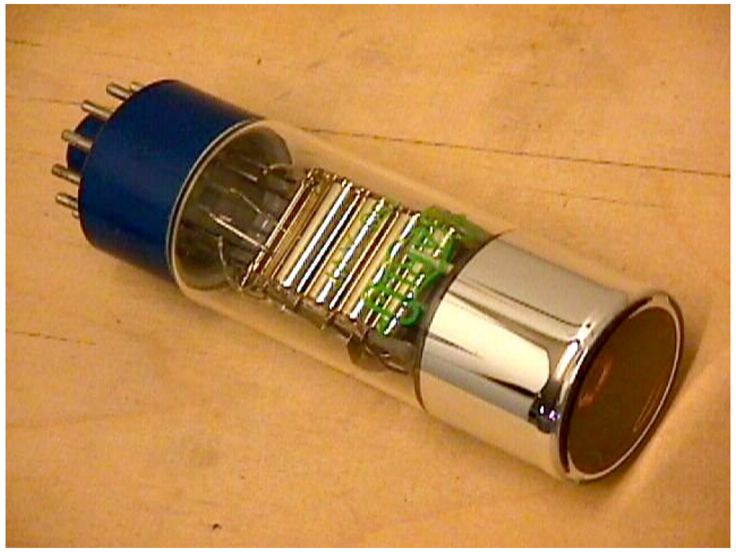
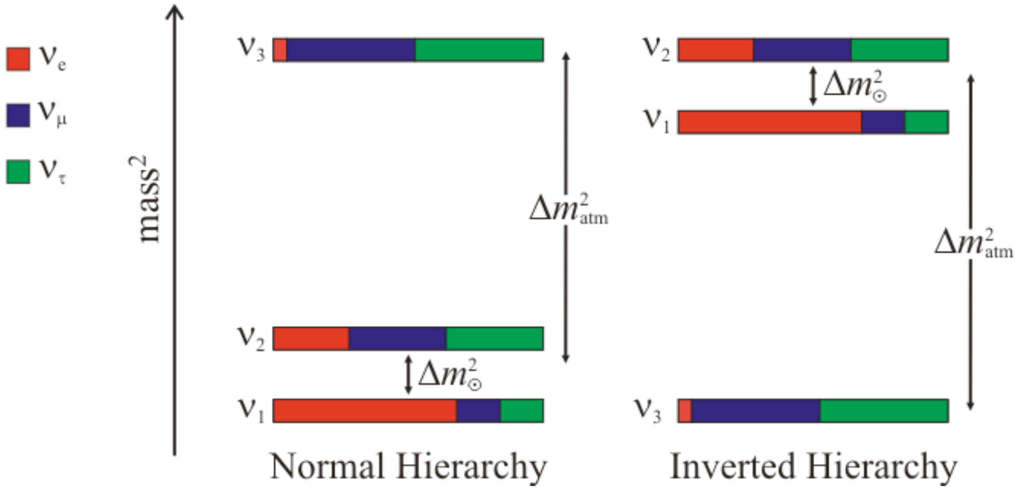
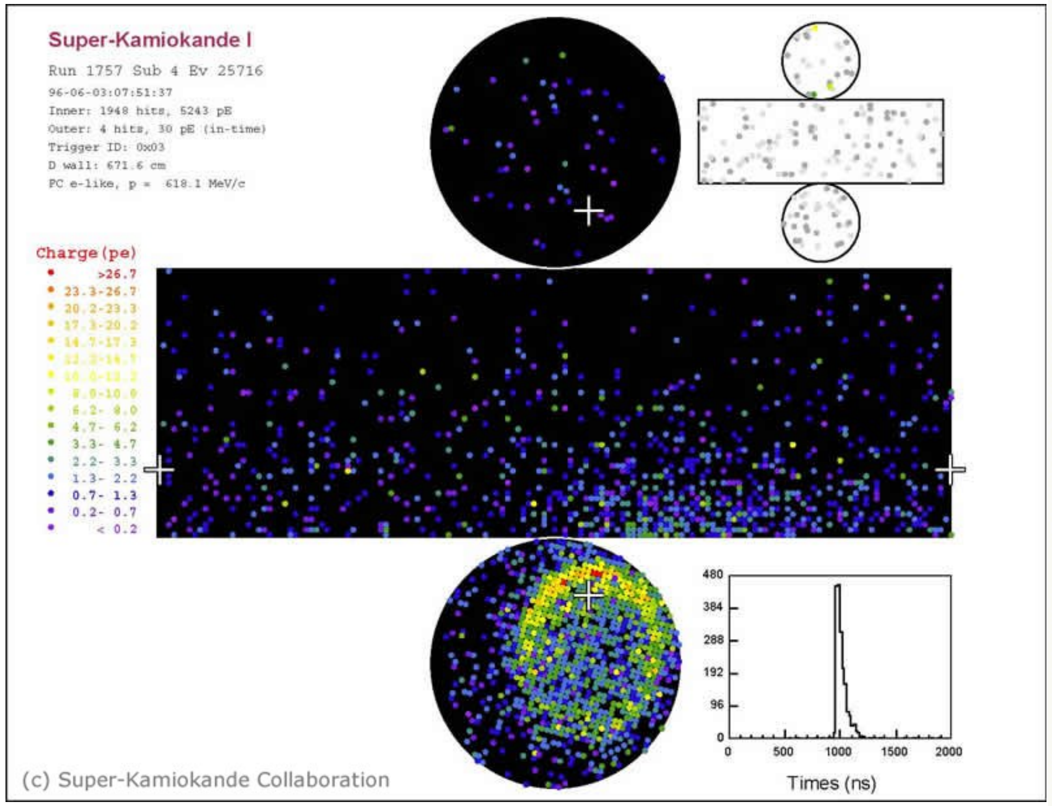
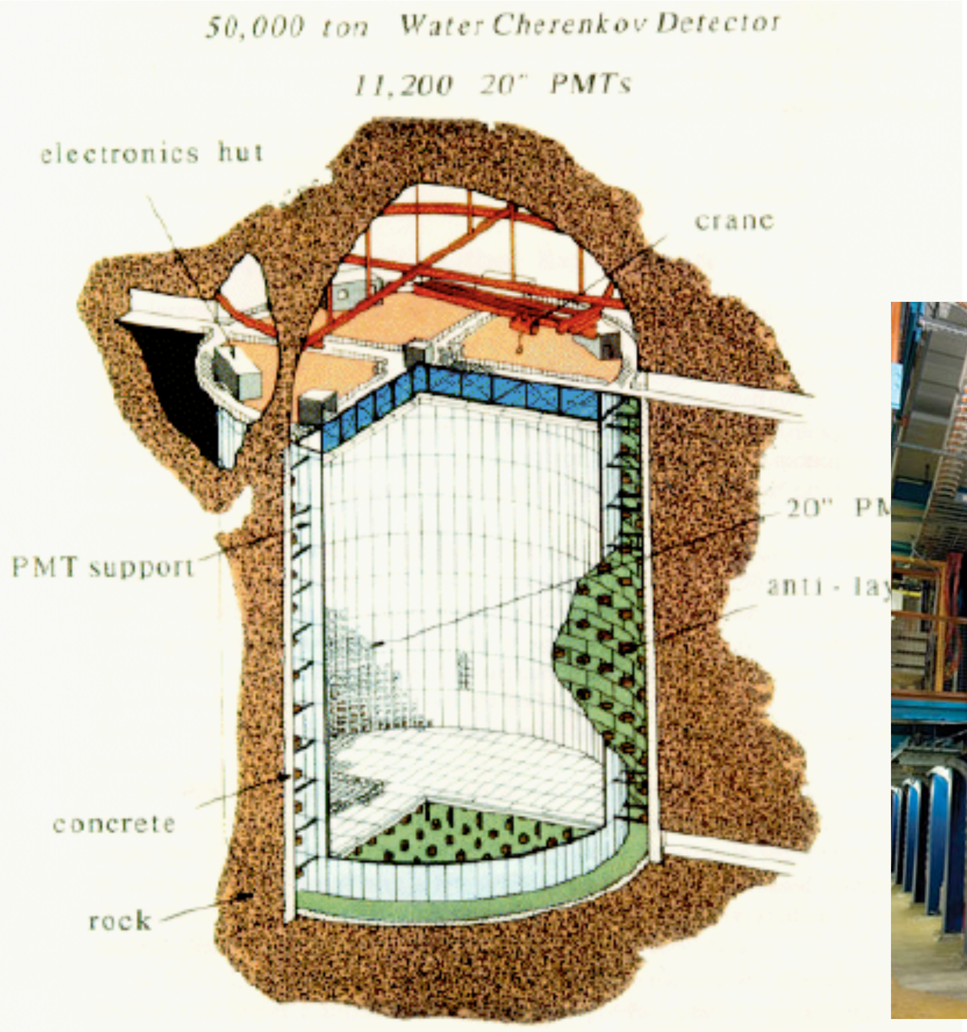
Experimental Neutrino Physics: Lecture 1



Jonathan M. Paley
BCVSPIN - MSPF - Mitchell
Manzanillo, Mexico
December 10, 2014



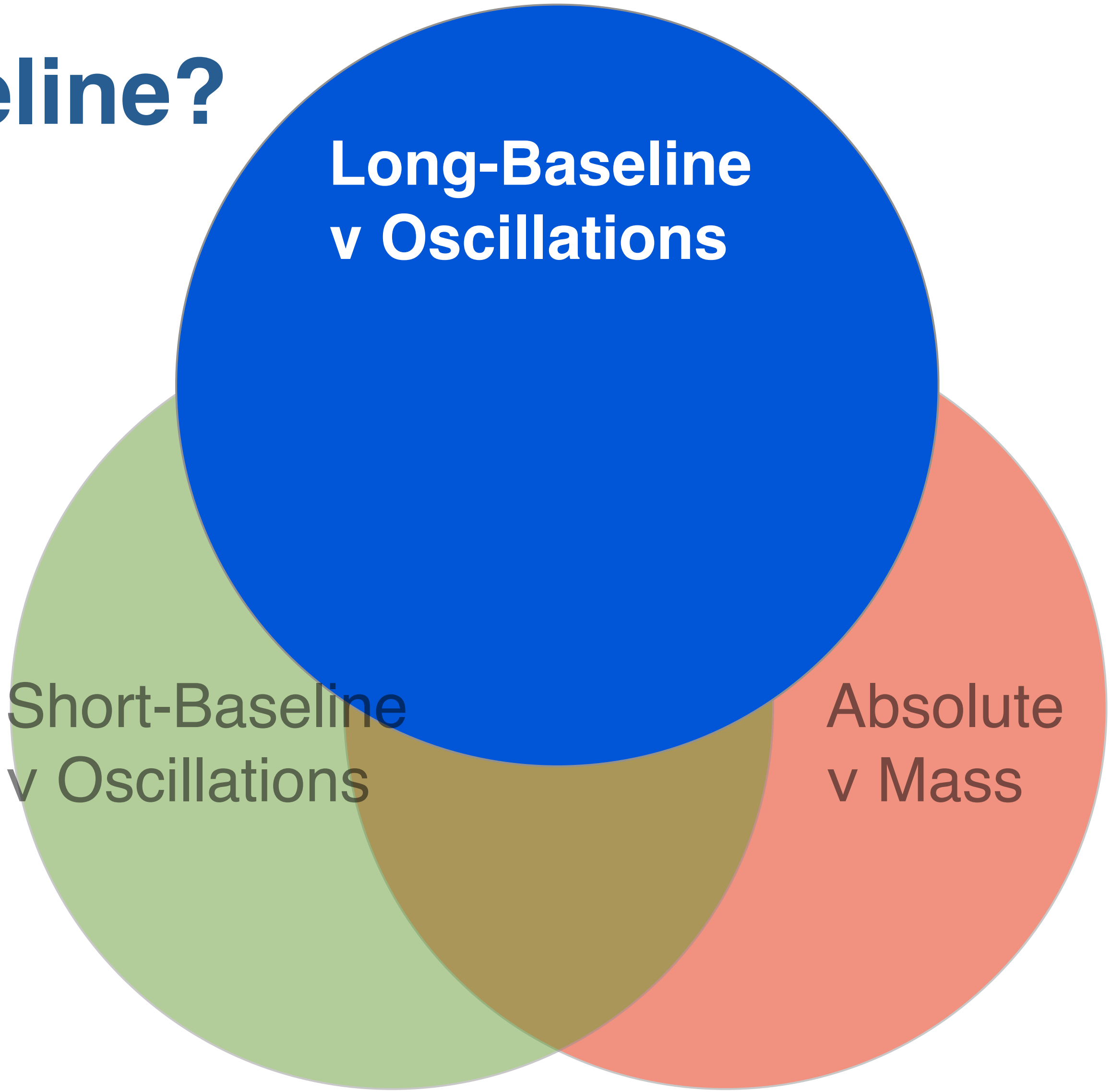




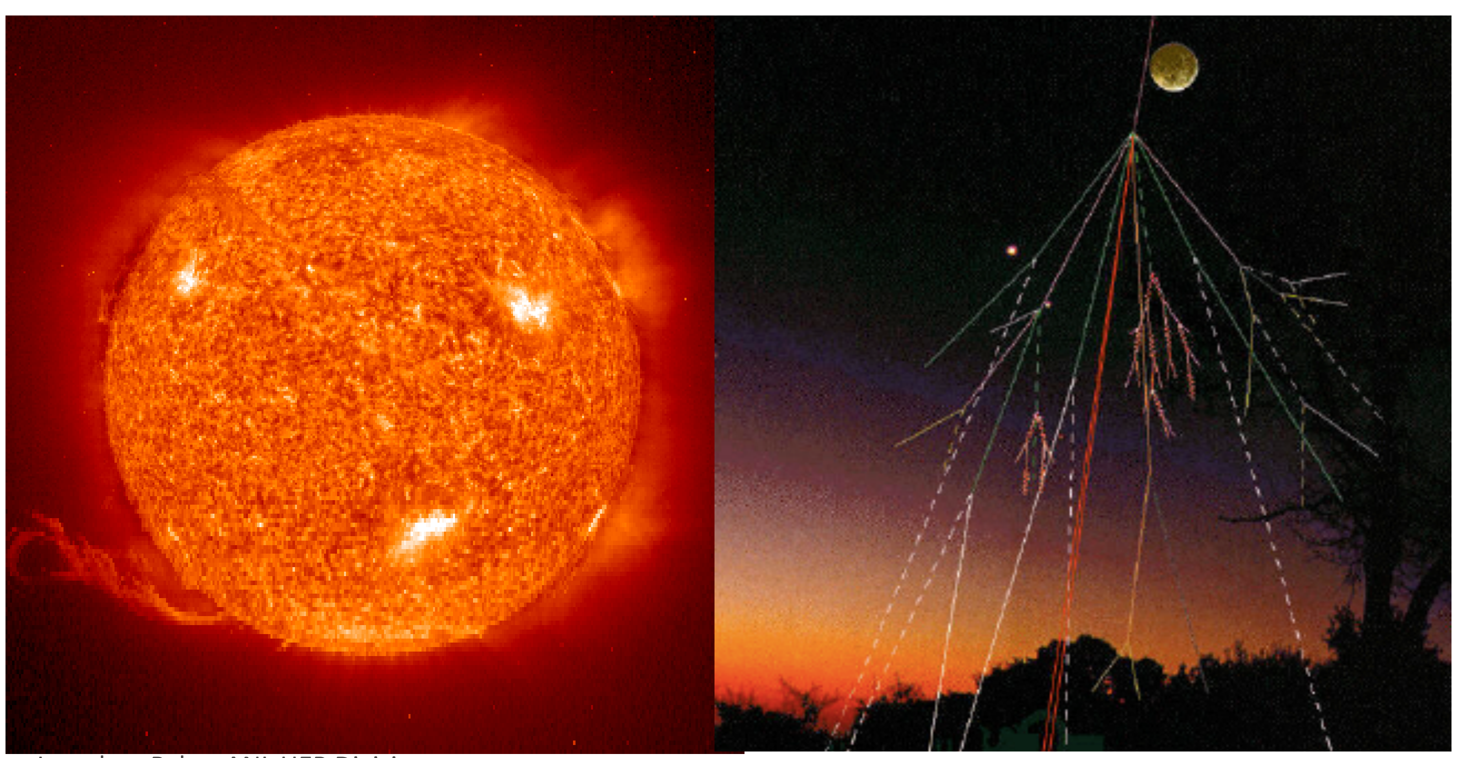
Outline

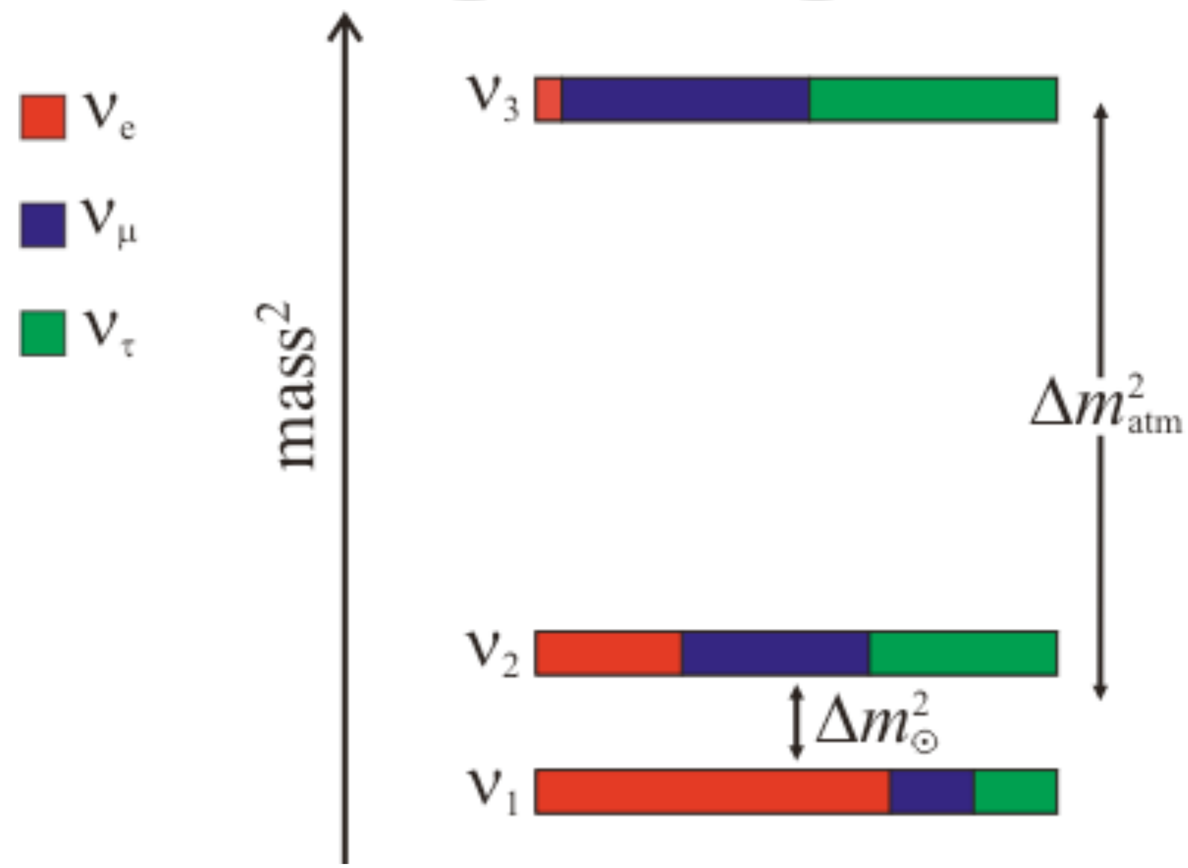
- Motivations
- Neutrino detectors for oscillation experiments
- Neutrino sources
- Long-baseline experiments, near-past, current and future
- Note: I will not be able to cover all experiments involving neutrinos, e.g. I am excluding experiments using cosmological sources. This is very exciting and important physics!

What Do I Mean By Long-Baseline?



- Long-baseline neutrino oscillations:
  - "solar" mass splitting
    - $\Delta m^2_{21} \equiv \Delta m^2_{\odot} \sim 8 \times 10^{-5}\ eV^2$
    - L/E ~ 15000 km/GeV
  - "atmospheric" mass splitting
    - $\Delta m^2_{32} \approx \Delta m^2_{31} \equiv \Delta m^2_{atm} \sim 2 \times 10^{-3}\ eV^2$
    - L/E ~ 500 km/GeV





Motivations

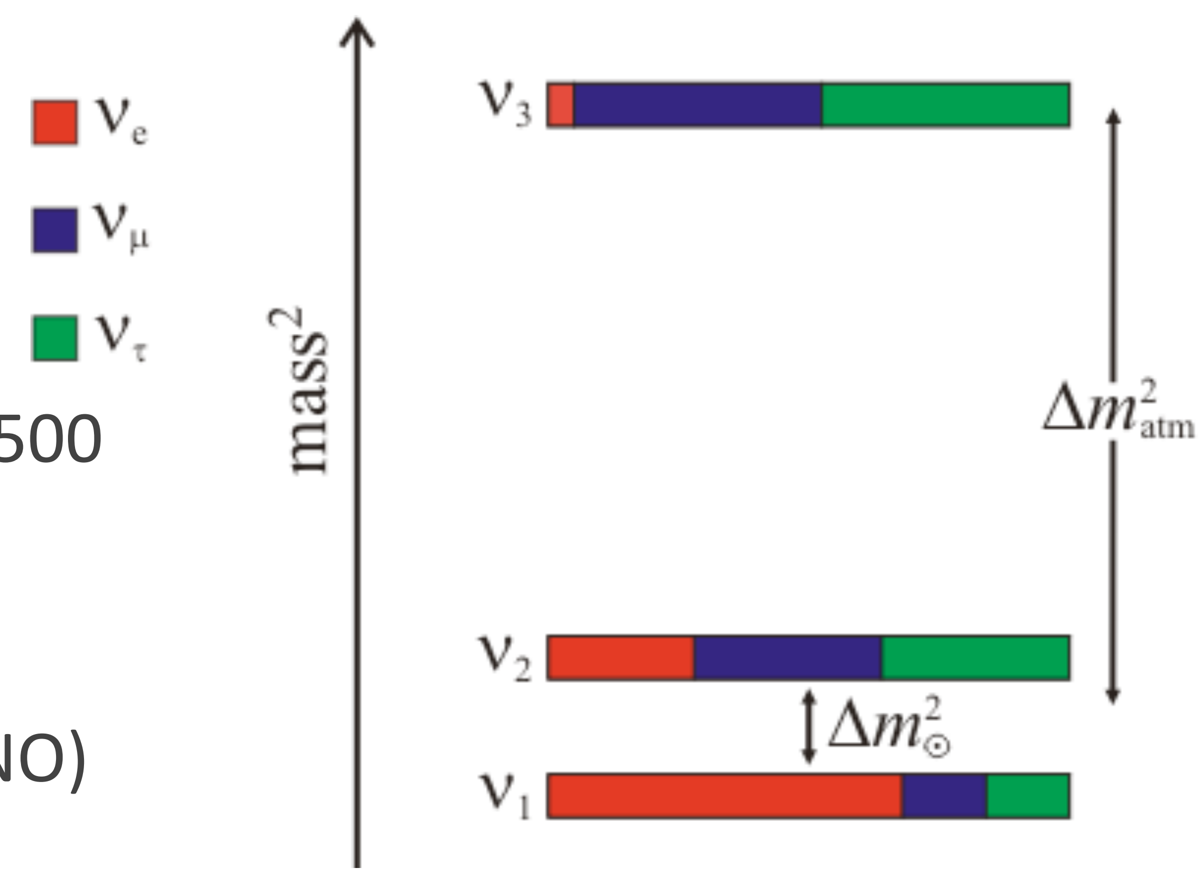
- You might have heard that neutrinos have mass.
- Depending on your point of view, this is already BSM
- Neutrinos are extremely abundant, and yet we know relatively very little about them:
  - mass ordering
  - absolute mass
  - Dirac or Majorana
  - do they violate CP?
  - cross-sections
- Need to provide guidance to theory
- Three experimental approaches allow for clear answers to some of these questions: neutrino oscillation measurements, direct mass measurements and searches for neutrinoless double-beta decay.

Neutrino Oscillations

- The mixing matrix may be factorized into components that are useful to experimentalists:

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{+i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- Furthermore, experimentally we have determined:
  - $\sin^2 2\theta_{32} \sim 1$
  - $\Delta m^2_{32} \approx \Delta m^2_{31} \equiv \Delta m^2_{atm} \sim 2 \times 10^{-3}\ eV^2$ (SuperK, MINOS) with characteristic L/E ~ 500 km/GeV
  - $\sin^2\theta_{12} \sim 0.3$
  - $\Delta m^2_{21} \equiv \Delta m^2_{\odot} \sim 8 \times 10^{-5}\ eV^2$ (KamLAND, SNO) with characteristic L/E ~ 15000 km/GeV
  - $\sin^2 2\theta_{13} \sim 0.1$



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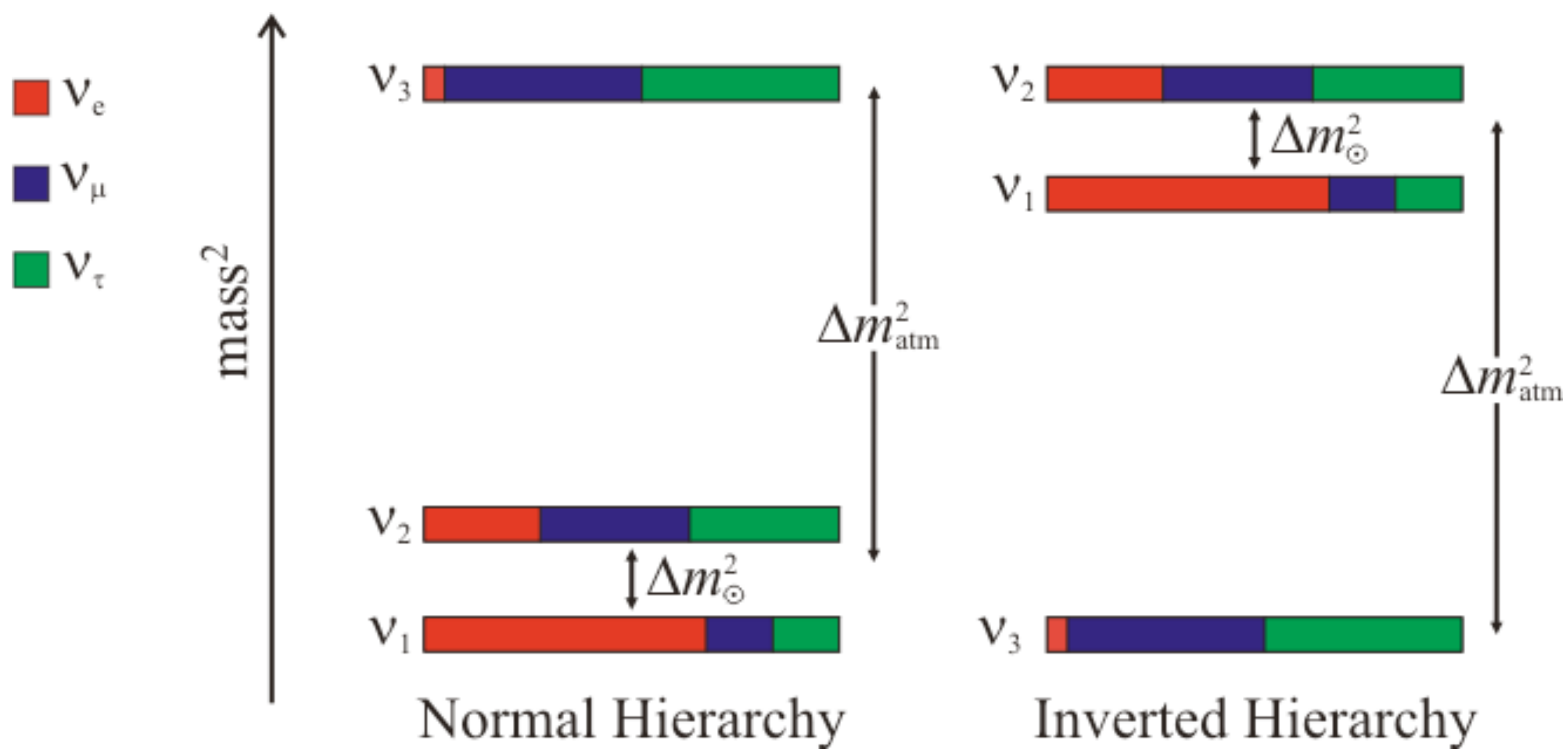

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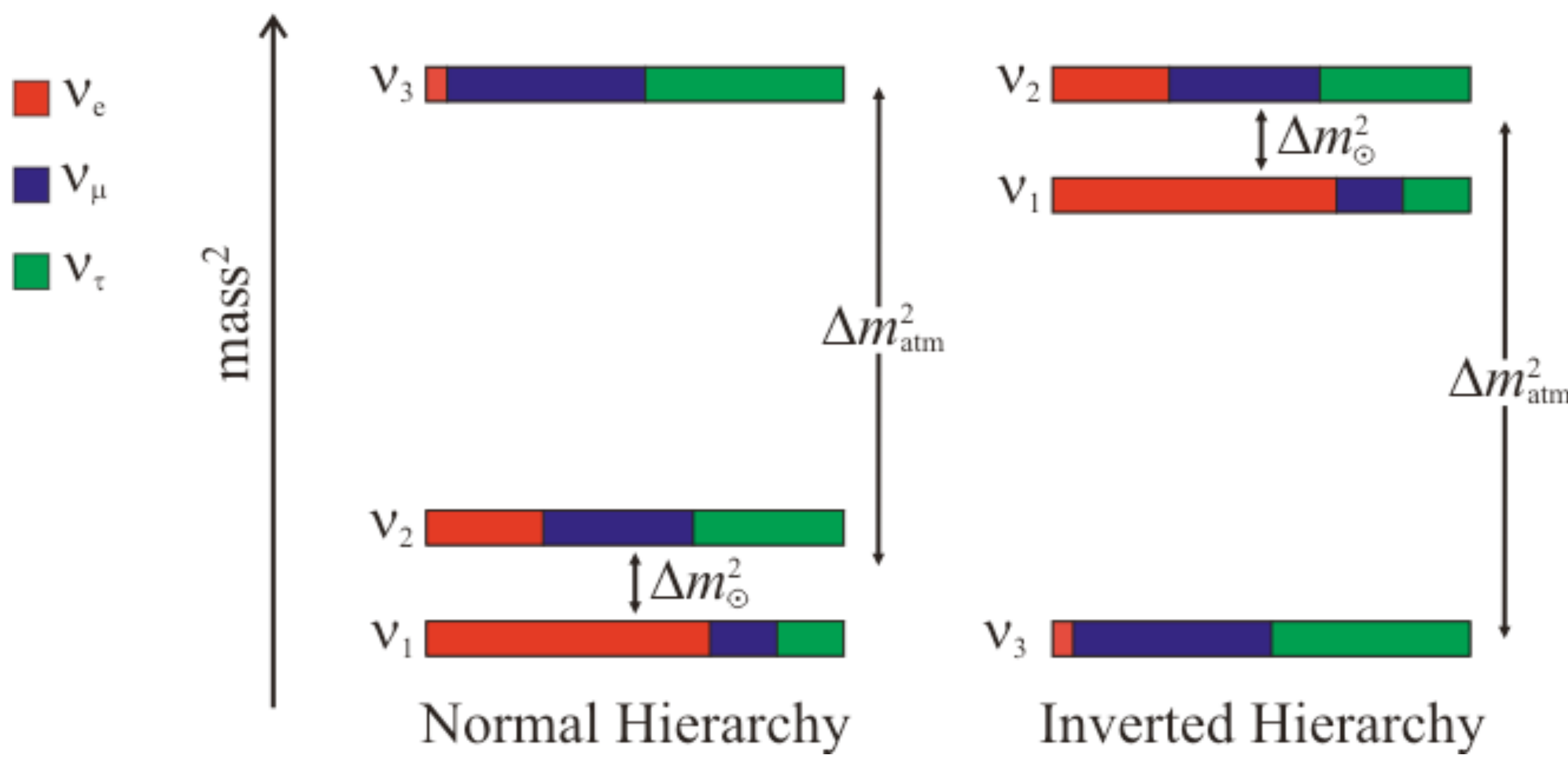

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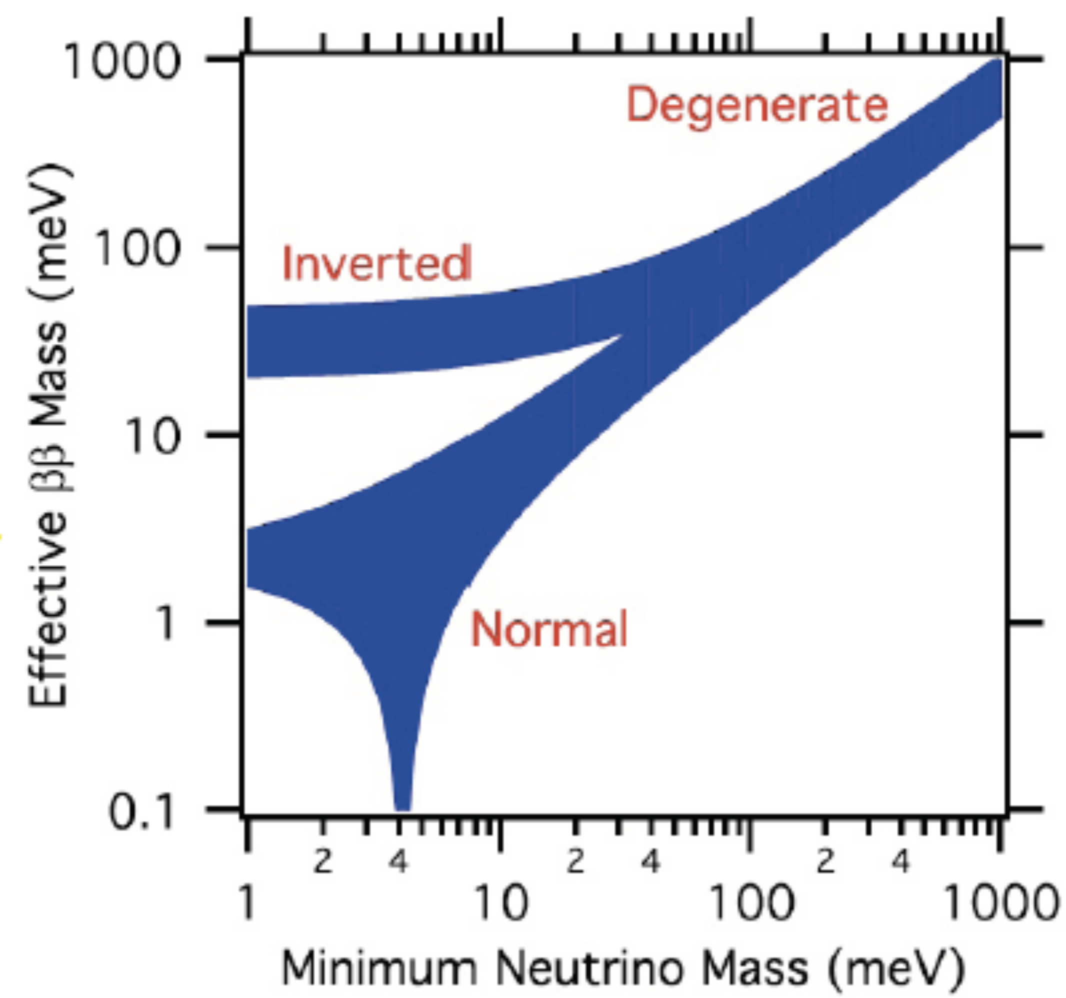
- If neutrino oscillation experiments establish the inverted hierarchy and the next generation 0vBB experiments see nothing, then it is very likely that neutrinos are Dirac particles.



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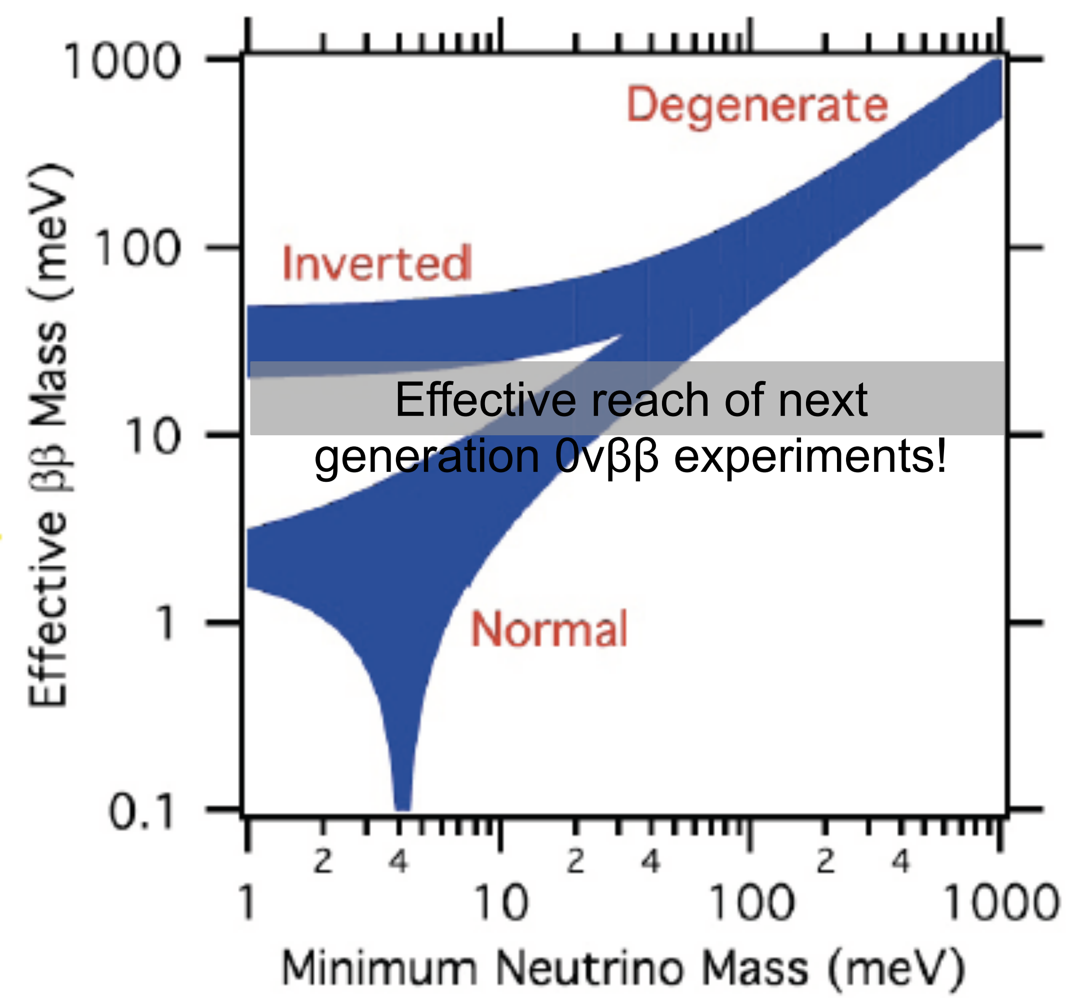

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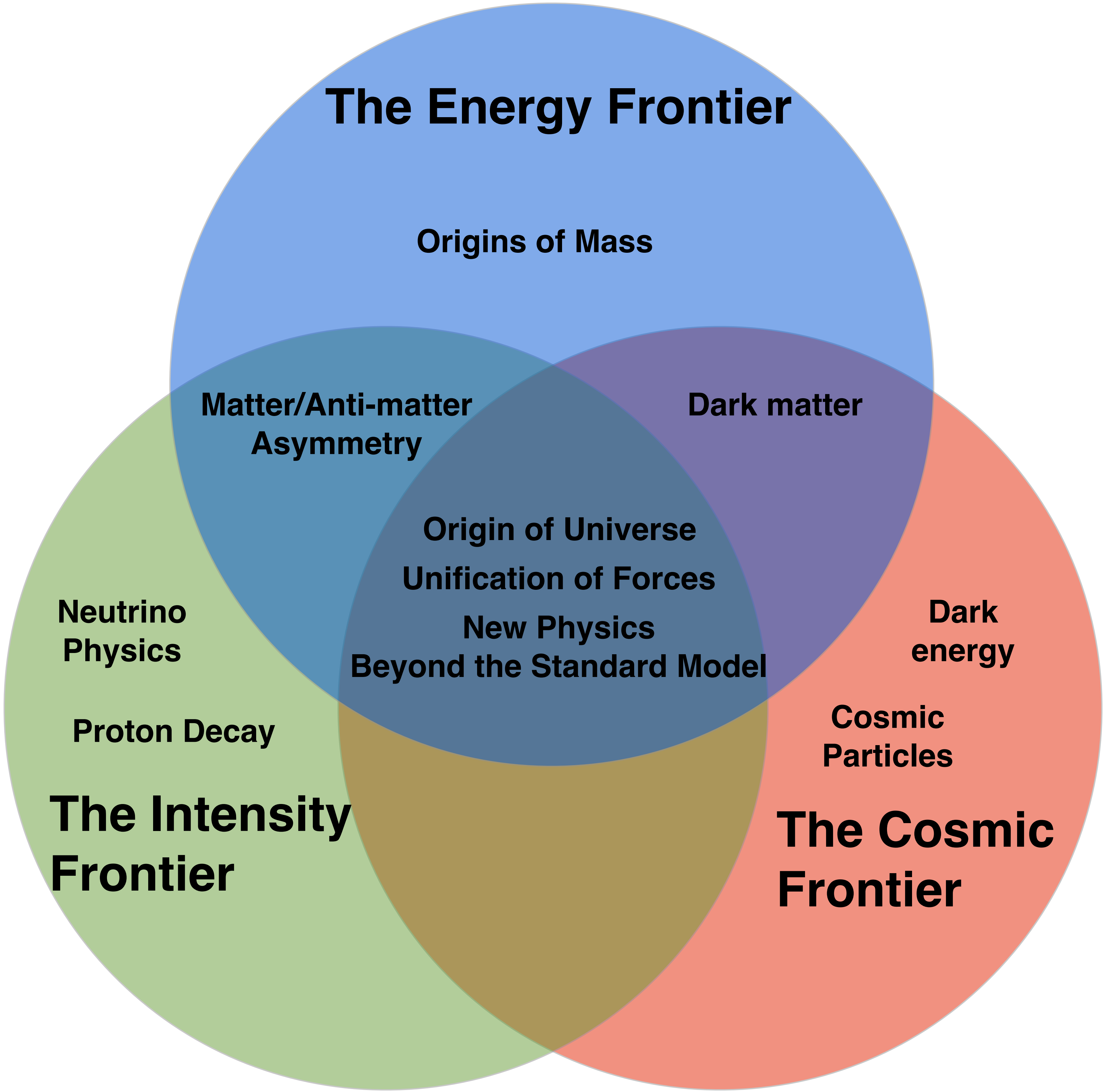
- Small neutrino masses suggest a heavy partner (eg, see-saw mechanism) - neutrinos provide a window to physics at the GUT scale!
- Want to overconstrain (squeeze) the 3-flavor mixing model - maybe we'll find some inconsistencies driven by new physics.

How It All Fits Together



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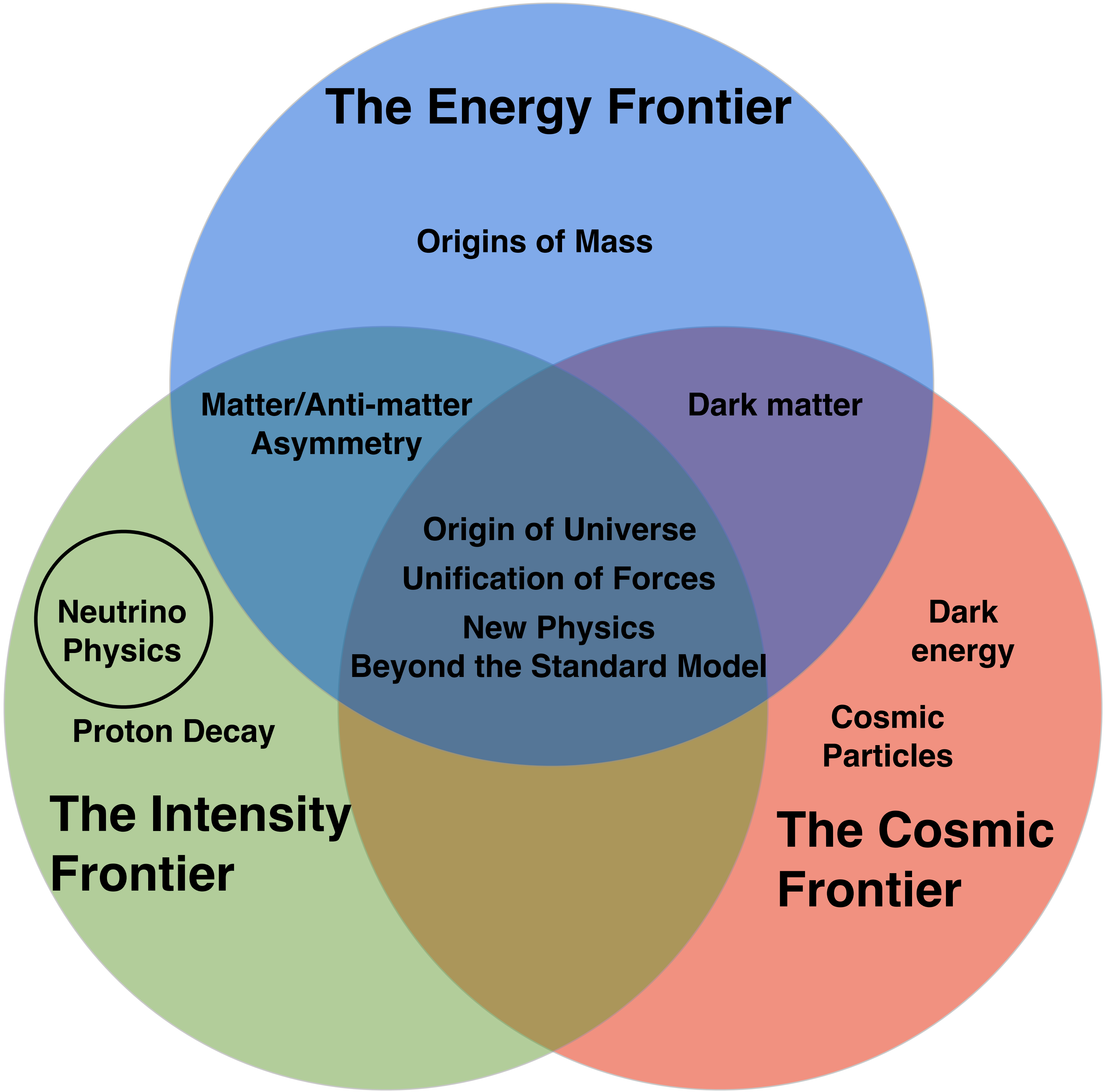

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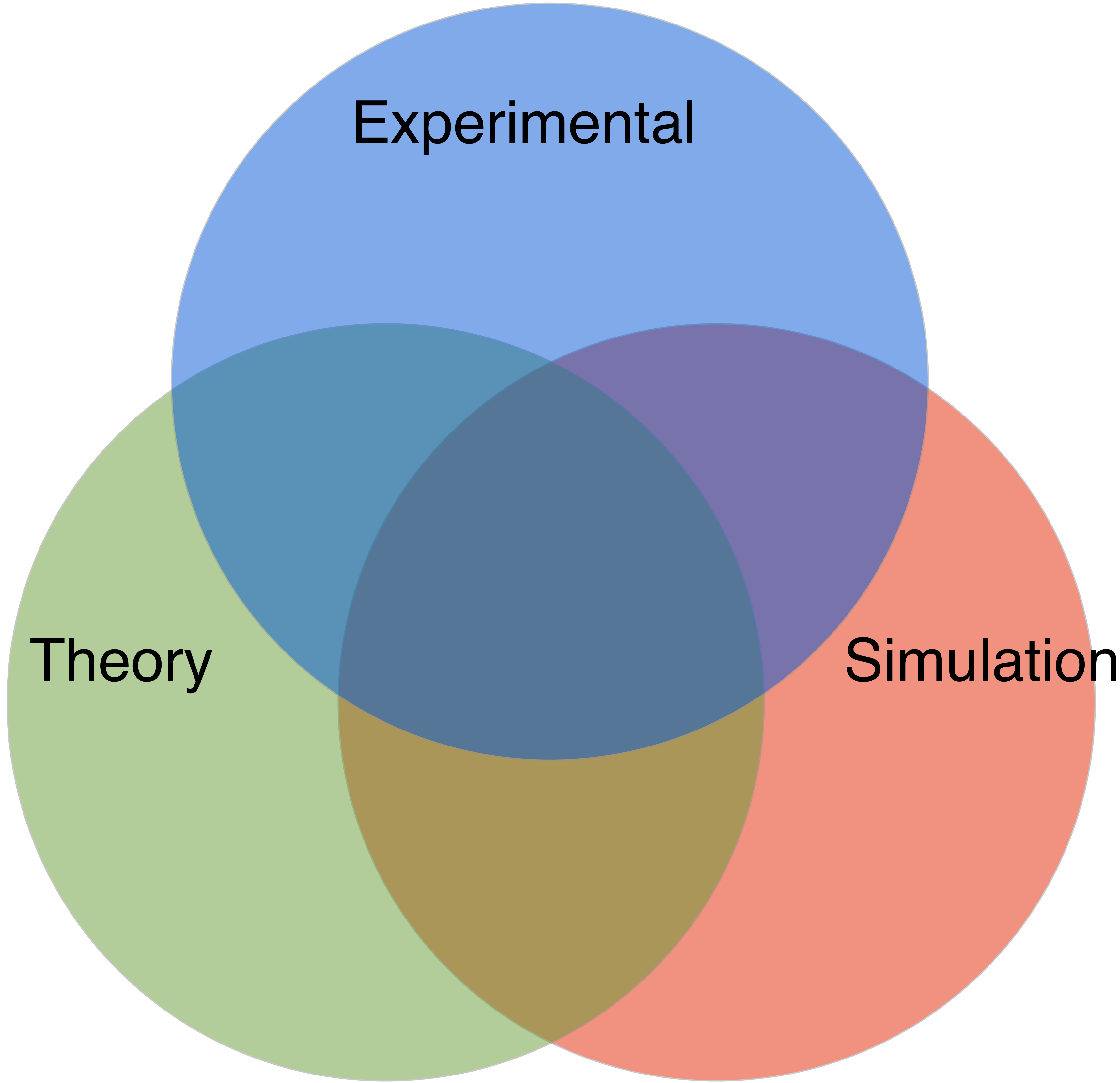

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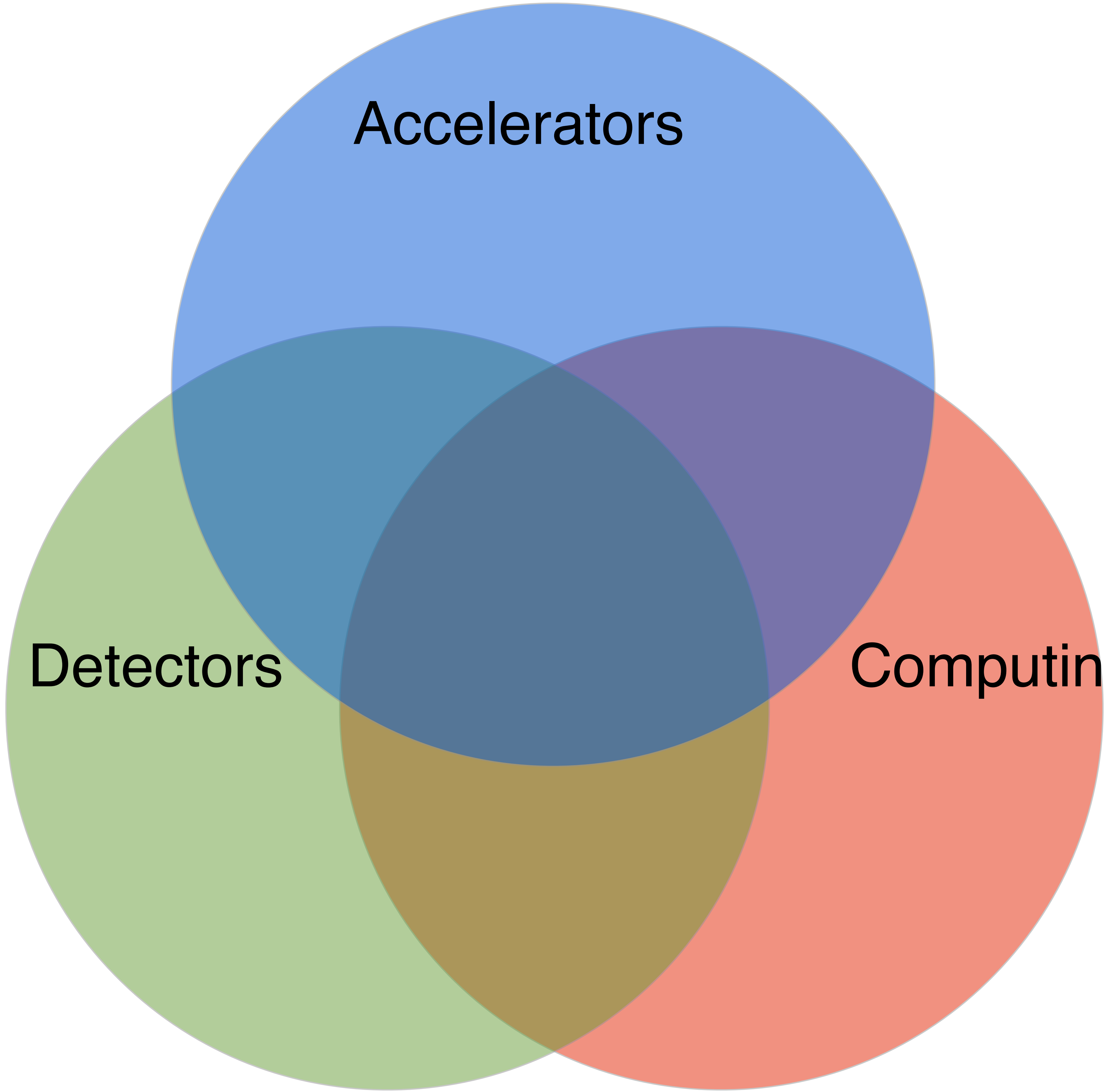

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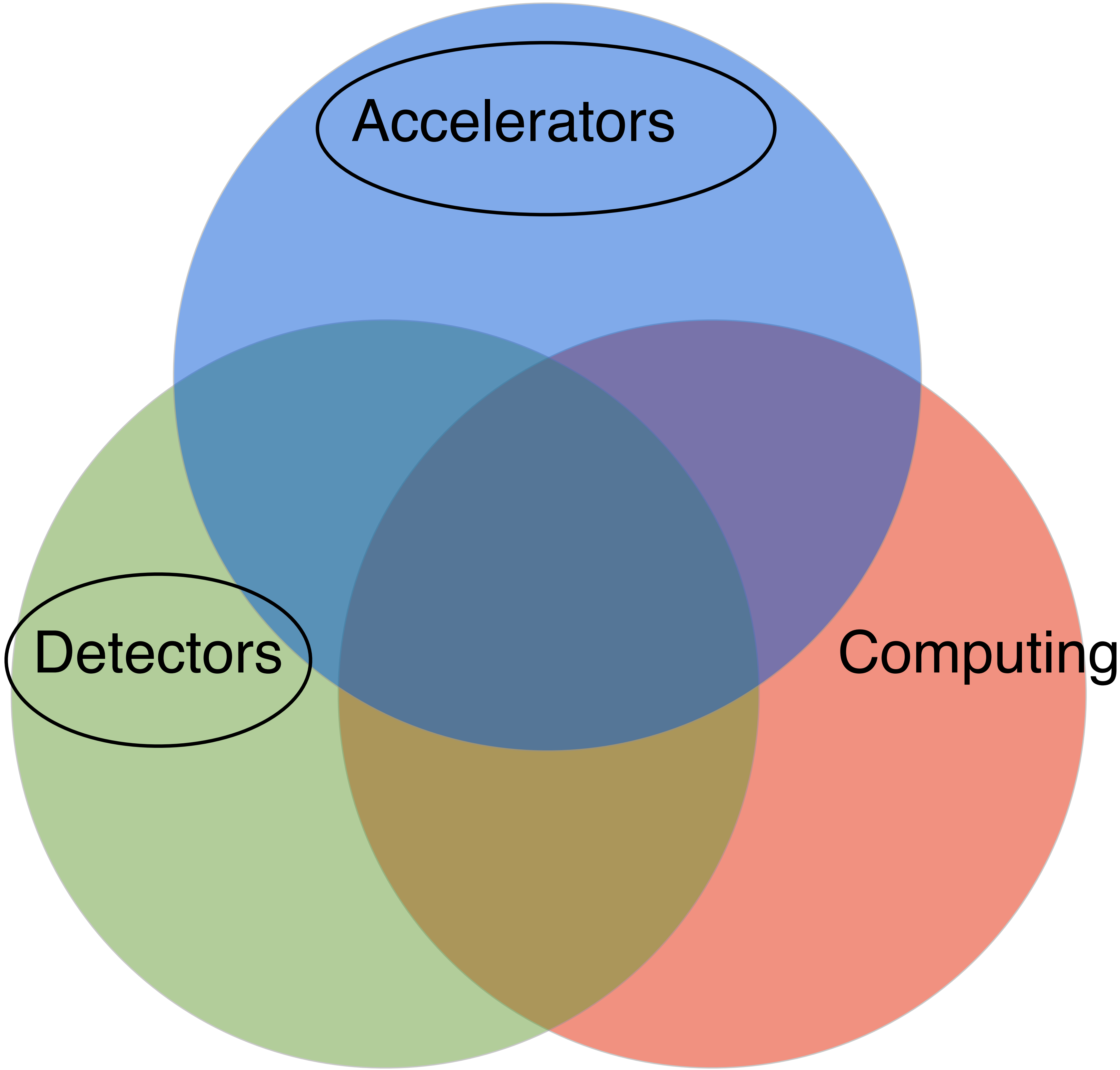

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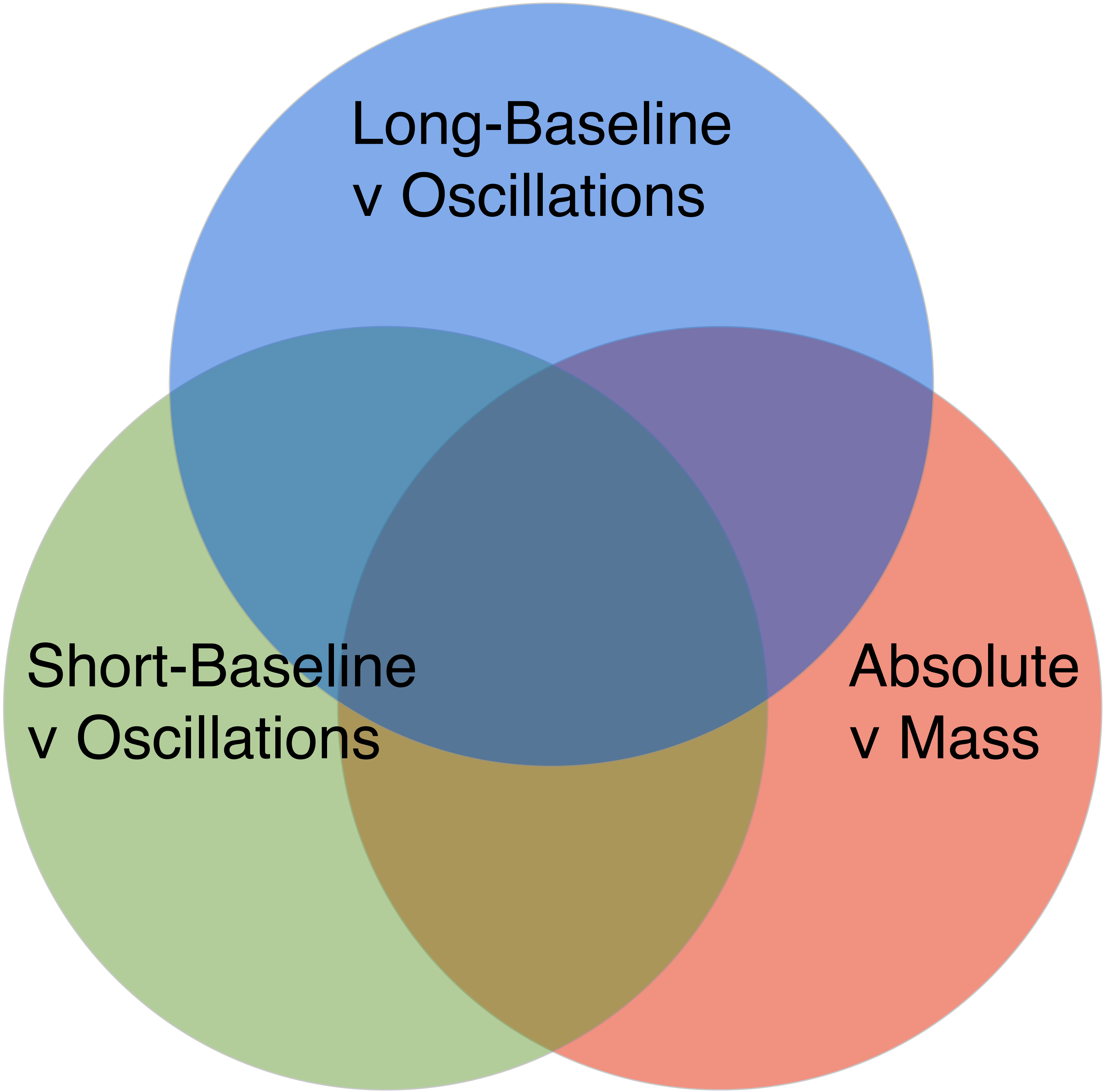

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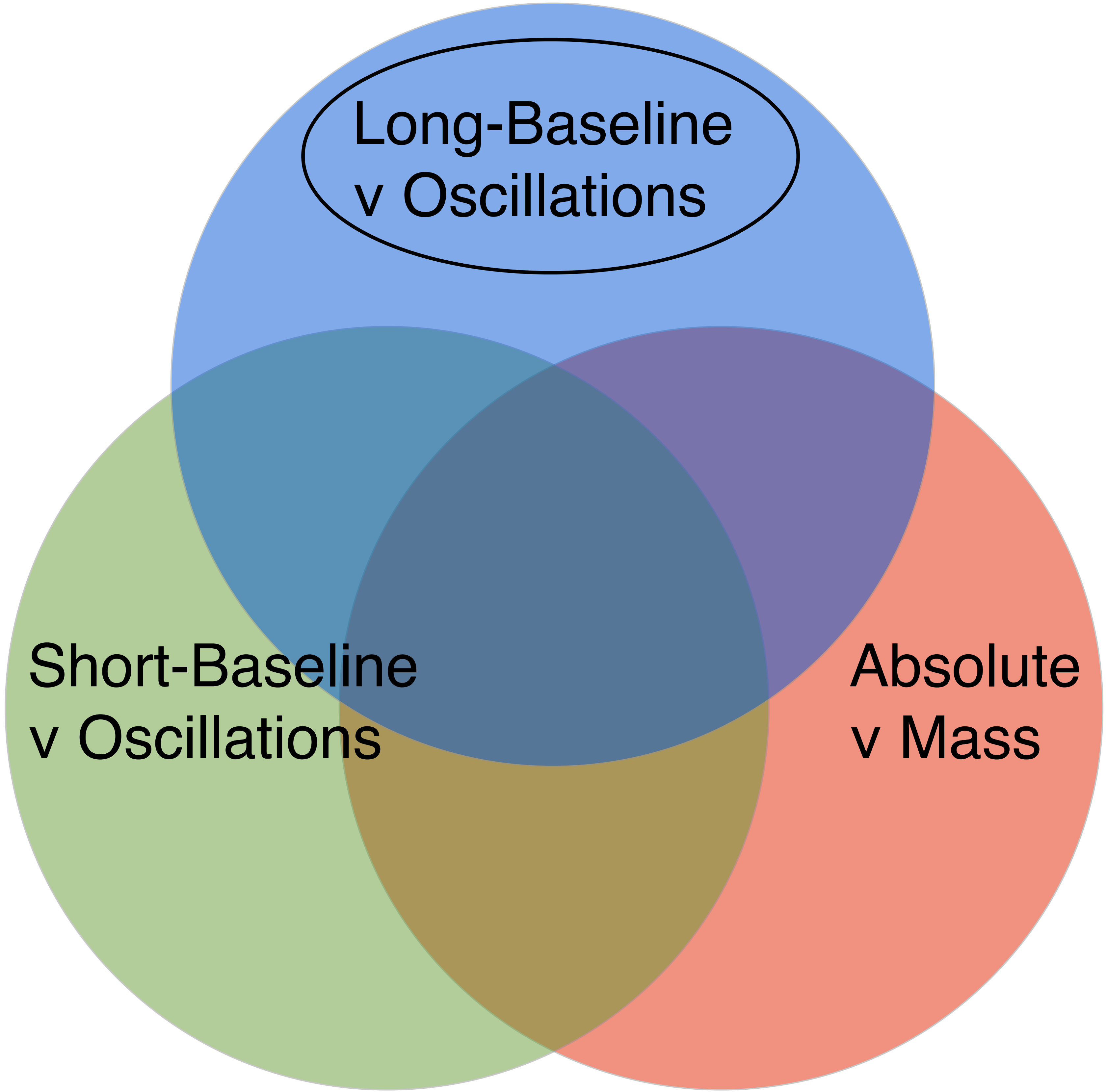

How Are Neutrinos Seen?

- Probability of a neutrino interaction is $\sim 10^{-38}/cm^2$
- Since neutrinos don't like to interact with matter, we need HUGE detectors!
- Typical size is tens to thousands of tons

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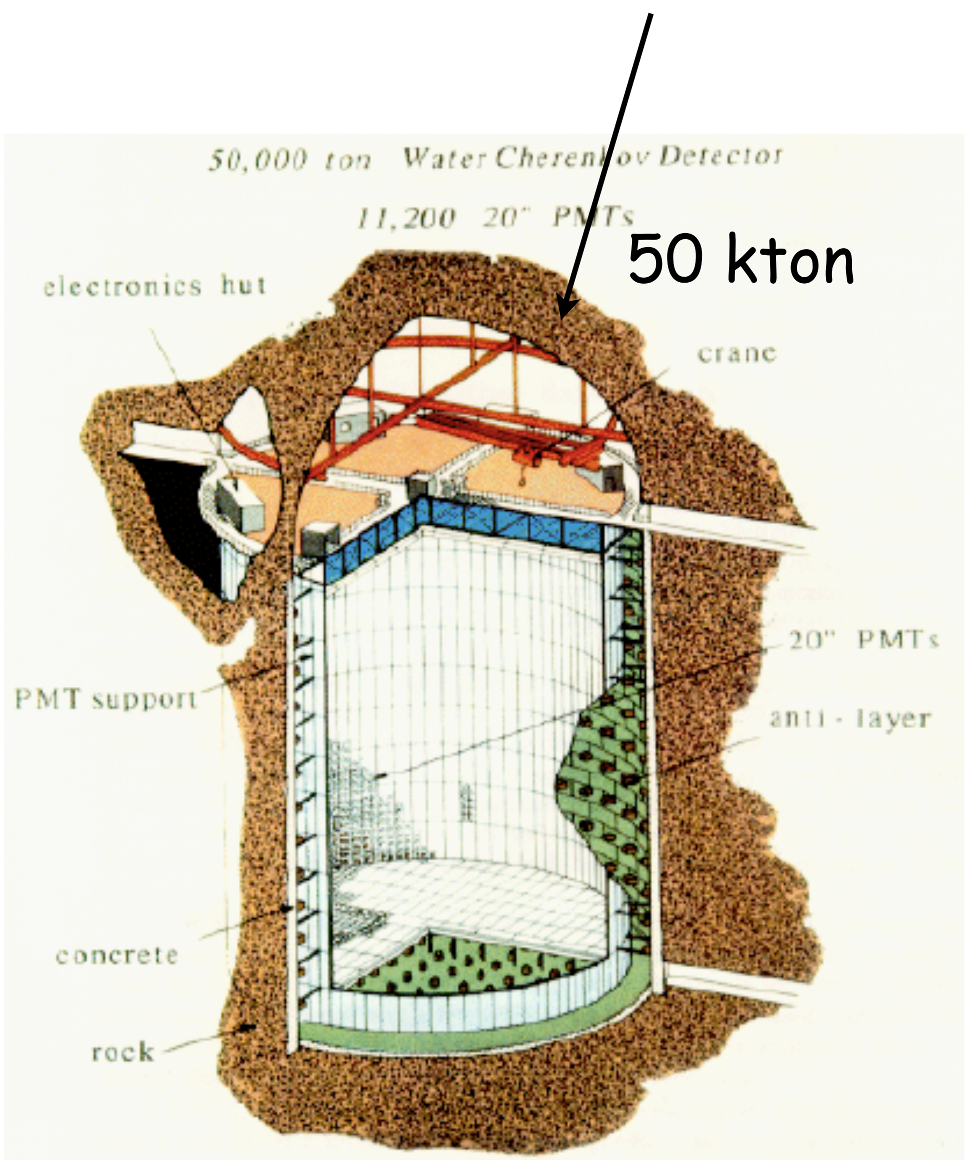

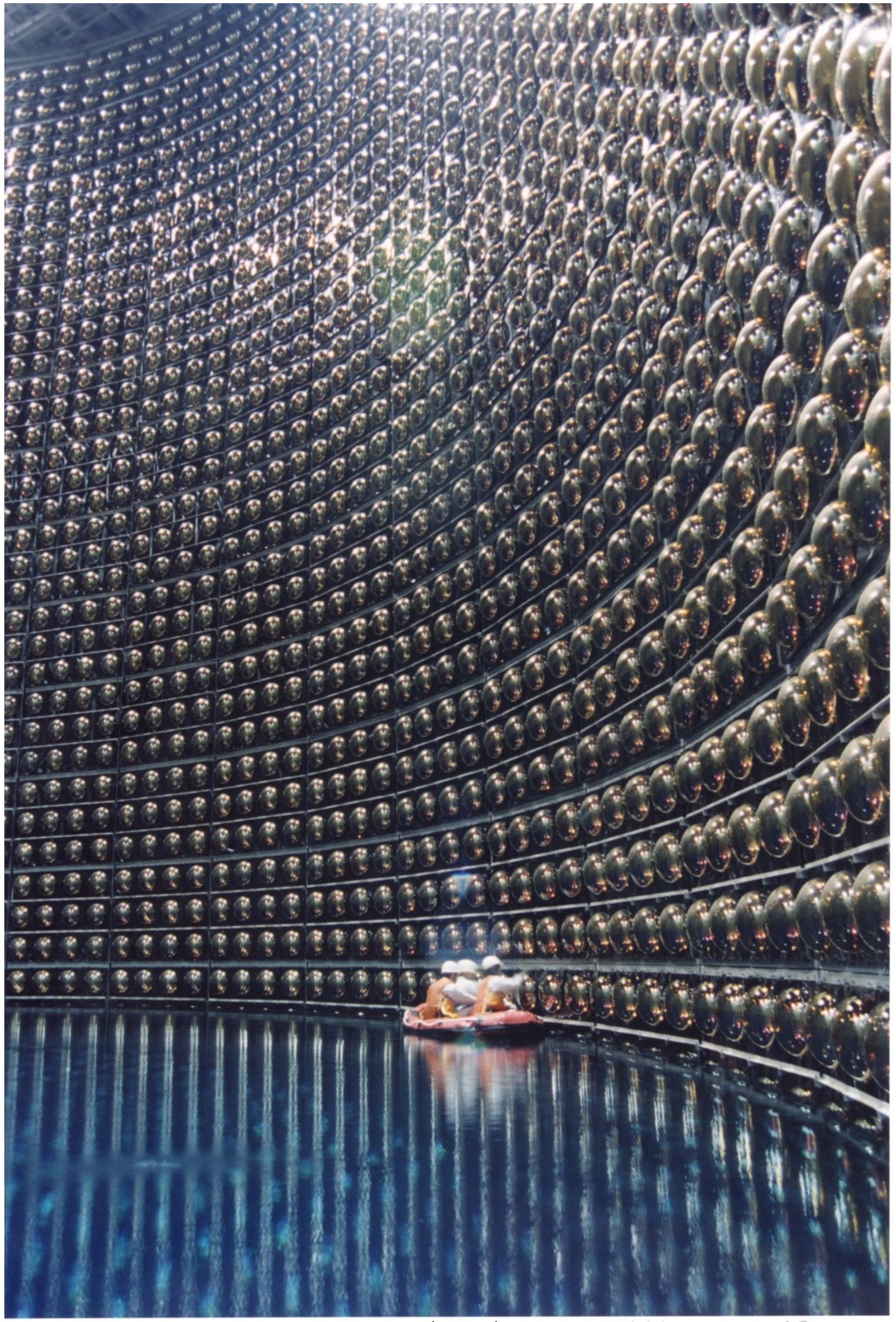

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- We don't actually see the neutrinos, only the particles they produce when they interact with nuclei.
- Two types of neutrino interactions:
  - **Charged-current** (CC, W-boson exchange). Final state includes a lepton (e, μ or τ) + hadron.
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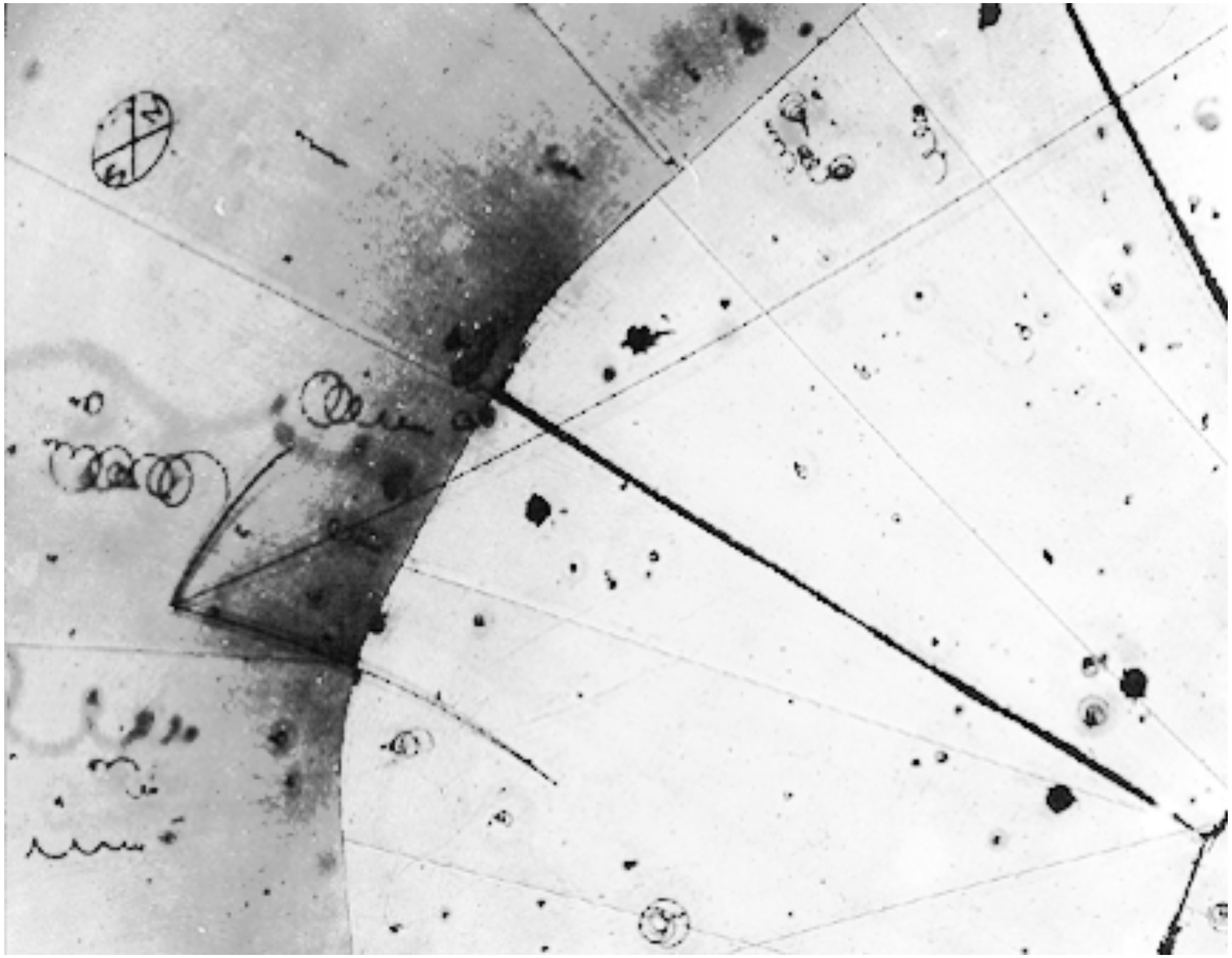

12 foot bubble chamber, Argonne National Lab. Nov. 13, 1970

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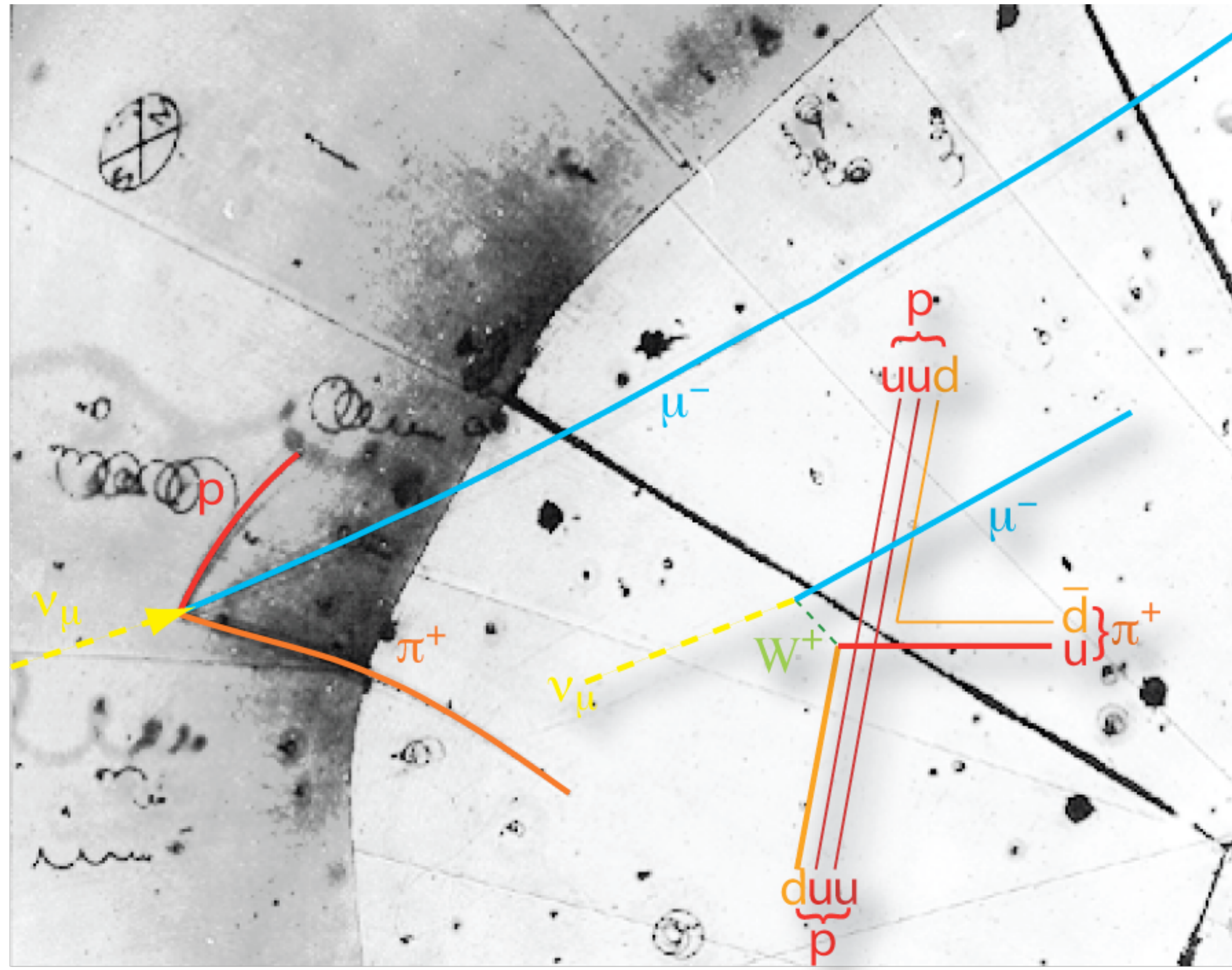

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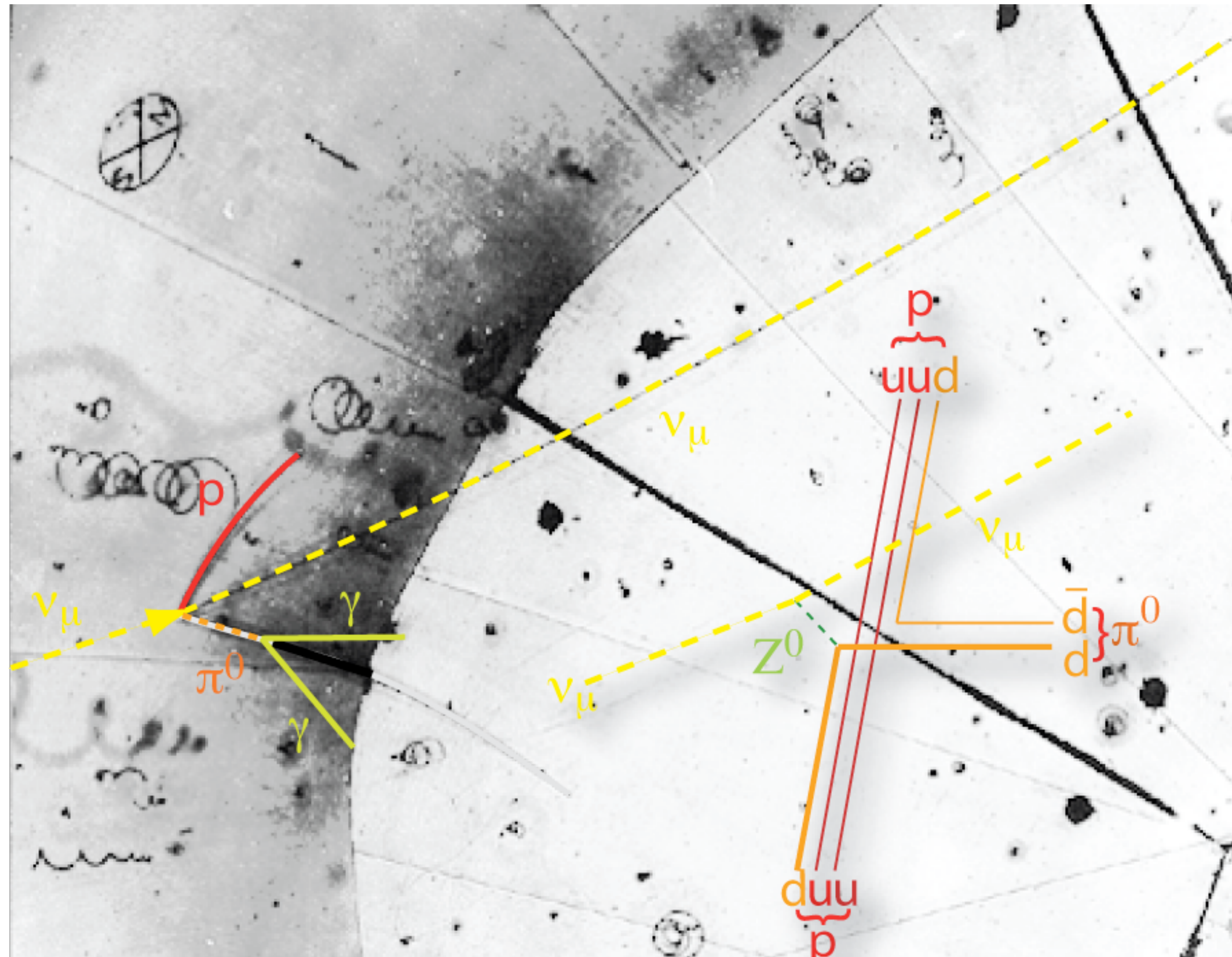

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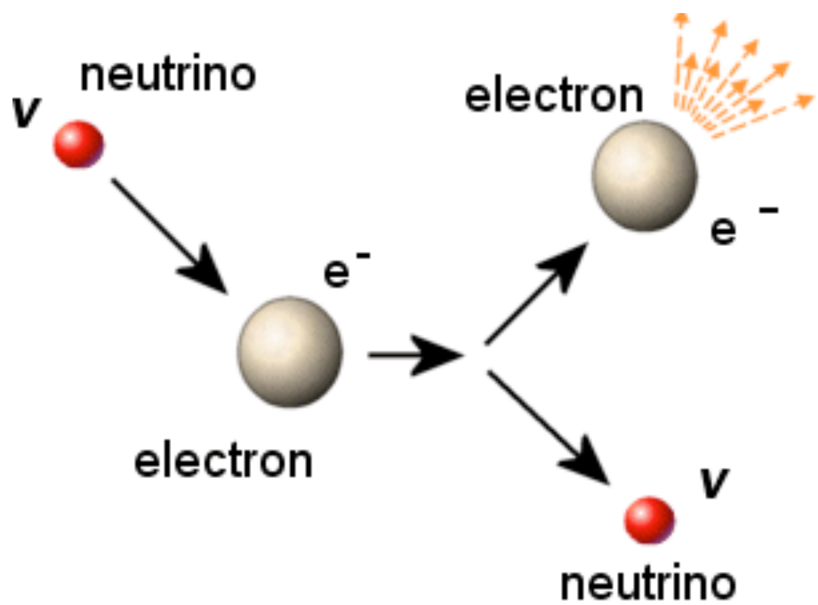
Neutrino Detection - Fundamentals



- ν_e CC off electron
- Not used by many experiments since cross-section is much smaller than CC interactions with nuclei

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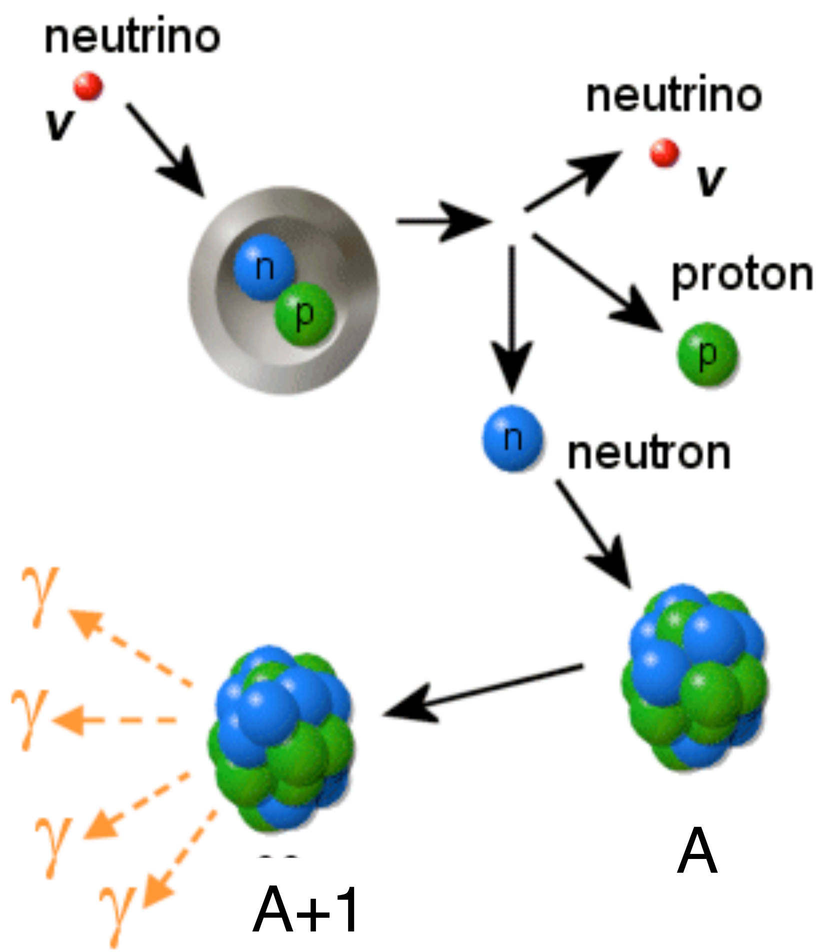

- ν_l NC off nucleus
- hadrons (only) in final state
- neutrinos carries off energy

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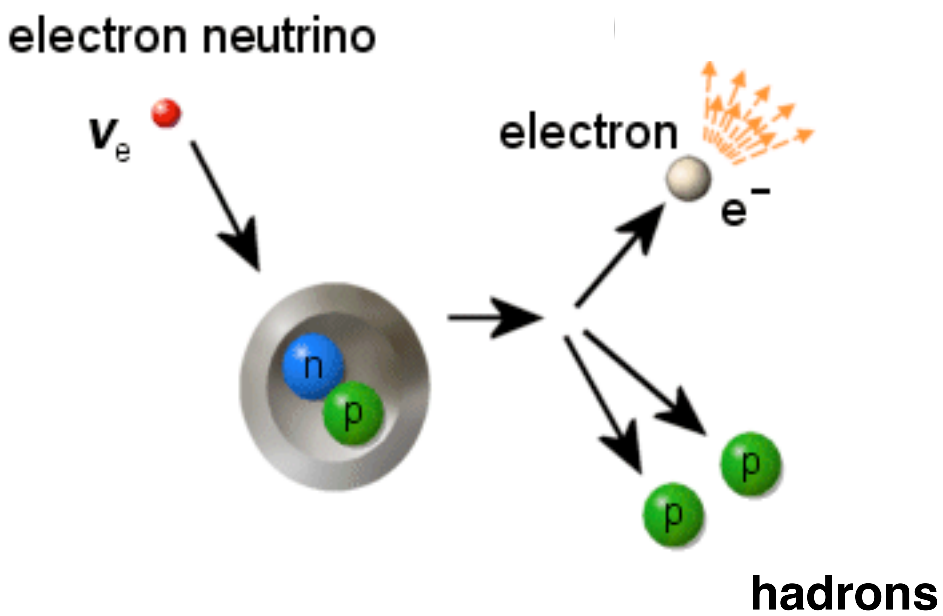
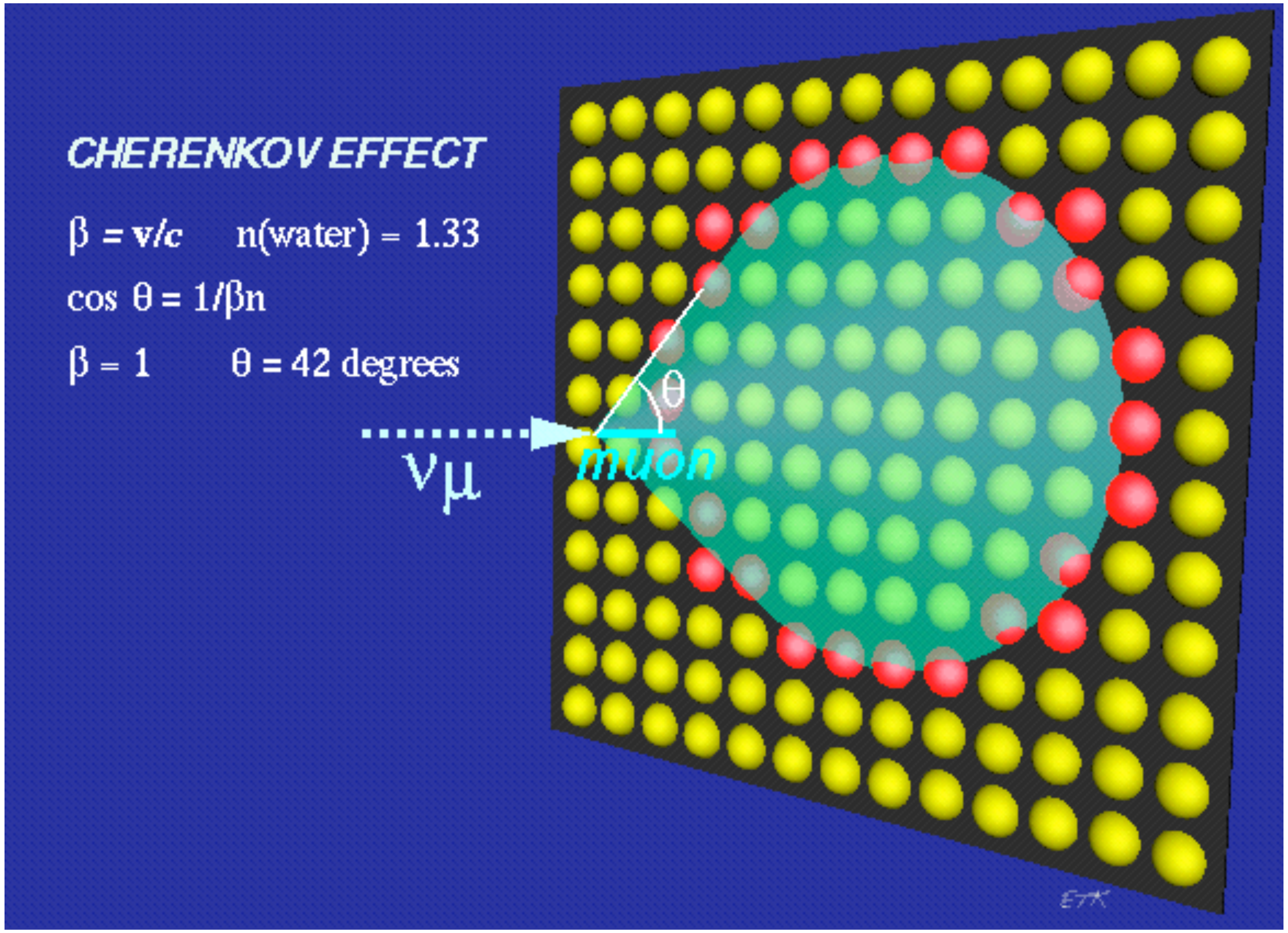


- ν_l CC off nucleus
- charged lepton (+ hadrons) in final state
- energy and flavor of neutrino are observable

Neutrino Detection

- Signal: appearance of photons or charged particles inside a detector.
  - Require no incoming charged particle within vicinity of interaction vertex (often pushes experiments to go deep underground)
  - Interactions in detector are often very "rare", O(0.1-1)/day
  - Signal energies can vary across many orders of magnitudes
  - Particle identification tells us the type of neutrino
  - Energy of incoming neutrino can be measured for CC events only.
  - NOTE: many commonalities between neutrino, proton-decay, dark matter and neutrino-less double beta decay search experiments!
- A VERY wide variety of detectors are used to detect neutrinos
- As in any experiment, the type of detector used depends on energy thresholds, energy resolution, signal identification (efficiency) and background rejection (purity) needed.

Neutrino Detectors - Some Examples



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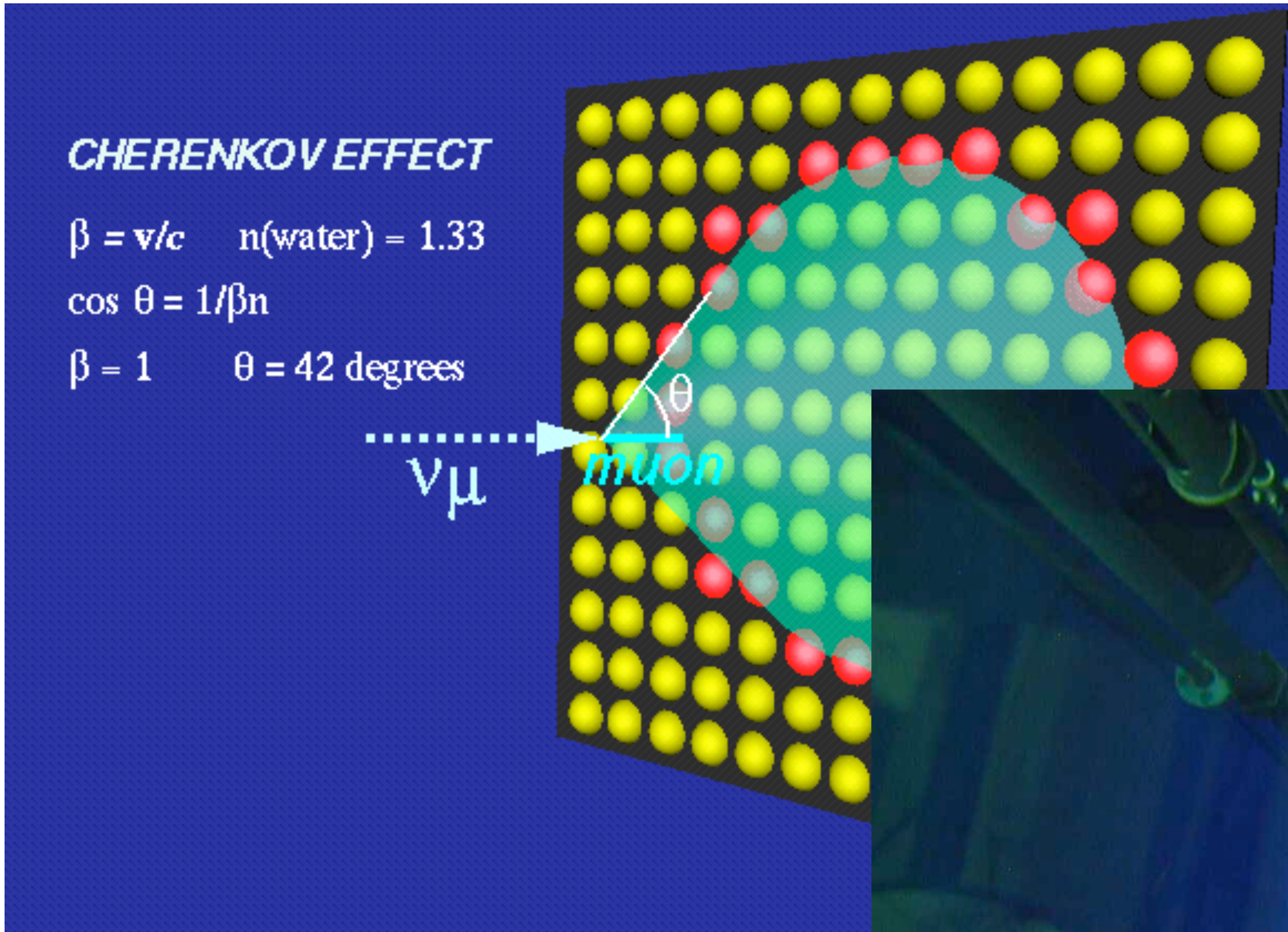

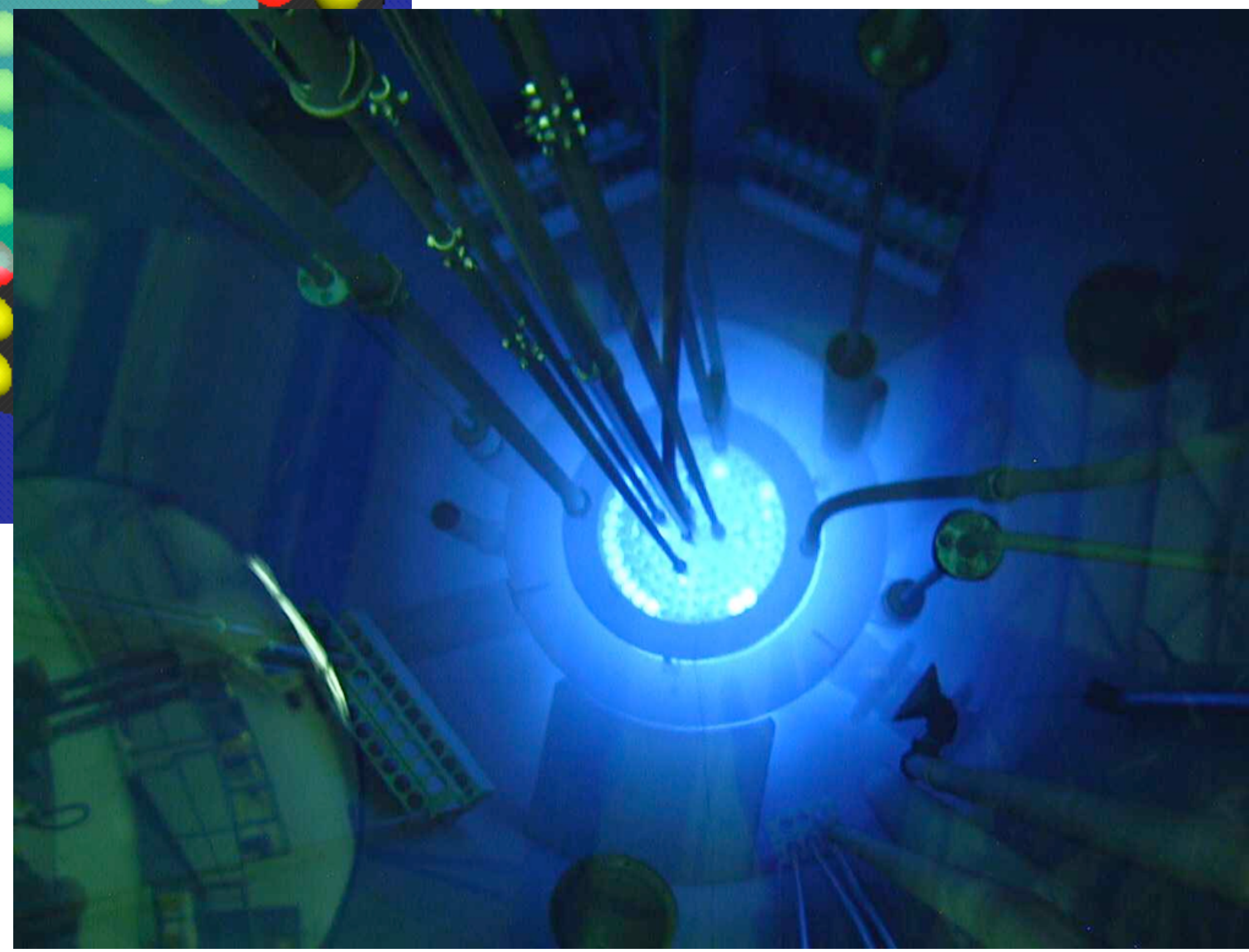

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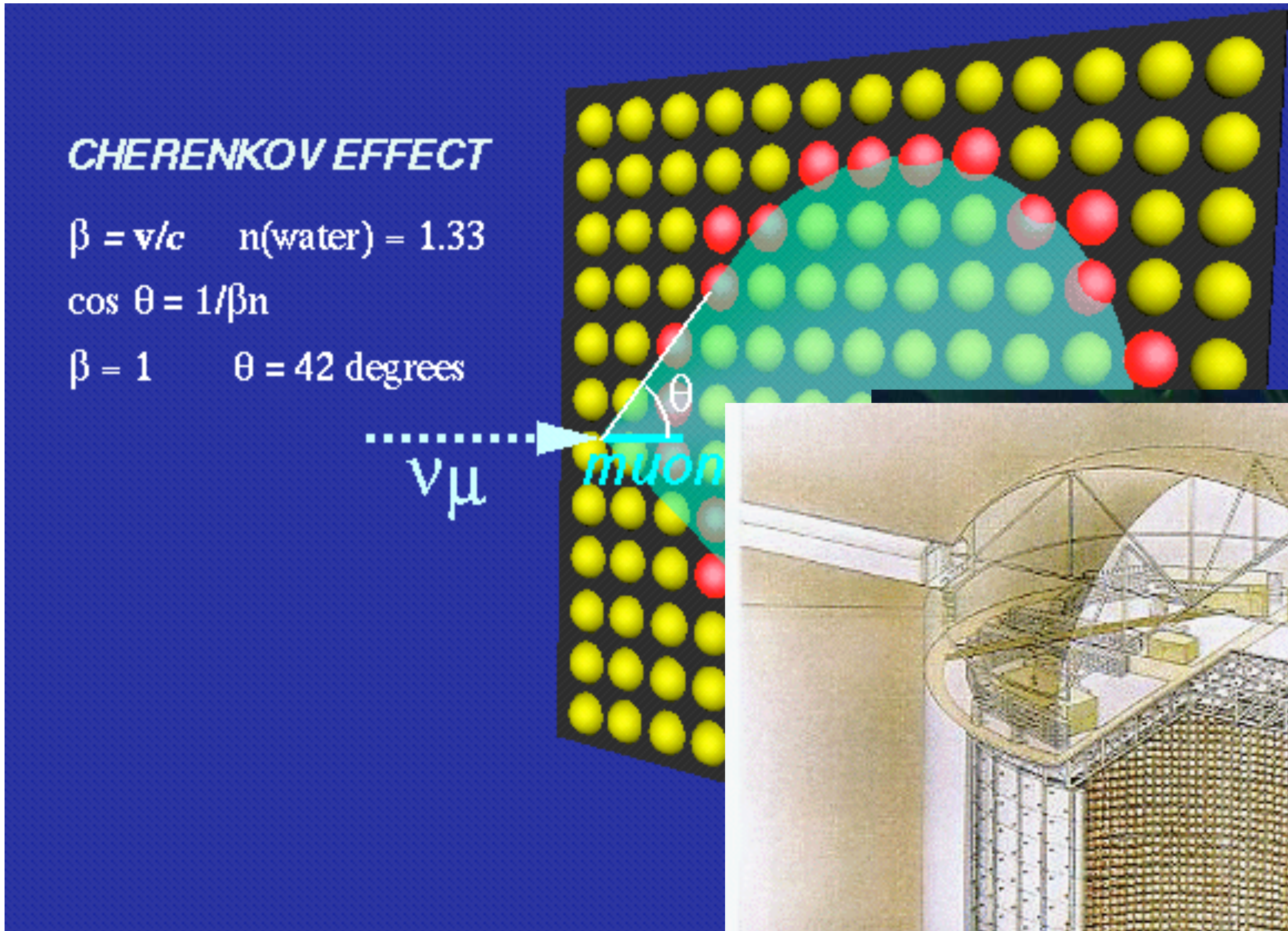

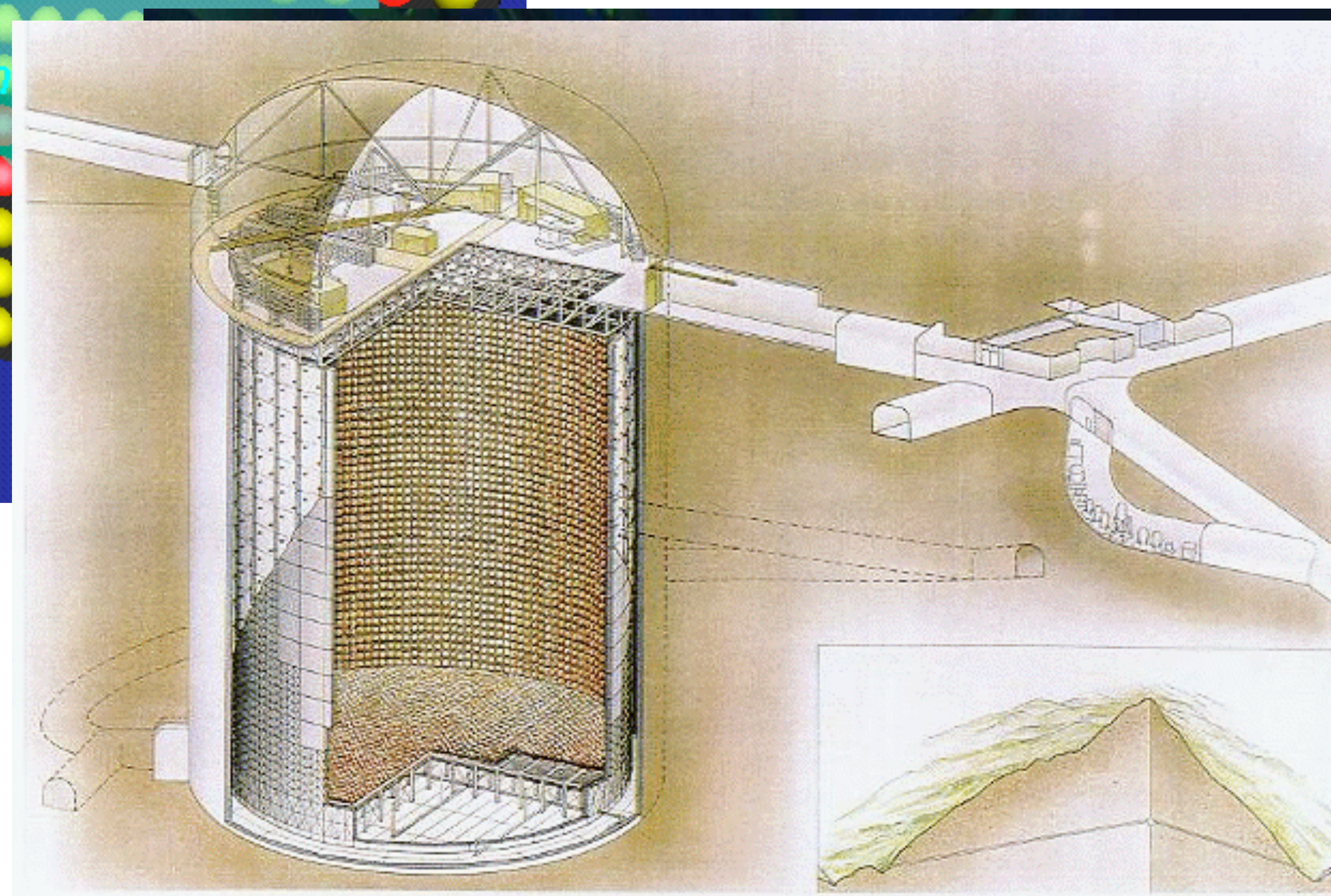

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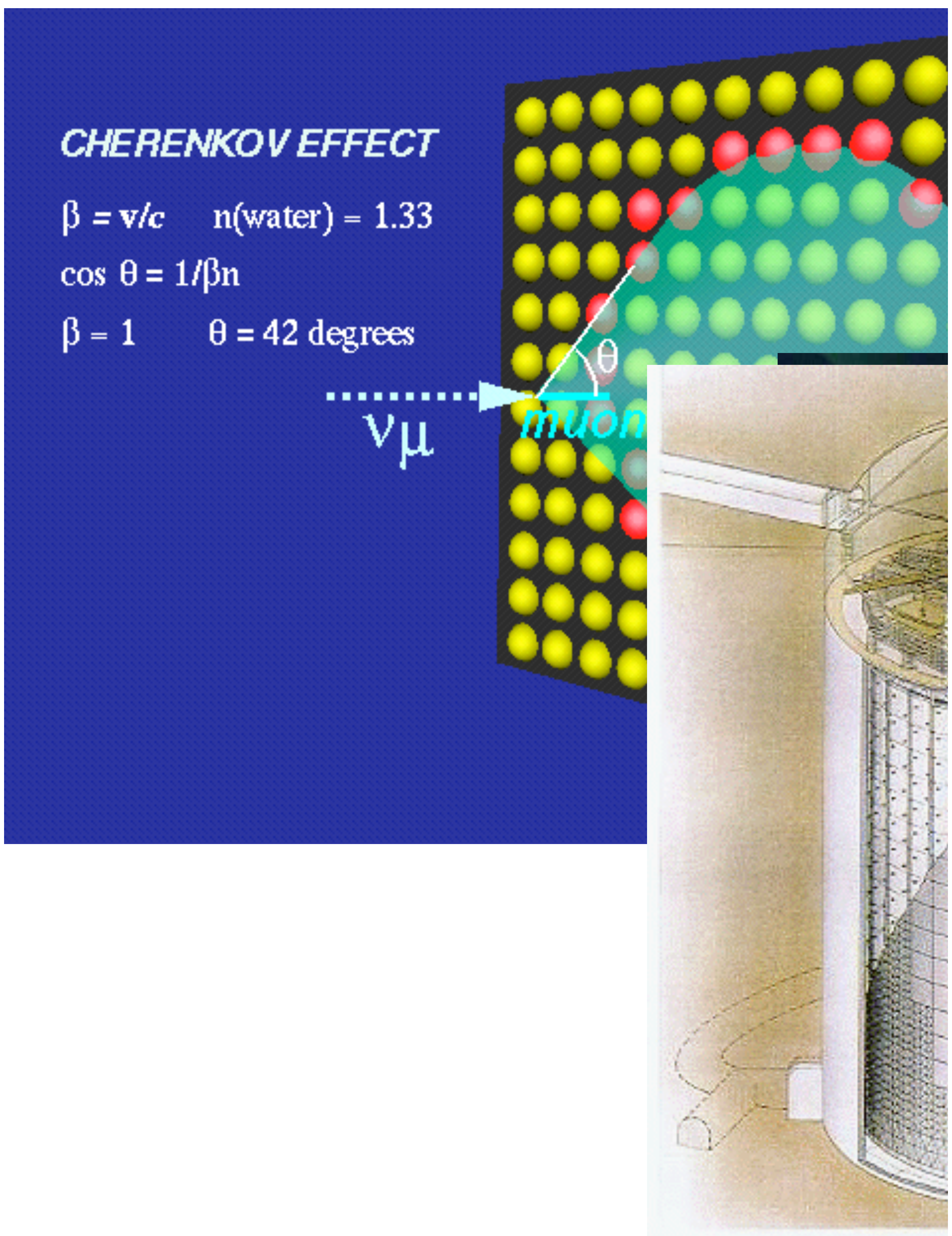

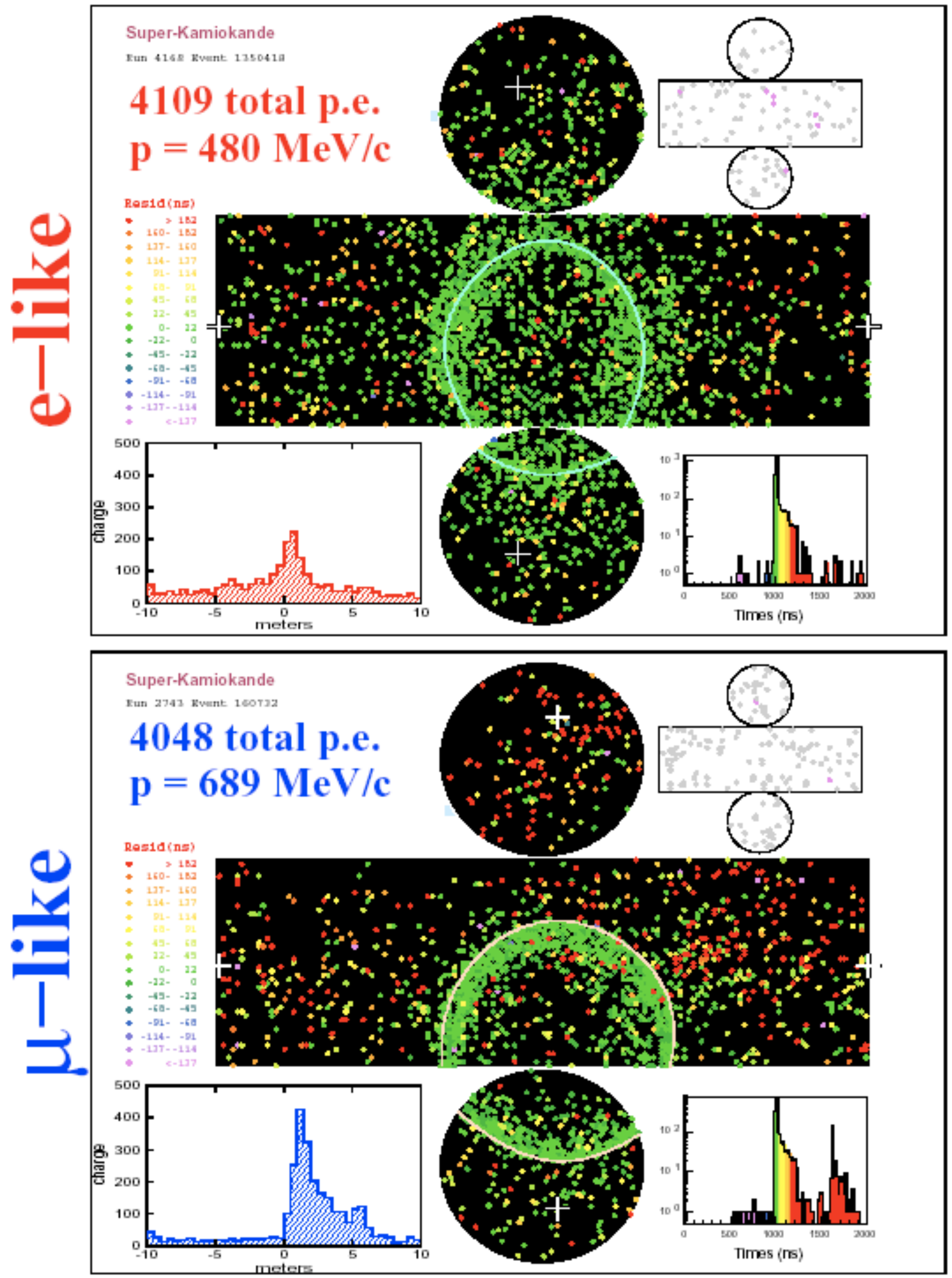

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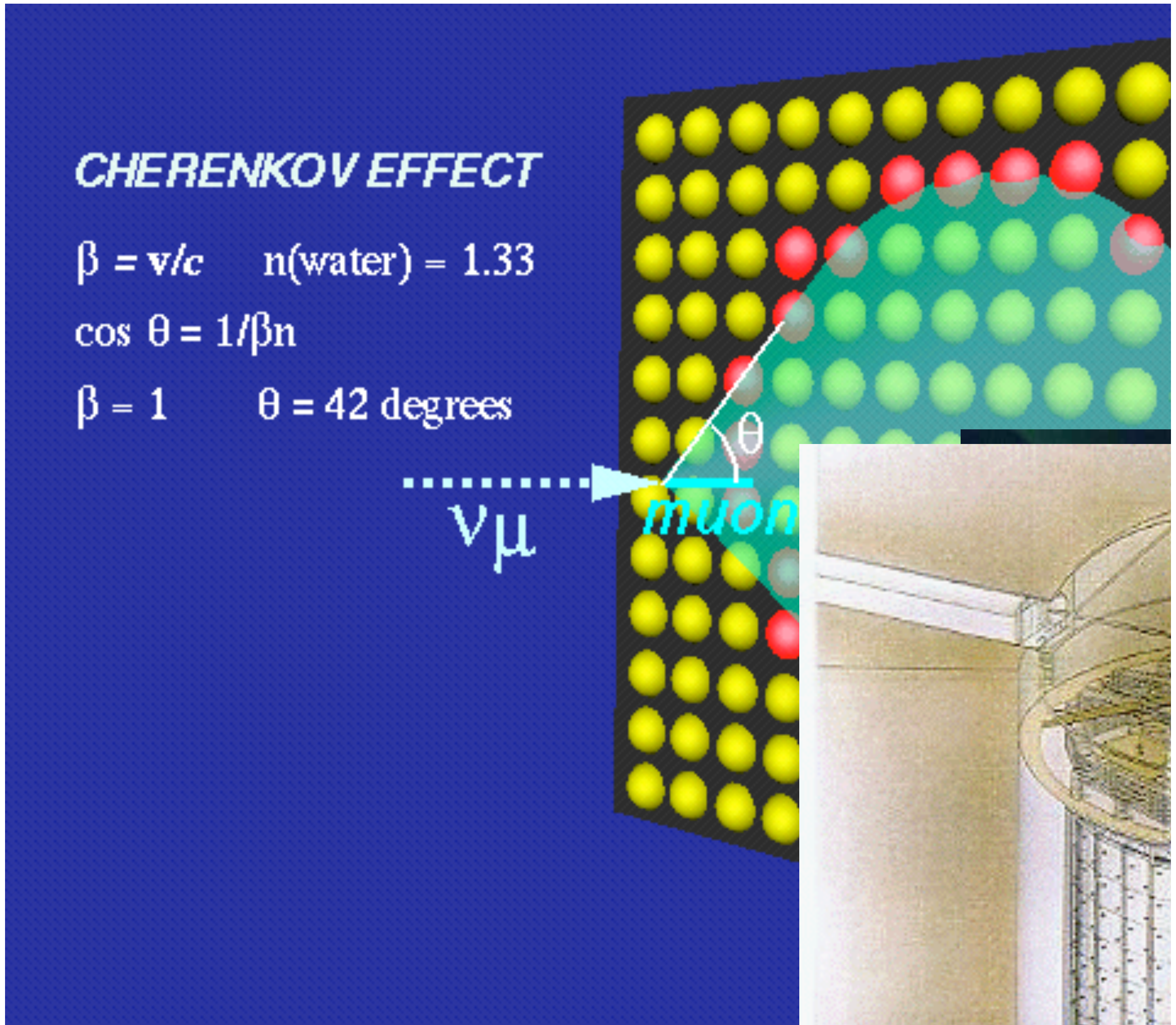

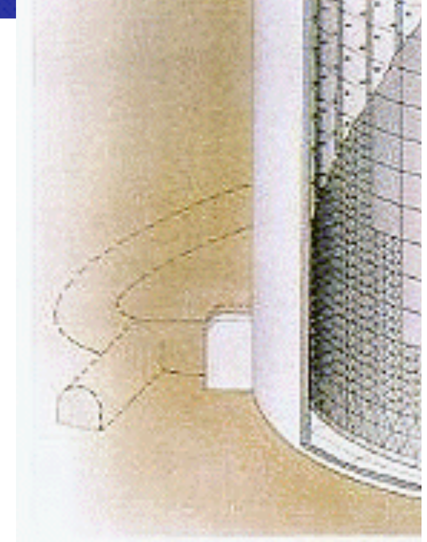

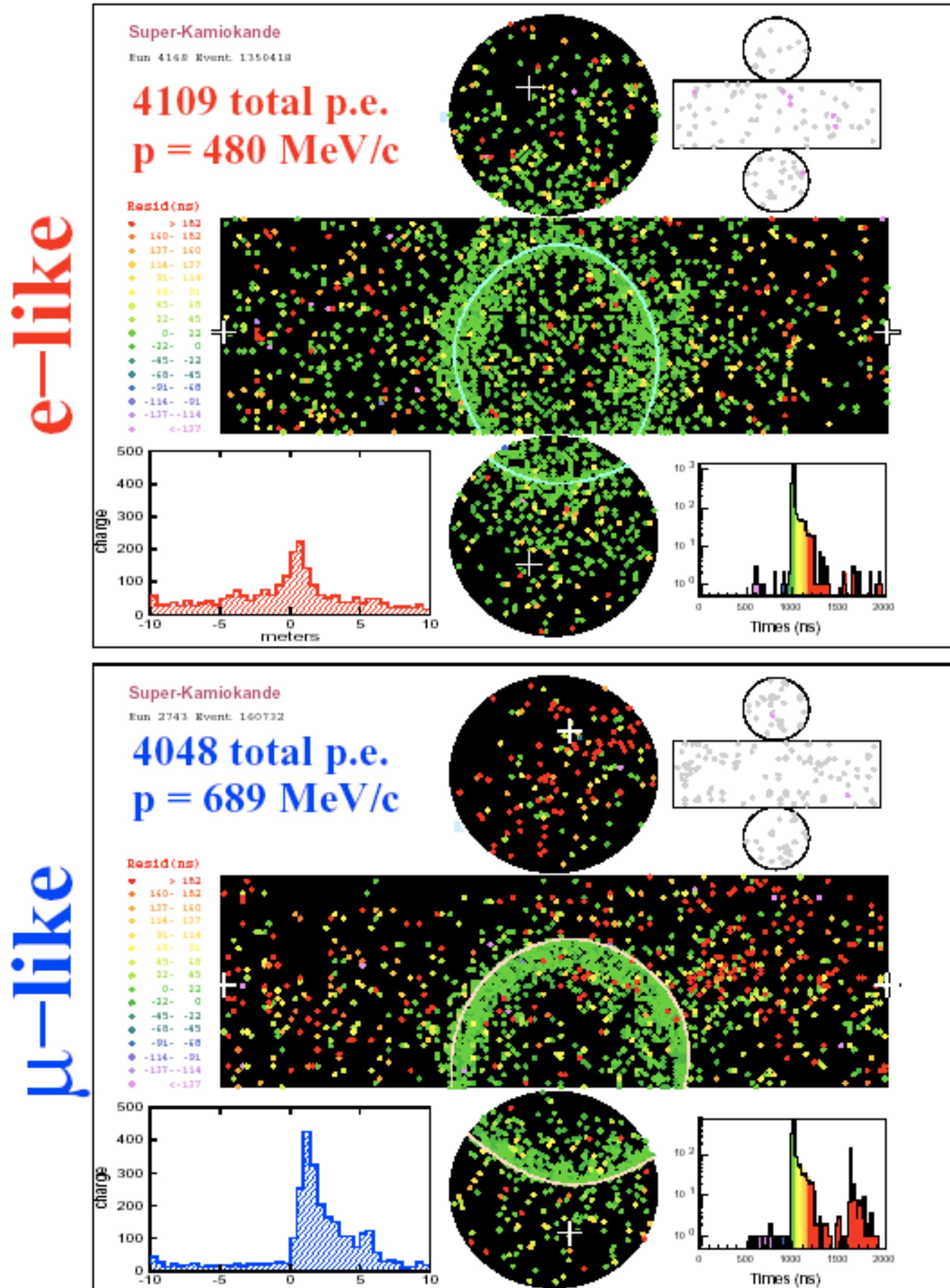

Energy thresholds:
muon: 120 MeV
proton: 1.06 GeV

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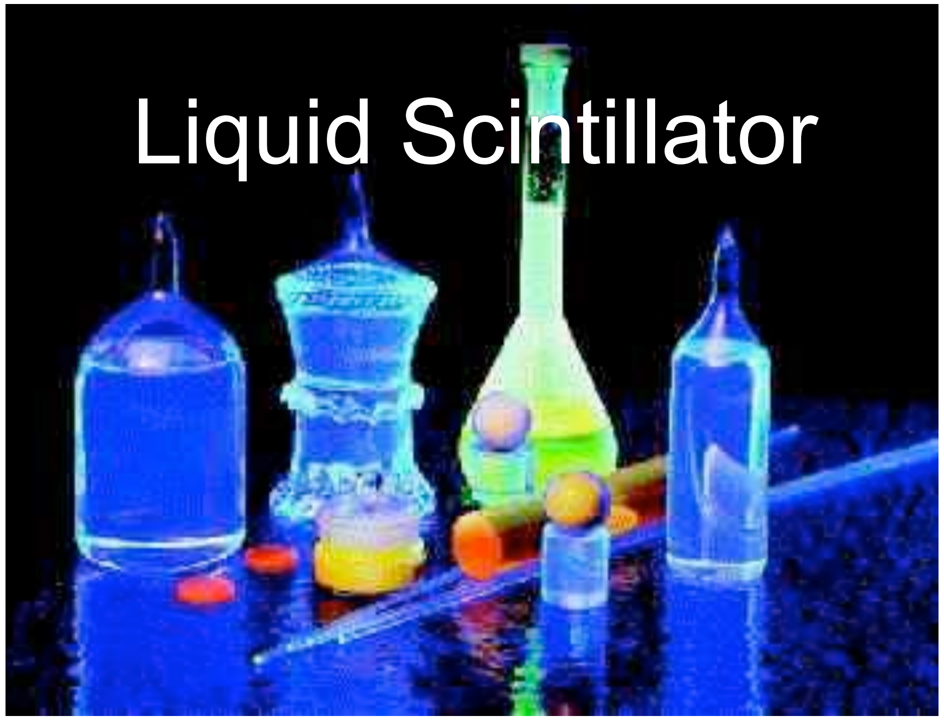

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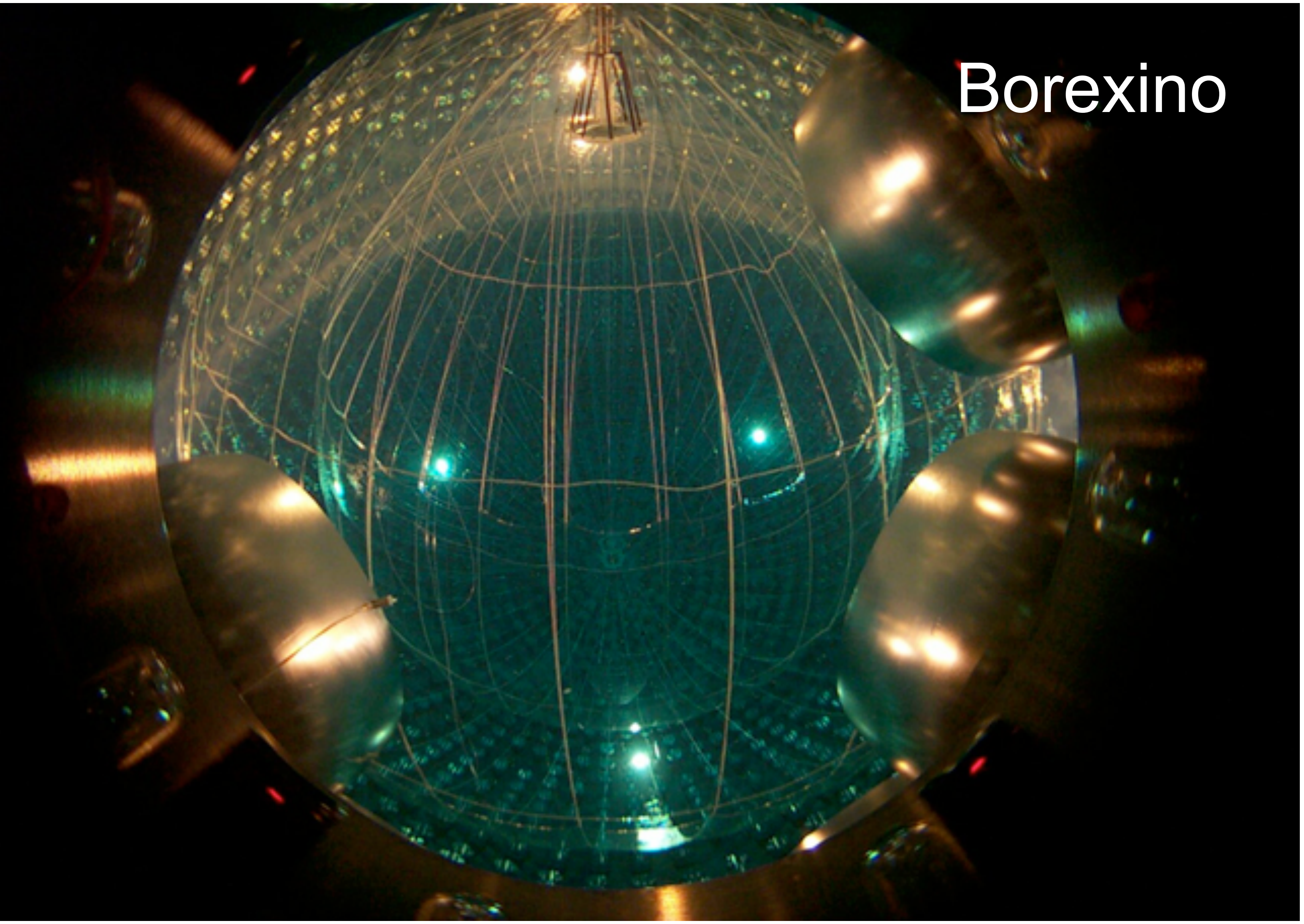

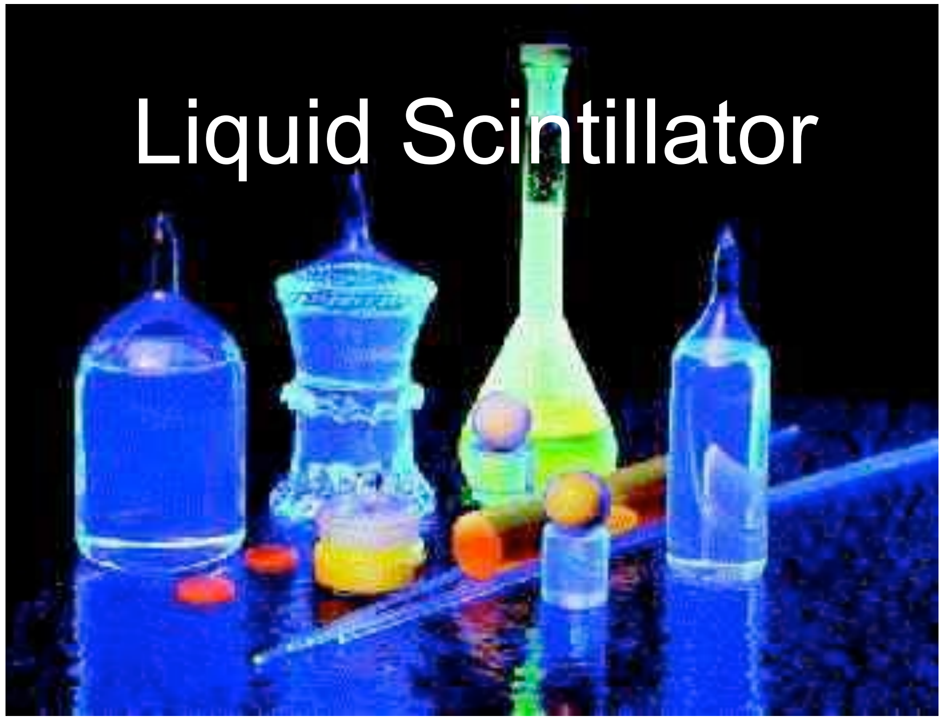

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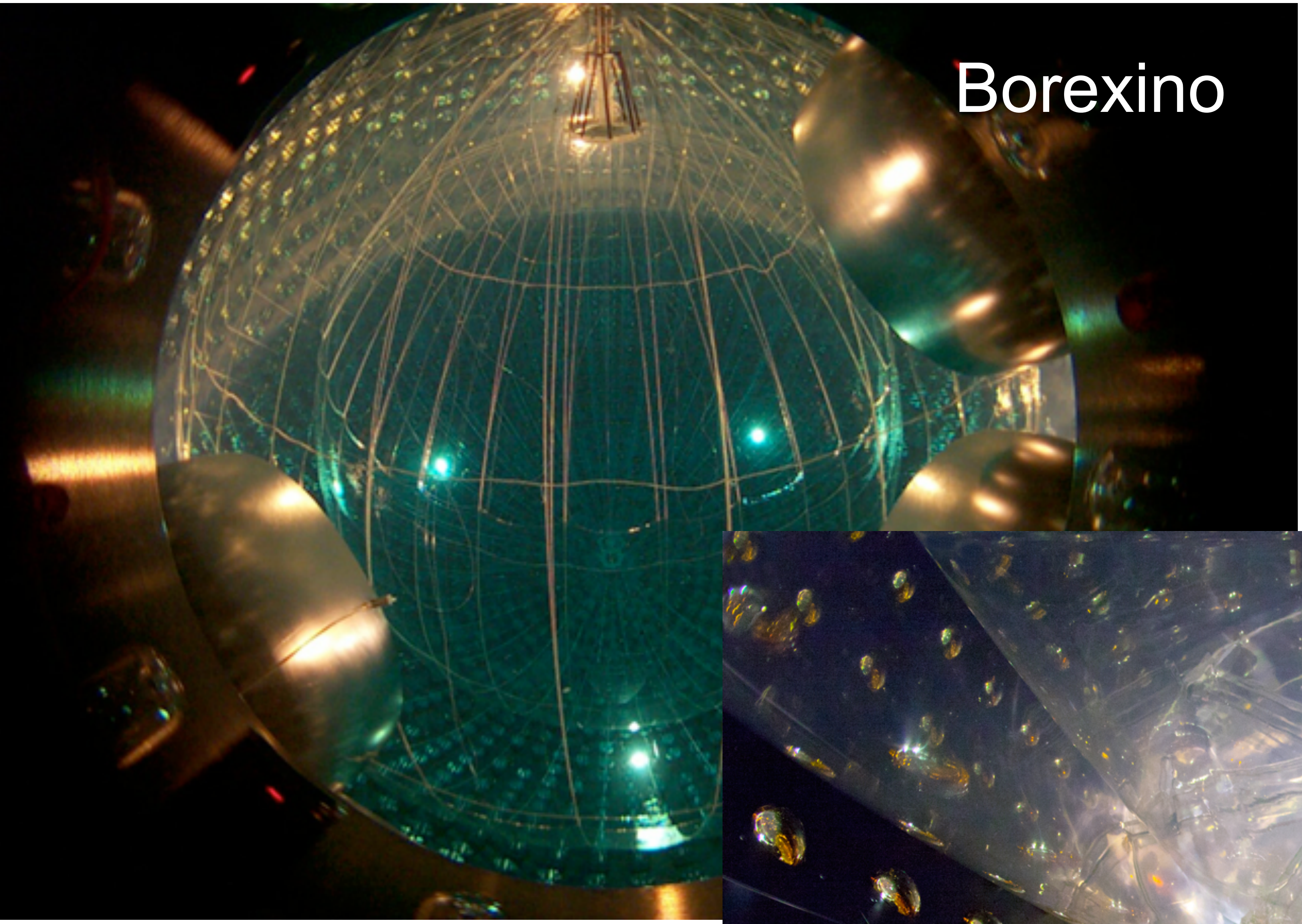

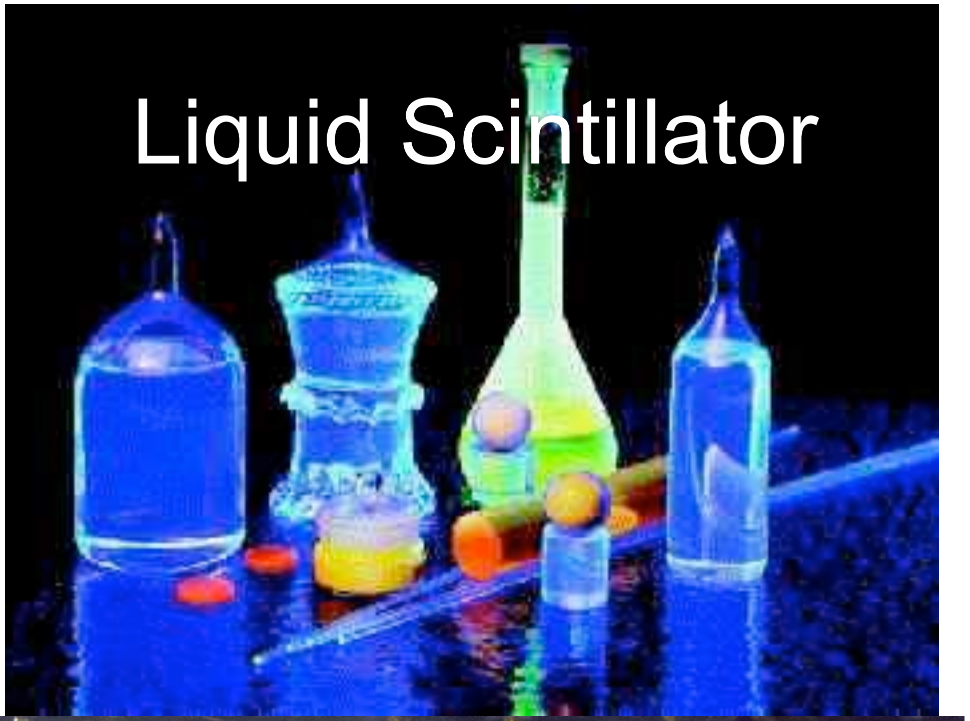

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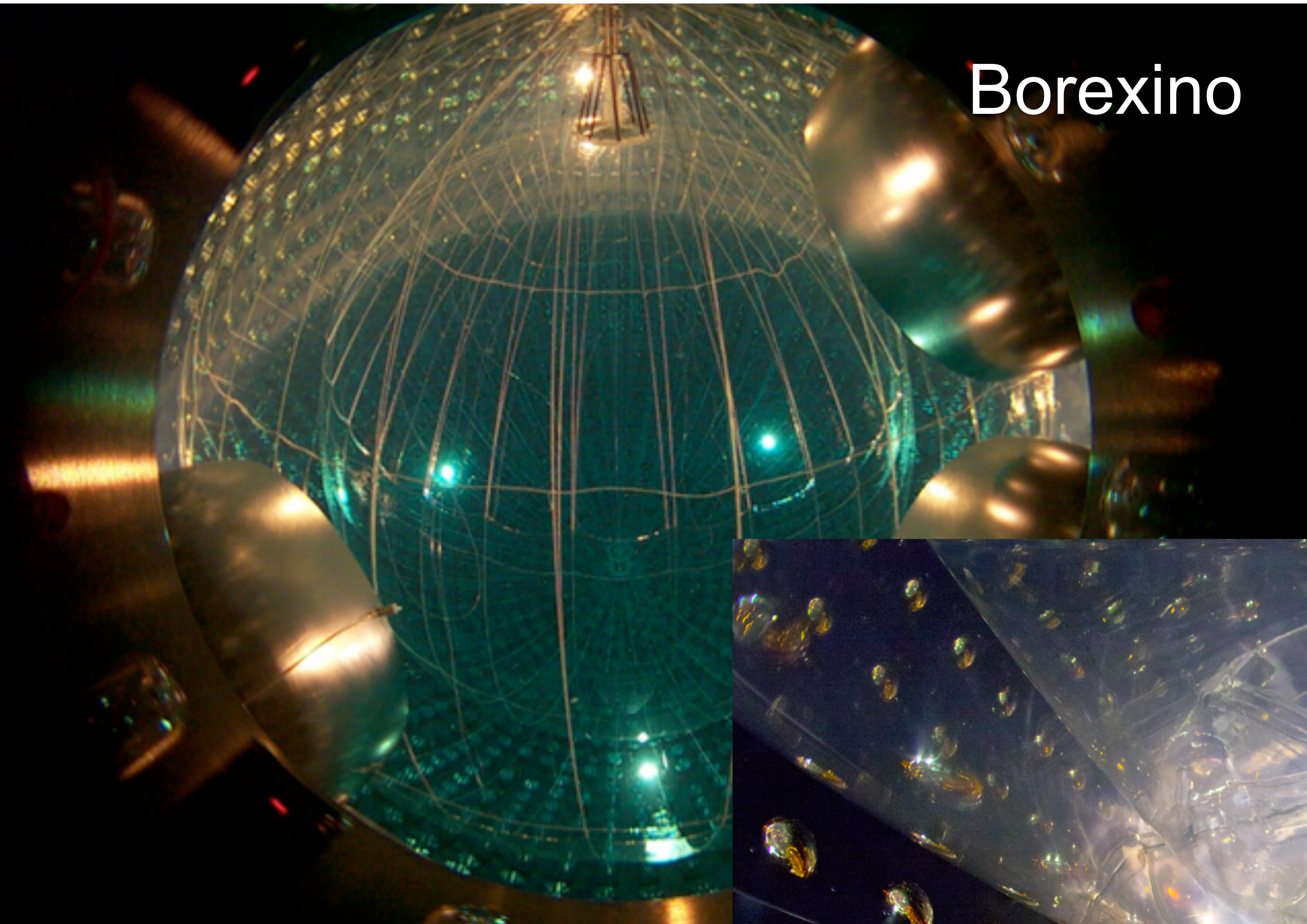
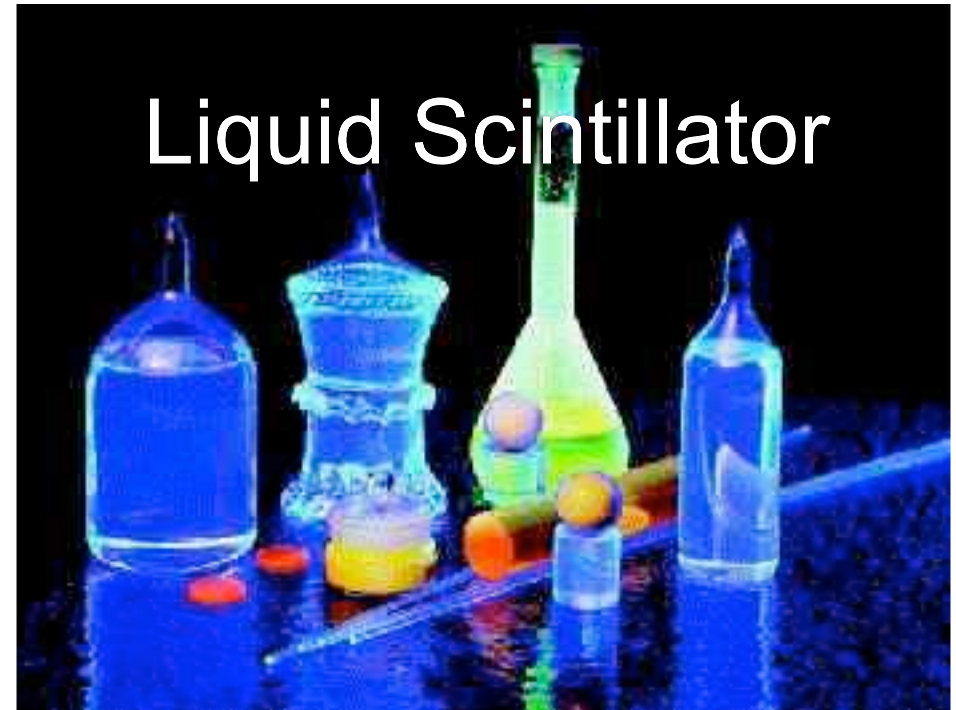
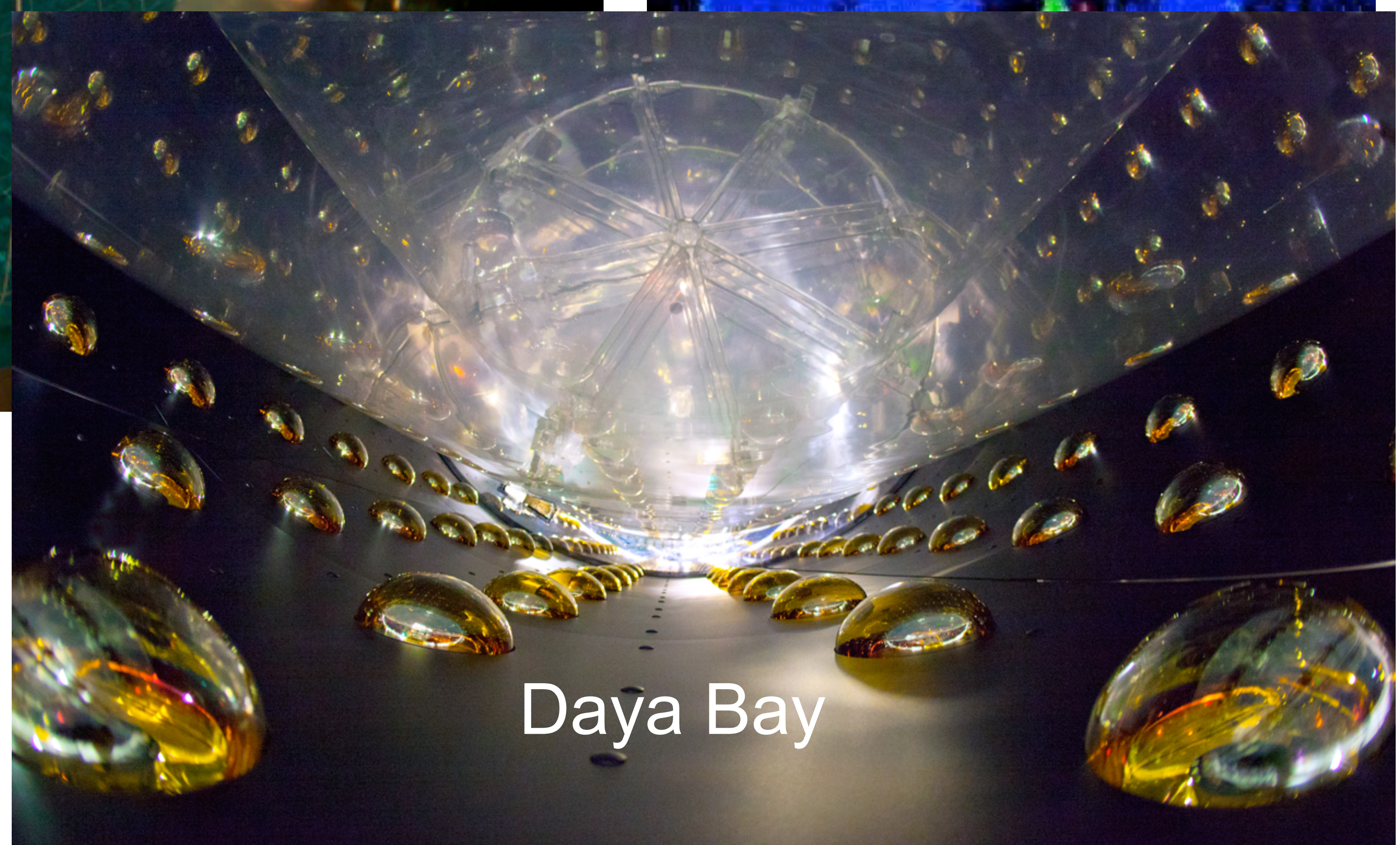
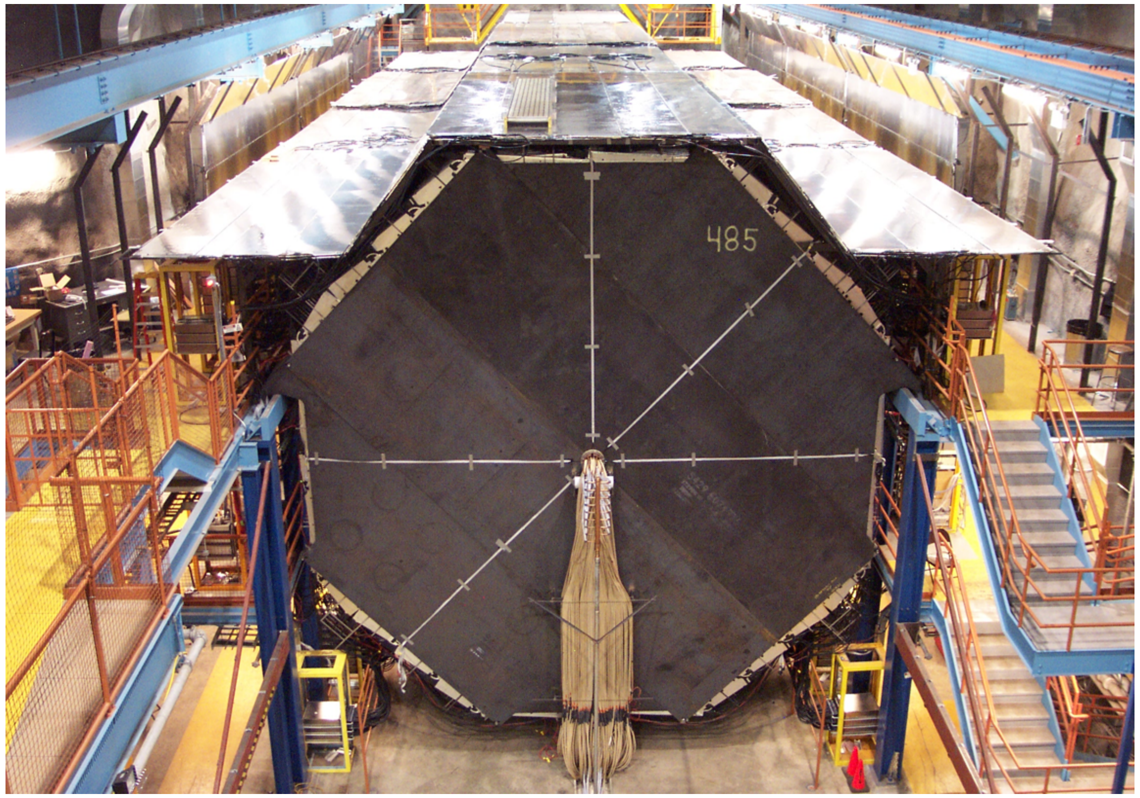






Energy threshold:
all particles: few MeV

Neutrino Detectors - Some Examples



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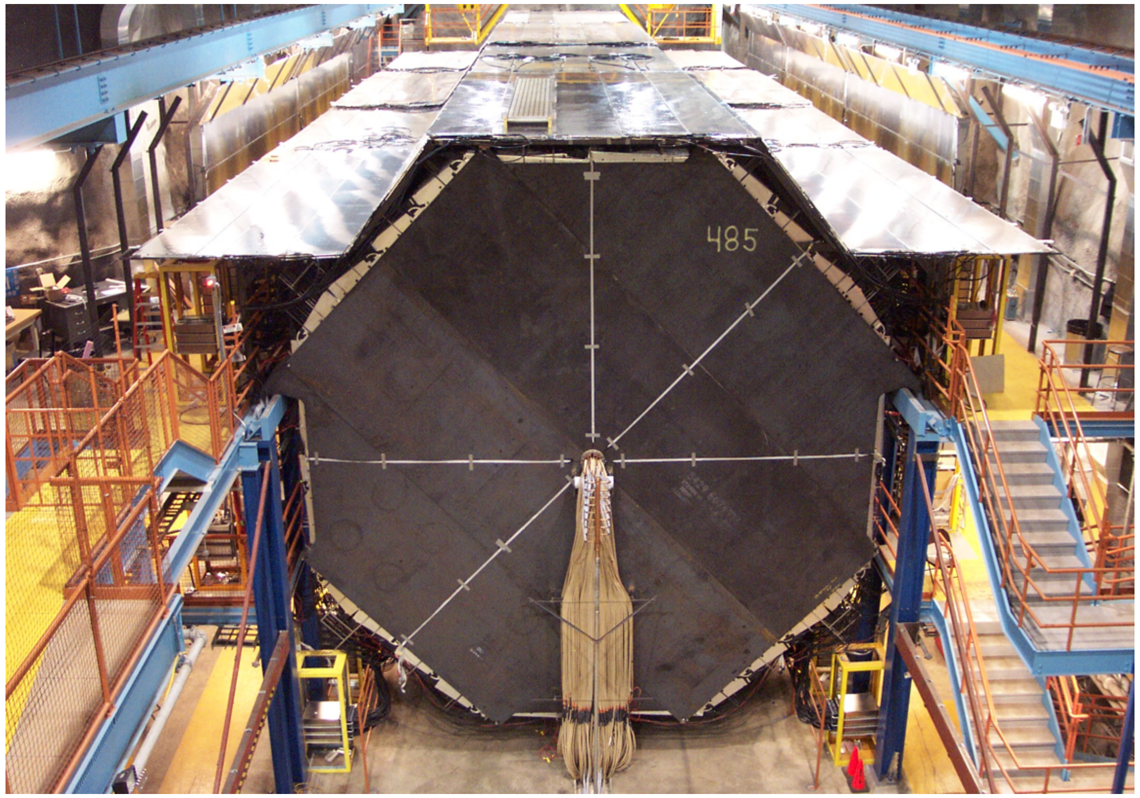

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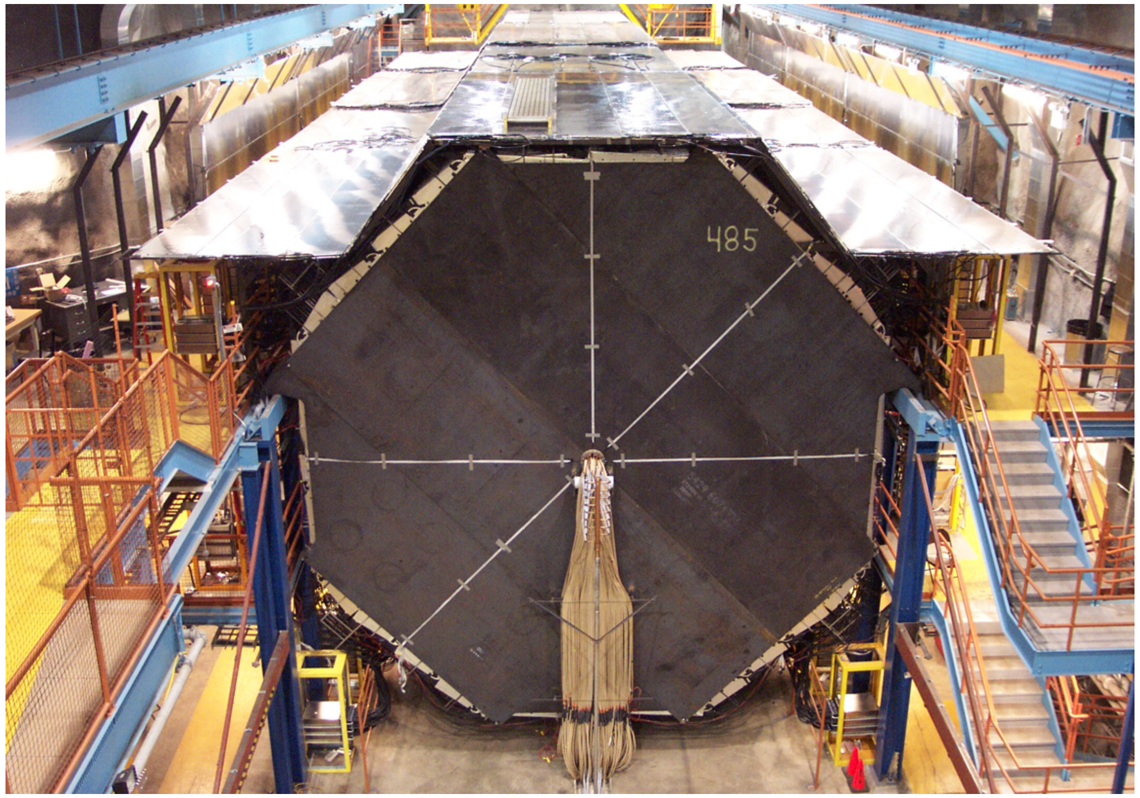

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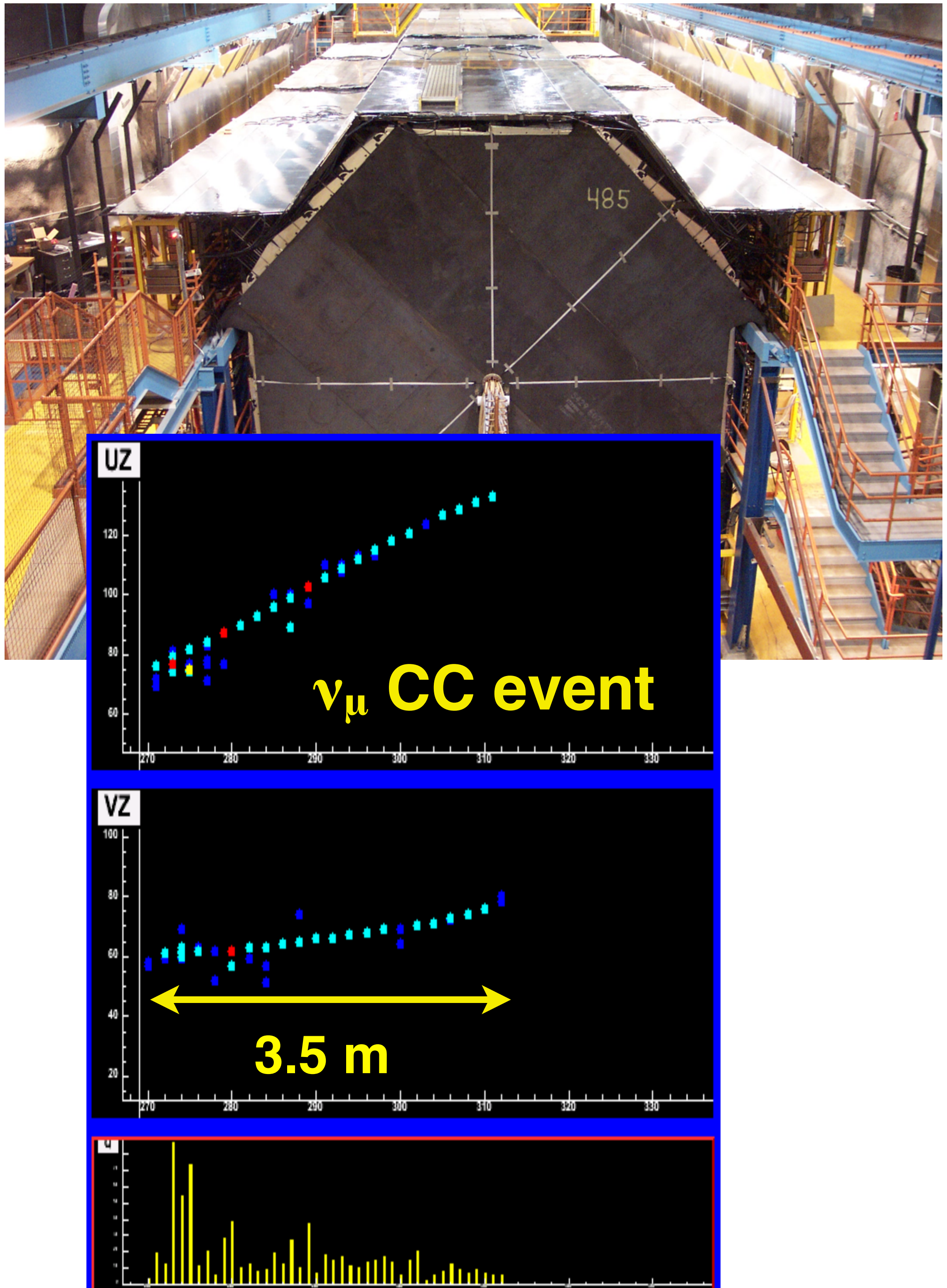
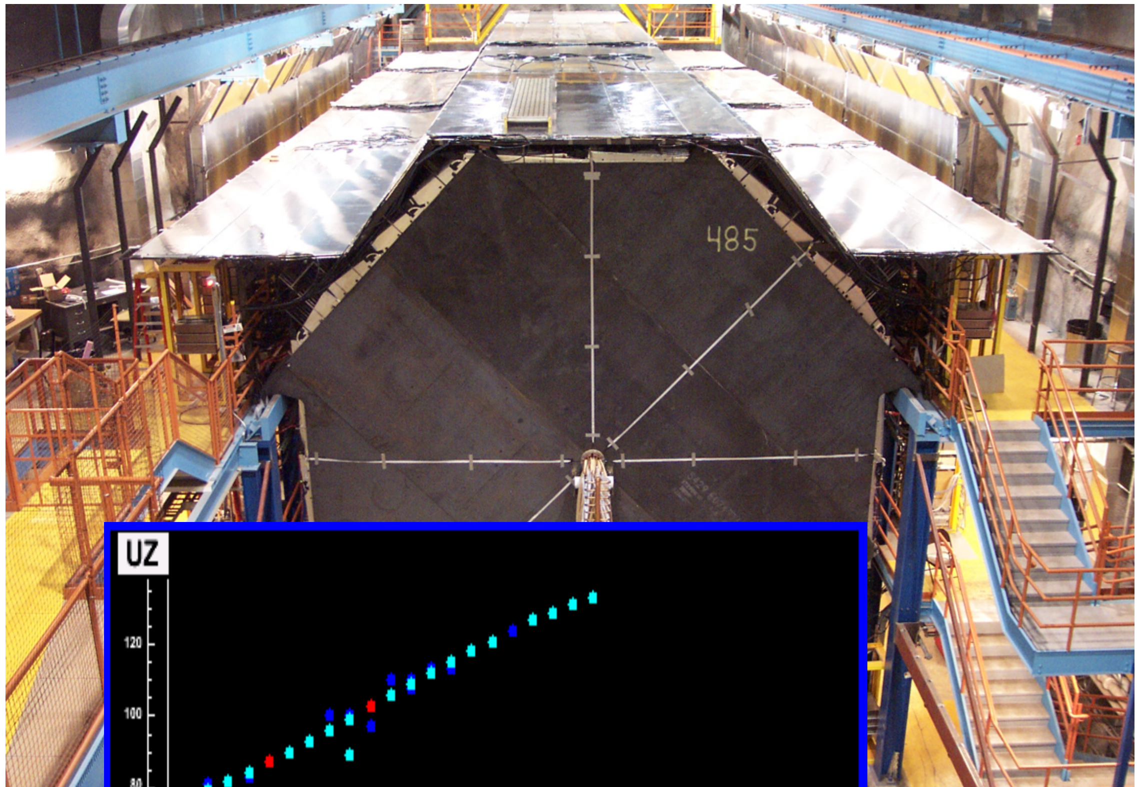
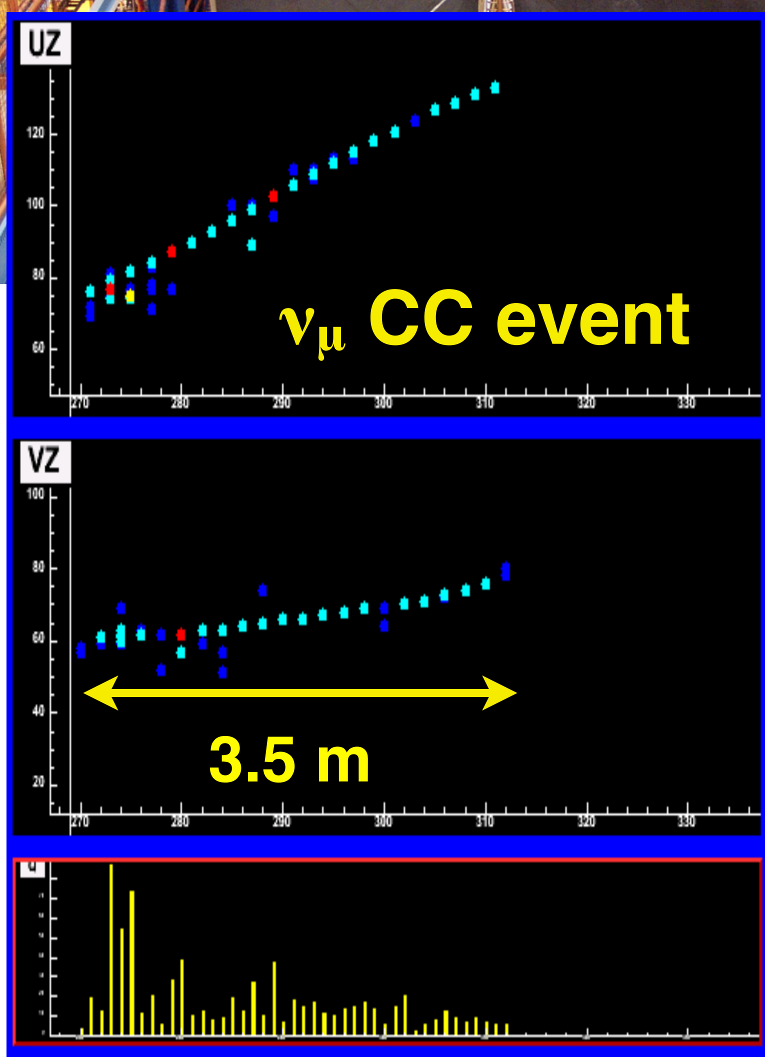


Long μ track +
shower at vertex

Neutrino Detectors - Some Examples

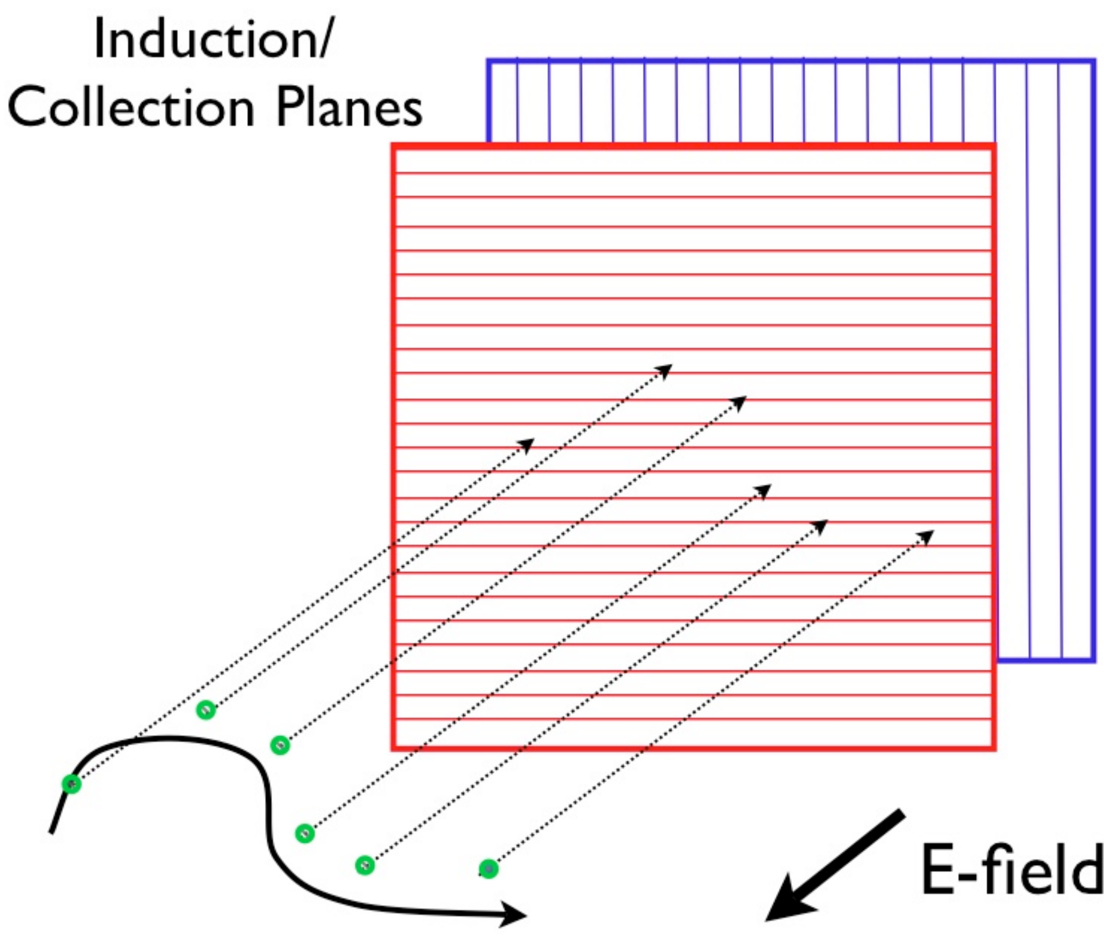




Long μ track +
shower at vertex

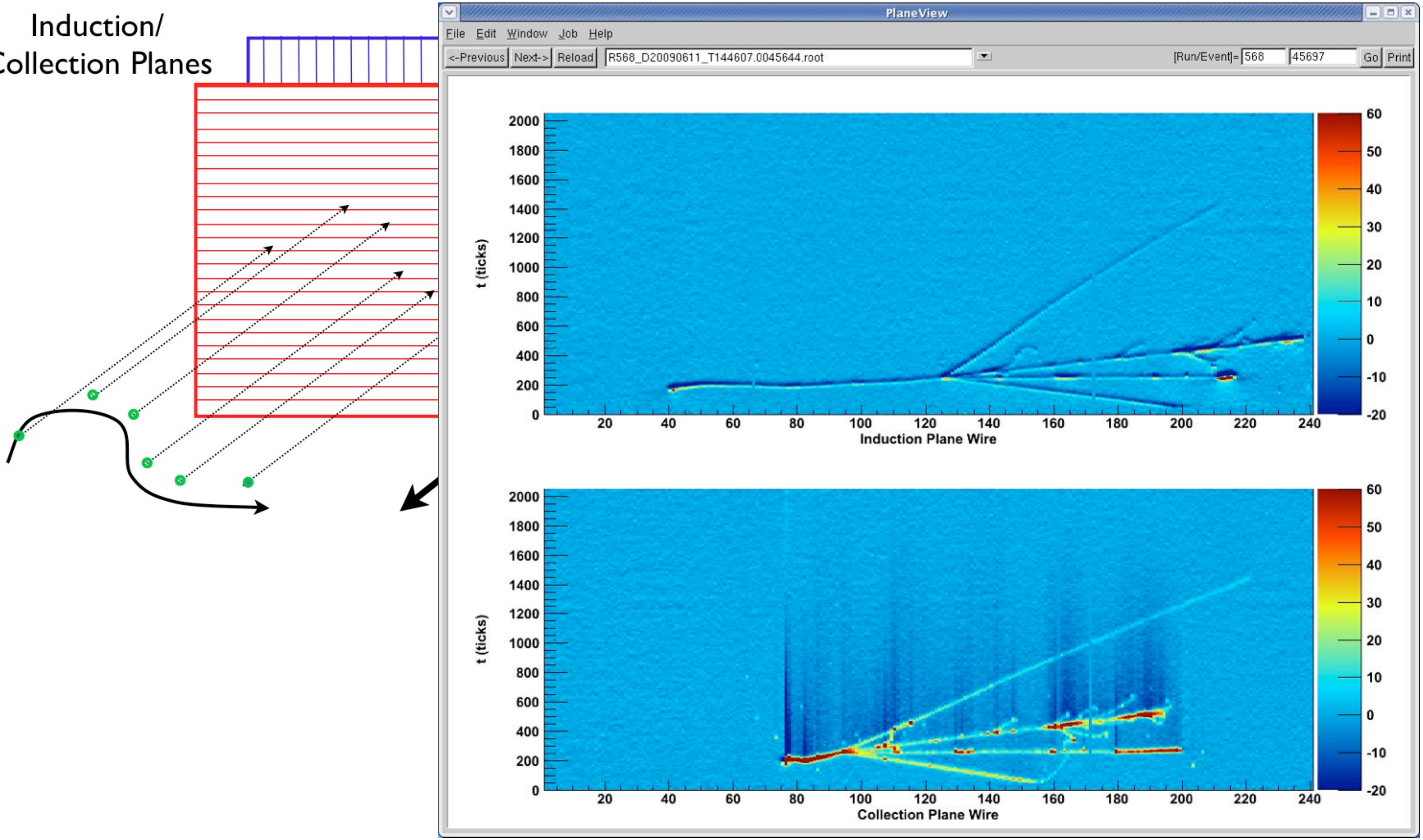
Effective energy threshold:
all particles: 10's - 100's MeV

Neutrino Detectors - Some Examples

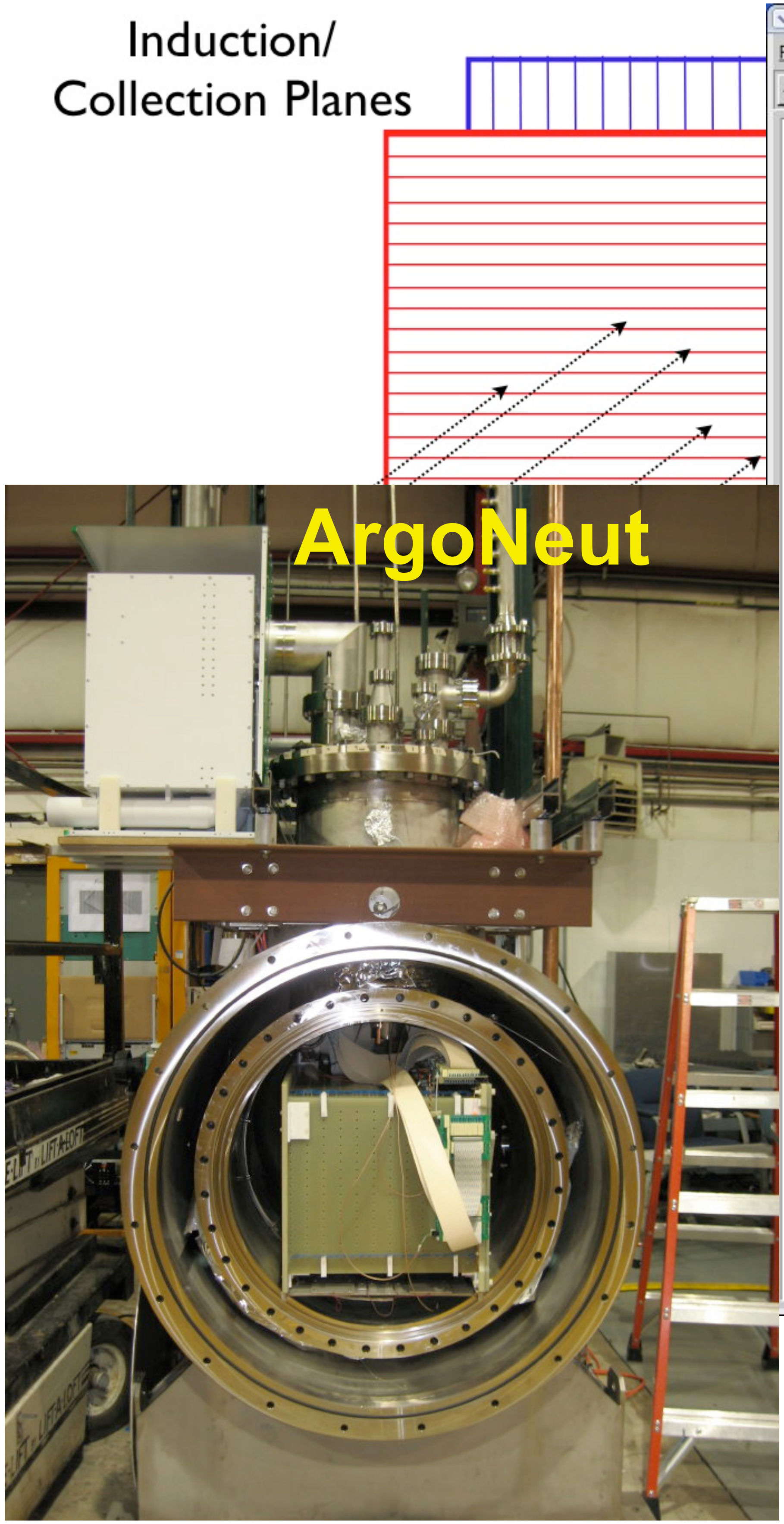


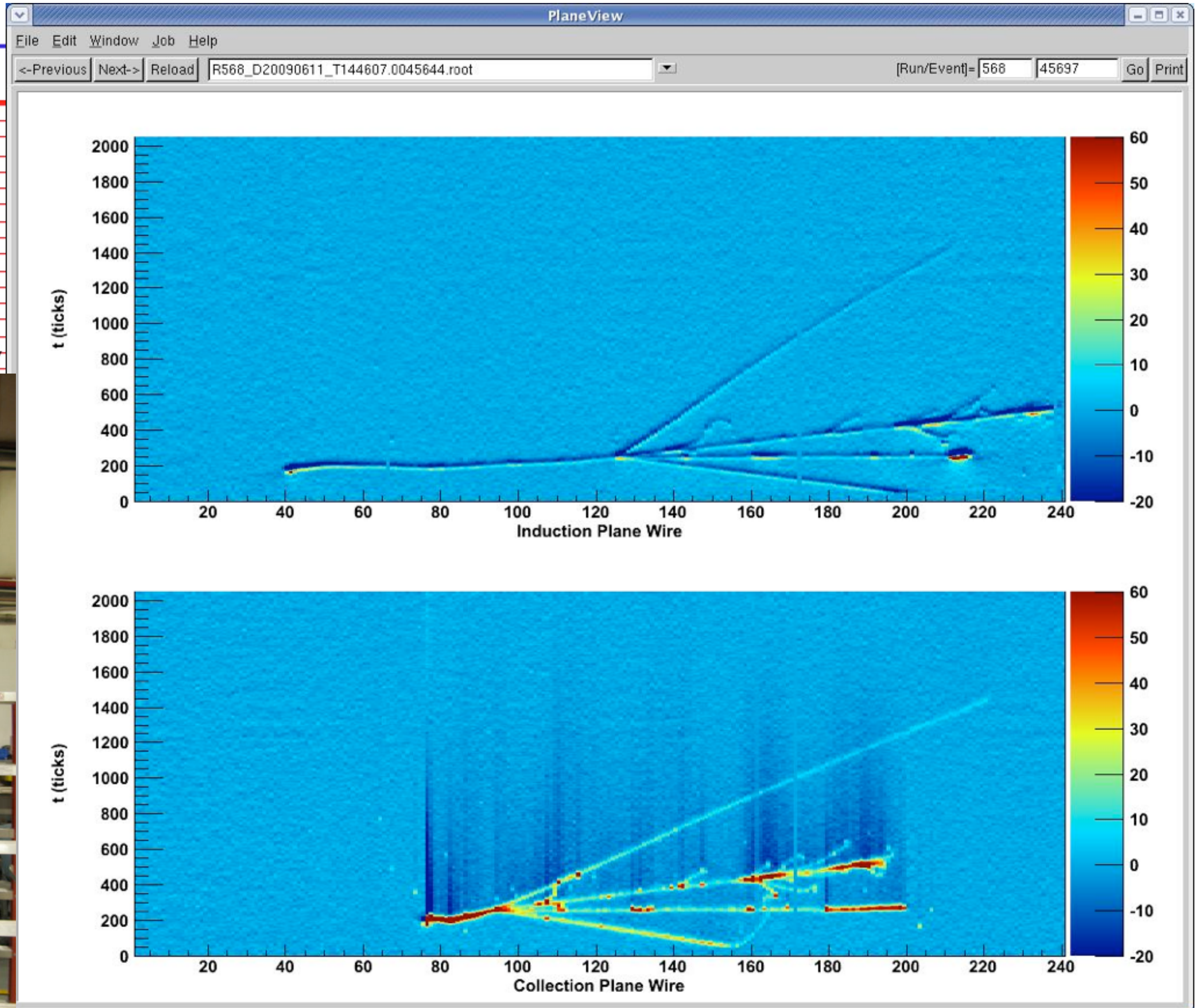
Neutrino Detectors - Some Examples

Induction/
Collection Planes

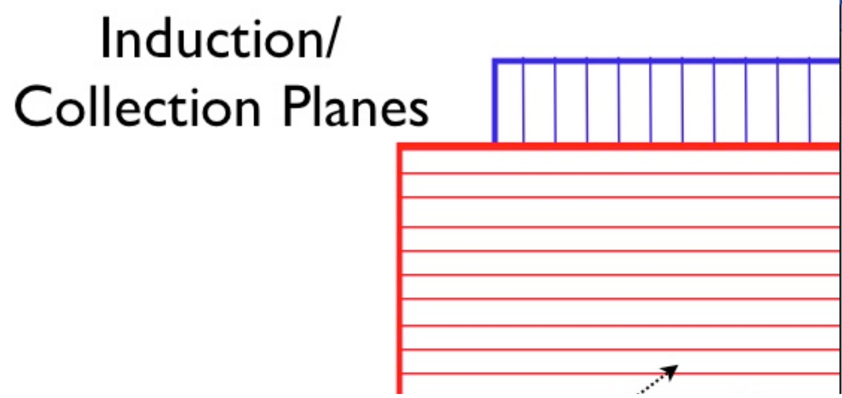


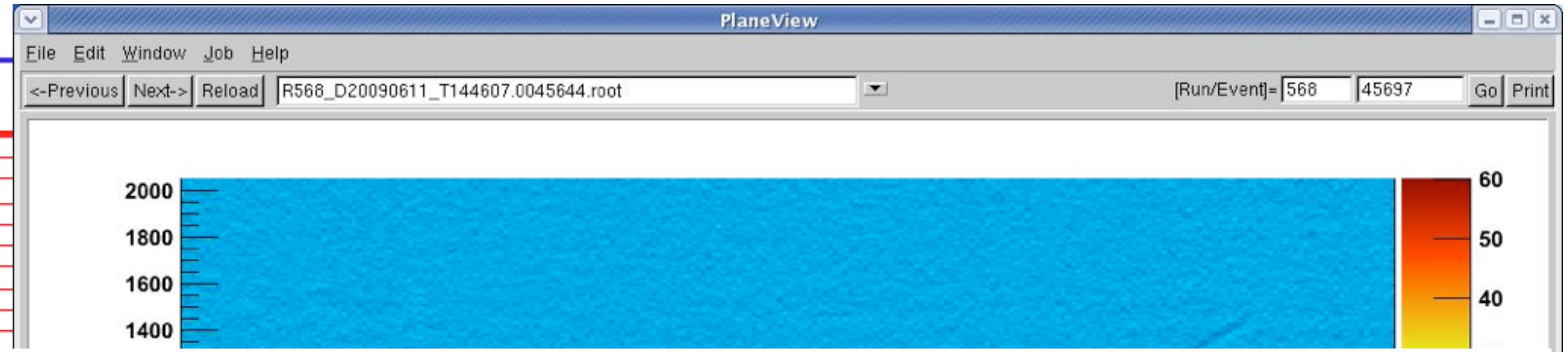
Neutrino Detectors - Some Examples

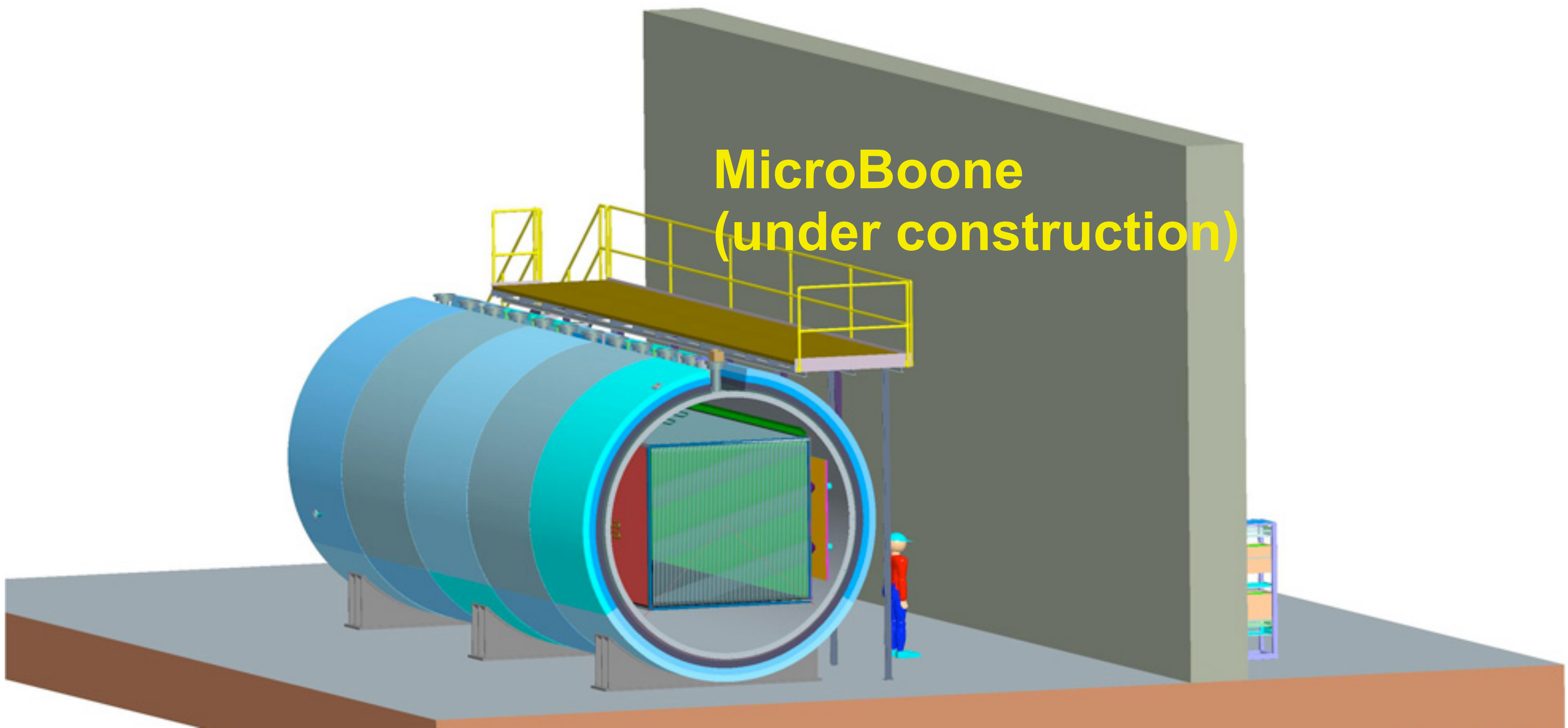




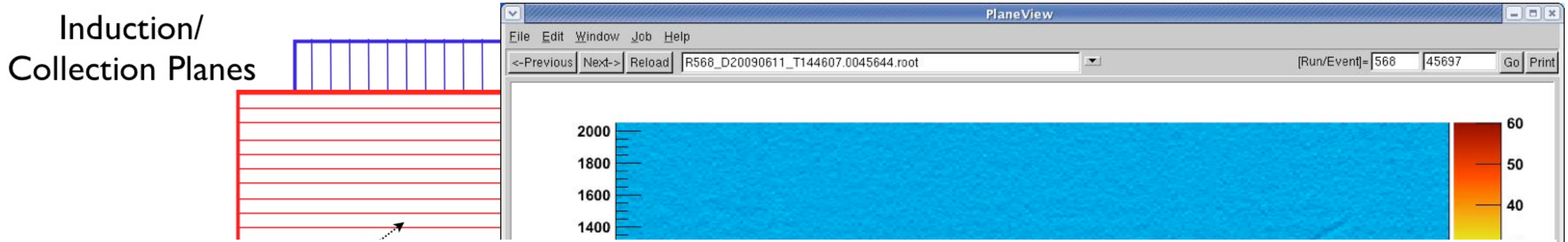
Neutrino Detectors - Some Examples



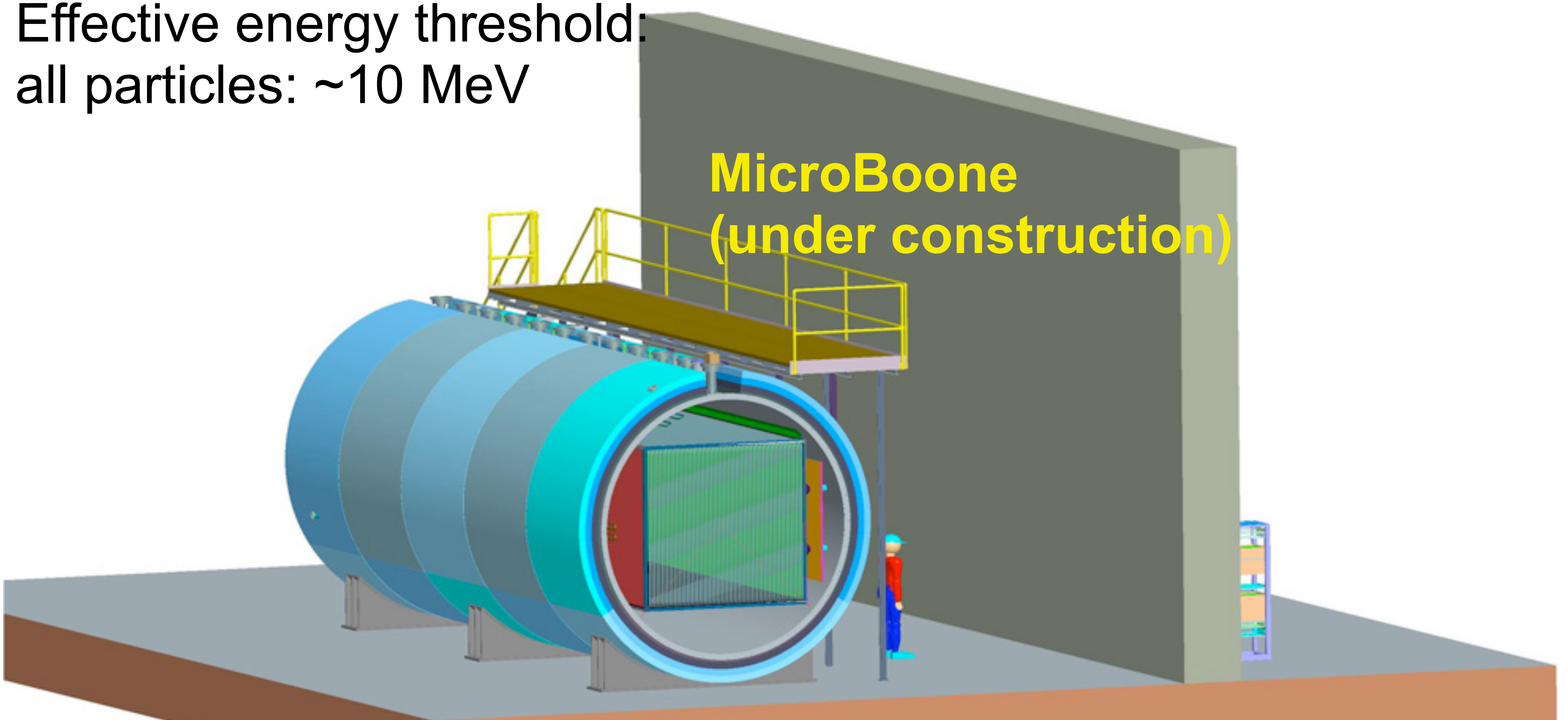




Neutrino Detectors - Some Examples

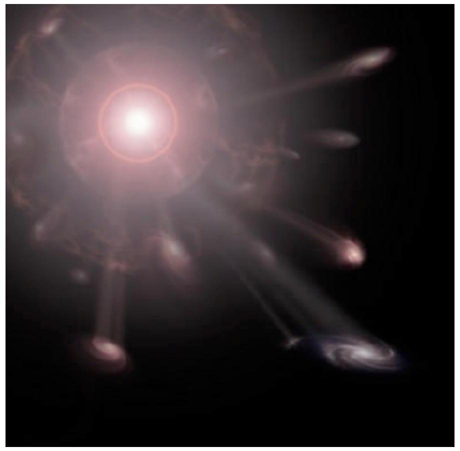


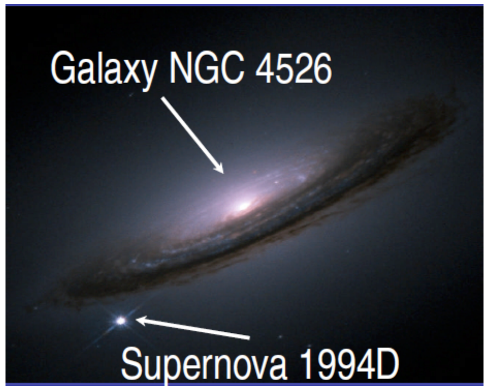
Effective energy threshold:
all particles: ~10 MeV

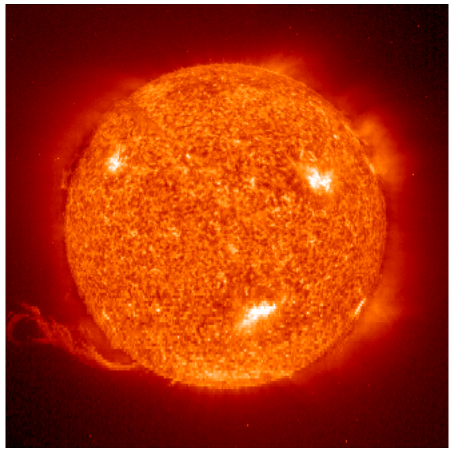


How Are Neutrinos Produced?

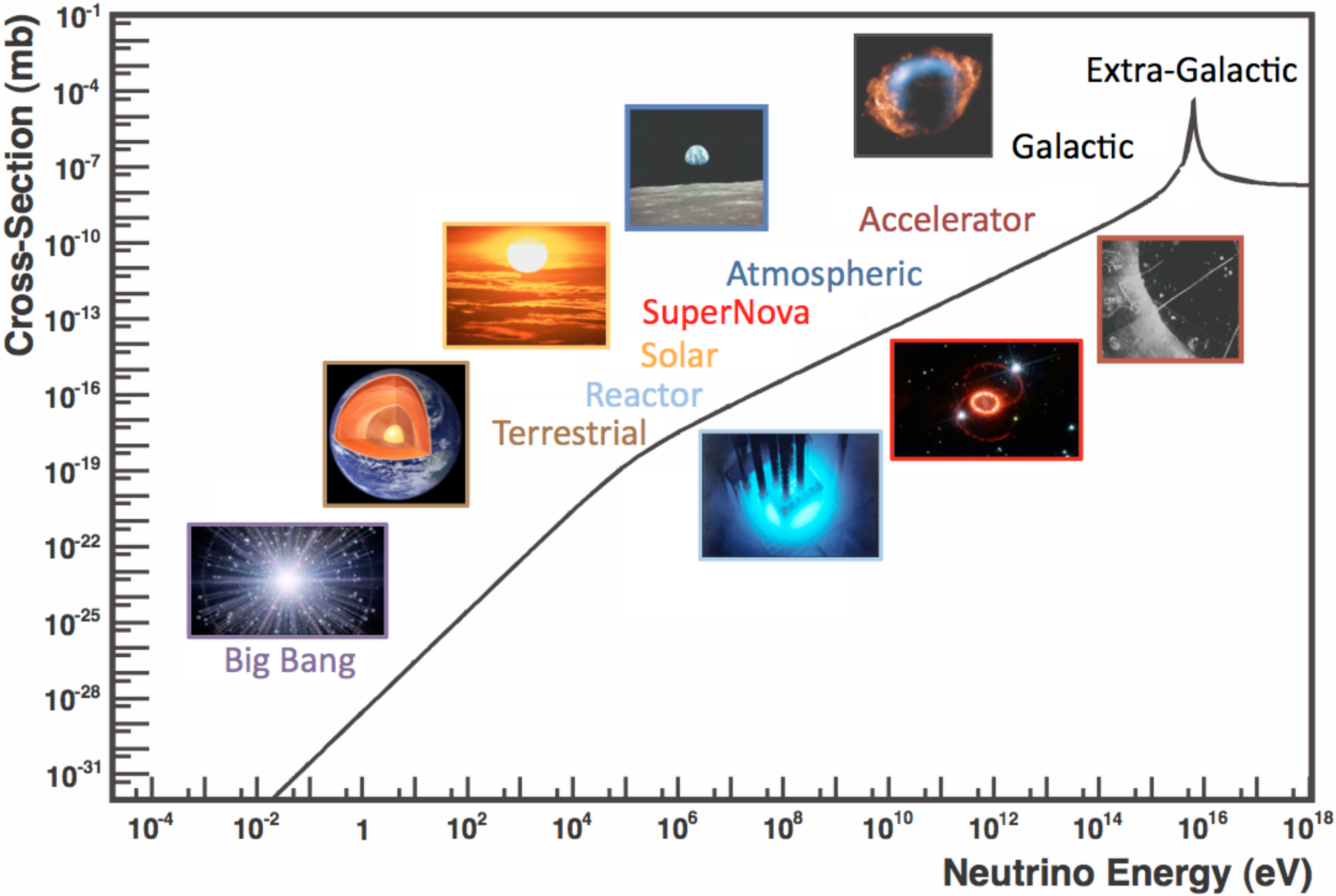
- The universe if full of neutrinos! About 10 x 10^{12} ν's pass through your body each second!
- Nature provides many sources of neutrinos:
  - The Big Bang (411/cm^3 everywhere in the universe)
  - Supernovae (99% of the energy in carried off by neutrinos!)
  - The sun (neutrinos regulate solar fusion)
  - Cosmic ray interactions with the upper atmosphere.
  - Bananas! (~1 million neutrinos/day!)
- Man also creates neutrinos:
  - Nuclear reactors
  - Particle accelerators



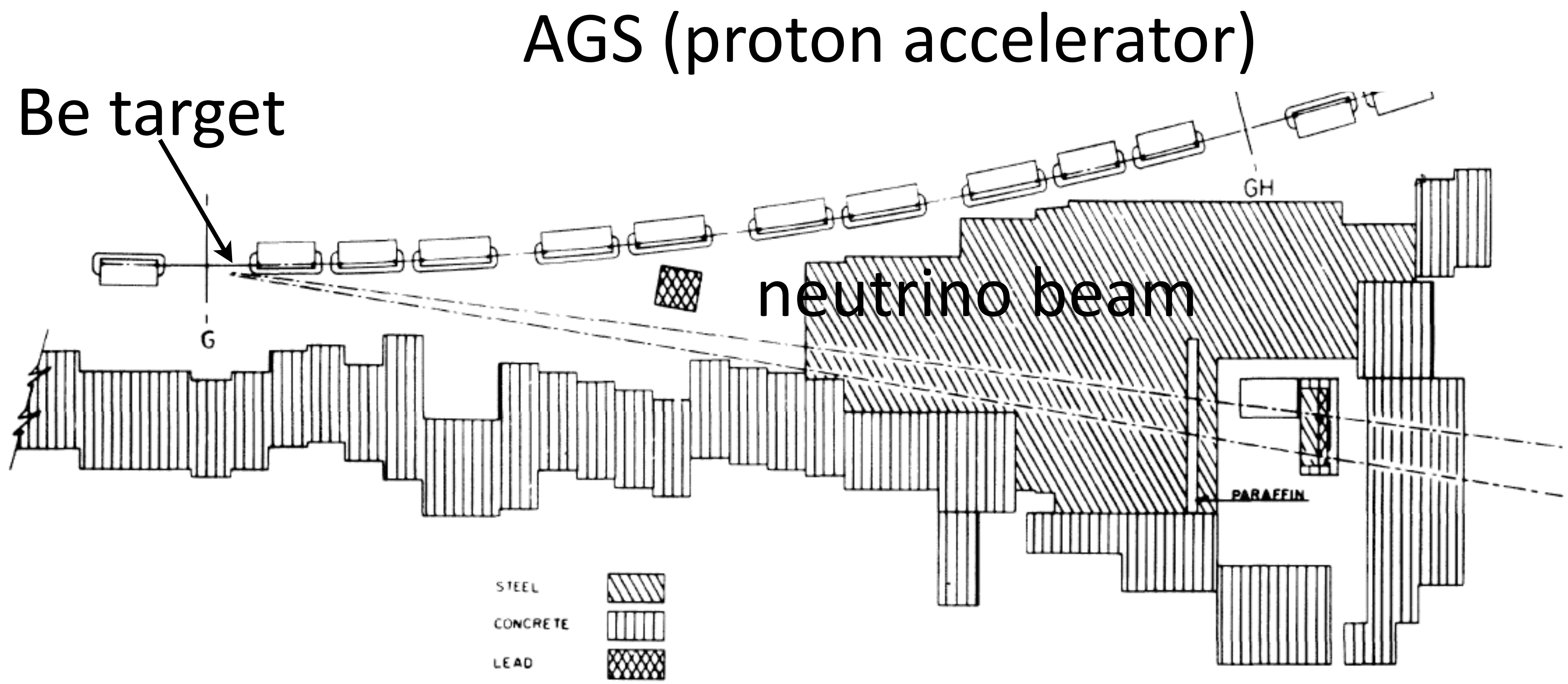




How Are Neutrinos Produced?



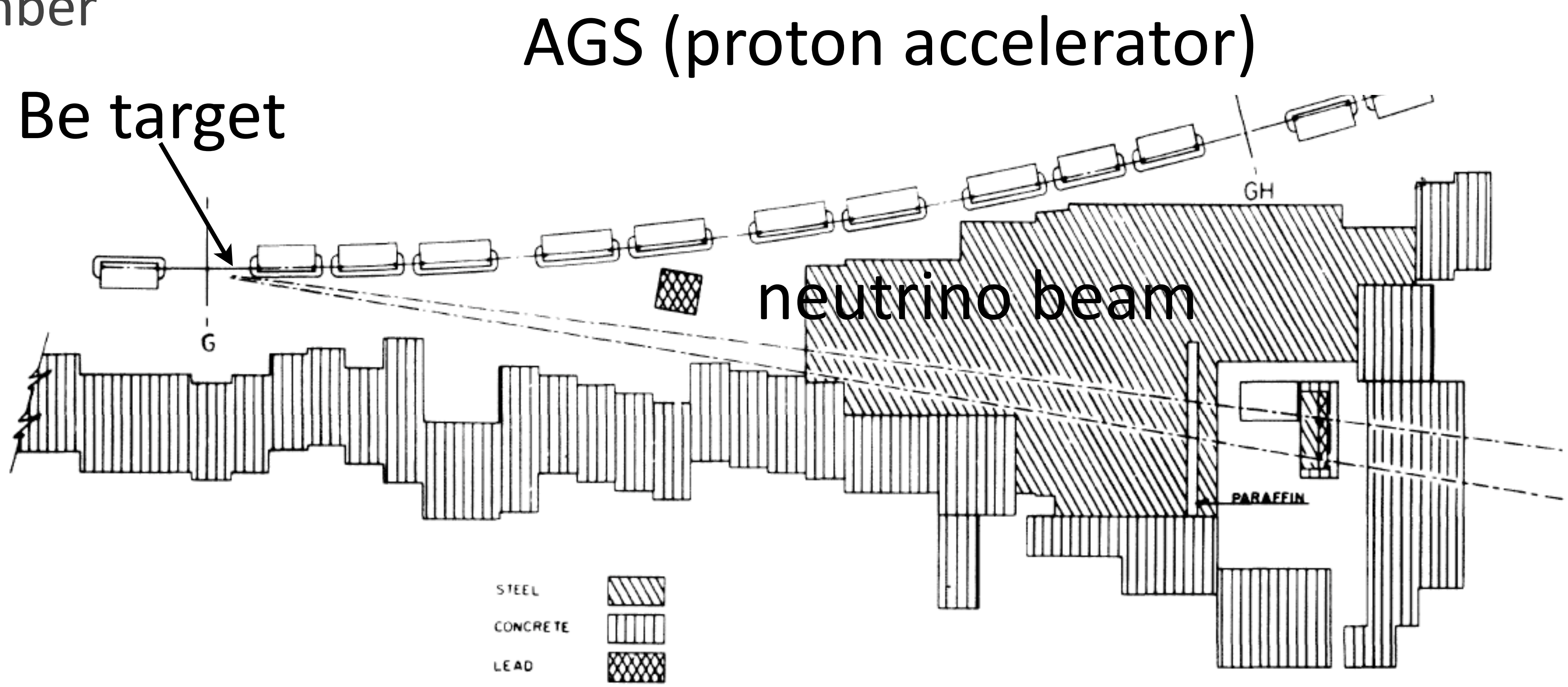
Neutrino Production via Accelerators



PRL, 9(1):36-44, Jul 1962

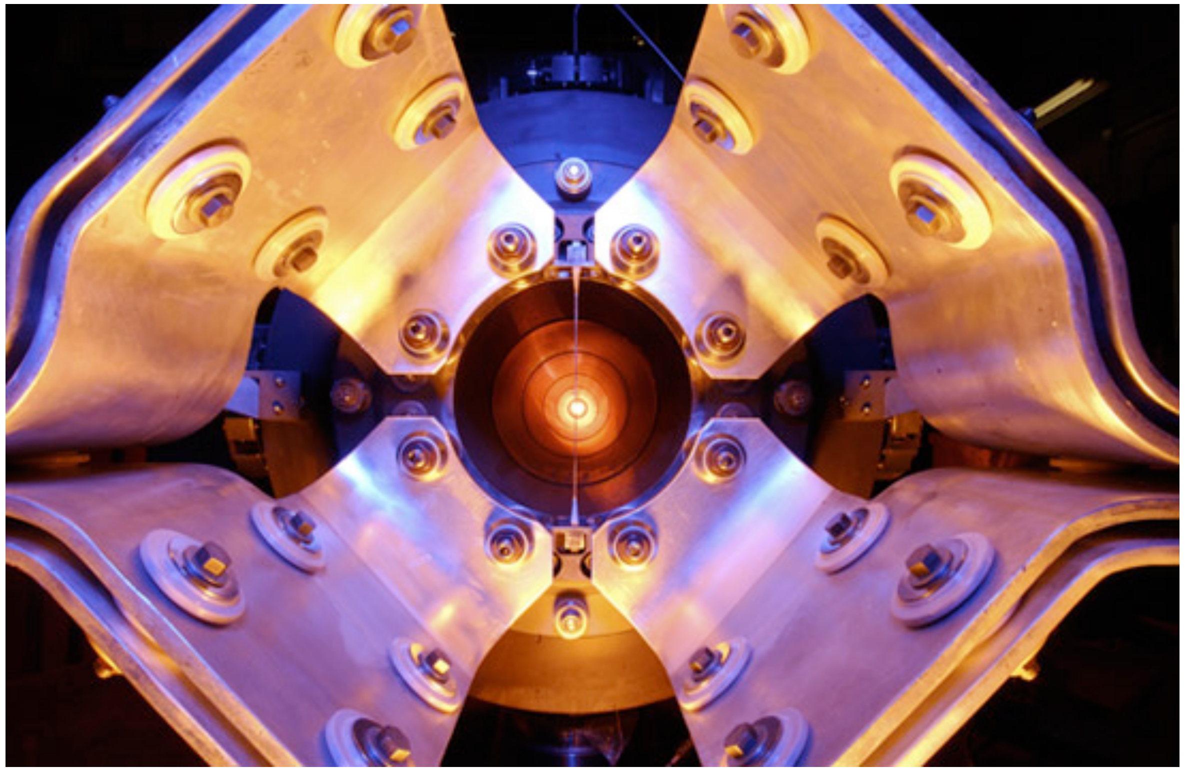
Neutrino Production via Accelerators

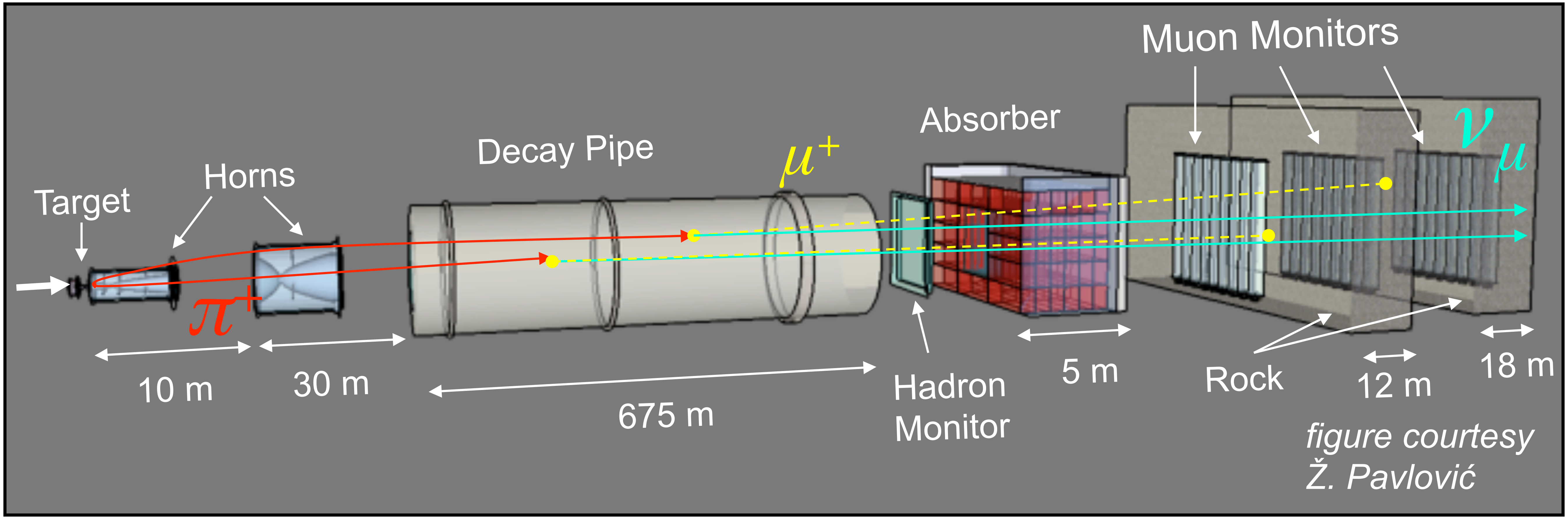
- First accelerator-based neutrino beam: Brookhaven, 1962
- 15 GeV proton beam struck Be target producing secondary hadrons (mostly π's)
- π's decay to neutrinos
- neutrinos interact in detector to produce electrons or muons
- detector: spark chamber



PRL, 9(1):36-44, Jul 1962

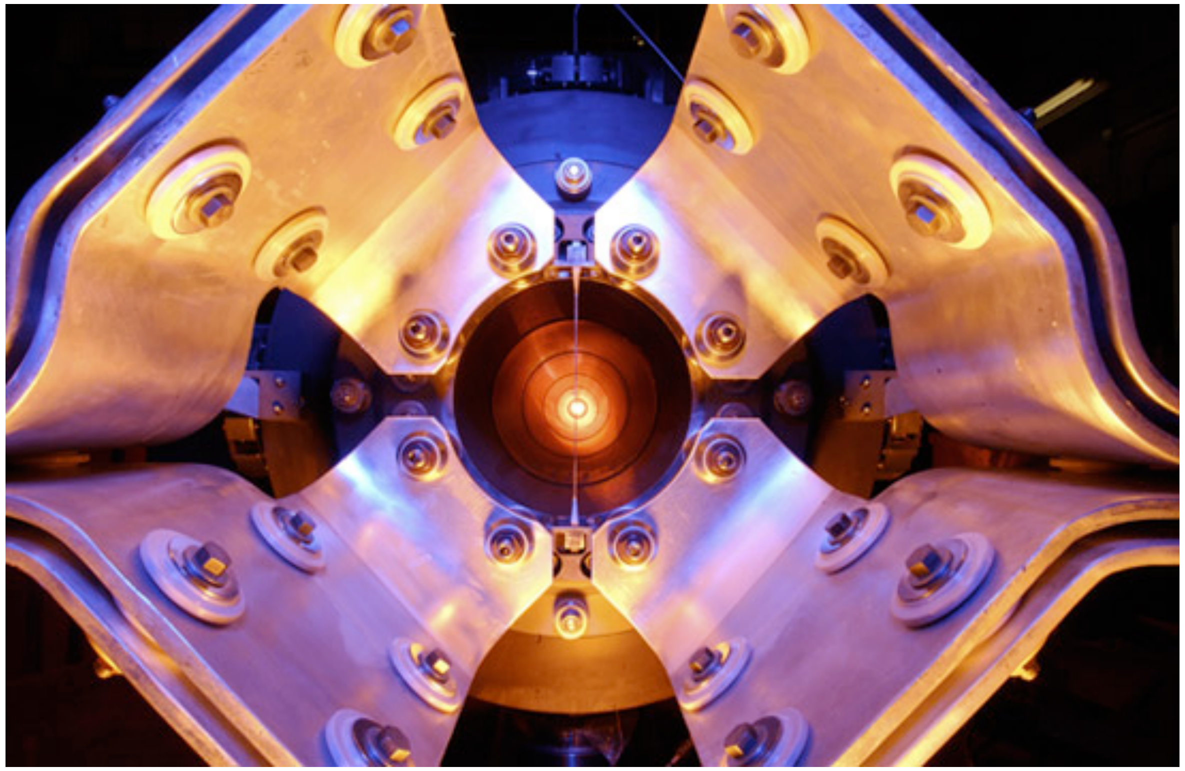
Neutrino Production via Accelerators

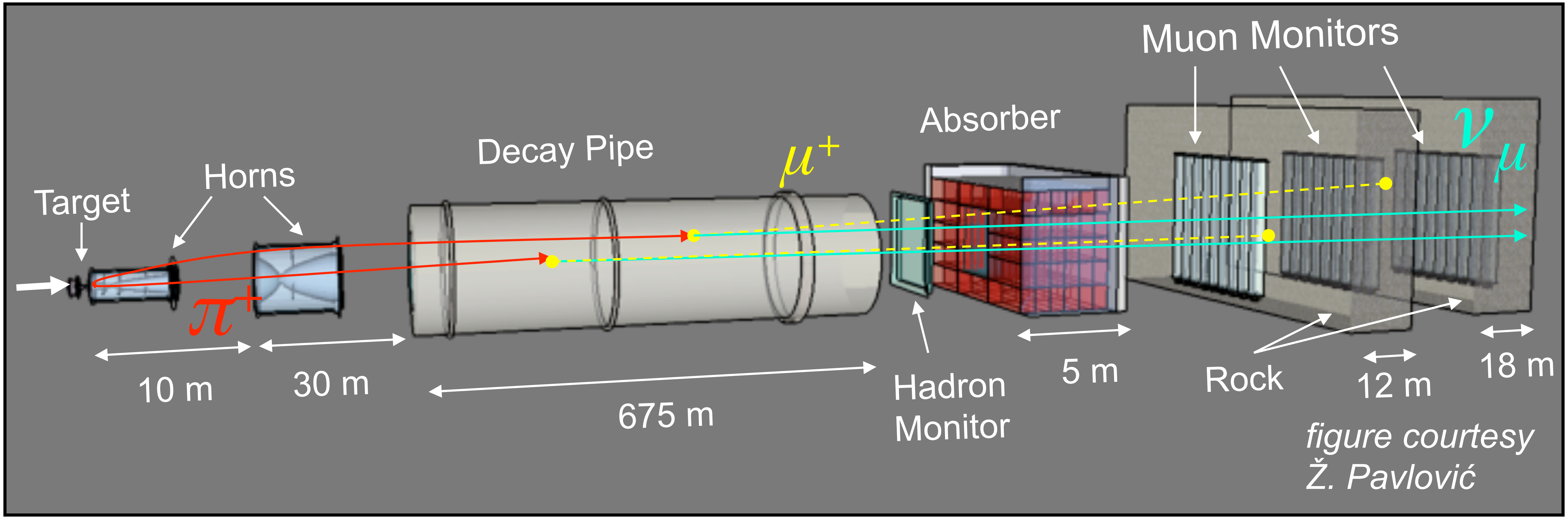




Neutrino Production via Accelerators

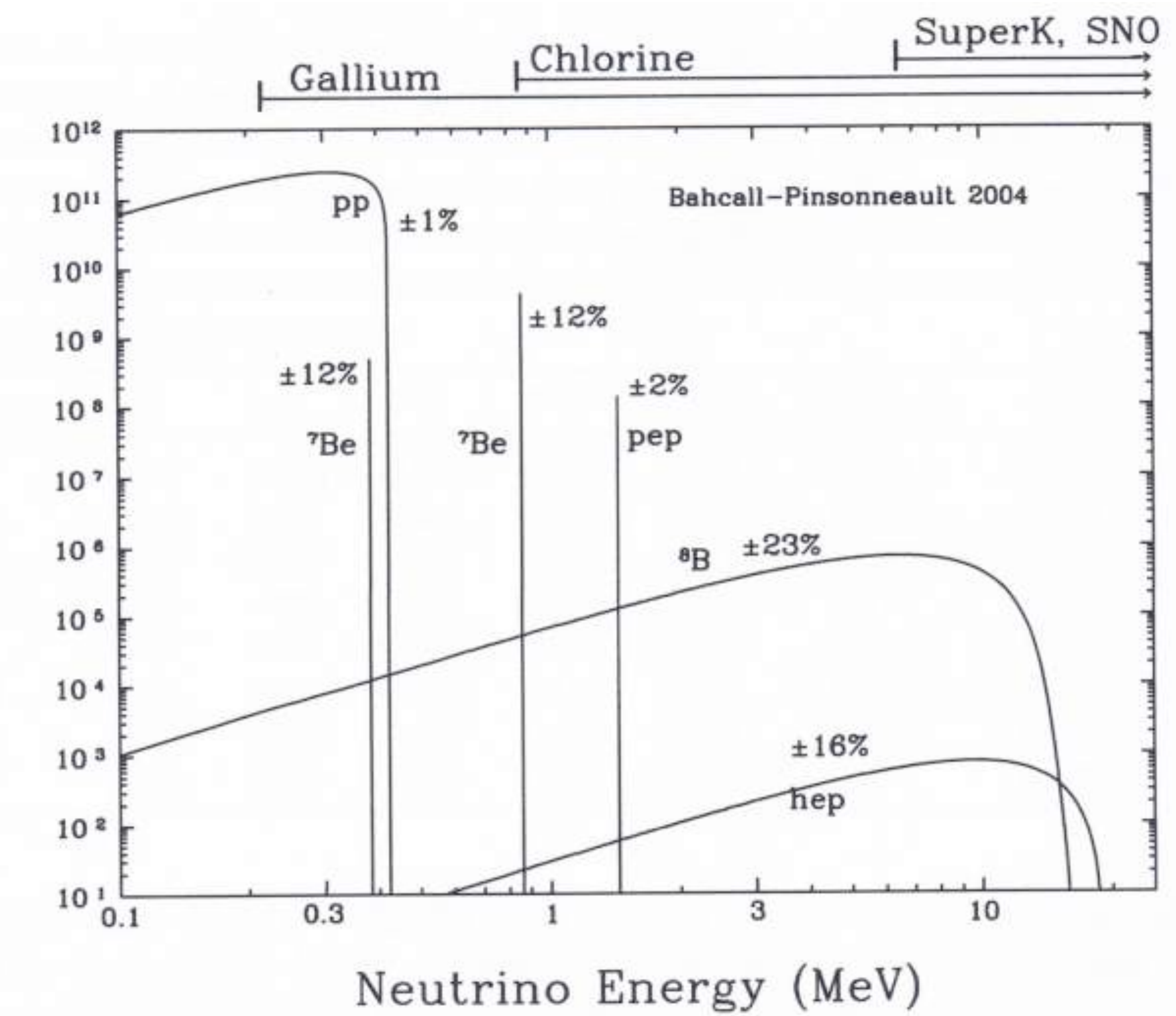
- Modern-day neutrino beams are not all that different.
- Main improvement is use of magnetic focusing horns, increase flux by ~6x.

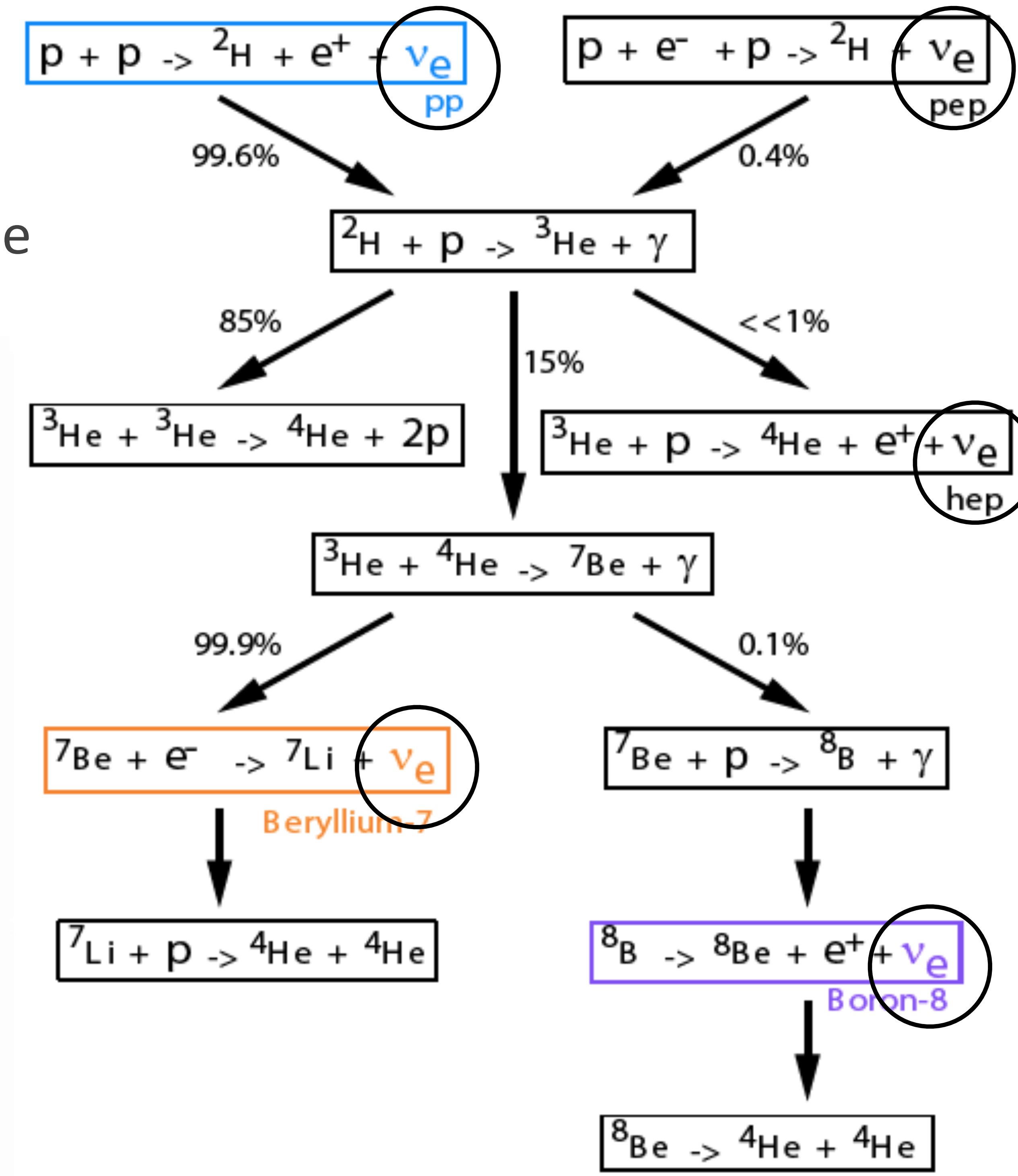




The Solar Neutrino Problem

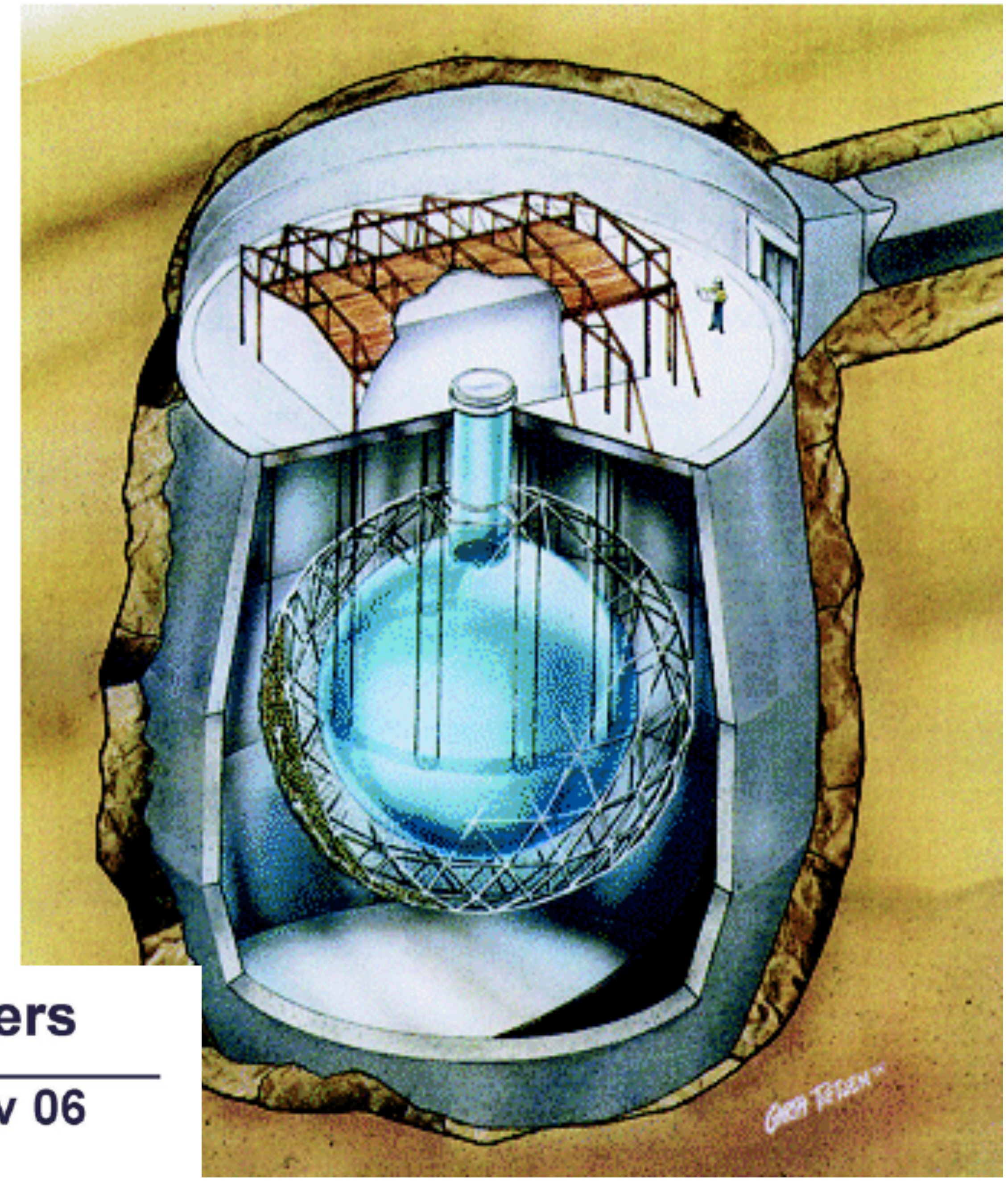
- We expect to see only ν_e coming from the sun.
- Precise solar models allow us to predict the energy spectra of neutrinos from the sun.
- A deficit (~1/2) of ν_es has been observed since the 1960's.





The Sudbury Neutrino Oscillation (SNO) Detector

- 1 kton of D2O (^2H_2O)
- Sensitive to:
  - CC: $\nu_e + {}^2H \rightarrow p + p + e^-$
  - ES: $\nu_\alpha + e^- \rightarrow \nu_\alpha + e^-$
  - NC: $\nu_\alpha + {}^2H \rightarrow n + p + \nu_\alpha$



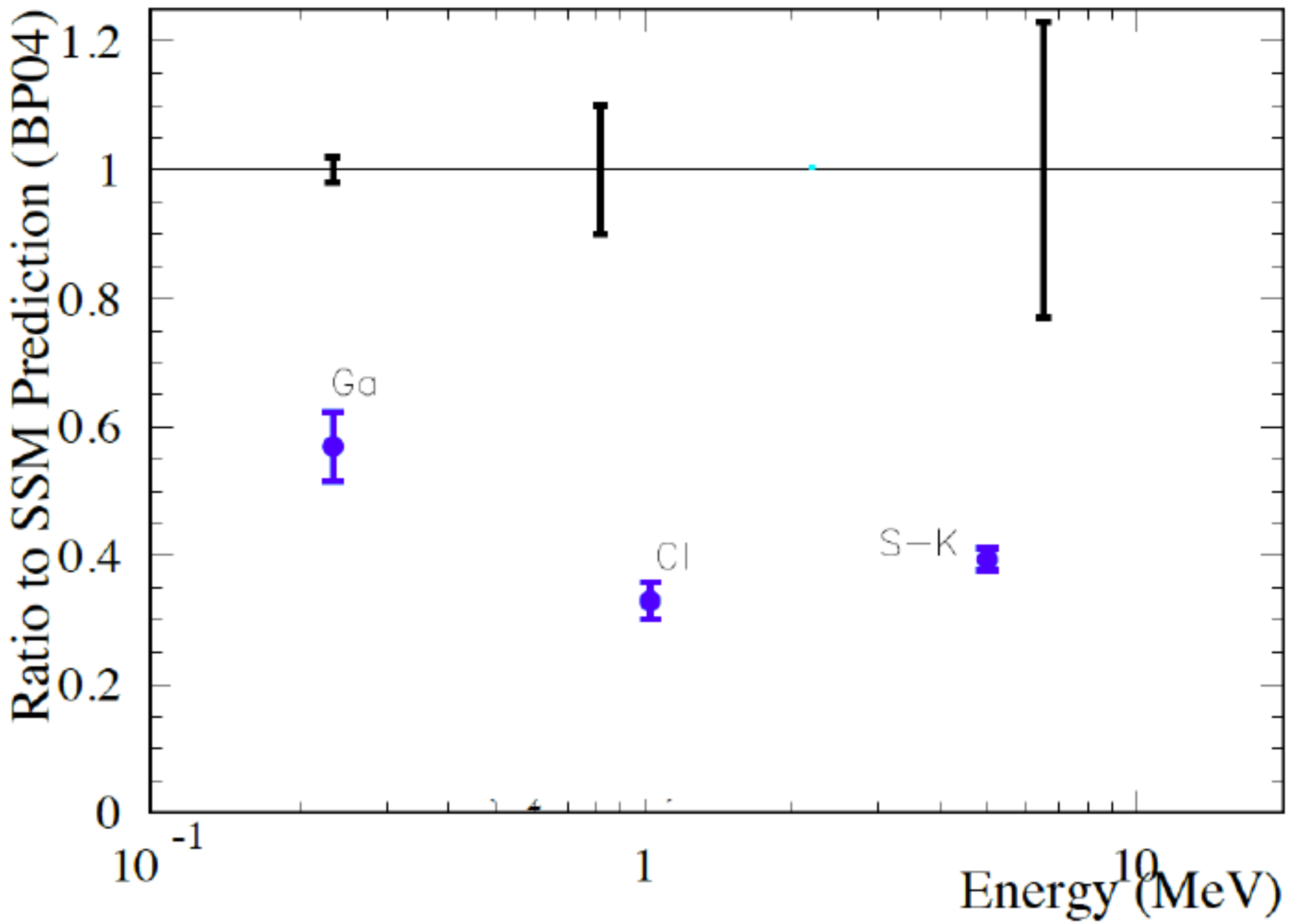
$$R_E = \frac{R_{CC}}{R_{ES}} \neq 1 \quad \text{or} \quad R_N = \frac{R_{CC}}{R_{NC}} \neq 1$$

means: $\nu_e \rightarrow \nu_{\mu,\tau}$

Pure D_2O	Salt	^{3}He Counters
Nov 99 – May 01	Jul 01 – Sep 03	Nov 04 – Nov 06
$n + d \rightarrow t + \gamma$	$n + {}^{35}Cl \rightarrow {}^{36}Cl + \Sigma\gamma$	$n + {}^3He \rightarrow t + p$
(E_γ = 6.25 MeV)	($E_{\Sigma\gamma}$ = 8.6 MeV)	proportional counters σ = 5330 b
	enhanced NC rate and separation	event-by-event separation

The Sudbury Neutrino Oscillation Detector

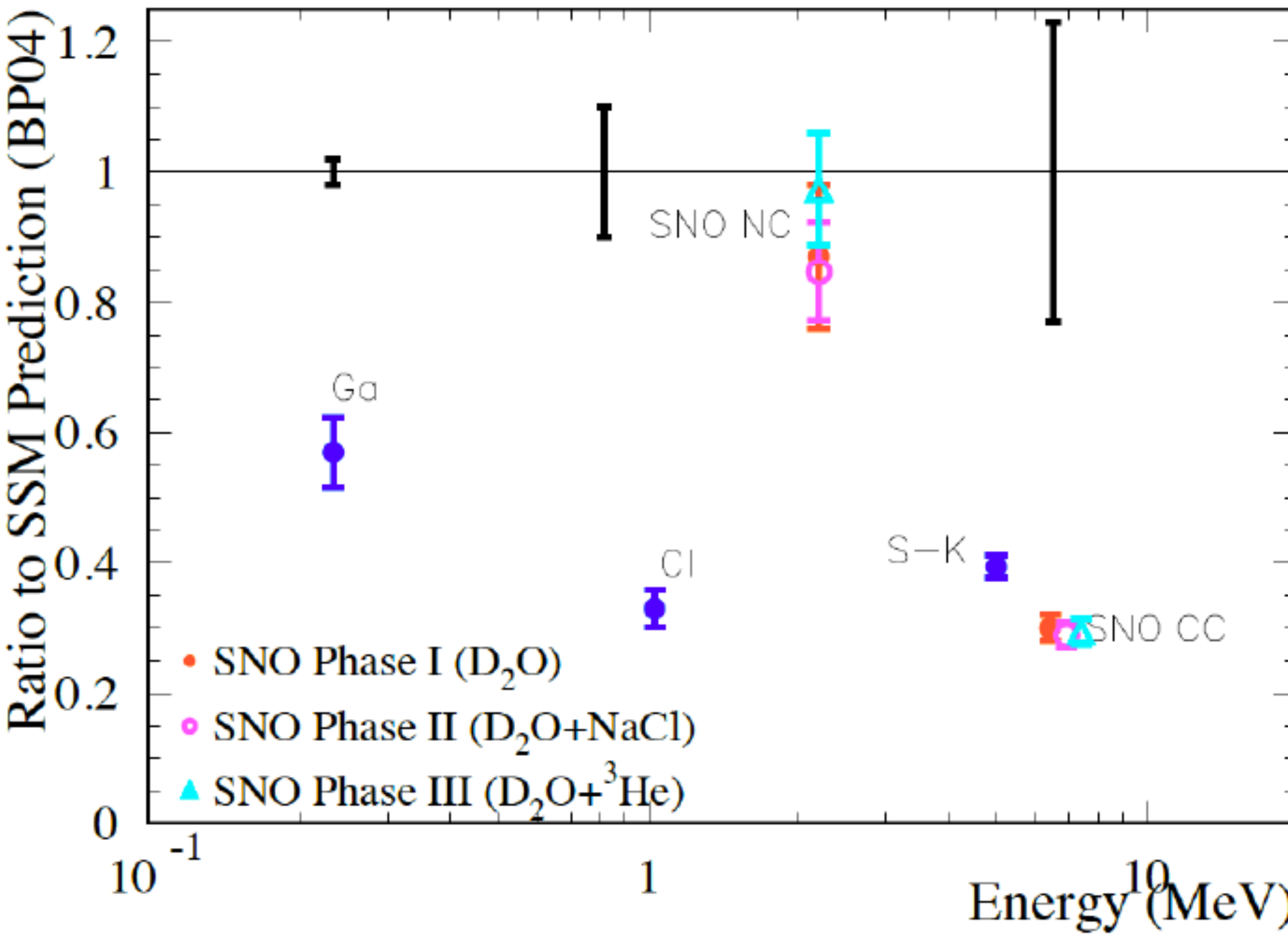
Solar Neutrino Problem



arXiv:1109.0763

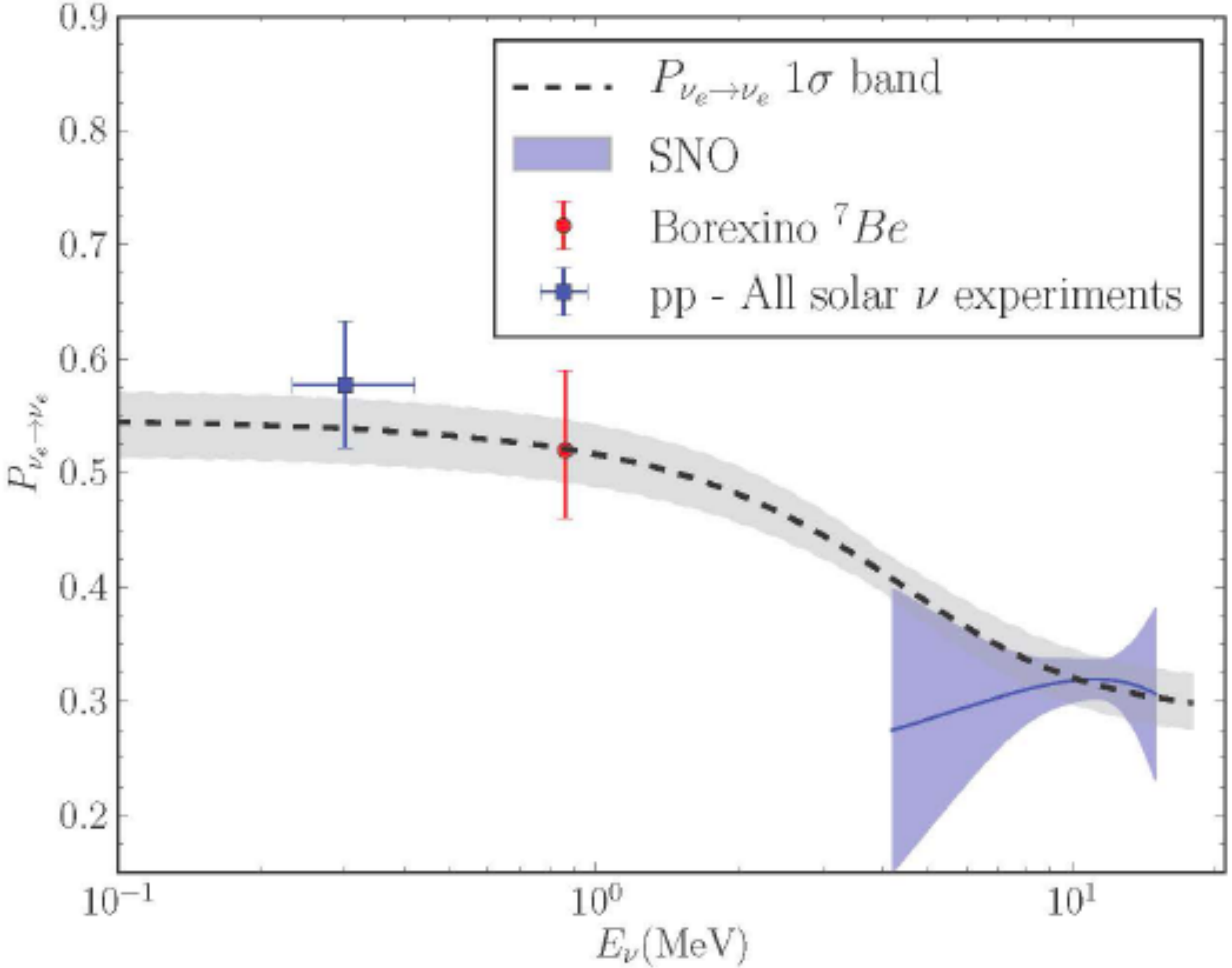
The Sudbury Neutrino Oscillation Detector

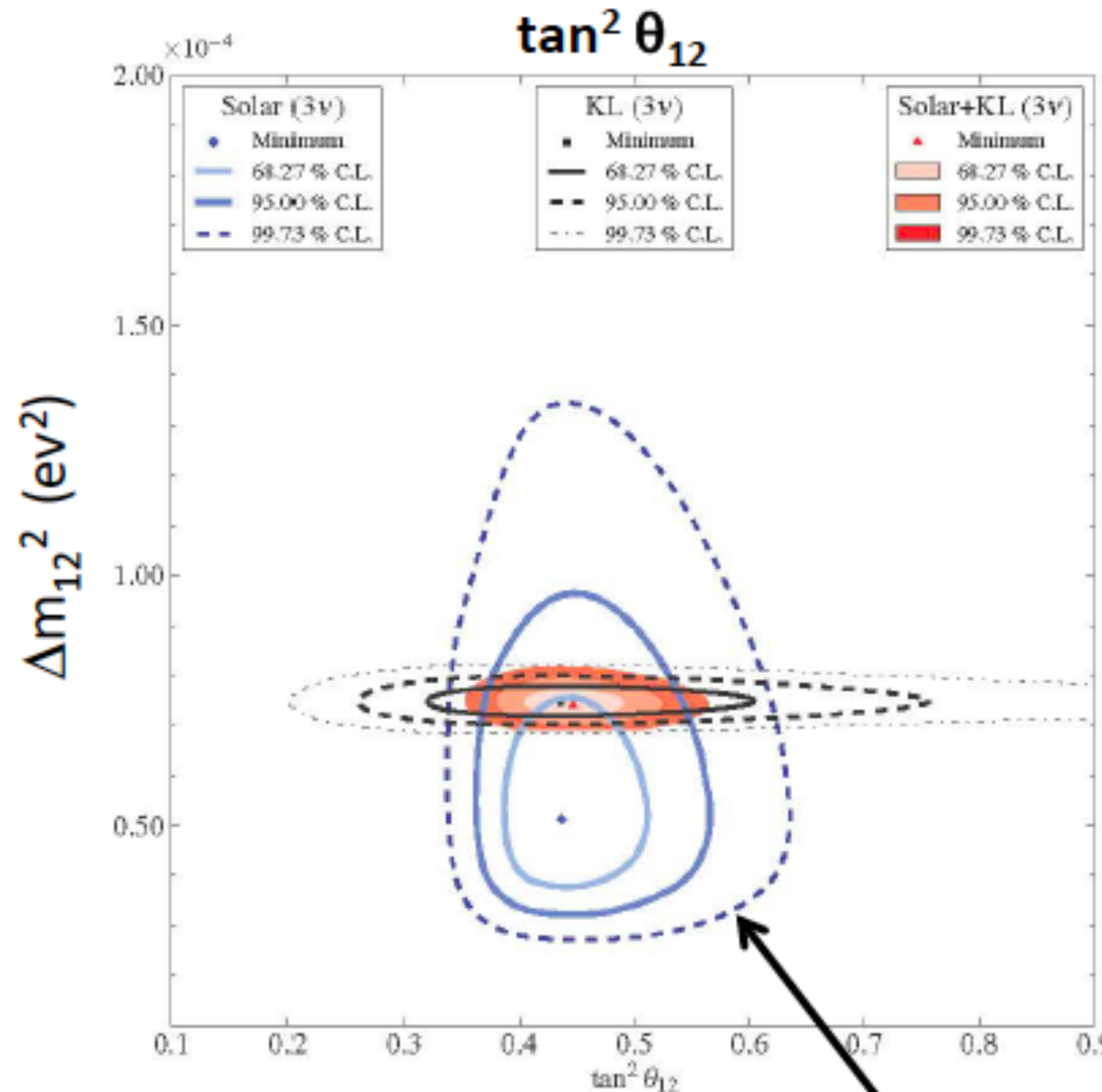
Solar Neutrino Problem Resolved



arXiv:1109.0763

The Sudbury Neutrino Oscillation Detector





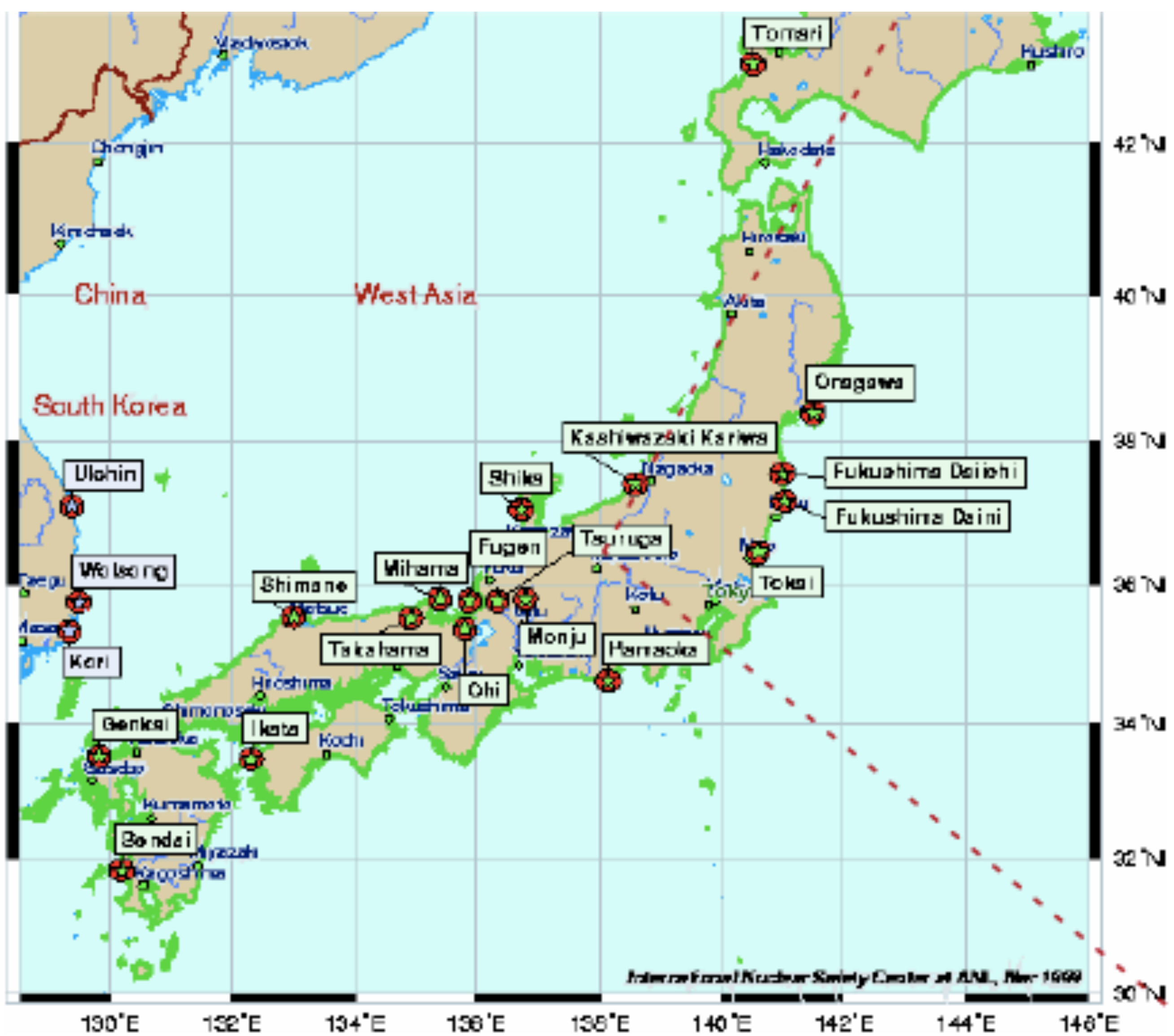
SNO defines θ_{12} to be non-maximal by more than 5 σ.

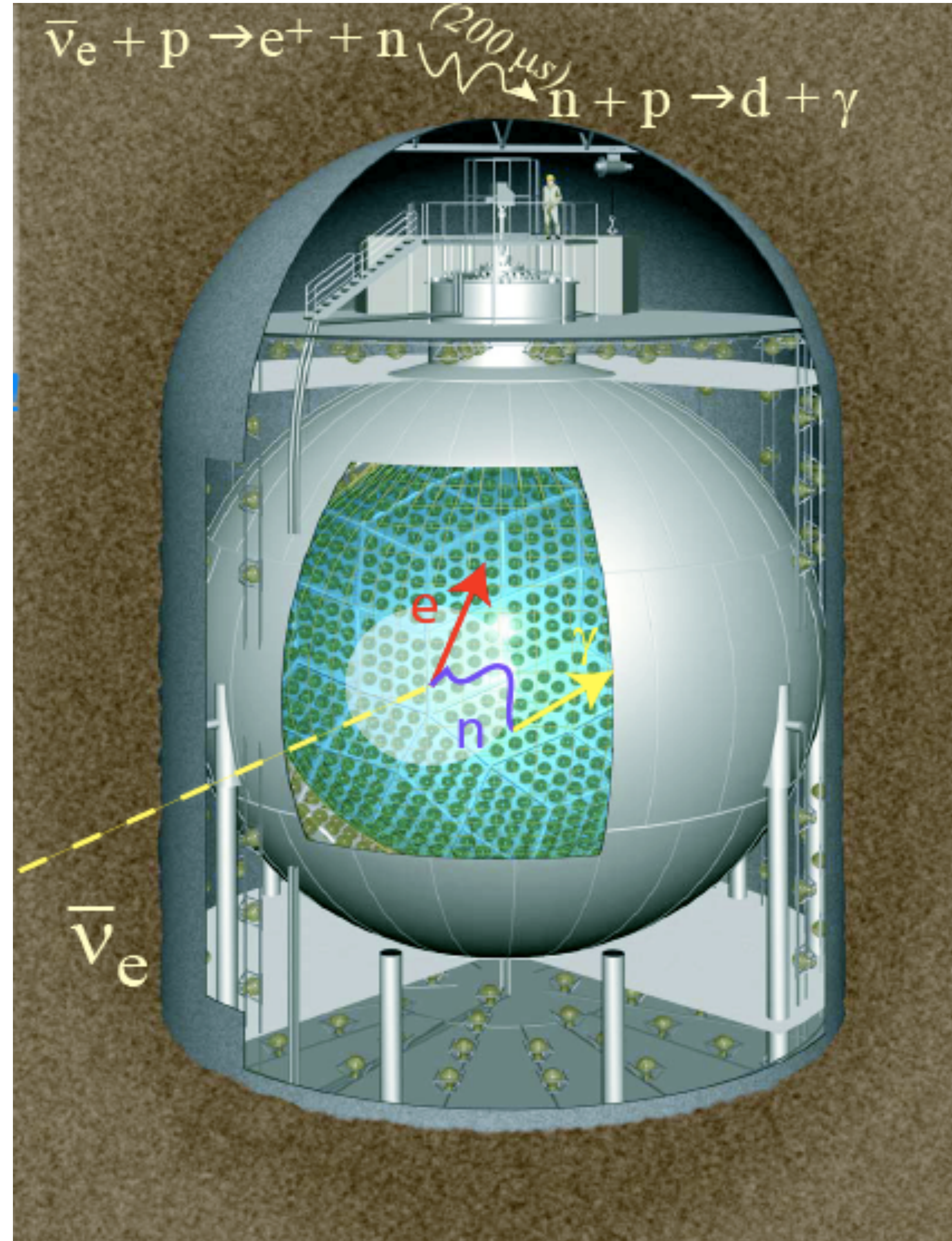
McDonald - Neutrino 2012

arXiv:1109.0763

The KamLAND Experiment

- 1 kton of liquid scintillator
- Antineutrinos came from 20 nuclear reactors in Japan and South Korea; flux weighted average baseline in ~180 km.
- Tests solar neutrino oscillations on Earth.



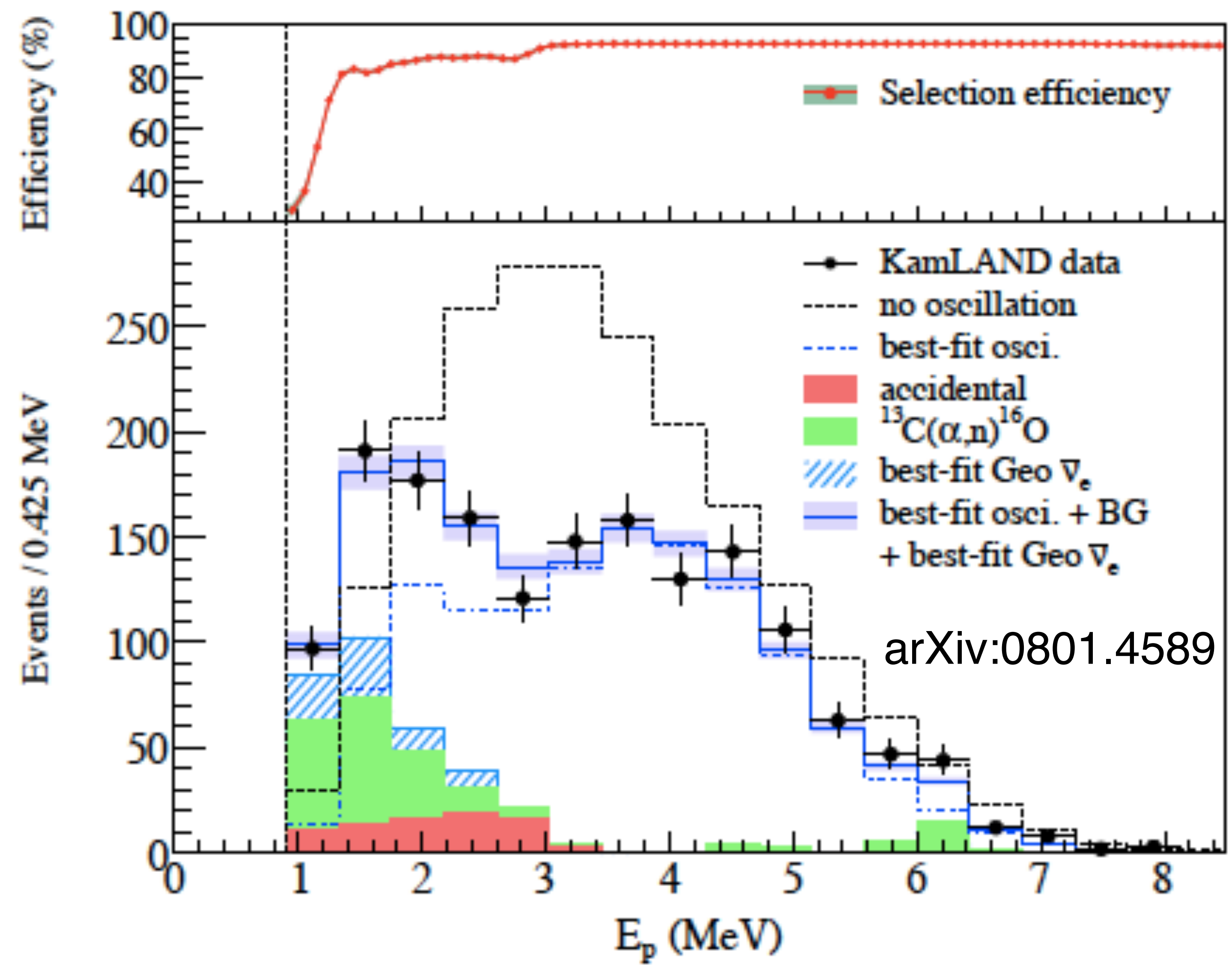


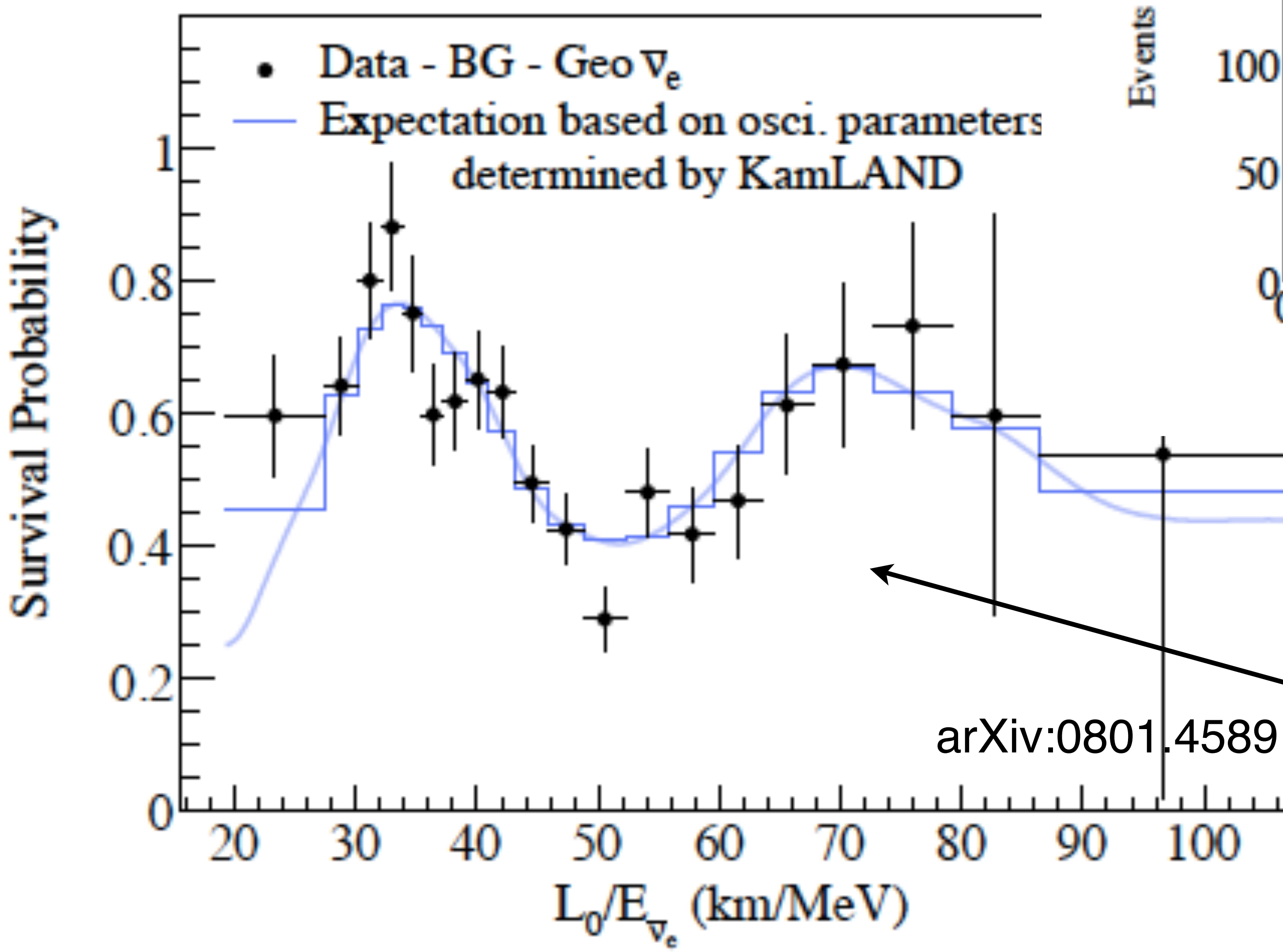
KamLAND Results

$$\Delta m^2_{21} = 7.59 \pm 0.21 \times 10^{-5}$$

$$\tan^2\theta_{12} = 0.47^{+0.06}_{-0.05}$$

(combined with solar data from SNO)

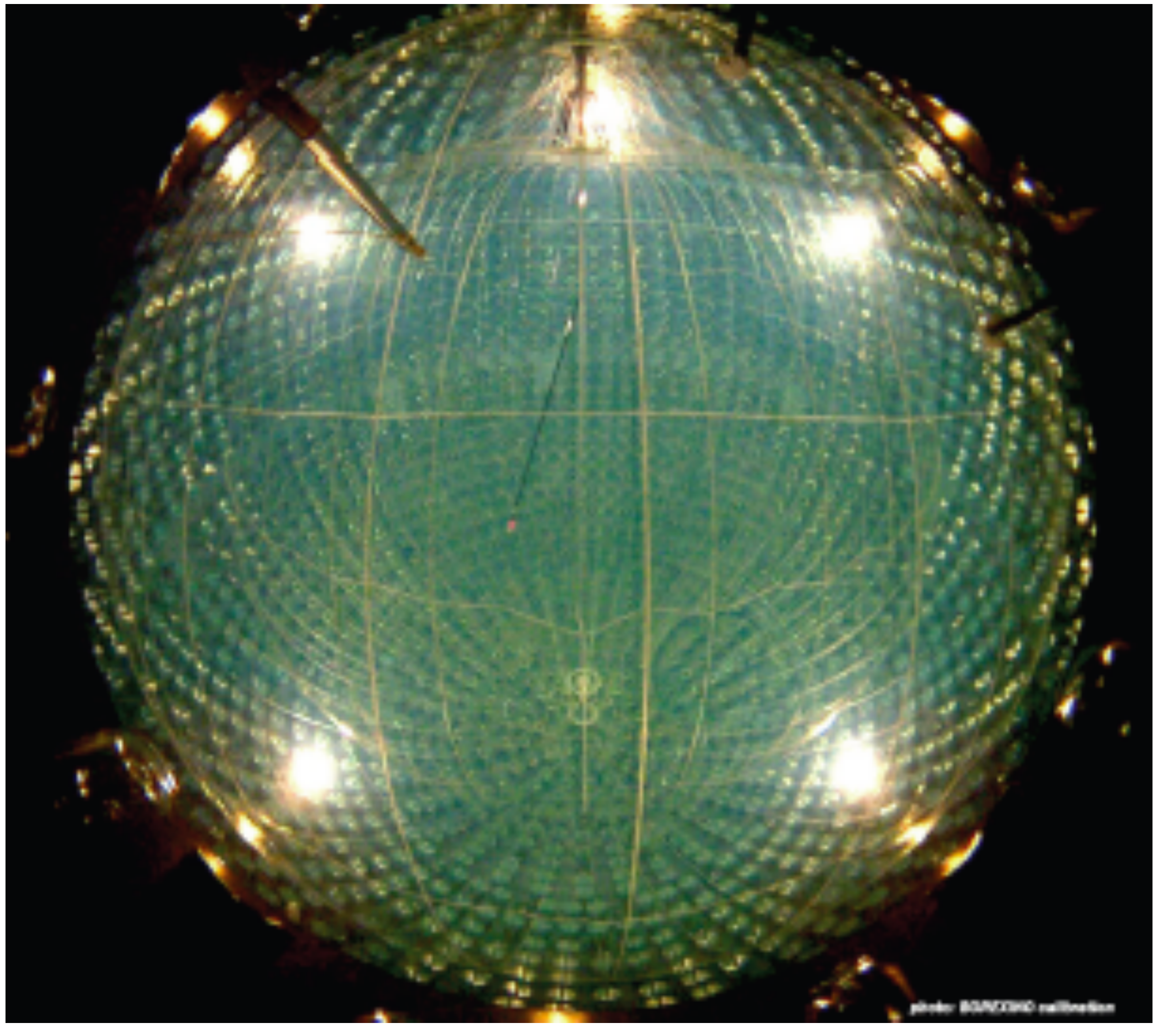


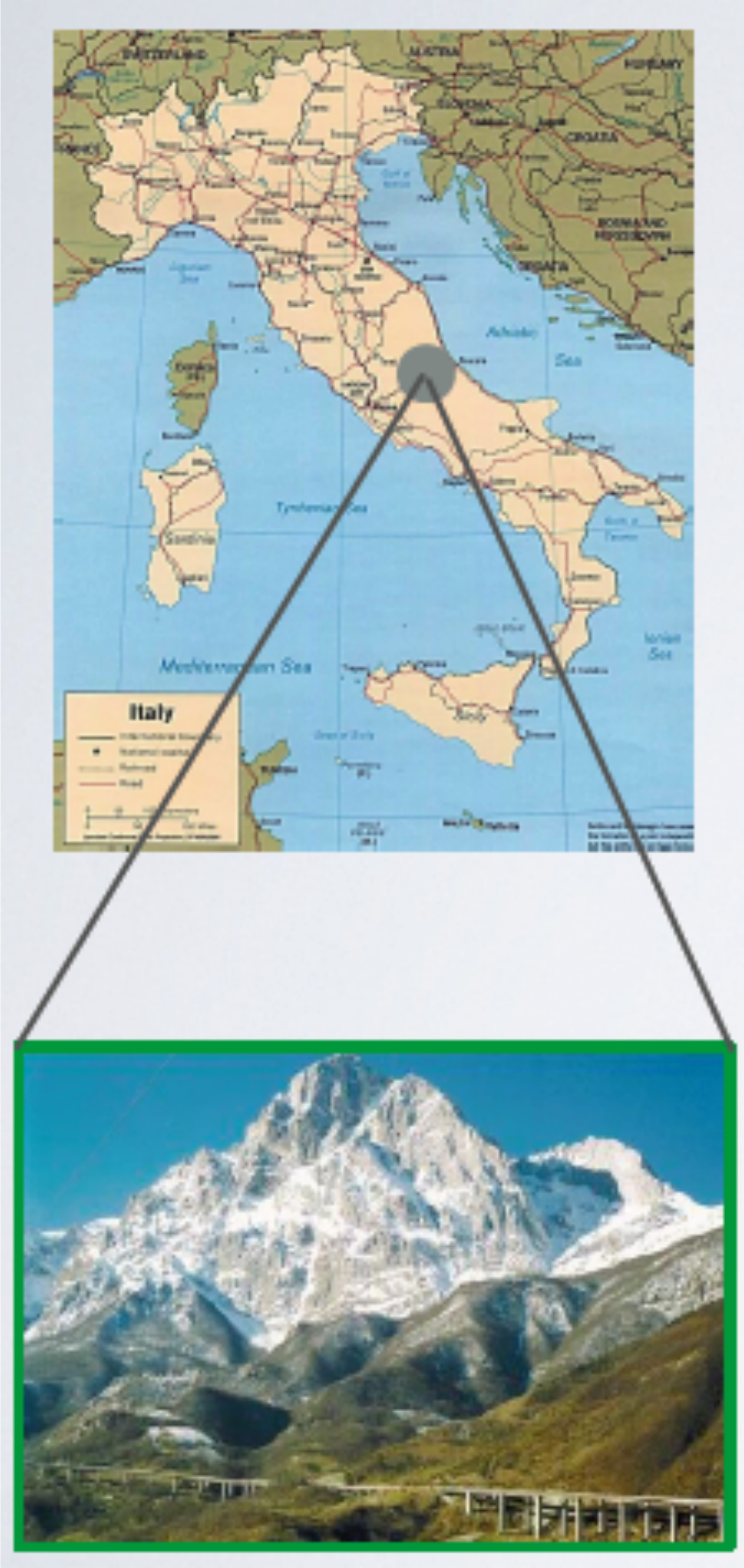


Oscillation for L = 180 km

The Borexino Experiment

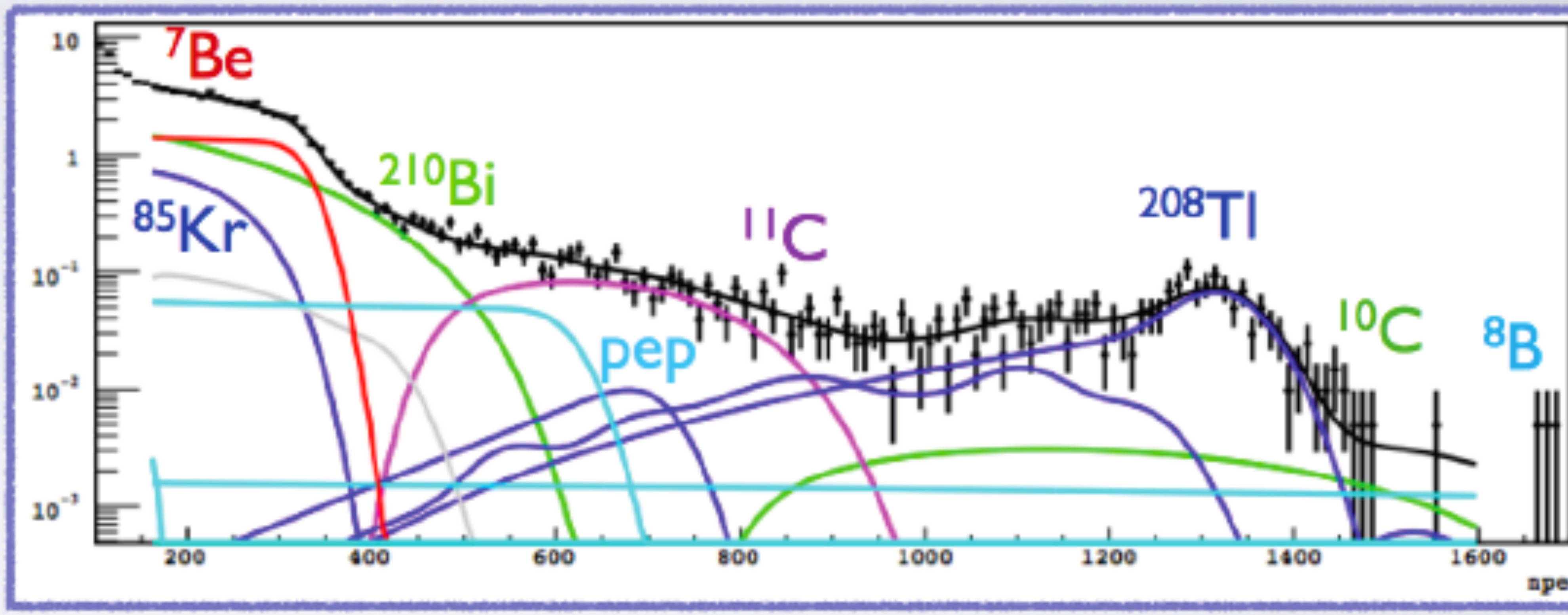
- 300 tons (100 ton fiducial) of liquid scintillator, surrounded by outer layer of ultra-pure water which acts as a shield against neutrons and gamma rays
- 2000 PMTs (20 cm diameter)
- Very radiopure environment
- Designed to detect very low energy solar neutrinos





The Borexino Experiment

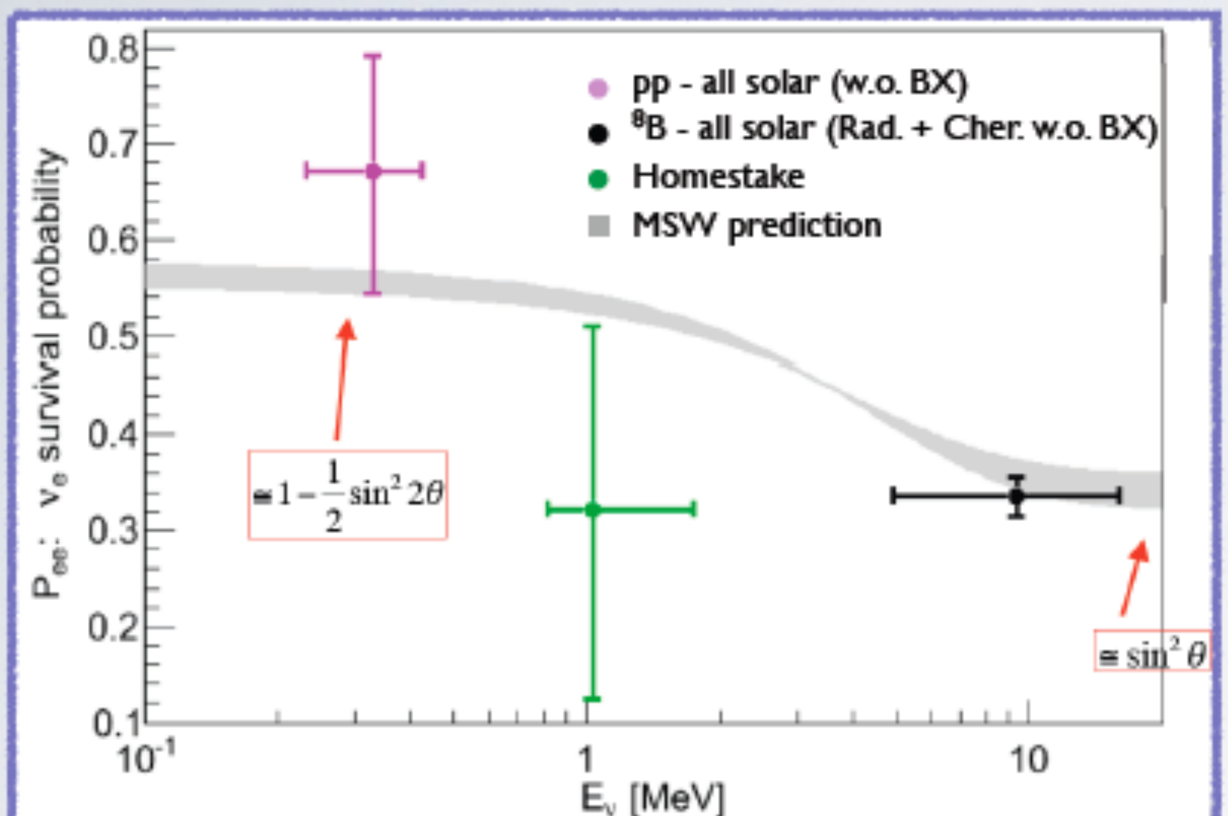
Spectrum after TFC veto

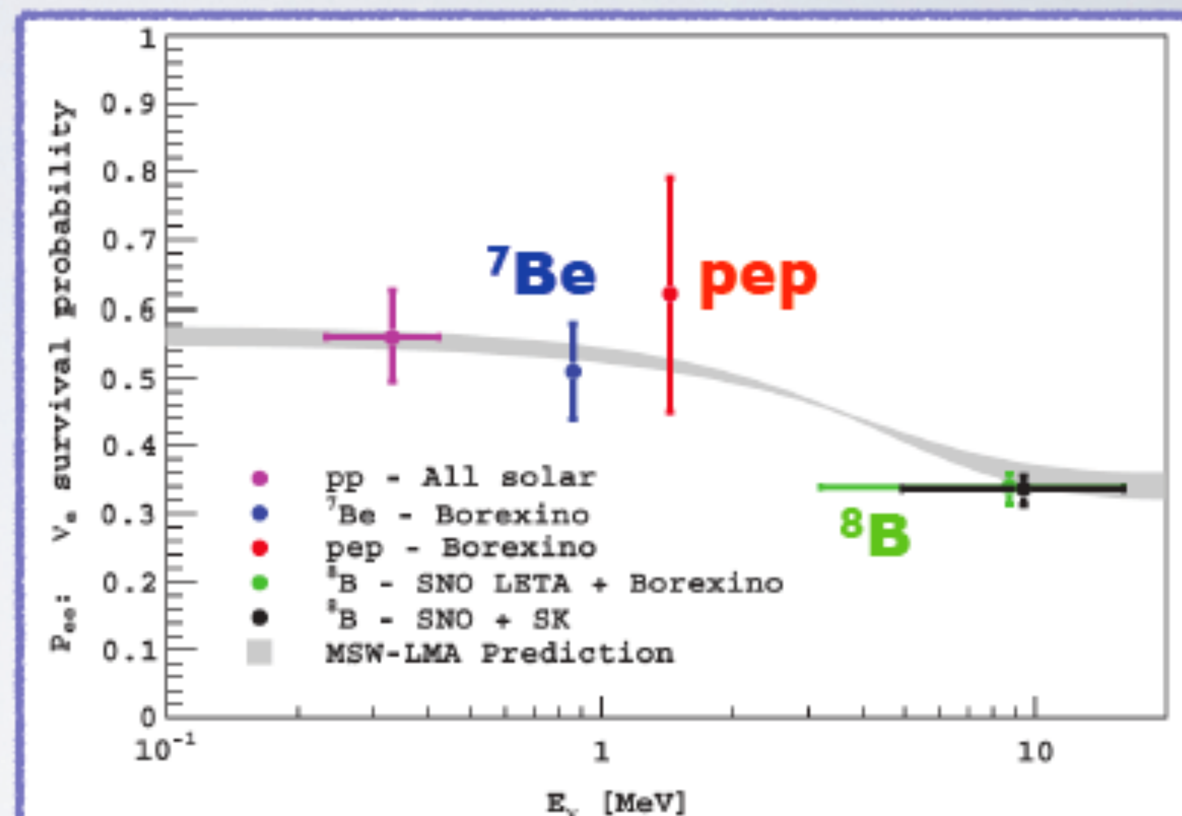


Before Borexino

Pallavicini - Neutrino 2012

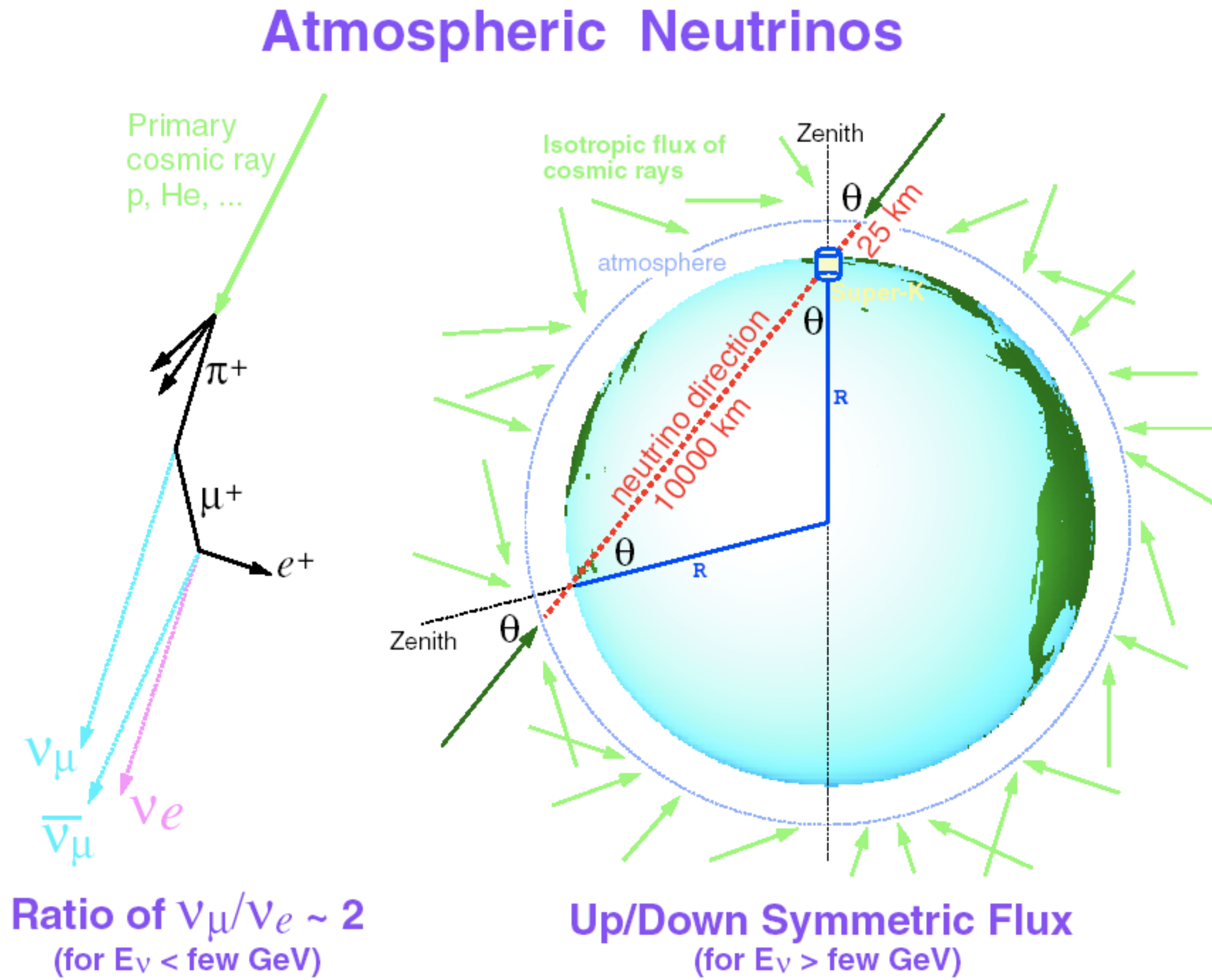
Borexino 2012





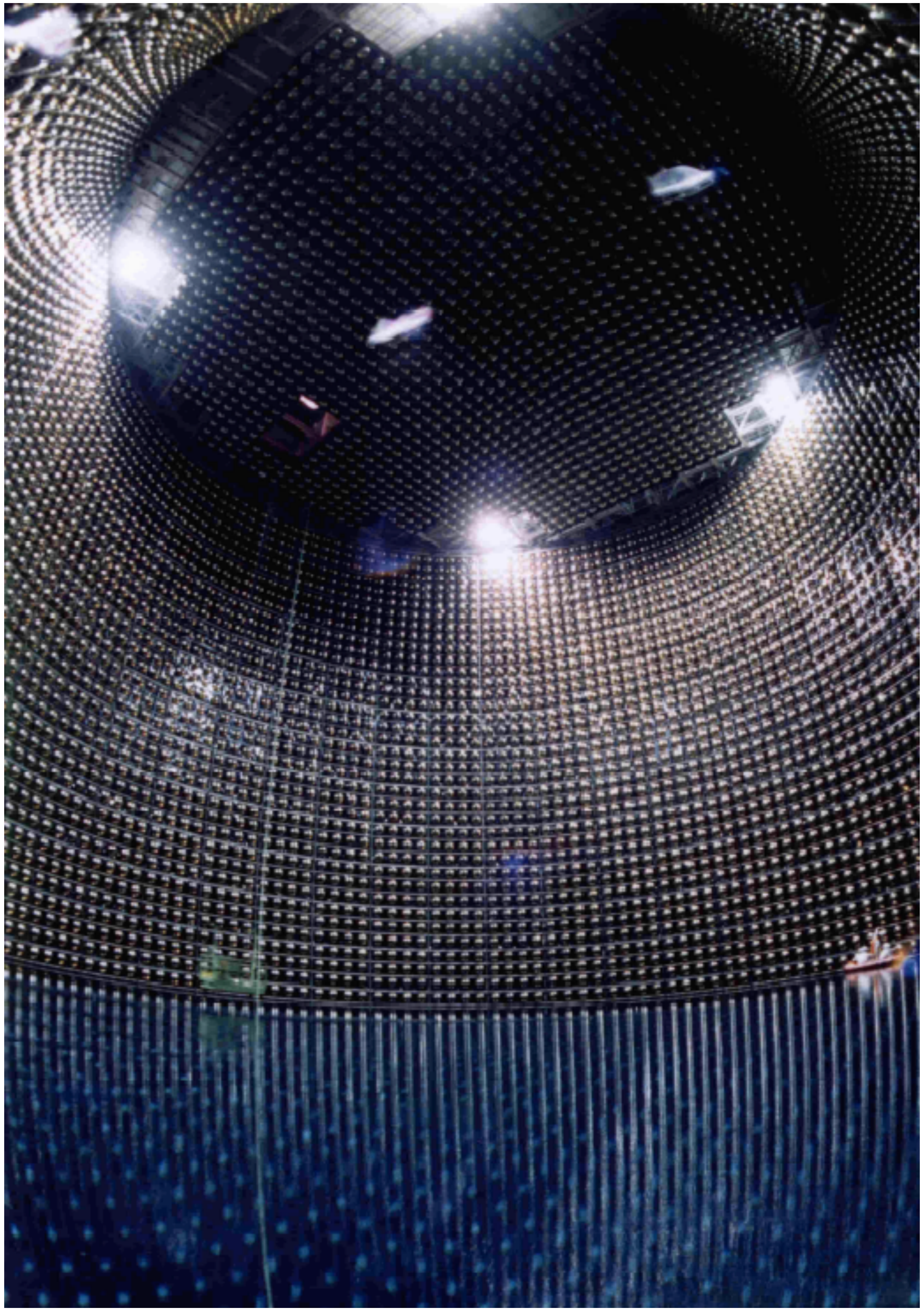
The Atmospheric Neutrino Anomaly

- We expect to see ~2x as many muon neutrinos as electron neutrinos coming from cosmic rays



The Super-Kamiokande Detector (Japan)

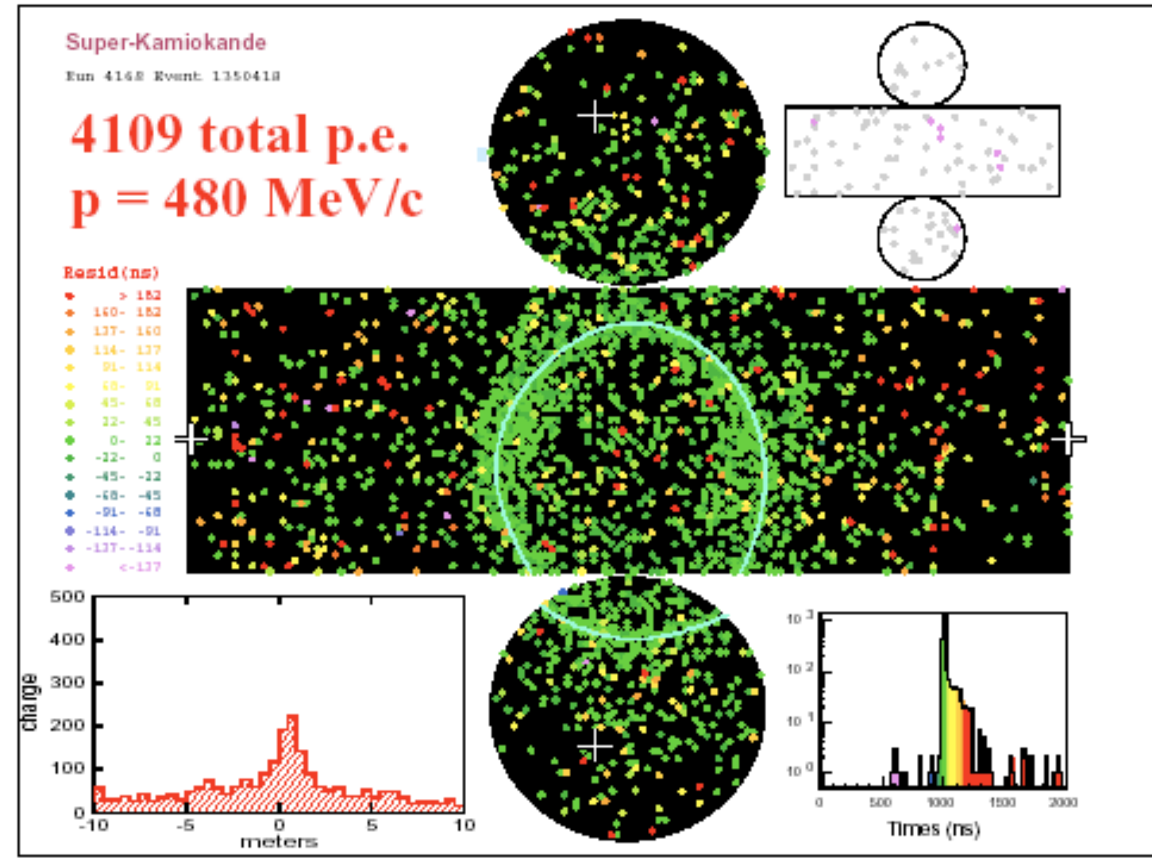
- Located in the Japanese Alps in a zinc mine.
- Covered by 1000m of rock.
- 50 kton water Cherenkov detector (39 m diameter, 42 m tall)
- Over 11,000 50 cm photomultiplier tubes (PMTs) detect faint light signals from neutrino interactions with pure water inside the tank.
- Began operation in 1996.



The Super-Kamiokande Detector (Japan)

- Neutrino energy is determined by the amount of light captured by the PMTs.
- Super-K is sensitive to a very wide range neutrino energies: 4.5 MeV - 1 TeV!
- Electron and muon neutrino interactions identified (separated) by the shape ("fuzziness") of the Ckov ring.

e—like



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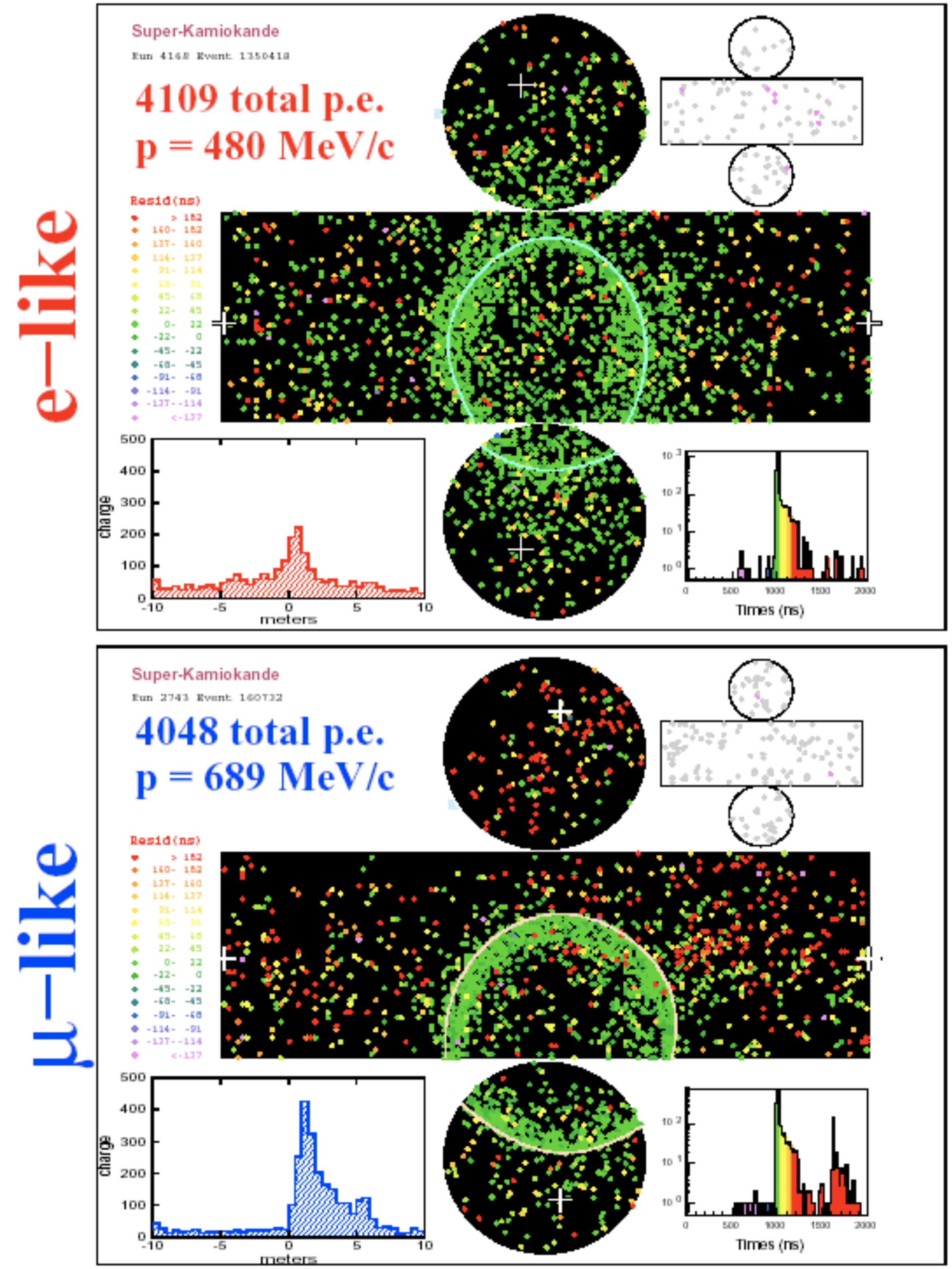
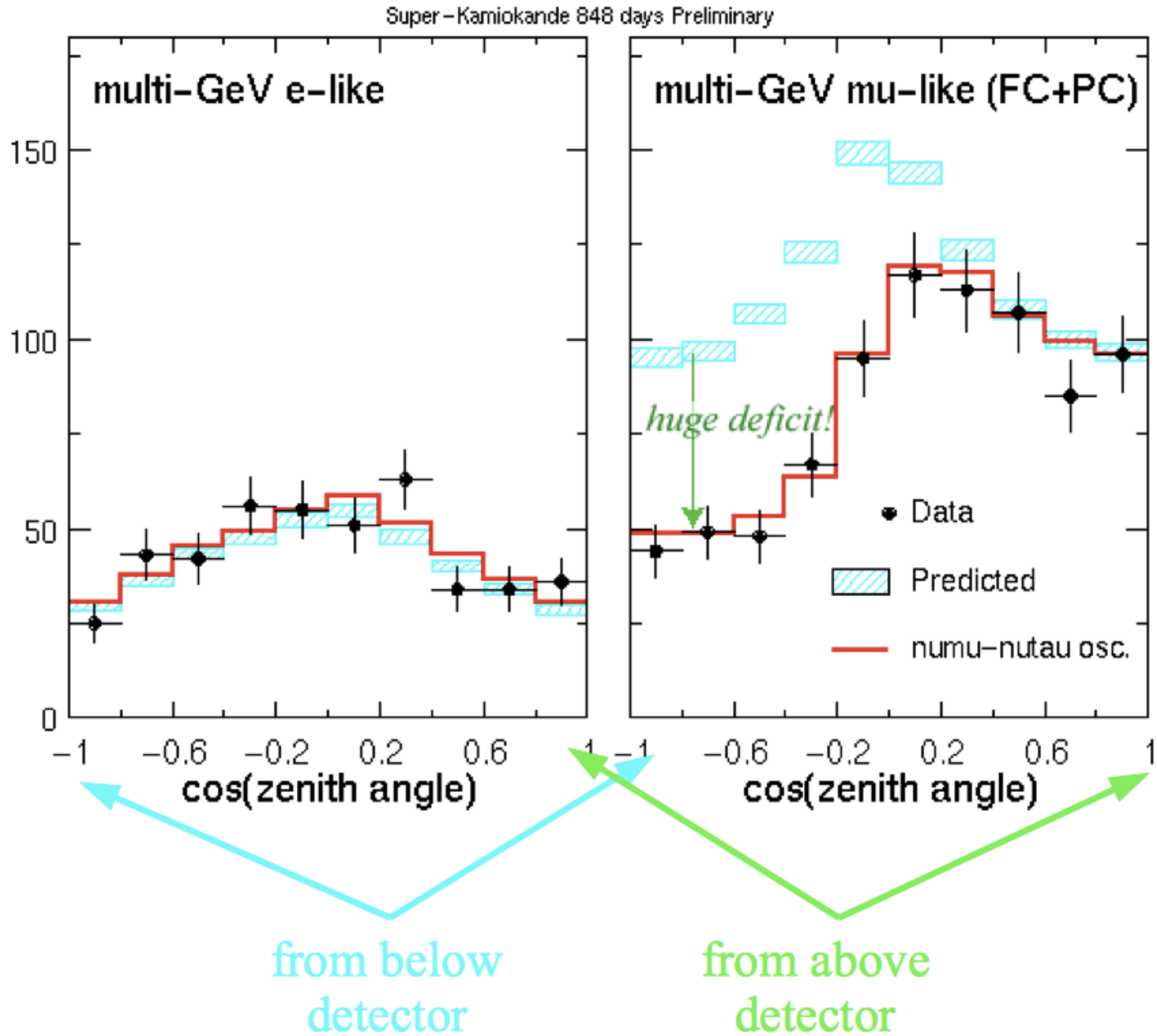
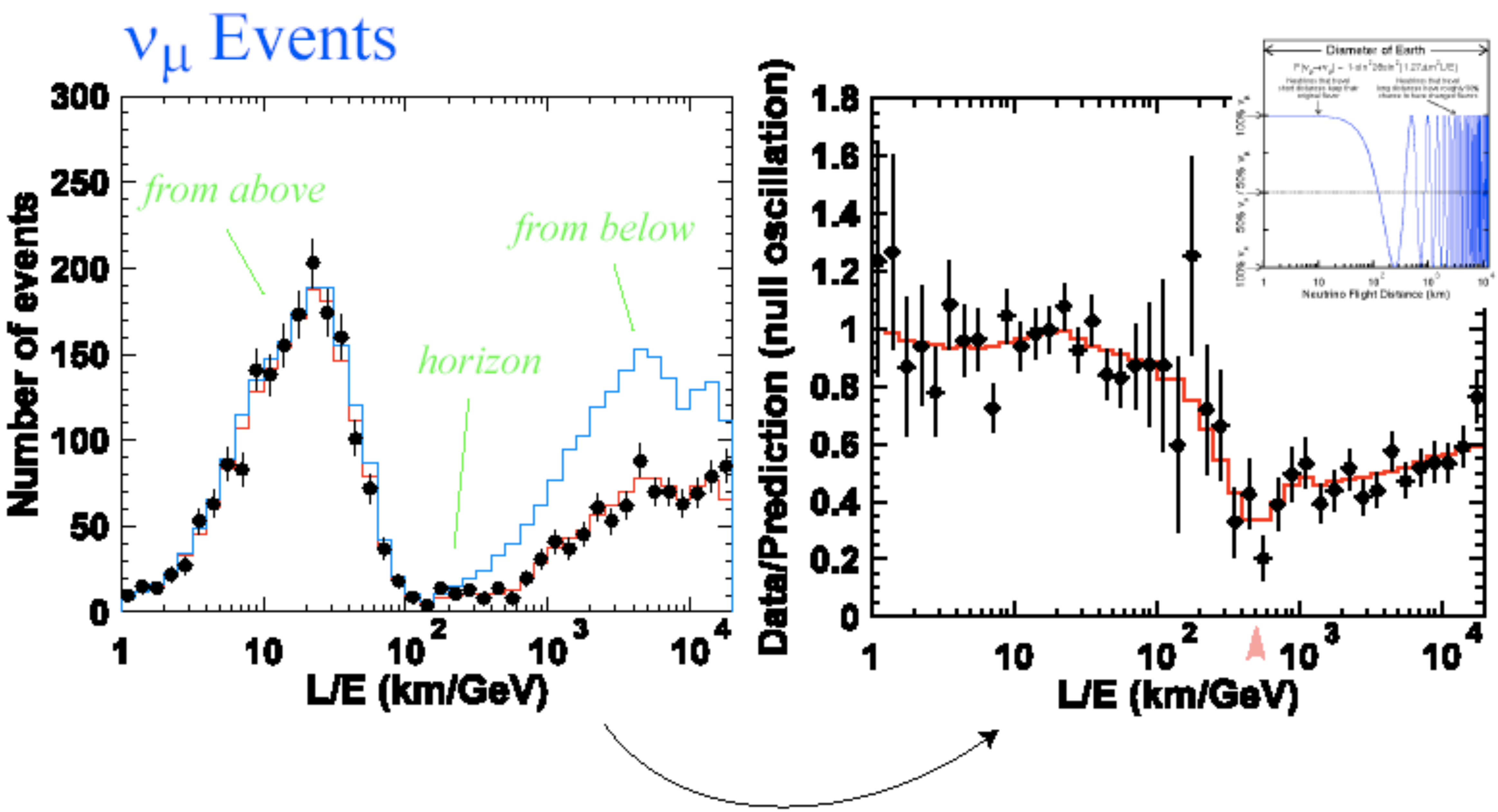


Evidence for Neutrino Oscillations from Super-K

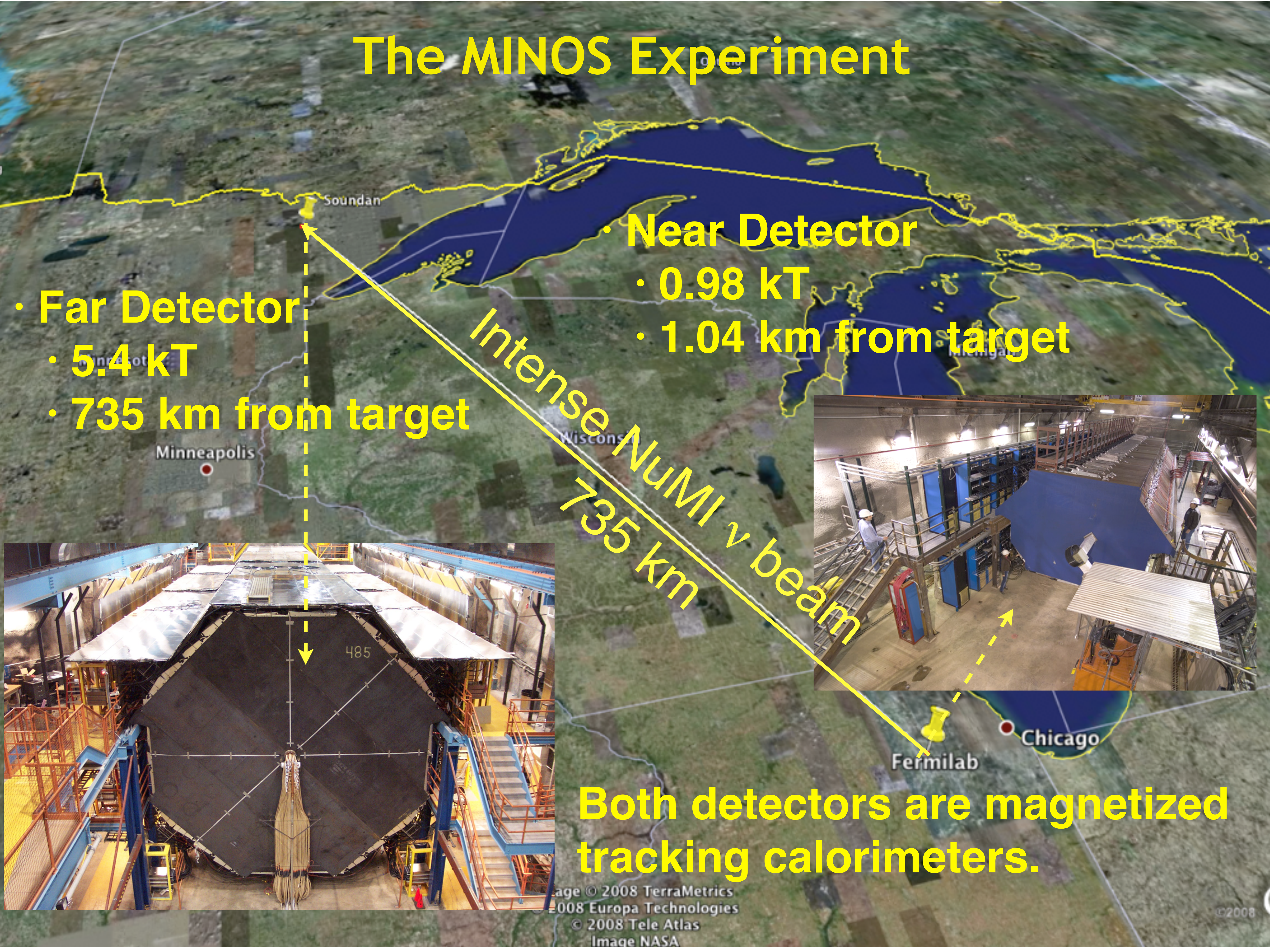
- Number of detected electron neutrino events agree very well with predicted number.
- Number of detected muon neutrino events strongly disagrees with the predicted number.
- Explained by $\nu_\mu \rightarrow \nu_\tau$ oscillations!



Super-K L/E Analysis

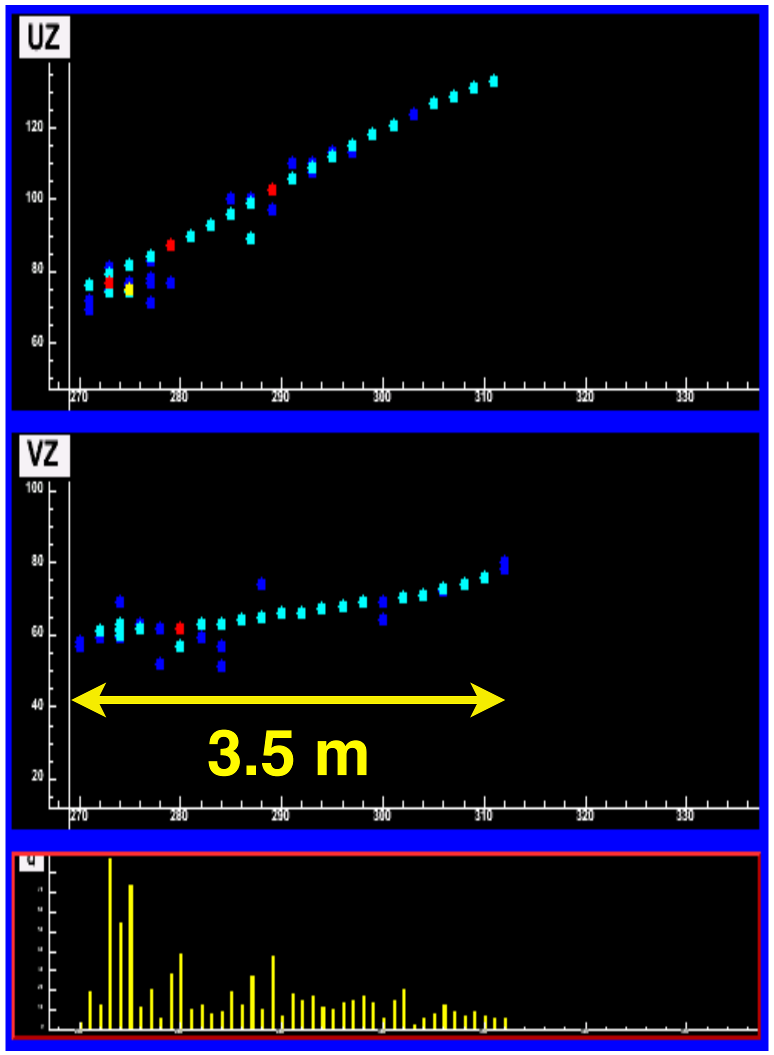


Divide data by prediction to look for L/E dependence of oscillation probability


The MINOS Experiment
· Far Detector
· 5.4 kT
· 735 km from target
· Near Detector
· 0.98 kT
· 1.04 km from target
Intense NuMI ν beam
735 km
Both detectors are magnetized tracking calorimeters.
Soundan
Minneapolis
Wisconsin
Fermilab
Chicago
485
© 2008 TerraMetrics
2008 Europa Technologies
© 2008 Tele Atlas
Image NASA

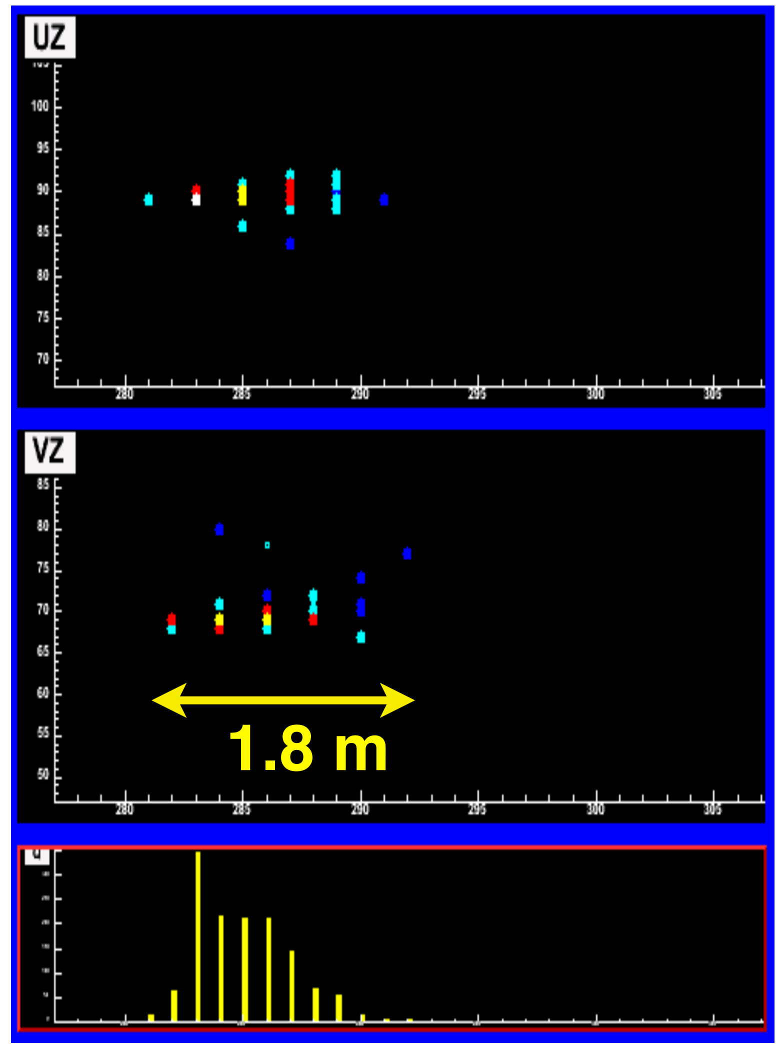
Identifying Events in MINOS

ν_μ CC event



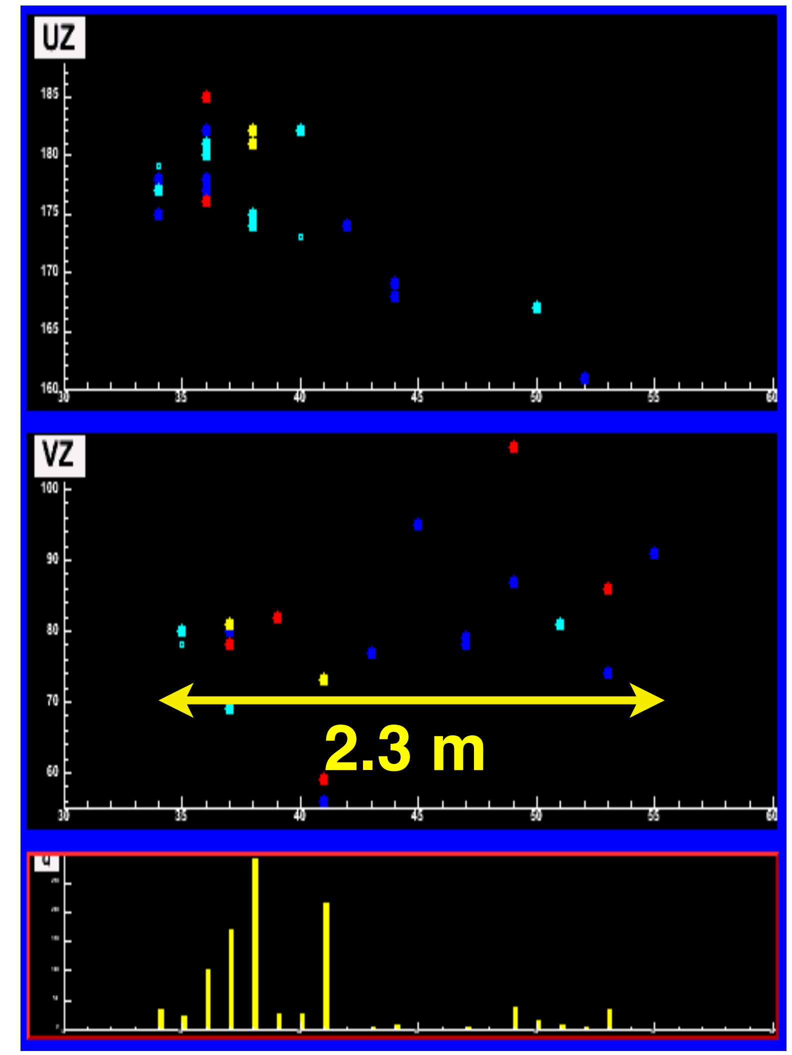
Long μ track + shower at vertex

ν_e CC event



Short event with EM shower profile.

NC event

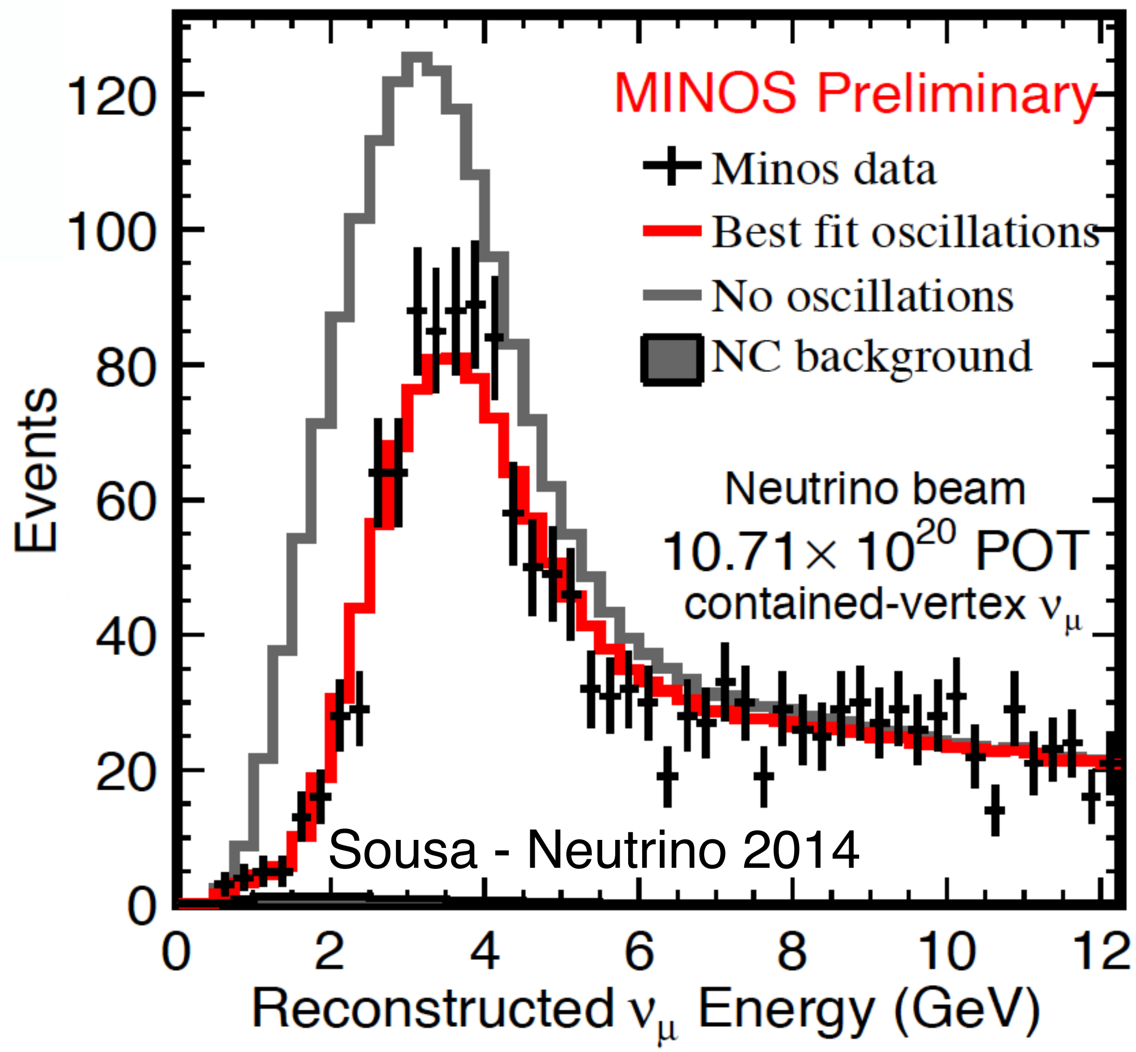


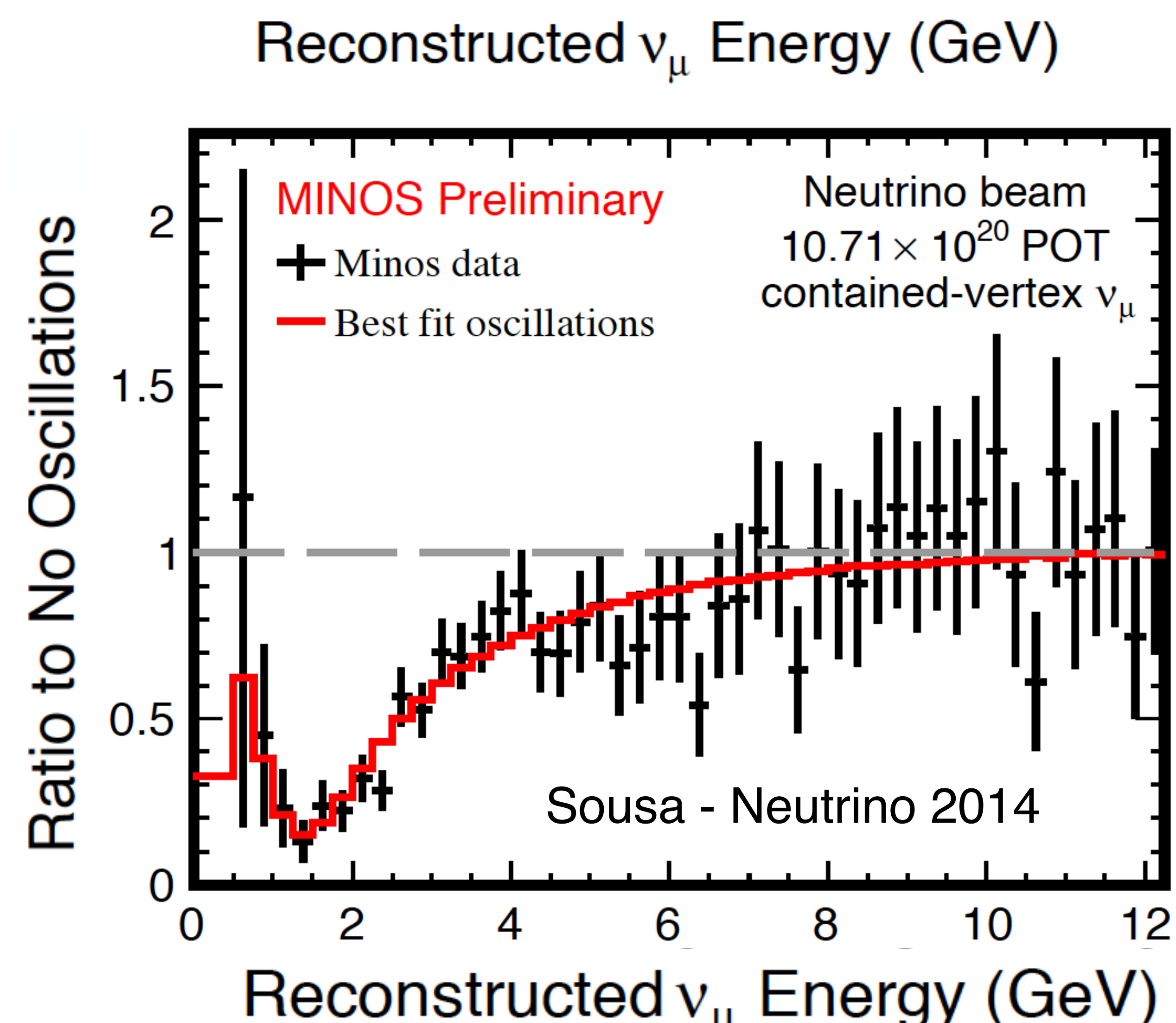
Short, diffuse event.

E_μ determined from curvature and/or range,
E_{shower} determined from MC tuned to external data.

MINOS Results

Neutrinos





Three-Flavor Oscillations Best Fit

Inverted Hierarchy

$|\Delta m^2_{32}| = 2.37^{+0.11}_{-0.07} \times 10^{-3} \mathrm{eV}^2$

$\sin^2\theta_{23} = 0.43^{+0.19}_{-0.05}$

$0.36 < \sin^2\theta_{23} < 0.65$ (90% C.L.)

Normal Hierarchy

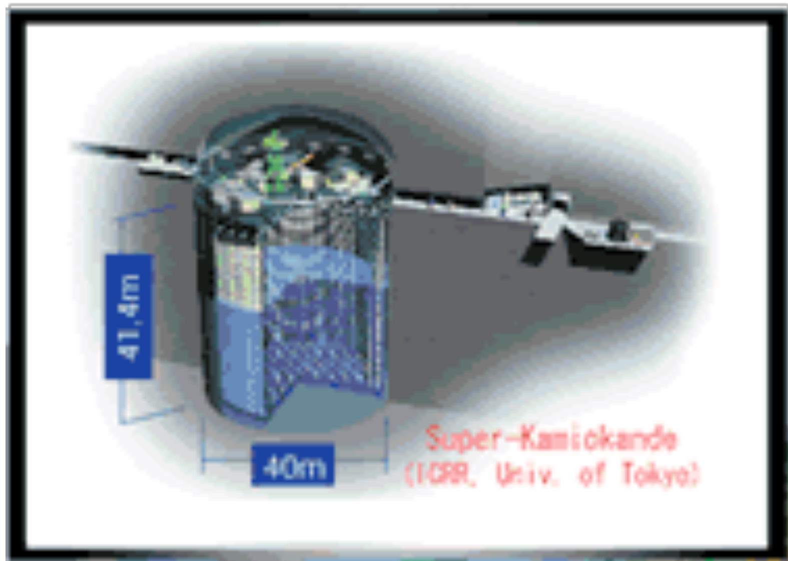
$|\Delta m^2_{32}| = 2.34^{+0.09}_{-0.09} \times 10^{-3} \mathrm{eV}^2$

$\sin^2\theta_{23} = 0.43^{+0.16}_{-0.04}$

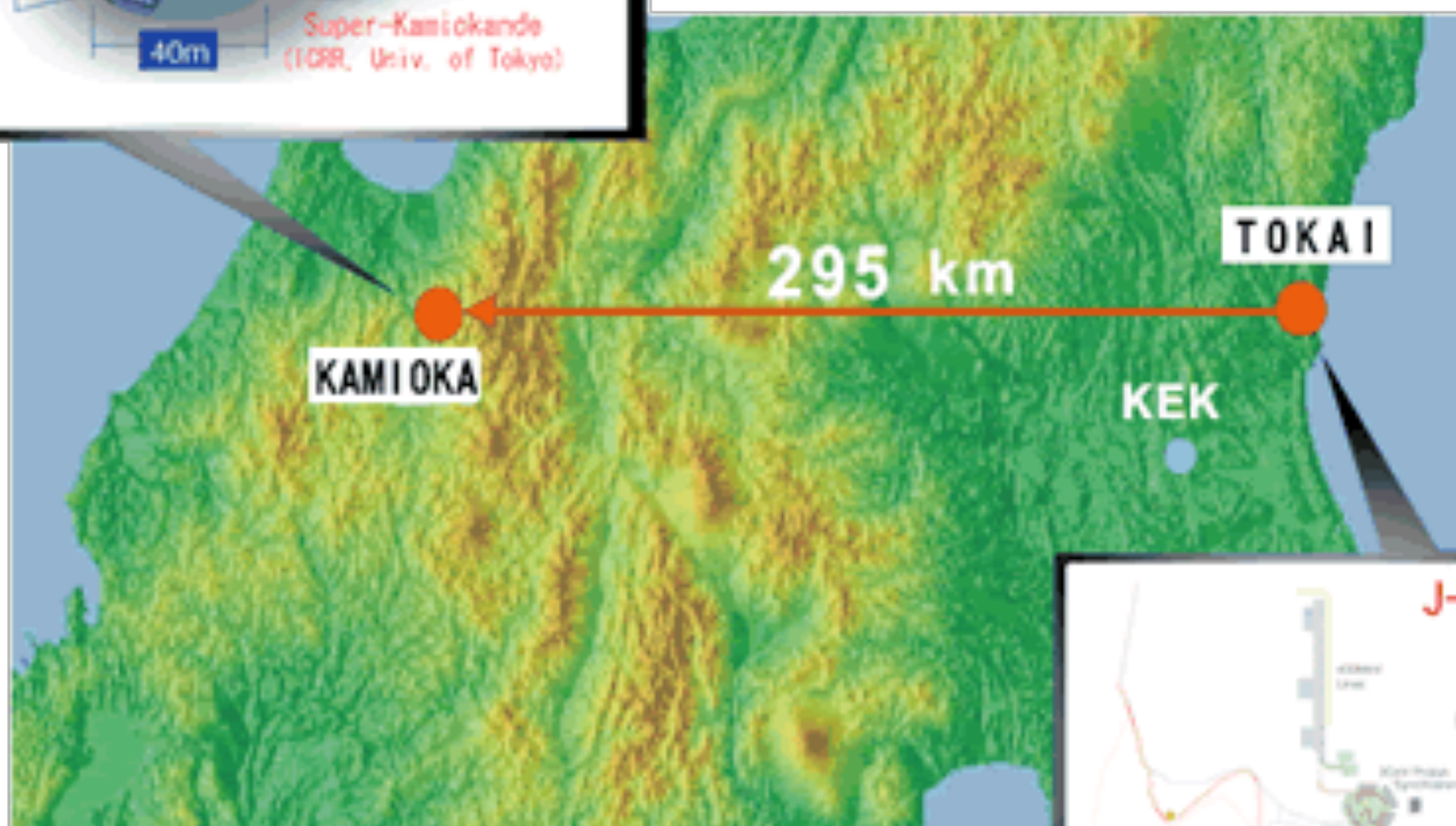
$0.37 < \sin^2\theta_{23} < 0.64$ (90% C.L.)

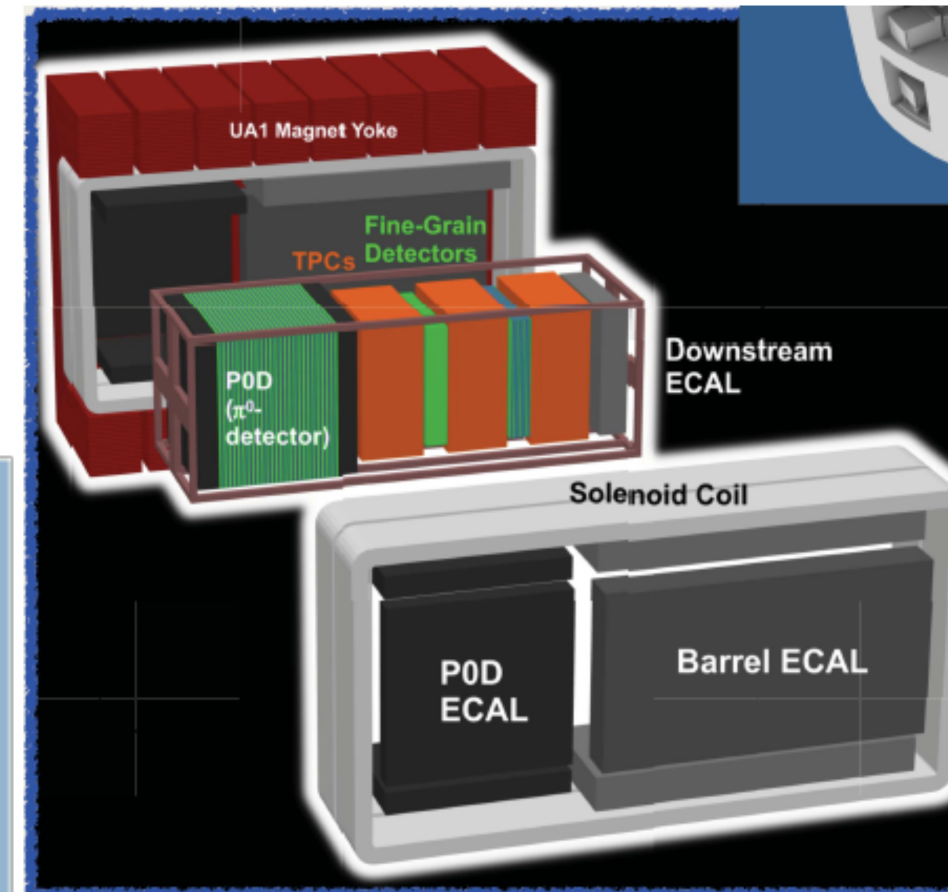
Looking to the Near Future...

The Tokai to Kamioka (T2K) Experiment



Use Super-K as far detector



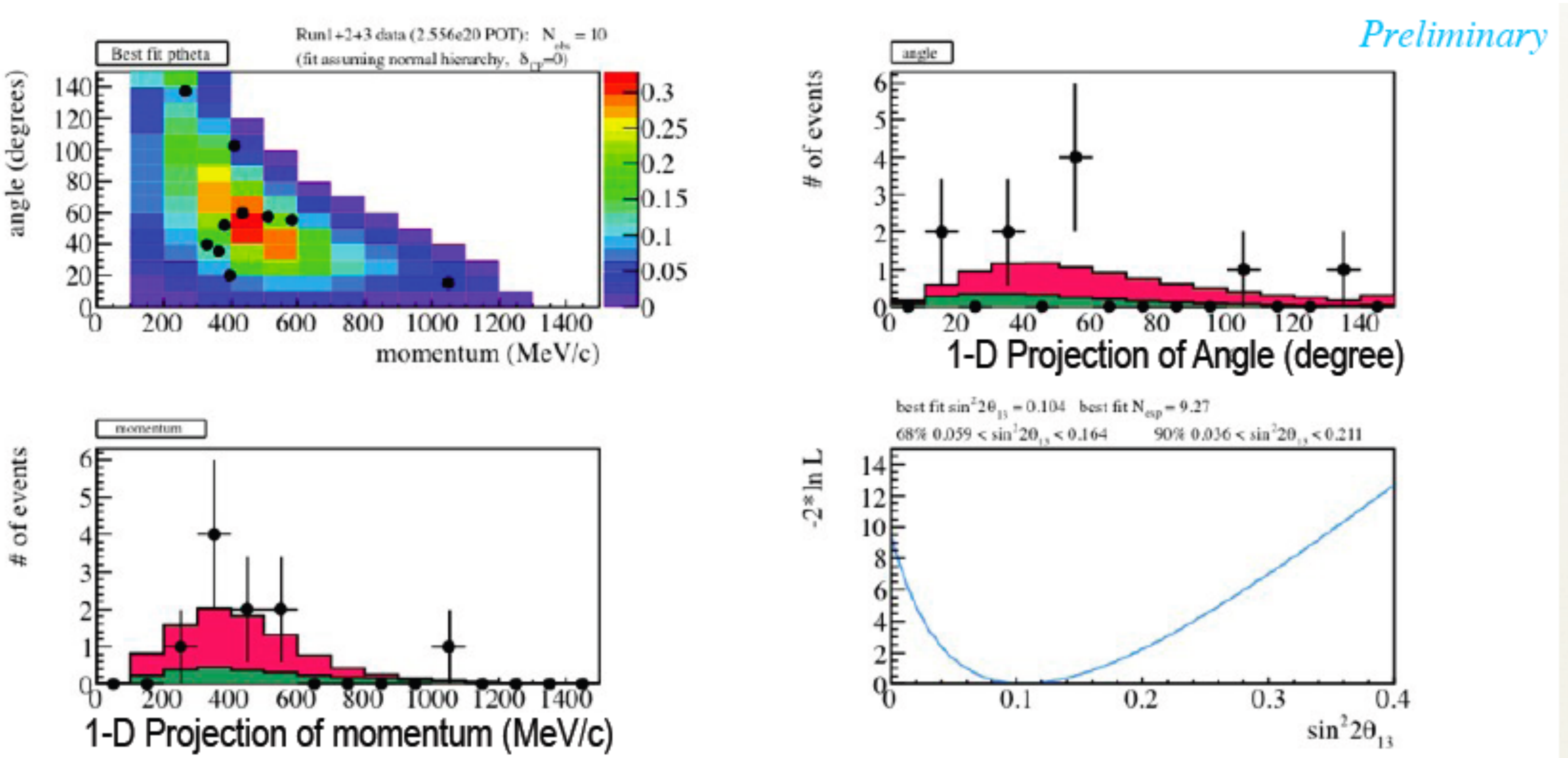


High resolution near detector

T2K Goals

- Primary goals:
  - Observe $\nu_\mu \rightarrow \nu_e$ oscillations and measure mixing angle θ_{13}
  - Search for CP violation in the neutrino sector.
- Secondary goals:
  - Improve measurement of $\sin^2(2\theta_{23})$
  - Search for sterile neutrinos
  - Measure neutrinos from galactic supernovae
  - Cross-section measurements using ND
- Currently taking data and beginning to show exciting results.

T2K Results from 2012

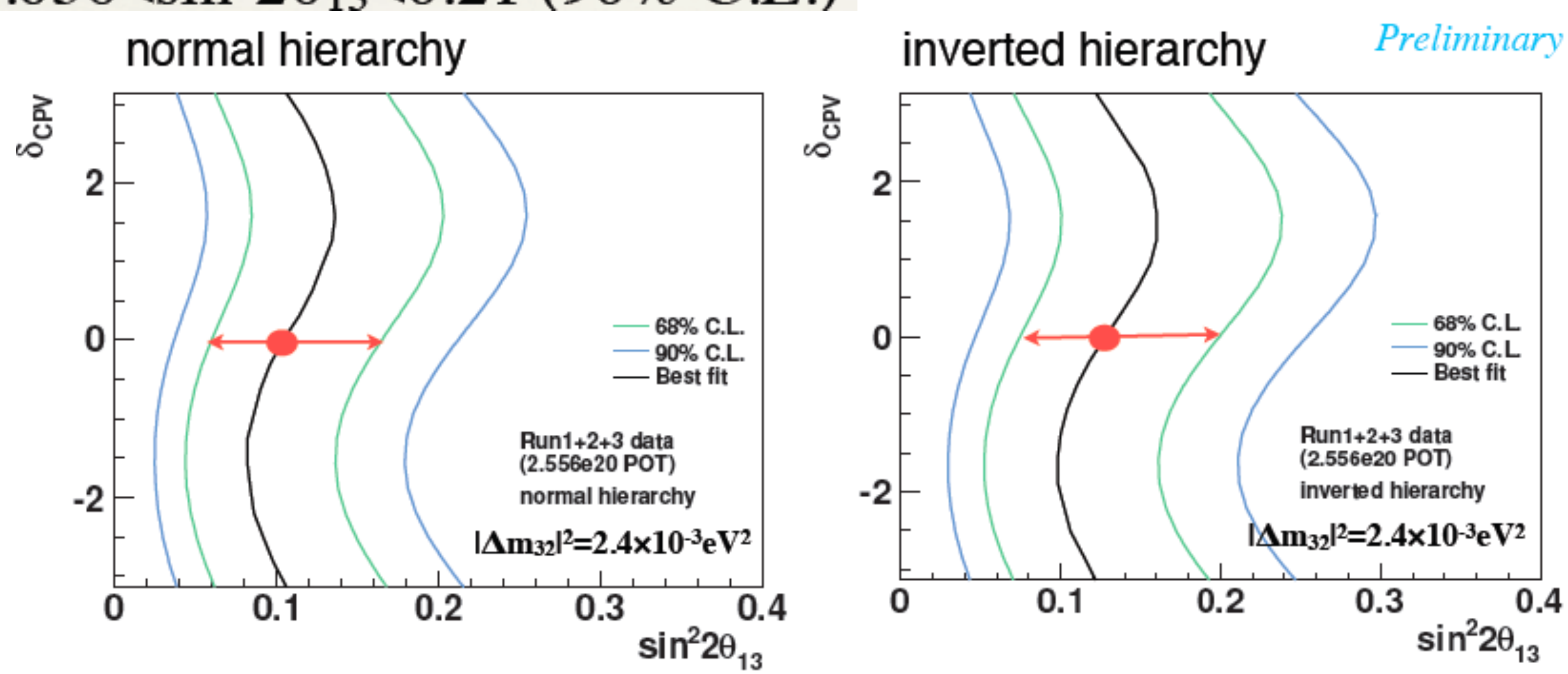


$$\sin^2 2\theta_{13} = 0.104^{+0.060}_{-0.045}$$

$(N_{\nu e}^{\text{best-fit}} = 9.27)$

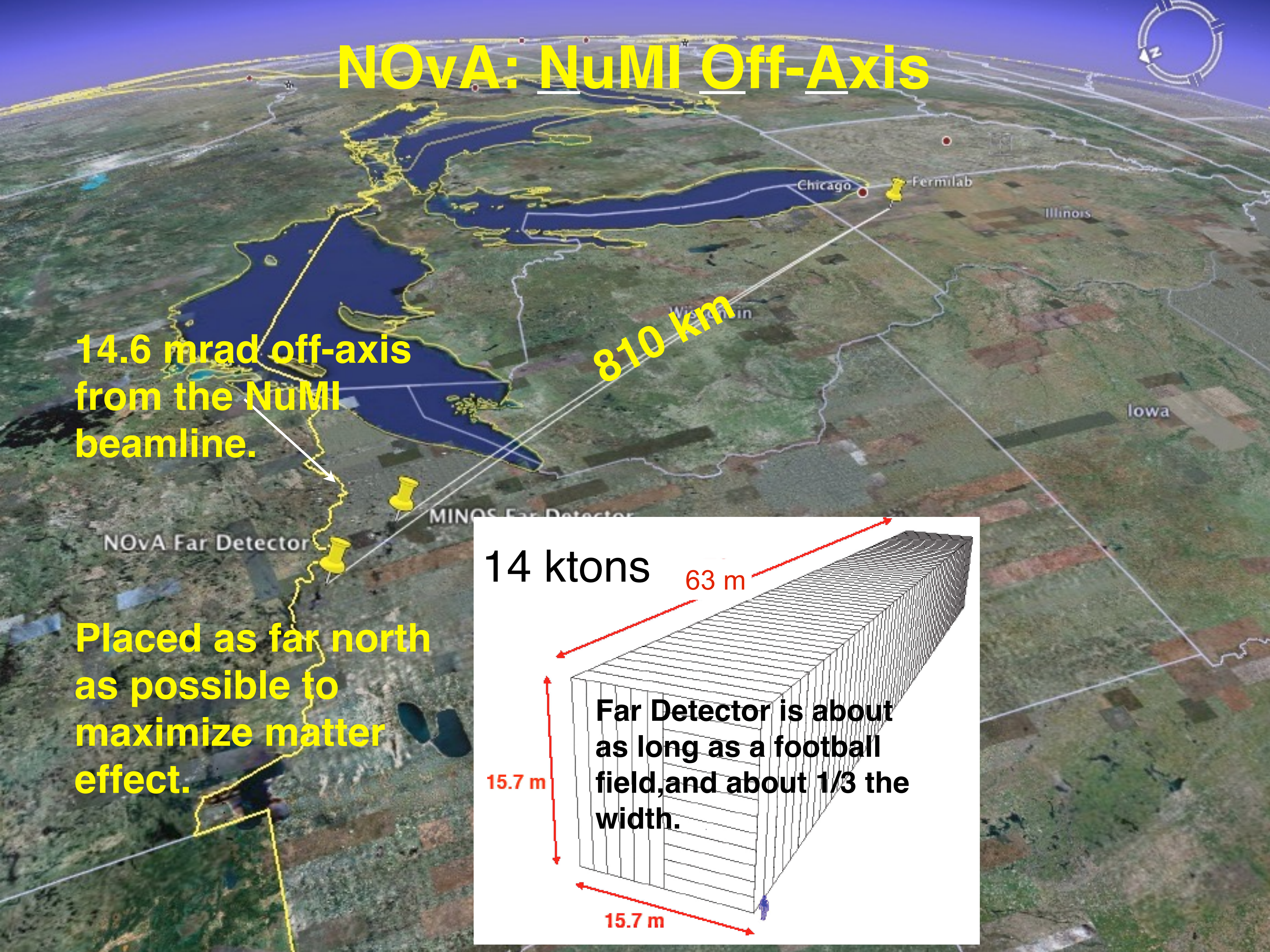
$0.036 < \sin^2 2\theta_{13} < 0.21$ (90% C.L.)

Nakaya - Neutrino 2012



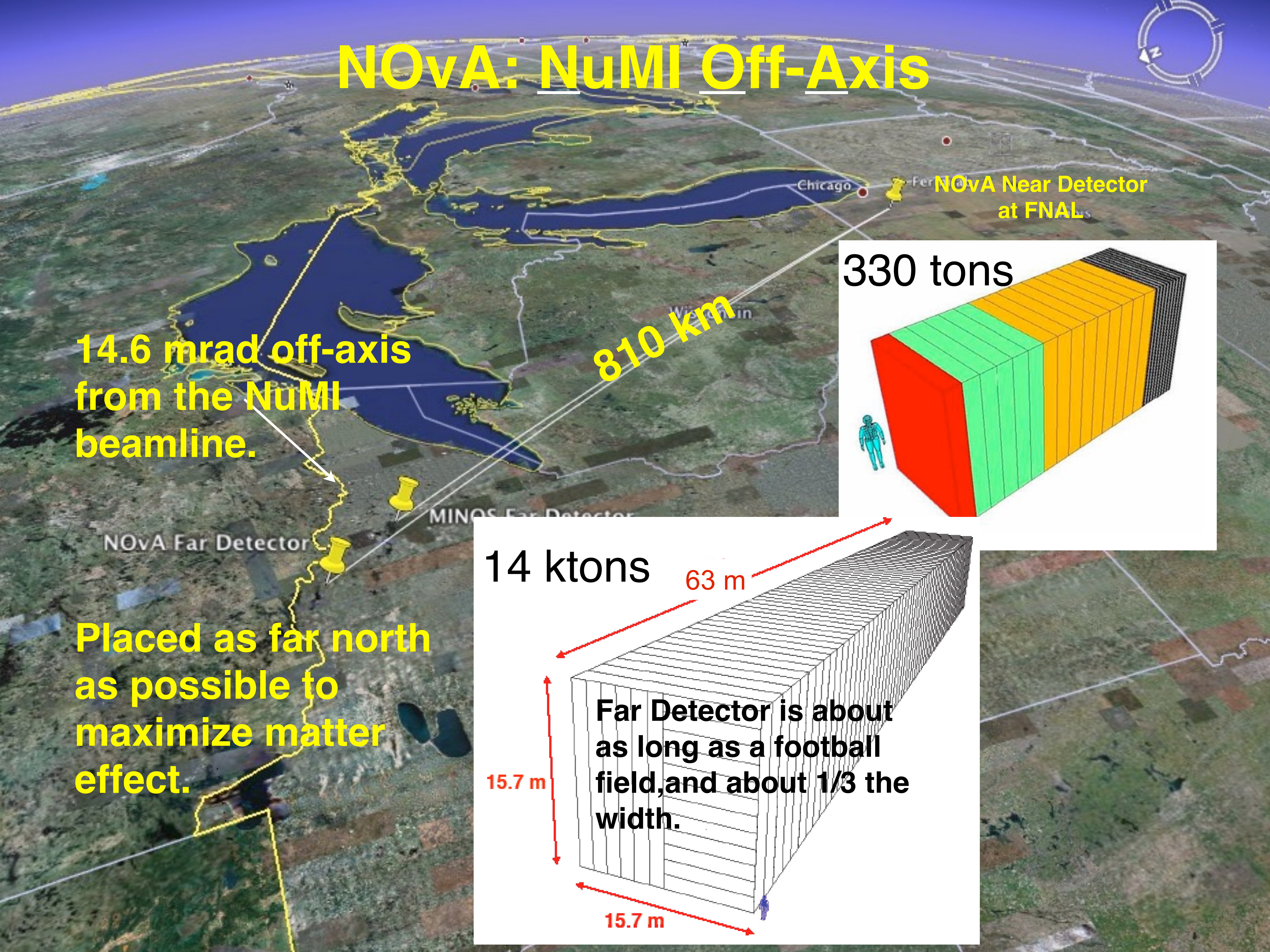
NOvA: NuMI Off-Axis

NOvA: NuMI Off-Axis



14.6 mrad off-axis from the NuMI beamline.

Placed as far north as possible to maximize matter effect.


NOvA: NuMI Off-Axis
NOvA Near Detector at FNAL
Chicago
330 tons
810 km
14.6 mrad off-axis from the NuMI beamline.
MINOS Far Detector
NOvA Far Detector
14 ktons
63 m
15.7 m
15.7 m
Far Detector is about as long as a football field,and about 1/3 the width.
Placed as far north as possible to maximize matter effect.

NOvA: NuMI Off-Axis

NOvA Near Detector at FNAL

Chicago

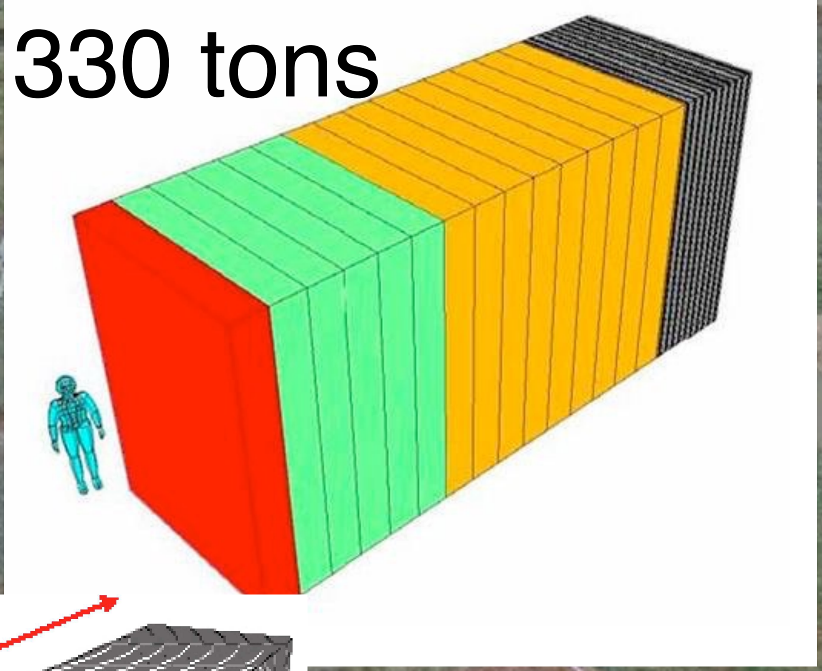
810 km

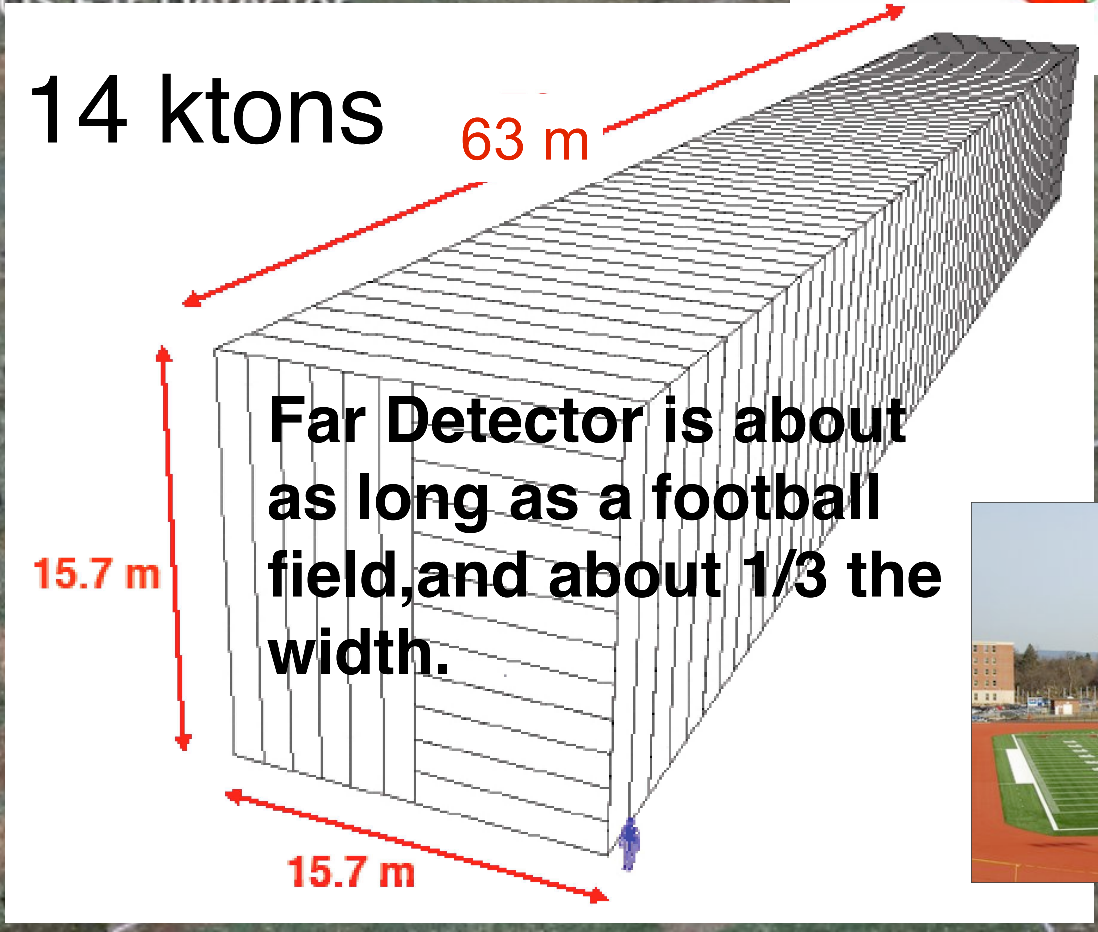
14.6 mrad off-axis from the NuMI beamline.

MINOS Far Detector

NOvA Far Detector

Placed as far north as possible to maximize matter effect.





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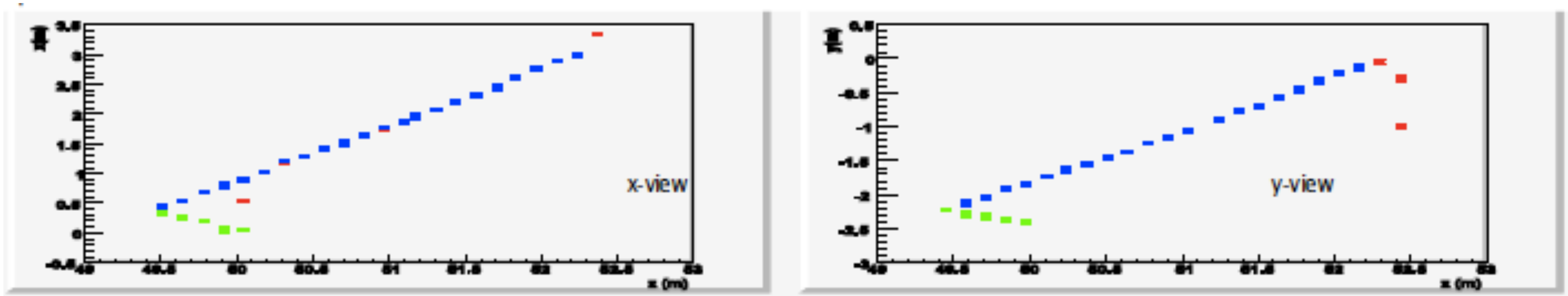
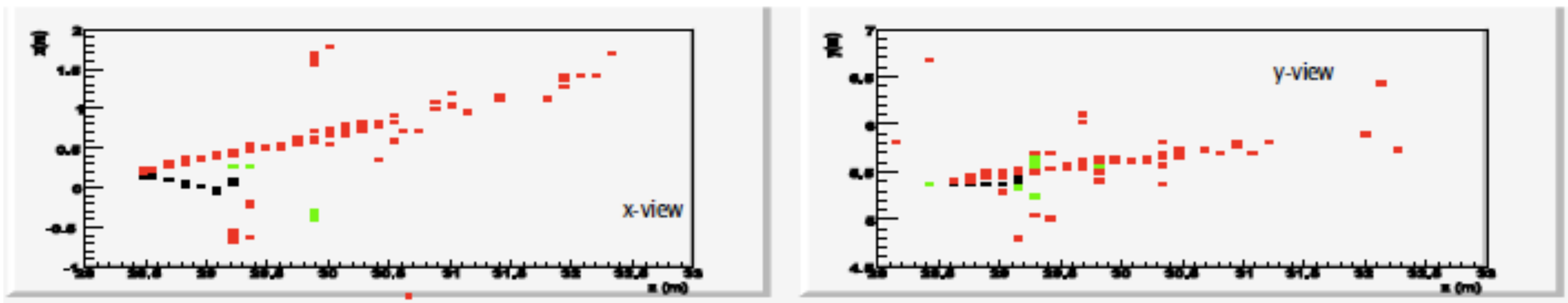
- Has begun taking data, first results expected in early 2015. Data taking will continue until at least 2020.

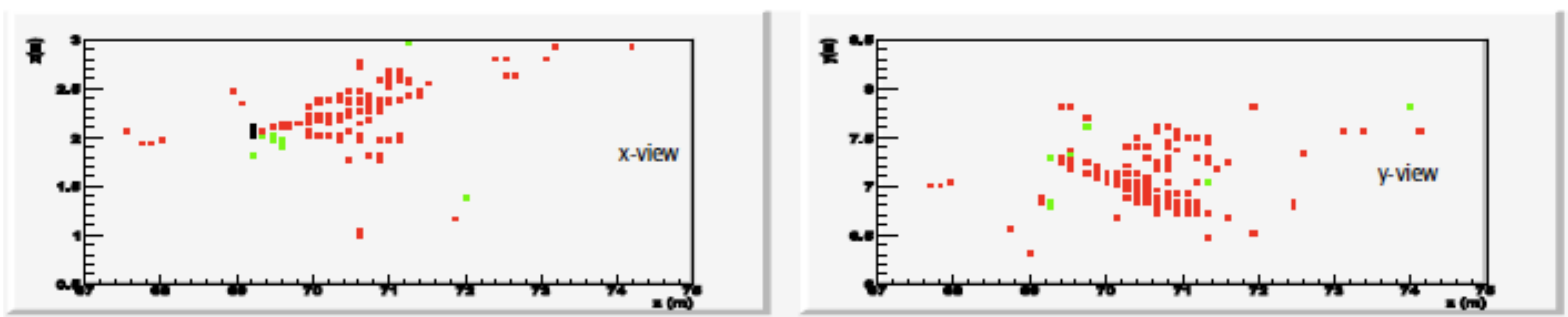
Events in NOvA



ν_μ (1.4 GeV) + N → μ^- (1.0 GeV) + X (QEL)



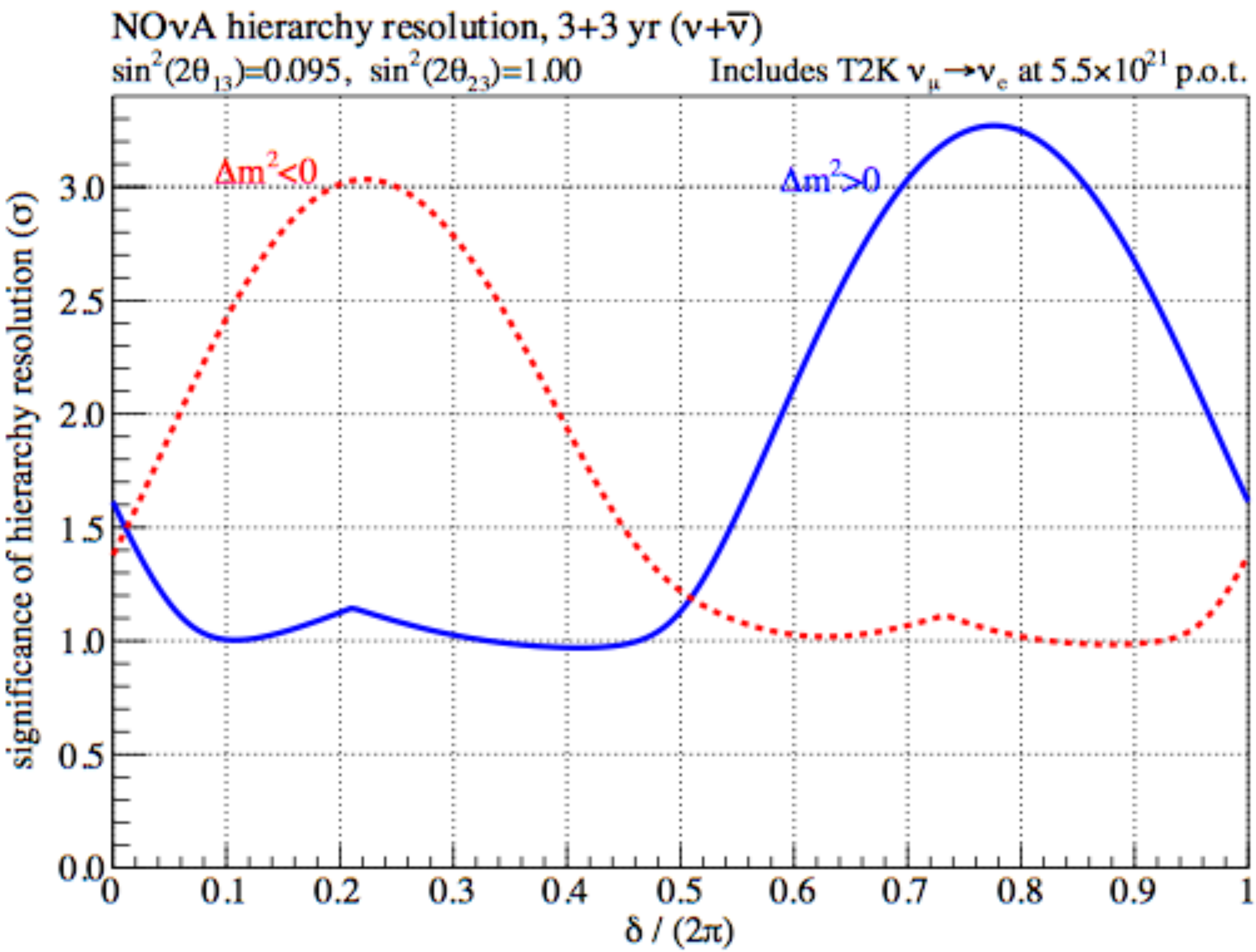
ν_e (2.4 GeV) + N → e^- (1.8 GeV) + X (Res)



ν_μ (5.6 GeV) + N → ν_μ + X (DIS), Y=0.82

The NOvA detectors are specifically designed to detect electrons, in the search for $\nu_\mu \rightarrow \nu_e$ appearance.

NOvA Sensitivities



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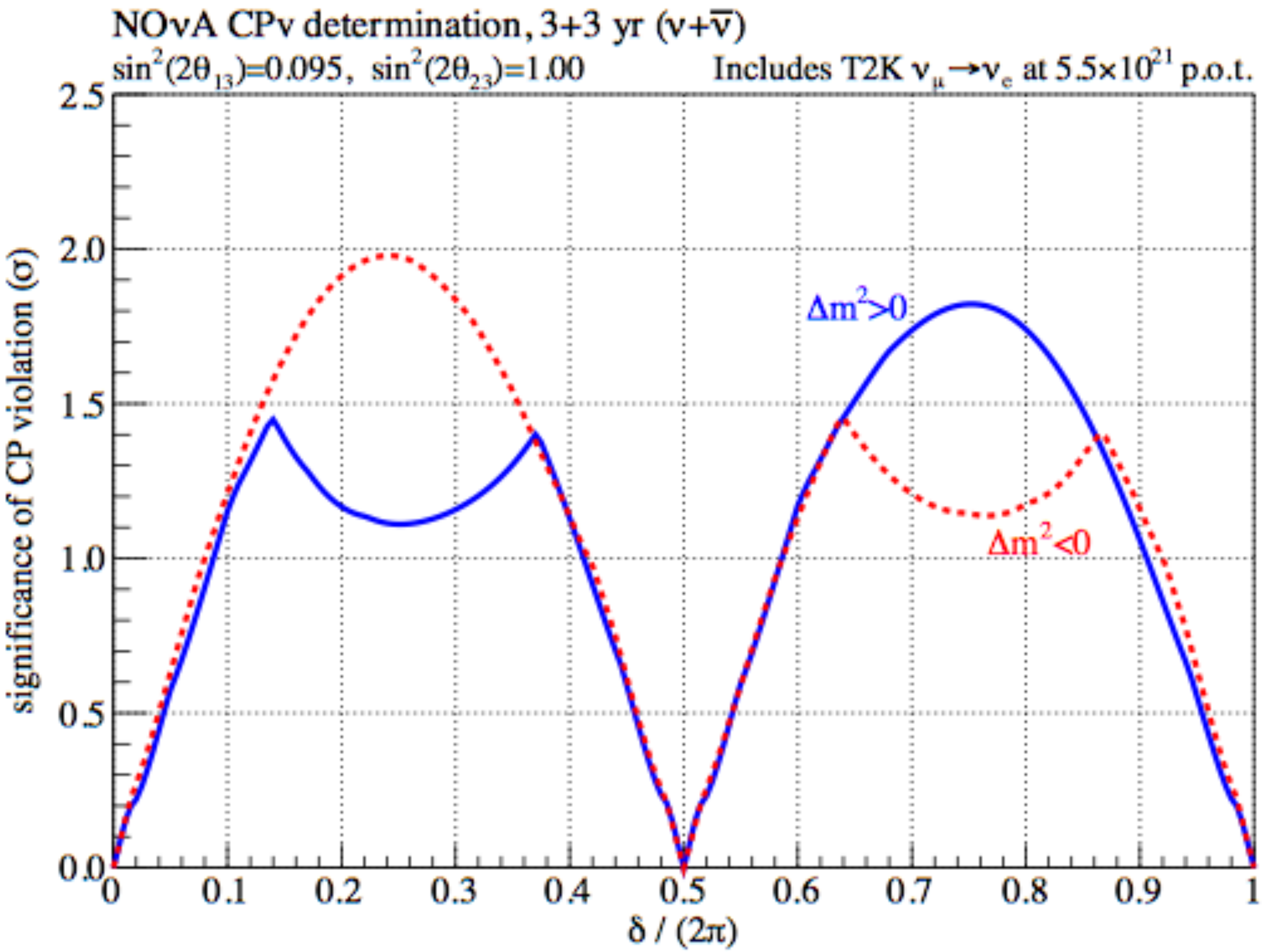
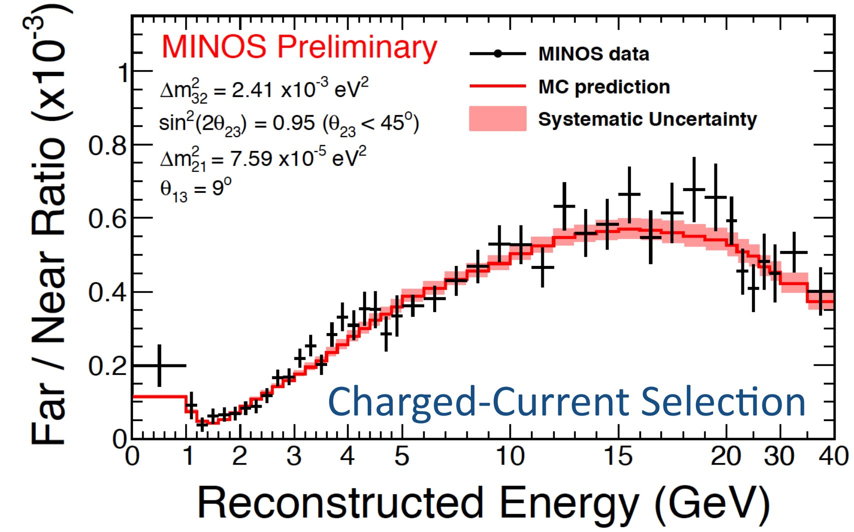
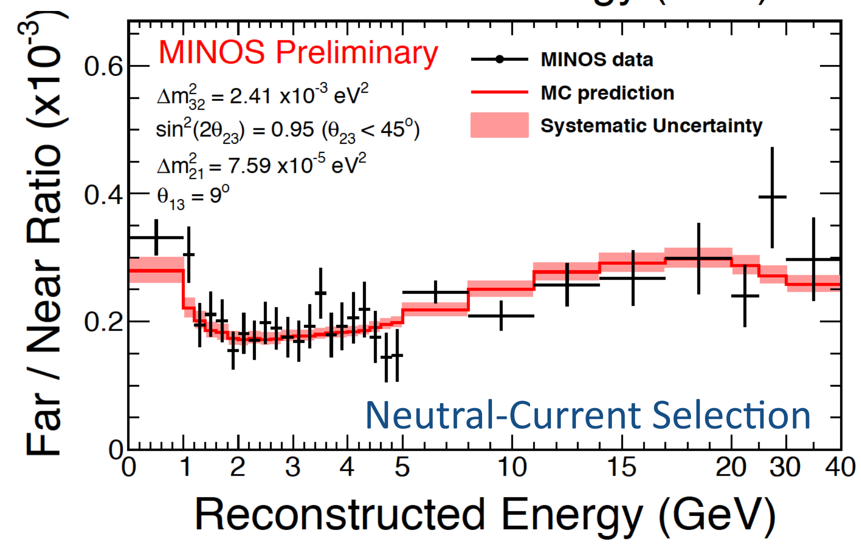
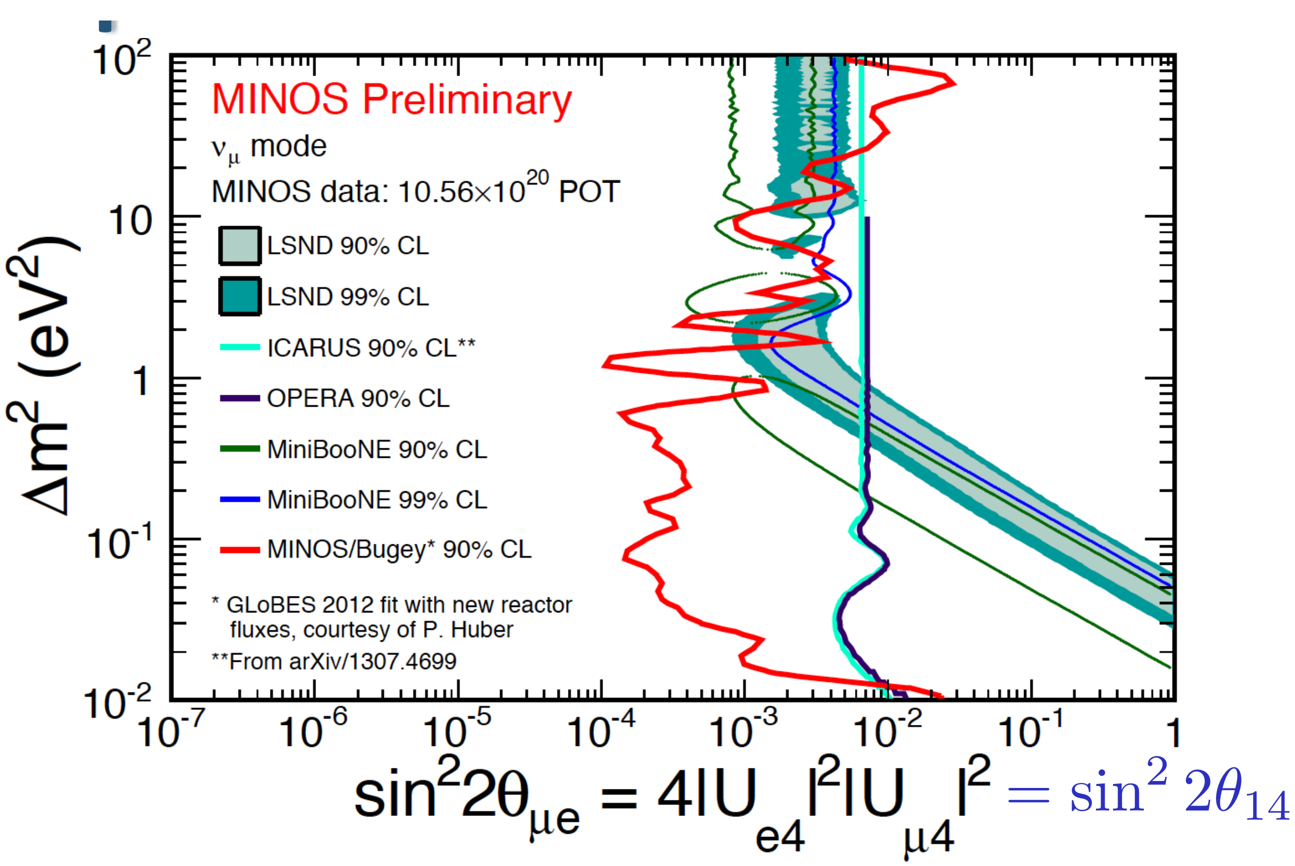


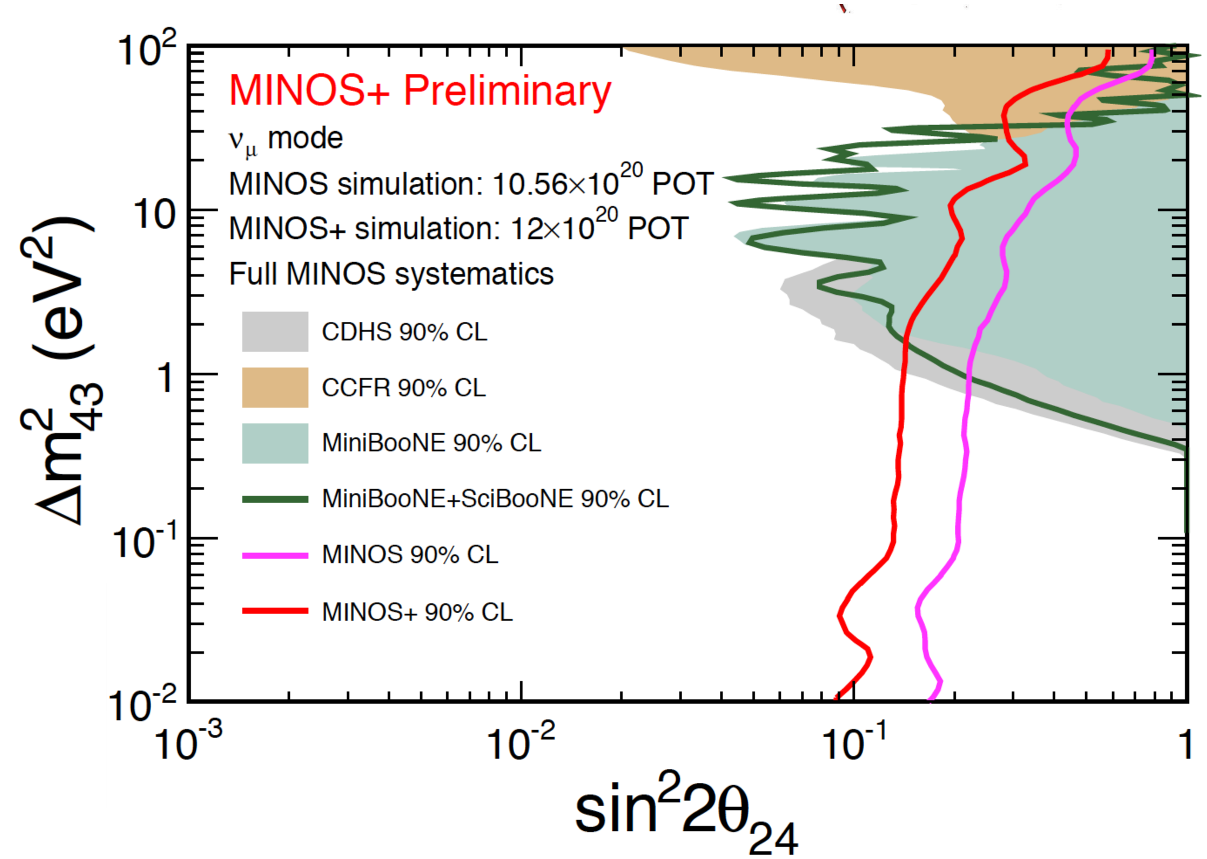
MINOS+

- With the recent NuMI upgrades, the MINOS FD should see ~4000 ν_μ events/year at higher energies.
- Offers an opportunity for a precise test of three-flavor mixing paradigm.
- Also sensitive to "exotic" signals as well as ~80 ν_τ CC events.









Looking to the Not-too-Distant Future...

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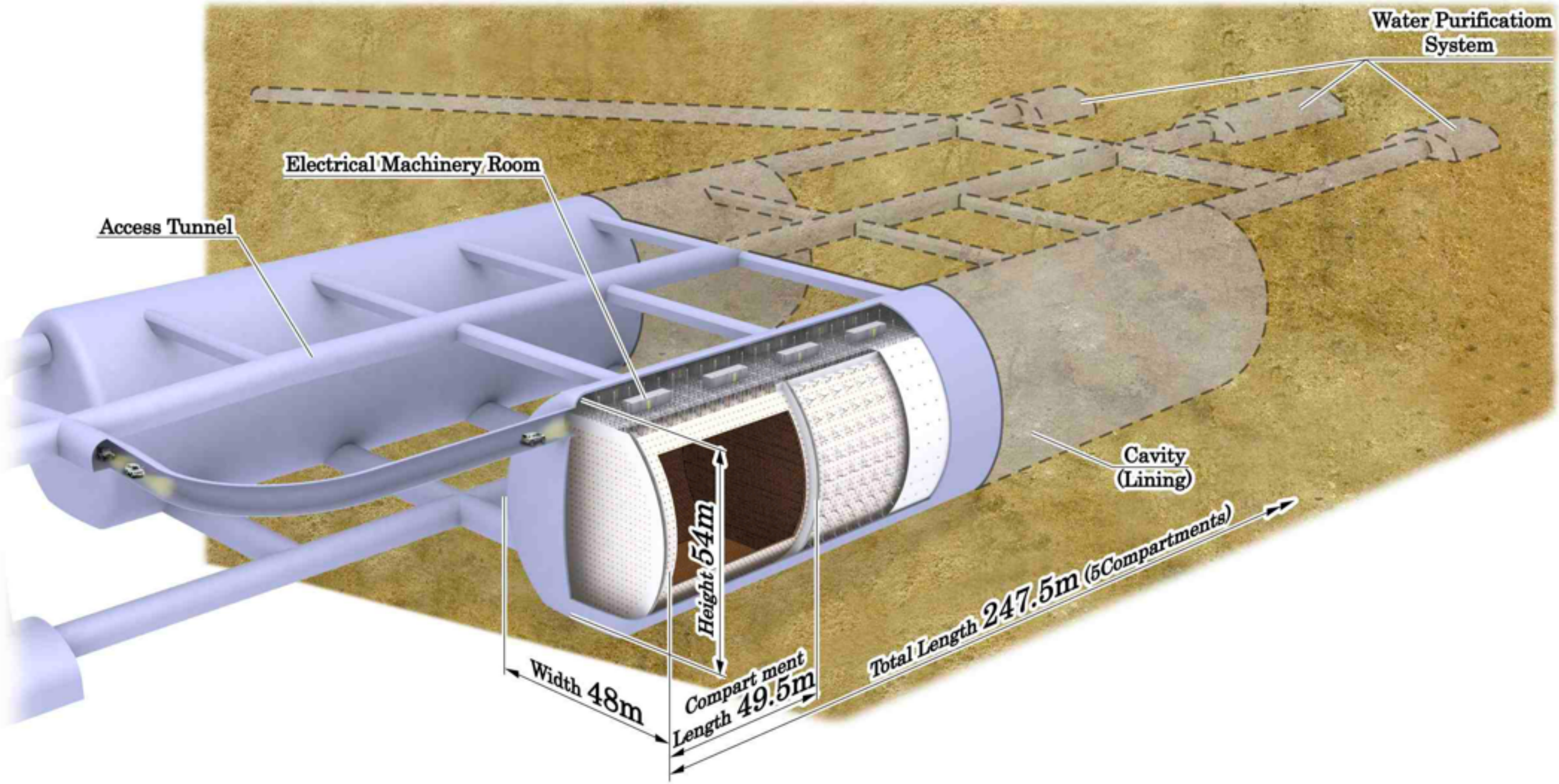

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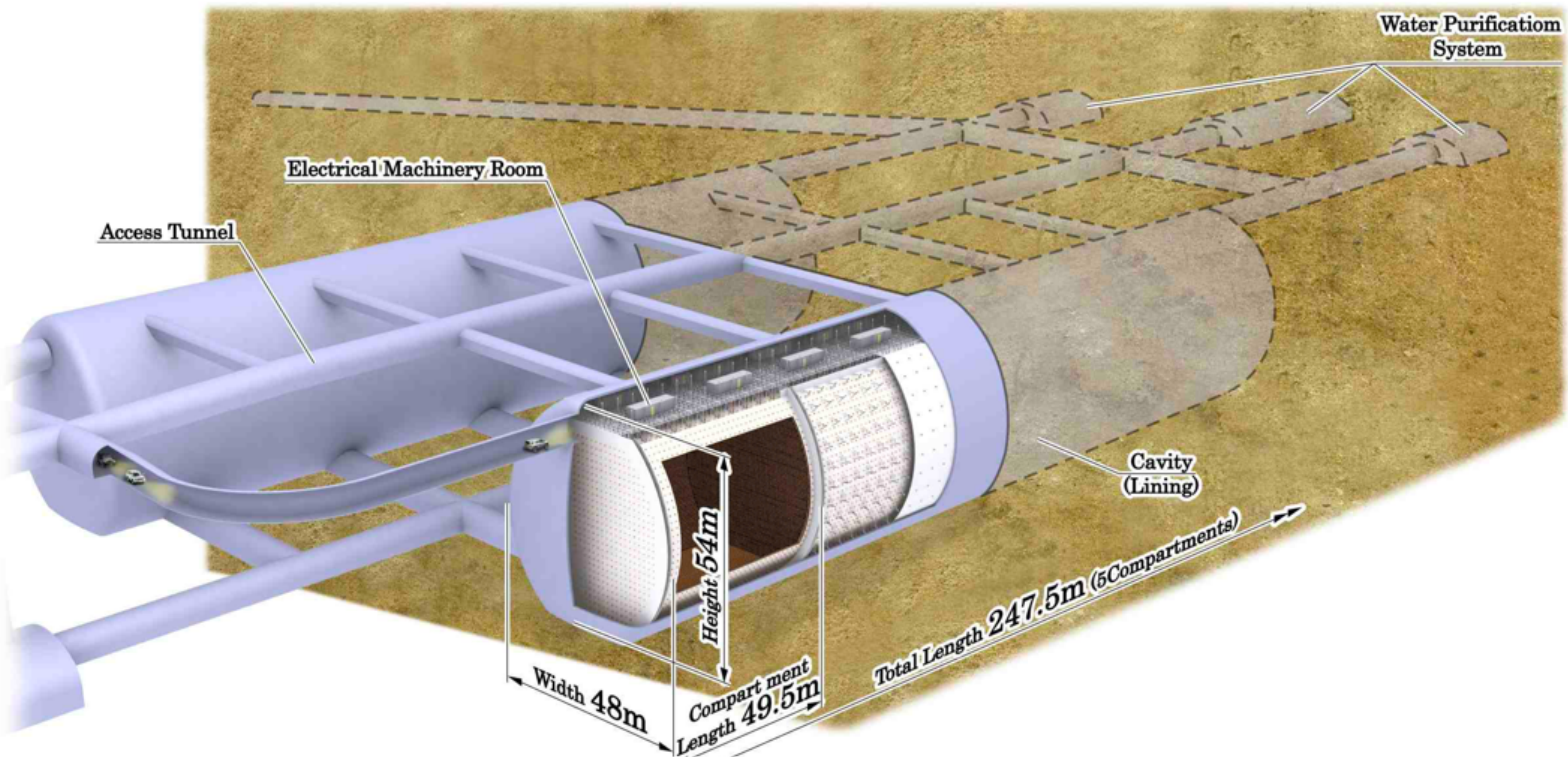

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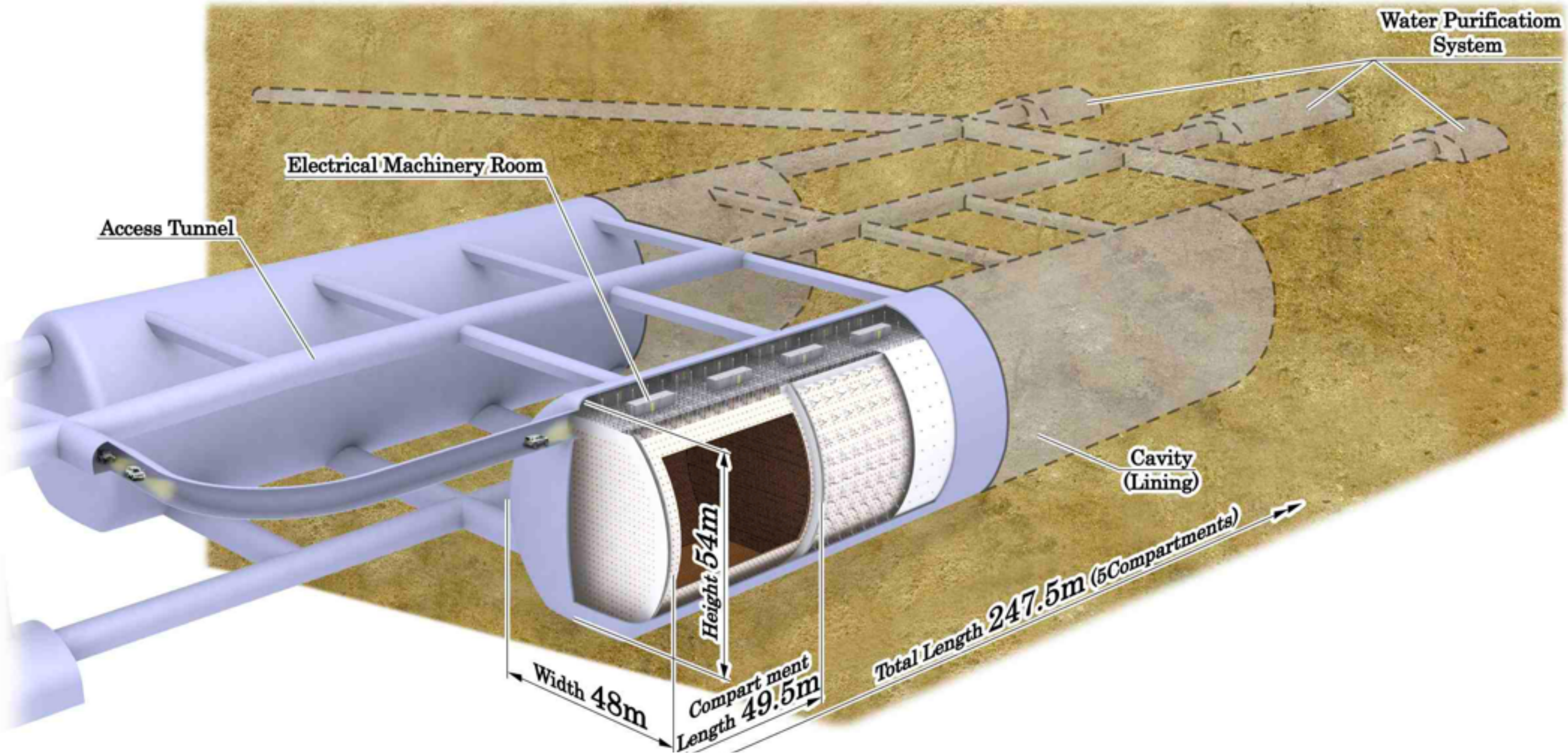

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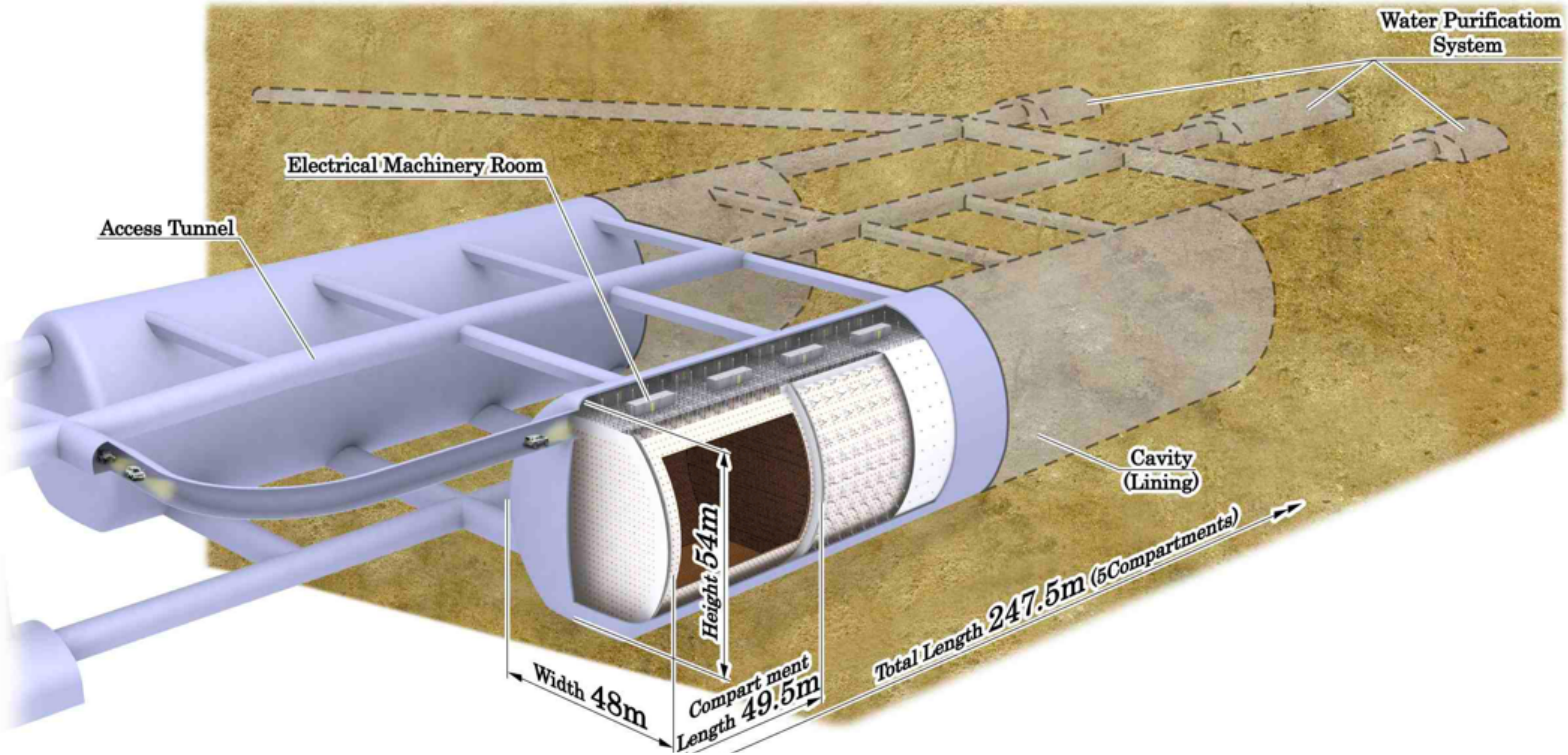

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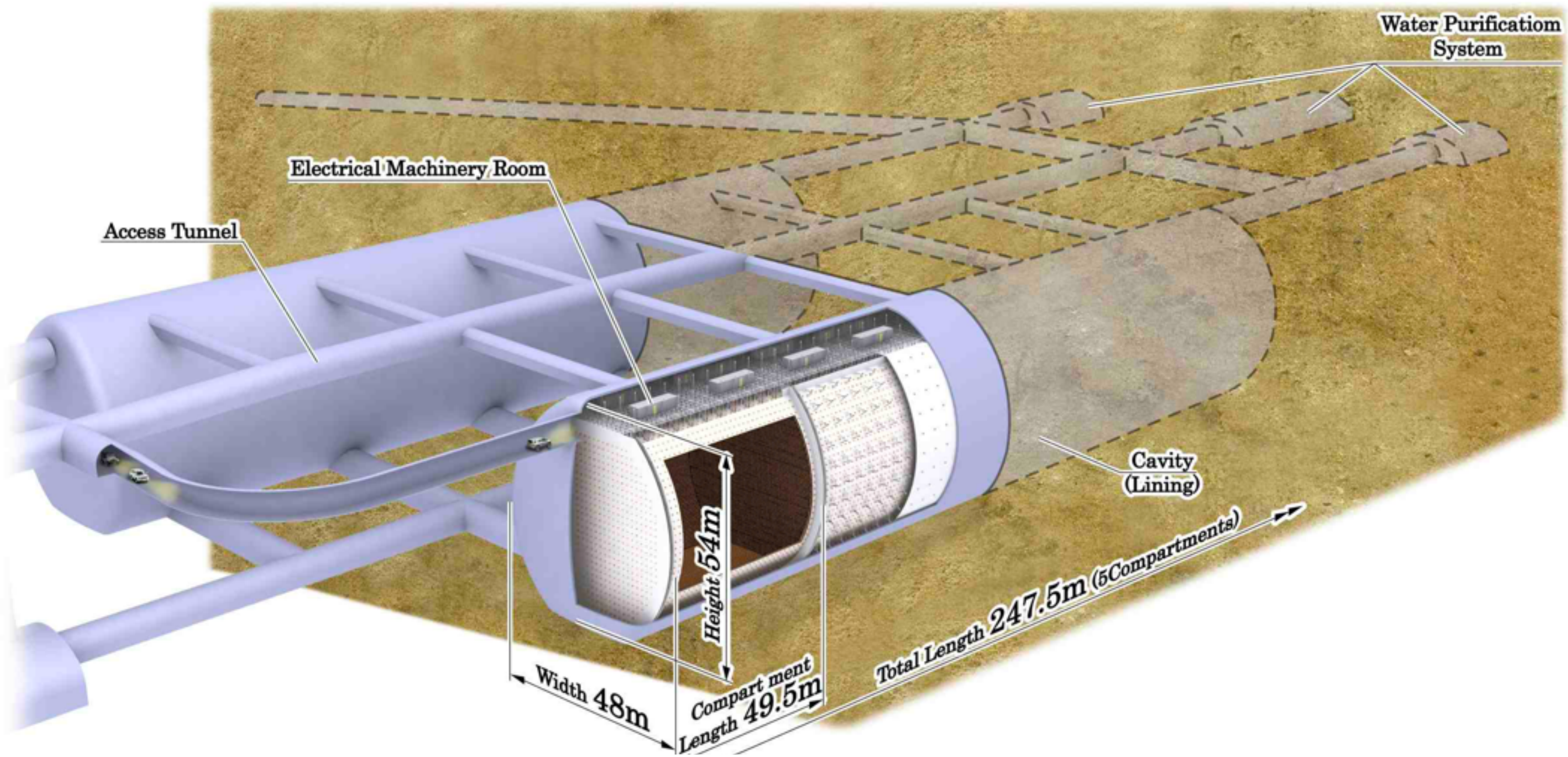

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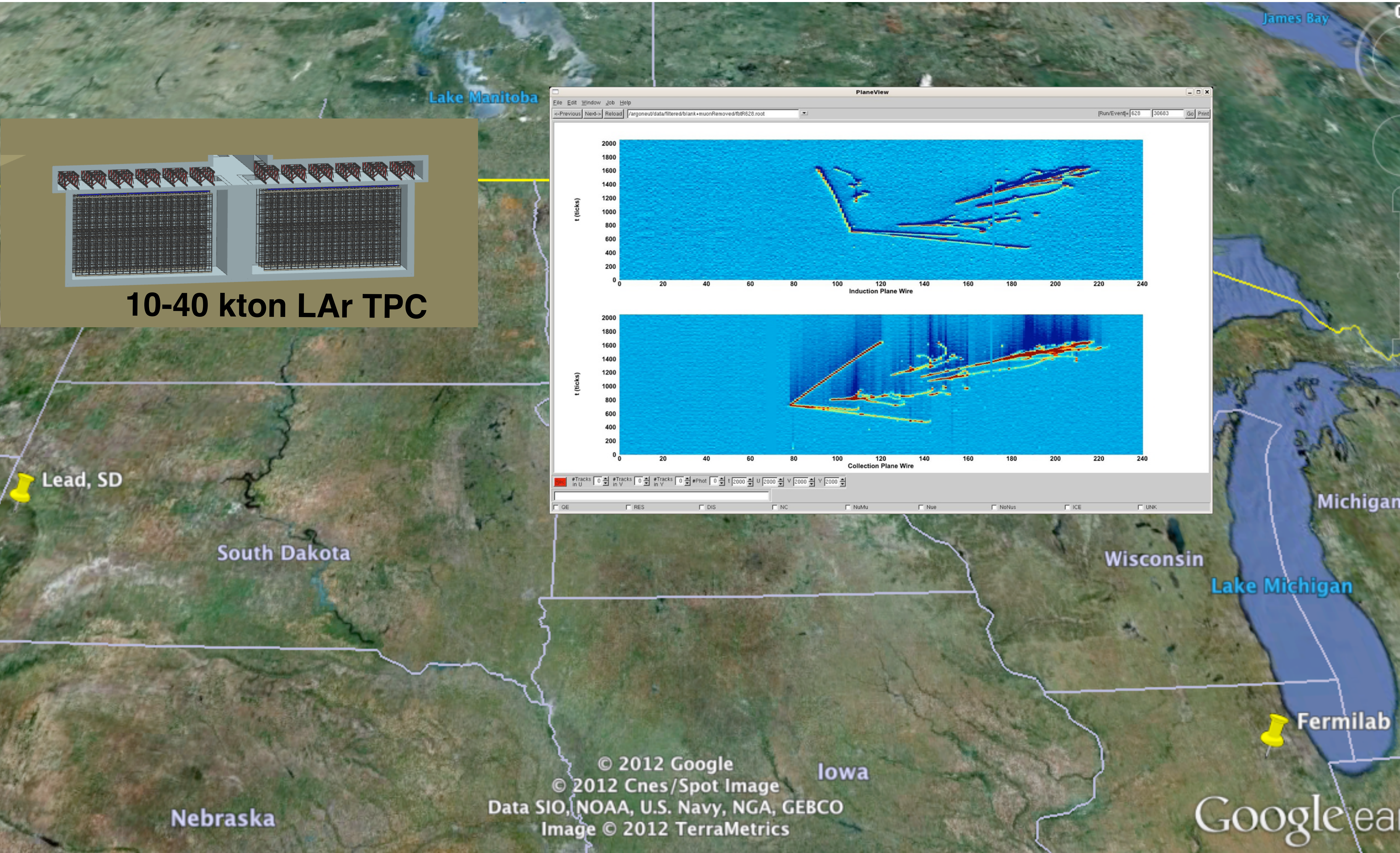
- Could also improve proton-decay limits by ~10x

The Long-Baseline Neutrino Facility (USA)



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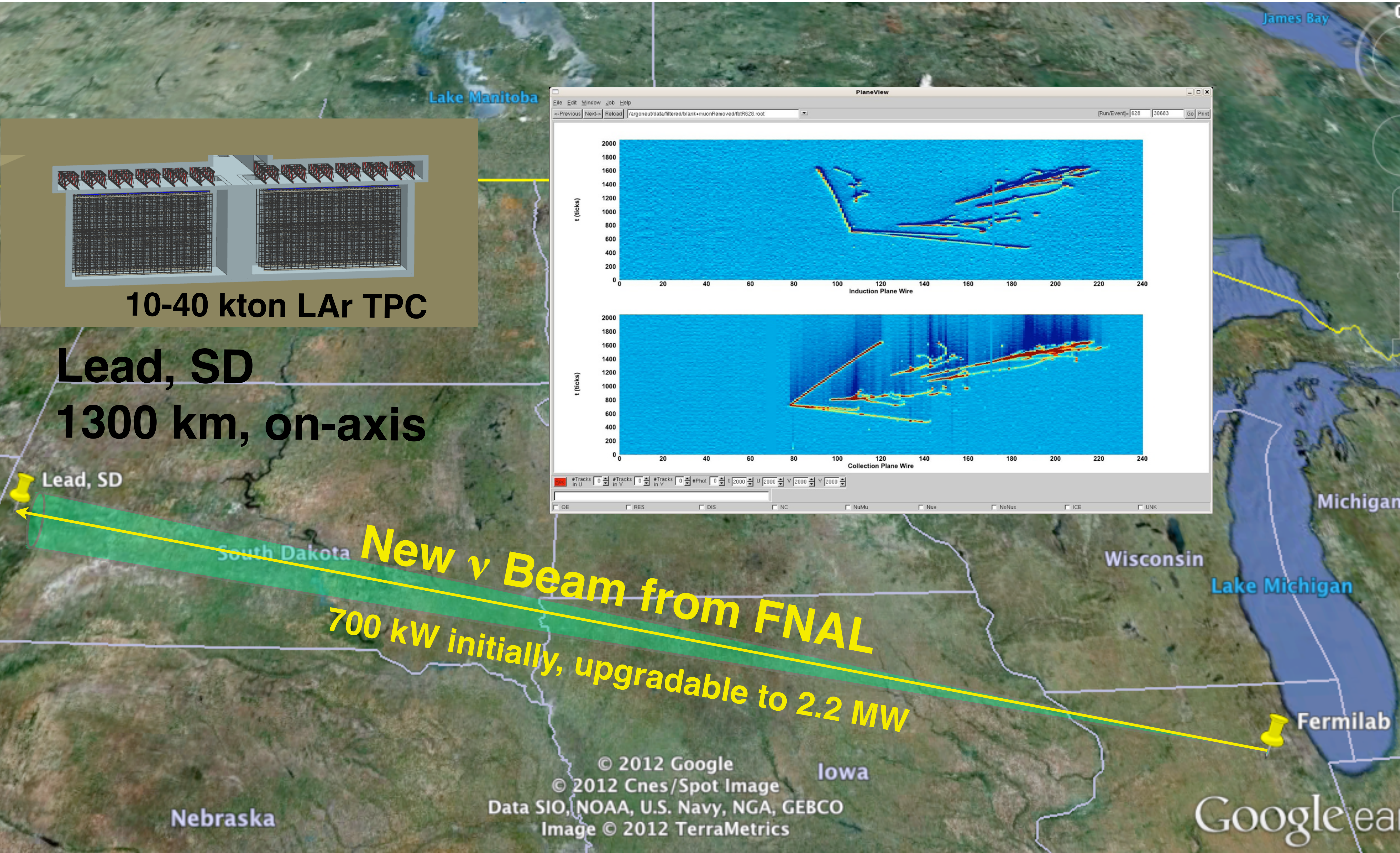
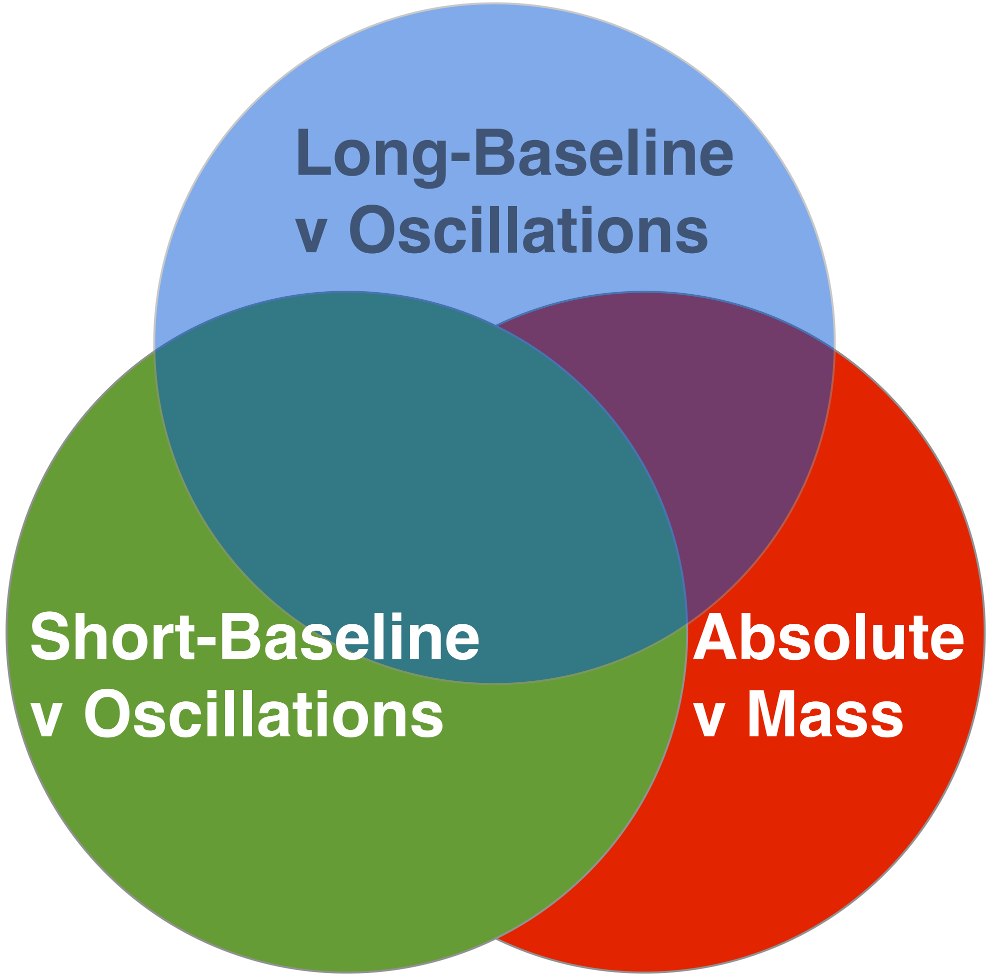


Summary

- Long baseline experiments have guided the development of the three-flavor neutrino mixing paradigm.
- The next decade promises to be very exciting as we make better and better measurements.
- Next lecture: Short-baseline and absolute mass experiments



Questions to Students

- List as many ways to reduce the following backgrounds in a long-baseline experiments:
  - cosmic rays
  - NC interactions
- Large uncertainties in neutrino fluxes and cross sections are often a limiting systematic in neutrino oscillation experiments. How may these uncertainties be mitigated? Are there any downsides to your approach? Any limitations?

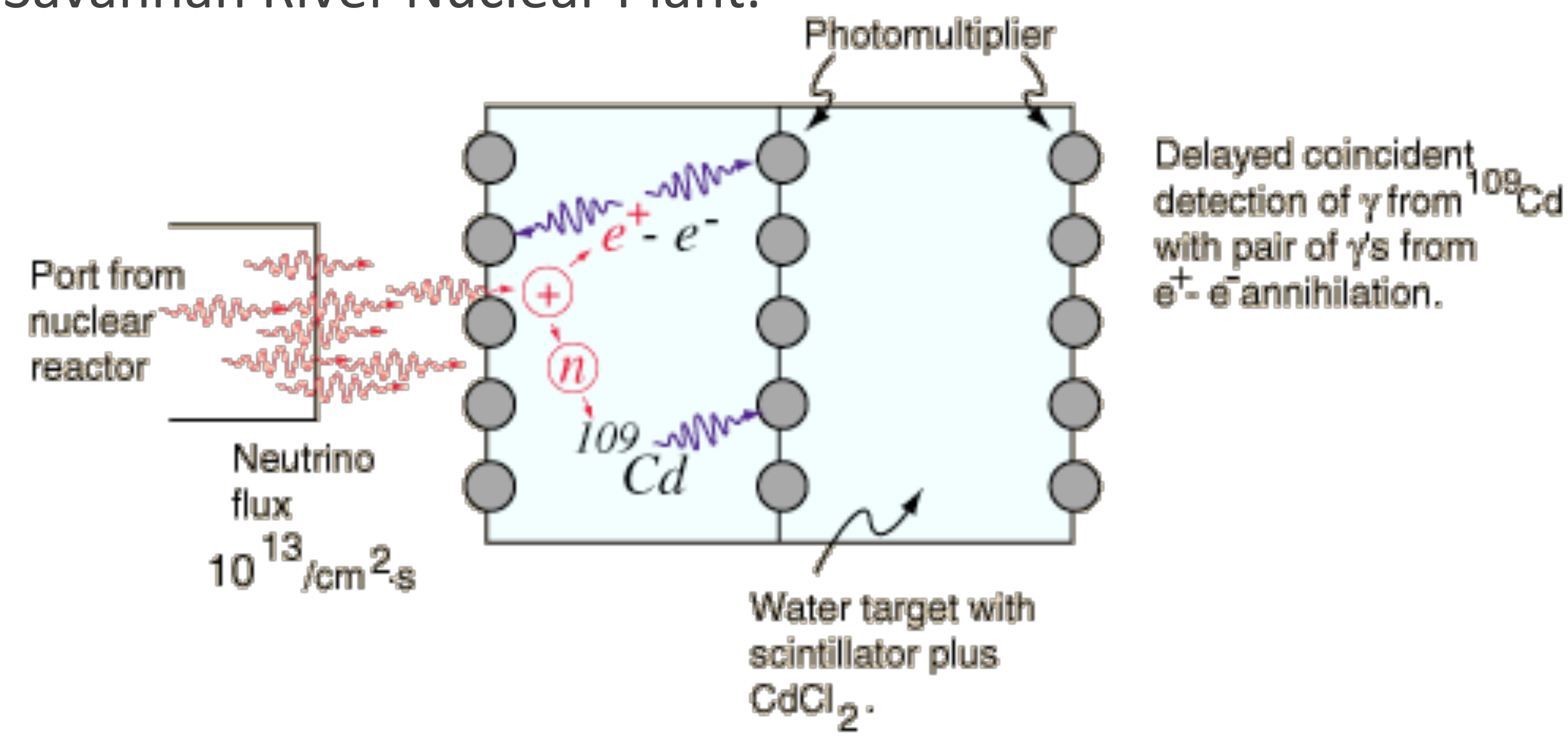
There are no "right" answers!

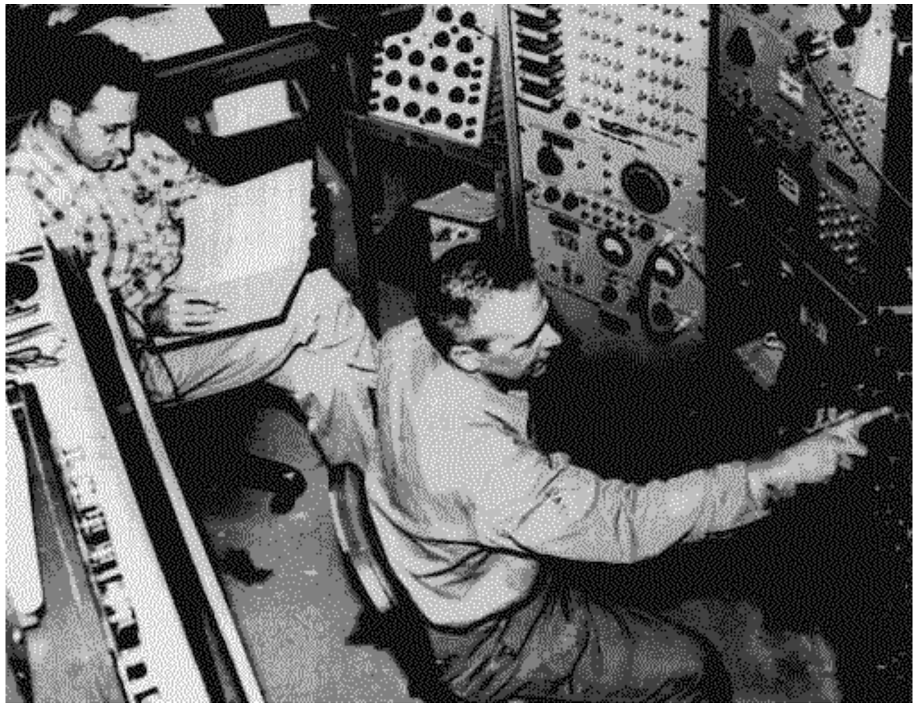
See me during before Friday to discuss
or send your thoughts to jpaley@fnal.gov

BACKUP

Some Neutrino History

- 1956: Reines and Cowan are the first to directly detect neutrinos via inverse beta decay ($\nu_e + p \rightarrow e^+ + n$) at the Savannah River Nuclear Plant.





Reines and Cowan

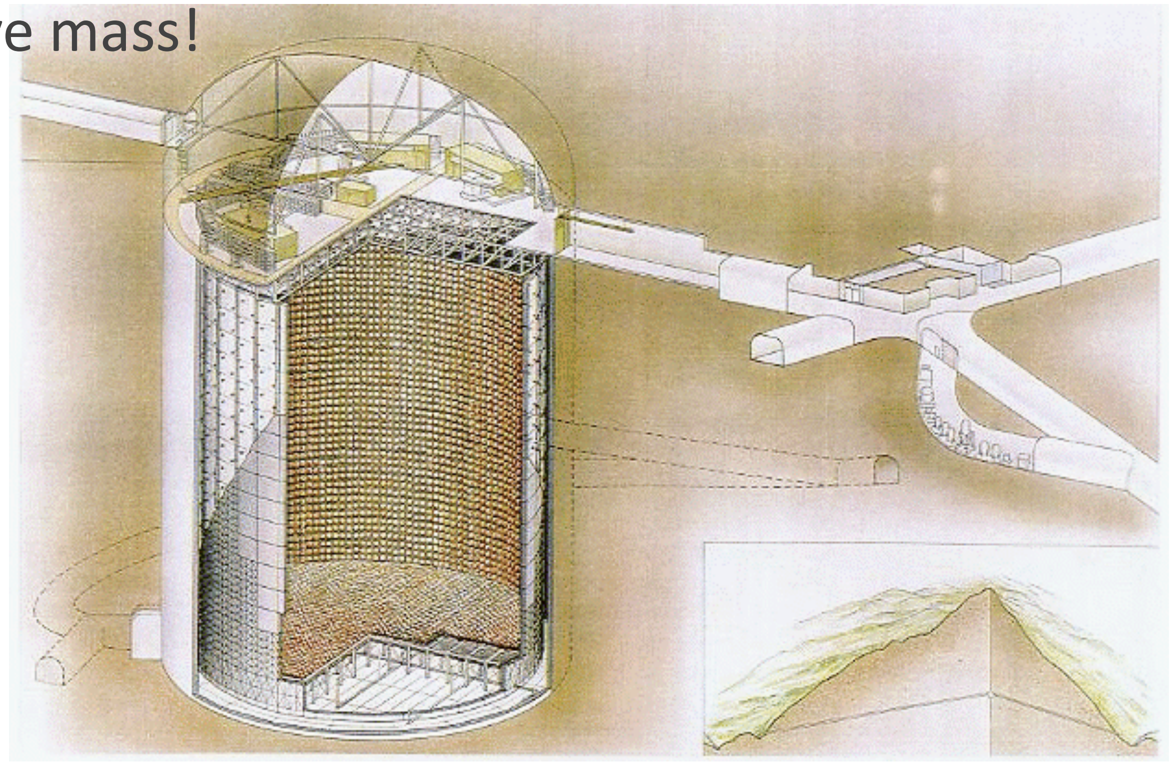
(L to R) Steinberger, Schwartz and Ledermen

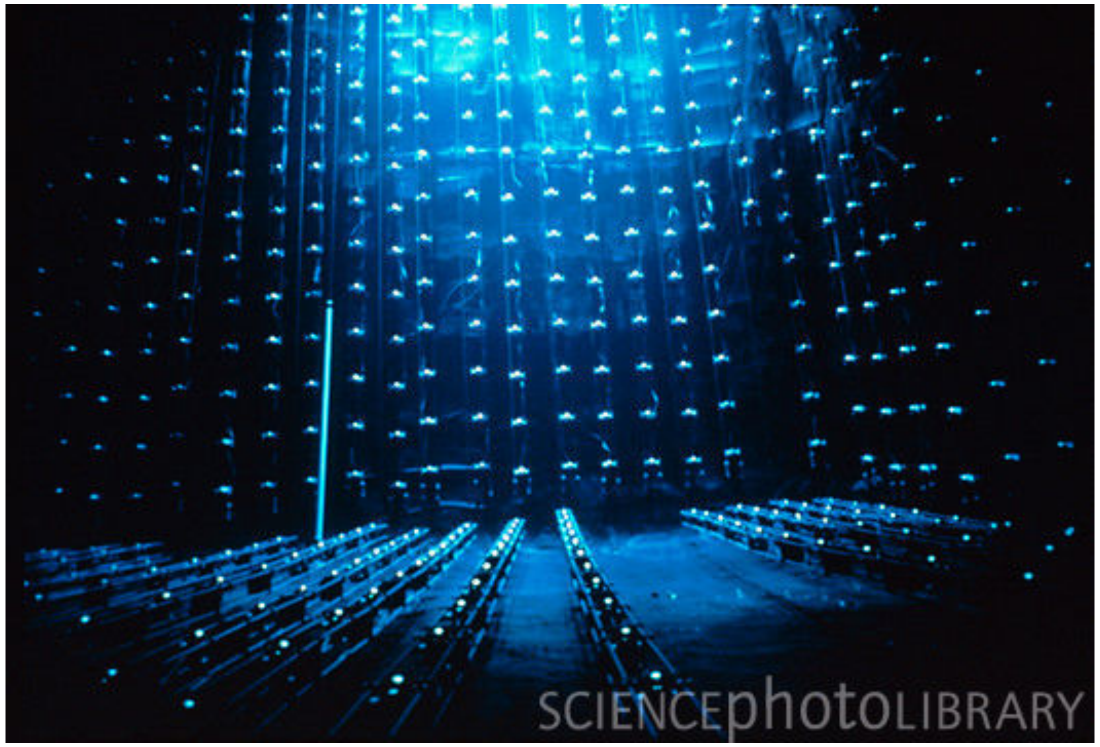
- Note: over 50 years later, modern-day experiments continue to implement this same technique of delayed coincidence!
- 1957: Neutrinos are found to be *left-handed* by Goldhaber, Grodzins and Sunyar by measuring the polarization .
- 1962: Muon neutrinos, different from electron neutrinos, are discovered by Ledermen, Schwartz, Steinberger and colleagues. *Neutrinos have **flavor**!*

Some Neutrino History

- 1968: Ray Davis and colleagues measure neutrino solar flux in the Homestake Mine (SD). The flux is too low by ~2x; this deficit becomes known as the "solar neutrino problem".

- 1985: IMB and Kamiokande experiments observe the "atmospheric neutrino anomaly". Note: both of these experiments were originally designed to search for proton-decay!
- 1996: Super-Kamiokande collaboration reports finding neutrino oscillations; muon neutrinos have mass!





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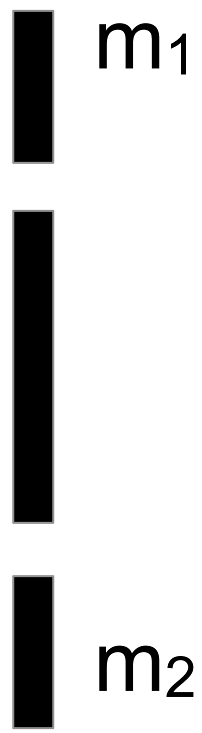

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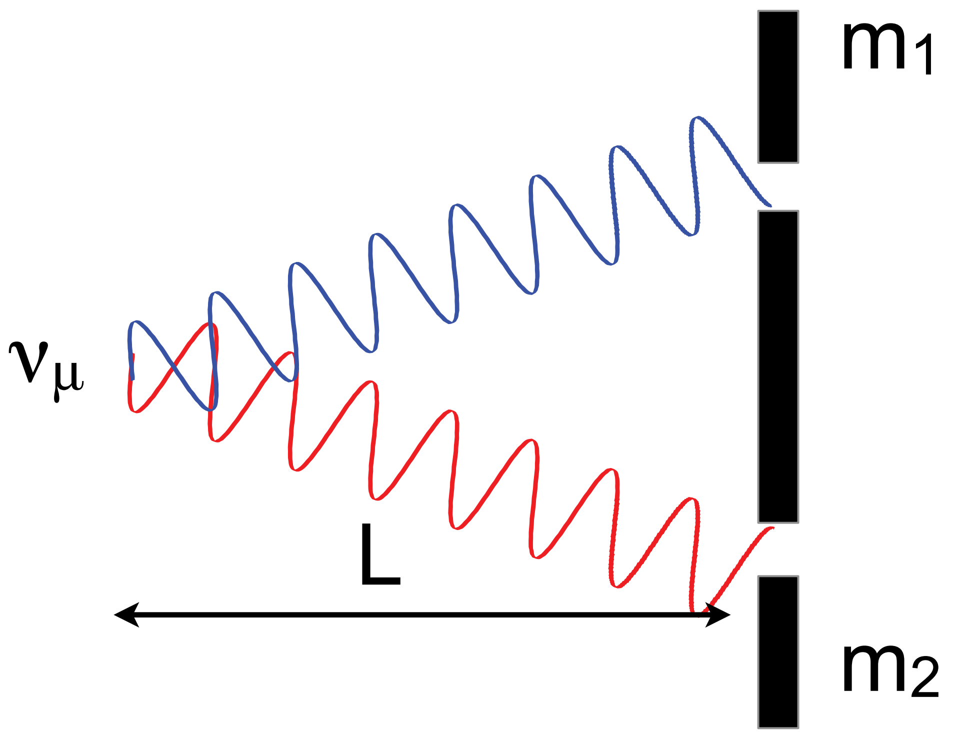

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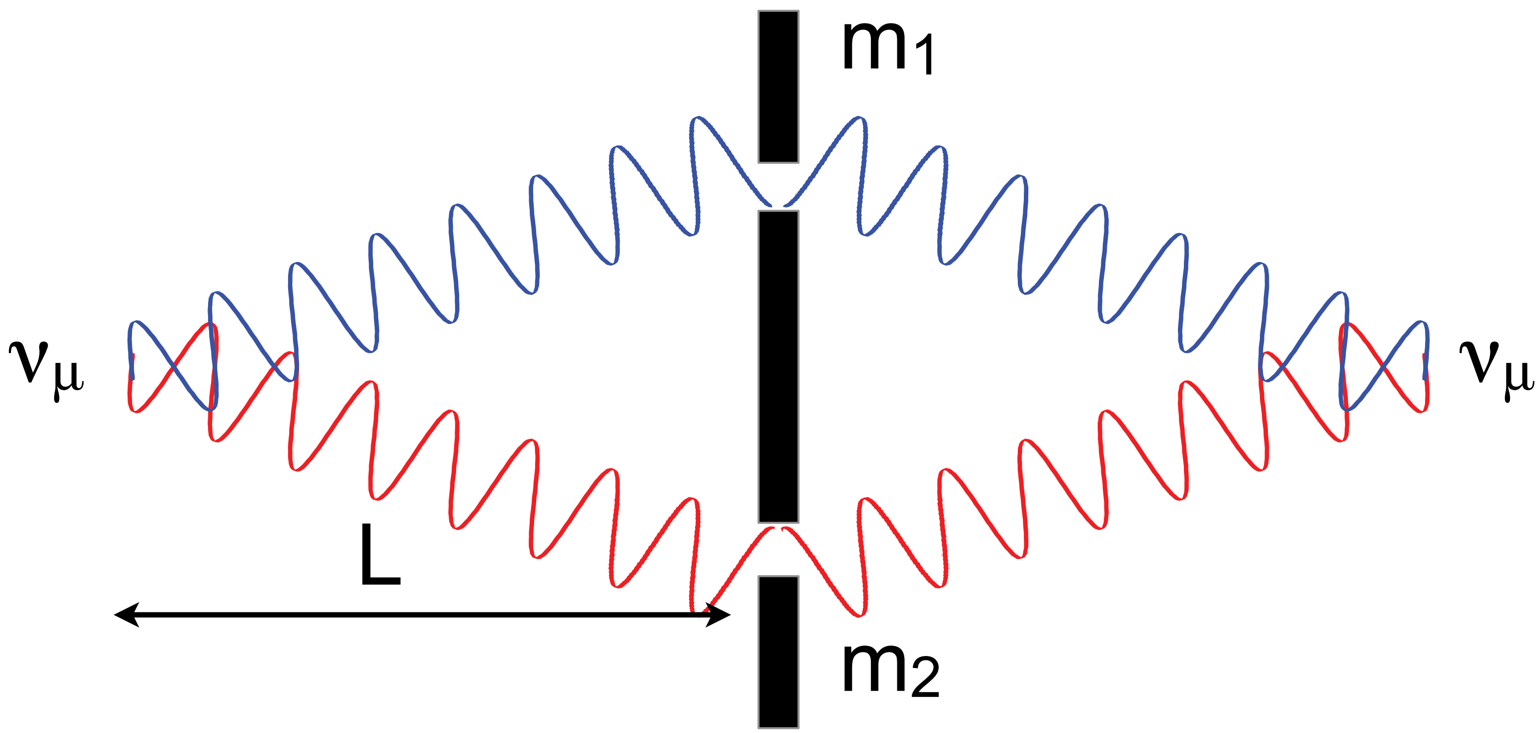

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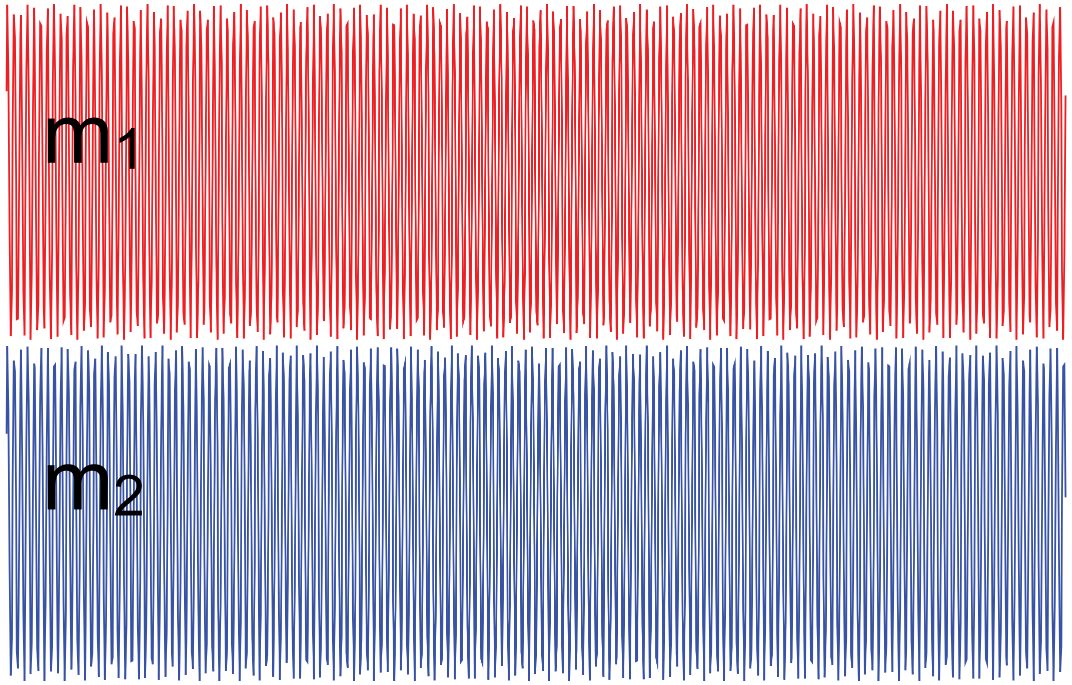

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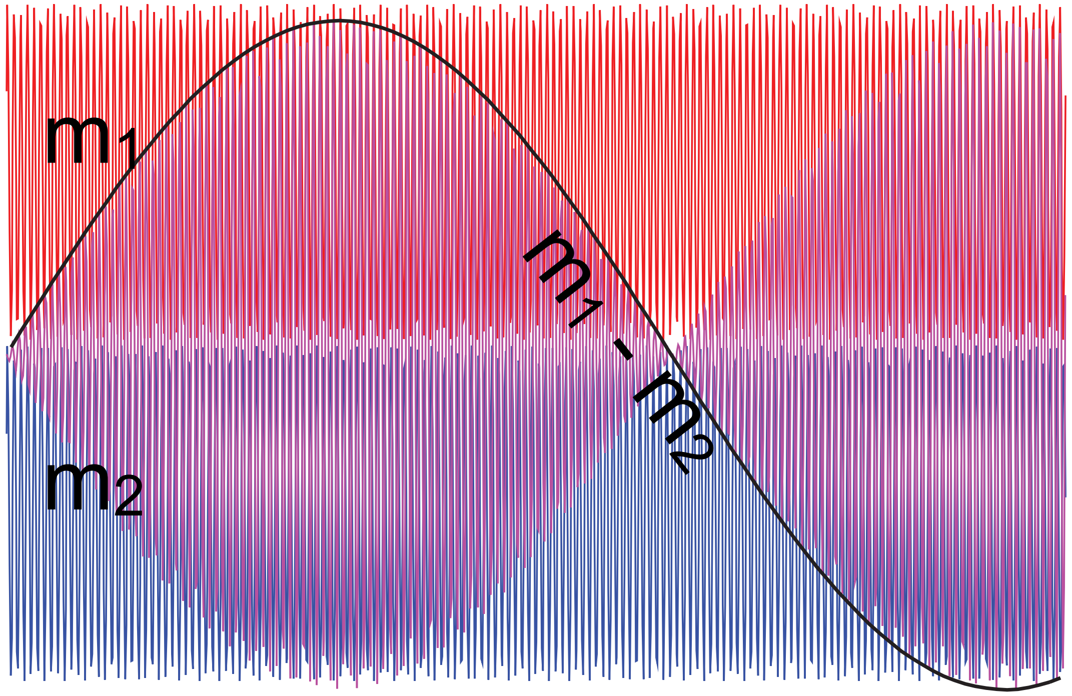

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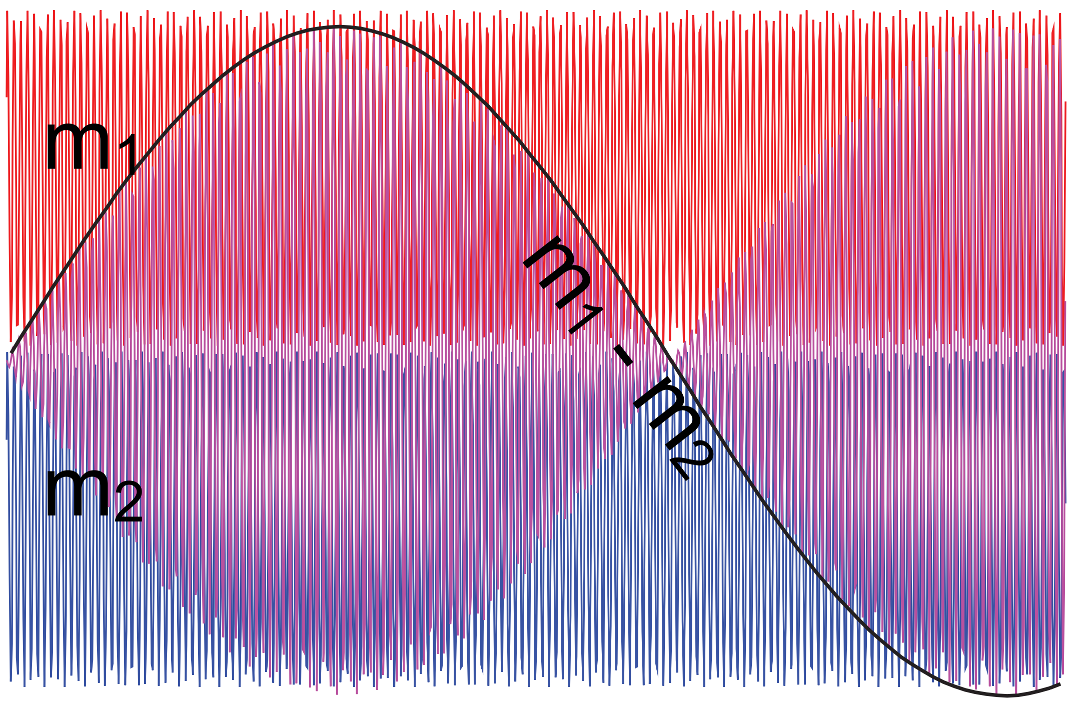

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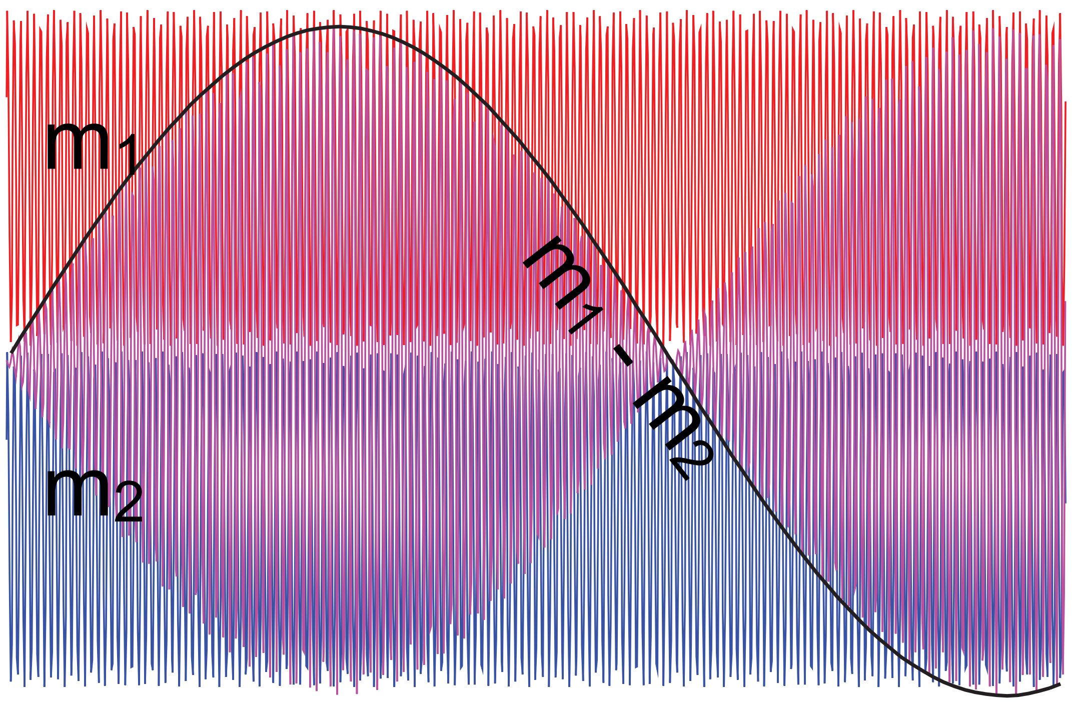

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Describes the amplitude of the oscillations.

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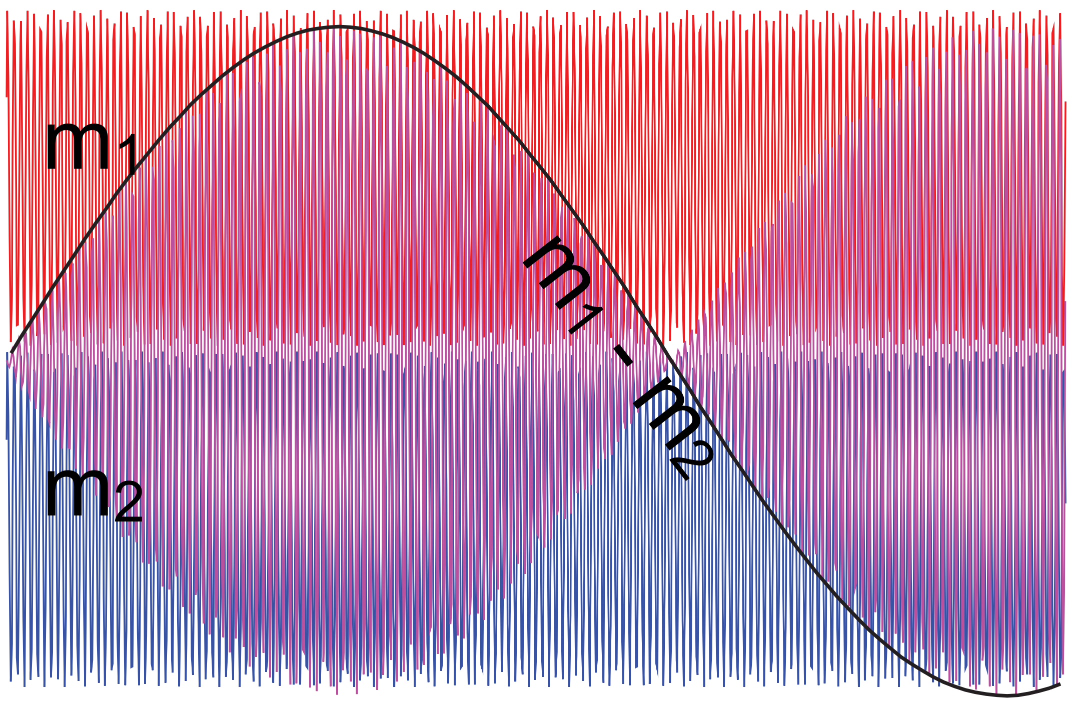
Neutrino Oscillations



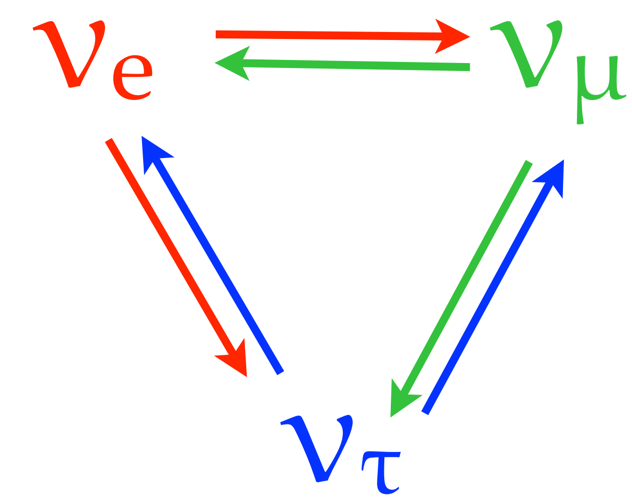
$$P(\nu_\mu \to \nu_\mu) \simeq 1 - \sin^2(2\theta)\sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

$\sin^2(2\theta)$: Describes the amplitude of the oscillations.

Δm^2: Determines the frequency of the oscillations.

- Neutrino masses are so small that no one has yet been able to directly measure them!
- However, if neutrinos have mass **and** if the v-flavor states are a quantum superposition of mass eigenstates, then neutrino oscillations occur. In other words, we can see the effect of neutrino mass by measuring their interference pattern!
- **Neutrino oscillations are a quantum-mechanical phenomenon that occur over very large length-scales!**

Neutrino Oscillations



- Neutrino oscillations occur because ν-flavor states are a quantum superposition of mass eigen states.

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

$$P(\nu_\alpha \to \nu_\alpha) = \left| \sum_j U^*_{\alpha j} e^{-i \frac{m_j^2 L}{2E}} U_{\alpha j} \right|^2$$

In vacuum:

$$P(\nu_\mu \to \nu_e) = \left| 2U^*_{\mu 3} U_{e3} \sin \Delta_{31} e^{-i\Delta_{32}} + 2U^*_{\mu 2} U_{e2} \sin \Delta_{21} \right|^2$$

$$\Delta_{ij} \equiv \frac{1.27 \Delta m^2_{ij} [\mathrm{eV}^2] L[\mathrm{km}]}{E[\mathrm{GeV}]}$$

Cross-Sections & Fluxes

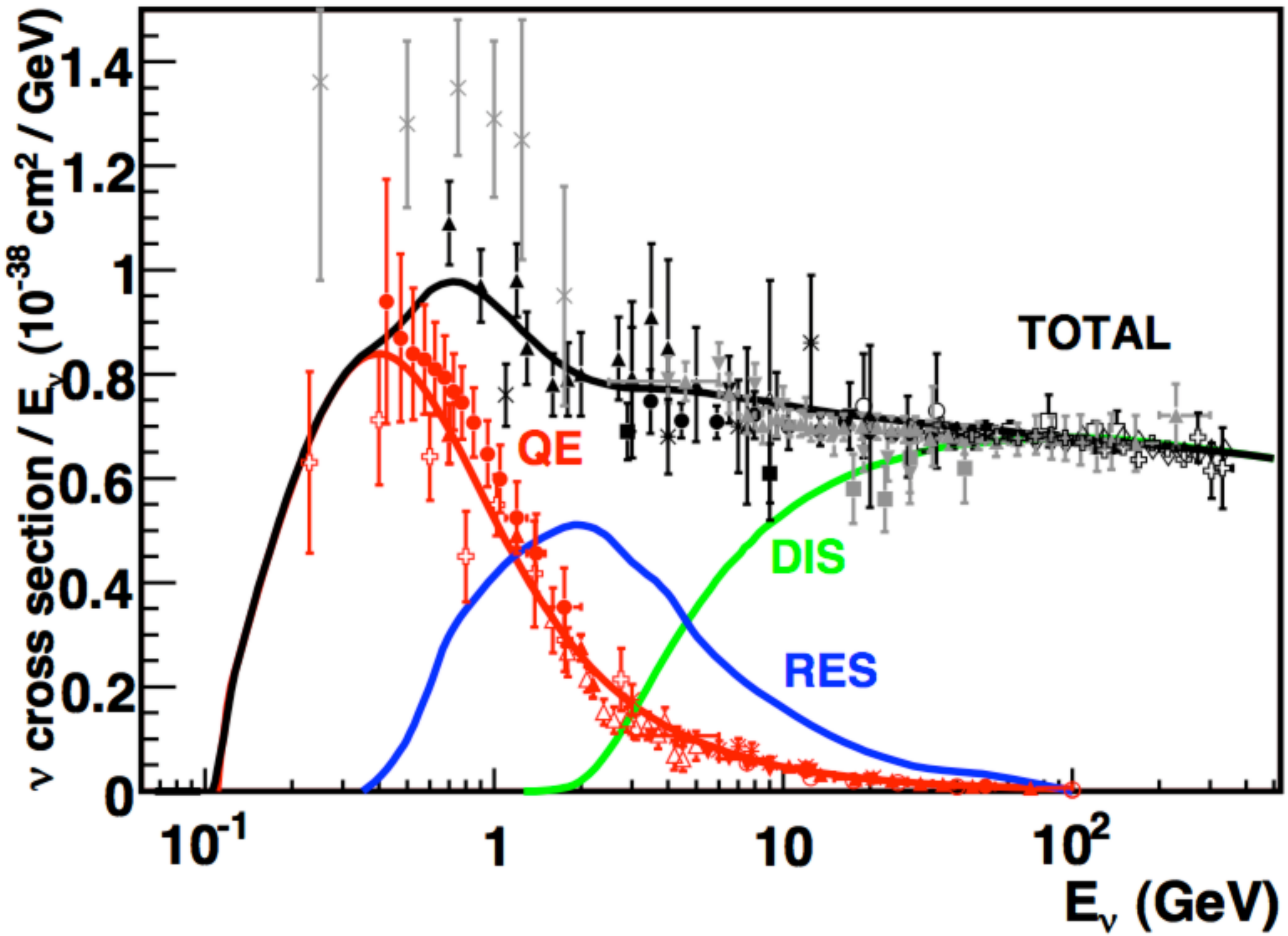
Cross-Sections & Fluxes

- Generally speaking, need to know how many neutrinos one expects to see in a detector

  $N_\nu(E) = \Phi_\nu(E)\sigma_\nu(E)$

- In oscillation experiments, this knowledge can be ~circumvented by using two detectors to cancel out our ignorance. One detector located near the source to measure $N_\nu(E)$ before the ν's oscillate, one detector located farther away after ν's have oscillated.
- However, this is not exactly a silver bullet:
  - some experiments only have one detector
  - some experiments have two detectors, but made of different materials/geometry
  - some experiments want to measure the cross-section

Cross-Sections



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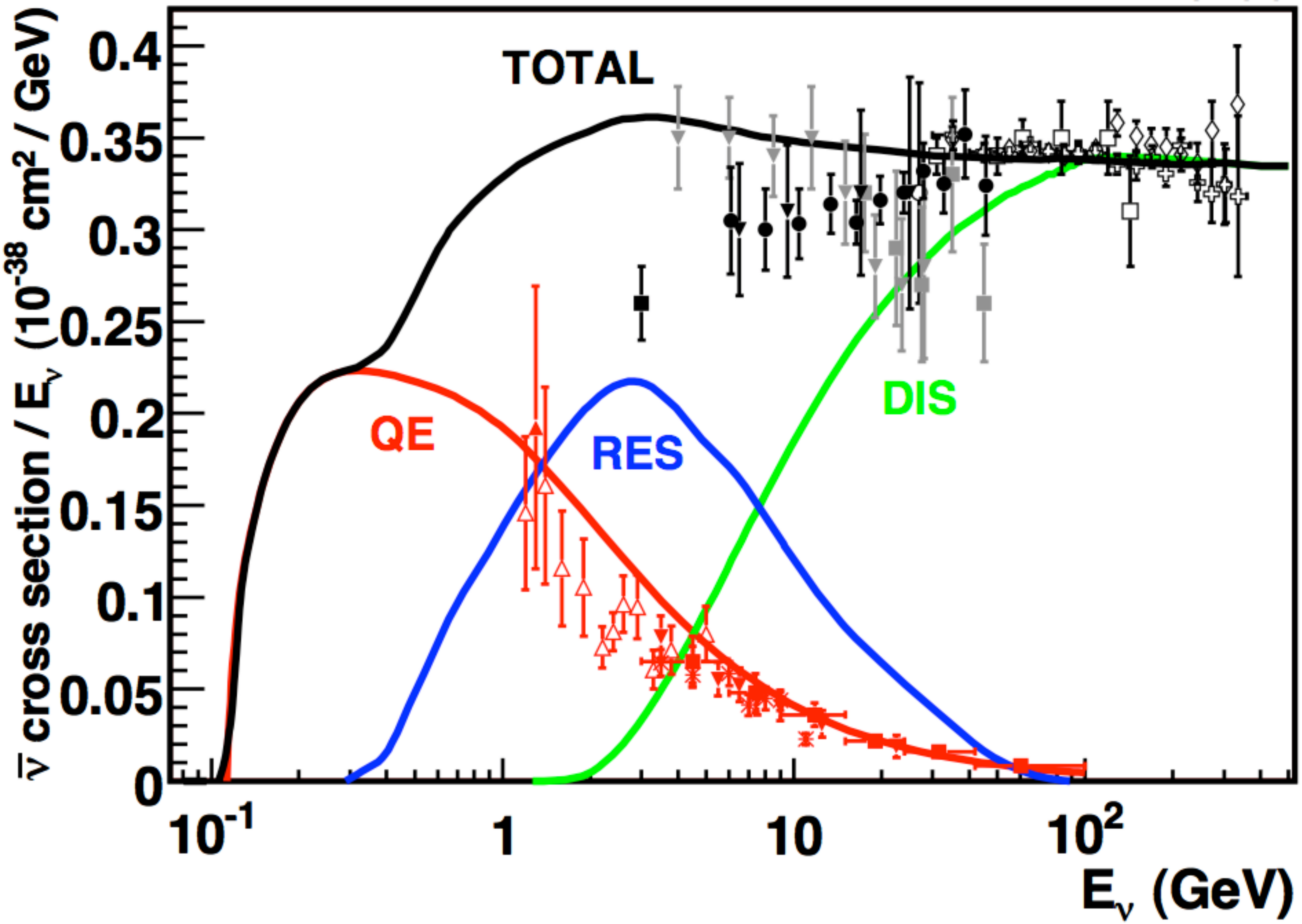
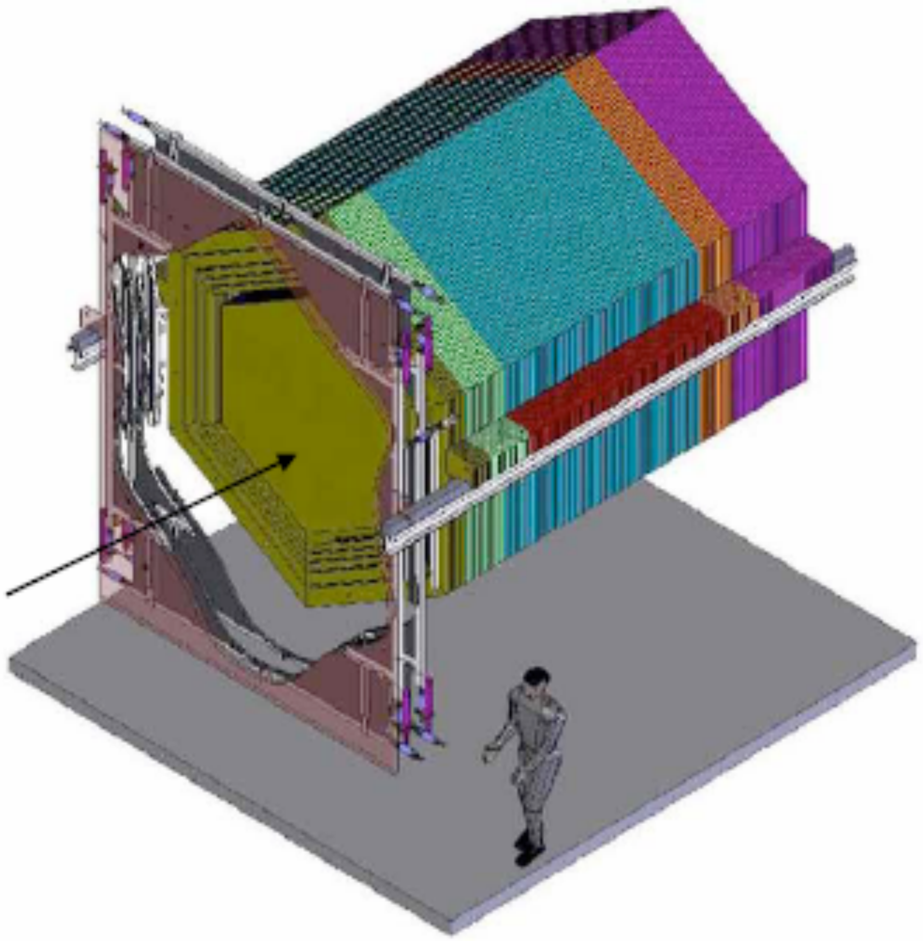
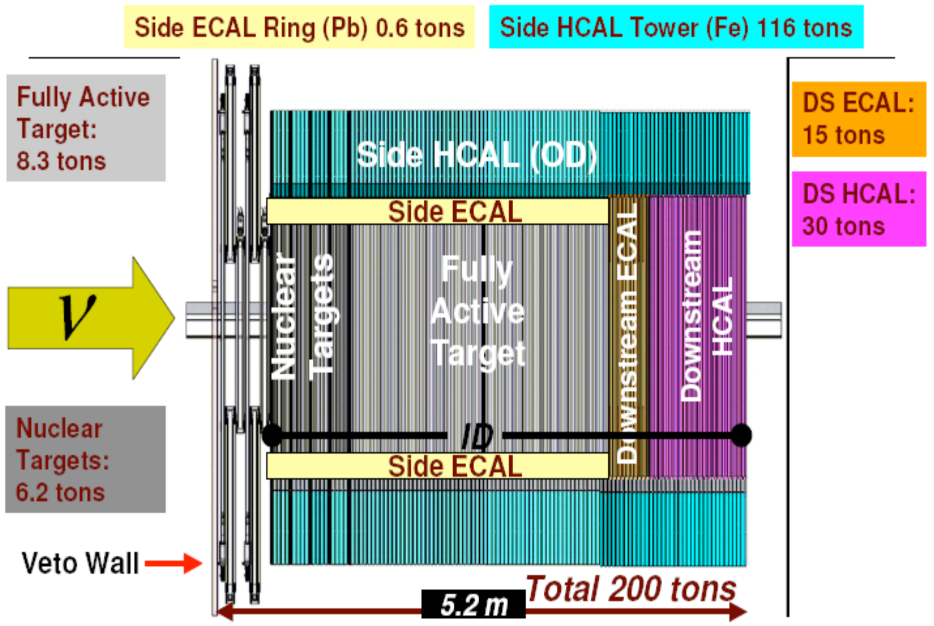


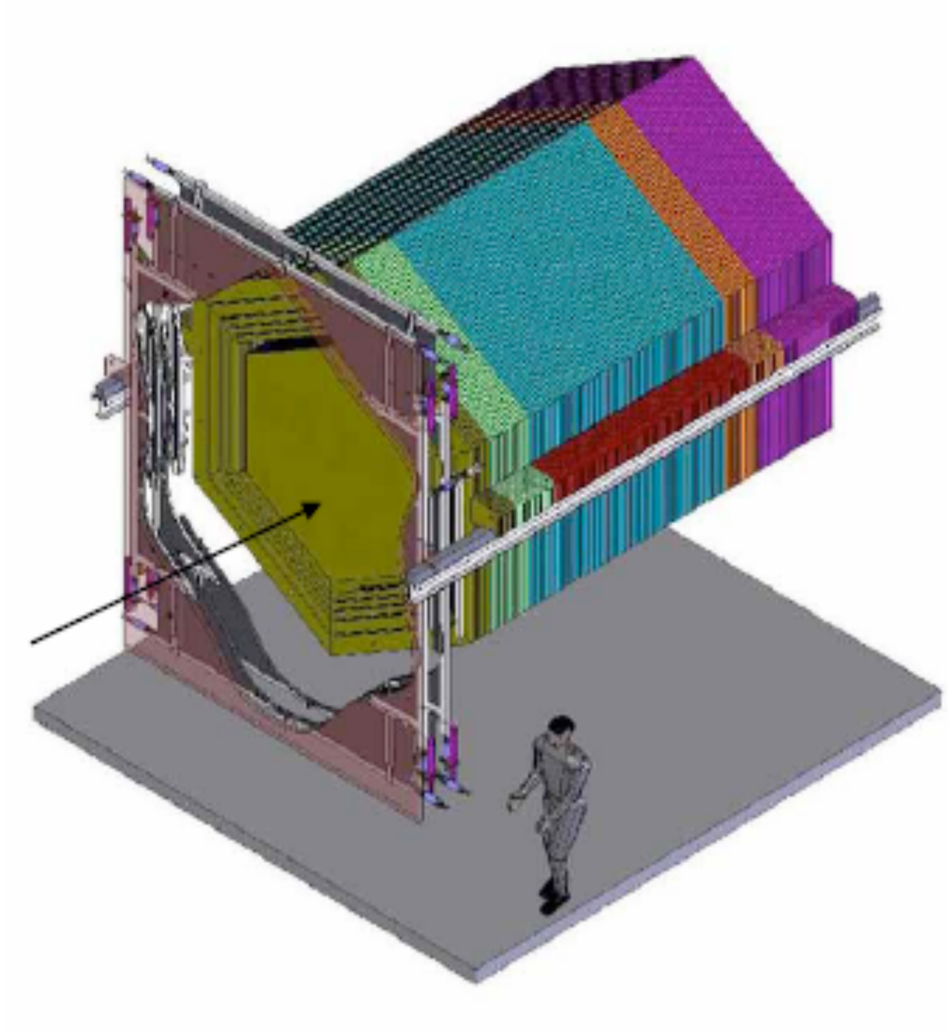
Cross-Sections & Fluxes

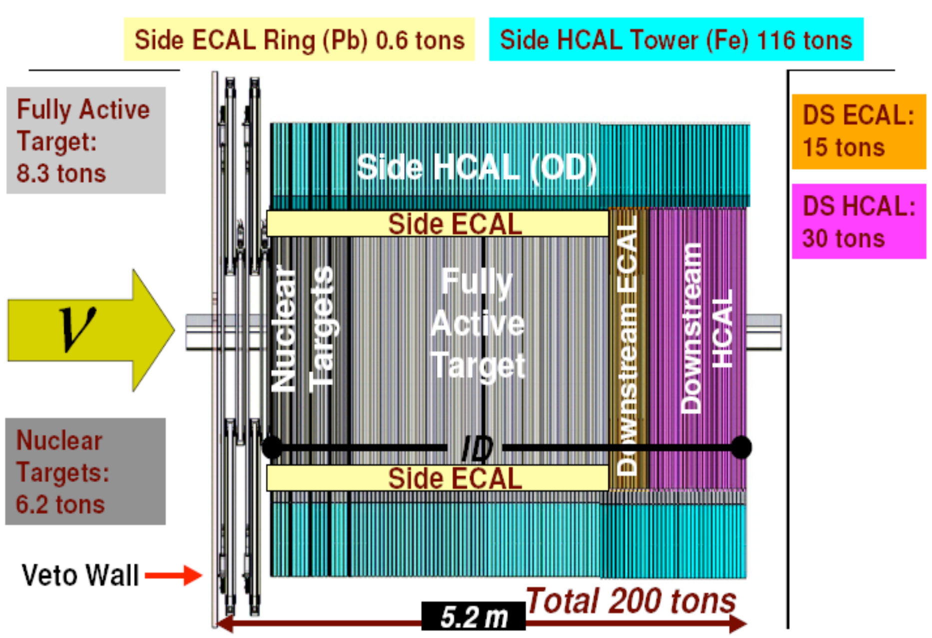




Cross-Sections & Fluxes

- MINERvA seeks to measure low-energy neutrino cross-sections to support neutrino oscillation experiments as well as to study the strong dynamics of the nucleon and nucleus that effect these interactions.





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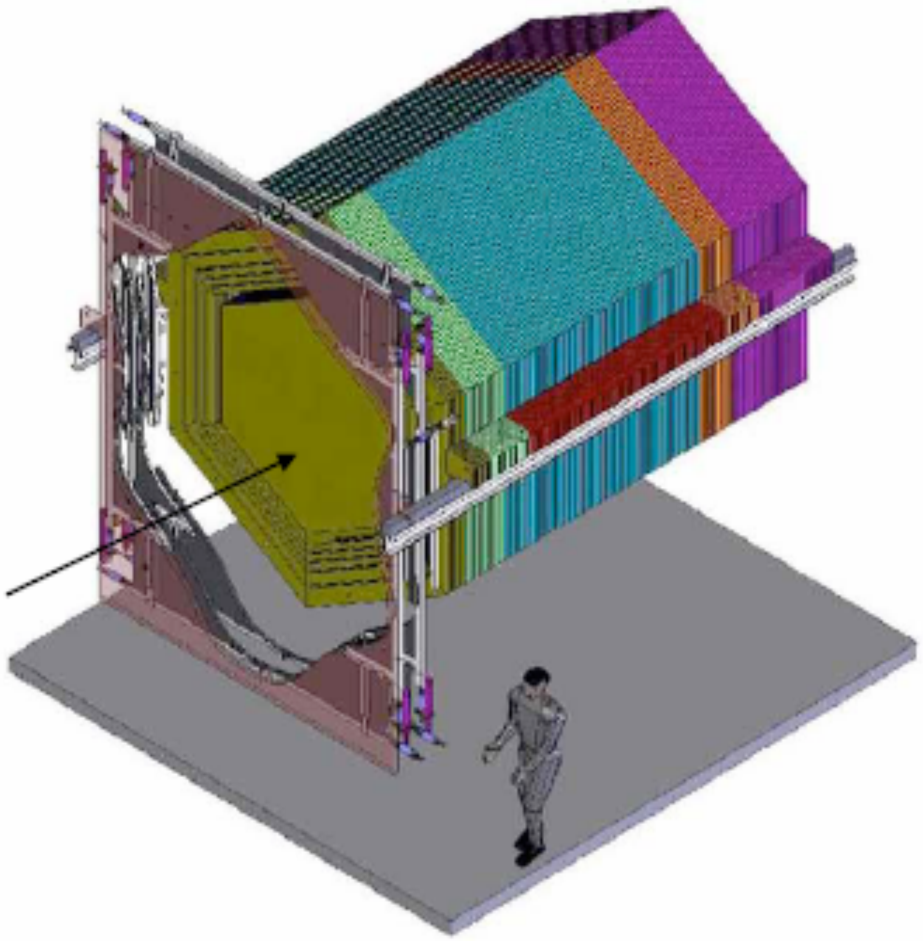

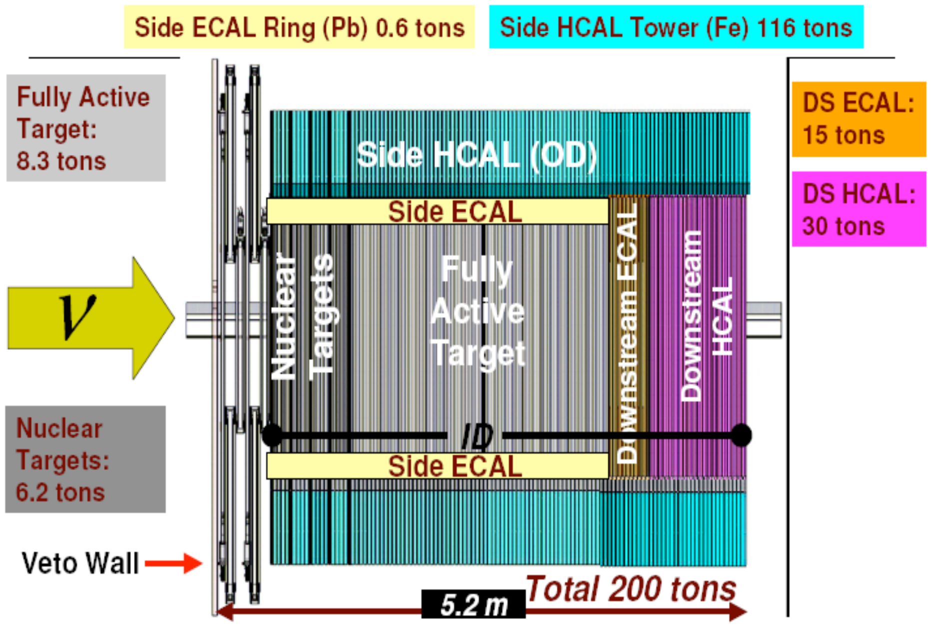

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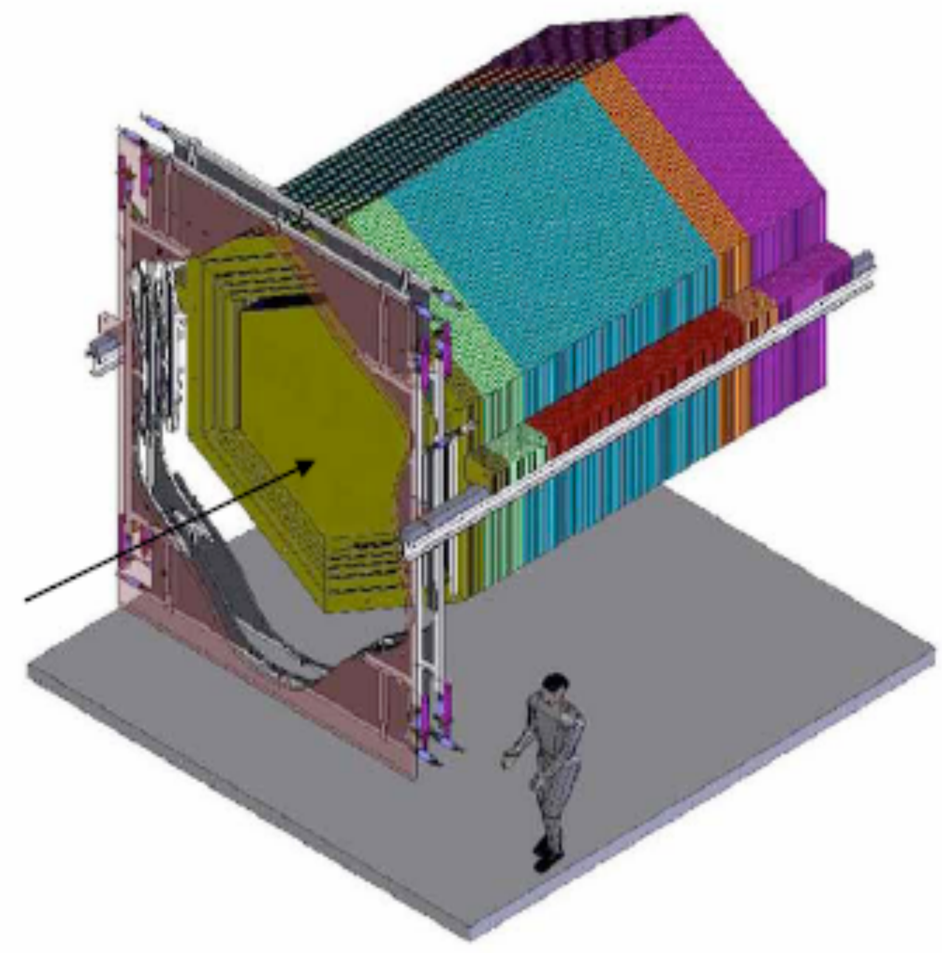

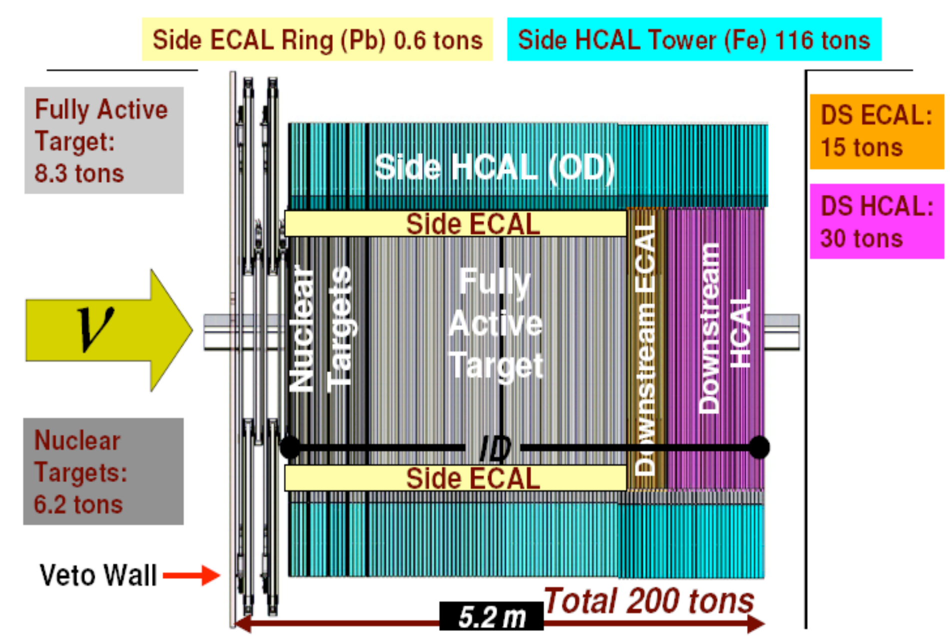

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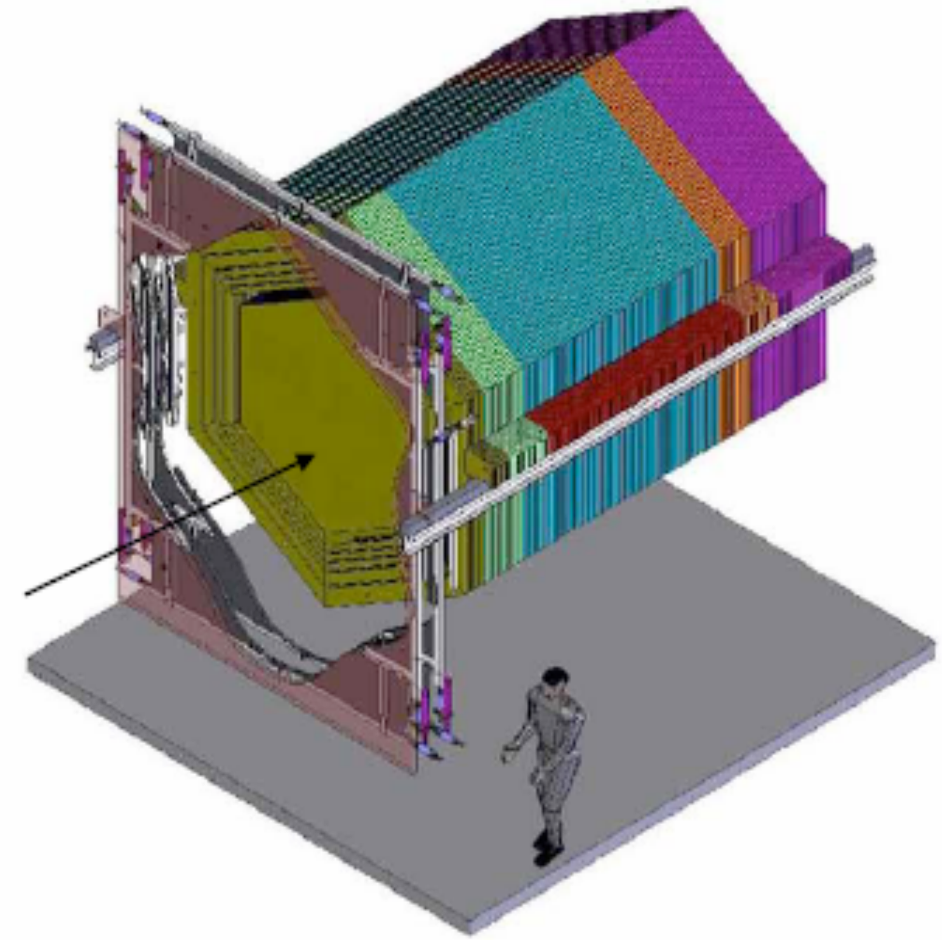

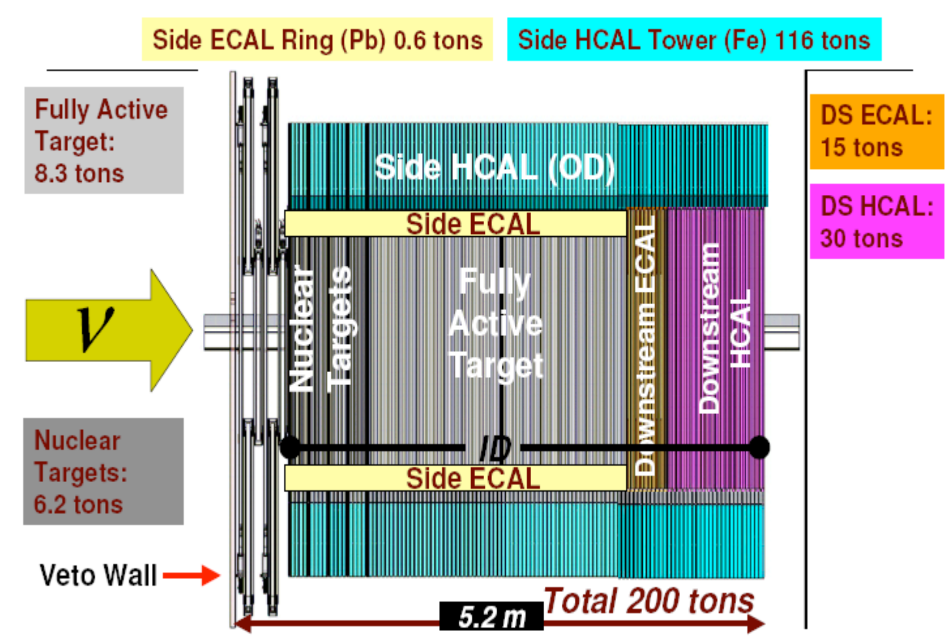

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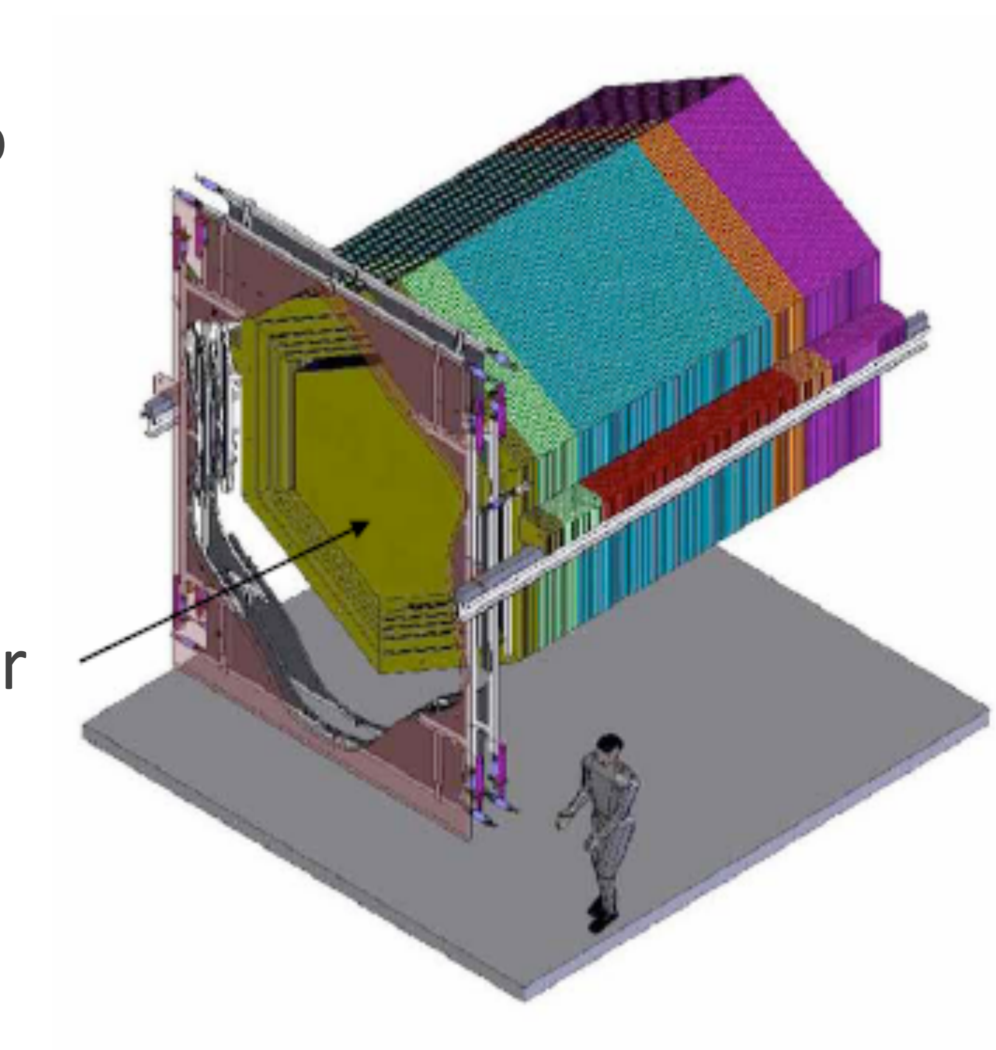

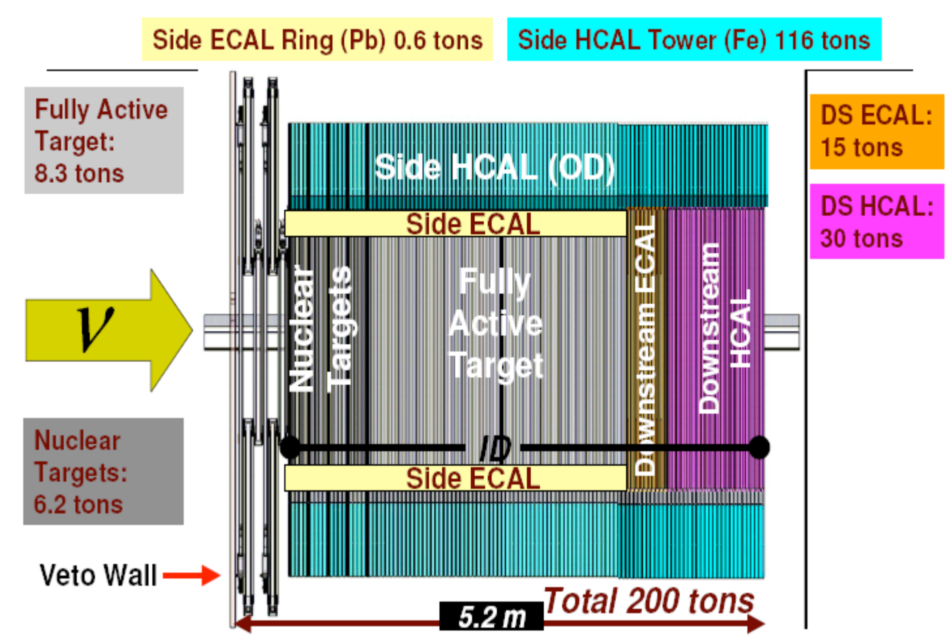

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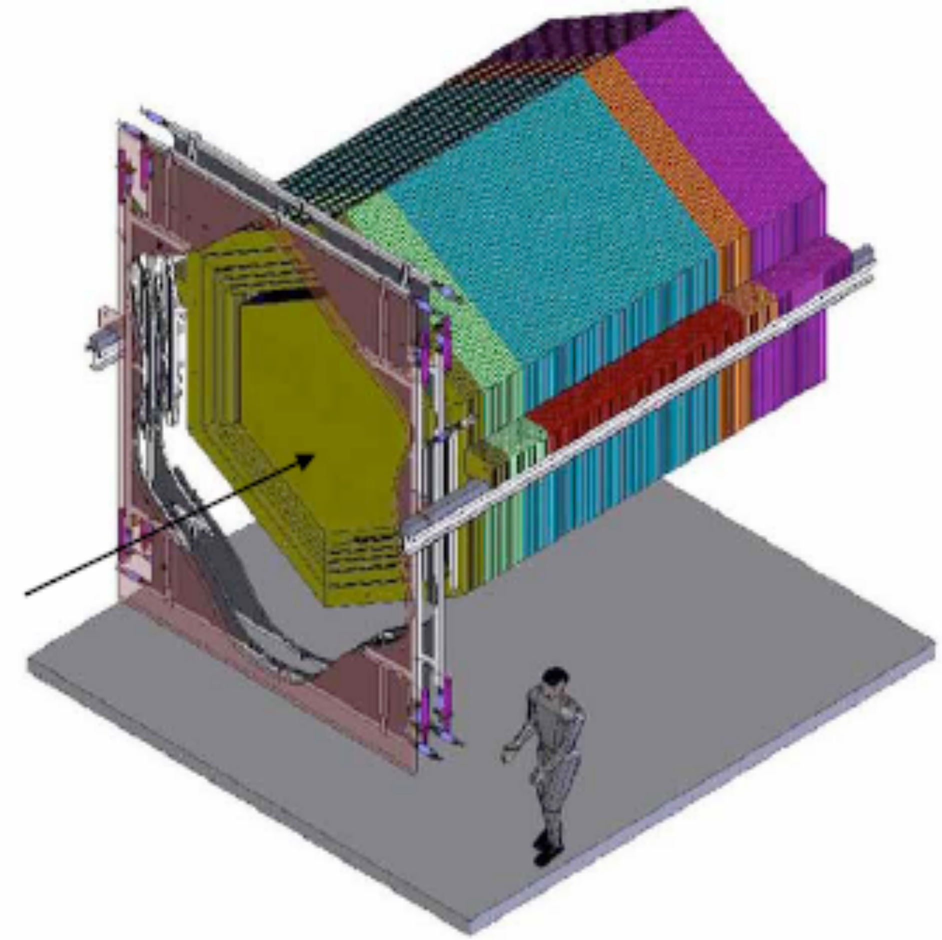
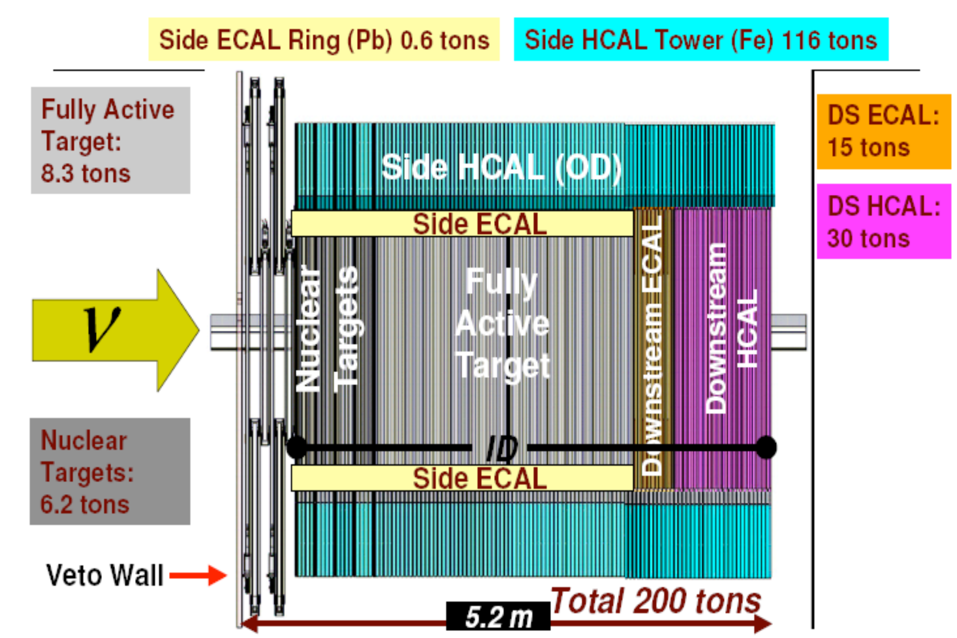
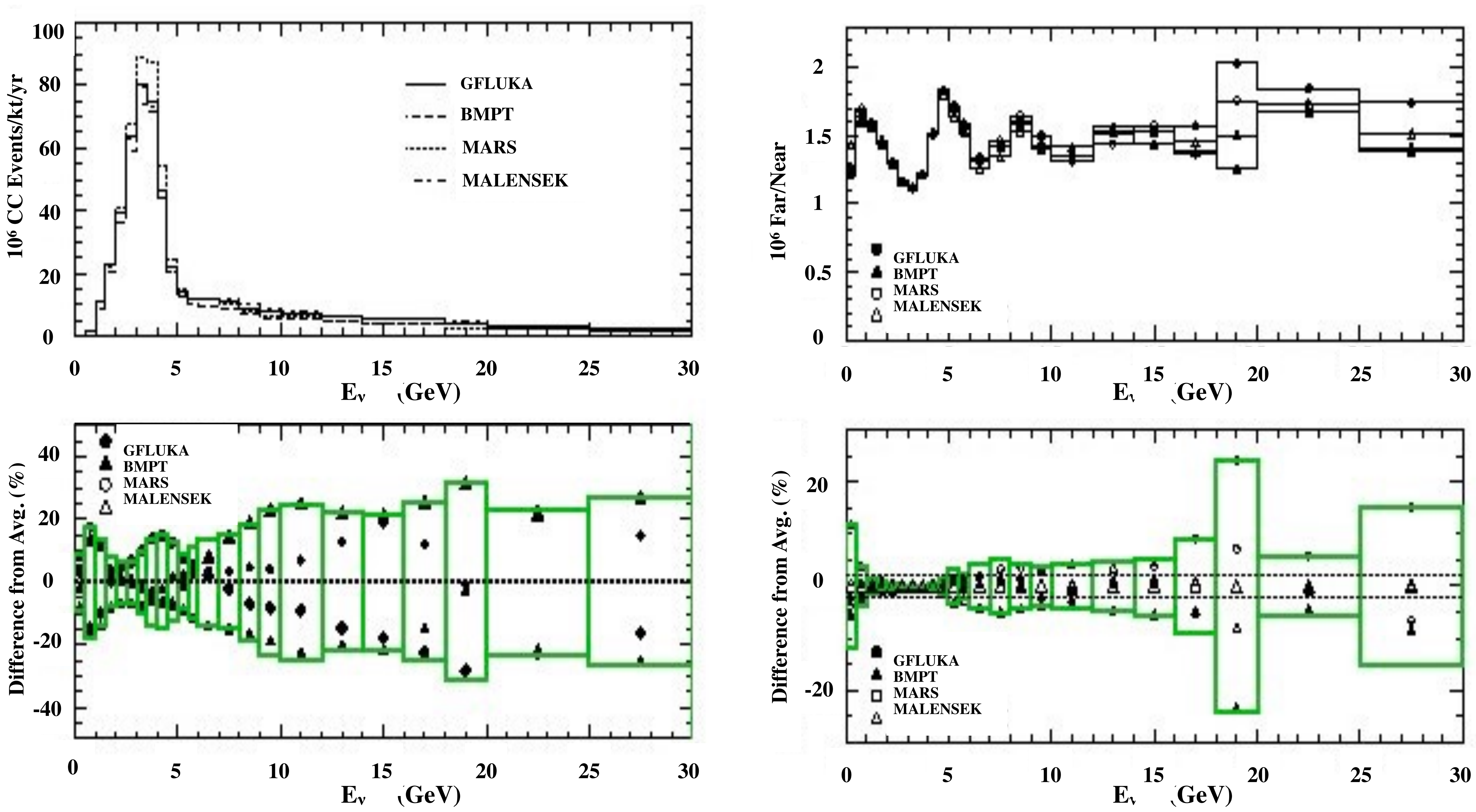
- Various targets will cover large A-range.



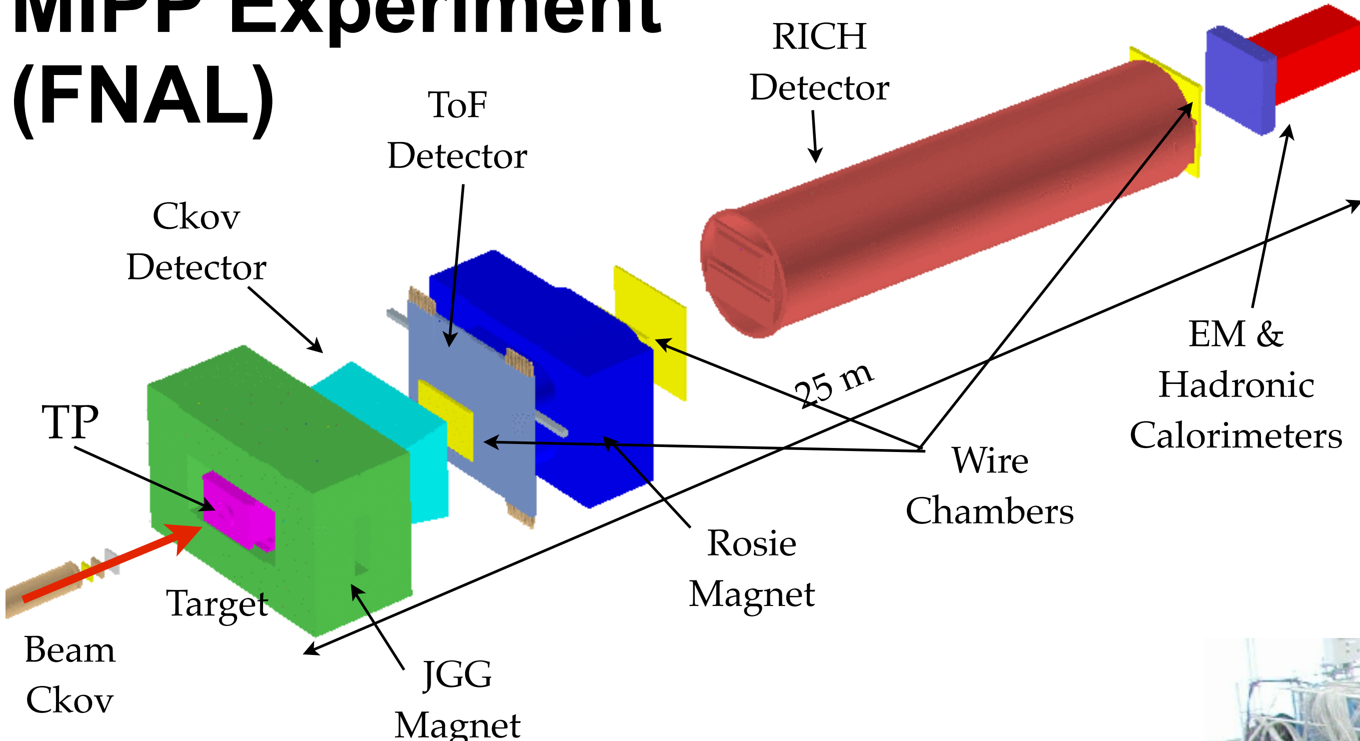


Neutrino Fluxes

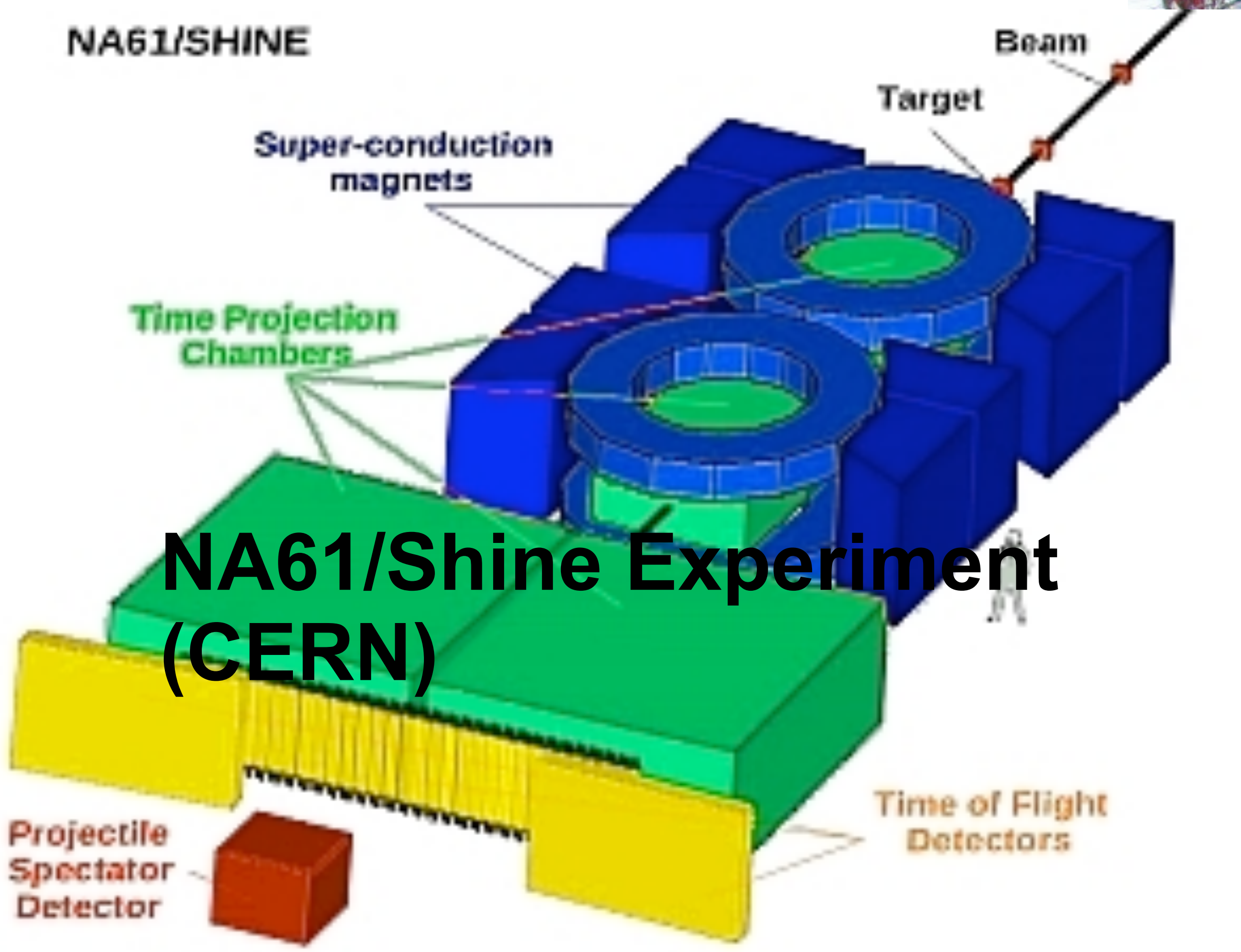


Neutrino Fluxes

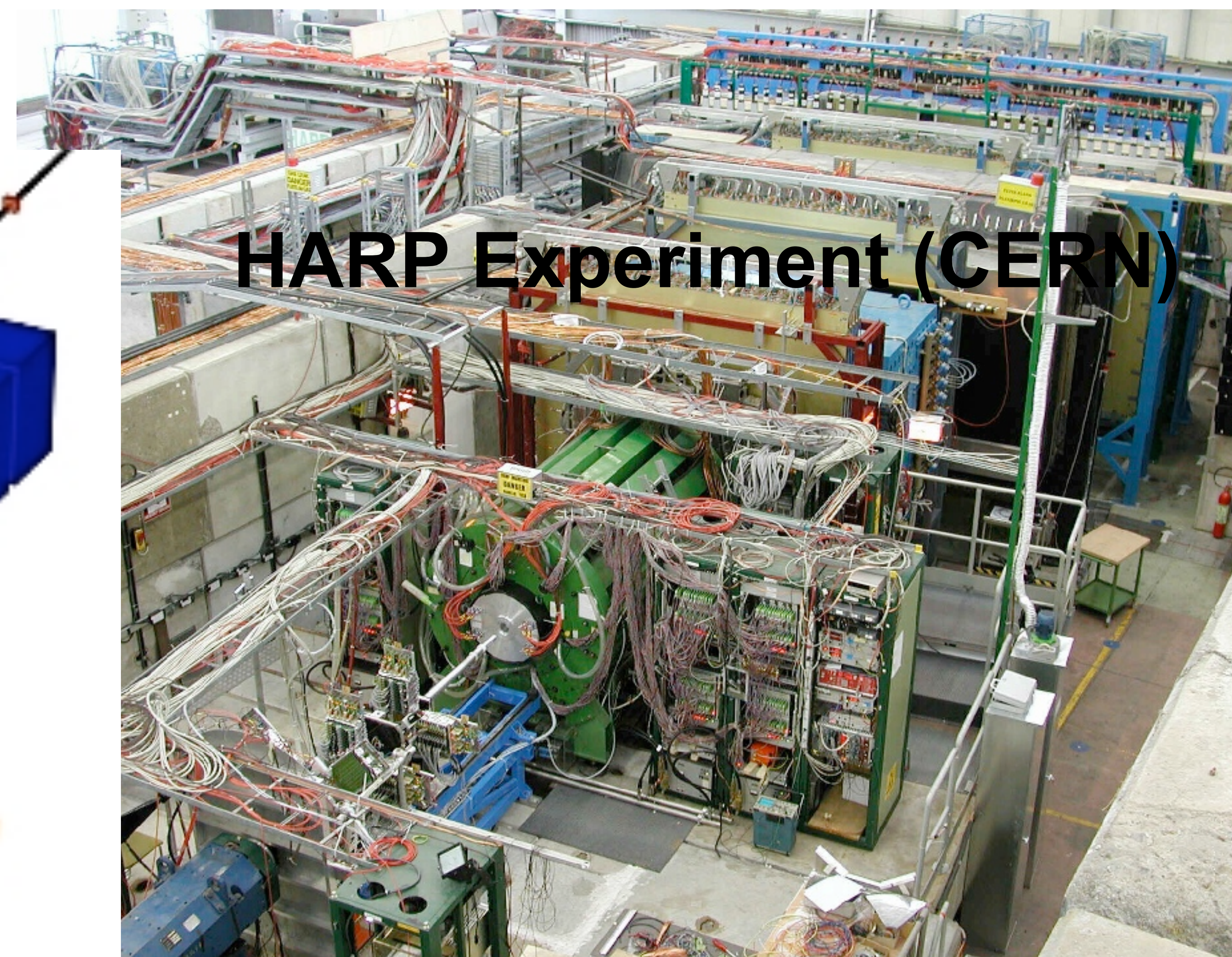
MIPP Experiment (FNAL)



NA61/Shine Experiment (CERN)

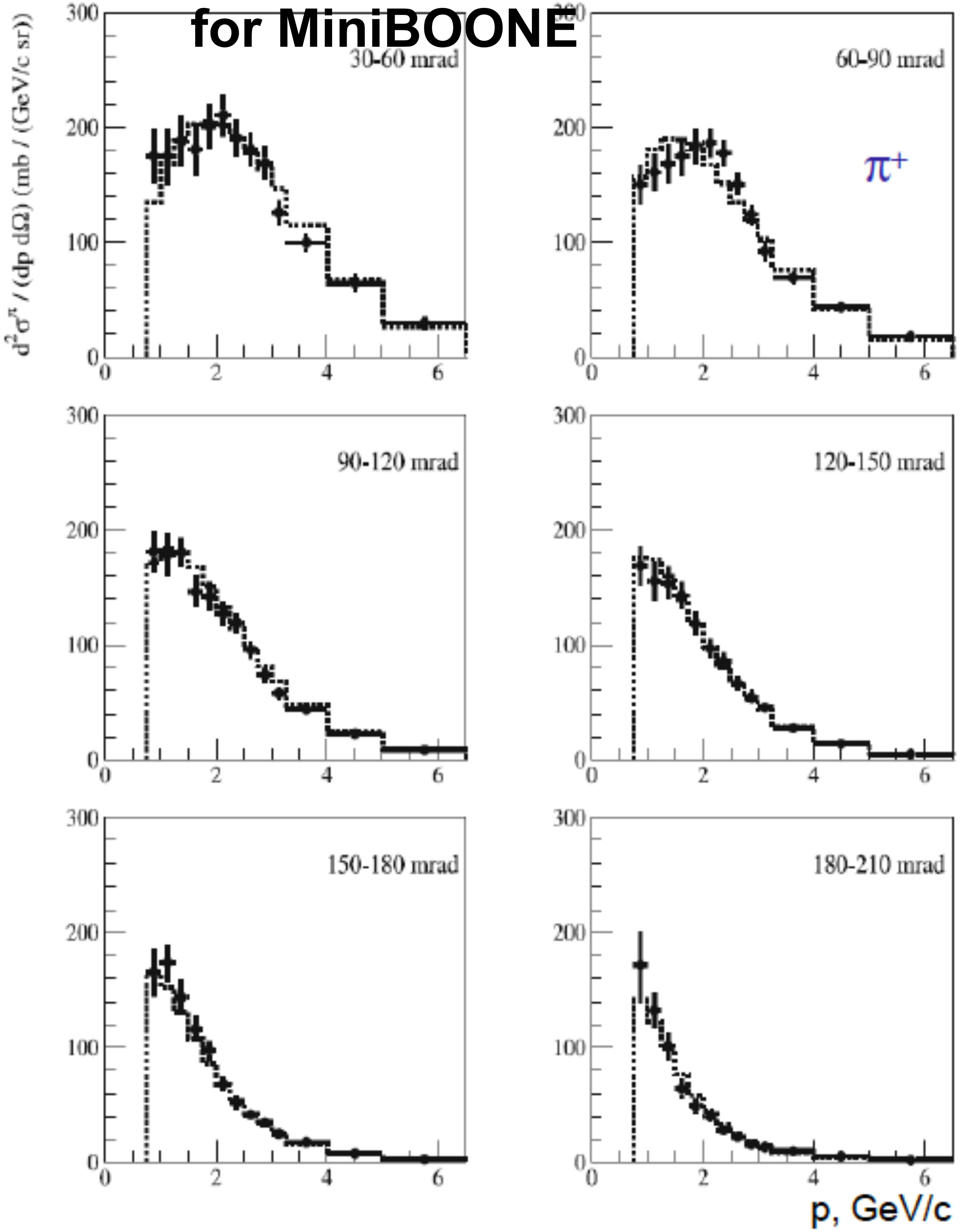


HARP Experiment (CERN)



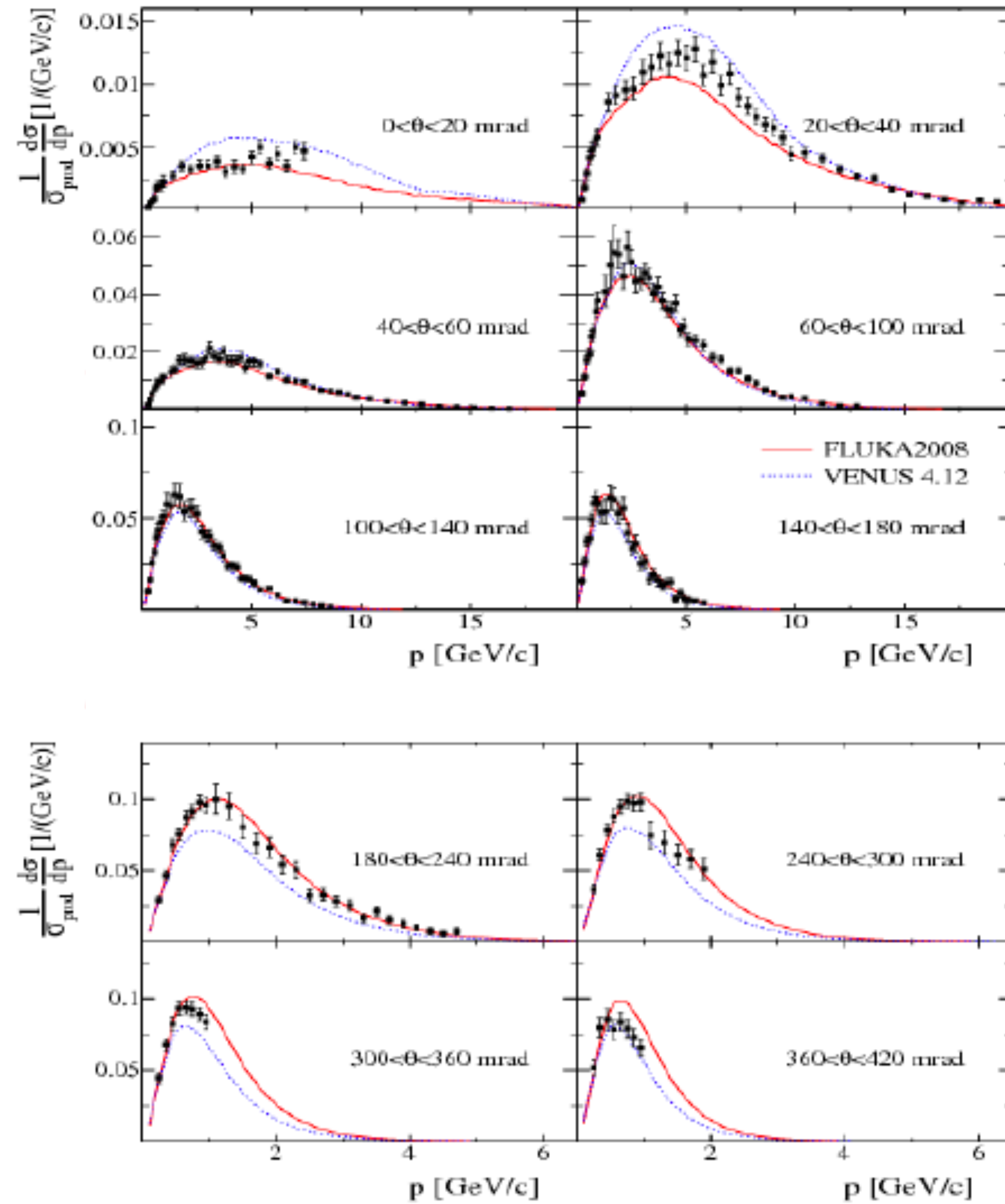
Neutrino Fluxes

HARP: p+Be @ 8.9 GeV/c for MiniBOONE



NA61: p+C @ 31 GeV/c for T2K

[Published in PRC 84 (2011) 034604]



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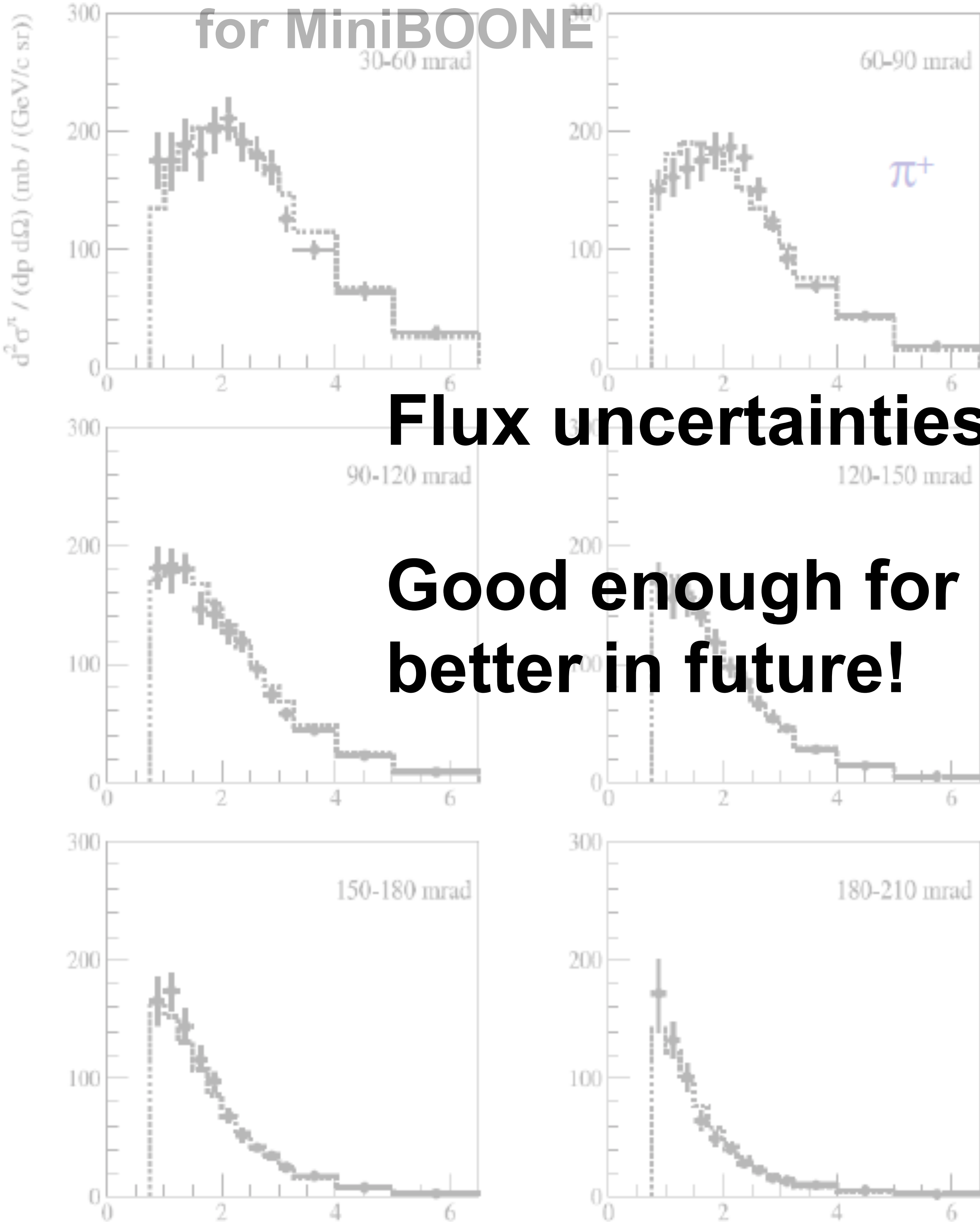

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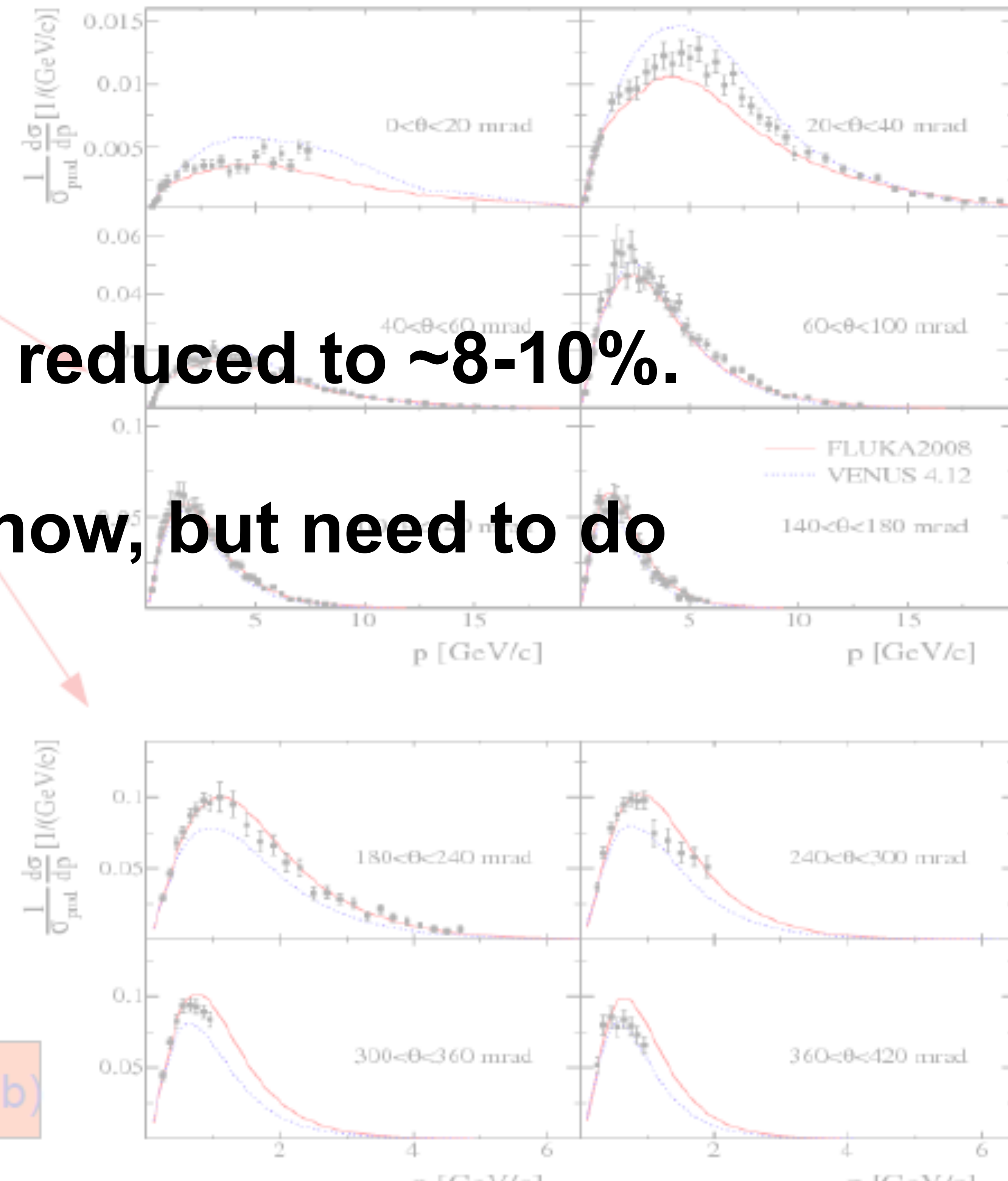
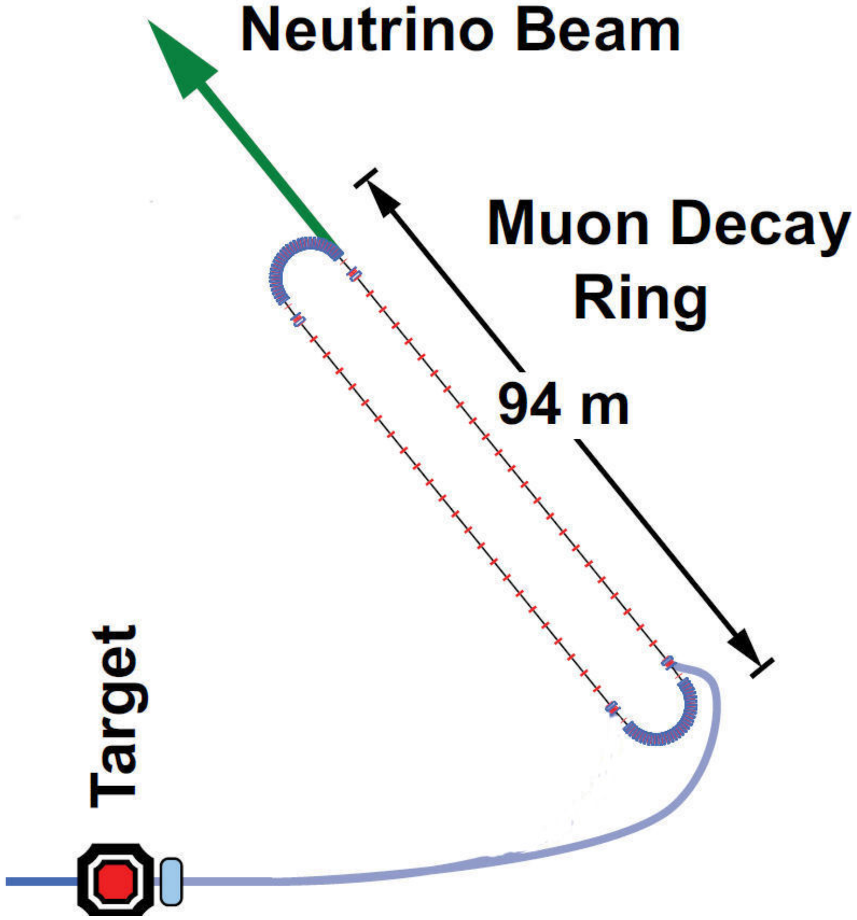


Flux uncertainties reduced to ~8-10%.

Good enough for now, but need to do better in future!

NuStorm: Future Solution to the Flux Problem?



$\mu^+ \to e^+ \nu_e \overline{\nu}_\mu$	$\mu^- \to e^- \overline{\nu}_e \nu_\mu$	
$\overline{\nu}_\mu \to \bar{\nu}_\mu$	$\nu_\mu \to \nu_\mu$	disappearance
$\overline{\nu}_\mu \to \bar{\nu}_e$	$\nu_\mu \to \nu_e$	appearance (challenging)
$\overline{\nu}_\mu \to \bar{\nu}_\tau$	$\nu_\mu \to \nu_\tau$	appearance (atm. oscillation)
$\nu_e \to \nu_e$	$\bar{\nu}_e \to \bar{\nu}_e$	disappearance
$\nu_e \to \nu_\mu$	$\bar{\nu}_e \to \bar{\nu}_\mu$	appearance: "golden" channel
$\nu_e \to \nu_\tau$	$\bar{\nu}_e \to \bar{\nu}_\tau$	appearance: "silver" channel

8/12 channels accessible!

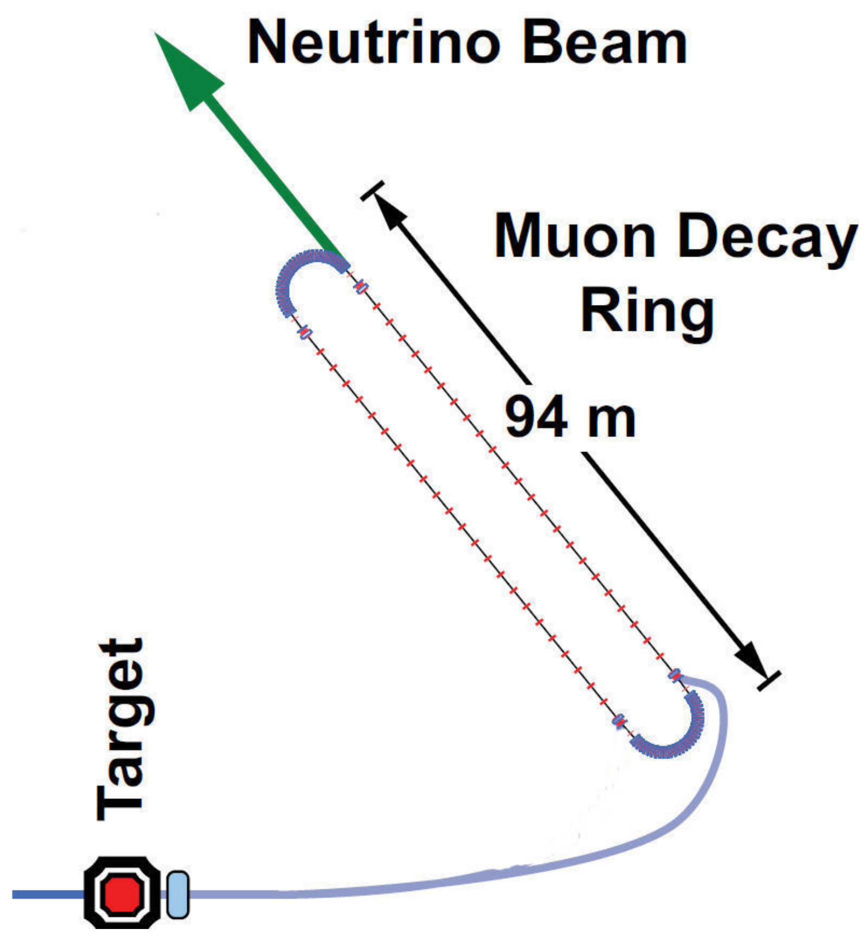
NuStorm: Future Solution to the Flux Problem?

- Staged approach to building high intensity neutrino factory
- Can be built TODAY with known technology
- Well understood neutrino source:

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

  $\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$

- Near absolute flux determination!



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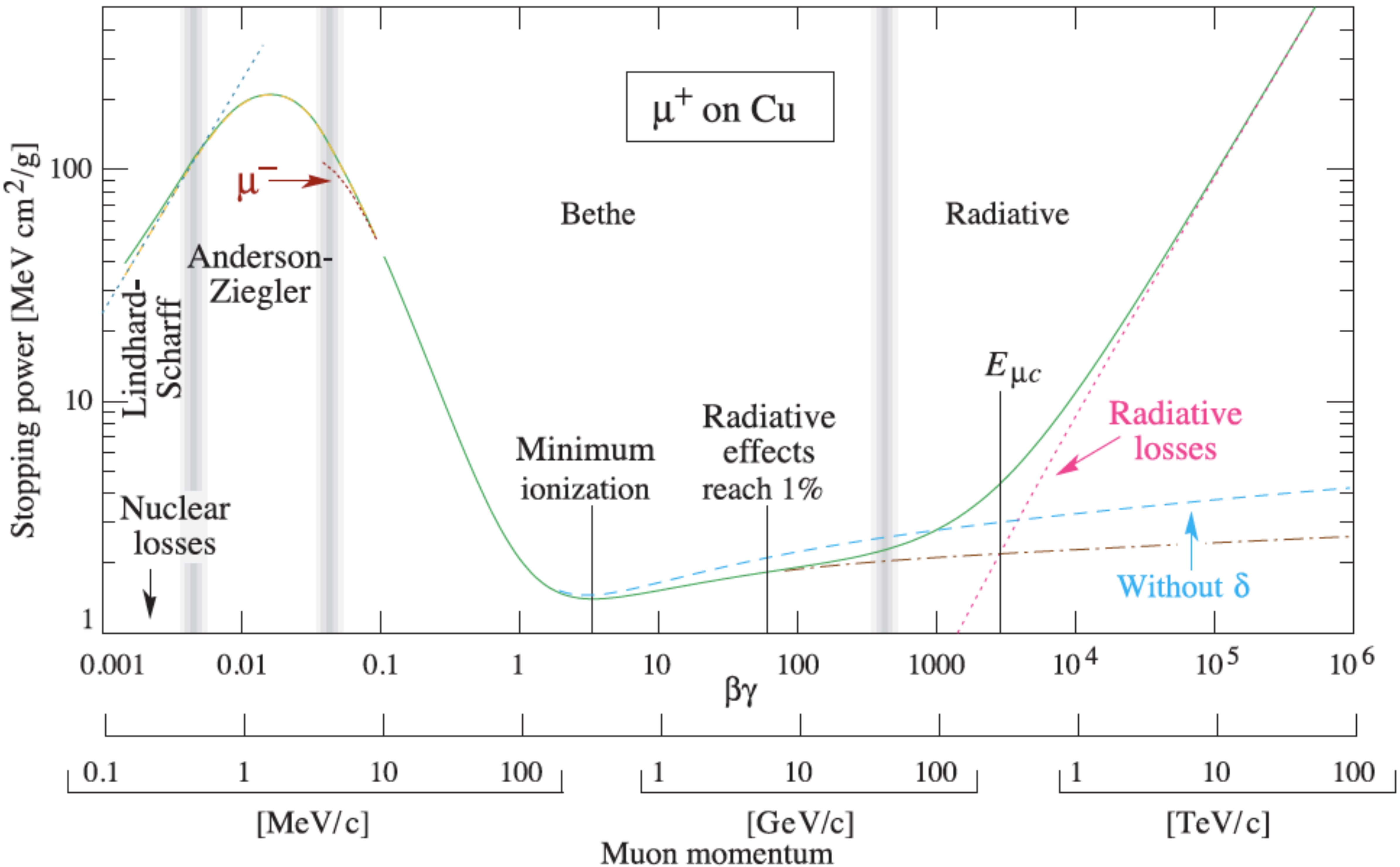
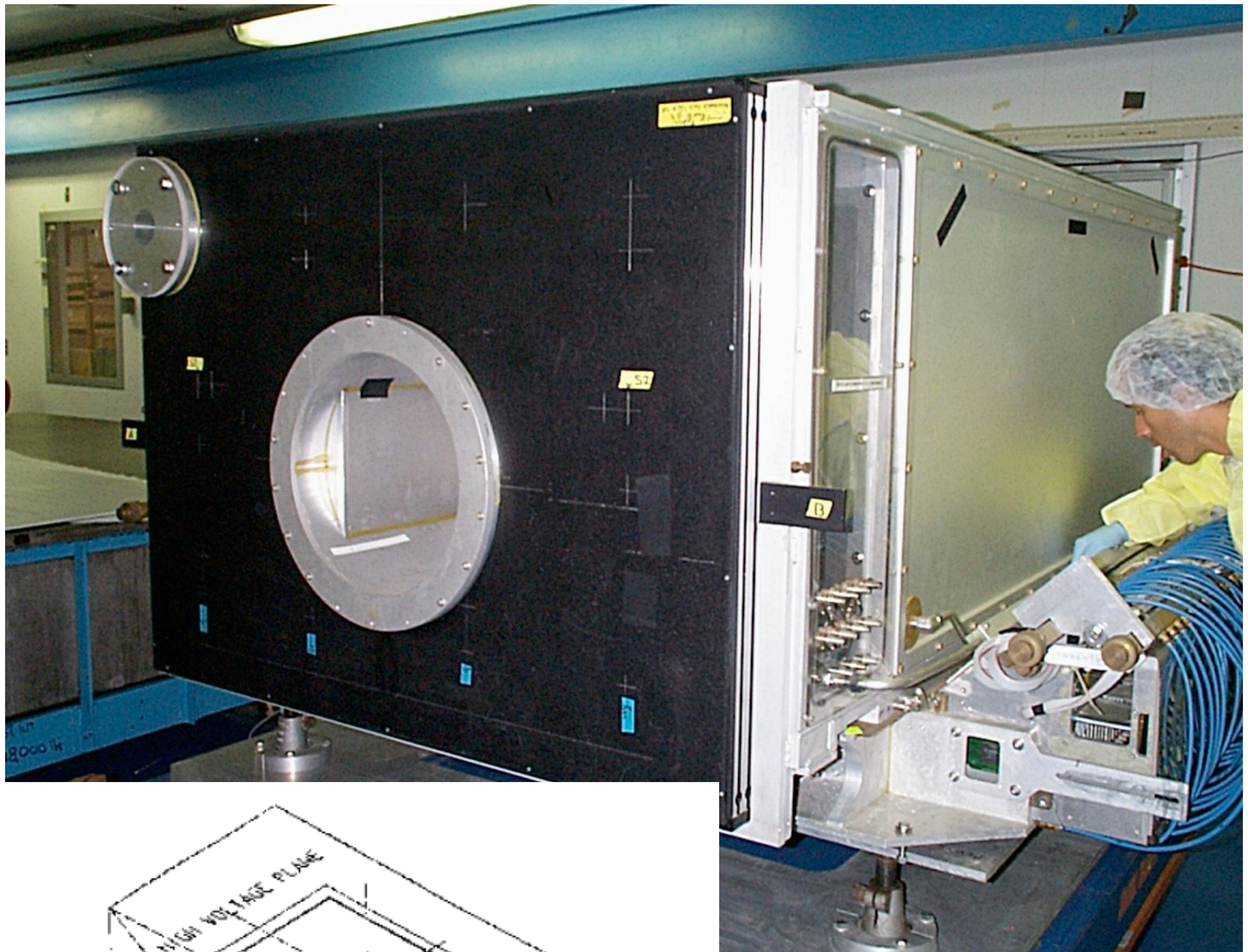
8/12 channels accessible!

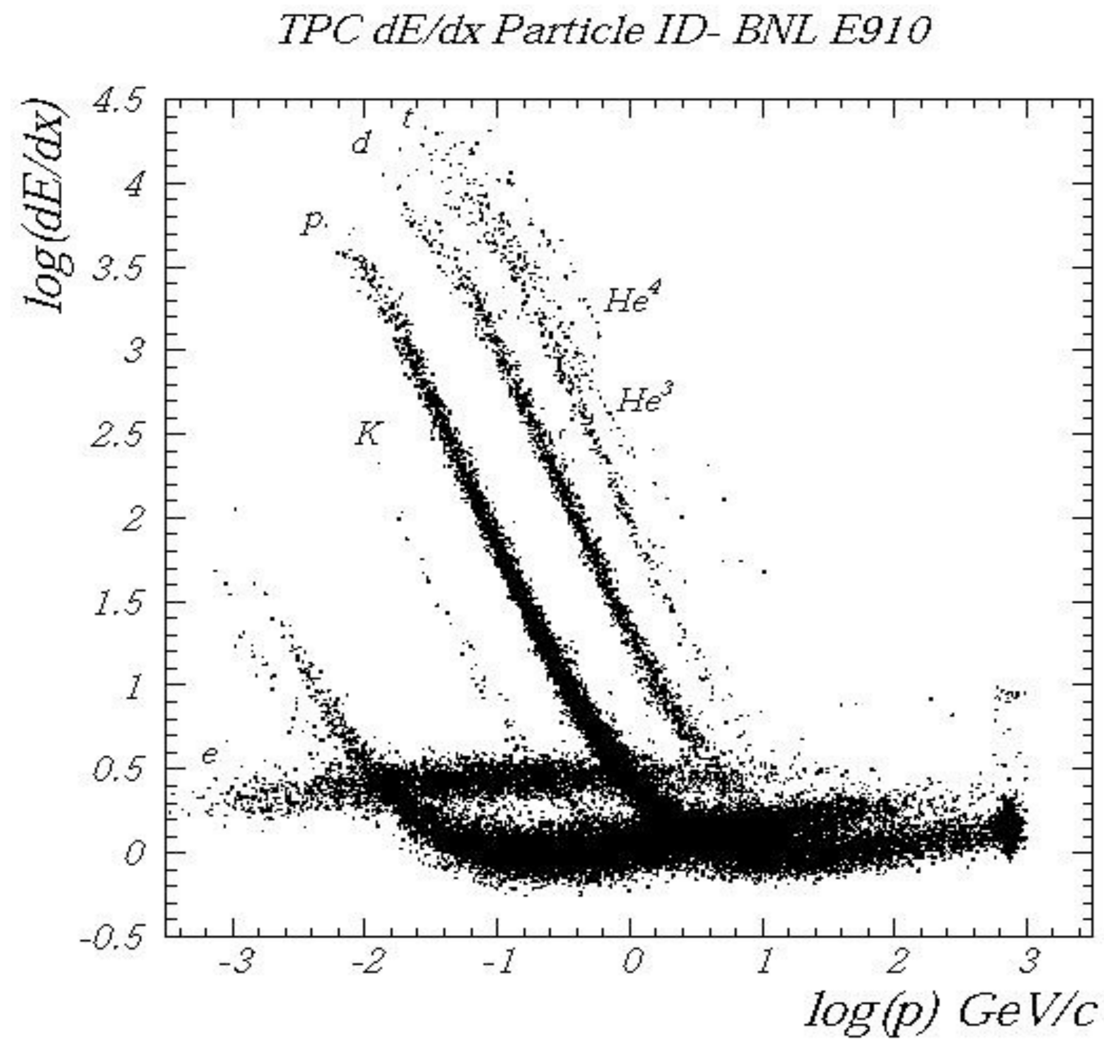
Bethe-Bloch Equation

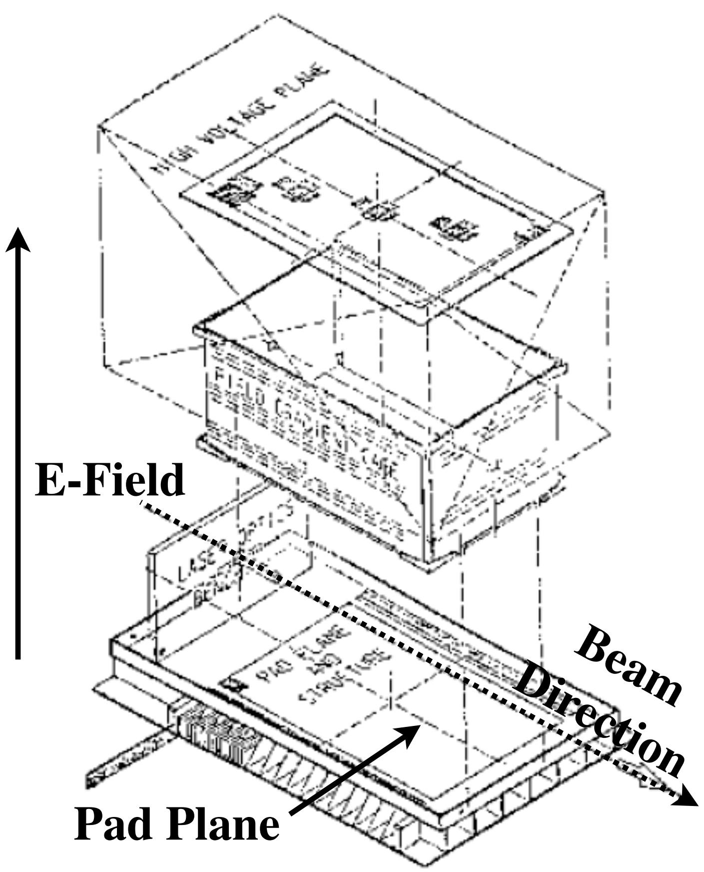


$$-\left\langle \frac{dE}{dx} \right\rangle = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

Time Projection Chamber







- (x,z) position → pad locations, y position → drift time.
- Active volume of ~1 m^3 and a resolution of ~0.5 cm^3.
- PID via <dE/dx> below ~1 GeV/c.

Calorimeters

- Detector designed to measure energy deposition and direction for electromagnetic (EM) or hadronic (H) showers.
- EM calorimeters are characterized by distance for an EM interaction to occur, the "radiation length", X_0
  - 13.8 g cm^{-2} (Fe)
  - 6.0 g cm^{-2} (U)
- Hadronic calorimeters are characterized by distance for a nuclear interaction to occur, the "interaction length", λ_I
  - 132.1 g cm^{-2} (Fe)
  - 209 g cm^{-2} (U)
- Calorimeters are usually many "lengths" deep in order to contain as much of the energy as possible
- EM calorimeters are usually placed in front of H calorimeters

Time-of-Flight Detectors

- Some knowns:
  - momentum (p)
  - traversal time (t)
  - distance (L)

$$m^2 = p^2 \left(\frac{t^2}{L^2} - 1 \right)$$

- Note: separation “power” of detector depends on time resolution:

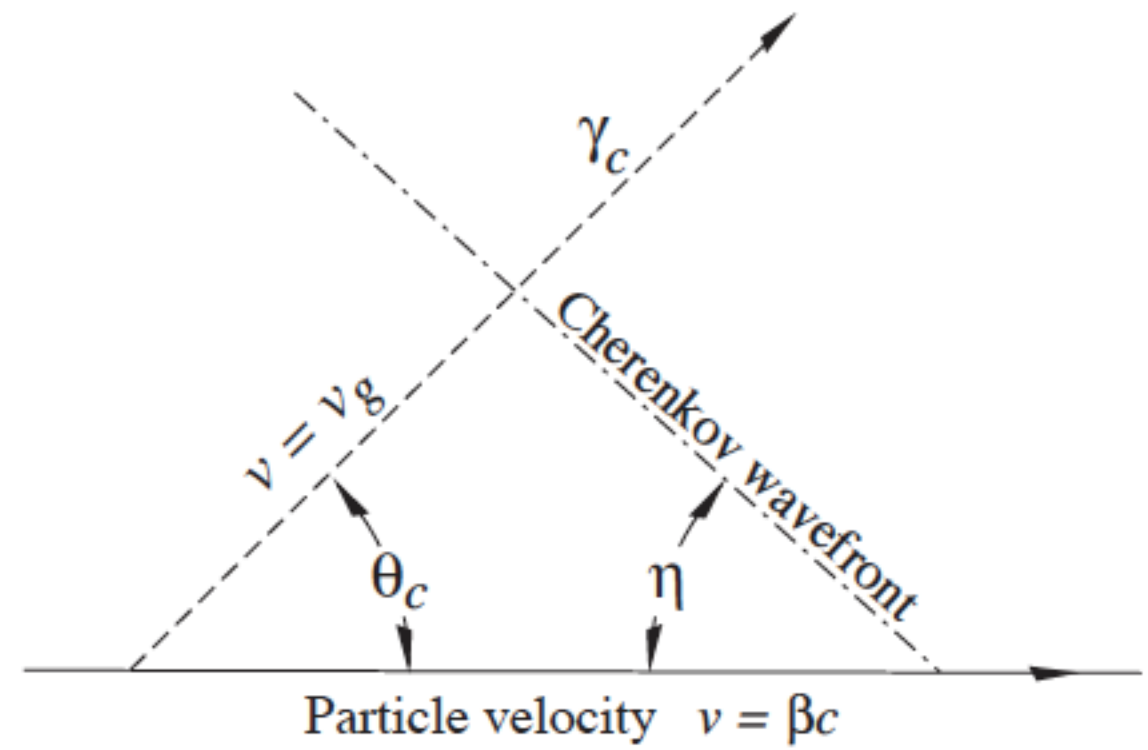
$$\delta t^2 = t_2^2 - t_1^2 = \frac{L^2}{p^2}(\Delta m^2)$$

- Typical timing resolution for ToF detectors: ~100 ps, usually good enough to separate particles up to a few GeV

Cherenkov Radiation

$$\cos\theta_c = (1/n\beta)$$

$$\frac{d^2N}{dx d\lambda} = \frac{2\pi\alpha z^2}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right)$$

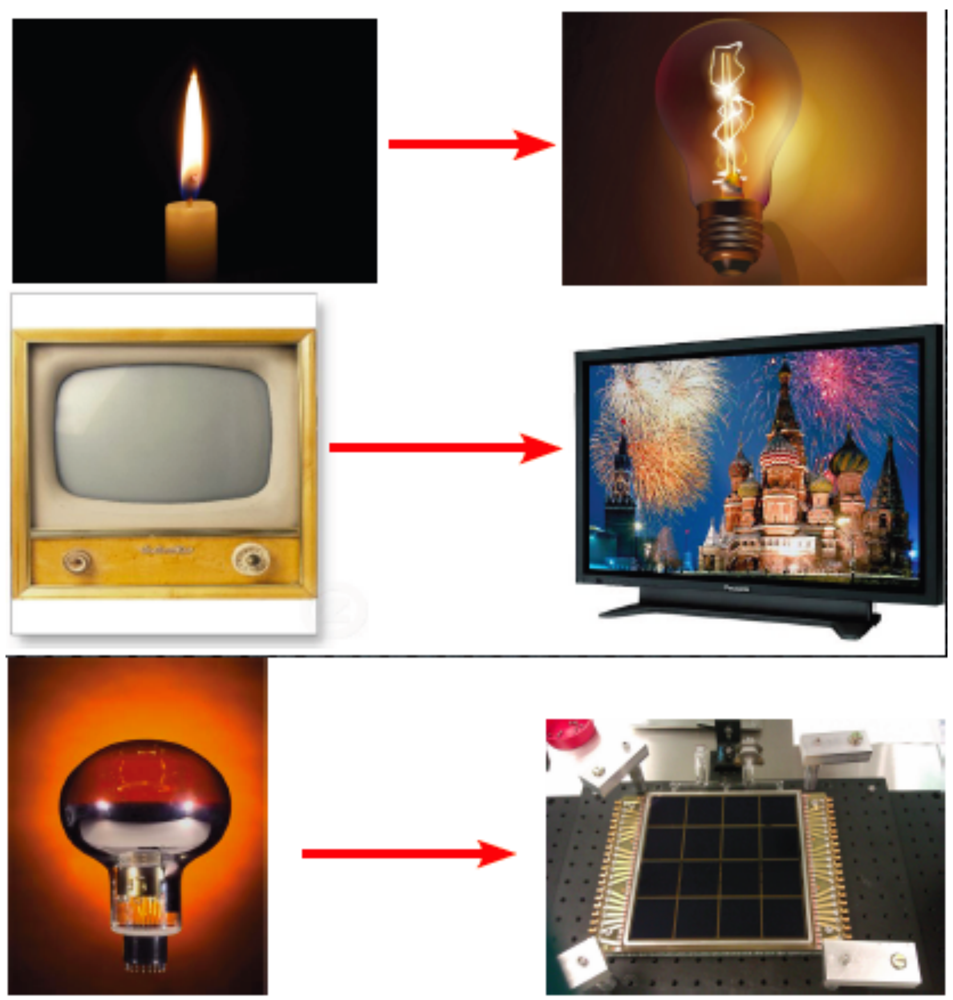


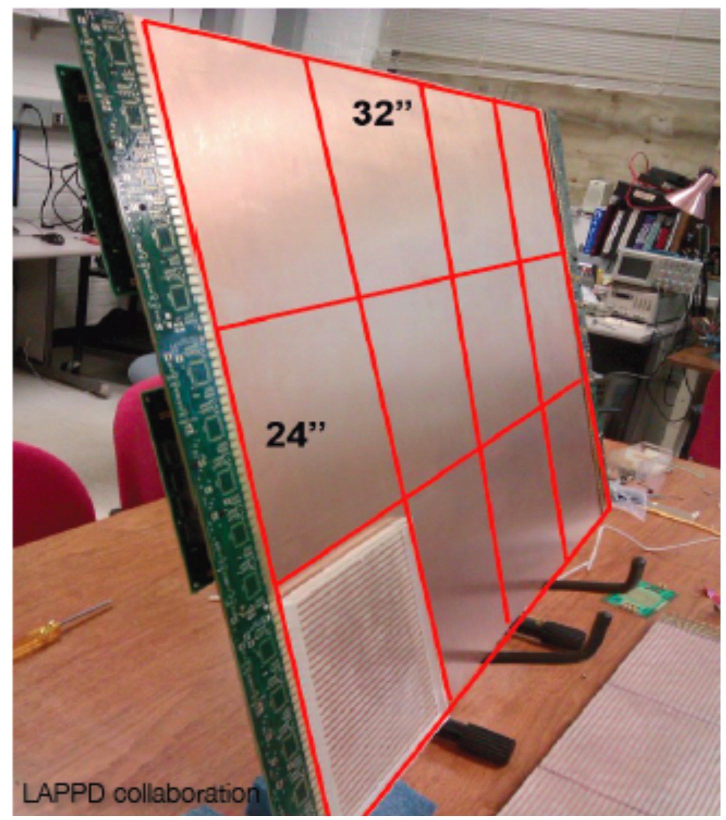
Common refractive indices & thresholds:

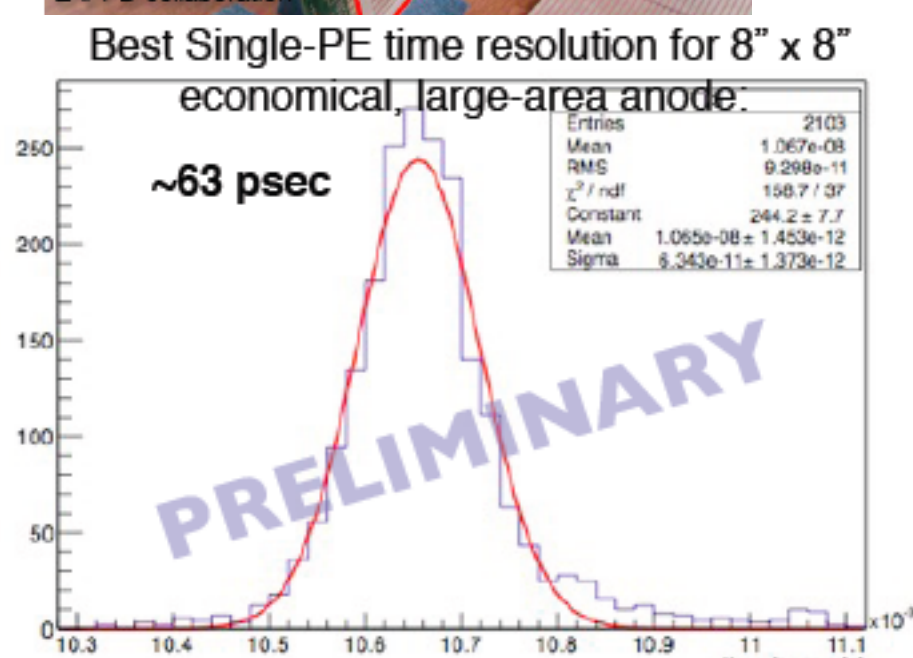
Material	Index	Muon momentum threshold (GeV):	Proton momentum threshold (GeV):
Air (at STP)	1.000277	4.490	39.849
CO2	1.00045	3.523	31.263
Aerogel	1.07	0.278	2.464
Water (Ice)	1.31	0.125	1.108
Water (at 20C)	1.333	0.120	1.064
Ethanol	1.361	0.114	1.016
Pyrex	1.47	0.098	0.871
Diamond	2.419	0.048	0.426

Large Area Photodetectors: Future Technology?

- Size of neutrino detectors creates an enormous strain on funding.
- Photodetectors are a cost driver; need to reduce cost, while increasing coverage inside detector (improved energy resolution = more precise measurements)





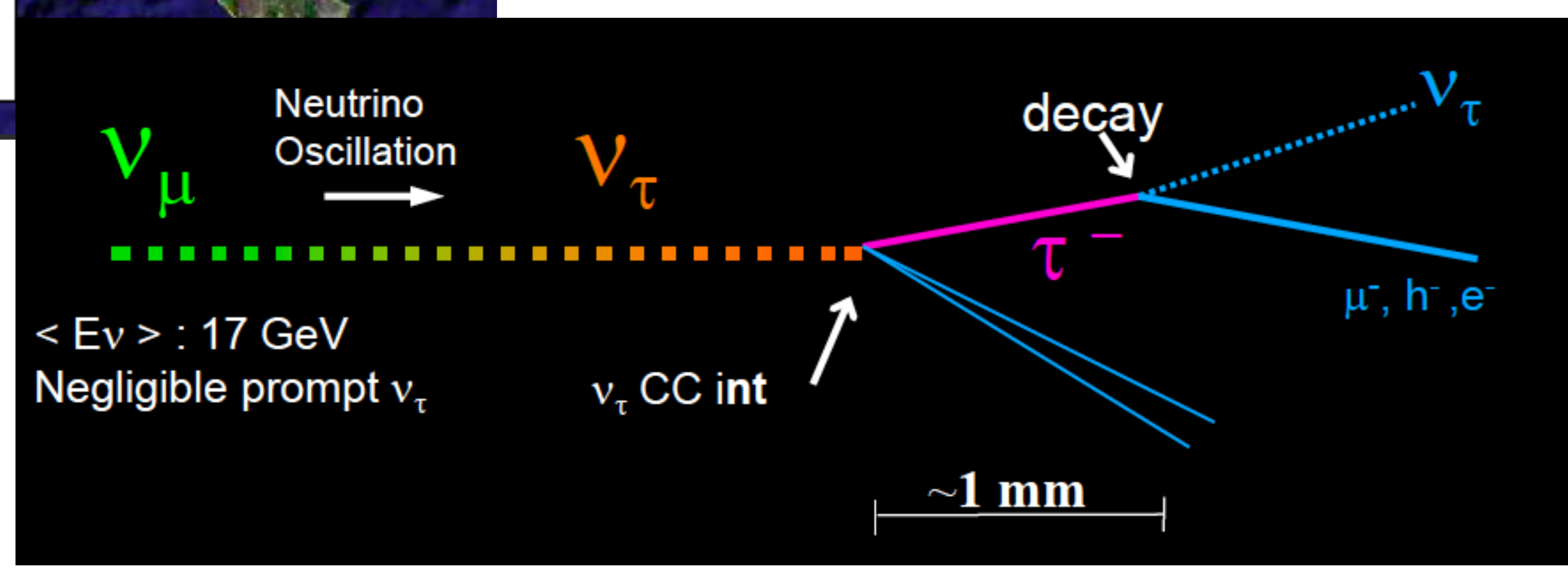


- 2 mm spatial resolution!
- ~60 ps timing resolution using economical anode design.

The OPERA Experiment

< Eν > (GeV)	17
$(\nu_e + \overline{\nu}_e) / \nu_\mu$	0.89, 0.06 %
$\overline{\nu}_\mu / \nu_\mu$	2.1 %
ν_τ prompt	Negligible

- Designed for $\nu_\mu \rightarrow \nu_\tau$ appearance detection.
- Extremely challenging due to the short distance that the tau travels before decaying!
- Need an extremely fine-grained detector.



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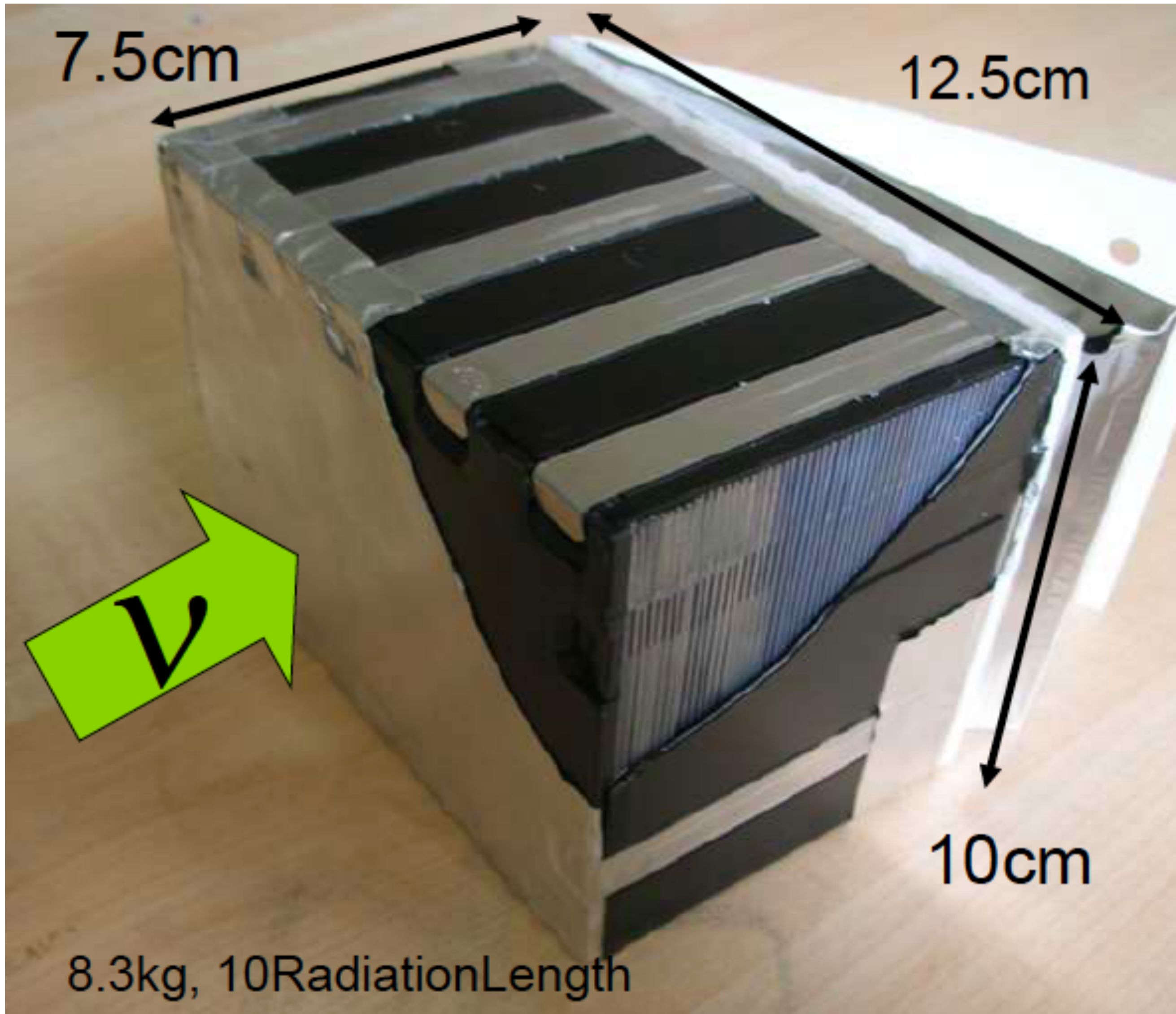
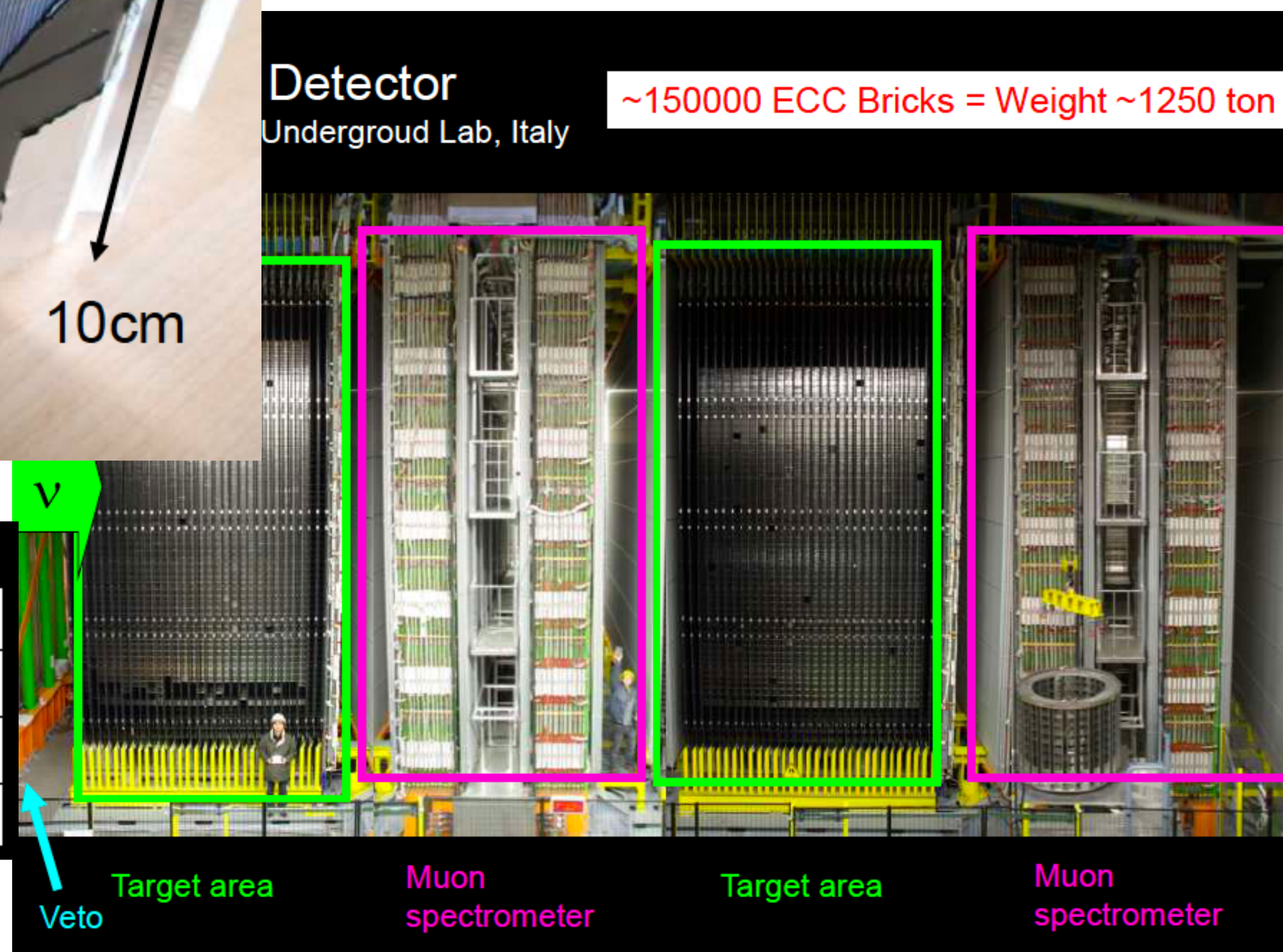


- Emulsion (~camera film) detector.
- Look for short tracks with kinks or “trident” (τ- → h+ h- h-)

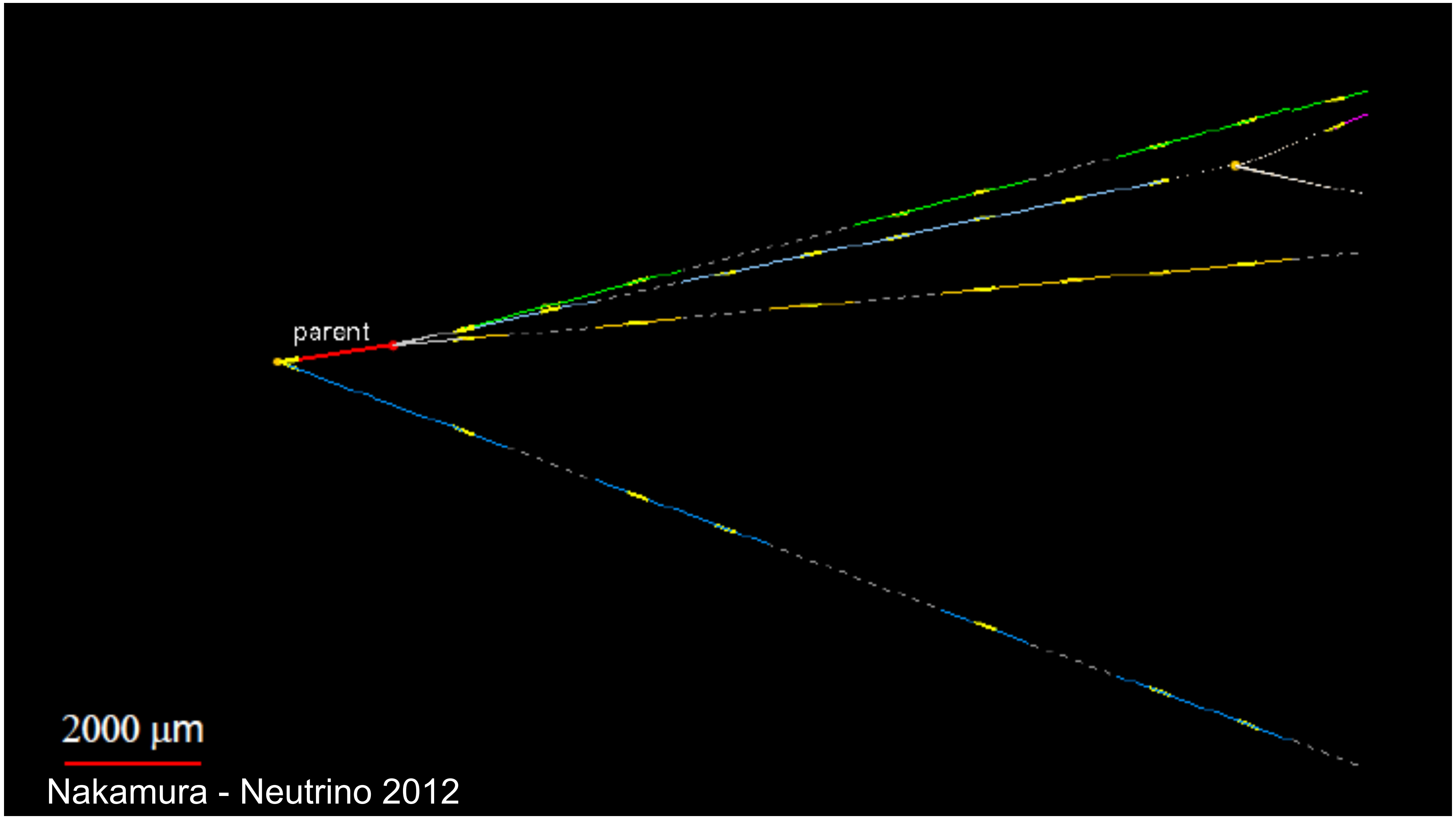
τ Decay mode

Kink	$\tau^- \rightarrow e^-$	17.8 %
	$\tau^- \rightarrow \mu^-$	17.4 %
	$\tau^- \rightarrow h^-$	49.5 %
Trident	$\tau^- \rightarrow h^- h^- h^+$	15.2 %



The OPERA Experiment

- So far, two ν_τ events have been reported



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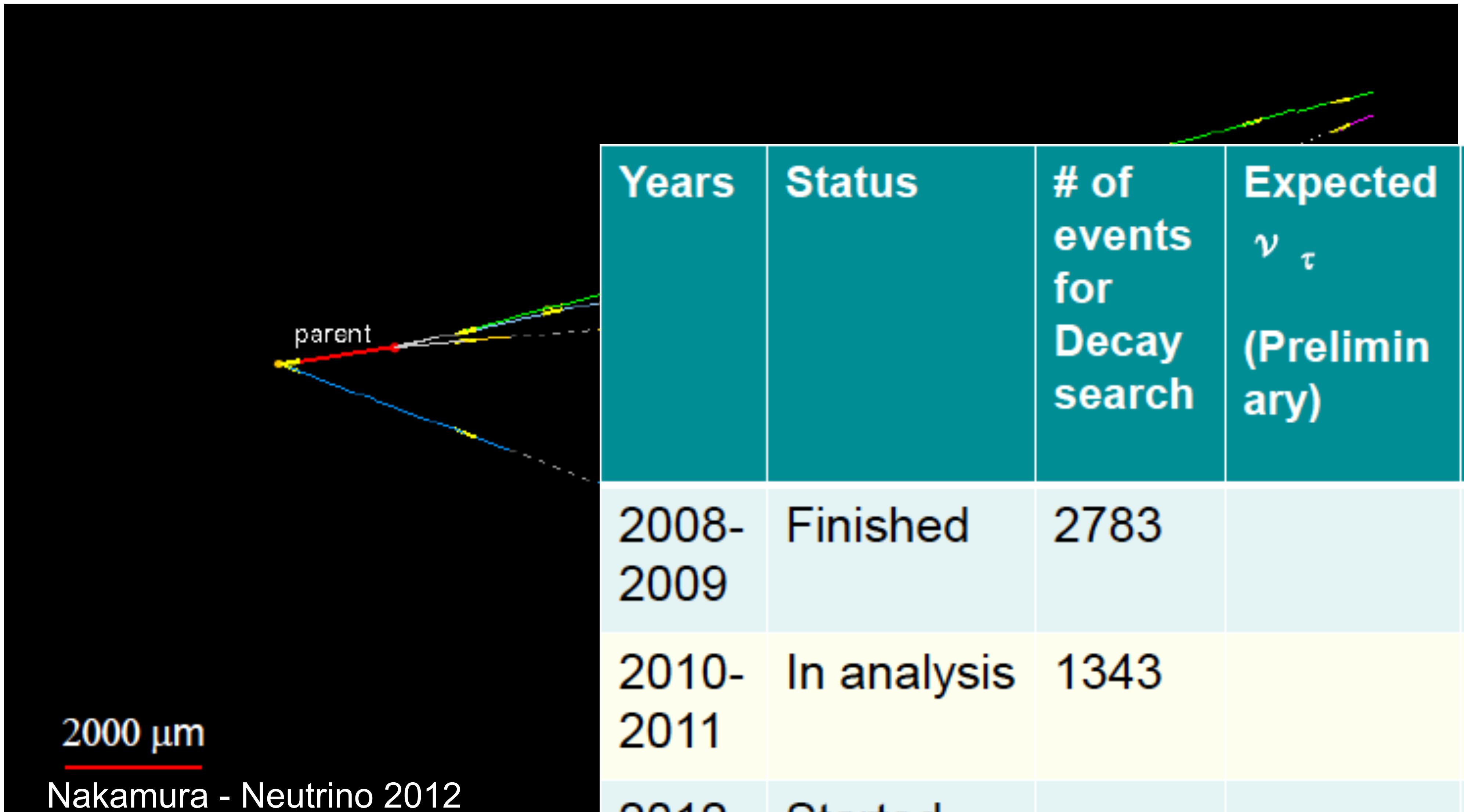

Nakamura - Neutrino 2012

Years	Status	# of events for Decay search	Expected ν_τ (Preliminary)	Observed ν_τ Candidate Events	Expected BG for ν_τ (Preliminary)
2008-2009	Finished	2783		1	
2010-2011	In analysis	1343		1	
2012	Started				
Total		4126	2.1	2	0.2

Nakamura - Neutrino 2012

Future Solar Neutrino Experiments (Beyond those already in operation)

pep/CNO	Medium	Status
SNO+	780 kg LAB Liq scintillator	Construction, start 2013
Kamland-2	780 lb Liq Scintillator	Following KamLAND-Zen

For pp, ^{7}Be neutrinos, measuring CC plus ES could extract electron and total neutrino fluxes

pp via ES		
XMASS	20 tons Liq Xe	835 kg since 2010 for $\beta\beta$
CLEAN	50 tons Liq Ne	MiniClean (500 kg) start 2013
P, ^{7}Be via CC		
LENS	10 tons ^{115}In	μLENS under development
MOON	3 tons ^{100}Mo	R&D in progress
IPNOS	^{115}In	R&D in progress
MEGAPROJECTS	Threshold defines: ^{8}B + ?	
HyperK, MEMPHYS	Megaton Water Cerenkov	
LBNE, GLACIER	50 to 100 kTon Liquid Ar	
LENA	50 kTon Liq Scintillator	

McDonald - Neutrino 2012