New Technologies for Neutrino Interactions

CPAD workshop - UT Arlington, TX

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Ornella Palamara

Fermilab & Yale University, USA*

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

Outline

- Why precise **neutrino interaction** measurements are needed?
- Why different neutrino targets are needed?
- Perspectives for neutrino interactions measurements across energy scales, from MeV to GeV:
  - low energy (10-100 MeV)
  - intermediate energy (0.1-20 GeV)
- Technology challenges for moving forward
- Ongoing detector R&D, upcoming experiments and new ideas for **neutrino interaction** measurements*

With material from many colleagues - Thanks!!

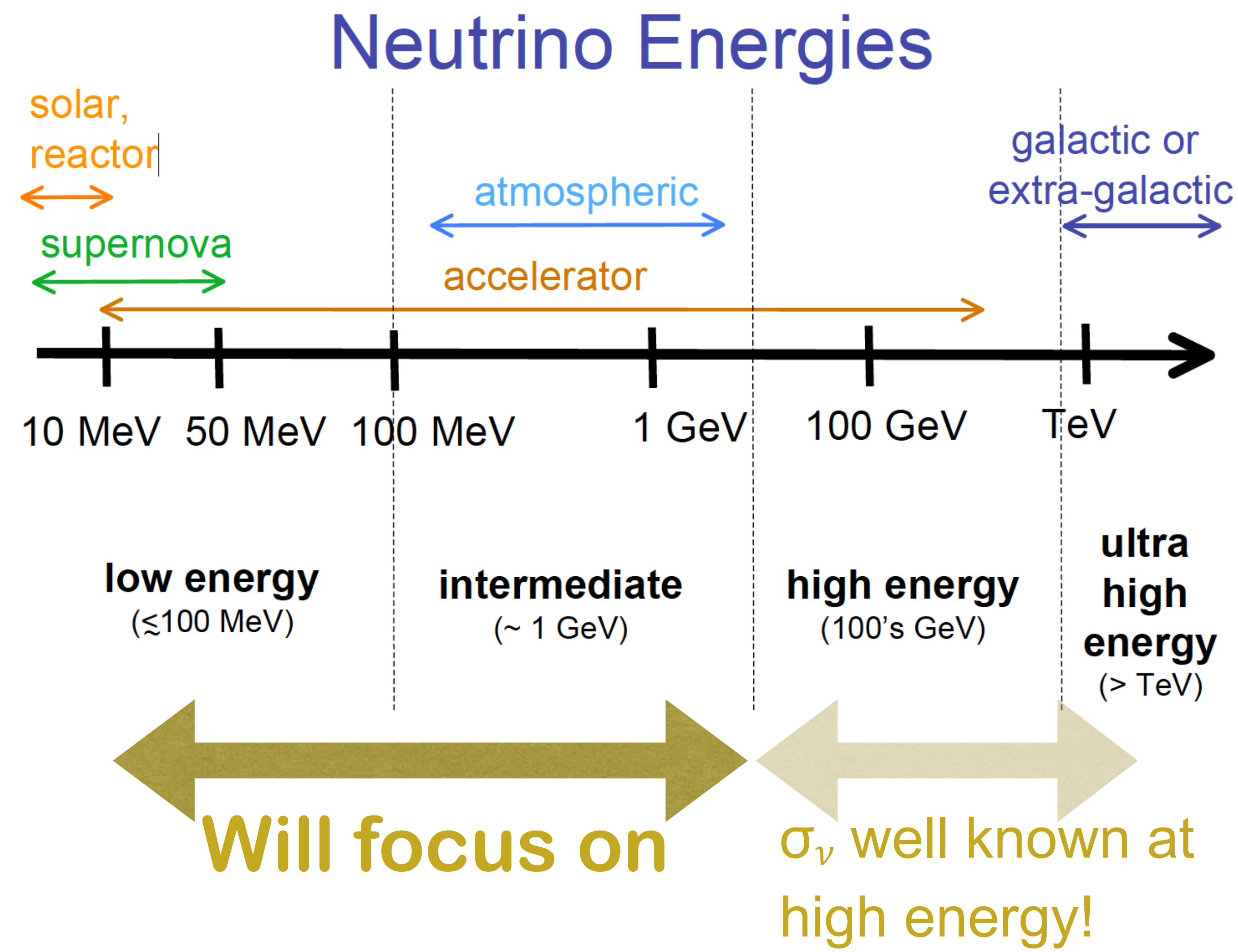
*Apologies for not covering all!

Neutrino Searches

Historically the studies of **neutrino interactions** played an important role in establish the validity of the theory of weak interactions.

ν sources

- Solar and supernova neutrinos
- Reactor neutrinos
- 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

Future of neutrino physics

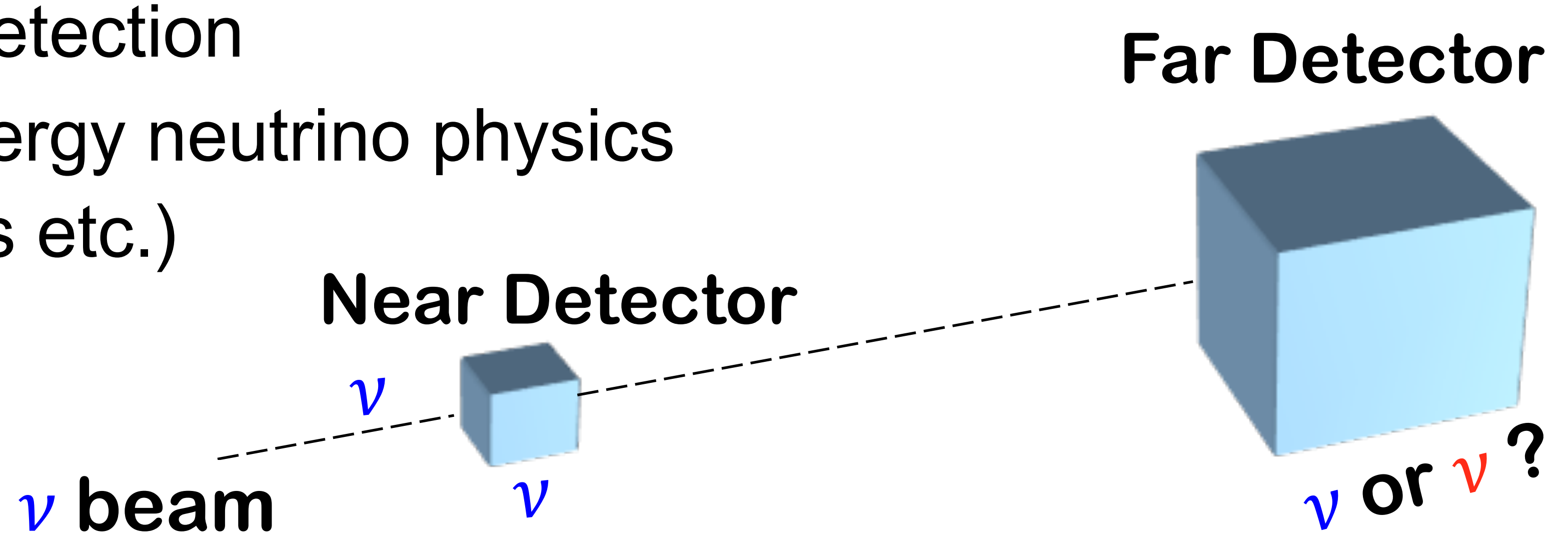
- There are some big questions about **neutrino properties** that forthcoming ν experiments will focus on:
  - what are the masses of the neutrinos?
  - are neutrinos their own anti-particles?

  β and ββ decay

  - what is the ν mass ordering?
  - do neutrinos violate CP?
  - How many ν species? Are there sterile neutrinos?

  Neutrino Oscillation Experiments

  - Supernova neutrino detection
  - Astrophysics: high energy neutrino physics (astrophysical sources etc.)



Near/Far Detector Oscillation Experiment

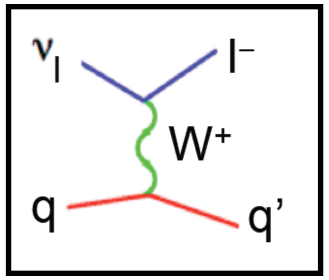
Neutrino interactions

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

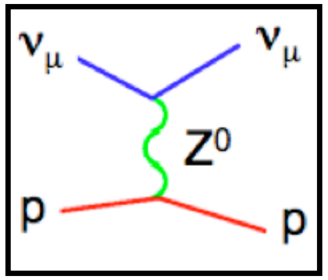
- We still need to understand a lot about **neutrino interactions** in view of **future experiments** aimed at **understanding neutrino properties**!

- **Neutrino cross section** depends on:
  - type of <u>ν interaction</u> (NC or CC)
  - <u>ν target</u> (electron, nucleus, nucleon, quark)
  - <u>ν energy</u> (MeV, GeV, or TeV)

CC



NC

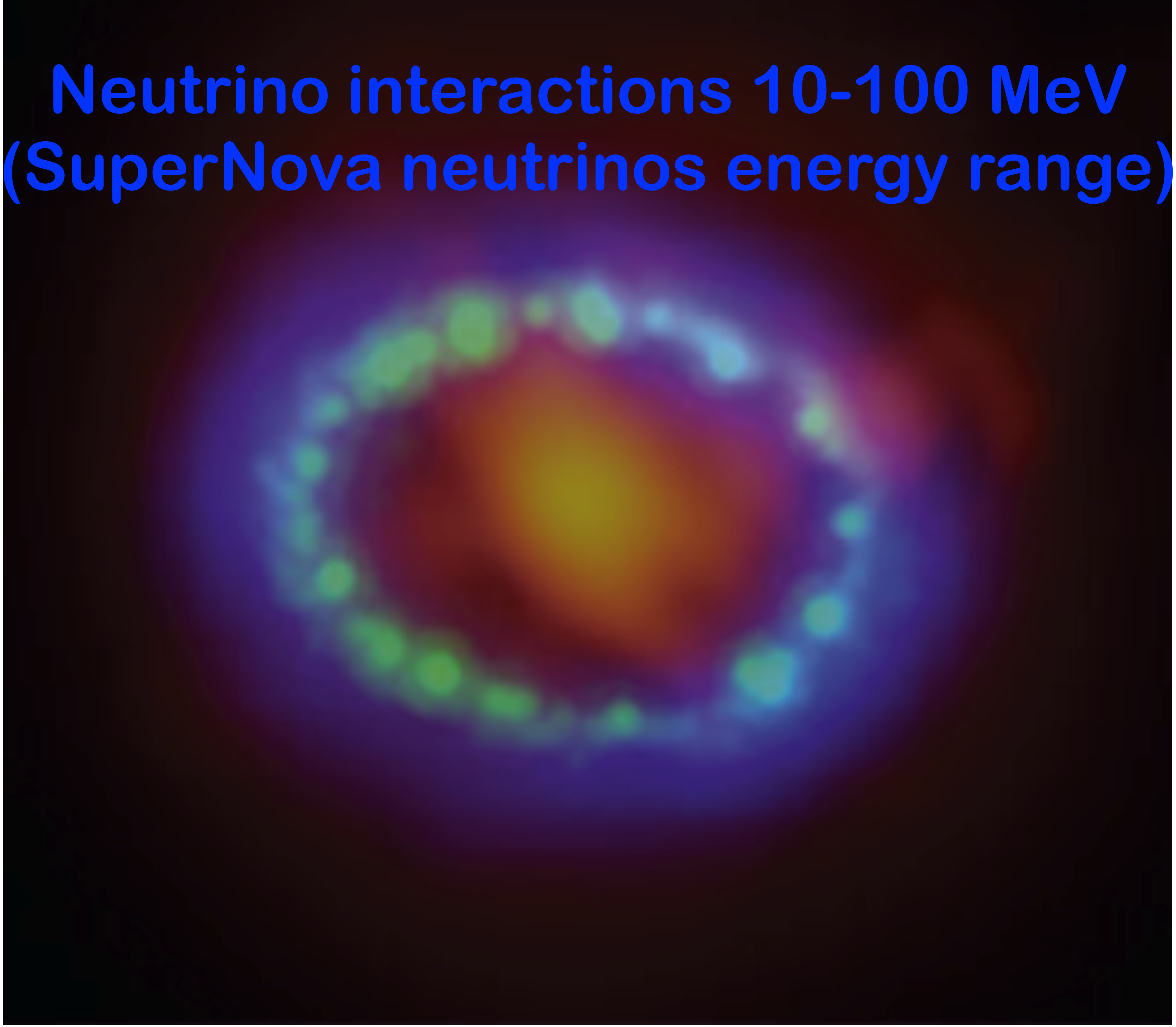


Why Precision Cross Section Measurements?

- Knowledge of **neutrino interaction cross-sections** is an important and necessary ingredient in any neutrino measurement and is an interesting study per se! (see NuInt "International Workshop on Neutrino-Nucleus Interactions in the Few-GeV Region" conference series)
- Scatter off nuclei: understand more about <u>how neutrinos interact with the nuclear environment</u> (complement e-scattering data) is very important.
- Neutrino cross-sections are a **dominant systematic** (absolute cross section uncertainties 10-15%) in oscillation experiments.
- A correct interpretation of the outcome of ν oscillation experiments requires precise understanding of ν and $\overline{\nu}$ interaction cross sections in a rather challenging energy regime.

Interest in neutrino scattering has recently increased!

Neutrino interactions 10-100 MeV
(SuperNova neutrinos energy range)

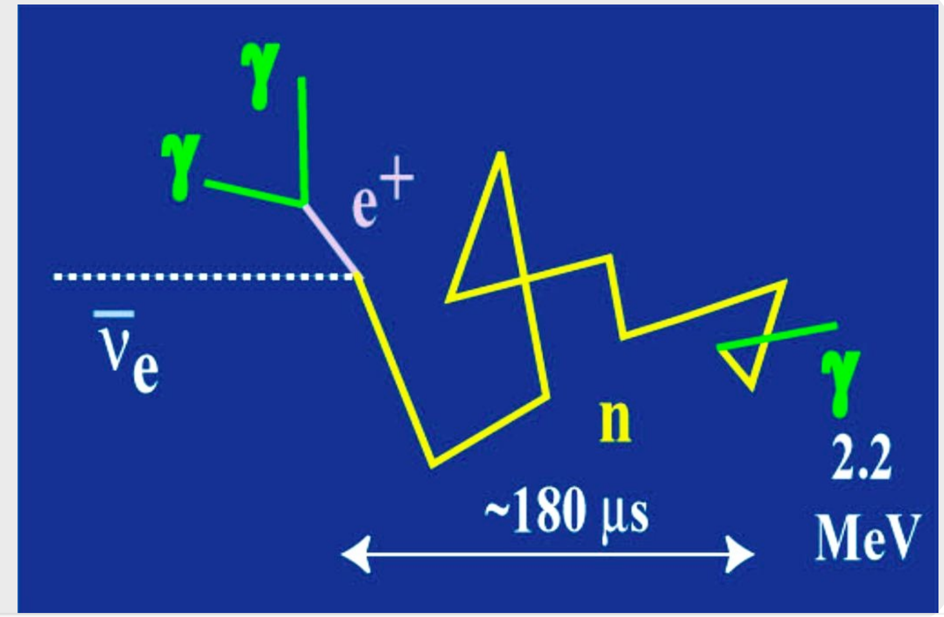


Neutrino interactions in the few-tens-of-MeV range

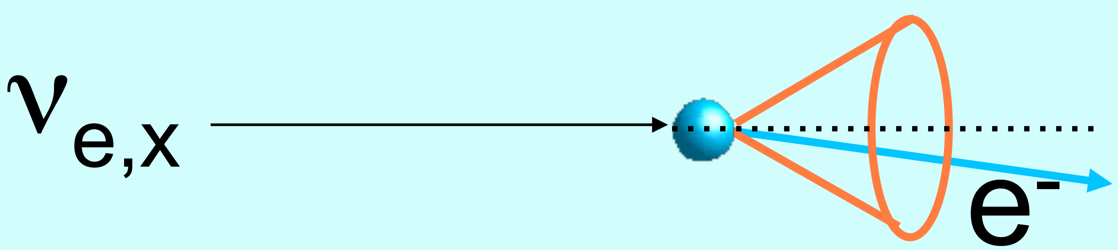
IBD - Inverse Beta Decay (CC)

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

In any detector with lots of
free protons



ES - Elastic Scattering on **atomic electrons**



$$\nu_{e,x} + e^- \rightarrow \nu_{e,x} + \boxed{e^-}$$

(useful for pointing)

Interactions on **nuclei**:

ABS - ν_e CC Absorption

$$\nu_e + (N,Z) \rightarrow (N-1, Z+1)^* + e^-$$

$$\bar{\nu}_e + (N, Z) \rightarrow (N+1, Z-1)^* + e^+$$

NE - ν_x NC Nuclear Excitation

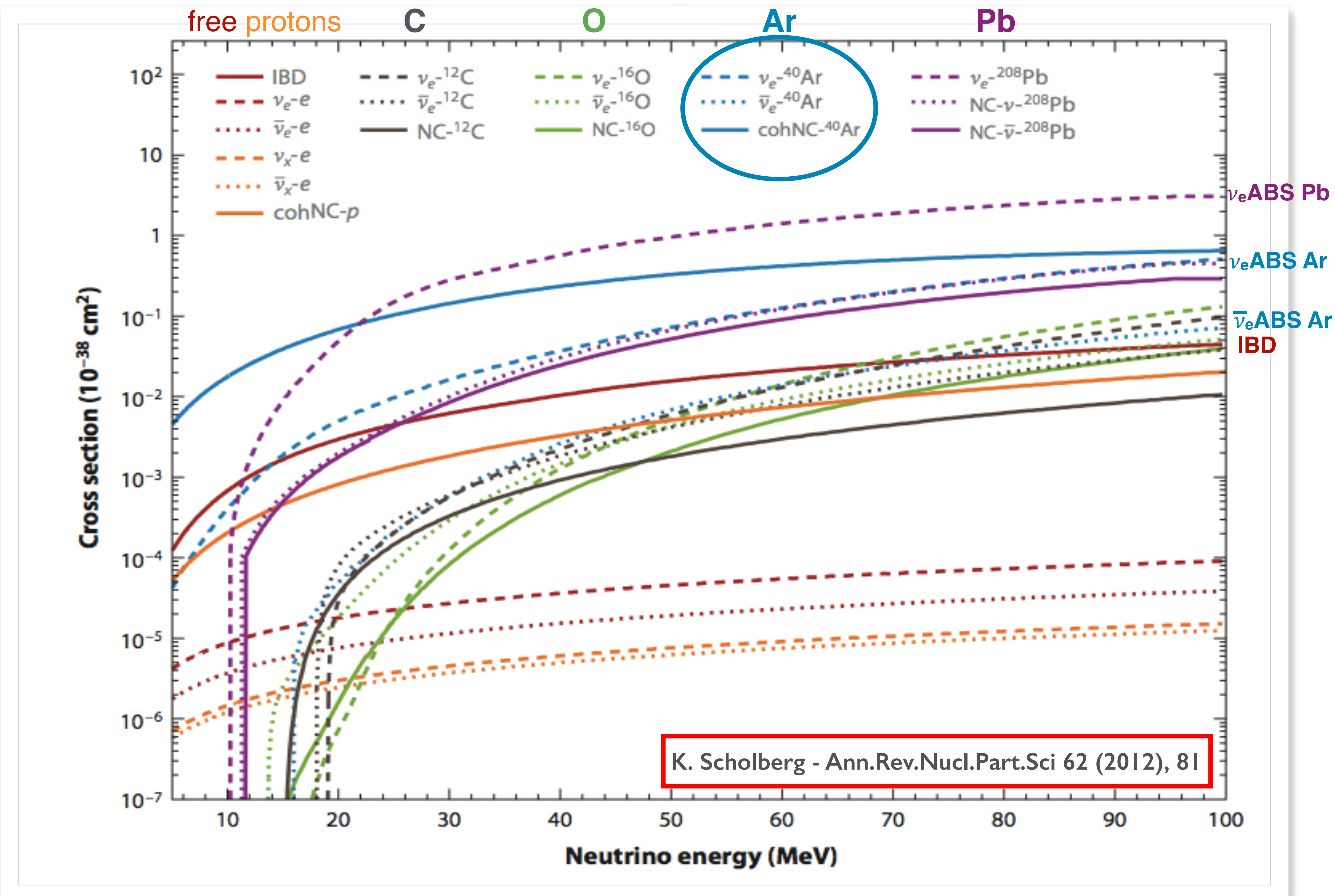
$$\nu_x + (A,Z) \rightarrow (A,Z)^* + \nu_x$$

$$\hookrightarrow (A,Z) + \gamma$$

Coh - ν_x NC Coherent Scattering

+ NC coherent scattering

The Cross Section Bible



Ar target - ν Cross Section

in the [10-100] MeV ν-energy range

- *NC+CC* **E**lastic **S**cattering (on e$^-$):

$$\boxed{\nu + e \rightarrow \nu' + e'}$$

  - Xsect linear increase with E_ν.
  - e.g. @ E_ν =20 MeV ↔ $\sigma_{ES} = Z_{Ar} \times 2 \cdot 10^{-43}$ cm^2

- *CC* ν_e **ABS**orption (on Ar):

$$\boxed{\nu_e + Ar \rightarrow K^* + e^-}$$

  - Xsect ~quadratic increase with E_ν.
  - e.g @ E_ν =20 MeV ↔ $\sigma_{abs} = 6 \cdot 10^{-41}$ cm^2

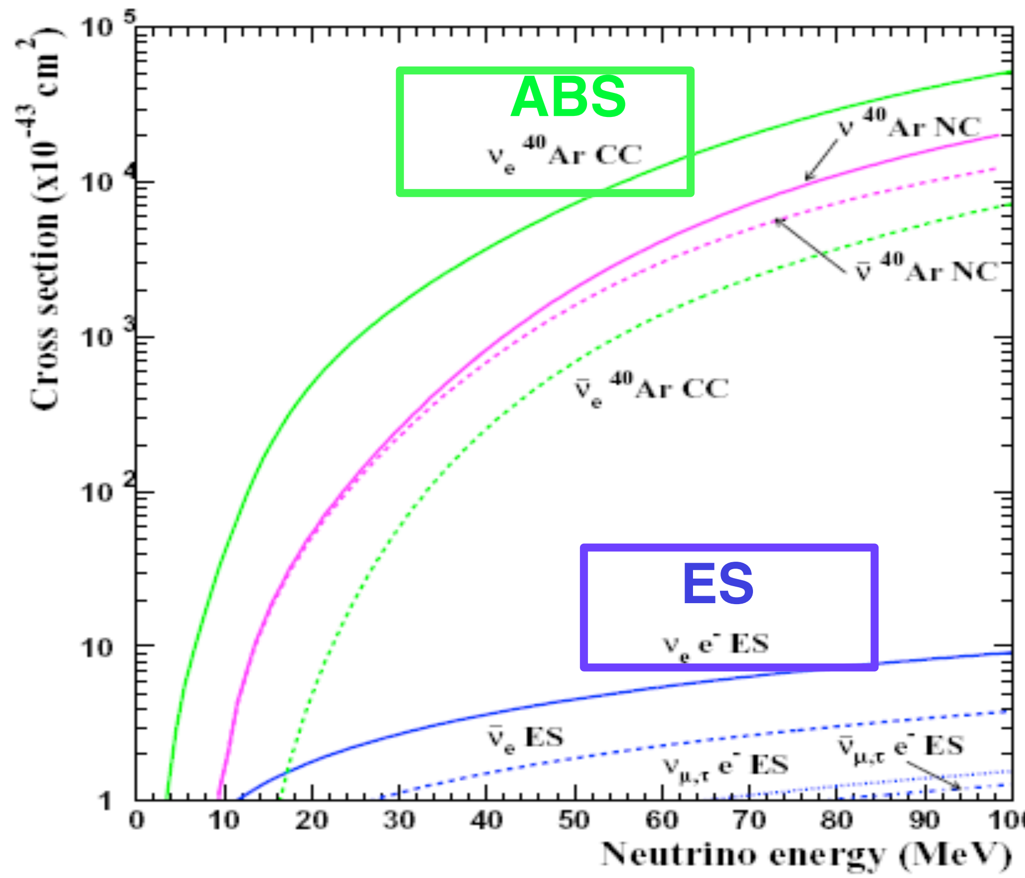


Figure 3: Neutrino cross sections relevant to the supernovae detection with a liquid Argon TPC detector.

Kolbe, Langanke, Martinez-Pinedo

- *CC* anti-ν_e **ABS**orption (on Ar): $(\bar{\nu}_e + Ar \rightarrow Cl^* + e^+)$

depressed by ***high Q-value*** wrt *CC* **ABS** for ν_e.

- *NC* **N**uclear **E**xcitation (on Ar): $\boxed{\nu + Ar \rightarrow \nu' + Ar^*}$

difficult for detection.

theoretical calculations

LAr supernova neutrino detectors

- Existing and proposed supernova-neutrino detectors worldwide are primarily sensitive to electron-antineutrinos (IMB & Kamiokande both observed SN ν's with this reaction channel)
- LAr detectors (ex. DUNE) have sensitivity to the **electron-neutrino flavor component**, which carries unique physics and astrophysics information

The Experimental challenge of SN Neutrino Detection in LArTPC

$$\nu_e + Ar \rightarrow K^* + \boxed{e^-}$$

One "leading ~10 wire electron" track

$\hookrightarrow \gamma_{(s)}$

Compton $\hookrightarrow \boxed{e_{(s)}}$ "*energy blip*"

A number of "1-2 wires electrons" localized en. deposits (spots) from de-excitation gammas

Measurement of the **Ar ABS XSect** Experimental validation of the existing theoretical calculations	Implementation of detailed MC generator for Ar in the 10-100 MeV ν en.range Cascade of de-excitation γ's from Ar-K* Nuclear transitions	Event **Detection & Identification & Reconstruction** in LAr TPC and extraction from Background

SN ν_e (ABS) "signature" in LArTPC

Topology somehow similar to what is expected from SN-ν_e ABS reactions!

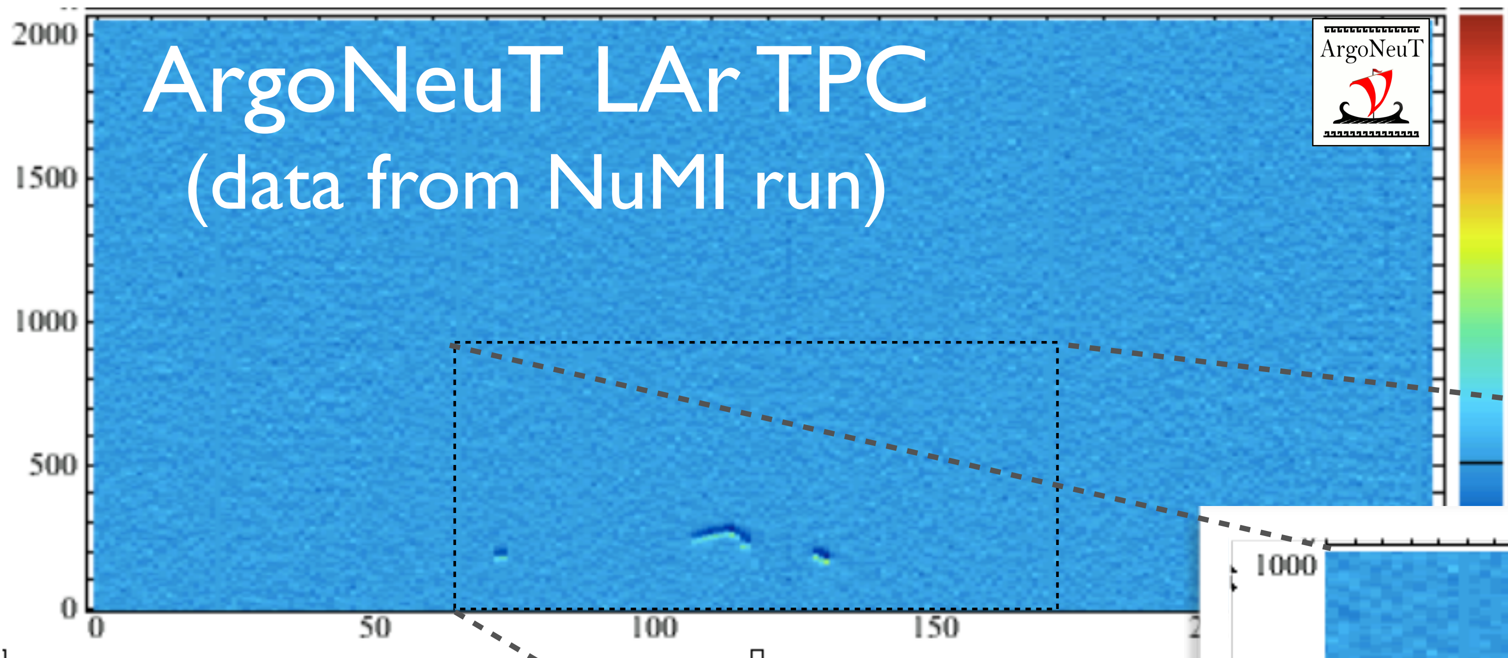
"leading trk"

$$\nu_e + Ar \rightarrow K^* + e^-$$

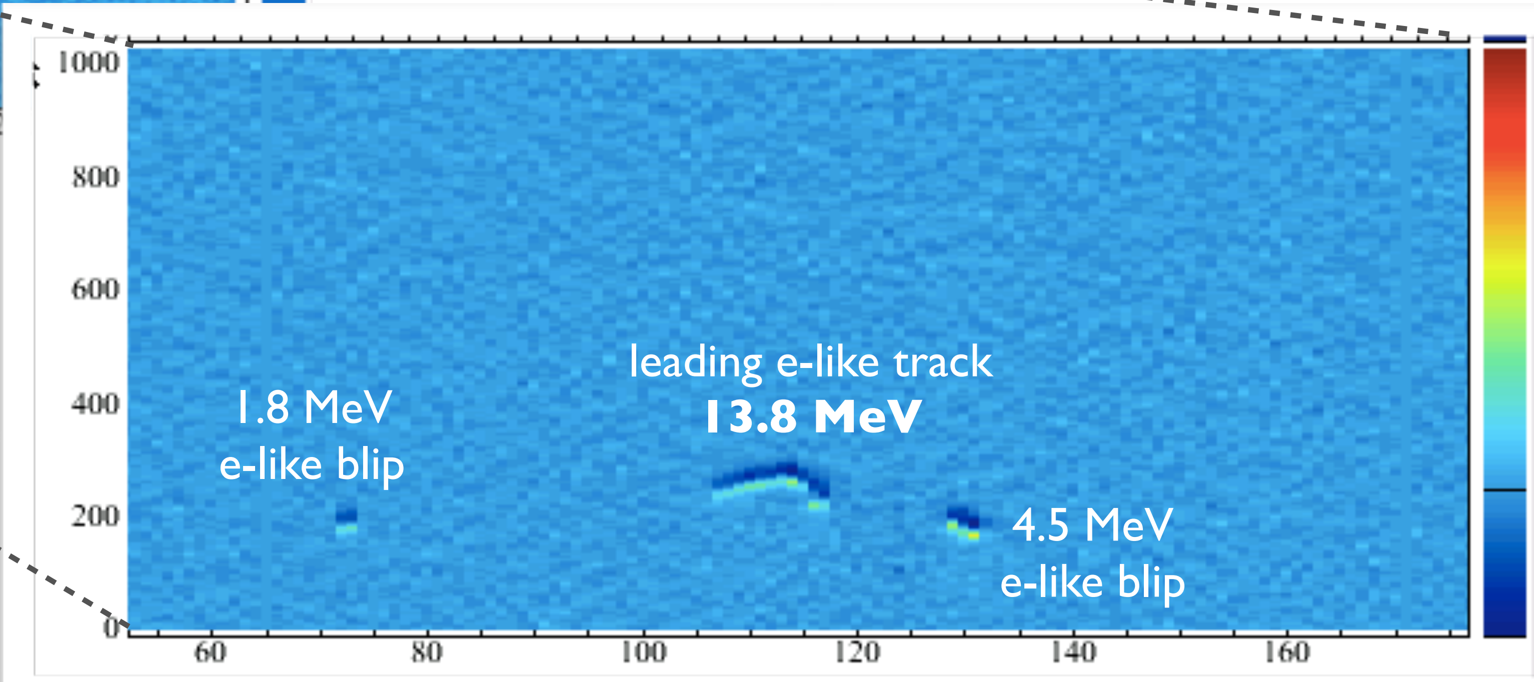
$\hookrightarrow \gamma$(s)

Compton $\hookrightarrow e$(s)

"energy blip"



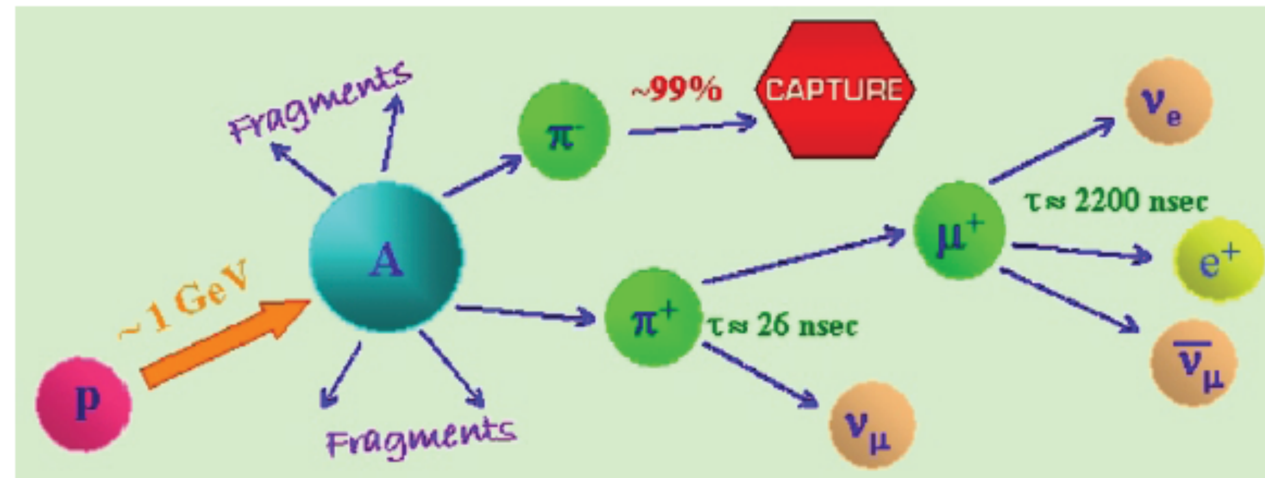
neutrino interaction in the material surrounding the TPC: induced el.m. punch-through event



Direct Cross Section Measurement

OAK RIDGE NATIONAL LABORATORY
NEUTRON SCIENCES
Spallation Neutron Source • High Flux Isotope Reactor

➲ NuSNS: Neutrino at the SNS



$\pi^+/p \simeq 0.13$ ⇨ π^+, μ^+DAR into ν's

Opportunities for Neutrino Physics at the Spallation Neutron Source: A White Paper

A. Bolozdynya[1], F. Cavanna[2], Y. Efremenko[3,4], G. T. Garvey[5], V. Gudkov[6], A. Hatzikoutelis[3], W. R. Hix[4,3], W. C. Louis[5], J. M. Link[7], D. M. Markoff[8], G. B. Mills[5], K. Patton[9], H. Ray[10], K. Scholberg[11], R. G. Van de Water[5], C. Virtue[12], D. H. White[5], S. Yen[13], J. Yoo[14]

arXiv:1212.1276 [hep-ex]

Snowmass white paper

EoI for νSNS (2012)

Cross section measurements at SNS

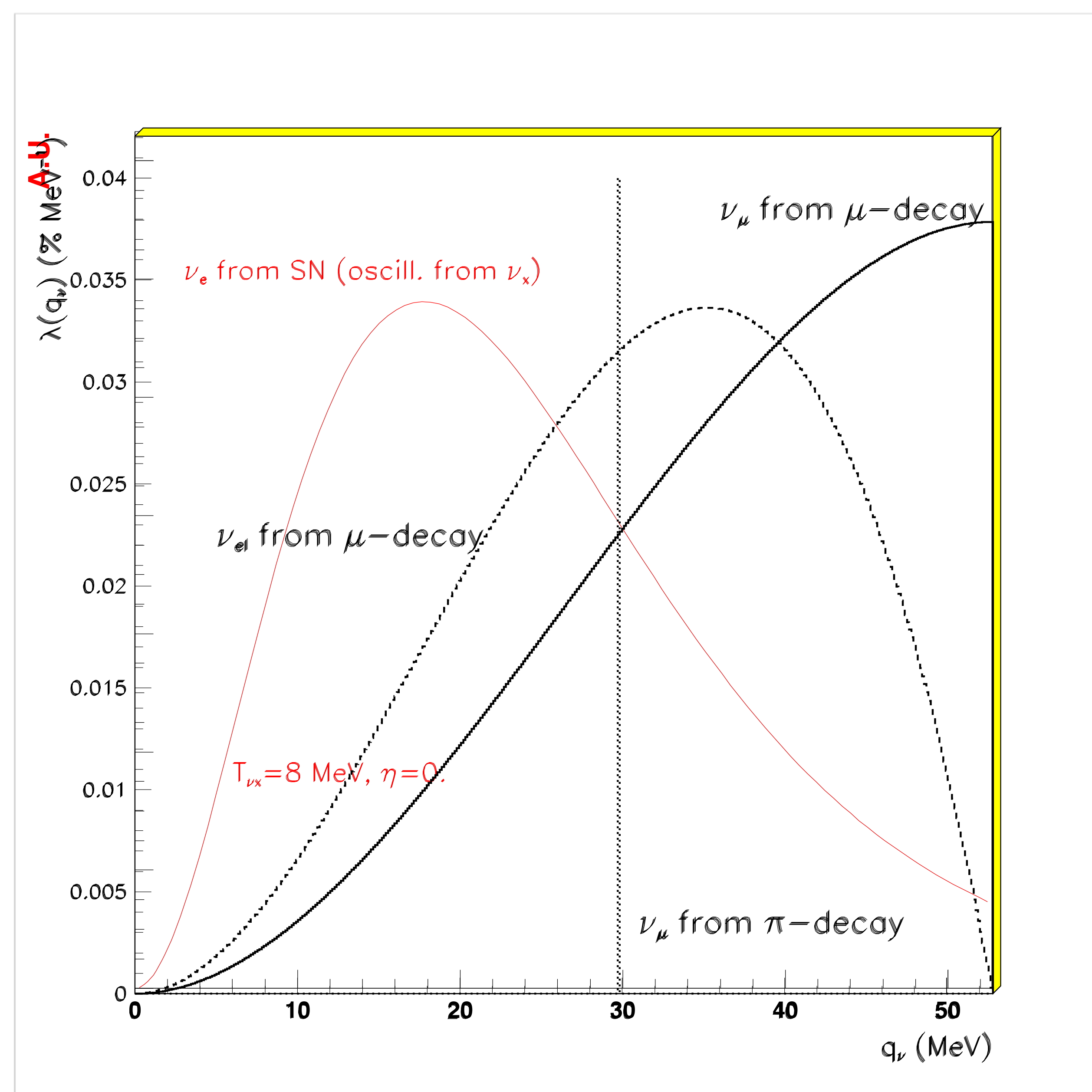
Number of each flavor of neutrinos produced at SNS:

2×10^{22} year^{-1} (1 yr = 200 d)

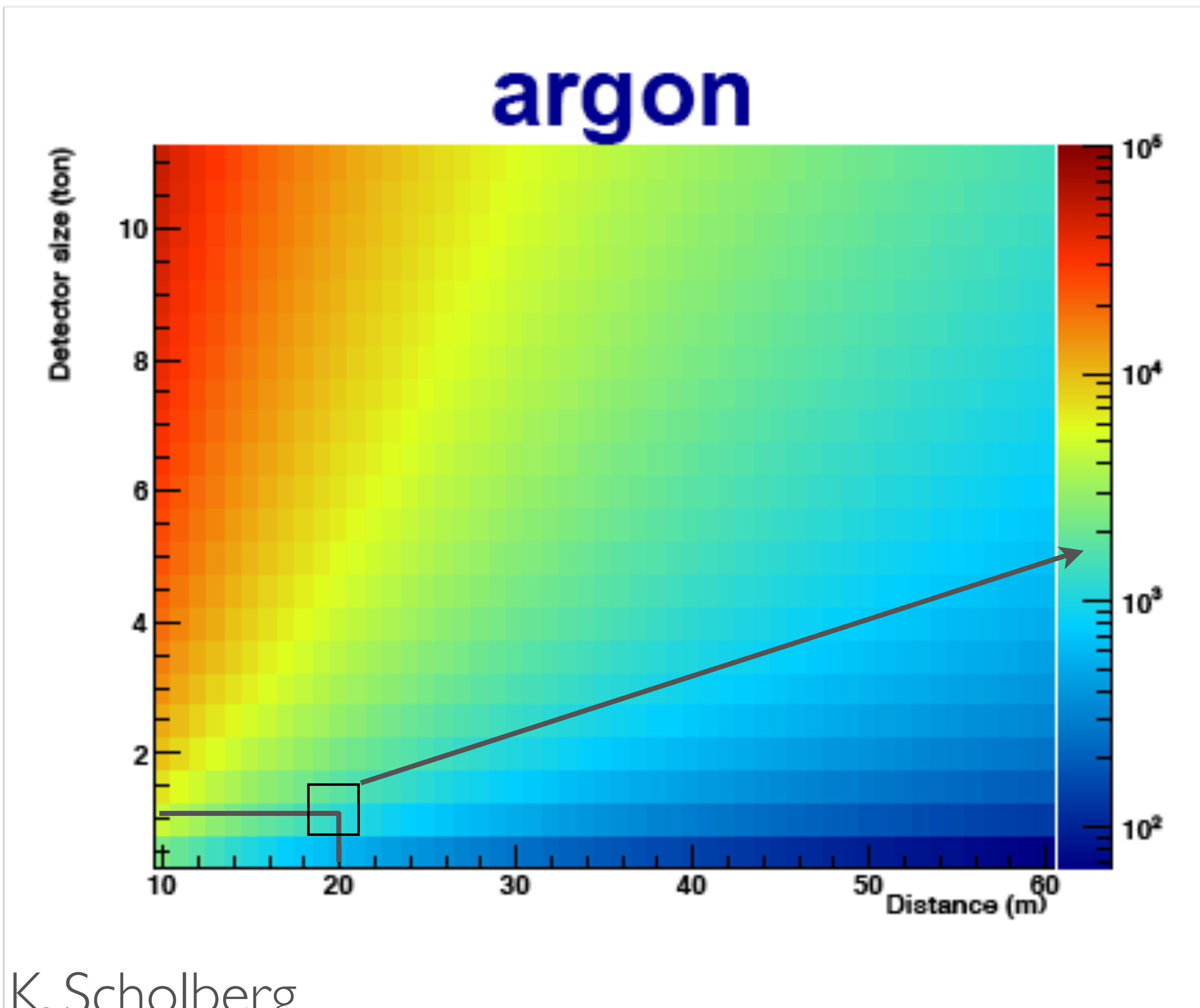
⇨ Neutrino Flux: ≃ 2.6×10^{7}/s/cm^{2} @ 20 m

ν_e spectra from μ^+ DAR and
ν_e spectra from SN (ν_x oscill.)
overlap!

NEUTRINO-SNS:
IDEAL NEUTRINO-SOURCE FOR XSECT MEASUREMENTS, OF INTEREST FOR LAR(TPC) SN DETECTION



Expected rates for LAr Detectors @ SNS



With the nominal ν SNS Fluence

$F(\nu_e) \simeq 5\times10^{14}\ \nu/cm^2$ at d=20m

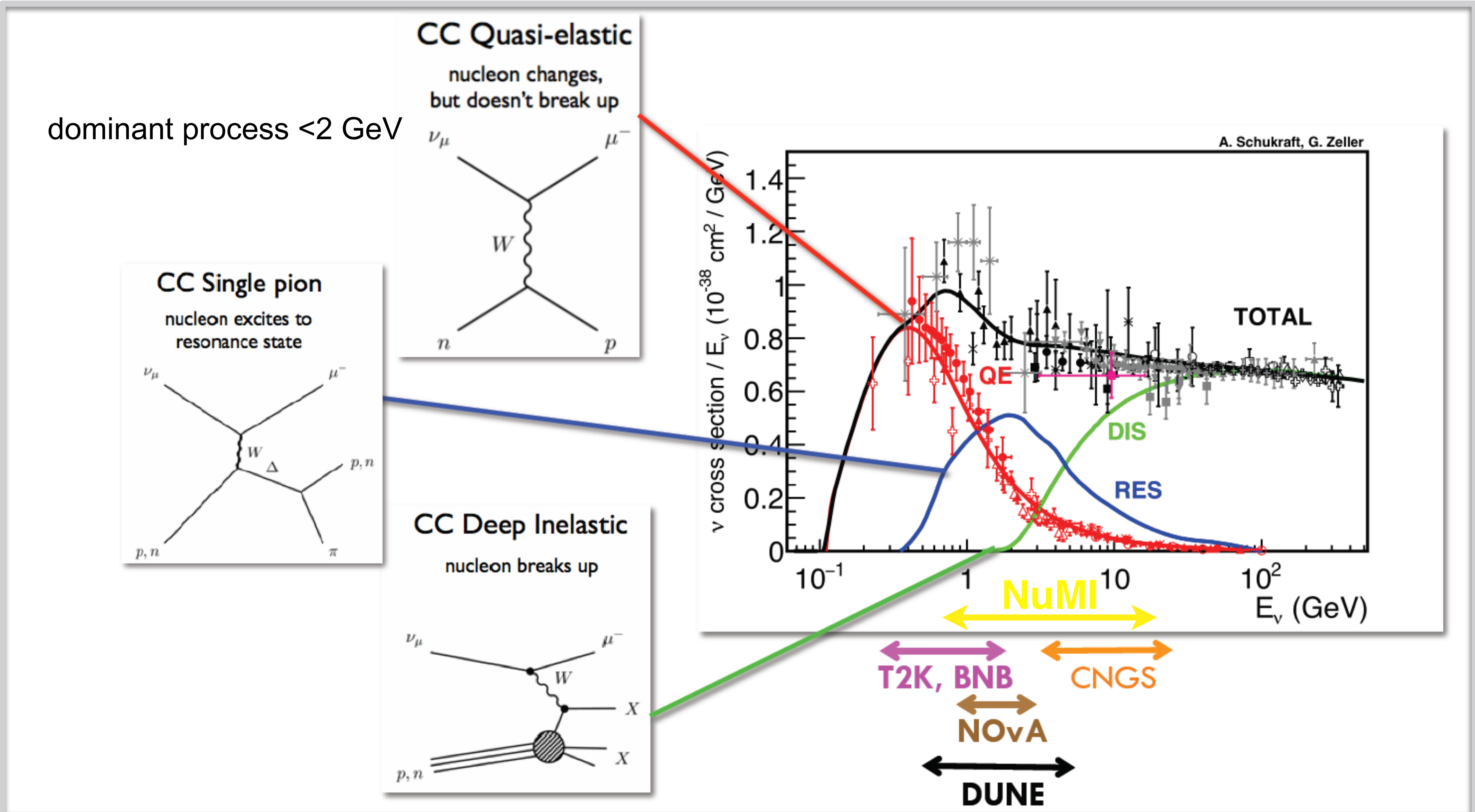
$N_{evt} \cong 1800$ per ton of LAr per yr

A $1\times1\times2\ m^3$ (~3t)

LArTPC looks adequate

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:



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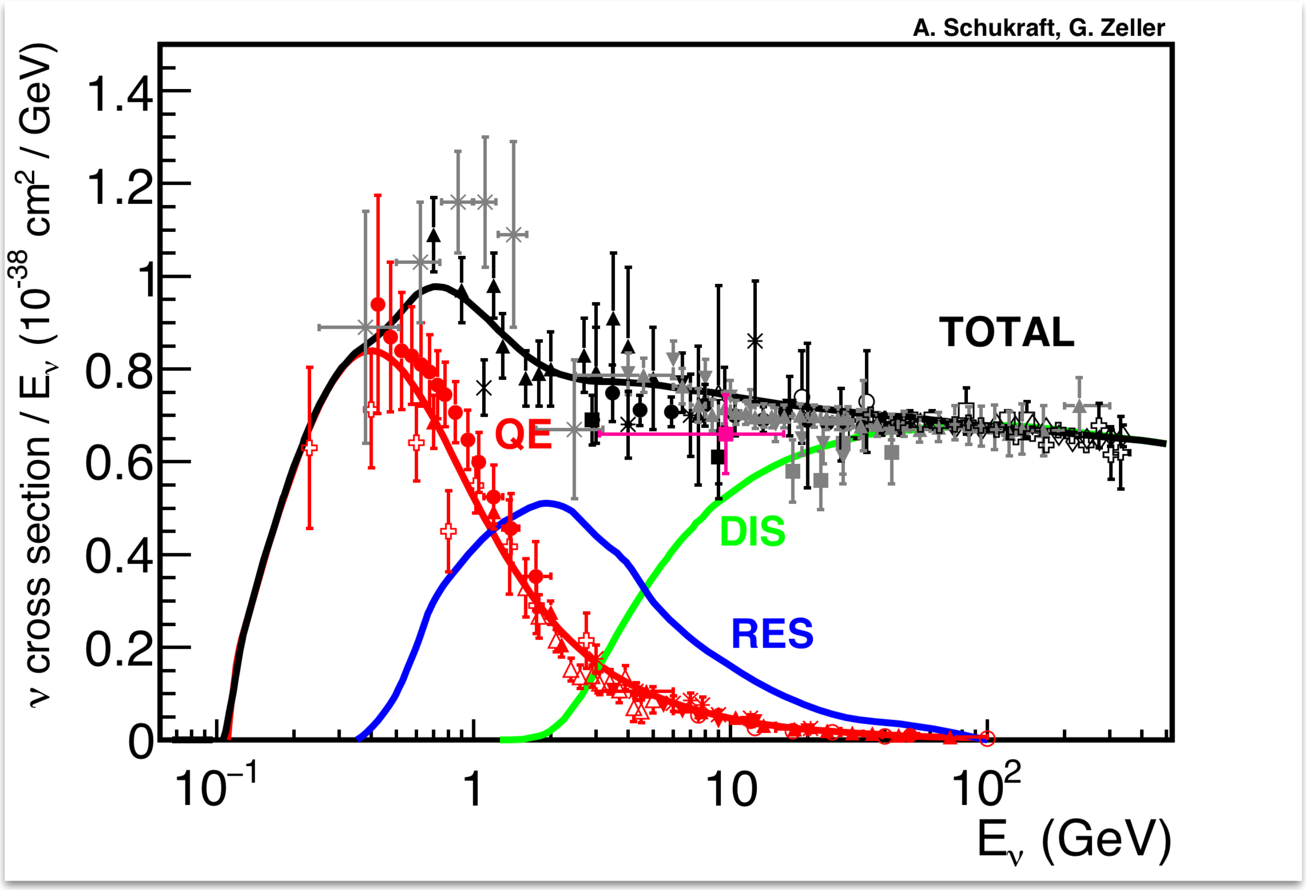
The dominant interaction channels change rapidly across the few GeV neutrino energy region



Few-GeV Region - ν Data

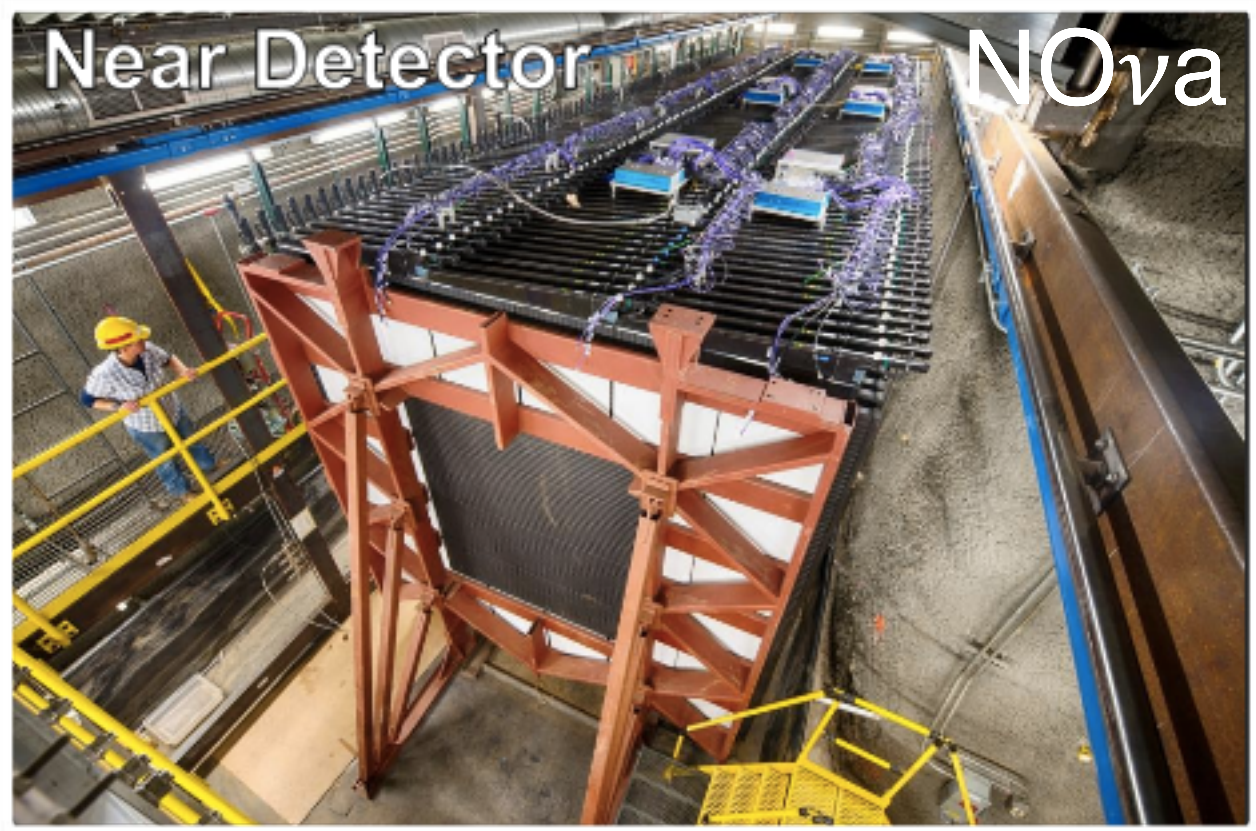
- **Neutrino scattering at intermediate energies** is complicated and is **not yet** well measured!
- Some data have large uncertainties (20-40%) or show discrepancies between different data set and/or with present MC predictions
- Most of our knowledge of neutrino cross sections in this energy range 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).
- Measured cross-sections with higher statistics in the 90's, 00's (ex. NuTeV), rich physics programs: DIS, structure functions, strange sea, QCD, neutrino energies generally higher

Few-GeV Region - ν Data

- 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**) in this energy range.
    - Recent results and/or currently analyzing and publishing new cross section data

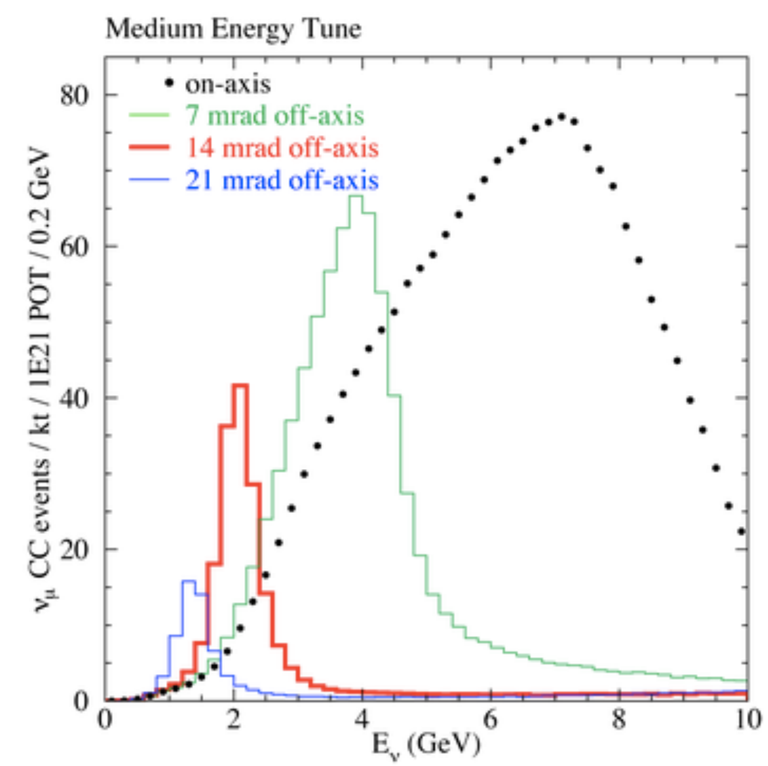
- Other experiments are coming online (NOνA, MicroBooNE)



ν scattering - Challenges (I)

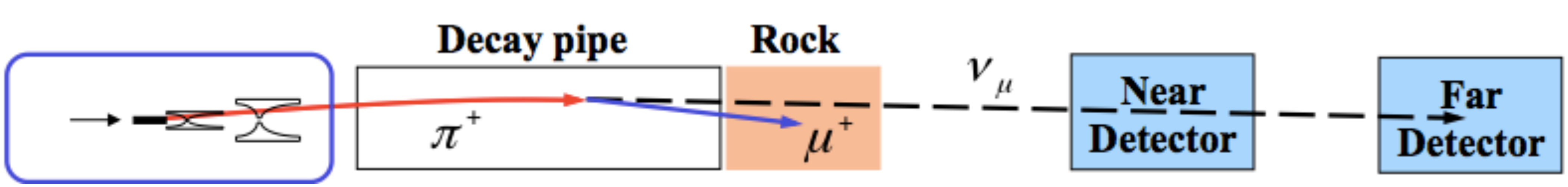
- **Main challenges of intermediate energy neutrino interaction measurements:**
  - Accelerator Neutrino beams are not monochromatic but distributed on **broad band spectra**! We have to infer E_ν from what we observe in the final state (technology dependent!!)
  - Cross sections are low and strongly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

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



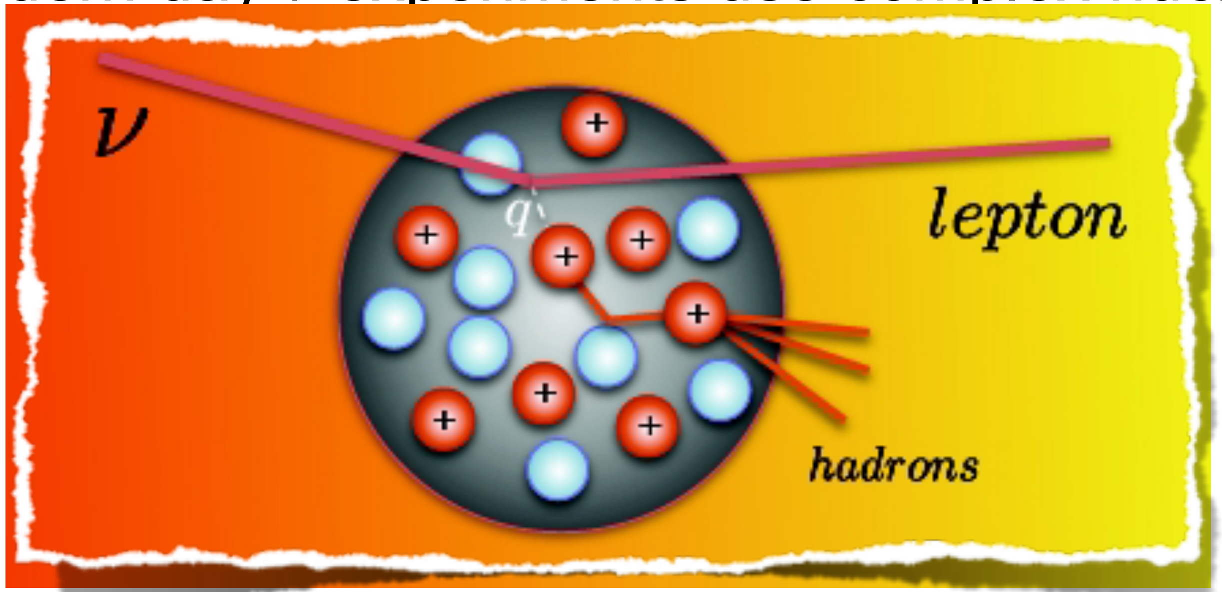
NuMI Medium Energy Flux

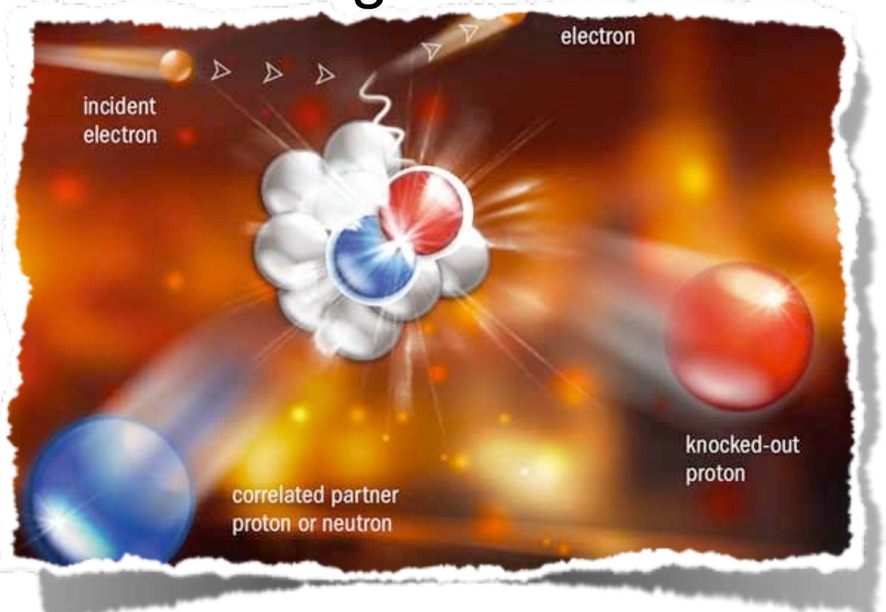
  - Flux has large uncertainties due to poor knowledge of hadron production. Flux is usually the dominant uncertainty in σ_ν measurements (~15-20% normalization uncertainties on the flux)



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.

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

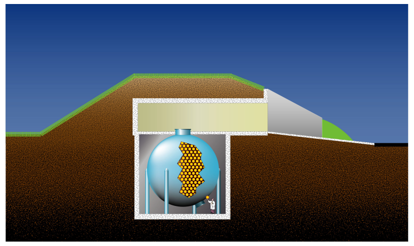
Future ν scattering measurements

- Improved experimental measurements and theoretical calculations in the intermediate energy region will be especially important for reducing systematics in future precision neutrino oscillation experiments. What we need:
    - Higher statistic
    - More well-known ν beams (need to know Φ_ν to measure σ_ν!)
    - Experiments should measure **model-independent exclusive final states**. Need technology capable to measure all the final state particles (including hadrons) with low energy threshold
    - Variety of nuclear targets: further studies of nuclear effects
    - Measure ν_e cross sections
    - Study antineutrinos (important for future $\cancel{CP}$ searches)

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

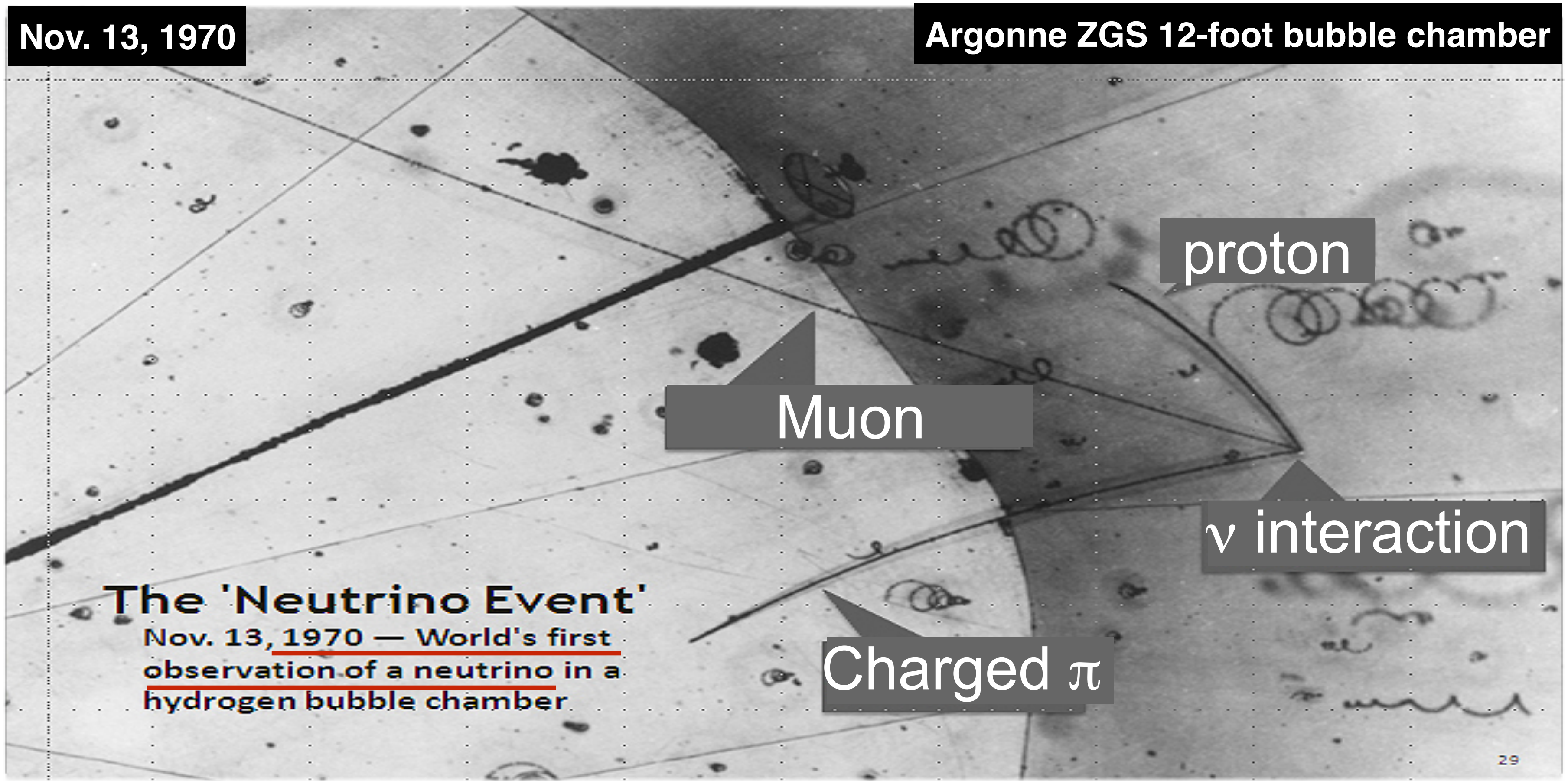
T2K = **H_2O**, **C**, Water Cherenkov

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**, LAr TPC

ν interactions in the Few-GeV Region
R&D and Upcoming/Proposed Experiments

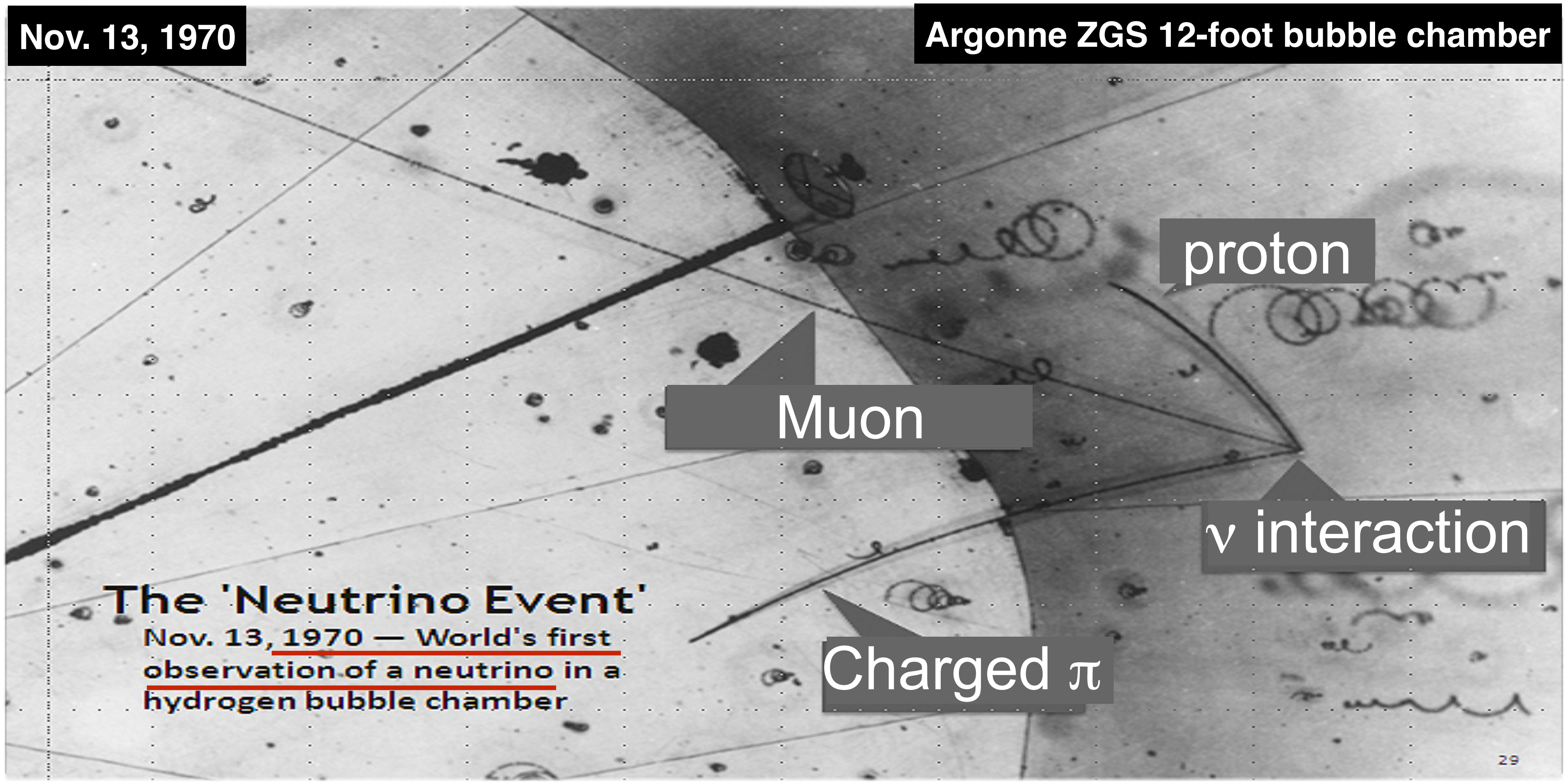
- Three LAr TPCs Short-Baseline Neutrino Program in the Fermilab Booster Neutrino Beam
- CAPTAIN/Minerva on the Fermilab NuMI beam
- ANNIE on the Fermilab BNB
- T2K ND upgrades at JPARK
- Cross section measurements with monoenergetic ν_μ at JPARK

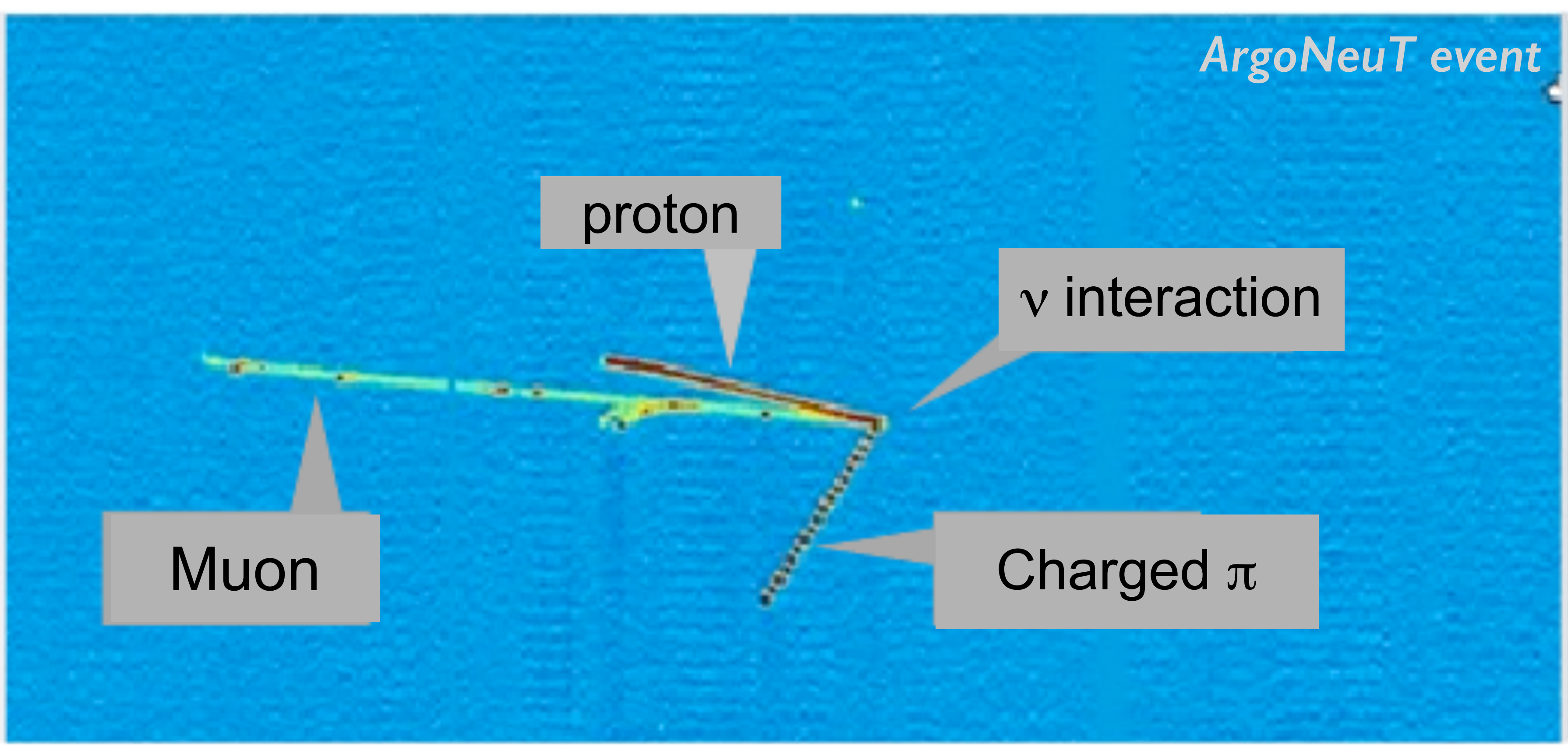


Why Liquid Argon Time Projection Chamber?

LAr TPC for detecting neutrinos:

- 1985 - Proposal for ICARUS T600 in Gran Sasso, starting the ICARUS R&D program
  - This program addressed many of the technical challenges of developing LAr TPCs as viable neutrino detectors





Why Liquid Argon Time Projection Chamber?

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

Can produce physics results with a “table-top” size experiment (**ArgoNeuT (240 Kg LArTPC)** - Neutrino cross sections, nuclear effects in neutrino-Ar scattering)

Why Liquid Argon Time Projection Chamber?

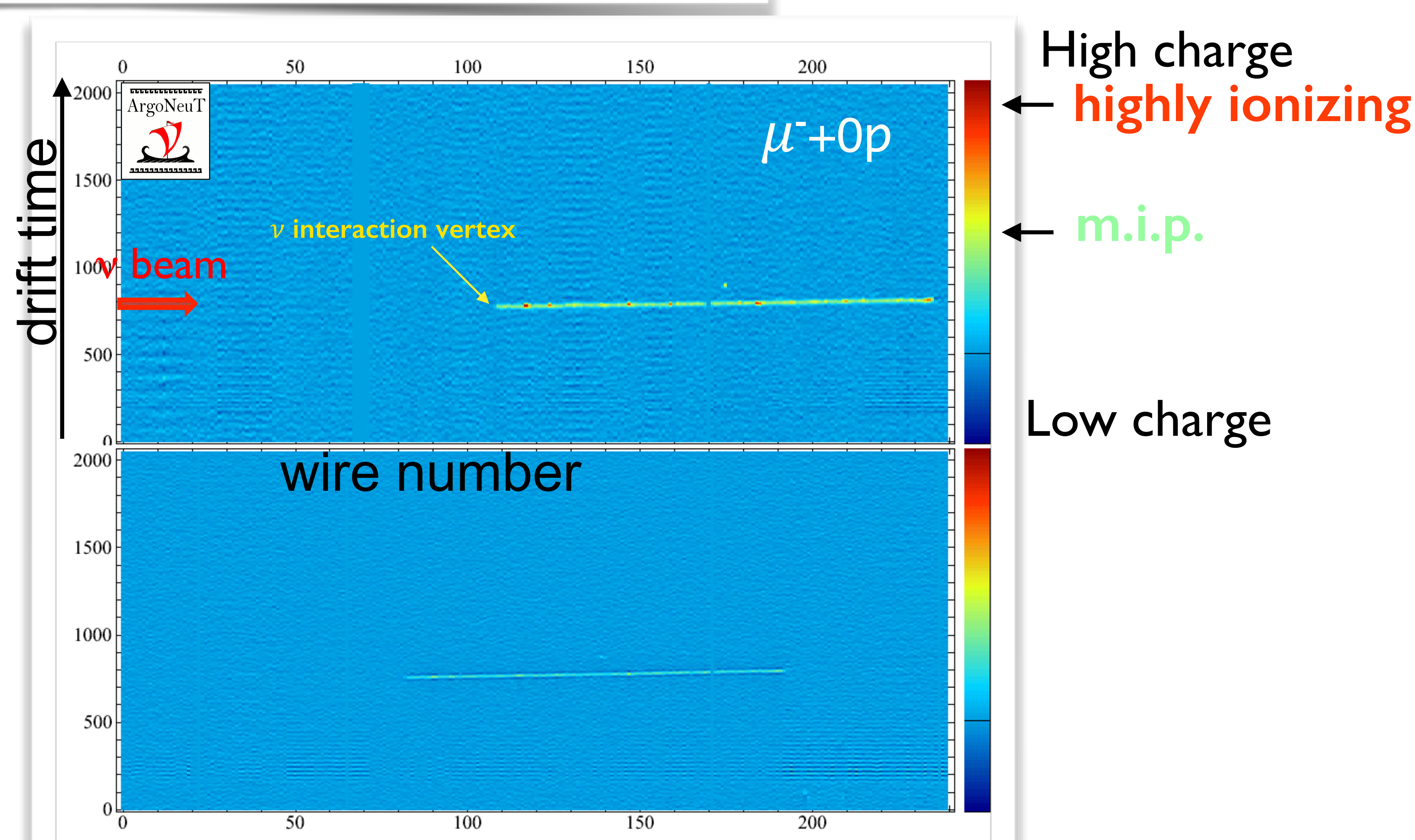
LAr TPC detectors, provide *full 3D imaging, precise calorimetric energy reconstruction and efficient particle identification* allow for **Exclusive Topology recognition** and **Nuclear Effects exploration** from detailed studies of the hadronic part of the final states

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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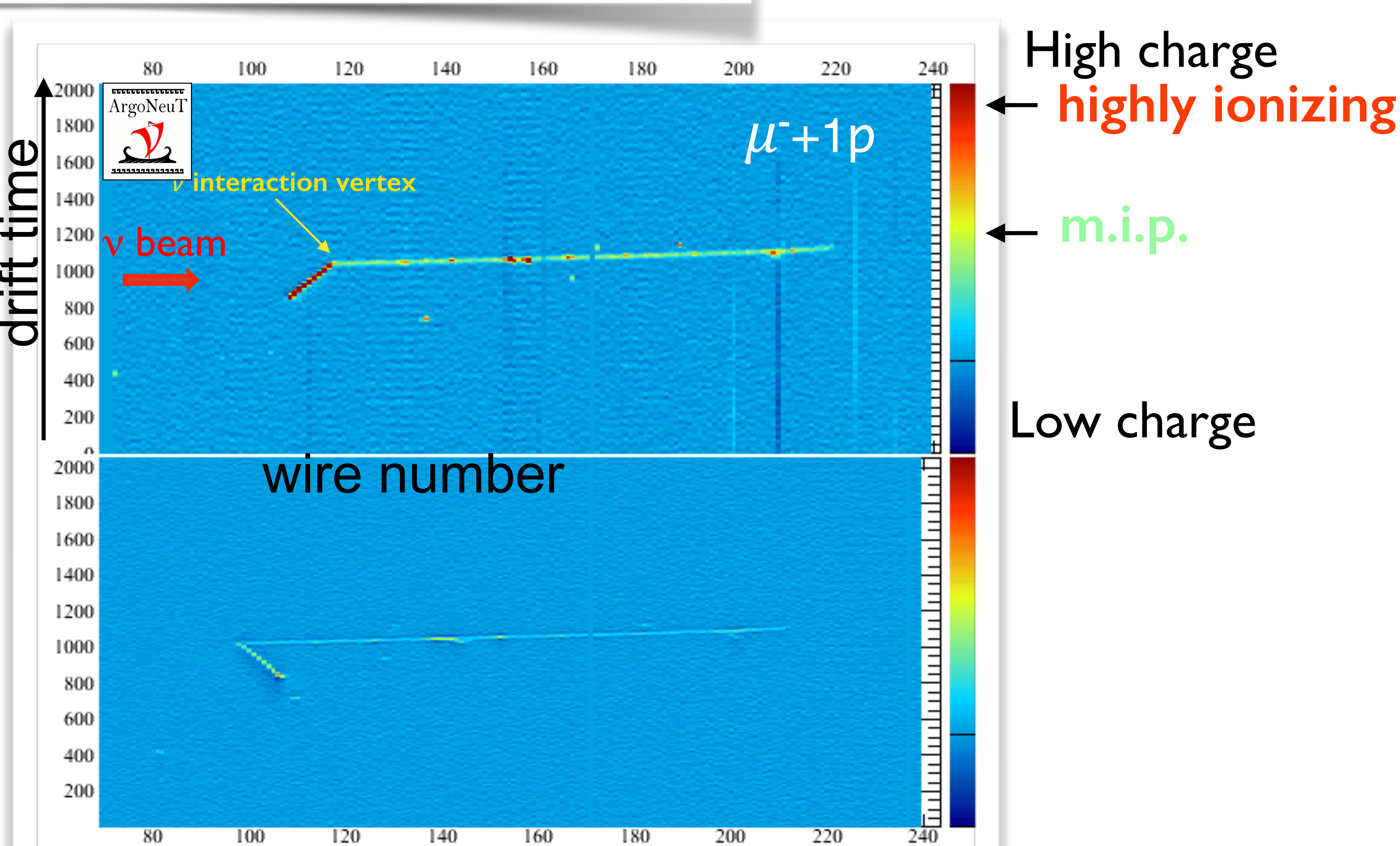

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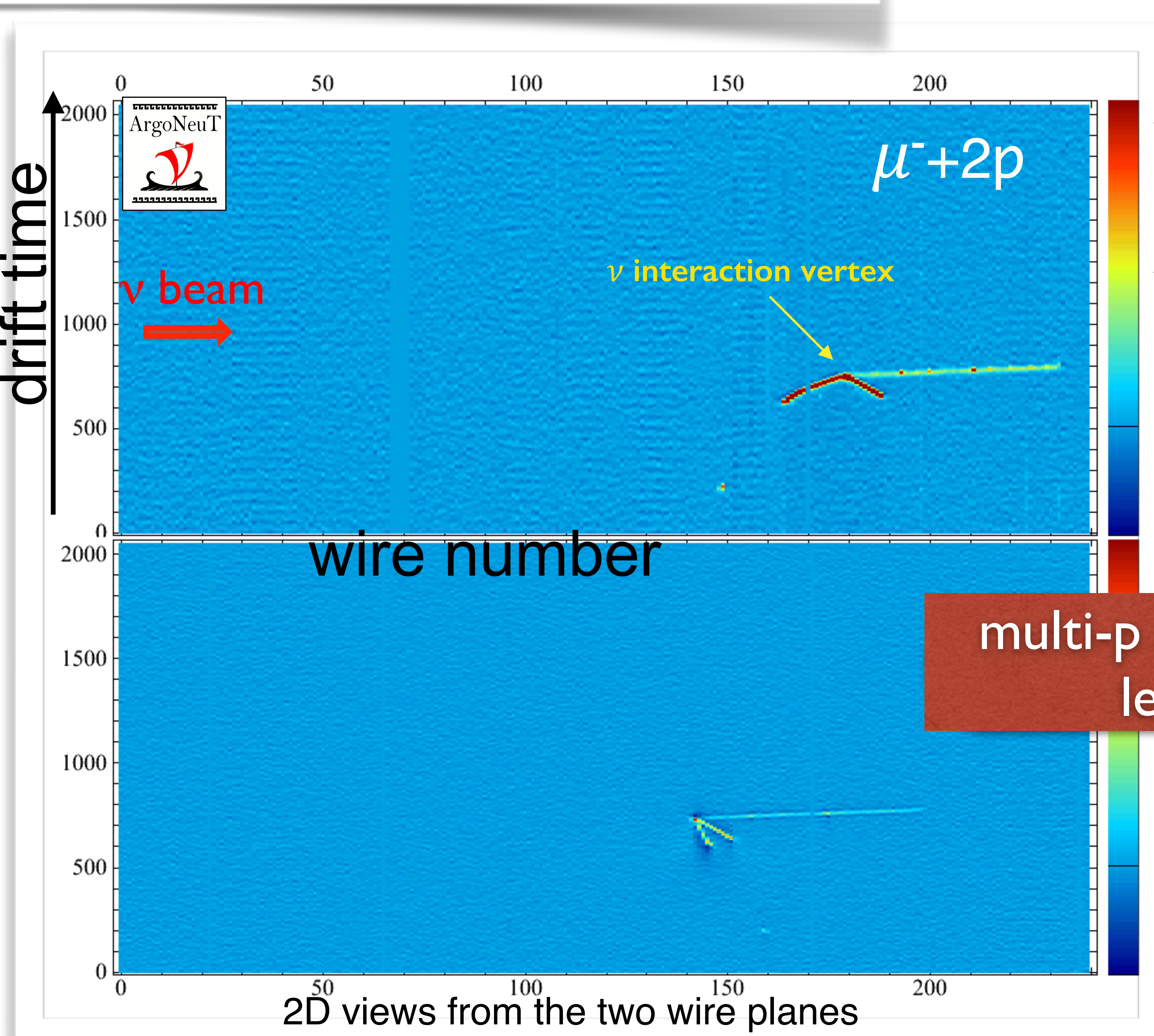


High charge
← highly ionizing
← m.i.p.
Low charge

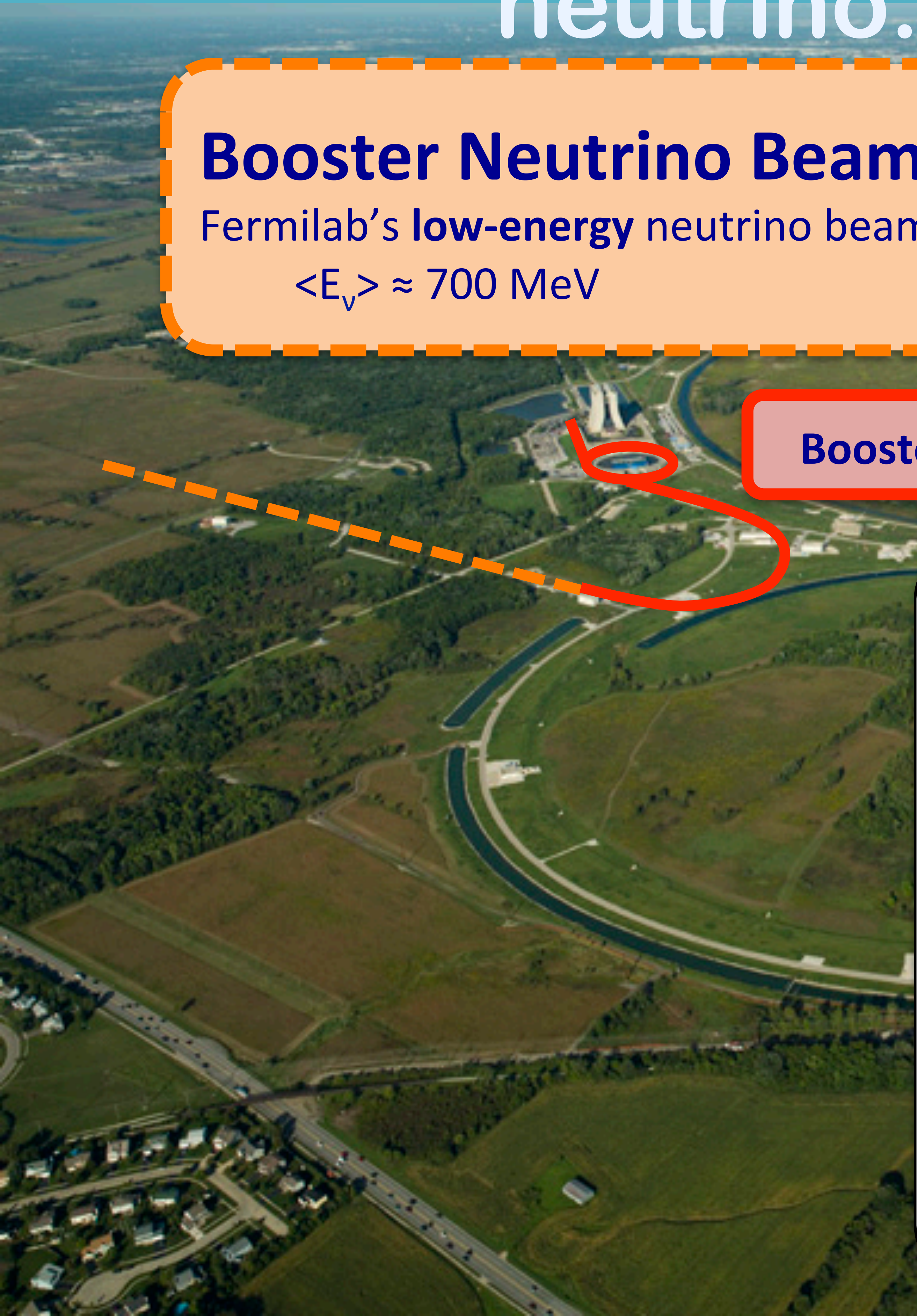
multi-p accompanying the leading muon

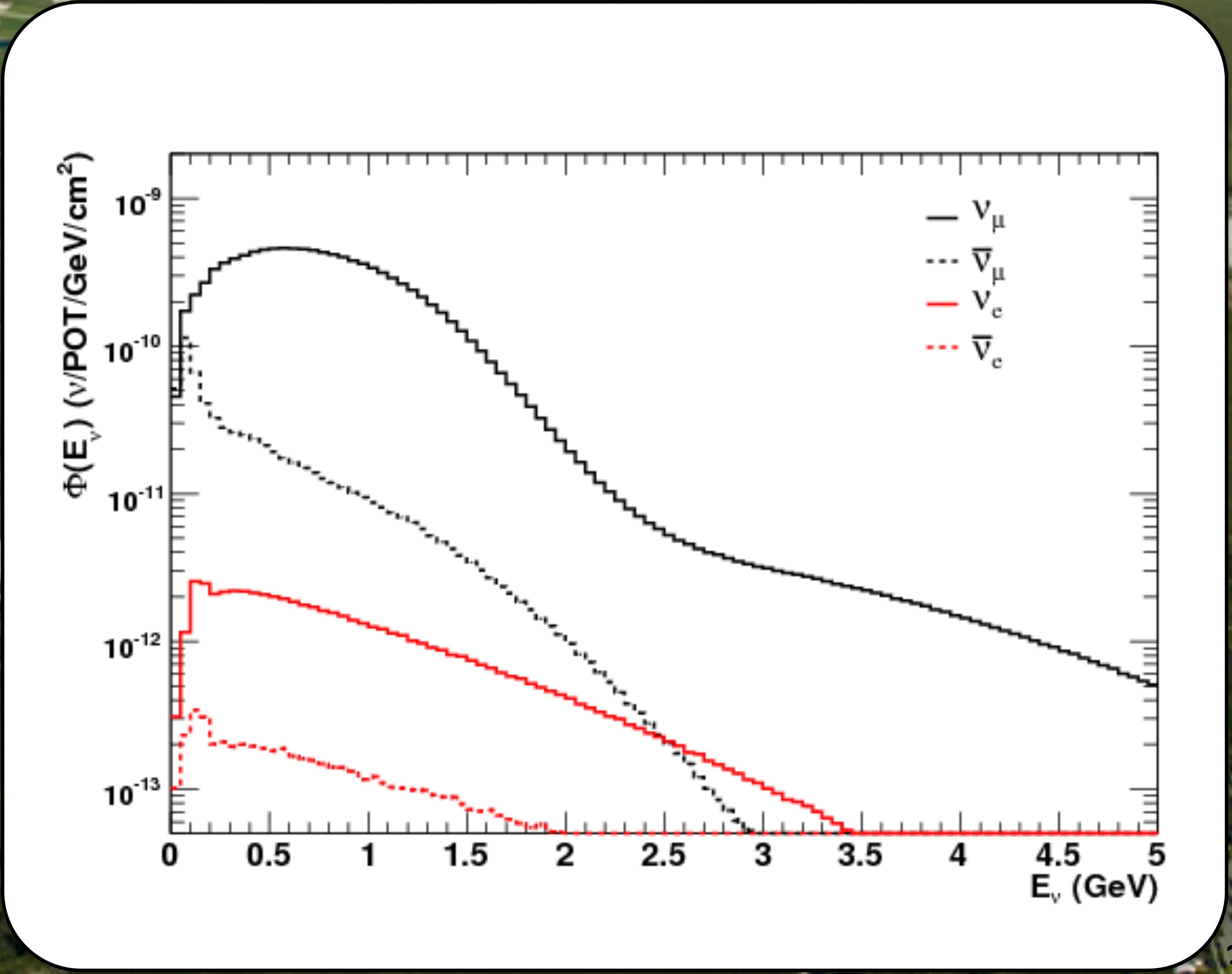
Source of intermediate energy neutrino: BNB @ FNAL

Booster Neutrino Beam (BNB)

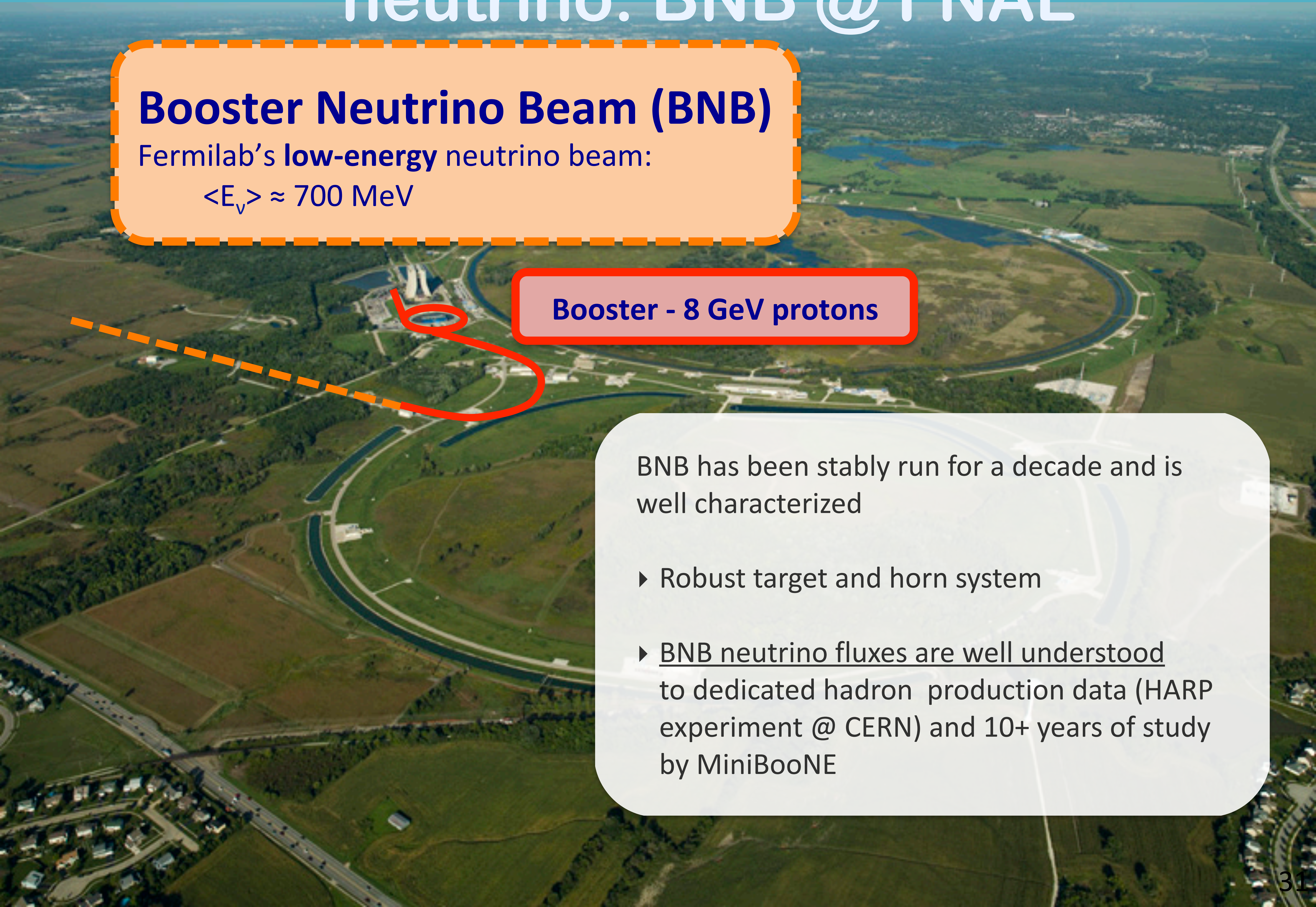
Fermilab's **low-energy** neutrino beam:

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





Source of intermediate energy neutrino: BNB @ FNAL



Booster Neutrino Beam (BNB)

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

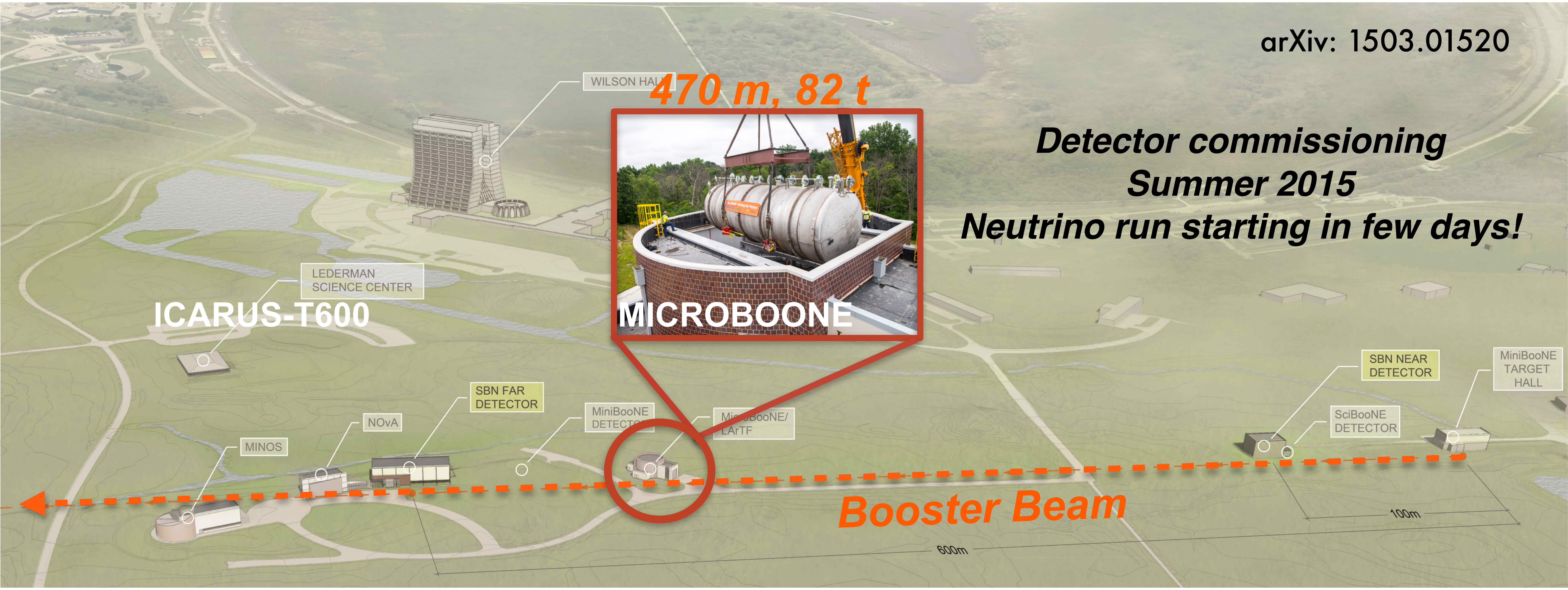
$\langle E_\nu \rangle \approx 700$ MeV

Booster - 8 GeV protons

BNB has been stably run for a decade and is well characterized

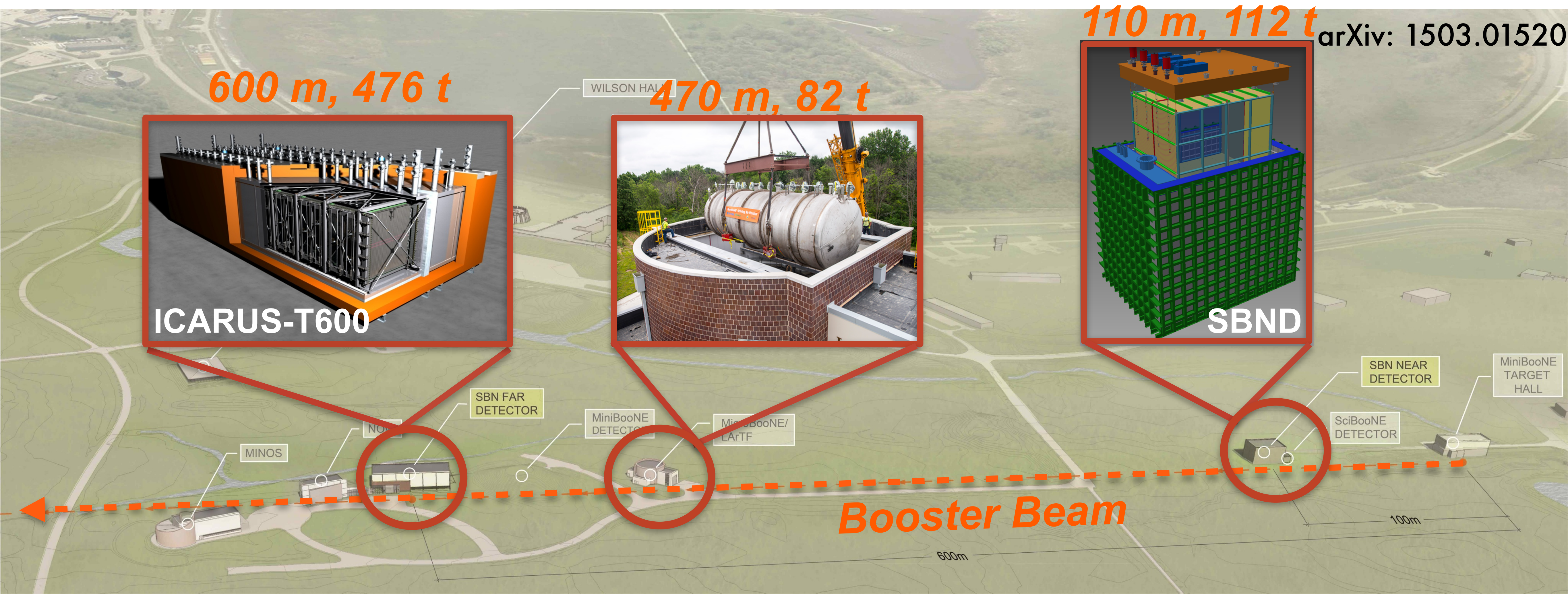
- Robust target and horn system
- <u>BNB neutrino fluxes are well understood</u> to dedicated hadron production data (HARP experiment @ CERN) and 10+ years of study by MiniBooNE

FNAL Short Baseline Neutrino program



I phase - MicroBooNE - MicroBooNE's core mission is to address the anomalous excess of electromagnetic events observed by MiniBooNE and **to apply the LArTPC technology to test for the same excess and determine its composition as electrons** (from ν_e appearance) **or photons** (unaccounted for background).

FNAL Short Baseline Neutrino program



II phase - By 2018, the MicroBooNE detector will be joined by two additional LAr-TPC detectors, the Short-Baseline Near Detector (**SBND**) and the **ICARUS-T600** detector, to form a three detectors **neutrino oscillation** program

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 SOON!
- 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)

Neutrino Cross Section in MicroBooNE

- MicroBooNE will build off of what has already been learned in MiniBooNE *(same beam)* and ArgoNeuT *(same technology)*

MicroBooNE projected event sample sizes after the first 6 months of running	**1e20 POT (~6 months)**
	numu
	87 tons active volume
CC inclusive	26226
CC 0 pi	16757
NC elastic	2493
NC single pi0	1771

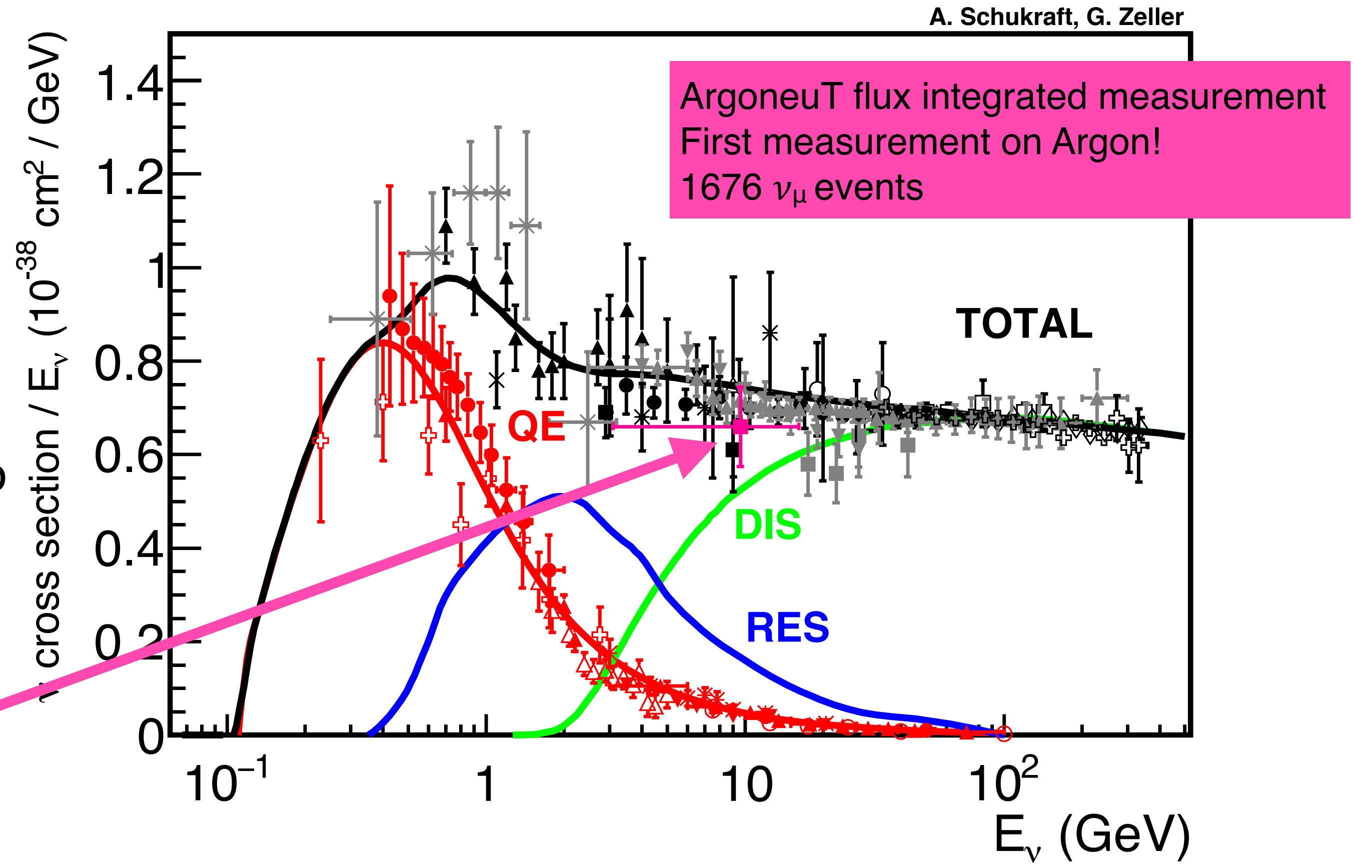
- MicroBooNE will make the first σ_ν measurements in ^{40}Ar at low energy (E_ν ~1 GeV)
- these analyses will benefit from the well-known BNB flux
  Aguilar-Arevalo et al., PRD 79, 072002 (2009)
- expect to collect an ArgoNeuT sized neutrino event sample in the first few months of running

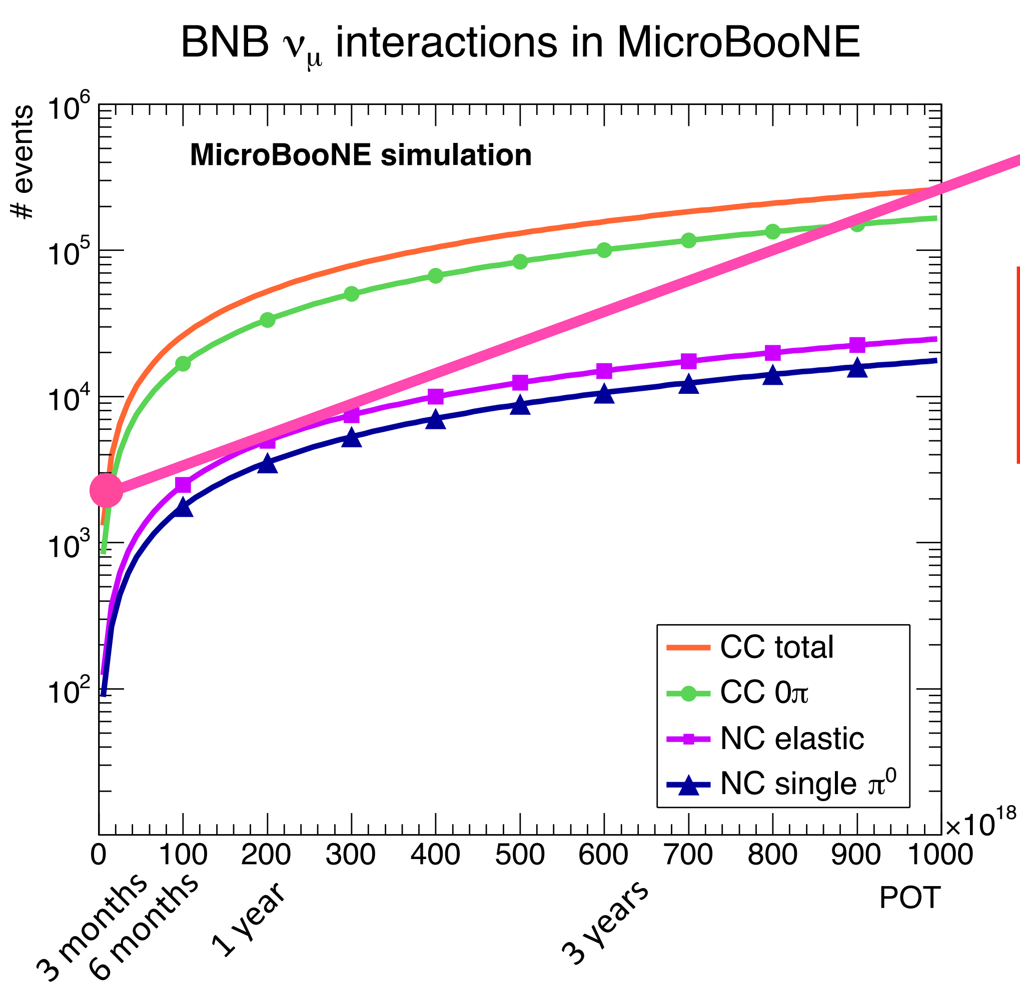
MicroBooNE experiment

	CC incl. events
1.5x10^{19} POT	3990
1x10^{20} POT	26553
2x10^{20} POT	53106

(87 tons, 100% efficiency)

Single differential cross section measurements as a function of muon angle, muon momentum, neutrino energy





MicroBooNE will reach ArgoNeuT statistics in ~ 1 month of beam

CC inclusive ν_μ events

MicroBooNE experiment

	CC incl. events
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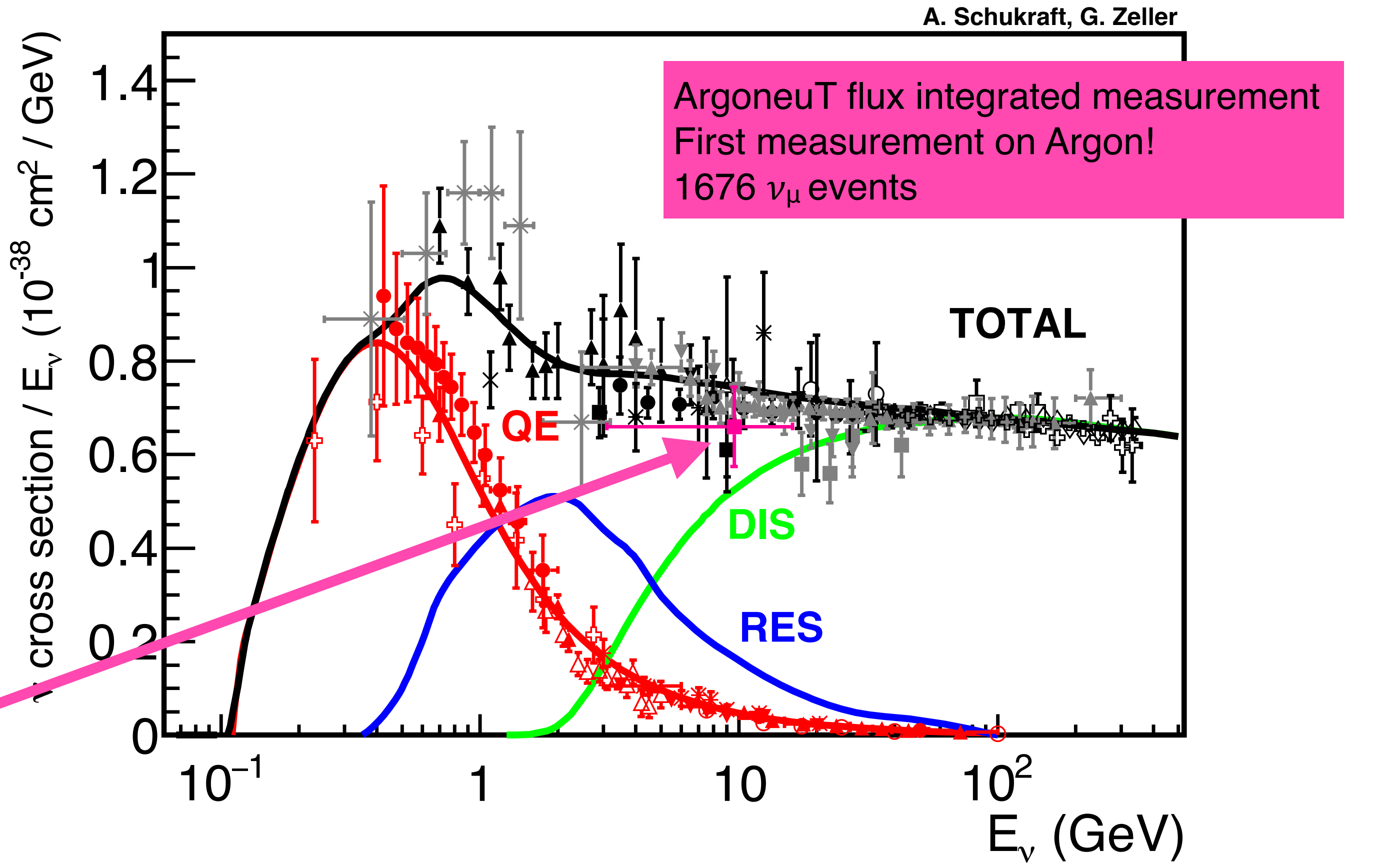
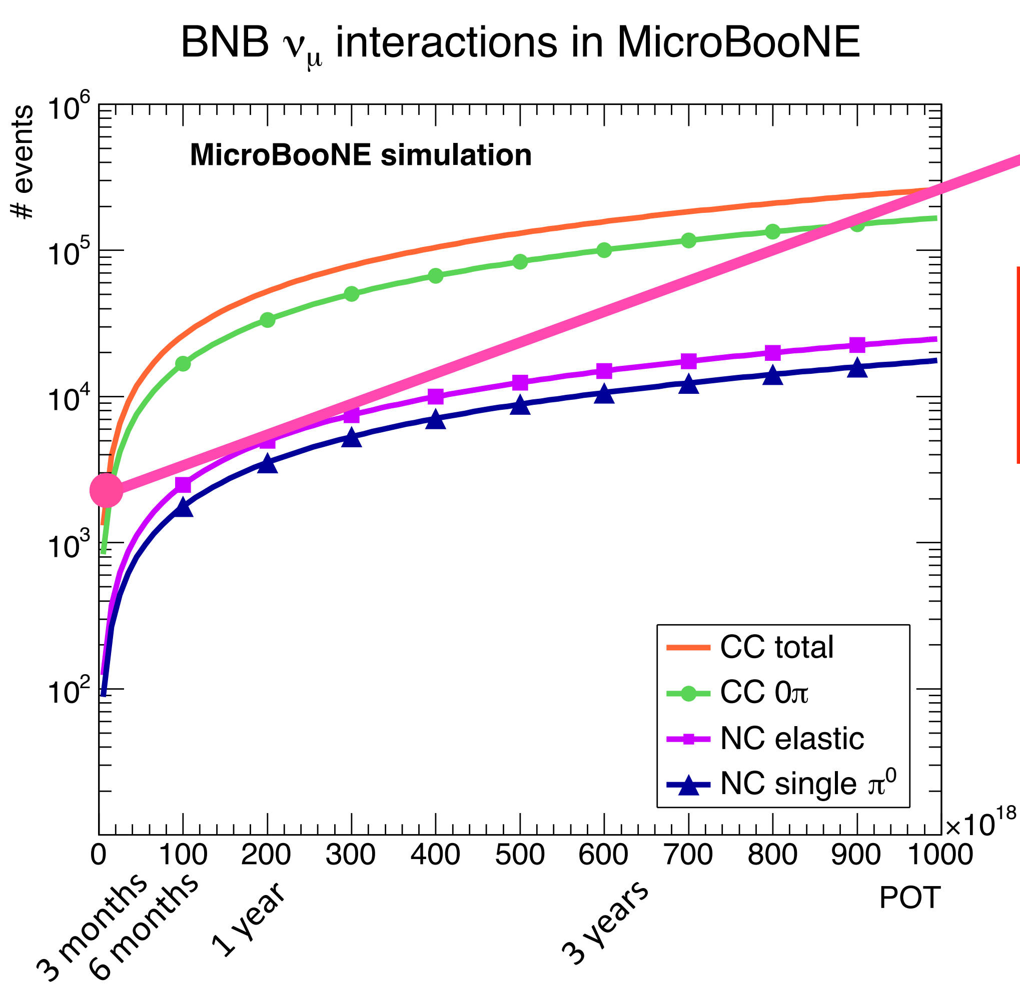




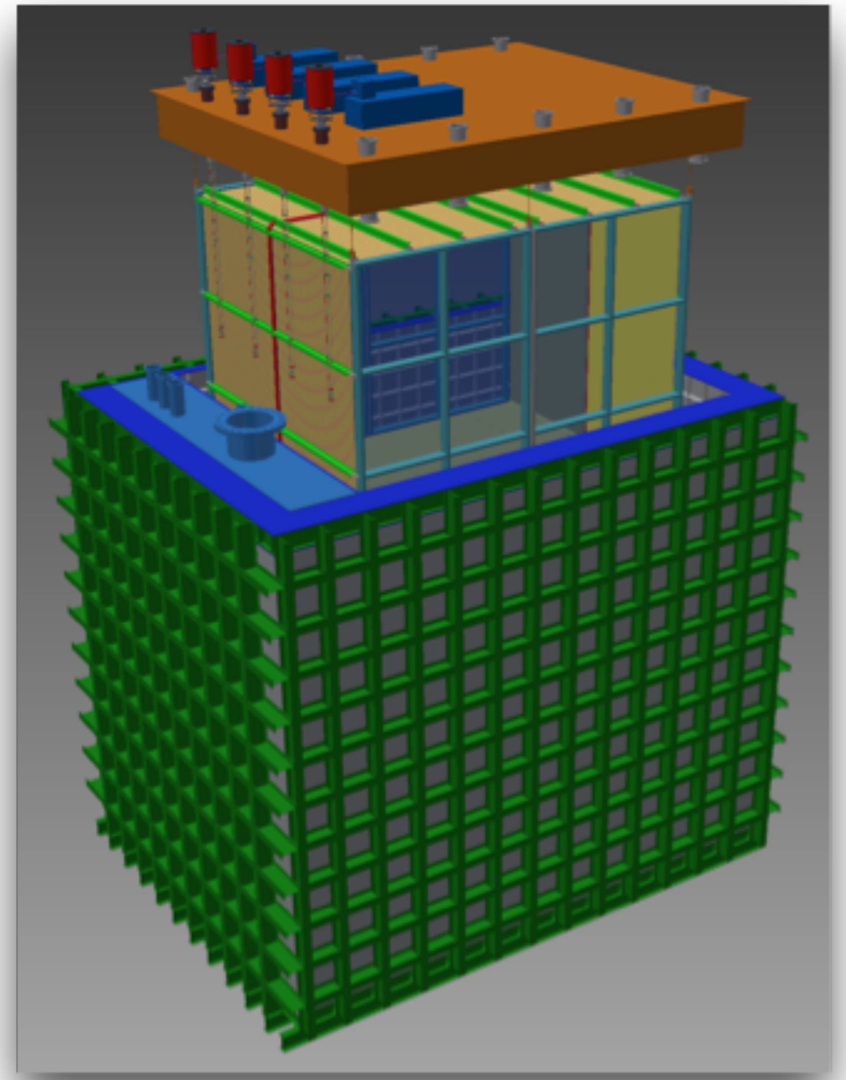
MicroBooNE will reach ArgoNeuT statistics in ~ 1 month of beam

CC inclusive ν_μ events

SBND - 2018 - (closer to the target, **30x higher rate**) will reach ArgoNeuT statistics in ~ 1 day of beam!!!

SBND - Cross section measurements

- Continuing the studies done by ArgoNeuT and MicroBooNE, SBND will make the **world's highest statistics cross section measurements** of ν_μ**-Ar and** ν_e**-Ar**, using well characterized neutrino fluxes, including
  - rarer processes such as ν-e scattering, strange particle production, and coherent scattering with an argon nucleus
  - expanded differential measurements and studies of nuclear effects ν-Ar interactions
- Event categorization in terms of **exclusive topologies** will be used to analyze data and provide precise cross section measurements in different ν_μ and ν_e exclusive channels.



SBND - ν Event rates

Process		No. Events	Events/ ton	Stat. Uncert.
	ν_μ *Events (By Final State Topology)*			
CC Inclusive		5,212,690	46,542	0.04%
CC 0 π	$\nu_\mu N \to \mu + Np$	3,551,830	31,713	0.05%
	$\cdot\ \nu_\mu N \to \mu + 0p$	793,153	7,082	0.11%
	$\cdot\ \nu_\mu N \to \mu + 1p$	2,027,830	18,106	0.07%
	$\cdot\ \nu_\mu N \to \mu + 2p$	359,496	3,210	0.17%
	$\cdot\ \nu_\mu N \to \mu + \geq 3p$	371,347	3,316	0.16%
CC 1 $\pi^\pm$	$\nu_\mu N \to \mu +$ nucleons $+ 1\pi^\pm$	1,161,610	10,372	0.09%
CC $\geq 2\pi^\pm$	$\nu_\mu N \to \mu +$ nucleons $+ \geq 2\pi^\pm$	97,929	874	0.32%
CC $\geq 1\pi^0$	$\nu_\mu N \to \mu +$ nucleons $+ \geq 1\pi^0$	497,963	4,446	0.14%
NC Inclusive		1,988,110	17,751	0.07%
NC 0 π	$\nu_\mu N \to$ nucleons	1,371,070	12,242	0.09%
NC 1 $\pi^\pm$	$\nu_\mu N \to$ nucleons $+ 1\pi^\pm$	260,924	2,330	0.20%
NC $\geq 2\pi^\pm$	$\nu_\mu N \to$ nucleons $+ \geq 2\pi^\pm$	31,940	285	0.56%
NC $\geq 1\pi^0$	$\nu_\mu N \to$ nucleons $+ \geq 1\pi^0$	358,443	3,200	0.17%
	ν_e *Events*			
CC Inclusive		36798	329	0.52%
NC Inclusive		14351	128	0.83%
Total ν_μ and ν_e Events		7,251,948	64,750	
	ν_μ *Events (By Physical Process)*			
CC QE	$\nu_\mu n \to \mu^- p$	3,122,600	27,880	
CC RES	$\nu_\mu N \to \mu^- \pi N$	1,450,410	12,950	
CC DIS	$\nu_\mu N \to \mu^- X$	542,516	4,844	
CC Coherent	$\nu_\mu Ar \to \mu Ar + \pi$	18,881	169	

ν_μ-Ar

(7 Million in 3 years)

ν_e-Ar

(50,000 in 3 years)

Estimated event rates (GENIE) in the SBND active volume (112 ton) for a $6.6\ 10^{20}$ POT exposure

MicroBooNE and SBND
Exclusive channels & Nuclear Effects

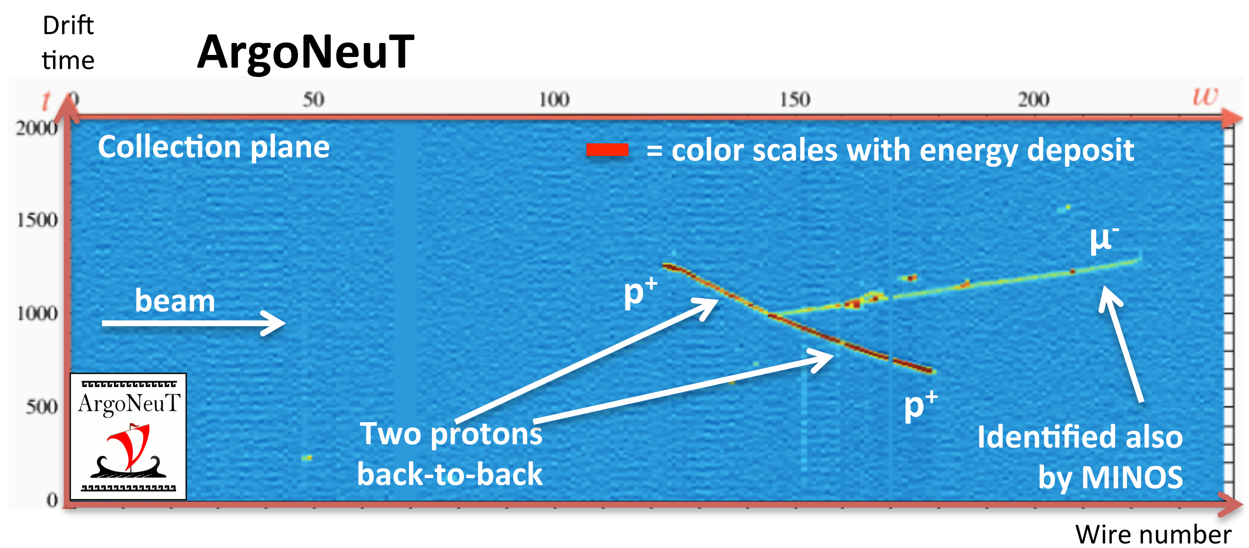
- At the BNB **CC 0 pion** (no pions in the event) is the **dominant channel**
- High statistics measurement of the ν_μ **and** ν_e **CC 0 pion events** will allow to quantify nuclear effects in neutrino-Ar scattering

μ+2p events

MicroBooNE

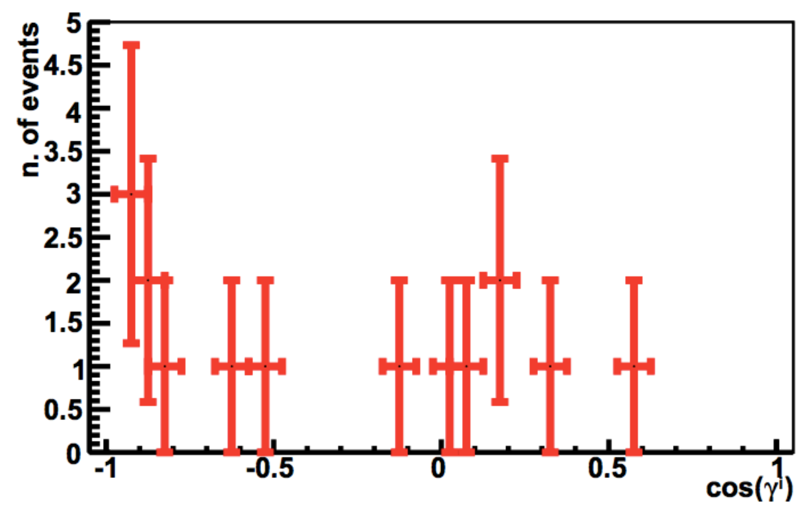
	$1\mu^- + 2p$
1.5×10^{19} POT	269
5×10^{19} POT	896
1×10^{20} POT	1791
2×10^{20} POT	3582
6.6×10^{20} POT	11820

SBND in 1 year:
360,000 μ+2p events



Phys. Rev. D 90, 012008 (2014)

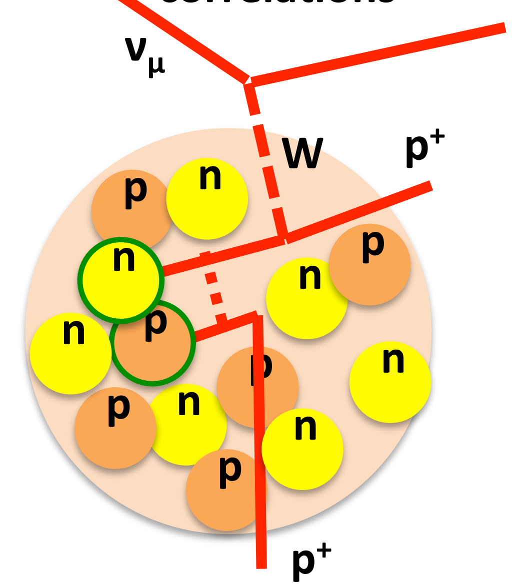
ArgoNeuT: hints of SRC in neutrino scattering, analysis of 30 μ+2p events



Why is this interesting?

- Our golden channel to study nucleon-nucleon correlations

Nucleon-nucleon correlations



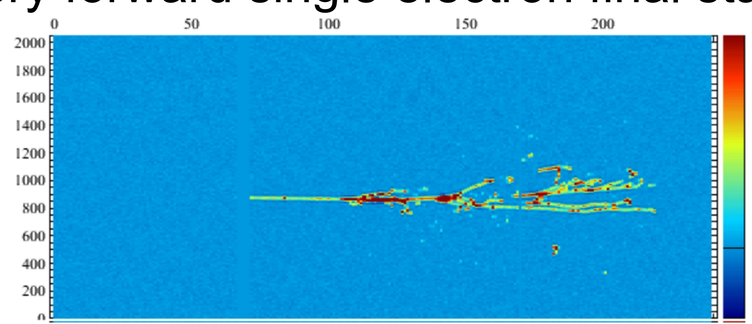
Two nucleons in correlation
Means for the experimentalist:
Multi-nucleon knockout!
The pair inside the nucleus has:
large relative momentum,
small total momentum

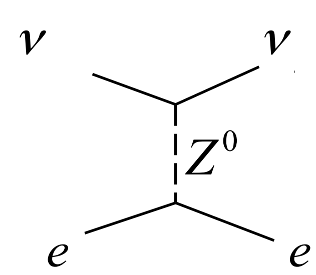
SBND - Measurement of the BNB flux with Neutrino-elastic scattering

- Uncertainty on flux is one of the most relevant in neutrino experiments. Short distance allows high event rate and no oscillation signal, perfect condition for flux measurement.
- SBND detector near BNB source: Flux measurement with high precision through the **neutrino elastic scattering interaction** (well known cross section)

$$\nu + e \rightarrow \nu + e$$

very forward single electron final state





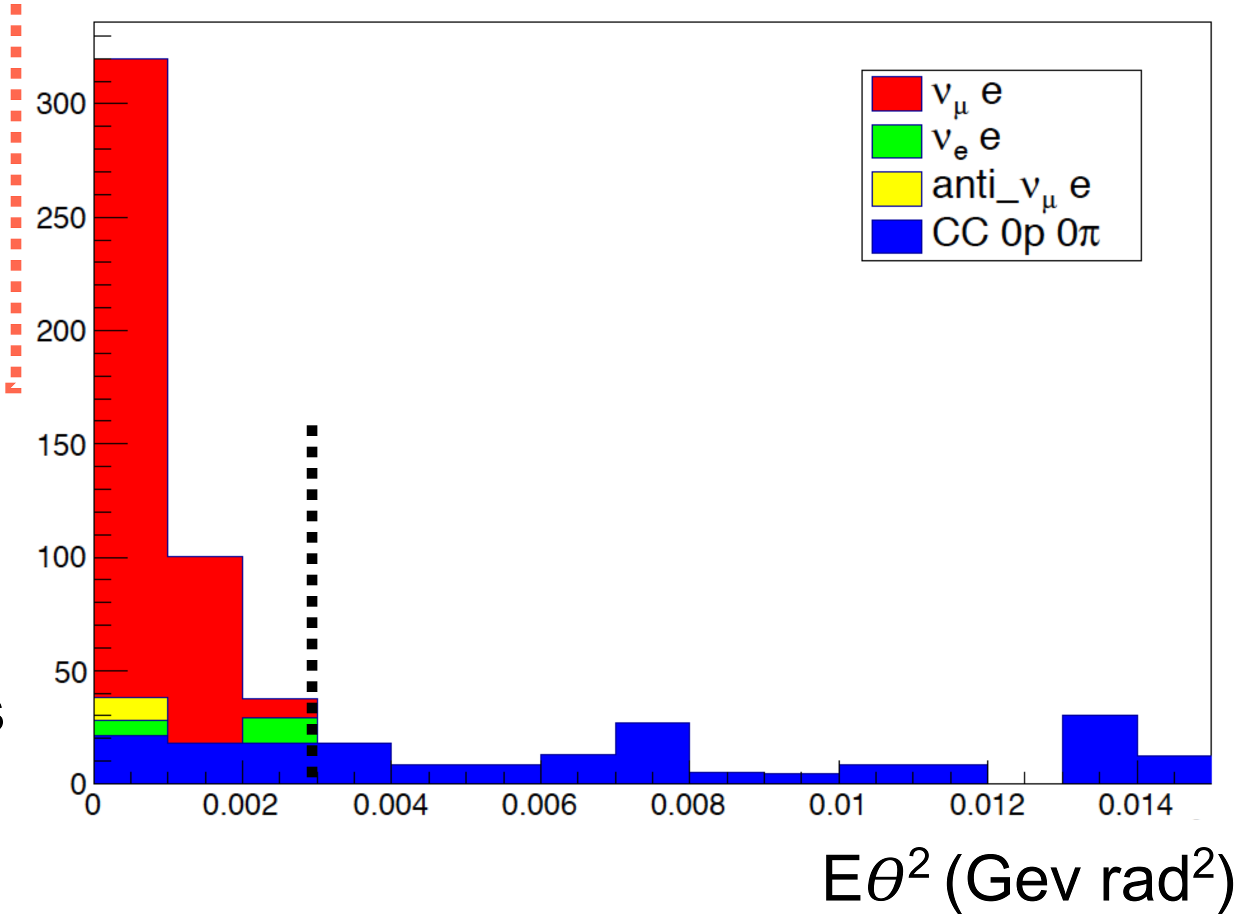
For 6.6 10^{20} POT:

Signal, ν-e scattering: 401 events

Background (ν_e CC 0 π) : 4534 events

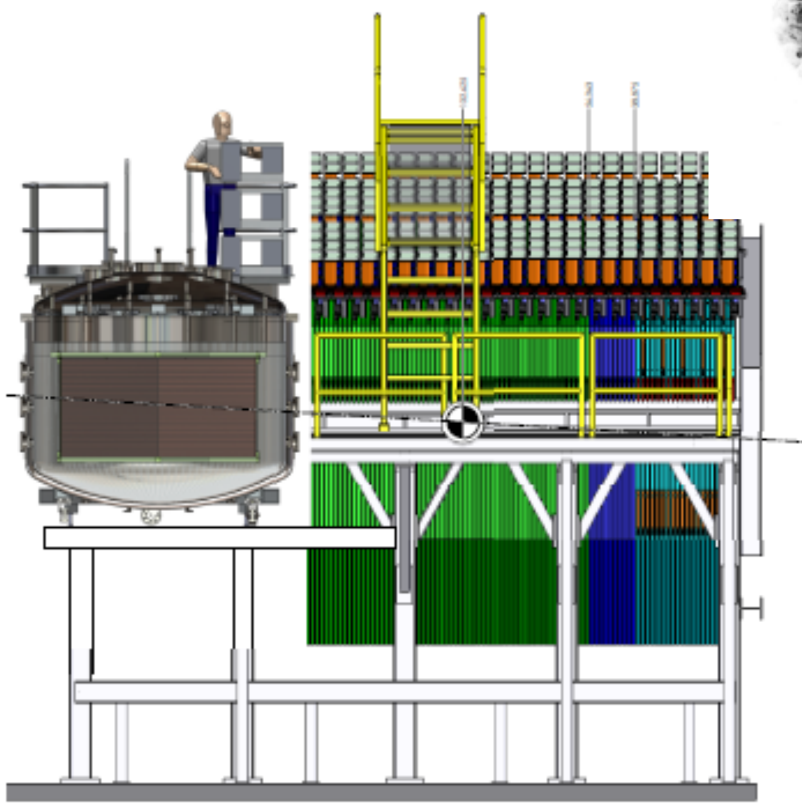
Cut on Eθ^2 very effective to reject background events

Eθ^2 cut



CAPTAIN/Minerνa

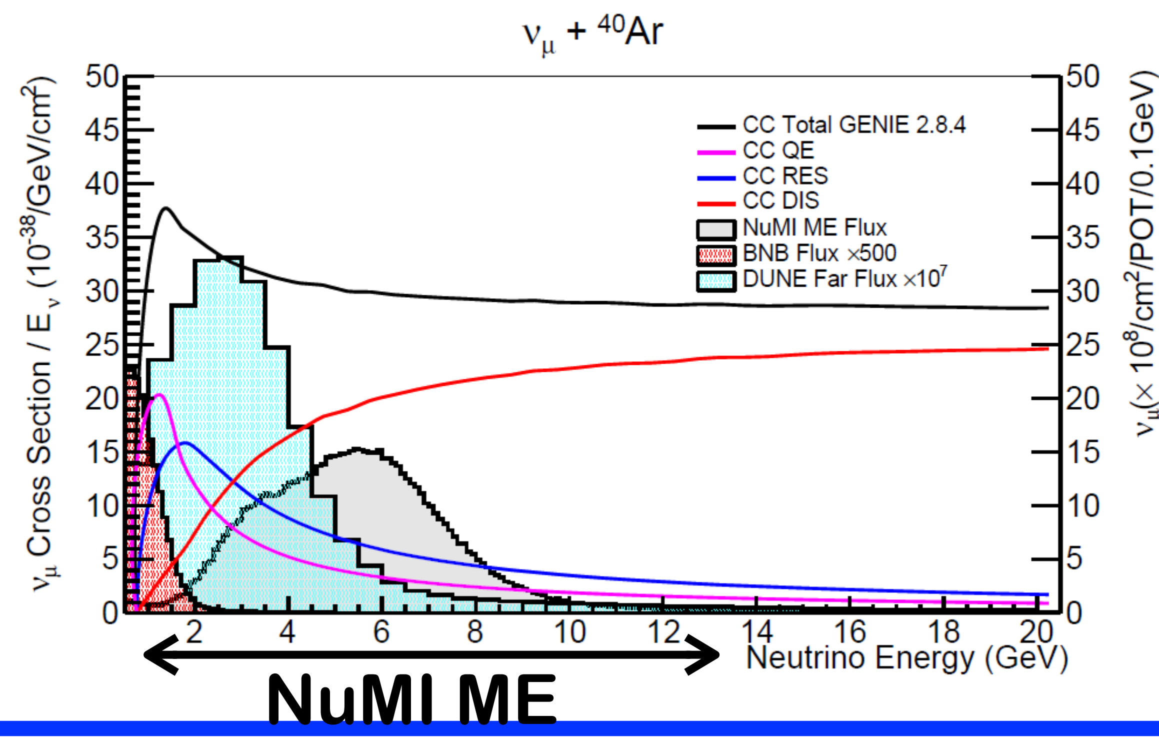
- Extend the physics reach of MINERvA by putting **5 tons of active LAr target** upstream of **6 or 9 ton scintillator target**
- High statistics measurements of **Ar/CH ratios** become available
- Direct probe of nuclear effects



For 6x10^{20} POT in neutrino mode	Contained Events in CAPTAIN	Contained events with muon in MINOS
CCQE-like	488k	255k-340k
CC1π^+	191k	59k-89k
CC1π^0	189k	48k-76k

Statistics in MINERνA will be comparable

- CAPTAIN is currently at Los Alamos, plan to commission at FNAL
- Received Stage I approval after June 2015, Fermilab PAC



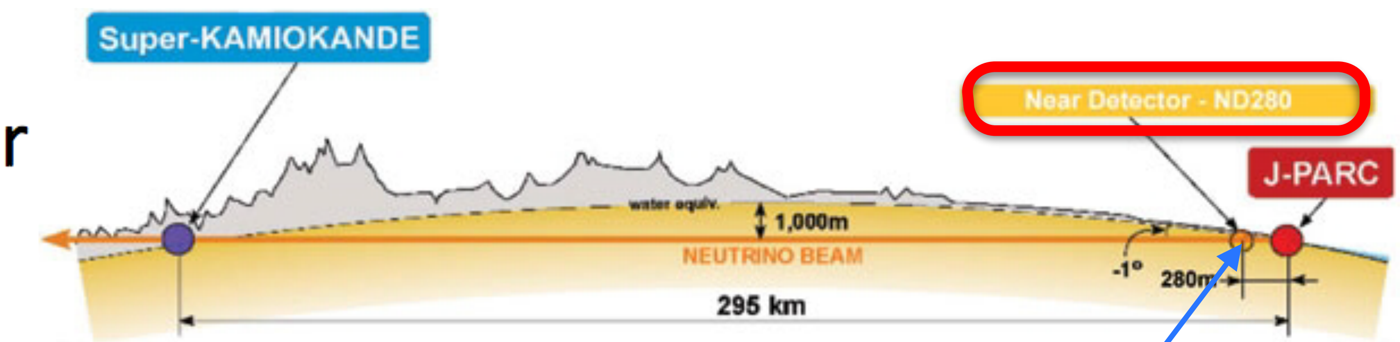
- CAPTAIN MINERνA will measure cross sections across a broad range of energies and processes
- CAPTAIN MINERνA can exploit fine granularity in both detectors to get exclusive channel cross section ratios

T2K ND upgrades

The largest systematic errors for T2K oscillation analyses are from neutrino interaction modeling

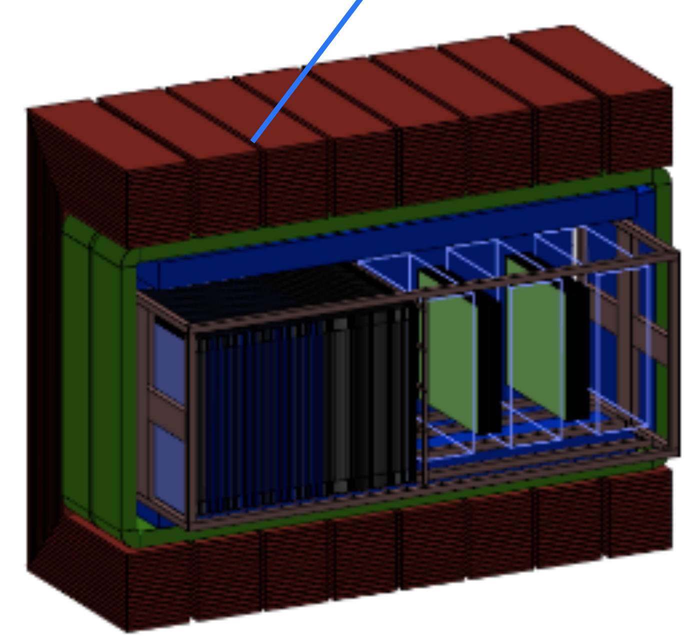
New ND280 Detectors

1. 3D grid water detector (WAGASCI - 2017)
2. High pressure TPC
3. Water based scintillator detector
4. Emulsion detector



Candidate intermediate detectors (1~2km from target)

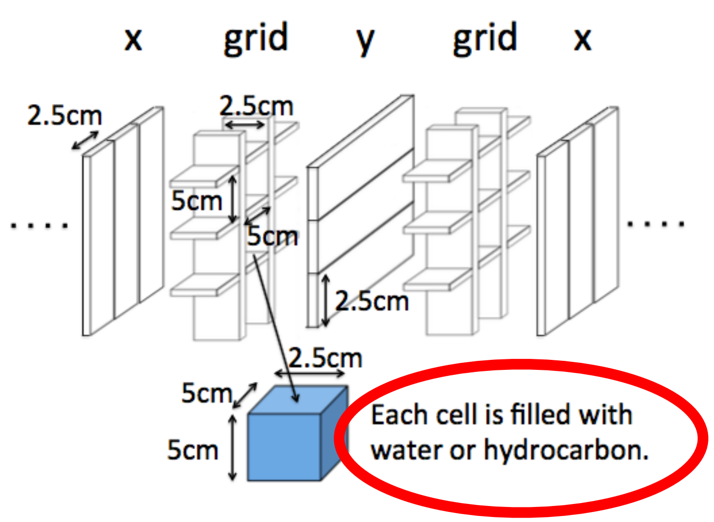
1. Water Cherenkov detector with wide off-axis angle coverage (νPRISM)
2. Gd-doped water Cherenkov detector

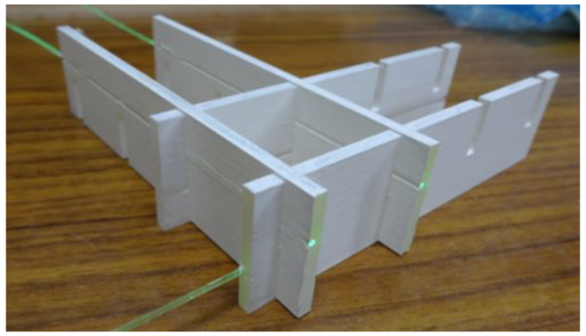


Near Detector

WAGASCI - 3D grid water Cherenkov detector

- 3D grid-like structure
  - x + grid + y + grid + ... layers
  - **4π angular acceptance** for charged particles
  - **H_2O(signal):CH(BG) = 79:21**

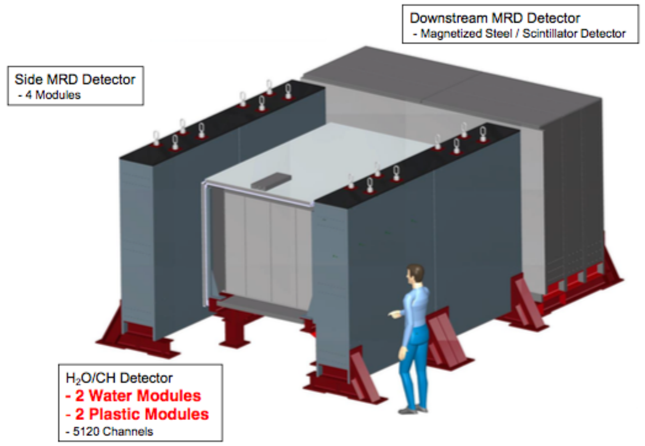




WLS fibers+MPPCs readout

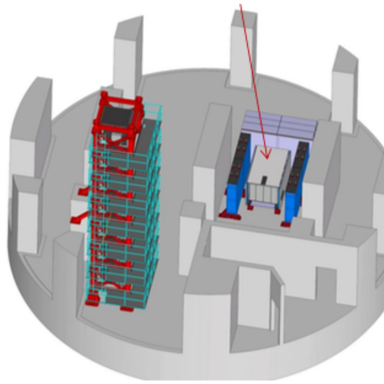
2.5 grid spacing allows to reconstruct short tracks originated from protons and charged pions with high efficiency

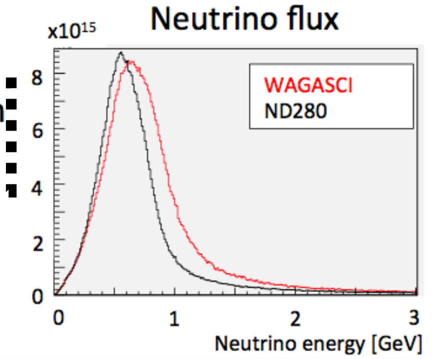
An approved test experiment by J-PARC PAC (T59).



B2 floor of ND280 pit

(Off-axis angle = 1.6 deg.)





Goals

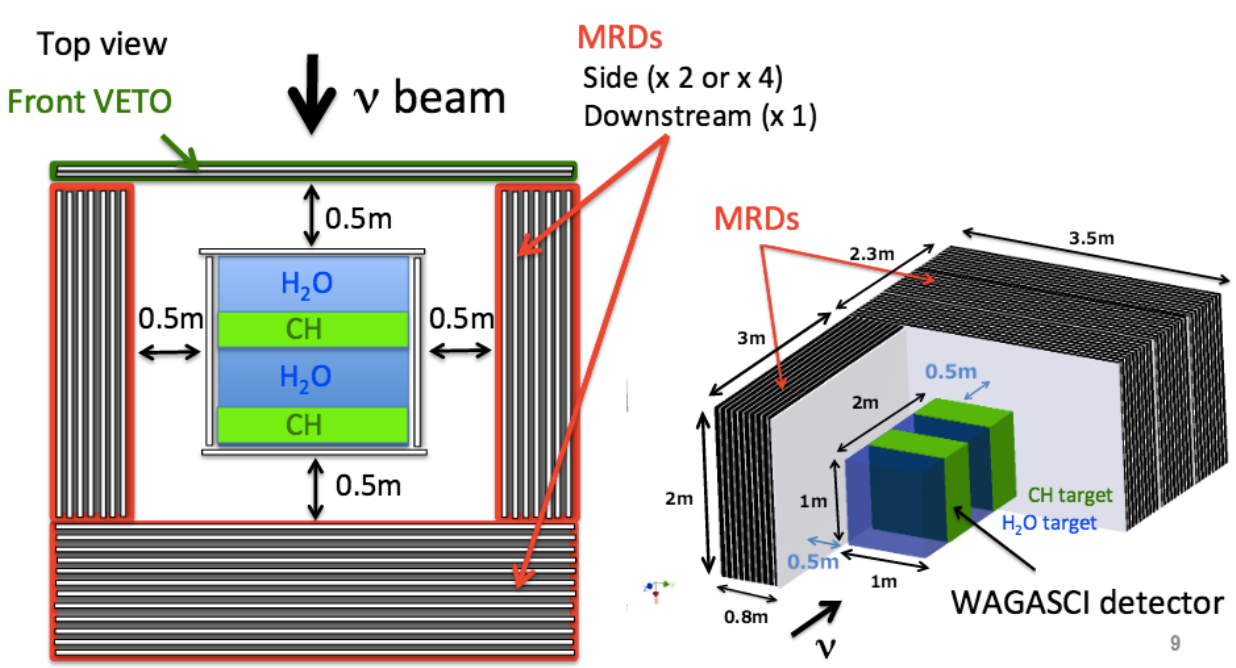
Measure cross section ratio between H_2O and CH with 4π acceptance/<3% error to increase T2K sensitivity.

Schedule

- 2016: Construction of detectors
- Early 2017: Start beam measurement

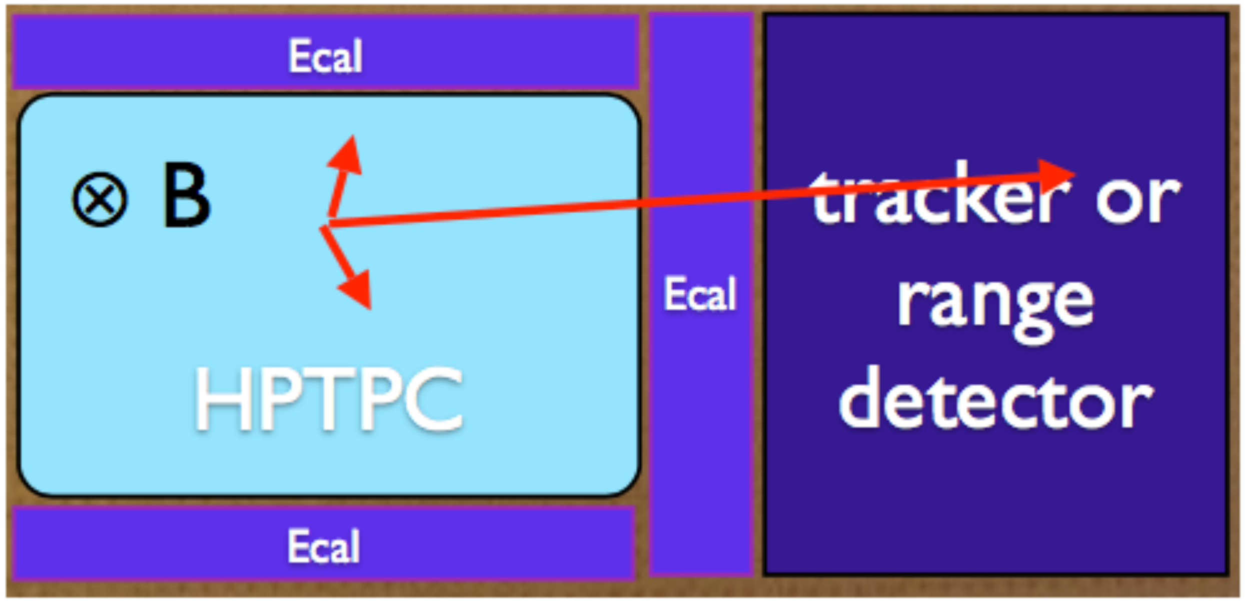
Detector configuration

- WAGASCI detector + muon range detectors (MRDs)
  - MRDs are located 50cm away from the WAGASCI detector to identify the charged particle directions from hit-timing diff. between the two detectors.



High-pressure gas TPC

- High-pressure TPC
  - Low thresholds. <100 MeV/c protons
    - ➔ Sensitive to hadronic final state.
  - excellent PID capabilities.
  - Momentum measurement.
  - Almost uniform 4π acceptance.



8m³ detector

# of CC events assuming full FV.

2x2x2 m³ 20°C		5 bars	10 bars
He		6.65 kg	13.3 kg
		520 evt/10^{21}pot	1040 evt/10^{21}pot
Ne		32.5 kg	67.1 kg
		2543 evt/10^{21}pot	5086 evt/10^{21}pot
Ar		66.5 kg	133 kg
		5203 evt/10^{21}pot	10406 evt/10^{21}pot
CF_4		146.3 kg	293 kg
		11450 evt/10^{21}pot	22893 evt/10^{21}pot

Expected ~1.6 10^{21} pot/year

- Goals
  - Multi-nucleon modeling.
  - Multi-pion resonance.
  - Final state interaction.
  - Secondary interaction in detector.

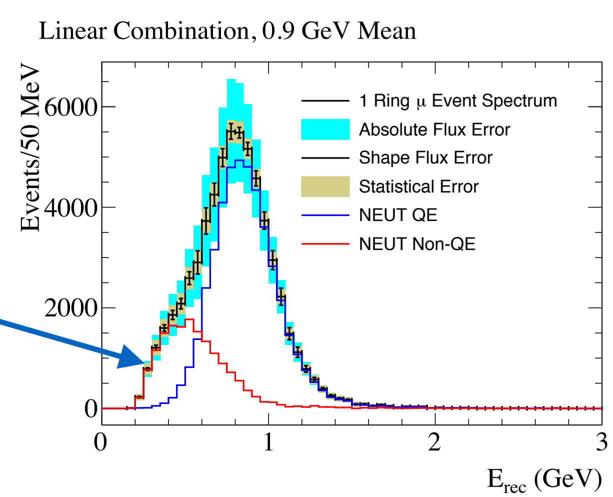
He, Ne, Ar, CF_4 targets to study A-dependence of cross sections and FSI

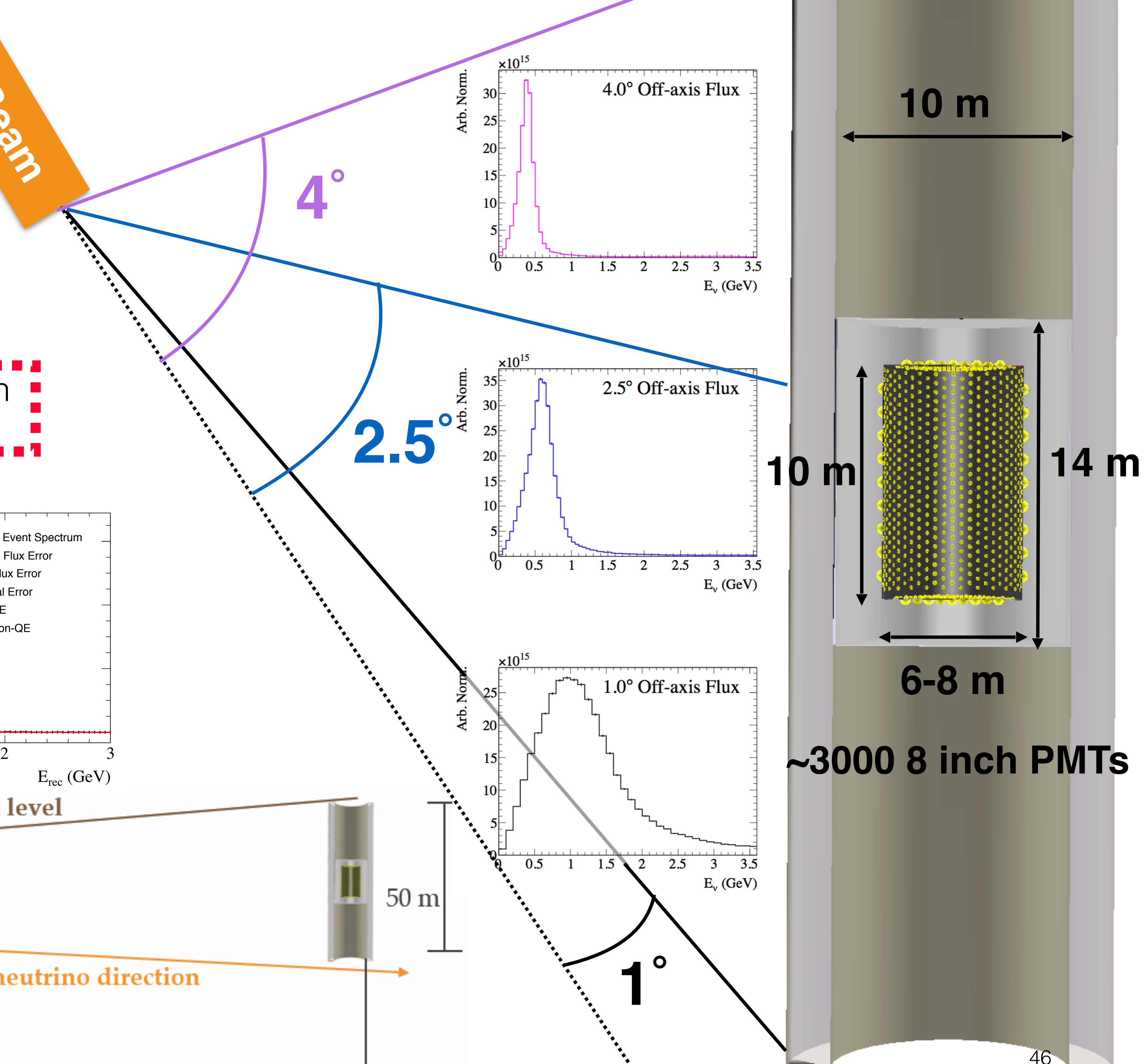
NuPRISM

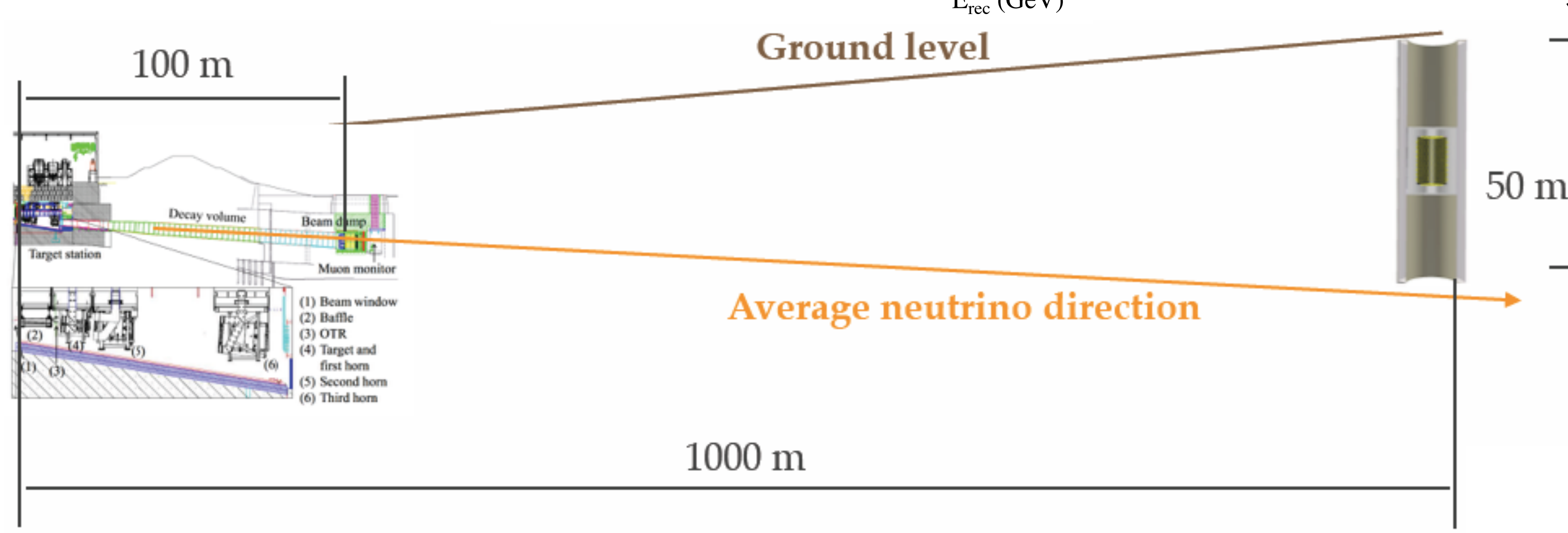
- **Water-Cherenkov** detector at **1 km in the J-PARC beam**
- Move up and down in the hall to take measurements at different off-axis angles
- Range of off-axis angles = Range of neutrino spectra
- Short-baseline ν_e appearance

Cross section measurements with **mono-chromatic beams**

Directly measure non-QE contributions







50 m height hall

Accelerator Neutrino Nucleus Interaction (ANNIE) Experiment @ FNAL BNB

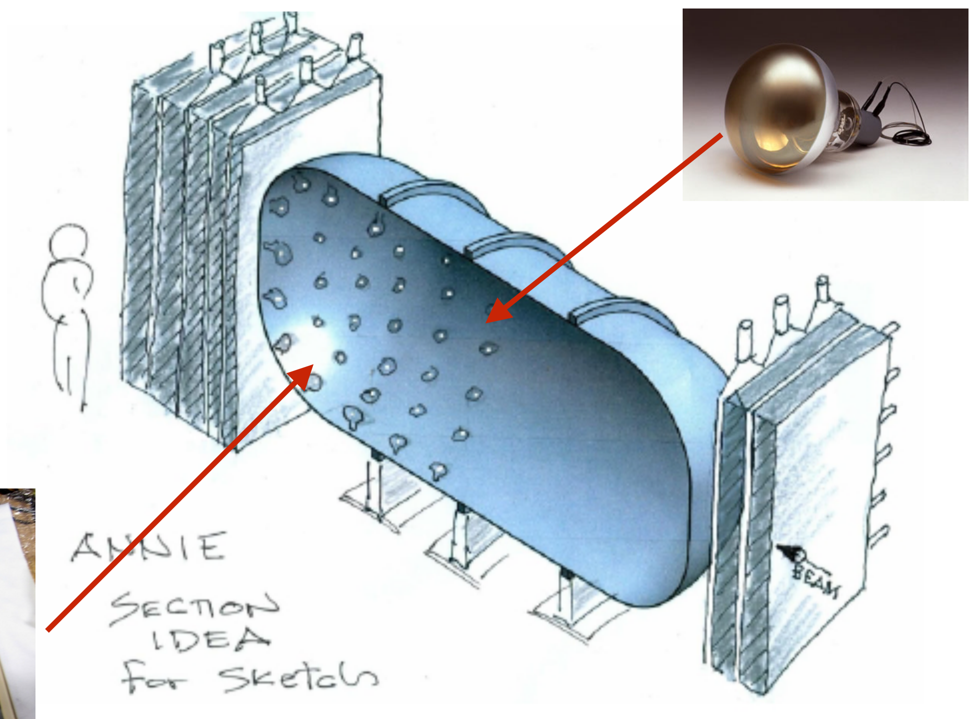
Primary physics objective:

Measurement of the abundance of final state neutrons ("neutron yield") from neutrino interactions in water, as a function of energy.

(~1 year)

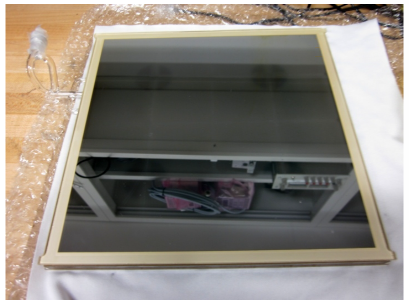
ν-type	Total Interactions	Charged Current	Neutral Current
ν_μ	9892	6991	2900
$\bar{\nu}_\mu$	130	83	47
ν_e	71	51	20
$\bar{\nu}_e$	3.0	2.0	1.0

Gadolinium-loaded water (~20 t)

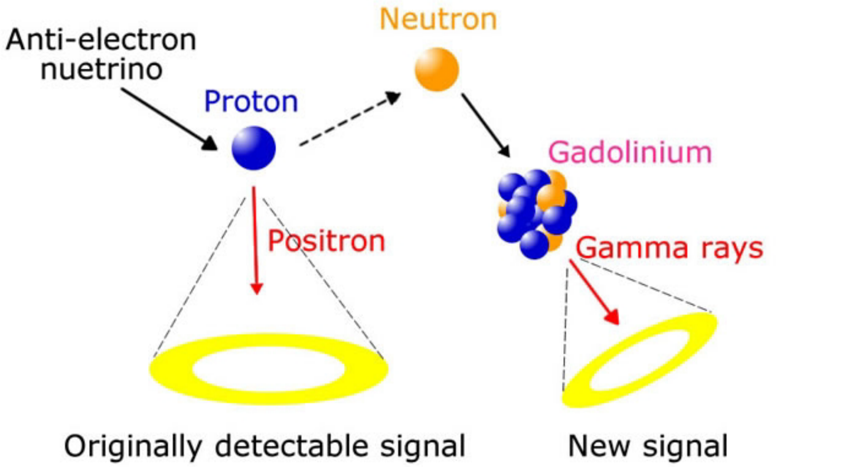


R. Northrop

LAPPDs ~100
8 inch squares
x 10 – 20

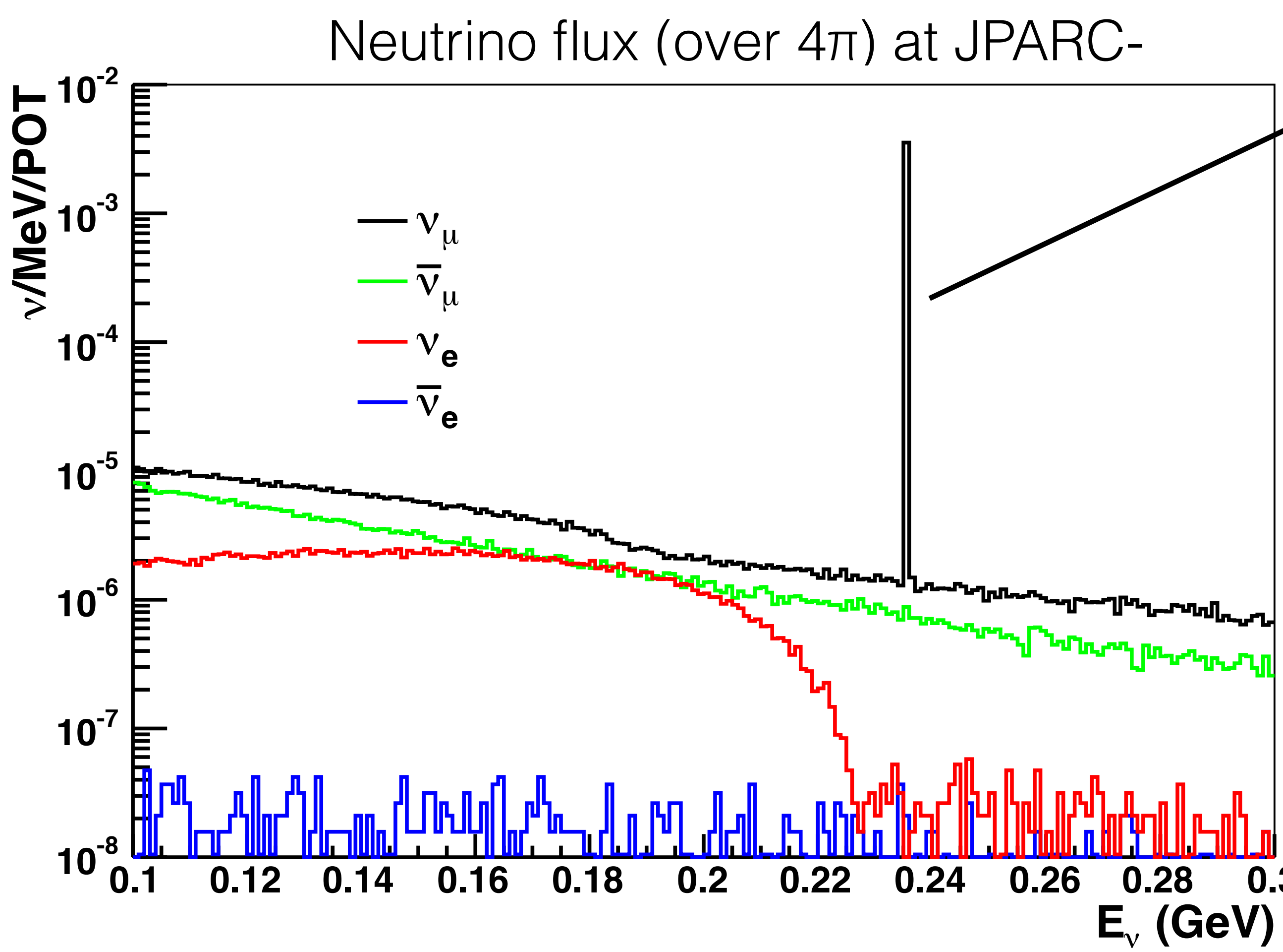


- First in situ test of **Large Area Picosecond Photo-Detectors** (LAPPDs) in a **water Cherenkov** experiment.
- First use of a **Gadolinum-doped WC** detector in a ν beam.



- ANNIE Phase I proposal approved by Fermilab PAC
- Application to future WC experiments (e.g., Hyper-Kamiokande)
  - Beam program can benefit from a new near detector similar to ANNIE (**TITUS** - 2 Kt Gd doped WC - proposal, ND for HyperK beam program)

Cross section measurements with monoenergetic ν_μ



236 MeV ν_μ from $K^+ \to \mu^+\nu_\mu$ (BR=63.6%) decay at rest

- Use this neutrino as a probe of the nucleus and as a standard candle for cross section and energy reconstruction near 236 MeV.
- For the first time ever:

  1. probe the nucleus with a known-energy, weak-interaction-only particle.

  2. measure ω (energy transfer) with neutrinos as a test of the underlying nuclear model.

Detector (source)	Target (mass)	Exposure	Distance from source	236 MeV ν_μ CC events
MicroBooNE (NuMI dump)	LAr (90 ton)	1.2×10^{21} POT (2 years)	102 m	2300
JSNS^2 (JPARC-MLF)	Gd-LS (50 ton)	1.875×10^{23} POT (5 years)	24 m	152000

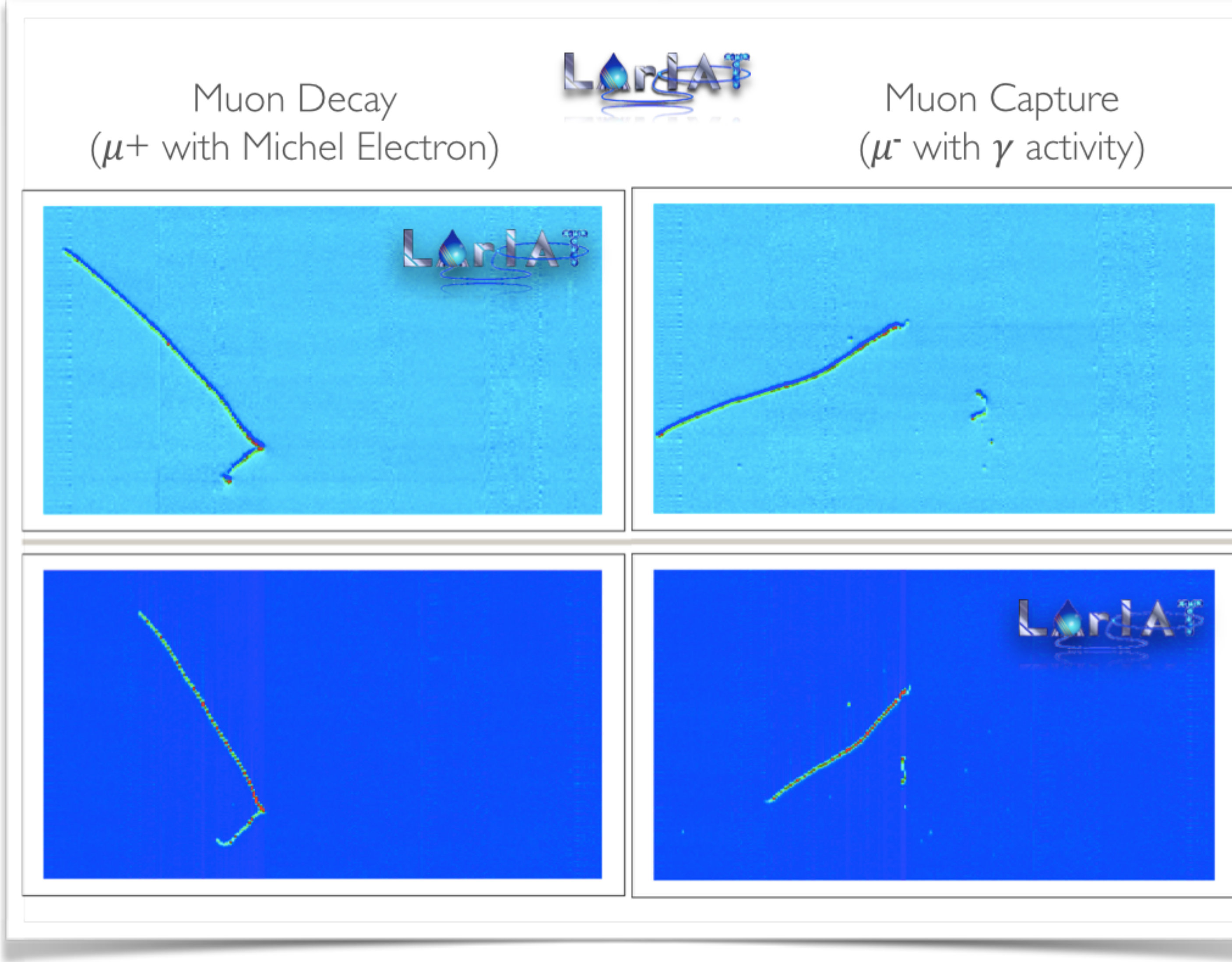
Received Stage-1 approval from the KEK and J-PARC in April 2015.
Expected taking data within 3 years.
R&D to produce lightly-doped, **gadolinium-loaded liquid scintillator** for detecting both Cerenkov and scintillation light.

J. Spitz, Phys. Rev. D 89 073007 (2014)

A look ahead...
Some ideas/technology challenges (I)

- Low energy cross section measurements at Spallation Neutron Source (in LAr TPC)

- R&D
  - LAr TPC test beam measurements: LArIAT experiment (FNAL, 2015-2016) and ProtoDUNE experiment (CERN, 2018)
  - LAr TPC R&D (ex. combining ionization charge and scintillation light, muon sign determination from capture vs decay - LArIAT test beam program)
  - Gd doped WC/LS in neutrino beam
  - Large area Picosecond Photo-Detectors (LAPPDs) for neutrino detectors
  - High pressure gas TPCs

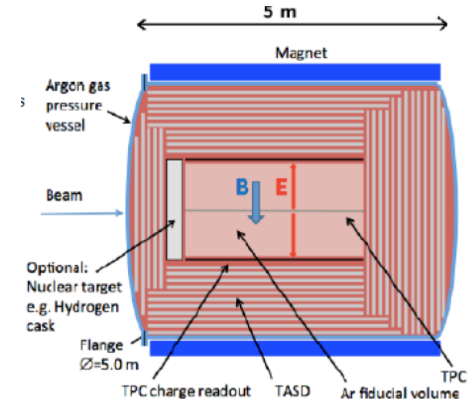


A look ahead…
Some ideas/technology challenges (II)

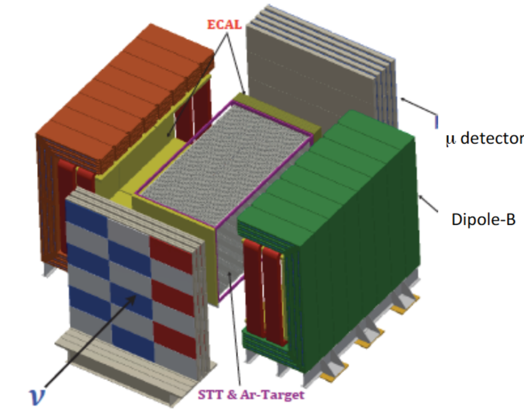
- DUNE Near Detector (technology choice to be taken)
  - Straw Tube Tracker
  - Gaseous Ar TPC
  - LAr TPC

- R&D program to **magnetize a large volume LAr TPC** (great improvement to the LAr TPC technique!)
  - A SC magnetic field of ~1 Tesla introduced inside the LAr volumes
  - Goal: particle charge identification and the momentum measurement (including **electrons**), complementing the multiple scattering technique presently used for muons.
  - Magnetic field in the vertical direction, orthogonal to the electric field direction, resulting in a track curvature along the drift time plane.

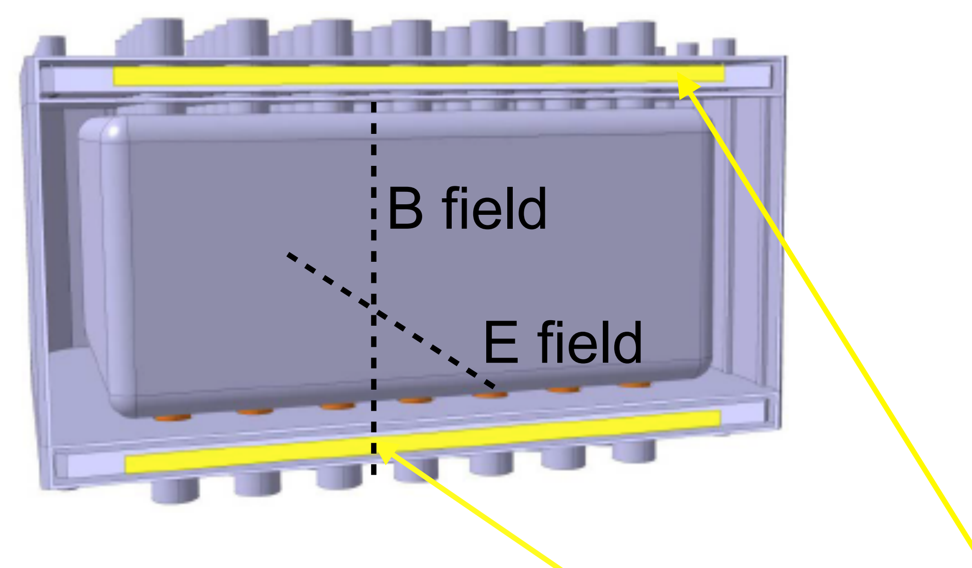
HP TPC



High Precision Magnetized Neutrino Detector



Magnetized LAr TPC



Ex: Double Racetrack Magnet

Conclusion

Precise **Neutrino-nucleus cross section measurements** are crucial for the success of the ν program moving forward (ν oscillations + also SN ν detection)

Many ideas for new measurements!

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

Studies of neutrino interactions are fascinating… a lot of fun ahead of us !

Backup

SBND - ν CC 0 pion events