



The Hunt for the Last Neutrino Mixing Angle

Morgan Wascko
Imperial College London

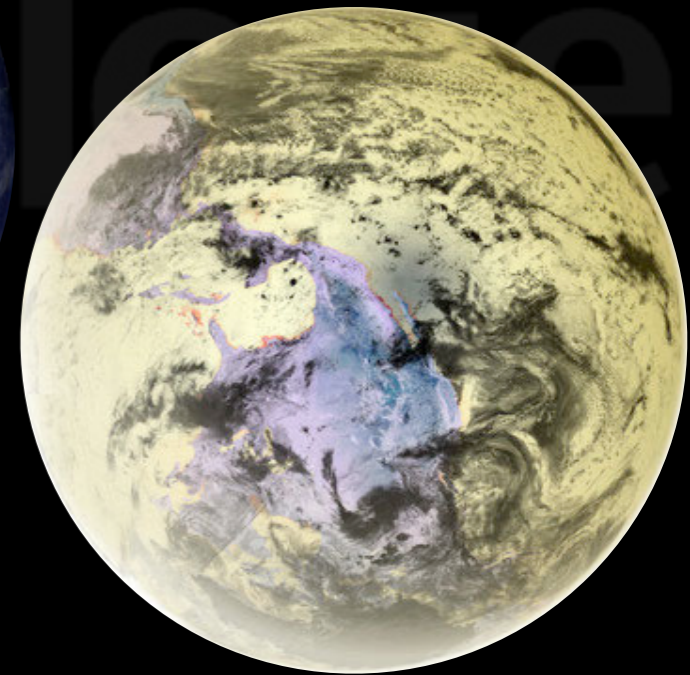
Motivation

Why are we here?

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



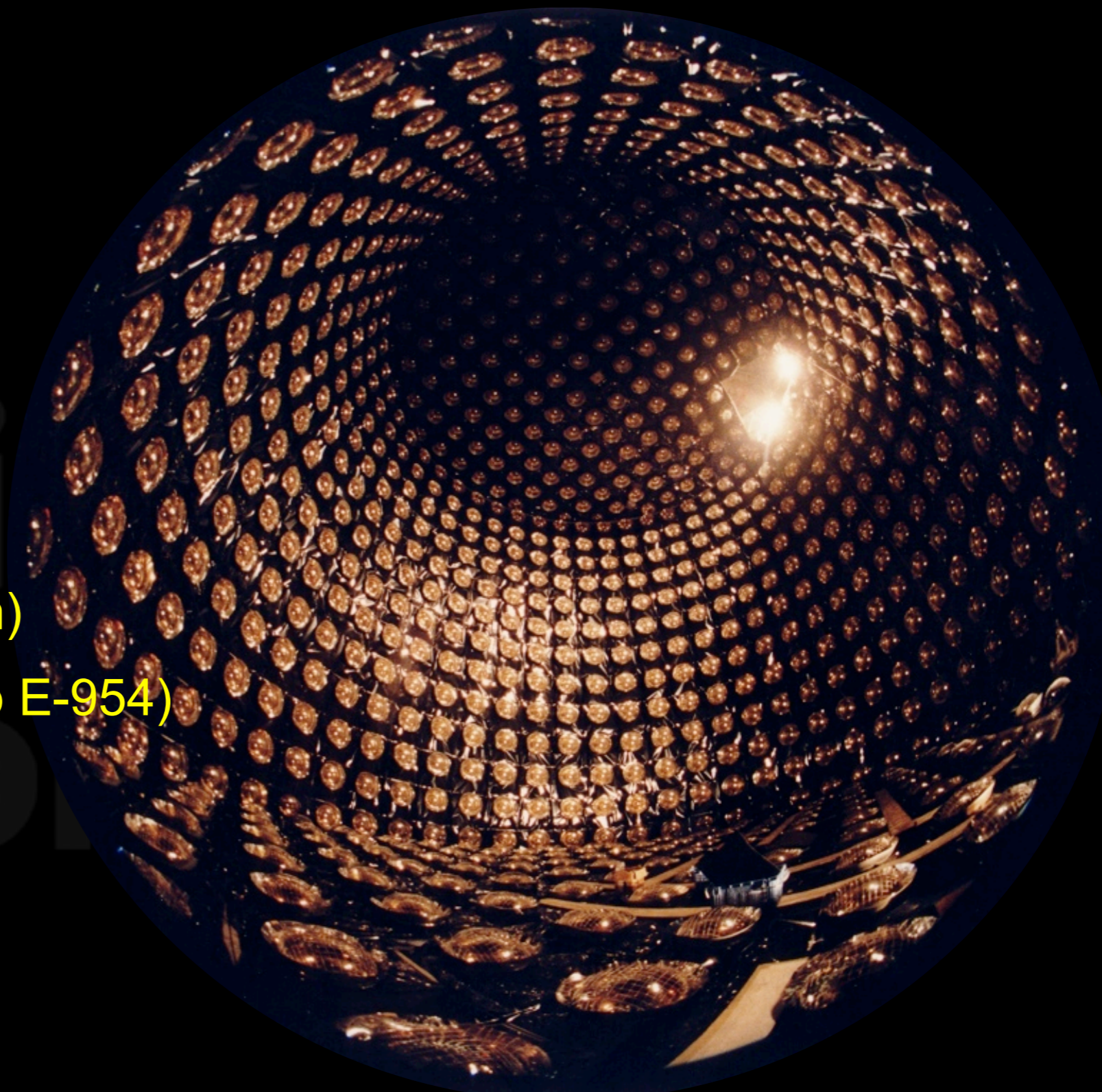
$$P(\nu_{\mu} \rightarrow \nu_e)$$



$$P(\bar{\nu}_{\mu} \rightarrow \bar{\nu}_e)$$

Outline

- Motivation
- Tools & Strategy
- T2K (J-PARC in Japan)
 - SciBooNE (Fermilab E-954)
- Looking Ahead



Kamiokande Detector

History

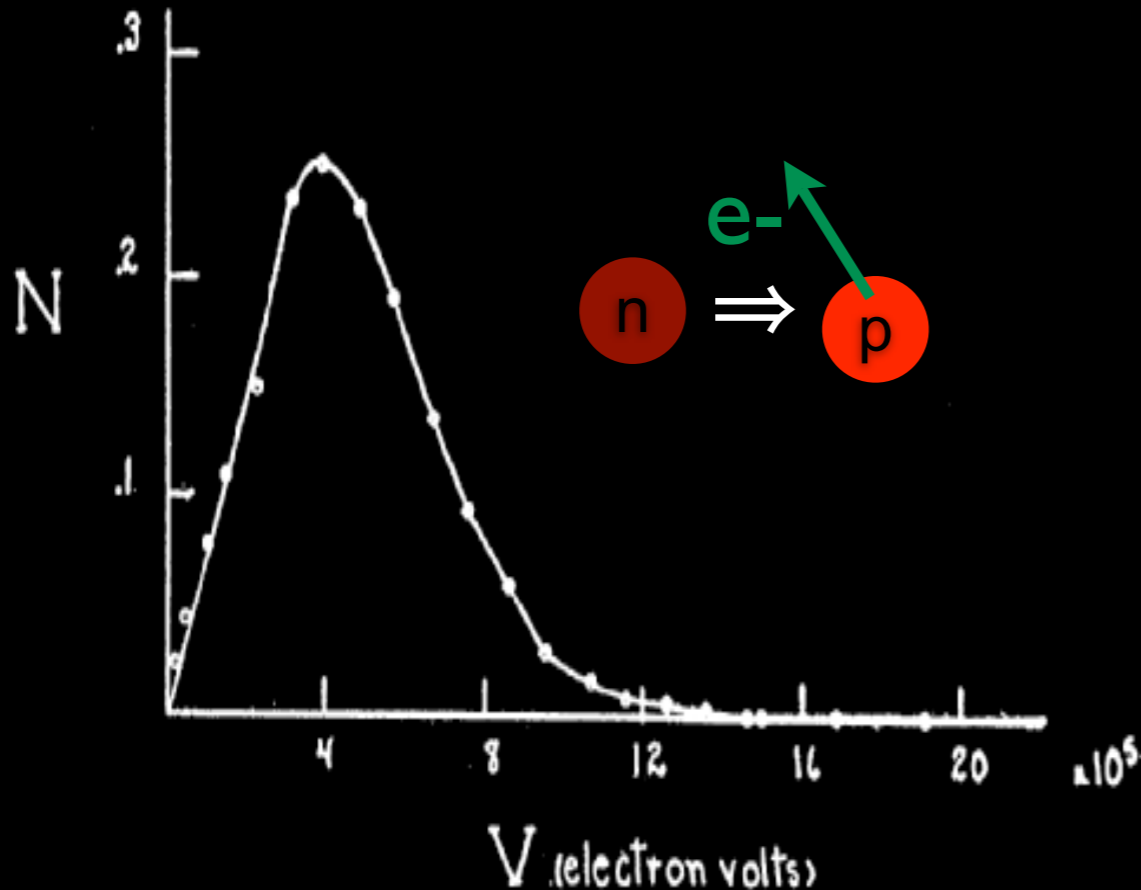


FIG. 5. Energy distribution curve of the beta-rays.
F.A. Scott, Phys Rev. 48, 391 (1935)

Original - Photocopy of PLC 0393
Abschrift/15.12.56 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 Ausschliessungsprinzip 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 Wirkung die
Neutronen wirken. Das wahrscheinlichste Modell für ein Neutron scheint
mir aus wellenmechanischen Gründen (siehe was der Ueberbringer
dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein
magnetischer Dipol von einem grossen Moment ist. Die Experimente
verlängen wohl, dass die ionisierende Wirkung eines solchen Neutrons
nicht grösser sein kann als die eines gamma-Strahls und darf dann
wohl nicht grösser sein als 10^{-13} cm.

Ich gebe vorläufig aber nicht, etwas über diese Idee
zu publizieren und werde mich erst vertrauensvoll an Euch, liebe
Radioaktive, mit der Frage, wie es um den experimentellen Nachweis
eines solchen Neutrons stände, wenn dieses ein ebensolches oder etwa
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Ich gebe zu, dass mein Ausweg vielleicht von vornherein
wenig wahrscheinlich erscheinen wird, weil man die Neutronen, wenn
sie existieren, wohl schon längst gesehen hätte. Aber nur wer wagt,
ganz und der Ernst der Situation beim kontinuierlichen beta-Spektrum
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Herrn Debye, beleuchtet, der mir kürzlich in Brüssel gesagt hat:
"O, daran soll man am besten gar nicht denken, sowie an die neuen
Steuern." Darum soll man jeden Weg zur Rettung ernstlich diskutieren.-
Also, liebe Radioaktive, prüfet, und richtet.- Leider kann ich nicht
persönlich in Tübingen erscheinen, da ich infolge eines in der Nacht
vom 6. zum 7. Dez. in Zürich stattfindenden Balles hier unakademisch
bin.- Mit vielen Grüssen an Euch, sowie an Herrn Baek, Euer
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ges. W. Pauli

"desperate remedy"

*"I have done something very bad today
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— Wolfgang Pauli (1930)*

History

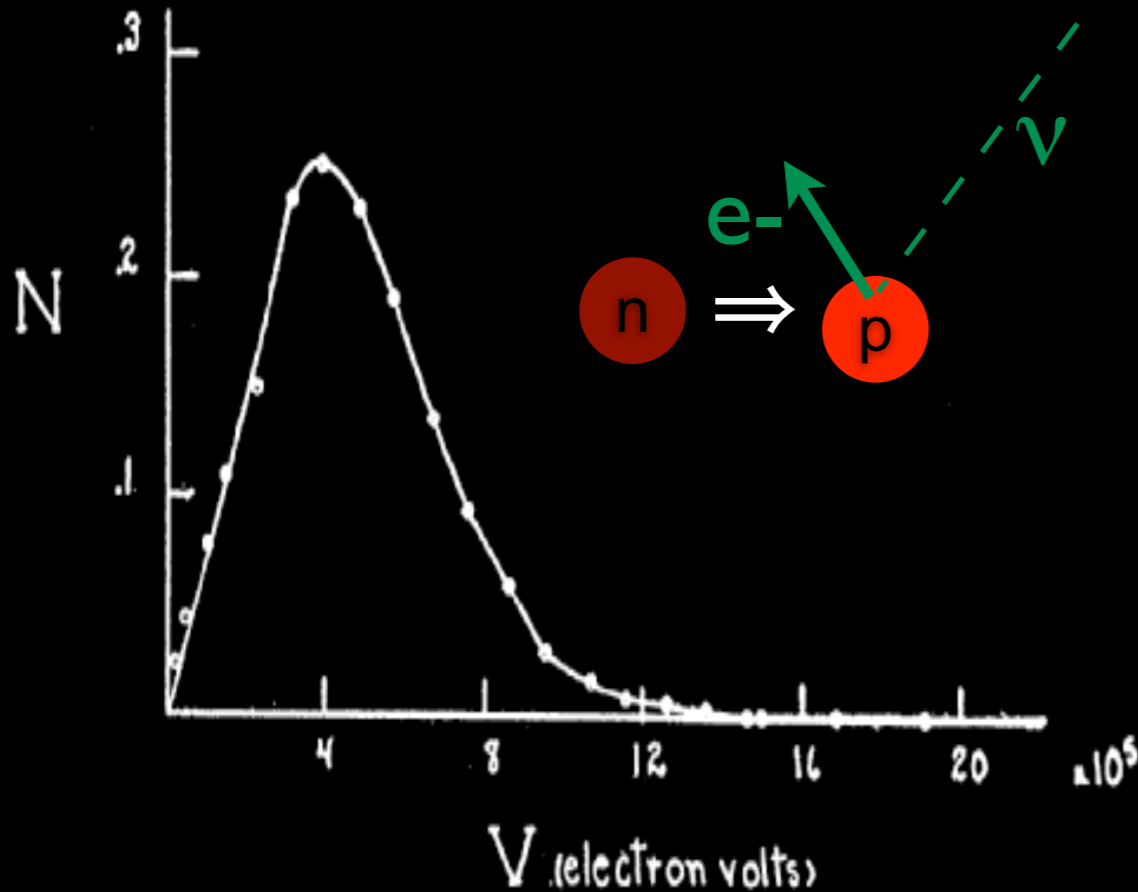


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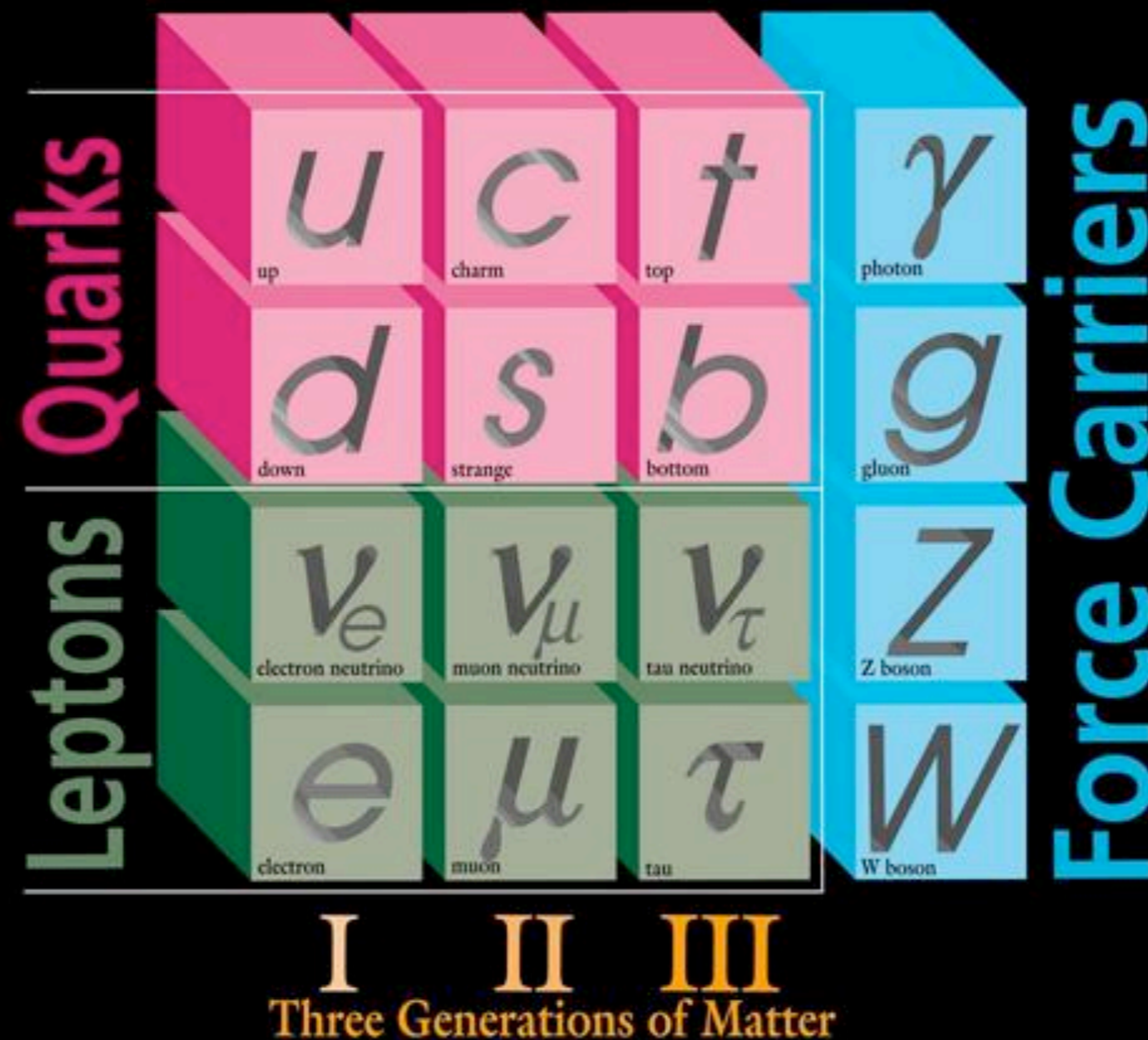
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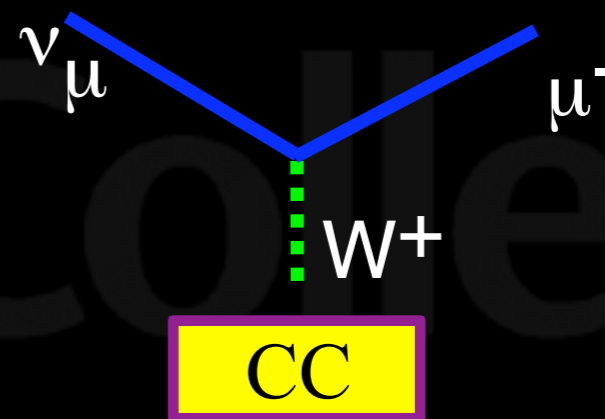
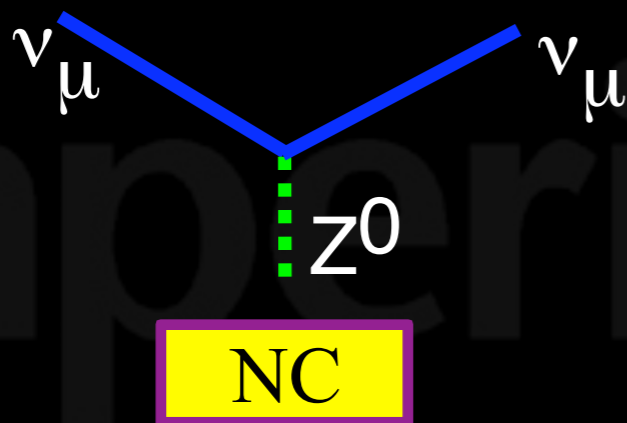
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Neutrinos 101

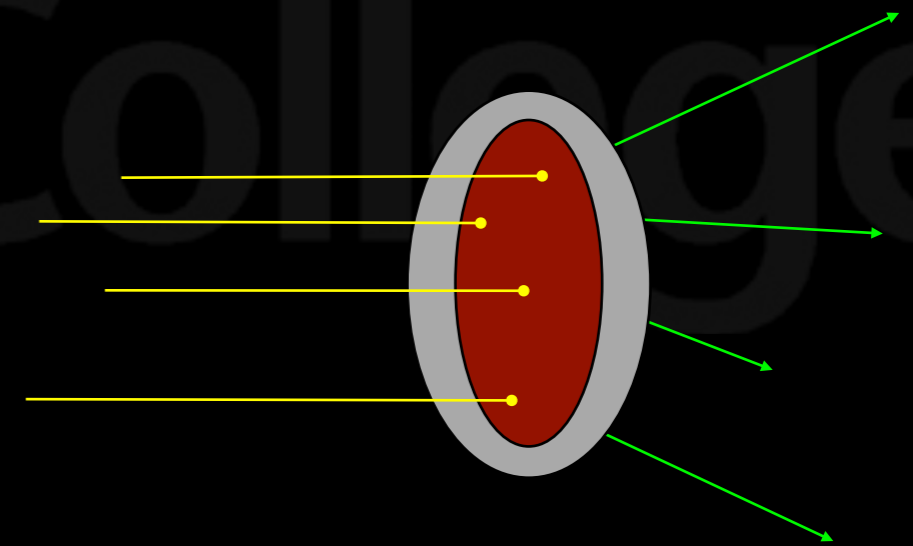
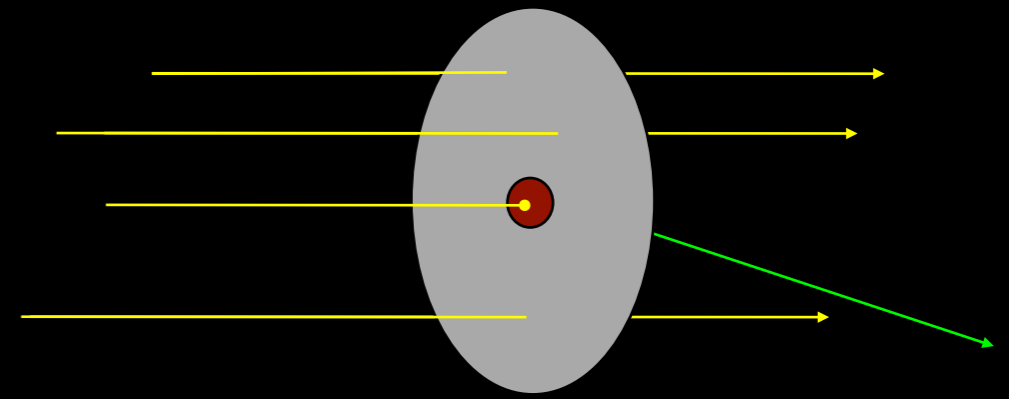
ELEMENTARY PARTICLES



Neutrino Interactions



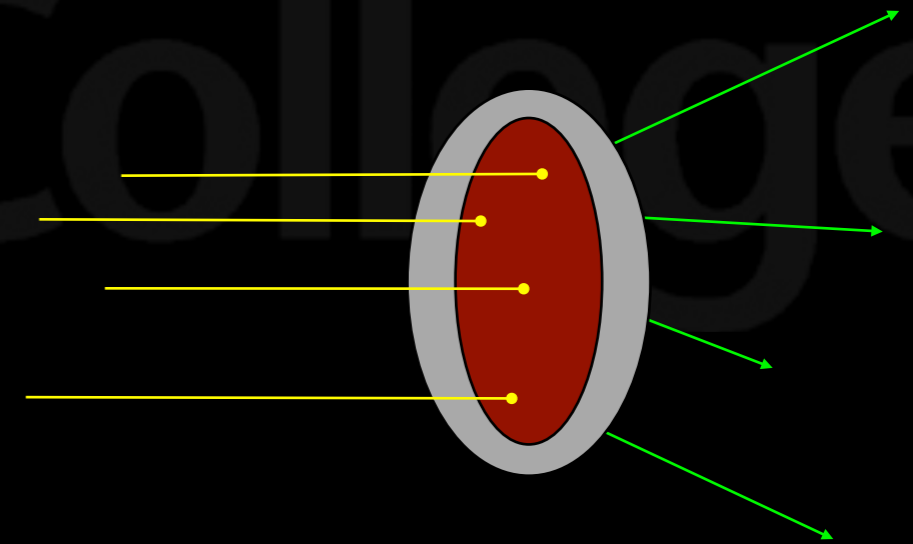
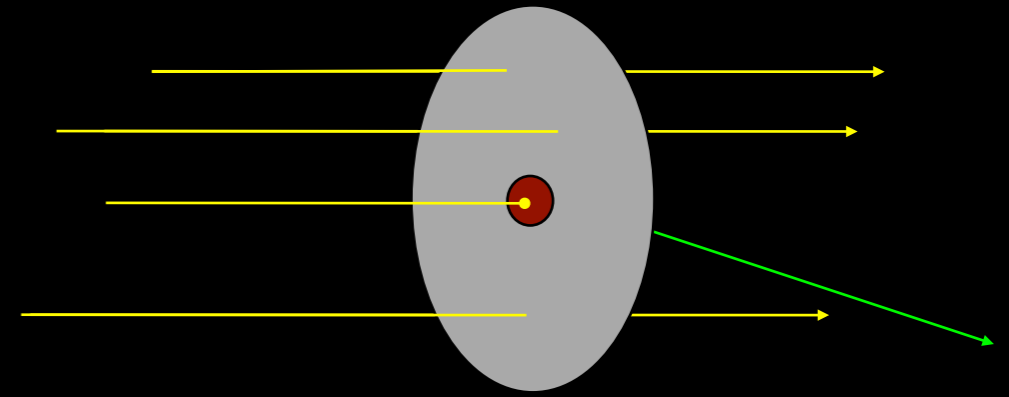
Neutrino Interactions 2



Imperial College
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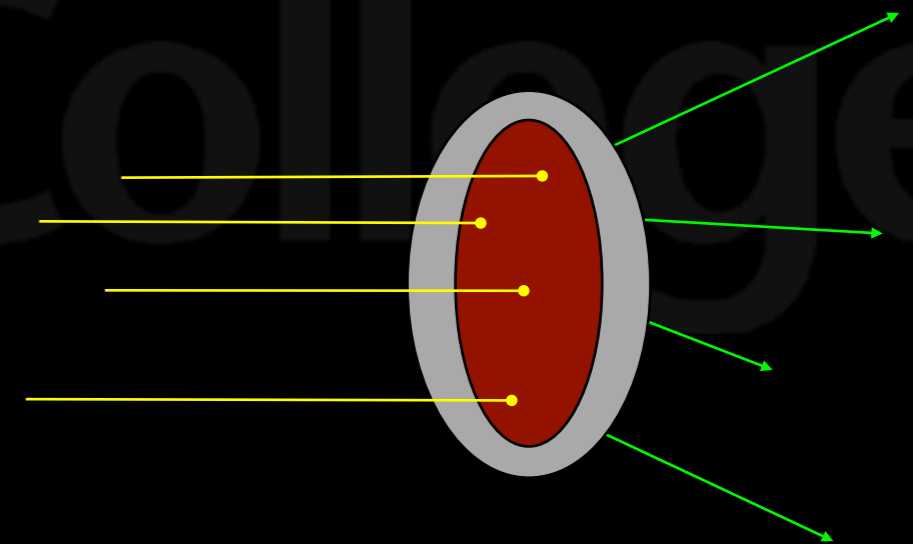
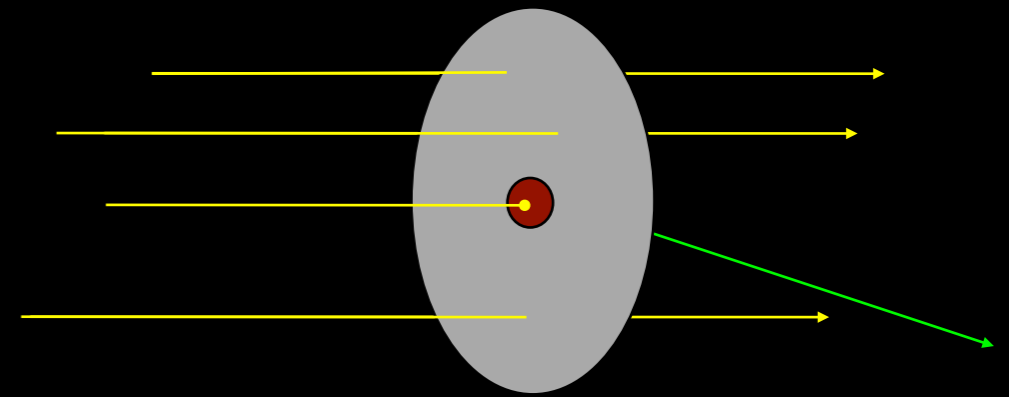
$$\nu\text{-N} \quad \sigma \sim 10^{-36} \text{ cm}^2$$



Neutrino Interactions 2

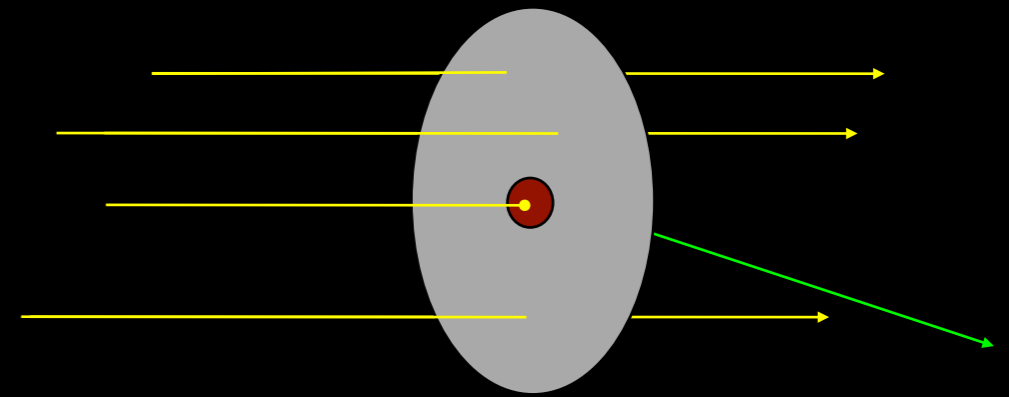
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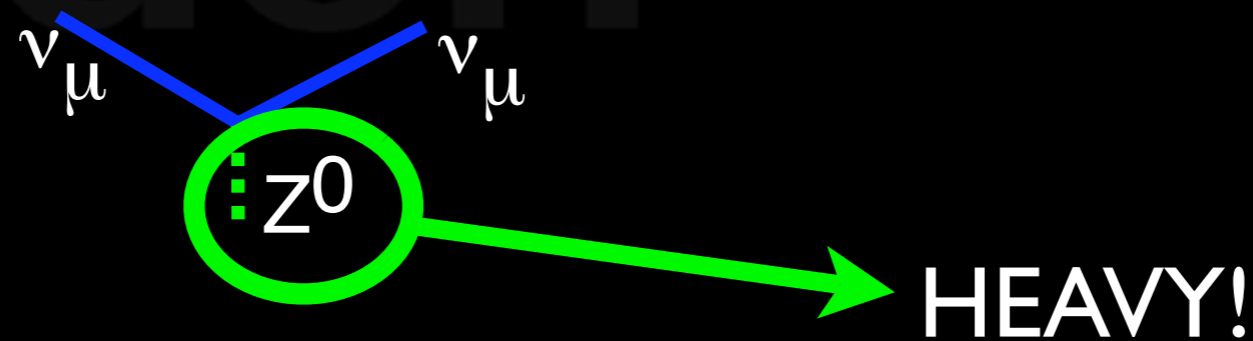
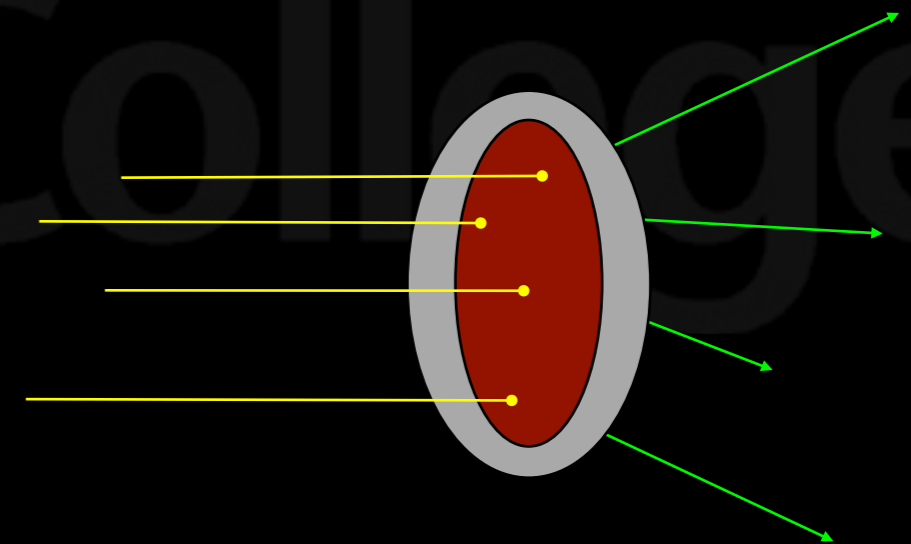


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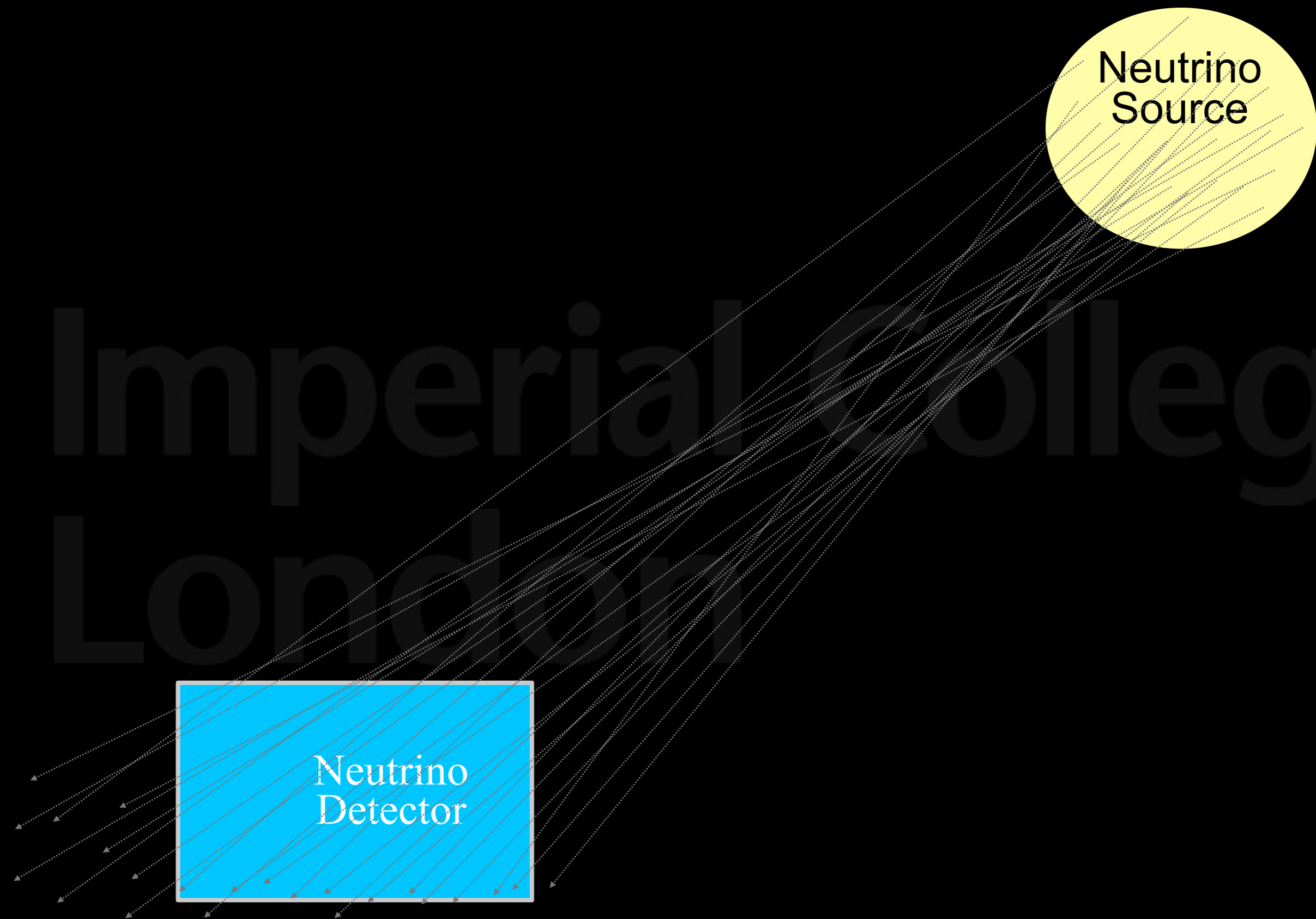
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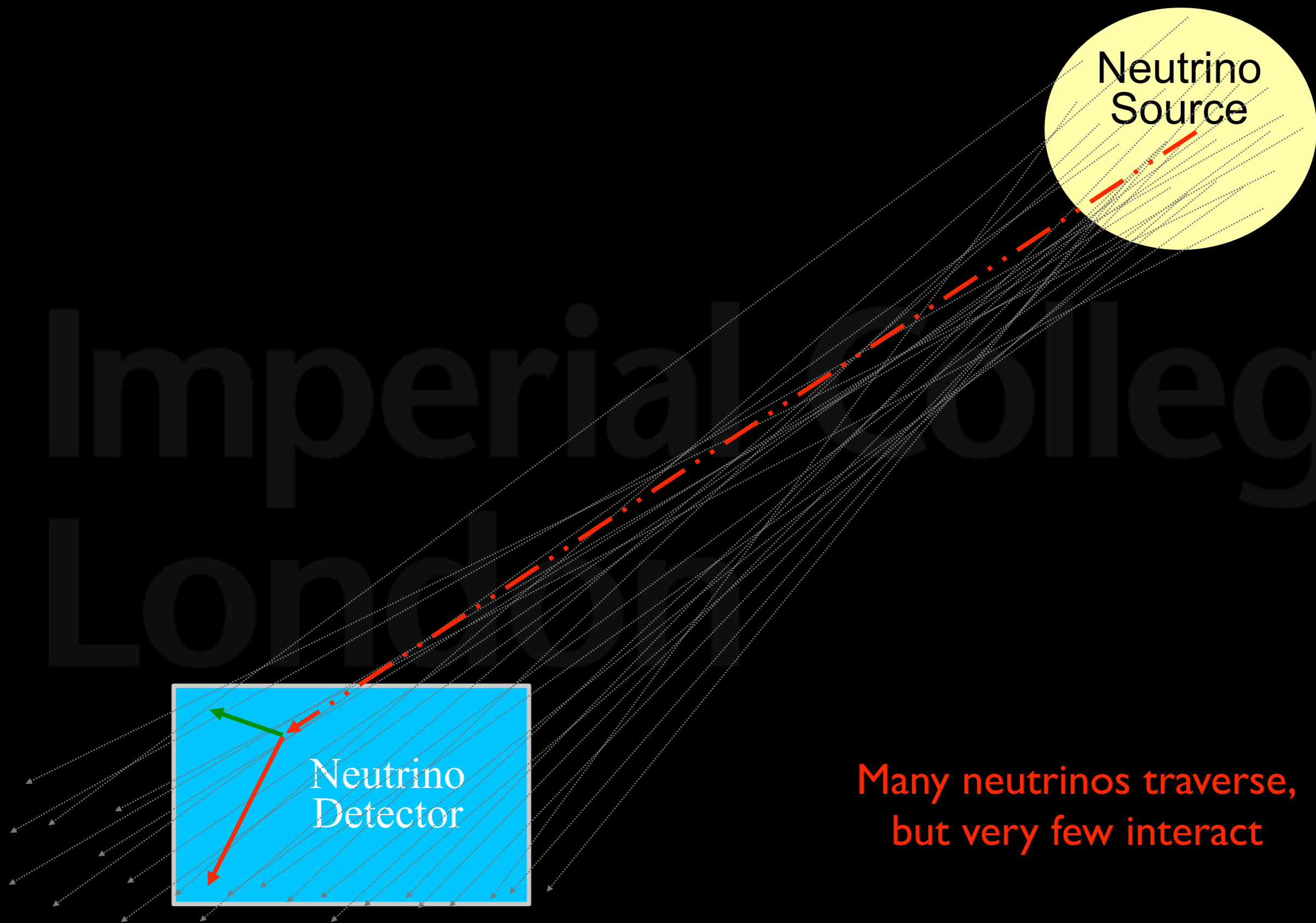
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Finding Neutrinos



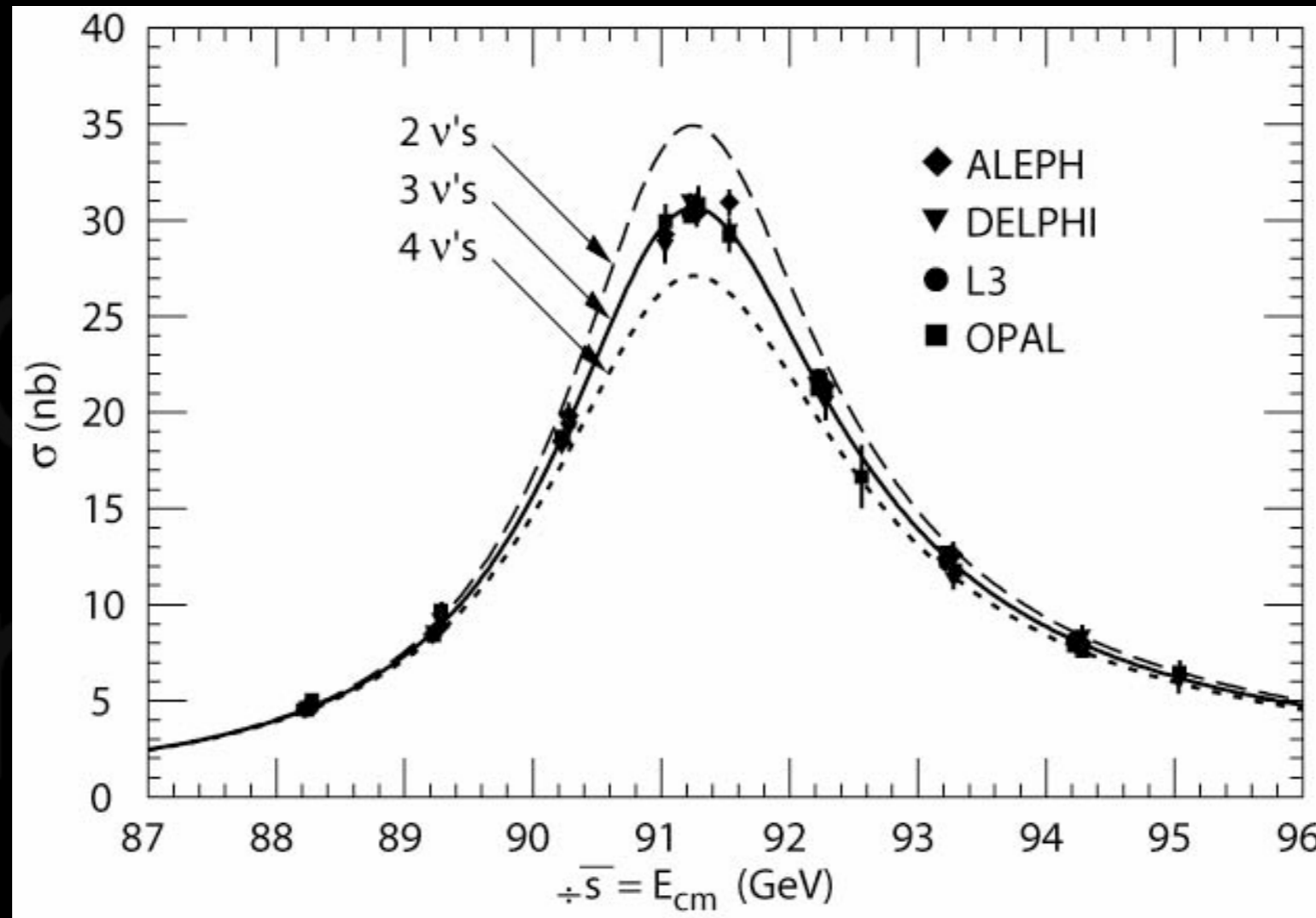
Finding Neutrinos



Many neutrinos traverse,
but very few interact

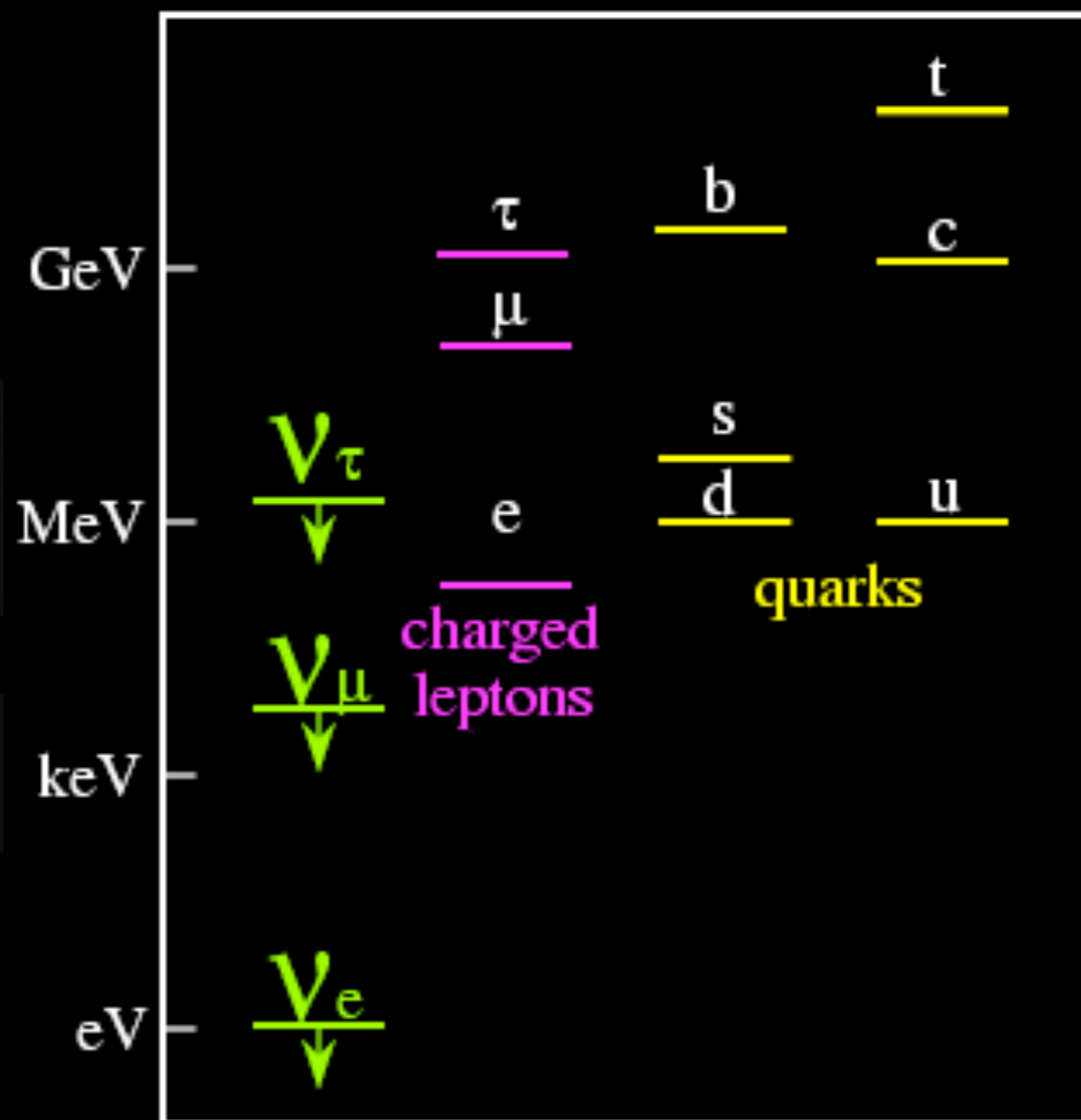
Neutrino Flavors

Invisible width of the Z^0 measured by LEP expts



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

Neutrinos Mass



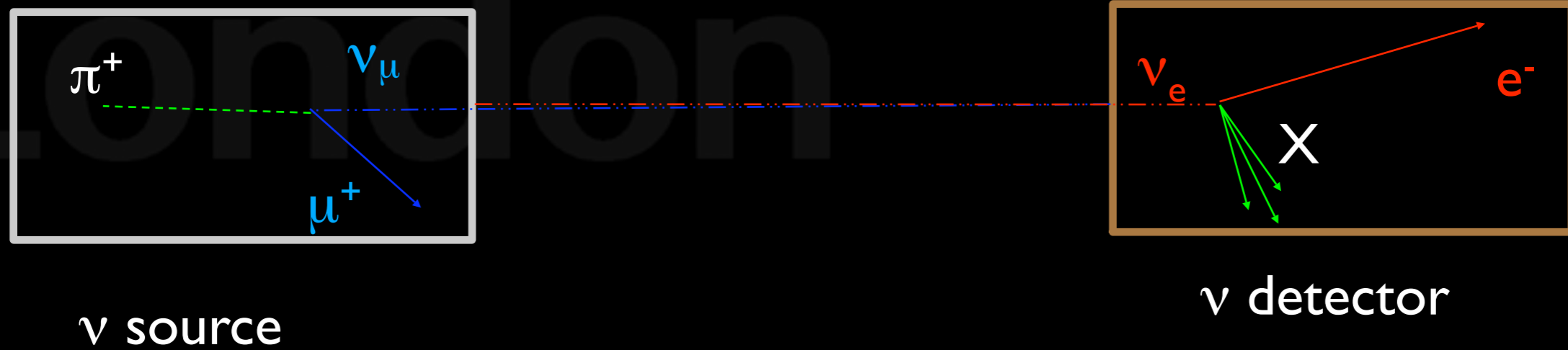
if neutrinos have mass...

a neutrino that is produced as a ν_μ

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

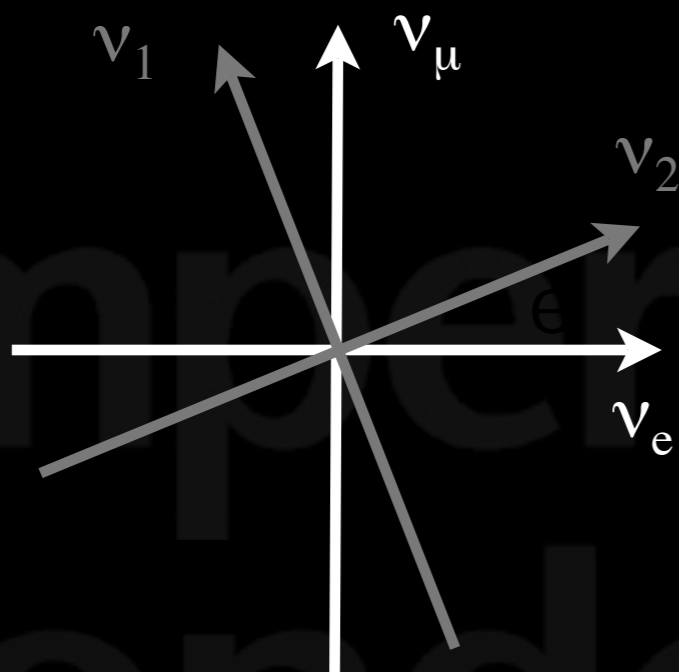
might some time later be observed as a ν_e

- (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

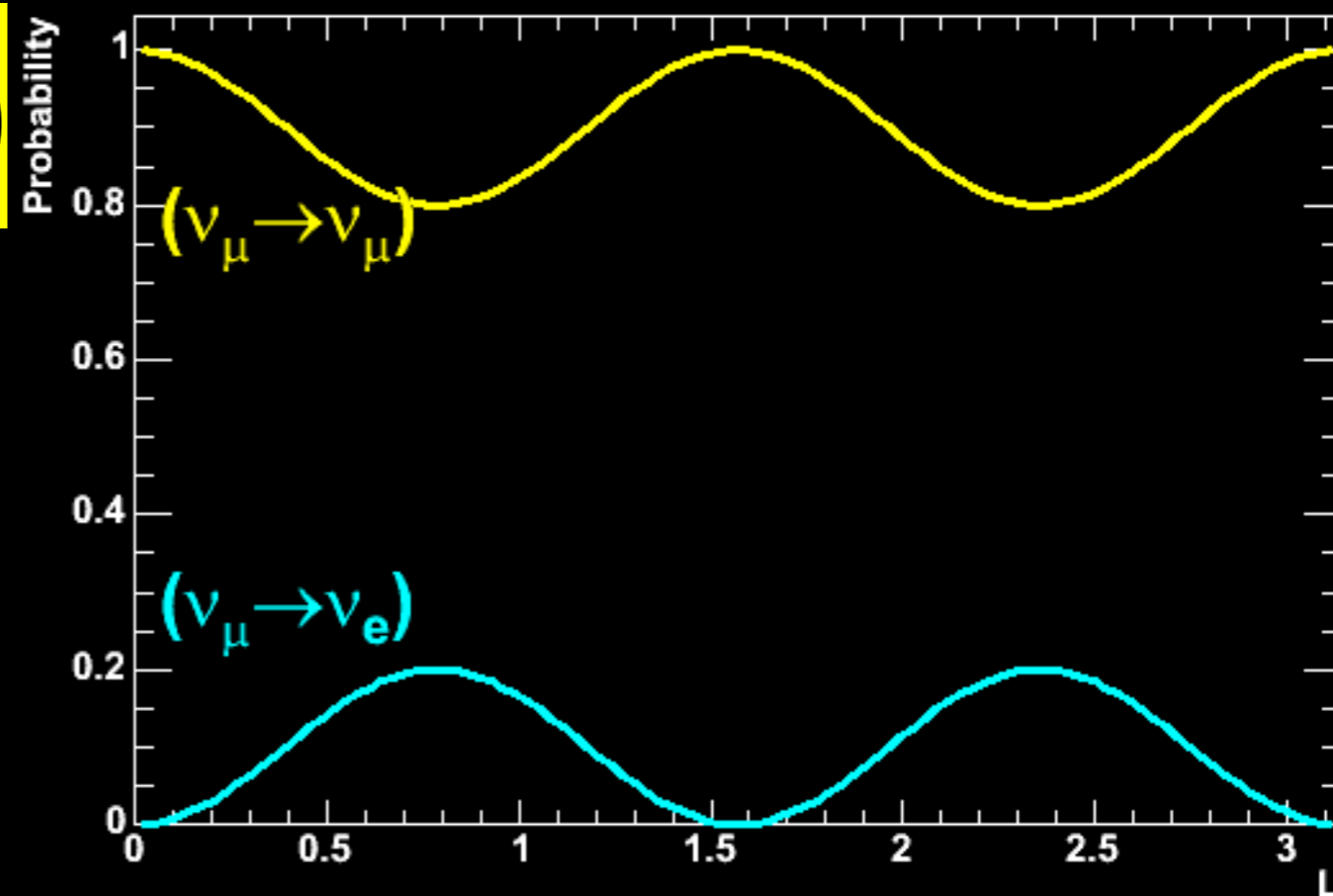
$$|\nu_\mu(t)\rangle = -\sin \theta |\nu_1\rangle e^{-iE_1 t} + \cos \theta |\nu_2\rangle e^{-iE_2 t}$$

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

- Probability to find ν_e when you started with ν_μ

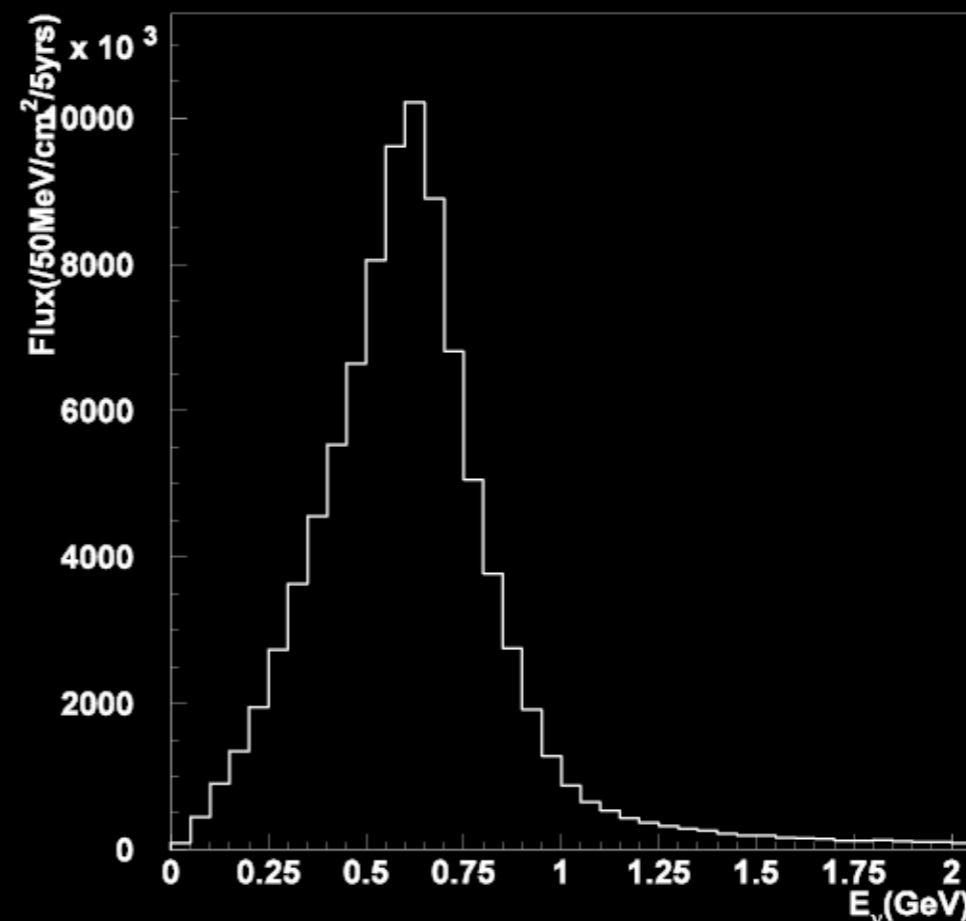
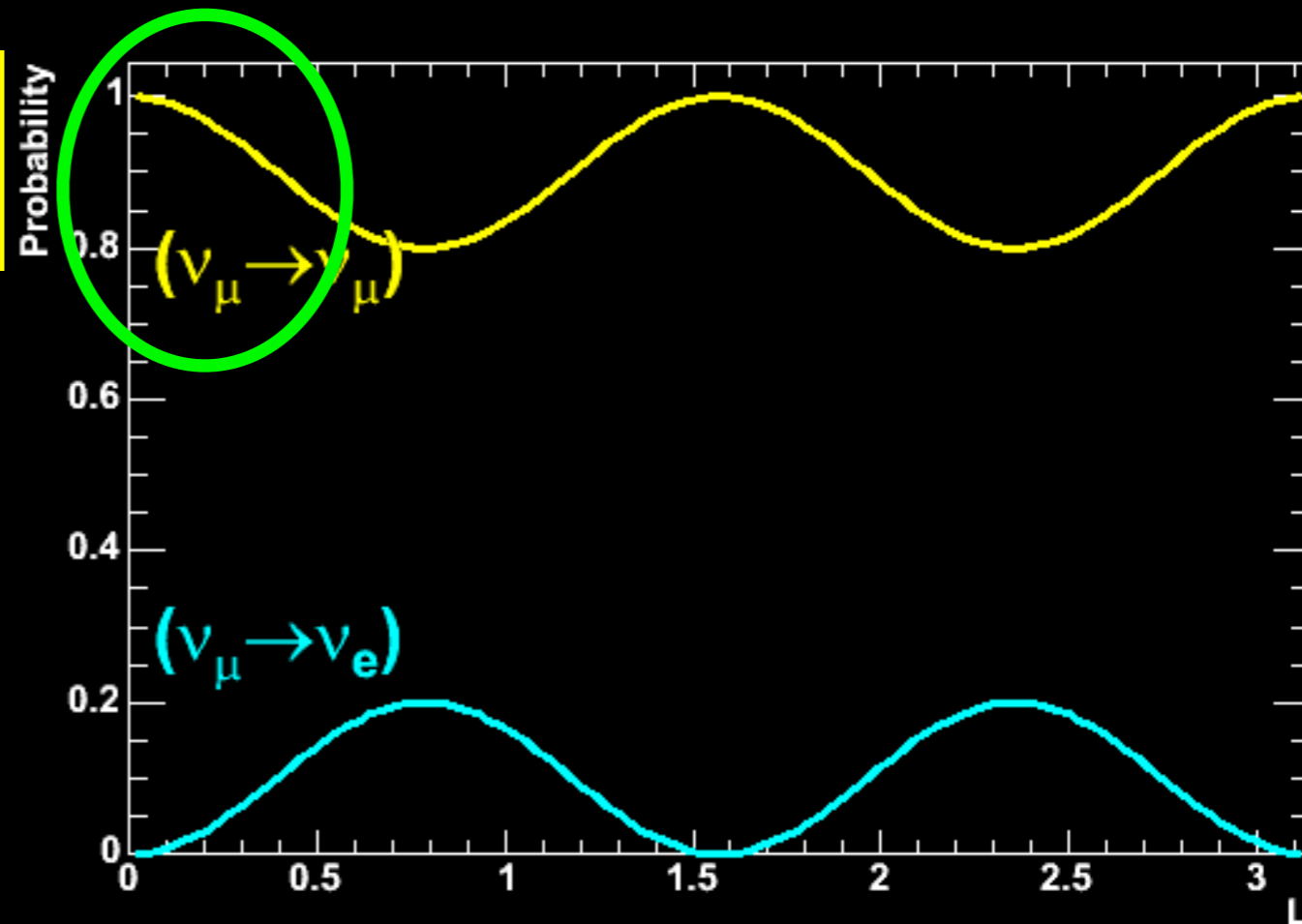
$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{12} \sin^2\left(1.27 \Delta m_{12}^2 \frac{L}{E}\right)$$

- 2 fundamental parameters
 - $\Delta m_{12}^2 (=m_1^2 - m_2^2) \leftrightarrow$ period
 - $\theta_{12} \leftrightarrow$ 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



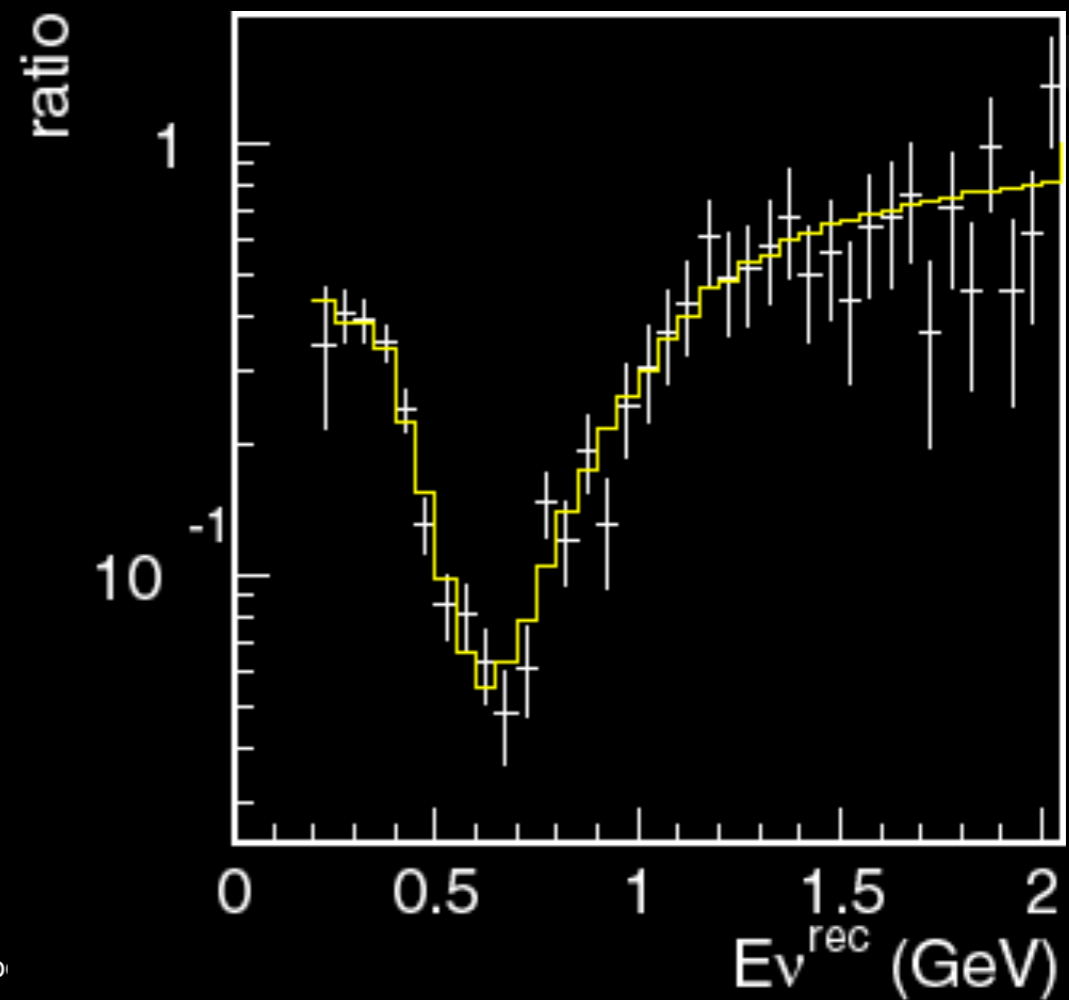
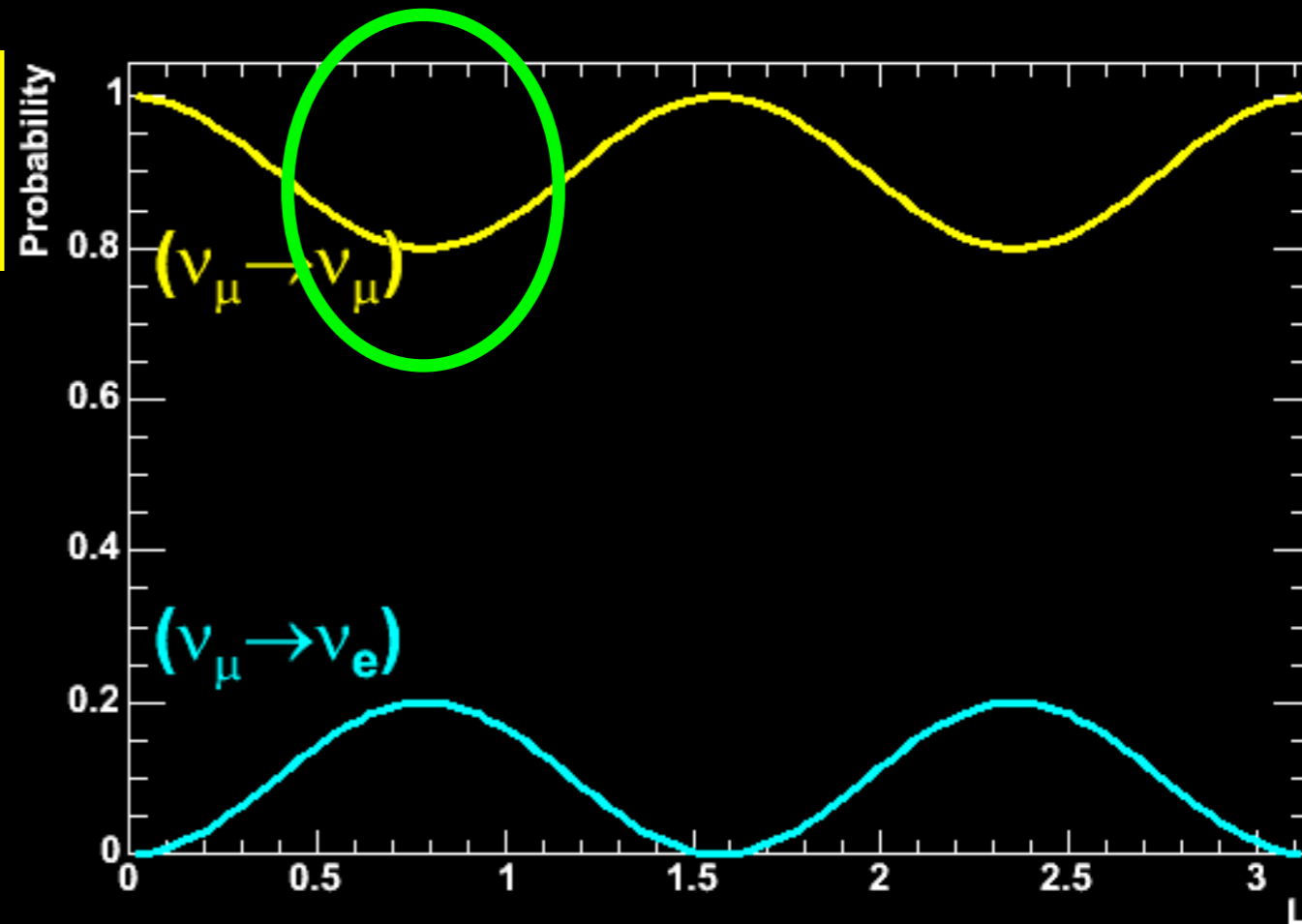
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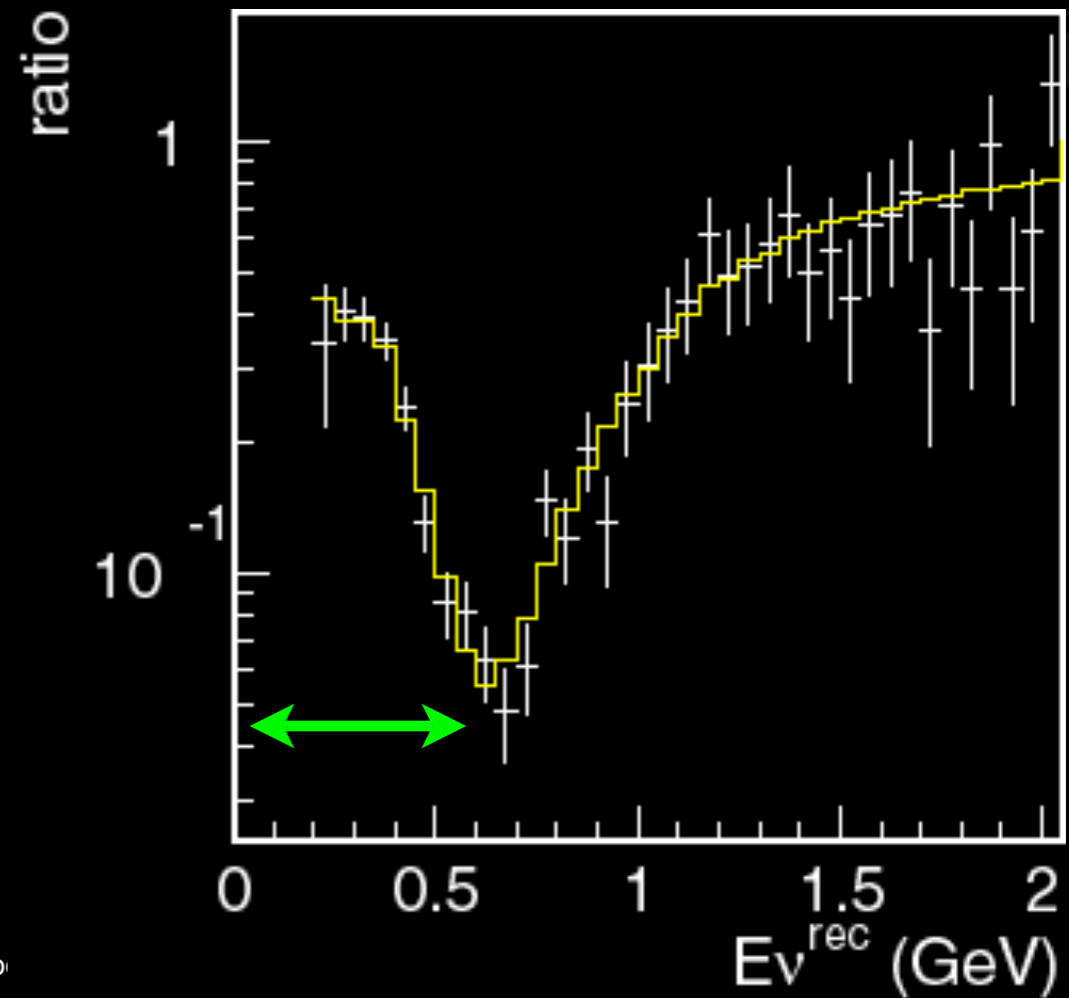
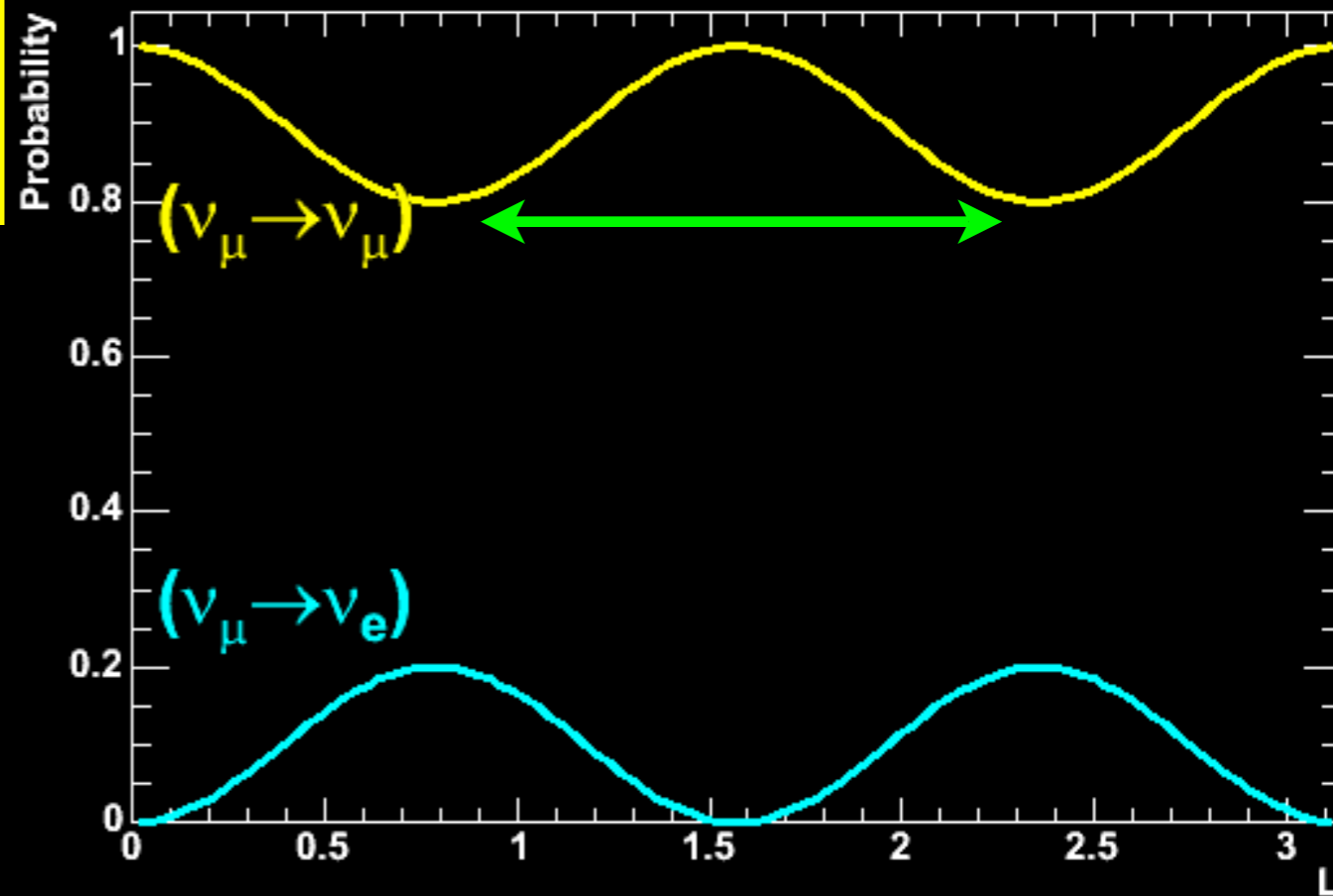
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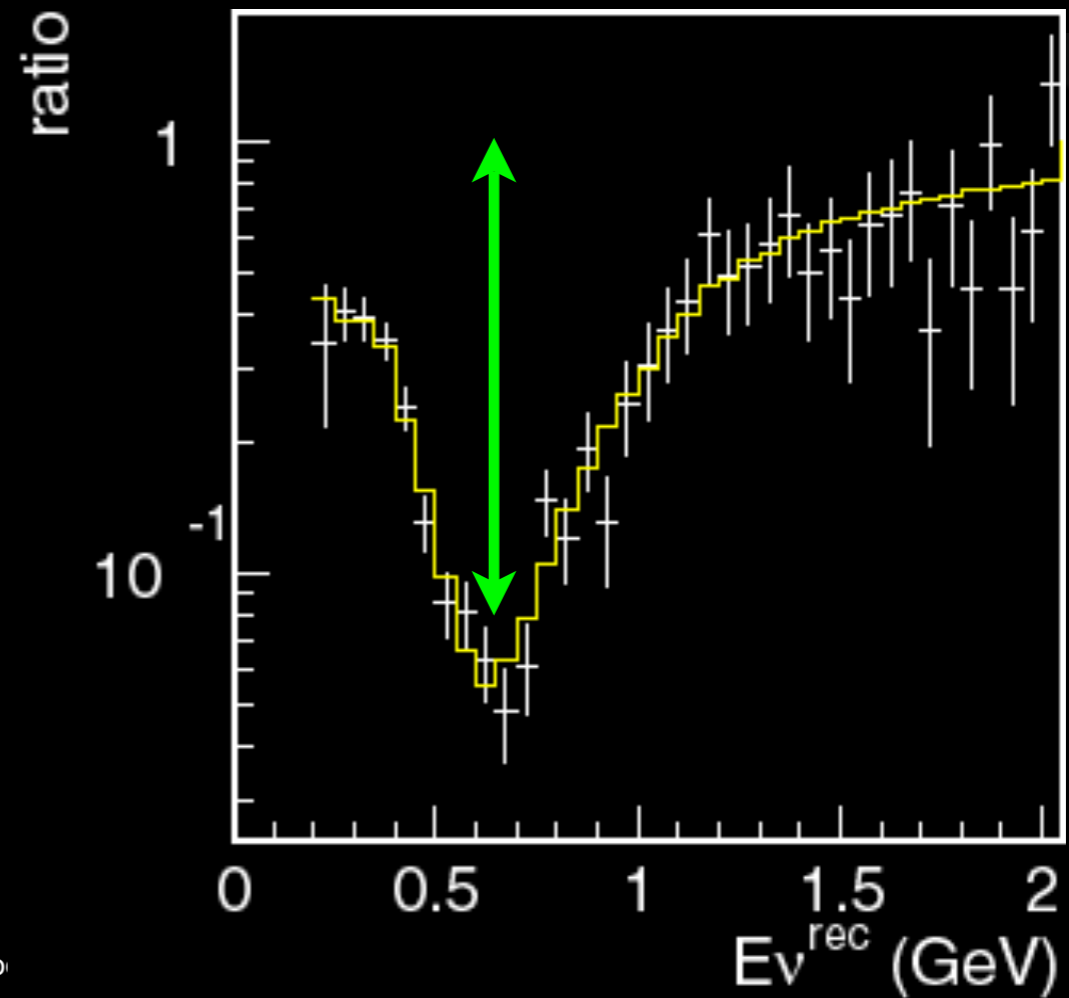
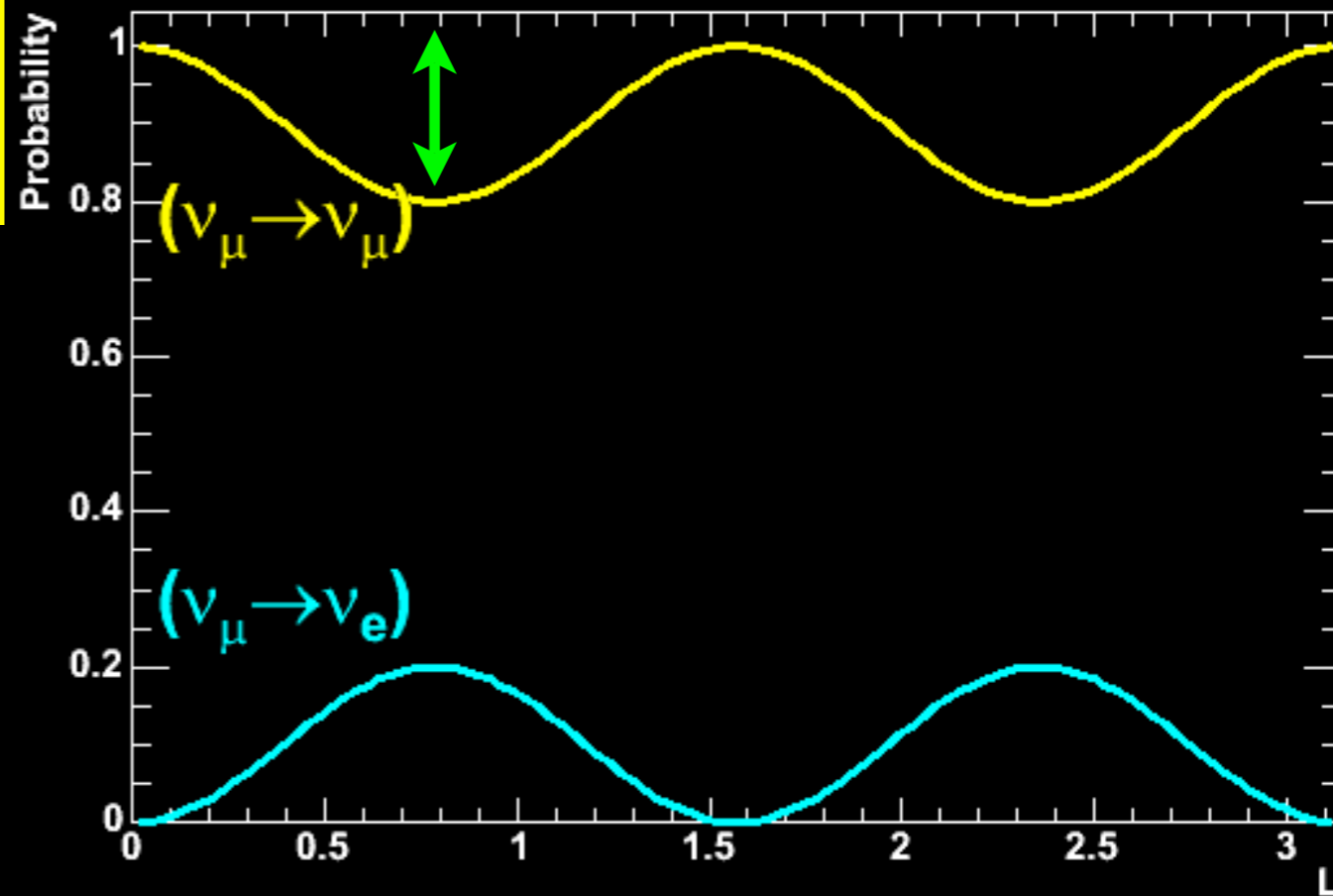
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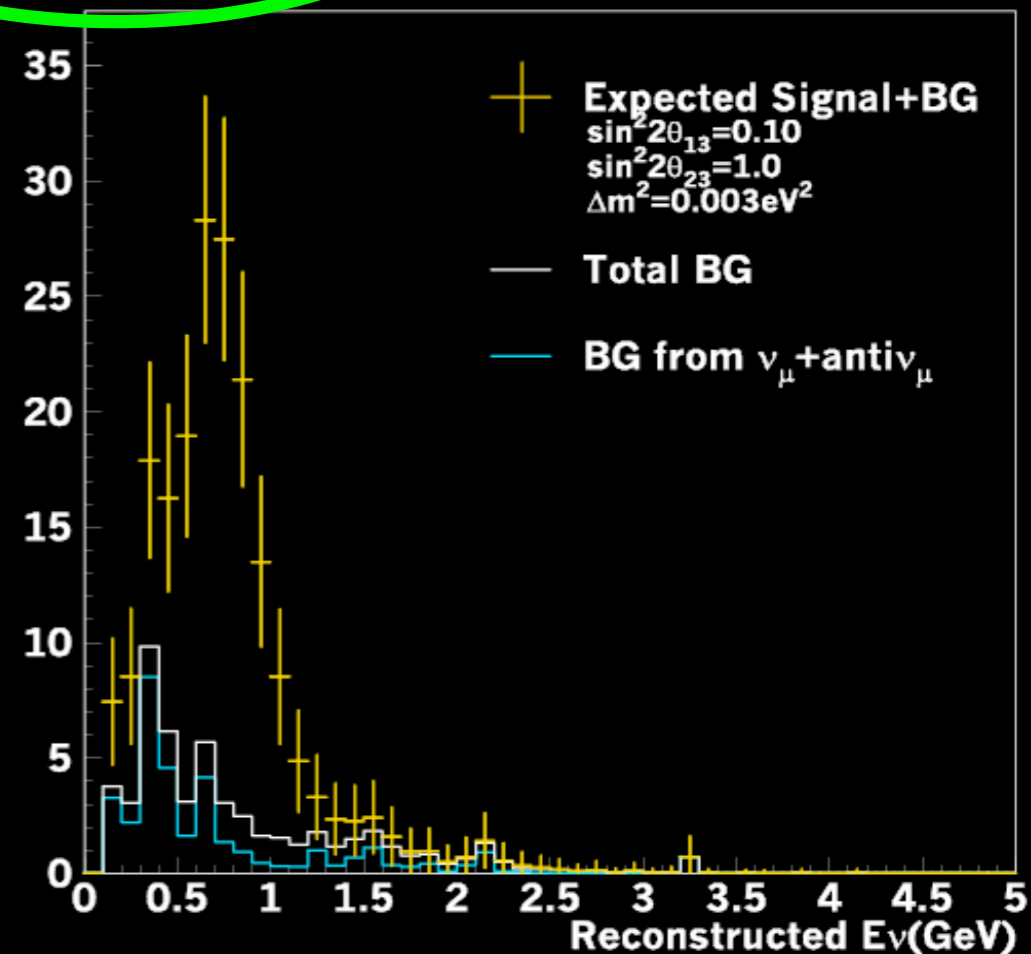
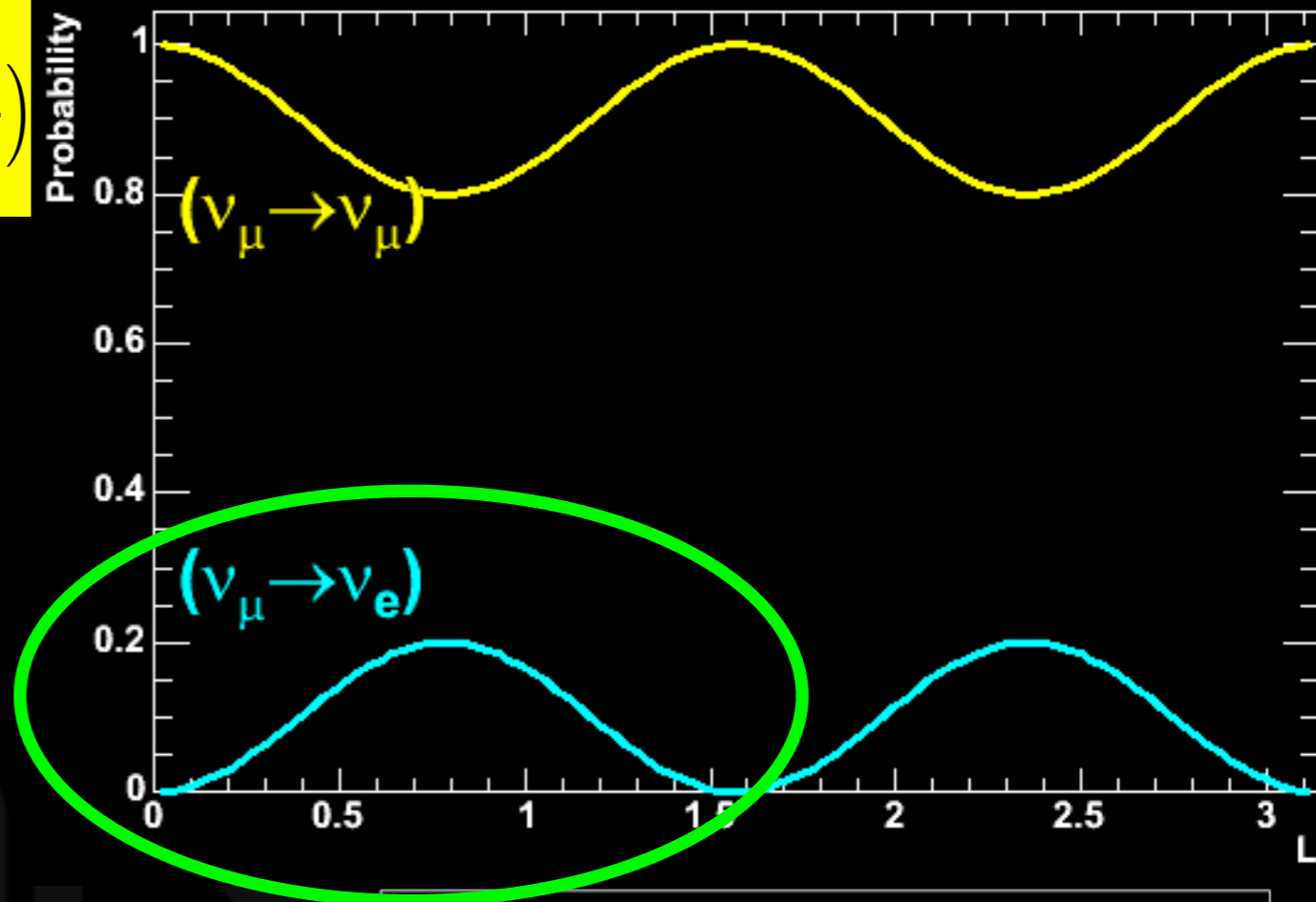
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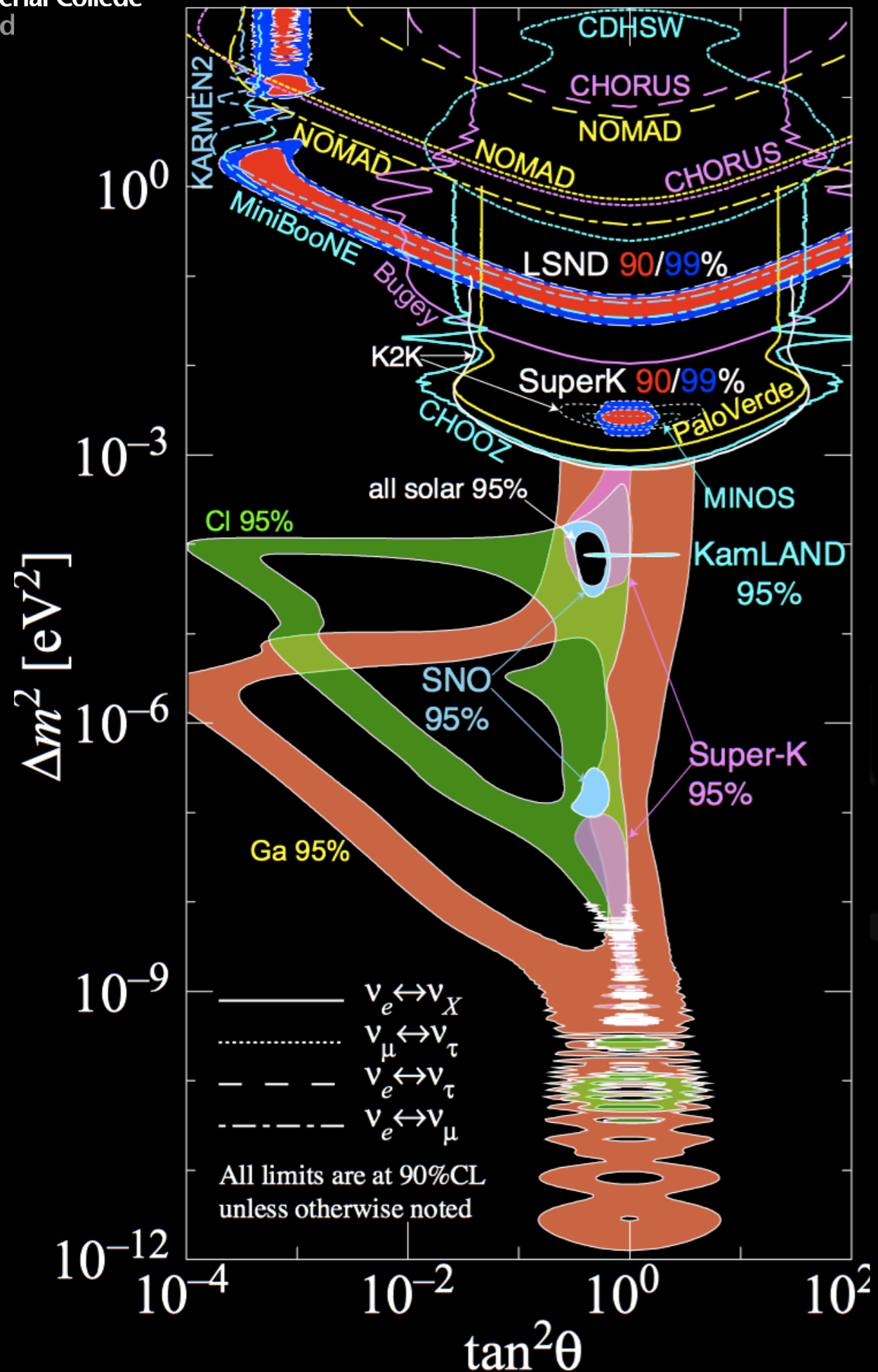
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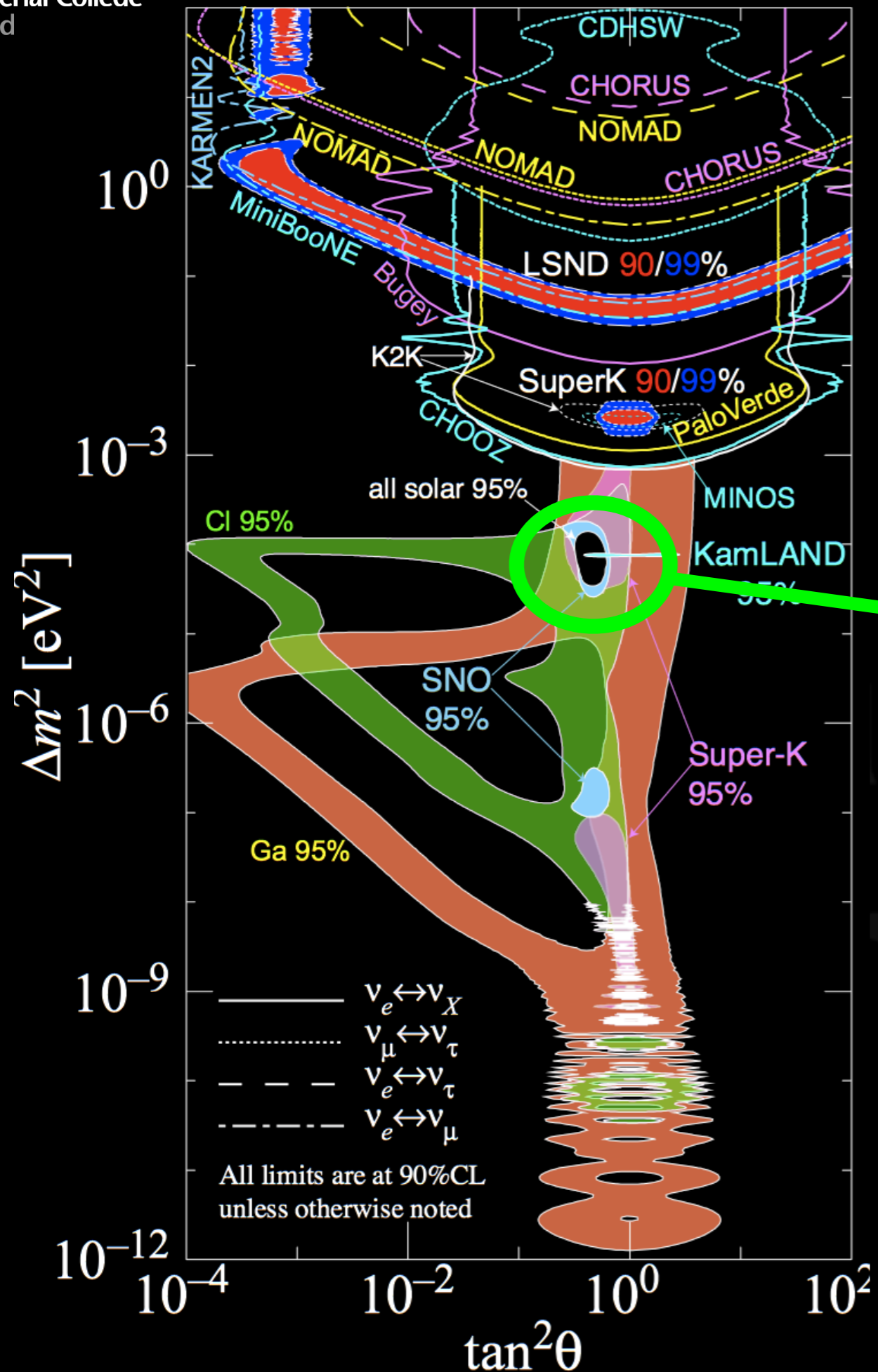
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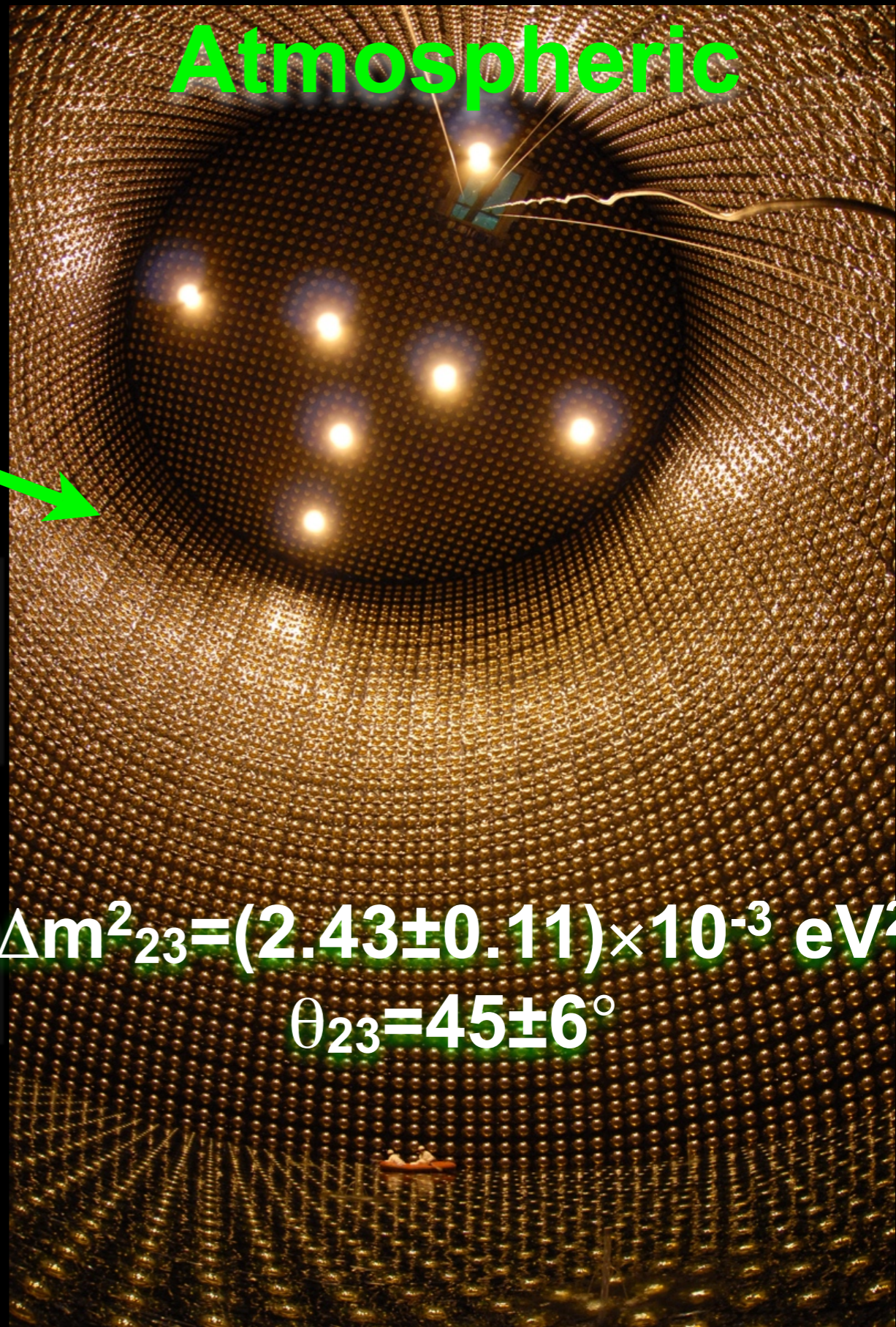
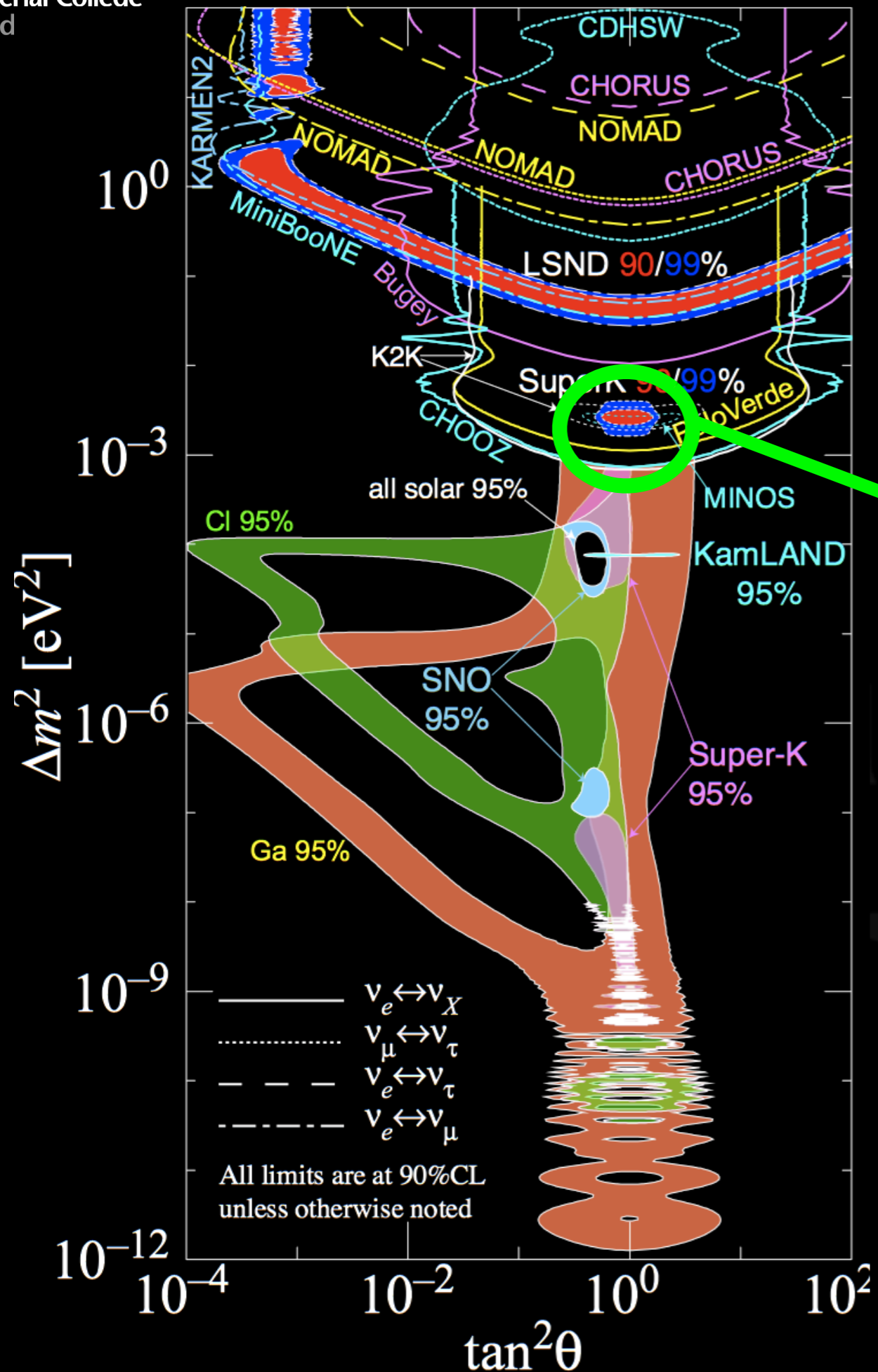


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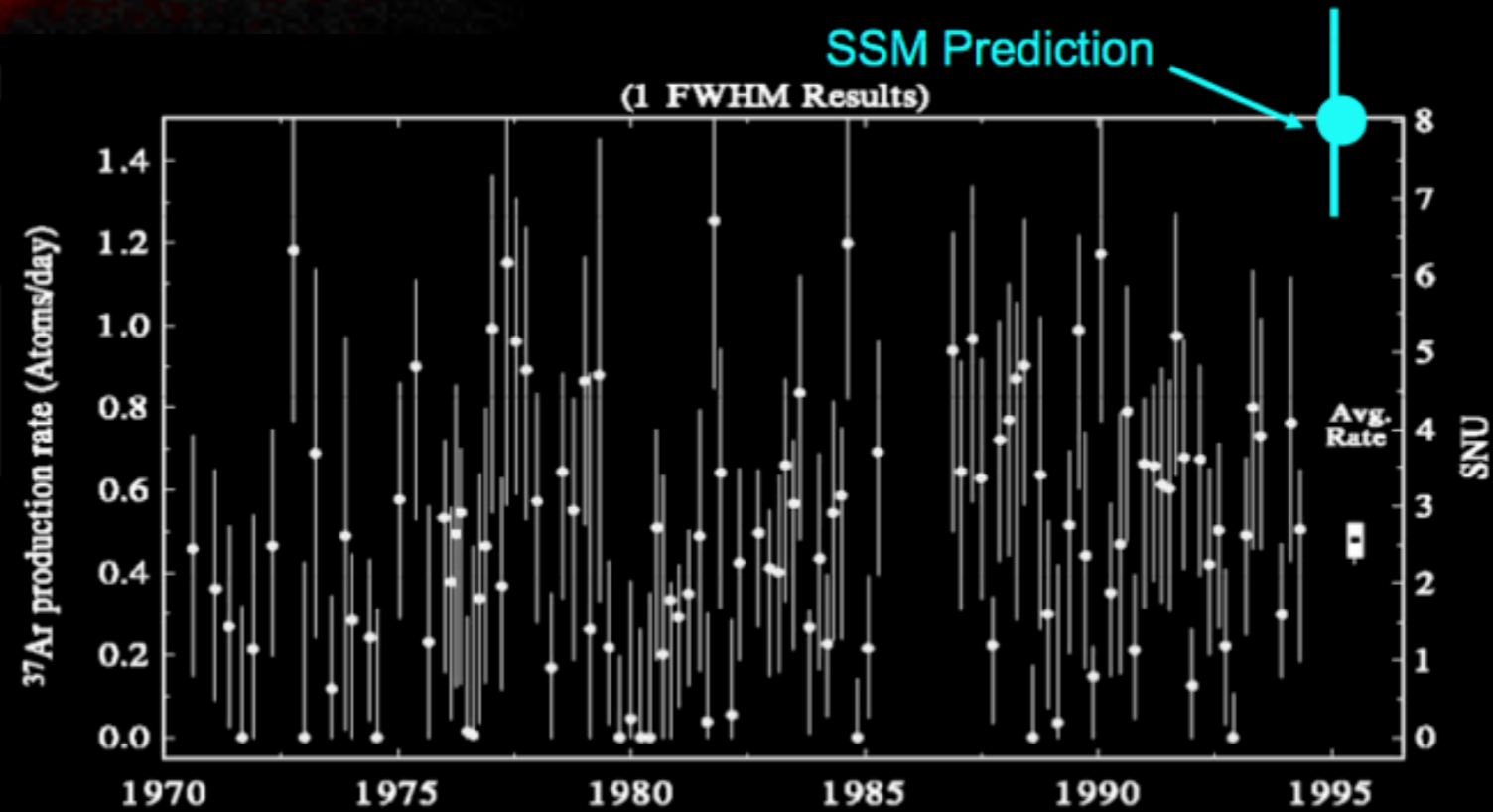
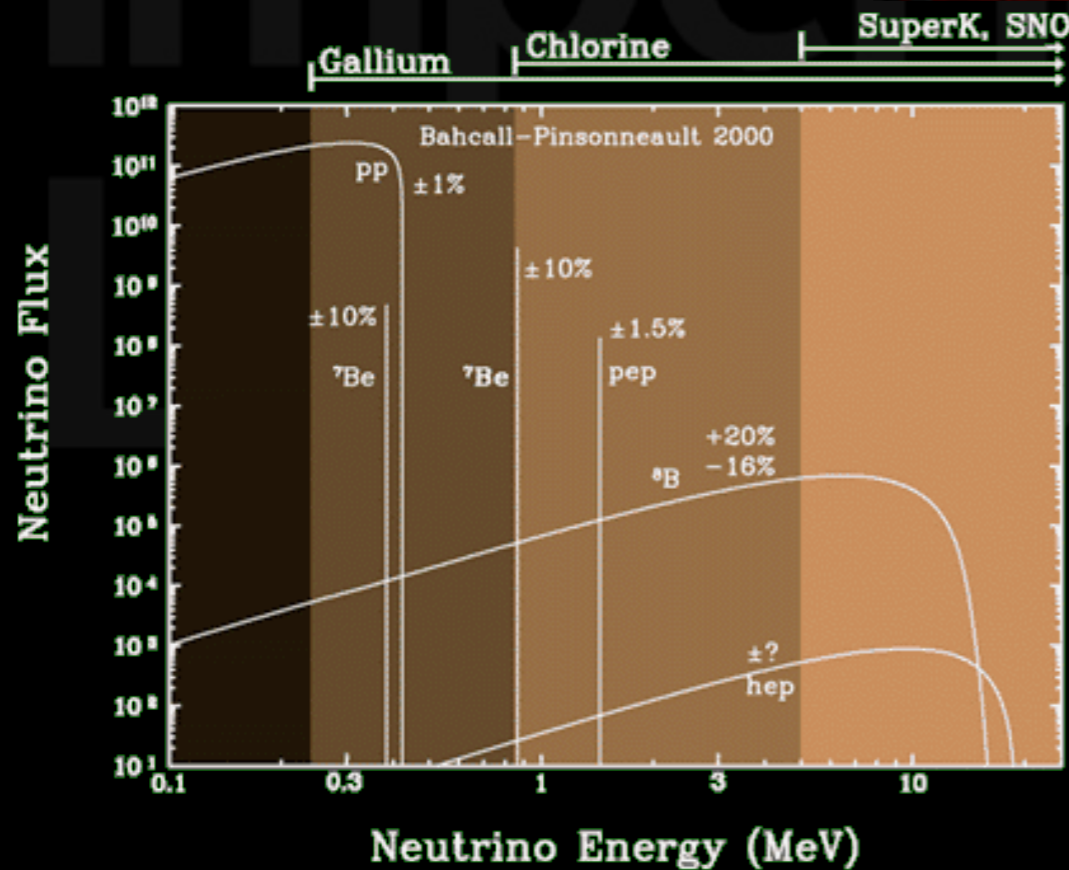
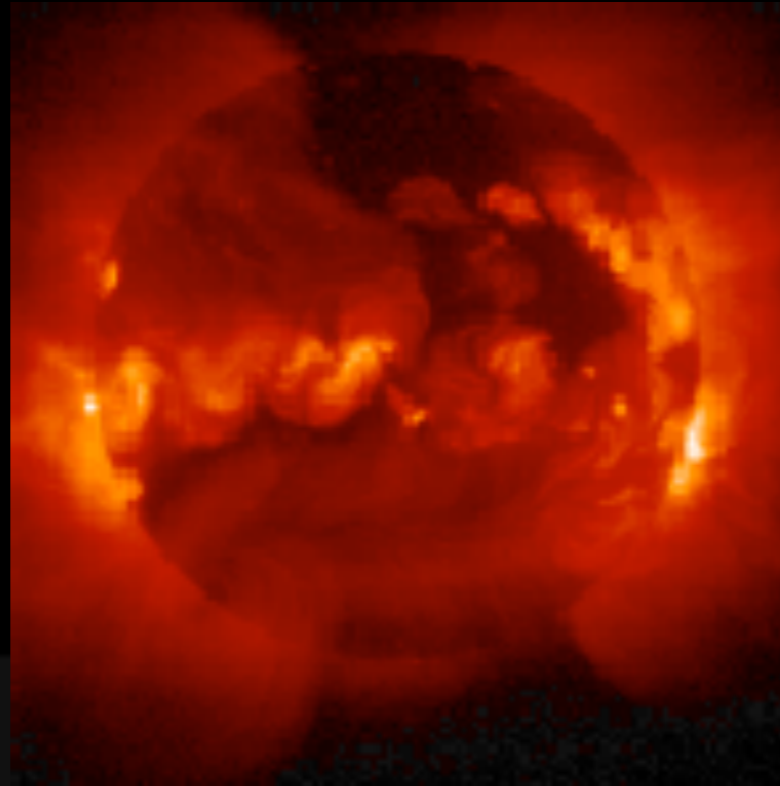


$$\Delta m^2_{12} = (7.59 \pm 0.21) \times 10^{-5} \text{ eV}^2$$

$$\theta_{12} = 34.4^\circ \begin{matrix} +1.6 \\ -1.5 \end{matrix}$$

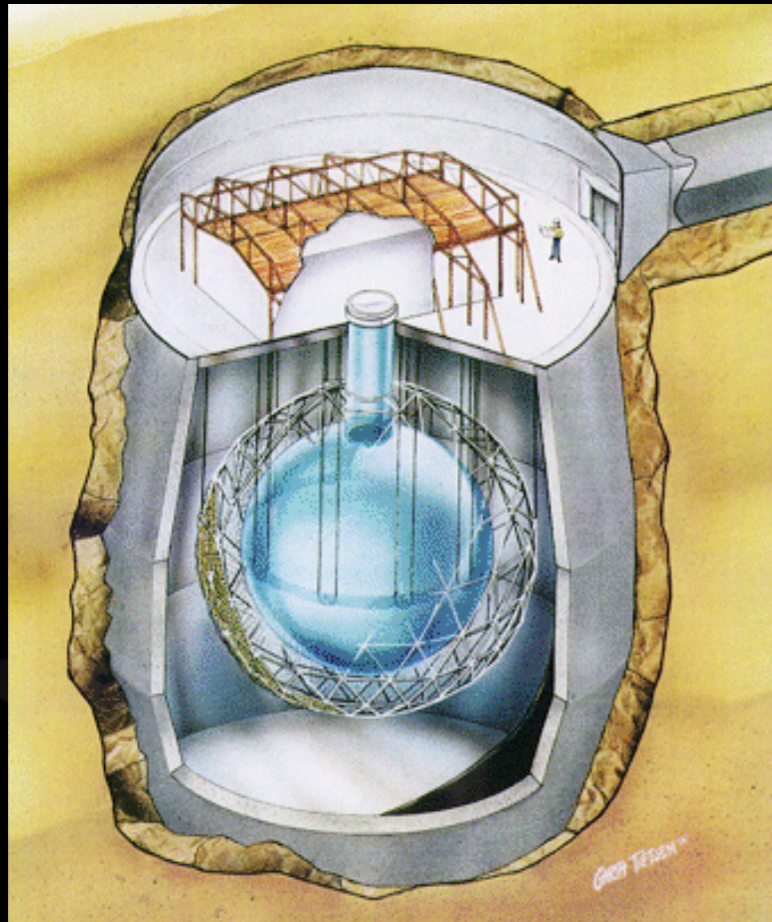


Neutrinos from the Sun



PRL 20 1205 (1968)

Solving Solar Problem

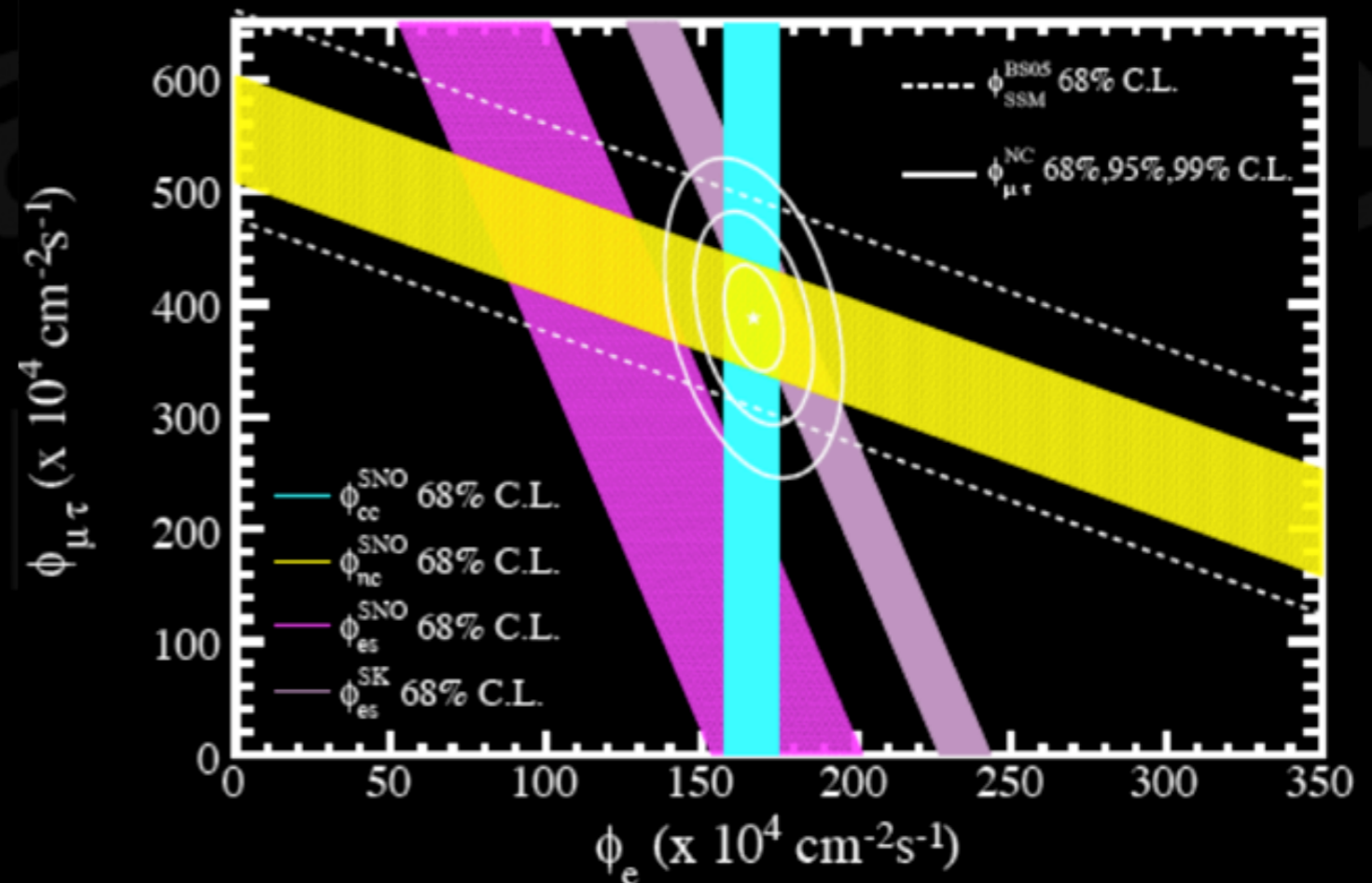


$$\frac{\phi_{CC}^{SNO}}{\phi_{NC}^{SNO}} = 0.301 \pm 0.033(\text{total})$$

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

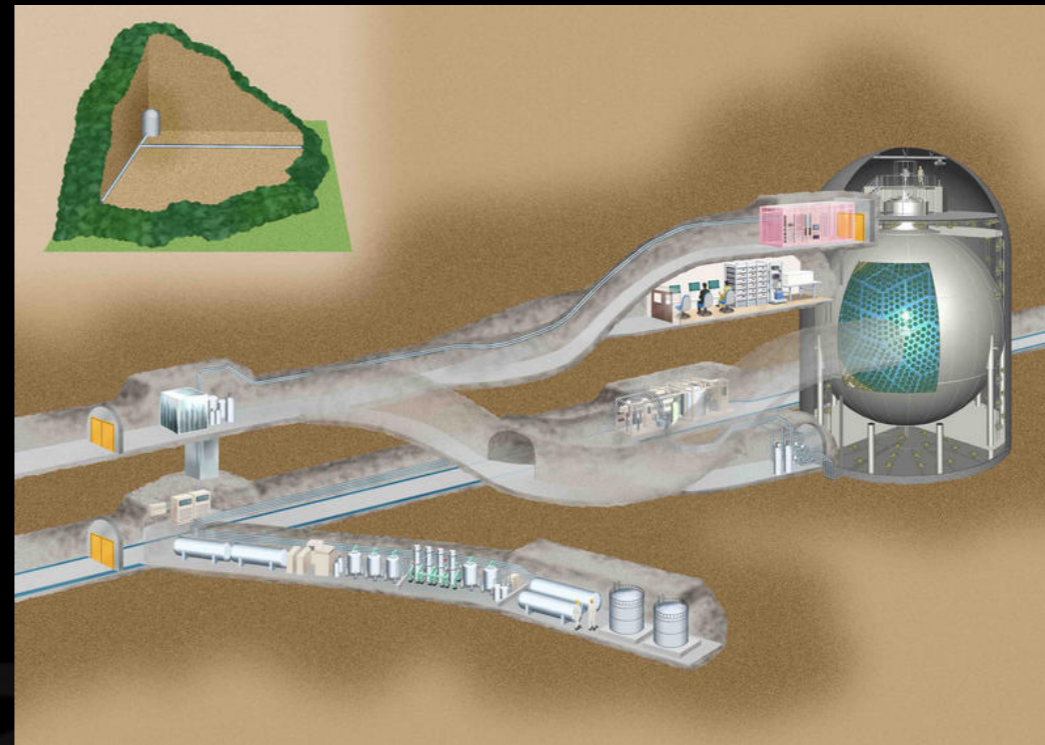
NC: $\nu_x + d \rightarrow p + n + e$

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

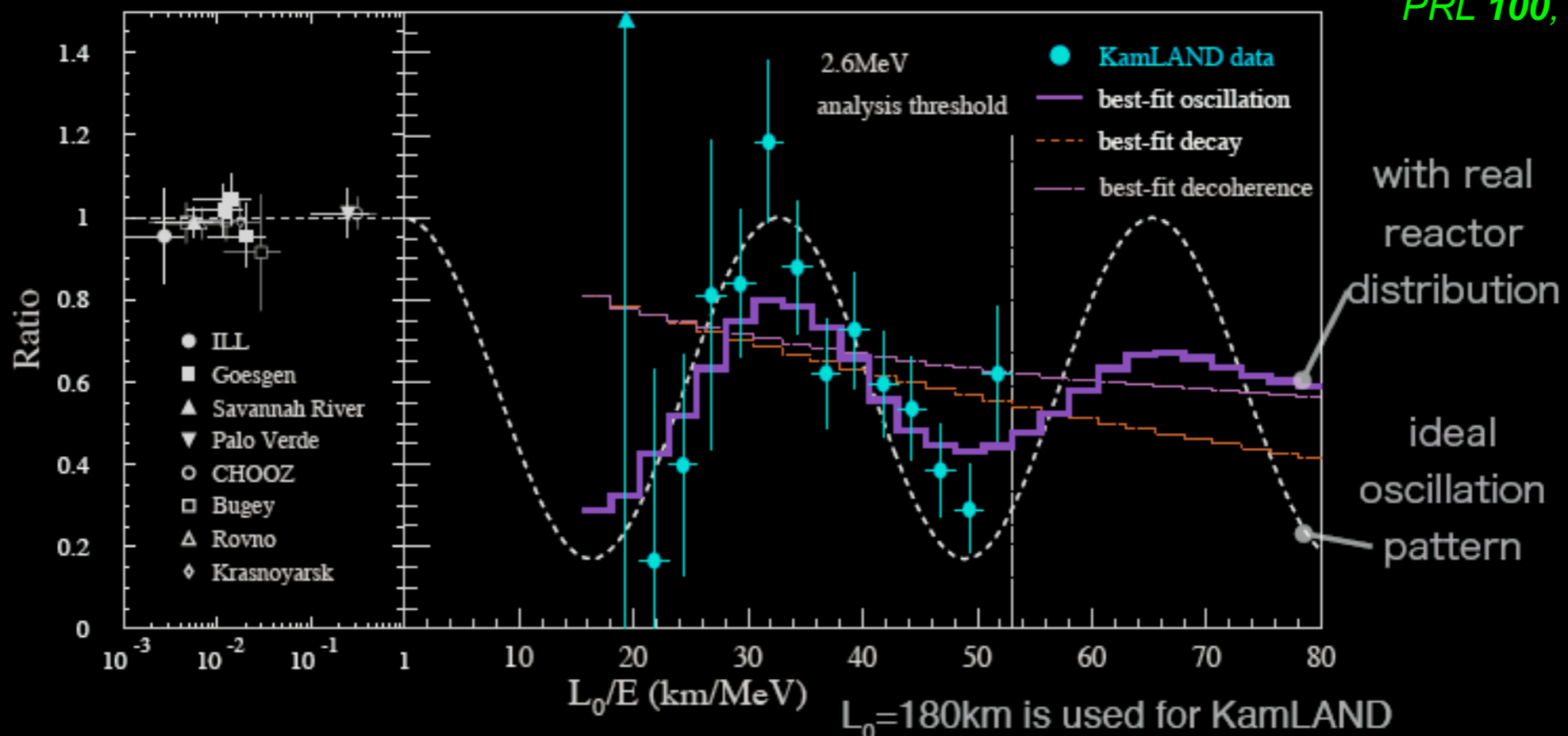


PRL 101, 111301 (2008)

Confirming Solar Results

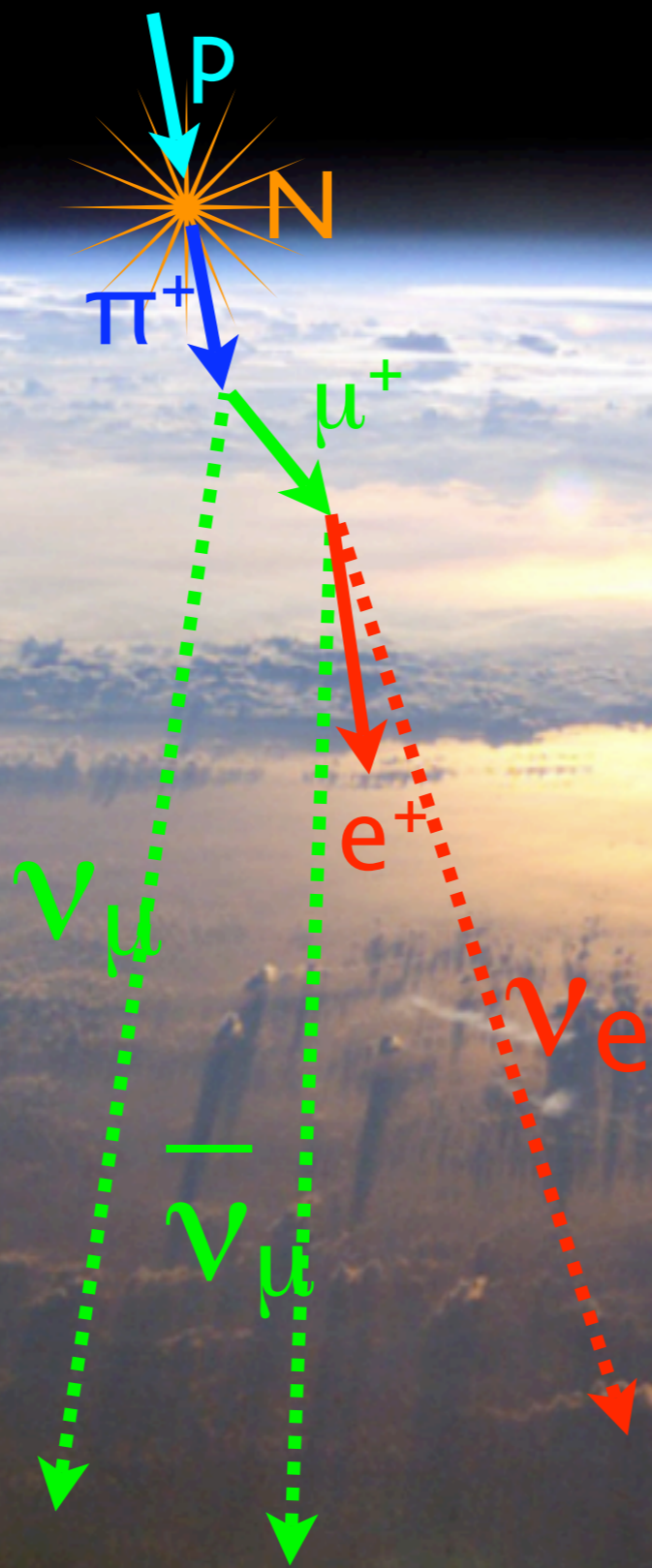


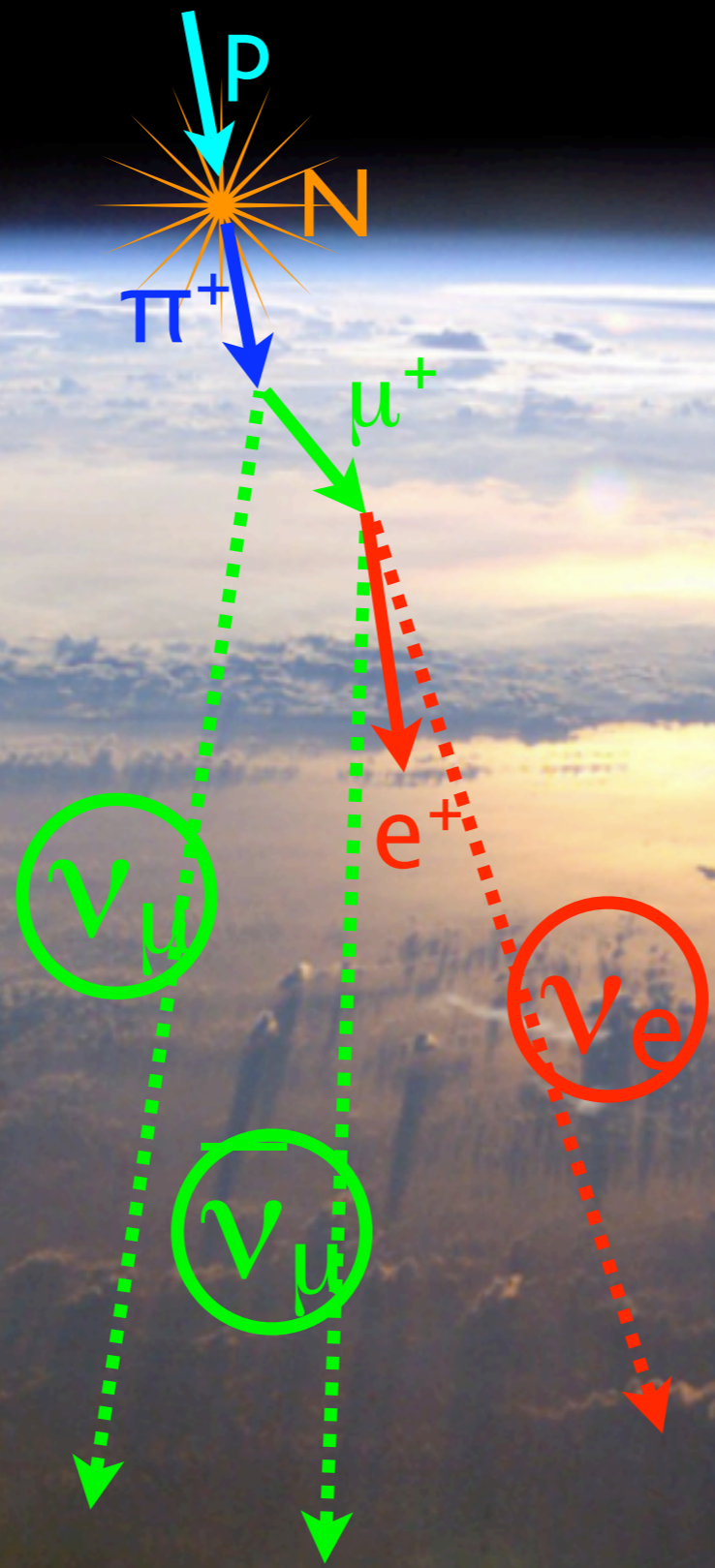
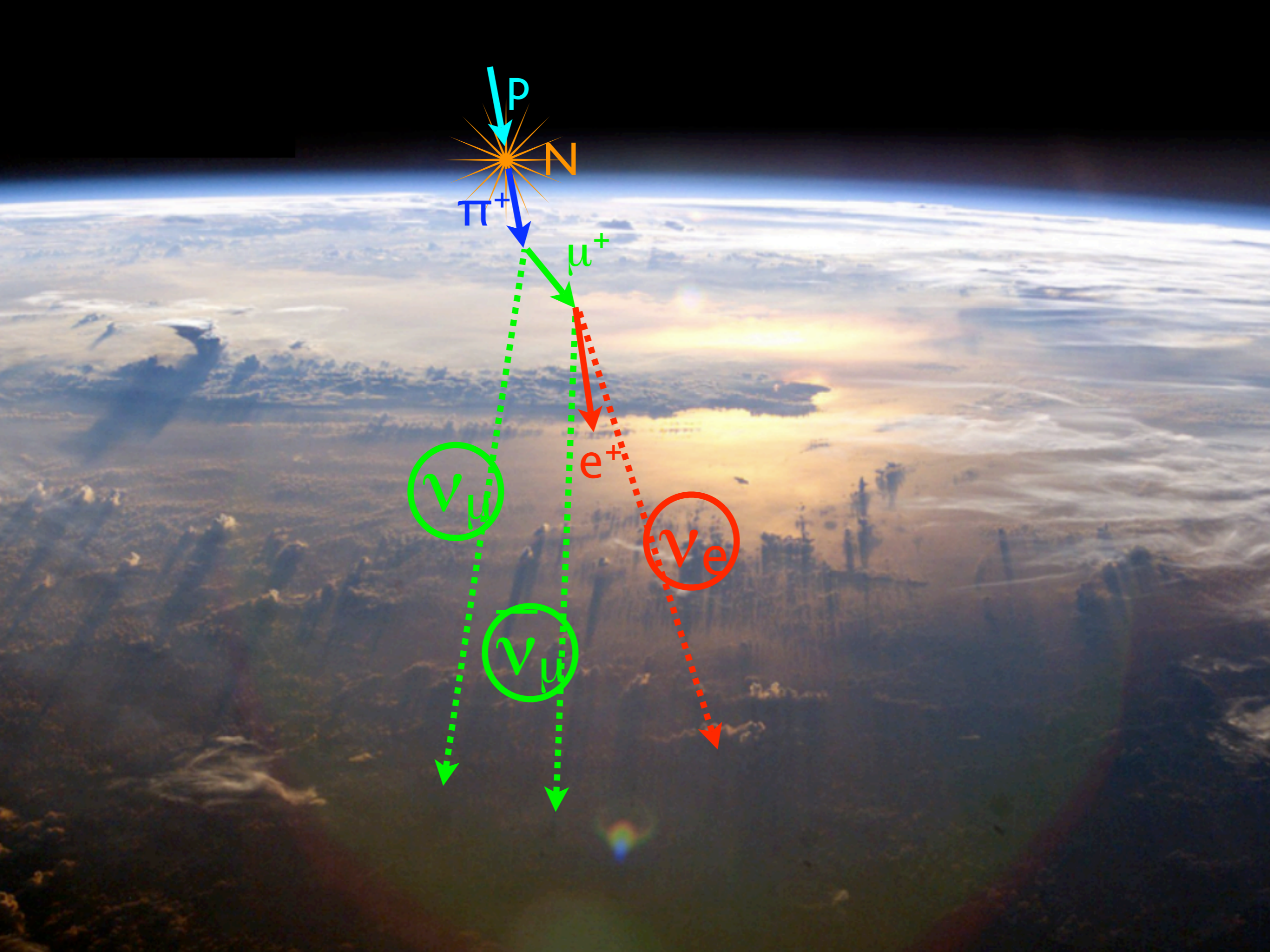
PRL 100, 221803 (2008)



$L_0 = 180\text{km}$ is used for KamLAND

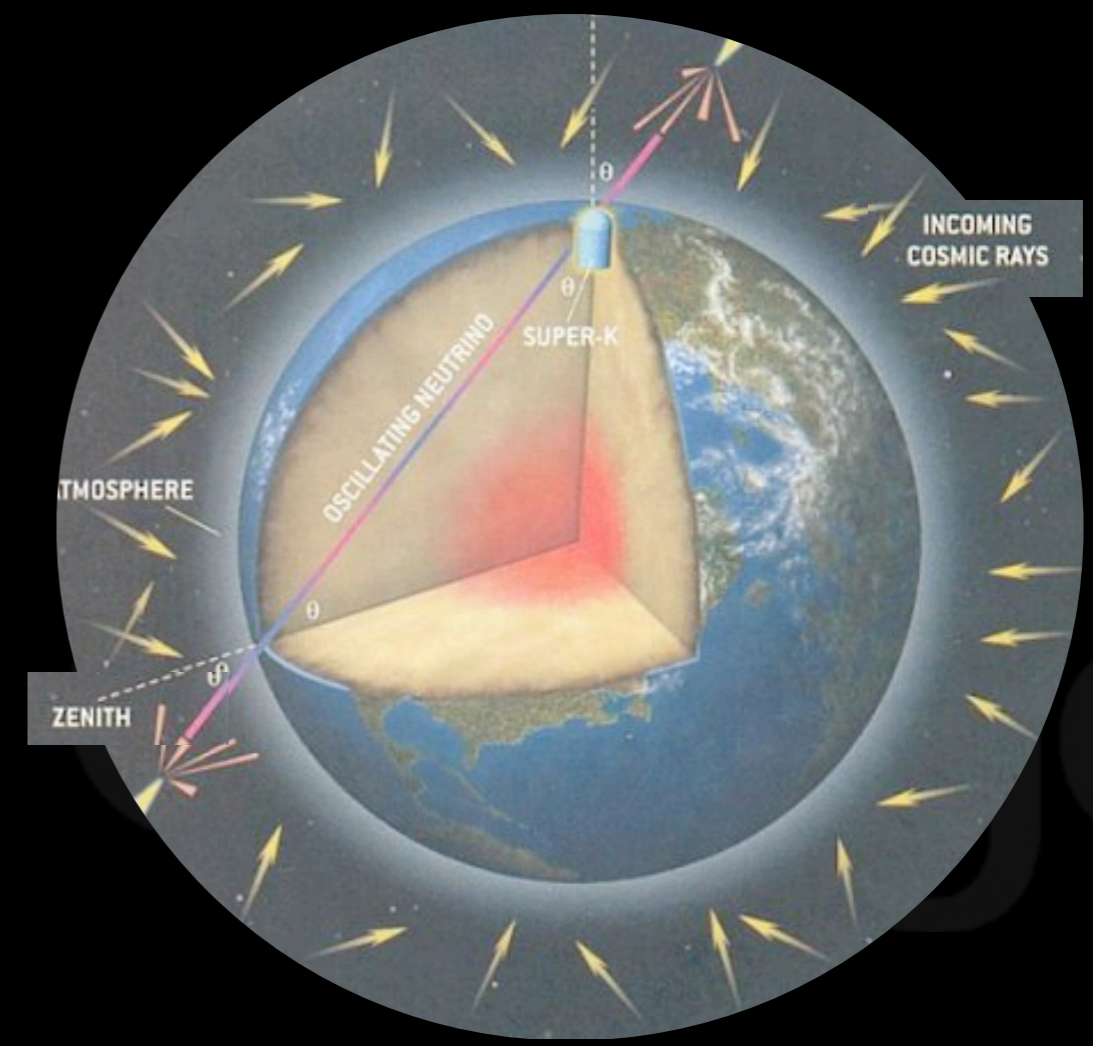
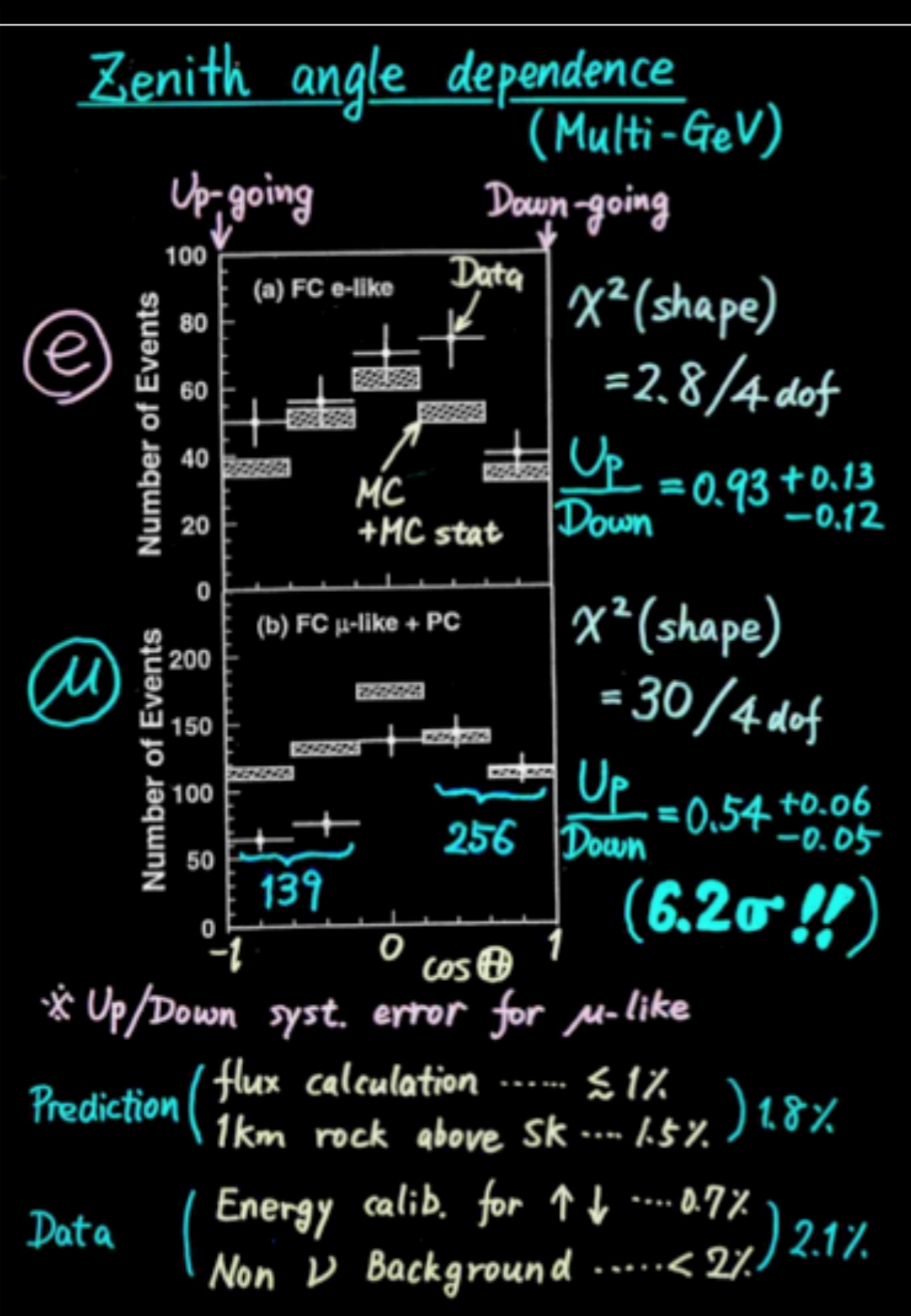






Atmospherics

- Super-Kamiokande @ Neutrino 98

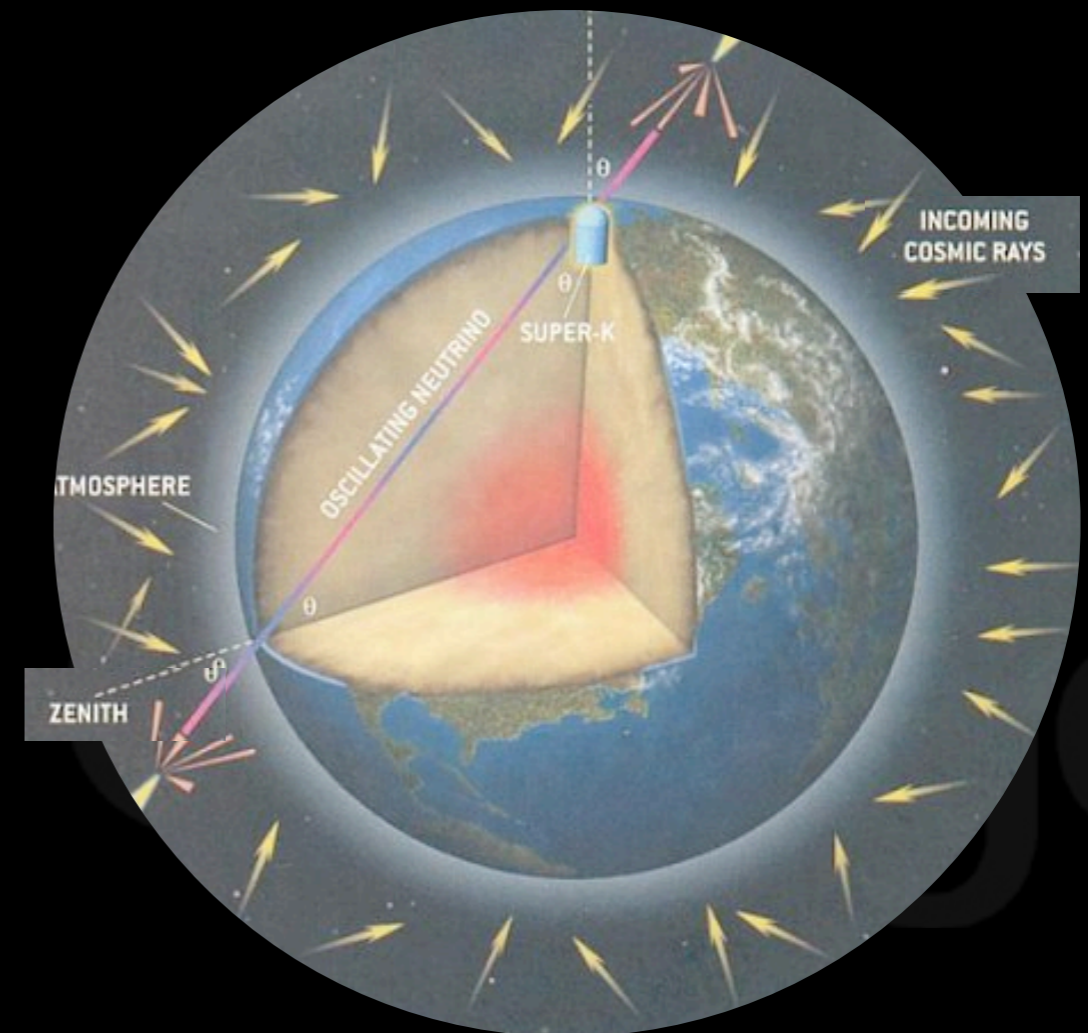
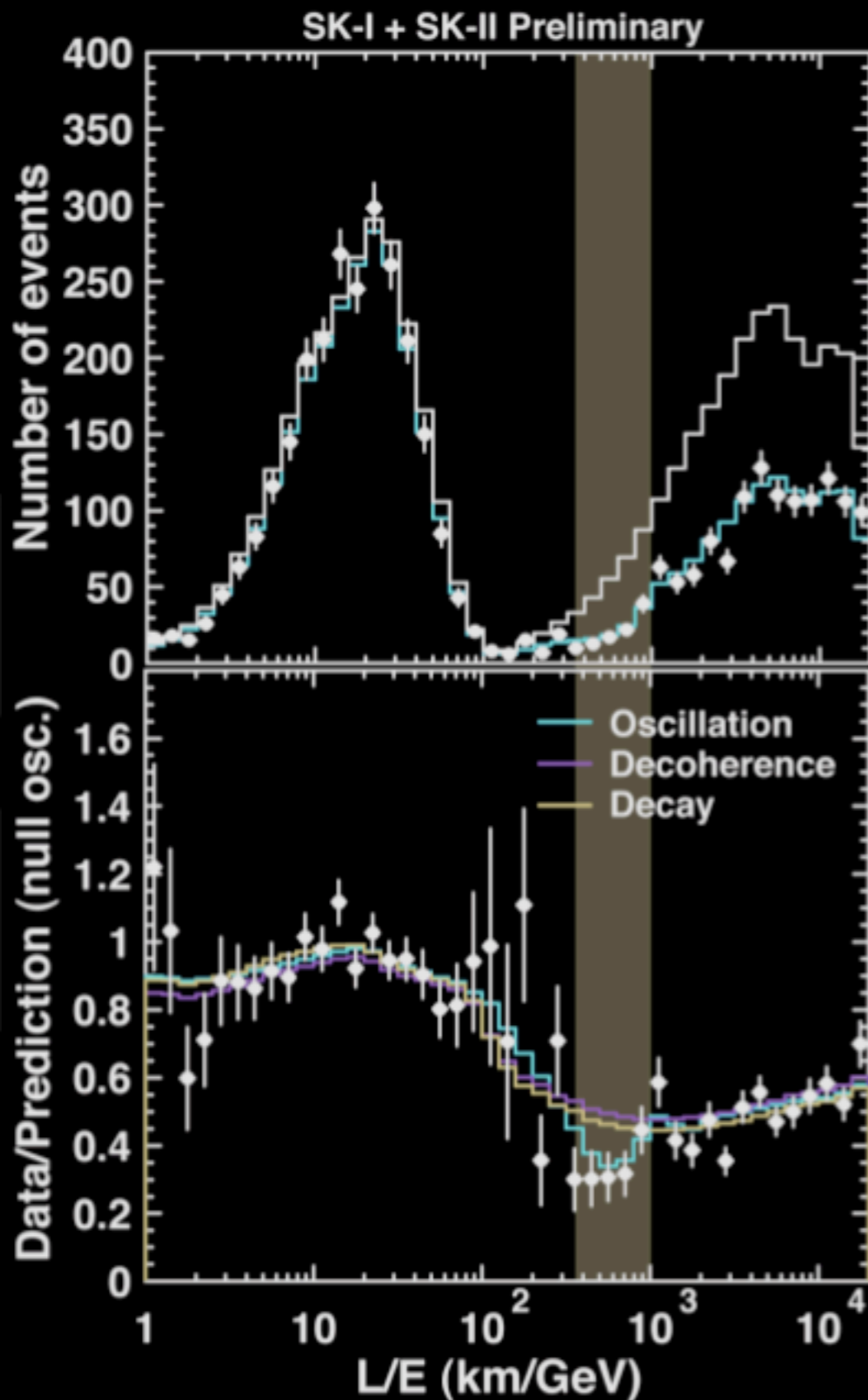


- Difference in observed atmospheric muon neutrino fluxes

- Depending on zenith angle!
PRL 81, 1562 (1998)

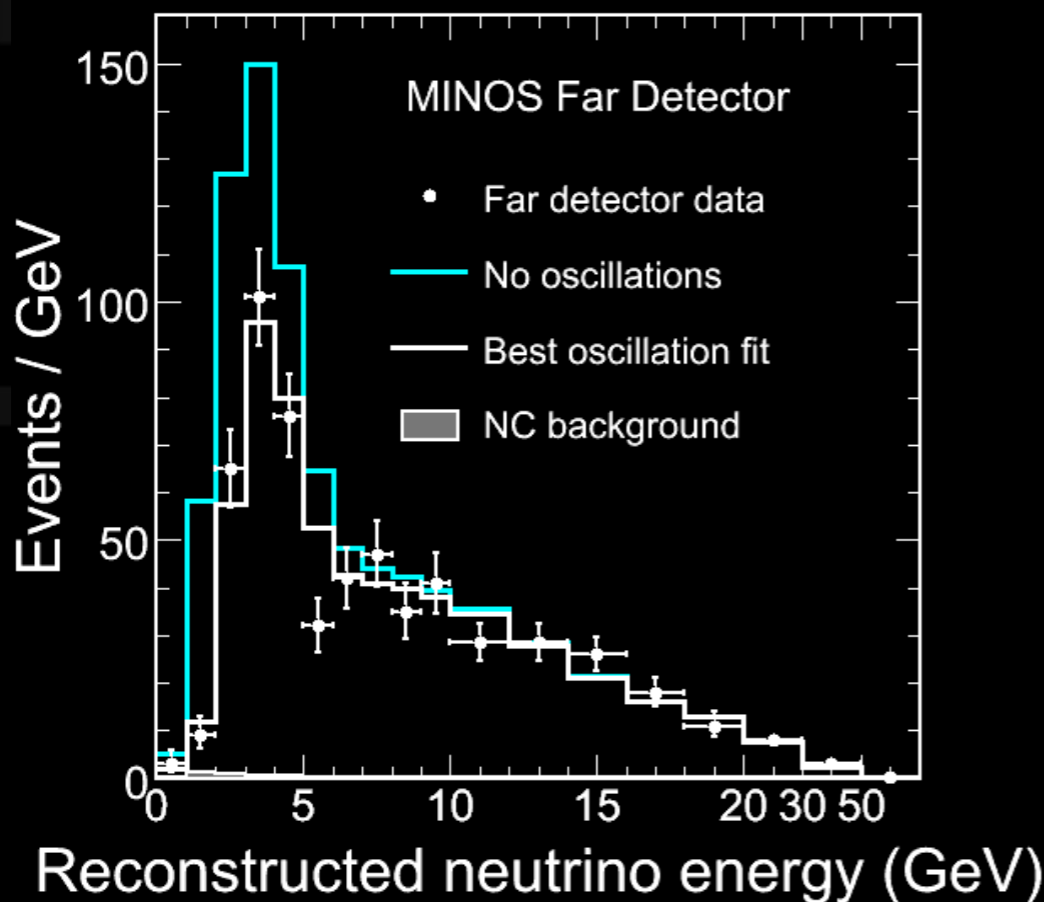
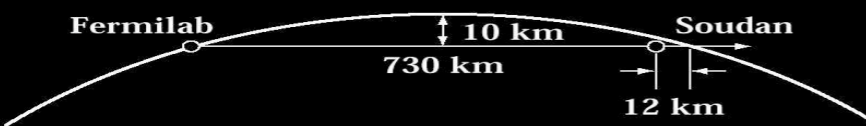
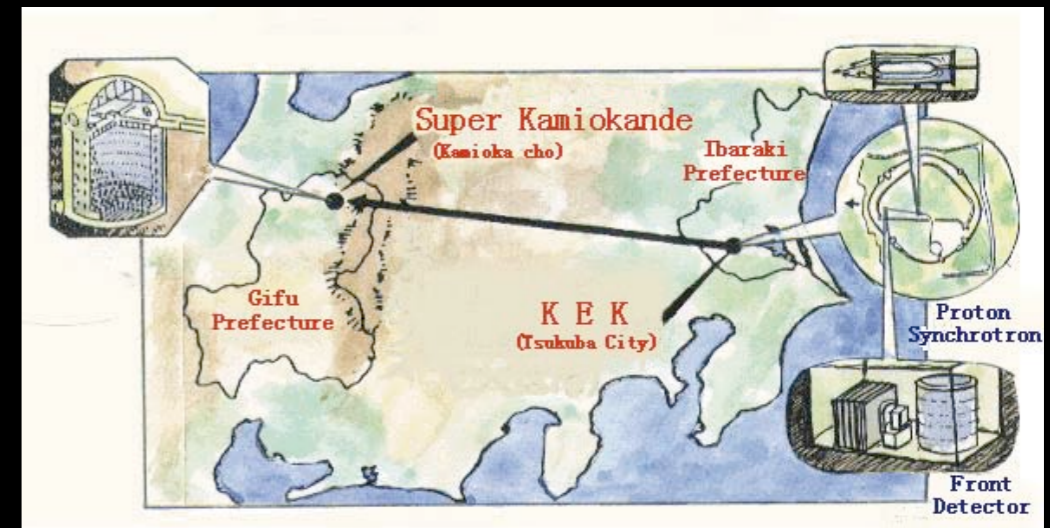
- L/E Analysis
Neutrino 2008

Atmospherics



- Difference in observed atmospheric muon neutrino fluxes
- Depending on zenith angle!
PRL 81, 1562 (1998)
- L/E Analysis
Neutrino 2008

Confirmation

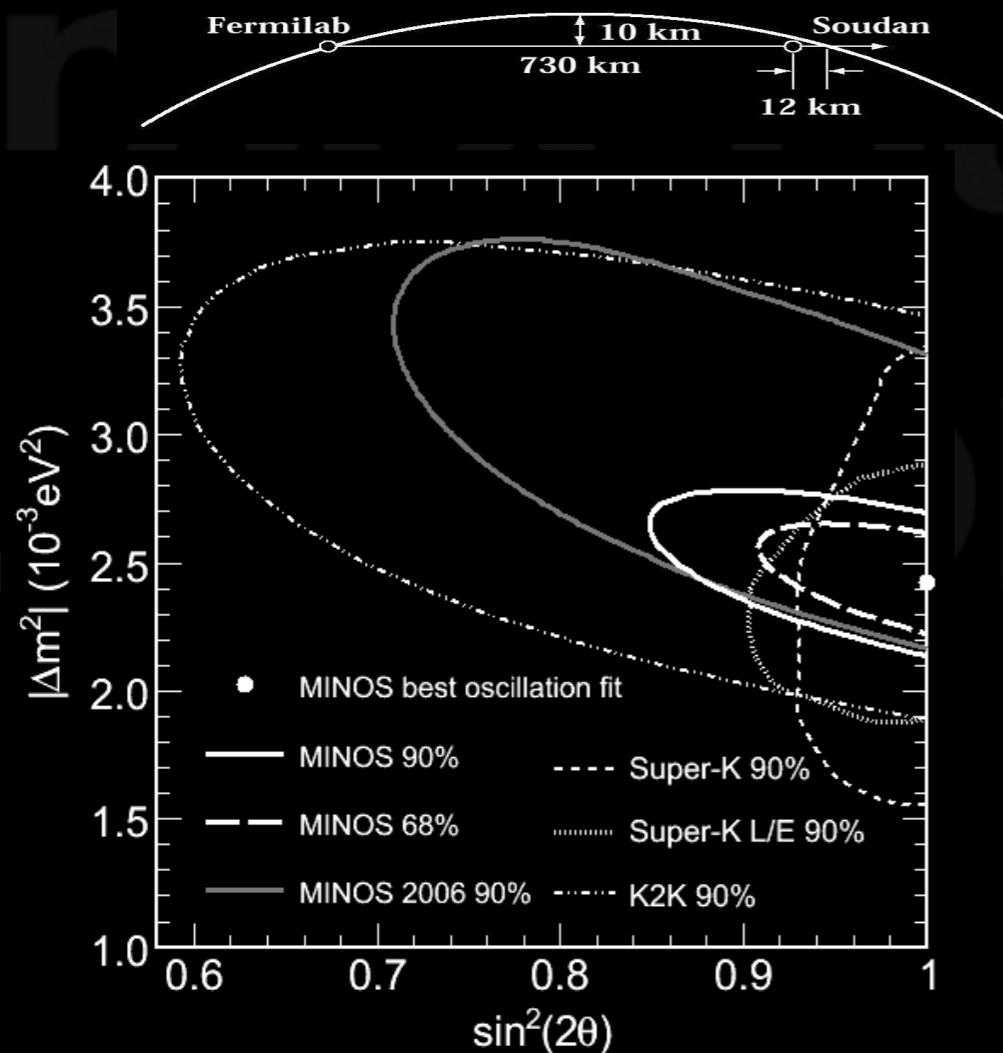
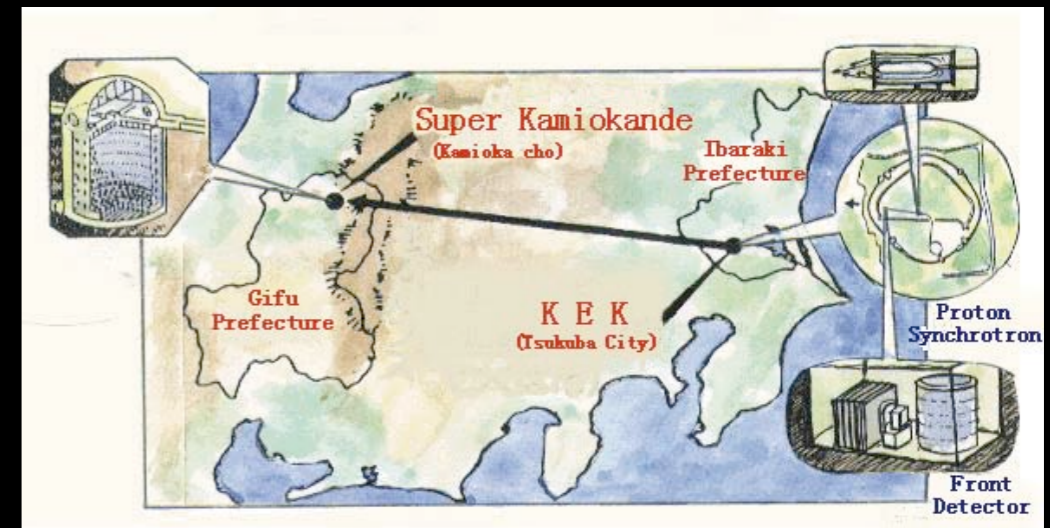


- Need same L/E to probe same Δm^2 region as atmospheric
- Confirmed with accelerator neutrinos
 - K2K and MINOS
 - Better Δm^2 measurements

K2K: PRL 98, 081802 (2005)

MINOS: PRL 101, 131802 (2008)

Confirmation



- Need same L/E to probe same Δm^2 region as atmospheric
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K2K: PRL 98, 081802 (2005)

MINOS: PRL 101, 131802 (2008)

3 Flavours

$$|v_{\alpha}\rangle = \sum_i U_{\alpha i} |v_i\rangle$$

flavor i mass

3 Flavours

$$\mathbf{U} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} = \begin{matrix} \text{Atmospheric} \\ \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \end{matrix} \begin{matrix} \text{Cross-Mixing} \\ \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \end{matrix} \begin{matrix} \text{Solar} \\ \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \end{matrix}$$

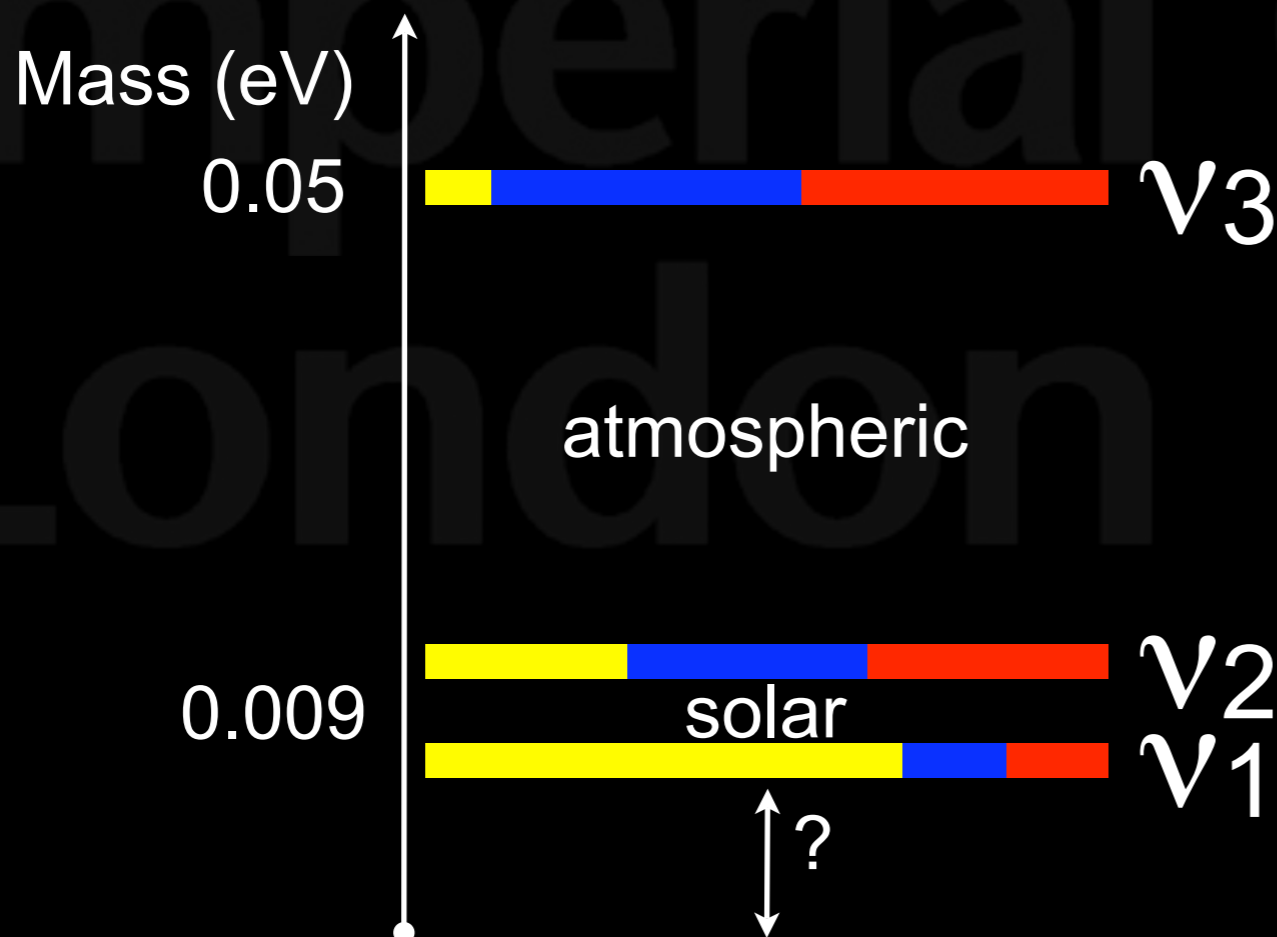
where $c_{ij} = \cos\theta_{ij}$, etc.

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3 Flavours

$$\mathbf{U} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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



flavour key:

ν_e ν_μ ν_τ

Getting at θ_{13} & δ_{CP}

In vacuum:

$$\begin{aligned}
 P(\nu_\mu(\bar{\nu}_\mu) \rightarrow \nu_e(\bar{\nu}_e)) \approx & \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \Delta_{31} && \text{Atmospheric} \\
 & + \sin 2\theta_{13} \cos \theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \times && \text{Interference -} \\
 & \quad \sin \Delta_{31} \sin \Delta_{21} \cos(\Delta_{32} \pm \delta) && \text{CP effects} \\
 & + \sin^2 2\theta_{12} \cos^2 \theta_{23} \cos^2 \theta_{13} \sin^2 \Delta_{21} && \text{Solar}
 \end{aligned}$$

where $\Delta_{ij} = 1.27 \Delta m_{ij}^2 (eV^2) L(km) / E(GeV)$

and the CP violating term $\pm \delta$ has opposite signs for $\nu, \bar{\nu}$

Getting at θ_{13} & δ_{CP}

In vacuum:

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

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \sim \sin^2 2\theta_{13} \cos(\Delta m_{23}^2 \pm \delta_{CP})$$

where $\Delta_{ij} = 1.27 \Delta m_{ij}^2 (eV^2) L(km) / E(GeV)$

and the CP violating term $\pm \delta$ has opposite signs for $\nu, \bar{\nu}$

Getting at θ_{13} & δ_{CP}

In vacuum:

$$P(\bar{\nu}_{\mu} \rightarrow \bar{\nu}_{e}) \sim \sin^2 2\theta_{13} \cos(\Delta m_{23}^2 \pm \delta_{CP})$$

where $\Delta_{ij} = 1.27 \Delta m_{ij}^2 (eV^2) L(km) / E(GeV)$

and the CP violating term $\pm \delta$ has opposite signs for $\nu, \bar{\nu}$

$$A_{CP} = \frac{P(\nu_{\mu} \rightarrow \nu_{e}) - P(\bar{\nu}_{\mu} \rightarrow \bar{\nu}_{e})}{P(\nu_{\mu} \rightarrow \nu_{e}) + P(\bar{\nu}_{\mu} \rightarrow \bar{\nu}_{e})} \cong \frac{1.27 \Delta m_{12}^2 [eV^2] L[km]}{E[GeV]} \times \frac{\sin 2\theta_{12}}{\sin \theta_{13}} \times \sin \delta$$

Getting at θ_{13} & δ_{CP}

In vacuum:

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Getting at θ_{13} & δ_{CP}

In vacuum:

$$P(\bar{\nu}_{\mu} \rightarrow \bar{\nu}_{e}) \sim \sin^2 2\theta_{13} \cos(\Delta_{23} \pm \delta_{CP})$$

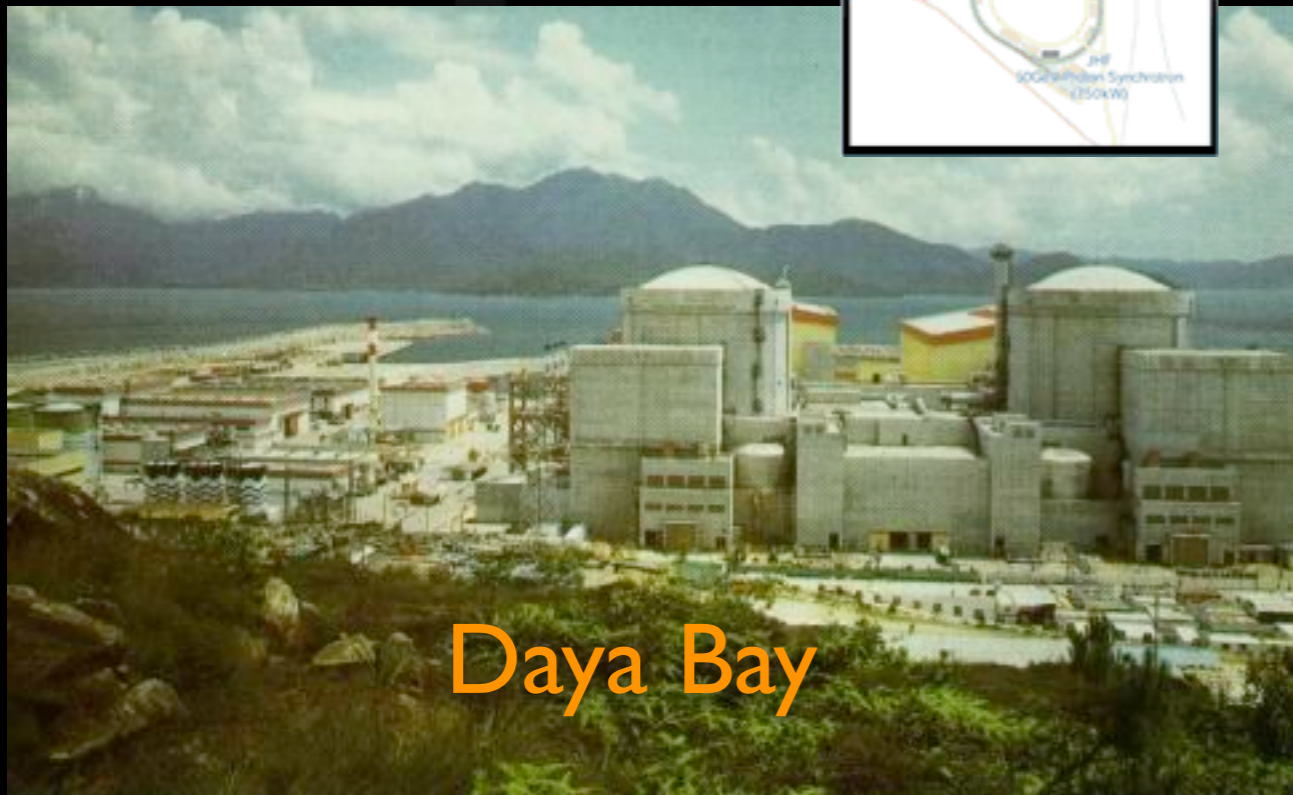
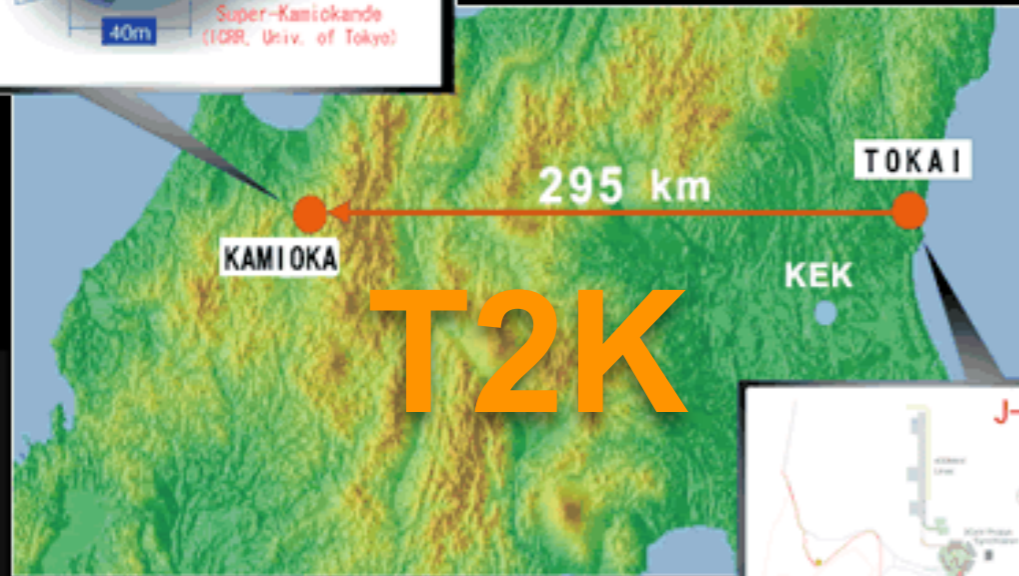
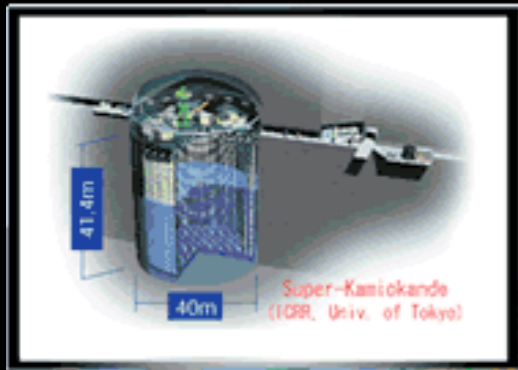
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Bottom Line: Need high precision measurements of *everything* to extract the value of δ_{CP} .

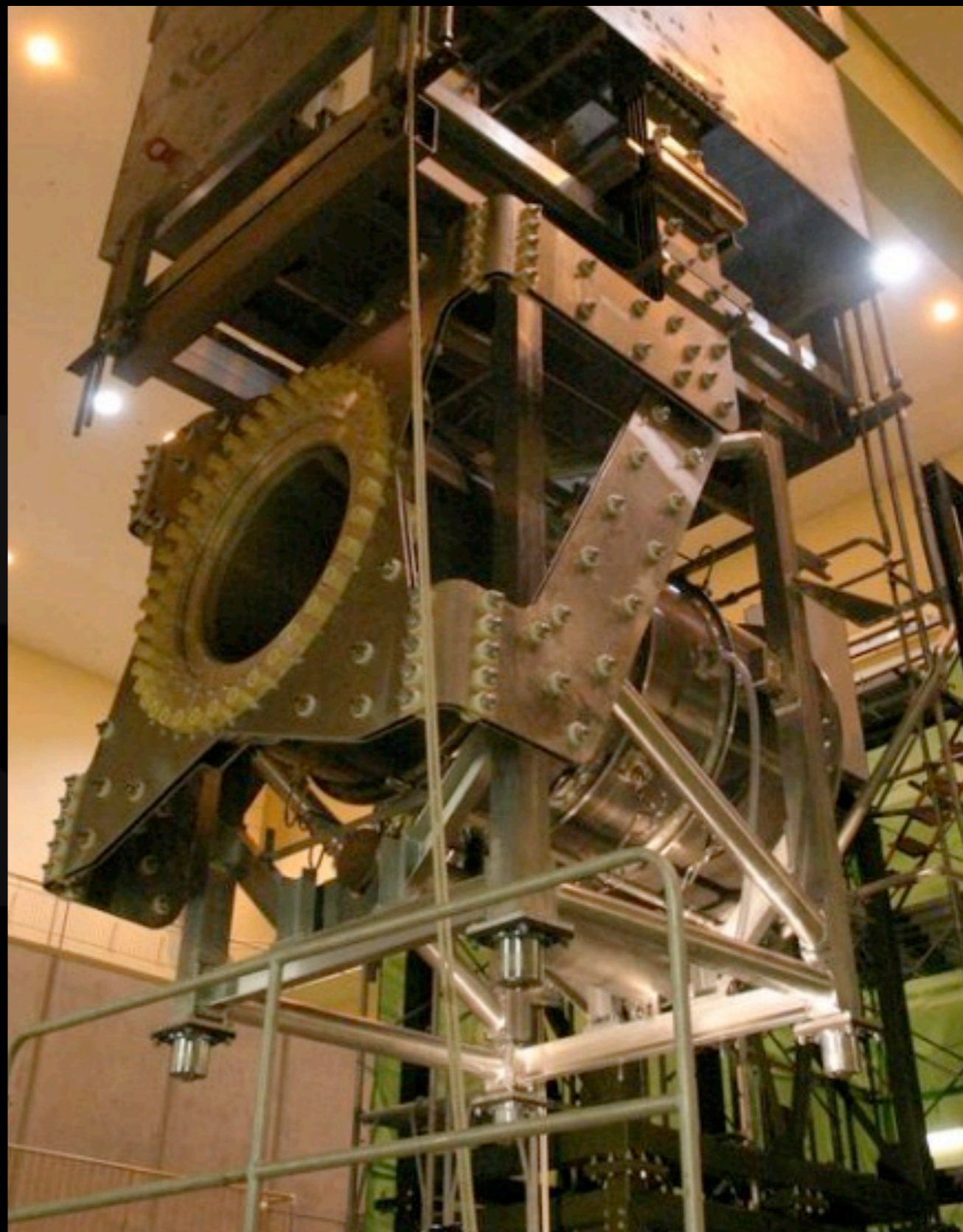
Campaign for θ_{13}



- Phase I (by 2016):
Accelerators and Reactors
 - T2K & NOvA; Daya Bay & Double CHOOZ
 - Measure value of θ_{13}
 $P(\nu_{\mu} \rightarrow \nu_e)$ and $P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$
 - If mixing $> \sim 0.01$
- Phase II (farther future):
Long baseline superbeams and Megaton detectors
 - Measure value of θ_{13}
 - If mixing $> \sim 0.002$
 - Search for appearance probability asymmetry

Outline

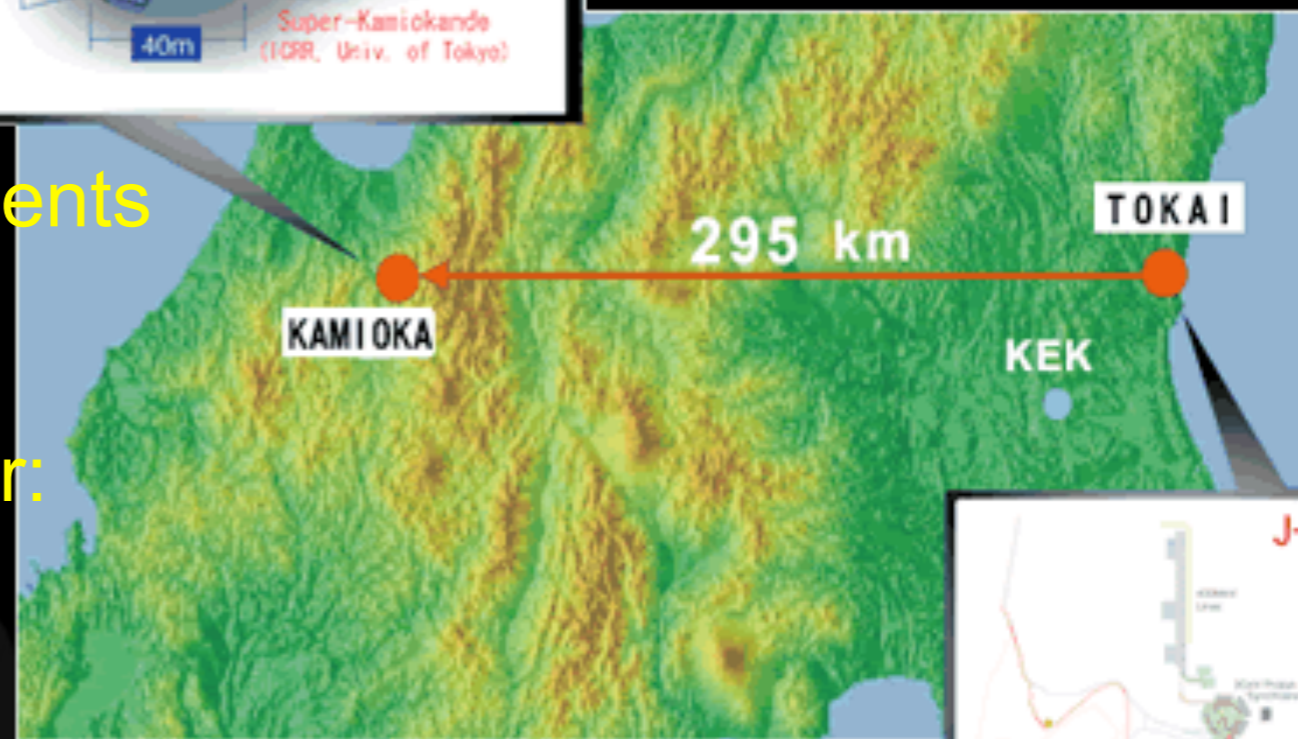
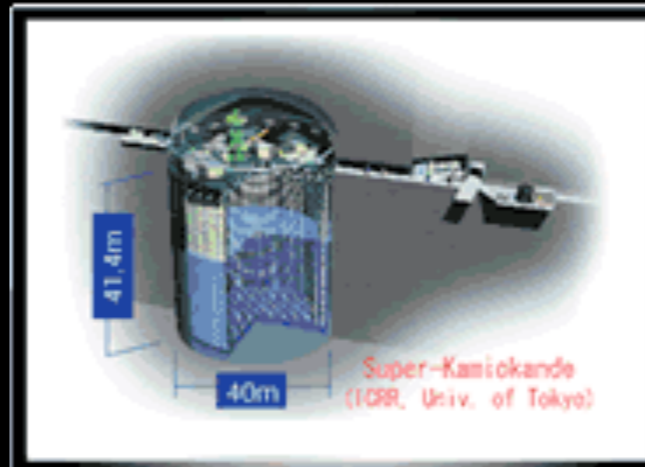
- Motivation
- Tools & Strategy
- T2K
 - SciBooNE
- Looking Ahead



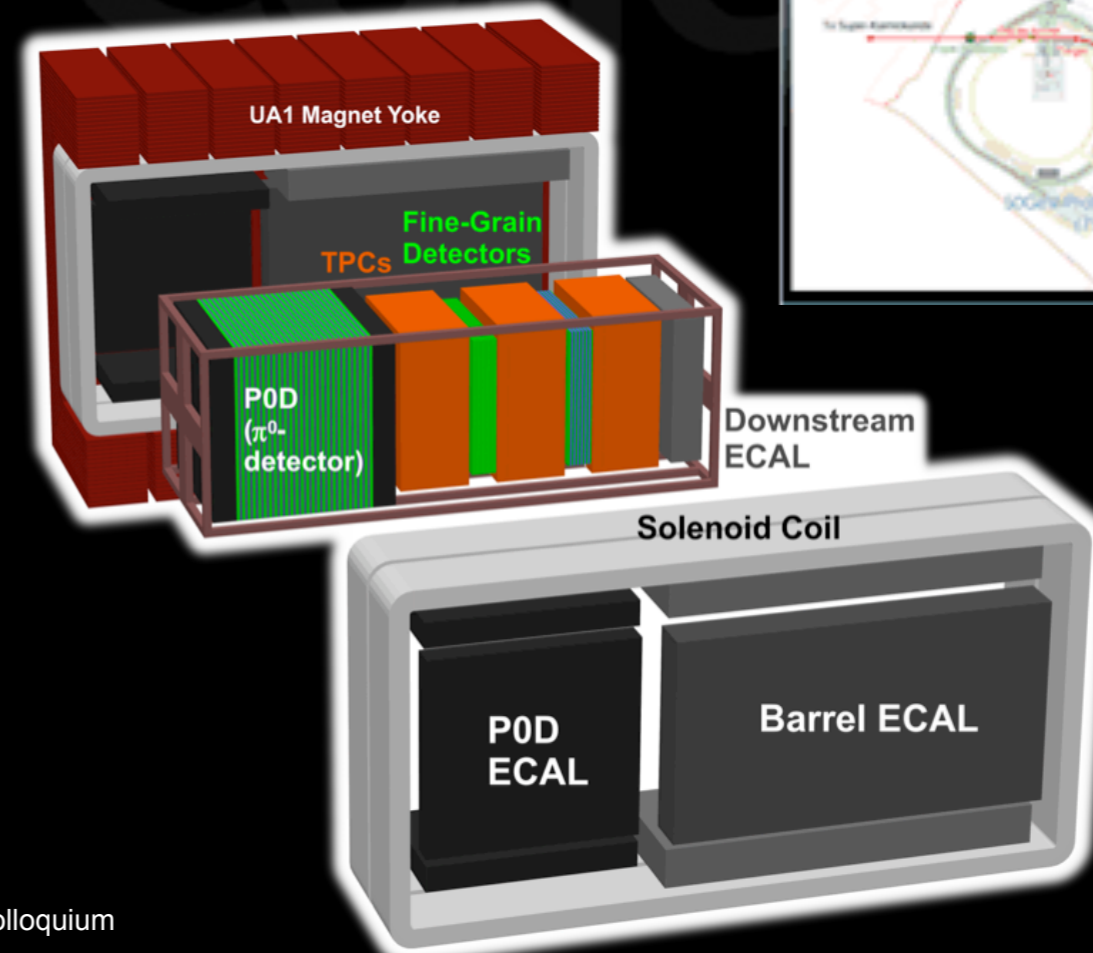
T2K Horn 3

T2K

“Tokai-To-Kamioka”



- Physics Goals:
 - precise $\Delta m^2_{23}, \theta_{23}$ measurements
 - search for θ_{13}
- Start with world's largest detector: Super-Kamiokande
- Build new neutrino beam
- Off-axis beam to Super-K
 - $L = 295$ km
 - $E = 0.6$ GeV
- Near detectors at 280m to constrain beam flux
- First protons on target: April 2009
- Expect $5E21$ POT in 5 years



T2K experimental strategy

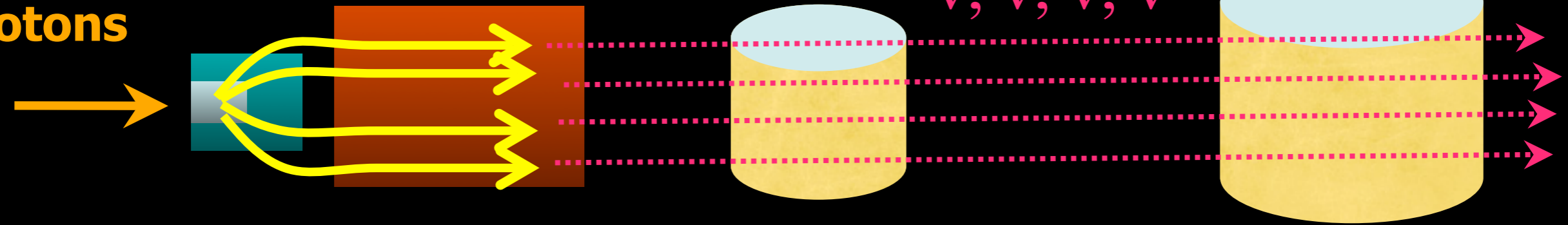
Intense beam

Gigantic detector

protons

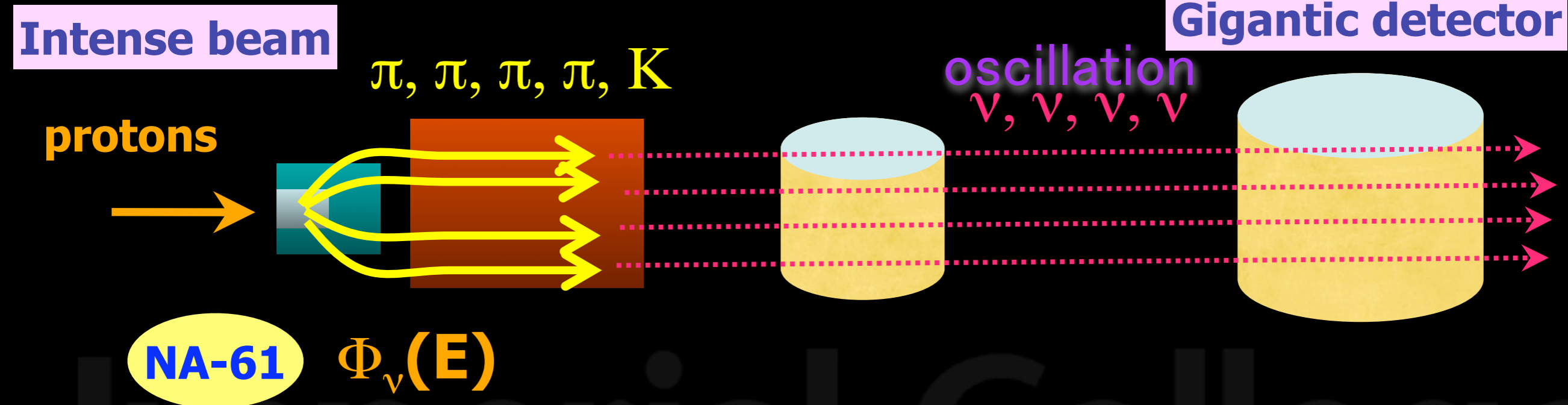
π, π, π, π, K

oscillation
 ν, ν, ν, ν



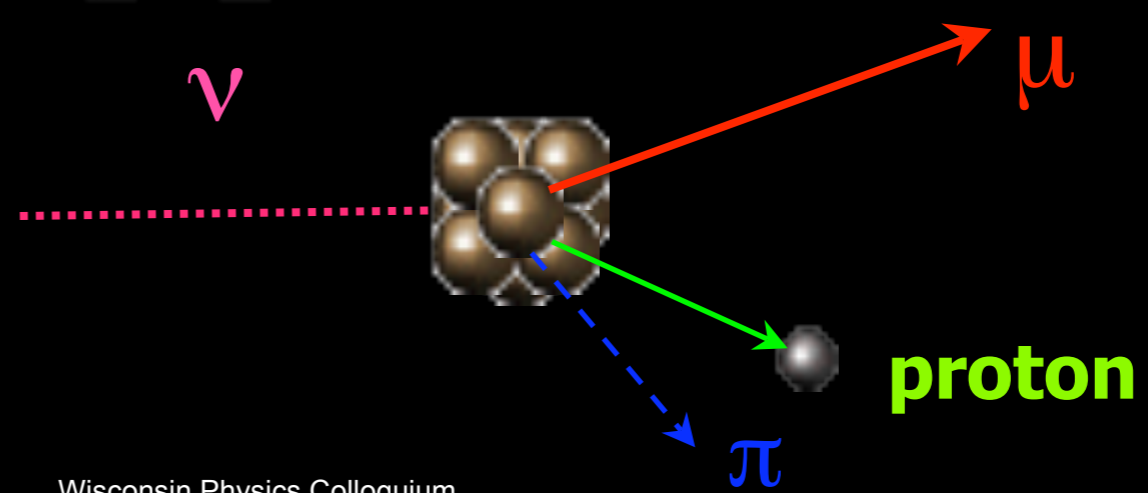
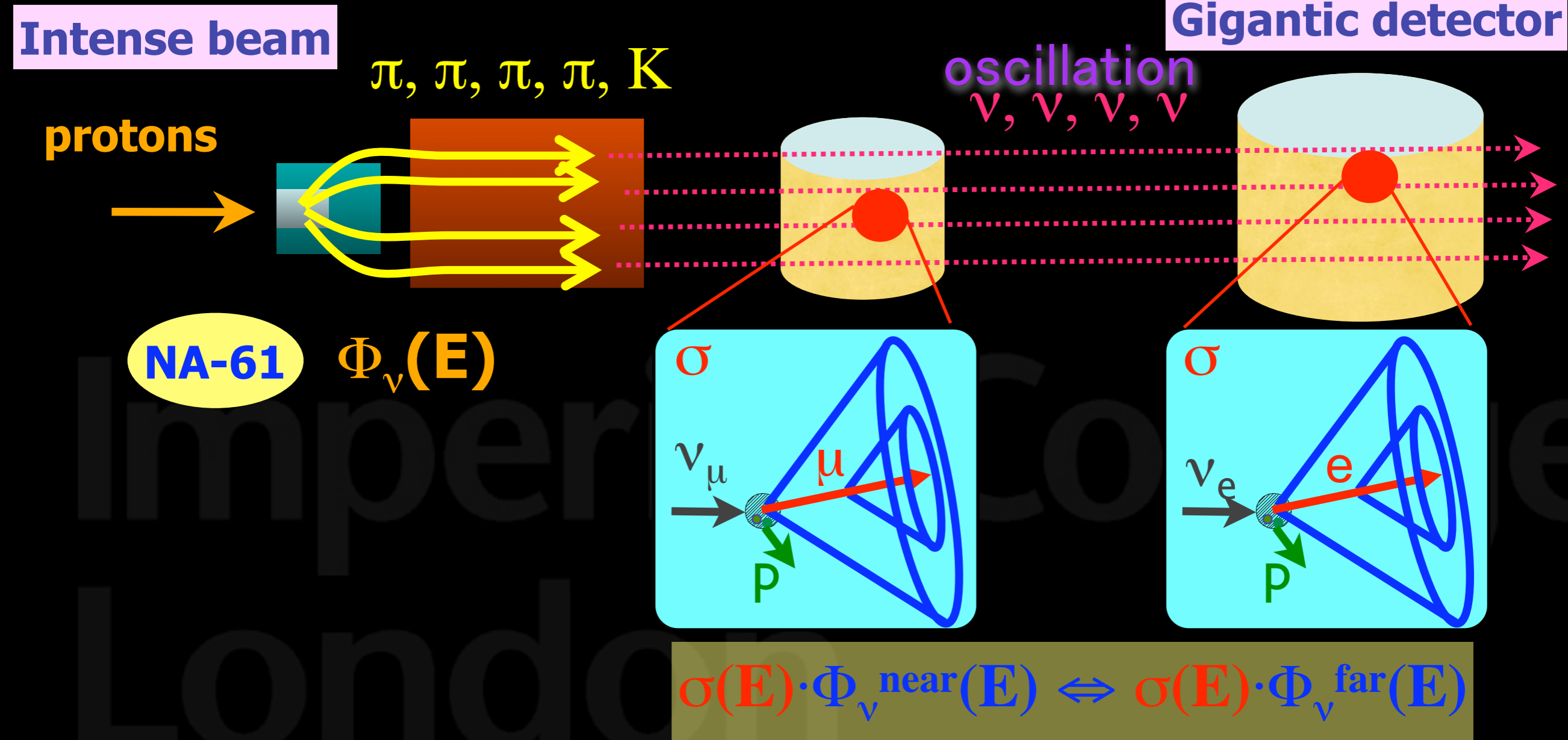
Imperial College
London

T2K experimental strategy

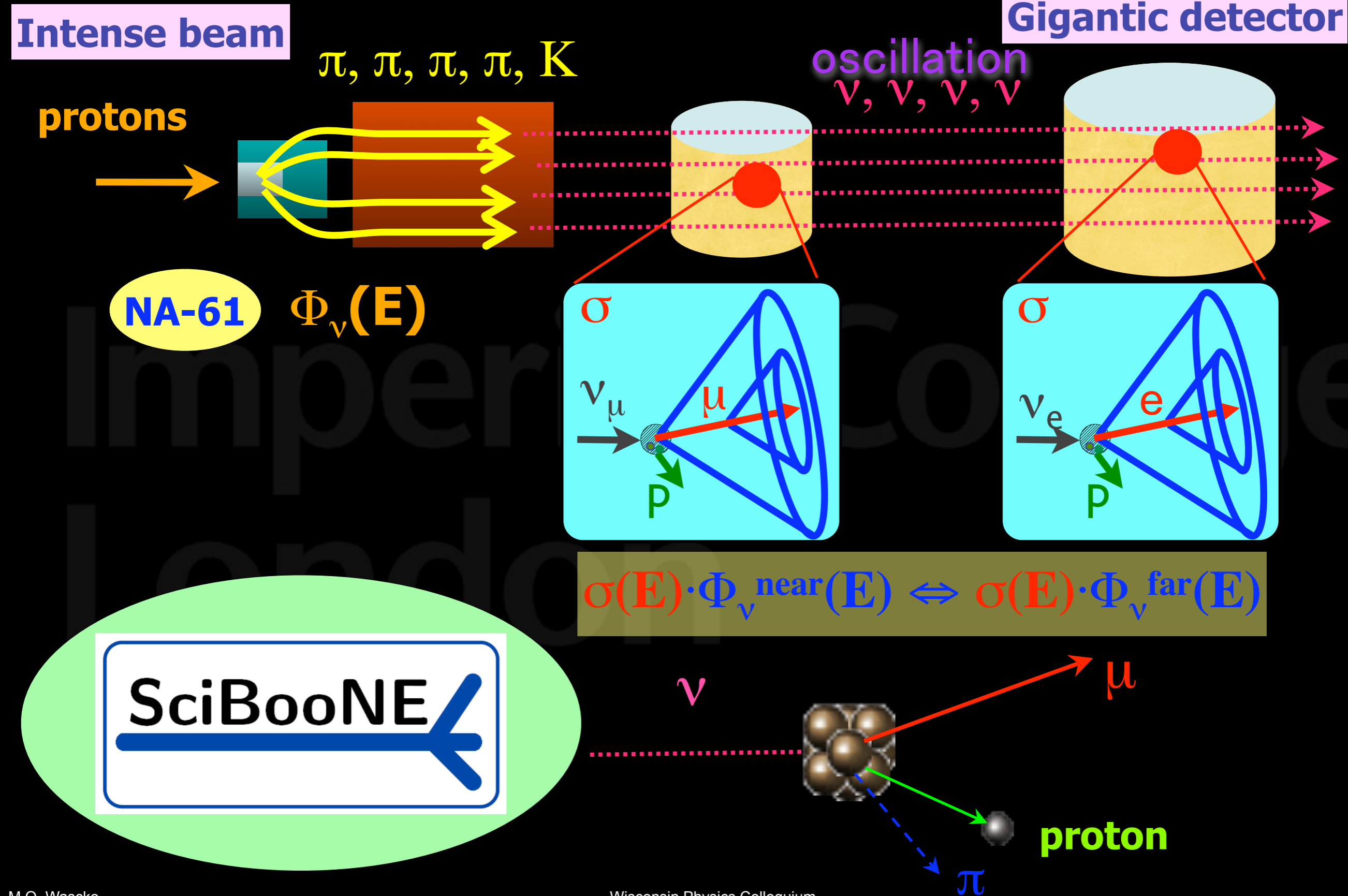


Imperial College
London

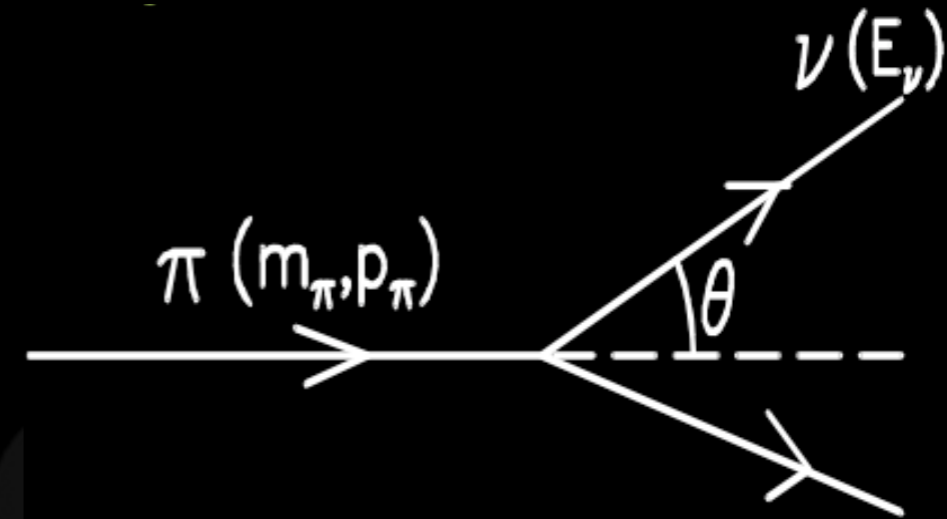
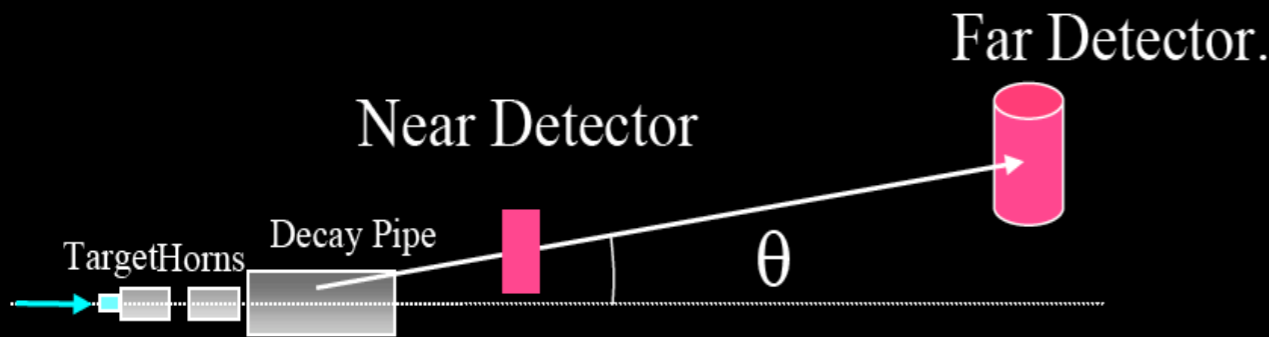
T2K experimental strategy



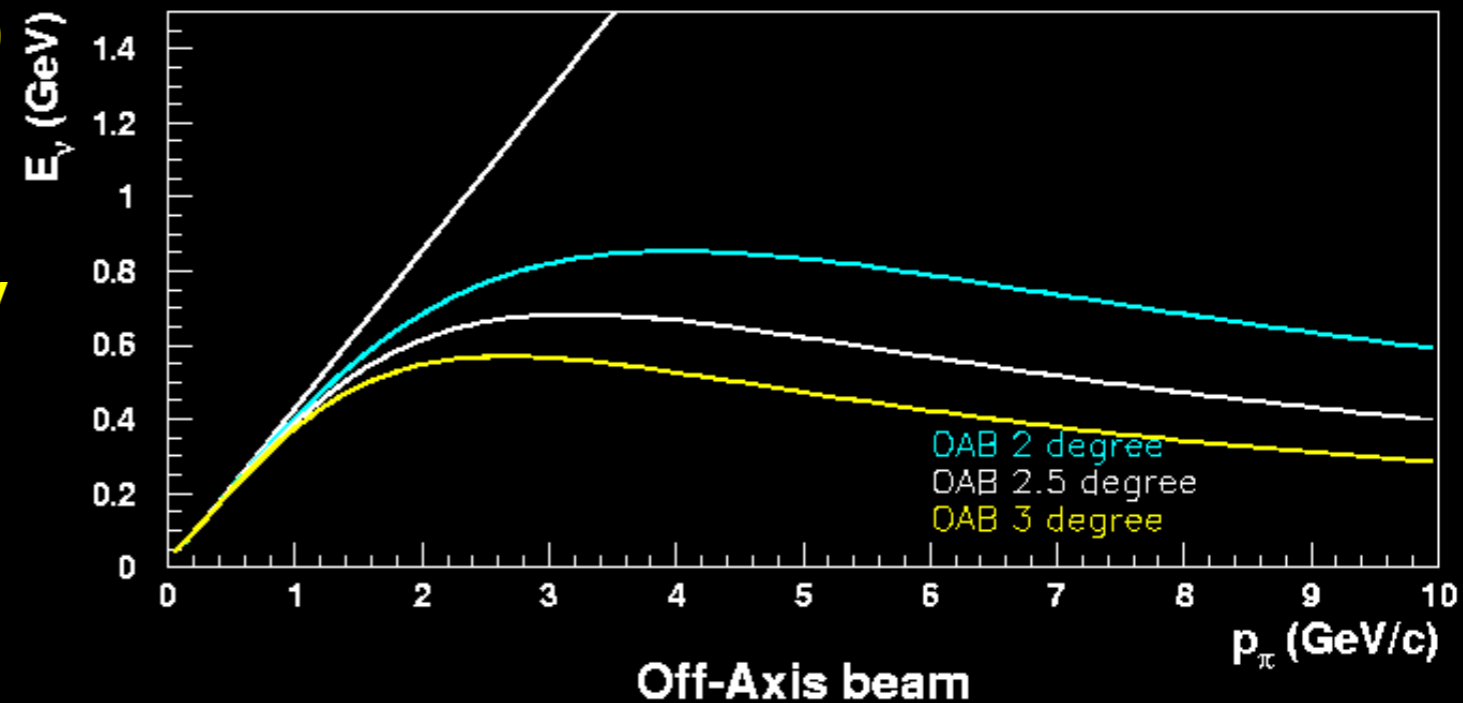
T2K experimental strategy



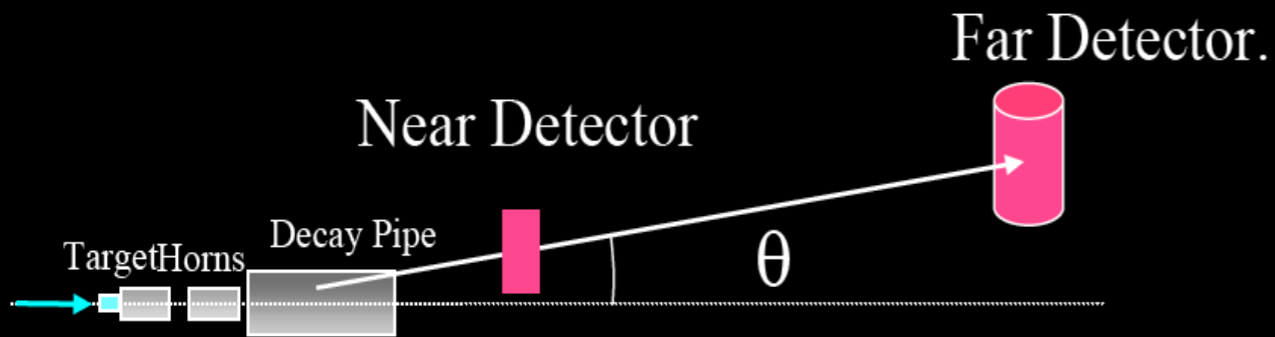
Off-Axis Beam



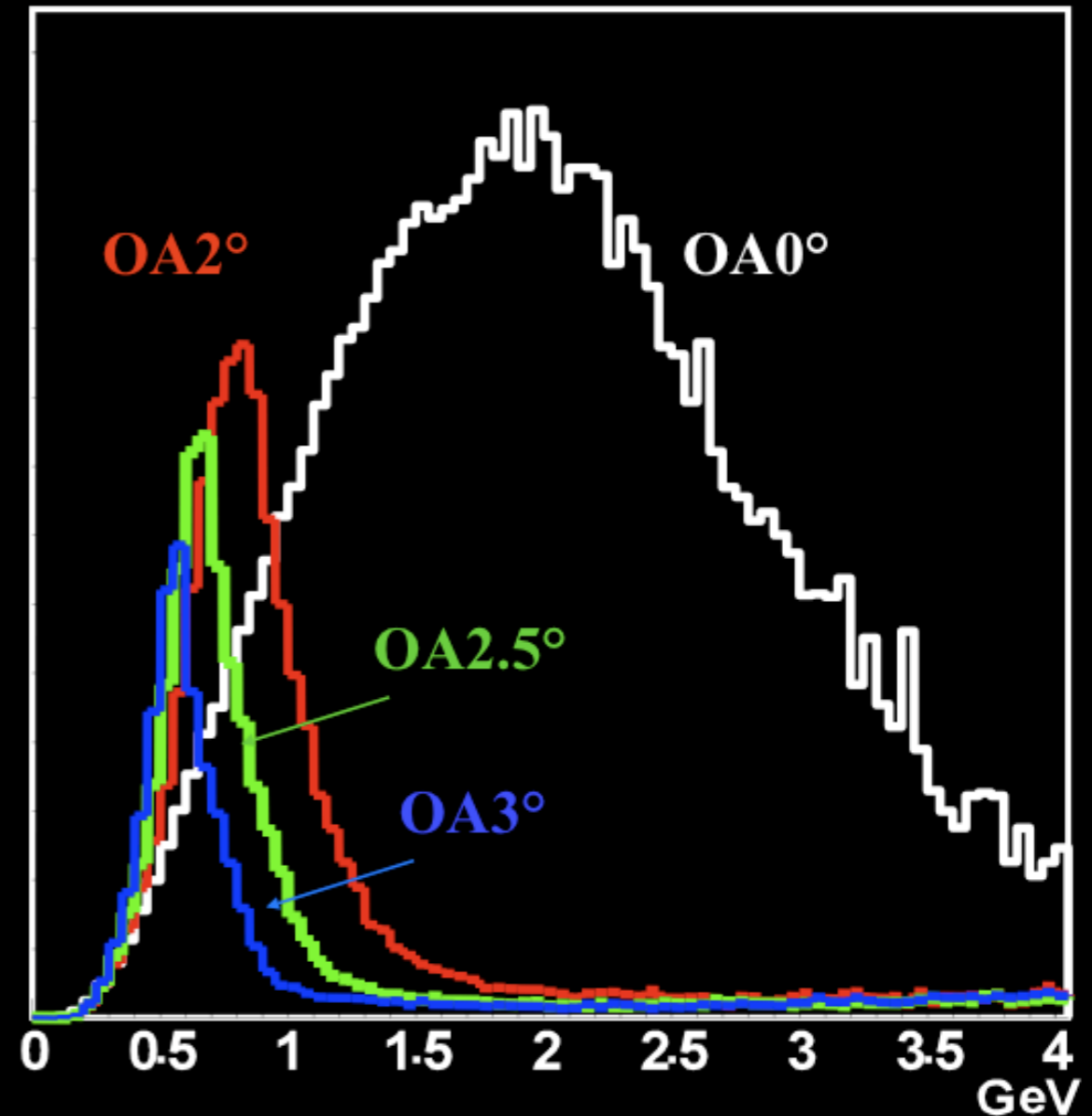
- Use kinematics of pion decay to tune the neutrino energy
- Flux peak at target energy for desired value of L/E
- E_ν well matched to Super-K



Off-Axis Beam



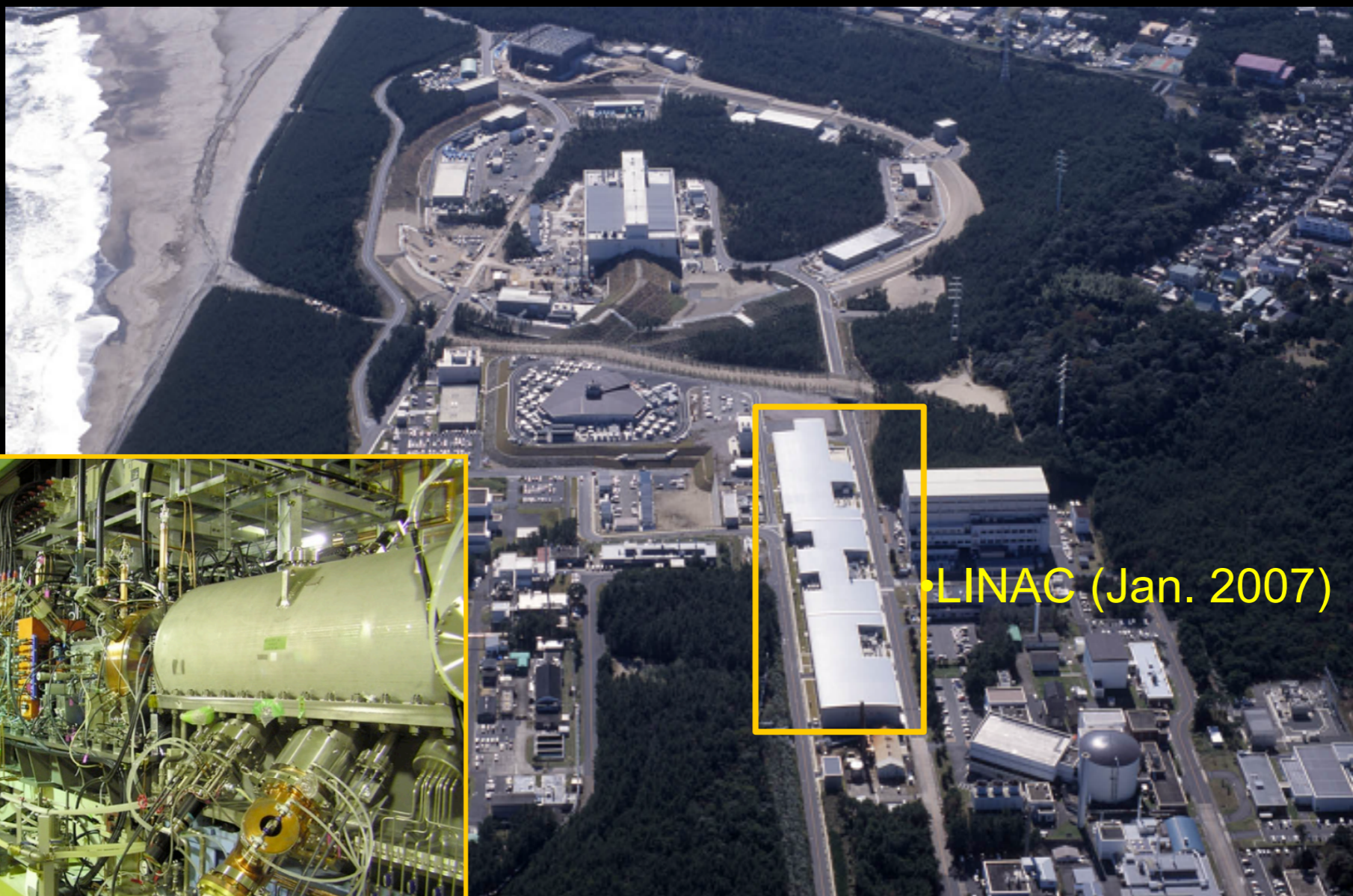
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J-PARC Overview



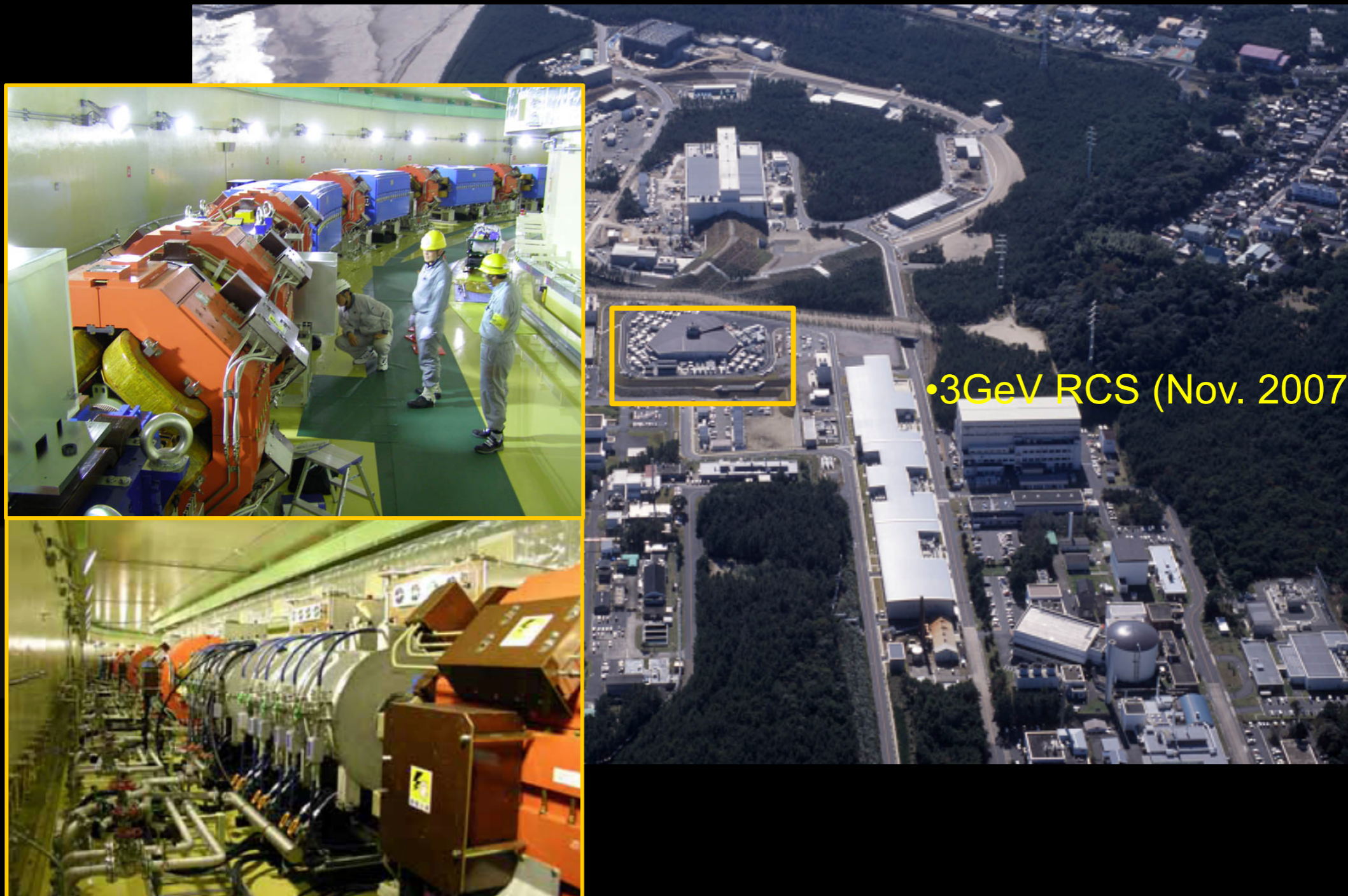
J-PARC Overview



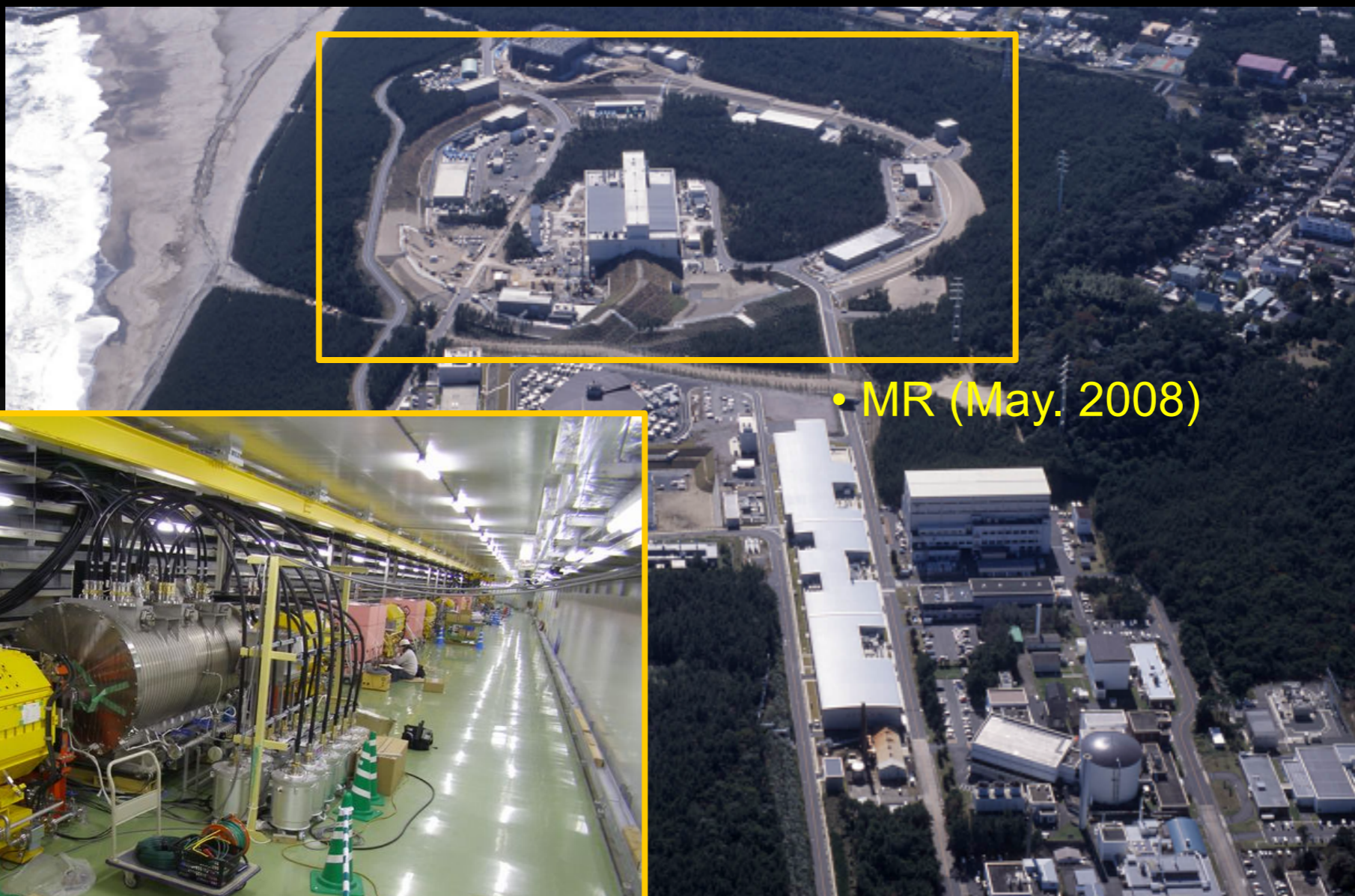
Linac Area

First beam on 1/24/07
Very stable beams

J-PARC Overview



J-PARC Overview



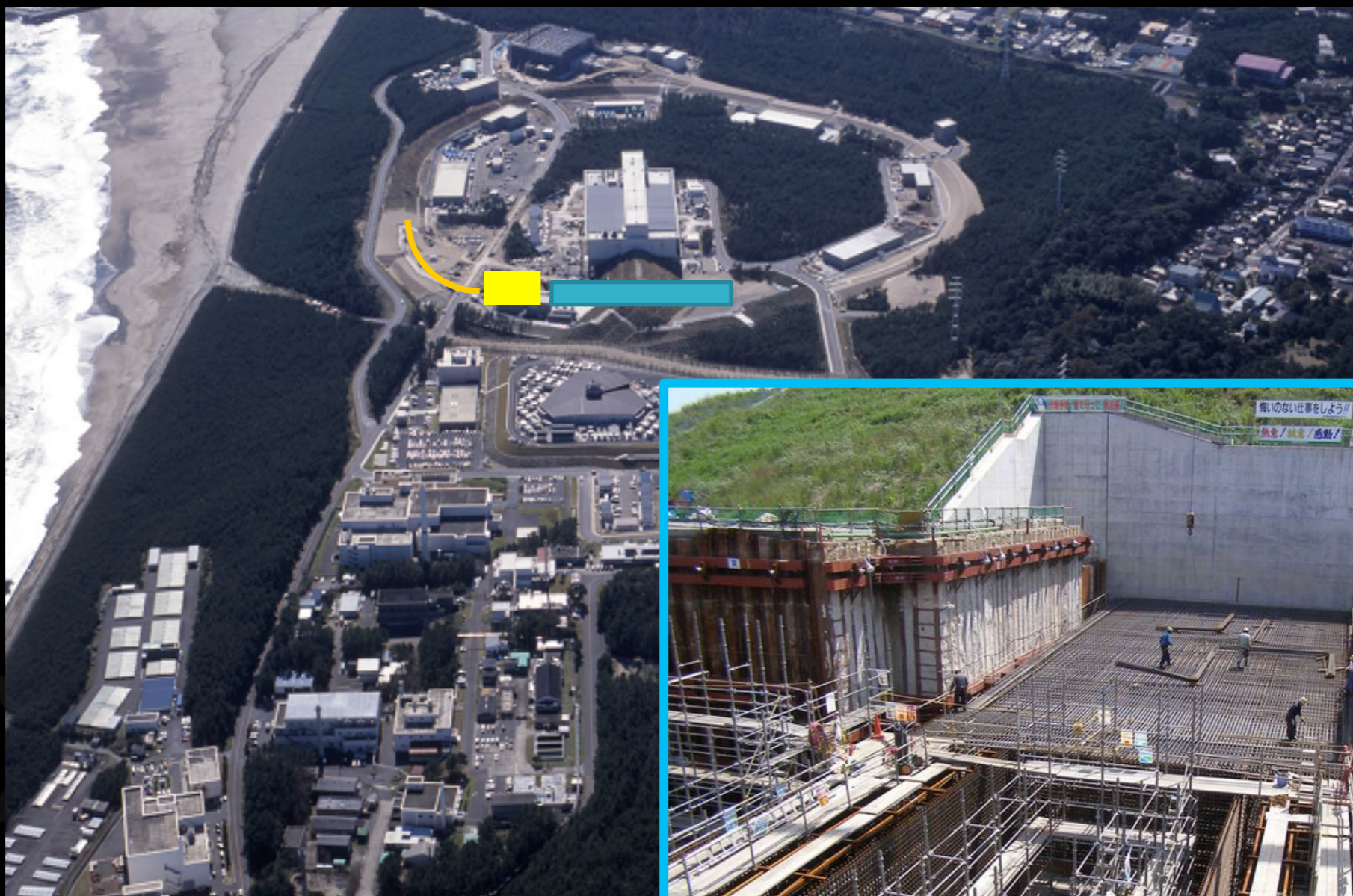
J-PARC Overview



J-PARC Overview



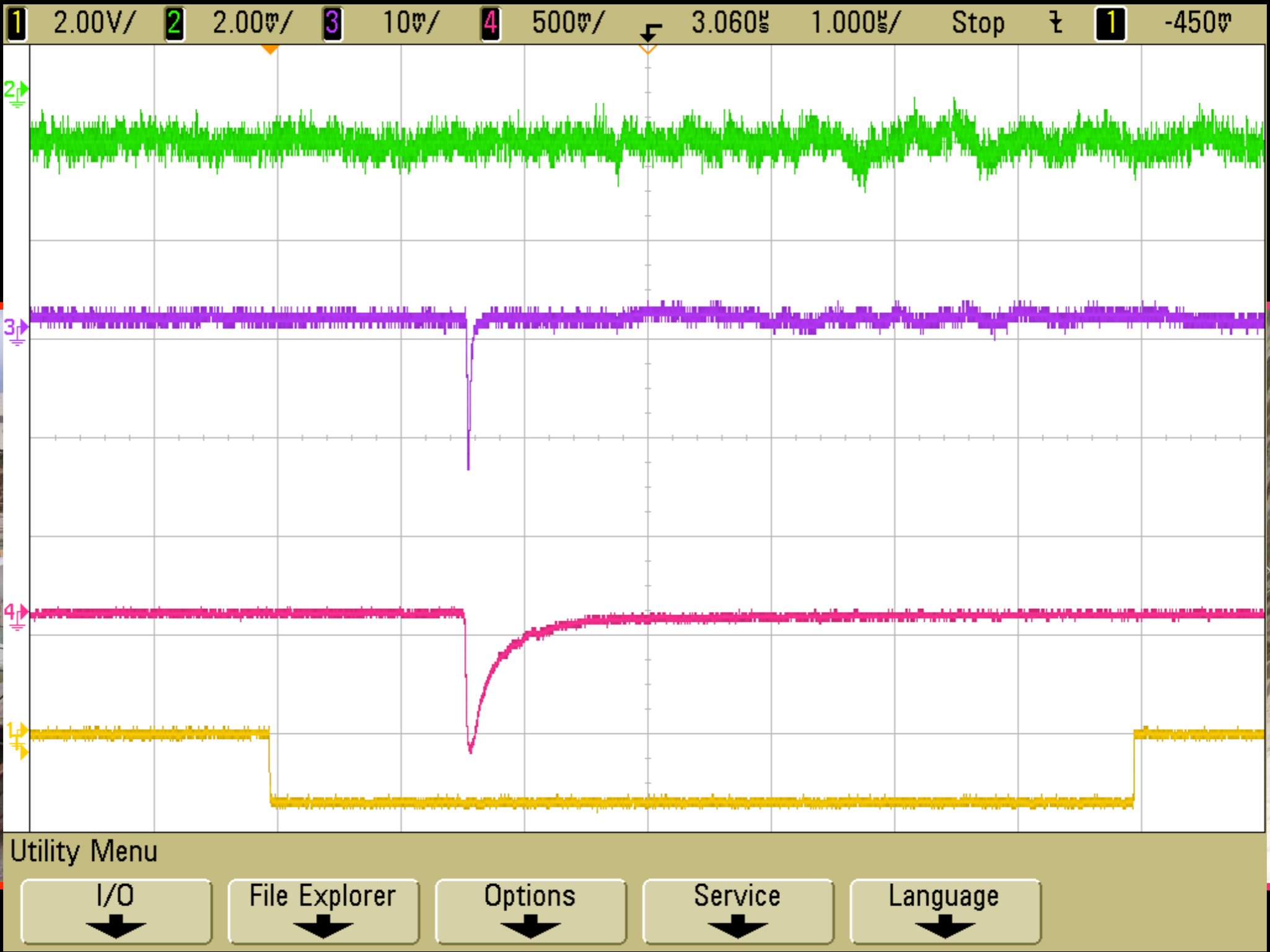
J-PARC Overview



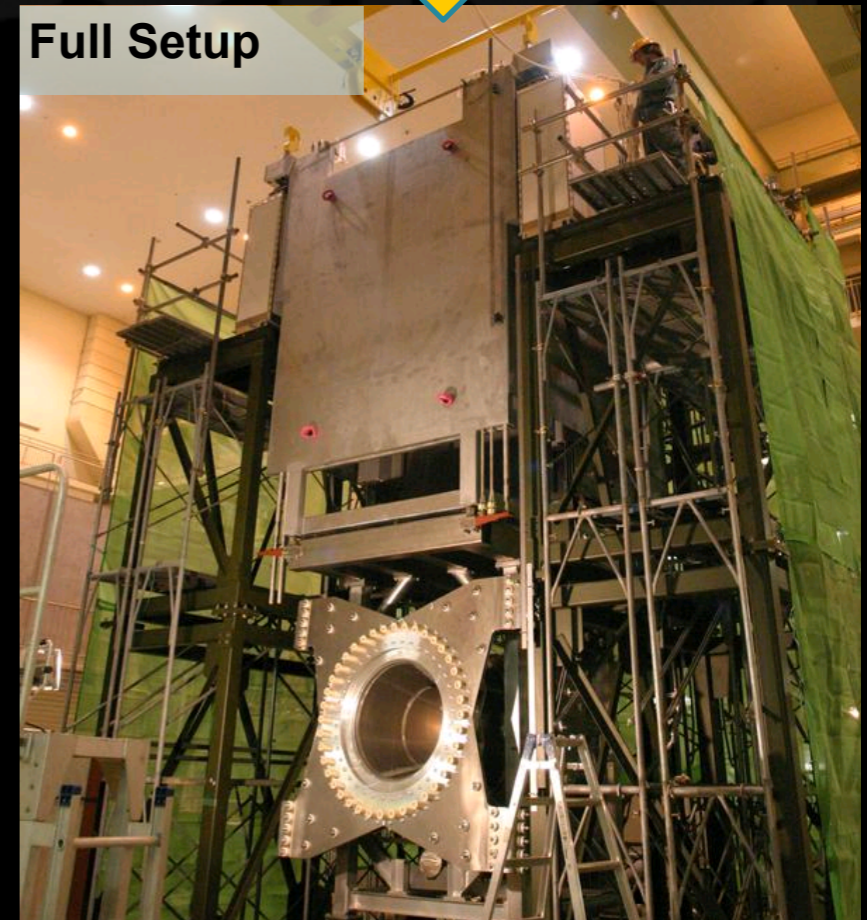
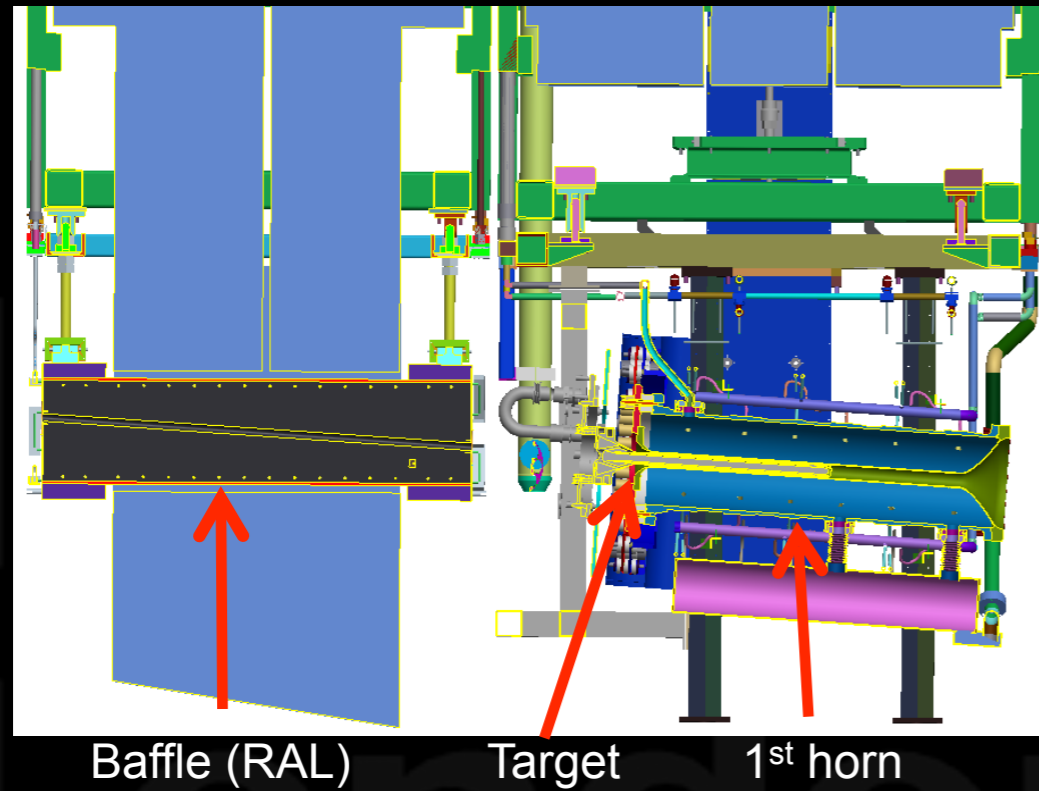
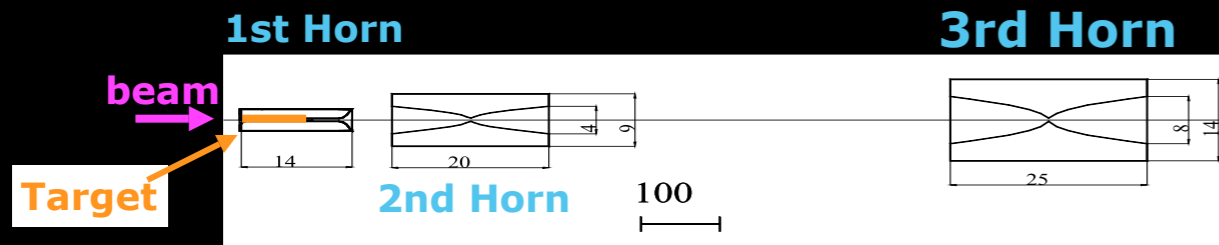
J-PARC Overview



J-PARC Overview

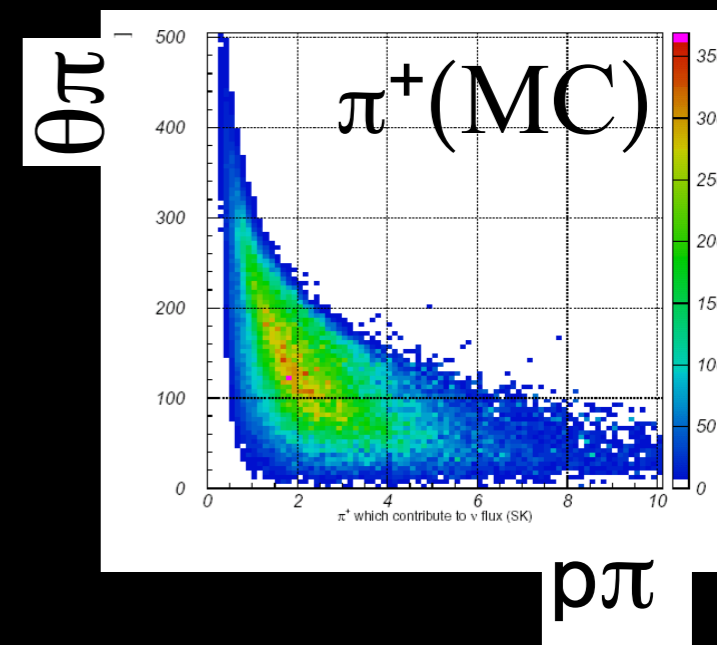
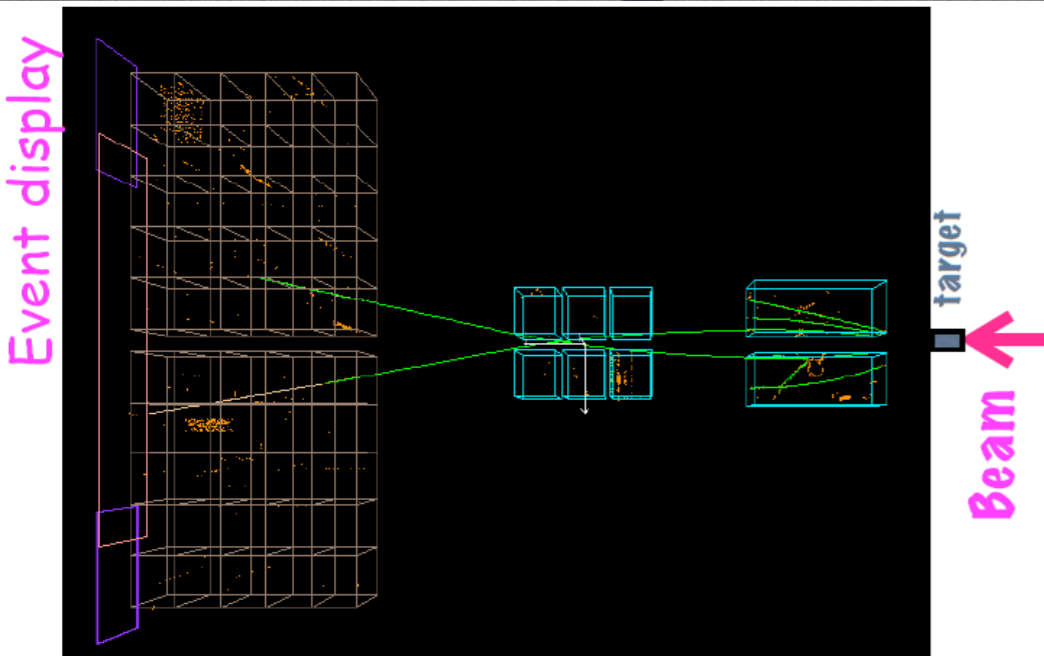
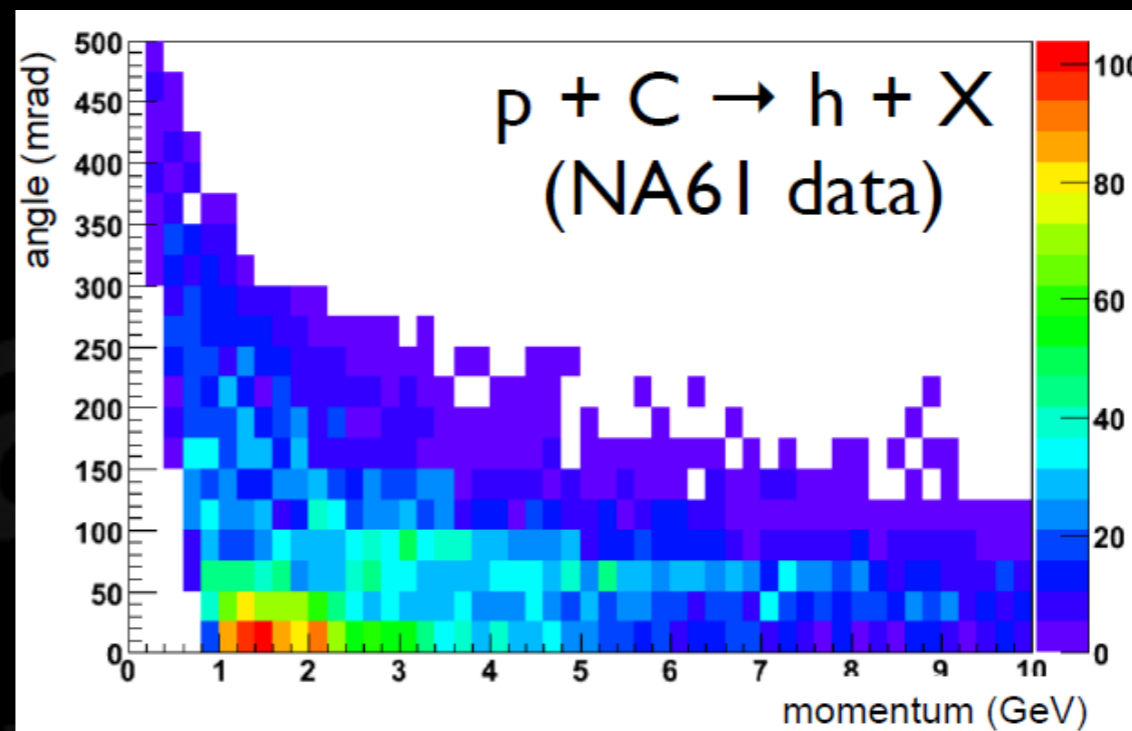
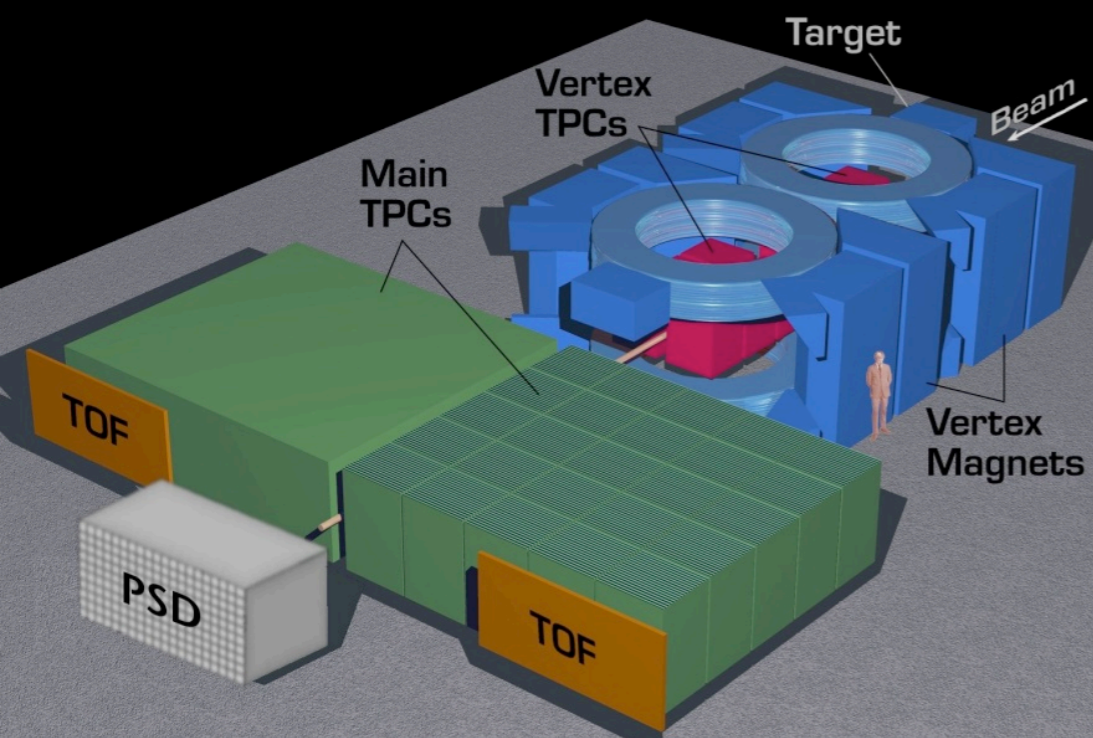


Target & Horns



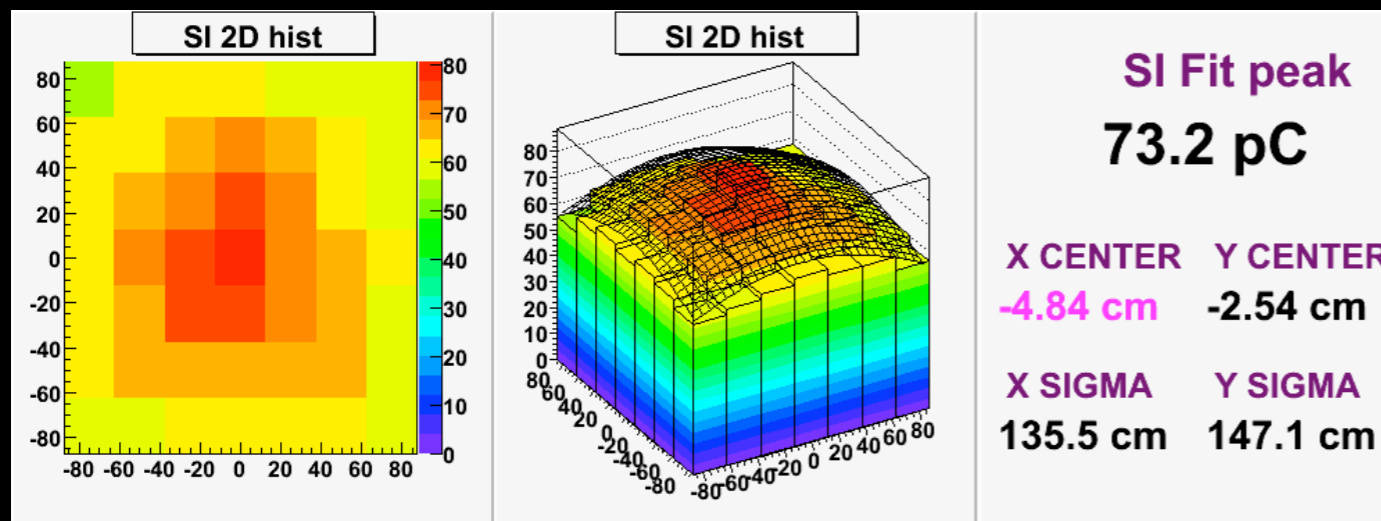
SPS Heavy Ions and Neutrino Experiment

- CERN NA61
 - (30GeV and 50GeV)

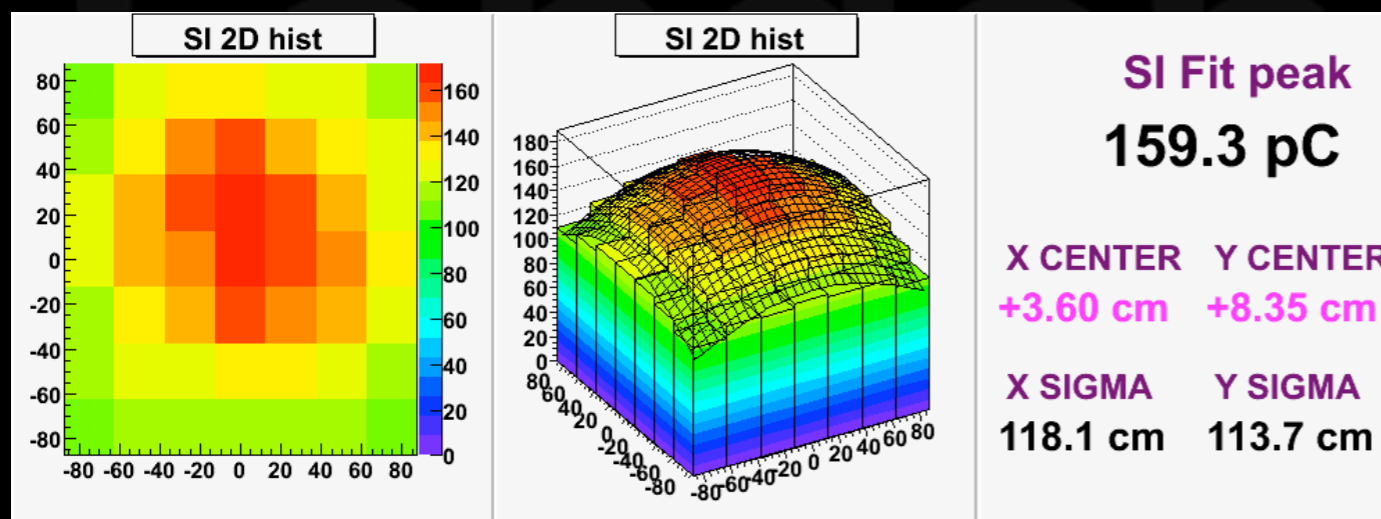


Beam Muon Monitors

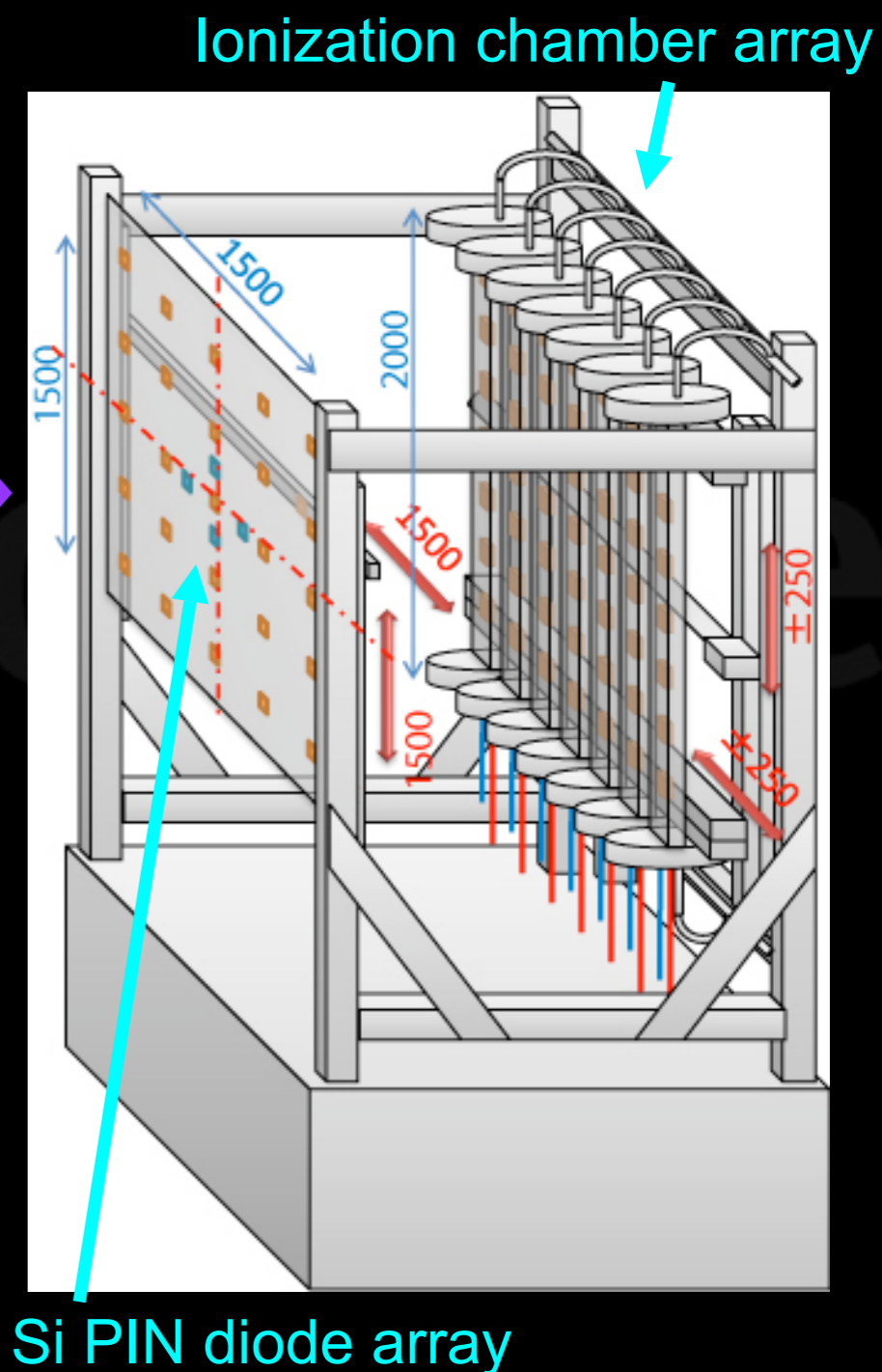
0 kA Horn Current



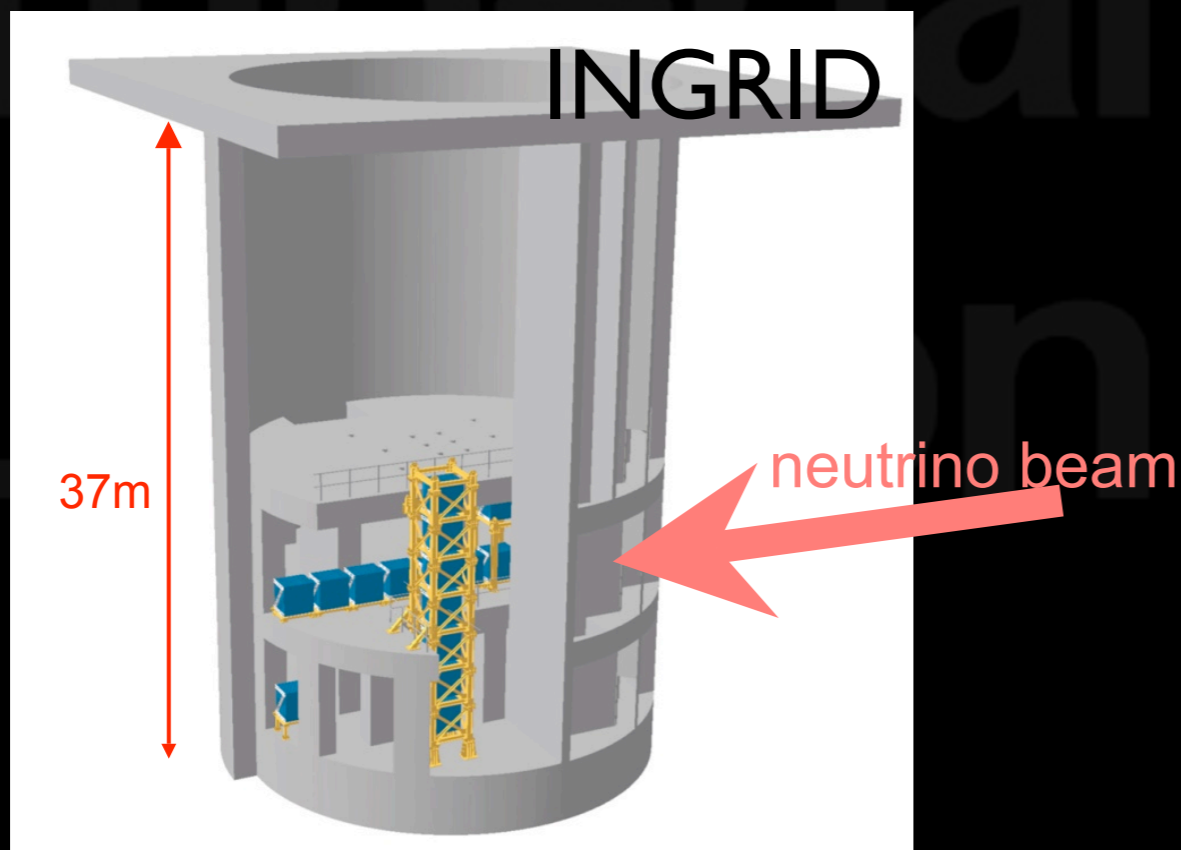
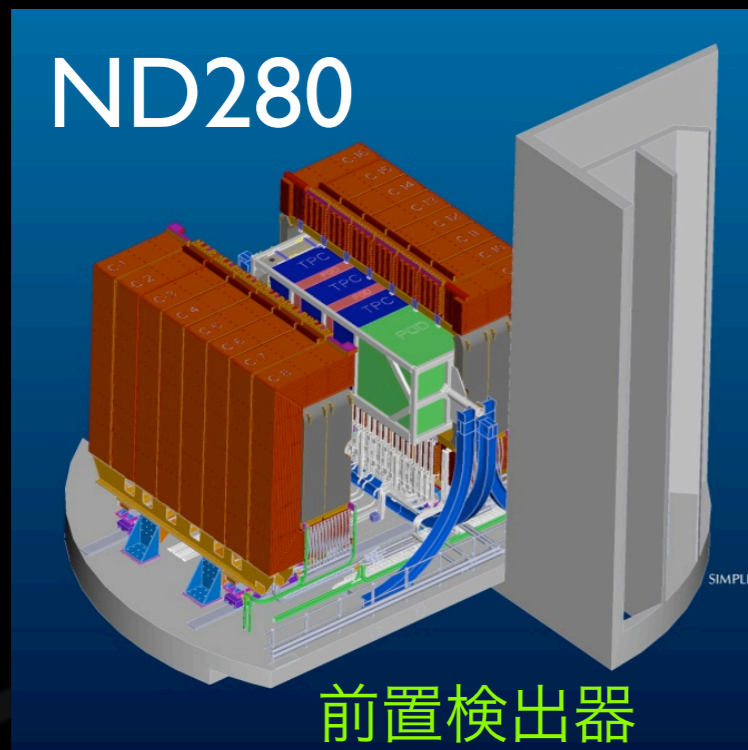
320 kA Horn Current



Beam



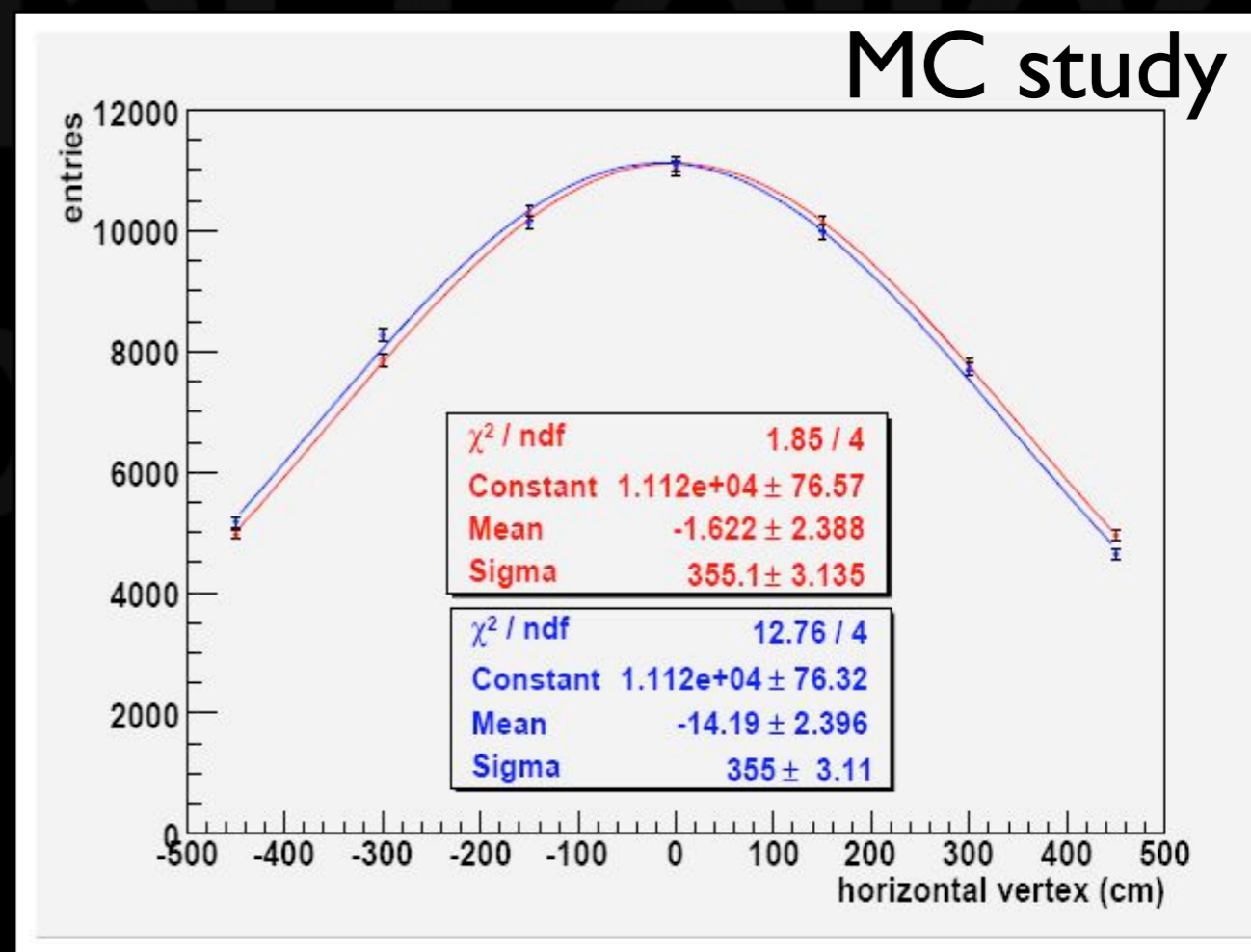
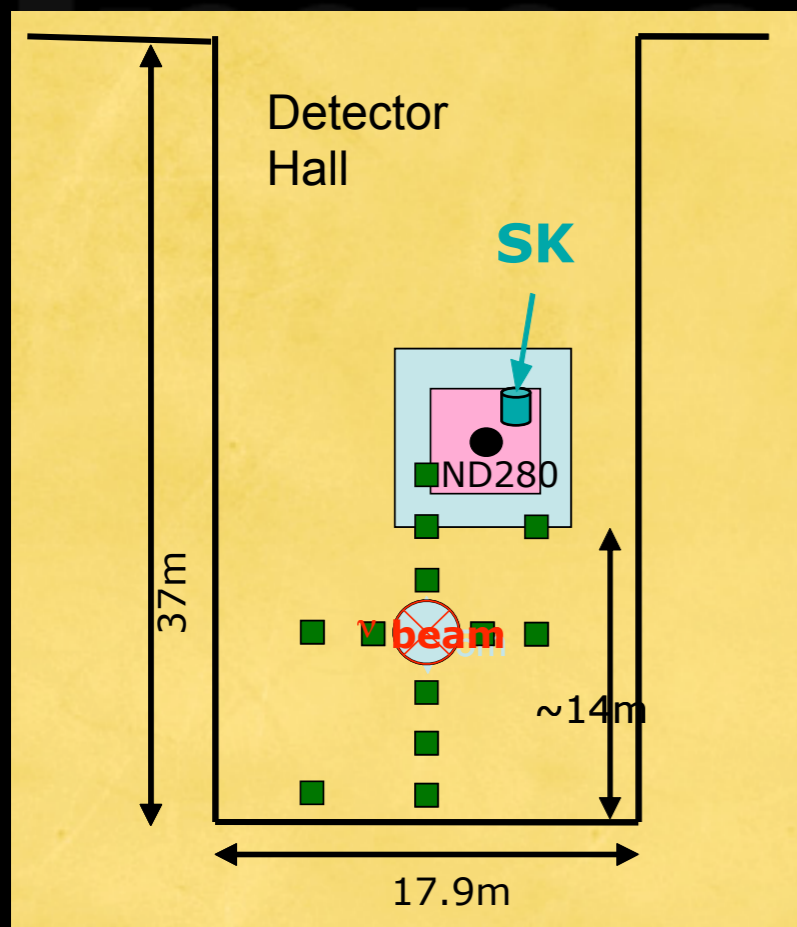
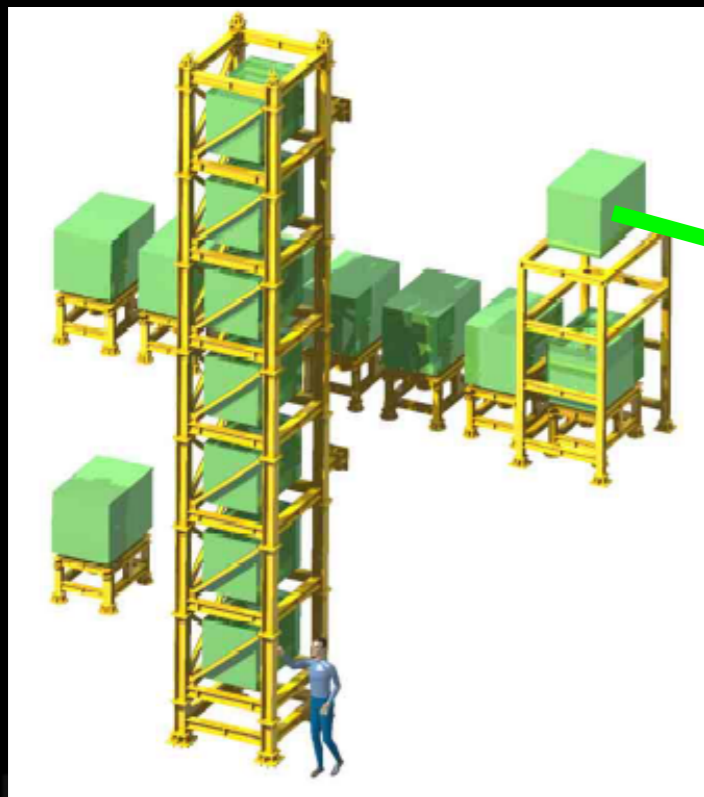
Near Detectors



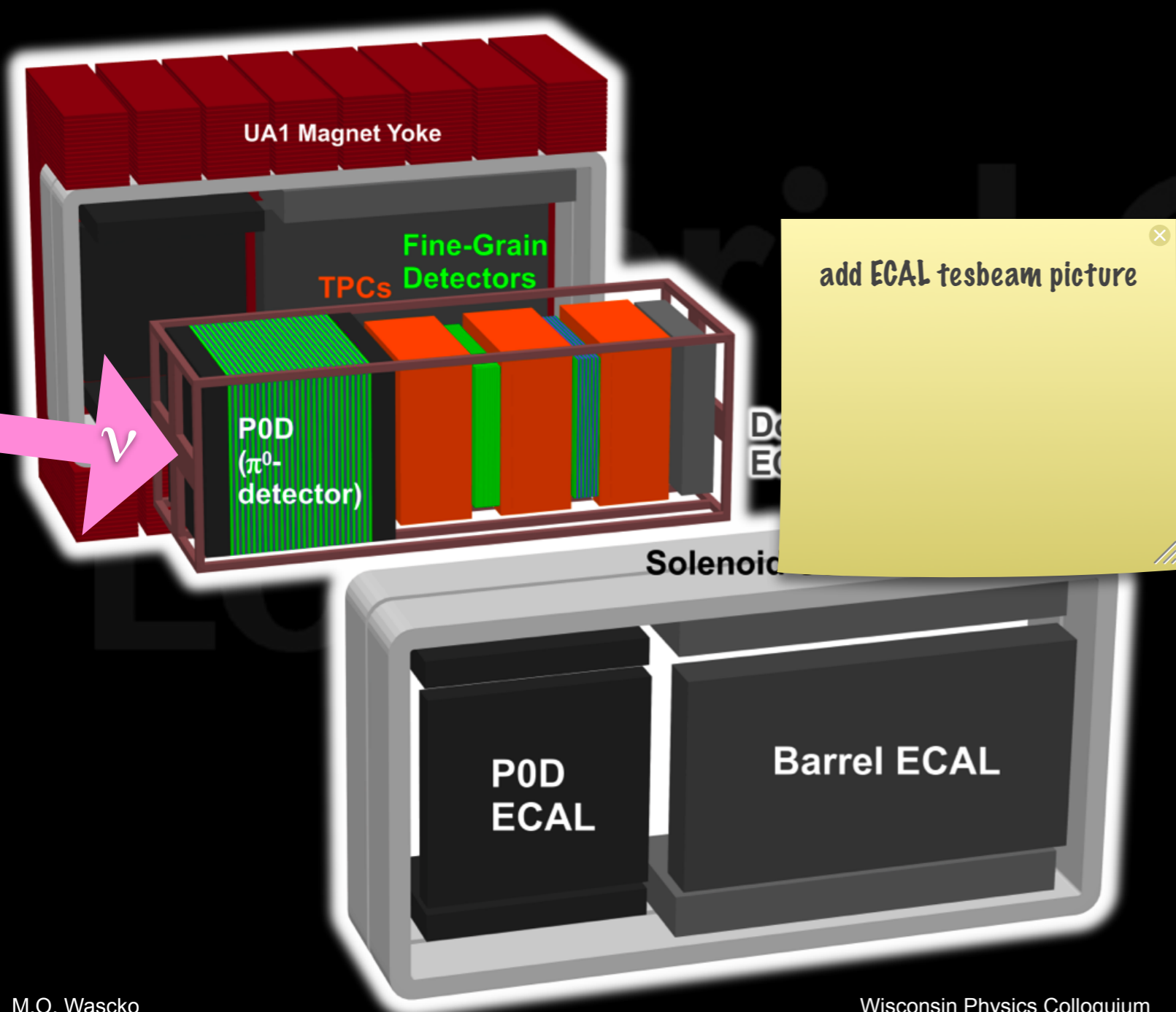
Performance Goals

- INGRID must measure
 - Beam profile and direction
 - High accuracy, short time
- ND280 designed to measure:
 - ν_μ flux: <5%
 - ν_μ energy scale: <2%
 - intrinsic ν_e content: <10%
 - ν_μ CC BGs <10%
- Magnetic field, fine segmentation, excellent tracking
- High complexity and non-trivial integration

INGRID

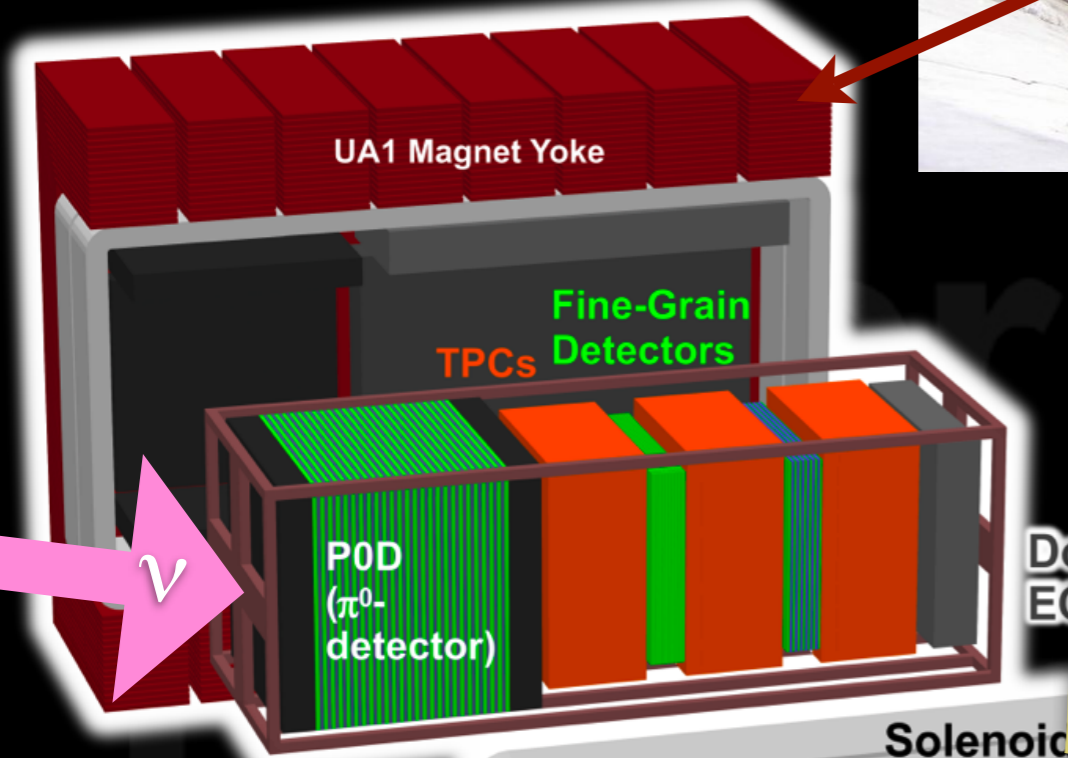
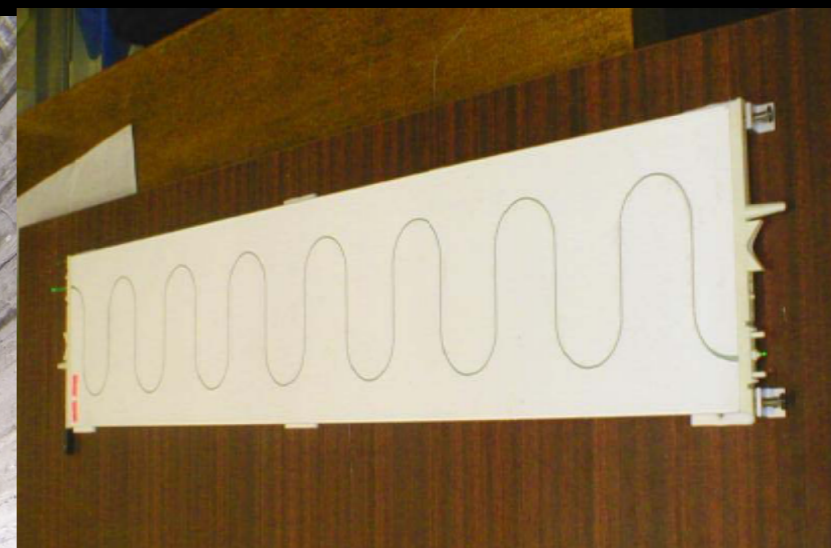


ND280

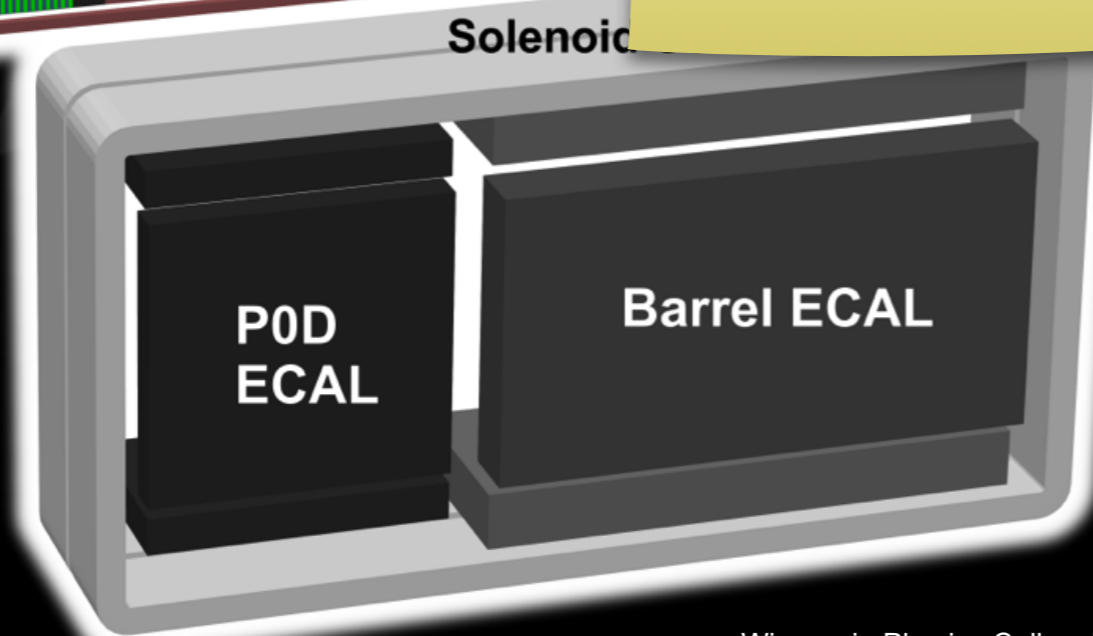


- ~0.2 T magnet
- Yoke contains SMRD
- Using MPPCs
- Tracker
 - π^0 Detector (P0D)
 - Time Projection Chambers (TPCs)
 - Fine grained detectors (FGD)
- ECAL

ND280

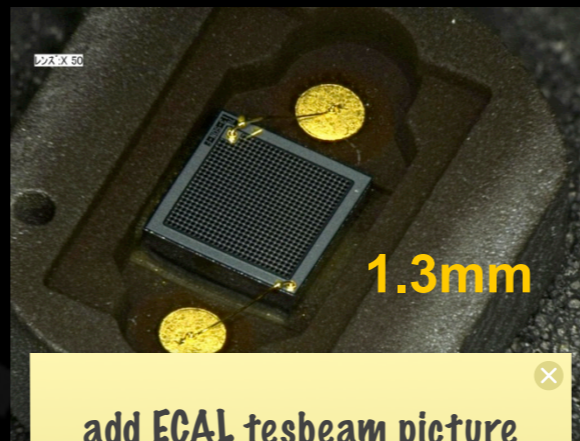
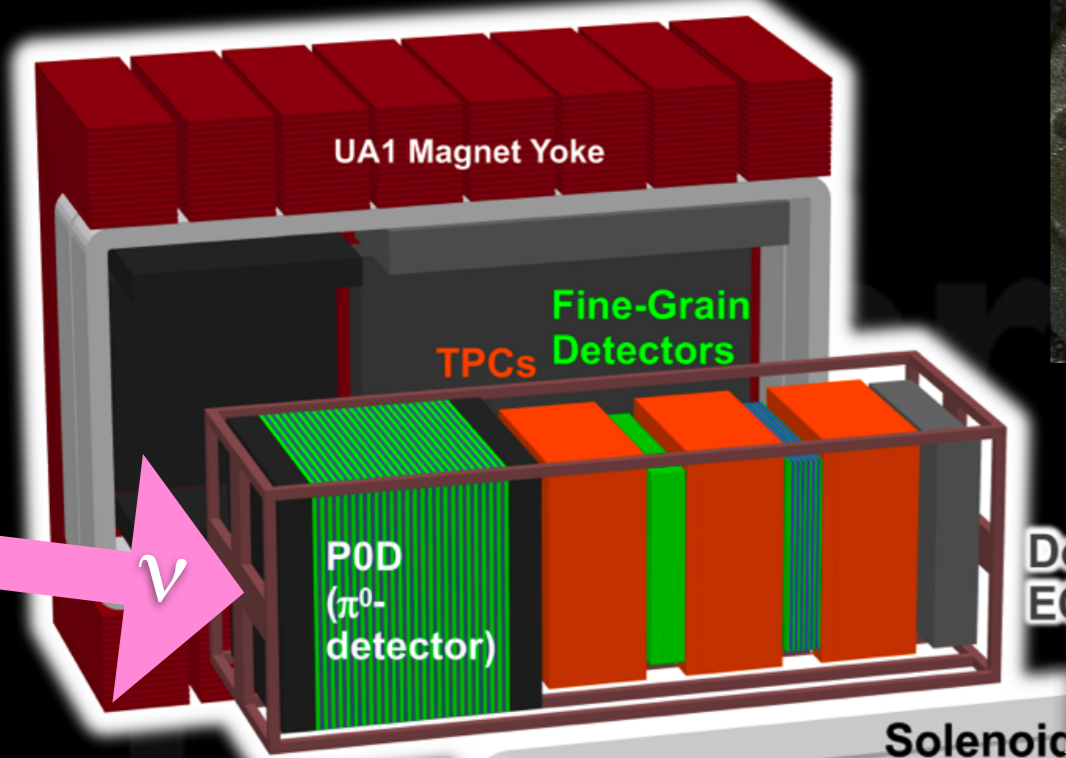
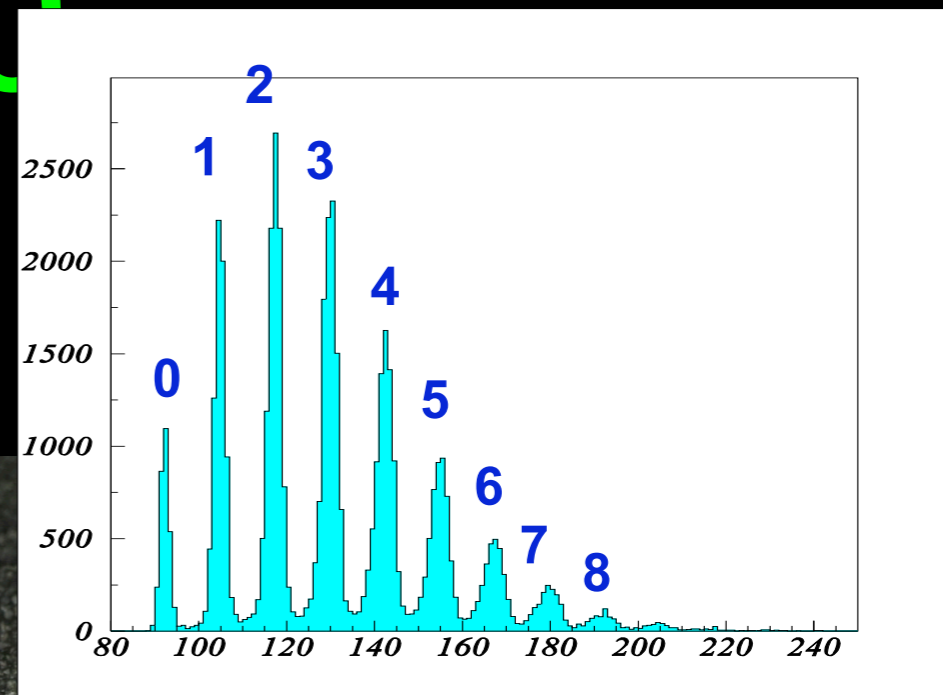


add ECAL tesbeam picture

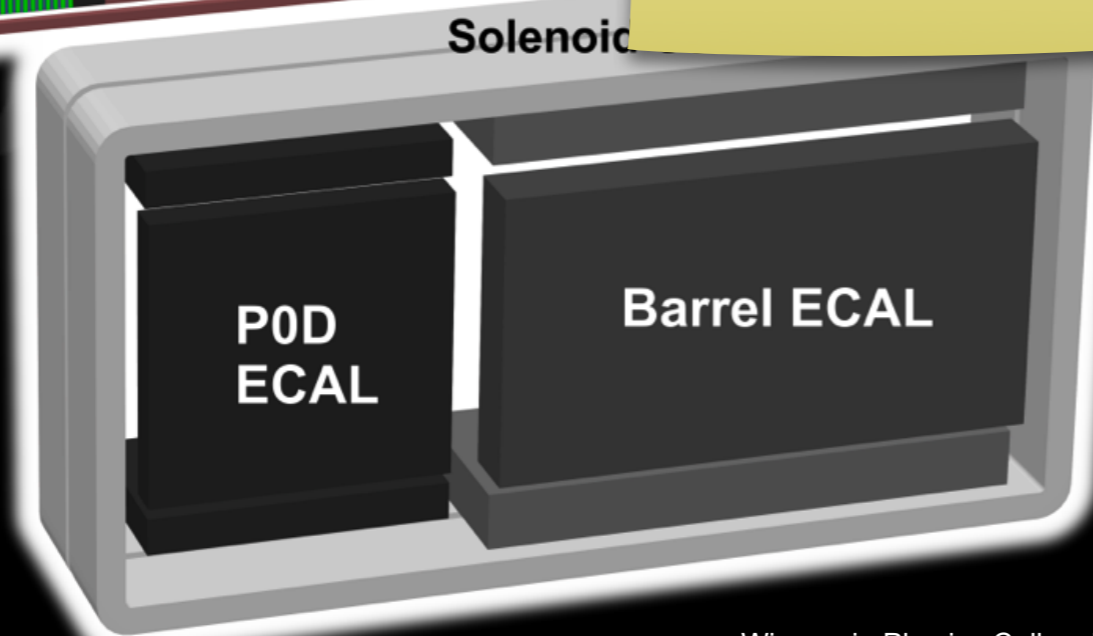


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ND280

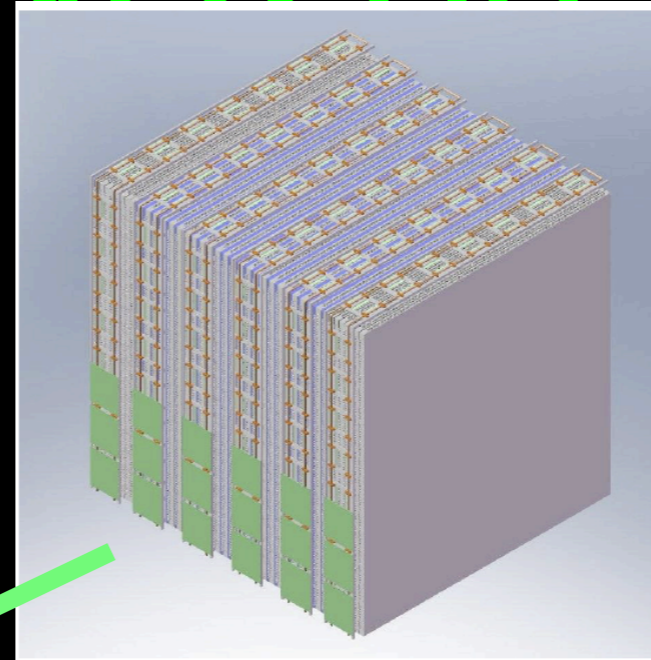
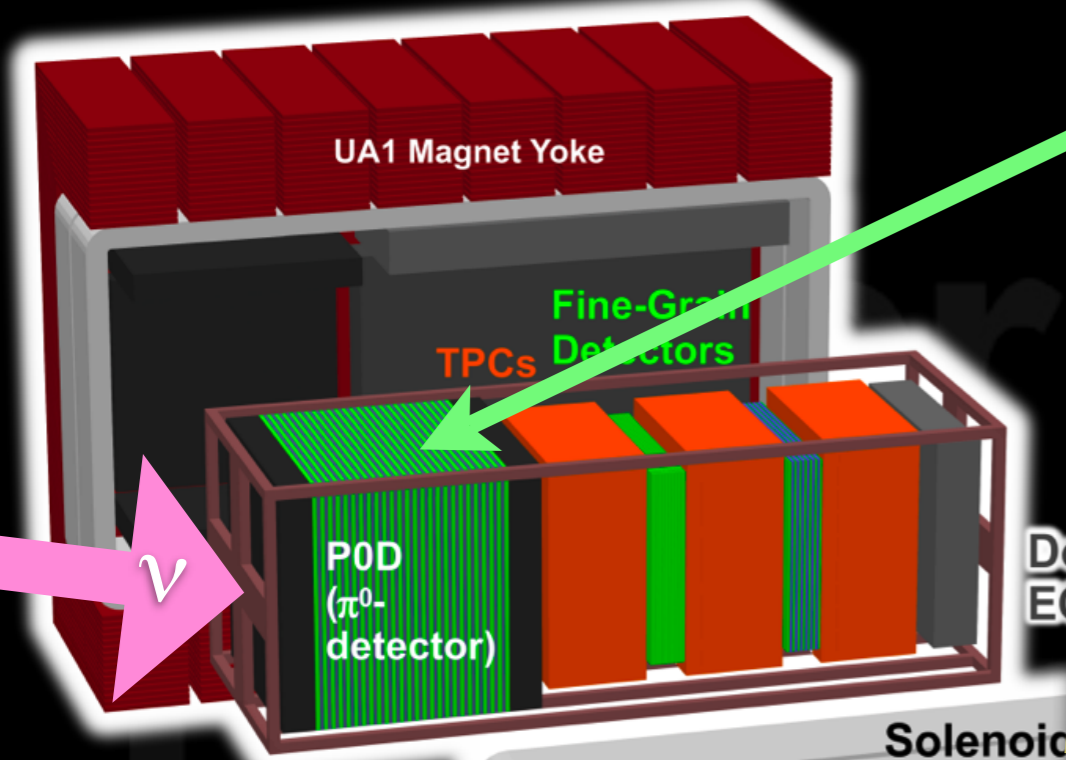


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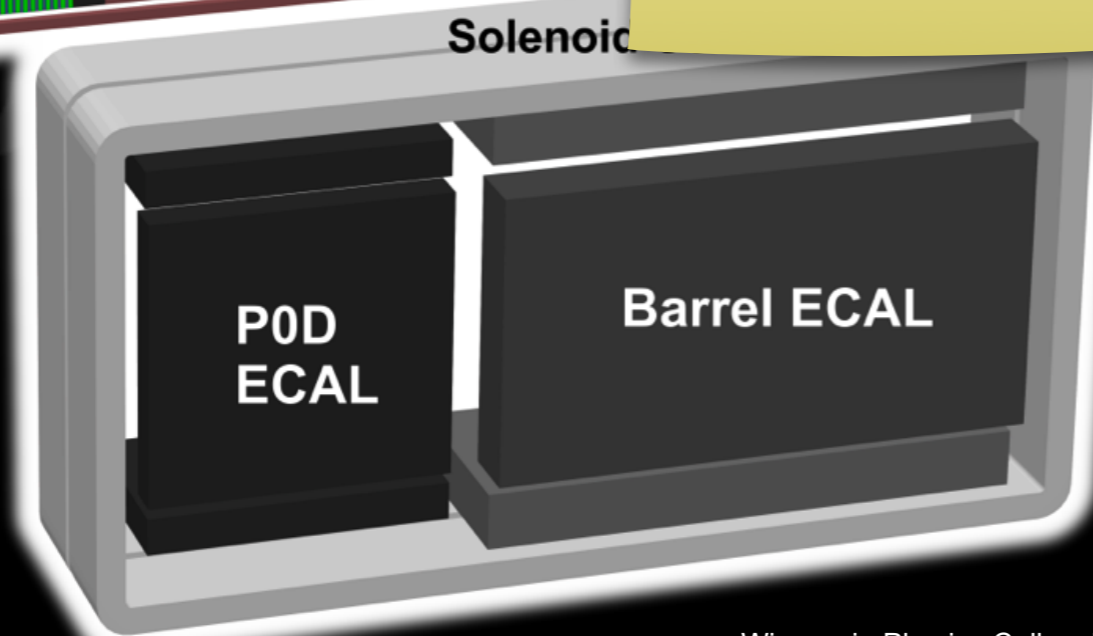
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ND280

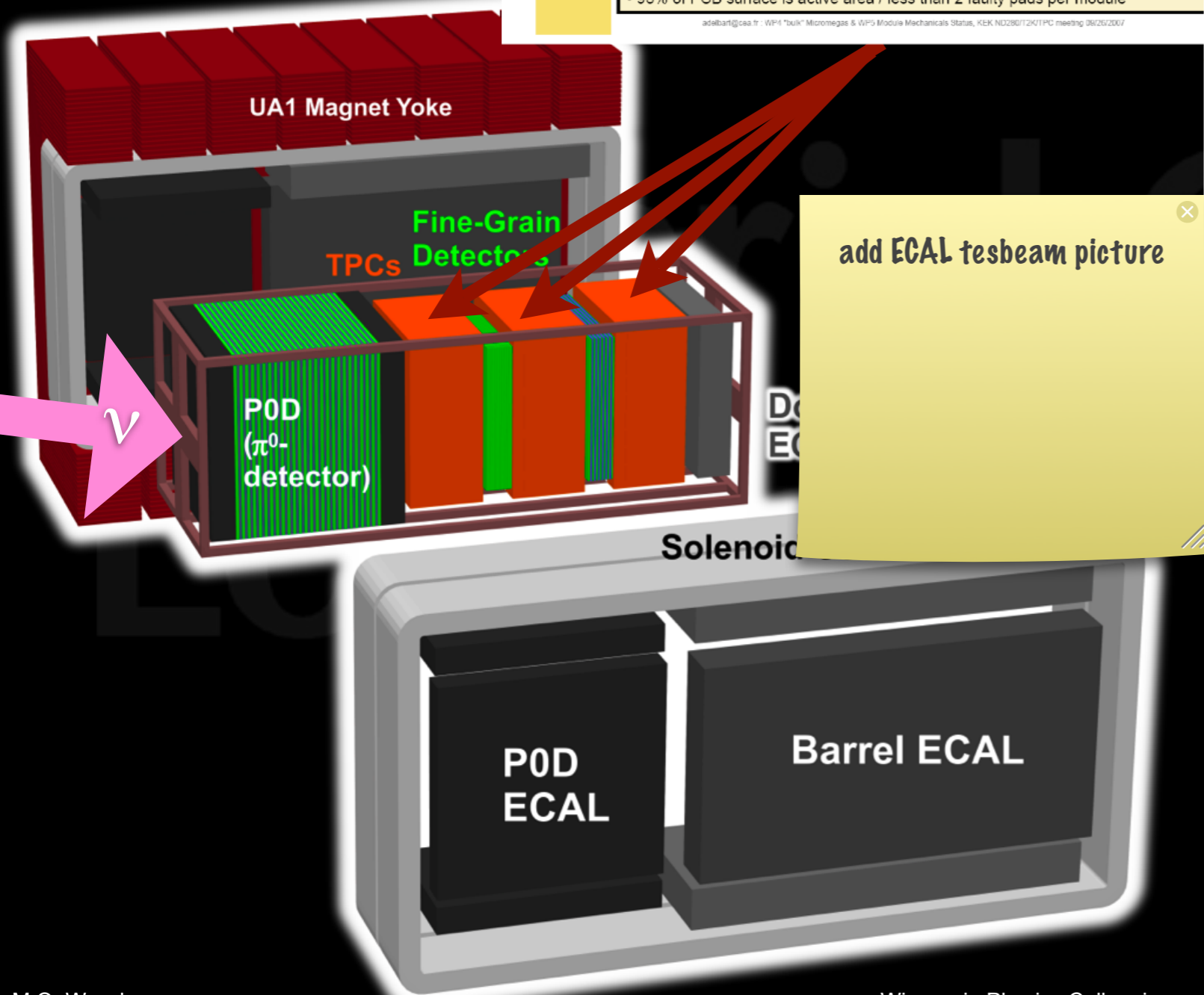
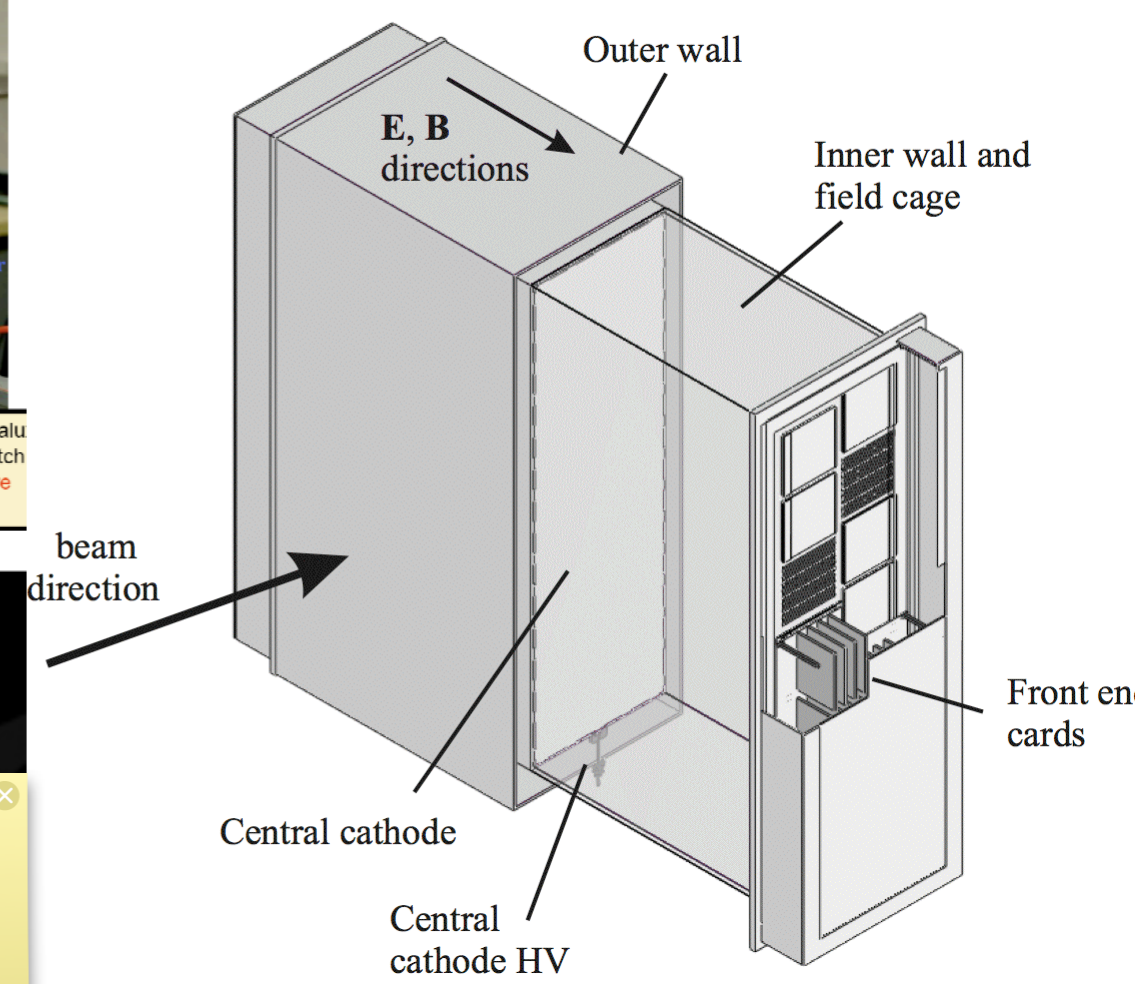
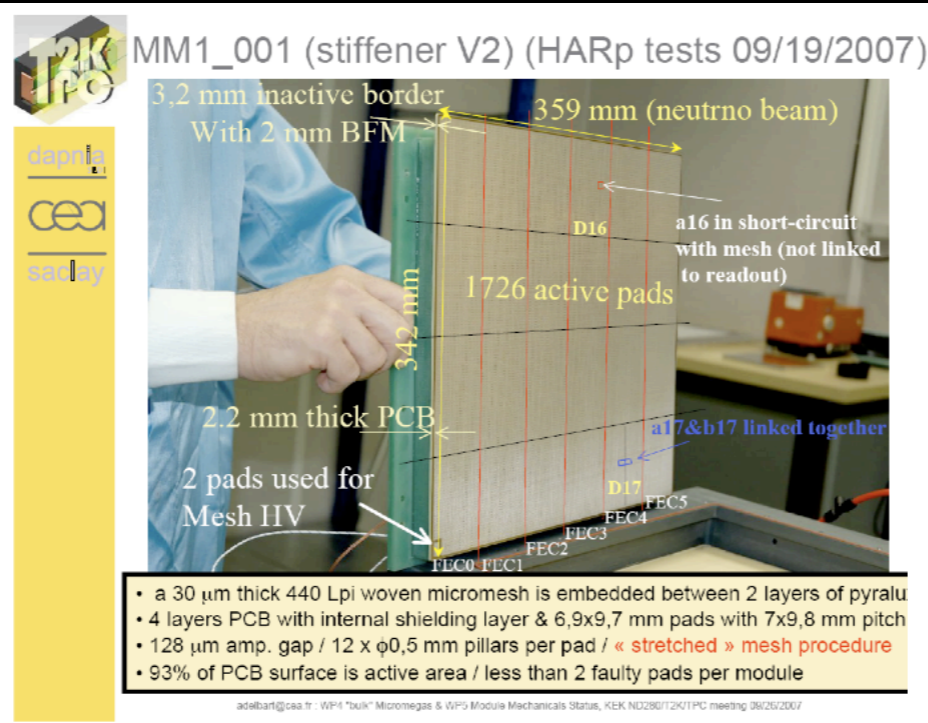


- 3 Super-PØDules
 - ◆ Upstream ECAL (3200 kg)
 - 7 PØDules
 - 7 4mm-thick lead radiators
 - ◆ Target (11000 kg)
 - 2857.3 kg water
 - 26 PØDules
 - 25 1.6mm brass radiators
 - 25 Water target layers
 - Split into 2 sub-units for pre-installation handling
 - ◆ Central ECAL (3200 kg)
 - 7 PØDules
 - 7 4mm-thick lead radiators
- Total Mass is 17600 kg

add ECAL tesbeam picture

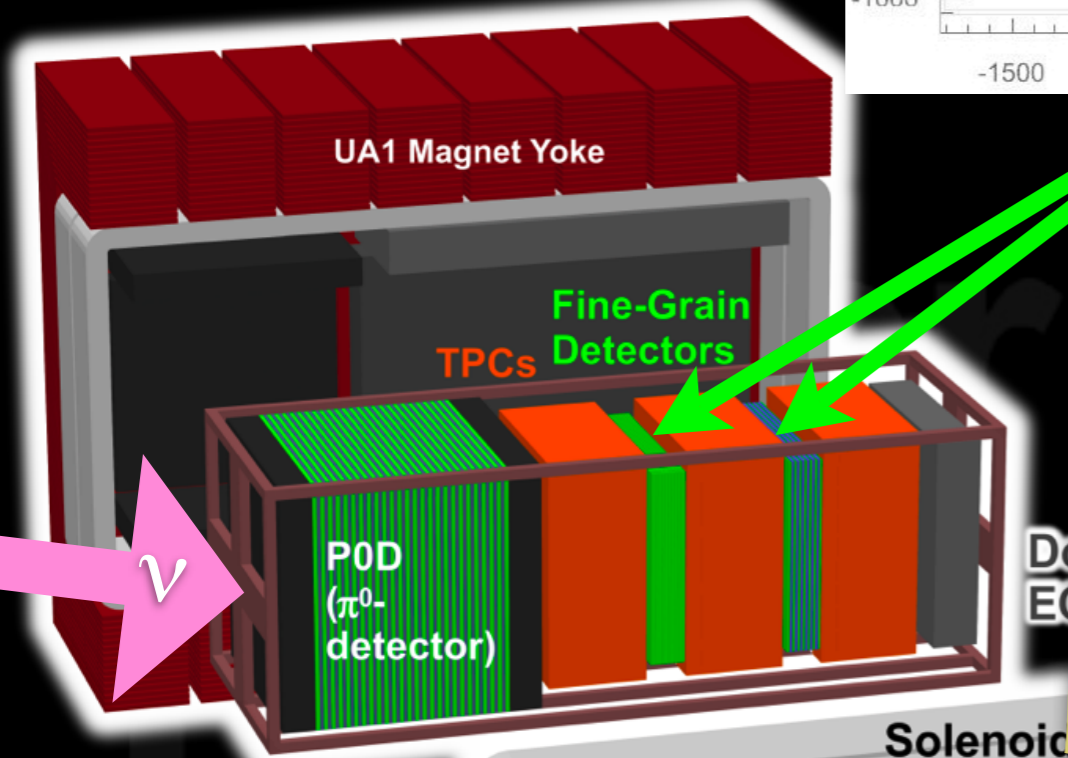
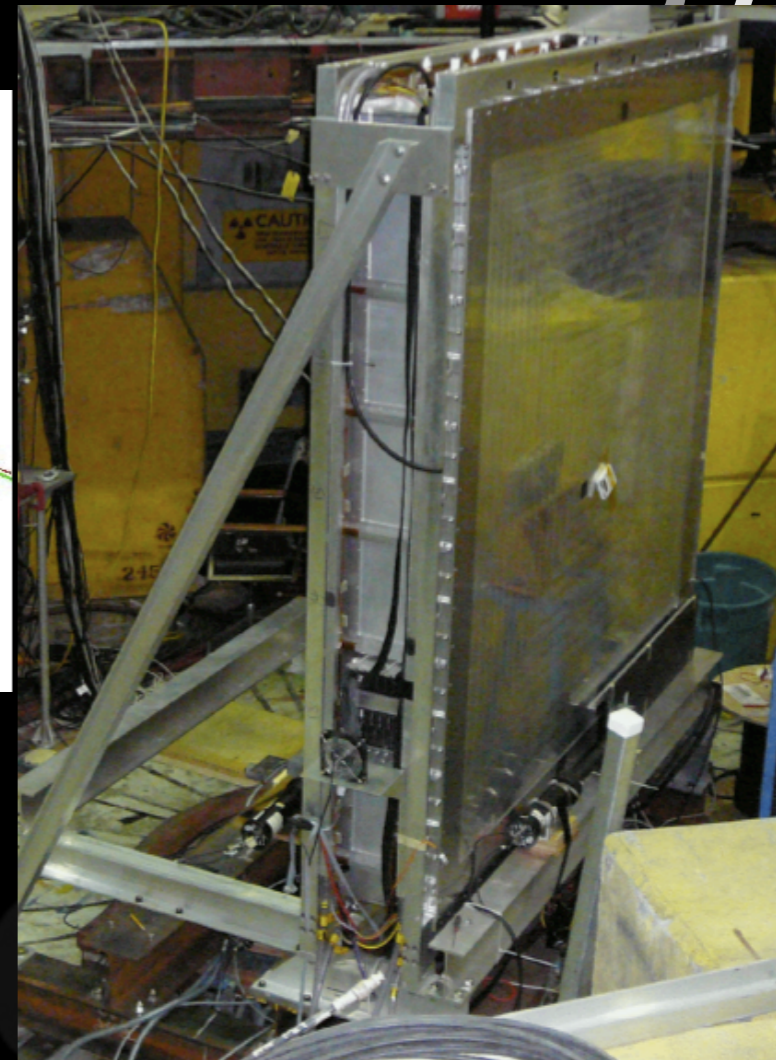
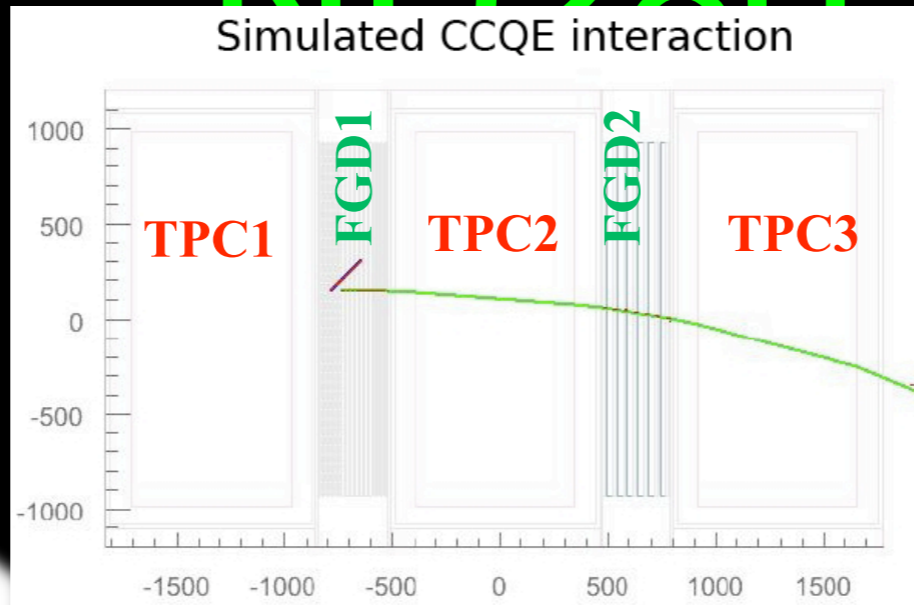


- ~0.2 T magnet
- Yoke contains SMRD
- Using MPPCs
- Tracker
 - π^0 Detector (POD)
 - Time Projection Chambers (TPCs)
 - Fine grained detectors (FGD)
- ECAL

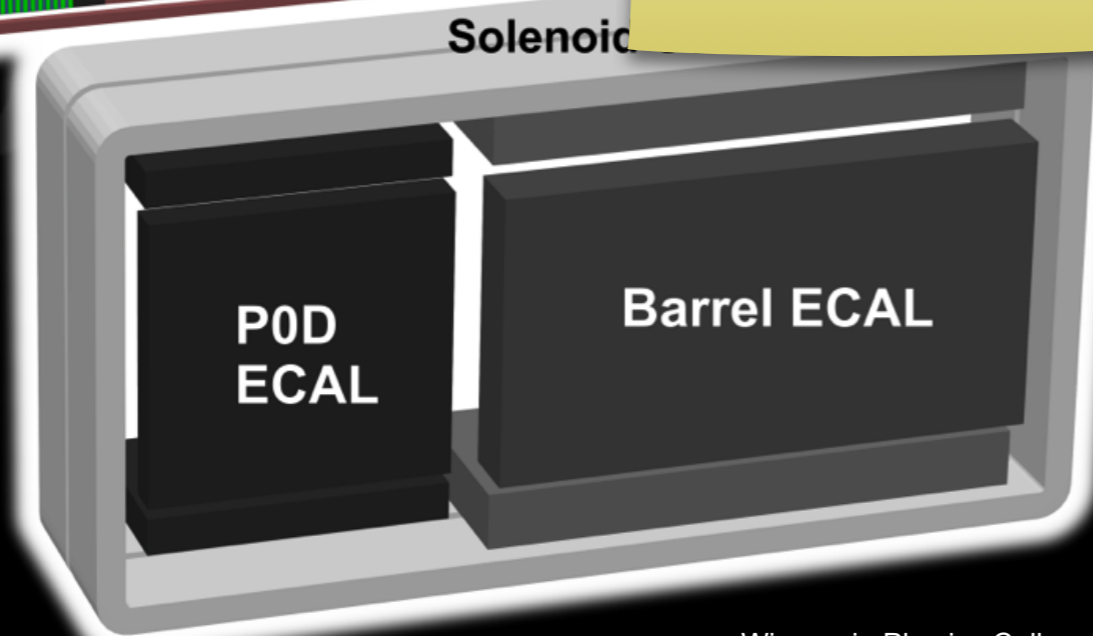


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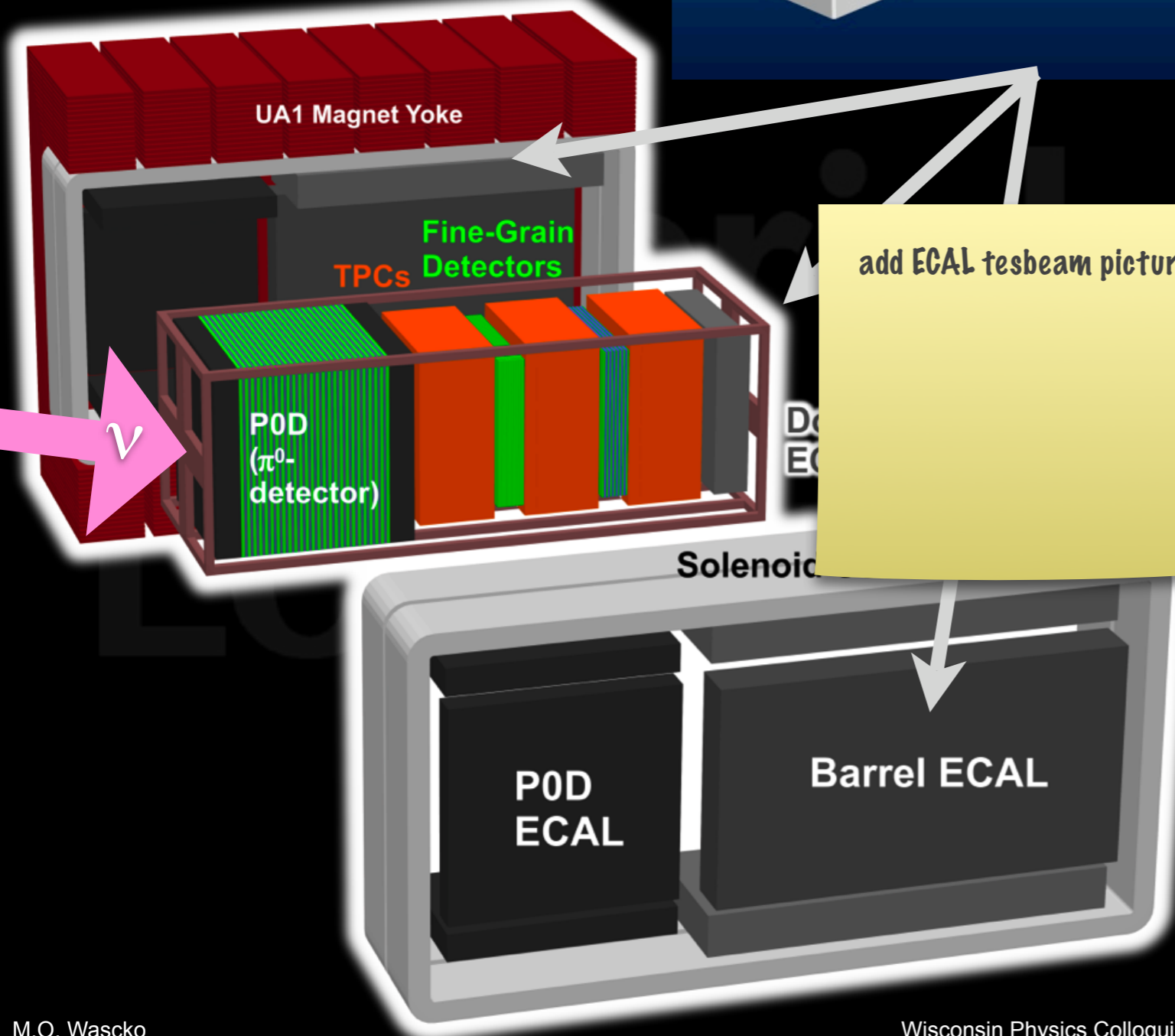
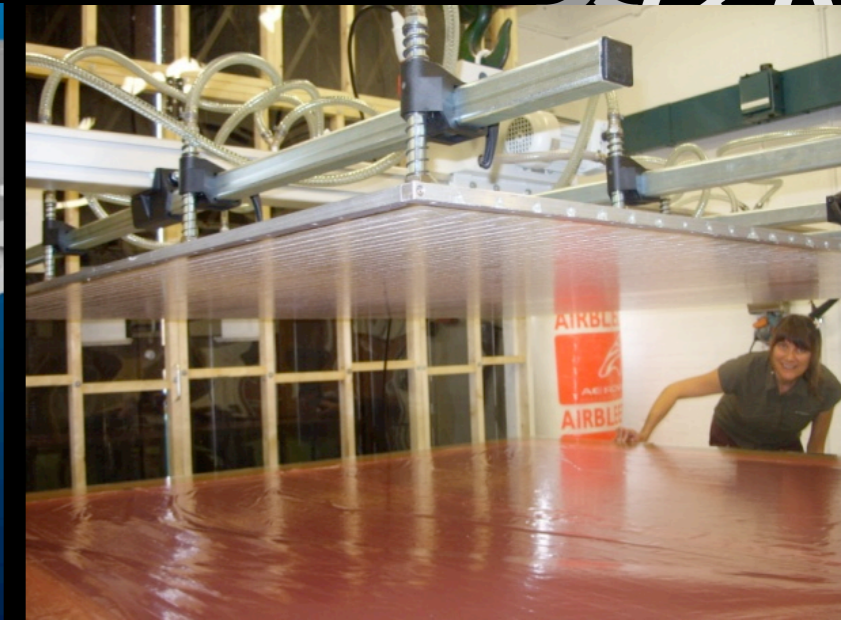
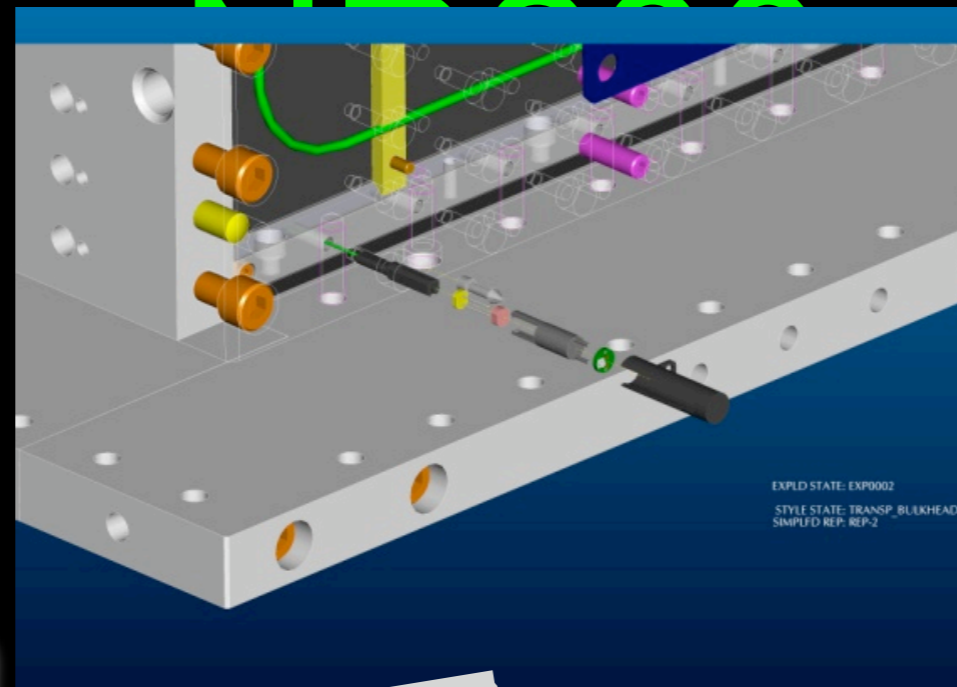
ND280



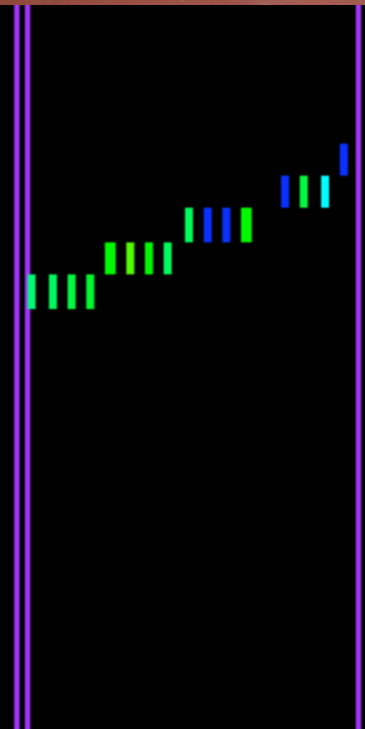
add ECAL tesbeam picture



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 - Time Projection Chambers (TPCs)
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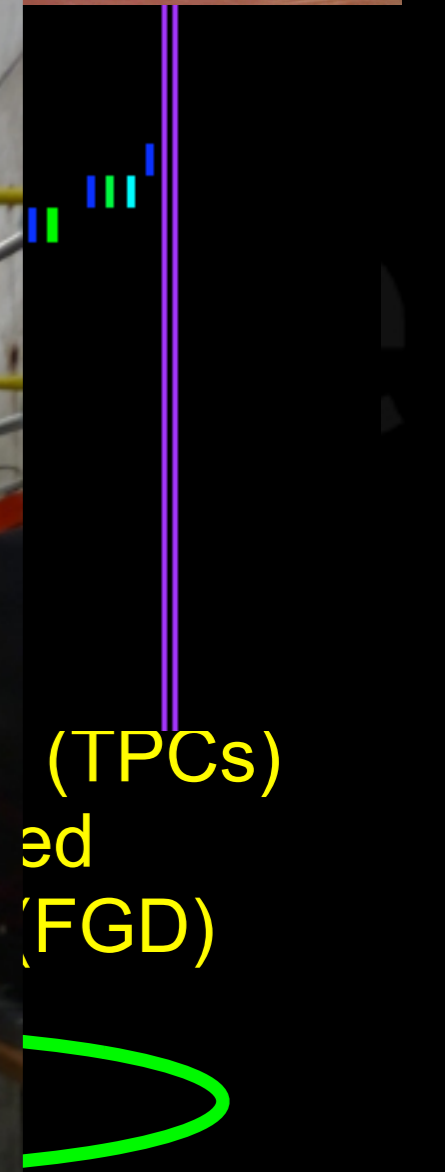
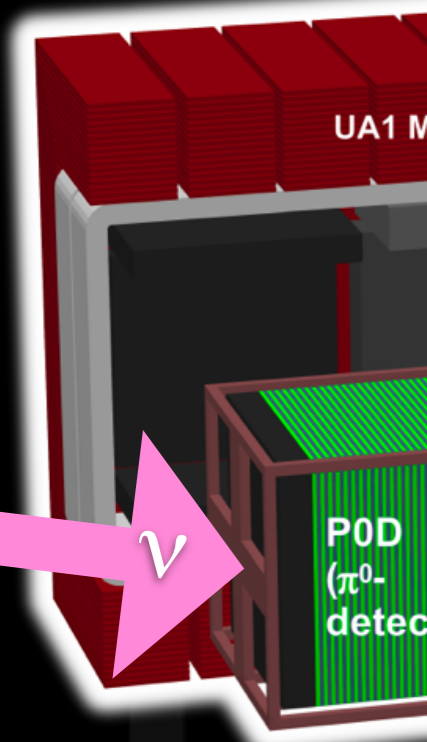
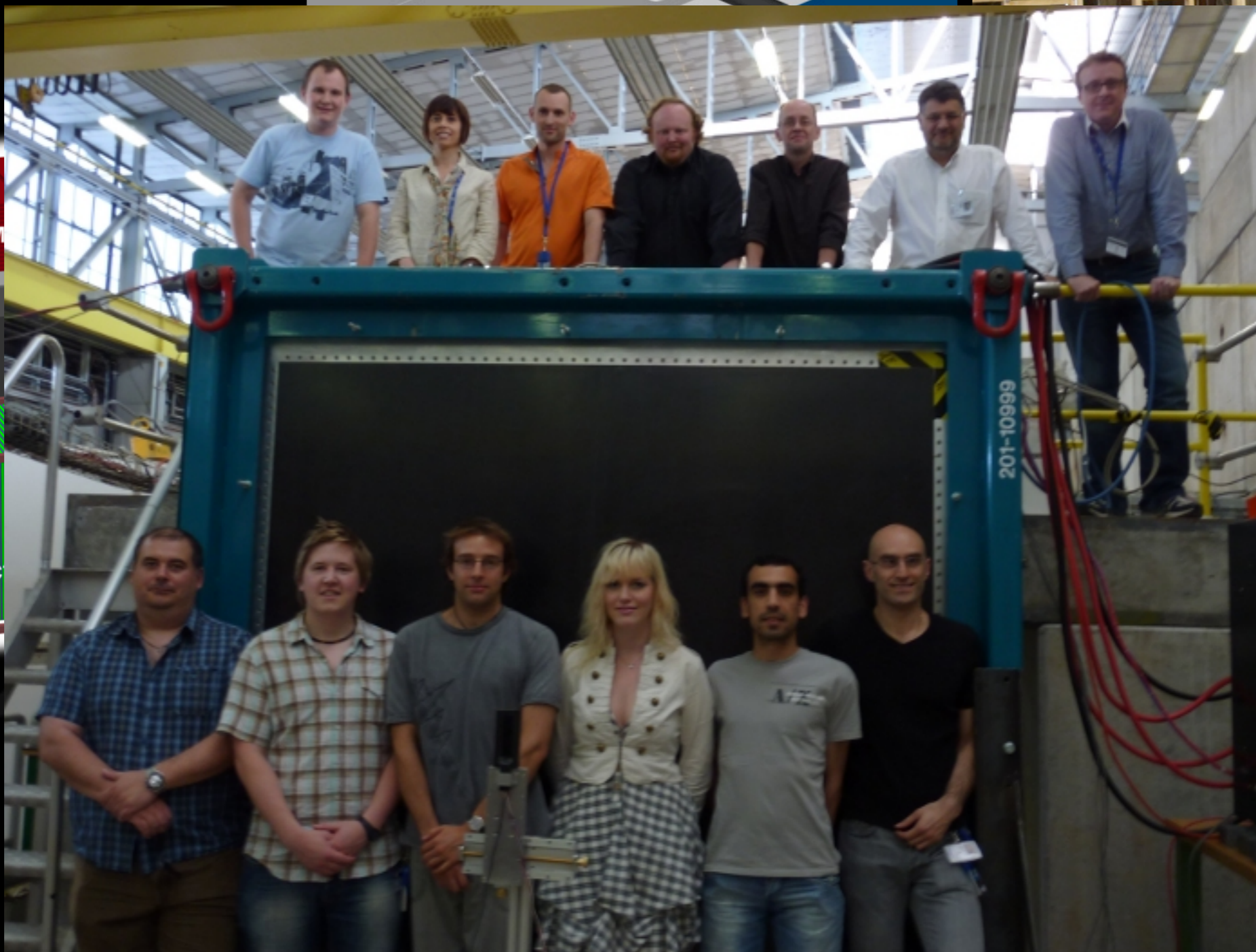


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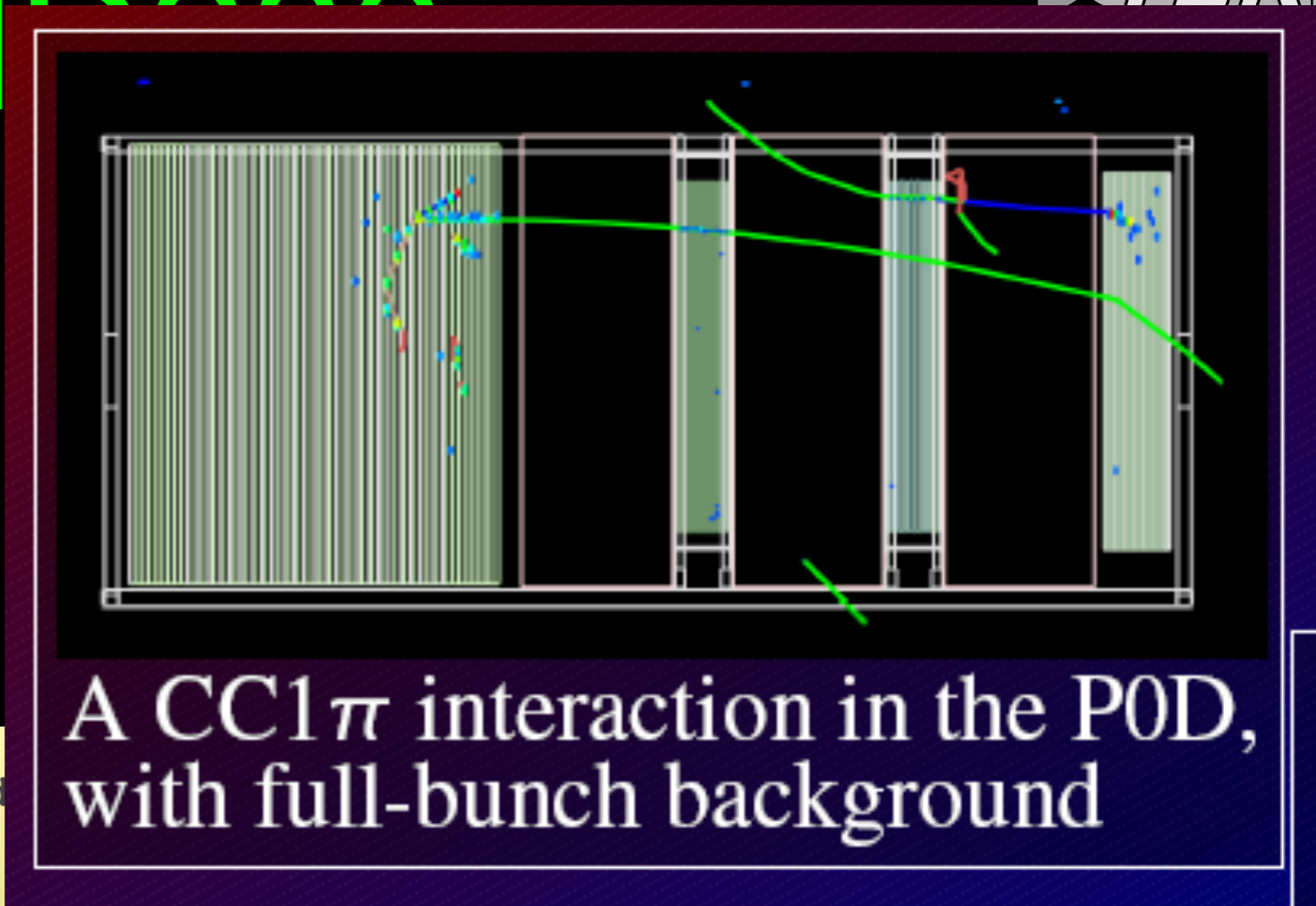
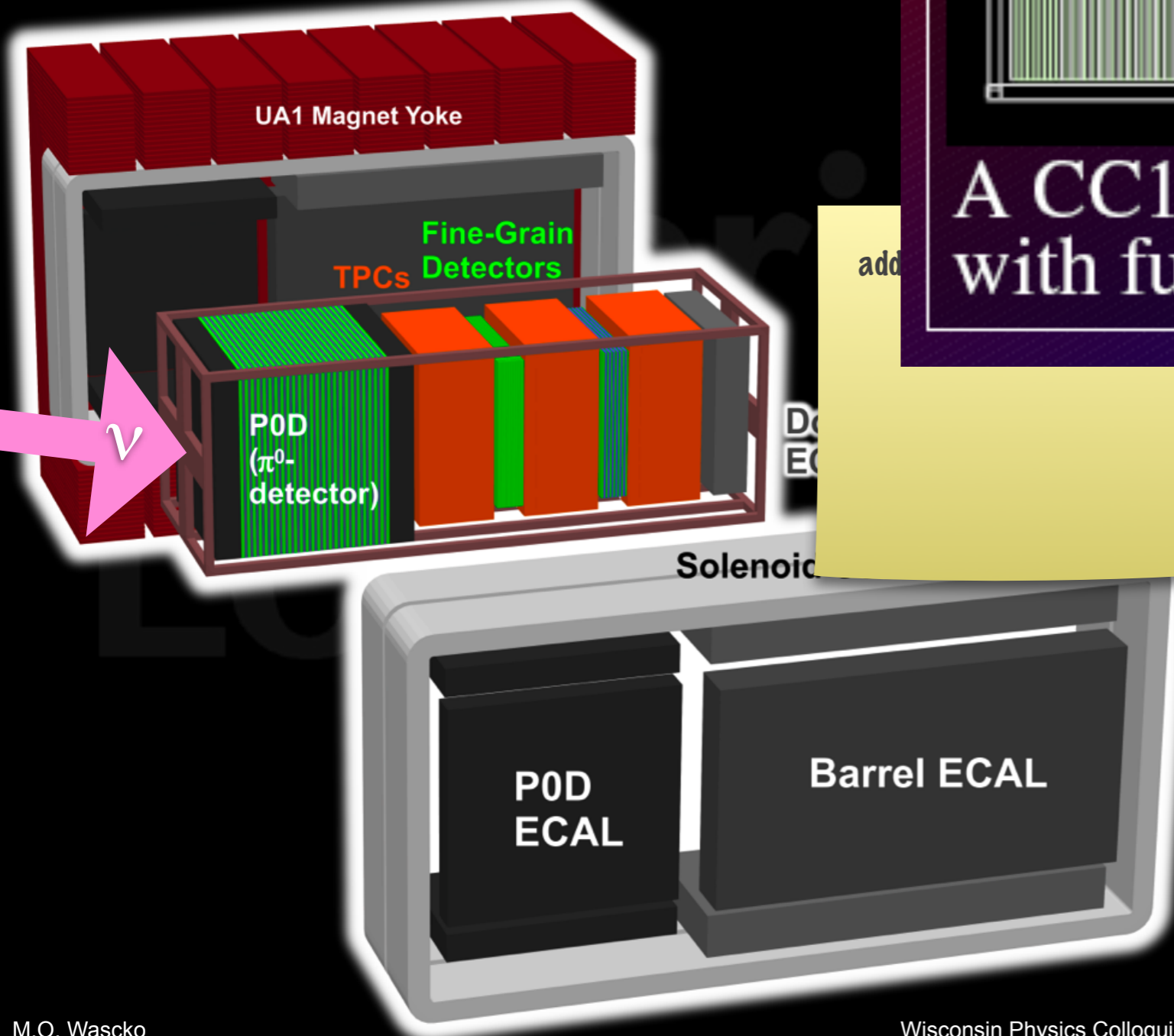


- Chambers (TPCs)
- Fine grained detectors (FGD)

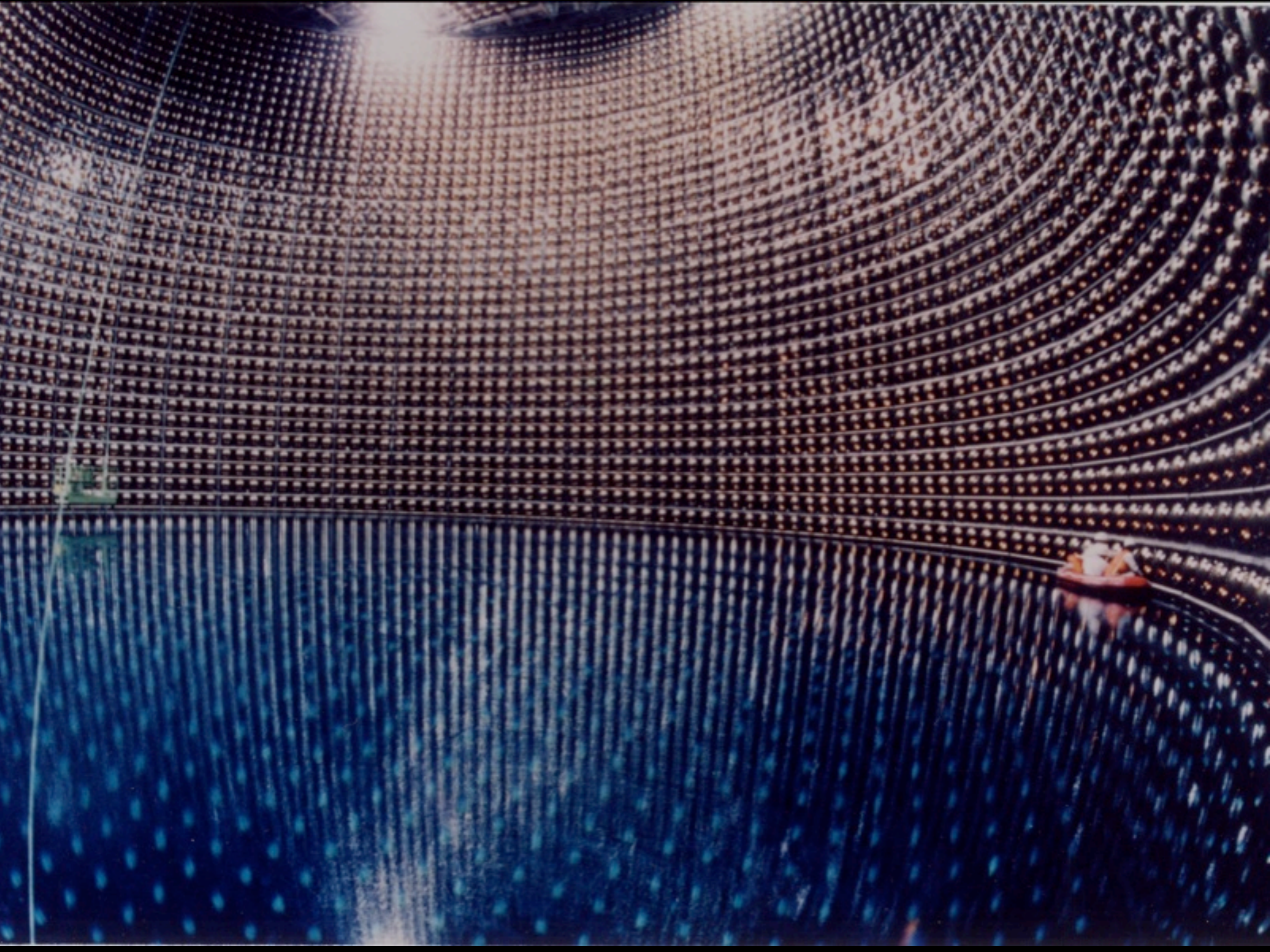
- ECAL

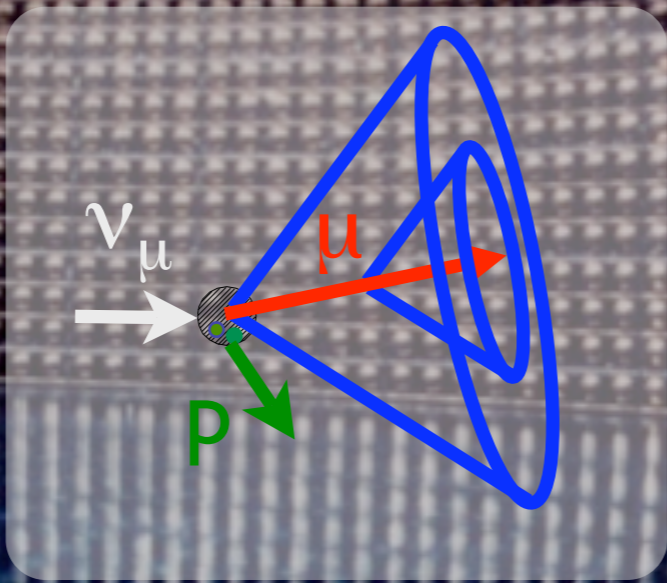
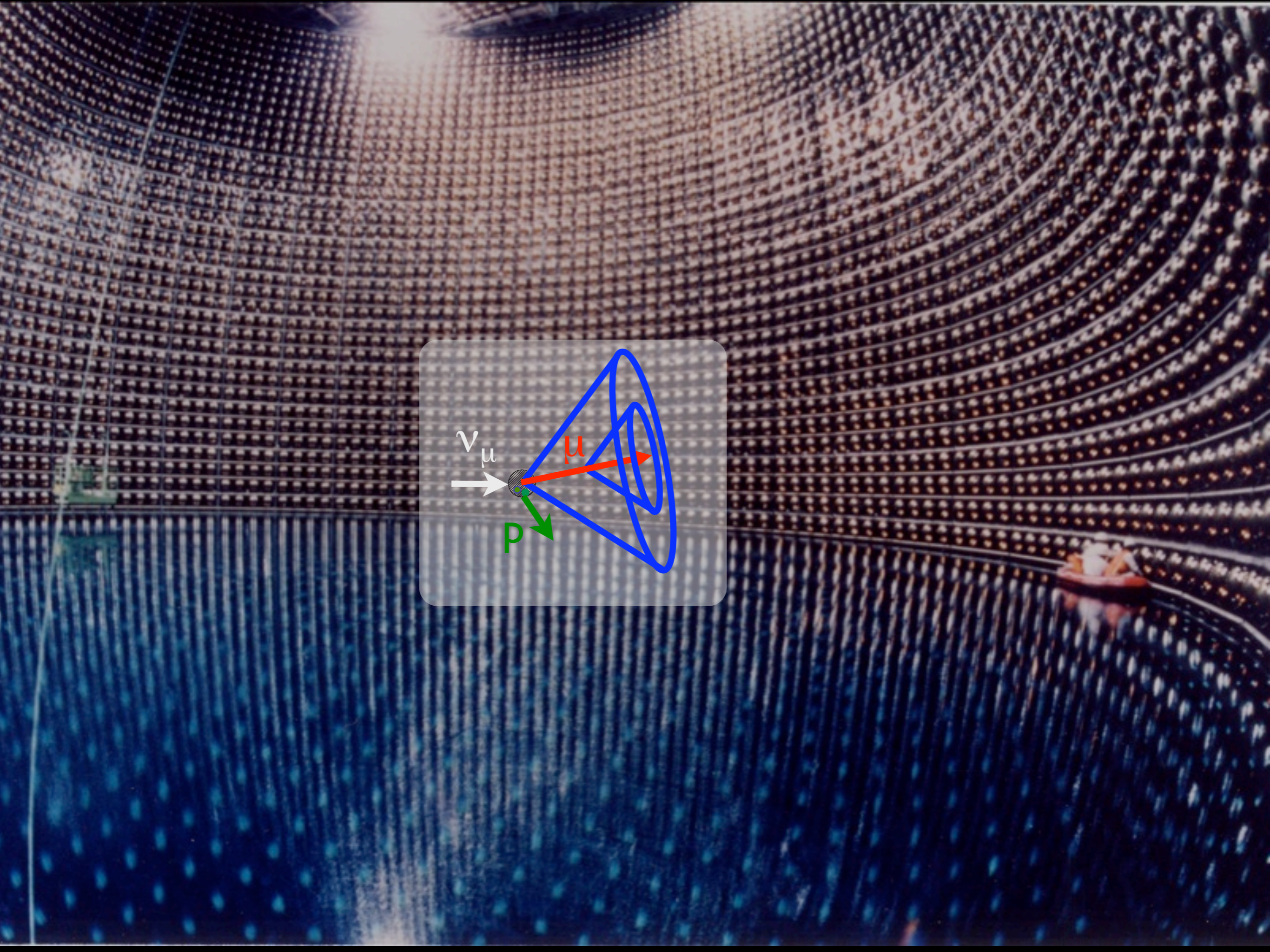


N 0000

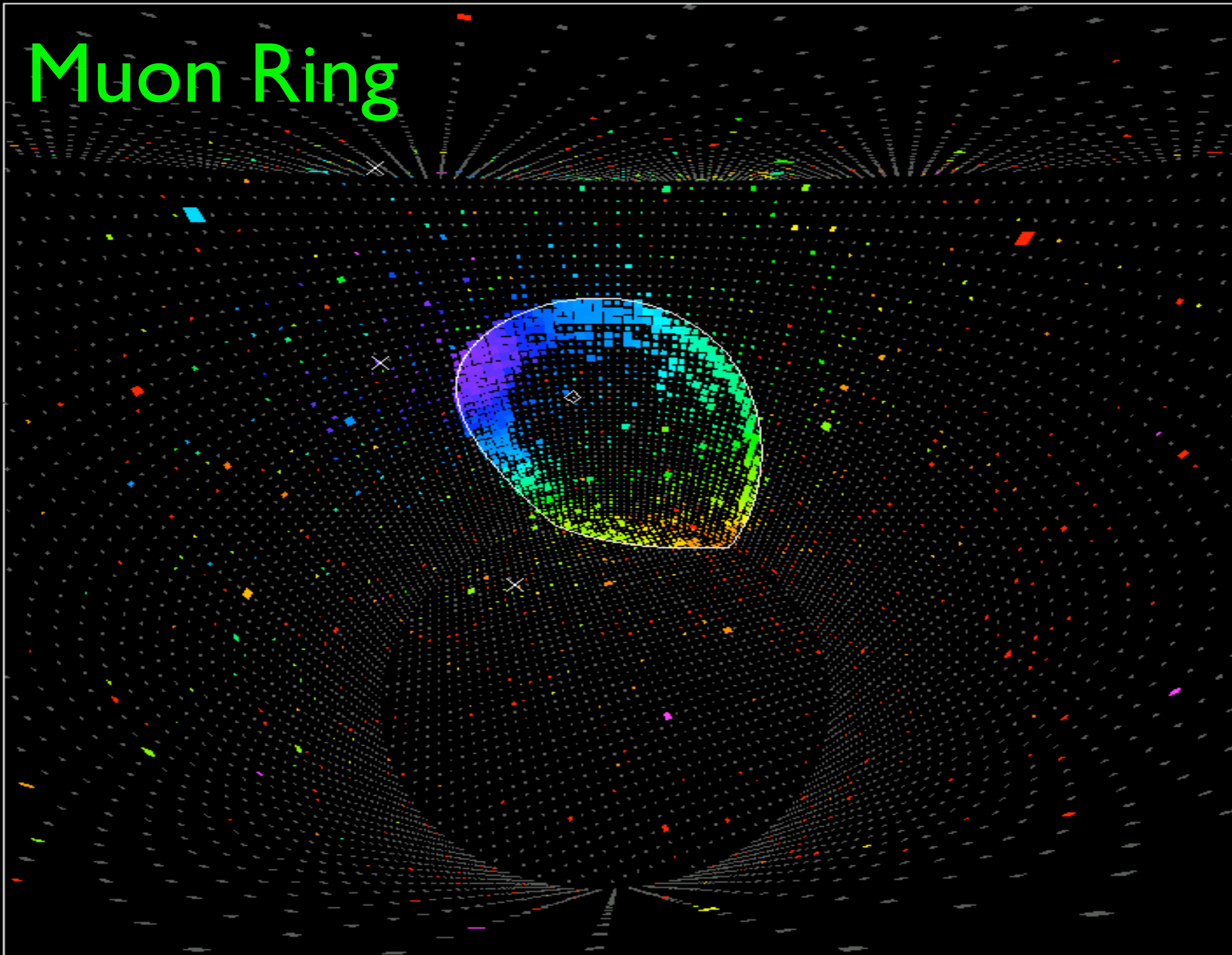


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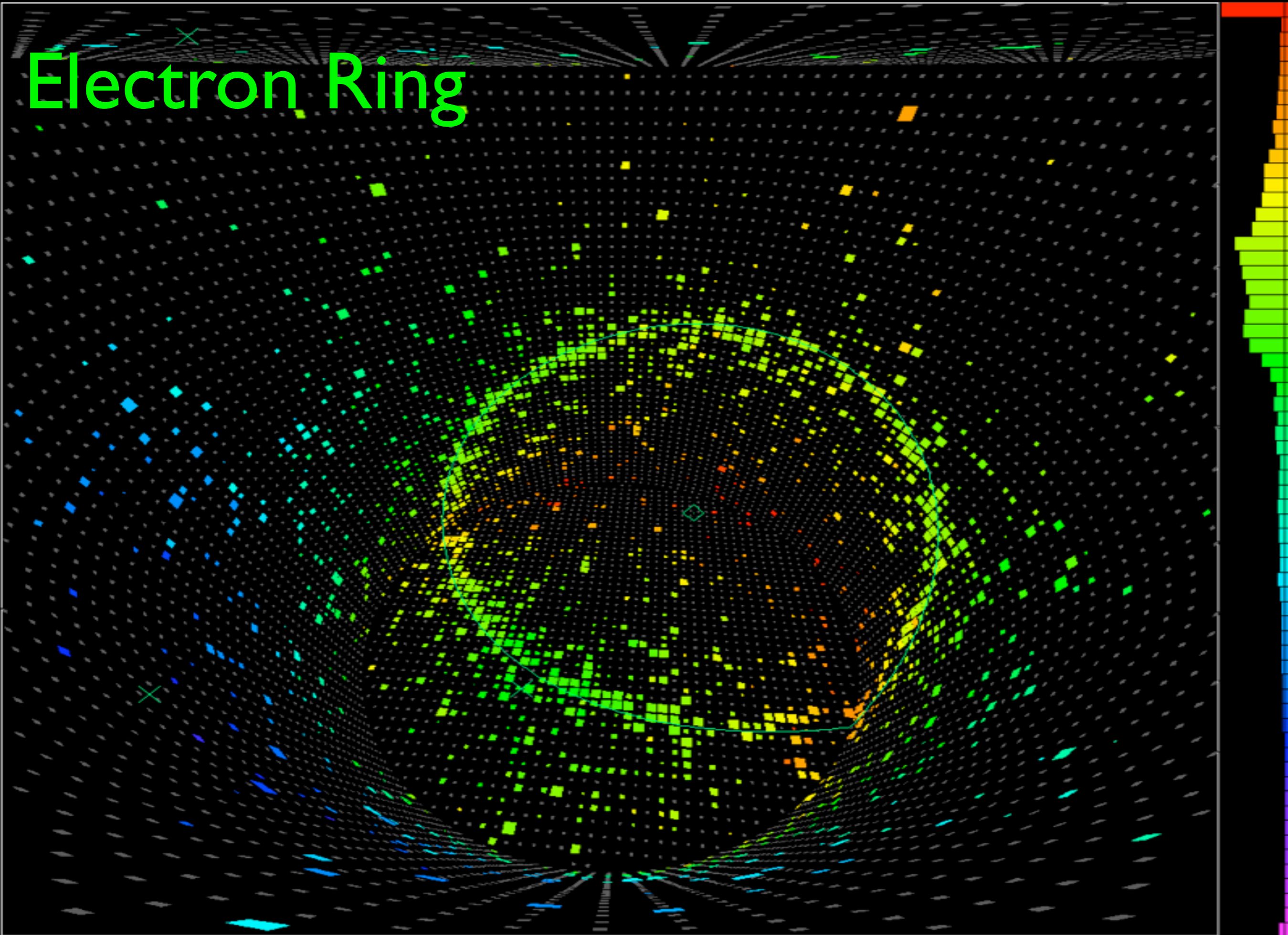




Muon Ring

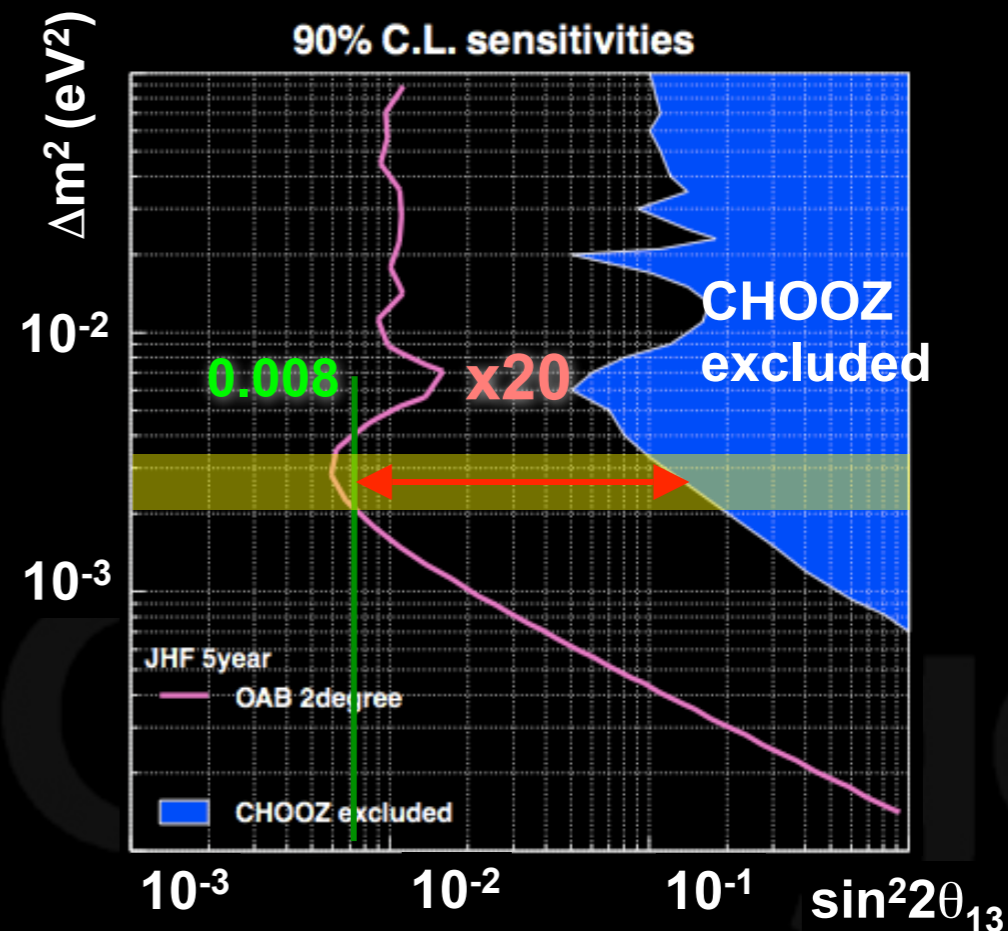


Electron Ring

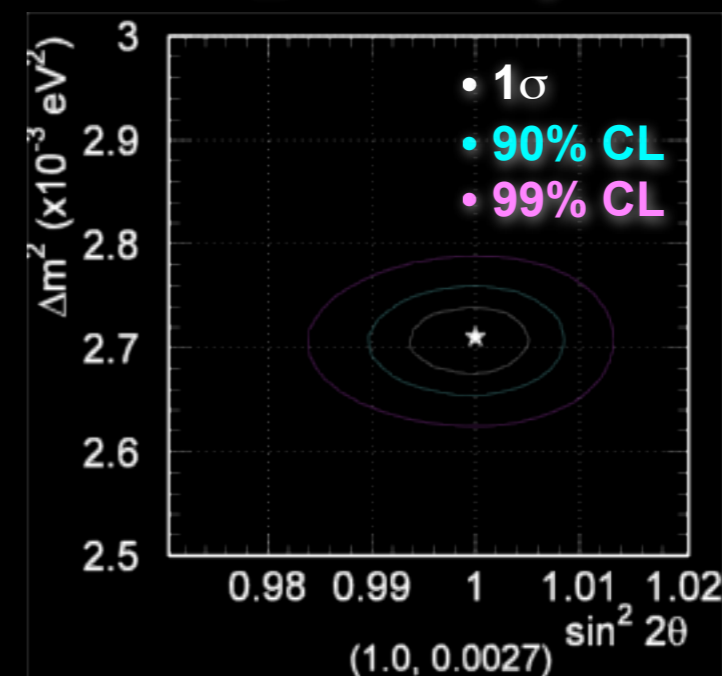


T2K Sensitivity

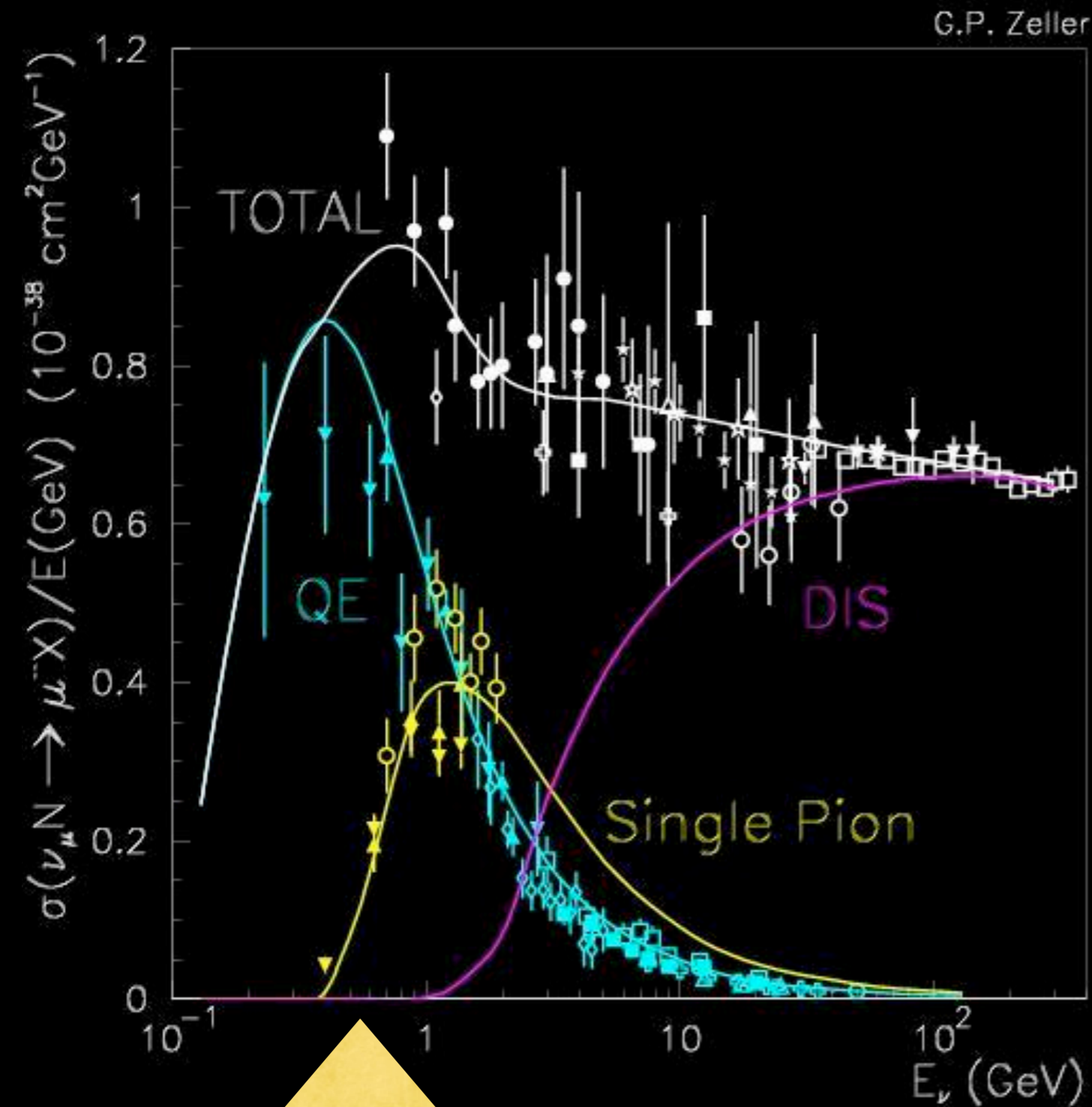
- ν_e appearance
 - Sensitivity to θ_{13}
 - Main backgrounds: intrinsic ν_e and mis-reconstructed ν_μ
 - 20x more sensitive than CHOOZ
 - (Plot assumes $\sin^2 2\theta_{23}=1$ & $\delta=0$)
- ν_μ disappearance
 - Sensitivity to $\Delta m^2_{23}, \theta_{23}$
 - Main backgrounds: mis-reconstructed ν_μ
 - Sensitive to non-maximal mixing below 0.99 at 90% CL



θ_{23} sensitivity

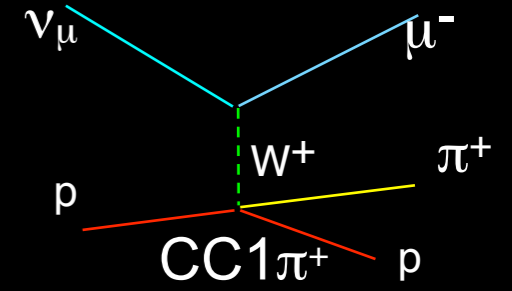
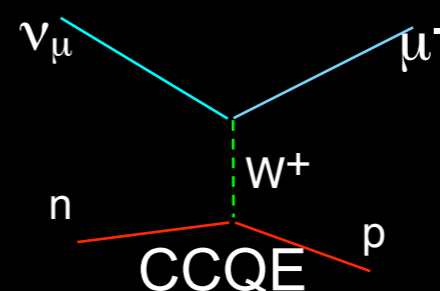


Background Uncertainties

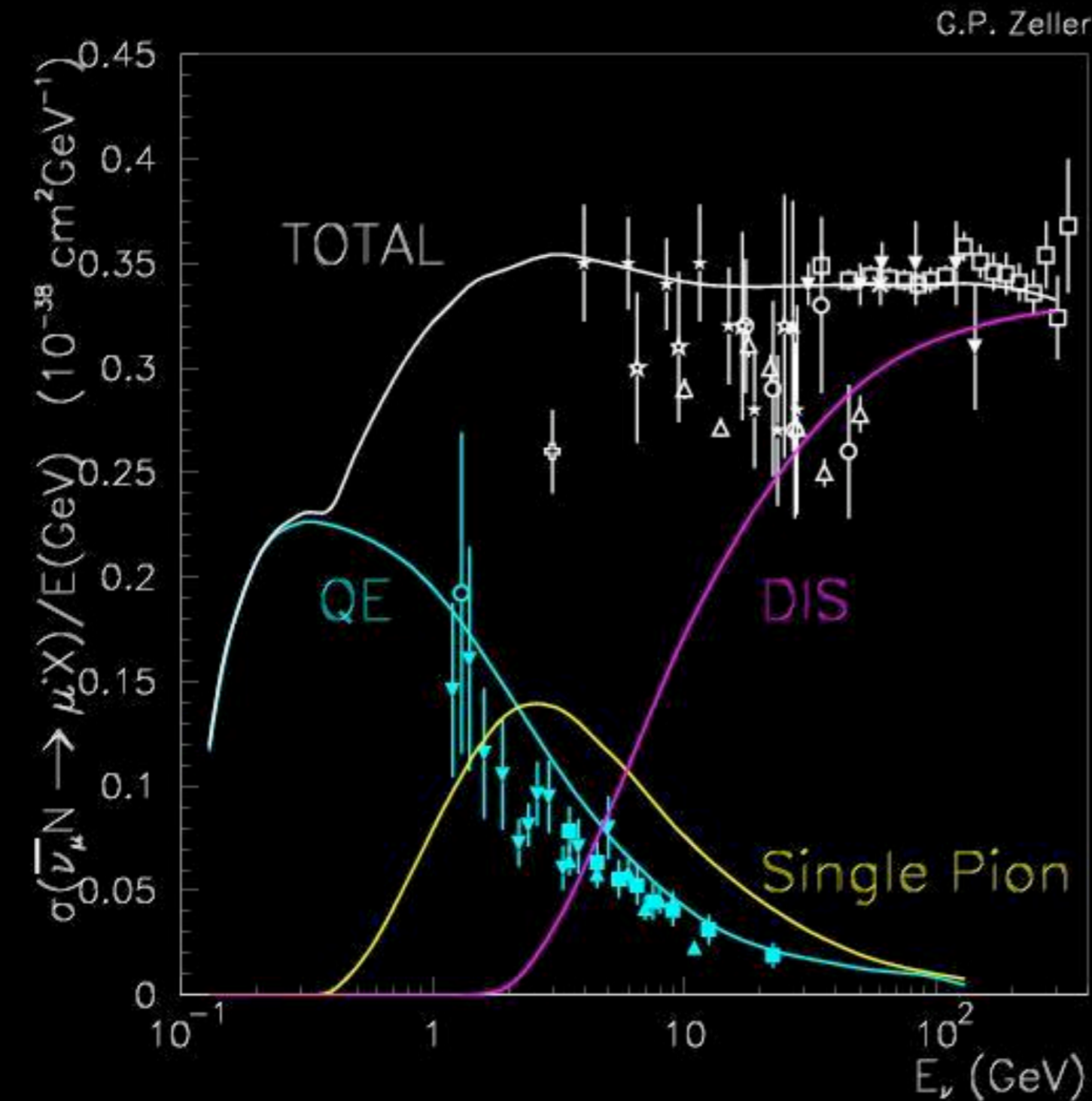


T2K Energy

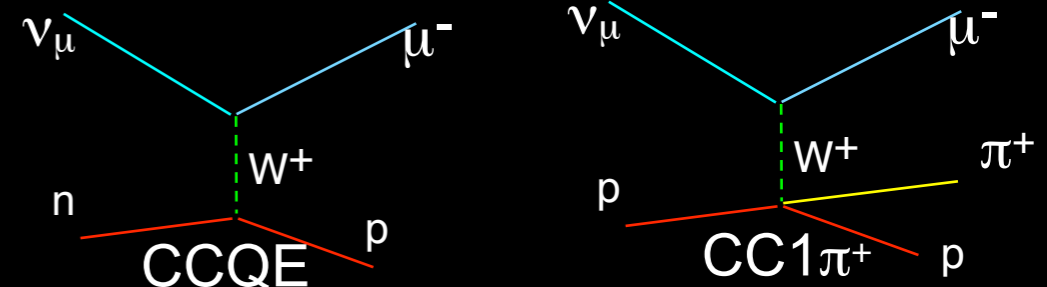
- Need precise cross section measurements
- ν_μ and $\bar{\nu}_\mu$



Background Uncertainties

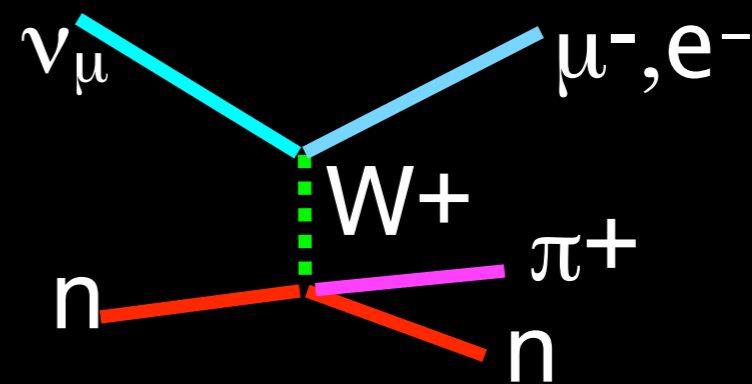


- Need precise cross section measurements
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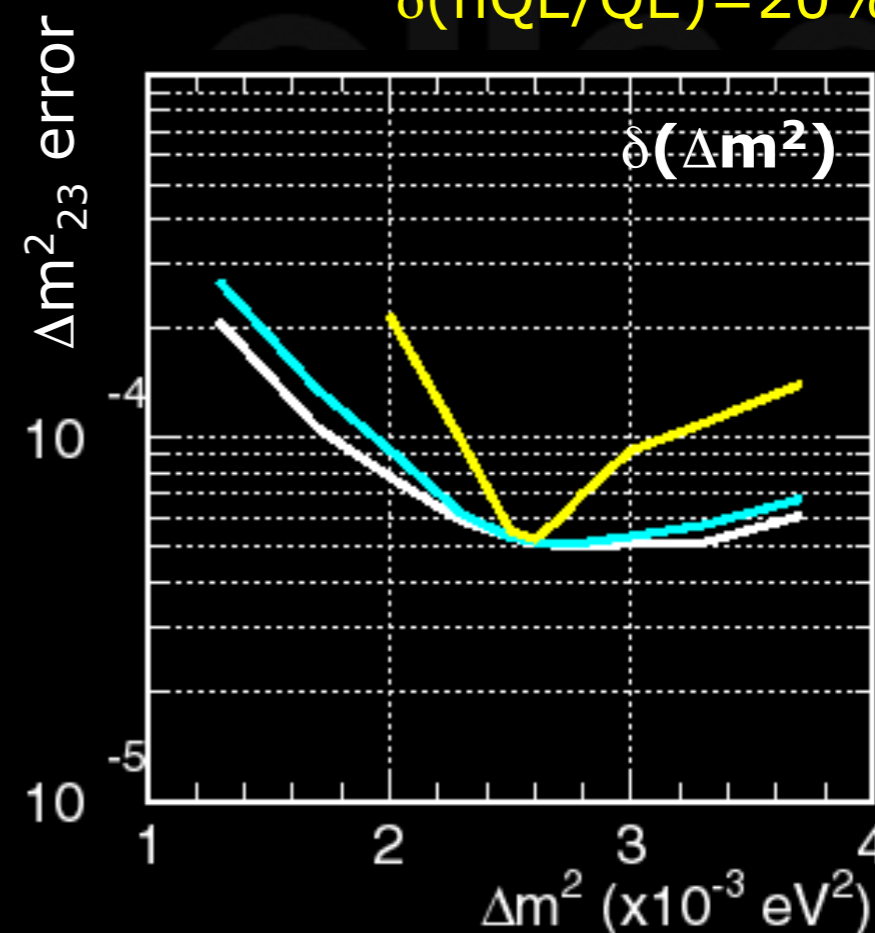
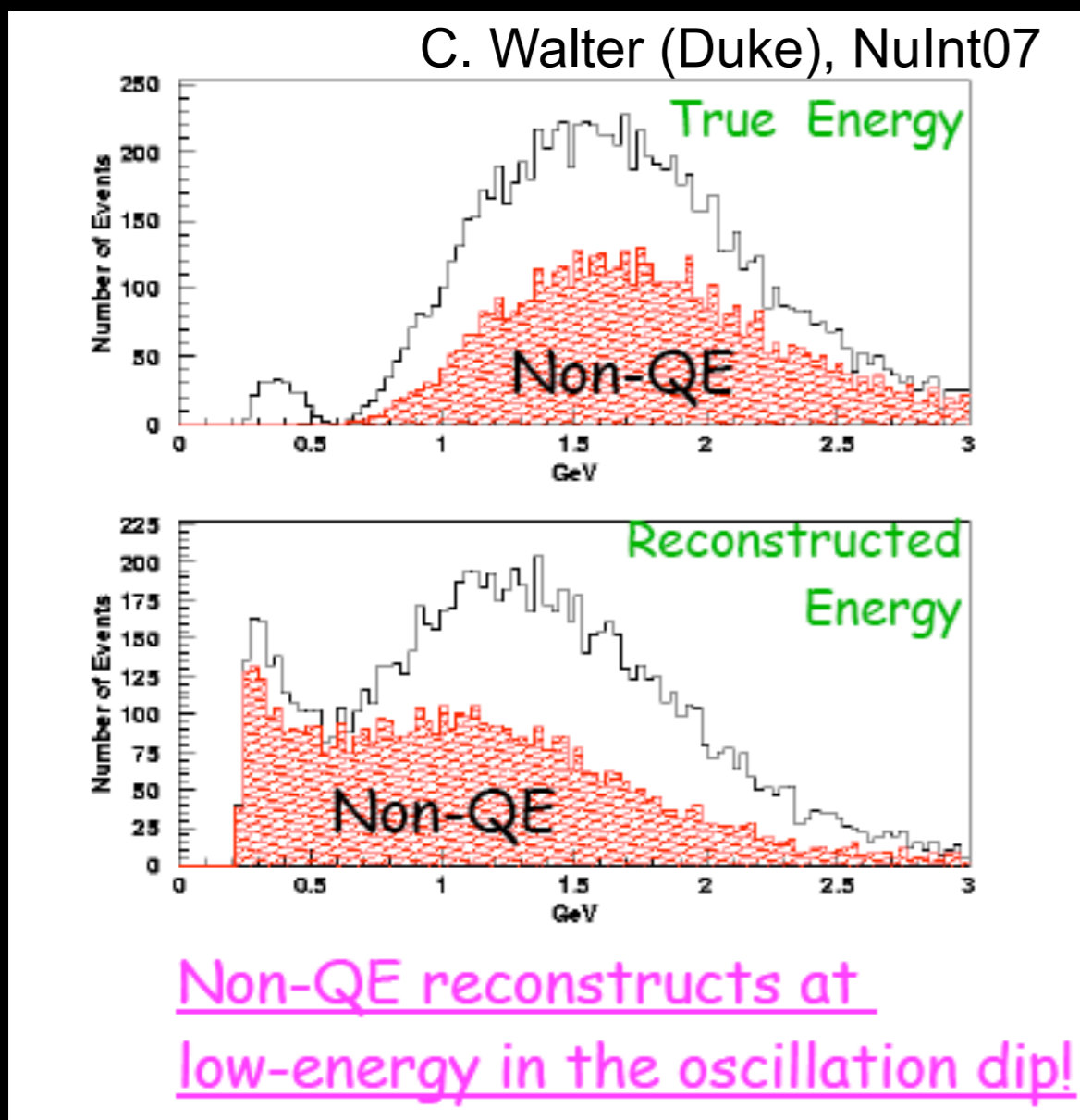


Need for CC σ_ν

In oscillation disappearance analysis,
CCQE = signal
CC1 π = background



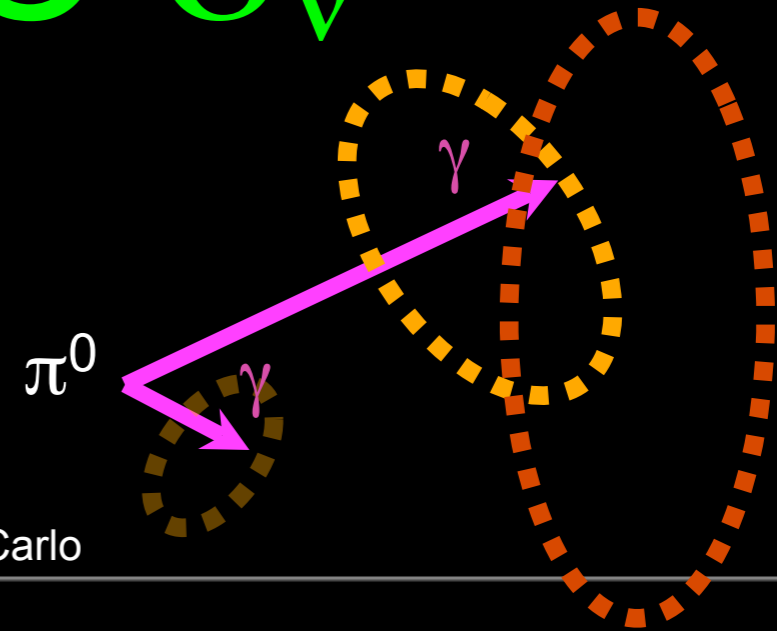
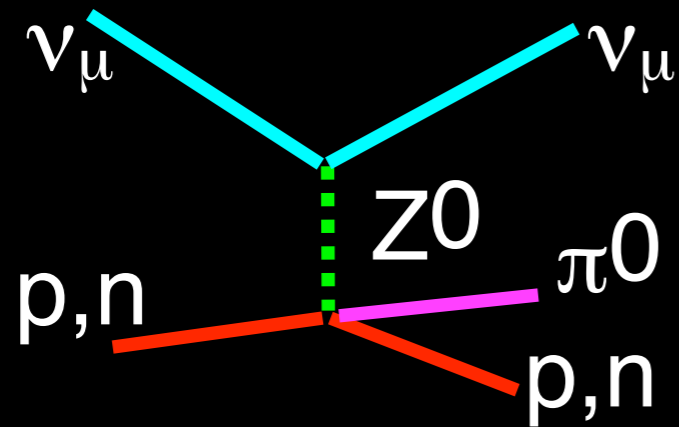
- stat. only
- $\delta(nQE/QE) = 5\%$
- $\delta(nQE/QE) = 20\%$



K. Hiraide

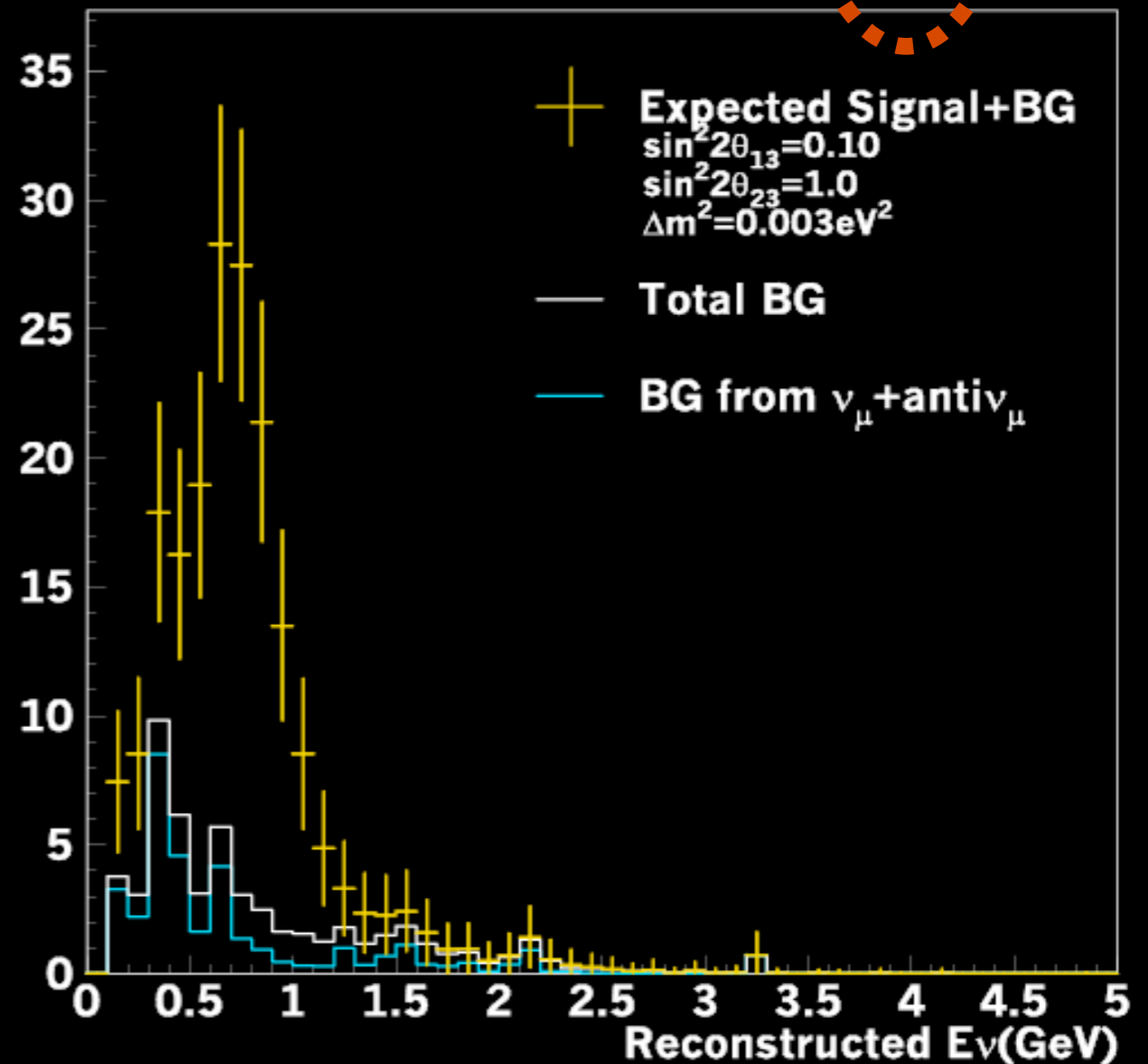
Goal: 5% uncertainty ($\sigma_{CC1\pi}/\sigma_{CCQE}$)

Need for NC σ_ν

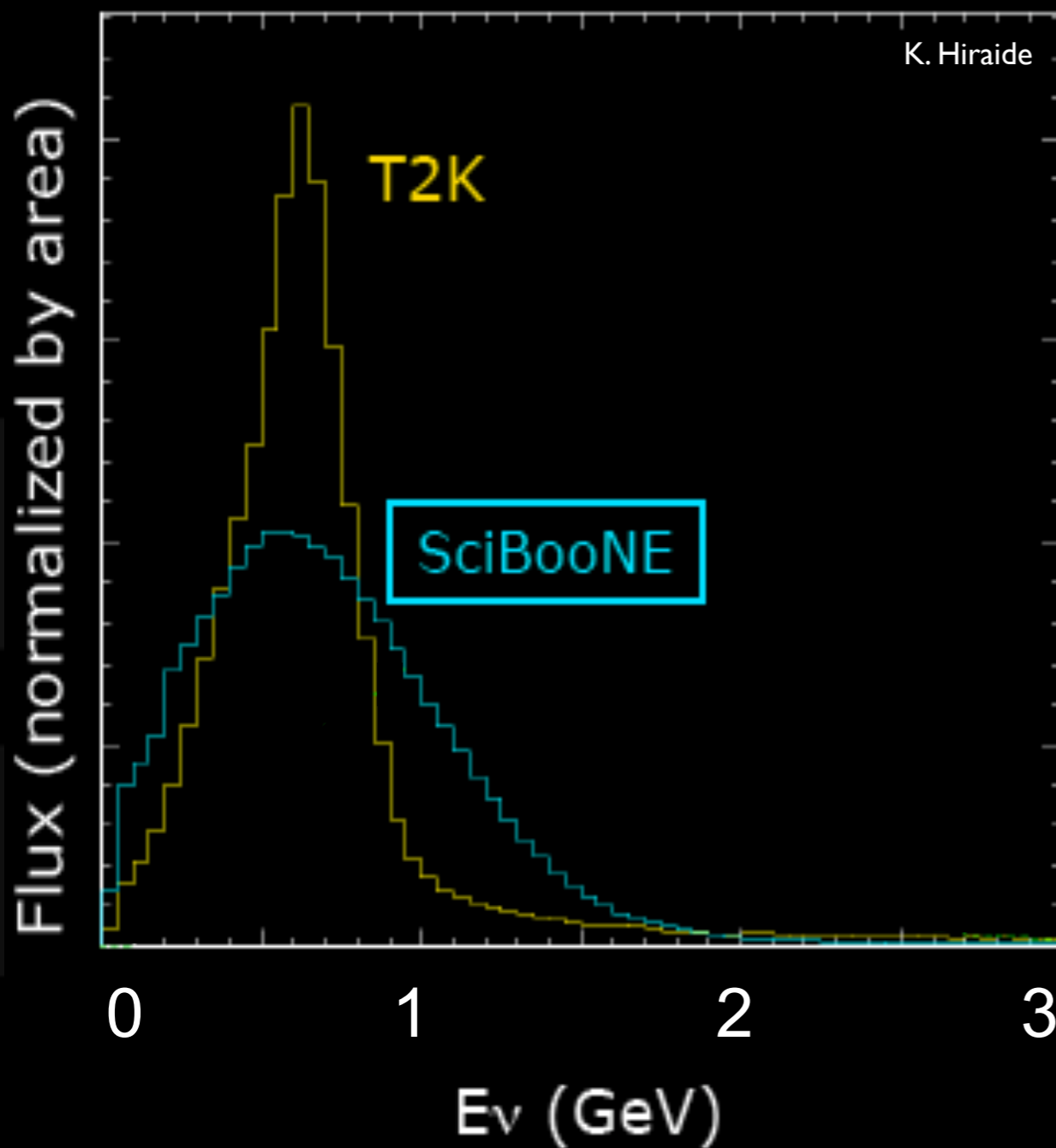


- Misidentified ν_μ NC1 π^0 events form major ν_e appearance background
- Currently $\sim 20\%$ uncertainty
- Goal: 10% NC1 π^0 uncertainty

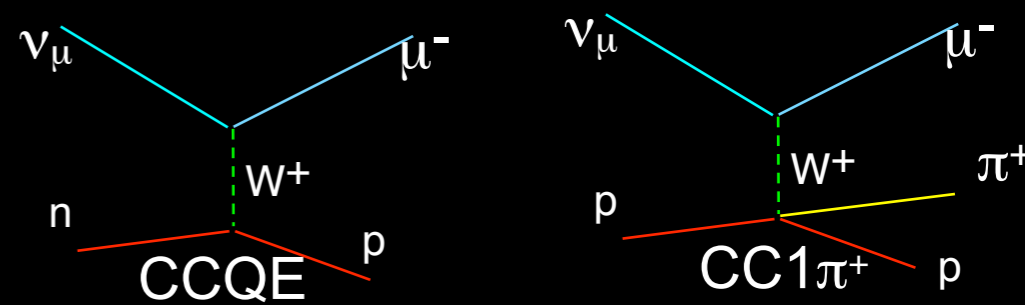
T2K Monte Carlo



Let's measure σ_ν



- SciBooNE well matched to T2K

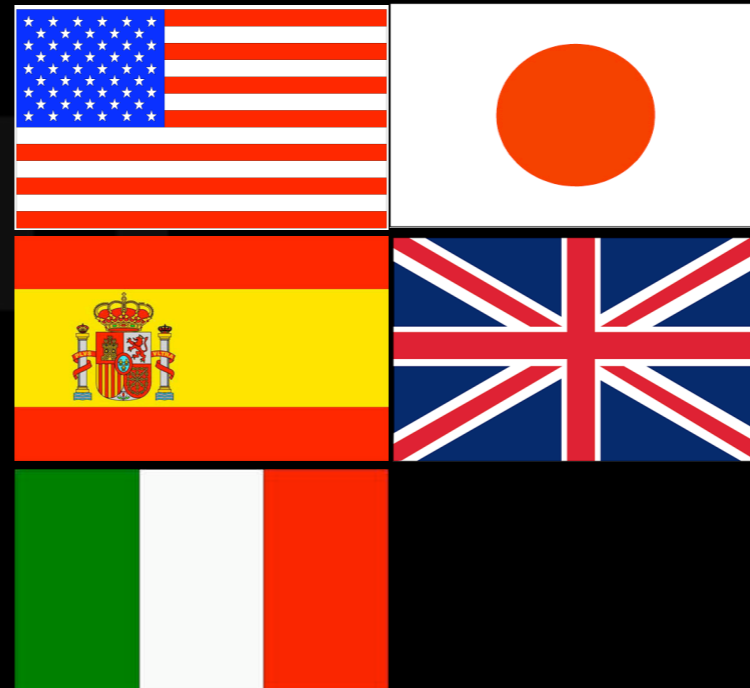


Outline

- Motivation
- Tools & Strategy
- T2K
 - SciBooNE
- Looking Ahead

SciBooNE collaboration

- Universitat Autònoma 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



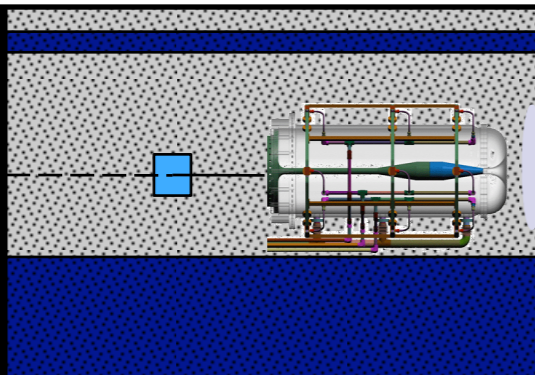
Spokespersons:
T.Nakaya, Kyoto University
M.O.Wascko, Imperial College

Overview



Fermilab Visual Media Services

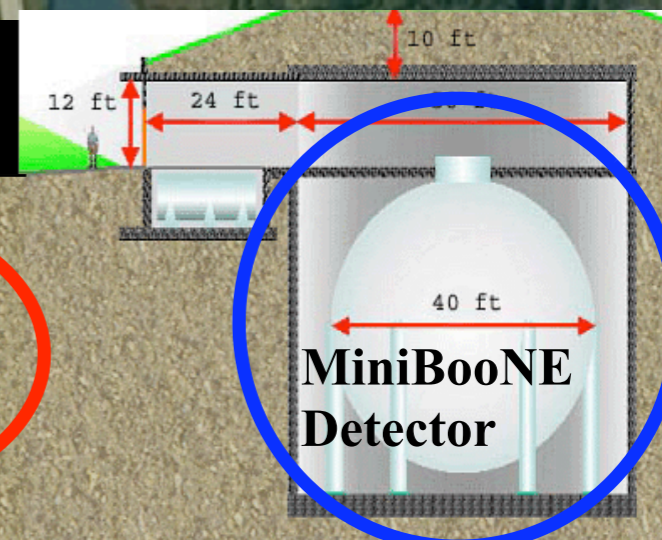
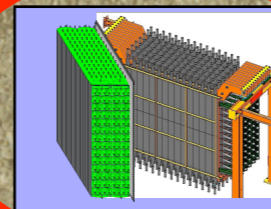
Booster ν beam



Decay region

50 m

SciBooNE



MiniBooNE
Detector

100 m

440 m

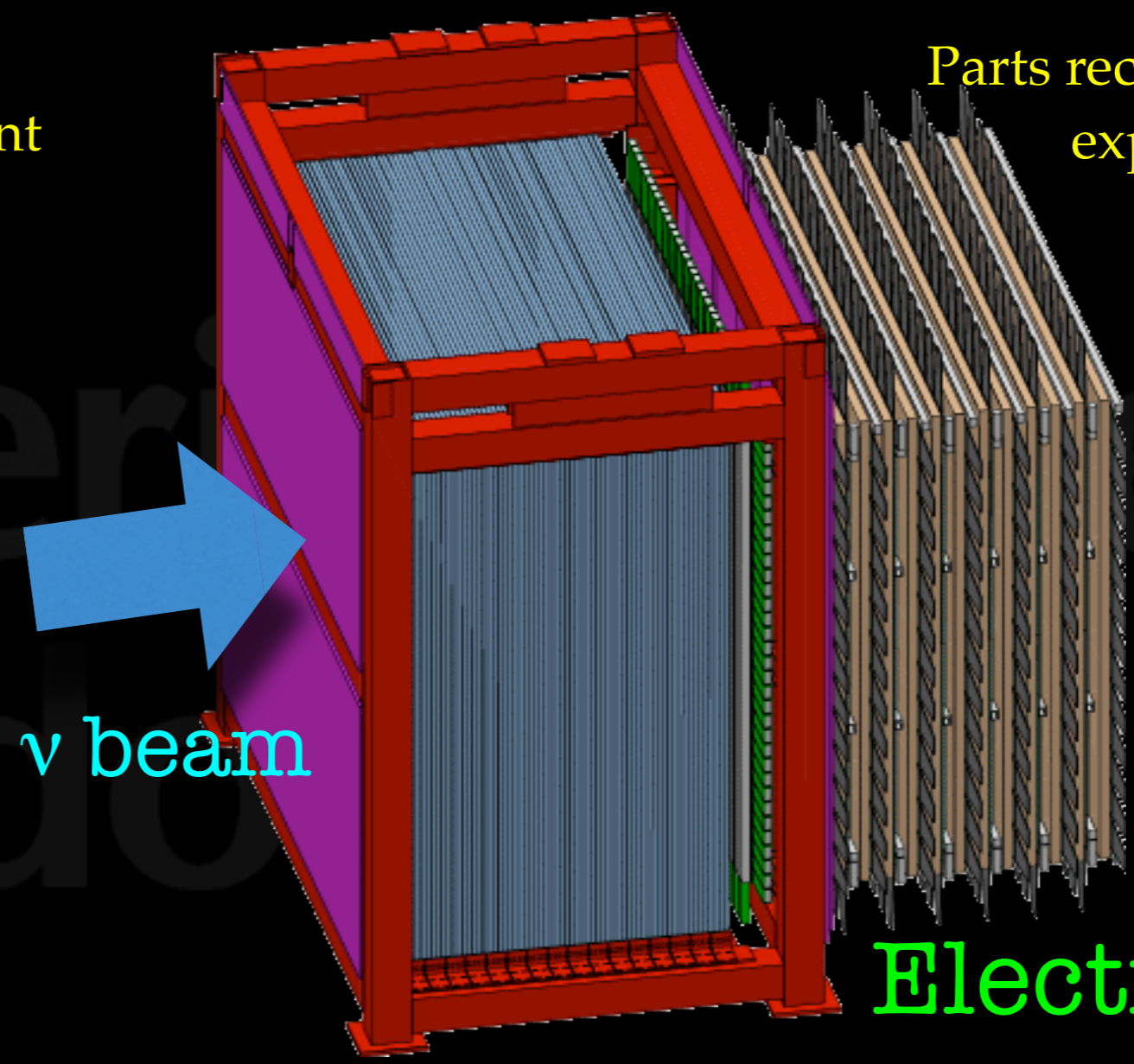
SciBooNE Detector

Scintillator Bar
(SciBar)

Used in K2K experiment

Muon Range
Detector (MRD)

Parts recycled from past
experiments



ν beam

Electron
Catcher (EC)

Used in CHORUS, HARP and K2K

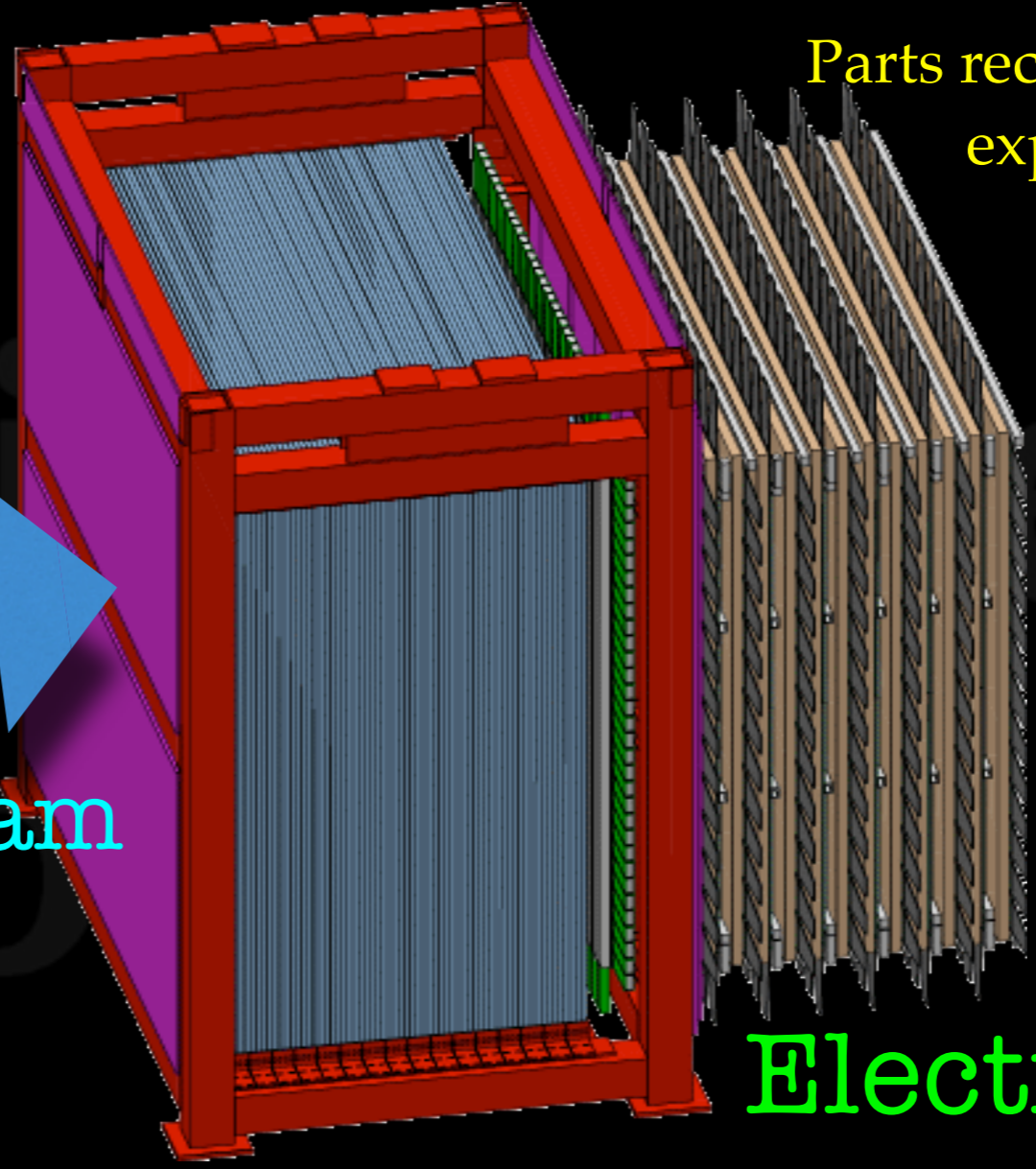
SciBooNE Detector

Scintillator Bar
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Muon Range
Detector (MRD)

Parts recycled from past
experiments



DOE-wide Pollution Prevention
Star (P2 Star) Award



ν beam

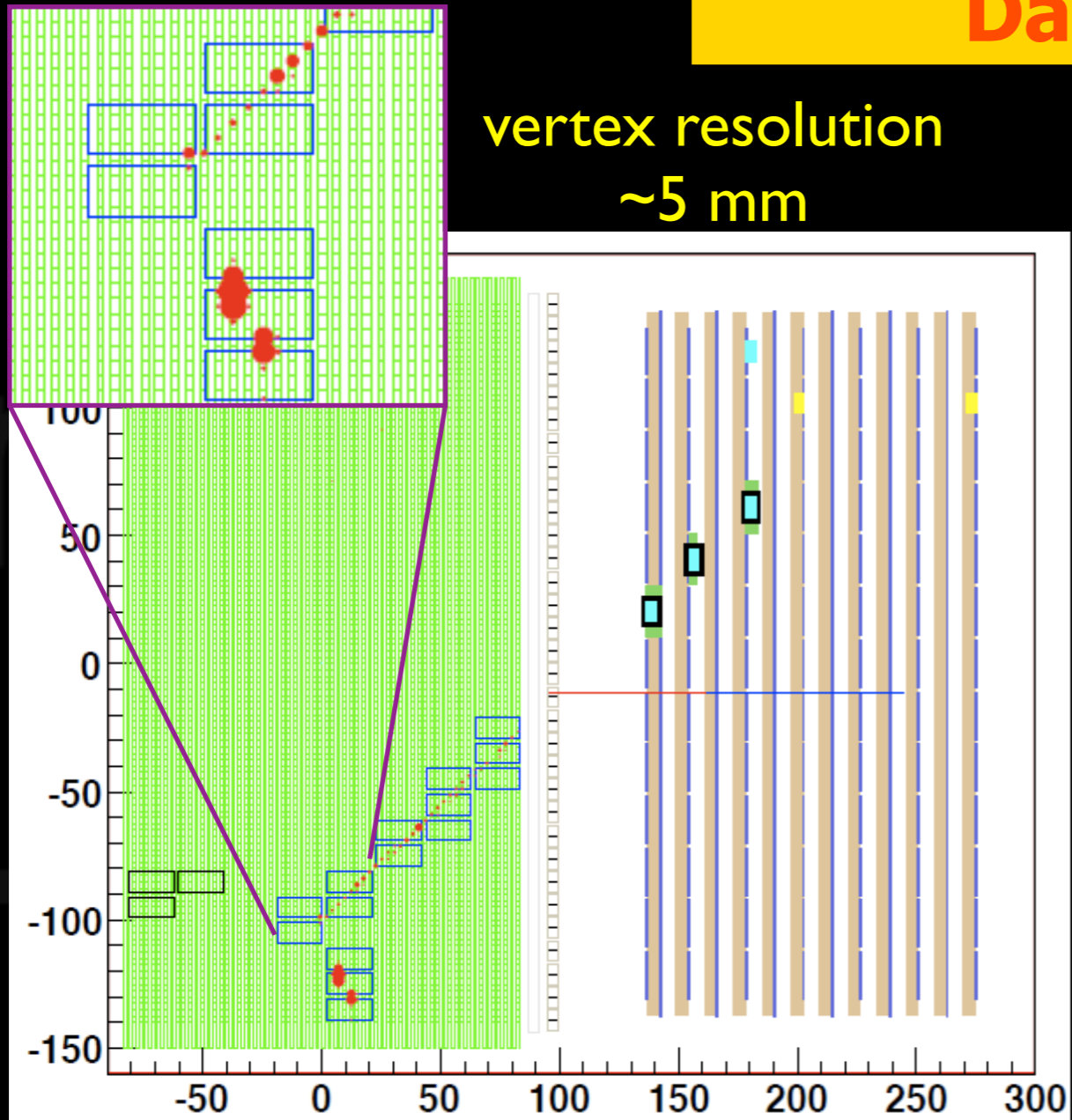
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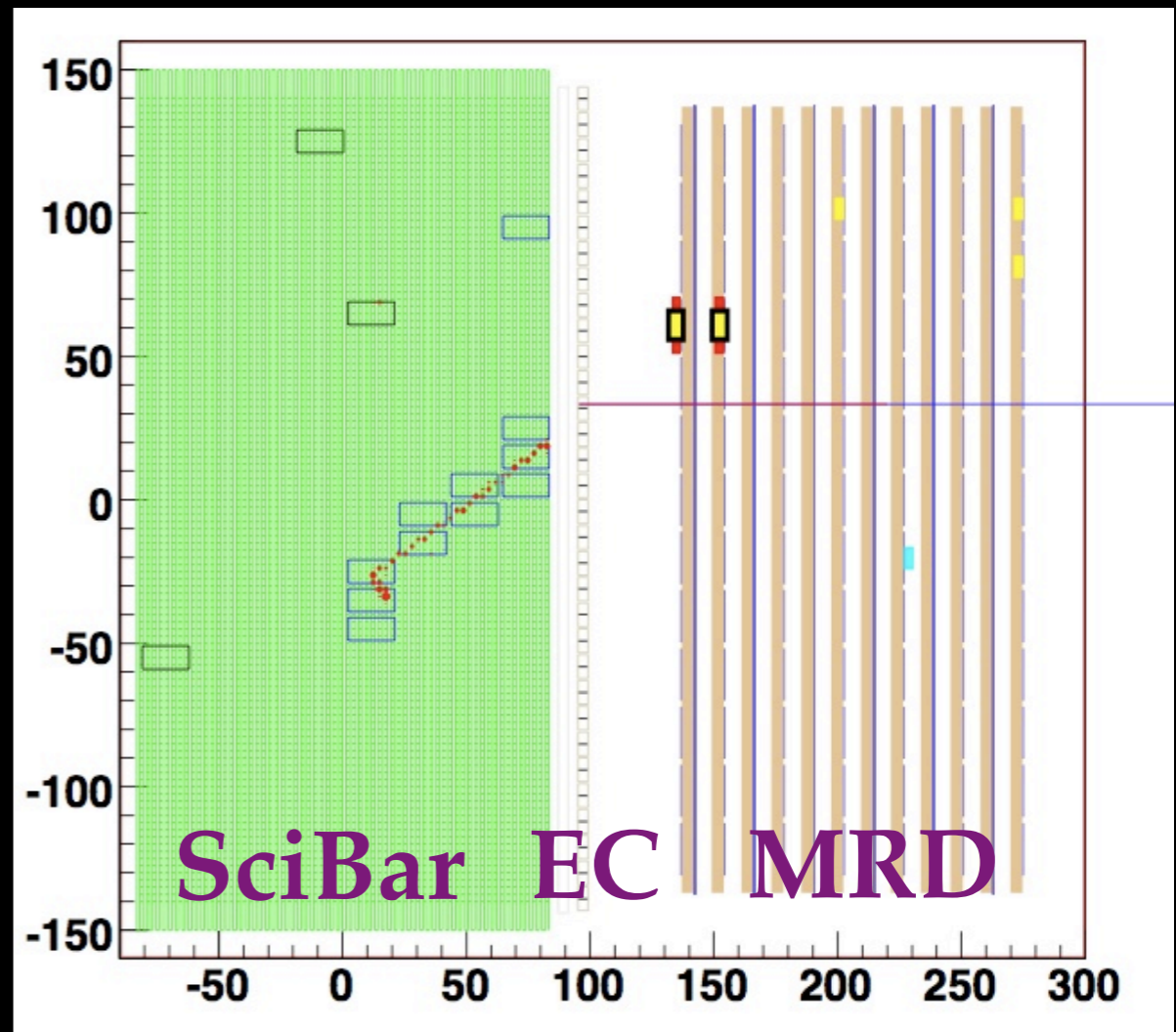
Neutrino event displays

**Real SciBooNE
Data**

● ADC hits (area \propto charge)
□ TDC hits (32ch "OR")



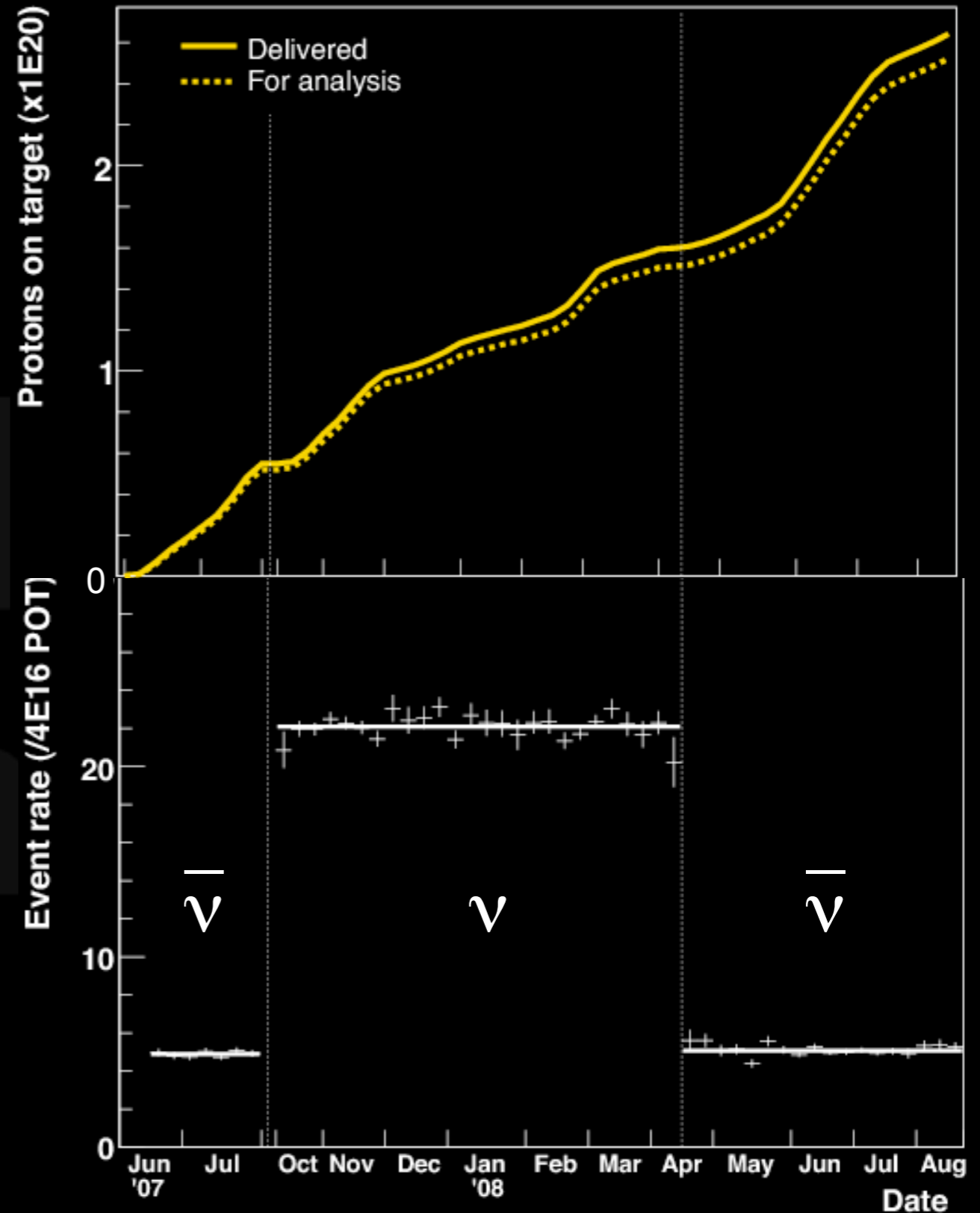
anti- ν_μ CC-QE candidate
 $(\bar{\nu}_\mu + p \rightarrow \mu + n)$



ν_μ CC-QE candidate
 $(\nu_\mu + n \rightarrow \mu + p)$

SciBooNE Performance

SciBooNE installed
and commissioned
in spring 2007



Many analyses!

- Oscillation searches with MiniBooNE
- Cross Sections
 - CCQE cross sections
 - Two separate data samples to expand phase space acceptance
 - Coherent Pion Production
 - Incoherent (resonant) $CC1\pi^+$
 - Neutral current elastic
 - Δs
 - $CC1\pi^0$ cross section
 - A-dependence
 - Antineutrino analyses!
- “Exotic” analyses
 - Short range nuclear correlations

11 PhD students

First publication Dec 2008
PhysRevD 78 112004

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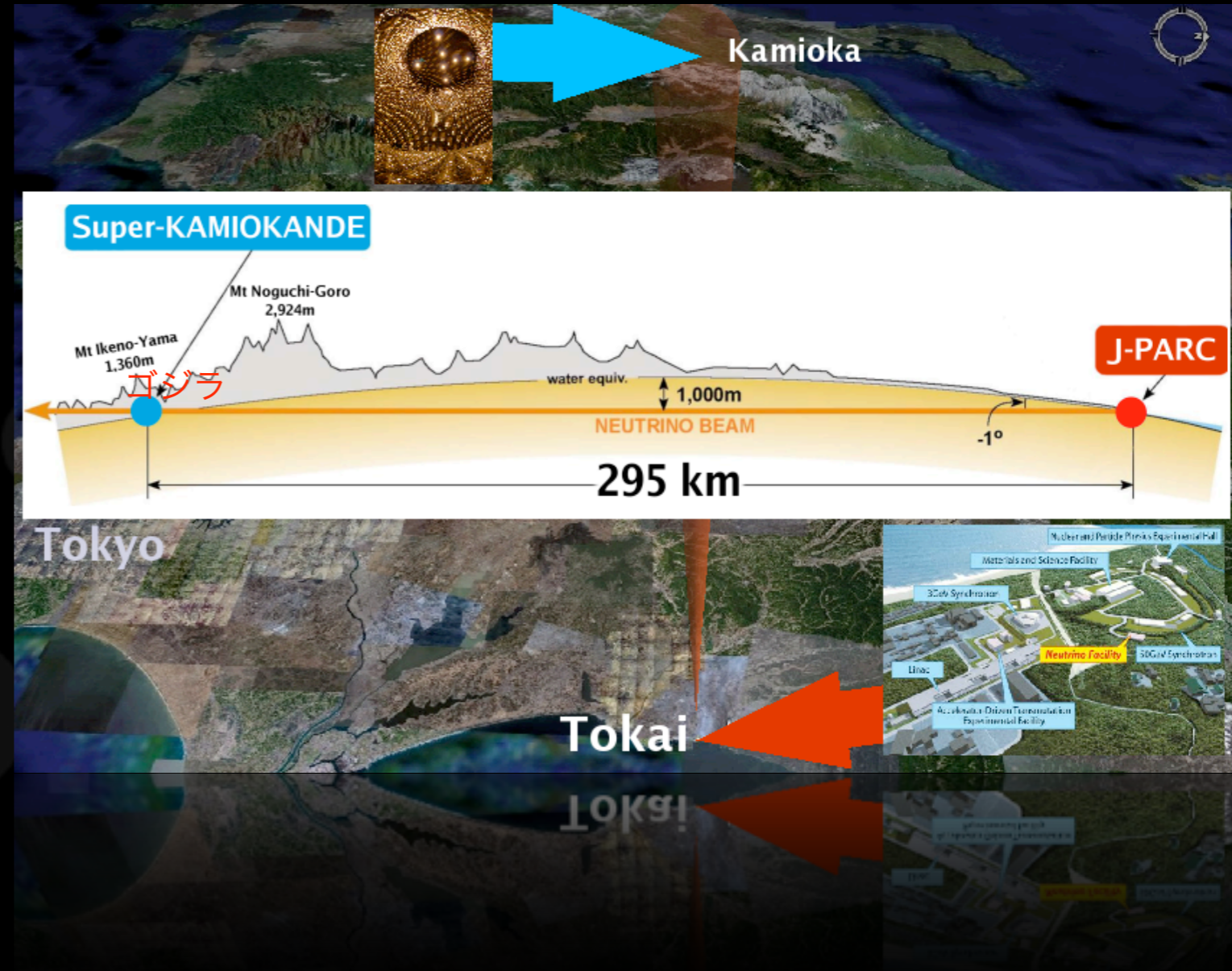
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Outline

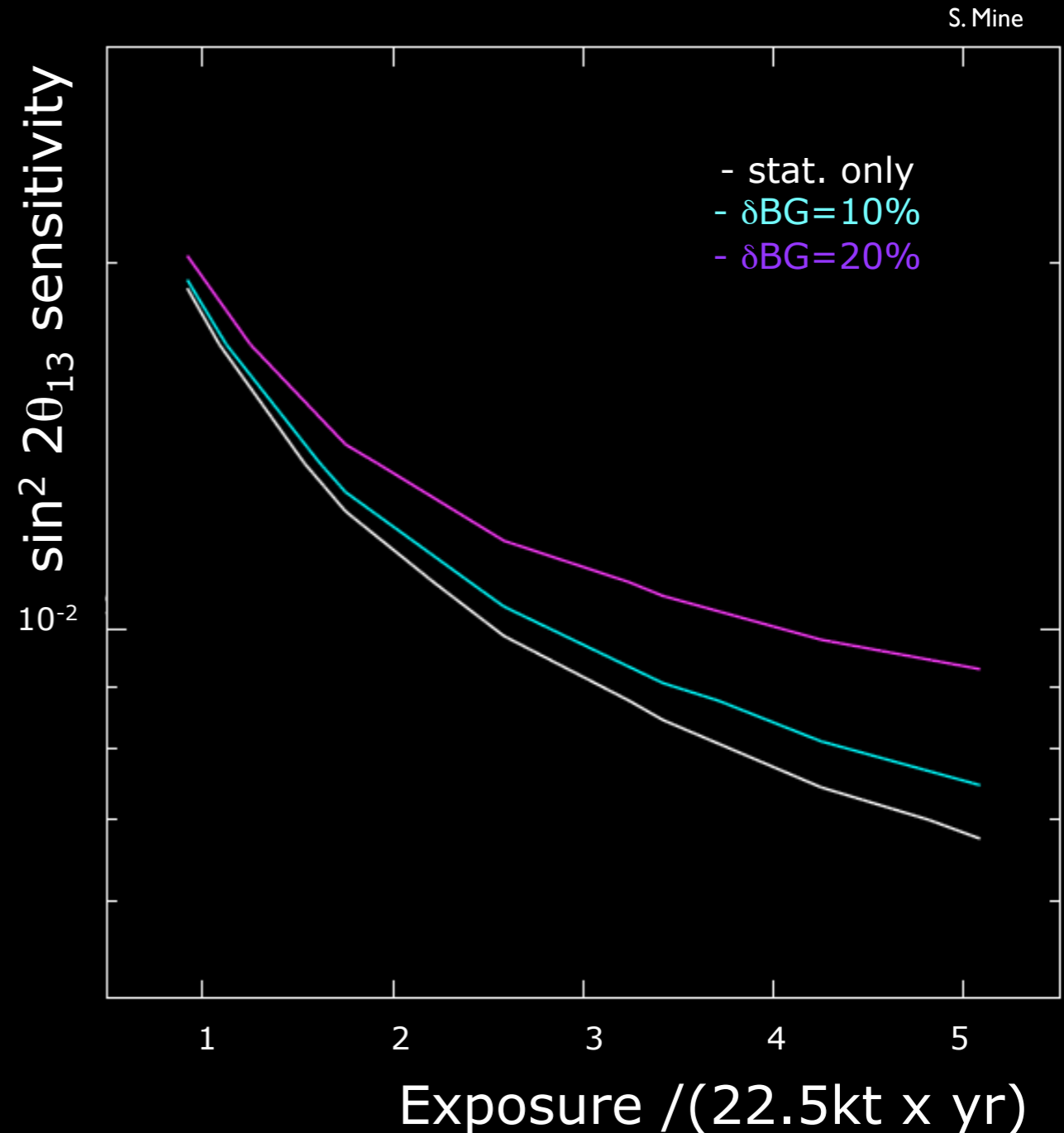
- Motivation
- Tools & Strategy
- T2K
 - SciBooNE
- Looking Ahead



T2K

Phase I: measure θ_{13}

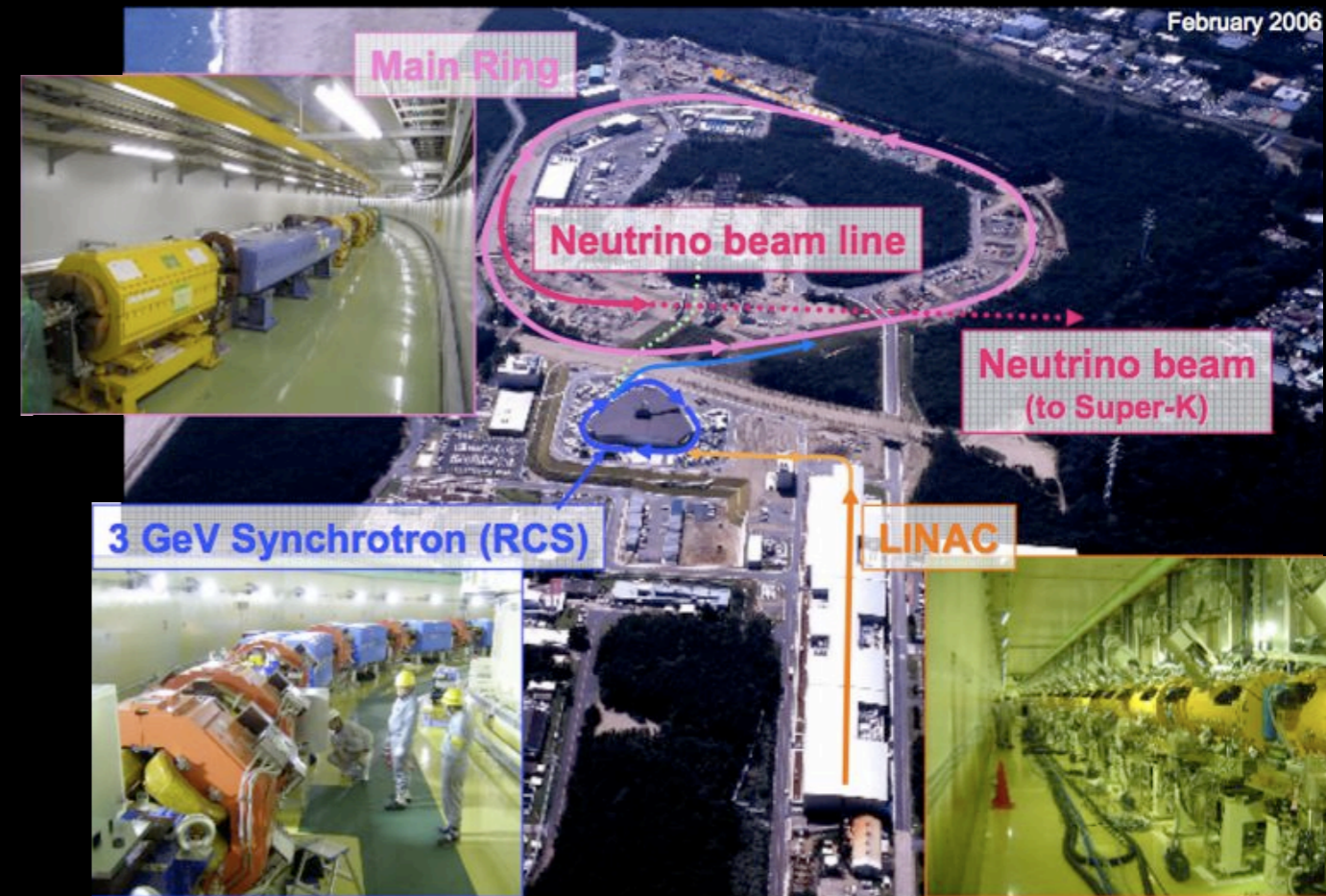
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 - SciBooNE (& MiniBooNE) data used to tune MCs
- T2K beam commissioned in April
 - Full power (0.75MW) soon
- Near detectors installed and running in 2009 (2010)



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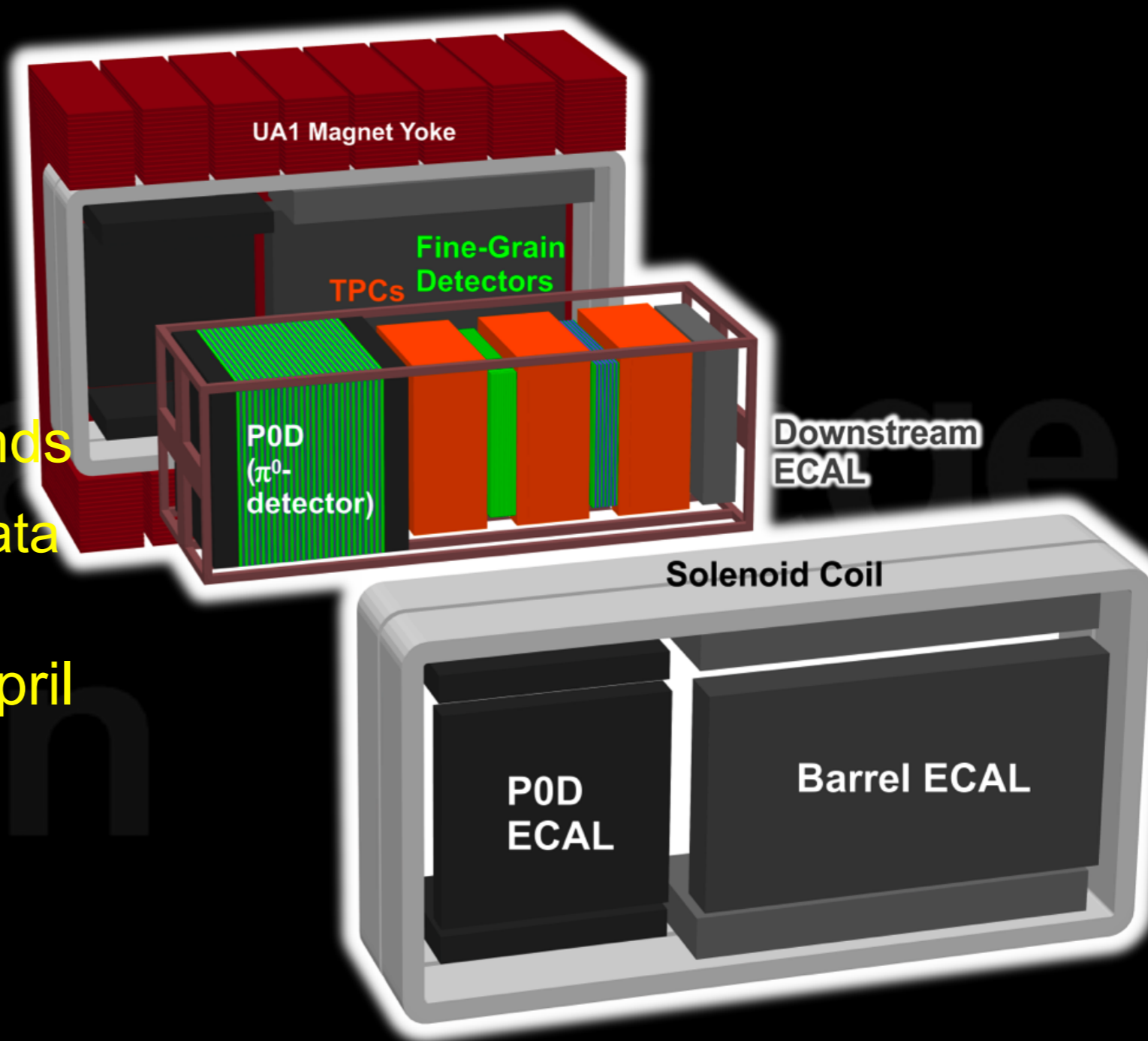
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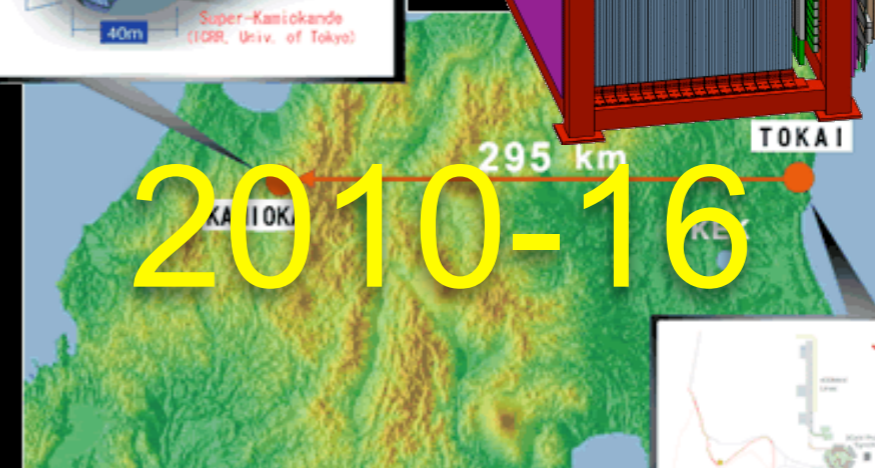
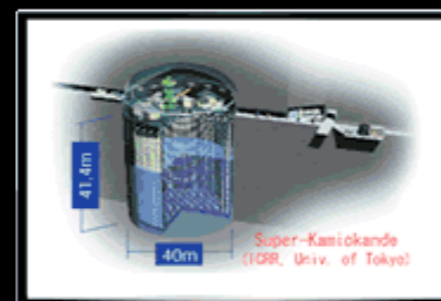
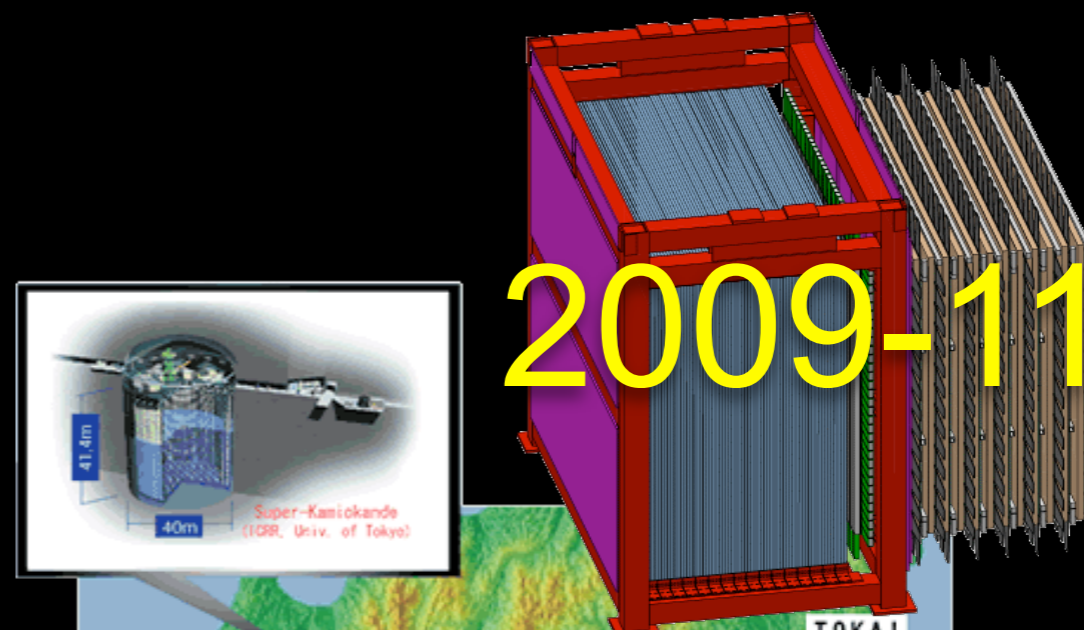
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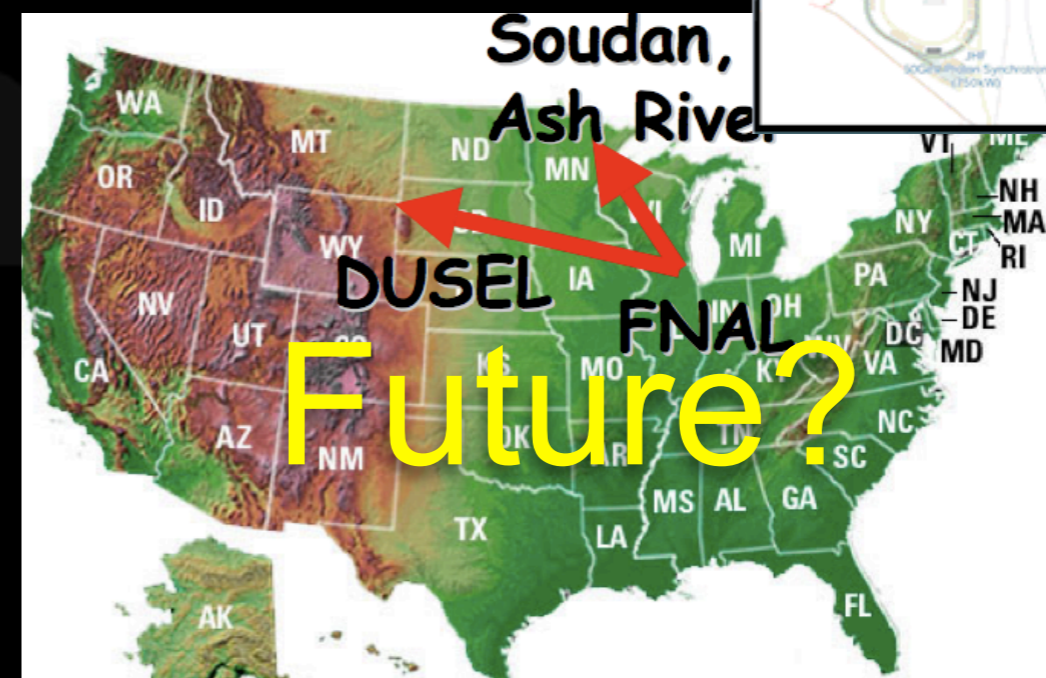
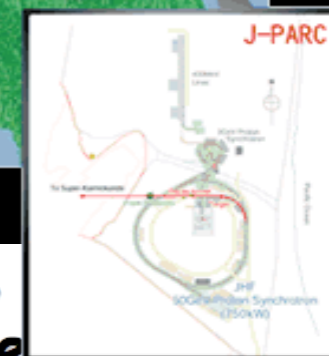


Can we measure CPV?

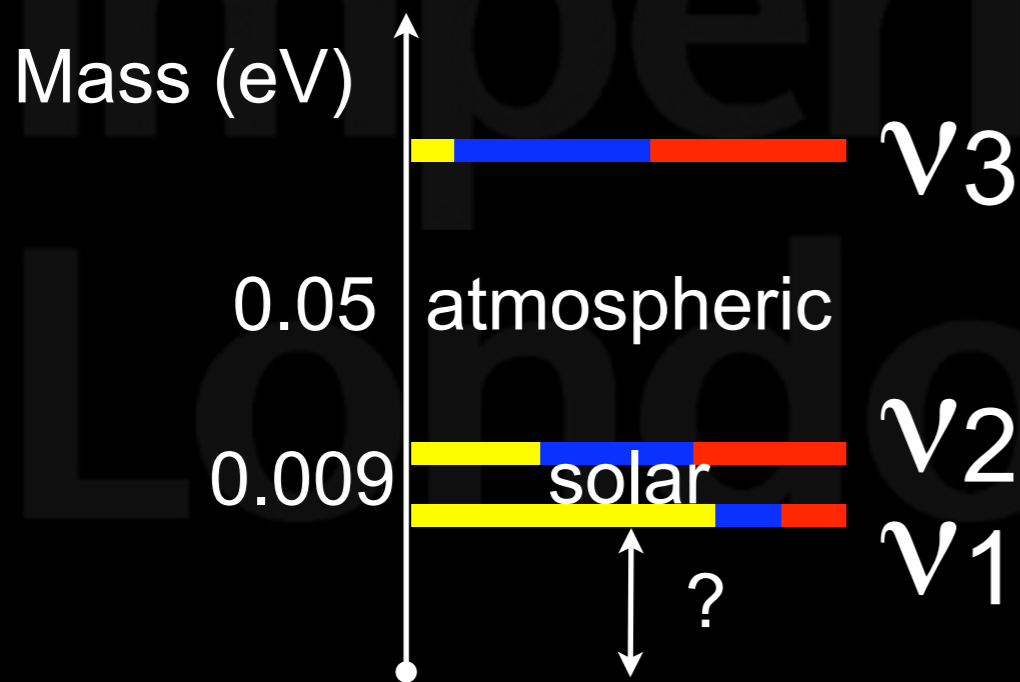
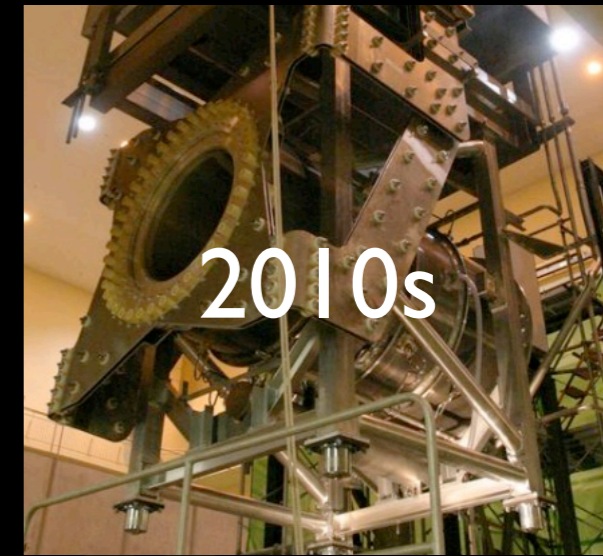
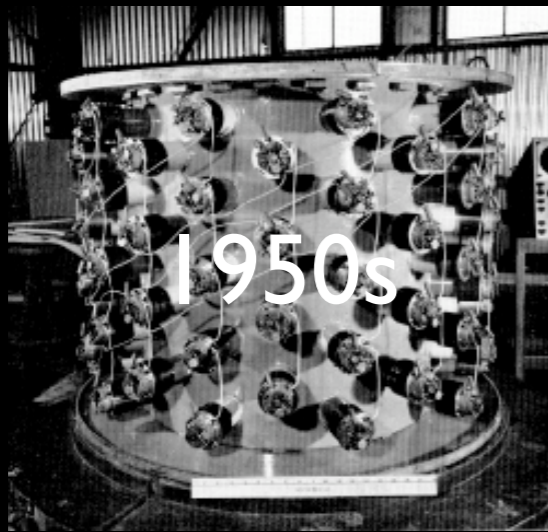
- 2010 - SciBooNE ν results
- 2010 - T2K first results
- 2011 - SciBooNE $\bar{\nu}$ results complete
- 2016 - T2K final results on θ_{13}
 - (& NOvA & Reactors)
- Farther Future - Phase II superbeam experiment
 - θ_{13} or $\bar{\nu}_{\mu} \rightarrow \bar{\nu}_{e}$



2010-16



Summary: Open Questions



- Neutrinos have mass!
- Moving from discovery to precision era
- Details of neutrino mixing?
- Do they violate CP?
- What is the mass hierarchy?
- What is the absolute scale?
- Are they Majorana or Dirac?

Worldwide program of experiments to answer these!

Conclusion

- Neutrino physics is entering a precision era
 - Including ν -nucleus scattering!
- T2K beginning this year
 - θ_{13} next open question to be tackled
- SciBooNE ran successfully at Fermilab in 2007-8
 - Collected high quality data needed by future experiments



There's never been a better time for neutrino physics!

Conclusion

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There's never been a better time for neutrino physics!

Join us!

Backups

Imperial College
London

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 \Rightarrow 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**

