Physics of Neutrino Detection

Neutrino University - Fermilab
August 18th, 2016

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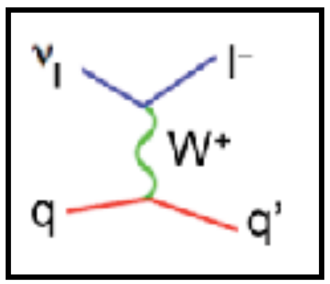
Fermilab & Yale University*

*on leave of absence from INFN, Laboratori Nazionali del Gran Sasso, Italy

Neutrino Physics*

CC



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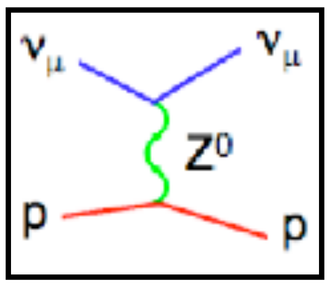
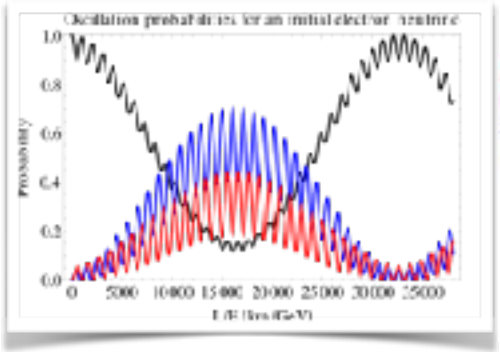
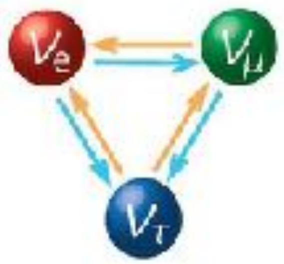
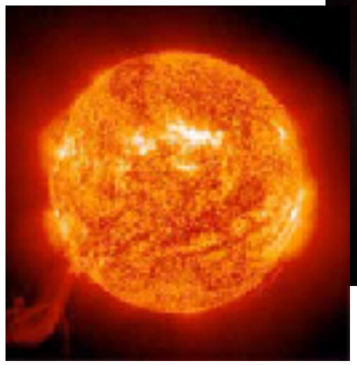


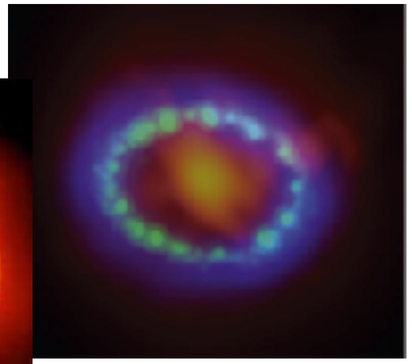
- Neutrino oscillations physics



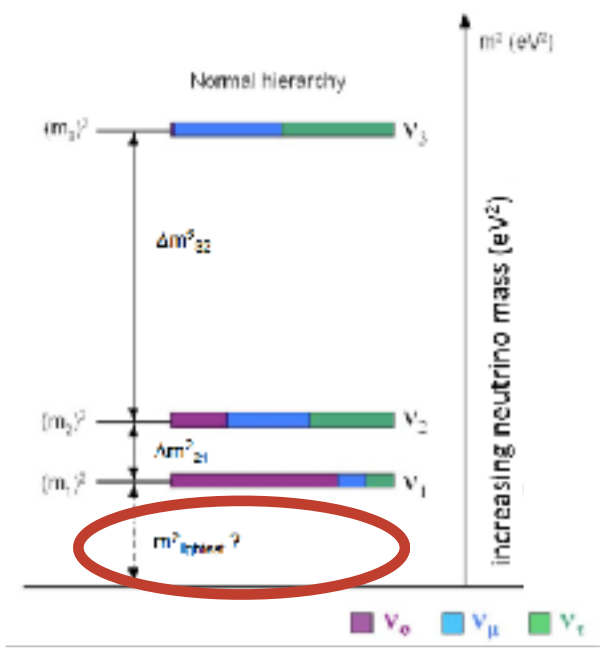


- Neutrino interactions physics
- Neutrino Astrophysics





- Neutrino Properties → see B. Kayser's lecture



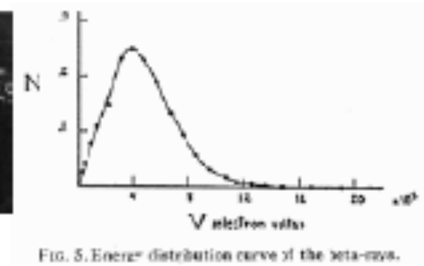
*Can't cover everything. I've chosen a few topics based on my personal biases (and focused on the Fermilab ν program)... apologies for not covering all.

Note: Many other topics covered in previous Lectures (intro to ν oscillation, ν cross sections, ν beams, sterile ν, new results)

Outline

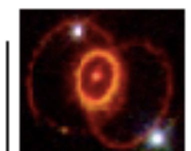
- Brief review: What we know and don't know about neutrinos
  - Neutrinos are not only "missing E_T"!!
- Neutrino measurements - The intermediate energy range (0.1-20 GeV)
  - Neutrino interaction: Why precise measurements are needed? Why different neutrino targets are needed?
  - Neutrino oscillation: Long- and short-baseline measurements
  - Why LAr as Active Target for Particle Detectors? LAr Time Projection Chamber (LAr TPC) at work.
- What we are planning for the future
  - Fermilab LAr TPC neutrino program

Neutrinos - The First 85 Years of Discoveries



1930 Pauli postulates neutrinos

1933 Fermi names neutrinos, formulates weak interactions theory



1987 SN 1987A

1998 SuperK reports evidence for oscillation of atmospheric neutrinos.

2015

2001/2002 SNO finds evidence for solar ν_e flavor change.

2003 KamLAND discovers disappearance of reactor $\overline{\nu}_e$

?

1968 Ray Davis detects solar neutrinos.

2002

1962 Steinberger, Lederman, Schwartz, et al demonstrate ν_e & ν_μ

1988

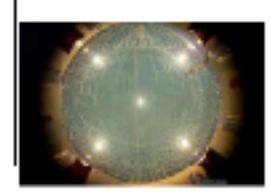
1958 Goldhaber, Grodzins, & Sunyar at BNL demonstrate left-handed helicity

1957 Pontecorvo: Neutrinos may oscillate

1956 Reines & Cowan report the first evidence of neutrinos

1995

2012 Daya Bay, RENO, Double Chooz measure θ_{13}



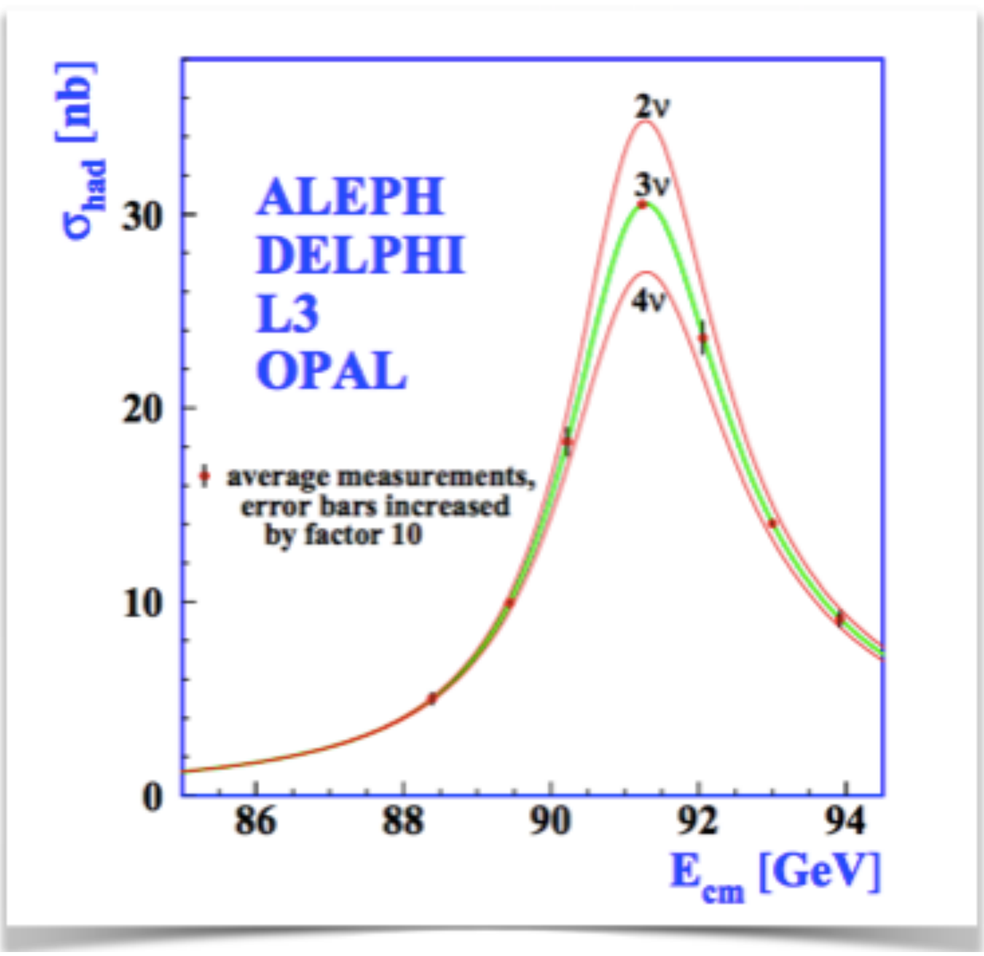
2007 Borexino detection of ^{7}Be solar neutrinos

Karsten Heeger, Yale University

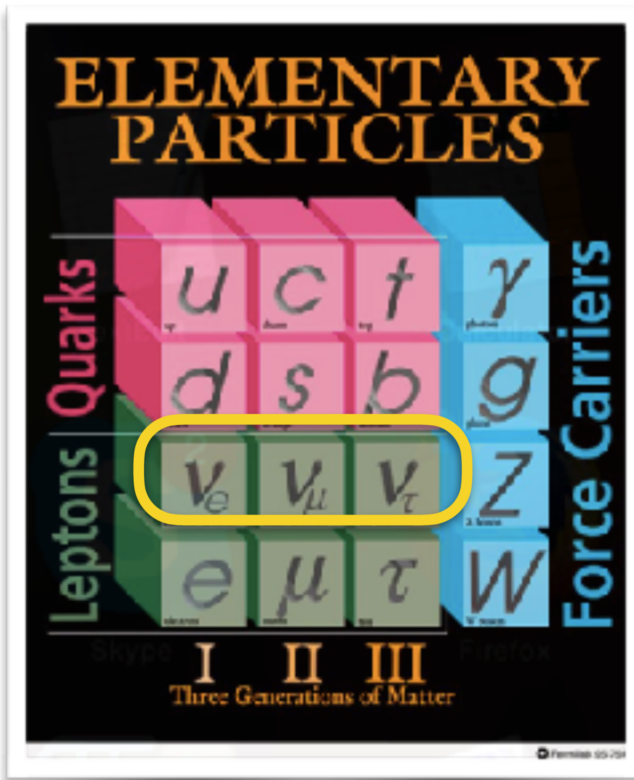
What we know about Neutrinos (I)

- Neutrinos are the second most abundant particles in the universe, and yet we know very little about them. We know neutrinos are
    - **electrically neutral fermions**,
    - only **weekly interacting** (W and Z exchange)
    - **assumed to be massless in the Standard Model**.

- Early '90: Measurement of the line-shape of the Z^0 at LEP puts tight constraints on the existence of three **(2.984±0.008)** neutrinos that couple to the Z^0.

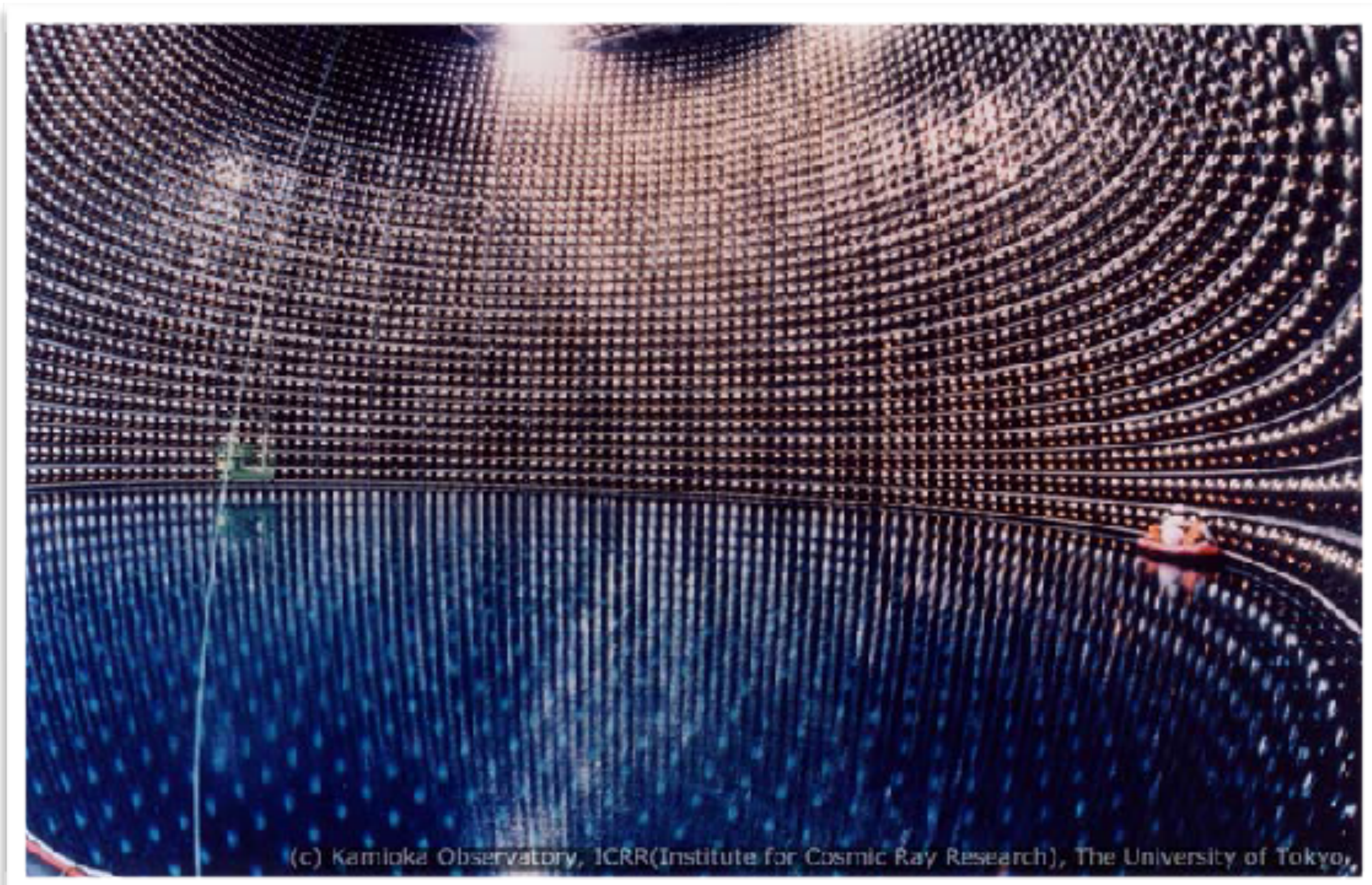


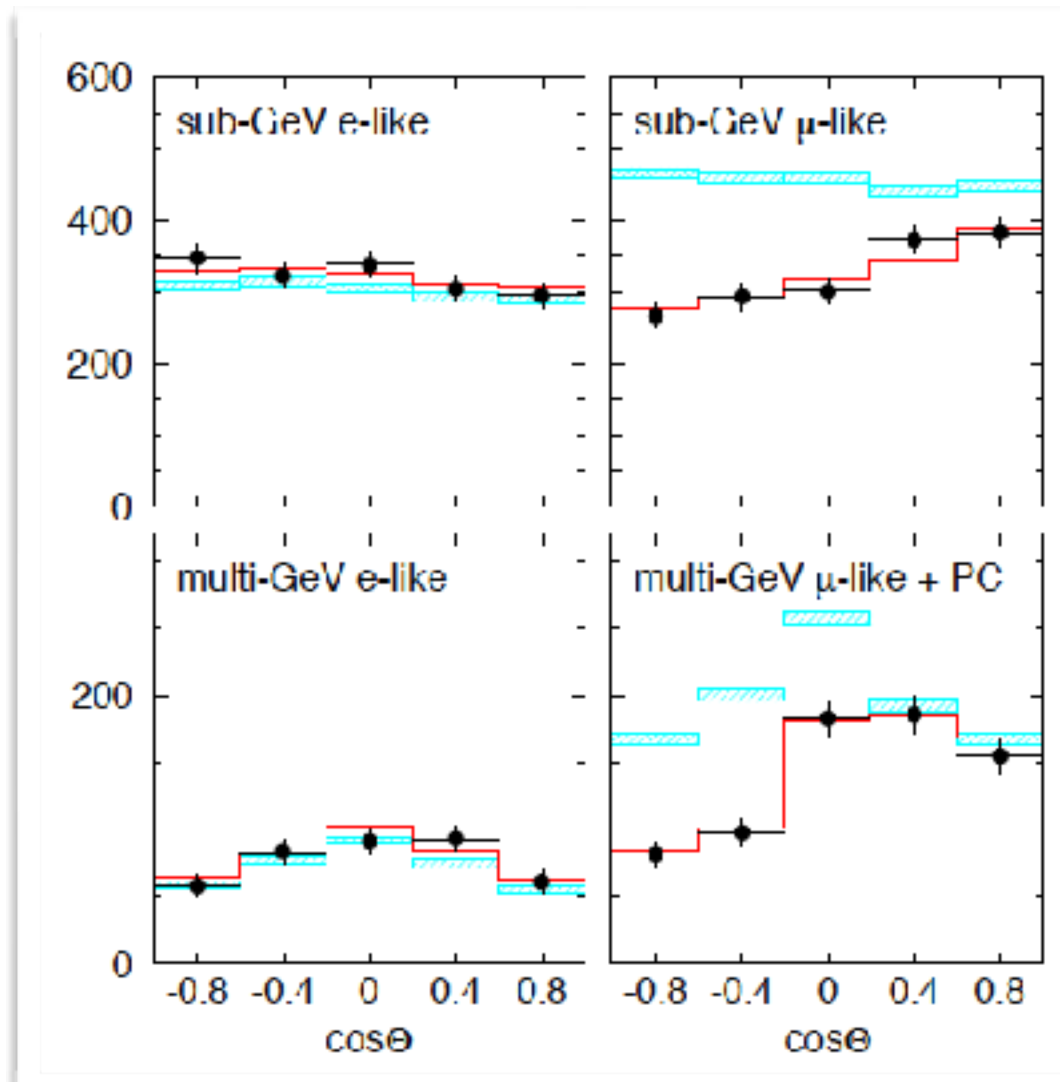
3 flavor states, 3 "active" (weakly interacting) neutrinos!



What we know about Neutrinos (II)

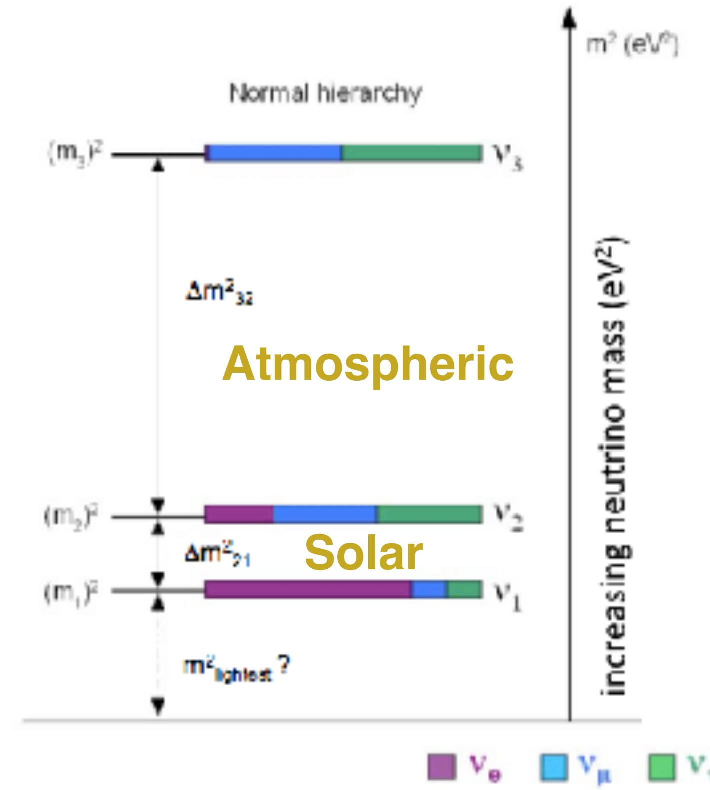
- **1998**: Measurement of atmospheric neutrinos in the Super-Kamiokande Water Cherenkov experiment conclusively demonstrates **neutrino oscillations** (*i.e. they change type as they move in space and time*).
  - The observed oscillation imply that **neutrinos do have mass**.





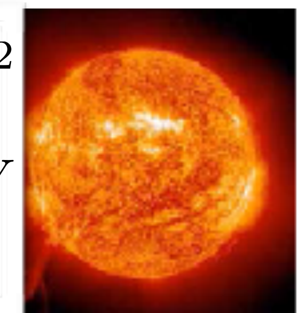
Three Neutrino Oscillation

- Three neutrino mixing is well established *(data from solar, atmospheric, reactor and accelerator neutrino experiments)*!
  - Picture consistent with the mixing of **3 neutrino flavors with 3 mass eigenstates** - with relatively small mass differences



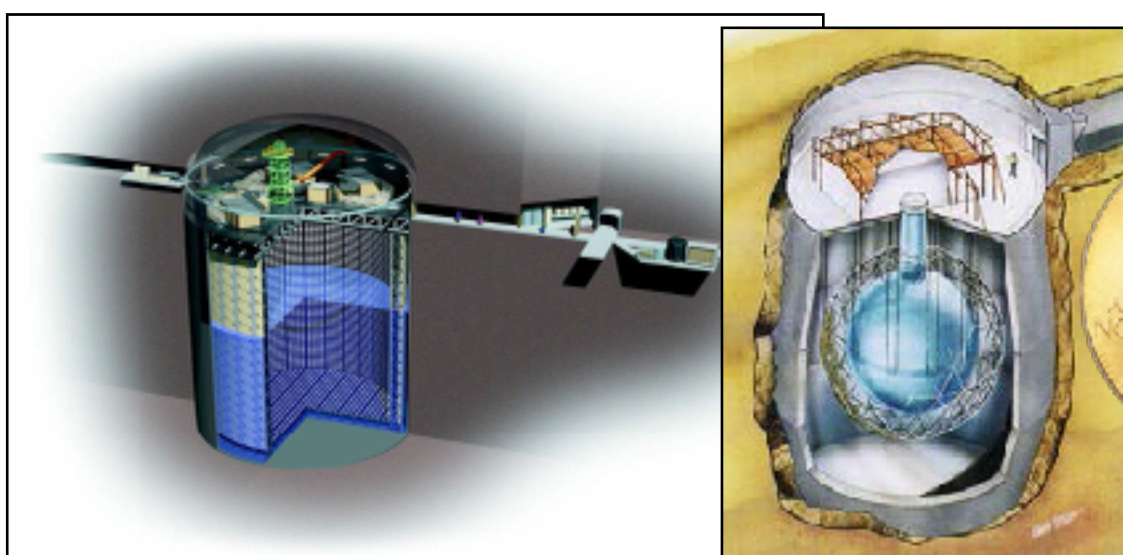
$$\Delta m^2_{32} \simeq 2.4 \cdot 10^{-3} eV^2$$
$$L/E = 500 Km/GeV$$
Atmospheric

$$\Delta m^2_{21} \simeq 7.5 \cdot 10^{-5} eV^2$$
$$L/E = 15,000 Km/GeV$$
Solar



- **2015 Nobel price-winning** discovery of Neutrino Oscillation

Super-Kamiokande (water Cherenkov, 50 kton) and SNO (heavy water, D_2O, 1 Kton) experiments

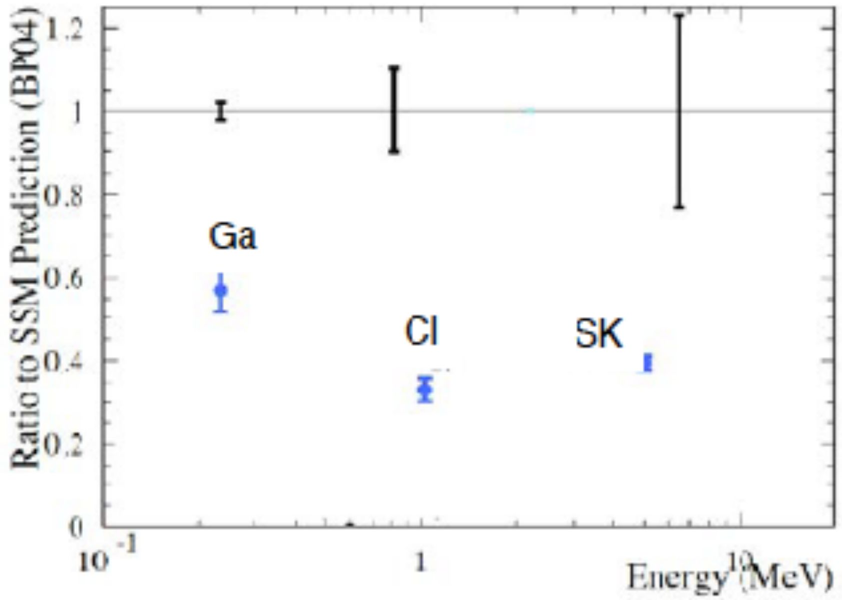


Takaaki Kajita and Arthur B. McDonald

From Anomalies to Precision Oscillation Physics

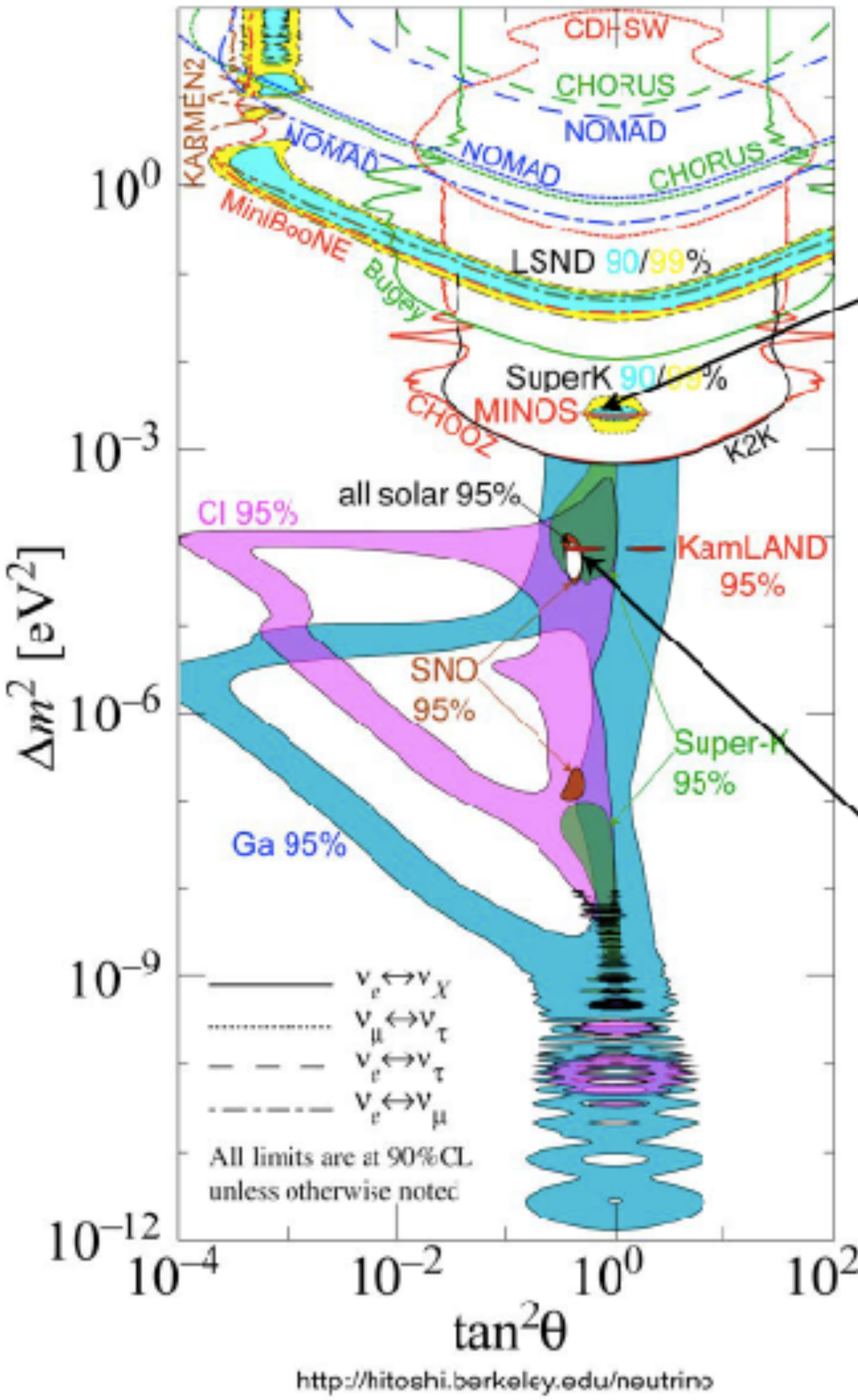
1960 -1990

solar neutrino problem



1990 - 2000

oscillation searches



atmospheric/beam neutrinos

θ_{23}, Δm^2_{23}

solar/reactor neutrinos

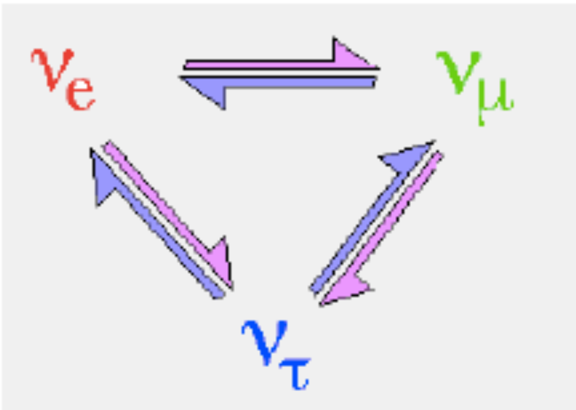
θ_{12}, Δm^2_{12}

Karsten Heeger, Yale University

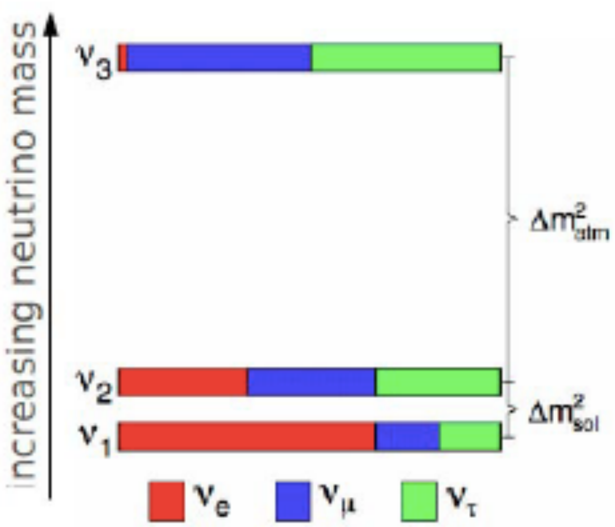
From Anomalies to Precision Oscillation Physics

1990 - 2000

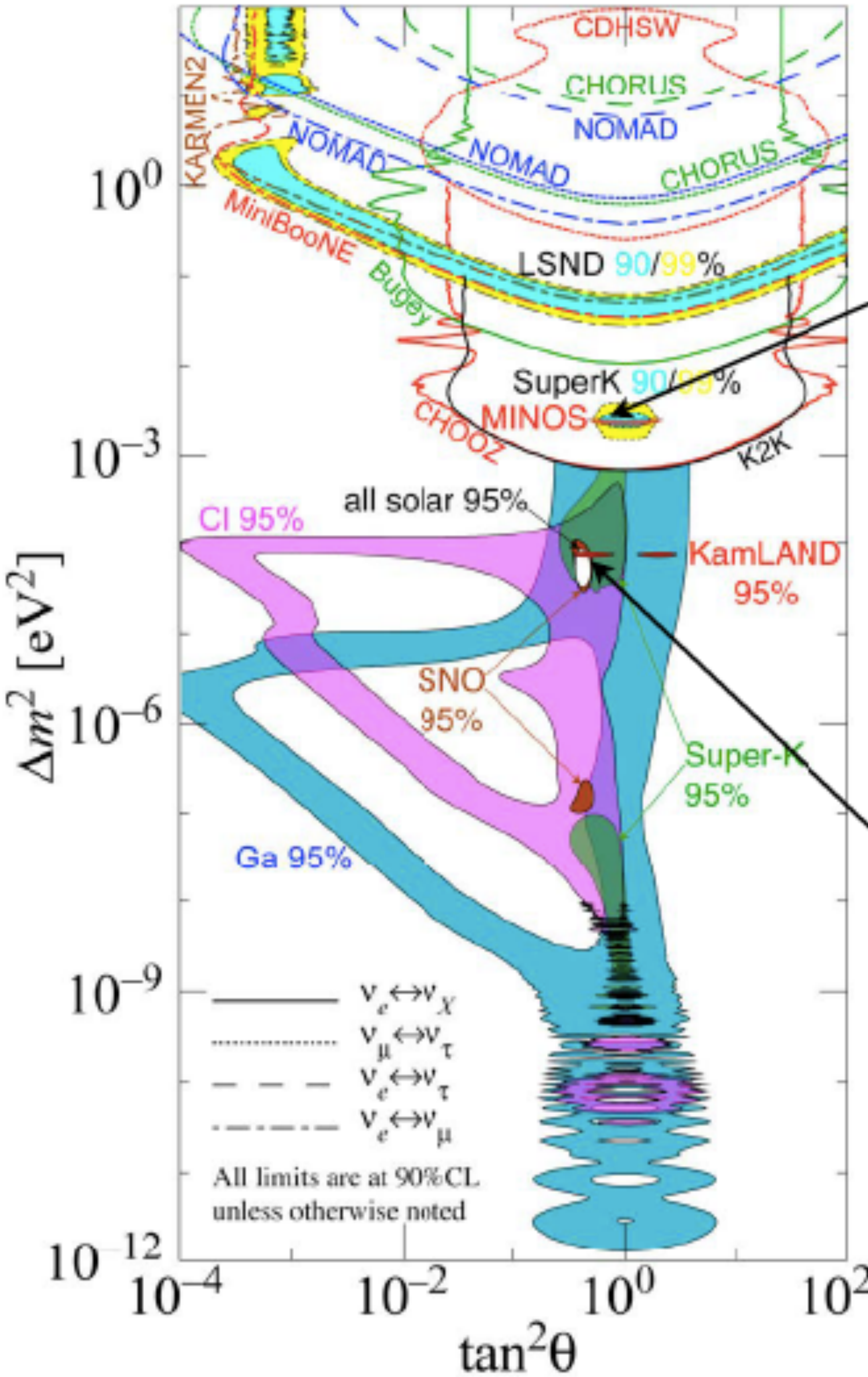
3-flavor picture needed



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



oscillation searches



http://hitoshi.berkeley.edu/neutrino

atmospheric/beam neutrinos

θ_{23}, Δm^2_{23}

solar/reactor neutrinos

θ_{12}, Δm^2_{12}

Karsten Heeger, Yale University

From Anomalies to Precision Oscillation Physics

1960 -1990
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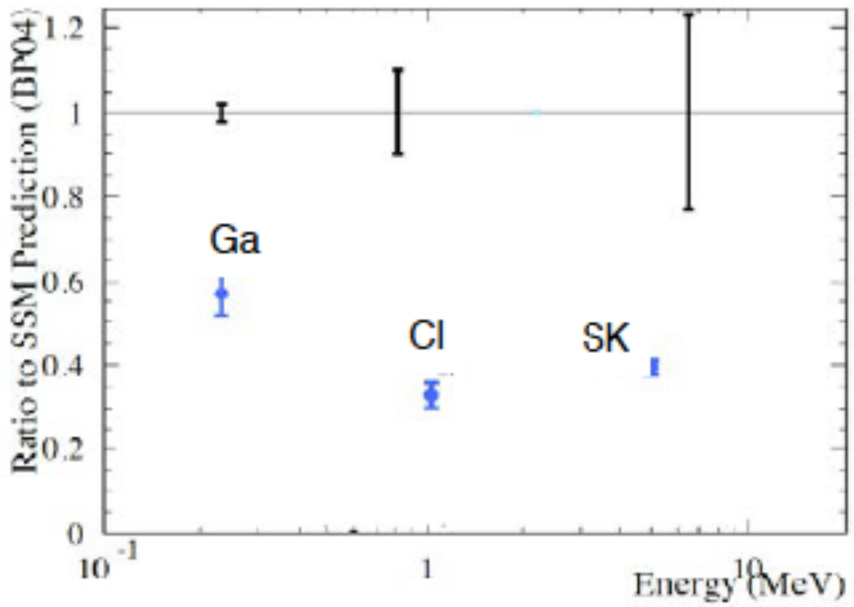
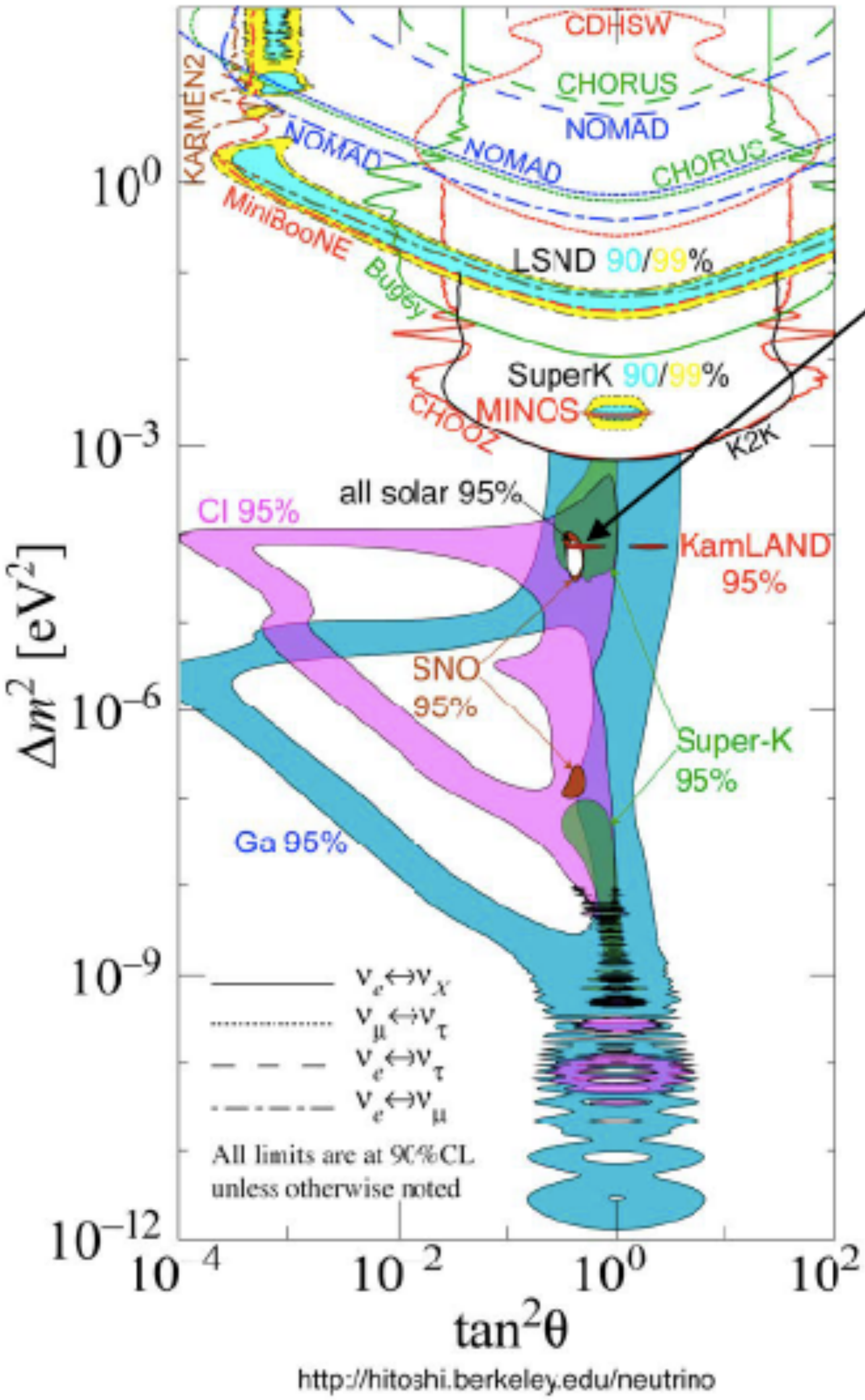
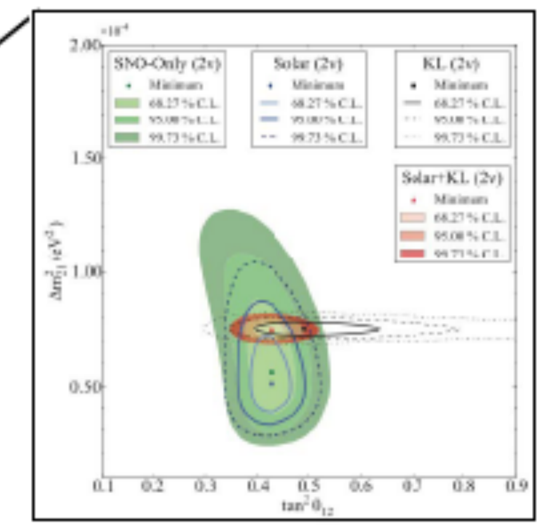


1990 - 2000
oscillation searches

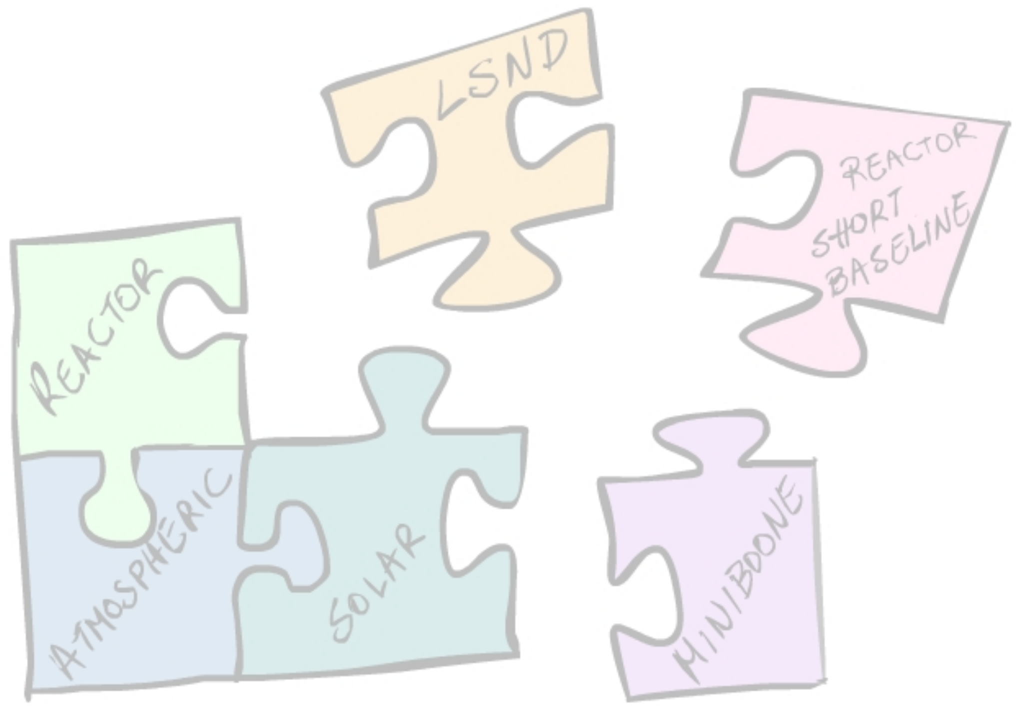


2000 - present
precision measurements



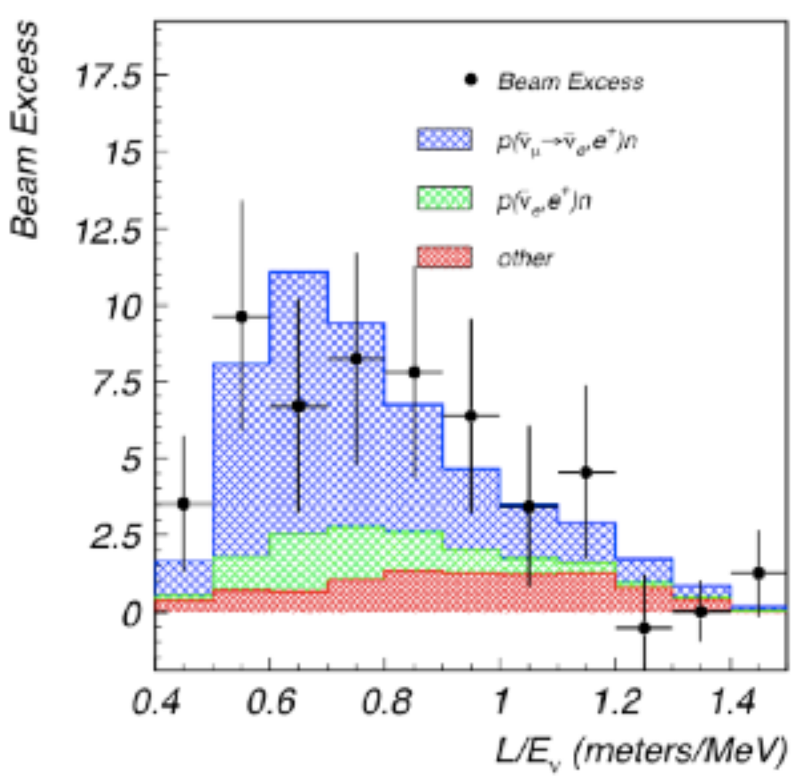
Karsten Heeger, Yale University

Experimental Hints for beyond the Three Neutrino Mixing



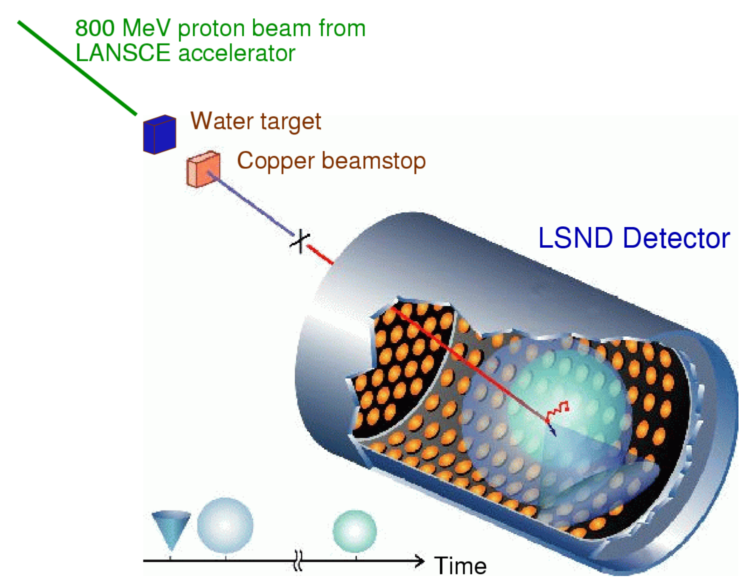
Hints from several areas (LSND, reactor antineutrino anomaly, gallium solar neutrino calibration experiments) seem to suggest the possibility of additional mass eigenstate(s)

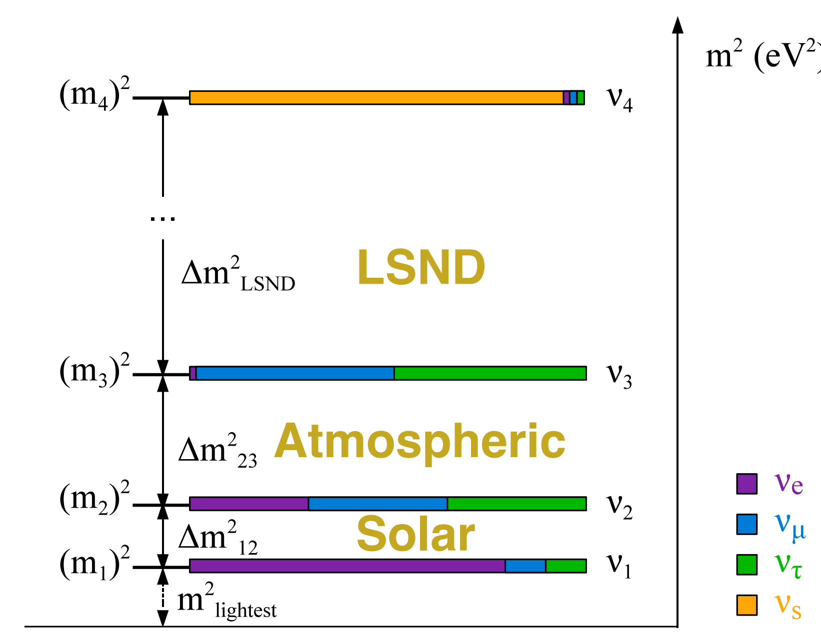
see J. Kopp's lecture



LSND - beam dump experiment in Los Alamos (1993-1998)
($\Delta m^2 \sim 1$ eV^2)

167 tons liquid scintillator

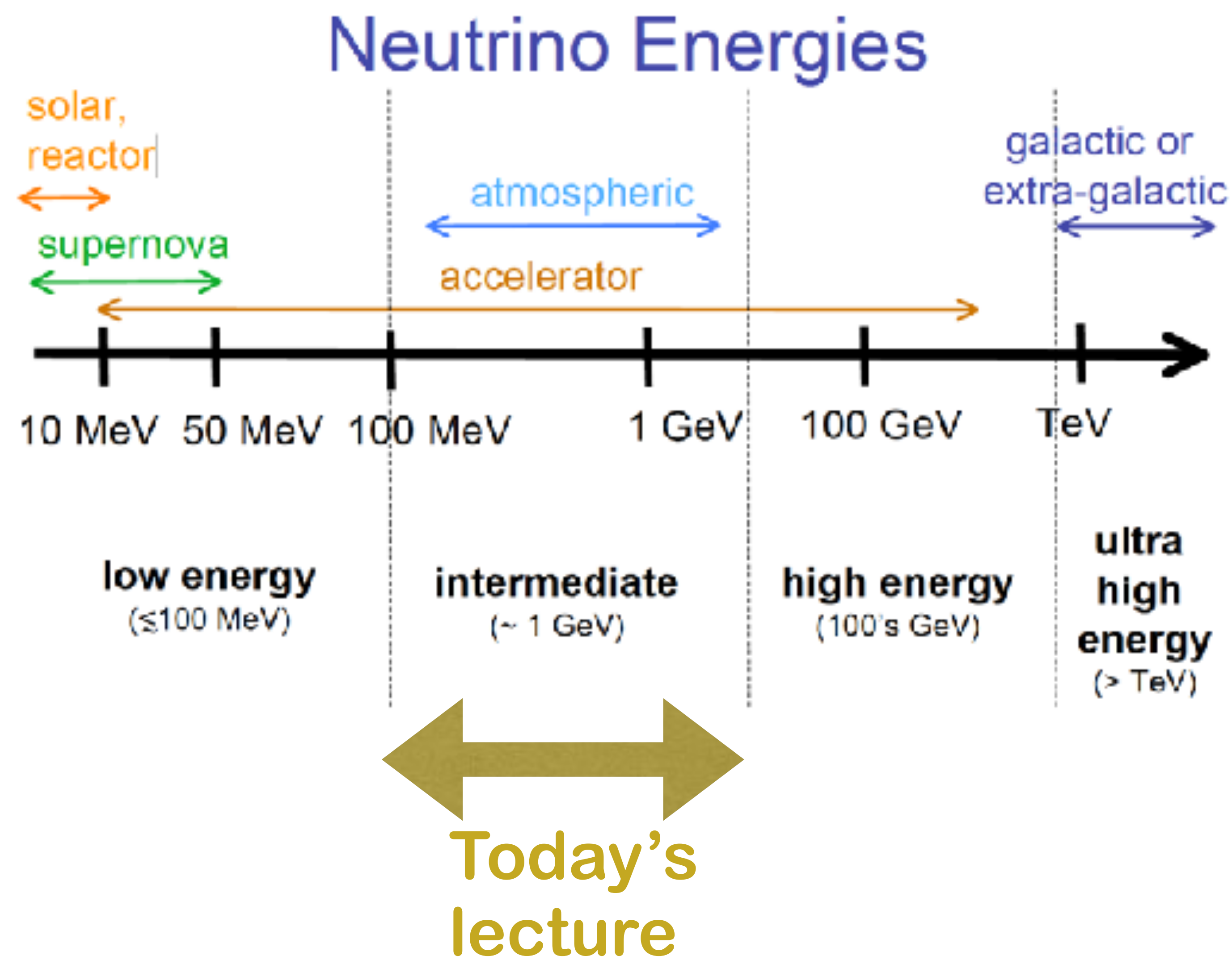




Neutrino Searches

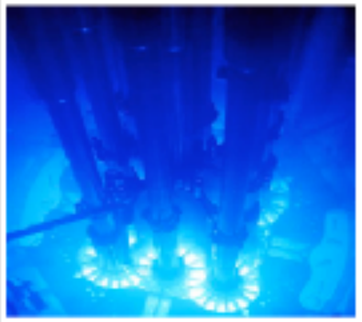
ν sources

- Solar and supernova neutrinos
- Antineutrinos from reactors
- Atmospheric neutrinos
- Accelerators neutrinos
- Neutrinos from space



Main ν detection technologies

Bubble chambers, Calorimeter detectors, Cherenkov light detectors, Radiochemical detectors, Liquid Argon/noble gas detectors



Neutrinos from reactors.

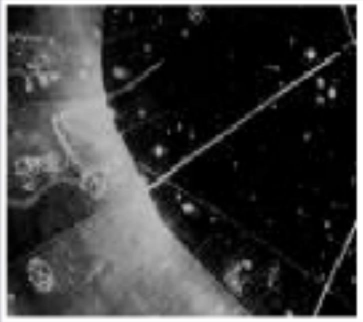
Detected (1950s)

Neutrinos from the sun.

Detected (1960s)

Neutrinos from the atmosphere.

Detected (1960s)



Neutrinos from accelerators.

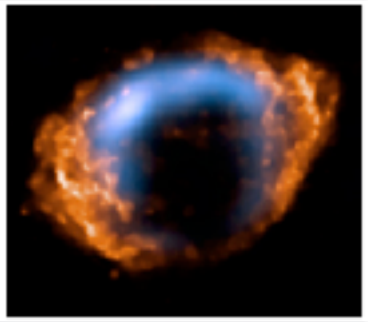
Created & detected (1960s)

Neutrinos from supernovae.

Detected (1980s)

Neutrinos from the Earth.

Detected (2000s)



Neutrinos from galactic sources.

~~Not yet (but close!)~~ Detected 2012

Neutrinos from the Big Bang.

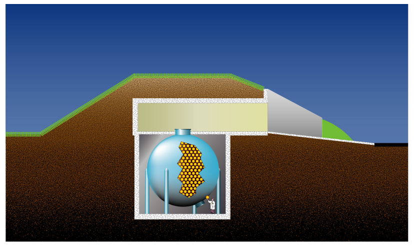
Not even close...

J.A. Formaggio, MIT

ν experiments - Target material

MINOS = **Fe**, magnetized Iron-scintillator calorimeter

MiniBooNE, SciBooNE, NOMAD, NOvA = **C**, MiniBooNE Cherenkov (CH_2), SciBooNE fine-grained tracking (CH), NOMAD drift chamber tracking detector, NOva liquid scintillator



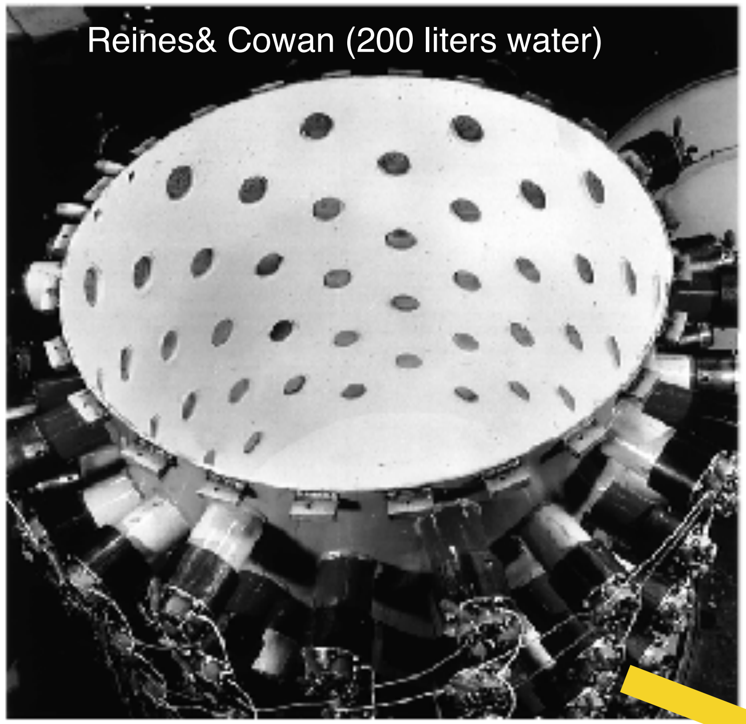
OPERA= **Pb**, Emulsion

T2K = **H_2O**, **C**, Water Cherenkov

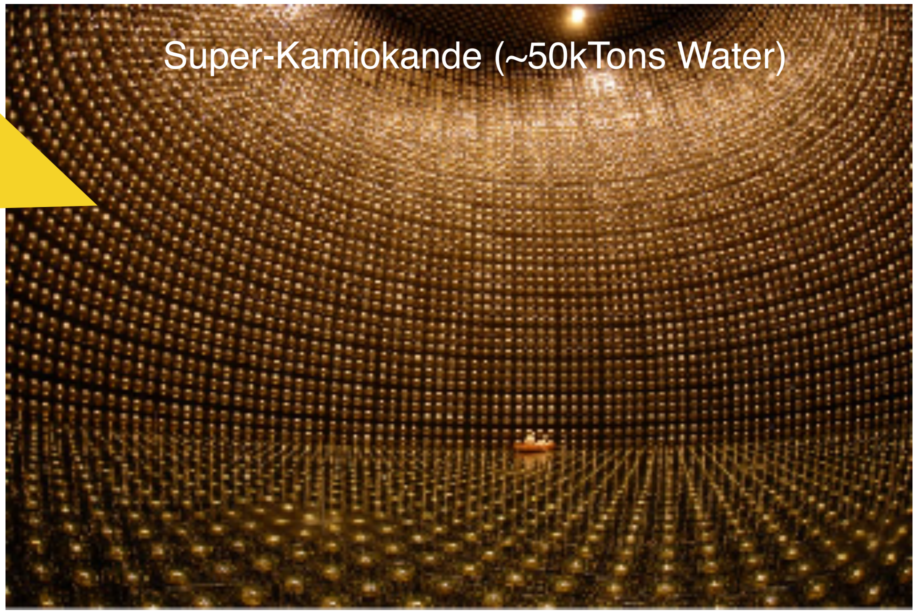
Minerva = range of nuclear targets (He, **C**, CH, **Fe**, Pb). Finely segmented, fully active scintillator tracking surrounded by ECAL and HCAL

ICARUS-T600, ArgoNeuT, MicroBooNE, CAPTAIN, SBND, DUNE = **Ar**, Liquid Argon Time Projection Chamber

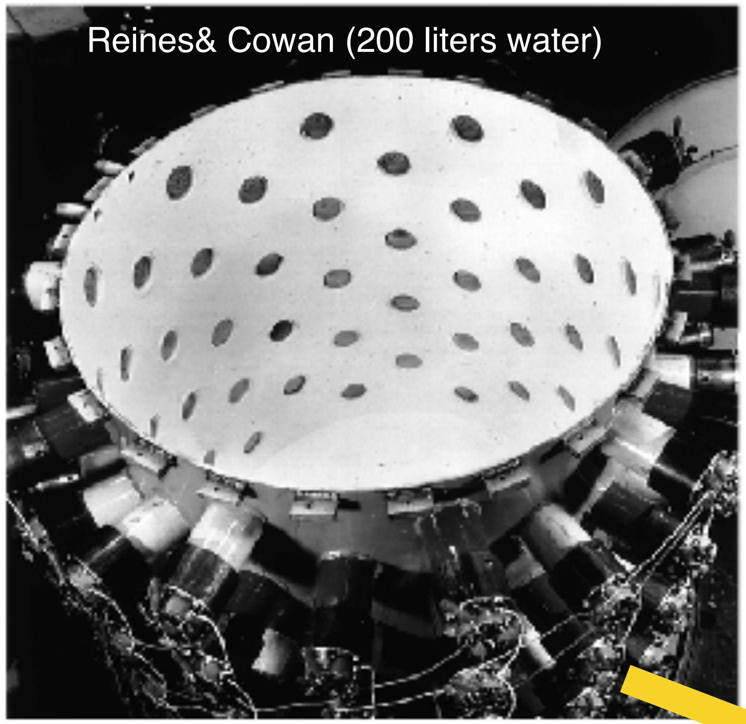
Technology challenge



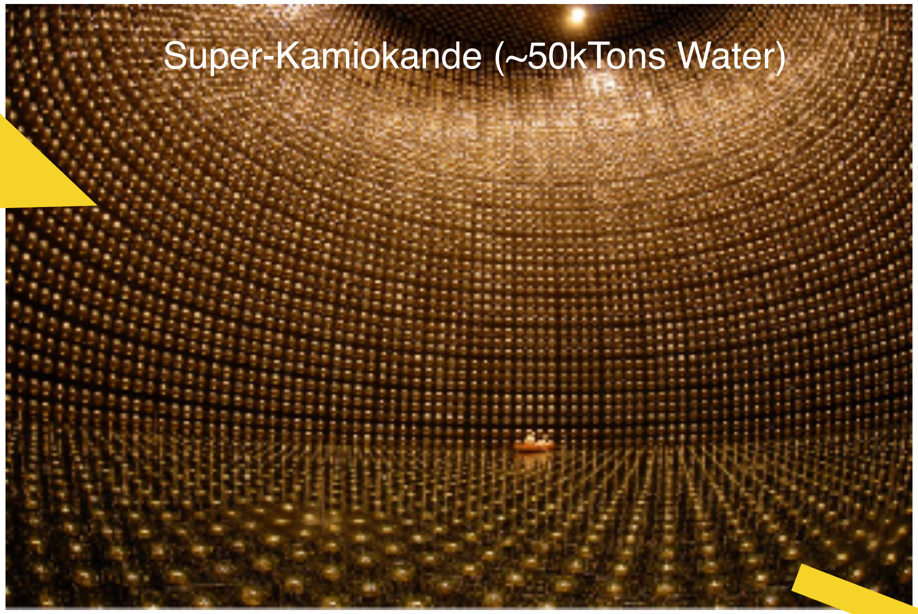
Innovation in instrumentation has driven discoveries in neutrino physics



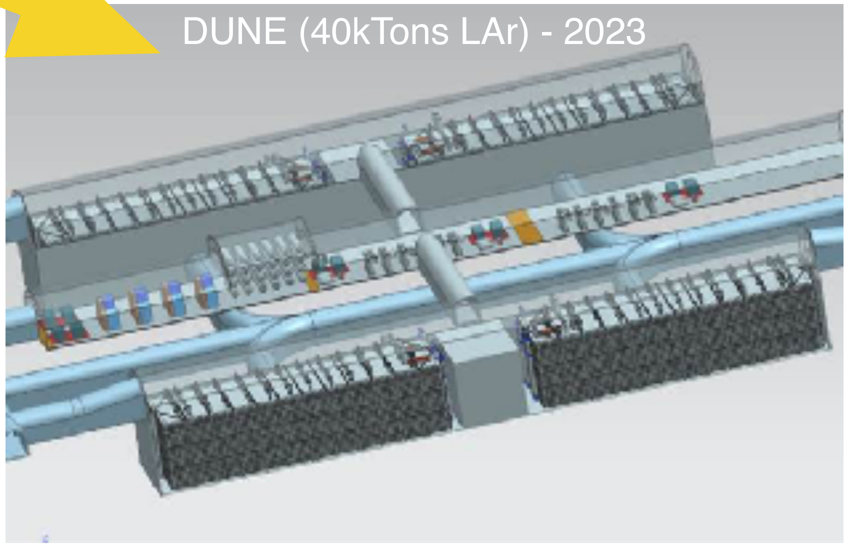
Technology challenge



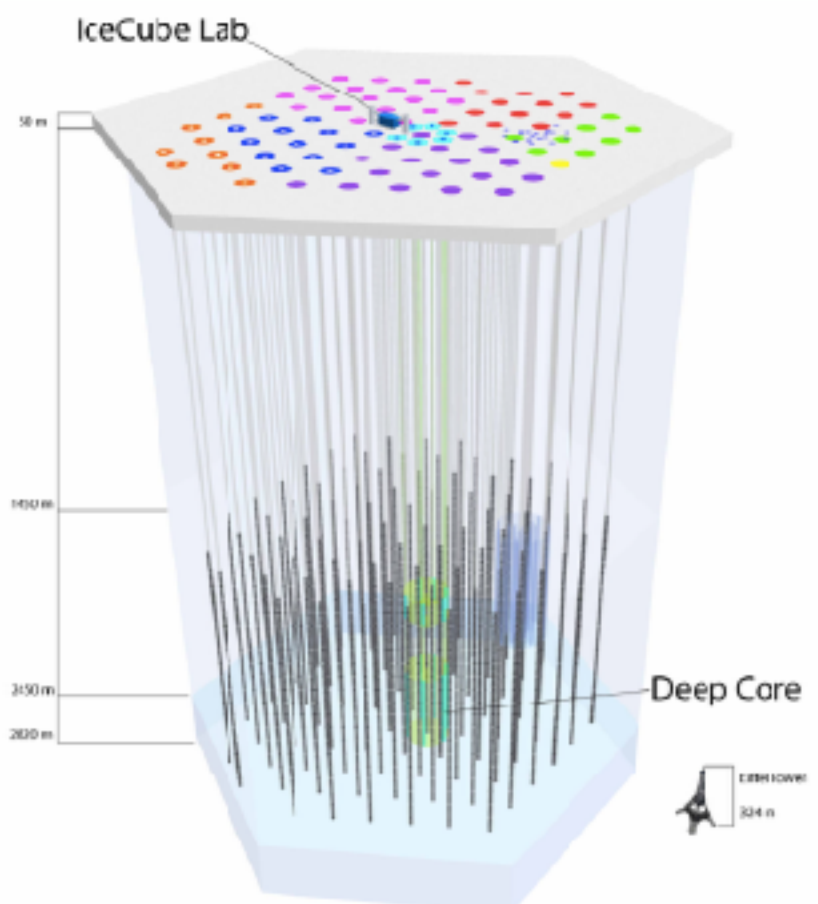
Innovation in instrumentation has driven discoveries in neutrino physics



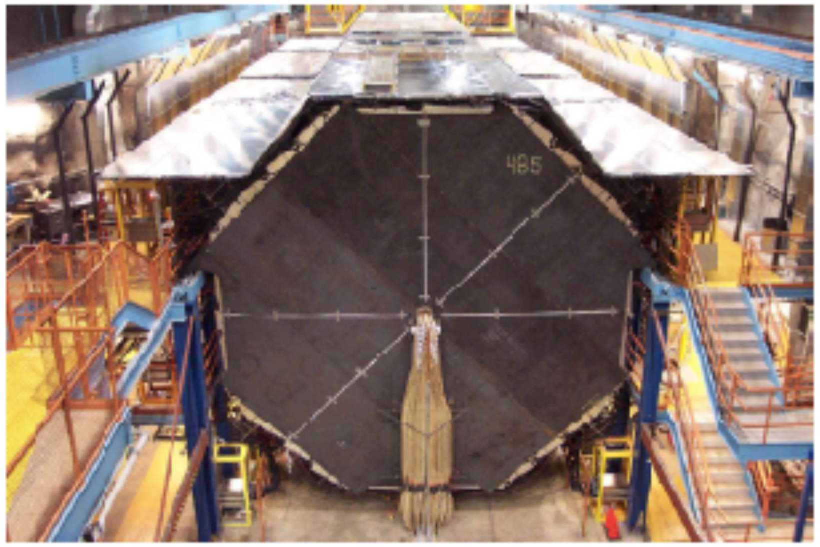
New discoveries?



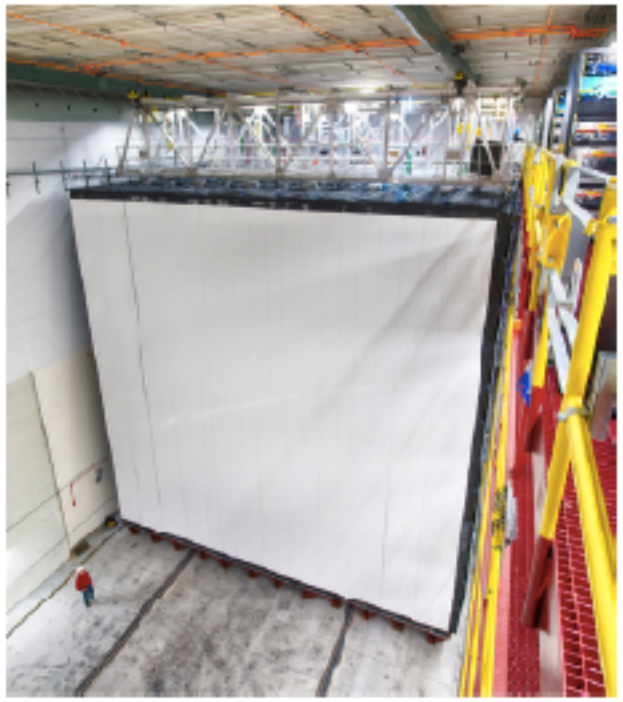
BIG DETECTORS!



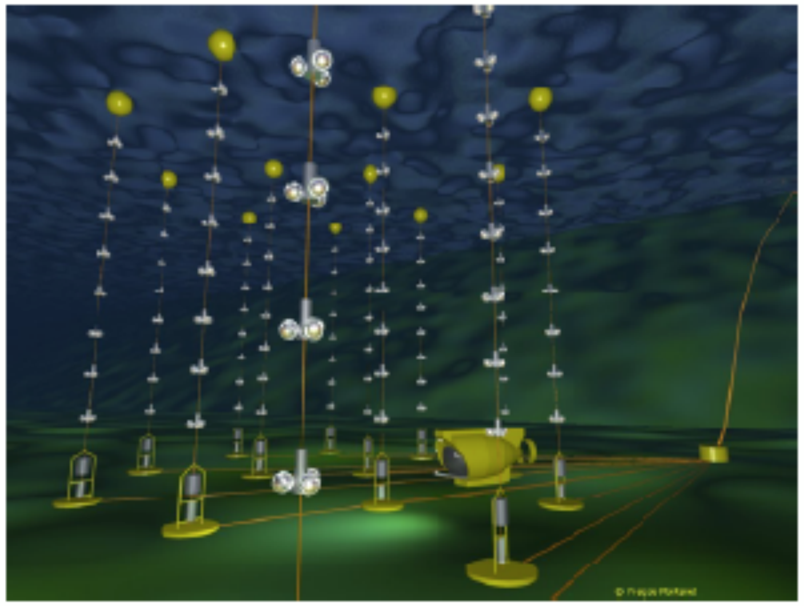
IceCube



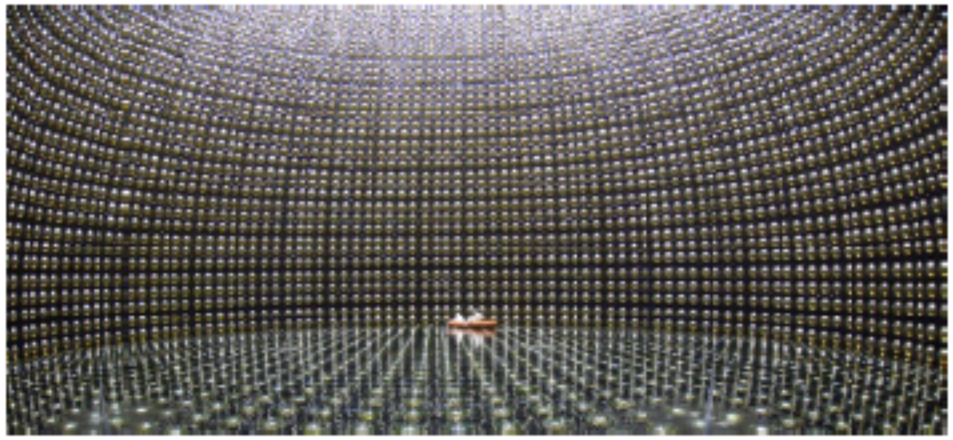
MINOS



NOvA

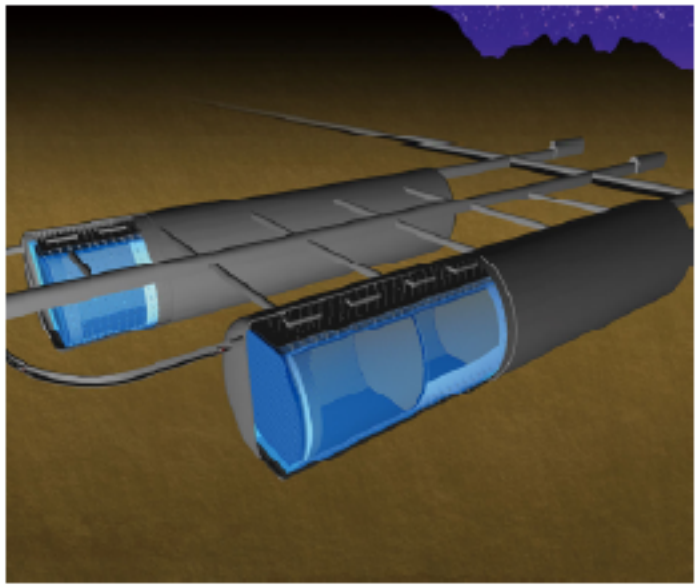


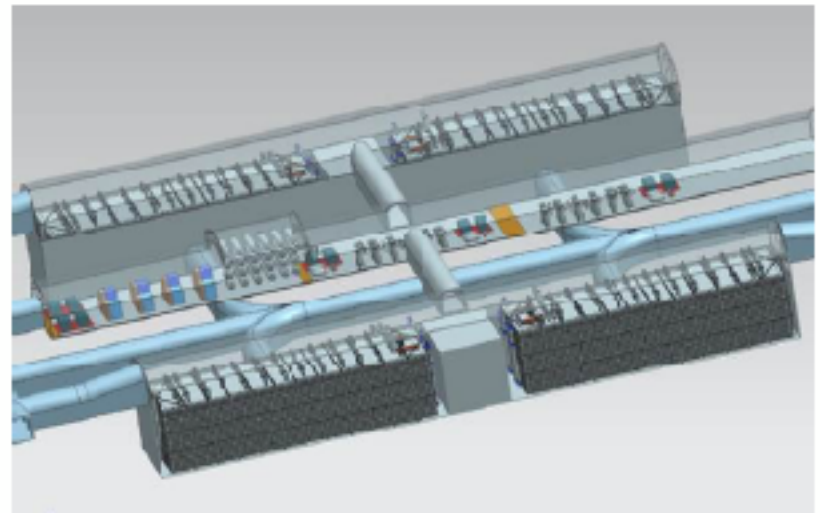
ANTARES

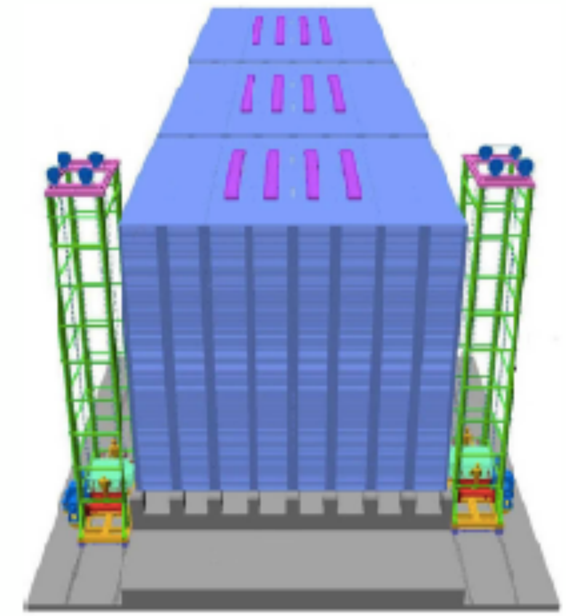


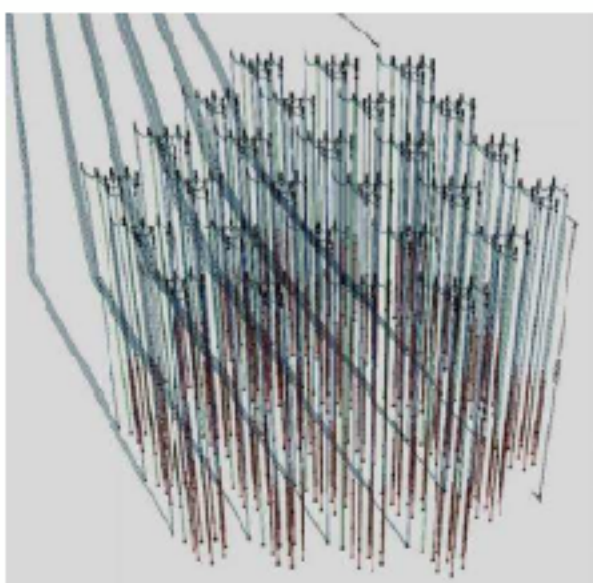
Super-Kamiokande

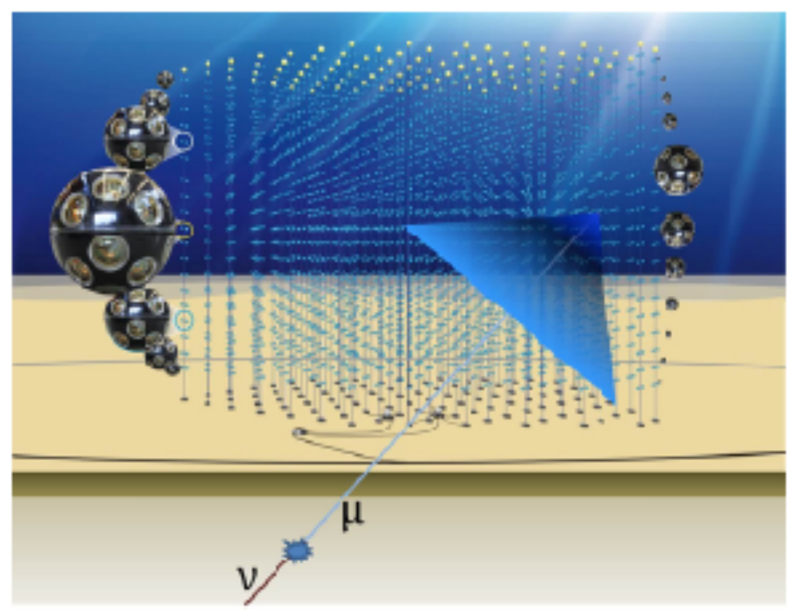
GOING BIGGER!


Hyper-Kamiokande

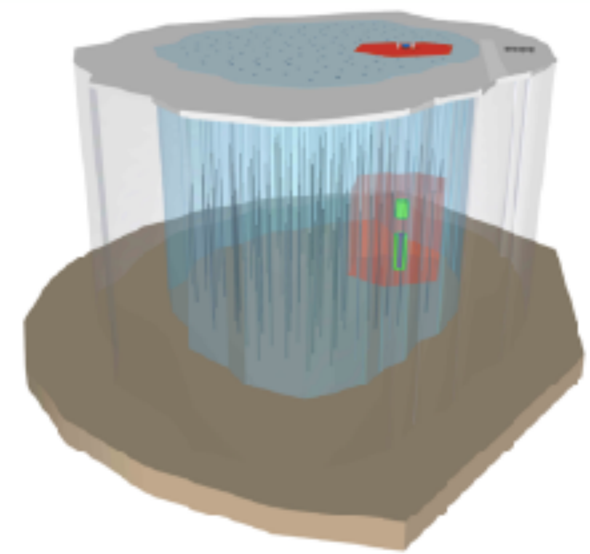

DUNE


INO


GVD (Lake Baikal)



KM3NET


IceCube-Gen2

Future of neutrino physics

- Many aspects of neutrino physics are still puzzling.
- Forthcoming experiments will address many questions related to neutrino properties:
  - What are the masses of the neutrinos?
  - Are neutrinos their own antiparticles?

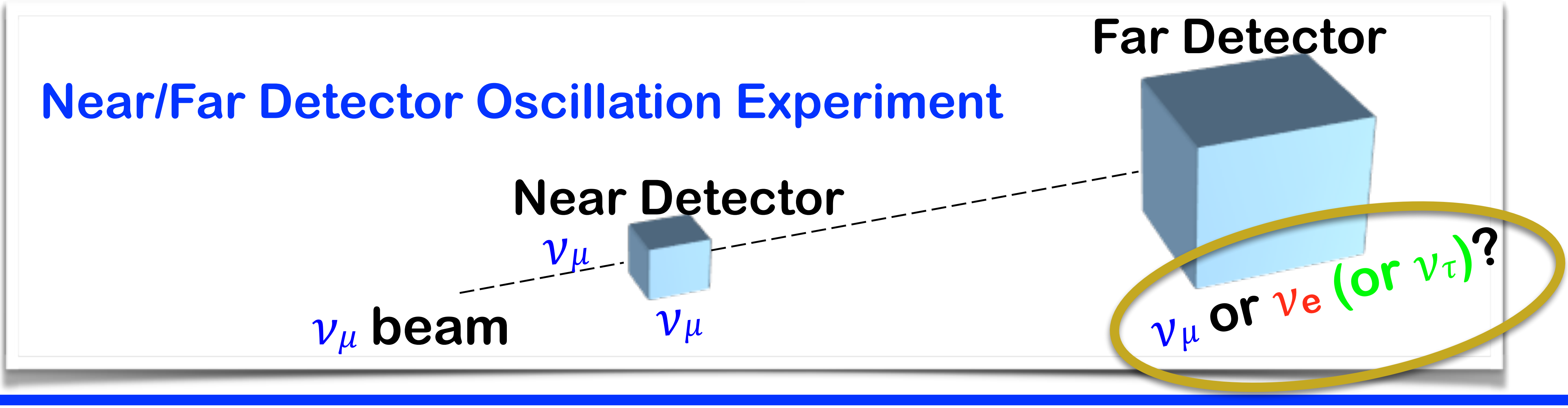
β and ββ decay experiments

Future of neutrino physics

- Many aspects of neutrino physics are still puzzling.
- Forthcoming experiments will address many questions related to neutrino properties:
  - What are the masses of the neutrinos?
  - Are neutrinos their own antiparticles?
  - How are the masses ordered (referred as mass hierarchy)?
  - Do neutrinos and antineutrino oscillate differently?
  - Are there additional neutrino types?

β and ββ decay experiments

Accelerator Neutrino Oscillation (Short- and Long-Baseline) Experiments



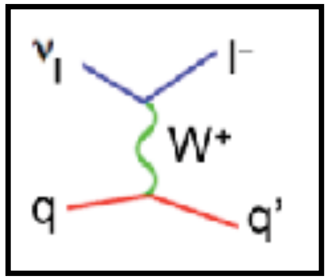
Neutrino interactions

- Today studies of the **properties of neutrinos** (masses and mixing) has a primary role, but…

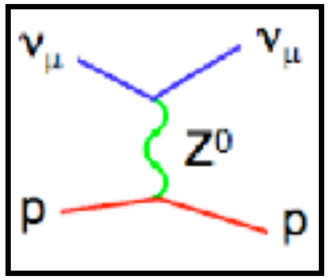
- We still need to understand a lot about neutrino interactions in view of **future experiments** aimed at **understanding neutrino properties**!

- **Neutrino cross sections are small** and depends on:
    - type of ν interaction (NC or CC)
    - ν target (electron, nucleus, nucleon, quark)
    - ν energy (MeV, GeV, or TeV)

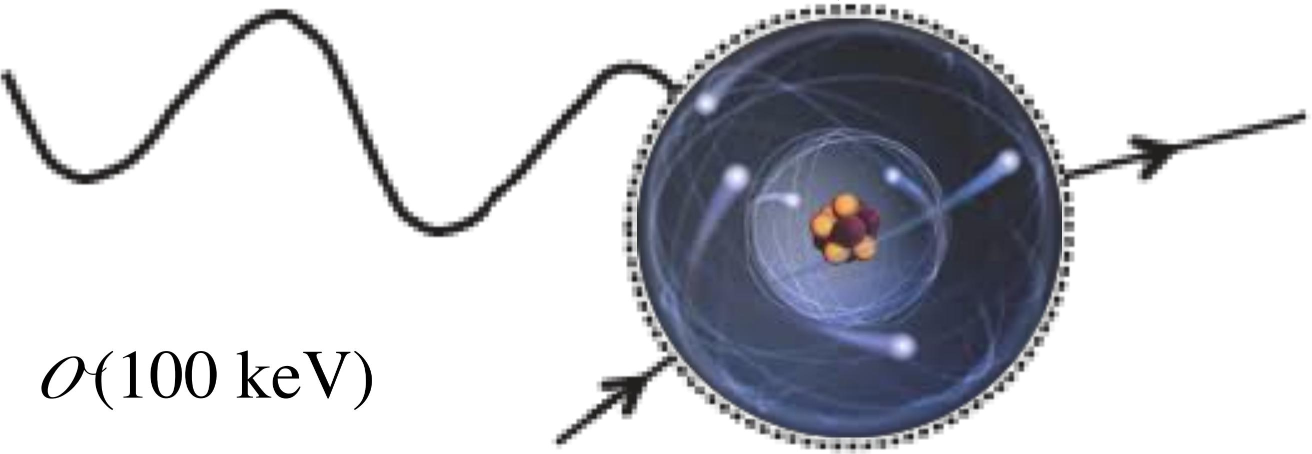
CC



NC

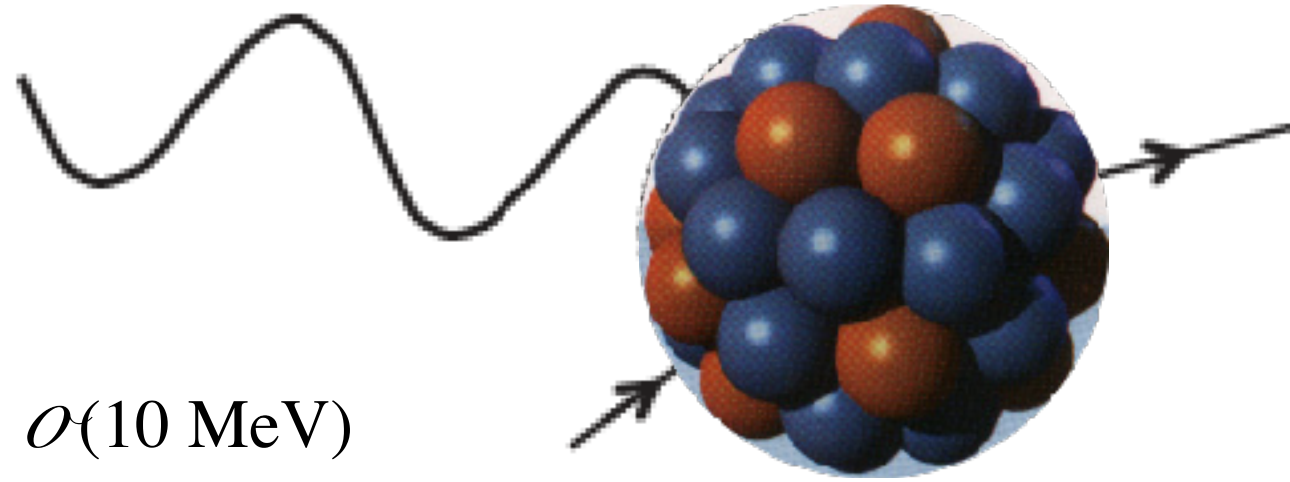


T= Atom (atomic electrons)



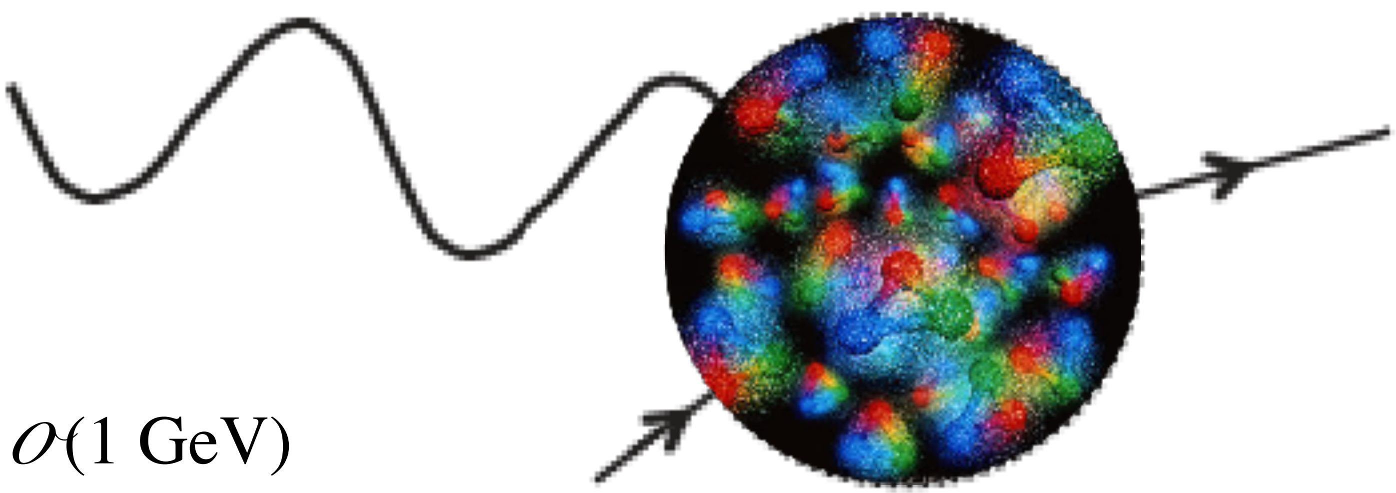
$\mathcal{O}$(100 keV)

T= Nucleus



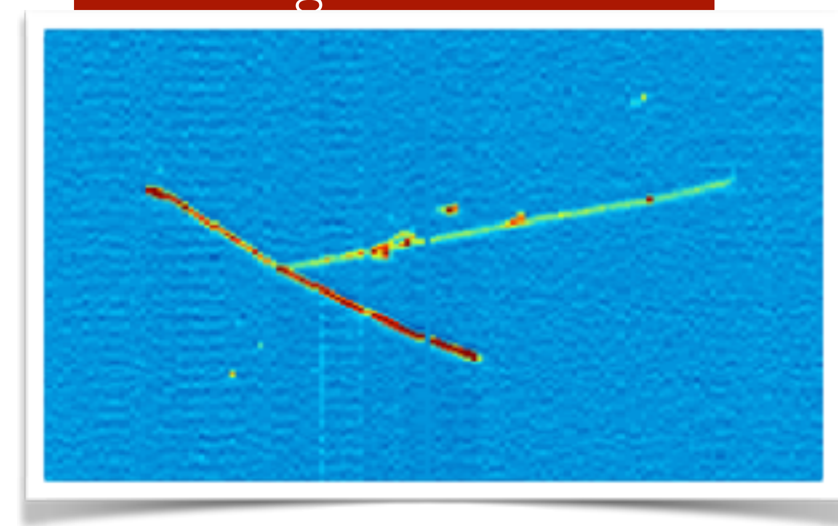
$\mathcal{O}$(10 MeV)

T= Nucleons (or clusters of Nucleons) in Nuclei

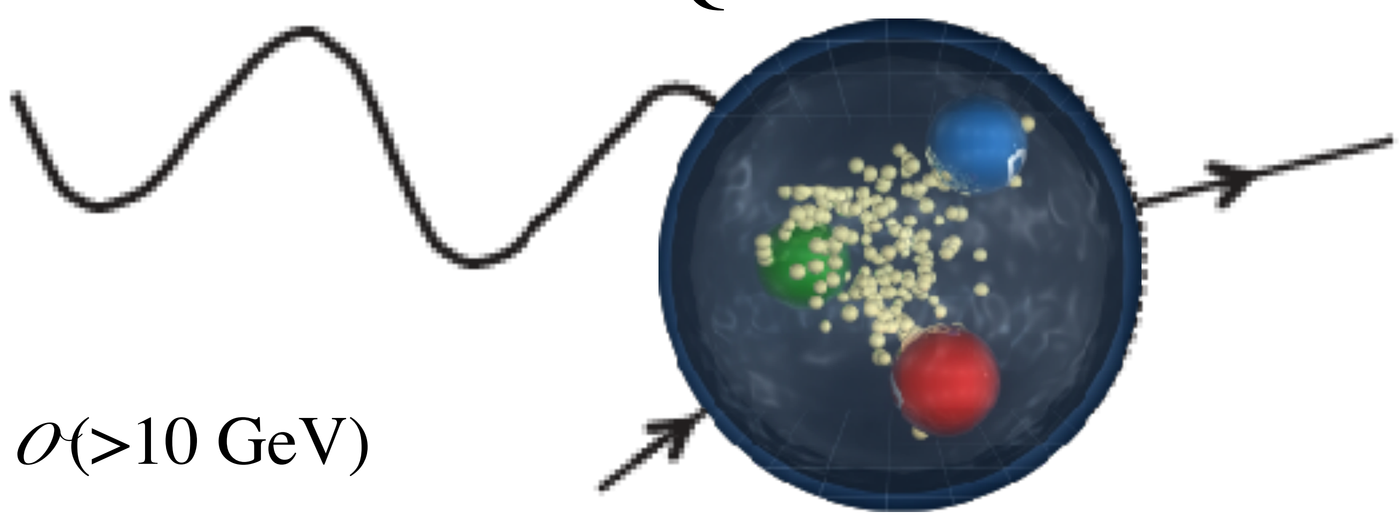


$\mathcal{O}$(1 GeV)

recent LArTPC results: the hammer events from ArgoNeuT



T= Quarks in Nucleons



$\mathcal{O}$(>10 GeV)

Neutrinos - over such extended range of energies - probe matter from its Atomic structure to the ultimate quark structure.

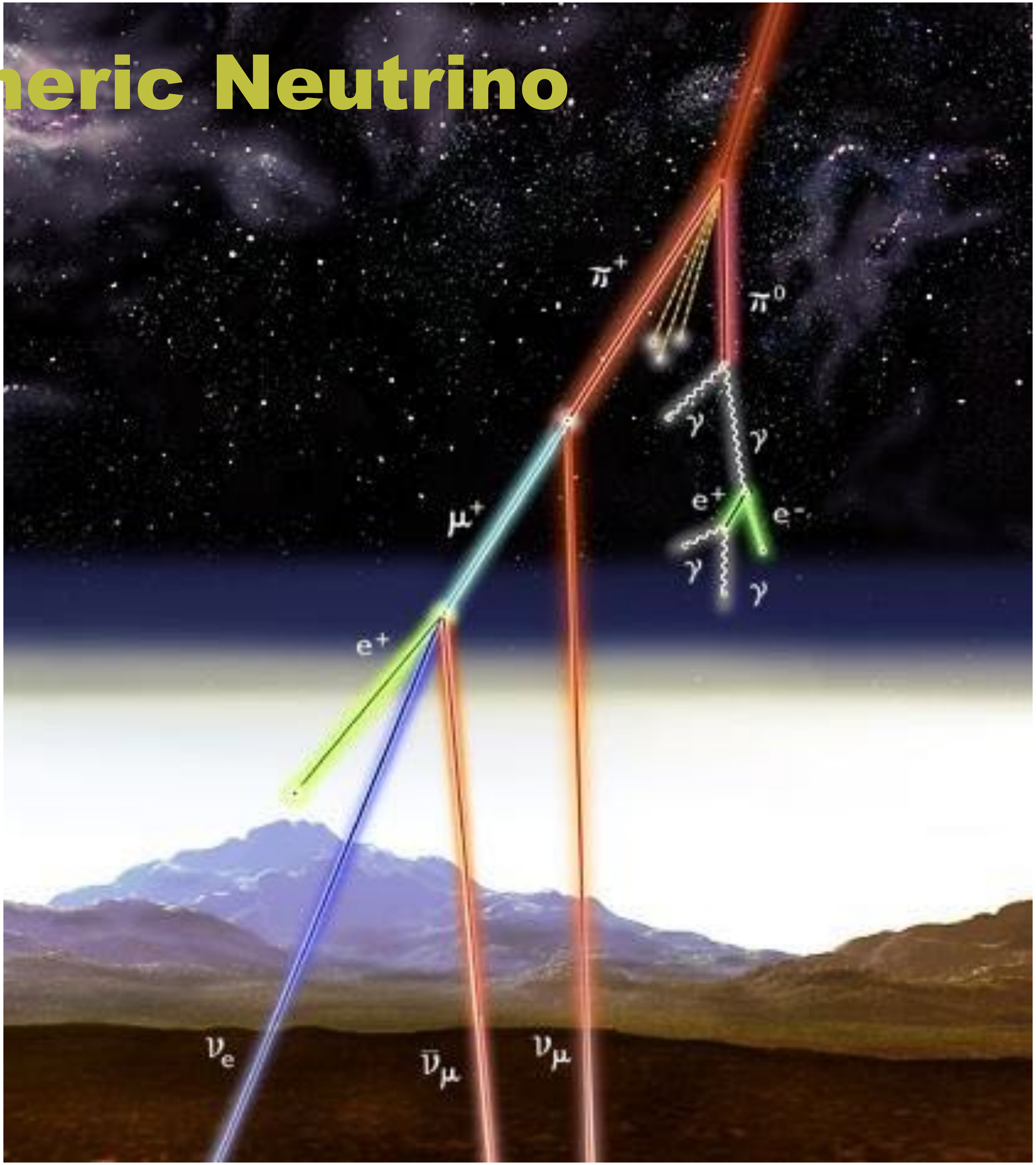
The Intermediate Energy range

Atmospheric Neutrinos

Short Baseline Accelerator Neutrinos

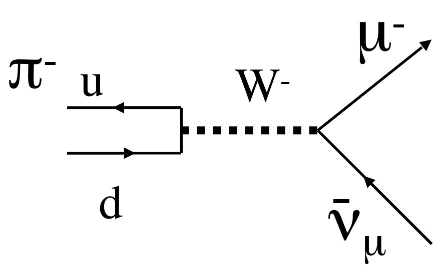
Long Baseline Accelerator Neutrinos

Atmospheric Neutrino



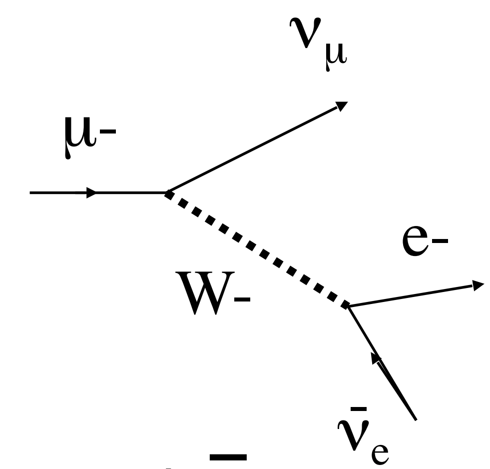
Cosmic Rays (p, A-nuclei) after entering the atmosphere collide with nuclei in the air

Pions and Kaons in the hadronic cascades decay in flight producing ν's and μ's. Muons can in turn decay into ν's.



$$\pi^- \rightarrow \mu^- + \overline{\nu}_\mu \quad ; \quad \mu^- \rightarrow e^- + \overline{\nu}_e + \nu_\mu$$

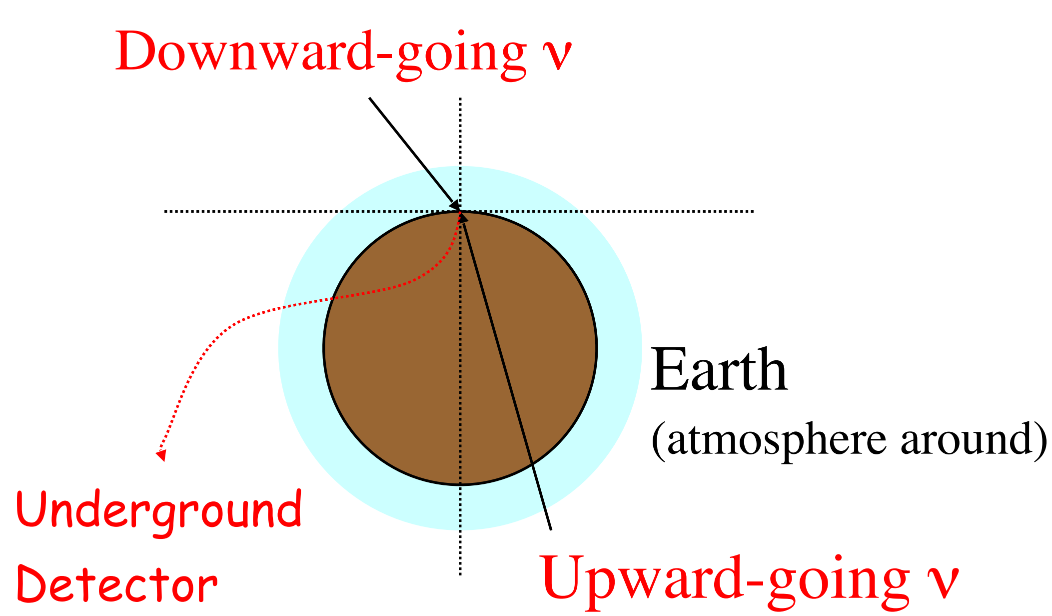
$$\pi^+ \rightarrow \mu^+ + \nu_\mu \quad ; \quad \mu^+ \rightarrow e^+ + \nu_e + \overline{\nu}_\mu$$

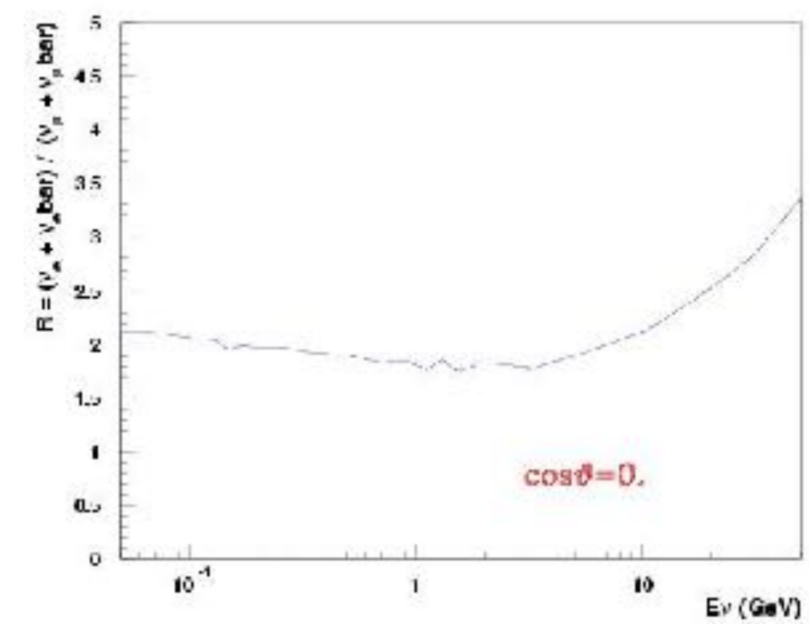


The ν-flavor Ratio at Earth surface is approximately constant

$$R = \frac{\nu_\mu + \overline{\nu}_\mu}{\nu_e + \overline{\nu}_e} \cong 2$$

.. however for $E_\nu \approx 1$ GeV, the parent muon reaches the surface of the Earth before it decays ⇒ the e-neutrino fluxes decreases and **R becomes larger**





Atmospheric neutrino event rate

Nuclear targets in atmospheric neutrino experiments:

O (Oxygen in H_2O) $\Leftarrow$ SuperKamiokande (Kamiokande and IMB)

Fe $\Leftarrow$ SOUDAN/MINOS

Ar $\Leftarrow$ LArTPC (ICARUS at GS) and DUNE

O(50%) + Si(30%) + … $\Leftarrow$ MACRO

SuperKamiokande Detector

$$\langle \sigma_{\text{Atm}} \rangle = \int \sigma_{QEL}^{CC}(E_\nu)\, \lambda_{\text{Atm}}(E_\nu, \cos\theta_Z)\, dE_\nu\, d\cos\theta_Z \approx 1.2 \times 10^{-38} cm^2$$

$$\text{"}SNU\text{"}\left[10^{-36} s^{-1}\right] = \langle \sigma_{\text{Atm}} \rangle \times \Phi_{\text{Atm}} \approx 0.033$$

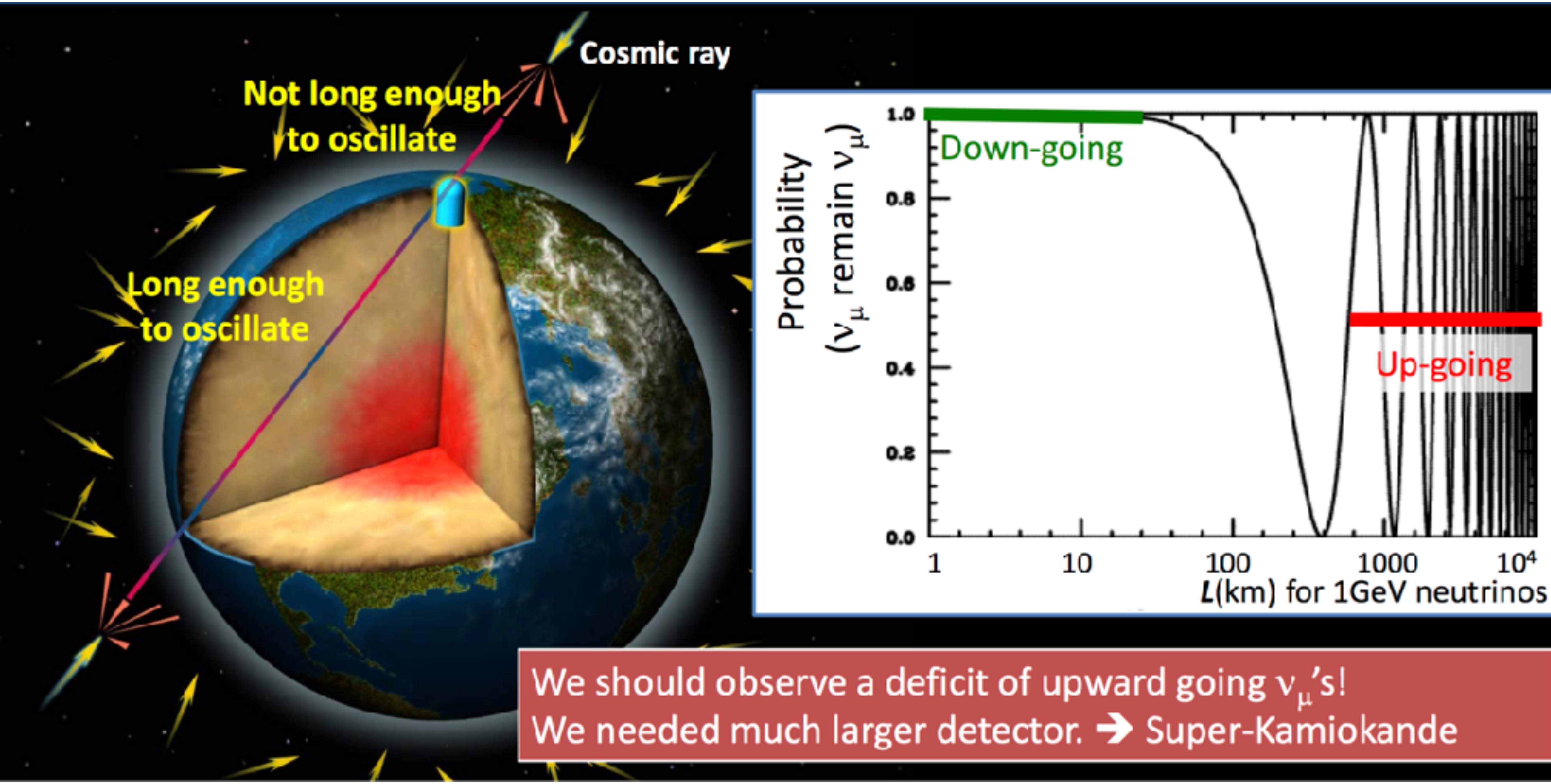
$$\text{Evt. Rate}\ :\ \frac{N_{evt}}{yr} \approx 300$$

for a detector Mass of 1 kt (!!!);

$\varepsilon_{\text{Det}} = 1,\ E_{\text{Det}}^{thr} = 0.$ (ideal case)

Summing up contributions of QEL (CC only) reactions from $\nu_\mu(47\%),\ \bar{\nu}_\mu(15\%),\ \nu_e(30\%),\ \bar{\nu}(8\%)$

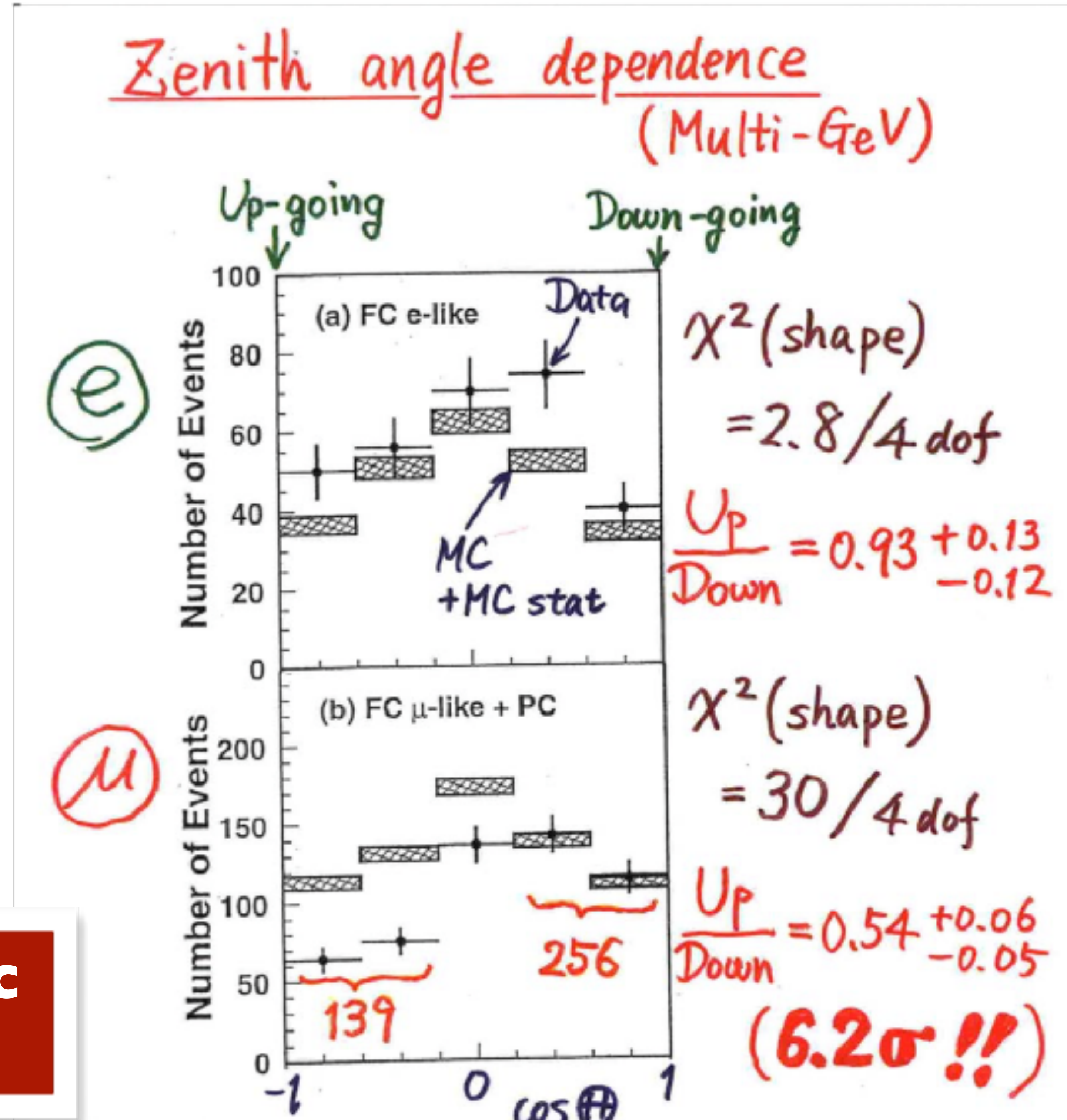
Oscillation (50% suppression of ν_μ rate) effect ARE NOT included!!



Cosmic ray
Not long enough to oscillate
Long enough to oscillate
1.0
0.8
0.6
0.4
0.2
0.0
Probability (ν_μ remain ν_μ)
Down-going
Up-going
1
10
100
1000
10^4
L(km) for 1GeV neutrinos
We should observe a deficit of upward going ν_μ's!
We needed much larger detector. → Super-Kamiokande

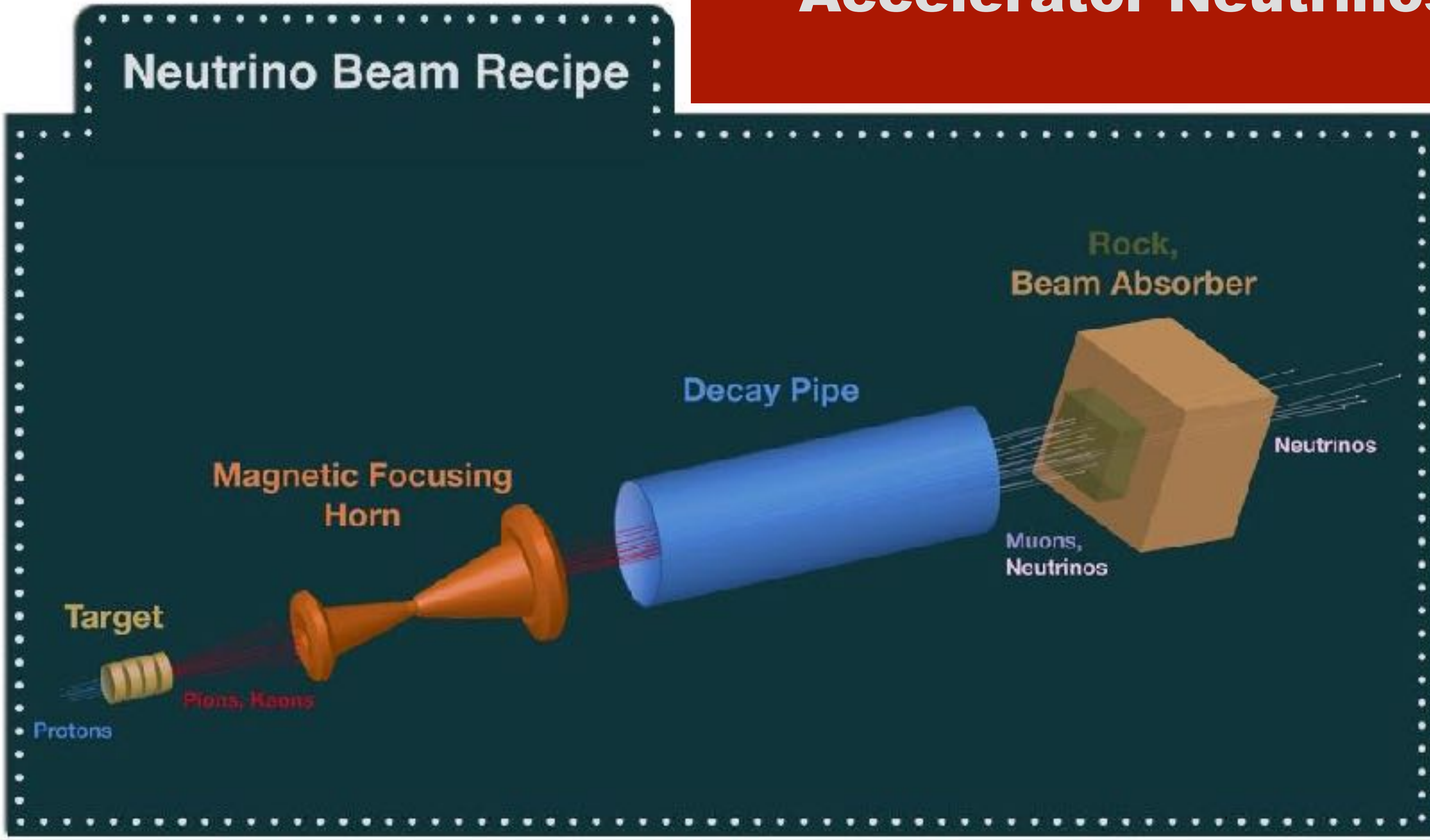
Discovery of Atmospheric Neutrino Oscillations

Takaaki Kajita Nobel Lecture (2015)



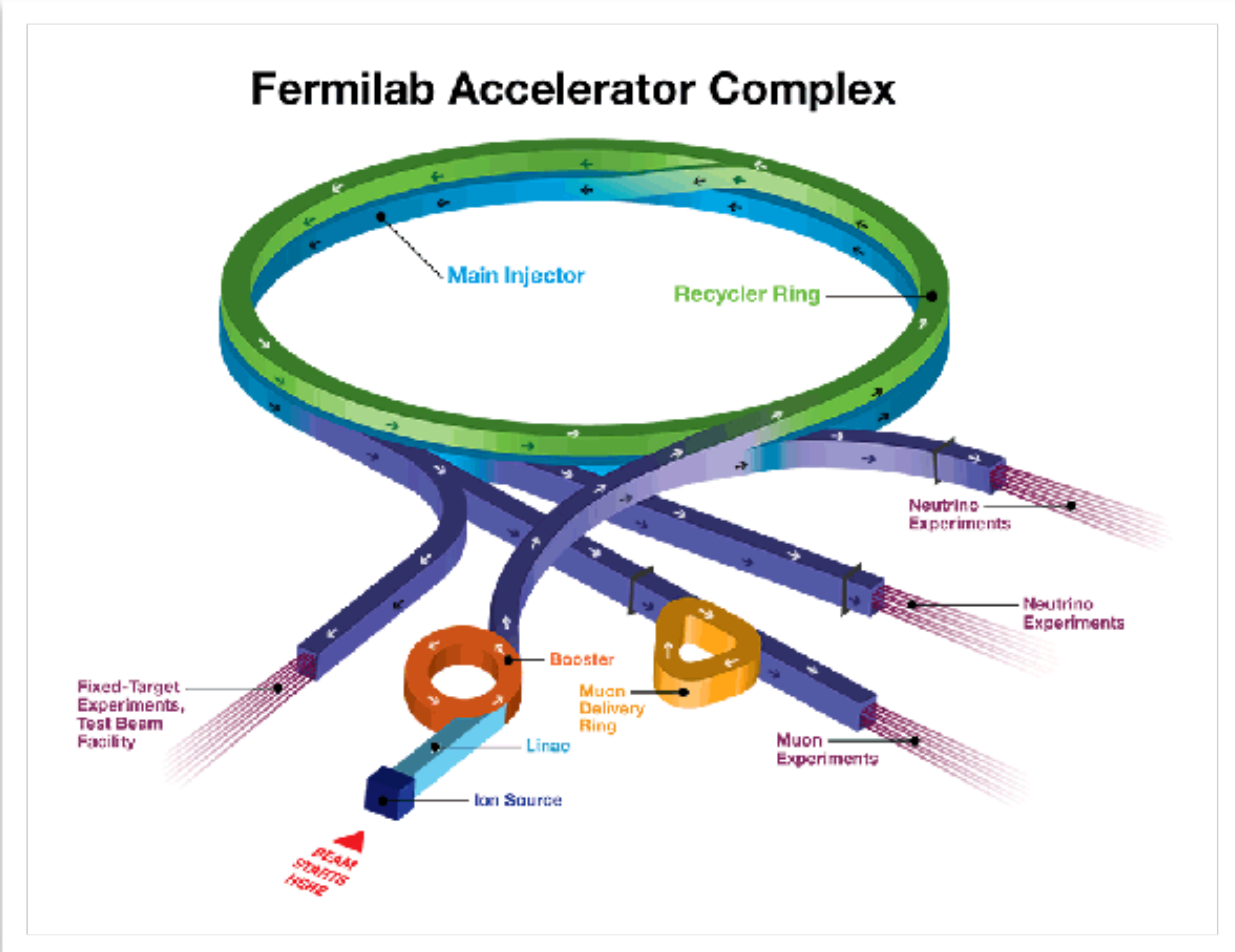
Accelerator Neutrinos

High Energy neutrinos



Best controlled fluxes of artificial neutrinos can be generated from beams of accelerated protons:
after hitting a dense material target, secondary pions (after the target) are focused in a long tunnel and decay-in-flight.
A collimated, high energy ν_μ beam is generated, pointing to the target (the experiment sensitive mass) located at near or far distance (short/long baseline).

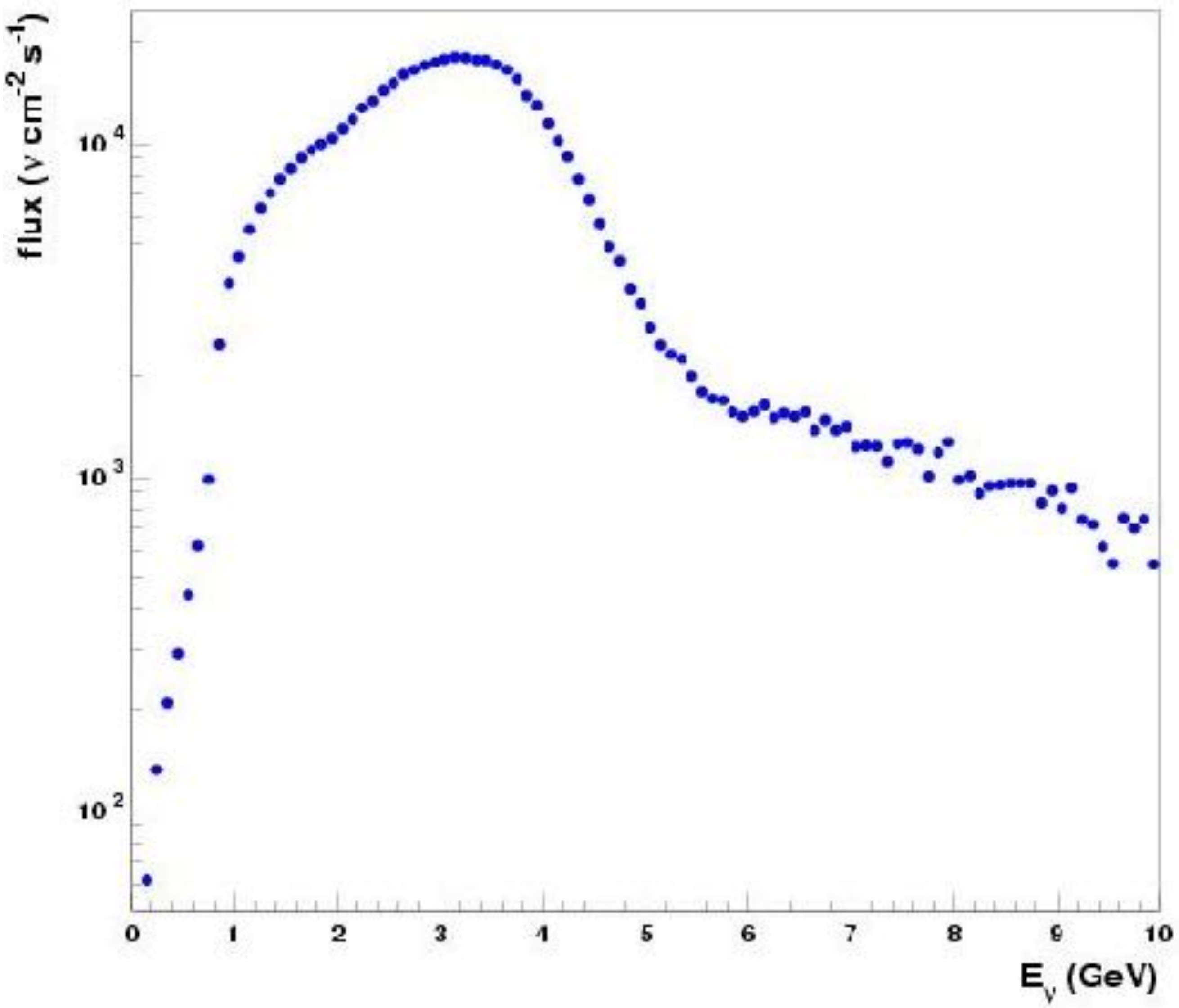
see Z. Pavlovic's lecture



Many neutrino beams have been built (FERMILAB, CERN, Russia, Japan, ..) in a >40 yrs long history.

Use the current NuMI long baseline beam at FERMILAB as an example.

	NuMI Beam Characteristics
p beam energy	120 GeV
P beam cycle	1.87 s
p beam intensity	$4x10^{13}$ PoT/cycle
proton on Target (PoT)	3.8×10^{20} PoT/yr
π decay tunnel	670 m



NuMI Beam Flux
"Low Energy Option"

	"Low Neutrino Energy Option"
ν_μ fluence	1.6×10^{13} ν/cm^2
Average ν_μ Flux	5×10^5 ν/ cm^{2}s
Energy Mean Value	≈ 3 GeV

NB: "Low Energy Option" corresponds to the "High-Intermediate" range in NeutrinoLand

Accelerator neutrino event rate

Huge unprecedented Rate at the near station

$$\langle \sigma_{\text{Beam}} \rangle = \int \sigma_{DIS}^{CC}(E_\nu)\, \lambda_{\text{Beam}}(E_\nu)\, dE_\nu \;\approx 2.2 \times 10^{-38}\, cm^2$$

$$"SNU" \left[10^{-36} s^{-1}\right] = \left\langle \sigma_{Beam}^{DIS} \right\rangle \times \Phi_{Beam}^{NuMI} \approx 1.14 \times 10^4$$

$$\text{Evt. Rate}: \frac{N_{evt}}{yr} \approx 8.5 \times 10^7$$

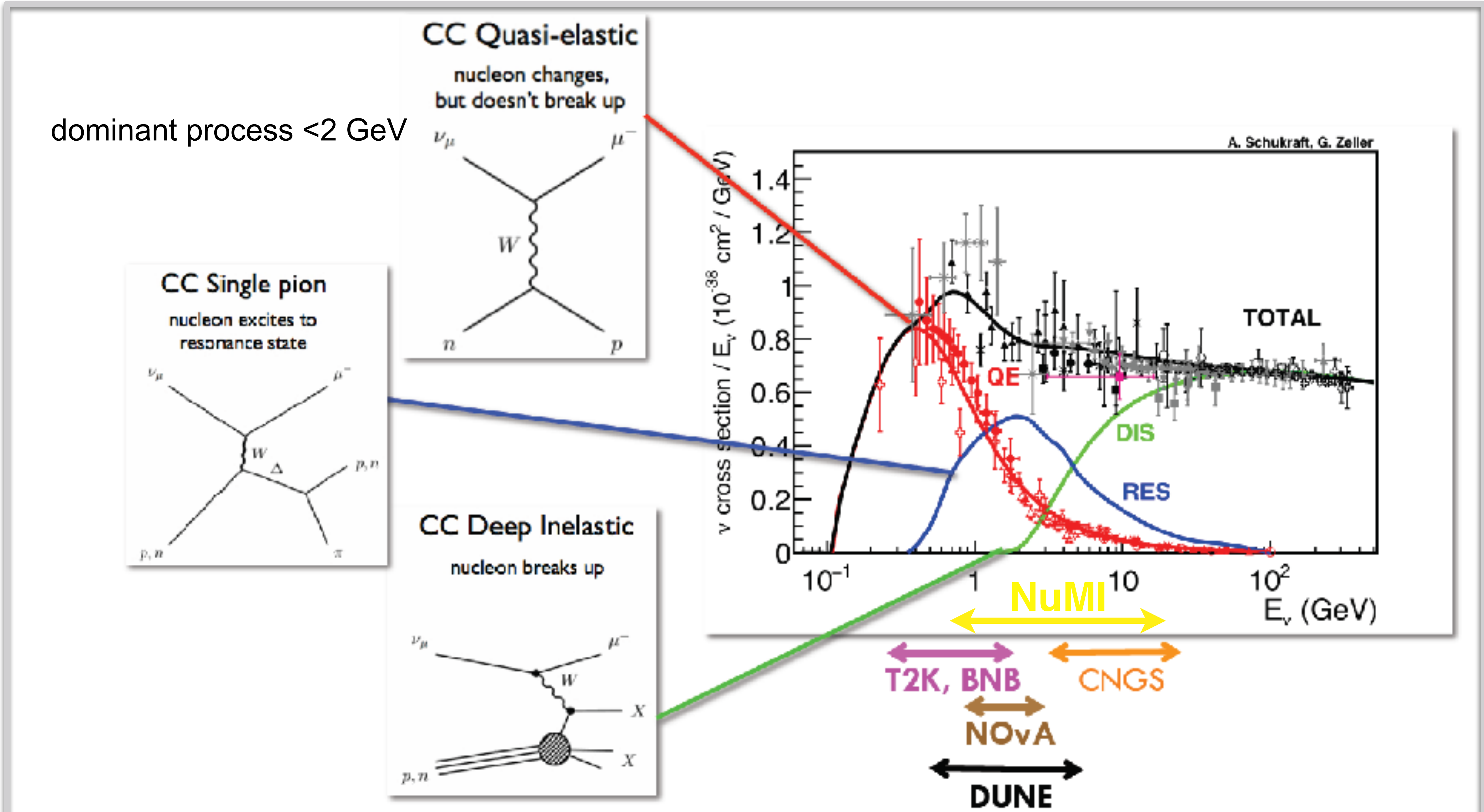
for a detector Mass of 1 kt (!!!);

$\varepsilon_{\text{Det}} = 1,\ E_{\text{Det}}^{thr} = 0.$ (ideal case)

Obviously the Flux at far distance is MUCH smaller due to the divergence of the neutrino beam.
However, the X-high intensity of the modern neutrino beams makes possible to steer the beam at a far site, hundreds miles away, for "long-baseline" neutrino oscillation studies

0.1-20 GeV - Different processes

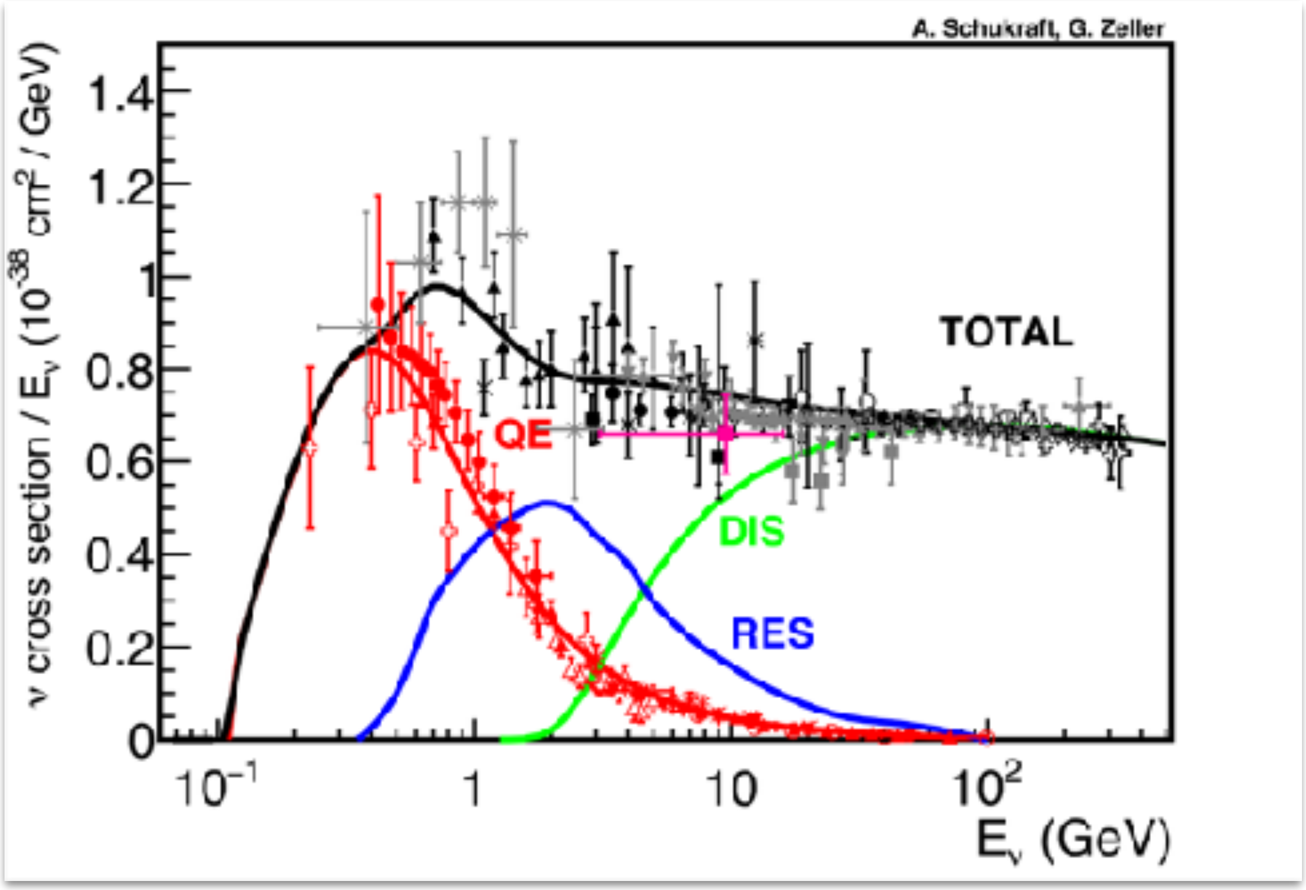
- At **intermediate energies (0.1-20 GeV)**, the description of neutrino scattering becomes complicated
- Several distinct neutrino scattering mechanisms start to play a role. Three main categories:



0.1-20 GeV - Different processes

- At higher energy the description of neutrino scattering becomes increasingly more complicated.
- At **intermediate energies (0.1-20 GeV)**, several distinct neutrino scattering mechanisms start to play a role. Three main categories:

The dominant interaction channels change rapidly across the few GeV neutrino energy region



Few-GeV Region - ν Data (I)

- **Neutrino scattering at intermediate energies** is complicated and is **not yet** well measured!
- Some data have large uncertainties (20-40%) or show discrepancies between different data set and/or with present MC predictions
- Most of our knowledge of neutrino cross sections in this energy range comes from experiments conducted in the 1970's and 1980's using either bubble chamber or spark chamber detectors, that collected relatively small data samples (tens-to-a-few-thousand events).

Few-GeV Region - ν Data (II)

- With the discovery of **neutrino oscillations** and the advent of **higher intensity neutrino beams** this situation has been rapidly changing

- New experiments have started to collect ν scattering data (**ArgoNeuT, K2K, MiniBooNE, MINERνA, MINOS, NOMAD, SciBooNE, and T2K, NOνA, MicroBooNE**) in this energy range.

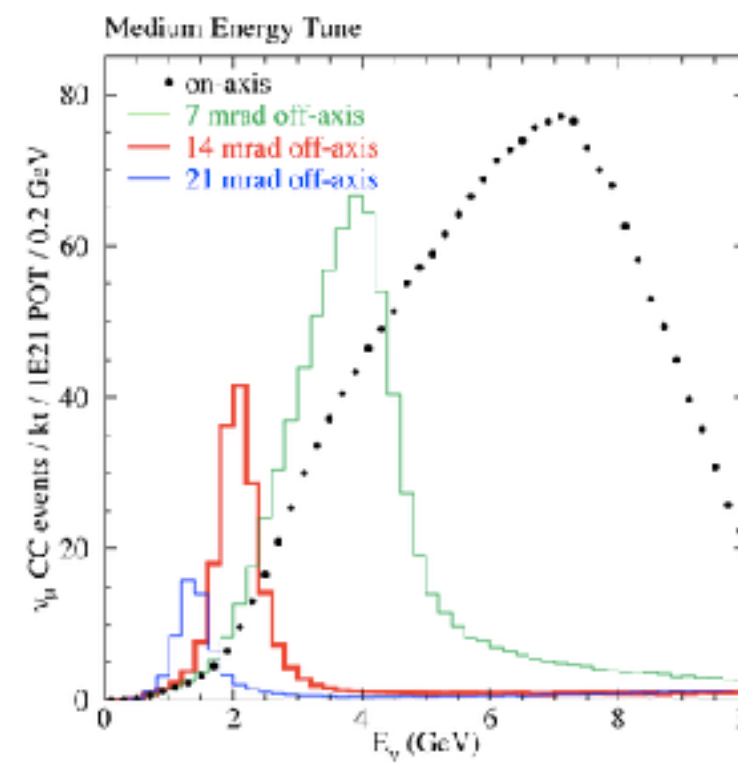
    - Recent results and/or currently analyzing and publishing new cross section data

see S. Parke's lecture

ν scattering - Challenges (I)

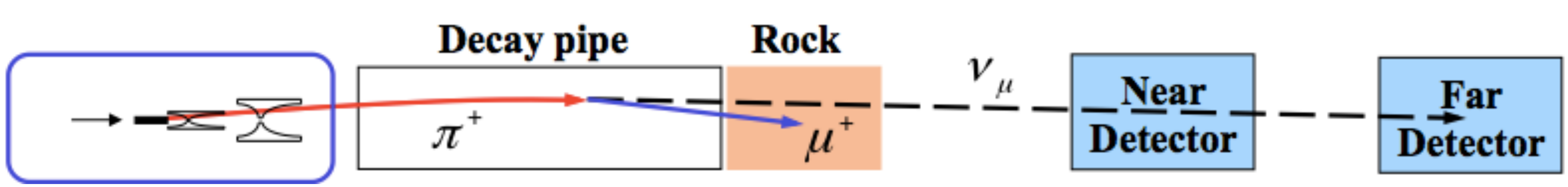
- **Main challenges of neutrino interaction measurements:**
  - Accelerator Neutrino beams are <u>not monochromatic</u> but distributed on **<u>broad band spectra</u>**! We have to infer E_ν from what we observe in the final state (technology dependent!!)
  - Cross sections are low and strongly energy dependent
  - Absolute σ_ν is a delicate measurement as it implies precise knowledge of normalization of incoming ν flux.

$$\sigma_\nu(E) \sim \frac{N_\nu(E)}{\phi_\nu(E)\times target}$$



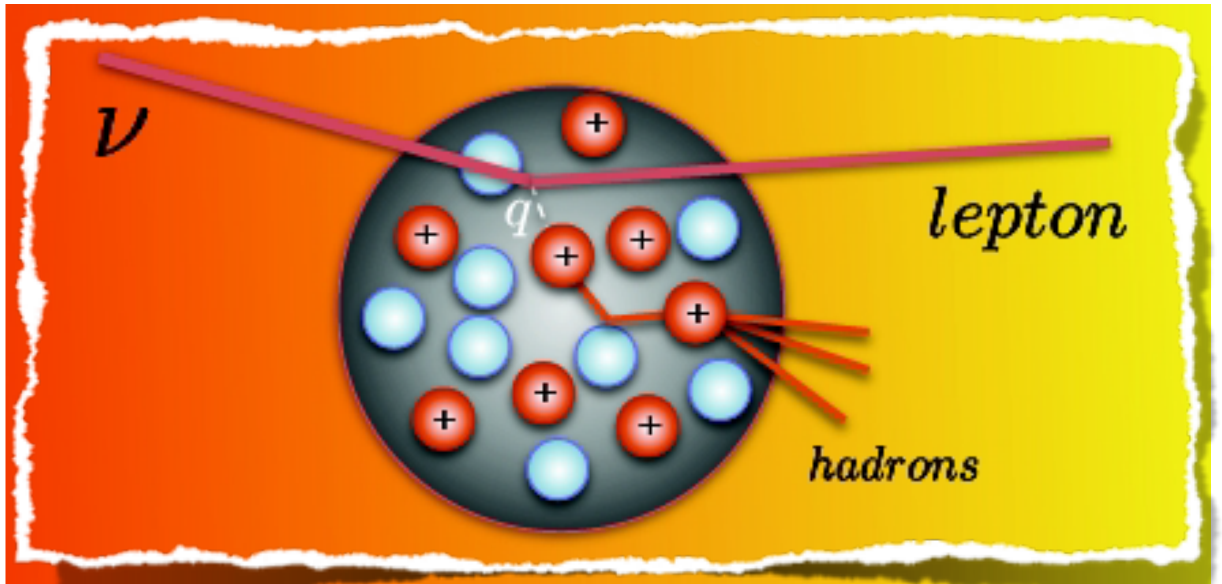
NuMI Medium Energy Flux

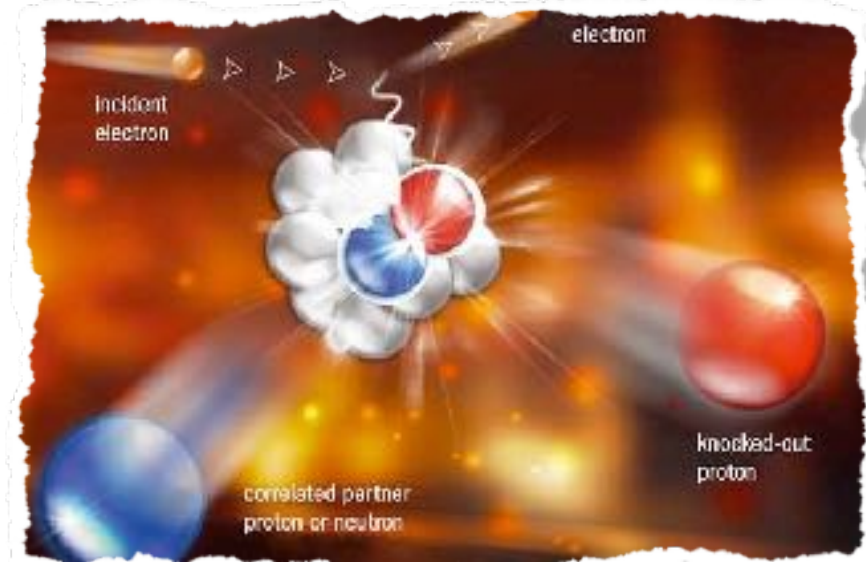
  - Flux has large uncertainties due to poor knowledge of hadron production. Flux is usually the <u>dominant uncertainty in σ_ν measurements</u> (~15-20% normalization uncertainties on the flux)



ν scattering - Challenges (II)

- Modern day ν experiments use complex nuclei as neutrino target: **Nuclear effects**

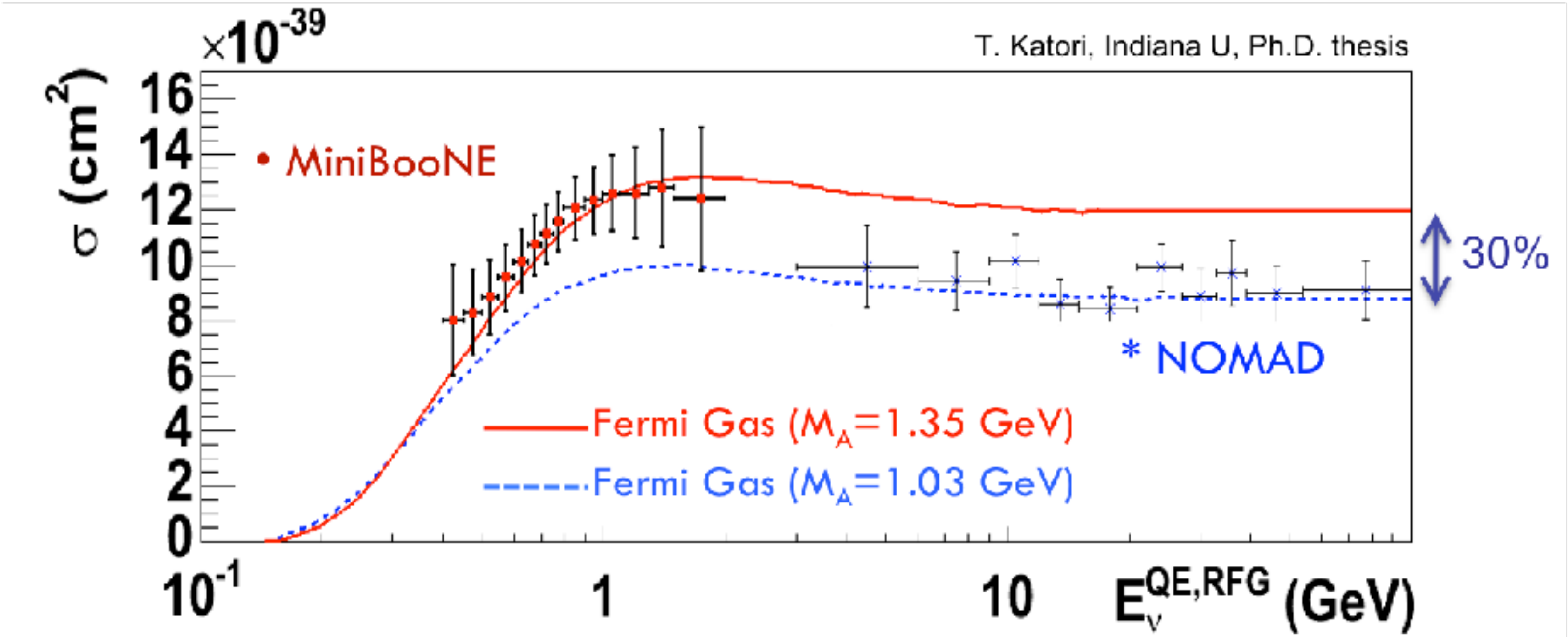




  - Significantly alter σ_ν's (100's MeV- few GeV), final state particle topology/ kinematics.
  - Due to ***Intra-nuclear re-scattering*** *(FSI, processes like pion absorption, charge exchange…)* and effects of ***correlation between target nucleons***, even a genuine QE interaction can often be accompanied by the *ejection of additional nucleons*, emission of many *de-excitation γ's* and sometimes by *soft pions* in the Final State.
  - Nuclear effects depend on the number and type of nucleons in the nucleus and therefore are different for different types of nuclei.

- **Modelling neutrino interactions** is very complicated. In this energy region neutrino target goes from nucleus to quark passing through interaction on nucleon.

The "XSECT battlefield"



Nuclear Effects:

long and short range nucleon correlations inside Nuclei

see more on slides 62-63

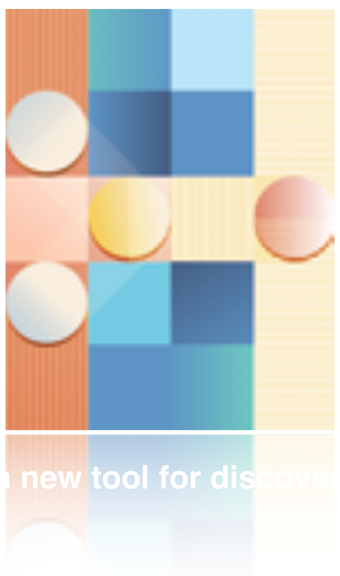
The Worldwide Neutrino Program in the U.S.

Building for Discovery

P5 - Strategic Plan for Particle Physics

The global High Energy Physics effort

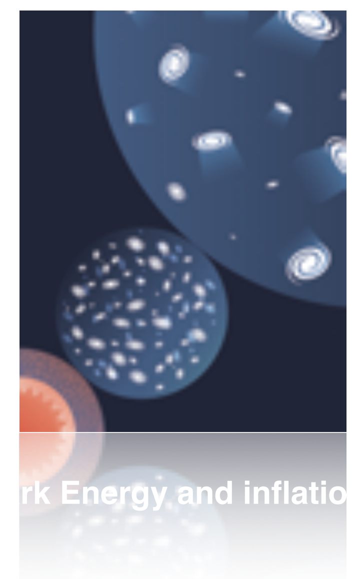
Higgs boson



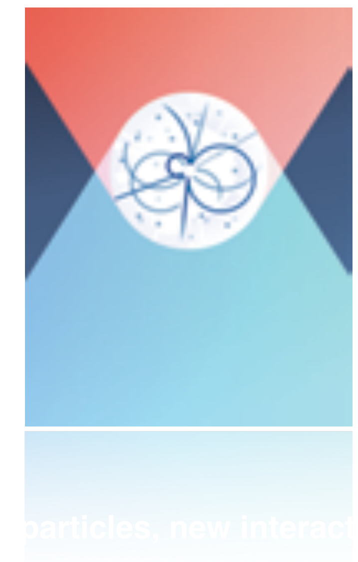
Neutrino mass

Dark matter

Cosmic acceleration



Explore the unknown



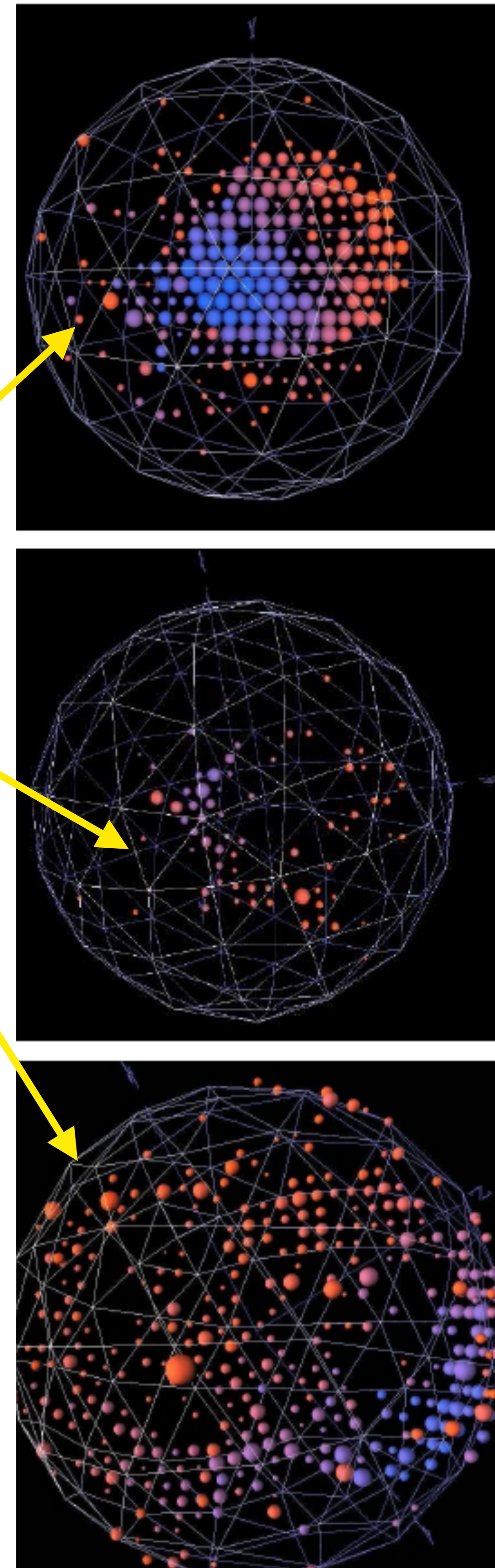
Host a unique, world-class facility in the U.S. for:

- Long Baseline Neutrino and Underground Search for Rare Phenomena
- Short-Baseline Neutrino experiments

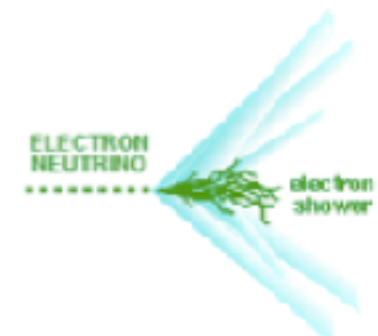
Technology choice

- Many fundamental results in neutrino physics from Cherenkov detectors *(water Cherenkov program in Japan/SK-K2K-T2K* ***and heavy water in Canada/SNO*** *and many liquid scintillator detectors around the world)*!
- Cherenkov detector - see Cherenkov rings of light generated by charged particles.
- Main limitation: cannot **distinguish electrons from single gammas**. In measuring ν_e interactions, background comes from interactions that have a single reconstructed photon in the final state.

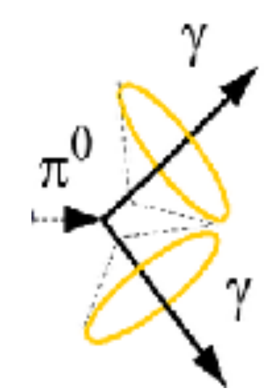
New Generation experiments
NEED new generation technology
(with superior electron/photon separation ability)



Muon candidate
sharp ring, filled in



Electron candidate
fuzzy ring, short track

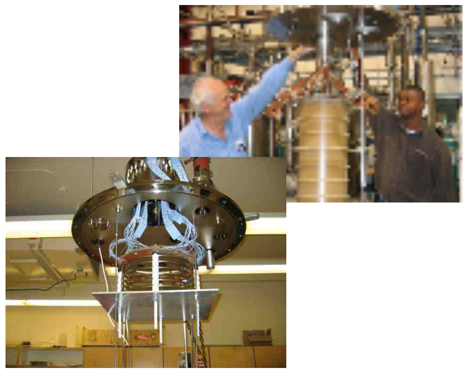


π^0 candidate
two “electron-like” rings

The US LAr TPC Program: a path toward DUNE

A rich R&D and physics program

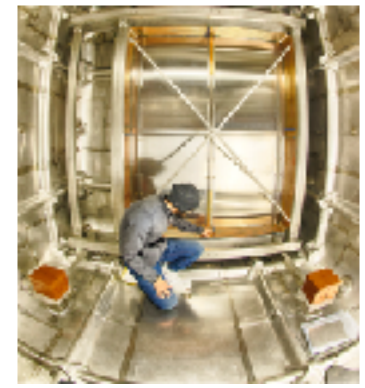
R&D



Yale TPC and Bo
(2008-2009)
Proof of Concept

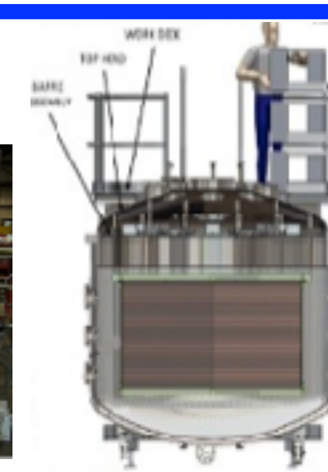
LUKE
(2008)
Material Teststand

LAPD
(2011)
LAr Purity



35Ton
(2013)
Cryostat Purity

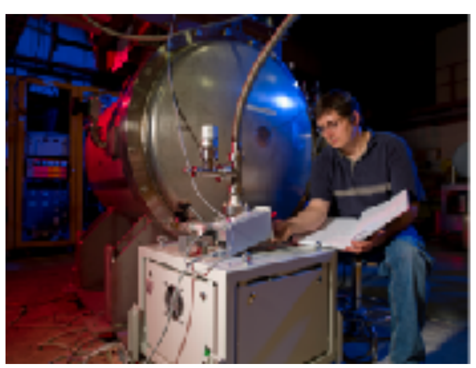
LArIAT
(2015)
LArTPC
Calibration



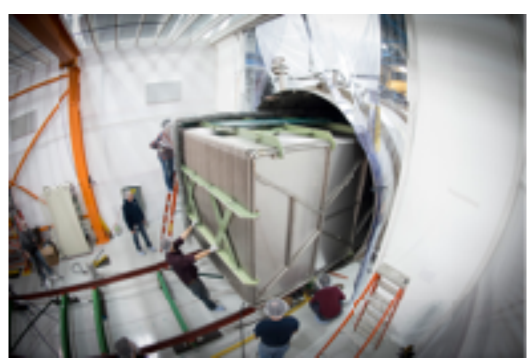
CAPTAIN

LArTPC
Calibration

Physics

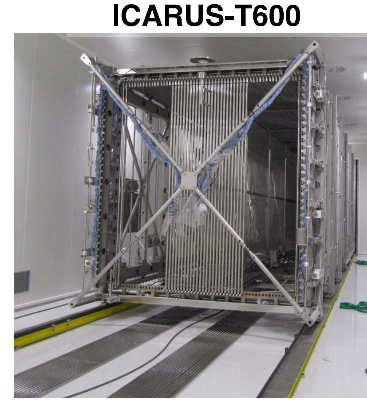


ArgoNeuT
(2009 - 2010)
ν-Ar Cross Sections

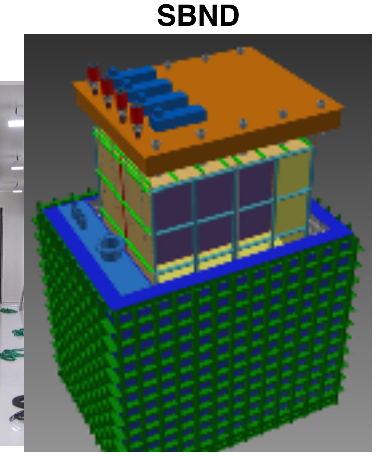


MicroBooNE
(2015 - 2018)
MiniBooNE
Low Energy Excess

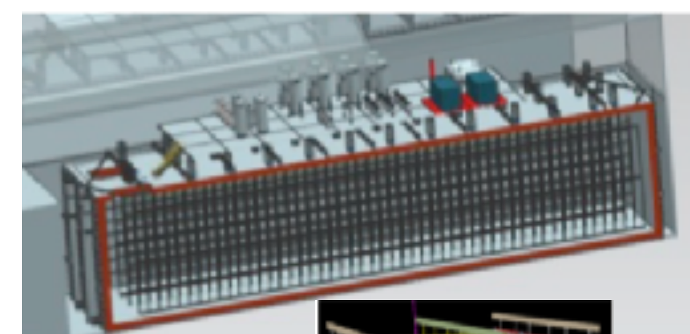
ICARUS-T600

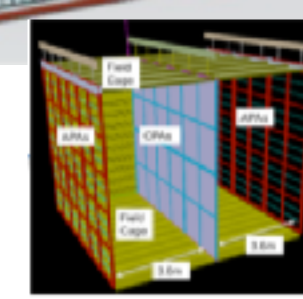


SBND



SBN (SBND, MicroBooNE, ICARUS-T600)
(2018 - 2021)
Searches for
Sterile Neutrino Oscillations

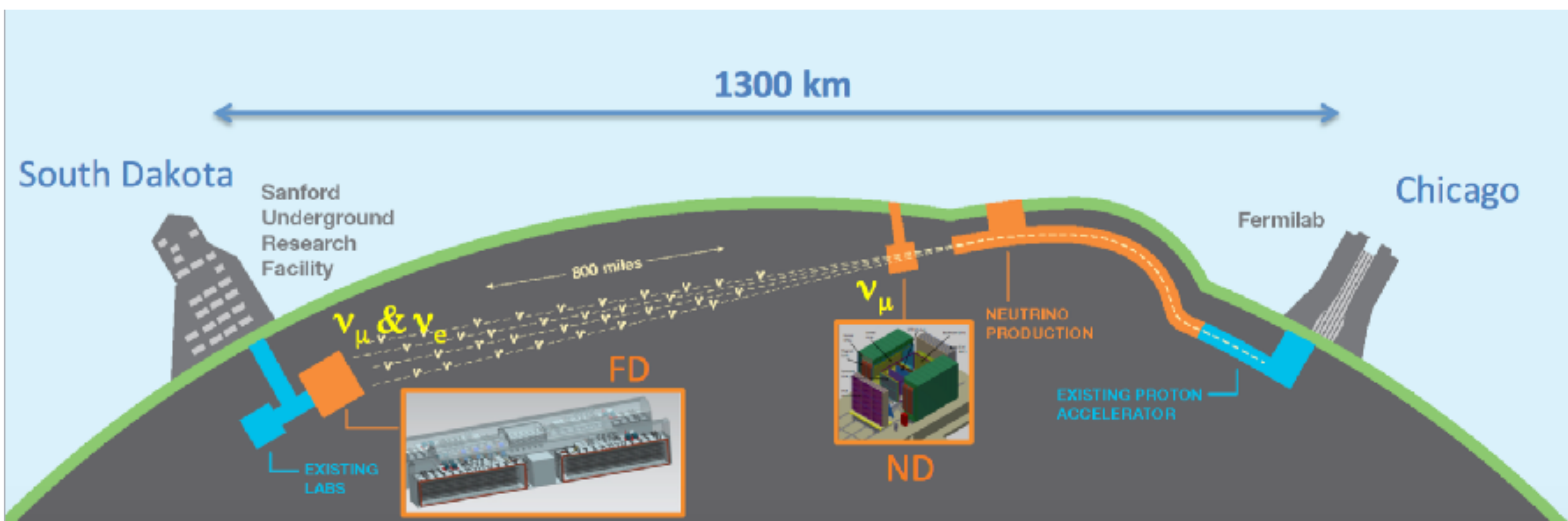




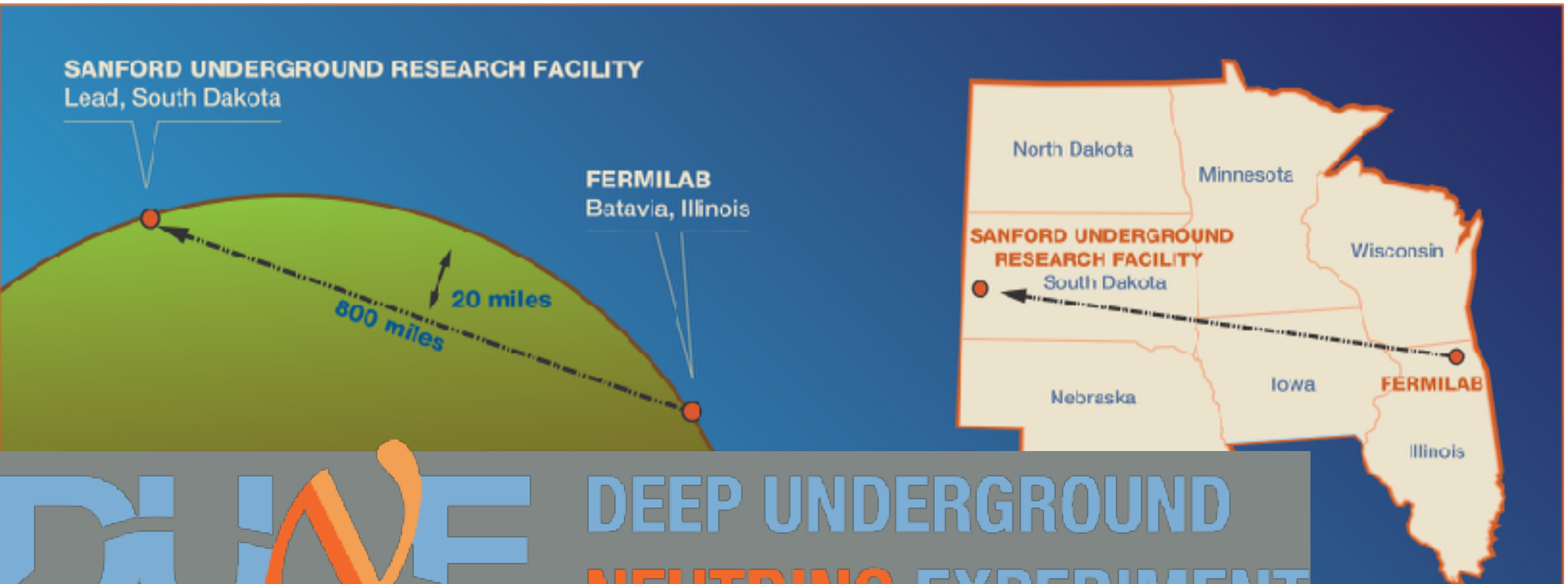
ProtoDUNE-DUNE
(2018) (2023+)

DUNE: the Long Baseline Neutrino program

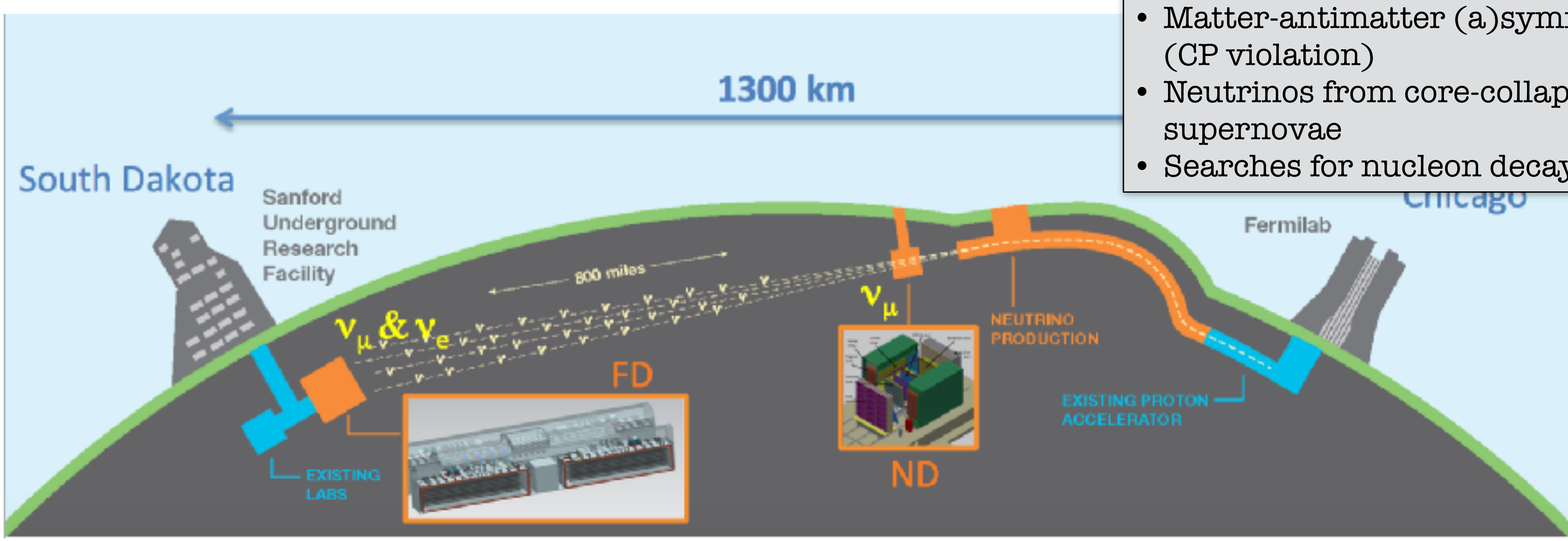
DEEP UNDERGROUND NEUTRINO EXPERIMENT



DUNE: the Long Baseline Neutrino program



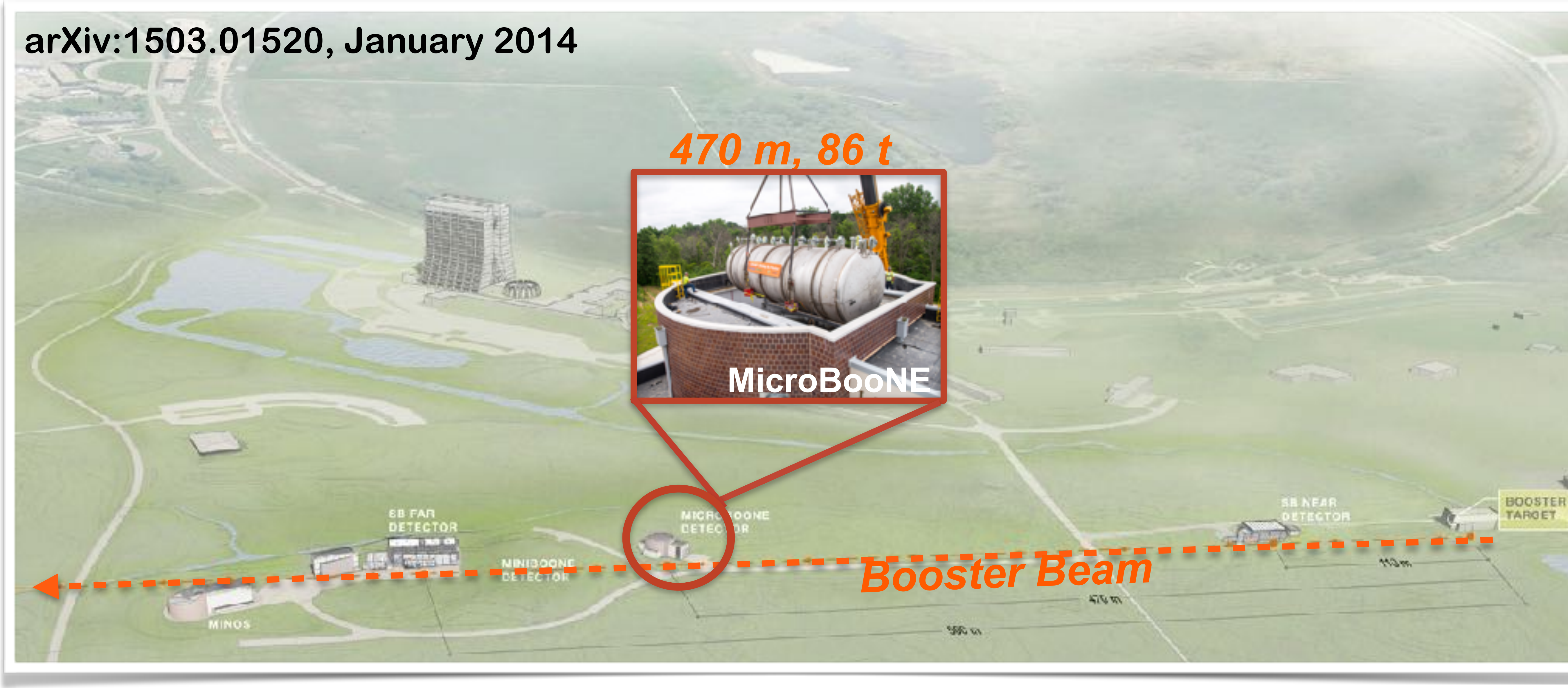
DEEP UNDERGROUND NEUTRINO EXPERIMENT



Main physics goals:

- Matter-antimatter (a)symmetry? (CP violation)
- Neutrinos from core-collapse supernovae
- Searches for nucleon decay

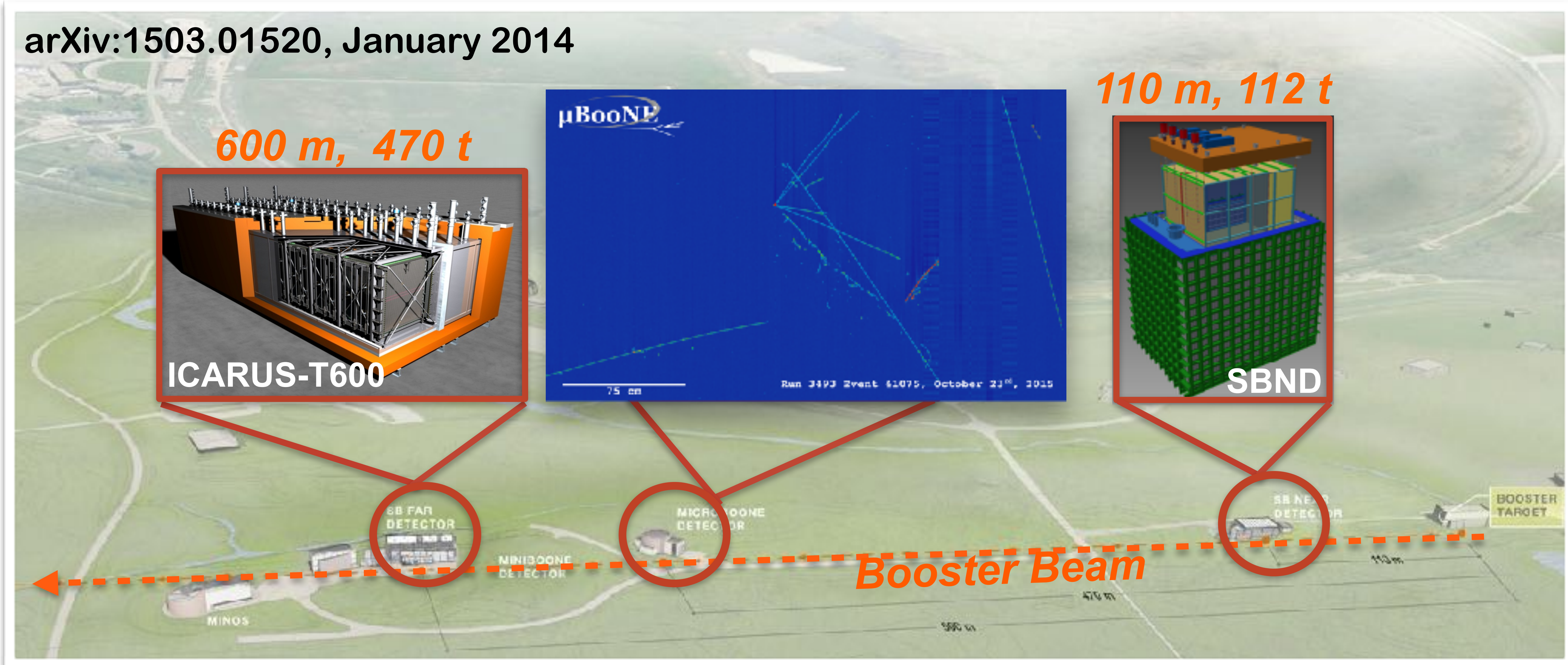
SBN: the Short Baseline Neutrino program



SBN program:

- The <u>MicroBooNE</u> now-running detector

SBN: the Short Baseline Neutrino program



SBN program:

- The **MicroBooNE** now-running detector to be joined in 2018 by two additional LAr-TPC detectors at different baselines
- the **SBND** detector and
- the **ICARUS-T600** detector

forming a **LAr TPC trio** for the SBN **neutrino oscillation** program

Fermilab – Neutrino beams

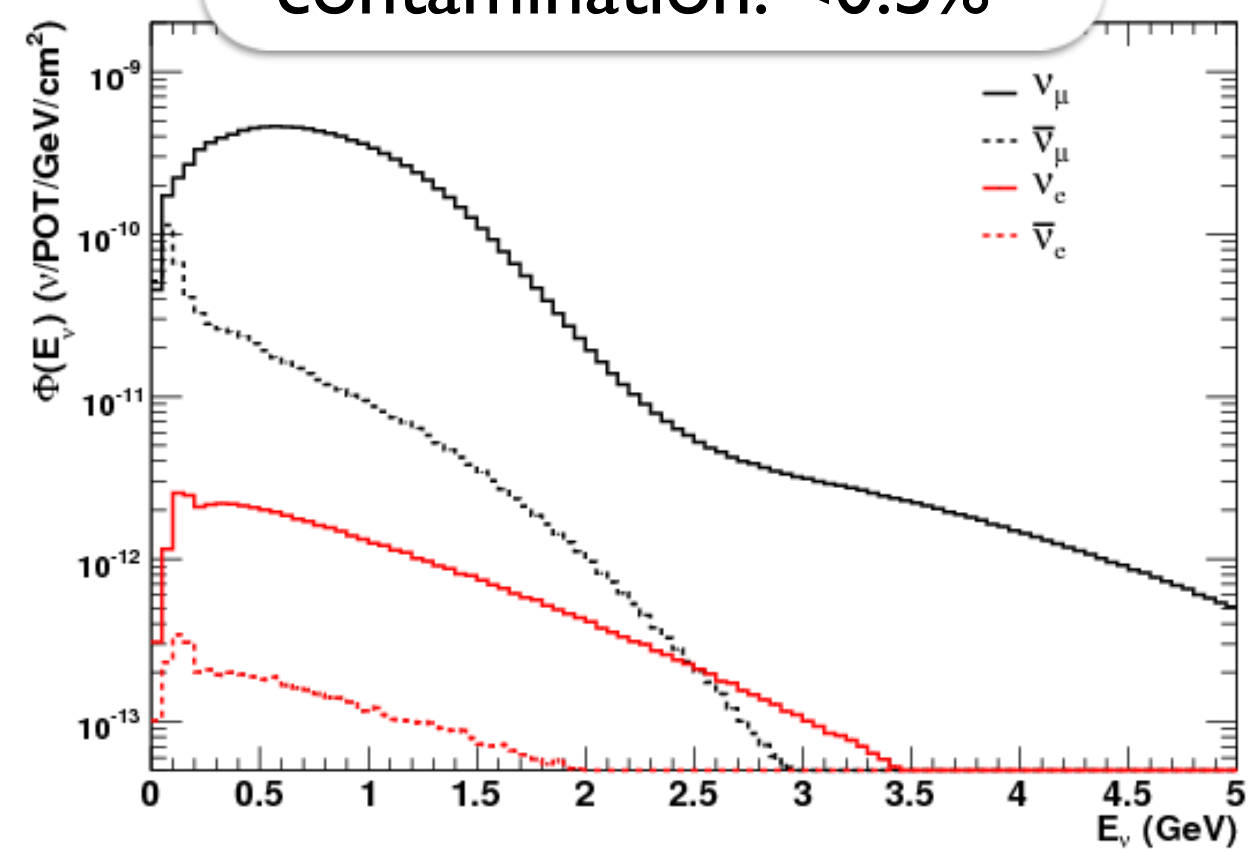
Booster Neutrino Beam (BNB)

Fermilab's **low-energy** neutrino beam:

$\langle E_\nu \rangle \approx 700$ MeV

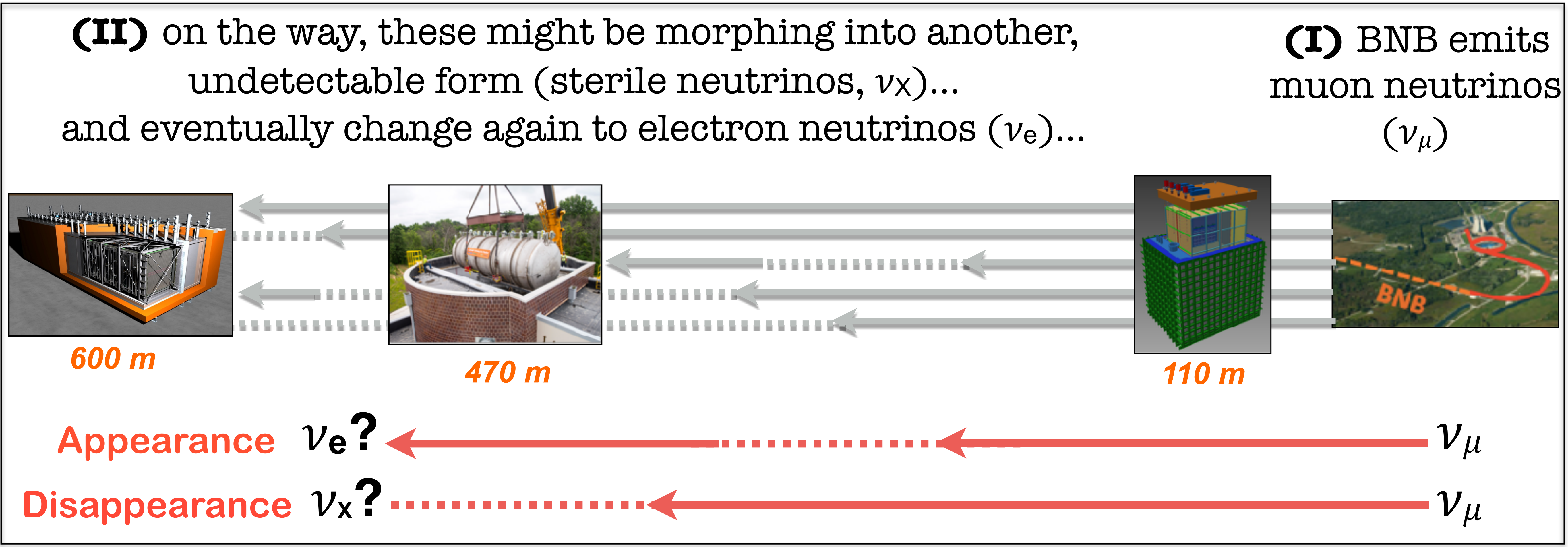
Booster - 8 GeV protons

Small electron neutrino contamination: <0.5%



- Beam of mostly muon neutrinos
- Search for flavor ν_μ disappearance and ν_e appearance
- BNB stably running for a decade (well characterized)
- Anomalies exist here (MiniBooNE)

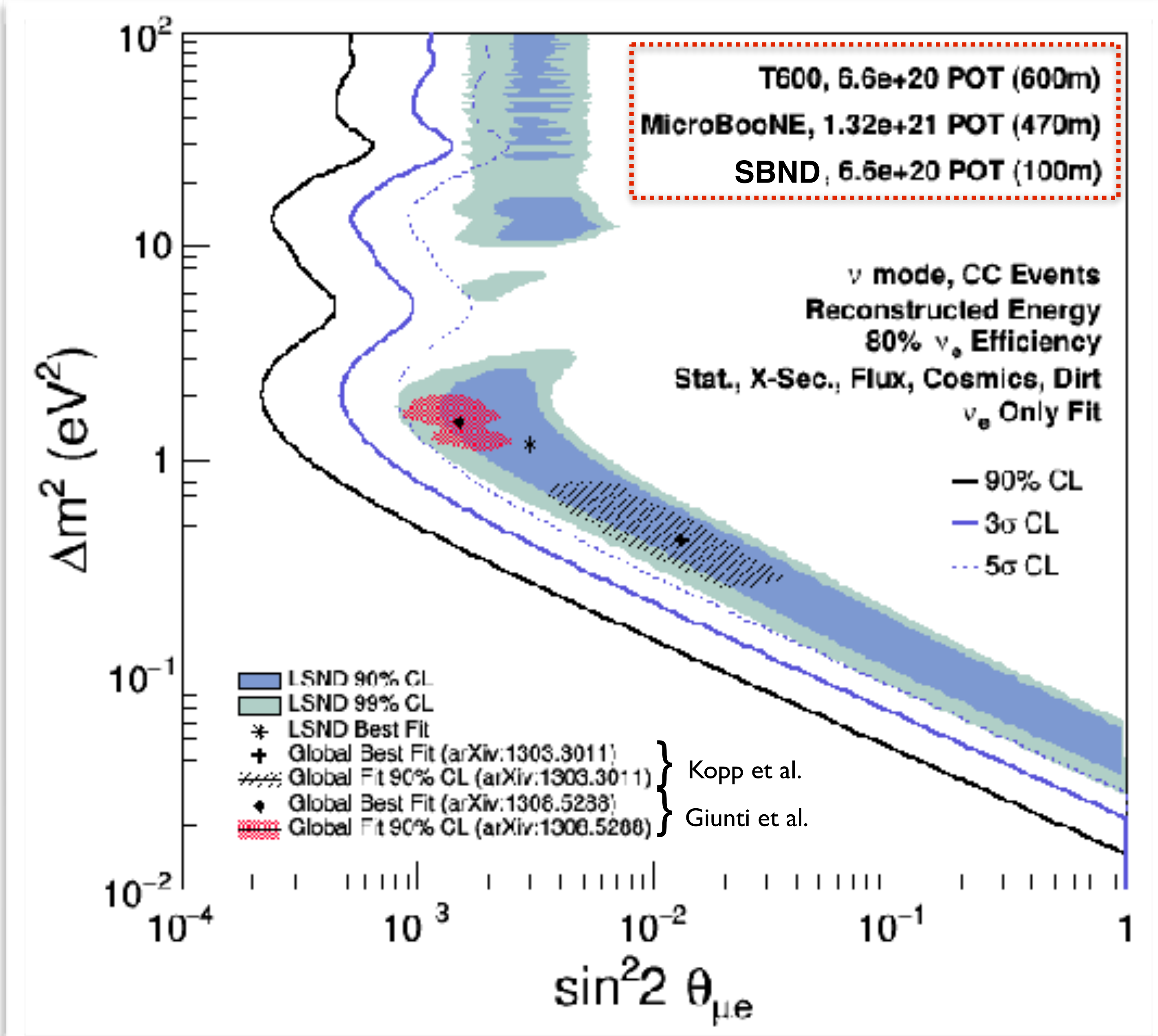
The search for the forth neutrino in SBN



Having multiple detectors allows simultaneous searches for oscillations in **appearance and disappearance** channels, a very important constraint for interpreting the experimental observations.

Physics reach of the SBN Program

$\nu_\mu \rightarrow \nu_e$ Appearance sensitivity

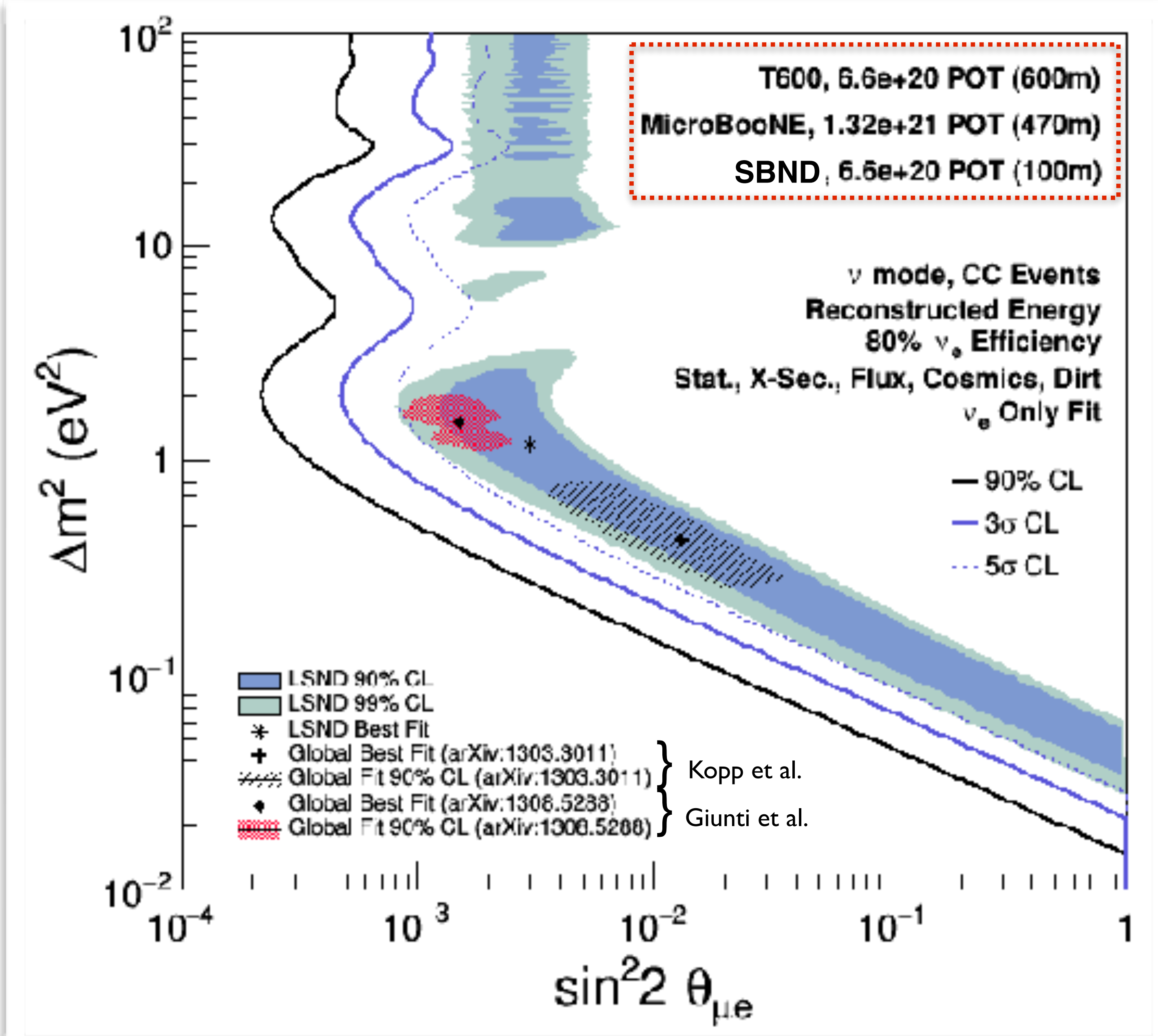


~3 years of run

A **large mass far detectors** and **a near detector of the same technology** is the key to large reductions of both statistical and systematic uncertainties (reduced to % level) in SBN oscillation searches,
allowing to address region of interest at 5σ

Physics reach of the SBN Program

$\nu_\mu \rightarrow \nu_e$ Appearance sensitivity



SBN will cover the LSND 99% C.L. allowed region with

≥ 5σ significance

(conclusive experiment w.r.t. LSND anomaly)

Not only oscillation physics: Cross Sections at the SBN

SBN detectors will provide huge data sets of ν-Ar interactions from the **BNB on-axis and the NuMI off-axis** fluxes

- Large samples in MicroBooNE are coming!
- SBND will record **~1.5 million** ν_μ **CC** and **~12,000** ν_e **CC interactions** per year*
- MicroBooNE and T600 sit in the **NuMI beam** far off-axis. ~100k NuMI off-axis events in T600 per year

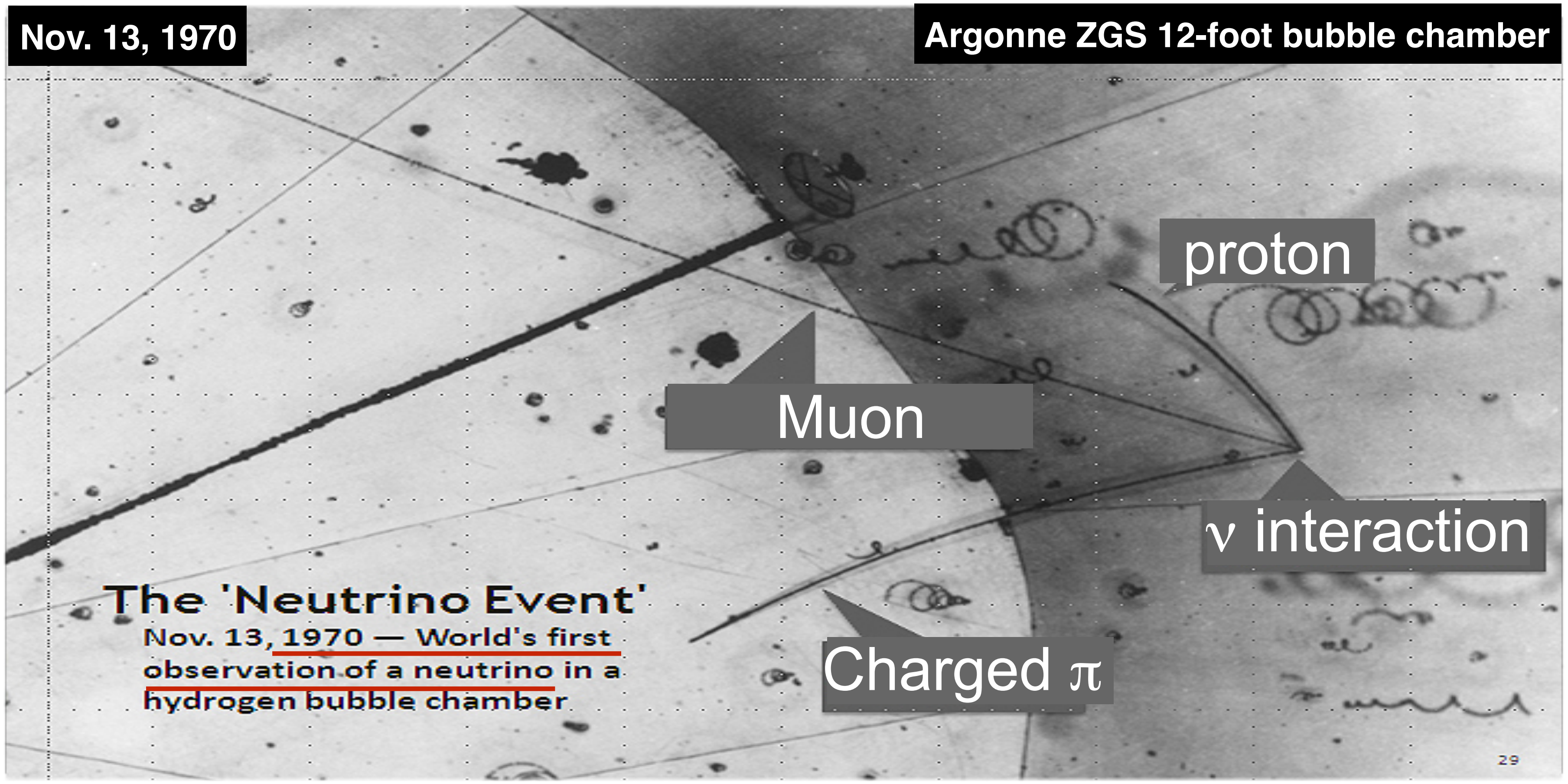
*only existing GeV neutrino-Ar scattering data are ~6000 events from ArgoNeuT (NuMI beam, 3 GeV peak energy)

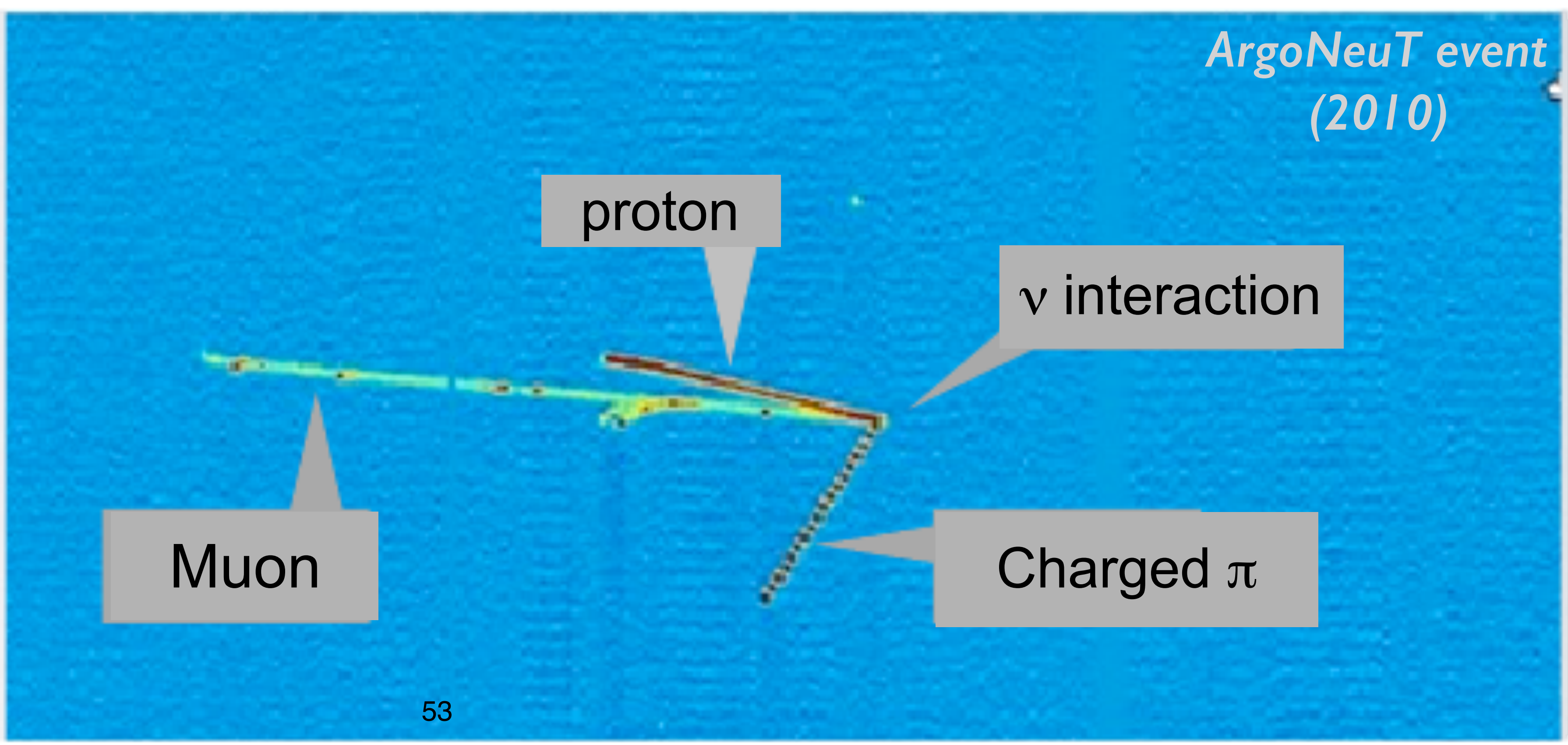
U.S. future Accelerator Neutrino Physics: **LAr TPC Technology**

- The future U.S. accelerator neutrino program is based on the **Liquid Argon Time Projection Chamber (LAr TPC)** technology.

- LArTPC offers the ability to measure interactions of neutrinos and other particles in real time with sub-millimeter position resolution, allowing for
    - **track reconstruction**
    - **particle identification and**
    - **electron/gamma separation**

  far beyond that offered by any other neutrino detection method.



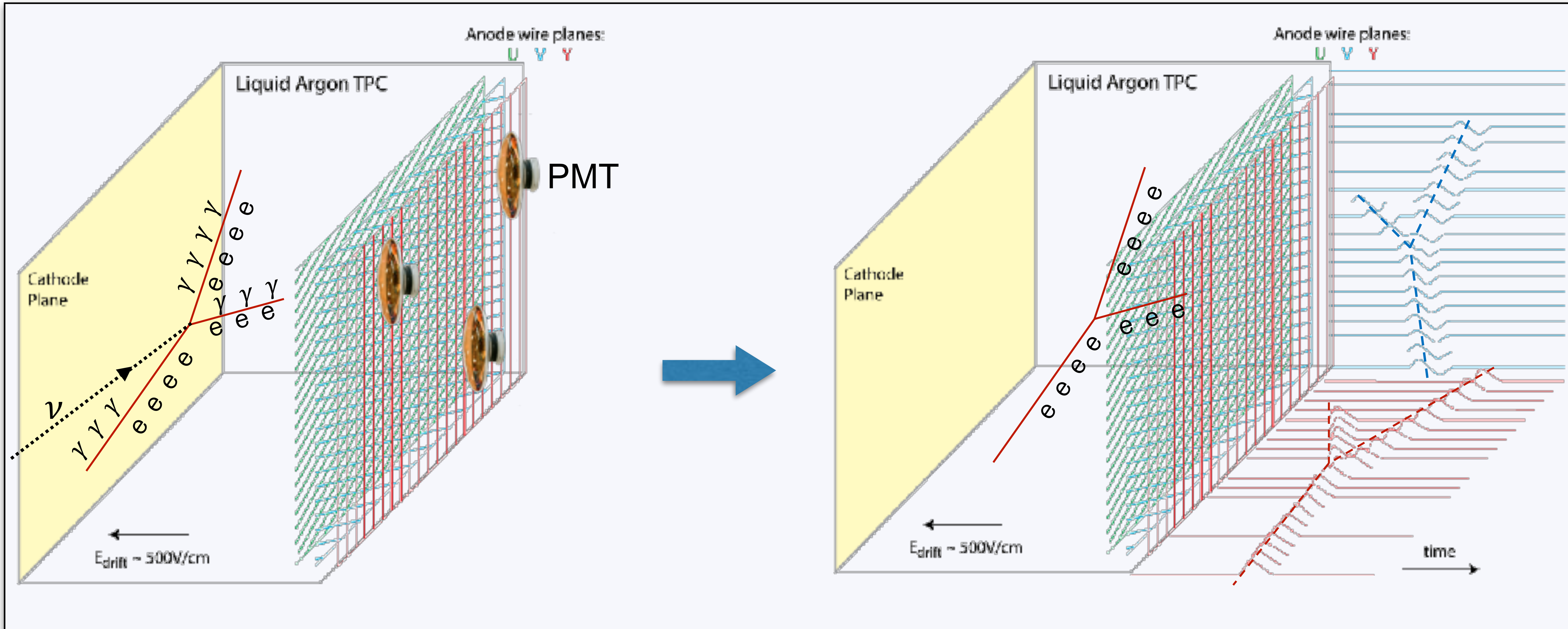


Why **Liquid Argon Time Projection Chamber**?

LAr TPC: Bubble chamber quality of data with added full calorimetry

ArgoNeuT produced physics results with a "table-top" size experiment [240 Kg LArTPC] - Neutrino cross sections, nuclear effects in neutrino-Ar scattering

LArTPC at work



Charged particles in LAr produce free ionization electrons and scintillation light

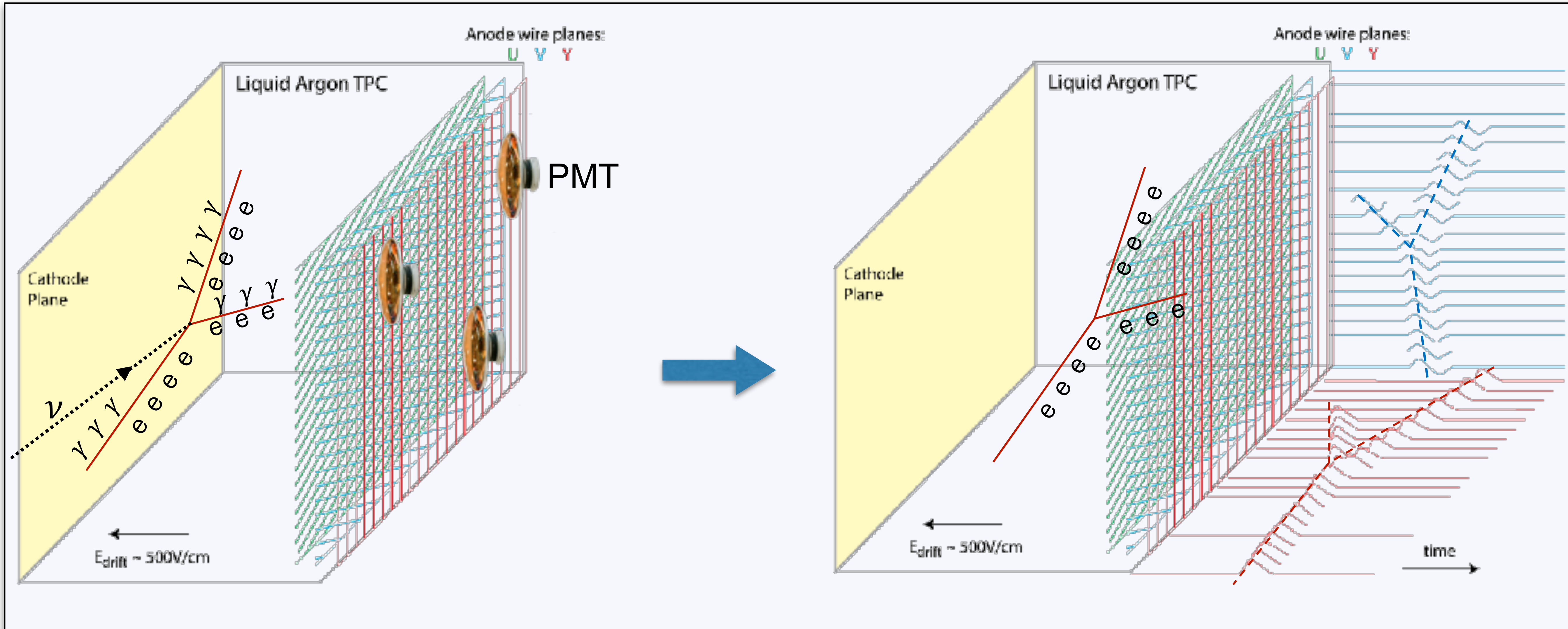
Ionization charge drifts in a uniform electric field towards the readout wire-planes

VUV photons propagate and are shifted into VIS photons

Digitized signals from the wires are collected [time of the wire pulses gives the drift coordinate of the track and amplitude gives the deposited charge].

Scintillation light signals from PMTs give event timing (t_0)

LArTPC at work



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- Multiple 2D and the 3D reconstruction of charged particles tracks $\Rightarrow$ **imaging**
- Total charge proportional to the deposited Energy $\Rightarrow$ **calorimetry**
- dE/dx along the track $\Rightarrow$ **Particle Identification**

Scintillation light signals from PMTs give event timing (t_0)

LAr TPC - scalability

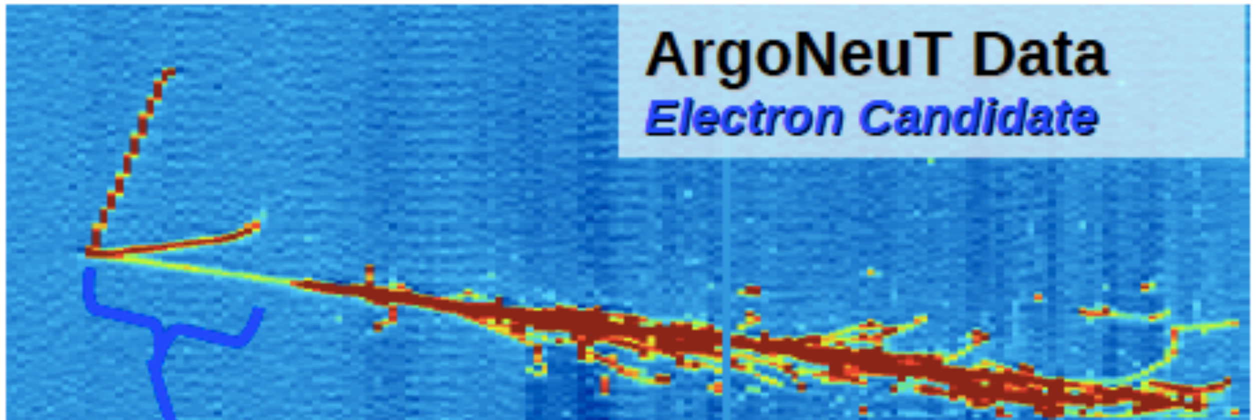
- One of the attractive aspects of this technology is we don't need to instrument the entire volume. Just drift liberated ionization over to anode plane

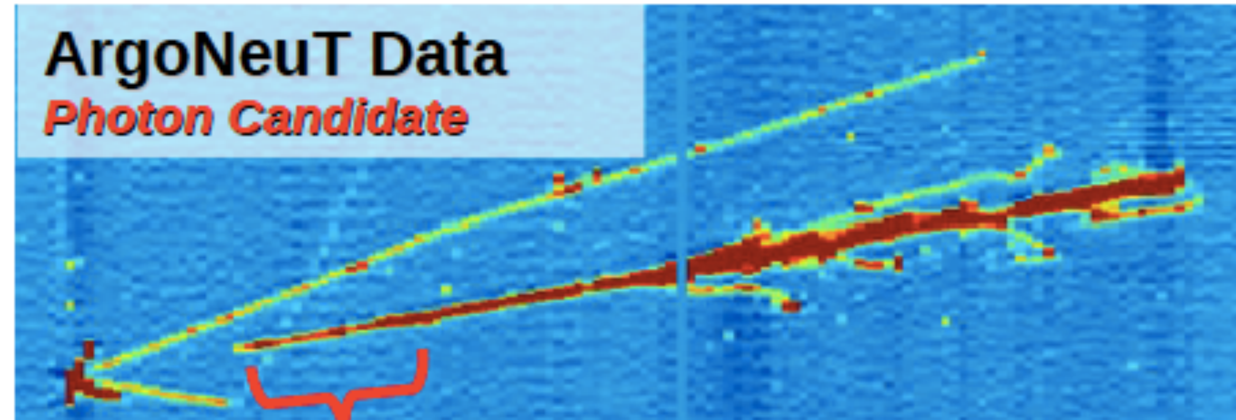
- This allows us to scale the detector to very large sizes

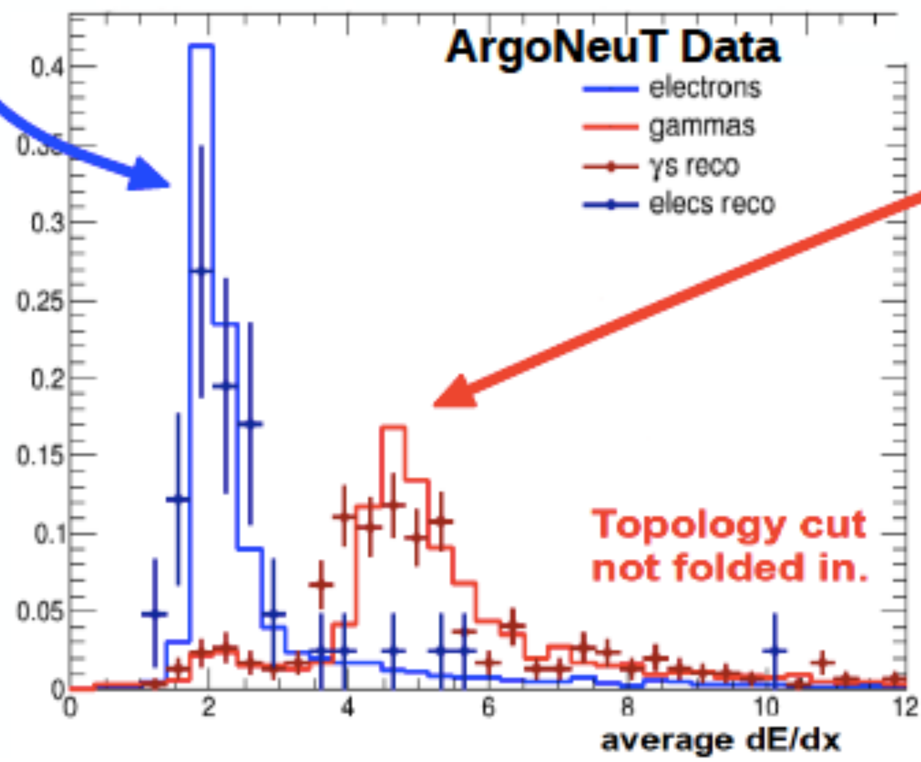
ICARUS T600 LAr TPC detector
(470 t active mass)

NB: The longer the drift length, the higher the demands on LAr purity and high-voltage capability.

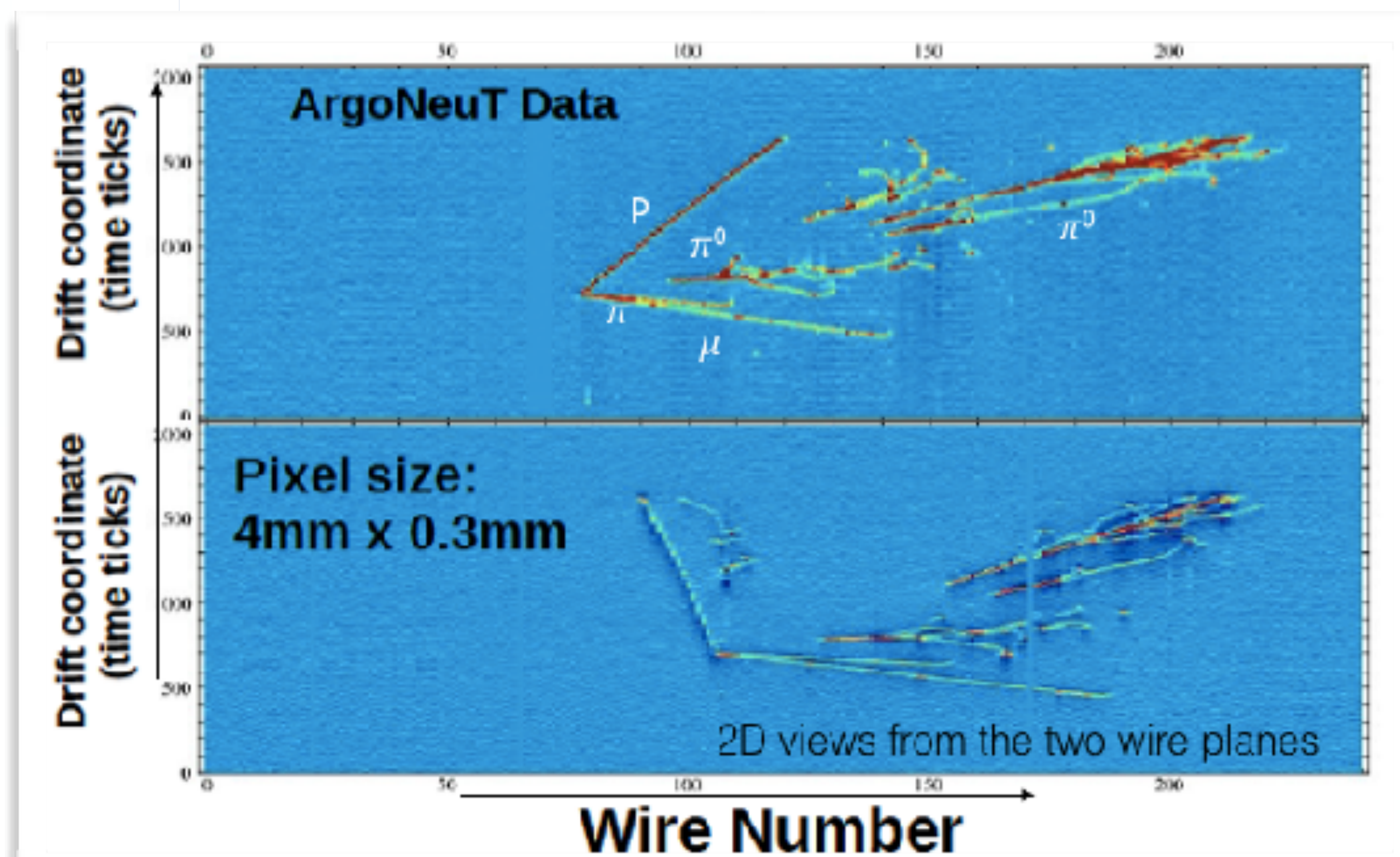
LAr TPC - Electron-γ separation







Analyzing topology and dE/dx



LAr TPC offers incredible fine tracking along with electron/photon separation

LAr TPC - Exclusive topologies & Nuclear Effects

LAr TPC detectors, provide *full 3D imaging, precise calorimetric energy reconstruction and efficient particle identification* allow for **Exclusive Topology recognition** and **Nuclear Effects exploration** from detailed studies of the hadronic part of the final states

MC independent measurement

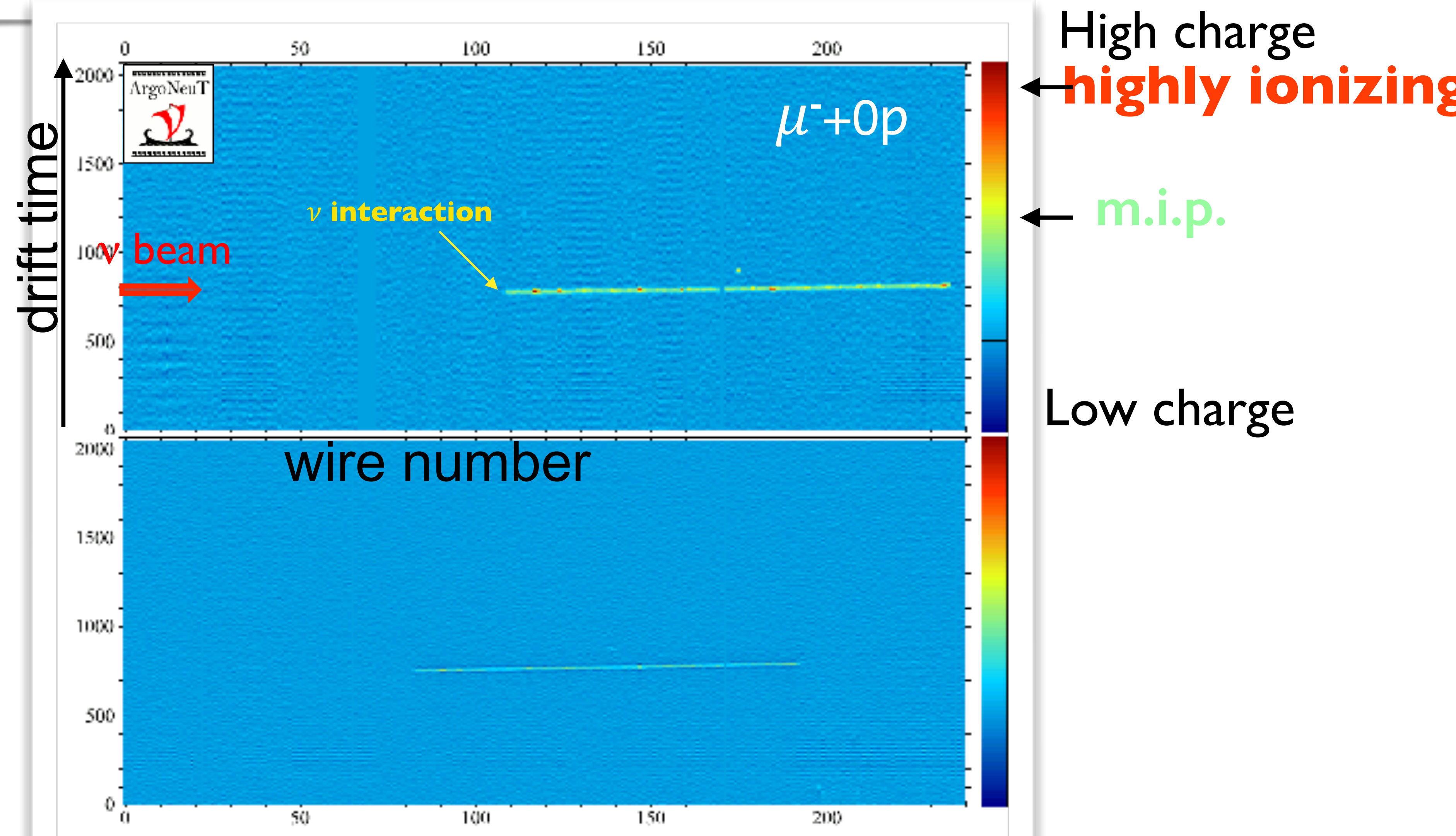
Ideal detector for Few-GeV ν scattering measurements

Low proton energy threshold

(21 MeV Kinetic energy - ArgoNeuT)

⇩

Neutrino energy reconstruction from all final state particles



2D views from the two wire planes

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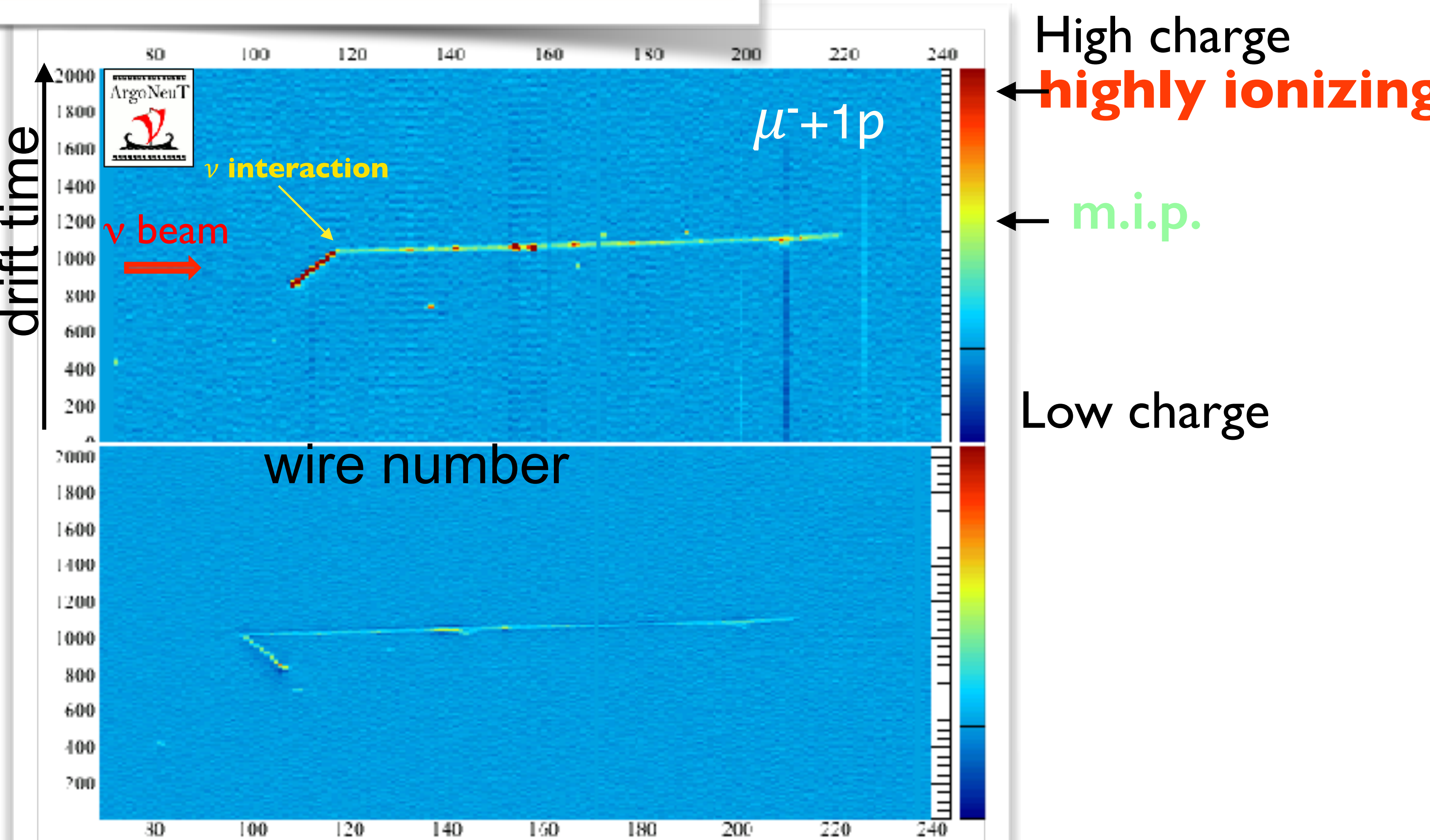

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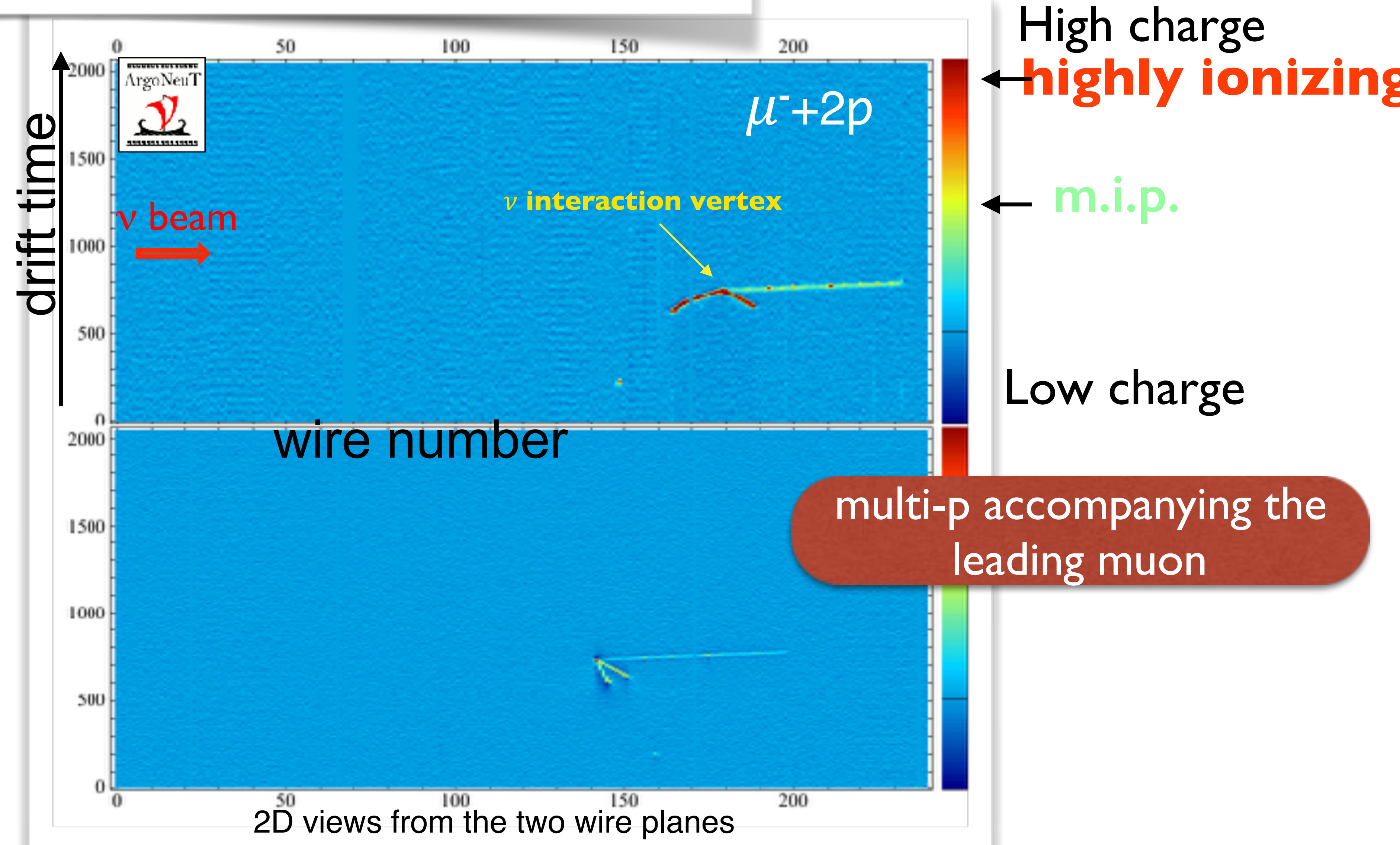
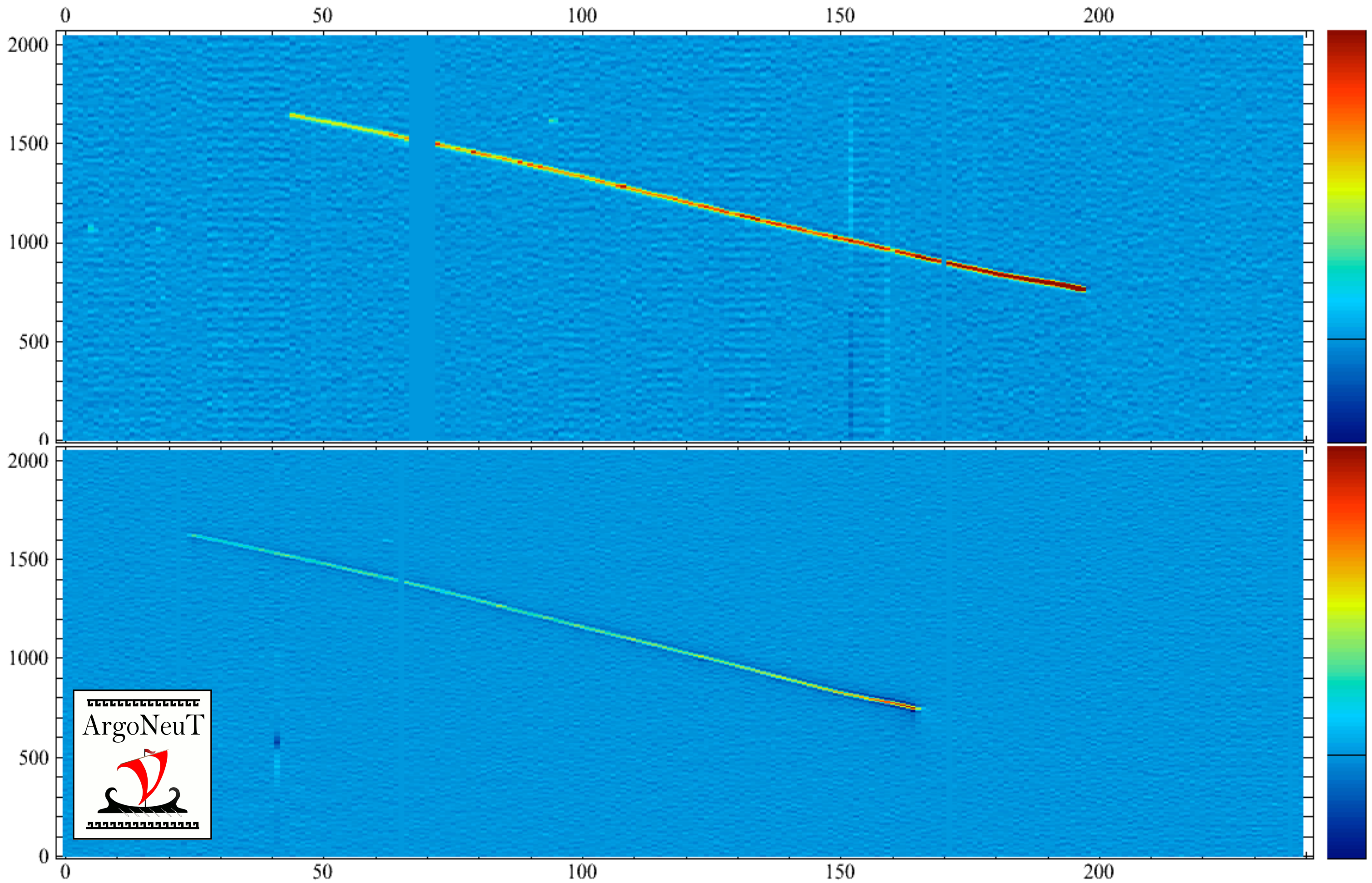
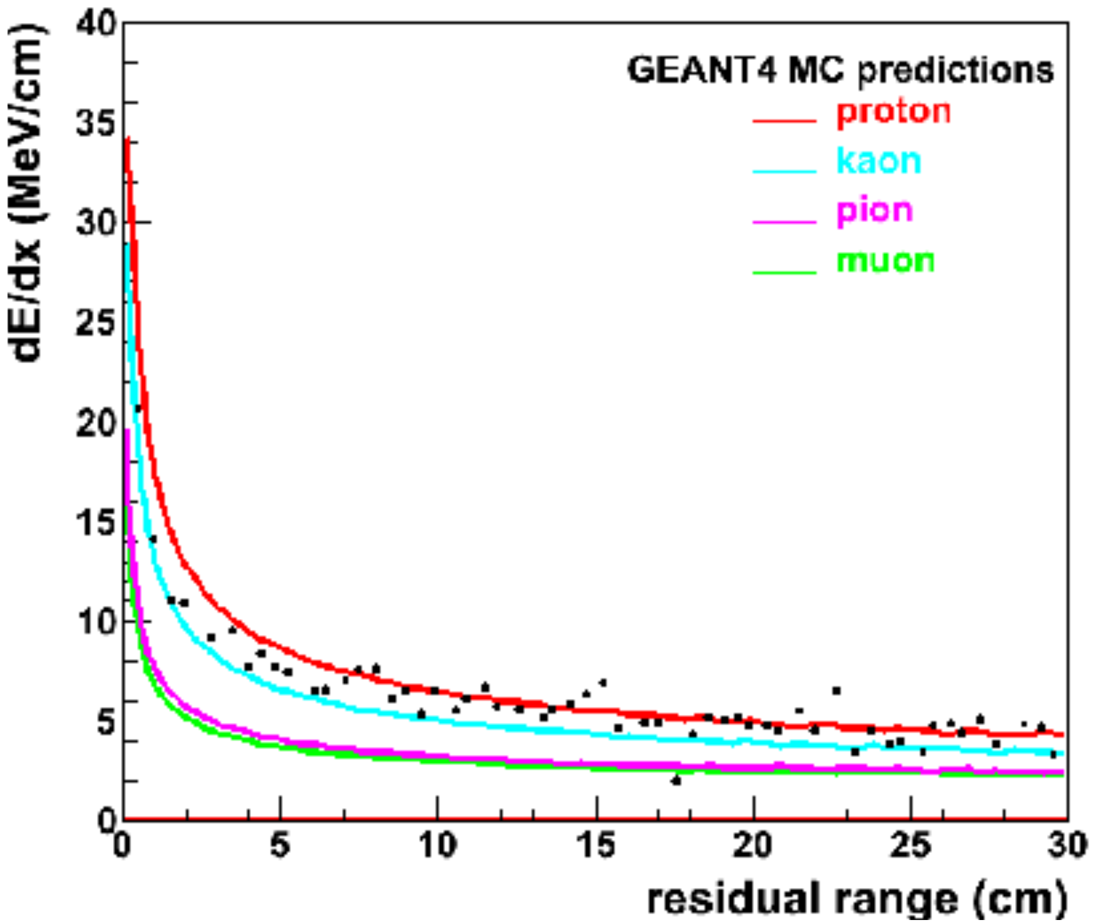


LAr TPC - Particle identification

- When incident particle slows down and stops in the LArTPC active volume, the energy loss as a function of the residual range (the path length to the end point of the track) is used as a powerful method for particle identification (PId).

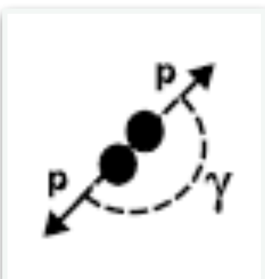
- Charged particles of different mass (or charge) have in fact different increasing stopping power at decreasing distance from the track end





LAr TPC - Sensitivity to Nuclear Effects in Neutrino Interactions

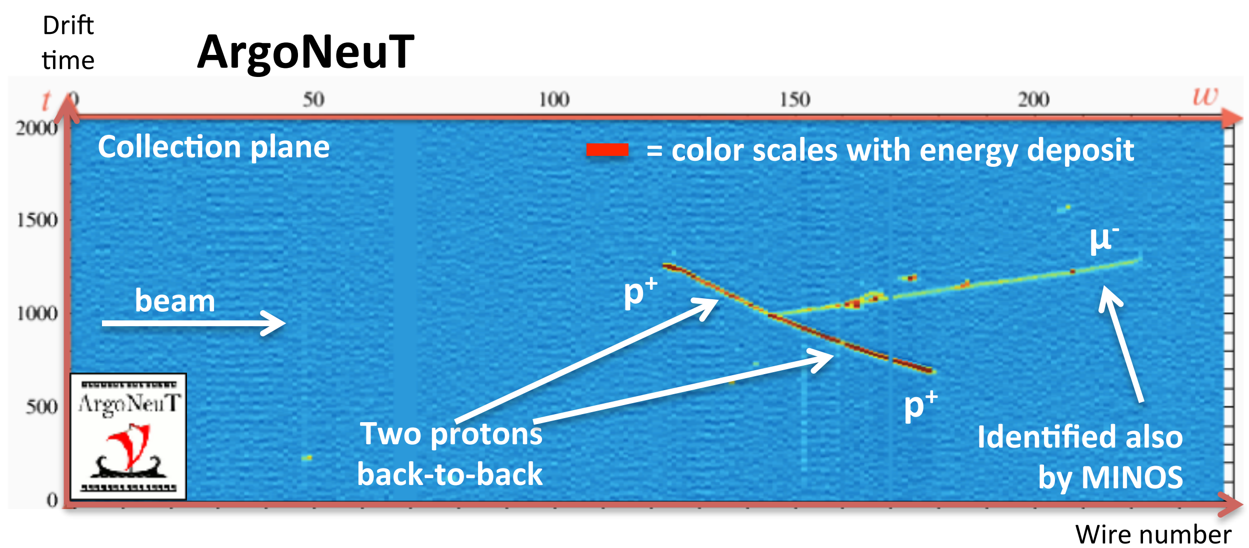
Visually the signature of these events gives the appearance of a hammer,
with the muon forming the handle and the back-to-back protons forming the head.



$\cos(\gamma) < -0.95$

"Hammer Events" in ArgoNeuT

μ+2p events



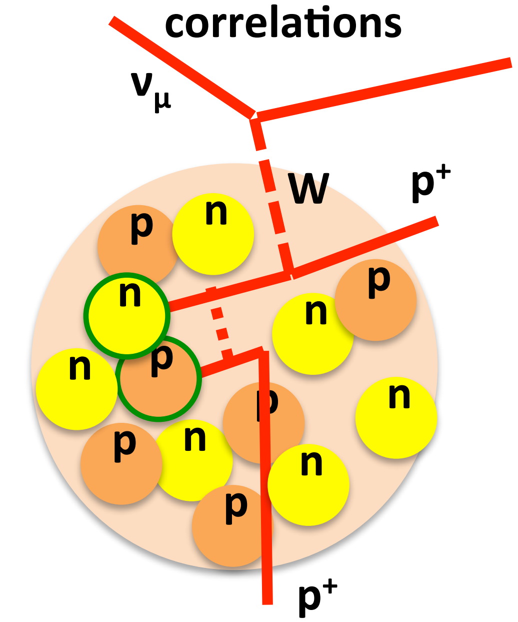
Phys. Rev. D 90, 012008 (2014)

ArgoNeuT: Hints of SRC in neutrino scattering.
Analysis of 30 μ+2p events

Why is this interesting?

- Our golden channel to study nucleon-nucleon correlations

Nucleon-nucleon correlations



Two nucleons in correlation
Means for the experimentalist:
Multi-nucleon knockout!
The pair inside the nucleus has:
large relative momentum,
small total momentum

LAr TPC - Sensitivity to Nuclear Effects in Neutrino Interactions

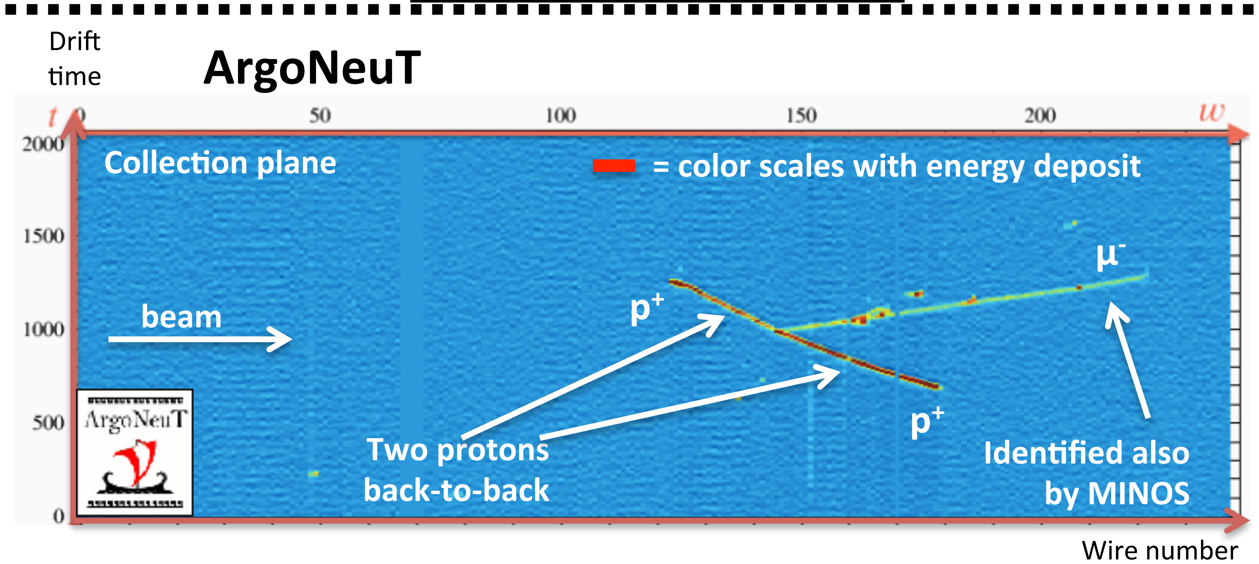
- At the BNB **CC 0 pion** (no pions in the event) is the **dominant channel**
- High statistics measurement of the ν_μ **and** ν_e **CC 0 pion events** will allow to quantify nuclear effects in neutrino-Ar scattering

μ+2p events

MicroBooNE

	$1\mu^- + 2p$
1.5×10^{19} POT	269
5×10^{19} POT	896
1×10^{20} POT	1791
2×10^{20} POT	3582
6.6×10^{20} POT	11820

SBND in 1 year:
360,000 μ+2p events



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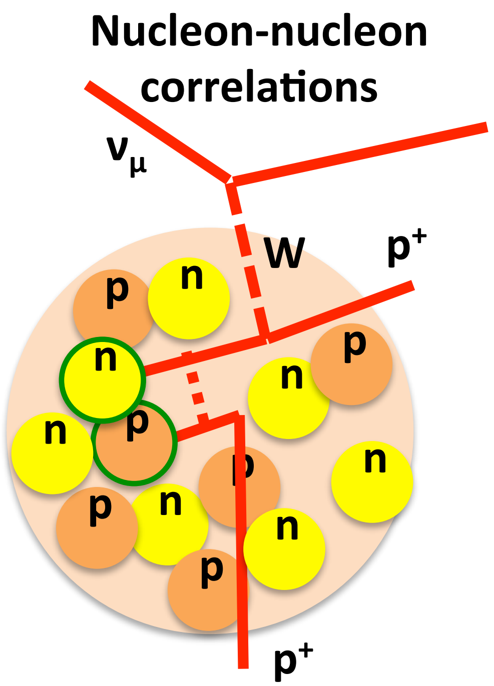

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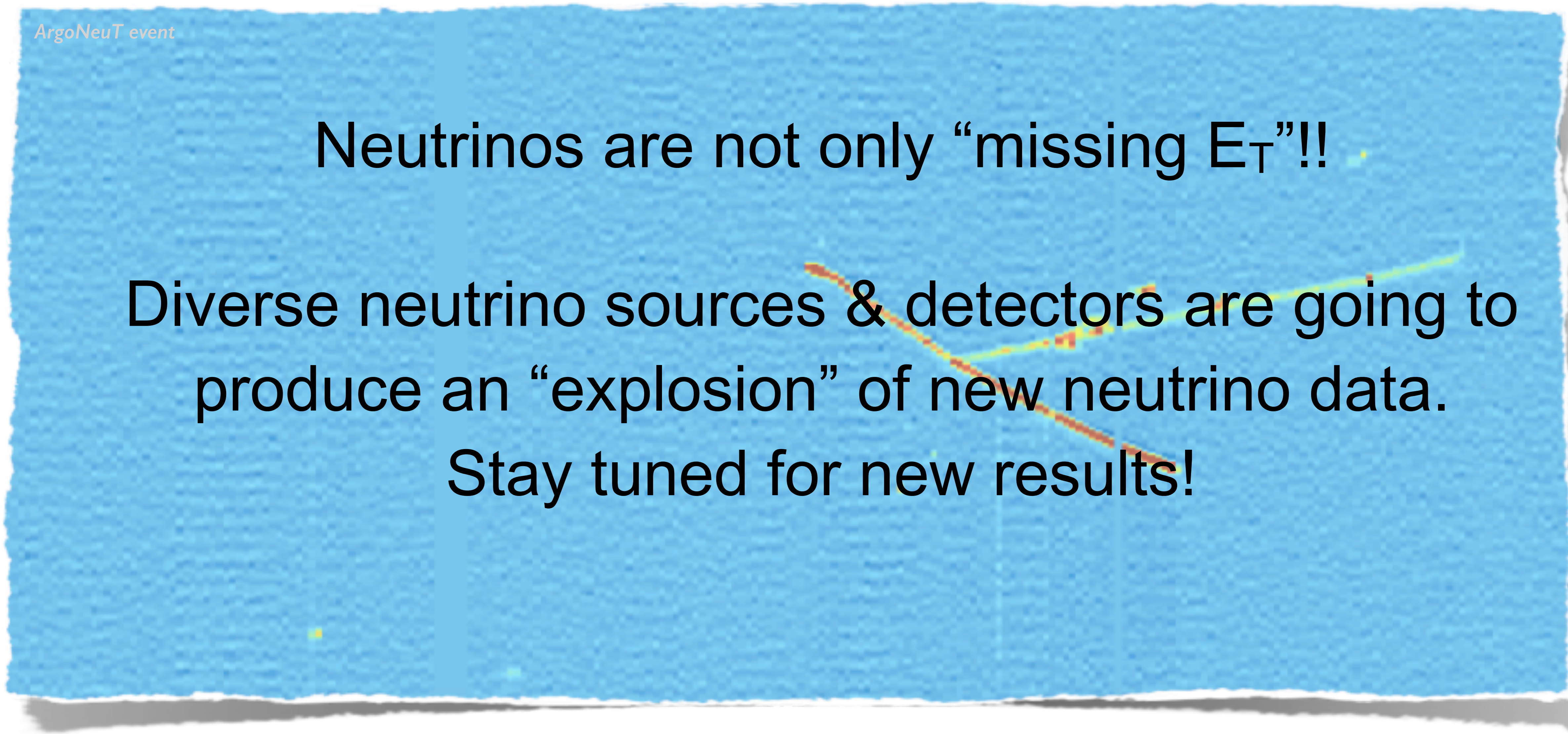
Summary: A look ahead...



Neutrinos are not only "missing E_T"!!

Diverse neutrino sources & detectors are going to produce an "explosion" of new neutrino data. Stay tuned for new results!

Studies of neutrino are fascinating...

A lot of fun ahead of us!*

*You may say I'm a dreamer. But I'm not the only one. I hope someday you'll join us!
(J. lenon)