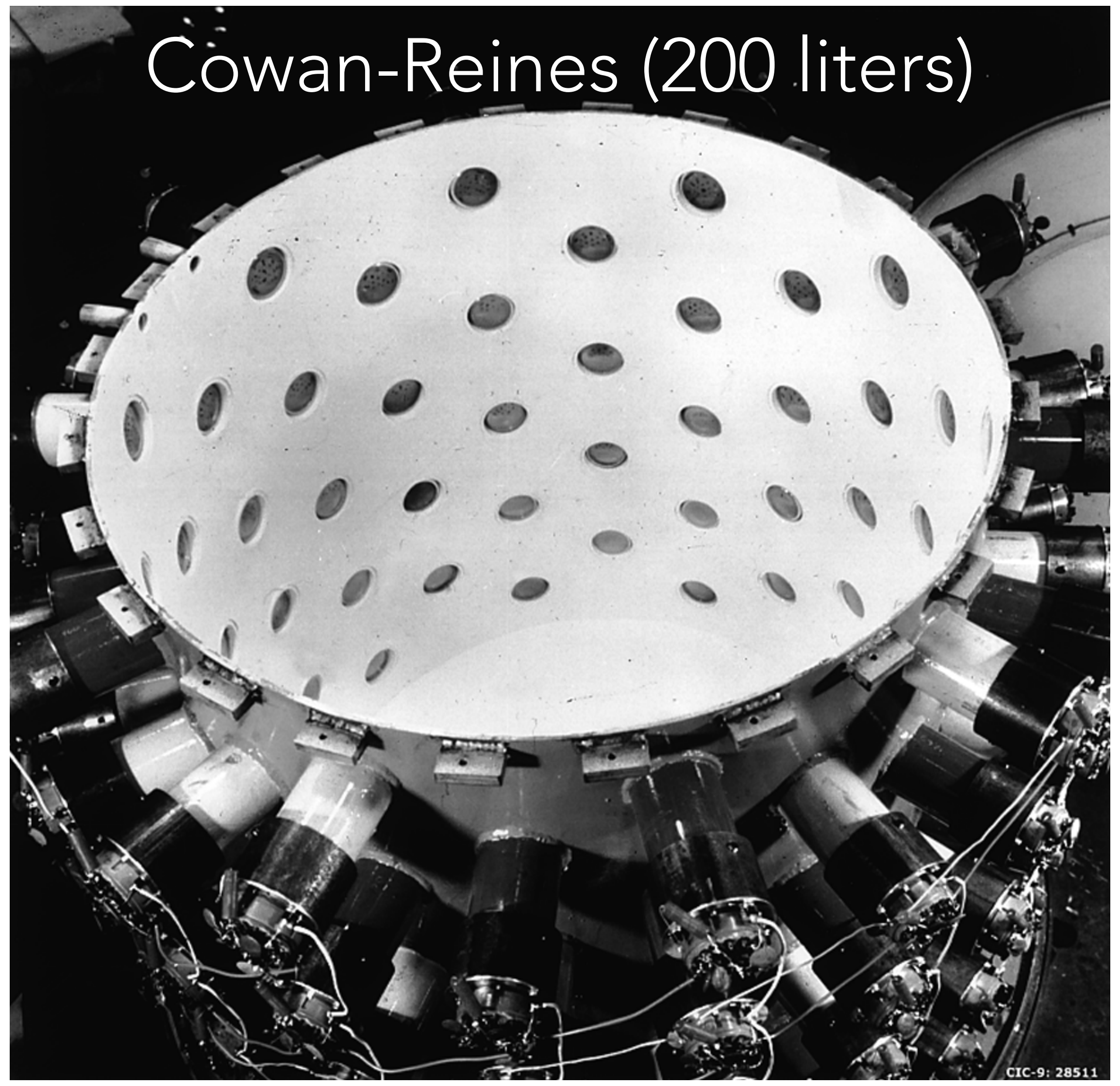
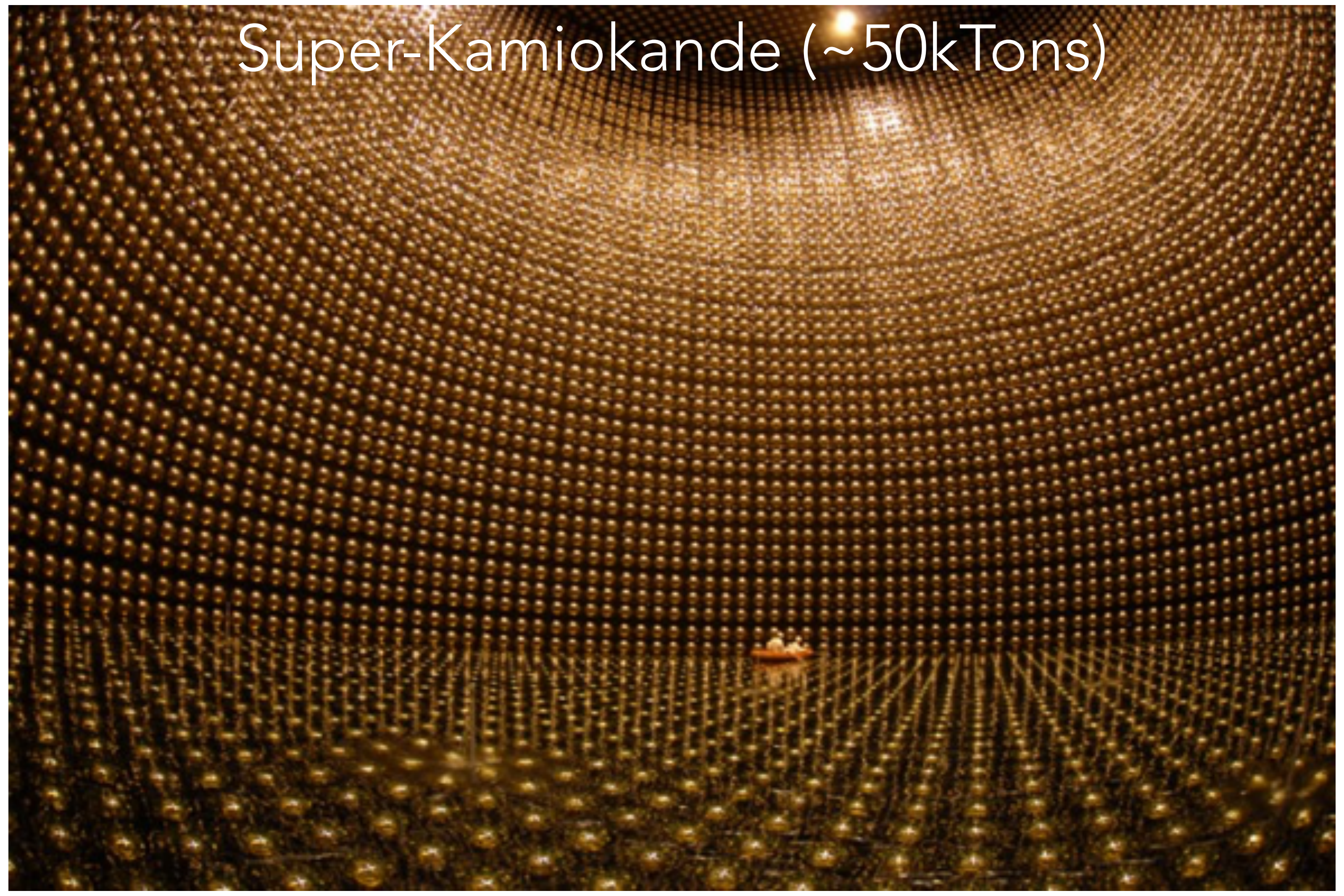
INSTRUMENTATION AND NEUTRINO MASS

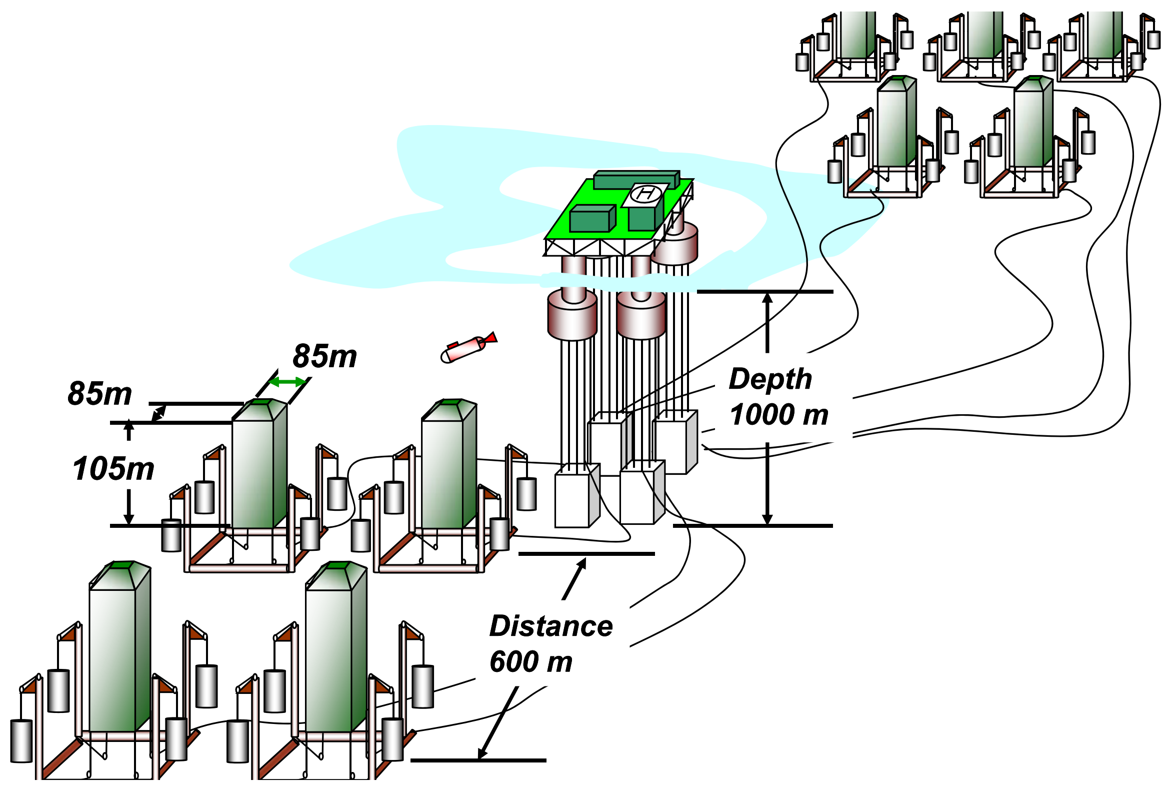
MITCH SODERBERG
SYRACUSE UNIVERSITY
OCTOBER 5, 2015

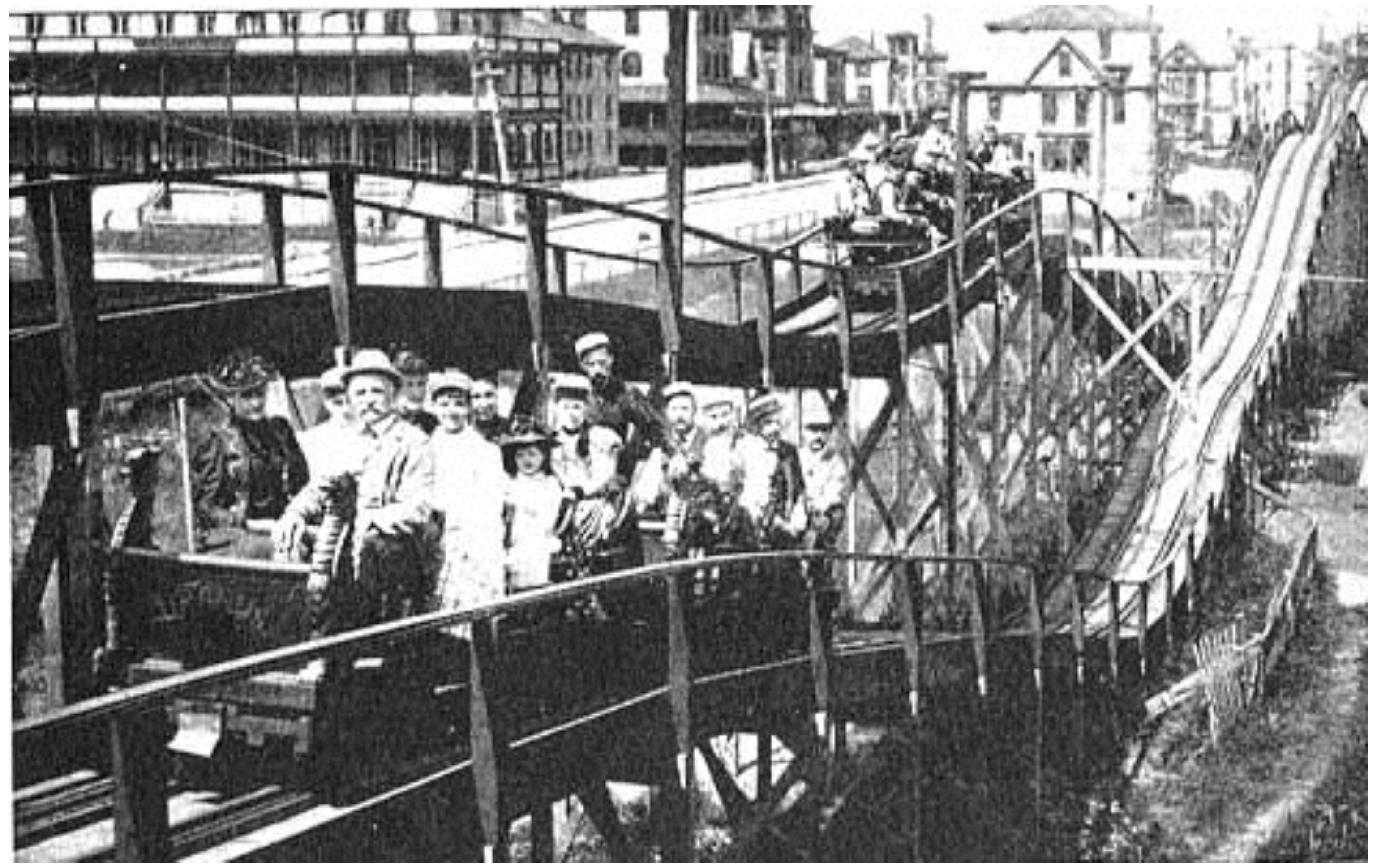
INNOVATION IN INSTRUMENTATION HAS DRIVEN DISCOVERY IN NEUTRINO PHYSICS





Deep-TITAND (~5 MTon), Y. Suzuki





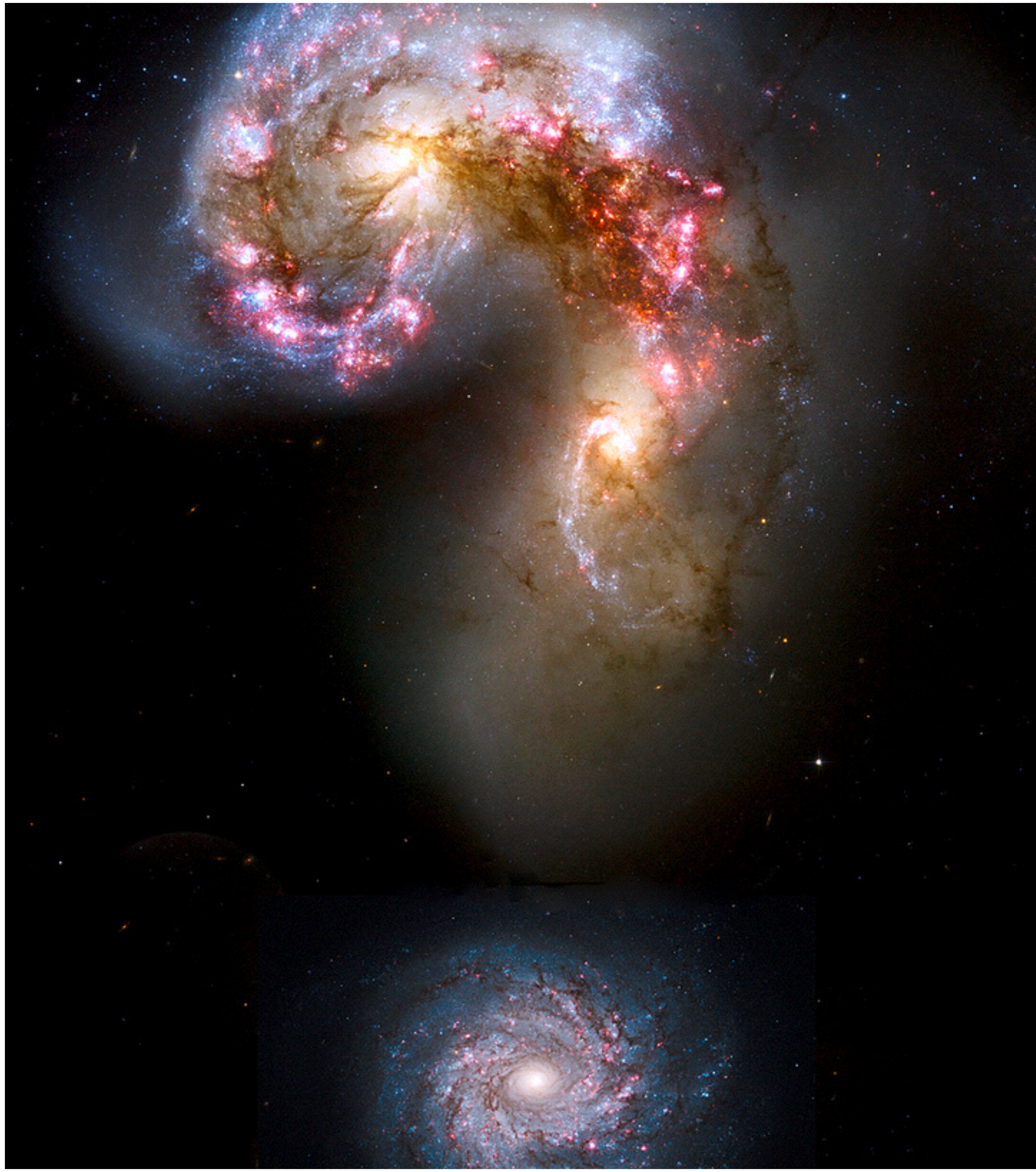
Titan @ Six Flags Over Texas.
A"hypercoaster"
(>200 ft. drop)

OUTLINE

I. What can we learn from neutrinos?

II. What are we planning for the future?

III. What are the challenges/opportunities in instrumentation and detectors?



WHAT CAN WE LEARN FROM NEUTRINOS?

FROM THE P5 REPORT

Pursue the physics associated with neutrino mass:

The U.S. is well positioned to host a world-leading neutrino physics program. Its centerpiece would be a next generation long-baseline neutrino facility (LBNF). LBNF would combine a high-intensity neutrino beam and a **large-volume precision detector sited underground a long distance away** to make accurate measurements of the oscillated neutrino properties. This large detector would also search for proton decay and neutrinos from supernova bursts. A powerful, wideband neutrino beam would be realized with Fermilab's PIP-II upgrade project, which provides very high intensities in the Fermilab accelerator complex. **Short-distance oscillation experiments, cosmic surveys, and a variety of other small experiments will also make important progress in answering these questions**.

NEUTRINOS

NEUTRINOS

- A thriving area of research. Can’t cover everything.

NEUTRINOS

- A thriving area of research. Can't cover everything.
- I've chosen a few topics based on my personal biases…apologies to those whose activities are not covered.

NEUTRINOS

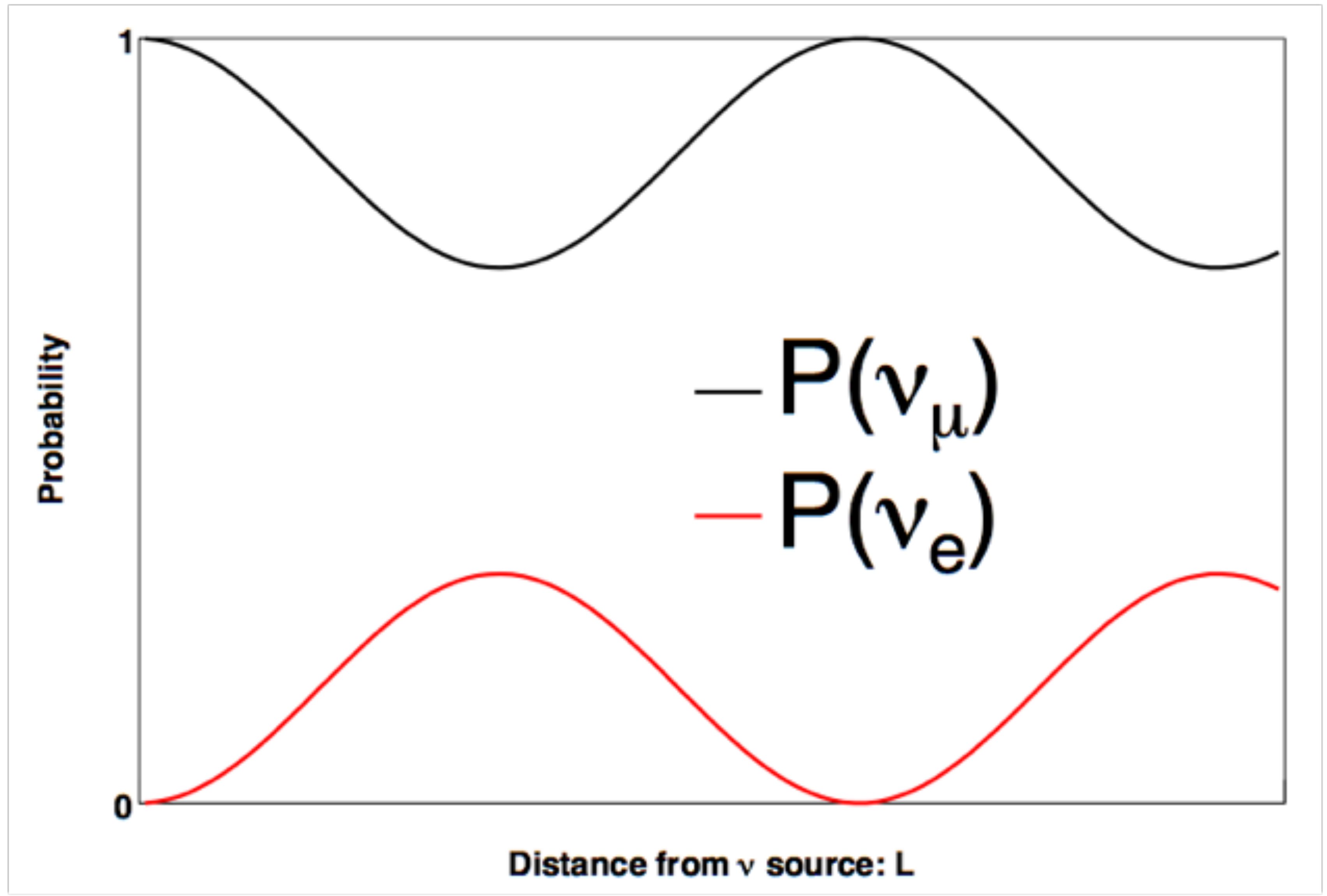
- A thriving area of research. Can't cover everything.
- I've chosen a few topics based on my personal biases…apologies to those whose activities are not covered.
- Talks during dedicated neutrino session this afternoon will have lots more details on specific experiments. Please attend!

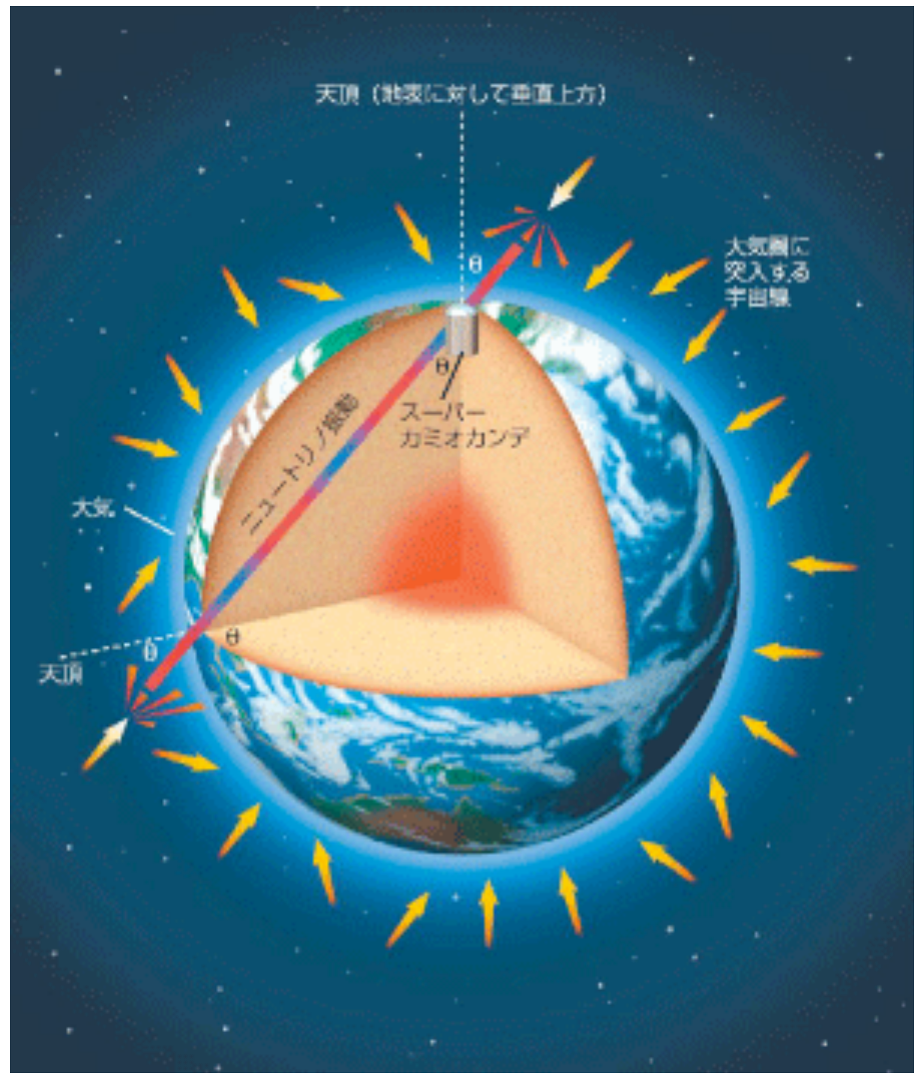
NEUTRINOS

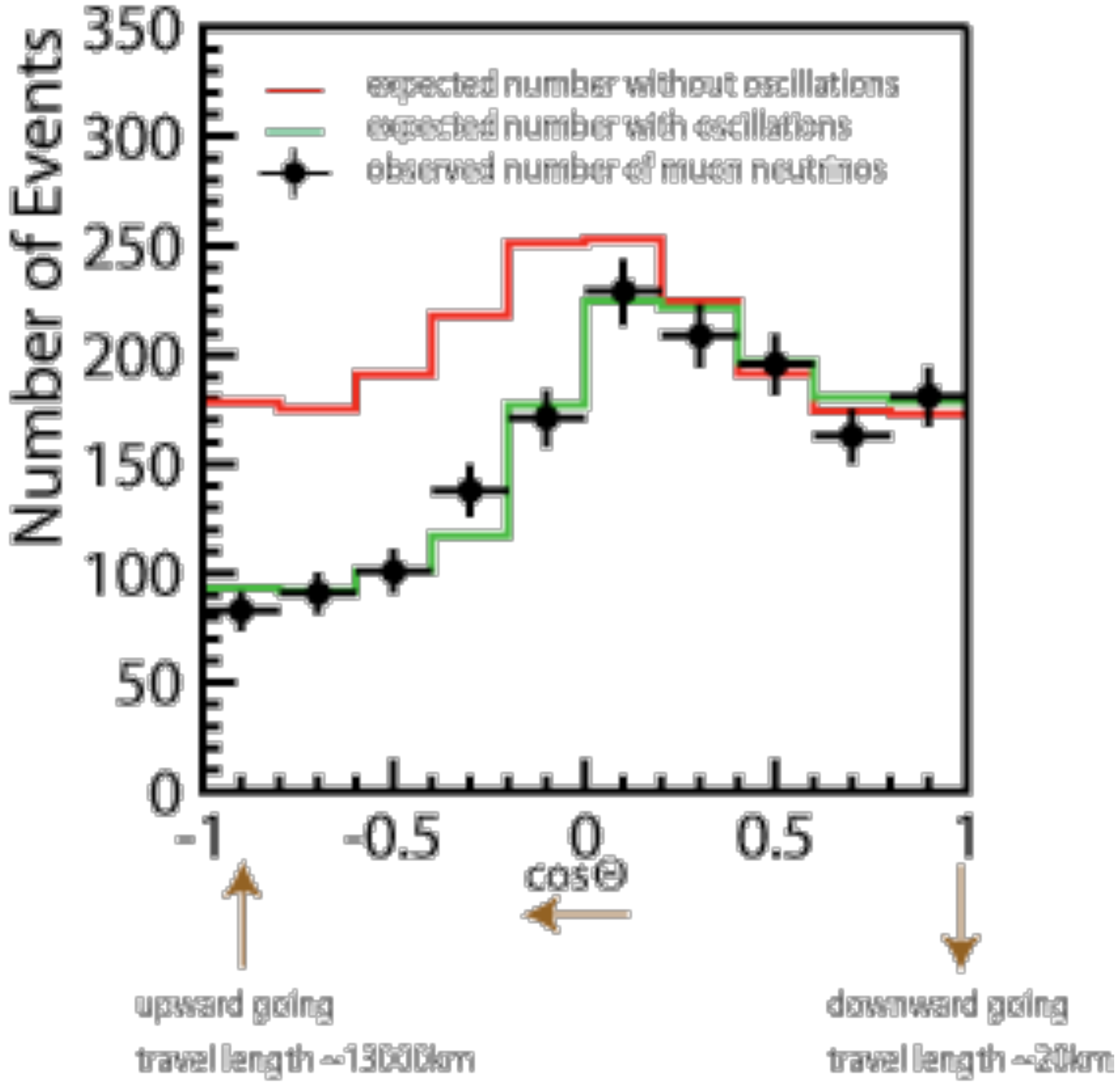
- A thriving area of research. Can't cover everything.
- I've chosen a few topics based on my personal biases…apologies to those whose activities are not covered.
- Talks during dedicated neutrino session this afternoon will have lots more details on specific experiments. Please attend!
- Let's start with a very brief review of the interesting physics for those who only think of the neutrino as "missing E_T".

NEUTRINOS HAVE MASS!

- This "recent" discovery drives much of the excitement in our field.
- Non-zero mass implied by quantum-mechanical mixing of flavor and mass eigenstates.







$$P_{osc} = \sin^2(2\theta)\sin^2(1.27\frac{\Delta m^2 L}{E})$$

NEUTRINOS: OSCILLATION PARAMETERS

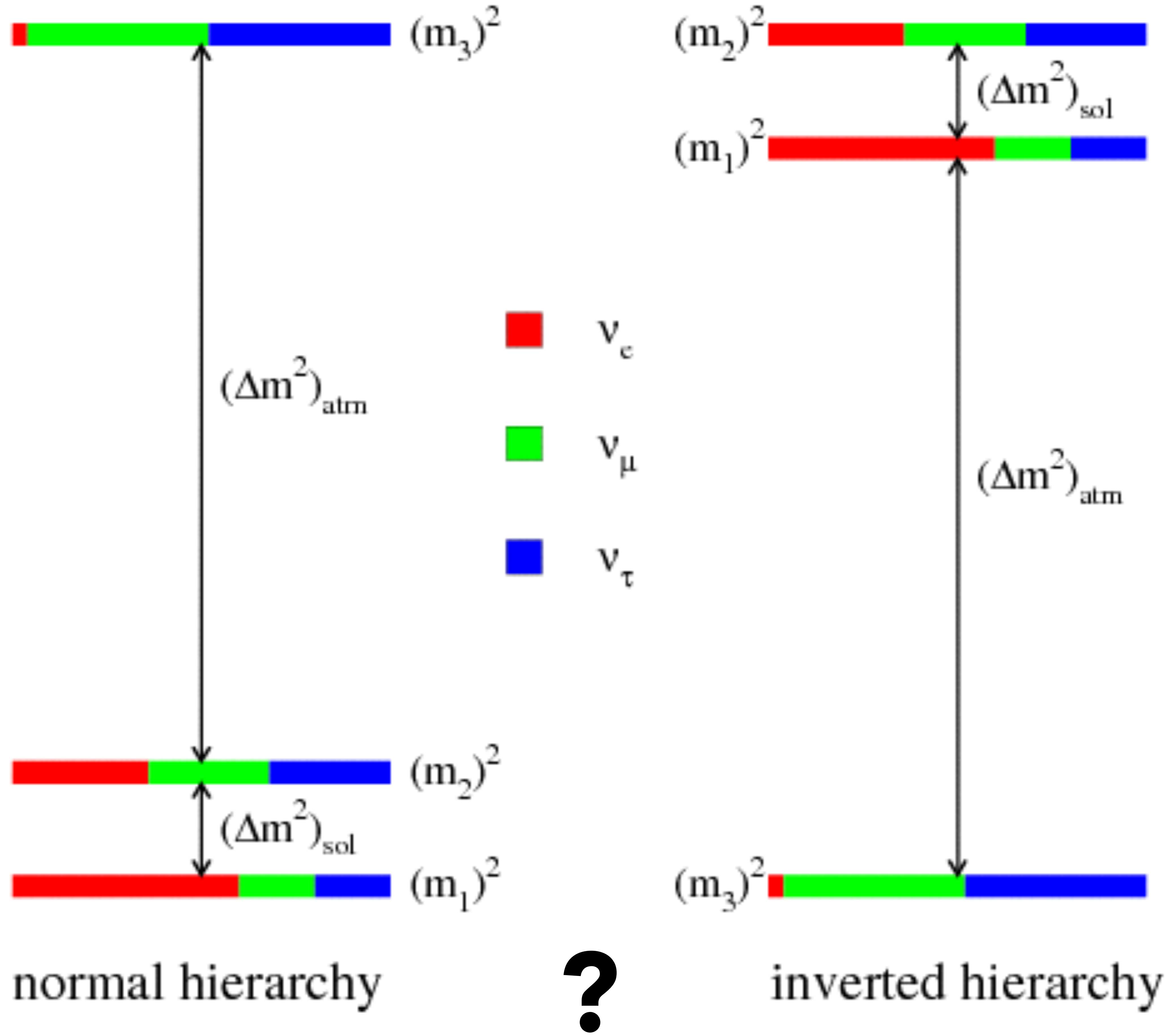
$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$$

Flavor state — Mass state

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) Mixing Matrix:

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(\theta_{23}) & \sin(\theta_{23}) \\ 0 & -\sin(\theta_{23}) & \cos(\theta_{23}) \end{pmatrix} \times \begin{pmatrix} \cos(\theta_{13}) & 0 & \sin(\theta_{13})e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin(\theta_{13})e^{i\delta} & 0 & \cos(\theta_{13}) \end{pmatrix} \times \begin{pmatrix} \cos(\theta_{12}) & \sin(\theta_{12}) & 0 \\ -\sin(\theta_{12}) & \cos(\theta_{12}) & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

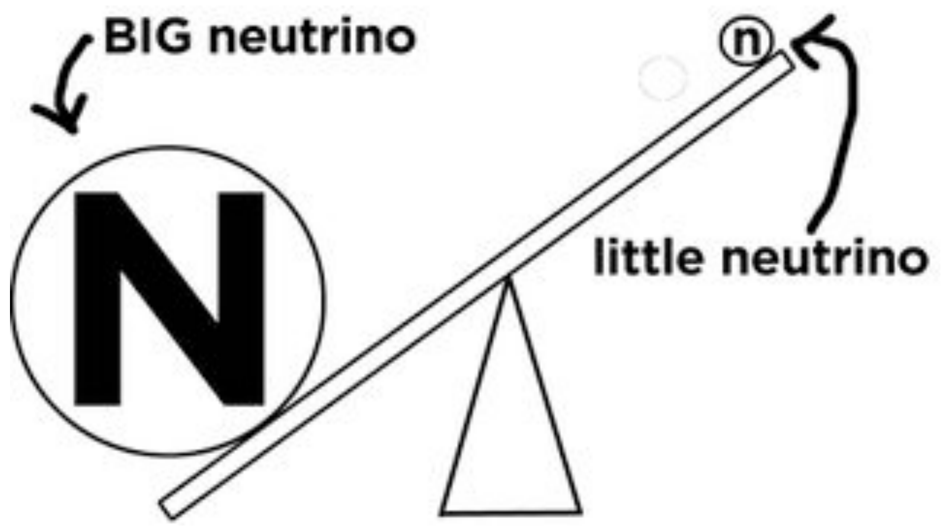
$\Delta m_{21}{}^2$	$(7.53\pm0.18)\times10^{-5}$ eV^2
$\Delta m_{23}{}^2$	$(2.44\pm0.06)\times10^{-3}$ eV^2
$\sin^2(2\theta_{12})$	0.846 ± 0.021
$\sin^2(2\theta_{23})$	$0.999^{+0.001}_{-0.018}$
$\sin^2(2\theta_{13})$	0.093 ± 0.008
δ_{CP}	CP Violation?

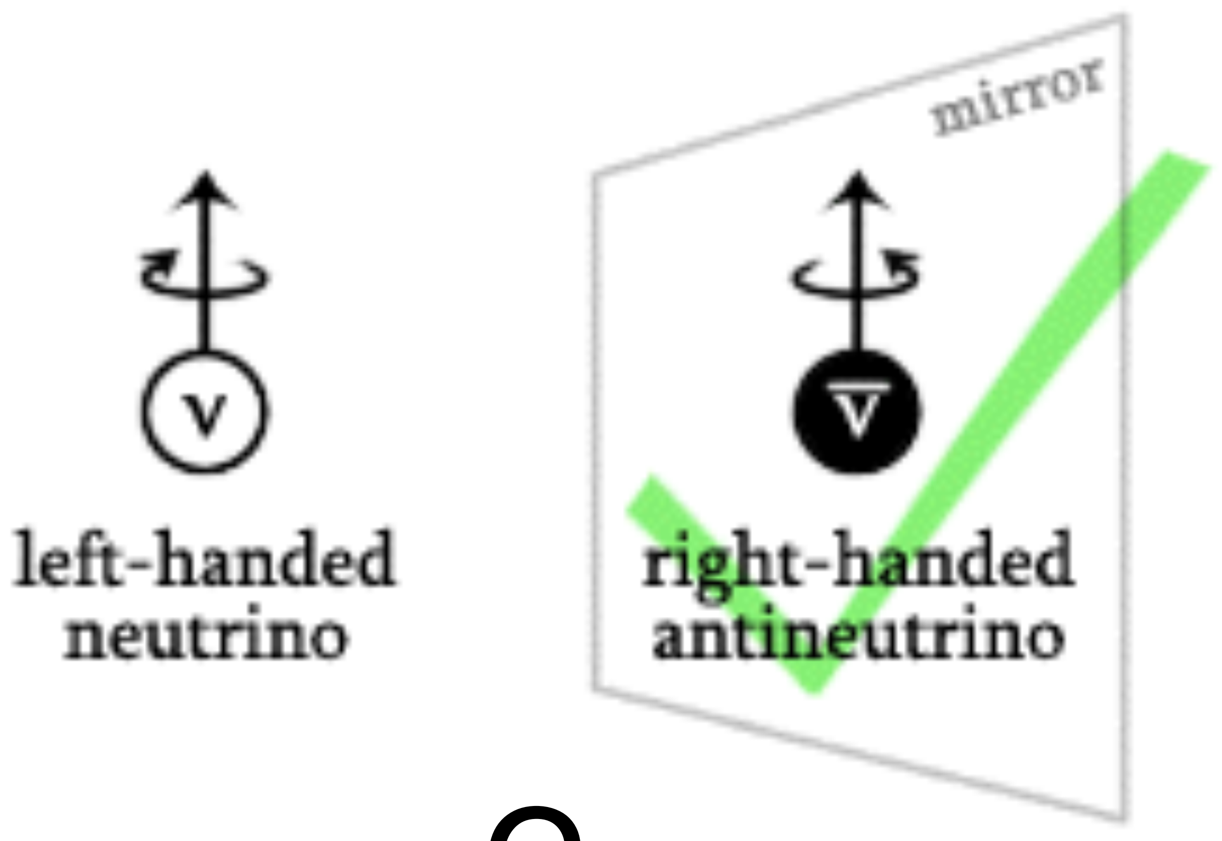


Refs:
1.) K.A. Olive et al. (Particle Data Group), Chin. Phys. C38, 090001 (2014)

NEUTRINOS: CP-VIOLATION?

- We know neutrinos violate Parity in a maximal fashion.
- "Leptogenesis"+"Seesaw" - Postulates very heavy right-handed neutrinos (N) with masses near the GUT (10^{15} GeV) scale, were produced in the Big Bang and undergo a leptonic decay that violates CP. Imbalance of charged-leptons gets converted into observed baryon asymmetry we observe today.
- Would like to know if neutrinos of Standard Model violate CP symmetry.





?

NEUTRINOS: PROPERTIES

Refs:
1.) KATRIN: A next generation tritium beta decay experiment with sub-eV sensitivity for the electron neutrino mass: LOI, KATRIN Collaboration, hep-ex/0109033
2.) Planck 2013 results. XVI. Cosmological Parameters

NEUTRINOS: PROPERTIES

- Absolute mass yet to be measured.

Refs:
1.) KATRIN: A next generation tritium beta decay experiment with sub-eV sensitivity for the electron neutrino mass: LOI, KATRIN Collaboration, hep-ex/0109033
2.) Planck 2013 results. XVI. Cosmological Parameters

NEUTRINOS: PROPERTIES

- Absolute mass yet to be measured.
- Constraints from astrophysics (*e.g.* Planck) give an upper limit for $\Sigma\nu$ of 0.933 eV at 95% C.L.

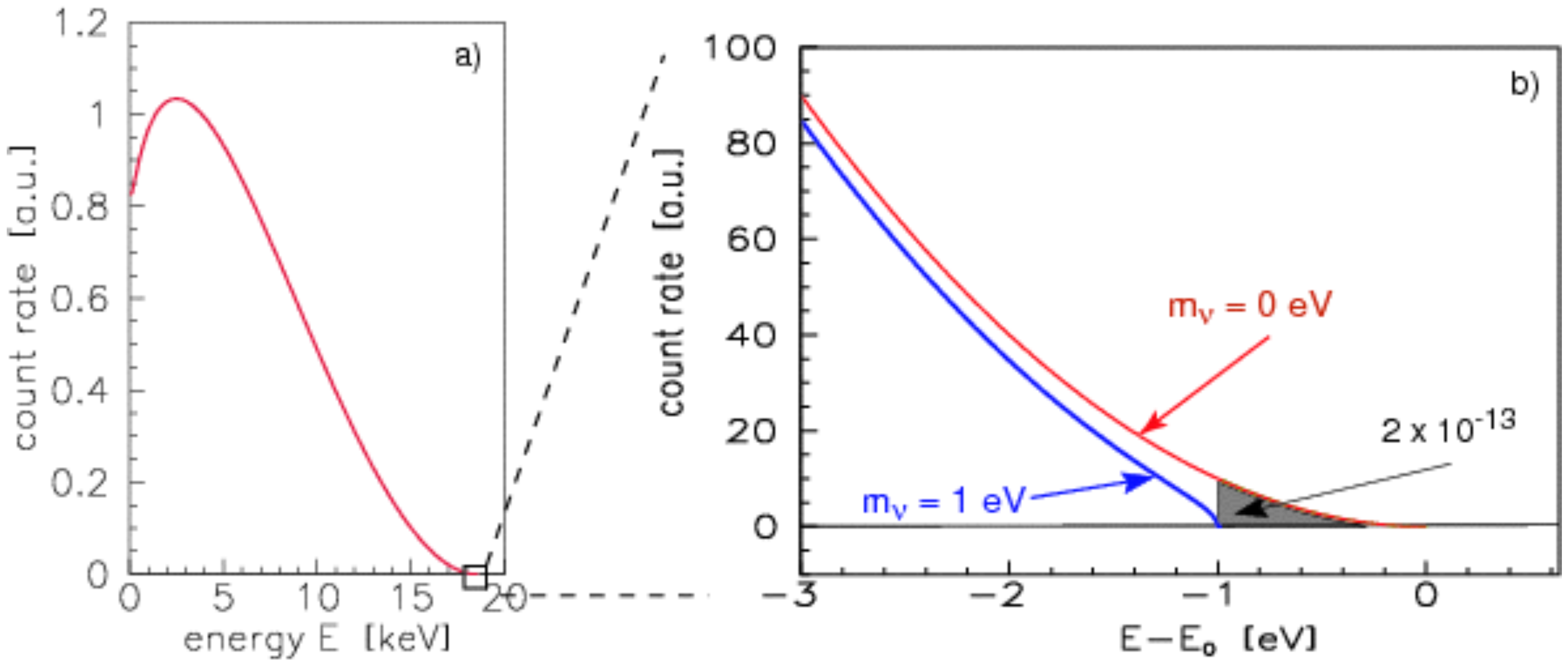
Refs:

1.) KATRIN: A next generation tritium beta decay experiment with sub-eV sensitivity for the electron neutrino mass: LOI, KATRIN Collaboration, hep-ex/0109033

2.) Planck 2013 results. XVI. Cosmological Parameters

NEUTRINOS: PROPERTIES

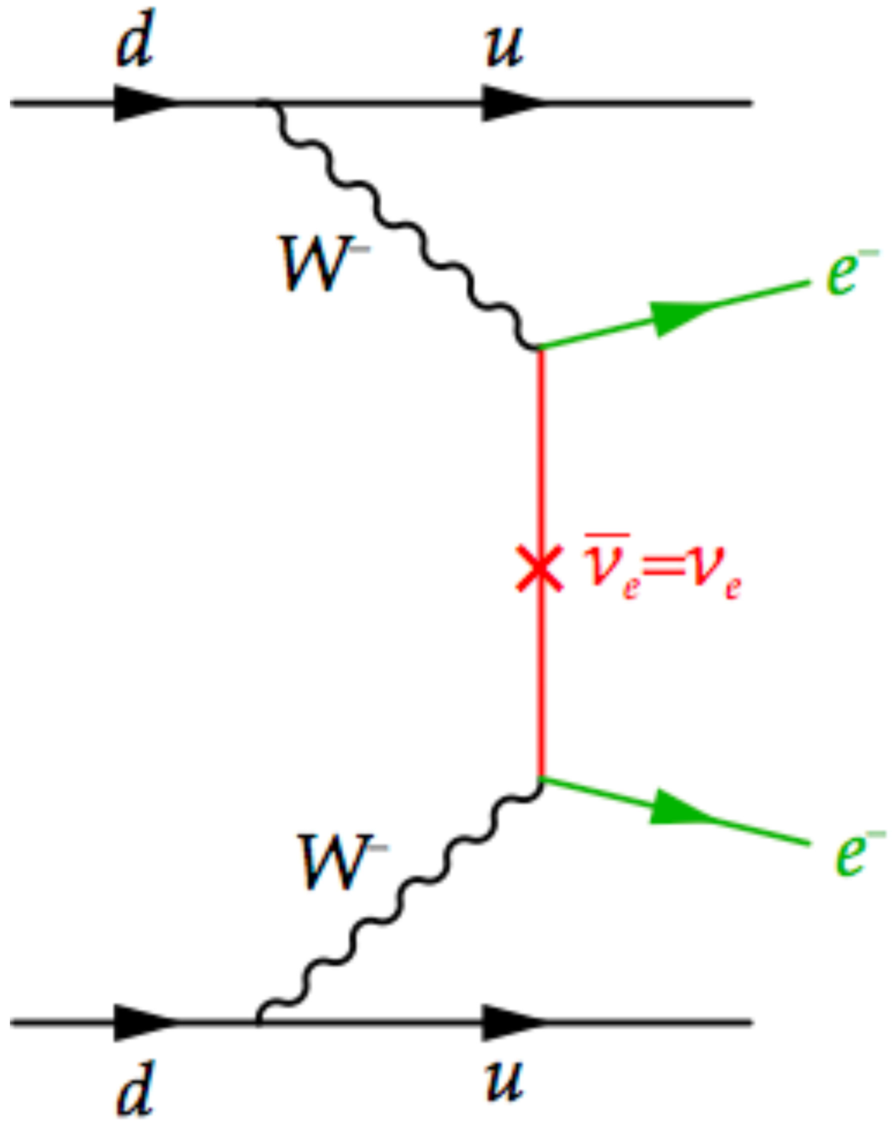
- Absolute mass yet to be measured.
- Constraints from astrophysics (*e.g.* Planck) give an upper limit for Σν of 0.933 eV at 95% C.L.
- Precision measurements of beta-decay allow direct probe of mass.

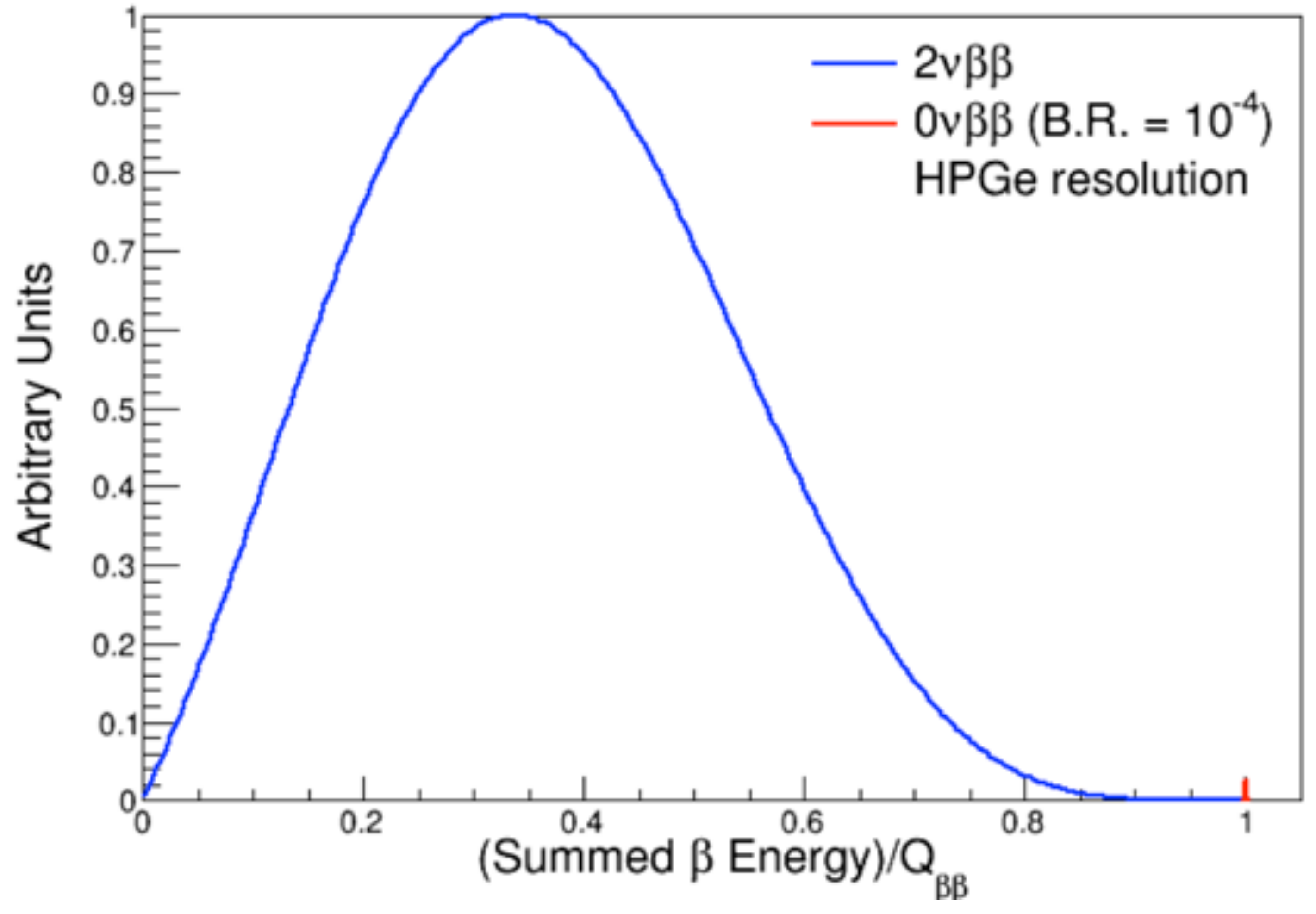


Refs:
1.) KATRIN: A next generation tritium beta decay experiment with sub-eV sensitivity for the electron neutrino mass: LOI, KATRIN Collaboration, hep-ex/0109033
2.) Planck 2013 results. XVI. Cosmological Parameters

NEUTRINOS: PROPERTIES

- Absolute mass yet to be measured.
- Constraints from astrophysics (*e.g.* Planck) give an upper limit for **Σν** of 0.933 eV at 95% C.L.
- Precision measurements of beta-decay allow direct probe of mass.
- Majarona or Dirac nature also undetermined. If Majarona, should be able to observe neutrino-less double-beta decay.



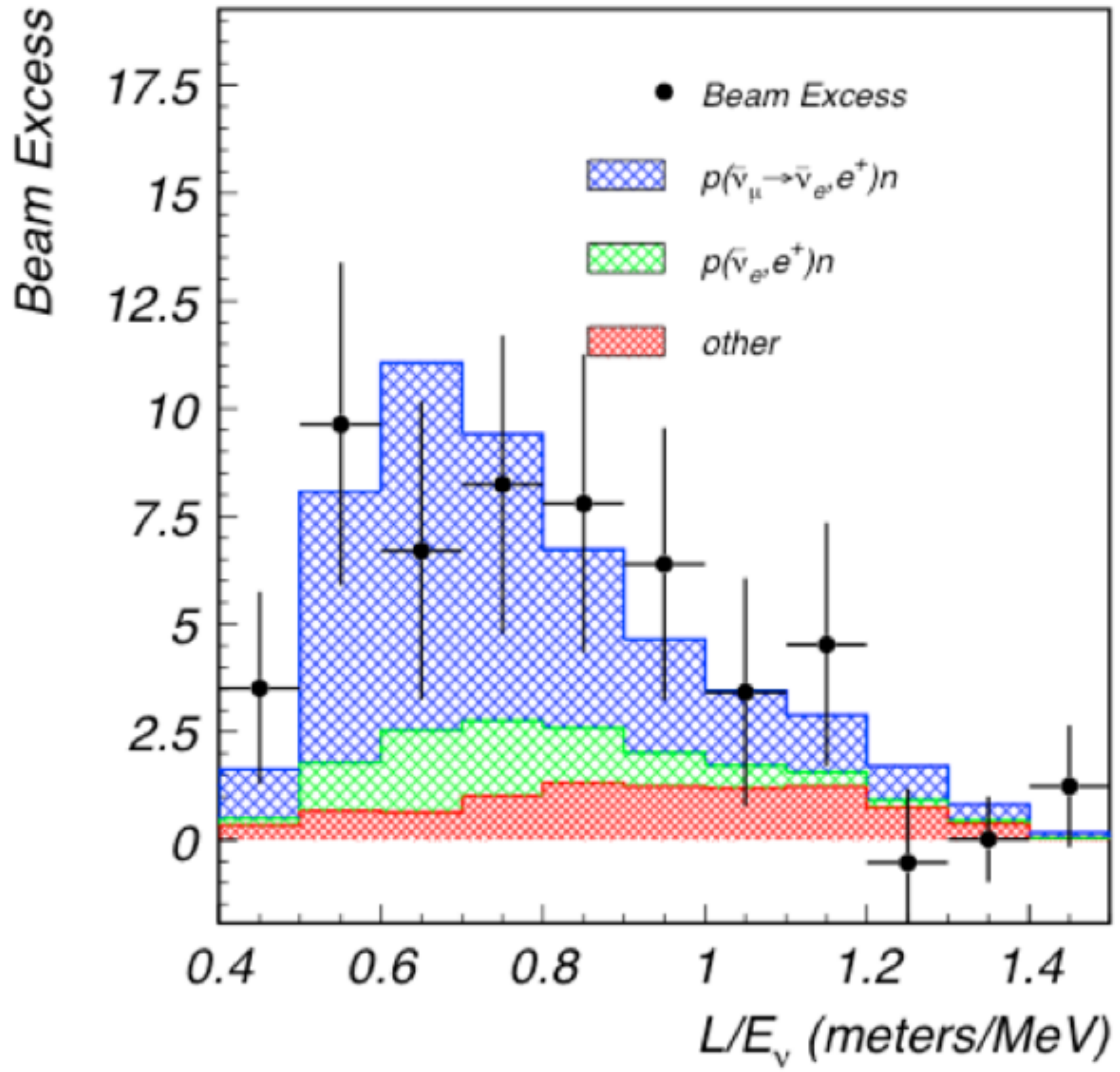


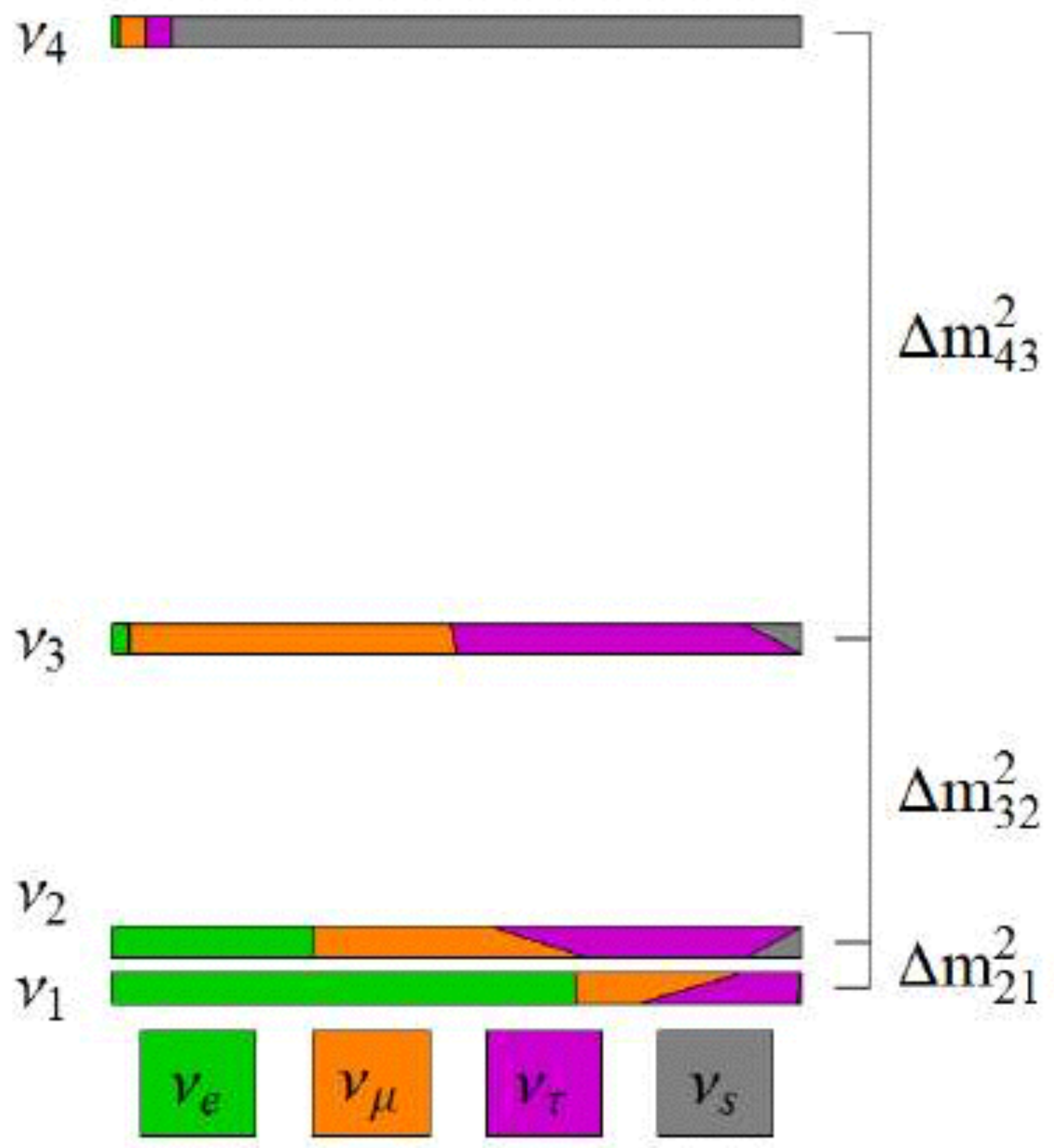
Refs:
1.) KATRIN: A next generation tritium beta decay experiment with sub-eV sensitivity for the electron neutrino mass: LOI, KATRIN Collaboration, hep-ex/0109033
2.) Planck 2013 results. XVI. Cosmological Parameters

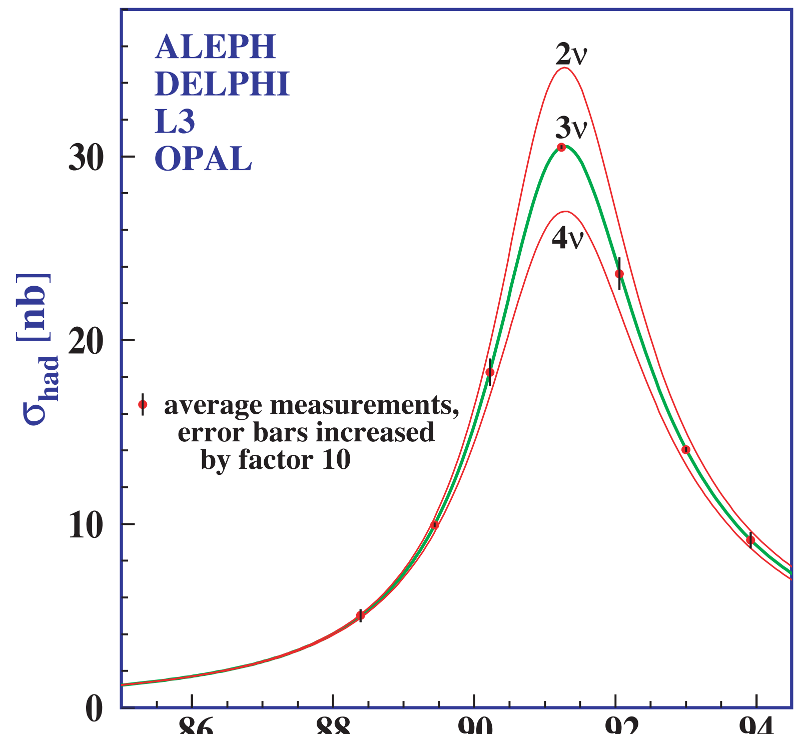
NEUTRINOS: HOW MANY TYPES ARE THERE?

LSND Experiment ($\Delta m^2 \sim 1$ eV^2)

- Hints from several areas (LSND, reactor antineutrino anomaly, gallium solar neutrino calibration experiments) seem to suggest the possibility of additional mass eignestate(s).
- How to understand such results in the context of astrophysical and collider constraints?







Refs:

1.) *Evidence for Neutrino Oscillations from the Observation of Electron Anti-neutrinos in a Muon Anti-Neutrino Beam*, A. Aguilar et al, PRD 64 112007 (2001)

2.) *The Reactor Antineutrino Anomaly*, G. Mention et al, PRD 83 073006 (2011)

NEUTRINOS: OTHER AREAS OF INTEREST

Refs:
1.) *Implication of neutrino backgrounds on the reach of next generation dark matter direct detection experiments*, J. Billard et al, PRD 89 023524 (2014)

NEUTRINOS: OTHER AREAS OF INTEREST

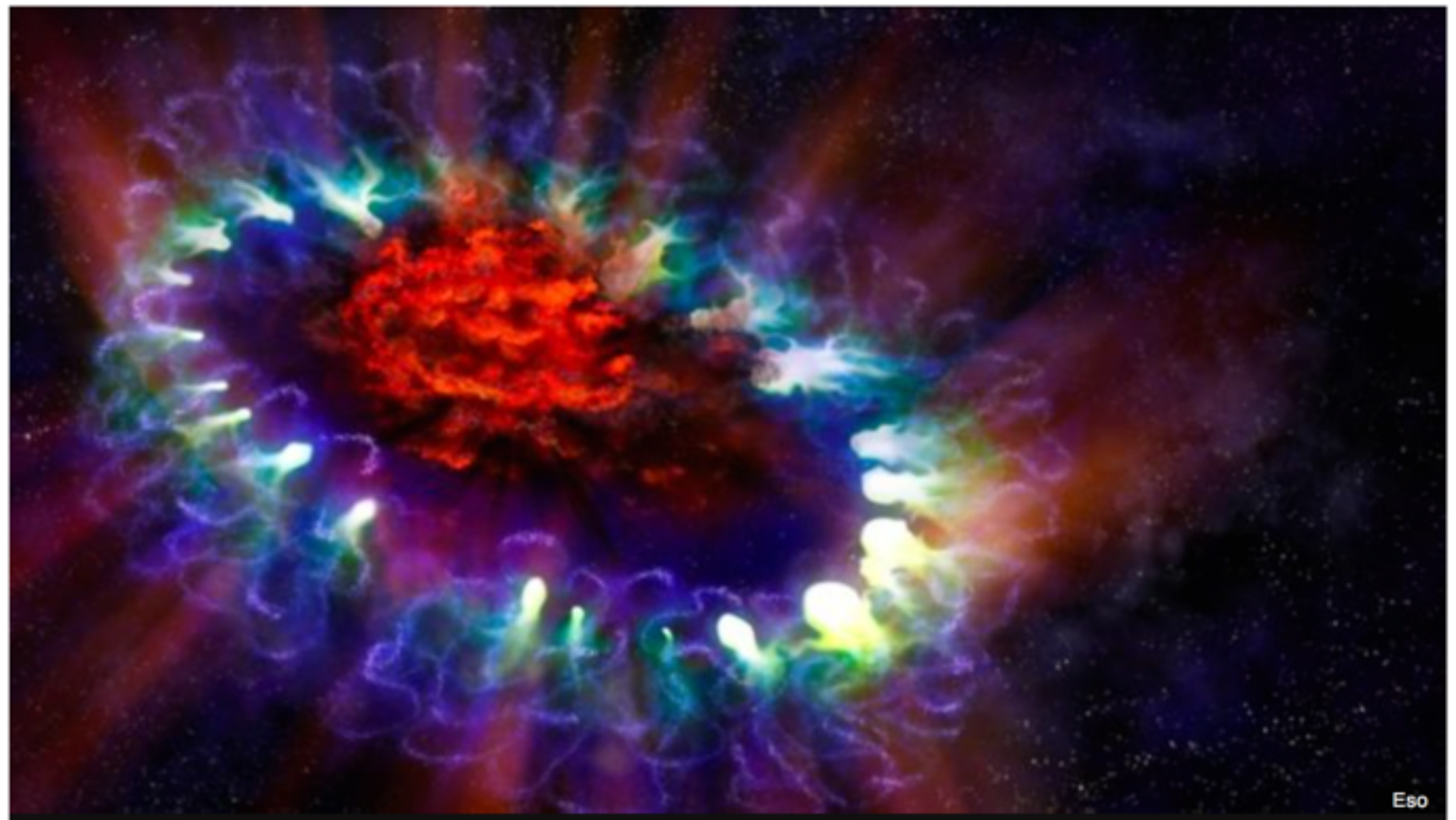
- astrophysics

Science & Environment

Supernova 'stream' in neutrino lab's sights

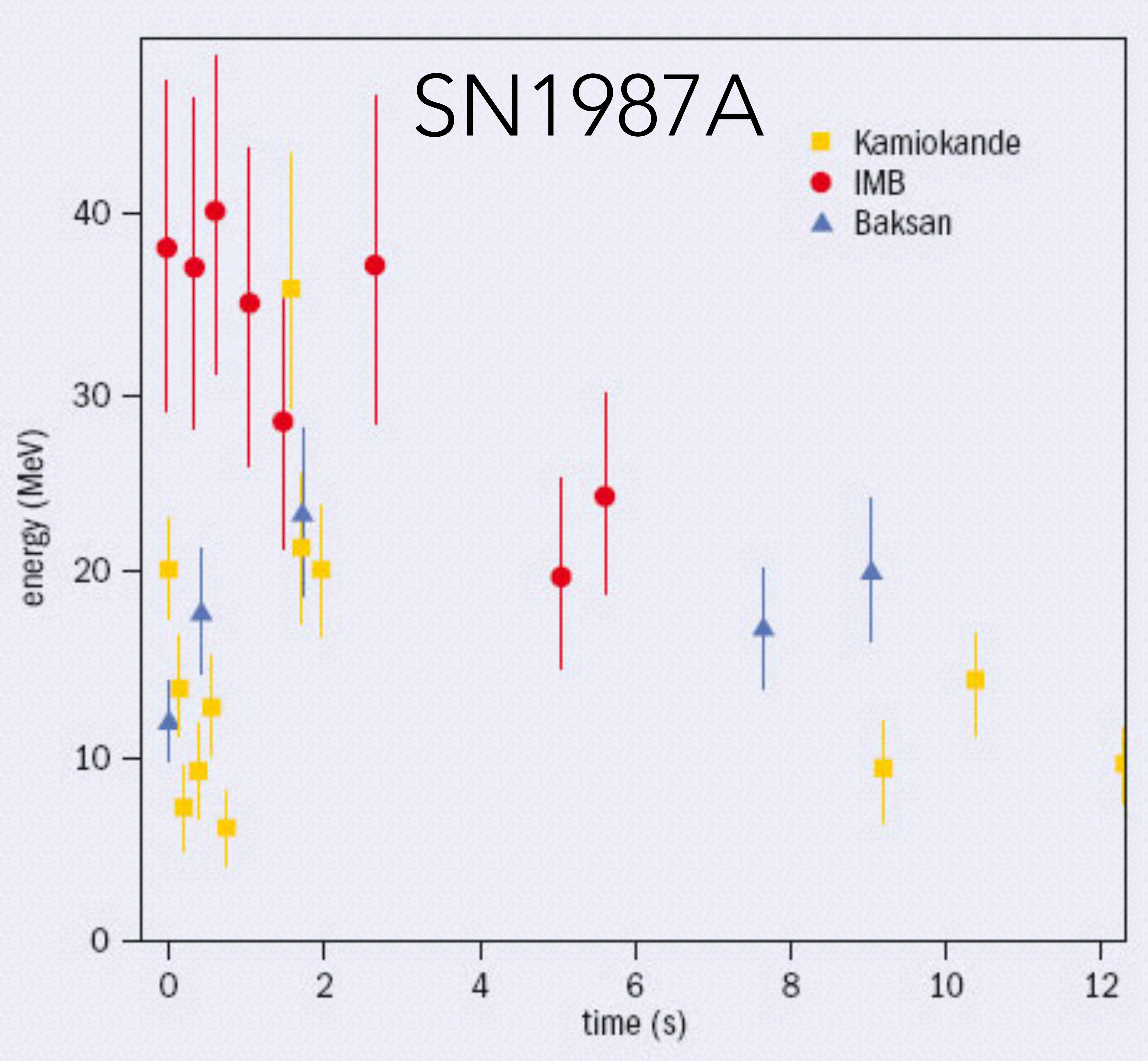
By Paul Rincon
Science editor, BBC News website

2 October 2015 | Science & Environment



The Dune collaboration might observe neutrinos from a supernova in our galaxy - if luck is on their side

A global collaboration will aim to unravel the mysteries of neutrinos - also known as "ghost particles".



Refs:
1.) *Implication of neutrino backgrounds on the reach of next generation dark matter direct detection experiments*, J. Billard et al, PRD 89 023524 (2014)

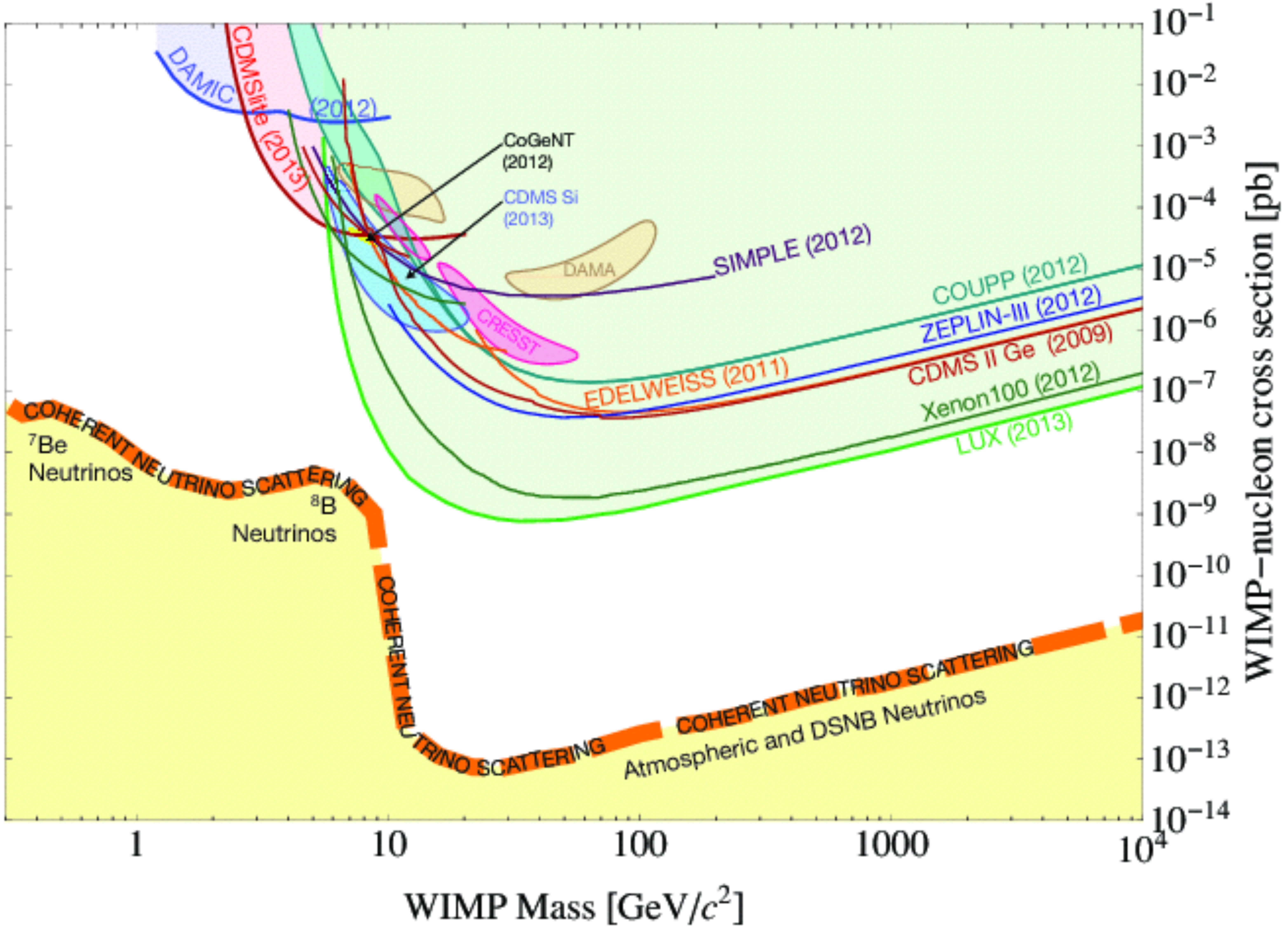
NEUTRINOS: OTHER AREAS OF INTEREST

- astrophysics
- proton decay

Refs:
1.) *Implication of neutrino backgrounds on the reach of next generation dark matter direct detection experiments*, J. Billard et al, PRD 89 023524 (2014)

NEUTRINOS: OTHER AREAS OF INTEREST

- astrophysics
- proton decay
- background to dark matter searches?

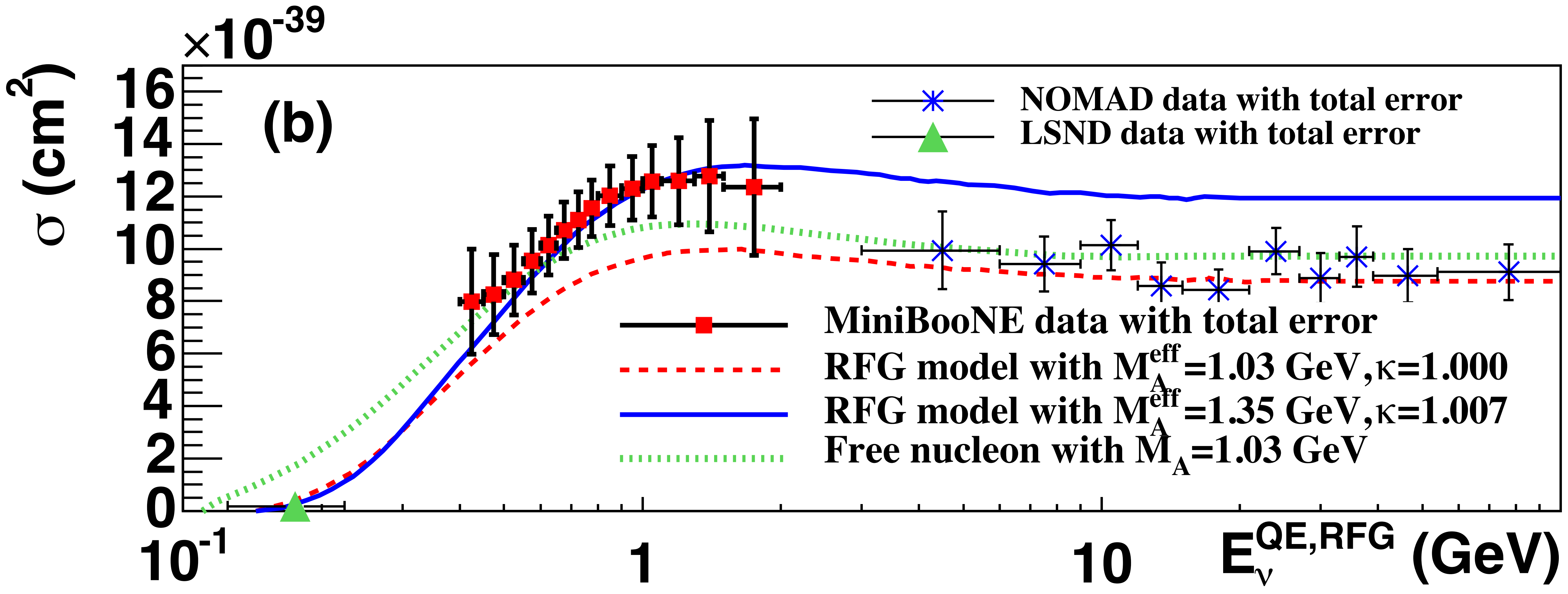


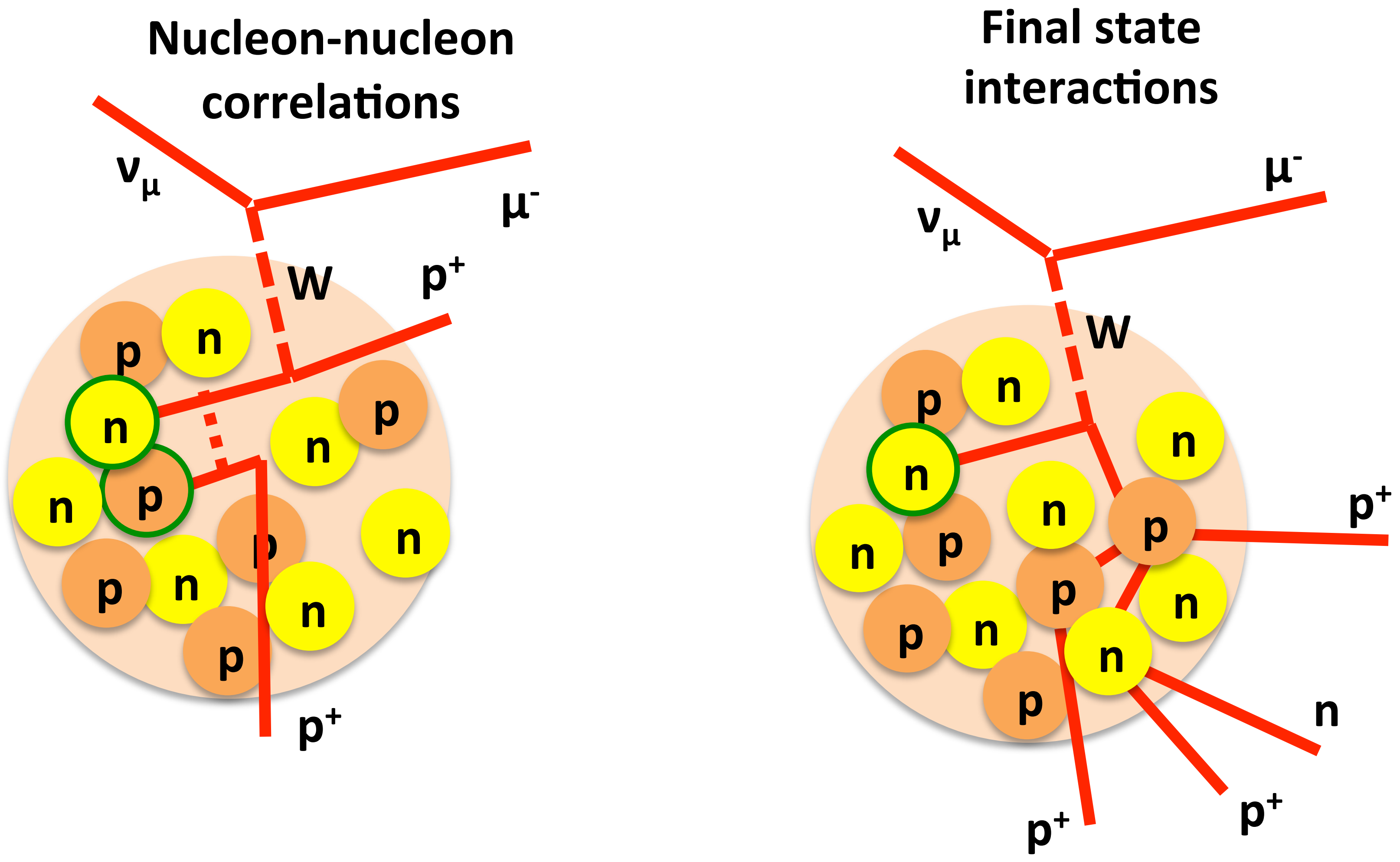
Refs:

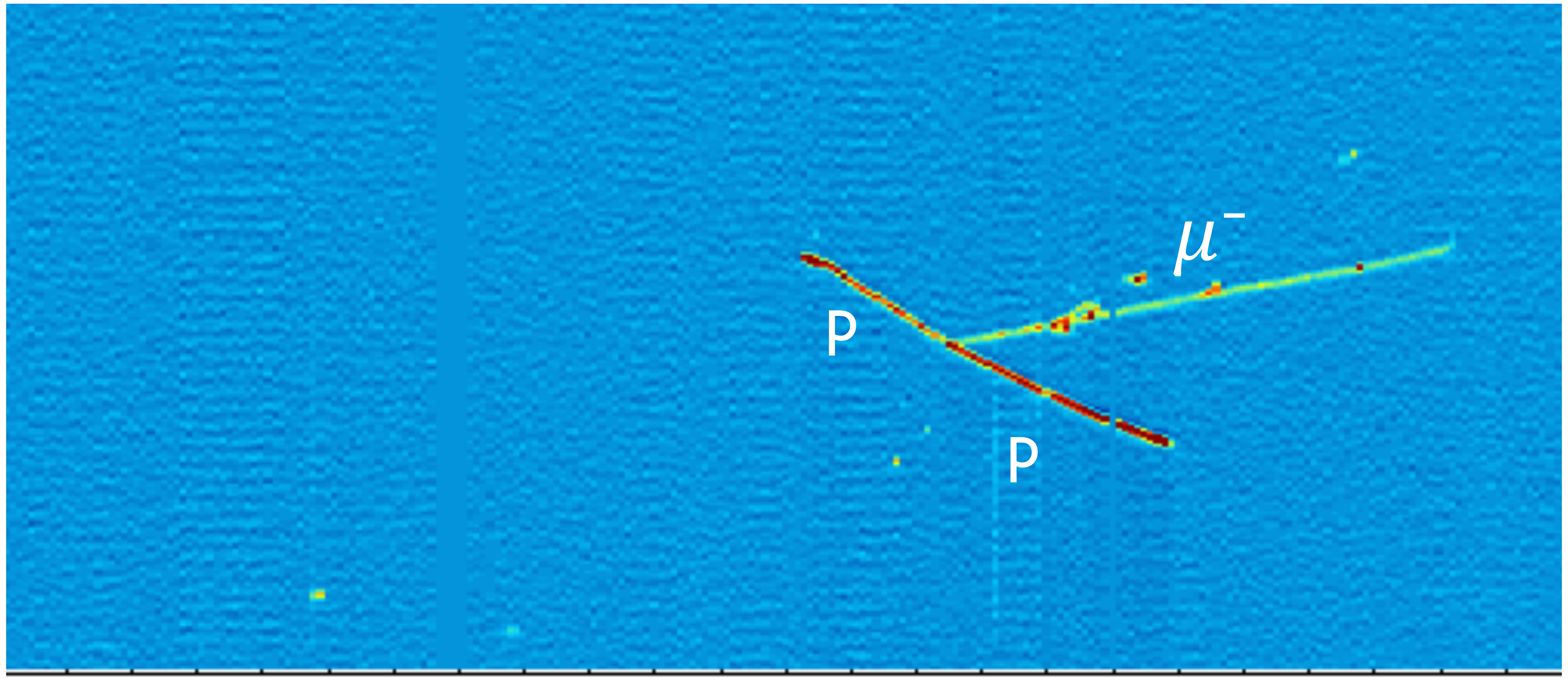
1.) *Implication of neutrino backgrounds on the reach of next generation dark matter direct detection experiments*, J. Billard et al, PRD 89 023524 (2014)

NEUTRINOS: OTHER INTERESTS

- Modern experiments utilize nuclear targets.
- Correlated nucleons and final-state interactions can influence what is inferred about the initial neutrino, directly impacting precision of oscillation measurements, CP-violation searches, etc…
- Imprint of these nuclear effects has been suggested from data of several neutrino experiments.
- Large fine-grained detector will provide statistics to do a precision measurement.







Refs:
1.) *First Measurement of the Muon Neutrino Charged Current Quasielastic Double Differential Cross Section*, MiniBooNE Collaboration, PRD 81 092005 (2010)
2.)*The detection of back-to-back proton pairs in Charged-Current neutrino interactions with the ArgoNeuT Detector in the NuMI low energy beam line*, R. Acciarri et al, PRD 90 012008 (2014)

INTERESTS

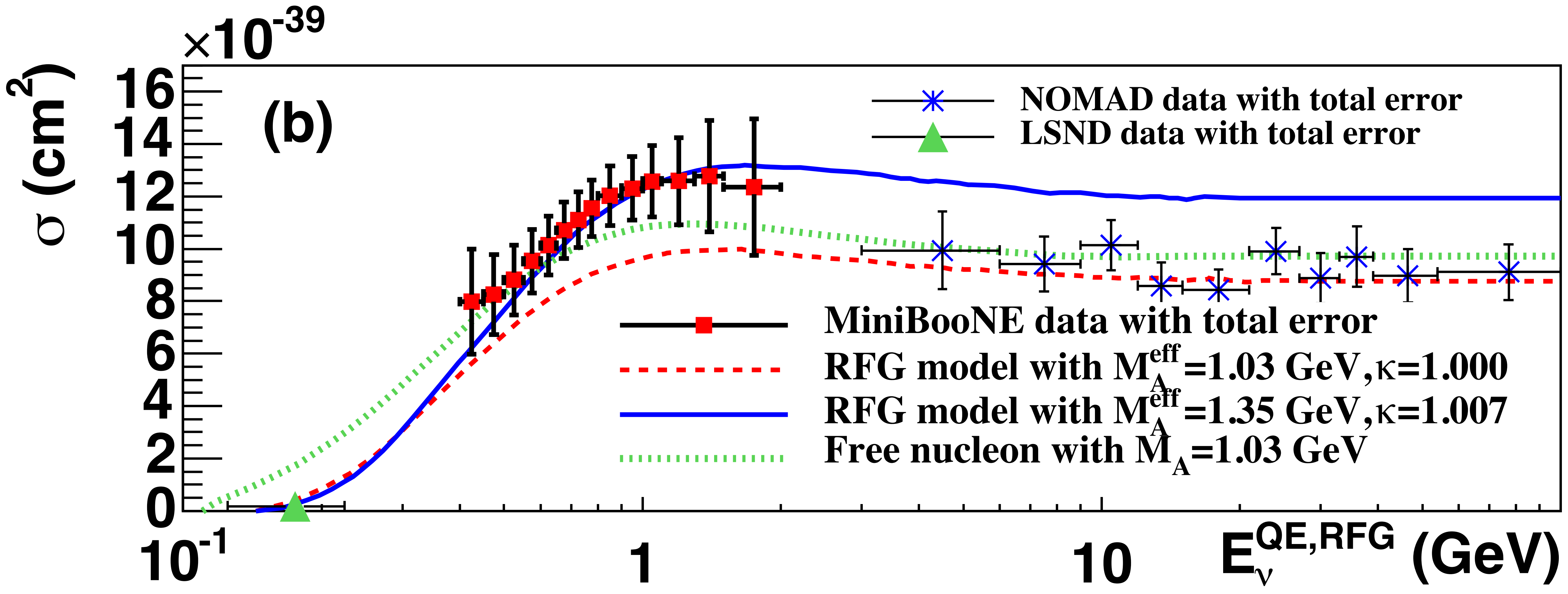
-
- hat
  n of
- of
- ion

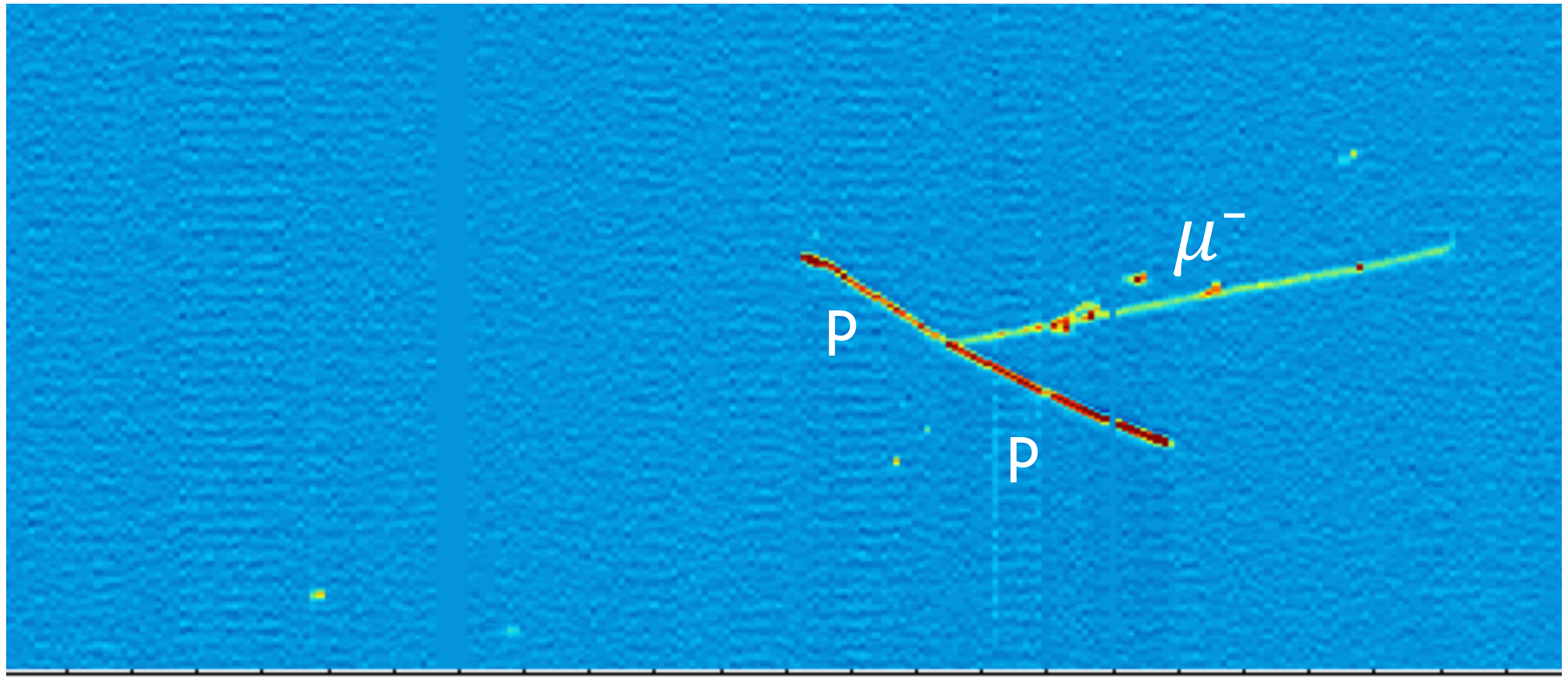
NEUTRINO REACTIONS ON NUCLEAR TARGETS ‡

R. A. SMITH ‡‡ and E. J. MONIZ ‡‡‡
Institute of Theoretical Physics, Department of Physics,
Stanford University, Stanford, California 94305

Received 15 December 1971
(Revised 29 February 1972)

Abstract: We examine the systematics of deep inelastic neutrino scattering from complex nuclei by computing the cross section for quasi-elastic scattering and for quasi-free resonance production. We retain relativistic kinematics for the recoiling particle and the full relativistic hadronic weak vertex. The isobar cross section is expressed in terms of helicity amplitudes of the weak current, defined through an application of the Jacob-Wick formalism to the general isobar-nucleon weak vertex. The cross section is computed analytically for the nuclear Fermi gas model. We stress that exactly the same model has already been very successfully applied to inelastic electron scattering from complex nuclei.





Re
1.) ...MiniBooNE Collaboration, PRD 81 092005 (2010)
2.) ...tector in the NuMI low energy beam line, R. Acciarri et al, PRD 90 012008 (2014)

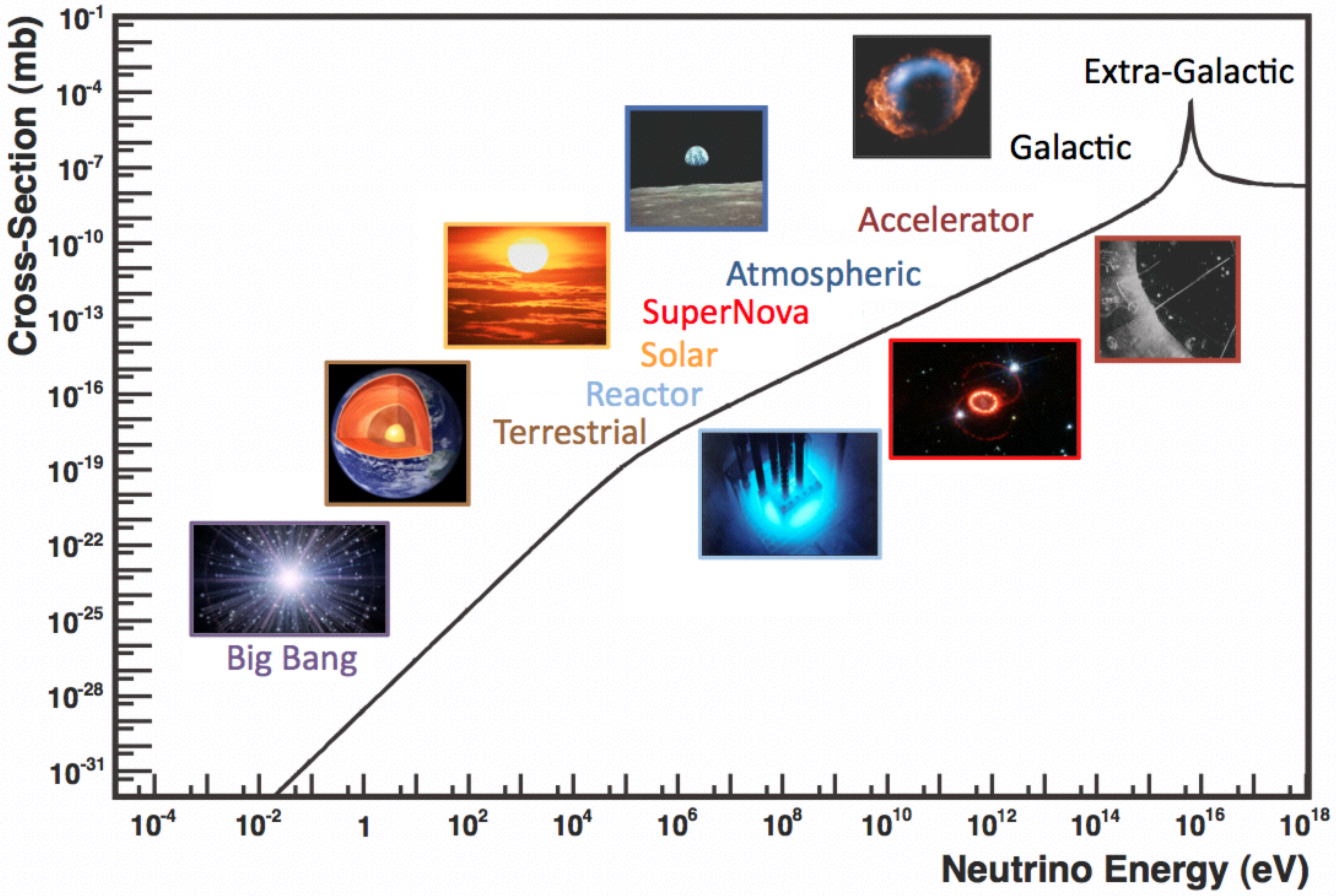
WHAT ARE WE PLANNING FOR THE FUTURE?

WHERE ARE WE GOING?

- Planning for the next generation of experiments already well underway
  - Oscillation experiments (atmospheric, accelerator, reactor) all trending towards much bigger detector volumes.
  - Double-beta experiments trending towards better precision + larger size + multiple isotopes.
- Let's highlight plans for a couple of the future areas of research and mention areas where instrumentation development may benefit.

EXPERIMENTAL CHALLENGES?

- Cross-sections are low.
- Many different sources.
- To tackle all the questions we have, need a diverse set of experiments across a wide range of energy.



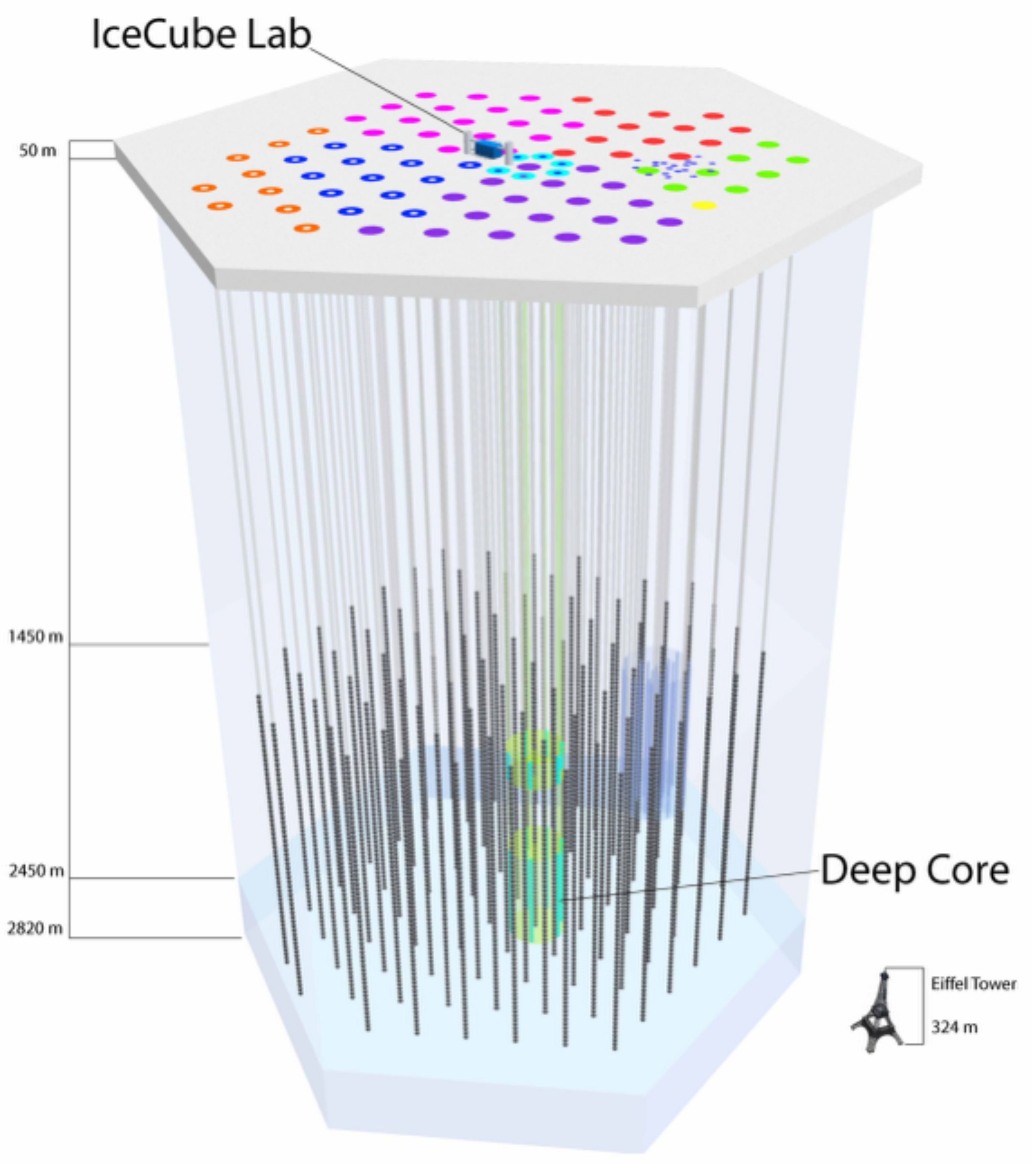
Refs:
1.) *From eV to EeV: Neutrino Cross Sections Across Energy Scales*, J.A. Formaggio, G.P. Zeller, Rev. Mod. Phys. 84, 1307 (2012)

A REMARKABLE ARRAY OF EXPERIMENTS

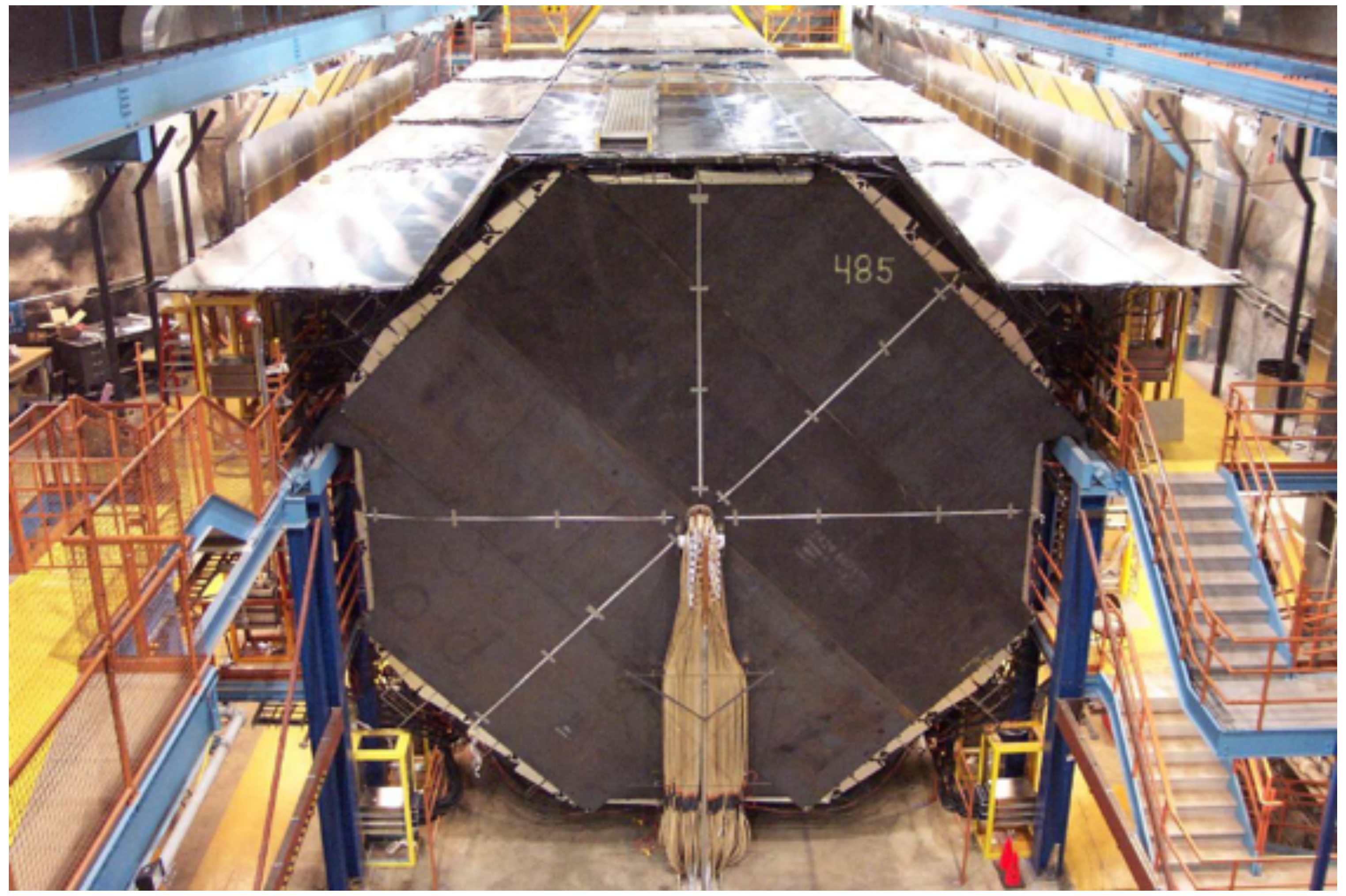
Challenge to list them all (I haven't), let alone get capitalization correct (I didn't)!

- Long-baseline: NOvA, MINOS+, T2K, OPERA,…
- Reactors: Double Chooz, RENO, Daya Bay, KamLAND,…
- Astrophysics: ICECUBE, ANTARES,…
- Interactions: MINERvA, MicroBooNE, MiniBooNE,…
- Double-Beta Decay: EXO, NEMO, GERDA, MAJARONA, CUORE, SNO+,…
- Direct mass: KATRIN, Project 8,…

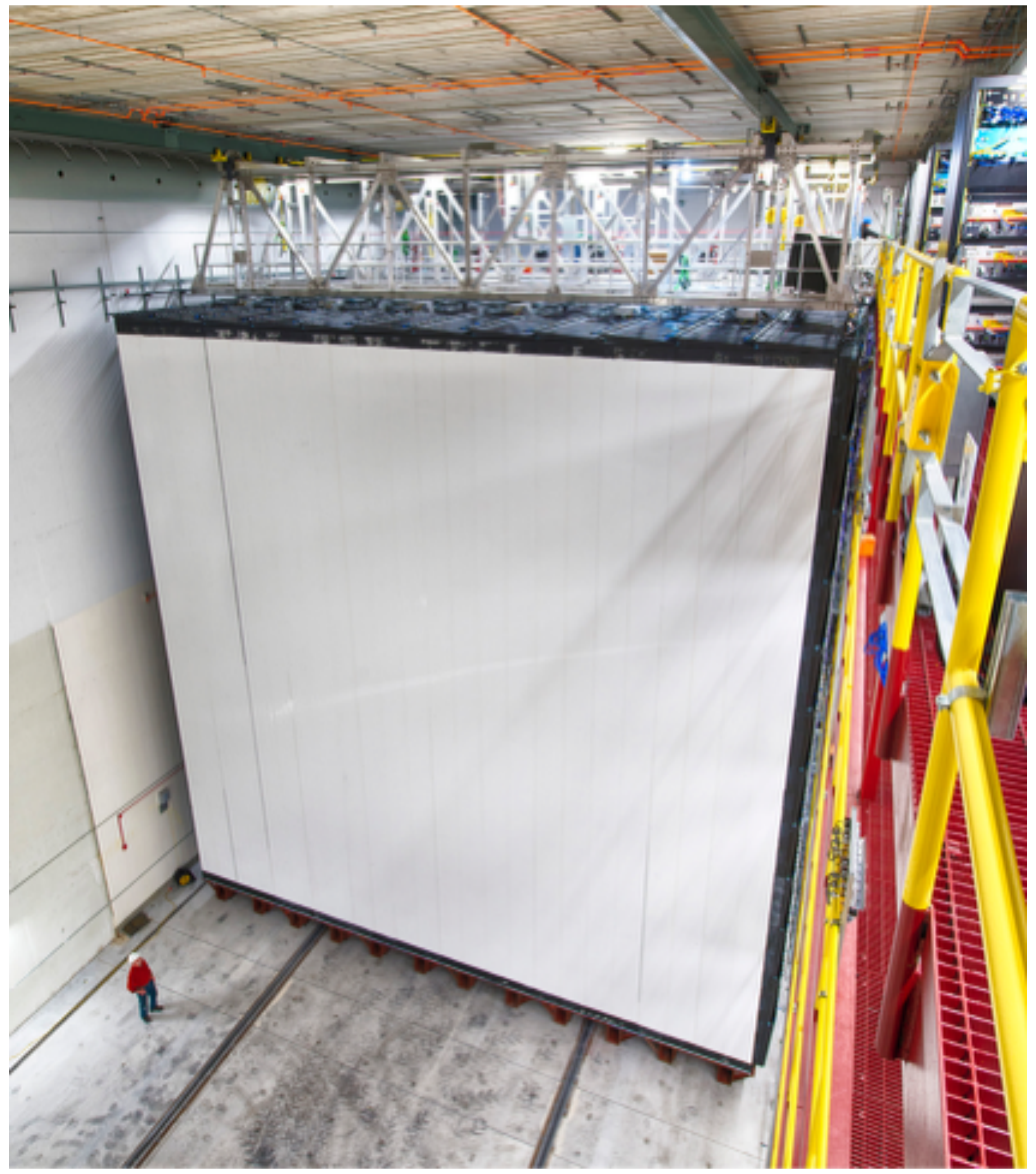
BIG DETECTORS!



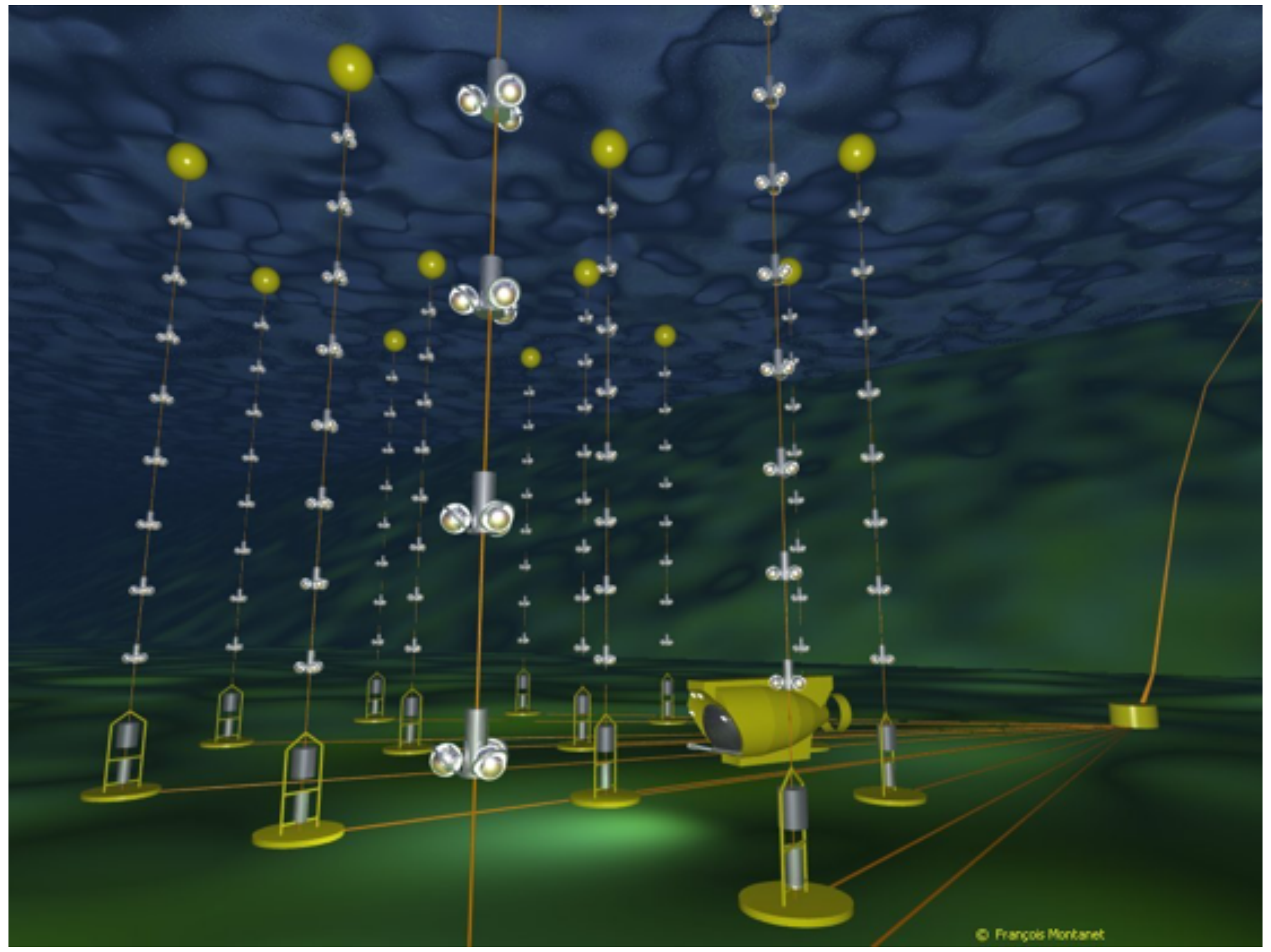
IceCube



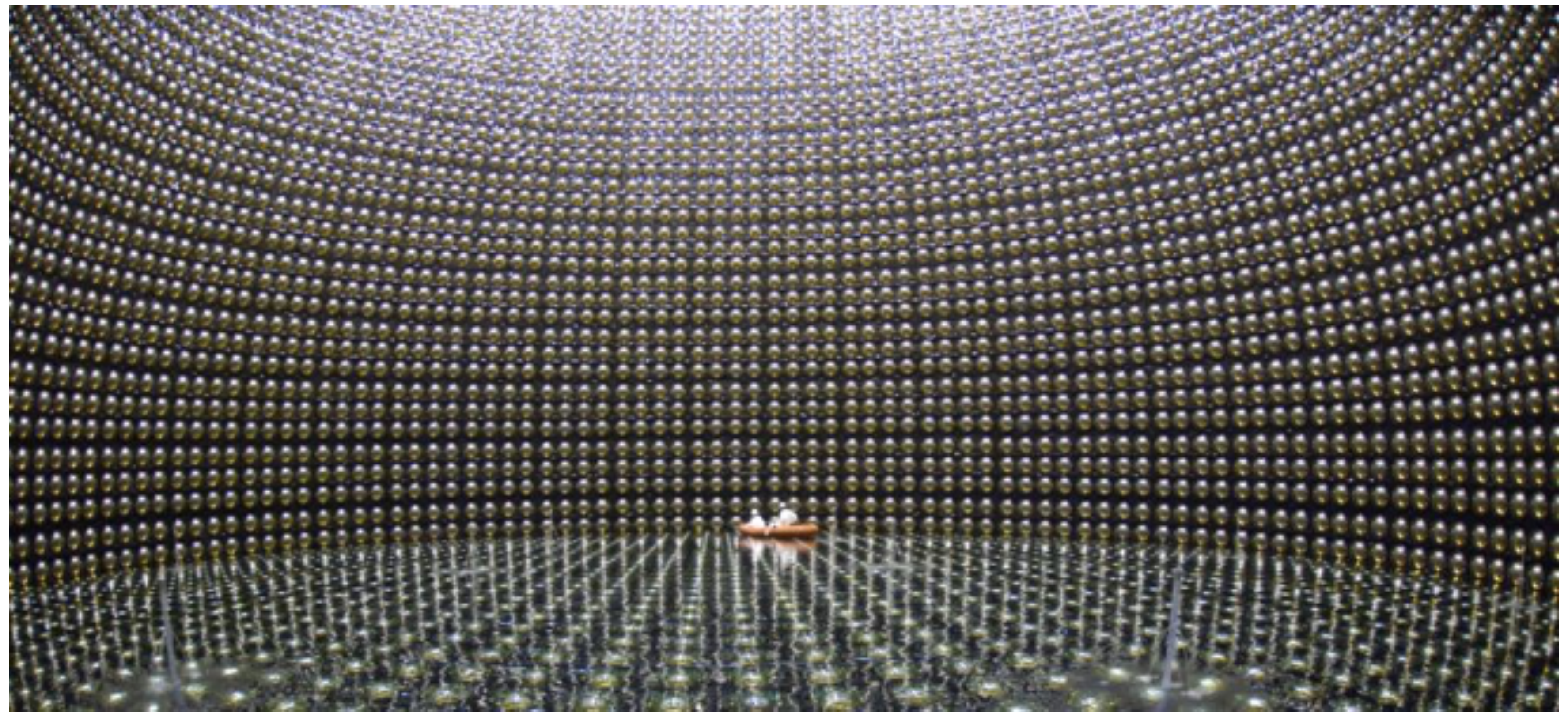
MINOS



NOvA

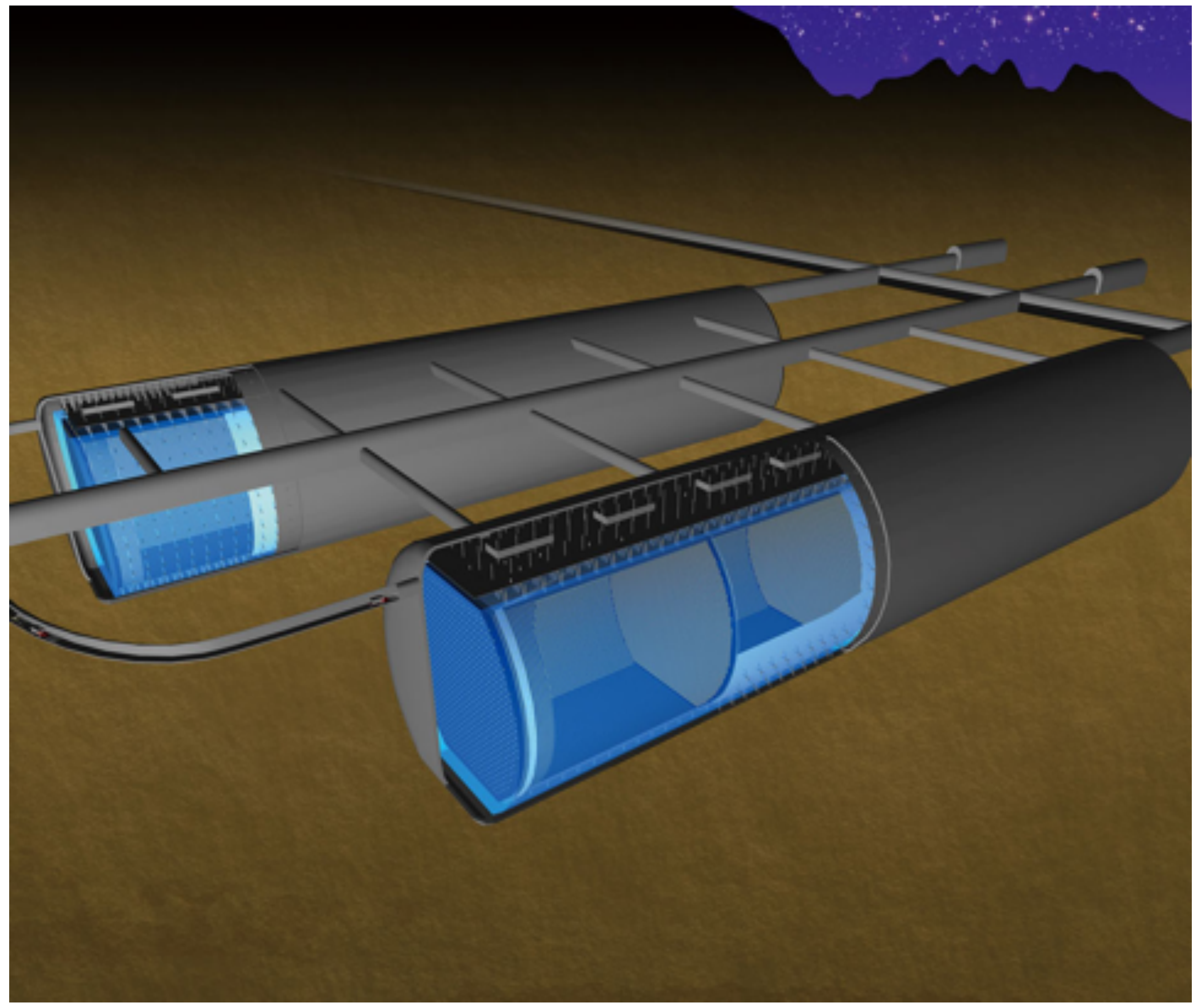


ANTARES

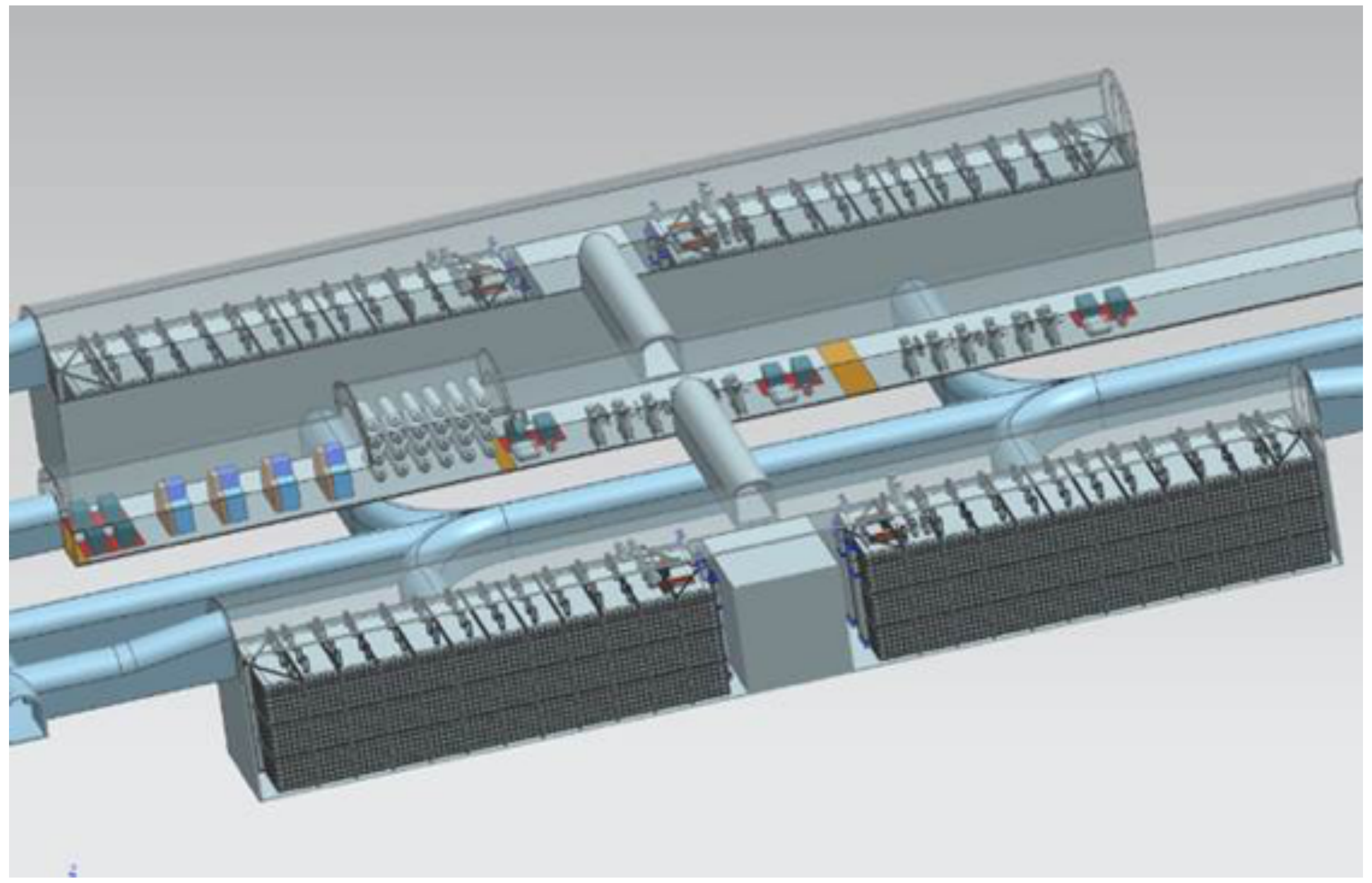


Super-Kamiokande

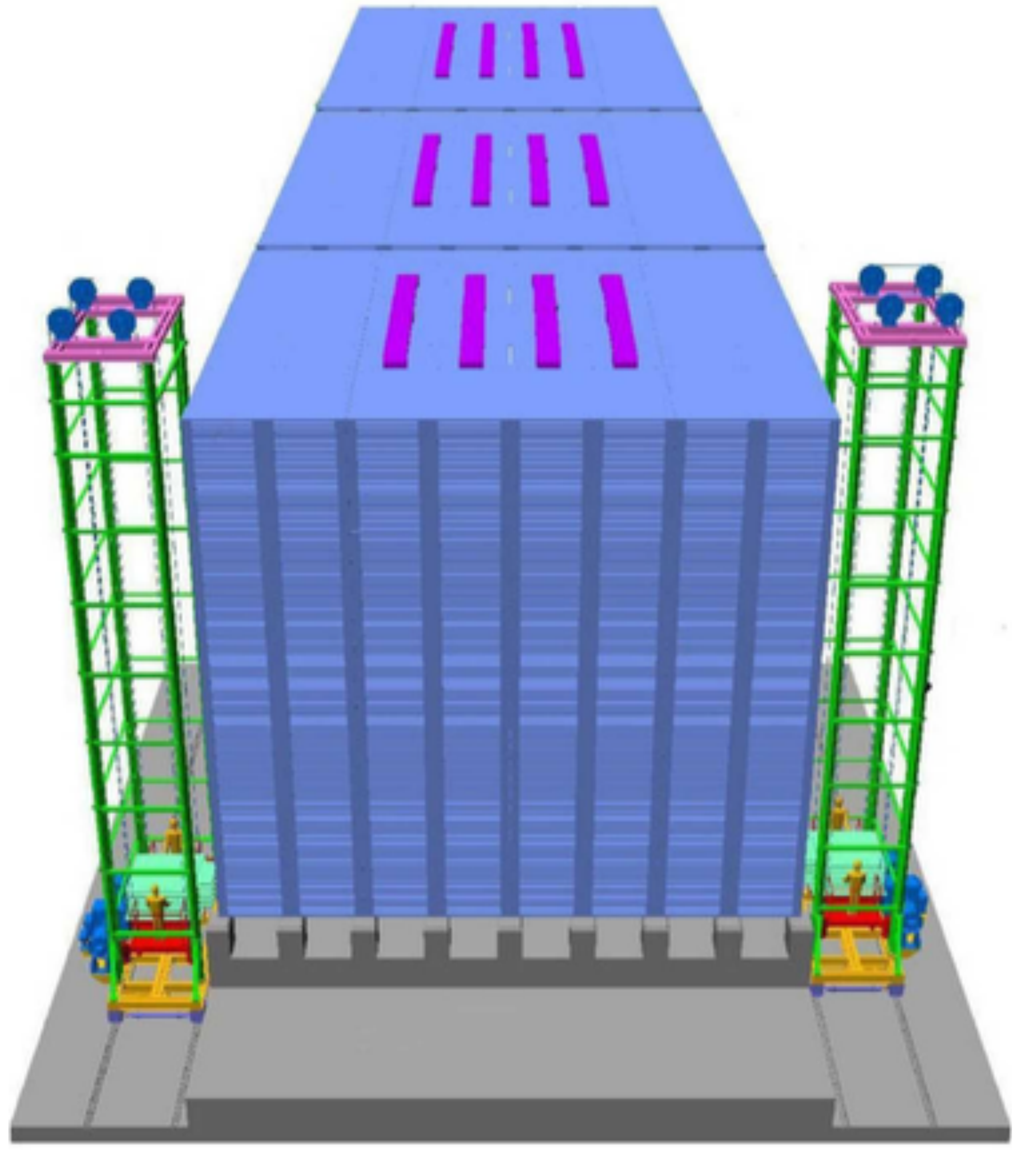
GOING BIGGER!



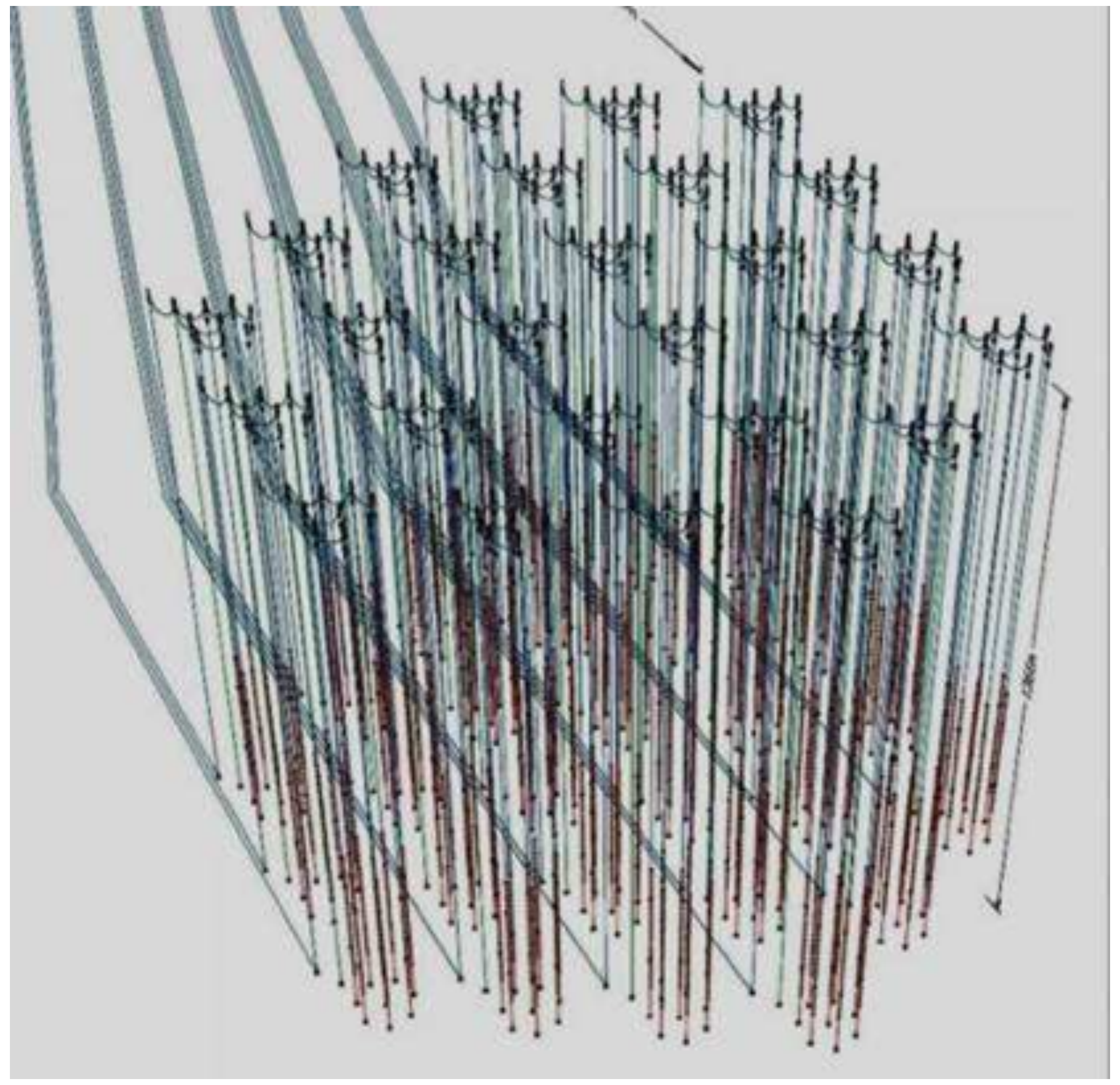
Hyper-Kamiokande



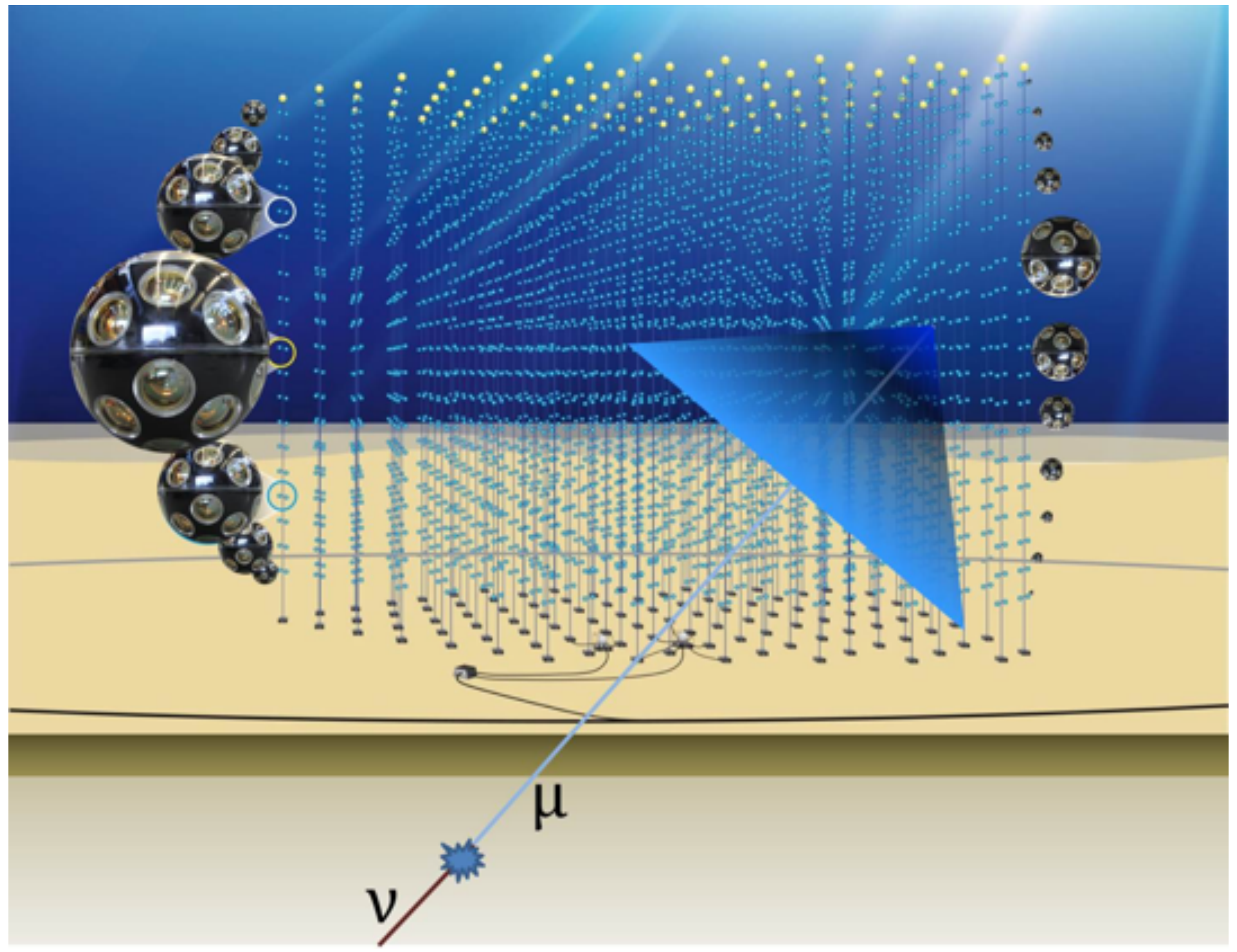
DUNE



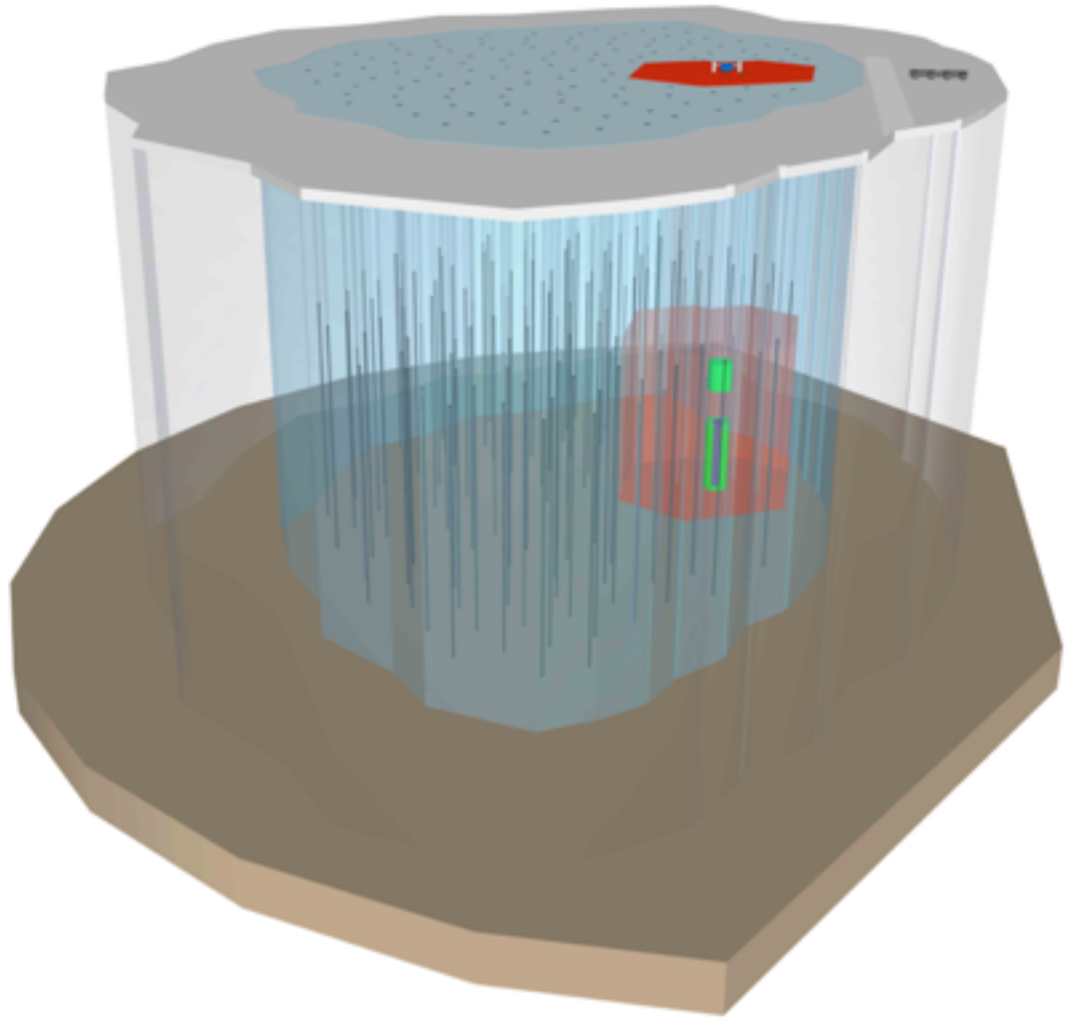
INO



GVD (Lake Baikal)



KM3NET



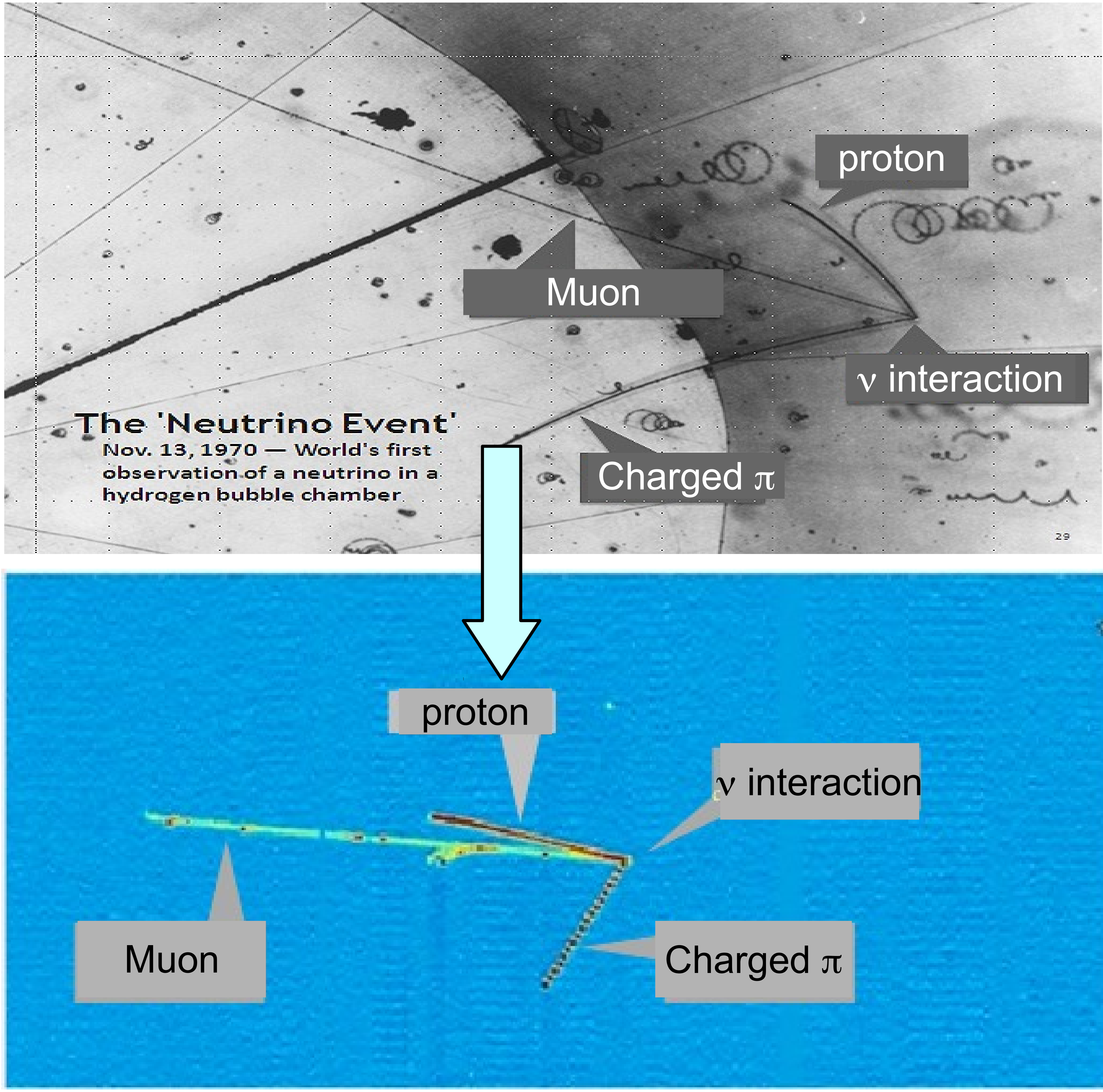
IceCube-Gen2

LIQUID ARGON DETECTORS

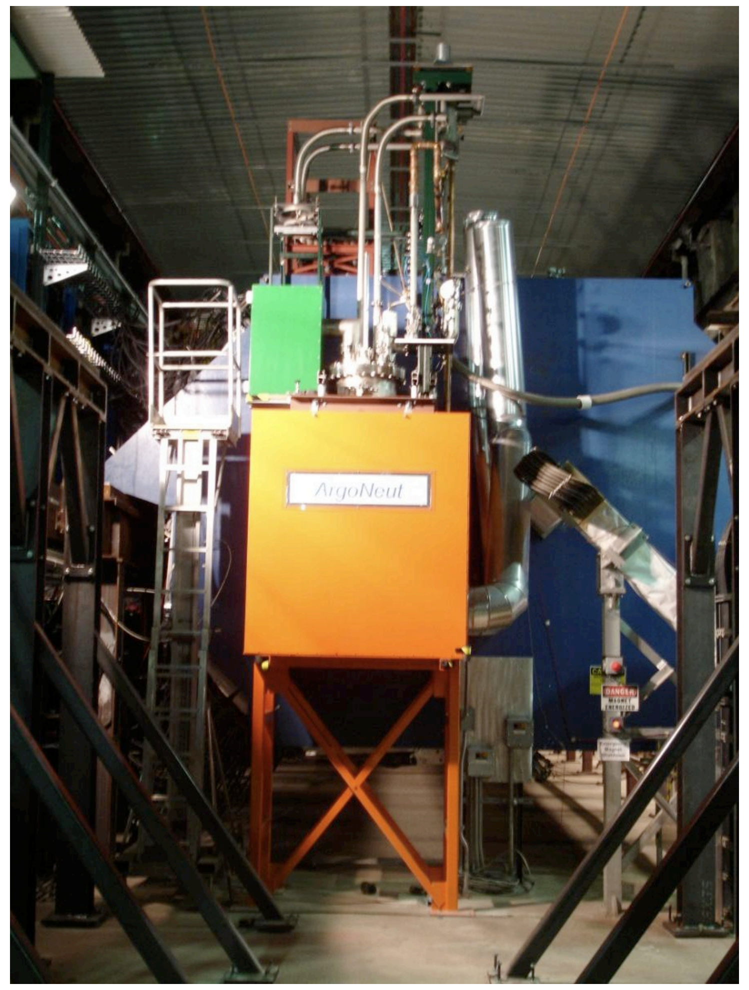
- Liquid argon detectors have emerged as an attractive technology for studying accelerator neutrinos.

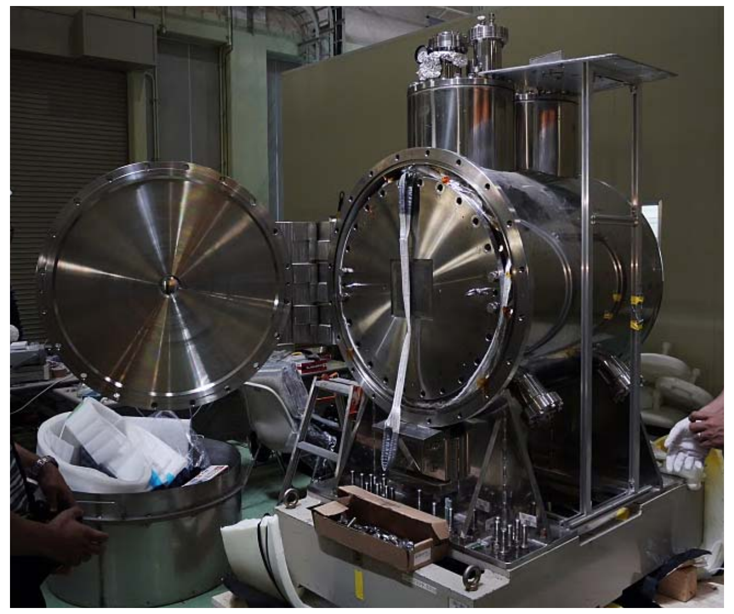
- Fine-grained tracking combined with electronics readout. Appear scalable to largest sizes imagined.

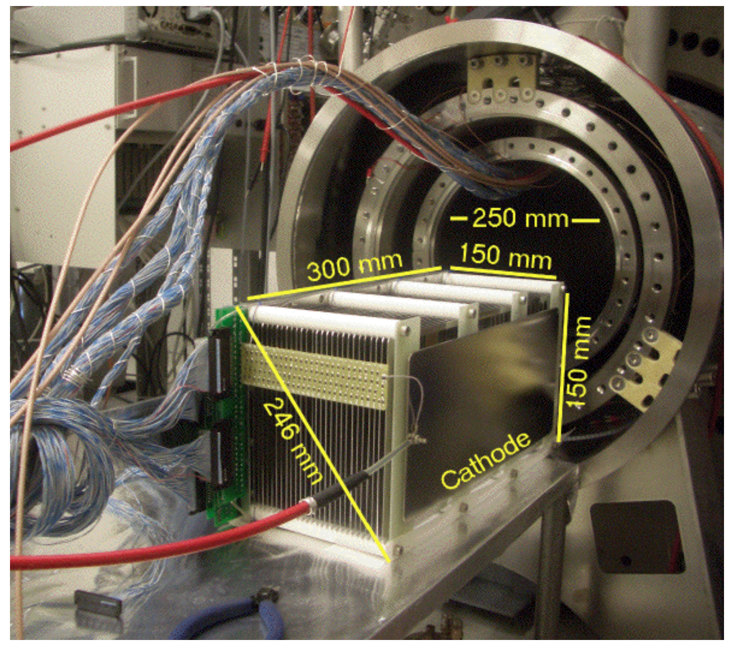
- Pioneering work done by ICARUS collaboration over last ~25 years. Recent program developed in U.S.

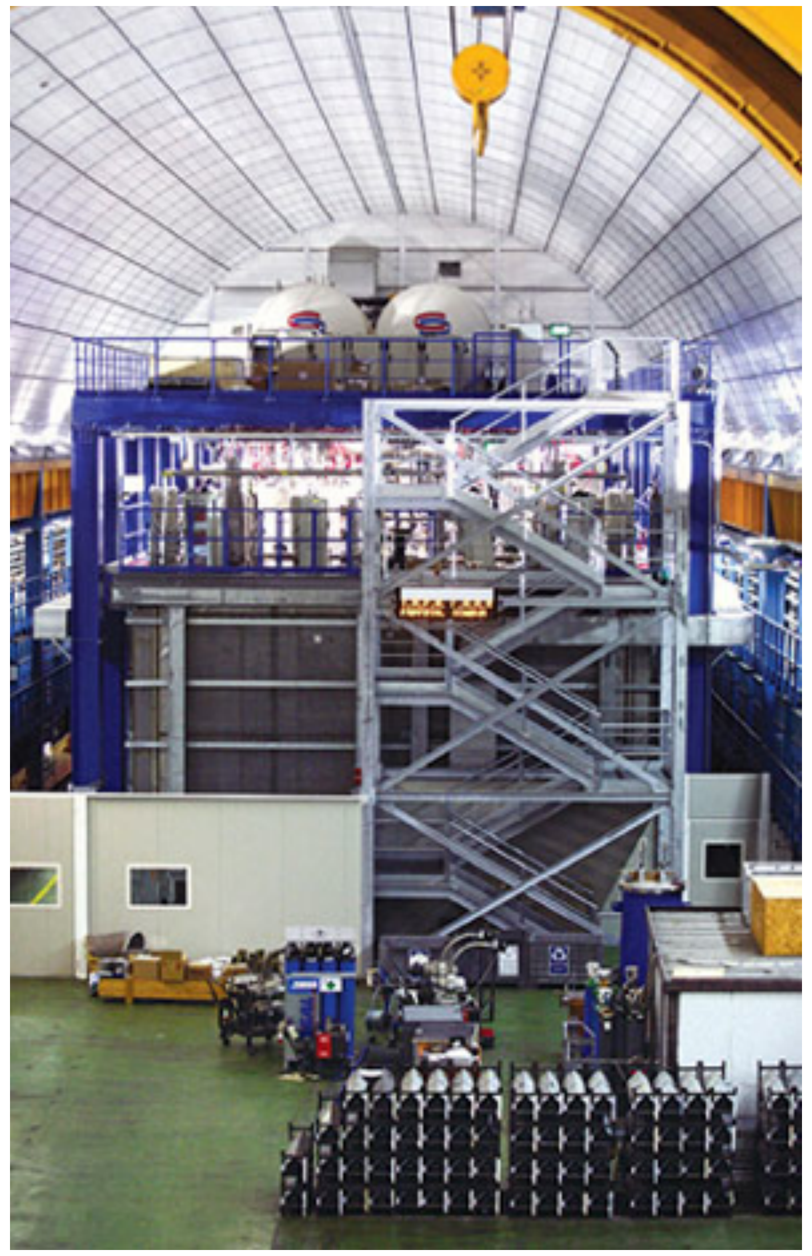


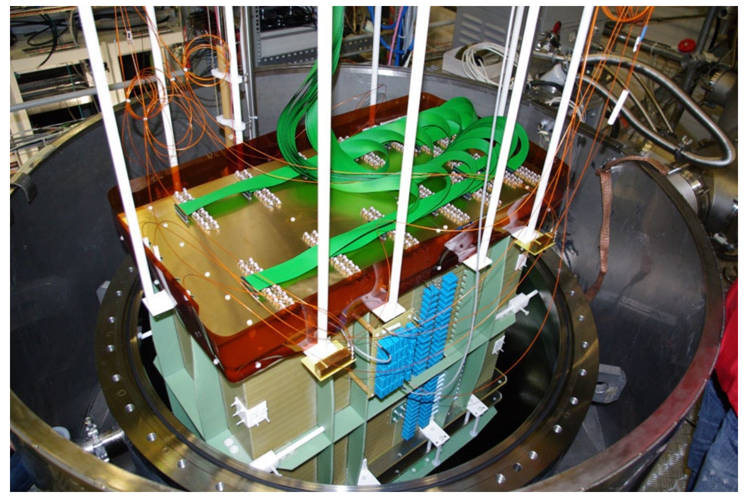
LIQUID ARGON DETECTORS: WORLDWIDE DEVELOPMENT

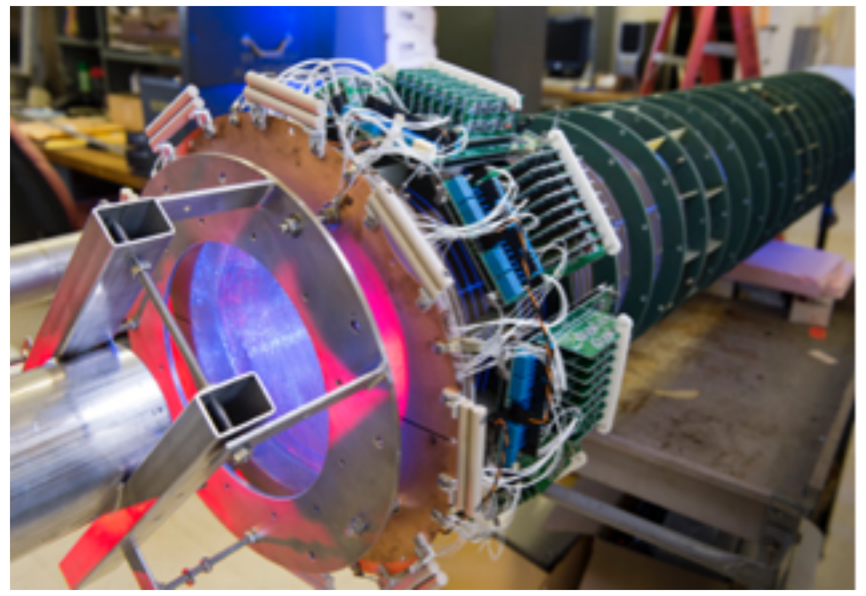






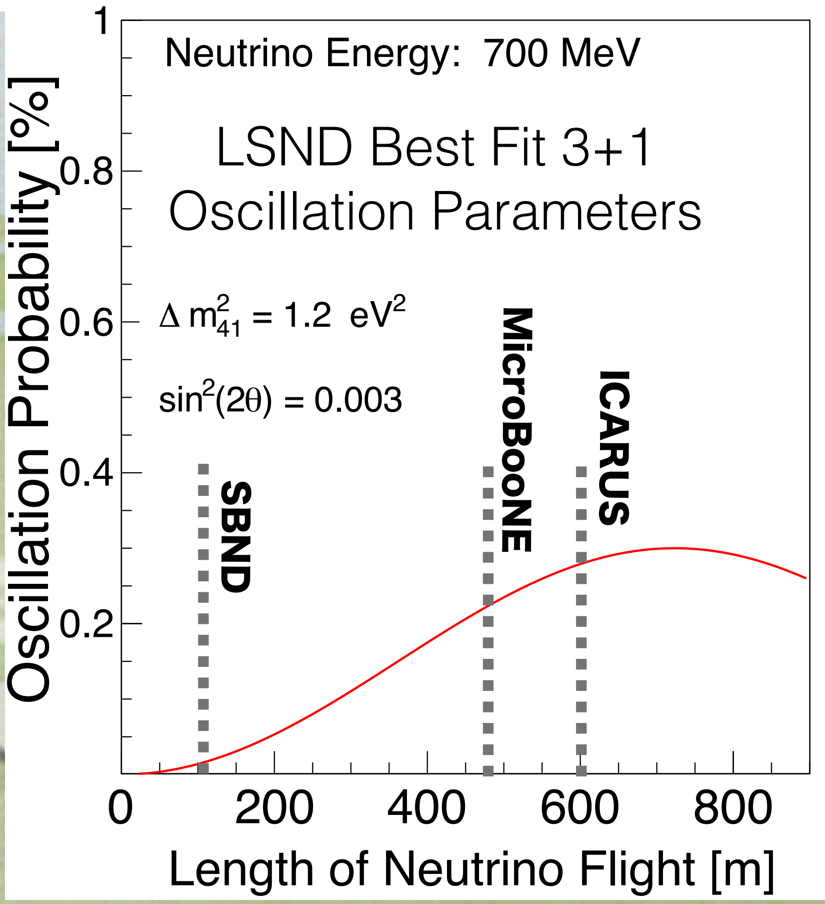


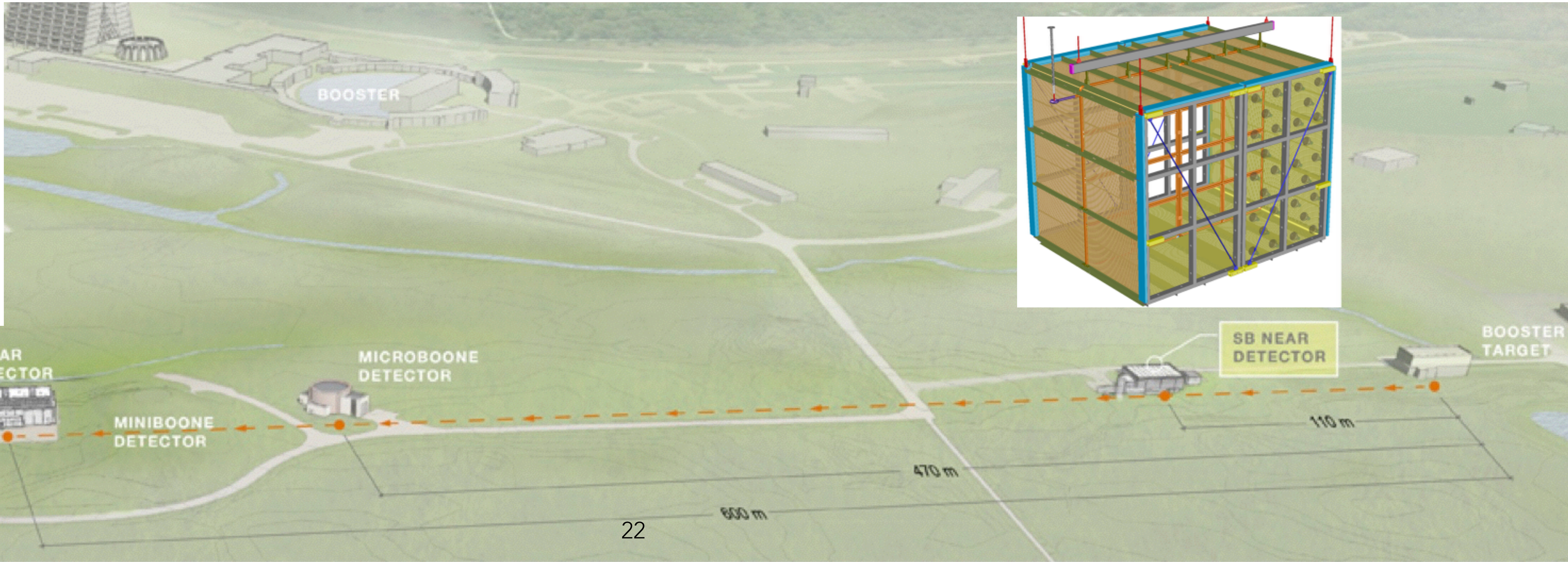




LIQUID ARGON DETECTORS: SHORT-BASELINE

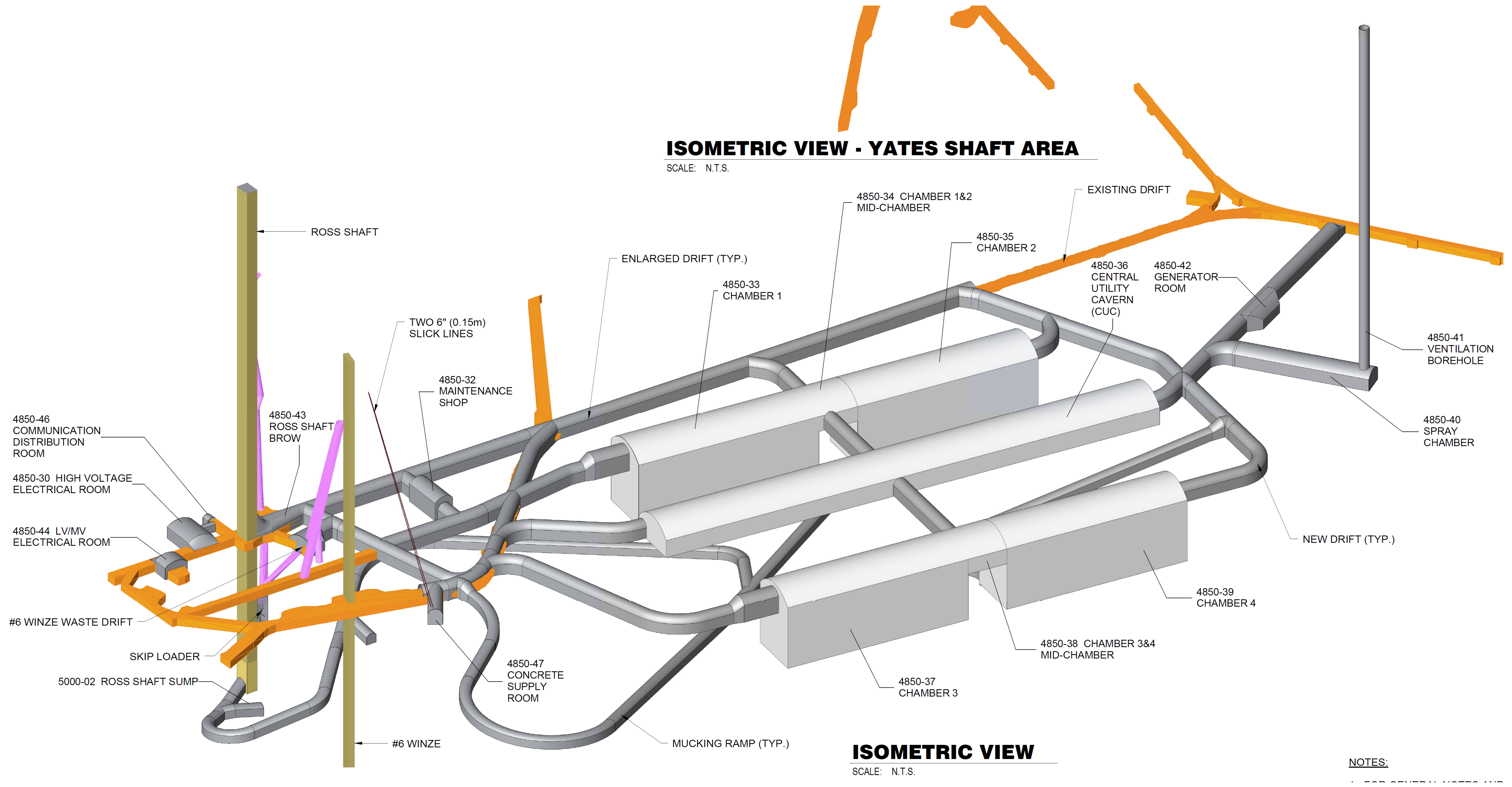
- Fermilab pursuing a plan to complement MicroBooNE with a “near” and “far” detector, to search for short-baseline neutrino oscillations.
- The “near” detector is called SBND, and the “far” detector will be the refurbished ICARUS detector, now at CERN.
- If sterile neutrinos active, the combined program will map out the oscillation curve.

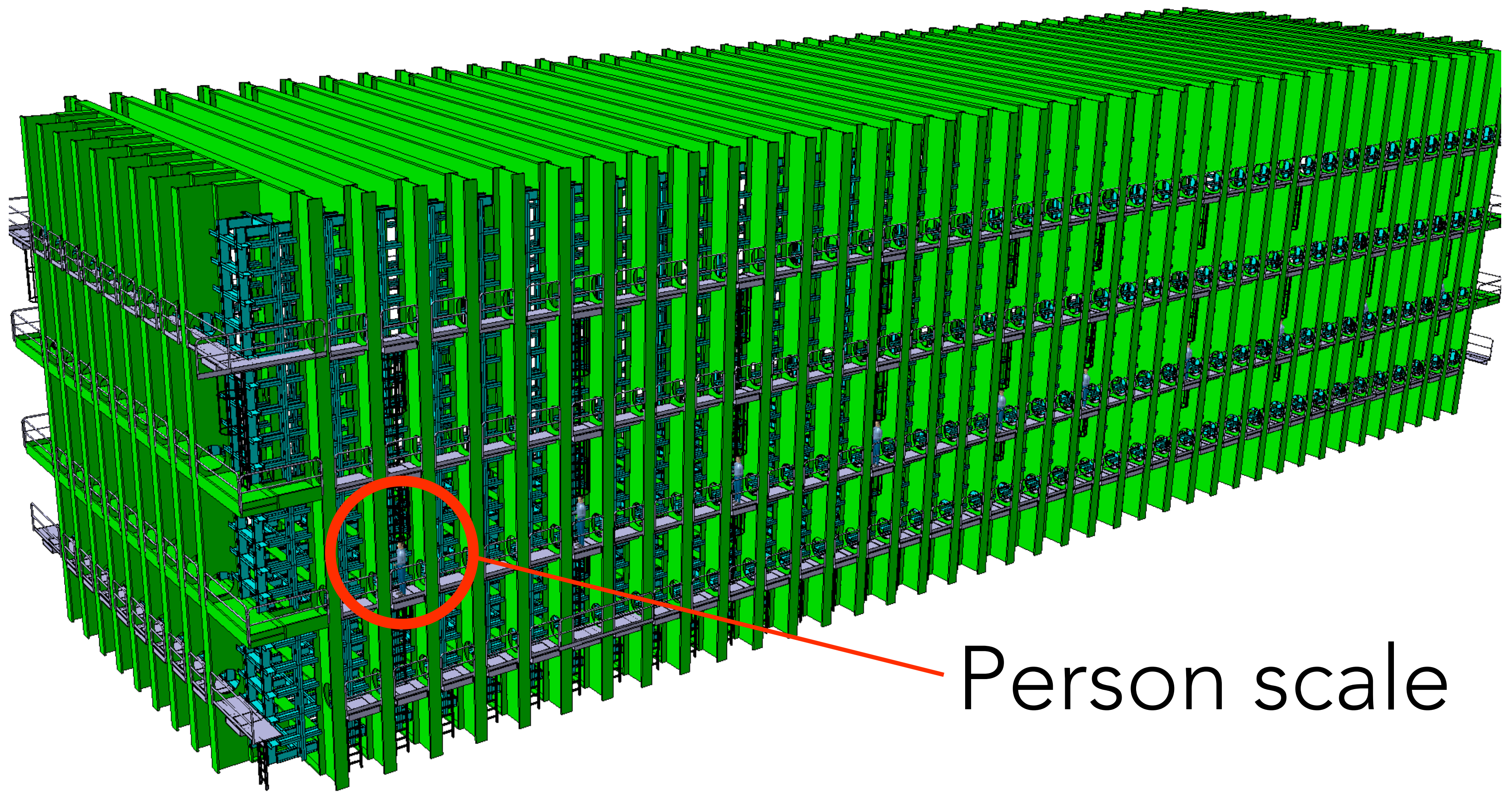




LIQUID ARGON DETECTORS: LONG-BASELINE

- Deep Underground Neutrino Experiment (DUNE) will feature ~40 kTon liquid argon detector.
- single-phase and double-phase options for various ~10 kTon modules.
- Industrial-scale scope of construction sure to benefit from advances in instrumentation used in fabrication and commissioning.

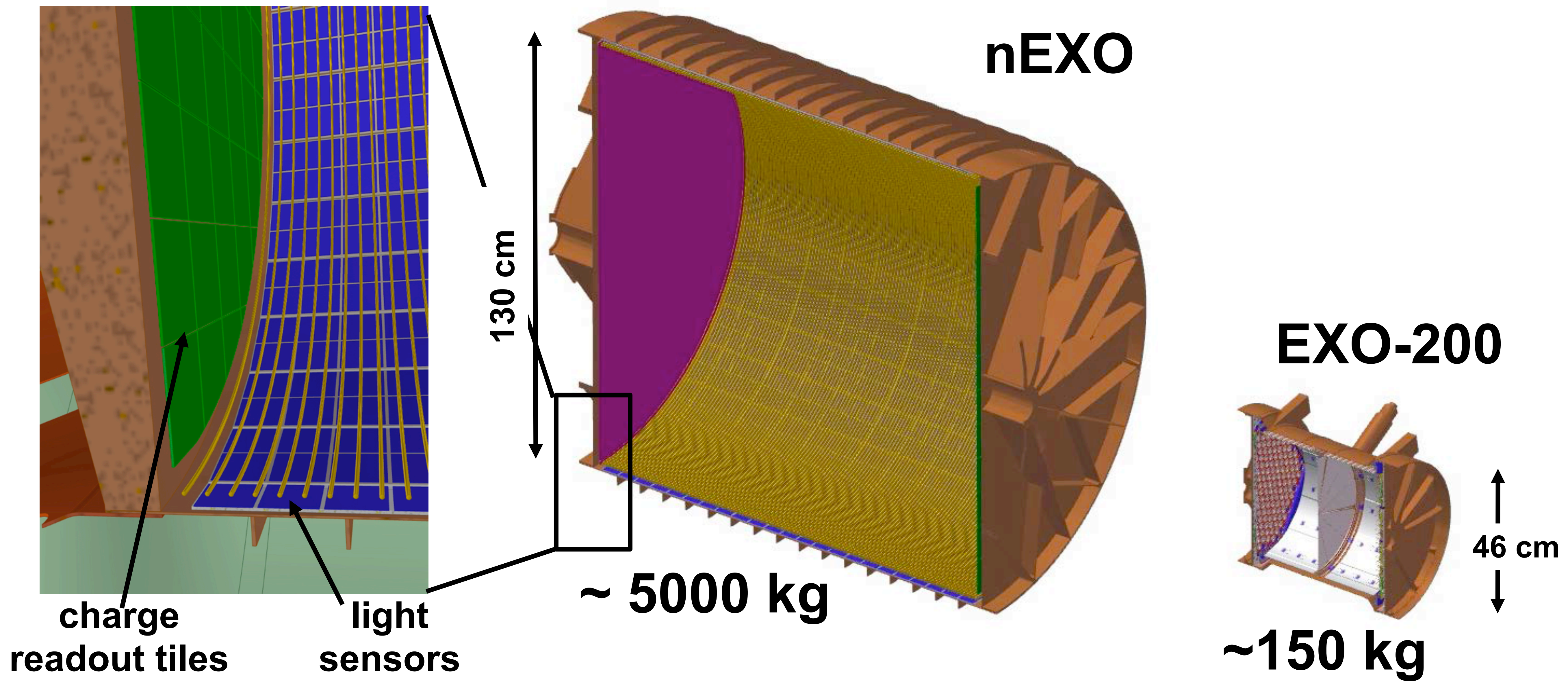


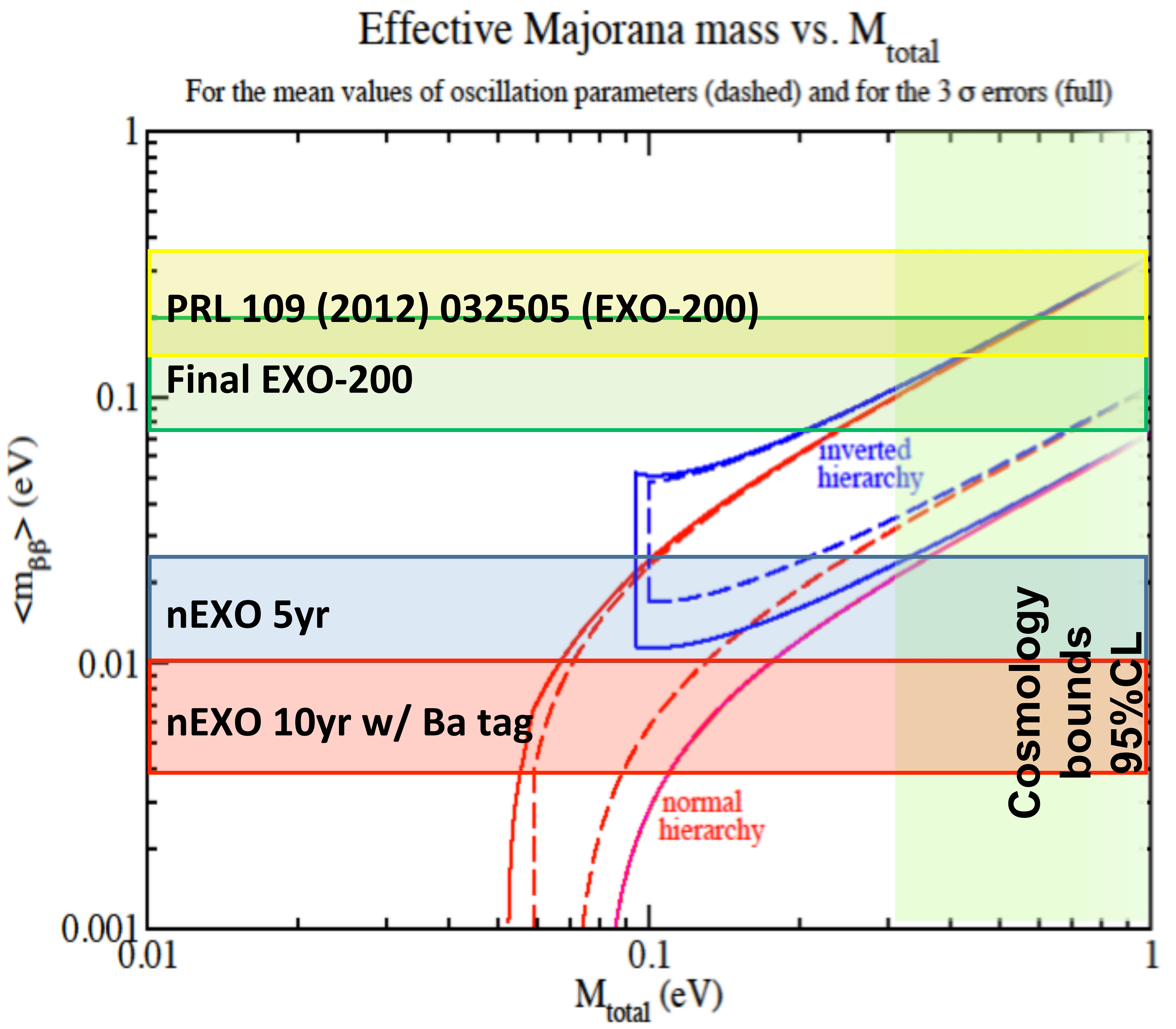


DUNE Far Detector Module (10 kTons)

MAJORANA OR DIRAC: EXO

- EXO-200 utilizing liquid xenon TPC to search for neutrinoless double-beta decay.
- nEXO would expand concept to ~5000kg detector.
- Barium tagging allows for significant reduction in backgrounds… several ideas being developed.

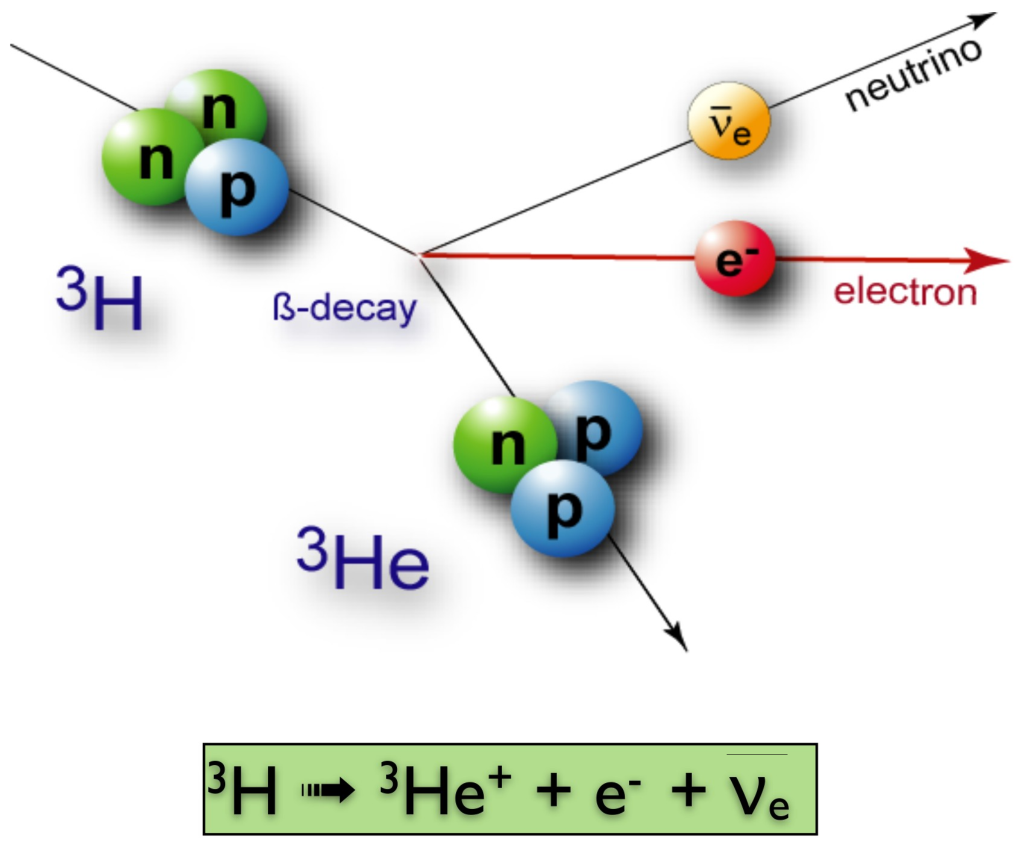


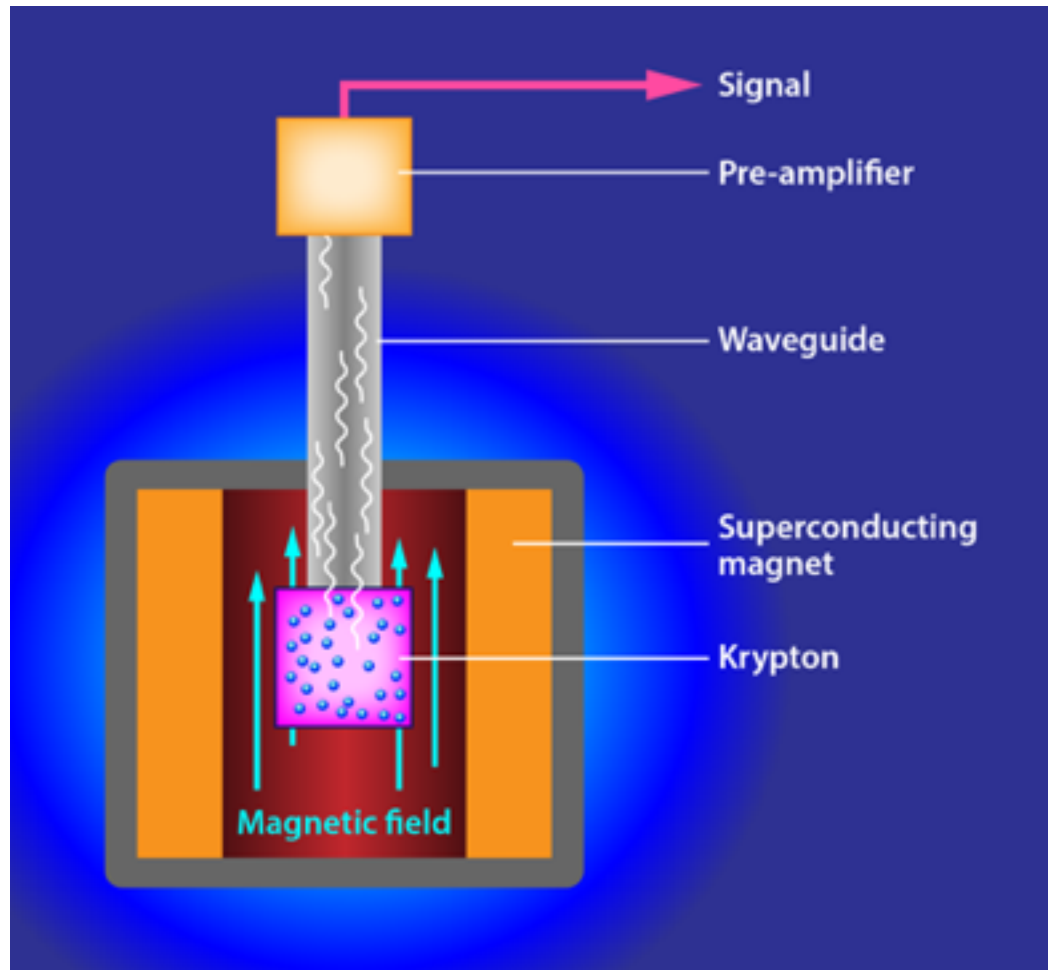


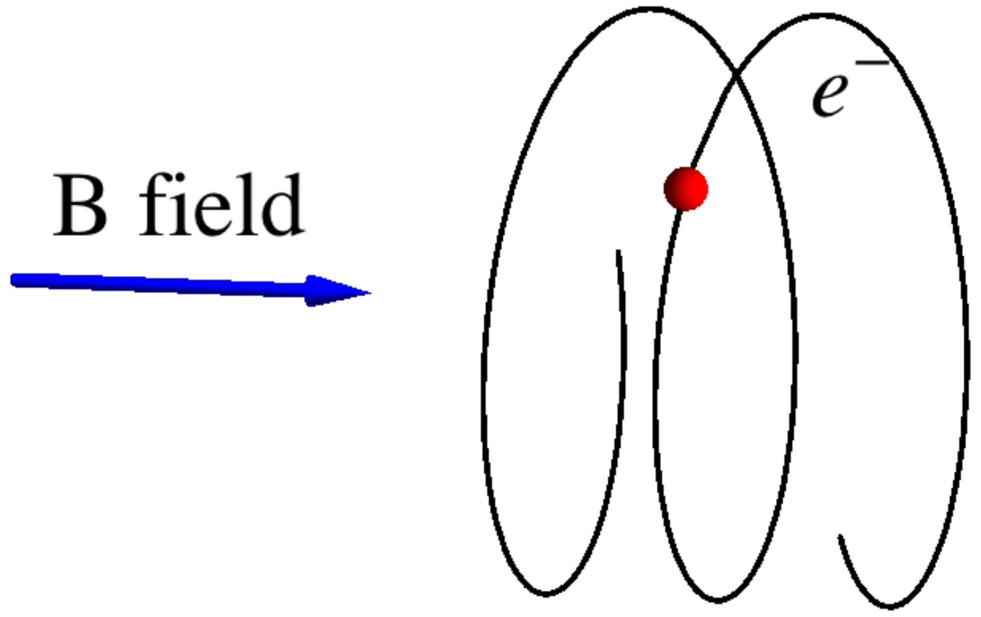
Refs:
1.)A. Pocar, NOW 2014

NEUTRINO MASS: PROJECT 8

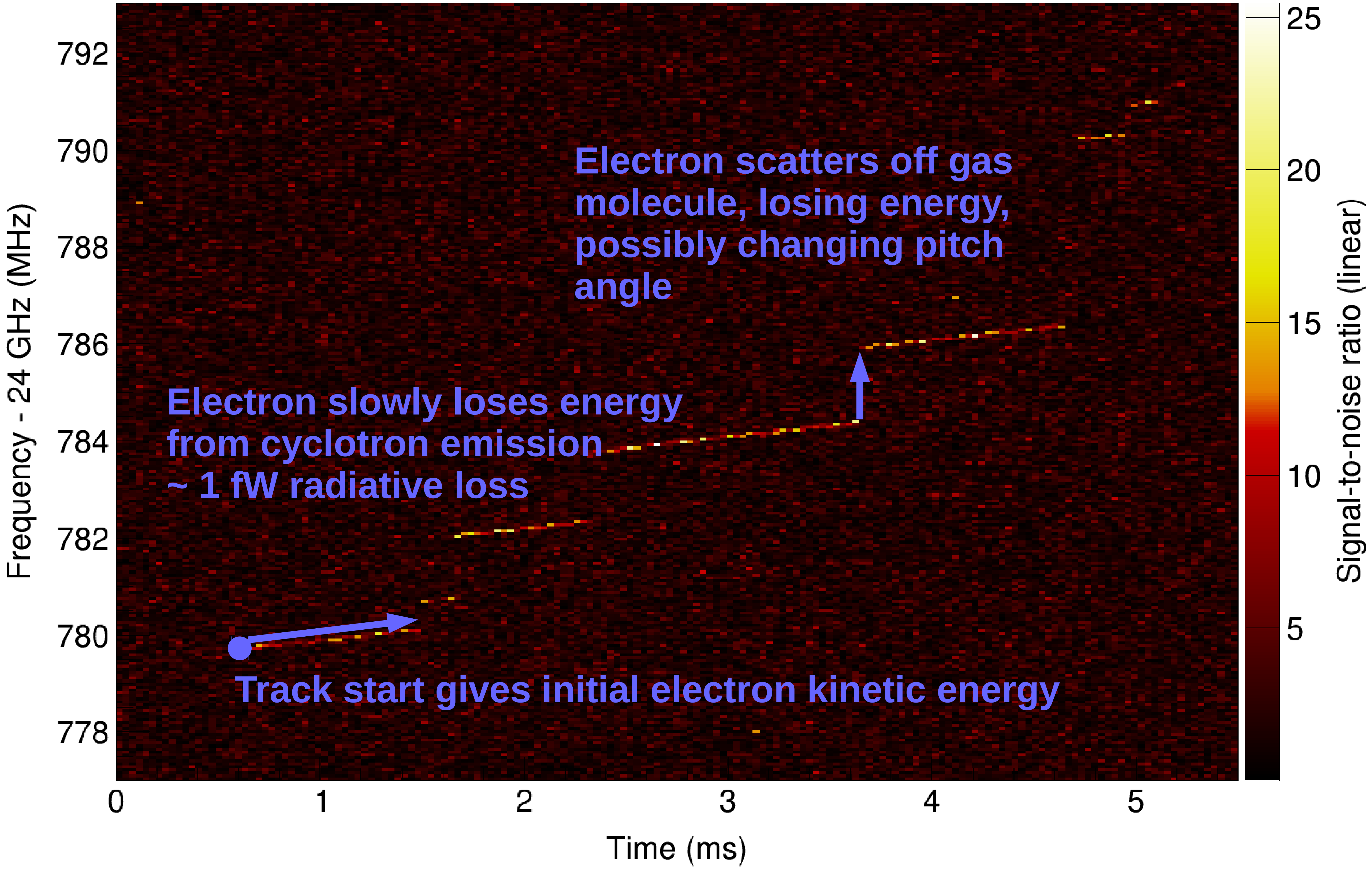
- Project 8 is pursuing a technique to measure the cyclotron frequency of single electrons emitted in Tritium beta-decay (now using Kr83 for testing/calibration).
- Potential mass reach down to 0.05 eV.







$$f = \frac{1}{2\pi} \frac{eB}{m_e + E_{kin}}$$



Refs:
1.) *Single-Electron Detection and Spectroscopy via Relativistic Cyclotron Radiation*, D.M. Asner et al, PRL 114 162501 (2015)

Build a better mousetrap and the world will beat a path to your door.
- Ralph Waldo Emerson

CHALLENGES/OPPORTUNITIES IN INSTRUMENTATION FOR NEUTRINOS

CHALLENGES

- Experiments get increasingly longer in duration (~decades)…qualifying lifetime of components (electronics, photon detectors, tracking chamber wires/connectors, etc…) non-trivial but crucial.

- Demands on precision only going to get more stringent (e.g. - energy reconstruction, timing, …). Variety of nuclear isotopes/targets in use requires input from NP community.

- To say nothing of needs for: intense beams/sources with well understood flux; computing/readout; stable long-term underground operation

OPPORTUNITIES?

"The program will place an emphasis on proposing new ideas for detection technologies"

- LAPPDs for large neutrino detectors (water, scintillator, cryogenic)…?
- New ideas for mitigating Ar-39 in large quantities of liquid argon?
- Magnetizing very large liquid argon detectors?
- …

FERMILAB NEUTRINO DETECTOR R&D WORKSHOP

- Fermilab will host a Neutrino Detector R&D Facility Workshop Jan. 20-22, 2016.
- Come up with a great idea here at this meeting and then go learn how to test it out!
- Formal advertisement coming soon.

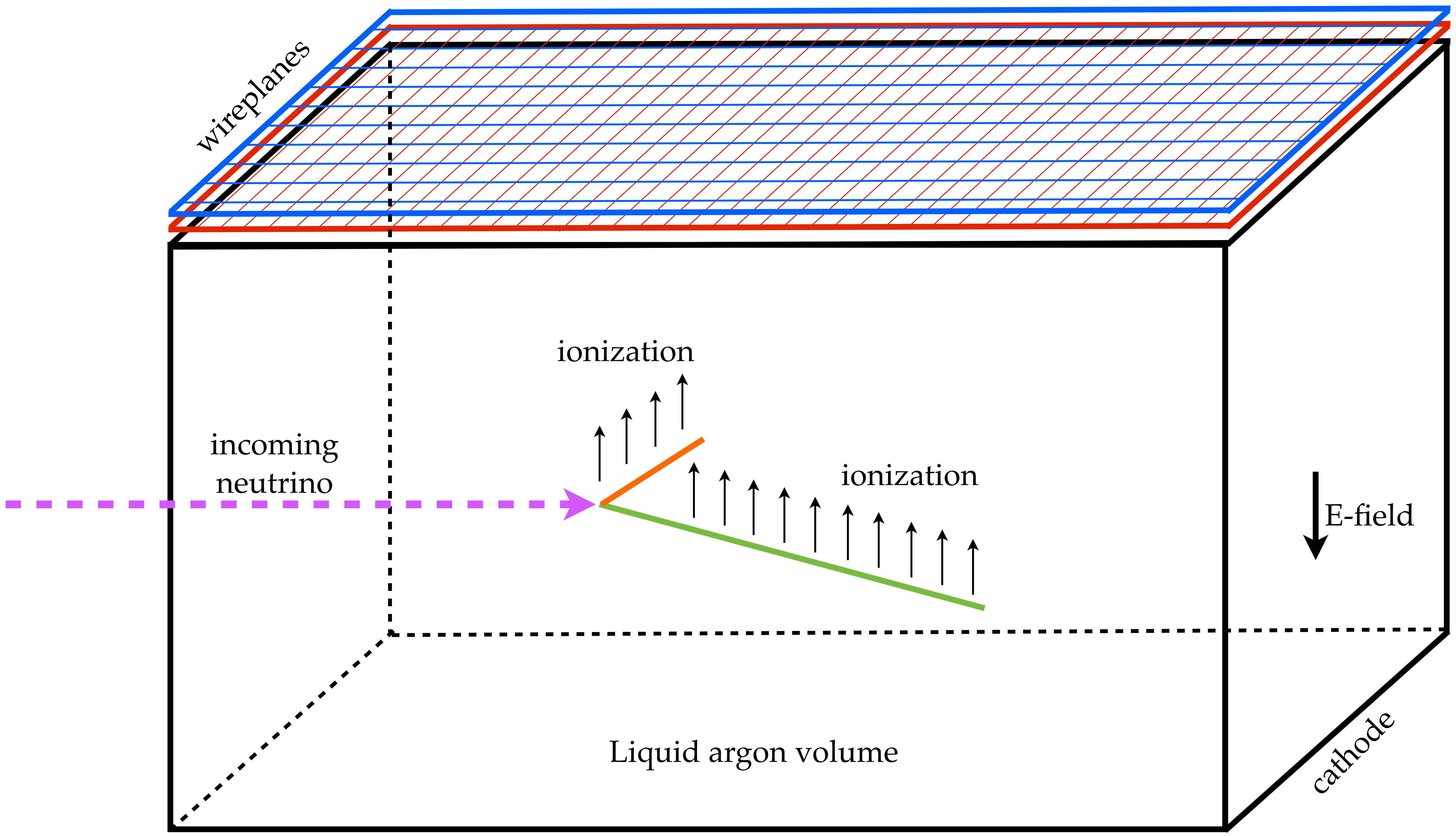
CONCLUSIONS

- The experimental study of neutrinos is an exciting field of research that is ripe for new discoveries in the coming years.
- Innovations in detectors and instrumentation are a necessary element for the next generation of experiments to be successful.
- Apologies to the many wonderful experiments I skipped…please go see the neutrino parallel session this afternoon!

BACK UP

LIQUID ARGON DETECTORS FOR NEUTRINOS

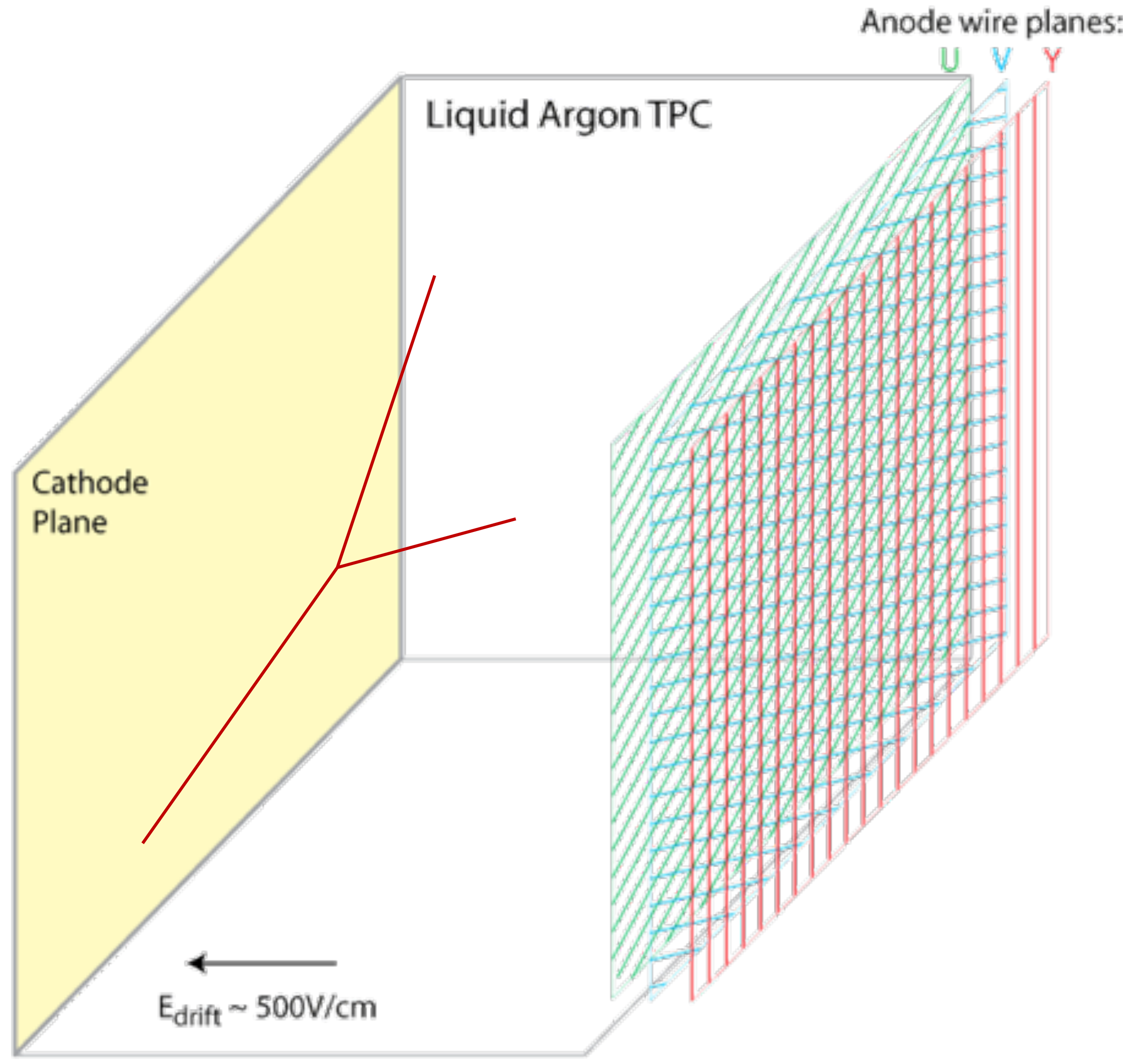
- Charged particles produced in a neutrino interaction ionize the liquid argon they travel through.
- That ionization is drifted to a set of anode planes that are samples in time by electronics.



Refs:
1.) *Design of Grid Ionization Chambers*, Bunneman, Cranshaw,Harvey, Can. J. Res. 27 (1949) 191
2.) *Design of Large LArTPCs*, B. Yu, TIPP 2011

LIQUID ARGON DETECTORS FOR NEUTRINOS

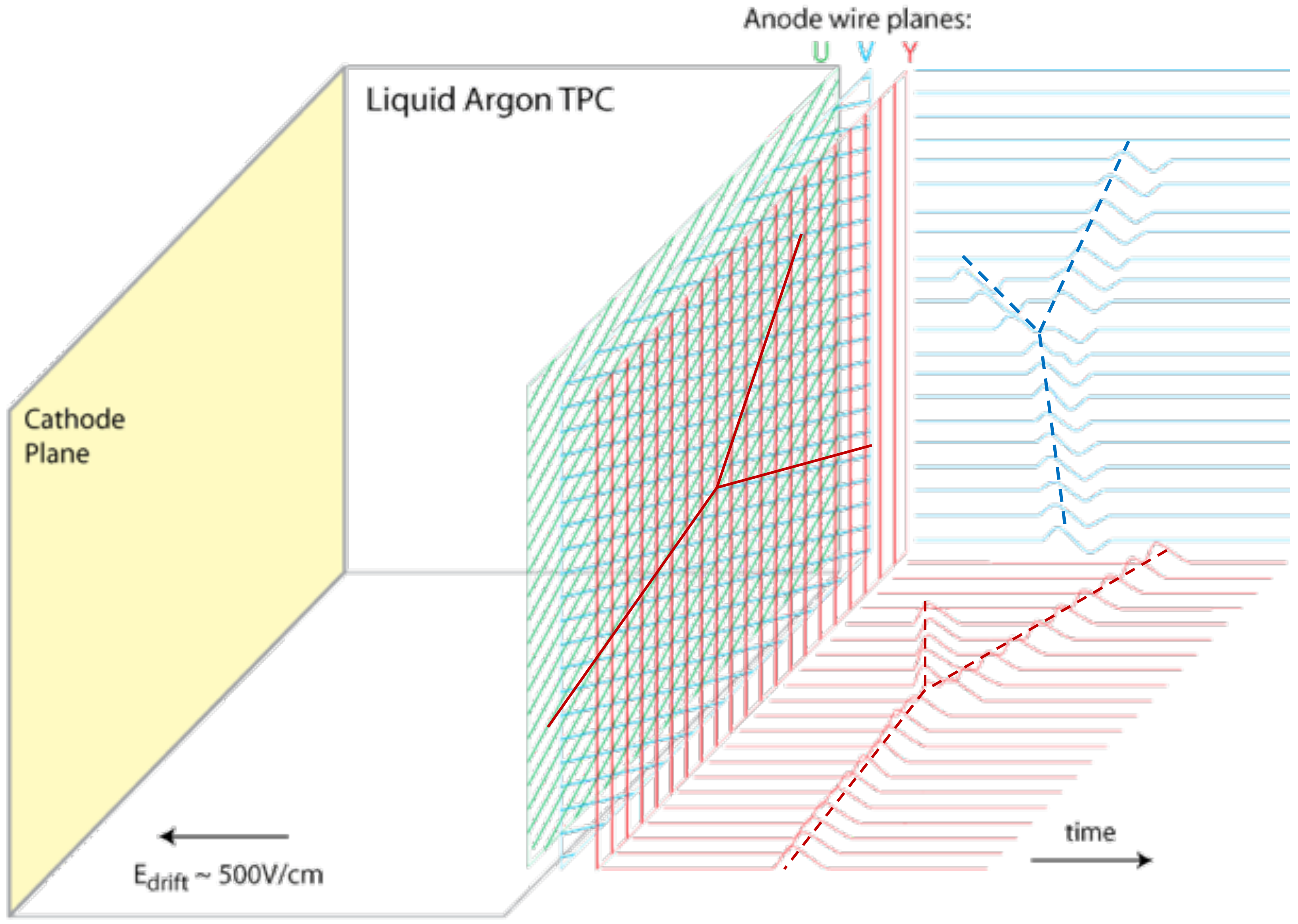
- Charged particles produced in a neutrino interaction ionize the liquid argon they travel through.
- That ionization is drifted to a set of anode planes that are samples in time by electronics.



Refs:
1.) *Design of Grid Ionization Chambers*, Bunneman, Cranshaw,Harvey, Can. J. Res. 27 (1949) 191
2.) *Design of Large LArTPCs*, B. Yu, TIPP 2011

LIQUID ARGON DETECTORS FOR NEUTRINOS

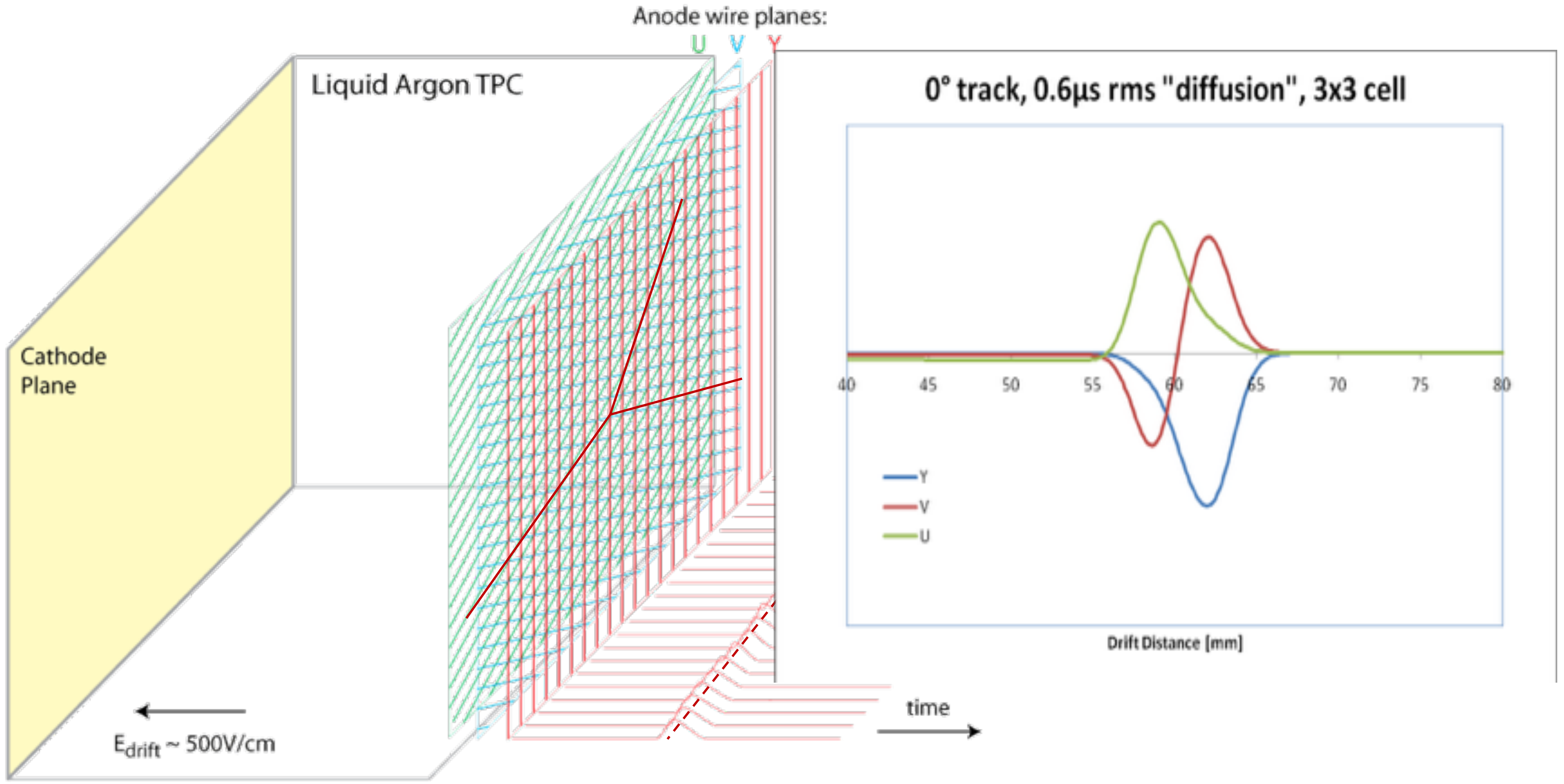
- Charged particles produced in a neutrino interaction ionize the liquid argon they travel through.
- That ionization is drifted to a set of anode planes that are samples in time by electronics.



Refs:
1.) *Design of Grid Ionization Chambers*, Bunneman, Cranshaw,Harvey, Can. J. Res. 27 (1949) 191
2.) *Design of Large LArTPCs*, B. Yu, TIPP 2011

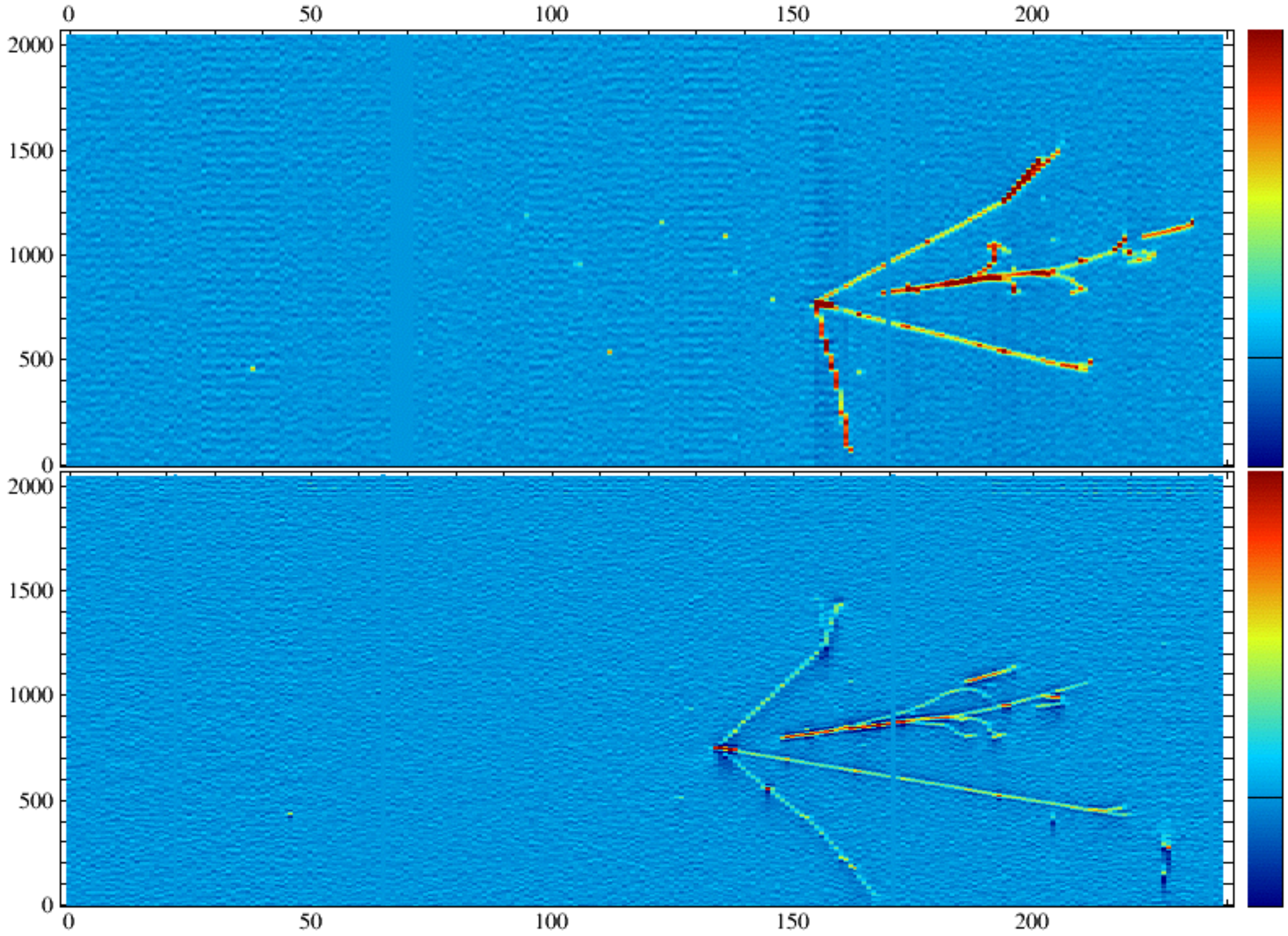
LIQUID ARGON DETECTORS FOR NEUTRINOS

- Charged particles produced in a neutrino interaction ionize the liquid argon they travel through.
- That ionization is drifted to a set of anode planes that are samples in time by electronics.



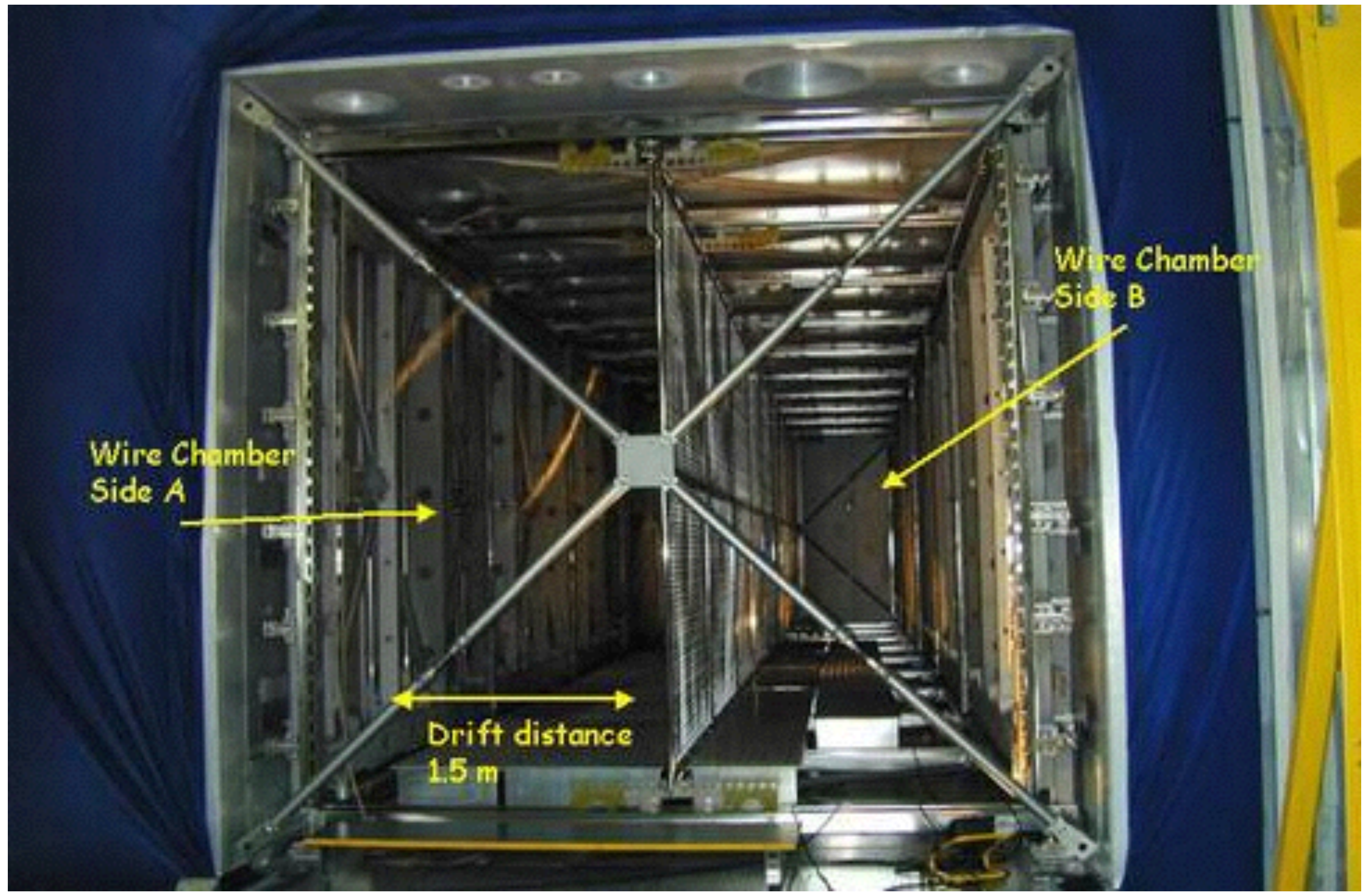
Refs:
1.) *Design of Grid Ionization Chambers*, Bunneman, Cranshaw,Harvey, Can. J. Res. 27 (1949) 191
2.) *Design of Large LArTPCs*, B. Yu, TIPP 2011

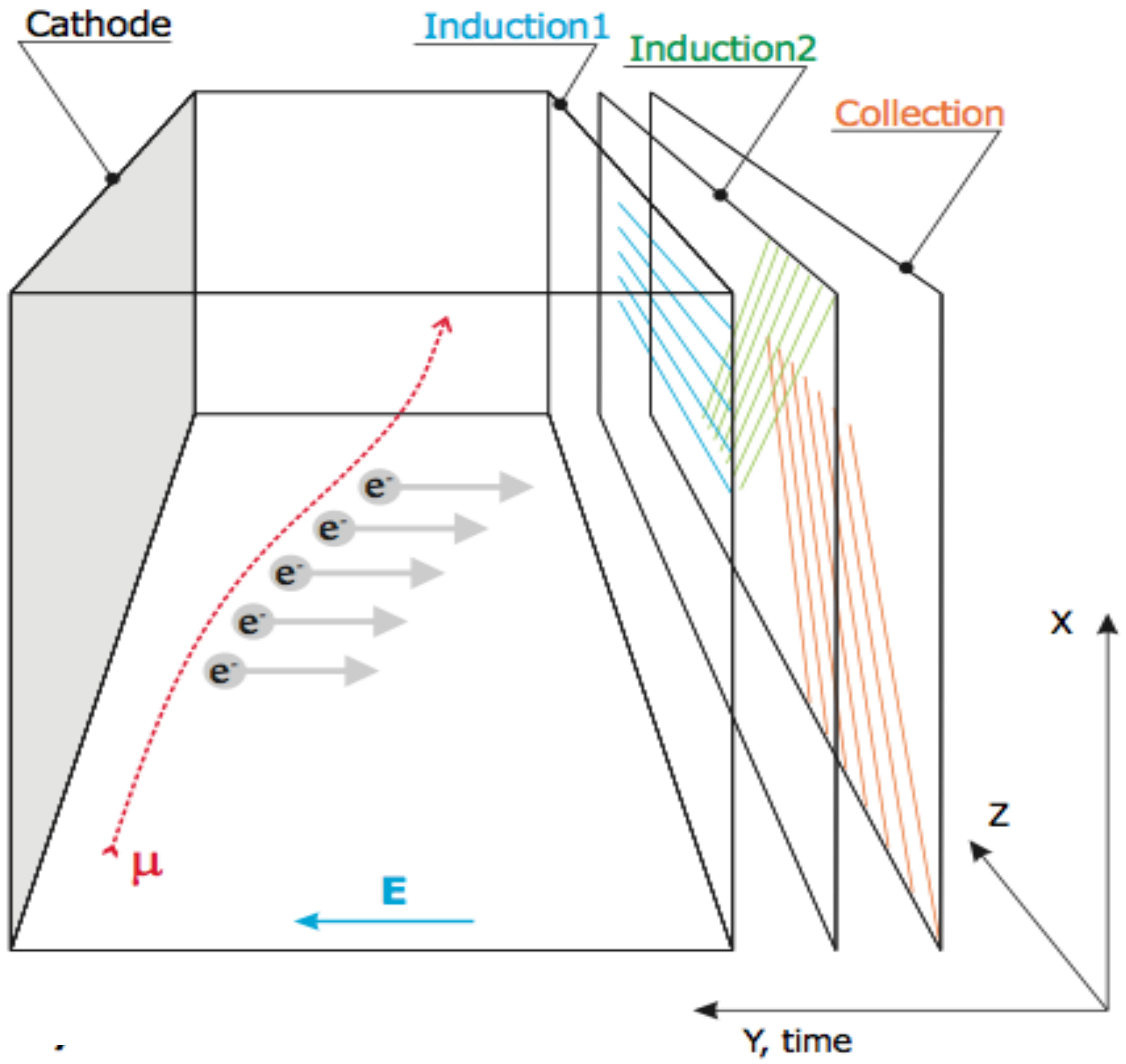
LIQUID ARGON DETECTORS FOR NEUTRINOS



LIQUID ARGON DETECTORS FOR NEUTRINOS

- 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.
- Allows us to scale the detector to very large sizes without the cost of electronics becoming prohibitive.
- The longer the drift length, the higher the demands on LAr purity and high-voltage capability.





NOBLE ELEMENTS…LIQUIFIED

	He	Ne	Ar	Kr	Xe
Atomic Number	2	10	18	36	54
Boiling Point [K] @ 1atm	4.2	27.1	87.3	120	165
Density [g/cm^3]	0.125	1.2	1.4	2.4	3
Radiation Length [cm]	755.2	24	14	4.9	2.8
dE/dx [MeV/cm]	0.24	1.4	2.1	3	3.8
Scintillation [γ/MeV]	19,000	30,000	40,000	25,000	42,000
Scintillation λ [nm]	80	78	128	150	175
Cost ($/kg)	52	330	5	330	1200

ADVANTAGES FOR LIQUID ARGON DETECTORS

- Fine spatial resolution allowed excellent particle ID, and hence excellent background rejection.
- Appear scalable to sizes necessary to be the "far detector" in a long-baseline neutrino experiment.