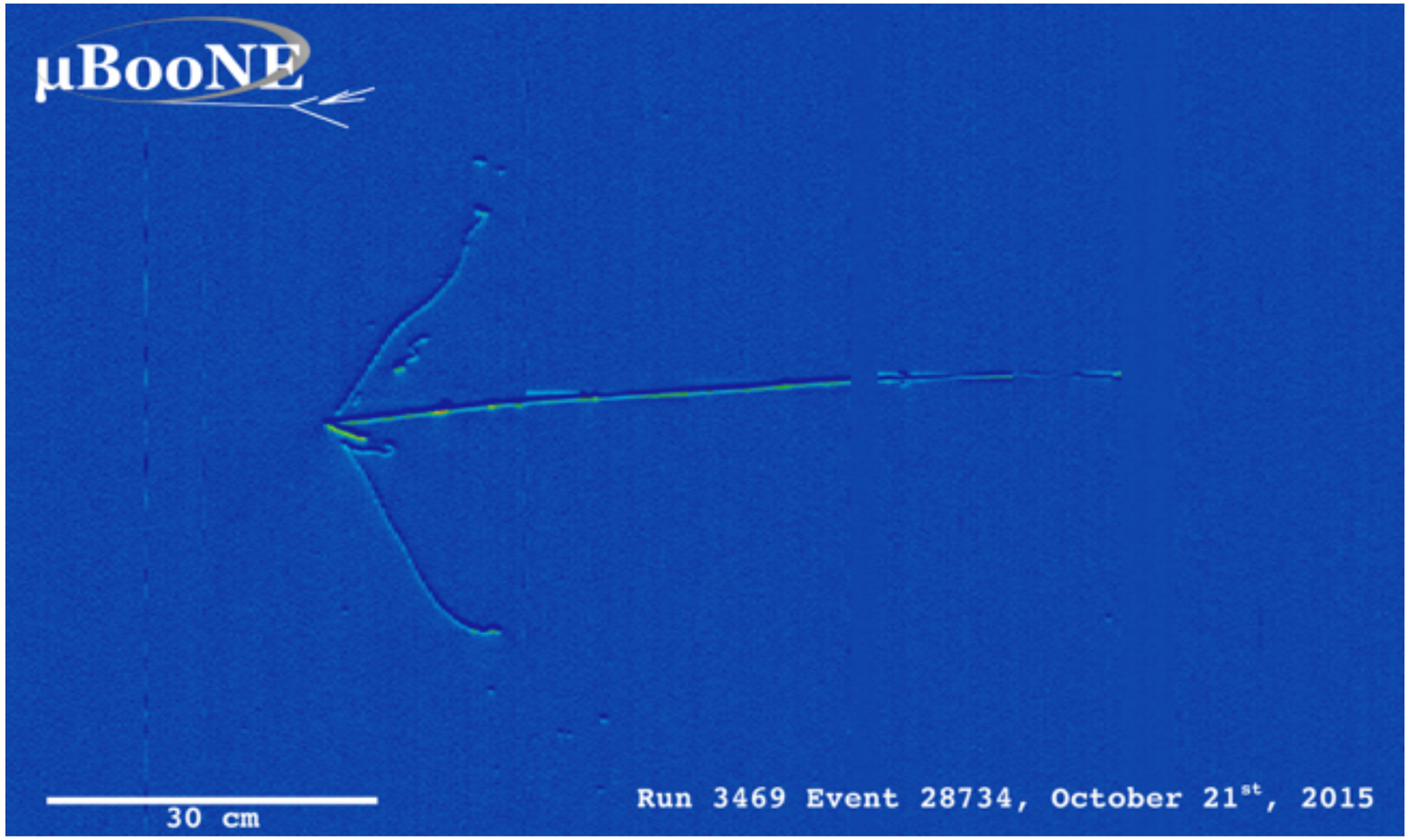
From MeV to GeV: Capturing New Physics With Liquid Argon TPCs

Bryce Littlejohn
Illinois Institute of Technology

February 18, 2016

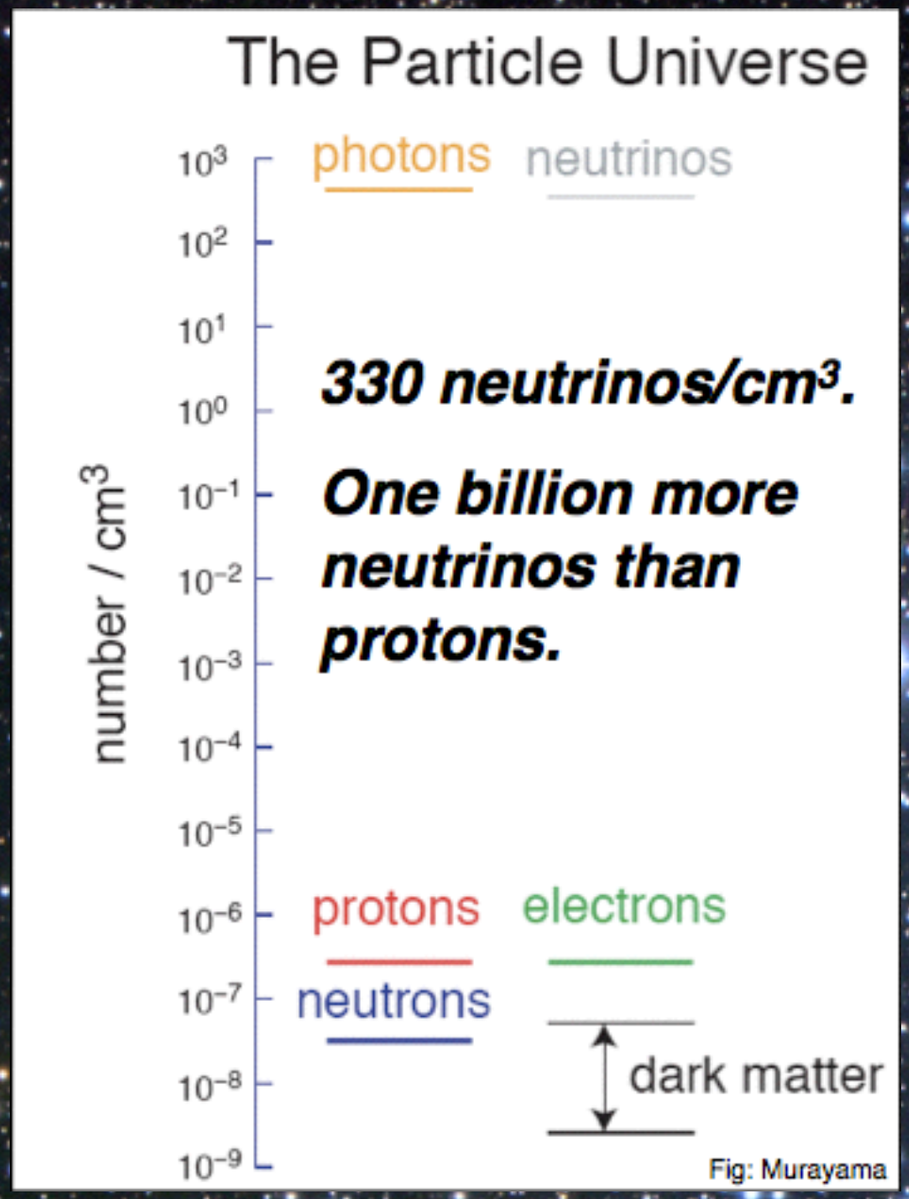


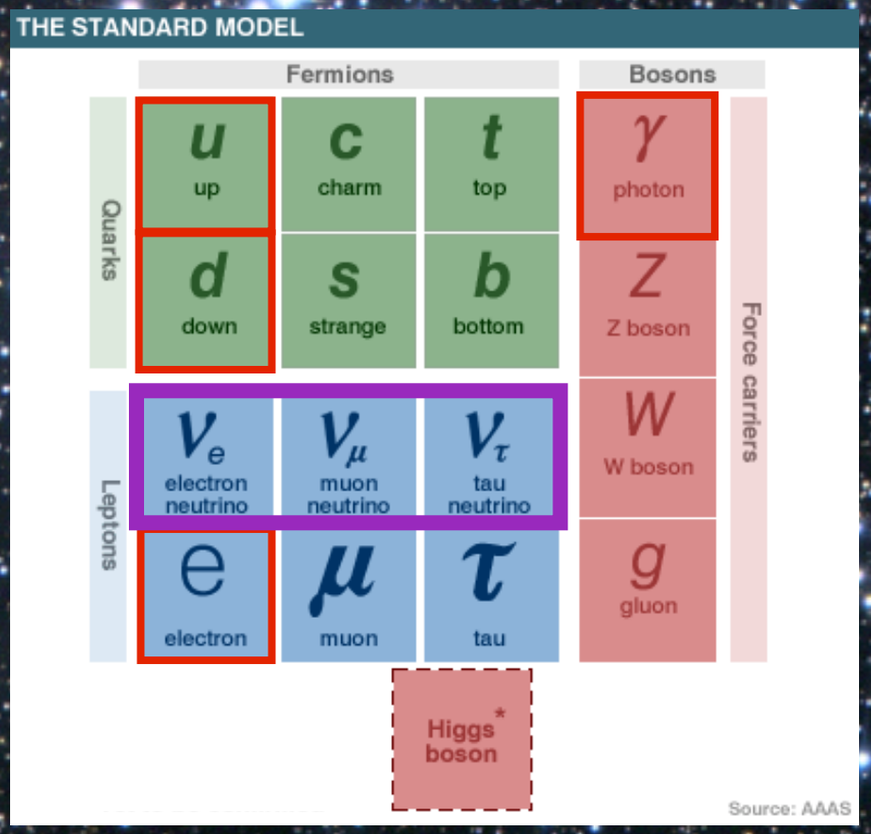
Outline

- What are neutrinos, and what do we know about them?
- Why do we study them?
- Liquid Argon Time Projection Chambers (LArTPCs): The ULTIMATE neutrino detection technology!
- What we're doing at IIT to make LArTPCs useful for a wide variety of physics topics.

Neutrinos

The Universe's most common particle, after photons!





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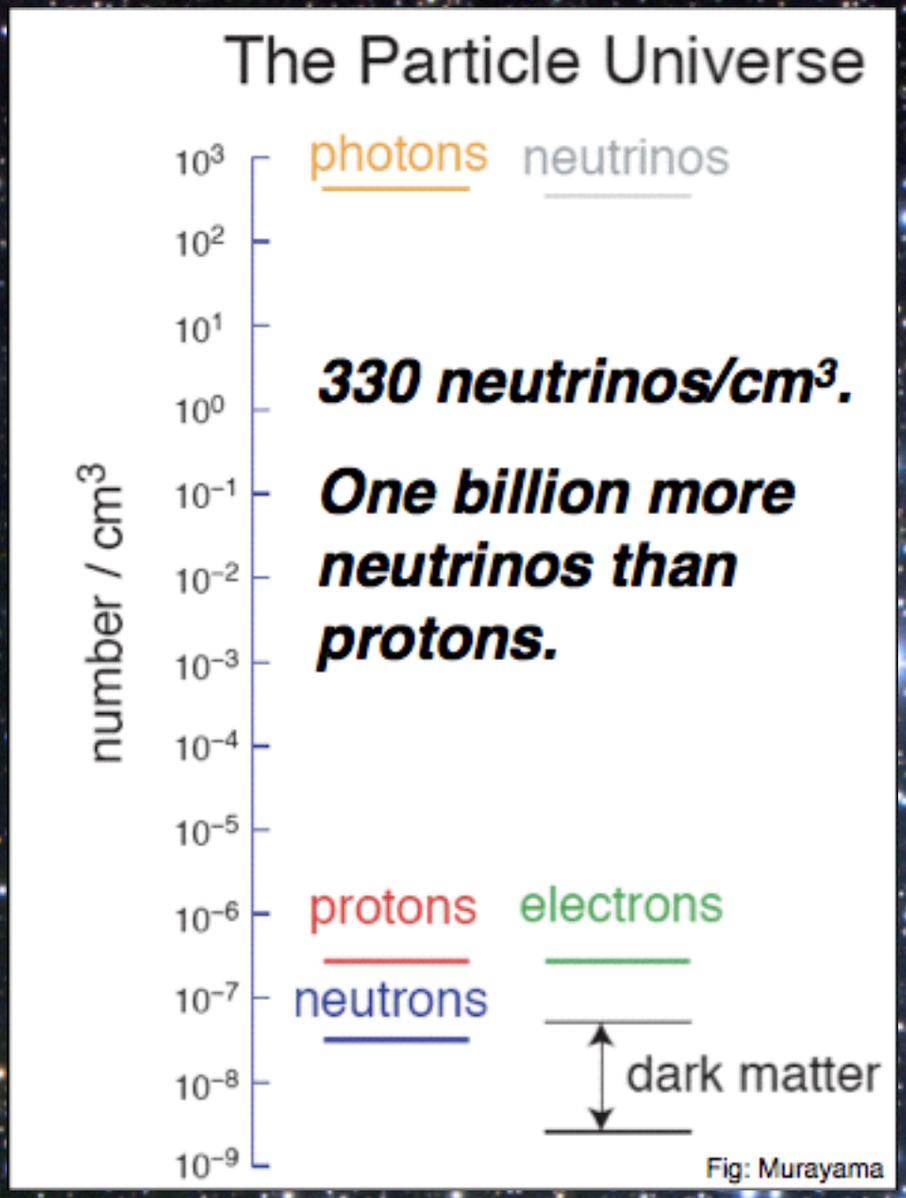
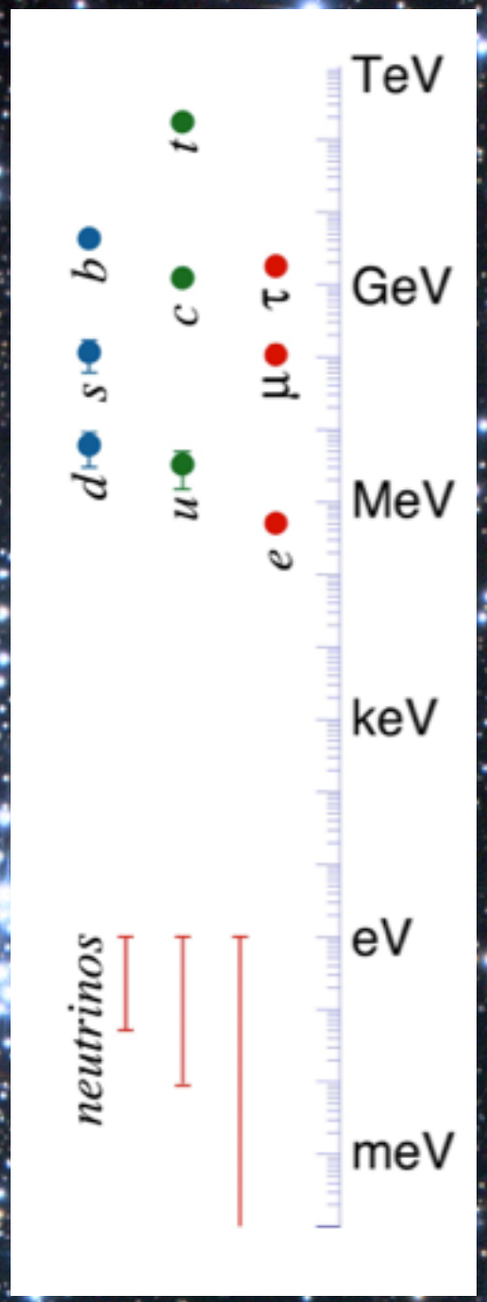
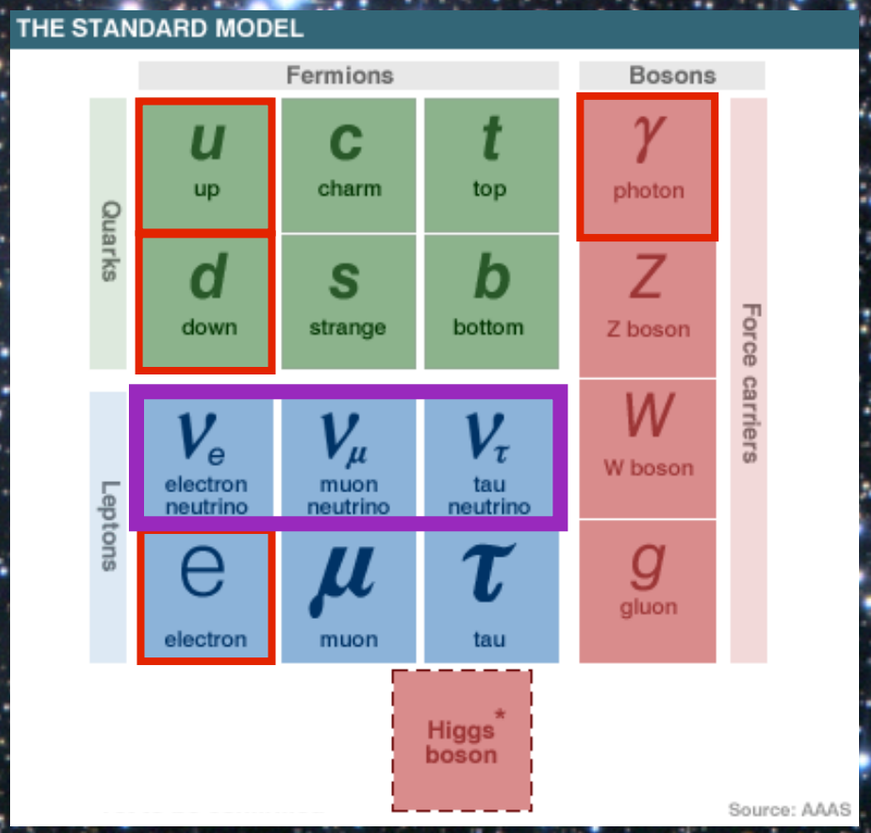






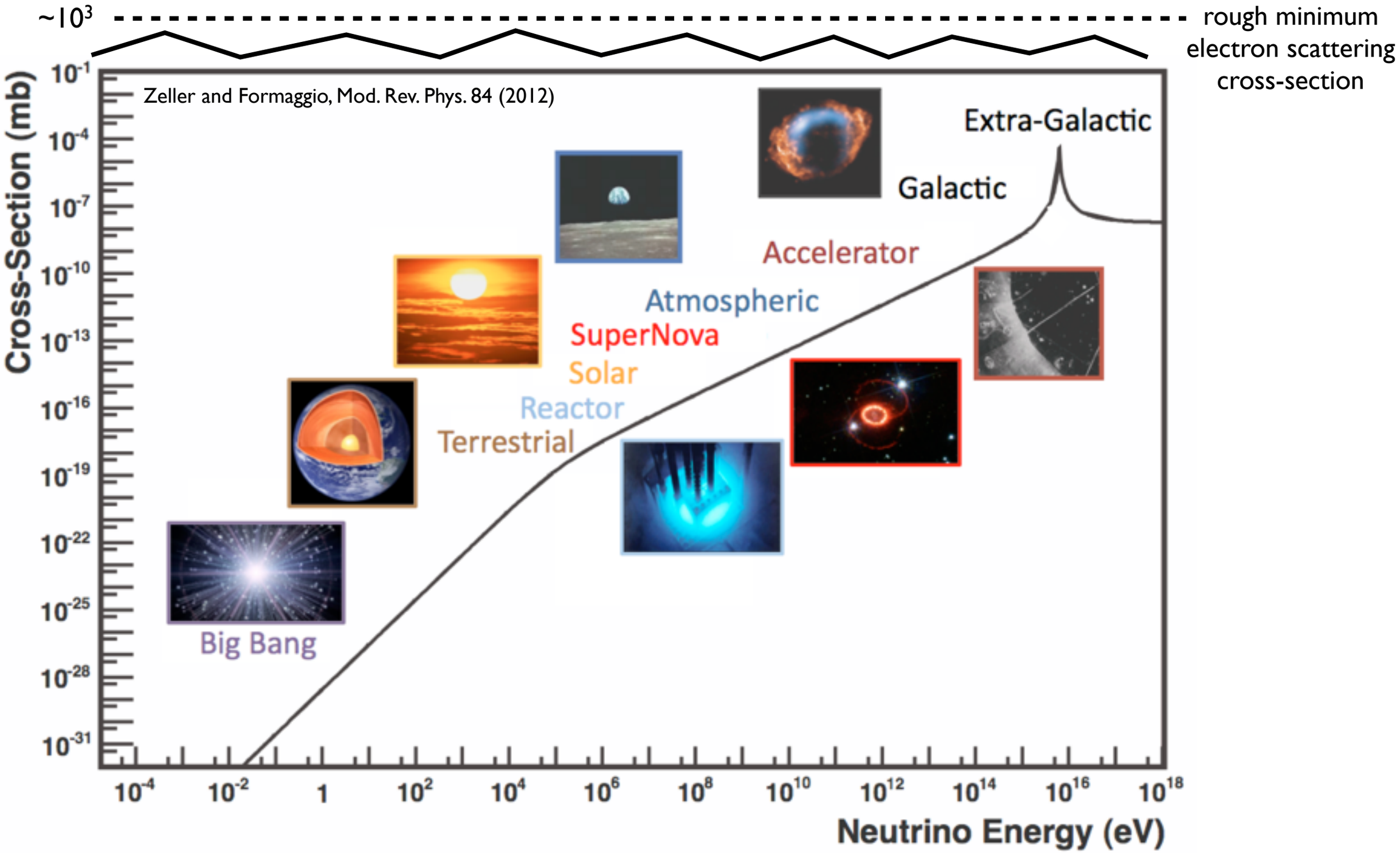
Far less massive than all other fermions

Also, no electric charge

Note: 1 eV ~1.6×10^{-19} J ~ 2×10^{-36} kg ($E=mc^2$)

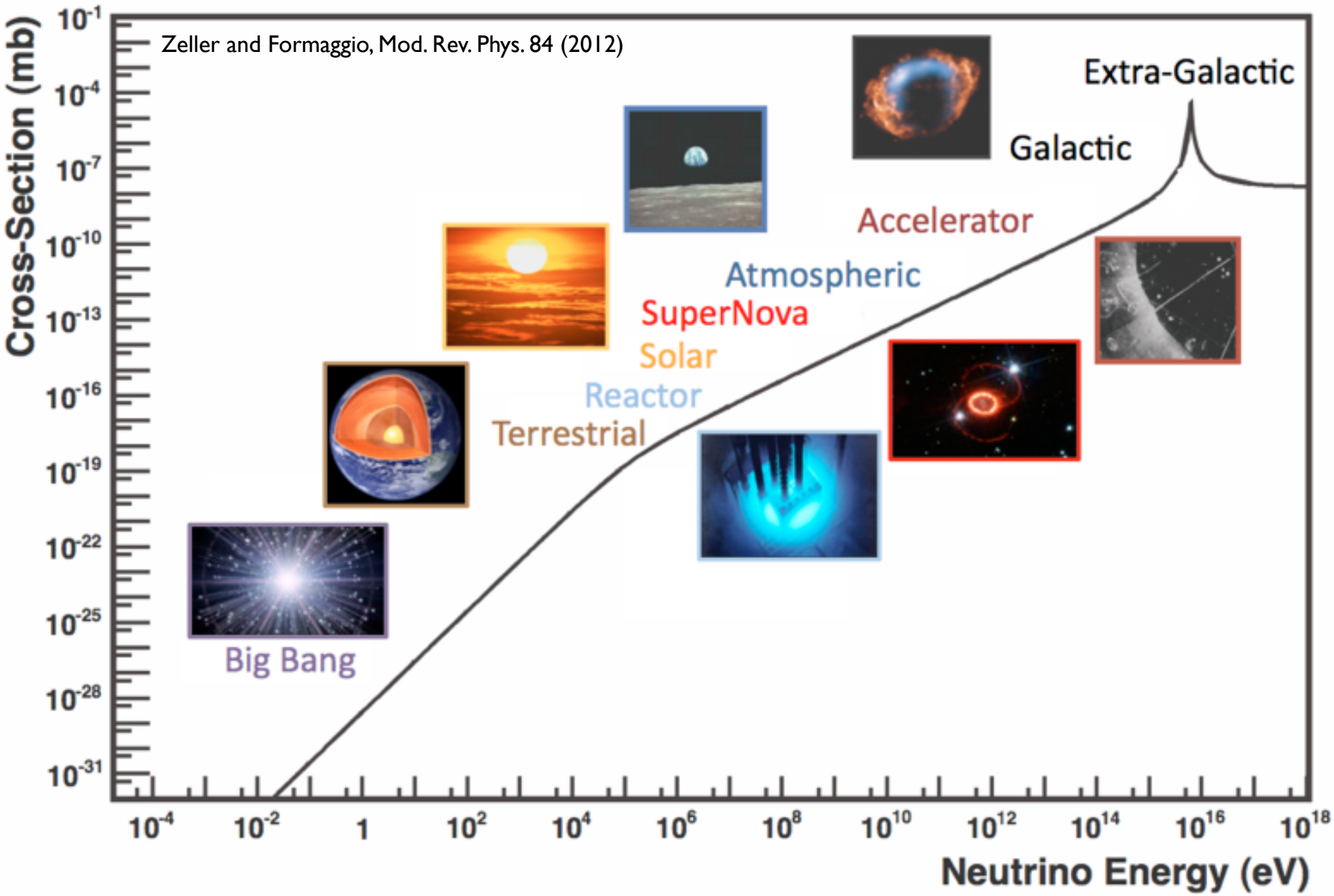
Neutrino Varietals

- Many neutrino sources and energies, interacting via weak force
  - Electrons circle nuclei in the Earth, neutrinos go right through… <u>THE EARTH!</u>



Neutrino Varietals

- Neutrino sources:
  - "Laboratory sources:" humans make them, understand them ~well.
  - "Other:" naturally produced, understood to varying degrees.



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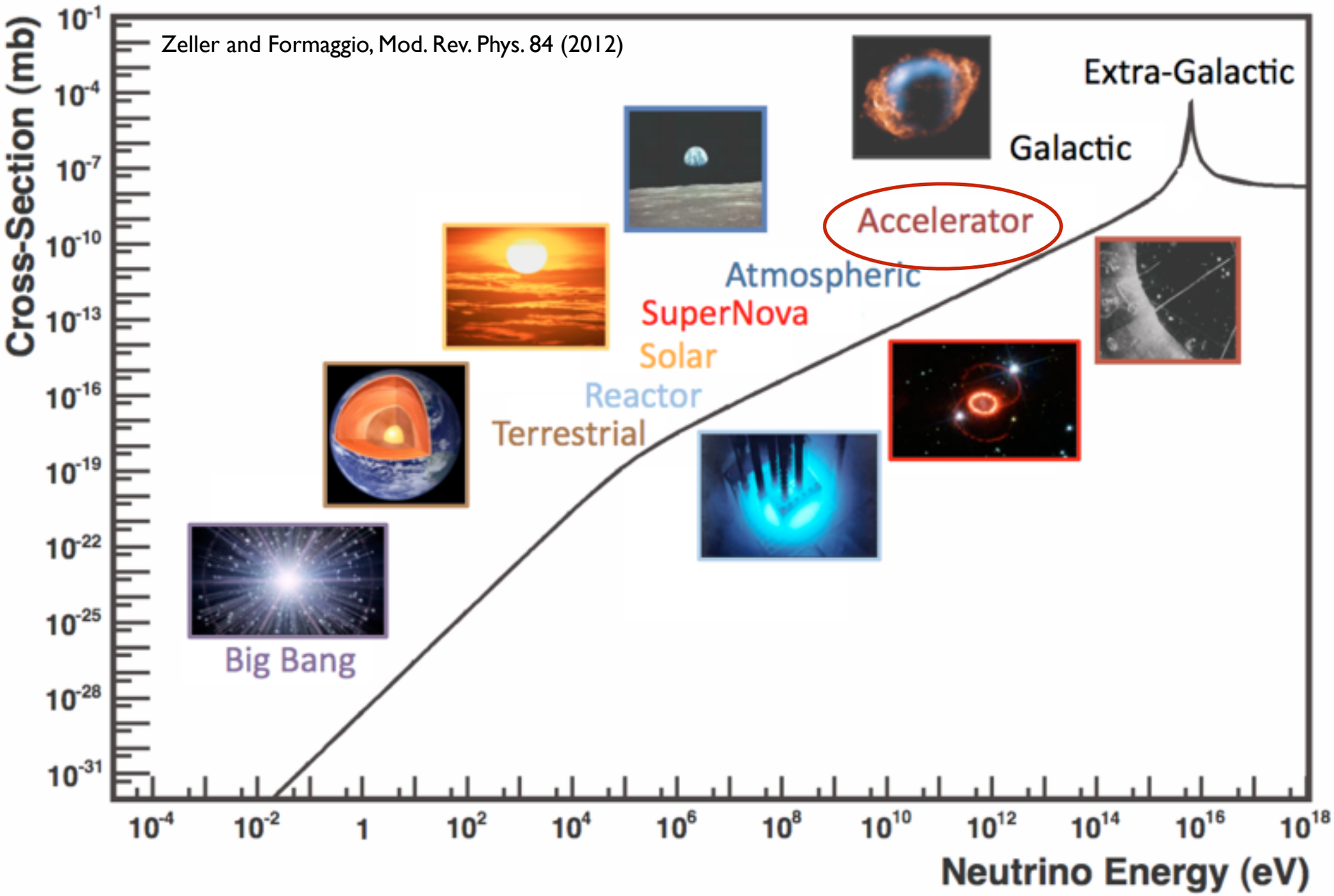
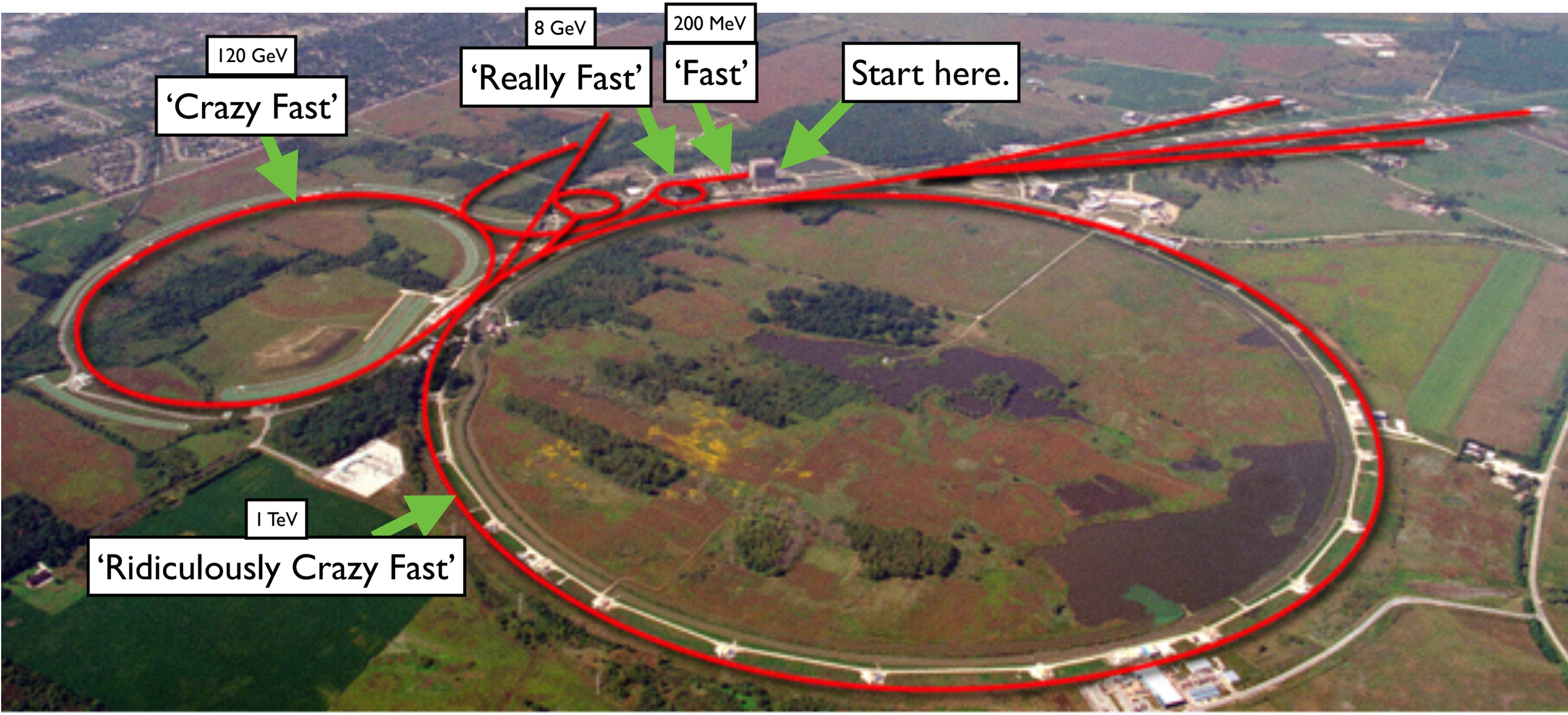


Example: Accelerators

- Fermilab: Masters of Proton Beams!
  - Accelerate protons (hydrogen nuclei) from 0 to 99.999% the speed of light in four steps



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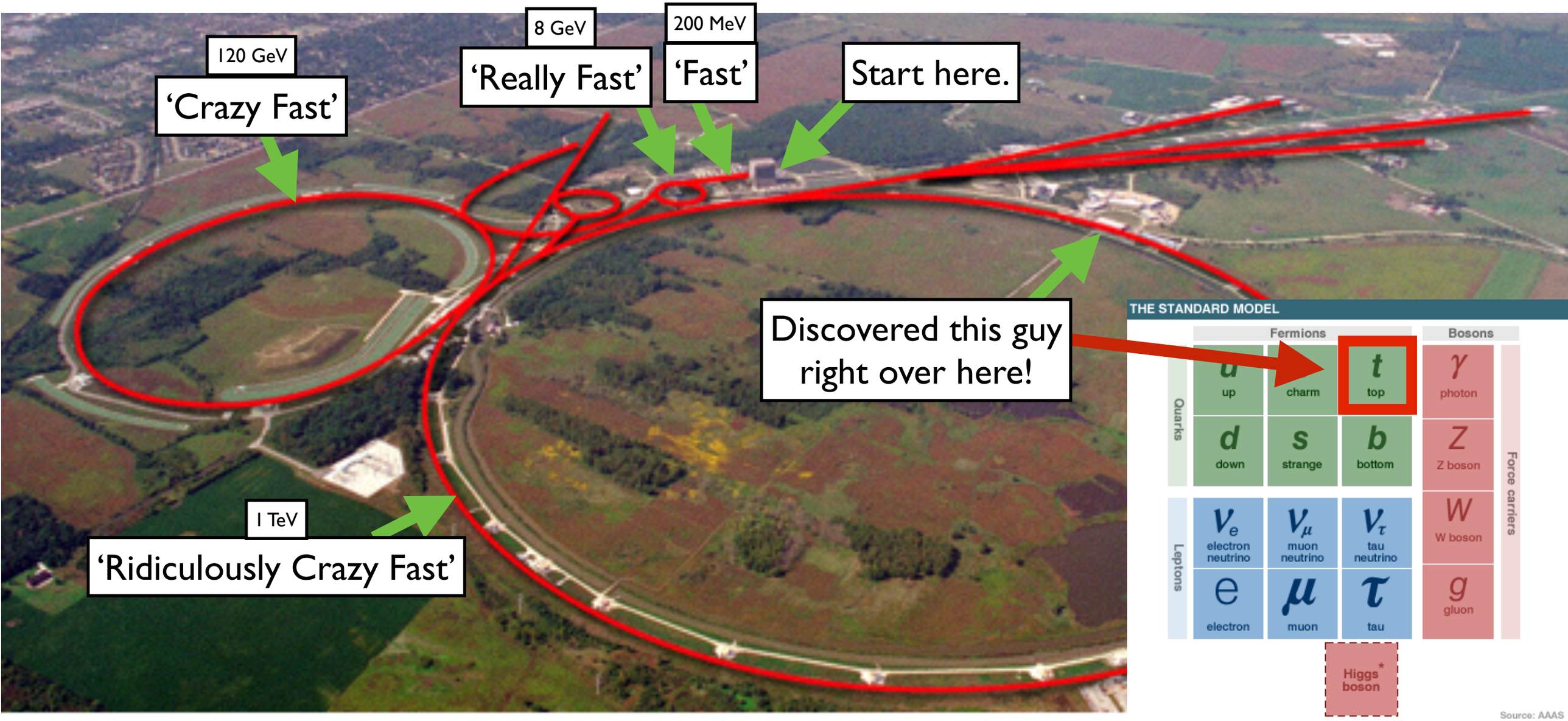
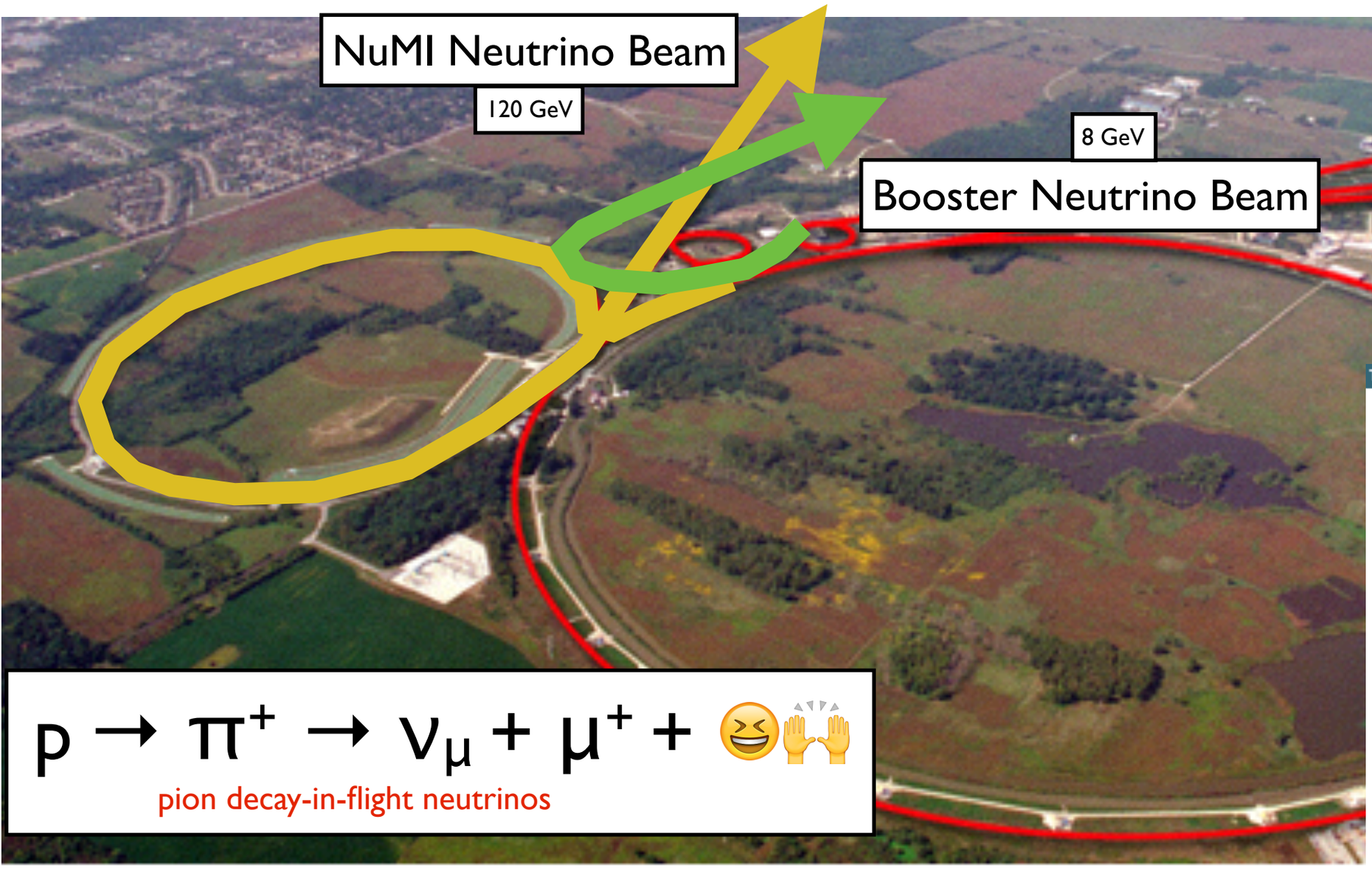
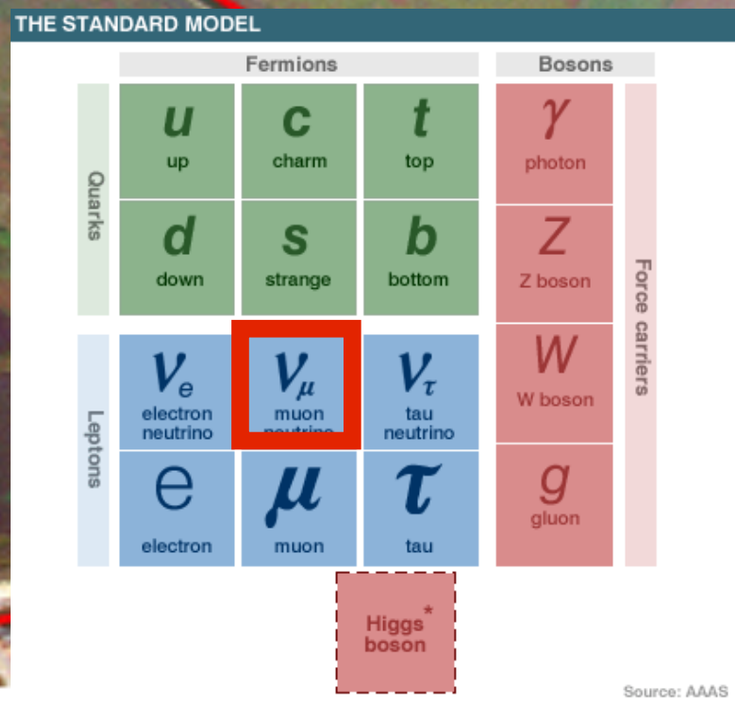


Example: Accelerators

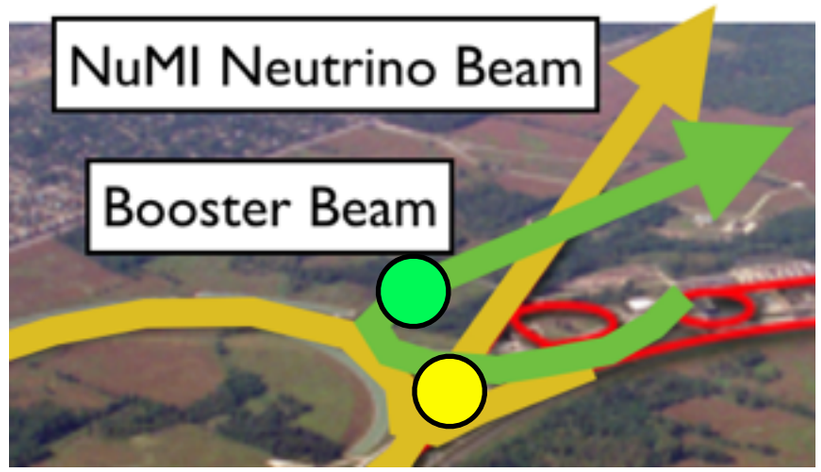
- Fermilab: Masters of Proton Beams!
  - Accelerate protons (hydrogen nuclei) from 0 to 99.999% the speed of light in four steps
- Use proton beams to make beams muon-type neutrinos

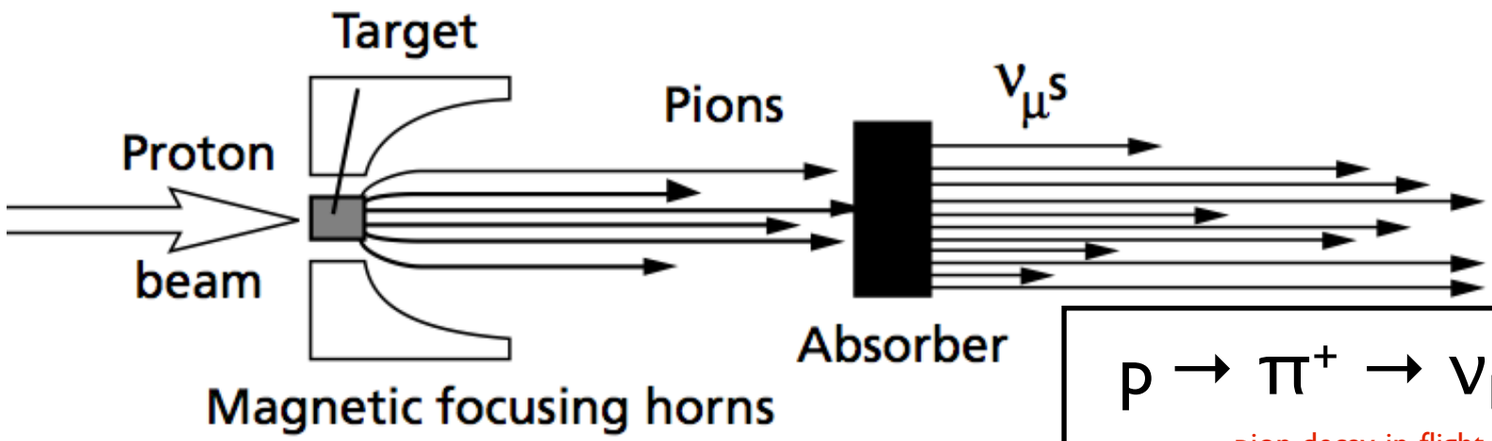




Example: Accelerators

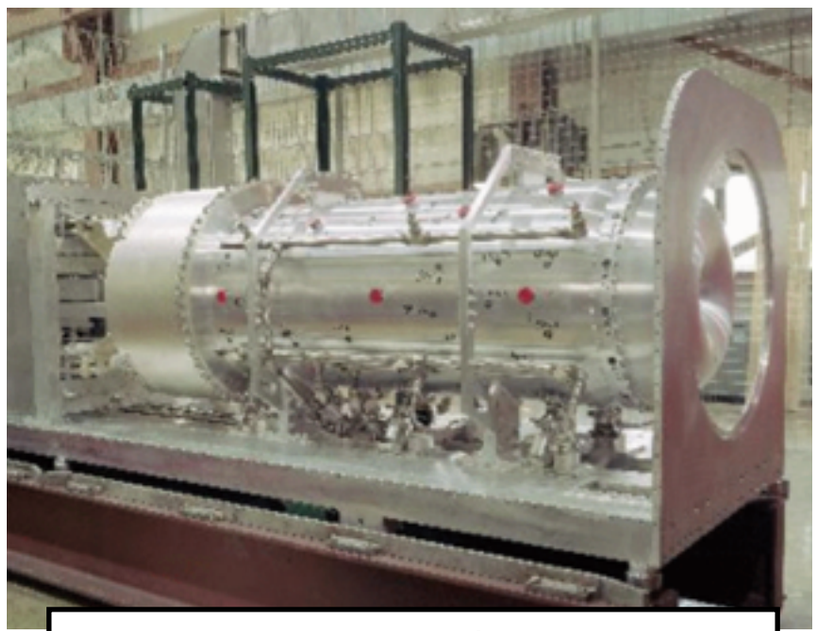
- How are the neutrinos ACTUALLY made?
  - Dump protons on a target
  - Electro-magnetically focus the products in a 'horn'
  - Let those products decay in flight to neutrinos!





$$p \rightarrow \pi^+ \rightarrow \nu_\mu + \mu^+ +$$ 😆🙌

pion decay-in-flight neutrinos

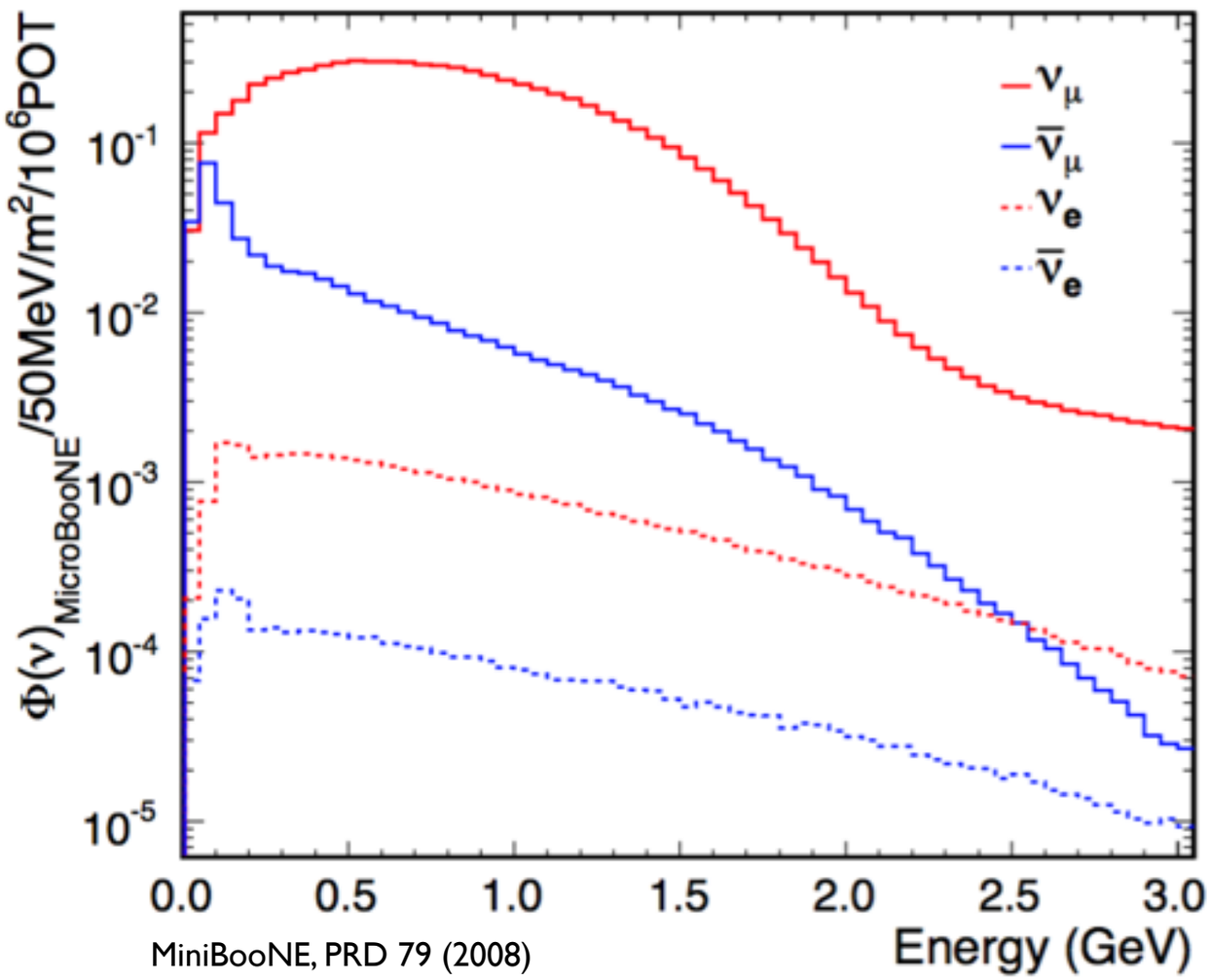


The Booster target/horn combo

The Booster 'coffin' — it MIGHT be a little radioactive….

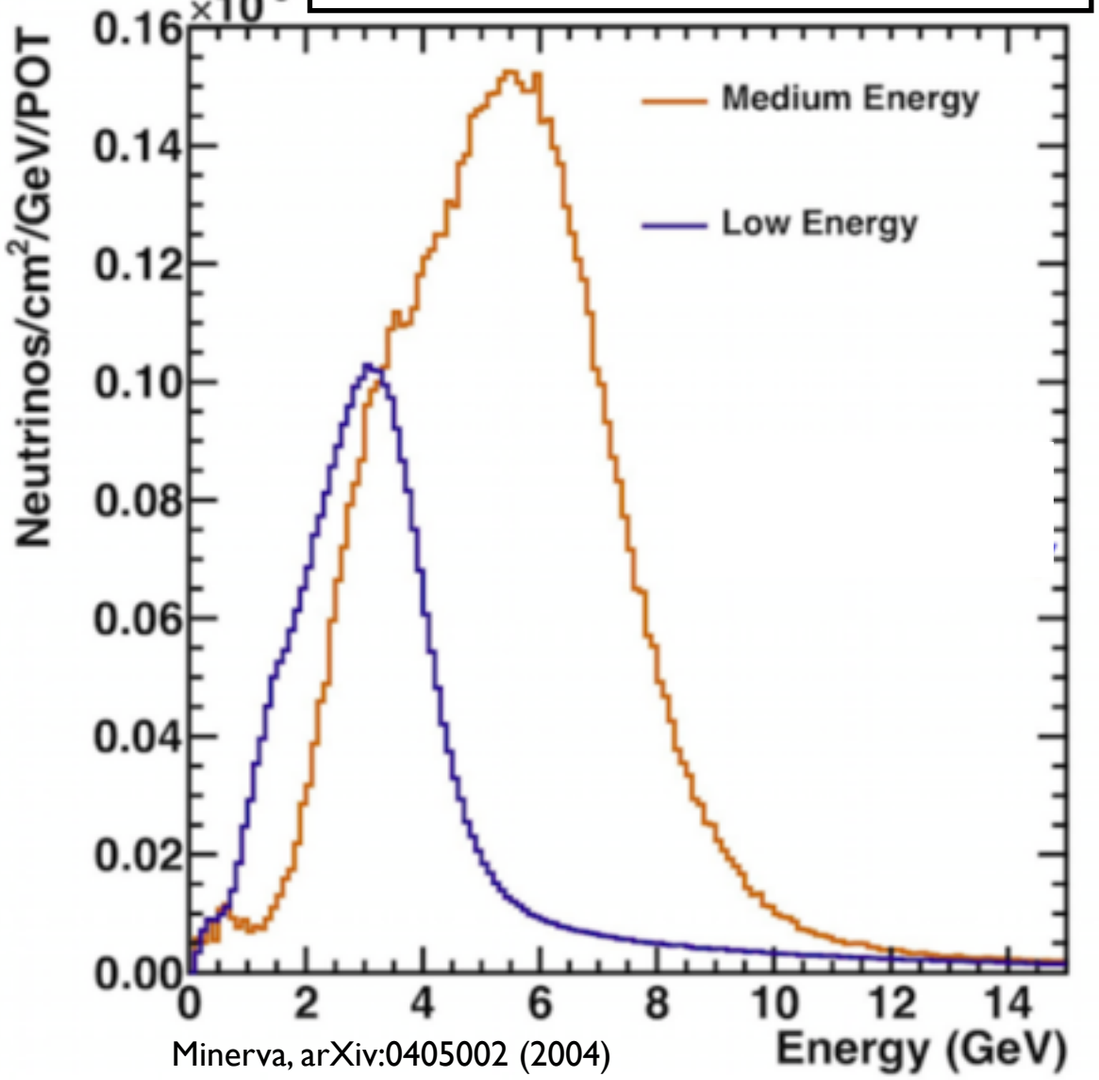
Example: Accelerators

Booster Neutrino Energy Spectrum



MiniBooNE, PRD 79 (2008)

NuMI Neutrino Energy Spectrum



Minerva, arXiv:0405002 (2004)

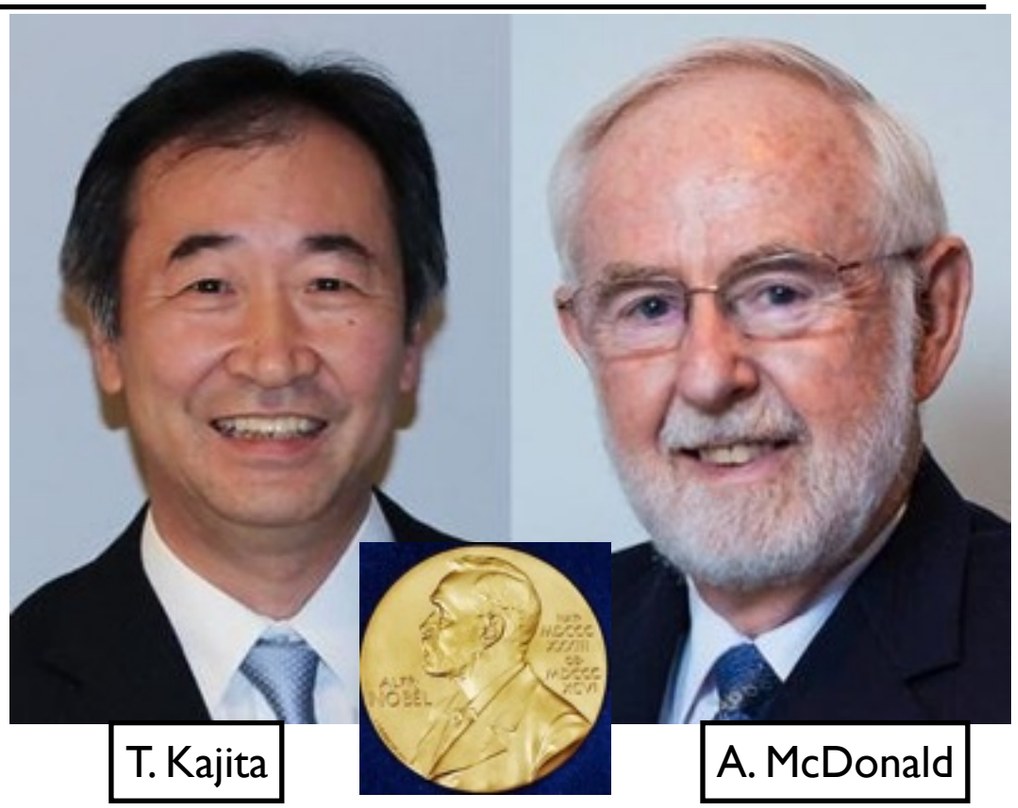
~0.5 - 10 GeV Neutrino Energies

Why Neutrinos?

- Why do we study neutrinos?

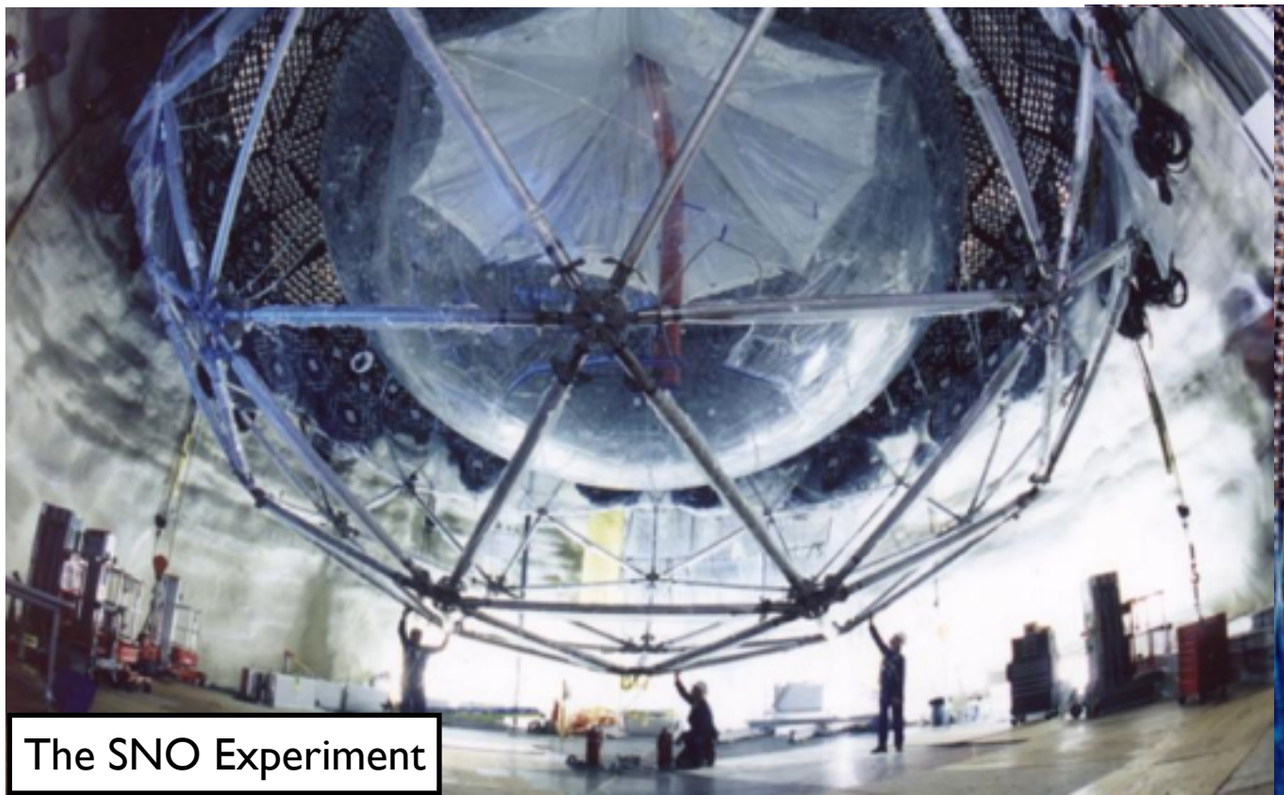
To Win Nobel Prizes!!!!!

- 2015 Physics Nobel prize: "for the discovery of neutrino oscillations, which shows that neutrinos have mass"
  - Not the only one either: 2002, 1995, 1988
- It's a very exciting time to be studying neutrino physics!

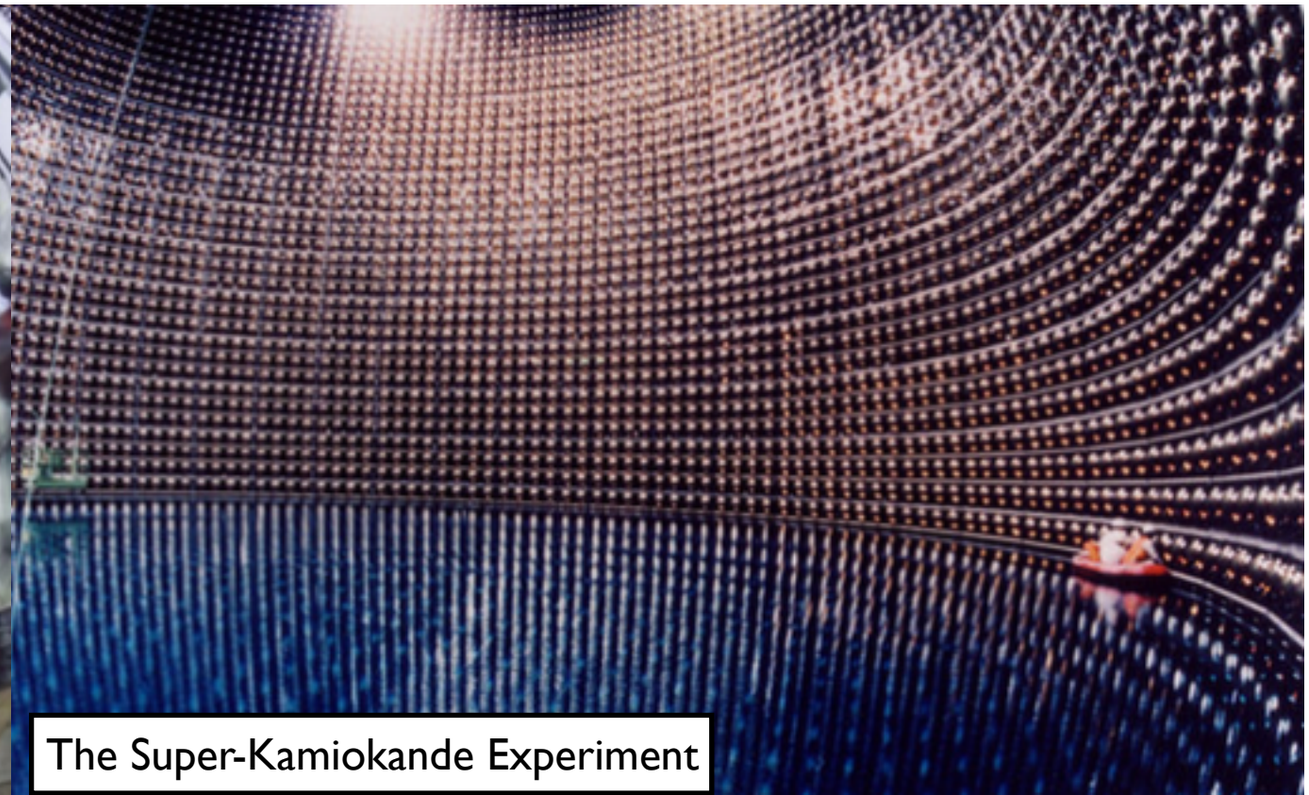


T. Kajita

A. McDonald



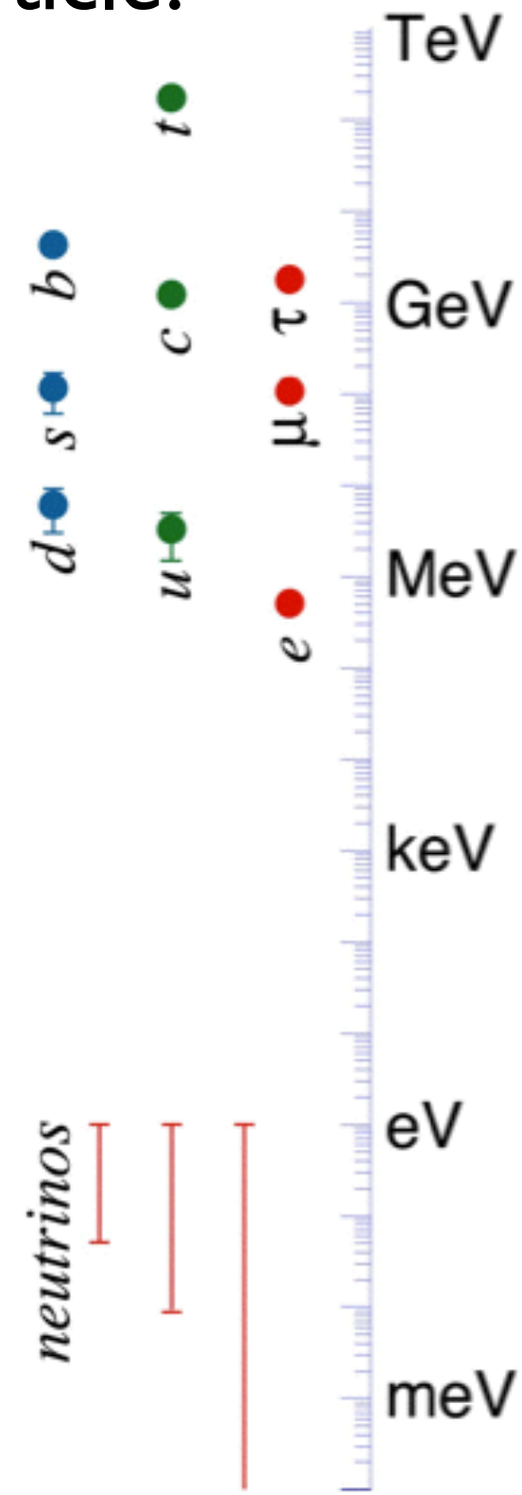
The SNO Experiment



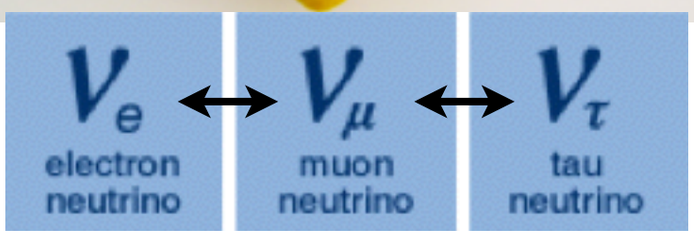
The Super-Kamiokande Experiment

Why Neutrinos?

- Learn more about the least-well-known SM particle!
  - How much do they weigh?
  - Related: how much to they oscillate?
  - Related: do neutrinos and antineutrinos behave differently?

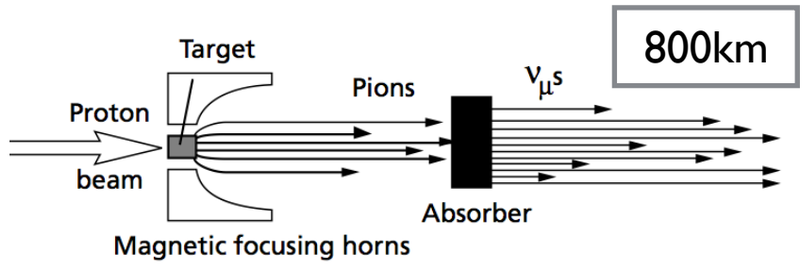


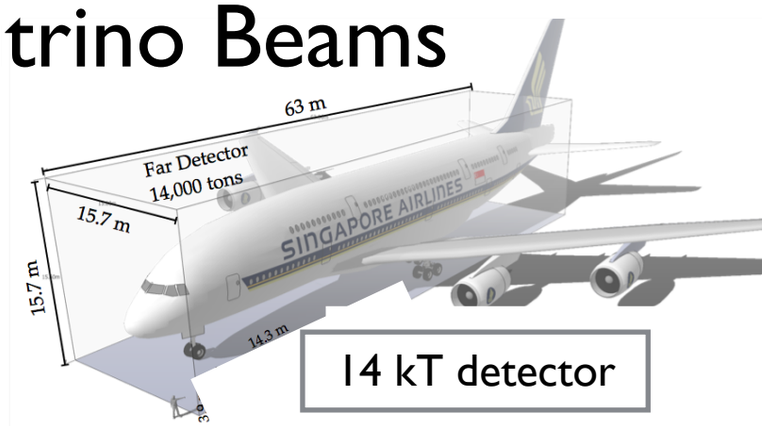
http://particlezoo.net: Go buy one!!!!



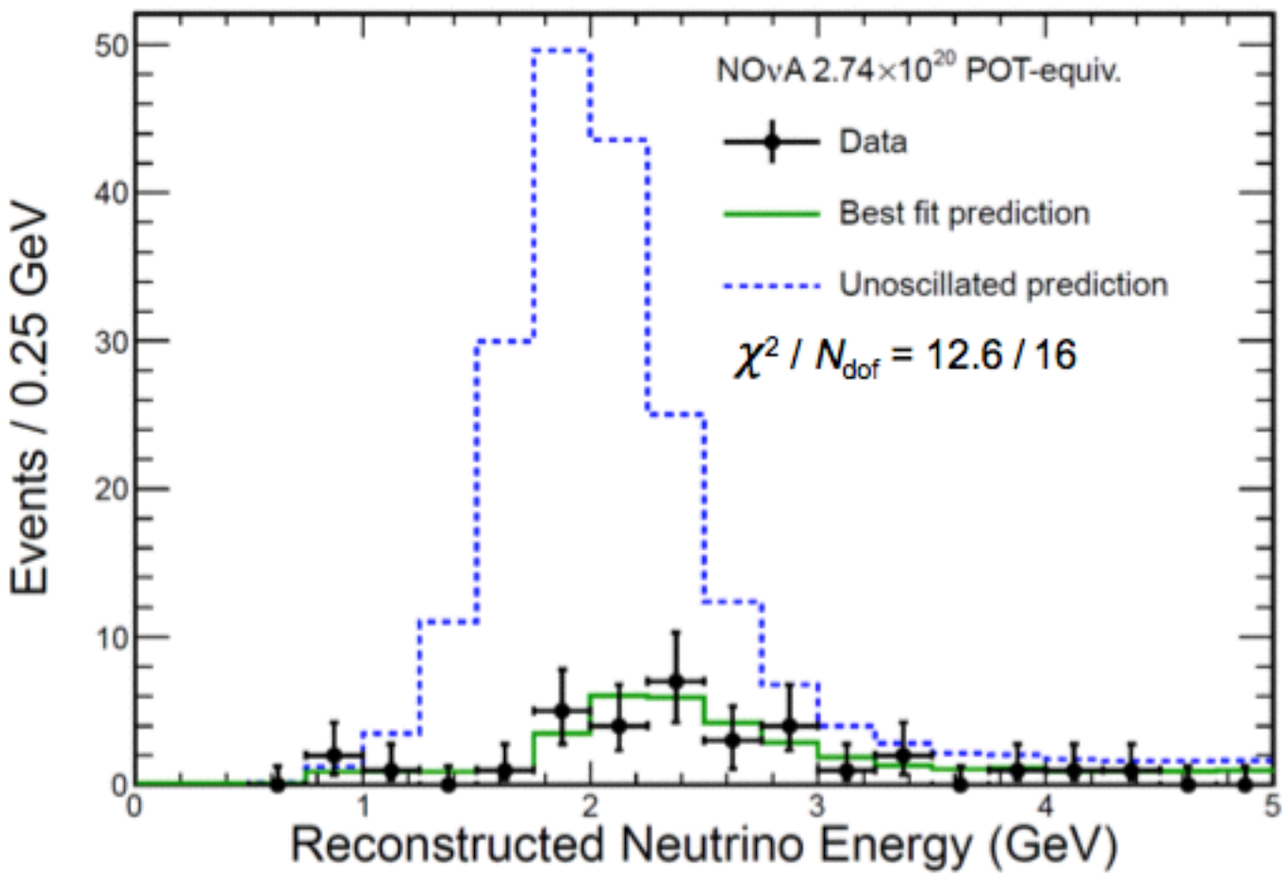
Example: Oscillations

- Looking Oscillations With Accelerator Neutrino Beams
- Example: NOvA



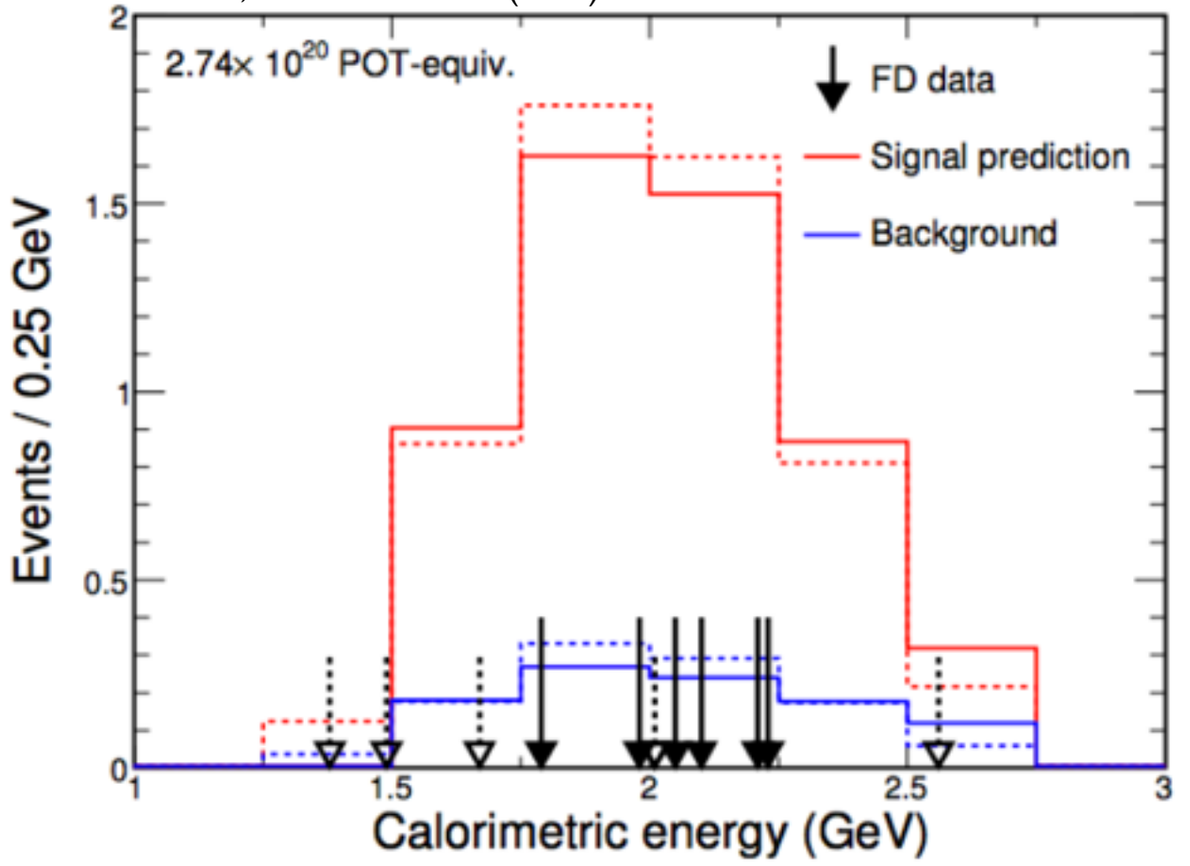


NOvA, arxiv:1601.05037 (2016)



Muon-type neutrinos disappearing!

NOvA, arxiv:1601.05022 (2016)



Electron-type neutrinos appearing!

Why Neutrinos?

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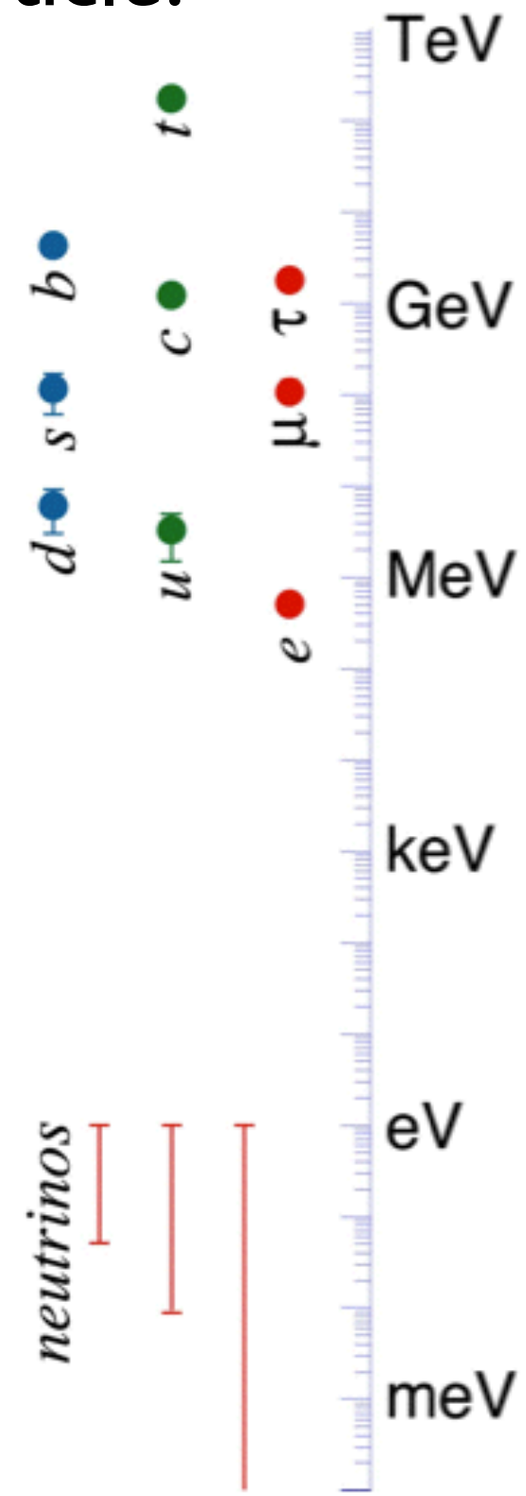
  - Related: how much to they oscillate?
  - Related: do neutrinos and antineutrinos OSCILLATE differently?



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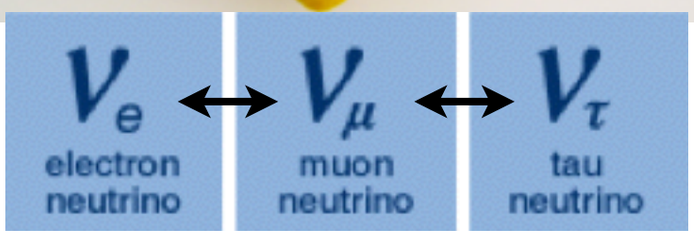


Oscillations Probe Some BIG Questions

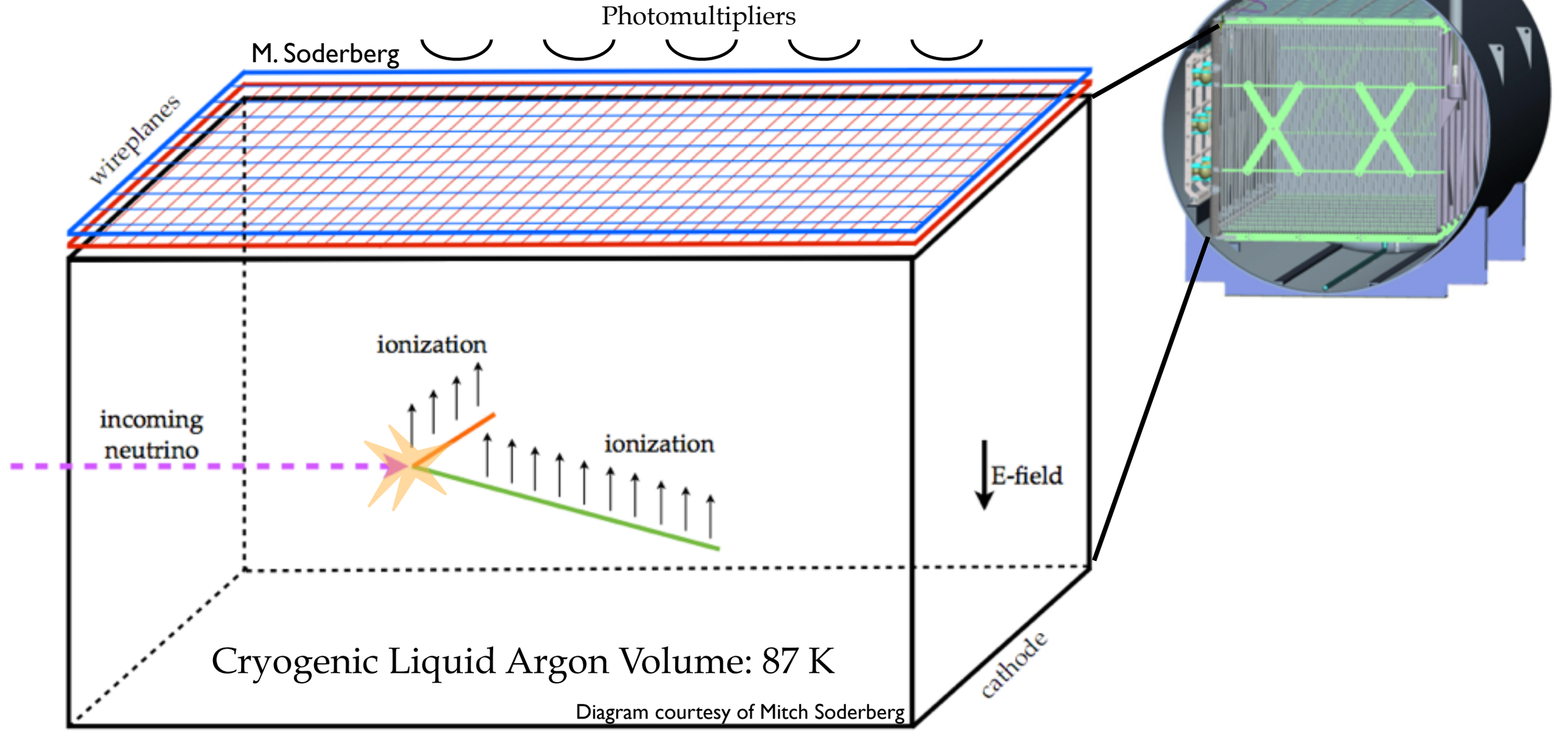
Where is the antimatter??

Neutrinos, antineutrinos should be able to oscillate differently.

Let's try to see this — Could be a BIG hint!

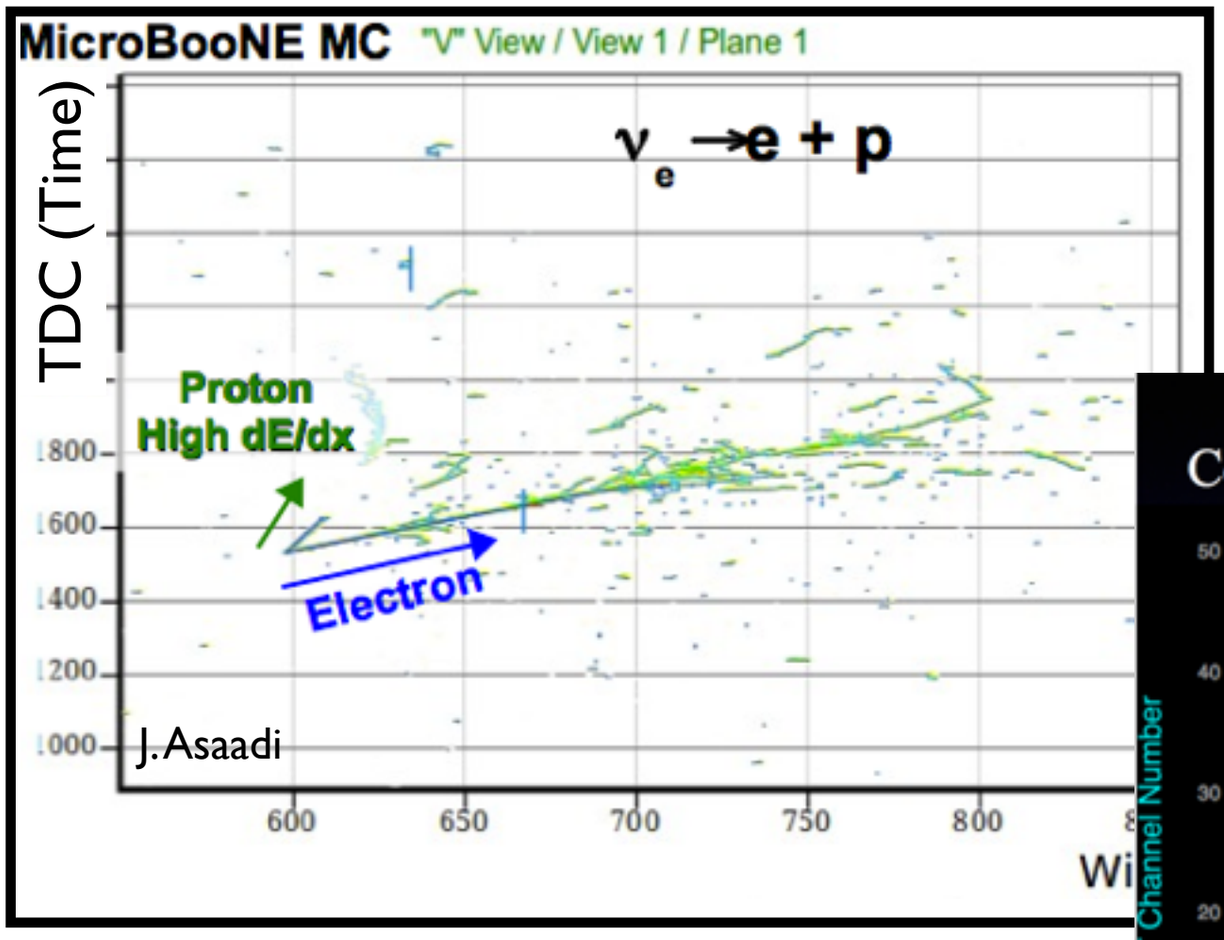
LArTPC Technology: MicroBooNE

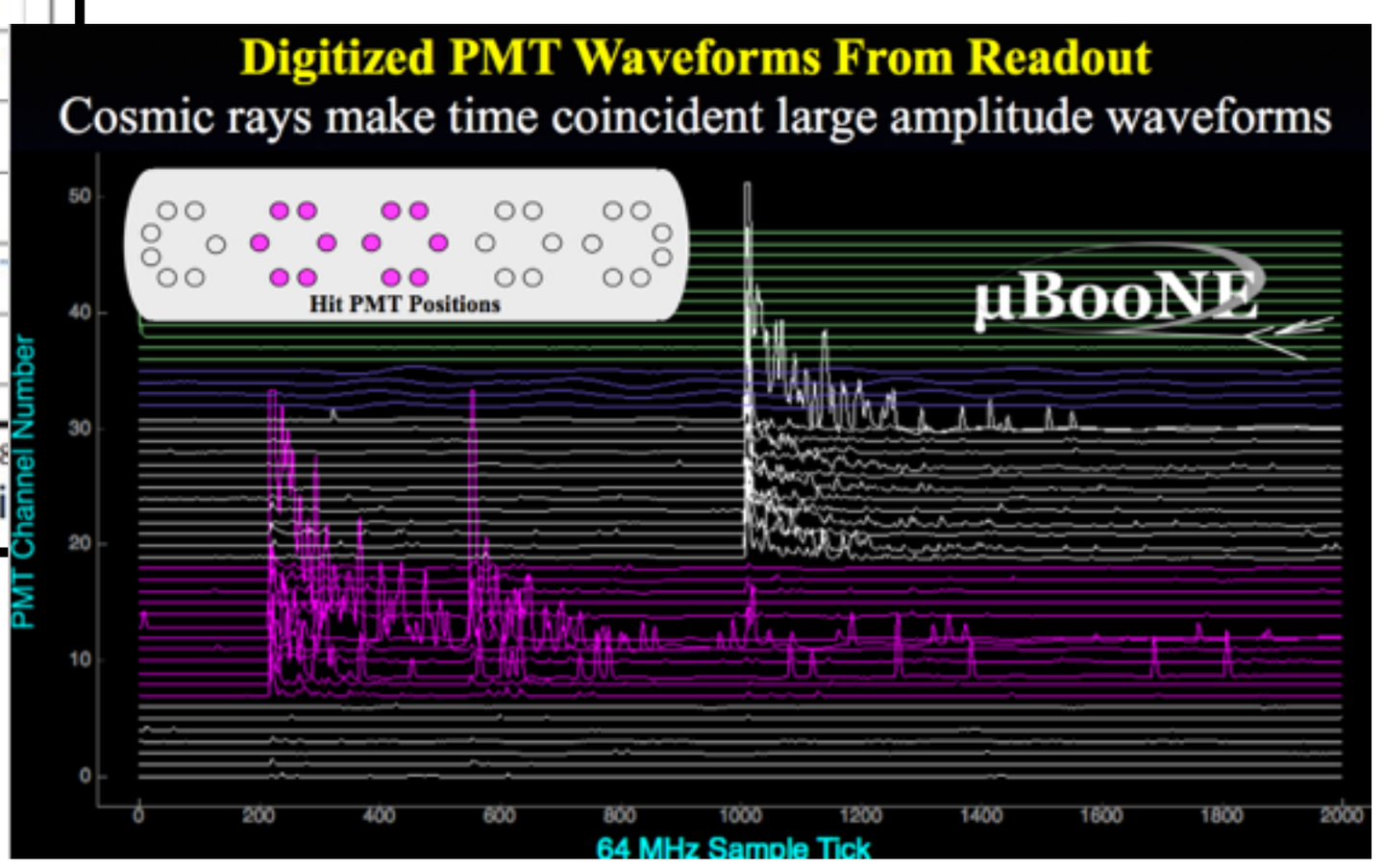
- Dense 170 ton liquid argon target provides excellent ν interaction medium
- Ionization drifted meters along uniform E-field to finely spaced wire planes
- Constant drift speed, fast scintillation light provide position in drift direction



LArTPC Event Detection: MicroBooNE

- Wires see induced and collected charge
- Photomultiplier tubes see collected light





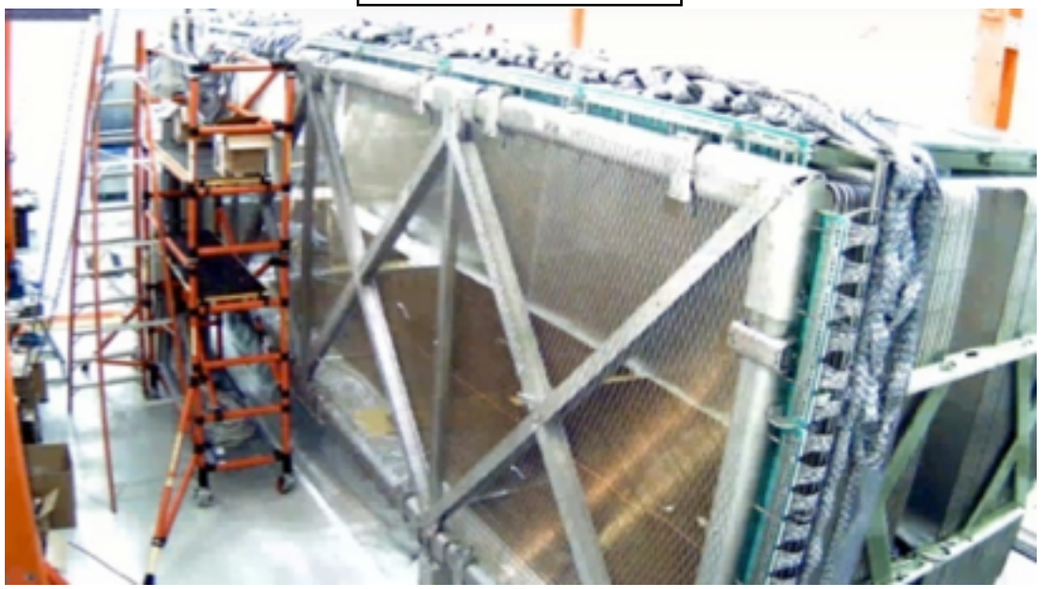
A Constructed LArTPC: MicroBooNE

Cathode

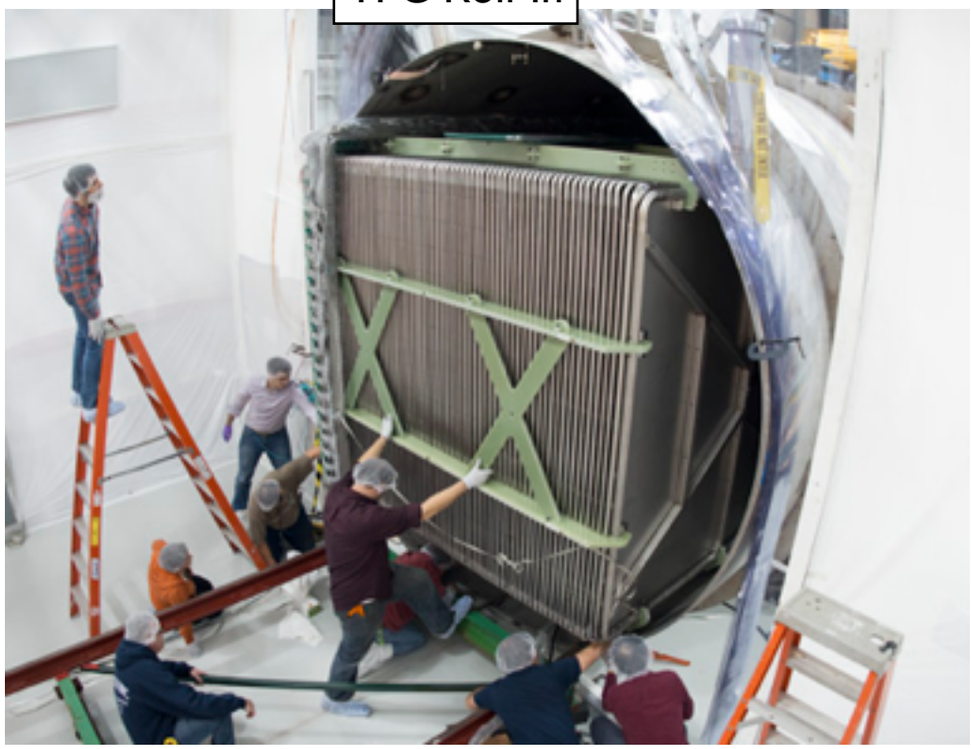
Field Shaping Tubes

Wire Planes

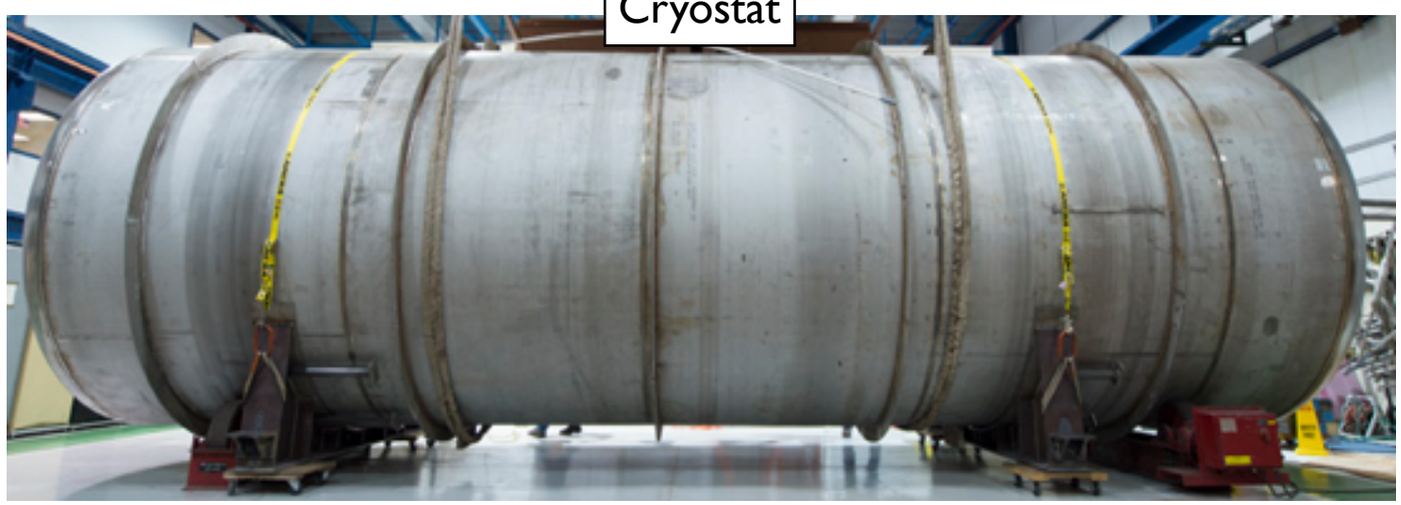
TPC Electronics



TPC Roll-In

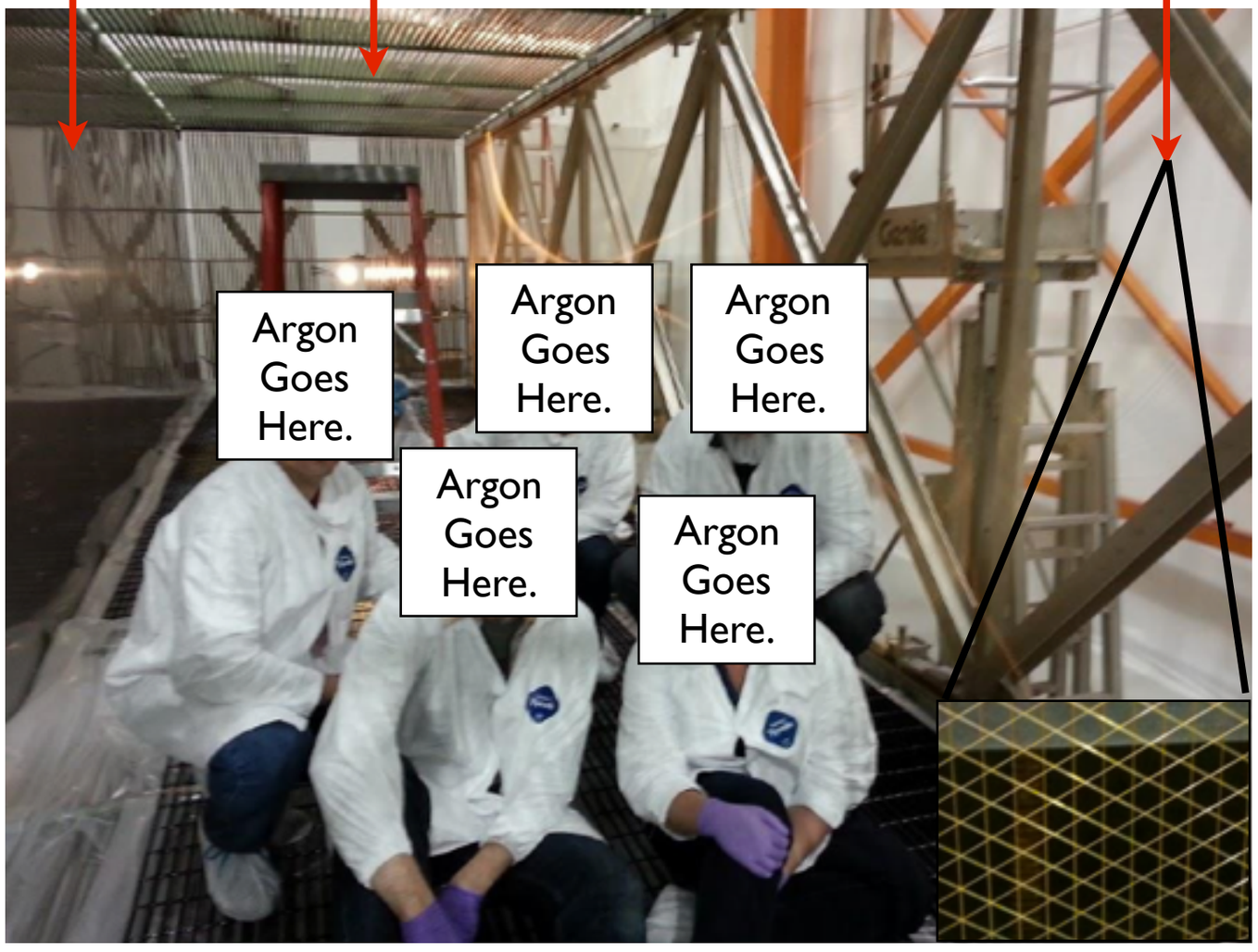


Cryostat

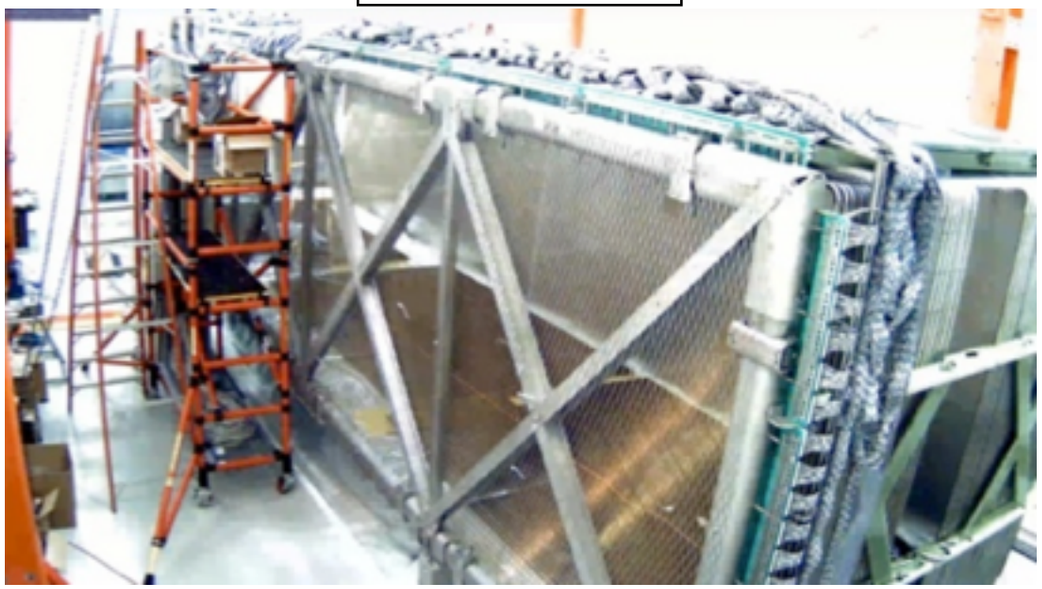


http://www-microboone.fnal.gov/

A Constructed LArTPC: MicroBooNE



TPC Electronics



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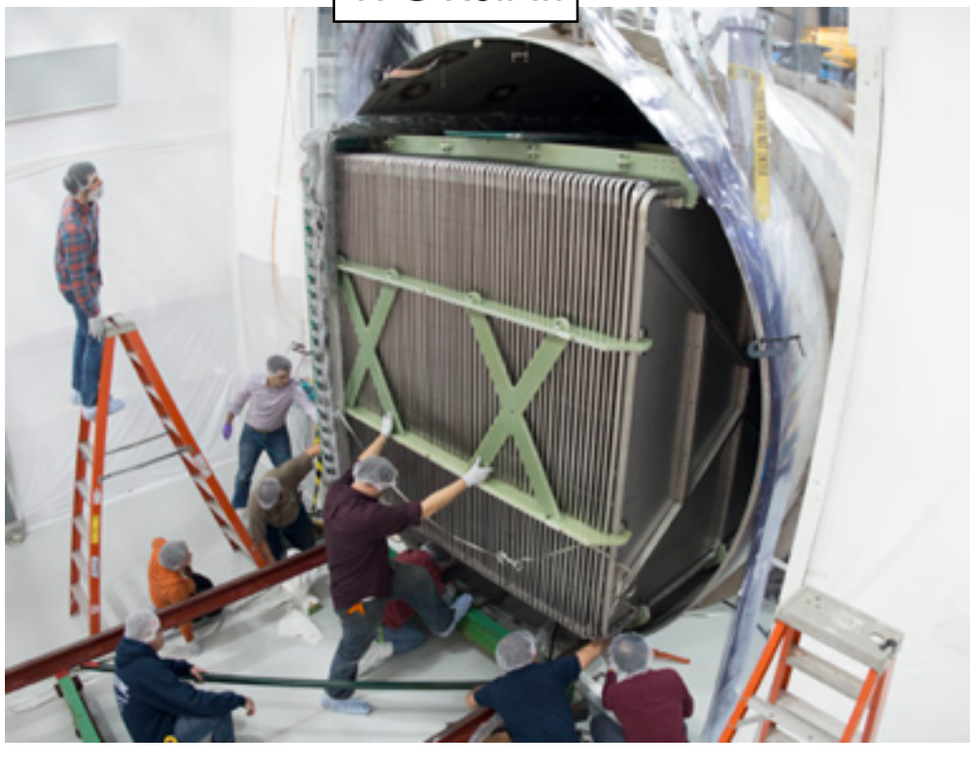


Cryostat

http://www-microboone.fnal.gov/

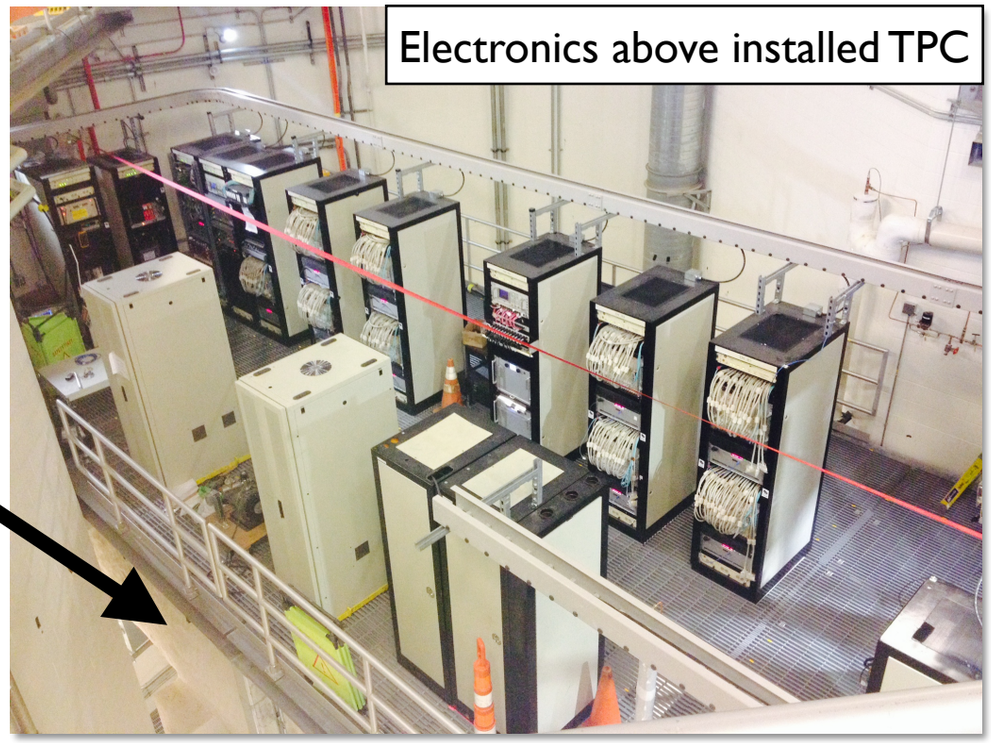
An Operating LArTPC: MicroBooNE

- The LArTPC is now installed, filled, and commissioned.

Installing TPC in Neutrino Beamline

Electronics above installed TPC

TPC is under here…

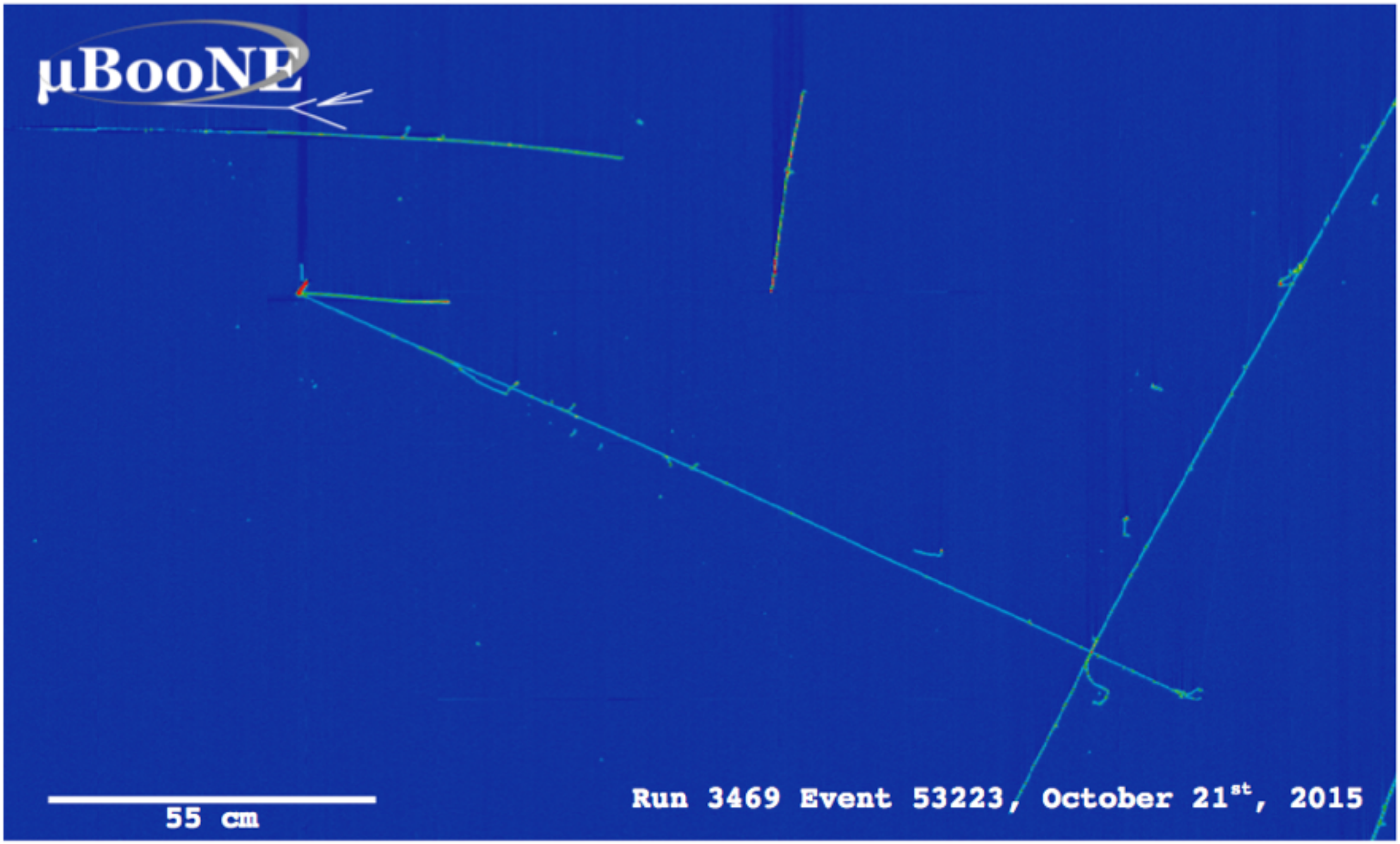


MicroBooNE control room: First physics run

http://www-microboone.fnal.gov/

A ν-Detecting LArTPC: MicroBooNE

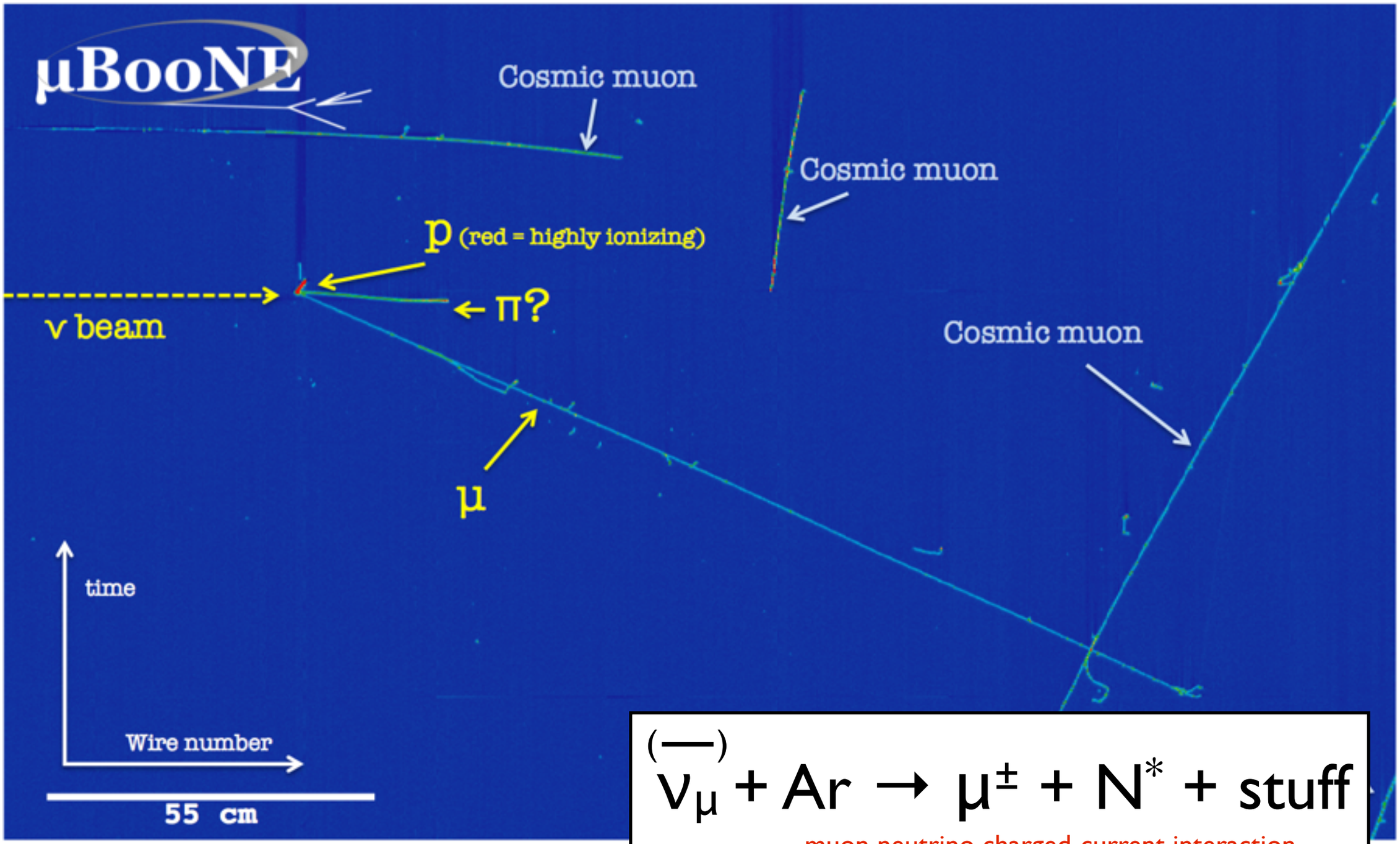
- We HAVE BUILT LArTPCs, and they are currently running!
- Note the exquisite precision: a digital bubble chamber!



See more at http://www-microboone.fnal.gov/first-neutrinos/index.html

A ν-Detecting LArTPC: MicroBooNE

- Already have >1e20 POT of data! >10,000 neutrinos!



$$\overset{(-)}{\nu}_\mu + Ar \rightarrow \mu^{\pm} + N^{*} + \text{stuff}$$

muon neutrino charged-current interaction

See more at http://www-microboone.fnal.gov/first-neutrinos/index.html

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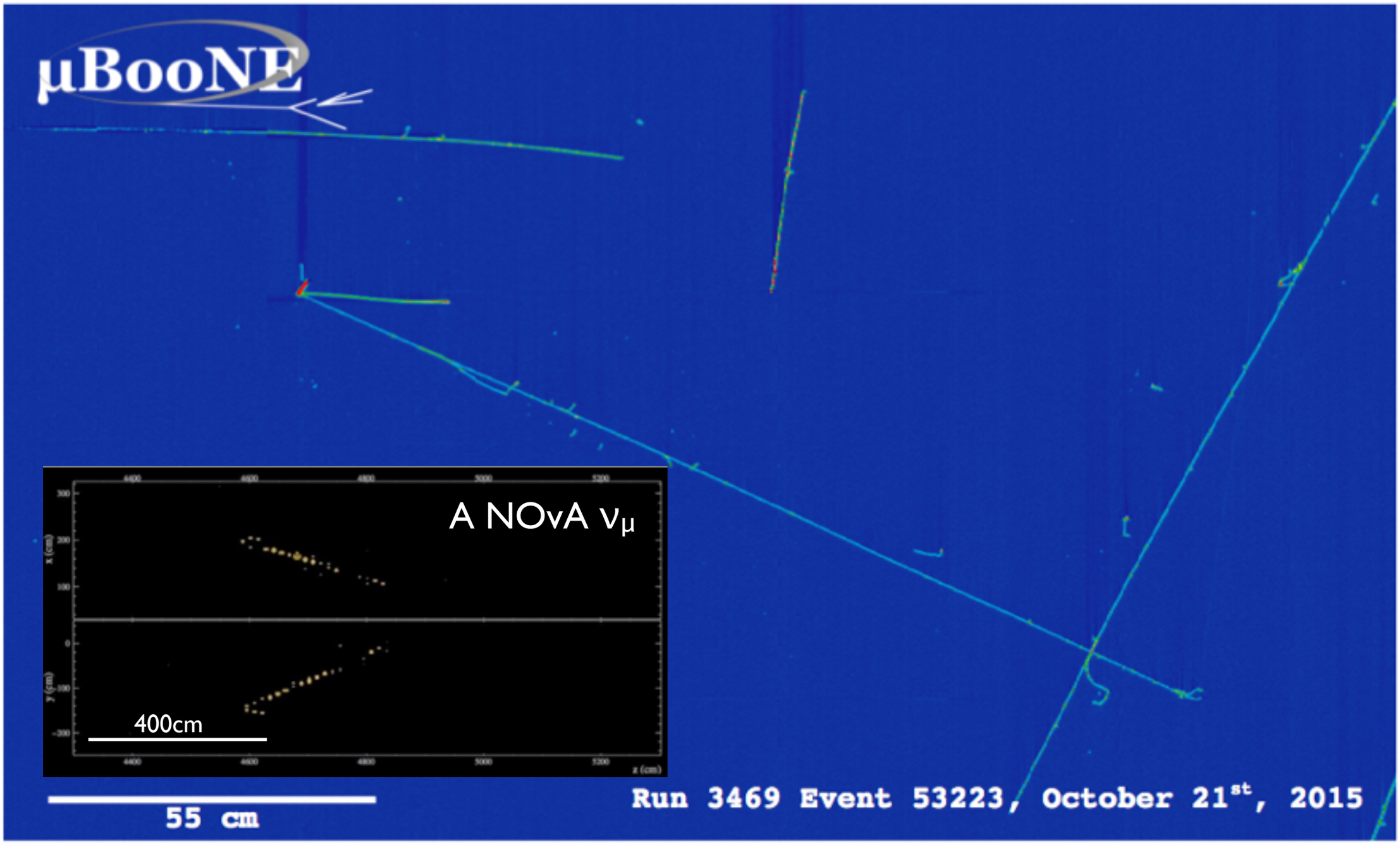

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Current LArTPC Studies: Fermilab SBN

- Measuring the rates of various neutrino interaction channels:

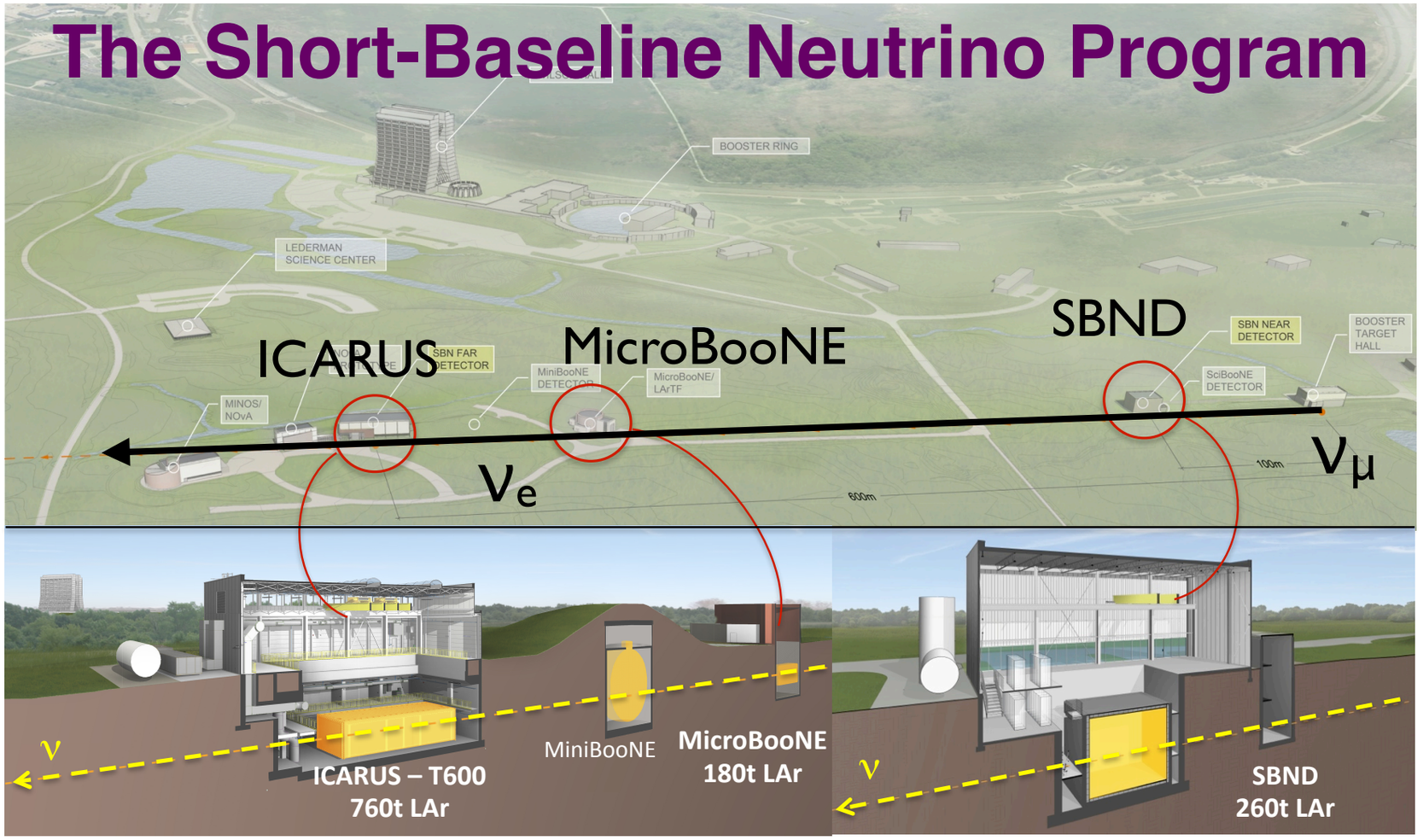
$$\overset{(-)}{\nu}_\mu + Ar \rightarrow \mu^\pm + N^* + \text{stuff}$$

muon neutrino charged-current interaction

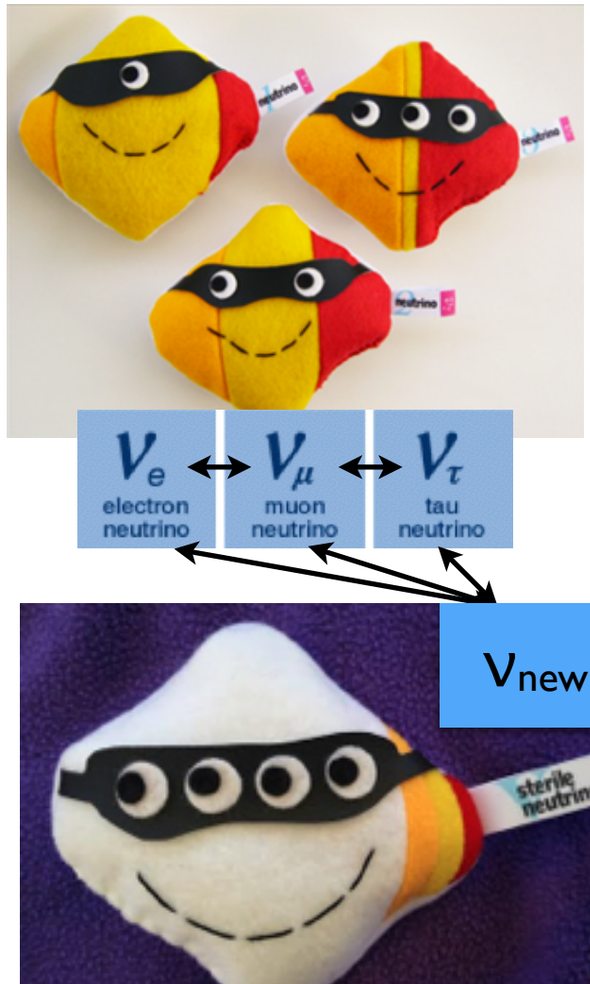
$$\overset{(-)}{\nu}_\mu + Ar \rightarrow \overset{(-)}{\nu}_\mu + N^* + \text{stuff}$$

muon neutrino neutral-current interaction

- Do a LArTPC-based oscillation search for <u>new</u> neutrino types



http://sbn.fnal.gov/



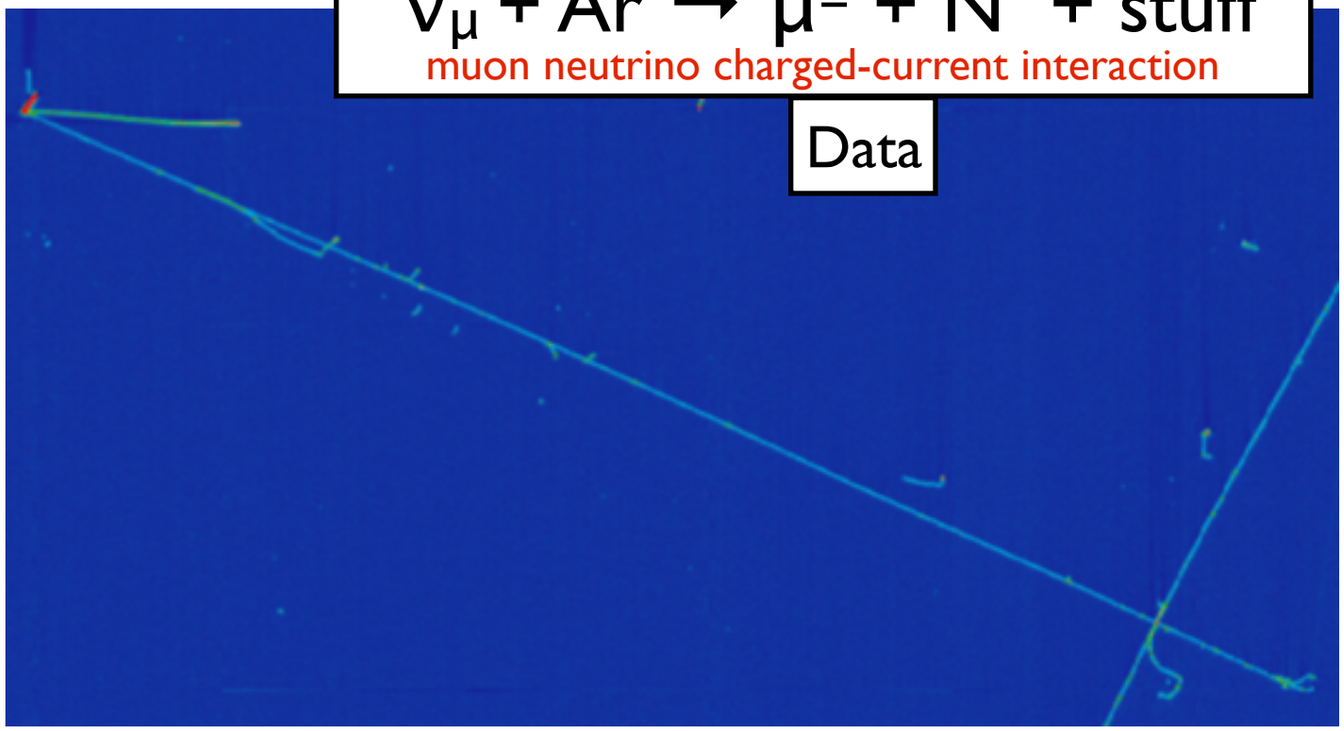
http://particlezoo.net: Go buy one!!!!

LArTPC Oscillation Signature

- Need to tell these:

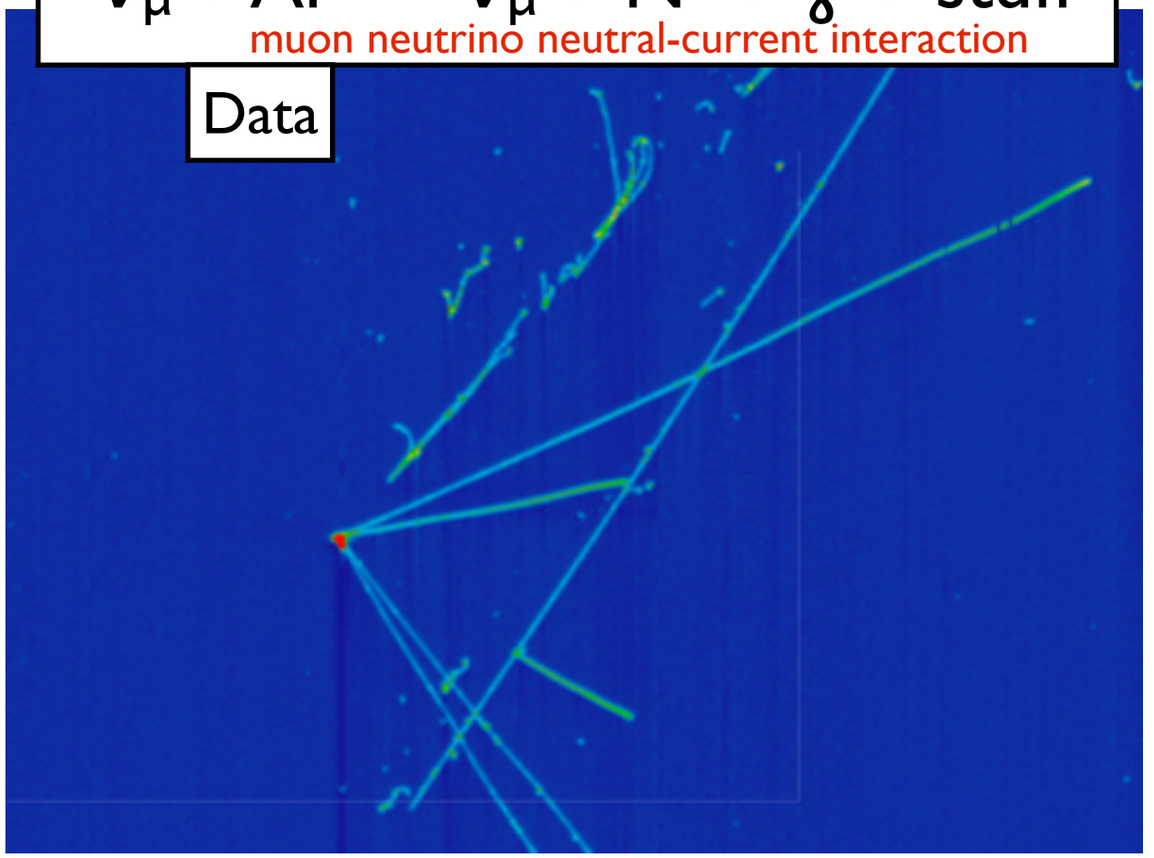
$\overset{(-)}{\nu}_\mu + Ar \rightarrow \mu^\pm + N^* + stuff$

muon neutrino charged-current interaction



$\overset{(-)}{\nu}_\mu + Ar \rightarrow \overset{(-)}{\nu}_\mu + N^* + \gamma + stuff$

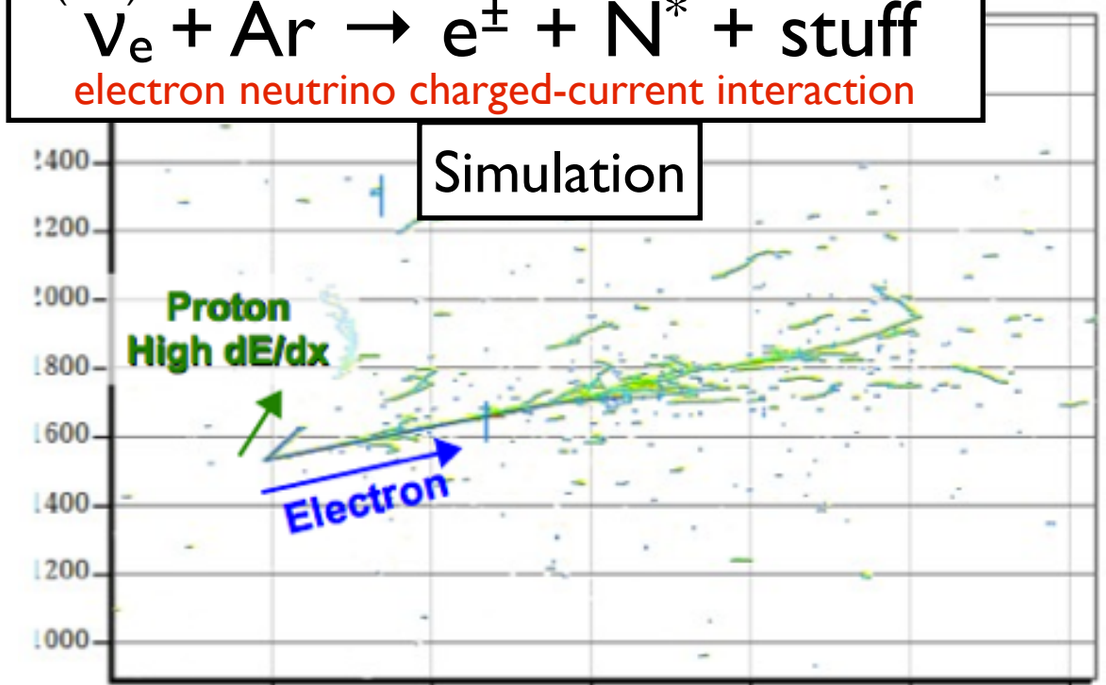
muon neutrino neutral-current interaction



- From this:
- Utilizing:
  - Shower versus track
  - >1 photon, photon gaps
- Extra electrons = oscillation!!!

$\overset{(-)}{\nu}_e + Ar \rightarrow e^\pm + N^* + stuff$

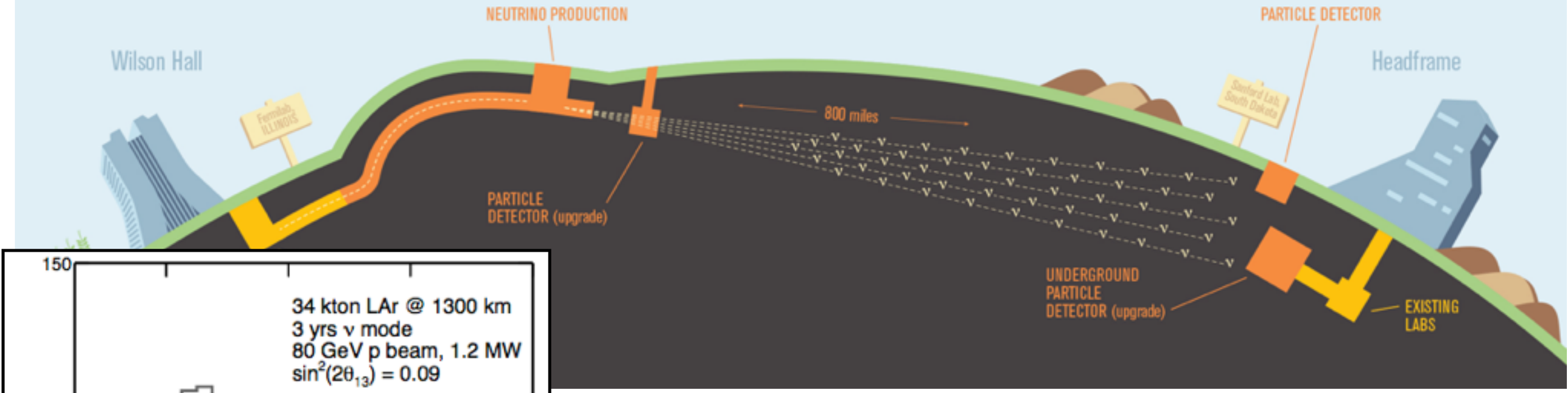
electron neutrino charged-current interaction

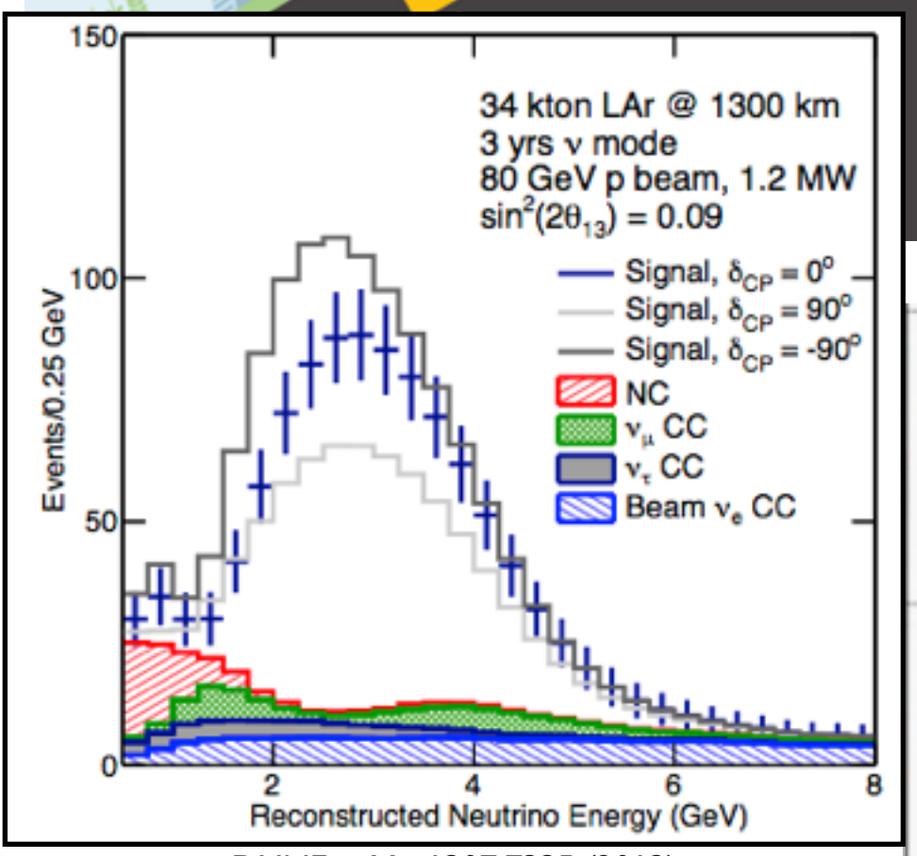


The Future: DUNE

- Do neutrinos and antineutrinos oscillate differently?
- Best place to look: accelerator neutrinos at ~1300km…

http://www.dunescience.org/





DUNE, arXiv:1307.7335 (2013)

MicroBooNE
Construction begins 2010
Physics: Investigate low-energy neutrino interactions

100 tons

LAr TPC for DUNE
R&D in progress
Physics: Measure neutrino oscillations at 1,000+ km

40,000 tons

Where's The Antimatter????

- IF DUNE measures differences ν and $\bar{\nu}$ oscillation, this is BIG!

Where's The Antimatter????

- IF DUNE measures differences ν and $\bar{\nu}$ oscillation, this is BIG!



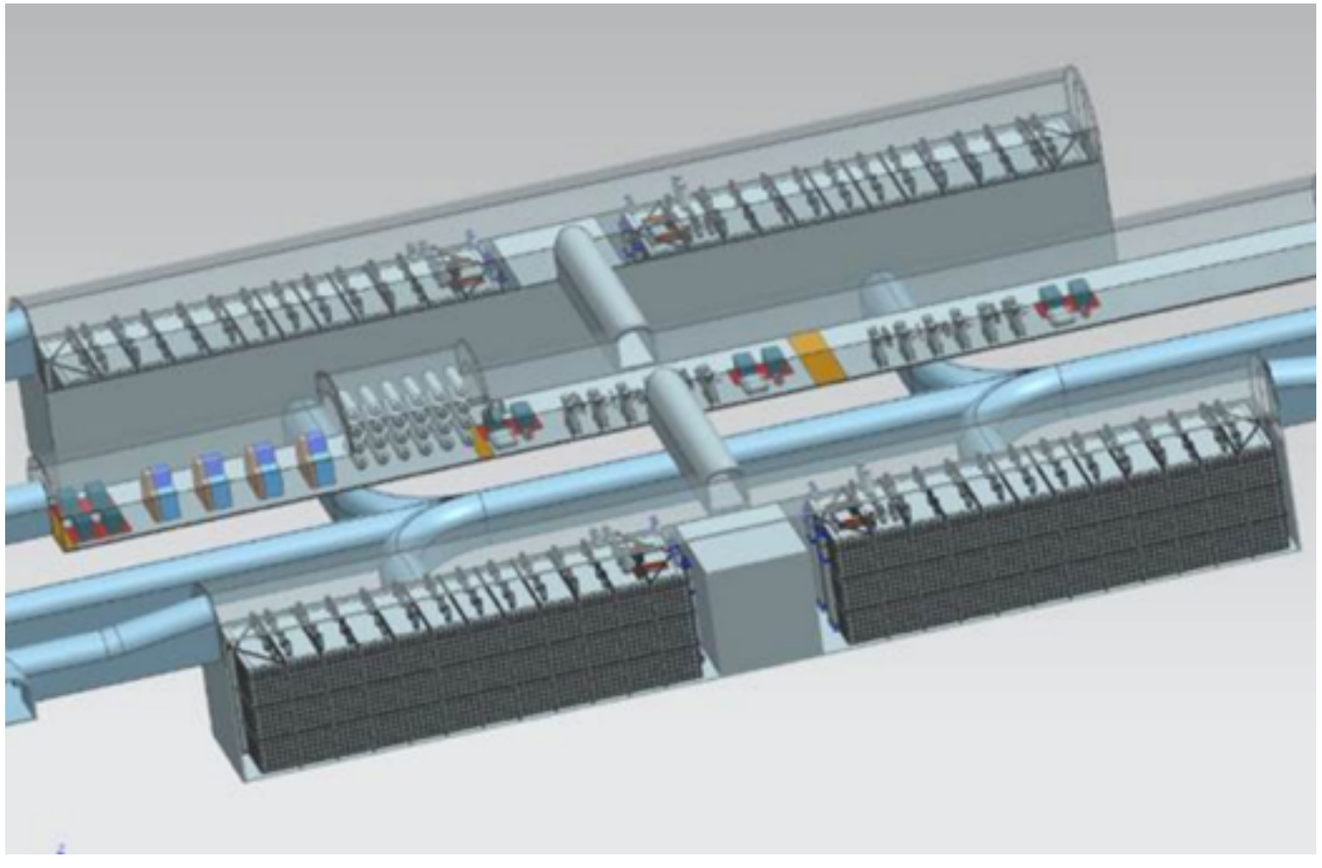


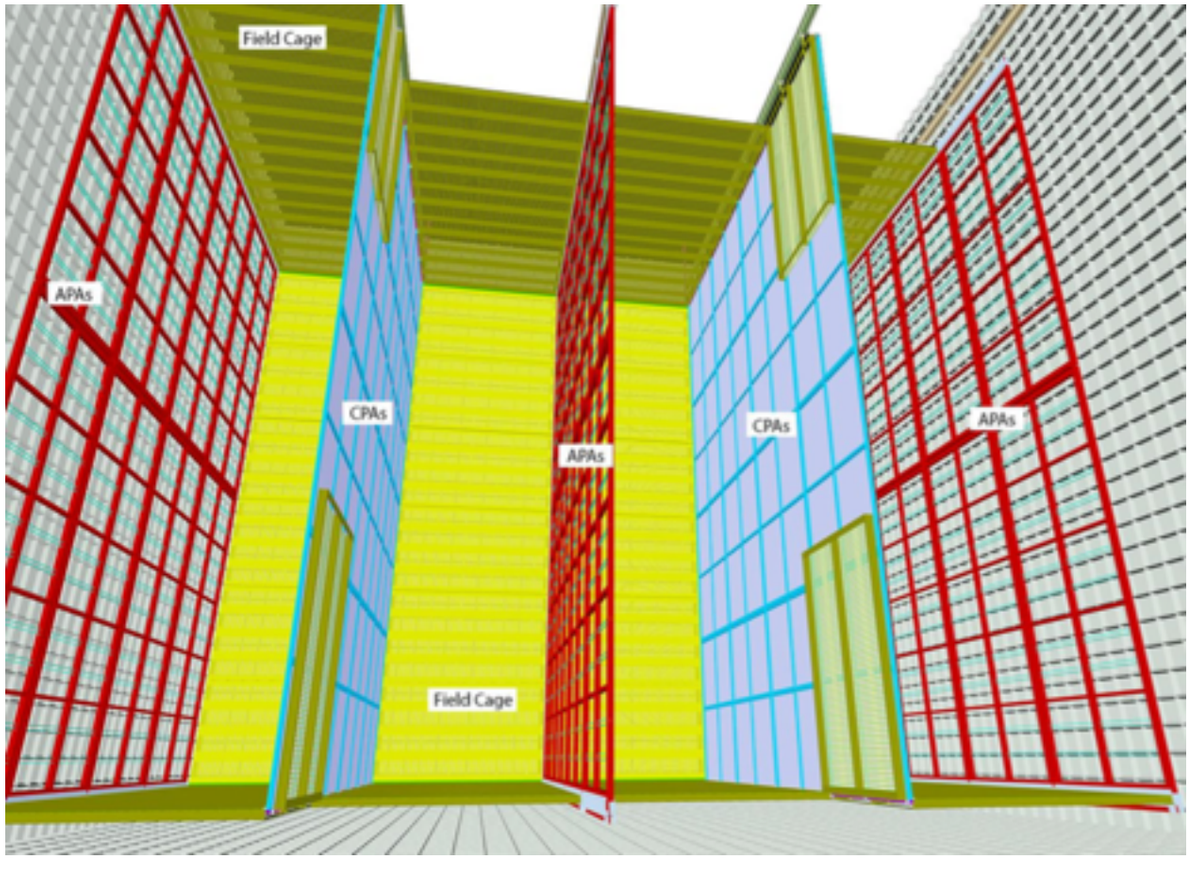


- Maybe all that antimatter is hanging around as non-interacting heavy new antineutrinos that we just can't see…
- Would bolster the only hypothesis for answering one of THE **CENTRAL** question in physics today!

What MORE Can We Do?

- This detector is going to cost a LOT of money, and we will have it for the next 20+ years once it is built
- Future richness of our field depends on broadening the physics program of this exquisite machine!

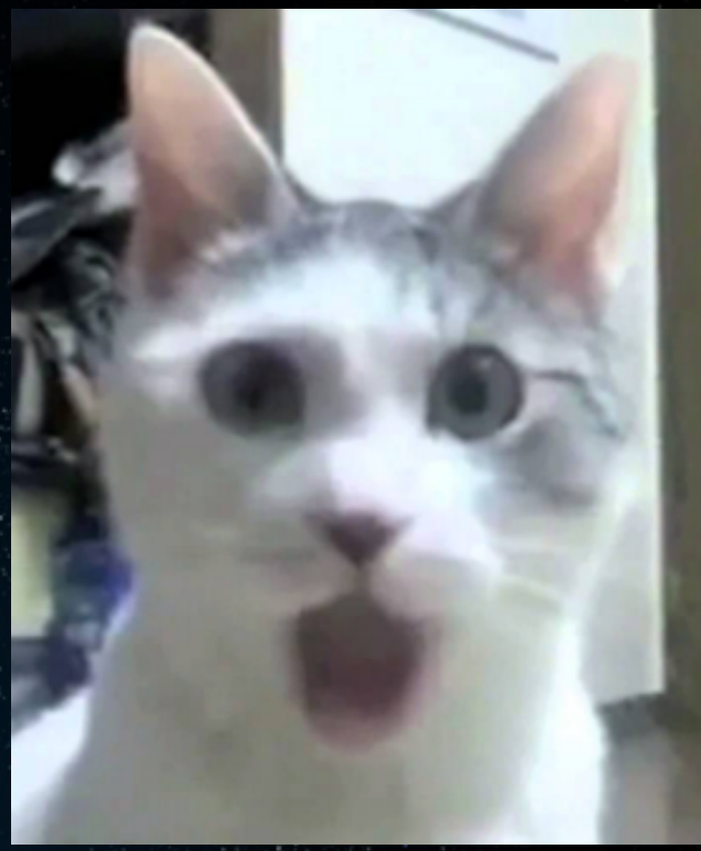




DUNE, arXiv:1601.02984 (2016)

Core Collapse Supernovae

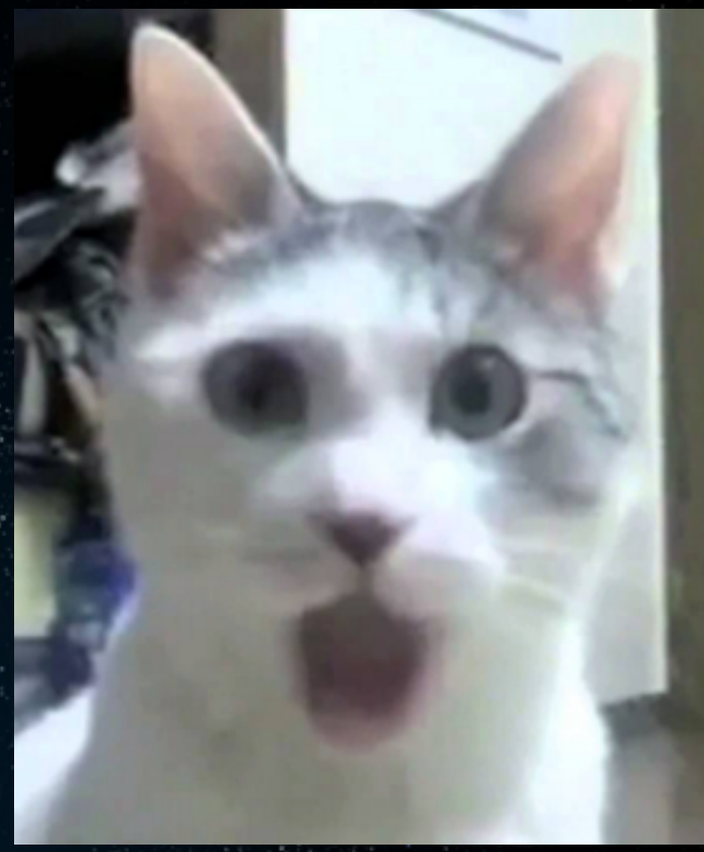
- Supernovae are AWESOME.



source: Wikipedia

Core Collapse Supernovae

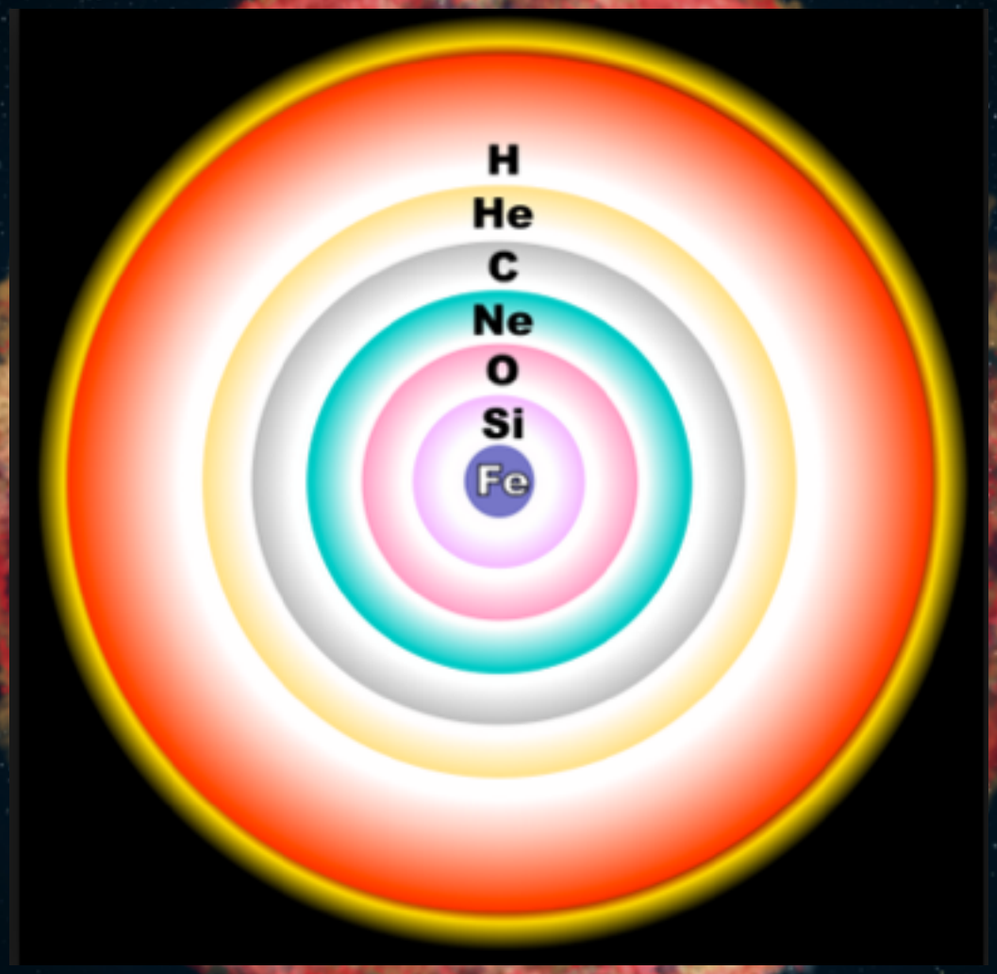
- Supernovae are <u>AWESOME.</u>
  - The source of the universe's heavy elements
  - Still don't understand WHY they explode, but we know neutrinos play a vital role.



source: Wikipedia

Before a Supernova

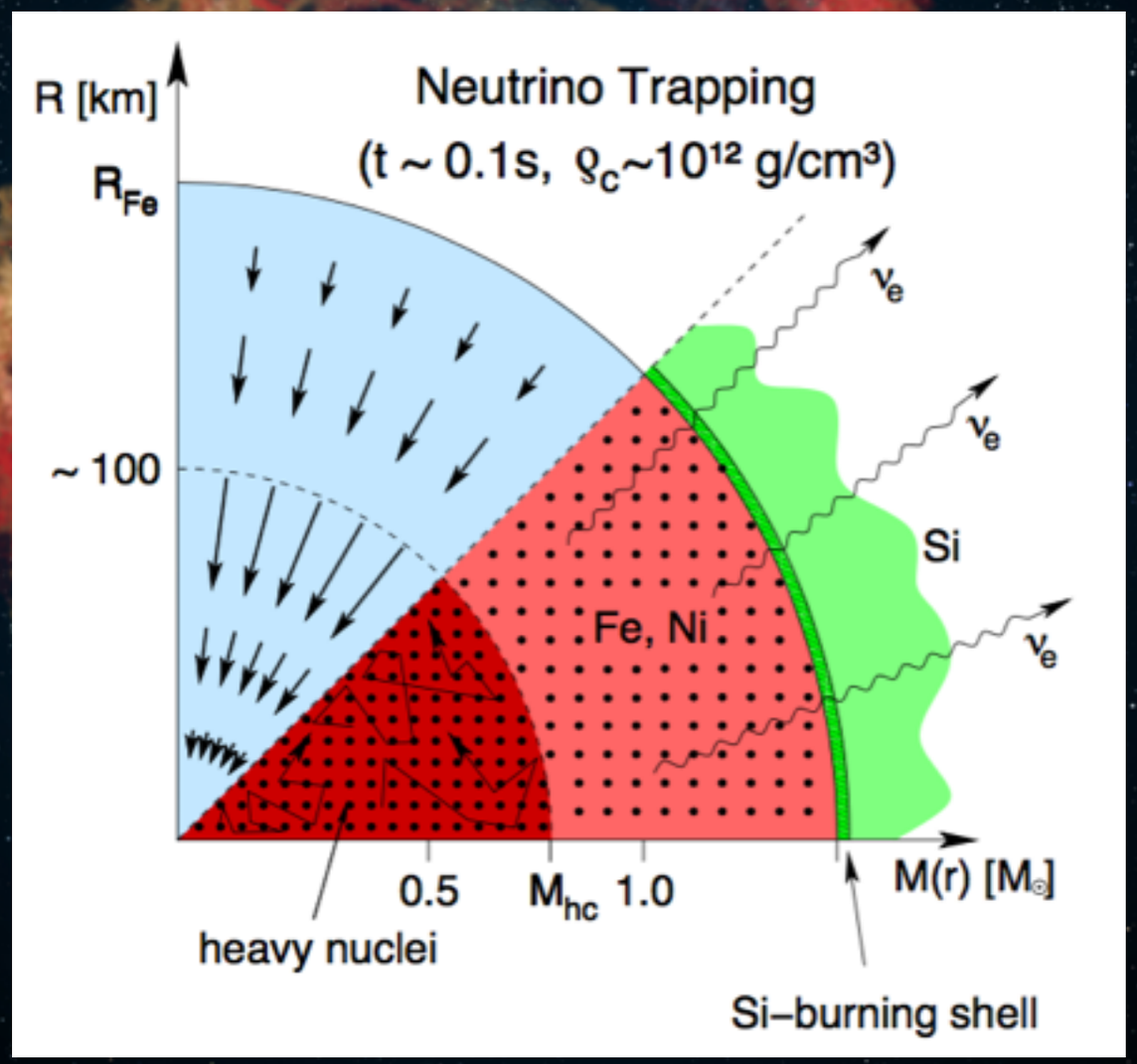
- A star: elements fuse and create energy plus heavier elements



Core Collapse

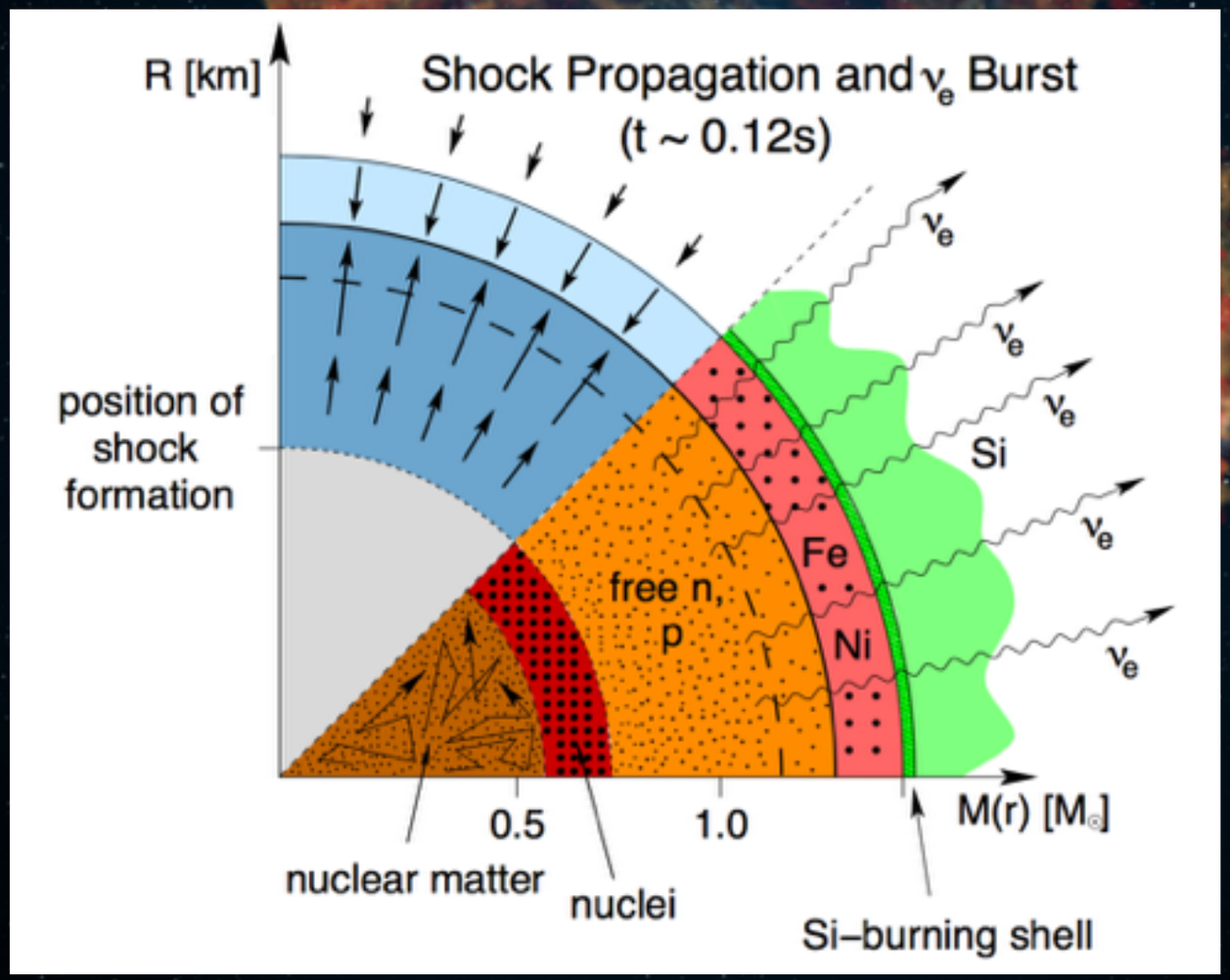
- Core collapse: Gravity in iron core is too strong! Protons start eating electrons! Inner core compacts to one gigantic nucleus!
  - Oh yeah — inner core is too dense for these neutrinos to escape.

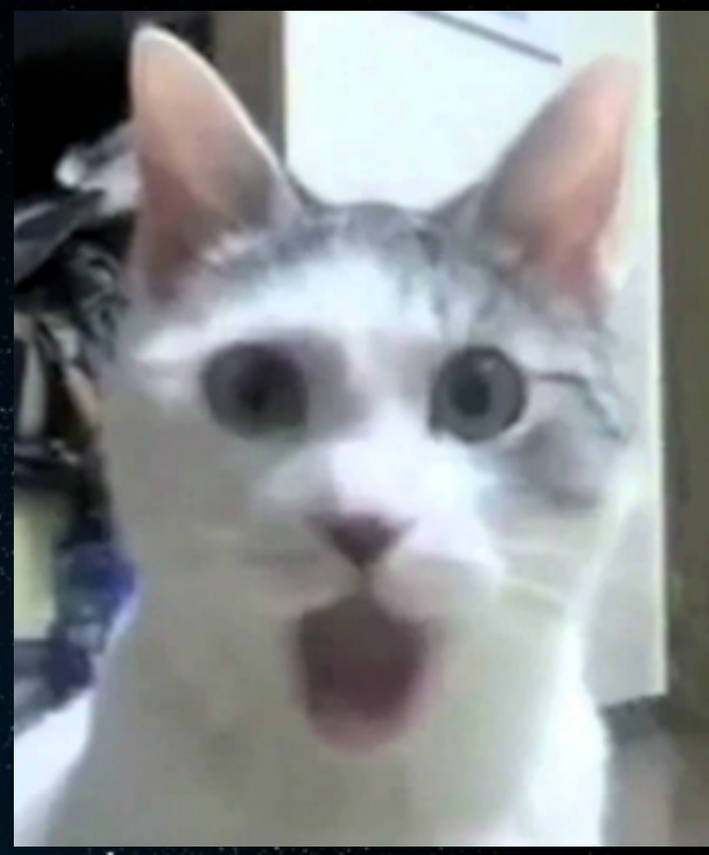
$$p + e^- \rightarrow n + \nu_e$$



Shock Formation

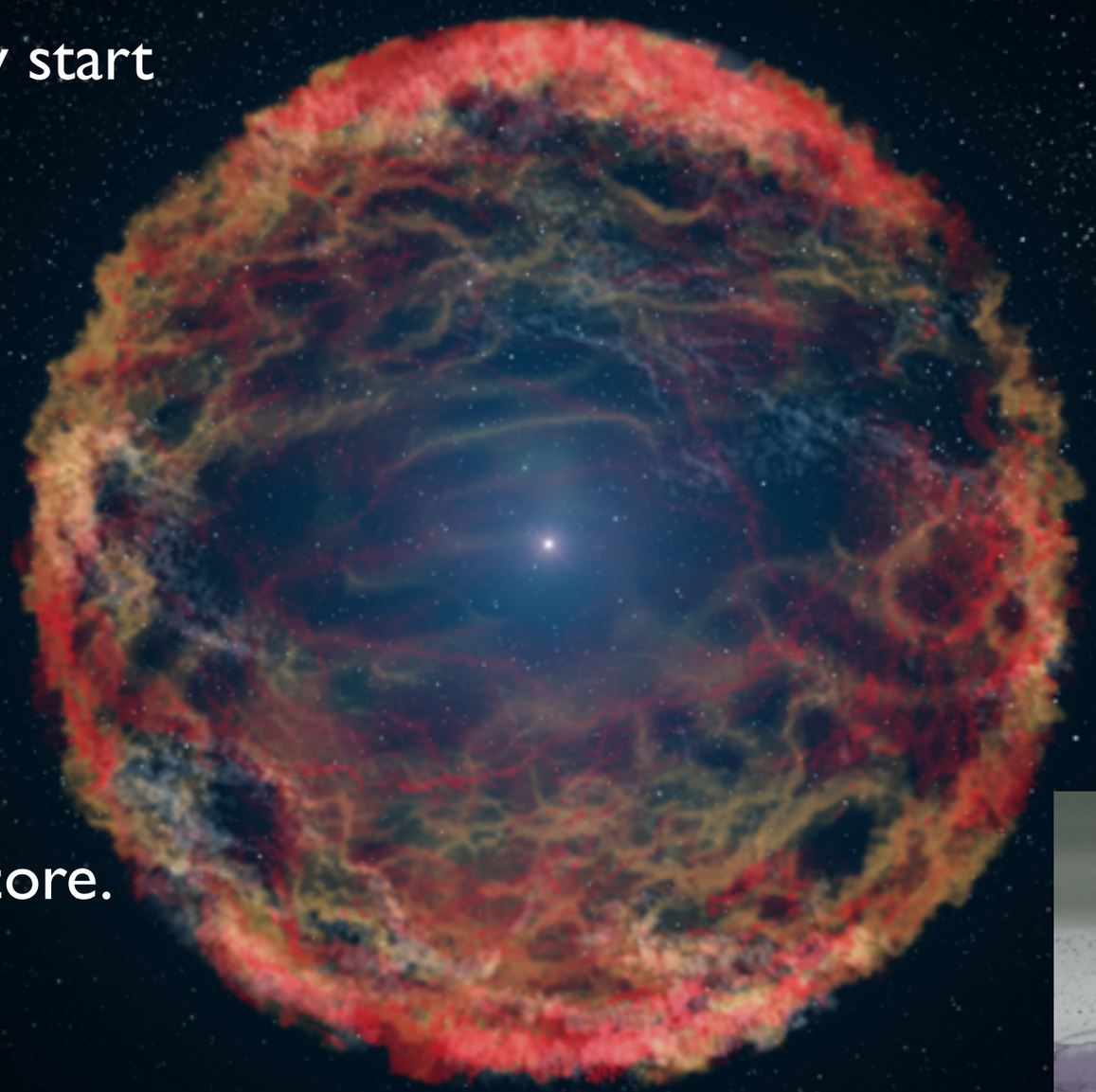
- Shock formation: Inner core now is very hard, so in-falling star bounces off of it
- Shock boils the iron nuclei in outer core
- Lots of neutrinos produced, released in this process





Supernova Explosion

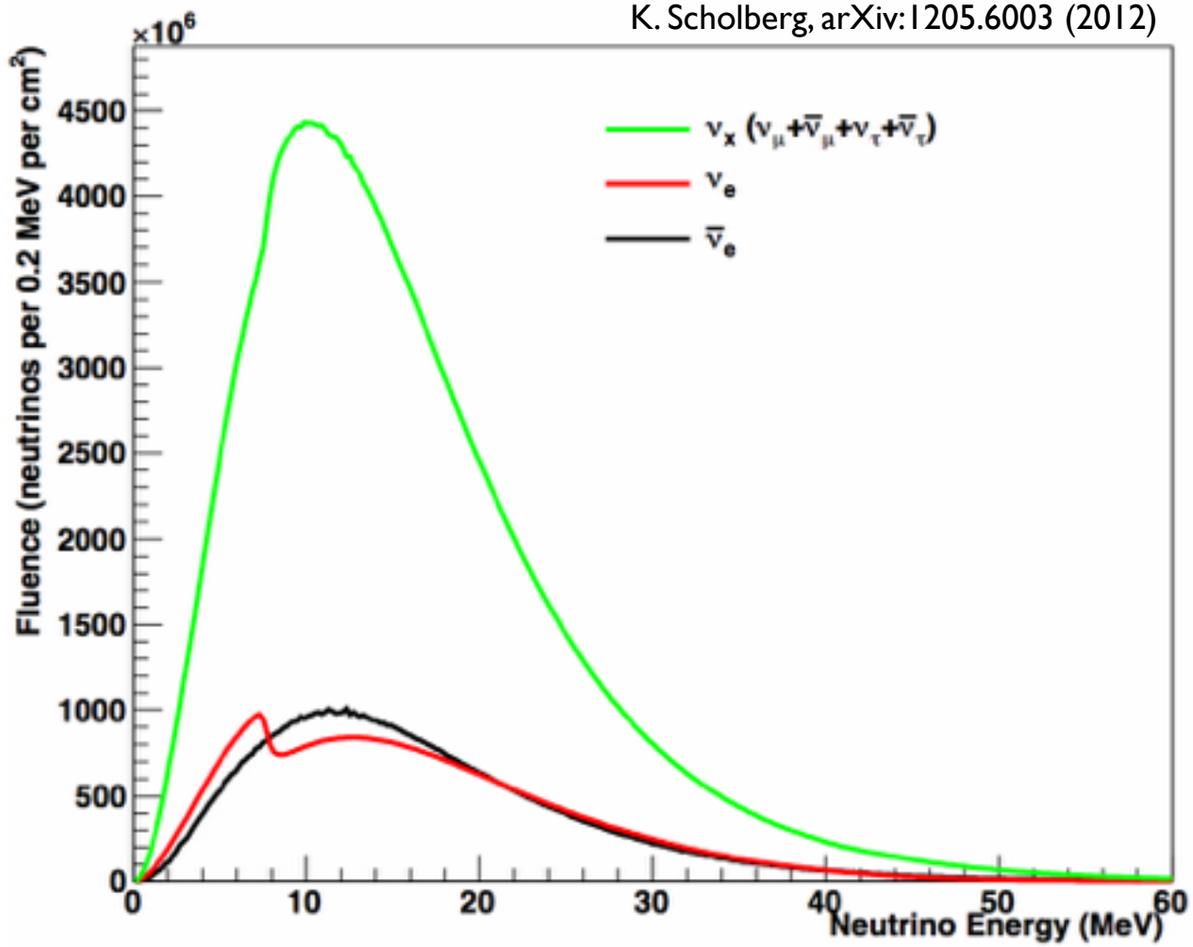
- Expulsion of material: caused by… ????????
  - The shockwave itself (not likely in most cases?)
  - Neutrinos finally start escaping from core and push away the outer star's bulk!!
  - Neutron star then cools by releasing neutrinos, the only thing that can escape the core.



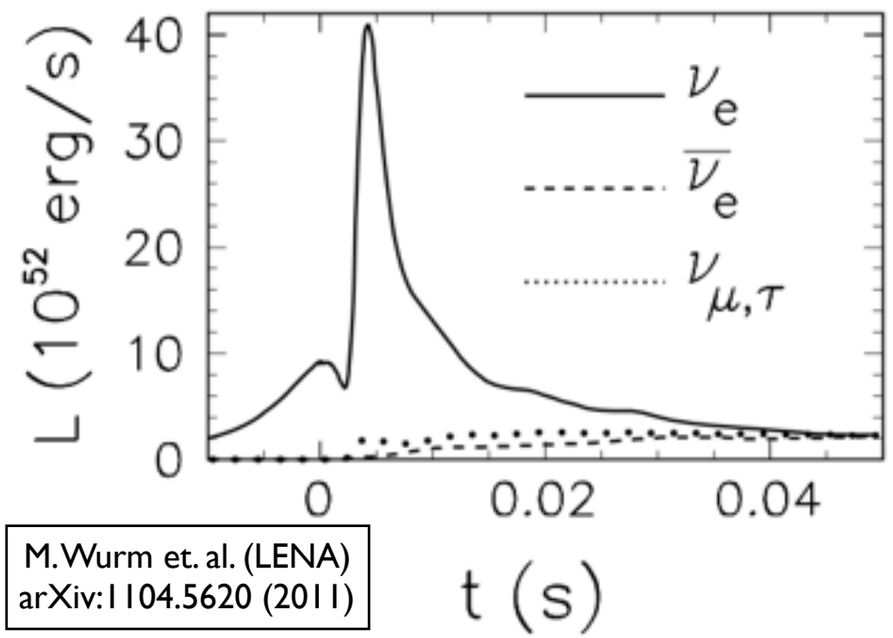
Supernova Neutrinos

- Needless to say, neutrinos play a huge role in supernovae
- >99% of energy is released as neutrinos: $>10^{58}$ of them!
- Seeing the neutrinos is the best way to verify this picture!
- Can we use DUNE for THIS?

K. Scholberg, arXiv:1205.6003 (2012)

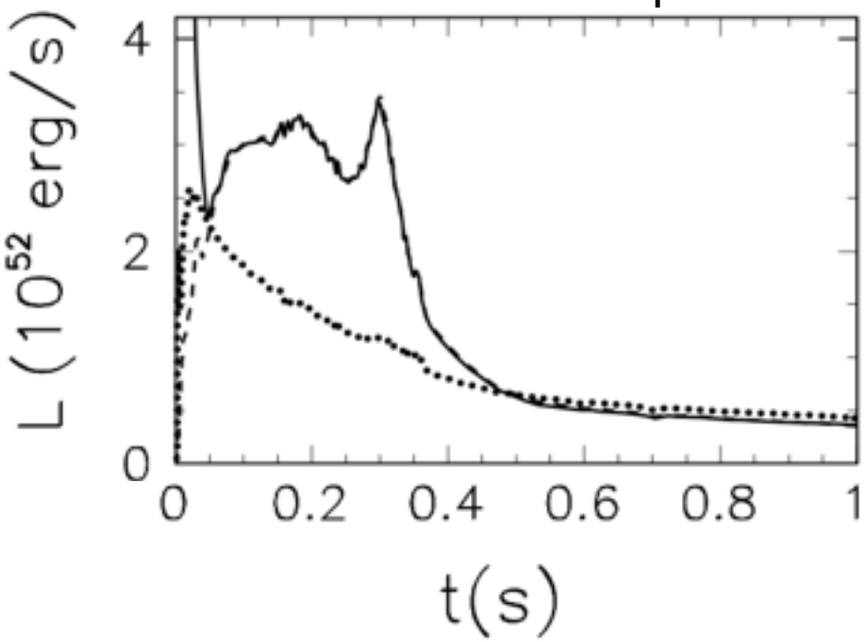


Neutrinos from initial shockwave

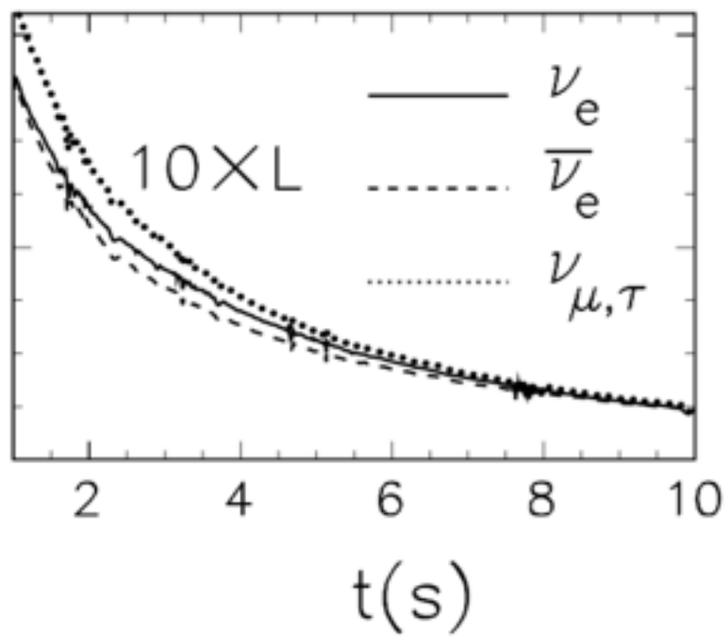


M. Wurm et. al. (LENA) arXiv:1104.5620 (2011)

Accretion: Neutrinos push out

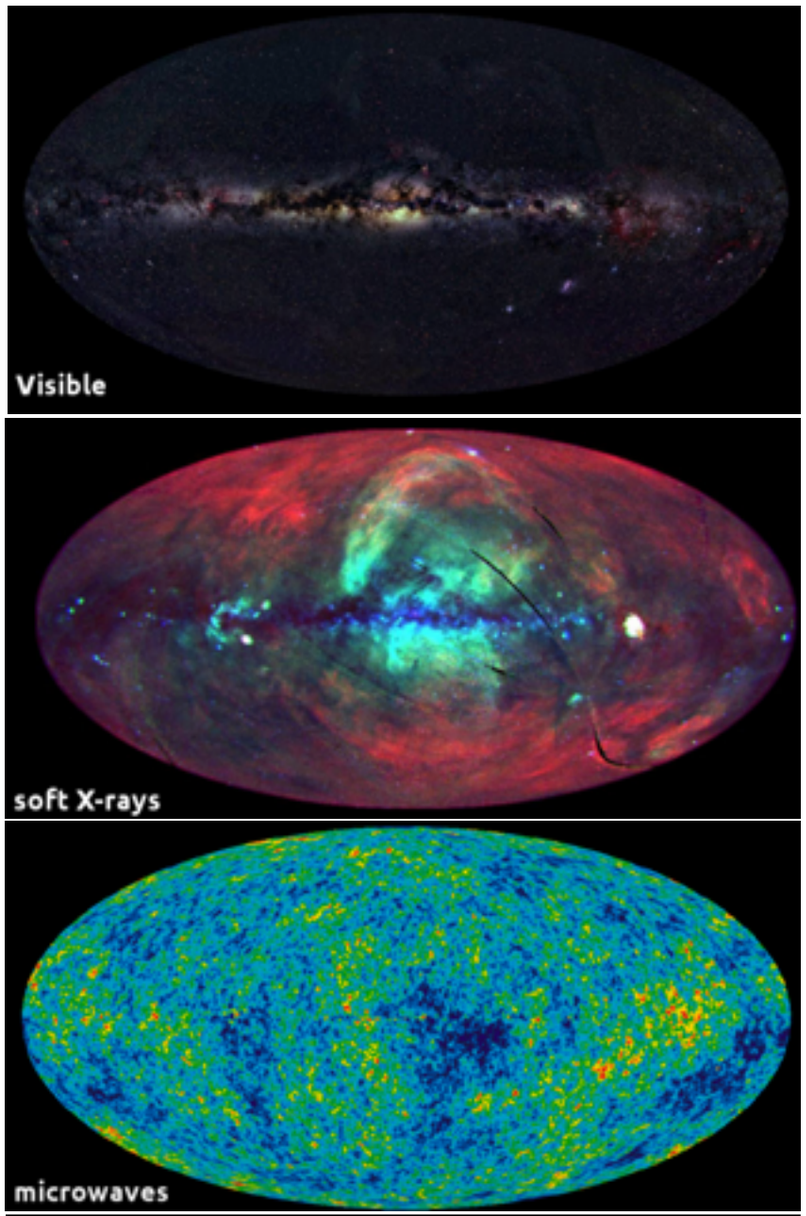


Neutrinos from cool-down

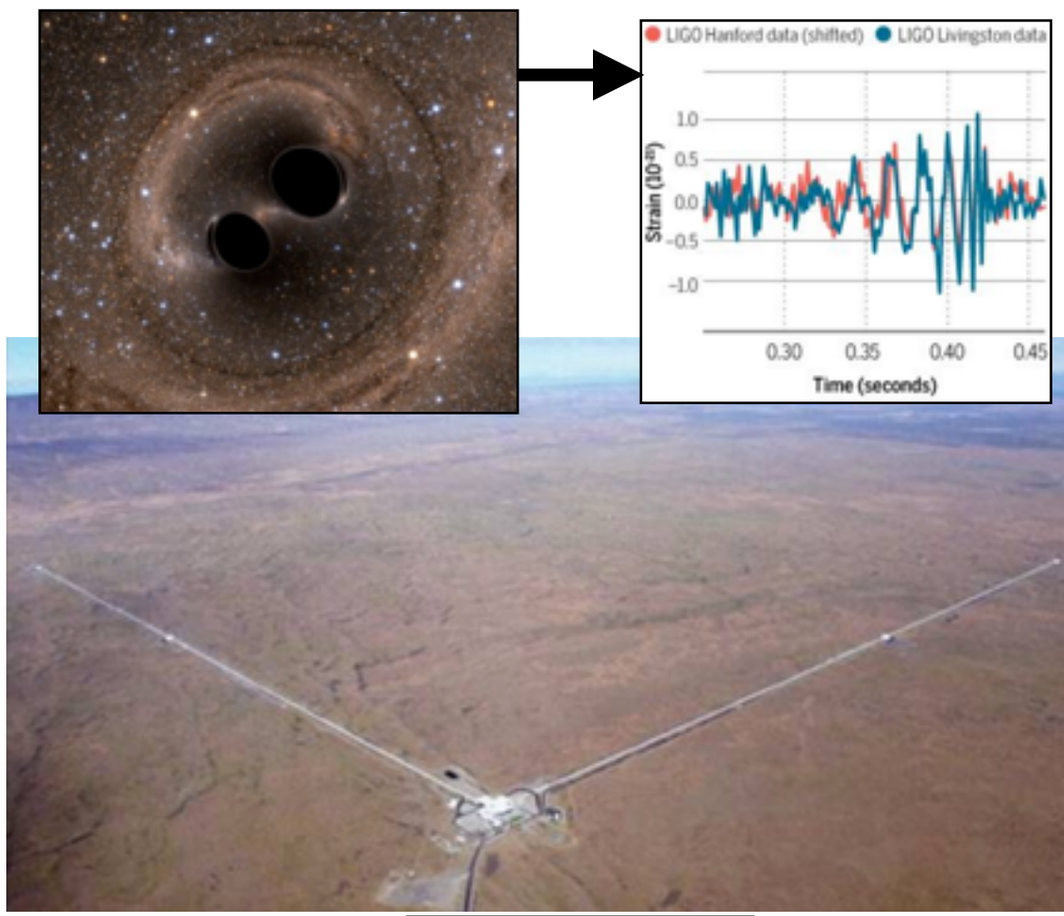


Supernova Neutrinos: Context

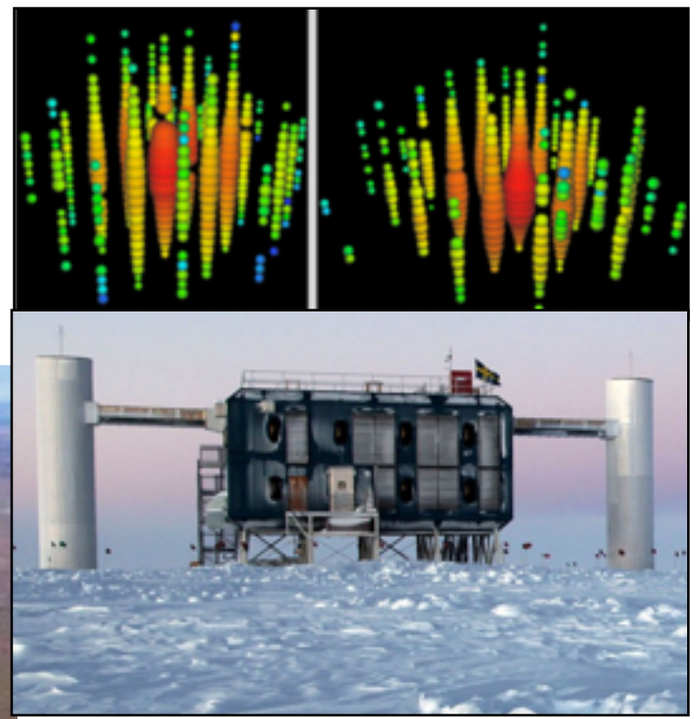
- Done it before: in 1987, 20 neutrinos detected!
- DUNE could see thousands from a similar supernova event.
- Think: another branch of 'multi-messenger astronomy'



EM: Different wavelengths, different views!



LIGO: new view of black holes

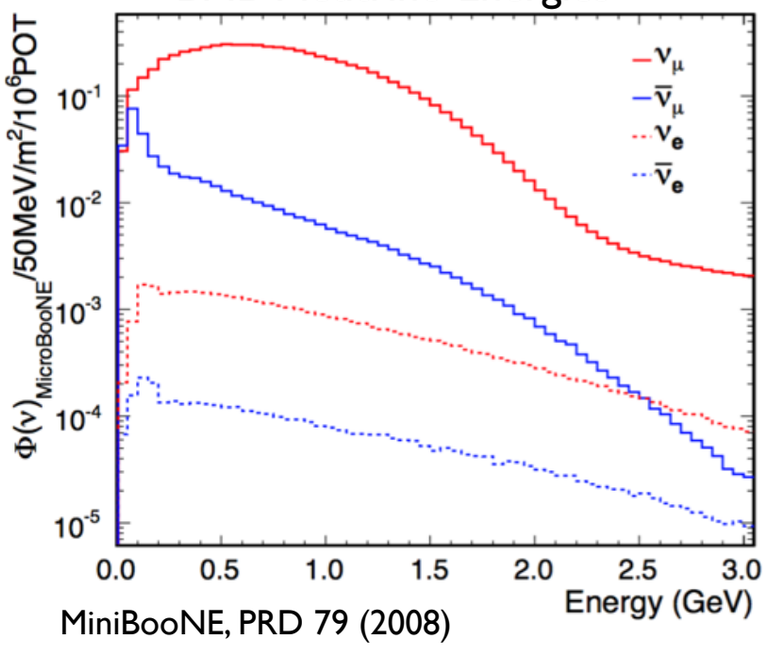


IceCube: New view of universe's highest energies

Supernova Neutrinos In LArTPCs

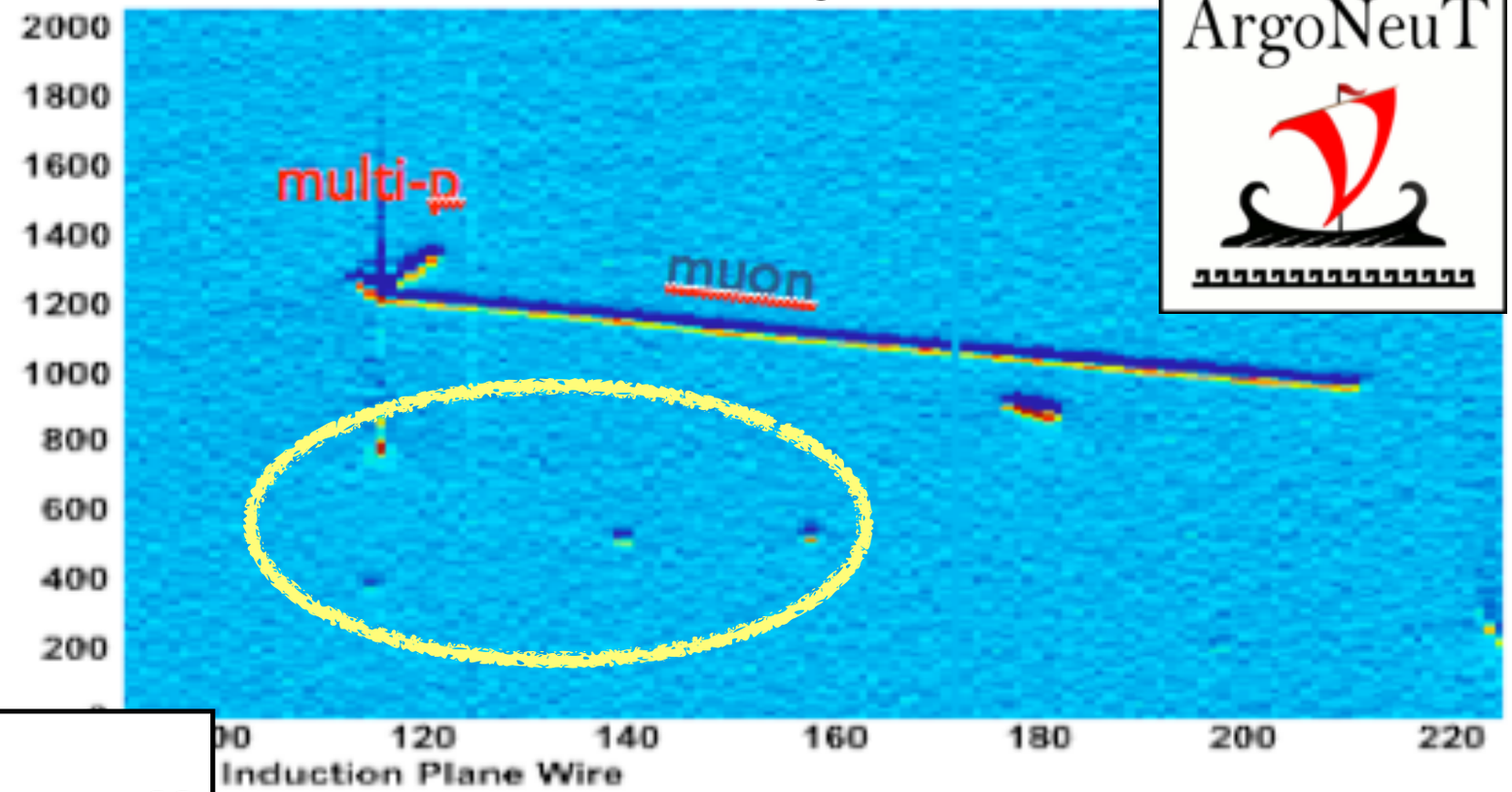
- So, from Fermilab's ~GeV neutrinos, we have enough energy to:
  - Produce a muon (~140 MeV)
  - Give that muon a lot of energy (>100 MeV) to make a meters-ish long track.
- This gives some clear points to start reconstructing a neutrino.

BNB Neutrino Energies



MiniBooNE, PRD 79 (2008)

A Data Event in the ArgoNeuT LArTPC



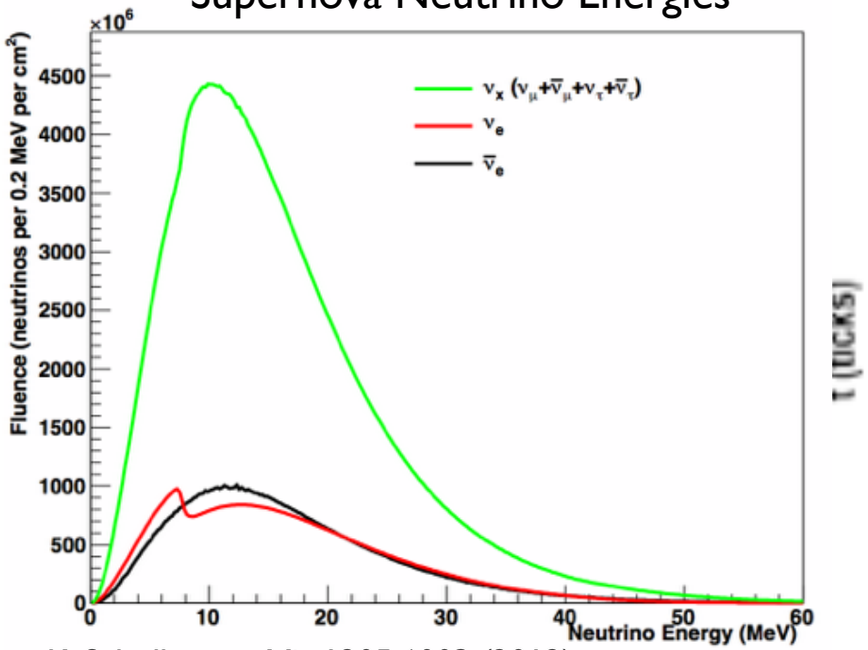
$\nu_\mu + Ar \rightarrow \mu^{\pm} + N^{*} + stuff$

muon neutrino charged-current interaction

Supernova Neutrinos In LArTPCs

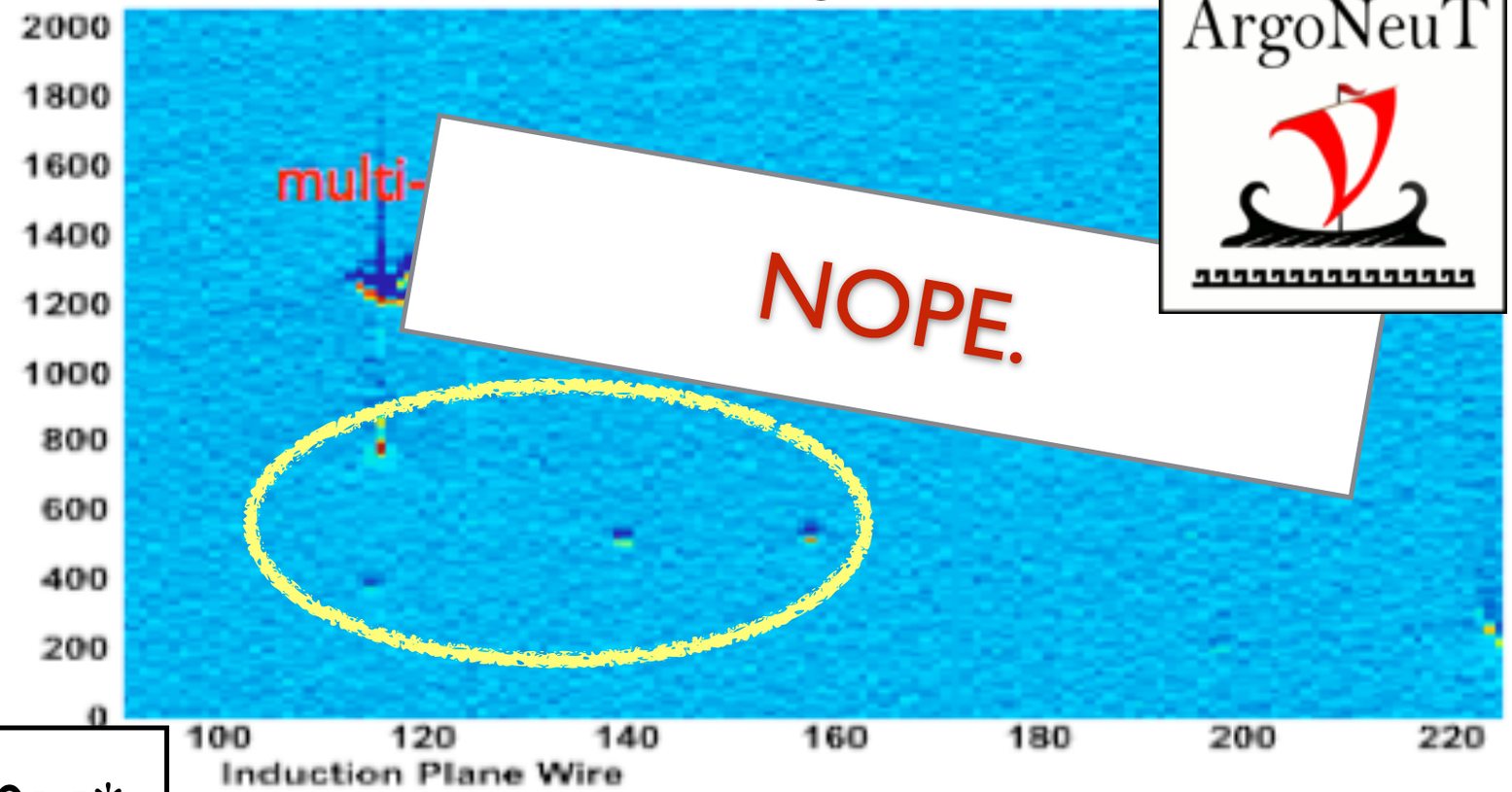
- Now, picture a supernova neutrino of 10 MeV
  - Nowhere near enough energy to produce a muon - only electrons.
  - No big long track; just a low-energy electron traveling a few cm.

Supernova Neutrino Energies



K. Scholberg, arXiv:1205.6003 (2012)

A Data Event in the ArgoNeuT LArTPC



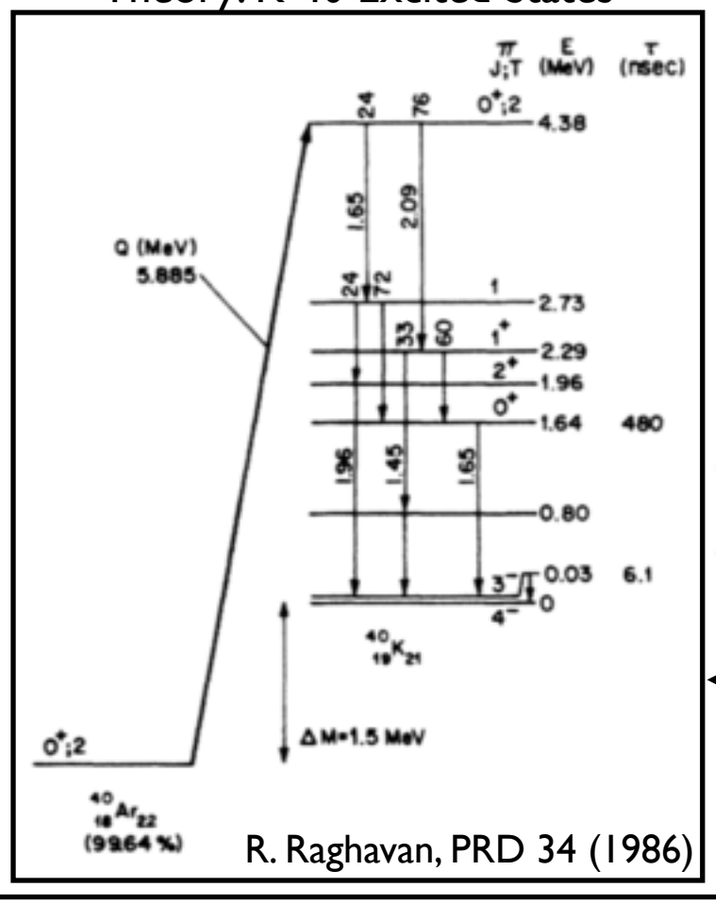
$$\nu_e + {}^{40}Ar \rightarrow e^{\pm} + {}^{40}K^*$$

electron neutrino charged-current interaction

Supernova Neutrinos In LArTPCs

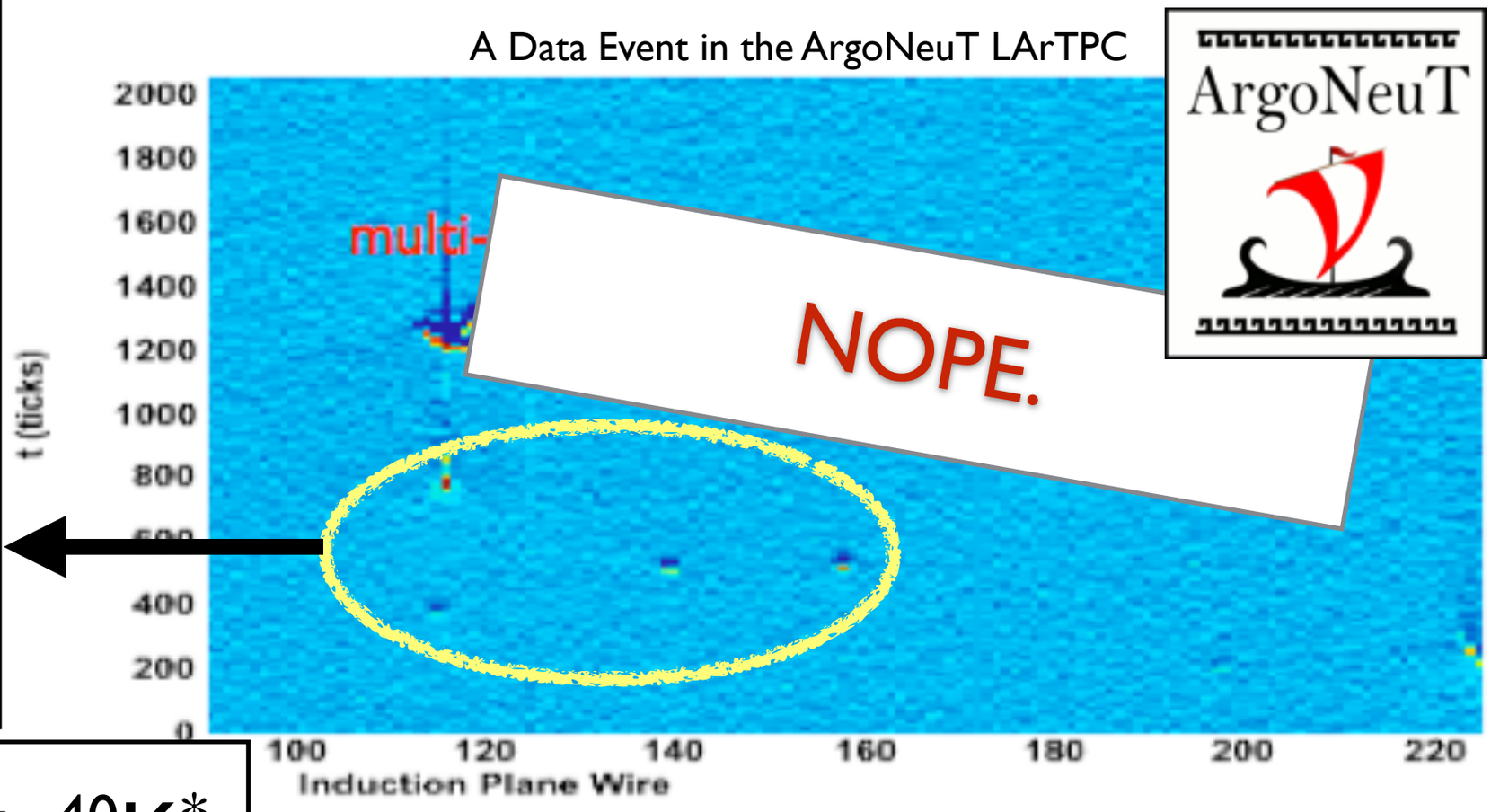
- Now, picture a supernova neutrino of 10 MeV
  - Nowhere near enough energy to produce a muon - only electrons.
  - No big long track; just a low-energy electron traveling a few cm.
  - Also some gammas from de-excitation of product nucleus

Theory: K-40 Excited States



R. Raghavan, PRD 34 (1986)

A Data Event in the ArgoNeuT LArTPC



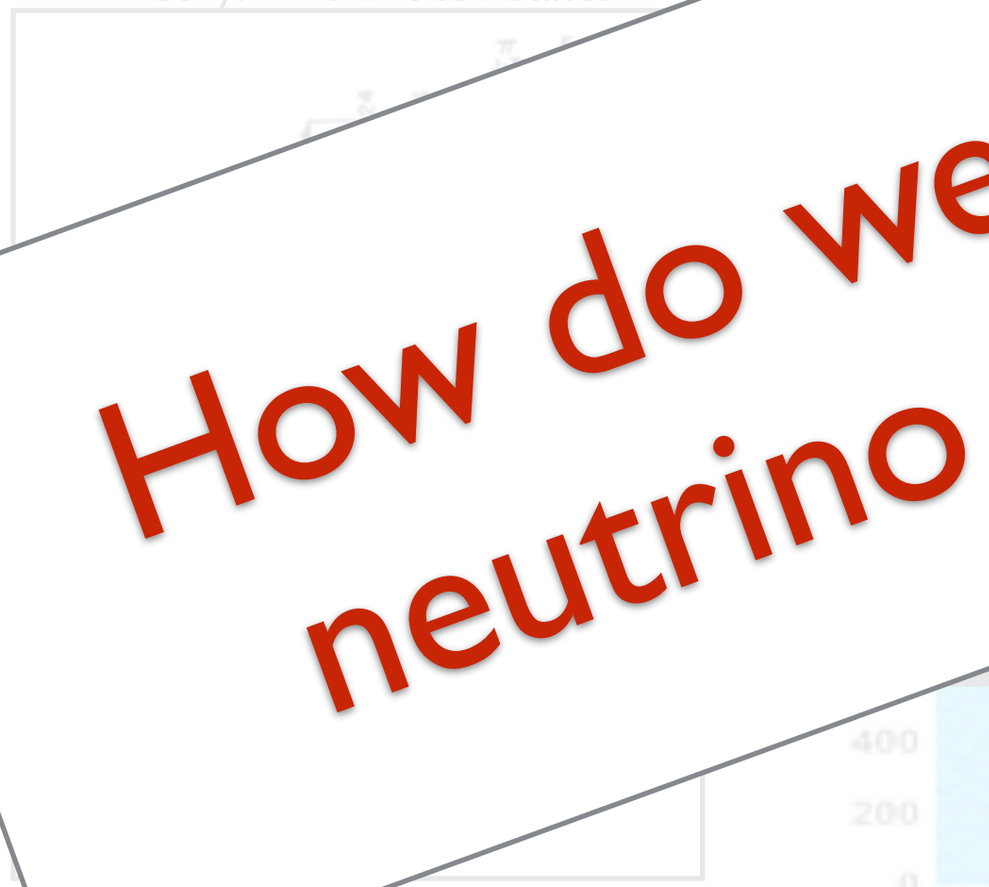
$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^{\pm} + {}^{40}\mathrm{K}^*$$

electron neutrino charged-current interaction

Supernova Neutrinos In LArTPCs

- Now, picture a supernova neutrino of 10 MeV
  - Nowhere near enough energy to produce a muon - only
  - No big long track; just a low-energy electron
  - Also some gammas from de-exci

How do we reconstruct a neutrino out of this????



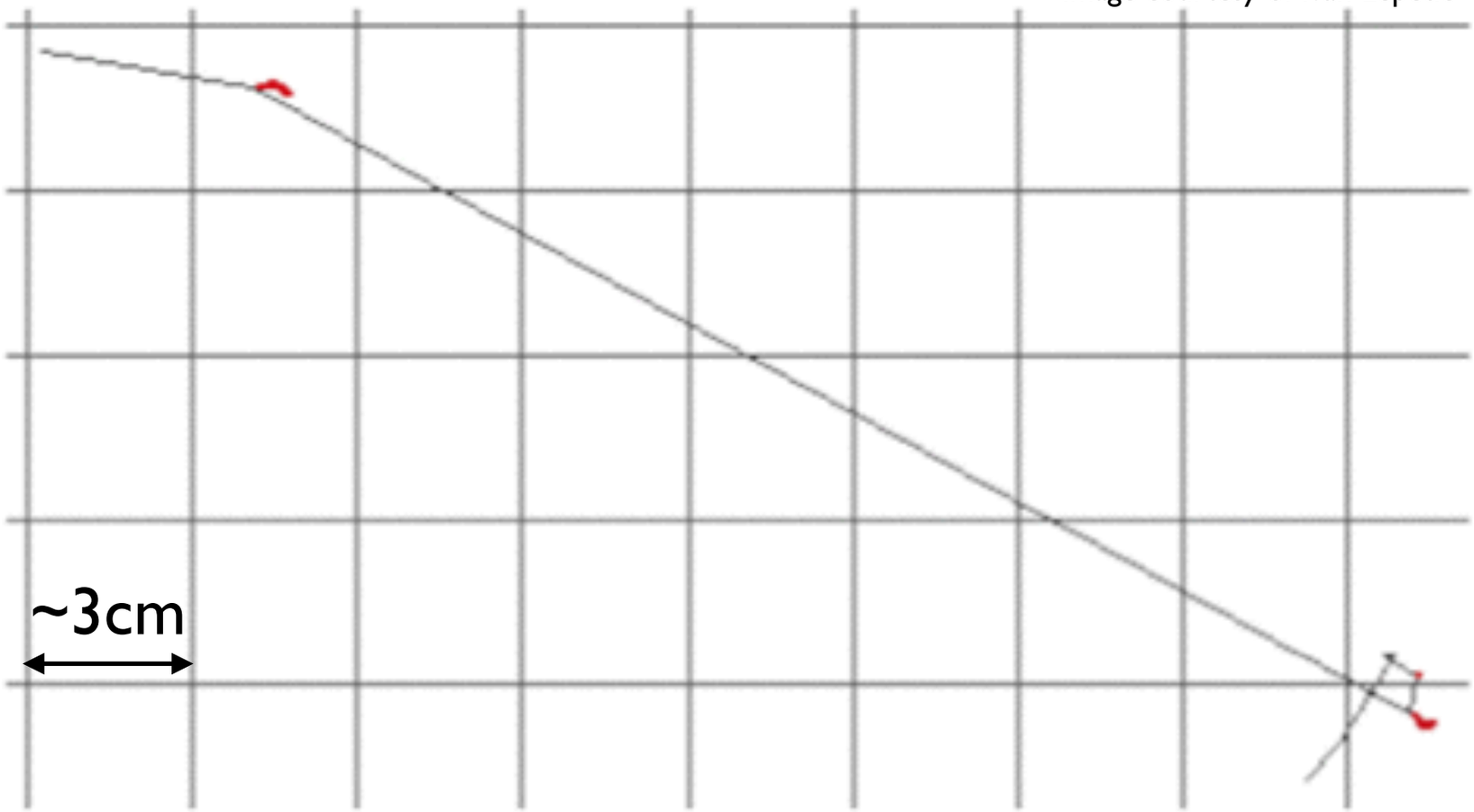
$\nu_e + {}^{40}Ar \rightarrow e^{\pm} + {}^{40}K^*$

electron neutrino charged-current interaction

Low-Energy Experimental Issues

- Many major experimental issues need to be addressed in order to tease out the interesting physics involved.

Image courtesy of Ivan Lepetic

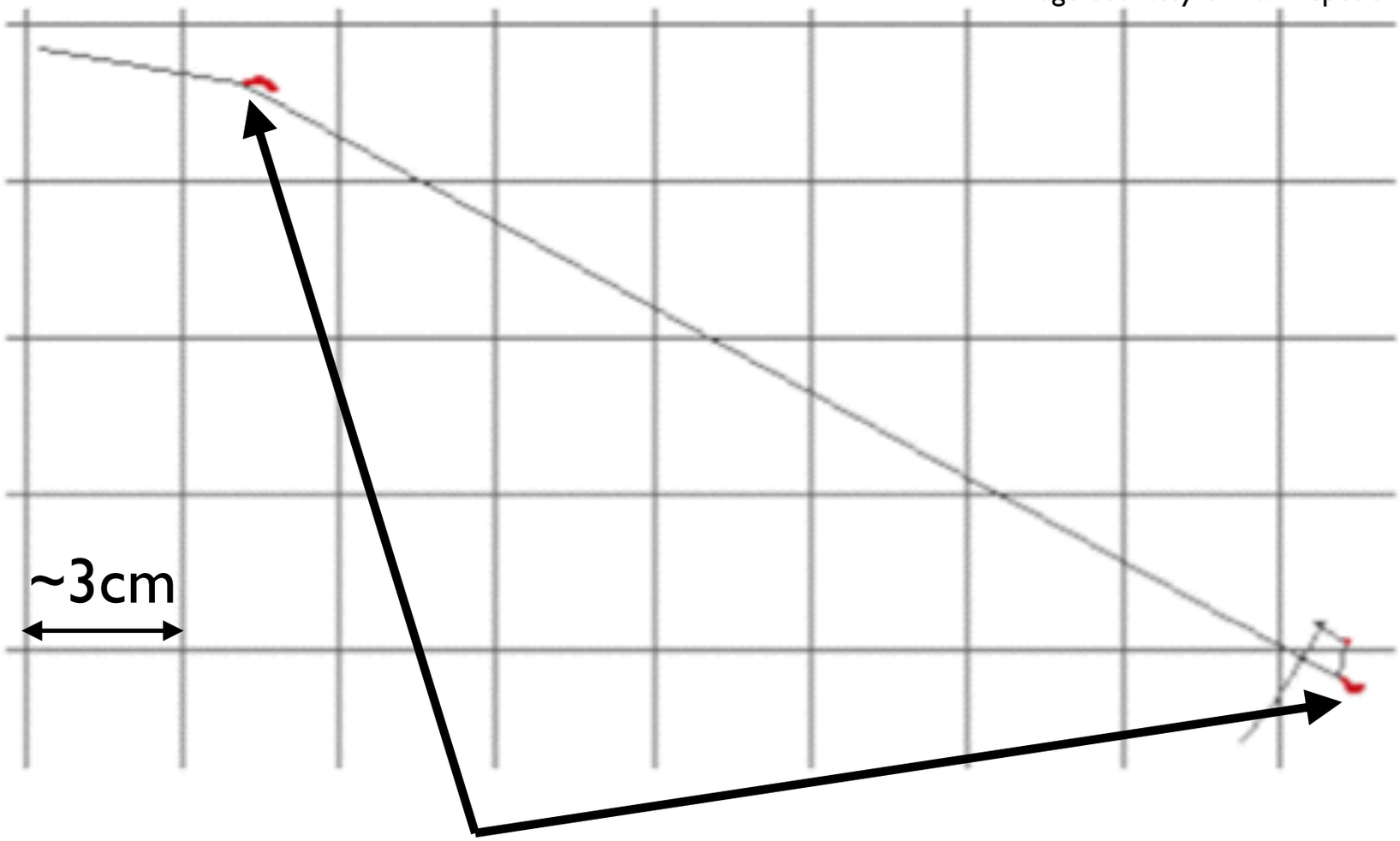


A 10 MeV Gamma in a LArTPC.
Think of this as de-excitation blips,
or as a supernova neutrino interaction.

Low-Energy Experimental Issues

- Many major experimental issues need to be addressed in order to tease out the interesting physics involved.

Image courtesy of Ivan Lepetic

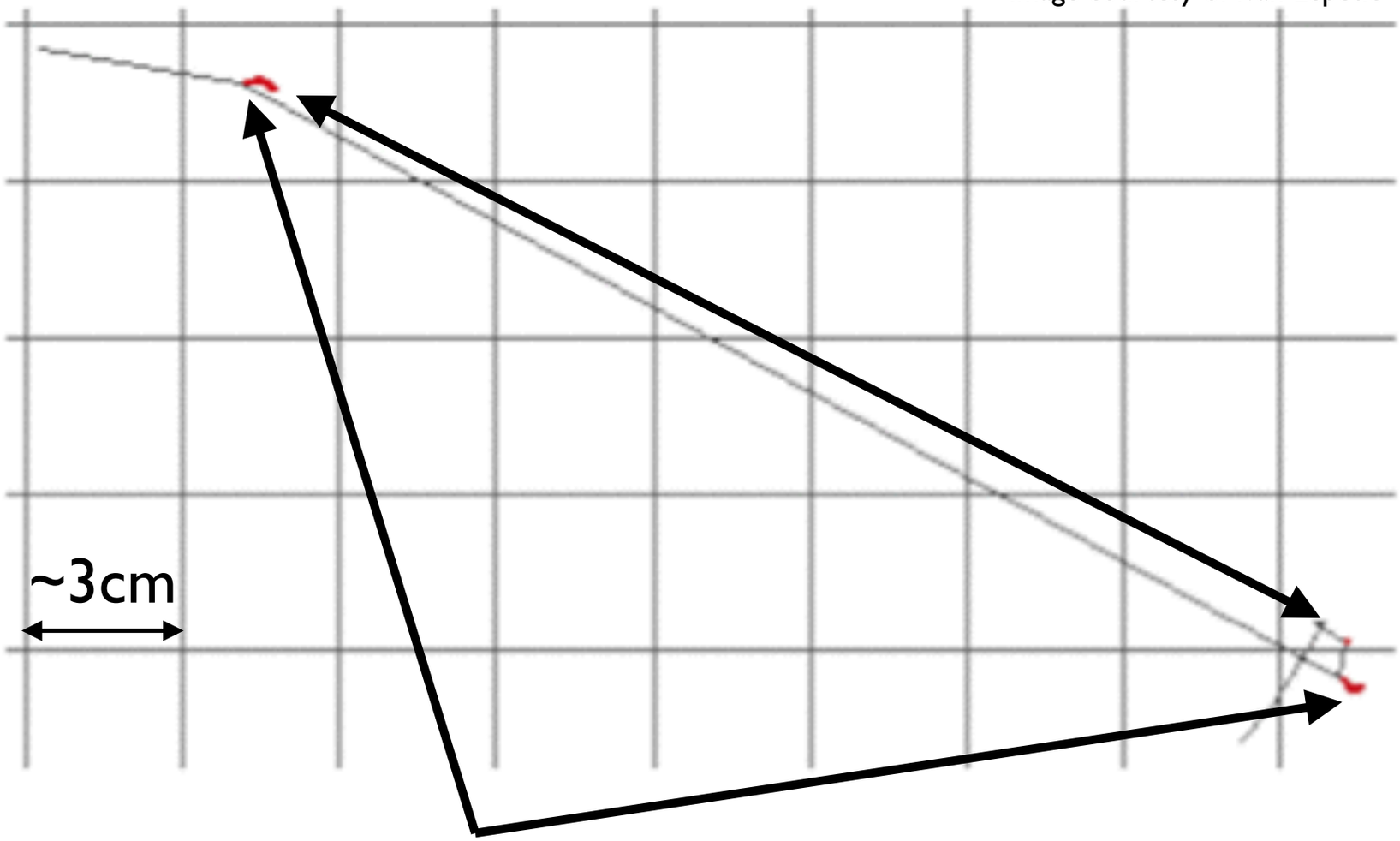


Need an algorithm to identify these blips, and then you need to calibrate them.

Low-Energy Experimental Issues

- Many major experimental issues need to be addressed in order to tease out the interesting physics involved.

Image courtesy of Ivan Lepetic

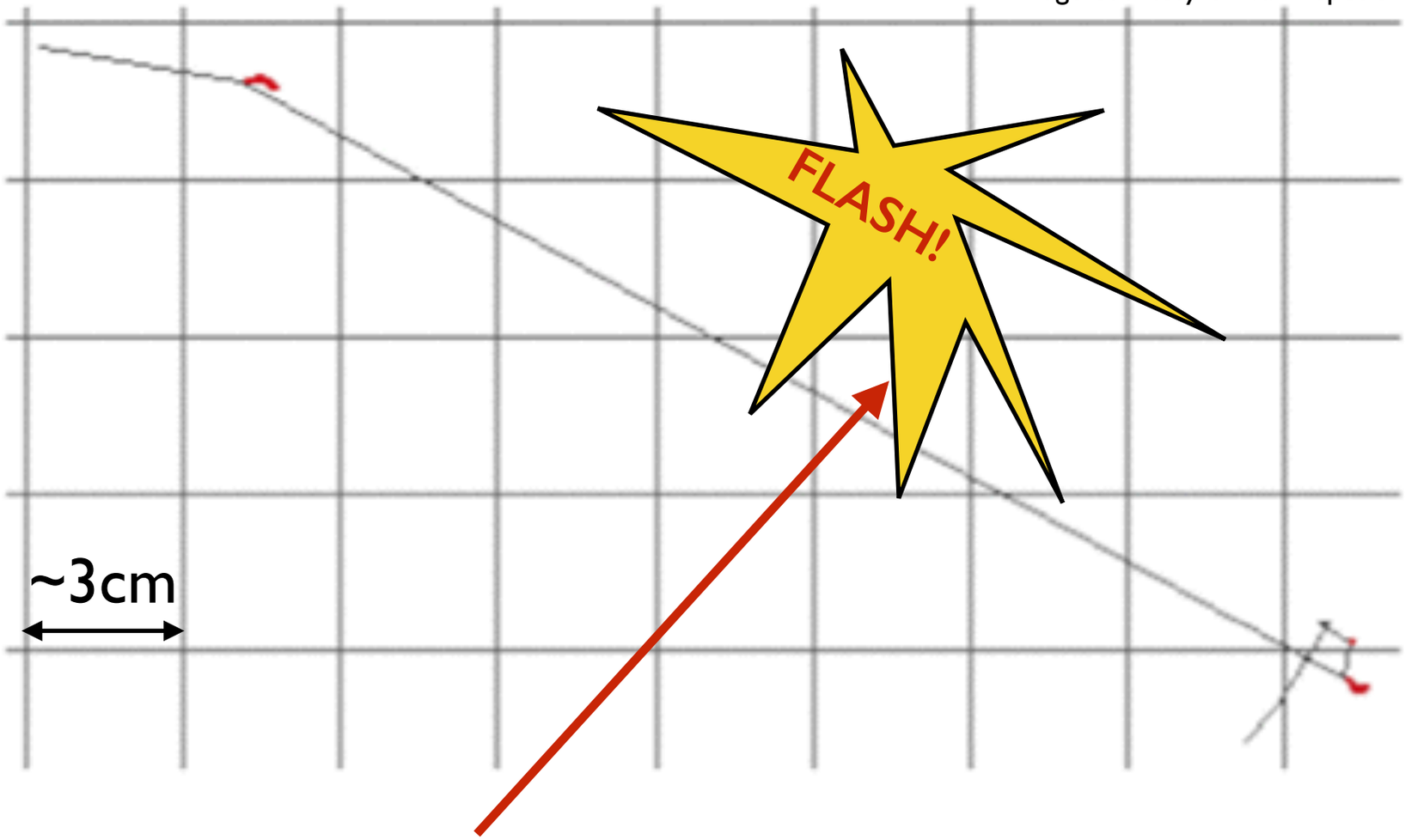


Need to write another algorithm to associate these blips with one another.

Low-Energy Experimental Issues

- Many major experimental issues need to be addressed in order to tease out the interesting physics involved.

Image courtesy of Ivan Lepetic



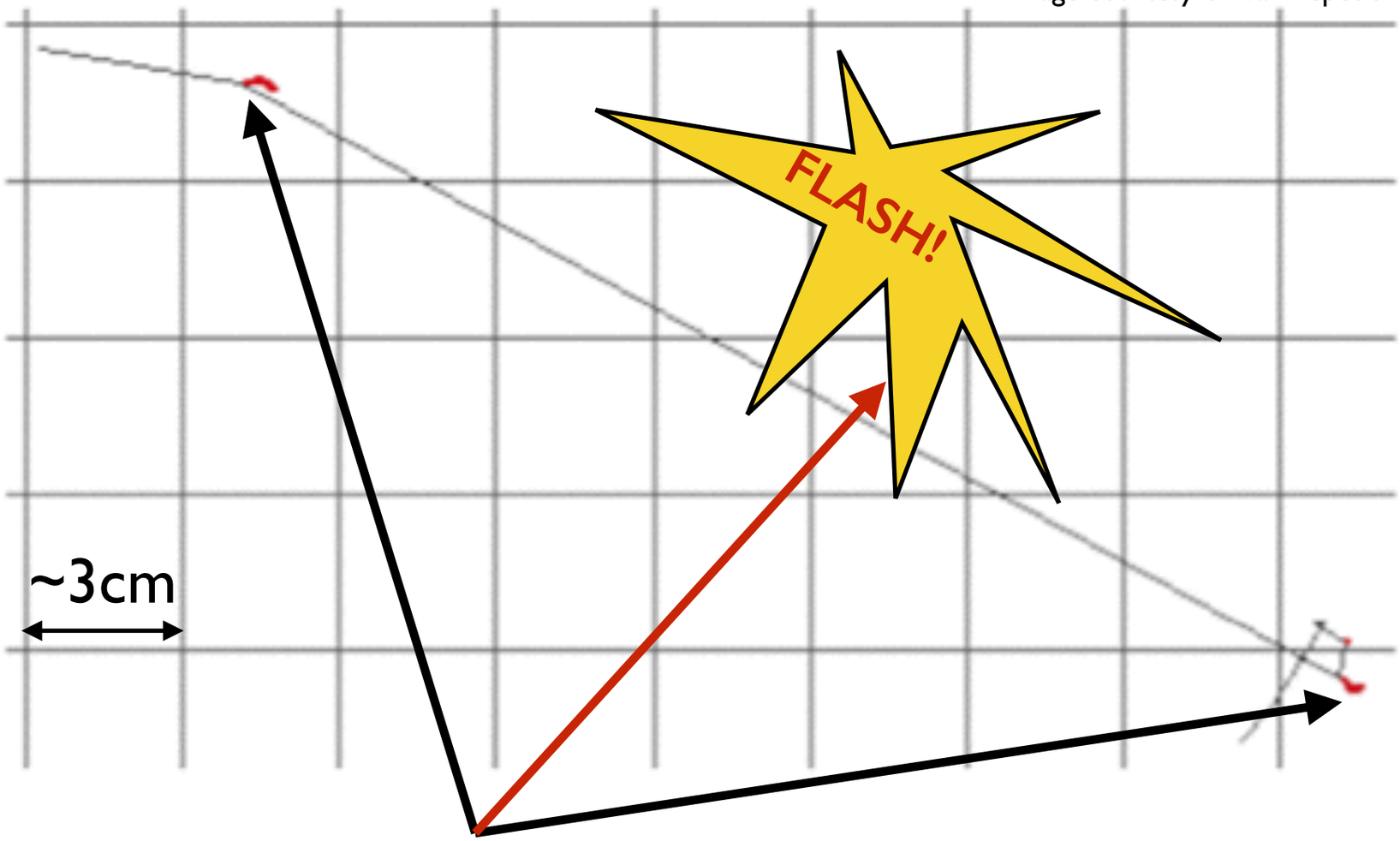
Need to be able to identify low-energy flashes.

This step is specifically relevant to supernova neutrinos
(BTW, if flash-only reco is excellent, that could be REALLY great…)

Low-Energy Experimental Issues

- Many major experimental issues need to be addressed in order to tease out the interesting physics involved.

Image courtesy of Ivan Lepetic

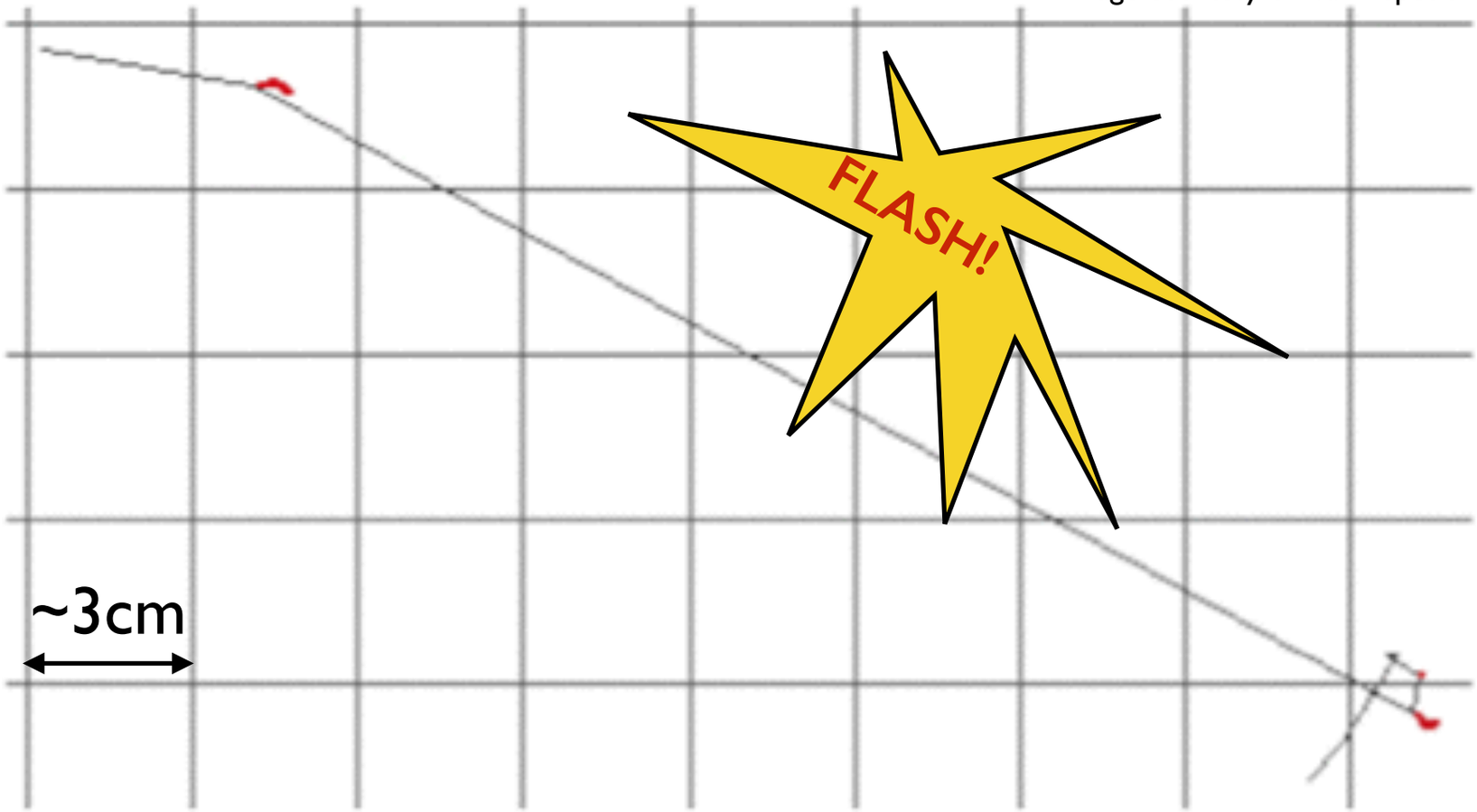


Need to be able to associate low-energy flashes to low-energy blips

Low-Energy Experimental Issues

- Many major experimental issues need to be addressed in order to tease out the interesting physics involved.

Image courtesy of Ivan Lepetic

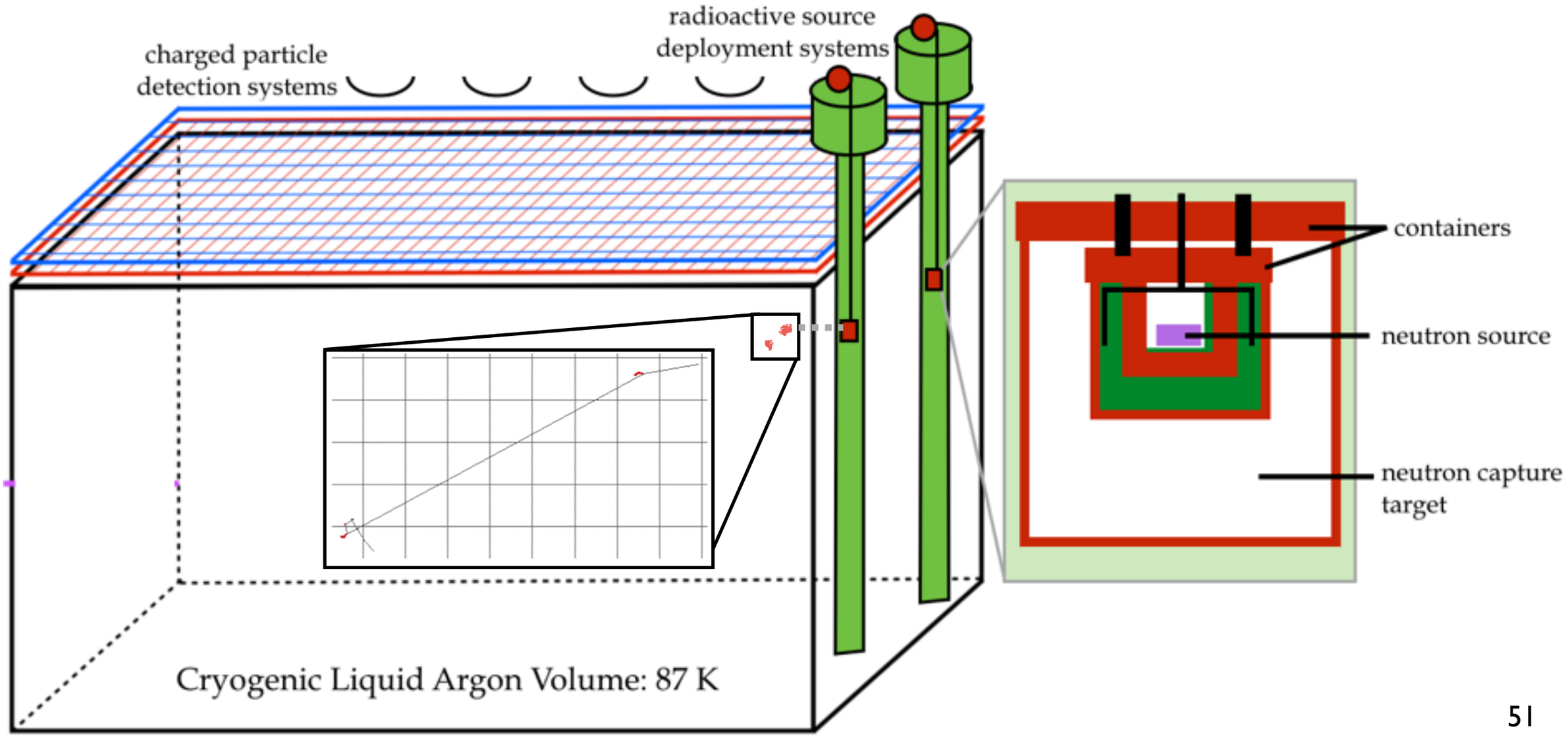


Need to precisely characterize all of these steps.
How do we accomplish this?????

This is one question we're trying to grapple with at IIT.

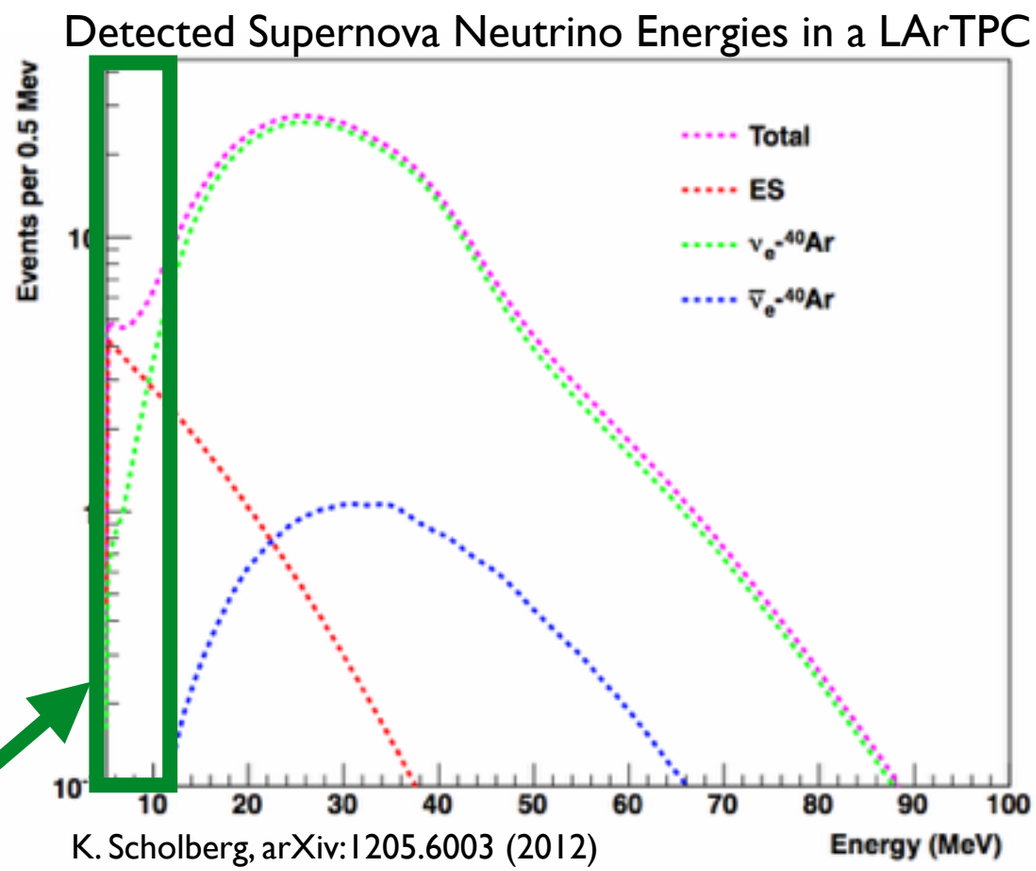
Low-Energy LArTPC Calibration Source

- Two dry calibration axes along exterior of a LArTPC.
  - Deploy radioactive sources at multiple vertical, drift-direction locations
  - Significant portion of gammas enter the TPC and deposit their full energy
  - Perform all characterization listed previously with a well-understood source

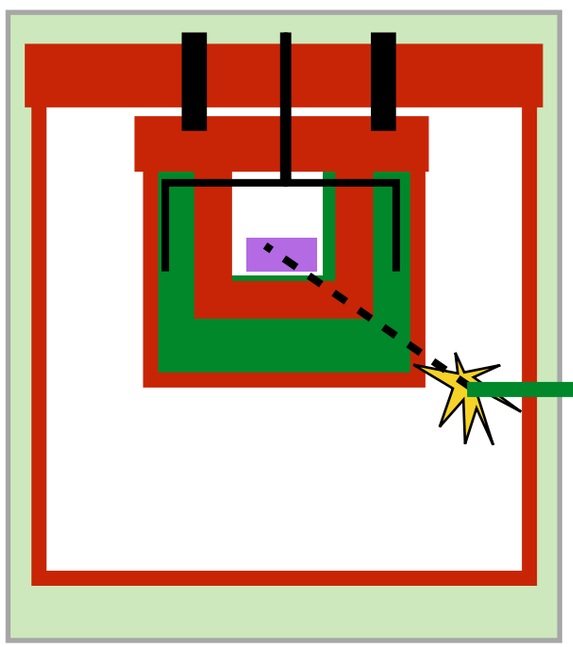


Low-Energy LArTPC Calibration Source

- Use a neutron calibration source to produce single gammas
- Similar in energy to supernova neutrinos of lowest energies
- These are the neutrinos we'll have the hardest time detecting.



K. Scholberg, arXiv:1205.6003 (2012)



Gamma Energy (MeV)	Production Method	Producing Source
1.17, 1.33, in coincidence	β^- product de-excitation	^{60}Co gamma
4.4, monoenergetic	(n,C) inelastic scattering	AmC neutron
5.2, monoenergetic 10.8, monoenergetic	n-^{14}N capture	^{252}Cf and AmC neutron
6.1, monoenergetic	(α,n) product de-excitation	AmC neutron
6.1, cascade	n-^{40}Ar capture	^{252}Cf and AmC neutron
7.6, monoenergetic	n-^{56}Fe capture	^{252}Cf and AmC neutron
9.3, monoenergetic	n-^{54}Fe capture	^{252}Cf and AmC neutron

Low-Energy LArTPC Calibration Source

- What we're doing at IIT to prepare for and design this system:
  - Working with Fermilab engineers to integrate calibration system designs into SBND LArTPC
  - Doing simulations to guide calibration system design
  - Prototyping and testing calibration sources

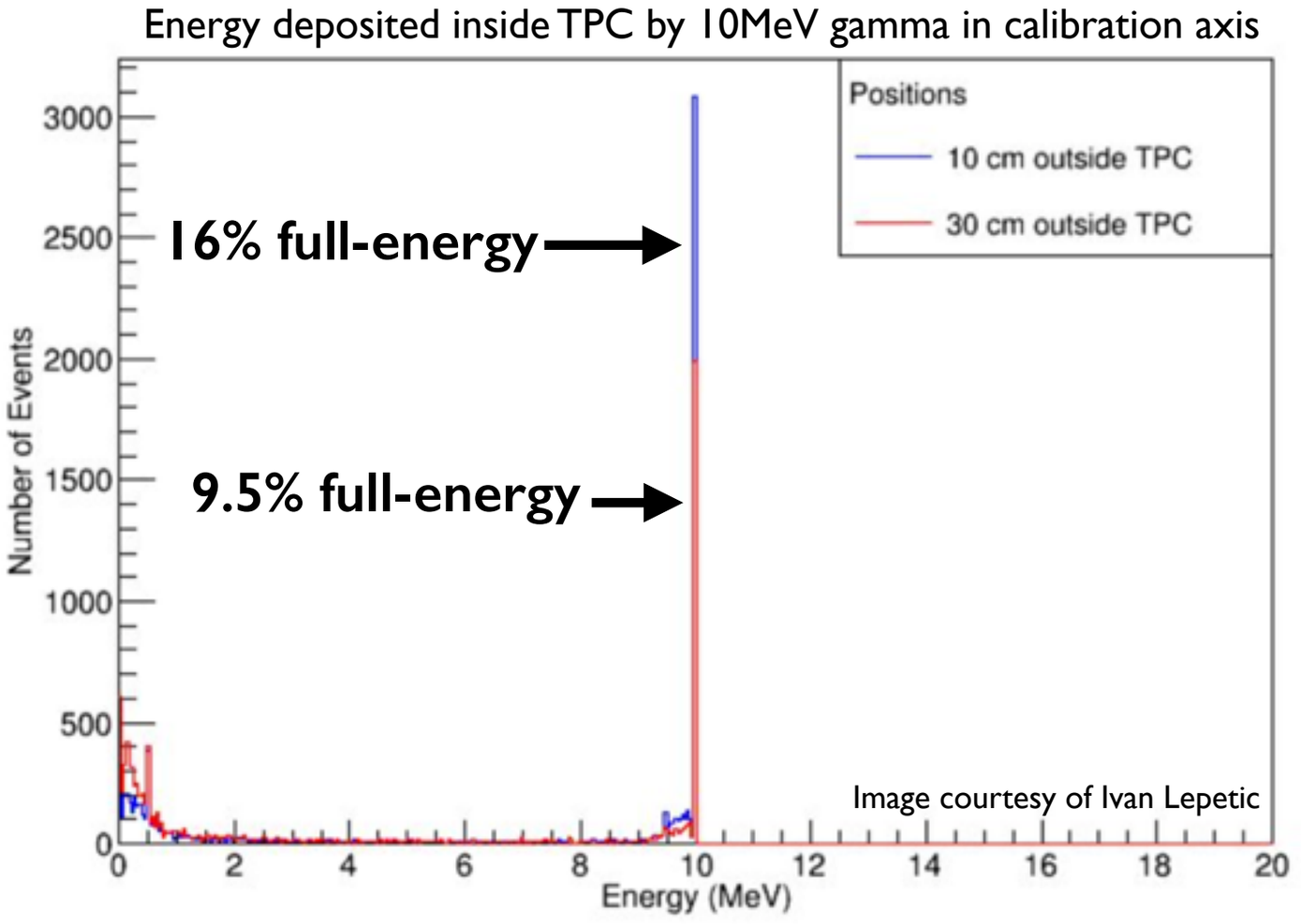
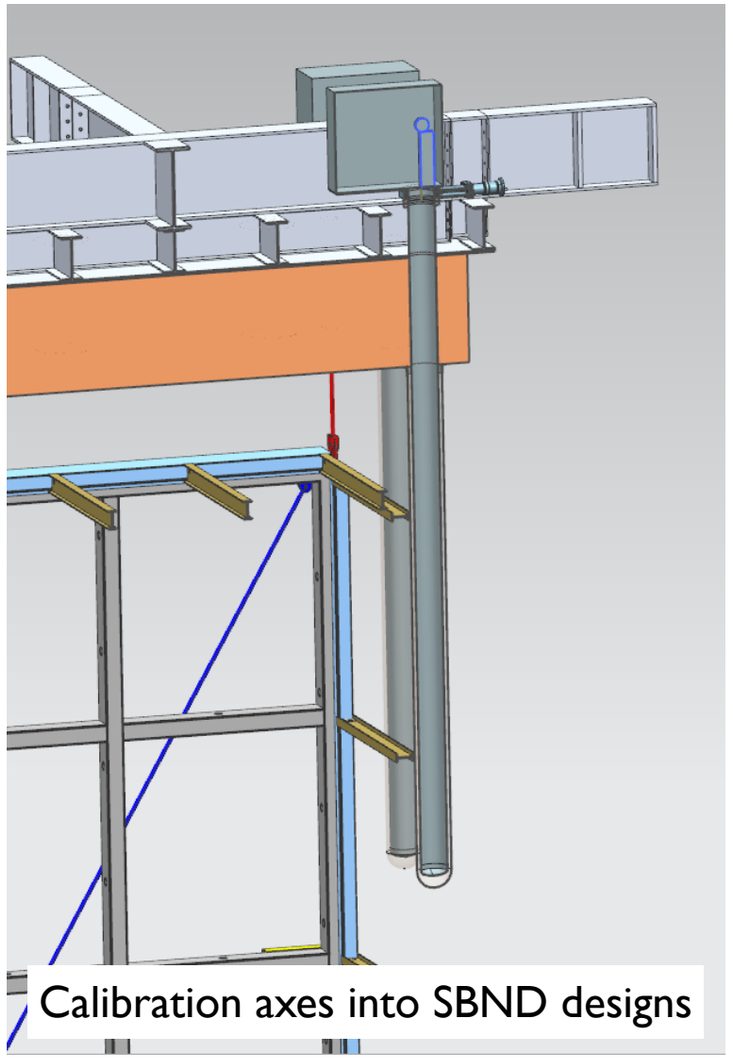
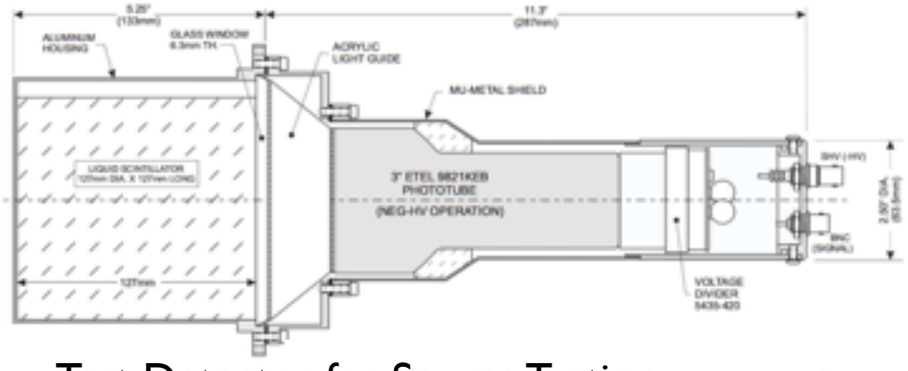


Image courtesy of Ivan Lepetic


Calibration axes into SBND designs

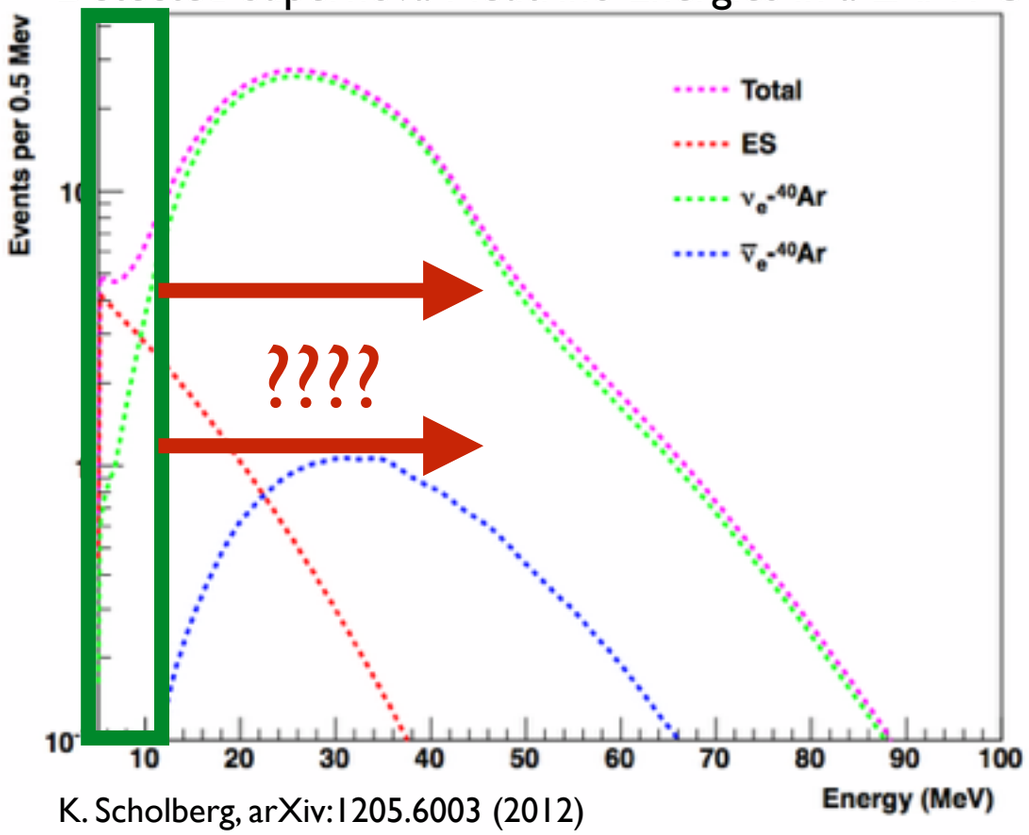


Test Detector for Source Testing

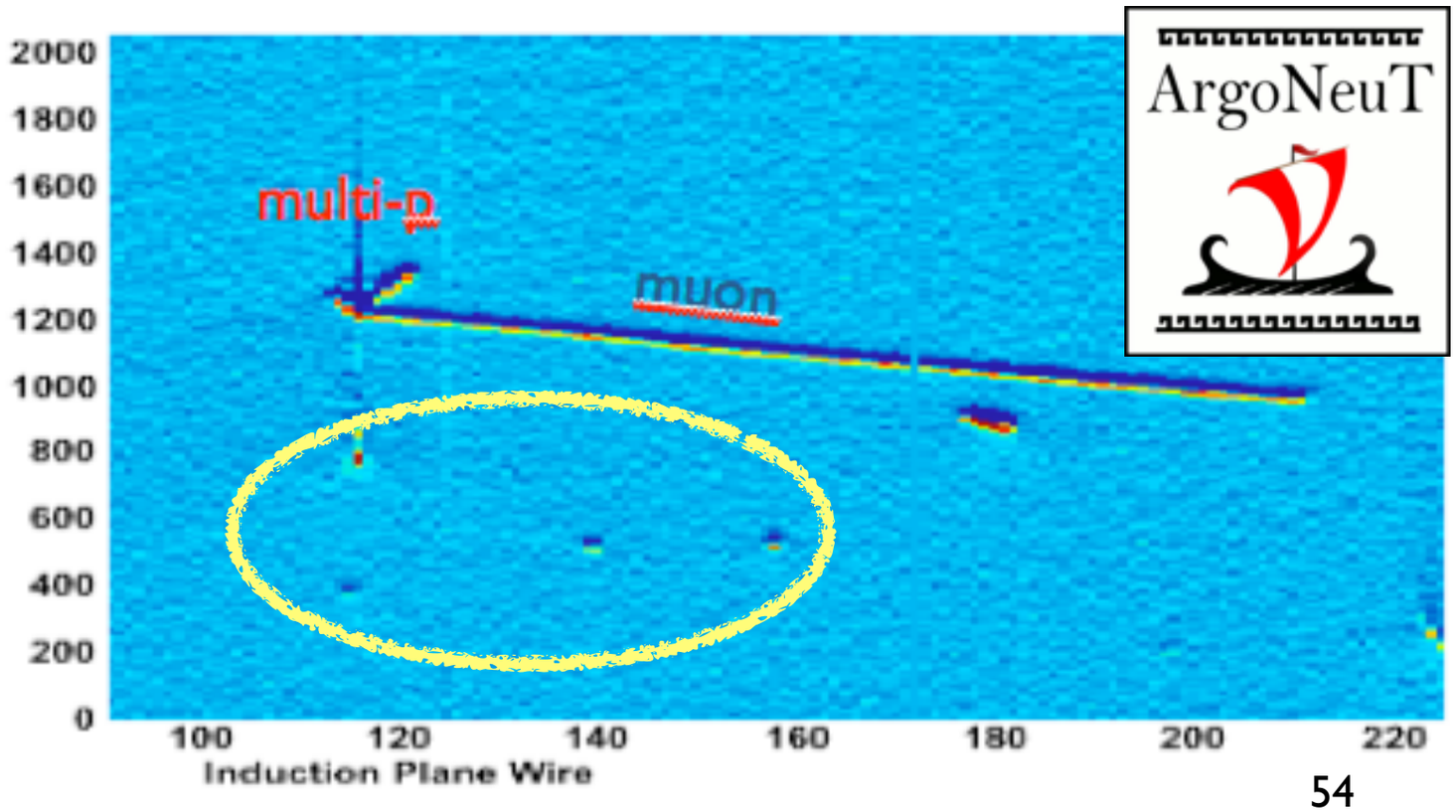
Other Ideas?

- Calibration source is great, but it isn't perfect.
  - Doesn't address response at higher supernova neutrino energies.
  - Doesn't give us any handle on these 'blips' from excited nuclear states, and how much of a supernova's total energy is contained in them…
- What else is there?

Detected Supernova Neutrino Energies in a LArTPC

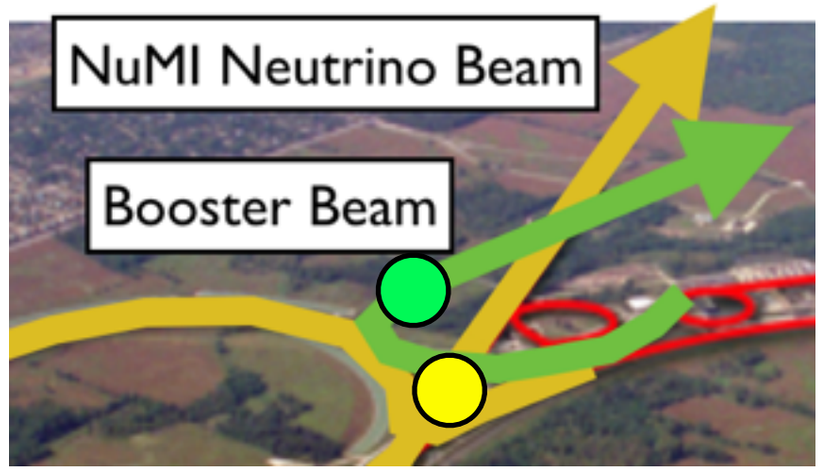


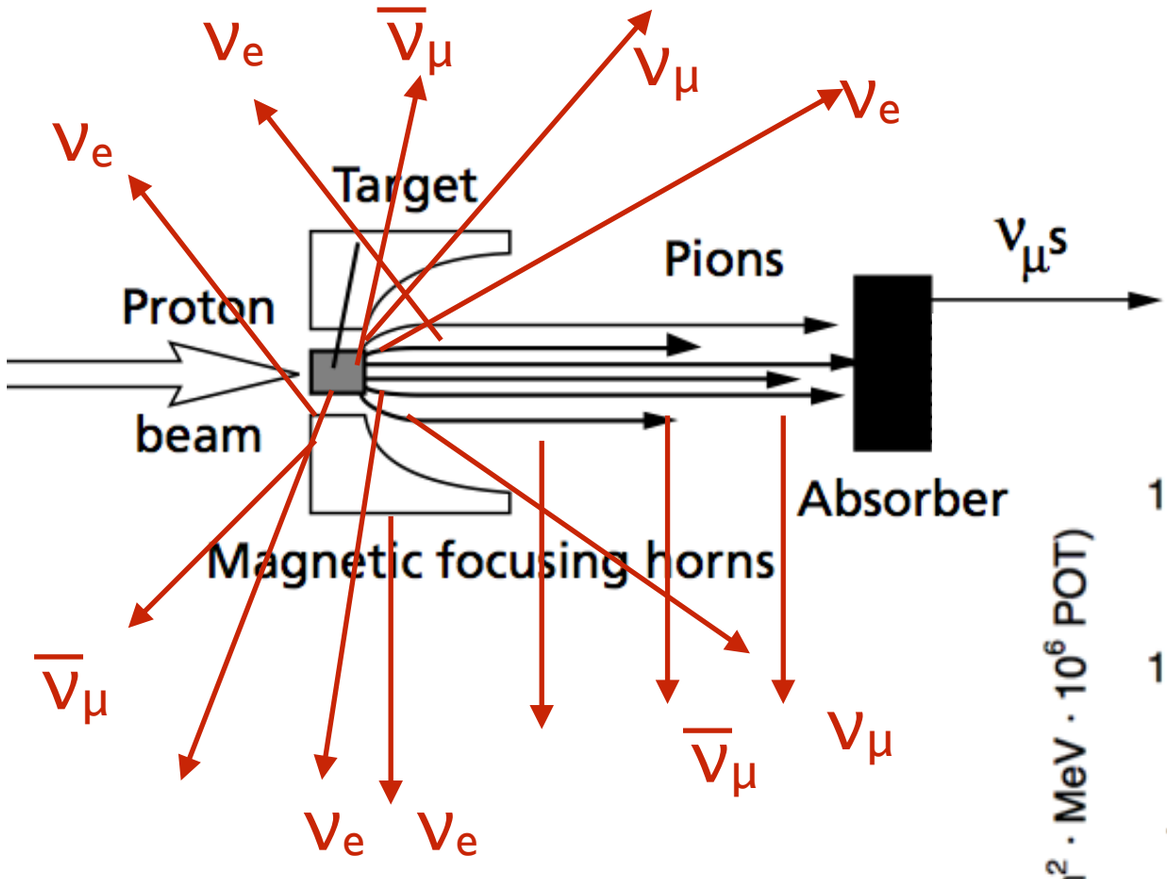
K. Scholberg, arXiv:1205.6003 (2012)



Decay-At-Rest Neutrinos in a LArTPC

- For every ~GeV accelerator neutrino, dozens of lower-energy ones are created
  - Energies are very similar to those of supernovae!





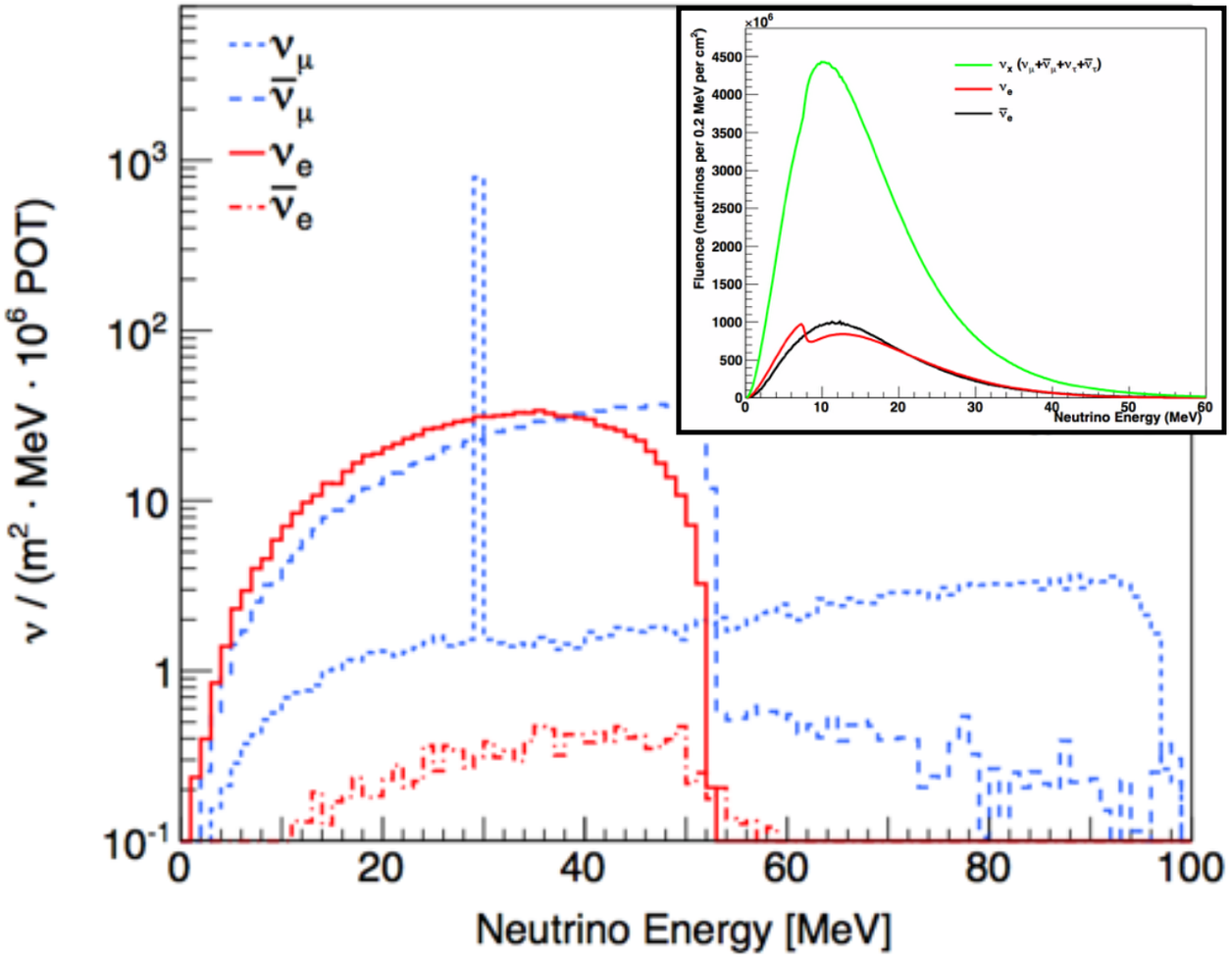
$$p \rightarrow \pi^+ \rightarrow \nu_\mu + \mu^+$$

pion decay-at-rest neutrinos

$$\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu}_\mu$$

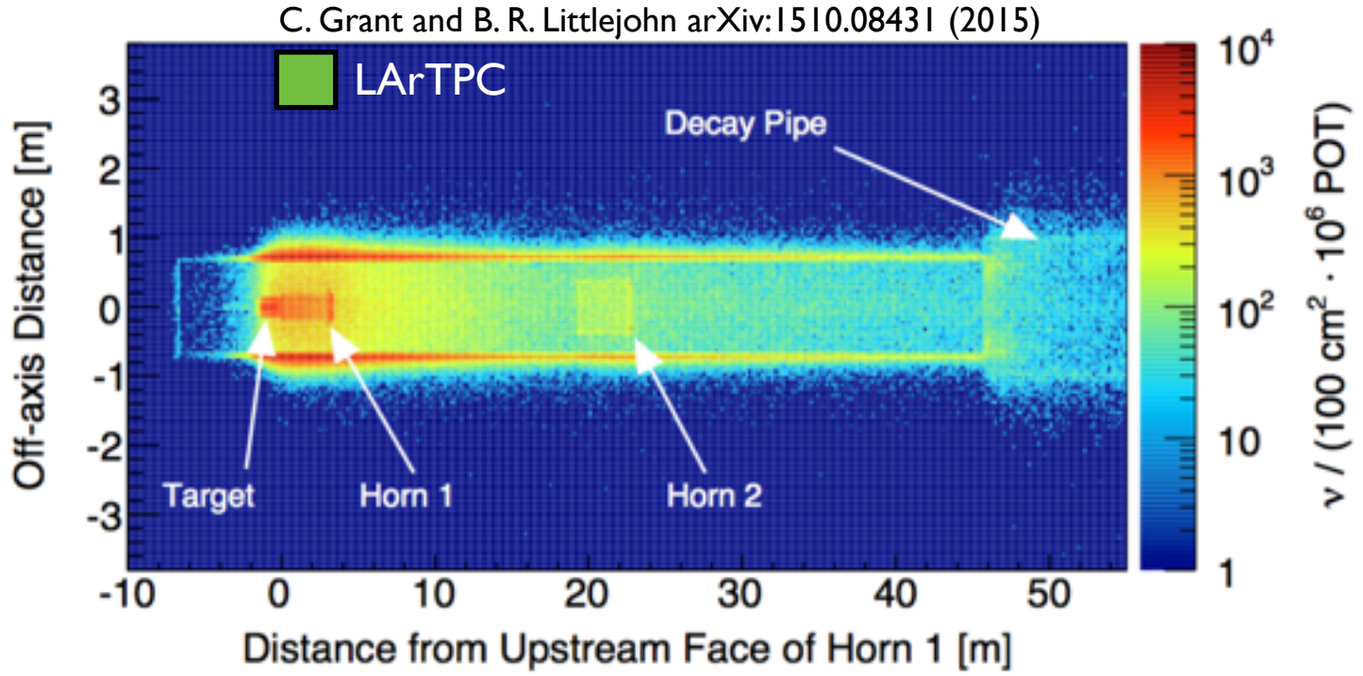
muon decay-at-rest neutrinos

C. Grant and B. R. Littlejohn arXiv:1510.08431 (2015)



Decay-At-Rest Neutrinos in a LArTPC

- A small LArTPC deployed close to the existing NuMI neutrino beam would yield 1000s of supernova-like events!
  - Allow us to prepare for seeing these events before a supernova happens
- Doing a number of studies at IIT to develop this idea further
  - Simulations of DUNE beam line: put a MicroBooNE-like LArTPC near DUNE's target?
  - Simulations of cosmogenic backgrounds: how far underground would detector need to be at Fermilab?



Interaction Rates Per Year In A LArTPC in Fermilab's NuMI Neutrino Beam

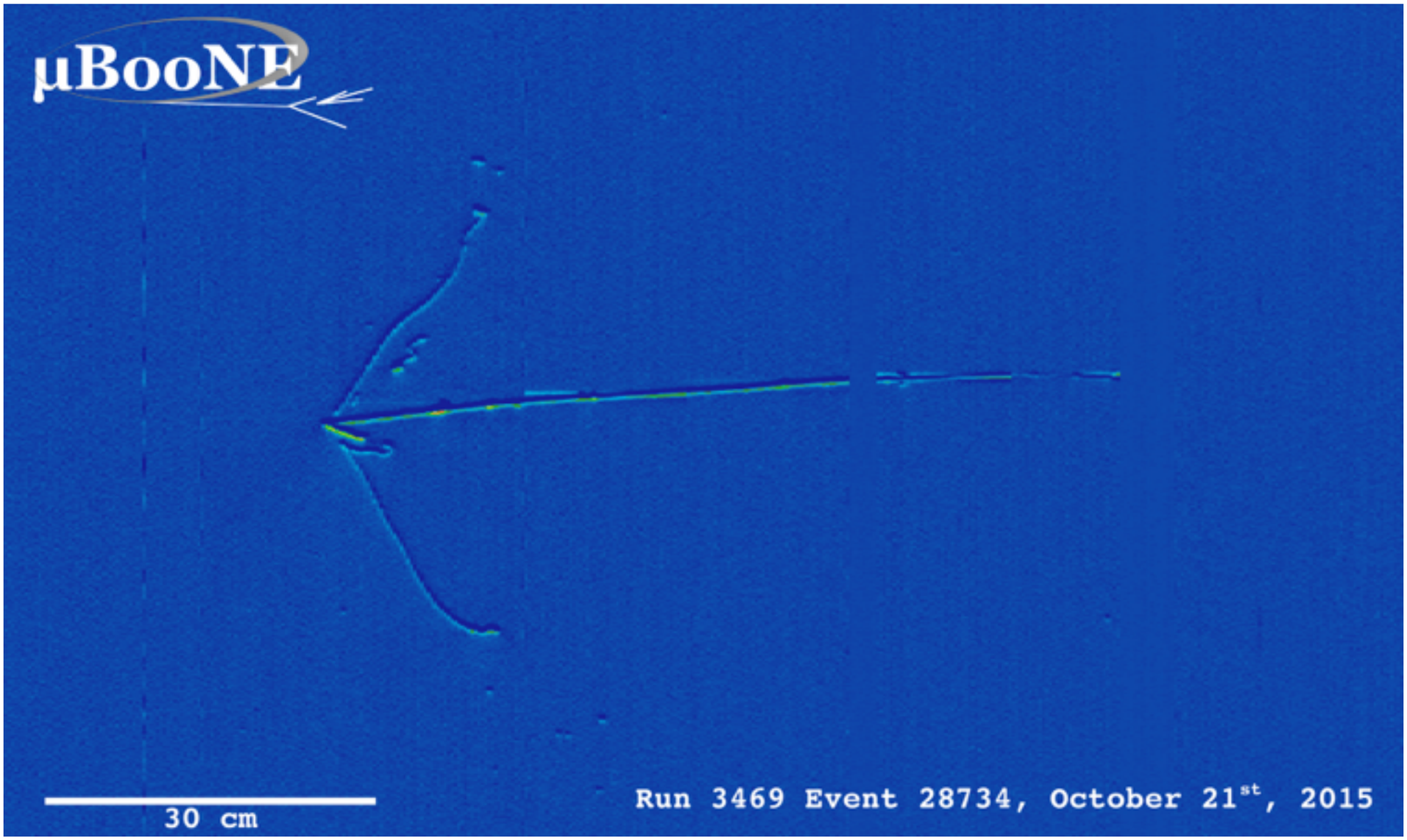
Location (x, y, z) [m]	LAr Mass [t]	CC ν_e	CC $\overline{\nu}_e$	NC ν_μ	NC $\overline{\nu}_\mu$	CC ν_μ (235.5 MeV)
$(15, 20, 0) \rightarrow$ 25 m from target	5.0	1.1×10^3	1.4	1.2×10^2	4.1×10^2	4.5×10^3
$(0, 40, 0) \rightarrow$ 40 m from target	5.0	4.9×10^2	0.6	5.0×10^1	1.8×10^2	2.0×10^3
$(15, -1, 753) \rightarrow$ 32 m from absorber	5.0	1.1×10^2	0.1	1.0×10^1	4.0×10^2	4.0×10^2
$(53, 76, 679) \rightarrow \mu$BooNE	60.4	1.8×10^2	0.3	1.9×10^1	6.5×10^1	6.9×10^2

Timescales

- MicroBooNE LArTPC running: Now!
- SBND installation, calibration source deployment: 2018
- DUNE installation: 2022-ish
  - Proposing DAR-detector deployment: 2022-ish as well
- DUNE running: into the 2030s!!!!
- A supernova explodes close by: ?????
  - Should happen every ~30 years or so…

Summary

- LArTPCs are remarkable new detectors that will be used to probe matter-antimatter asymmetry in the DUNE experiment.
- We are working to add an additional new capability for learning about supernovae and the neutrinos they produce.



Summary

- LArTPCs are remarkable new detectors that will be used to probe matter-antimatter asymmetry in the DUNE experiment.
- We are working to add an additional new capability for learning about supernovae and the neutrinos they produce.

Thanks for listening!

END

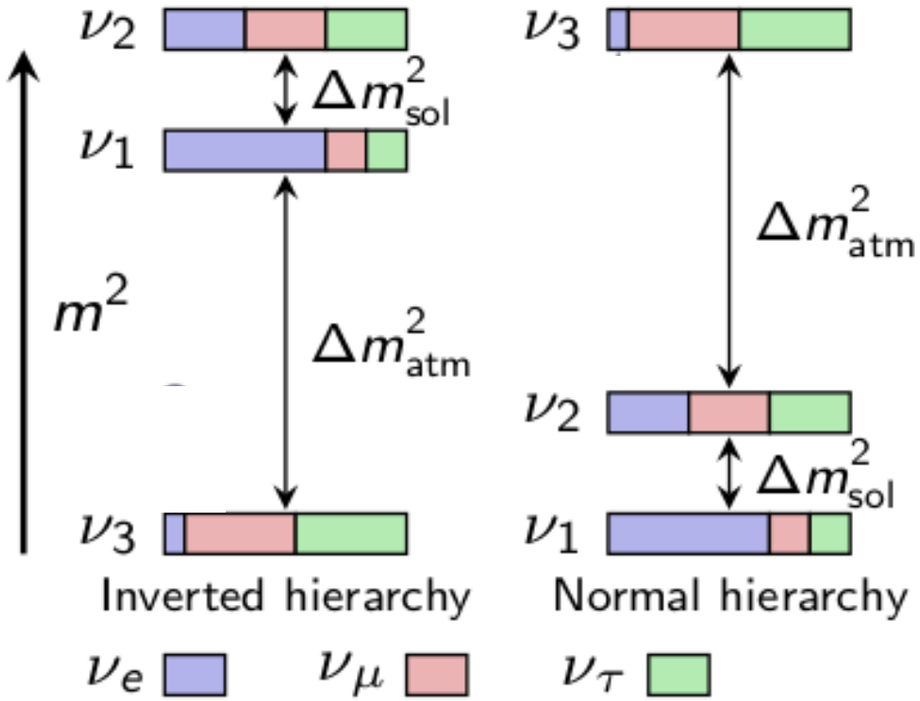
Neutrino Oscillations

Weak and mass eigenstates need not correspond:

1. How they interact
2. How they propagate

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha,i} \, |\nu_i\rangle$$

Neutrino Oscillations



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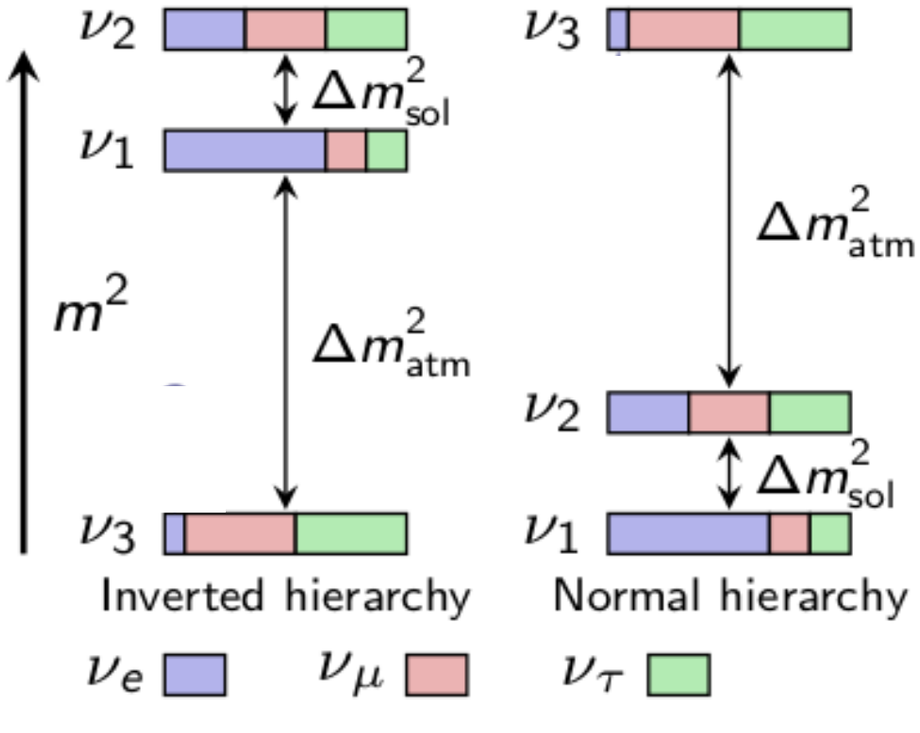
$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha,i} \, |\nu_i\rangle$$

$|\Delta m^2_{atm}| = \sim 0.0025 \text{ eV}^2$

$\Delta m^2_{sol} = \sim 0.00008 \text{ eV}^2$

Neutrino Oscillations



Weak and mass eigenstates need not correspond:

1. How they interact
2. How they propagate

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha,i} \, |\nu_i\rangle$$

Neutrino flavor changing determined by mixing angles θ and mass splittings Δm^2

$|\Delta m^2_{atm}| = \sim 0.0025\ eV^2$
$\Delta m^2_{sol} = \sim 0.00008\ eV^2$

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

Atmospheric/Accelerators: $\theta_{23} \sim 45°$

θ_{13} recently well-established!

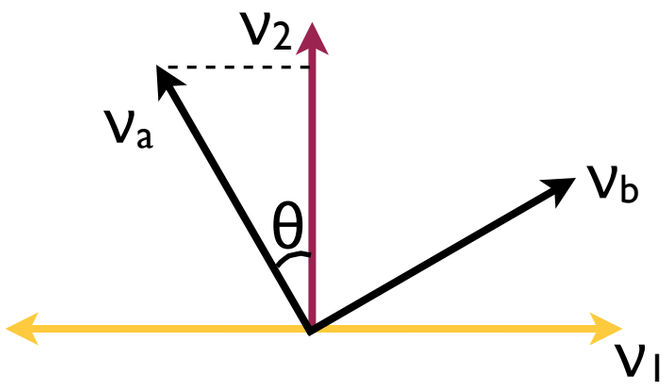
Extra CP-violating phase

Solar/KamLAND: $\theta_{12} \sim 23°$

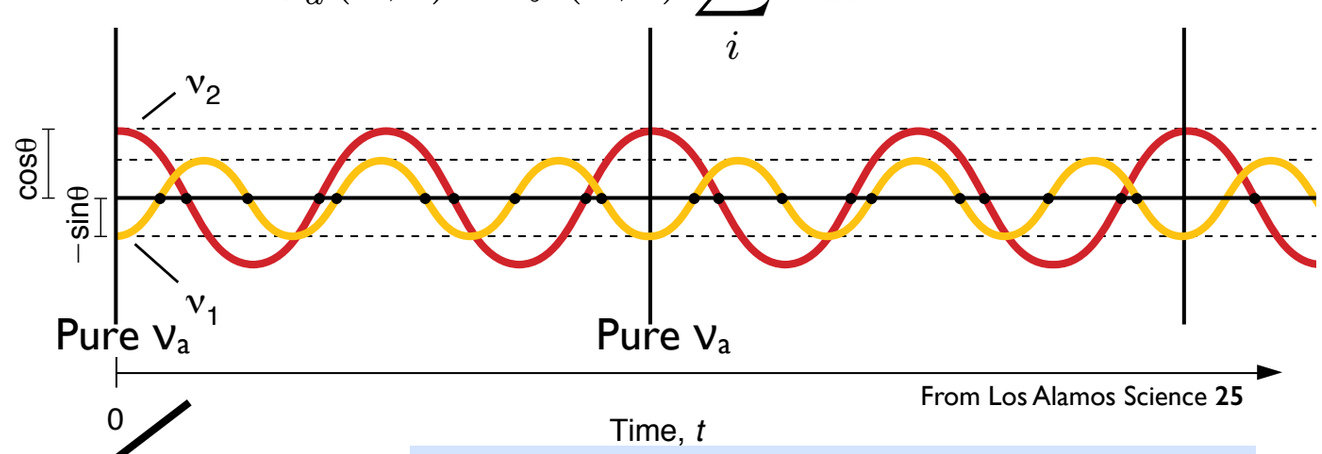
Neutrino Oscillations

- Two neutrino case:

$$\begin{pmatrix}\nu_b\\ \nu_a\end{pmatrix} = \begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}$$



$$\Psi_{\nu_a}(x,t) = f(x,t)\sum_i U_{ai}e^{-i(m_i t/2E)}$$



$$P(\nu_a \to \nu_b) = \sin^2 2\theta \sin^2\left[1.27\Delta m^2(eV^2)\frac{L(km)}{E_\nu(GeV)}\right]$$

- Important quantities:
  - θ: Oscillation amplitude
  - Δm^2: Oscillation frequency
  - L/E: Experimental parameter

- Example L/E, reactor experiments: $\bar{\nu}_e$ disappearance
  - Daya Bay: ~500 m/MeV (measure Δm^2_{31} mixing)
  - KamLAND: ~50,000 m/MeV (measure Δm^2_{21} mixing)
- Accelerators at 500 m/MeV: $\nu_\mu \to \nu_e$
- Can we use neutrino oscillations to solve <u>today's</u> big mysteries?

Other Physics with DAR

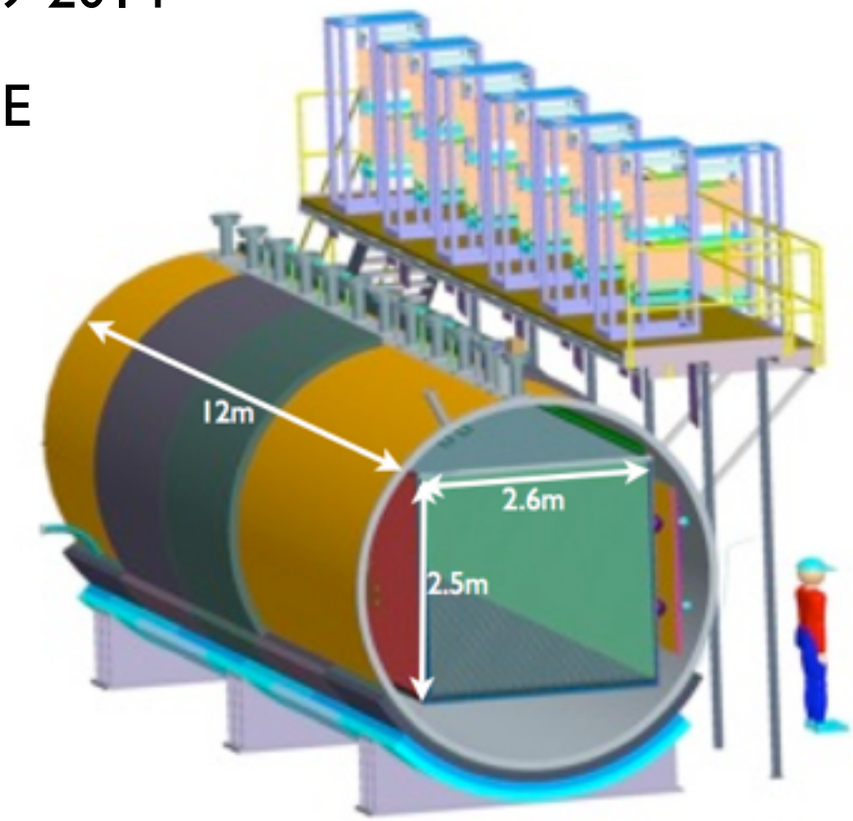
- BLAH

Supernova Signal in a LArTPC

- Existing demonstrations in existing detectors
  - Can we see peaks from various features?
  - n-Argon capture gammas?
  - Radon?
  - None of this is exactly perfect….

MicroBooNE: Genesis

- This goes quite a WAYS back! First uBooNE DocDB in 2008!
- Some perspective:
  - First miniBooNE result: 2007; 'low-energy excess' first osc-interpreted by mB in 2009!
  - 2009: ArgoNeuT takes first beam data…
  - Argon purity methods (MTS, LAPD, filters) publicized 2009-2014
  - Physics, R&D reality being established WHILE MicroBooNE is being designed and prepared for (sometimes BY uB…)
- LArTF ground-breaking: 2012

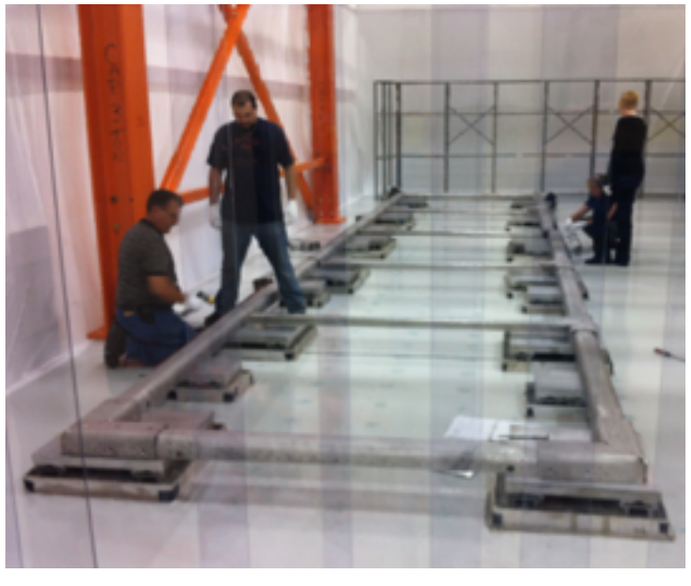


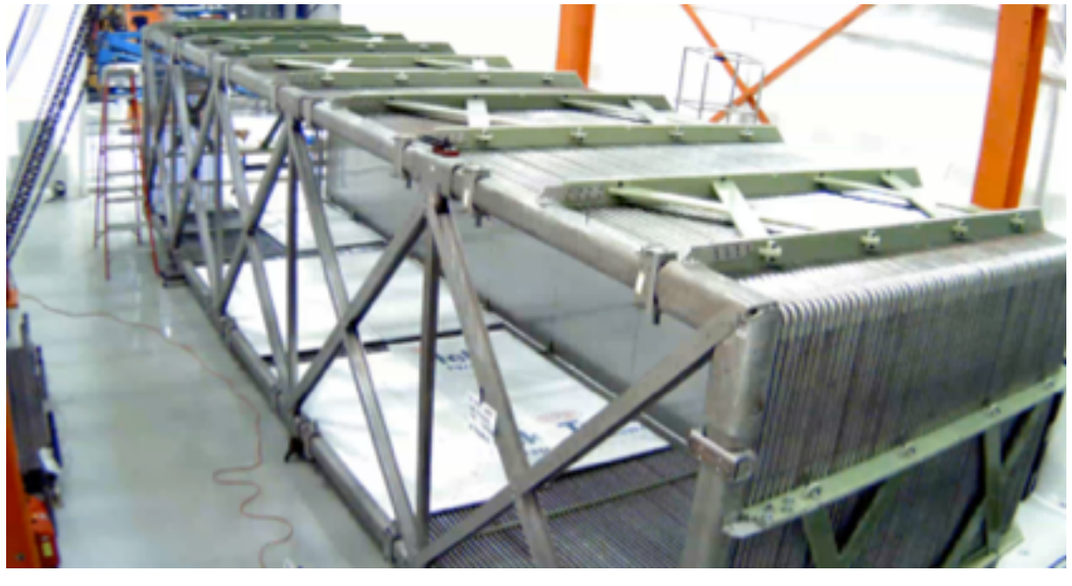
M. Soderberg, 2008 Seminar: looks kinda close to the real thing circa 2016…!

MicroBooNE: 2012-2014

- 2012-2014: Constructing the TPC
- MicroBooNE was establishing LArTPC parameters all throughout this process
  - How do we installed/tensioned 8000+ wires?
  - How do we install/test cold electronics?
  - How do we ensure safe operation of a large TPC in the presence of HV?

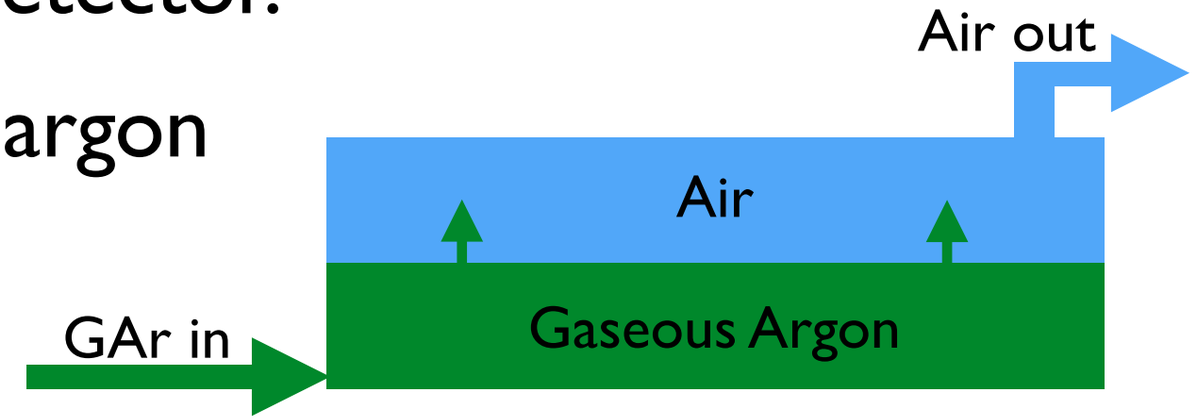
1 week → ~10 weeks → ~1+ year!



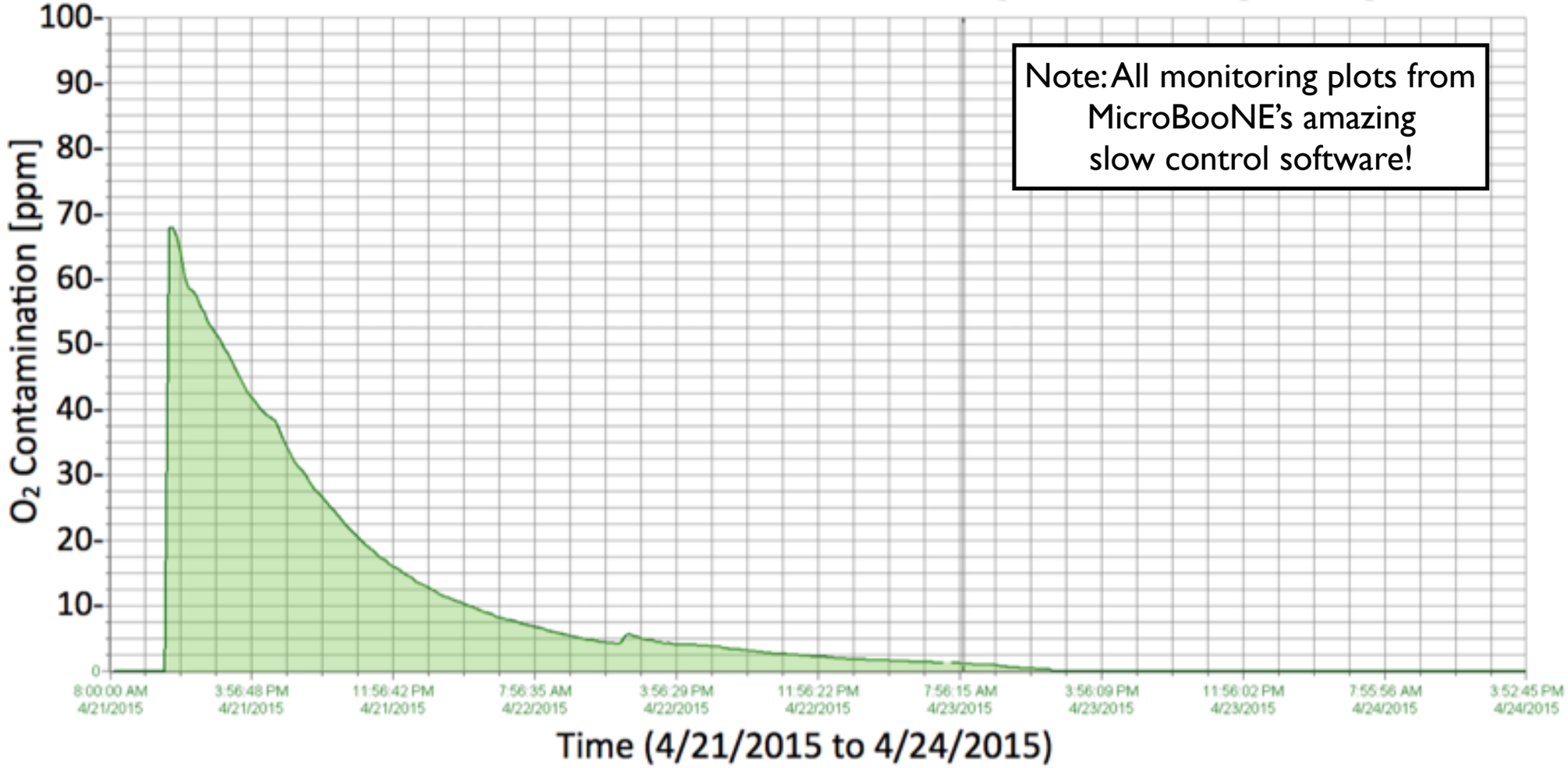


MicroBooNE: 2015 Filling

- After installing/testing all electronics and laying all cryo pipe, it's time to prepare for filling our detector.
- Step 1: Purge tank with gaseous argon

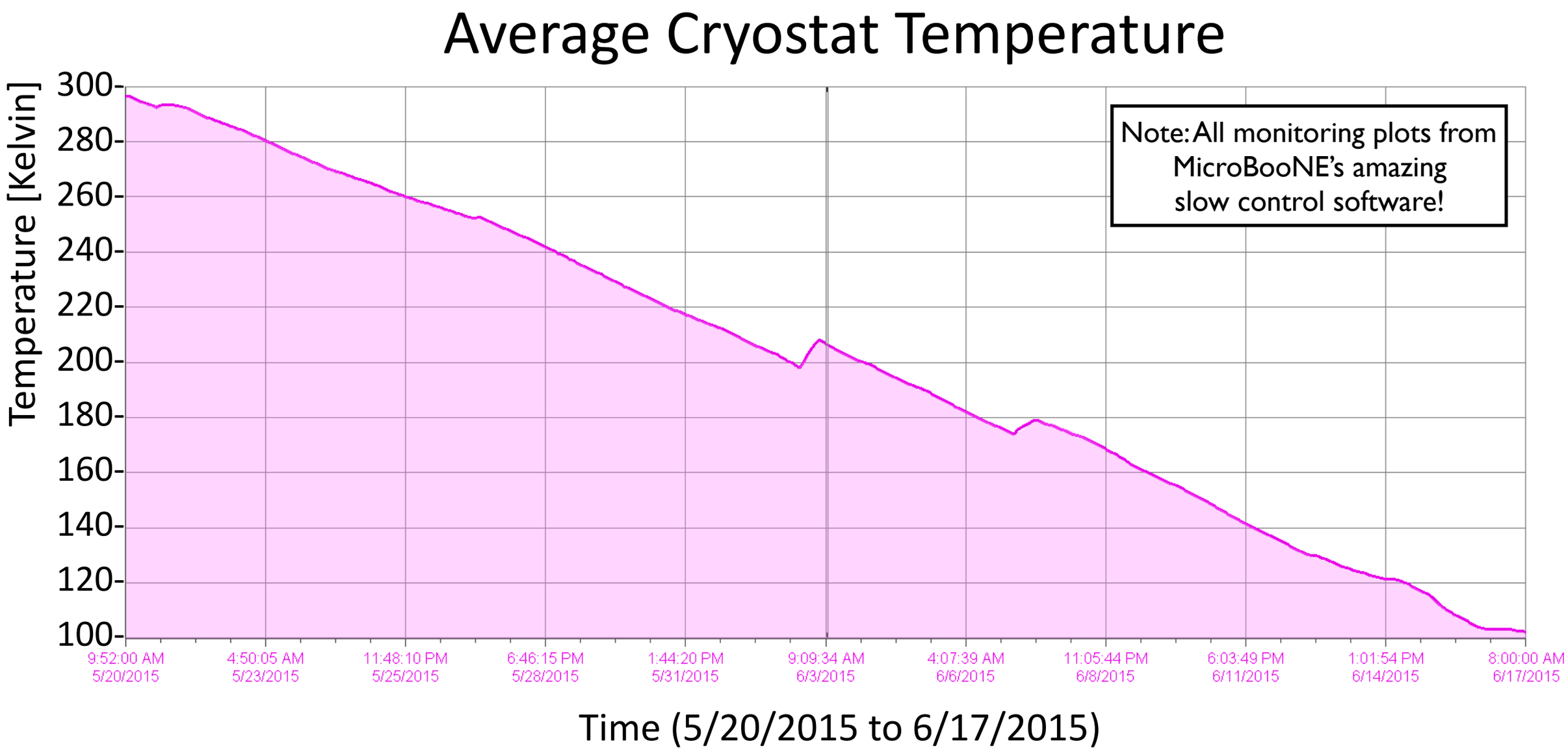


O_2 Contamination of Gaseous Argon During Purge



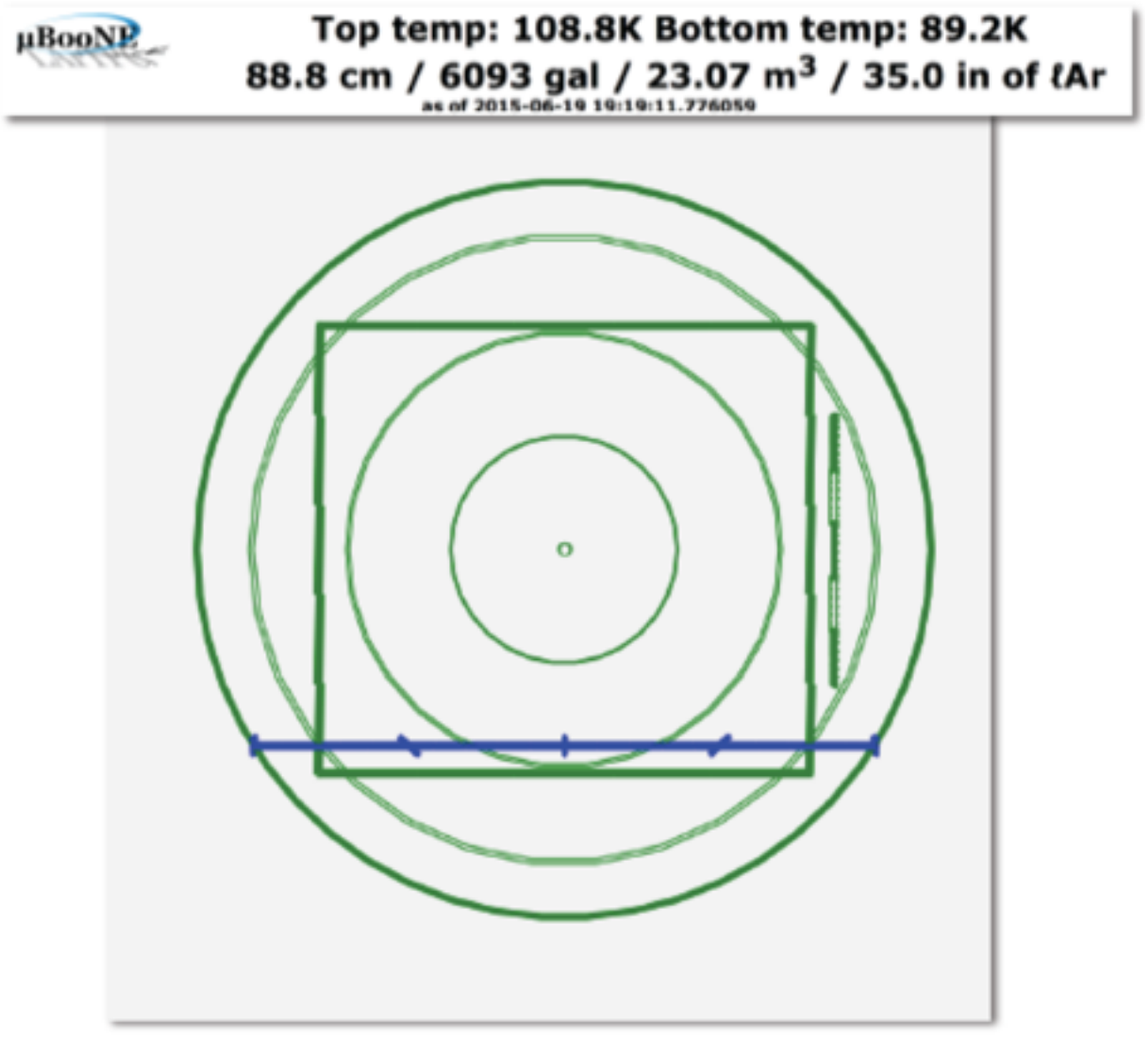
MicroBooNE: 2015 Filling

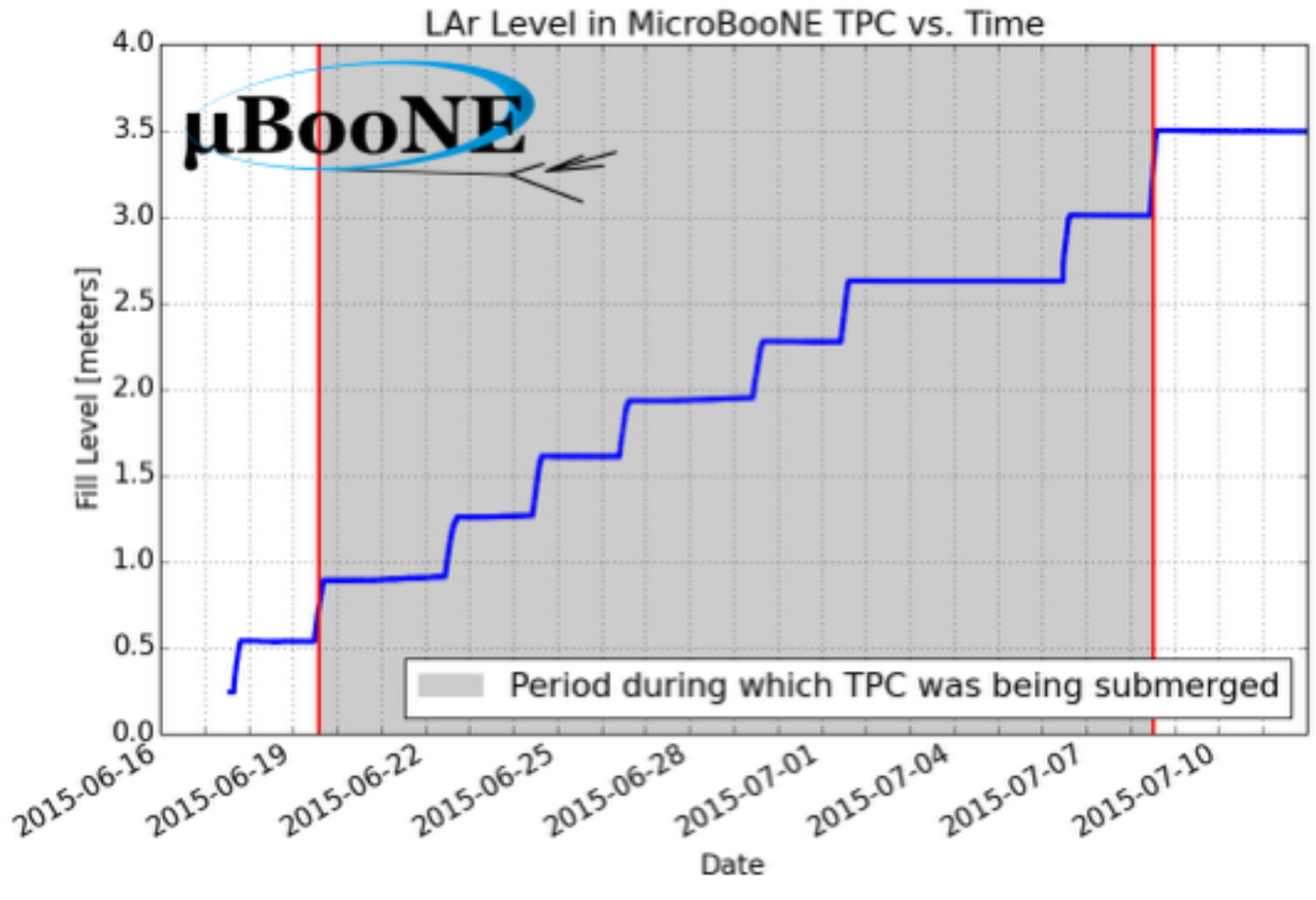
- Step 1: Purge tank with gaseous argon
- Step 2: Cool down the relatively pure gaseous argon



MicroBooNE: 2015 Filling

- Step 1: Purge tank with gaseous argon
- Step 2: Cool down the relatively pure gaseous argon
- Step 3: Fill with Liquid Argon
  - Lesson: make sure your argon meets your delivery specs!

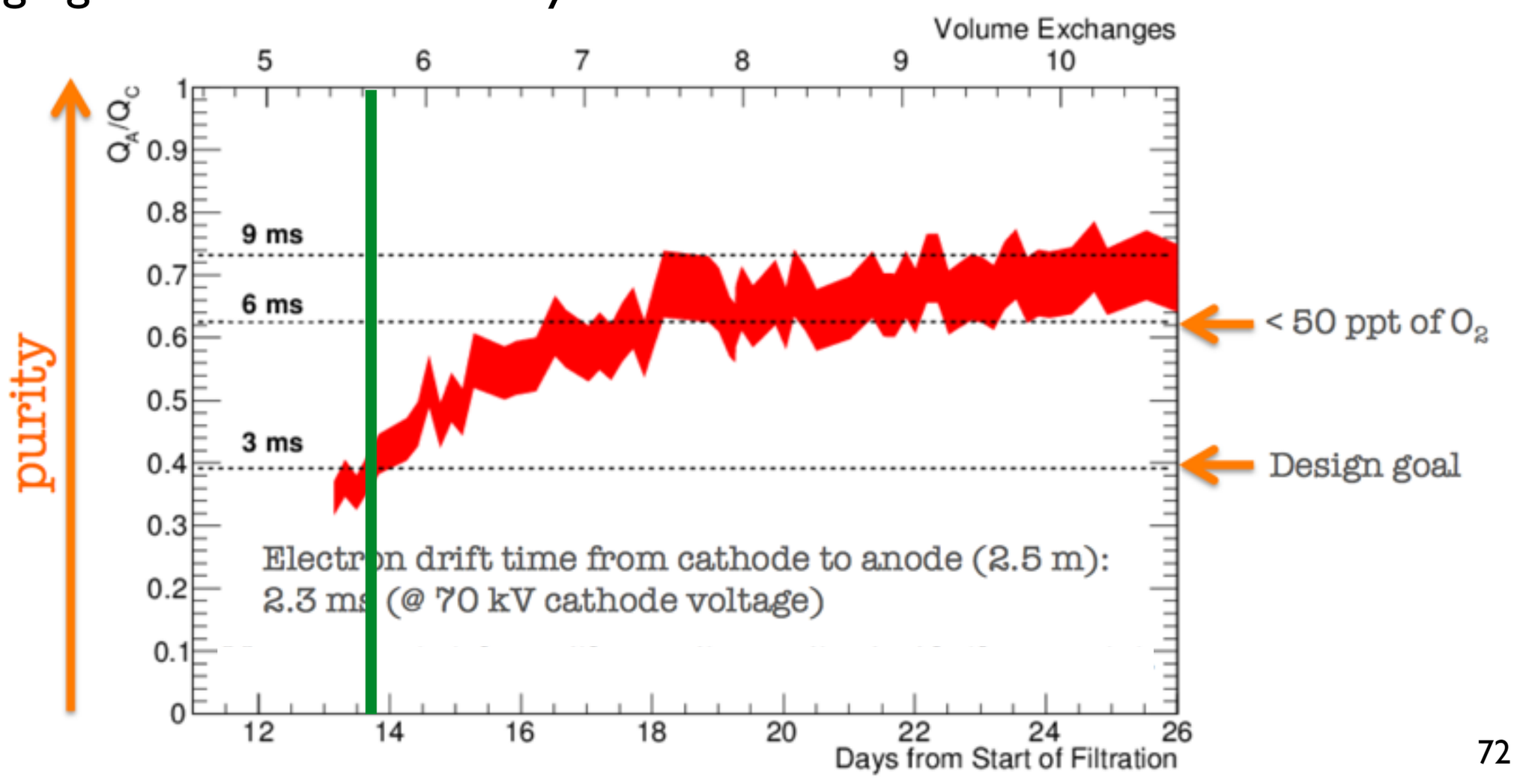




http://argo-microboone.fnal.gov/FillLevel/

MicroBooNE: 2015 Filling

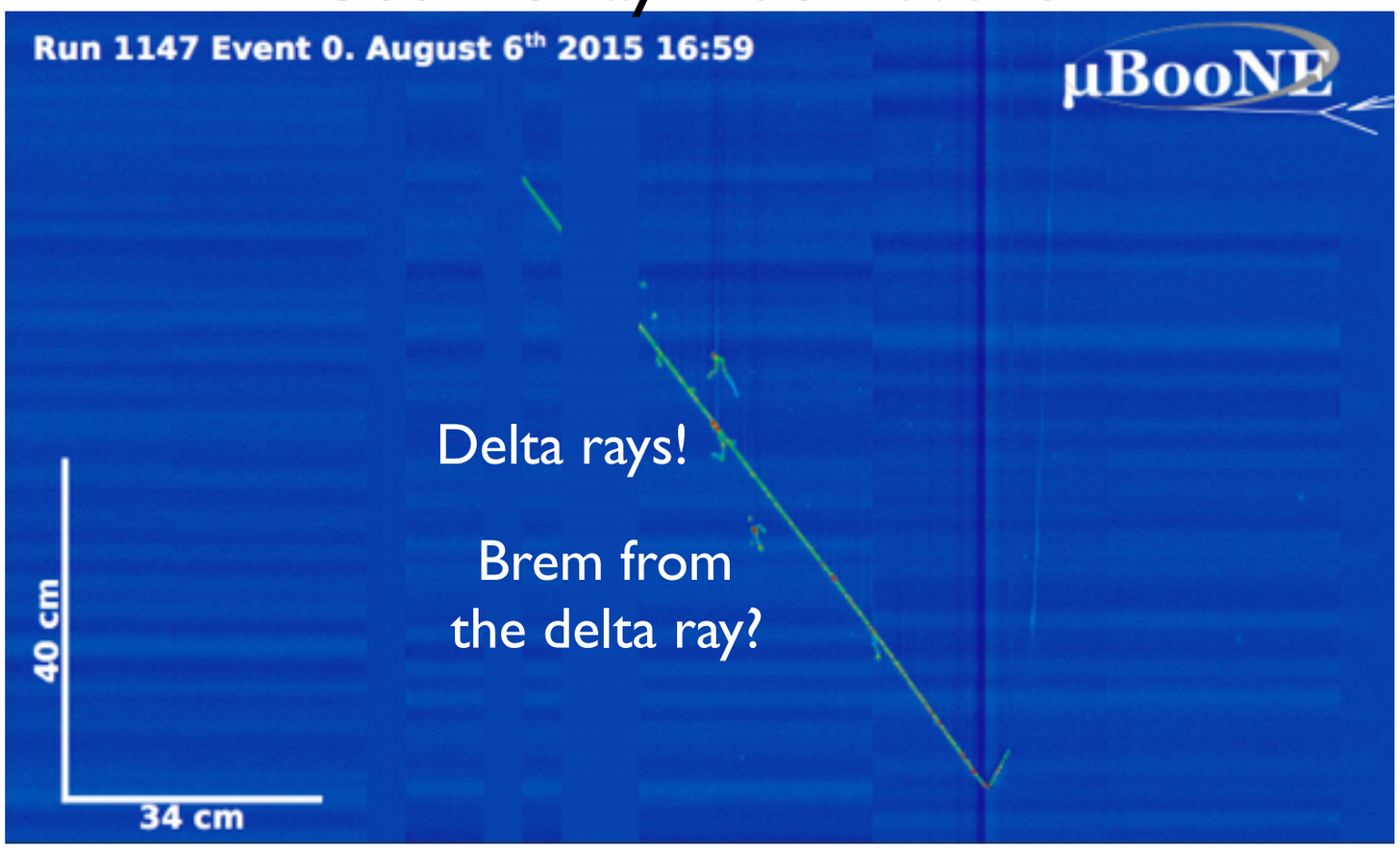
- Step 1: Purge tank with gaseous argon
- Step 2: Cool down the relatively pure gaseous argon
- Step 3: Fill with Liquid Argon
- Step 4: Filter while doing other commissioning, analysis
  - Met design goal within 6 volume cycles!



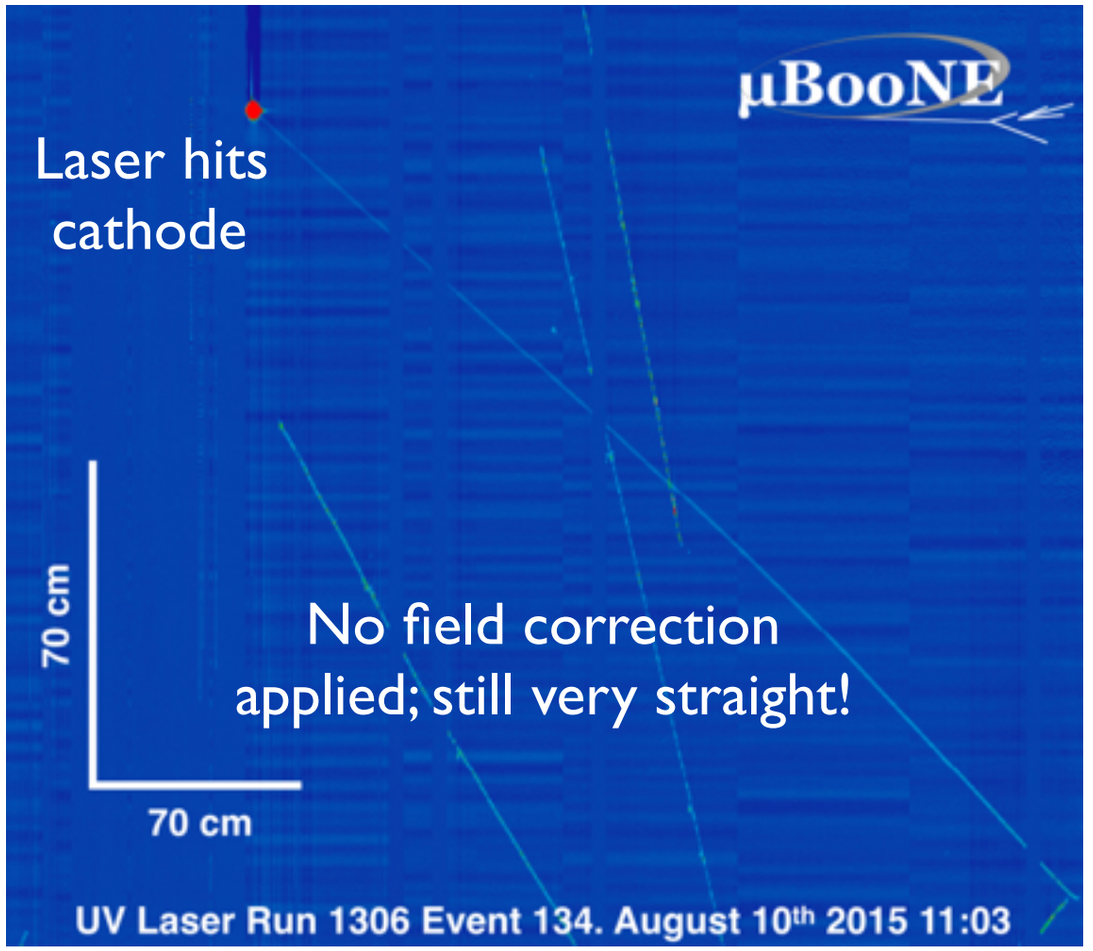
MicroBooNE: 2015 DATA!

- After filling and HV ramp, start to look for tracks, and find them (from cosmics) in short order!
  - Analyzers are hard at work pulling reconstruction, detector physics results out of this first (and ongoing) set of cosmic MicroBooNE triggers
  - Drift loss, re-combination, diffusion, etc. etc!

Cosmic ray muon event



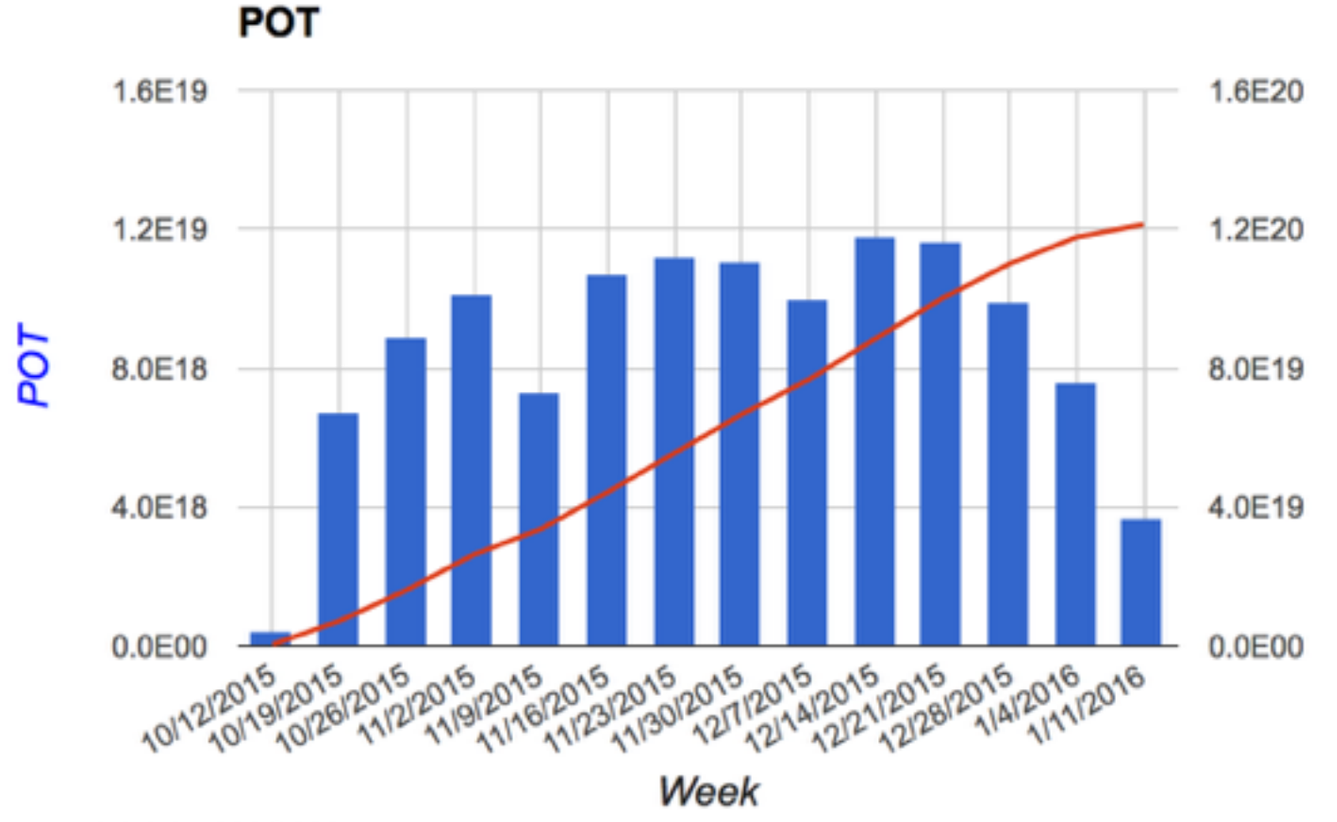
UV laser event

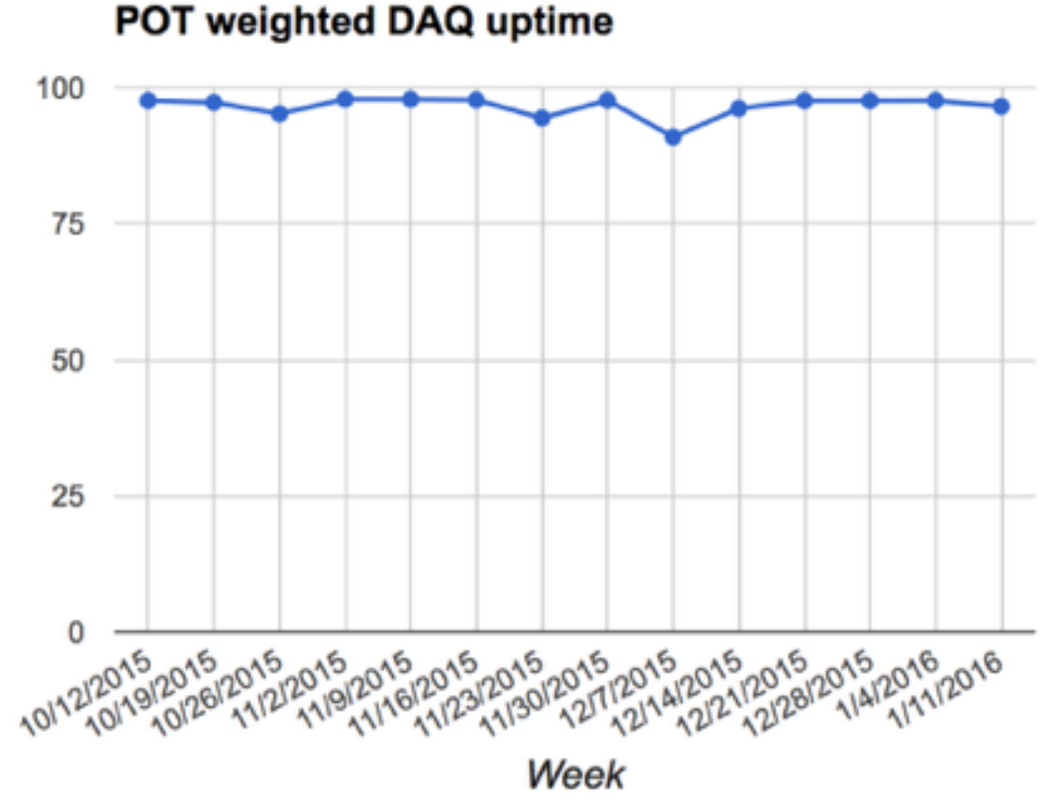


2008: WOW. — 2012 — 2014 — 2015: DATA!

MicroBooNE: 2015 BEAM!

- We started getting BNB beam in 15 October 2015
- We have had excellent DAQ uptime for beam-on periods
- We are getting spills on tape from NuMI, as well.





2008: WOW. 2012 2014 2015: BEAM!

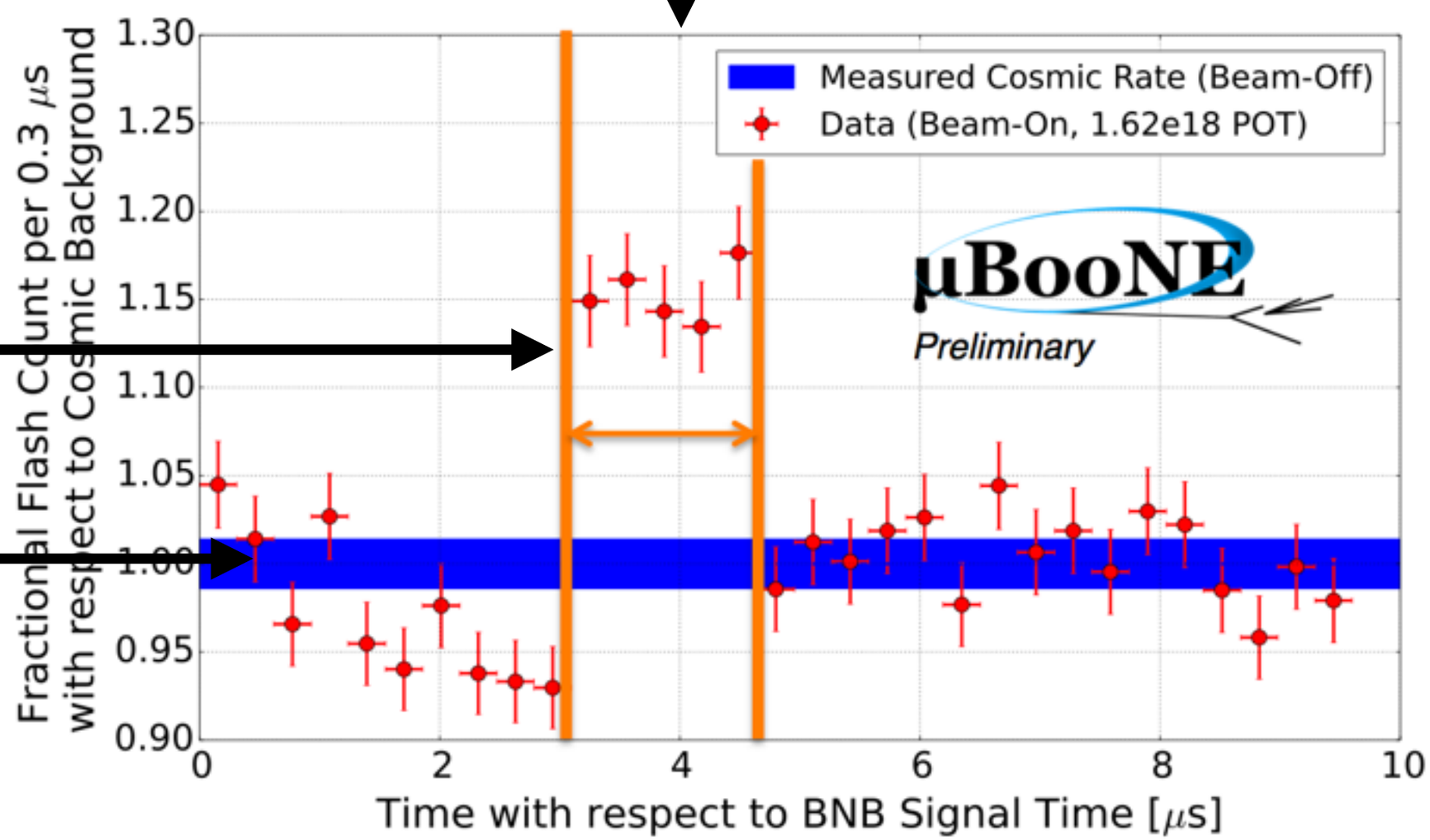
MicroBooNE: 2015 NEUTRINOS!

- First we saw them with PMTs…

1.6 us beam spill window

cosmics plus… neutrinos!

cosmics



2008: WOW. 2012 2014 2015: BEAM!

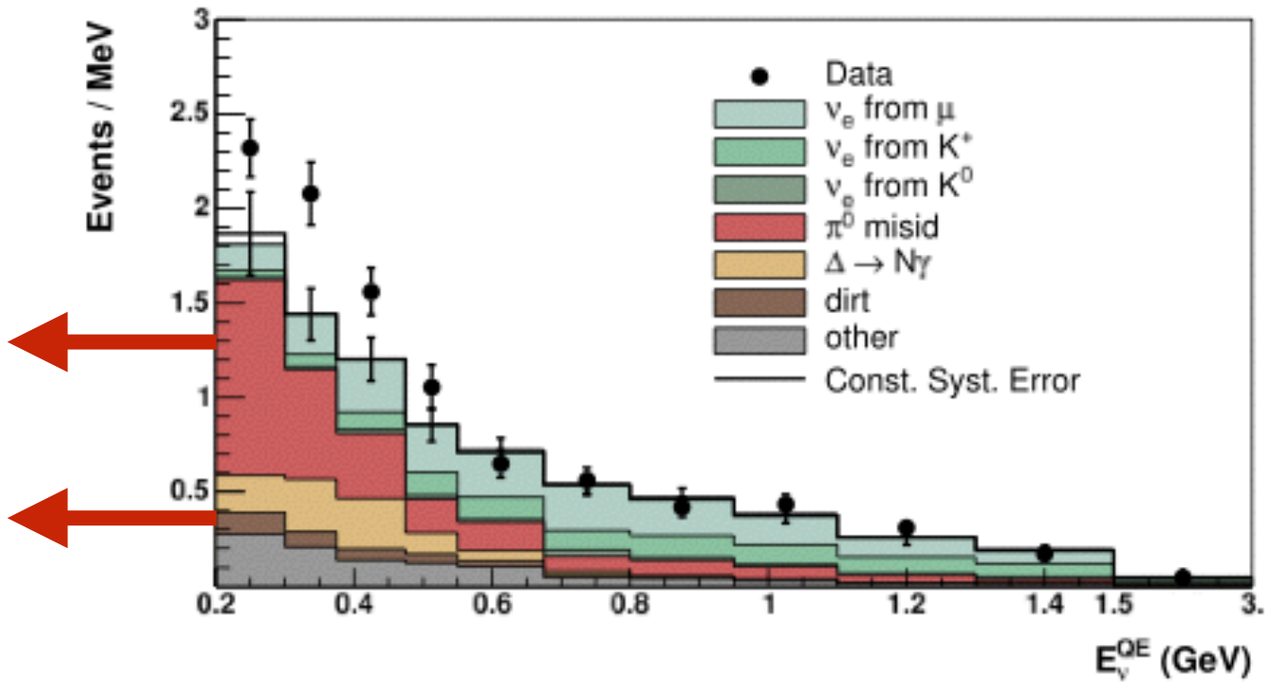
MicroBooNE: 2015 NEUTRINOS!

- …then we saw them with the TPC.
- TPC neutrino ID possible with a cuts on a few key quantities
- For example, the analysis using *automated* 3D-reconstruction:
  - Two or more reconstructed tracks with start points within 5cm of each other
  - All tracks must be fully-contained
  - Longest track must satisfy $\cos(\theta) > 0.8$
  - >5sigma CL observation of neutrinos with the TPC!
- Have a similar *automated* algorithm for 2D reconstruction

Number of events	Optical + 3D-based	Optical + 2D-based
Non-beam background (expected from off-beam measurements)	4.6 ± 2.6	385 ± 24
Total observed (during beam)	18	463

Electron-Like Excess: Differences

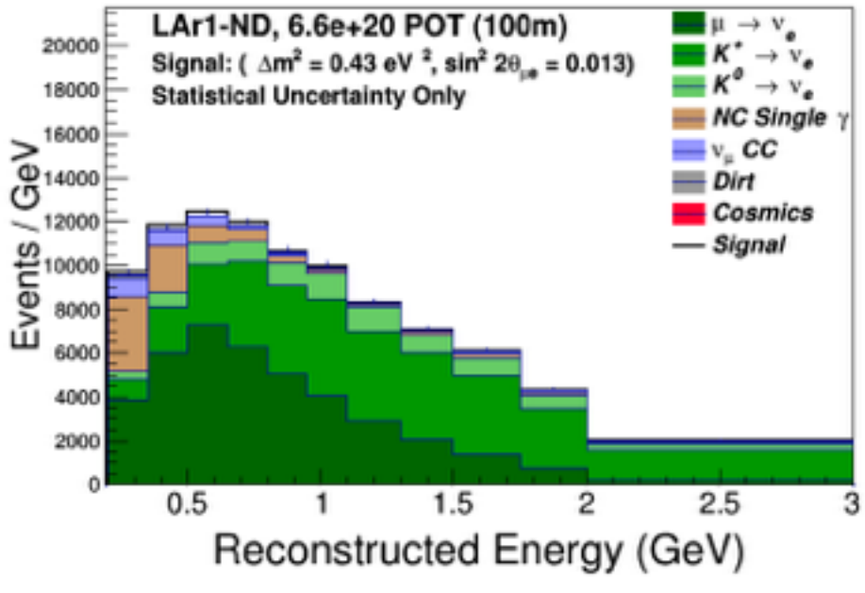
- How will the electron-like result look different than MiniBooNE?
  - Gamma-related backgrounds should be way smaller in this stack.
  - TPC-external beam backgrounds might look different: more of them, but also new rejection methods.
  - There will likely be a new (small) color in here from cosmogenic backgrounds
  - You might see a totally different x-axis metric: instead of CCQE, maybe lepton+vertex energy, or maybe something else!
  - You might also see a different range on this plot: no Cerenkov thresholds and excellent 3D position information could enable a lowered threshold.

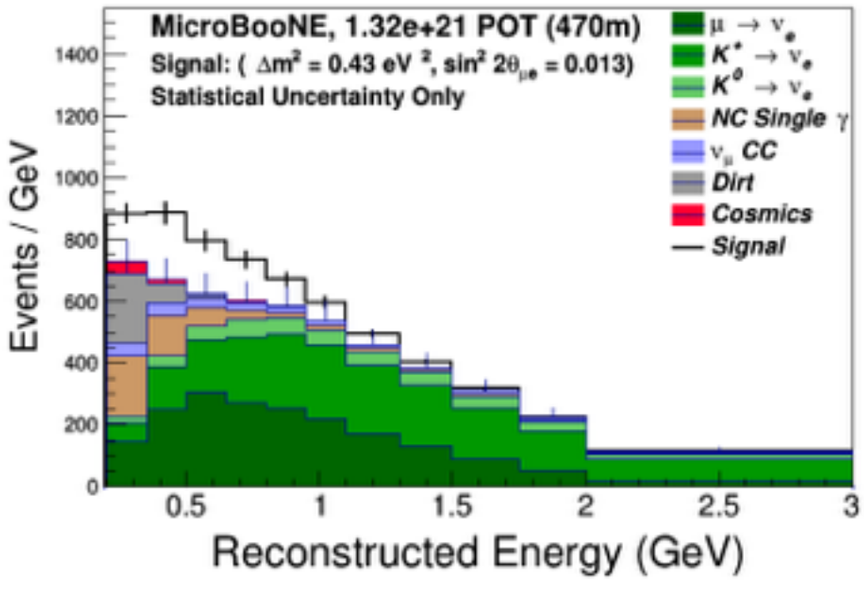


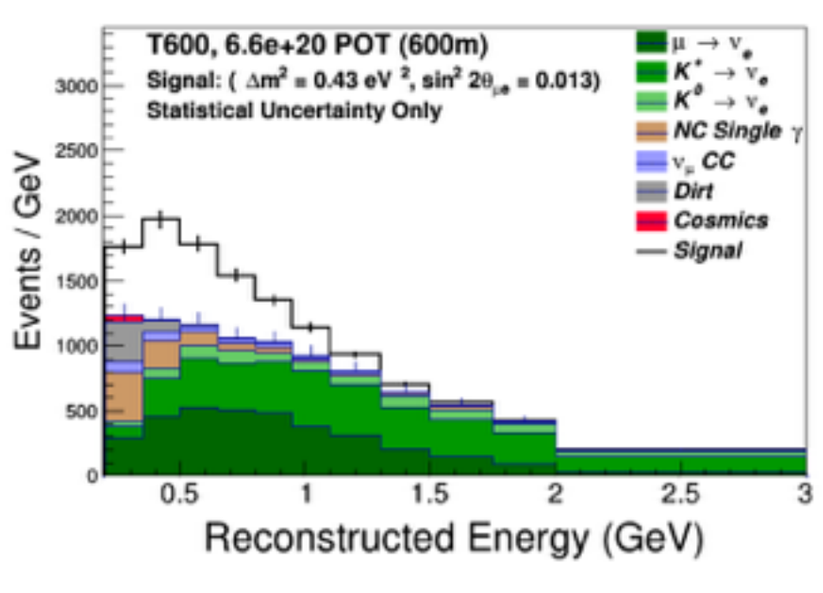
- So more than just an improvement in e/γ separation.

Electron-Like Excess: Scenarios

- If we see an electron-like excess, this would be amazing!
  - SBND would collect statistics quickly at its shorter baseline, giving very convincing confirmation of the nue appearance interpretation.
  - Full SBN would then provide the precision measurement of this oscillation.
  - Must be diligent in our proper estimation of TPC-external beam backgrounds and cosmic backgrounds.

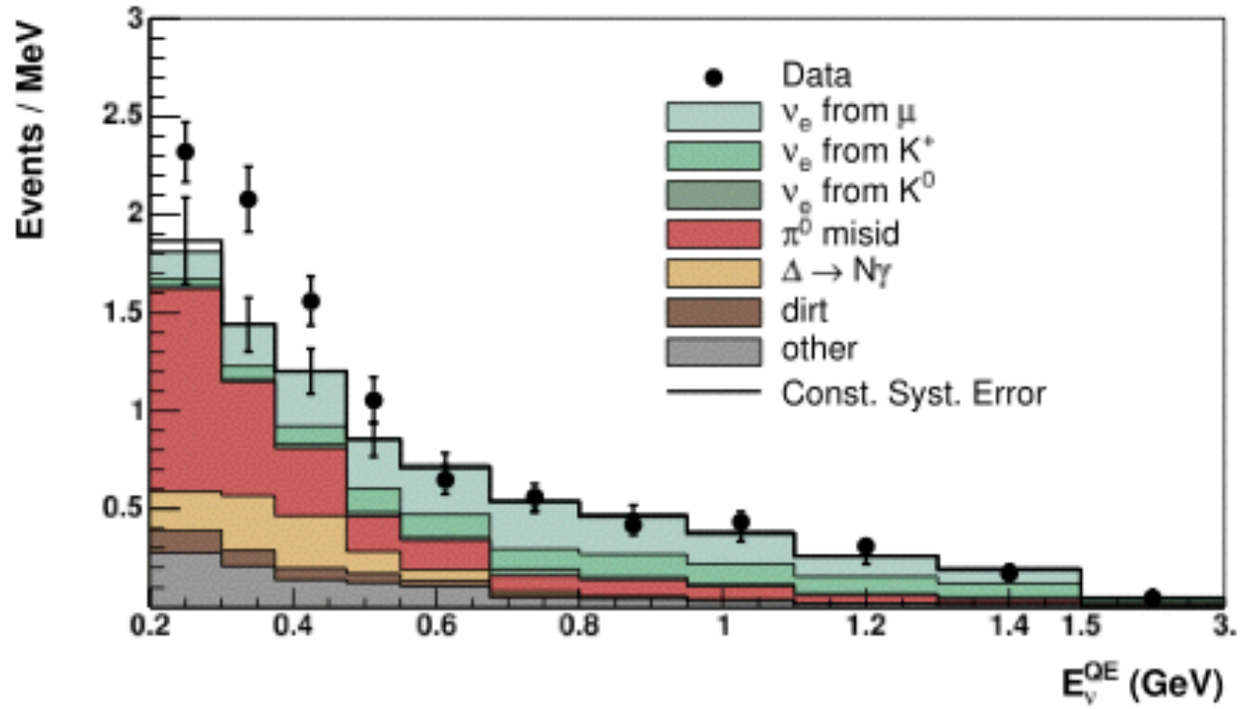






Photon-Like Excess: Scenarios

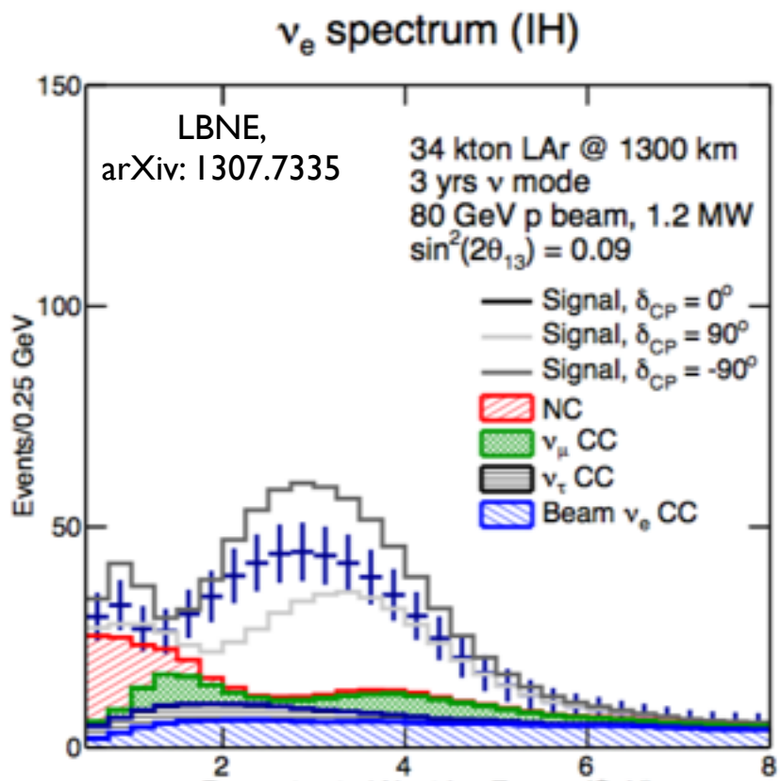
- A big question in this case: where is the excess?
  - If excess picks up at lowest energies, this could point an issue with π^0s:
    - Issues with neutrino NC π^0 mis-identification estimates?
    - Improper estimation of external single-gammas-from-π^0 ?

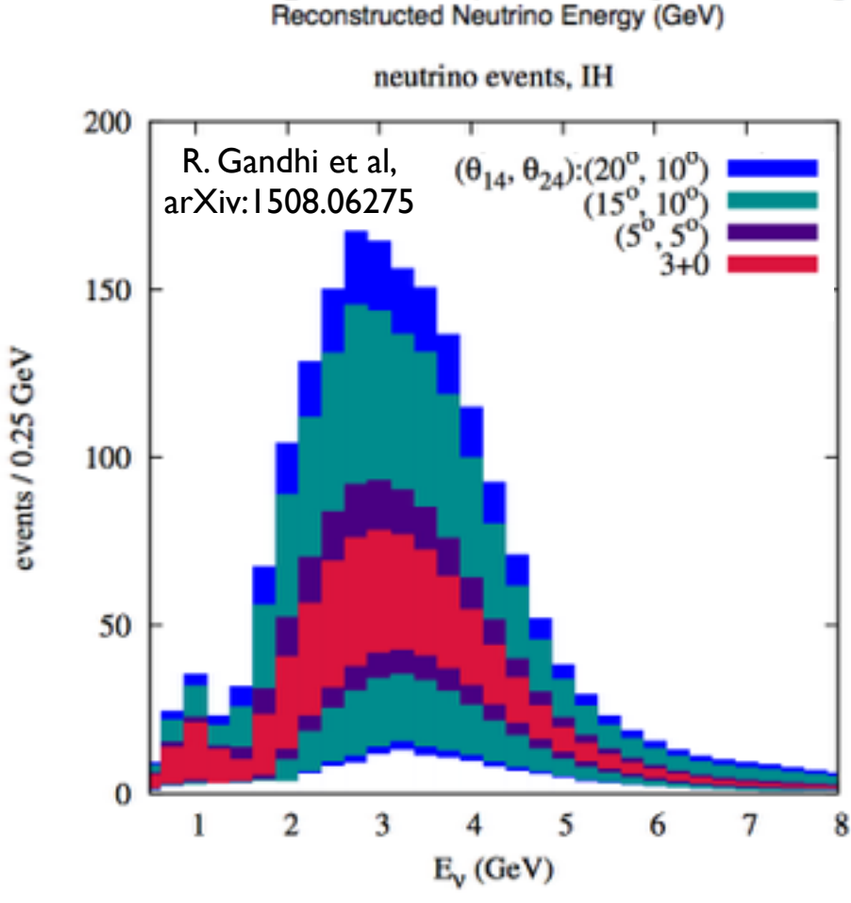


  - Excess at low-energy, but not TOO low: additional single-gamma processes…
  - Massive uptick at very low energies could come from cosmic mis-estimation.
- In all these scenarios, subsequent SBND measurement is <u>crucial</u>
  - If it's 'BITE'- or cosmic-related, SBND's signature will look totally different.
  - If it's a neutrino cross-section thing, SBND, ICARUS will provide very valuable high-statistics measurements for…

DUNE Impacts

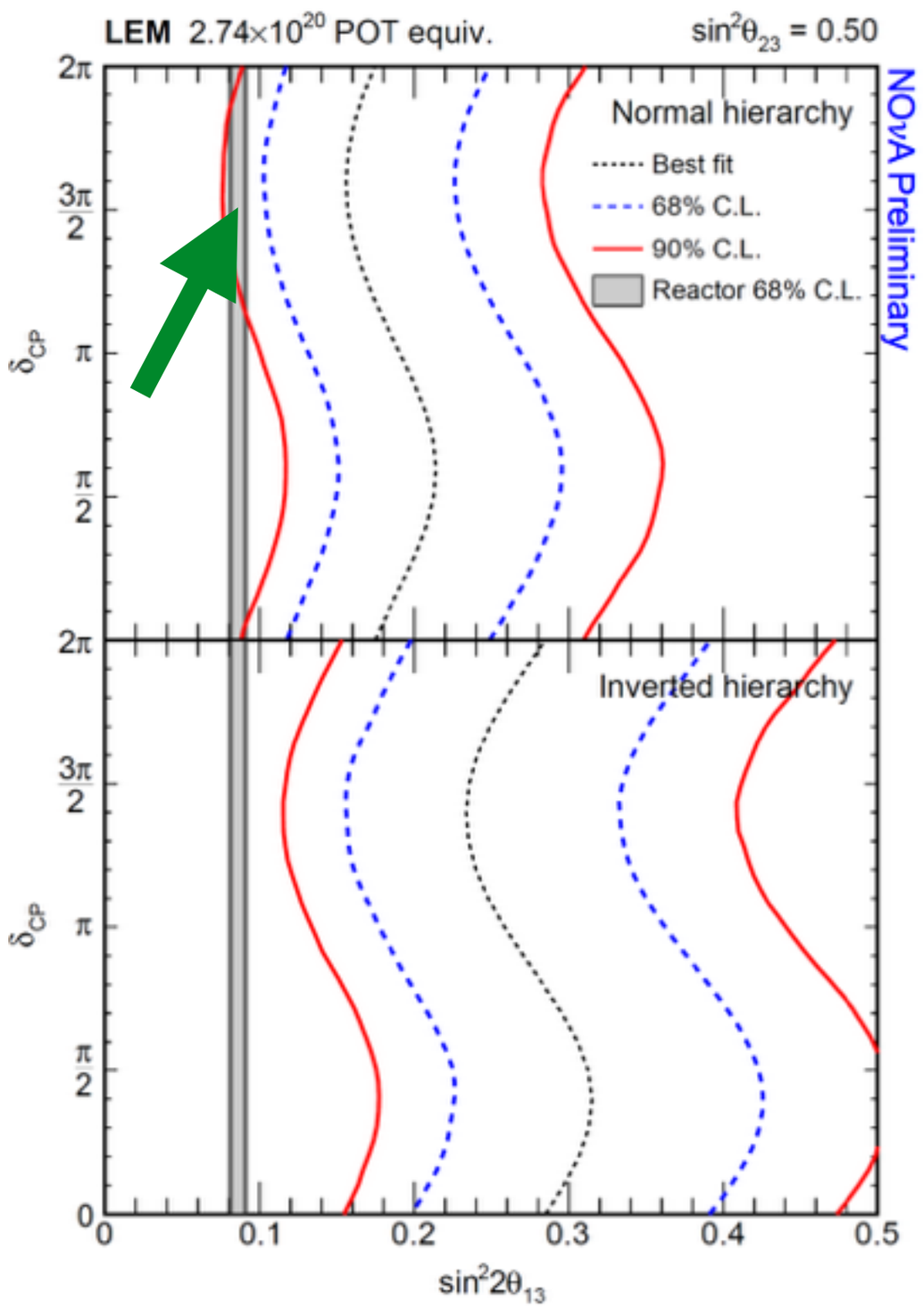
- Crucial for DUNE that MicroBooNE (and the rest of SBN) tell us what is causing the excess.
- If electrons:
  - We must correct our predictions for the existence of a new short-baseline oscillation!
- If photons:
  - We must properly re-configure our background estimates; particularly valuable for properly understanding the 2nd oscillation maximum
- If both electron and photon excess, ditto, for same reasons as above.
- If no excess in MicroBooNE:
  - Still extremely important to address sterile phase space in full to properly interpret DUNE results — i.e. DUNE would still need SBN





Early Hints: NOvA

Selection 1



Selection 2