Neutrino Experiments

Lecture 1

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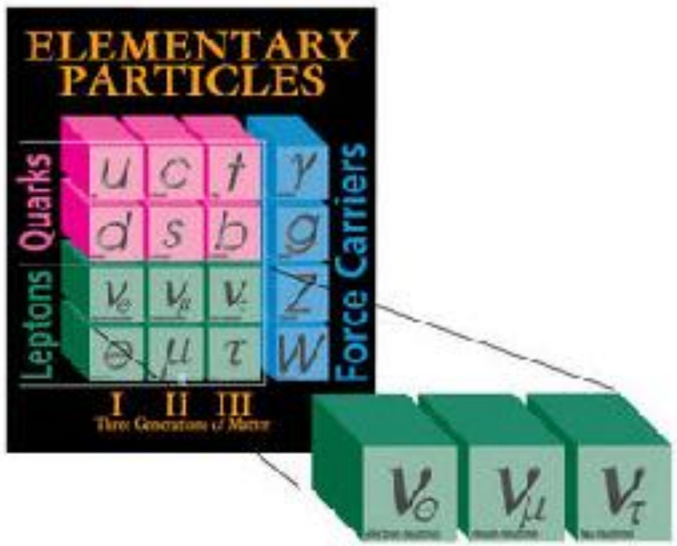
8th IDPASC School, Valencia (Spain), May 2018

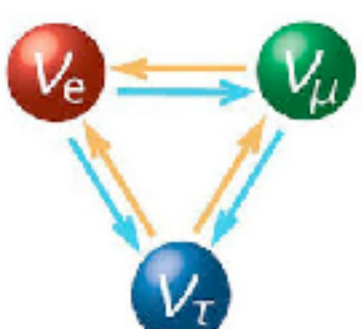
Neutrinos: what we know

(see M. Tortola's lectures)



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

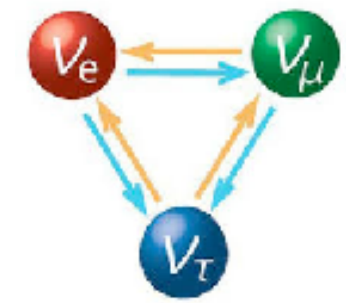
- Neutrino number density in Universe only
- outnumbered by photons
  - $n(\nu+\bar{\nu}) \approx 100\ \mathrm{cm}^{-3}$ per flavor



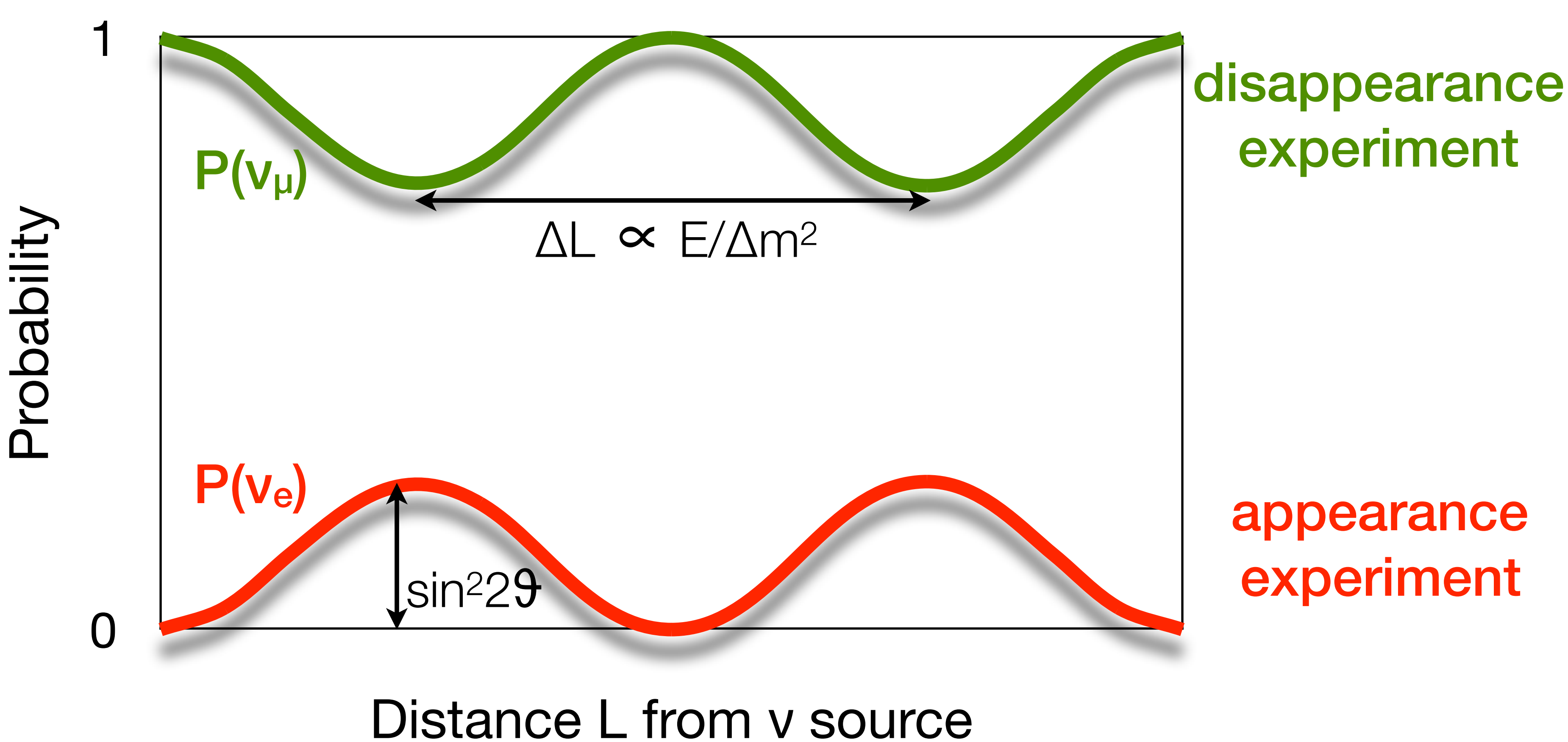
- From neutrino oscillations:
- Lightest known fermions, but massive
- Large flavor mixing

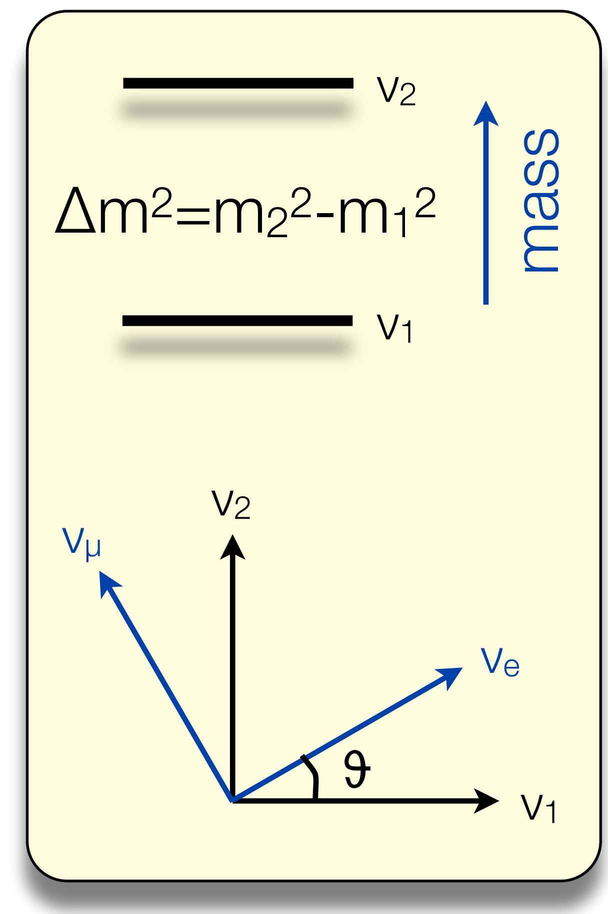
Neutrino flavor oscillations

(see M. Tortola'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 M. Tortola's lectures)

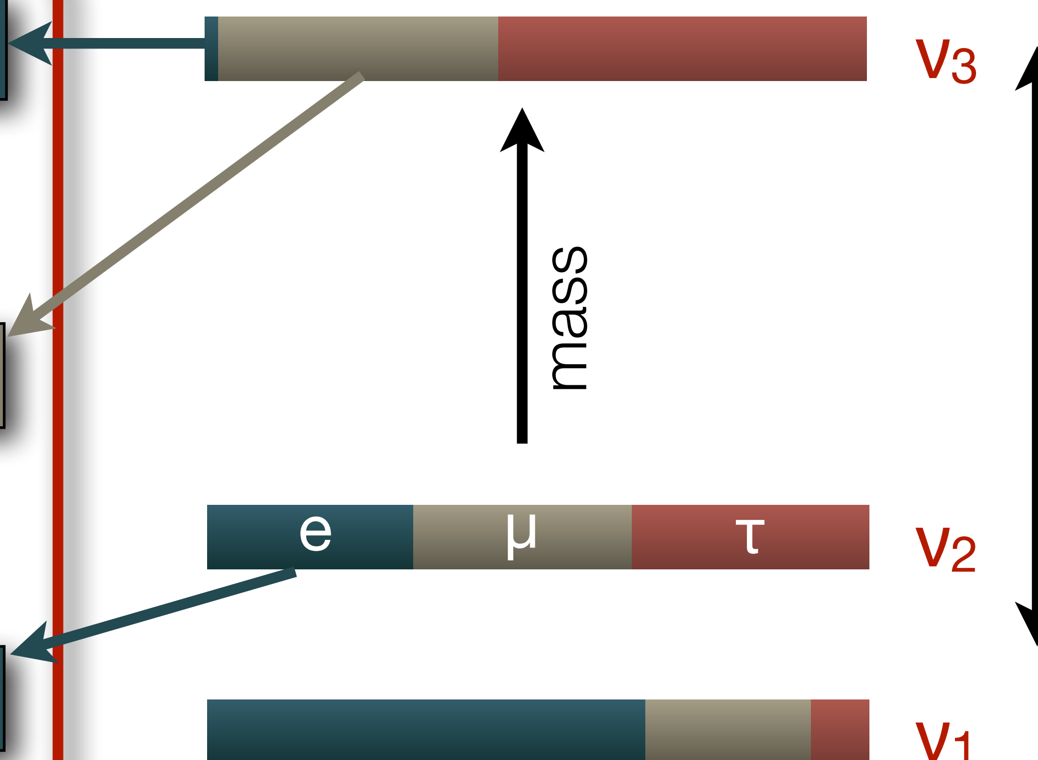
Mass splittings and mixing angles measured with 10% precision or better*

$\sin^2\vartheta_{13} = 0.0221 \pm 0.0008$

$\sin^2\vartheta_{23} = 0.538 \pm 0.069$*

* $\sin^2\vartheta_{23} < 0.5$ allowed
(octant degeneracy)

$\sin^2\vartheta_{12} = 0.307 \pm 0.013$



$|\Delta m^2_{atm}| = (2.49 \pm 0.03) \cdot 10^{-3}\ \mathrm{eV}^2$

$\Delta m^2_{sol} = (7.40 \pm 0.21) \cdot 10^{-5}\ \mathrm{eV}^2$

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 M. Tortola's lectures)

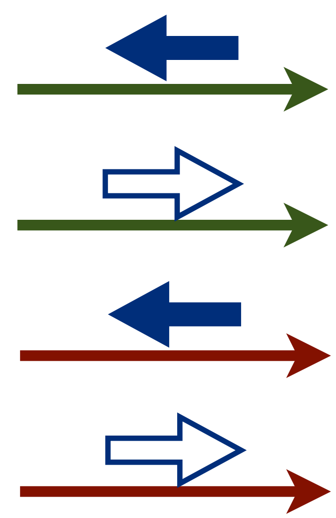
Identity	Dirac or Majorana fermion?
Mass scale	What is the neutrino mass value?
Mass ordering	Normal or inverted?
Mixing	Is CP symmetry violated in the neutrino sector?
Species	Are there light sterile neutrinos?

Neutrino question 1: Identity

Dirac or Majorana fermion?

Dirac:

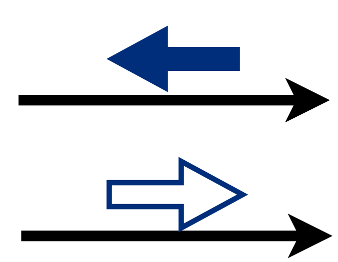
- 4 states
- $\nu \neq \bar{\nu}$



	Helicity	Conserved Lepton Number	Lepton production rate	Anti-lepton production rate
ν	-1/2	+1	1	0
ν	+1/2	+1	$(m/E)^2 \ll 1$	0
$\bar{\nu}$	-1/2	-1	0	$(m/E)^2 \ll 1$
$\bar{\nu}$	+1/2	-1	0	1

Majorana:

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

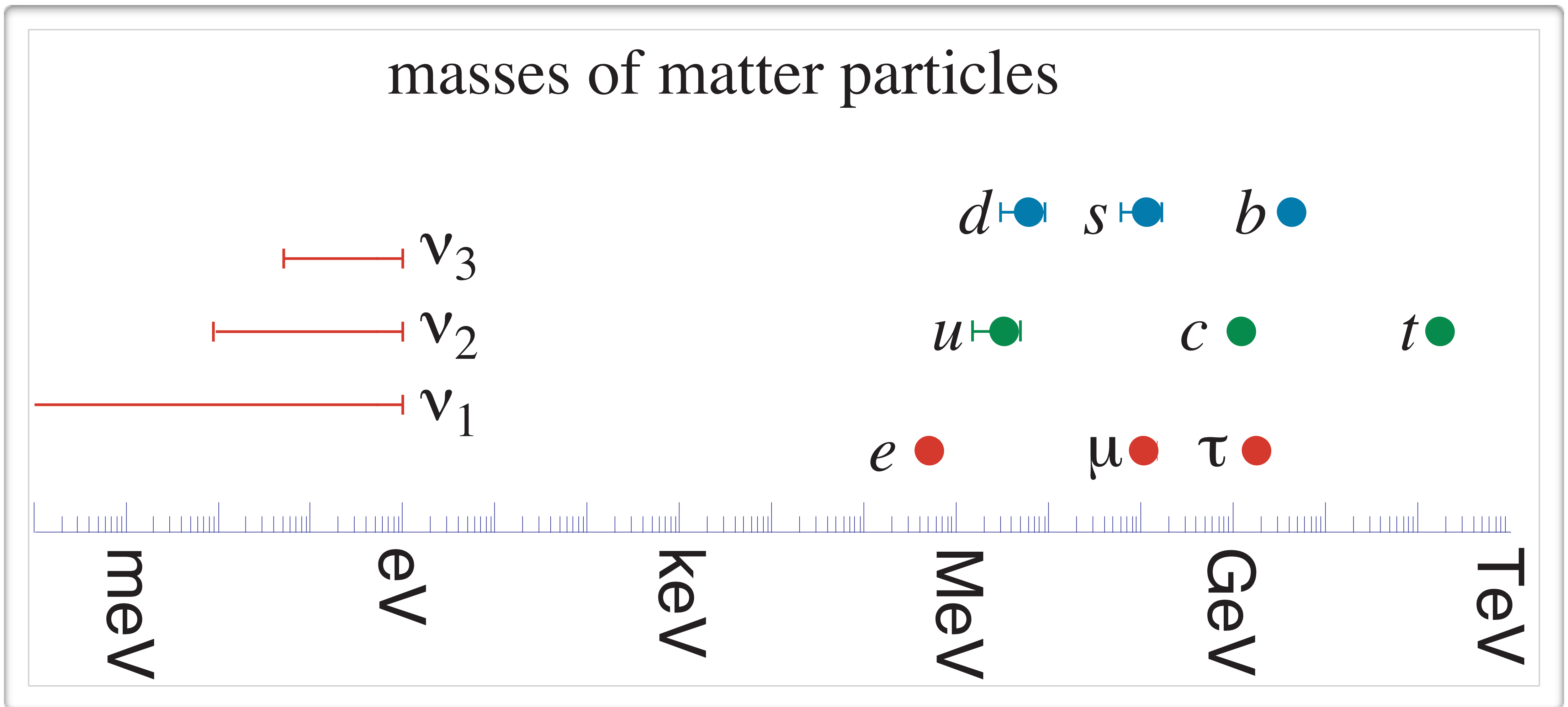


	Helicity	Conserved Lepton Number	Lepton production rate	Anti-lepton production rate
$\nu = \bar{\nu}$	-1/2	none	1	0
$\nu = \bar{\nu}$	+1/2	none	0	1

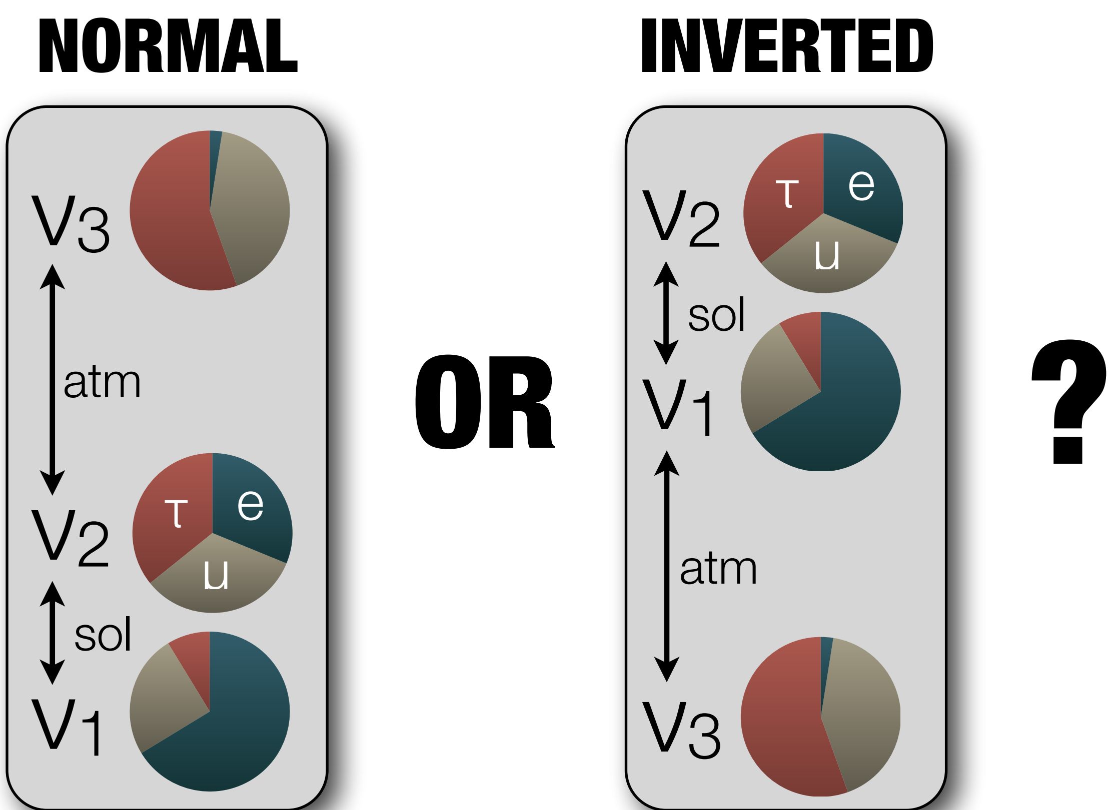
Neutrino question 2: Mass scale

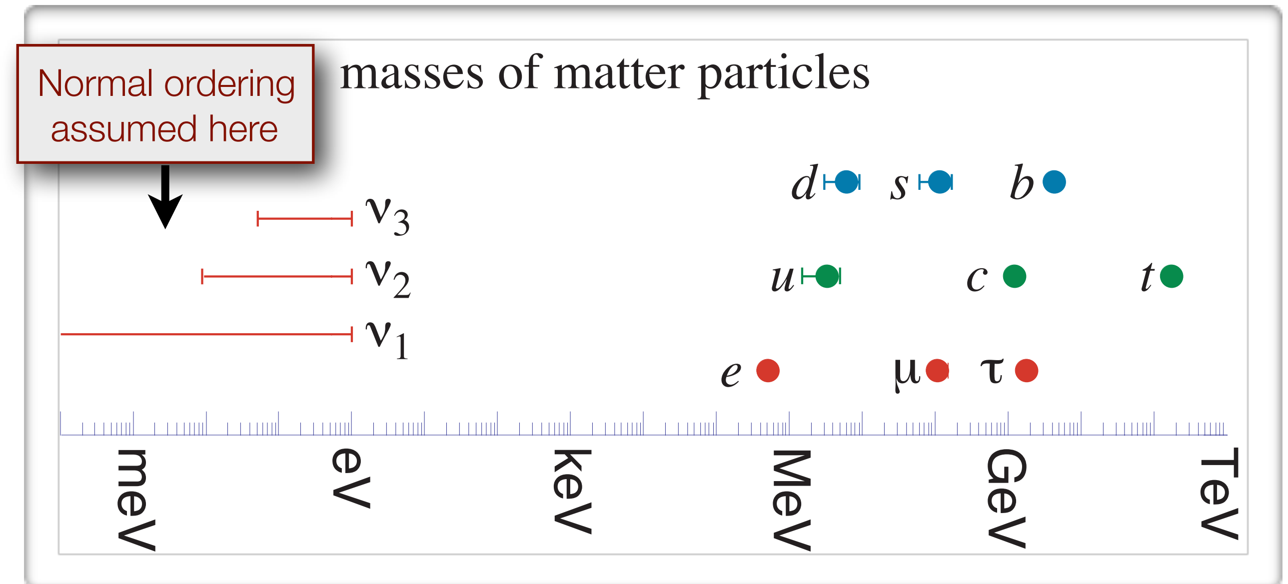
We know it is non-zero, but... What is the neutrino mass value?

- 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

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

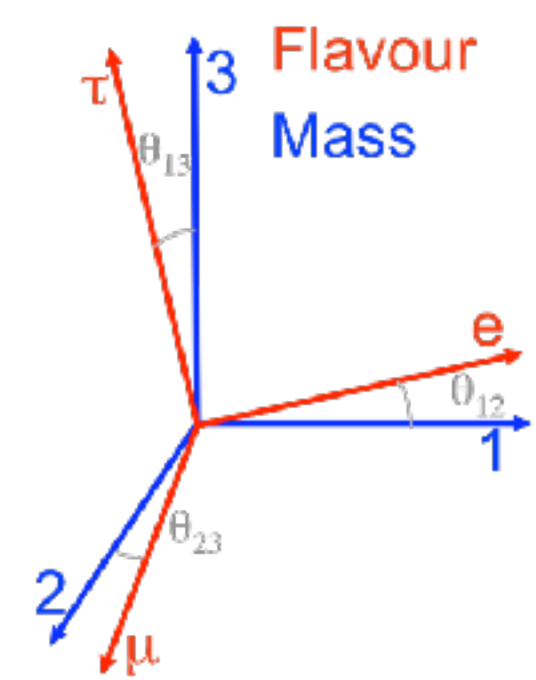
$c_{23} = \cos\theta_{23}$ etc...

Interference

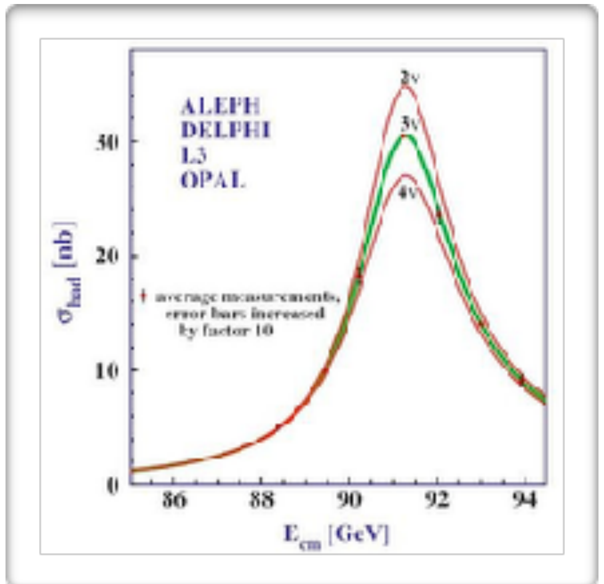
Is CP symmetry violated in the neutrino sector?

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

$\delta \neq 0, \pi \Leftrightarrow$ oscillation probabilities violate CP invariance: different probabilities for neutrinos and antineutrinos!



Neutrino question 5: Species

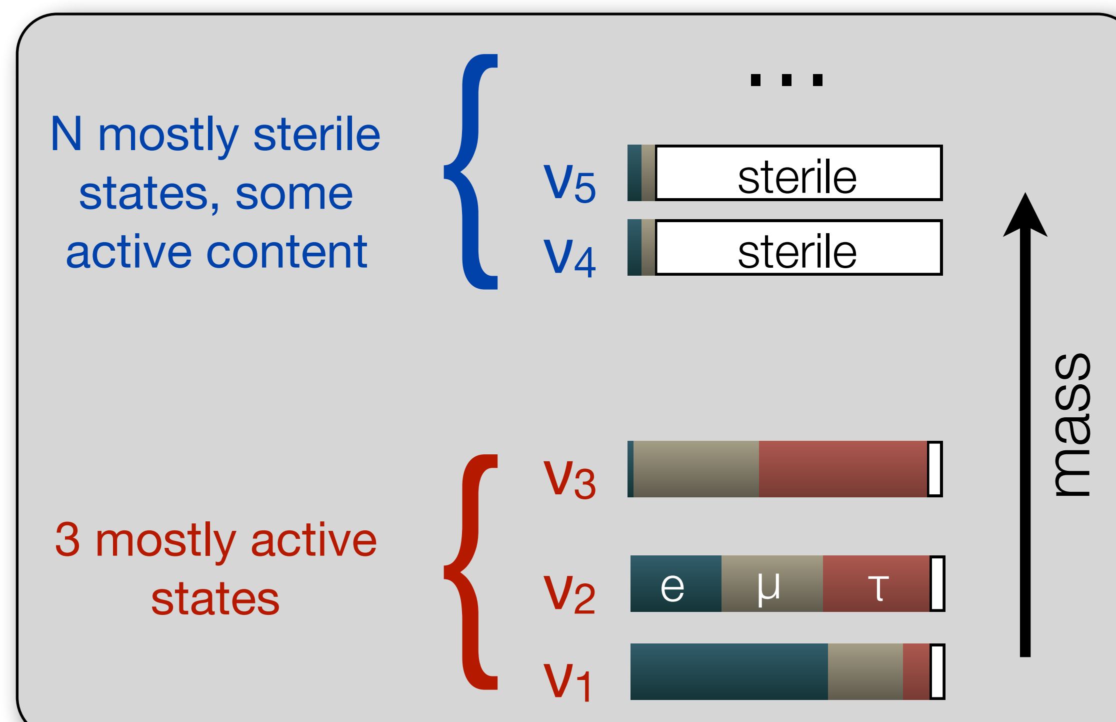


- LEP: three neutrino flavors participating in the weak interactions and with mass $<m_Z/2$. But...

...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	10-20	5	$\bar{\nu}_e \to \bar{\nu}_s$	~3



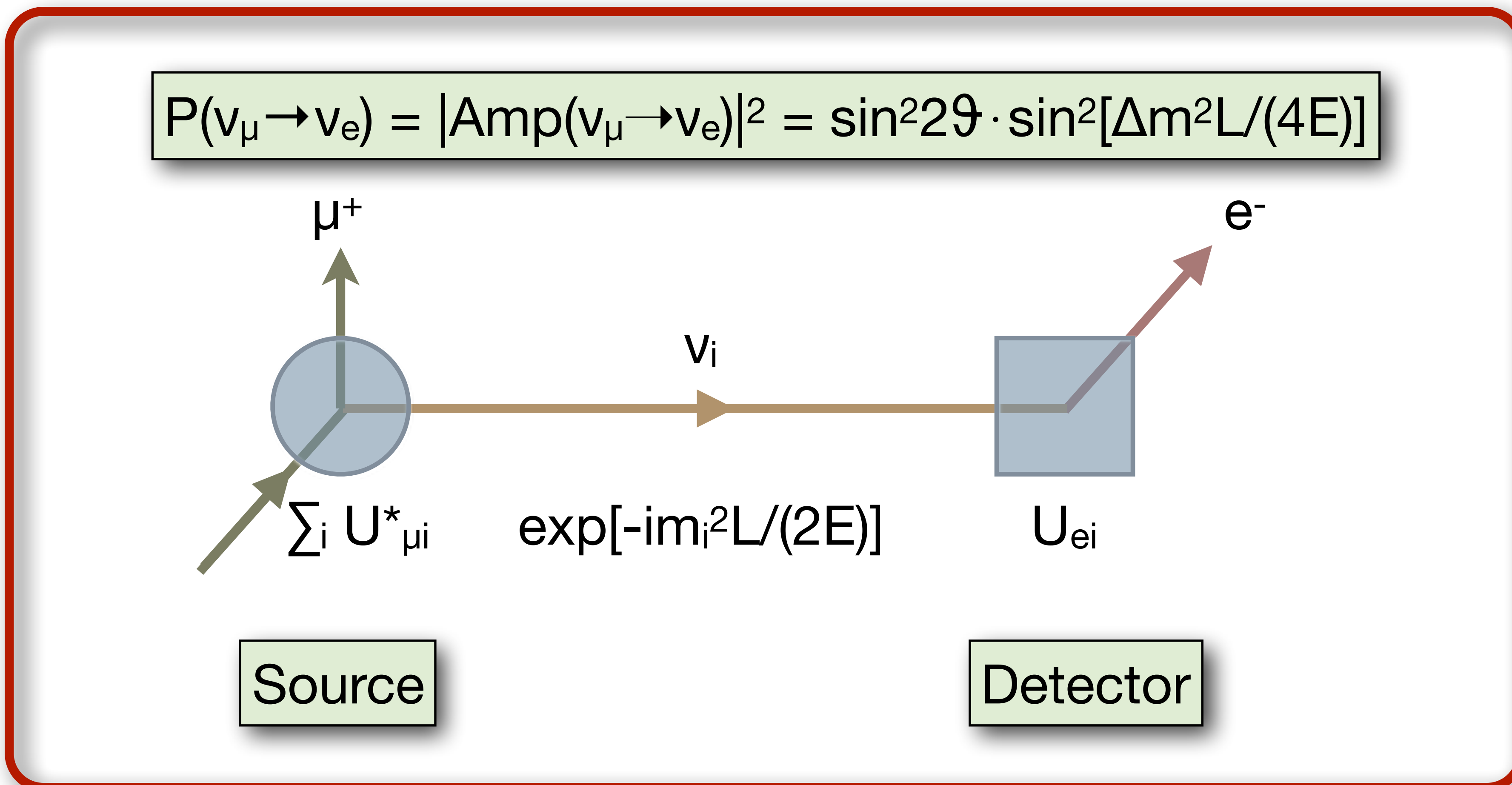
How to experimentally address neutrino questions

(topic of these lectures, see also J. Zornoza, M. Spurio, S. Pastor)

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

Different ways to probe neutrino properties (1/3)

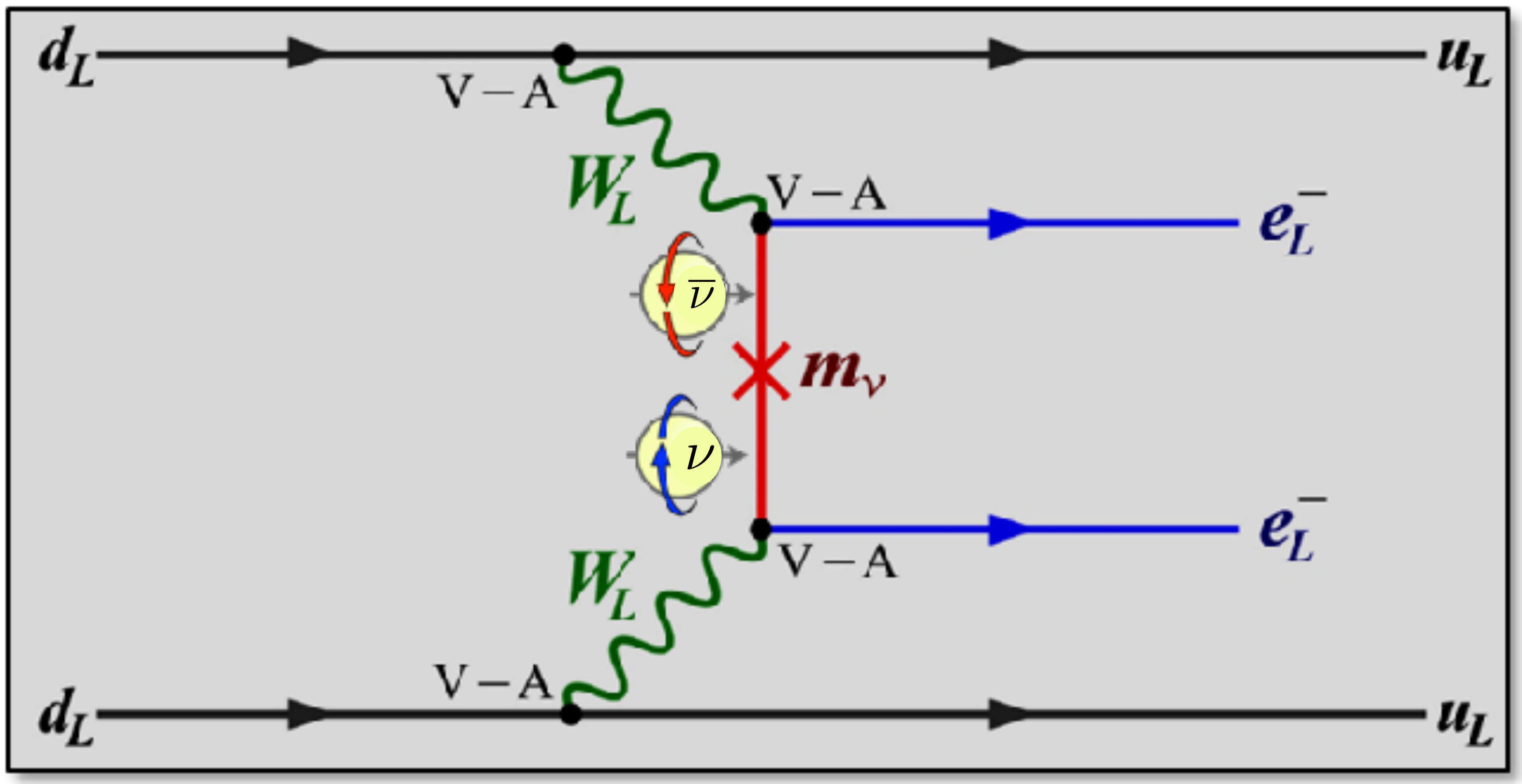
Neutrino oscillations



- **Neutrino source**: several
- **Neutrino properties**: from direct neutrino detection (flavor, energy)

Different ways to probe neutrino properties (2/3)

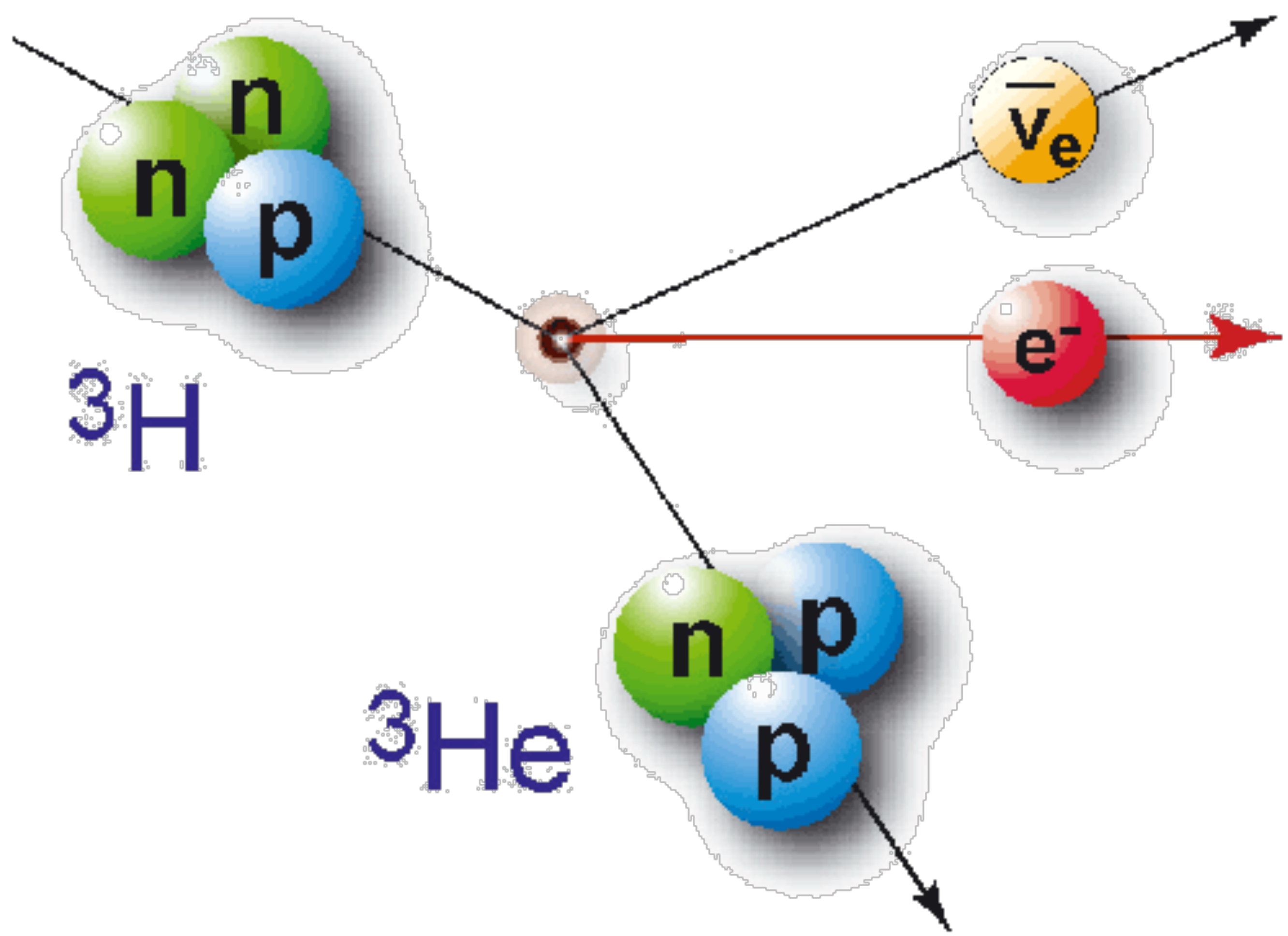
Neutrinoless double beta decay



- **Neutrino source**: natural radioactivity (double β)
- **Neutrino properties**: from virtual neutrino exchange contributions

Different ways to probe neutrino properties (3/3)

Direct neutrino mass measurements



- **Neutrino source**: natural radioactivity (single β)
- **Neutrino properties**: from kinematics of final state electron

Message:

neutrino properties can be probed either through direct neutrino detection, or indirectly

Direct neutrino detection probes:

- *My lectures (Neutrino Experiments)*
- *J. Zornoza's lectures (Neutrino Telescopes)*
- *M. Spurio (Multi-messenger astronomy)*

Indirect probes:

- *My lectures (Neutrino Experiments)*
- *S. Pastor's lectures (Neutrino Cosmology)*

A wealth of neutrino experiments!

Experiments to be presented at Neutrino 2018 Conference next week

Plan for these lectures

Today: neutrino experiments basics

- Neutrino open questions ✓
- How to measure neutrino oscillation parameters
- Neutrino sources
- Neutrino interactions with matter
- Neutrino detector technologies

Wednesday: neutrino experiments specifics

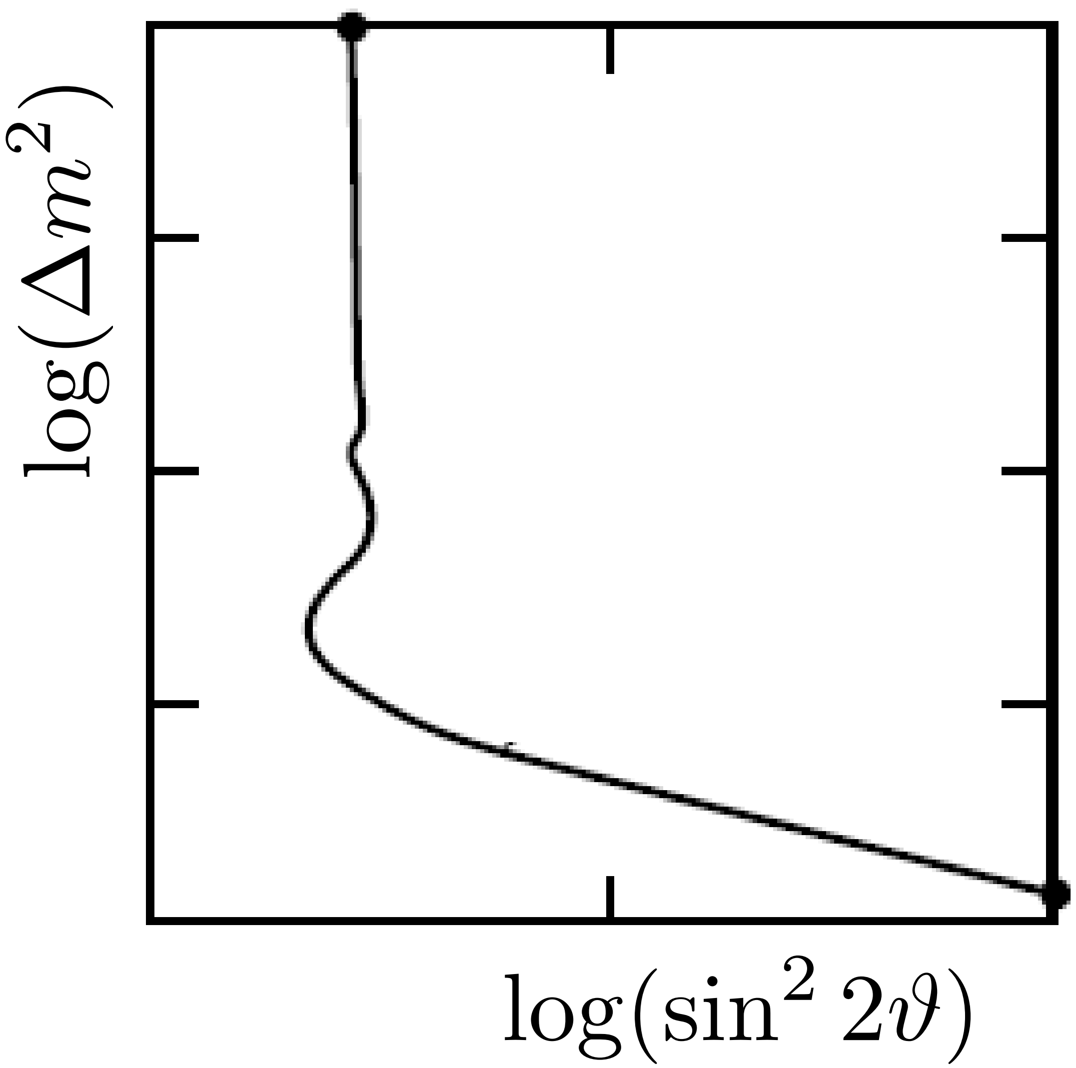
- Selected current and future ν oscillation experiments
- Neutrinoless double beta decay experiments
- Experiments for direct neutrino mass measurements

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:

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



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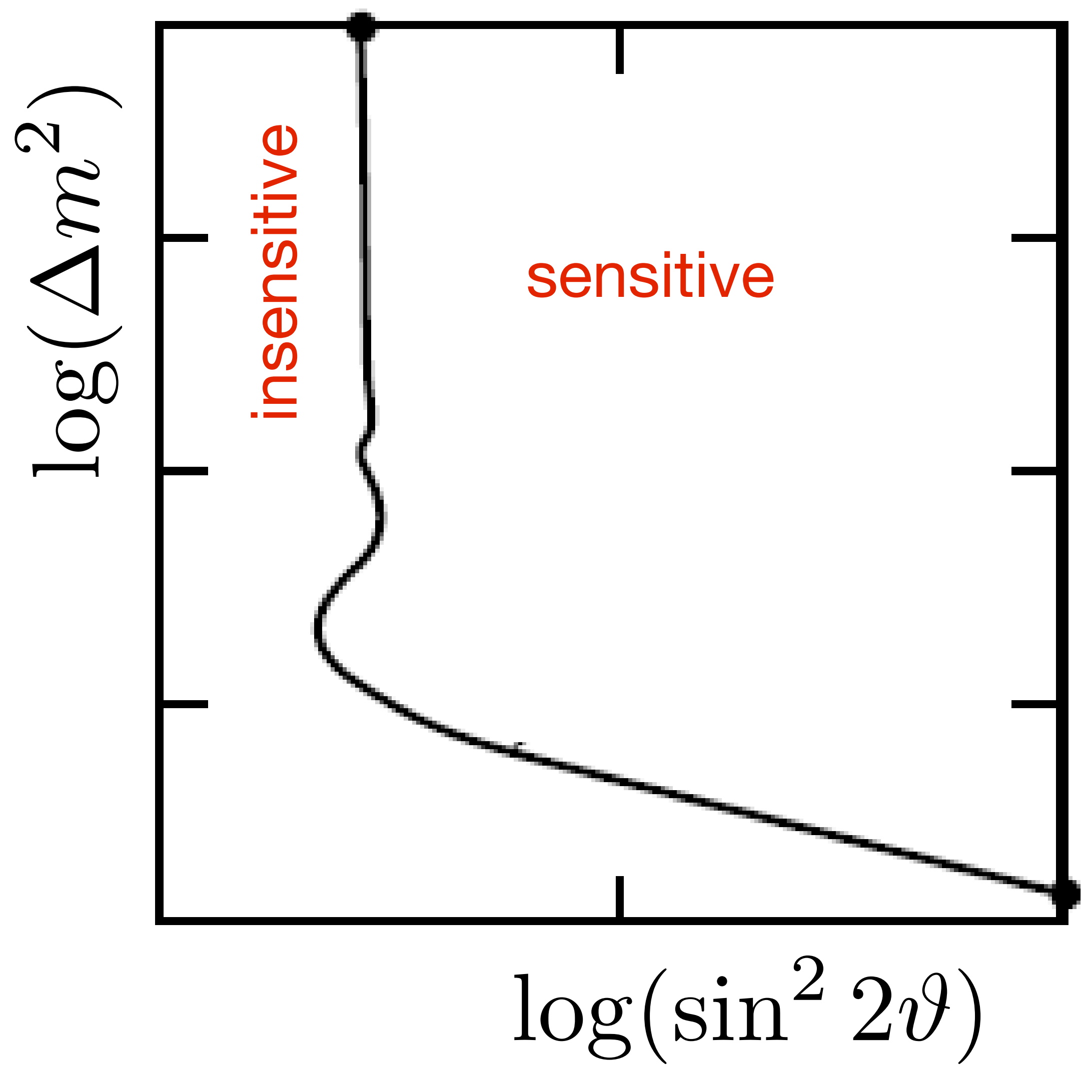
- Sensitivity curve (drawn before carrying out experiment): can potentially measure oscillation parameters to the right and above it.



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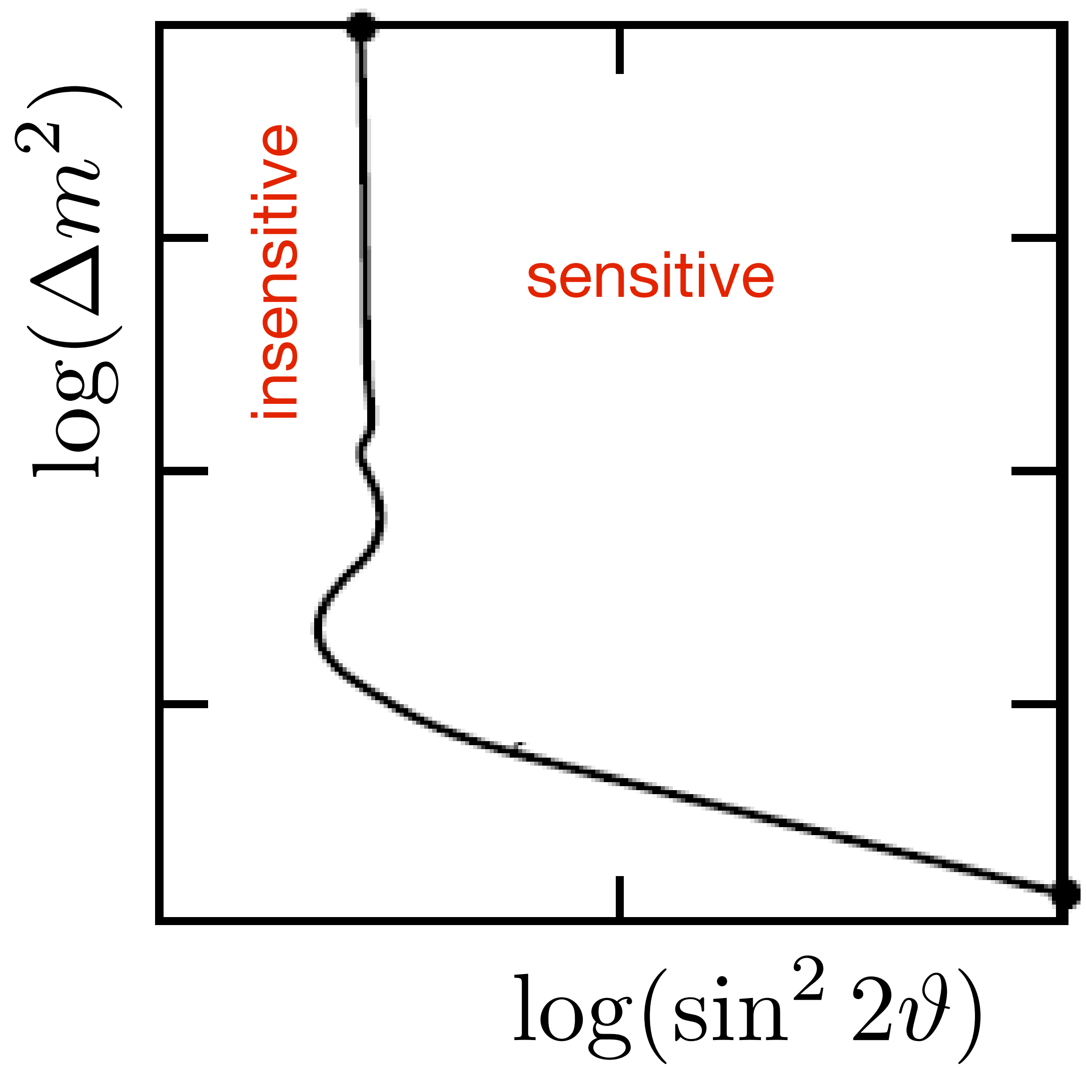
    - upper limit on $\sin^2 2\vartheta$ for each Δm^2, resembling sensitivity curve



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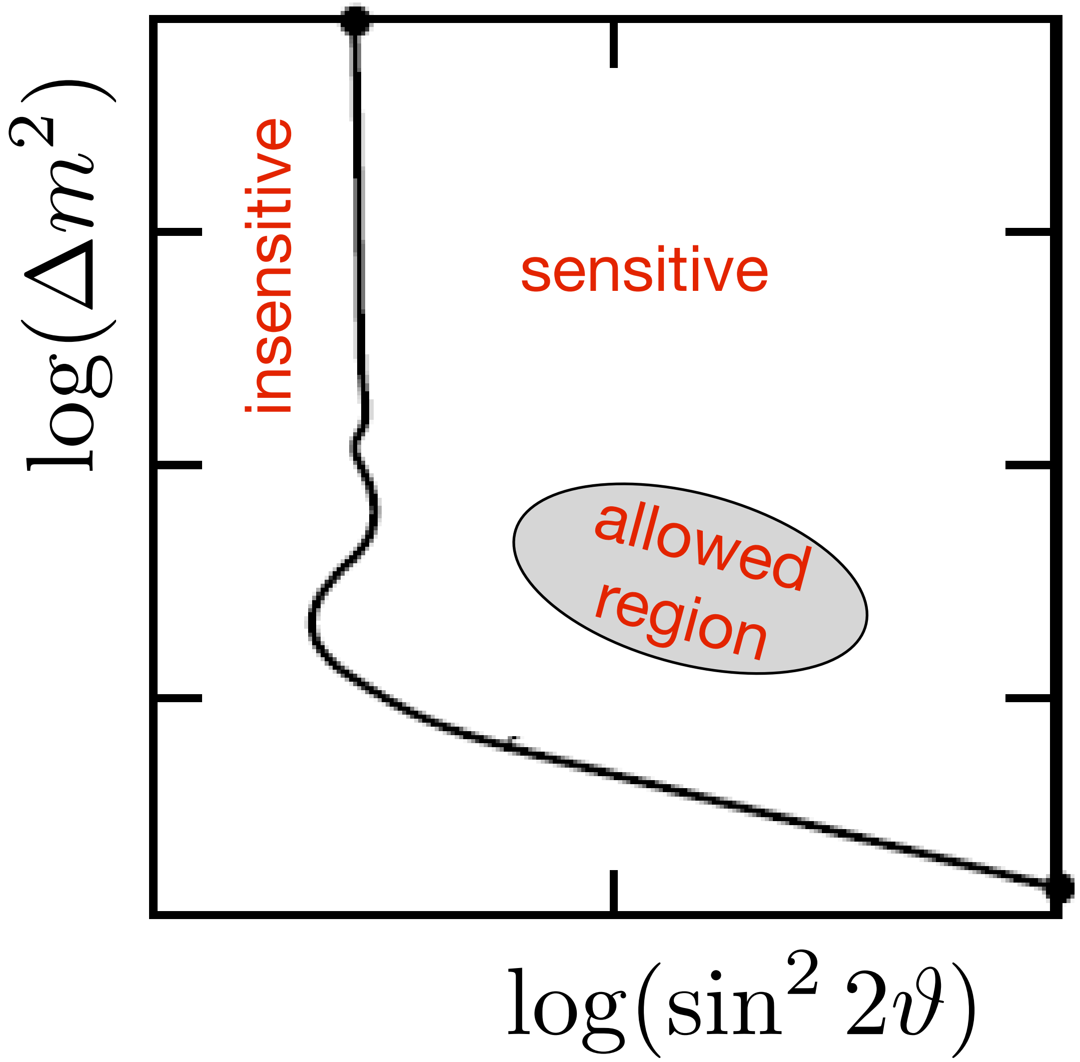
- If an experiment sees oscillations, "potato-like" allowed region in parameter space obtained in sensitive area



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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Experimental sensitivity to neutrino oscillation parameters

Short- and long-baseline experiments

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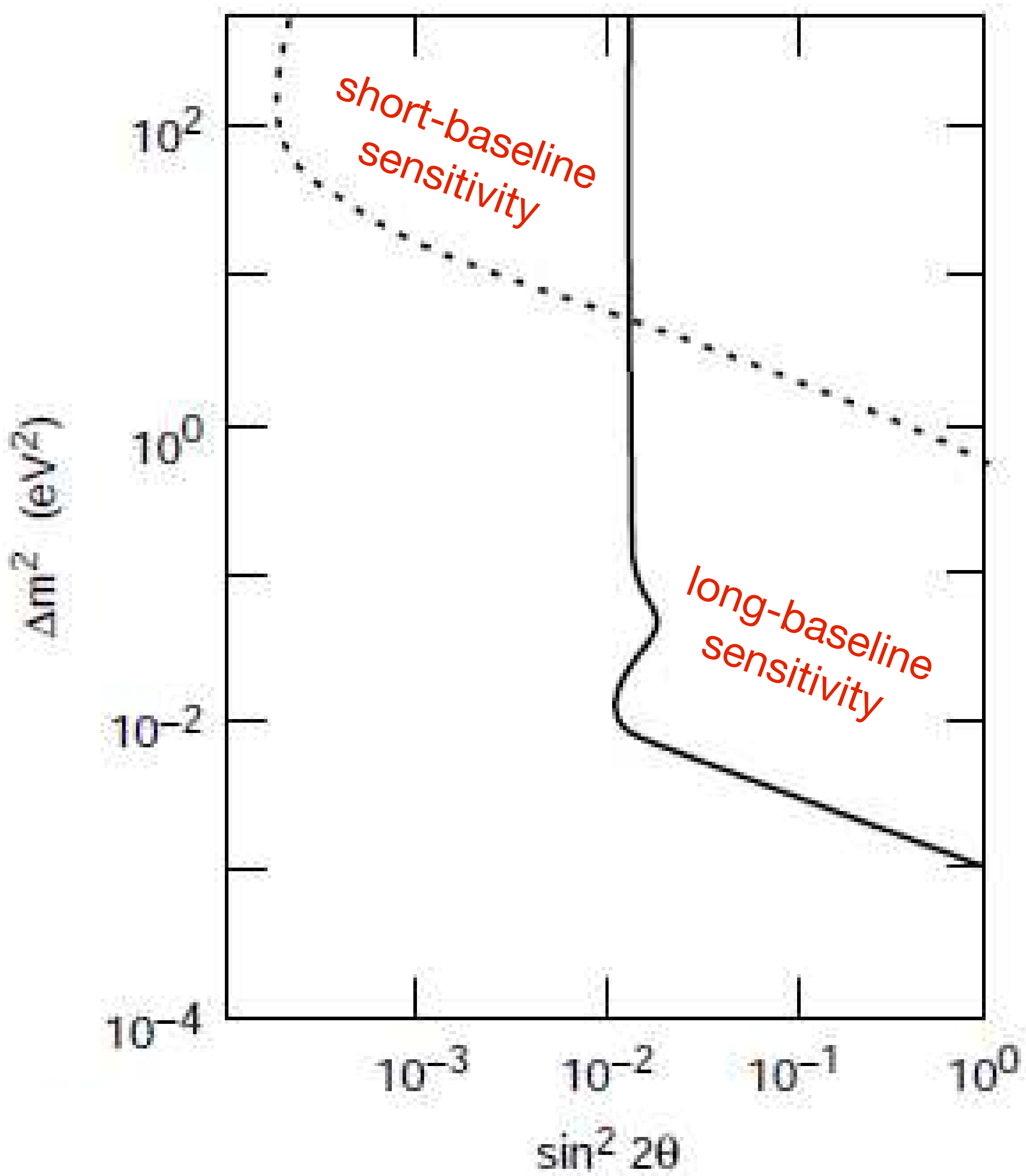
- Drawback: number of events scale with $1/L^2$ →less statistics → worse $\sin^2 2\vartheta$ sensitivity than short-baseline experiment at high Δm^2

- 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

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

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/(cm²·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

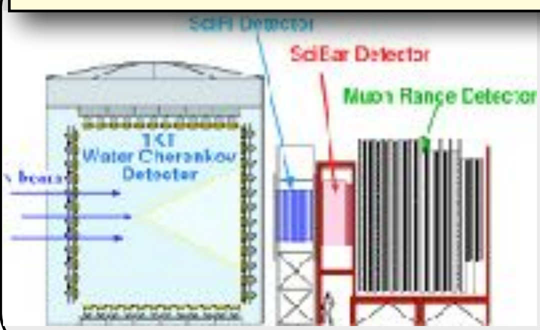
maximize efficiency

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)



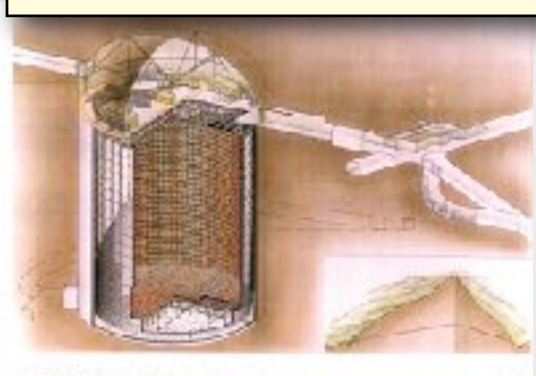
Measure rate, energy of neutrinos

Interaction Model

Infer neutrino flux at near detector(s) before oscillations

Flux Model

Far Detector(s)



Measure rate, energy of neutrinos

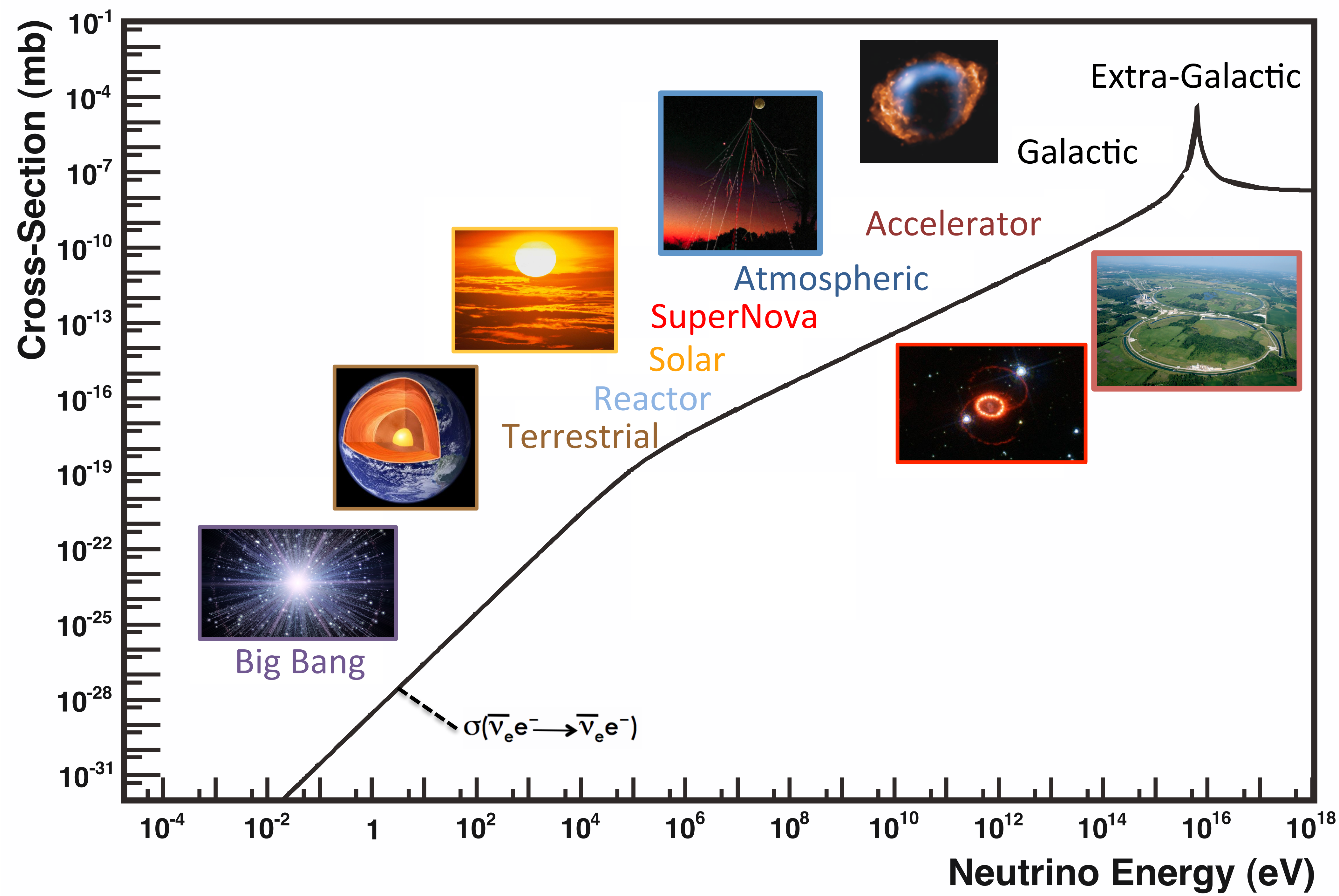
Interaction Model, Oscillation Fit

Predict unoscillated neutrino flux at far detector(s)

Neutrino sources

Neutrino sources

Neutrinos are everywhere!



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

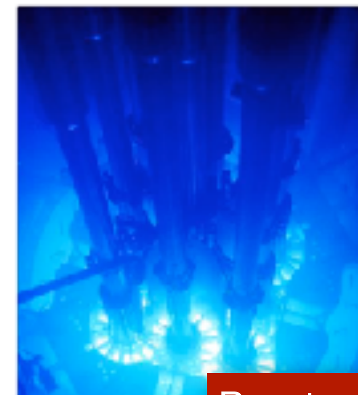
Reactor neutrinos

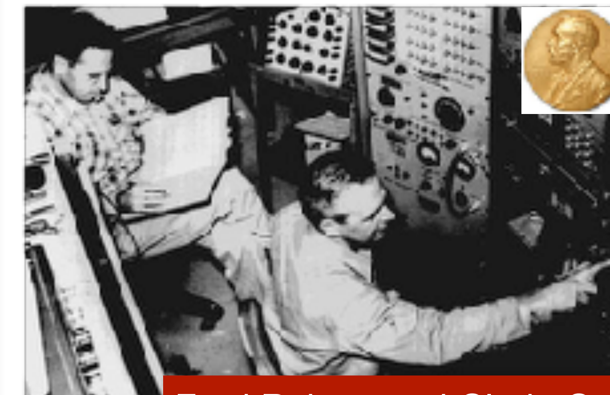
Flavors: $\bar{\nu}_e$

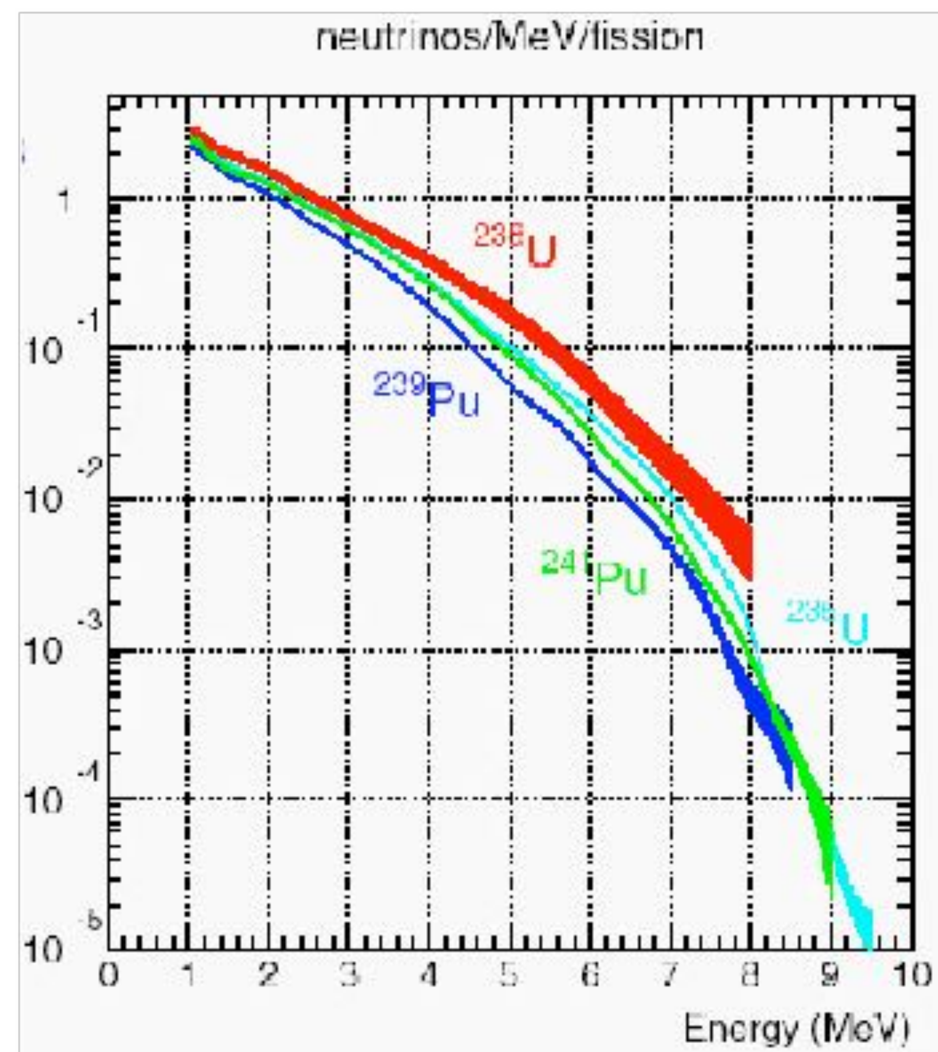
E_ν ~ 1-10 MeV

- 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



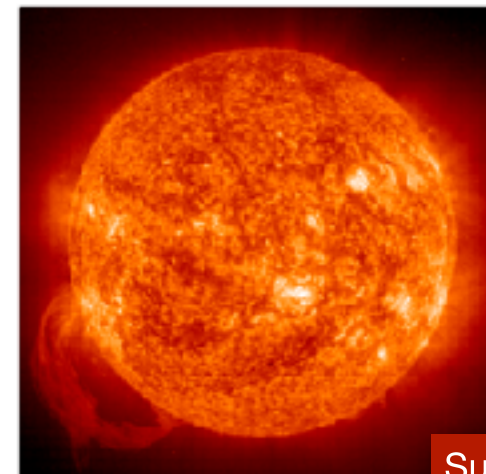
Solar neutrinos

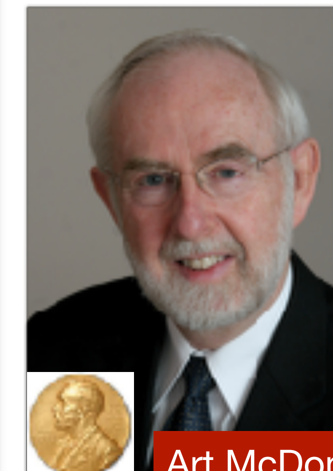
Flavors: ν_e

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

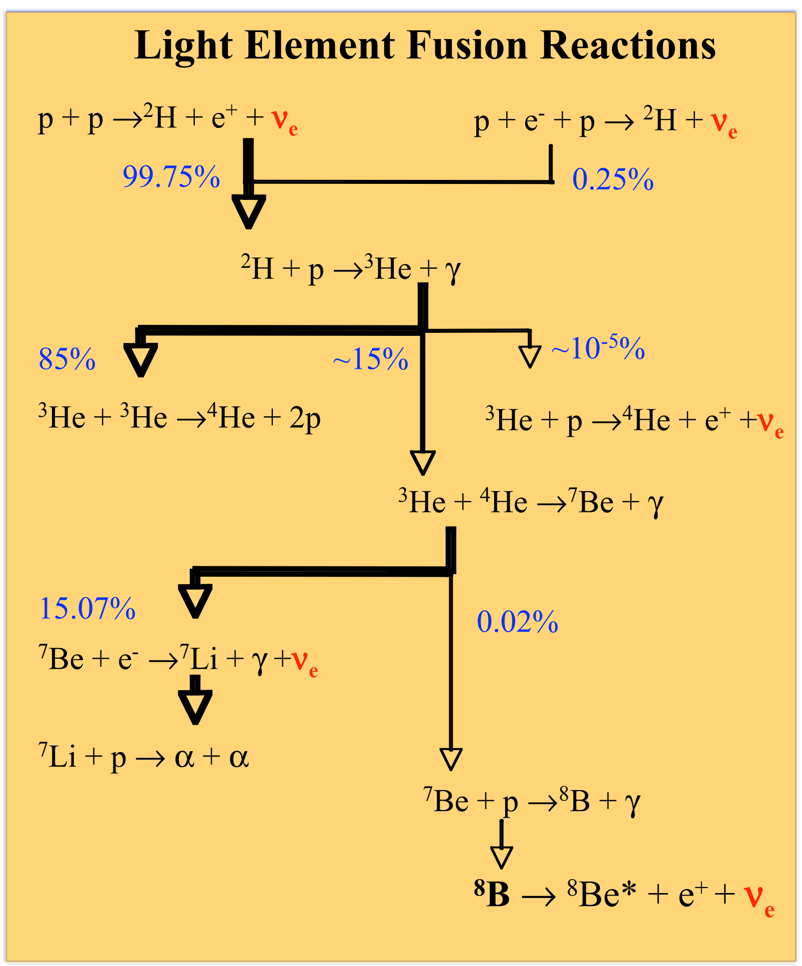
- Source providing first hint for neutrino oscillations!
- Nuclear fusion processes in the Sun produce neutrinos:

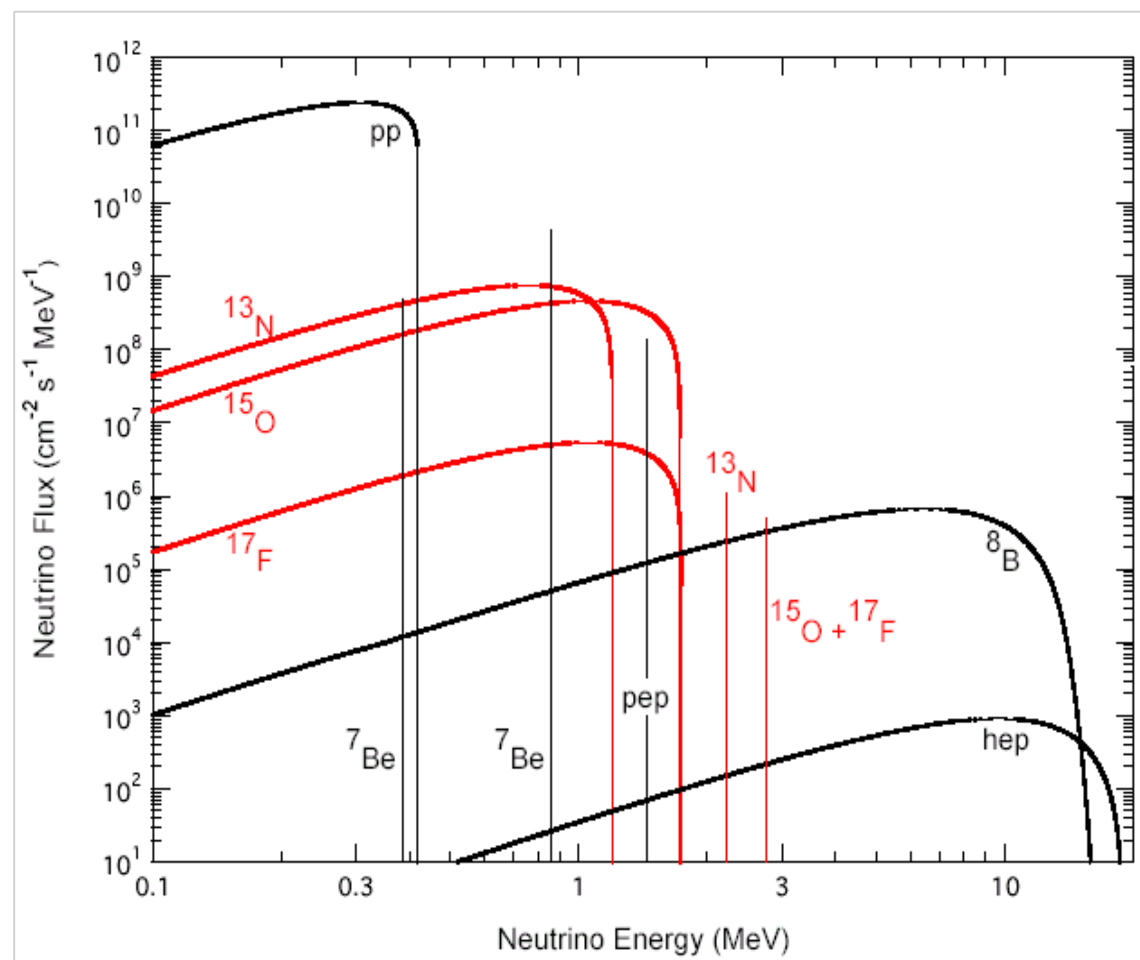
$$4p + 2e^- \rightarrow He + 2\nu_e + 26.7\ \text{MeV}$$


Sun


Art McDonald

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



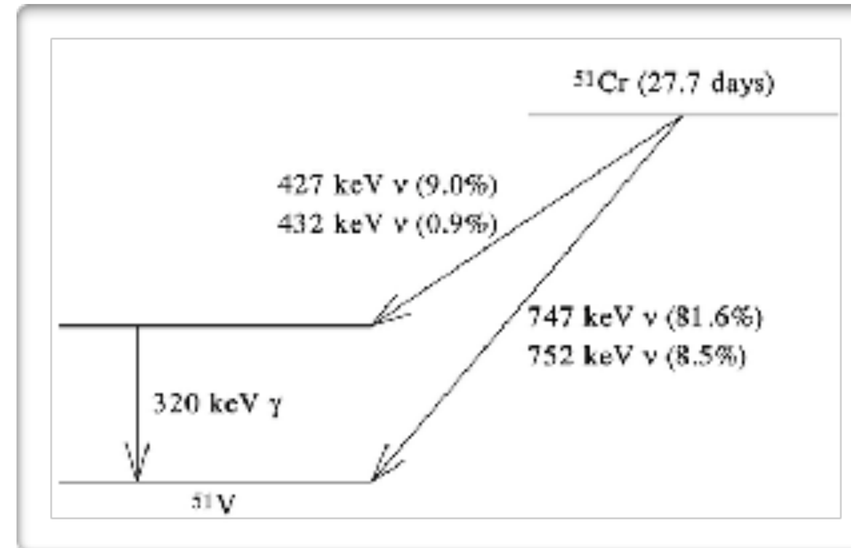


Radioactive source neutrinos

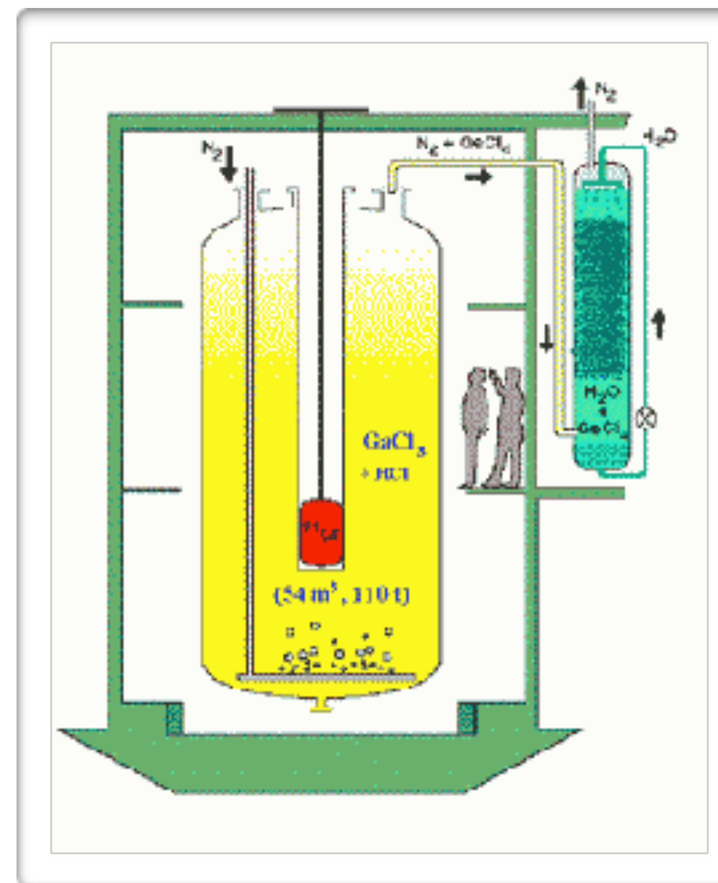
Flavors: ν_e, $\bar{\nu}_e$

E_ν ~ 0.1-5 MeV

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



- 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!
- **Wed**: β/ββ sources also for direct neutrino mass measurements, neutrinoless double beta decay searches



Accelerator neutrinos

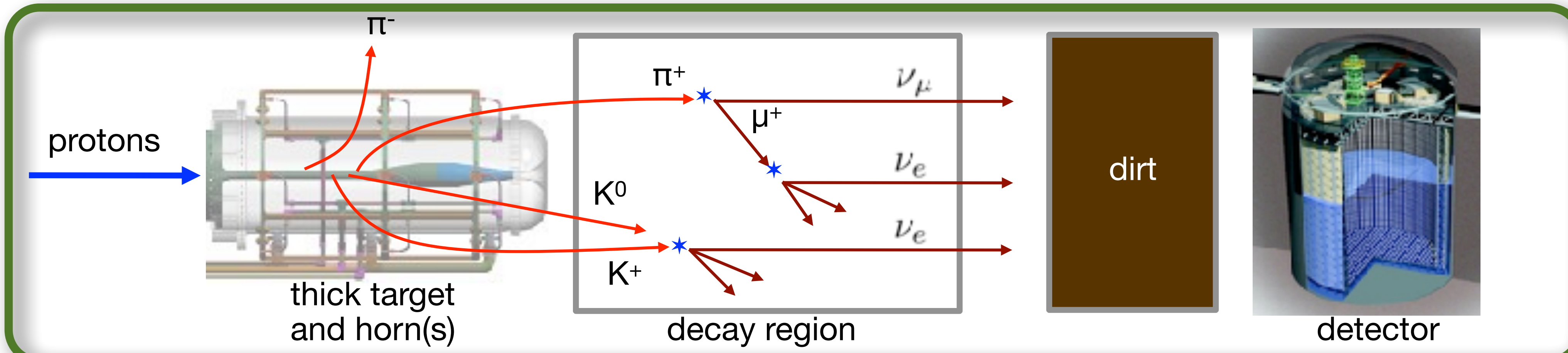
Flavors: ν_μ, $\bar{\nu}_\mu$, ν_e, $\bar{\nu}_e$

$E_\nu \sim 0.1\text{-}100$ 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, $\bar{\nu}_e$

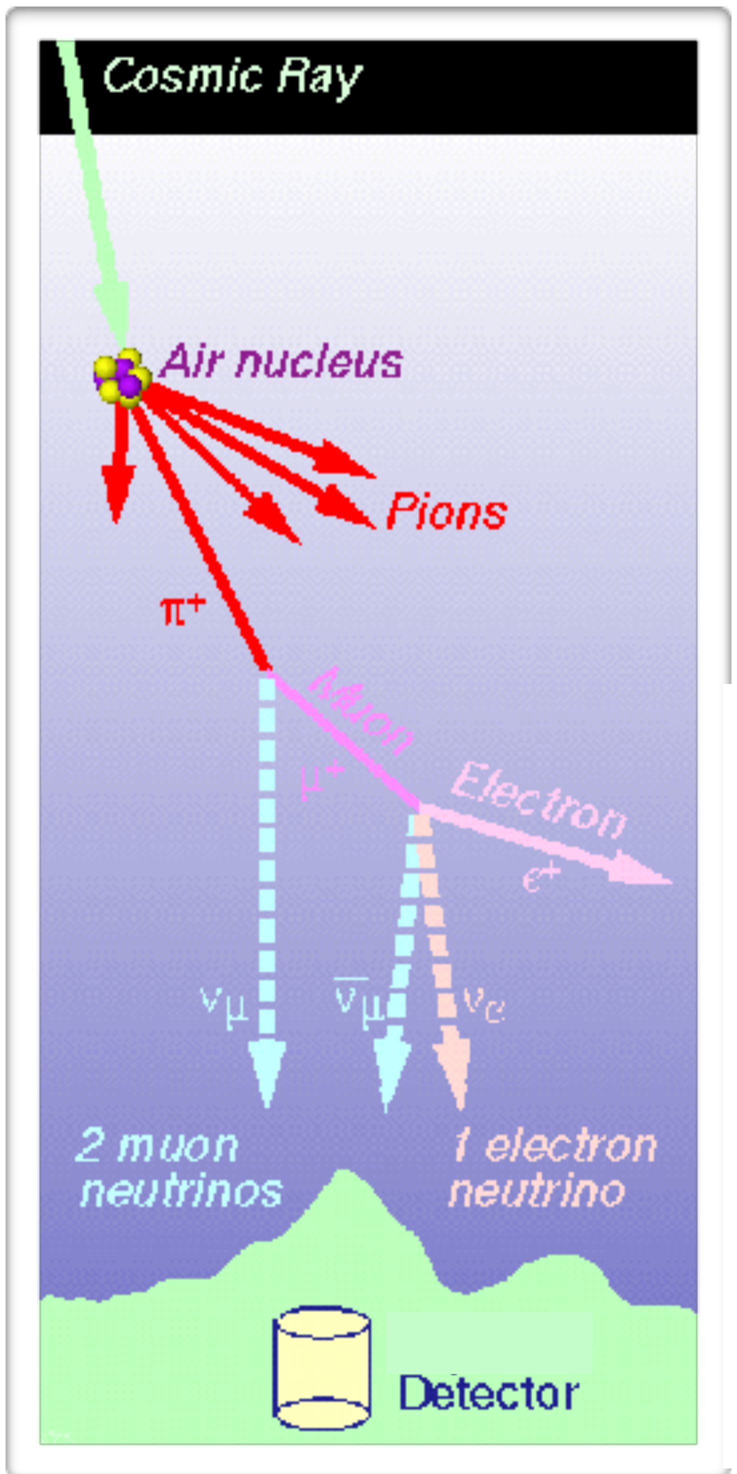
E_ν ~ 0.1-100 GeV

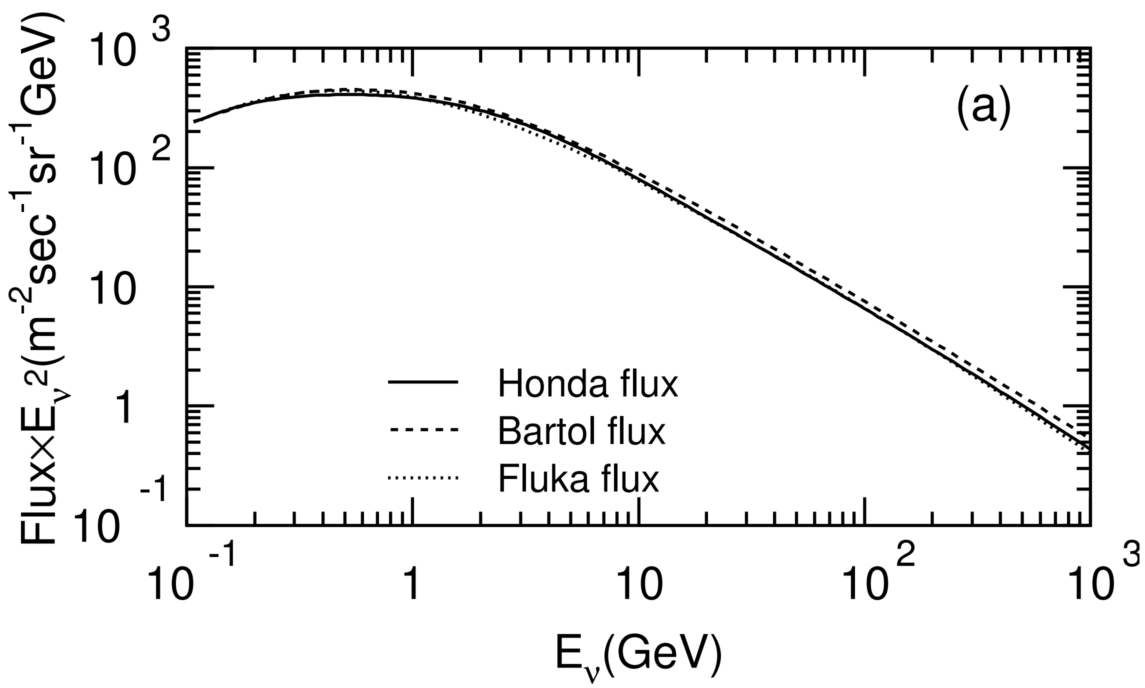
	Booster (Fermilab)	Main Injector (Fermilab)	SPS (CERN)	Main Ring (JPARC)	Main Injector (Fermilab)
Date	2002	2005	2006	2017	2017
Proton kinetic energy (GeV)	8	120	400	30 (50)	120
Beam power (kW)	29	350	510	500 (750)	720
Target material	beryllium	graphite	graphite	graphite	graphite
Target length (cm)	71	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

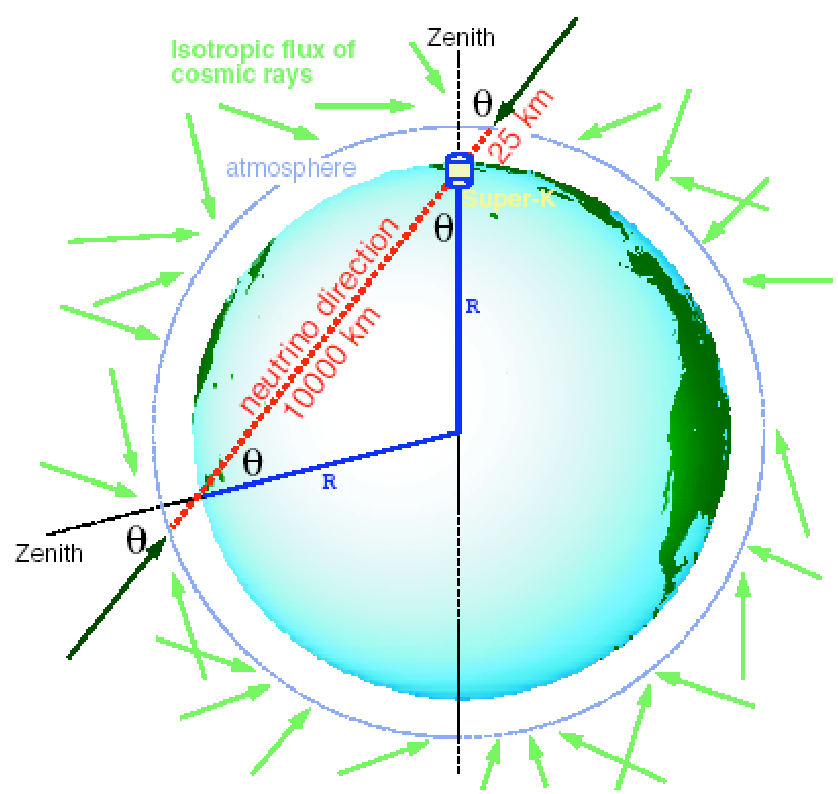
Flavors: ν_μ, $\bar{\nu}_\mu$, ν_e, $\bar{\nu}_e$

E_ν ~ 0.1-100 GeV





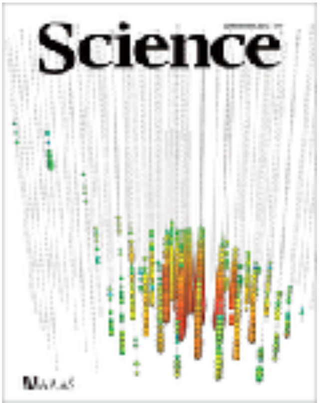

Takaaki Kajita

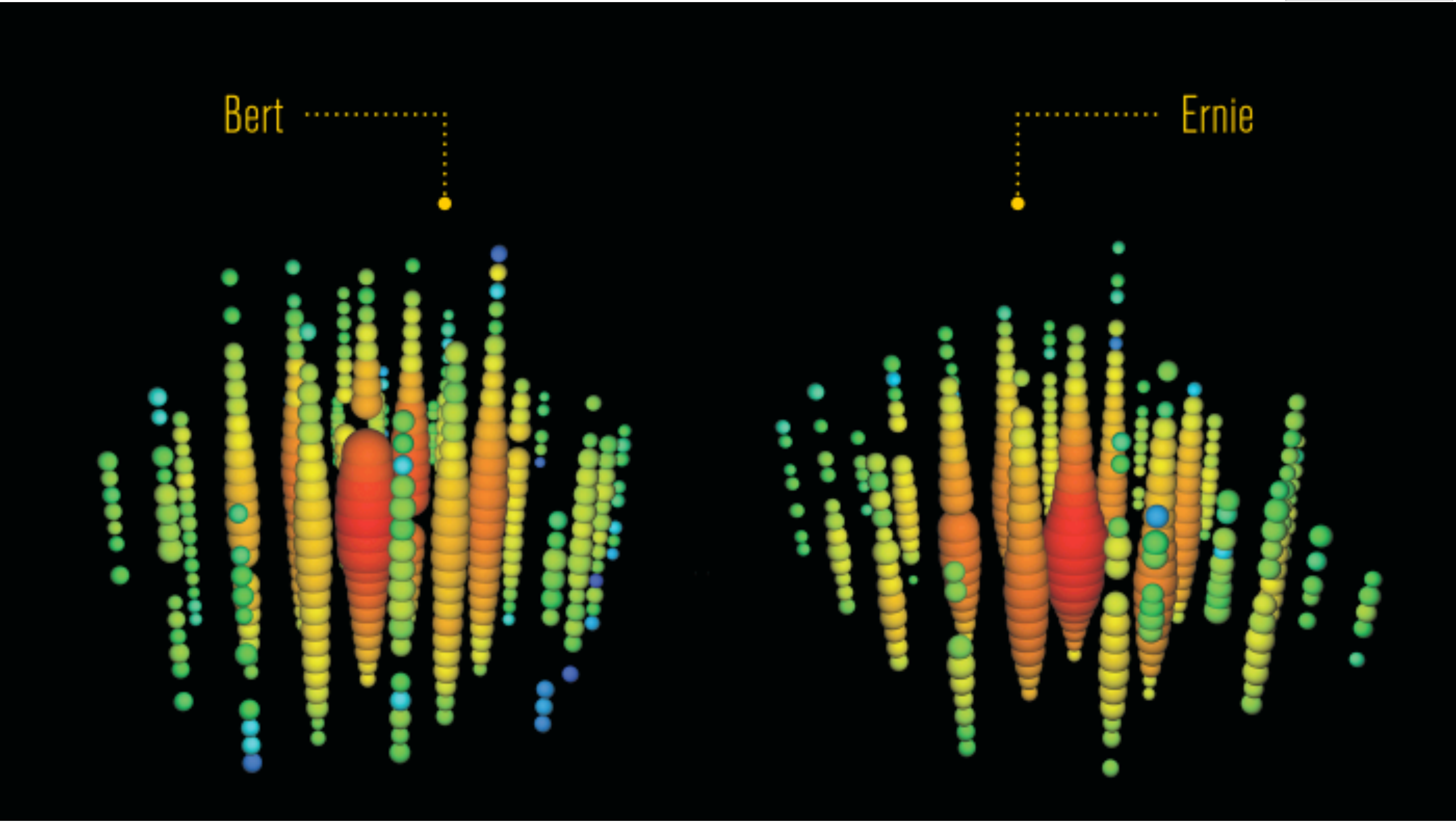


- Source conclusively establishing neutrino oscillations!
- Produced by cosmic ray interactions in the atmosphere
- Pion/muon decay chain yield yield ν_μ:ν_e ratio close to 2
- All directions

High-energy astrophysical neutrinos

See J. Zornoza's, M. Spurio's lectures





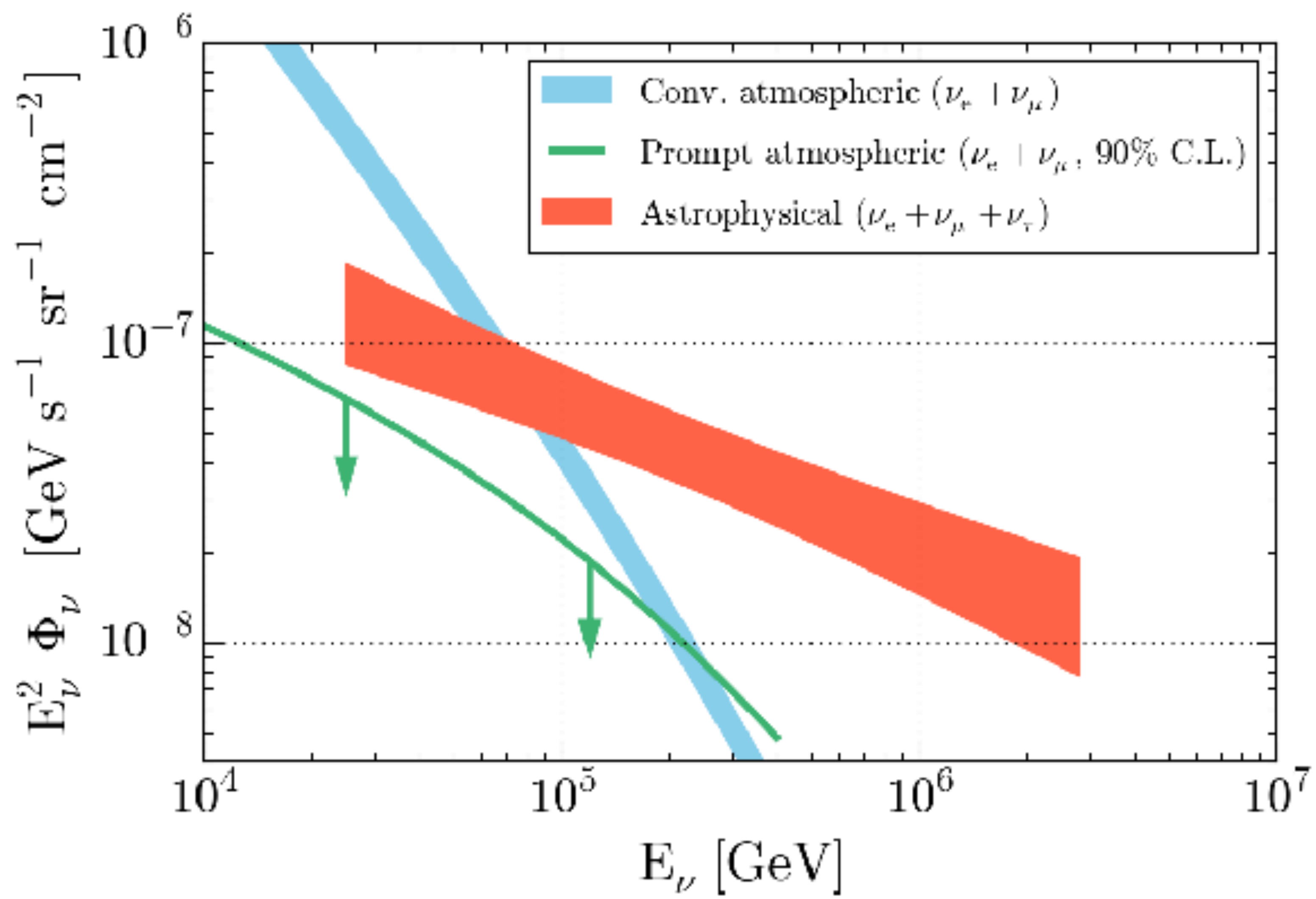
High-energy astrophysical neutrinos

See J. Zornoza's, M. Spurio's lectures

Flavors: all?

E_ν ~ 10-1000 TeV

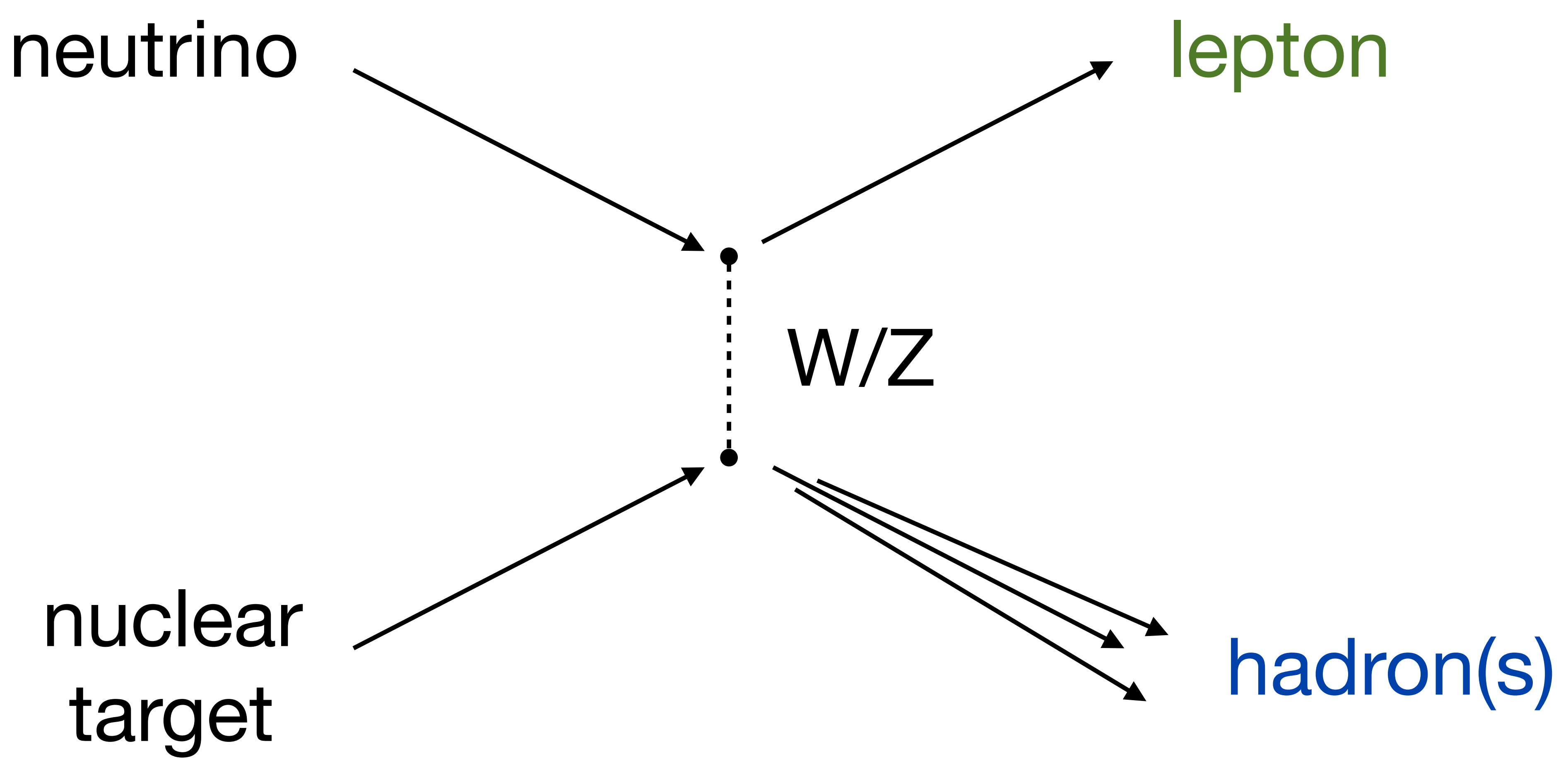
- Recently observed by IceCube!
- Clear excess above atmospheric neutrino background
- Origin: yet to be determined
- Neutrinos produced from decay of unstable mesons, as in atmosphere
- Expect ν_e:ν_μ:ν_τ = 1:1:1 flavor composition on Earth from oscillations



Neutrino interactions with matter

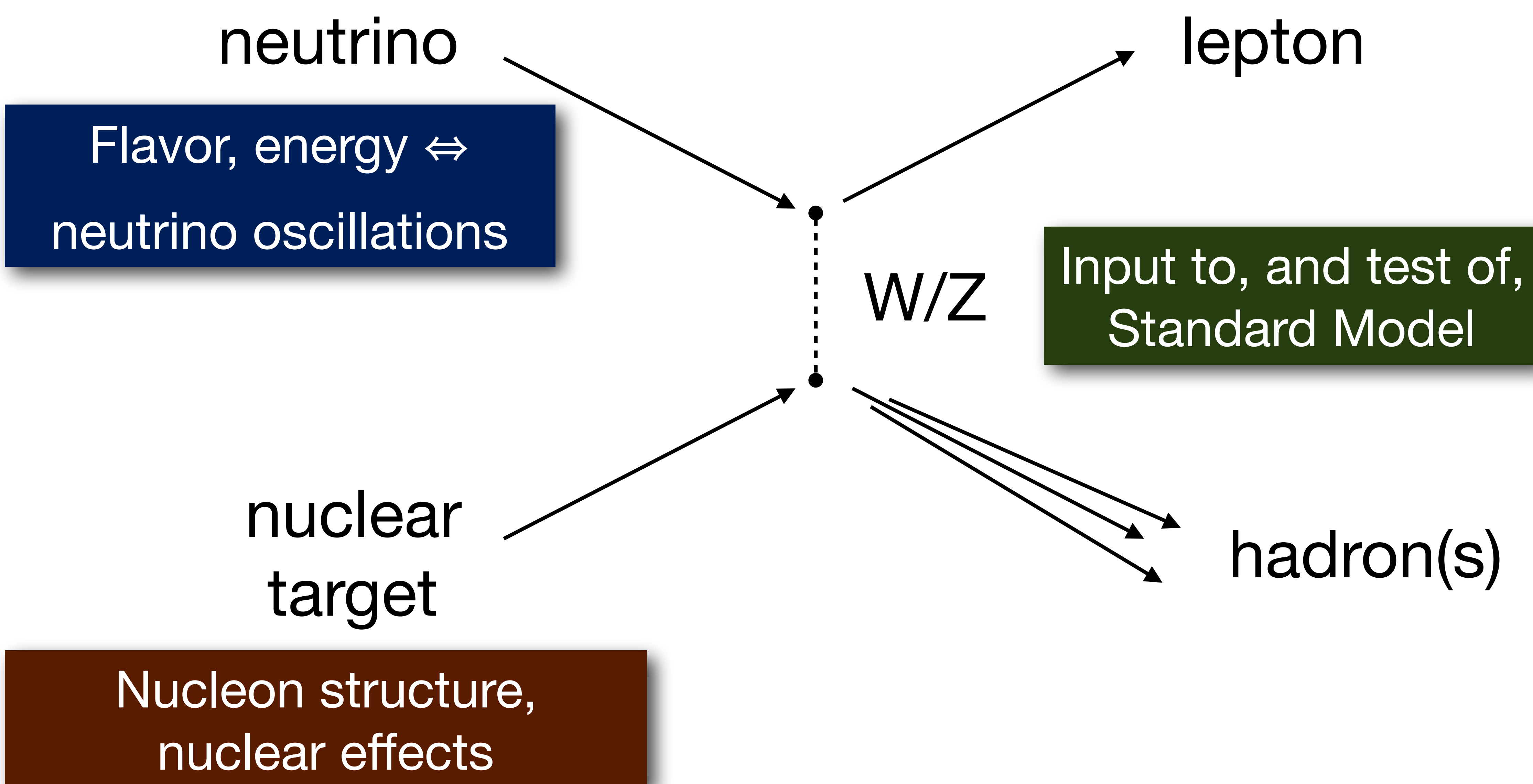
Why study neutrino interactions?

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



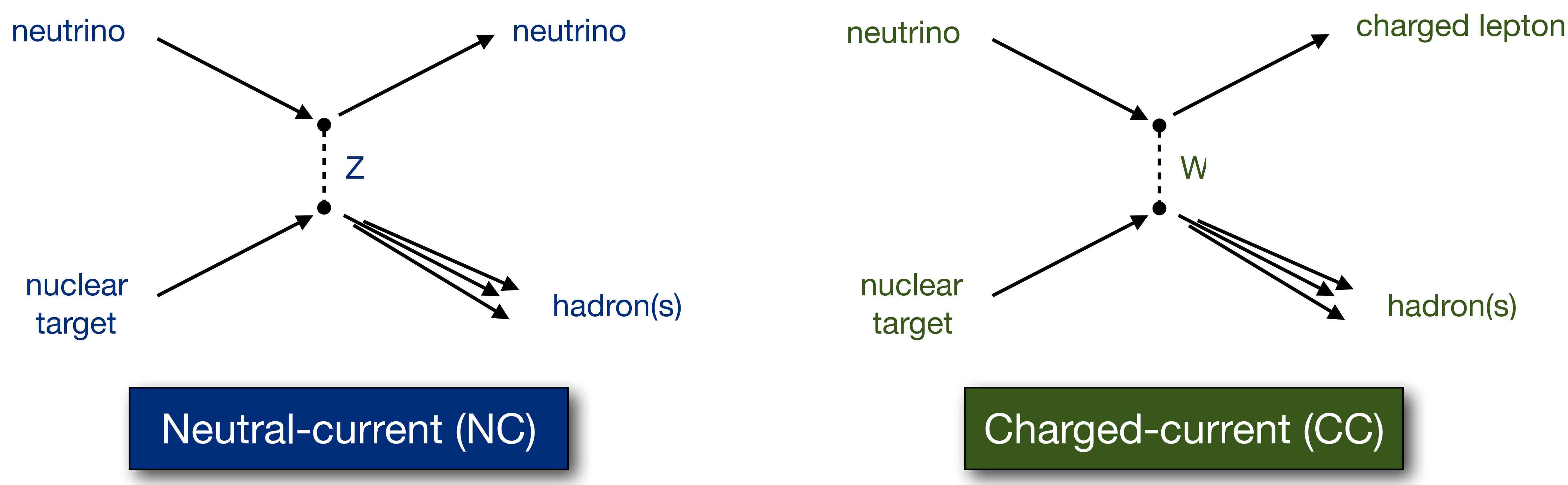
Why study neutrino interactions?

- Infer electroweak, nuclear, neutrino properties



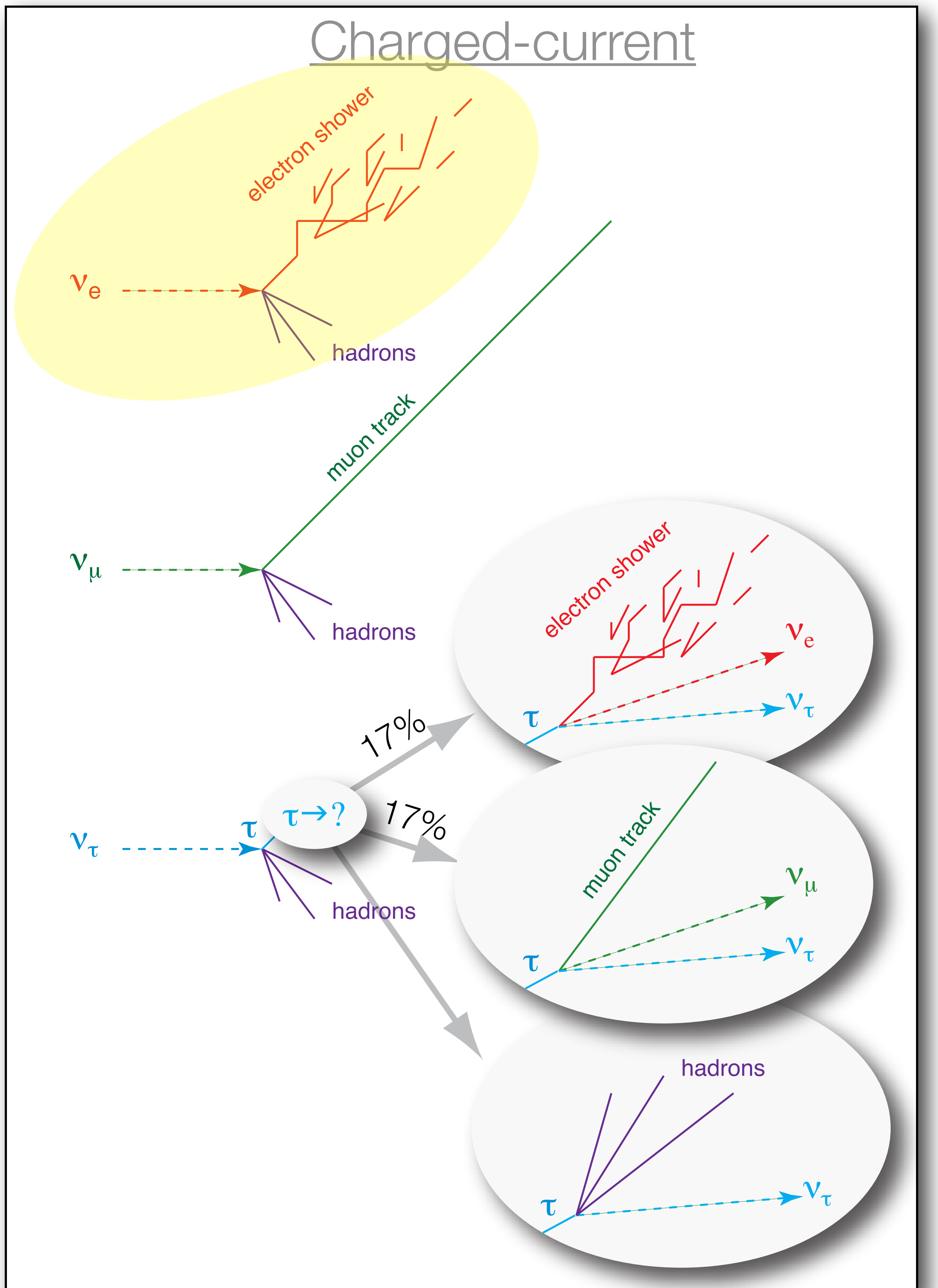
Neutrino interactions and oscillations

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

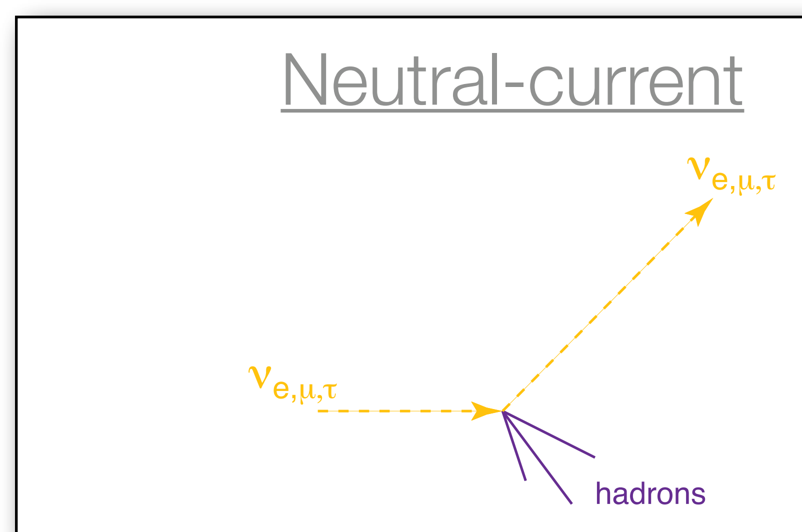


- We identify the neutrino flavor via the CC interaction
  - CC interactions used for oscillation measurements
  - NC interactions are not affected by oscillations, but can be background to CC signals!
- In CC interactions, nearly all the neutrino energy is deposited in the detector
  - Not so for NC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

Neutrino interaction signatures

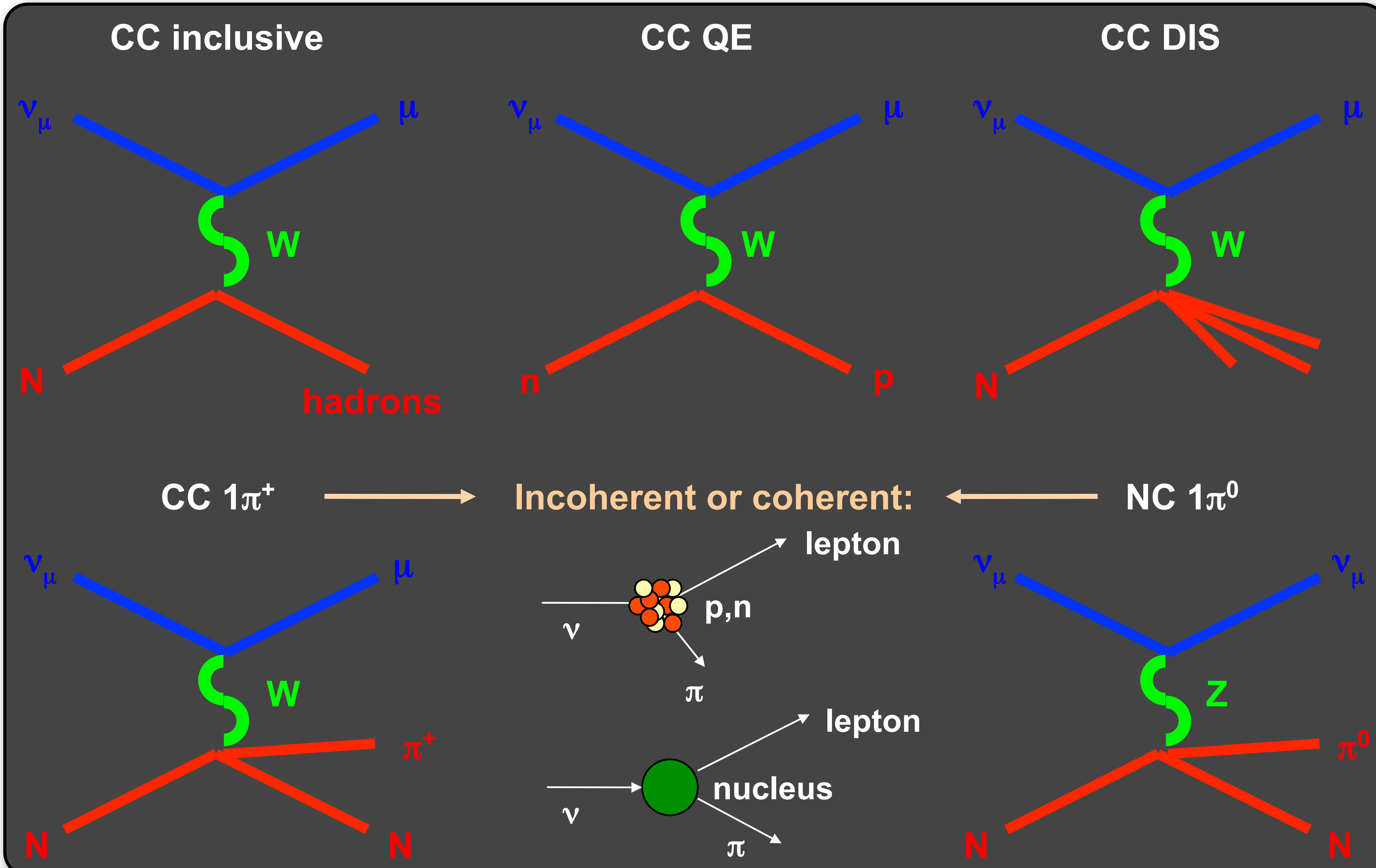


- Experiments can typically distinguish the
- following neutrino interaction products:
  - *Electrons and electron showers*
  - *Muon tracks*
  - *Hadrons and hadronic showers*
  - *Tau decay products*



Some important neutrino interactions

Examples for few-GeV muon neutrino interactions

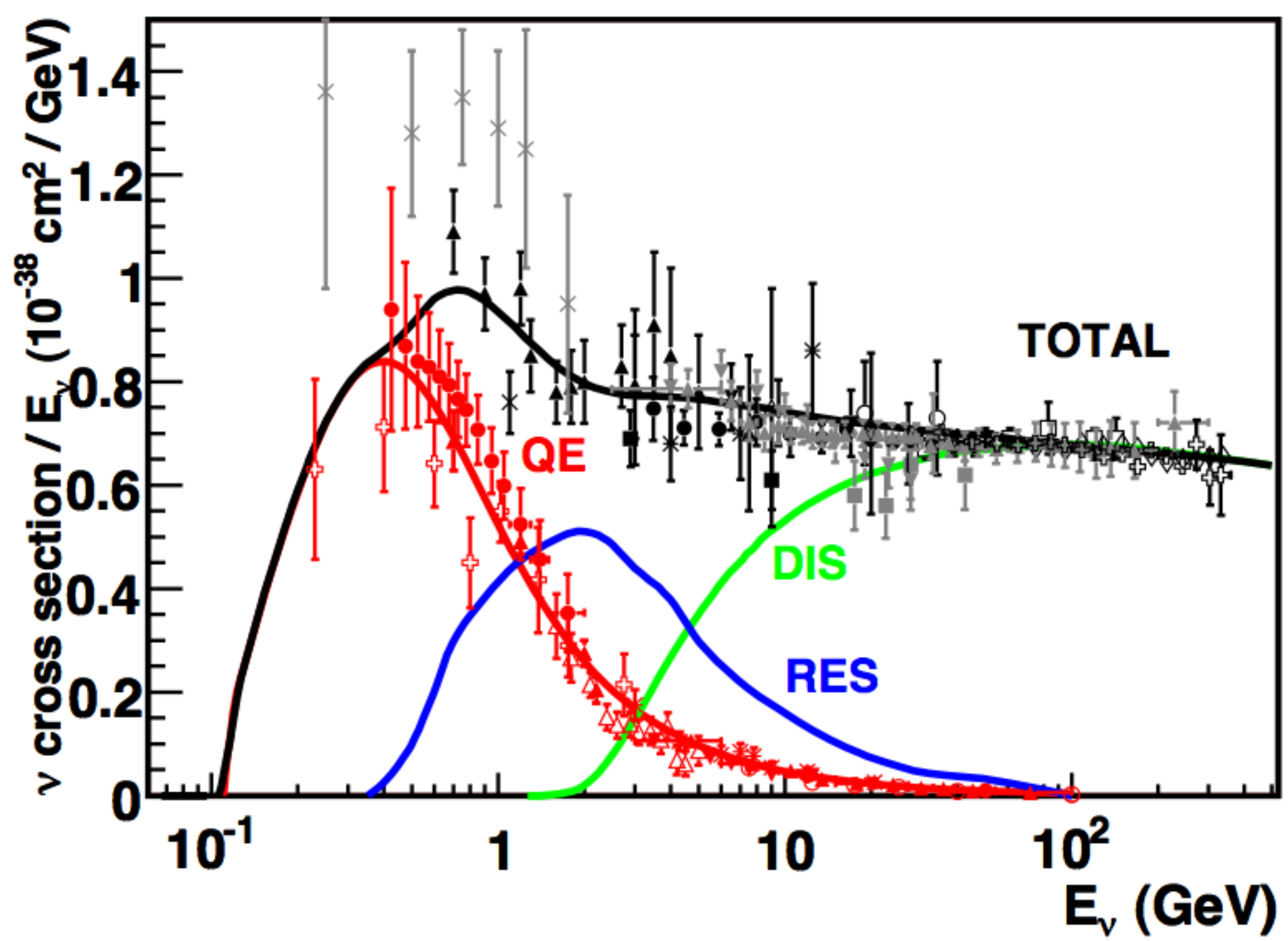


Current knowledge of neutrino interactions

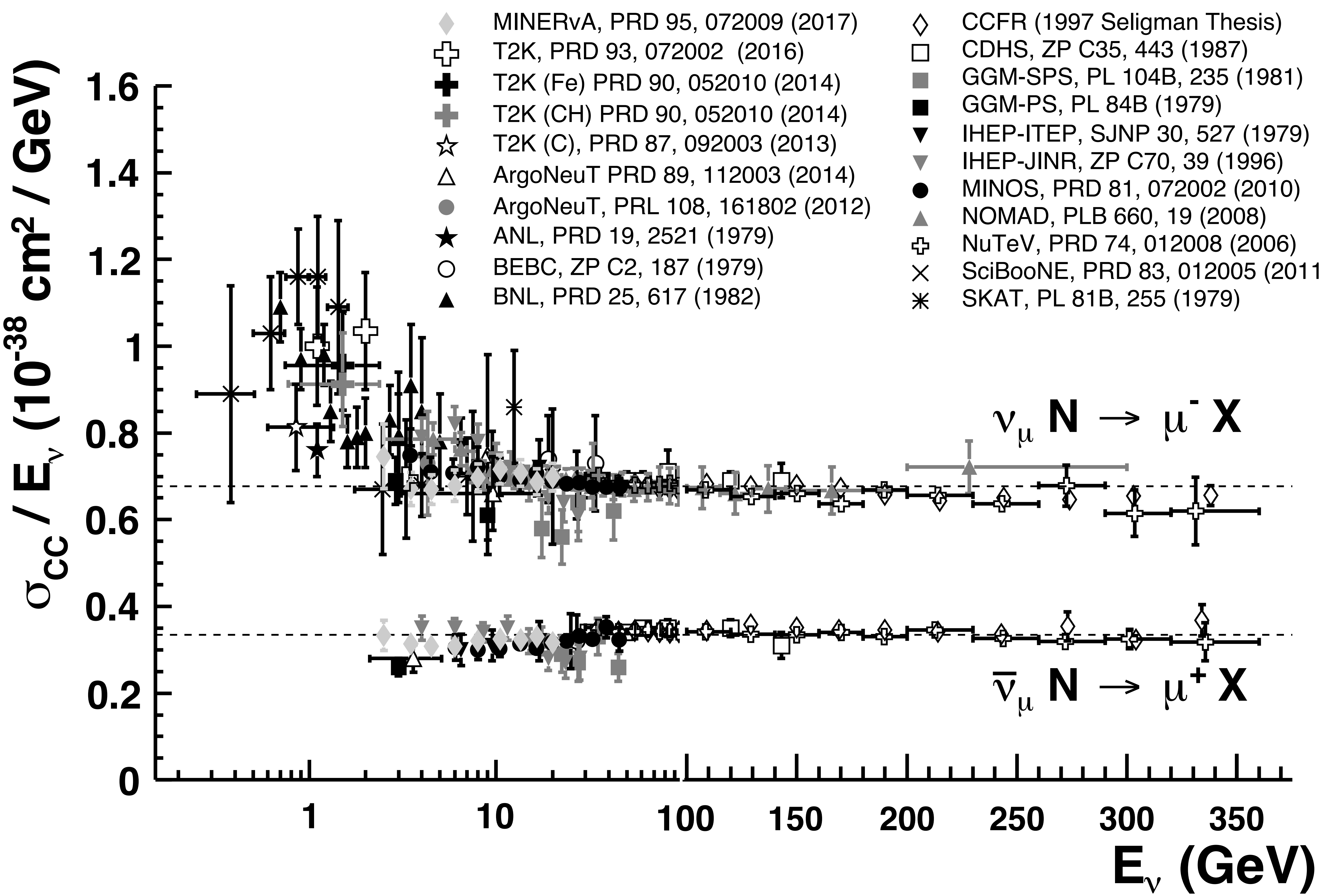
- 1-100 MeV energy: $\overline{\nu}_e + p \rightarrow e^+ + n$ known with ±0.5% accuracy!
  - If scattering not off free protons, more uncertain because of nuclear effects
- 0.1-20 GeV energy: many processes, insufficient knowledge (10-20% level)
- 20-300 GeV energy: DIS interactions off quarks, known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

- Muon neutrino cross sections
- Note: divided by neutrino energy!

  (to 1st order: σ proportional to E_ν)

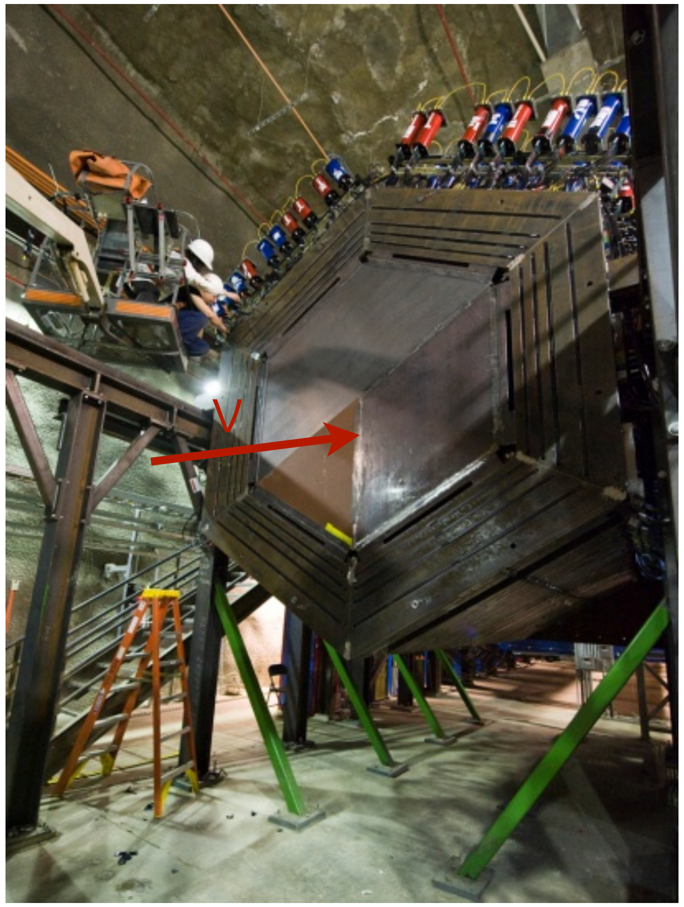


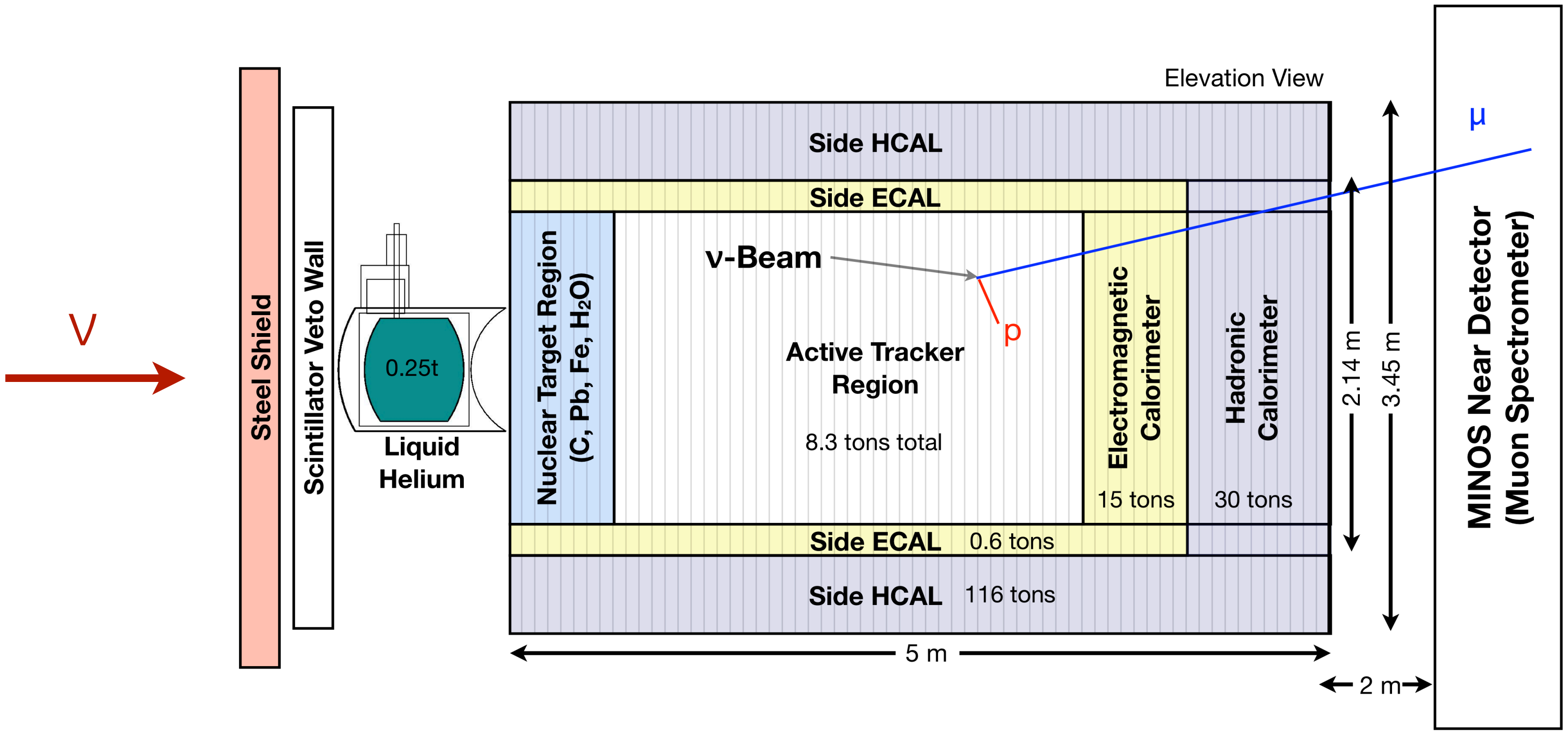
CC inclusive scattering cross sections



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



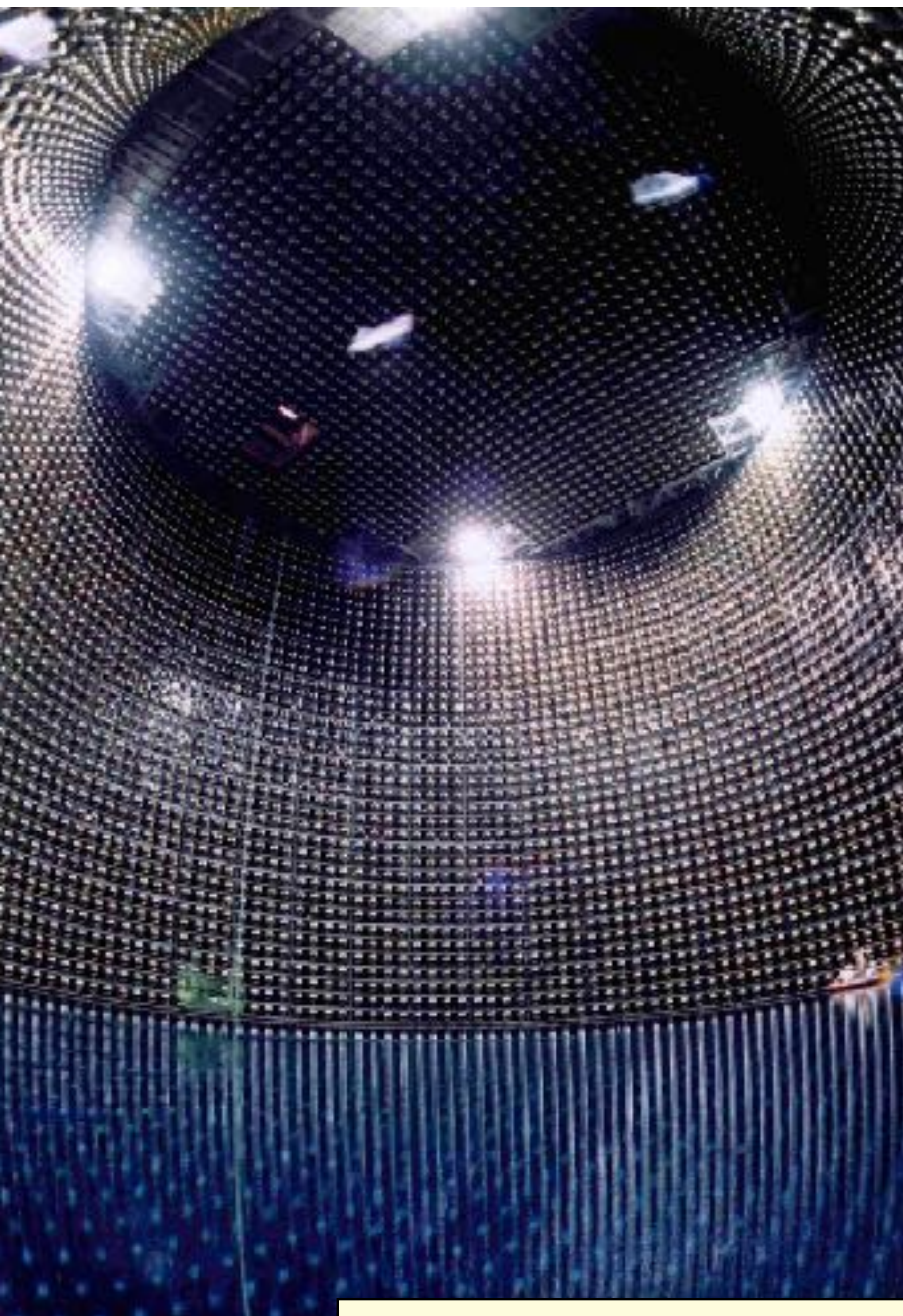


Accelerator-based experiments studying neutrino scattering

Experiment	beam	$\langle E_\nu \rangle$, $\langle E_{\overline{\nu}} \rangle$ GeV	neutrino target(s)	run period
ArgoNeuT	$\nu, \overline{\nu}$	4.3, 3.6	Ar	2009 – 2010
ICARUS (at CNGS)	ν	20.0	Ar	2010 – 2012
K2K	ν	1.3	CH, H_2O	2003 – 2004
MicroBooNE	ν	0.8	Ar	2015 –
MINERvA	$\nu, \overline{\nu}$	3.5 (LE), 5.5 (ME)	He, C, CH, H_2O, Fe, Pb	2009 –
MiniBooNE	$\nu, \overline{\nu}$	0.8, 0.7	CH_2	2002 – 2012
MINOS	$\nu, \overline{\nu}$	3.5, 6.1	Fe	2004 – 2016
NOMAD	$\nu, \overline{\nu}$	23.4, 19.7	C–based	1995 – 1998
NOvA	$\nu, \overline{\nu}$	2.0, 2.0	CH_2	2010 –
SciBooNE	$\nu, \overline{\nu}$	0.8, 0.7	CH	2007 – 2008
T2K	ν, $\overline{\nu}$	0.6, 0.6	CH, H_2O, Fe	2010 –

Neutrino detector technologies

Cherenkov detectors

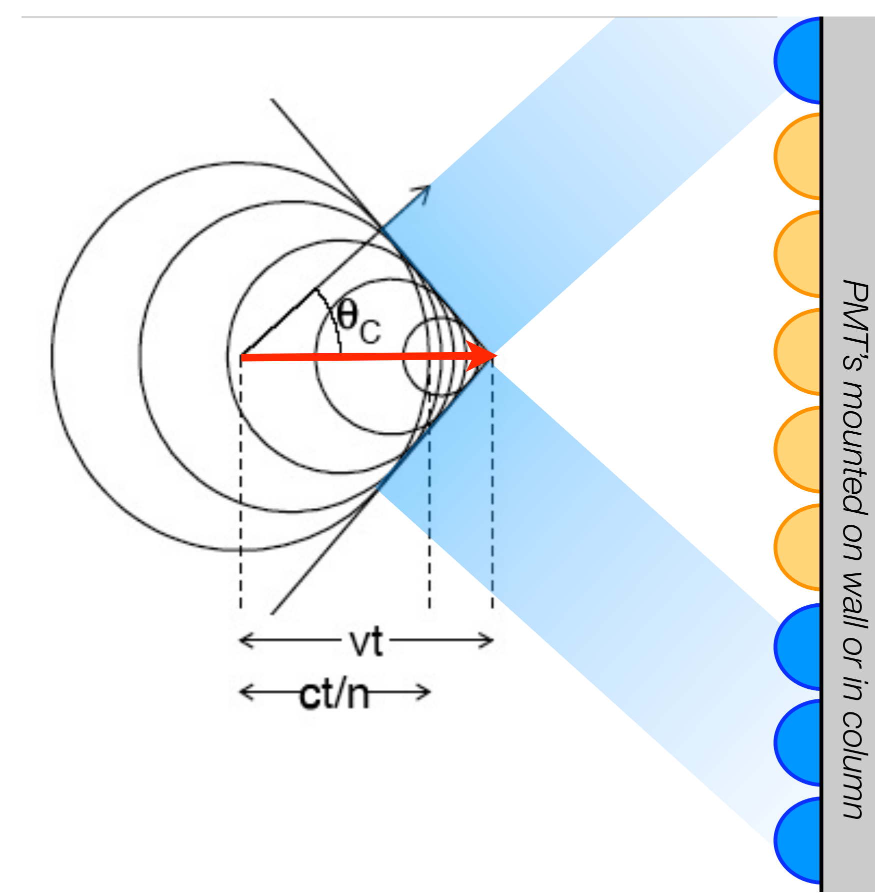


Super-Kamiokande detector

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

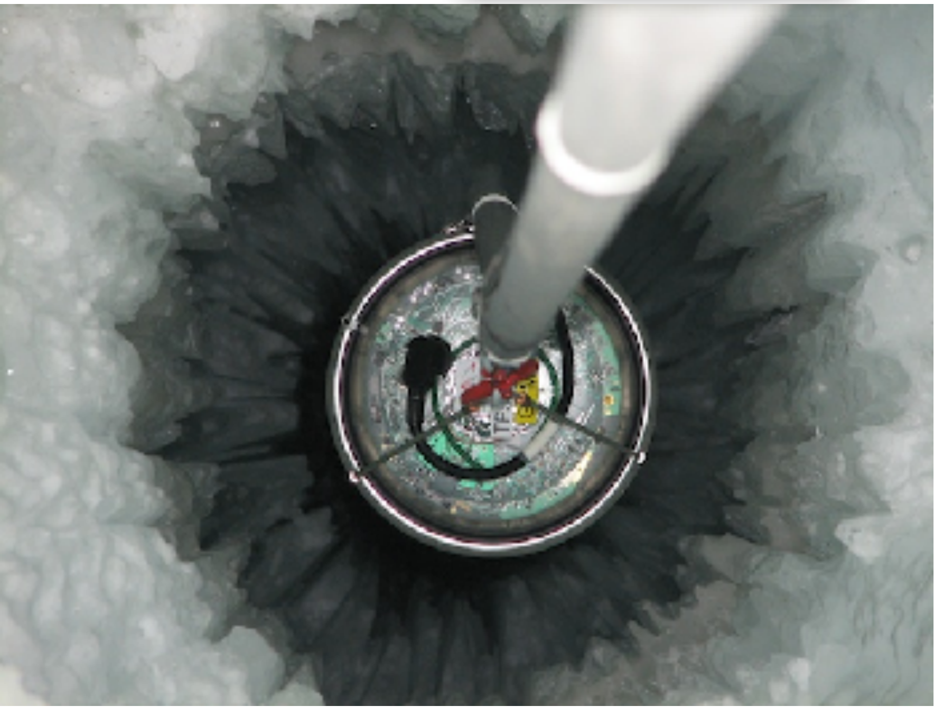
$$\boxed{\cos\theta_C = \frac{1}{\beta n}, \beta > \frac{1}{n}}$$

- 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

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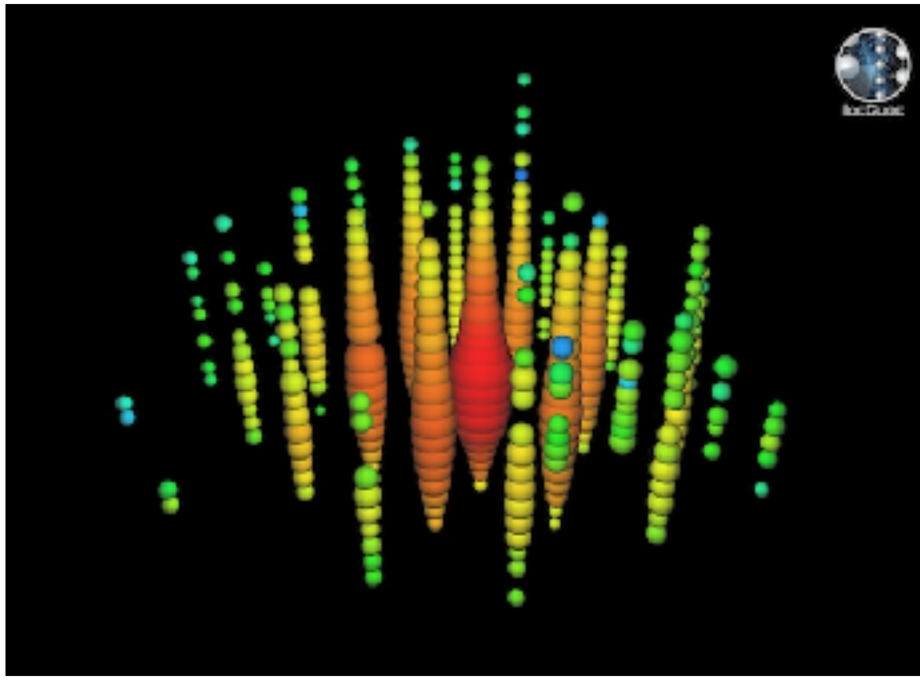
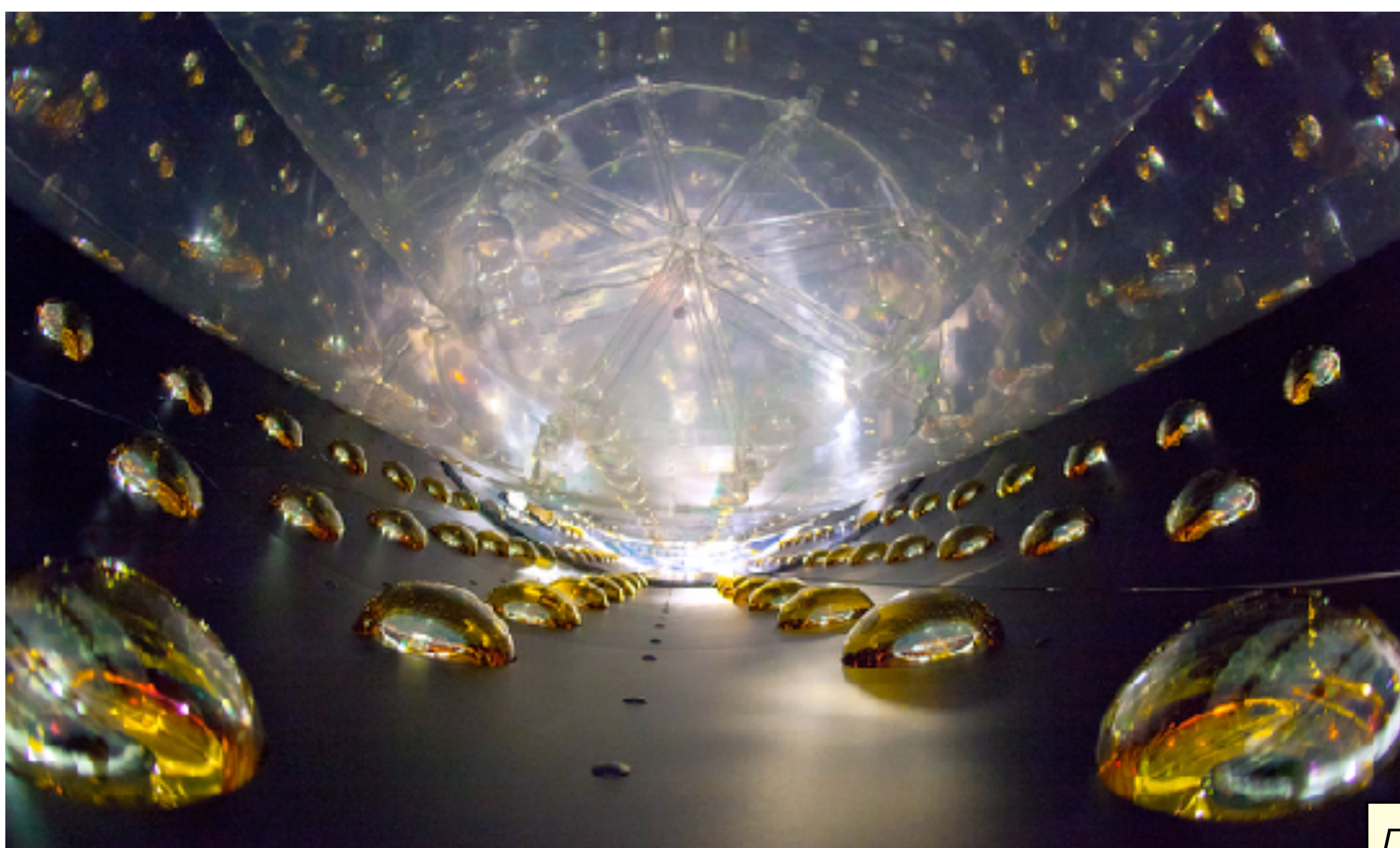
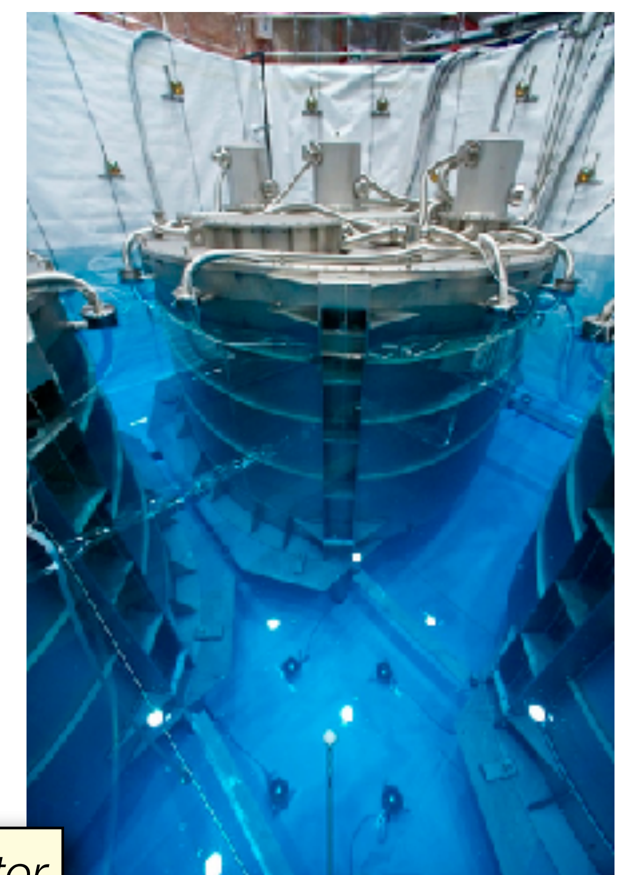


Liquid scintillator detectors

- 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



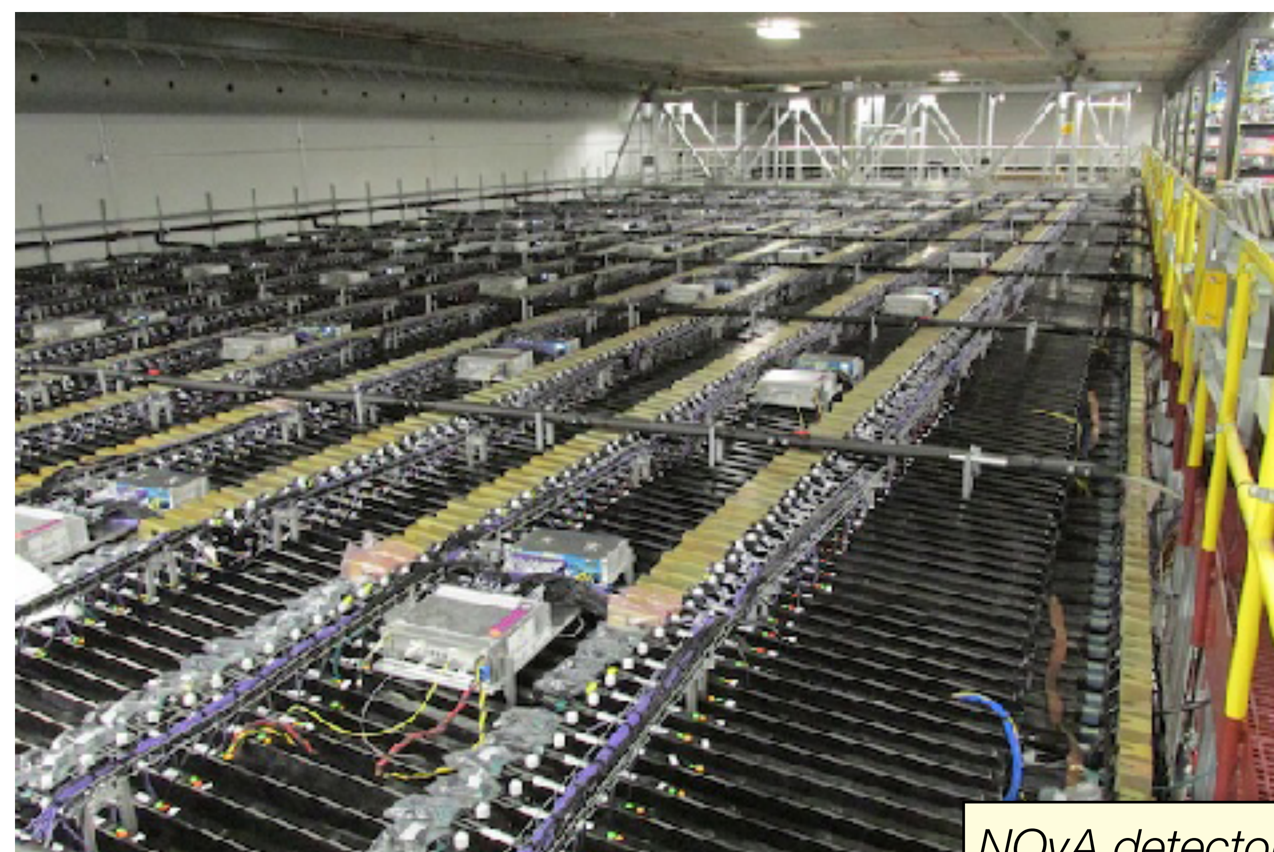


Daya Bay detector

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
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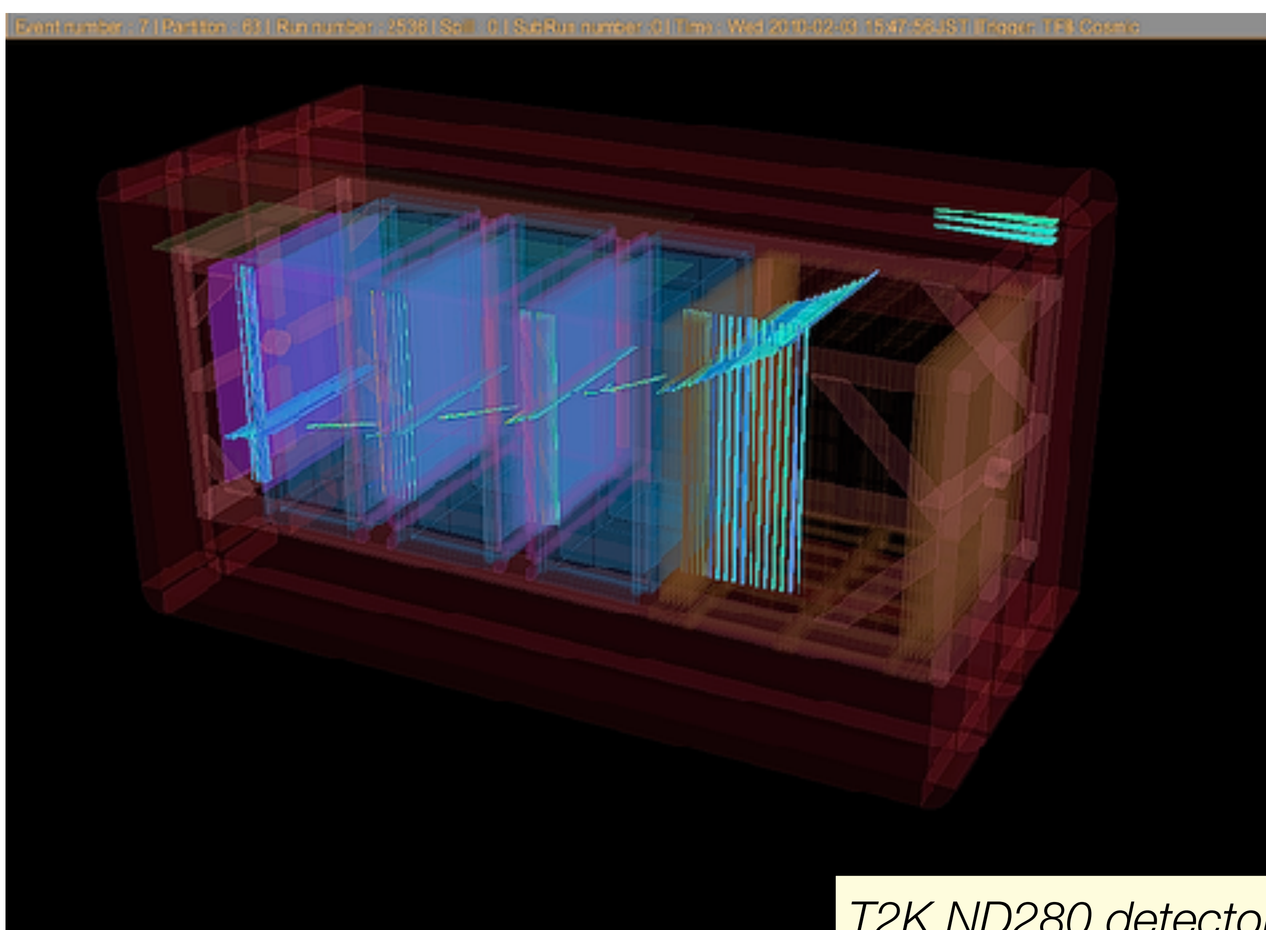
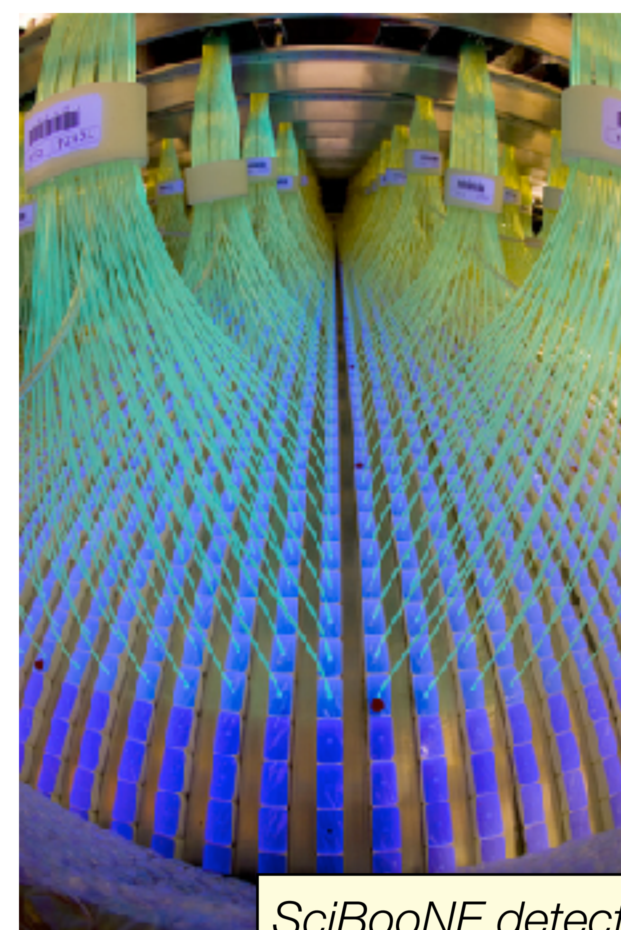


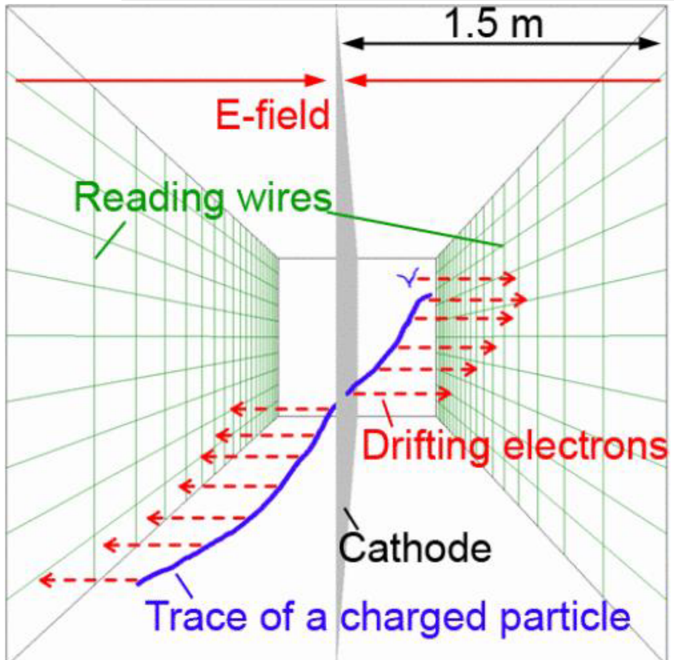
T2K ND280 detector



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
- Scintillation light gives fast trigger signal and absolute event timing

Advantages:

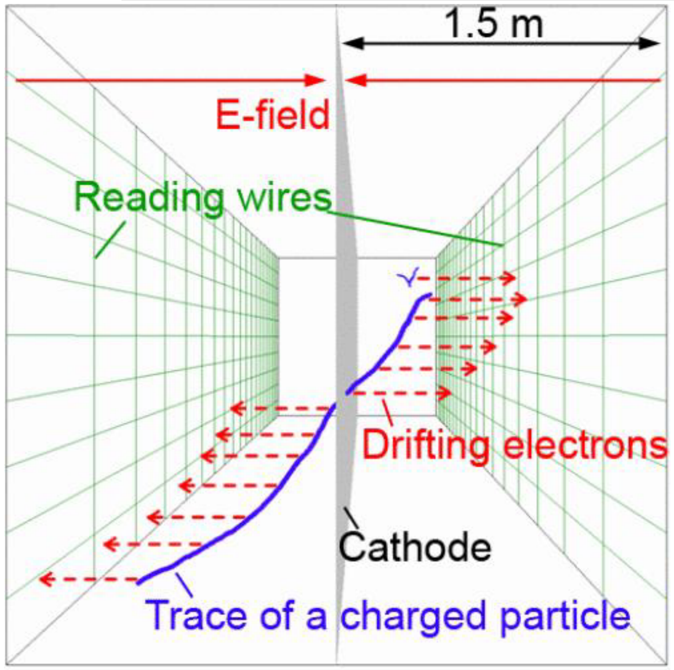
- Excellent imaging from mm-scale resolution
- Accurate calorimetry from fully active volume and large ionization signal (1 electron / 24 eV deposited energy)
- Particle identification from dE/dx information

Disadvantages: technically challenging!

- Argon purity, cryogenics, HHV

Liquid argon time projection chambers

LAr TPCs



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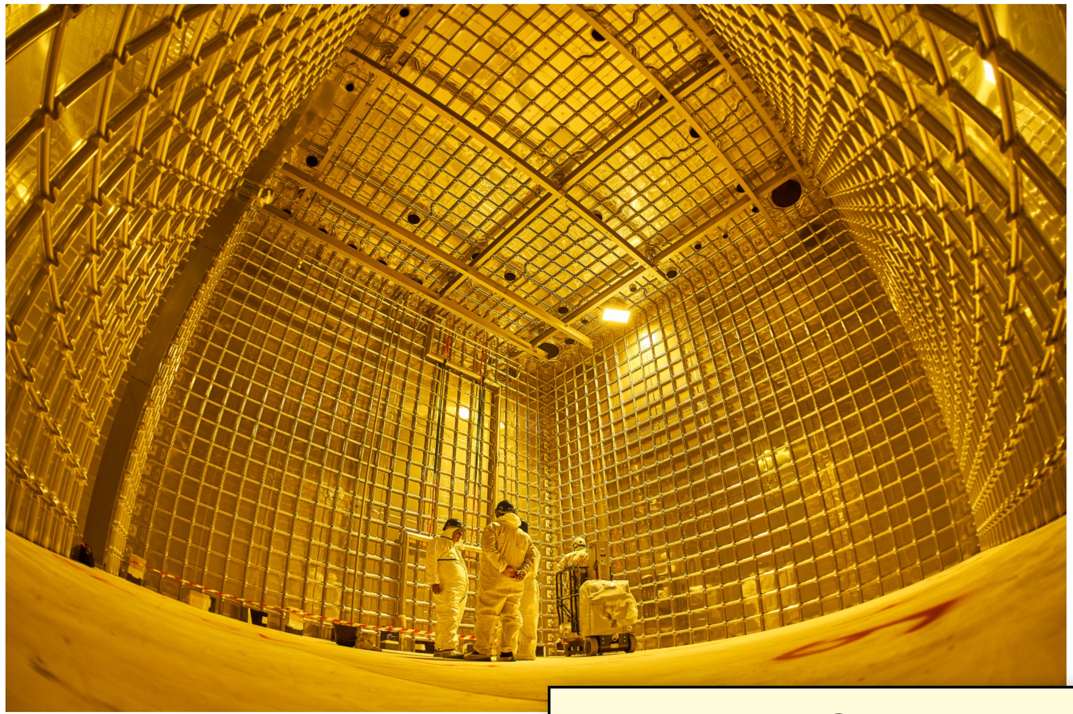


ProtoDUNE-SP detector

Advantages:

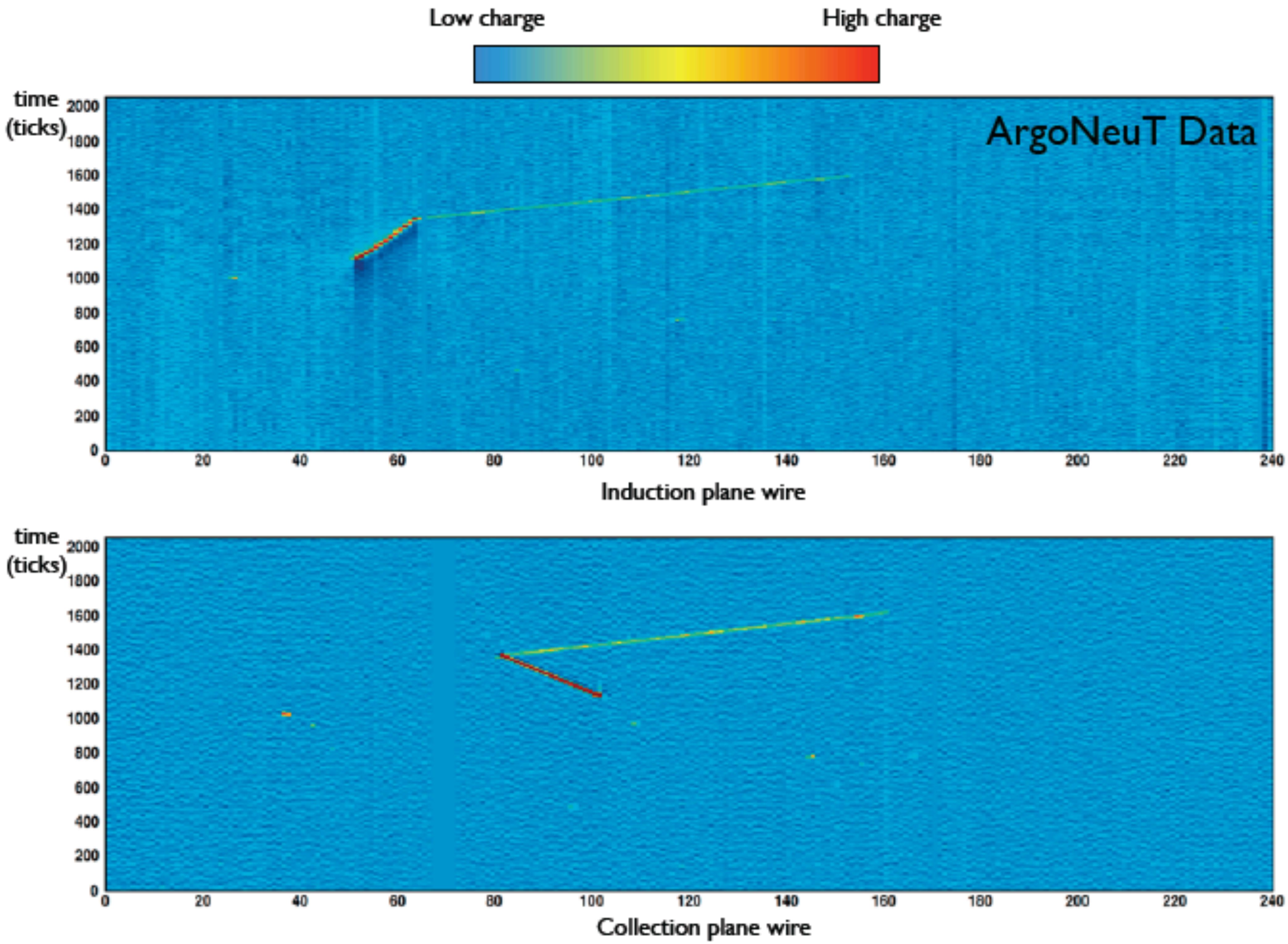
- Excellent imaging from mm-scale resolution
- Accurate calorimetry from fully active volume and large ionization signal (1 electron / 24 eV deposited energy)
- Particle identification from dE/dx information

Disadvantages: technically challenging!

- Argon purity, cryogenics, HHV

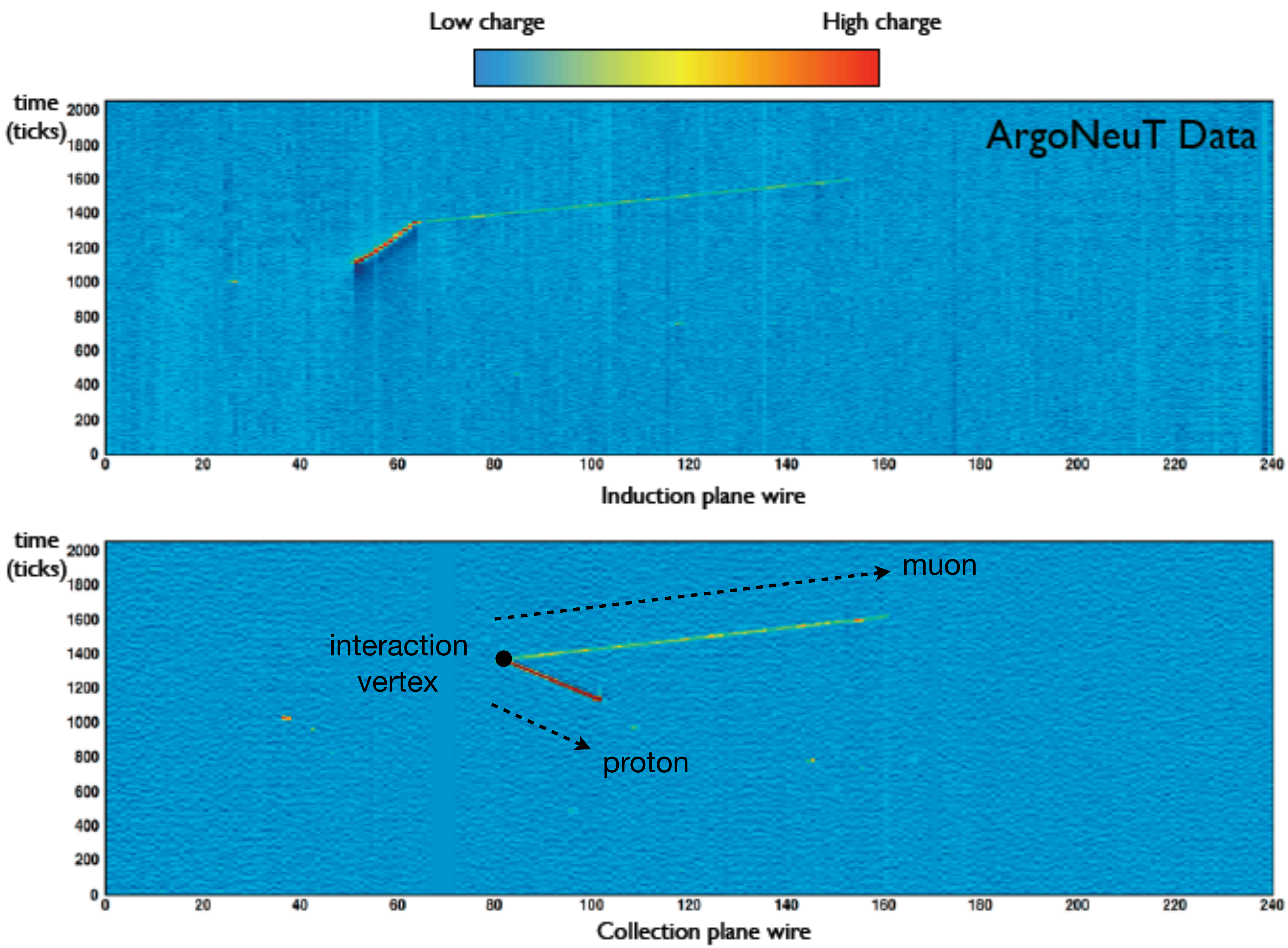
Liquid argon time projection chambers

What is going on in this event?



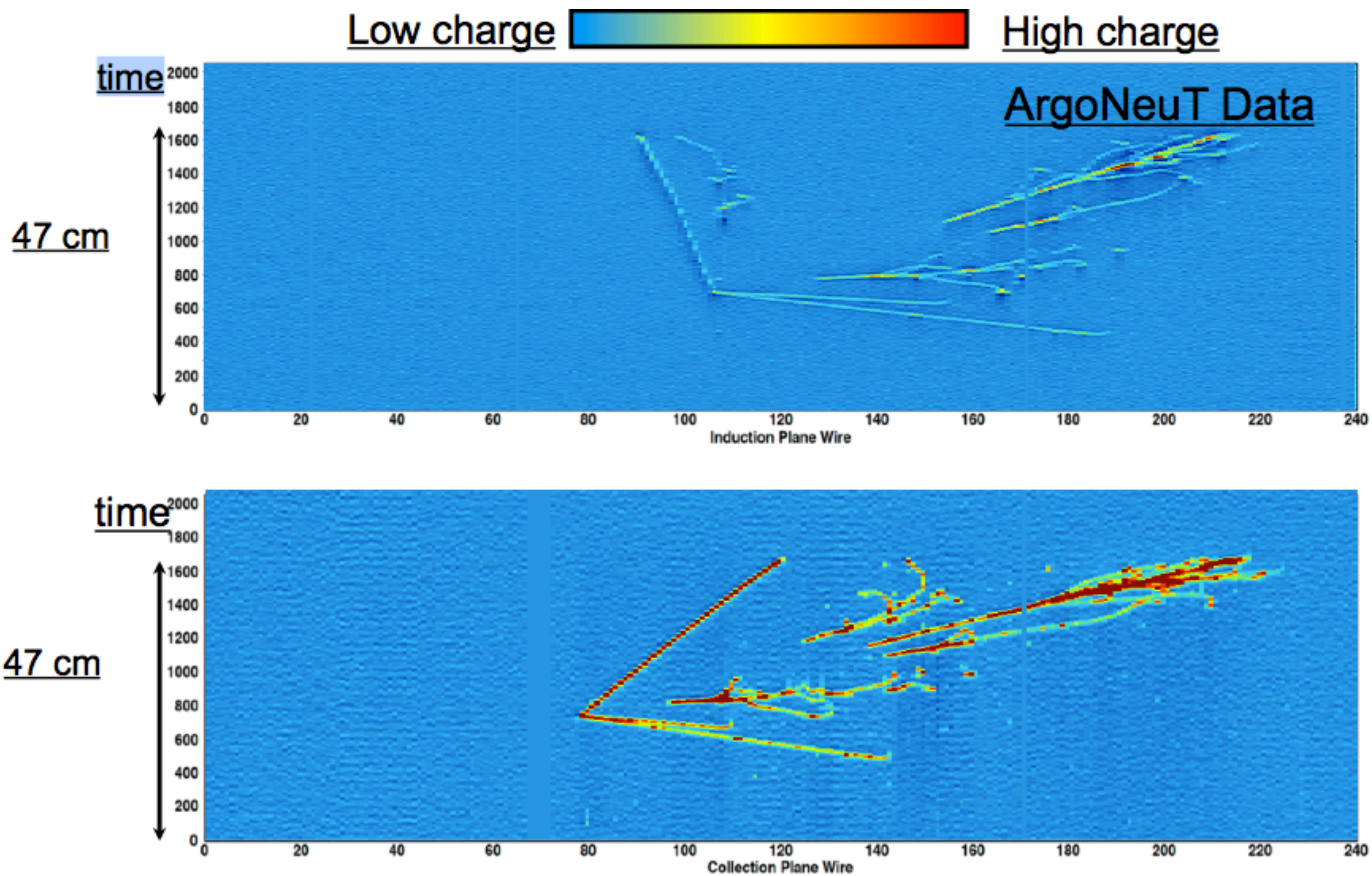
Liquid argon time projection chambers

What is going on in this event?



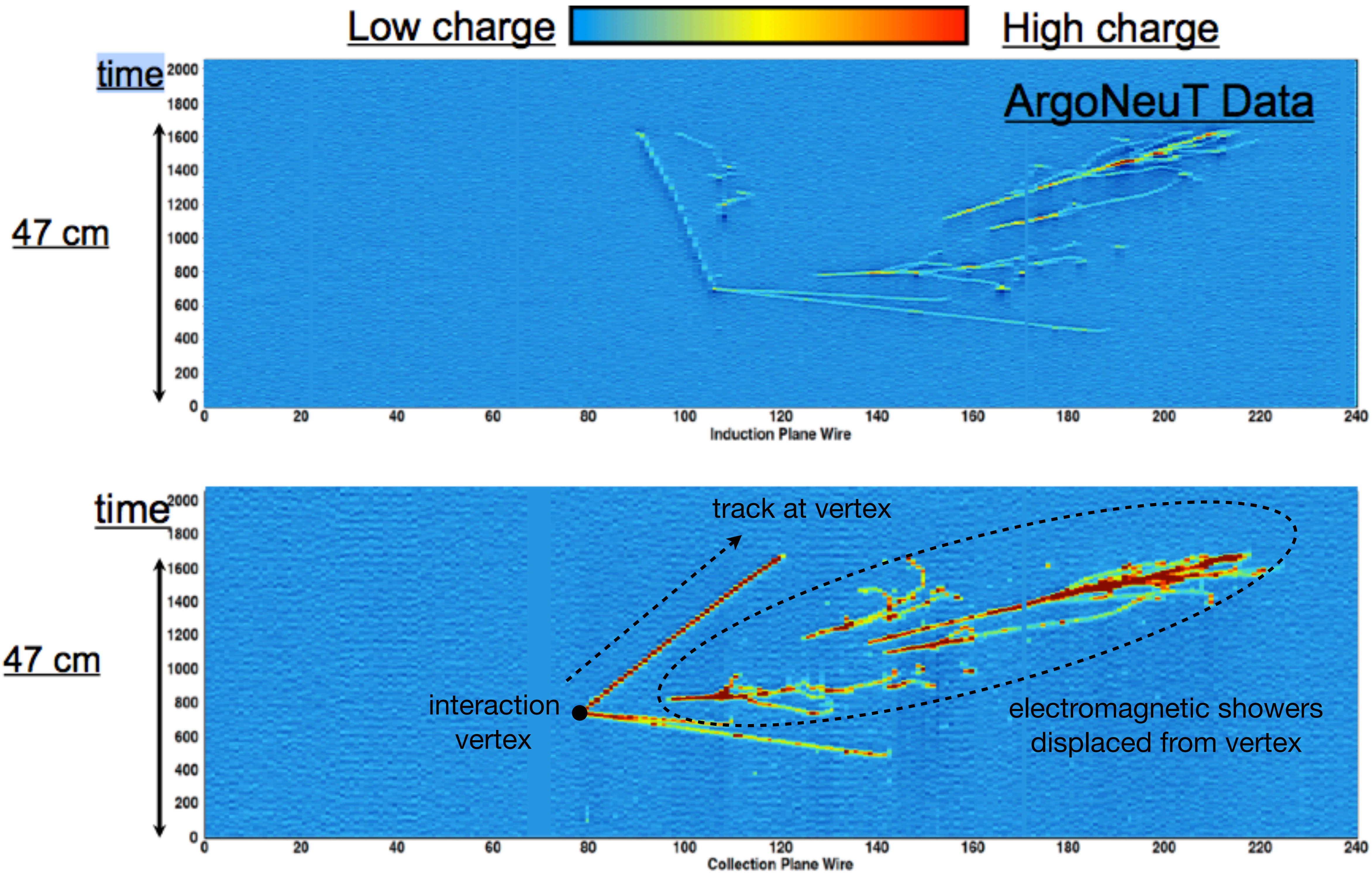
Liquid argon time projection chambers

What is going on in this other event?



Liquid argon time projection chambers

What is going on in this other event?



Lecture 1 End!

Today: neutrino experiments basics

- Neutrino open questions ✓
- How to measure neutrino oscillation parameters ✓
- Neutrino sources ✓
- Neutrino interactions with matter ✓
- Neutrino detector technologies ✓

Wednesday: neutrino experiments specifics

- Selected current and future ν oscillation experiments
- Neutrinoless double beta decay experiments
- Experiments for direct neutrino mass measurements