Manmade Neutrinos

Morgan Wascko
Imperial College London

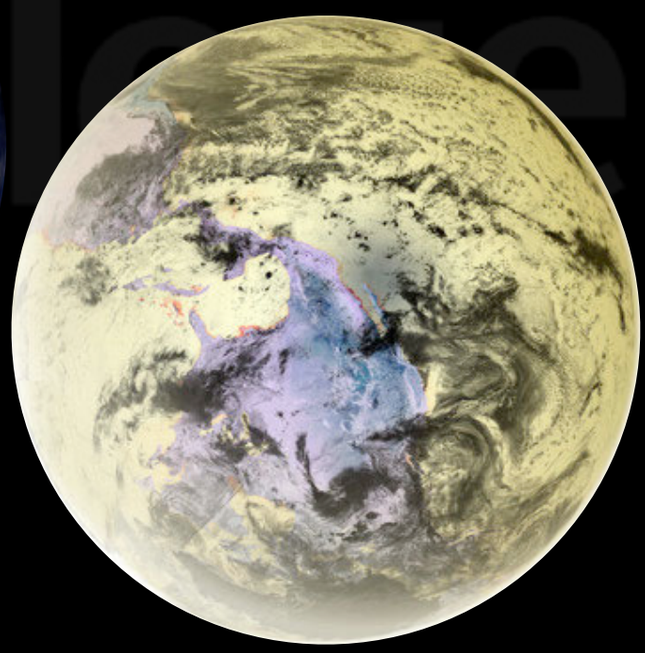
Super-K muon event

Motivation

Why are we here?

- Where is all the antimatter?
- Neutrino oscillation offers a new test of CP symmetry

$P(\nu_\mu \rightarrow \nu_e)$



Outline

- Experimental methods to determine neutrino properties
- Early days
  - Standard Model
- Neutrino Mass
  - Discovery
  - Open Questions

Hints

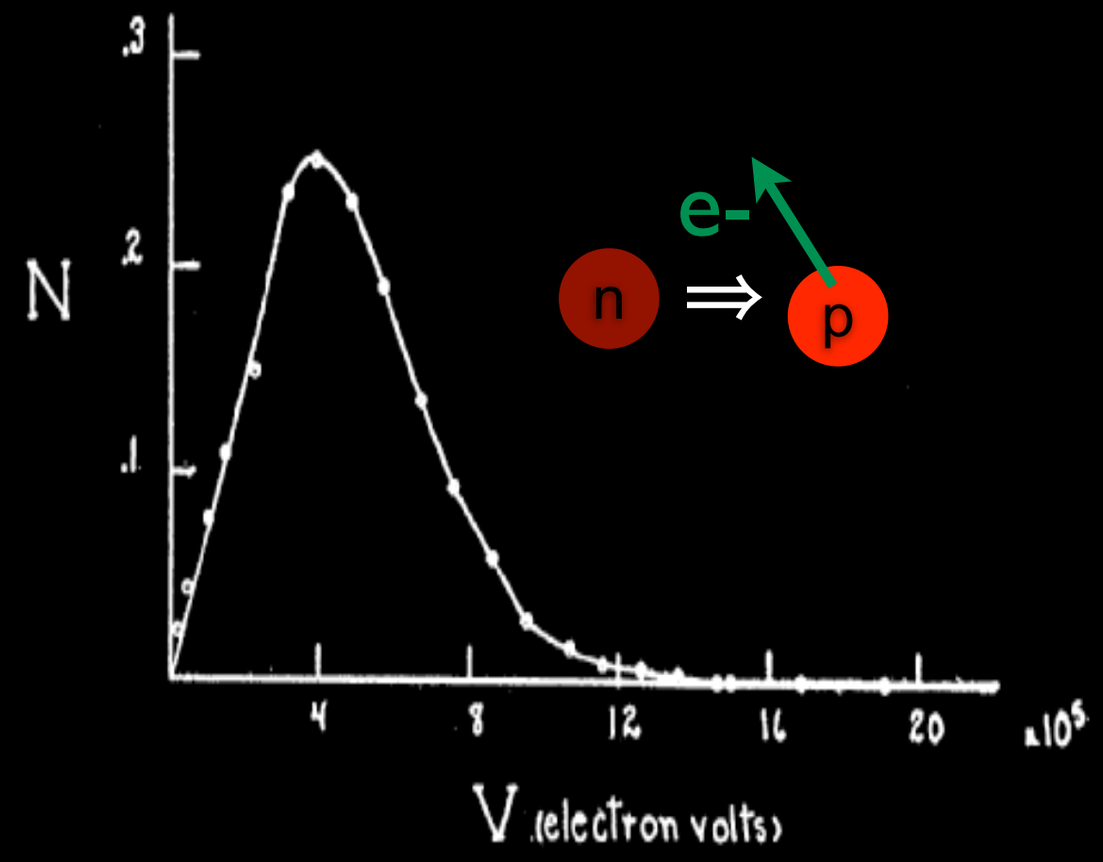


FIG. 5. Energy distribution curve of the beta-rays.

*F.A. Scott, Phys Rev. **48**, 391 (1935)*

Original - Photocopie of PLC 0393

Abschrift/15.12.30 PW

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst ansuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinsip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grössenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein magnetischer Dipol von einem gewissen Moment μ ist. Die Experimente verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons nicht grösser sein kann als die eines gamma-Strahls und darf dann μ wohl nicht grösser als $e \cdot (10^{-13}$ cm).

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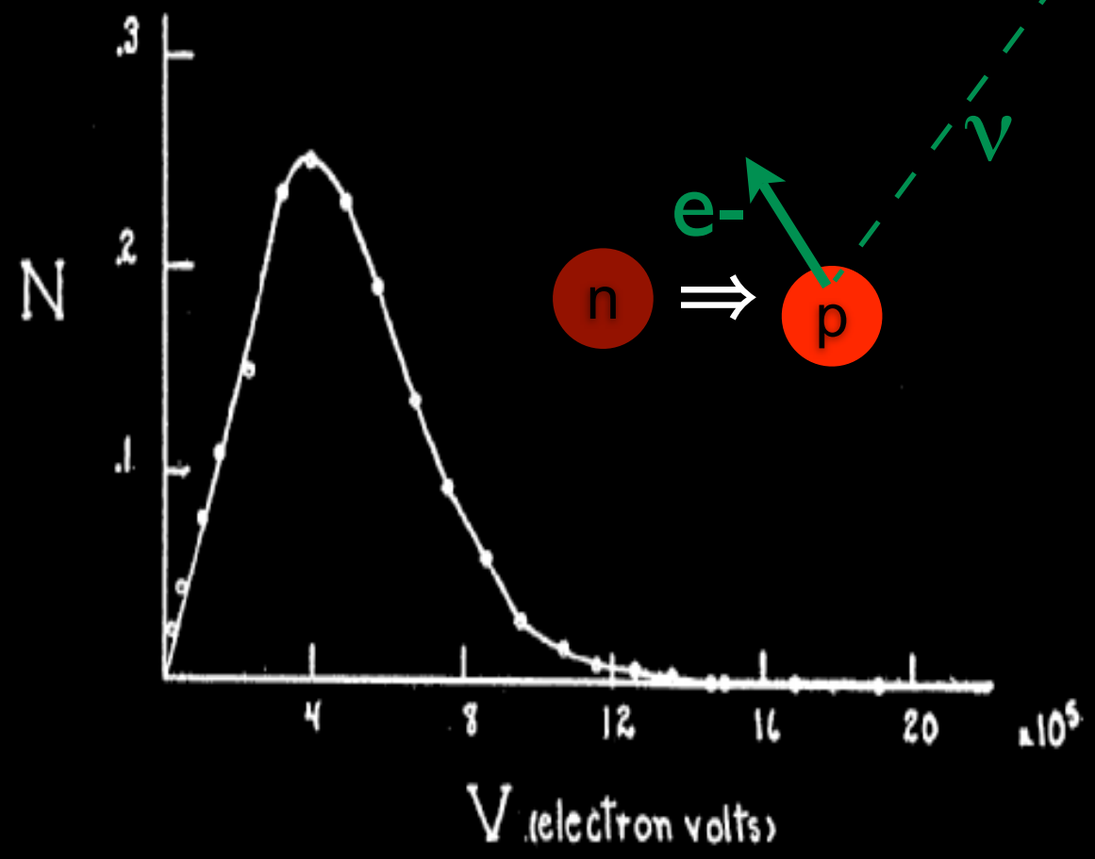
gez. W. Pauli

"desperate remedy"

"I have done something very bad today by proposing a particle that cannot be detected; it is something no theorist should ever do."

— **Wolfgang Pauli** (1930)

Hints



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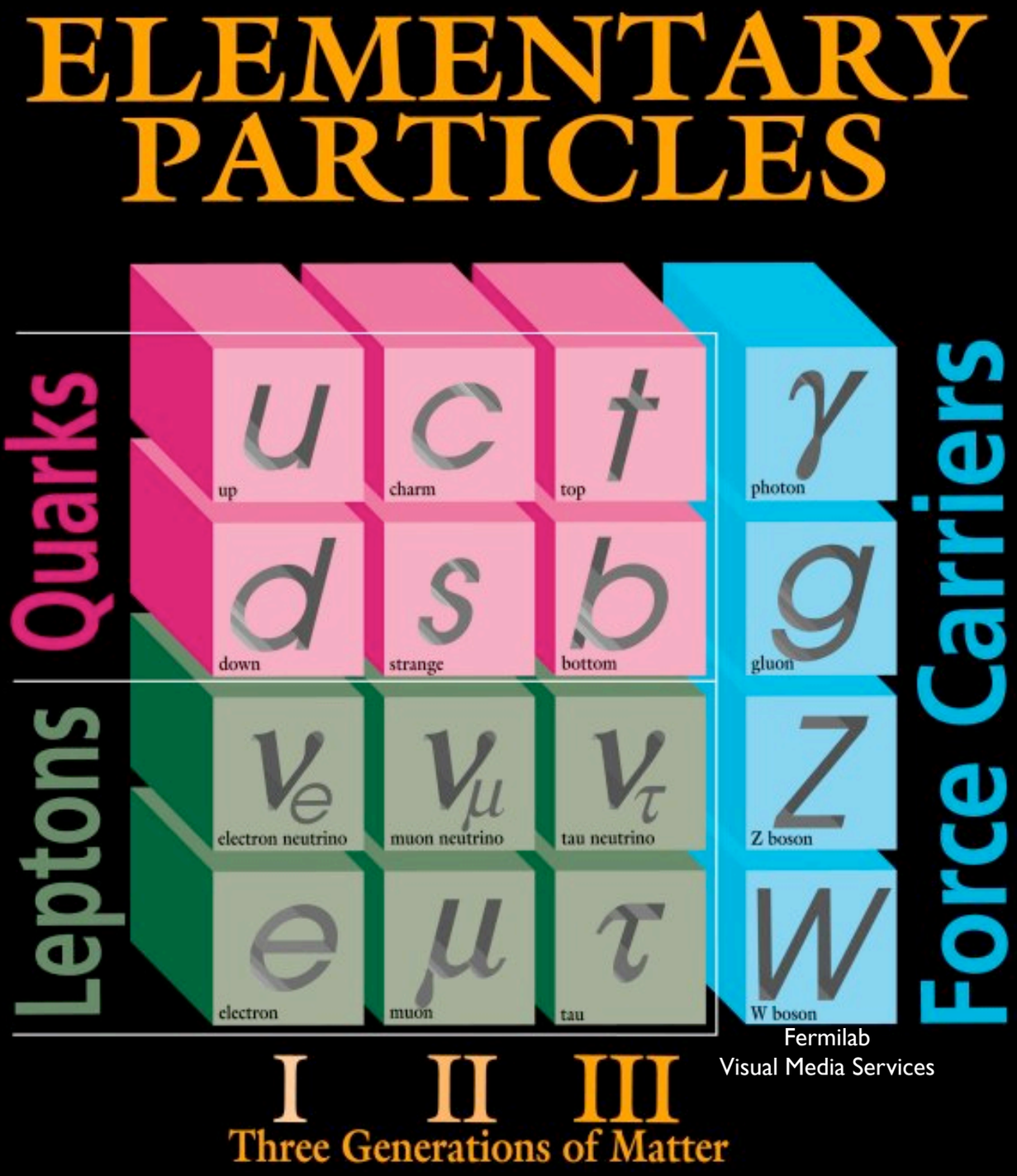
νs in Standard Model

- No charge
- No color
- Fixed helicity
- No mass
- Flavors don't mix

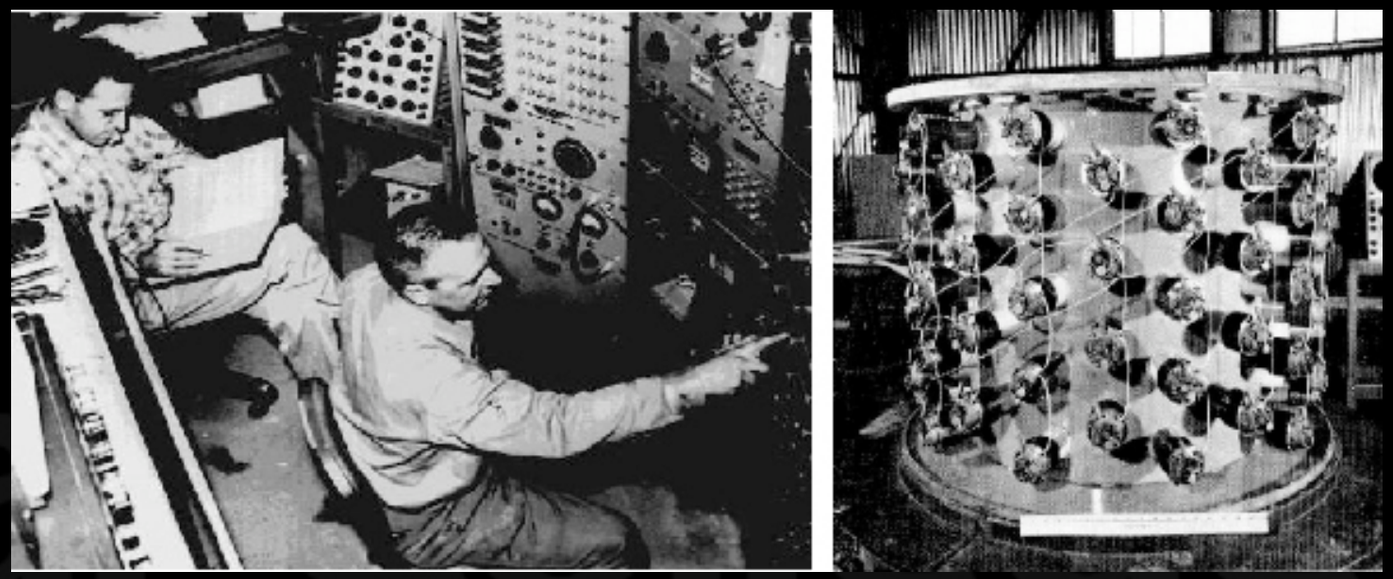


Fermilab
Visual Media Services

Discovery

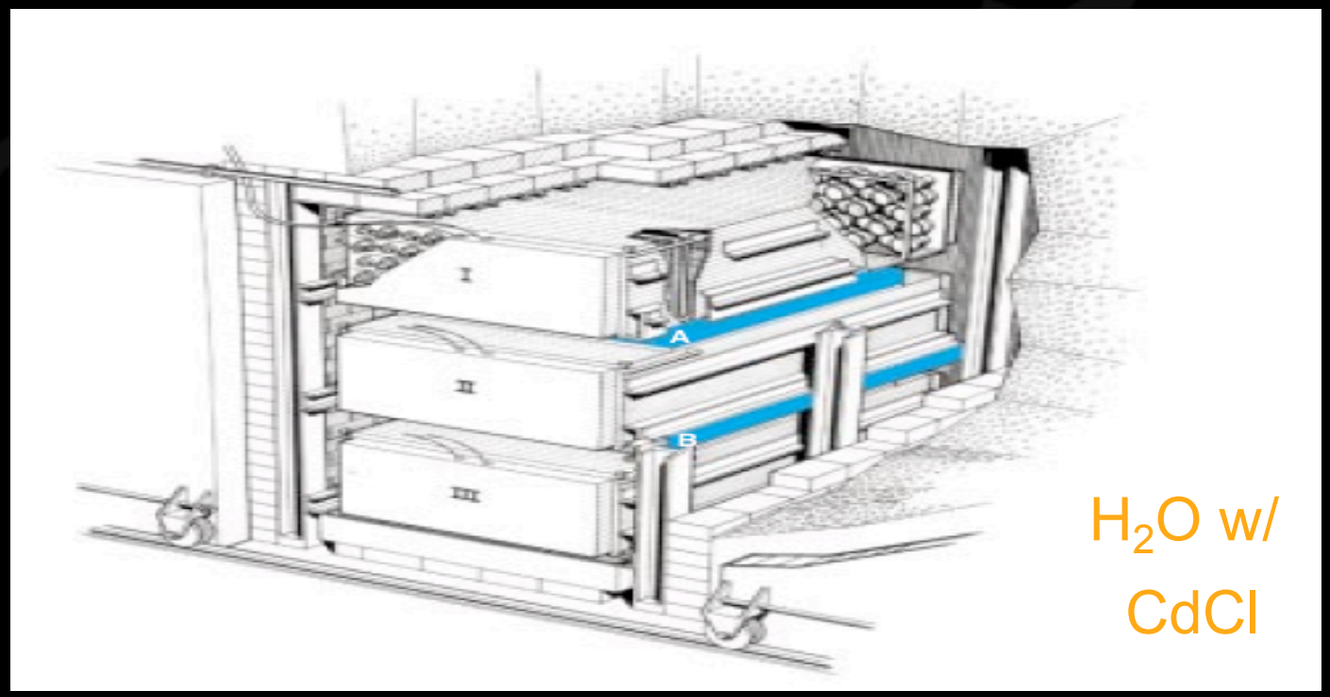
$\bar{\nu}N(n,p) \rightarrow N'(n-1,p+1)+e^{+}$

- Reines & Cowan - reactors



- First try at Hanford
  - Cosmic backgrounds too high

- Second try at Savannah River
  - Success!



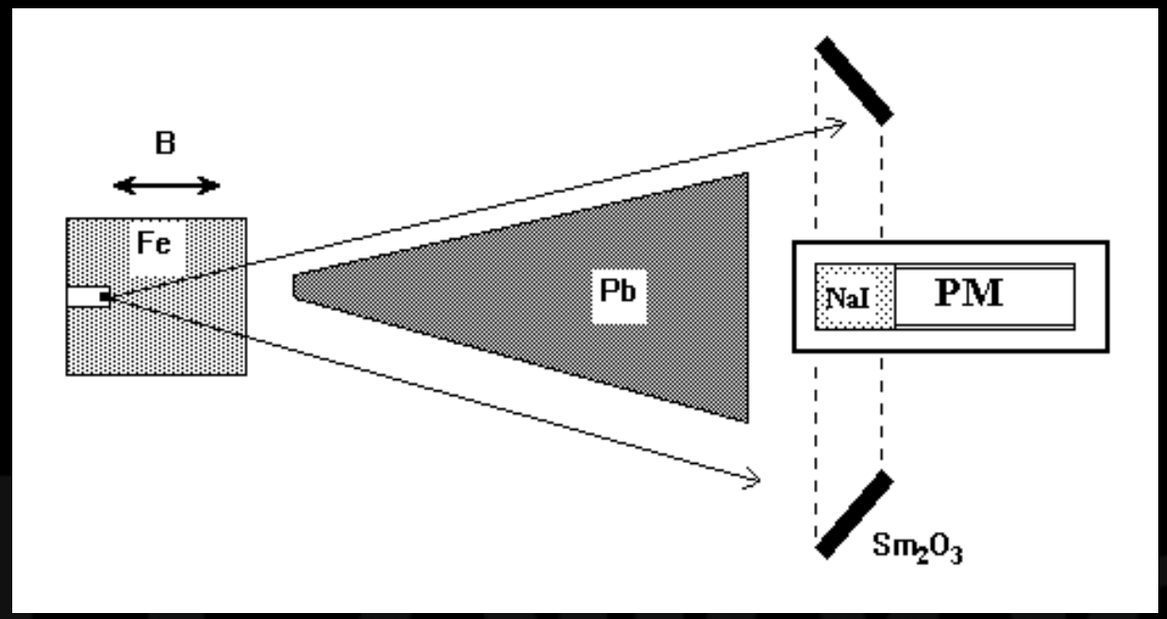
H_2O w/ CdCl

Science 124, 103 (1956)

Phys. Rev. 117, 159 (1960)

Helicity

- Goldhaber 1958
- ^{152}Eu decays via atomic electron capture
  - $^{152}Eu \rightarrow {}^{152}Sm^{*}\nu_e$
- Results in neutrino and recoil nucleus
- ^{152}Sm* decays rapidly to ground state via ~900 keV photon
- Measuring the polarisation of the photons yields helicity of neutrinos!



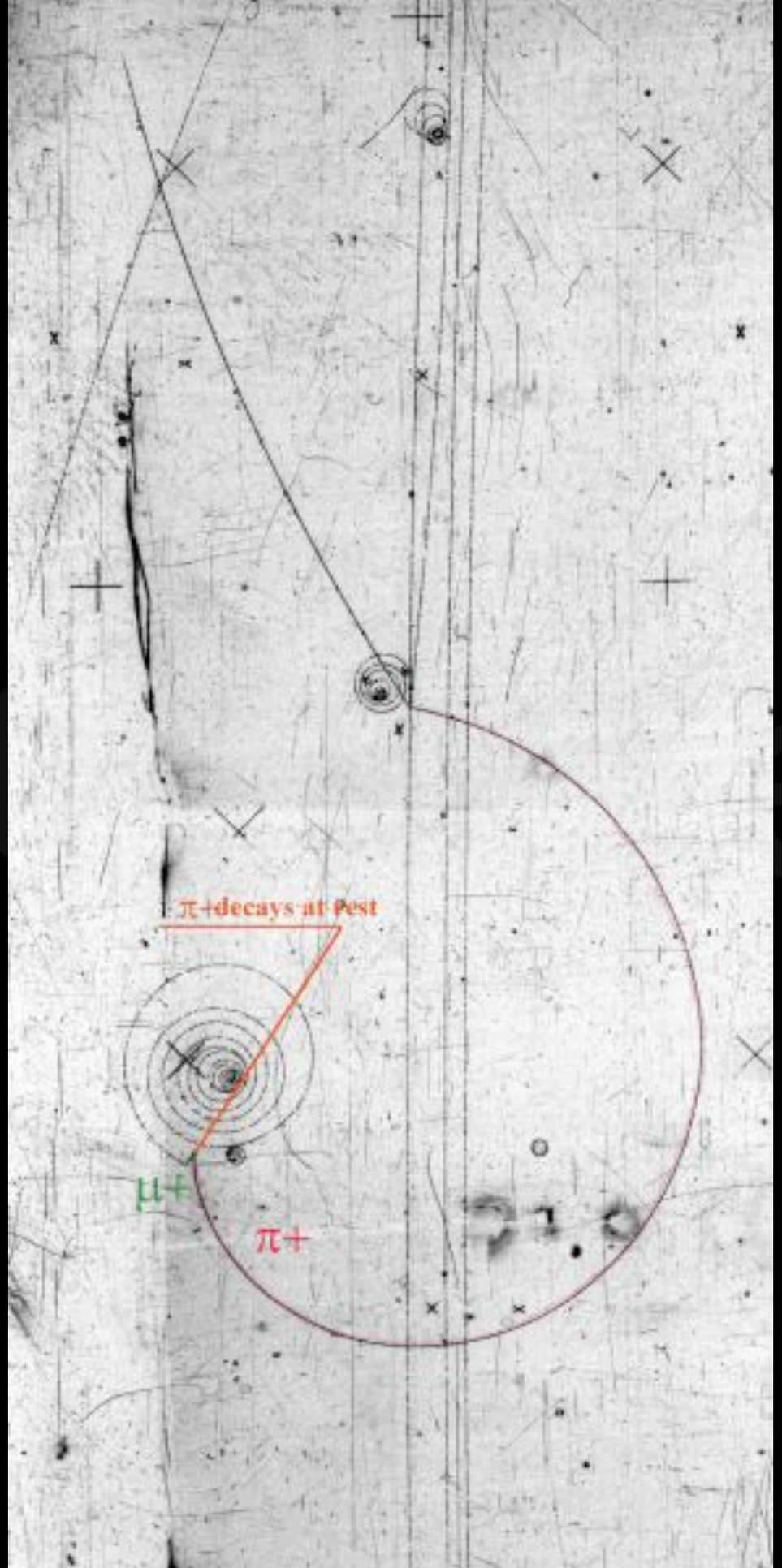
- Place ^{152}Eu in a magnetic field, and oscillate field
- Look for asymmetry
- Result: neutrinos are left handed!

Phys.Rev. 109, 1015 - 1017 (1958)

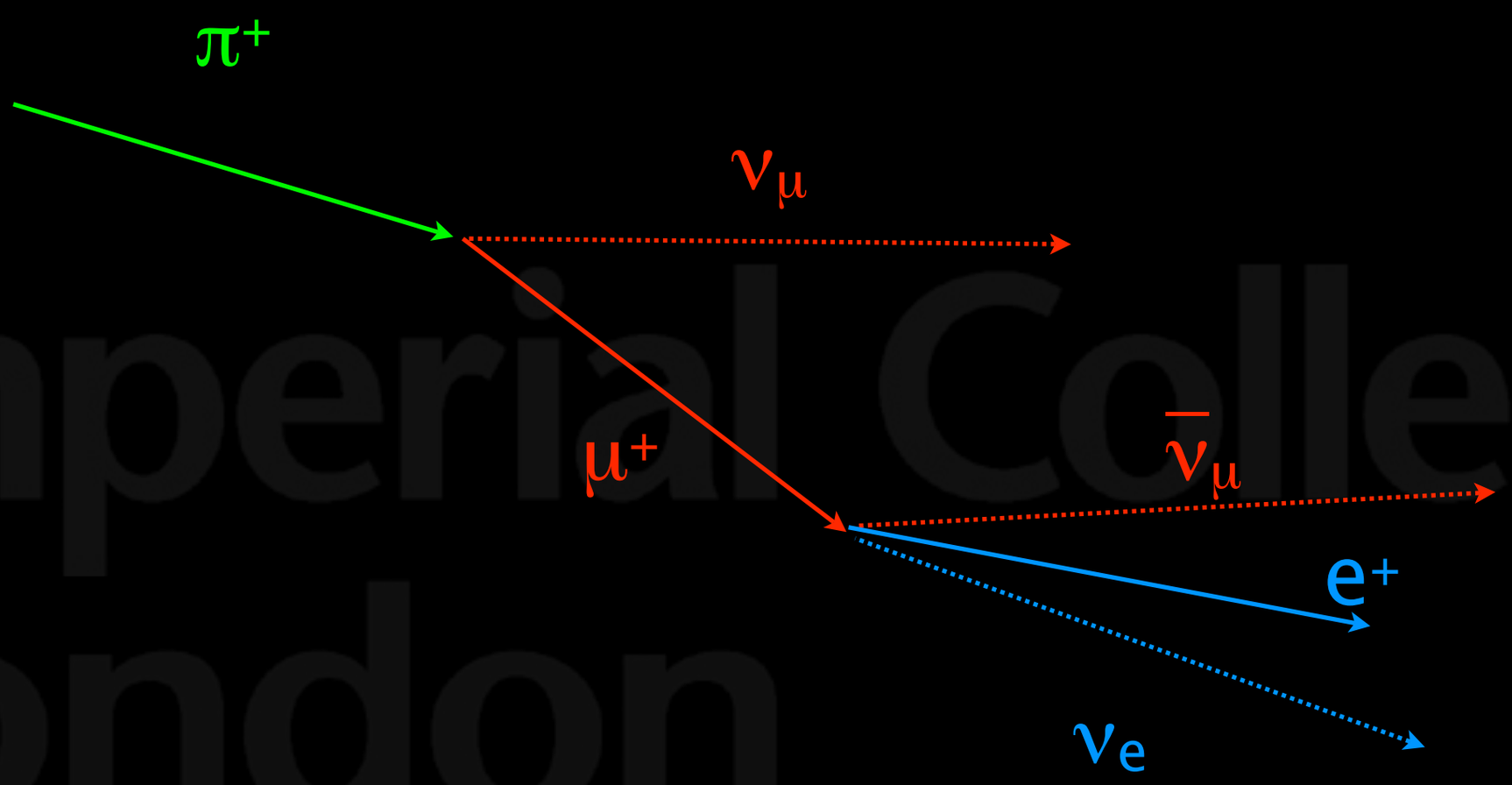
Expanding the Toolbox

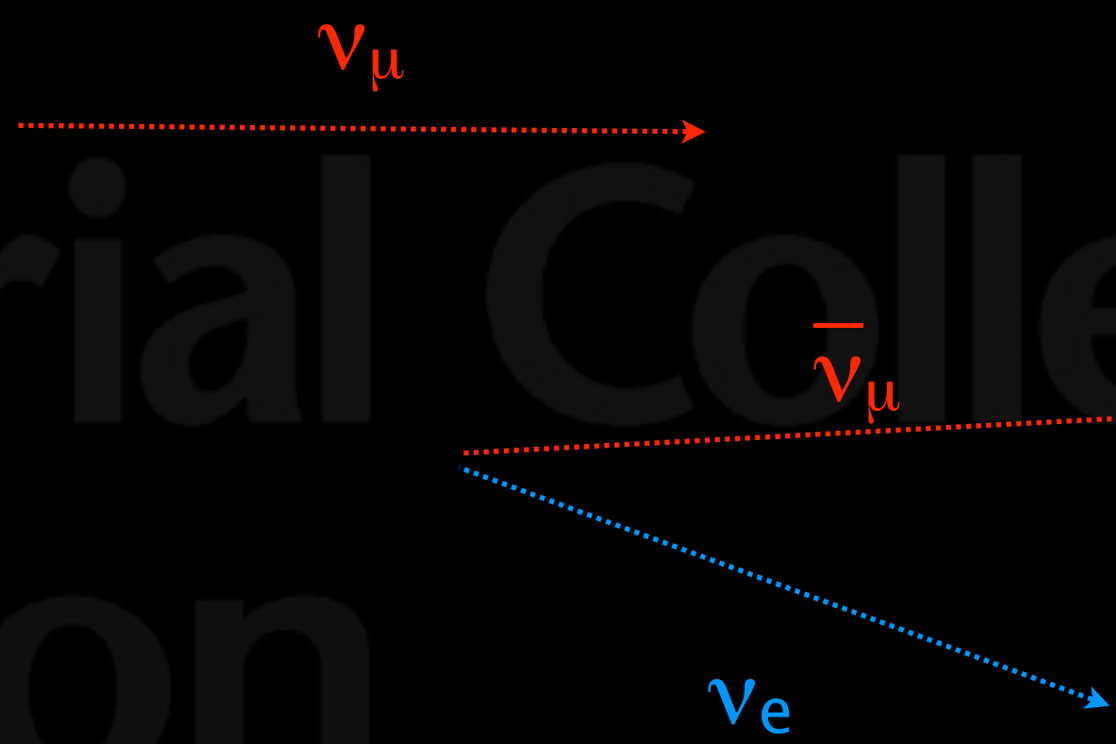
Pion Decay

$\pi \rightarrow \mu\nu$



Pion Decay Chain





Neutrino Beam

First Neutrino Beam

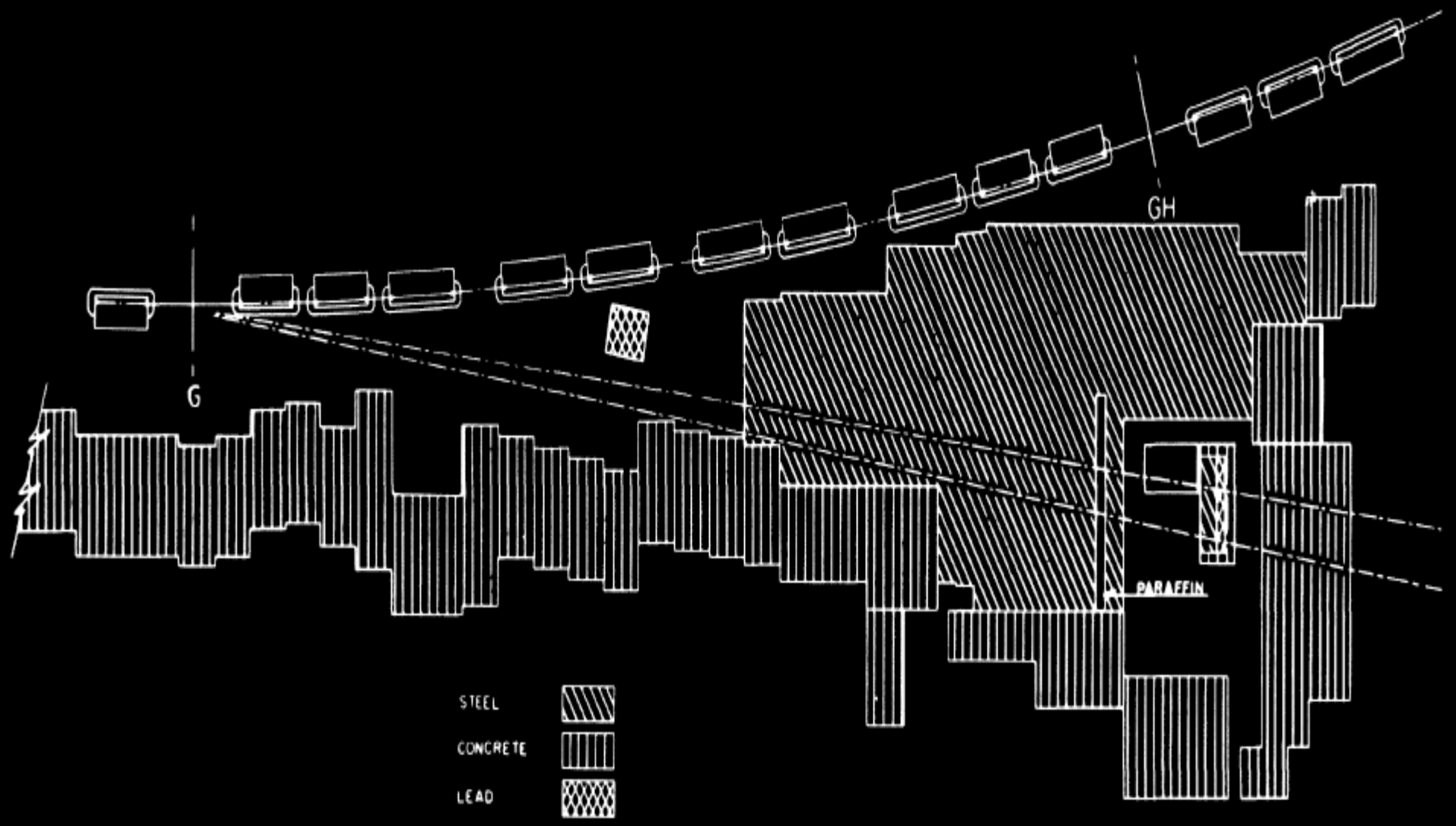


FIG. 1. Plan view of AGS neutrino experiment.

Phys. Rev. Lett. 9, 36 - 44 (1962)

Muon neutrinos!

$\nu A \rightarrow \mu^- X$

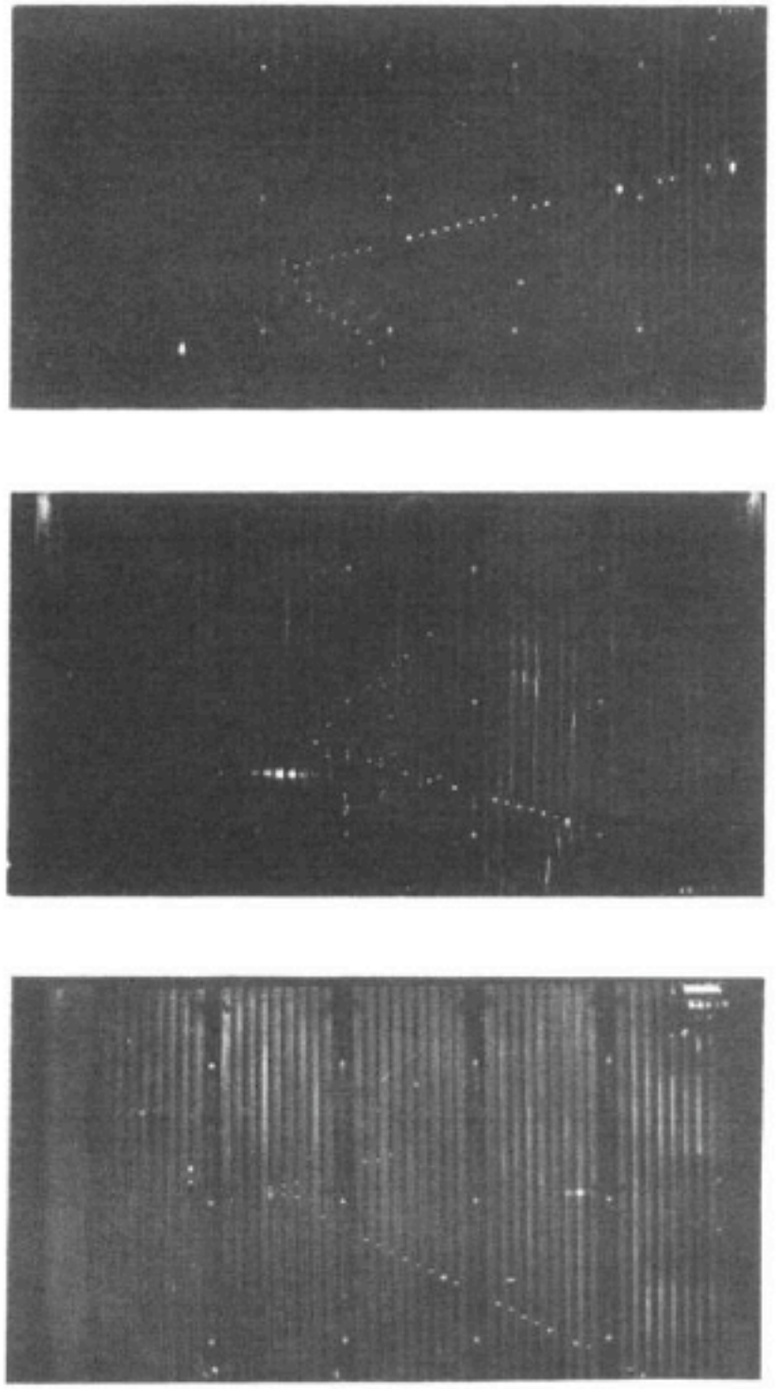
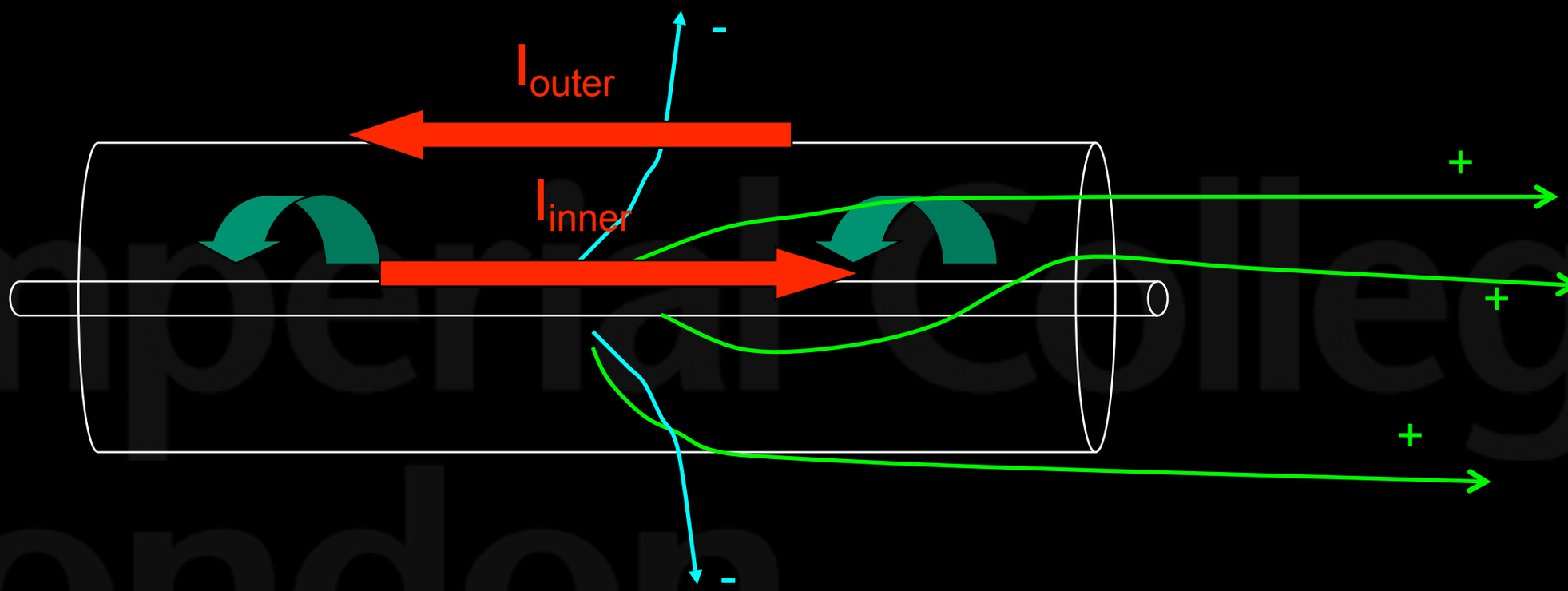
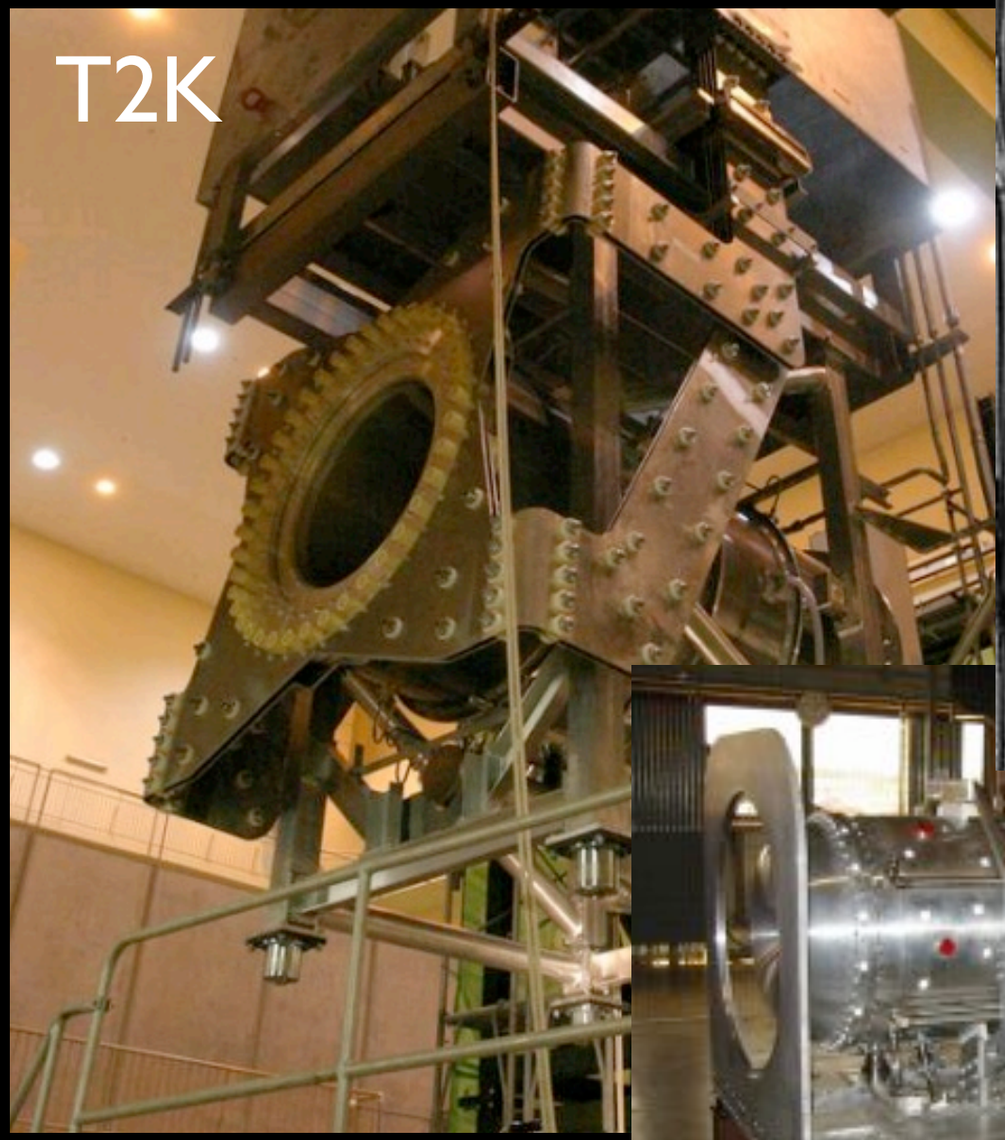


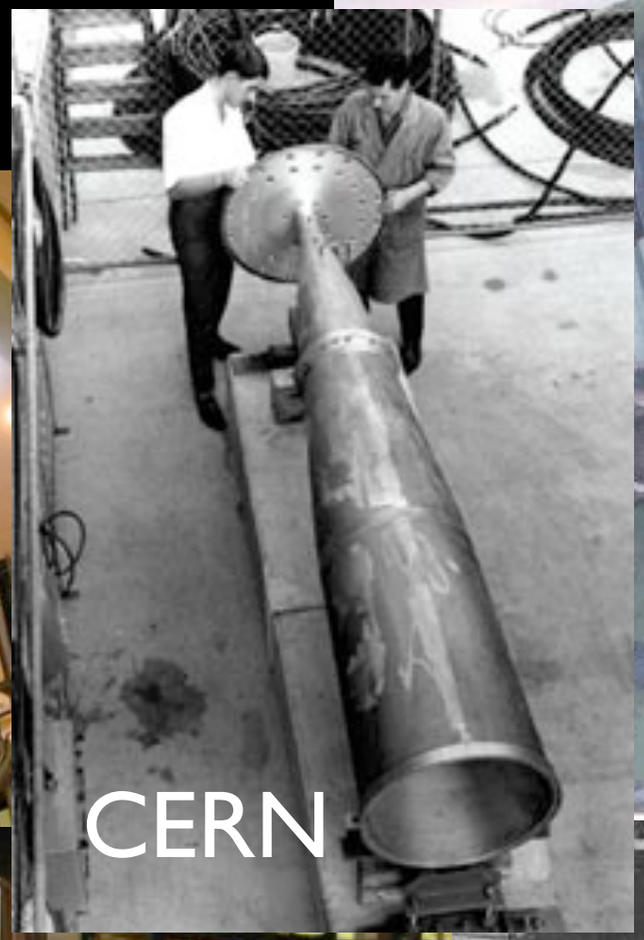
FIG. 6. Vertex events. (A) Single muon of $p_\mu > 500$ MeV and electron-type track; (B) possible example of two muons, both leave chamber; (C) four prong star with one long track of $p_\mu > 600$ MeV/c.

Increasing the flux

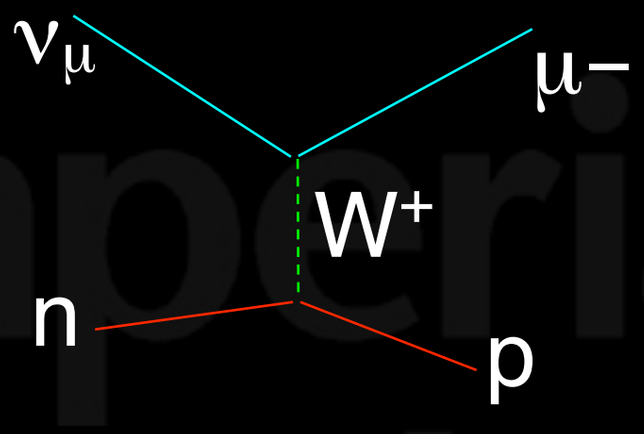


Neutrino horns

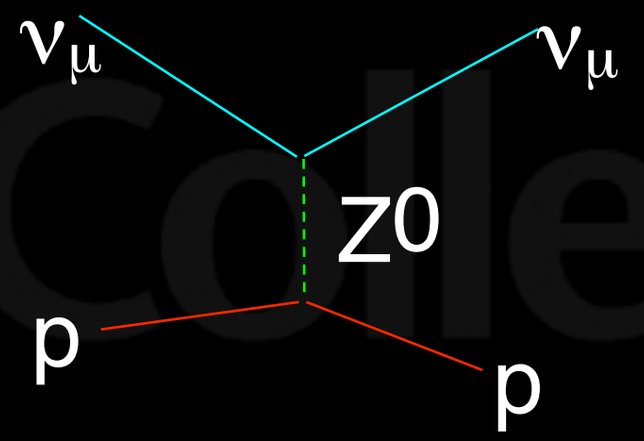




Reminder



Charged Current

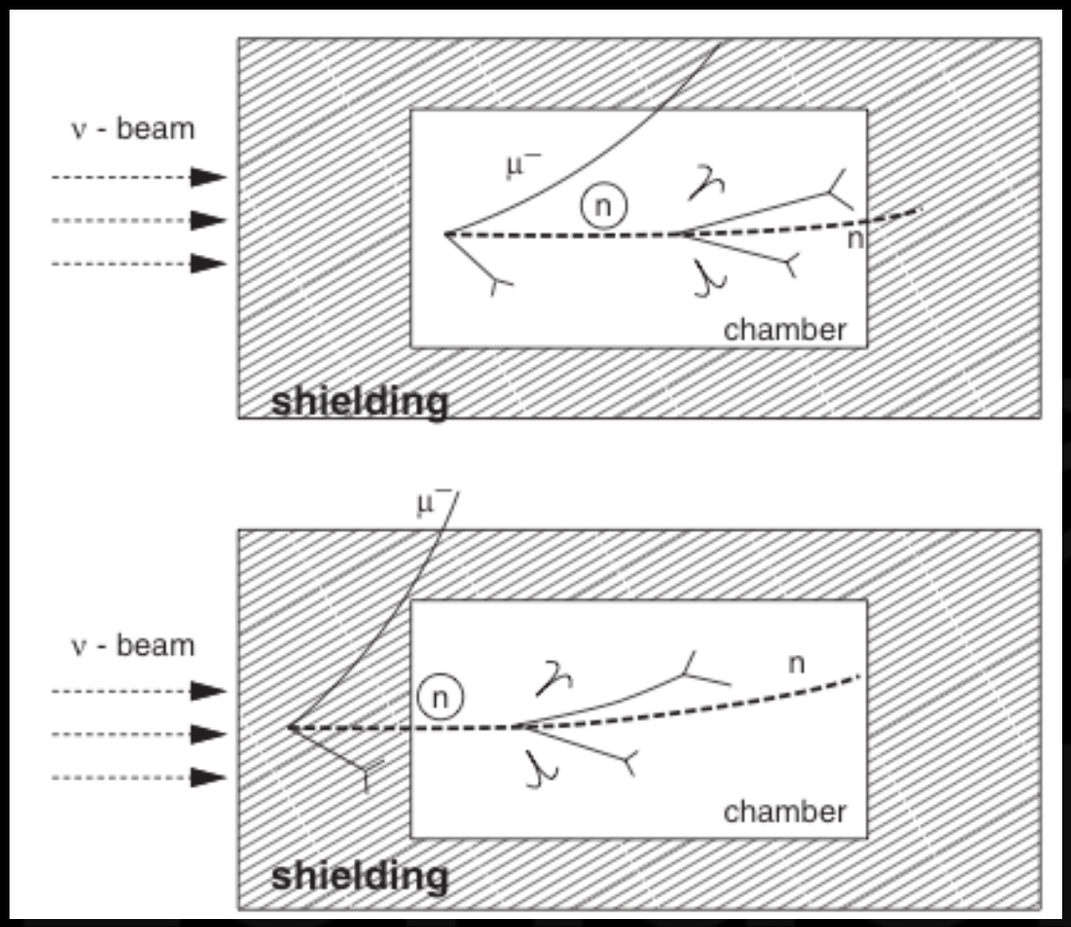


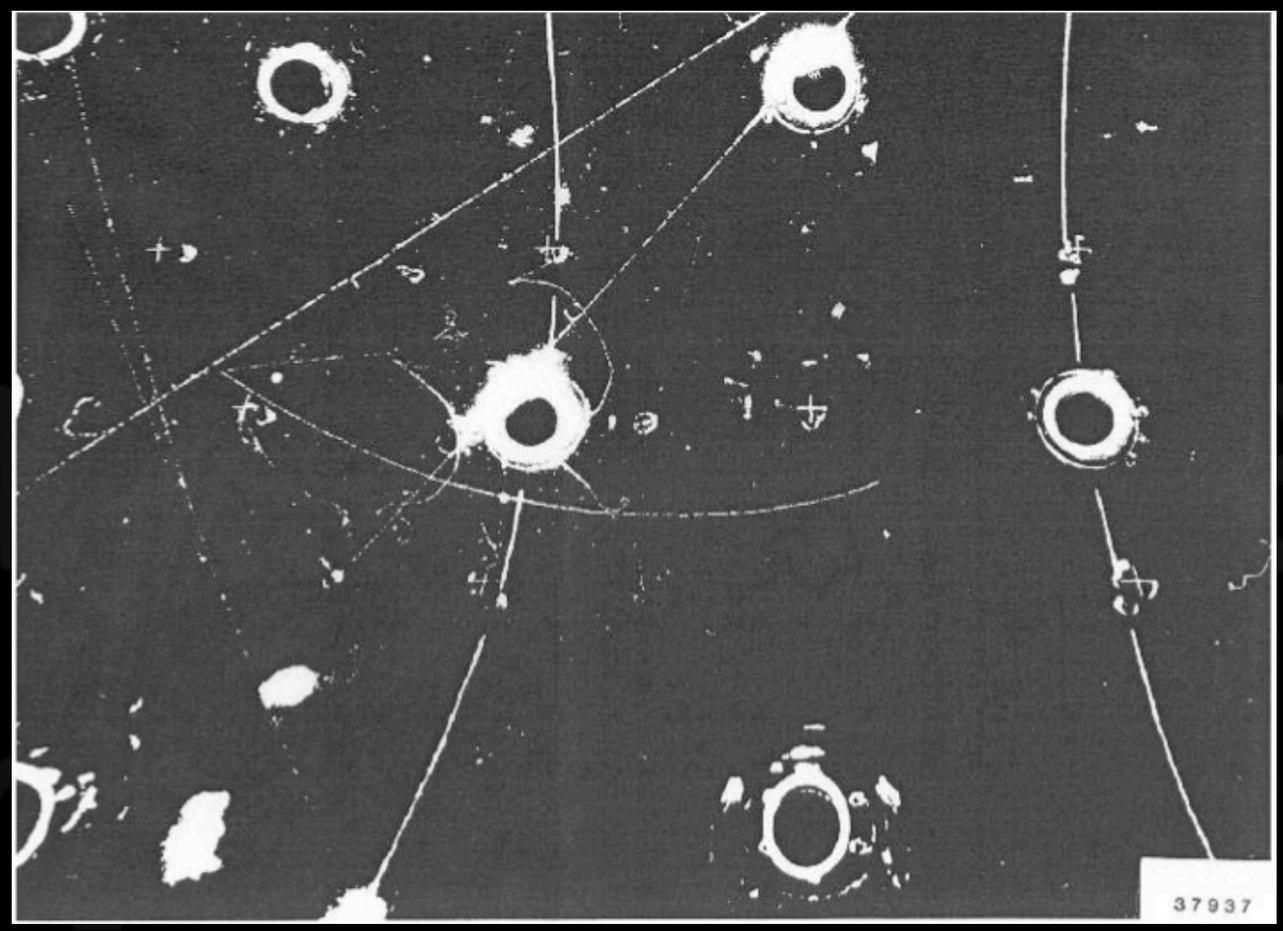
Neutral Current

Gargamelle

NC Signals & BGs

$\nu p \rightarrow \nu p$

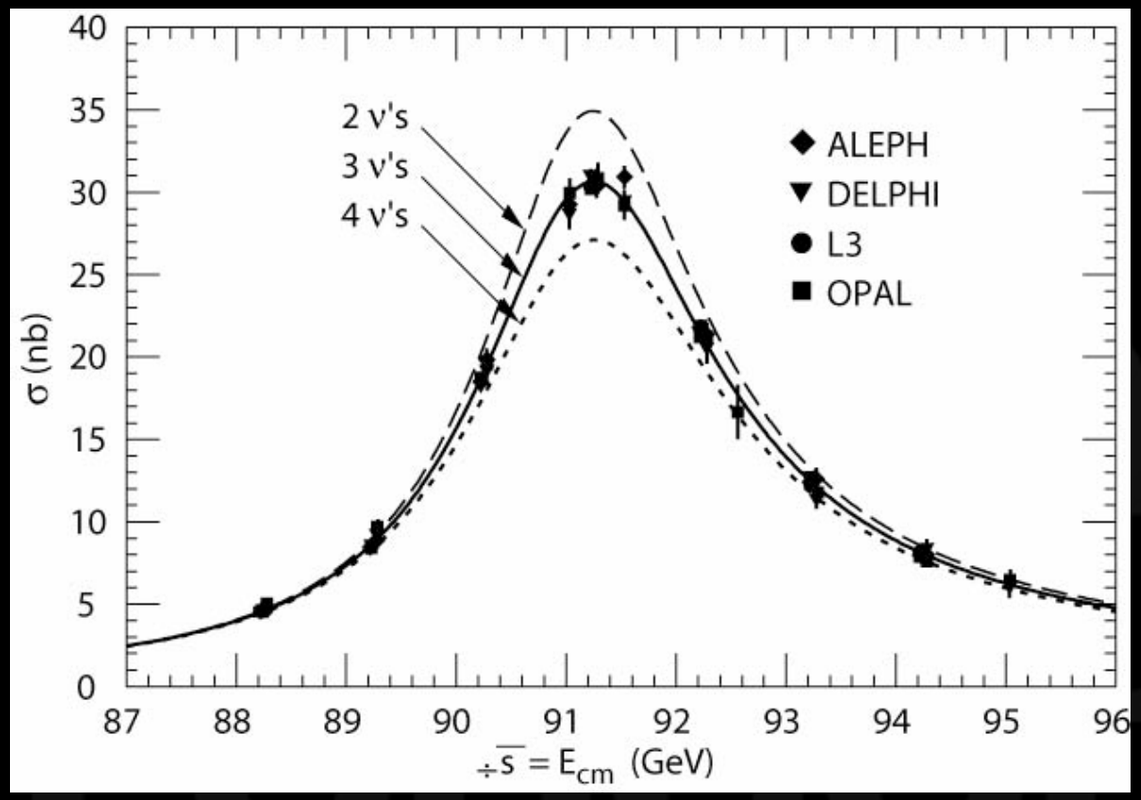




F J Hasert et al. 1973 Phys. Lett. 46B 12 1

(Also get $\nu e \rightarrow \nu e$, of course)

3 generations



C. Caso et al., Euro.Phys.J C3, 1 (1998)
and (URL: http://pdg.lbl.gov/)

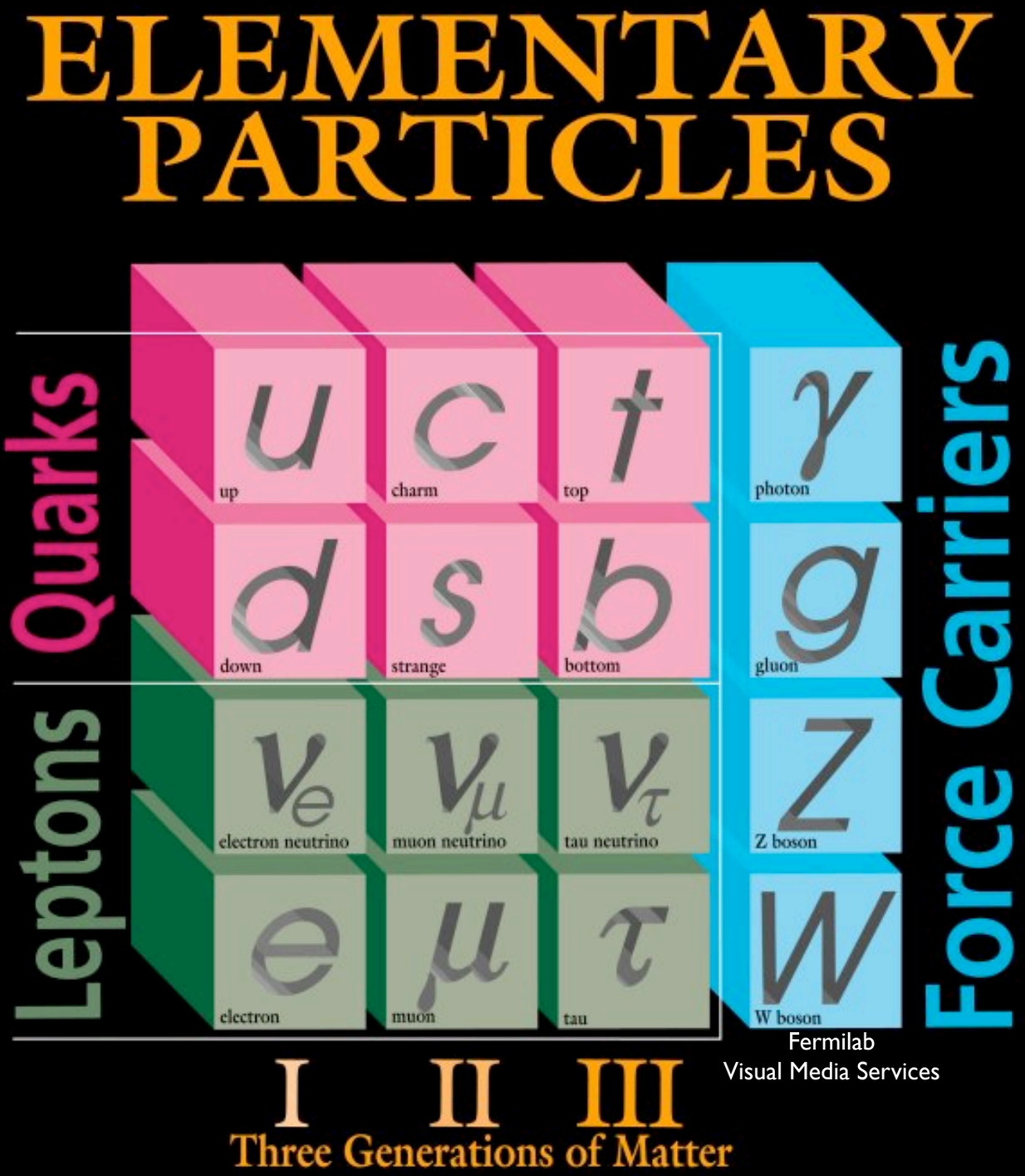
- Look at invisible width around Z^0 resonance
- Favors 3 light neutrinos
- Not sensitive to neutrinos heavier than Z^0

See: J. Dress at the XX International Symposium on Lepton and Photon Interactions at High Energy, Rome, Italy (July 2001).

$2.984 \pm 0.008 \rightarrow 2\ \sigma$ away from 3!

νs in Standard Model

- ✓ No charge
- ✓ No color
- ✓ Fixed helicity
- ✓ No mass
- ✓ Flavors don't mix



Fermilab
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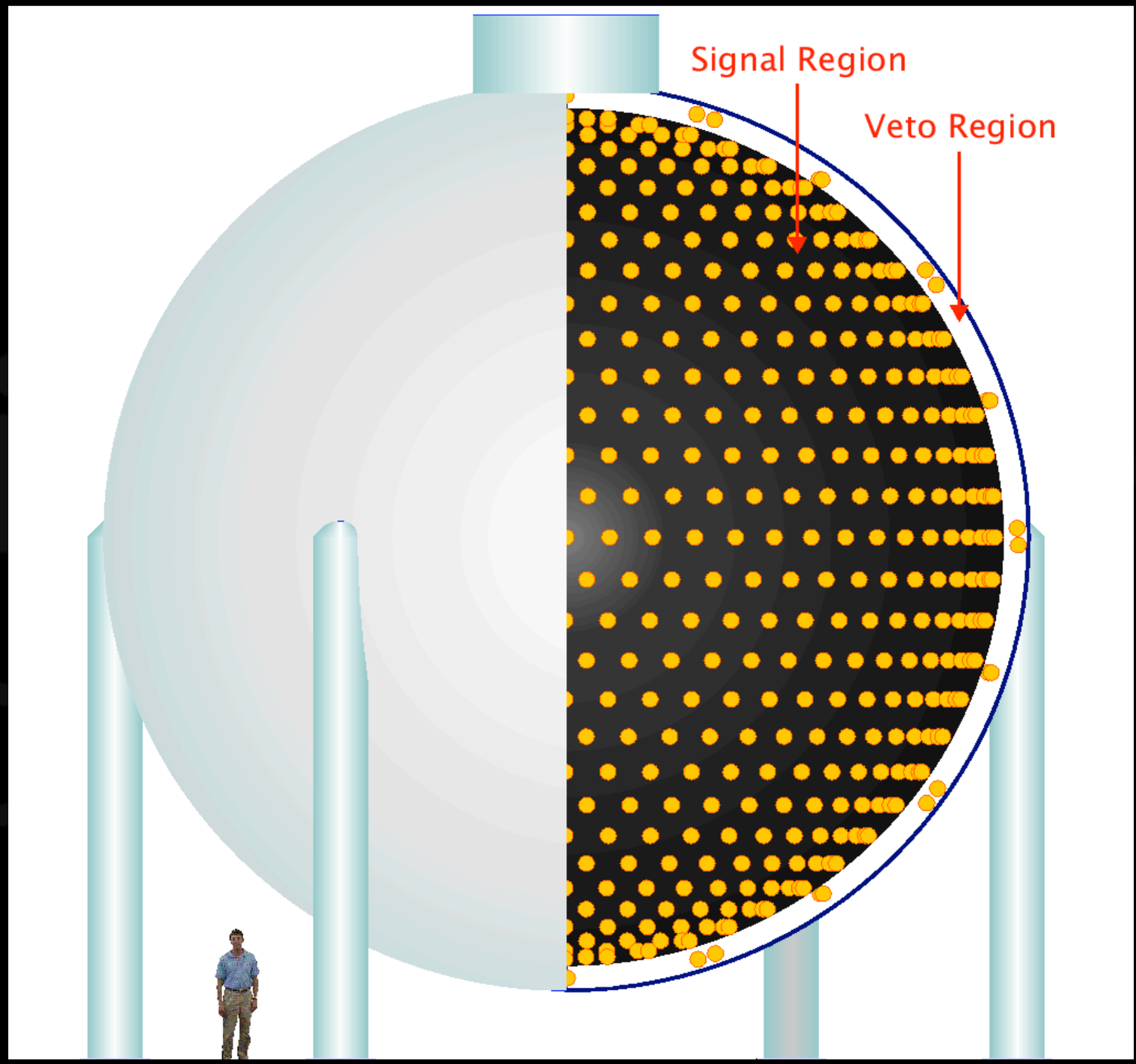
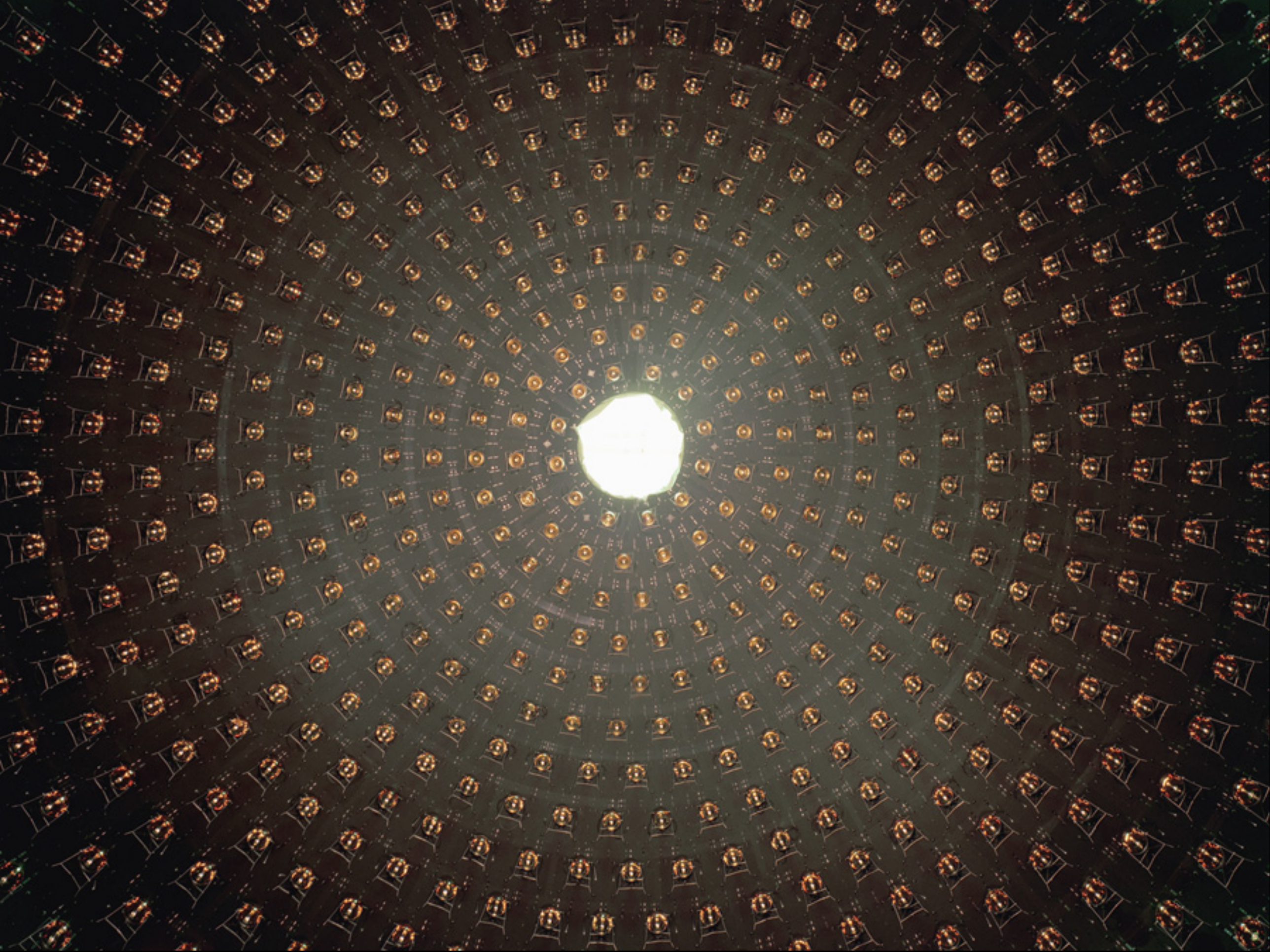
An example

MiniBooNE Detector

- 800 tons of pure mineral oil
- 6m radius steel sphere
- ~2m earth overburden
- 1520 8" PMTs
  - 1280 in main tank (sphere)
  - 240 in veto region (shell)
- DAQ records t,Q
  - "Hits"





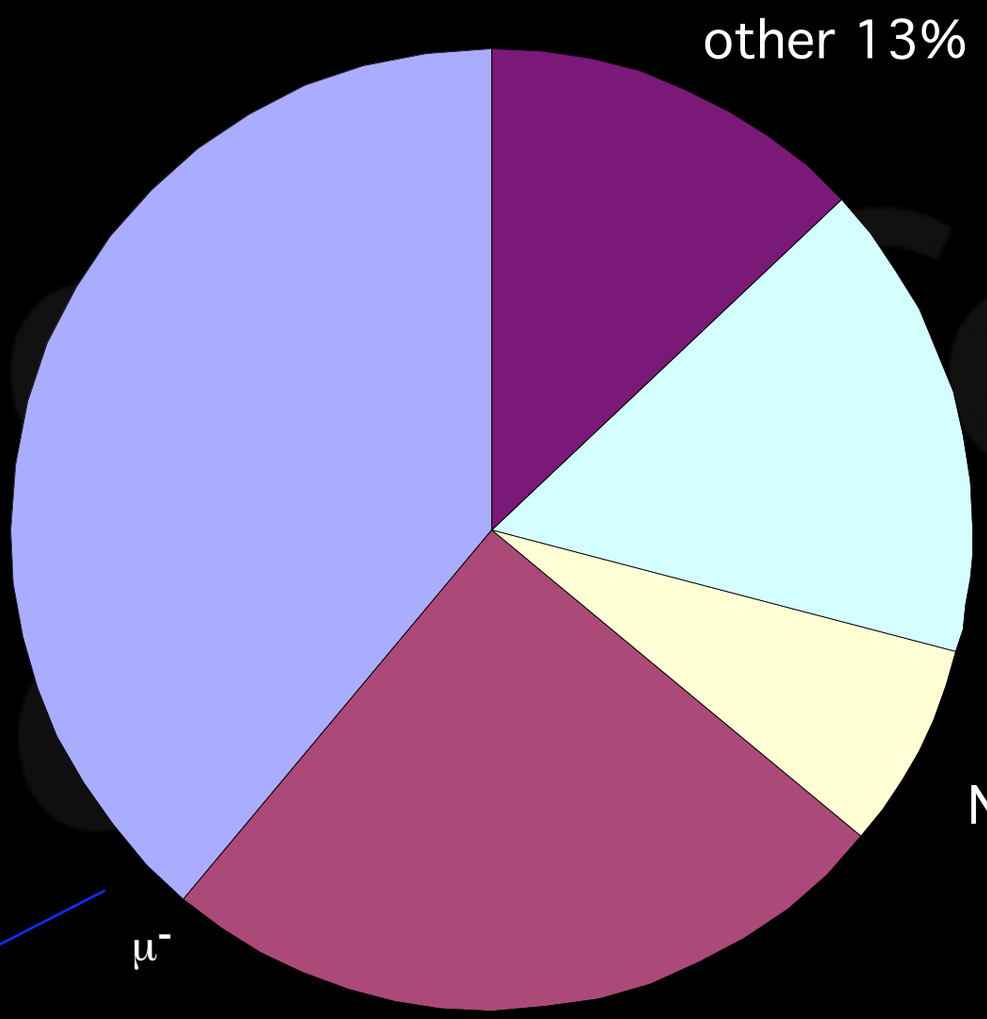
Neutrinos in oil

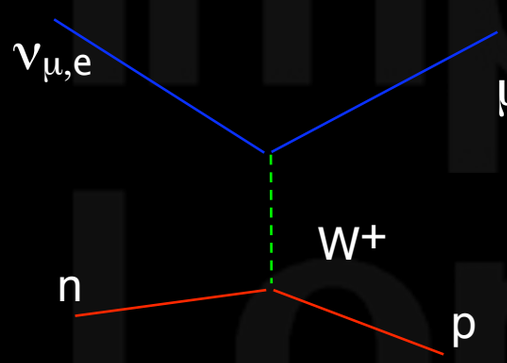
A neutrino can do many things in mineral oil...

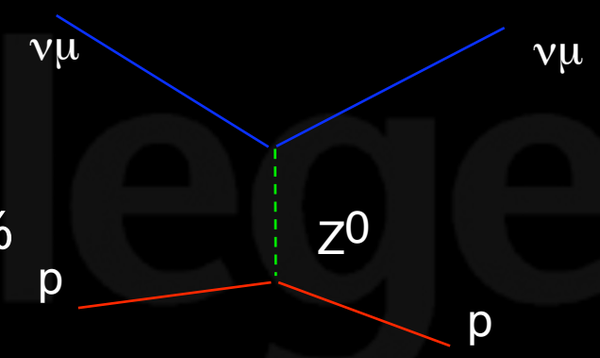
About 75% CC, 25 % NC

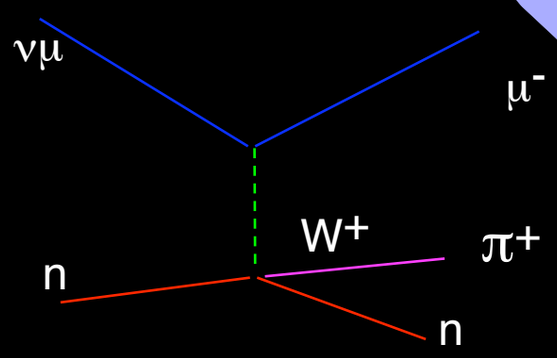
NC events lose energy when neutrino escapes detector

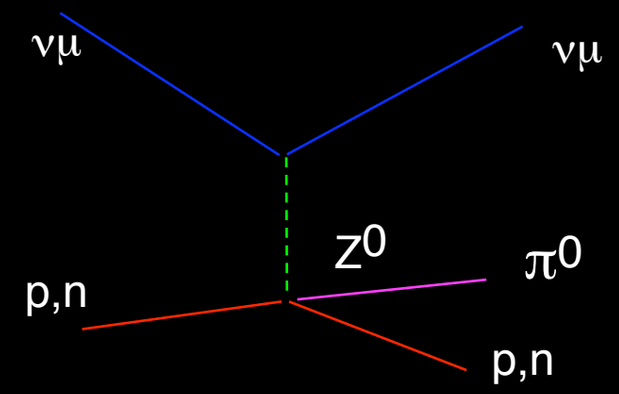
CC events deposit all energy in detector





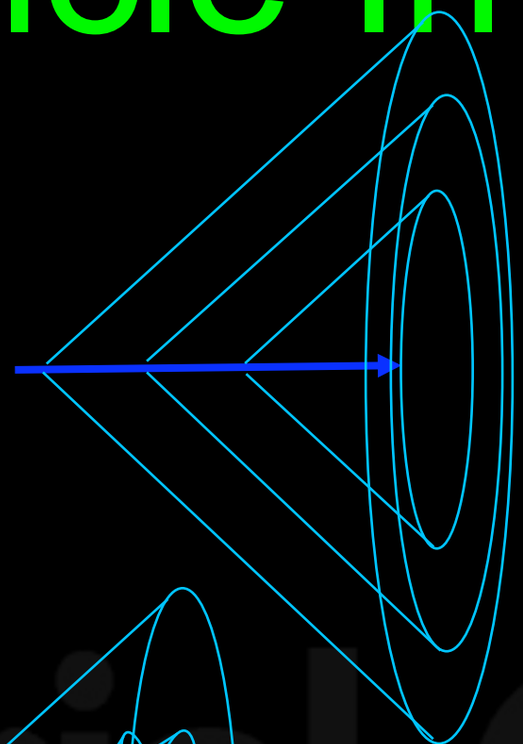


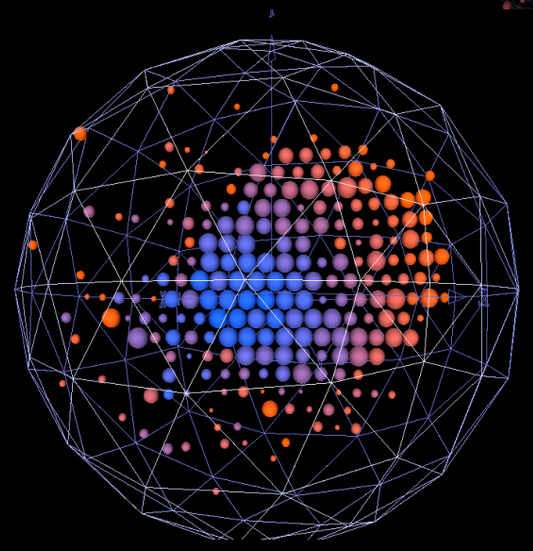




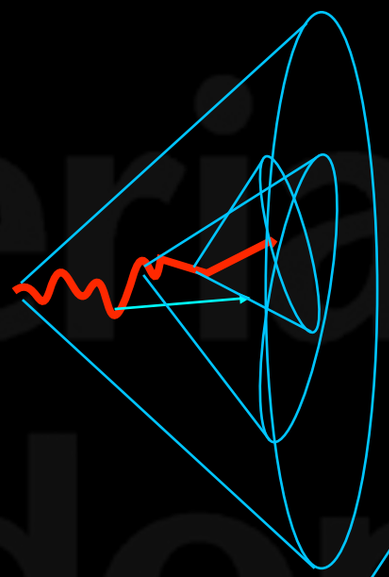
Particle Images

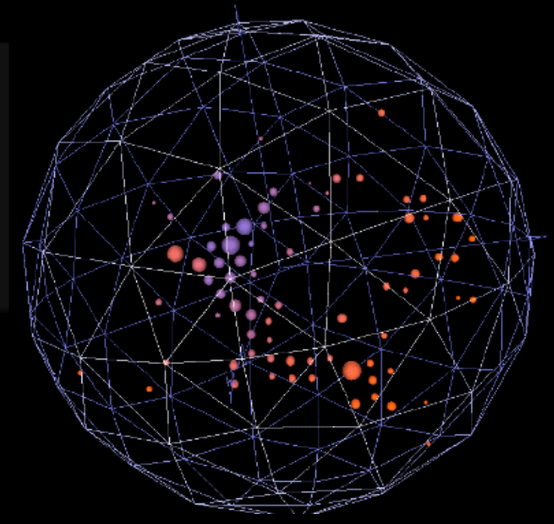
- Muons
  - Sharp, clear rings
    - Long, straight tracks



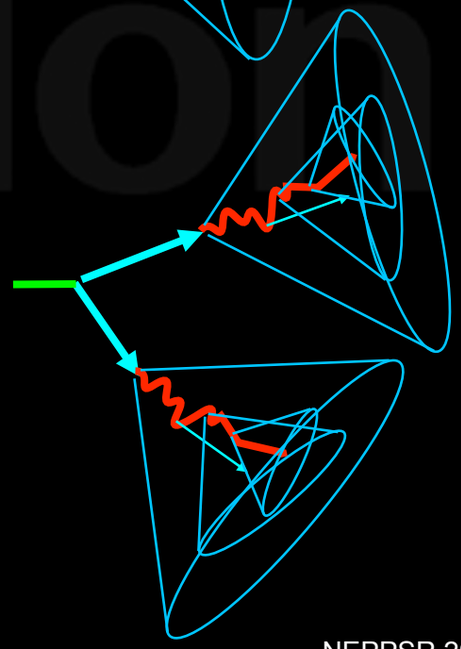


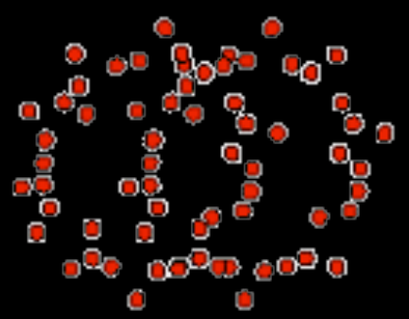
- Electrons
  - Scattered rings
    - Multiple scattering
      - Radiative processes

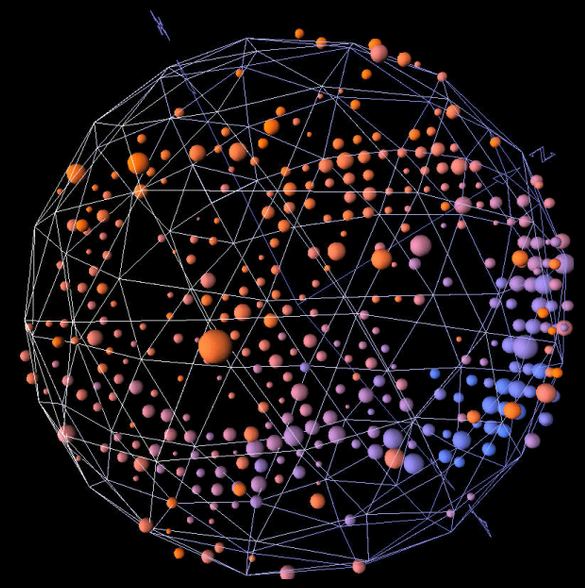




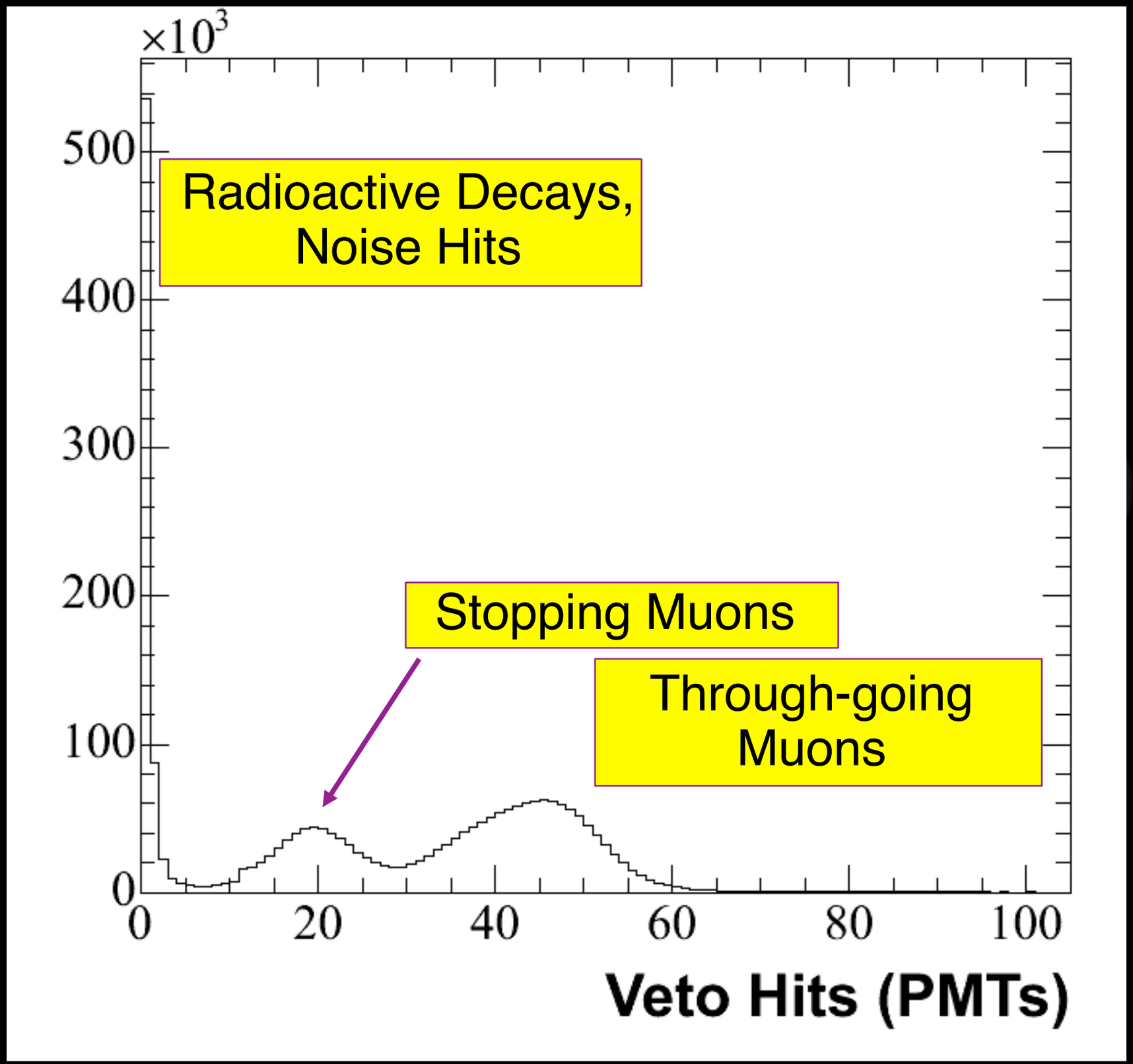
- Neutral Pions
  - Double rings
    - Decays to two photons
      - Photons pair produce

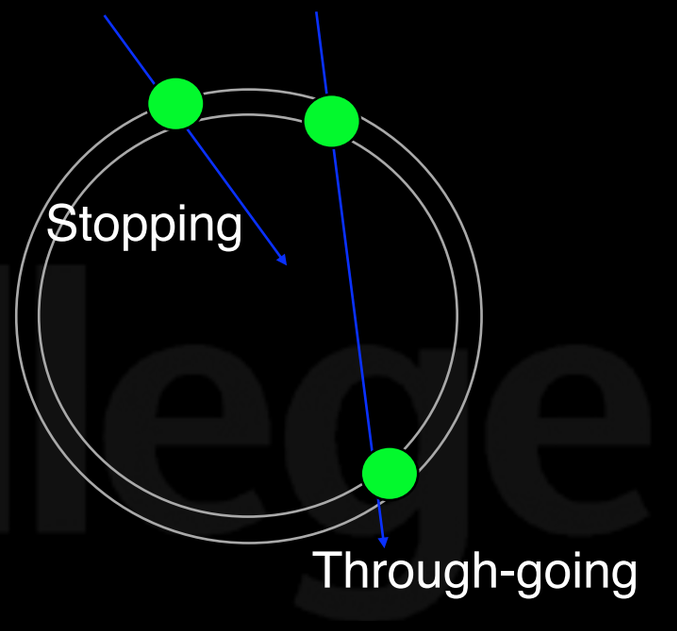






Looking at Tank Data





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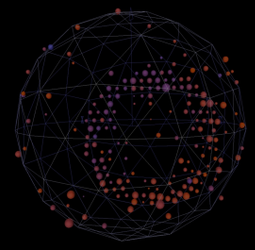

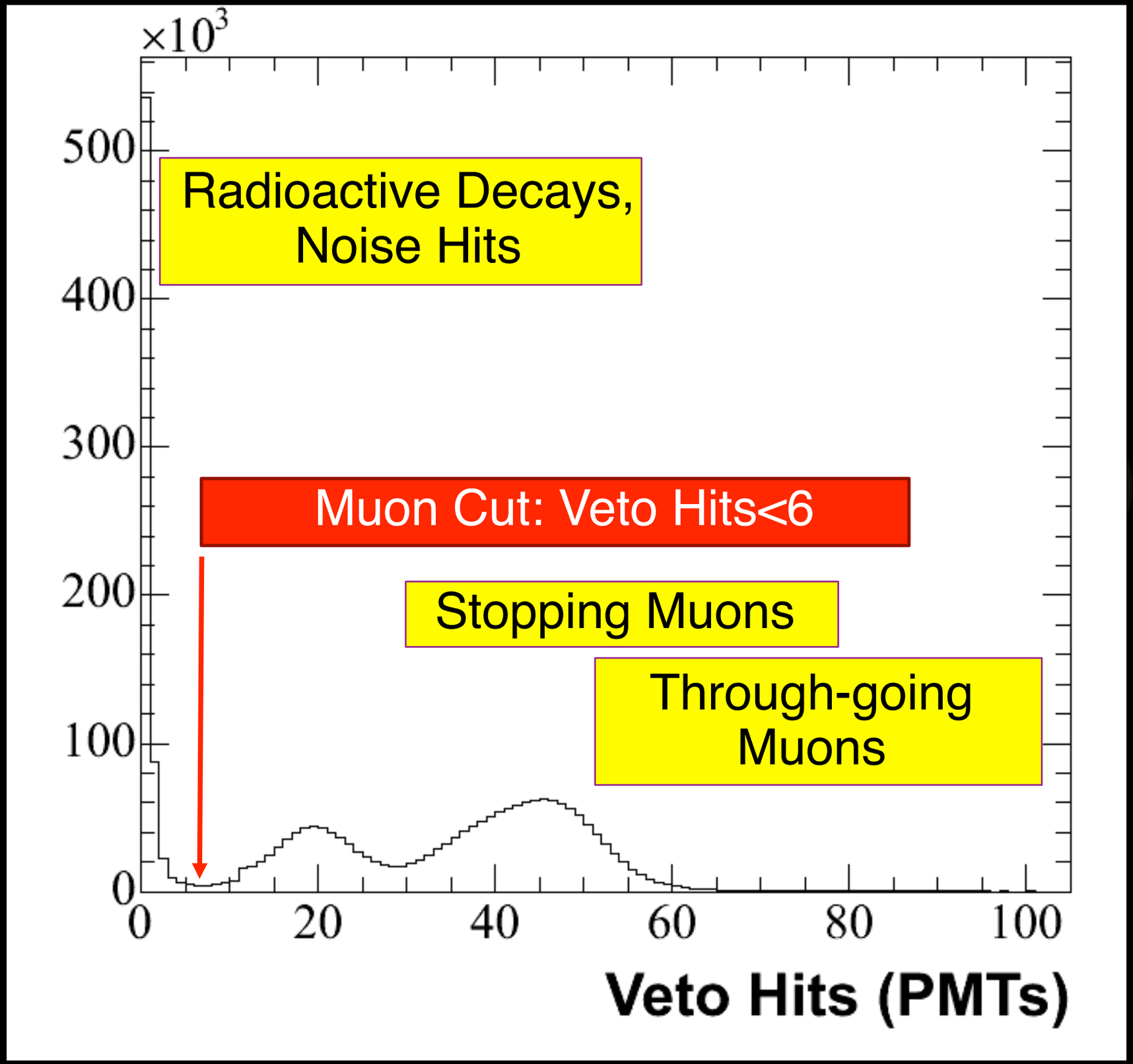

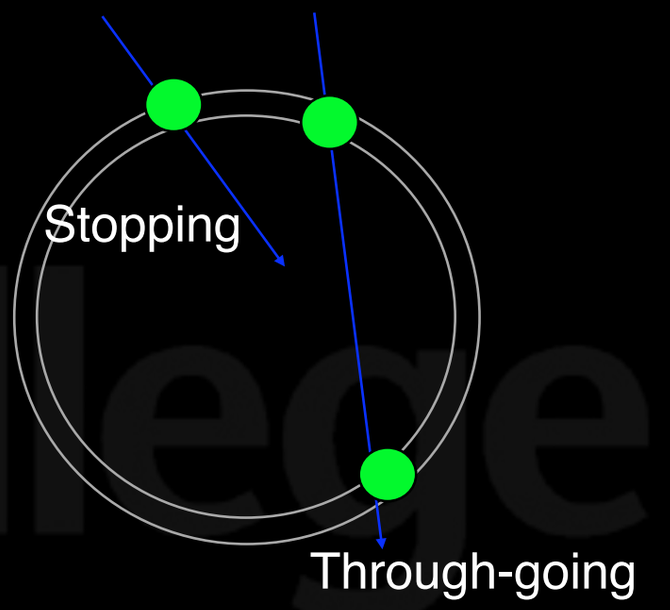

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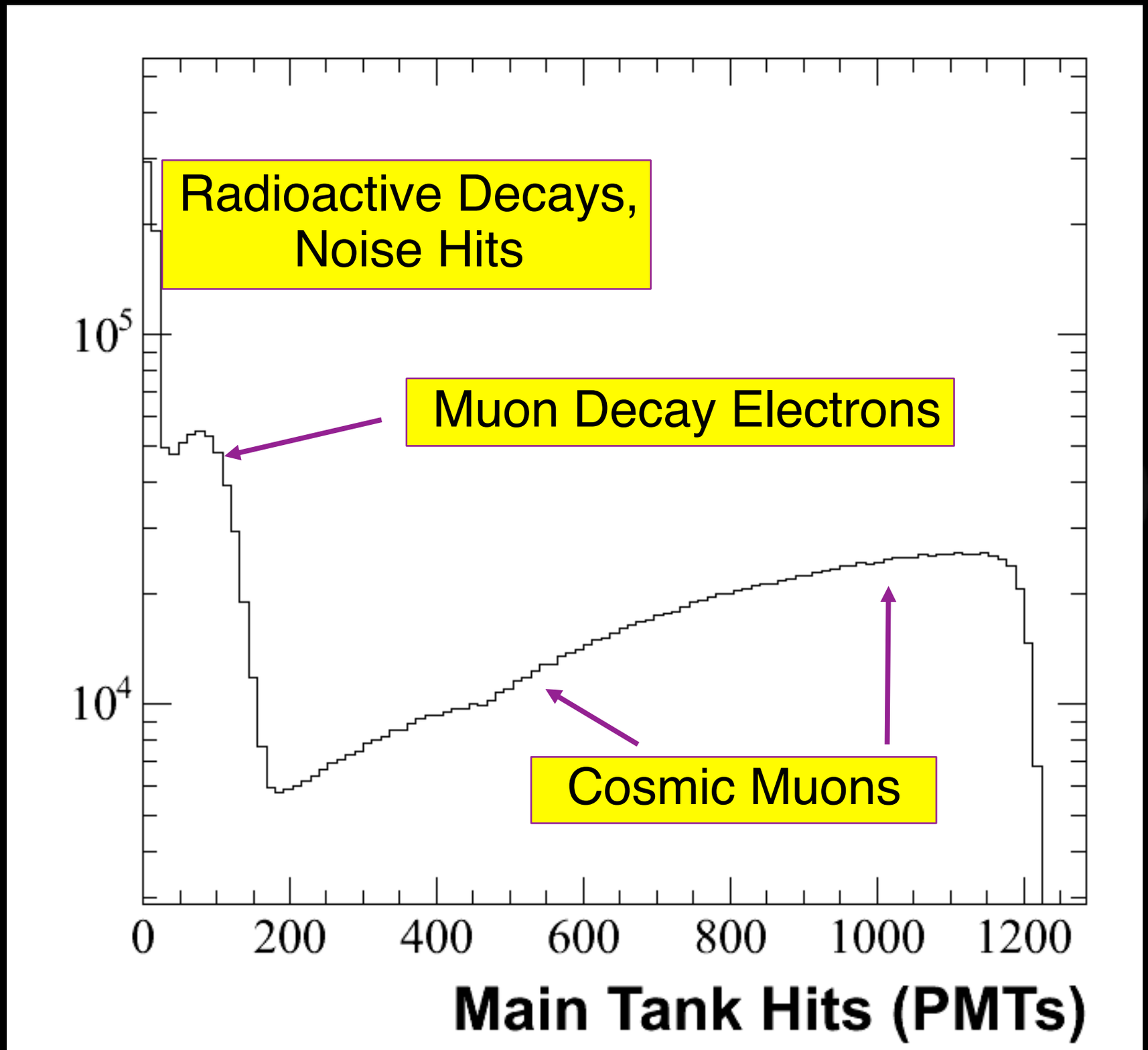
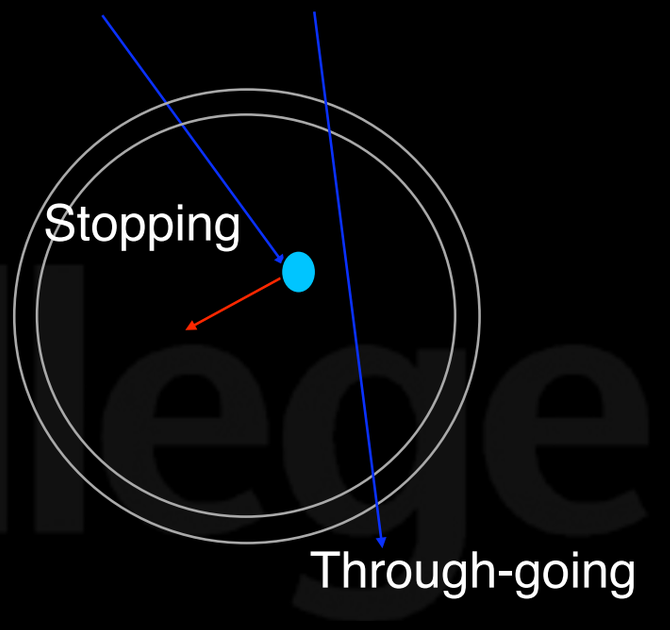


Putting it all together...



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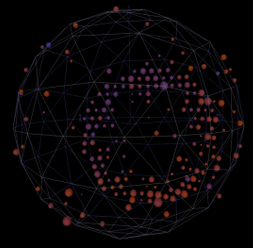

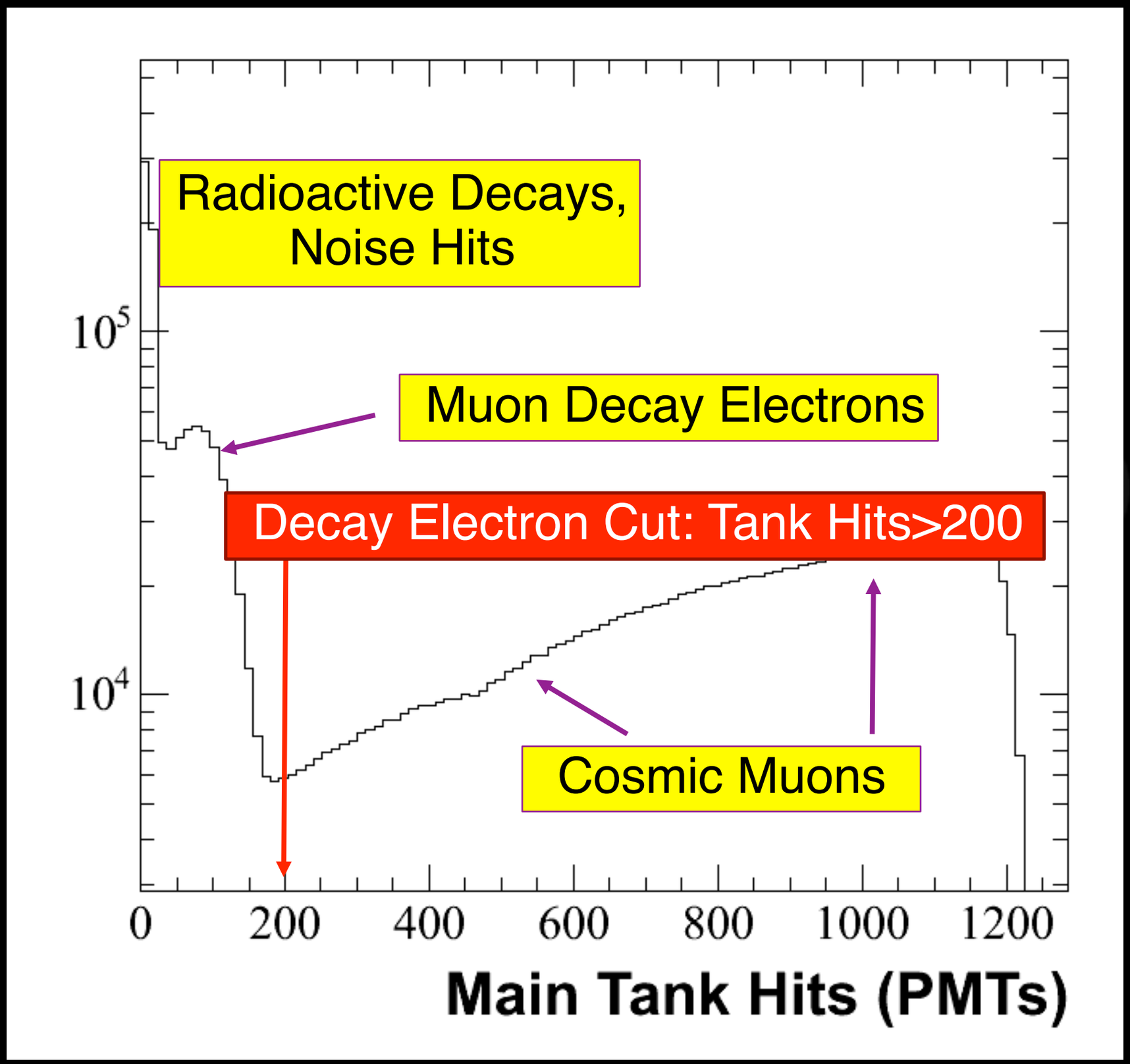

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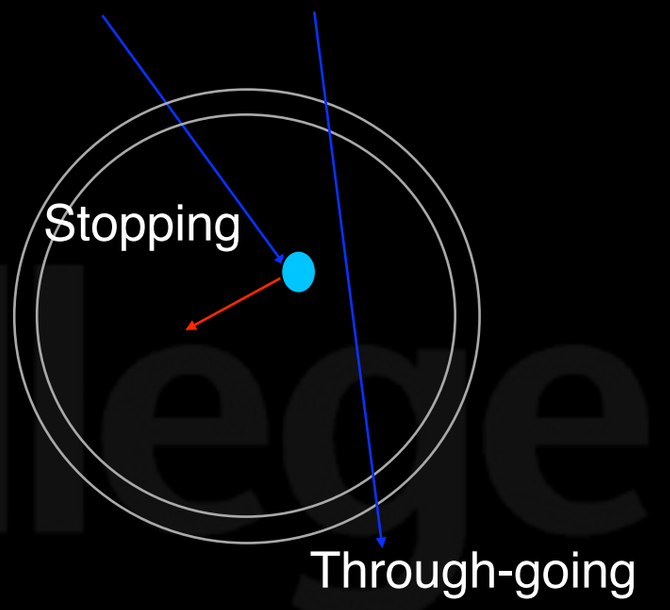

Imperial College
London

Triggering on Neutrinos

- MiniBooNE's neutrino trigger is unbiased
- The Booster dumps protons onto our target in 1.6μs intervals, several times per second
  - "Beam spill"
- We know exactly when neutrinos from the beam are passing through the detector
- When this happens, we record all detector activity in a 20μs interval around the beam spill

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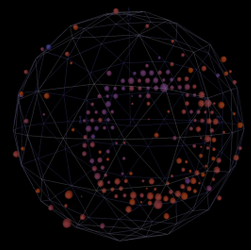

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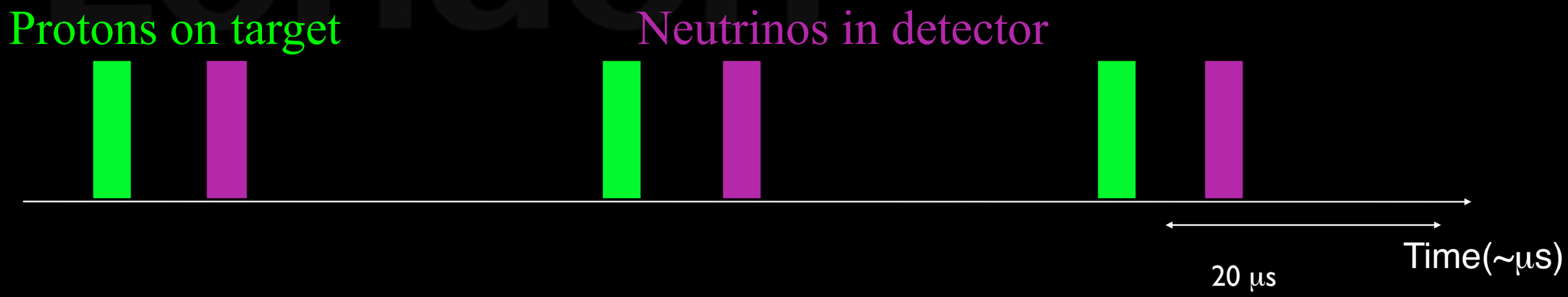

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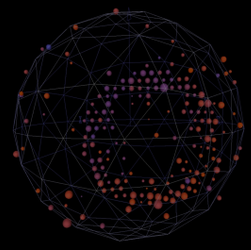

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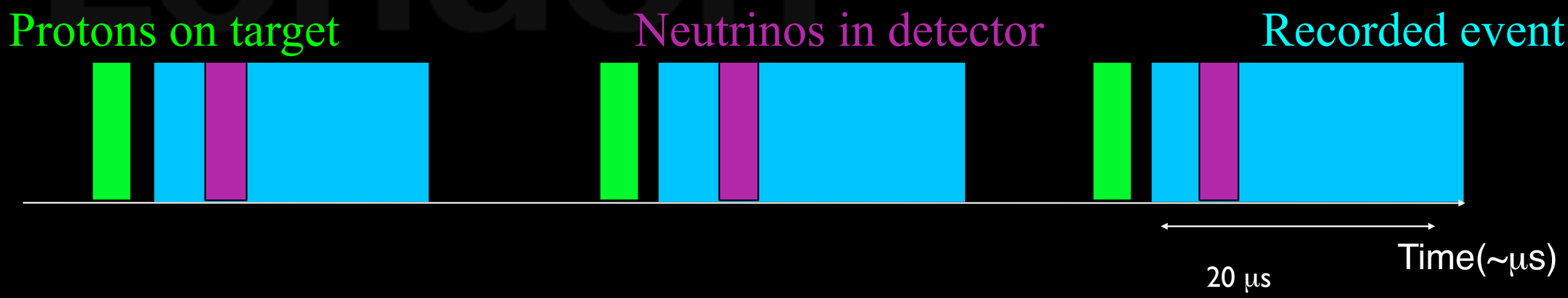
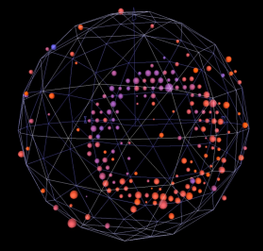
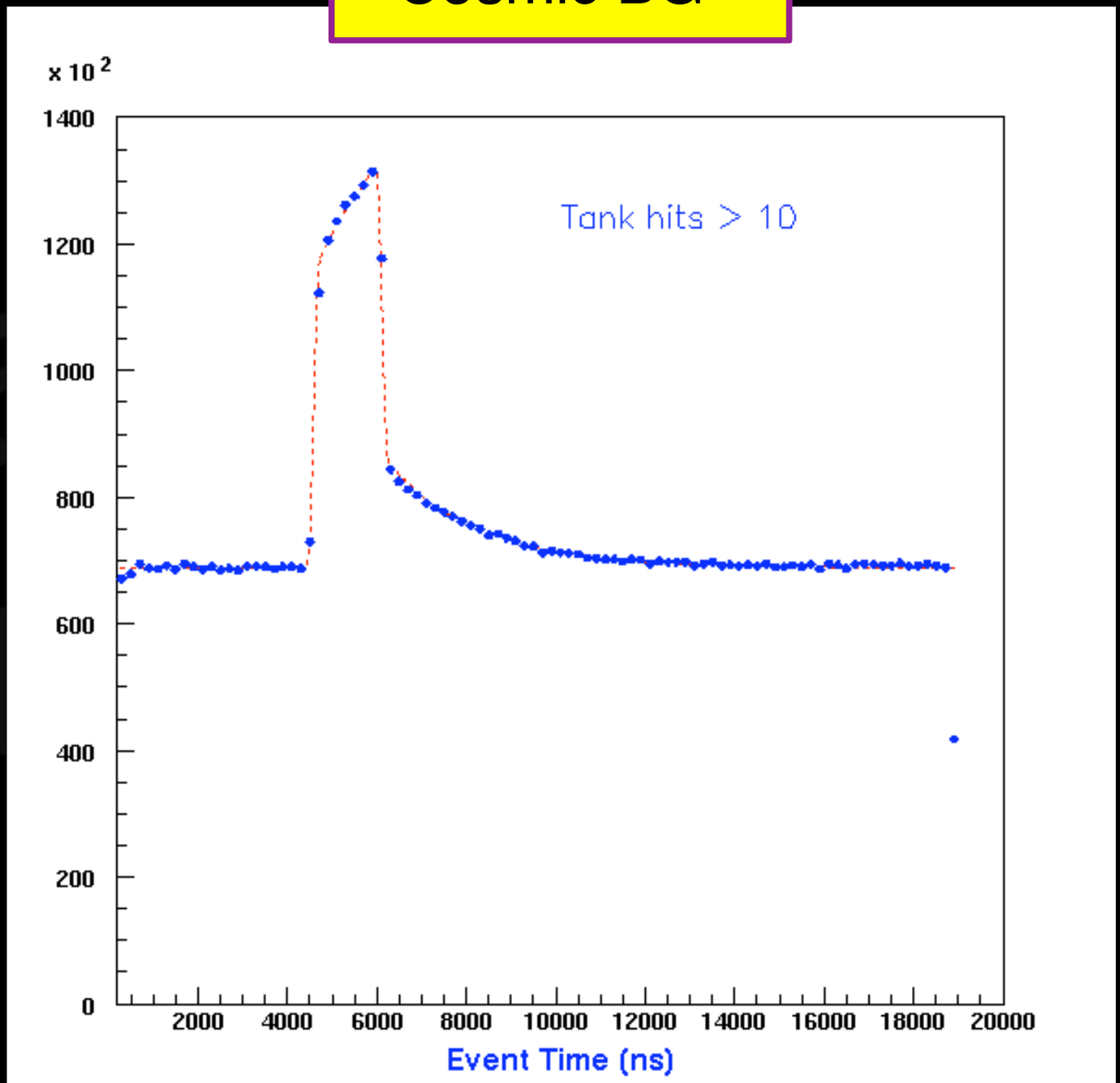


Picking out Neutrinos



- Times of hit-clusters
- Beam spill clearly evident
  - simple cuts eliminate cosmic backgrounds
- Neutrino Candidate Cuts
  - <6 veto PMT hits
  - >200 tank PMT hits
  - Only neutrinos are left!

Beam and Cosmic BG



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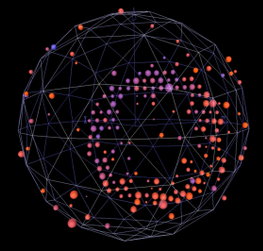

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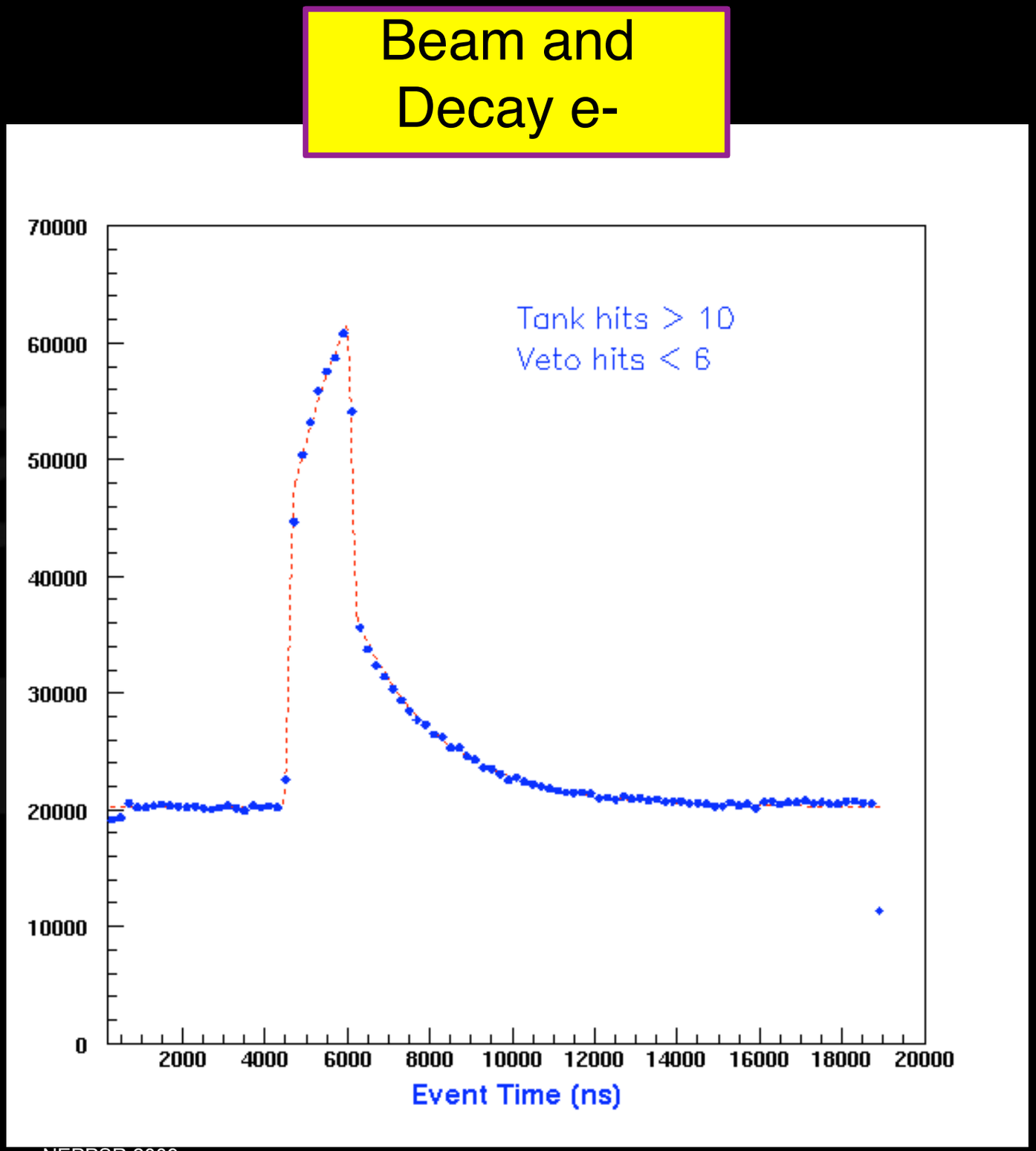

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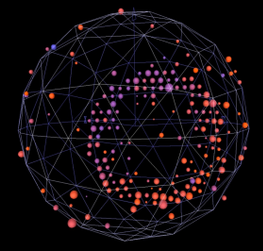

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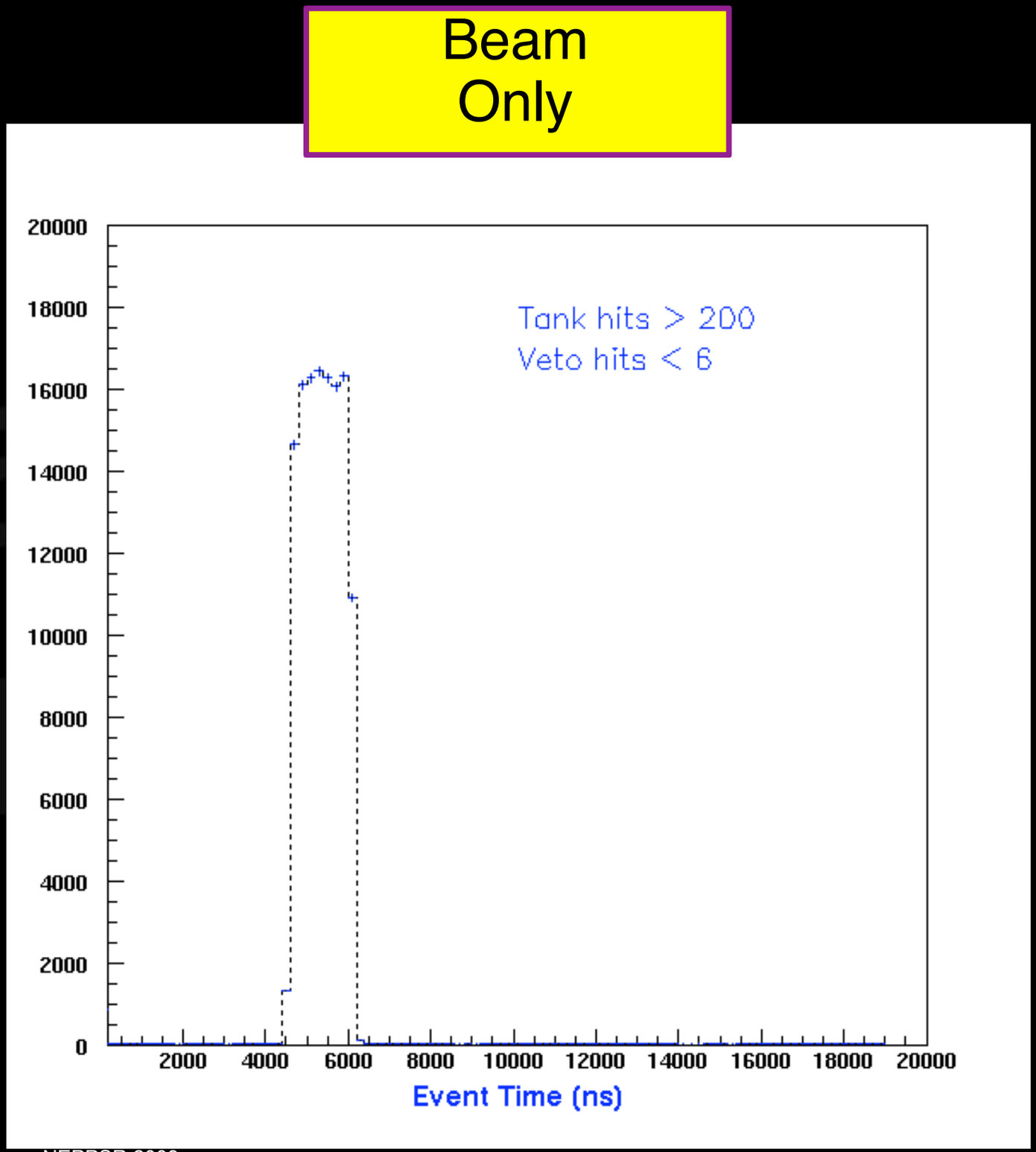


Discovery of Neutrino Mass

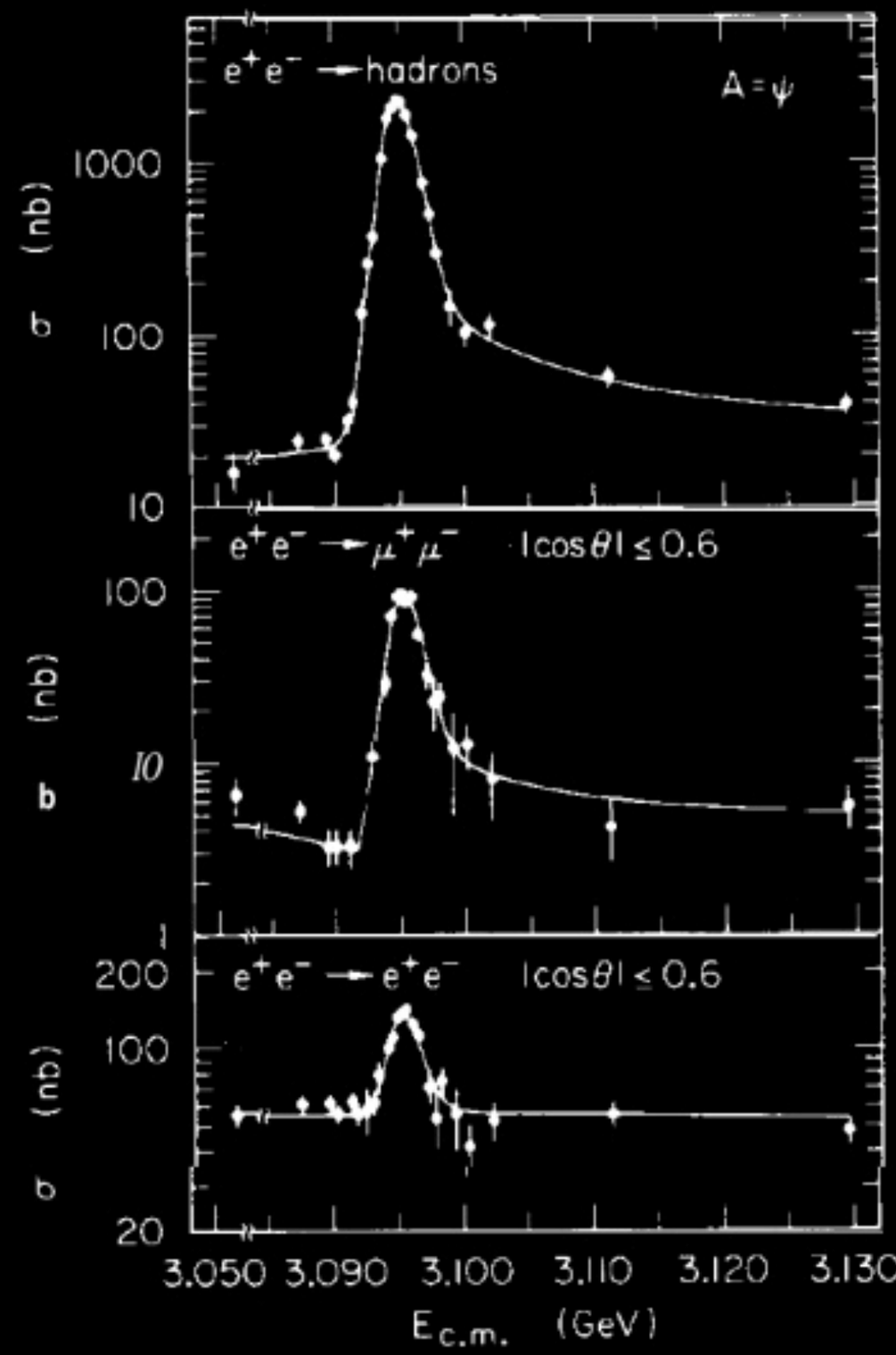
Super Kamiokande

Why ν mass is difficult

- Usual techniques
  - Mass reconstruction
  - Spectrometry

- Cannot directly measure ν mass eigenstates!

- Must use less direct techniques



Phys Rev. Lett. ***33****, 1406 (1974)*

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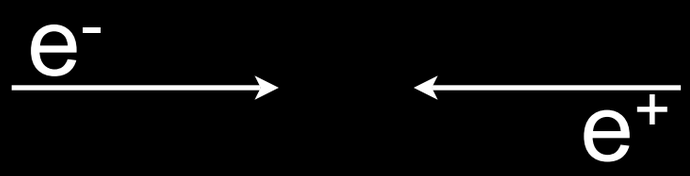

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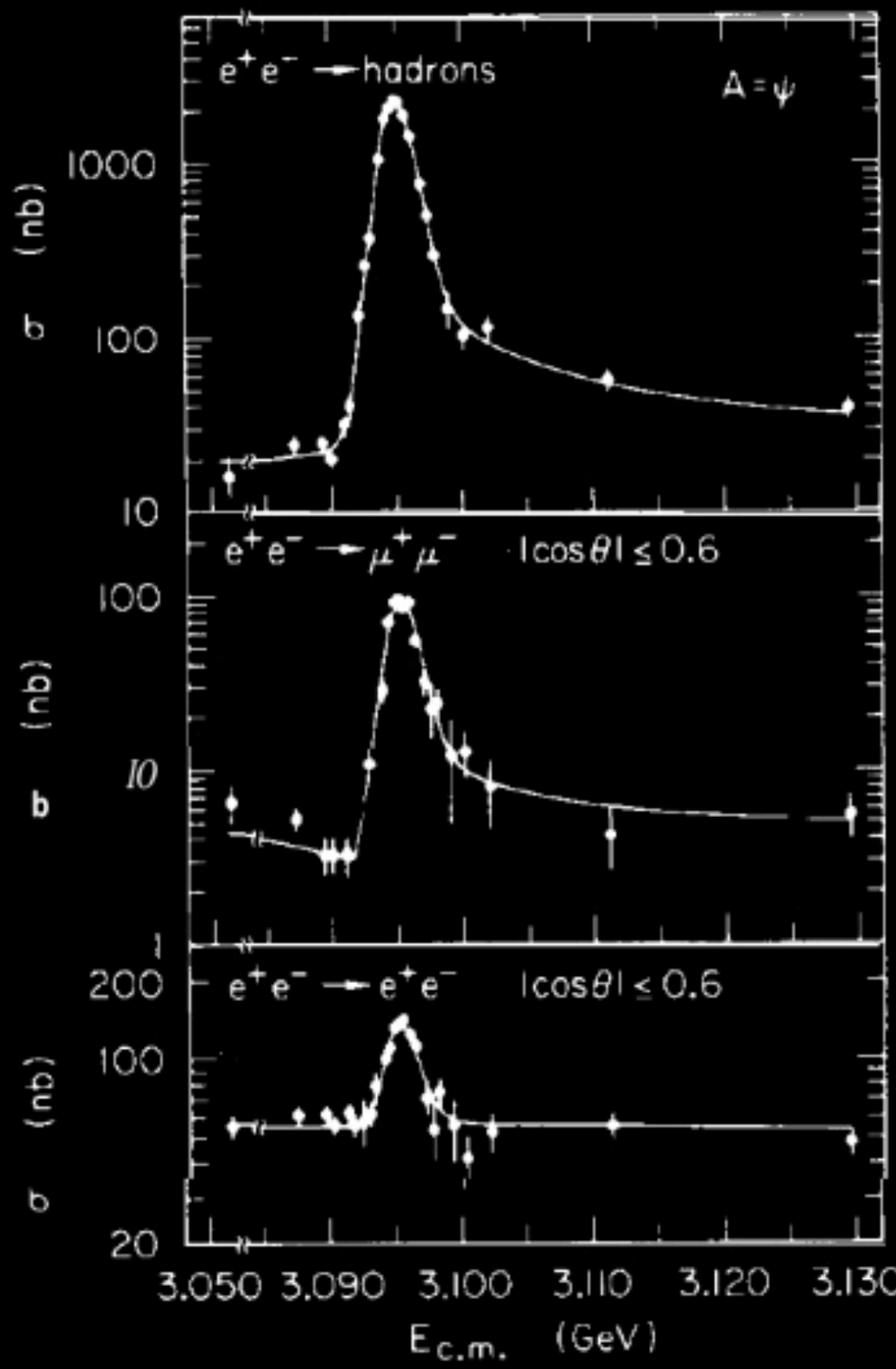

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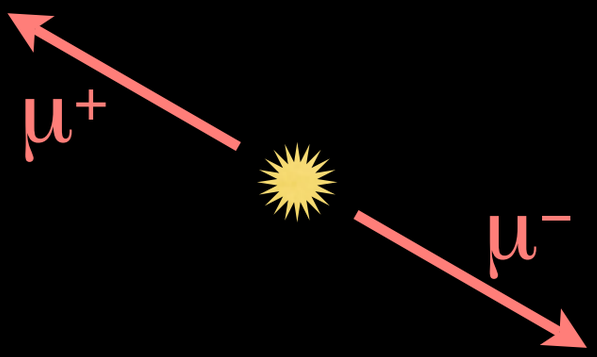

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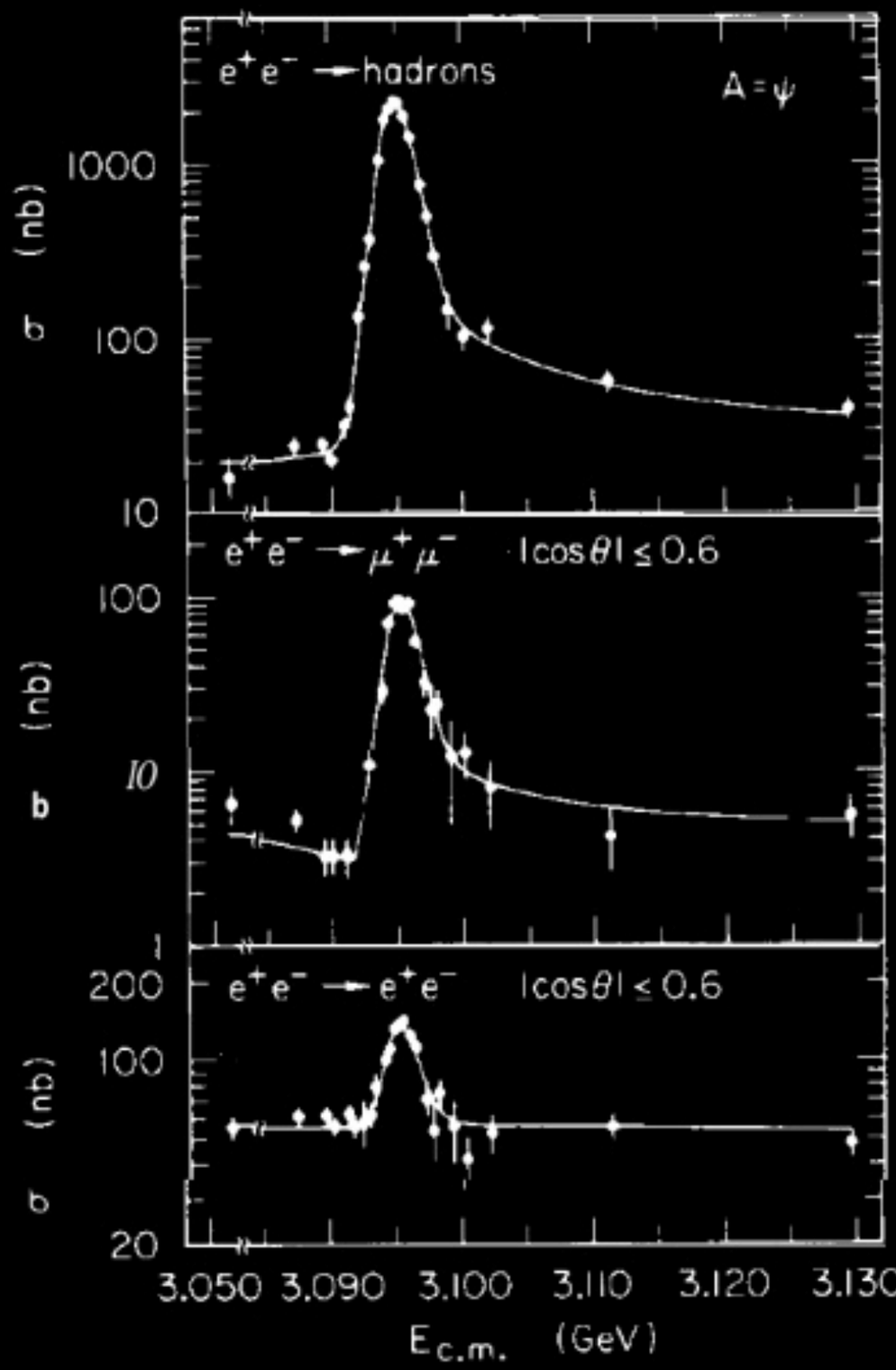

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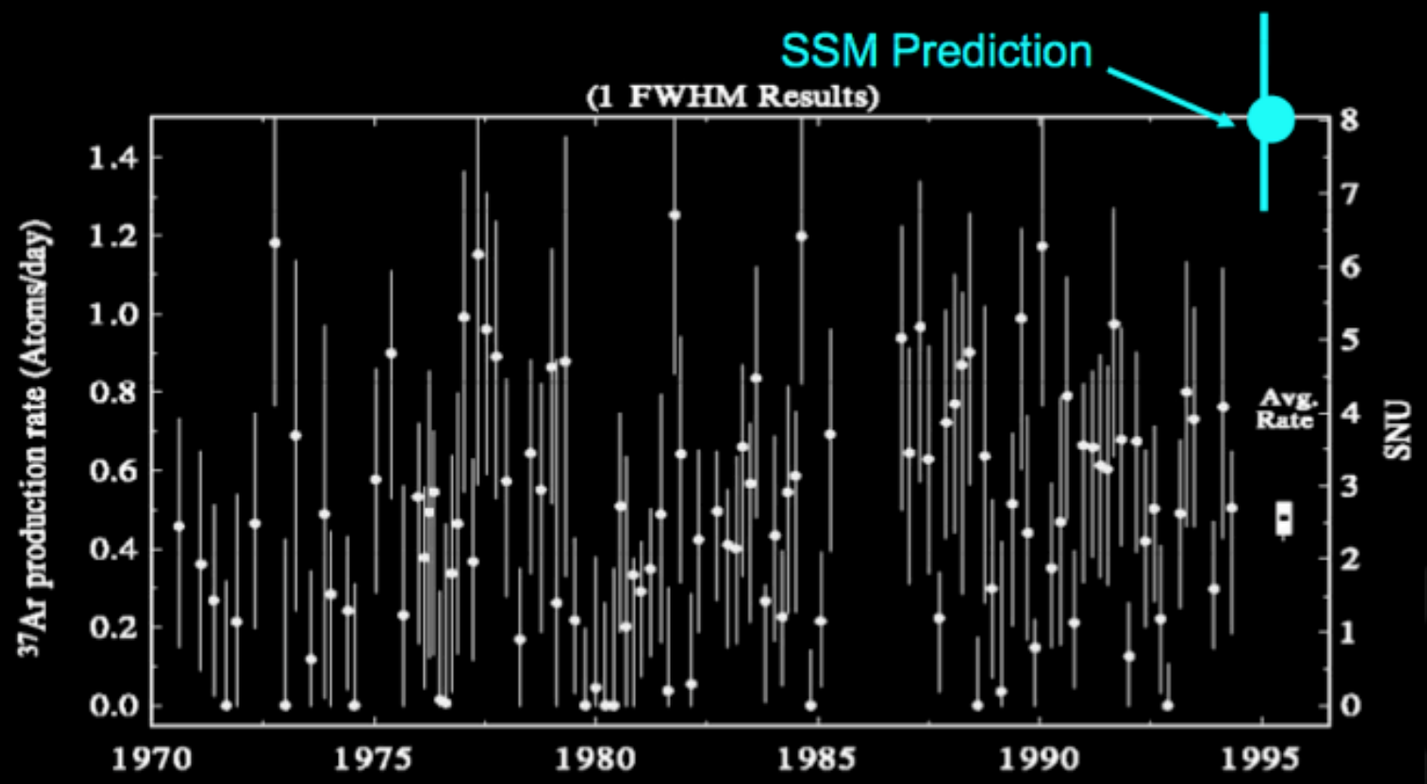
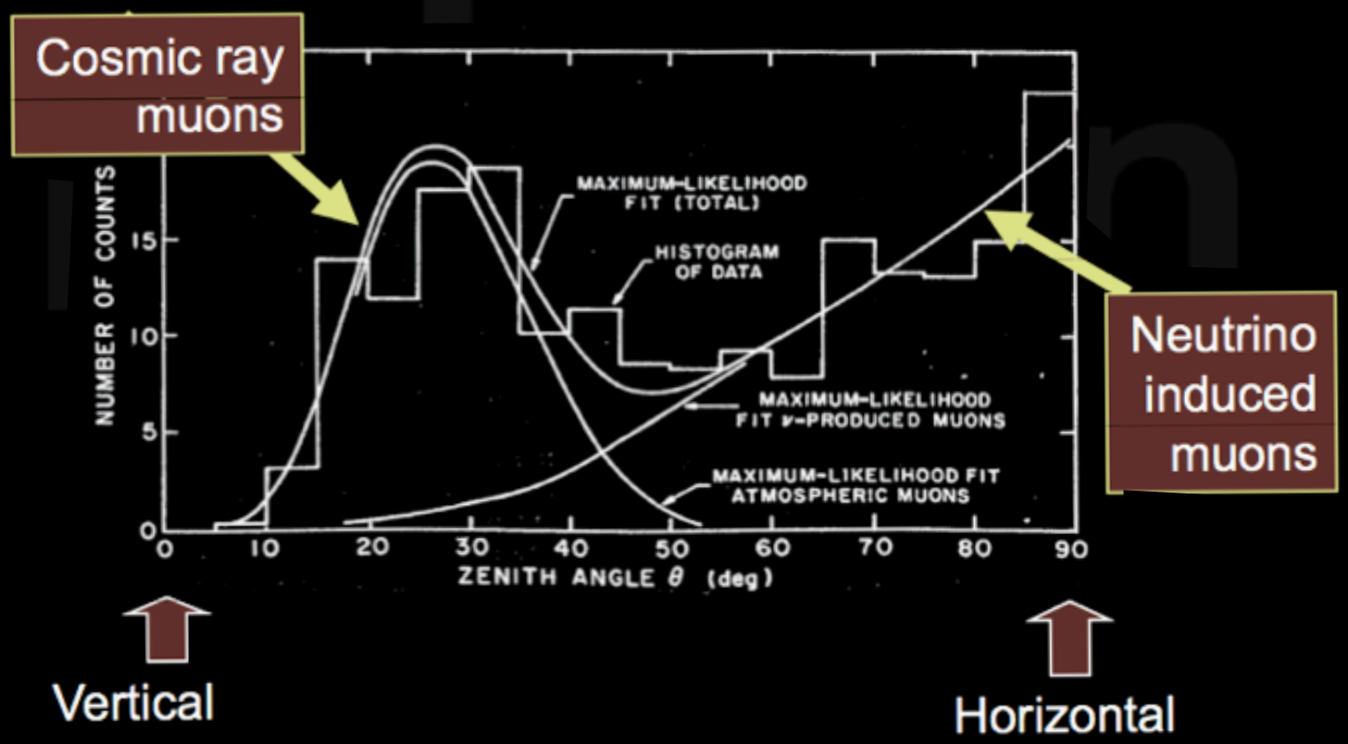
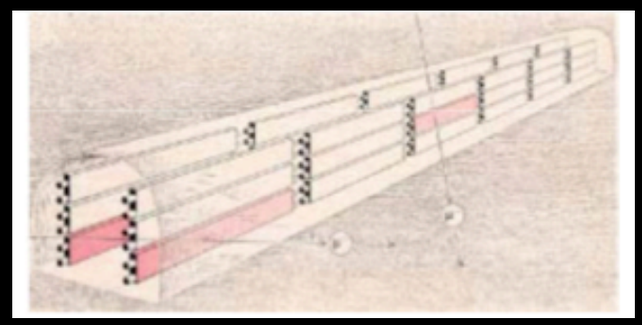
Hints



- Solar Neutrino Problem
  PRL **20** 1205 (1968)



- Atmospheric Muon Neutrino Deficit
  PRD **18** 2239 (1978)



Neutrino Oscillation

Pontecorvo, Maki, Nakagawa, Sakata

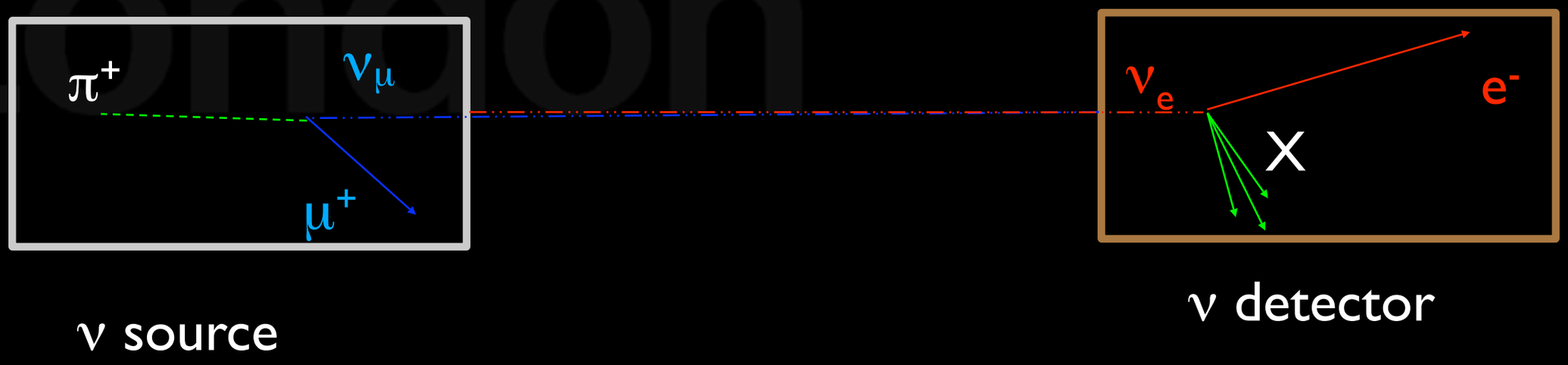
if neutrinos have mass...

a neutrino that is produced as a ν_μ

- (e.g. $\pi^+ \rightarrow \mu^+ \nu_\mu$)

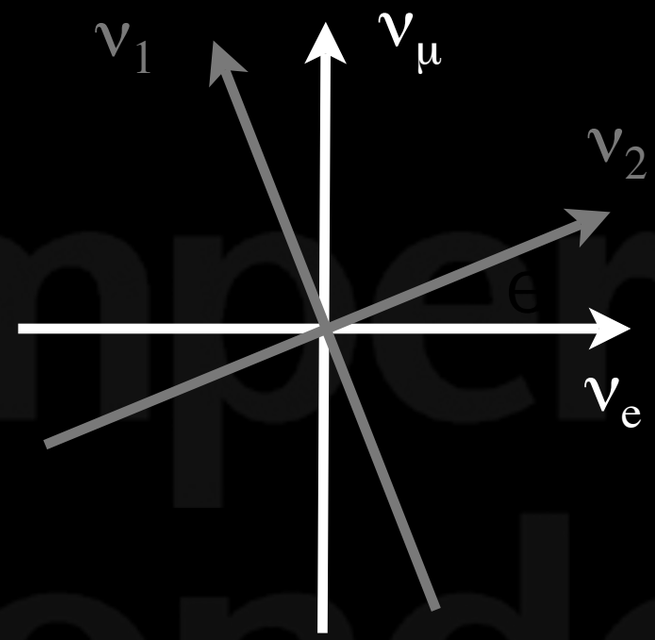
might some time later be observed as a ν_e

- (e.g. $\nu_e\, n \rightarrow e^-\, p$)



Neutrino Oscillation

$$\begin{pmatrix} \nu_\mu \\ \nu_e \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$



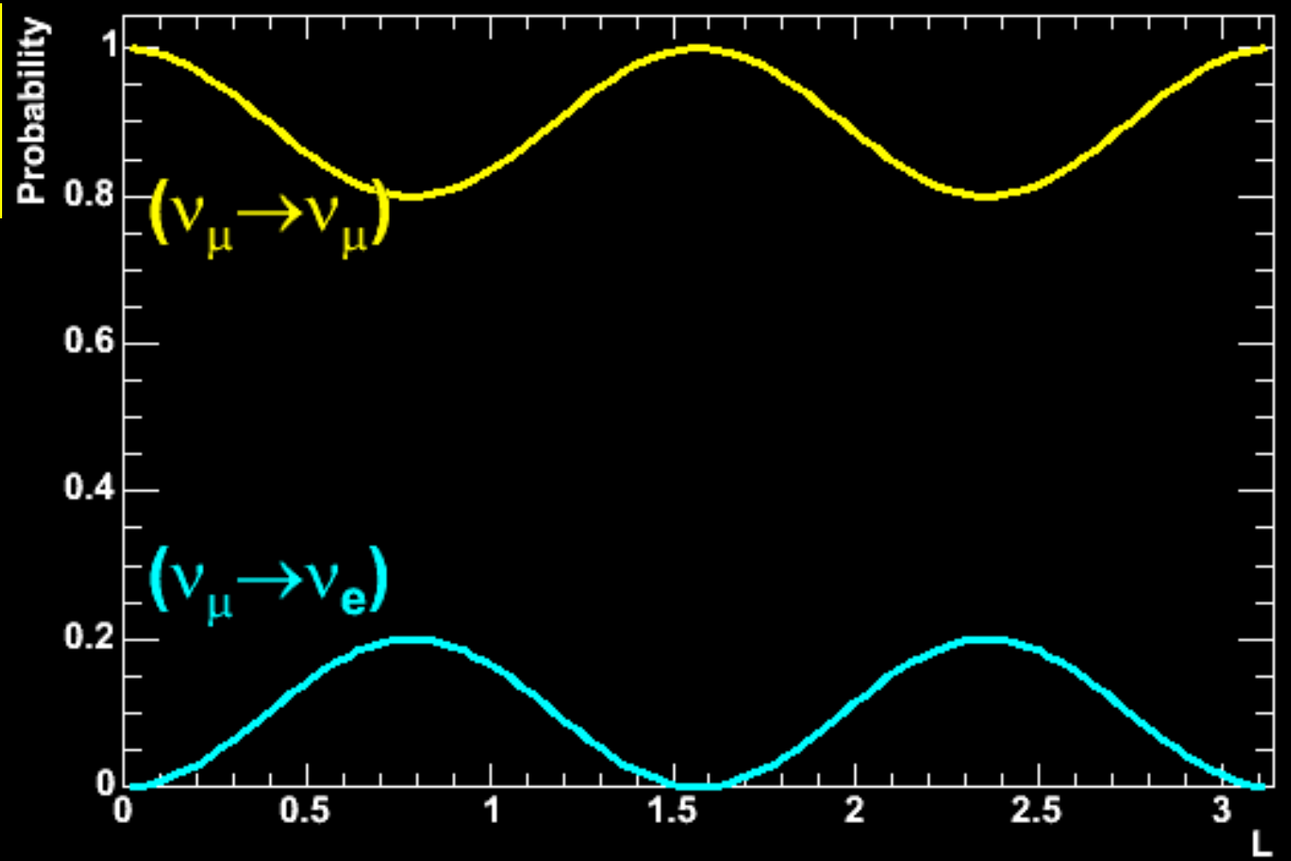
- Consider only two types of neutrinos
- If weak states differ from mass states
  - i.e. $(\nu_\mu\ \nu_e) \neq (\nu_1\ \nu_2)$
- Then weak states are mixtures of mass states

$$|\nu_\mu(t)> = -\sin\theta|\nu_1> e^{-iE_1 t} + \cos\theta|\nu_2> e^{-iE_2 t}$$

$$P_{osc}(\nu_\mu \rightarrow \nu_e) = |<\nu_e|\nu_\mu(t)>|^2$$

- Probability to find ν_e when you started with ν_μ

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta_{12} \sin^2\left(1.27\Delta m^2_{12}\frac{L}{E}\right)$$



- 2 fundamental parameters
  - Δm^2_{12} (=m_1^2-m_2^2) ↔ period
  - θ_{12} ↔ magnitude
- 2 experimental parameters
  - L = distance travelled
  - E = neutrino energy
- Tune L&E for Δm^2 range, uncertainties determine θ sensitivity
- Neutrino disappearance and appearance

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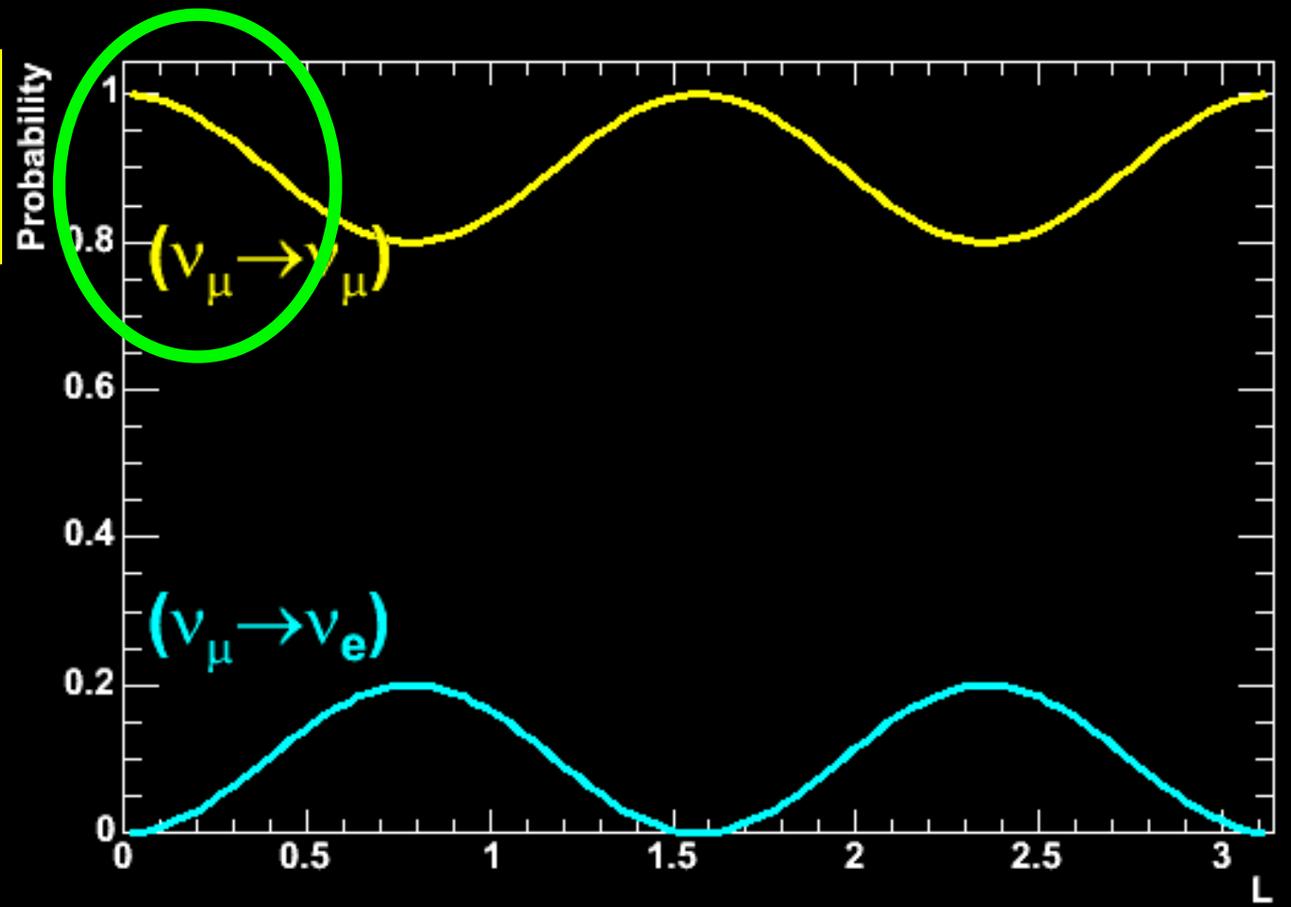

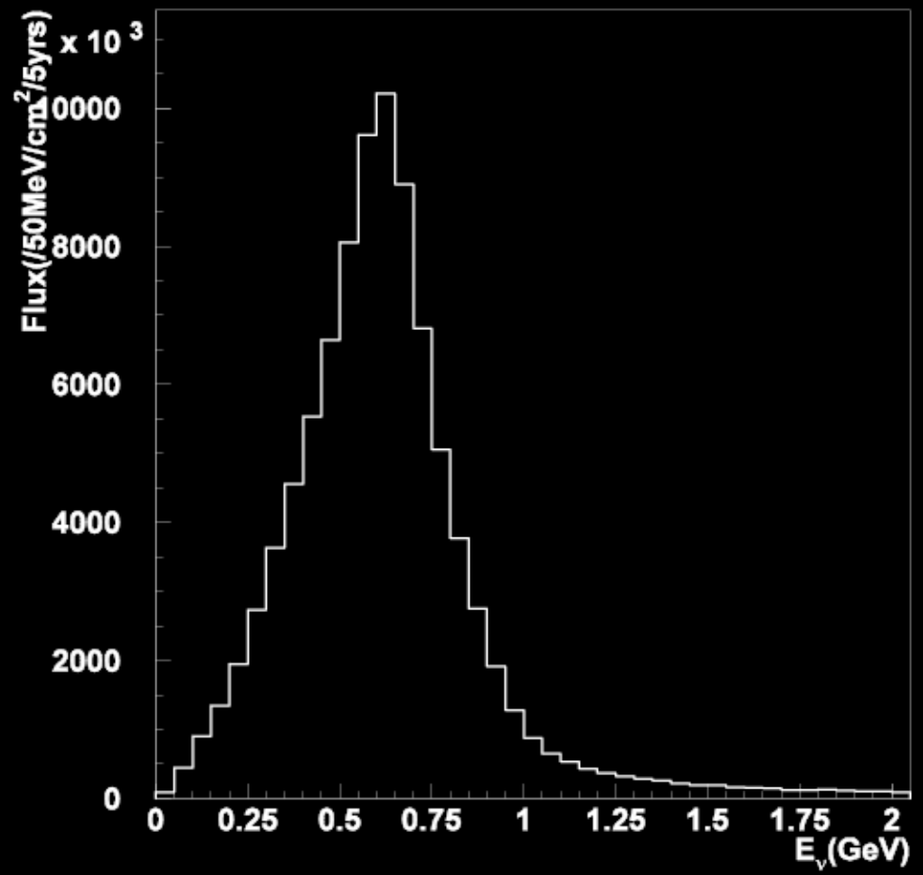

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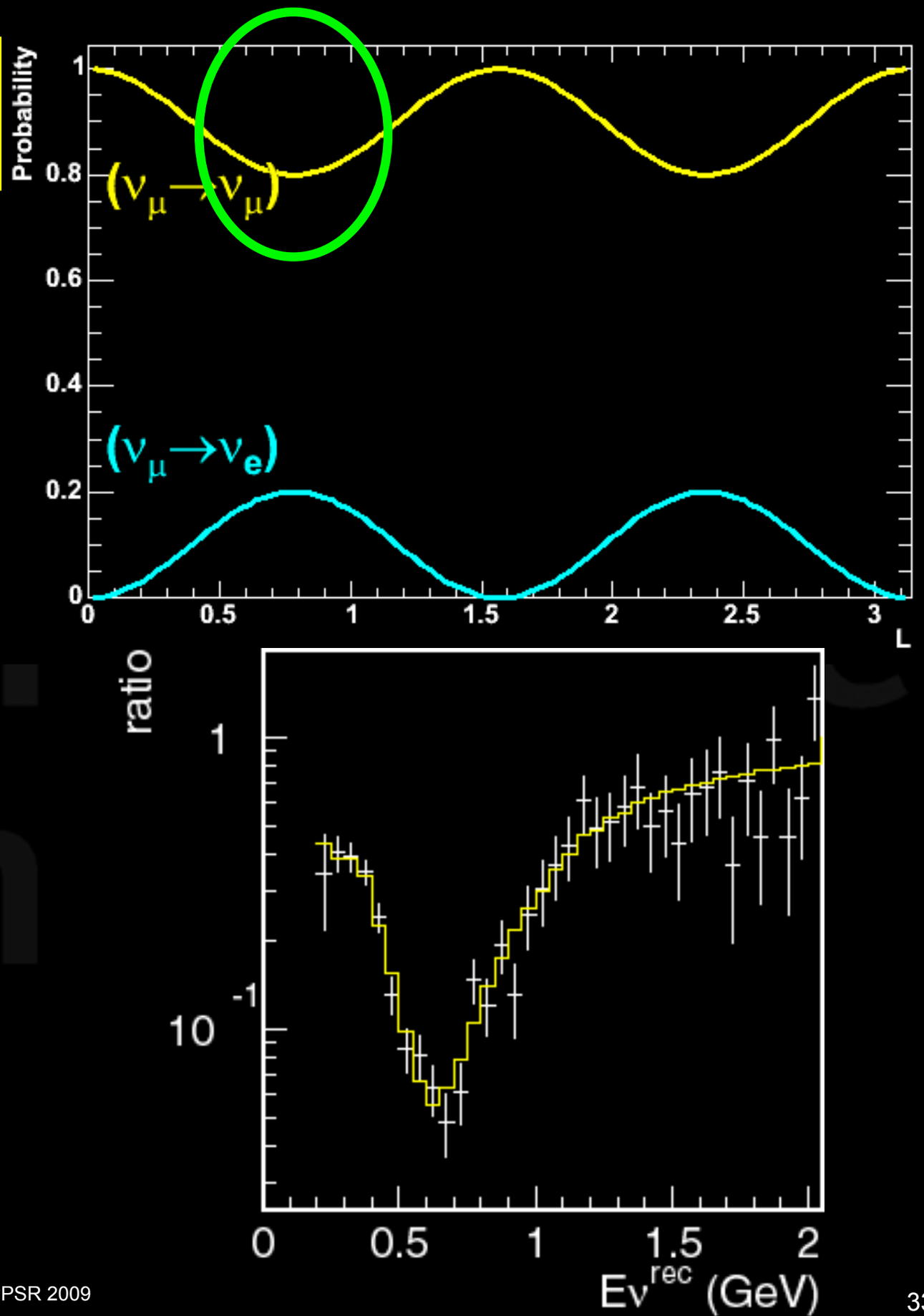

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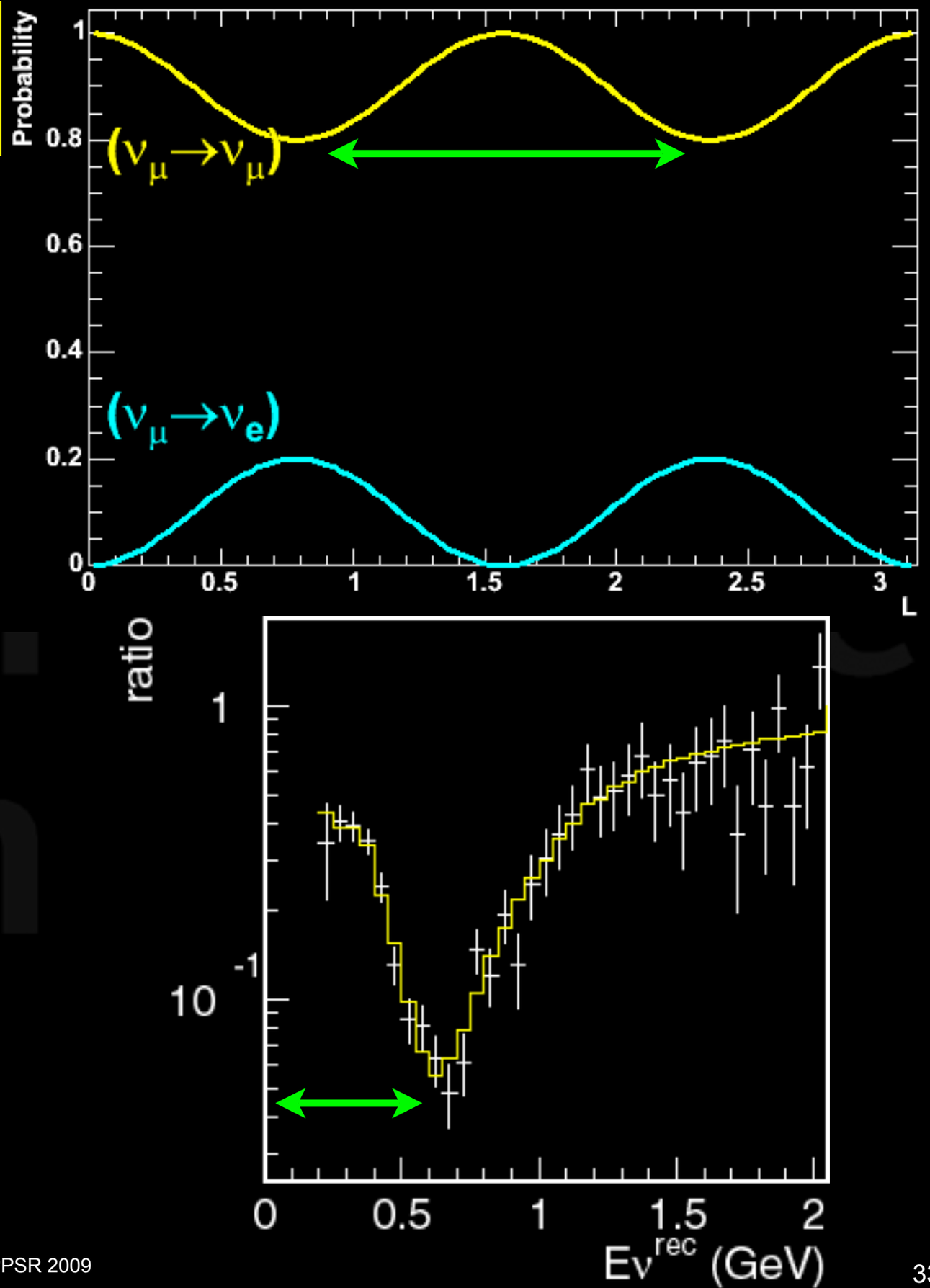

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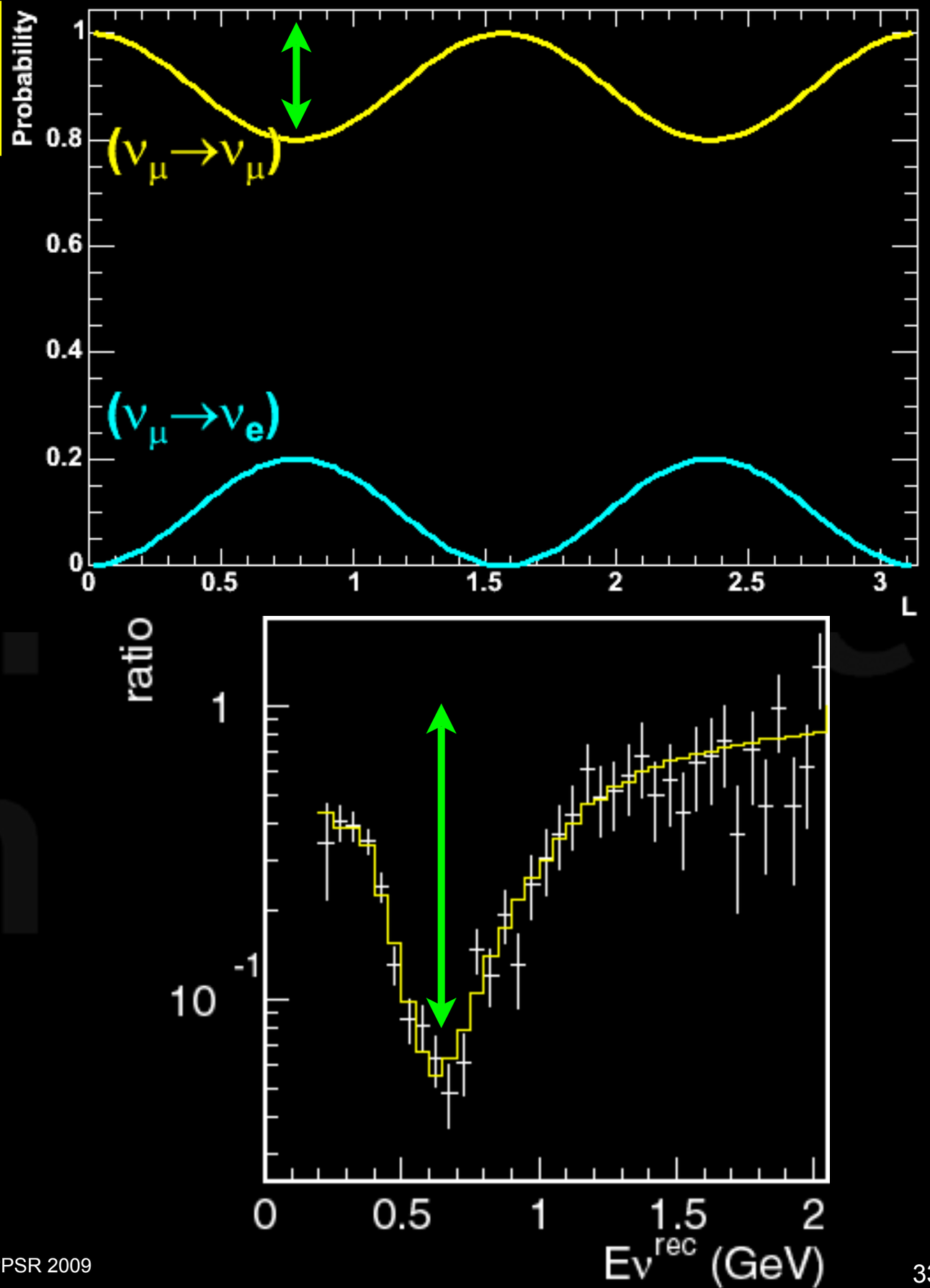

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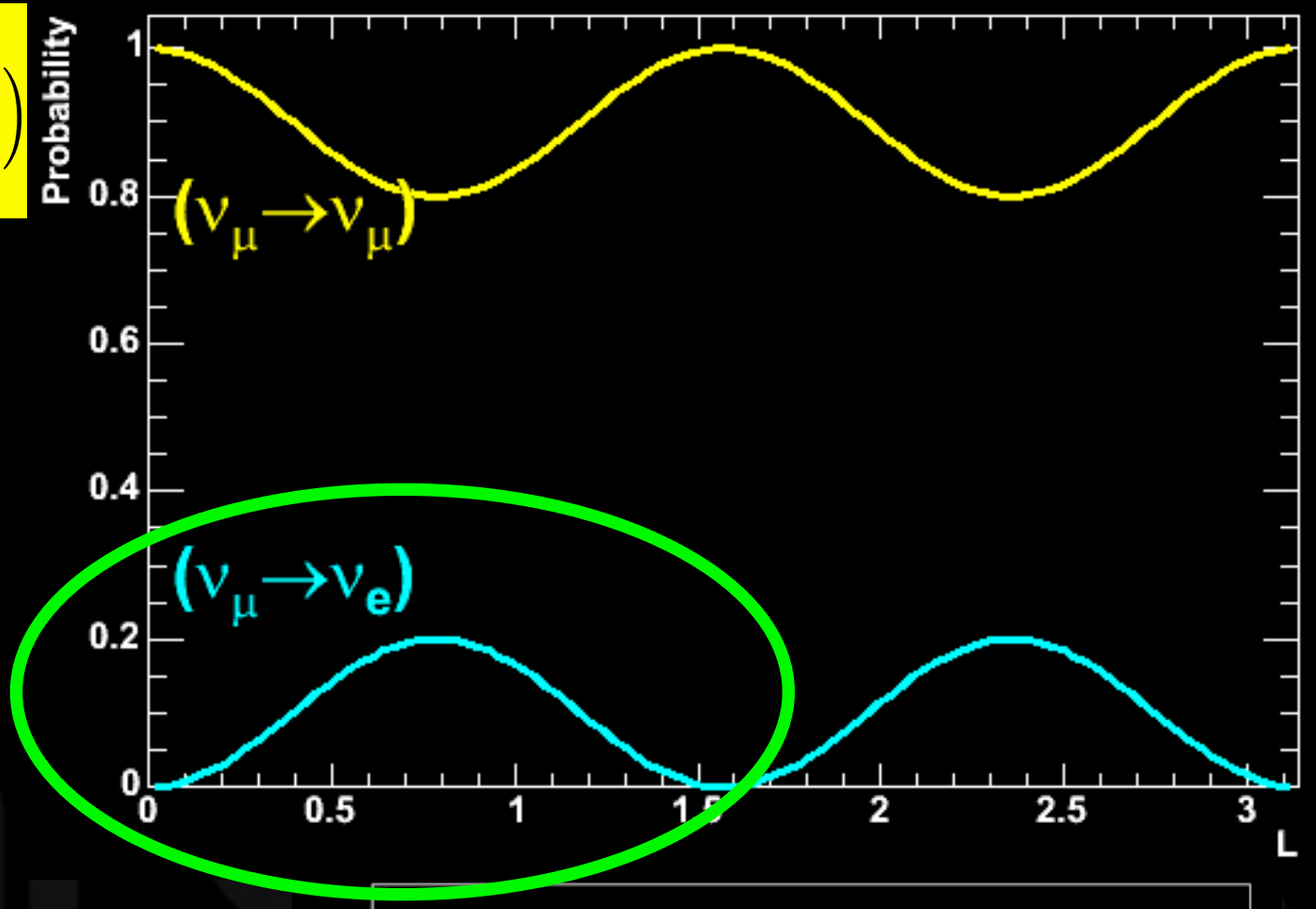
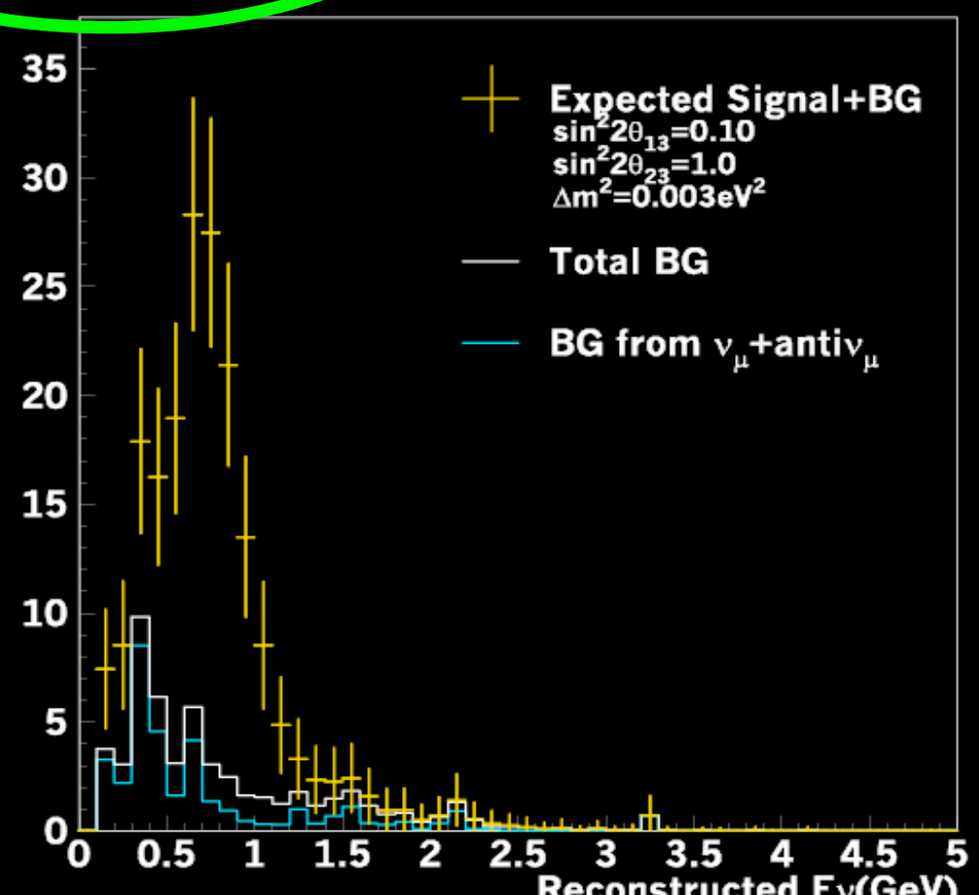
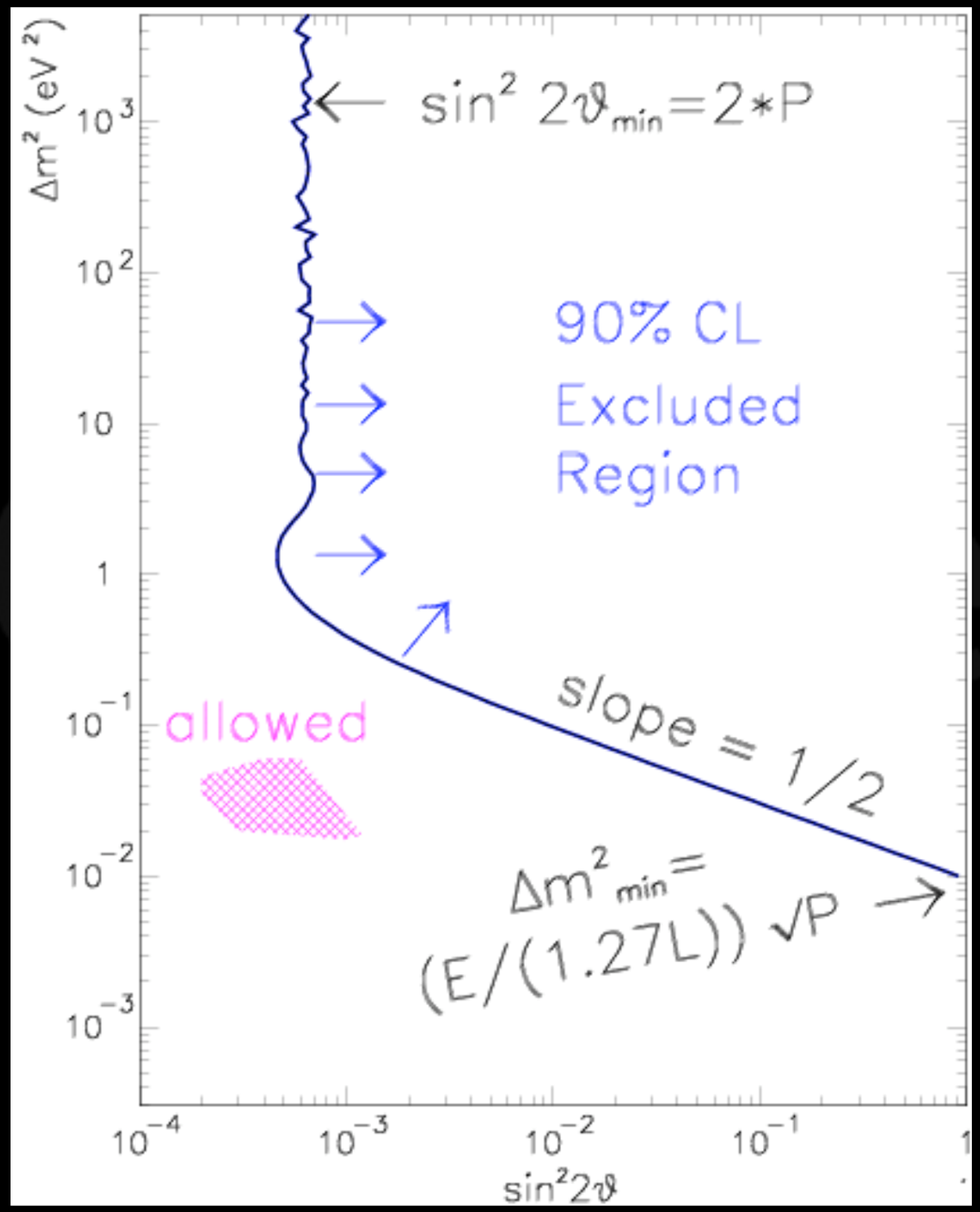


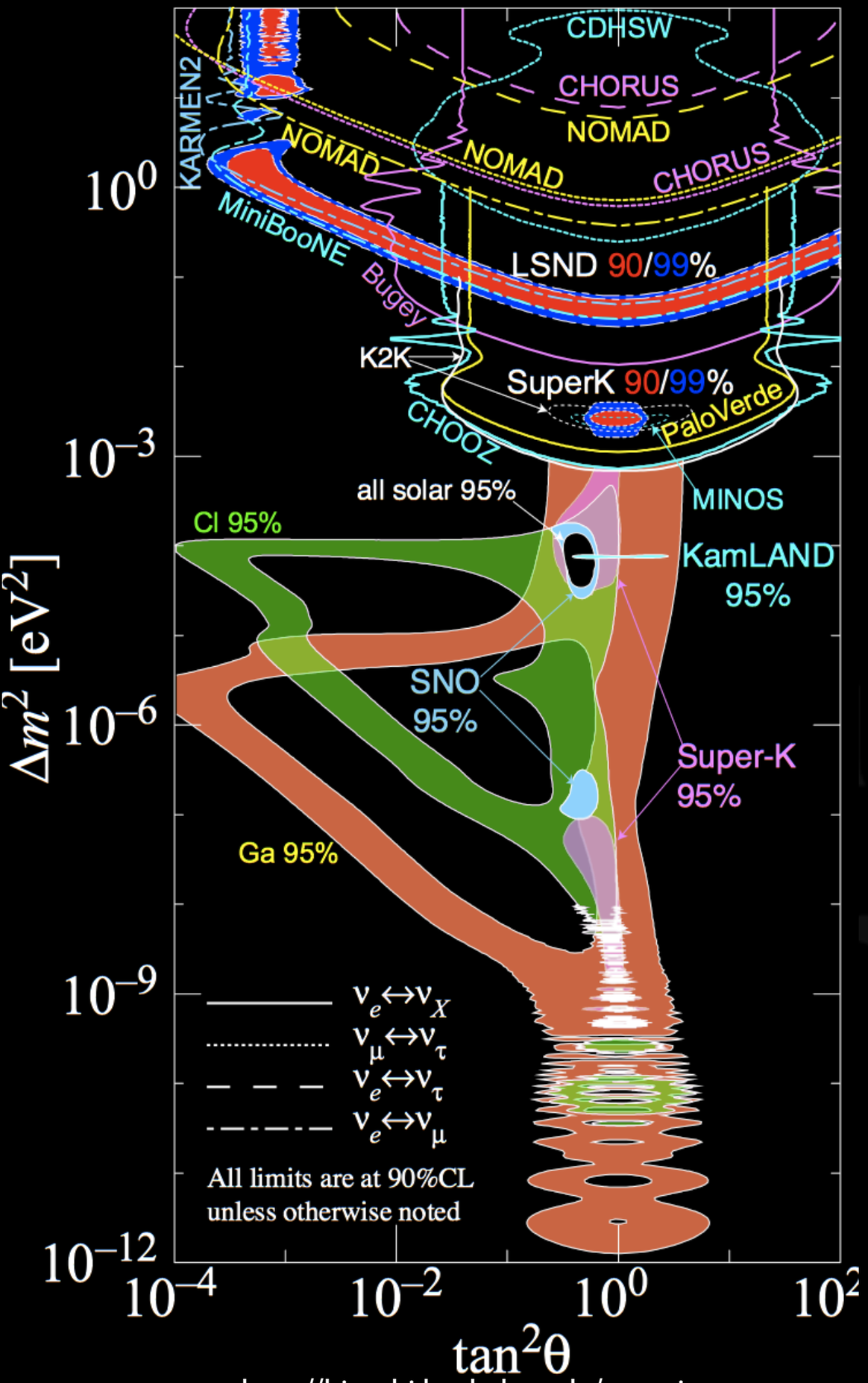


Presenting Oscillations

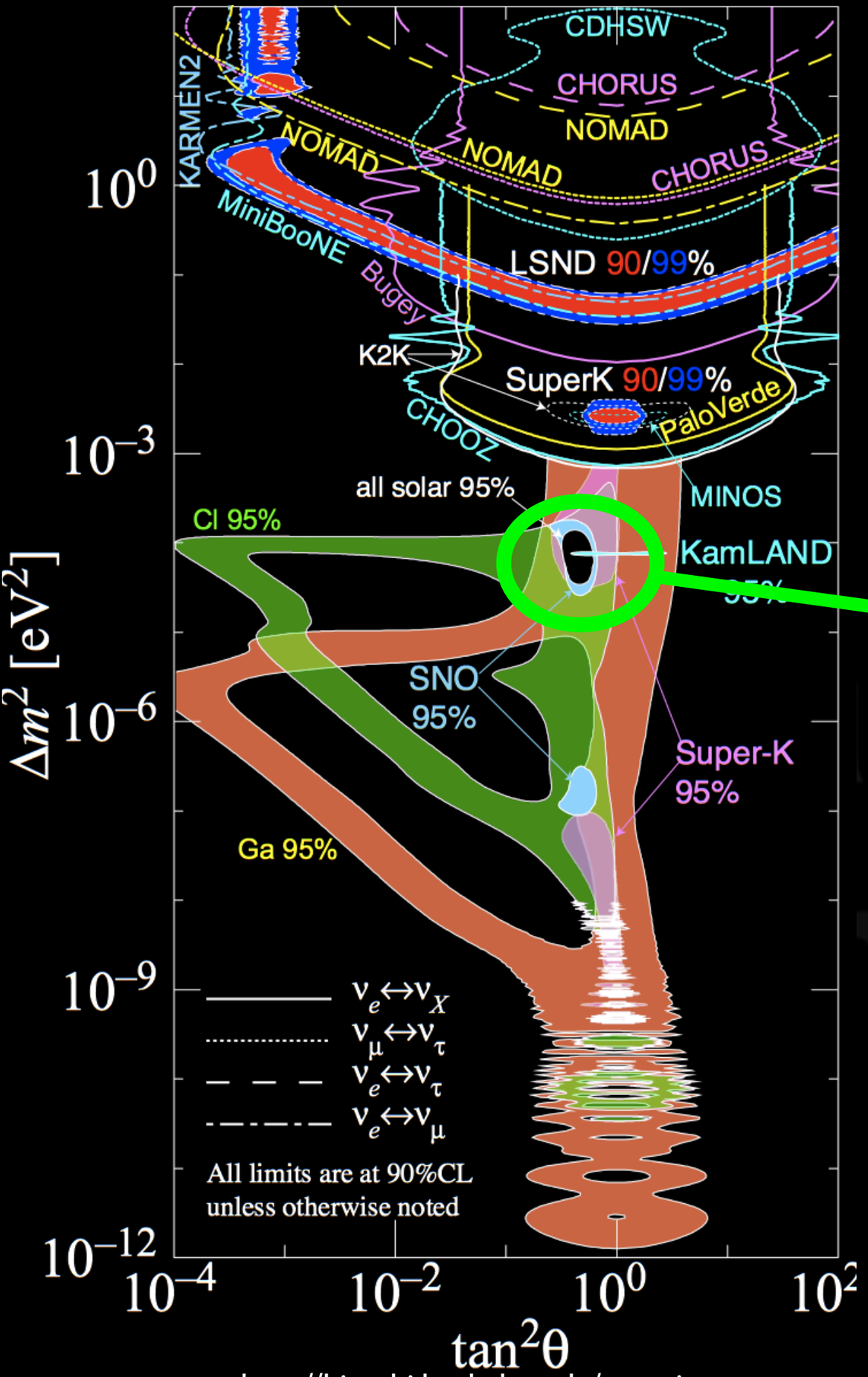
$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta_{12} \sin^2(1.27\Delta m^2_{12}\frac{L}{E})$$

- Recall:
  - L and E determine the Δm^2 sensitivity region
  - $\sin^2 2\theta$ gives amplitude of oscillations
- No signal: exclusion regions
  - Inside the region: excluded
  - Outside the region: cannot be ruled out
- Signal: allowed regions
  - Shown by shaded areas specifying Δm^2 and $\sin^2 2\theta$
  - Size of allowed region determined by experimental uncertainties





http://hitoshi.berkeley.edu/neutrino



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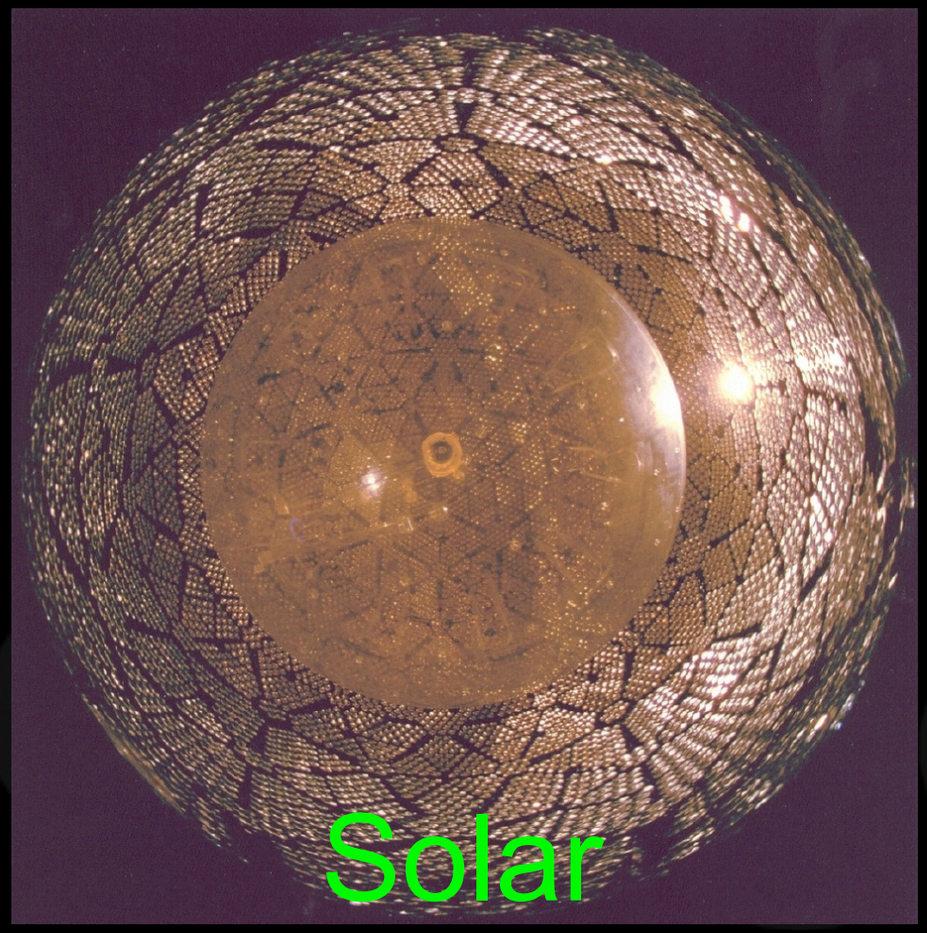
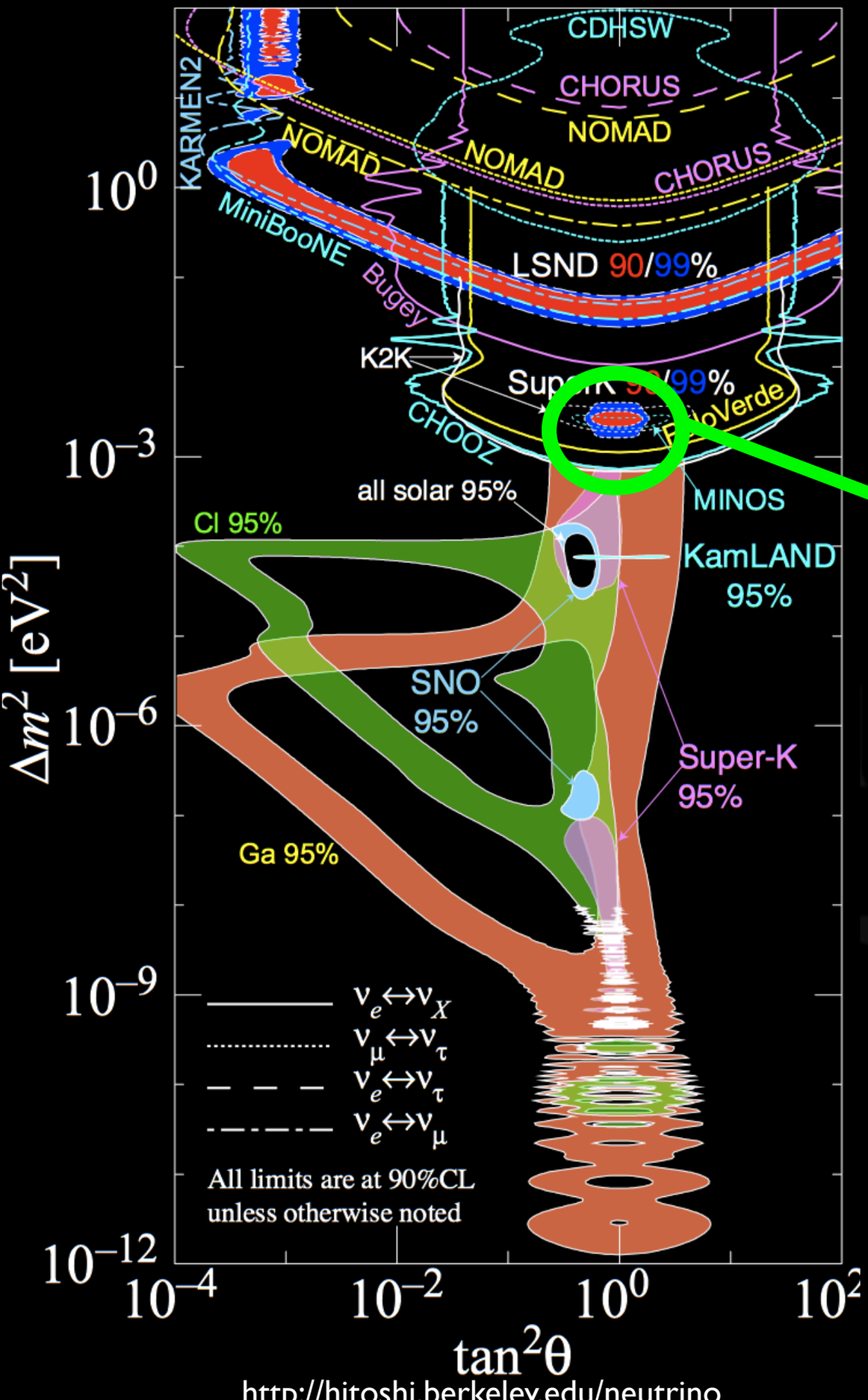


$\Delta m^2_{12} = (7.59 \pm 0.21) \times 10^{-5}$ eV^2

$\theta_{12} = 34.4^\circ {}^{+1.6}_{-1.5}$



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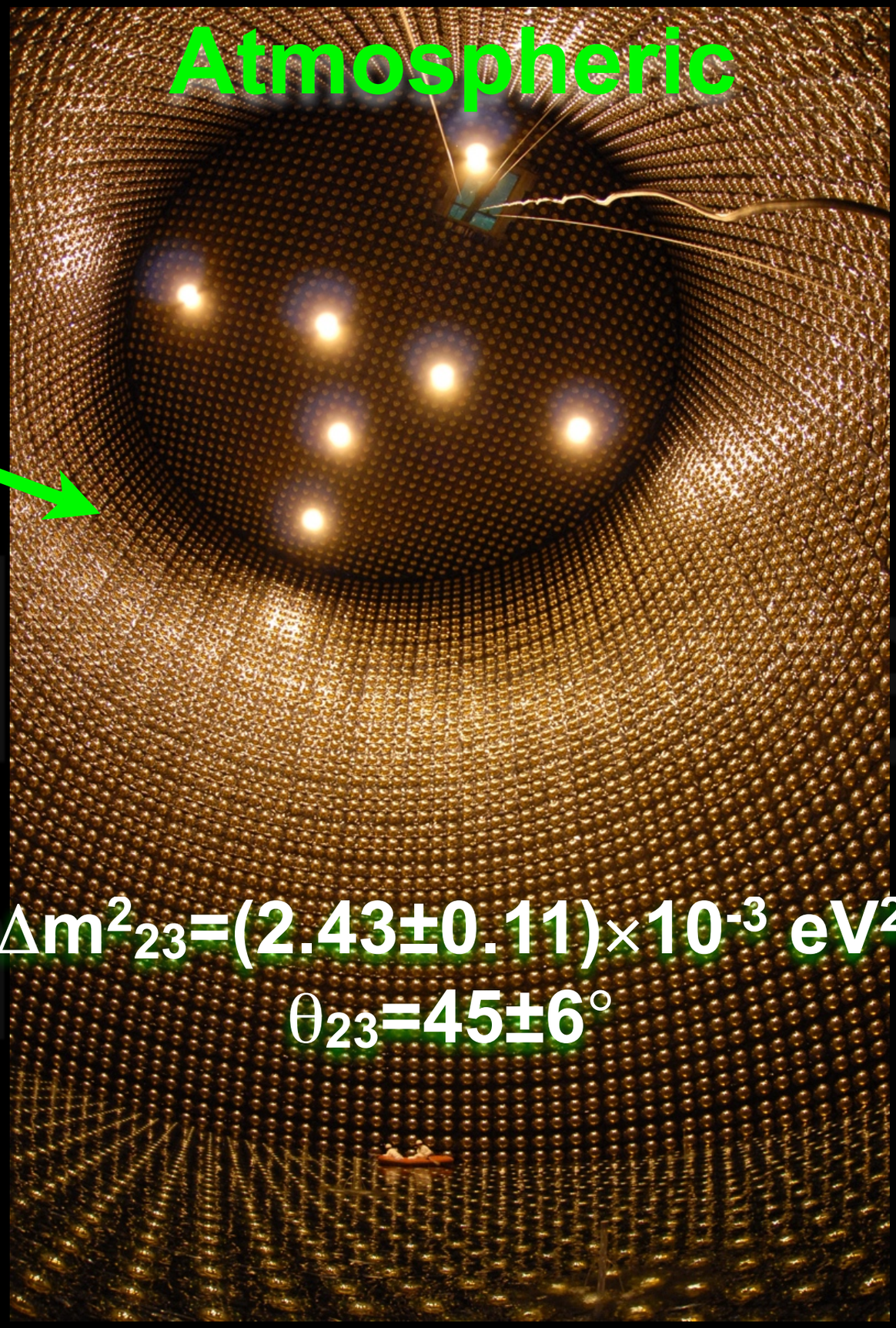
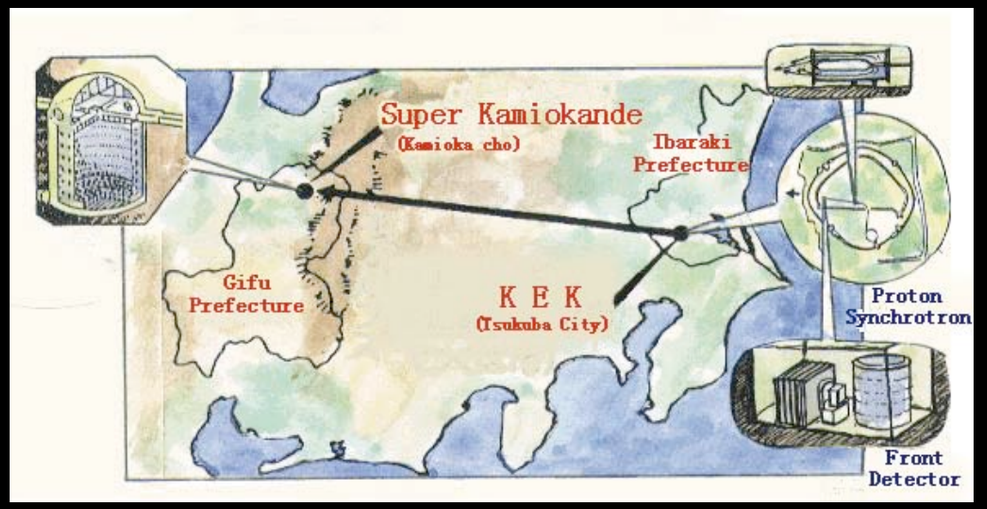
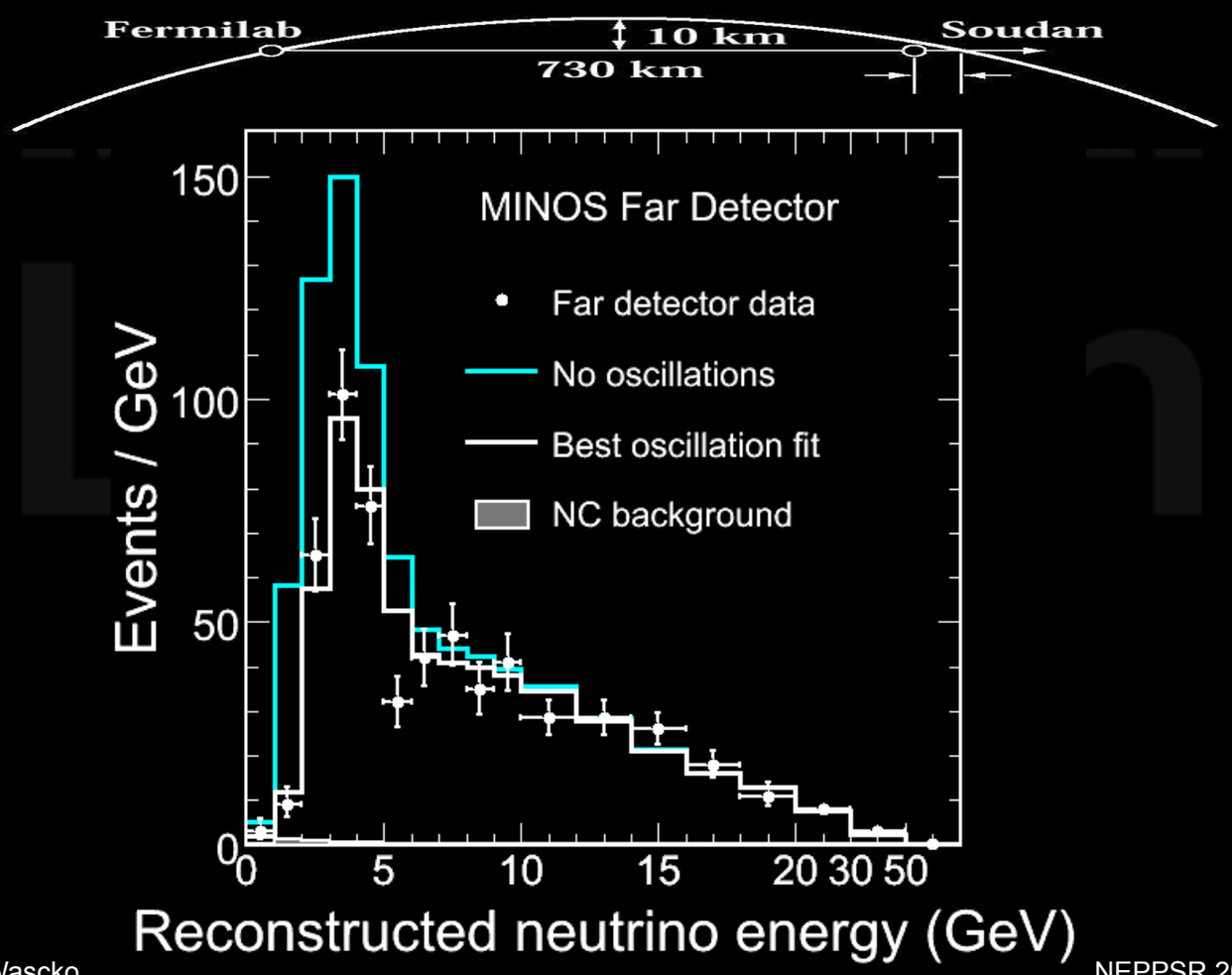


Confirming Atmospherics



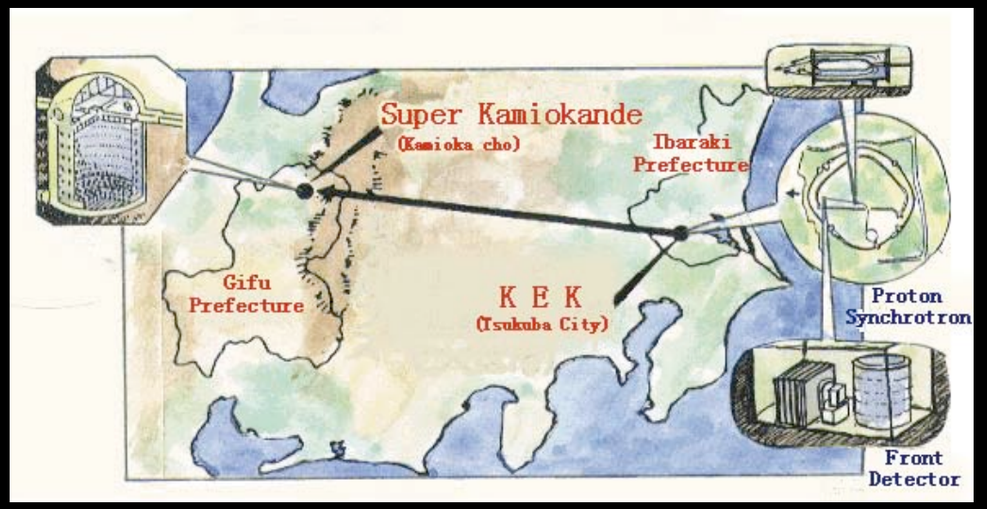


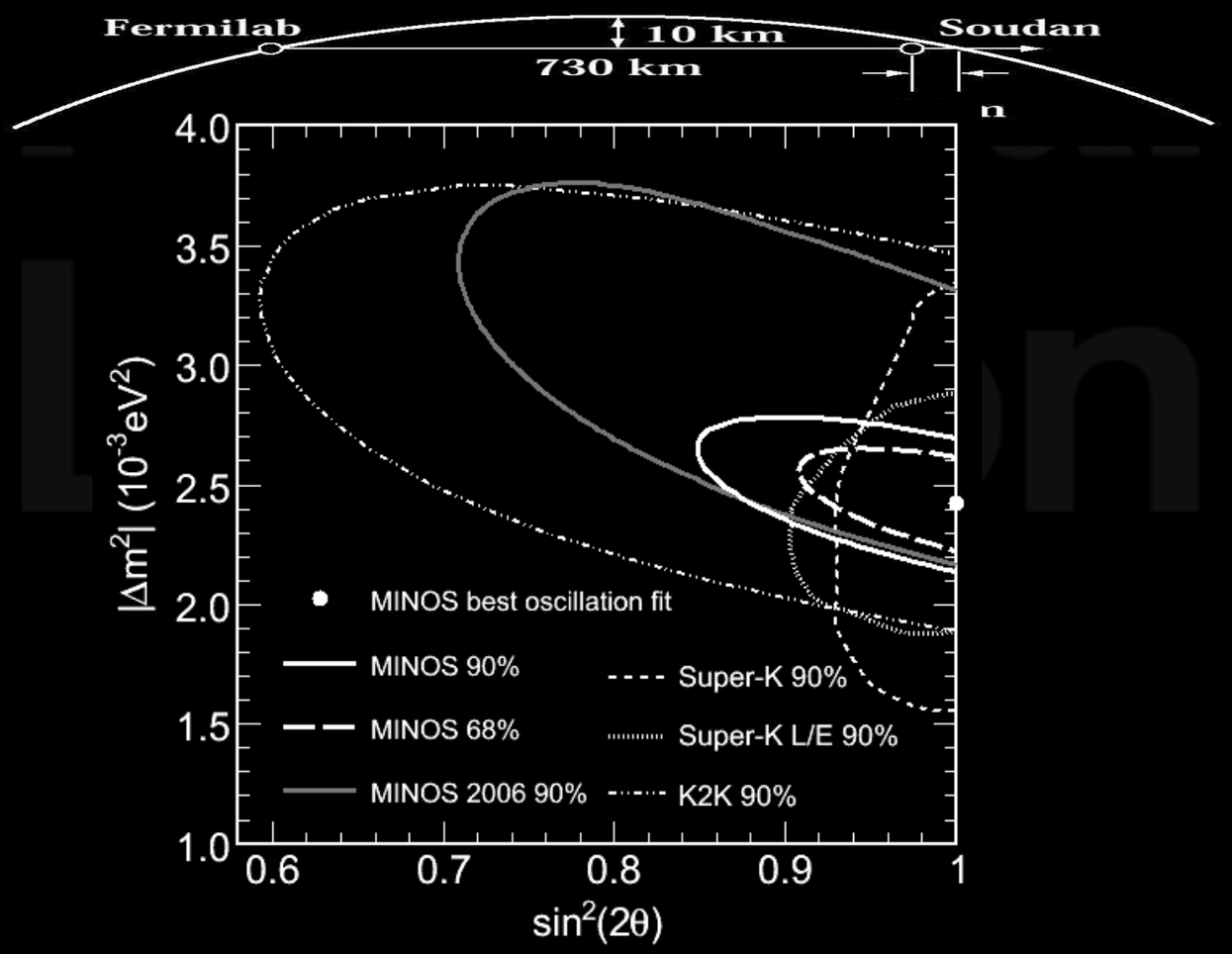
$\nu_\mu + N \rightarrow \mu + X$

- Need same L/E to probe same Δm^2 region as atmospheric
- Confirmed with accelerator neutrinos
  - K2K and MINOS

*K2K: PRL **98**, 081802 (2005)*
*MINOS: PRL **101**, 131802 (2008)*

Confirming Atmospherics





$\nu_\mu + N \rightarrow \mu + X$

- Need same L/E to probe same Δm^2 region as atmospheric
- Confirmed with accelerator neutrinos
  - K2K and MINOS

*K2K: PRL **98**, 081802 (2005)*
*MINOS: PRL **101**, 131802 (2008)*

3 Flavors

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle$$

flavor — mass

3 Flavors

Atmospheric Cross-Mixing Solar

$$\mathbf{U}=\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}=\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix}\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

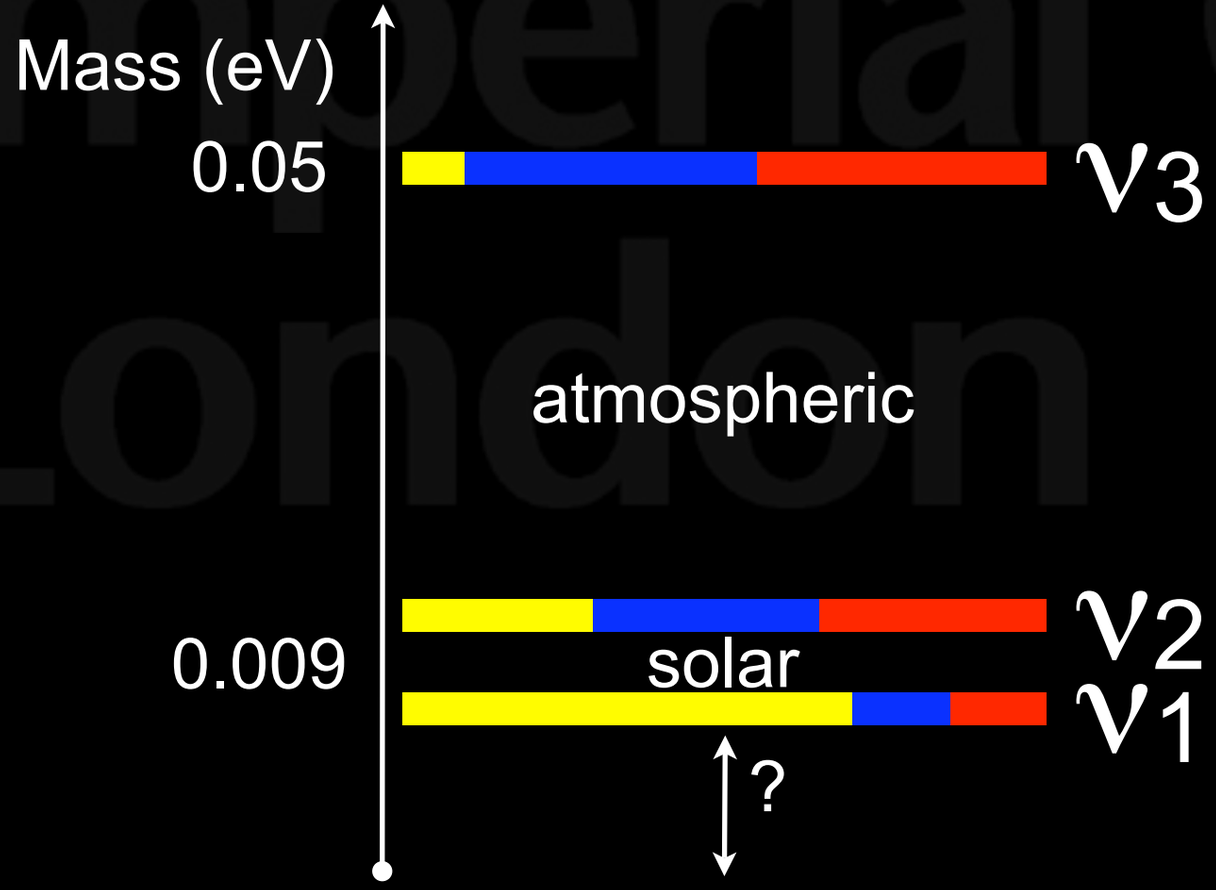
where $c_{ij} = \cos\theta_{ij}$, etc.

3 Flavors

$$\mathbf{U}=\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}=\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix}\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric — Cross-Mixing — Solar

where $c_{ij} = \cos\theta_{ij}$, etc.



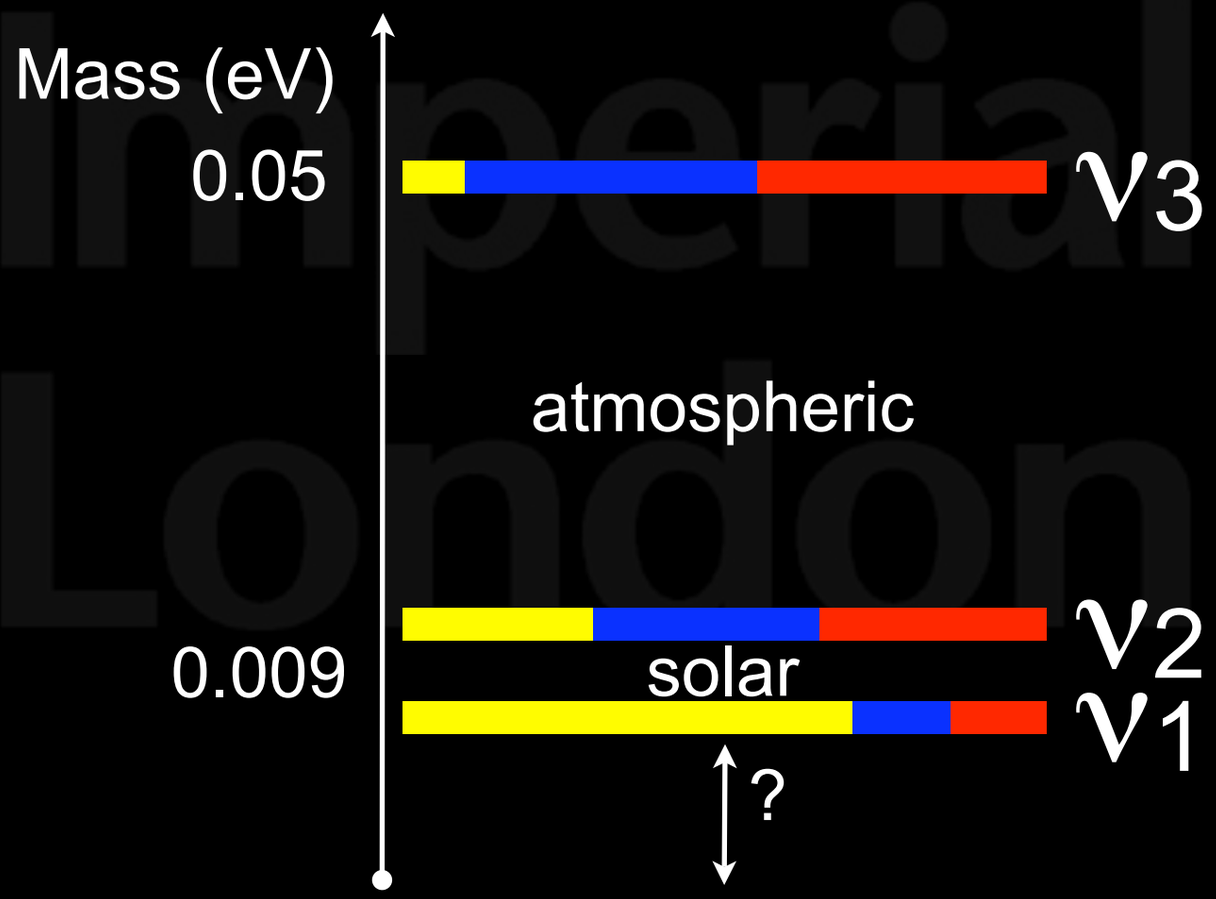
flavour key:

ν_e ν_μ ν_τ

Open Questions

flavour key:

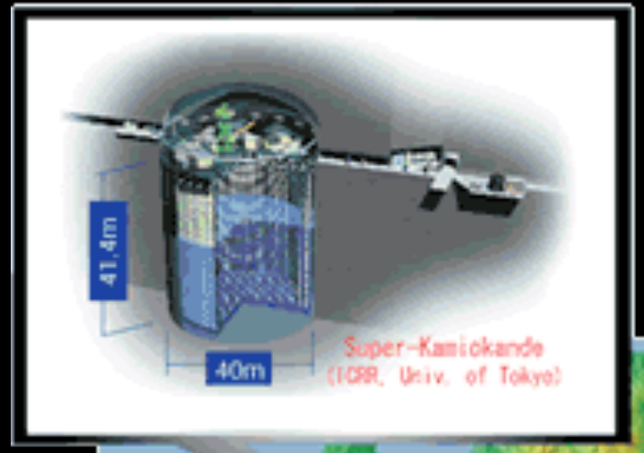
ν_e ν_μ ν_τ



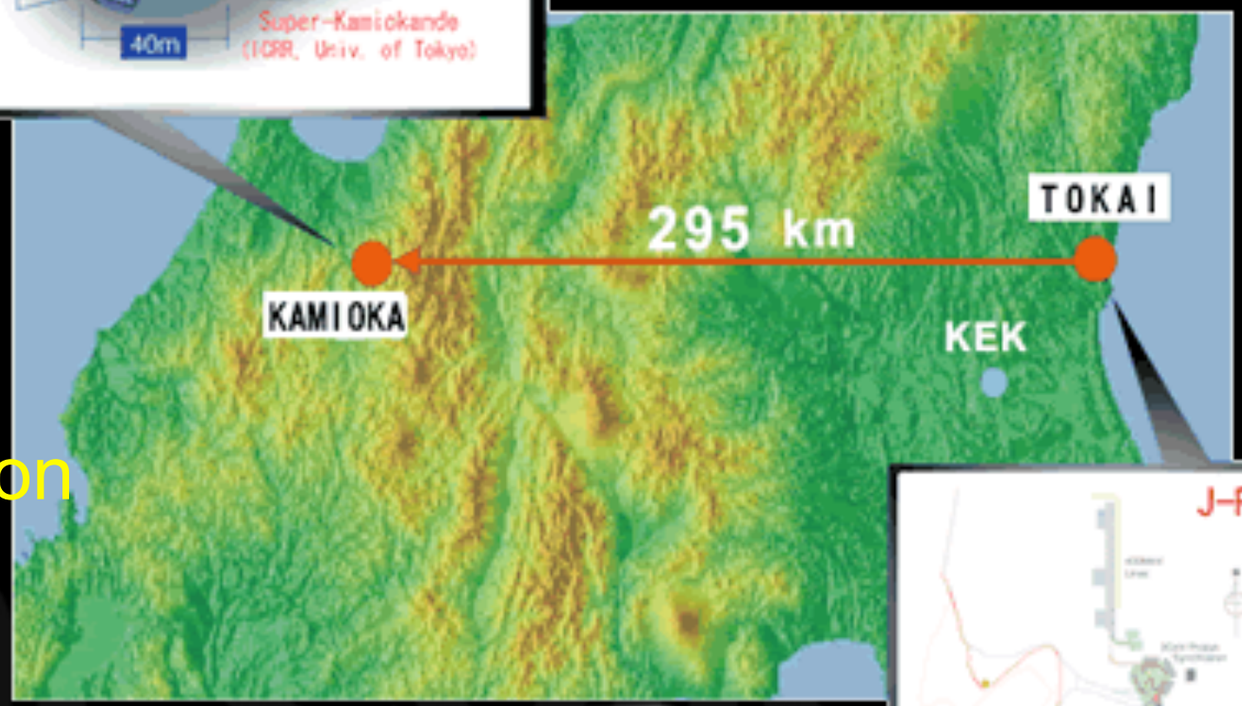
- What is the last mixing angle?
- Do νs violate CP symmetry?
- What is the mass hierarchy?
- What is the absolute mass scale?
- Are νs the same as $\bar{\nu}$s?

Searching for θ_{13}

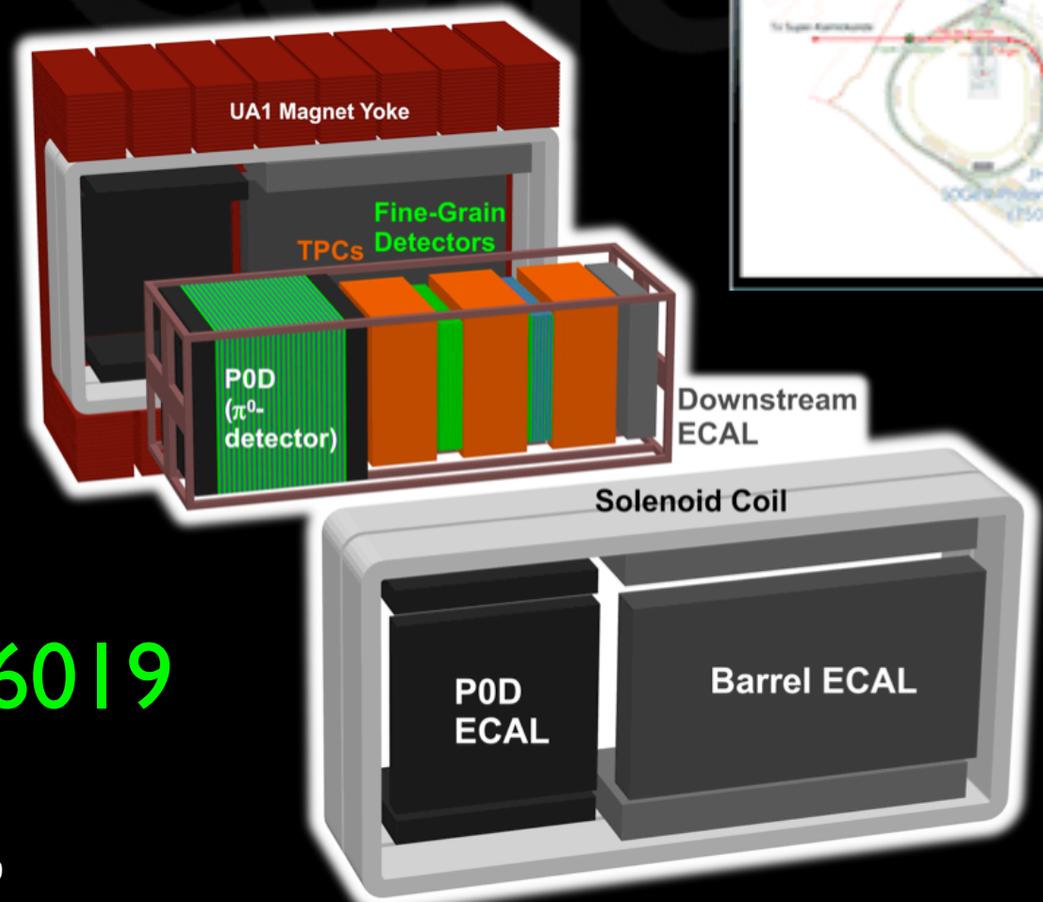
T2K



"Tokai-To-Kamioka"



- Physics Goals:
  - precise atmospheric oscillation measurements
  - search for θ_{13}
- Start with world's largest detector: Super-Kamiokande
- Build new neutrino beam
- Near detectors at 280m to constrain beam flux



http://xxx.lanl.gov/abs/hep-ex/0106019

T2K experimental strategy

Intense beam

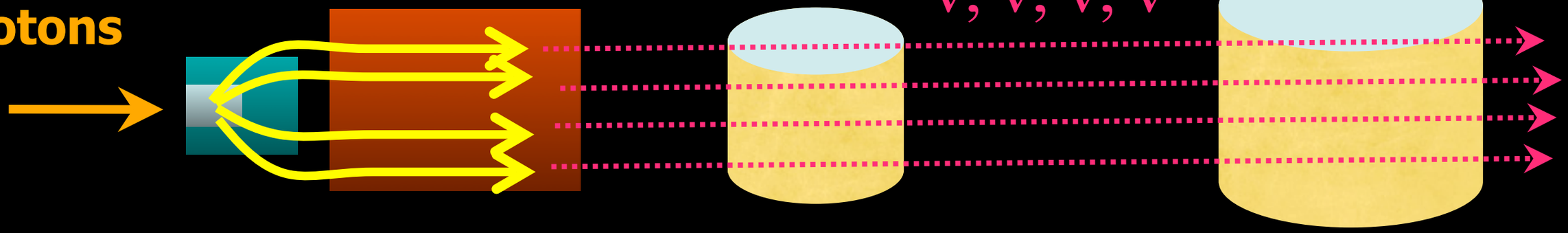
protons

π, π, π, π, K

Gigantic detector

oscillation

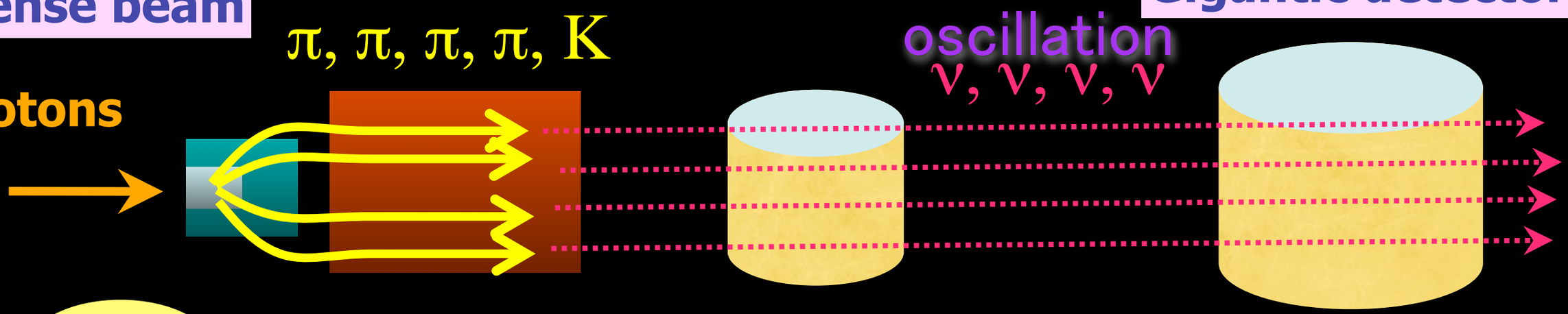
ν, ν, ν, ν



T2K experimental strategy

Intense beam

Gigantic detector



T2K experimental strategy

Intense beam

Gigantic detector

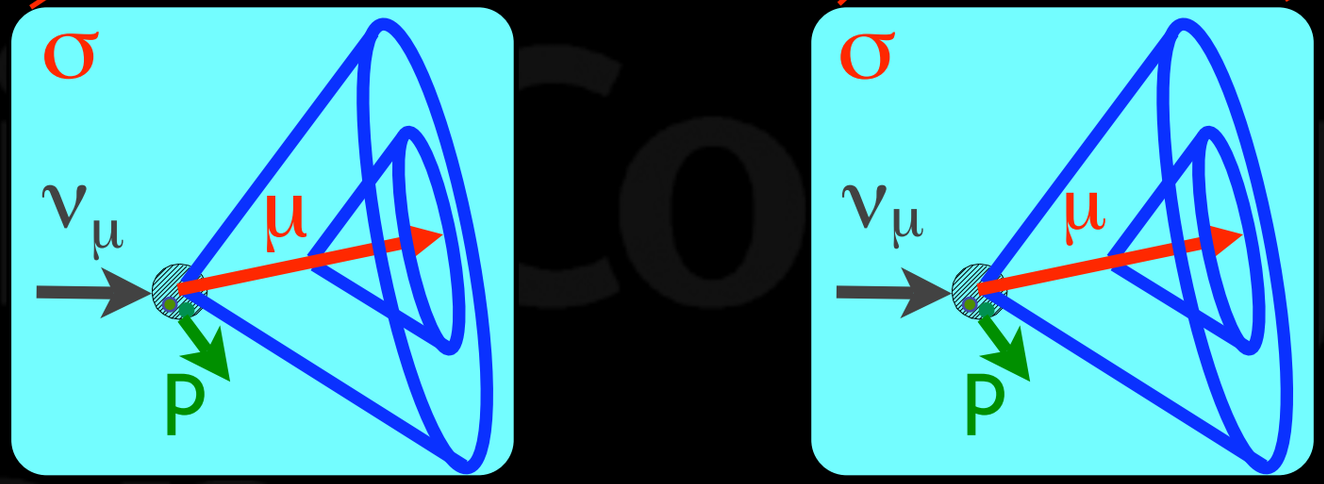
π, π, π, π, K

oscillation

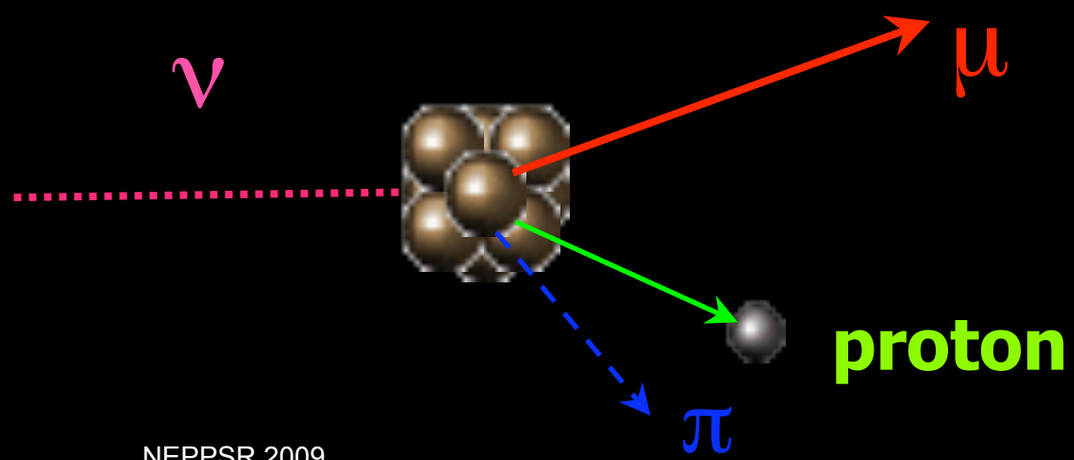
ν, ν, ν, ν

protons

NA-61 $\Phi_\nu(E)$



$$\sigma(E)\cdot\Phi_\nu^{near}(E) \Leftrightarrow \sigma(E)\cdot\Phi_\nu^{far}(E)$$



T2K experimental strategy

Intense beam

protons

π, π, π, π, K

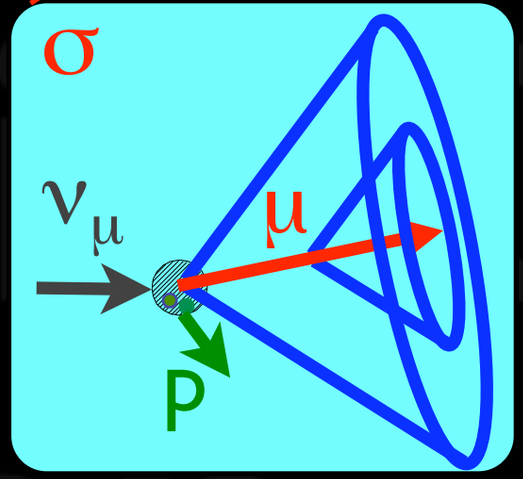
NA-61

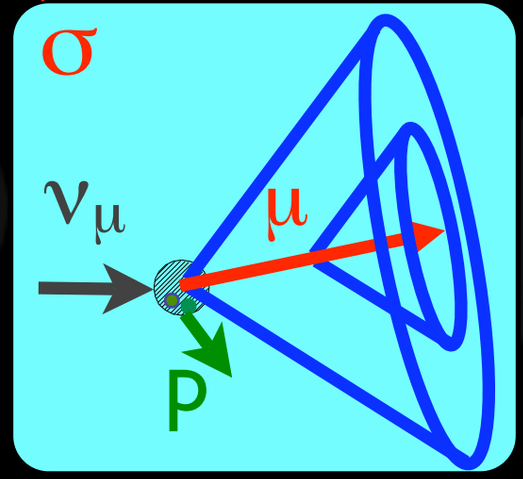
$\Phi_\nu(E)$

Gigantic detector

oscillation

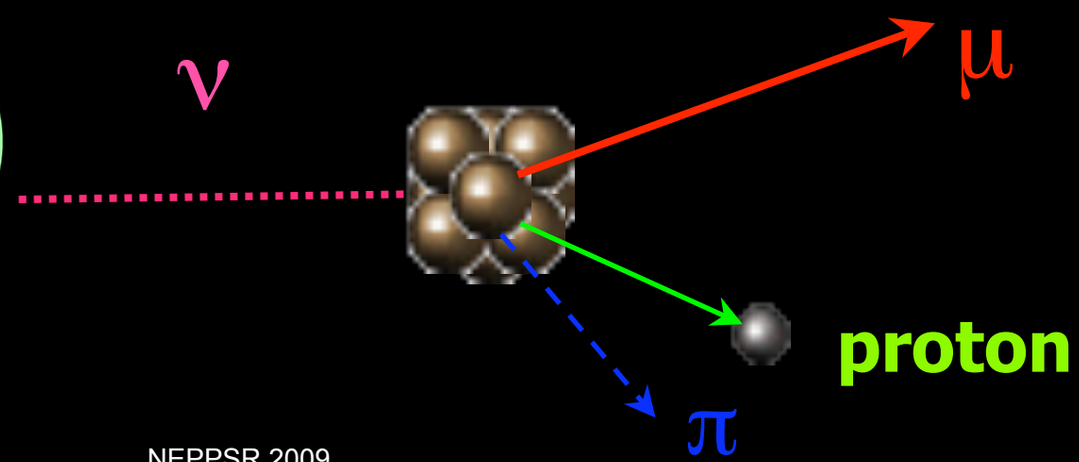
ν, ν, ν, ν



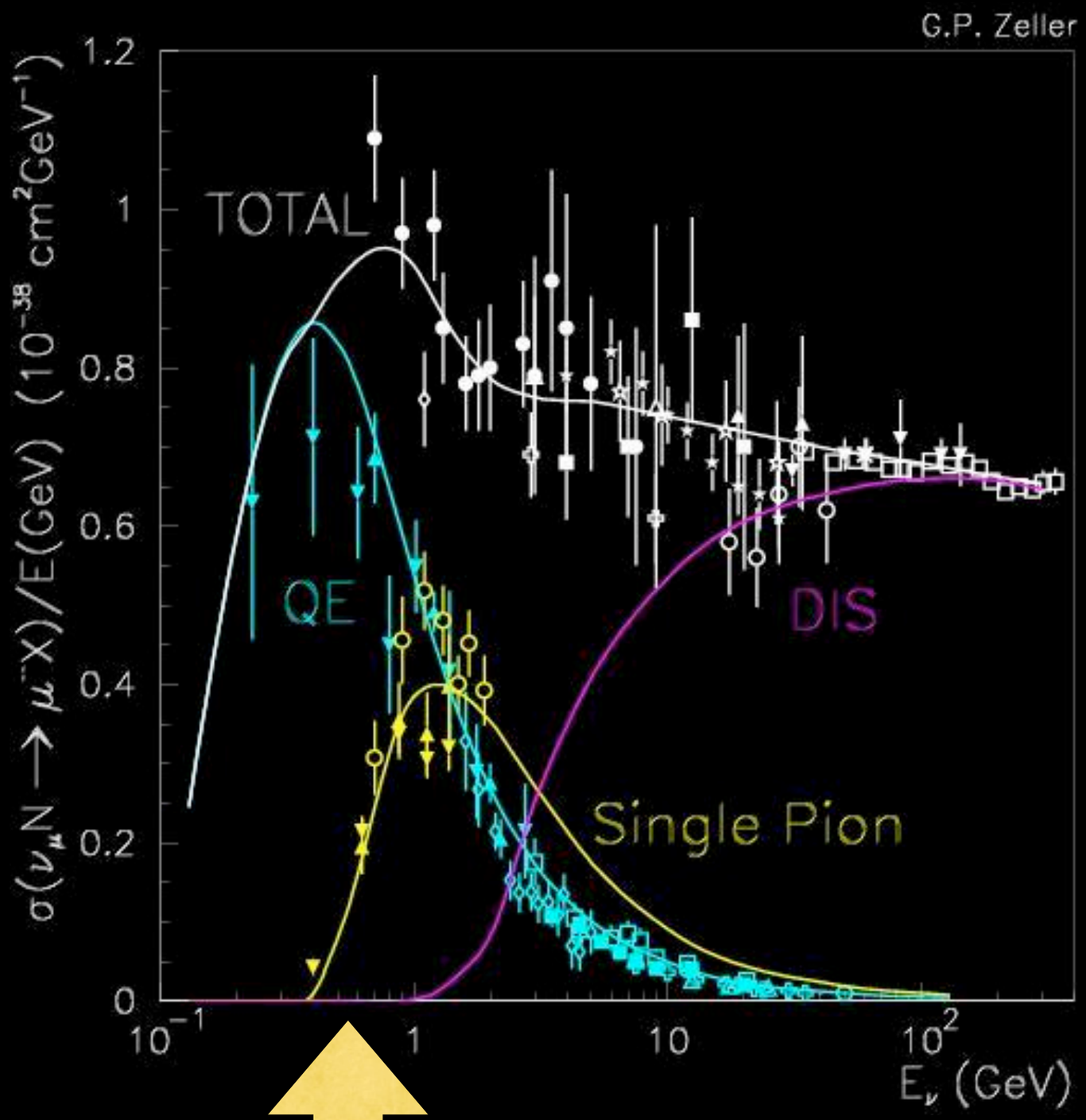


$$\sigma(E)\cdot\Phi_\nu^{near}(E) \Leftrightarrow \sigma(E)\cdot\Phi_\nu^{far}(E)$$

SciBooNE

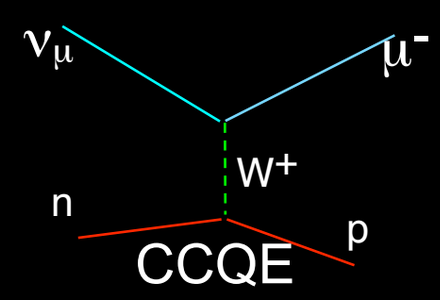


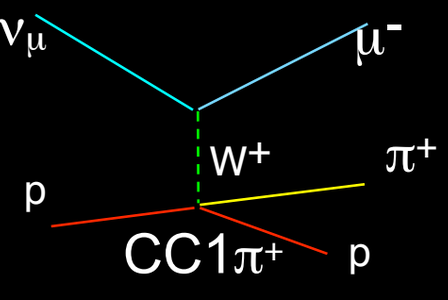
Background Uncertainties



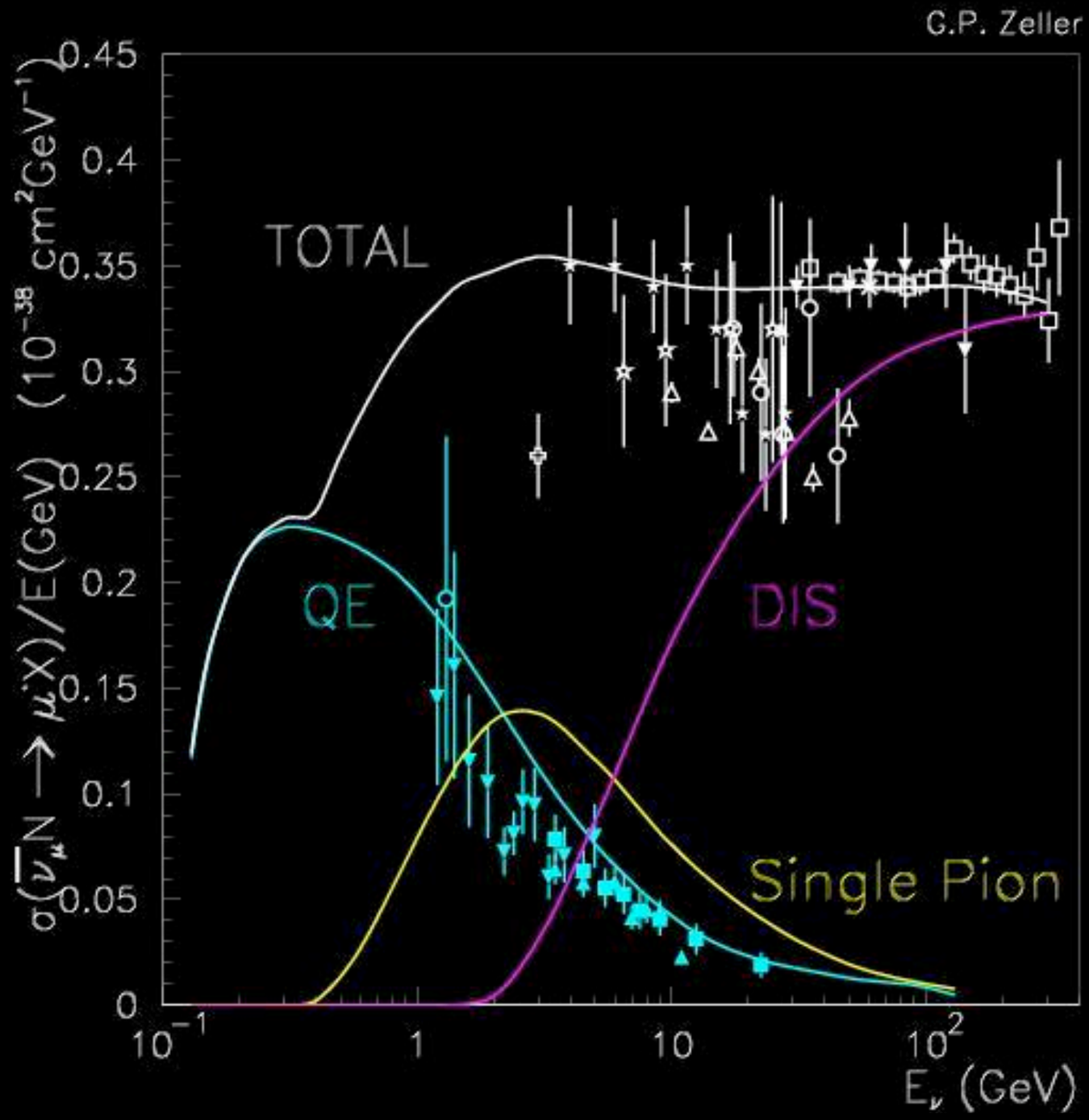
T2K Energy

- Need precise cross section measurements
  - ν_μ and $\bar{\nu}_\mu$

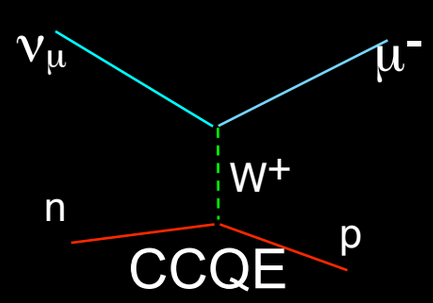


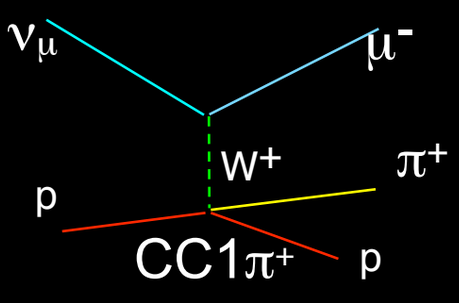


Background Uncertainties

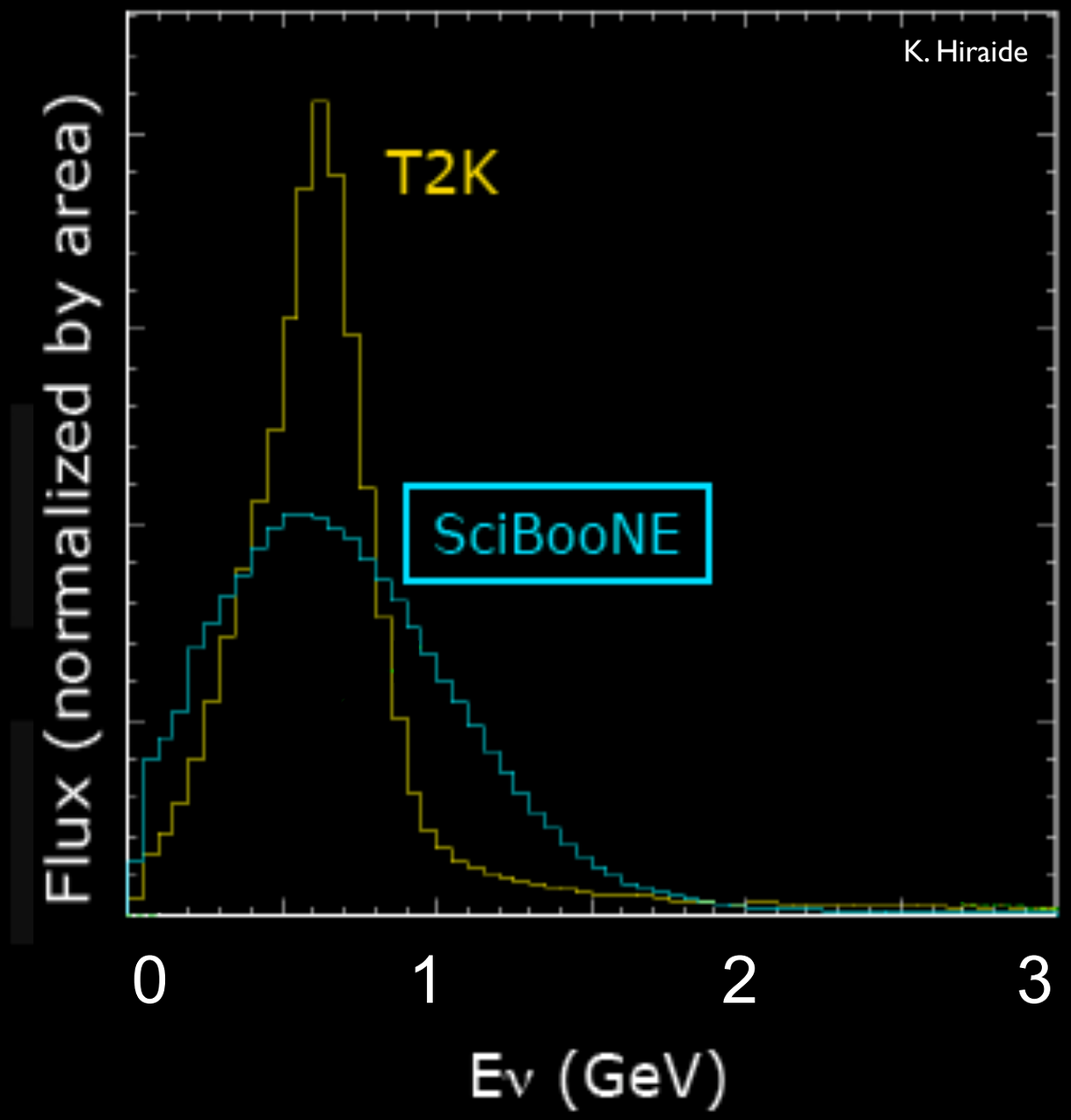


- Need precise cross section measurements
  - ν_μ and $\bar{\nu}_\mu$

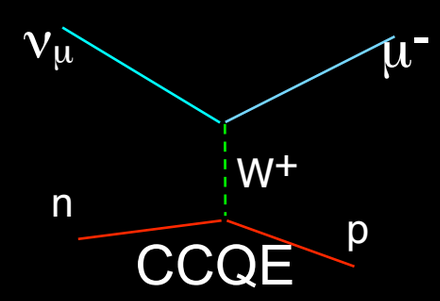


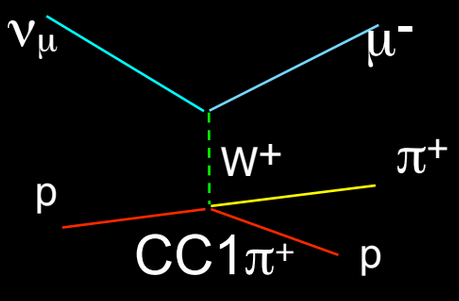


Let's measure σ_ν



- SciBooNE well matched to T2K



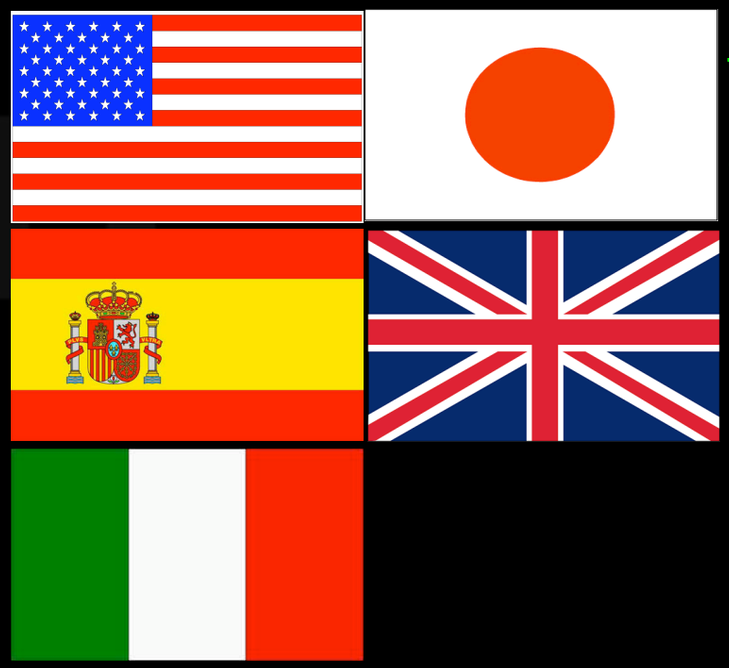


Imperial College London

SciBooNE collaboration

- Universitat Autonoma de Barcelona
- University of Colorado
- Columbia University
- Fermi National Accelerator Laboratory
- High Energy Accelerator Research Organization (KEK)
- Imperial College London*
- Indiana University
- Institute for Cosmic Ray Research
- Kamioka Observatory
- Kyoto University*
- Los Alamos National Laboratory
- Louisiana State University
- Massachusetts Institute of Technology
- Purdue University Calumet
- Università degli Studi di Roma and INFN-Roma
- Saint Mary's University of Minnesota
- Tokyo Institute of Technology
- Universidad de Valencia


SciBooNE, 2008



Spokespersons:
T.Nakaya, Kyoto University
M.O.Wascko, Imperial College

Imperial College
London

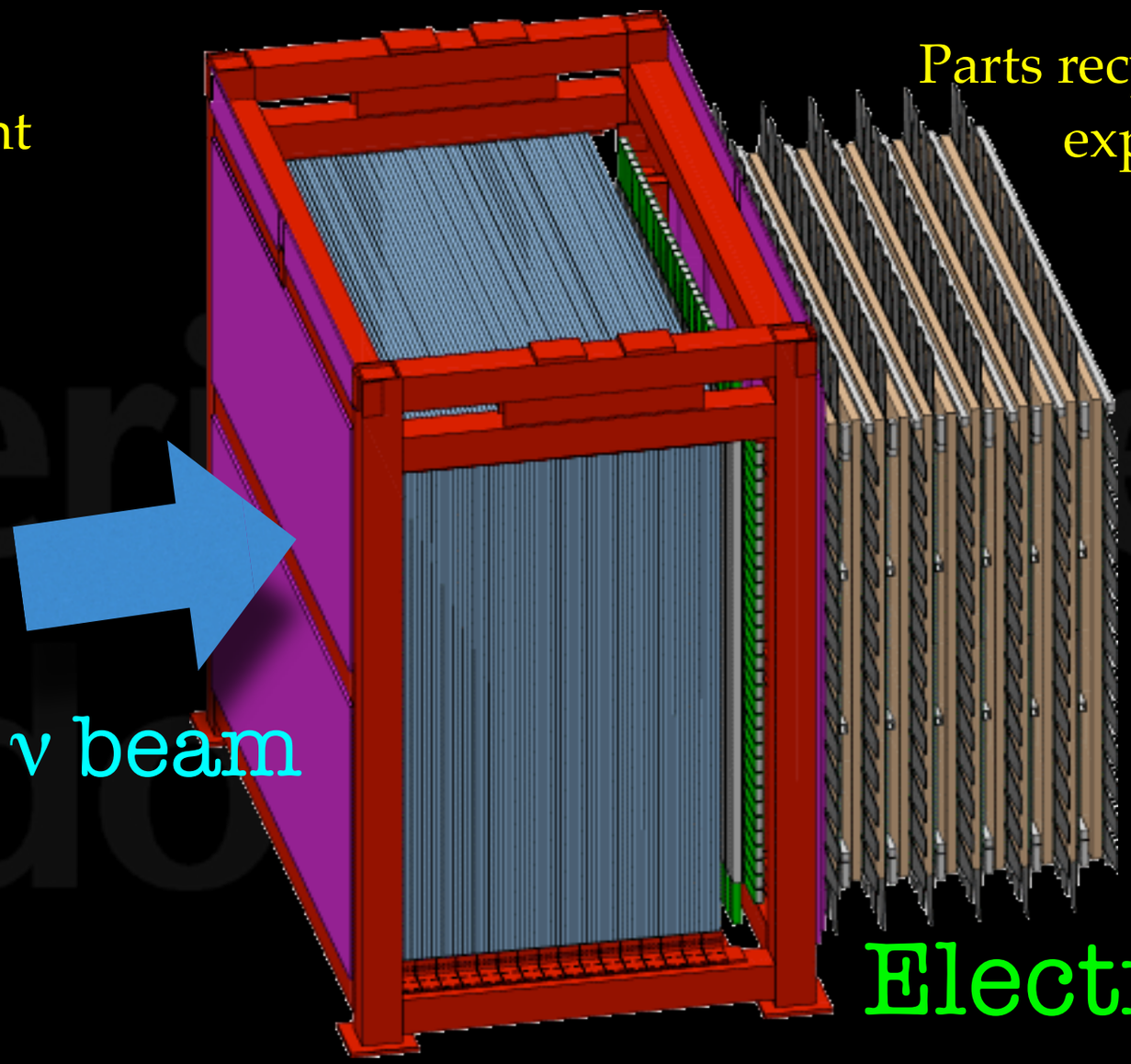
SciBooNE Detector

Scintillator Bar (SciBar)

Used in K2K experiment

Muon Range Detector (MRD)

Parts recycled from past experiments



Electron Catcher (EC)

Used in CHORUS, HARP and K2K

Imperial College
London

SciBooNE Detector

SciBooNE

Scintillator Bar (SciBar)

Used in K2K experiment

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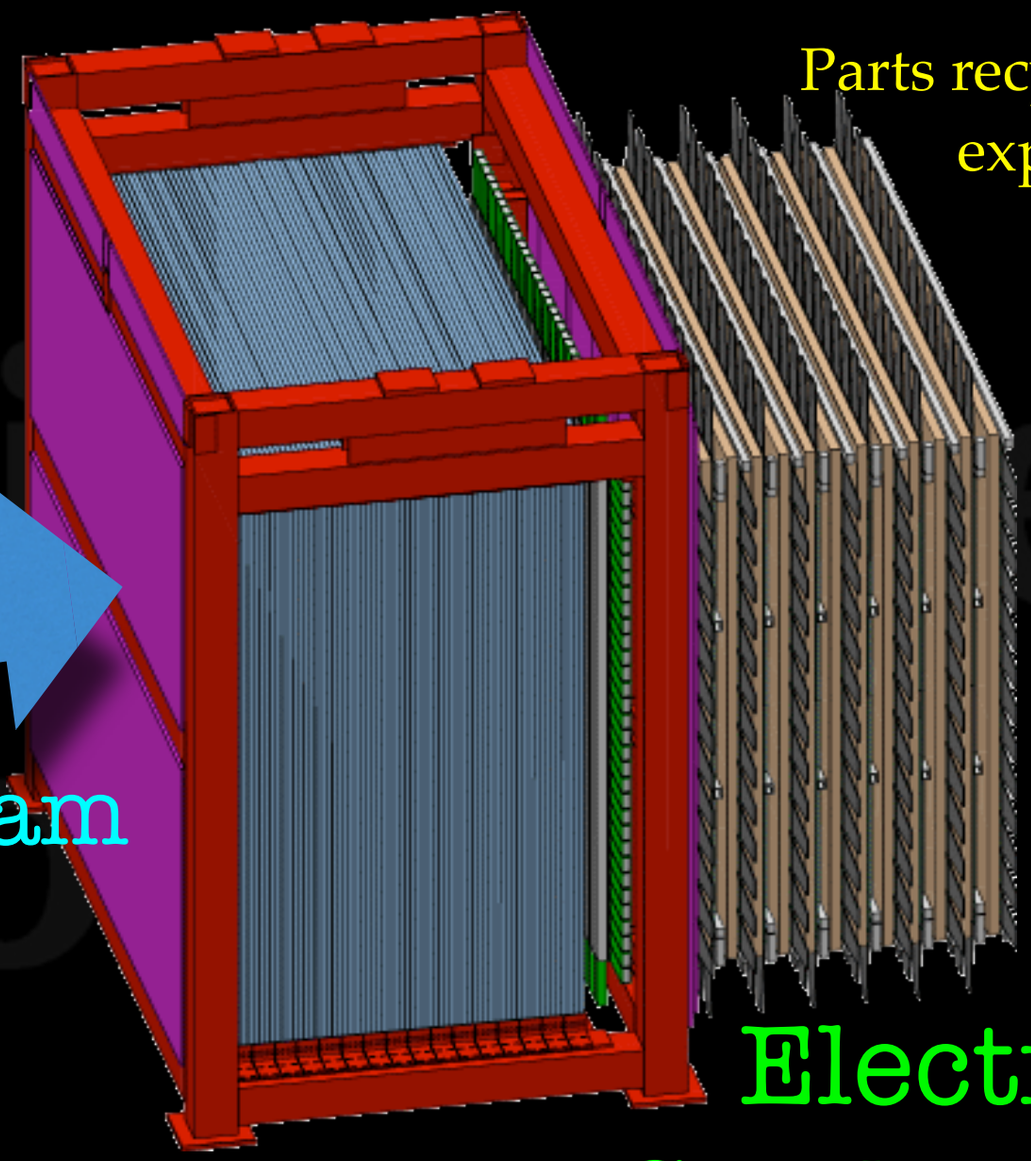


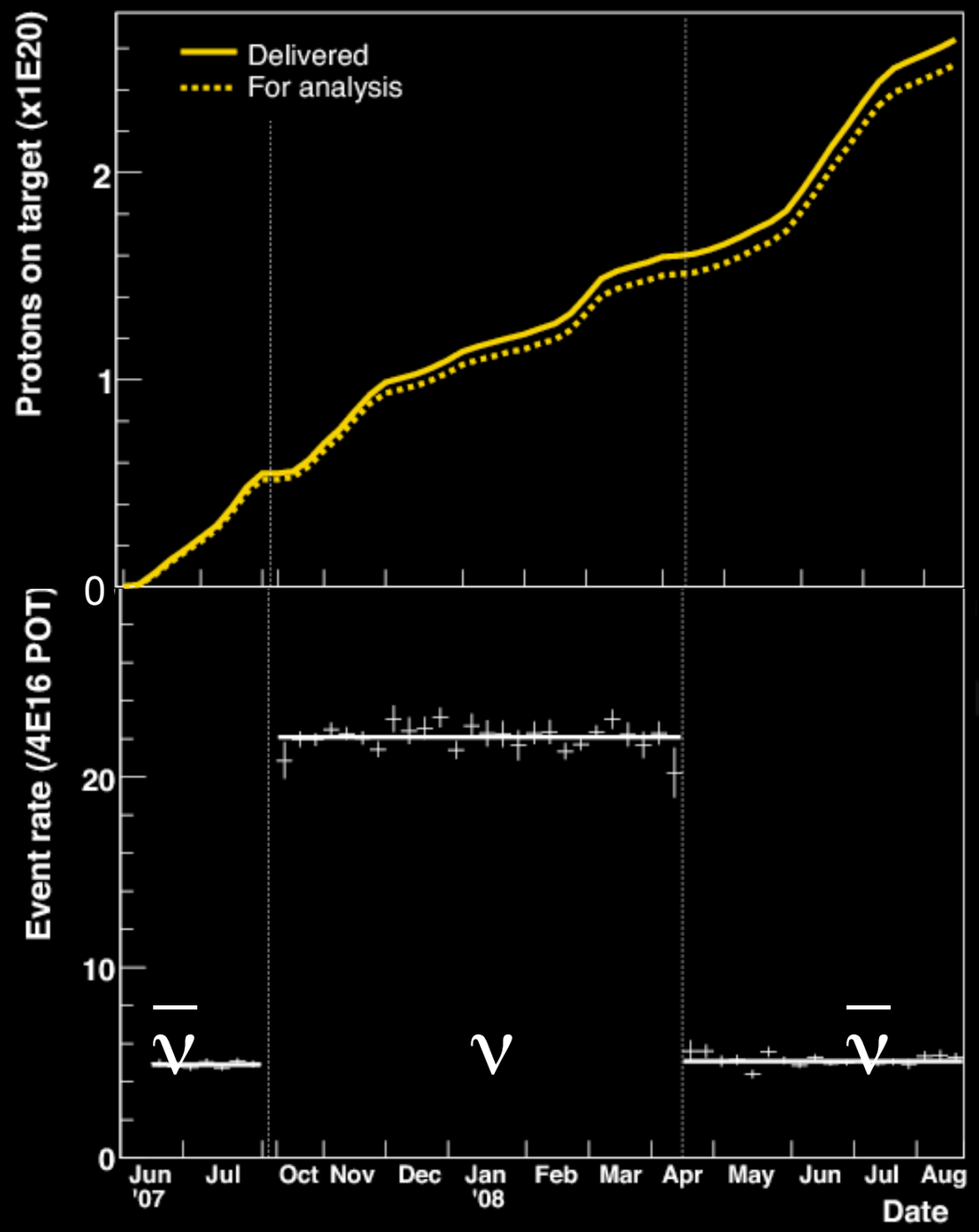
DOE-wide Pollution Prevention Star (P2 Star) Award

ν beam

Electron Catcher (EC)

Used in CHORUS, HARP and K2K

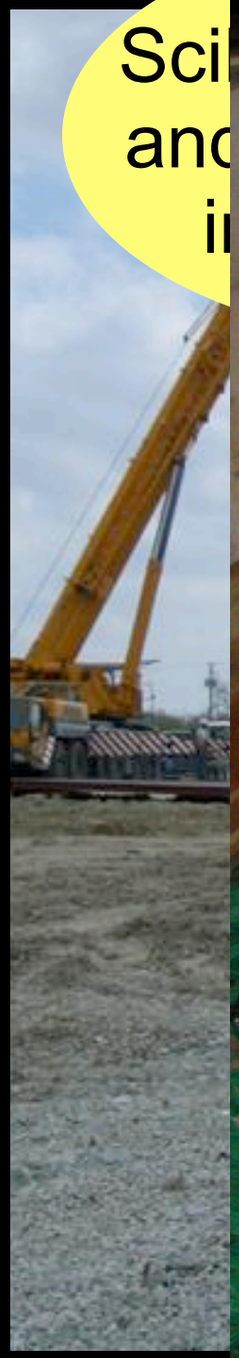
SciBooNE Performance



Phys.Rev.D ***78*** *112004 (2008),* *arXiv:0811.0369*

http://nuint09.ifae.es

SciBooNE Performance



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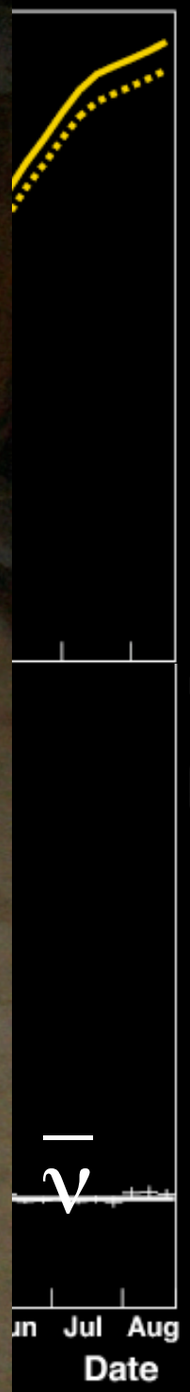

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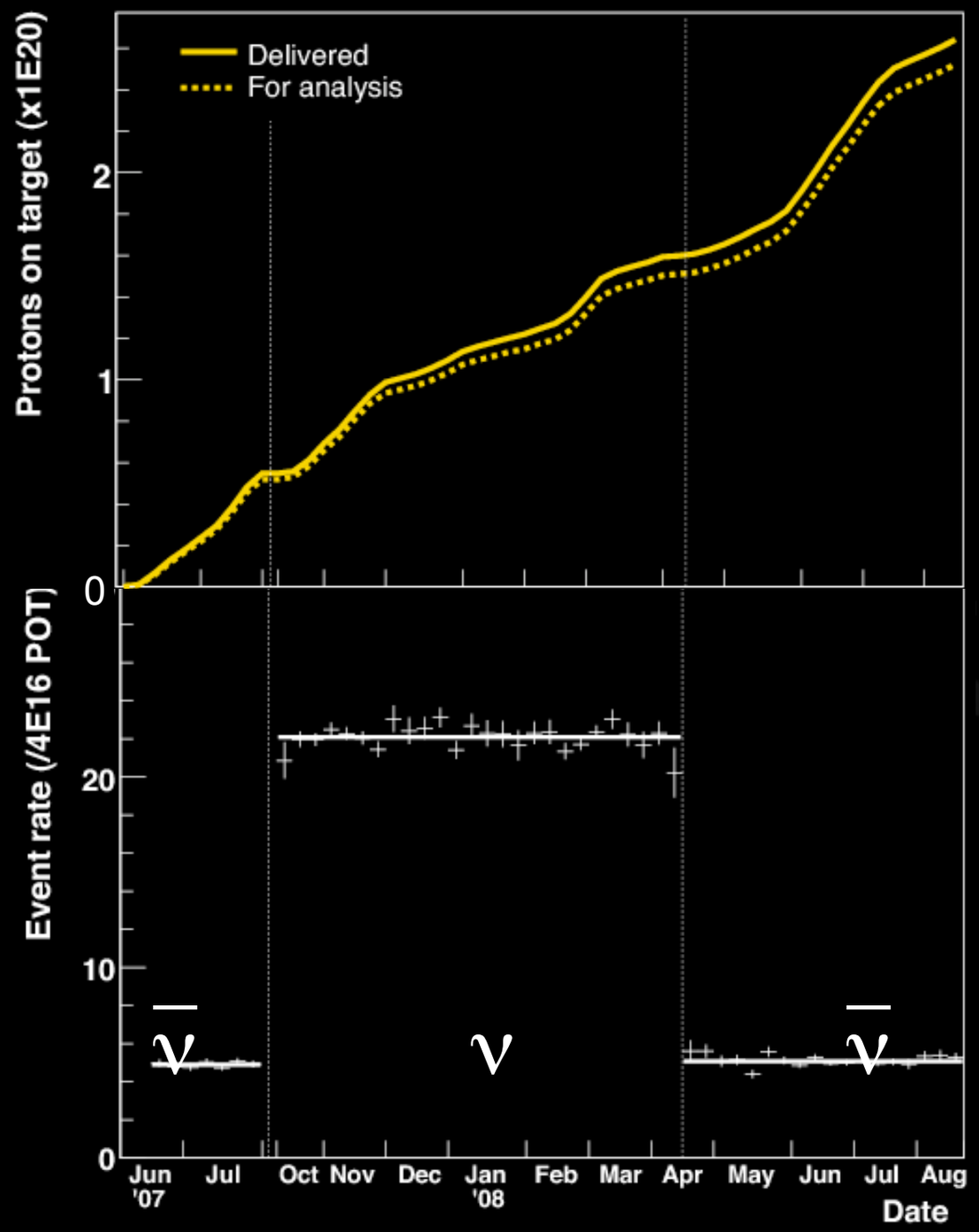
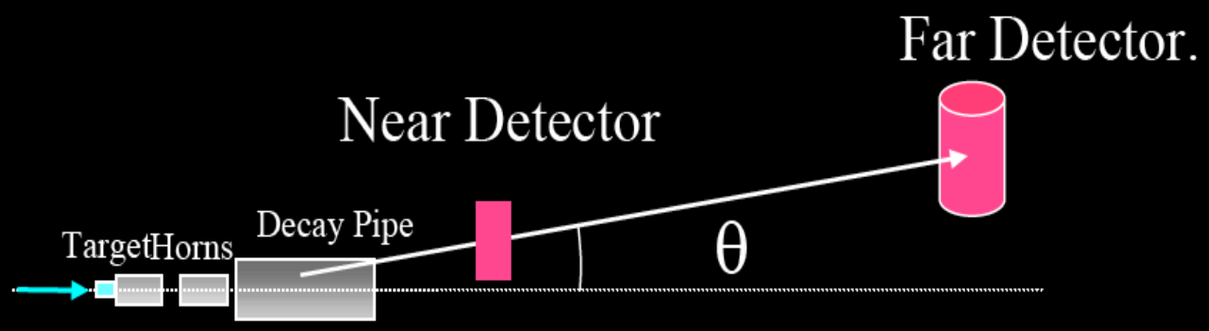
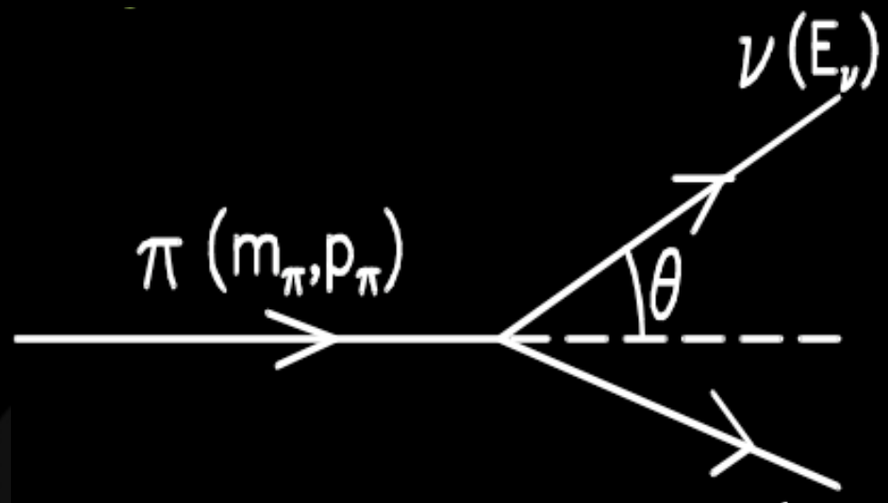


Phys.Rev.D ***78*** *112004 (2008),* *arXiv:0811.0369*

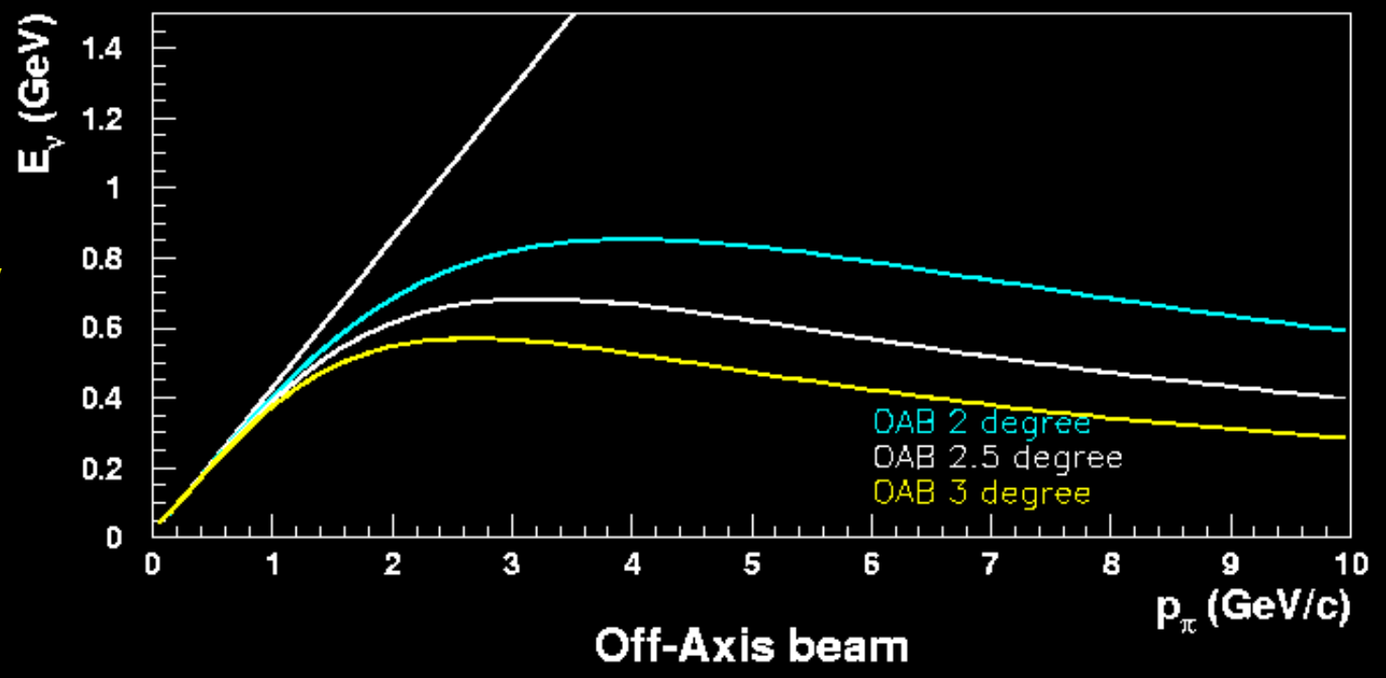
http://nuint09.ifae.es

Off-Axis Beam

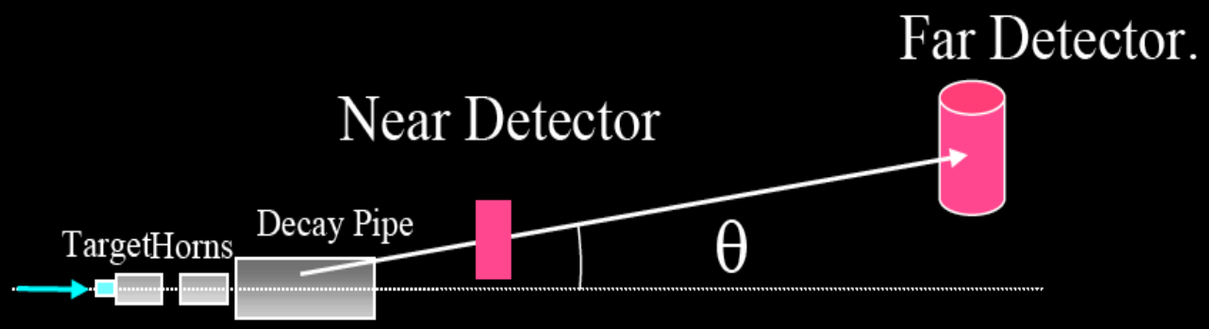




- Use kinematics of pion decay to tune the neutrino energy
- Flux peak at target energy for desired value of L/E
  - E_ν well matched to Super-K



Off-Axis Beam



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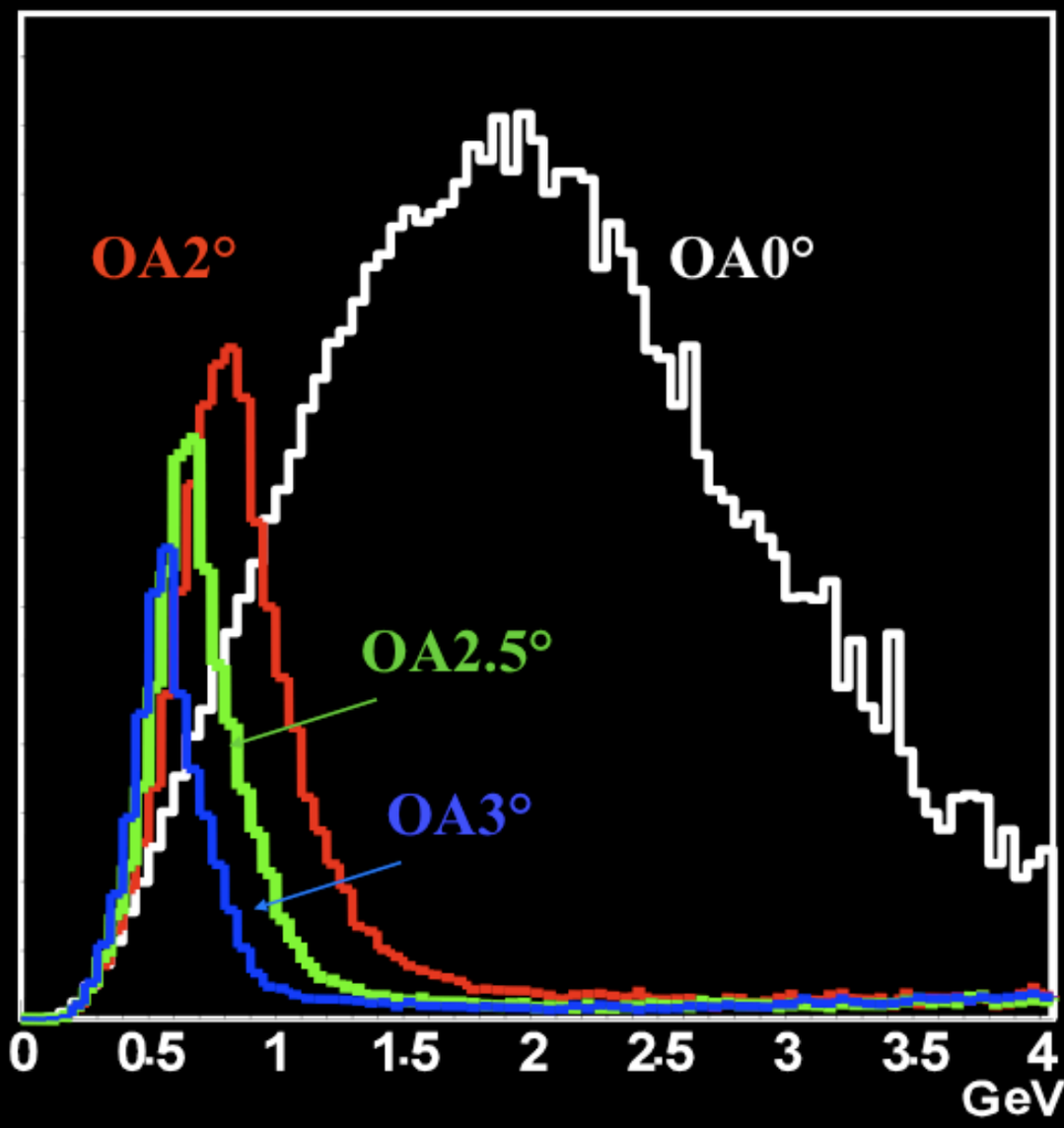
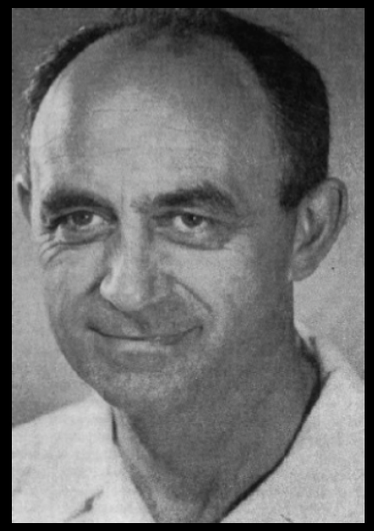
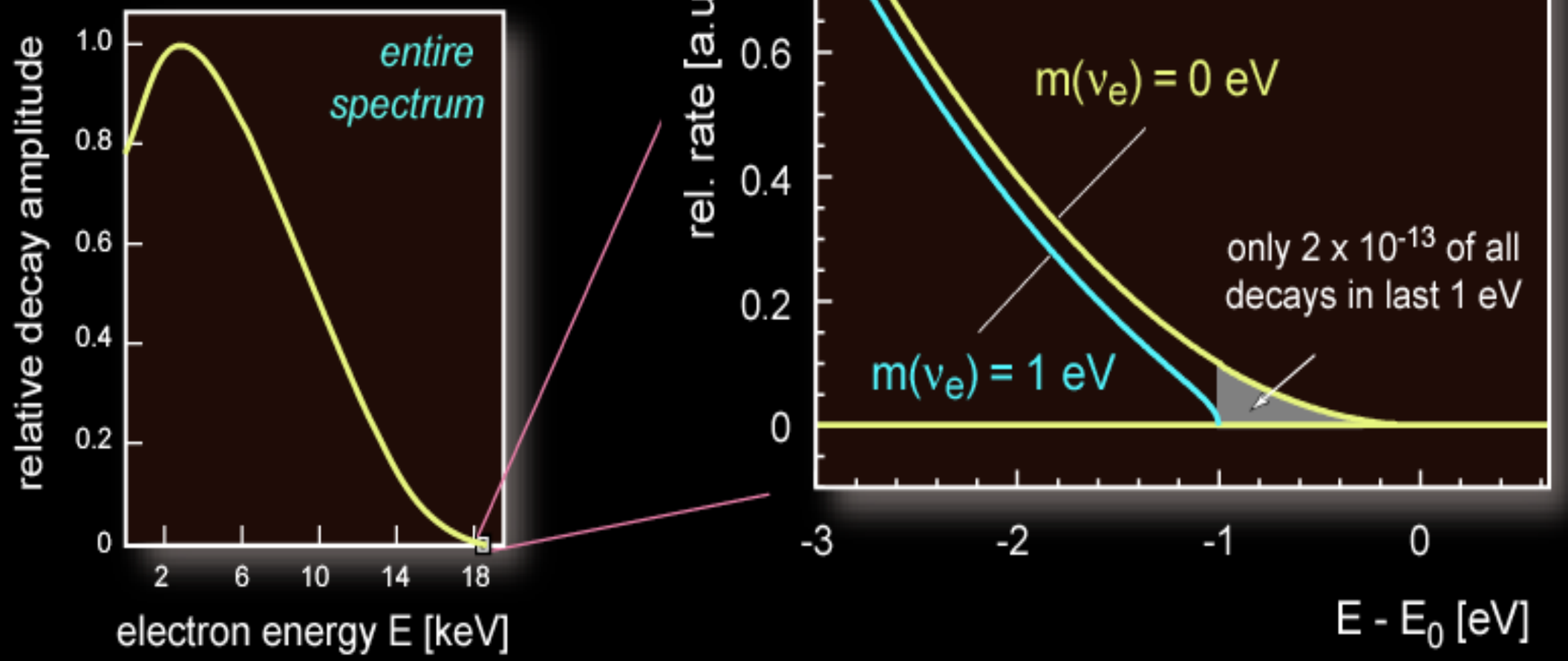


Absolute Scale of Neutrino Mass

Beta decay endpoint

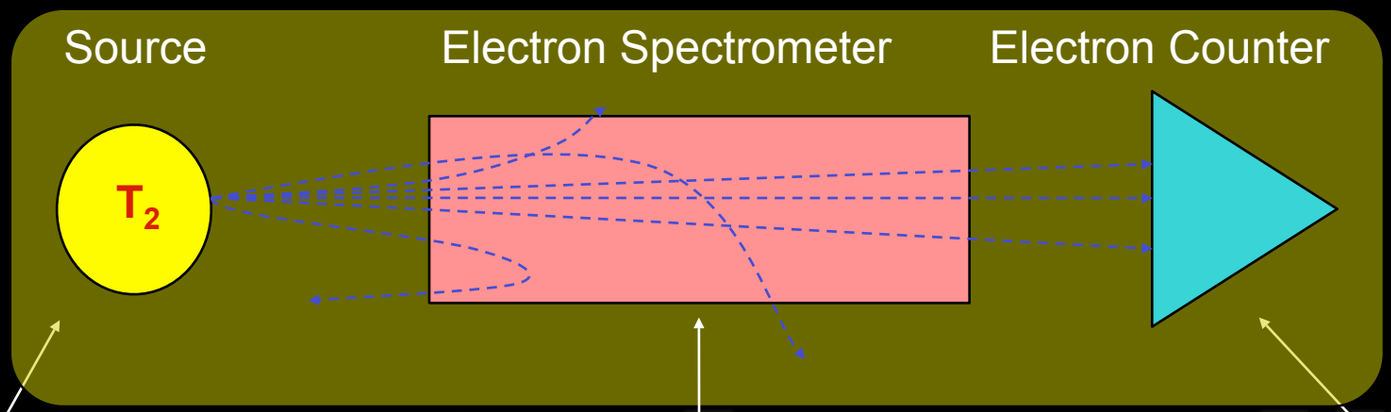




- Sensitive to $\langle m_\beta \rangle = \sqrt{(\sum |U_{ei}|^2 m_i^2)}$

Tritium Decay
Spectrometers

Source = ^3H

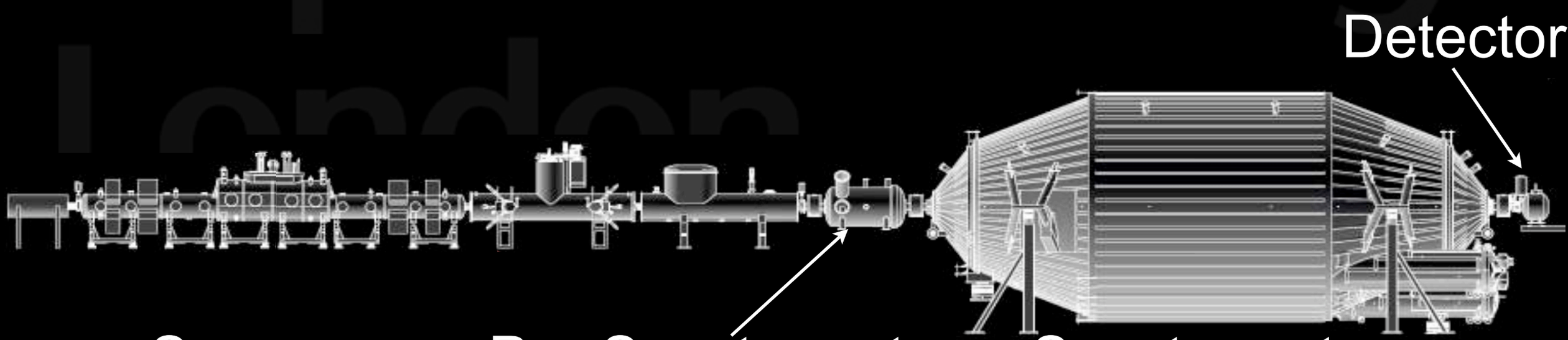


Nuclear Physics A **719** (2003) C153

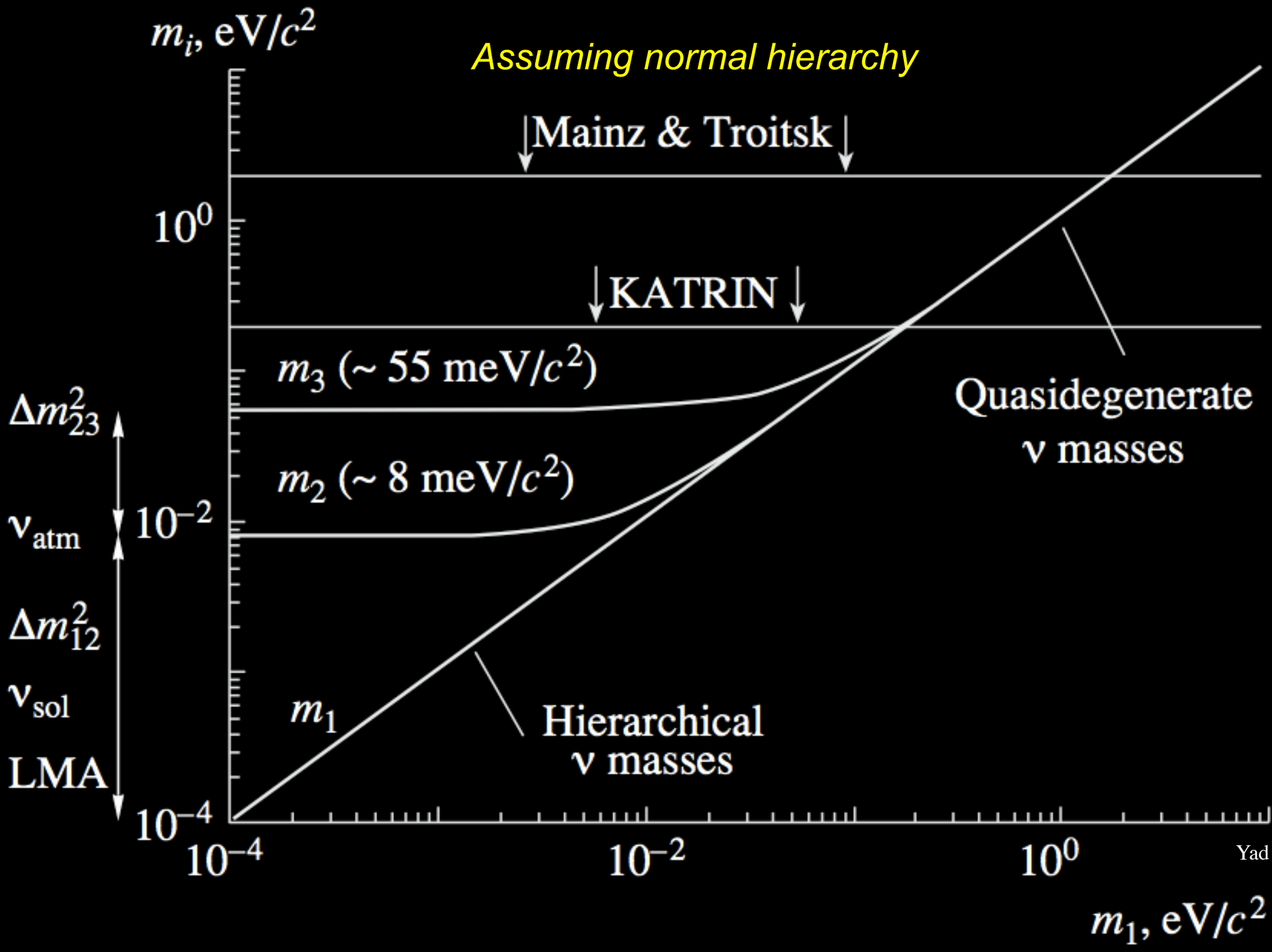
high activity

- high energy resolution
- integral spectrum: select $E_e > E_{th}$

- high efficiency
- low background



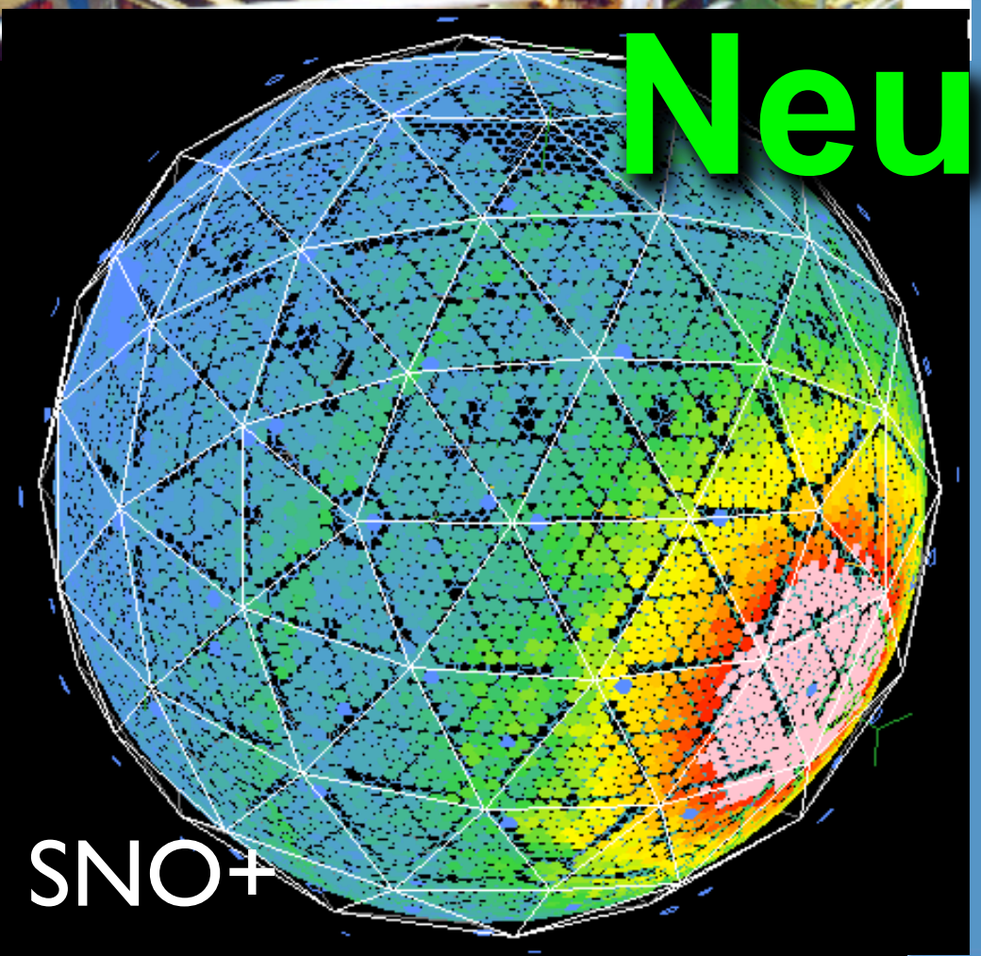
Physics Reach

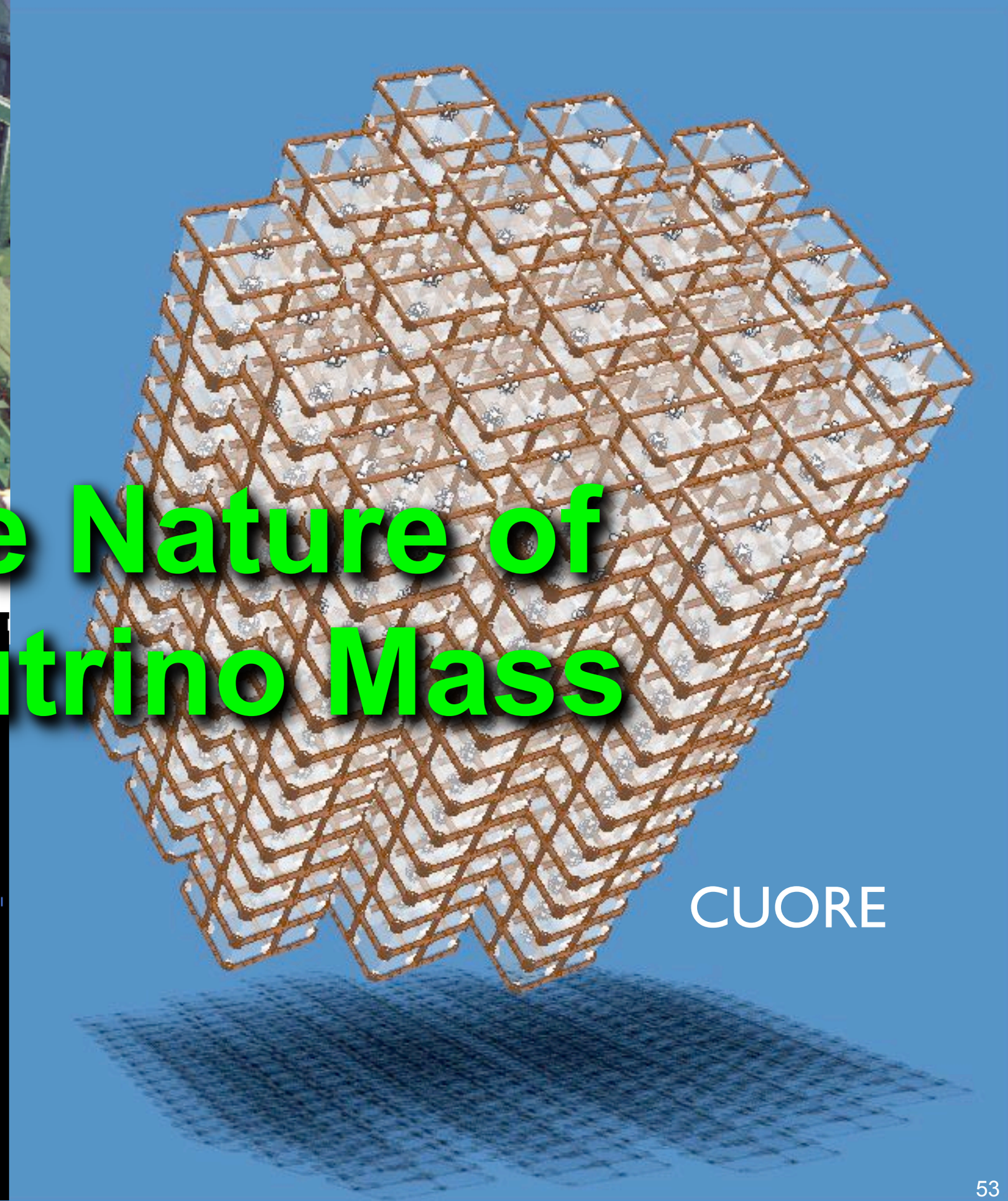


Yad Fiz **67**, No. 11 (2004), pp. 1977–1982

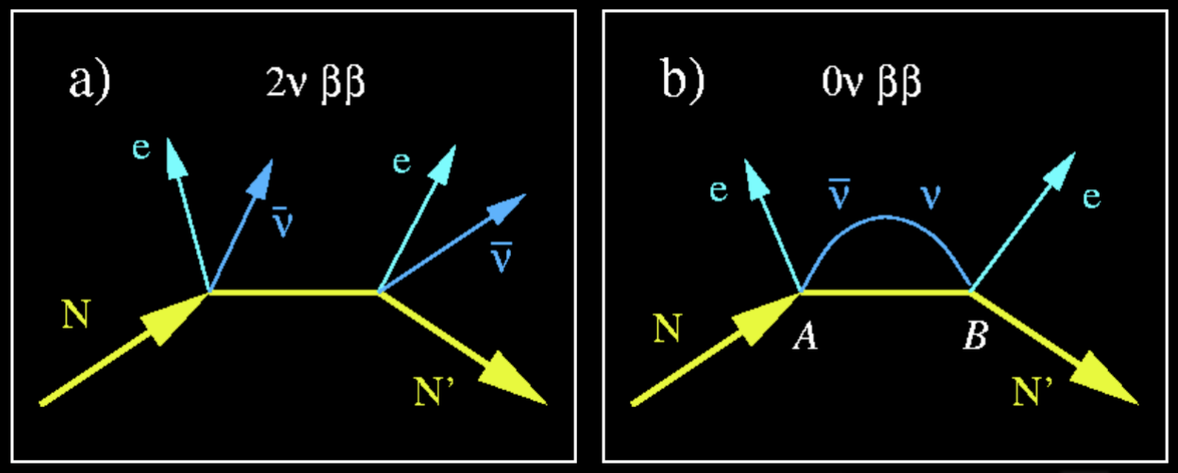
KATRIN Spectrometer

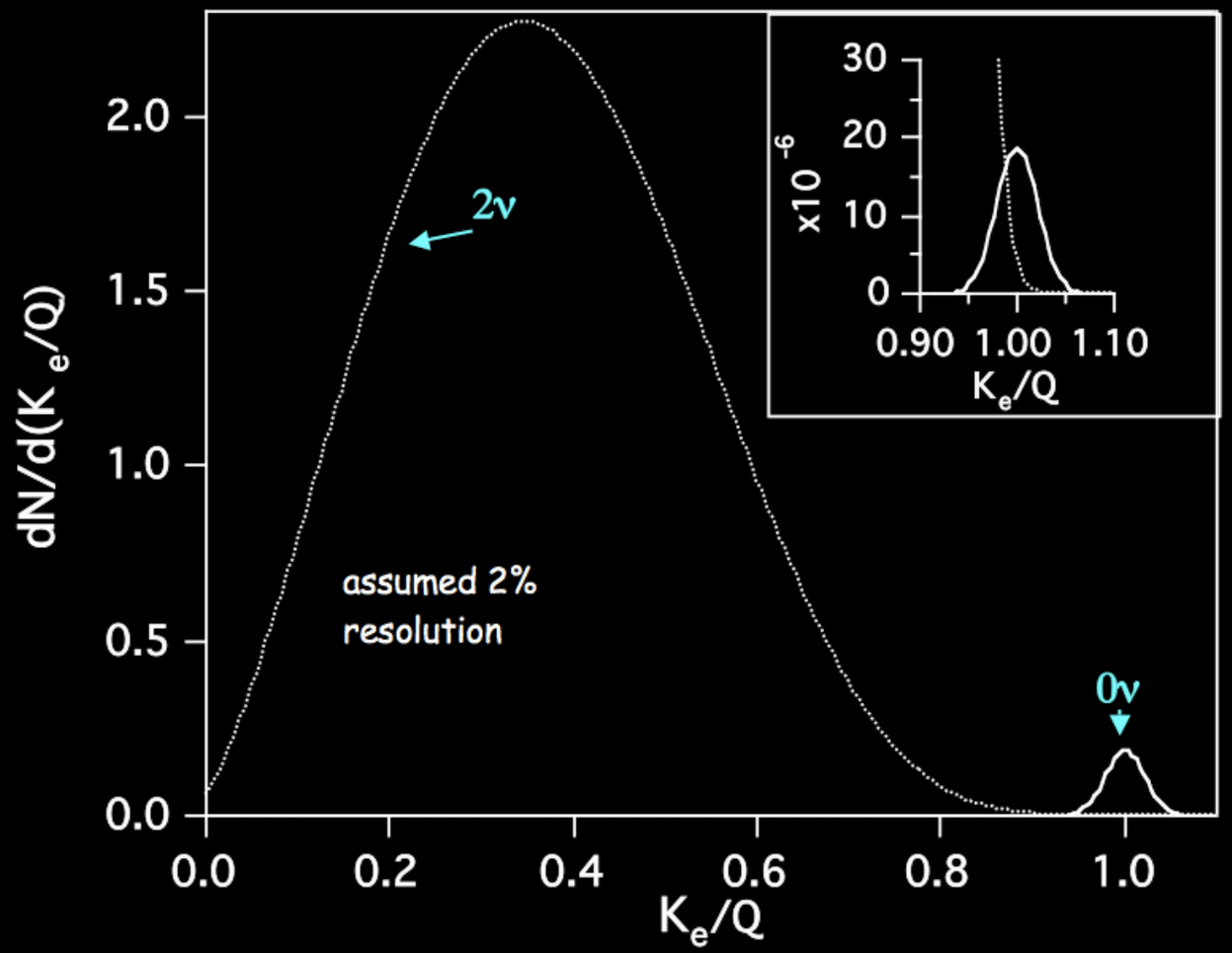
The Nature of Neutrino Mass





Double Beta Decay





- Can happen if single β decay is energetically forbidden
- $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\nu$

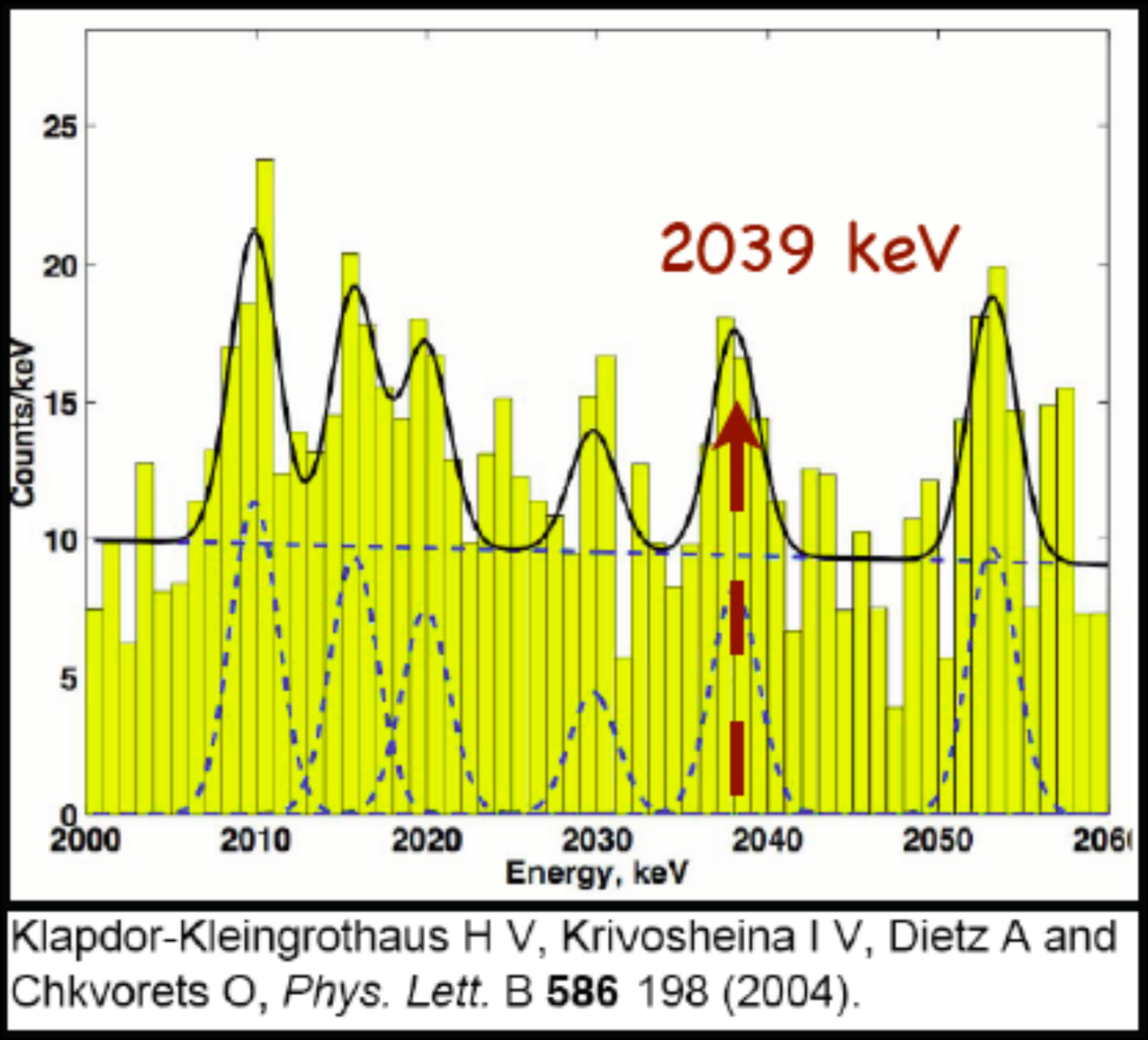
- If $\nu = \bar{\nu}$, then can have $0\nu\beta\beta$ decay
  - $(A,Z) \rightarrow (A,Z+2) + 2e^-$
  - Best way to search for Majorana particles

- $1/\tau = G(Q,Z)\,|M|^2\,\langle m_{\beta\beta}\rangle^2$
- $m_{\beta\beta} = \sum |U_{ei}|^2 m_i^2 \varepsilon_i$

Experimental techniques

Technique	Nuclei	Experiments
Bolometers	^{130}Te	CUORICINO →CUORE
Semiconductors	^{76}Ge	Heidelberg-Moscow, GERDA, MAJORANA, COBRA
Scintillators	^{48}Ca, ^{116}Cd, ^{150}Nd	MOON, CANDLES, ELEGANT, KIEV, SNO+
Xenon	^{136}Xe	EXO, XMASS, NEXT
Tracker/Calo	Ca, Cd, ^{100}Mo, Nd, Se, Te, ^{96}Zr	NEMO3 →SuperNEMO

Observation?



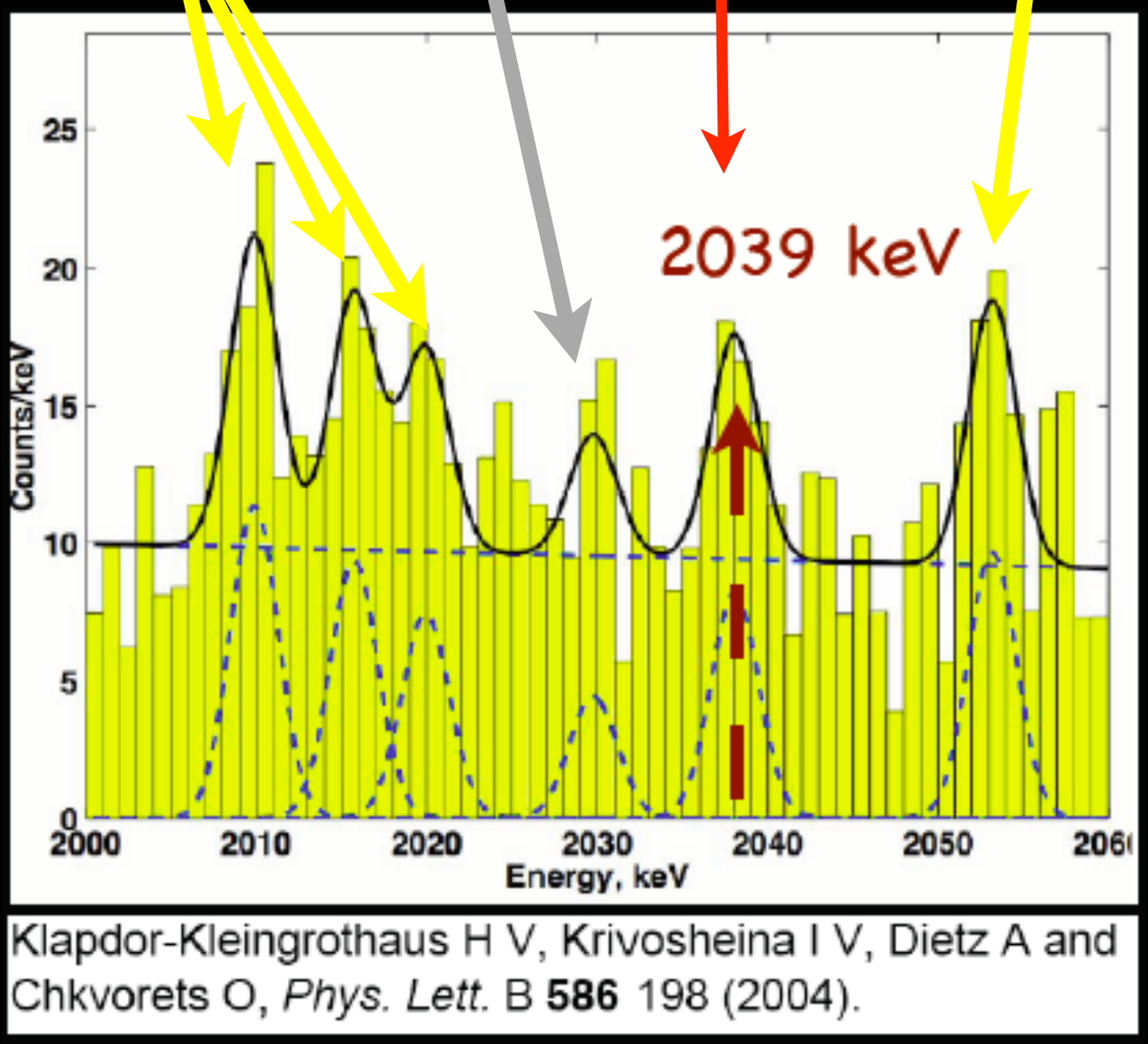
Klapdor-Kleingrothaus H V, Krivosheina I V, Dietz A and Chkvorets O, *Phys. Lett.* B **586** 198 (2004).

- In 2001, a subgroup of the Heidelberg-Moscow experiment released a discovery claim
- Somewhat controversial

- $m_{\beta\beta}$ = 440 meV (4.2σ)

Next generation can confirm or rule out

Observation?



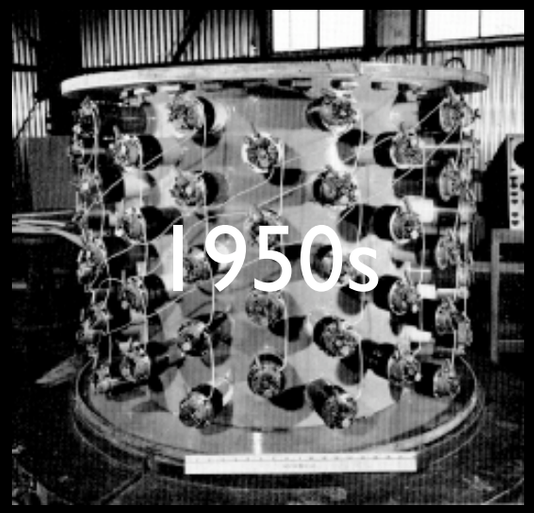
Klapdor-Kleingrothaus H V, Krivosheina I V, Dietz A and Chkvorets O, *Phys. Lett.* B **586** 198 (2004).

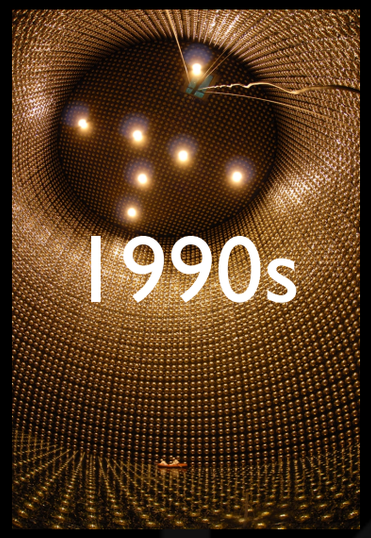
- In 2001, a subgroup of the Heidelberg-Moscow experiment released a discovery claim
- Somewhat controversial

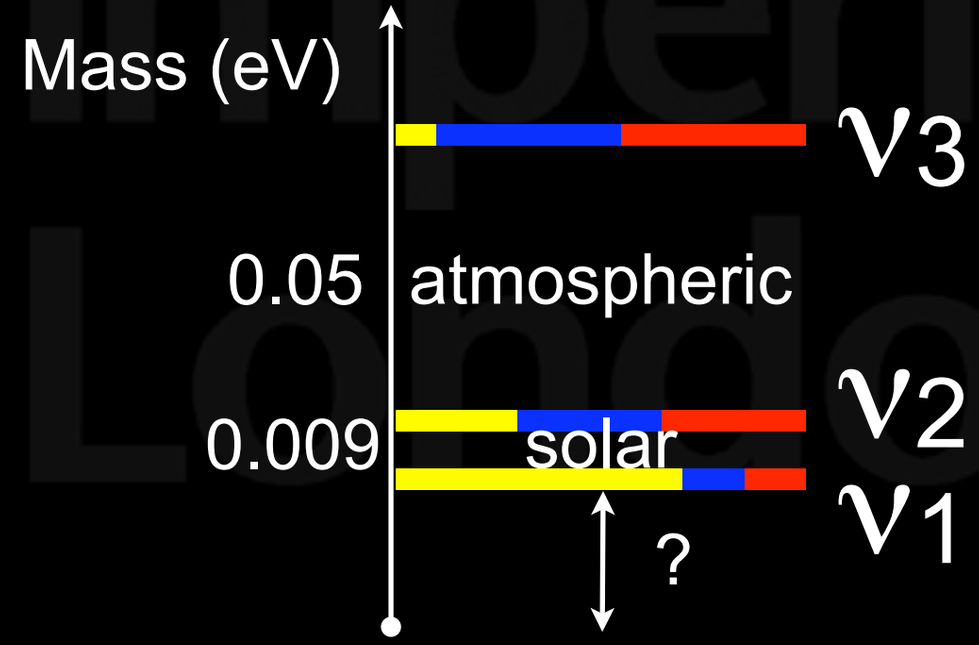
- $m_{\beta\beta}$ = 440 meV (4.2σ)

Next generation can confirm or rule out

Open Questions

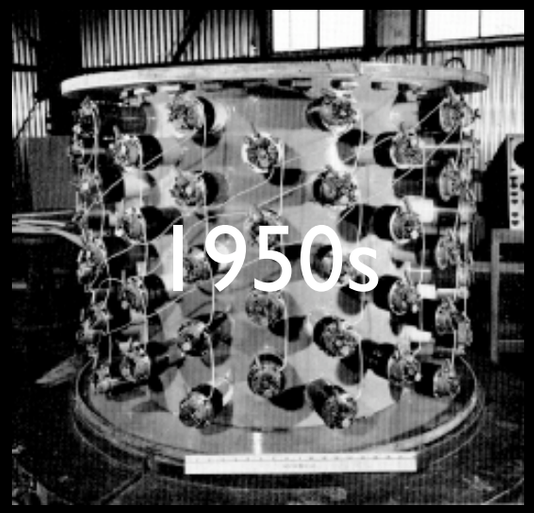


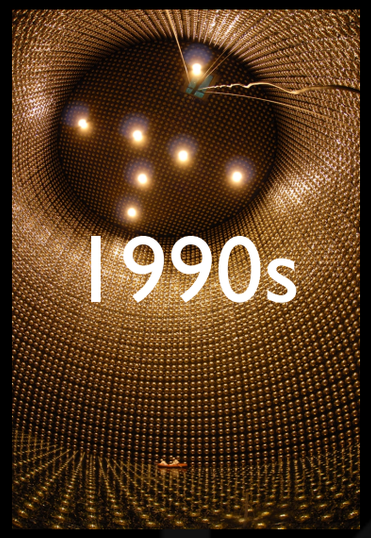


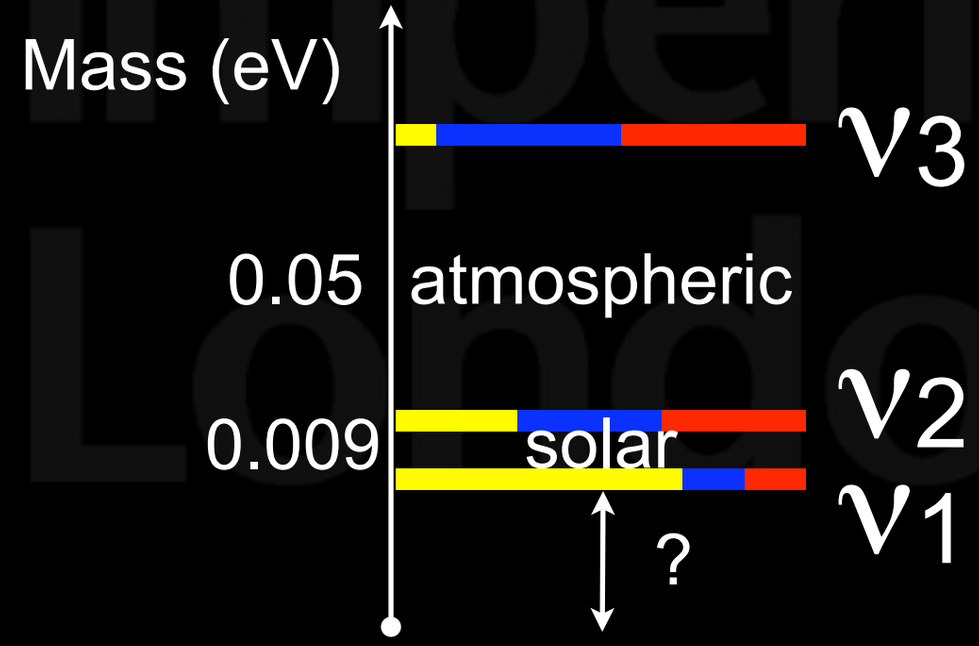


- Is CP violated by neutrinos?
- What is the mass hierarchy?
- What is the absolute scale?
- Are they Majorana or Dirac?
- Why are they so small?

Open Questions







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Worldwide program to answer these - join us!


Thanks!