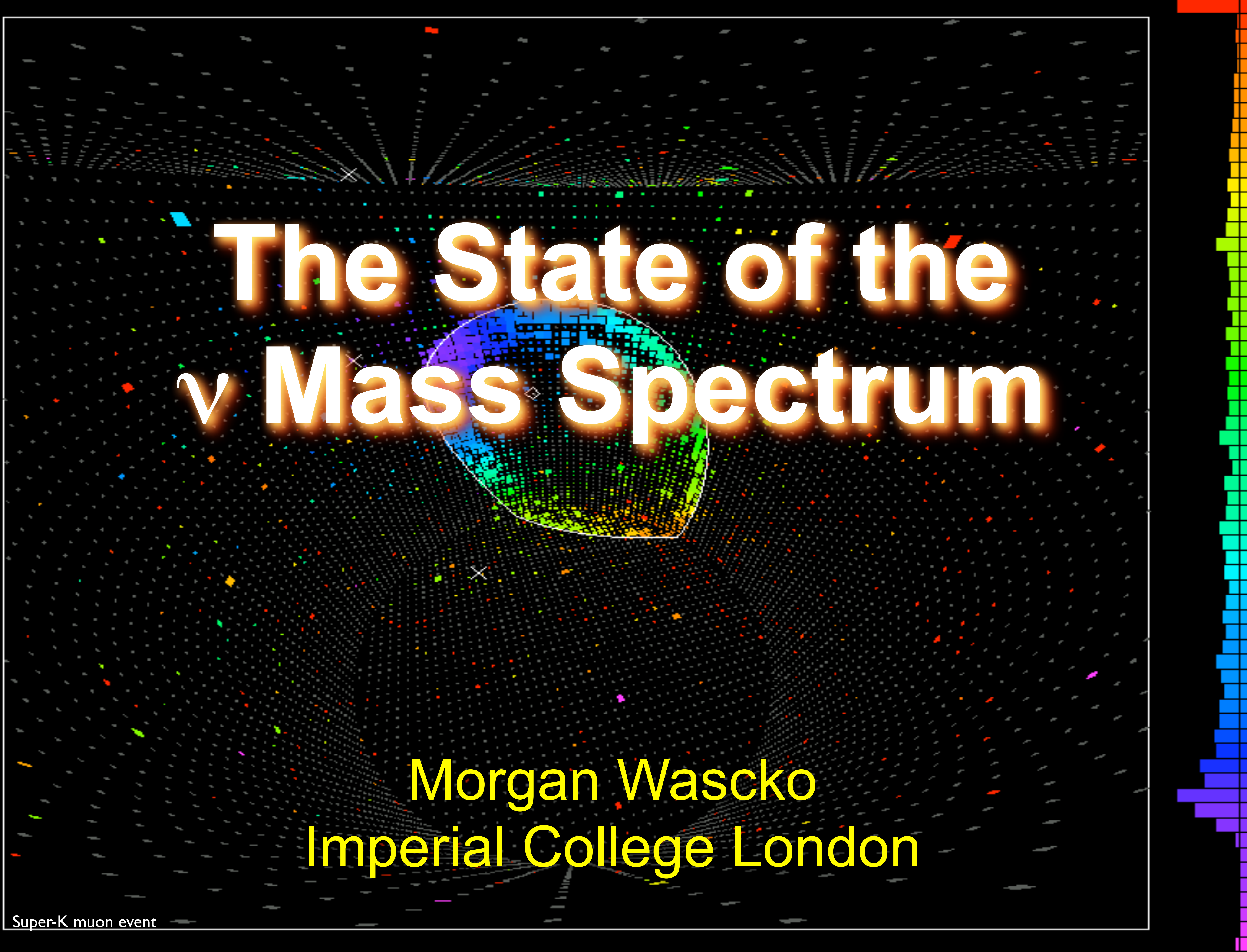
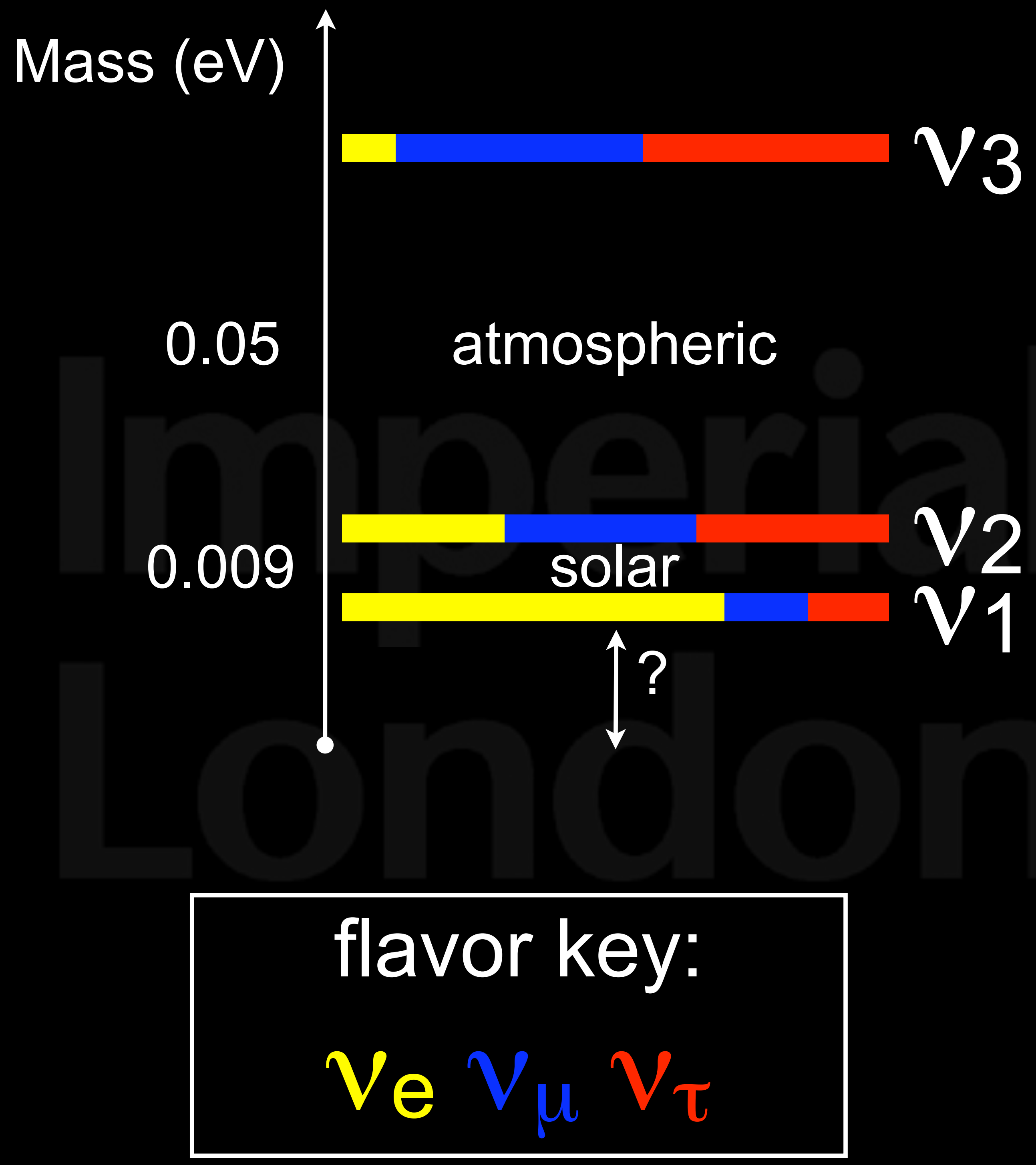
The State of the ν Mass Spectrum

Morgan Wascko
Imperial College London



Super-K muon event

Outline



- Introduction
- Discovery
  - Oscillation measurements
- Absolute scale of mass
  - Beta decay endpoint
  - Cosmology
- Nature of neutrino mass
  - Double beta decay
- Summary

History

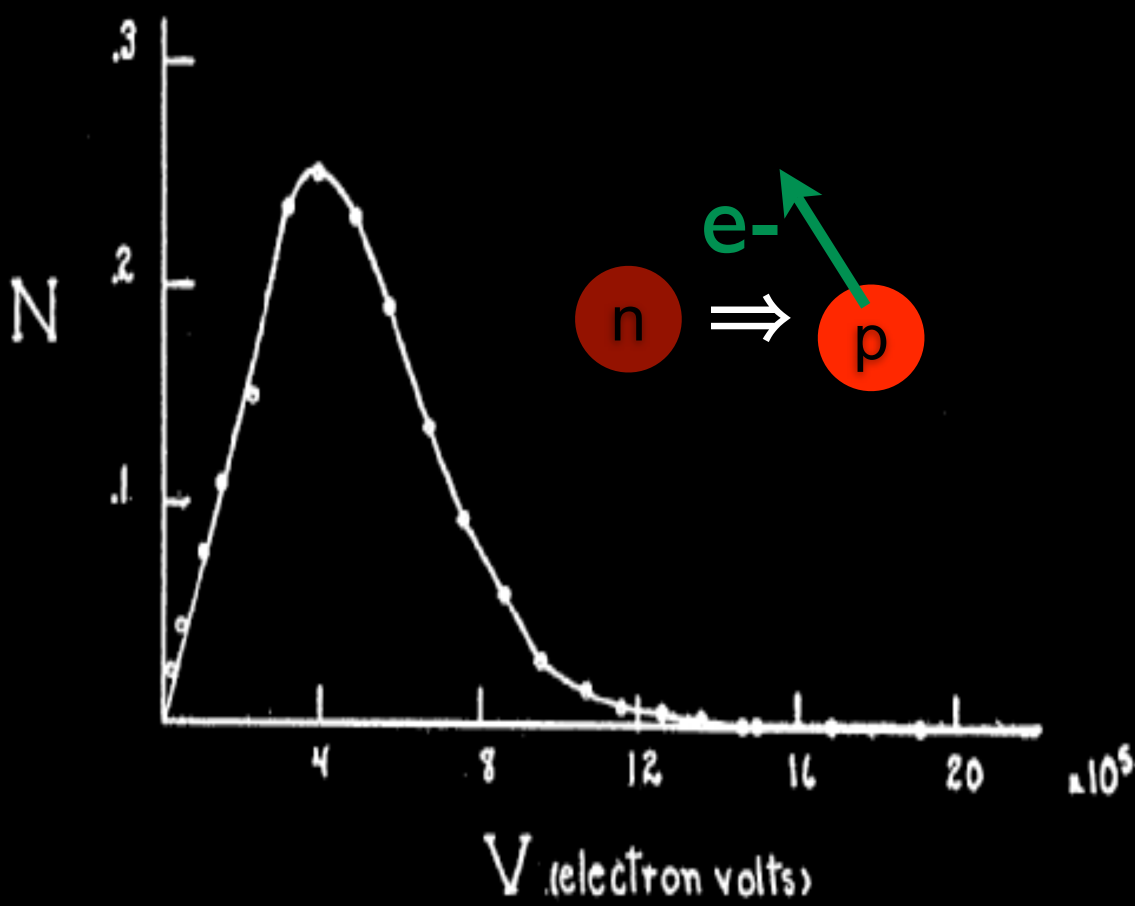
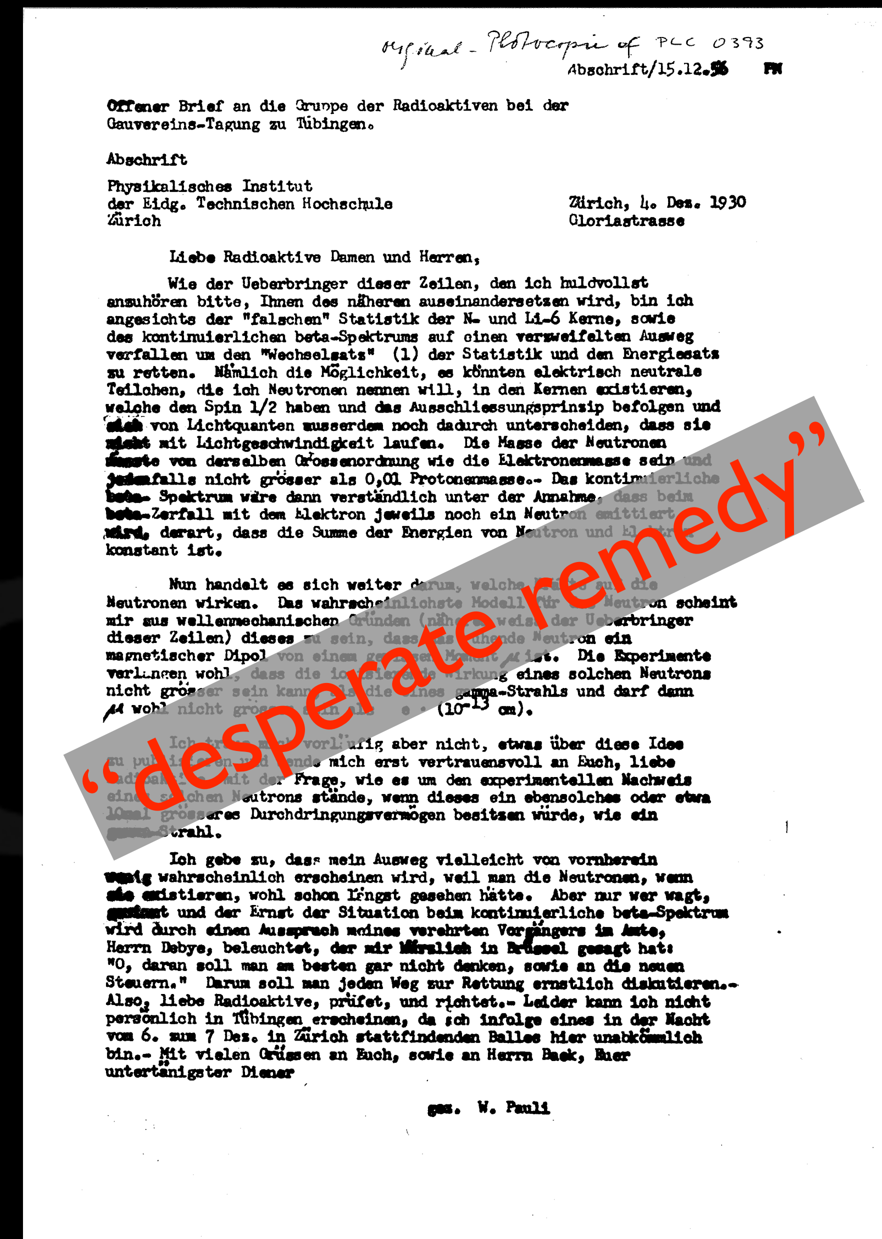


FIG. 5. Energy distribution curve of the beta-rays.

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



Original - Photocopie of PLC 0393
Abschrift/15.12.56 PM

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 anzuhören 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 Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung 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 sein als e · (10^{-13} cm).

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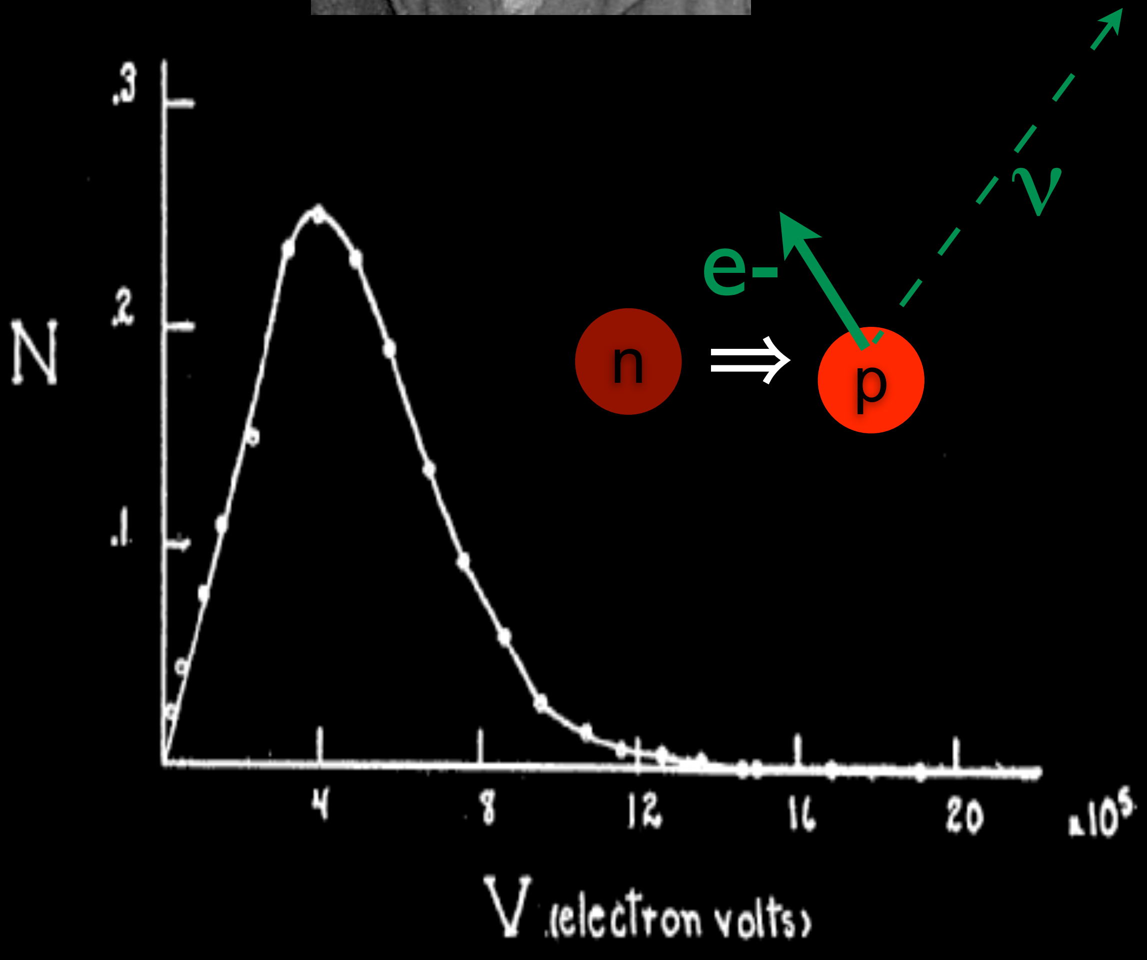
History



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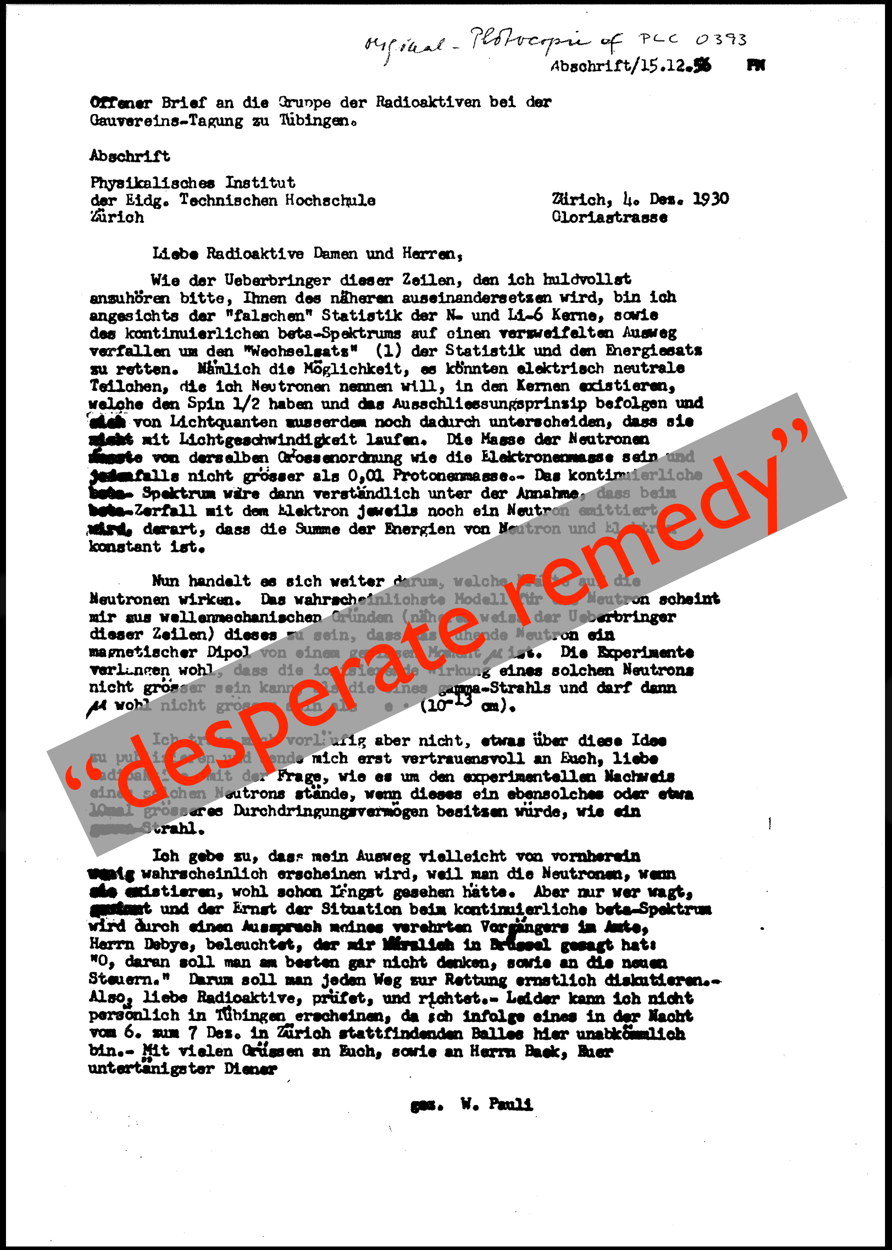

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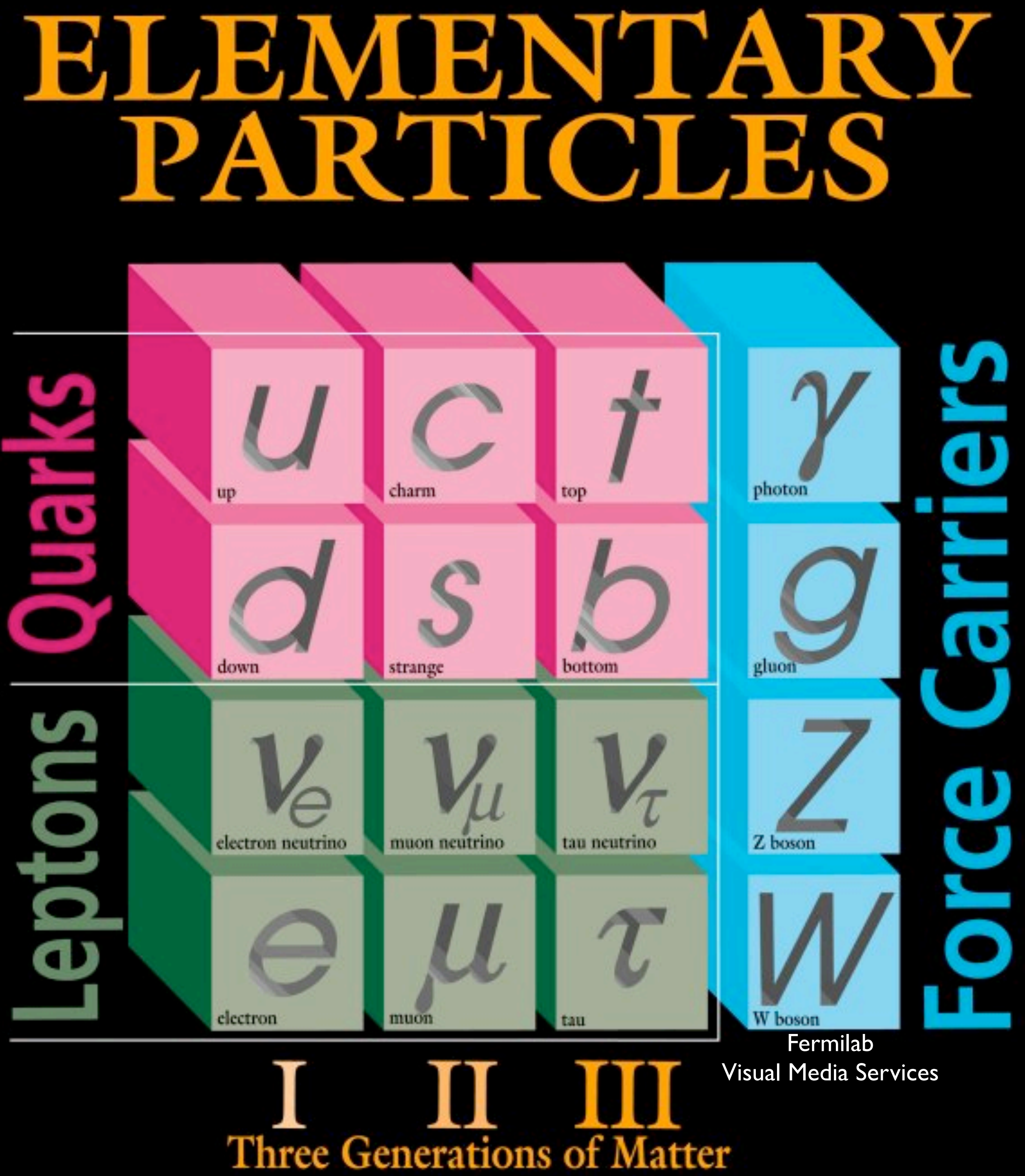
νs in Standard Model

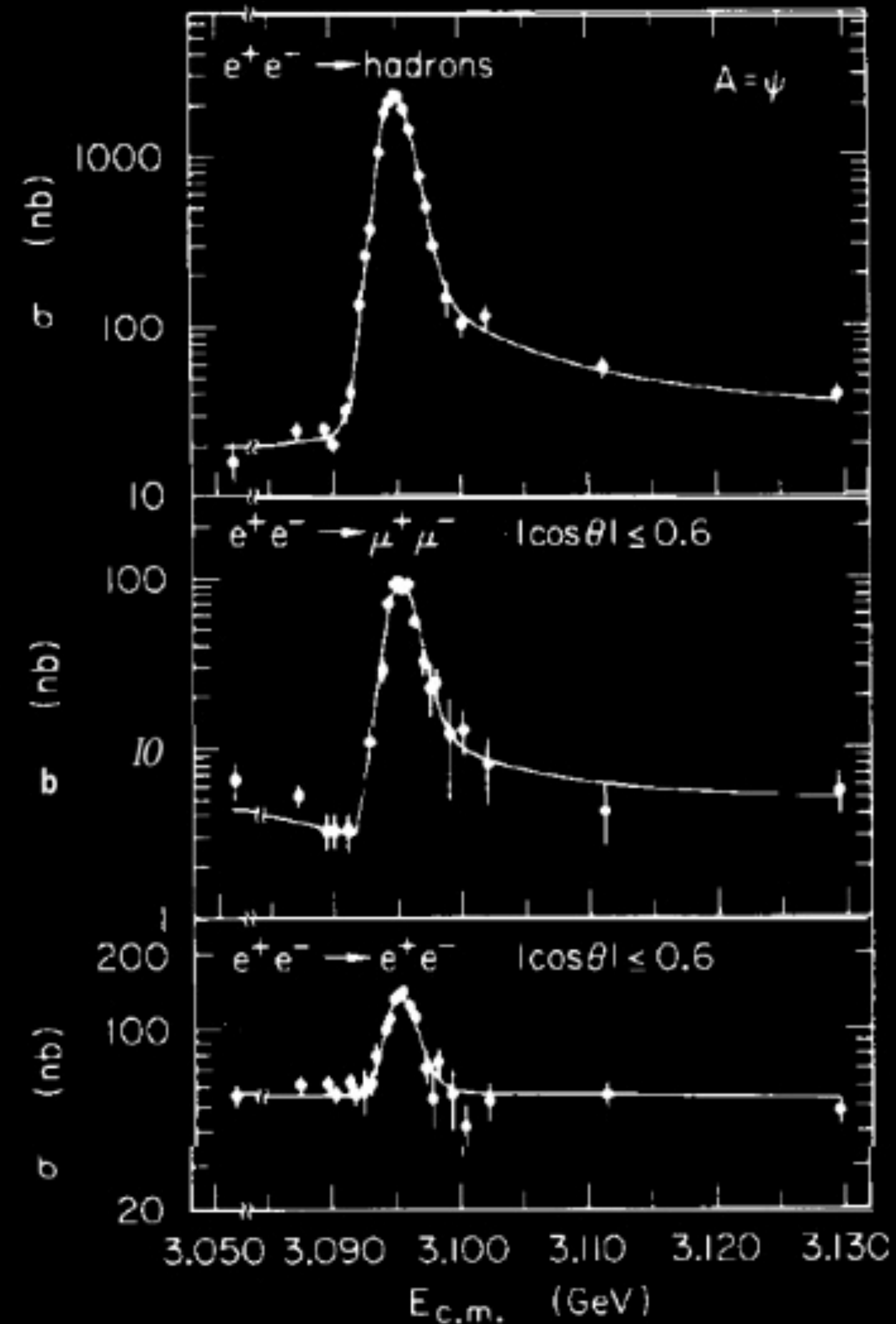
- Electrically Neutral
- Colorless
- Massless
- Flavors don't mix



Fermilab
Visual Media Services

Why ν mass is difficult

- Usual techniques
  - Mass reconstruction
  - Spectrometry
- Cannot directly measure ν mass eigenstates!
- Must resort to indirect techniques



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

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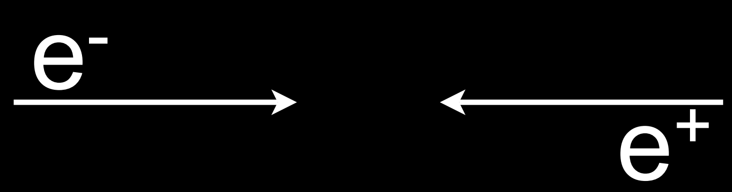

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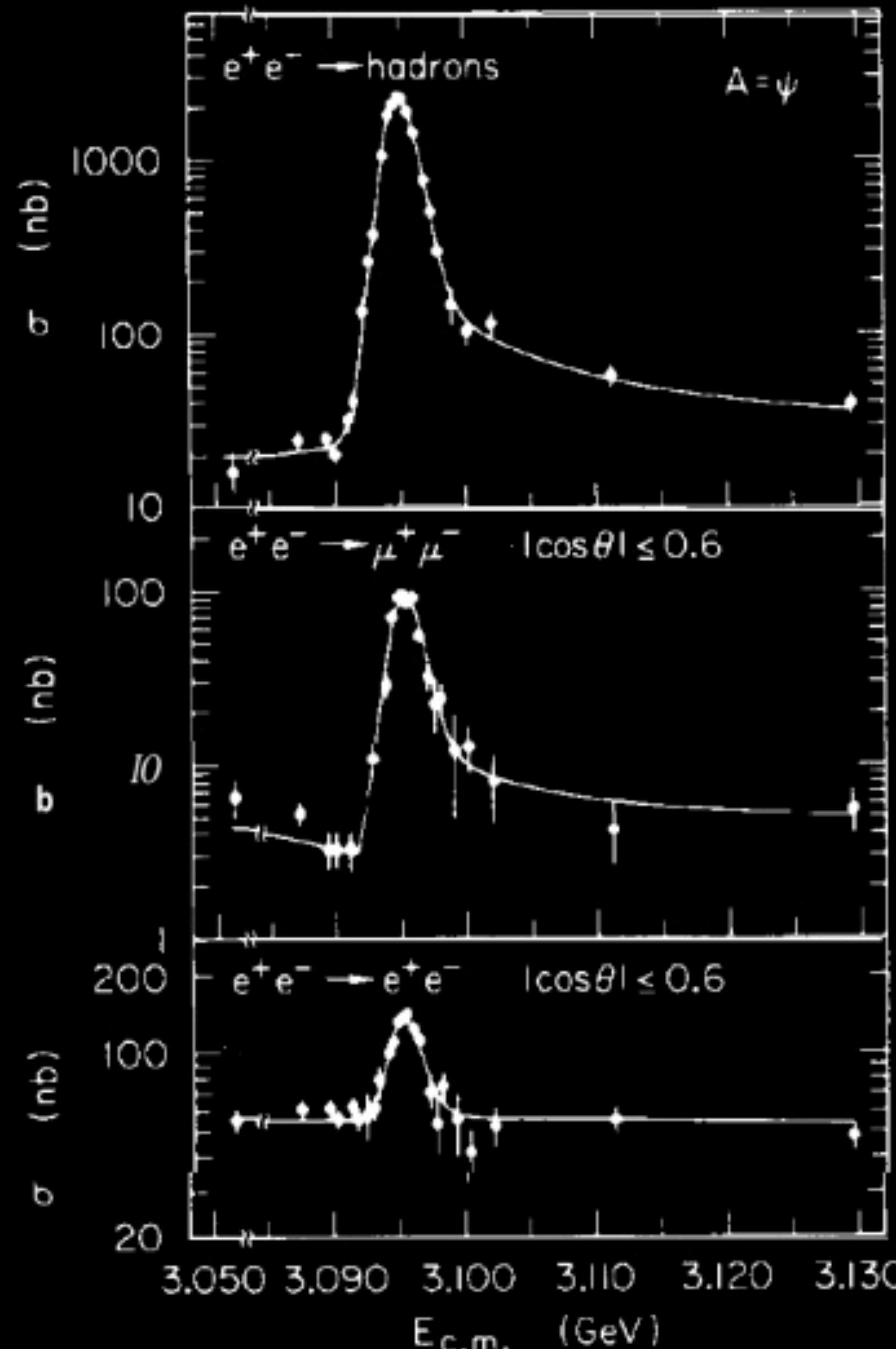

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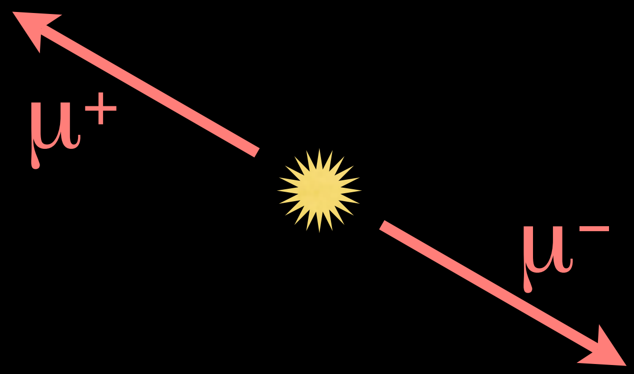

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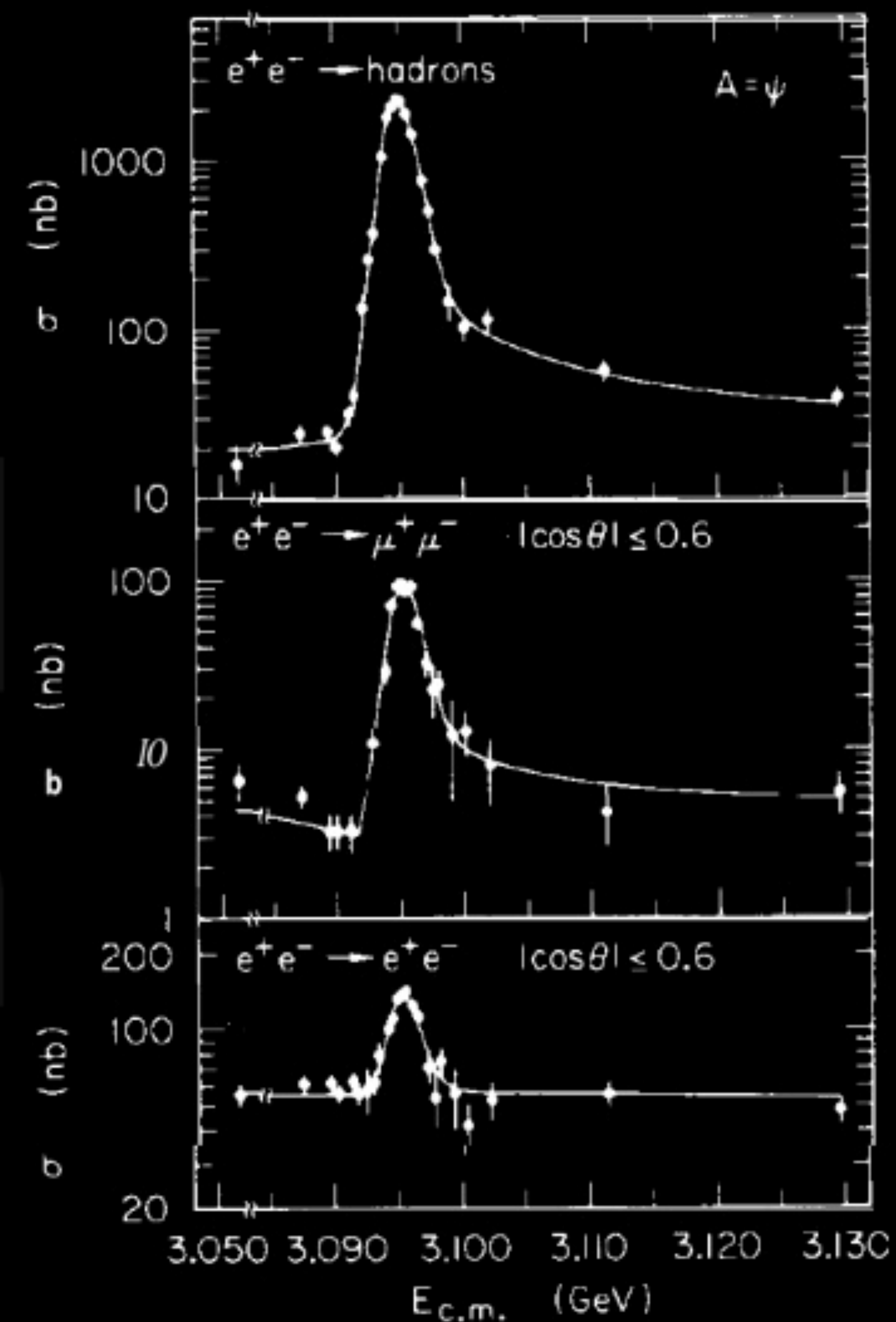
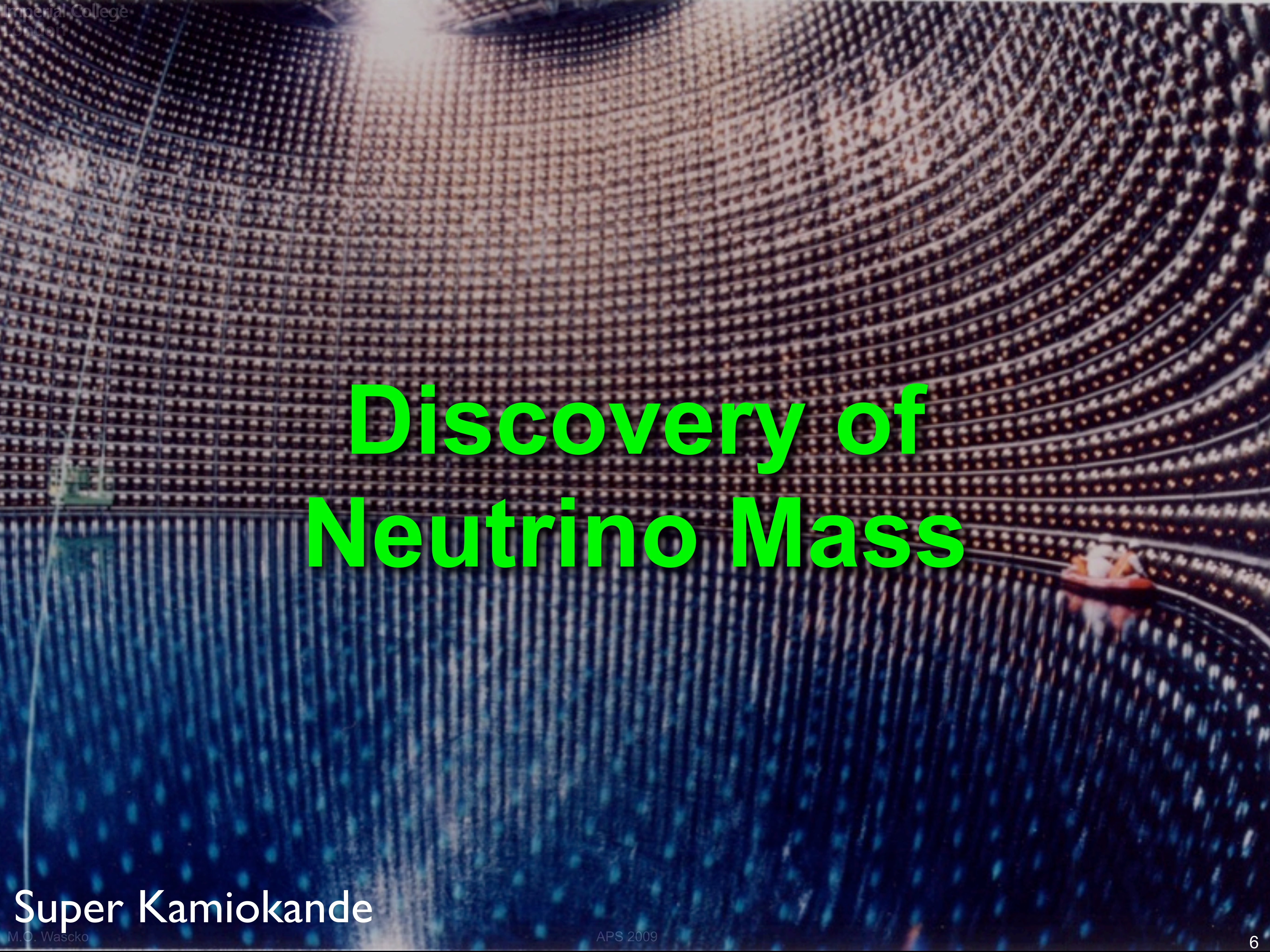
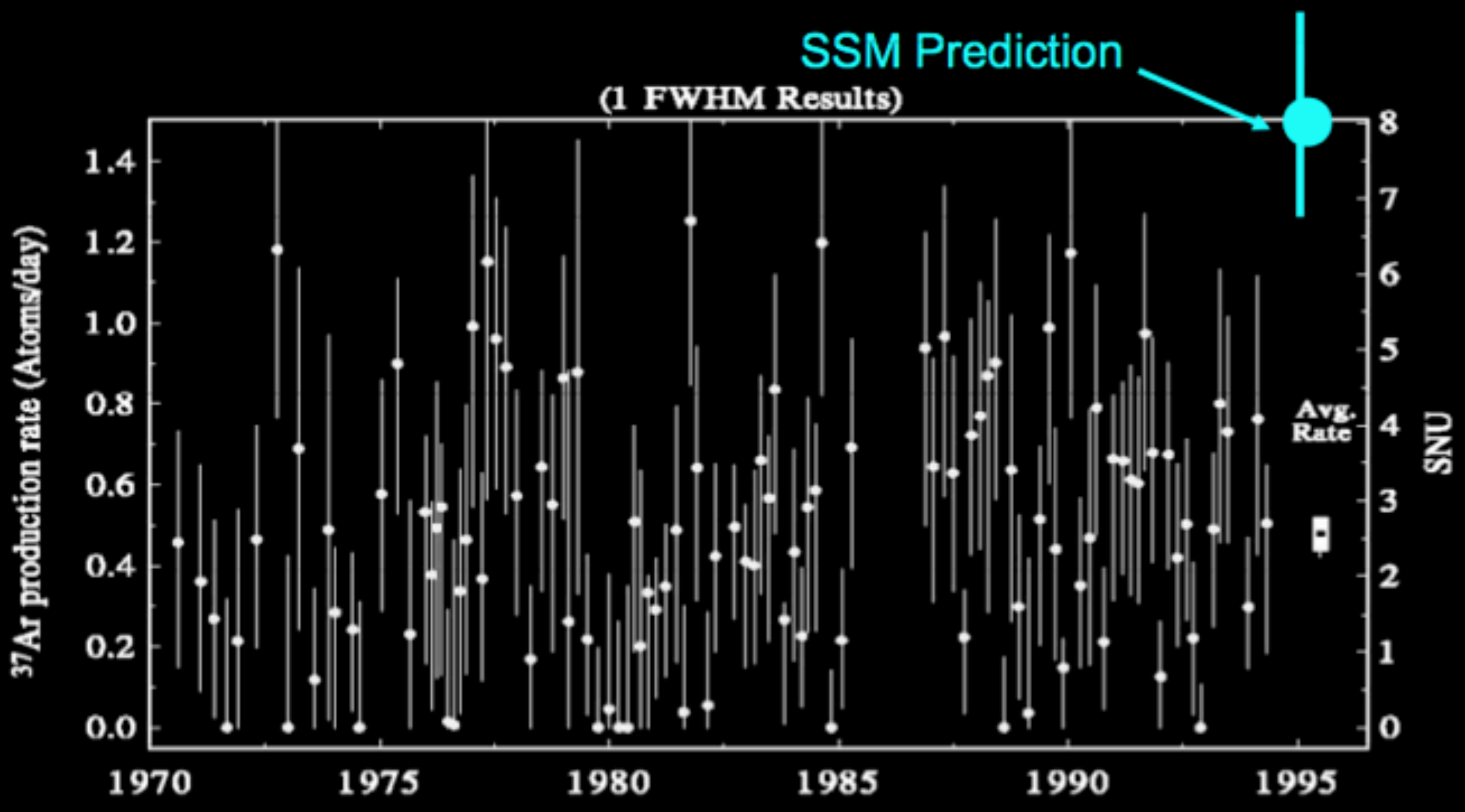


Phys Rev. Lett. ***33****, 1406 (1974)*

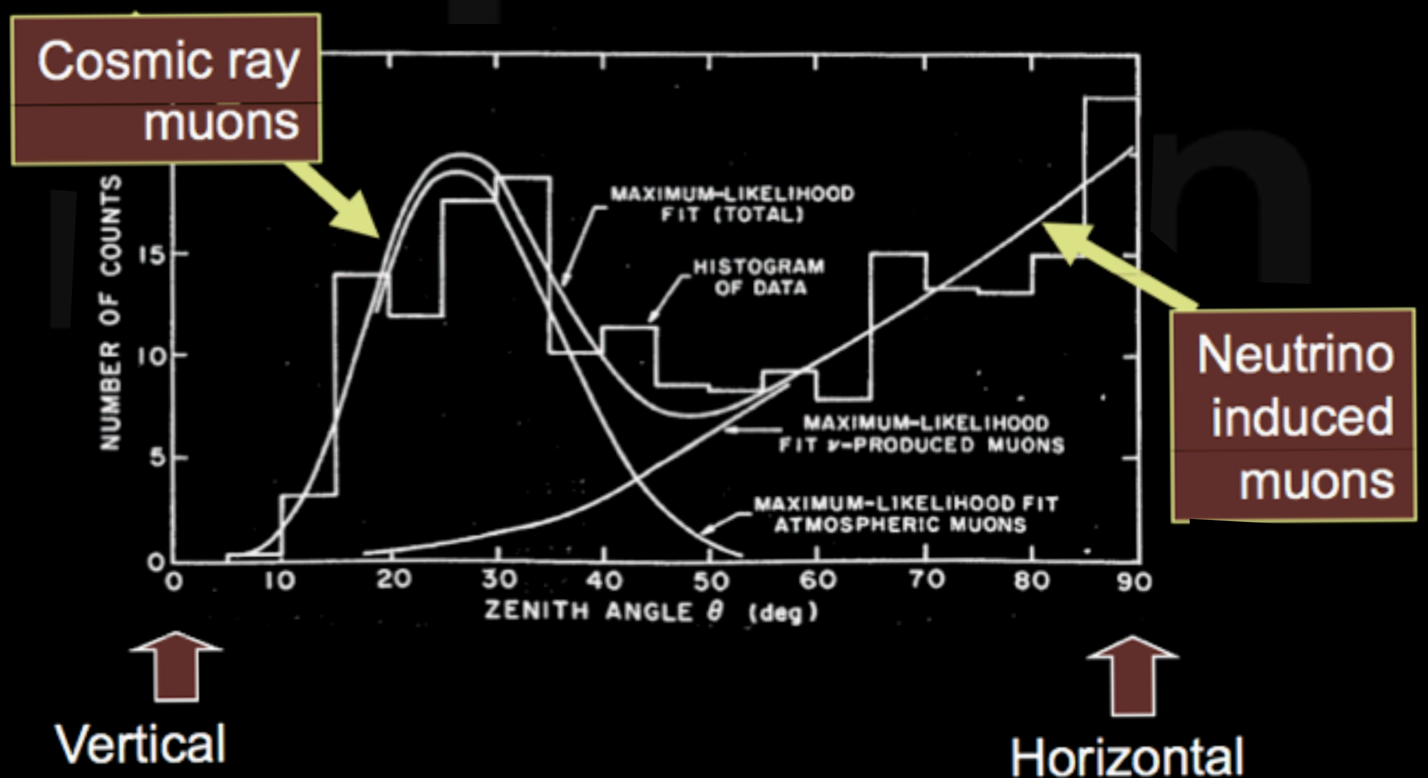
Discovery of Neutrino Mass



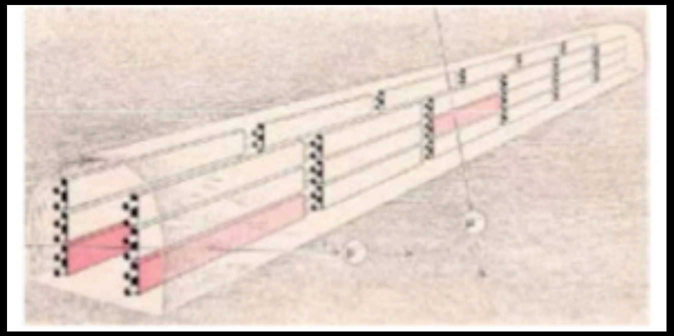
First hints



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



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



Neutrino Oscillation

Pontecorvo, Maki, Nakagawa, Sakata

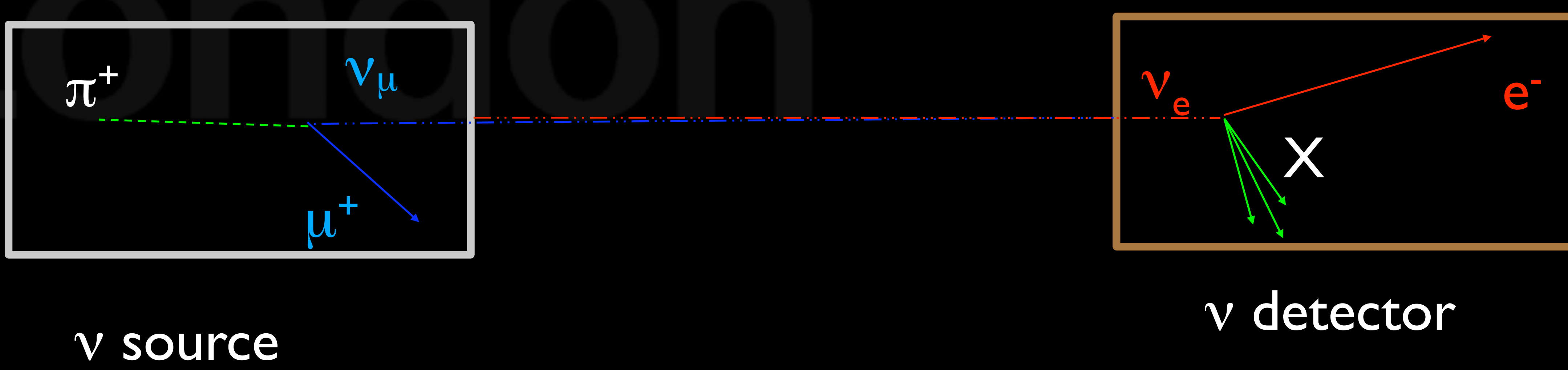
if neutrinos have mass...

a neutrino that is produced as a ν_μ

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

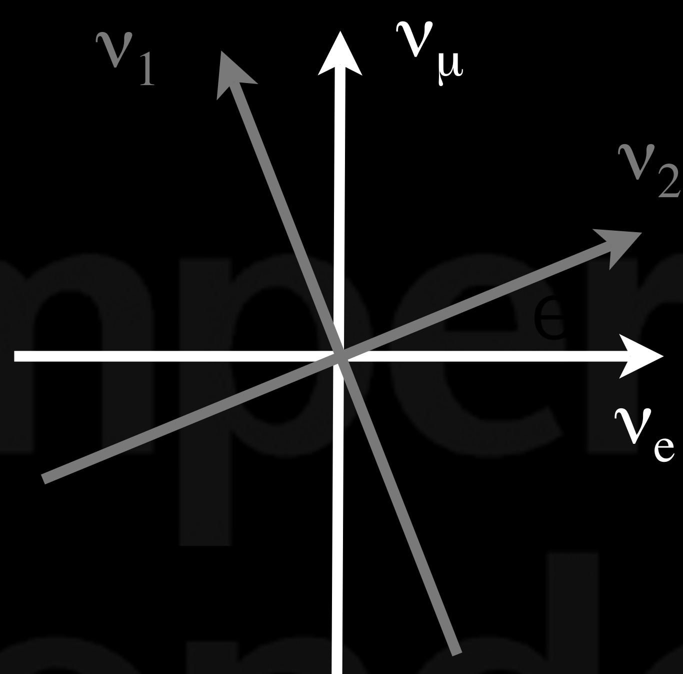
might some time later be observed as a ν_e

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



Neutrino Oscillation

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



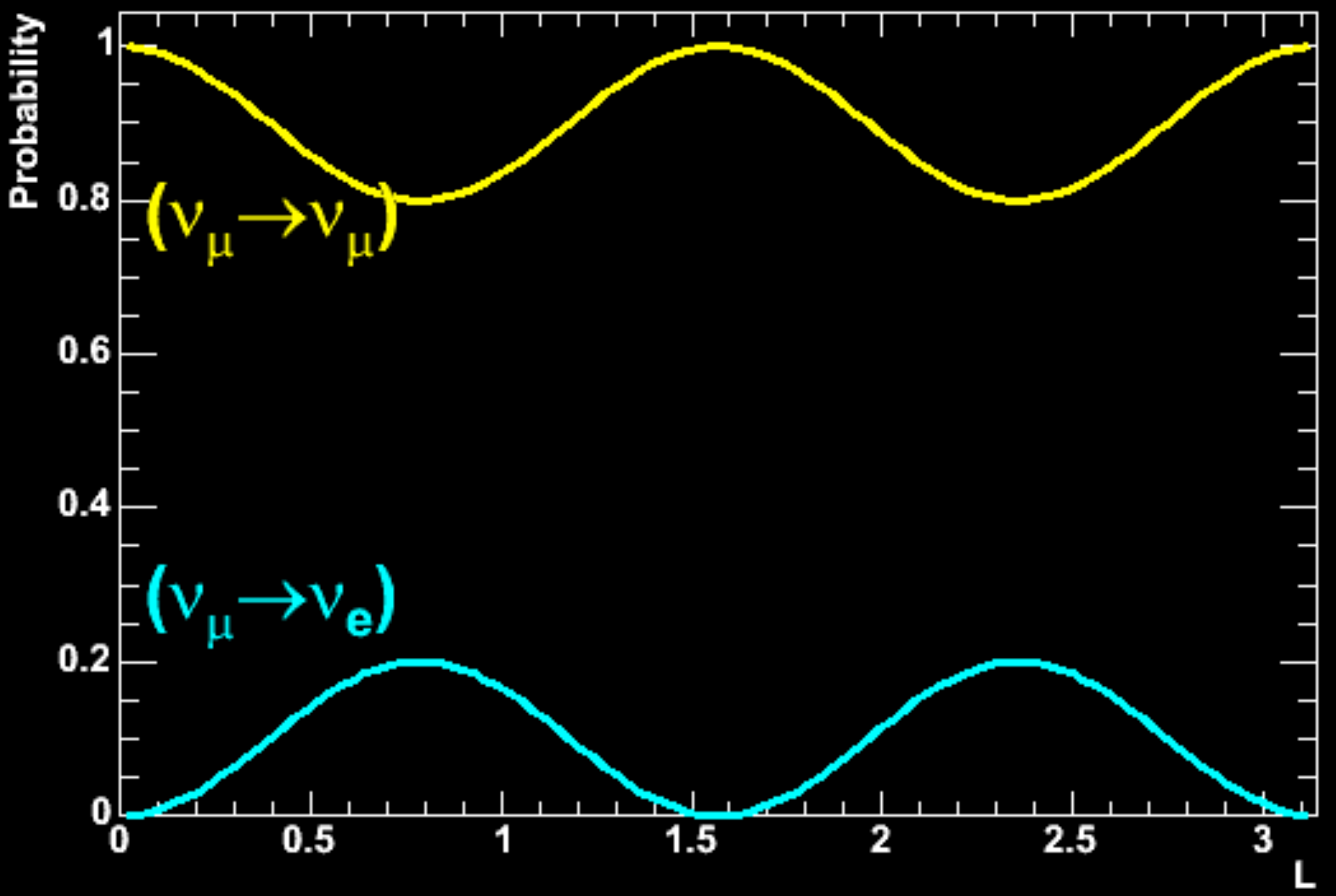
- Consider only two types of neutrinos
- If weak states differ from mass states
  - i.e. $(\nu_\mu\ \nu_e) \neq (\nu_1\ \nu_2)$
- Then weak states are mixtures of mass states

$$|\nu_\mu(t)> = -\sin\theta|\nu_1> e^{-iE_1t} + \cos\theta|\nu_2> e^{-iE_2t}$$

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

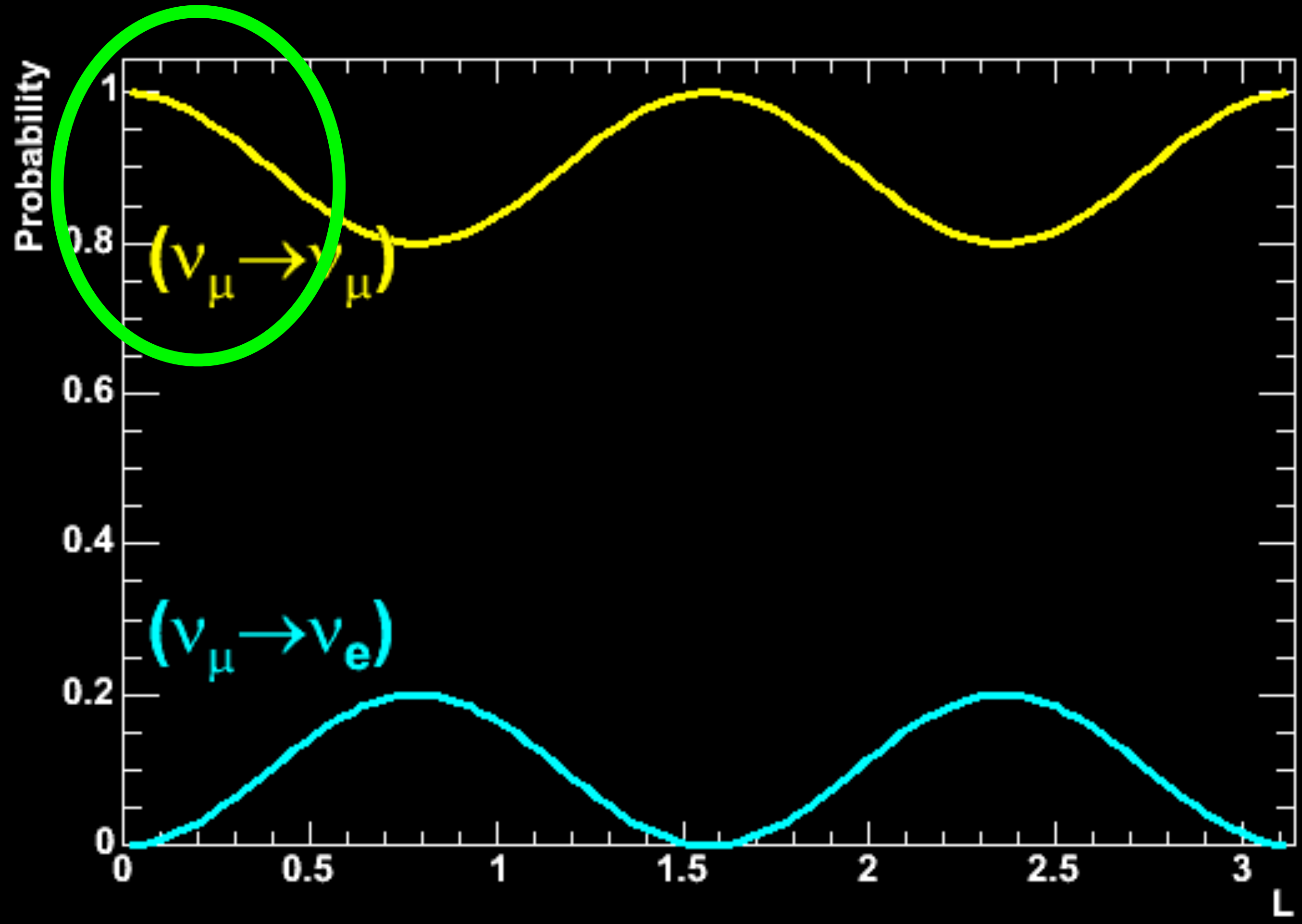
- Probability to find ν_e when you started with ν_μ

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



- 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

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



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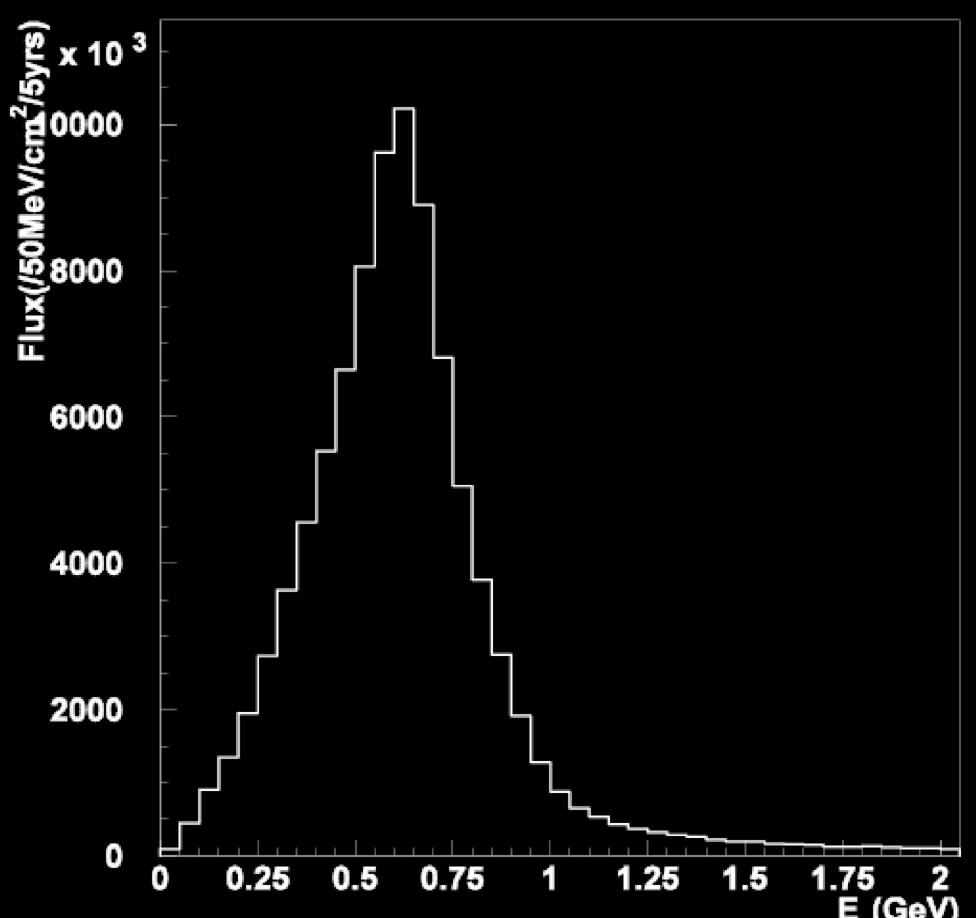

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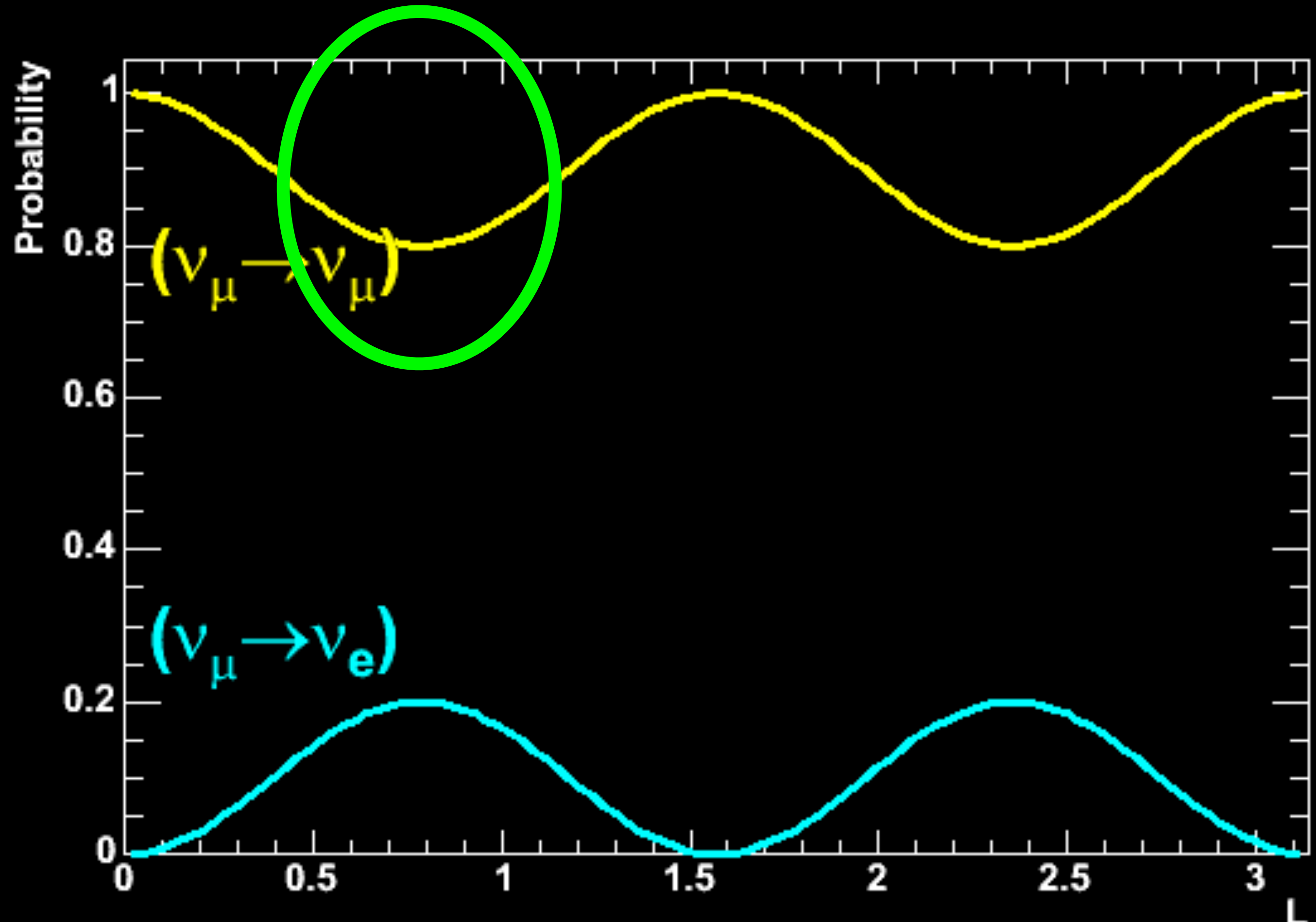

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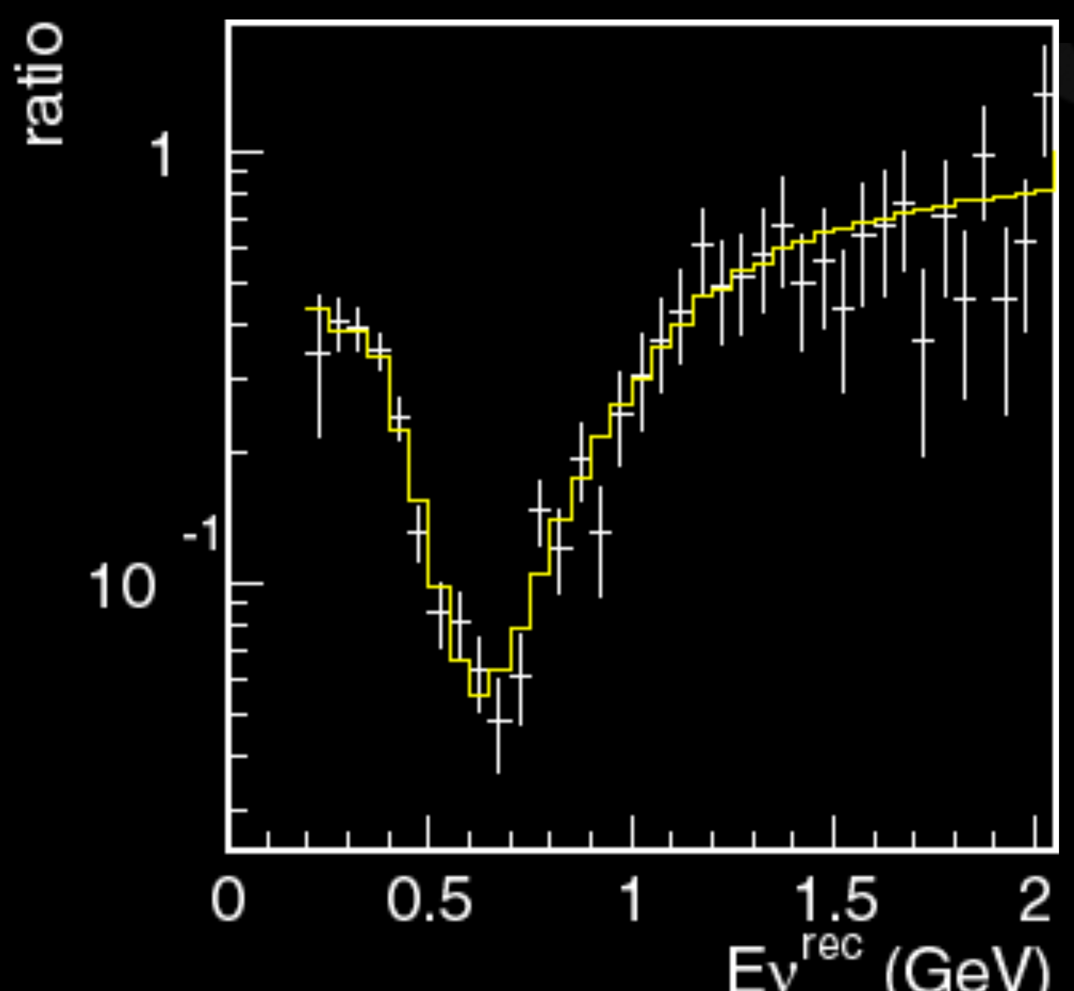

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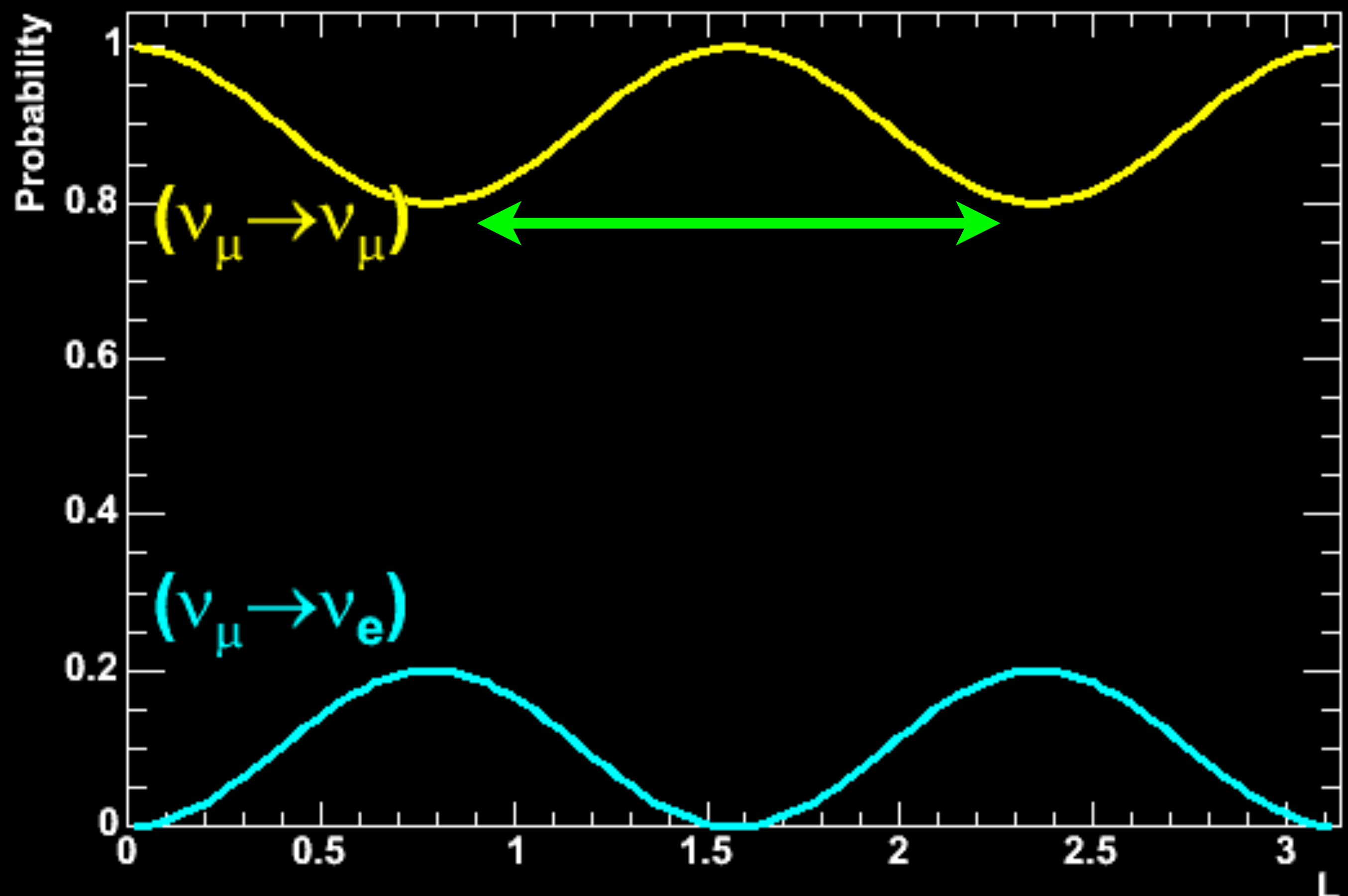

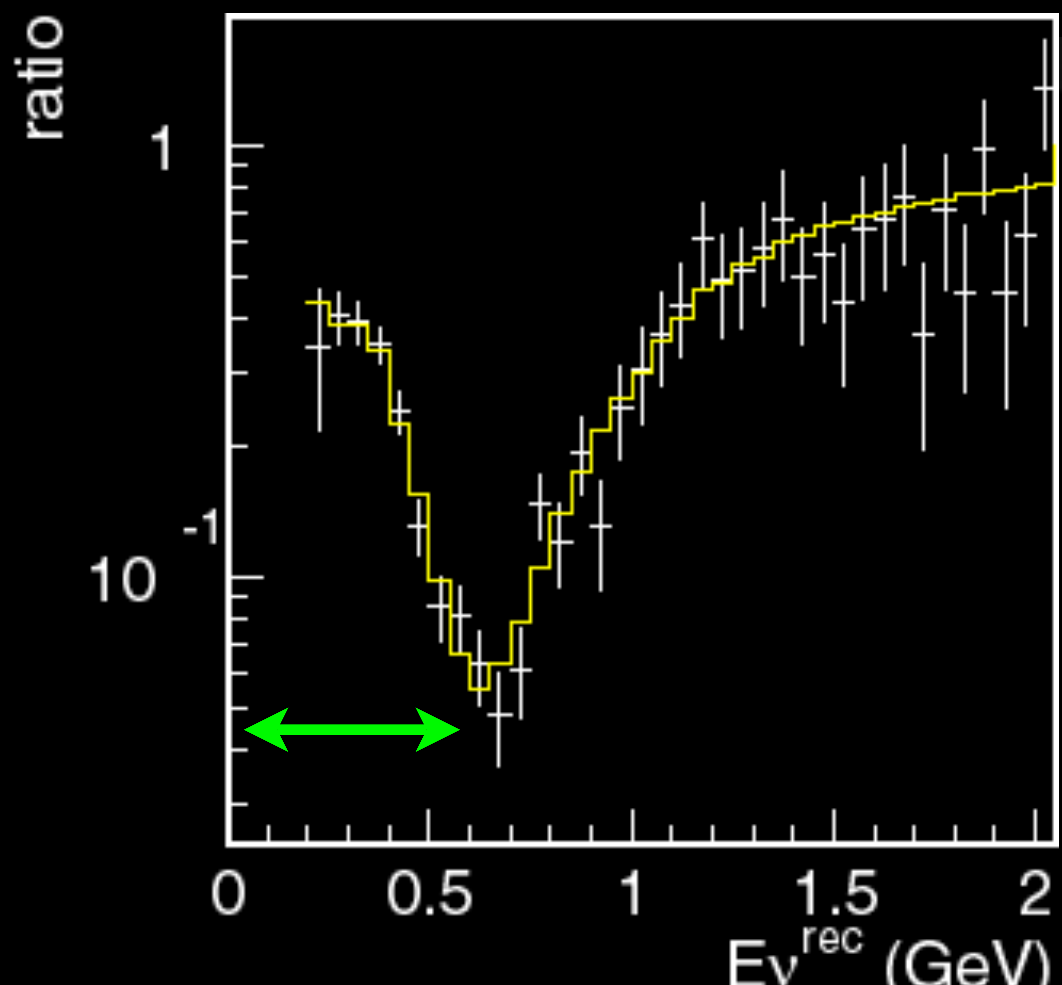

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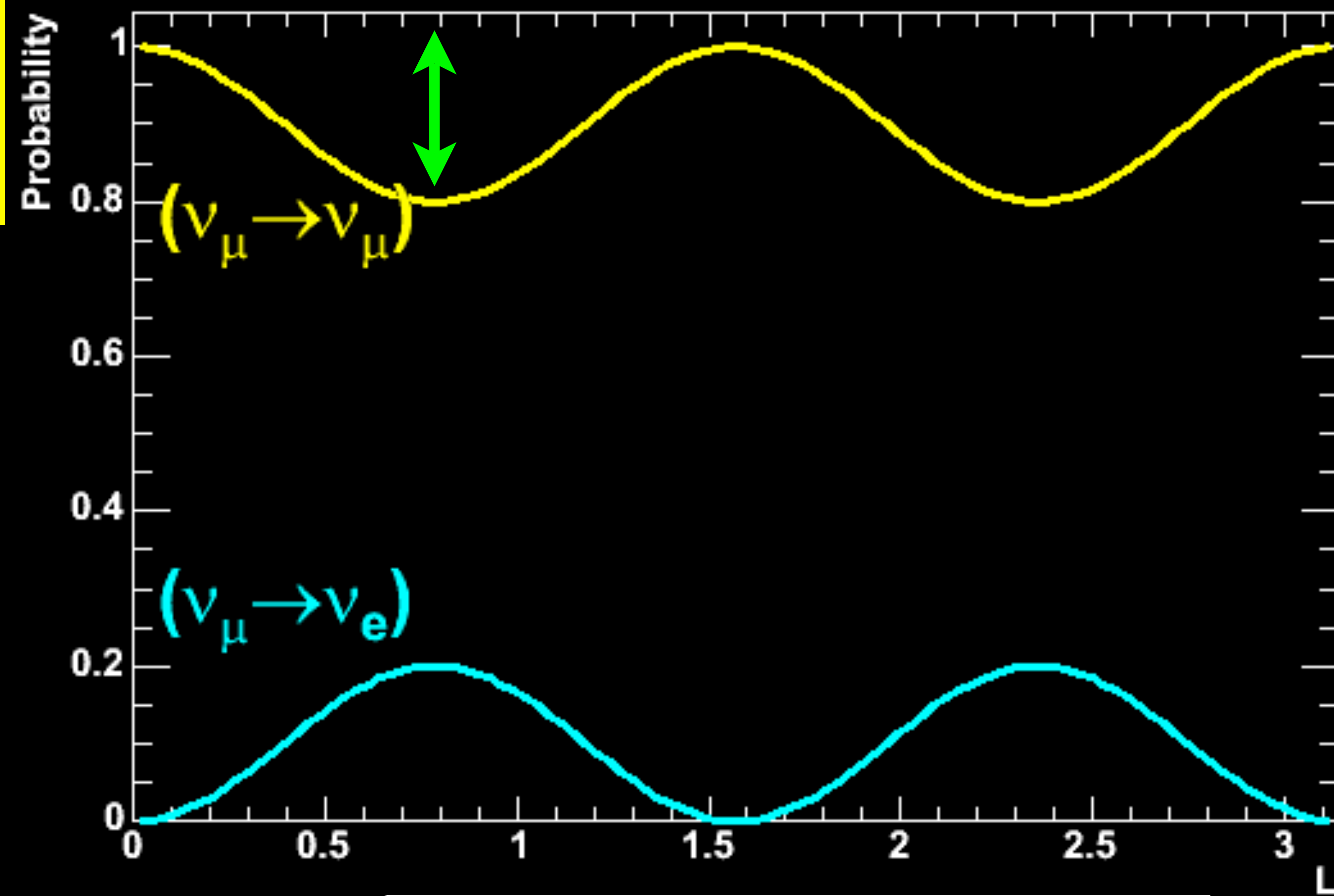

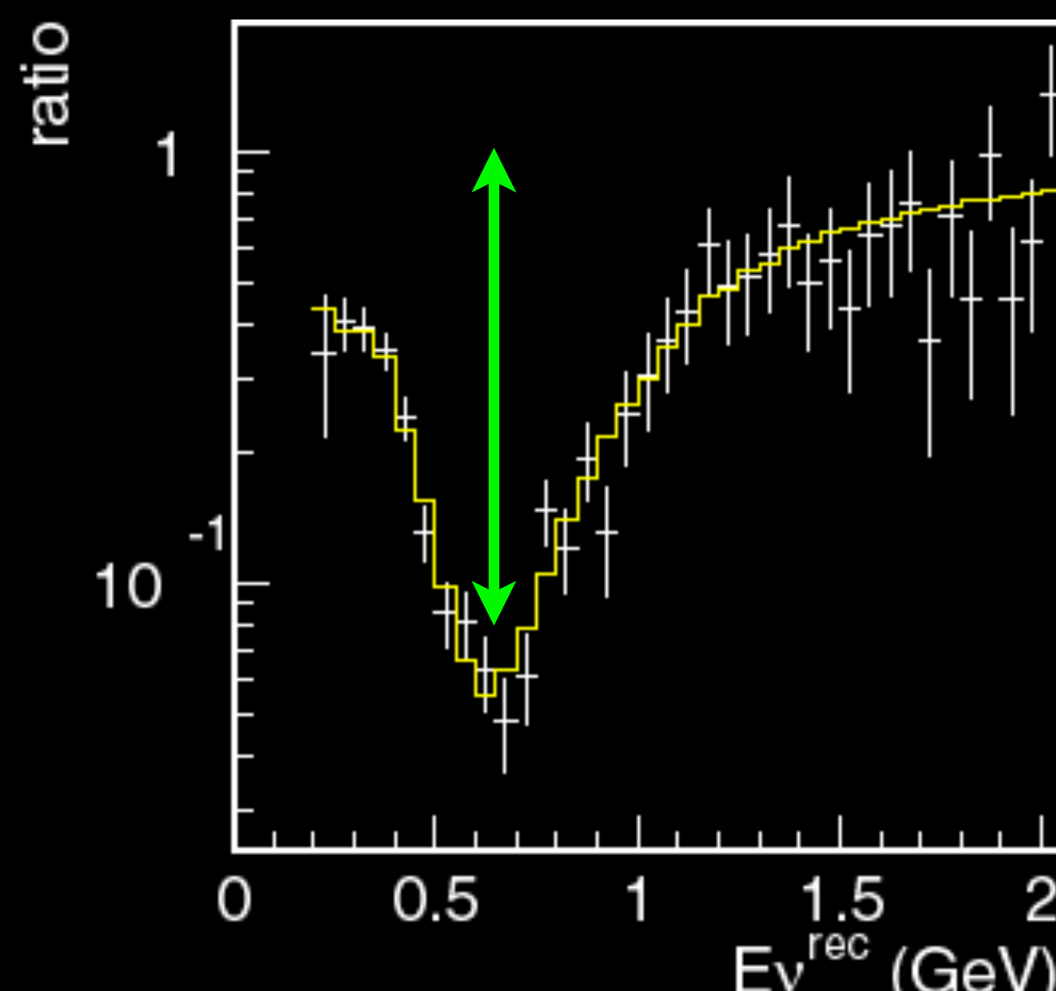

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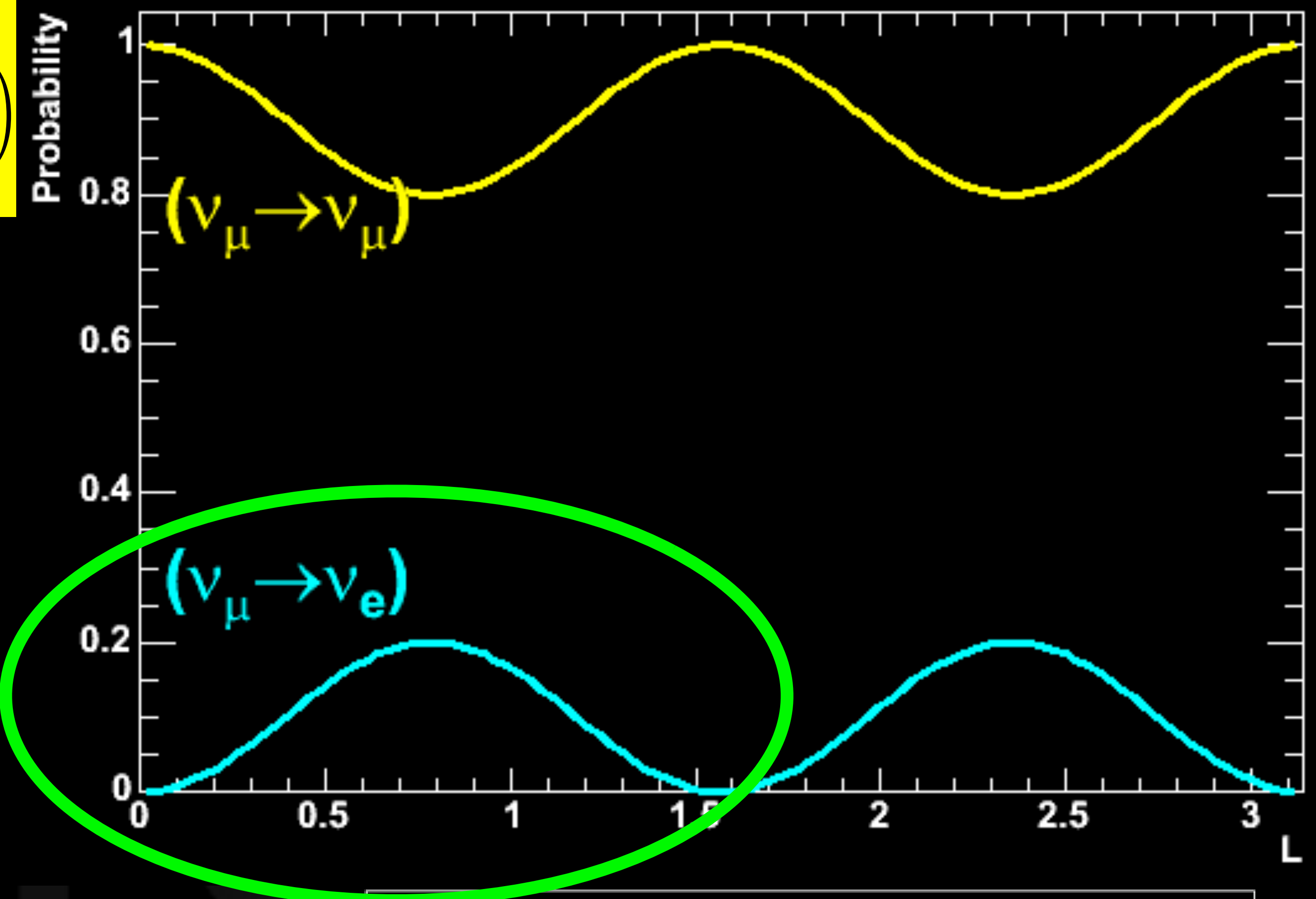

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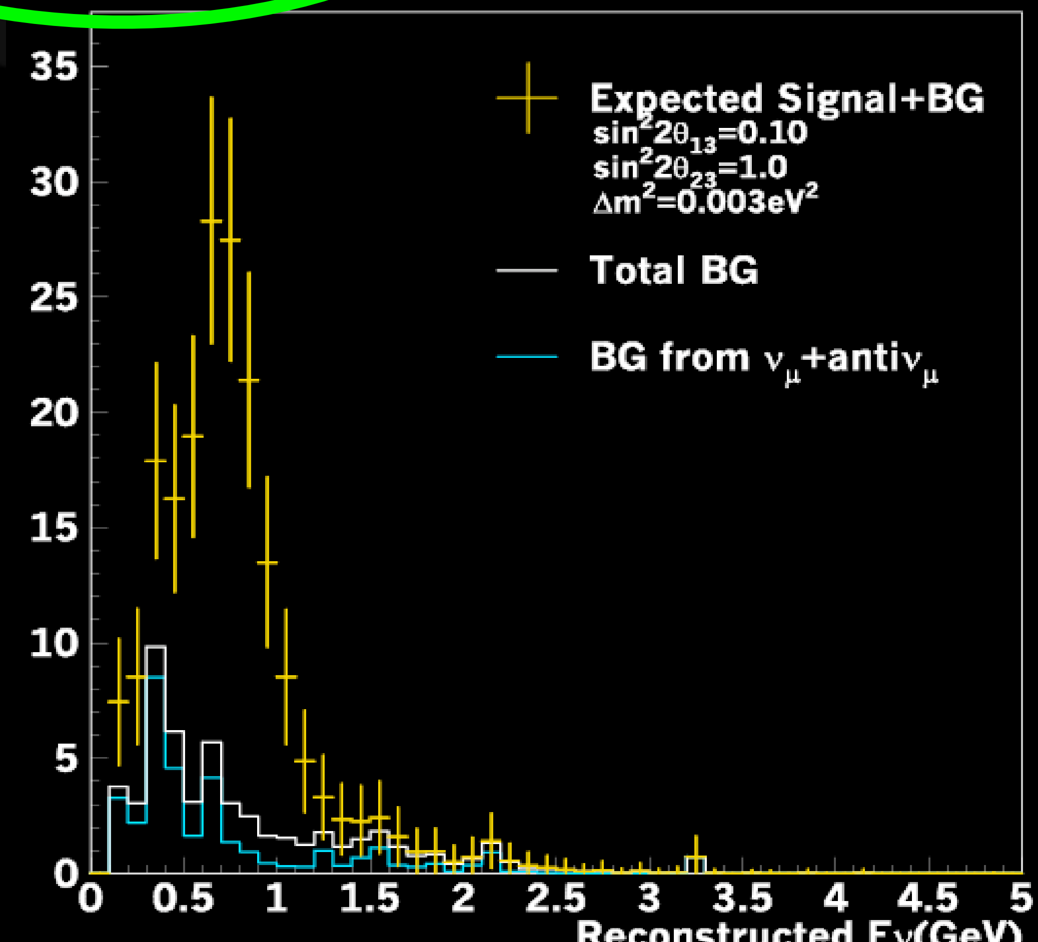

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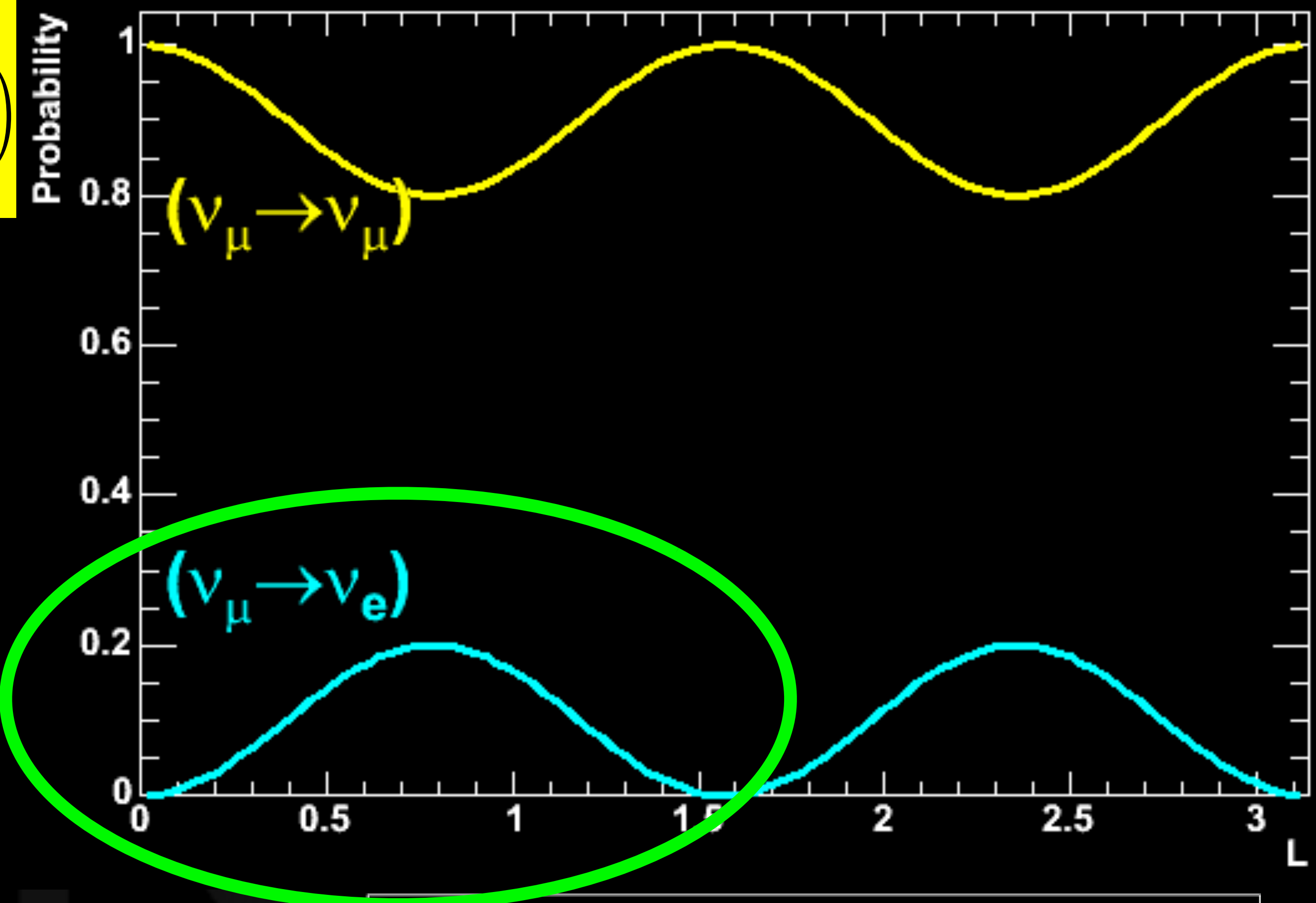
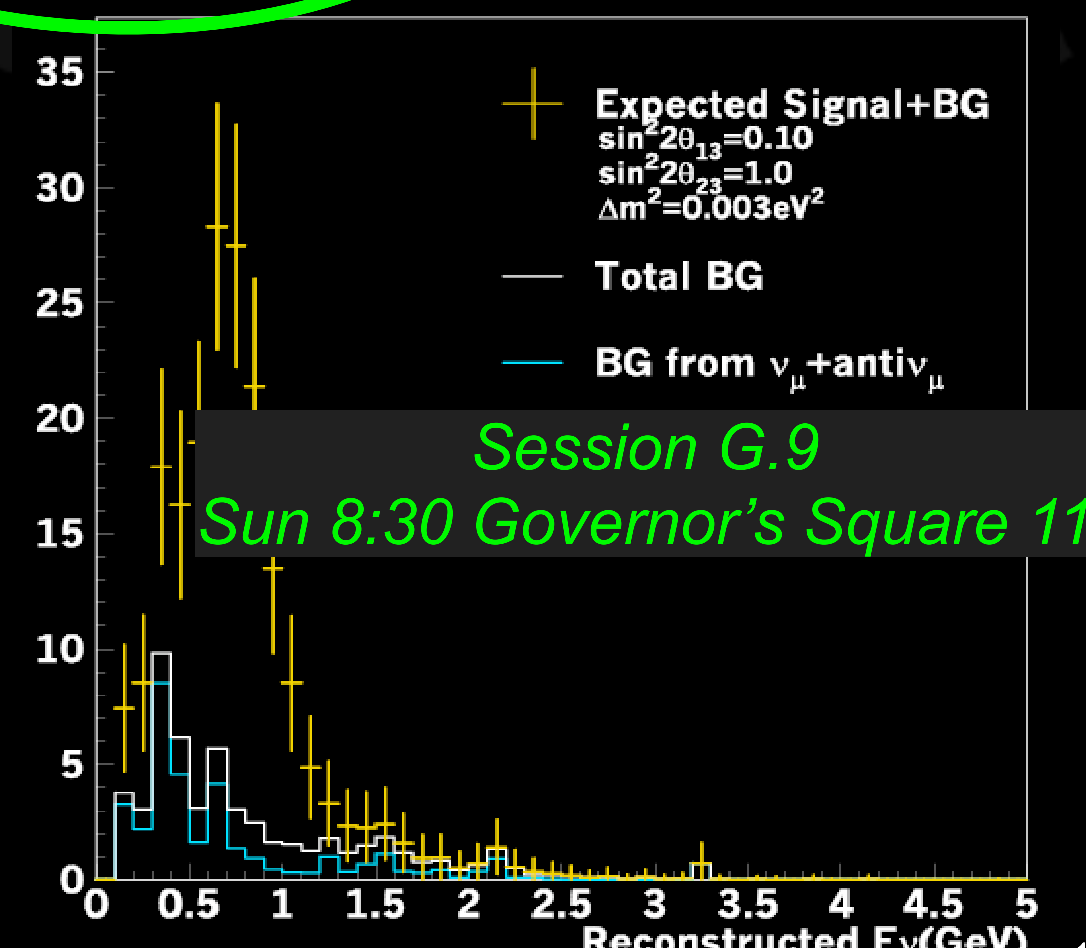
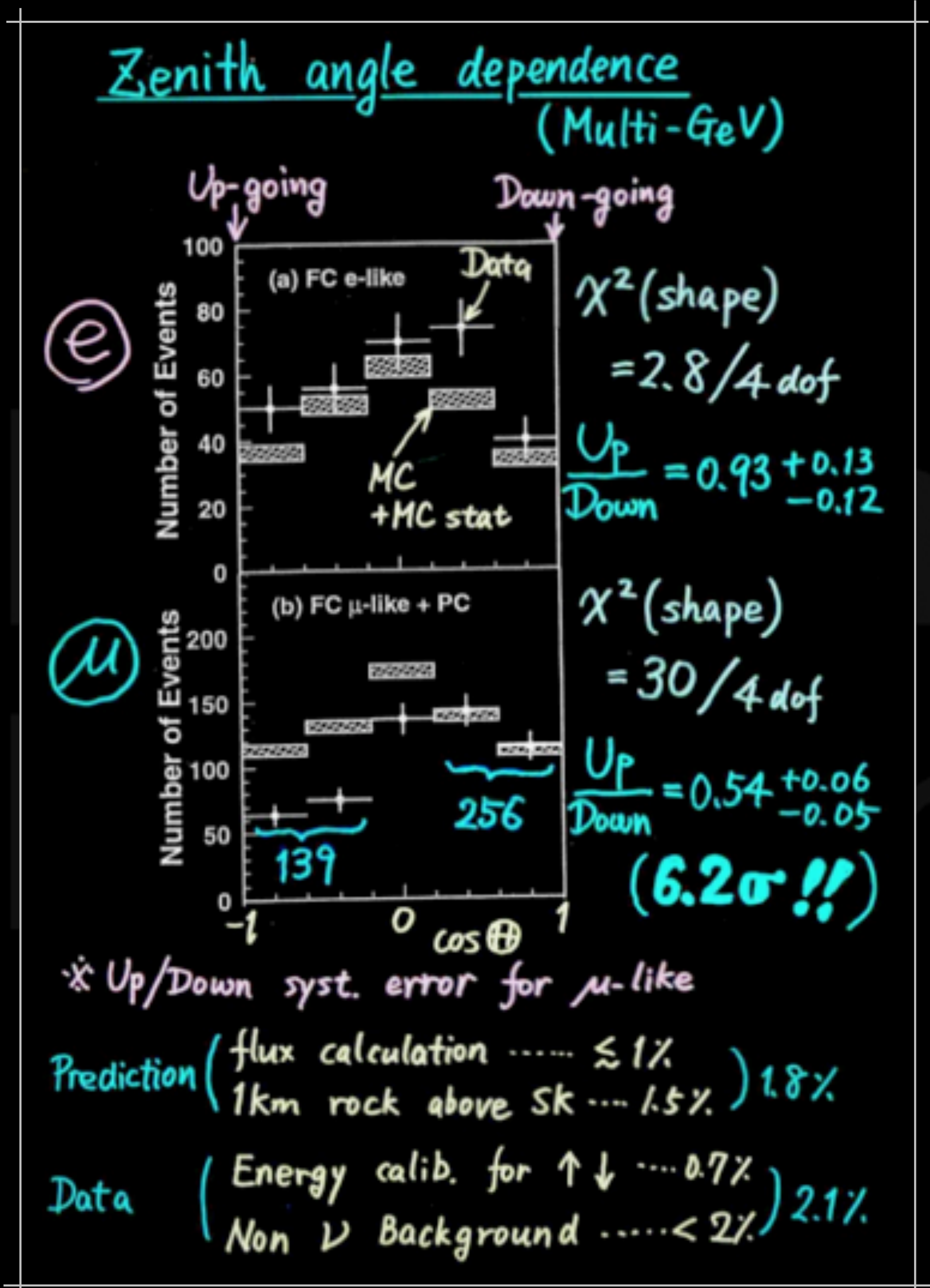


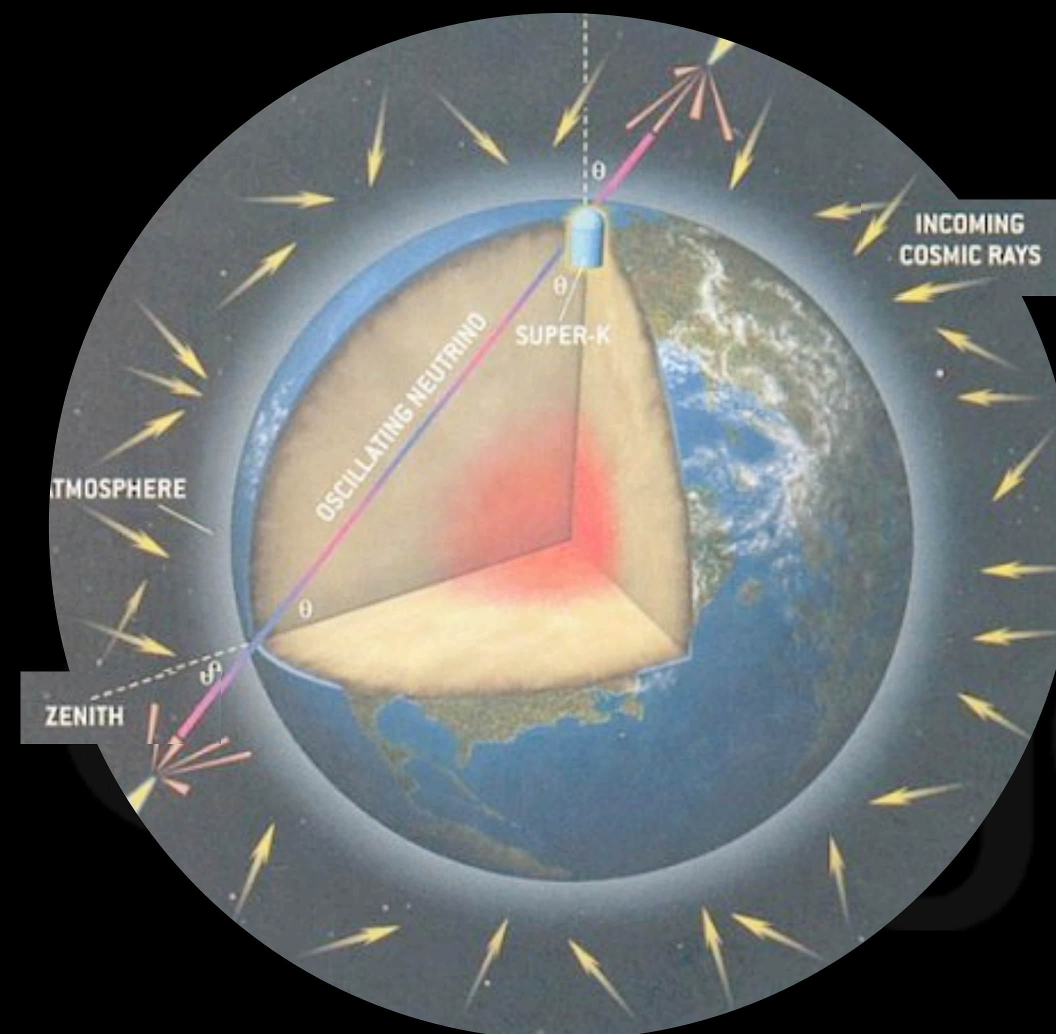


Session G.9
Sun 8:30 Governor's Square 11

Discovery

- Super-Kamiokande @ Neutrino 98

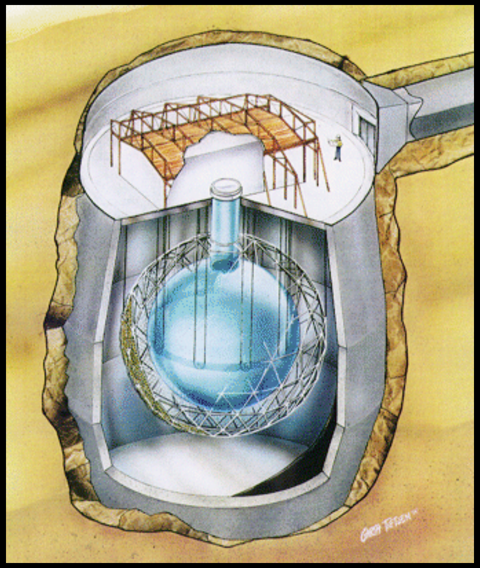




- Difference in observed atmospheric muon neutrino fluxes
  - Depending on zenith angle!
  - 5×10^{-4} eV^2 < Δm^2 < 6×10^{-3} eV^2

*PRL **81**, 1562 (1998)*

Solving Solar Problem



CC: $\nu_e + d \rightarrow p + p + e$

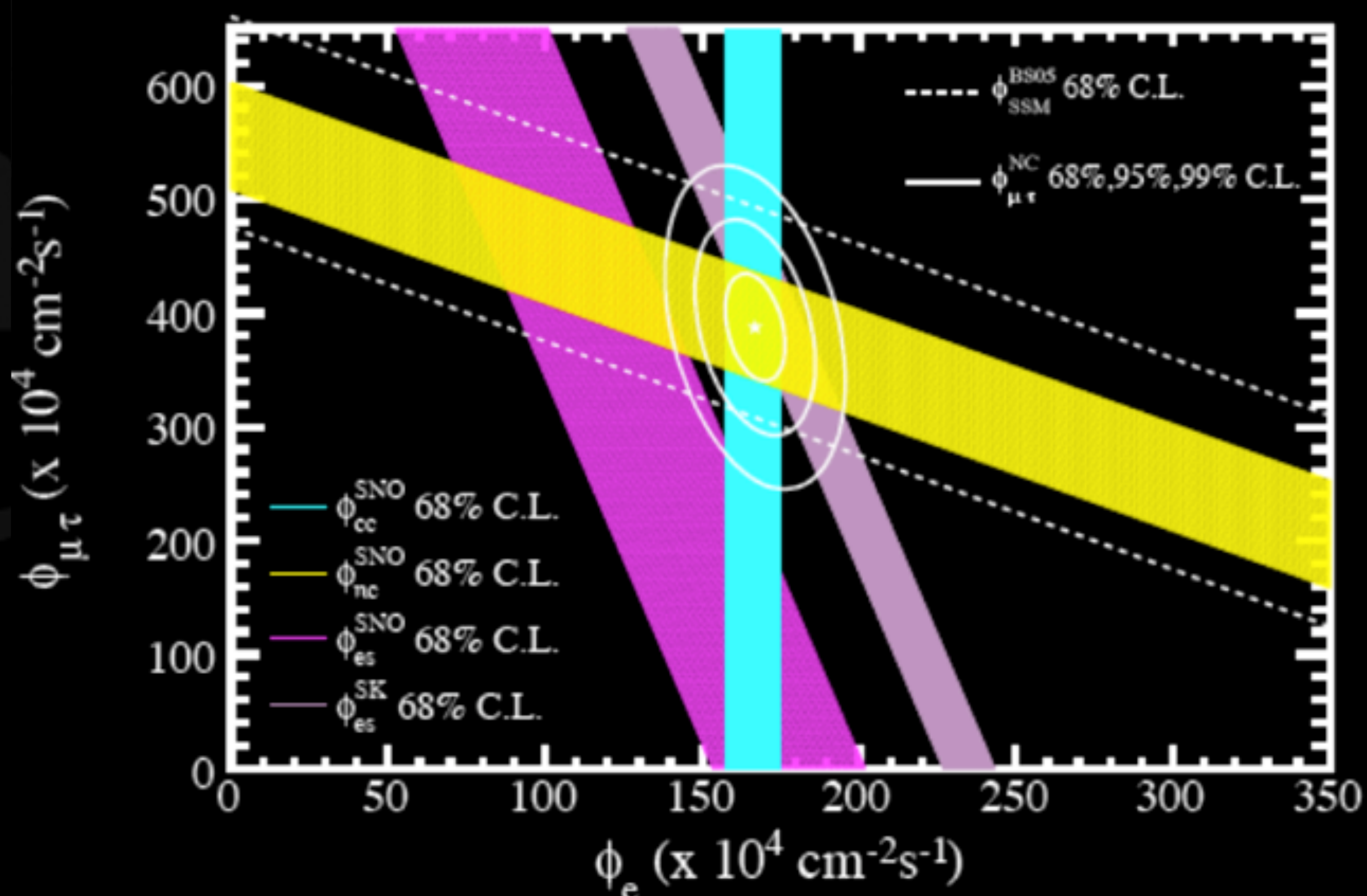
NC: $\nu_x + d \rightarrow p + n + e$

ES: $\nu_x + e^- \rightarrow \nu_x + e^-$

$$\frac{\phi_{CC}^{SNO}}{\phi_{NC}^{SNO}} = 0.301 \pm 0.033(\text{total})$$

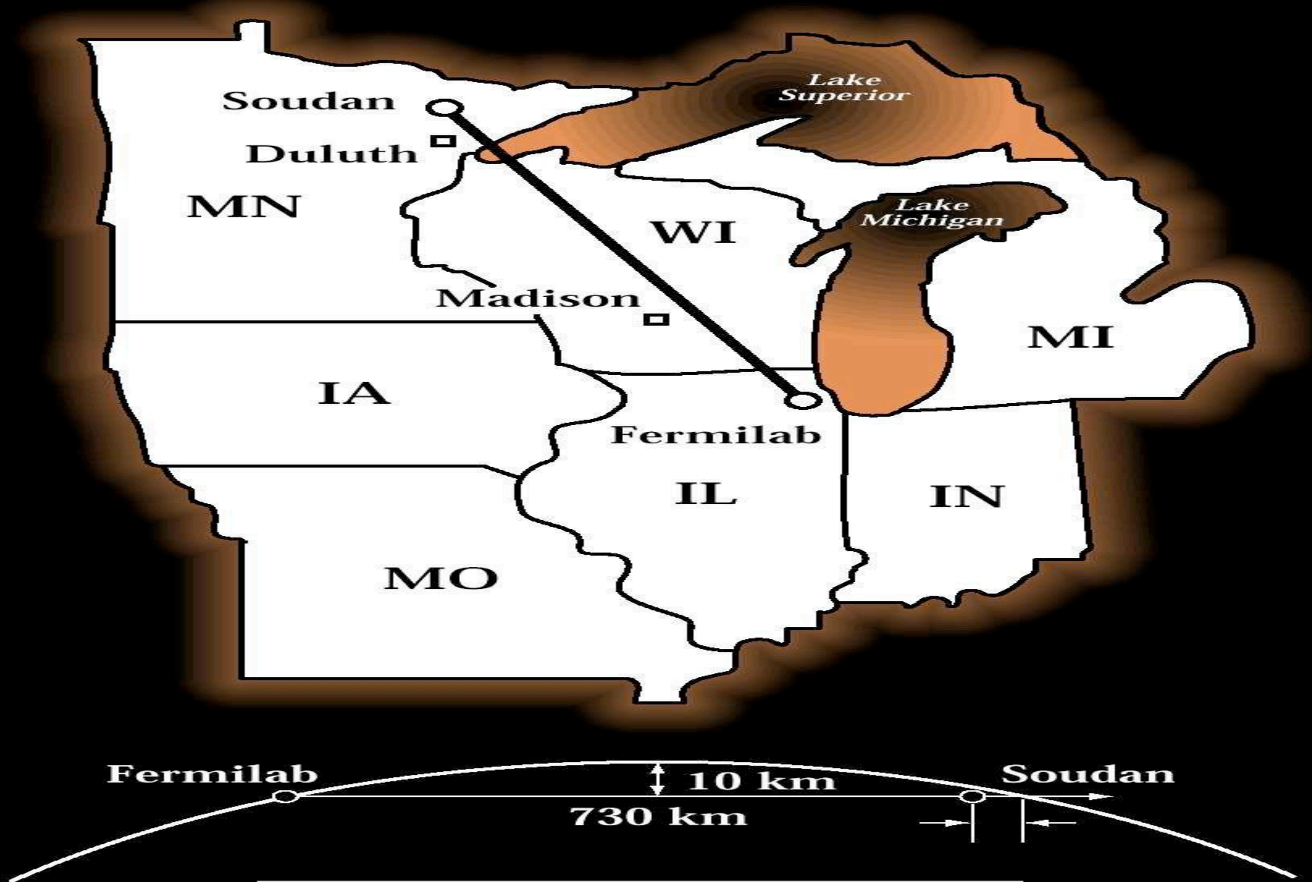
- Sensitive to all flavors
  - CC and NC channels
- Neutrinos transform flavor!
  - Electron flux = 30% of total neutrino flux
  - $\Delta m^2 = 4.6^{+2.8}_{-1.1} \times 10^{-5}\, eV^2$

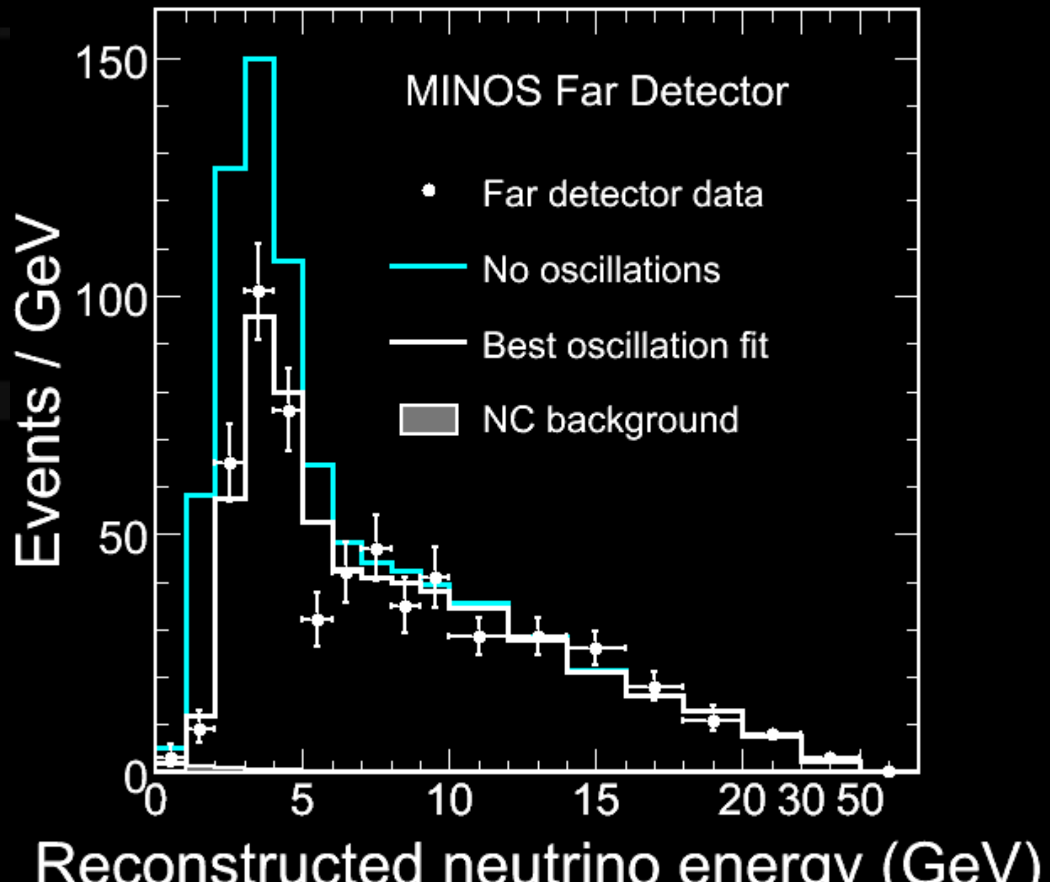
*PRL **101**, 111301 (2008)*

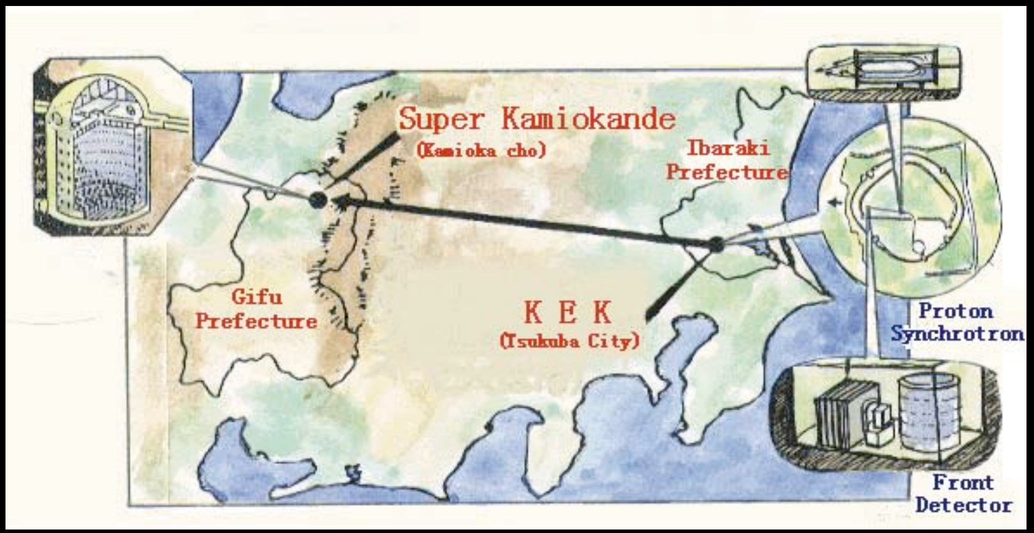


See T. Vahle's talk for more information on mixing

Confirmation





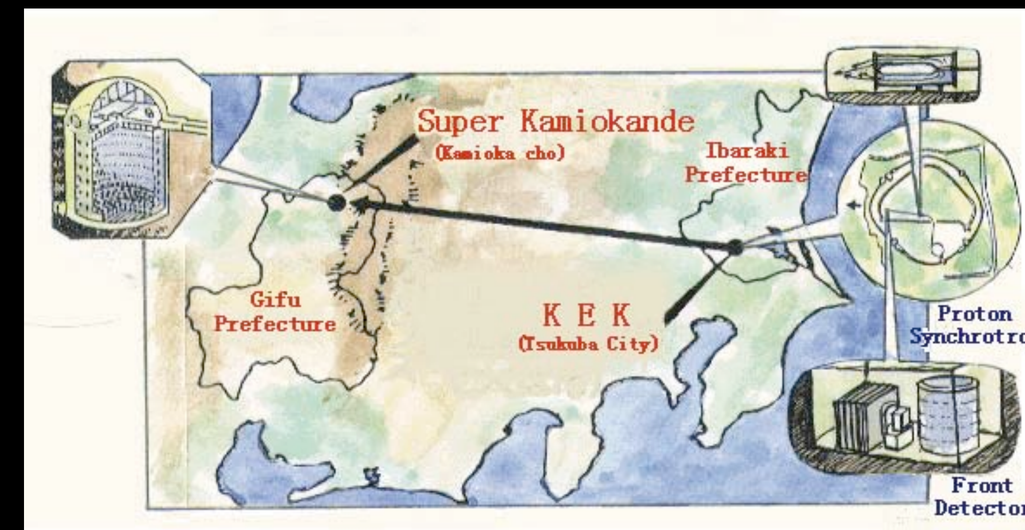


$\nu_\mu + N \rightarrow \mu + X$

- Need same L/E to probe same Δm^2 region as atmospheric
- Confirmed with accelerator neutrinos
  - K2K and MINOS
  - $\Delta m^2 = 2.43 \pm 0.13 \times 10^{-3}$ eV^2

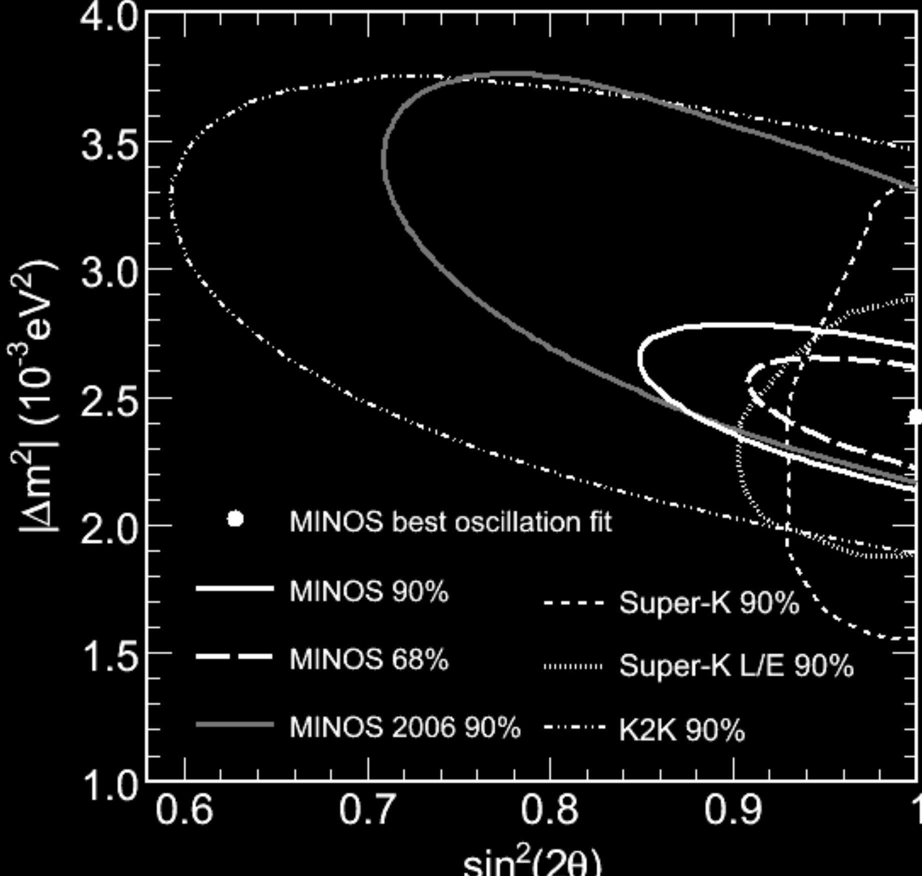
*K2K: PRL **98**, 081802 (2005)*
*MINOS: PRL **101**, 131802 (2008)*

Confirmation



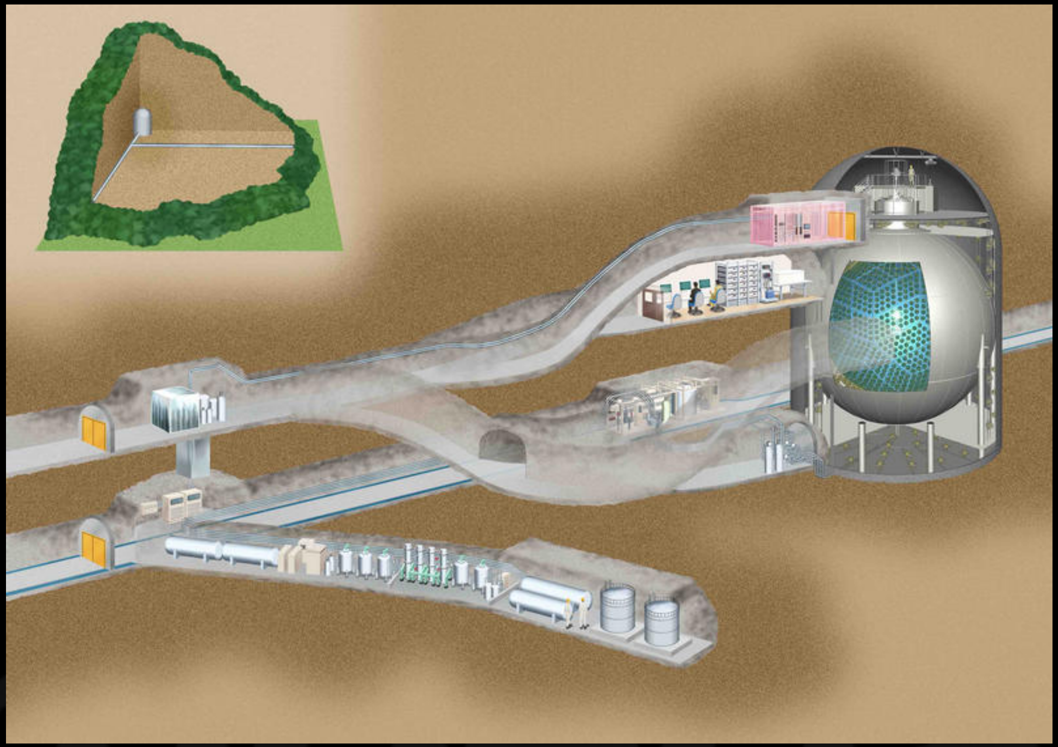
$\nu_\mu + N \rightarrow \mu + X$

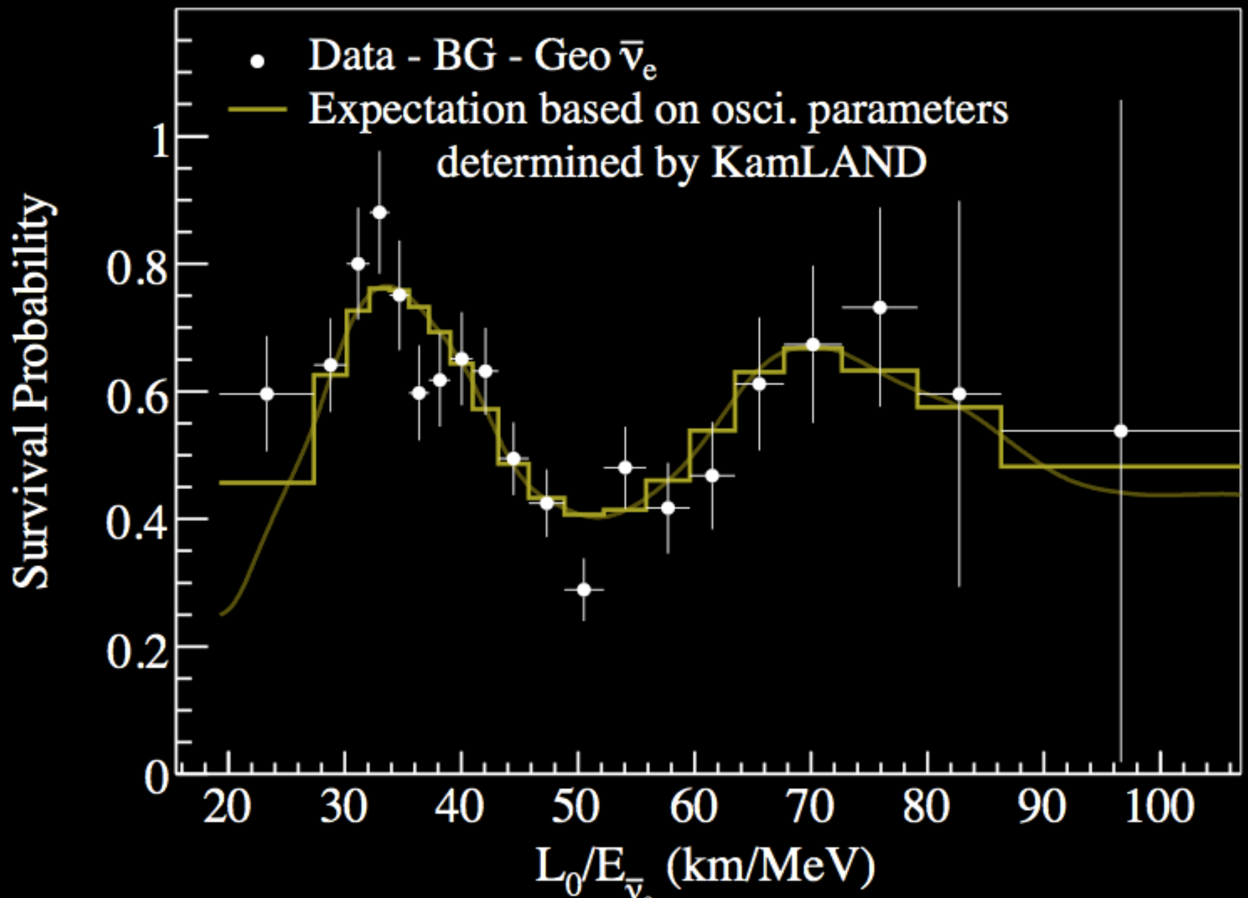
- Need same L/E to probe same Δm^2 region as atmospheric
- Confirmed with accelerator neutrinos
  - K2K and MINOS
  - $\Delta m^2 = 2.43 \pm 0.13 \times 10^{-3}\ eV^2$



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

Confirming Solar



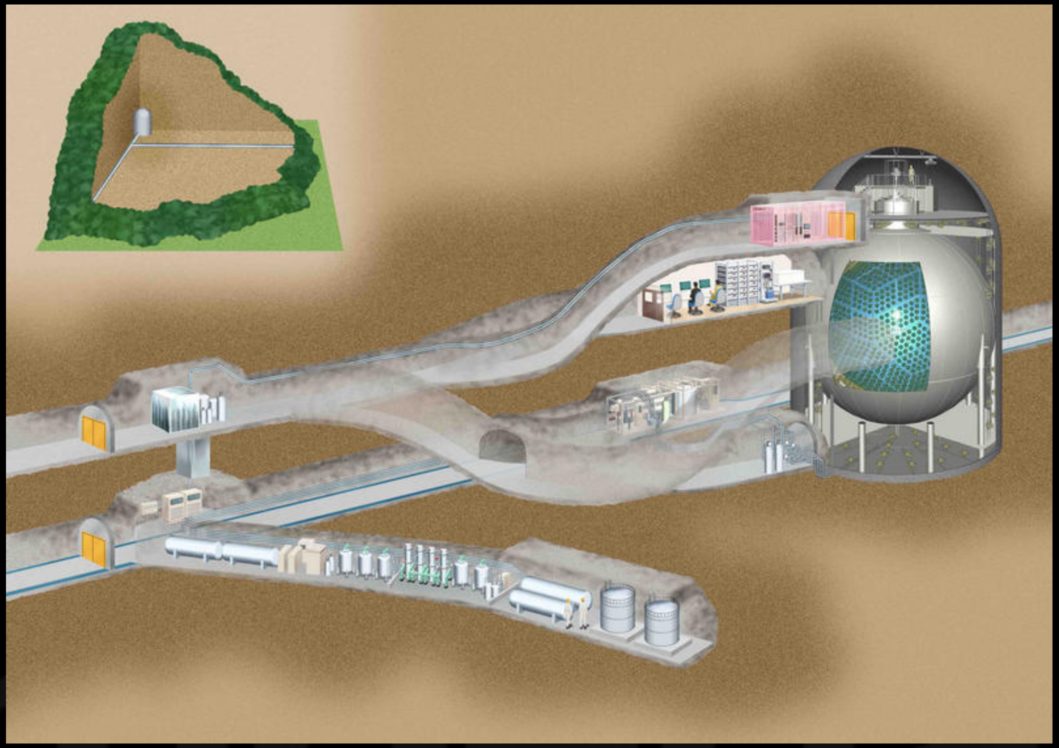


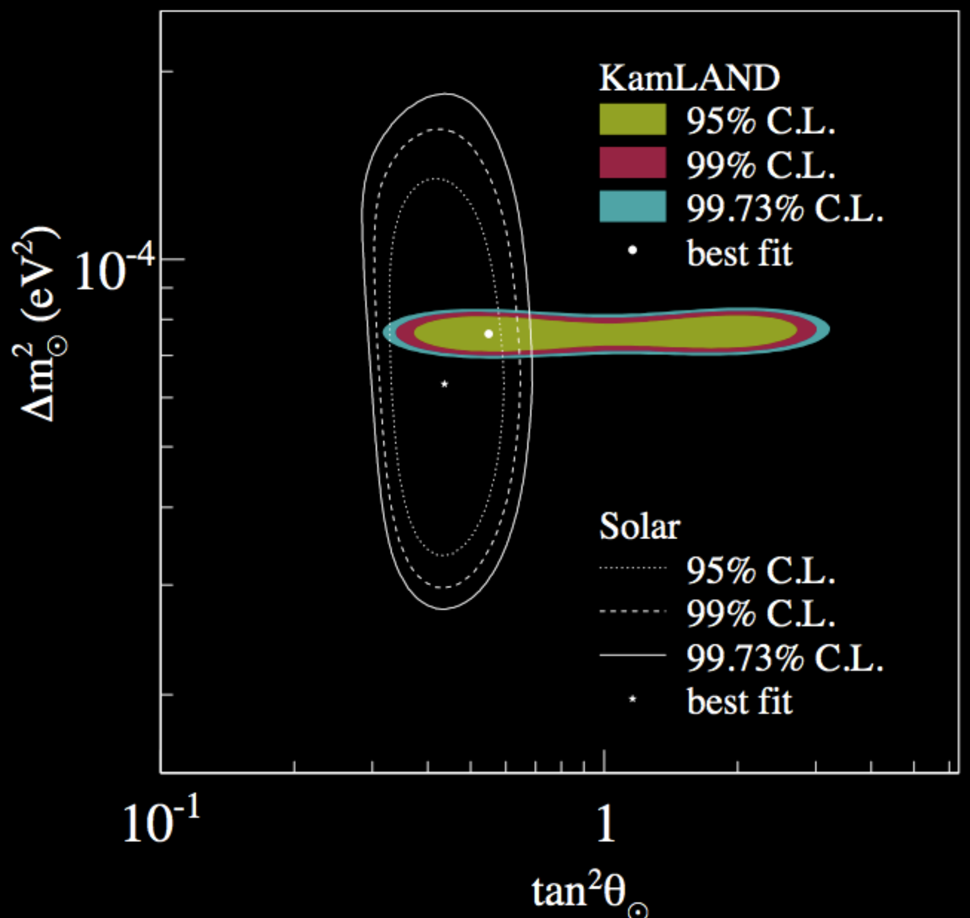
$\bar{\nu}_e + p \rightarrow e^+ + n$

- Solar oscillation confirmed with reactor antineutrinos
- KamLAND experiment sensitive to antineutrinos from several reactors
  - Similar mixing angle
  - $\Delta m^2 = 7.58^{+0.21}_{-0.20} \times 10^{-5}\, eV^2$

*PRL **100**, 221803 (2008)*

Confirming Solar





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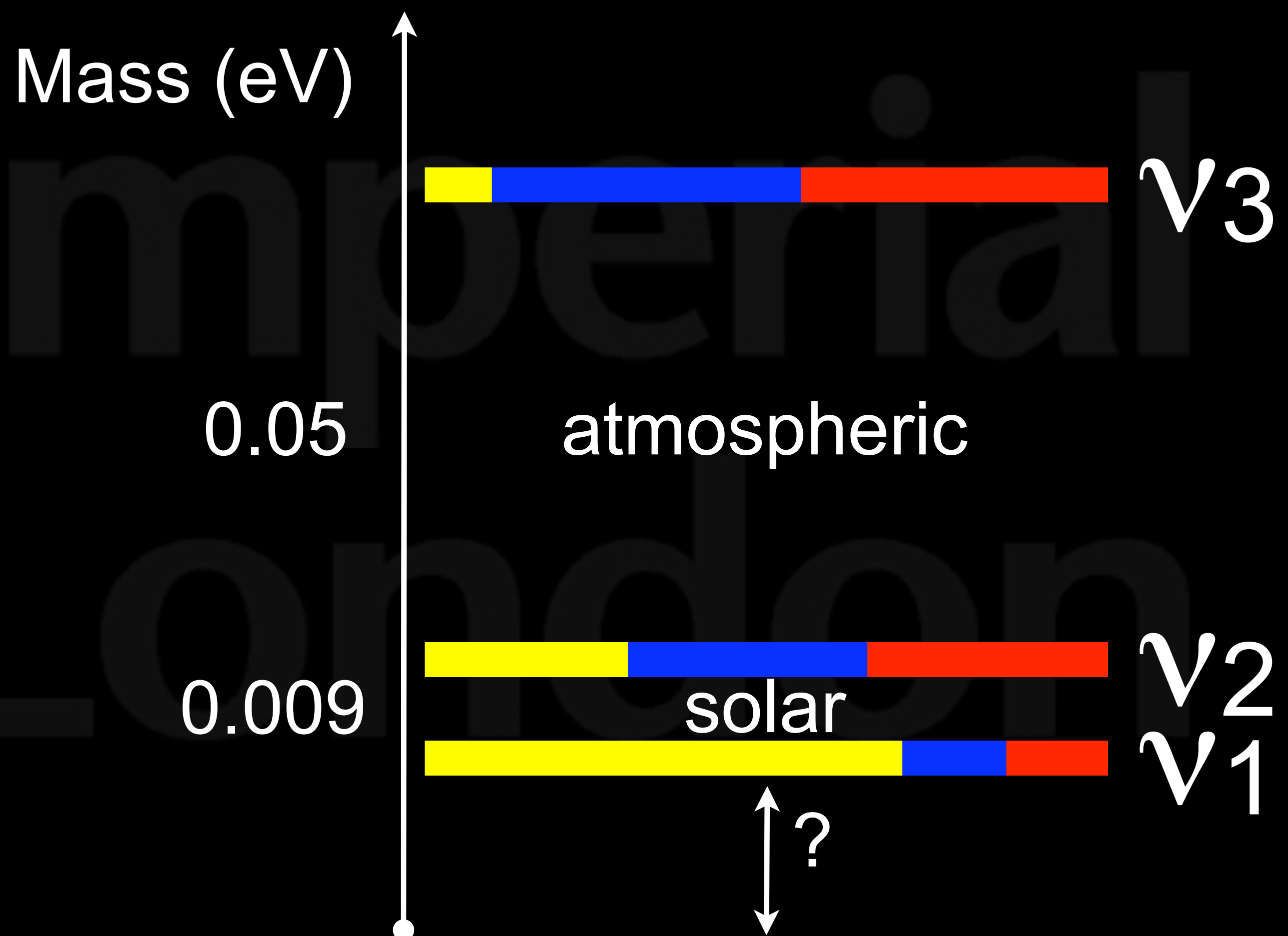
*PRL **100**, 221803 (2008)*

Mass Spectrum

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

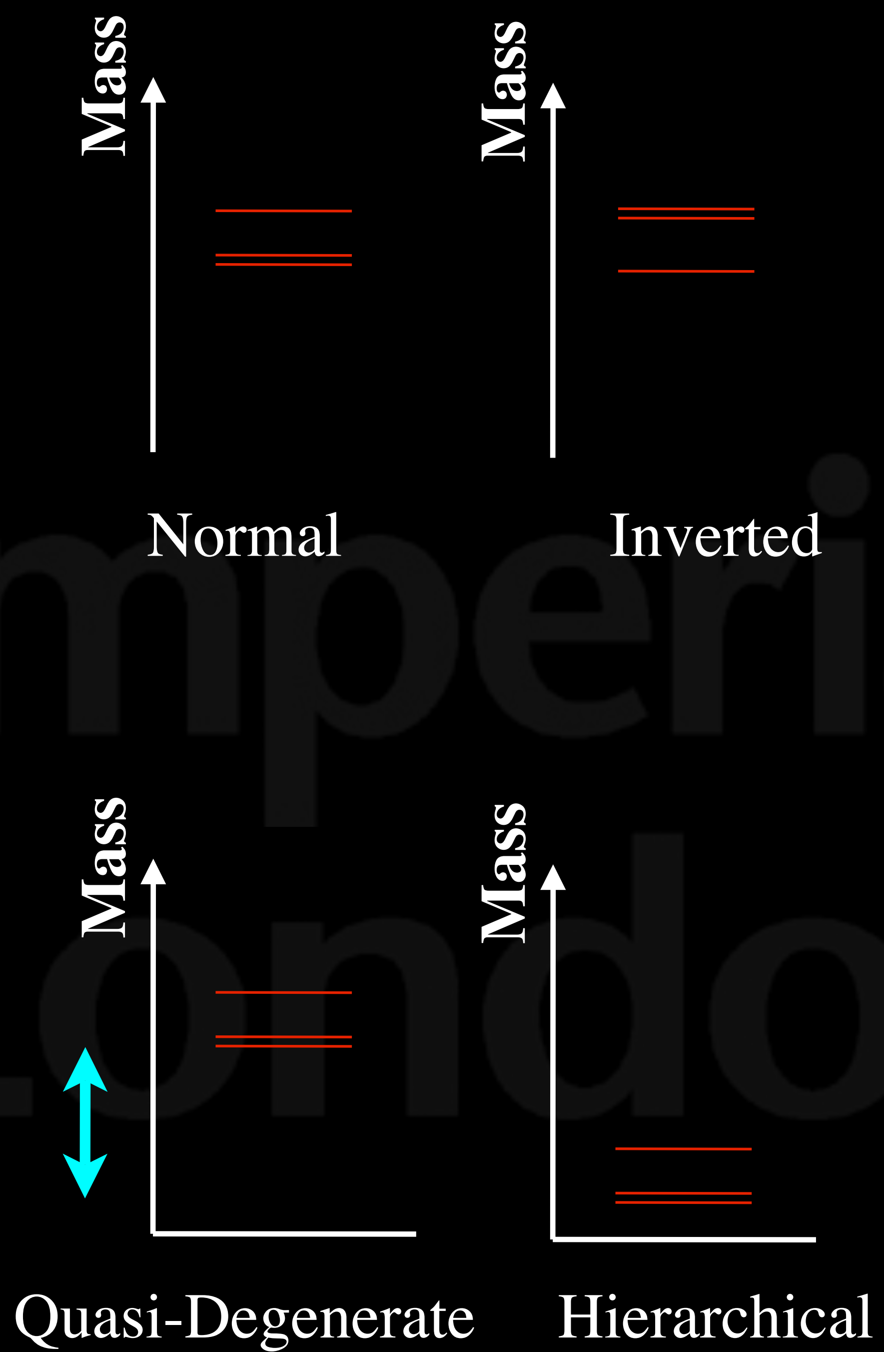
flavor mass



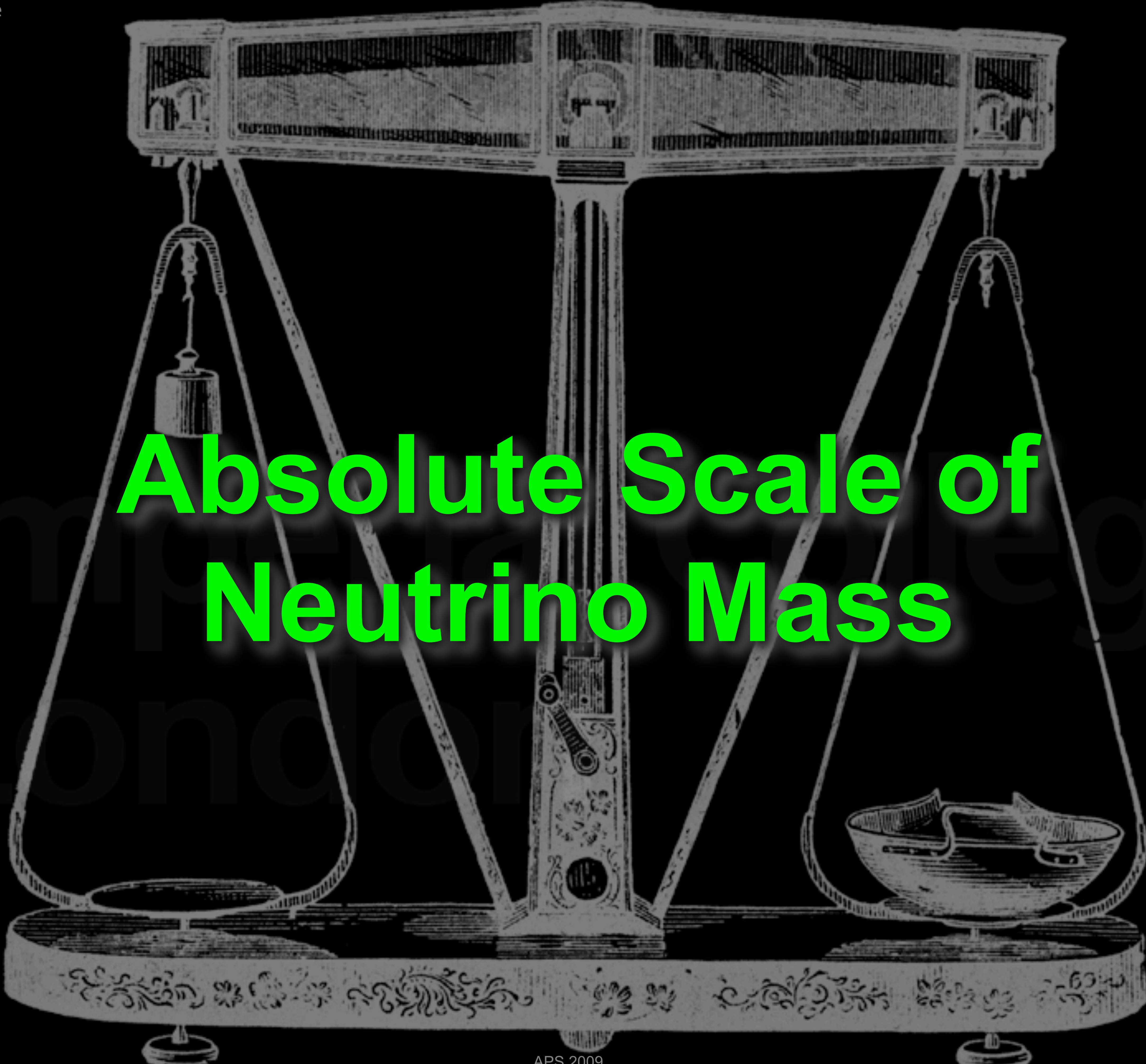
flavor key:

ν_e ν_μ ν_τ

Open Questions

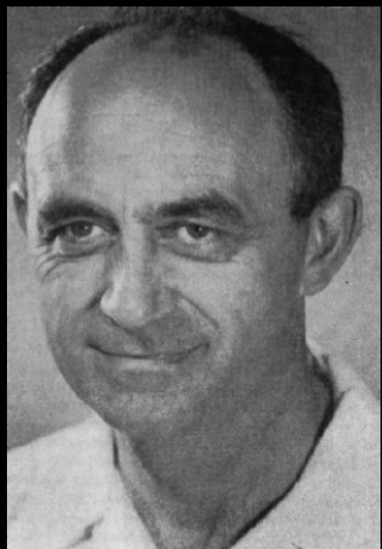


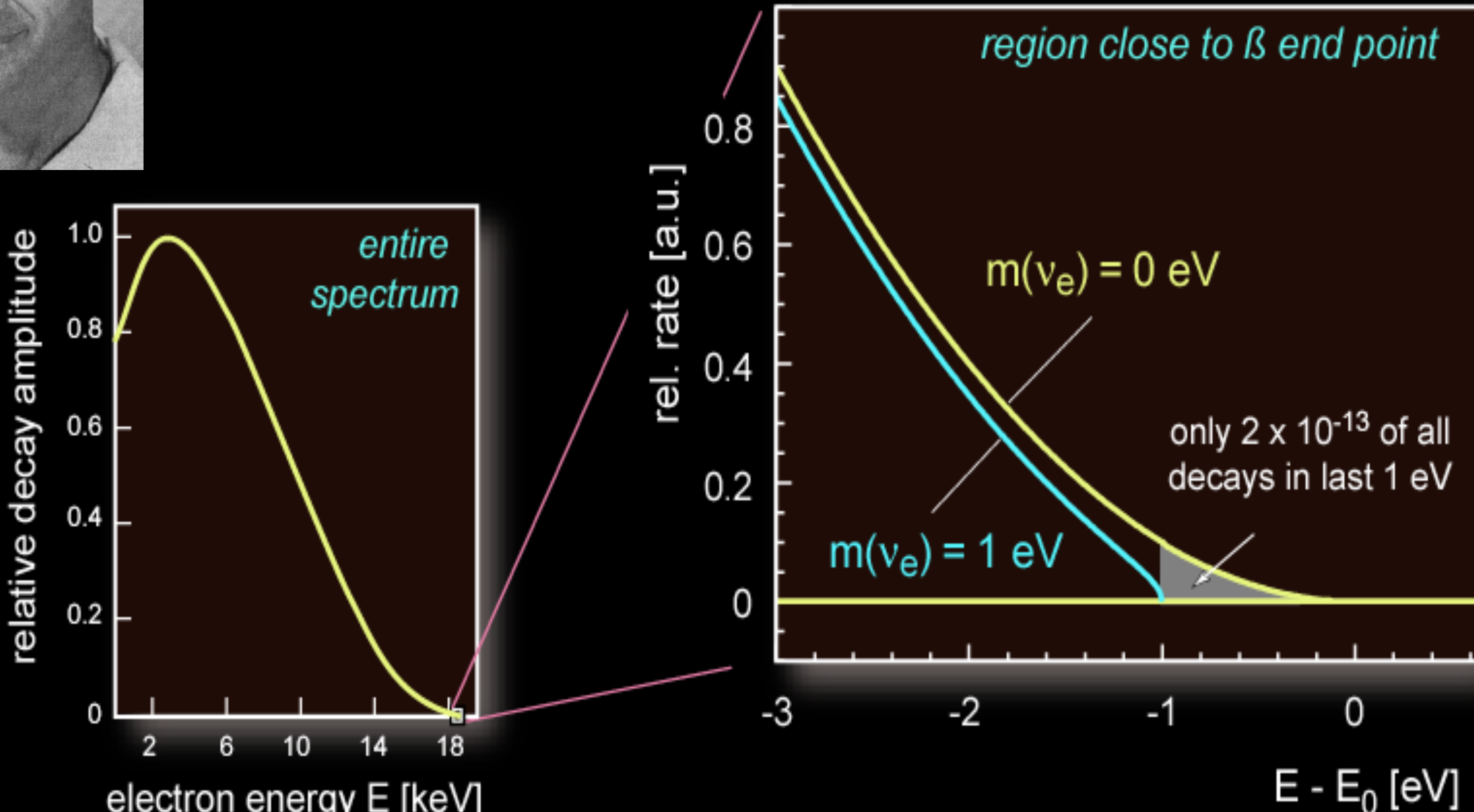
- What is the mass hierarchy?
- What is the absolute mass scale?
- What is the nature of neutrino mass?
  - Dirac or Majorana?
- Answers important for theories about origins of neutrino mass
  - Relations to flavor? GUTs?
- Cosmological and astrophysical implications



Absolute Scale of Neutrino Mass

Beta decay endpoint

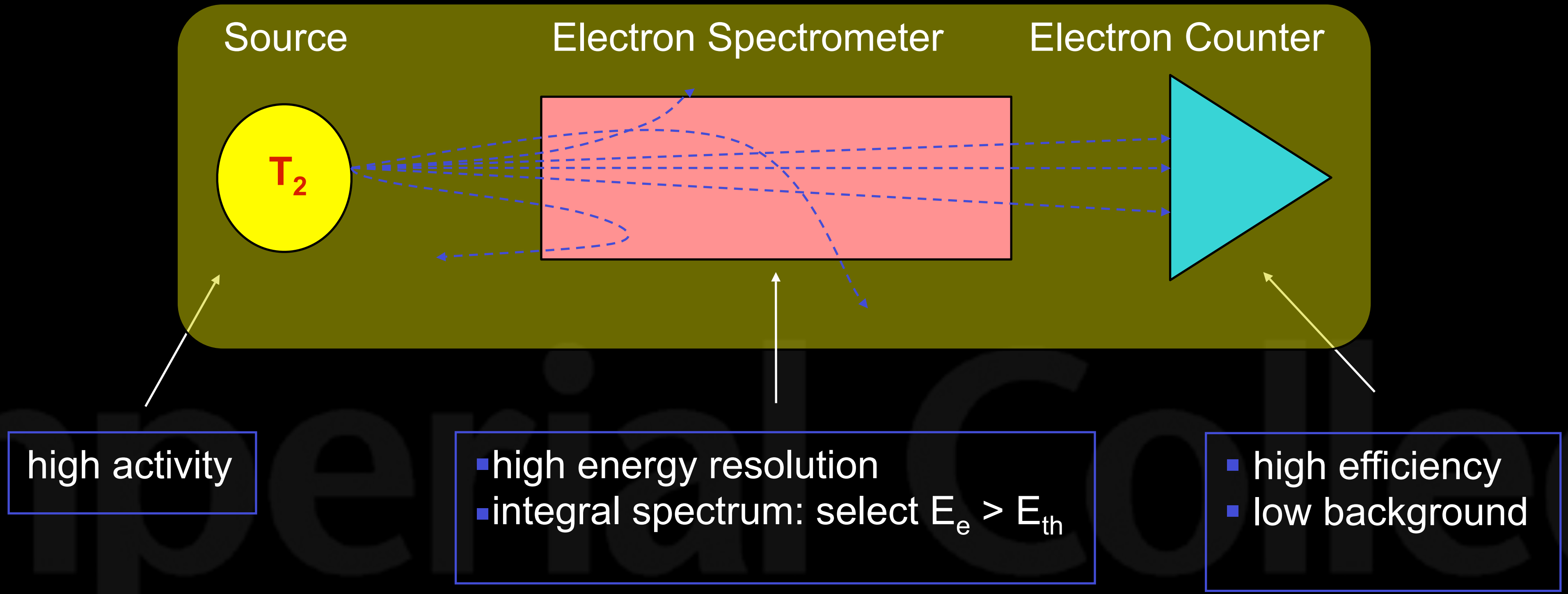




- Sensitive to $\langle m_\beta \rangle = \sqrt{(\sum |U_{ei}|^2 m_i^2)}$

Tritium Decay
Spectrometers

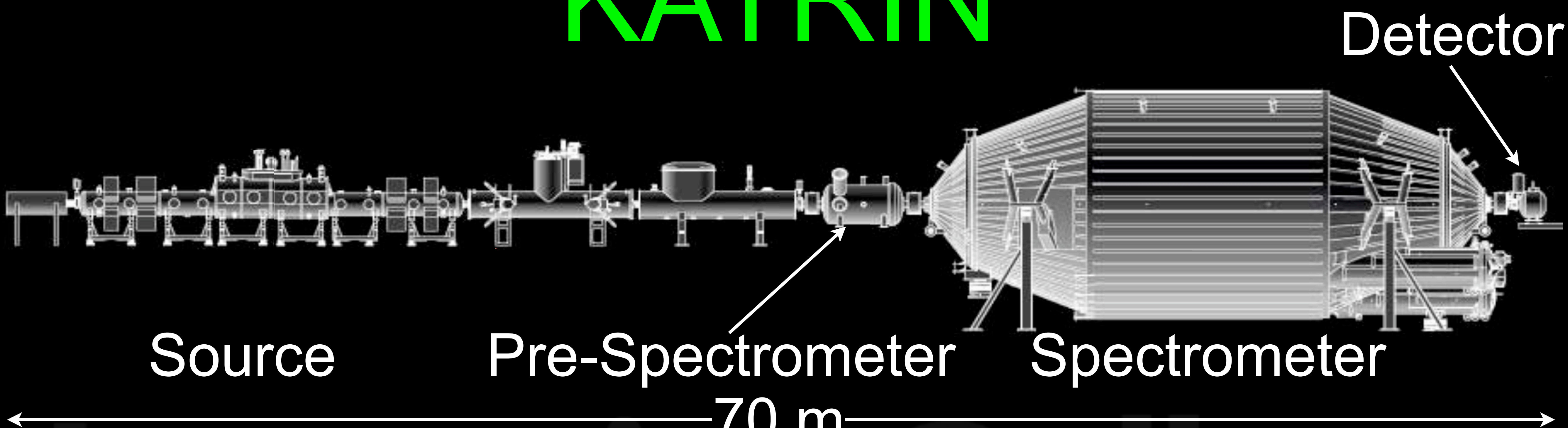
Source = ^3H



- Tritium has short half life but high Q value (18.6 keV)
- Previous measurements
  - Troitsk: $m_\beta < 2.05$ eV (95% CL)
  - Mainz: $m_\beta < 2.3$ eV (95% CL)

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

KATRIN



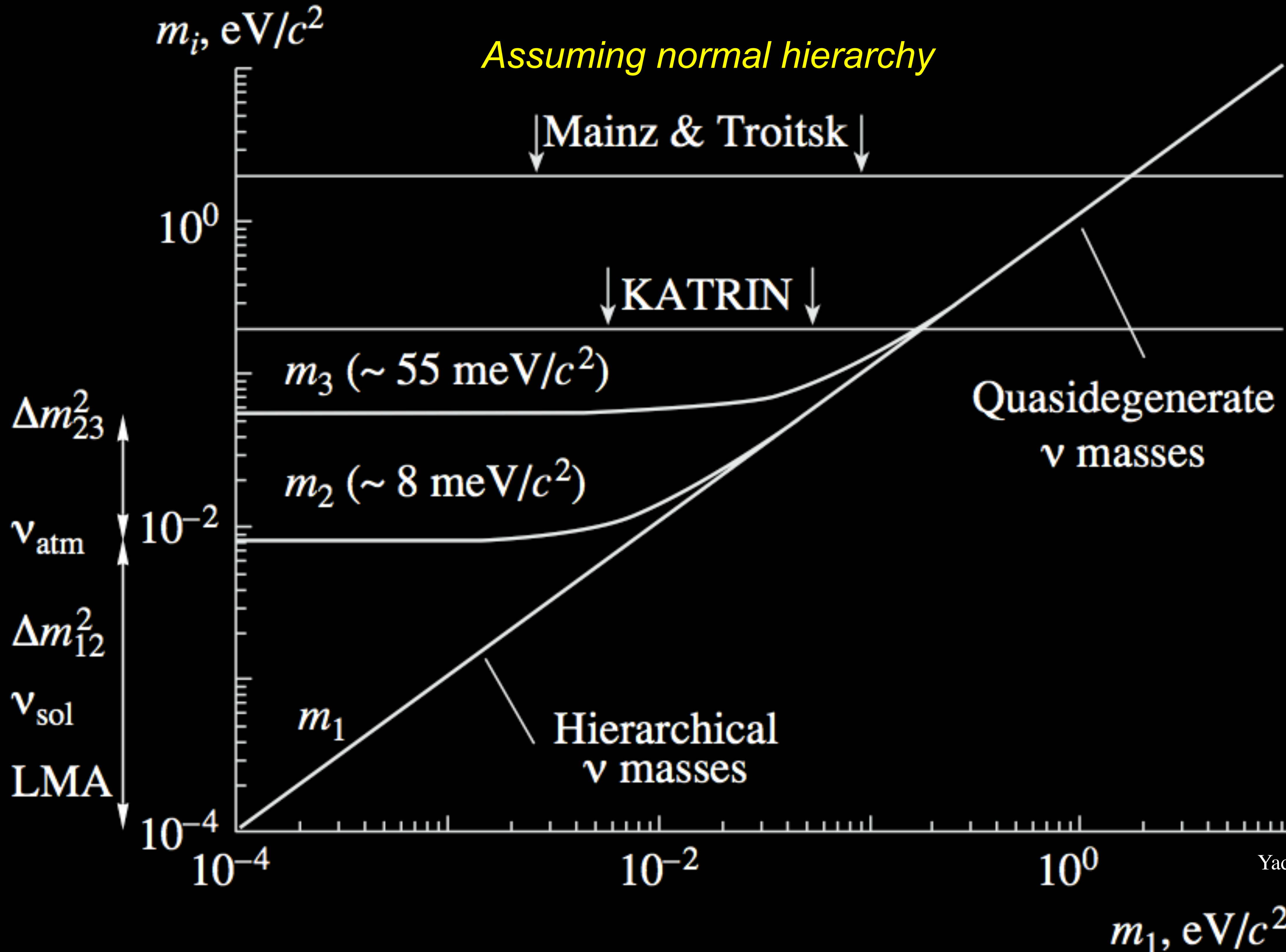
- Powerful T_2 source (1.7×10^{11} Bq!)
- Pre-spectrometer removes all βs with no m_ν information (10^7 reduction!)
- Excellent energy resolution (0.93 eV)
- Sensitivity: m_β < 200 meV (90% CL) (1000 days)
- Discovery potential: m_β = 350 meV (5σ)

The ultimate tritium decay experiment

http://www-ik.fzk.de/tritium/


KATRIN Spectrometer

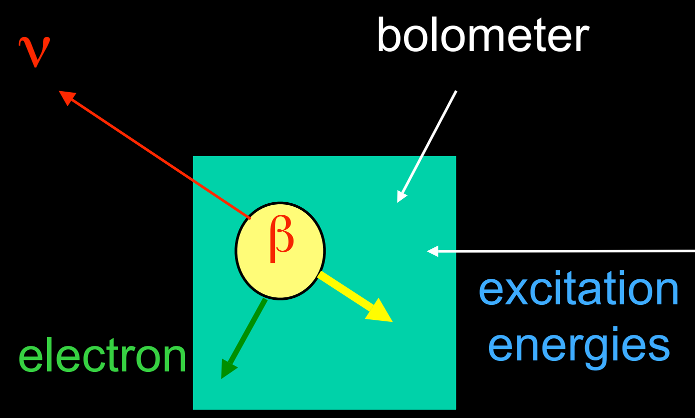
Physics Reach



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

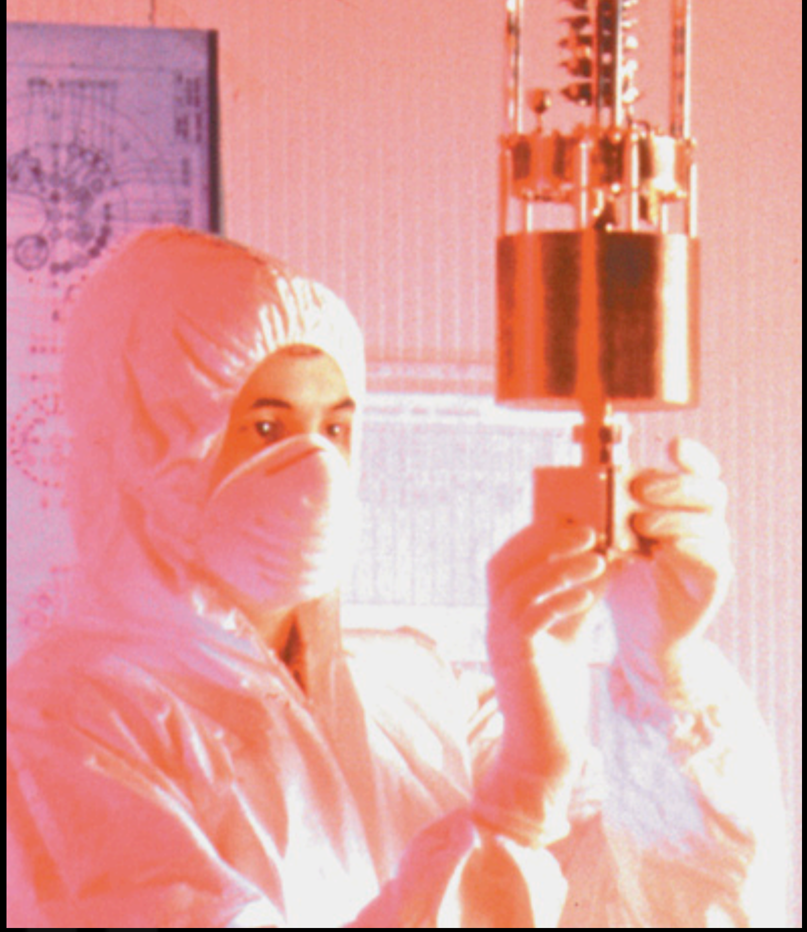
Rhenium Decay
Bolometers

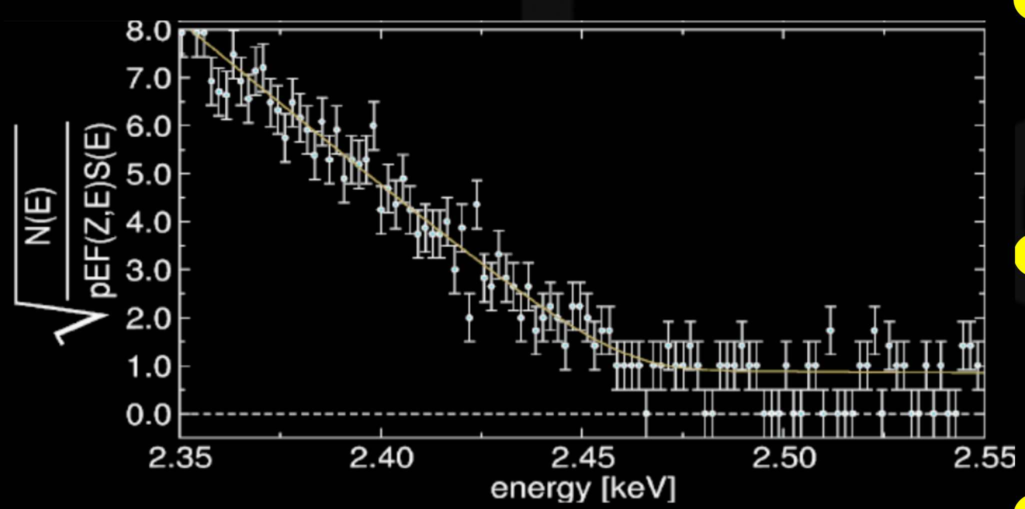
Source = ^{187}Re



high energy resolution
- differential spectrum: dN/dE

When in presence of decays to excited states, the calorimeter measures both the electron and the de-excitation energy



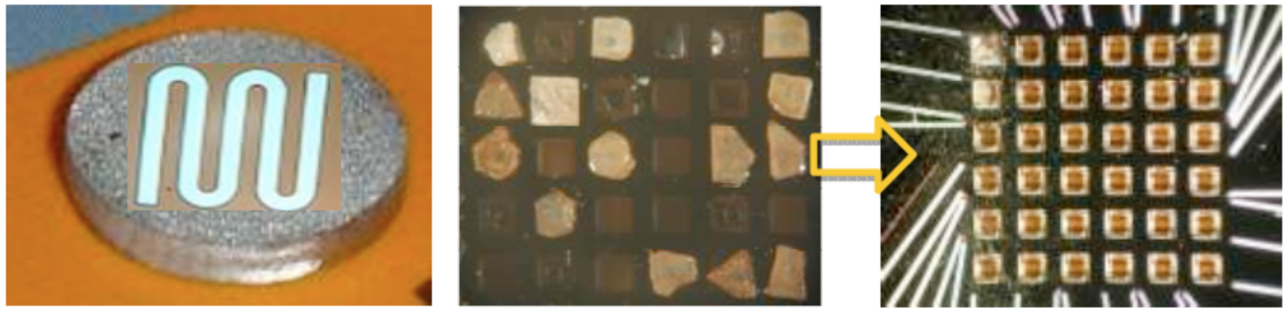


- Rhenium has long half life and low Q value (2.47 keV)
- MIBETA (AgReO4); MANU (metallic Re)
- m_β < 15.0 eV (90% CL)

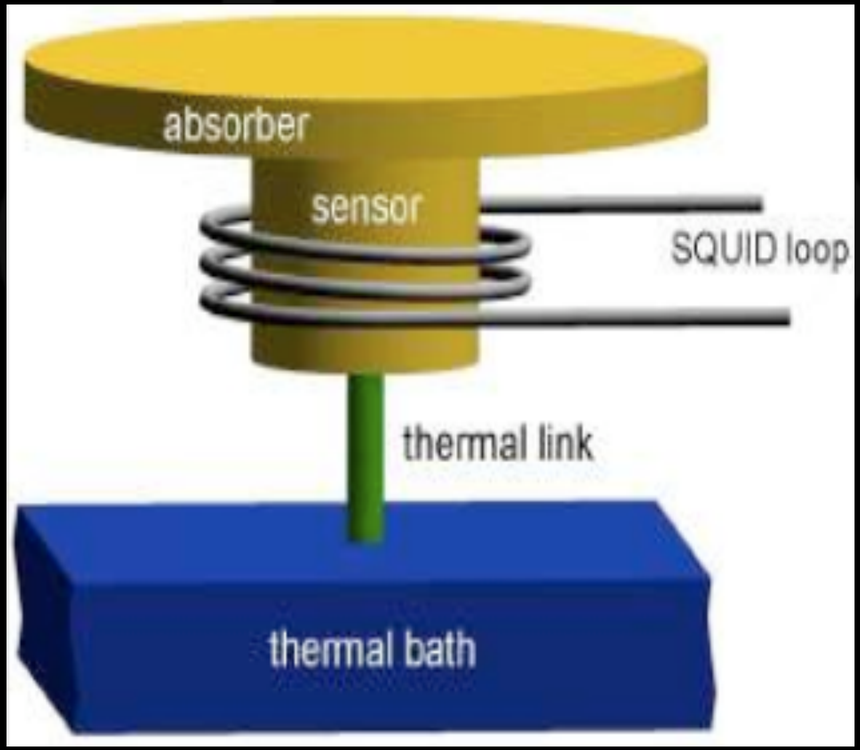
PRL ***91****, 161802 (2003)*
MARE Proposal

MARE

New collaboration:
MANU + MIBETA + US groups



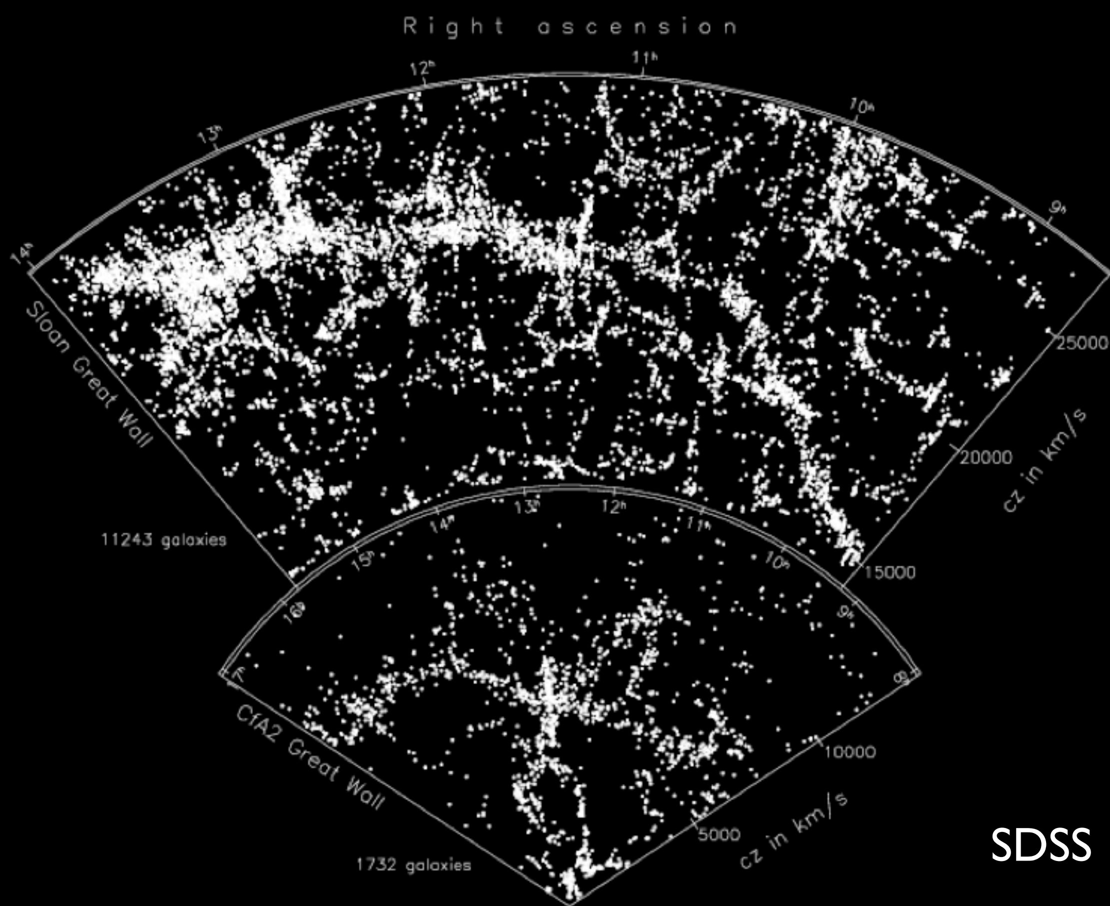
Genova: Re metal   Milan: pixel arrays of $AgReO_4$



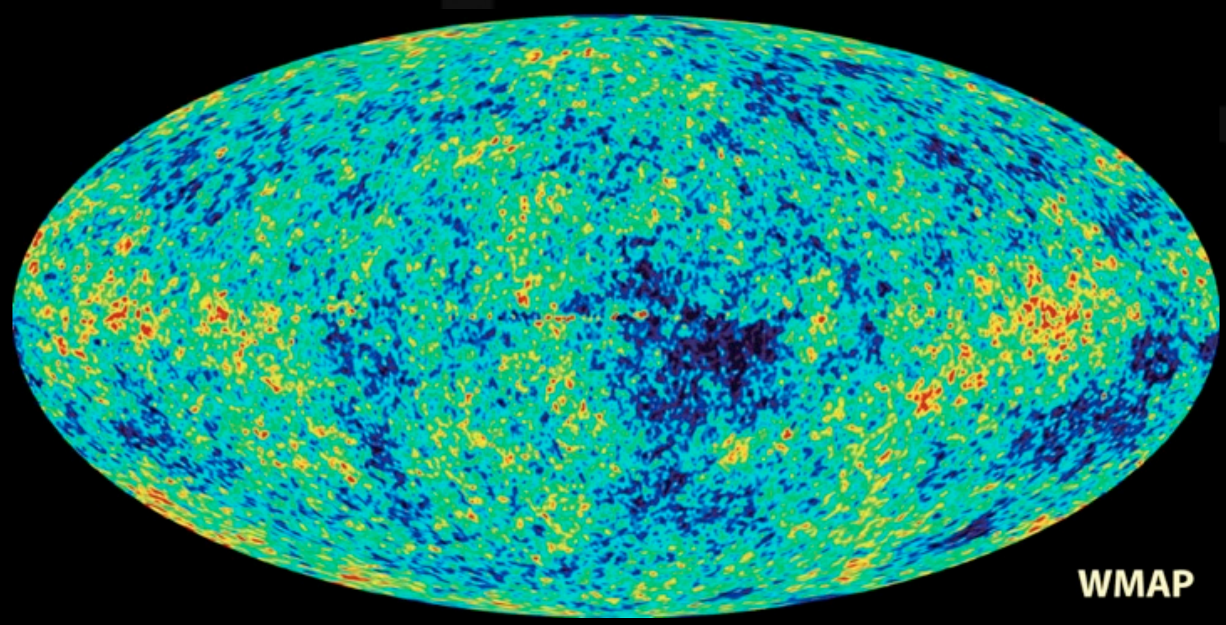
- Phase 1: Improve by factor 10
  - $m_\beta < 2$ eV
  - 10^{10} β decays
  - Exploring detector options
- Phase 2: Another factor 10
  - $m_\beta < 0.2$ eV
  - 10^{14} β decays
  - R&D for new detector technology
    - Magnetic micro-calorimeter with SQUID readout
  - Goal: 2015

Scalable technology

Cosmology



SDSS

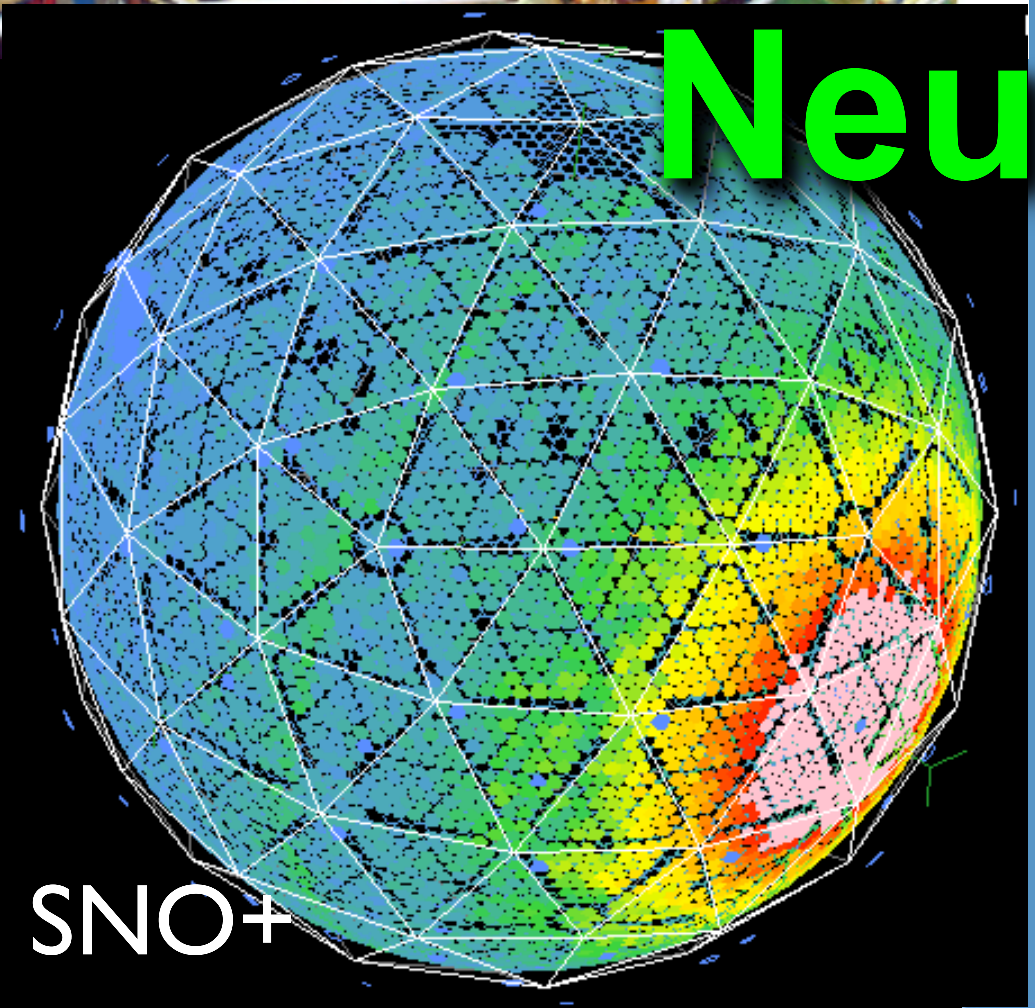


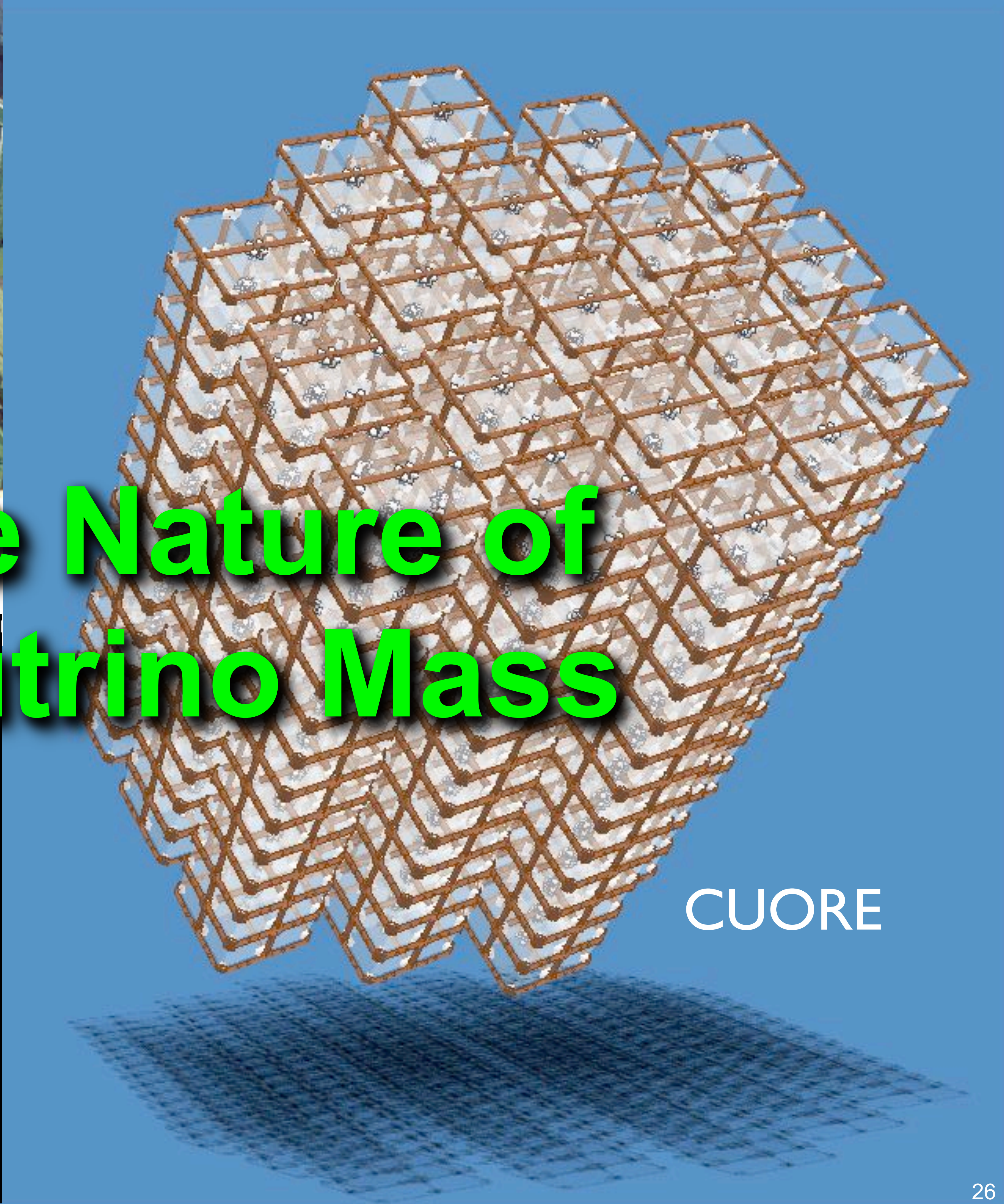
WMAP

- m_ν can be inferred from cosmological data + cosmological assumptions
    - $\sum m_i < (0.17 - 0.32)$ eV

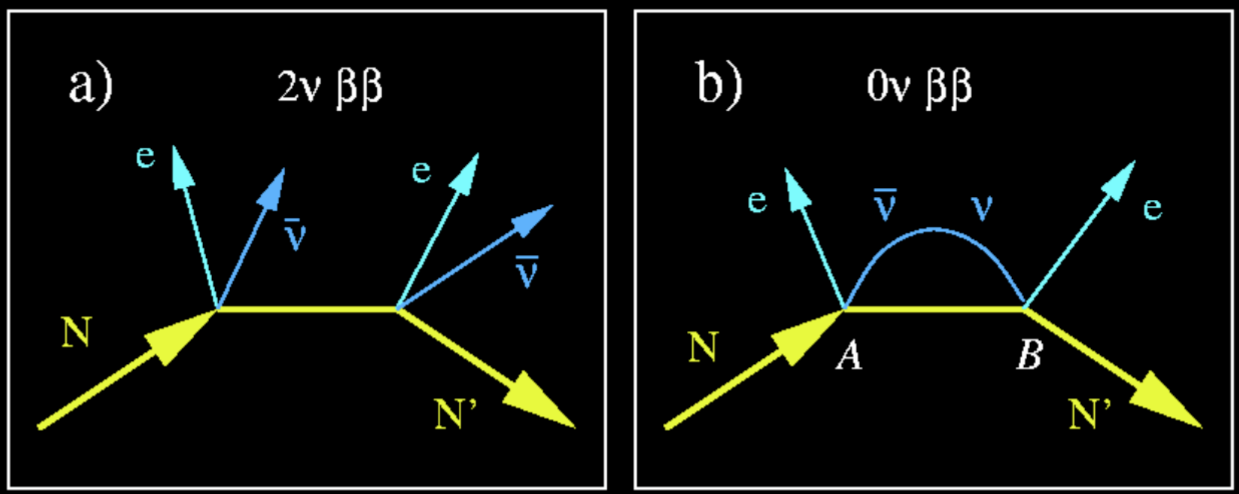
      JCAP 0610:014, 2006, astro-ph/0604335
- Degeneracies between some parameters
    - H_0 and m_ν
- Best approach:
    - Observe neutrino mass, then use as cosmological *input*

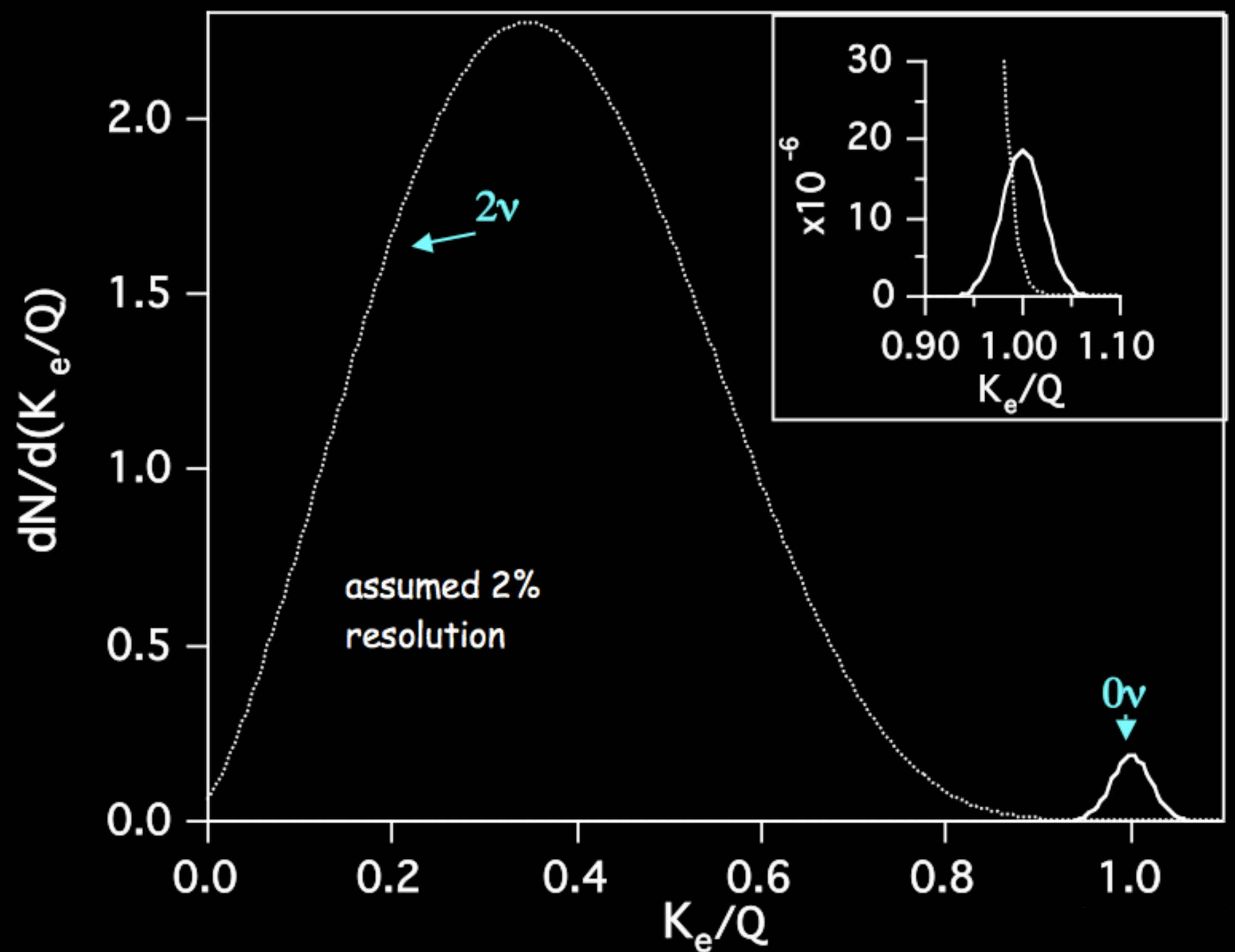
The Nature of Neutrino Mass





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

More detailed info in Session D.10
Sat 3:30 pm, Governor's Square

Current Limits

Experiment	Nucleus	Mass Limit
CUORICINO	^{130}Te	$m_{\beta\beta} < (0.2\text{-}0.68)$ eV
NEMO3	^{100}Mo	$m_{\beta\beta} < (0.8\text{-}1.3)$ eV
NEMO3	^{82}Se	$m_{\beta\beta} < (1.4\text{-}2.2)$ eV
ELEGANT V	^{100}Mo	$m_{\beta\beta} < 1.7$ eV
NEMO3	^{150}Nd	$m_{\beta\beta} < (1.7\text{-}2.4)$ eV
NEMO3	^{96}Zr	$m_{\beta\beta} < (7.4\text{-}20.1)$ eV
NEMO3	^{48}Ca	$m_{\beta\beta} < 29.6$ eV

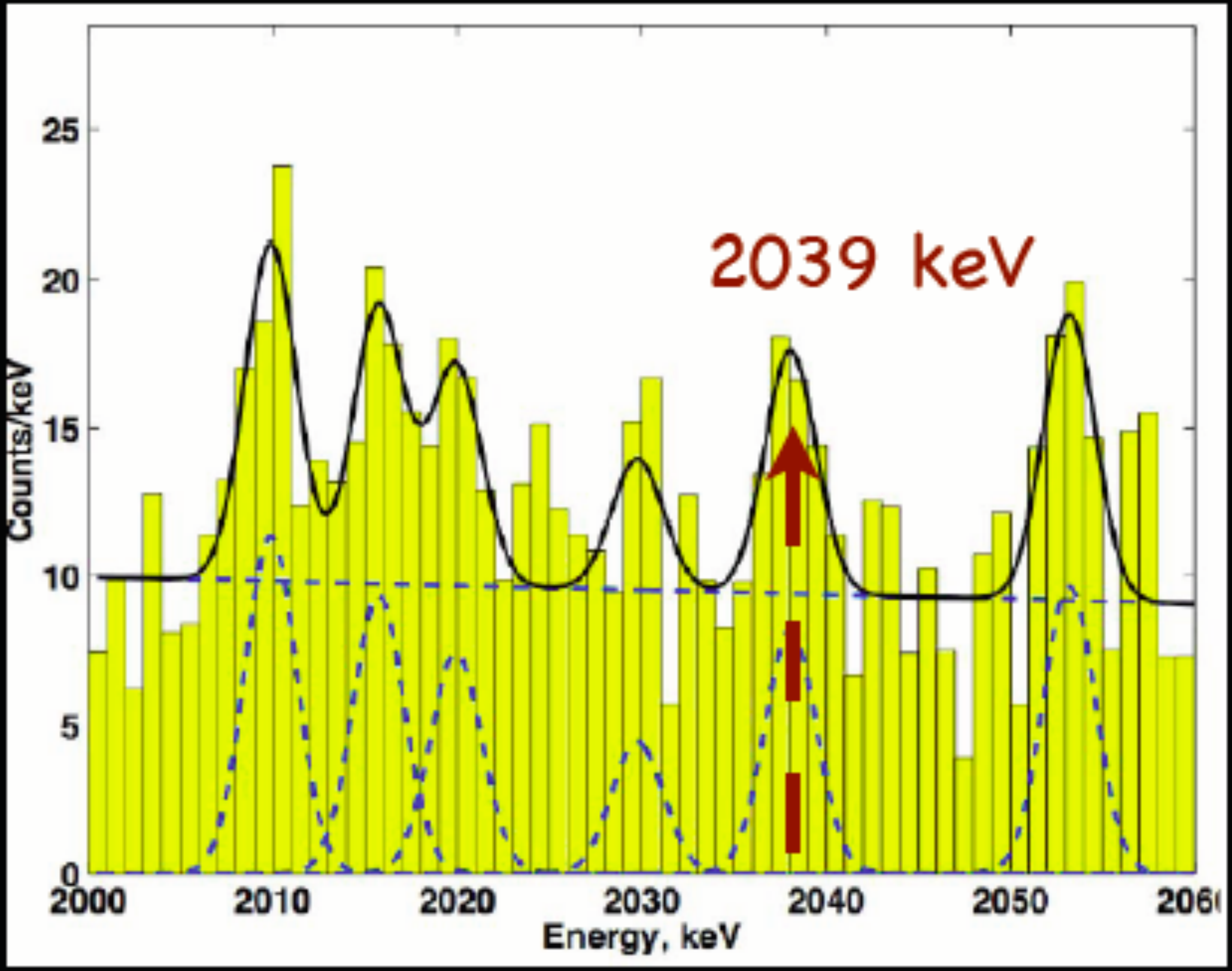
Ranges due to nuclear matrix elements

Future Mass reach

Not a complete list!

Experiment	Nucleus	Mass Limit
GERDA	^{76}Ge	m_ν < 0.11-0.27 eV
MAJORANA	^{76}Ge	m_ν < 0.12 eV
NEXT	^{136}Xe	m_ν < 0.06 eV
SNO+	^{150}Nd	m_ν < 0.04 eV
CUORE	^{130}Te	m_ν < (0.014-0.047) eV
SuperNEMO	^{82}Se or ^{150}Nd	m_ν < (0.04-0.11) eV
EXO	^{136}Xe	m_ν < (0.005-0.007) eV

Observation?

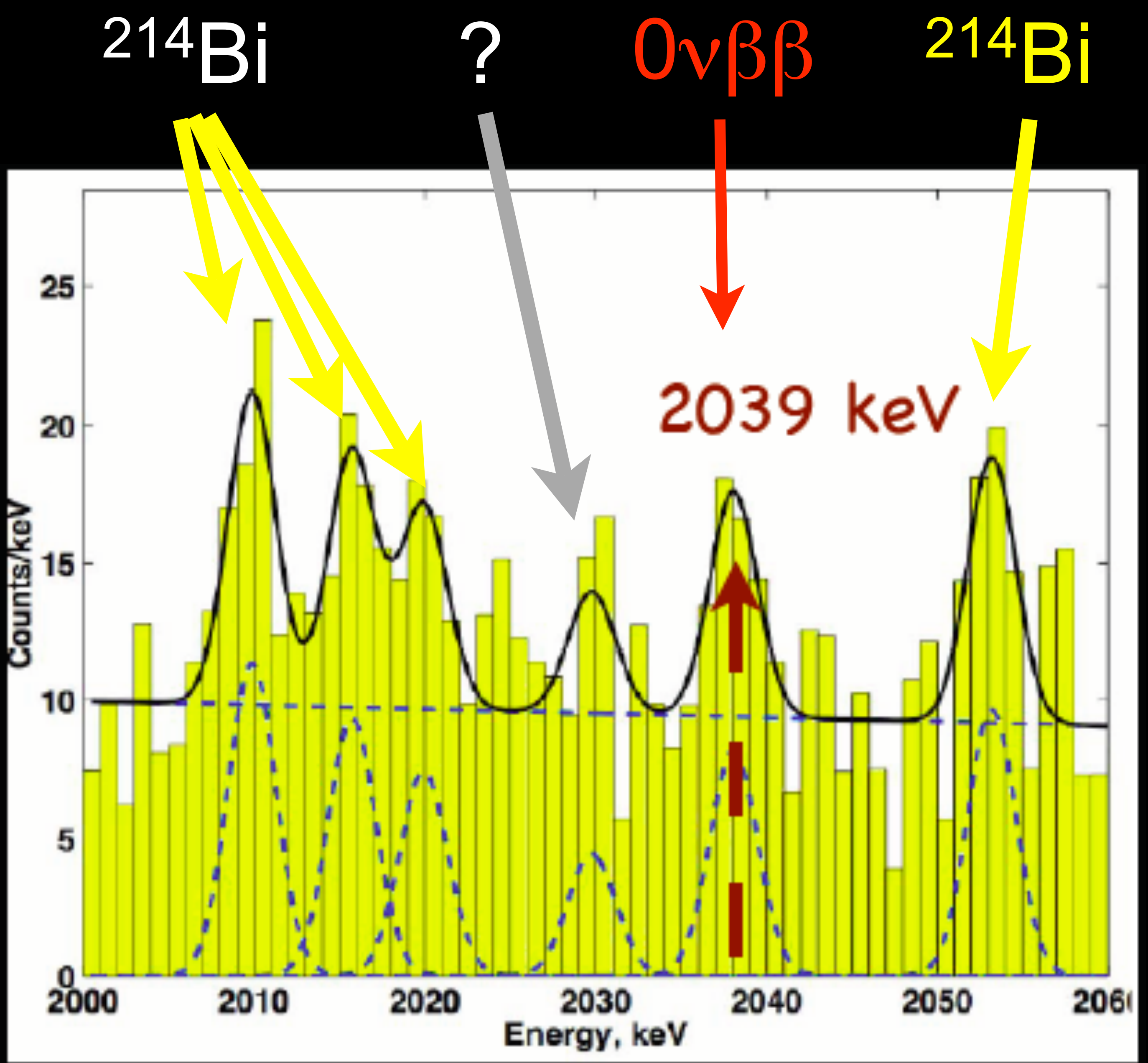


Klapdor-Kleingrothaus H V, Krivosheina I V, Dietz A and Chkvorets O, *Phys. Lett.* B **586** 198 (2004).

- In 2001, a subgroup of the Heidelberg-Moscow experiment (^{76}Ge) released a discovery claim
- Somewhat controversial

- $T_{1/2}^{0\nu} = 1.2\times10^{25}$ y
- $m_{\beta\beta}$ = 440 meV (4.2σ)

Observation?



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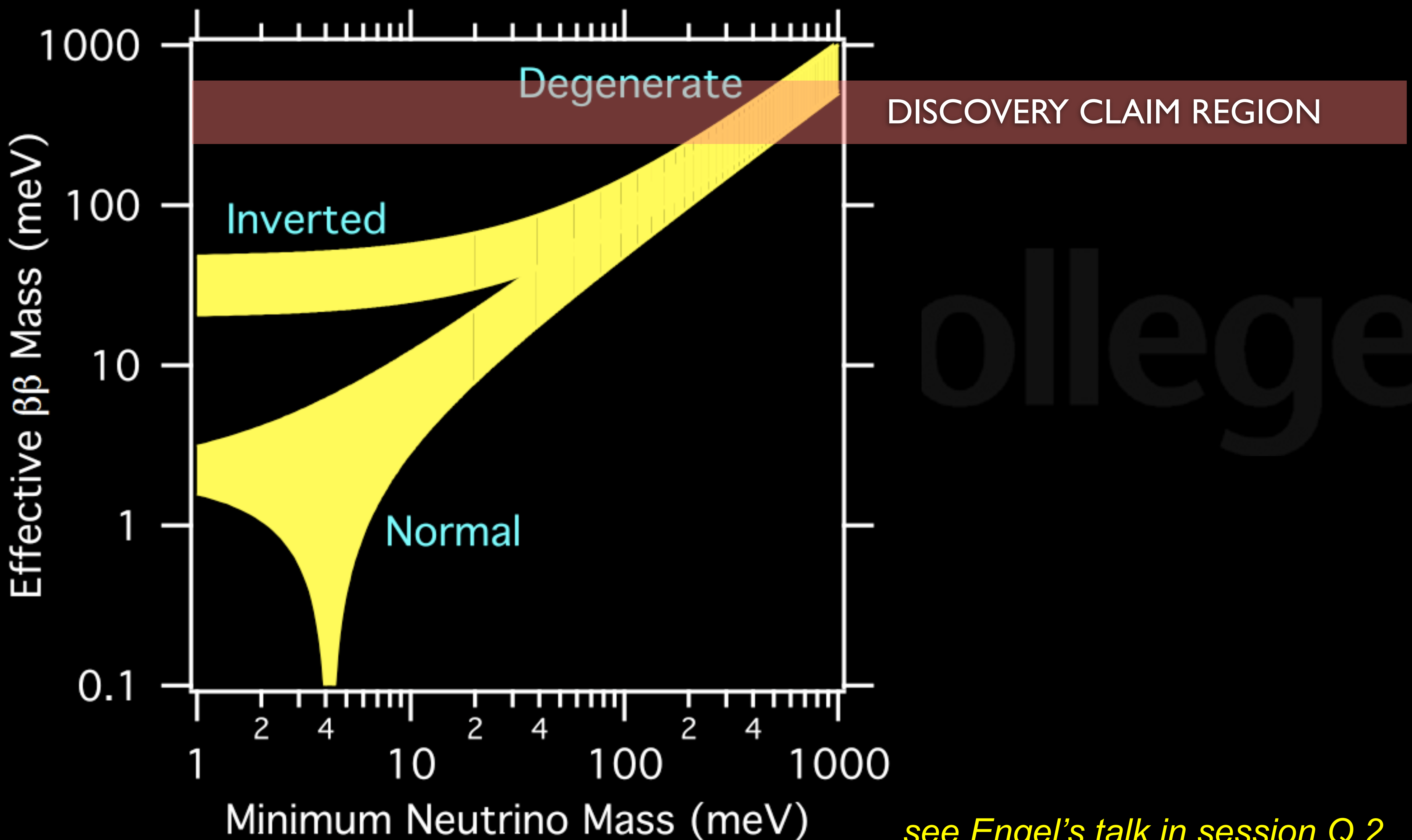
Mass Reach

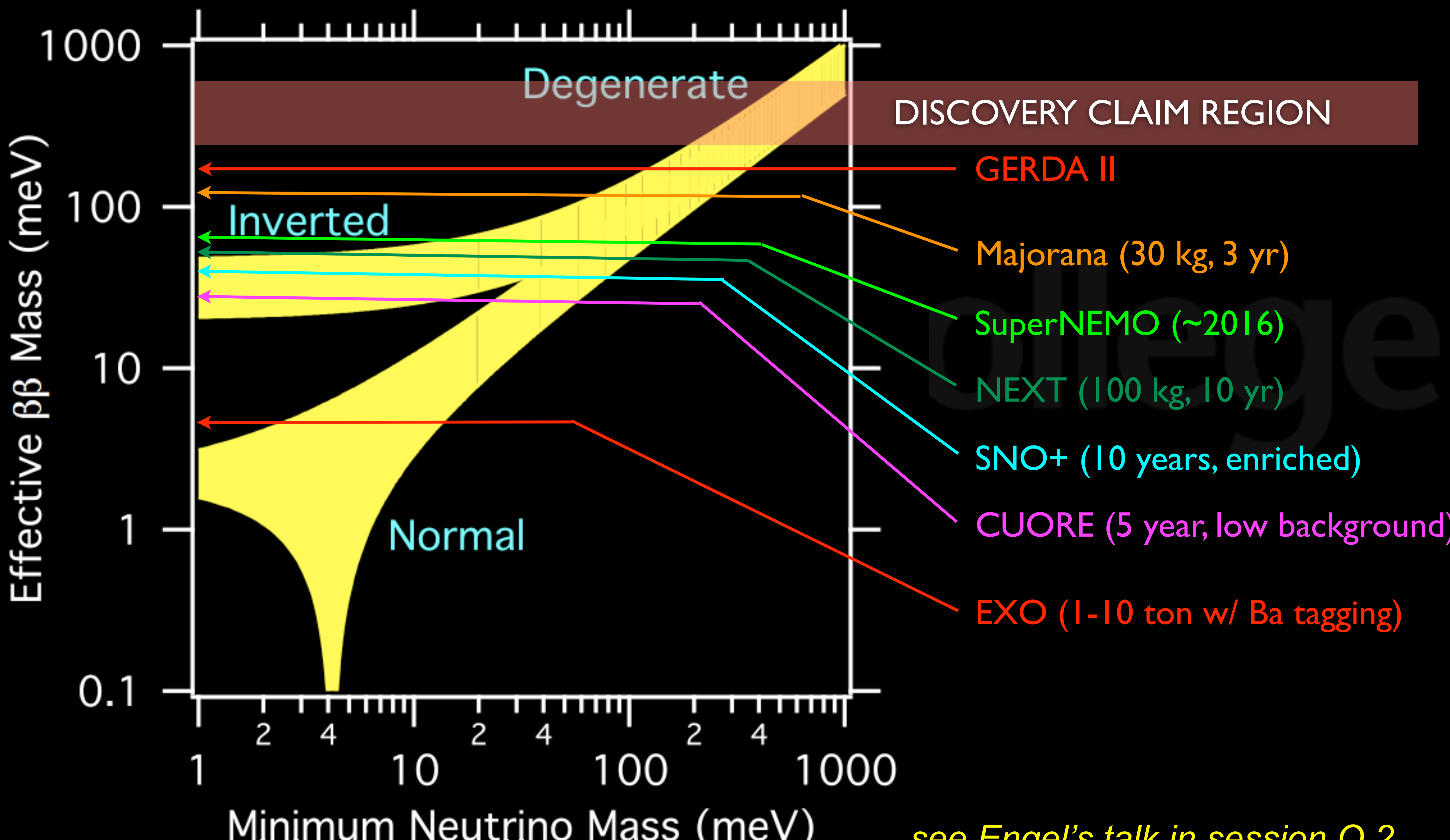


Avignone, Elliot, Engel arXiv:0708.1033 (2007)

see Engel's talk in session Q.2, Monday 10:45 in Plaza D

Mass Reach

All planned experiments can test the 440 meV claim



Avignone, Elliot, Engel arXiv:0708.1033 (2007)

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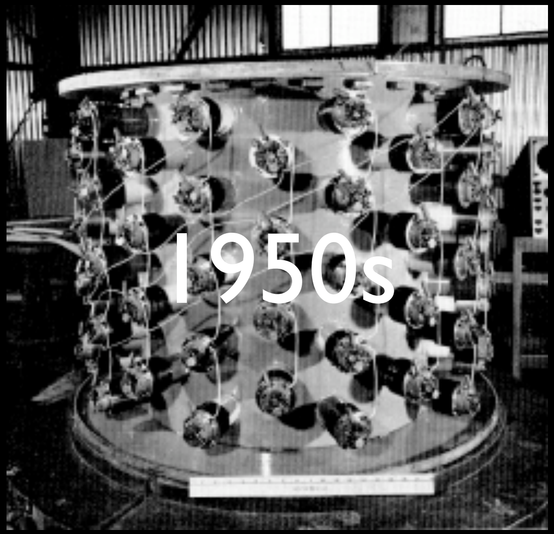
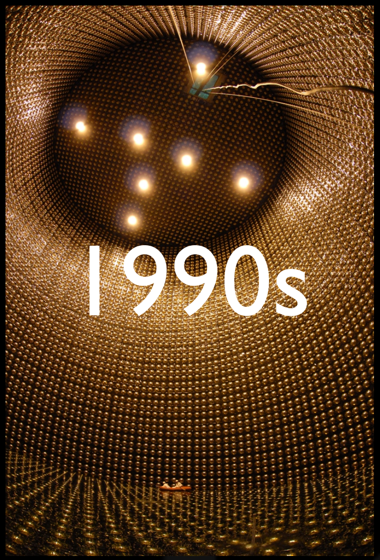
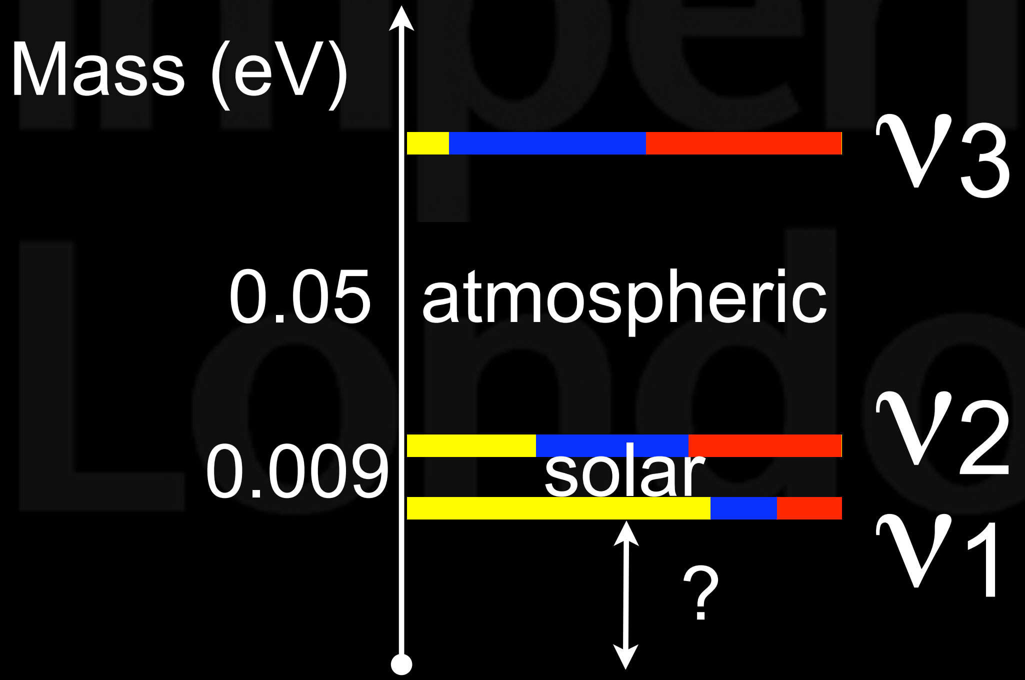
Summary: Open Questions







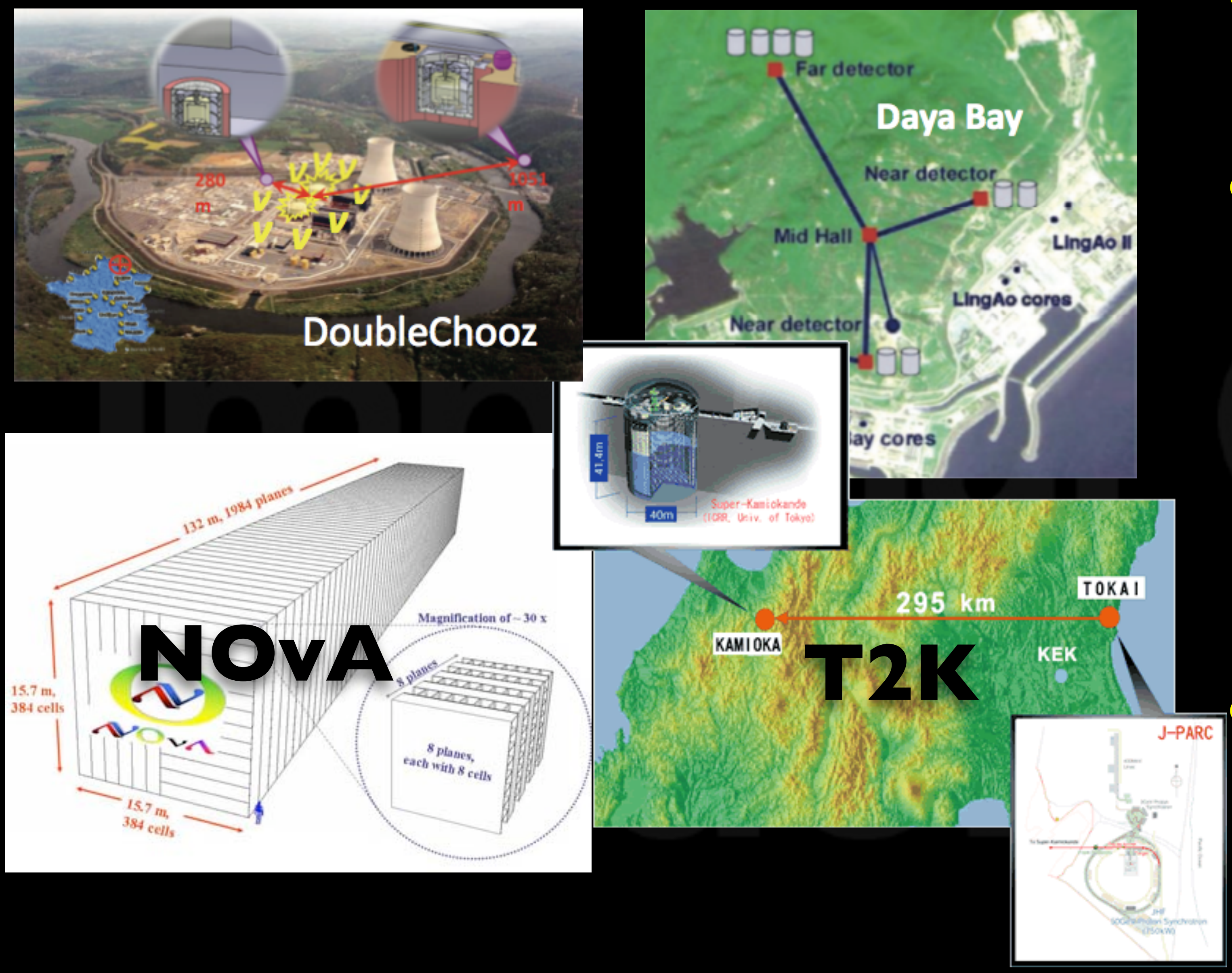
- Neutrinos have mass!
- Moving from discovery to precision era

- What is the mass hierarchy?
- What is the absolute scale?
- Are they Majorana or Dirac?
- Why are they so small?

Worldwide program of experiments to answer these!

Denver Skyline

Sign of Δm^2



- $\Delta m^2_{ij} = m_i^2 - m_j^2$
- Solar experiments explained by MSW (matter) effects
  - Resonant enhancement of oscillation ⇒ sun emits ν_2
  - $m_2 > m_1$
- No such information (yet) for Δm^2_{23}
  - Need to observe matter effects in θ_{13} measurement ν and $\bar{\nu}$ to sort that out

➡ NOvA + T2K + Reactors

See T. Vahle's talk for more information