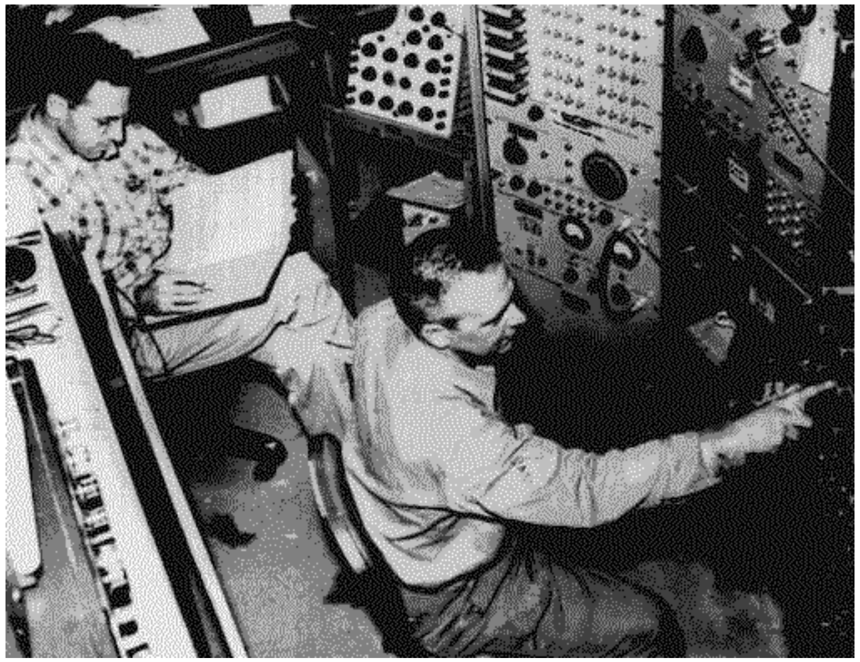
Experimental Neutrino Physics

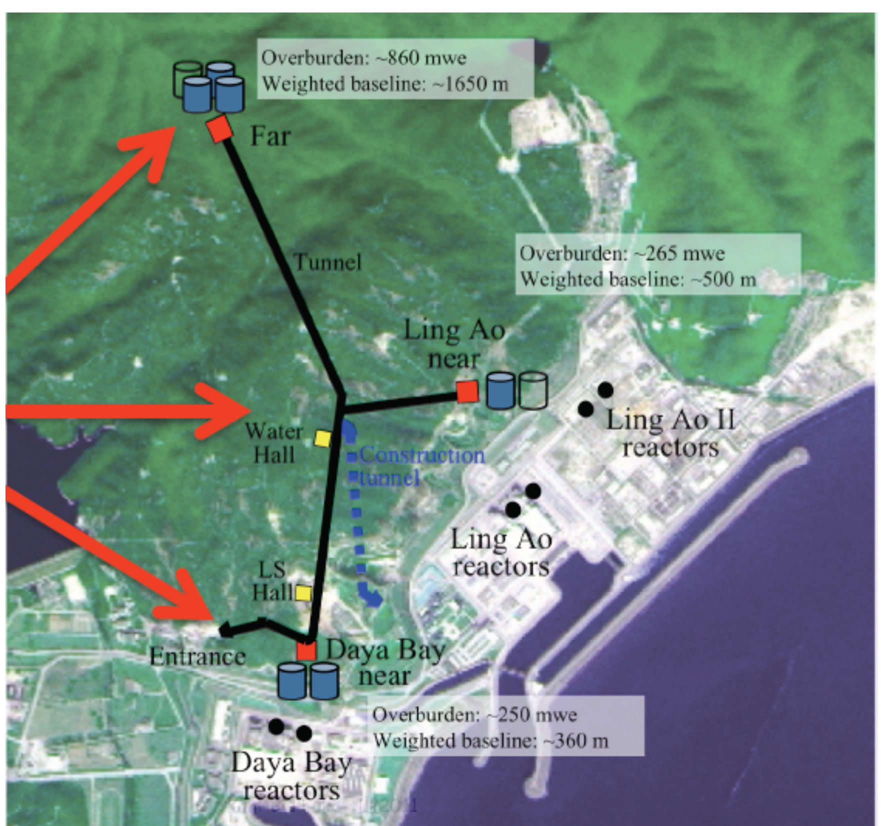
Jonathan M. Paley

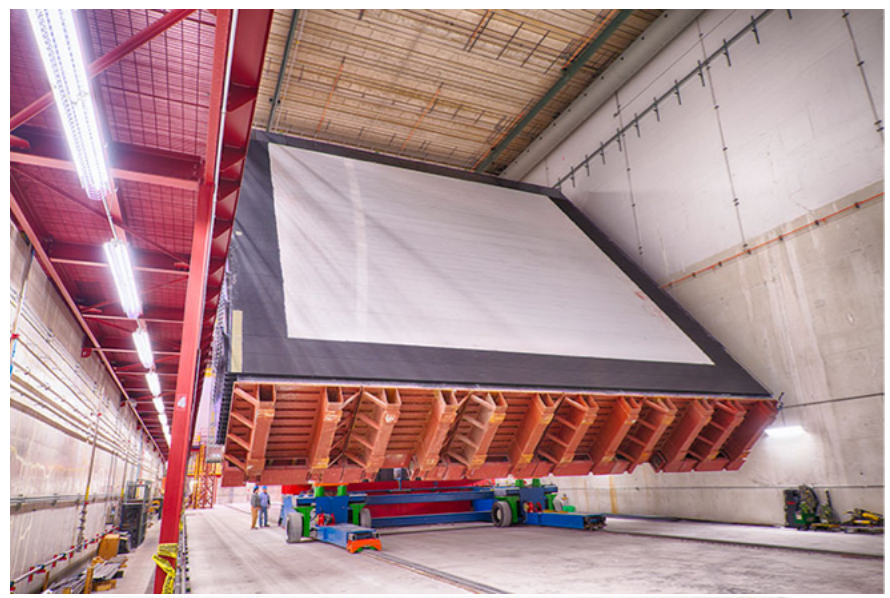
CTEQ Lecture

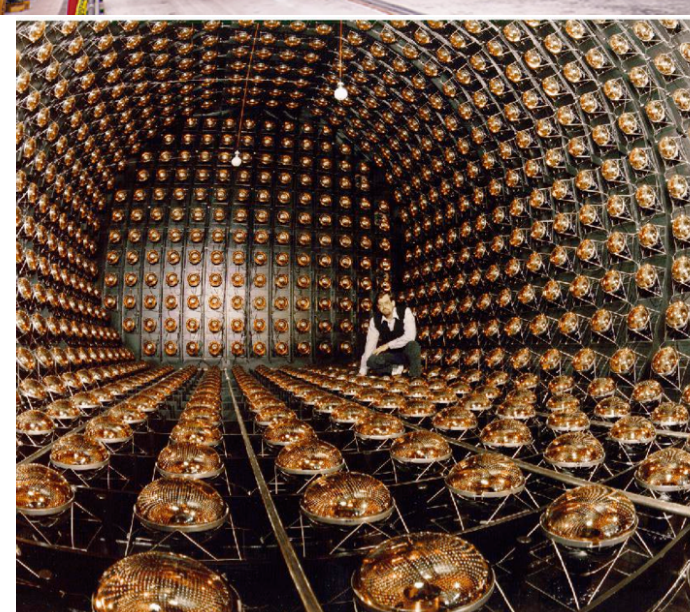
University of Pittsburgh

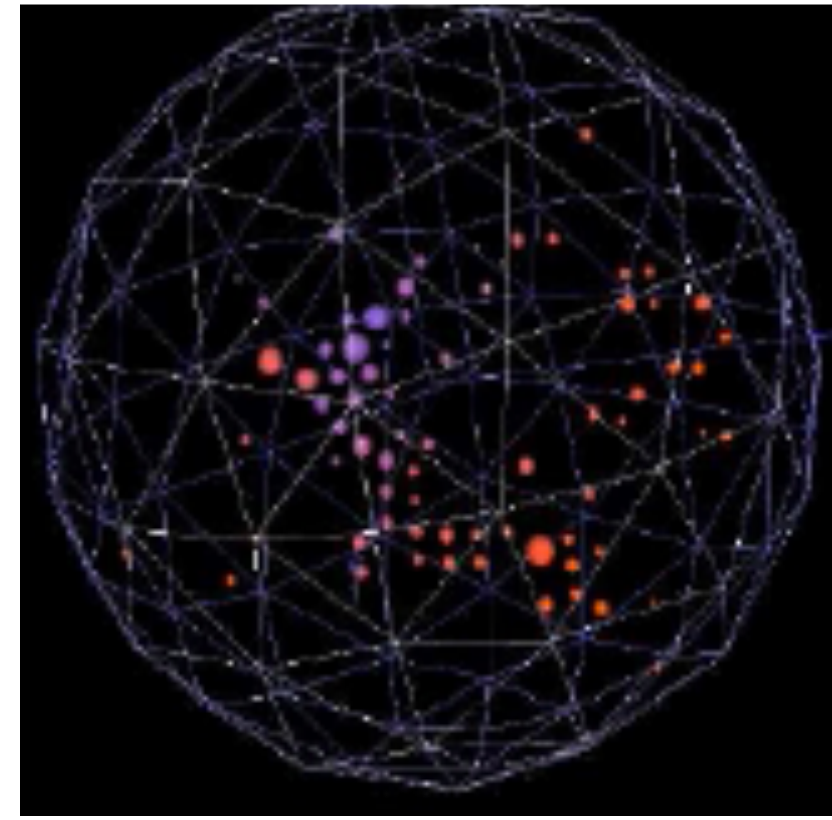
July 26, 2017

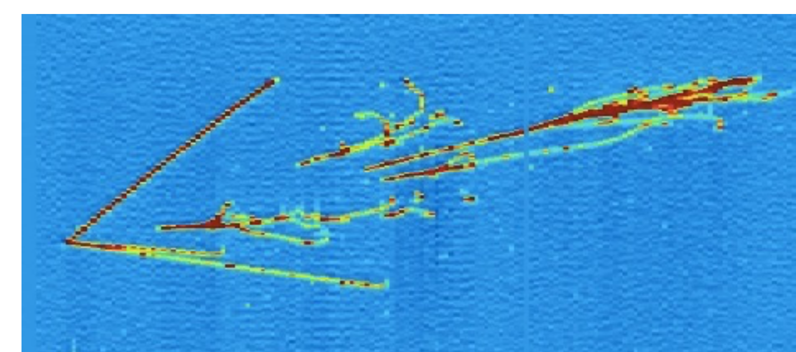


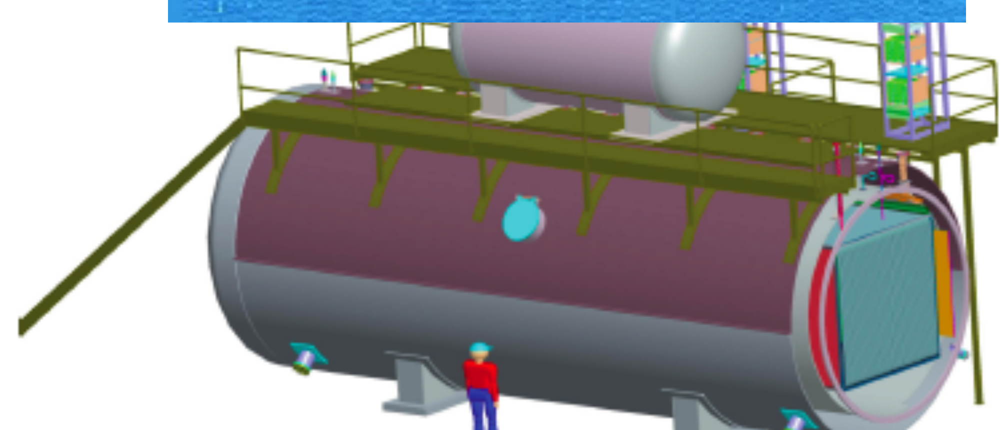






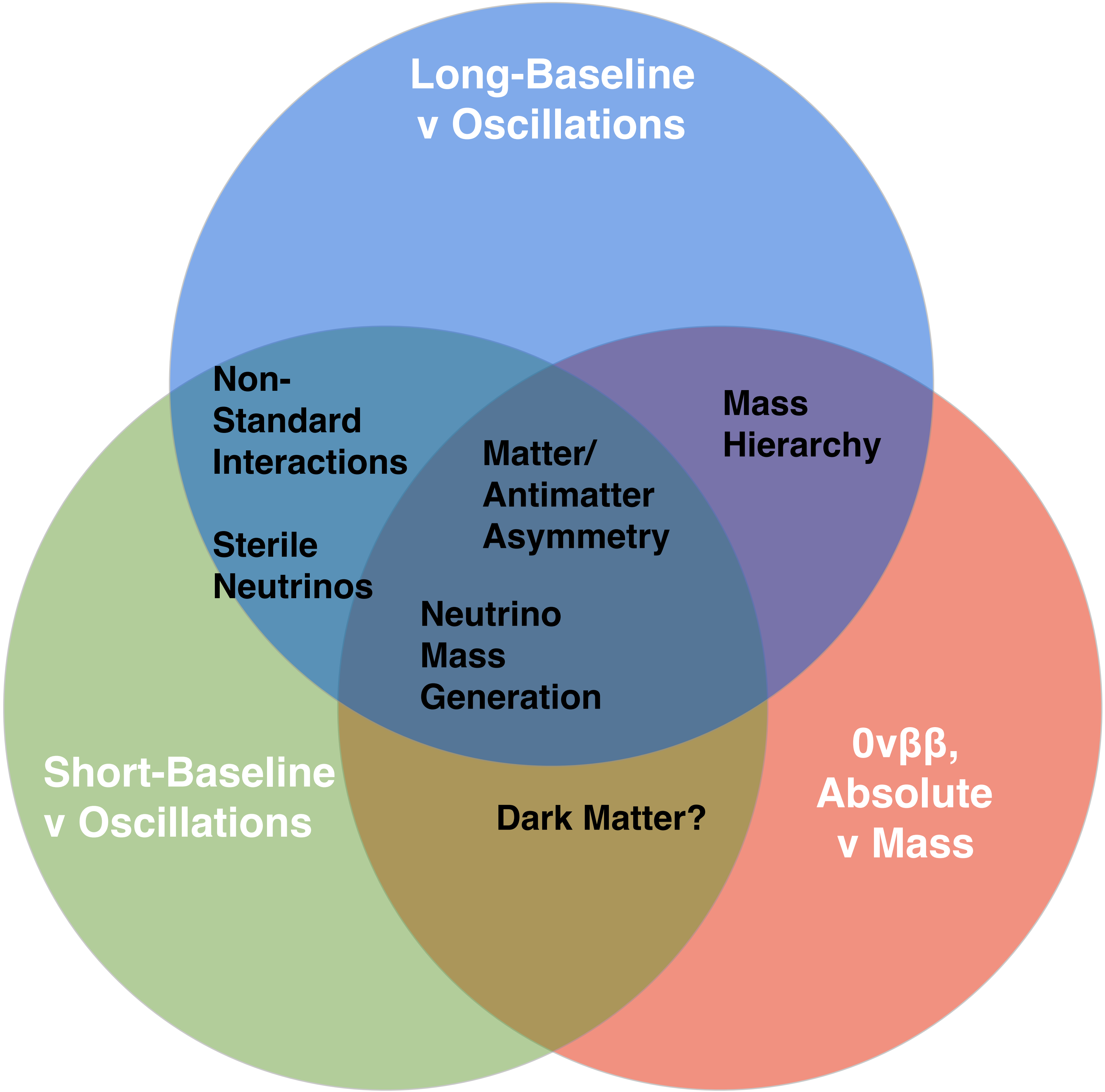


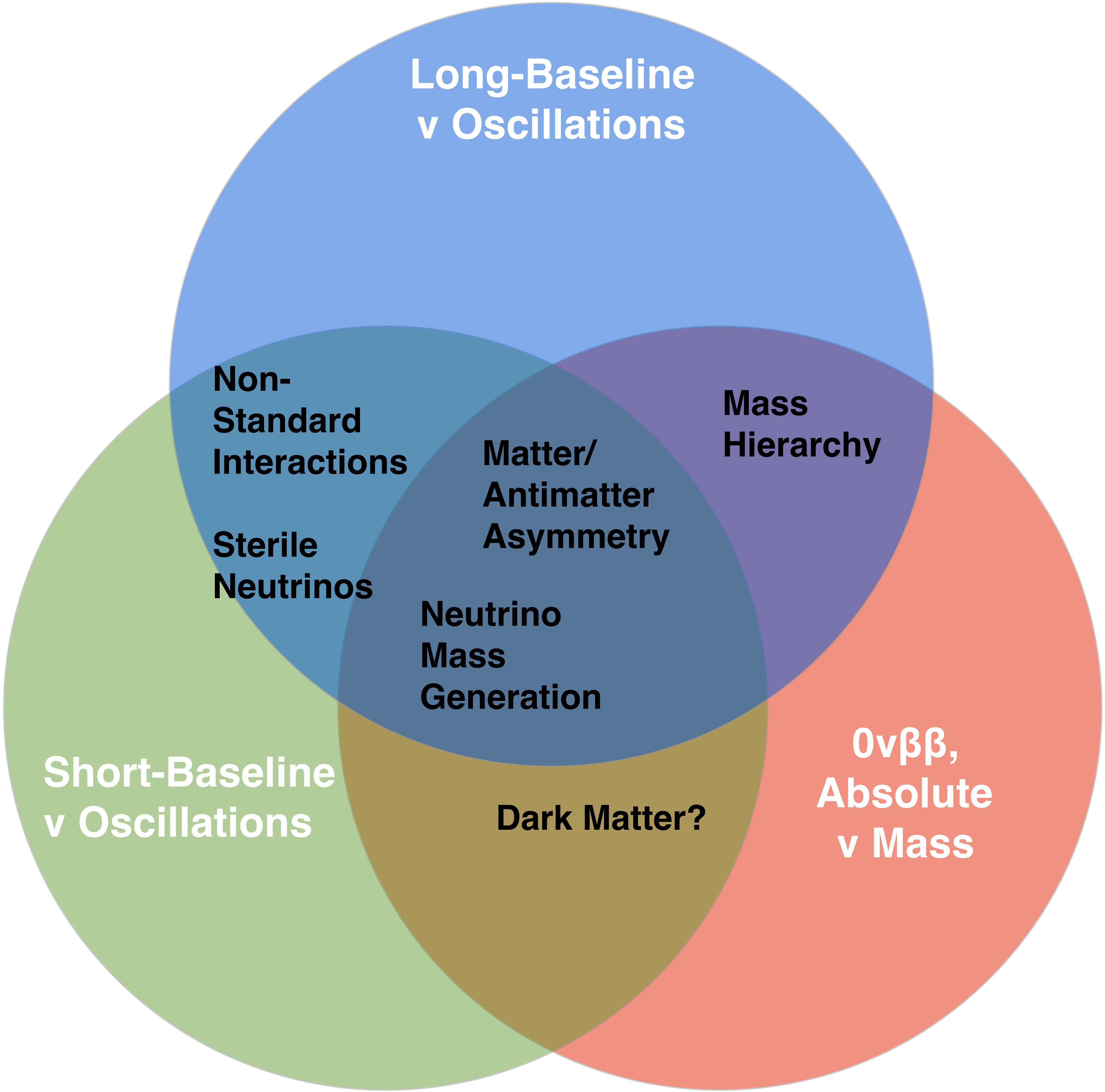




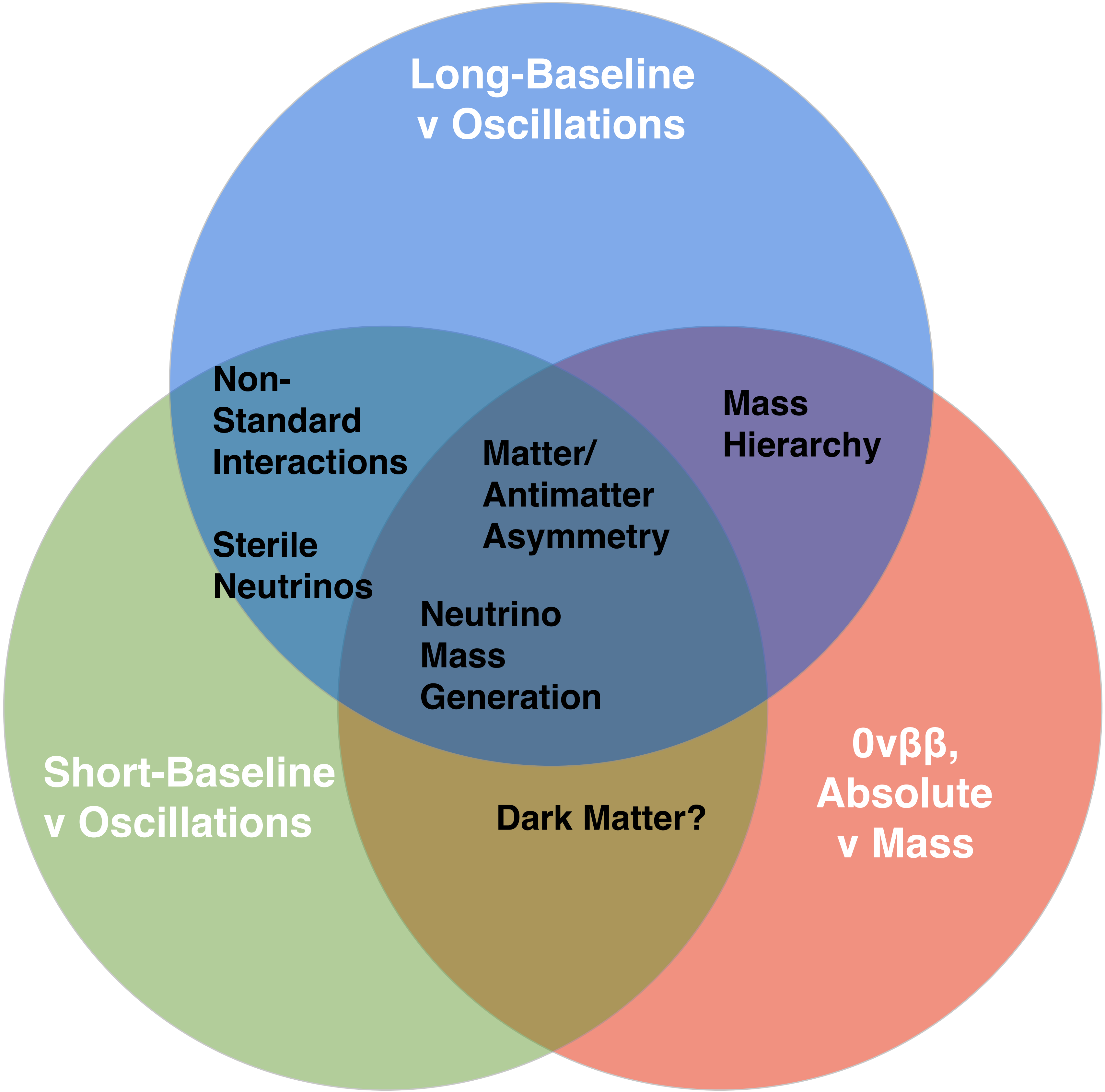
Motivations

- As you just heard, there are several key questions regarding neutrinos now that we know they have mass:
  - mass ordering?
  - absolute mass?
  - Dirac or Majorana?
  - do they violate CP?
  - are there sterile neutrinos?
  - couplings to other BSM?
- Three experimental approaches allow for clear answers to these questions: neutrino oscillation measurements, direct mass measurements and searches for neutrinoless double-beta decay.
- There is some overlap between these different approaches too!


Long-Baseline
ν Oscillations
Non-
Standard
Interactions
Sterile
Neutrinos
Matter/
Antimatter
Asymmetry
Mass
Hierarchy
Neutrino
Mass
Generation
Short-Baseline
ν Oscillations
Dark Matter?
0νββ,
Absolute
ν Mass



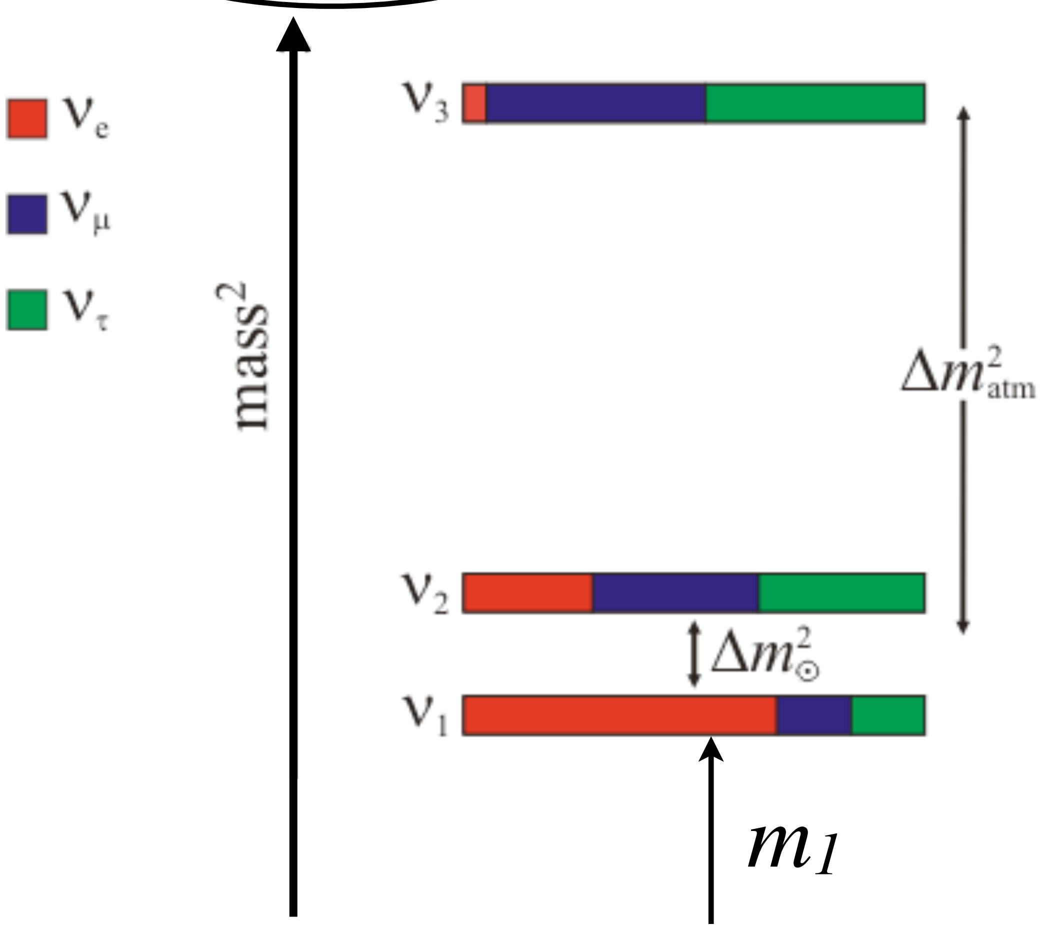
Note: I have spent most of my career working on long-baseline oscillations. Today's lecture will focus more on oscillations…

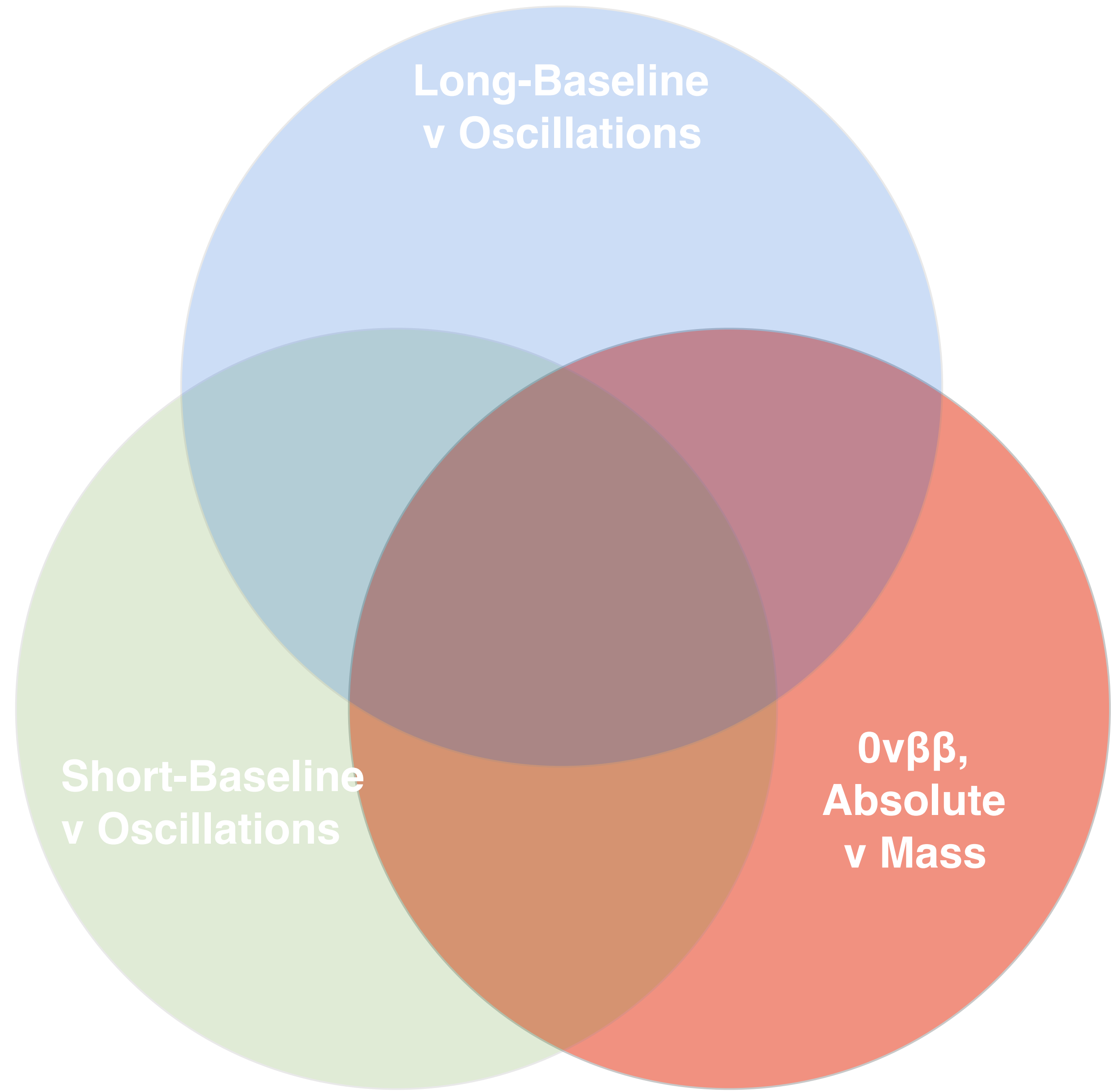


Note: I also have way too many slides… I'll have to skip through many of them but I leave them here for posterity.

Paths to Measuring Neutrino Mass

- Indirect Measurements
  - 0νββ → Majorana vs. Dirac!
  - cosmology
- Direct Measurements
  - Time-of-flight
  - Beta-decay





Neutrinoless Double Beta Decay

heavy dependence on nuclear models…QCD!

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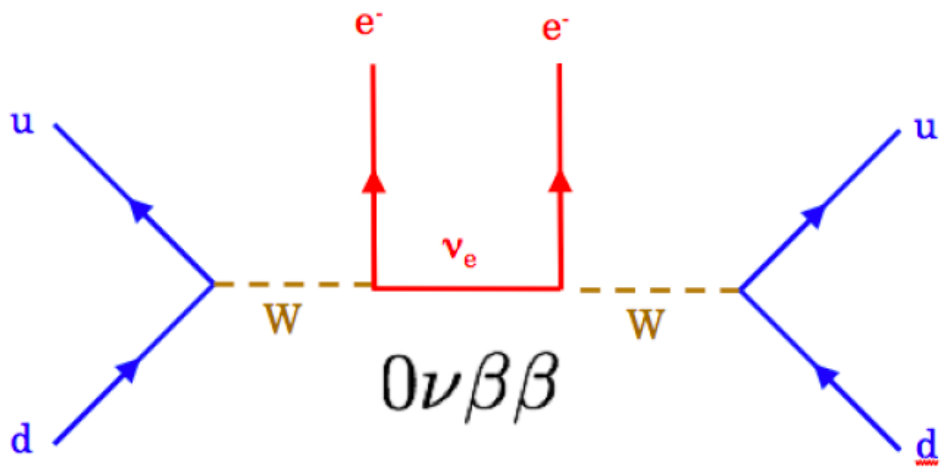

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}\left|M^{0\nu}\right|^2\left(\frac{\langle m_\nu\rangle}{m_e}\right)^2$$

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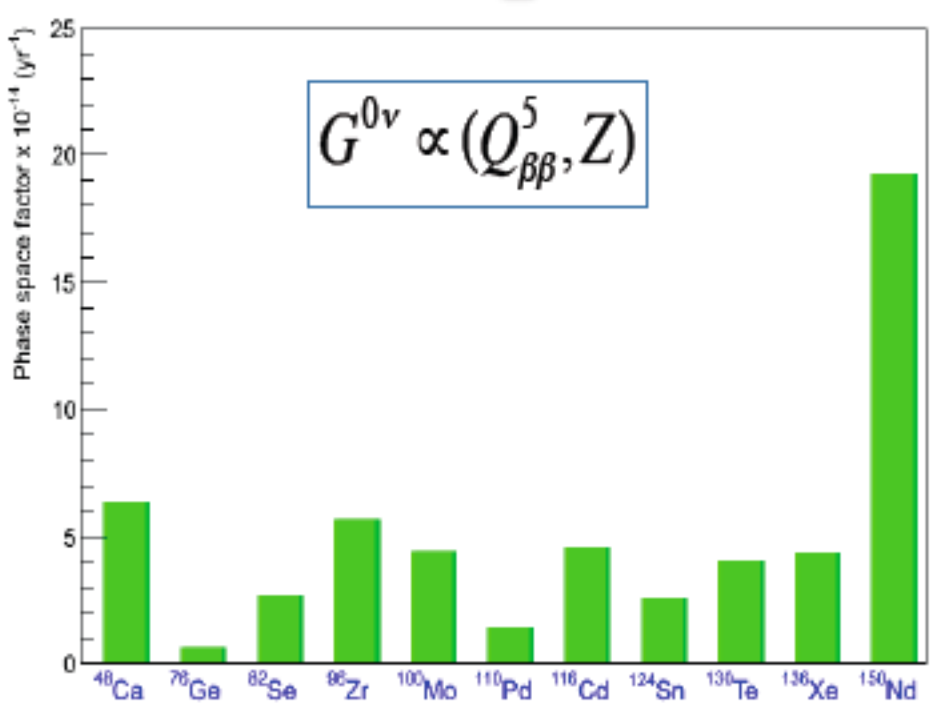
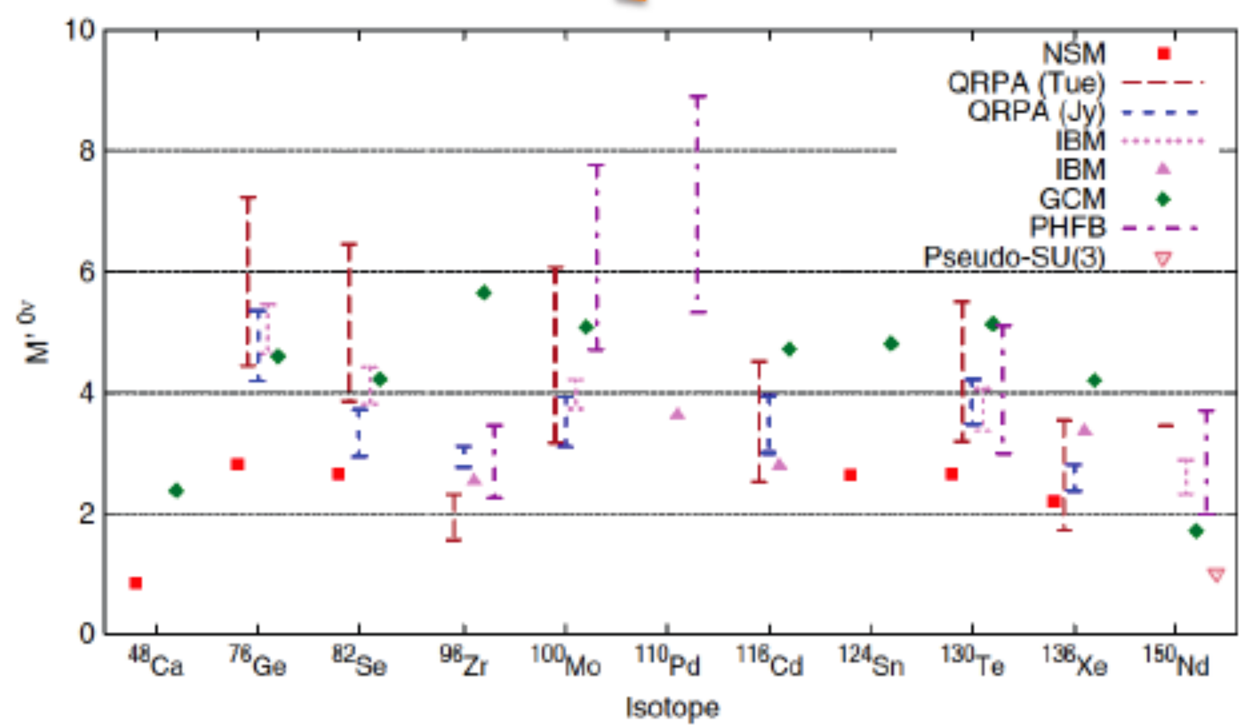
Piquemal - Neutrino 2012





Dueck et al. Phys,. Rev. D **83** 113010(2011)

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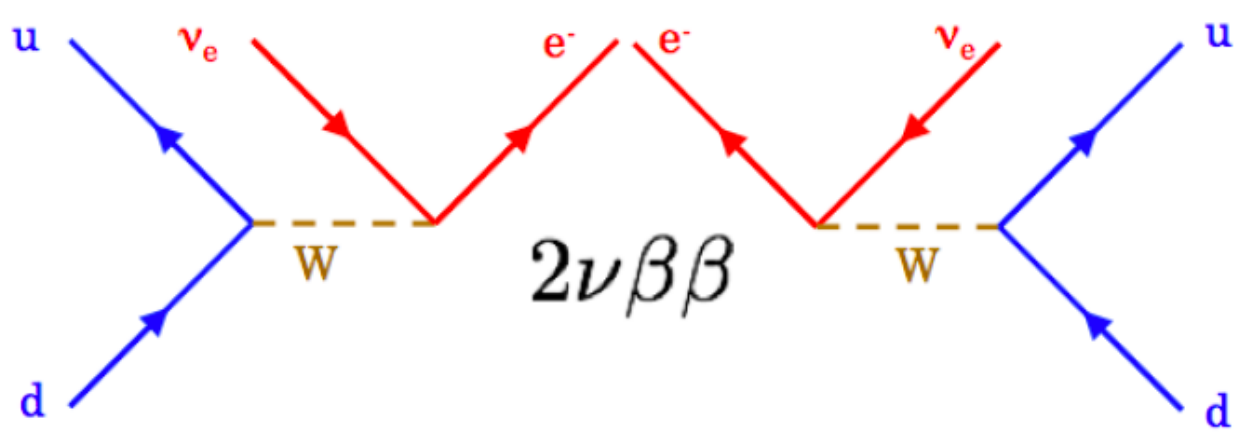
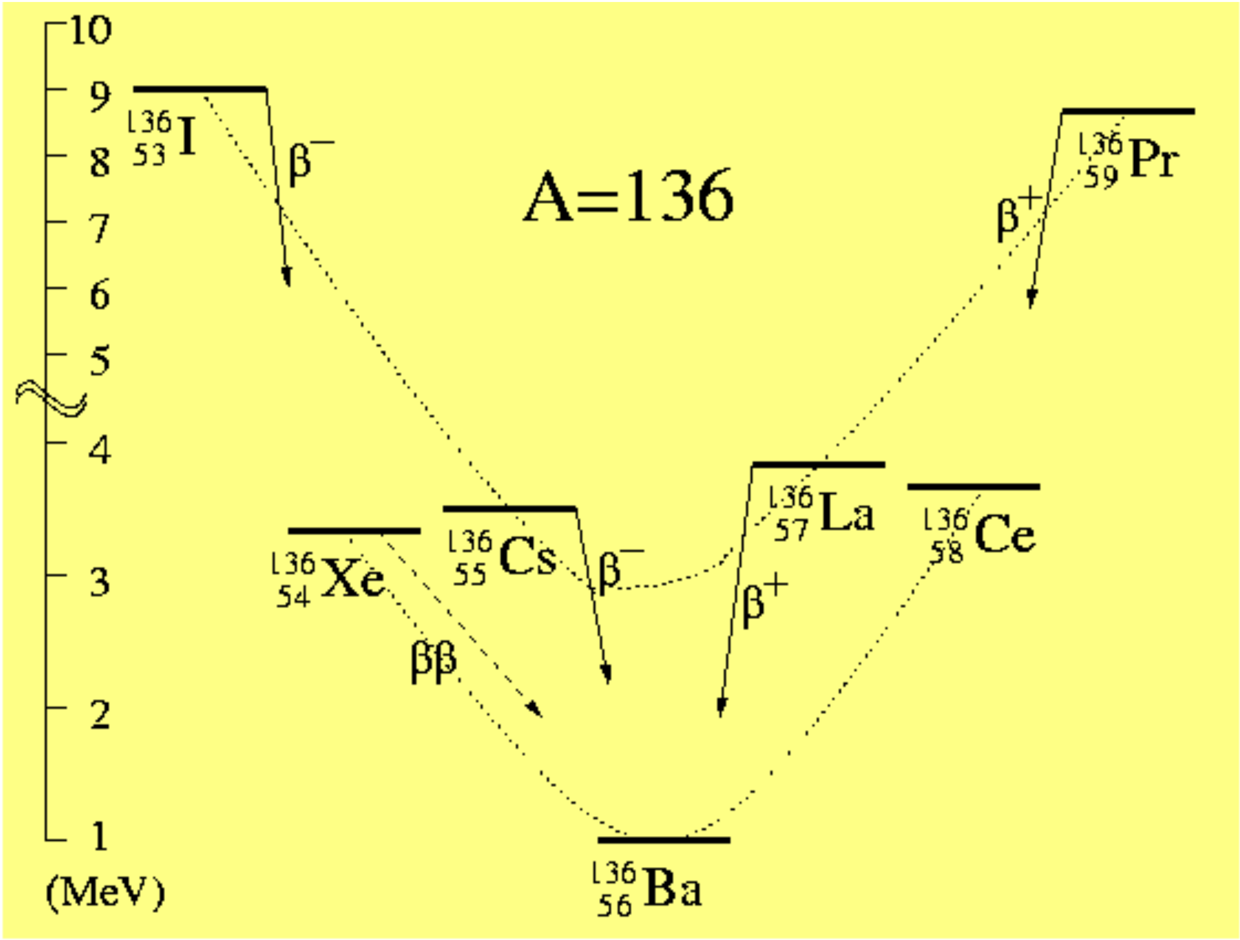




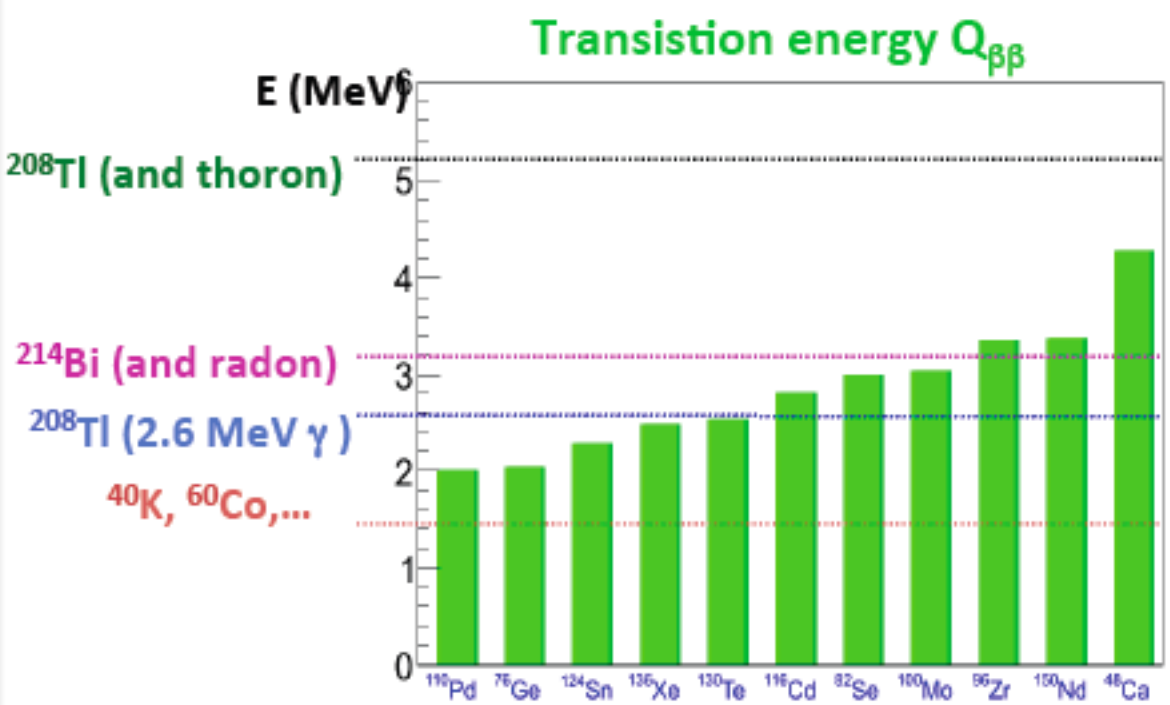
Neutrinoless Double Beta Decay

WITH Background $$T_{1/2}^{0\nu}(y) \propto \frac{\varepsilon}{A}\sqrt{\frac{M\,.\,t}{N_{Bckg}\,.\,\Delta E}} \qquad \langle m_\nu \rangle \propto \sqrt[4]{M}$$

ε :efficiency, M: Mass, t: time, N_{bckg}: Background events, ΔE: energie resolution, A: isotope mass

Background origins

Natural radioactivity



Other sources of background:

- Muons (underground labs)
- γ from ((n,γ) reactions , μ bremstrahlung
- Muon spallation products
- α emitters from bulk or surface contaminations for calorimeters
- ββ(2ν) if modest energy resolution

Neutrinoless Double Beta Decay

- In general, there are two types of 0νββ experiments:

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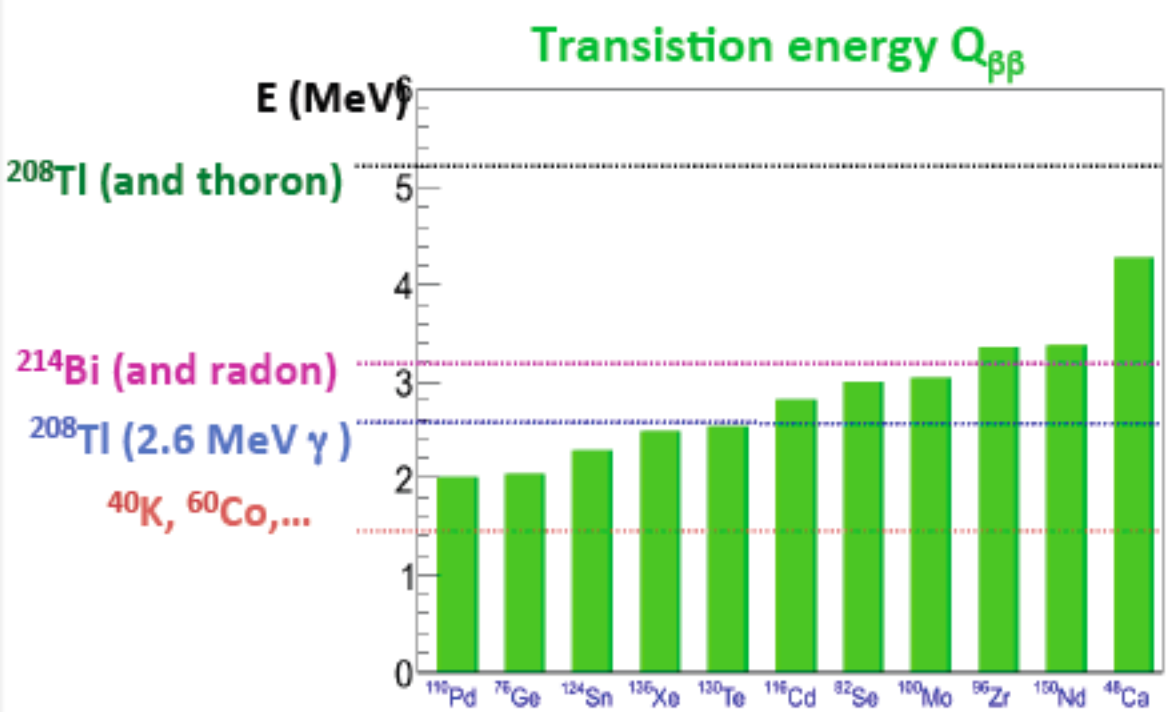

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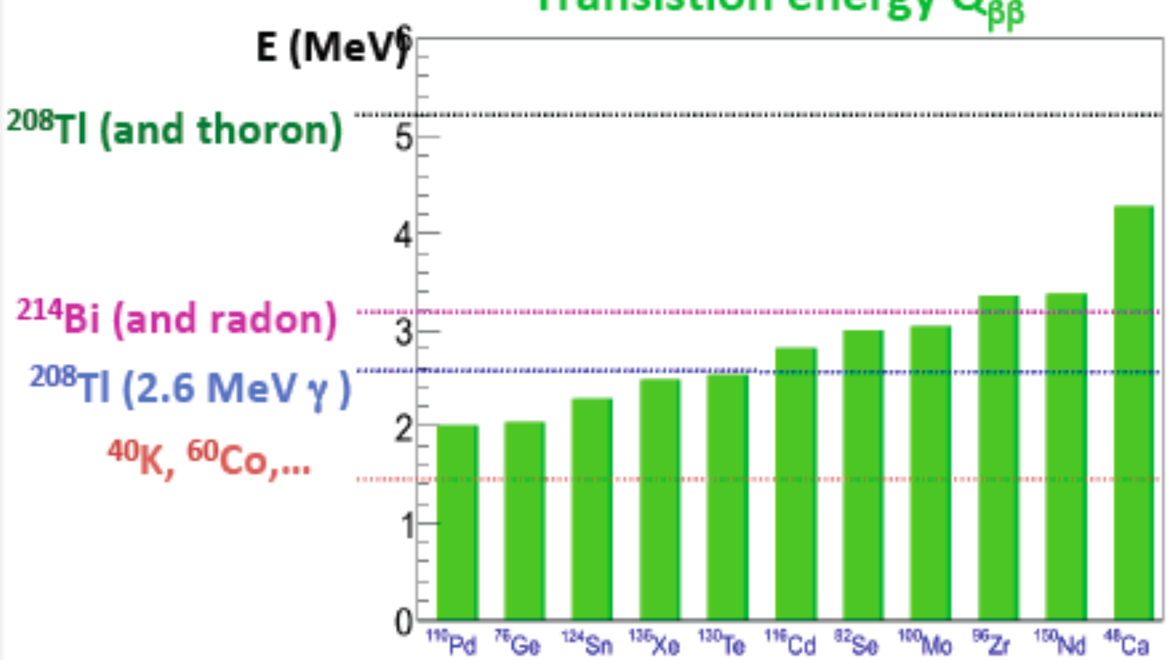

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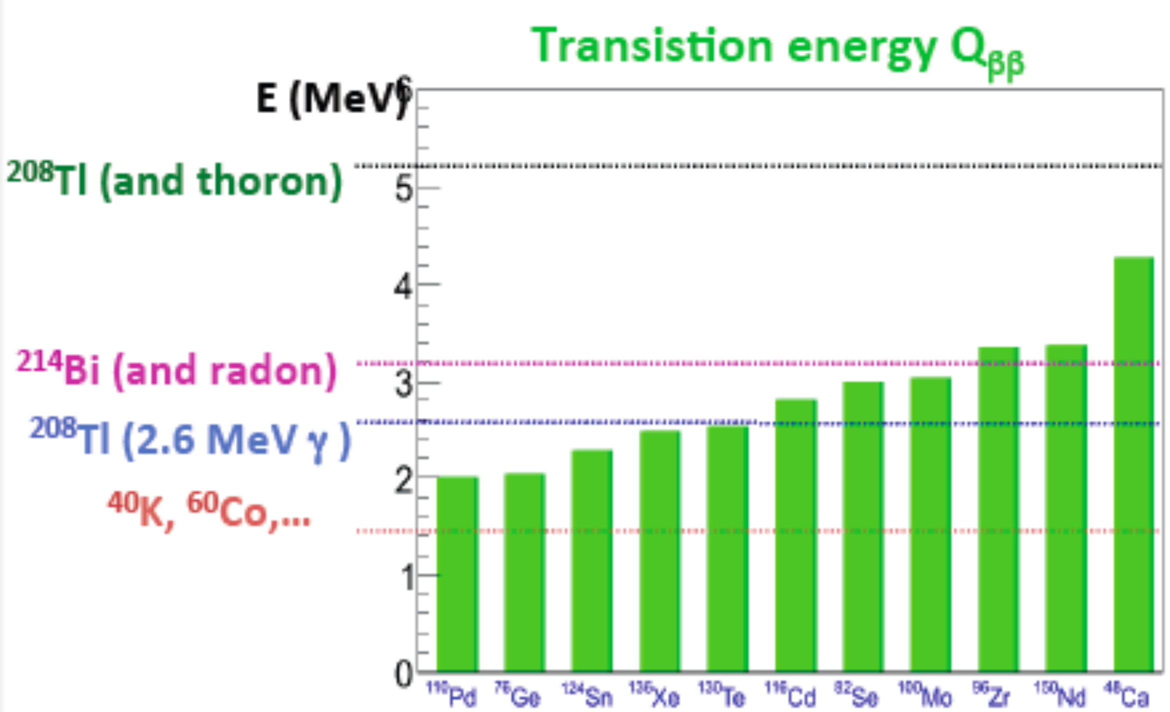

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Neutrinoless Double Beta Decay

- In general, there are two types of $0\nu\beta\beta$ experiments:
  - Tracking
  - Calorimeter
- **These experiments are INCREDIBLY difficult!**

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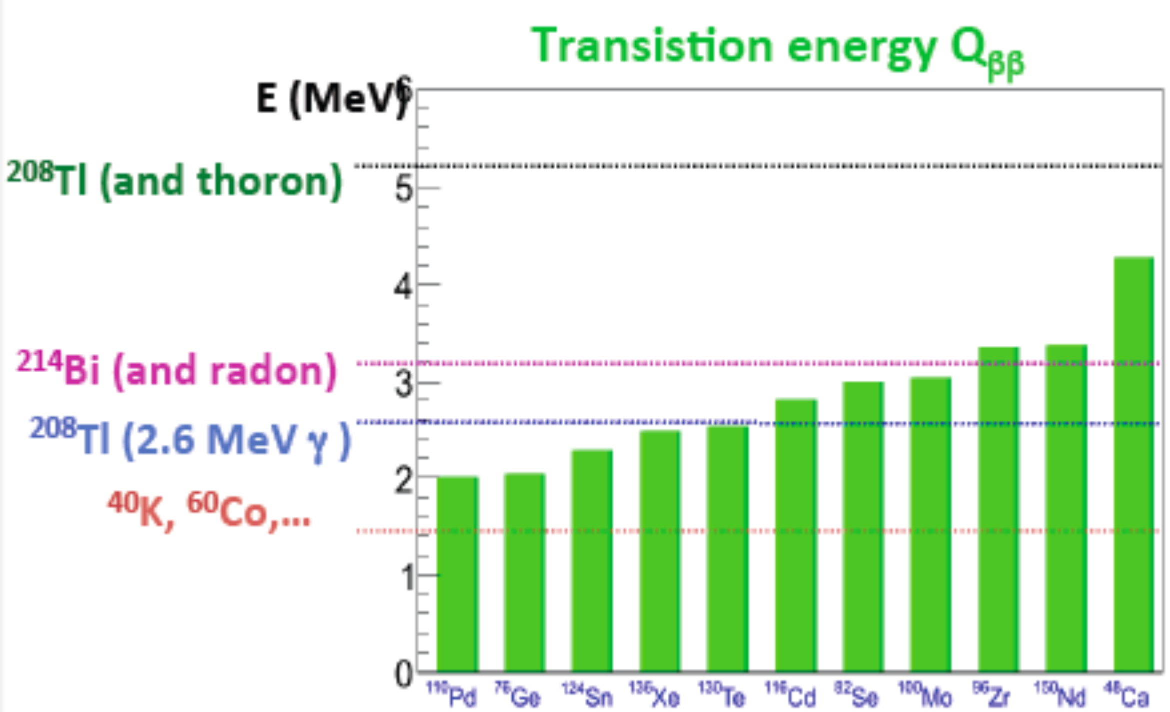

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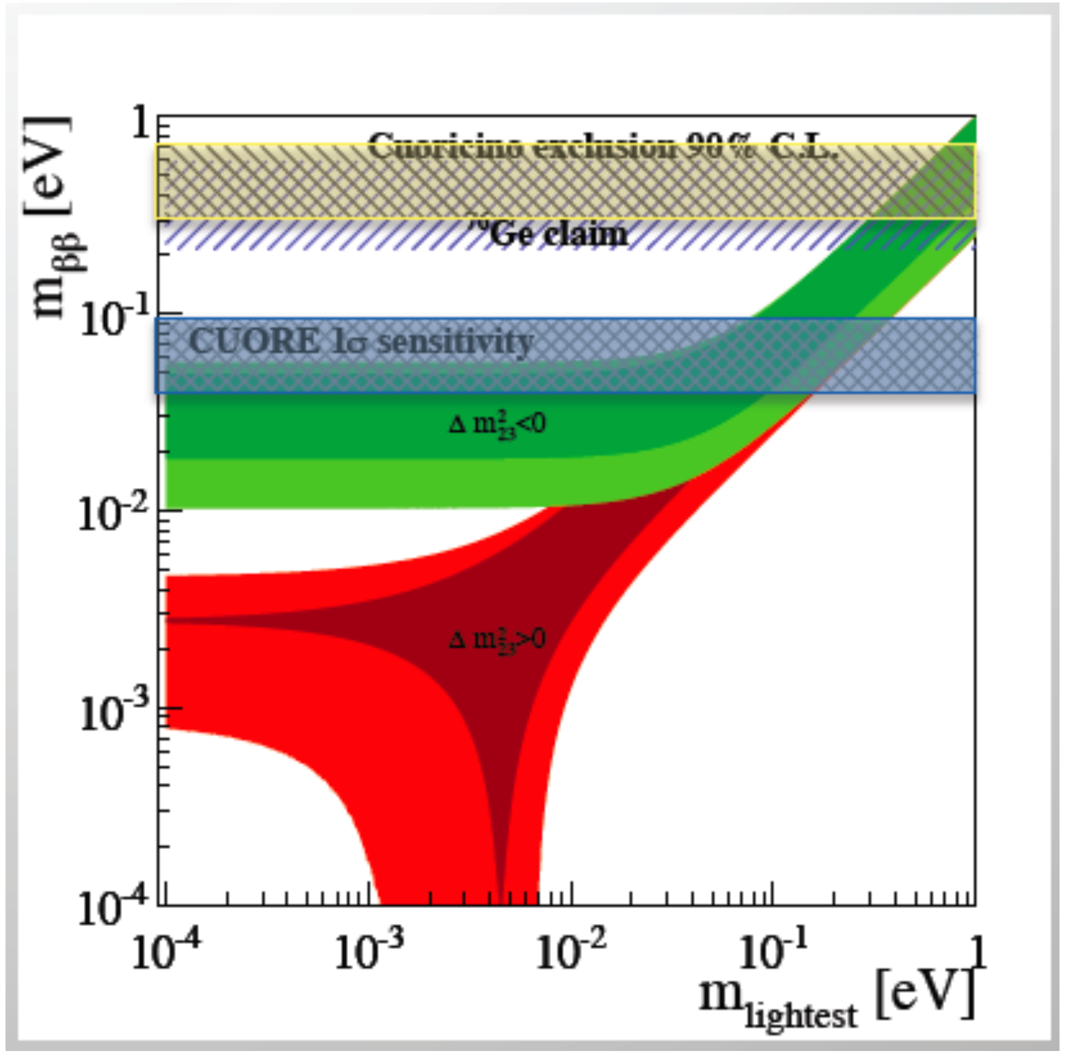
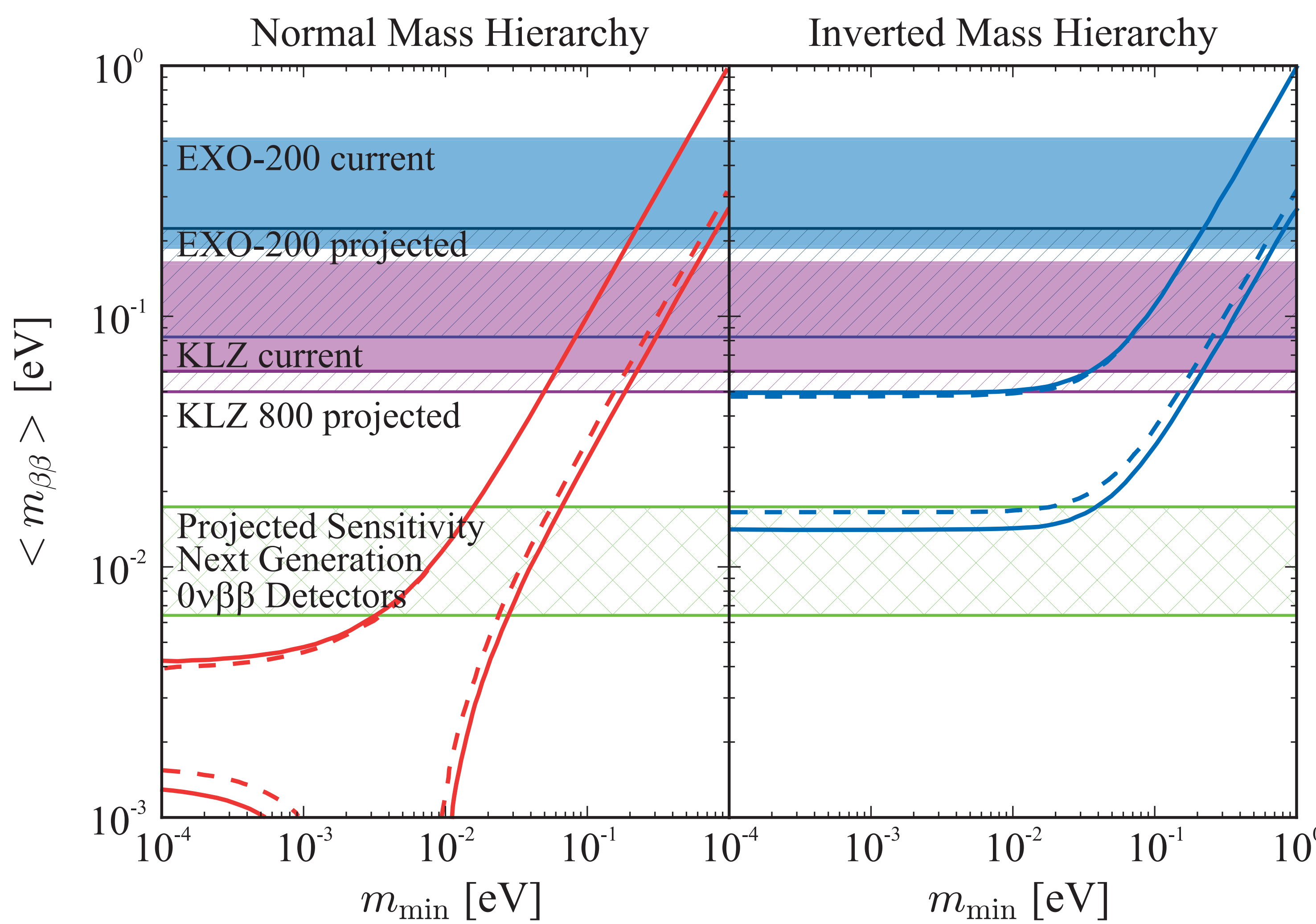
Neutrinoless Double Beta Decay - Where We're At



Pedretti, Neutrino 2012



T. Brunner and L. Winslow, arXiv: 1704.01528v1

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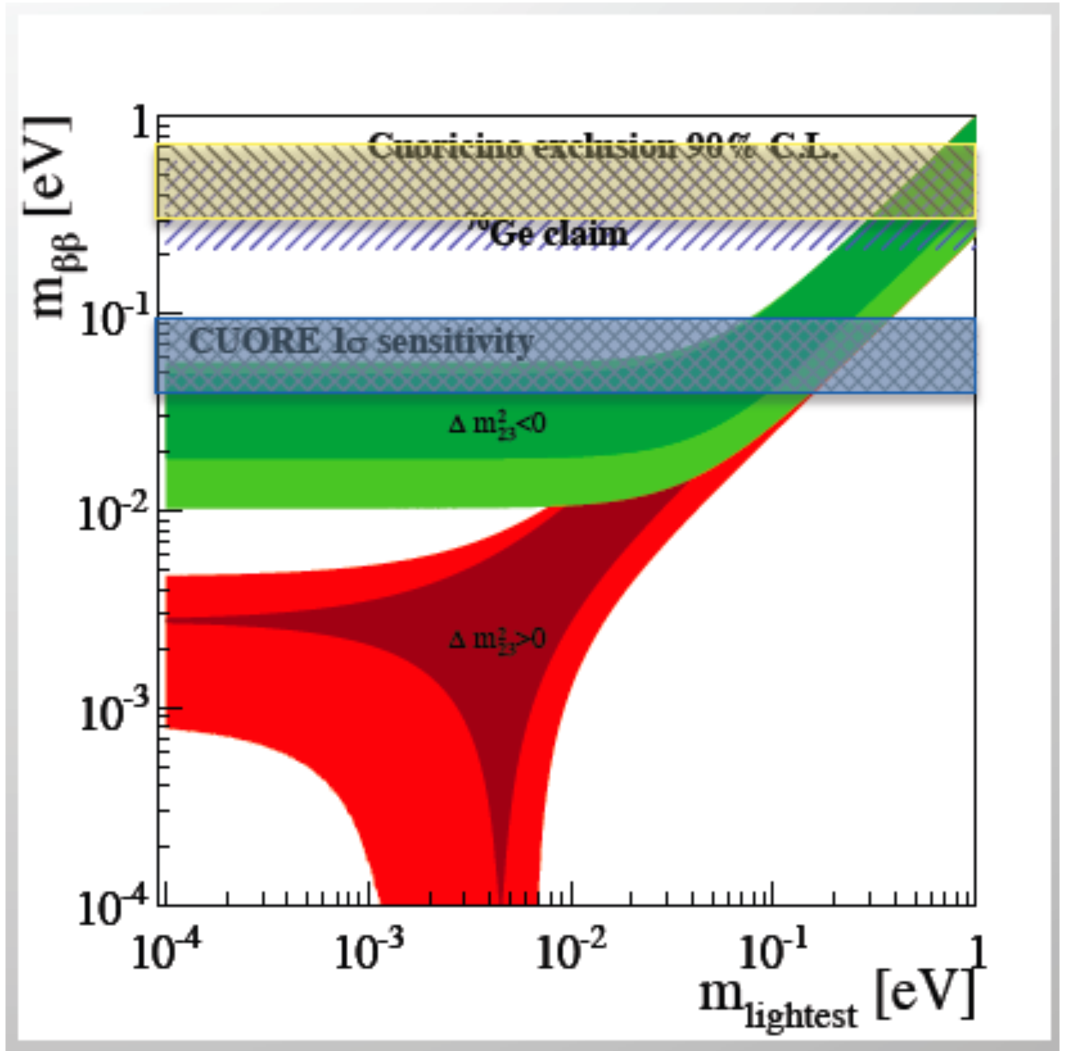

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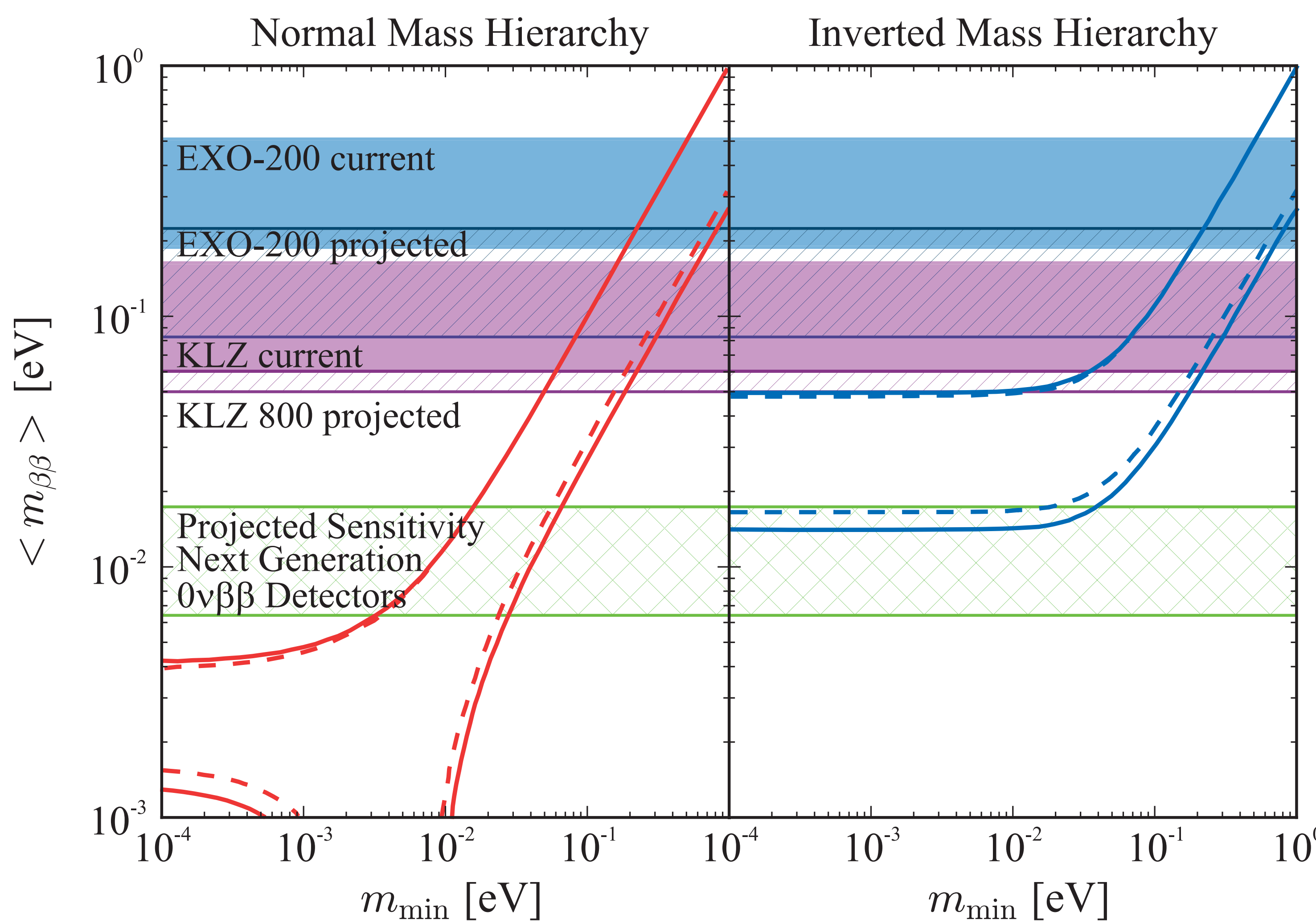

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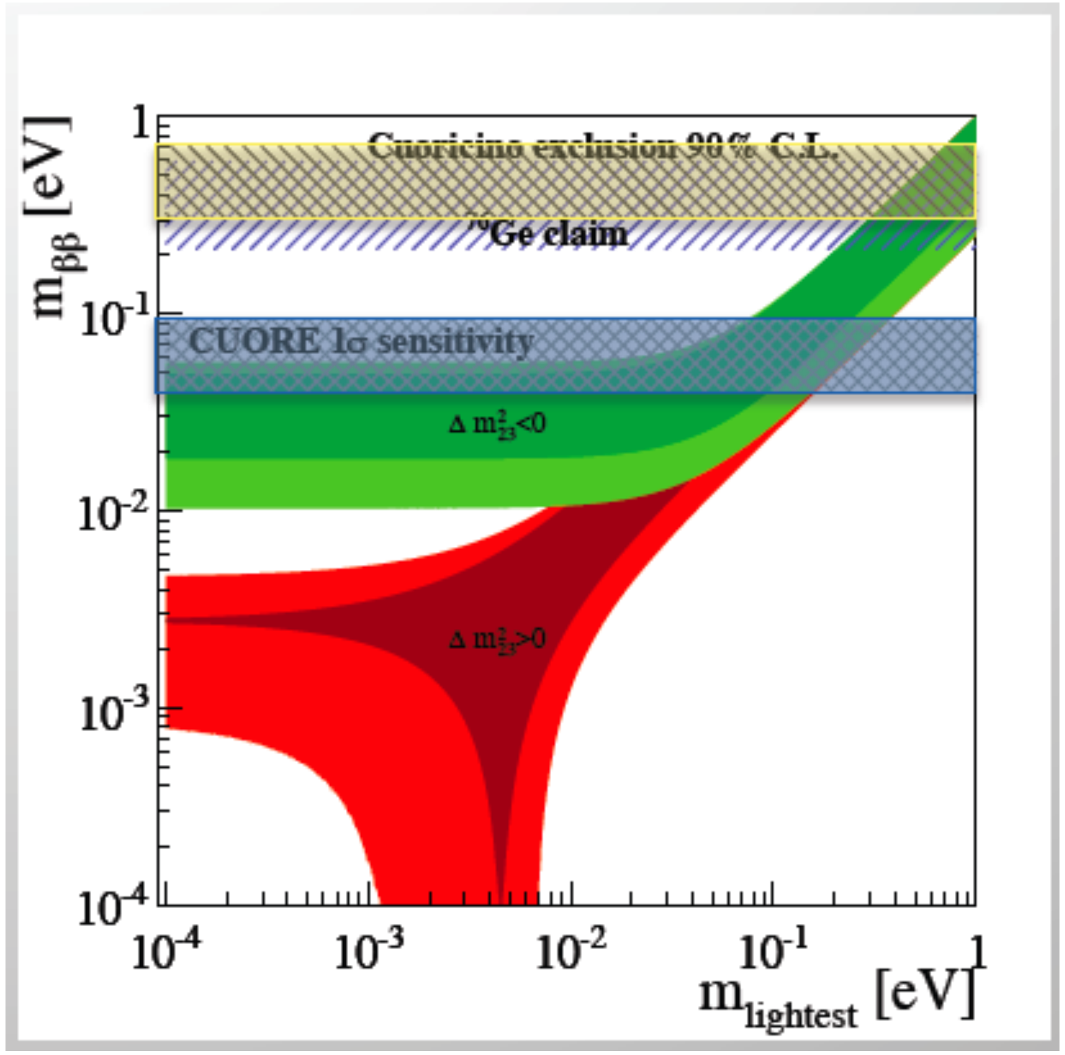

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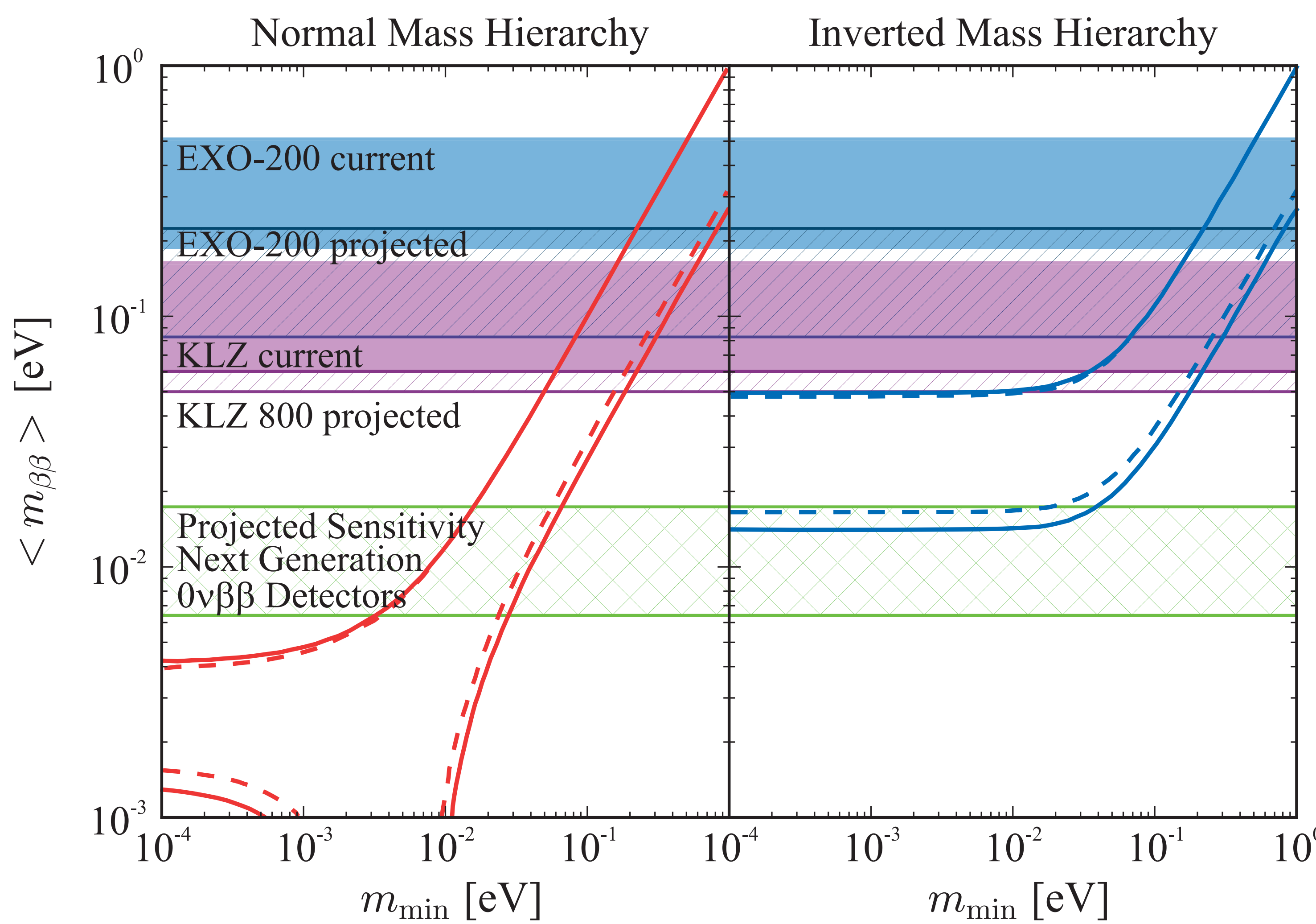

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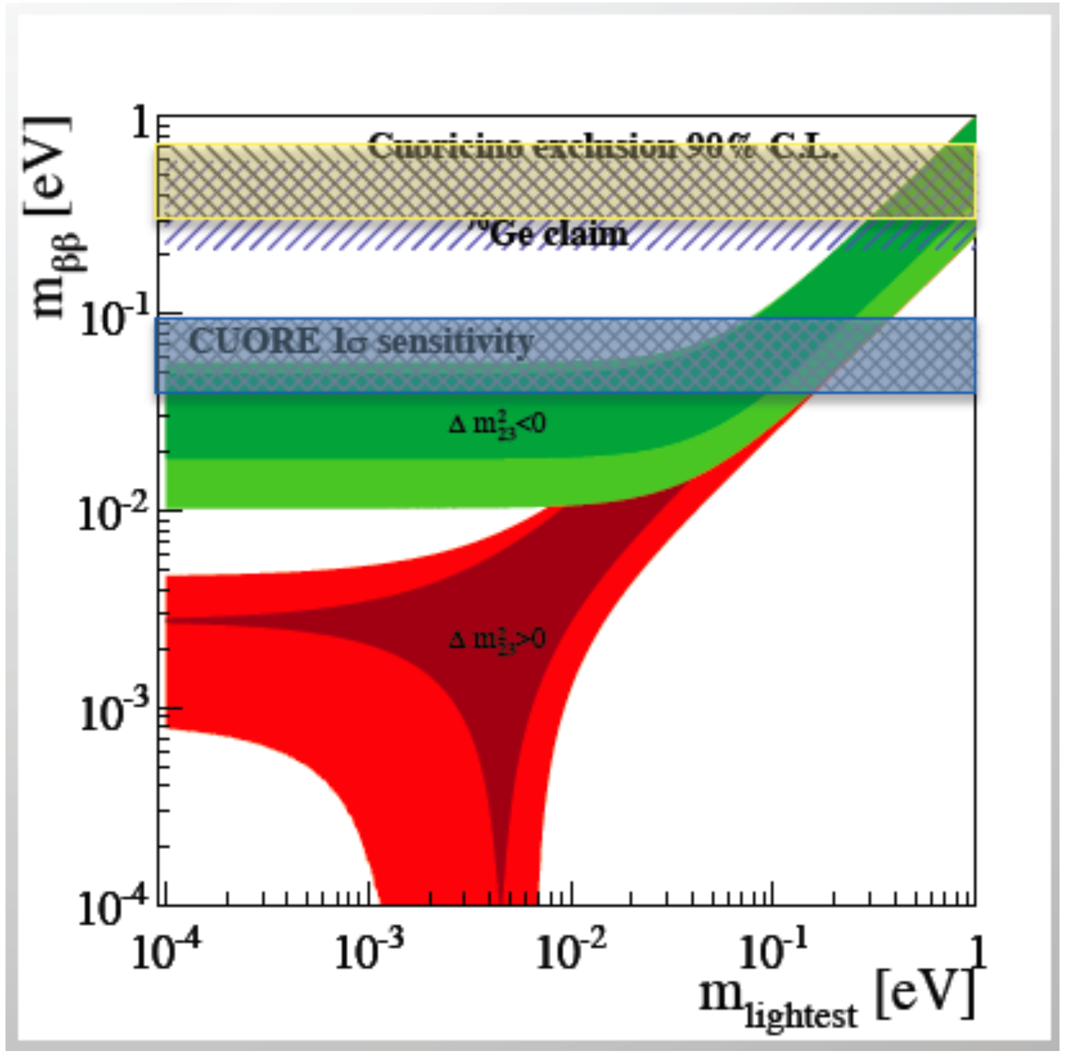

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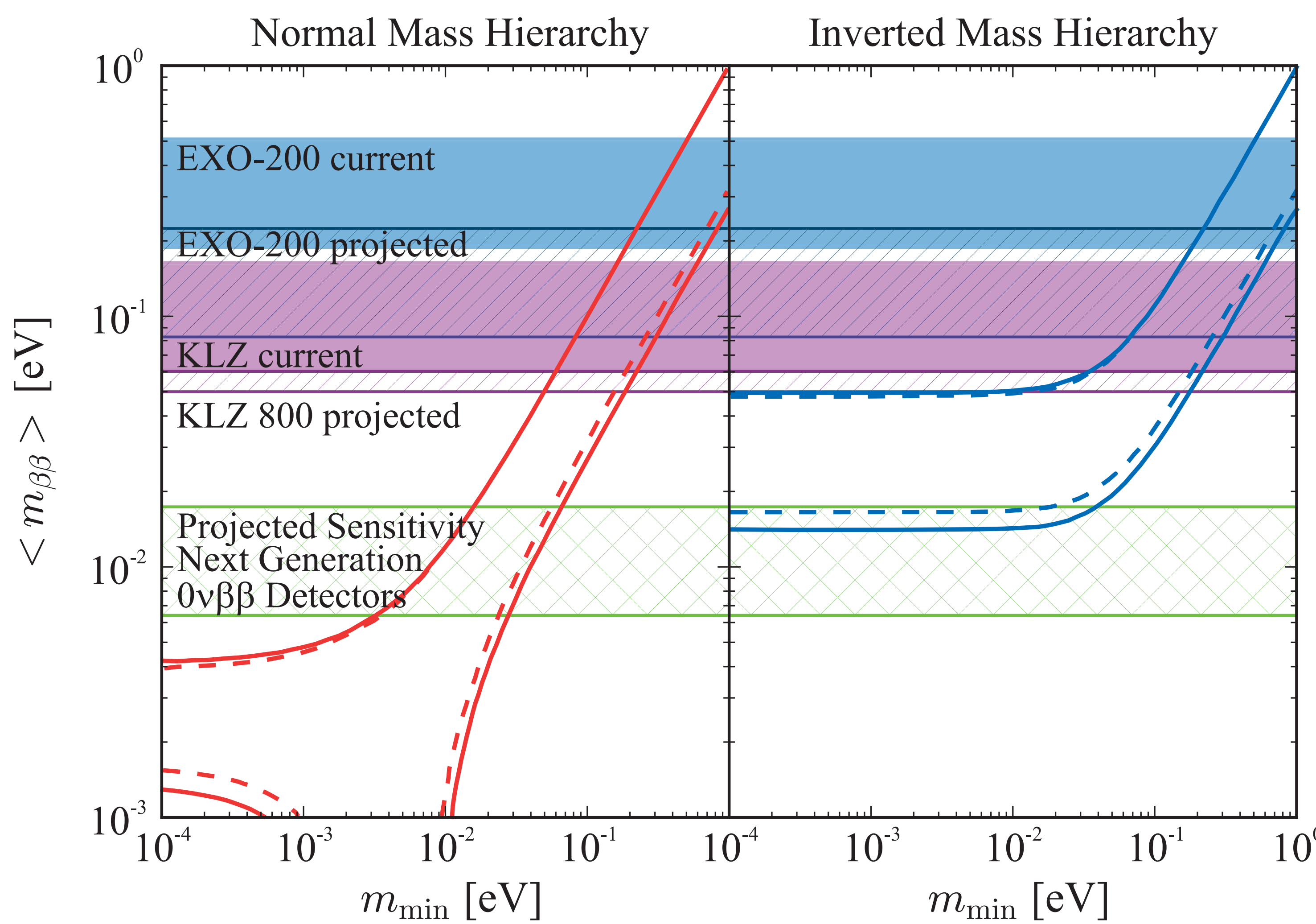

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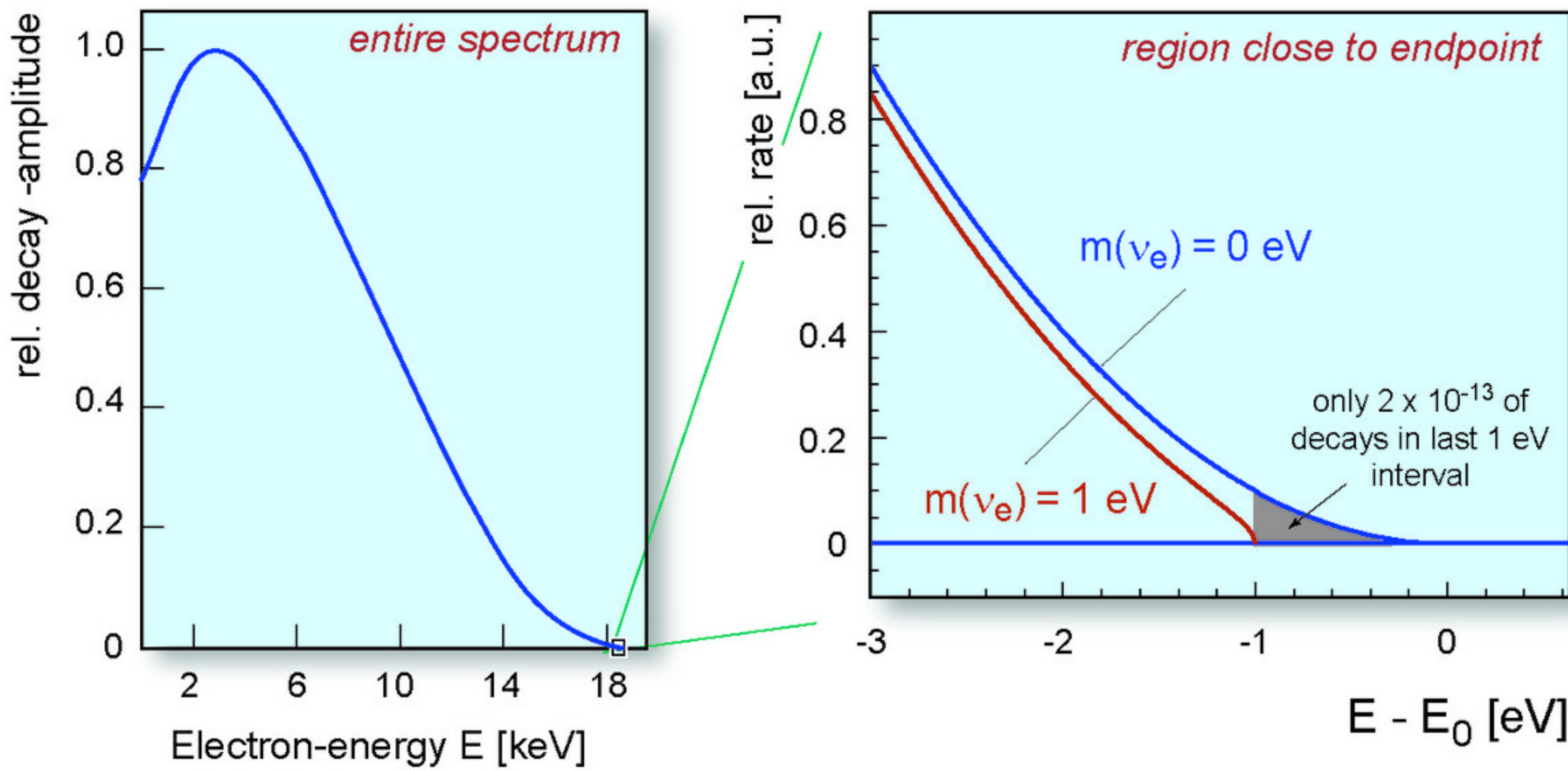
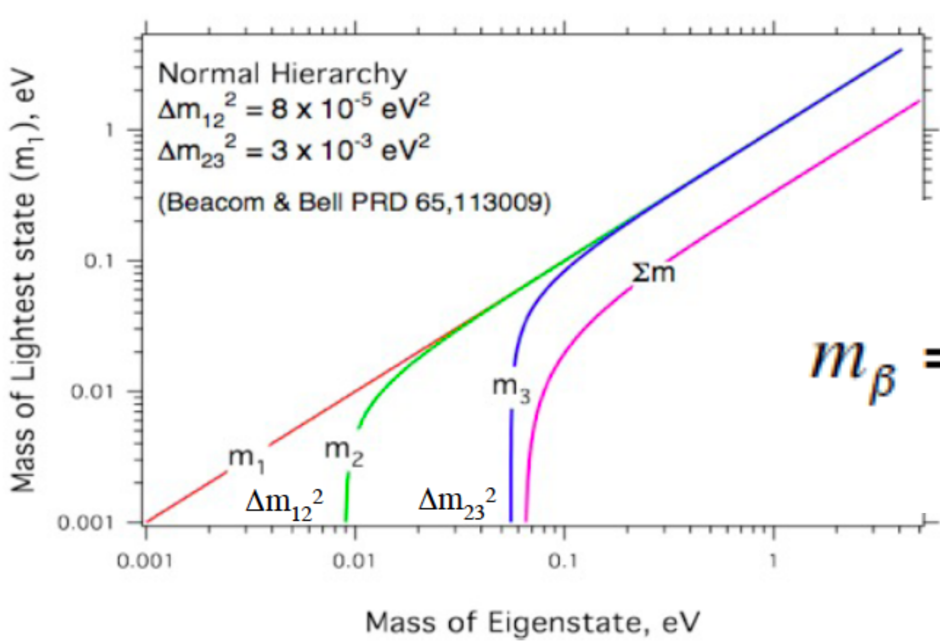
- Widths of bands arises from uncertainties in Majorana and Dirac phases, oscillation parameters and nuclear matrix elements.

Mass Measurement Using Beta Decay



$$\frac{dN}{dE} = |< l| < \nu_l|T|I >|^2 = \left|\sum_i U_{li}^* < l| < \nu_i|T|I >\right|^2 \propto p_e E(E-E_0)^2\left[1-\frac{m_\nu^2}{(E-E_0)^2}\right]^{1/2}$$

Beta-decay Experiments



$$m_\beta = \left[\sum_i |U_{ei}|^2 m_i^2\right]^{\frac{1}{2}}$$

Final results from measurement by Mainz experiment:

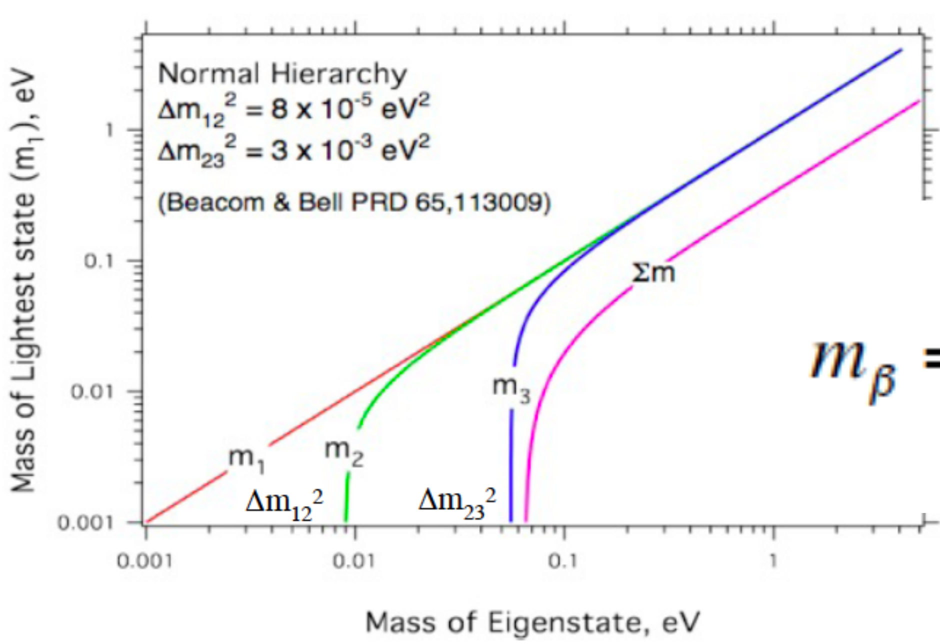
$$m^2(\nu_e) = (-0.6 \pm 2.2_{\rm stat} \pm 2.1_{\rm syst})\ \mathrm{eV}^2/\mathrm{c}^4$$
$$\chi^2/\mathrm{d.o.f.} = 208/194$$

$$m(\nu_e) < 2.3\ \mathrm{eV}/\mathrm{c}^2 \quad (95\%\ \mathrm{C.L.})$$

Limited by energy resolution.

Beta-decay Experiments

- Tritium is an ideal source!



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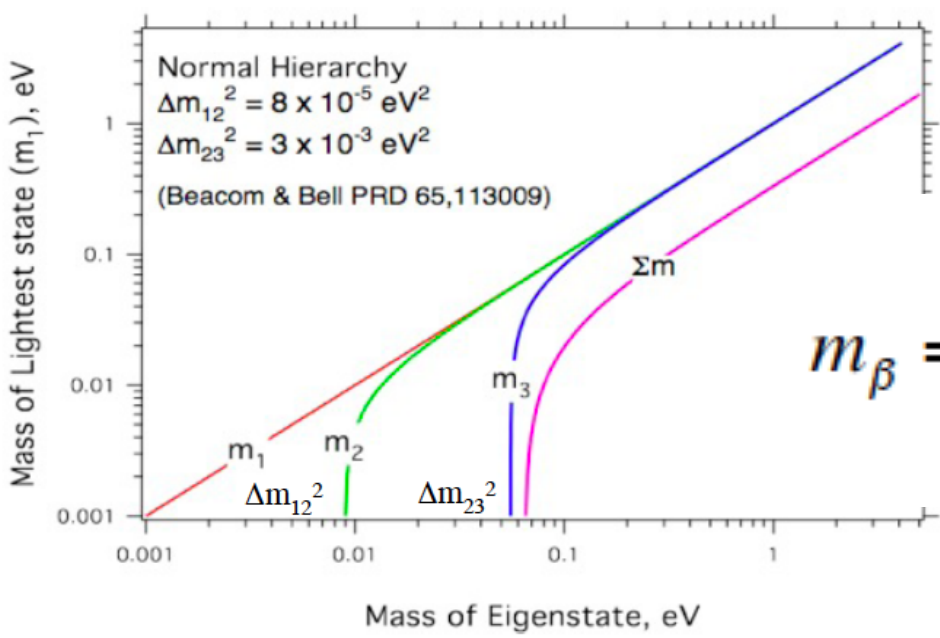

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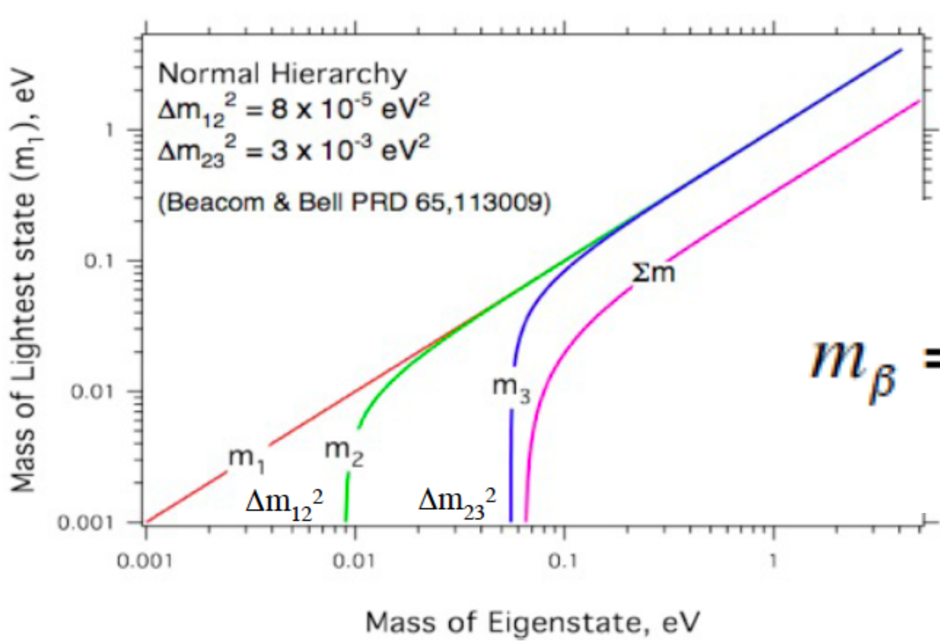

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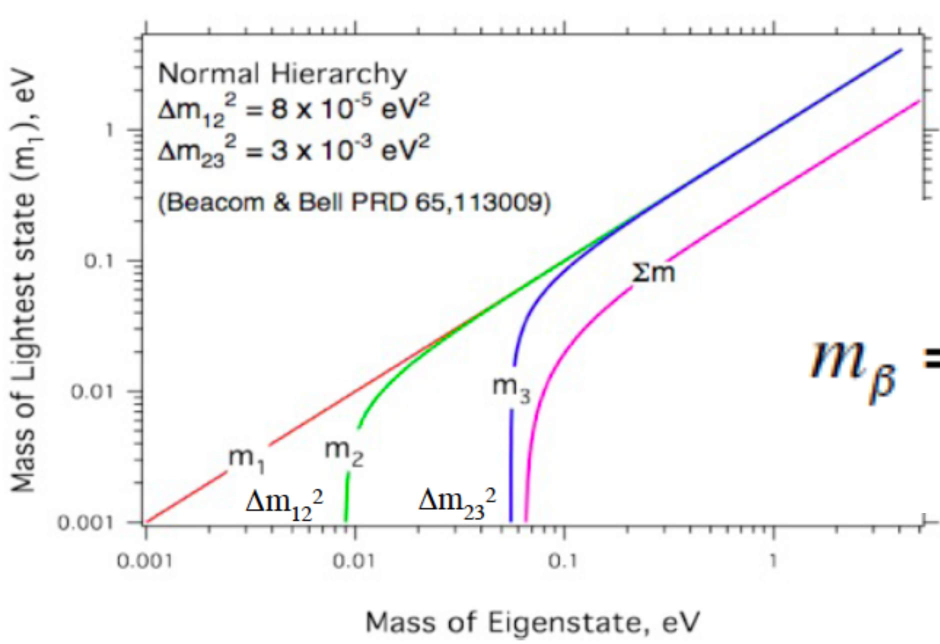

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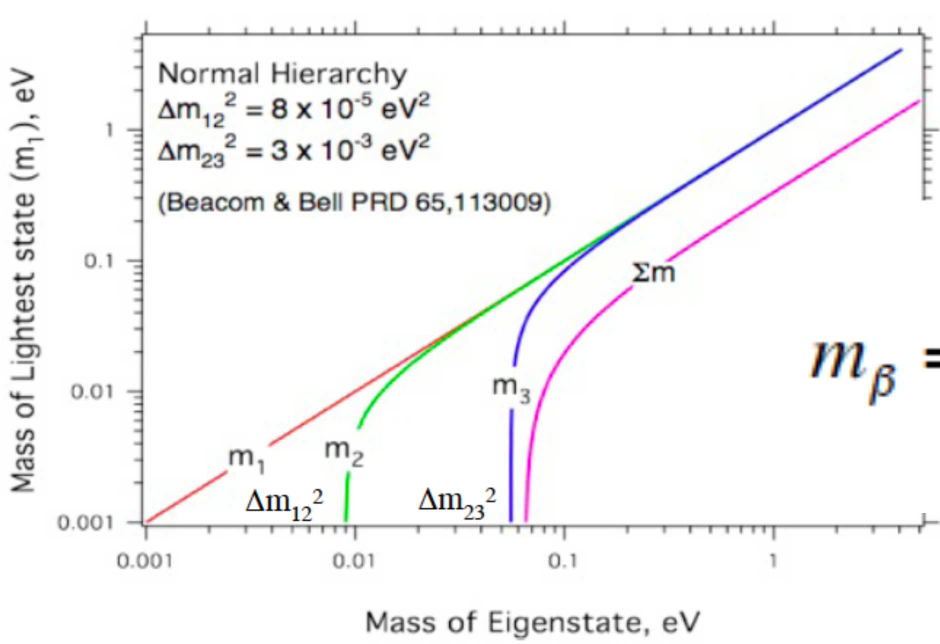

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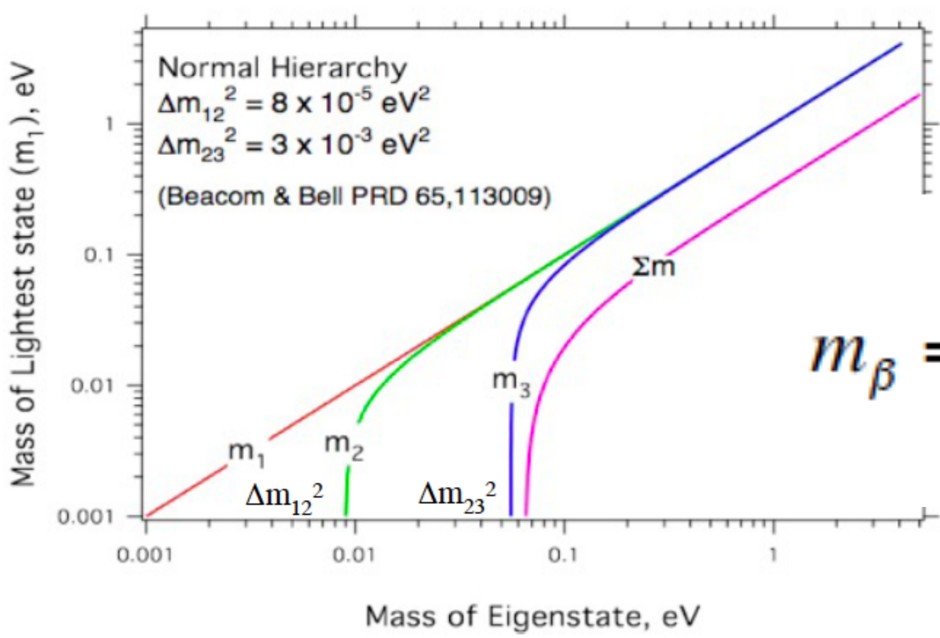

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Limited by energy resolution.

Beta-decay Experiments

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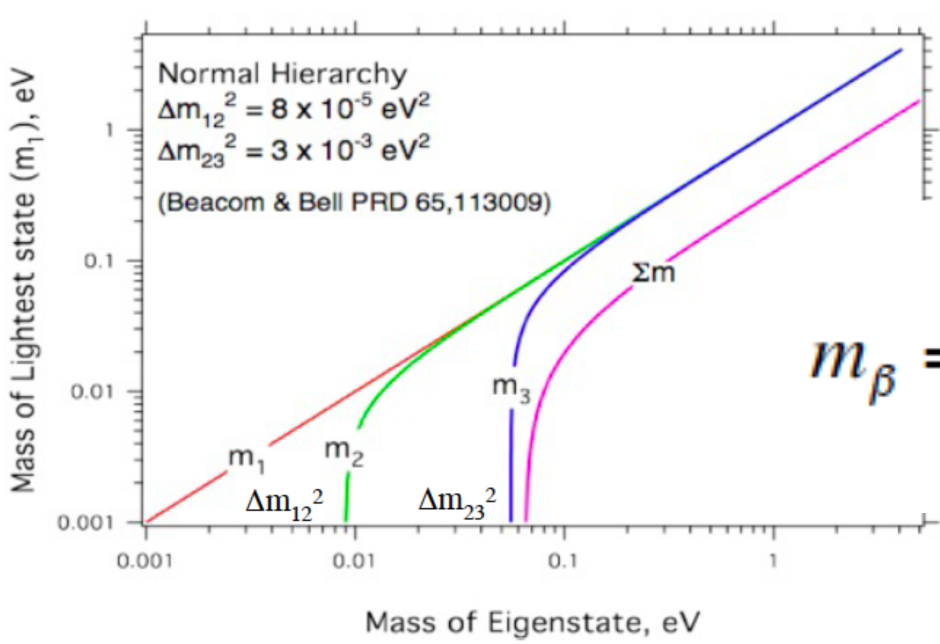

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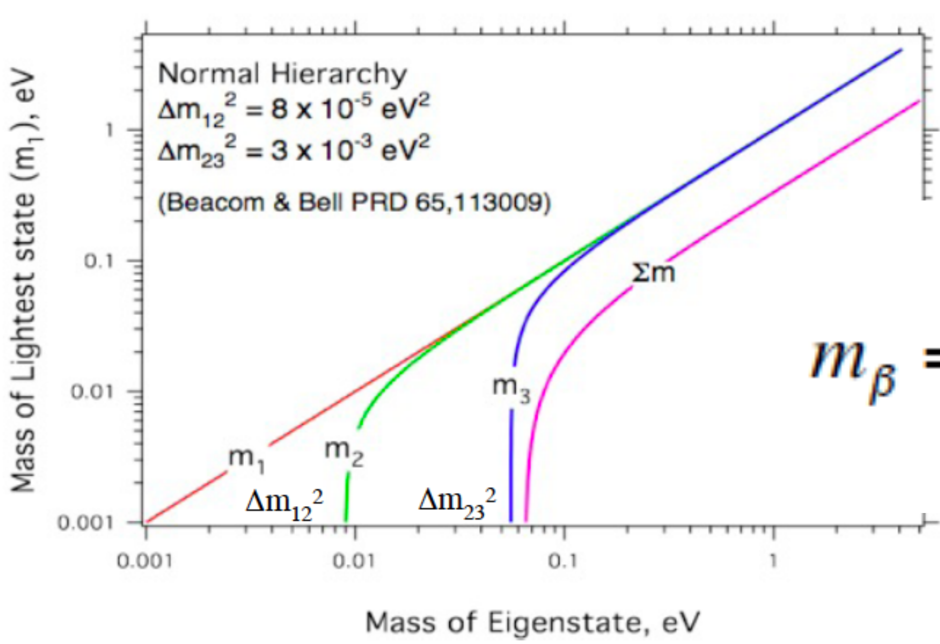

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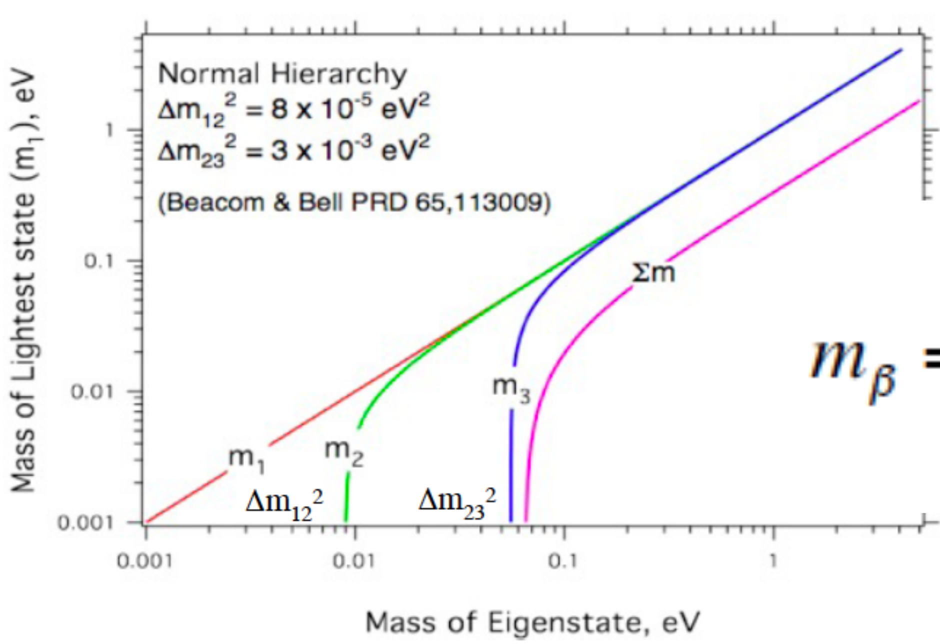

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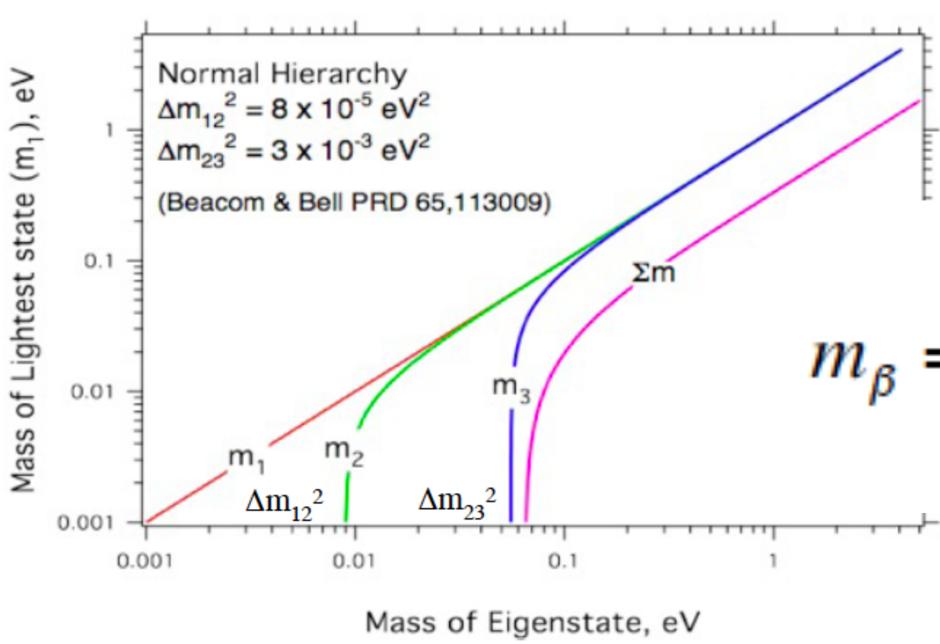

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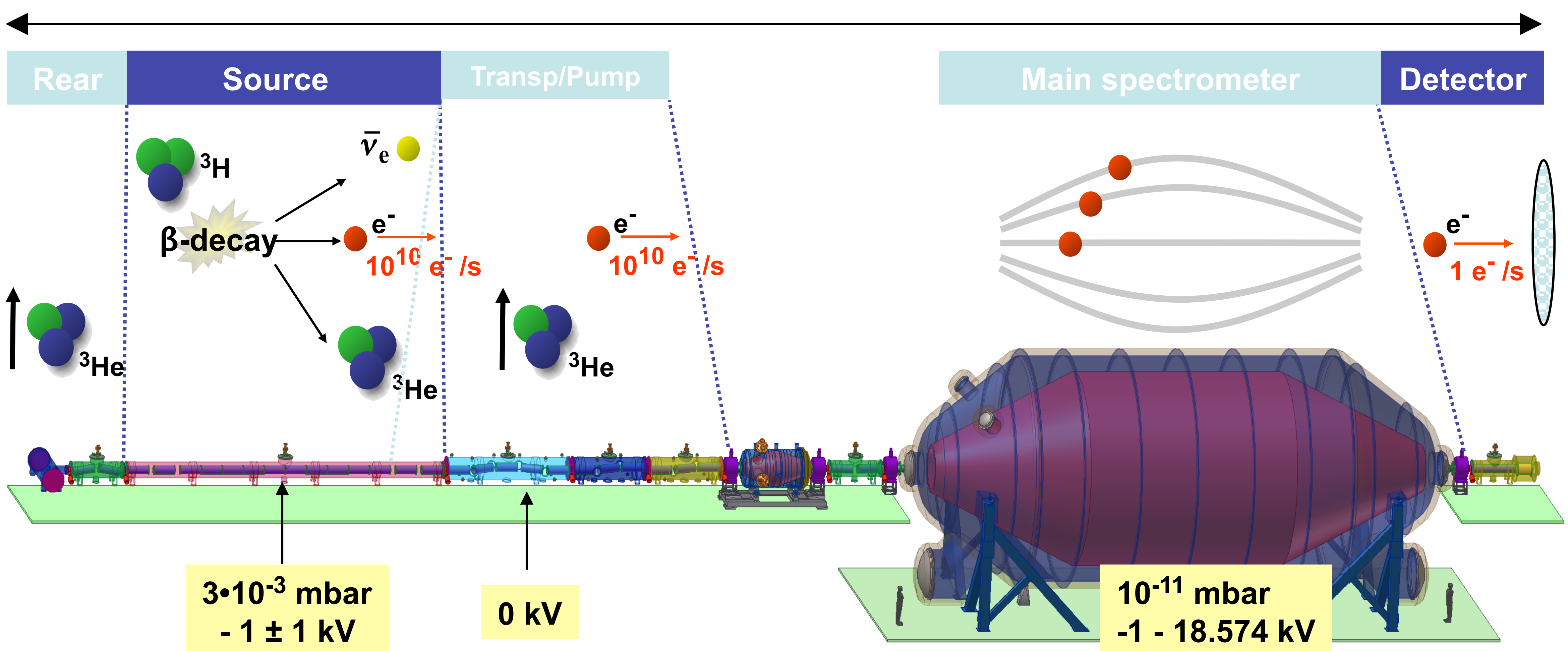
The KArlsruhe TRItium Neutrino (KATRIN) Experiment



Rear System:
Monitor source parameters

Source:
Provide the required tritium column density

Transp. & Pump system:
Transport the electrons, adiabatically and reduce the tritium density significantly

Main-spectrometer:
Rejection of electrons below endpoint and adiabatic guiding of electrons

Detector:
Count electrons and measure their energy

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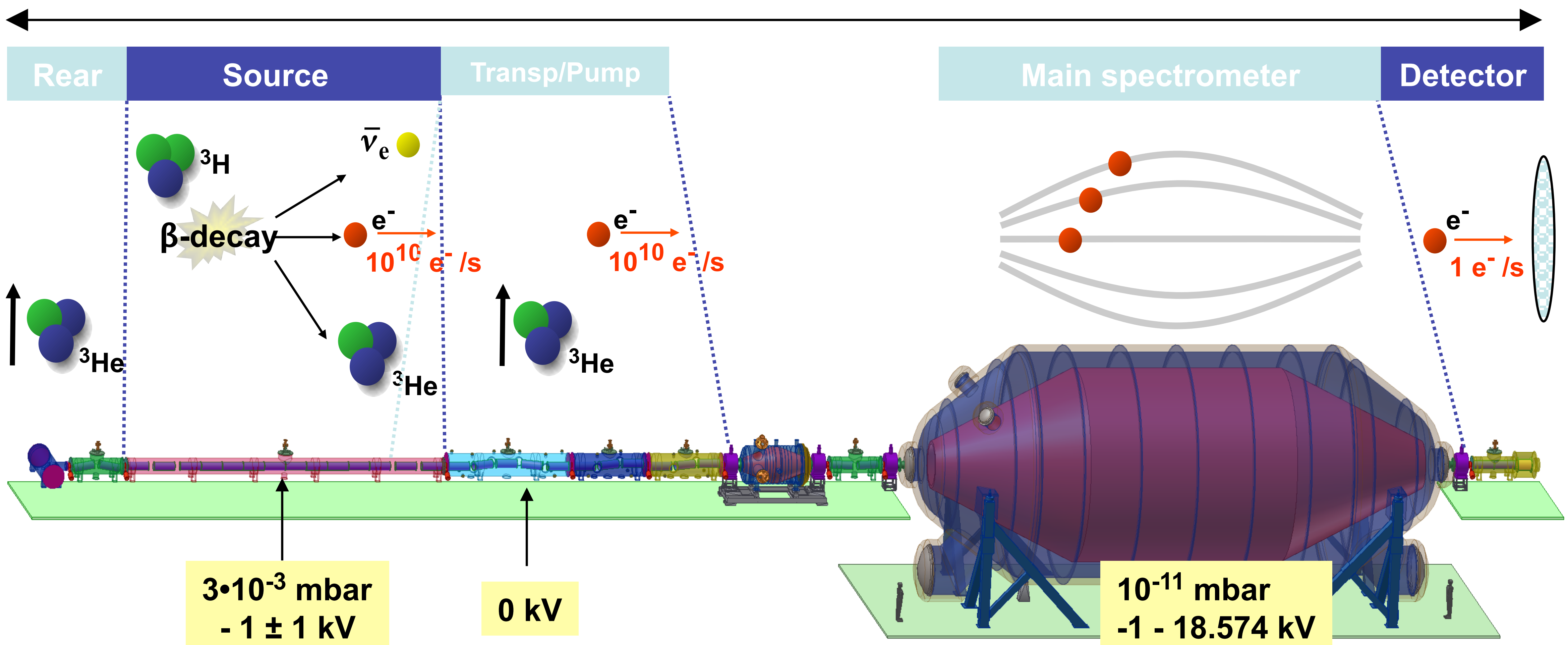
Next generation experiment, with goal of measurement down to 0.2 eV (100x improvement in energy resolution!)



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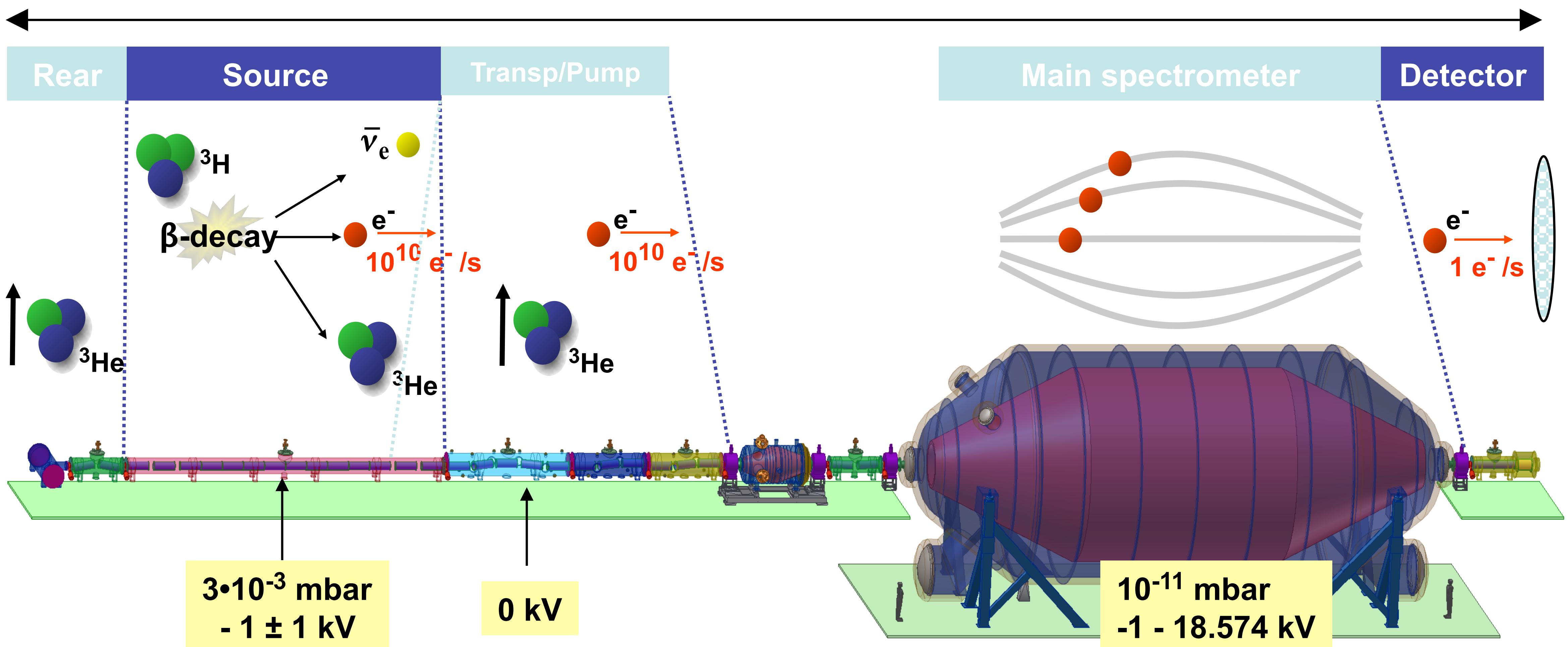

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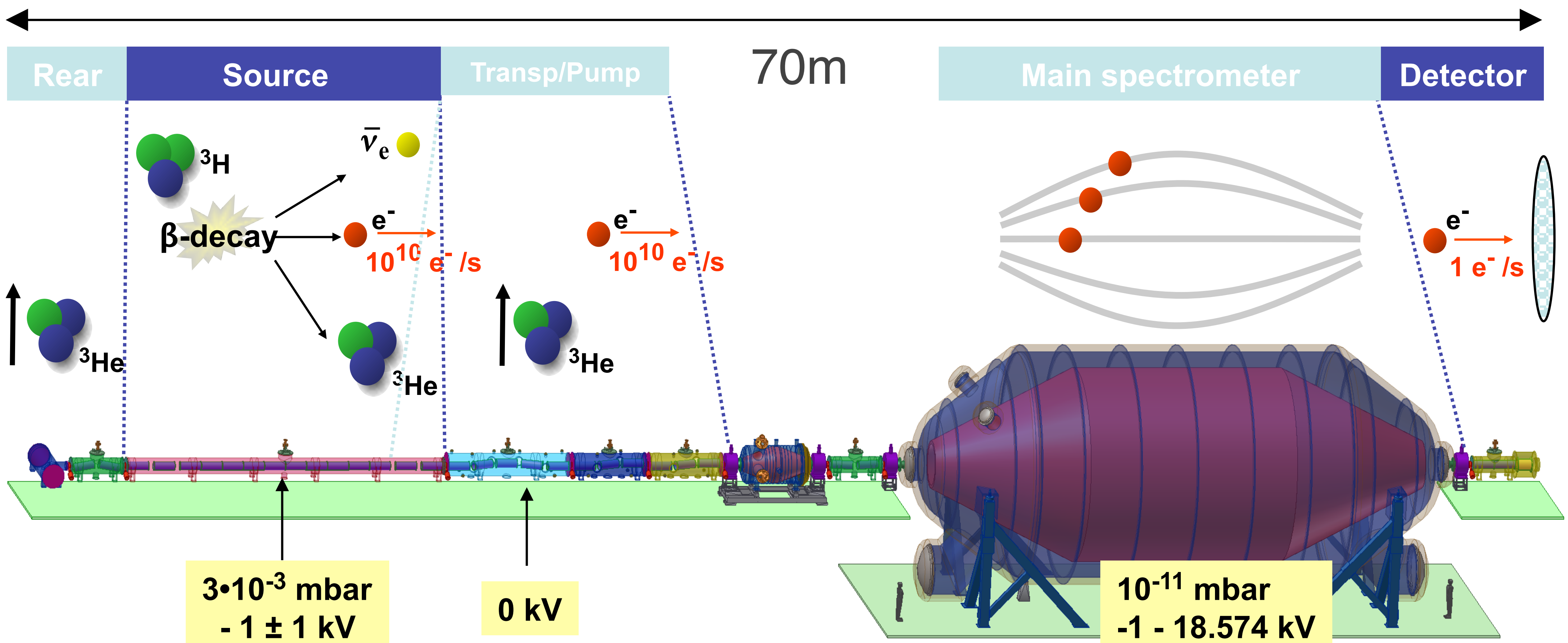

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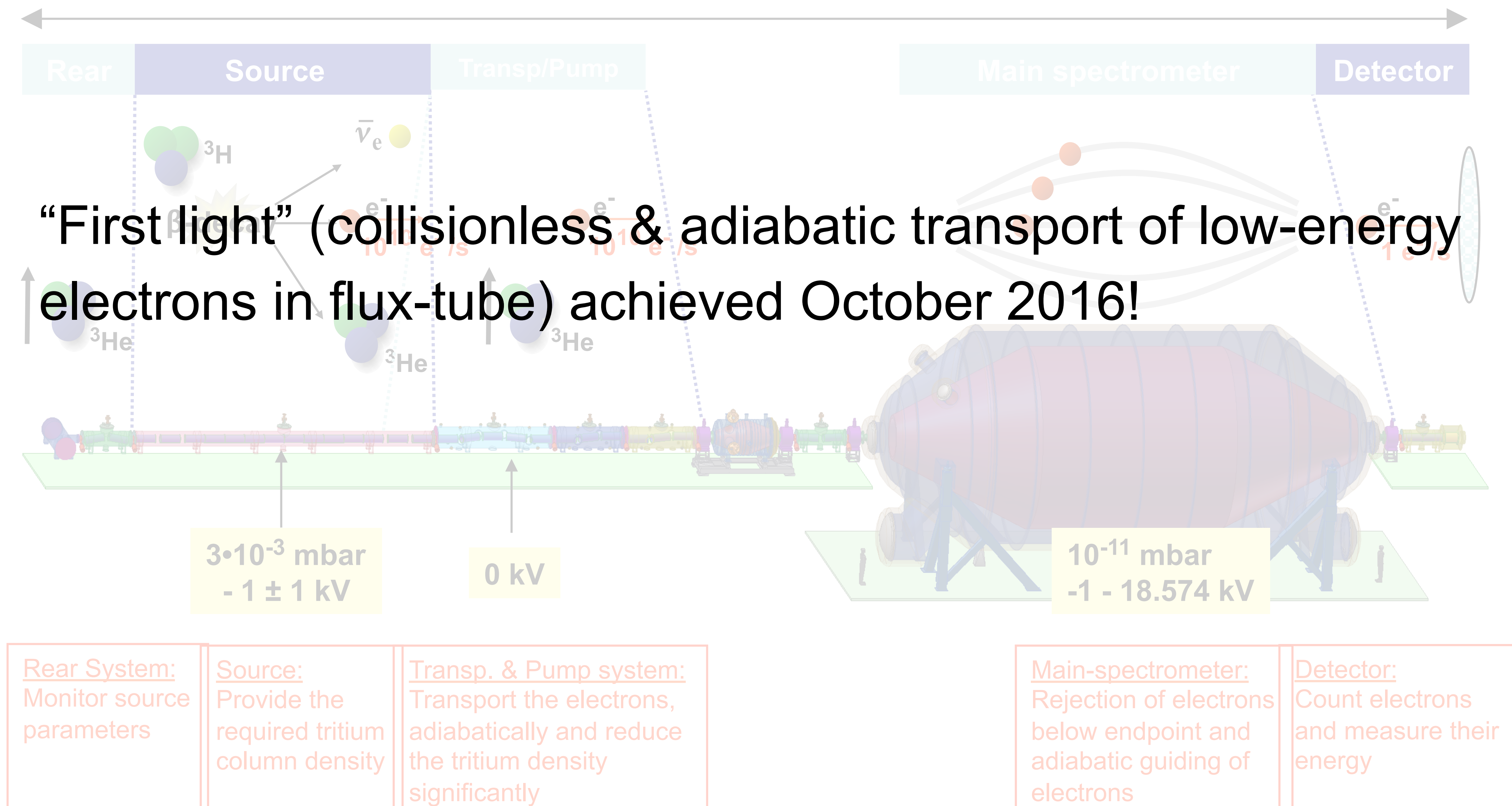

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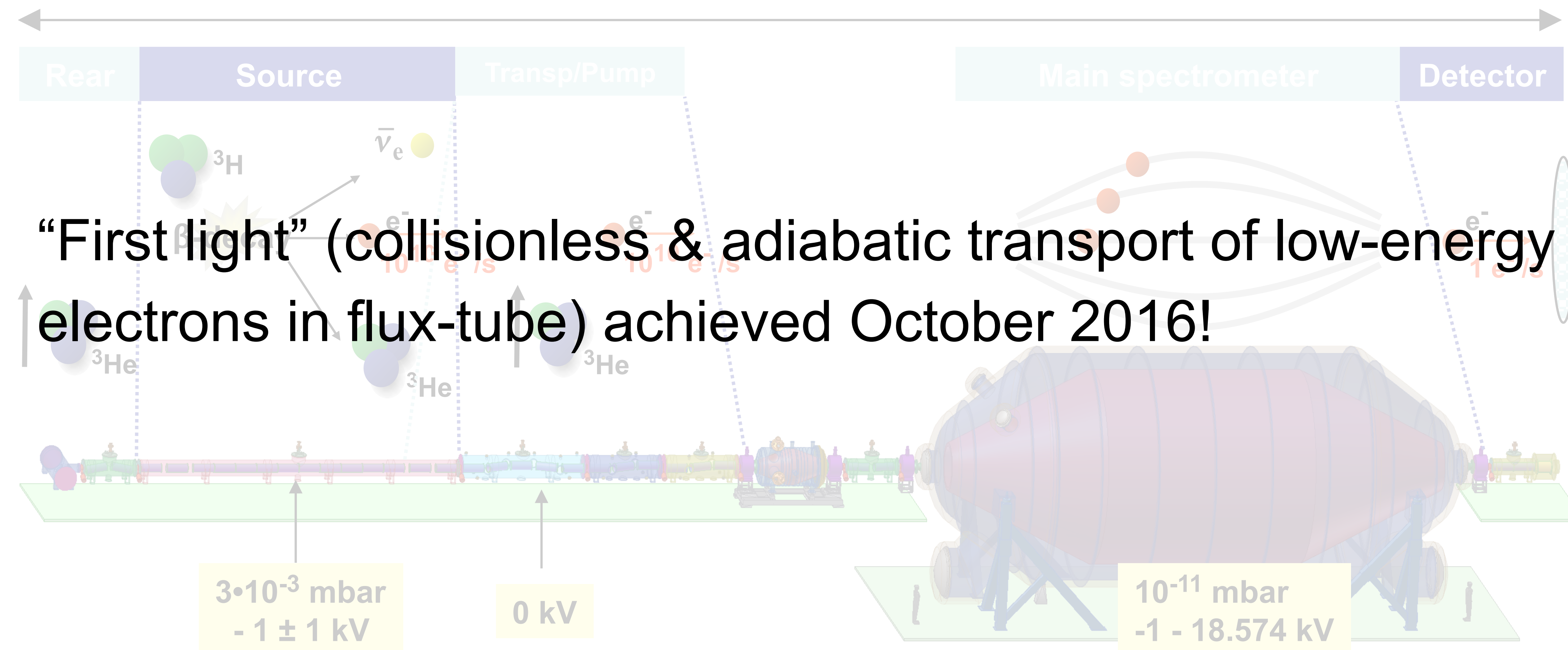

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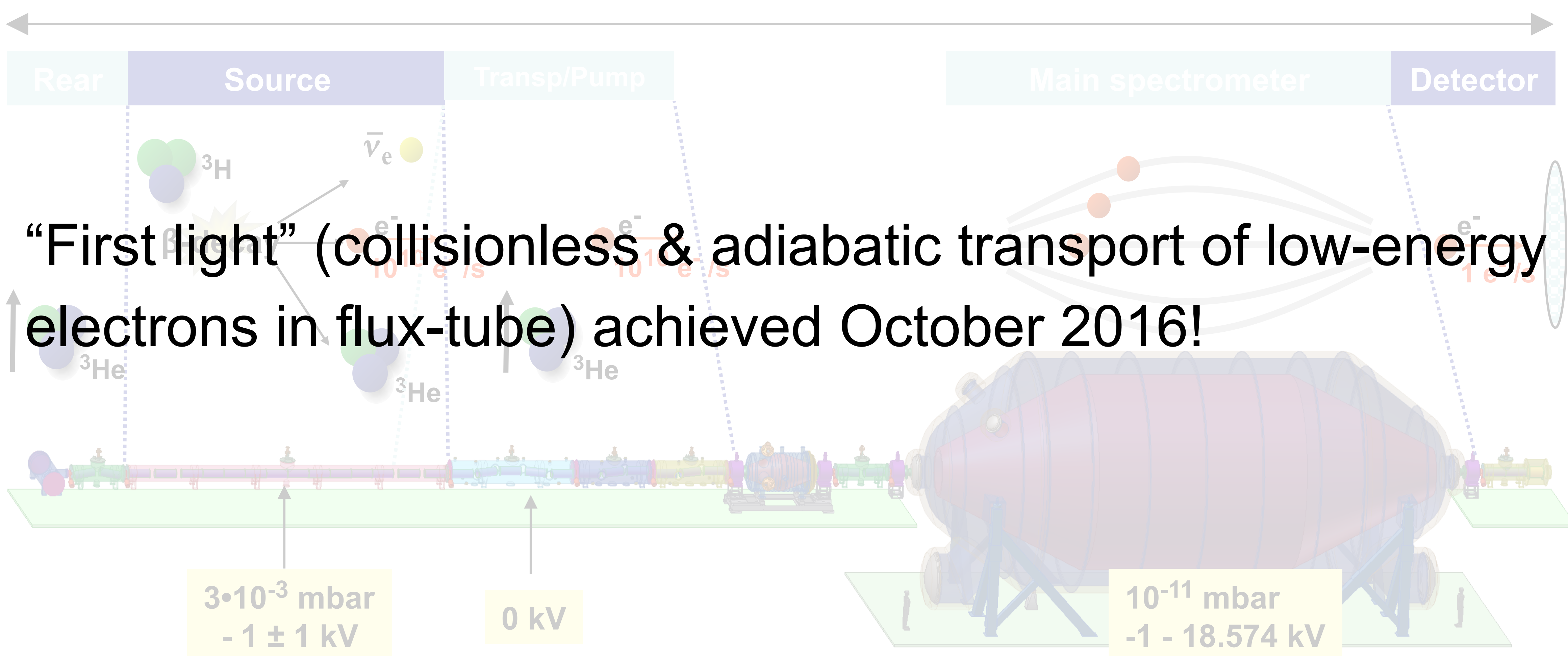

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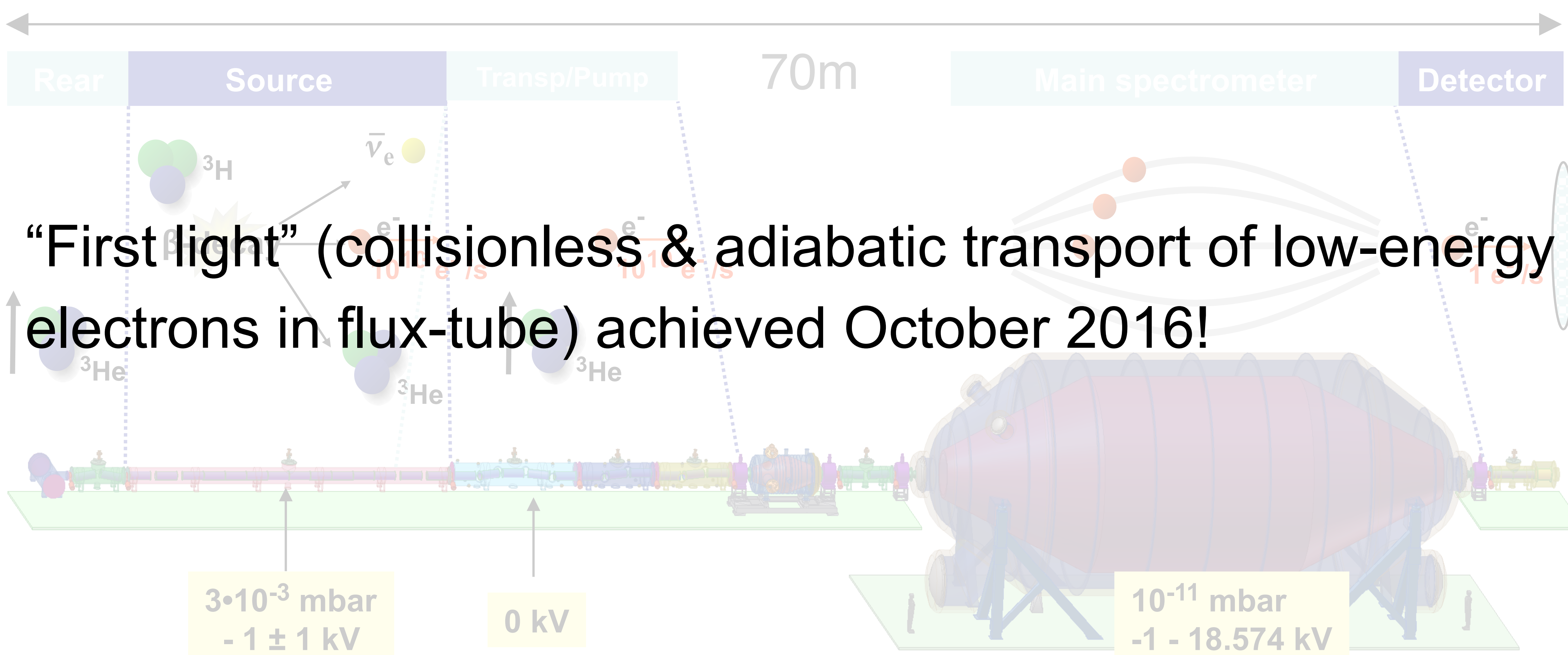

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Neutrino Oscillations

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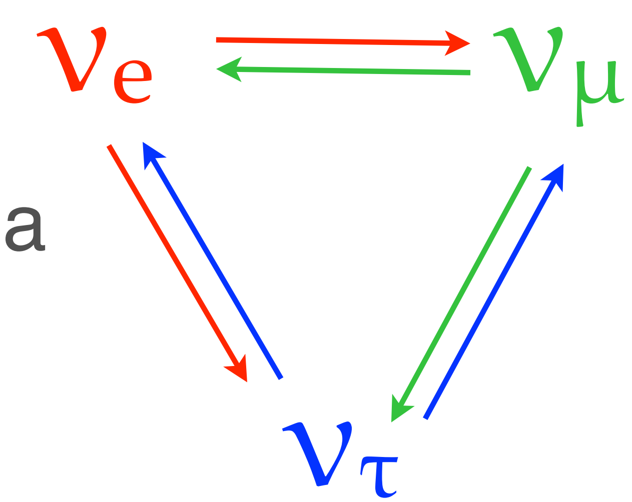


- Neutrino oscillations occur because ν flavor states are a quantum superposition of mass eigen states.

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

$$P(\nu_\alpha \to \nu_\alpha) = \left|\sum_j U^*_{\alpha j} e^{-i\frac{m_j^2 L}{2E}} U_{\alpha j}\right|^2 \qquad U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

In vacuum:

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

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

Neutrino Oscillations

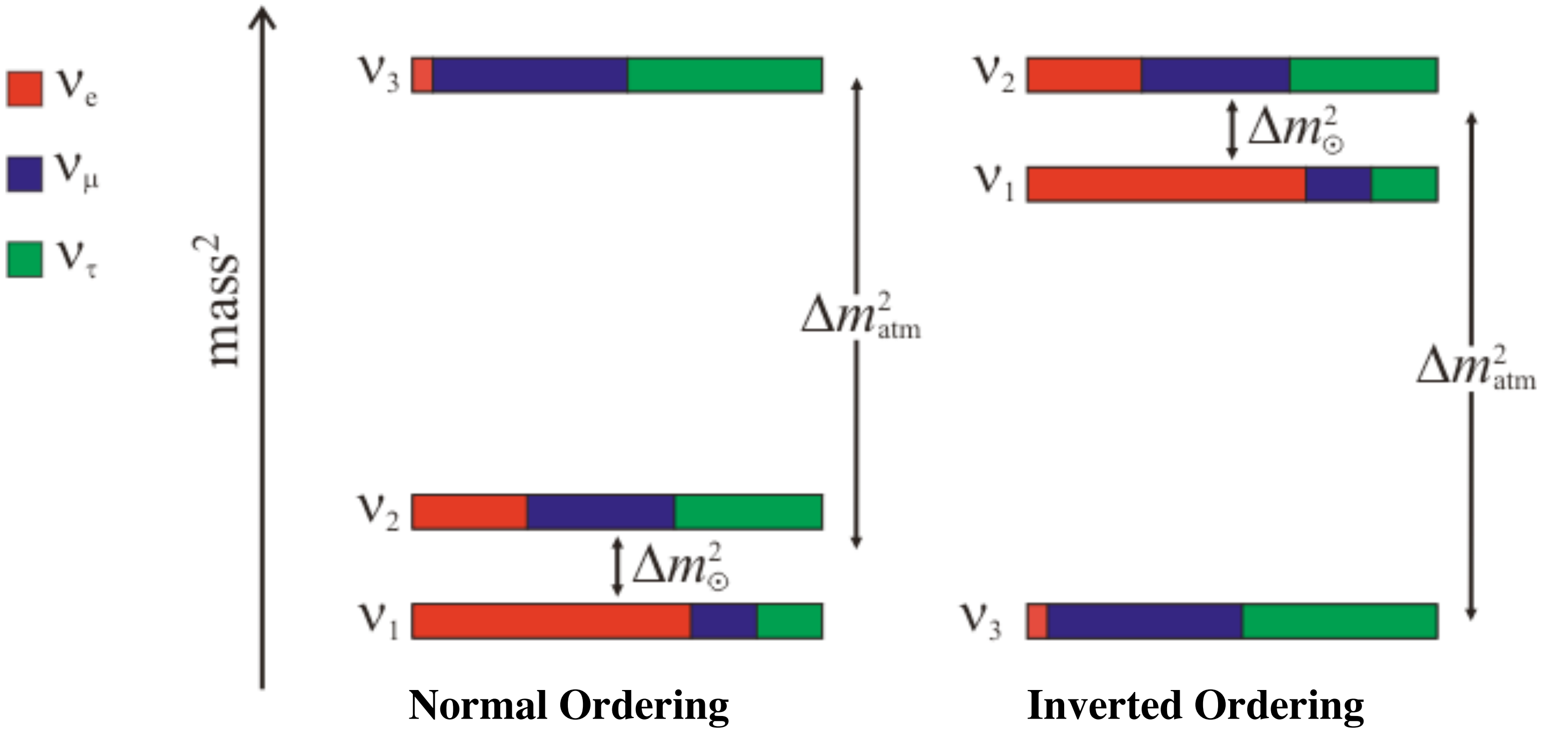
- Oscillation probabilities depend on terms like $\sin(1.27\Delta m^2_{ij} L/E)$
- With 3 flavors of neutrinos, there are two independent mass-squared differences:
  - $\Delta m^2_{21} \equiv \Delta m^2_{sol} \sim 7.6 \times 10^{-5}\ eV^2$
  - $\Delta m^2_{32} \approx \Delta m^2_{31} \equiv \Delta m^2_{atm} \sim 2.5 \times 10^{-3}\ eV^2$
- Δm^2_{sol} terms have characteristic L/E ~ 15000 km/GeV
- Δm^2_{atm} terms have characteristic L/E ~ 500 km/GeV.
- The mixing matrix may be factorized into components that are convenient for experimentalists:

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

- δ is a CP violating phase.

Neutrino Oscillations - The Current State

Parameter	Value	Uncertainty
$\sin^2\theta_{12}$	0.31	5%
$\sin^2\theta_{13}$	2.2×10^{-2}	5%
$\sin^2\theta_{23}$	1	9%
δ_{CP}	?	?
Δm^2_{21}	7.6×10^{-5} eV^2	2%
$\lvert\Delta m^2_{32}\rvert$	2.5×10^{-3} eV^2	2%



- We've made great progress over the last 20 years!
- But we still don't know:
  - if θ_{23} is maximal
  - the sign of Δm^2_{32}; aka the mass hierarchy or mass ordering
  - is δ_{CP} non-zero?
  - is U unitary?

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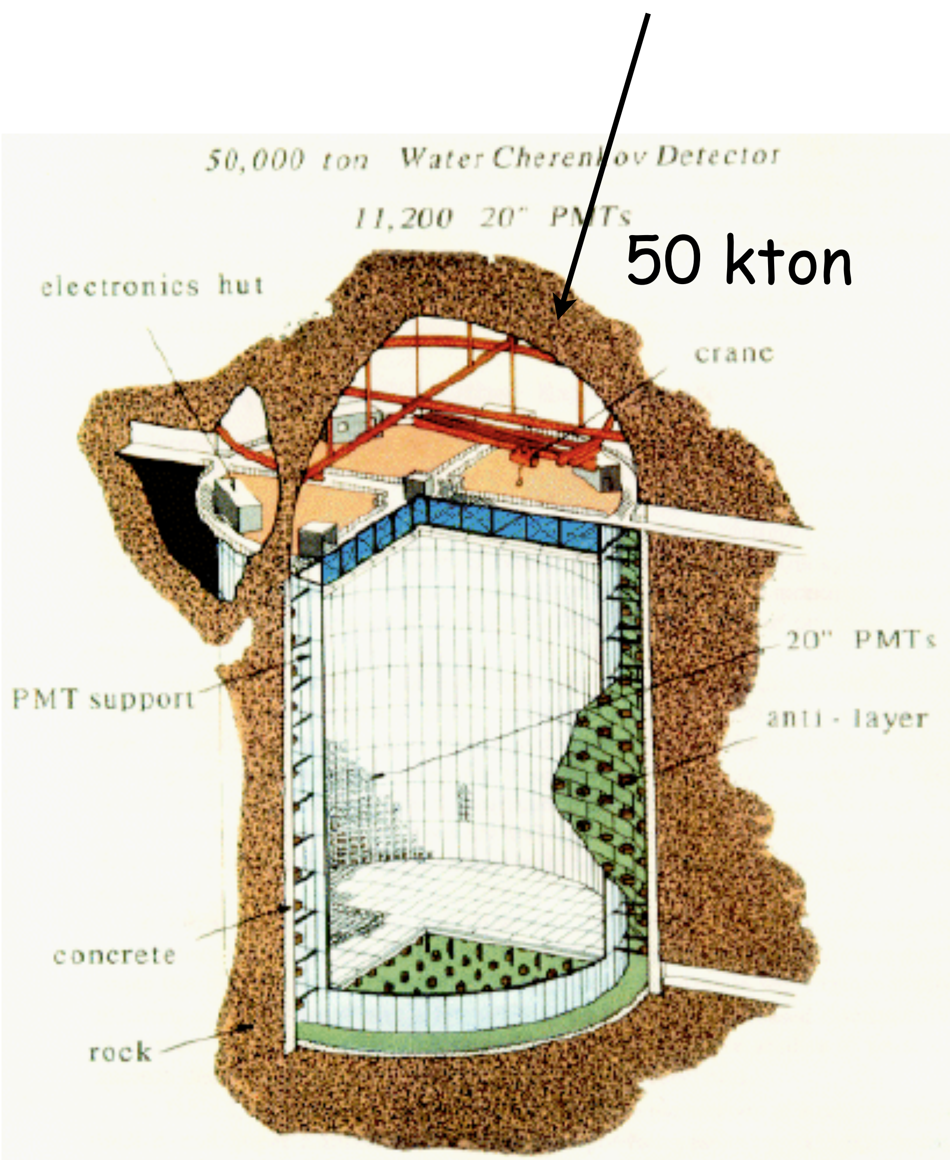

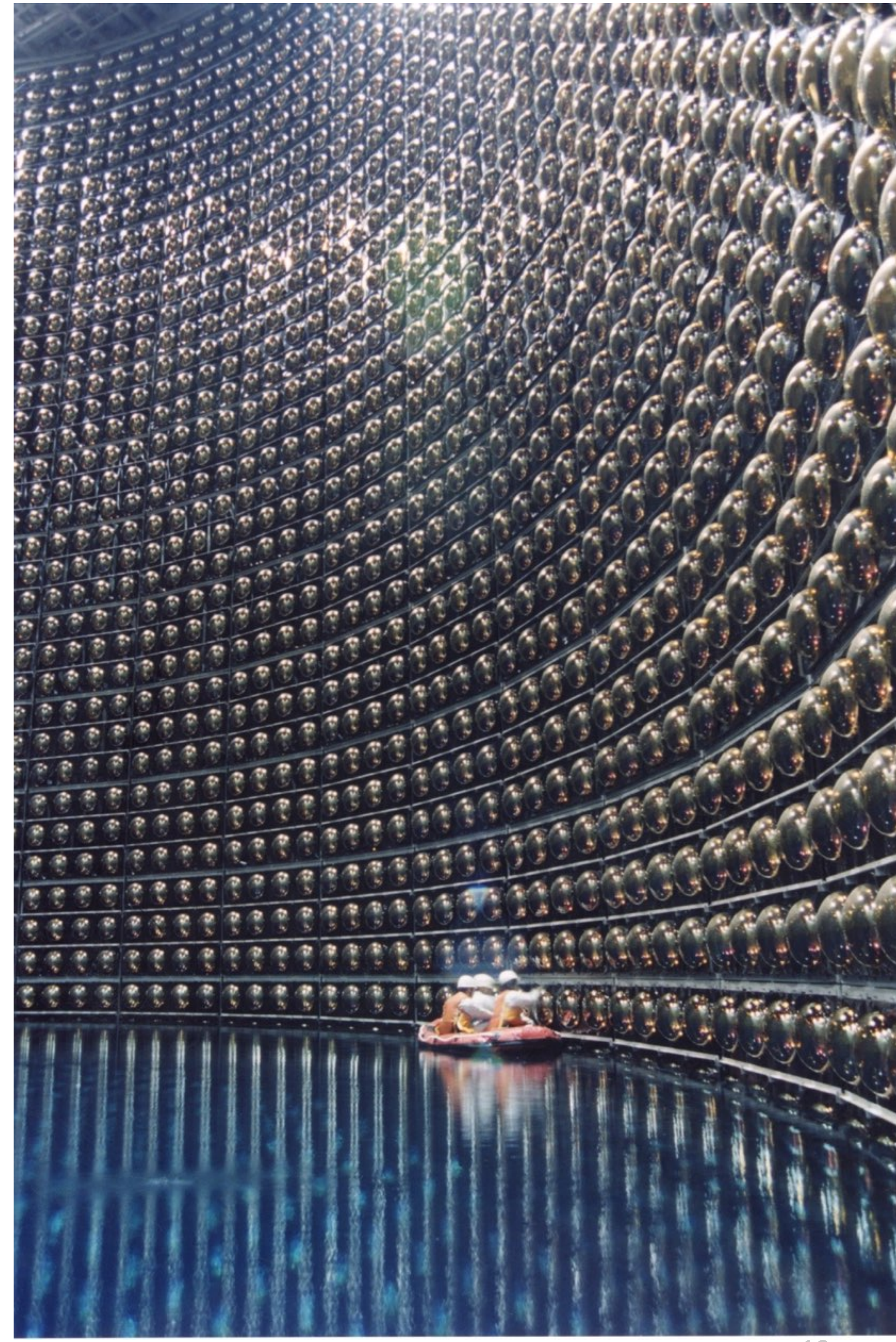

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- Two types of neutrino interactions:
  - **Charged-current** (CC, W-boson exchange). Final state includes a lepton (e, μ or τ) + hadron.
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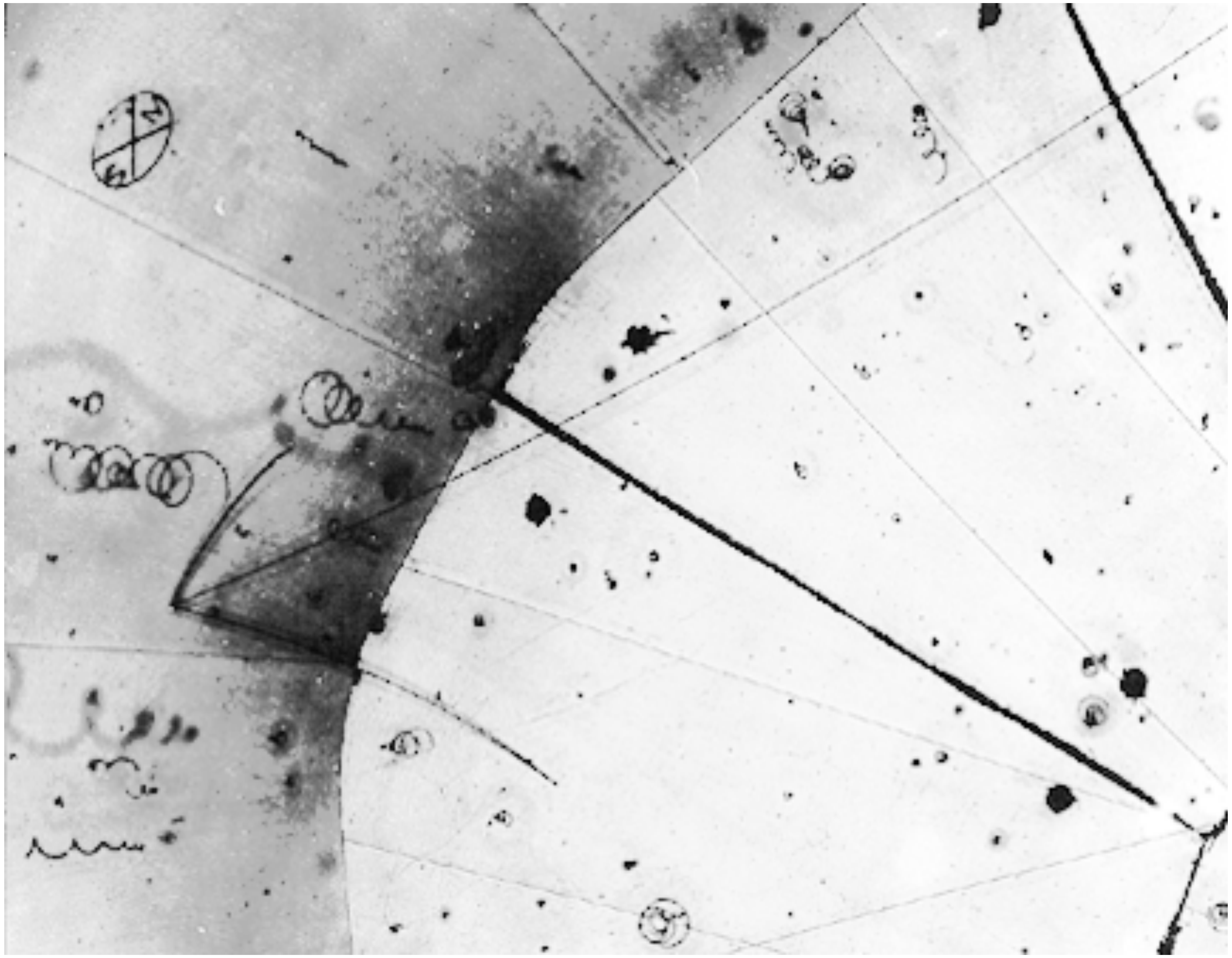

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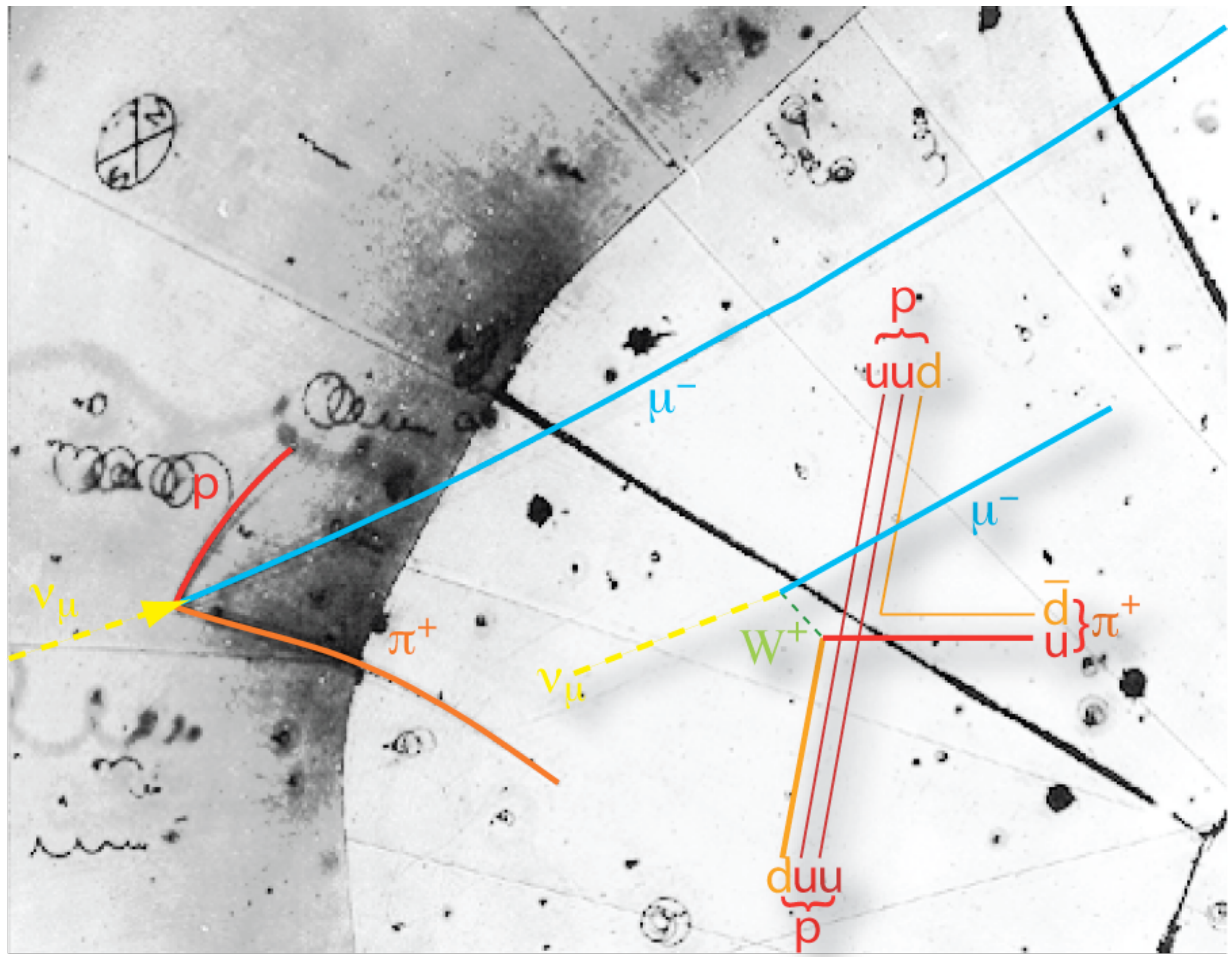

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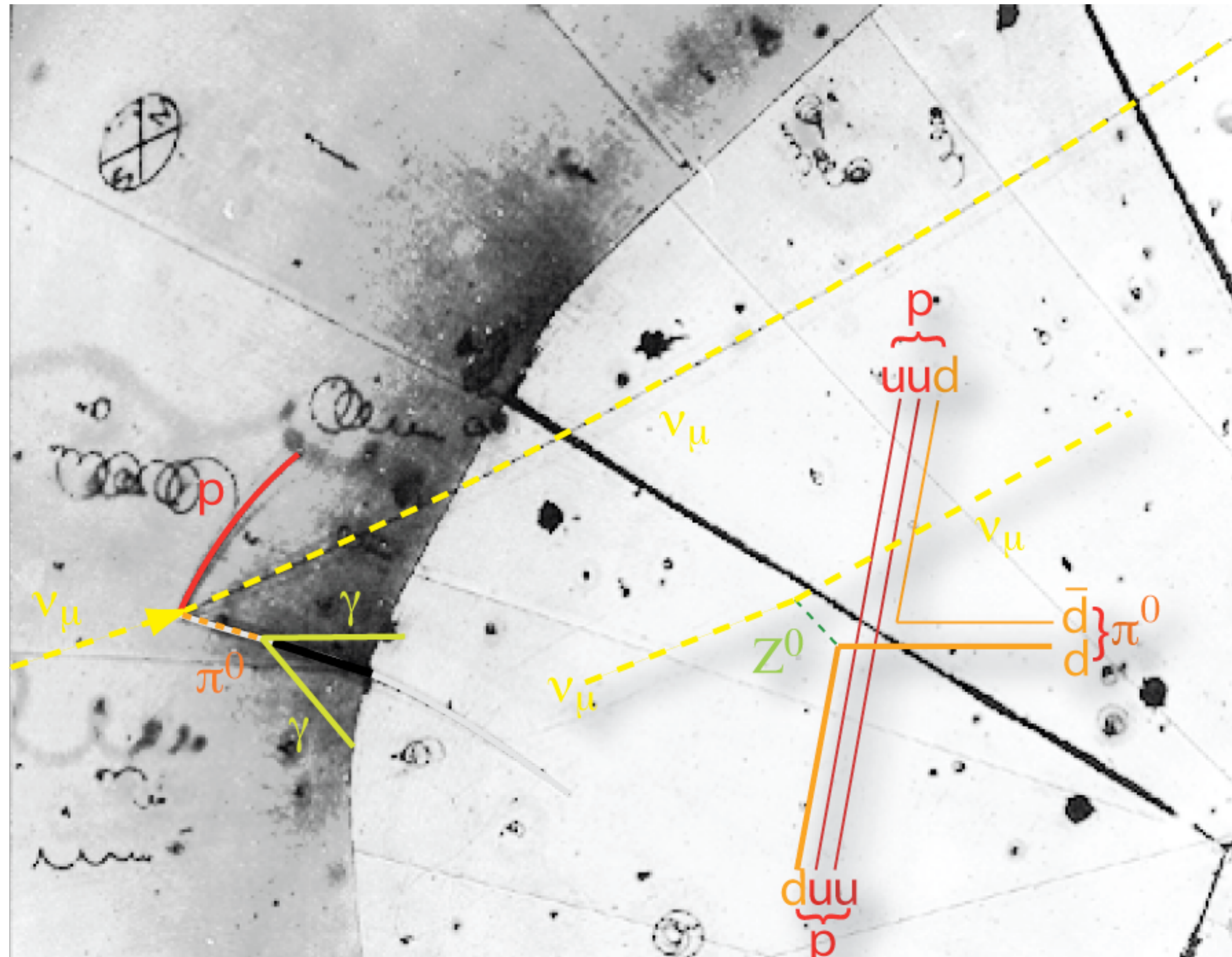

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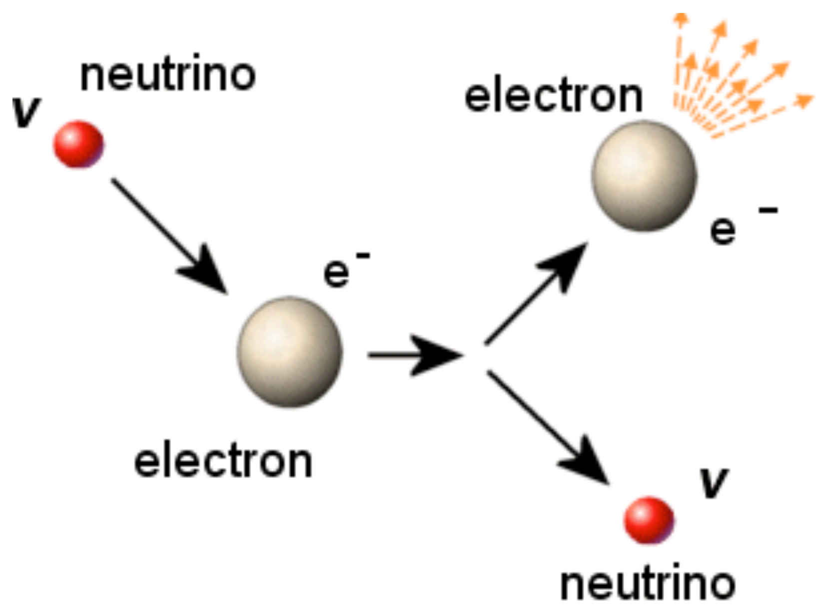
Neutrino Detection - Fundamentals



- 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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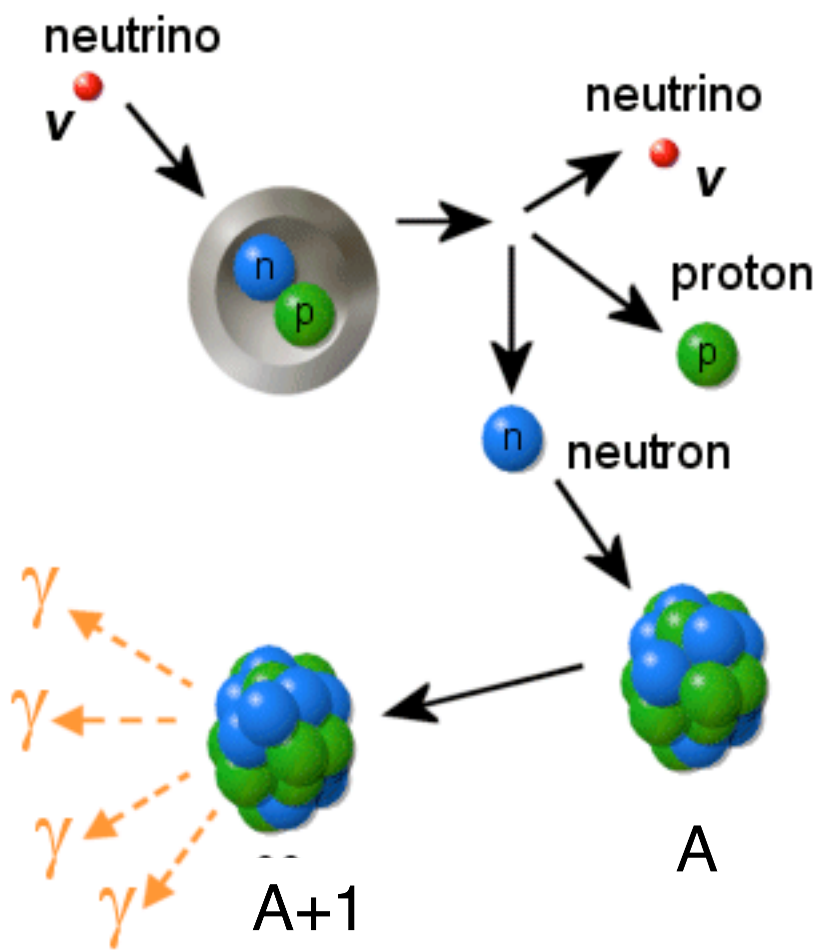

- ν_l NC off nucleus
- hadrons (only) in final state
- neutrinos carries off energy

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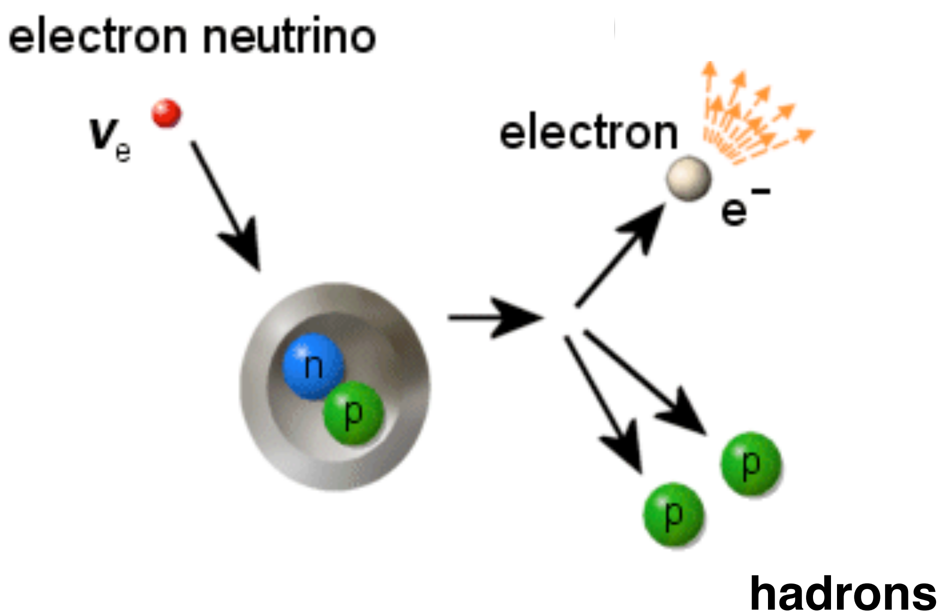
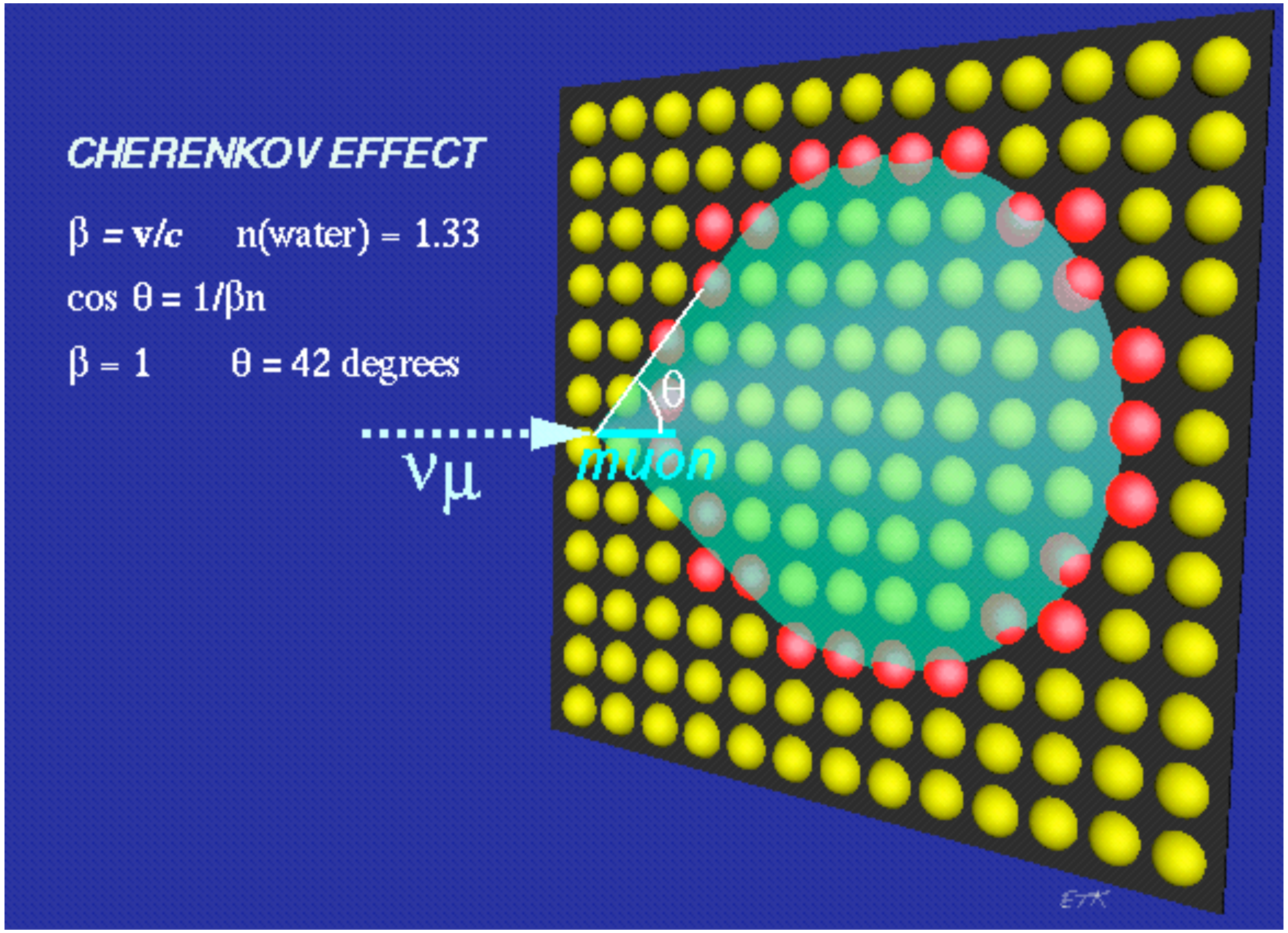


- ν_l CC off nucleus
- charged lepton (+ hadrons) in final state
- energy and flavor of neutrino are observable

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-few)/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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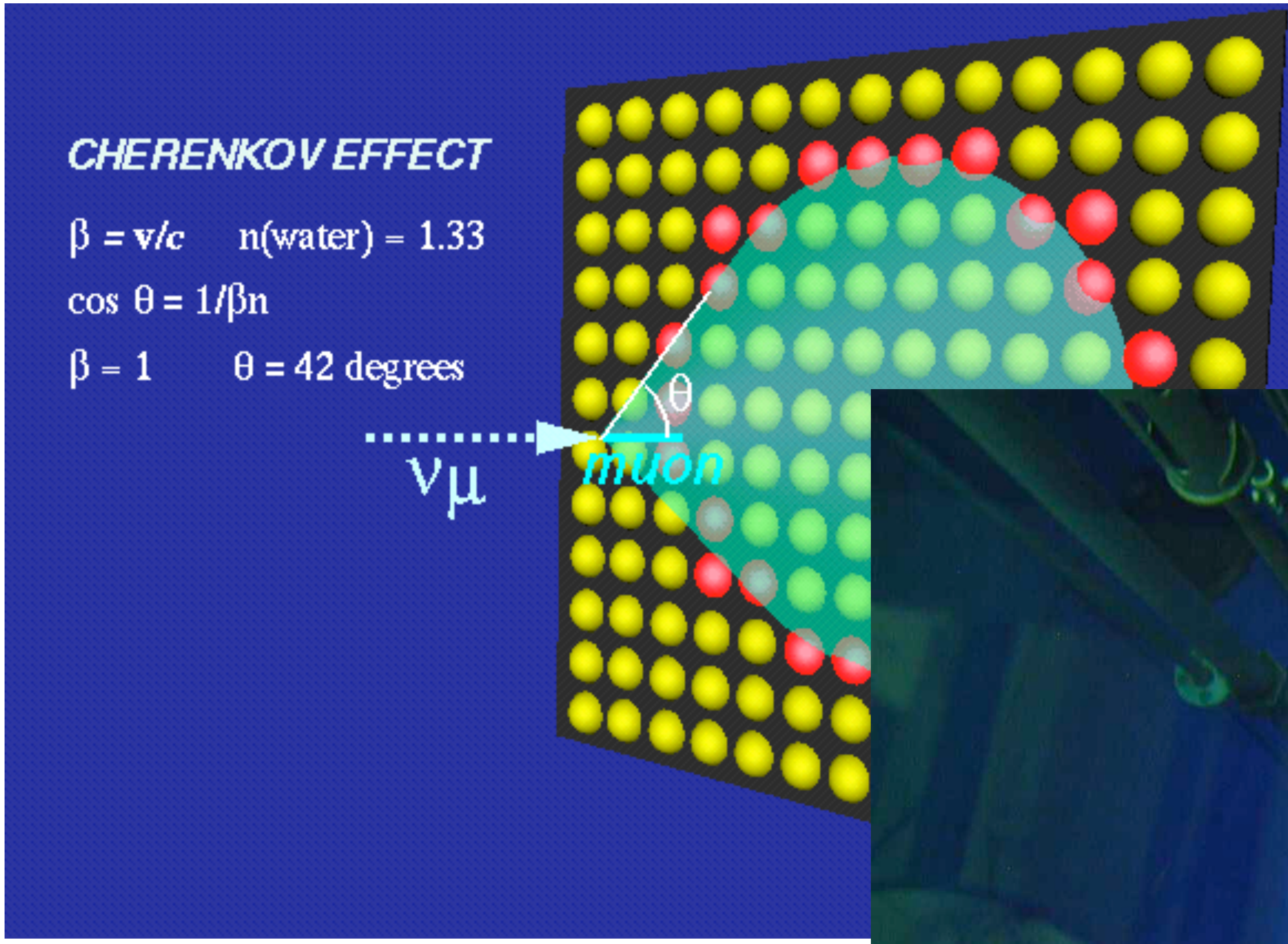

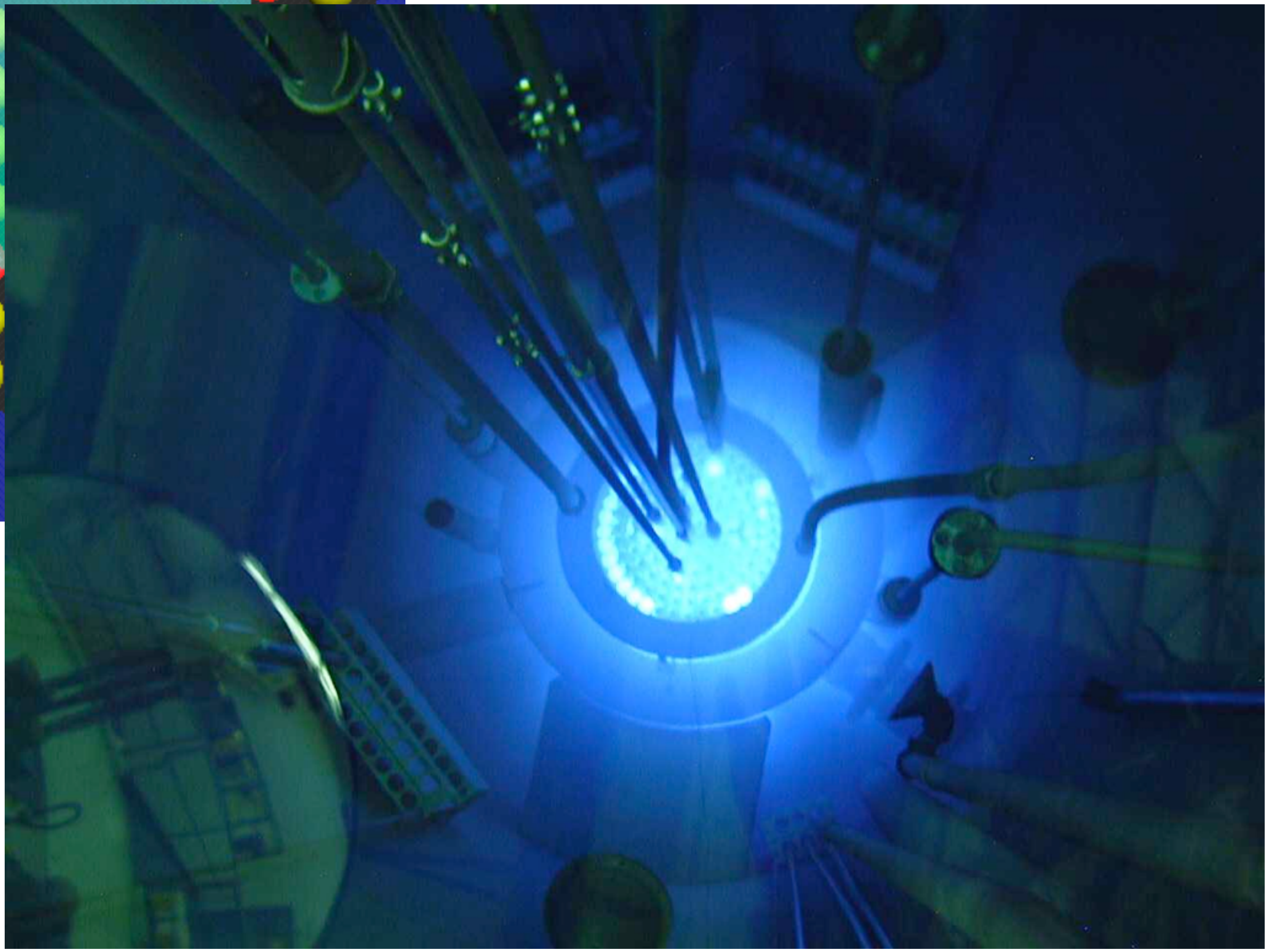

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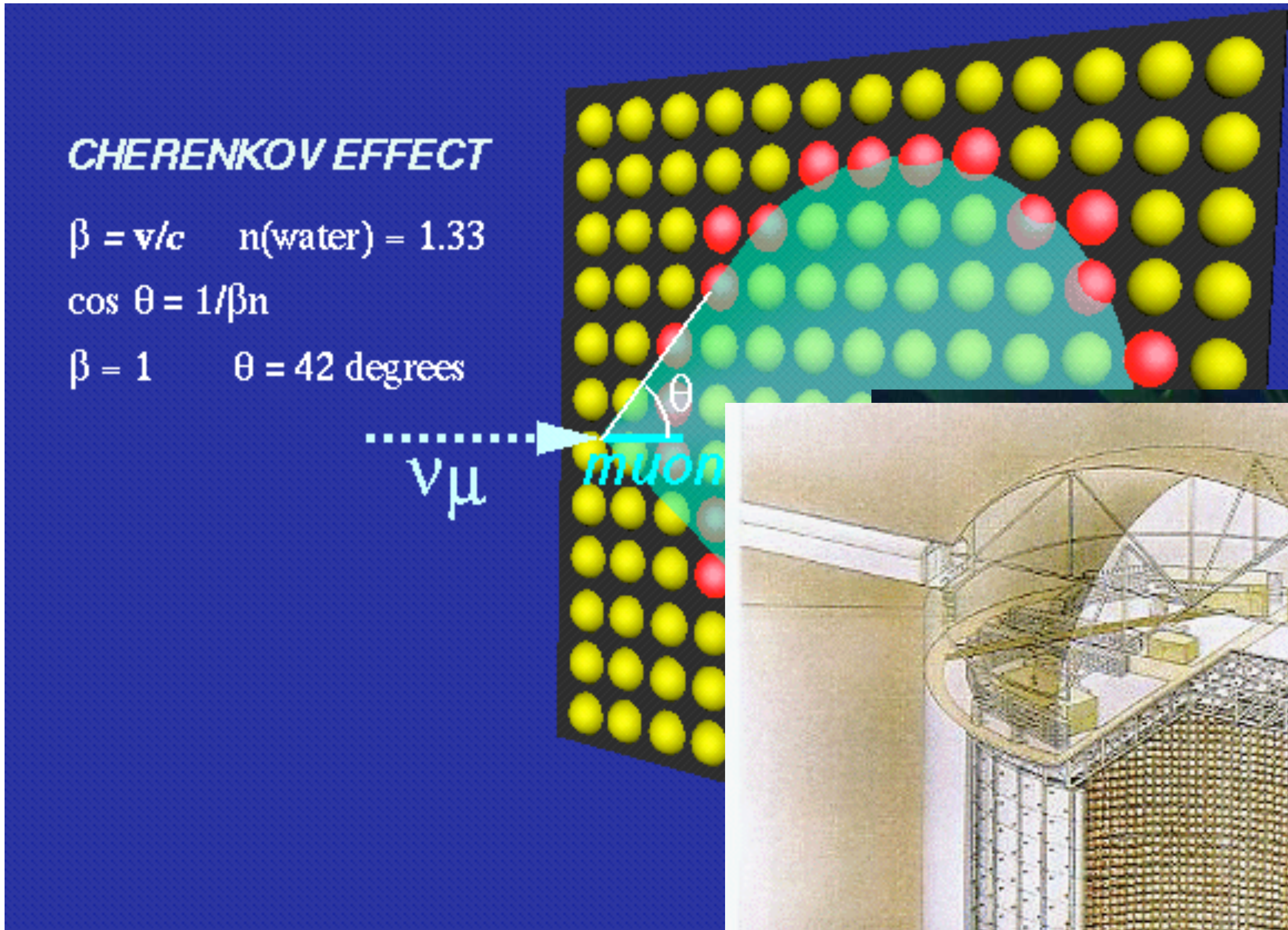

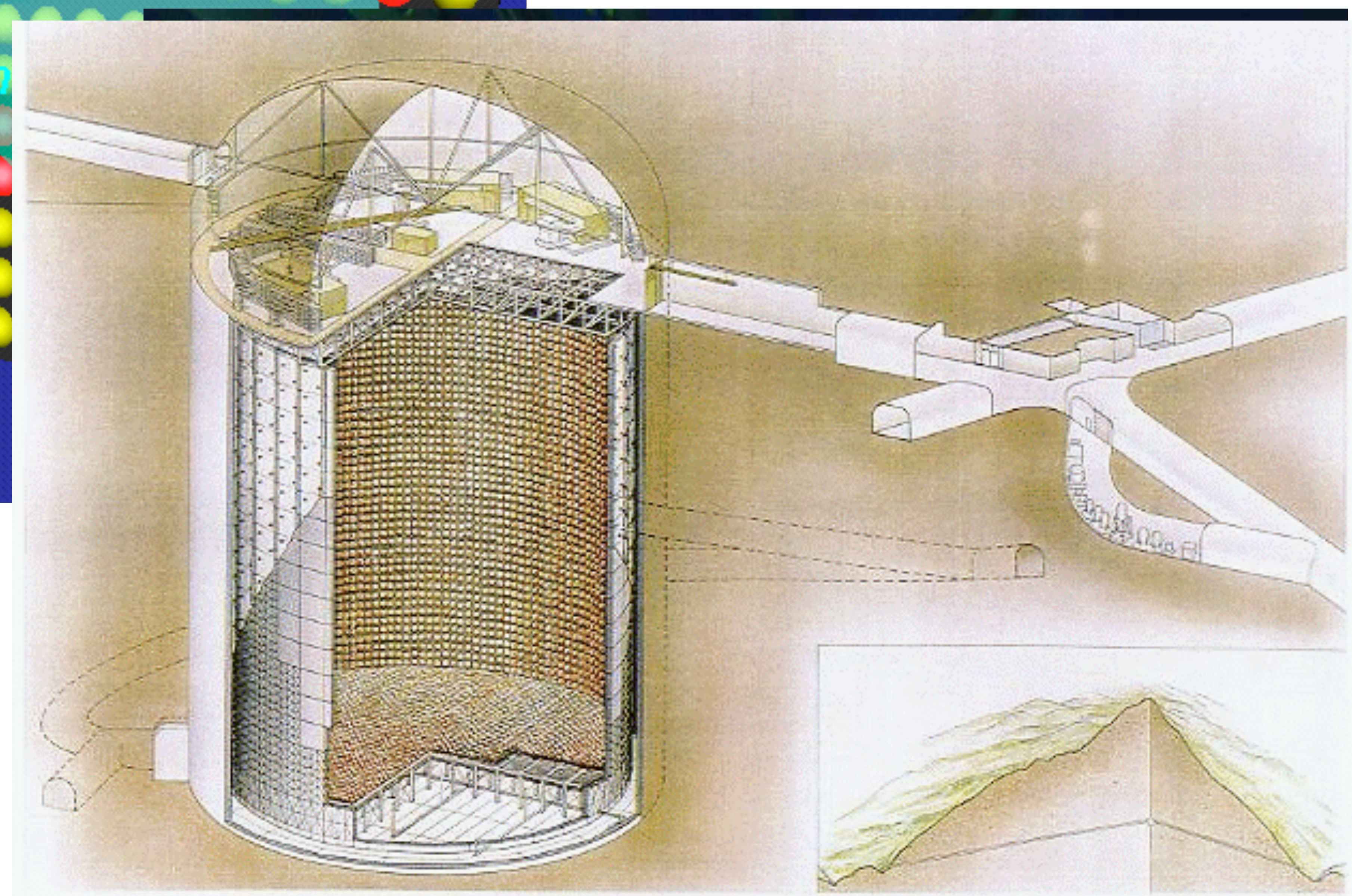

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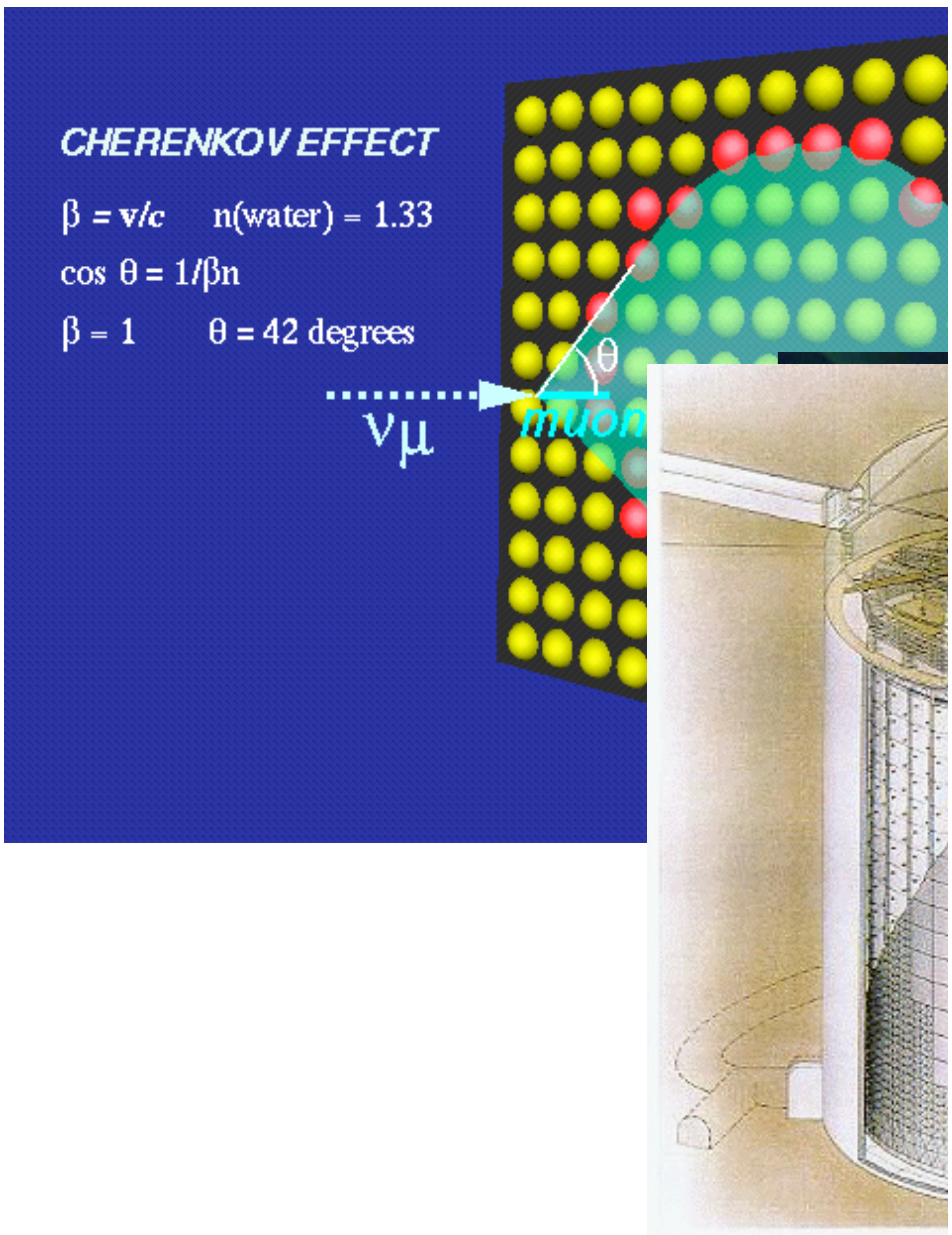

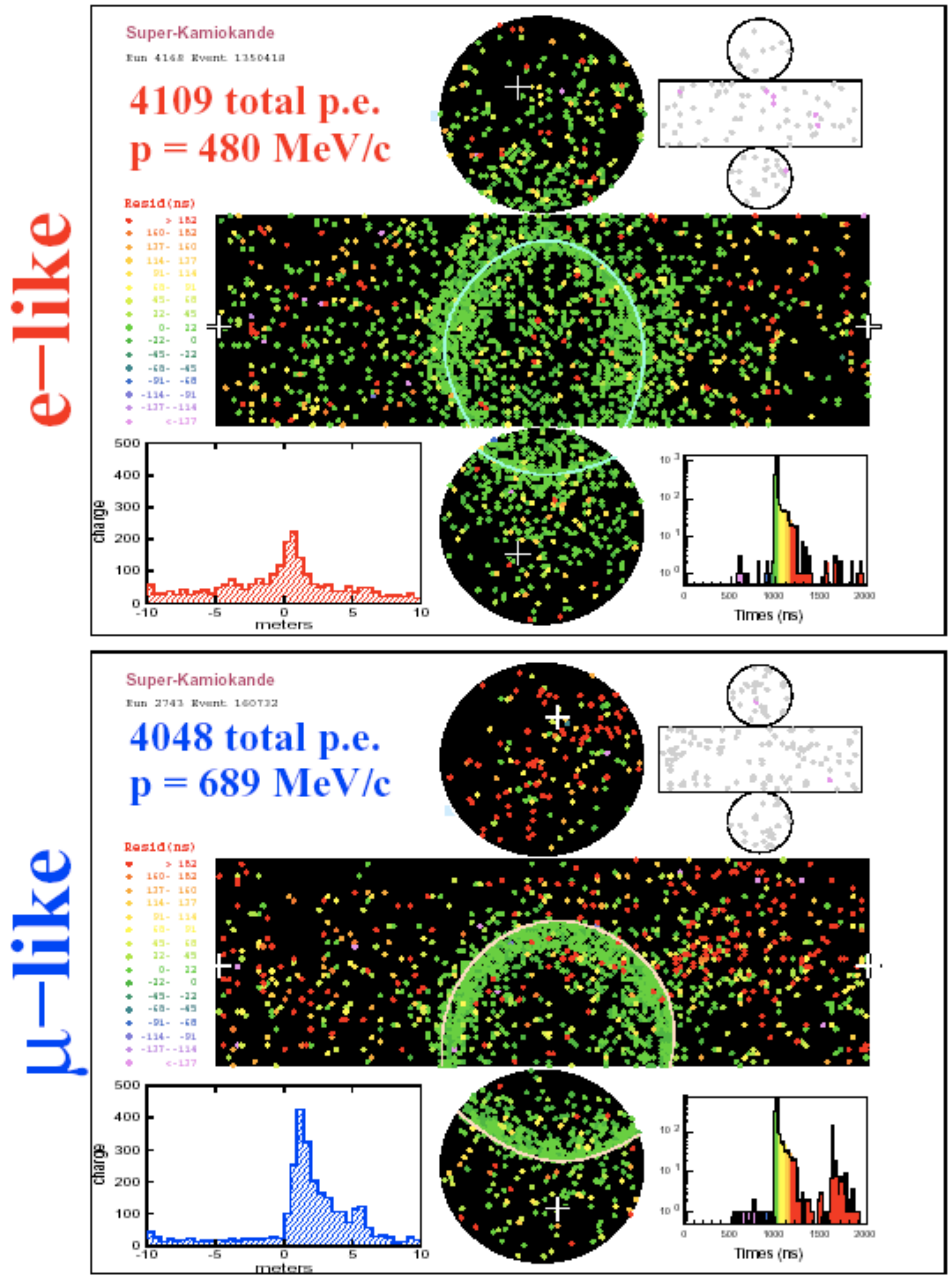

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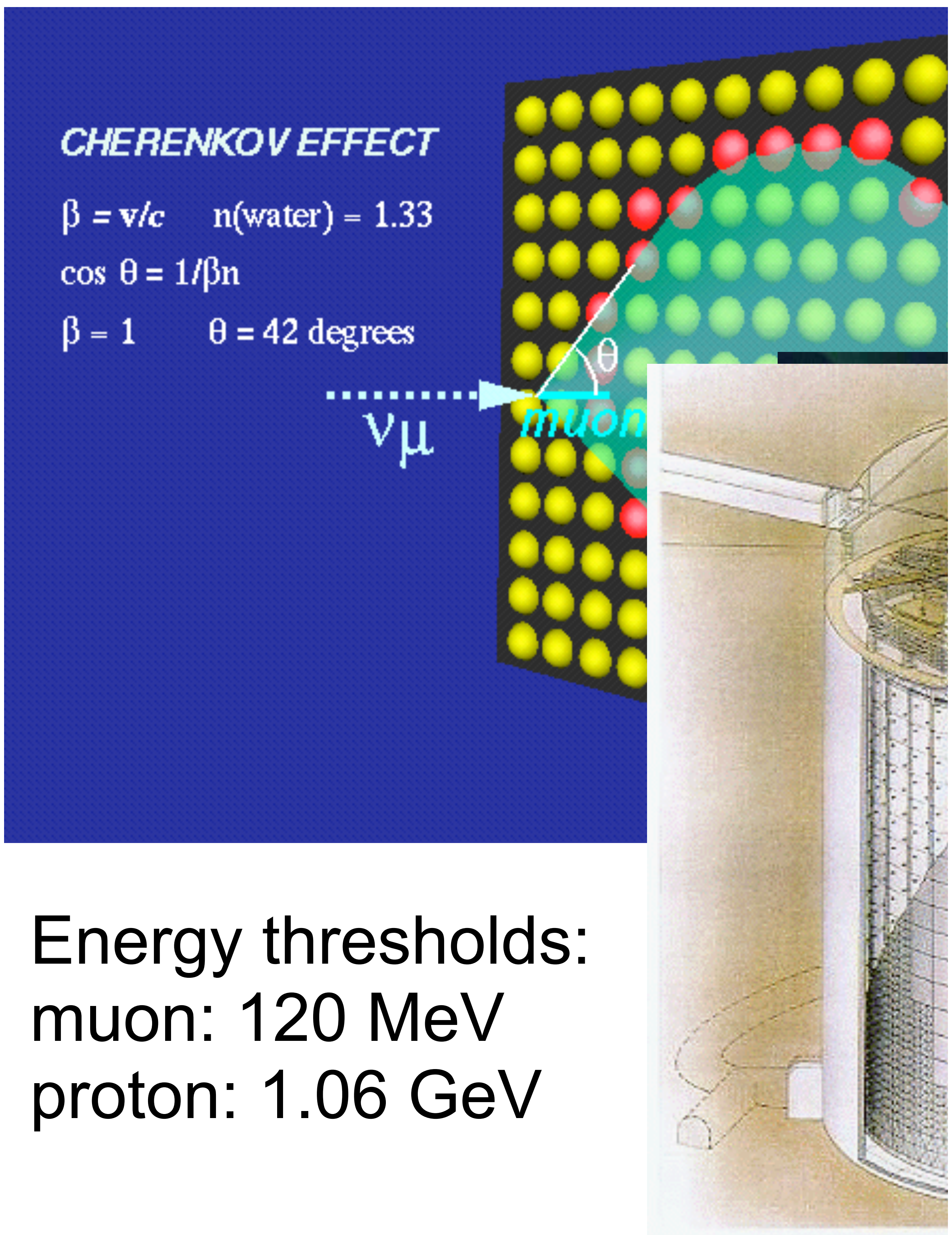

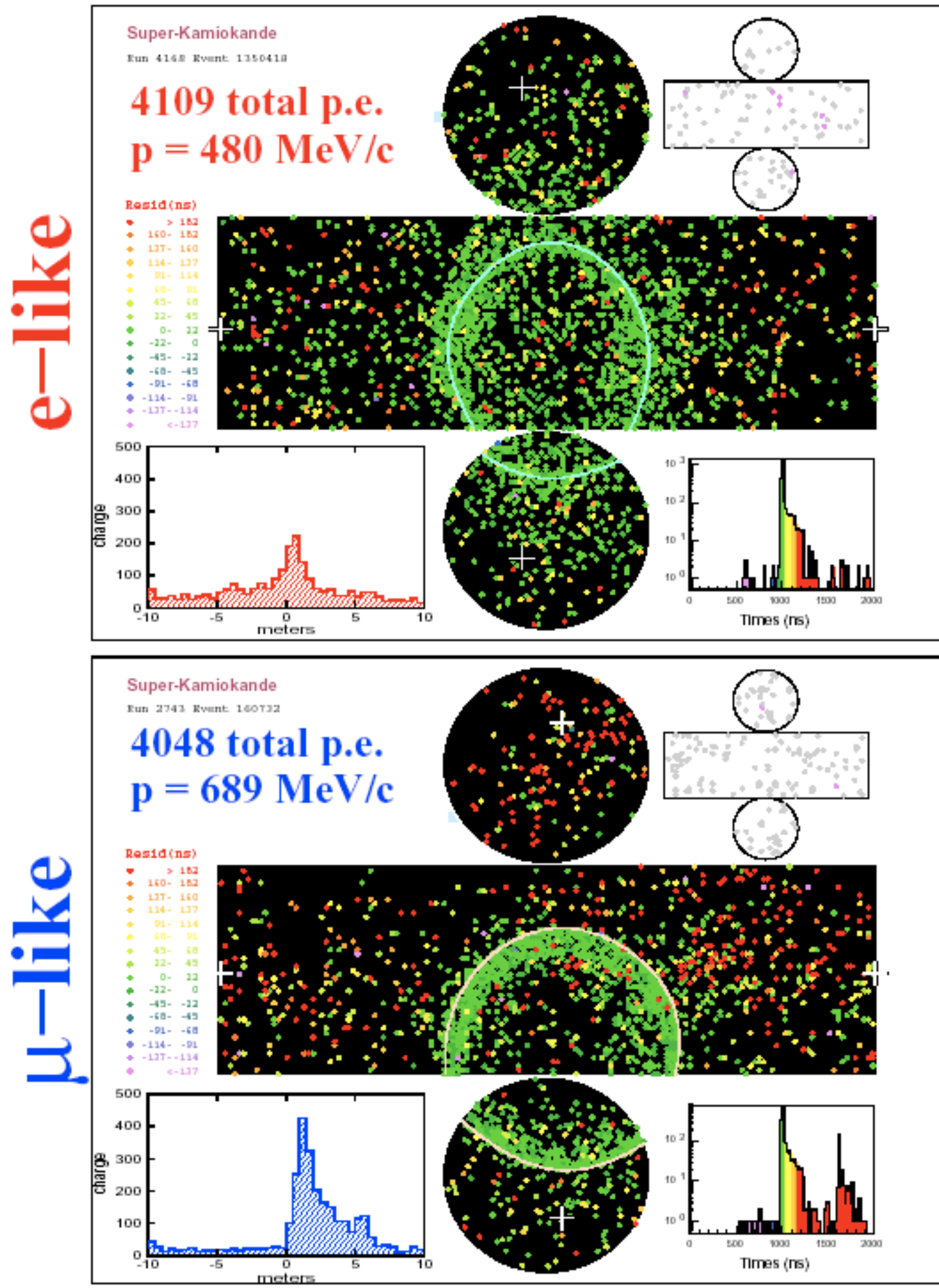

Energy thresholds:
muon: 120 MeV
proton: 1.06 GeV

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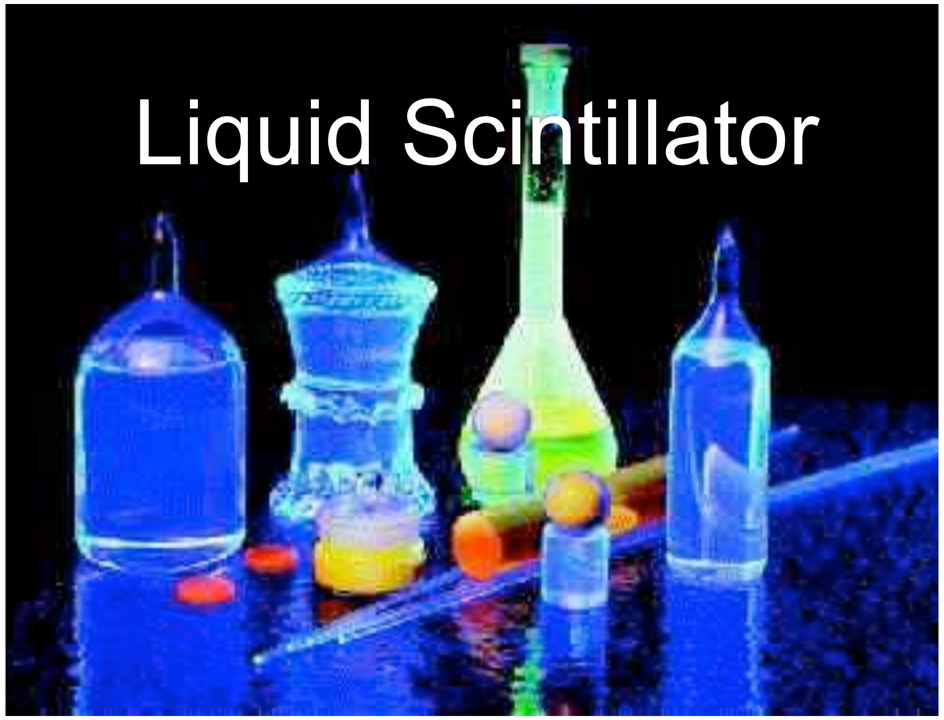

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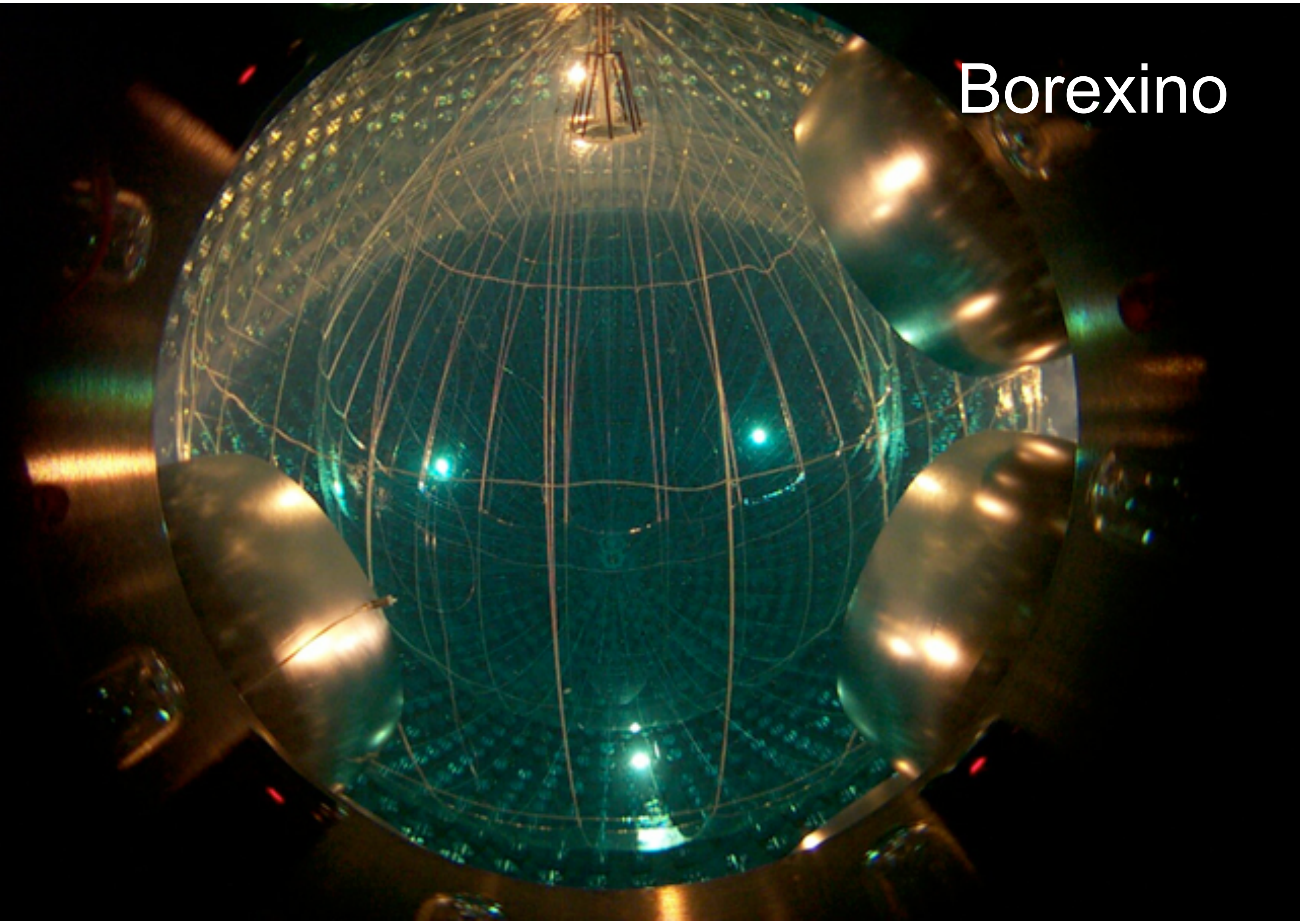

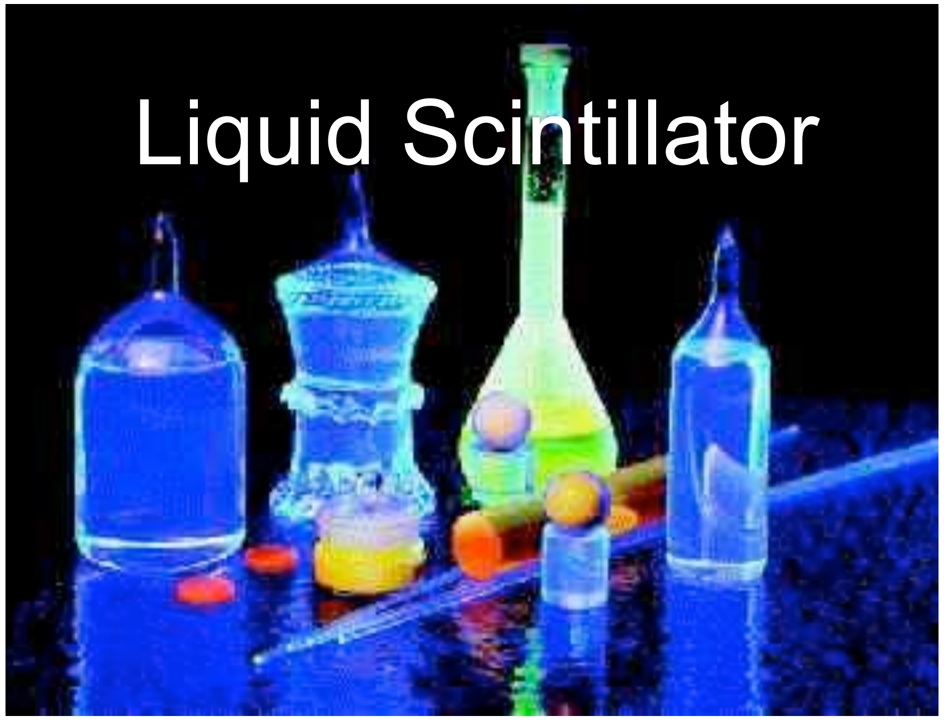

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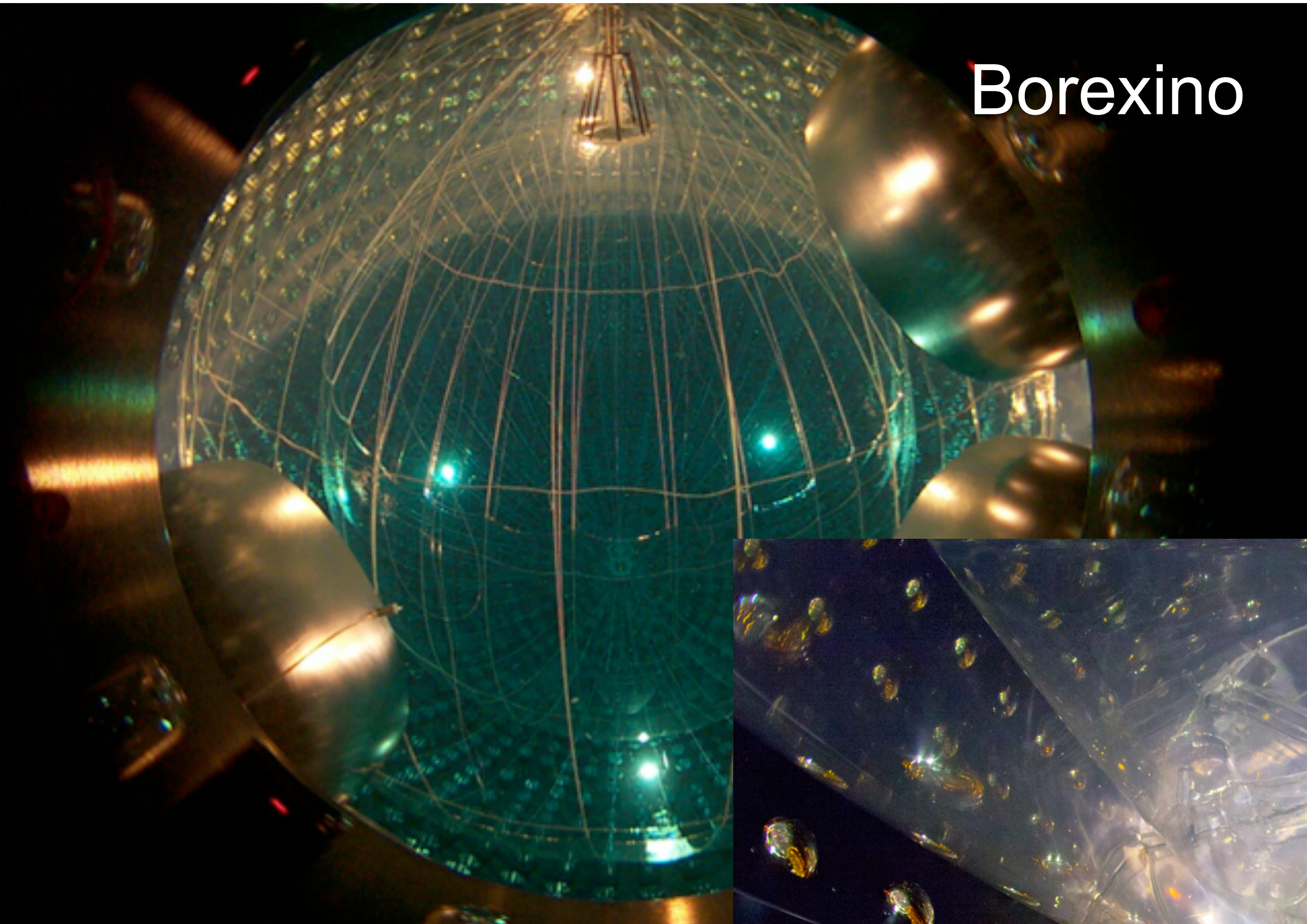

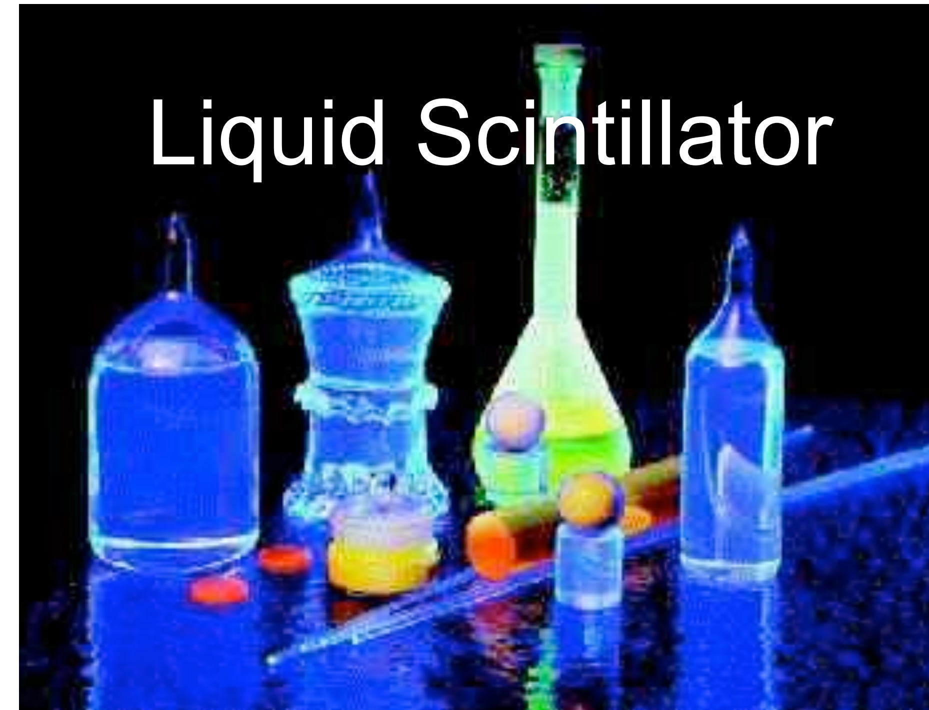

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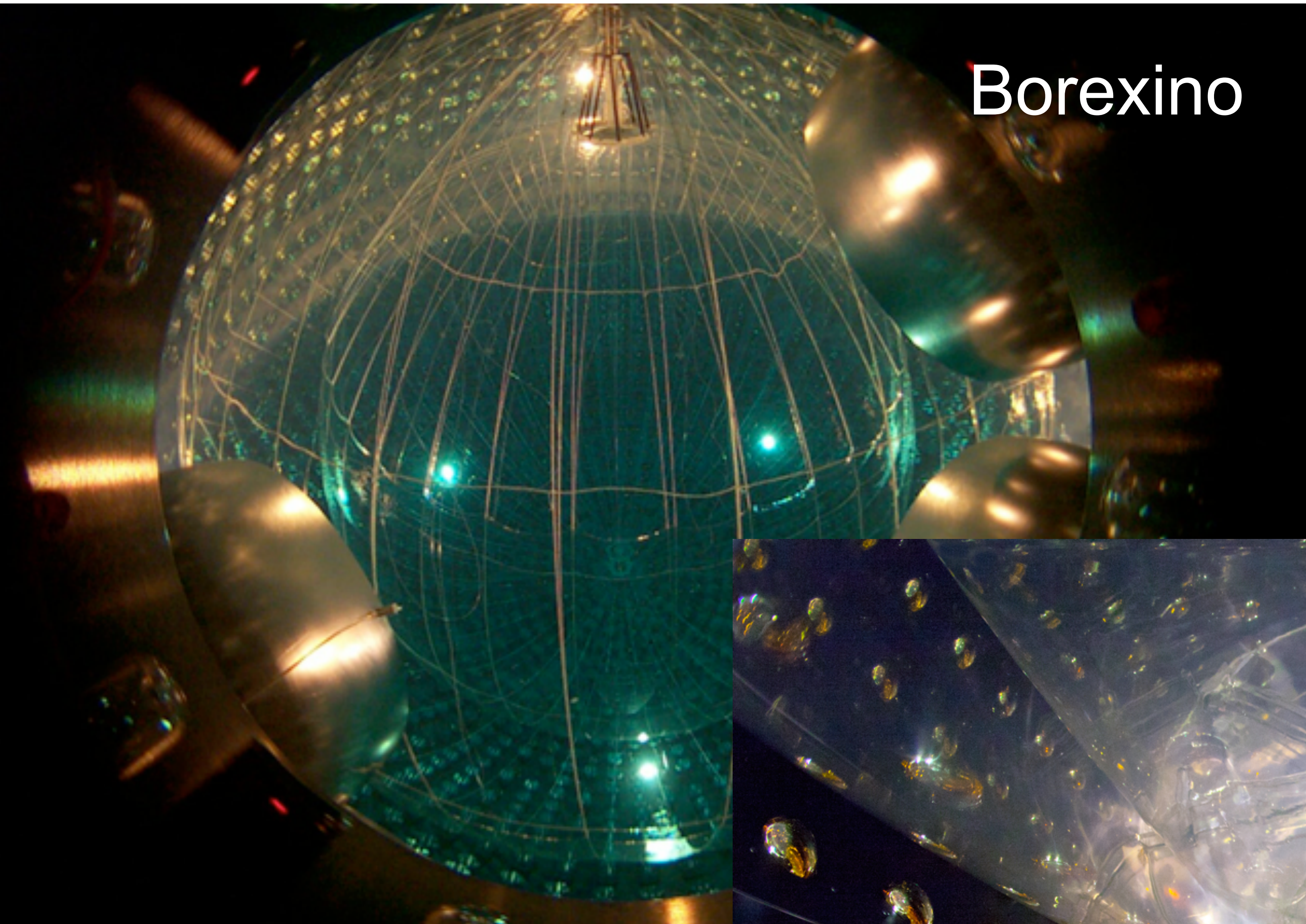

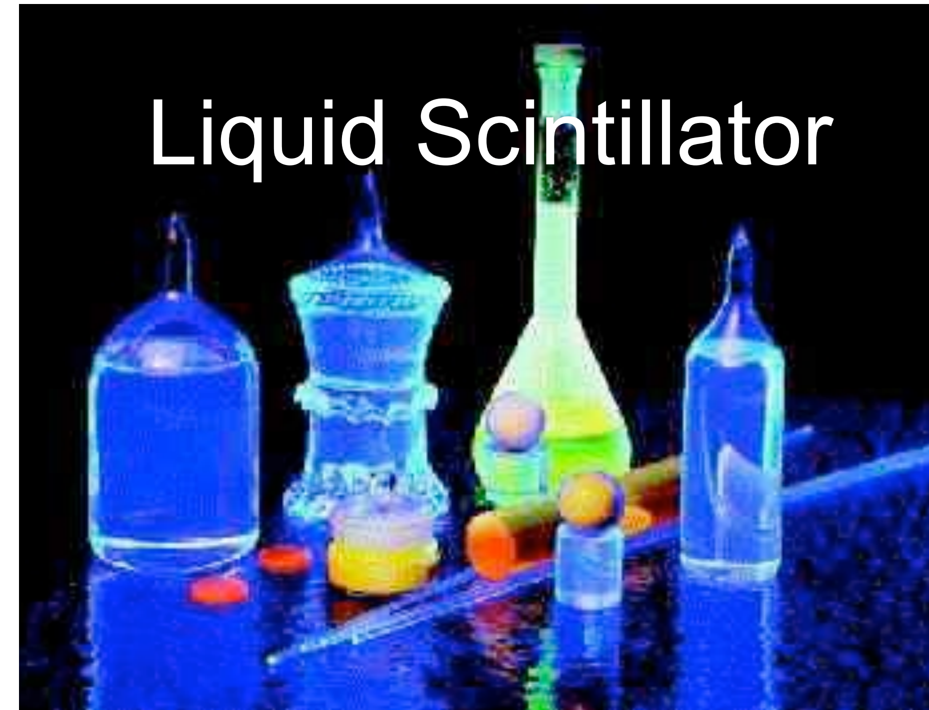

Energy threshold:
all particles: few MeV

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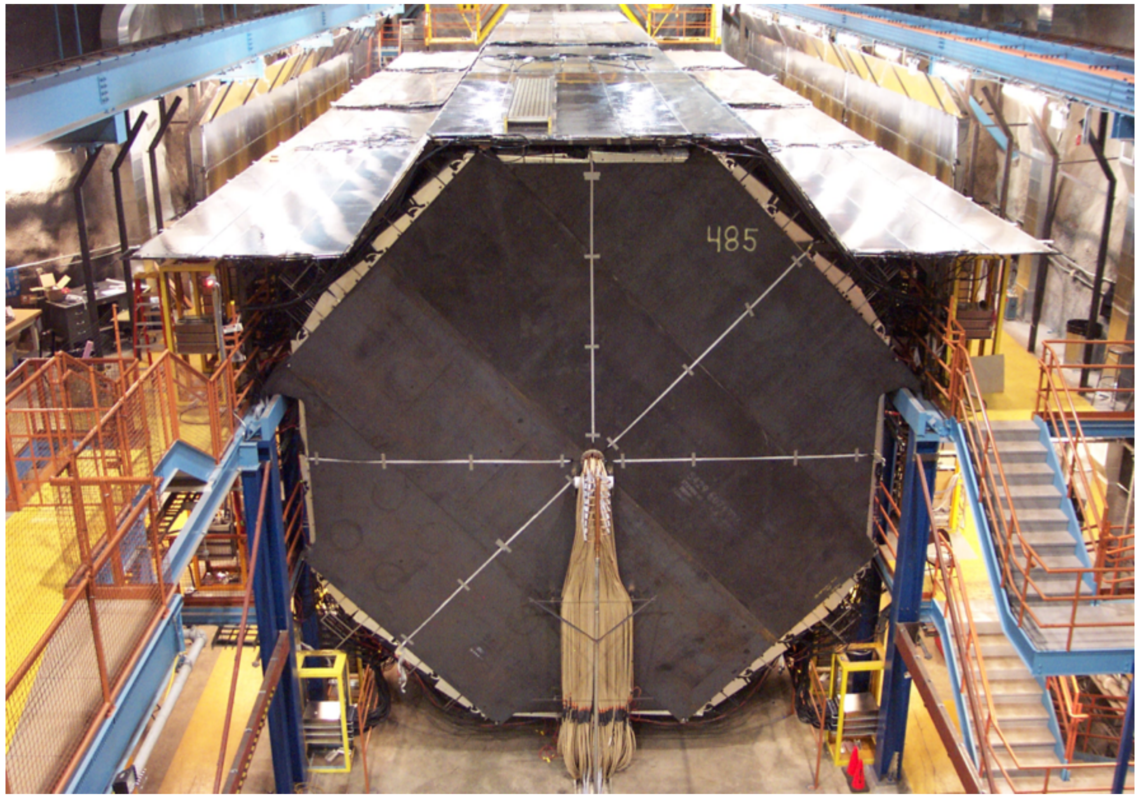

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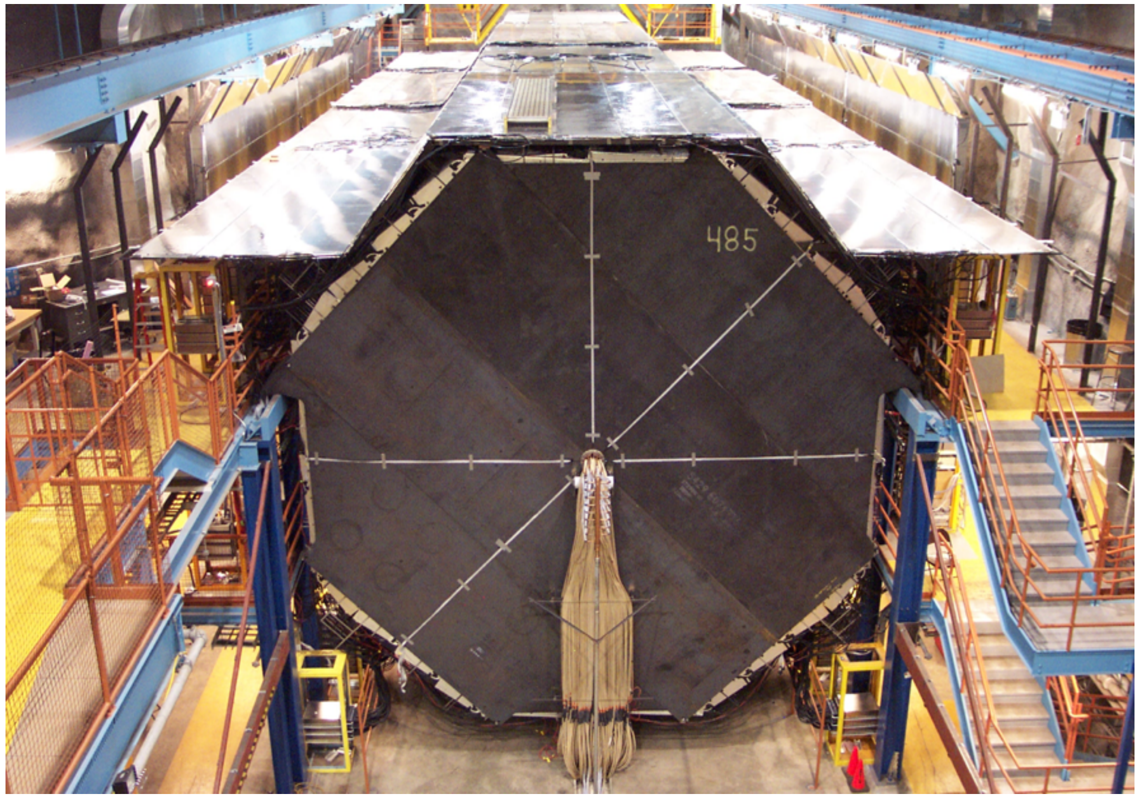

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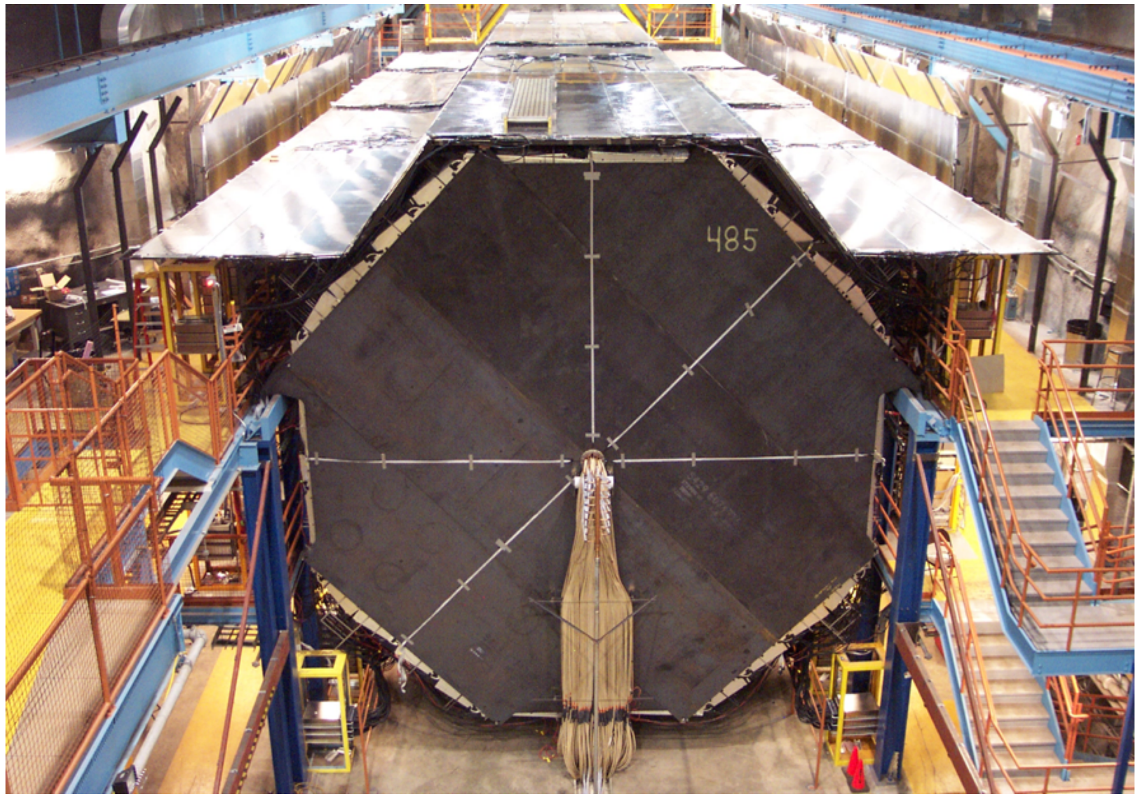

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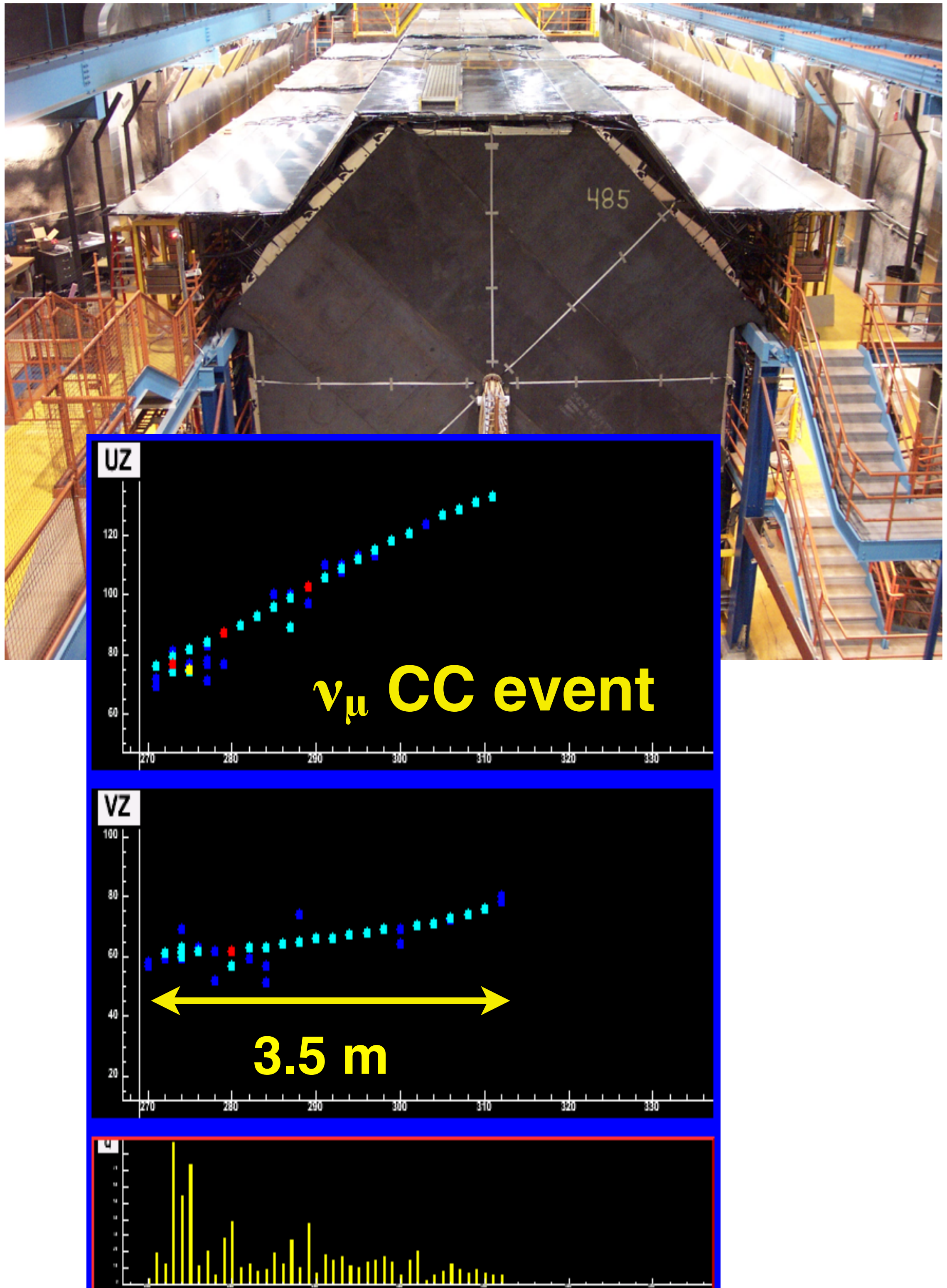

Long μ track + shower at vertex

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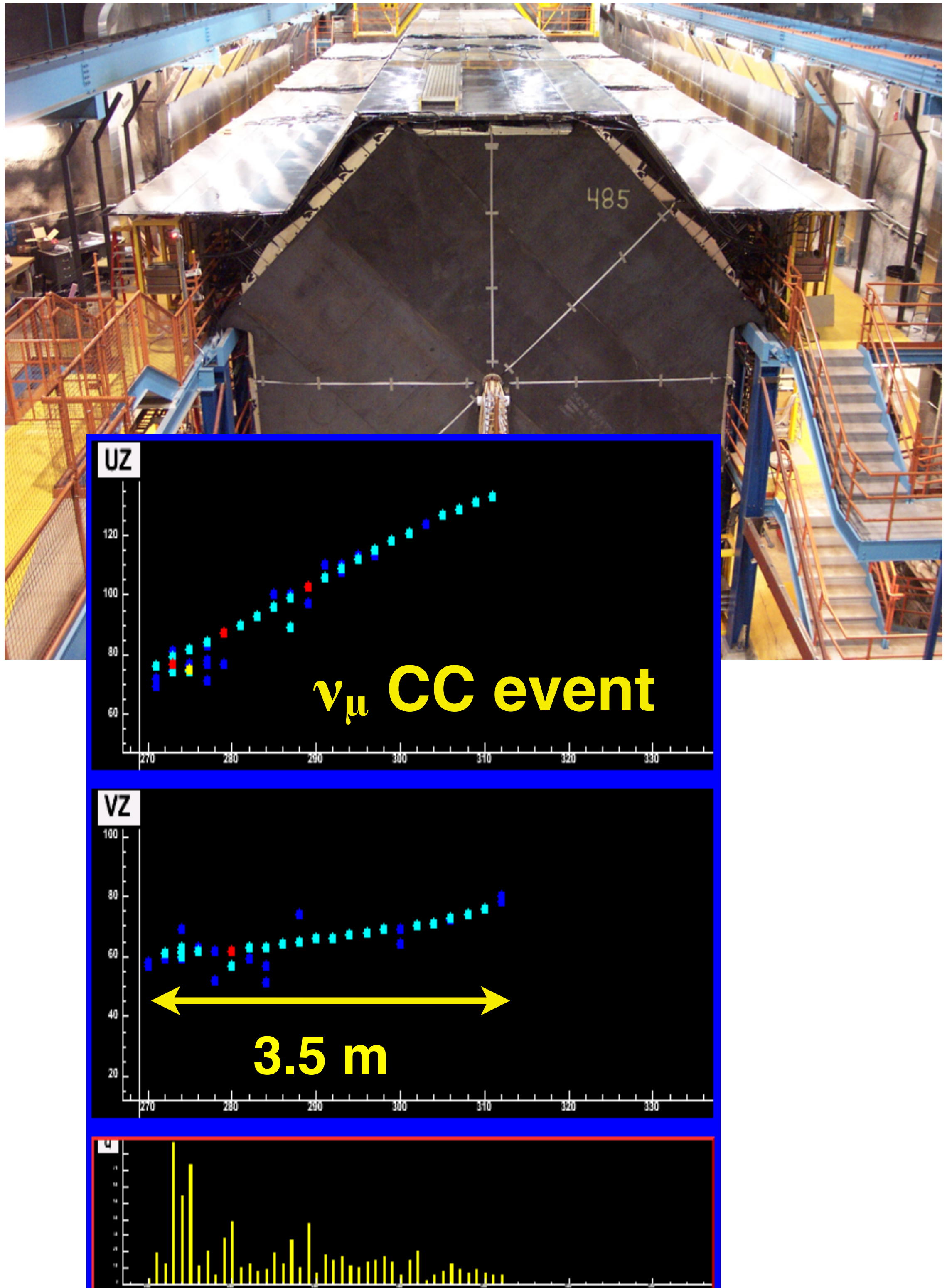

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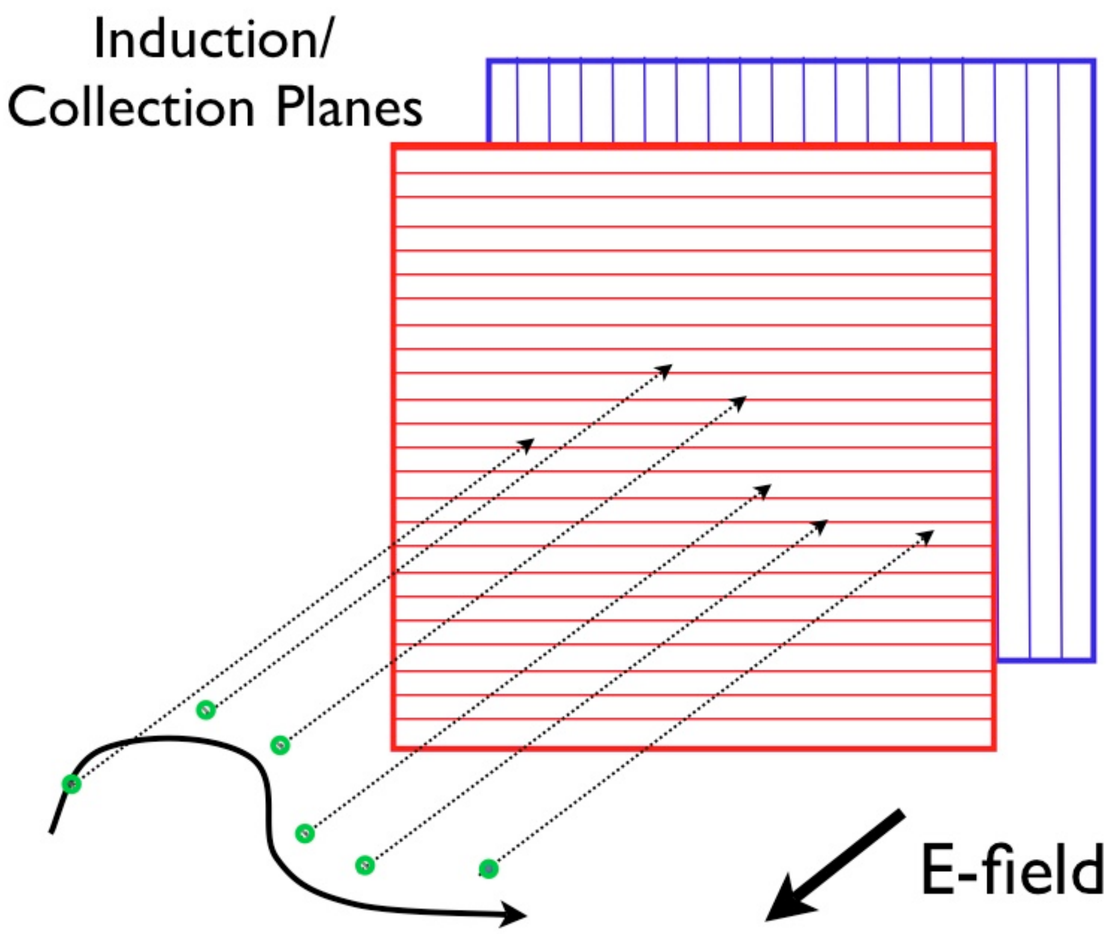
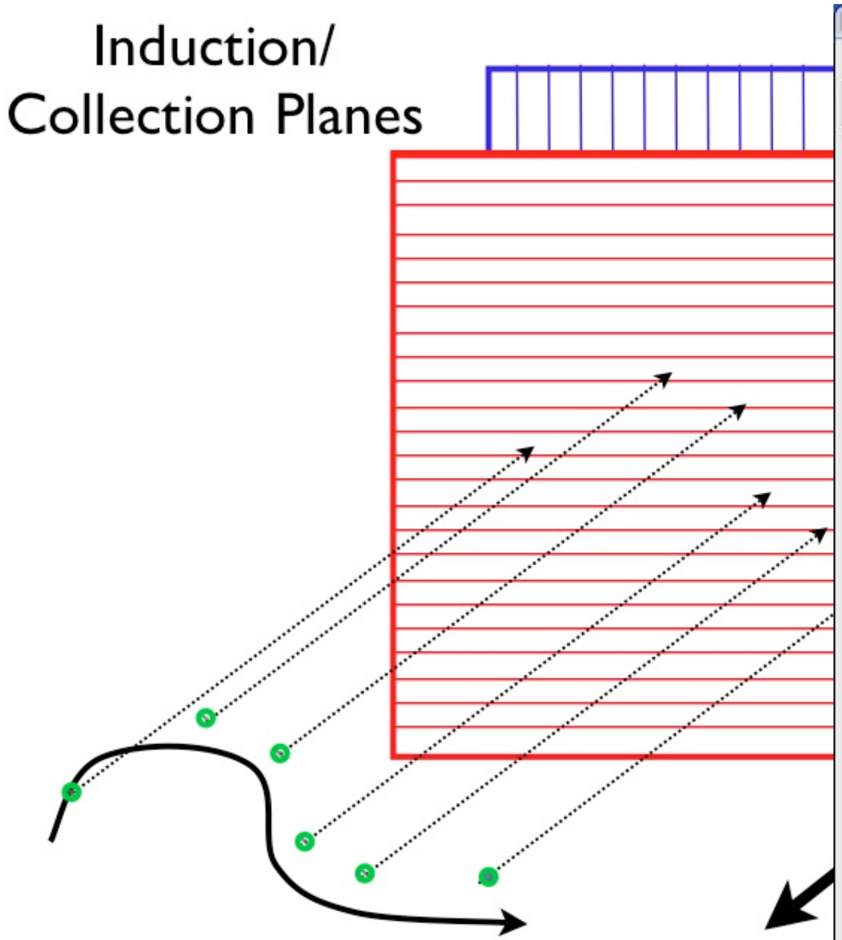
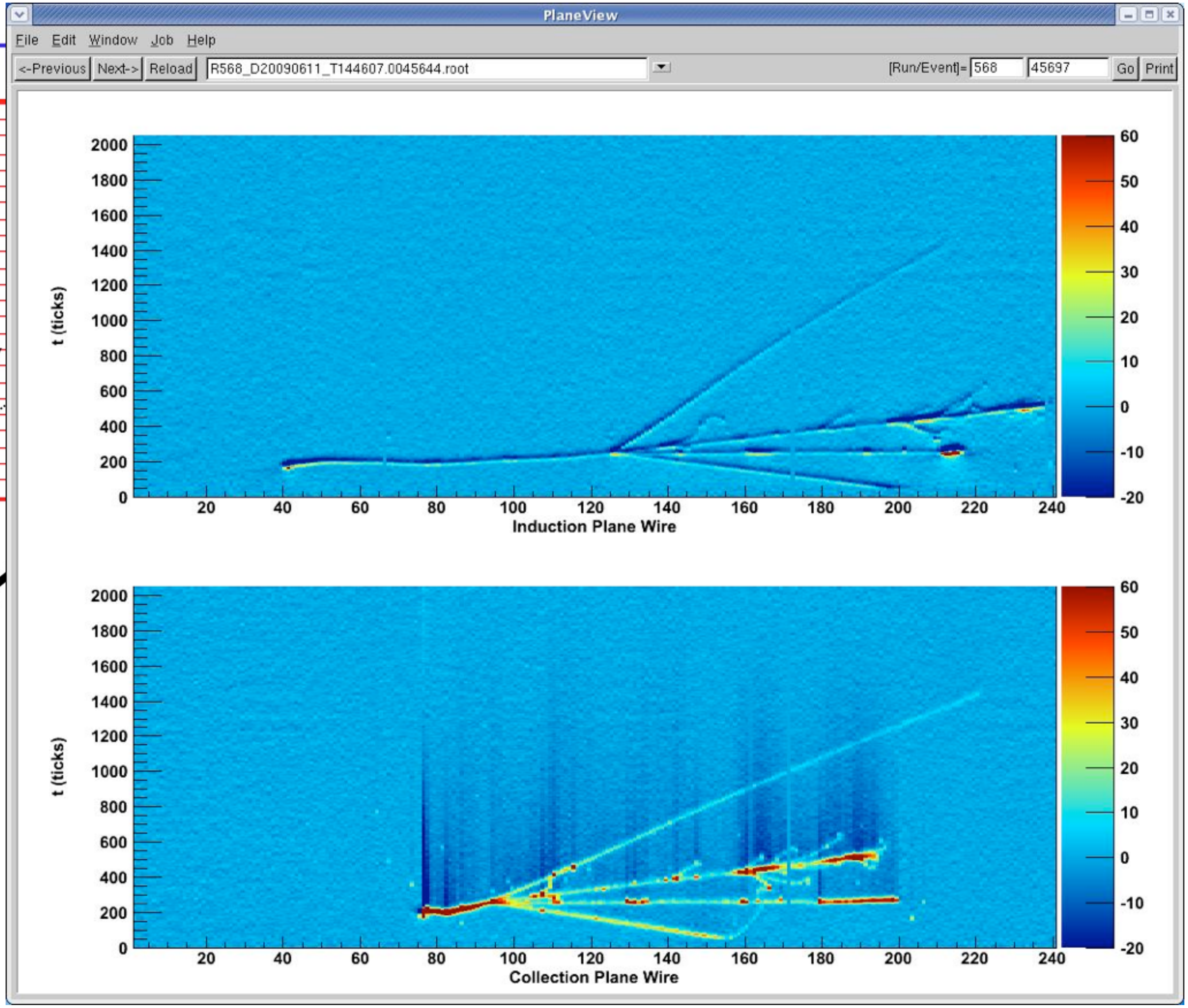


Neutrino Detectors - Some Examples





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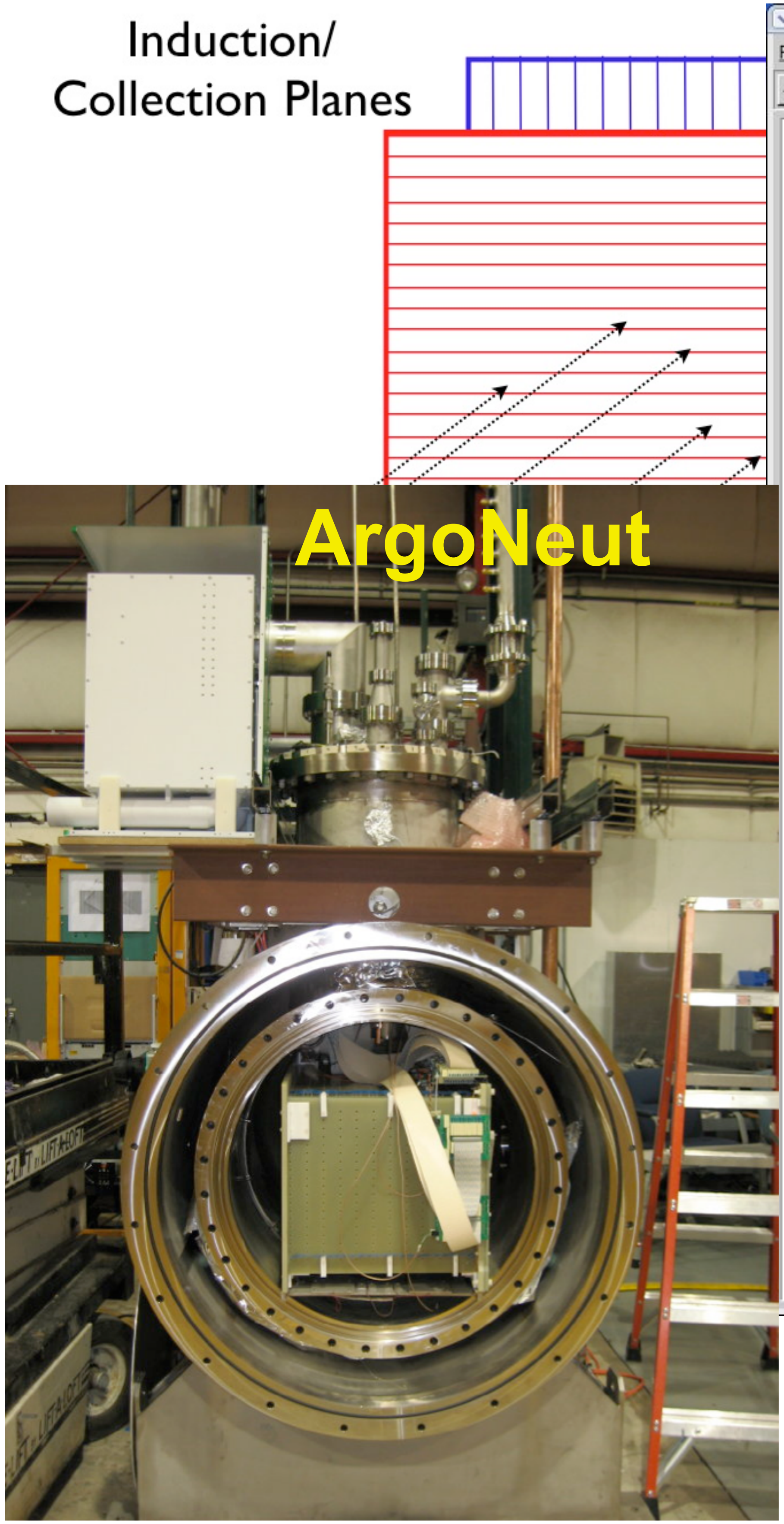

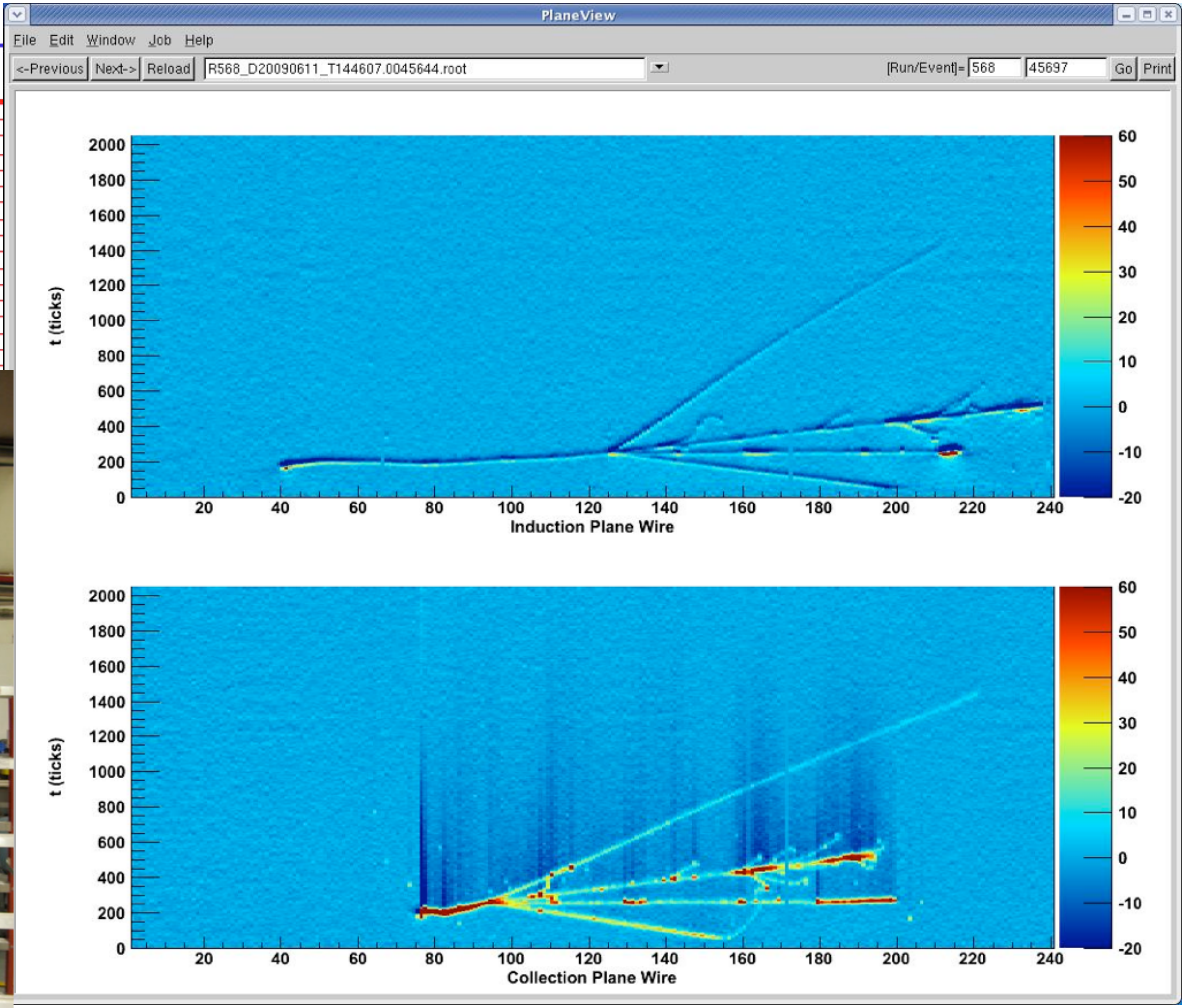

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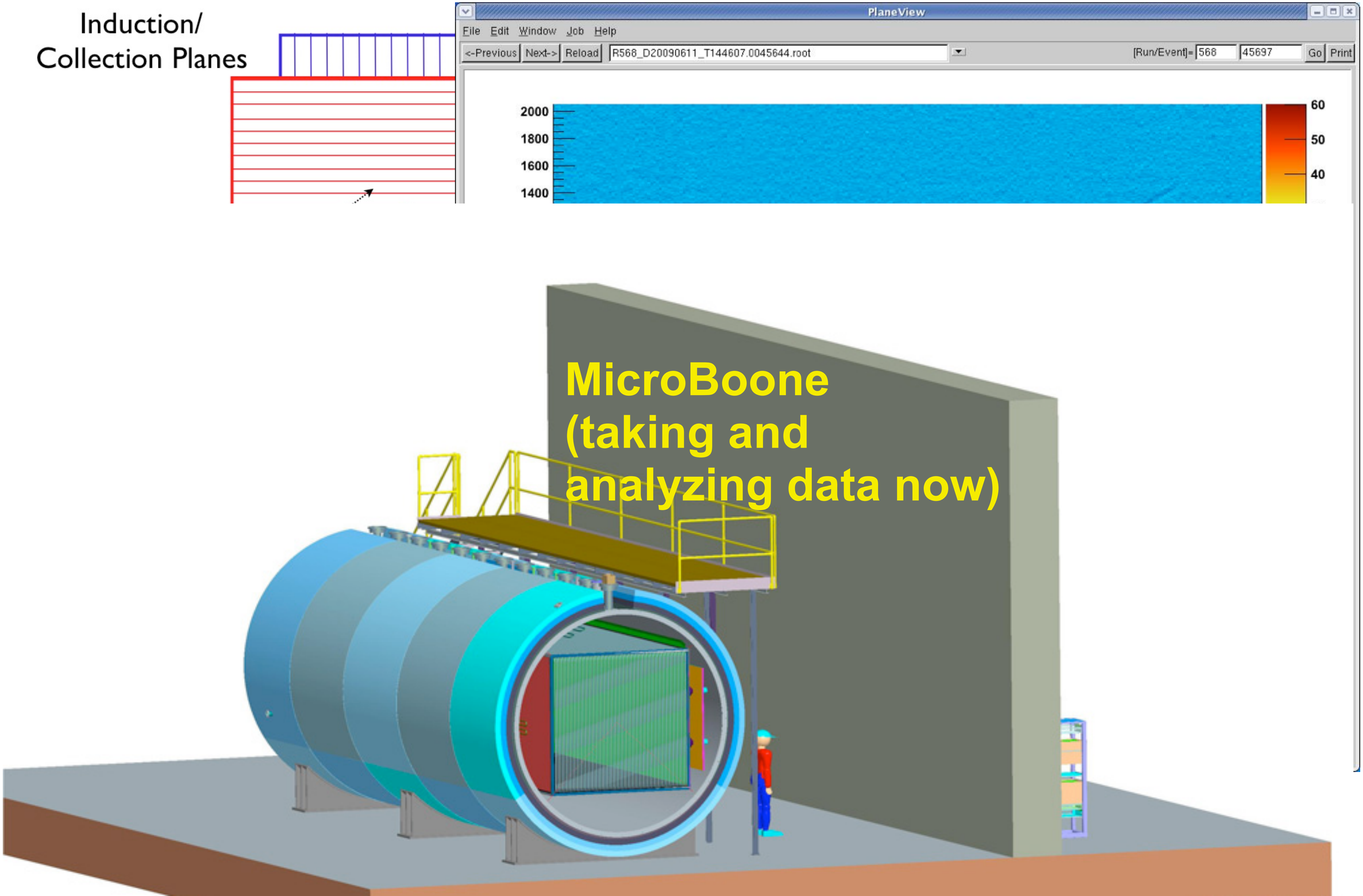
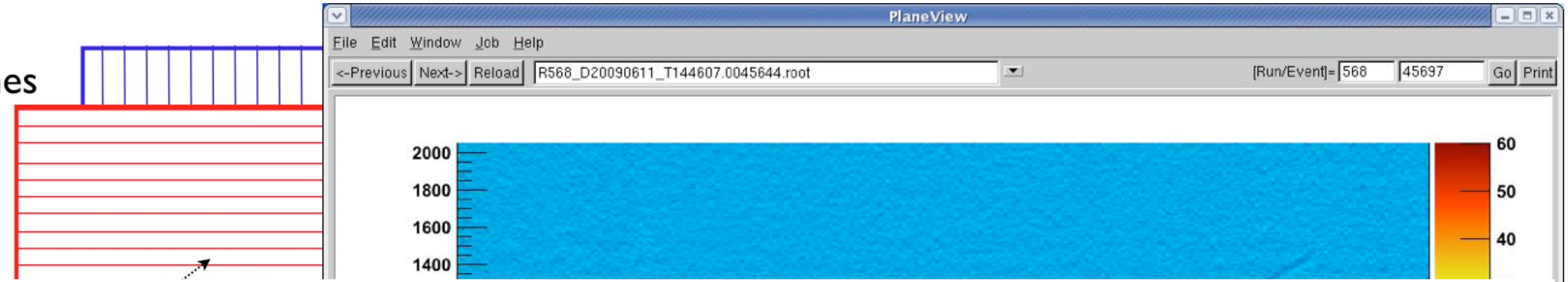
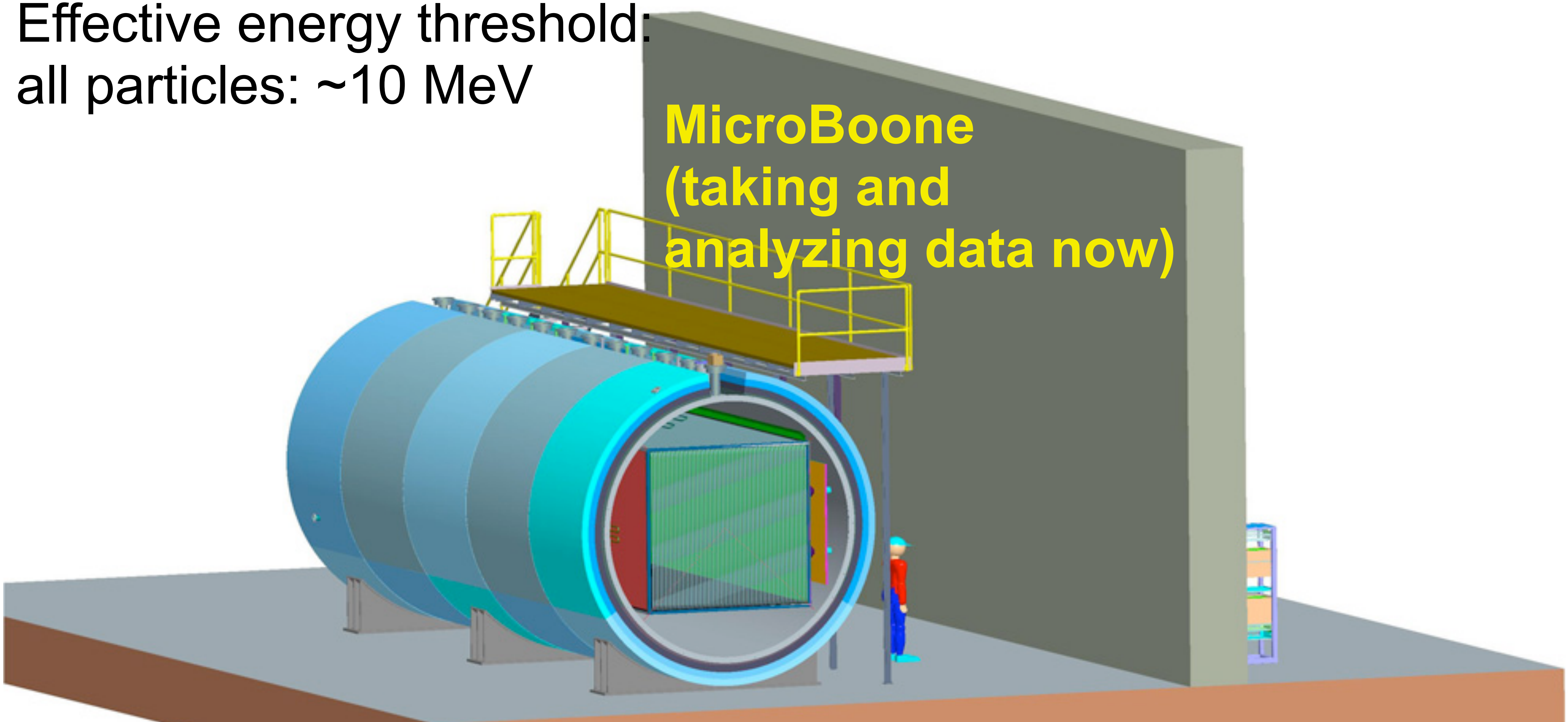


Neutrino Detectors - Some Examples

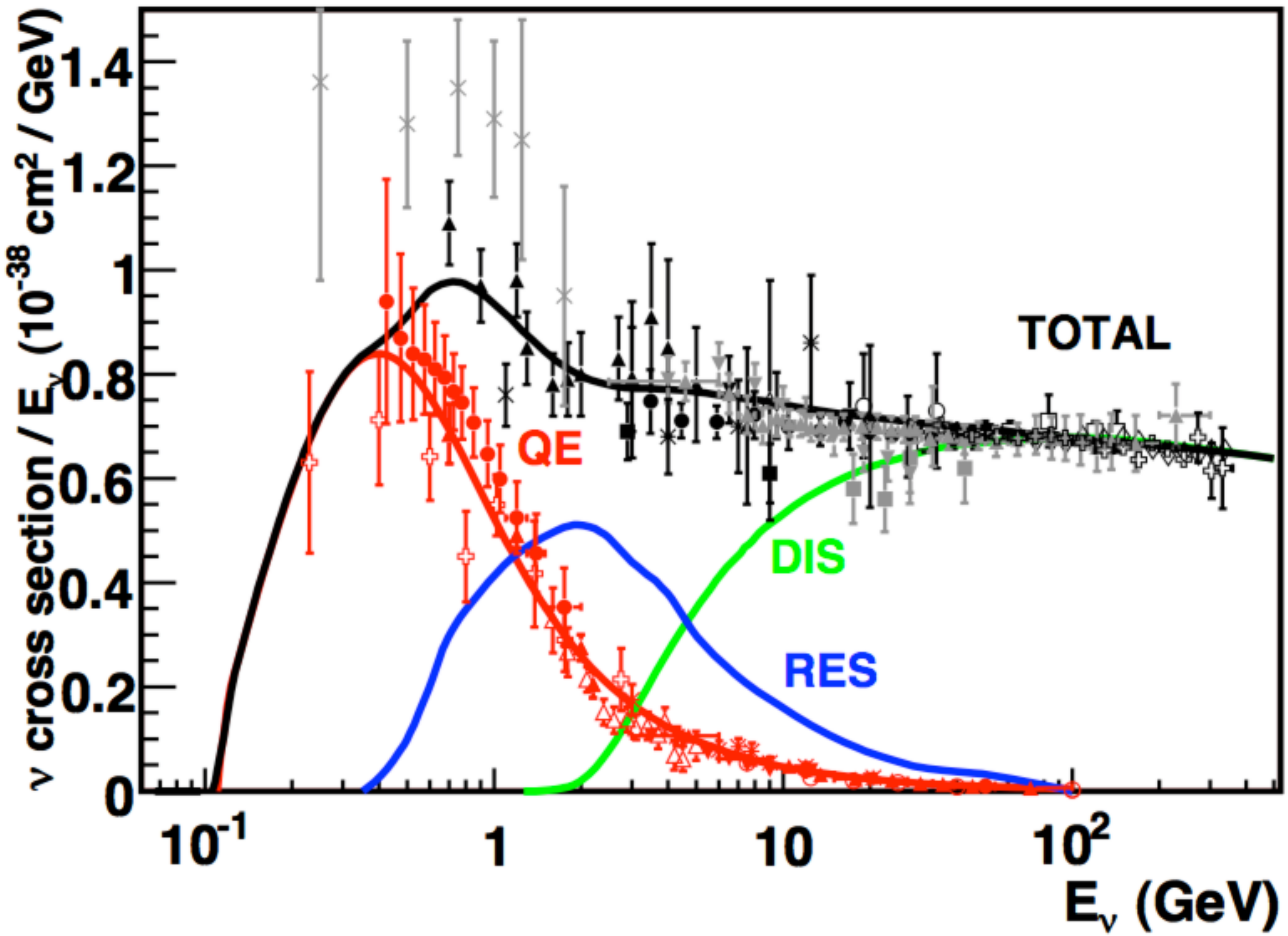
Induction/
Collection Planes



Effective energy threshold:
all particles: ~10 MeV



Neutrino Cross Sections



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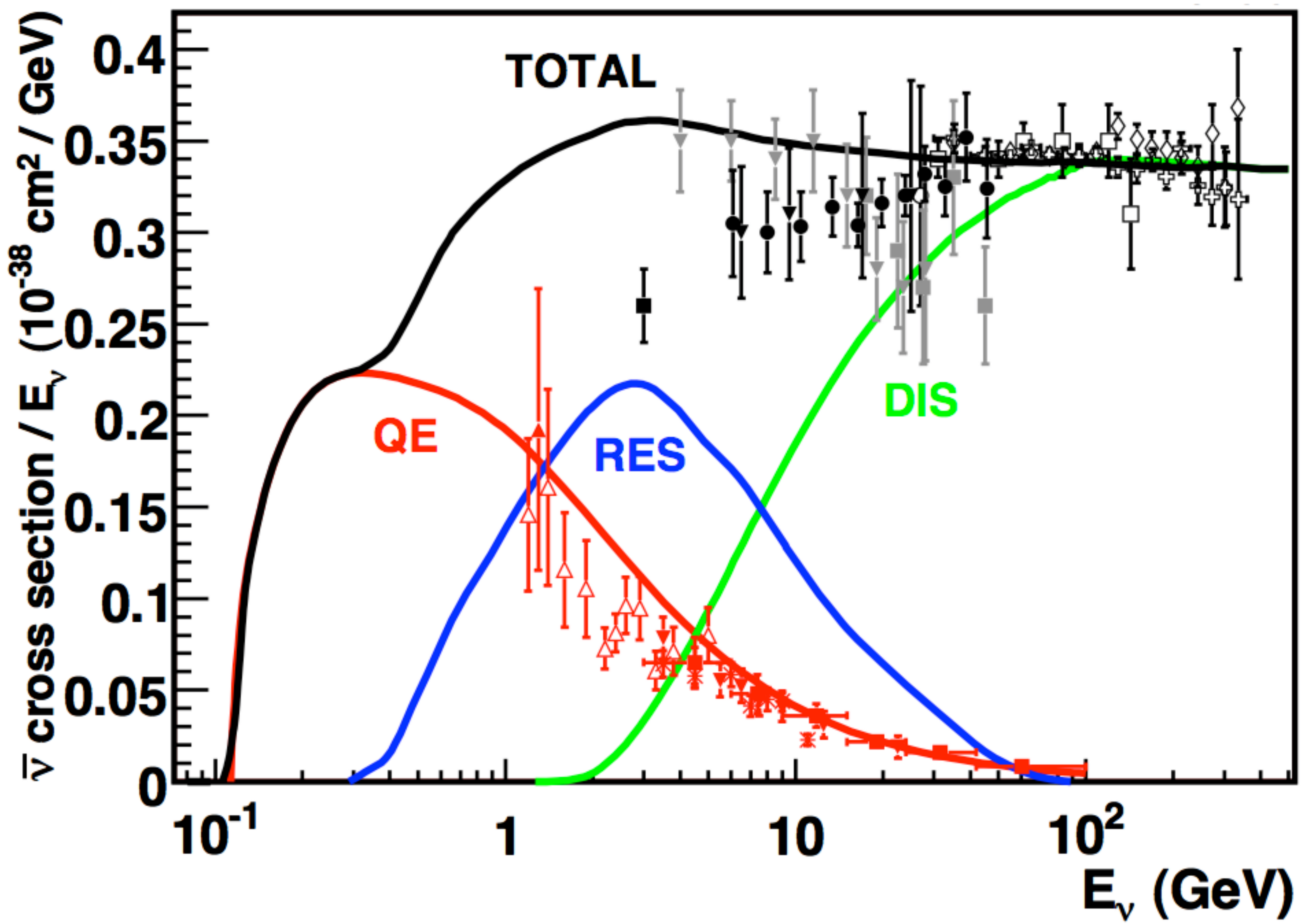

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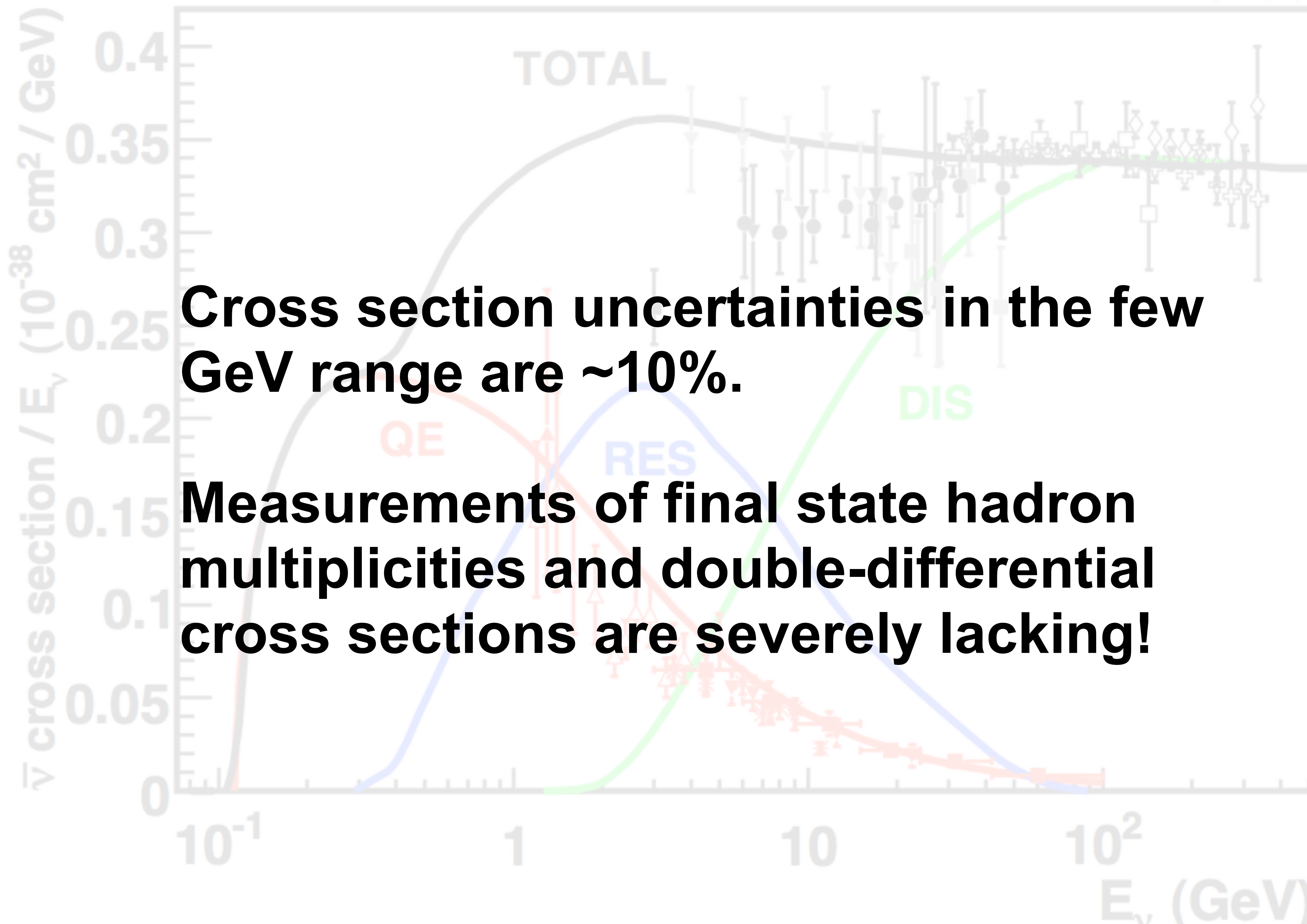
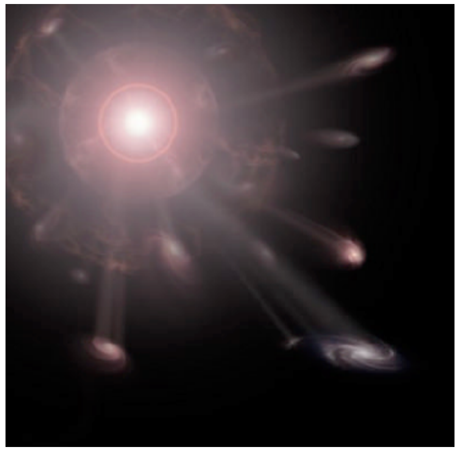


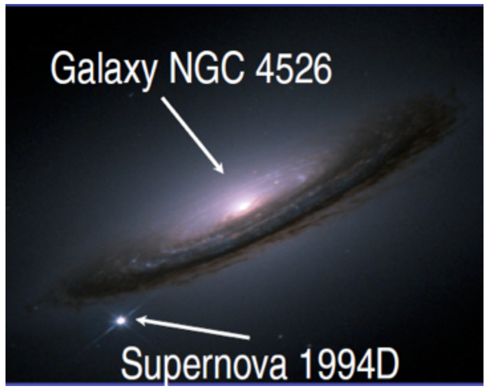
Cross section uncertainties in the few GeV range are ~10%.

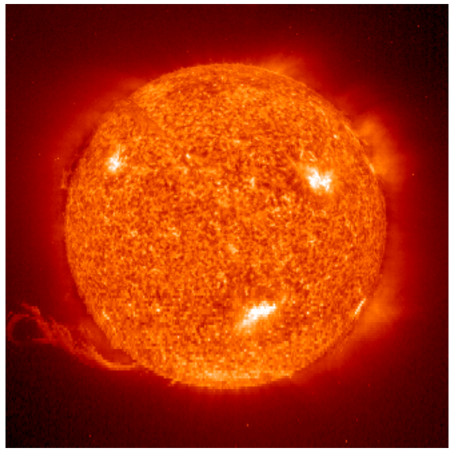
Measurements of final state hadron multiplicities and double-differential cross sections are severely lacking!

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







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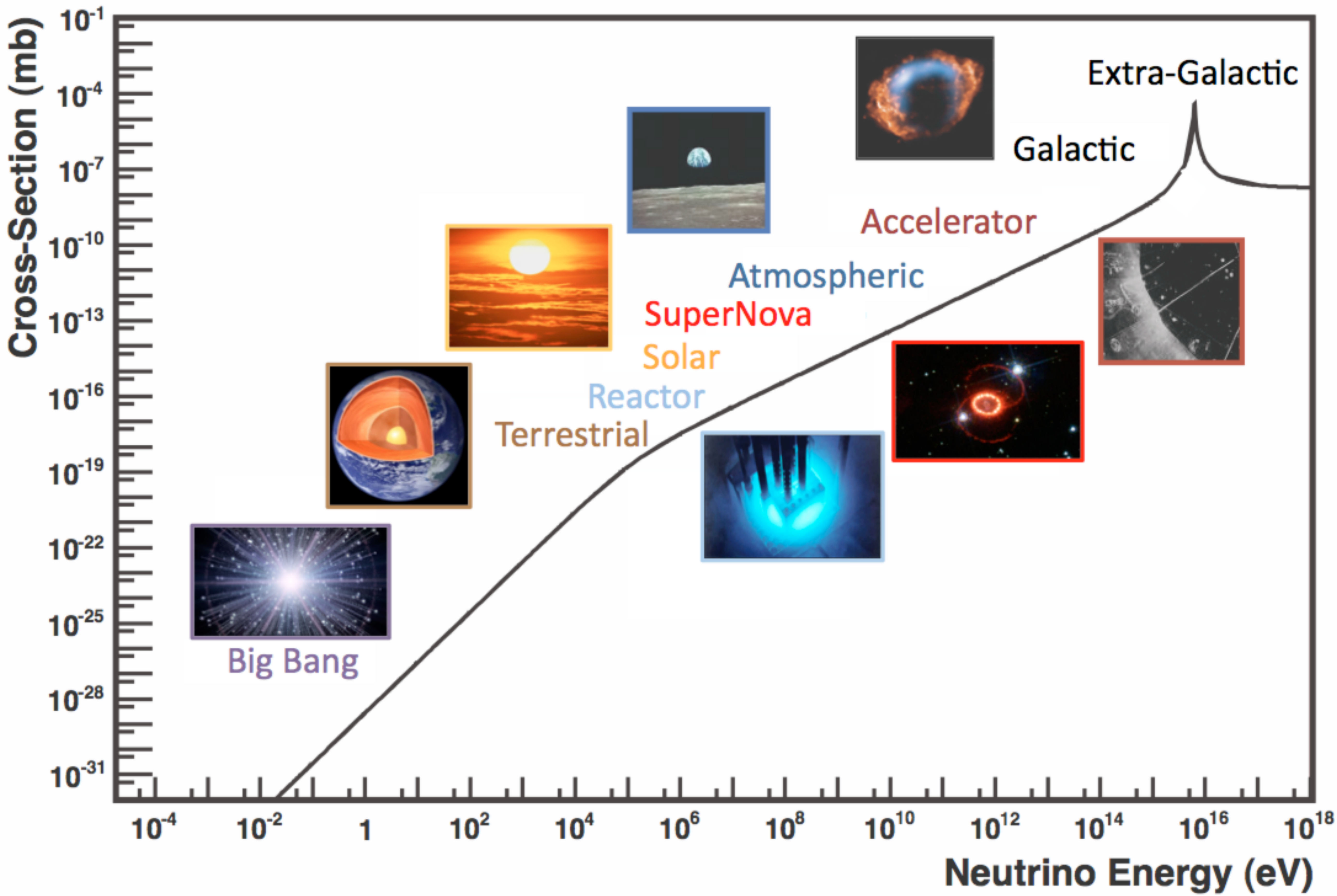
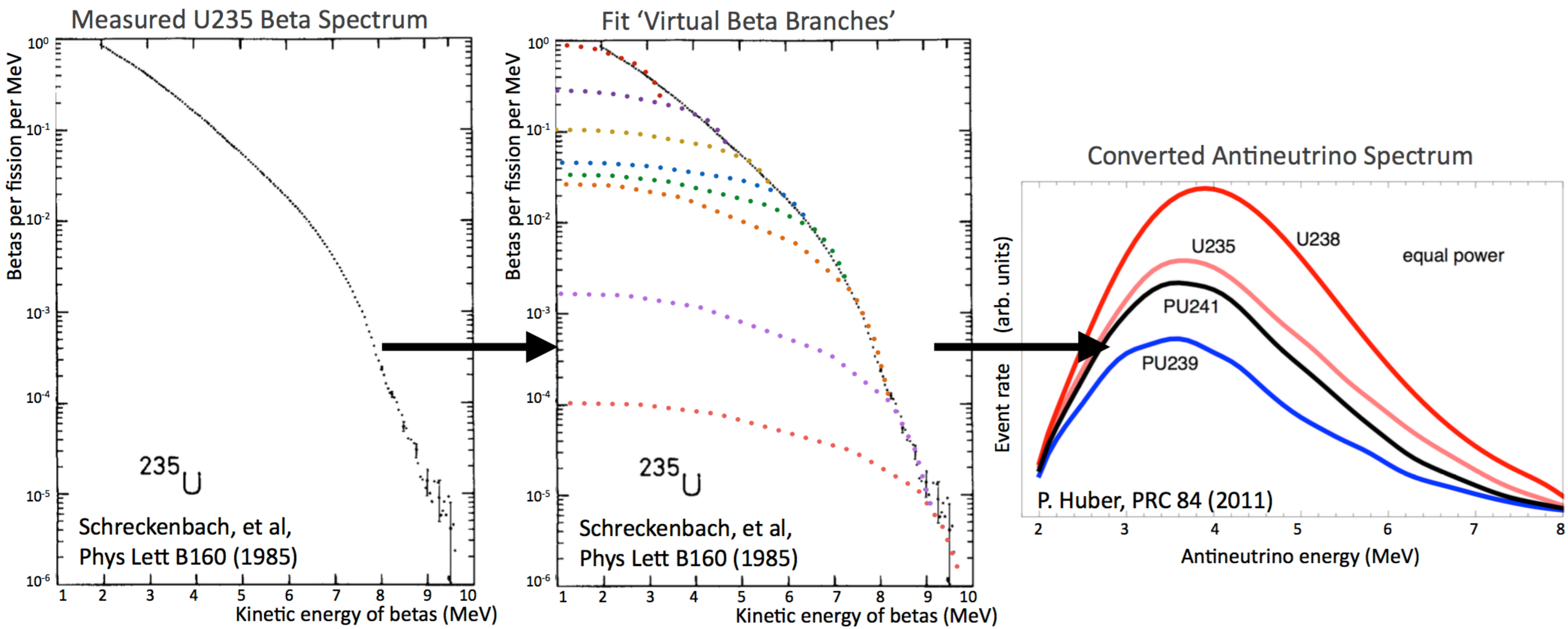


Neutrino Production via Reactors



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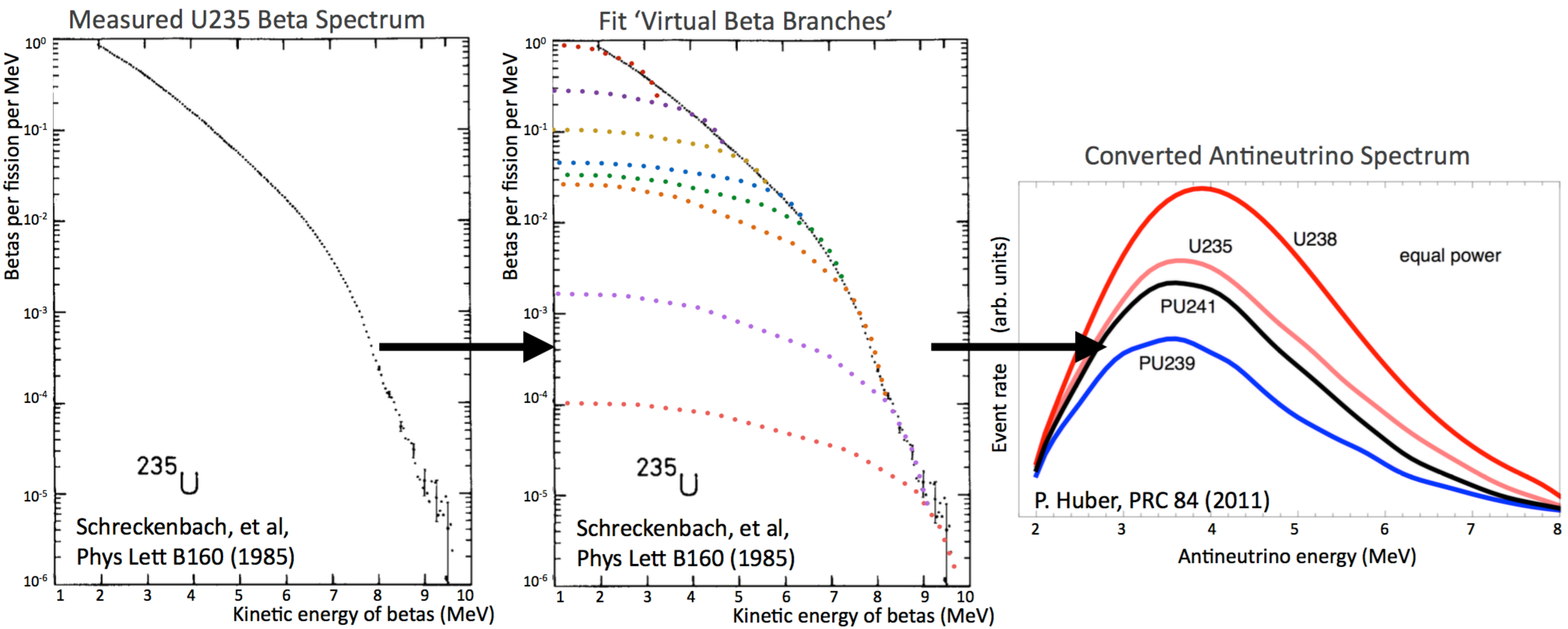

- The Beta spectra of the dominant fission isotopes are fit to the observed (measured) Beta spectrum.
- The fitted spectra are used to calculate the final antineutrino spectrum.

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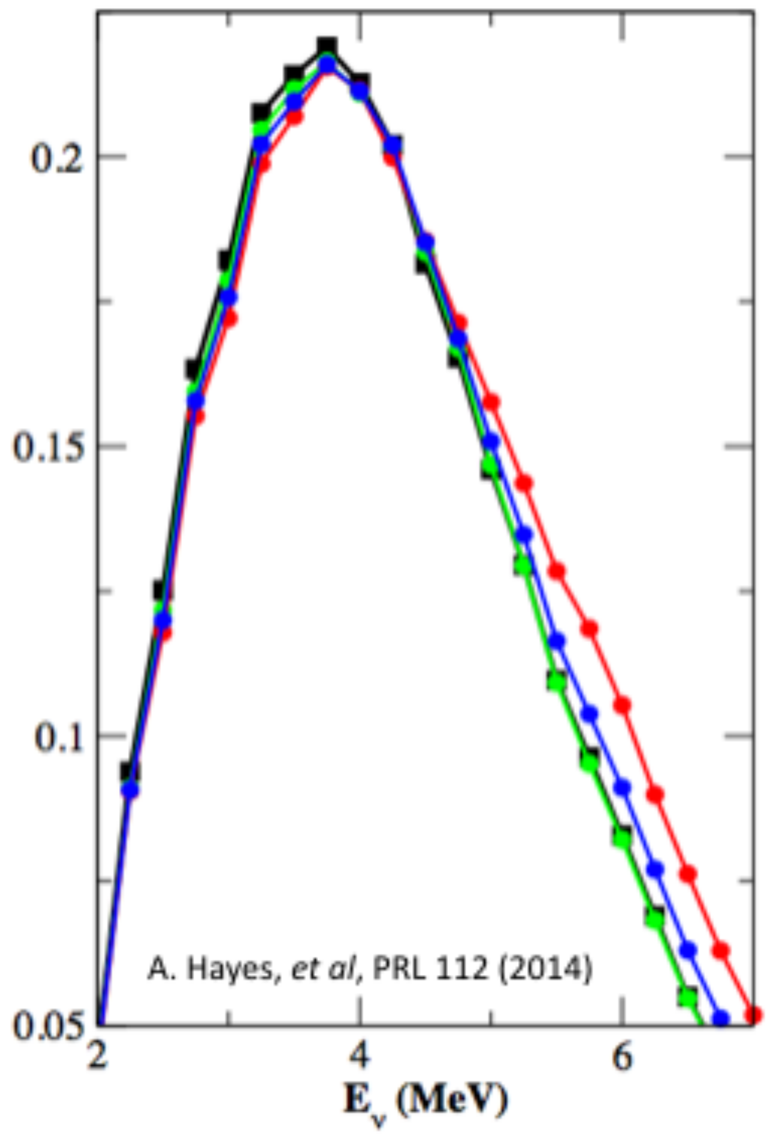

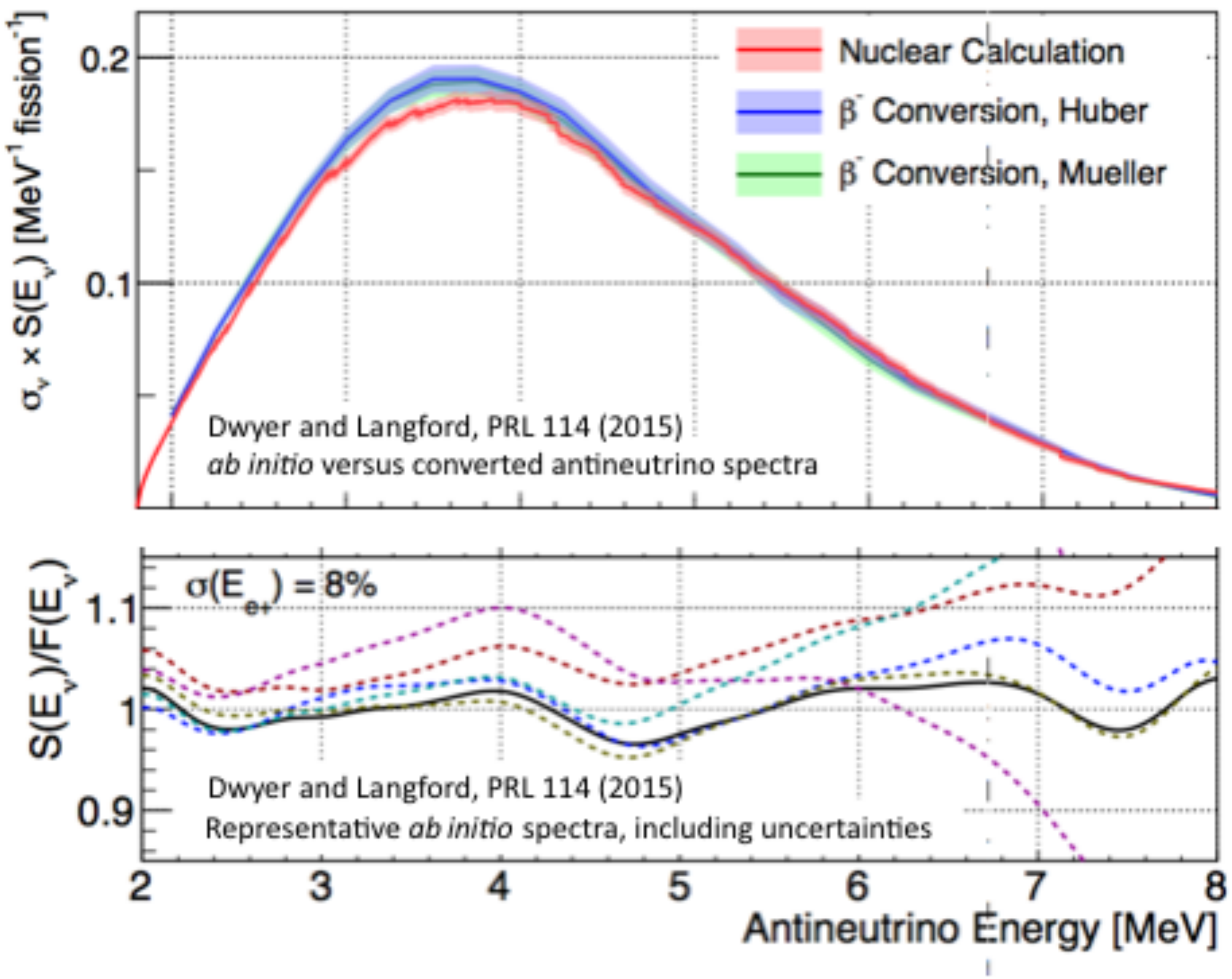

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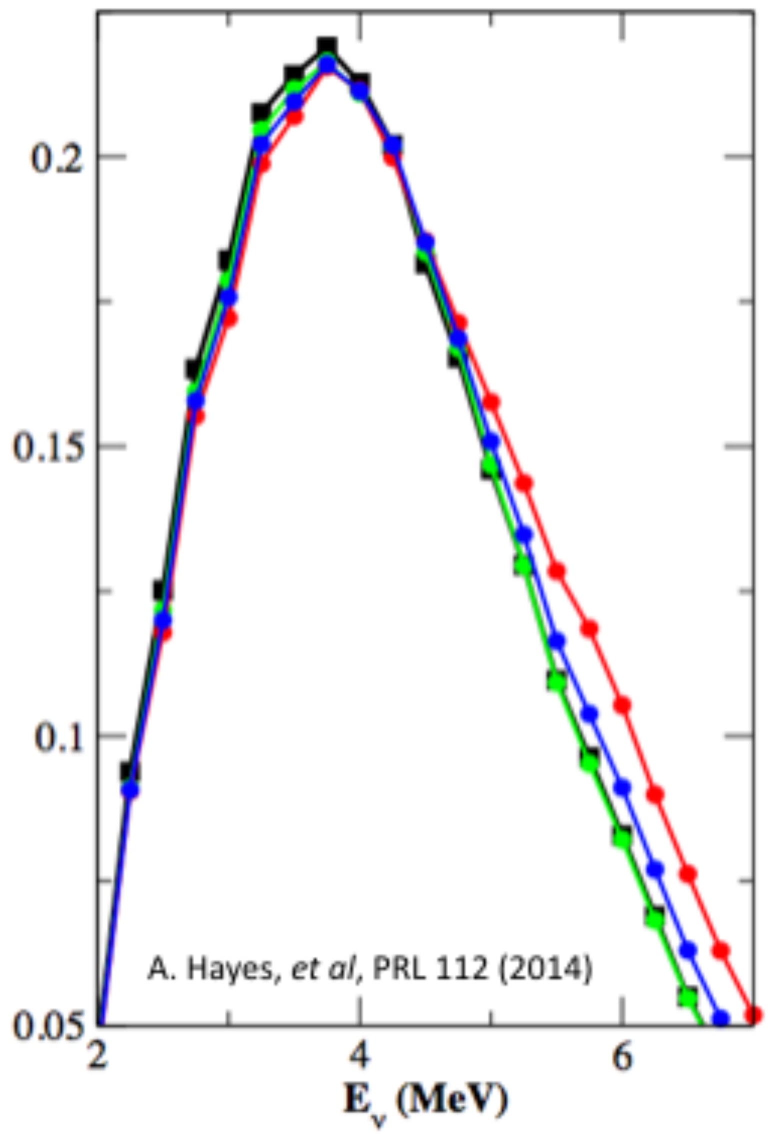
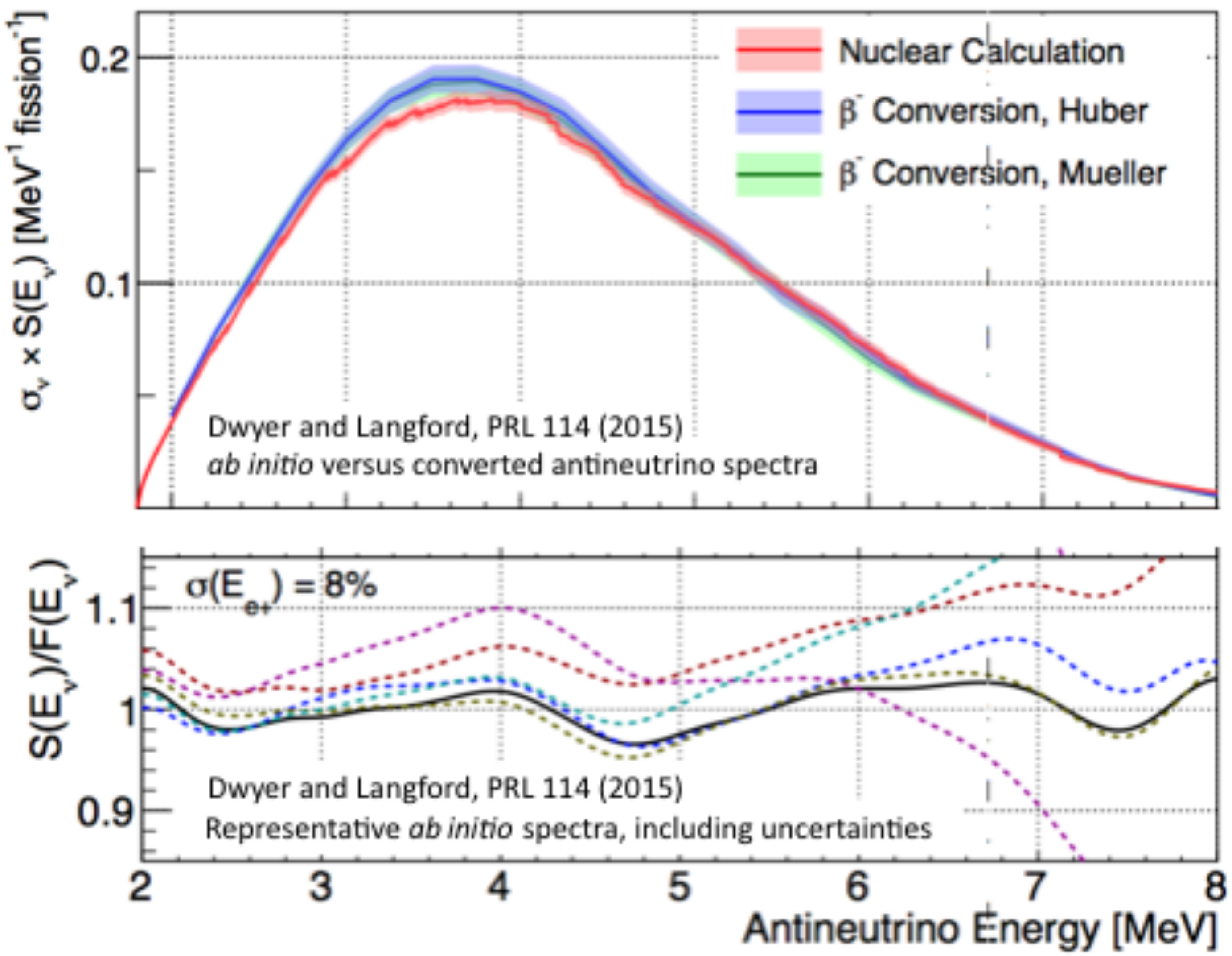
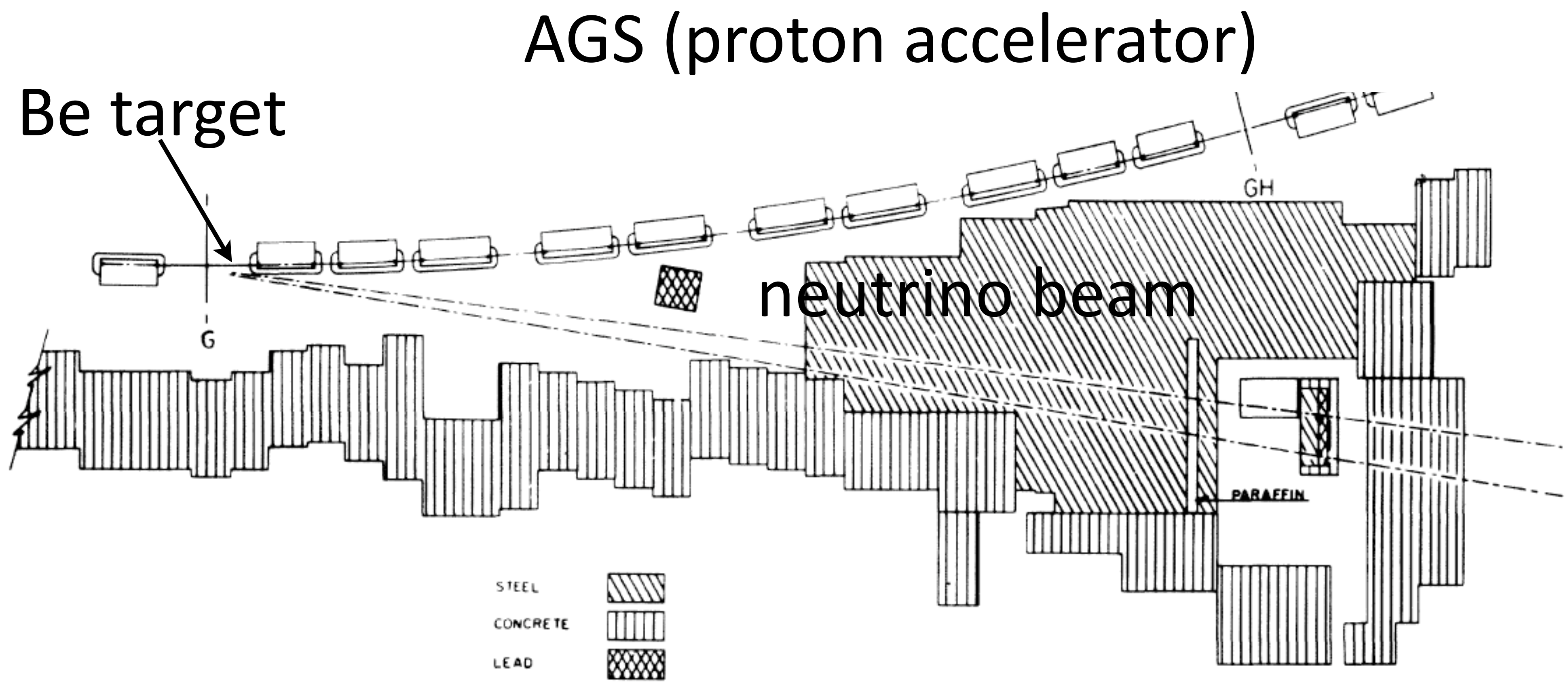




- The Beta spectra of the dominant fission isotopes are fit to the observed (measured) Beta spectrum.
- The fitted spectra are used to calculate the final antineutrino spectrum.
- However, ab-initio approaches using measured fission yields differs by up to 10%.
- Currently reactor antineutrino flux prediction uncertainties are ~5%.

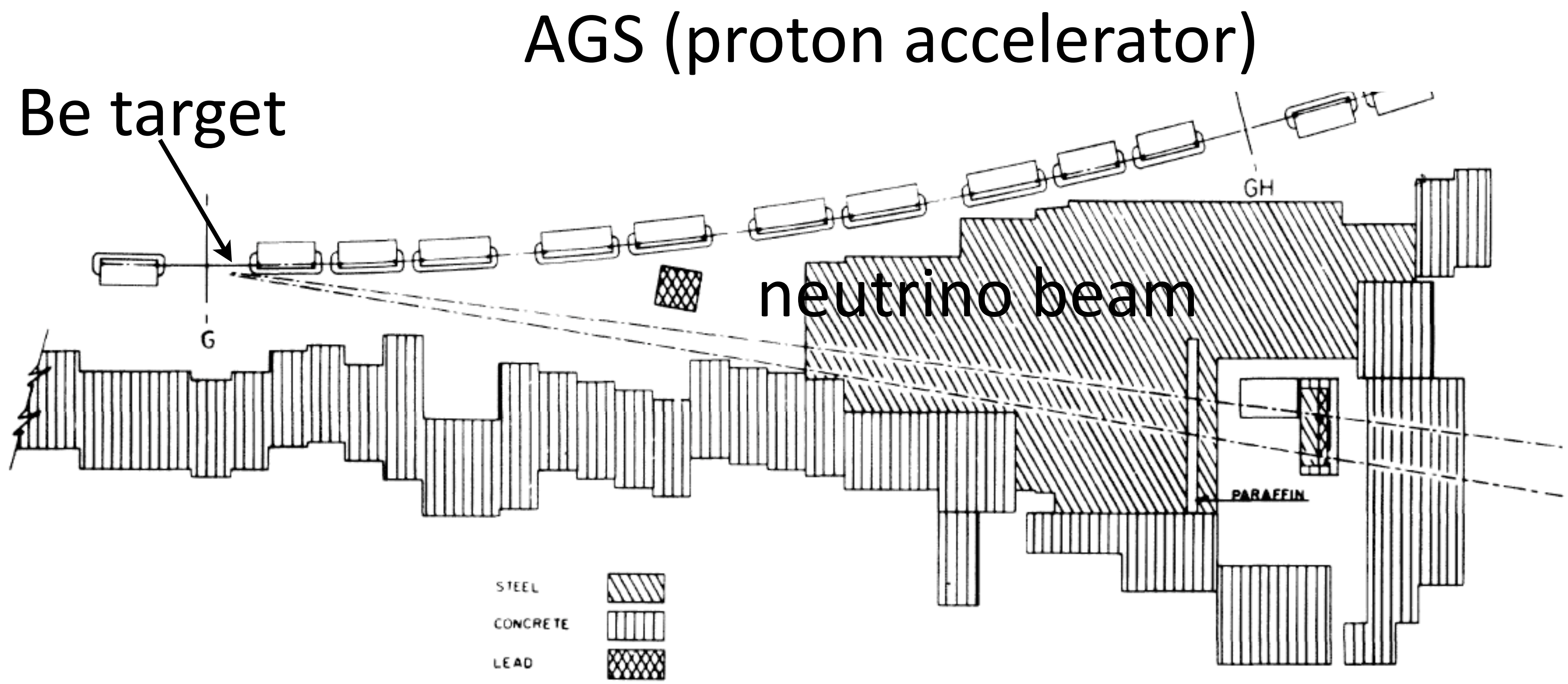
Neutrino Production via Accelerators



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



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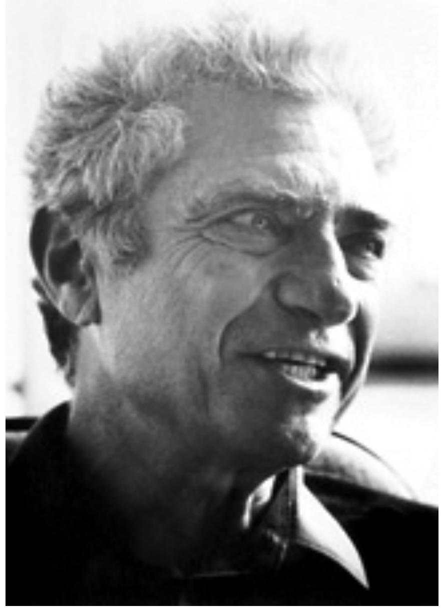
Neutrino Production via Accelerators

Leon Lederman

Melvin Schwartz



Jack Steinberger

Discovery of the Muon Neutrino!
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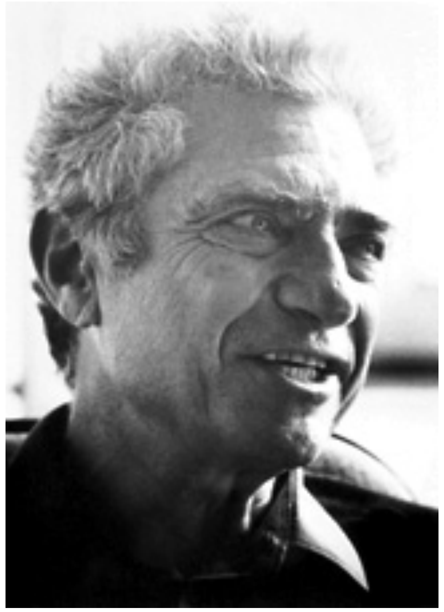
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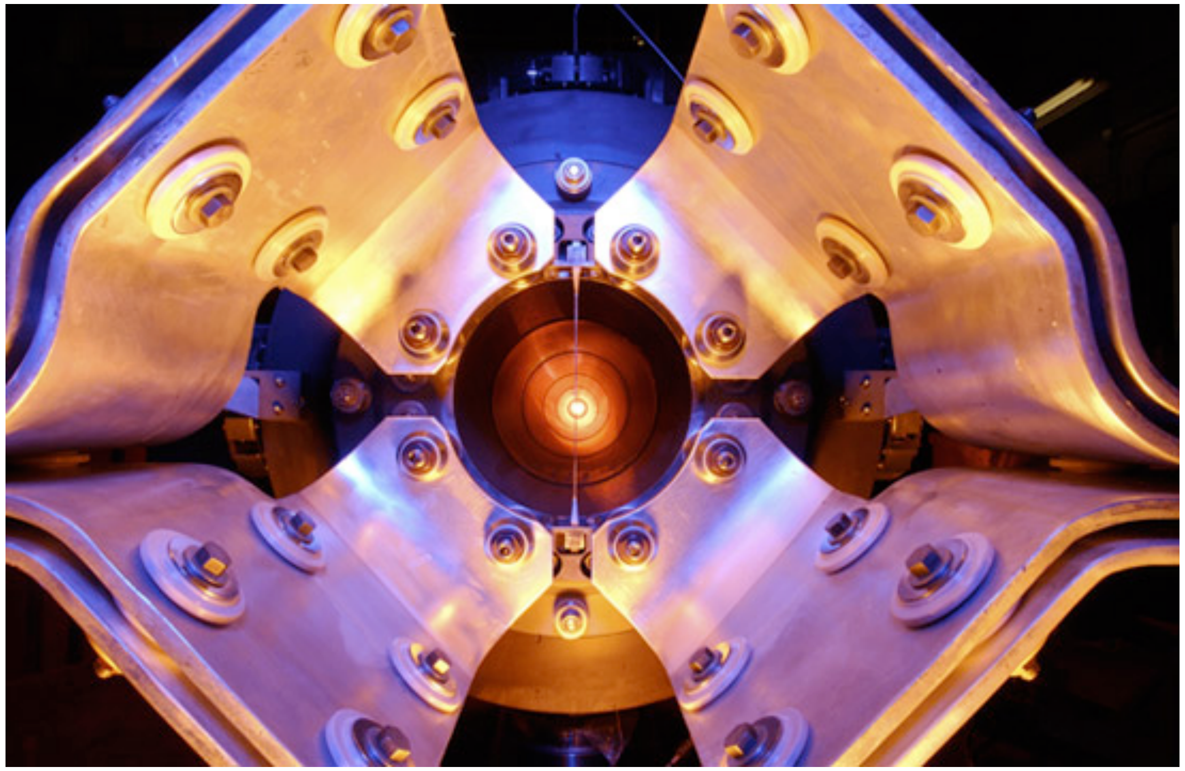
PRL, 9(1):36-44, Jul 1962

Neutrino Production via Accelerators

- High-energy protons strike a light-Z target, producing mesons that decay and produce neutrinos.
- Magnetic focusing horns increase flux by ~6x, allow for sign-selection.
- However, for these 0.5-10 GeV neutrino beams:
  - absolute flux is only known to 8-10%.
  - absolute neutrino-nucleon cross sections around 1 GeV are known to 10-20%.



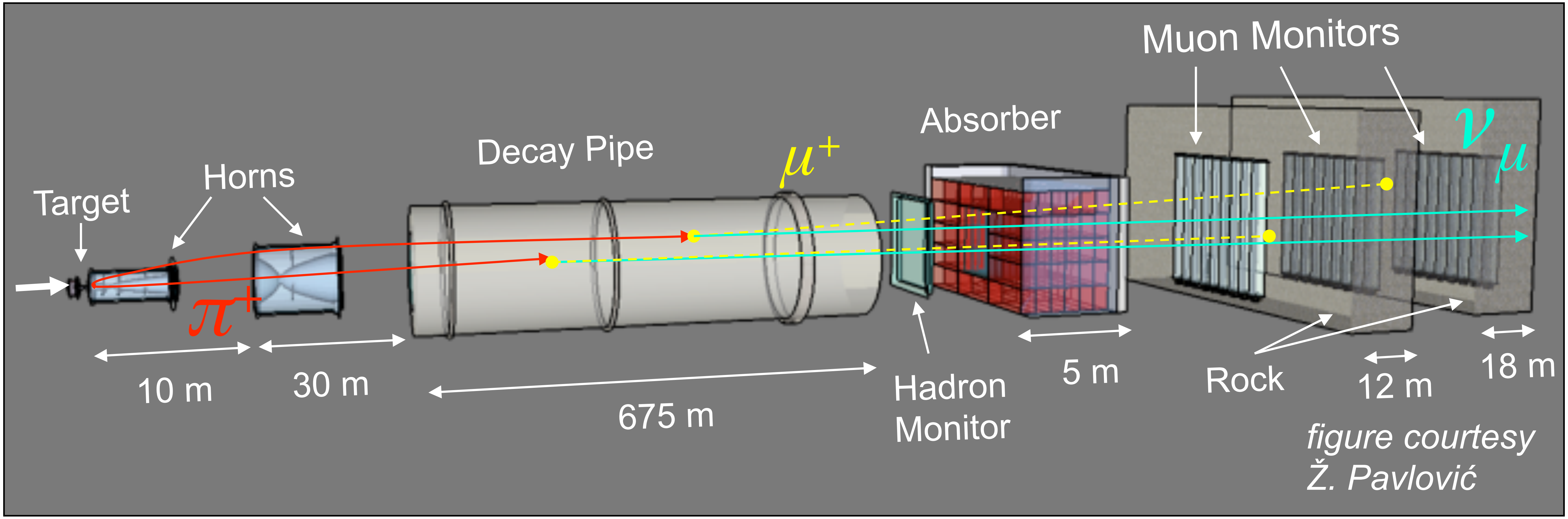
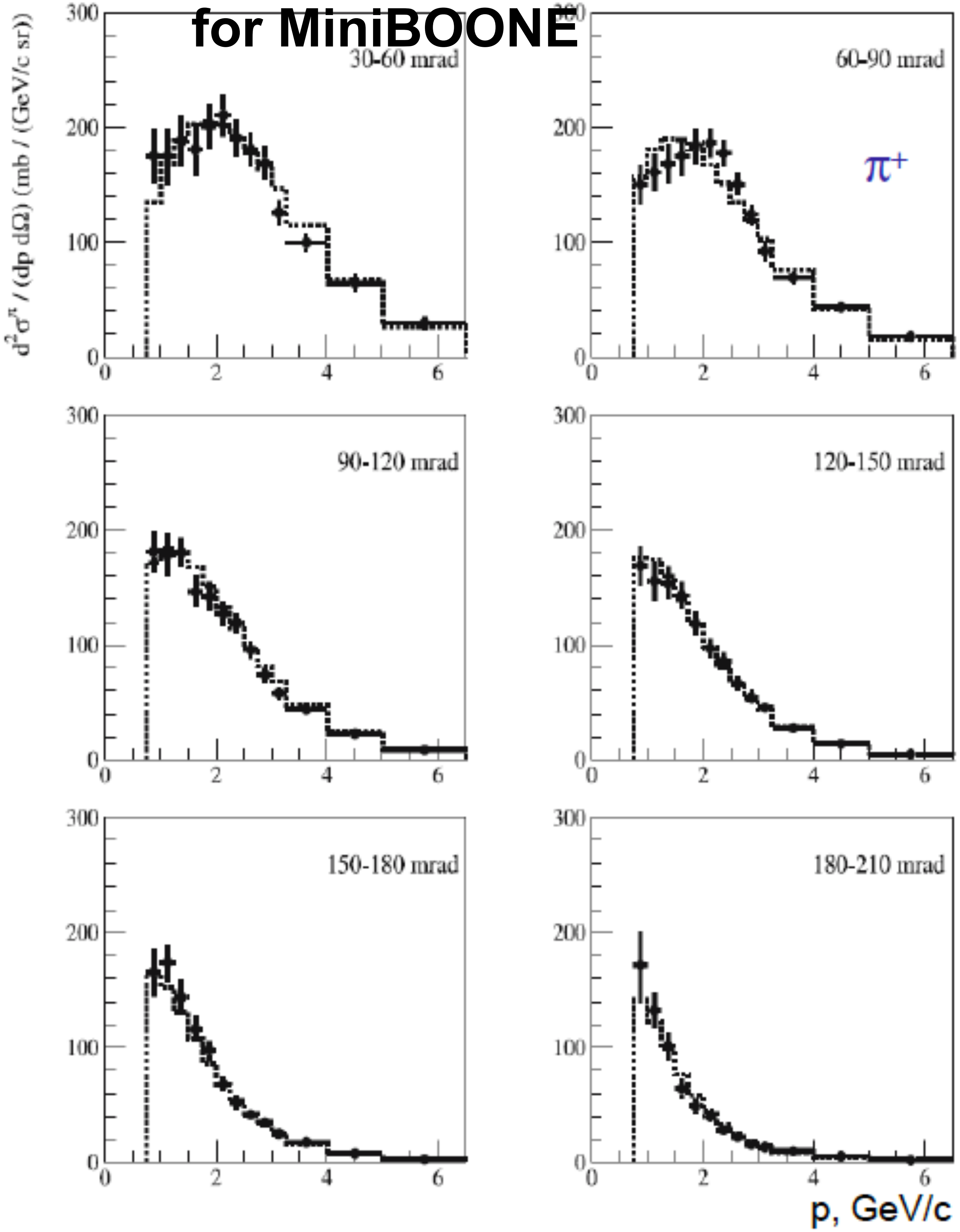


figure courtesy Ž. Pavlović

Hadron Production Measurements for Neutrino Fluxes

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



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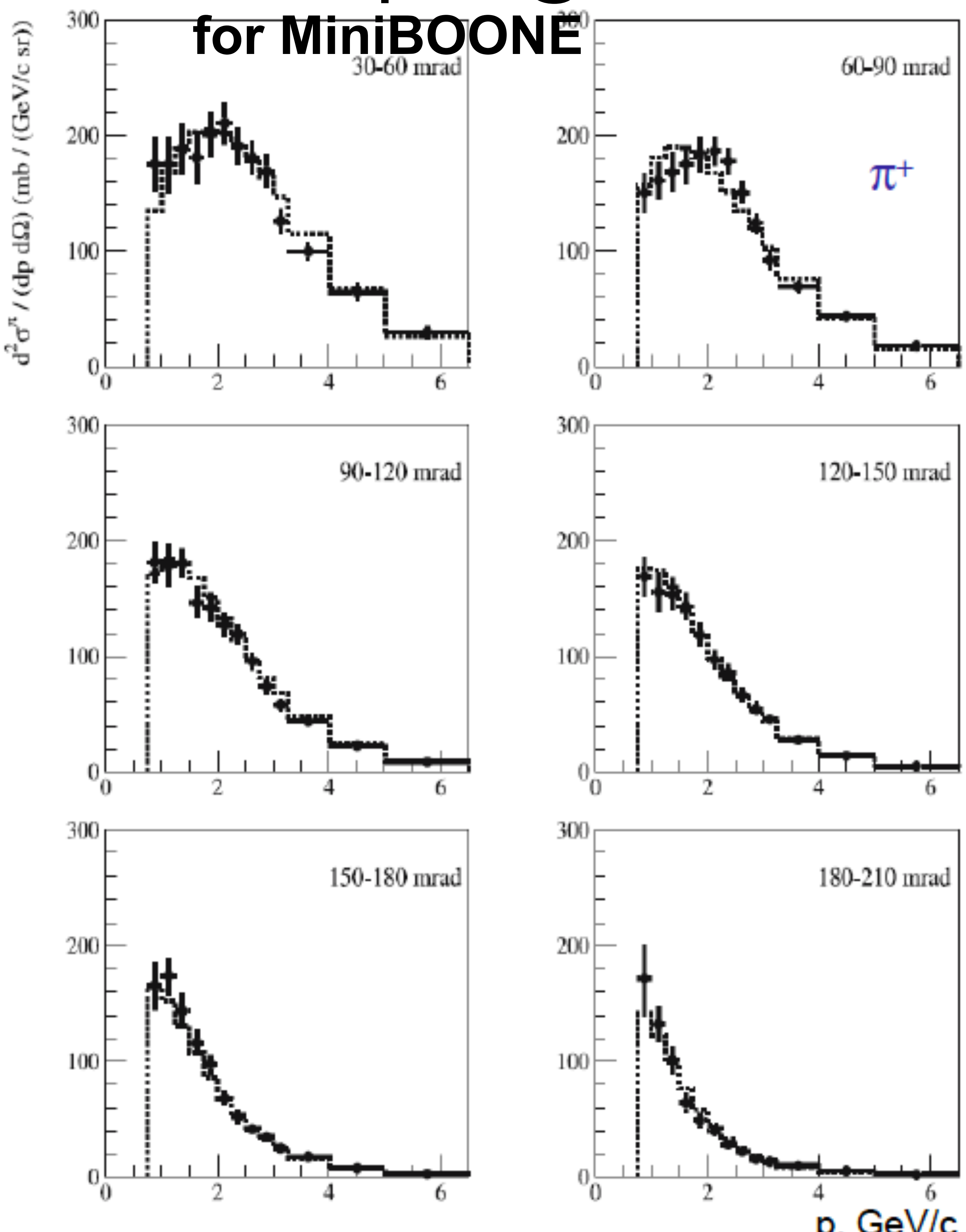
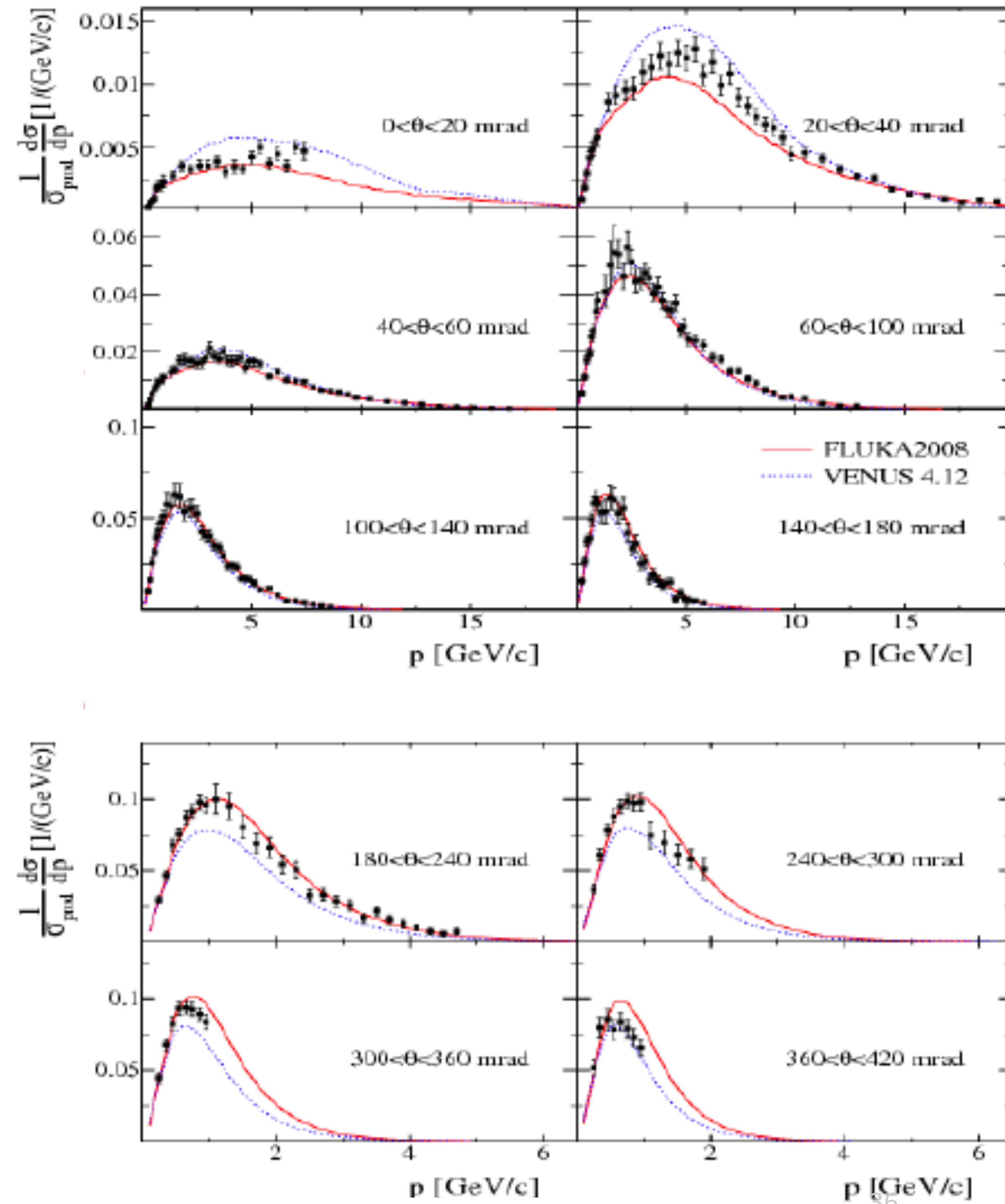


NA61: p+C @ 31 GeV/c for T2K

[Published in PRC 84 (2011) 034604]



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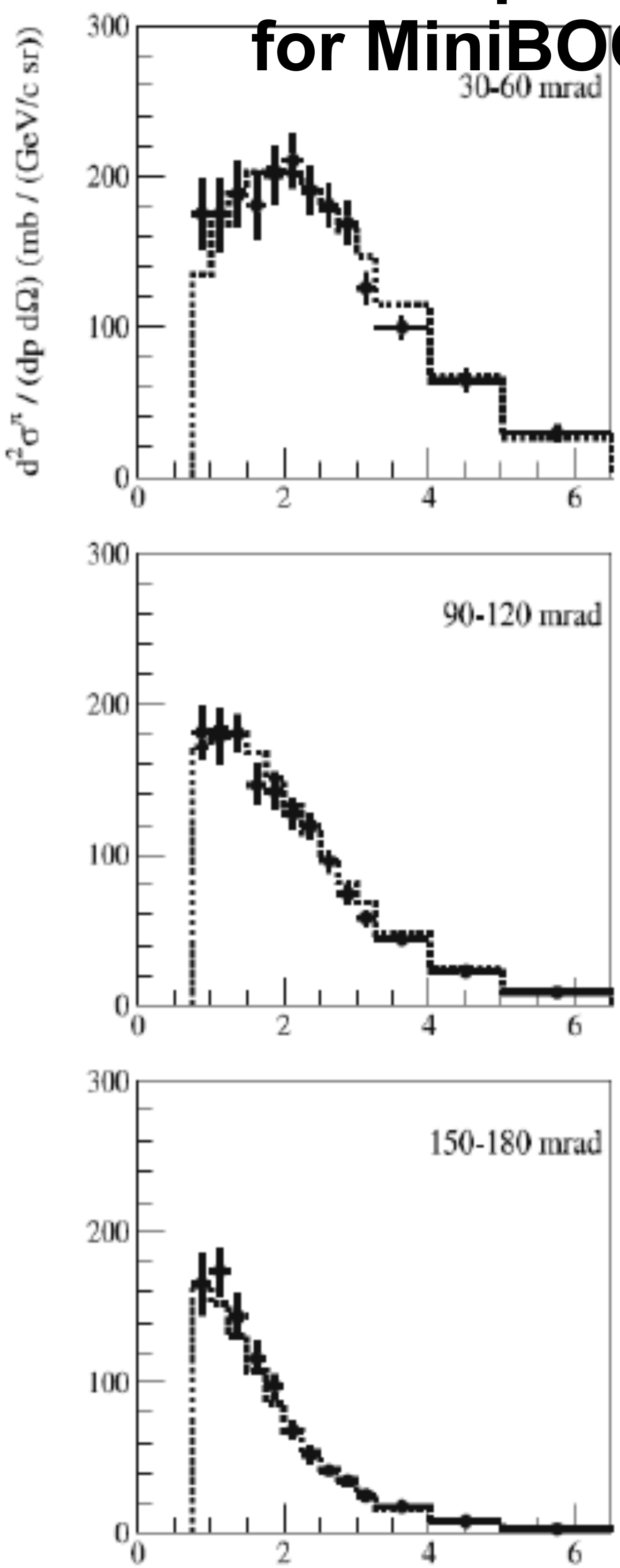
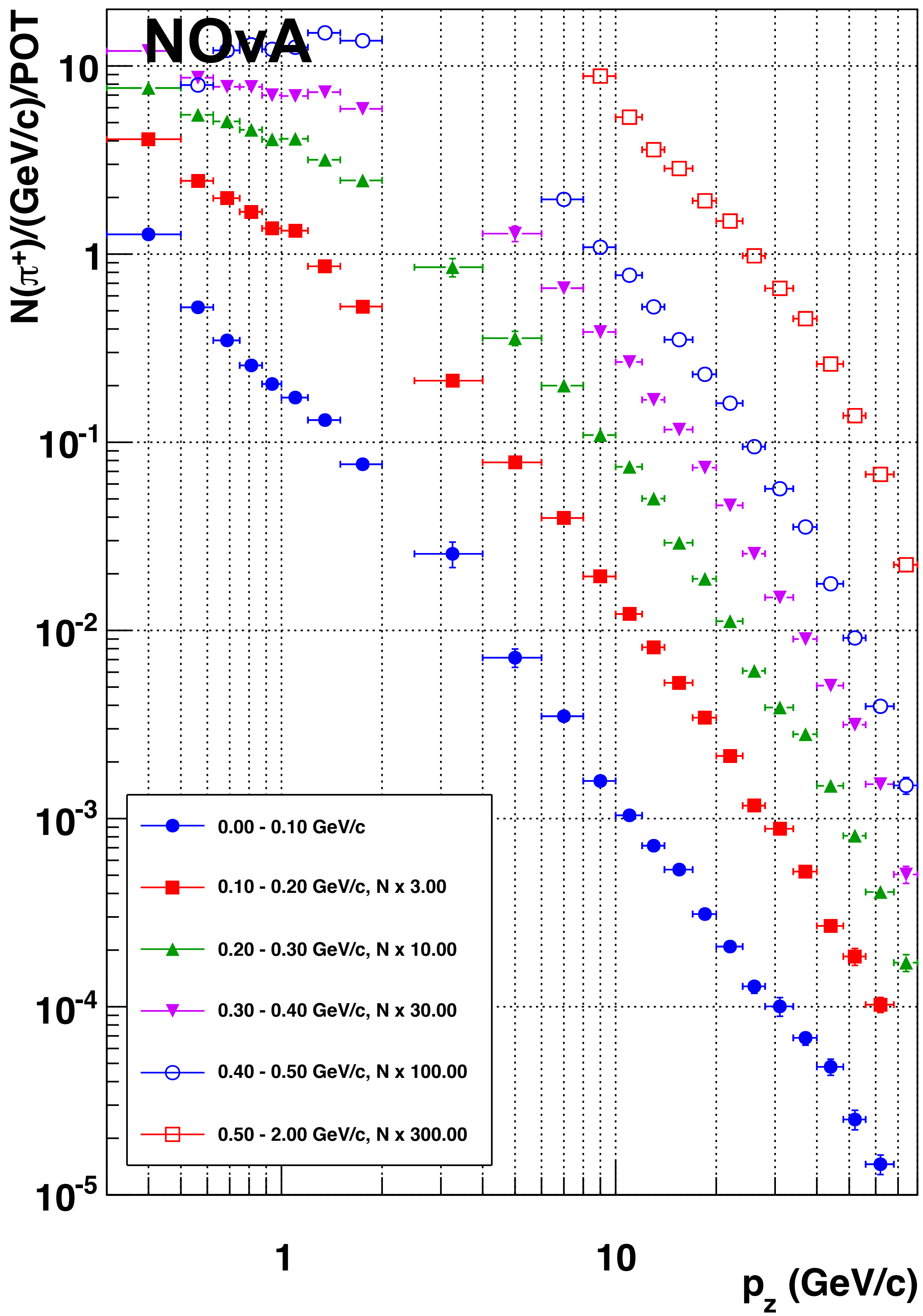


MIPP: p+NuMI Target for MINERvA/MINOS/ NOvA



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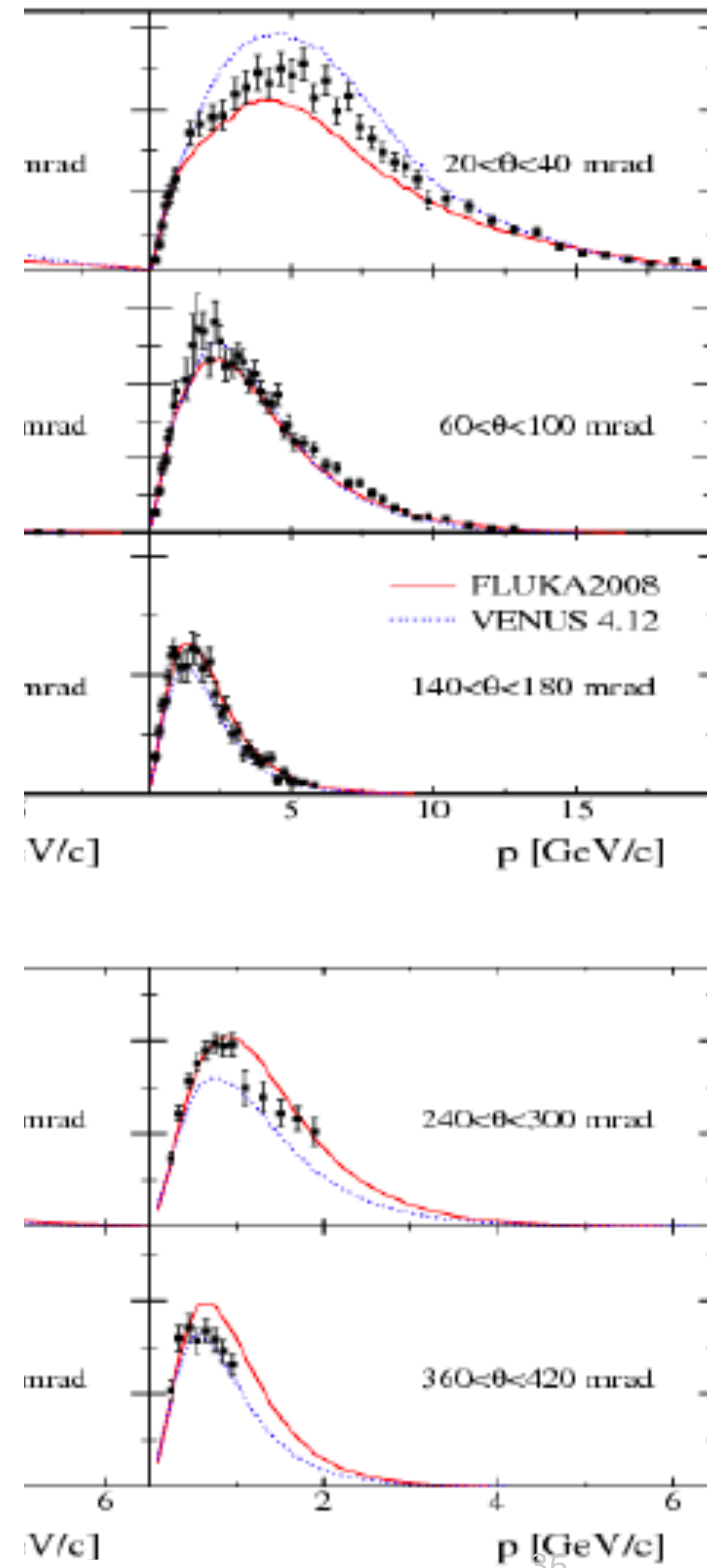
RC 84 (2011) 034604



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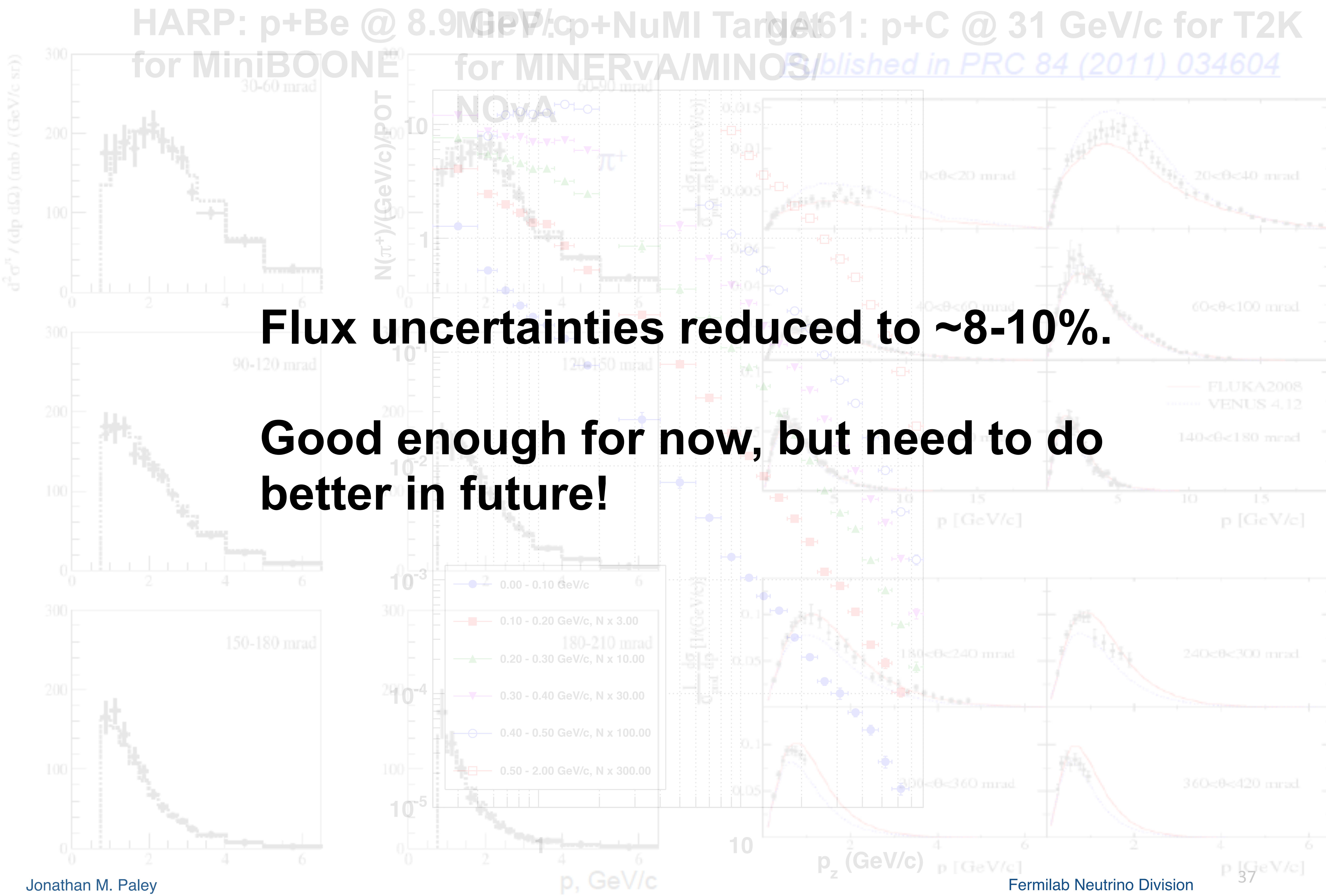
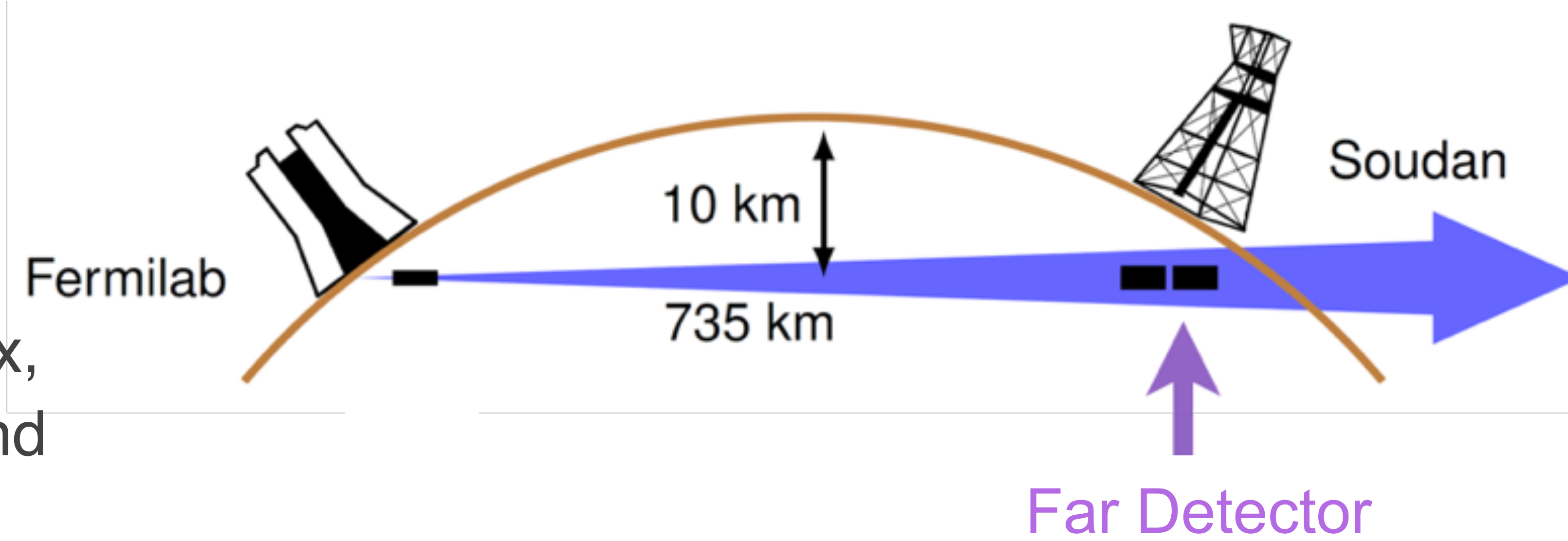


Flux uncertainties reduced to ~8-10%.

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

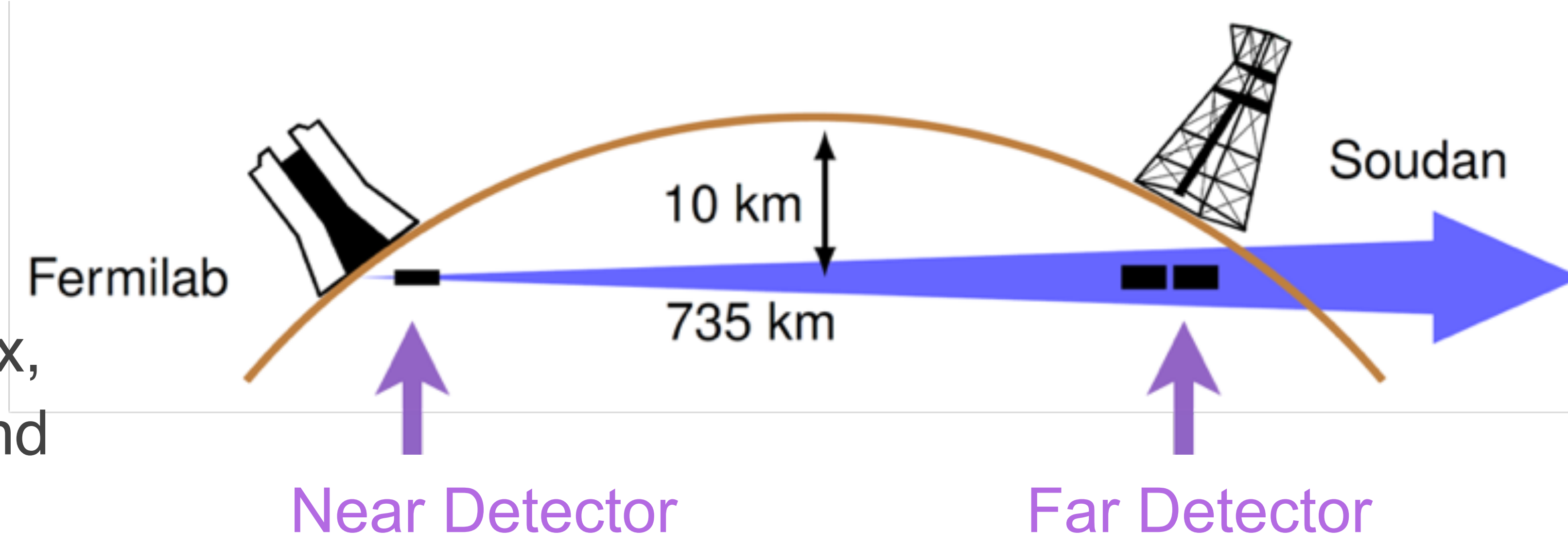
Precision Oscillation Measurements with Neutrinos



- A [large] “far detector” measures the oscillated energy spectrum.
- What is measured is a product of flux, cross section, detection efficiency and oscillation probability.
  - All are functions of neutrino energy.
  - Efficiency can depend on final state topology (differential ν-A cross sections).

$$N_{\mathrm{FD}}(E_{\nu_j}) = \Phi_{\mathrm{FD}}(E_{\nu_j}) \times \sigma(E_{\nu_j}, A_{\mathrm{FD}}) \times \epsilon_{\mathrm{FD}} \times P_{\mathrm{osc}}(i \to j)$$

Precision Oscillation Measurements with Neutrinos



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- What is measured is a product of flux, cross section, detection efficiency and oscillation probability.
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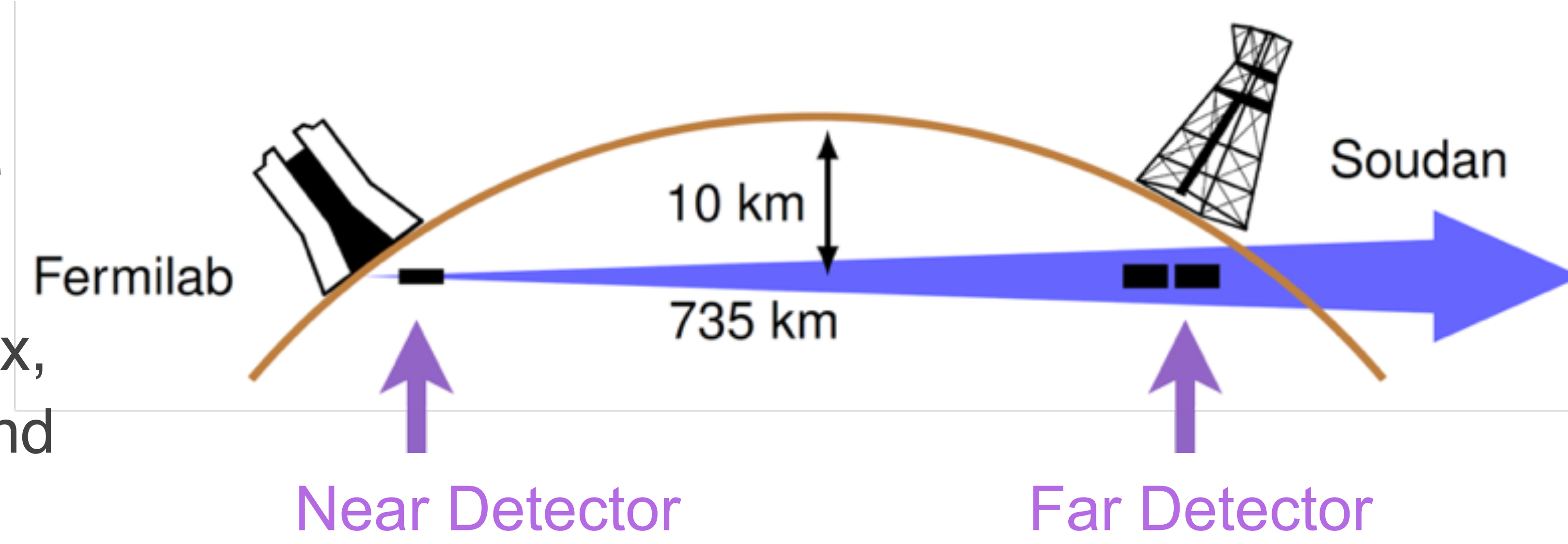
  - Efficiency can depend on final state topology (differential v-A cross sections).
- Impact of uncertainties in flux and cross section are largely mitigated by having two-detector experiments, eg, a [small] “near detector” located close to the measures the energy spectrum prior to oscillations.

$$N_{\mathrm{ND}}(E_{\nu_i}) = \Phi_{\mathrm{ND}}(E_{\nu_i}) \times \sigma(E_{\nu_i}, A_{\mathrm{ND}}) \times \epsilon_{\mathrm{ND}}$$

$$N_{\mathrm{FD}}(E_{\nu_j}) = \Phi_{\mathrm{FD}}(E_{\nu_j}) \times \sigma(E_{\nu_j}, A_{\mathrm{FD}}) \times \epsilon_{\mathrm{FD}} \times P_{\mathrm{osc}}(i \to j)$$

Precision Oscillation Measurements with Neutrinos



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Want to keep these all as similar as possible to minimize systematic uncertainties!

$$N_{\mathrm{ND}}(E_{\nu_i}) = \Phi_{\mathrm{ND}}(E_{\nu_i}) \times \sigma(E_{\nu_i}, A_{\mathrm{ND}}) \times \epsilon_{\mathrm{ND}}$$

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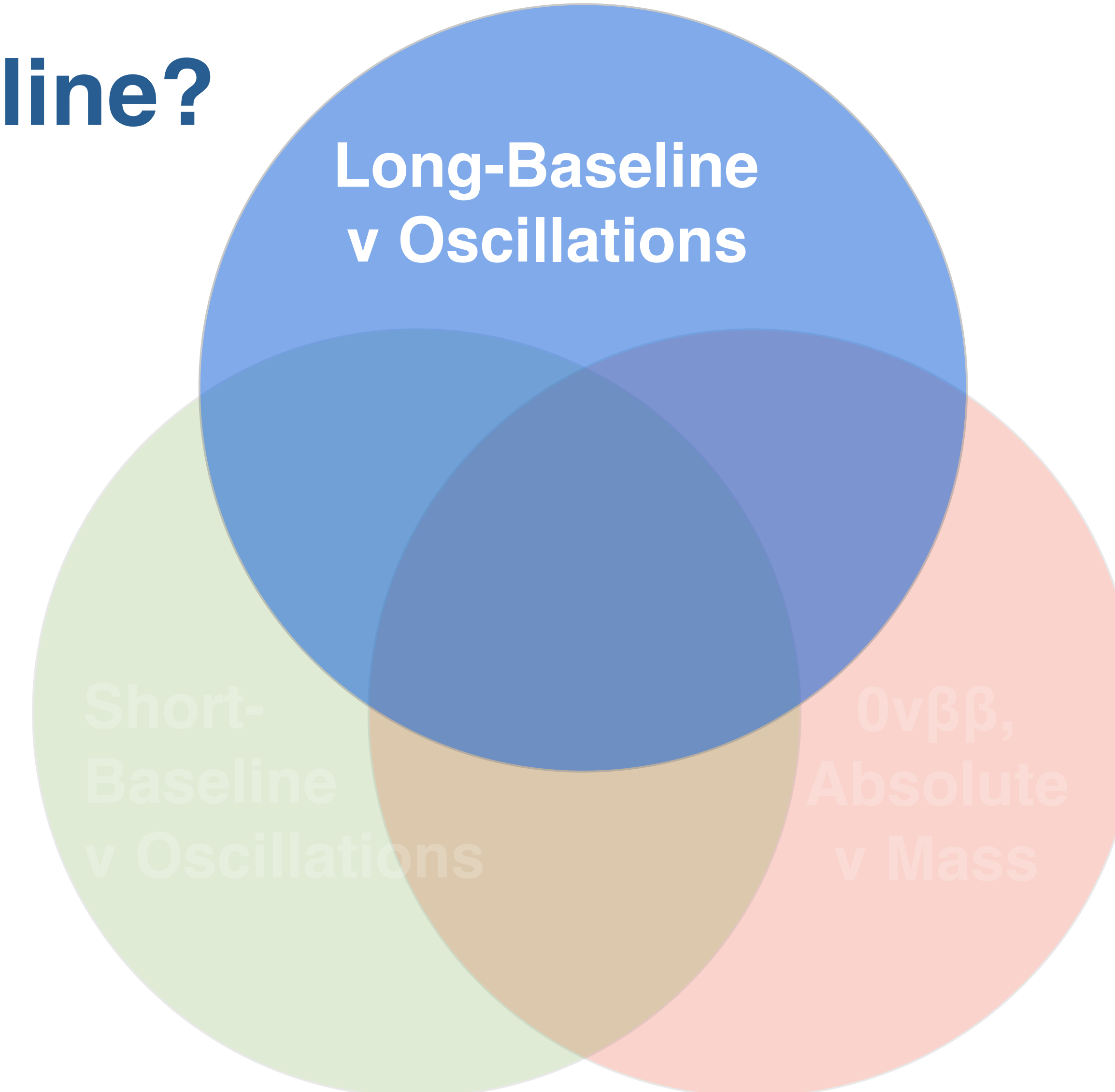
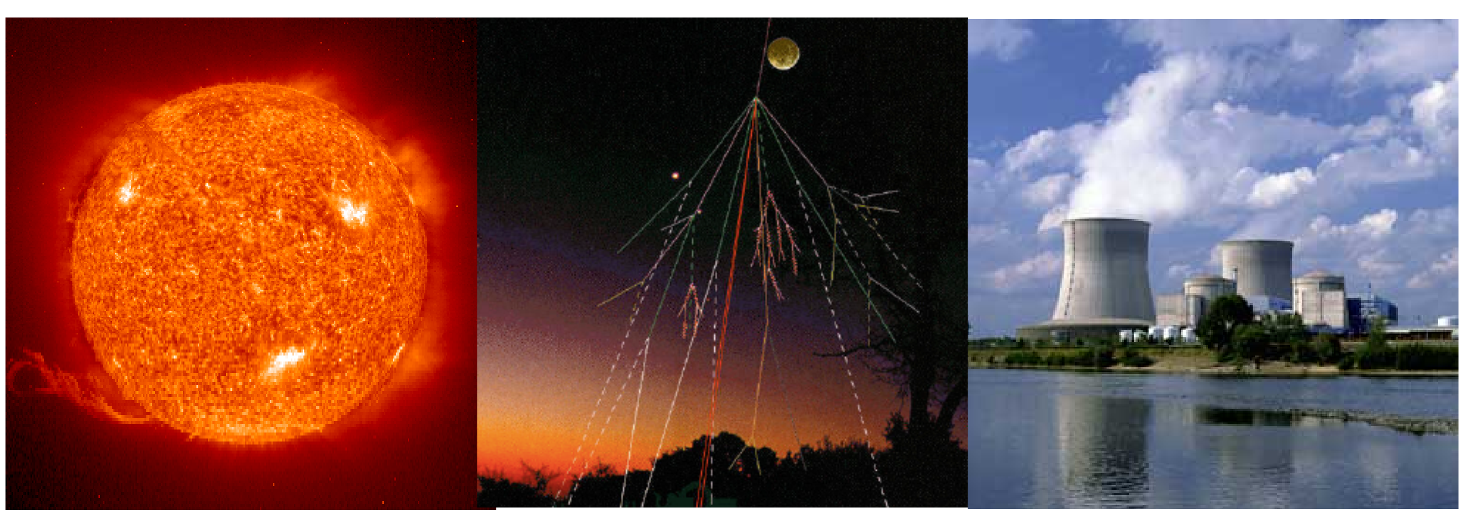
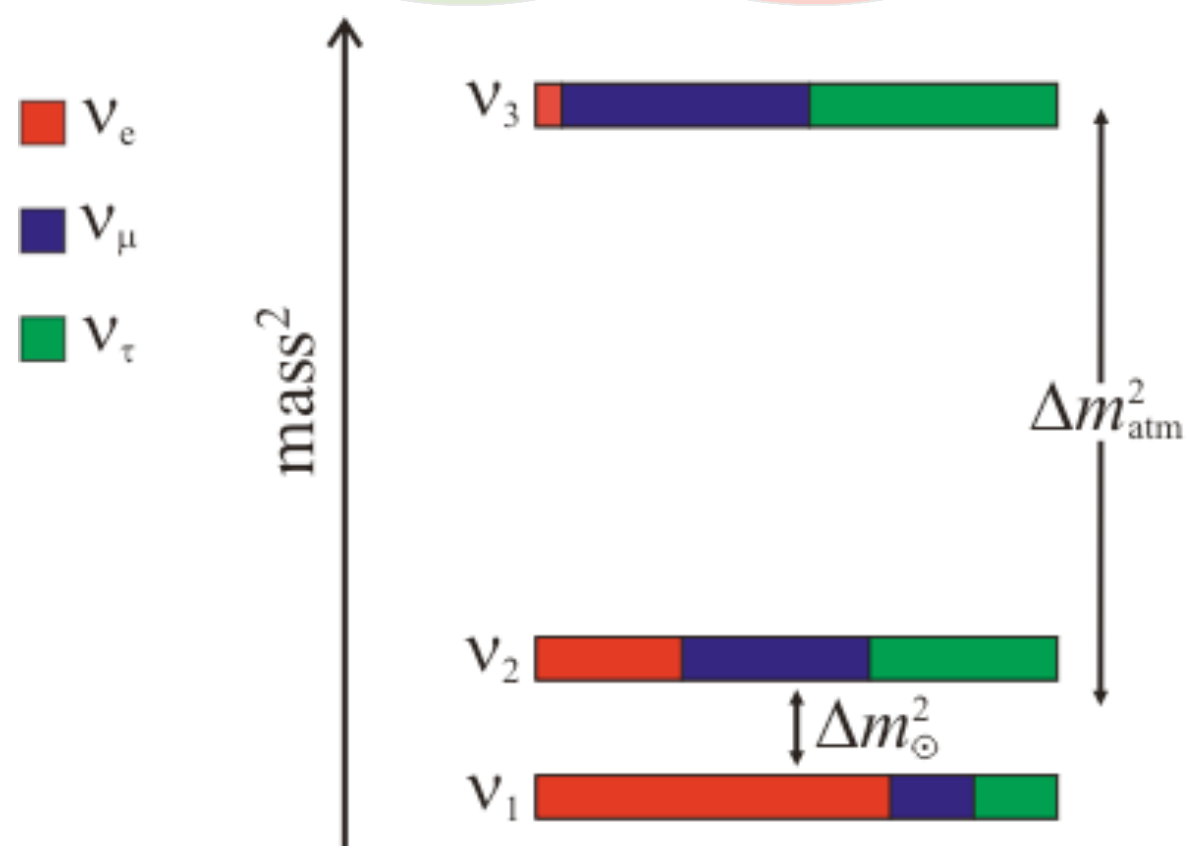
What Do We Mean By Long-Baseline?



- 3-flavor oscillations, defined by the Δm^2 terms of the oscillation probability
- "solar" mass splitting
  - $\Delta m^2_{21} \equiv \Delta m^2_{\odot} \sim 8 \times 10^{-5}\ eV^2$
  - $L/E \sim 15000$ km/GeV
- "atmospheric" mass splitting
  - $\Delta m^2_{32} \approx \Delta m^2_{31} \equiv \Delta m^2_{atm} \sim 2 \times 10^{-3}\ eV^2$
  - $L/E \sim 500$ km/GeV
- Nothing to do with the distance between source and detector!





ν_μ Oscillations in Long-baseline Experiments

- Long-baseline $\nu_\mu \to \nu_e$ experiments have the potential to simultaneously measure θ_{13}, δ_{CP}, sign(Δm_{31}^2), sign(θ_{23}-45°):

$$\Delta = \Delta m_{31}^2 L/(4E_\nu)$$

$$A = 2\sqrt{2} G_F n_e E_\nu / \Delta m_{31}^2$$

$$\alpha = \Delta m_{12}^2 / \Delta m_{31}^2$$

$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2((A-1)\Delta)}{(A-1)^2} +$$

$$\alpha \sin\delta \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \sin\Delta \sin(A\Delta)\frac{\sin((1-A)\Delta)}{A(1-A)} +$$

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M. Freund, Phys. Rev. D64 (2001) 053003

Note: want to maximize $A\Delta \simeq L/(2000 \text{ km})$

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$$P(\nu_\mu \rightarrow \nu_e) \simeq \sin^2\theta_{23} \sin^2 2\theta_{13} \frac{\sin^2((A-1)\Delta)}{(A-1)^2} +$$

$$\alpha \sin\delta \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \sin\Delta \sin(A\Delta) \frac{\sin((1-A)\Delta)}{A(1-A)} +$$

$$\alpha \cos\delta \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos\Delta \sin(A\Delta) \frac{\sin((1-A)\Delta)}{A(1-A)} + \mathcal{O}(\alpha^2)$$

M. Freund, Phys. Rev. D64 (2001) 053003

Note: want to maximize $A\Delta \simeq L/(2000 \text{ km})$

ν_μ Oscillations in Long-baseline Experiments

- Long-baseline $\nu_\mu \rightarrow \nu_e$ experiments have the potential to simultaneously measure θ_{13}, δ_{CP}, sign(Δm_{31}^2), sign(θ_{23}-45°):

$$\Delta = \Delta m_{31}^2 L/(4E_\nu)$$

$$A = 2\sqrt{2} G_F n_e E_\nu / \Delta m_{31}^2$$

$$\alpha = \Delta m_{12}^2 / \Delta m_{31}^2$$

$$P(\nu_\mu \rightarrow \nu_e) \simeq \sin^2\theta_{23} \sin^2 2\theta_{13} \frac{\sin^2((A-1)\Delta)}{(A-1)^2} +$$

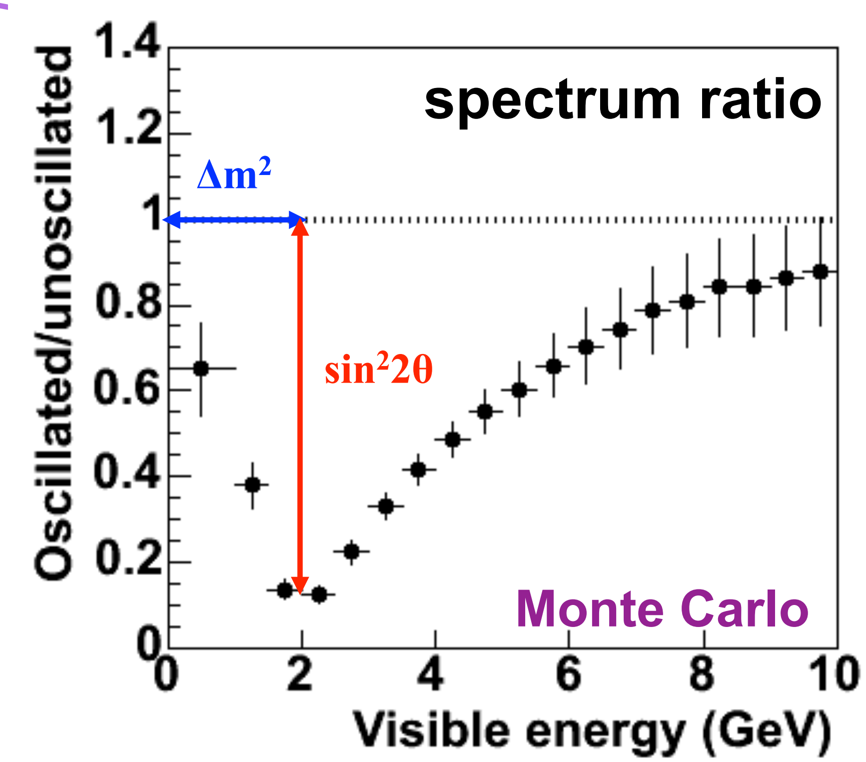
$$\alpha \sin\delta \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \sin\Delta \sin(A\Delta) \frac{\sin((1-A)\Delta)}{A(1-A)} +$$

$$\alpha \cos\delta \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos\Delta \sin(A\Delta) \frac{\sin((1-A)\Delta)}{A(1-A)} + \mathcal{O}(\alpha^2)$$

Note: want to maximize $A\Delta \simeq L/(2000\ \mathrm{km})$

- Separate measurement of $\nu_\mu \rightarrow \nu_\mu$ gives access to $\sin^2(2\theta_{23})$ and Δm^2_{32}:

$$P(\nu_\mu \rightarrow \nu_\mu) \simeq 1 - \sin^2(2\theta_{23}) \sin^2\left(1.27 \Delta m_{32}^2 \frac{L}{E}\right)$$



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$$\Delta = \Delta m^2_{31} L/(4E_\nu)$$

$$A = 2\sqrt{2} G_F n_e E_\nu / \Delta m^2_{31}$$

$$\alpha = \Delta m^2_{12} / \Delta m^2_{31}$$

$$P(\nu_\mu \rightarrow \nu_e) \simeq \sin^2\theta_{23} \sin^2 2\theta_{13} \frac{\sin^2((A-1)\Delta)}{(A-1)^2} +$$

$$\alpha \sin\delta \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \sin\Delta \sin(A\Delta) \frac{\sin((1-A)\Delta)}{A(1-A)} +$$

$$\alpha \cos\delta \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos\Delta \sin(A\Delta) \frac{\sin((1-A)\Delta)}{A(1-A)} + \mathcal{O}(\alpha^2)$$

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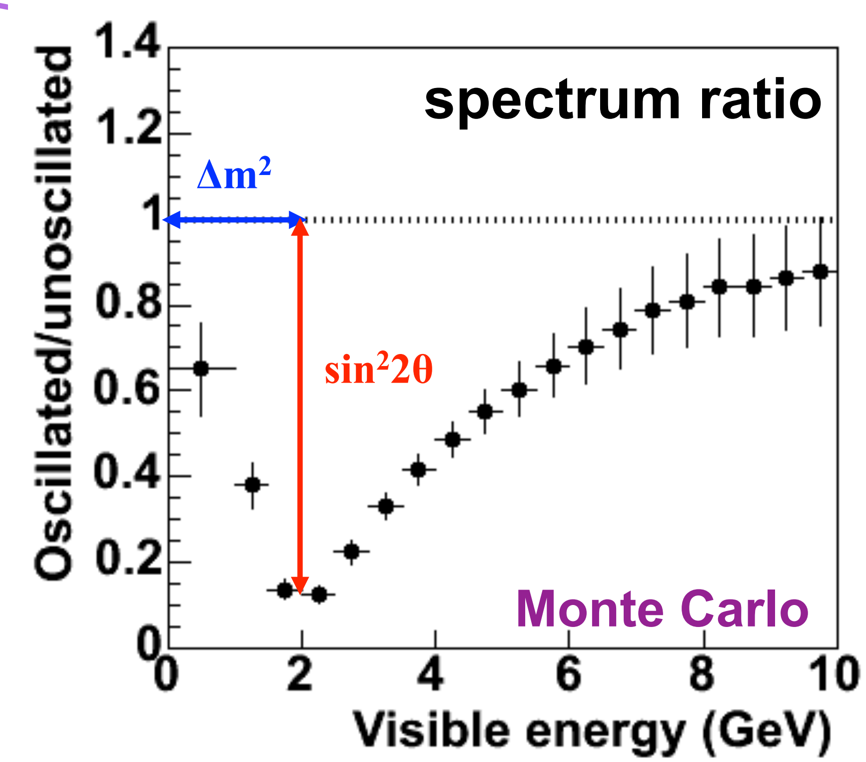
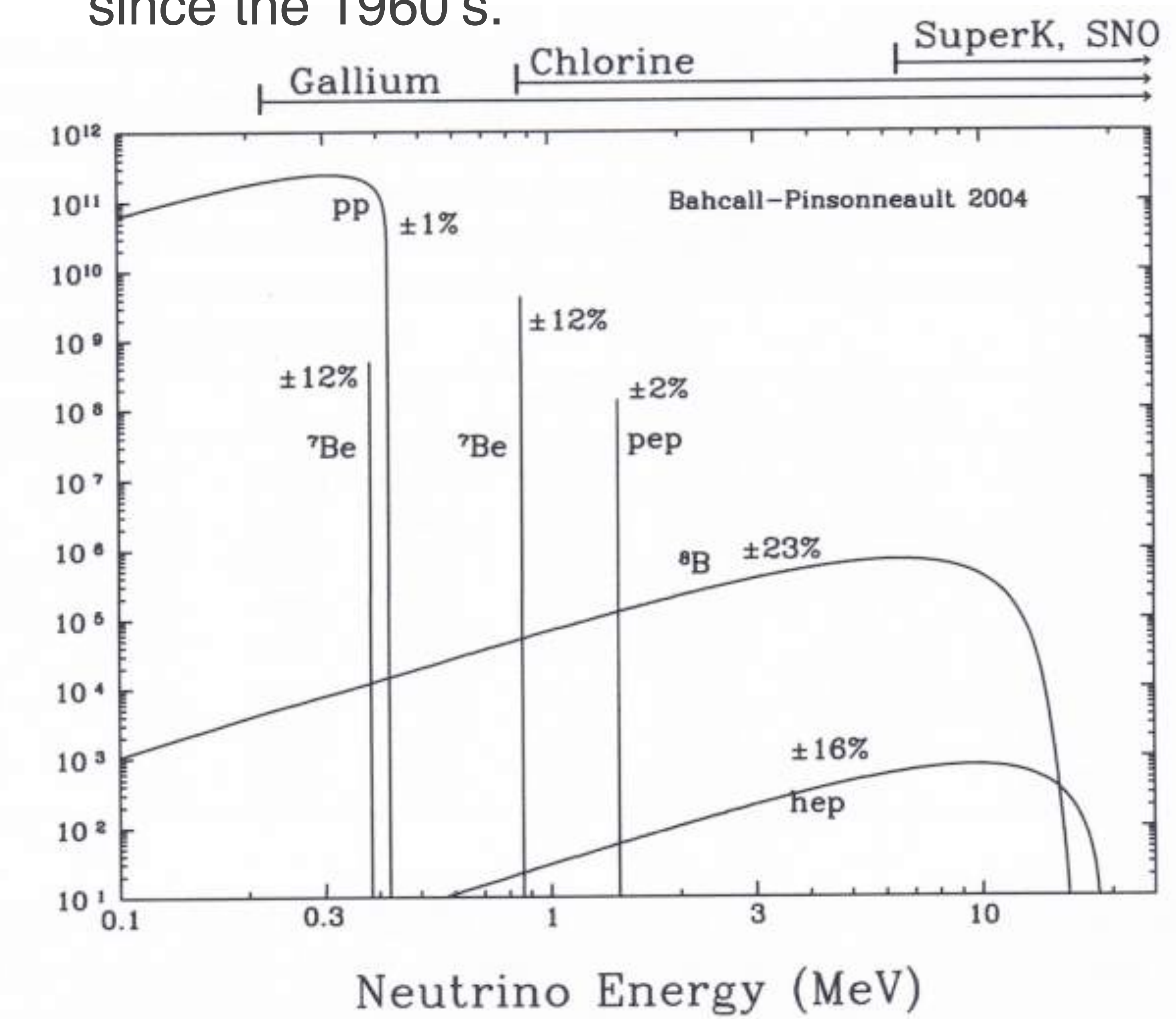
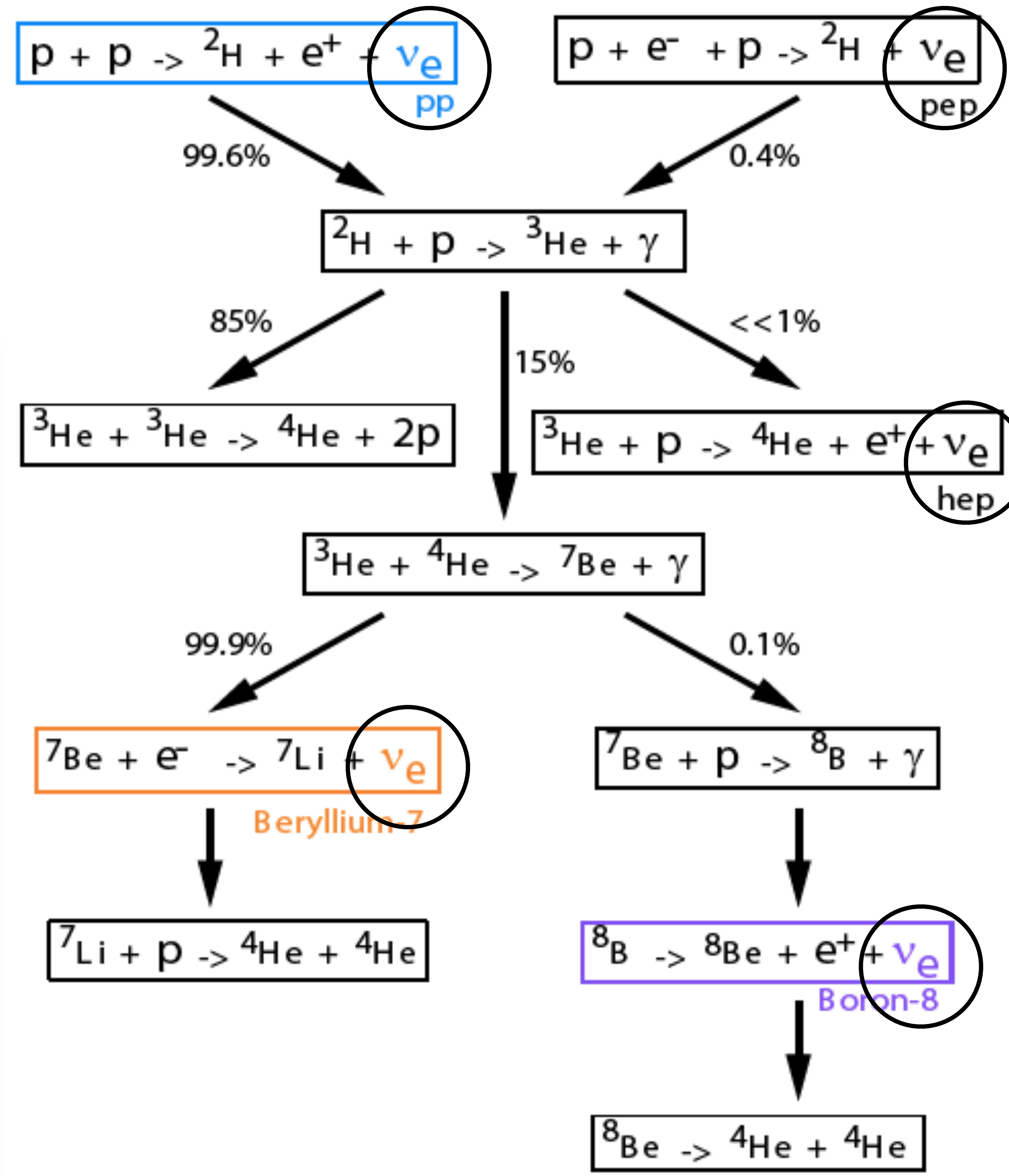


The Solar Neutrino Problem

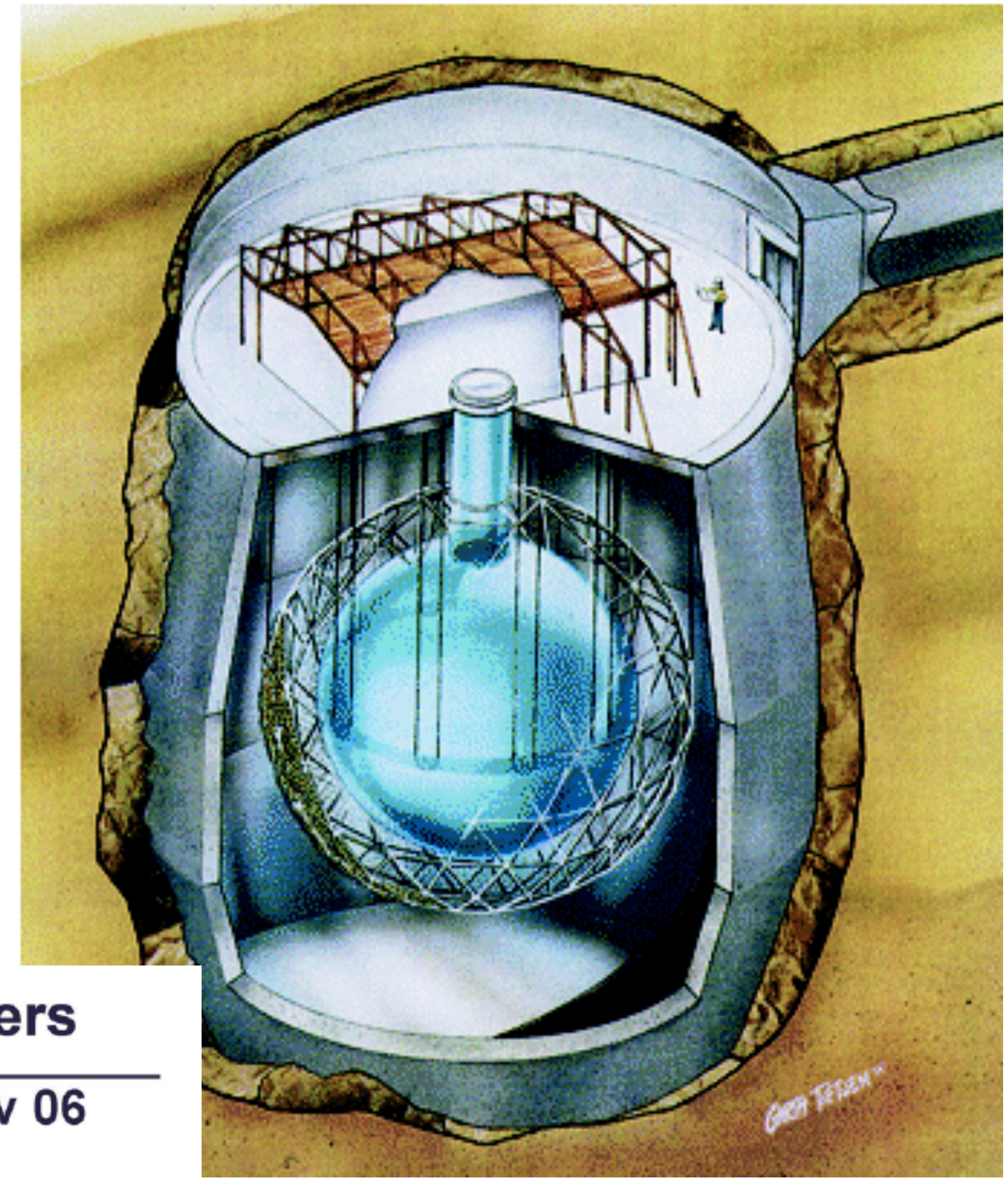
- We expect to see only ν_e coming from the sun.
- Precise solar models allow us to predict the energy spectra of neutrinos from the sun.
- A deficit (~1/2) of ν_es has been observed since the 1960's.





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: $\nu_\alpha + {}^2H \rightarrow n + p + \nu_\alpha$



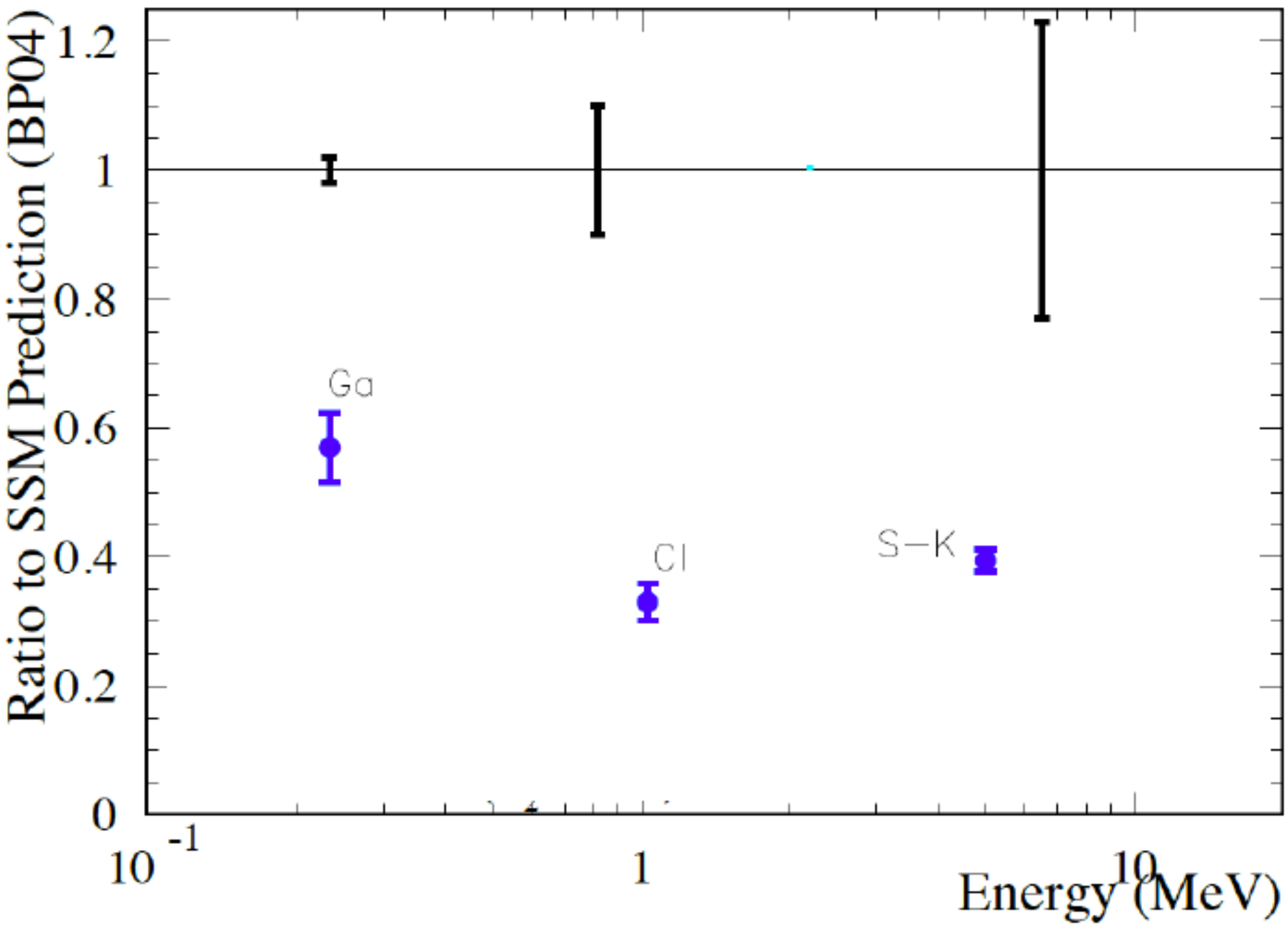
$$R_E = \frac{R_{CC}}{R_{ES}} \neq 1 \quad \text{or} \quad R_N = \frac{R_{CC}}{R_{NC}} \neq 1$$

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

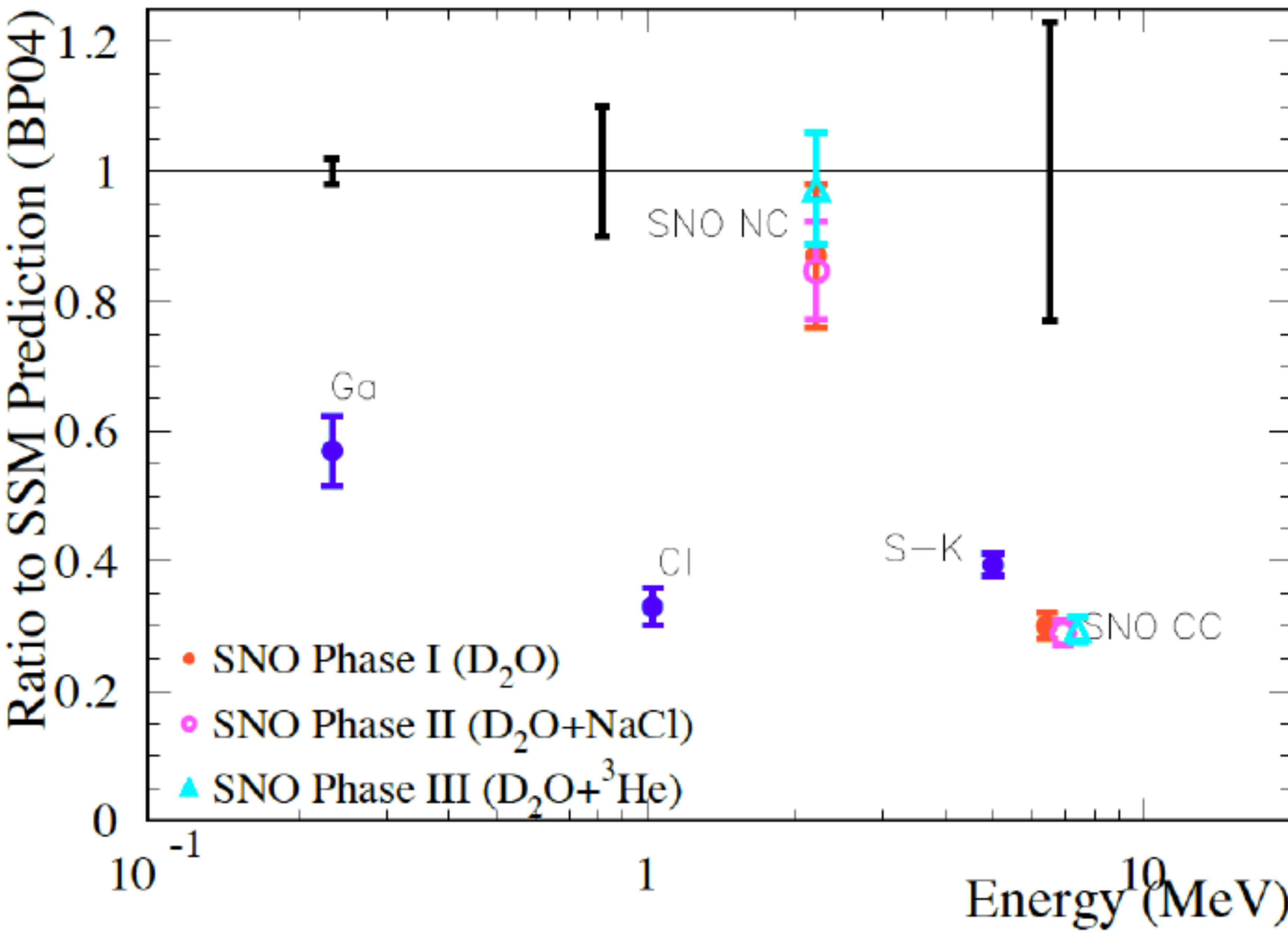
Solar Neutrino Problem



arXiv:1109.0763

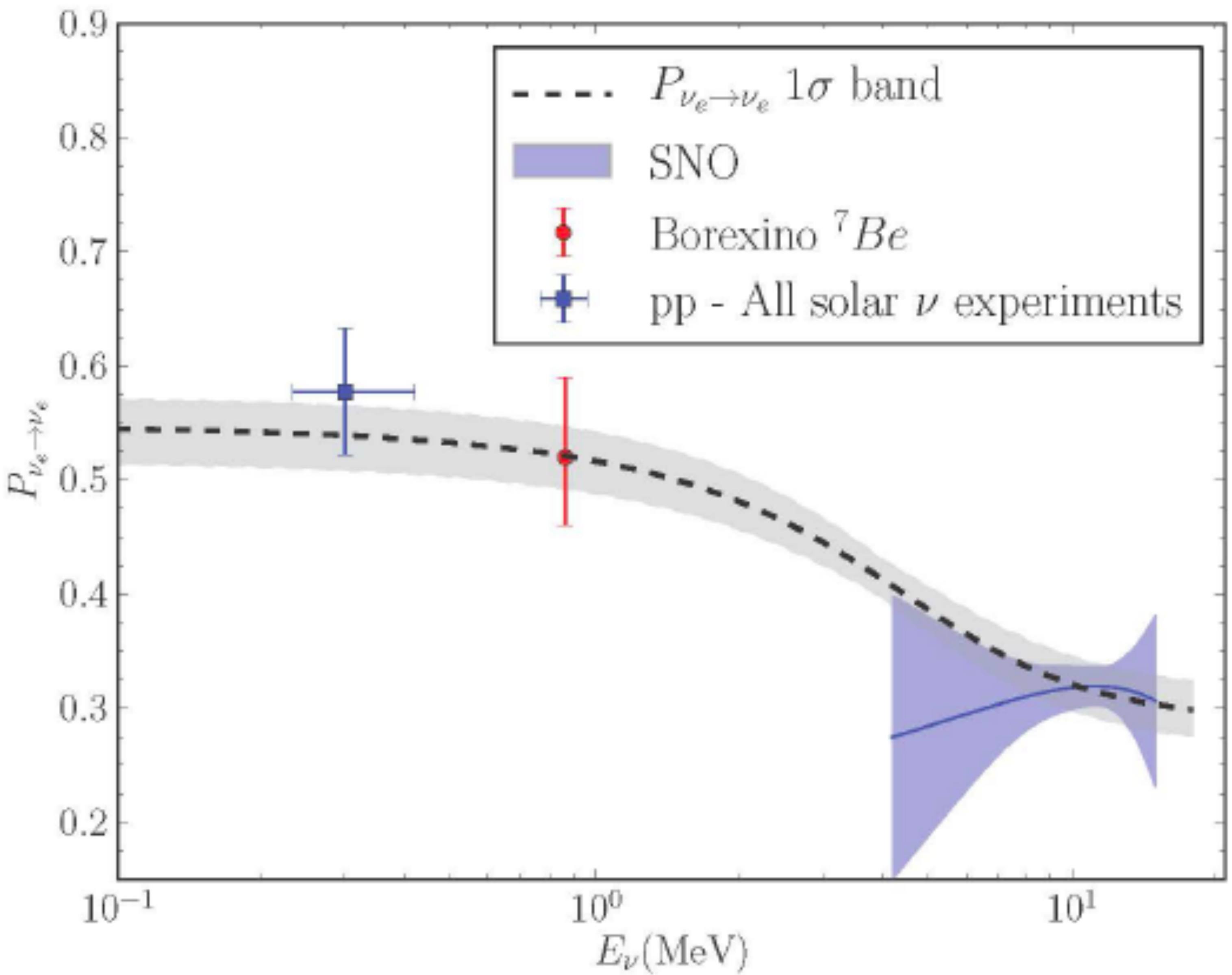
The Sudbury Neutrino Oscillation Detector

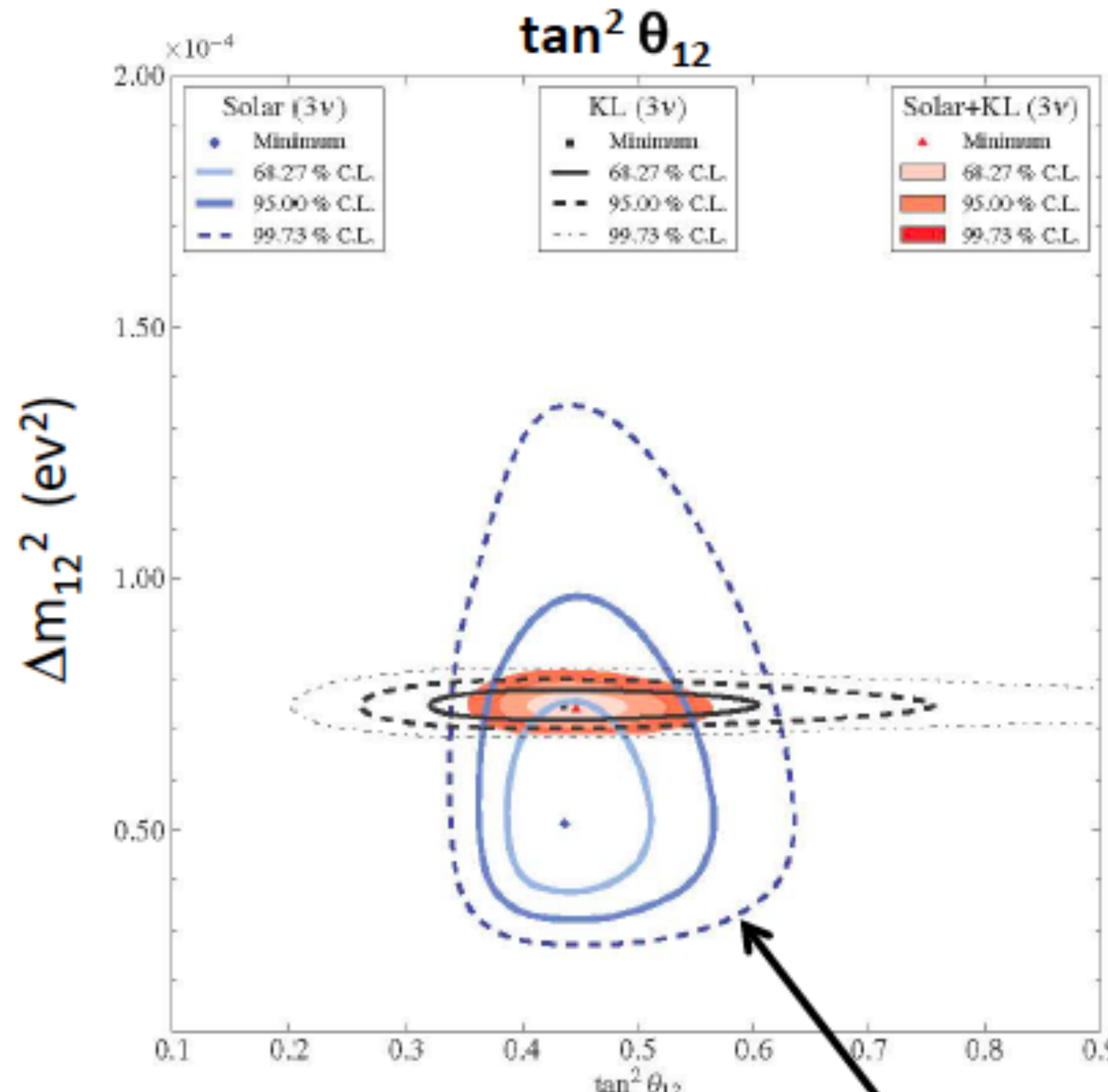
Solar Neutrino Problem Resolved



arXiv:1109.0763

The Sudbury Neutrino Oscillation Detector





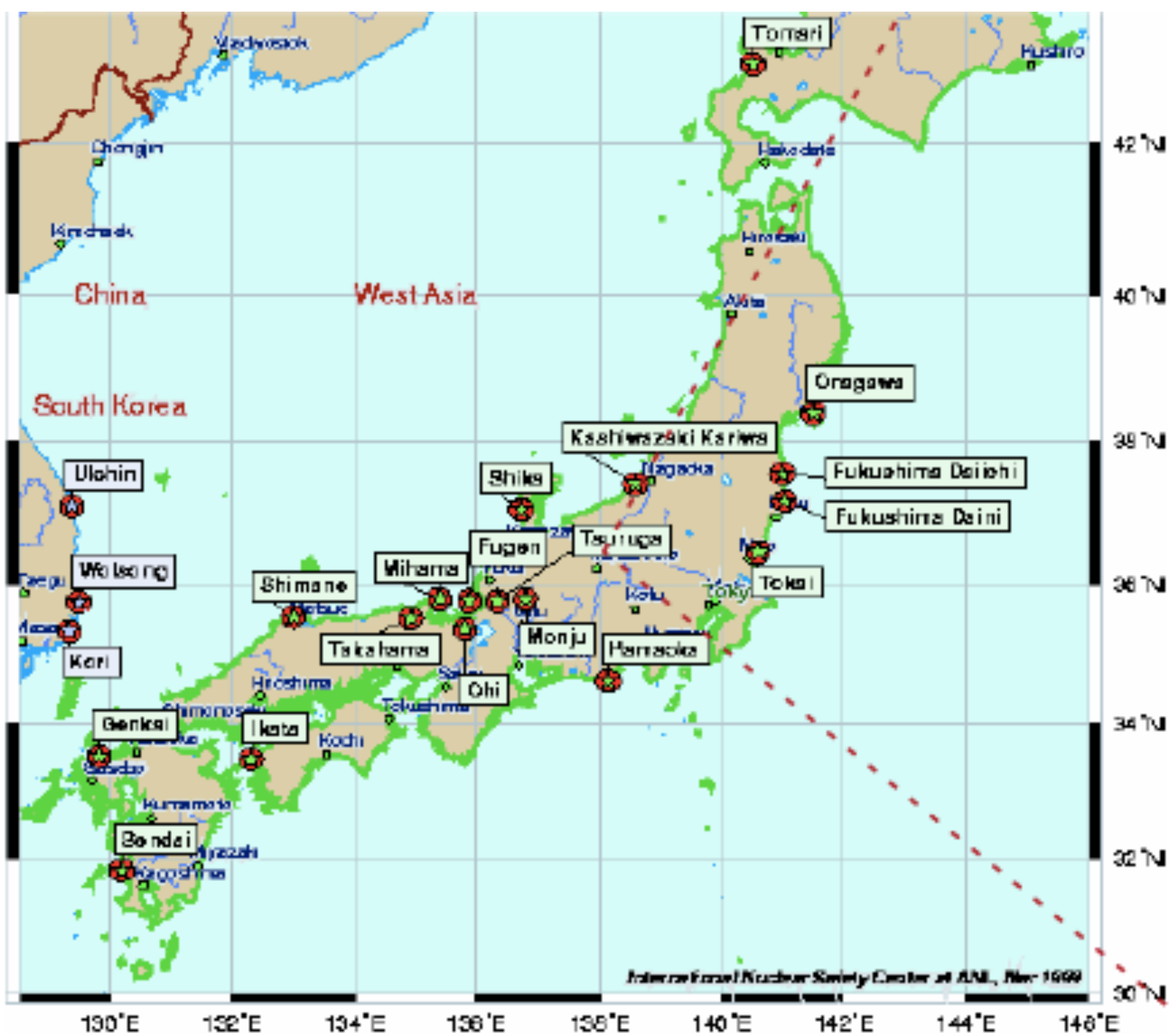
SNO defines θ_{12} to be non-maximal by more than 5 σ.

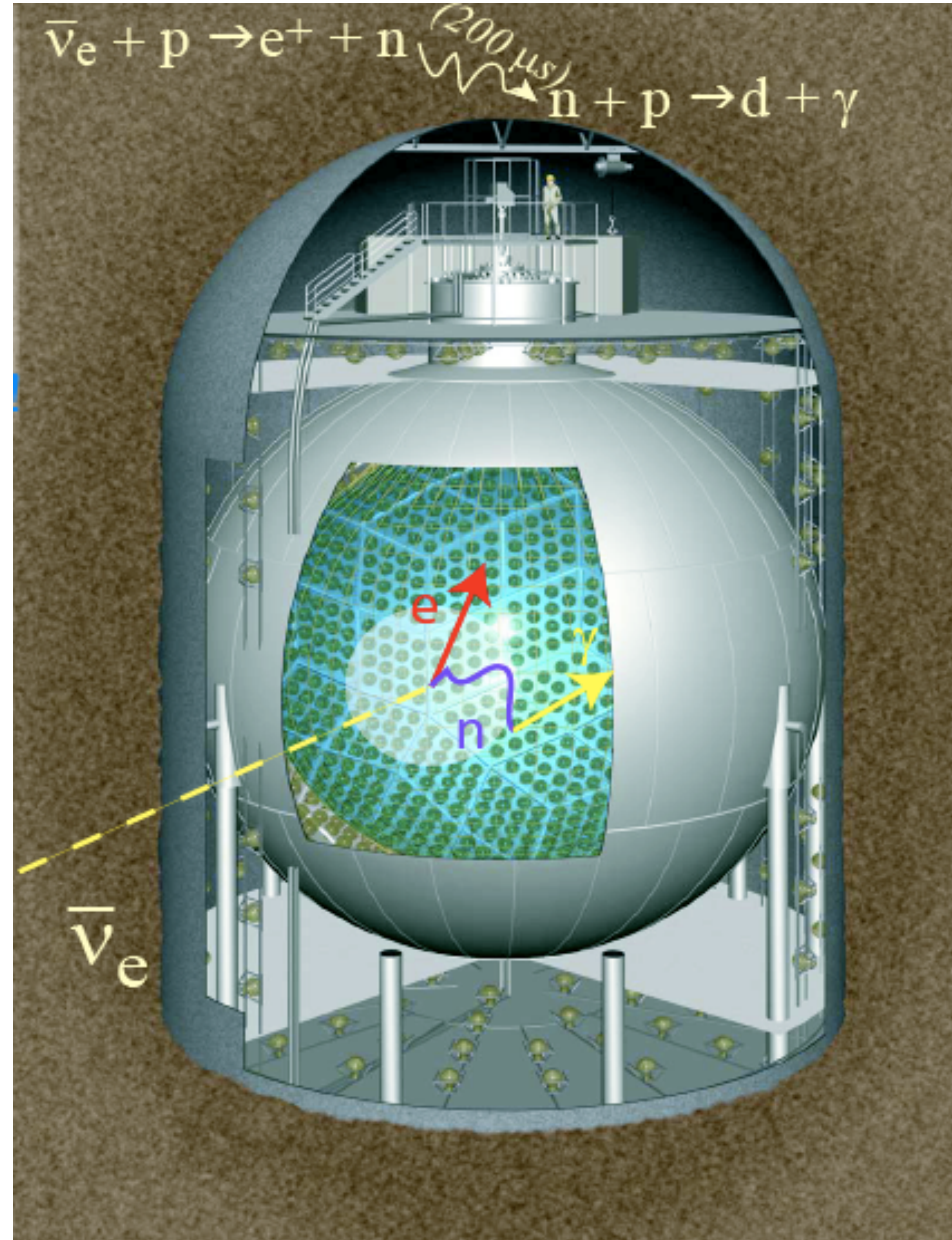
McDonald - Neutrino 2012

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.



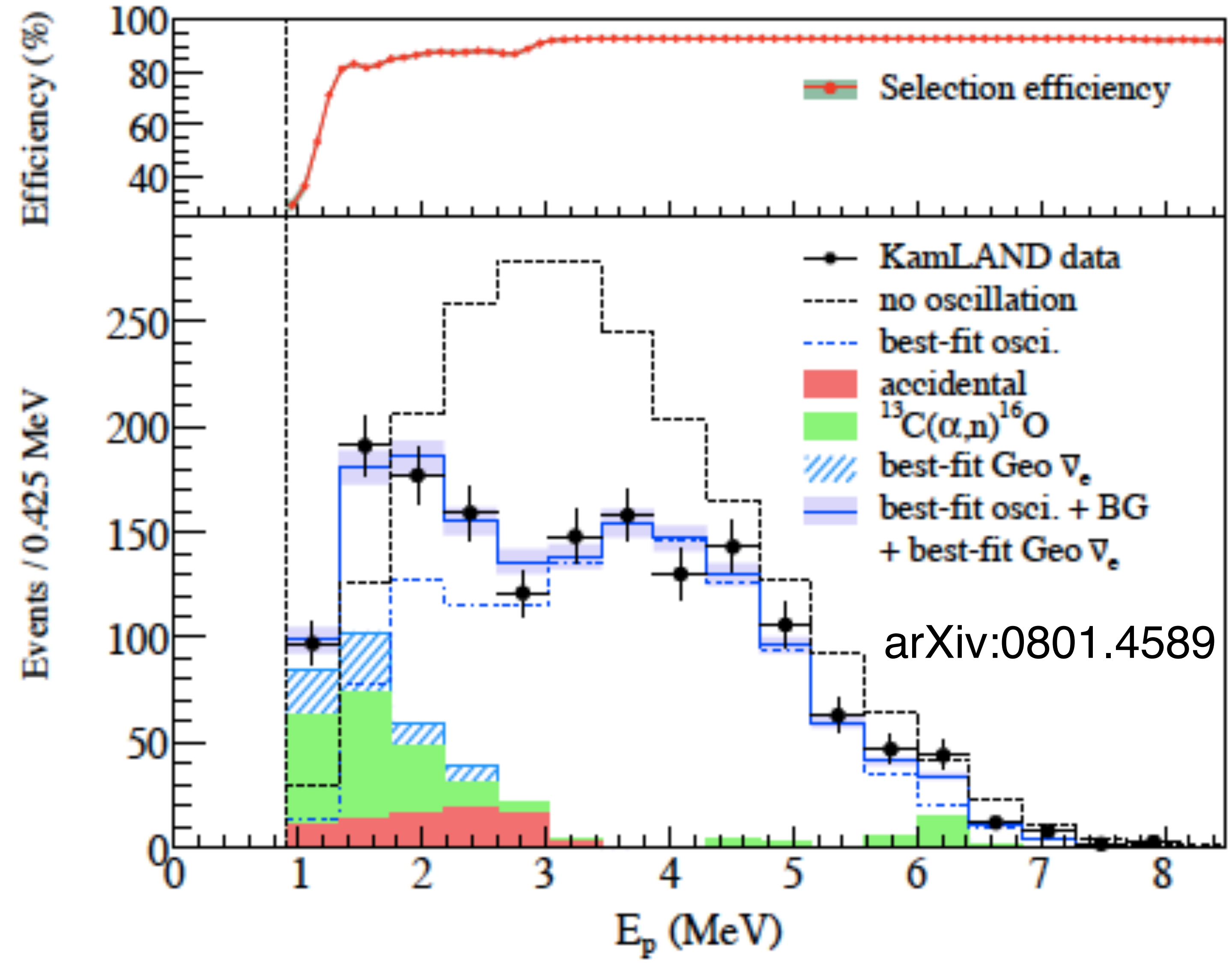


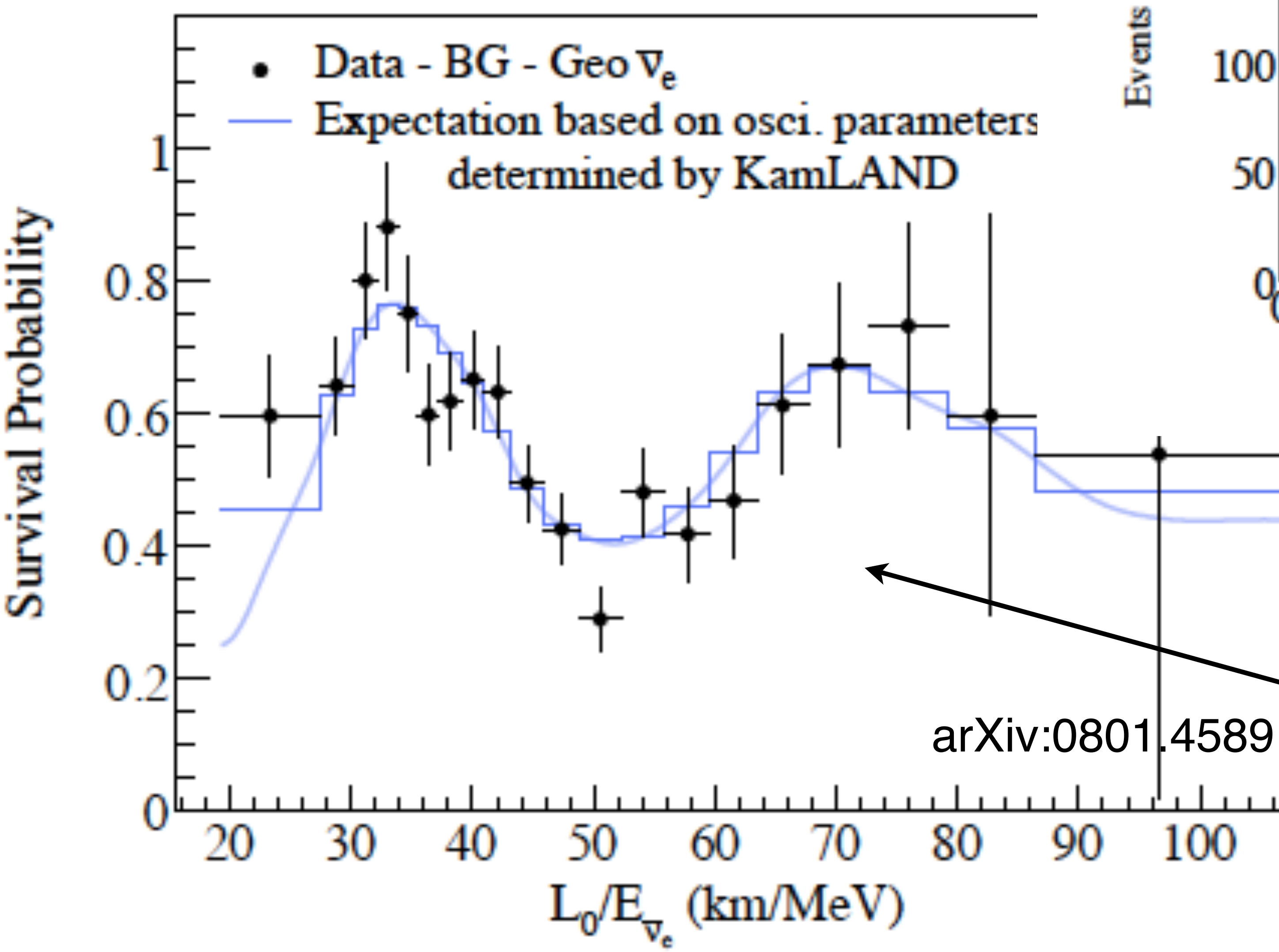
KamLAND Results

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

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

(combined with solar data from SNO)

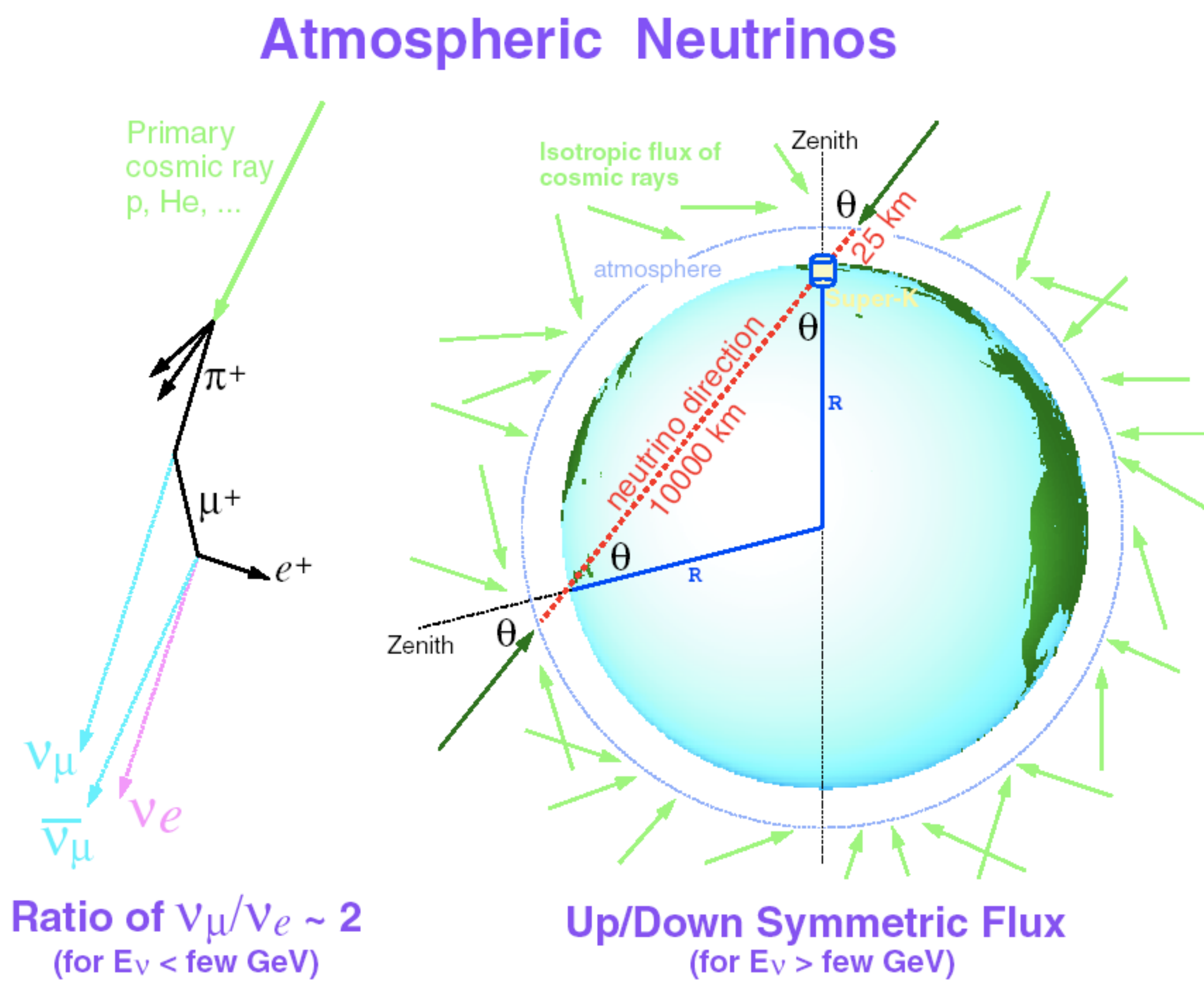




Oscillation for L = 180 km

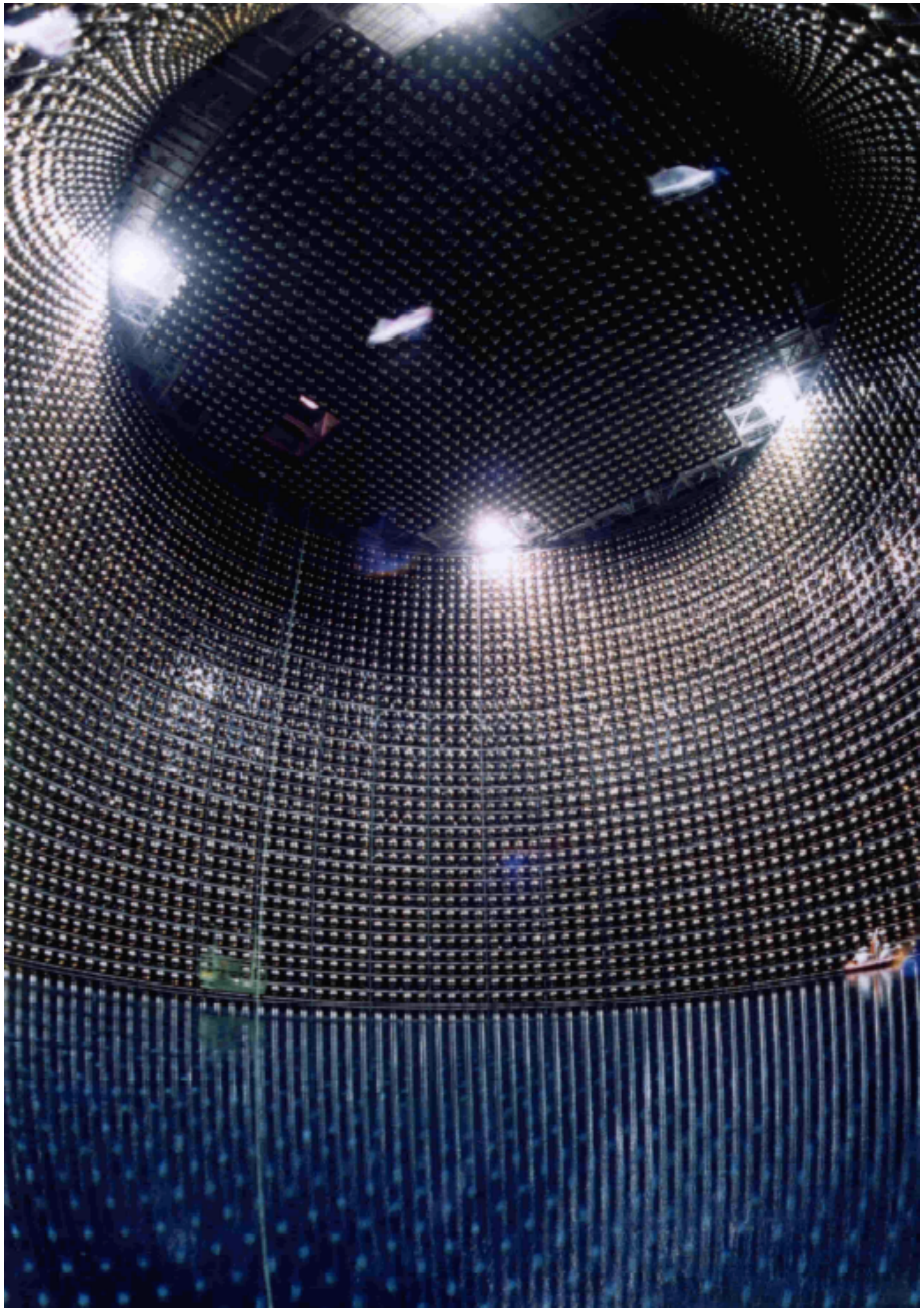
The Atmospheric Neutrino Anomaly

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



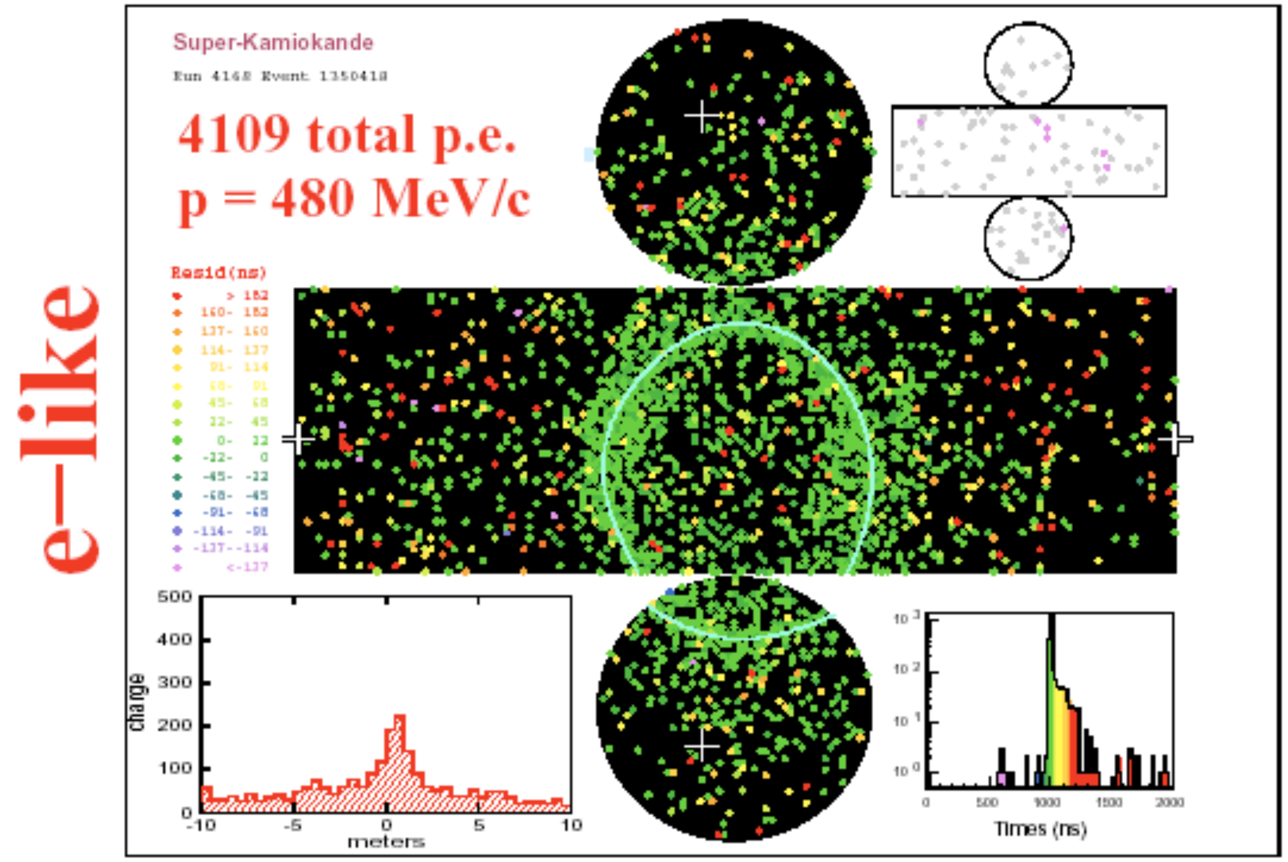
The Super-Kamiokande Detector (Japan)

- 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.



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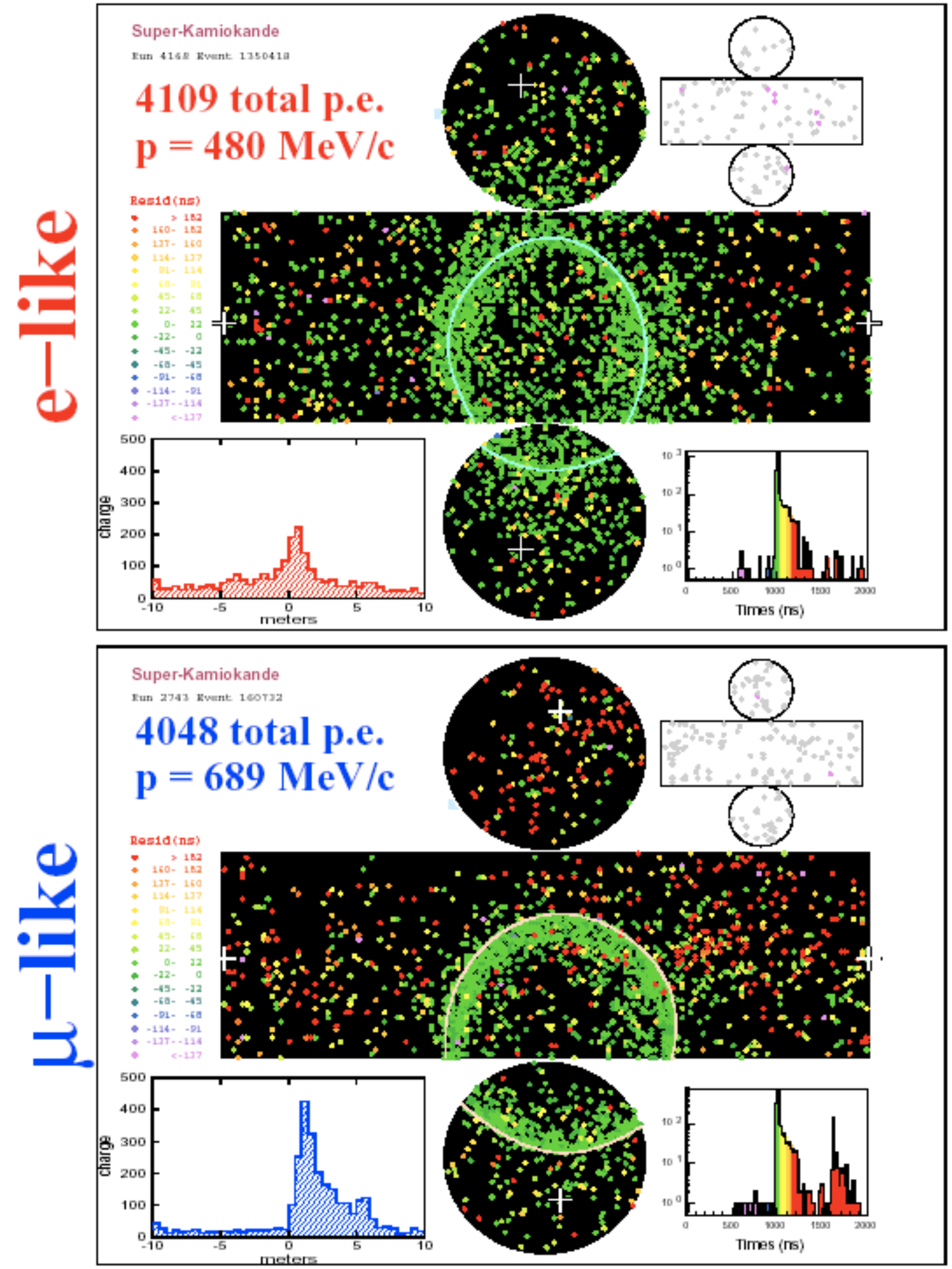
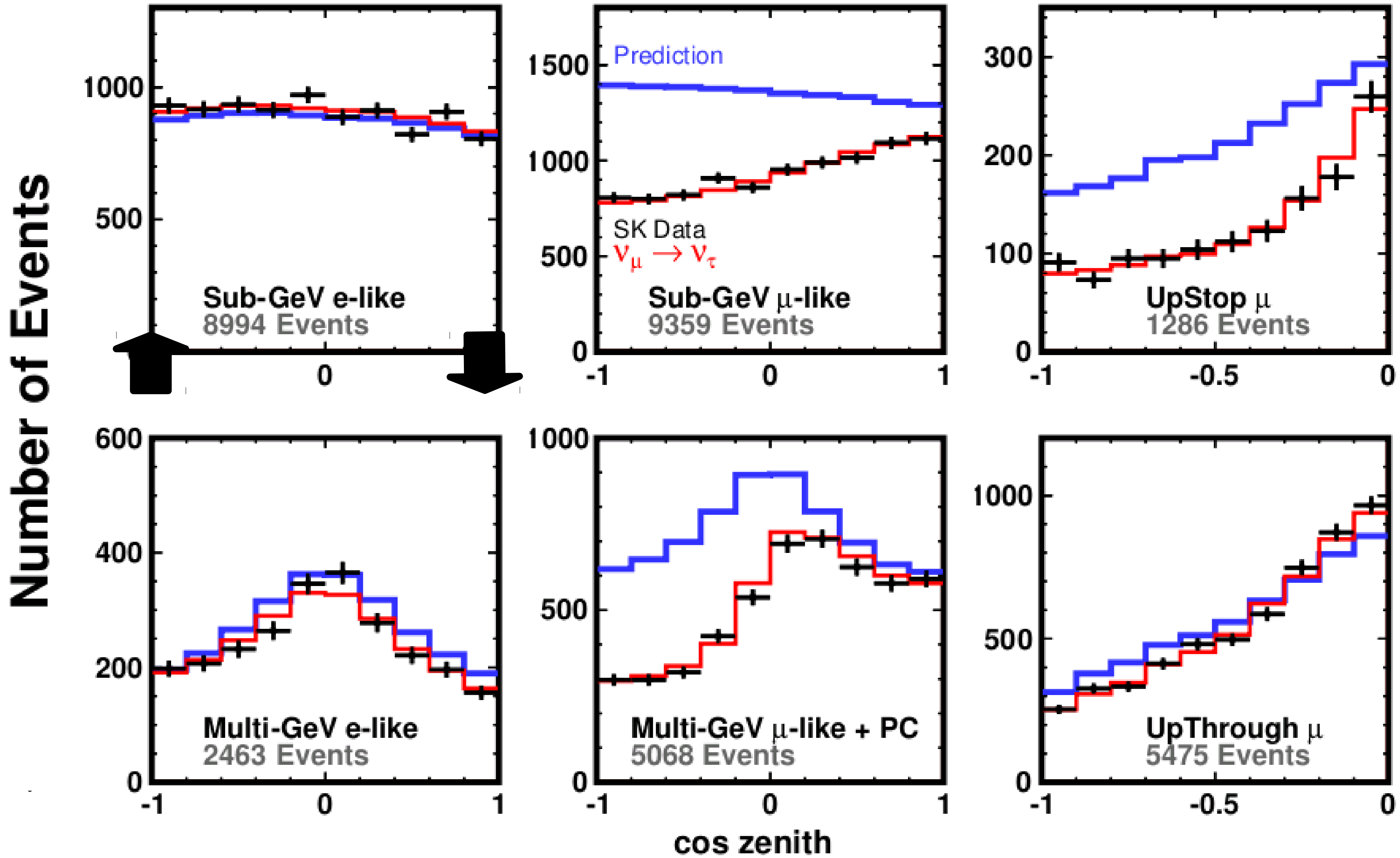


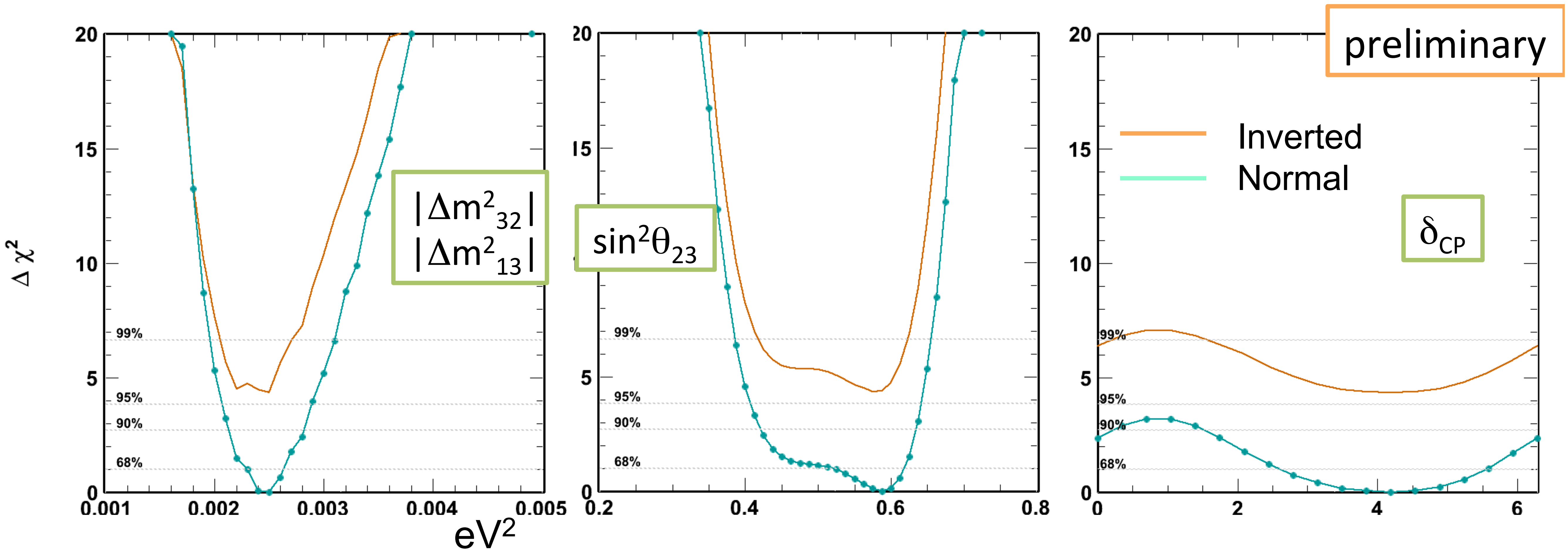
Atmospheric Neutrino Oscillations in Super-K

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



R. Wendell, Neutrino 2014

Atmospheric Neutrino Oscillations in Super-K



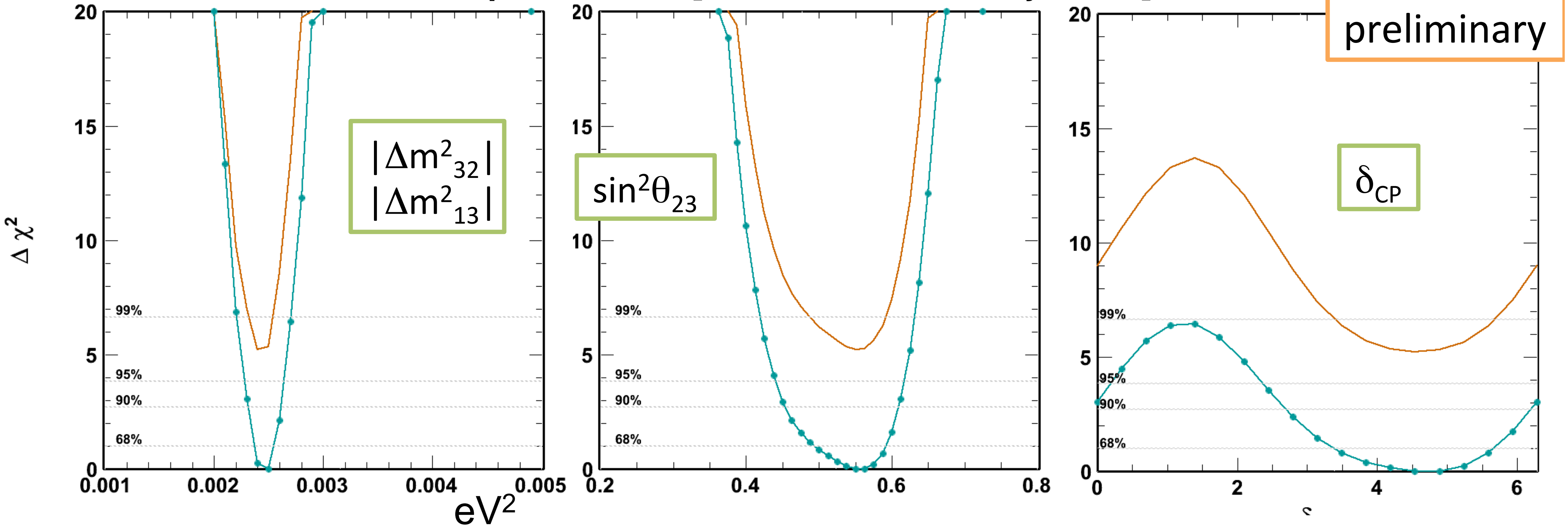
Fit (517 dof)	χ^2	$\sin^2\theta_{13}$	δ_{CP}	$\sin^2\theta_{23}$	$\lvert\Delta m^2_{32}\rvert$ eV^2
SK (IH)	576.08	0.0219 (fix)	4.189	0.575	2.5×10^{-3}
SK (NH)	571.74	0.0219 (fix)	4.189	0.587	2.5×10^{-3}

$\Delta\chi^2$ = -4.3 (-3.1 expected)

Moriyama, Neutrino 2016

Atmospheric Neutrino Oscillations in Super-K

Super-K + T2K [external data, not a joint fit]



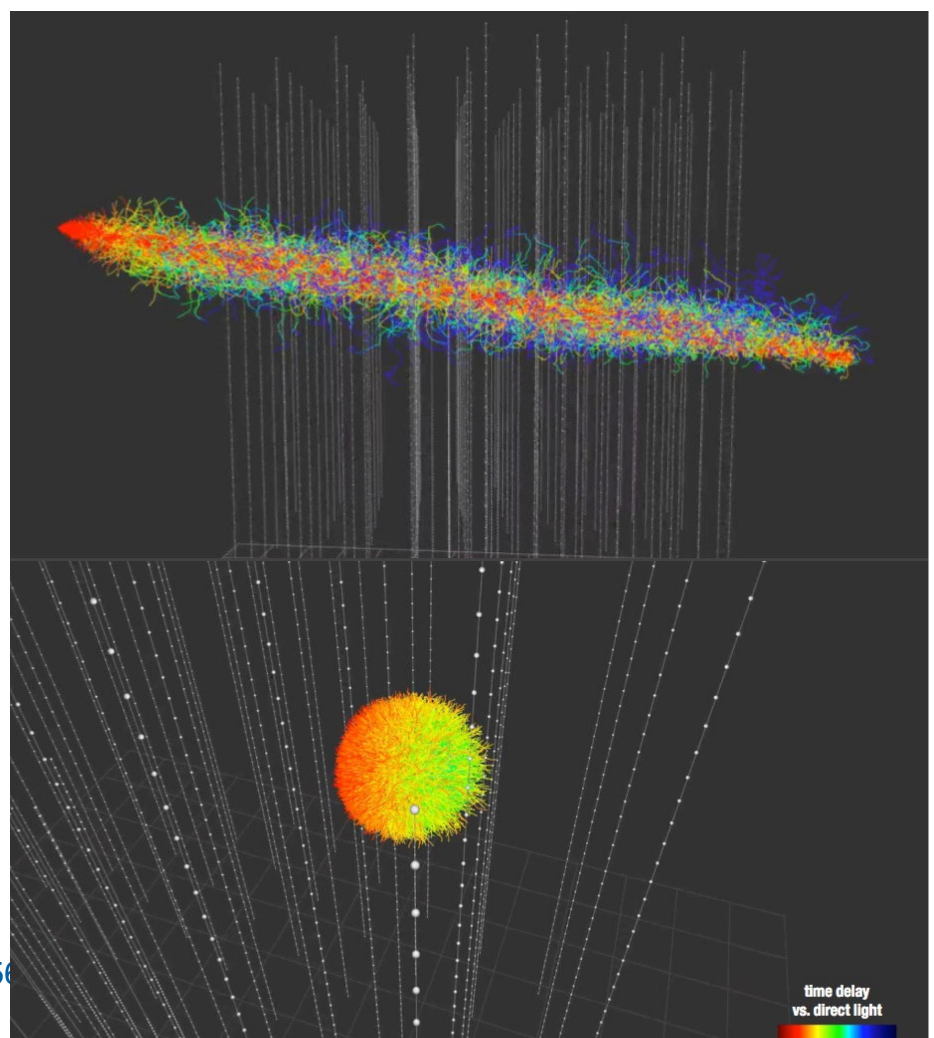
Fit (585 dof)	χ^2	$\sin^2\theta_{13}$	δ_{CP}	$\sin^2\theta_{23}$	$\lvert\Delta m^2_{32}\rvert eV^2$
SK+T2K (IH)	644.82	0.0219 (fix)	4.538	0.55	2.5×10^{-3}
SK+T2K (NH)	639.61	0.0219 (fix)	4.887	0.55	2.4×10^{-3}

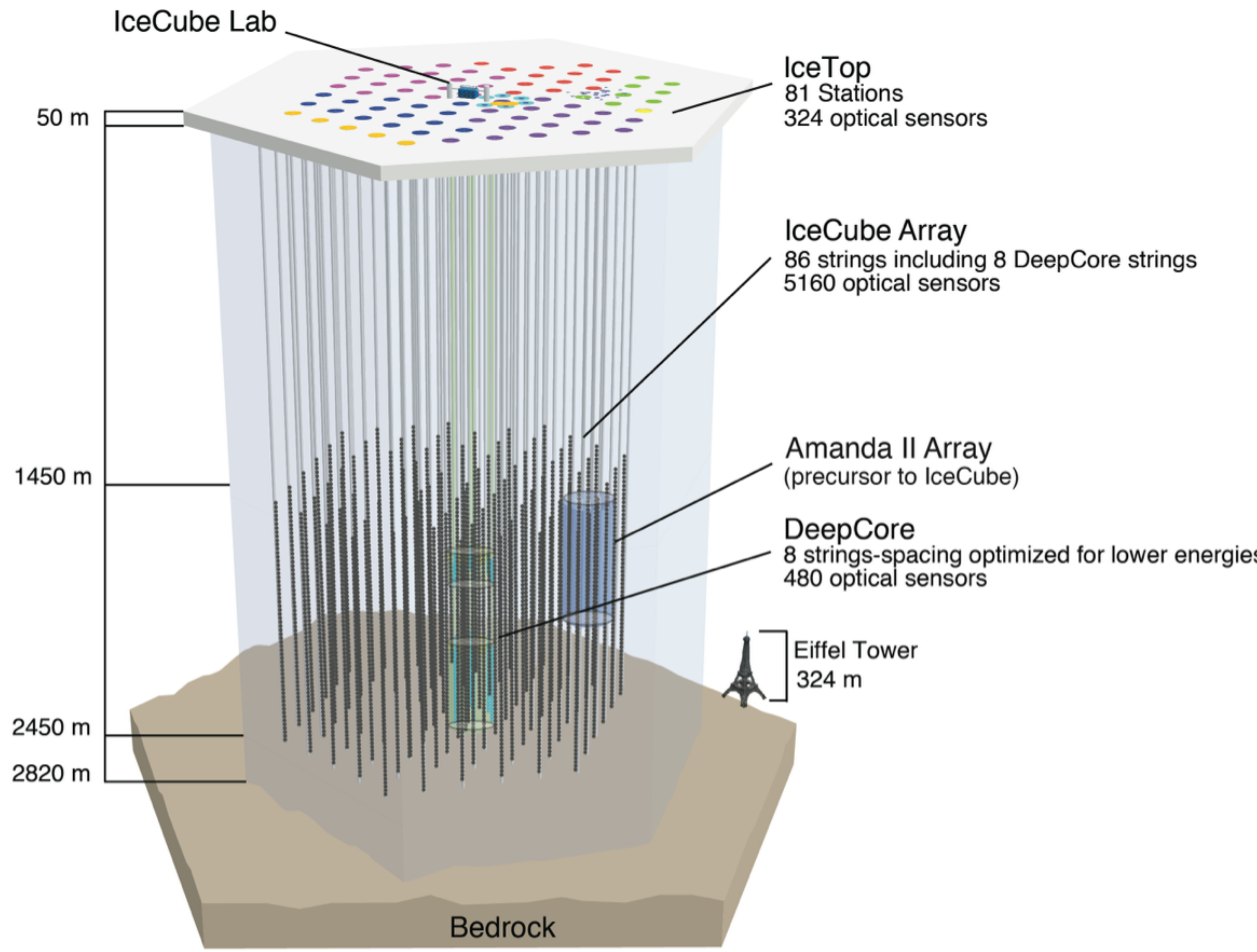
$\Delta\chi^2$ = -5.2 (-3.1 expected)

Moriyama, Neutrino 2016

The IceCube/DeepCore Experiment

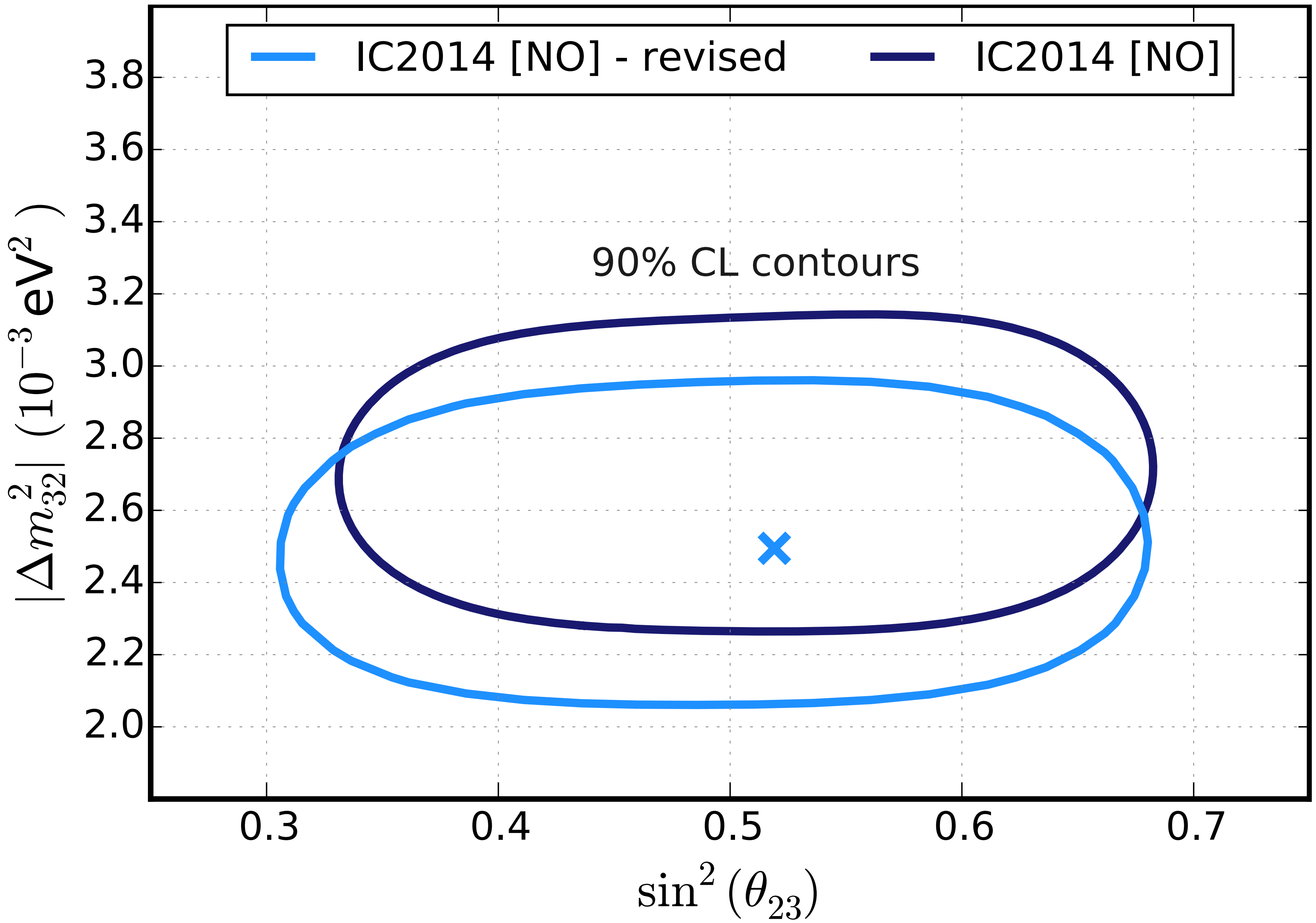
- Located at the South Pole.
- Covered by 1450m of ice.
- 5160 optical sensors evenly distributed throughout 600 ktons of ice.
- 480 densely-packed optical sensors in the center for improved sensitivity at lower energies





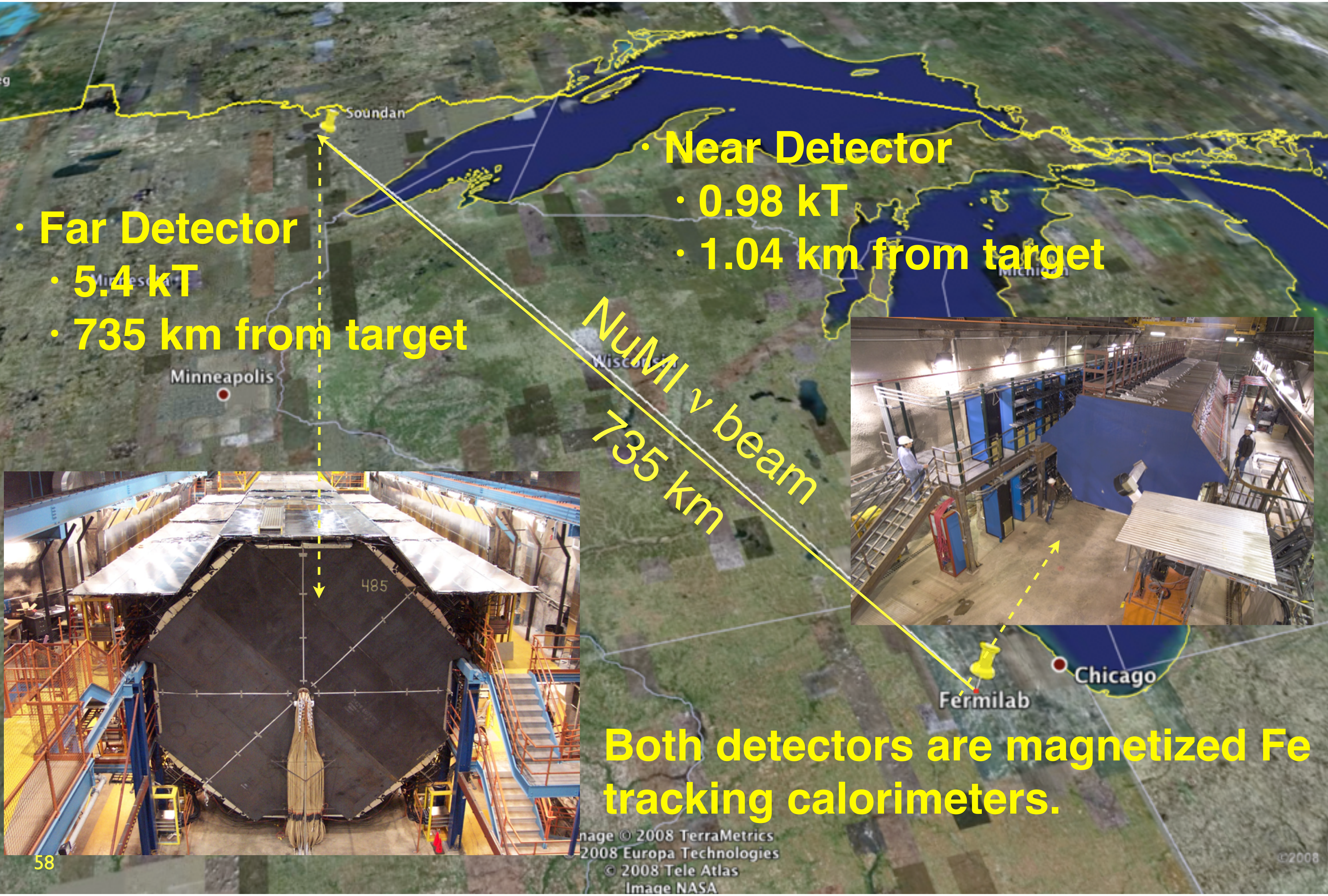
Recent IceCube Oscillation Results

- Updated 2014 results with improved detector simulation, flux prediction, background rejection and systematics.
- Consistent with previous result and maximal mixing.
- Inclusion of non-golden events and 3 years additional data should reduce uncertainties of parameters by ~2x.



Koskinen, Neutrino 2016

The MINOS Experiment

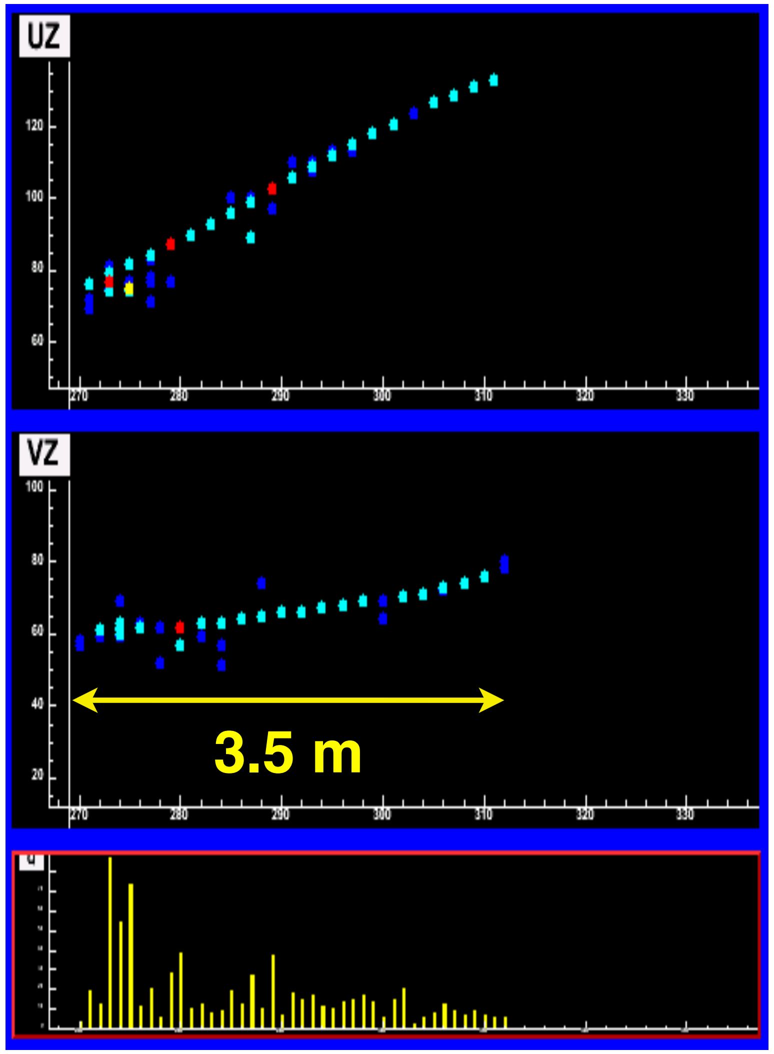


- Far Detector
  - 5.4 kT
  - 735 km from target
- Near Detector
  - 0.98 kT
  - 1.04 km from target

Both detectors are magnetized Fe tracking calorimeters.

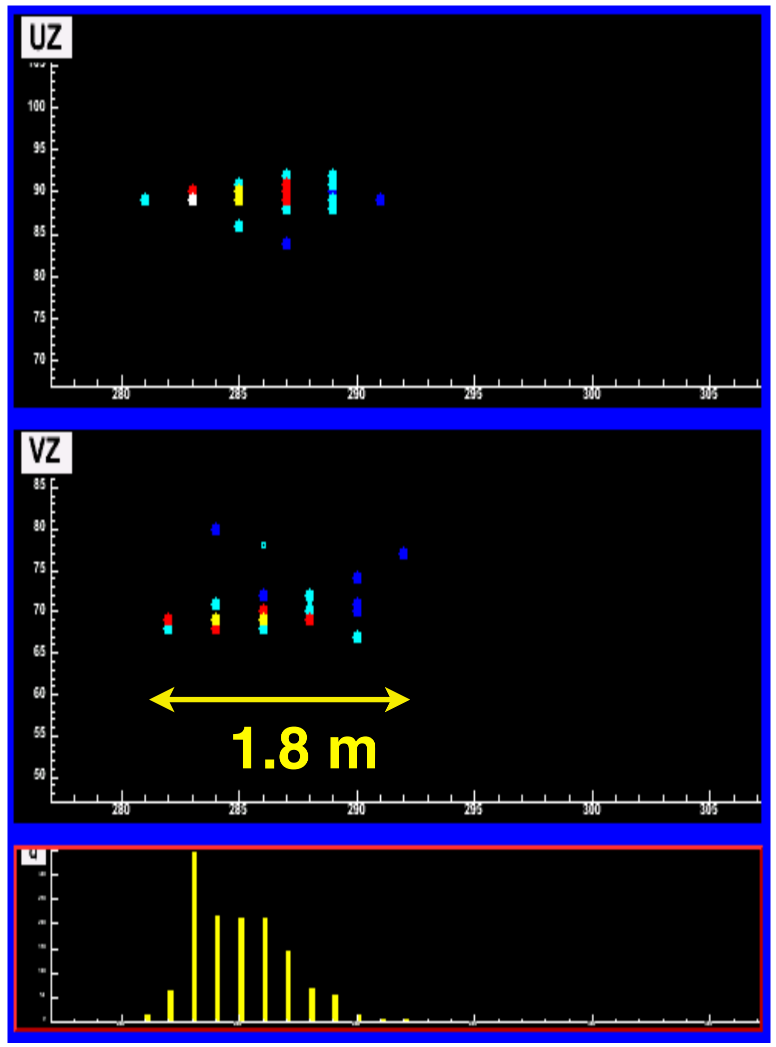
Identifying Events in MINOS

ν_μ CC event



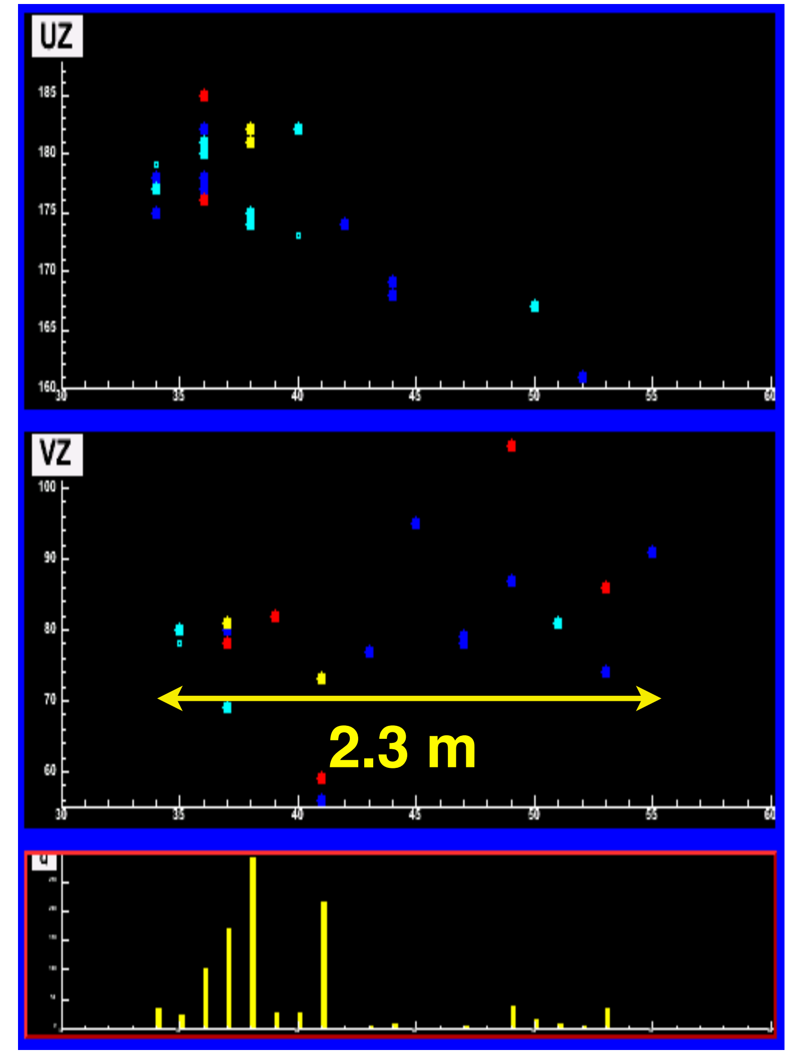
Long μ track + shower at vertex

ν_e CC event



Short event with EM shower profile.

NC event



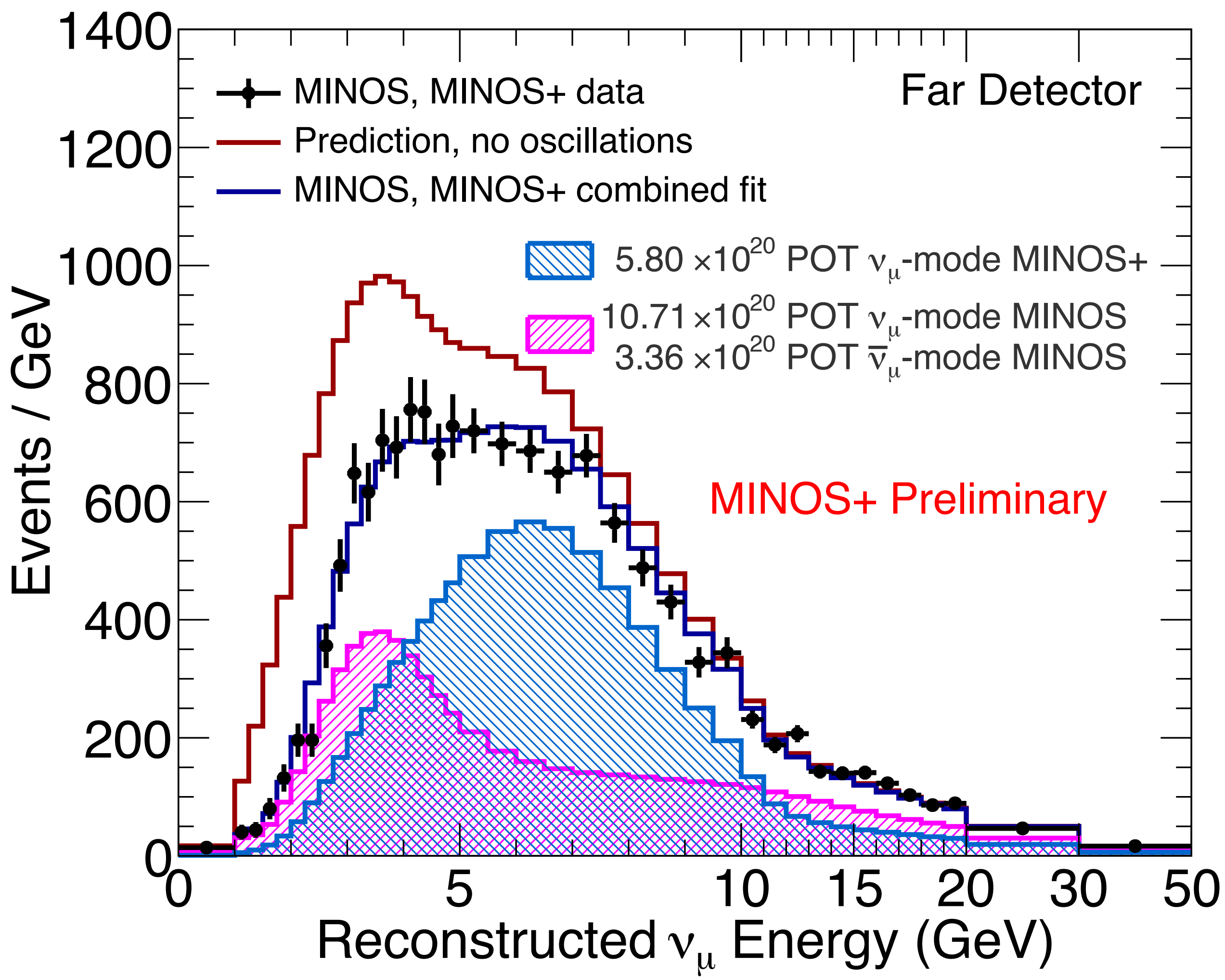
Short, diffuse event.

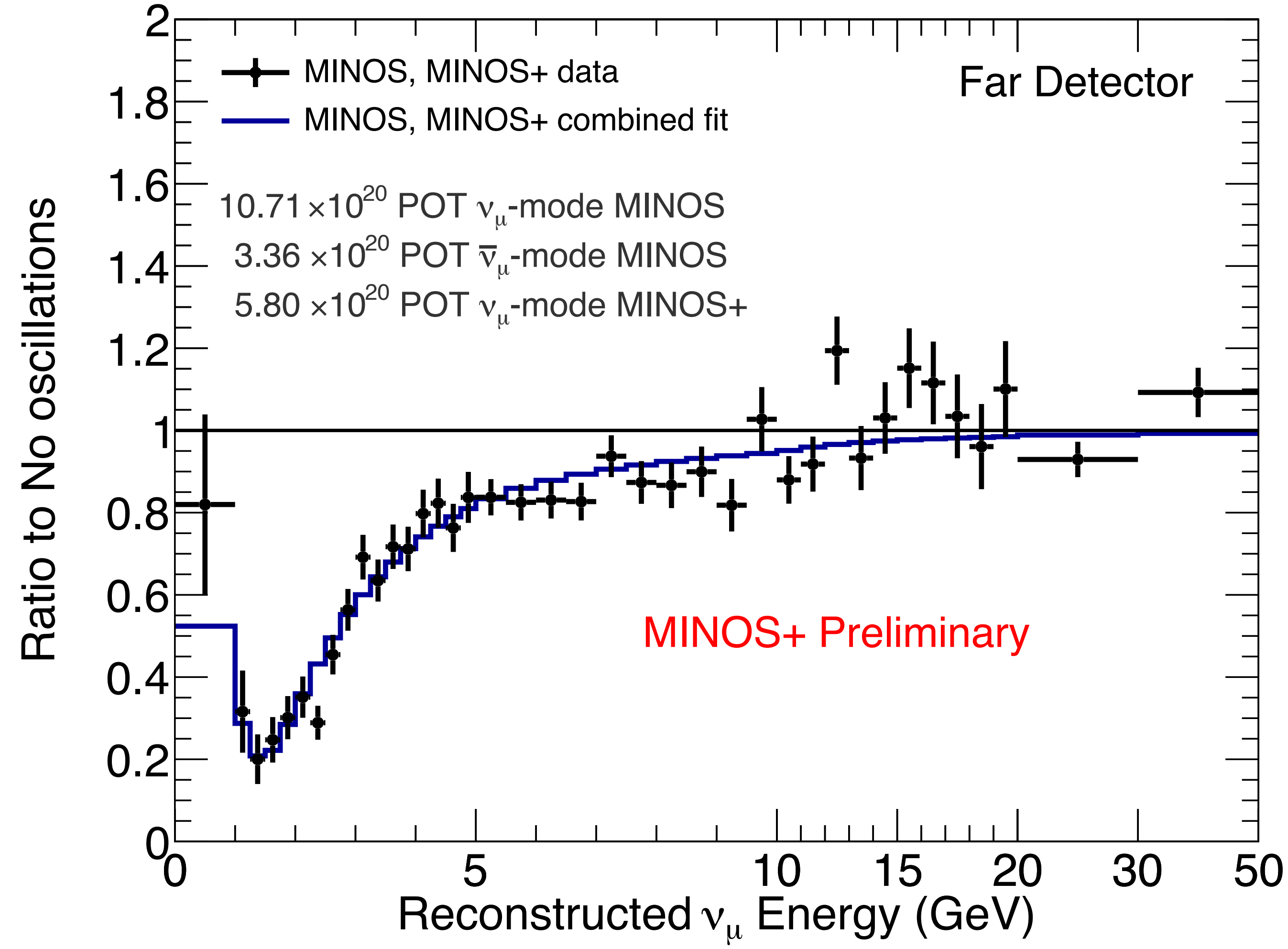
E_μ determined from curvature and/or range,

E_{shower} determined from MC tuned to external data.

MINOS Results

Evans, Neutrino 2016

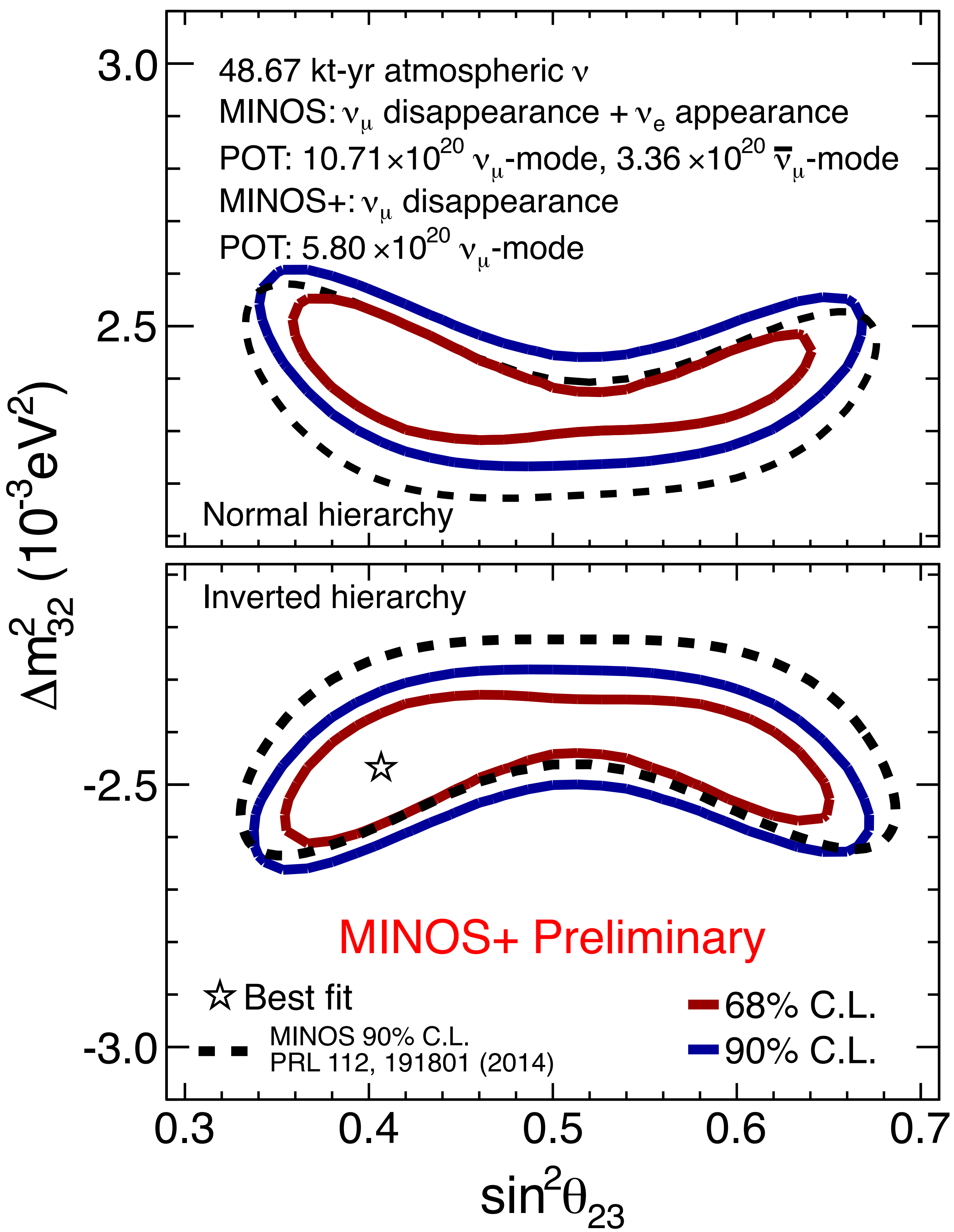


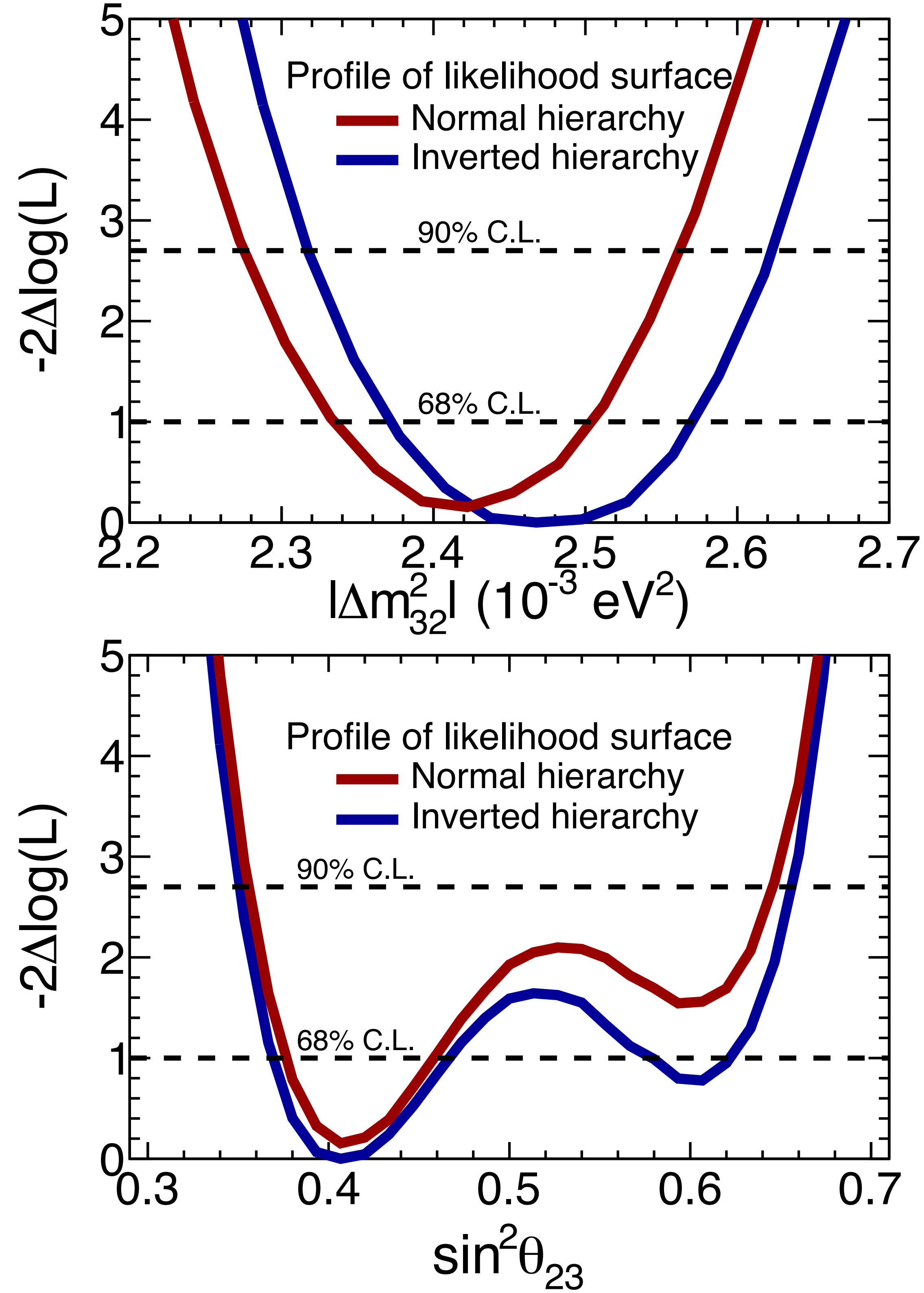


- Includes all data collected since 2005.
- The far detector has now been shut off after a decade of excellent performance.

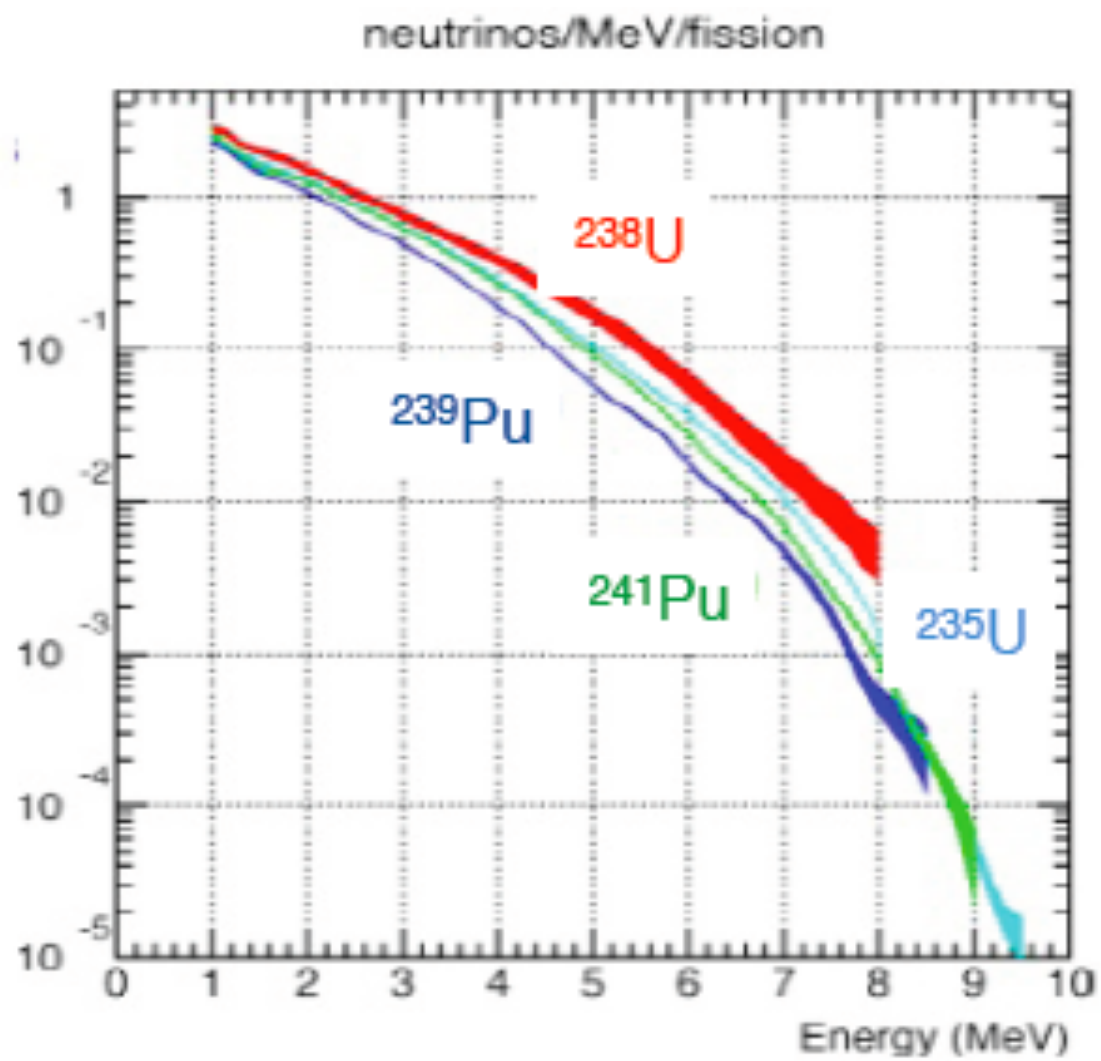
MINOS Results

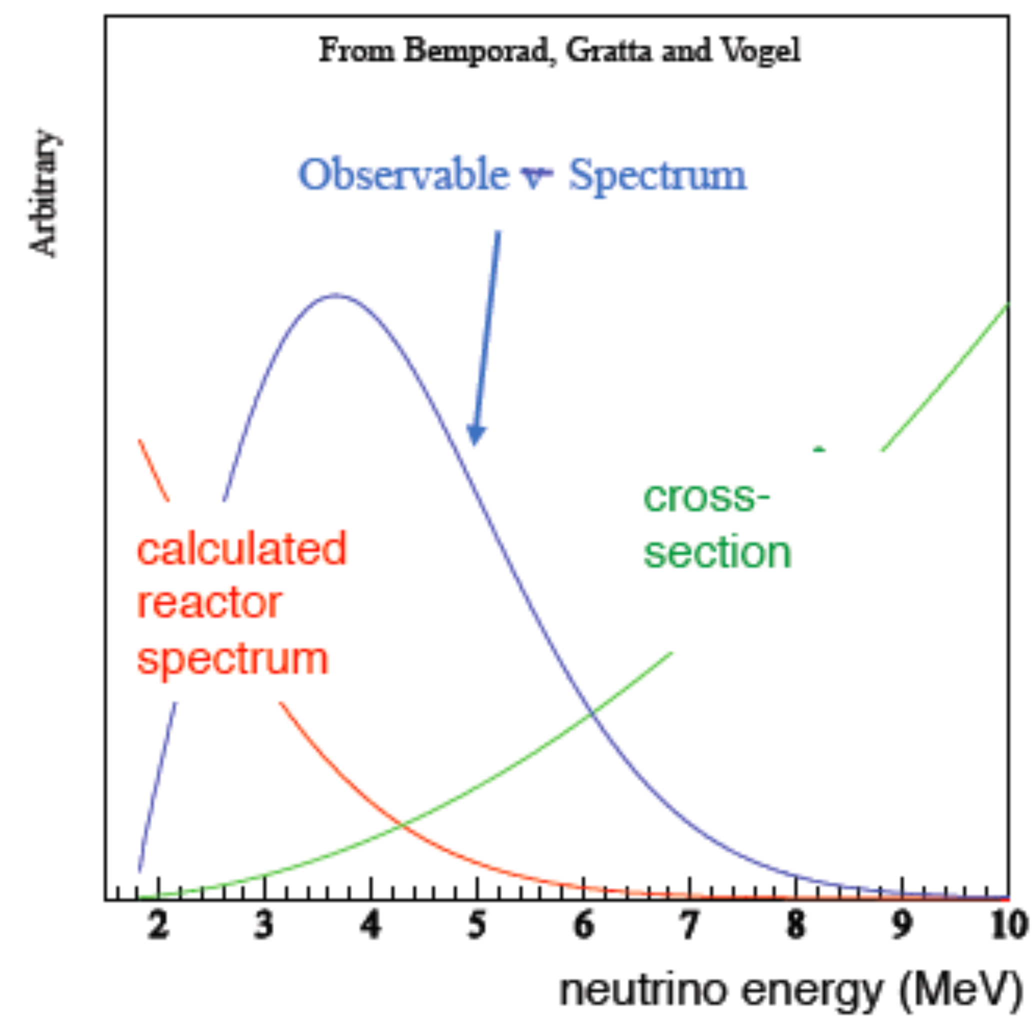
Evans, Neutrino 2016





Reactor Experiments





$^{235}U:^{238}U:^{239}Pu:^{241}Pu = 0.570 : 0.078 : 0.0295 : 0.057$

detection method: inverse beta decay

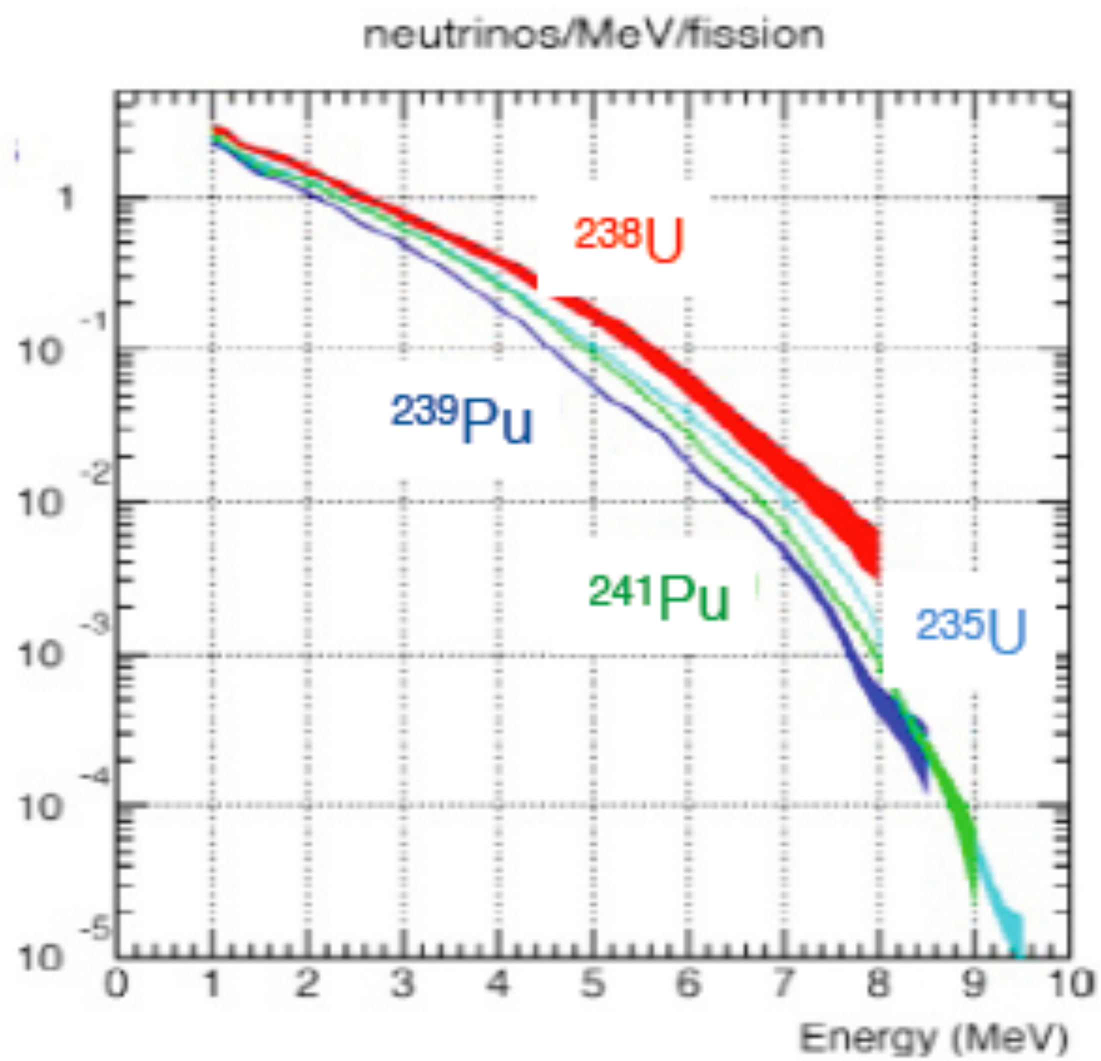
$\bar{\nu}_e + p \rightarrow e^+ + n$

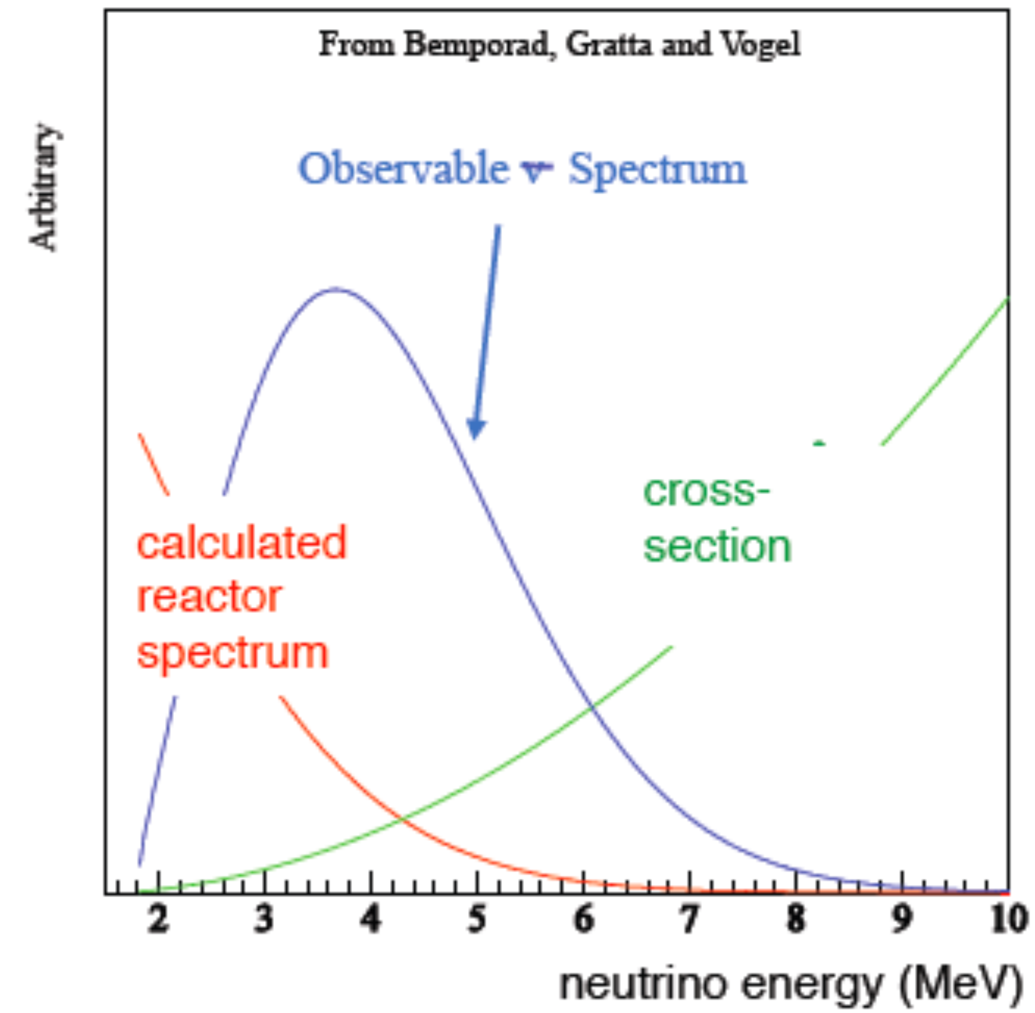
6 antineutrinos per fission, ~200 MeV per fission

~2 x 10^{20} $\bar{\nu}_e/GW_{th}/sec$

Reactor Experiments

- Measure $P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$ using reactors as the anti-neutrino source





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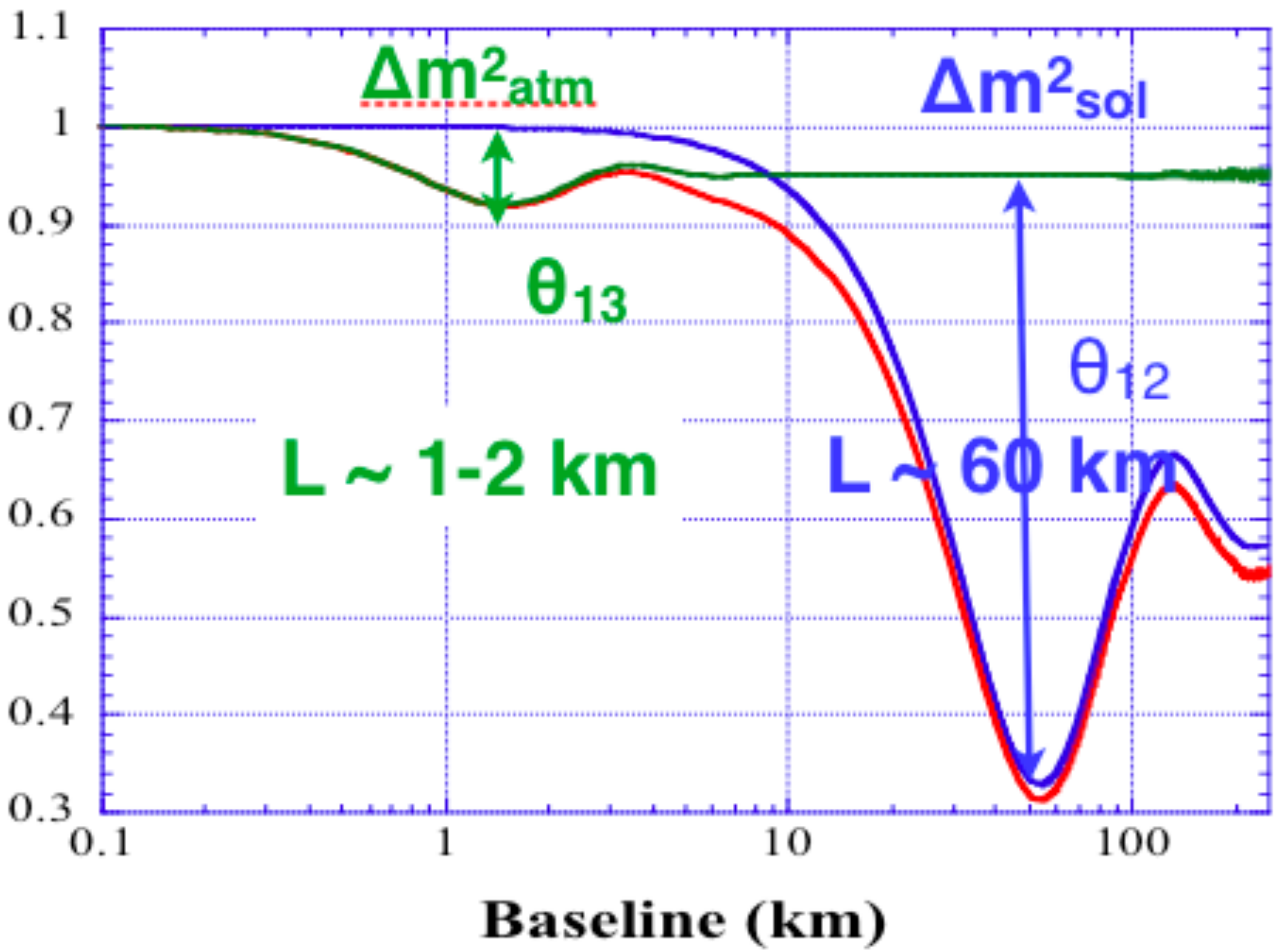
detection method: inverse beta decay
$\bar{\nu}_e + p \rightarrow e^+ + n$

Reactor Experiments

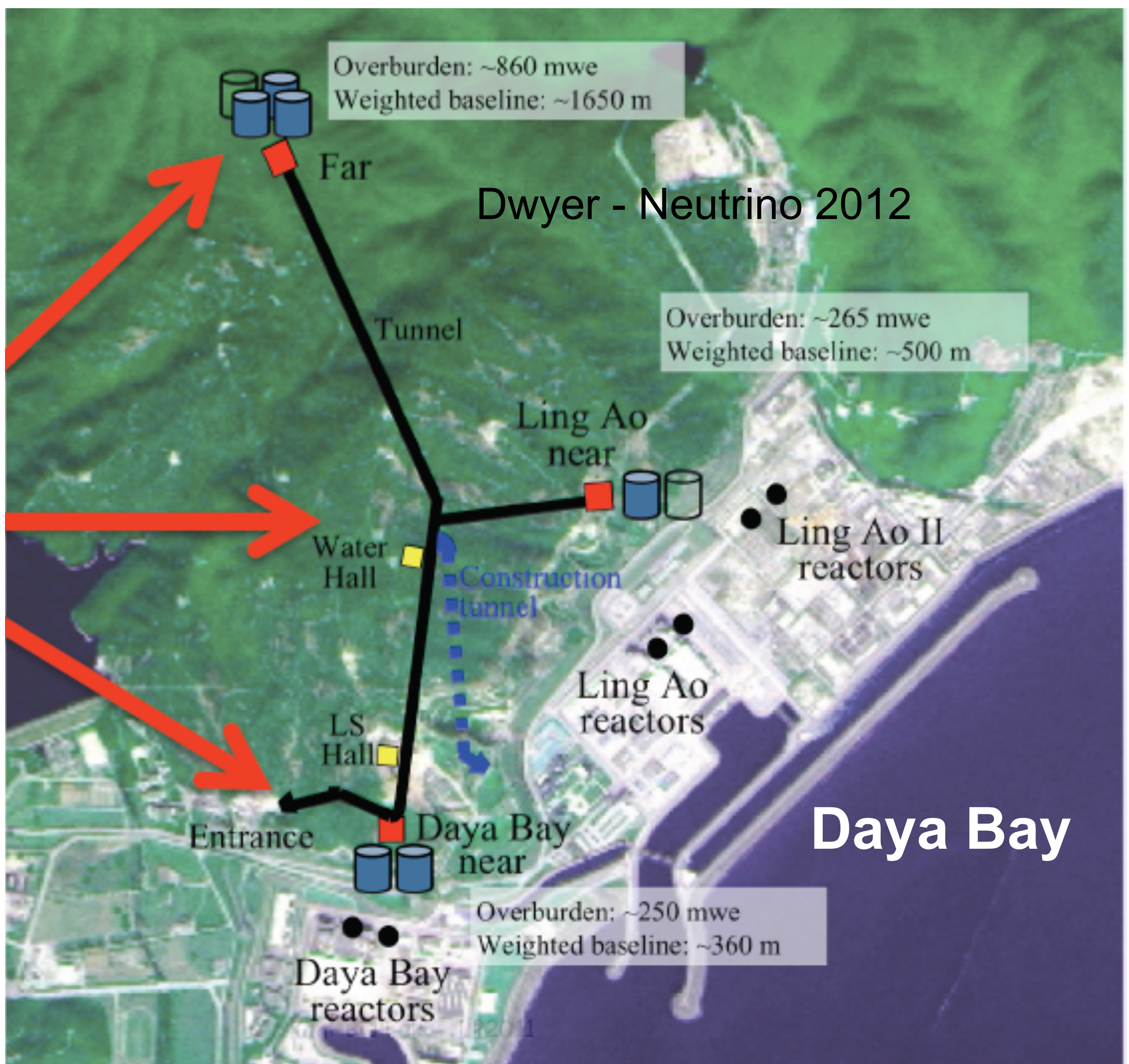
$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}{}^2 L}{4E_\nu}\right) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m_{21}{}^2 L}{4E_\nu}\right)$$

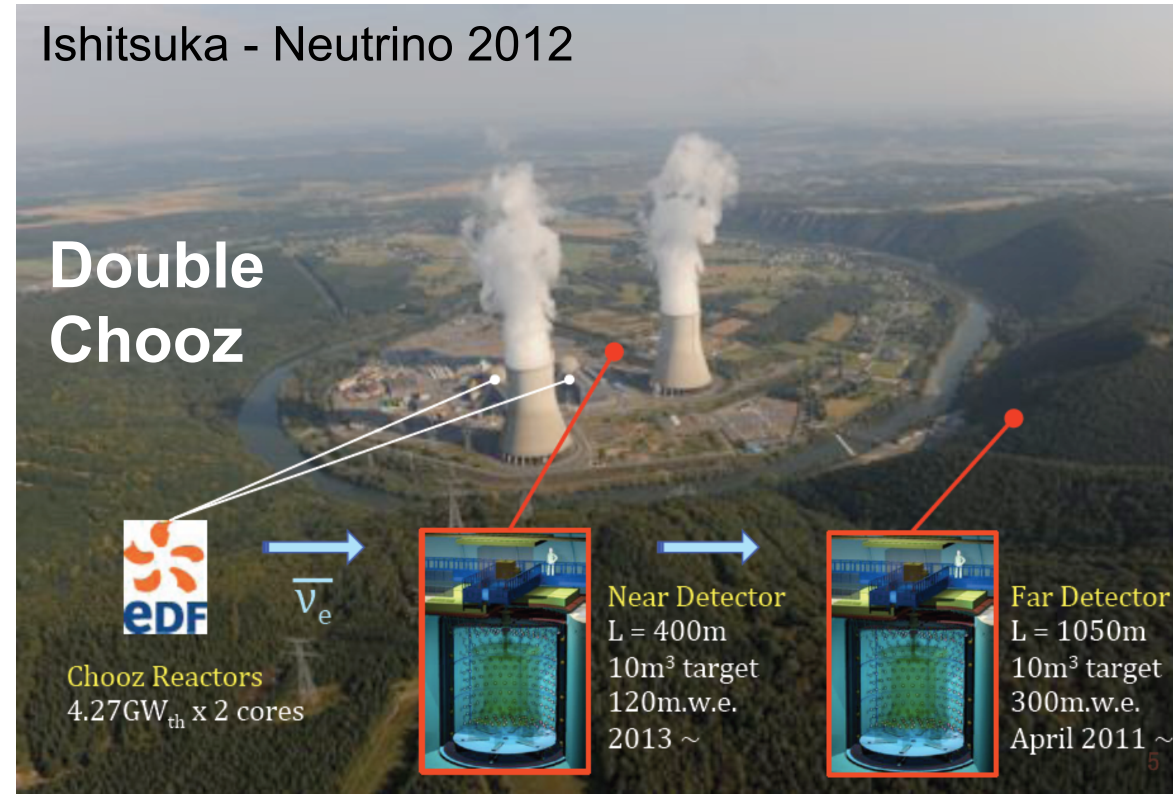


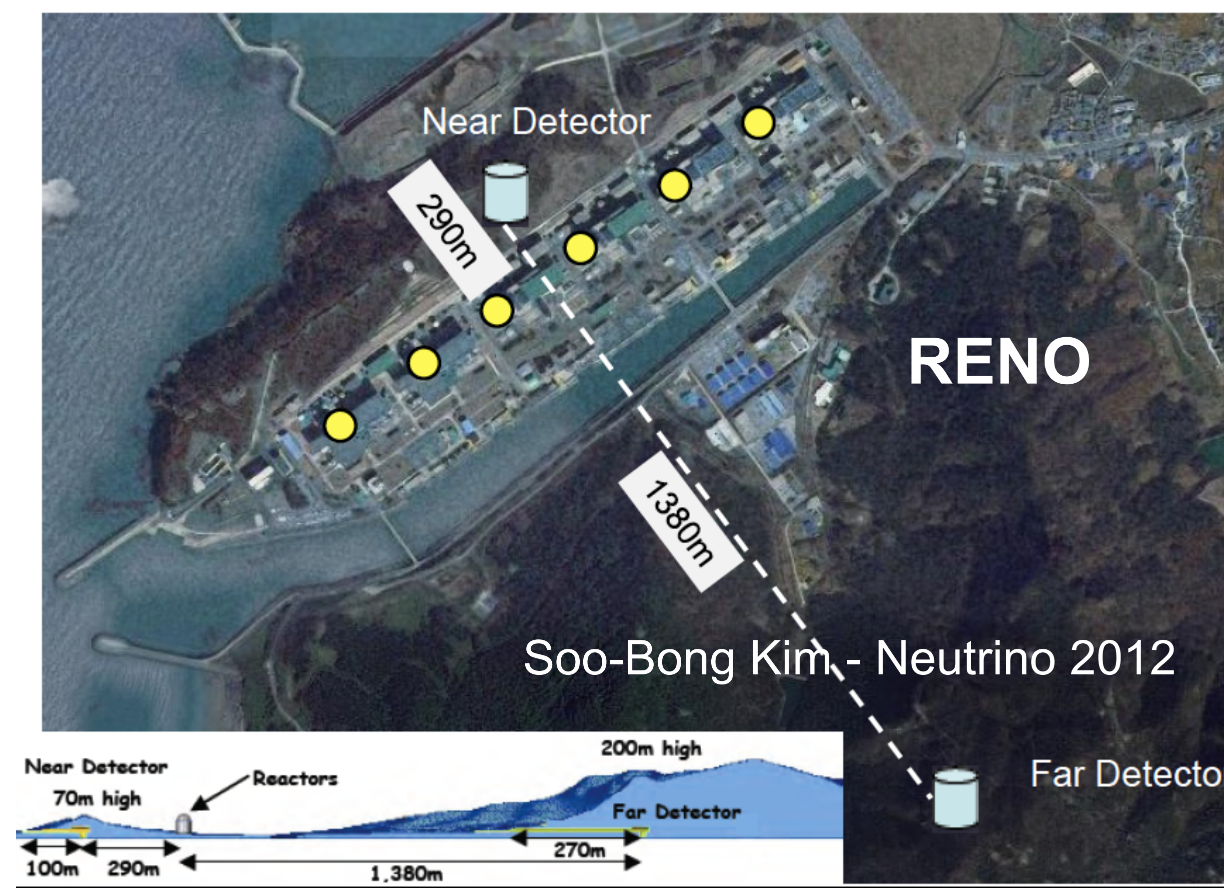
- "Long-baseline" reactor experiments (eg, KamLAND) are sensitive only to the solar mass splitting.
- "Short-baseline" reactor experiments (eg, Double Chooz, Daya Bay) are sensitive only to the atmospheric mass splitting and θ_{13}!

2012: The Year of the Reactor Experiments!

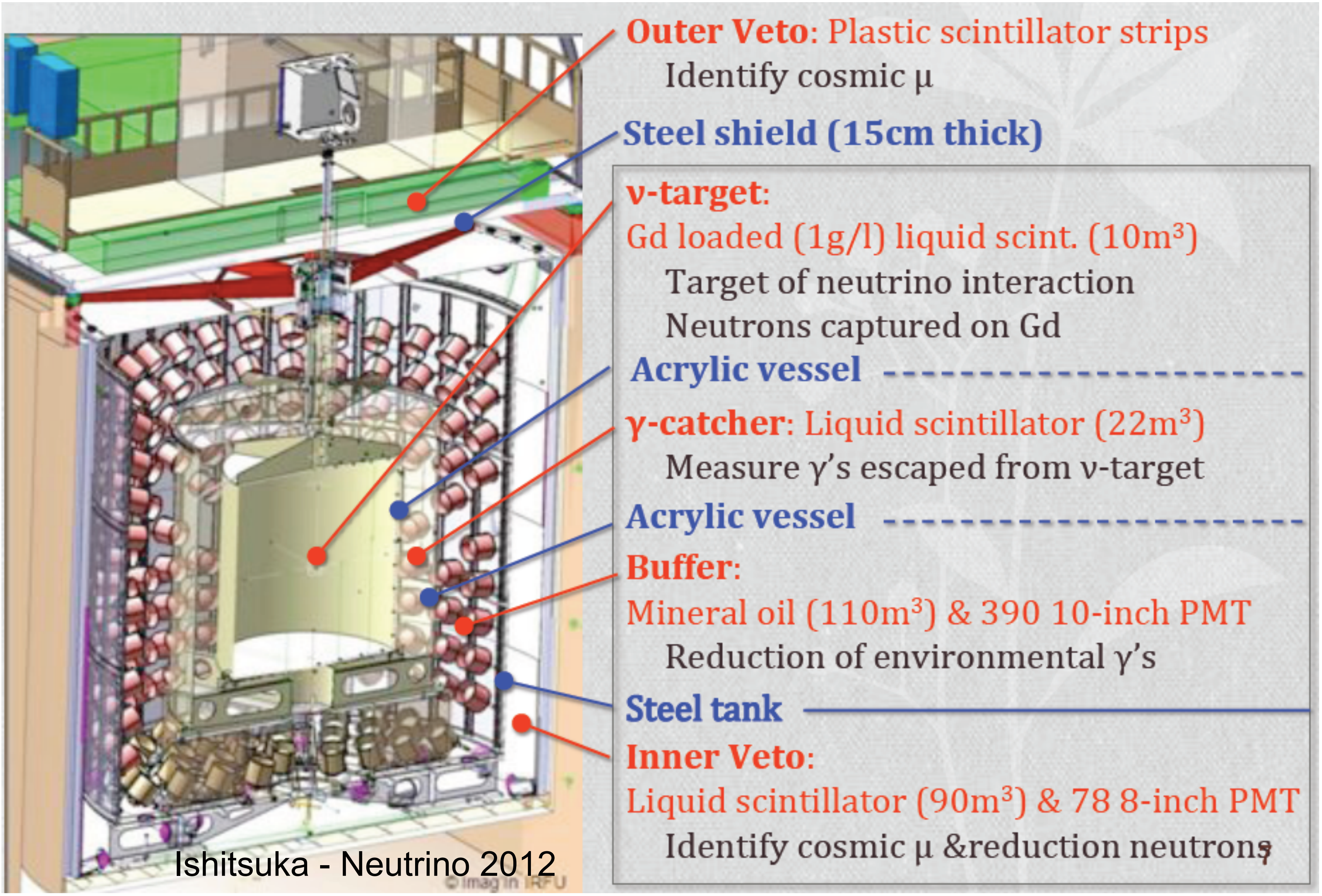
- In 2012, three reactor neutrino experiments reported measurements of θ_{13}.







2012: The Year of the Reactor Experiments!



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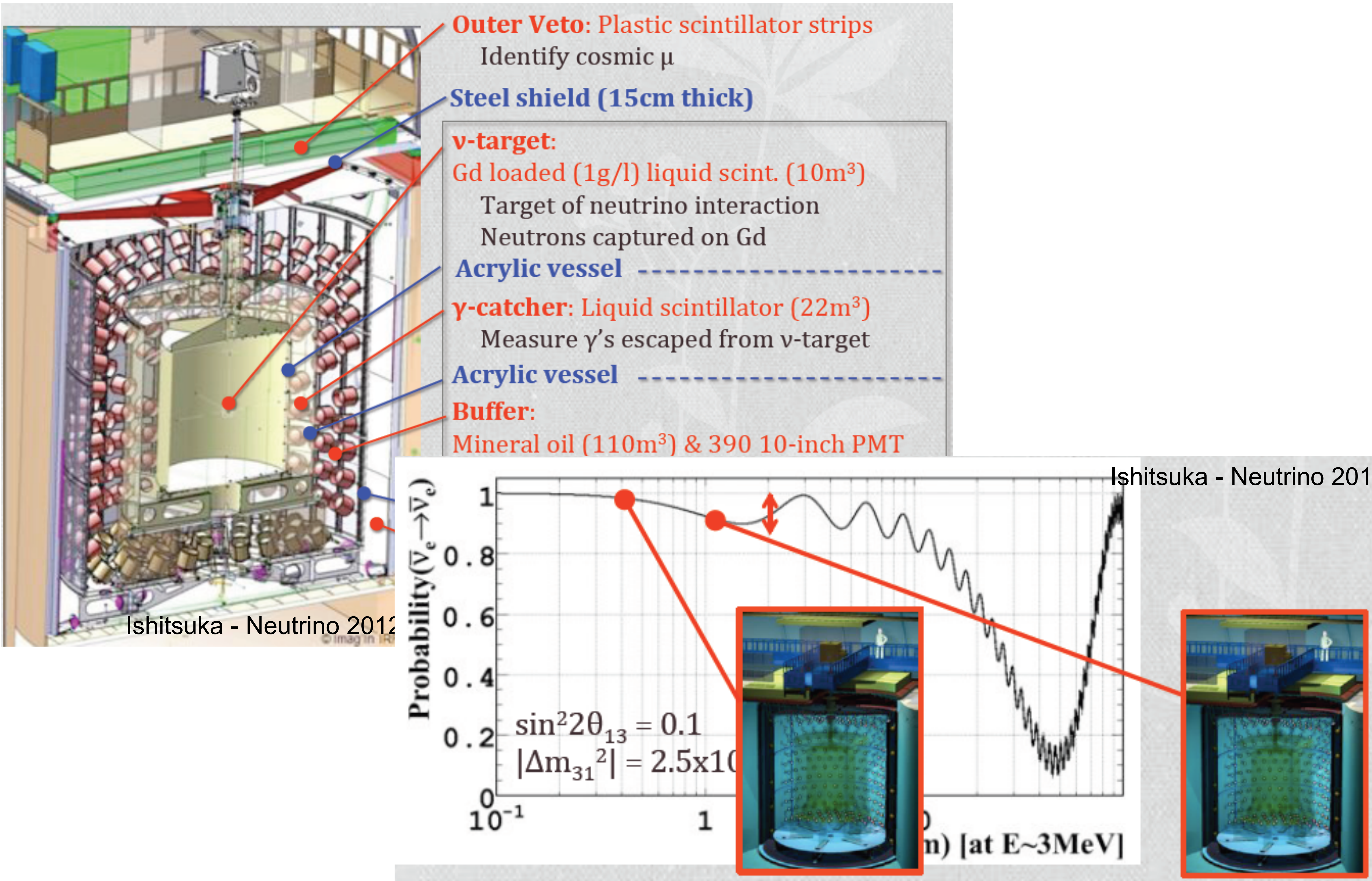
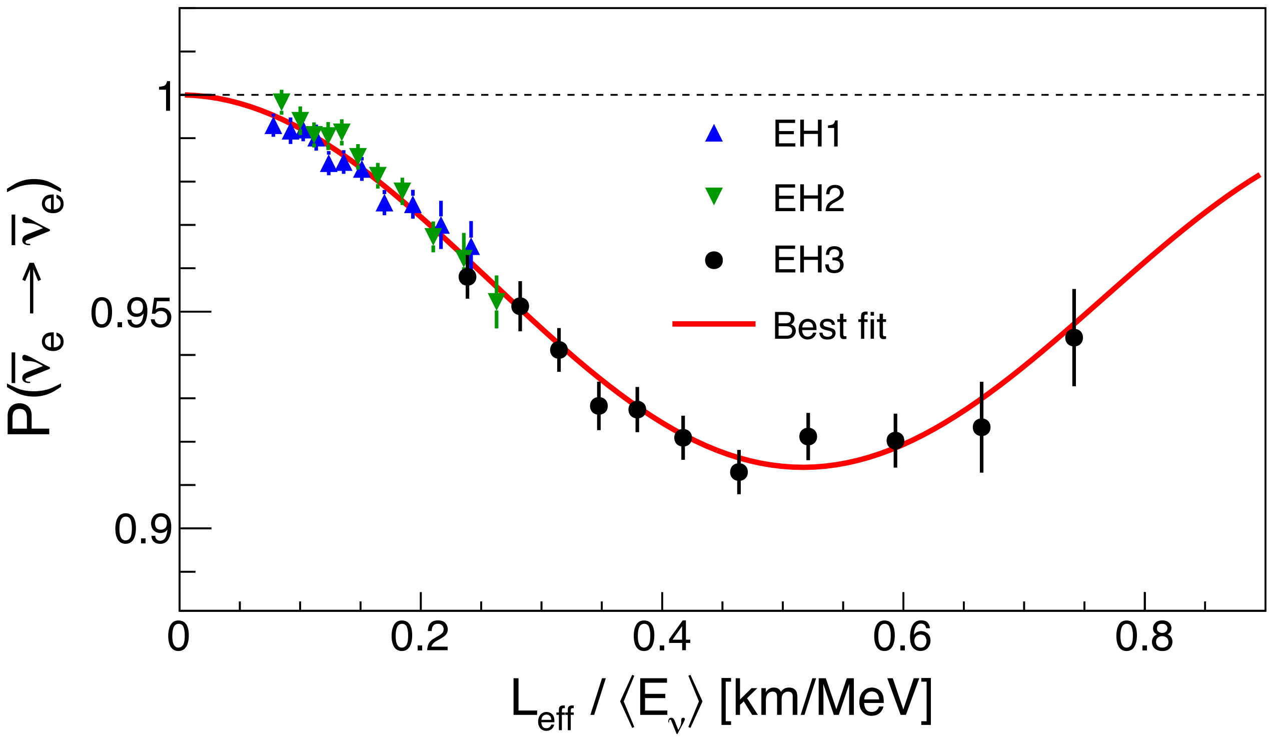
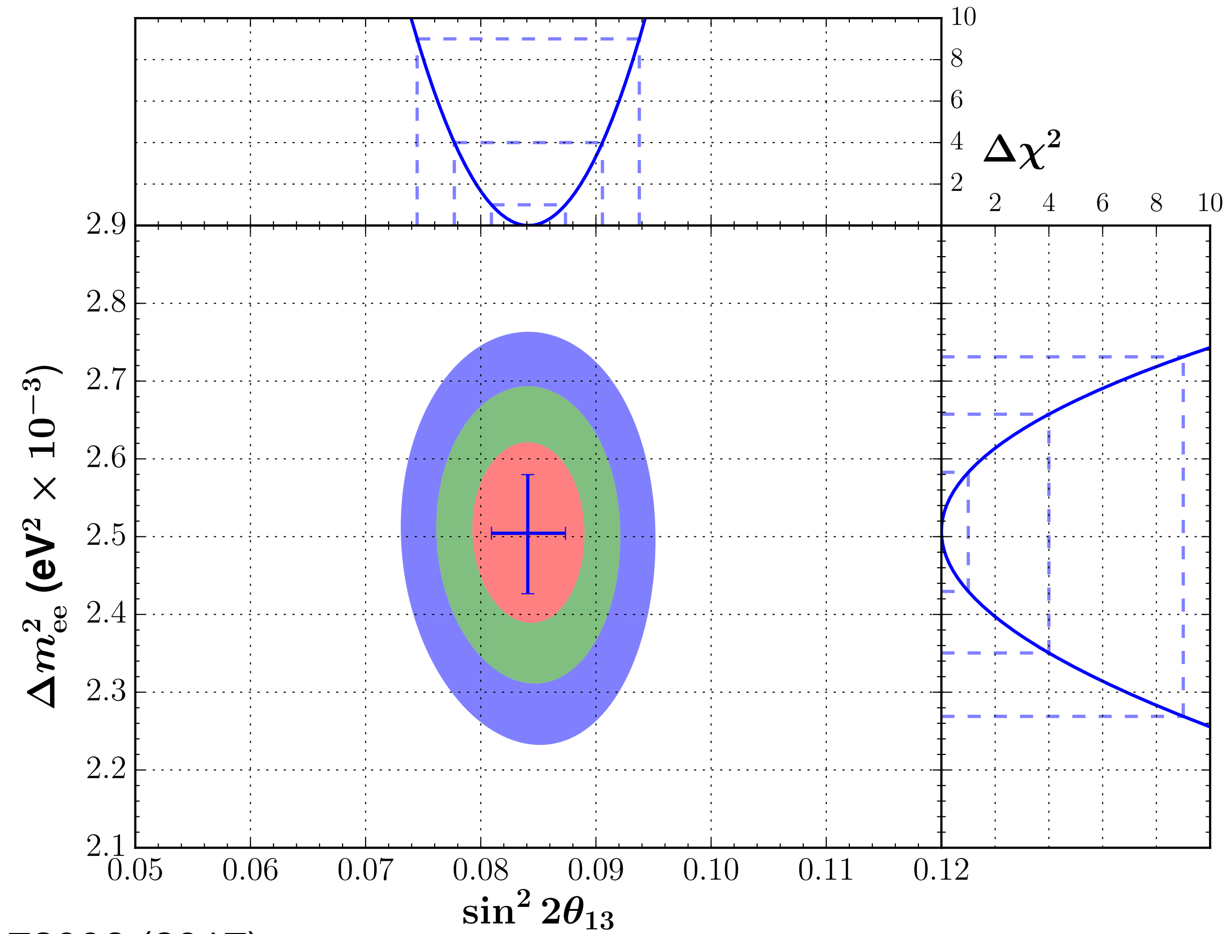


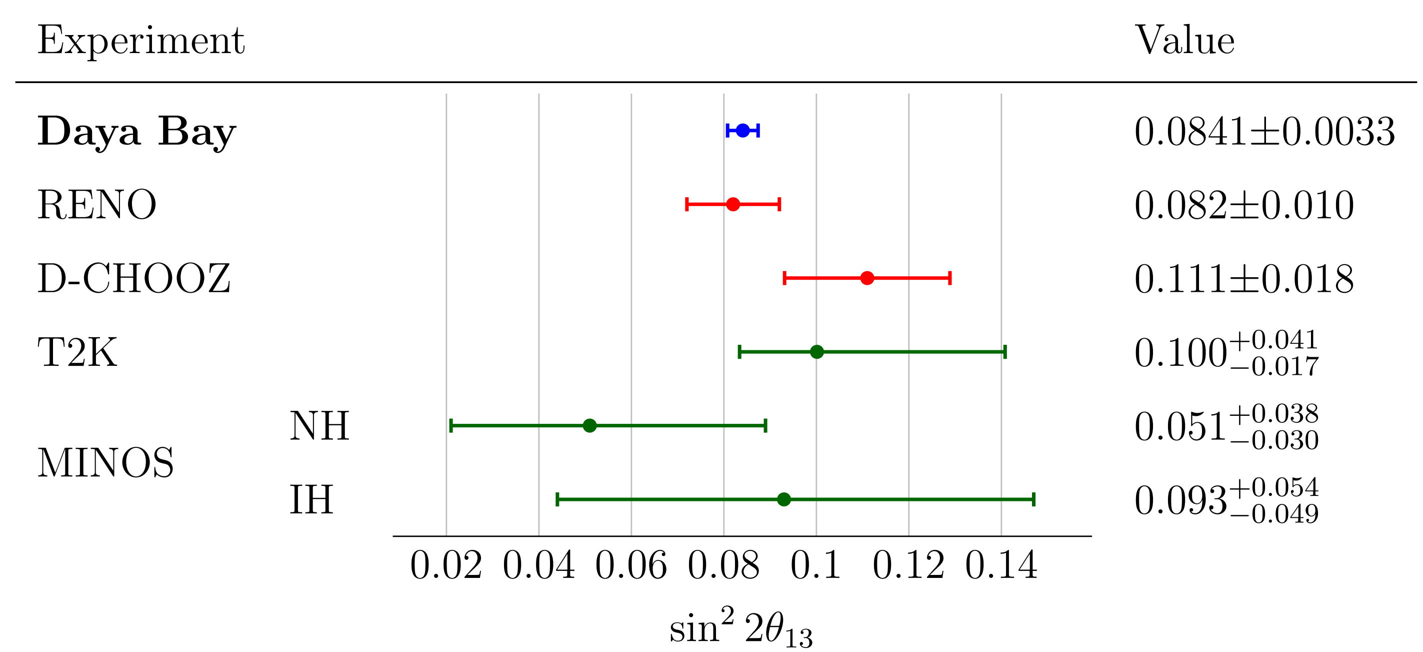
Four Years of Measurements of θ_{13}





Phys. Rev. D 95, 072006 (2017)

- 11% (2012) → 4% (2016), close to their 3% goal.
- Spectral analysis also provides measurement of Δm^2_{31} (~ Δm^2_{ee}), consistent with MINOS results (and comparable precision)



The NOνA Experiment

Ash River, MN

14 kton, 810 km, 14.6 mrad off-axis

NOνA Far Detector

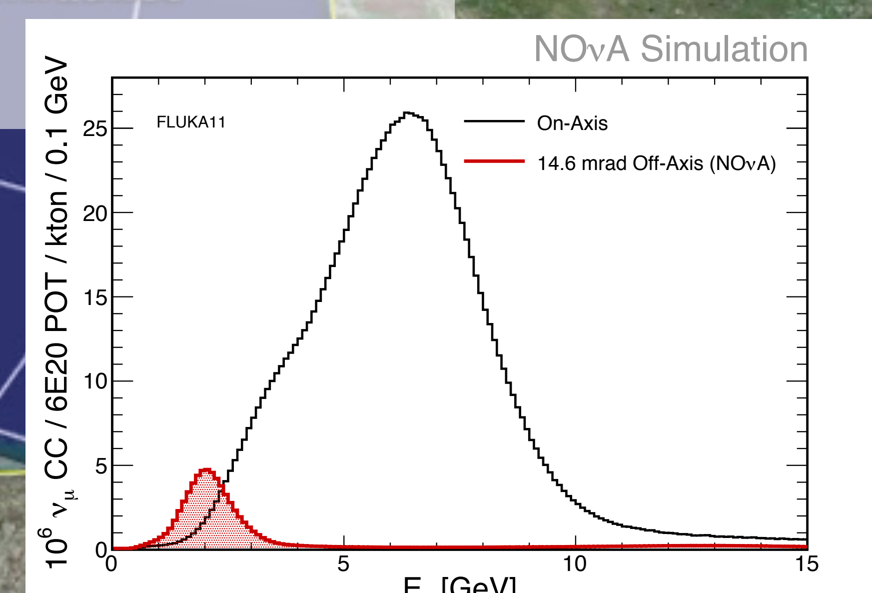
MINOS Far Detector

Existing NuMI Beam from FNAL

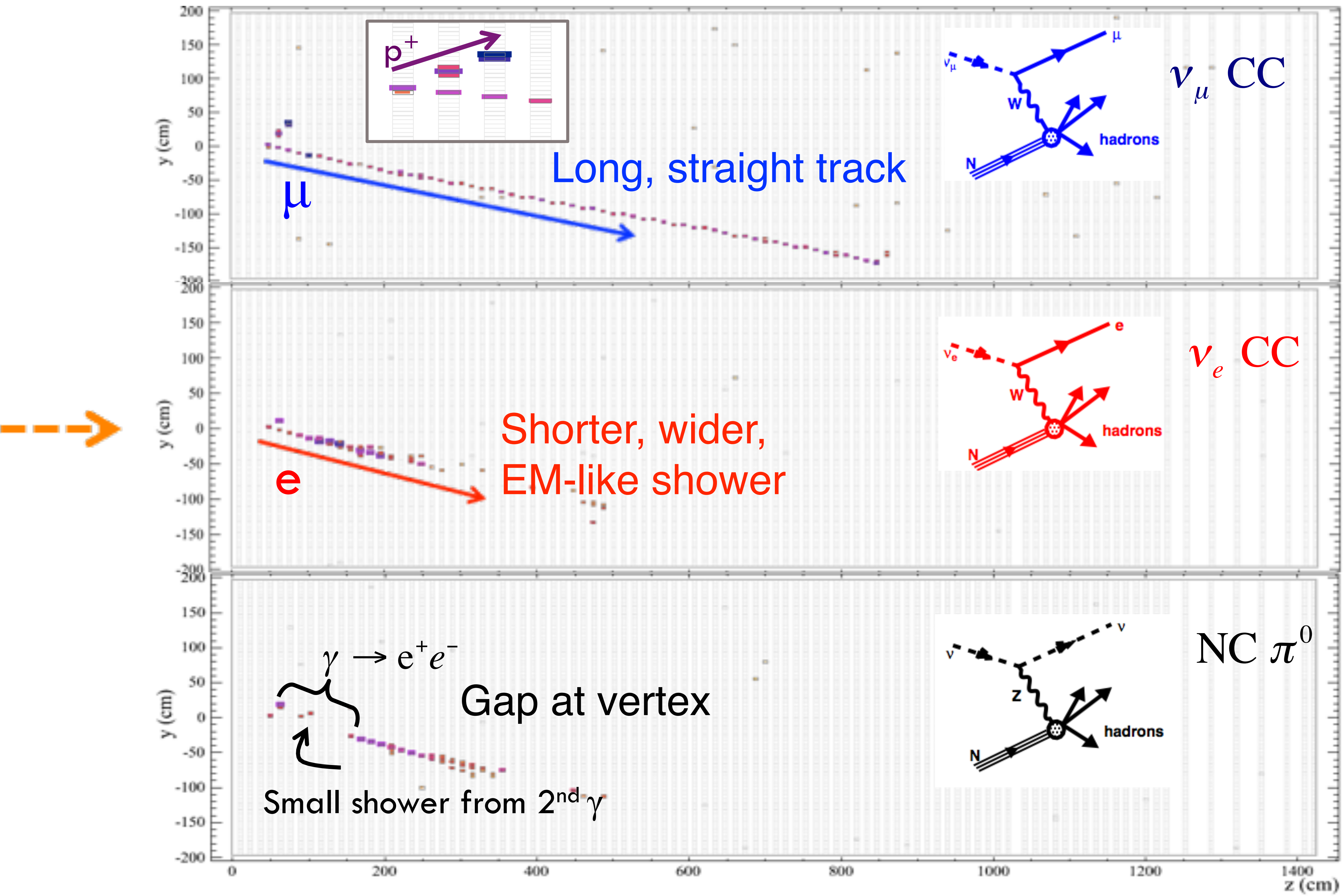
Upgrade from 330 kW to 700 kW in progress

- **Primary Goals:**
- **Observe $\nu_\mu \rightarrow \nu_e$ and measure the mixing angle θ_{13}.**
- **Resolution of the neutrino mass hierarchy**
- **Search for CP violation in the neutrino sector**
- **Improved measurements of $\sin^2(2\theta_{23})$ to within a few percent.**
- **Determine the octant of θ_{23}**

Nearly identical 330 ton detector located at FNAL, 14 mrad off-axis & 1 km from source will measure ν spectrum before oscillations occur.

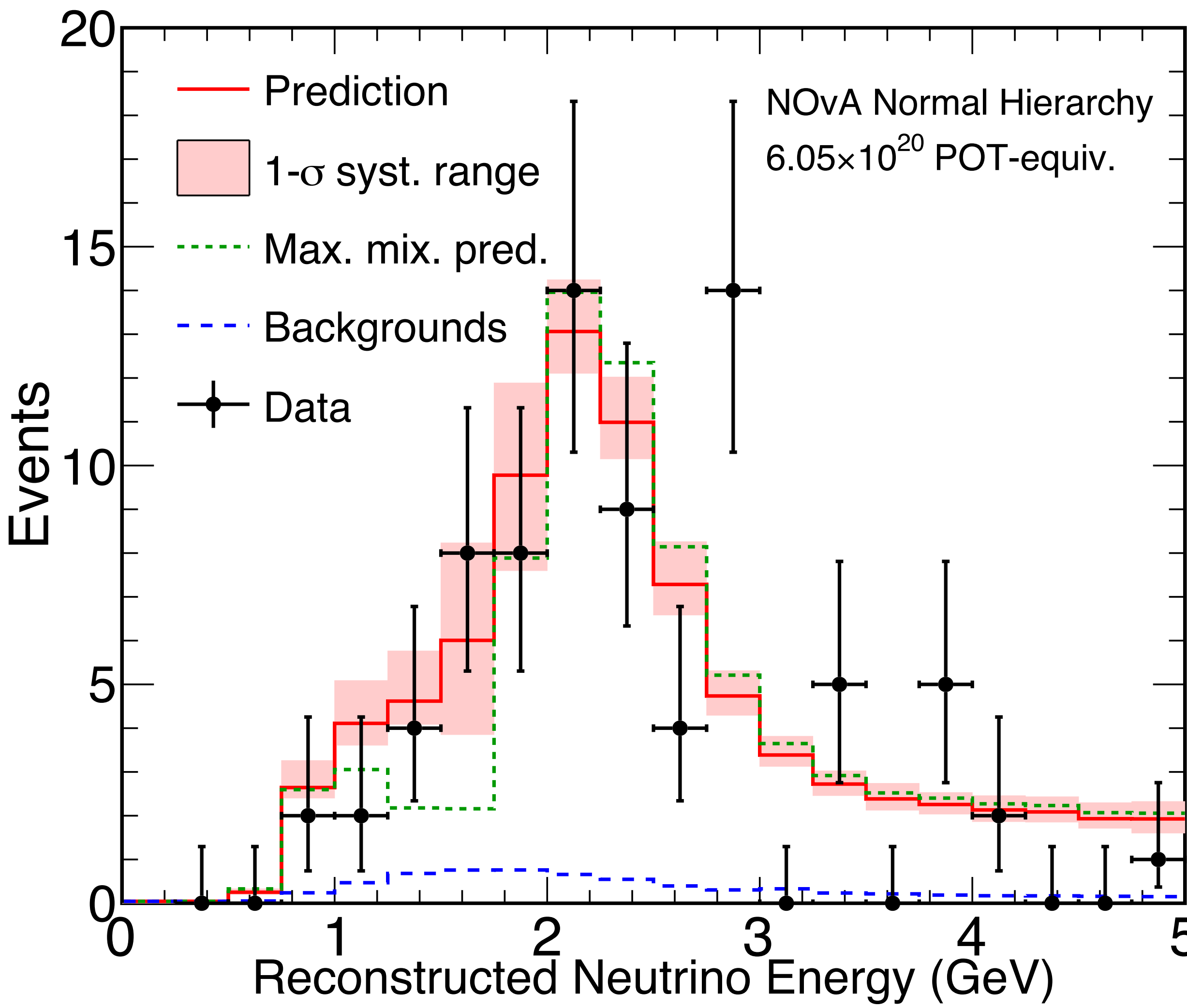


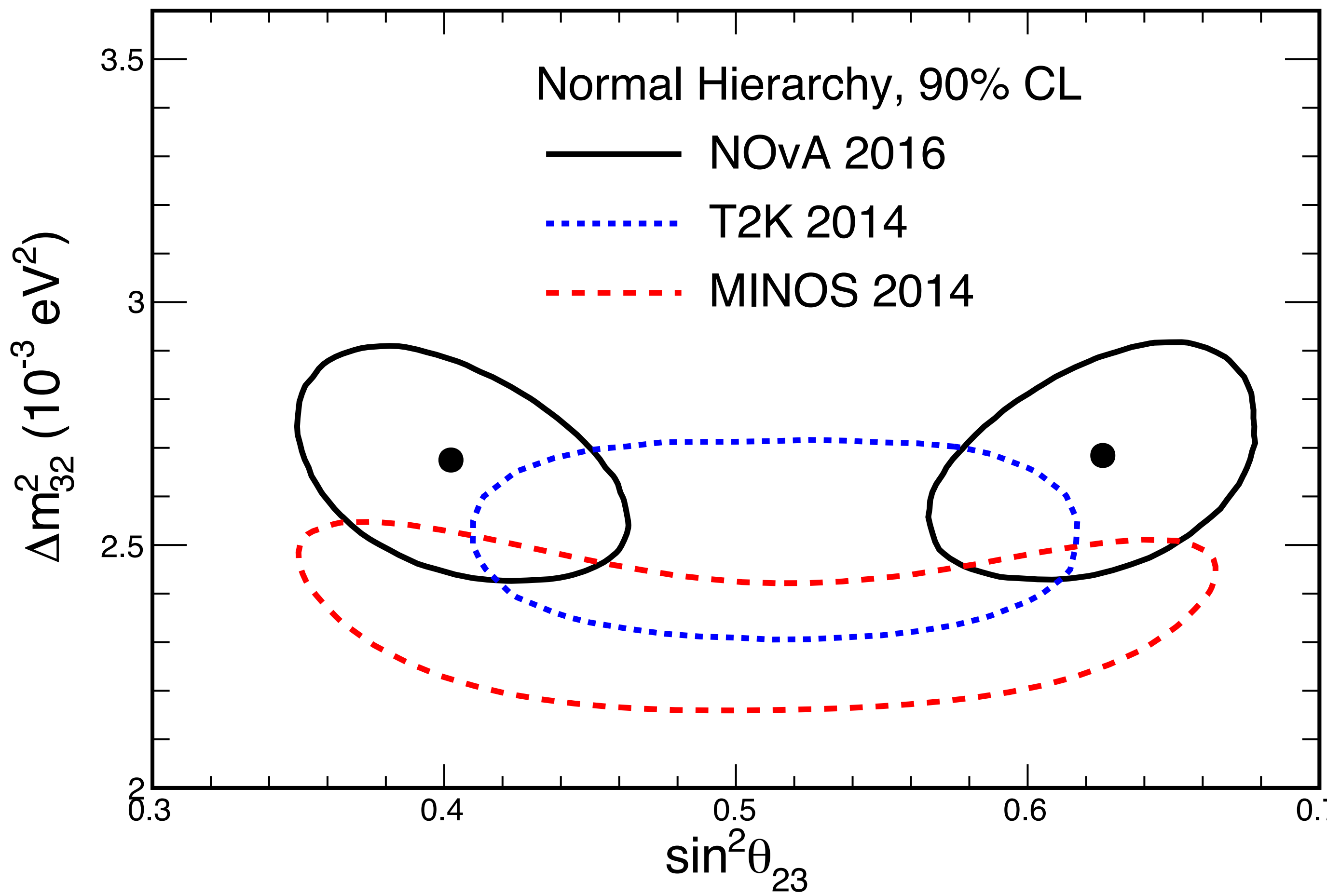
Distinguishing Neutrino Events in NOνA



Simulated Events

Recent Results from NOνA





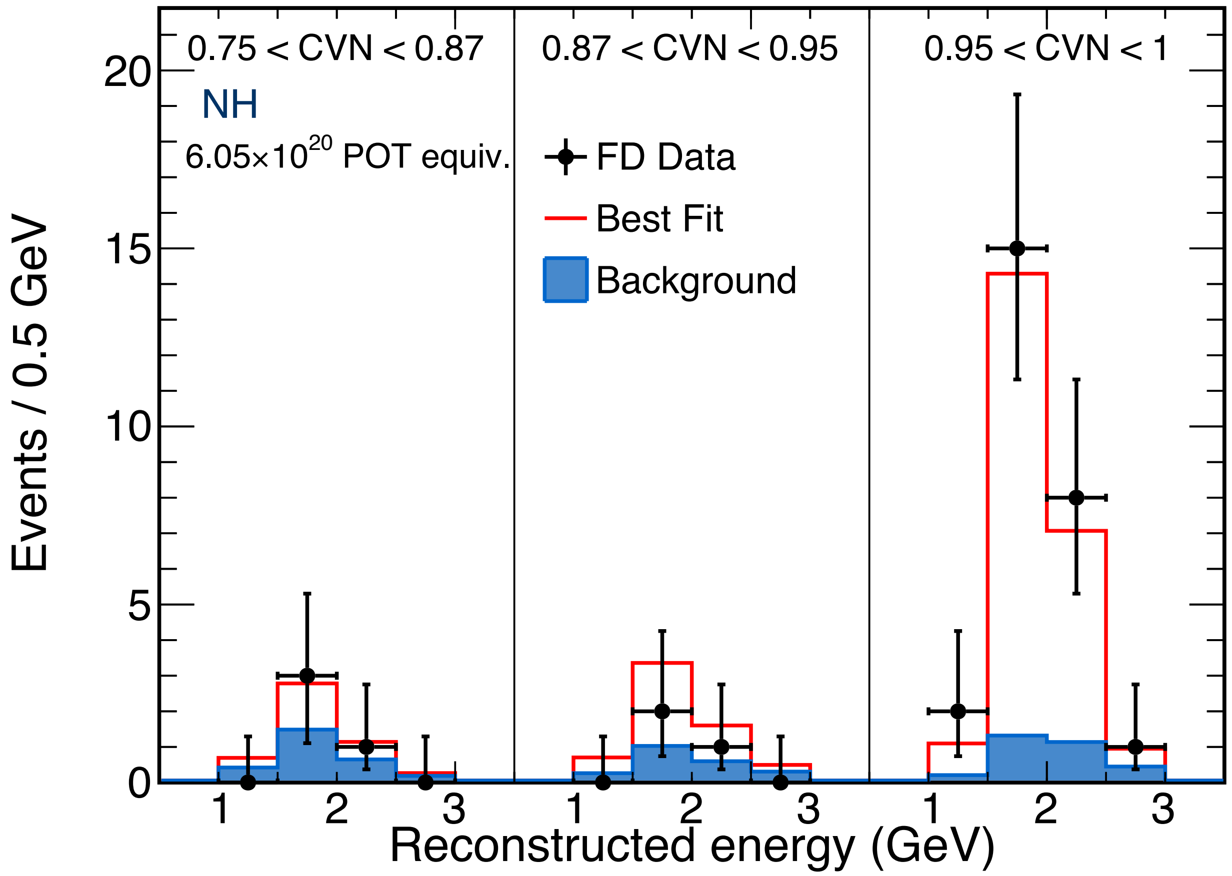
Phys. Rev. Lett. 118, 151802 (2017)

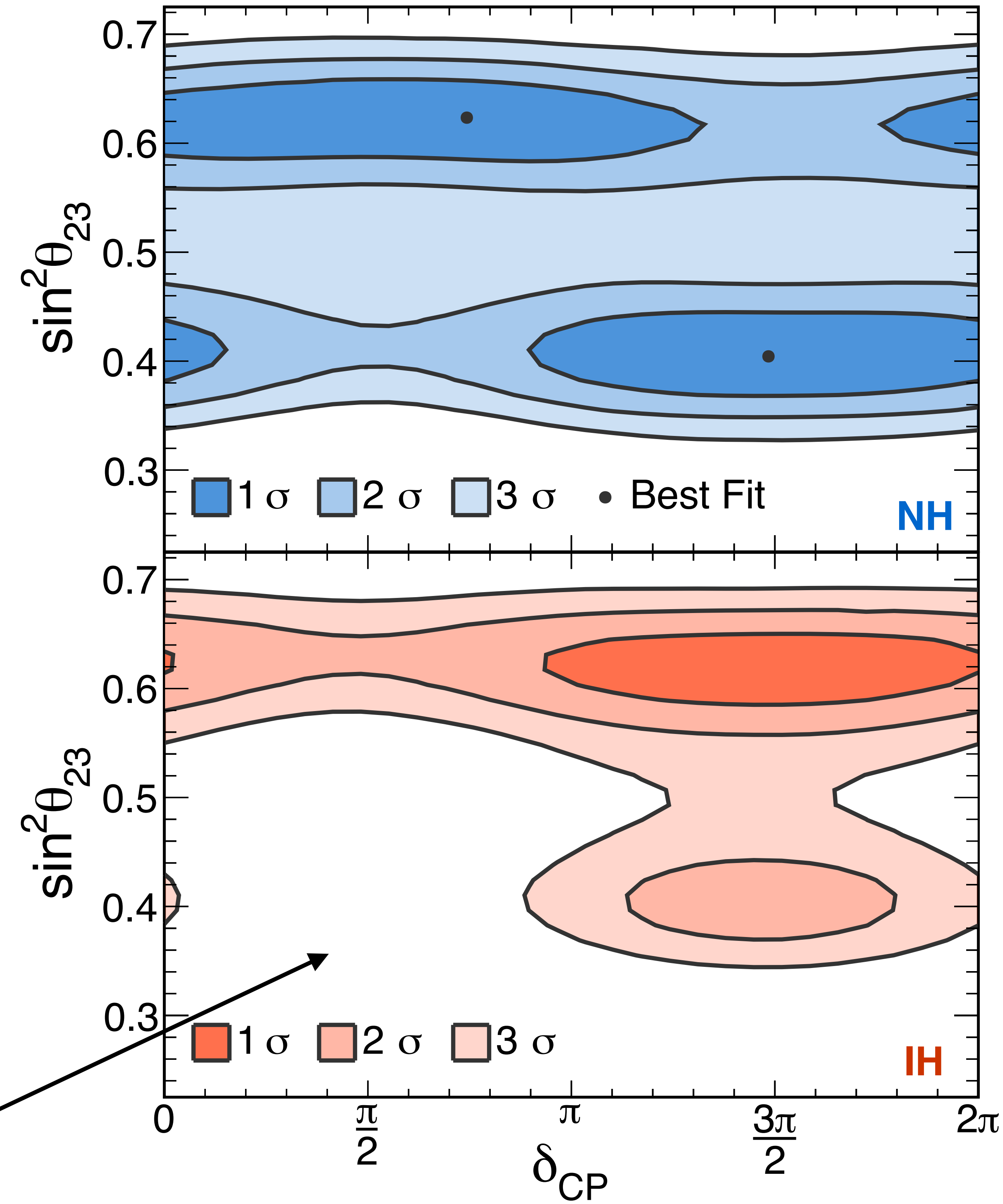
$$|\Delta m^2_{32}| = 2.67 \pm 0.12 \times 10^{-3}\ \mathrm{eV}^2$$

$$\sin^2\theta_{23} = \begin{cases} 0.40^{+0.03}_{-0.02}, \text{Normal} \\ 0.63^{+0.02}_{-0.03}, \text{Inverted} \end{cases}$$

Maximal mixing excluded at 2.6 σ

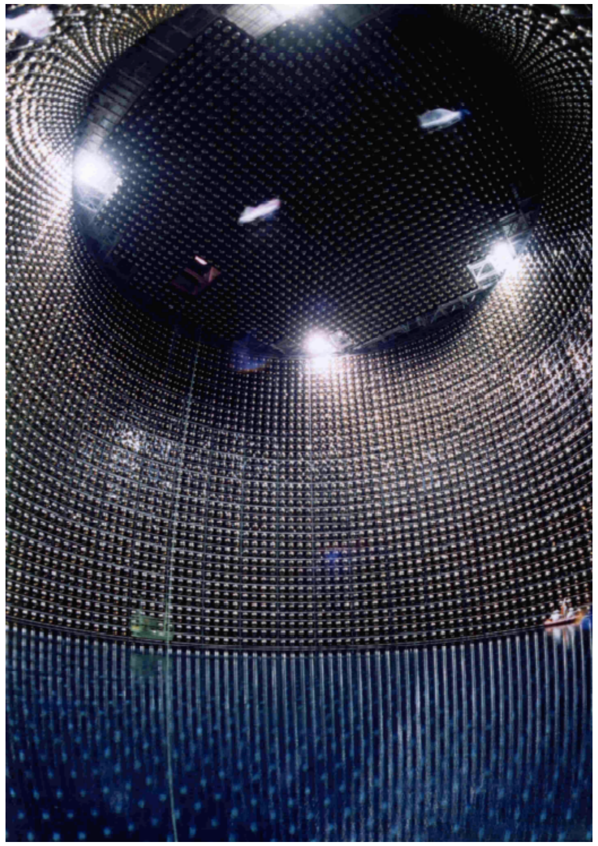
Recent Results from NOνA

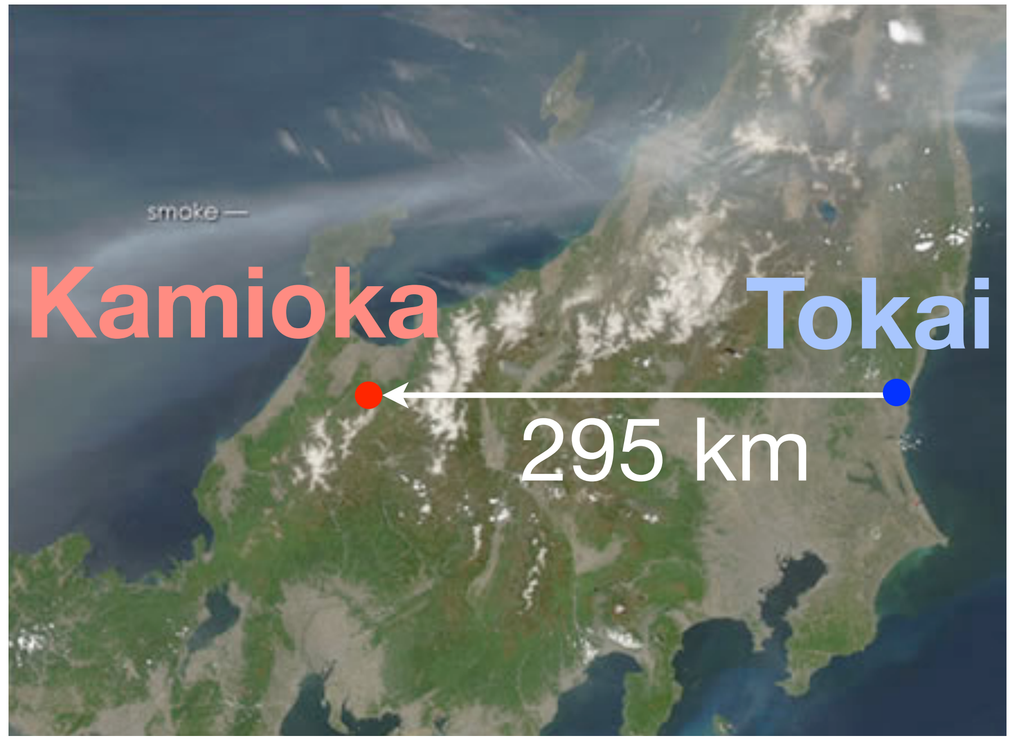


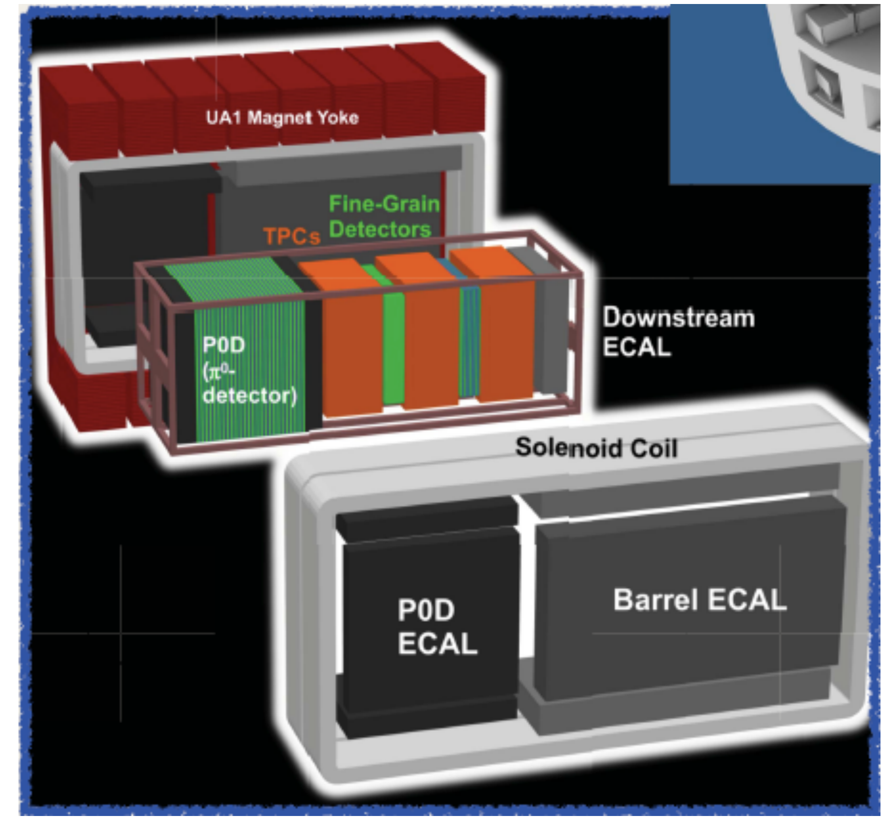


- Observed 33 events, with an expected background of 8.2 ± 0.8 events.
- Right: Δm^2 and θ_{23} are constrained from NOvA disappearance fits.
- Best fit: Normal Hiearchy, δ_{CP}=1.5π, $\sin^2(\theta_{23})$ = 0.40.
- 93% CL exclusion of IH

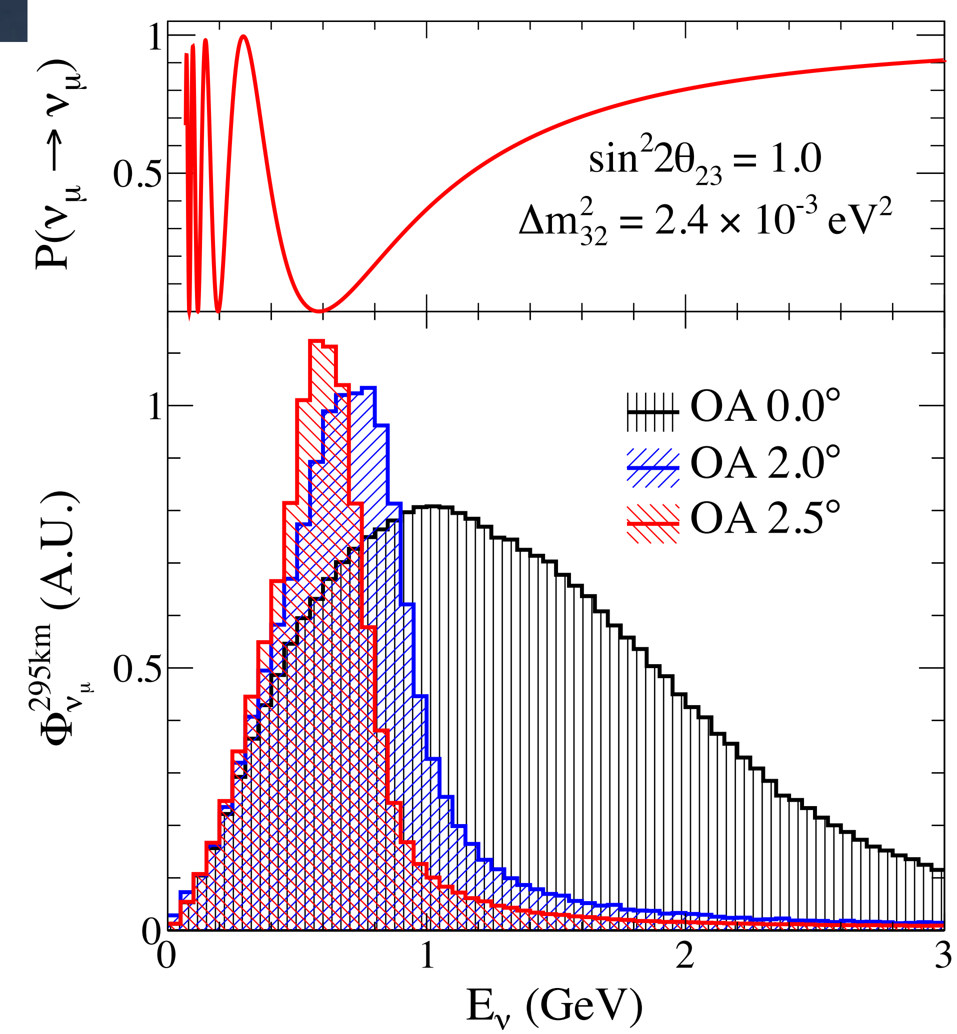
The Tokai to Kamioka (T2K) Experiment



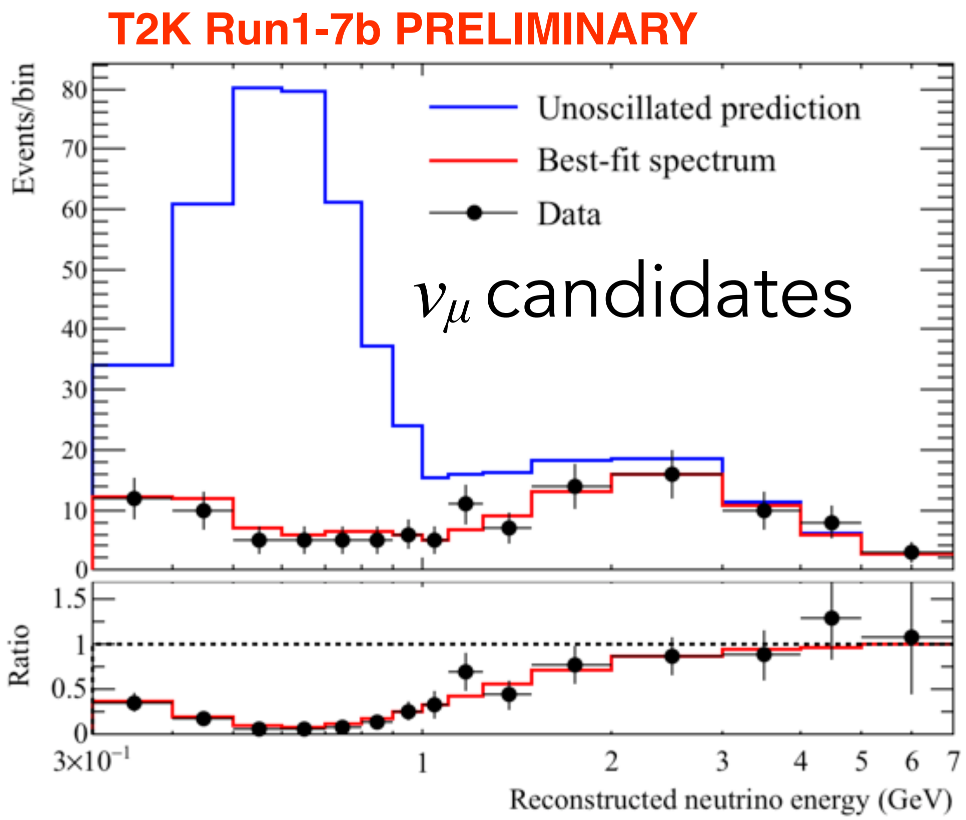


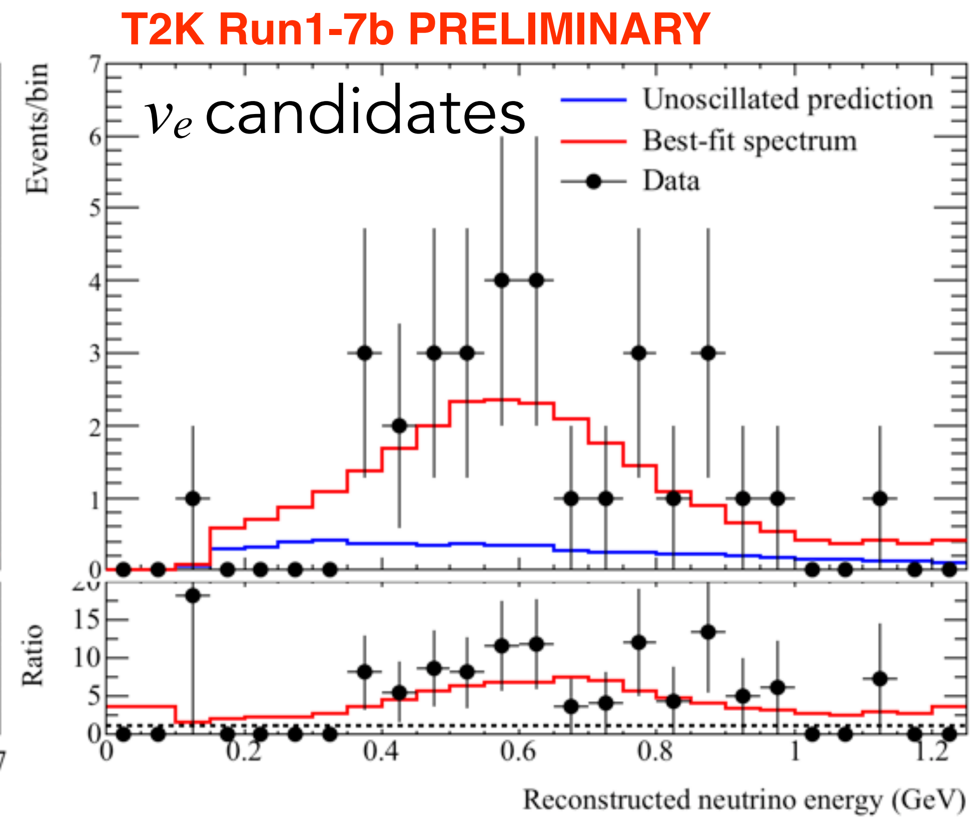


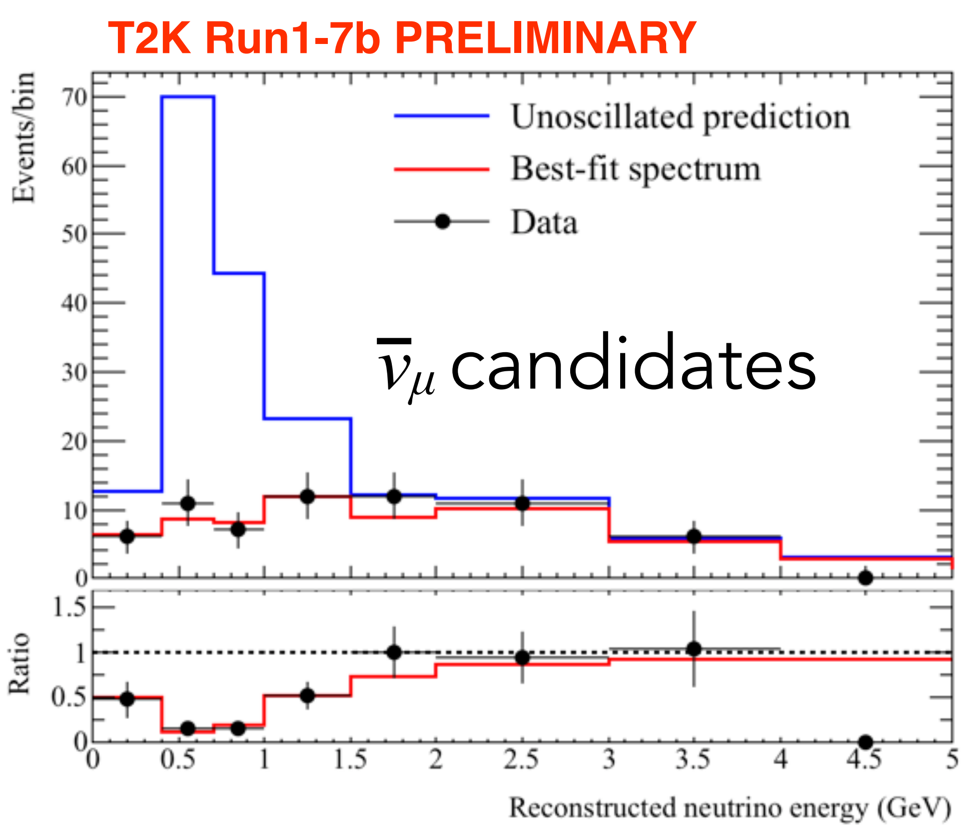
- Beam is directed 2.5° off-axis w.r.t. Super-K far detector: narrow spectrum peaked at 600 MeV.
- High resolution near detector but with different nuclear targets.
- Fairly insensitive to matter effects due to shorter baseline.
- Has collected ~equal amounts of neutrino and anti-neutrino beam data.

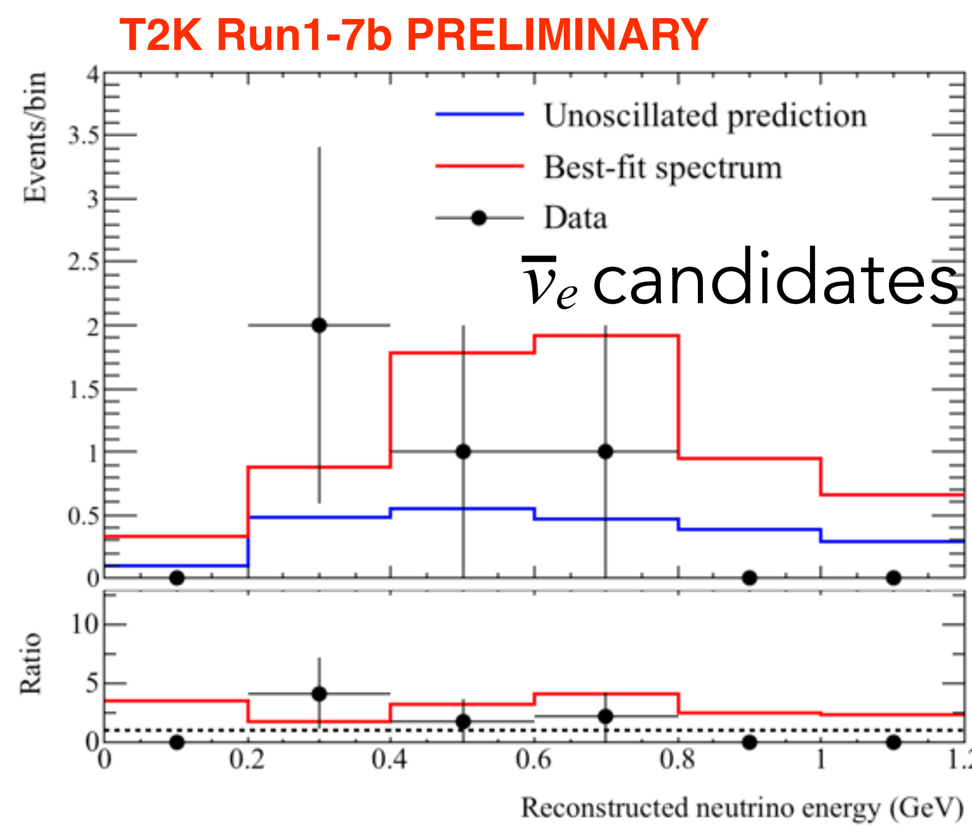


Recent T2K Results





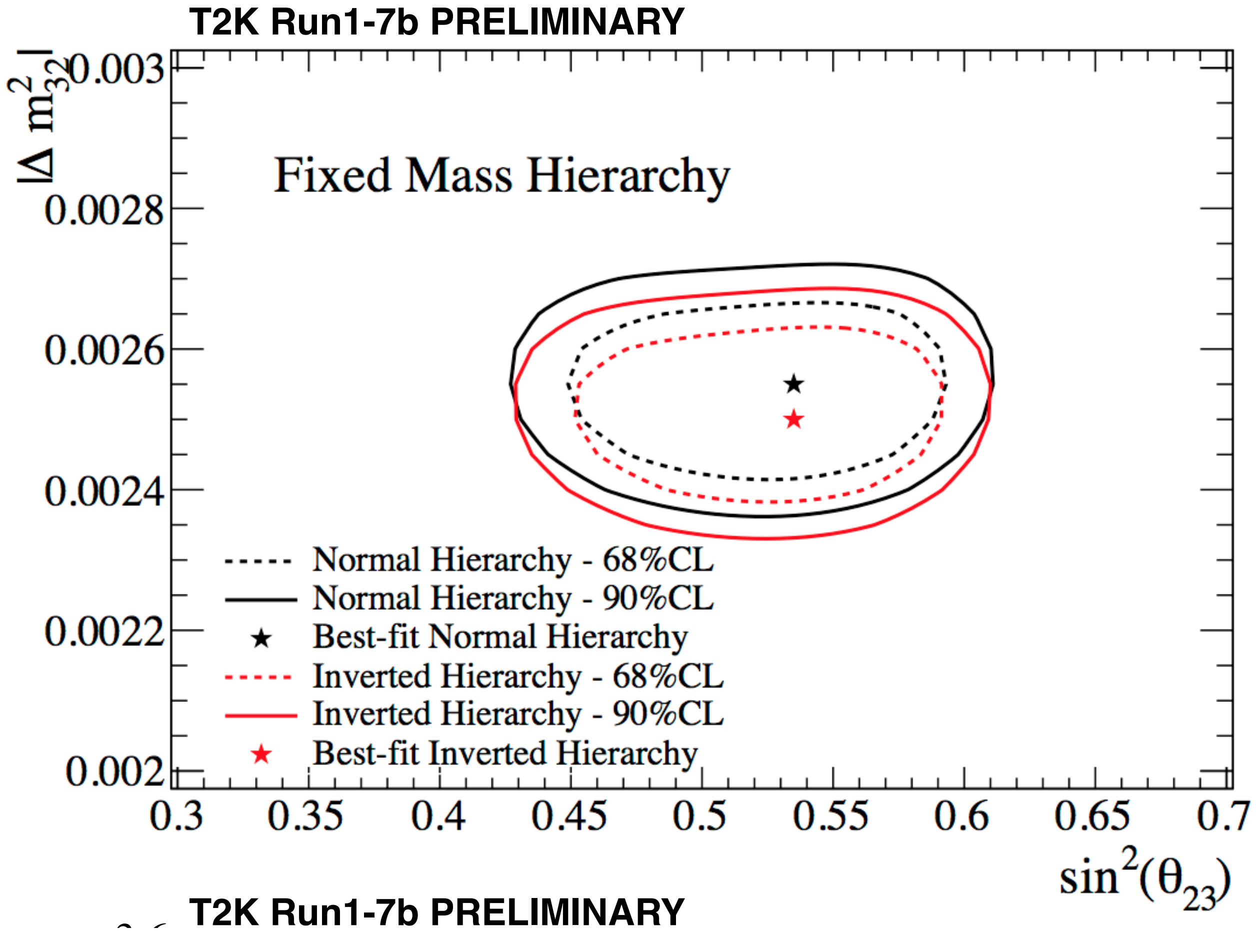


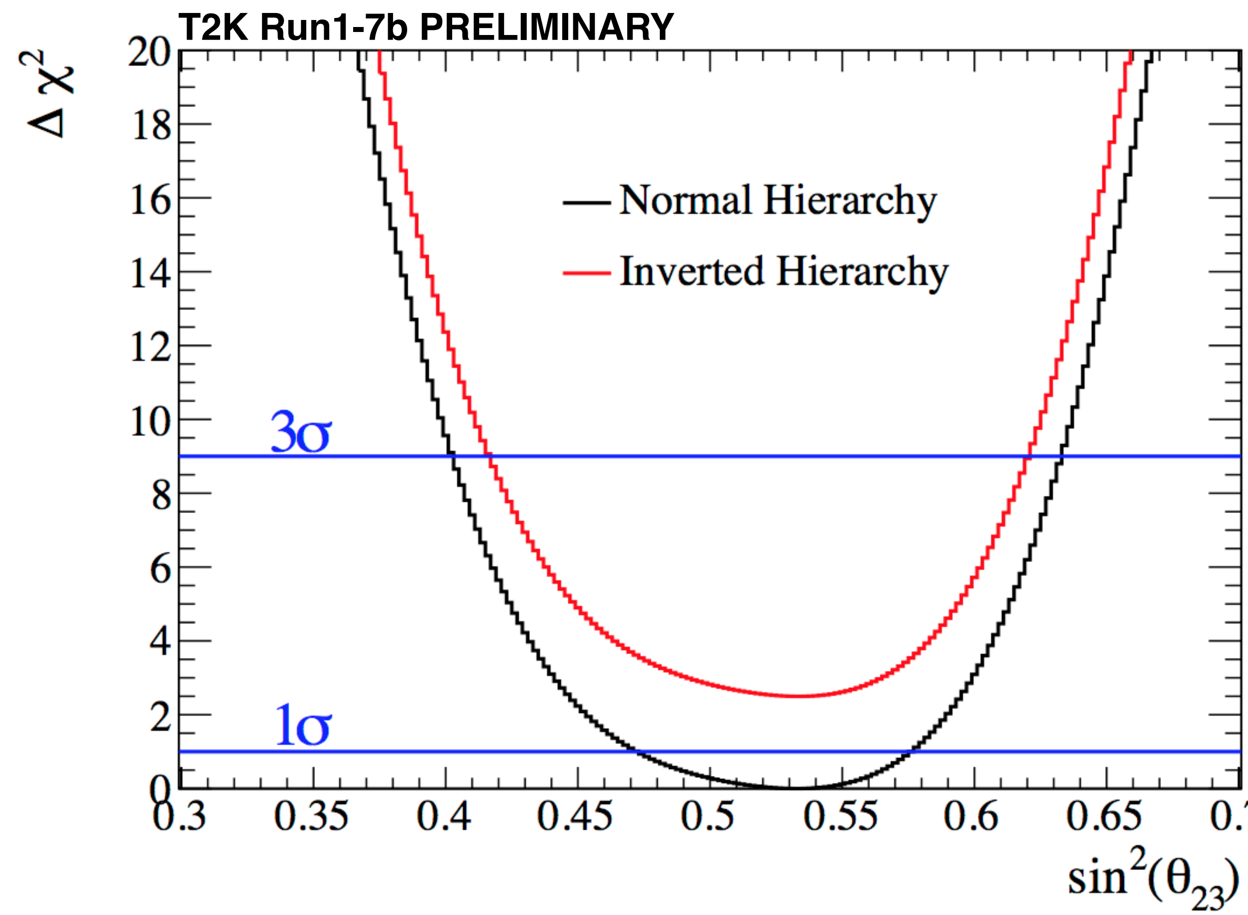


Joint 3-flavor fit performed on all data sets.

Tanaka, Neutrino 2016

Recent T2K Results

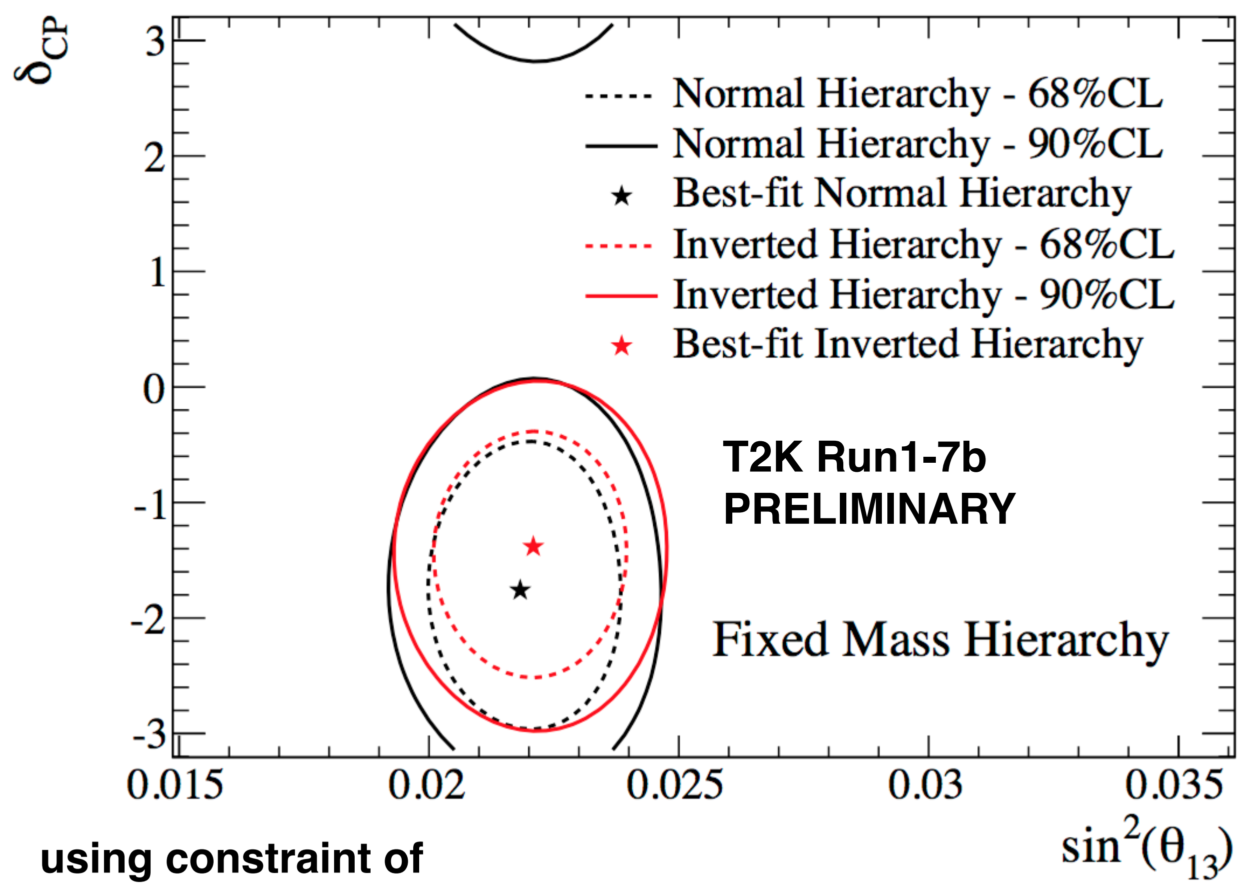


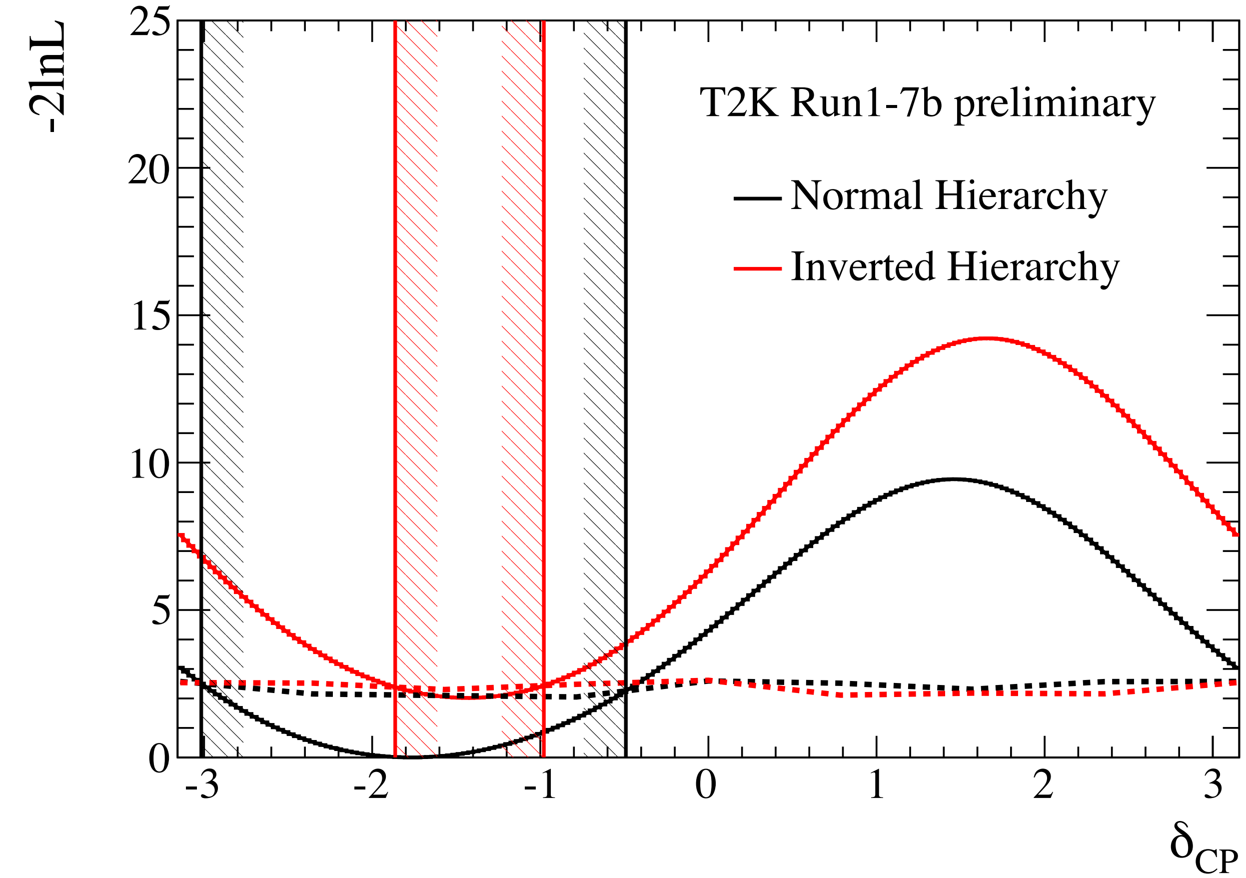


	NH	IH
$\sin^2\theta_{23}$	$0.532^{+0.044}_{-0.060}$	$0.534^{+0.041}_{-0.059}$
$\lvert\Delta m^2_{32}\rvert$ ($/10^{-3}$eV^2)	$2.545^{+0.084}_{-0.082}$	$2.510^{+0.082}_{-0.083}$

Tanaka, Neutrino 2016

Recent T2K Results



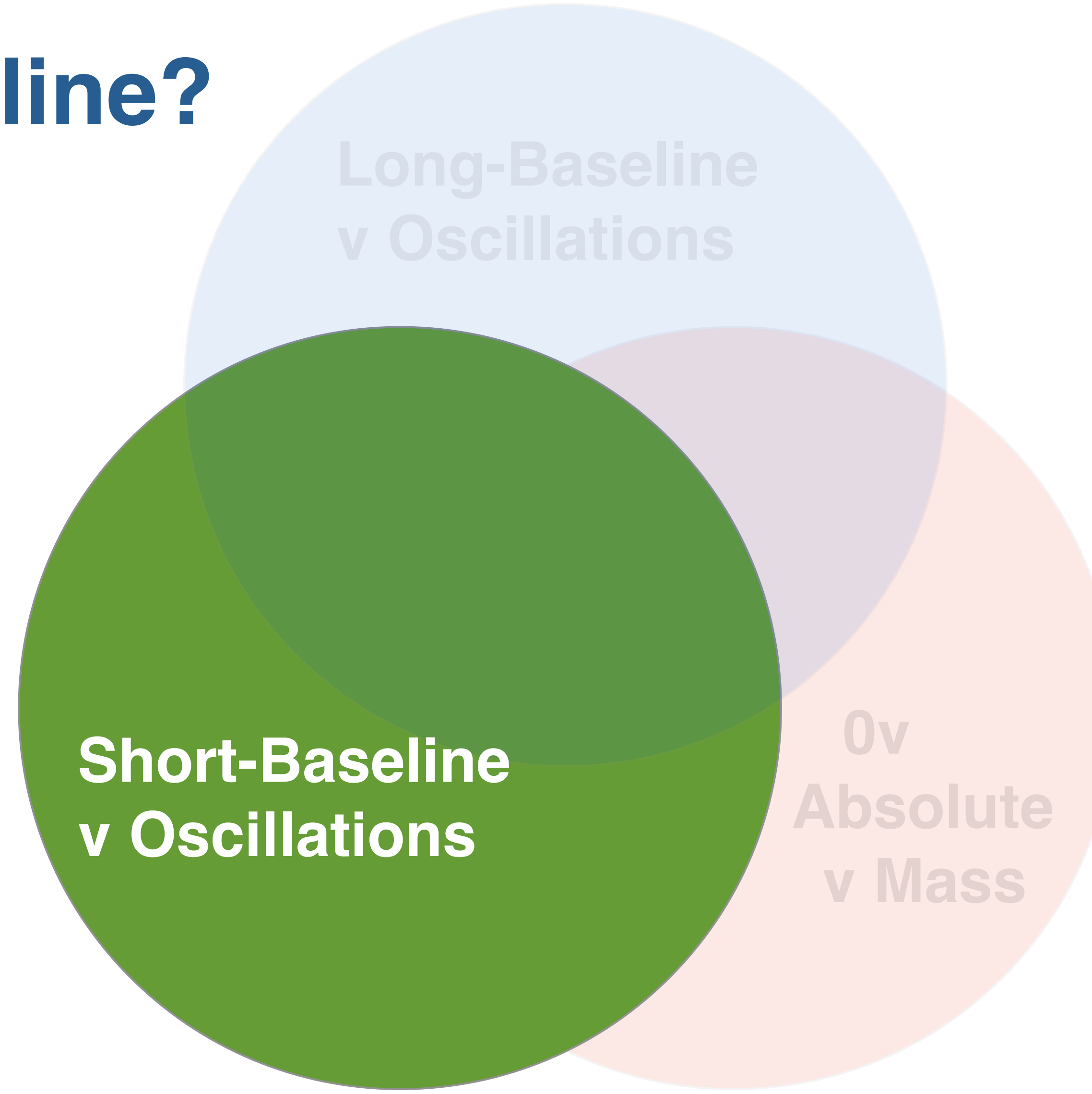


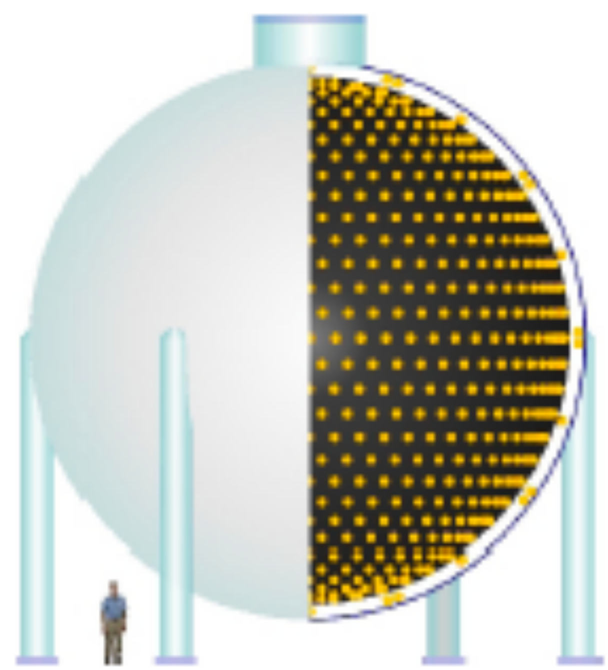
using constraint of
$\sin^2 2\theta_{13} = 0.085 \pm 0.005$

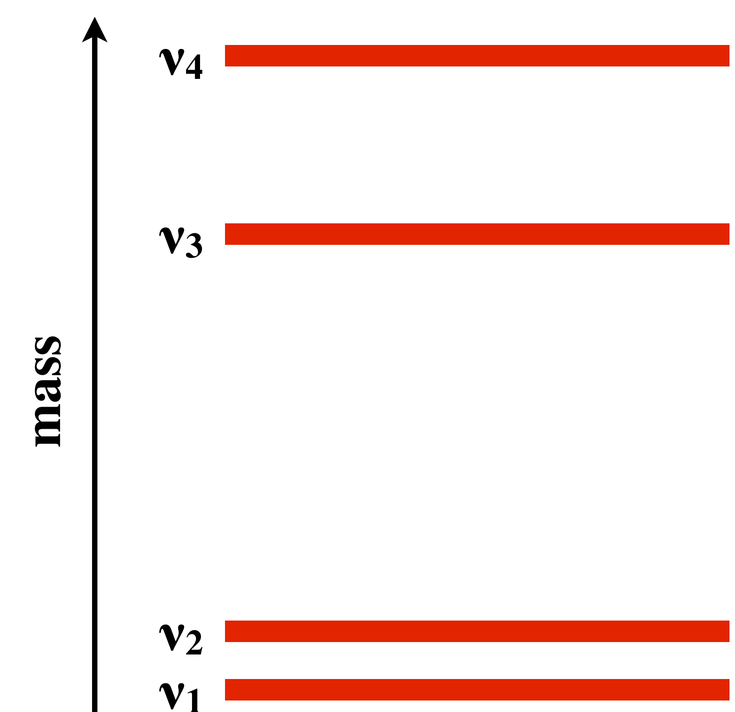
		EXPECTED (NH, $\sin^2\Theta_{23}$=0.528)			
	OBS.	$\delta_{CP}=-\pi/2$	$\delta_{CP}=0$	$\delta_{CP}=+\pi/2$	$\delta_{CP}=\pi$
ν_e	**32**	27.0	22.7	18.5	22.7
$\overline{\nu}_e$	**4**	6.0	6.9	7.7	6.8

What Do We Mean By Short-Baseline?

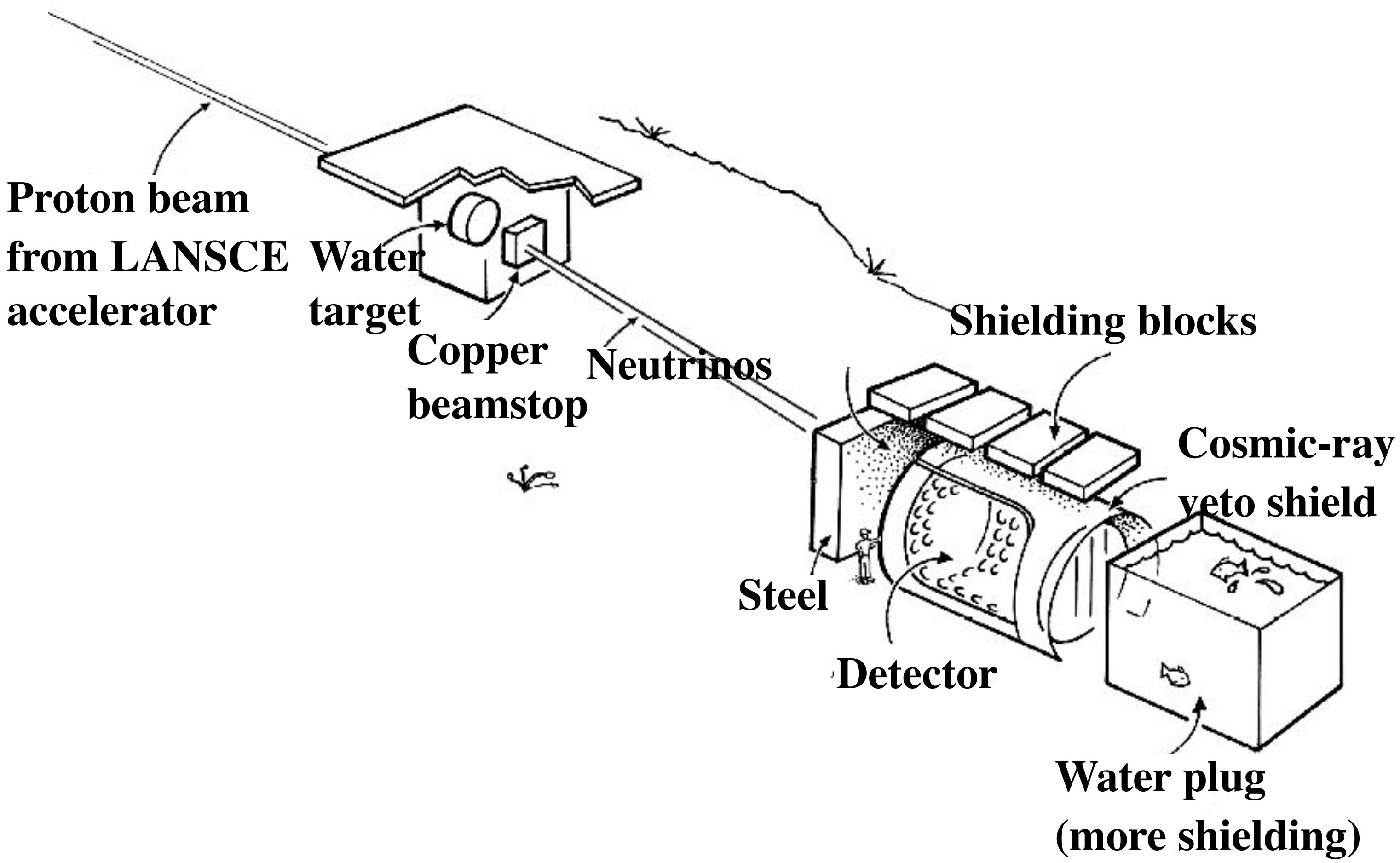
- Measurements involving ν_e appearance with L/E ~ 1 km/GeV (1 m/MeV)
- LSND, MiniBooNE
- Implies existence of neutrinos that do not interact via the weak force… aka ***sterile***

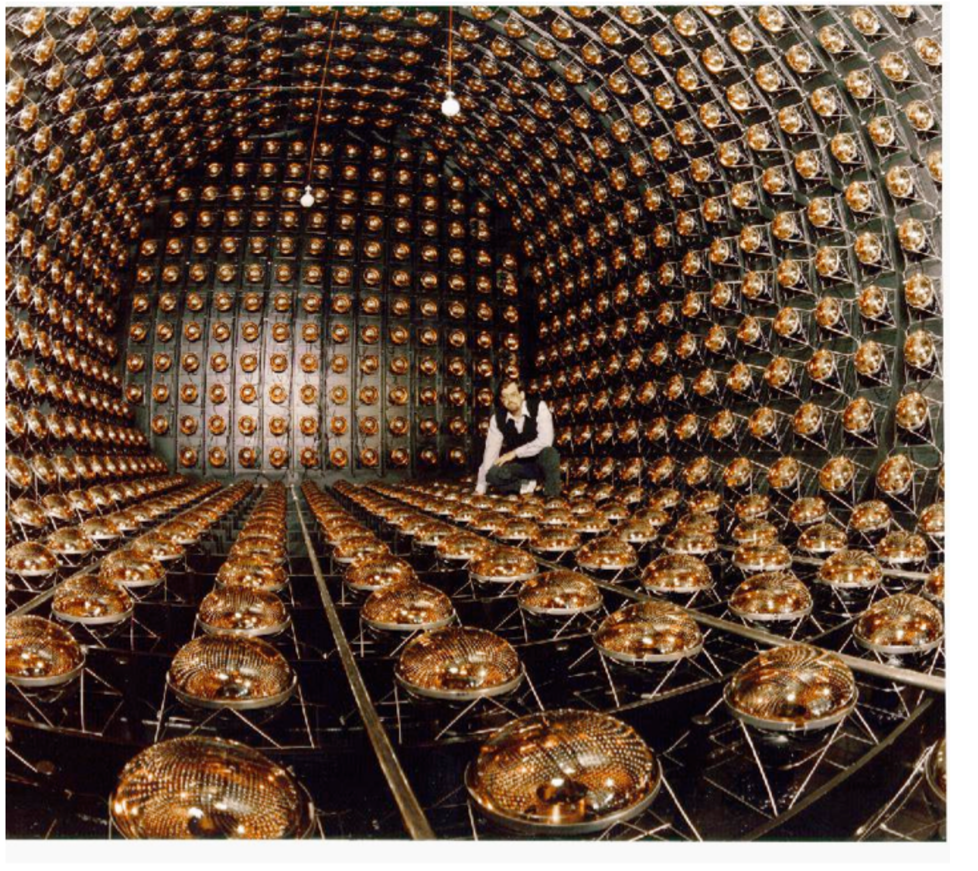






The LSND Anomaly





- Single 167 ton liquid scintillator detector (1000 PMTs)
- Used stopped pion beam, E_ν ~ 20-53 MeV, L ~ 30 m

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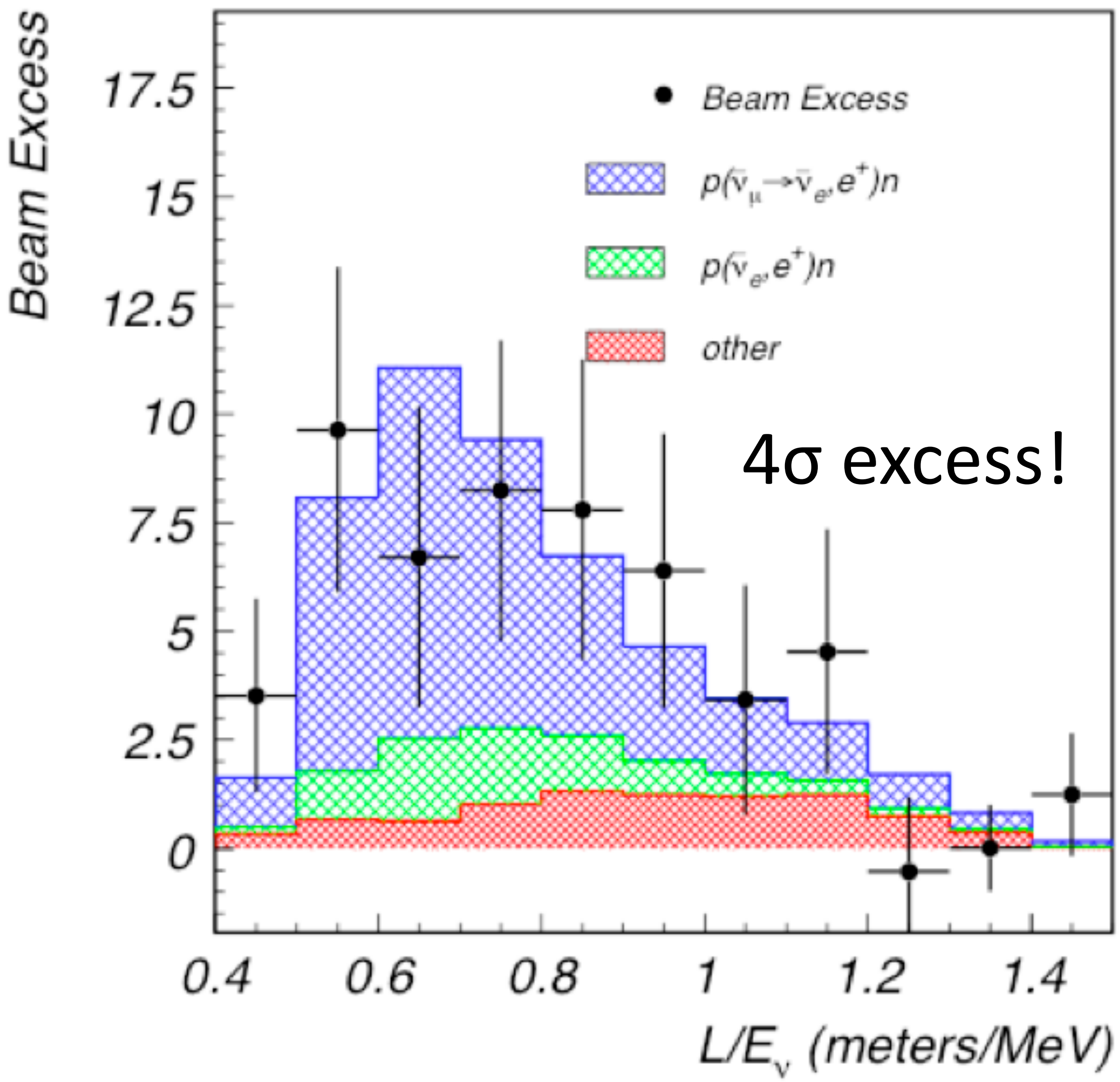
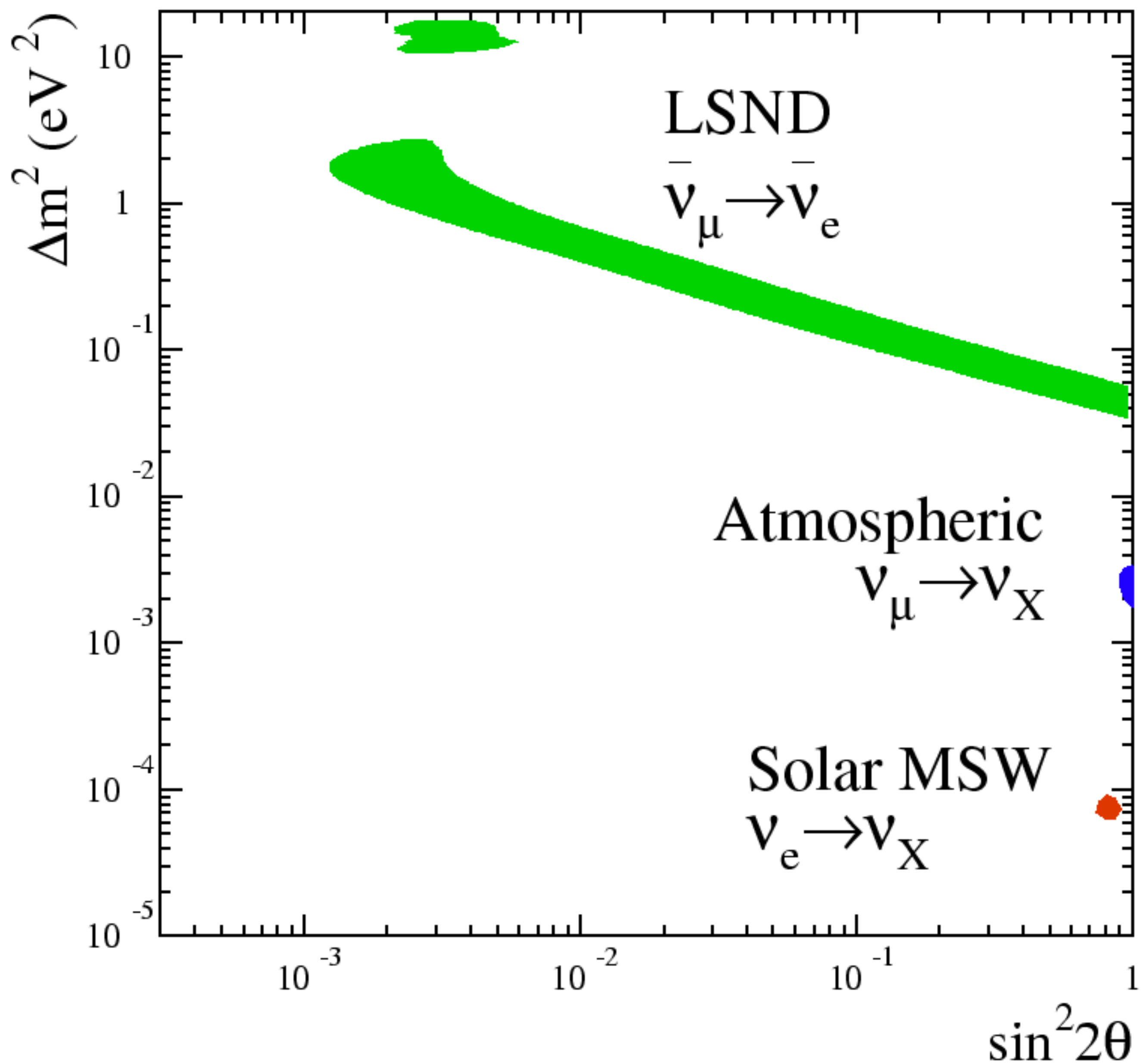
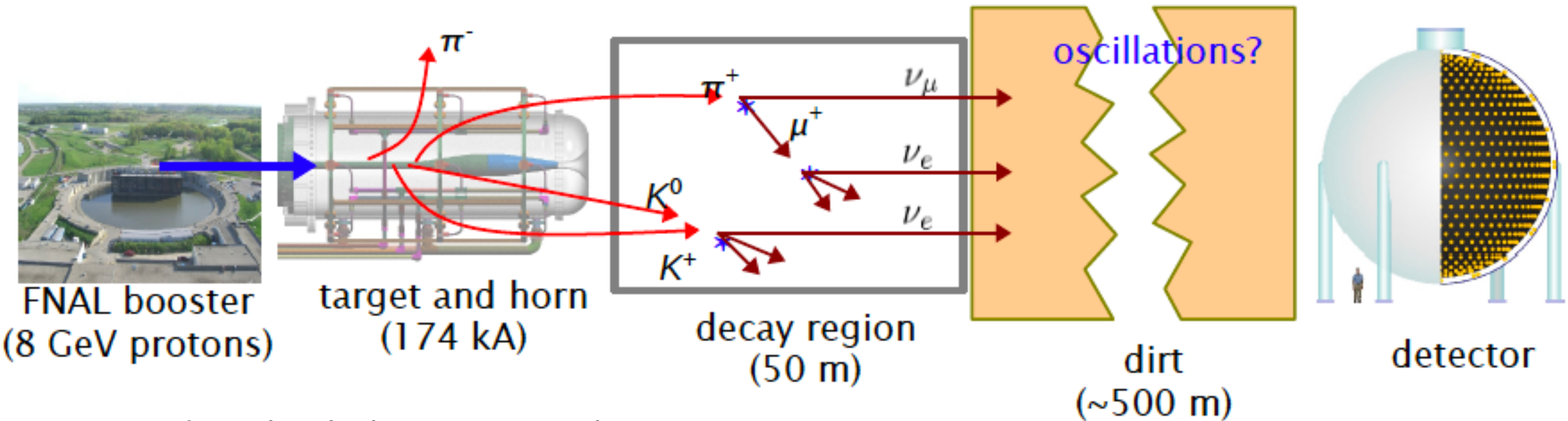




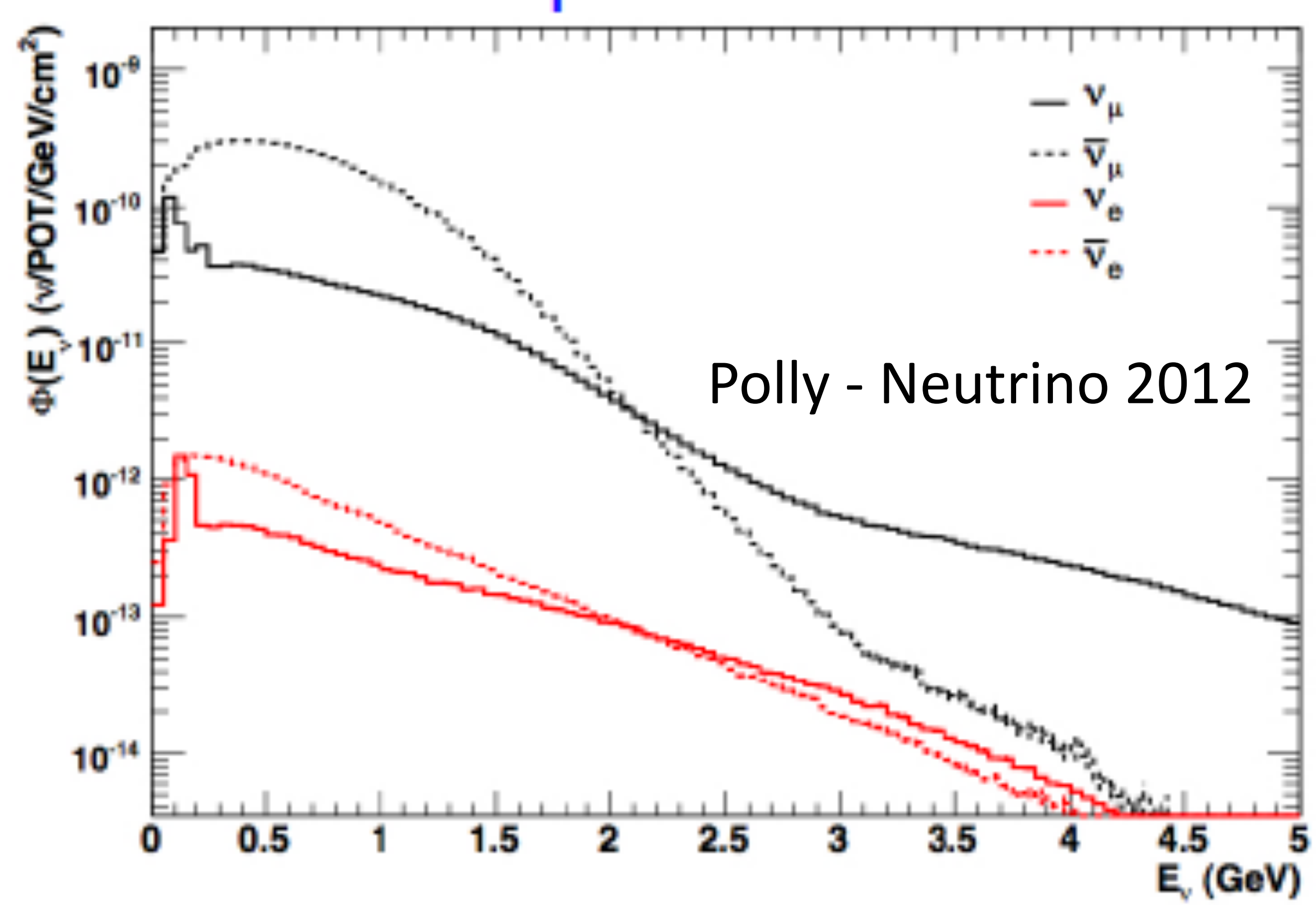
- Taking the LSND result at face value, the most straightforward explanation is the existence of another neutrino.
- Neutrino does not interact via the weak force: STERILE

And Along Comes MiniBooNE...



- Designed to check the LSND result
- Average energy of neutrinos ~10x larger than LSND, so x10 increase in cross-section (more neutrino interactions in detector)
- Use of horn increased neutrino flux, allows one to measure rates for either neutrinos or anti-neutrinos
- However, different backgrounds than LSND, eg:
  - wrong-sign neutrinos
  - intrinsic beam ve from K-decays

anti-ν_μ Mode Flux



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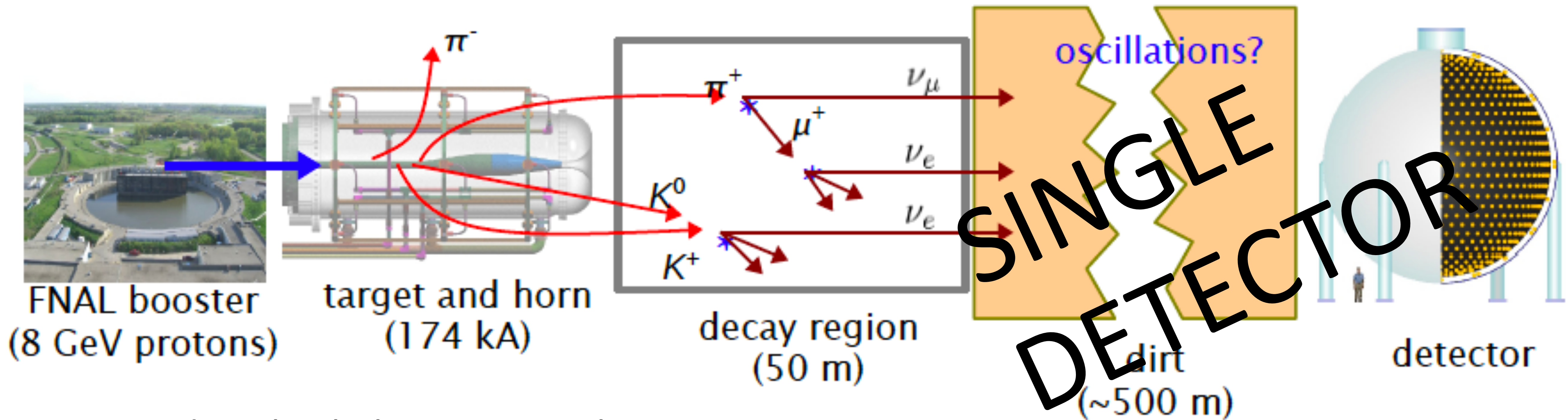

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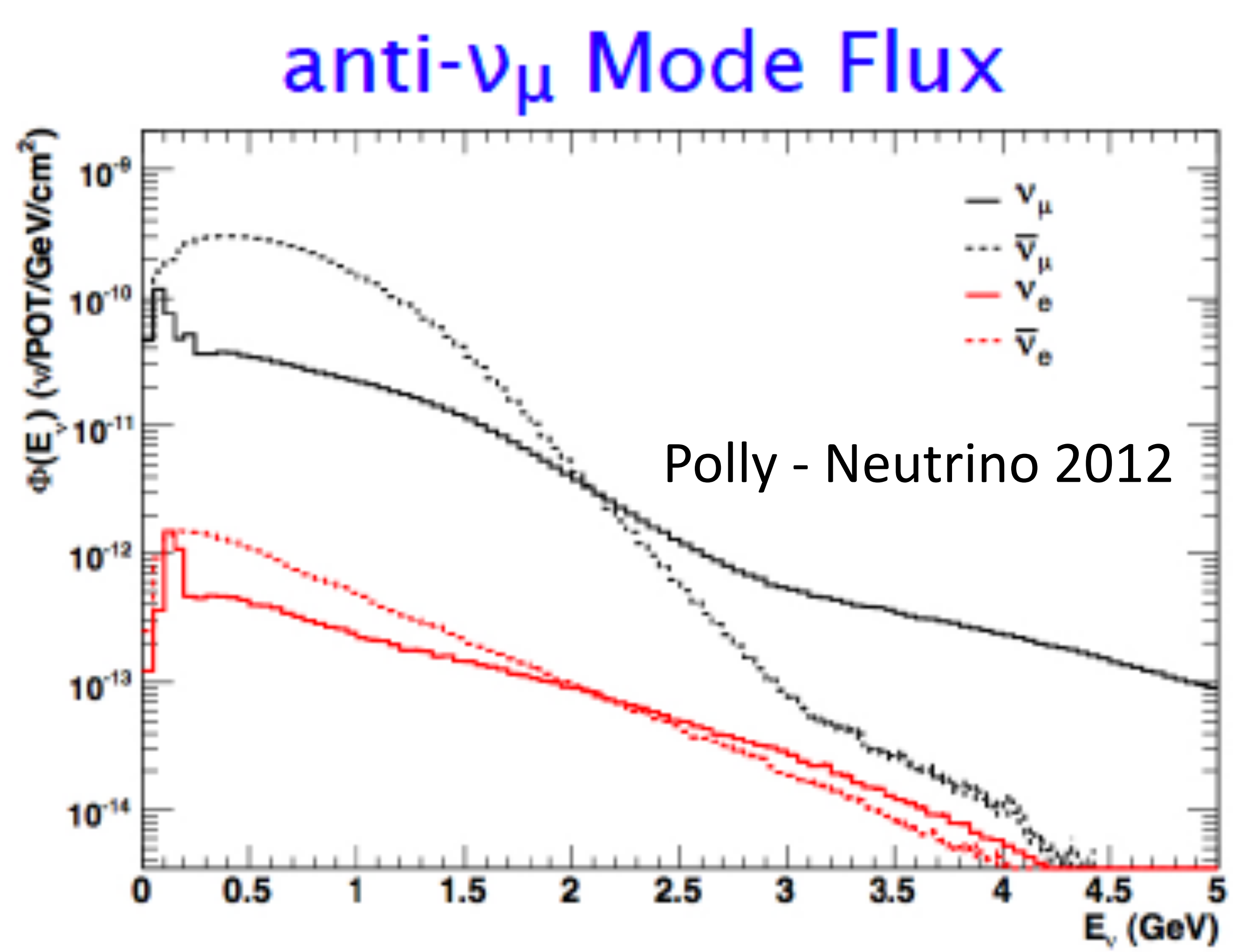
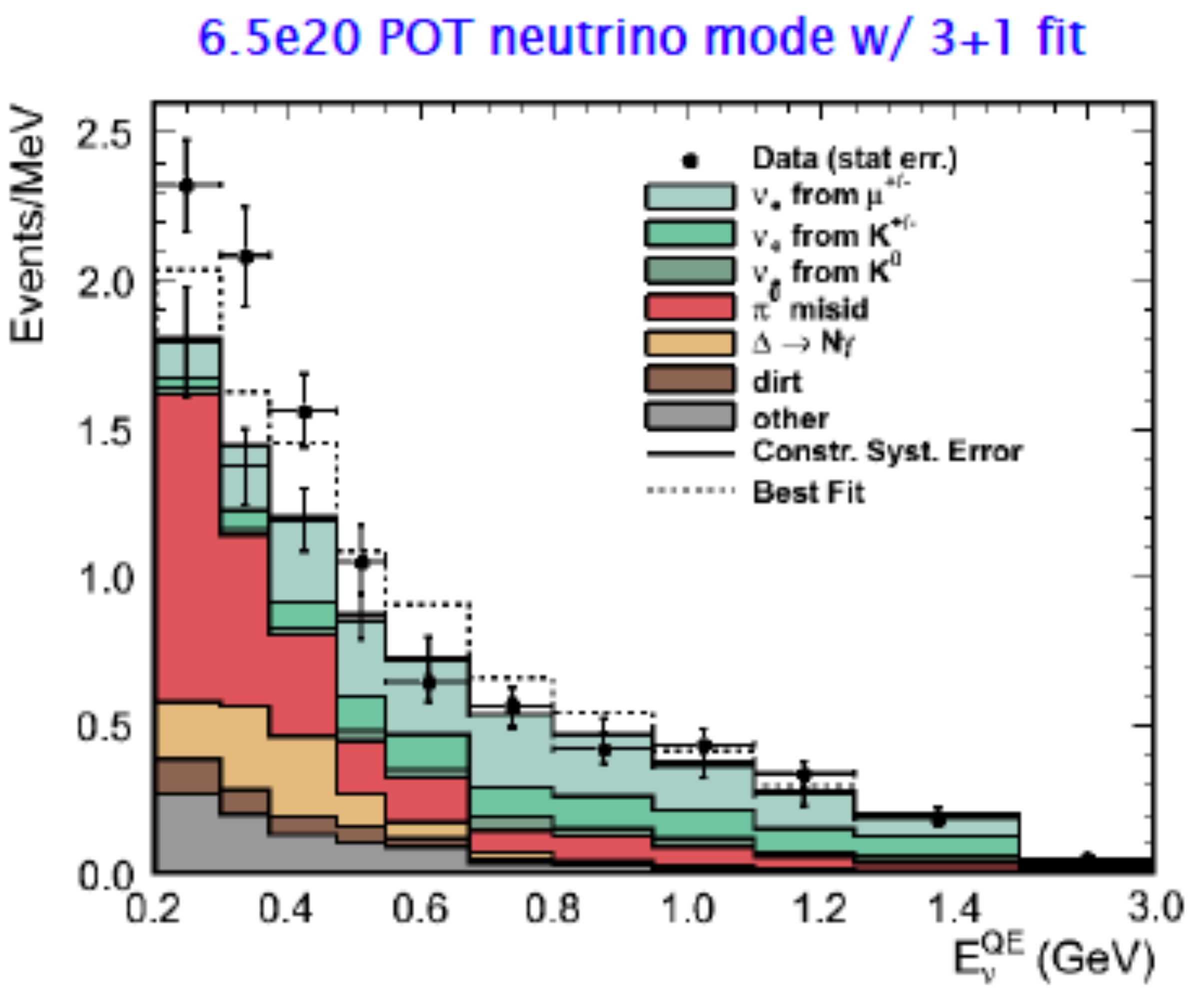
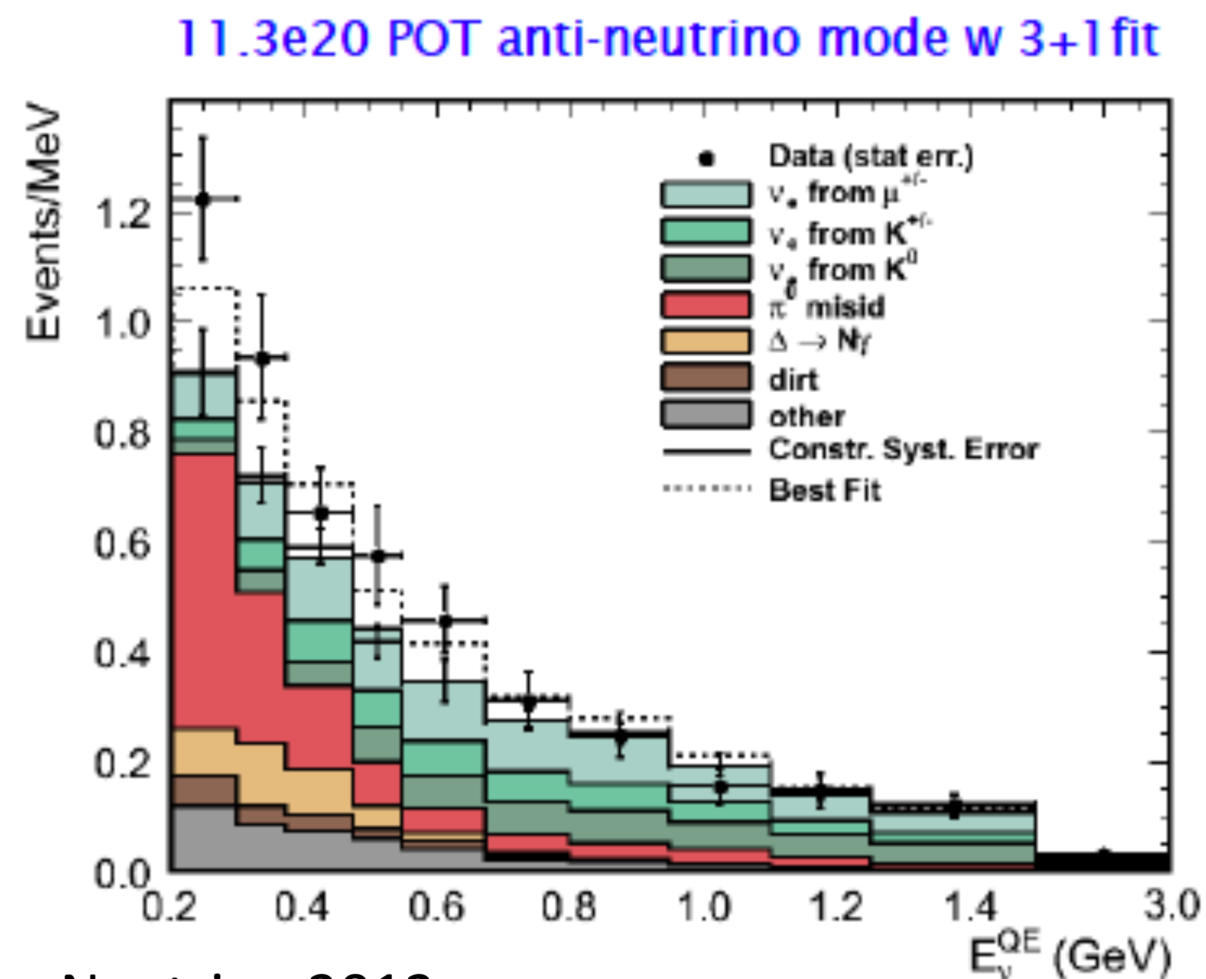


MiniBooNE Results





Polly - Neutrino 2012

- neutrino-mode:
  - excess of ν_e from 200-1250 MeV
  - however, excess is all at lower energies (< 475 MeV) where backgrounds are very large
  - LSND result predicts that excess should be in the range of 600-800 MeV
- Similar results in latest measurement of anti-neutrinos
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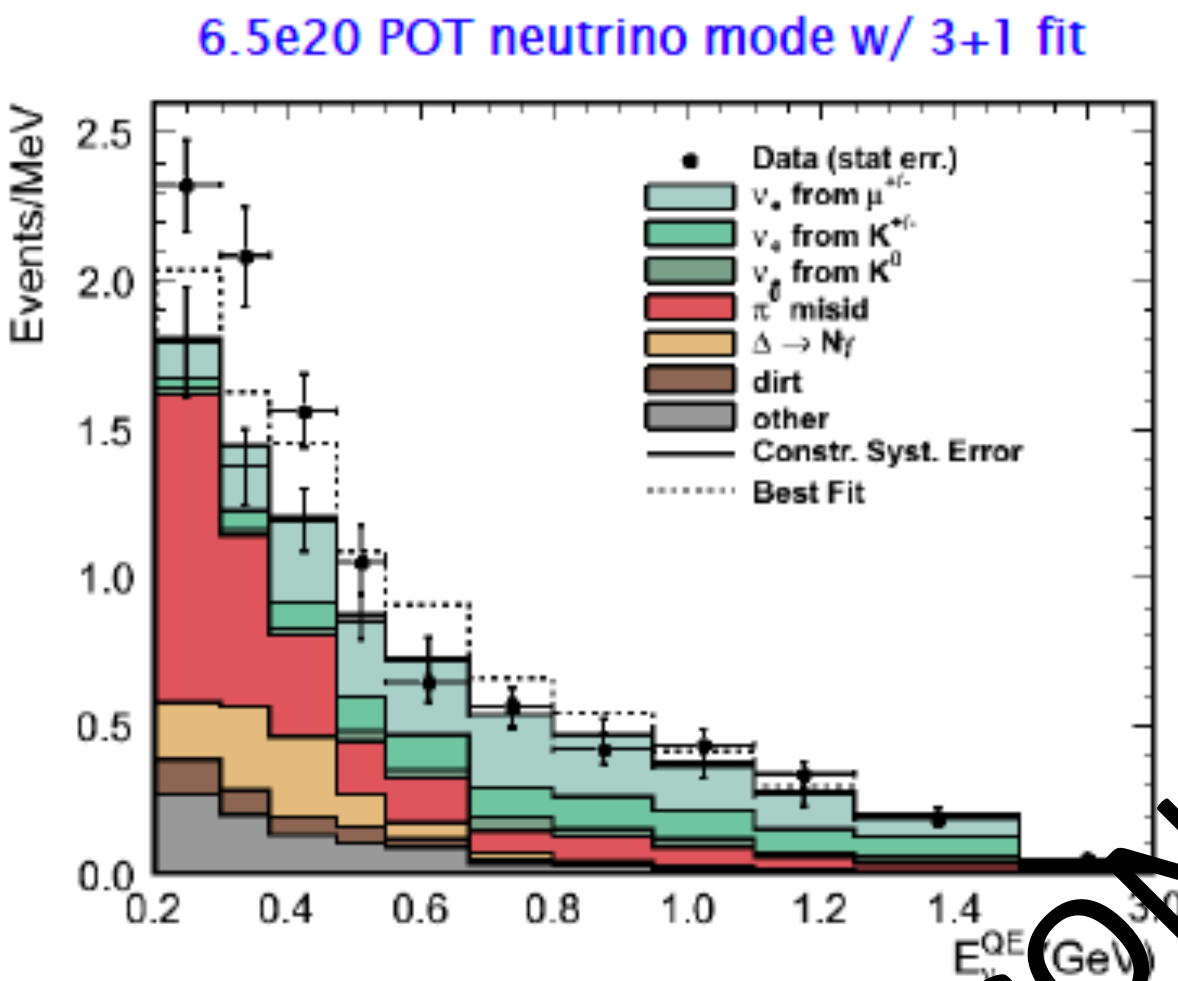

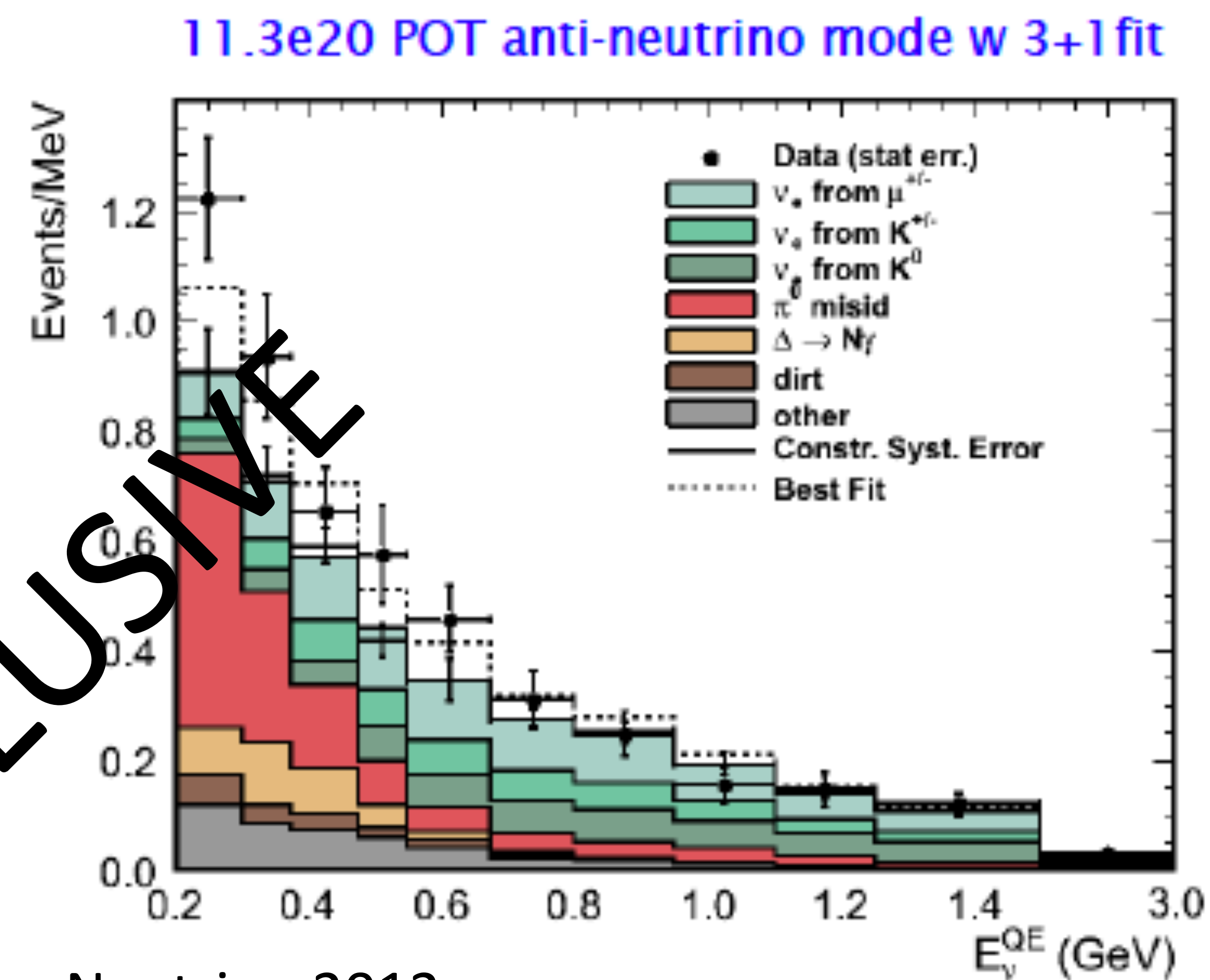

INCONCLUSIVE

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

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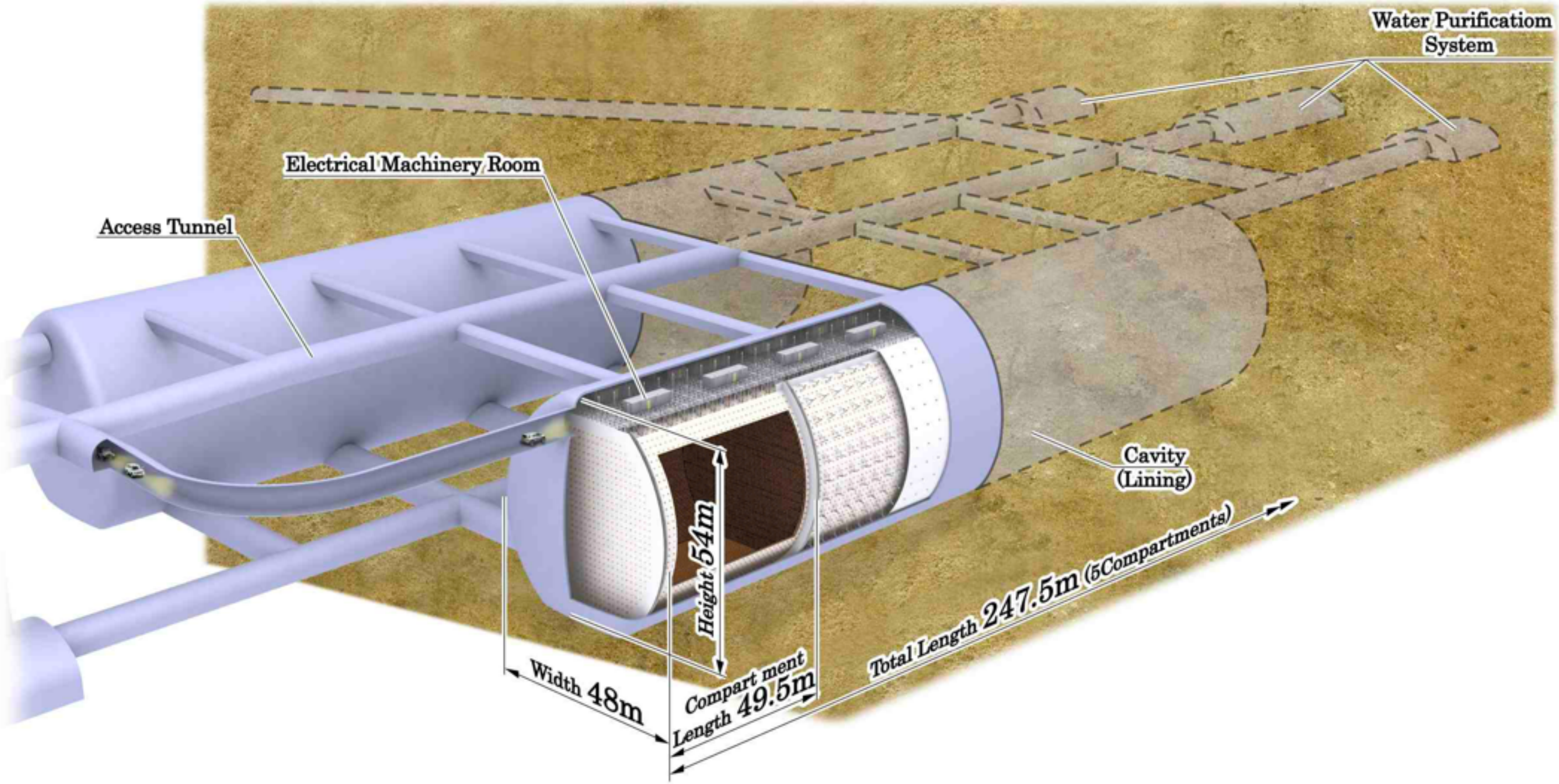
  - Much much more

Hyper Kamiokande (Japan)



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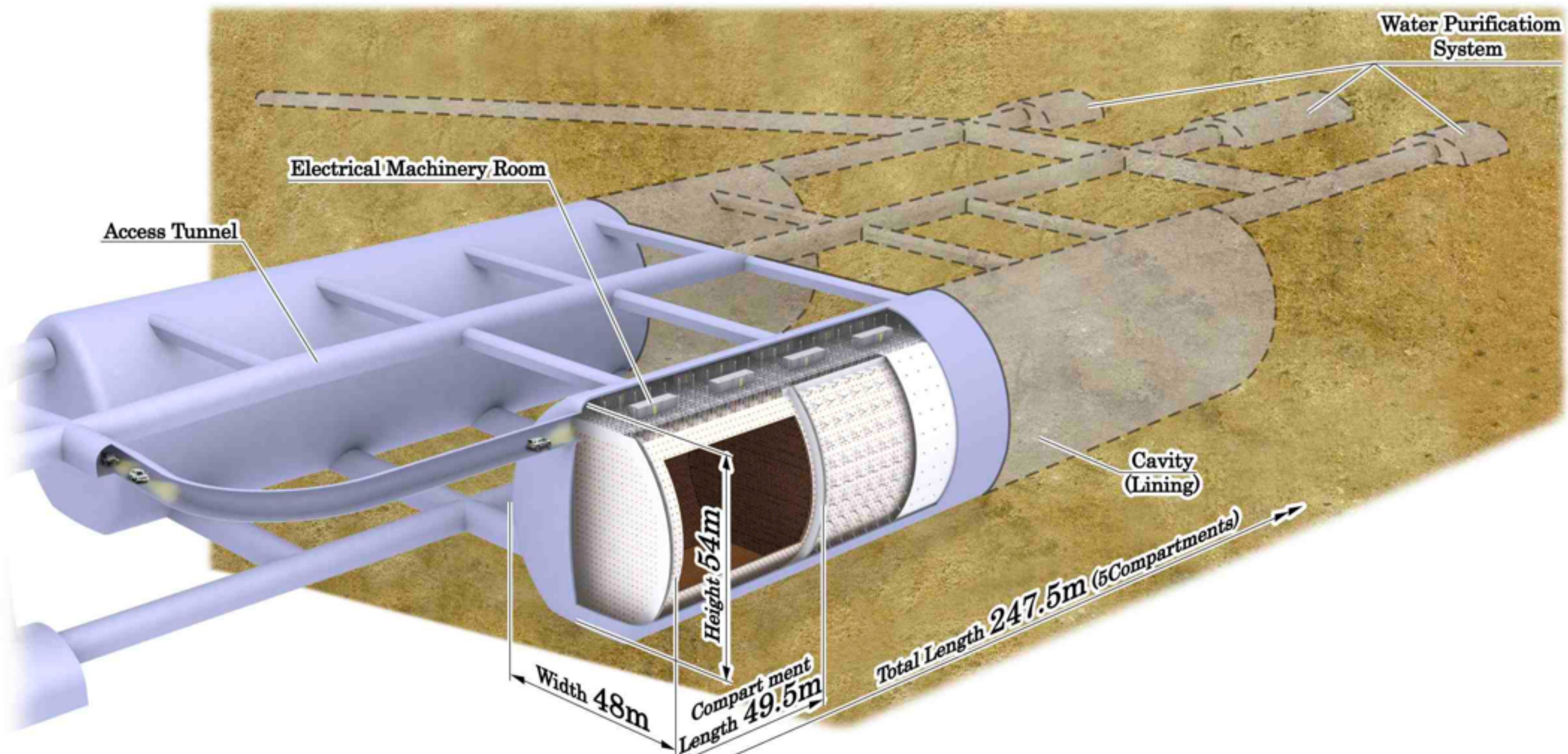

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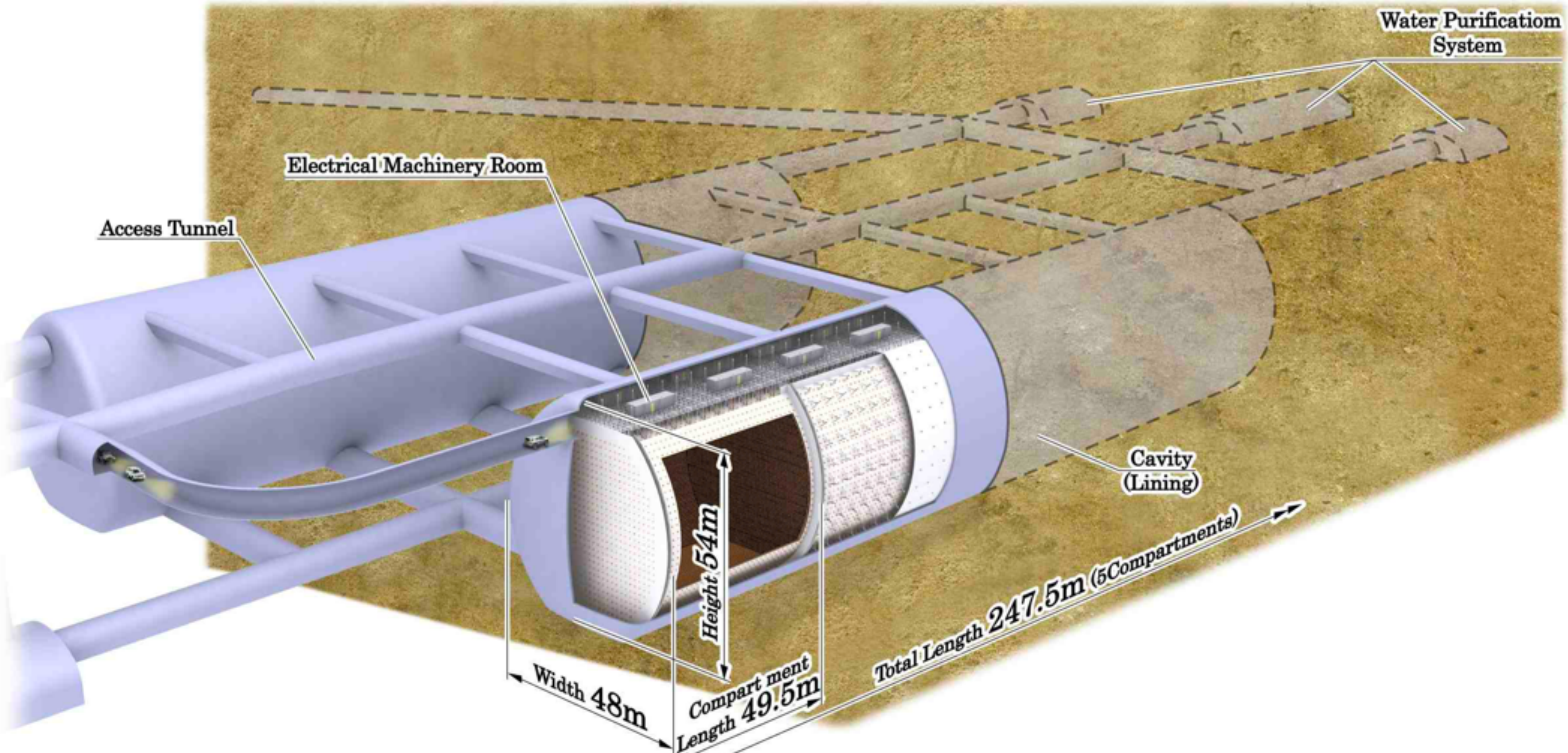

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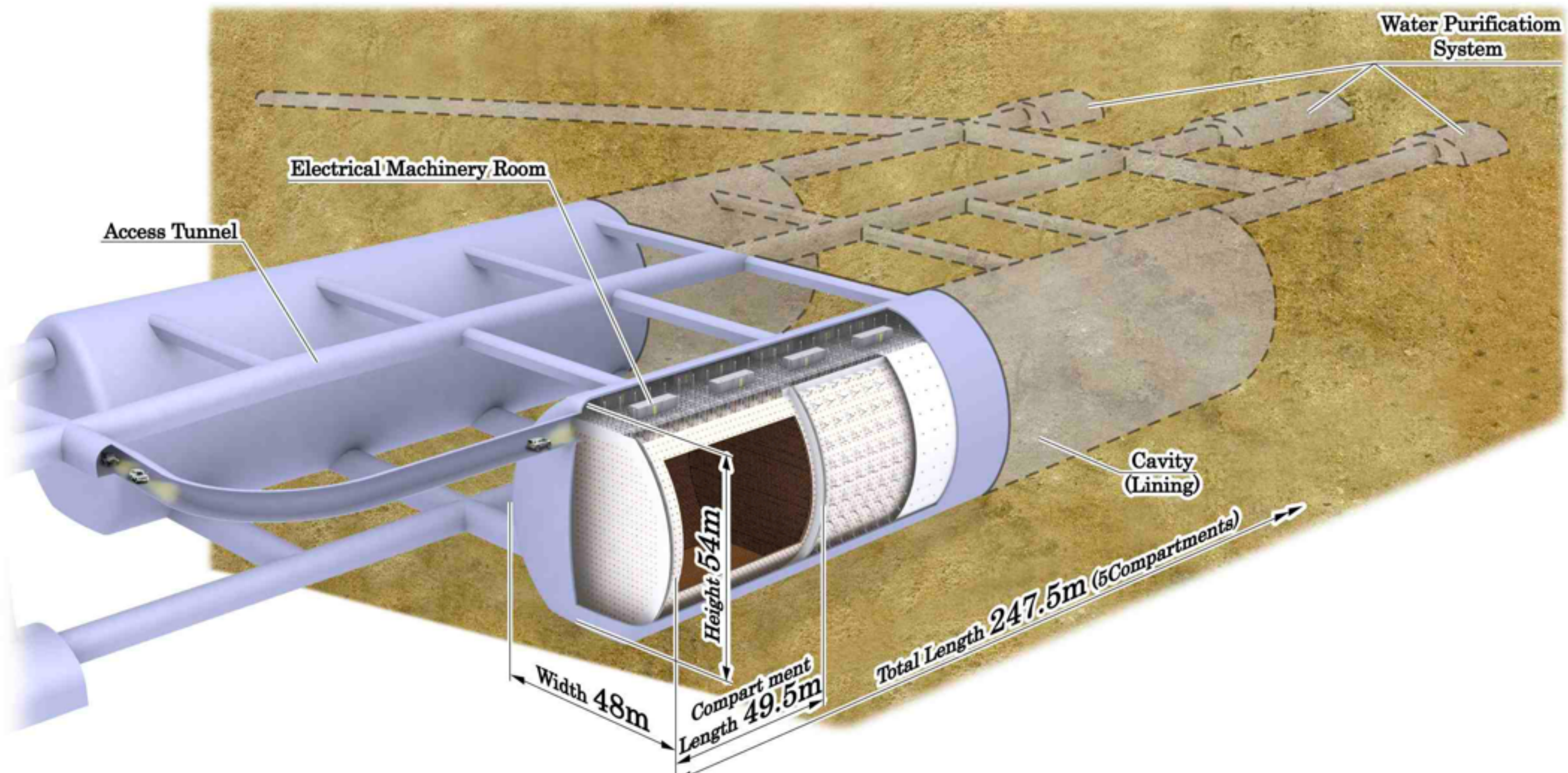

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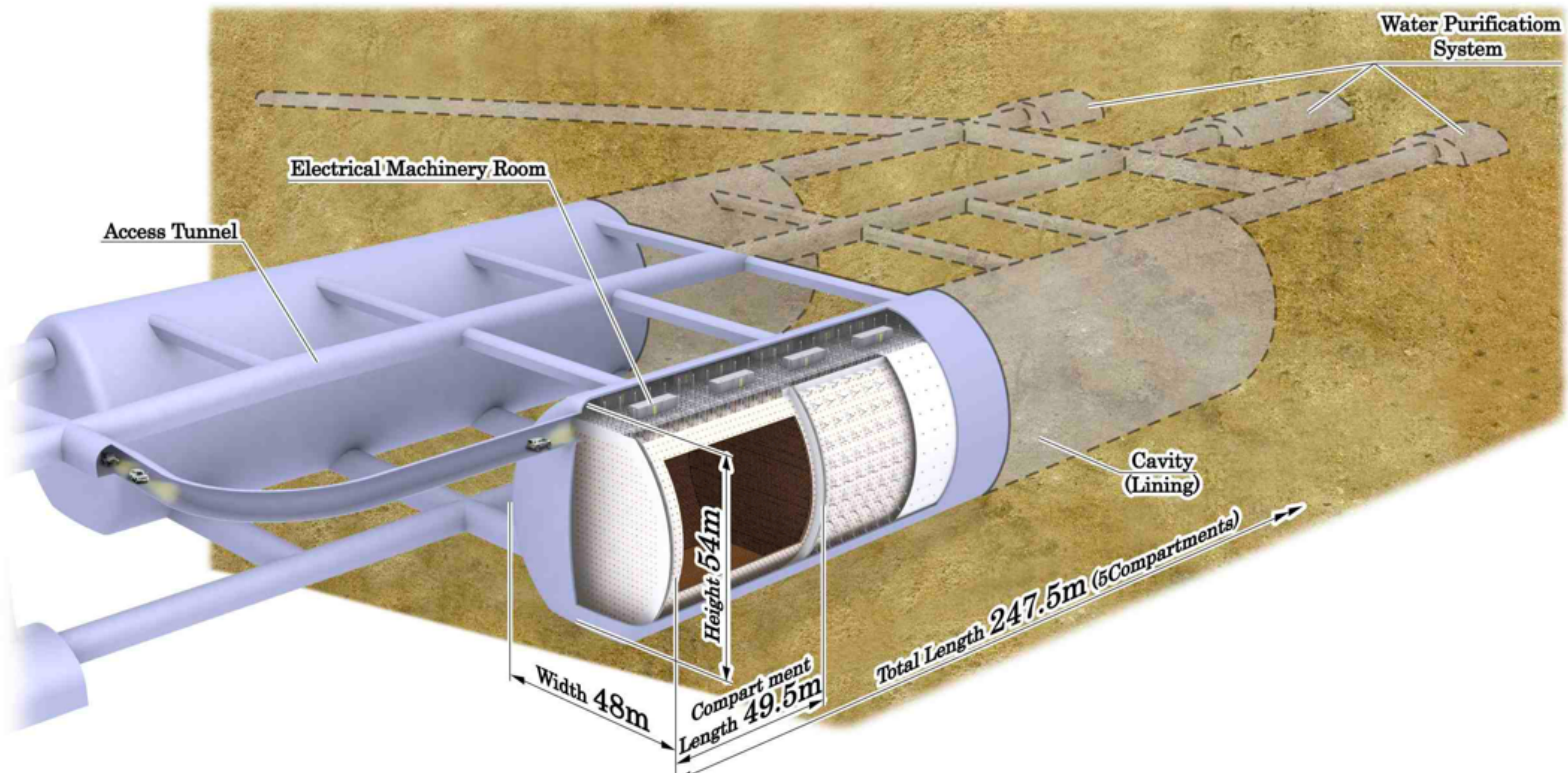

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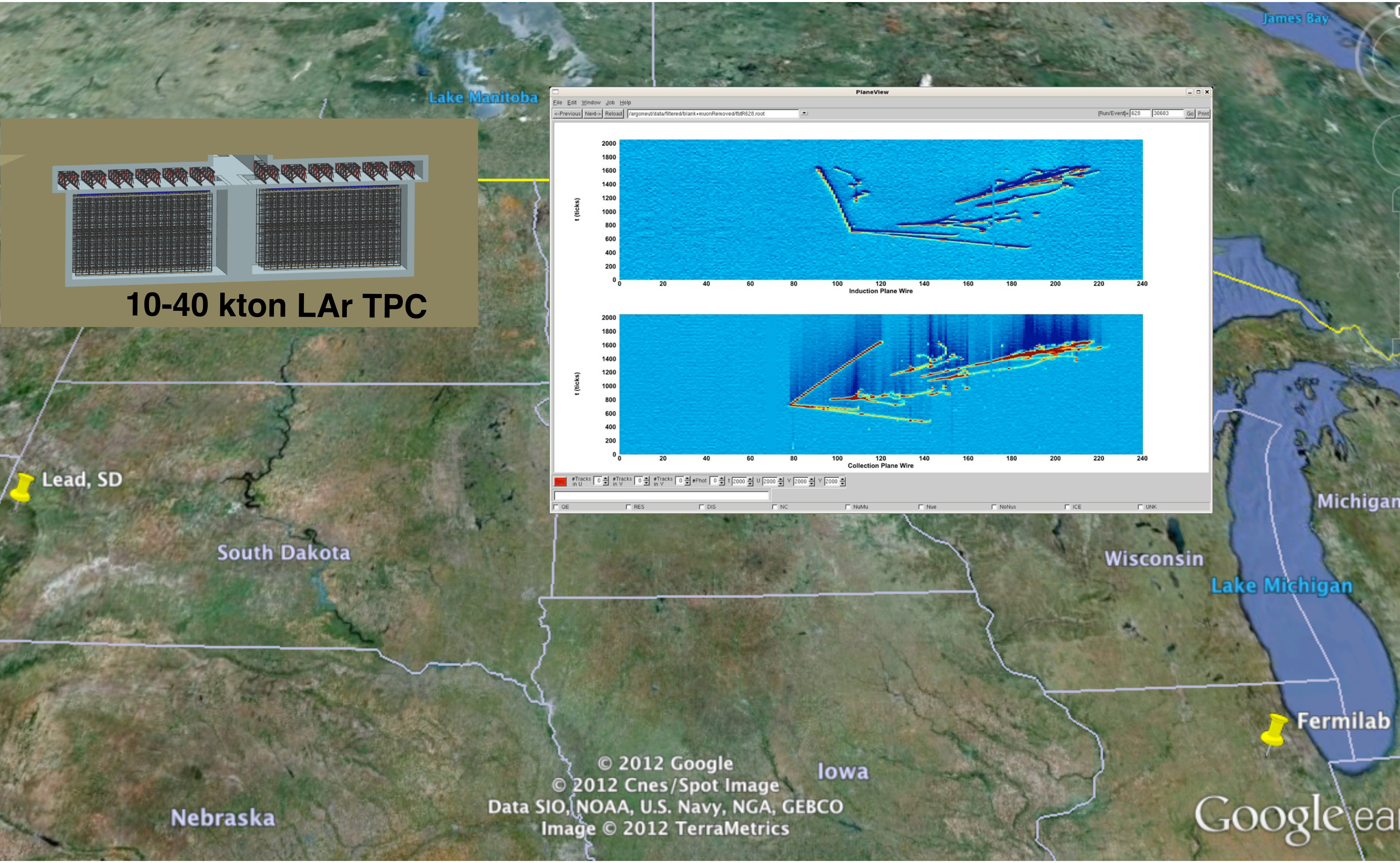
- 295 km baseline
- Could also improve proton-decay limits by ~10x

The Deep Underground Neutrino Experiment (DUNE, USA)



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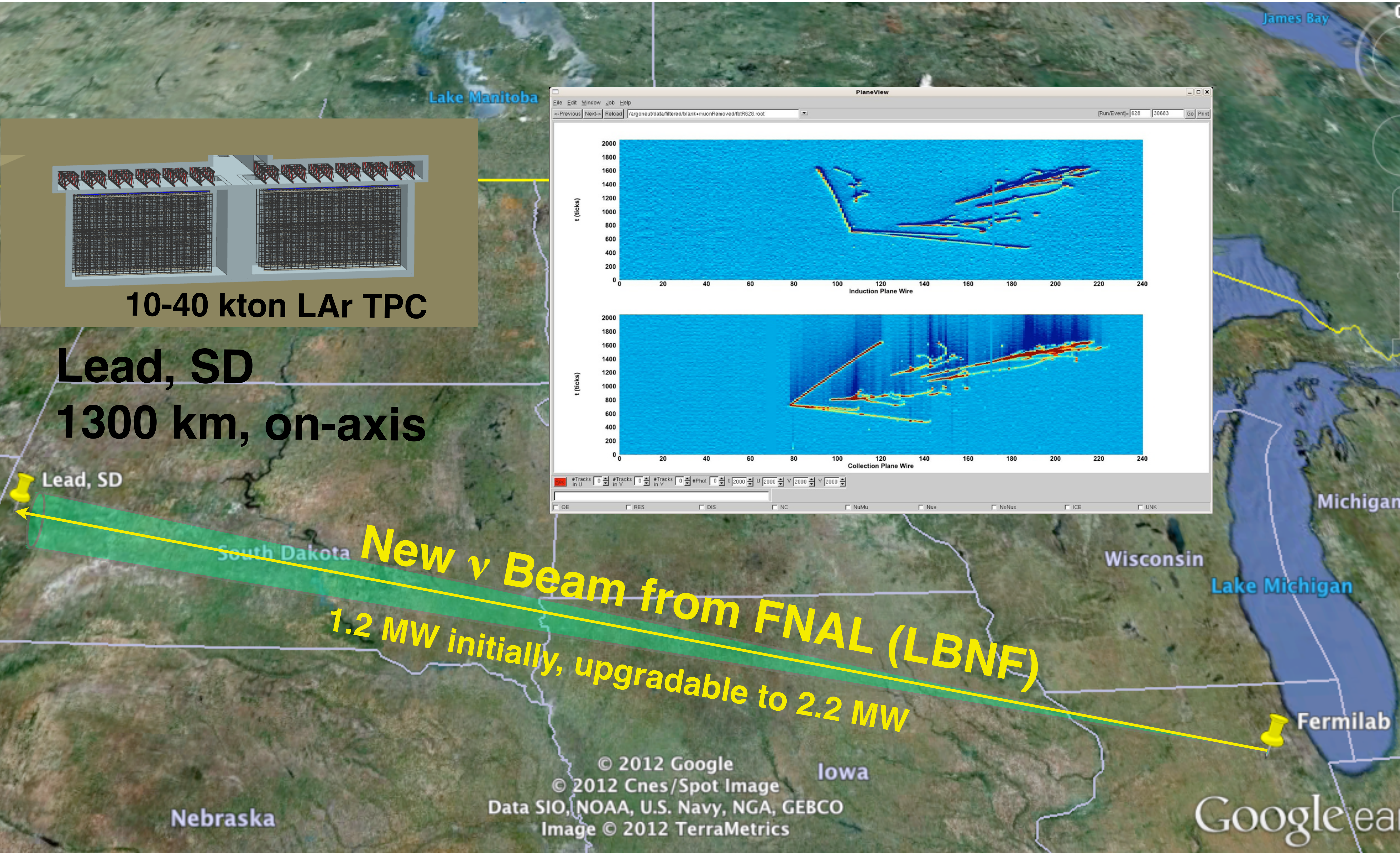
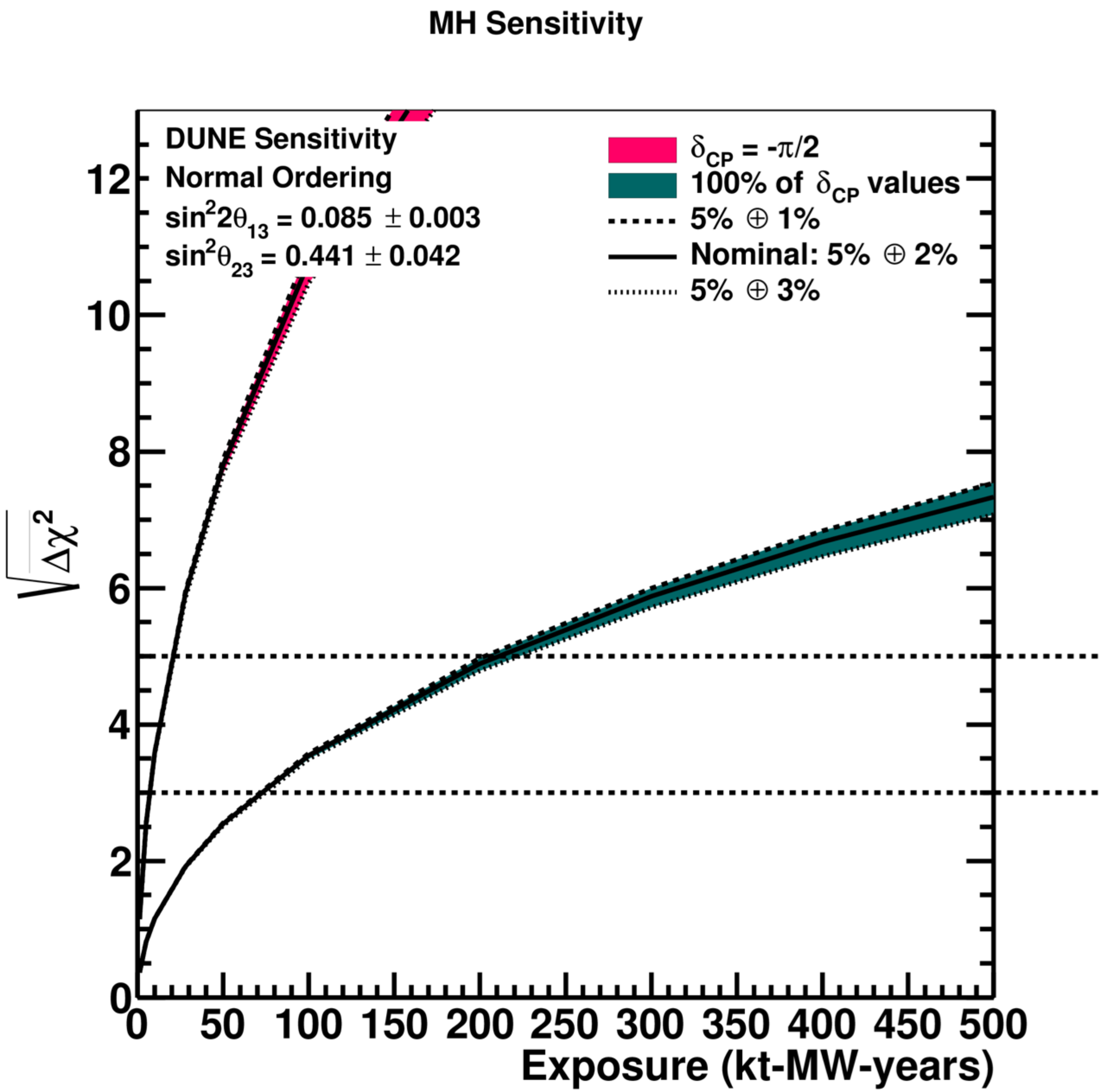


DUNE Sensitivities



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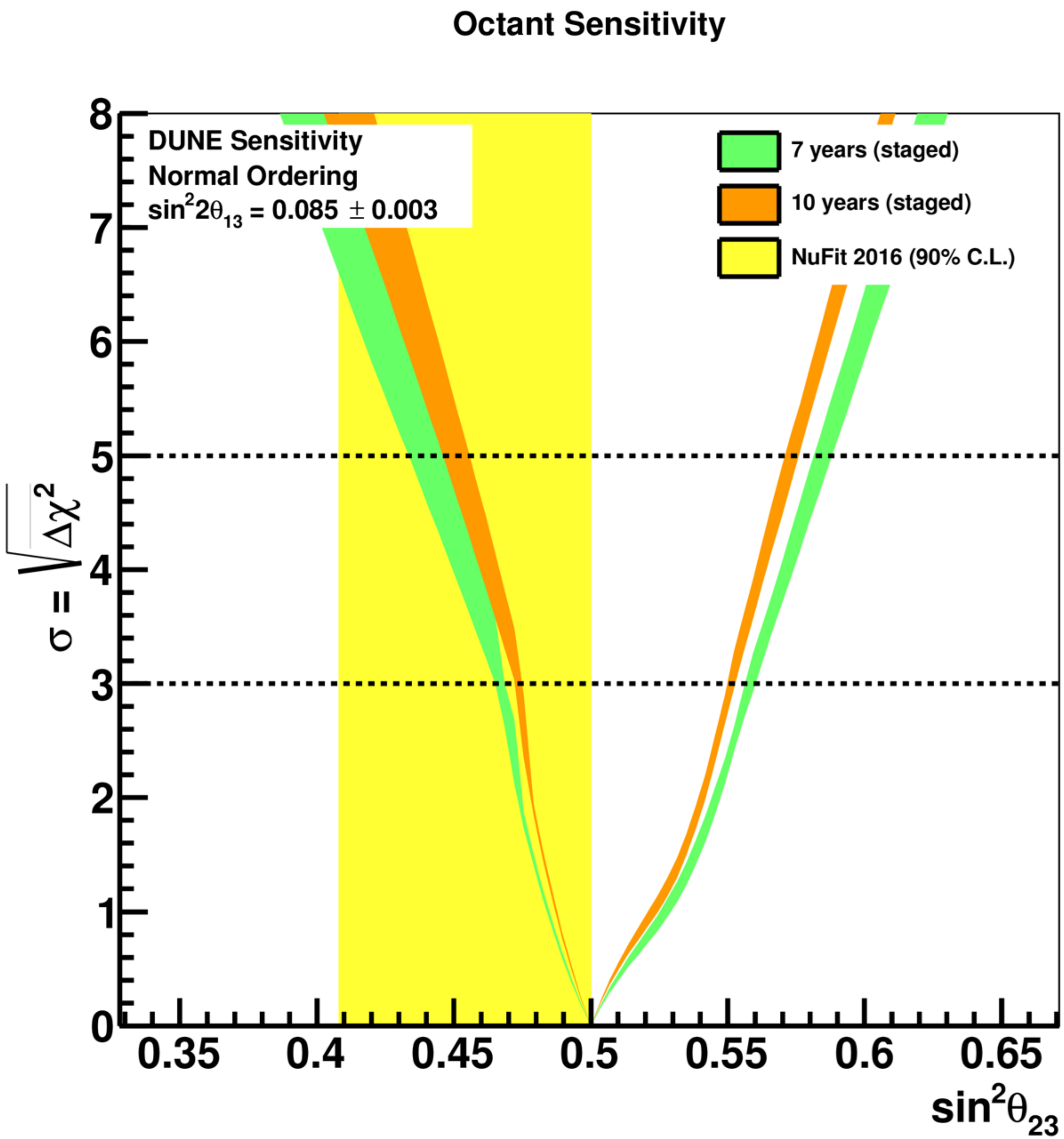

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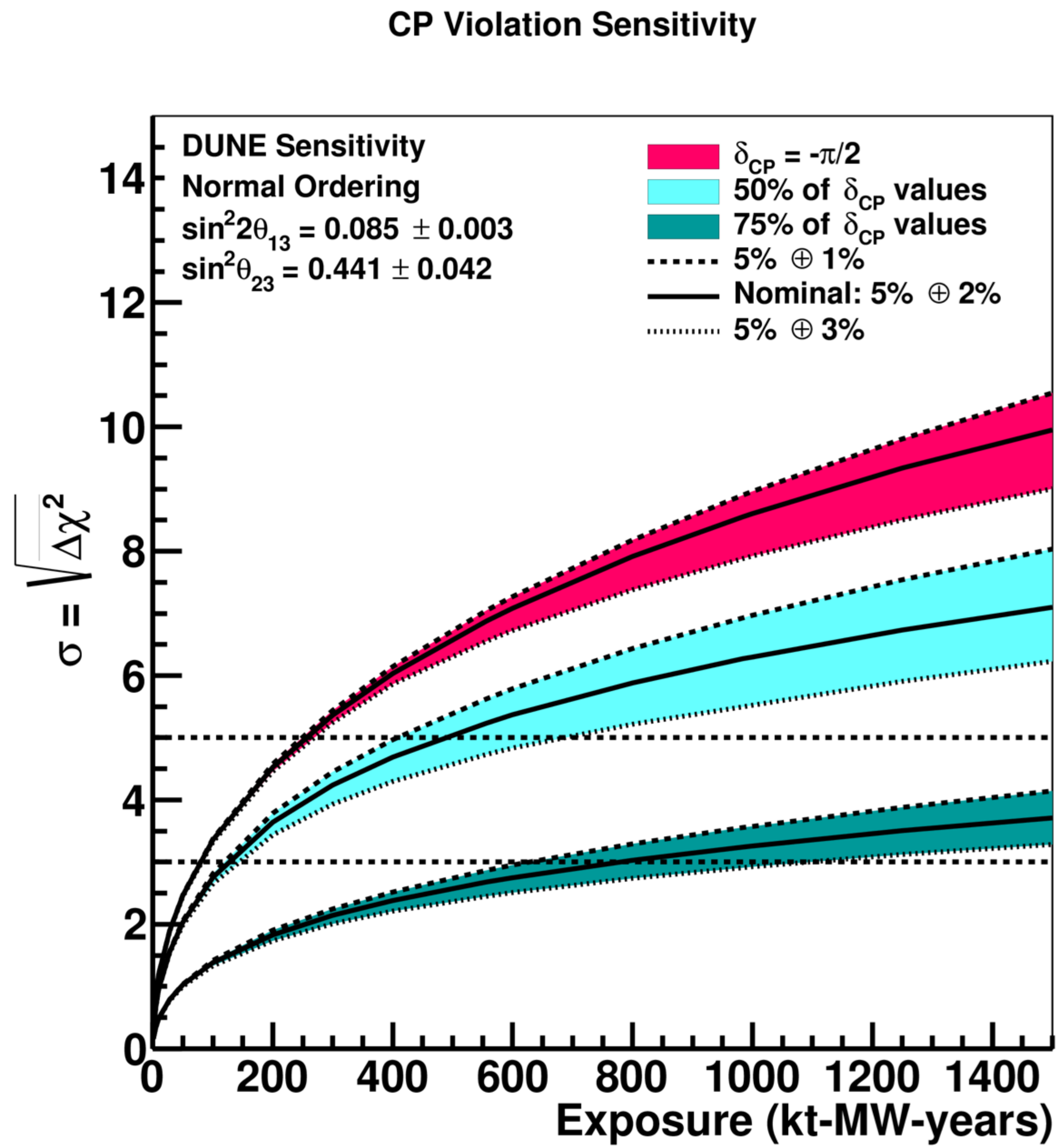

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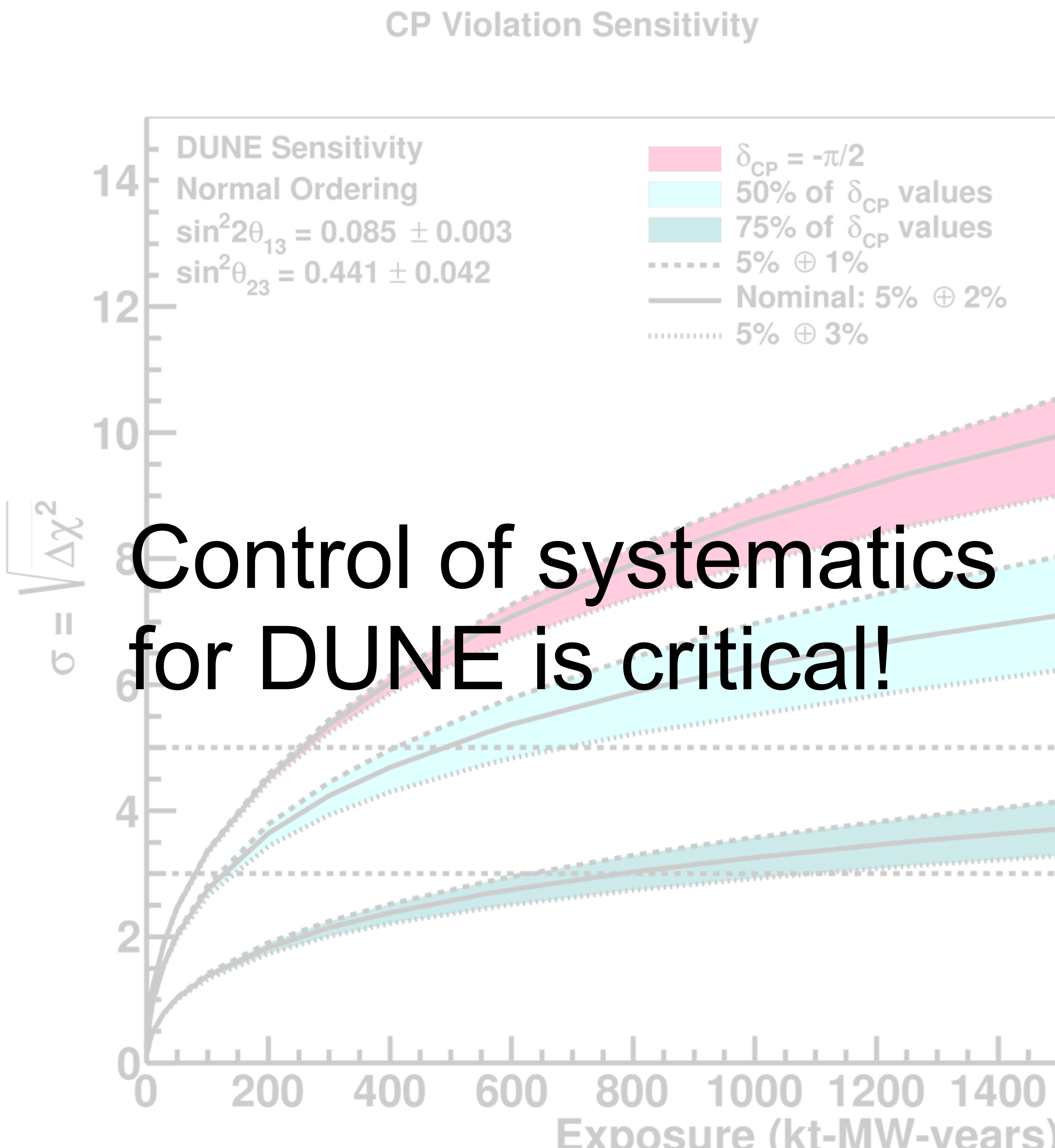

Control of systematics for DUNE is critical!

Short-Baseline Neutrino Program

- DUNE poses some challenges:
  - At least 10 years for data collection to begin.
  - LAr TPCs are new technology, the community is generally inexperienced.
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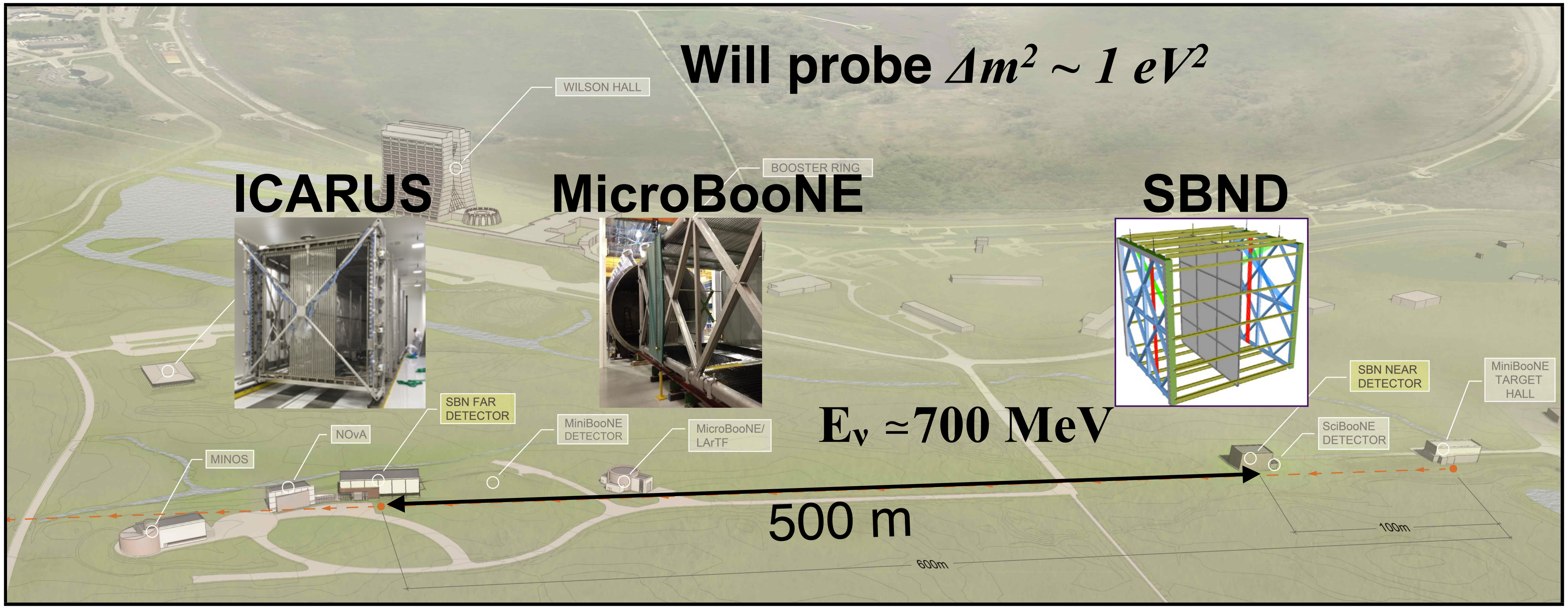
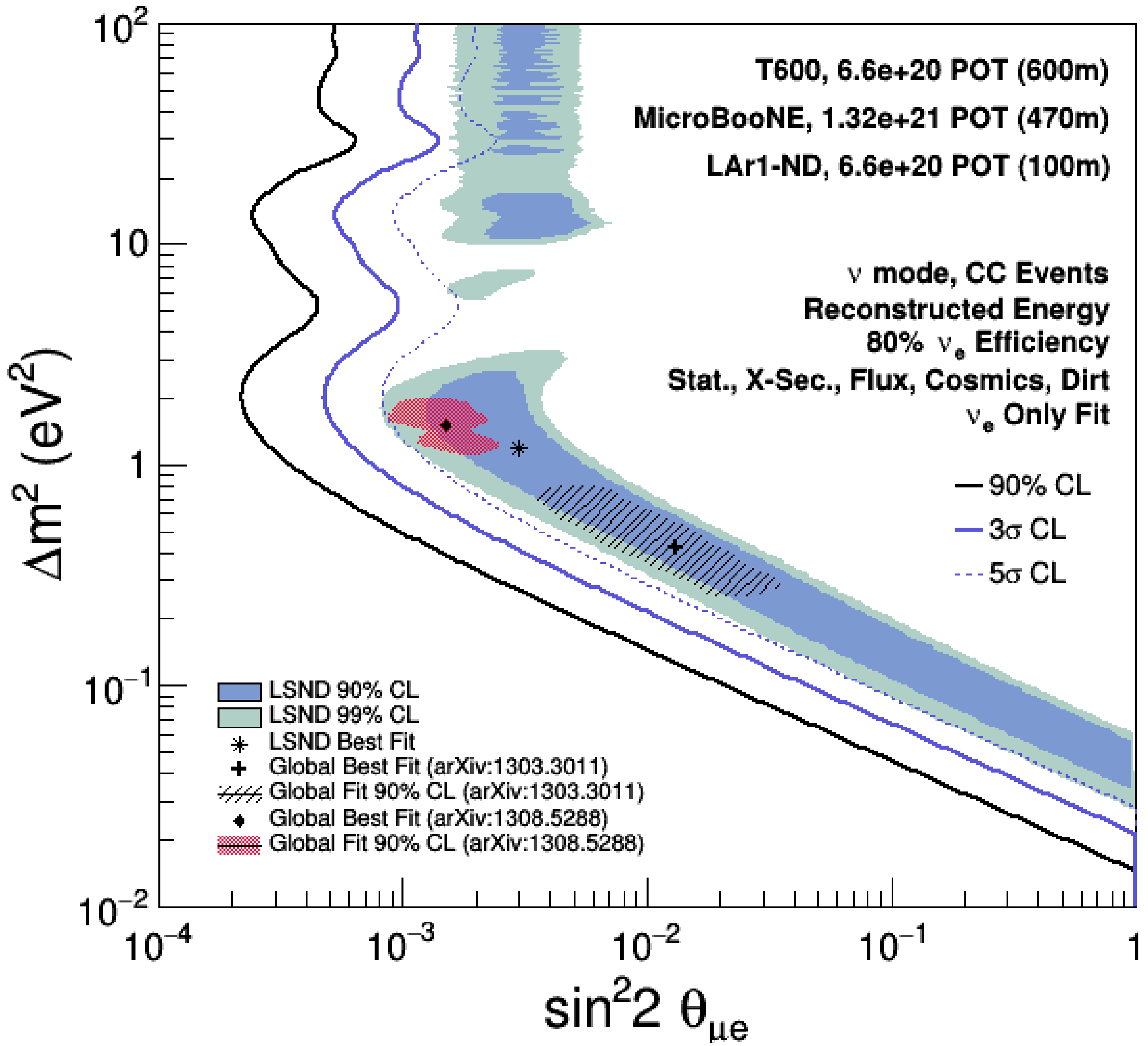
  - LAr TPCs are new technology, the community is generally inexperienced.
  - Simulations and reconstruction software need improvement.
- To address these issues, a short-baseline neutrino oscillation program featuring three LAr TPC detectors is being developed at Fermilab.
- **MicroBooNE is up and running, and ICARUS will be installed later this year!**



Short-Baseline Neutrino Program



Summary

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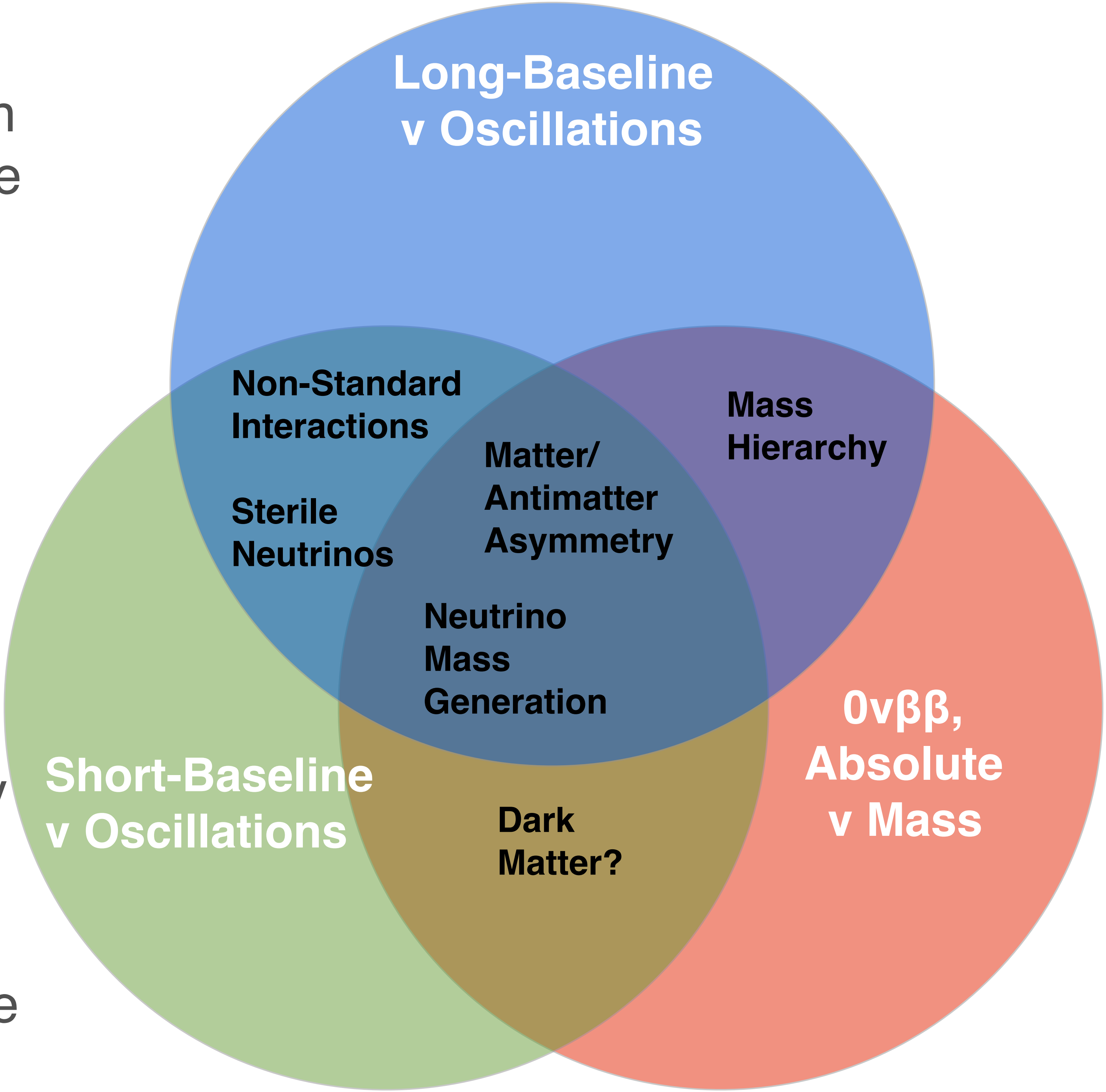
- Although we have learned much in the last 20 years, there is much we still do not know.
- Future 0νββ and direct mass measurements will reach sub-eV sensitivity in the mass, but we need truly massive detectors to determine the nature of the neutrino.
- Future oscillation experiments are well-positioned to determine many of the other "unknowns".
- Data and results will continue to flow for the next decade; the future is bright for neutrino physics!



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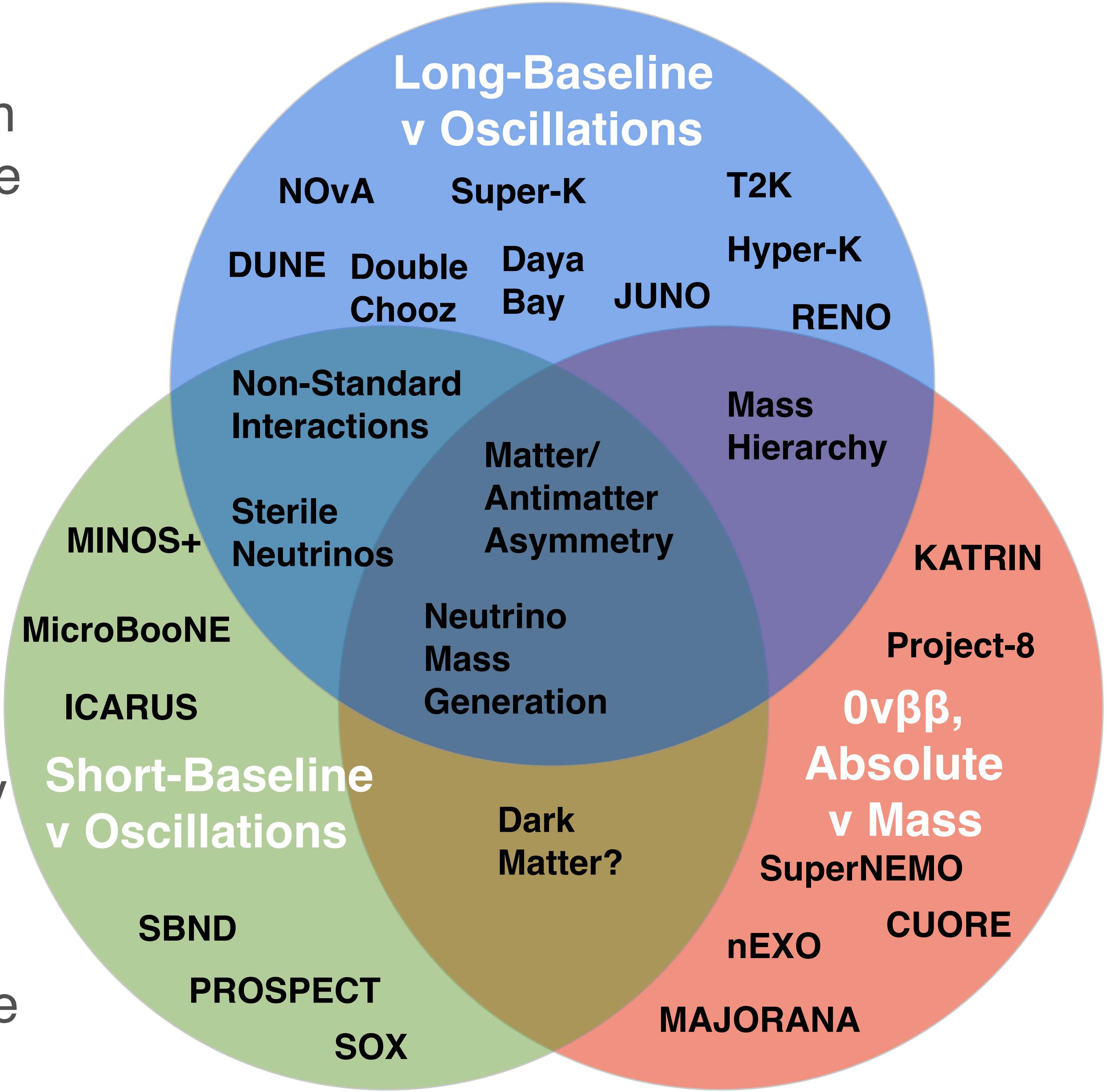

QUESTIONS?

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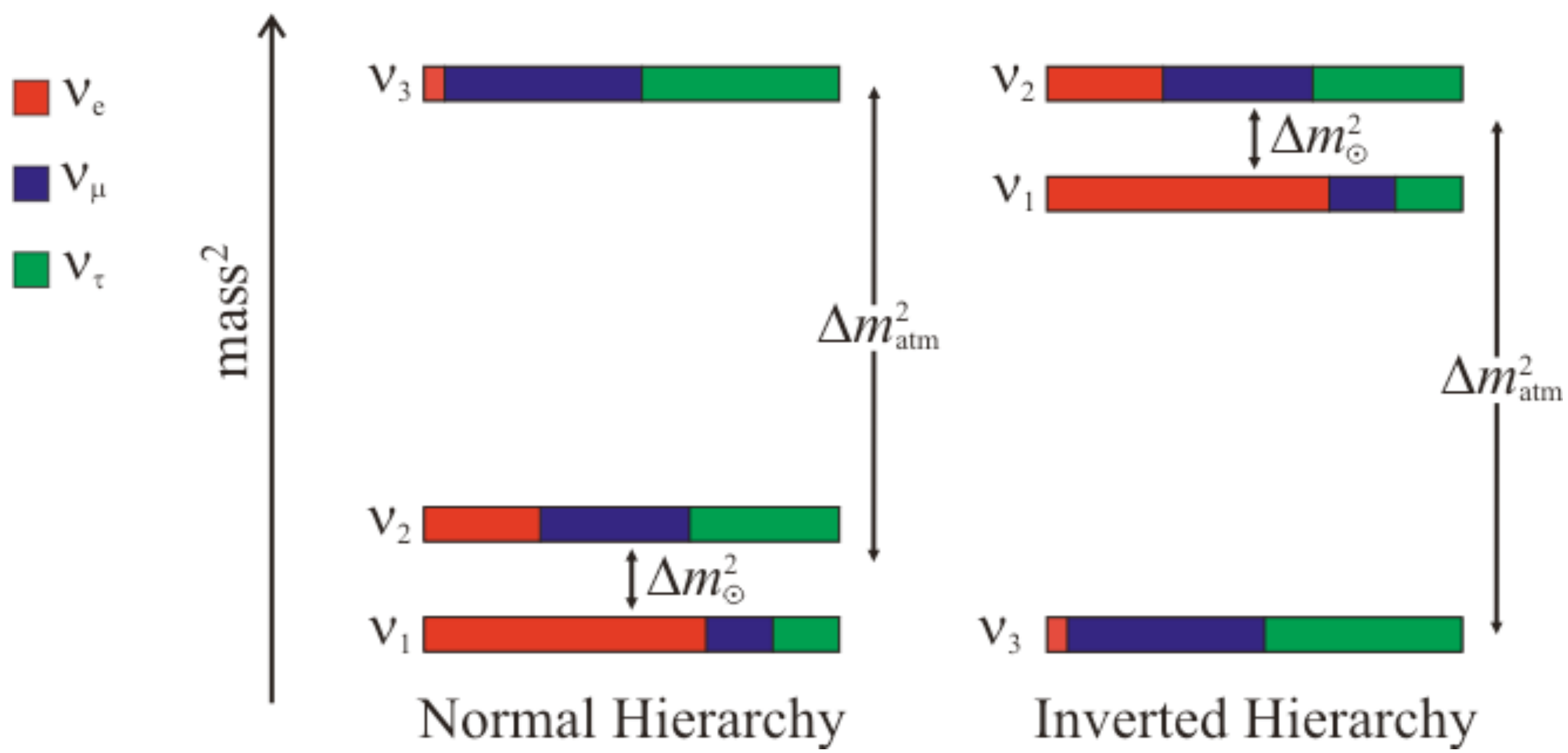

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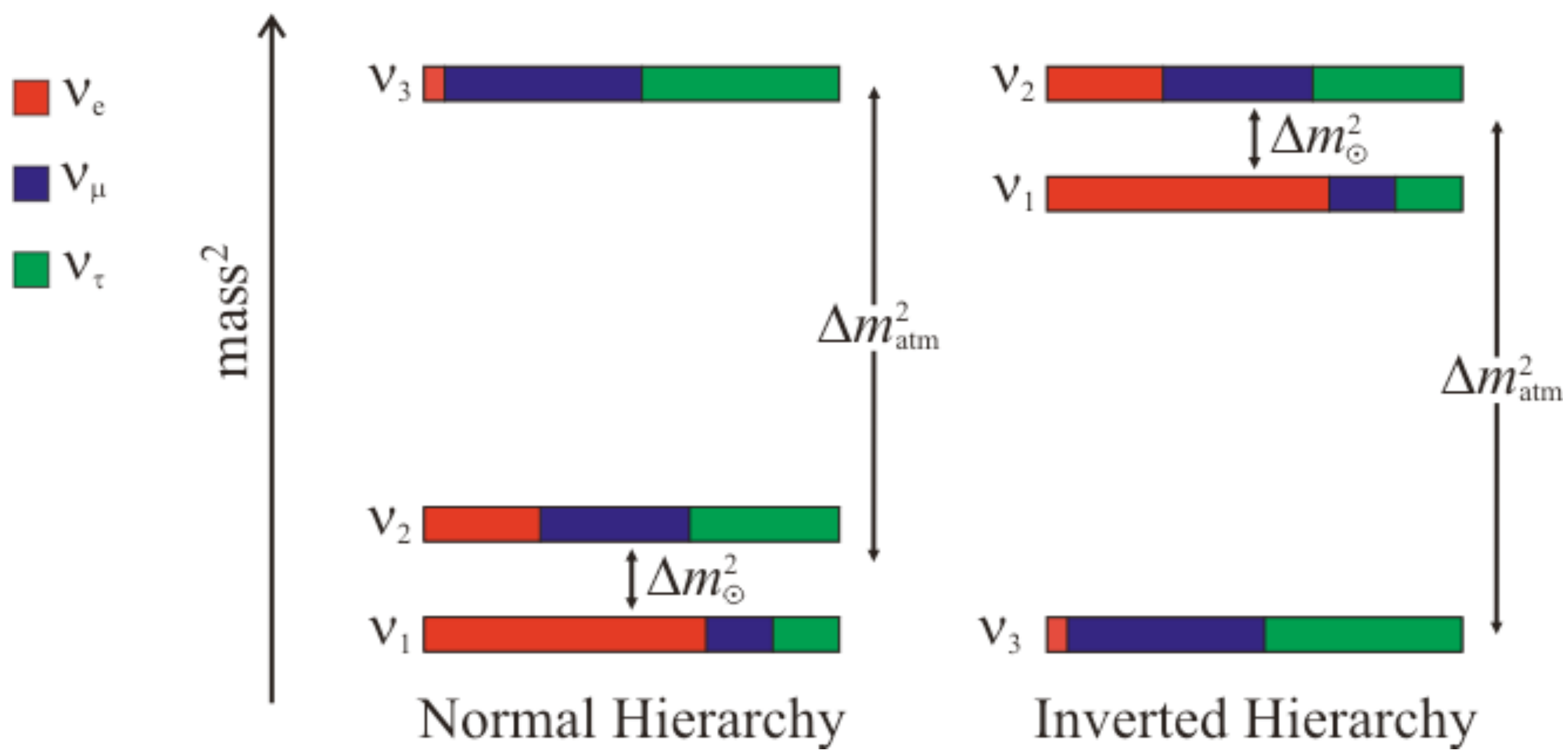

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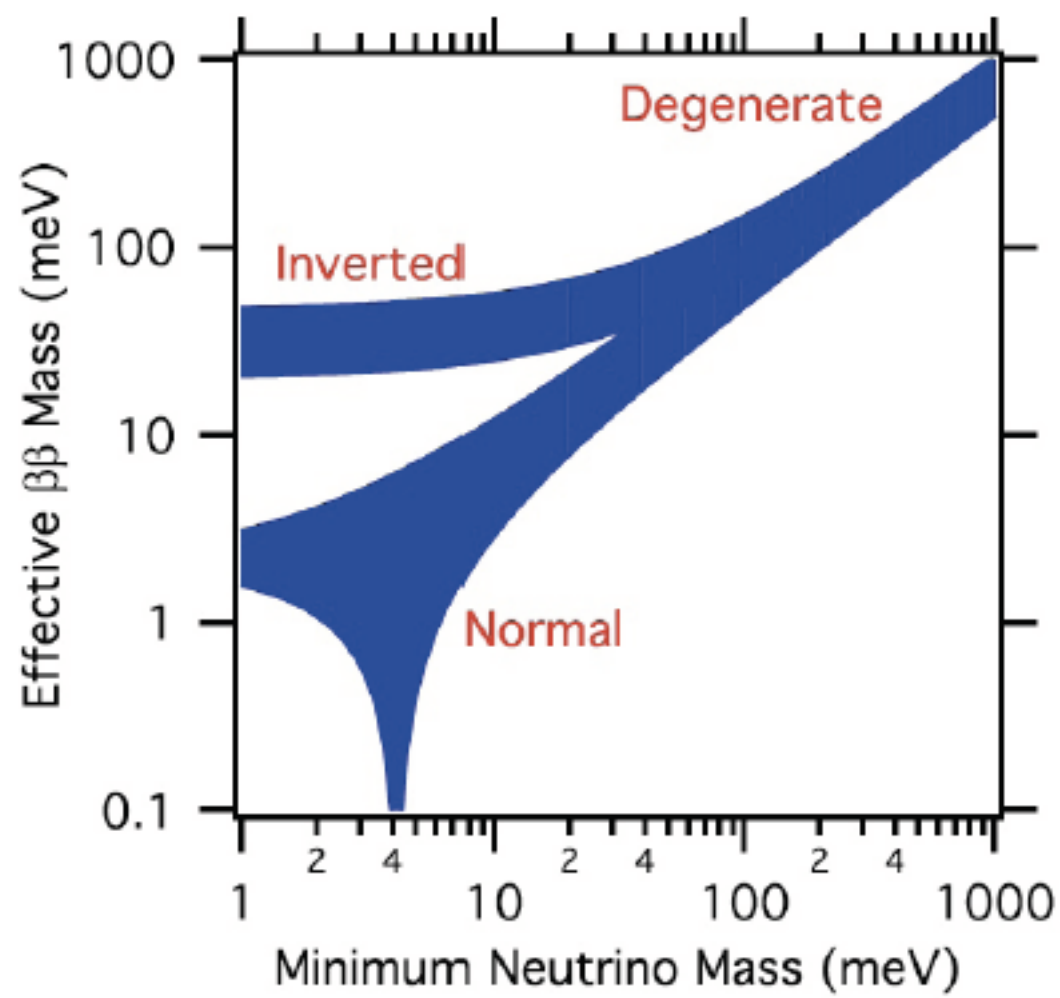

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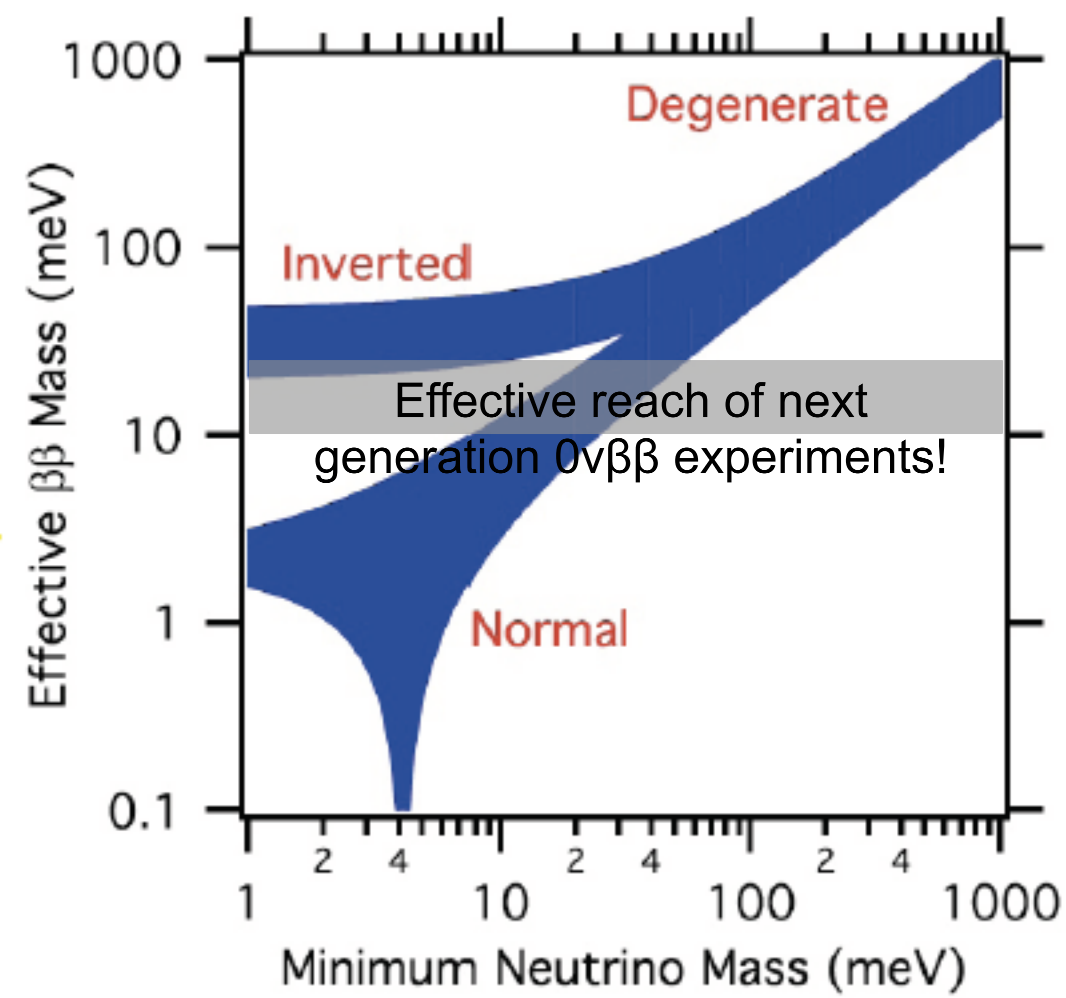

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- Want to overconstrain (squeeze) the 3-flavor mixing model - maybe we’ll find some inconsistencies driven by new physics.