degeneracy)

$\sin^2\vartheta_{12} = 0.307 \pm 0.018$



$|\Delta m^2_{atm}| = (2.43 \pm 0.10) \cdot 10^{-3}\ eV^2$

$\Delta m^2_{sol} = (7.54 \pm 0.26) \cdot 10^{-5}\ eV^2$

Neutrino mixing different from quark mixing

$$|V_{CKM}| = \begin{pmatrix} 1 & 0.2 & 0.004 \\ 0.2 & 1 & 0.04 \\ 0.008 & 0.04 & 1 \end{pmatrix}$$

$$|V_{PMNS}| = \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

Outstanding Questions in Neutrino Physics

(see E. Lisi's lectures)

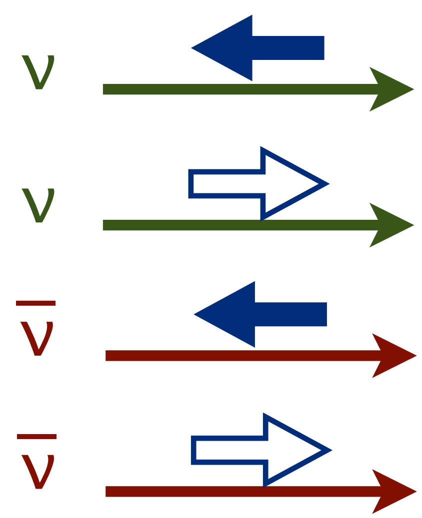
Identity	Dirac or Majorana fermion?
Mass scale	What is the neutrino mass value?
Mass ordering	Normal or inverted?
Mixing	Is CP symmetry violated in the neutrino sector?
Species	Are there light sterile neutrinos?

Neutrino question 1: *Identity*

Dirac or Majorana fermion?

Dirac:

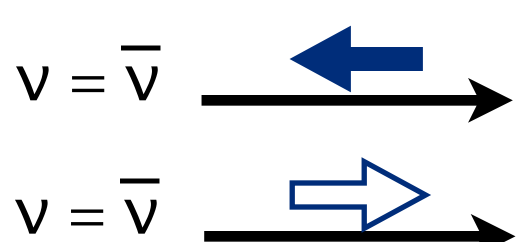
- 4 states
- $\nu \neq \bar{\nu}$



Helicity	Conserved Lepton Number	Lepton production rate	Anti-lepton production rate
-1/2	+1	1	0
+1/2	+1	$(m/E)^2 << 1$	0
-1/2	-1	0	$(m/E)^2 << 1$
+1/2	-1	0	1

Majorana:

- 2 states
- $\nu = \bar{\nu}$



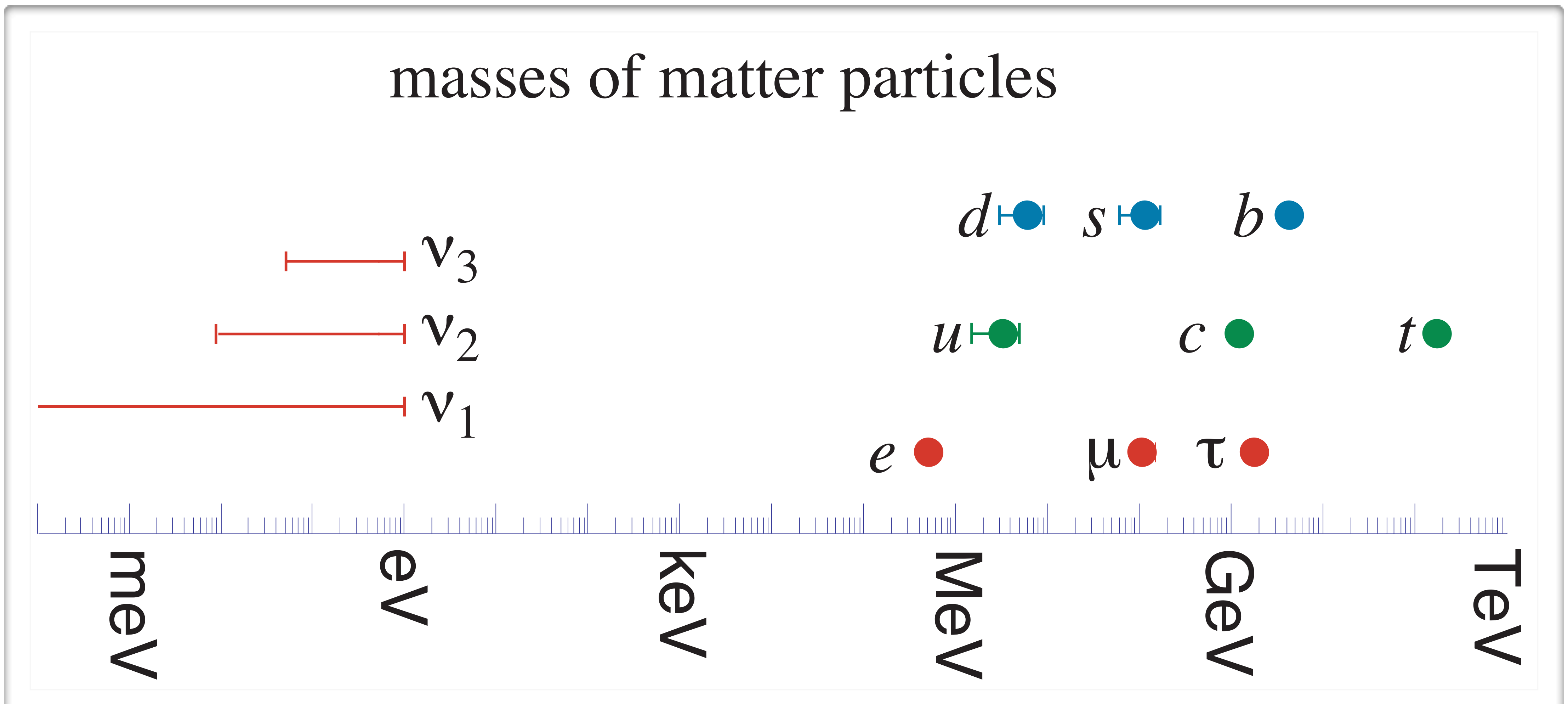
Helicity	Conserved Lepton Number	Lepton production rate	Anti-lepton production rate
-1/2	none	1	0
+1/2	none	0	1

Neutrino question 2: *Mass scale*

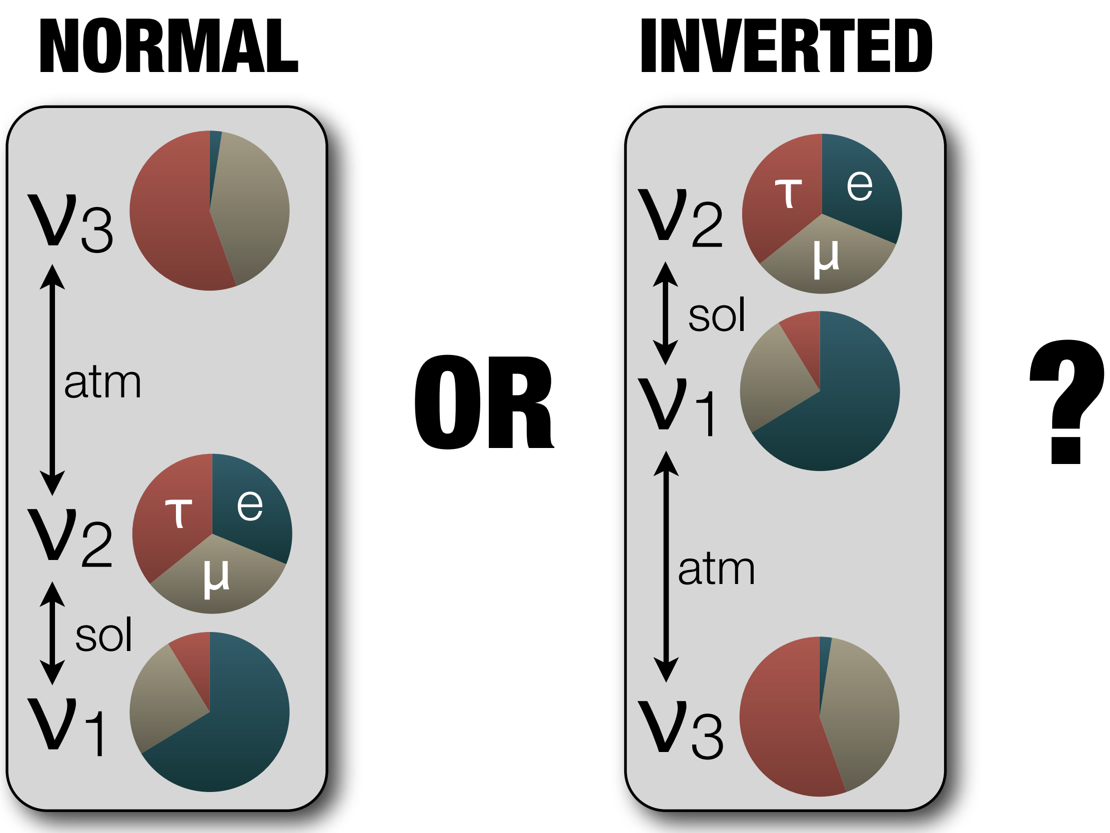
We know it is non-zero, but... **What is the neutrino mass value?**

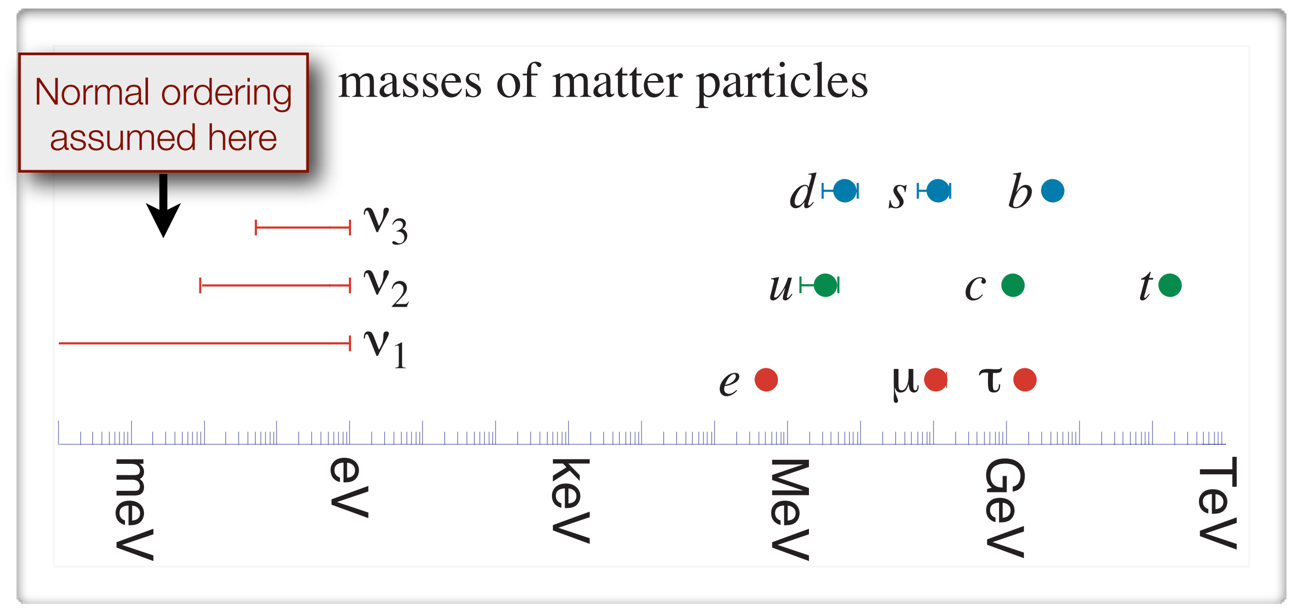
- Neutrino mass could be anywhere between 0 and ~1 eV

➩ how different from quarks and charged leptons?



Neutrino question 3: *Mass ordering*





- If ν_1 taken as most electron-rich state, $m_1 < m_2$ from solar neutrinos
- **Normal** mass ordering: $m_{light} = m_1$ ⇨ similar to quarks and charged leptons
- **Inverted** mass ordering: $m_{light} = m_3$ ⇨ "opposite" to quarks and charged leptons

Neutrino question 4: Mixing

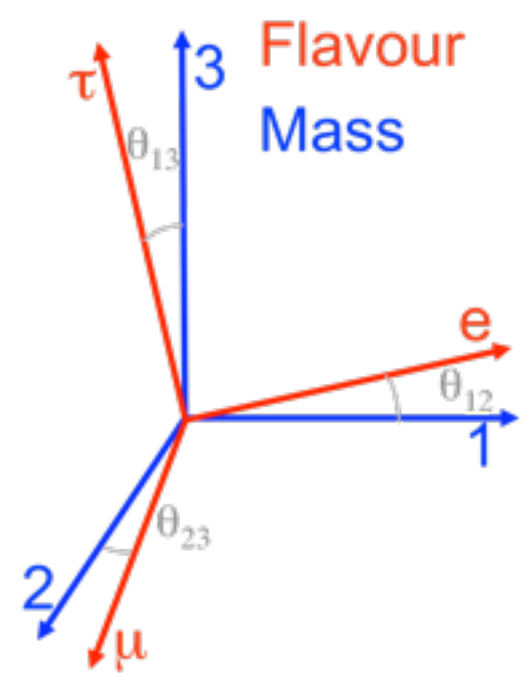
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \overbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}^{\text{Atmospheric Oscillations}} \underbrace{\begin{pmatrix} c_{13} & 0 & \boxed{s_{13}e^{-i\delta}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}}_{\text{Interference}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar Oscillations}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$c_{23} = \cos\theta_{23} \text{ etc...}$$

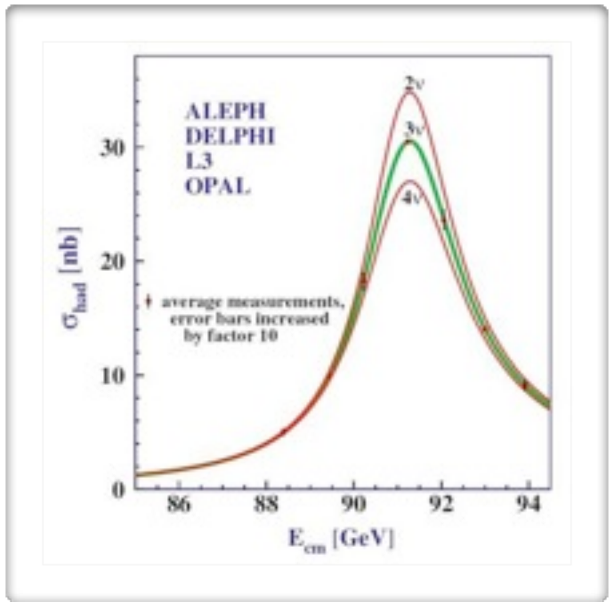
Is CP symmetry violated in the neutrino sector?

Possible source of CP violation in neutrino sector that can be measured with oscillations: Dirac CP-odd phase δ

δ ≠ 0, π ⇔ oscillation probabilities violate CP invariance: different probabilities for neutrinos and antineutrinos!



Neutrino question 5: Species

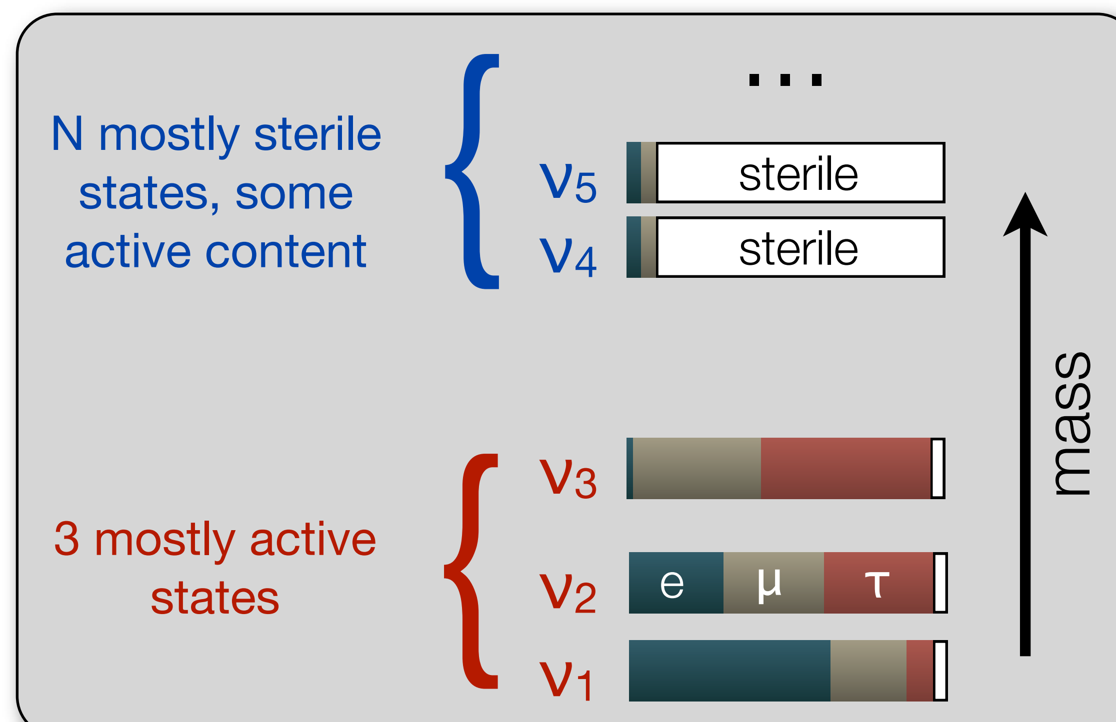


- LEP: three neutrino flavors participating in the weak interactions and with mass <m_Z/2. But...

...are there light "sterile" neutrino states, in addition to the three "active" ones?

- Hinted by anomalous results at short baselines:

Anomaly	Baseline (m)	Energy (MeV)	Oscillation interpretation	Significance (σ)
LSND	30	50	$\bar{\nu}_\mu \to \bar{\nu}_e$	3.8
MiniBooNE ν	500	600	$\nu_\mu \to \nu_e$	3.4
MiniBooNE $\bar{\nu}$	500	600	$\bar{\nu}_\mu \to \bar{\nu}_e$	2.8
Gallium	2	1	$\nu_e \to \nu_s$	2.8
Reactor	20	5	$\bar{\nu}_e \to \bar{\nu}_s$	2.9



How to experimentally address neutrino questions

(topic of these lectures)

Identity	Neutrinoless double beta decay
Mass scale	Direct neutrino mass measurements, neutrino cosmology, neutrinoless double beta decay
Mass ordering	Neutrino oscillations, neutrino cosmology
Mixing	Neutrino oscillations
Species	Neutrino oscillations, neutrino cosmology

A wealth of neutrino experiments!

Abstracts about neutrino experiments submitted to ICHEP 2014 Conference

ZICOS
NEMO-3
KATRIN NEXT
SOX HOLMES SoLid
INO-ICAL
nEXO CANDLES OPERA Majorana LUNA
AMoRE Daya-Bay Double-Chooz NESSIE
IsoDAR LAGUNA/LBNO MiniTimeCube
MicroBooNE Hyper-Kamiokande LAr1-ND
T2K SuperNEMO LUMINEU GADZOOKS NOvA
MINERvA Super-Kamiokande Borexino ORCA
LUCIFER NA61/SHINE nuSTORM ICARUS
Daedalus KamLAND-Zen EXO-200 SNO+
GERDA JUNO LBNE
COBRA
ESS ECHo CUORE
PINGU

Plan for these lectures

- Today: neutrino oscillation experiments
  - How to measure neutrino oscillation parameters
  - Neutrino sources
  - Neutrino interactions with matter
  - Neutrino detector technologies
  - A selection of current and future experiments

- Tomorrow: other neutrino experiments
  - Neutrinoless double beta decay experiments
  - Direct neutrino mass measurements
  - Neutrino cosmology

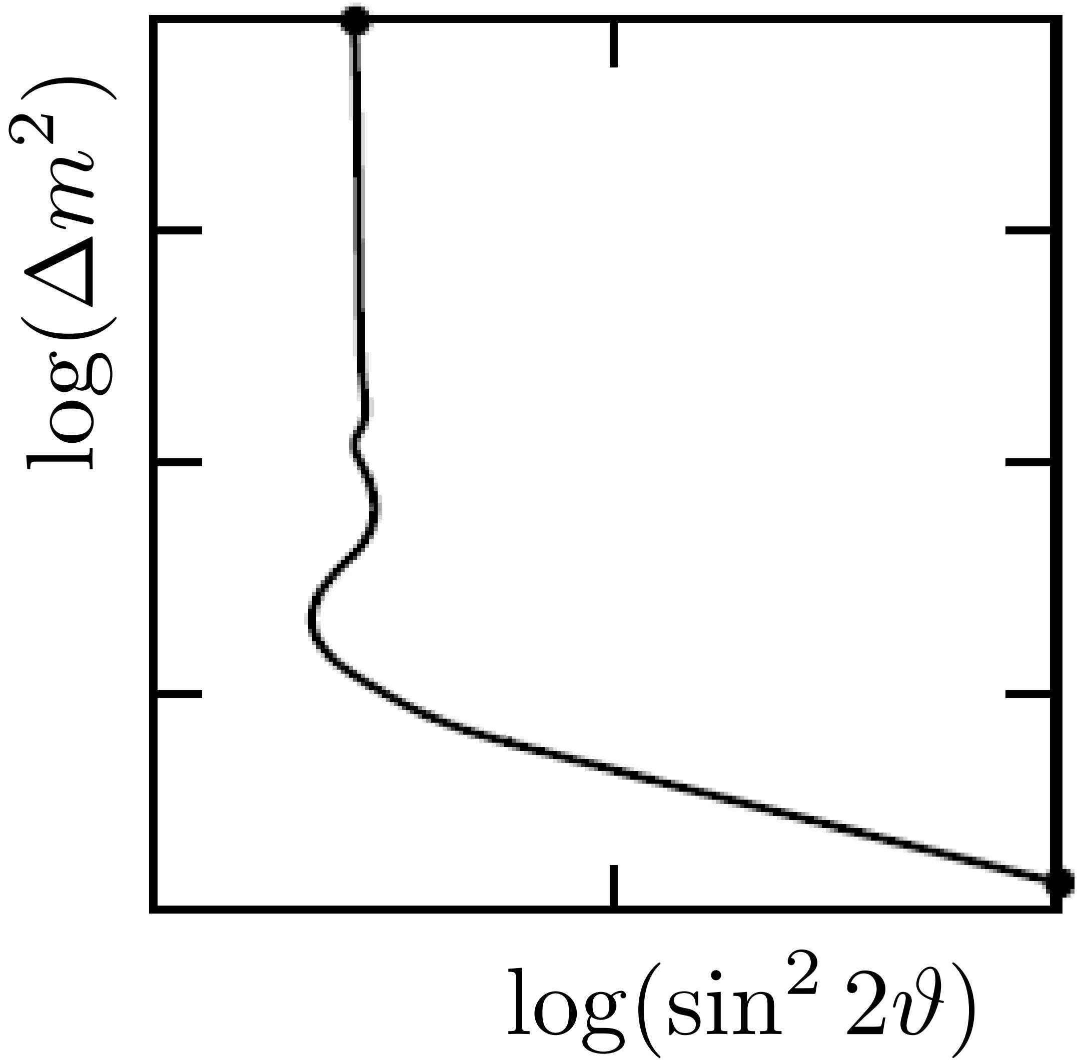
Neutrino oscillation experiments

How to measure neutrino oscillation parameters

Experimental sensitivity to neutrino oscillation parameters

- Often neutrino oscillation results given in (Δm^2, $\sin^2 2\vartheta$) space, where Δm^2 and $\sin^2 2\vartheta$ are parameters from simple 2-neutrino oscillations:

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\vartheta \cdot \sin^2(1.27\Delta m^2 \frac{L}{E})$$



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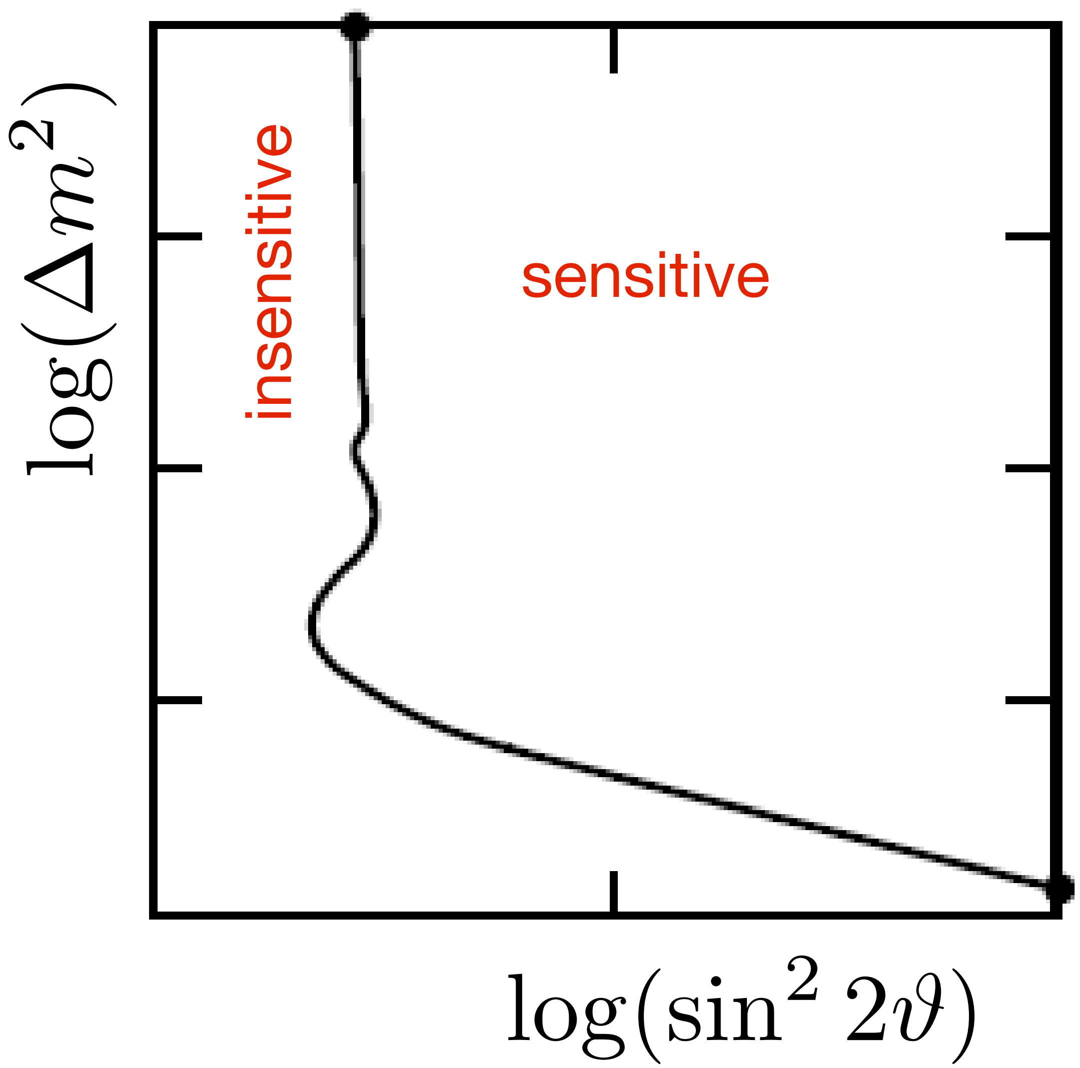
- Sensitivity curve (drawn before carrying out experiment): can potentially measure oscillation parameters to the right and above it.



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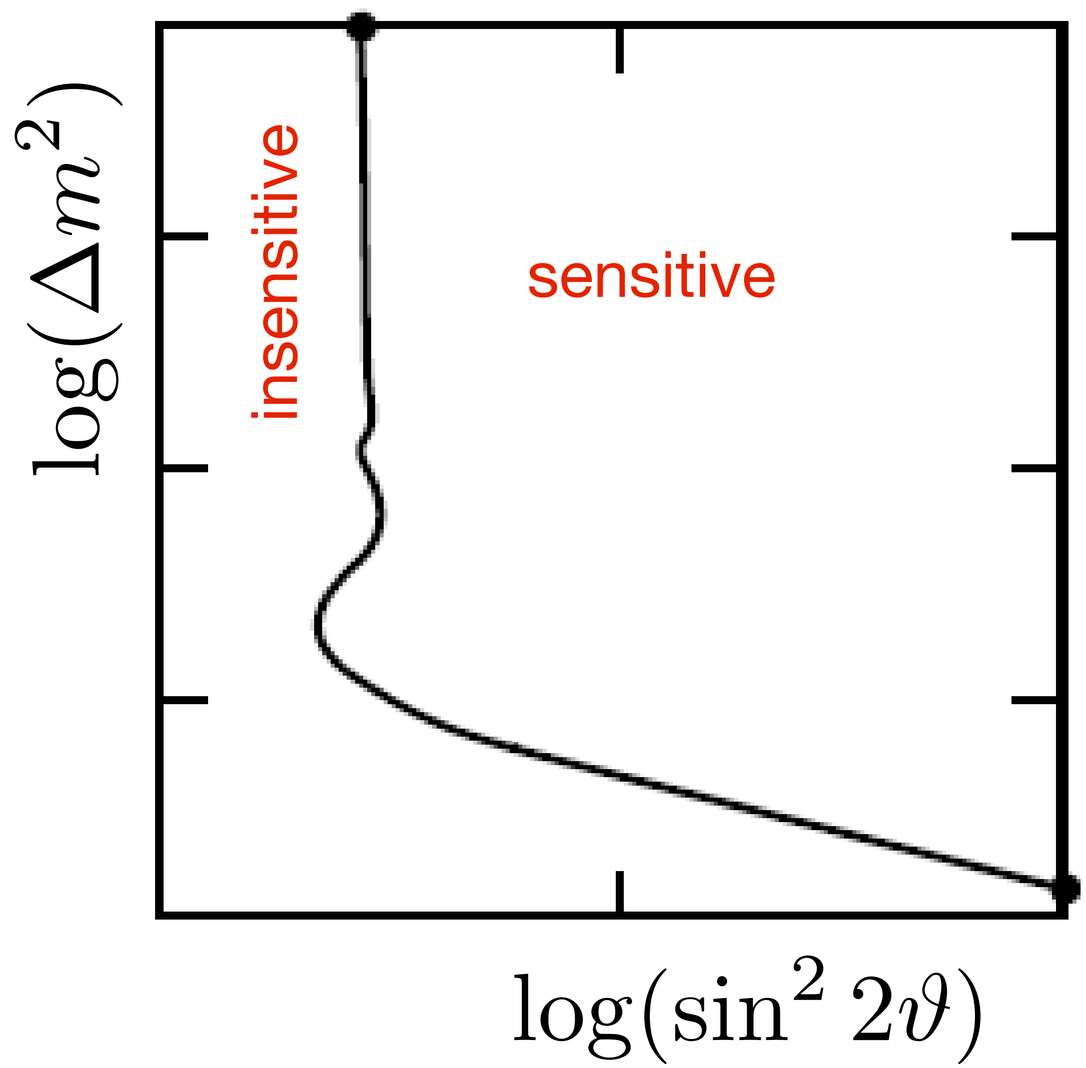
    - upper limit on $\sin^2 2\vartheta$ for each Δm^2, resembling sensitivity curve



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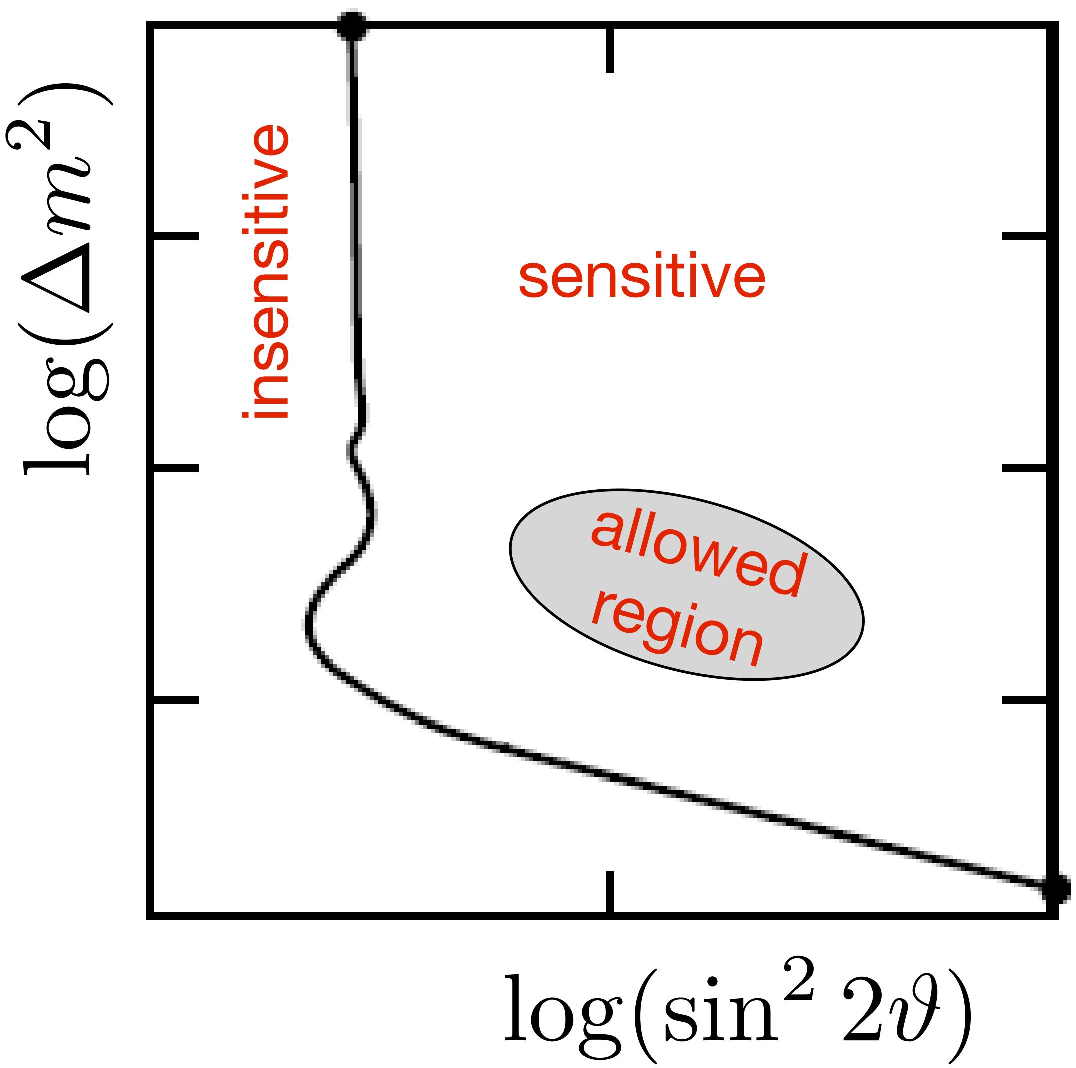
- If an experiment sees oscillations, "potato-like" allowed region in parameter space obtained in sensitive area



Experimental sensitivity to neutrino oscillation parameters

Short- and long-baseline experiments

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$$\Delta m^2(L/E) < 1$$

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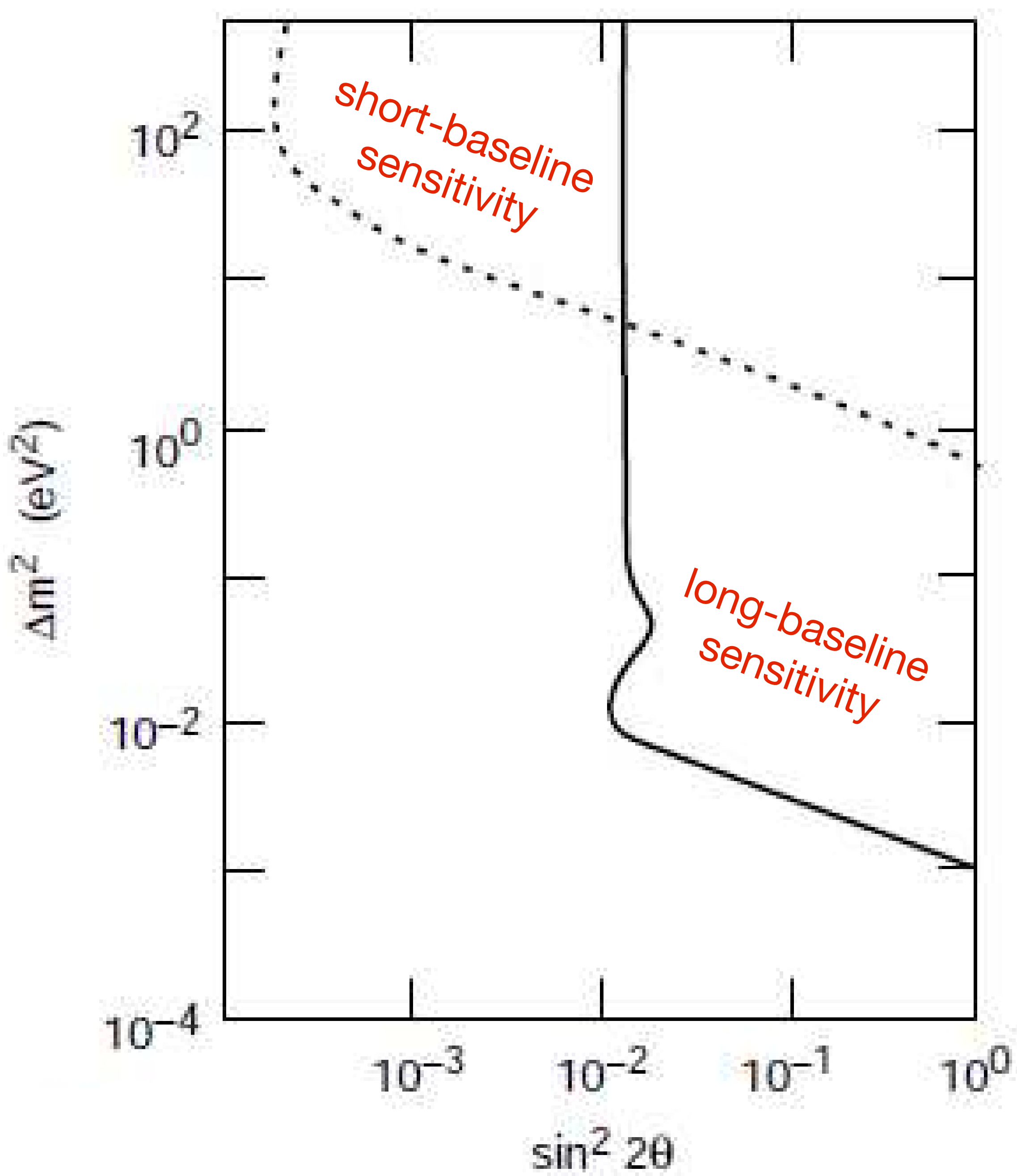
- Bottom line: optimize (L, E) for each oscillation search, and maximize number of events!



Facts of life for the neutrino experimenter...

Numerical example for long-baseline accelerator-based experiment

$$N_{\rm obs} = \left[\int \mathcal{F}(E_\nu)\sigma(E_\nu,...)\epsilon(E_\nu,...)dE_\nu d...\right]\frac{M}{A\ m_N}T$$

N_{obs}	:	number of neutrino events recorded
$\mathcal{F}$	:	Flux of neutrinos ($\#/{\rm cm}^2/{\rm s}$)
σ	:	neutrino cross section per nucleon $\simeq 0.7\frac{E_\nu}{[\rm GeV]}\times 10^{-38}{\rm cm}^2$
ϵ	:	detection efficiency
M	:	total detector mass
A	:	effective atomic number of detector
m_N	:	nucleon mass
T	:	exposure time

$\mathcal{F}$ = 1/(cm^2·s)

typical "super-beam" flux at 1000 km

typical accelerator up time in one year

$$N_{\rm obs} = \left[\frac{\mathcal{F}}{{\rm cm}^2{\rm s}}\right]\left[0.7\times 10^{-38}\frac{E_\nu}{\rm GeV}{\rm cm}^2\right][\epsilon]\,[1\ {\rm GeV}]\left[\frac{M}{20\cdot 1.67\times 10^{-27}\ {\rm kg}}\right]\left[2\times 10^7\ {\rm s}\right]$$

$$\boxed{N_{\rm obs} = 4\times 10^{-6}\cdot \mathcal{F}[({\rm cm}^2\cdot {\rm s})^{-1}]\cdot E_\nu[{\rm GeV}]\cdot \varepsilon\cdot M[{\rm kg}]}$$

push beam power as high as you can

work at high energies if you can

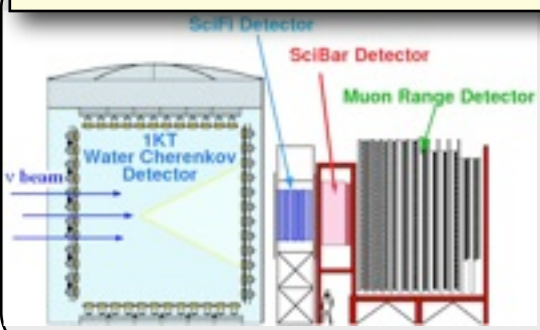
maximize efficiency

need 10^6 kg = 1 kton detector masses to get in the game

Dual- or multi-baseline experiments

Example for accelerator-based experiment, similar for reactor experiments

Near Detector(s)



Measure rate,
energy of neutrinos

Interaction Model

Infer neutrino flux at
near detector(s)
before oscillations

Flux Model

Far Detector(s)

Measure rate,
energy of neutrinos

Interaction Model,
Oscillation Fit

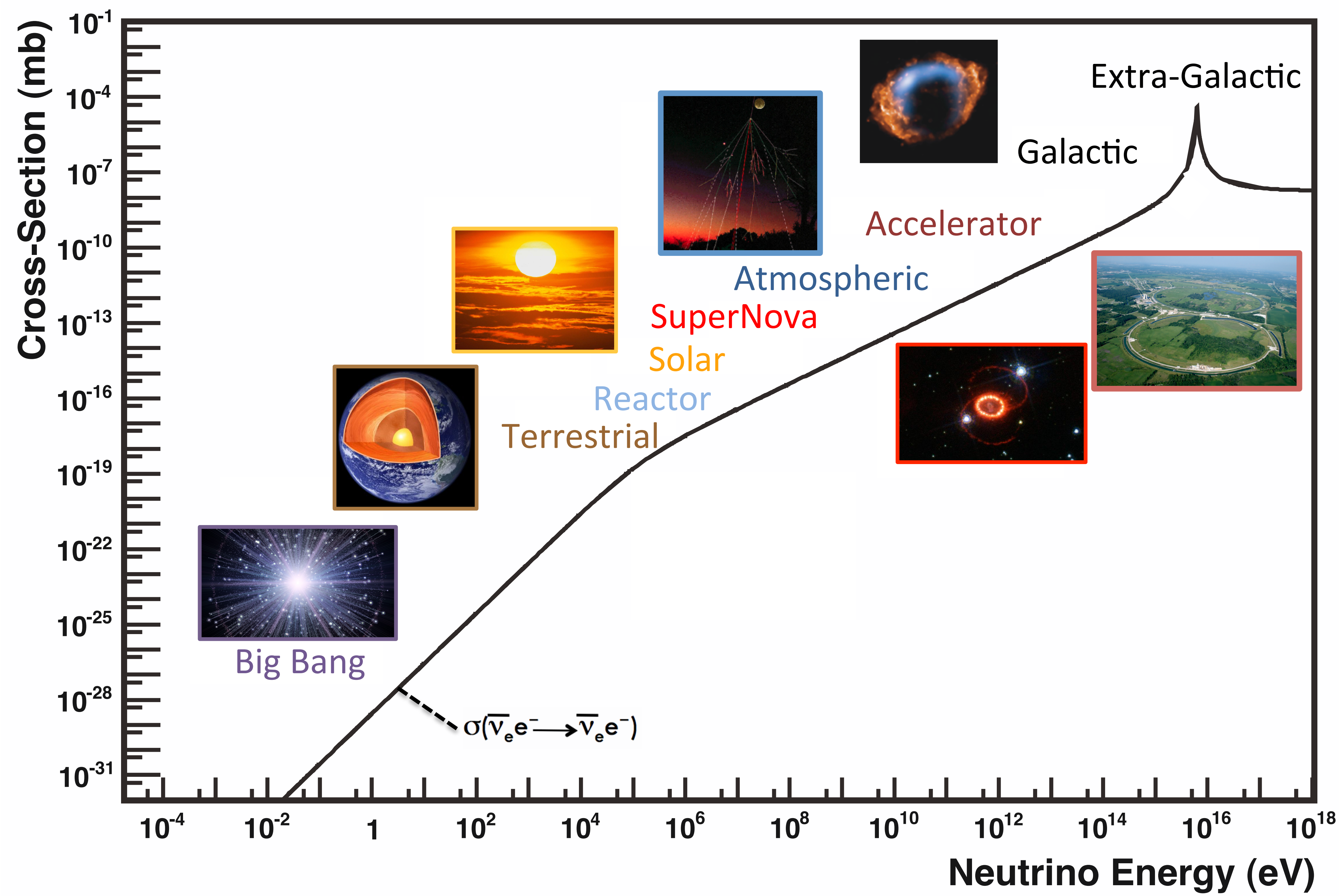
Predict unoscillated
neutrino flux
at far detector(s)

Neutrino oscillation experiments

Neutrino sources

Neutrino sources

Neutrinos are everywhere!



We have directly detected neutrinos from all these sources, except Big Bang neutrinos

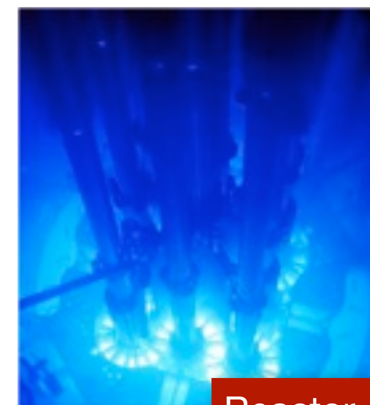
Reactor neutrinos

Flavors: $\bar{\nu}_e$

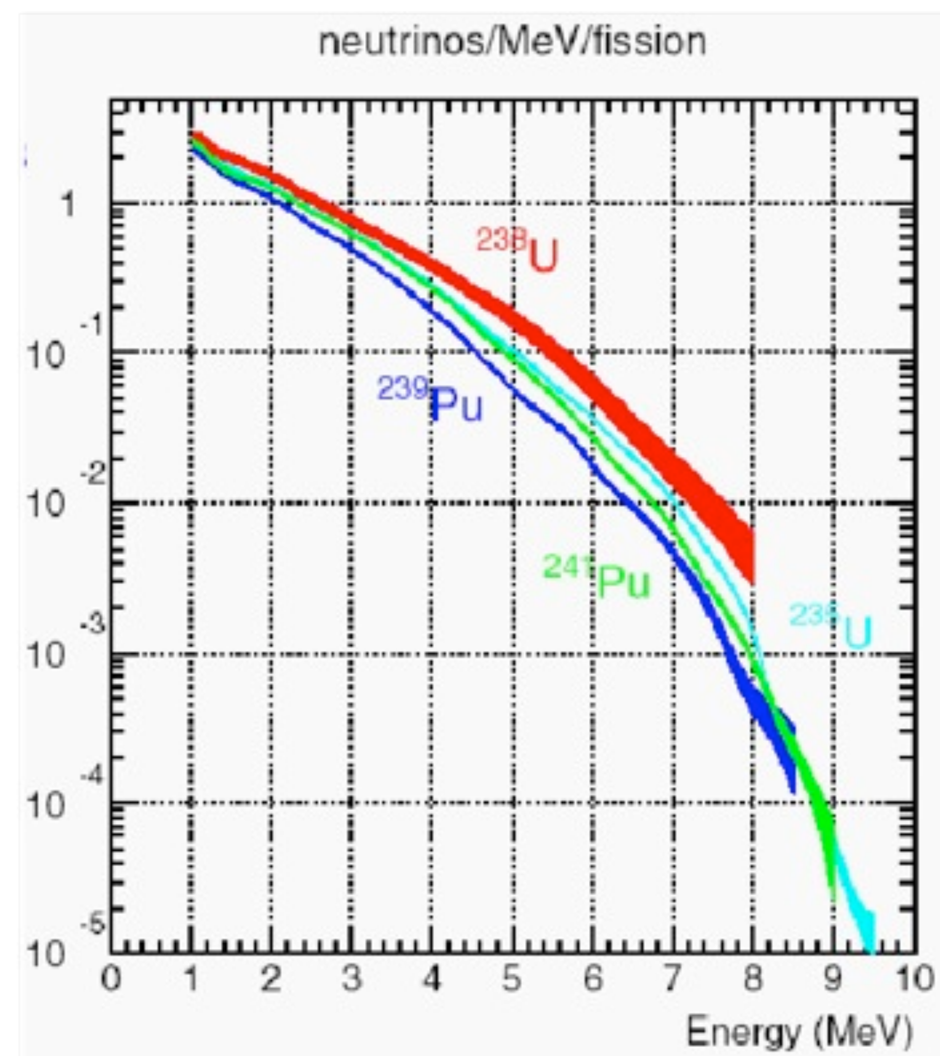
E_ν ~ 1-10 MeV

- Source used for neutrino discovery!
- Electron antineutrinos emitted from β^- decays of neutron-rich fission fragments
- Four main sources: ^{235}U, ^{239}Pu, ^{241}Pu and ^{238}U
- About 6 antineutrinos per fission cycle
- Since each fission cycle produces 200 MeV thermal energy, one can convert power to neutrino flux:

1 GW (thermal) ~ 1.8×10^{20} $\bar{\nu}_e$ / second


Reactor core


Fred Reines and Clyde Cowan



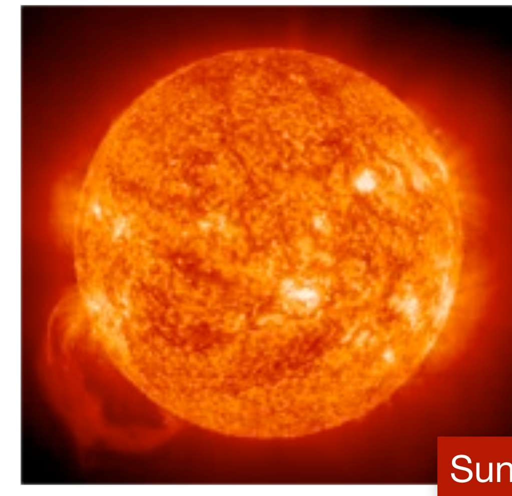
Solar neutrinos

Flavors: ν_e

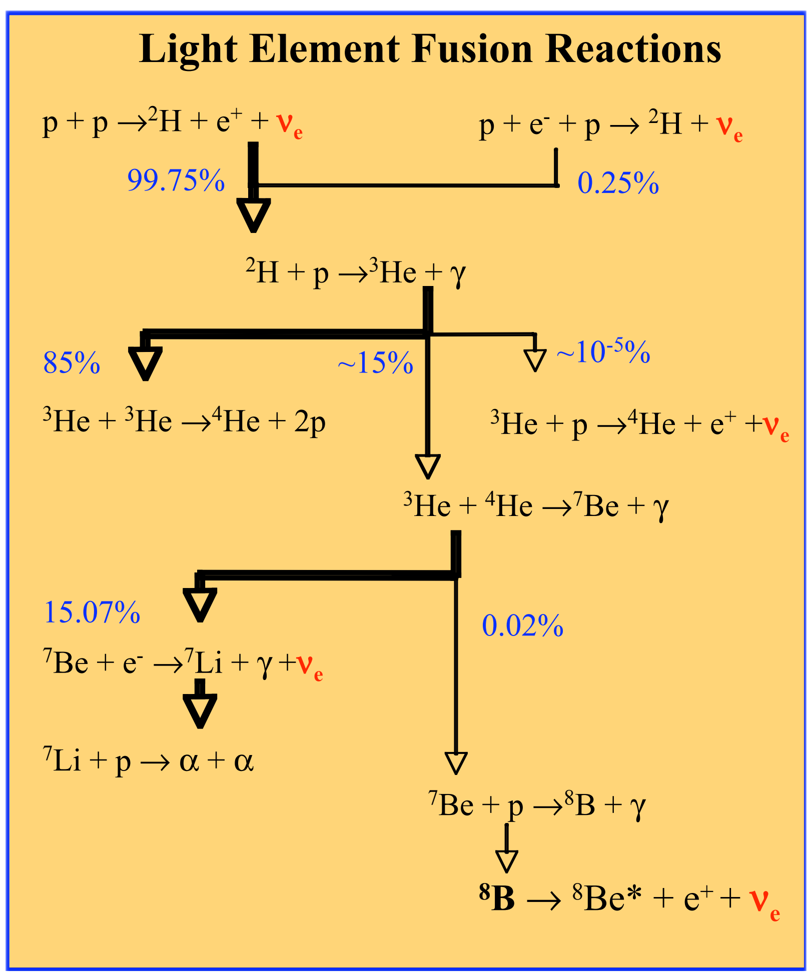
$E_\nu \sim 0.1\text{-}10$ MeV

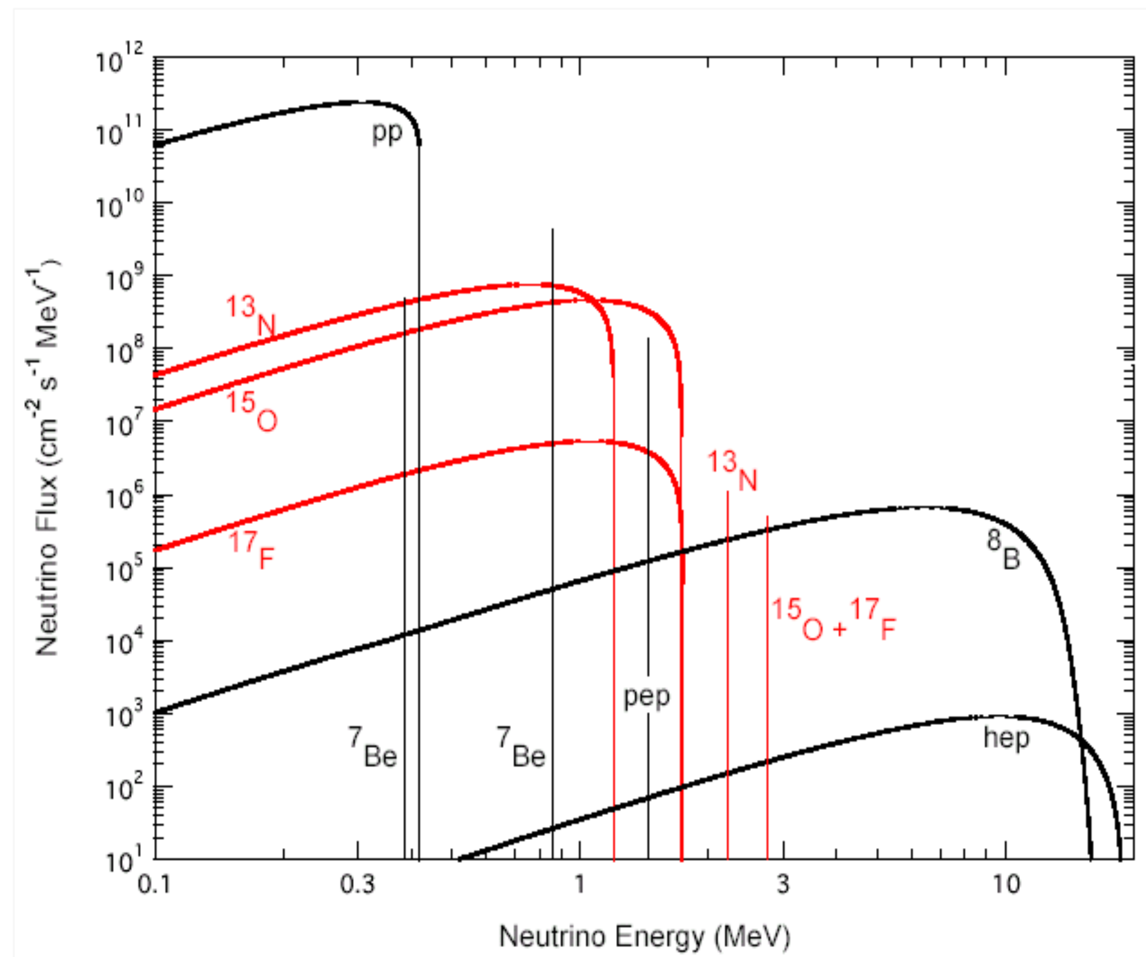
- Source providing first hint for neutrino oscillations!
- Nuclear fusion processes in the Sun produce neutrinos:

$$4p + 2e^- \rightarrow He + 2\nu_e + 26.7\ \mathrm{MeV}$$



- More detailed (pp chain, also sub-dominant CNO cycle):





Accelerator neutrinos

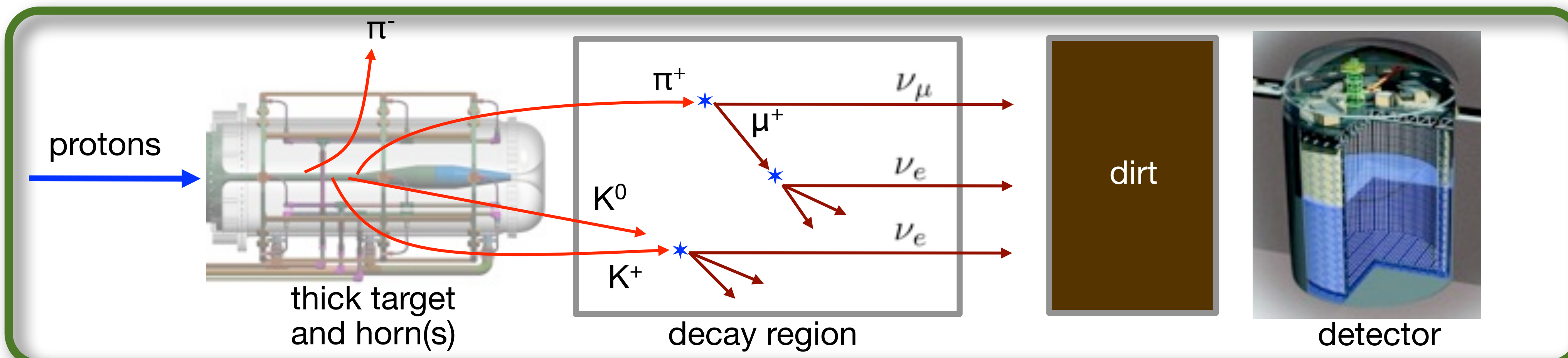
Flavors: ν_μ, $\bar{\nu}_\mu$, ν_e, $\bar{\nu}_e$

E_ν ~ 0.1-100 GeV

- First source providing high-energy neutrinos, and of muon flavor type!

Neutrino primary beamline

Steinberger, Schwartz, Lederman



- Neutrinos from decay-in-flight of magnetically focused mesons. Can choose polarity!
- Mesons produced through hadronic interactions of primary protons with thick target
- Energy of on-axis neutrinos ~ 0.1 proton energy, less for off-axis neutrinos
- Dedicated hadron production experiments to understand neutrino flux

Accelerator neutrinos

Parameters from modern-day beamlines

Flavors: ν_μ, $\bar{\nu}_\mu$, ν_e, $\bar{\nu}_e$

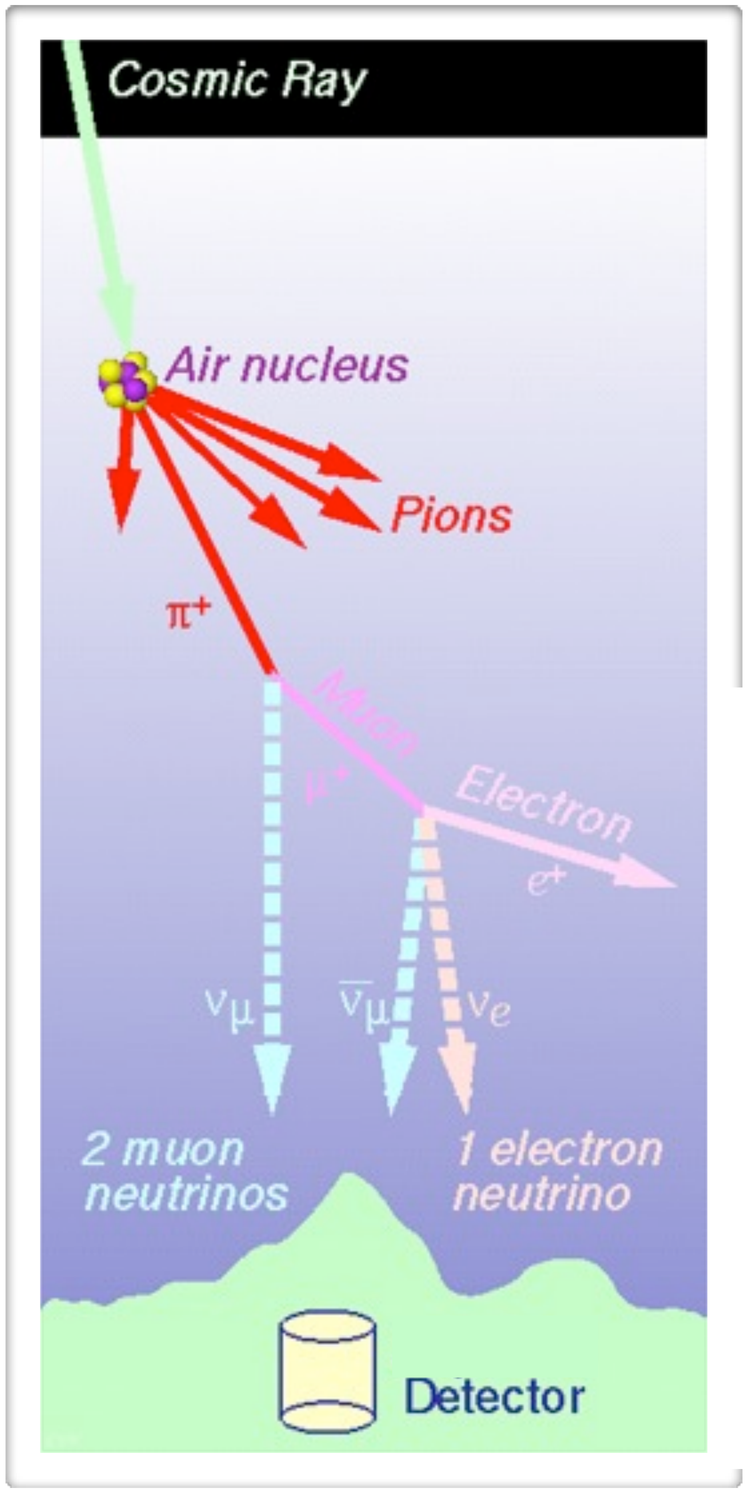
E_ν ~ 0.1-100 GeV

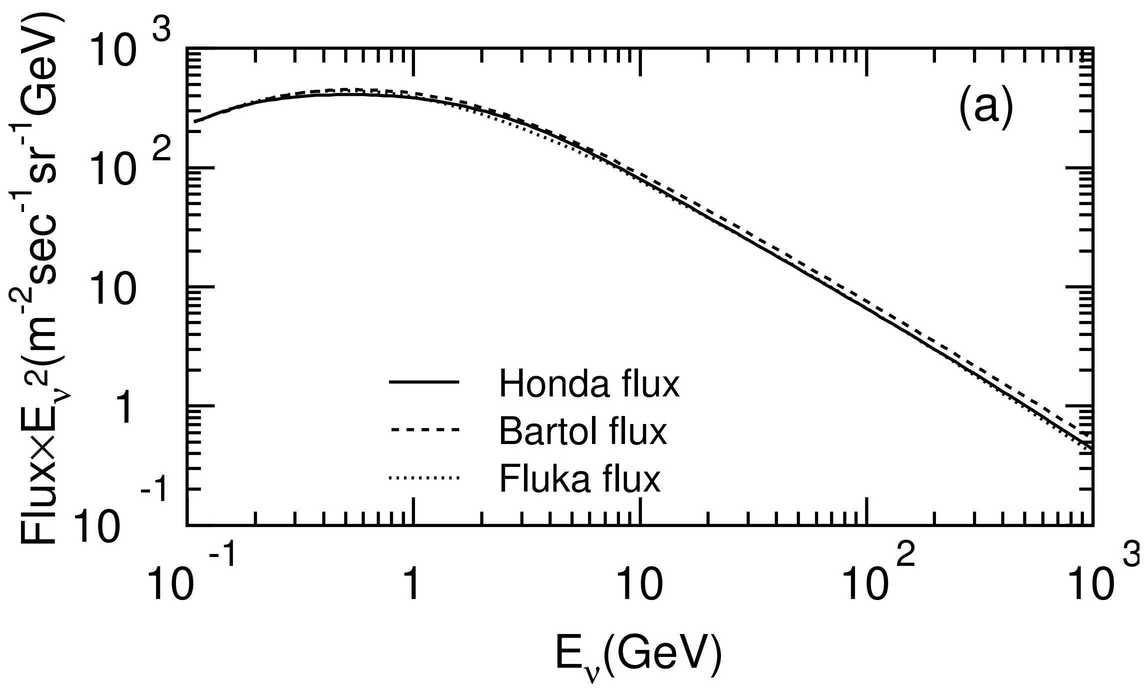
	Booster (Fermilab)	Main Injector (Fermilab)	SPS (CERN)	Main Ring (JPARC)	Main Injector (Fermilab)
Date	2002	2005	2006	2009	2013
Proton kinetic energy (GeV)	8	120	400	30 (50)	120
Beam power (kW)	12	350	510	240 (750)	700
Target material	beryllium	graphite	graphite	graphite	graphite
Target length (cm)	71	95	1000	91	120
Secondary focusing	1 horn WBB	2 horn WBB	2 horn WBB	3 horn off-axis	2 horn off-axis
Decay region length (m)	50	675	130	96	675
Typical neutrino energy (GeV)	1	3-20	17	0.6	2
Experiments	MiniBooNE, SciBooNE, MicroBooNE	MINOS, MINERvA	OPERA, ICARUS	T2K	NOvA, MINERvA, MINOS+

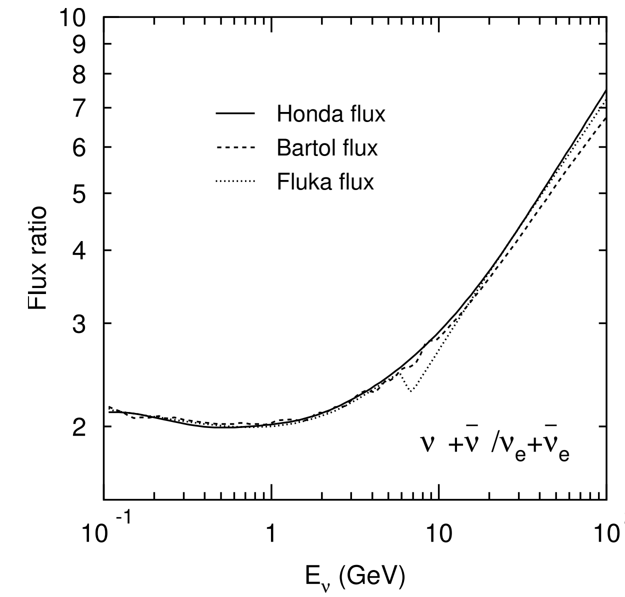
Atmospheric neutrinos

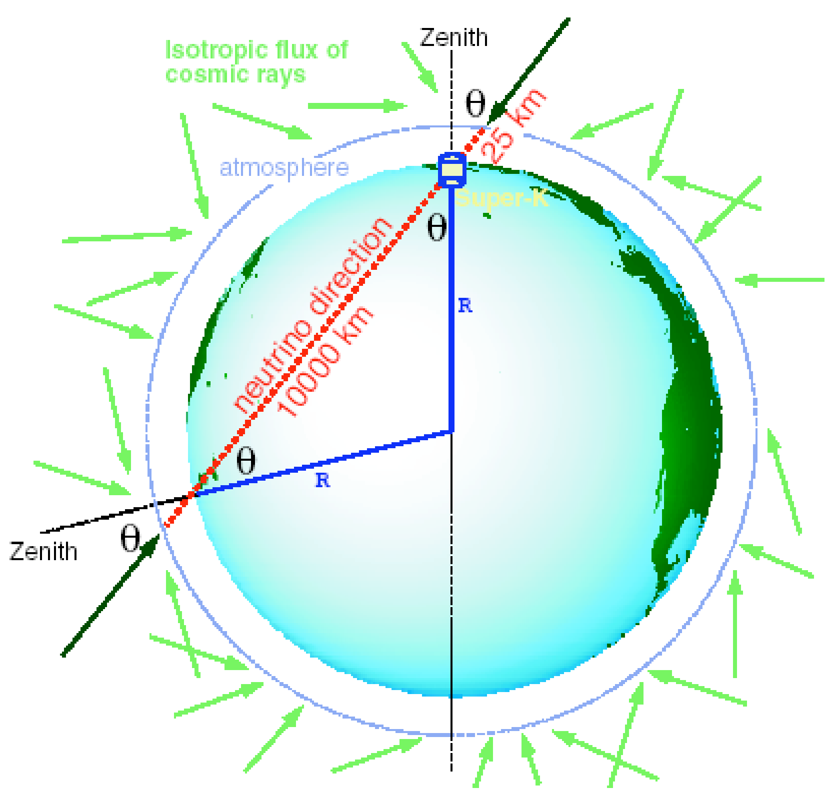
Flavors: ν_μ, $\bar{\nu}_\mu$, ν_e, $\bar{\nu}_e$

E_ν ~ 0.1-100 GeV









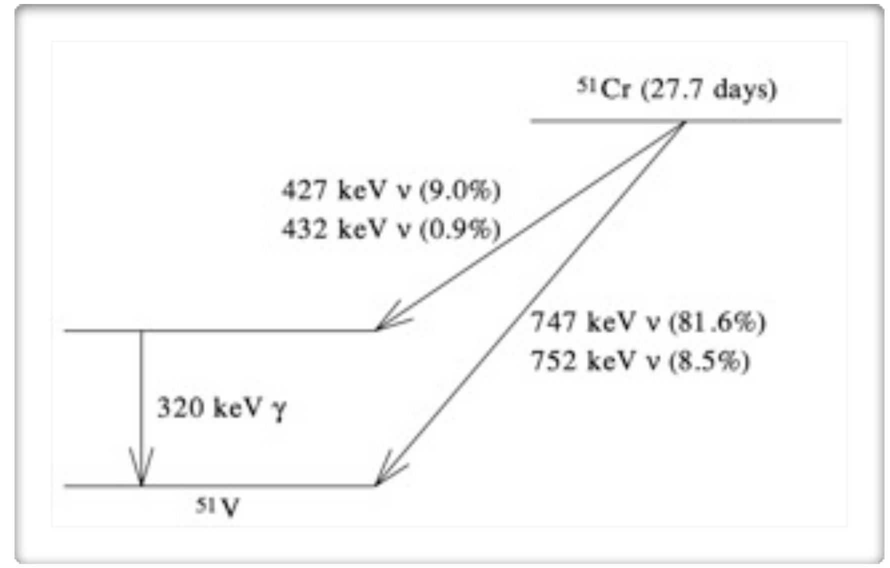
- Source conclusively establishing neutrino oscillations!
- Produced by cosmic ray interactions in the atmosphere
- Pion/muon decay chain yield yield ν_μ:ν_e ratio close to 2
- All directions

Radioactive source neutrinos

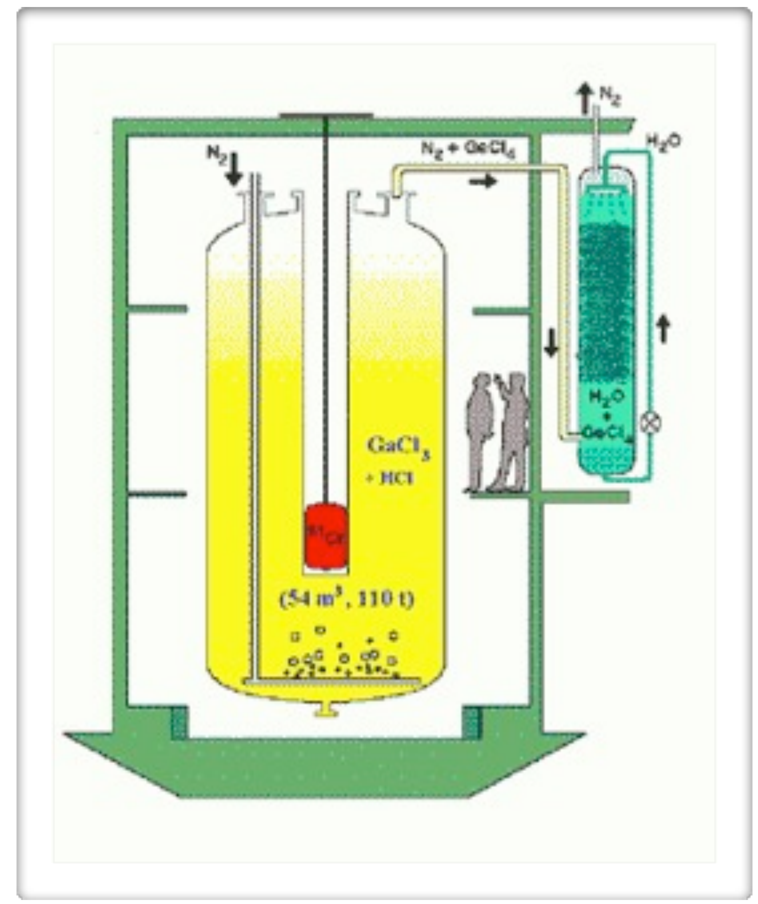
Flavors: ν_e, $\bar{\nu}_e$

E_ν ~ 0.1-5 MeV

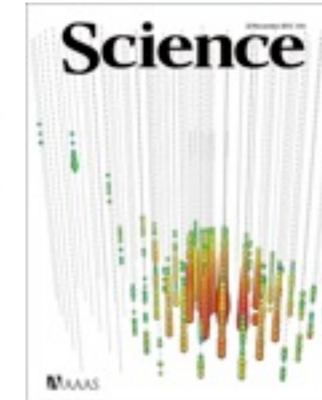
- Three types of (1st order) nuclear transitions producing neutrinos or antineutrinos:
  - β^- decay: $(Z,A) \rightarrow (Z+1,A) + e^- + \bar{\nu}_e$
  - β^+ decay: $(Z,A) \rightarrow (Z-1,A) + e^+ + \nu_e$
  - Electron Capture (EC): $(Z,A) + e^- \rightarrow (Z-1,A) + \nu_e$

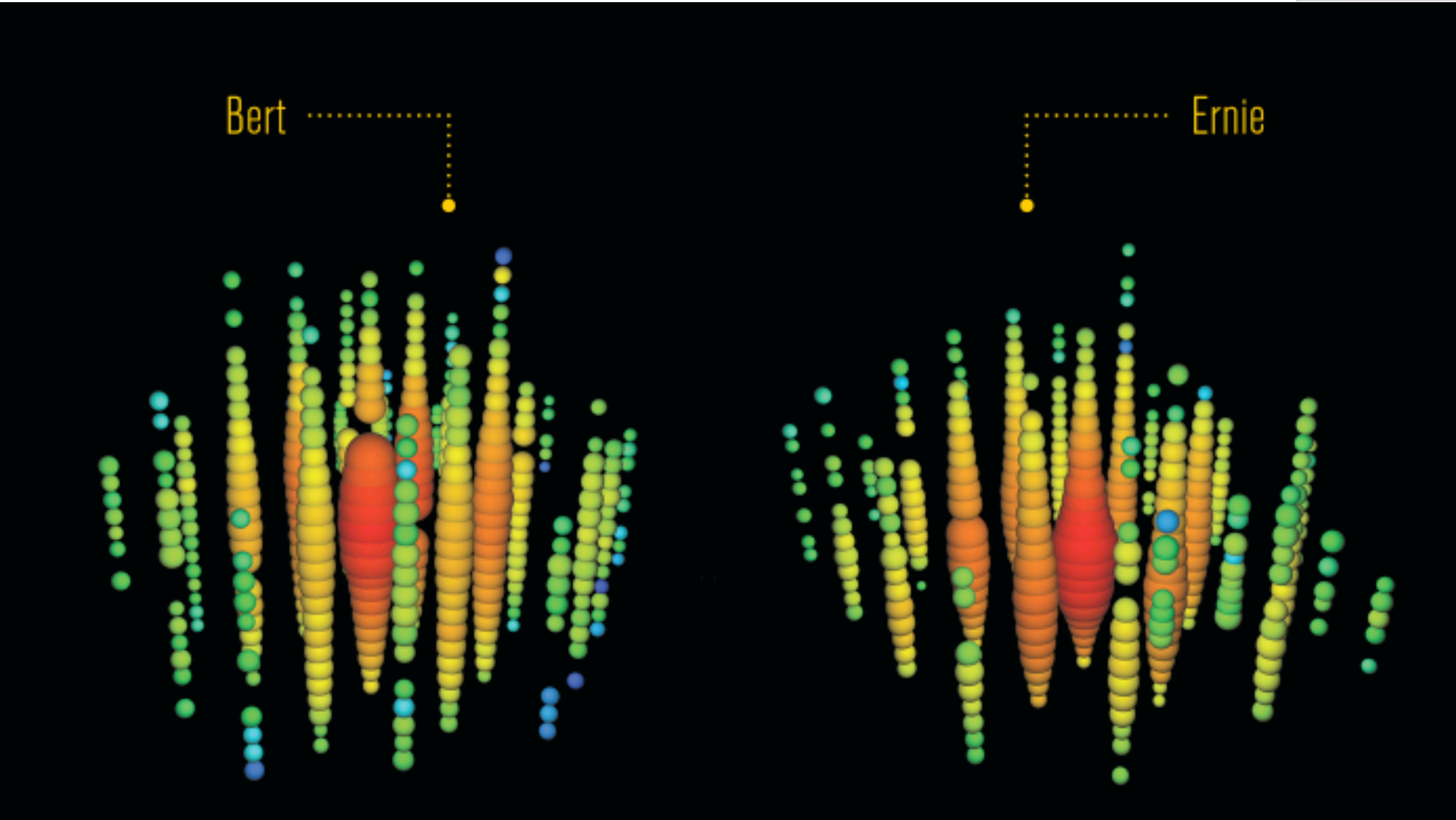


- Very intense radioactive sources have been used to calibrate solar neutrino detectors
- Have also been proposed for oscillometry experiments to study short-baseline neutrino anomalies
- Possible sources: electron capture of ^{51}Cr, β^- decay of ^{144}Ce
- GALLEX: 1.7 MCi ^{51}Cr source! Emitted ~300 W of heat!



High-energy cosmic neutrinos!





High-energy cosmic neutrinos!

Flavors: all?

$E_\nu \sim$ 10-1000 TeV

- Recently observed by IceCube!

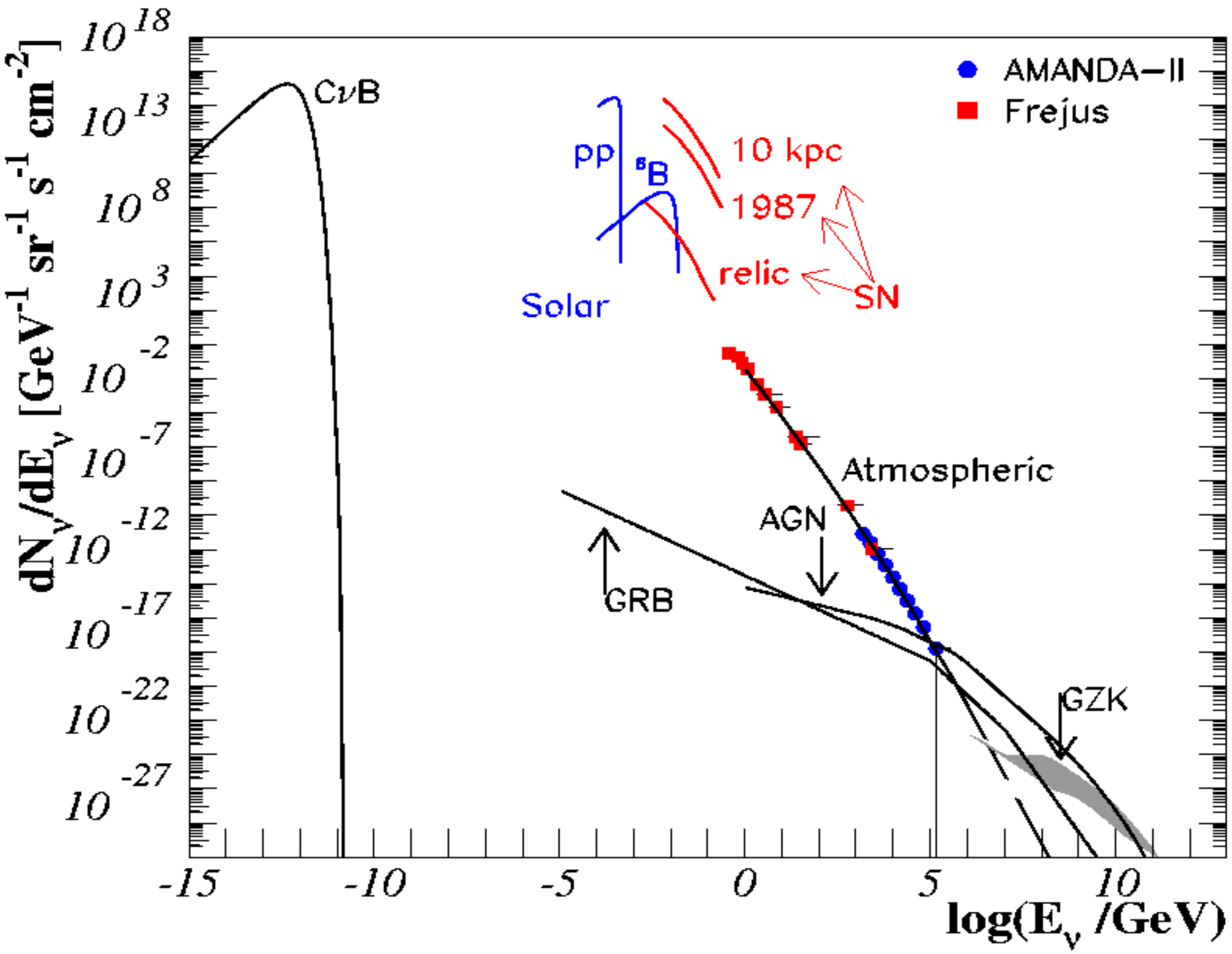
- Applications: mostly neutrino astronomy, also neutrino oscillations

- Ultra-high energy cosmic rays (protons, etc.) from cosmic accelerators
  - Gamma-Ray Bursts (GRBs)
  - Active Galactic Nuclei (AGNs)

- Neutrinos produced from decay of unstable mesons, as in atmosphere

- At even higher energies: cosmogenic GZK neutrinos from the interactions of UHE cosmic rays with CMB photons

- Expect $\nu_e:\nu_\mu:\nu_\tau$ = 1:1:1 flavor composition on Earth from oscillations

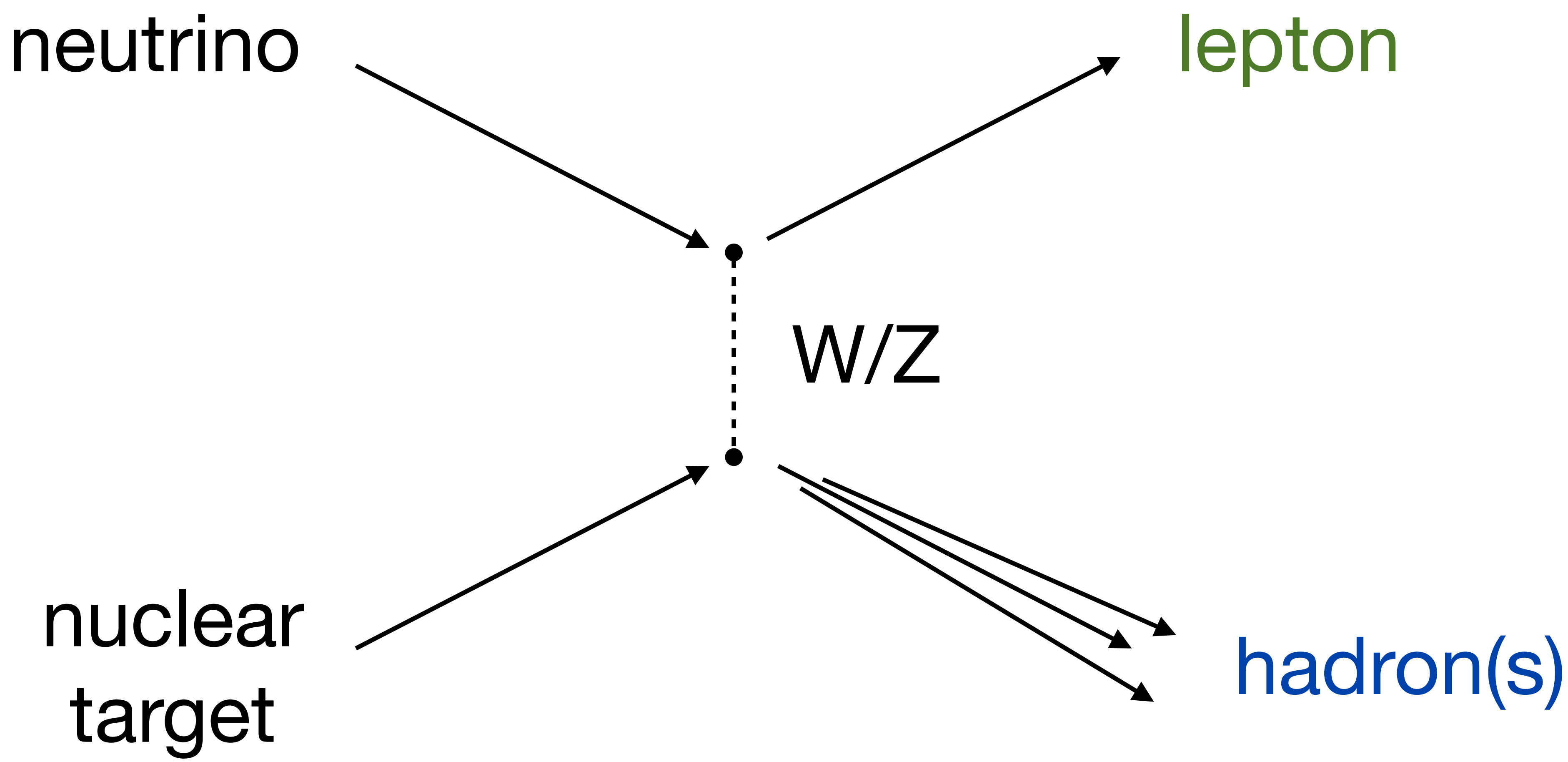


Neutrino oscillation experiments

Neutrino interactions with matter

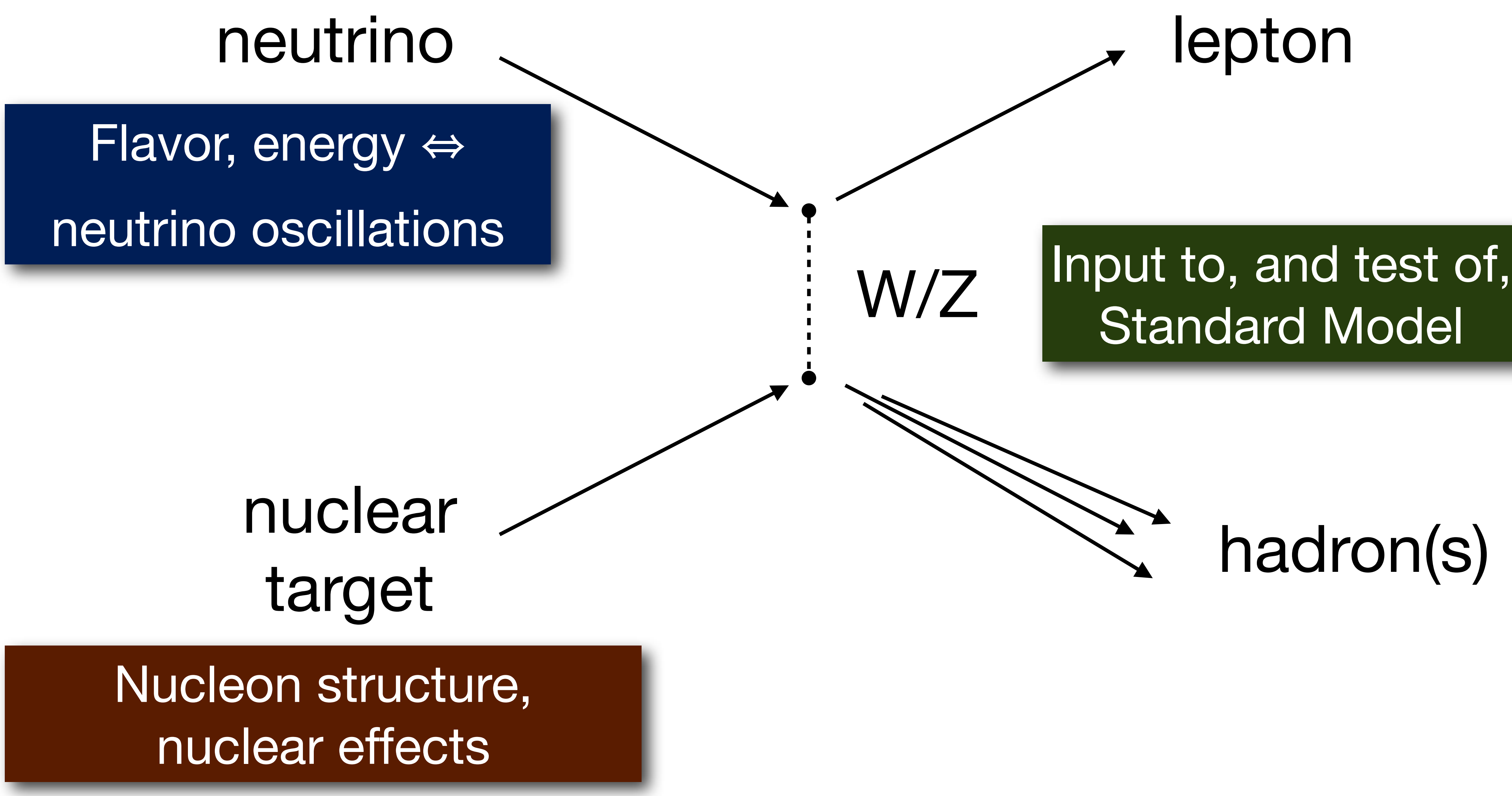
Why study neutrino interactions?

- Measure final state lepton and/or hadron(s)



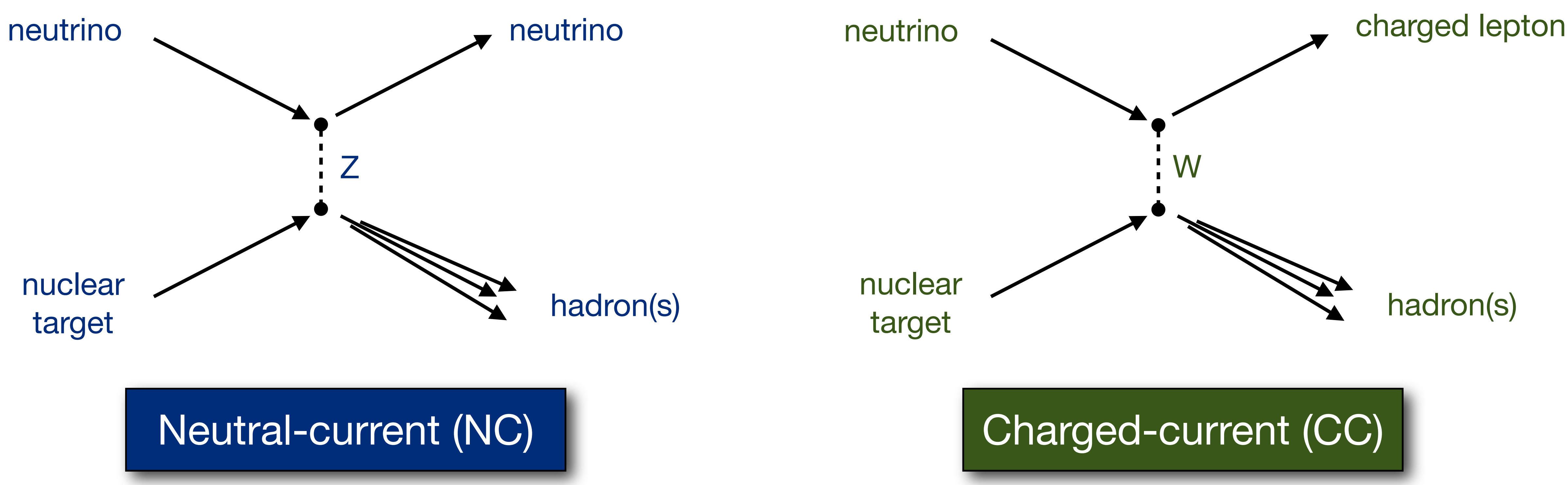
Why study neutrino interactions?

- Infer electroweak, nuclear, neutrino properties



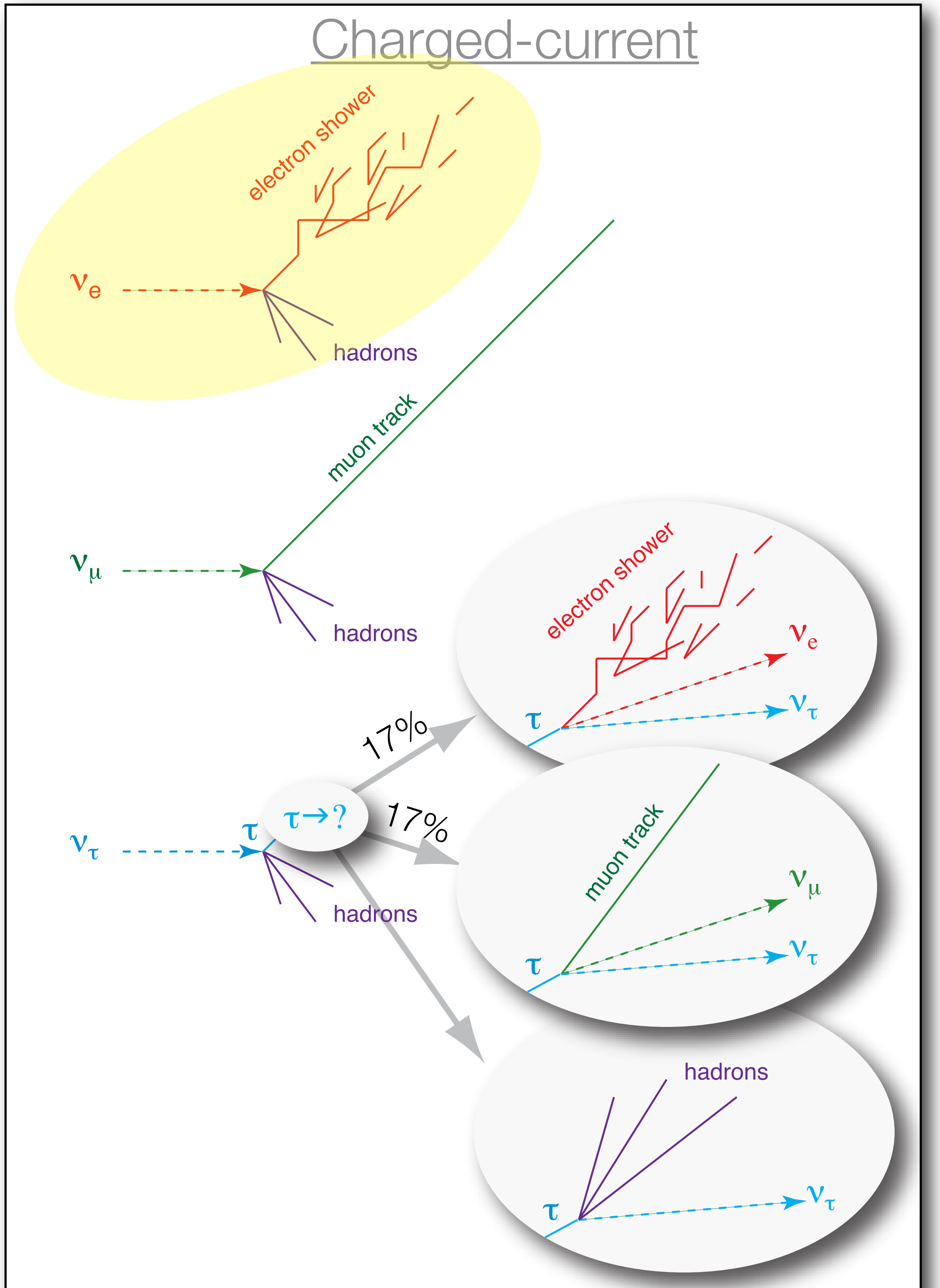
Neutrino interactions and oscillations

- Neutrinos interact only via the weak interaction
  - Either neutral- or charged-current

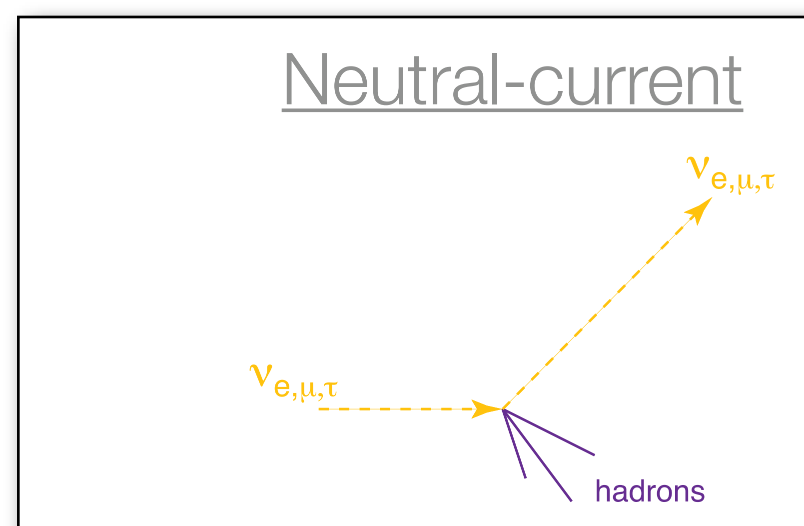


- We identify the neutrino flavor via the CC interaction
  - CC interactions used for oscillation measurements
  - NC interactions are not affected by oscillations, but can be background to CC signals!
- In CC interactions, nearly all the neutrino energy is deposited in the detector
  - Not so for NC interactions

Neutrino interaction signatures

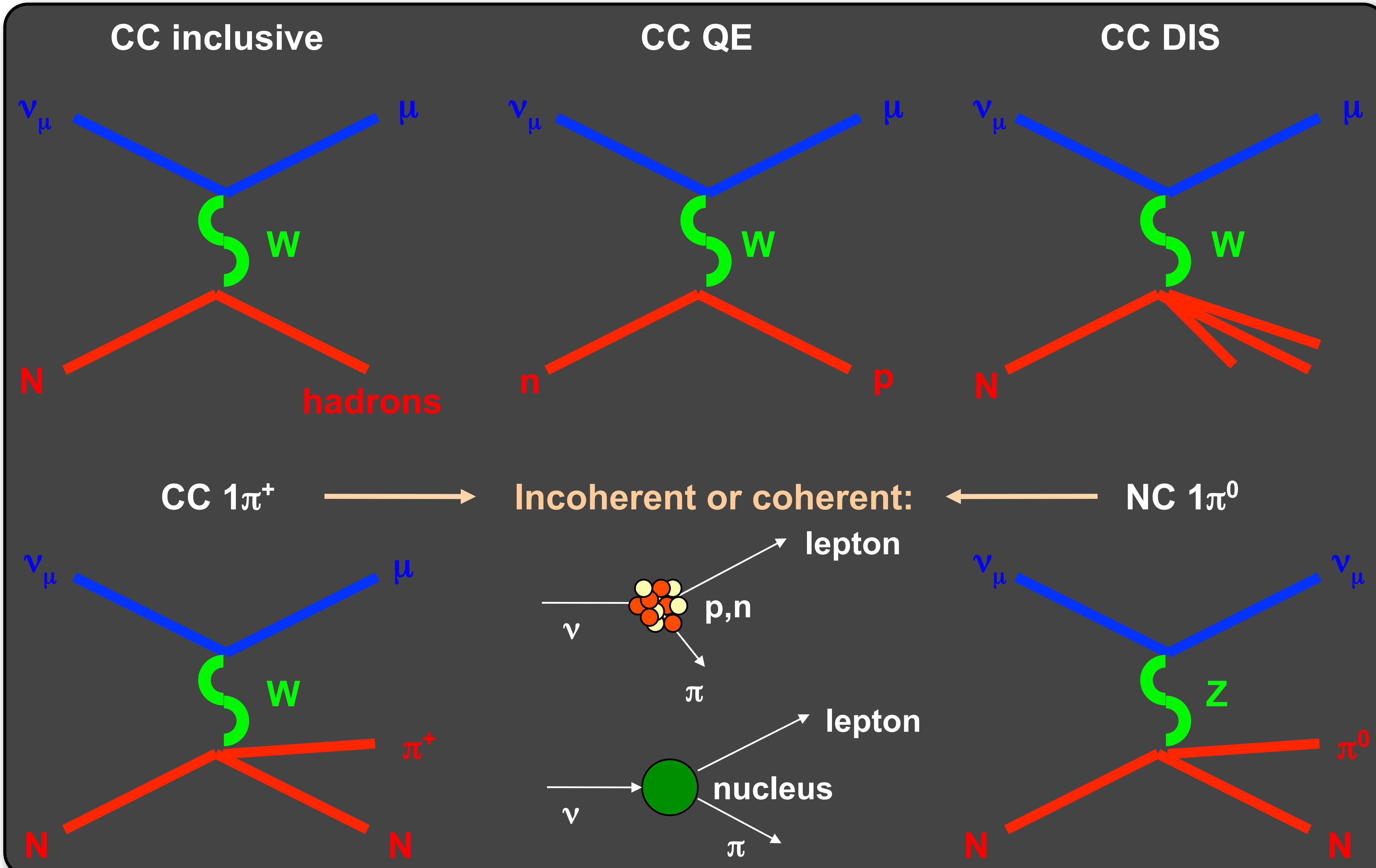


- Experiments can typically distinguish the following neutrino interaction products:
  - Electrons and electron showers
  - Muon tracks
  - Hadrons and hadronic showers
  - Tau decay products



Some important neutrino interactions

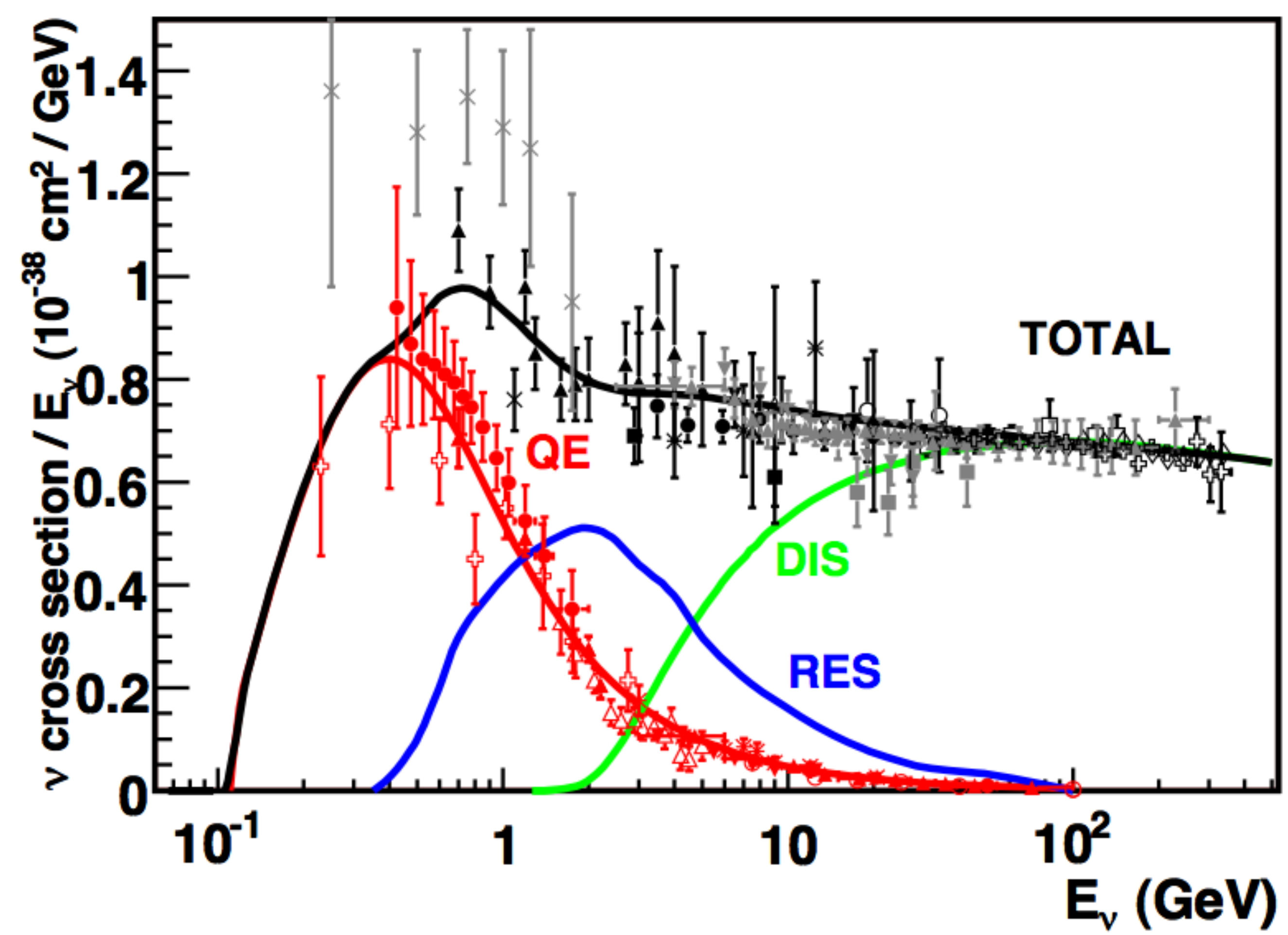
Examples for few-GeV muon neutrino interactions



Current knowledge of neutrino interactions

- 1-100 MeV energy: $\bar{\nu}_e + p \rightarrow e^+ + n$ known with ±0.5% accuracy!
  - If scattering not off free protons, more uncertain because of nuclear effects
- 0.1-20 GeV energy: many processes, insufficient knowledge (10-20% level)
- 20-300 GeV energy: DIS interactions off quarks, known with few % accuracy

- Muon neutrino cross sections
- Note: divided by neutrino energy! (to 1st order: σ proportional to E_ν)

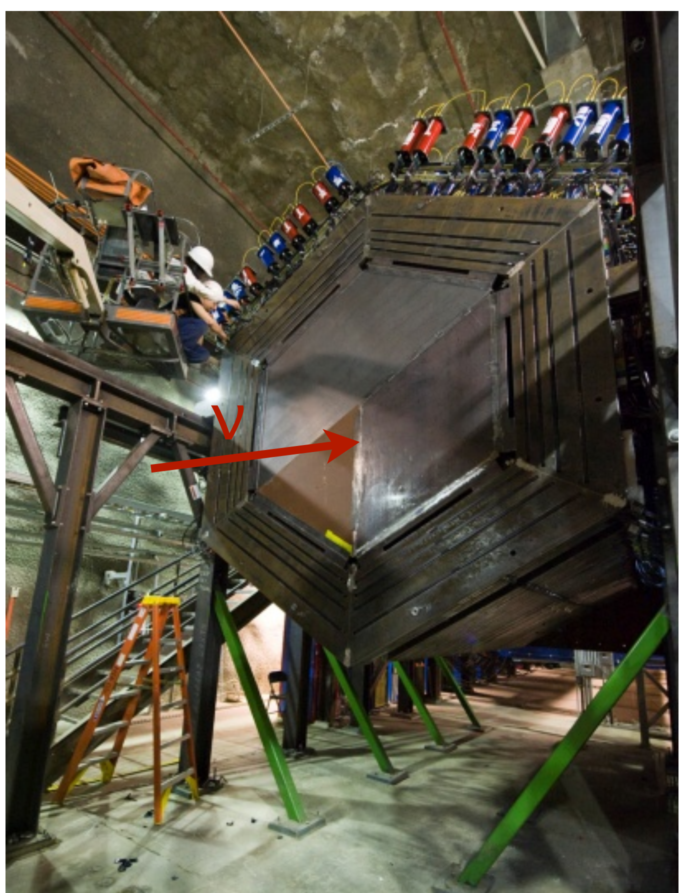


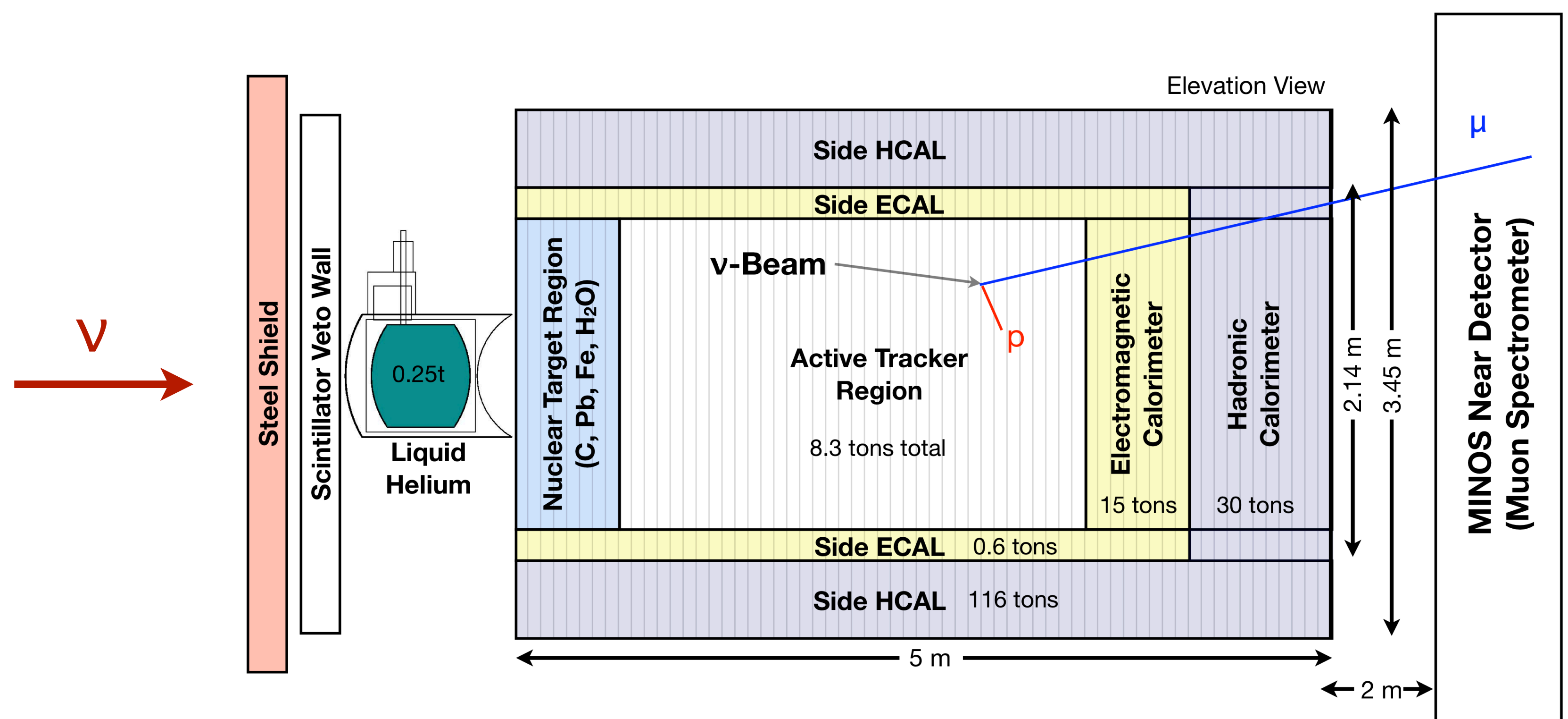
Neutrino scattering measurements

- Accurate knowledge of neutrino interactions (both signal and background processes) is essential for sensitive neutrino oscillation searches!

- Need of dedicated neutrino scattering experiments. Example: MINERvA experiment

- Neutrino interaction studies also with “near detectors” at oscillation experiments

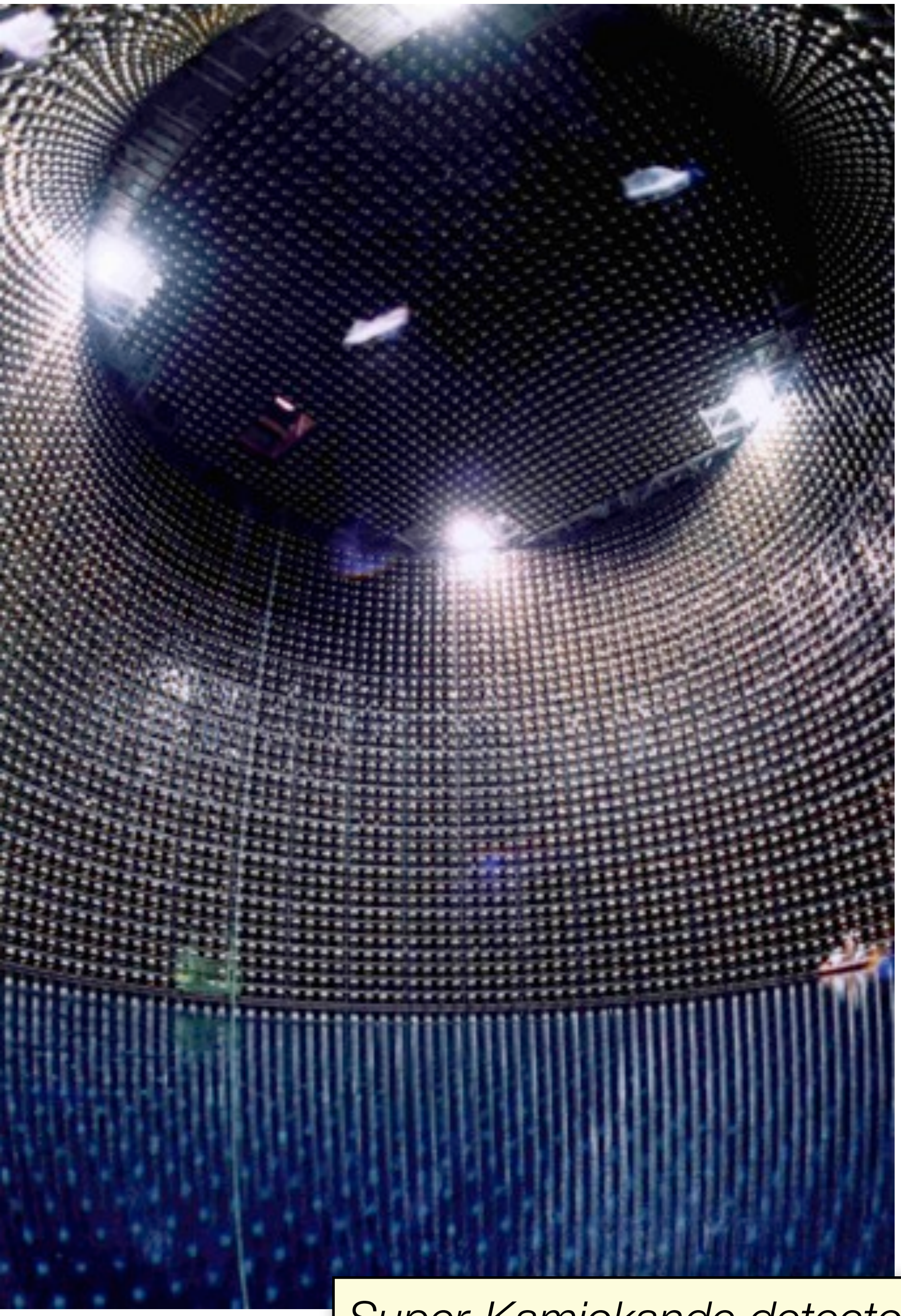




Neutrino oscillation experiments

Neutrino detector technologies

Cherenkov detectors

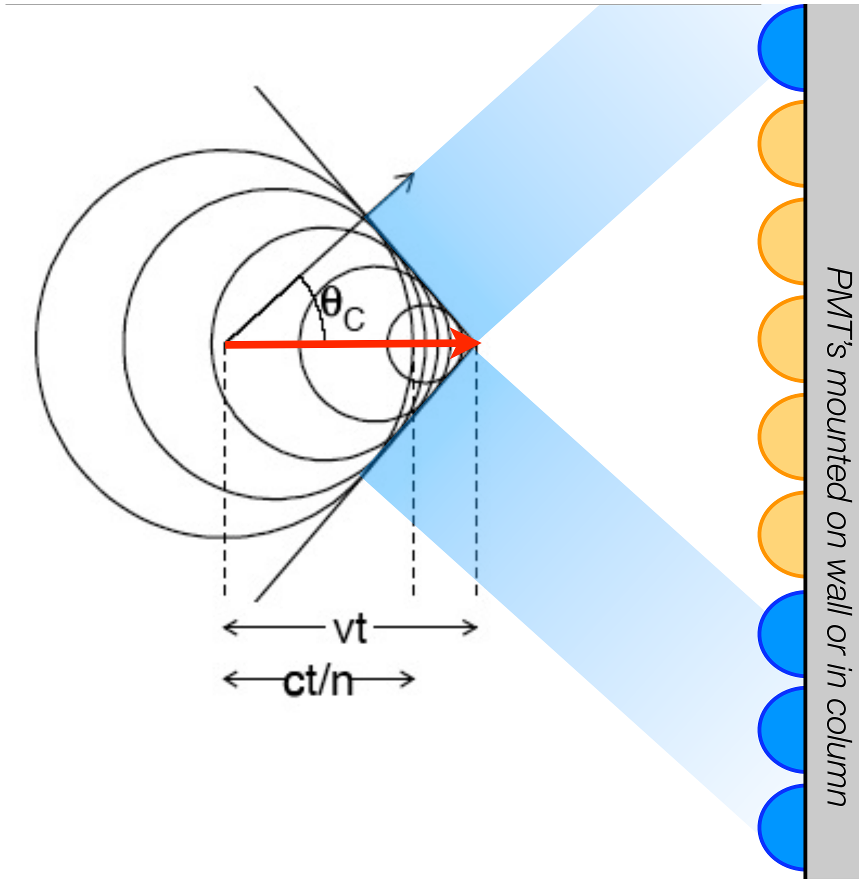


Super-Kamiokande detector

- If speed of charged particle exceeds speed of light in detector medium (eg, water), Cherenkov radiation produced

$$\boxed{\cos\theta_C = \frac{1}{\beta n}, \beta > \frac{1}{n}}$$

- PMTs charge and time information can reconstruct:
  - vertex position
  - number of tracks
  - direction of tracks
  - energy of tracks
  - particle types

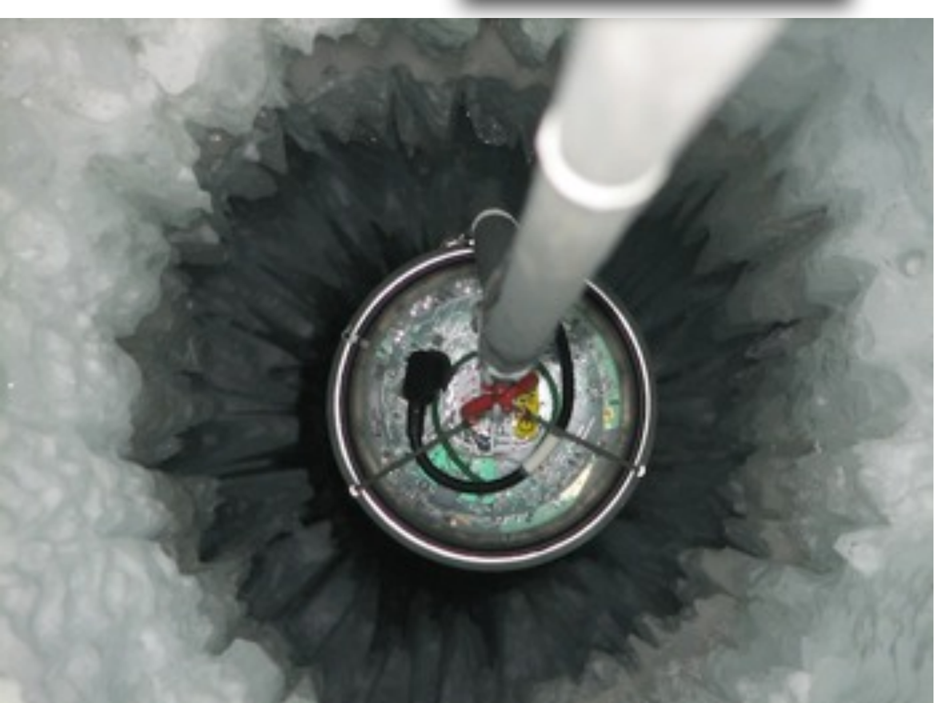


Cherenkov detectors

IceCube detector

- If speed of charged particle exceeds speed of light in detector medium (eg, water), Cherenkov radiation produced

$$\boxed{\cos\theta_C = \frac{1}{\beta n}, \beta > \frac{1}{n}}$$



- PMTs charge and time information can reconstruct:
  - vertex position
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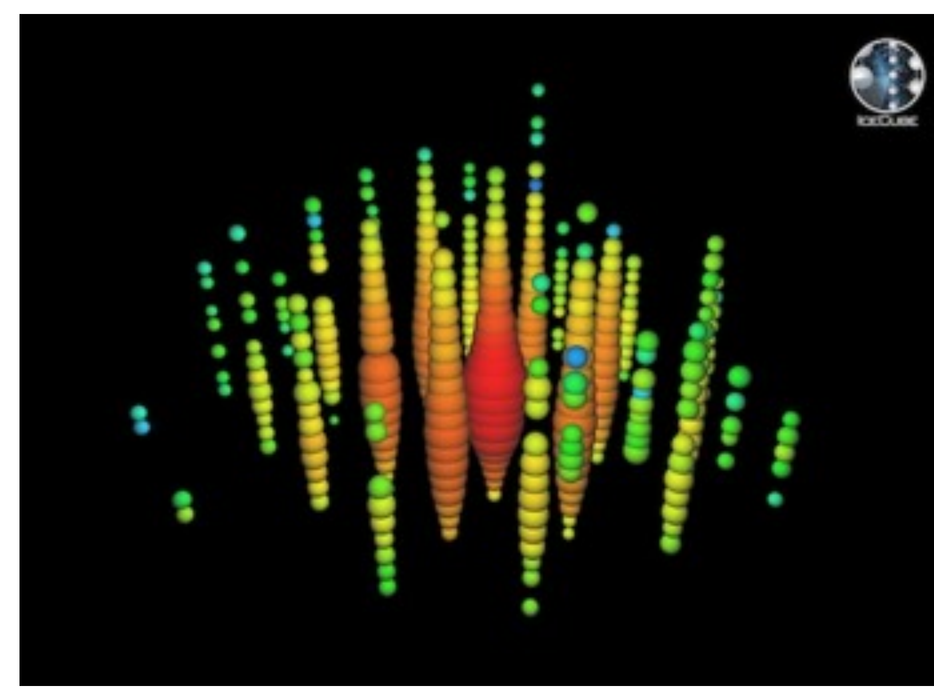
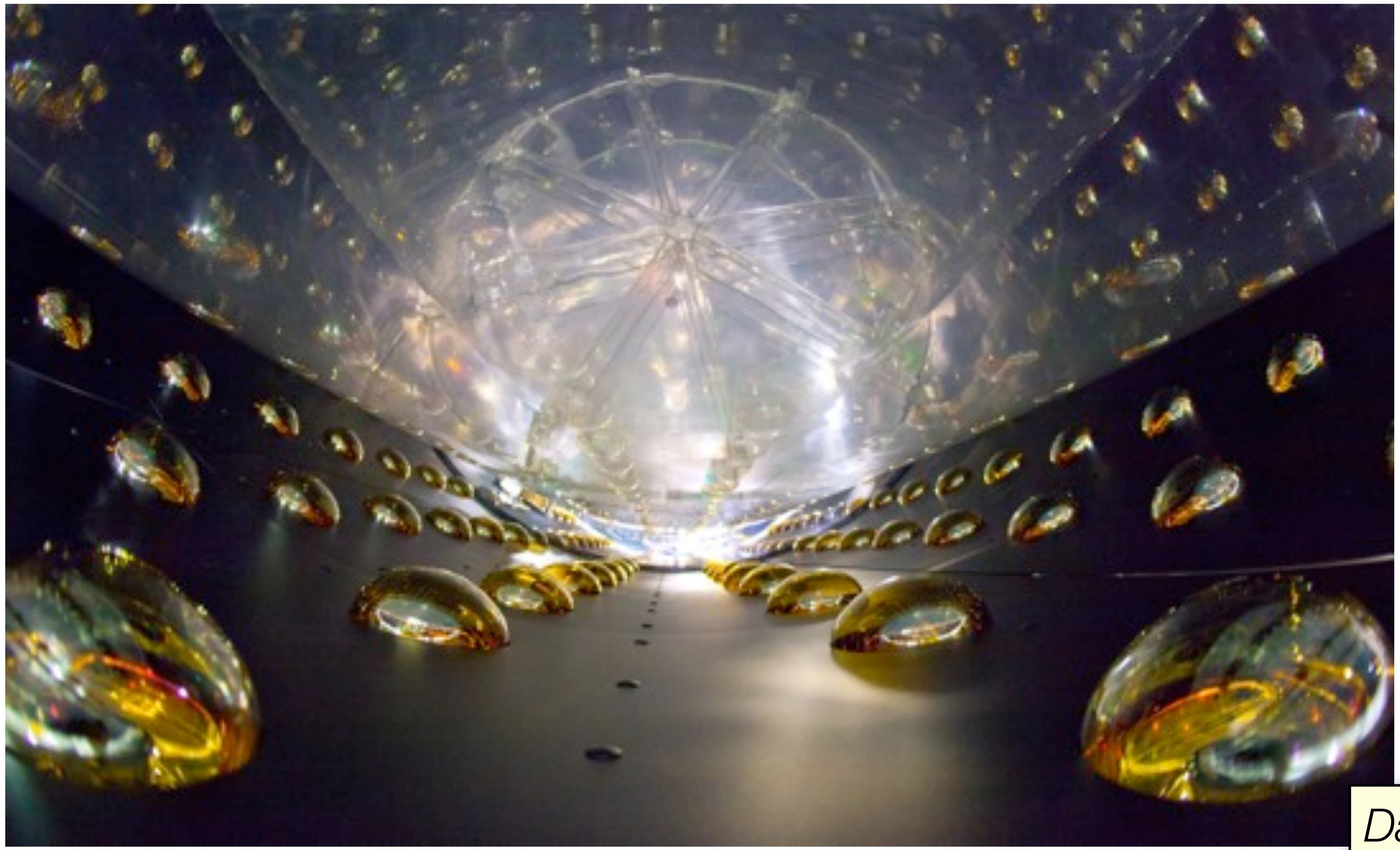
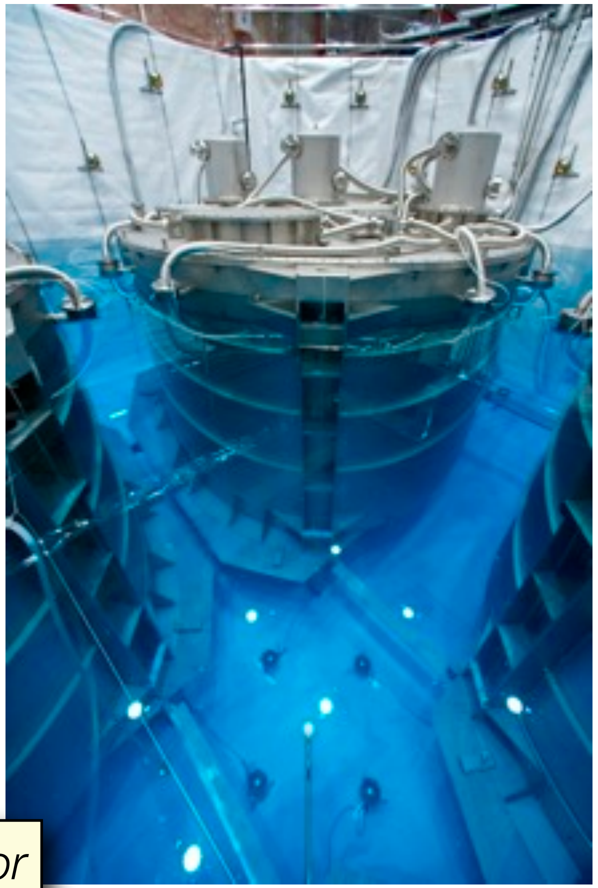
  - energy of tracks
  - particle types



Liquid scintillator detectors

- Large volume of liquid scintillator viewed by PMTs
- Larger light collection than water Cherenkov, lower energy threshold (~1 MeV)
- Key factor at low energies is radioactive background suppression ("onion-shell" designs)
- Scintillation light emitted isotropically → lose directionality information
- As antineutrino detector, background suppression by requiring (e^+,n) double coincidence following $\bar{\nu}_e + p \rightarrow e^+ + n$ signal





Daya Bay detector

Segmented tracking calorimeters

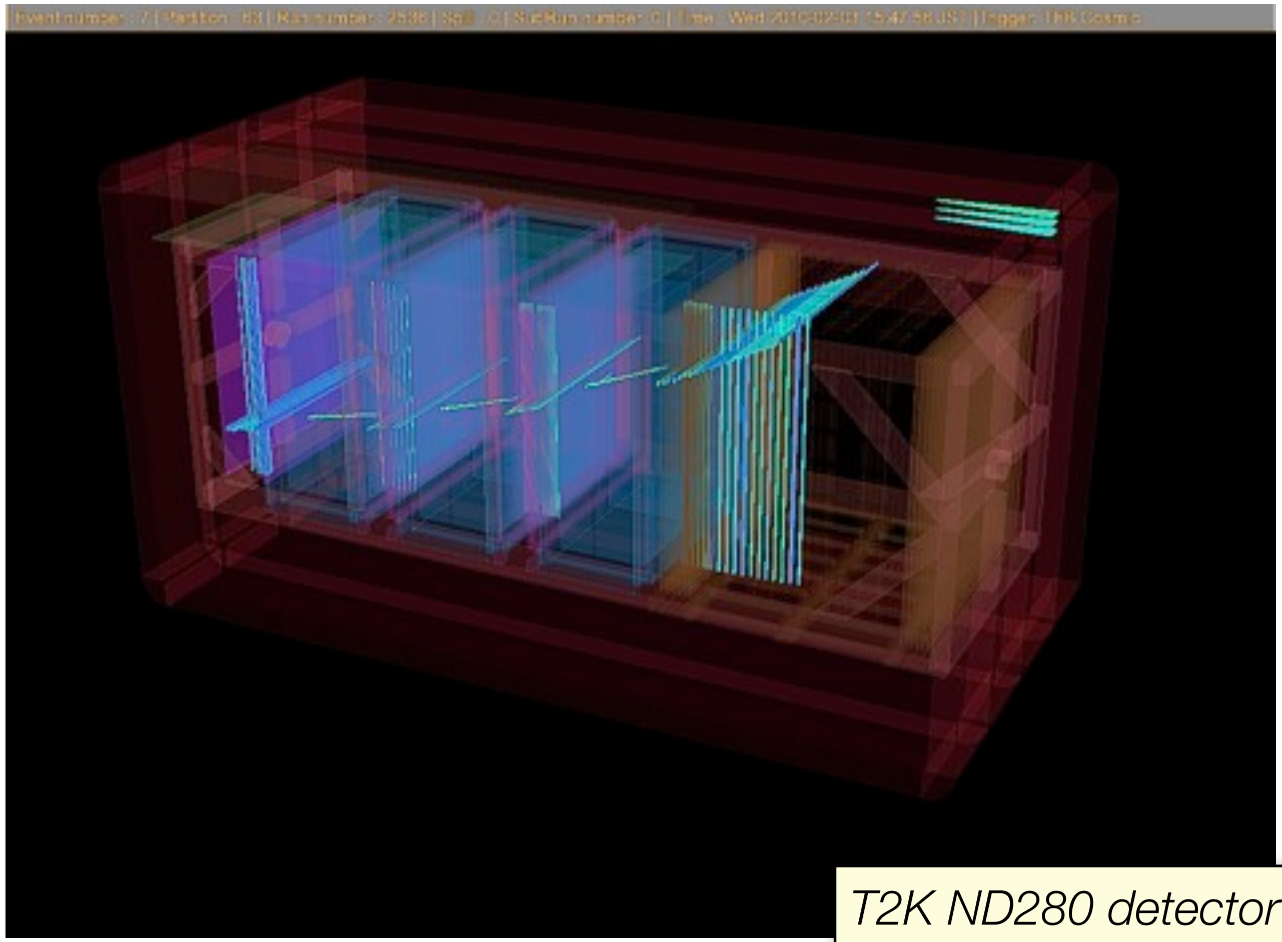
- Stack of scintillator planes (plastic or liquid), each made of bars providing xz or yz view
- Alternate xz and yz planes for full 3D track reconstruction
- Can be either fully active calorimeter, or sampling calorimeter (alternate active and passive planes of material)
- Can be magnetized, to measure track momentum by curvature and charge sign

MINOS detector

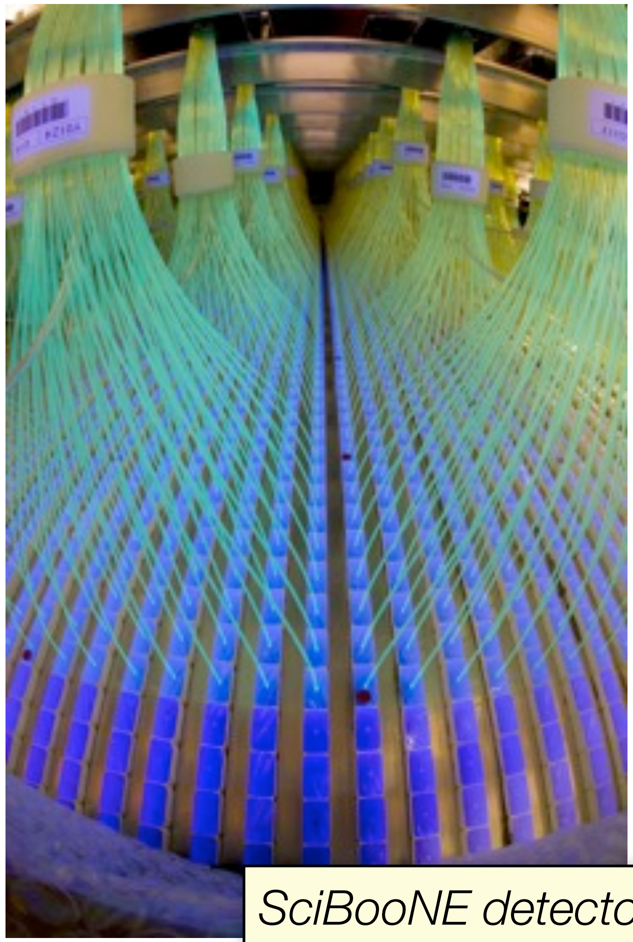
NOvA detector

Segmented tracking calorimeters

- Stack of scintillator planes (plastic or liquid), each made of bars providing xz or yz view
- Alternate xz and yz planes for full 3D track reconstruction
- Can be either fully active calorimeter, or sampling calorimeter (alternate active and passive planes of material)
- Can be magnetized, to measure track momentum by curvature and charge sign



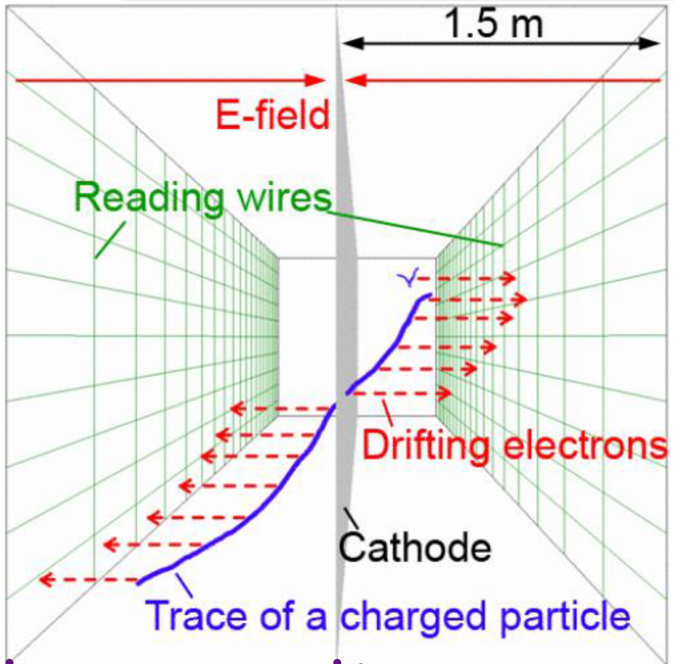
T2K ND280 detector



SciBooNE detector

Liquid argon time projection chambers

LAr TPCs



ICARUS T600 detector

- Charged particles deposit energy in LAr via ionization and scintillation
- Ionization electrons collected by establishing drift field between cathode and readout planes
- TPC detection principle: full 3D imaging from 2D image on readout planes (wires, pads) as a function of electron drift time (3rd dimension)
- Scintillation light provides fast trigger signal and absolute event timing

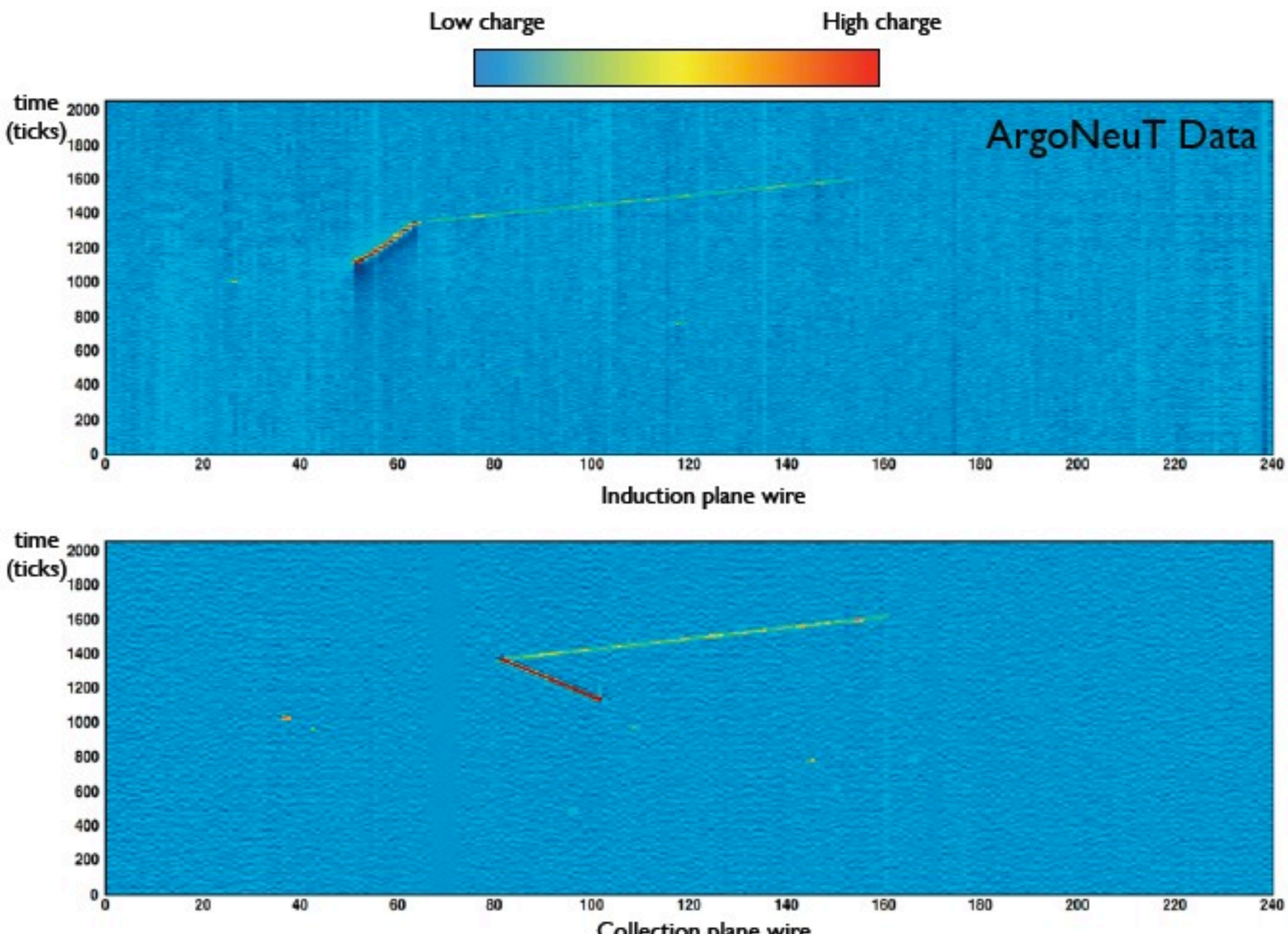
<u>Advantages</u>:

- Excellent imaging from mm-scale resolution
- Accurate calorimetry from fully active volume and large ionization signal (1 electron / 24 eV deposited energy)
- Particle identification from dE/dx information

<u>Disadvantage</u>: technically challenging! (Argon purity, cryogenics, HHV)

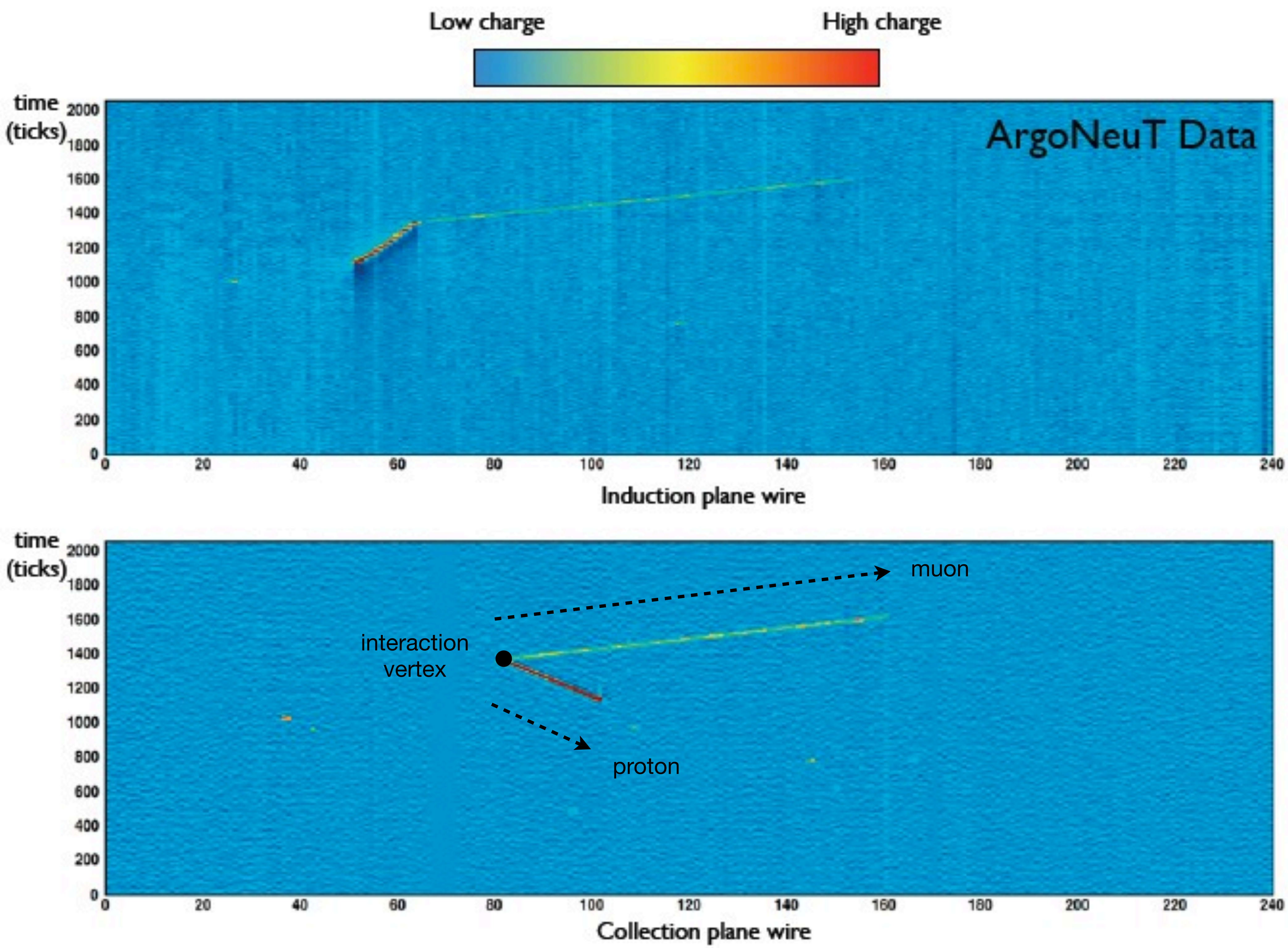
Liquid argon time projection chambers

What is going on in this event?



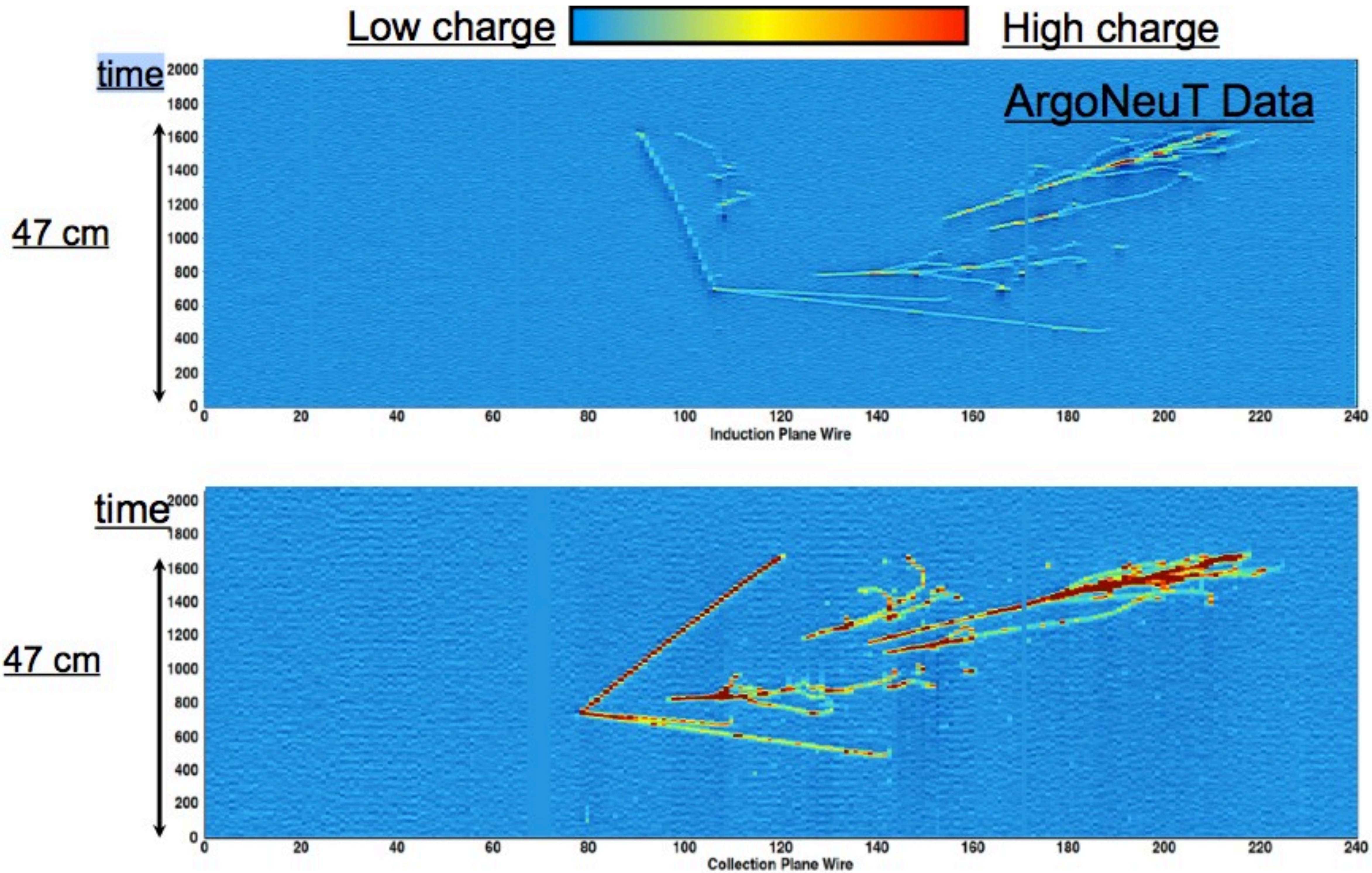
Liquid argon time projection chambers

What is going on in this event?



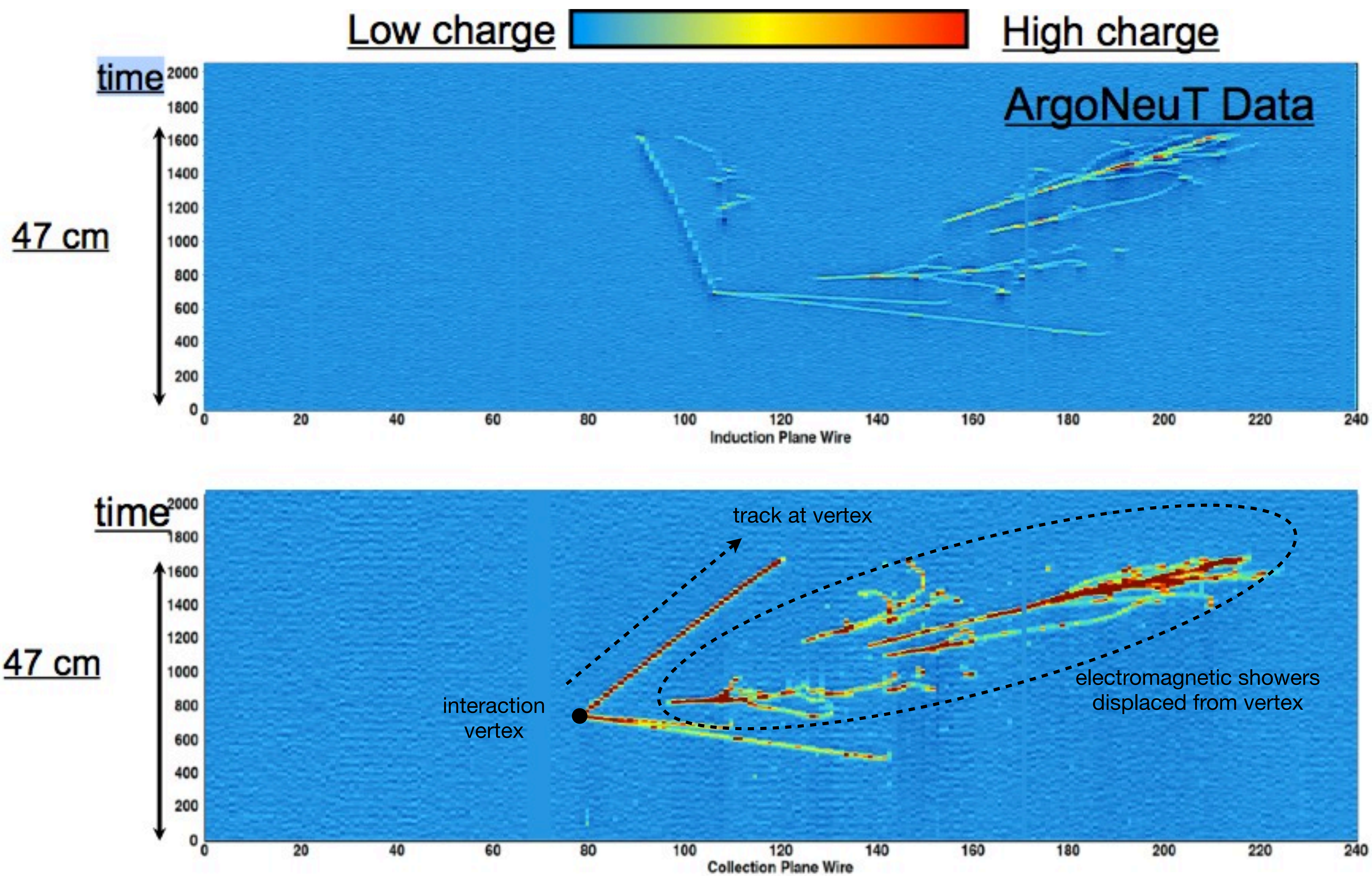
Liquid argon time projection chambers

What is going on in this other event?



Liquid argon time projection chambers

What is going on in this other event?

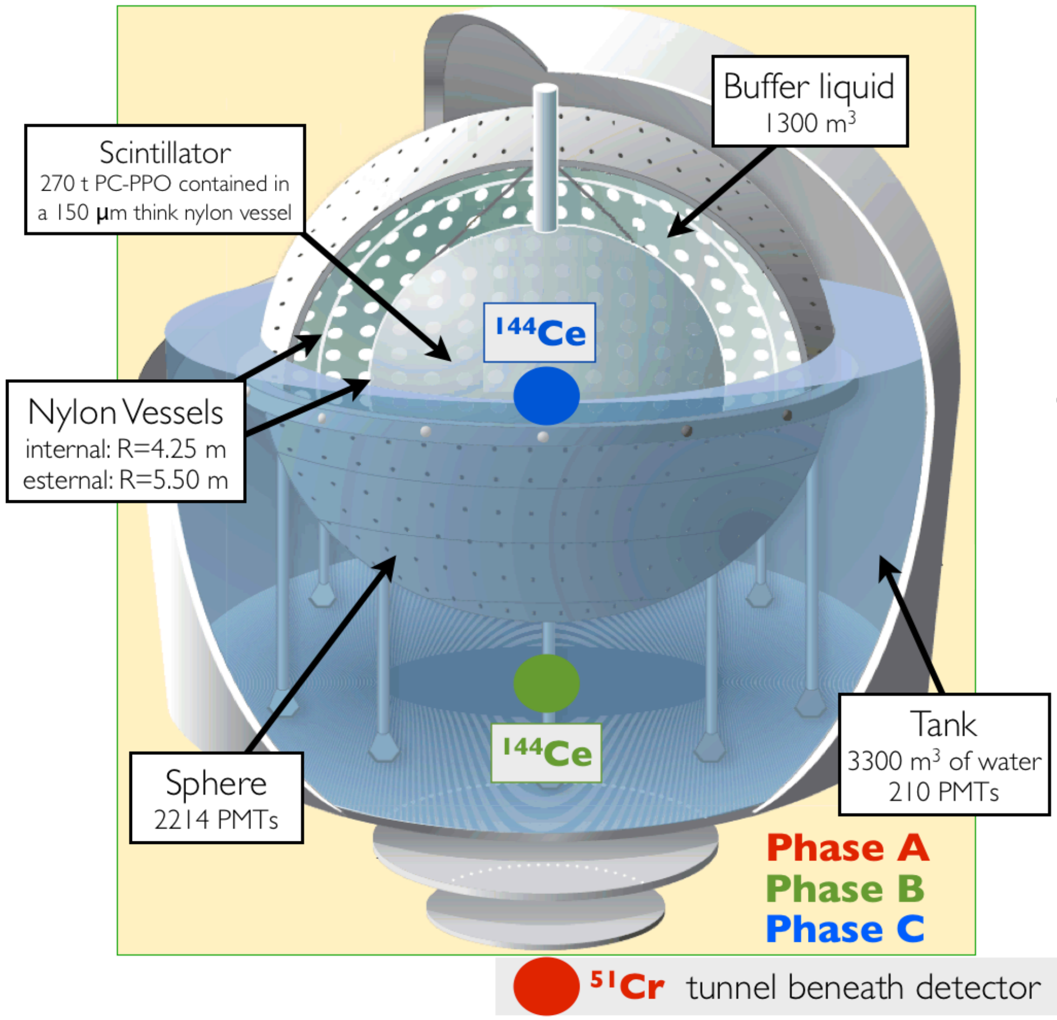


Neutrino oscillation experiments

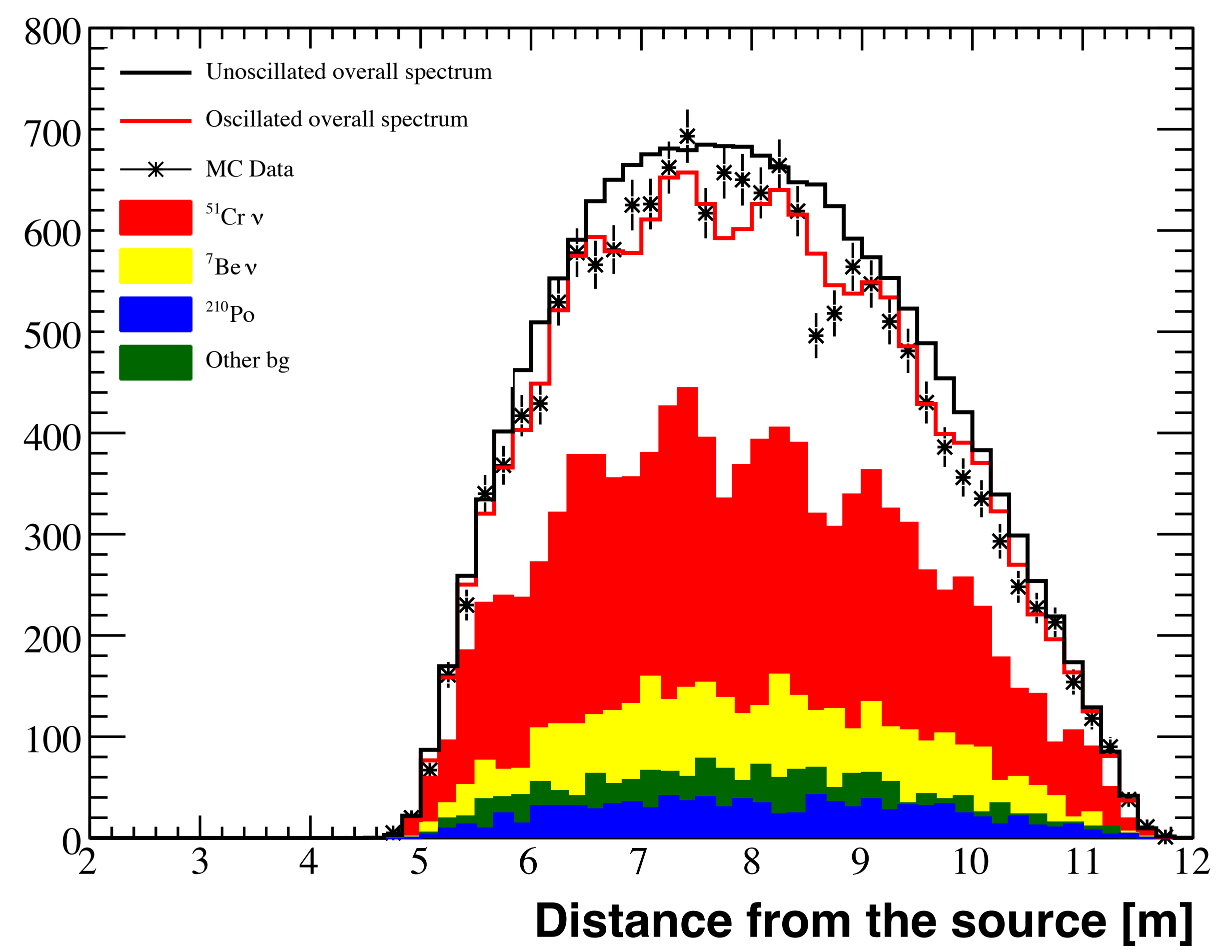
A selection of current and future experiments

SOX

Starting in 2015?



- SOX: short distance neutrino oscillations with Borexino liquid scintillator detector
- Chromium and Cerium sources to be deployed under the experiment (phases A and B)



- Unmistakable spatial wave pattern in case of oscillations into sterile neutrinos
- Sensitive to reactor anomaly

MicroBooNE

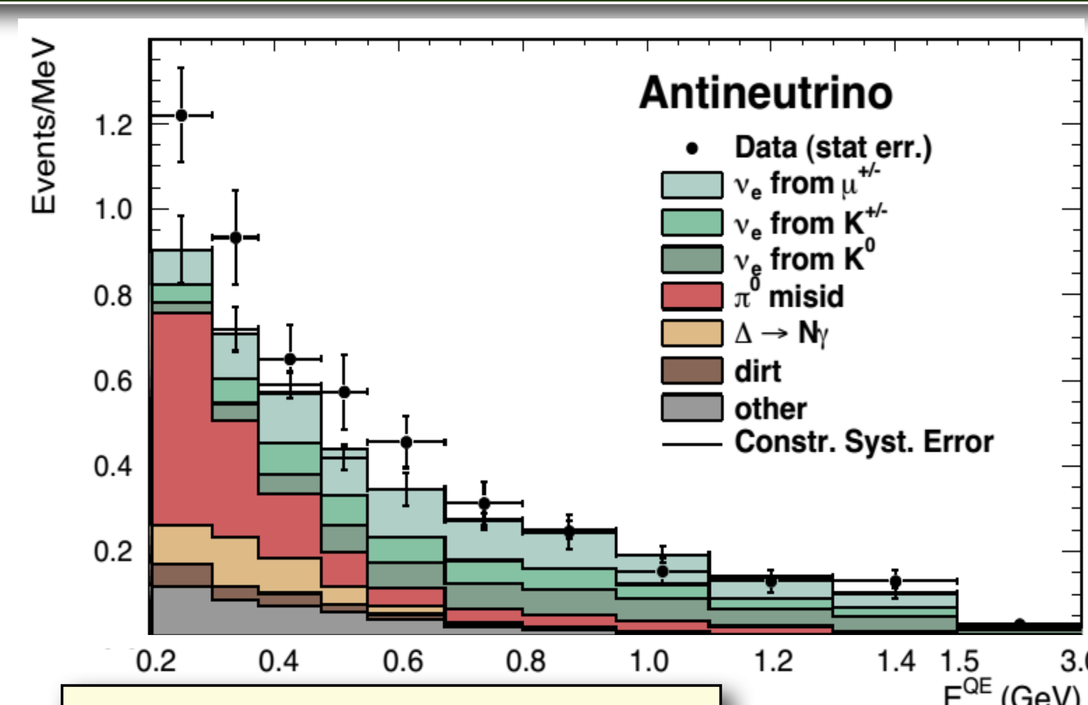
Starting in 2014

- 170 ton LAr TPC in Booster Neutrino Beamline at Fermilab

Physics goals:

- MiniBooNE low-energy excess: electrons (oscillation signal) or gammas (background)?
- Neutrino cross sections on argon

- R&D goals:
  - Long drift (2.5 m)
  - Cold electronics (preamplifiers in liquid)
  - Purity without evacuation

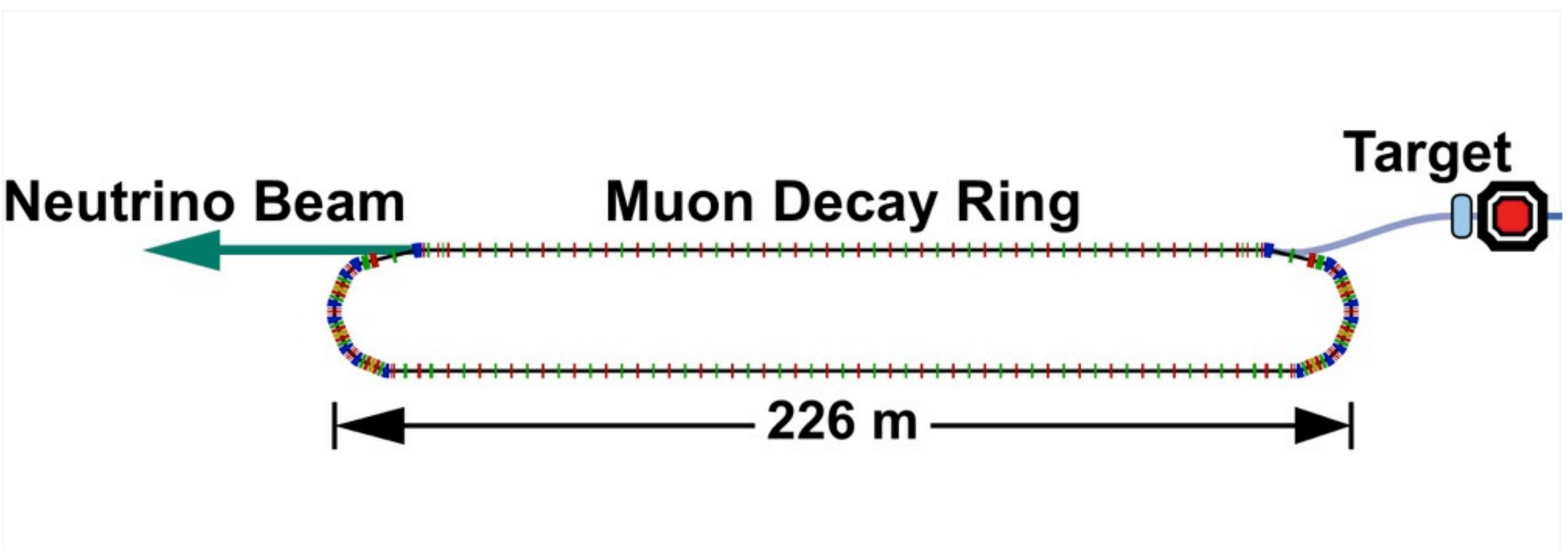


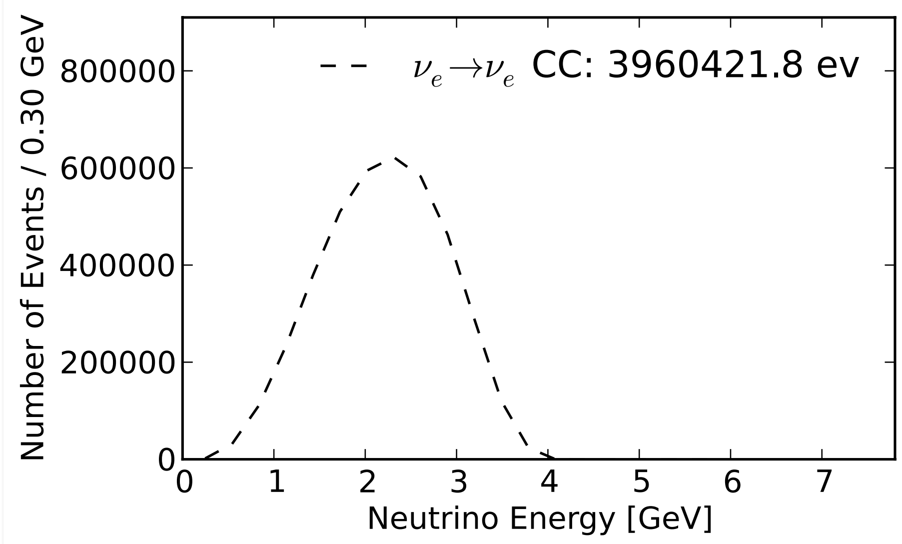
MiniBooNE low-energy excess

nuSTORM

Starting in 2022?

- Advanced neutrino beam from stored $\mu^\pm$: $\mu^+ \to e^+ \bar{\nu}_\mu \nu_e$, $\mu^- \to e^- \nu_\mu \bar{\nu}_e$
- Would be FIRST facility of this type ever built
- Baseline detector: magnetized iron calorimeter





Goals:

- Sterile neutrino searches (up to 8 channels)
- Percent-level $\nu_{e,\mu}$ interaction measurements
- Muon accelerator technology test bed: first step toward a multi-TeV $\mu^+\mu^-$ collider!

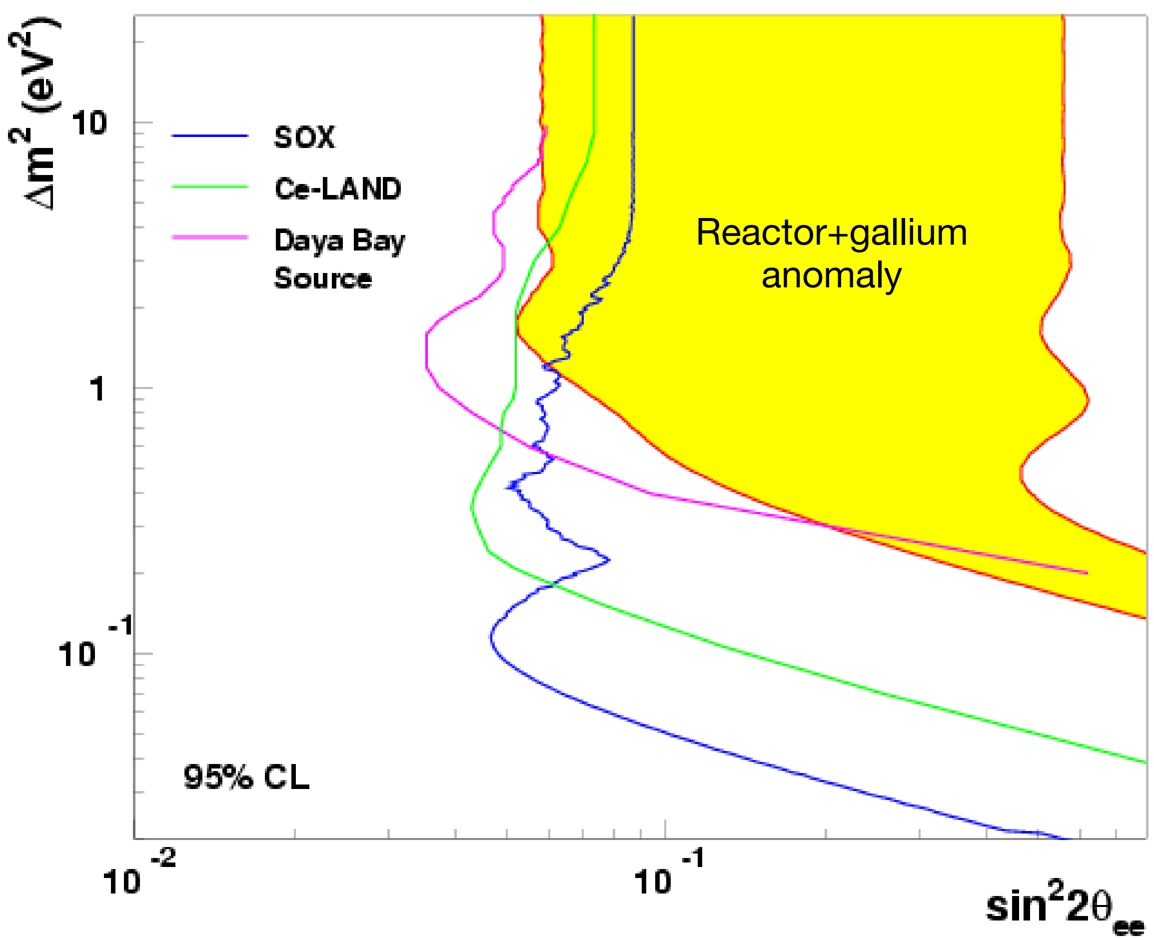
$\mu^+ \to e^+ \bar{\nu}_\mu \nu_e$	$\mu^- \to e^- \nu_\mu \bar{\nu}_e$
$\bar{\nu}_\mu \to \bar{\nu}_\mu$	$\nu_\mu \to \nu_\mu$
$\bar{\nu}_\mu \to \bar{\nu}_e$	$\nu_\mu \to \nu_e$
$\nu_e \to \nu_e$	$\bar{\nu}_e \to \bar{\nu}_e$
$\nu_e \to \nu_\mu$	$\bar{\nu}_e \to \bar{\nu}_\mu$

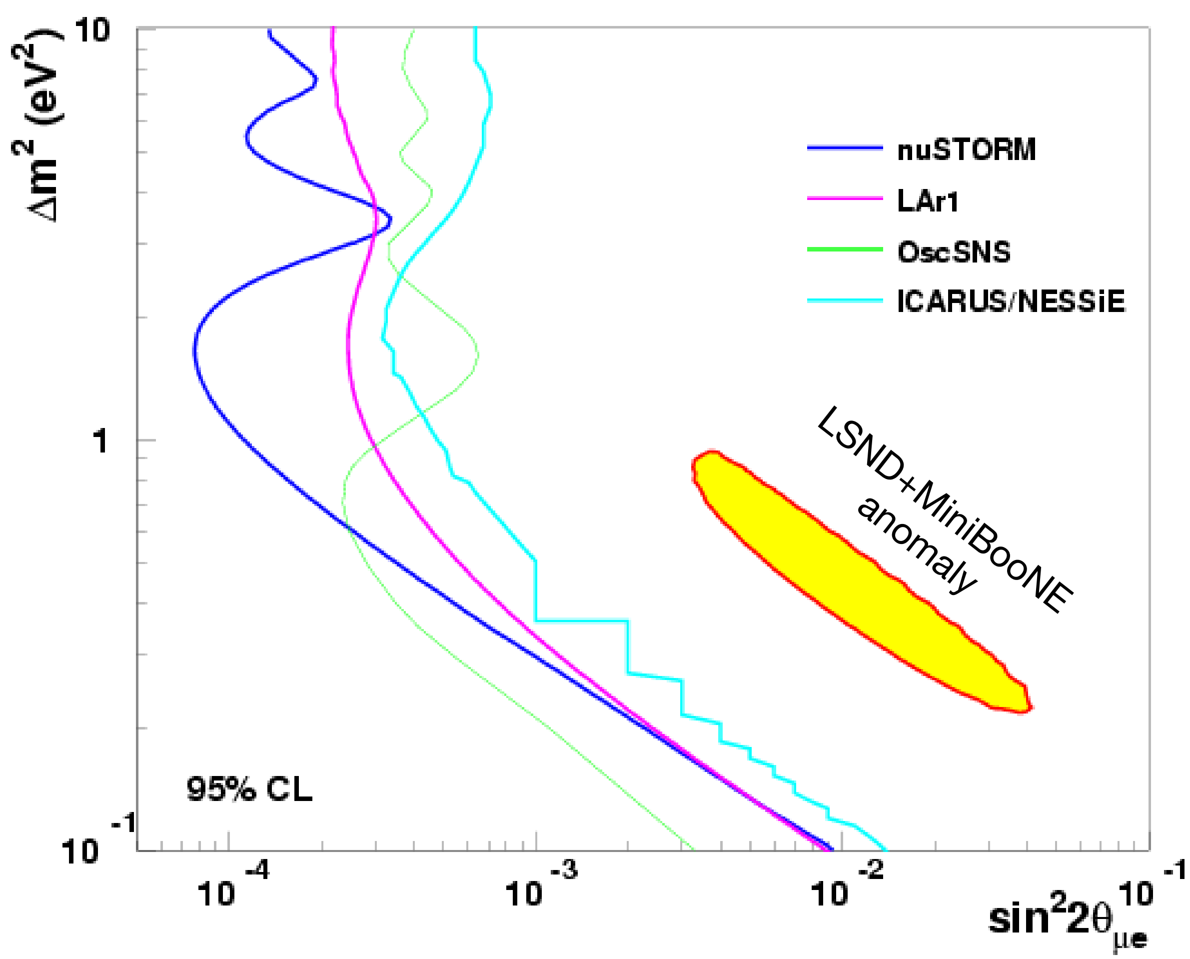
Prospects to discover light sterile neutrinos

- Source-based (and reactor-based) proposals sensitive to reactor+gallium anomaly

- Accelerator-based proposals sensitive to LSND+MiniBooNE anomaly

Anomaly	Baseline (m)	Energy (MeV)	Oscillation interpretation	Significance (σ)
LSND	30	50	$\bar{\nu}_\mu \to \bar{\nu}_e$	3.8
MiniBooNE ν	500	600	$\nu_\mu \to \nu_e$	3.4
MiniBooNE $\bar{\nu}$	500	600	$\bar{\nu}_\mu \to \bar{\nu}_e$	2.8
Gallium	2	1	$\nu_e \to \nu_s$	2.8
Reactor	20	5	$\bar{\nu}_e \to \bar{\nu}_s$	2.9

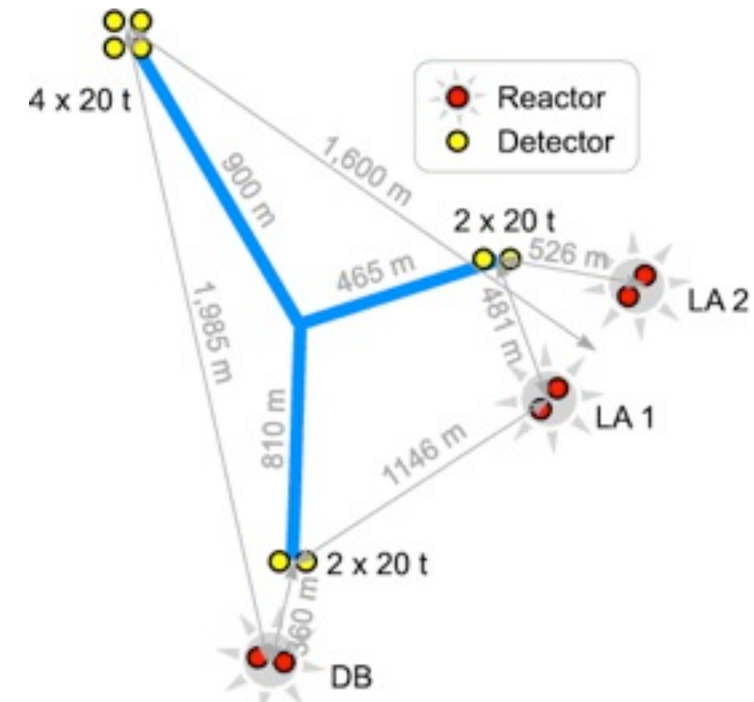


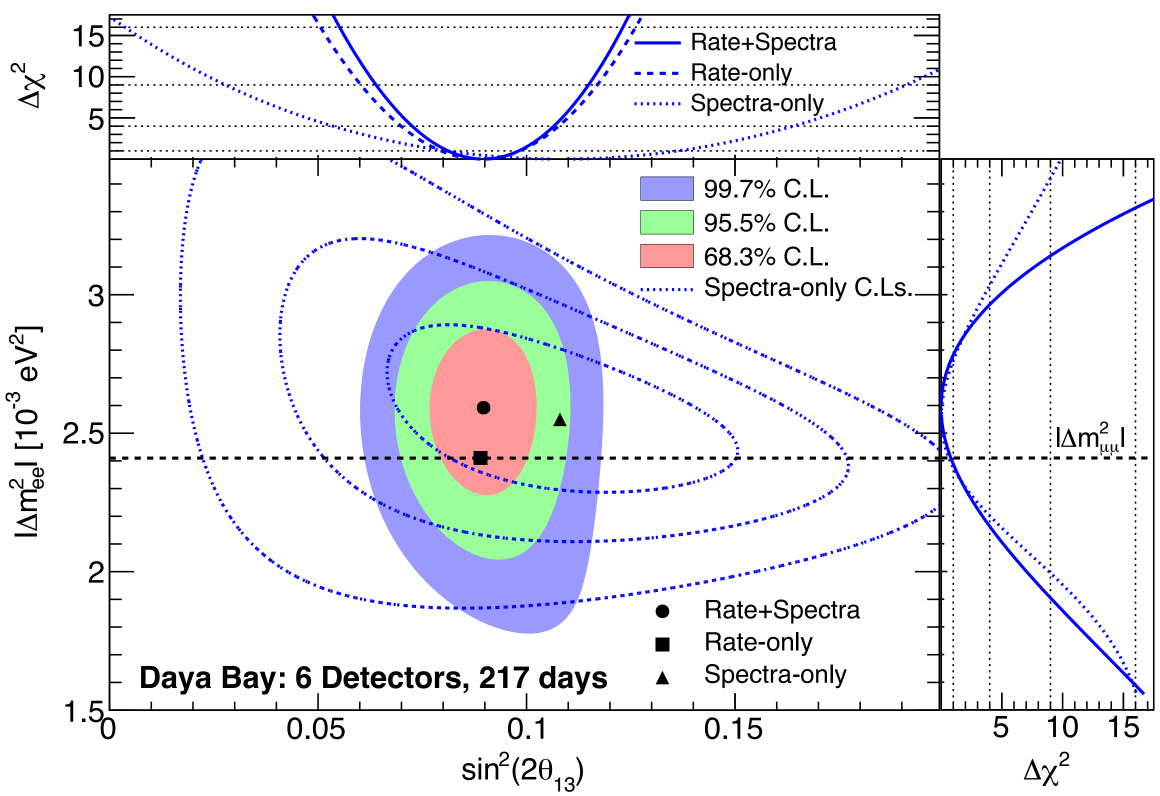


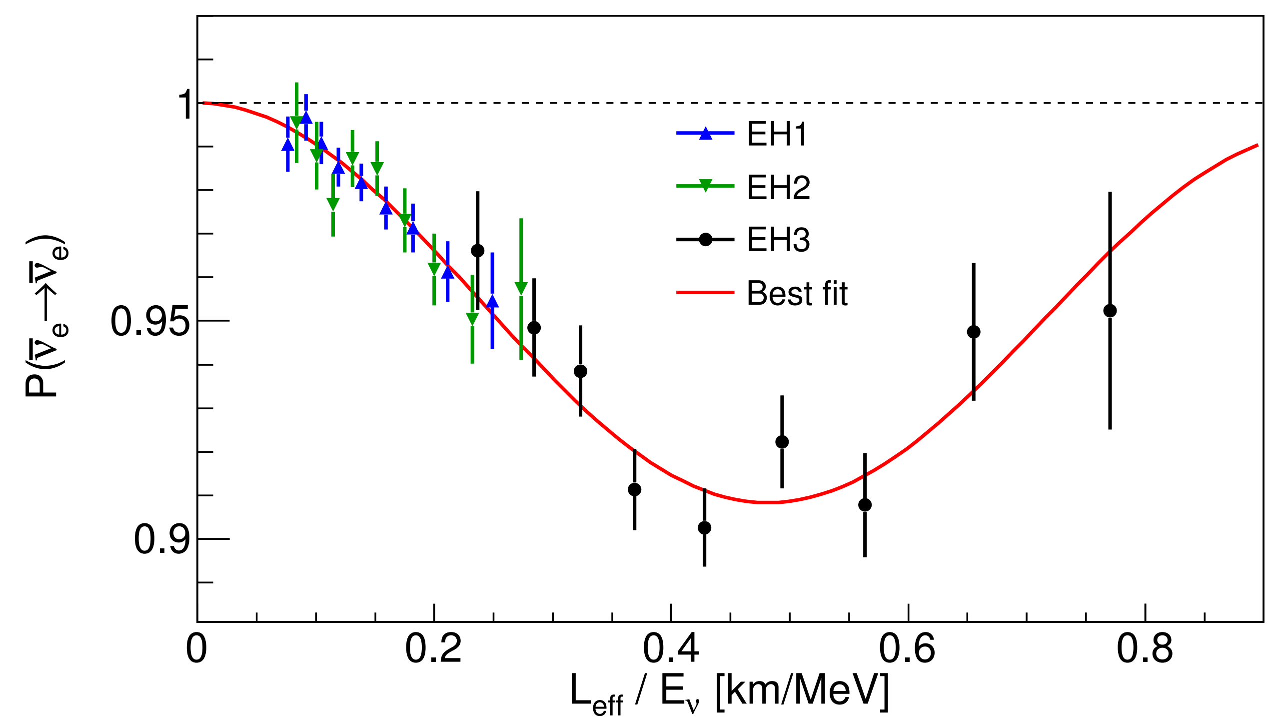
Daya Bay

Started in 2011

- Liquid scintillators measuring reactor electron antineutrino disappearance over km-long baselines
- Most precise measurement of $\sin^2 2\vartheta_{13}$ to date
- Consistent results from Reno and Double Chooz
- JUNO: proposal to measure neutrino mass hierarchy with reactor neutrinos



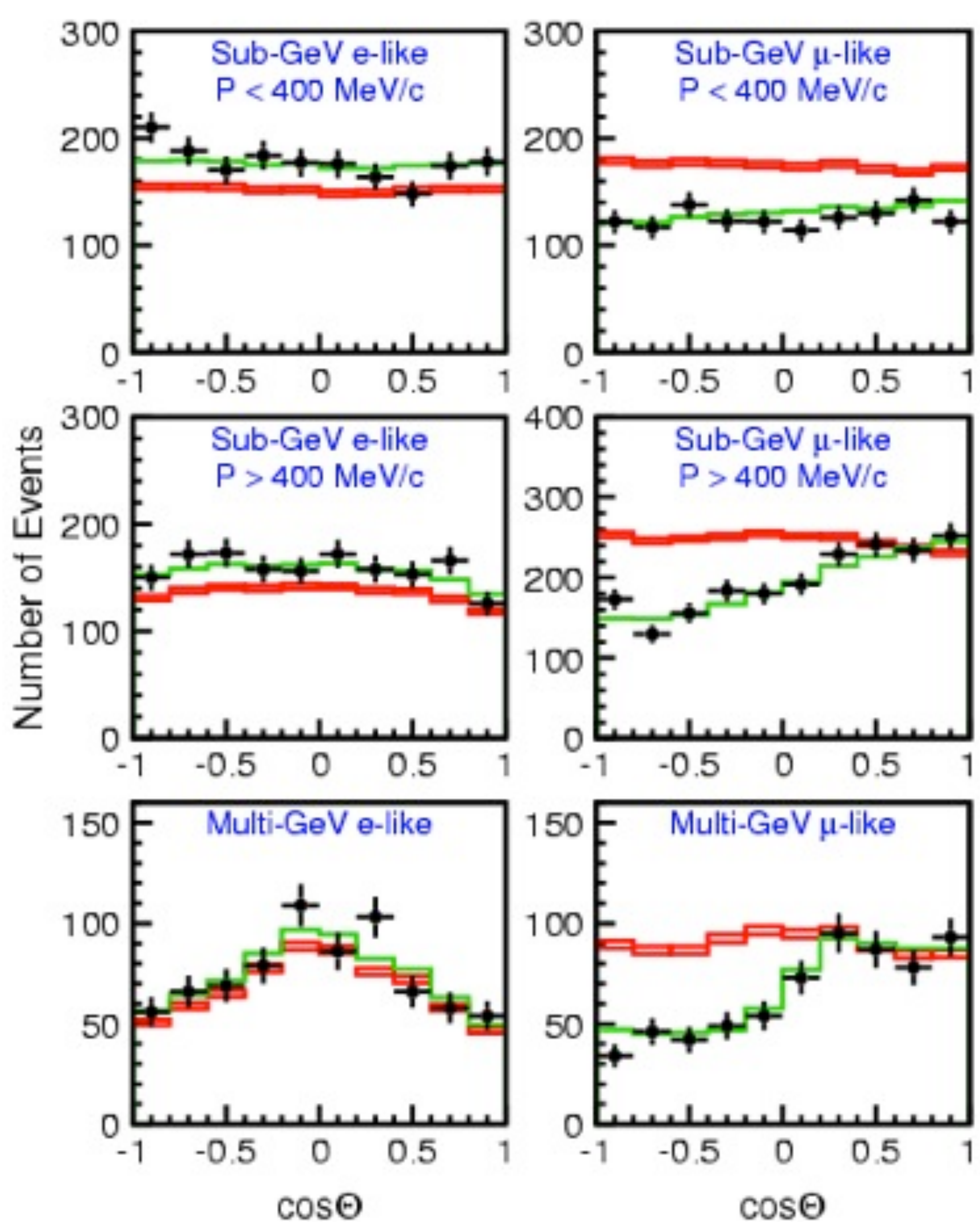




Super-Kamiokande atmospheric

Started in 1996

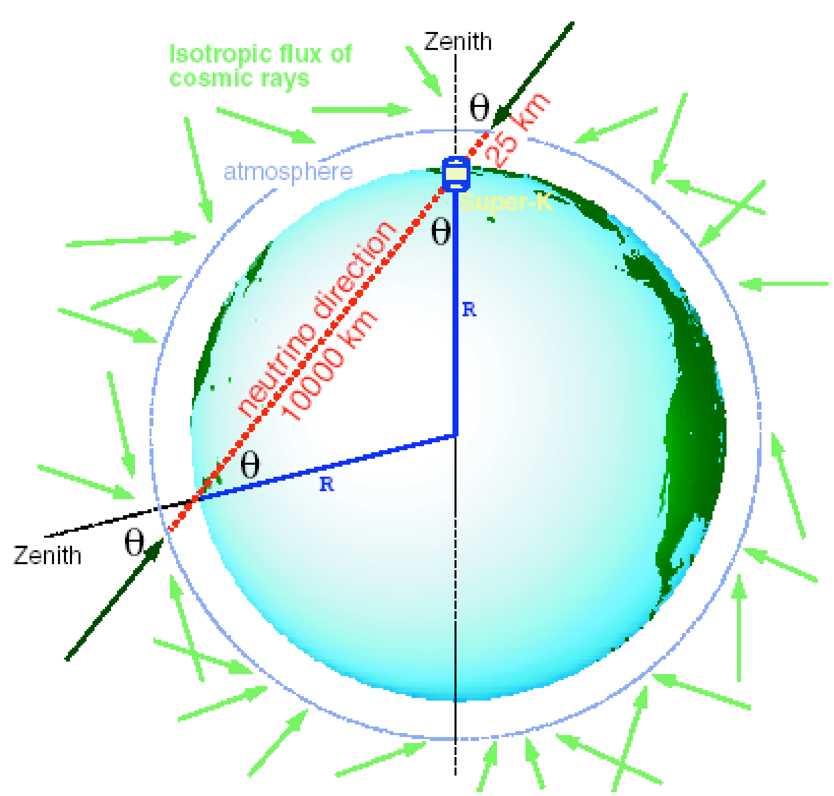
- Water Cherenkov detector measuring atmospheric neutrinos (both ν_μ and ν_e)
- First conclusive evidence for oscillations, from zenith angle-dependent deficit of ν_μ's!



– expected without oscillations
– expected with oscillations
+ observed

$\cos\vartheta = 1 \Leftrightarrow$ travel length ~ 20 km

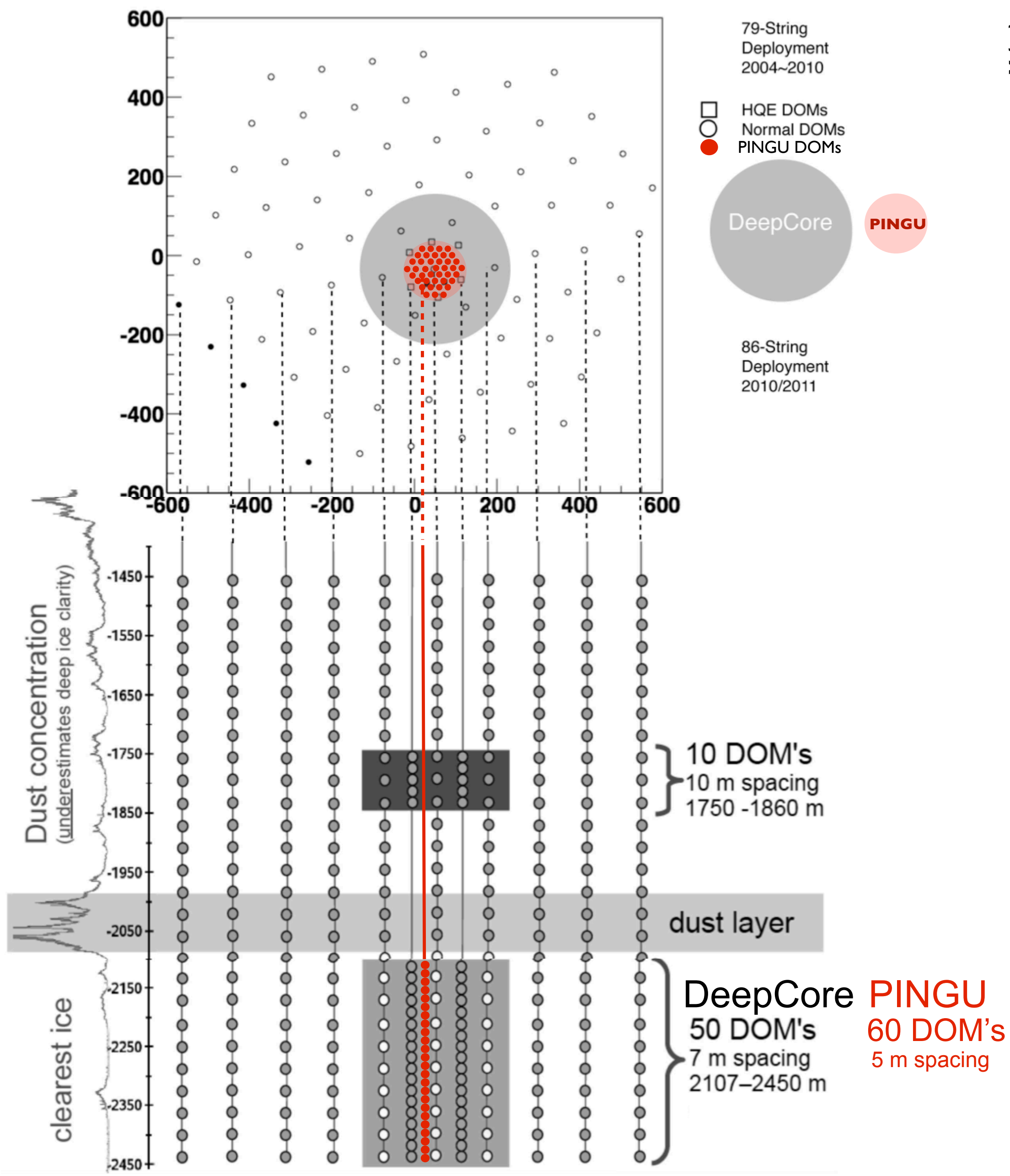
$\cos\vartheta = -1 \Leftrightarrow$ travel length ~ 13000 km

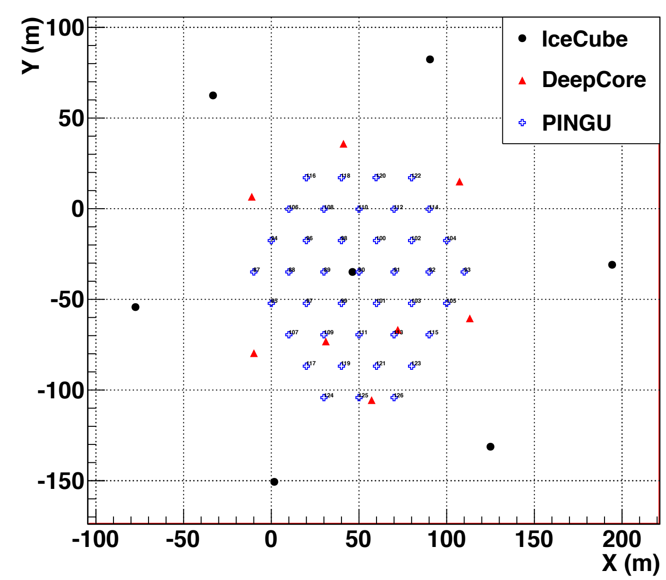


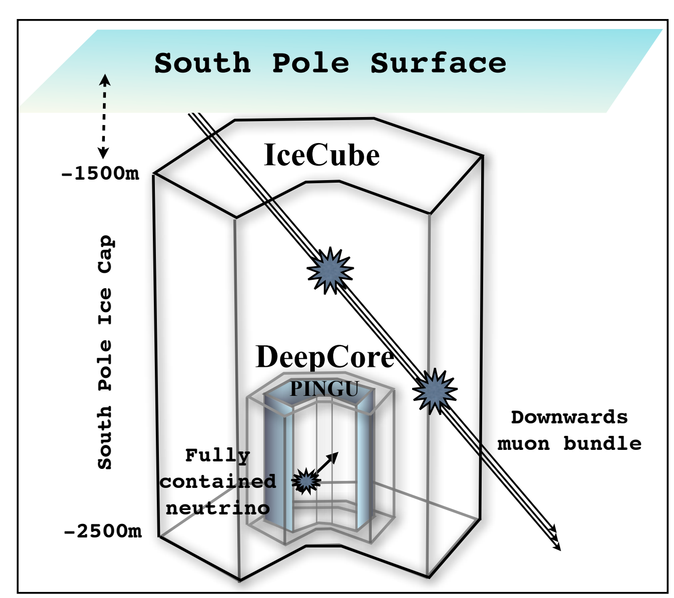
PINGU atmospheric

Starting in 2020?

- Huge atmospheric neutrino Cherenkov detector with few GeV energy threshold
- Survival probability of oscillating muon neutrinos affected by Earth matter effects
→sensitive to neutrino mass hierarchy!



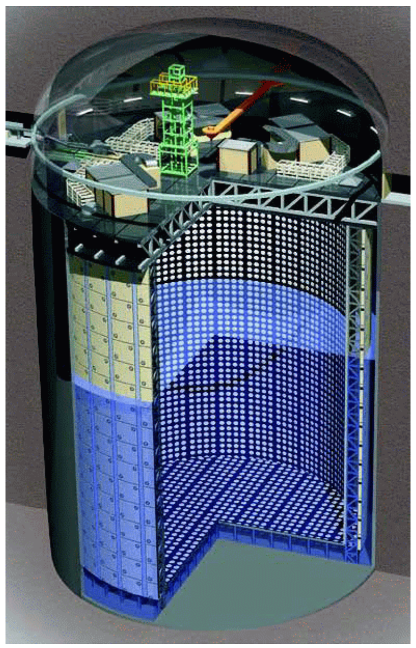


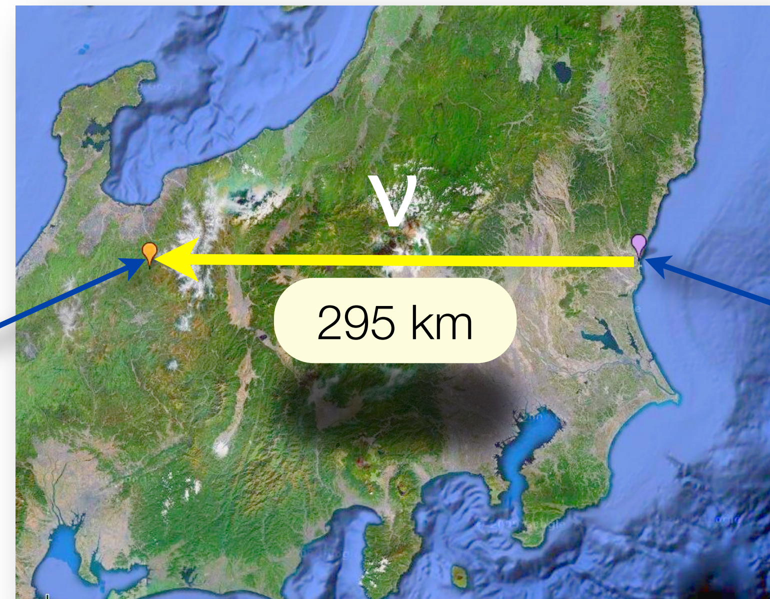


T2K

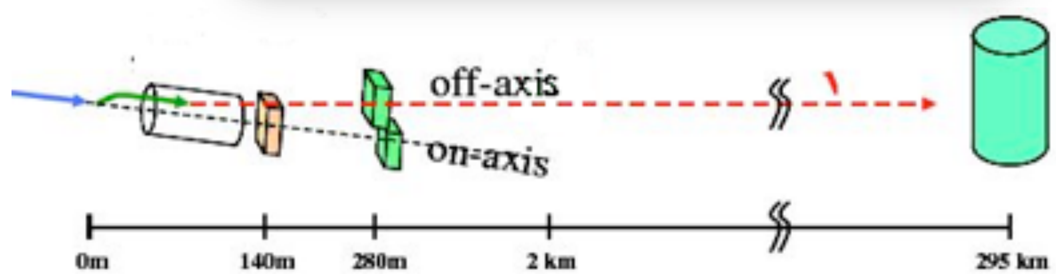
Started in 2010

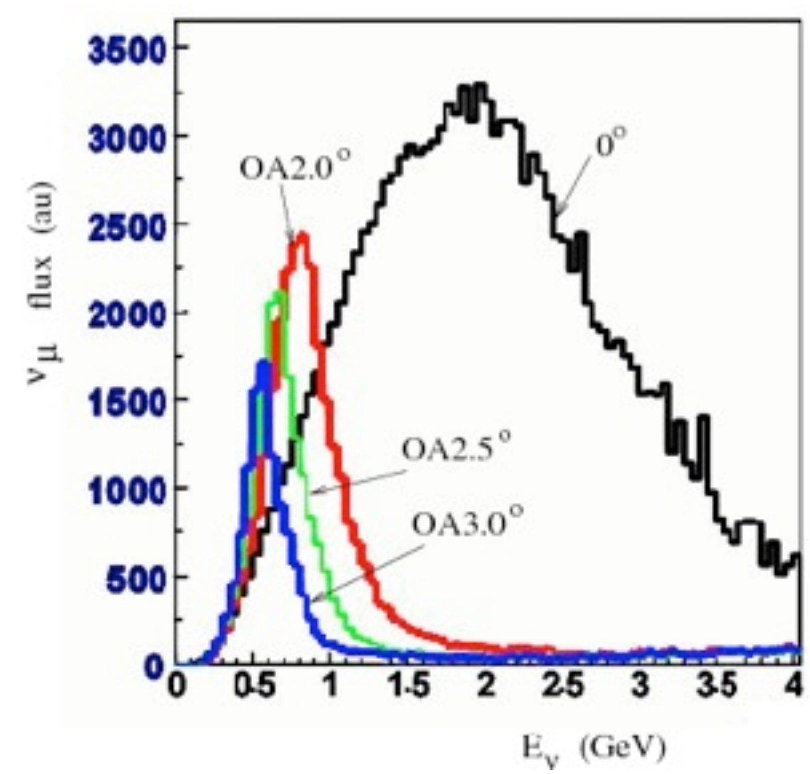
Super-K Detector





J-PARC Accelerator and
Near Detectors (ND280, INGRID)



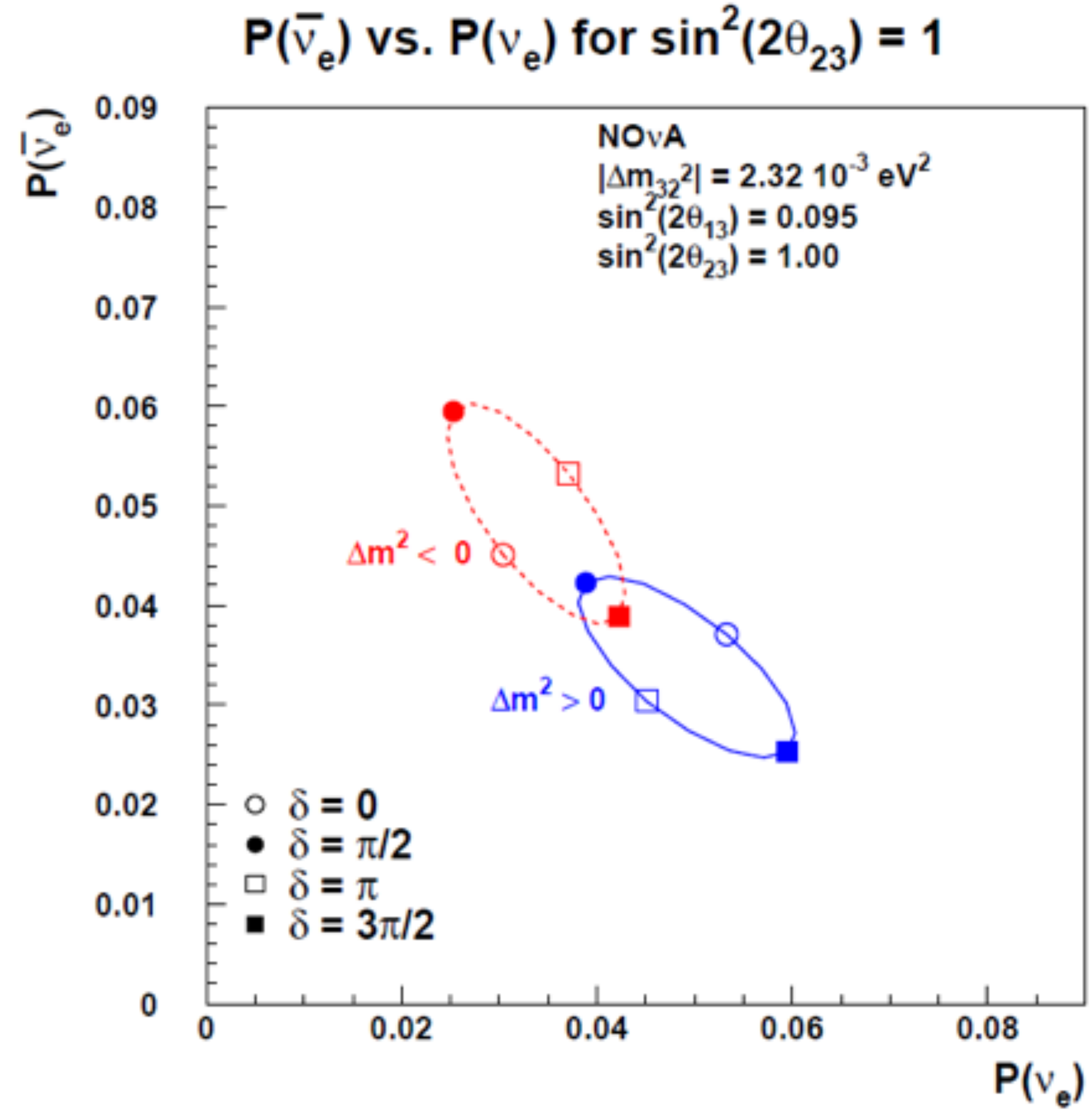


- Super-K also sees JPARC off-axis neutrino beam
- T2K has conclusively shown that ν_μ transform into ν_e
  - Non-zero ϑ_{13} mixing angle at 7.5 σ significance
  - T2K + reactor data prefers maximal CP violation!
- Data until 2020, up to 2.5 σ significance to CP violation

NOvA

Started in 2014

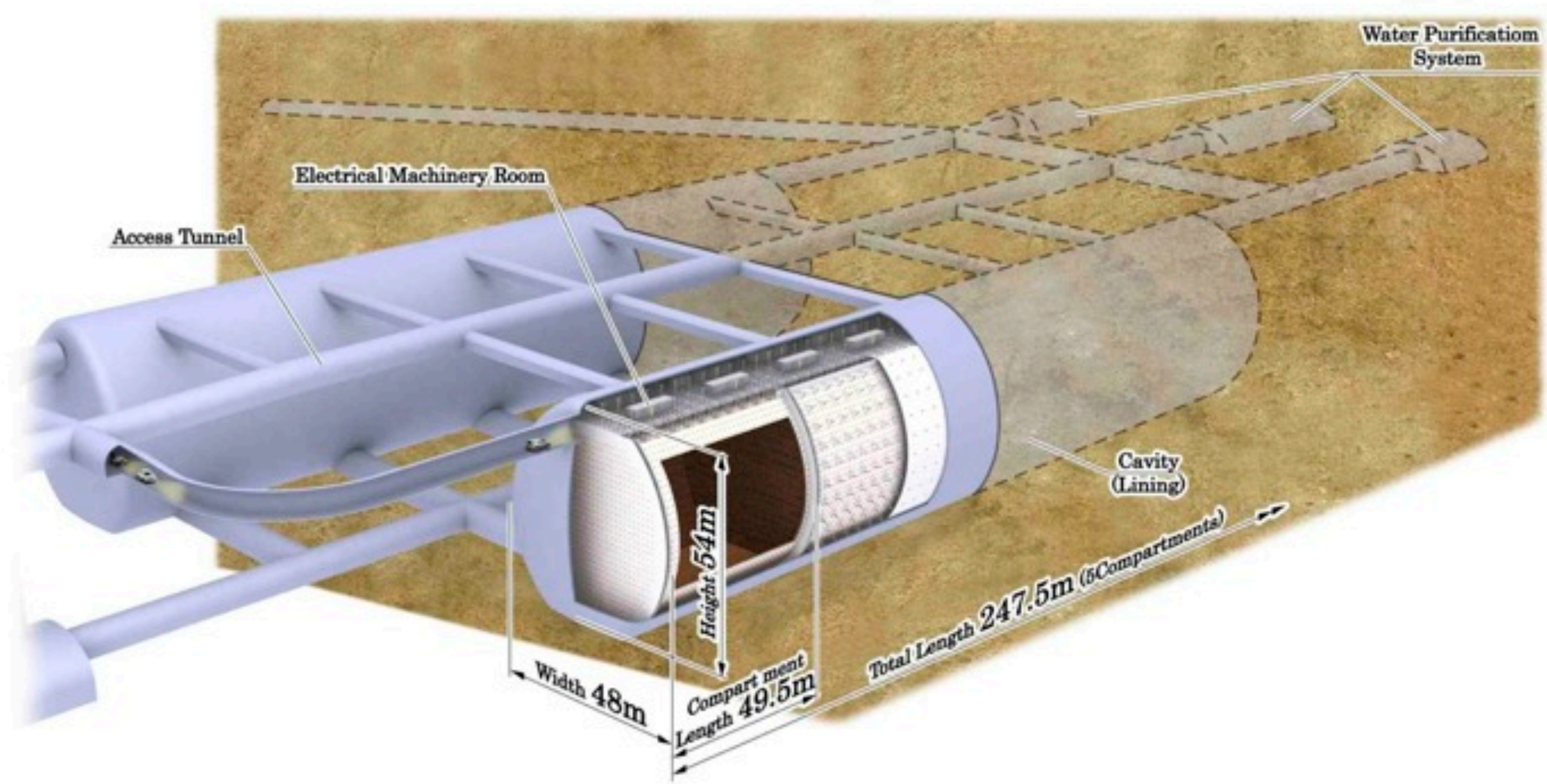
- With T2K, other current-generation long-baseline experiment in off-axis configuration
- Separately measure $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ to extract CP violation and mass hierarchy
- Compared to T2K:
    - Longer baseline (735 km), better for hierarchy
    - Segmented tracker rather than water Cherenkov



Hyper-Kamiokande

Starting in 2025?

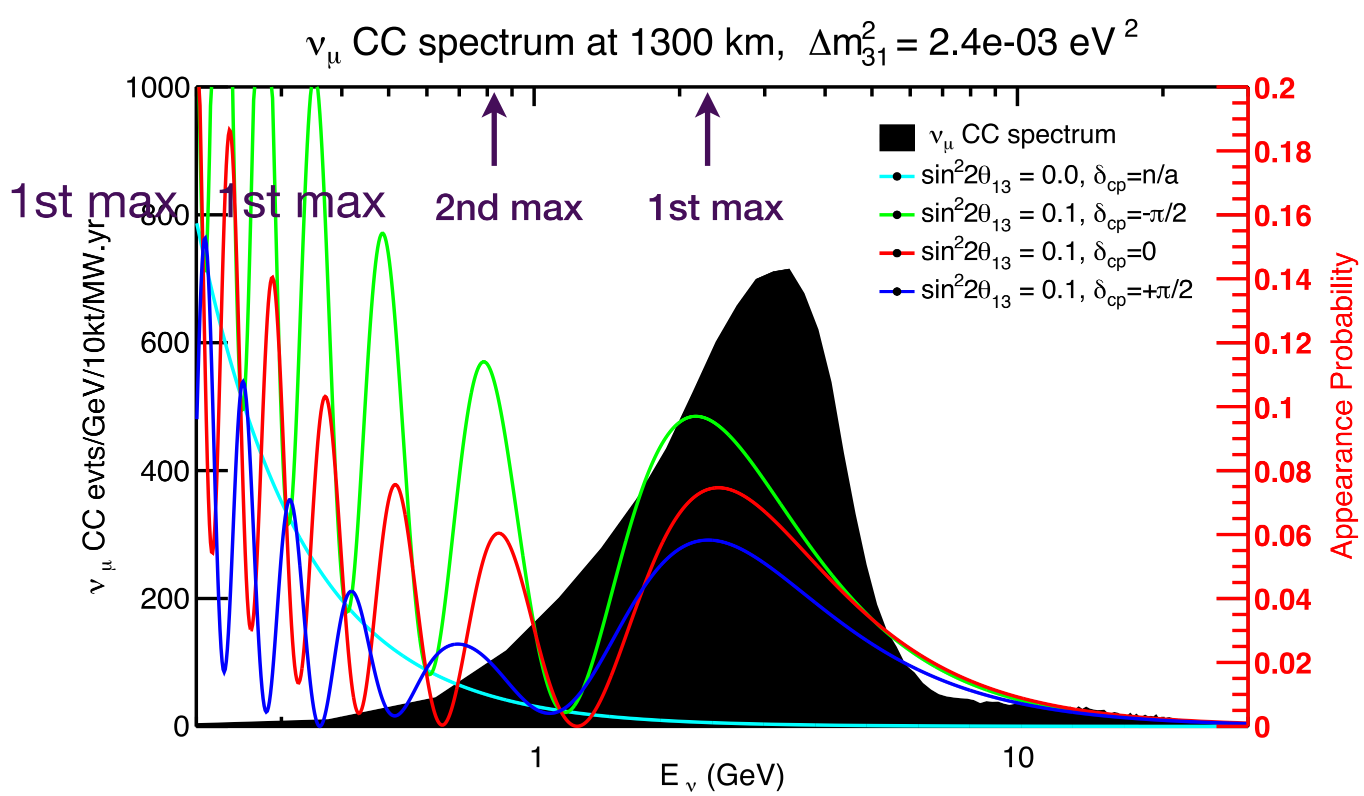
- Same concept as T2K (and NOvA): separately measure $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ in an off-axis beam to extract CP violation and mass hierarchy, but...
  - more powerful beam: 1.7 MW!
  - more massive detector: 1 Mton!
- Mostly "counting" experiment at low (< 1 GeV) energies → water Cherenkov detector
- Mass hierarchy from atmospheric neutrinos

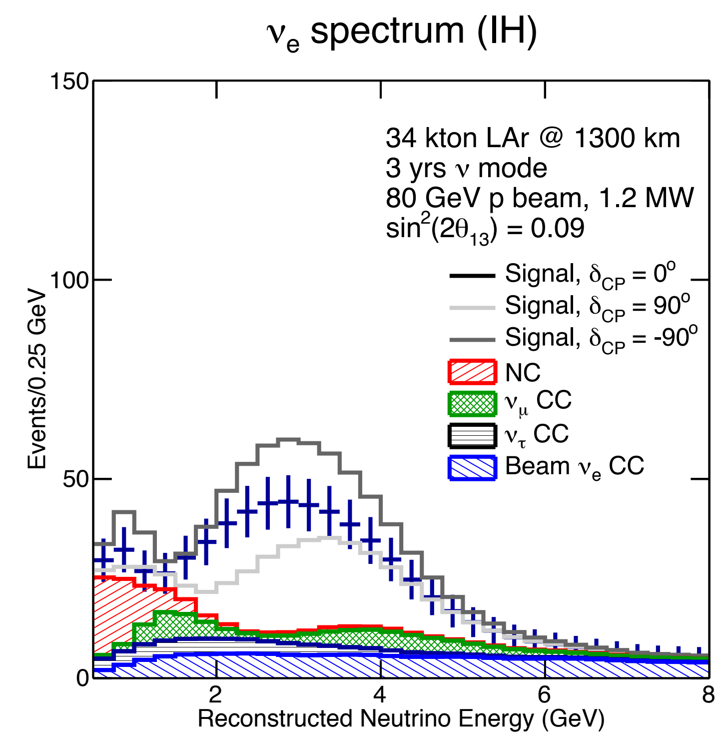


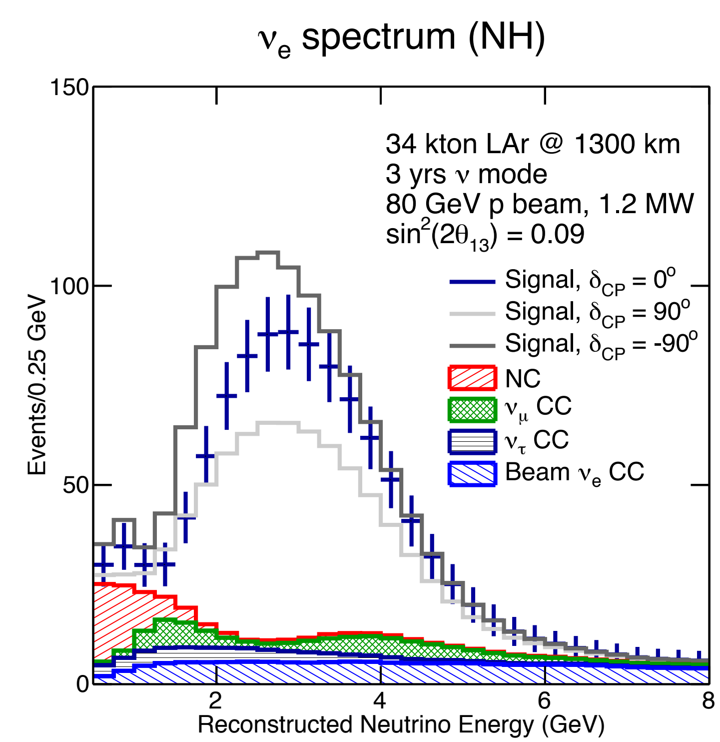
LBNE

Starting in 2025?

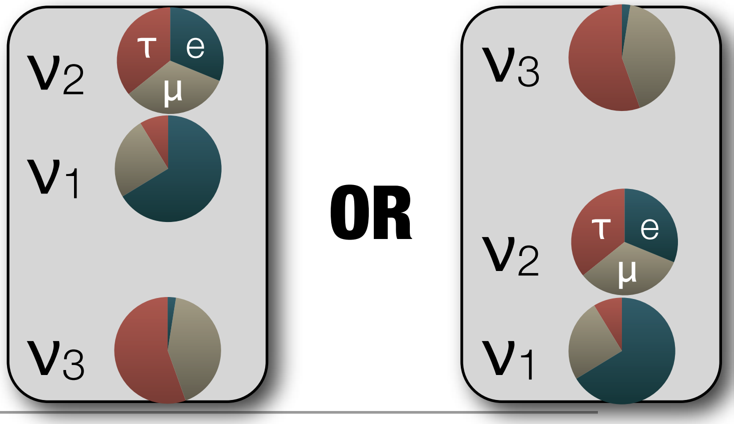
- Other next-generation long-baseline oscillation experiment
- <u>On-axis</u> 1-6 GeV ν beam covering 1st and 2nd oscillation maximum to disentangle mass ordering and CP effects
- Requires detector for high-energy neutrinos and with good energy resolution → LAr TPC
- Underground detector offers other physics opportunities: proton decay, supernova neutrinos, etc.

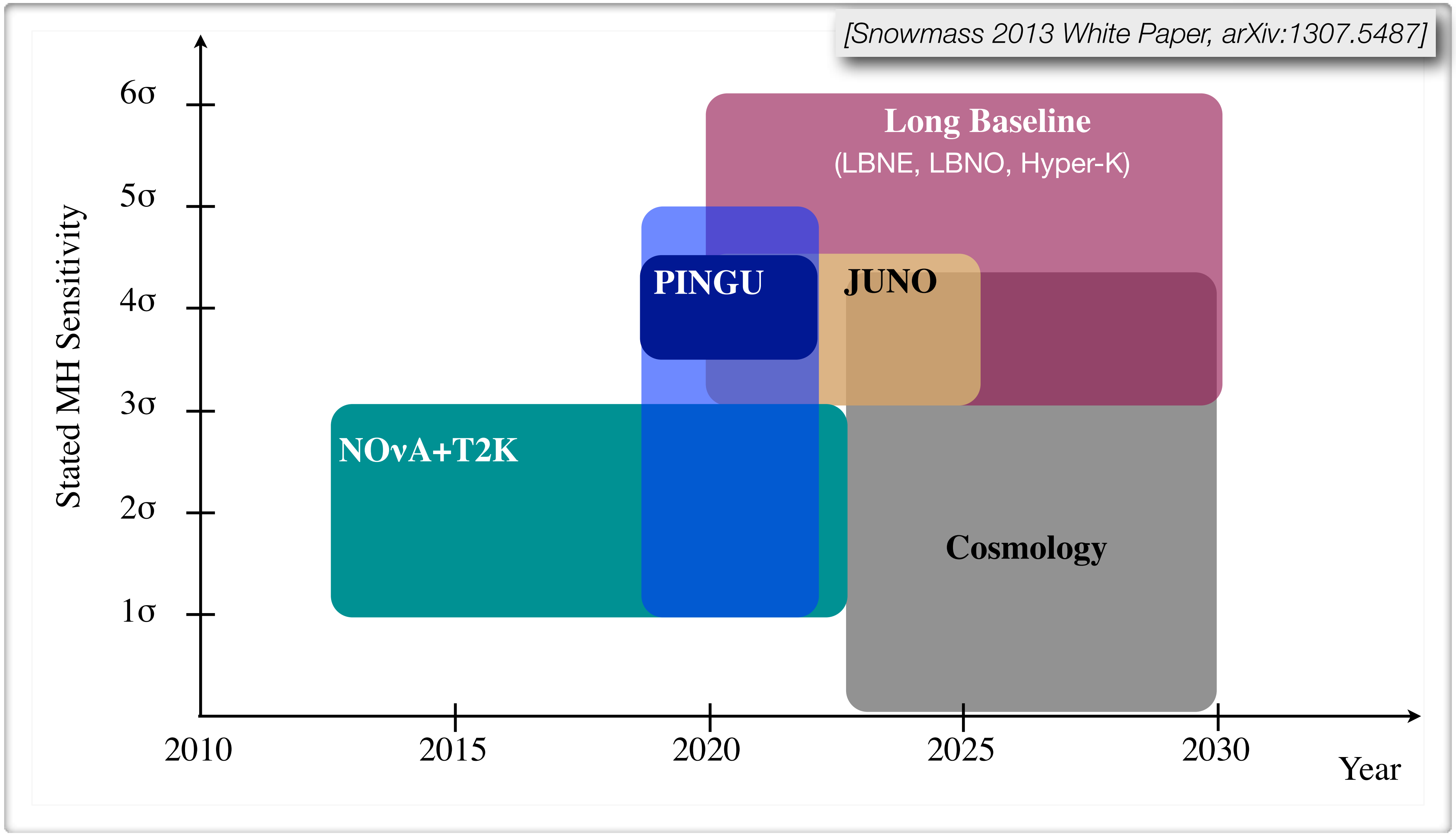






Prospects to measure the neutrino mass ordering



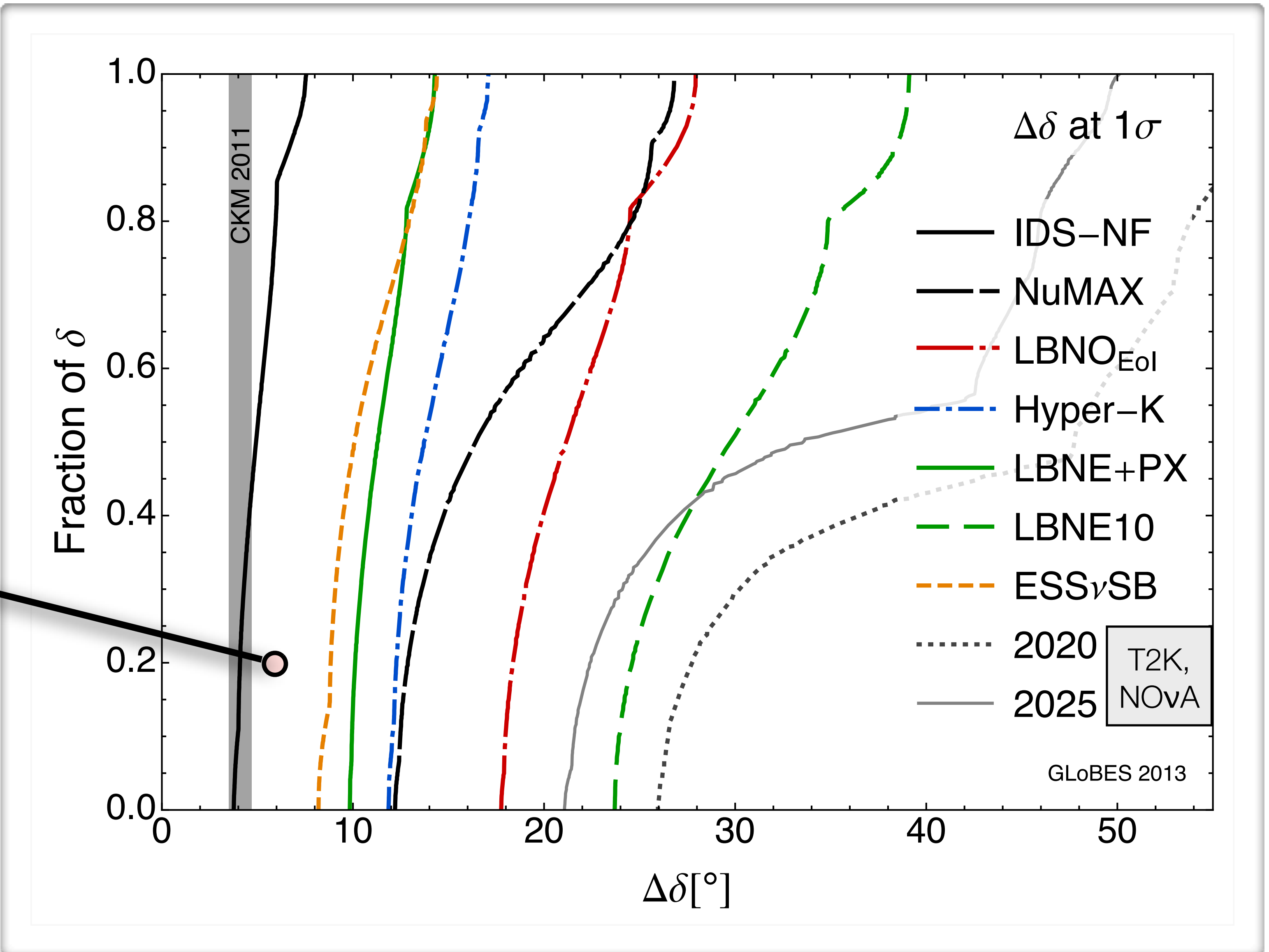


- Current-generation accelerator experiments: T2K, NOνA
- Next-generation accelerator experiments: LBNE, LBNO, Hyper-K
- Other techniques: atmospheric and reactor neutrino oscillations, cosmology

Prospects to measure leptonic CP violating phase δ_{CP}

Fraction of δ values for which a given precision $\Delta\delta$ is expected

Example: $\Delta\delta$ = 6 deg accuracy for 20% fraction of possible δ values



- Current-generation conventional ν beams: T2K, NOνA
- Next-generation conventional ν beams: LBNO, Hyper-K, LBNE, ESSνSB
- Future advanced ν beams: Neutrino Factory (IDS-NF, NuMAX)

Lecture 1 End