Neutrino Physics – Past, Present, and Future

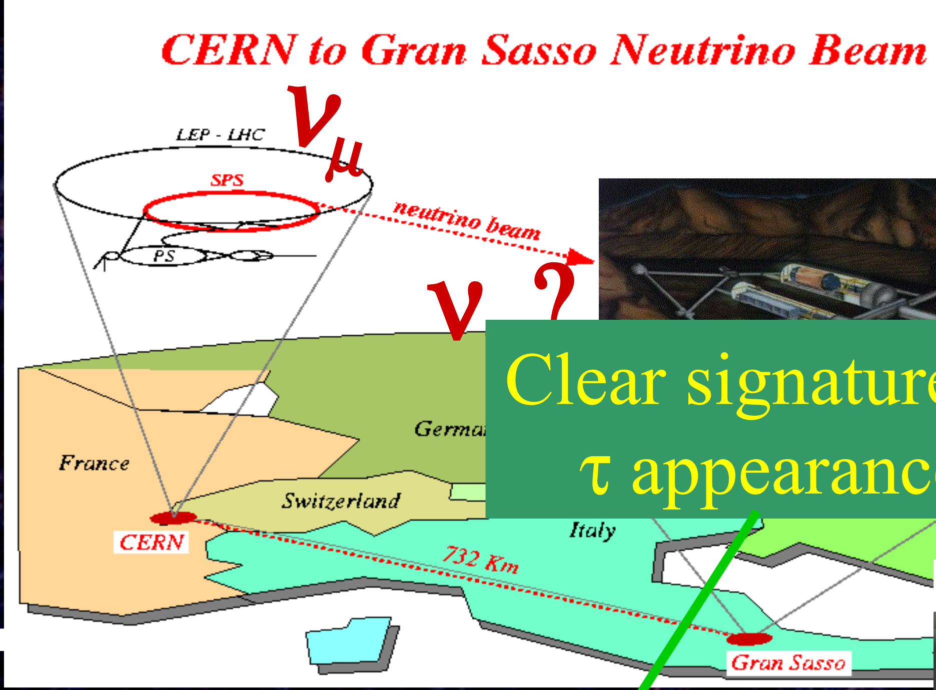
Cracow School
Zakopane
June 20-21, 2007

Dave Wark
Imperial/RAL

Science & Technology Facilities Council

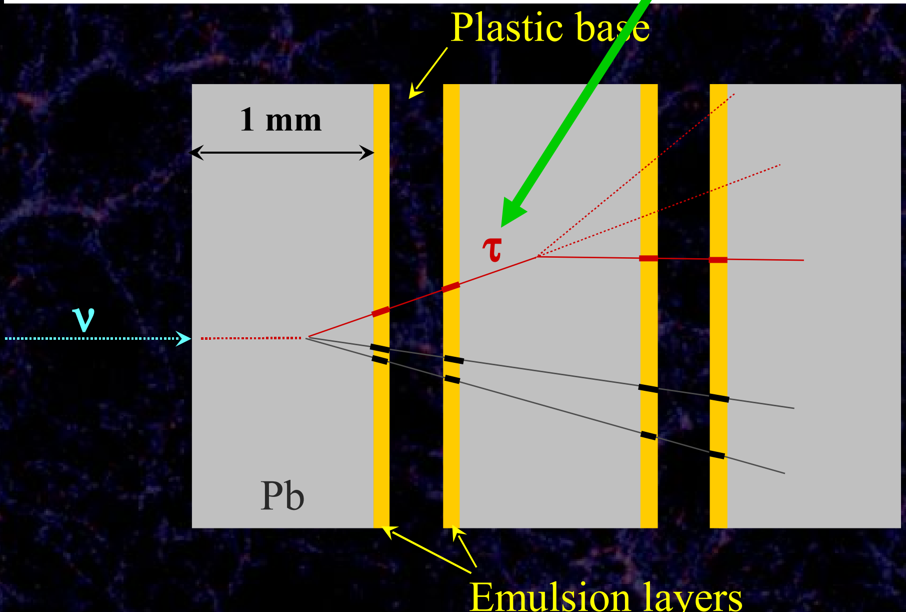
Imperial College London

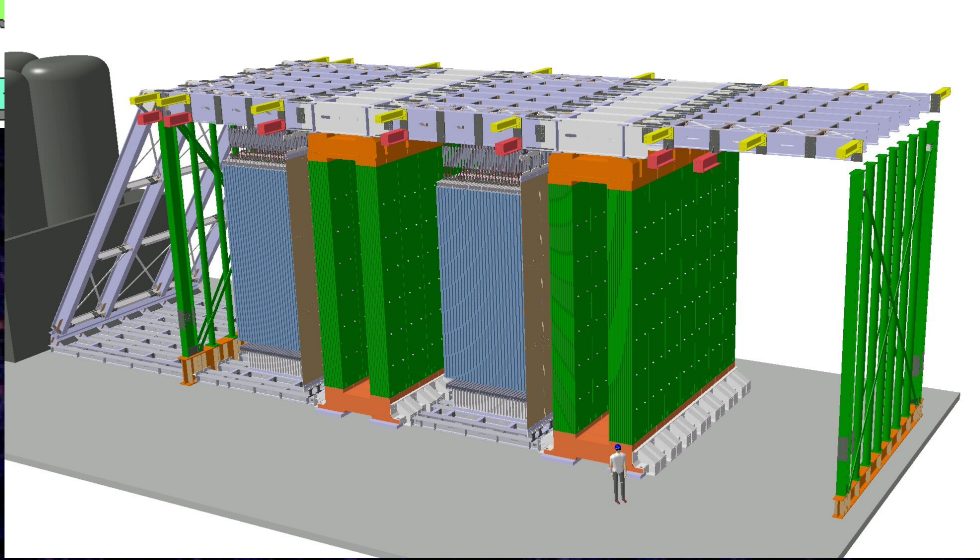
CNGS and OPERA



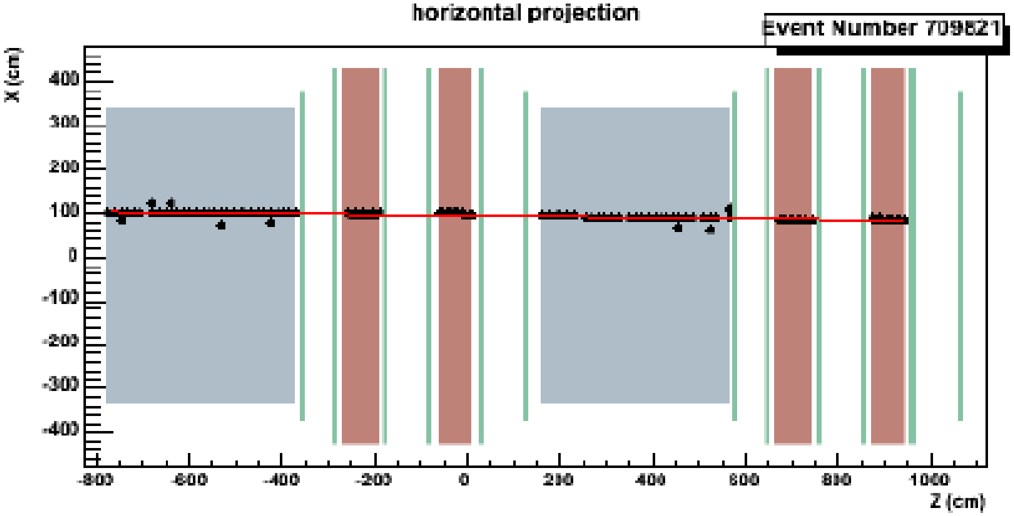
OPERA

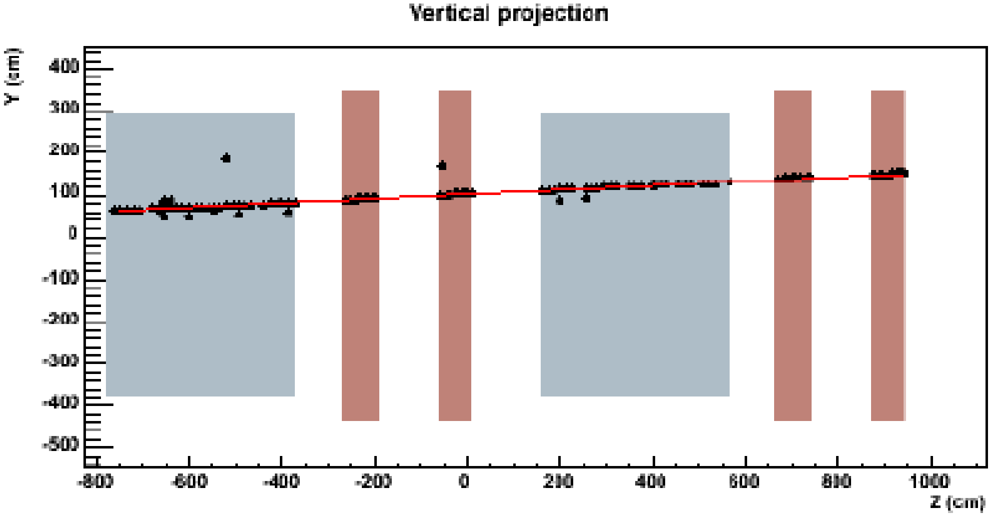
Clear signature of τ appearance





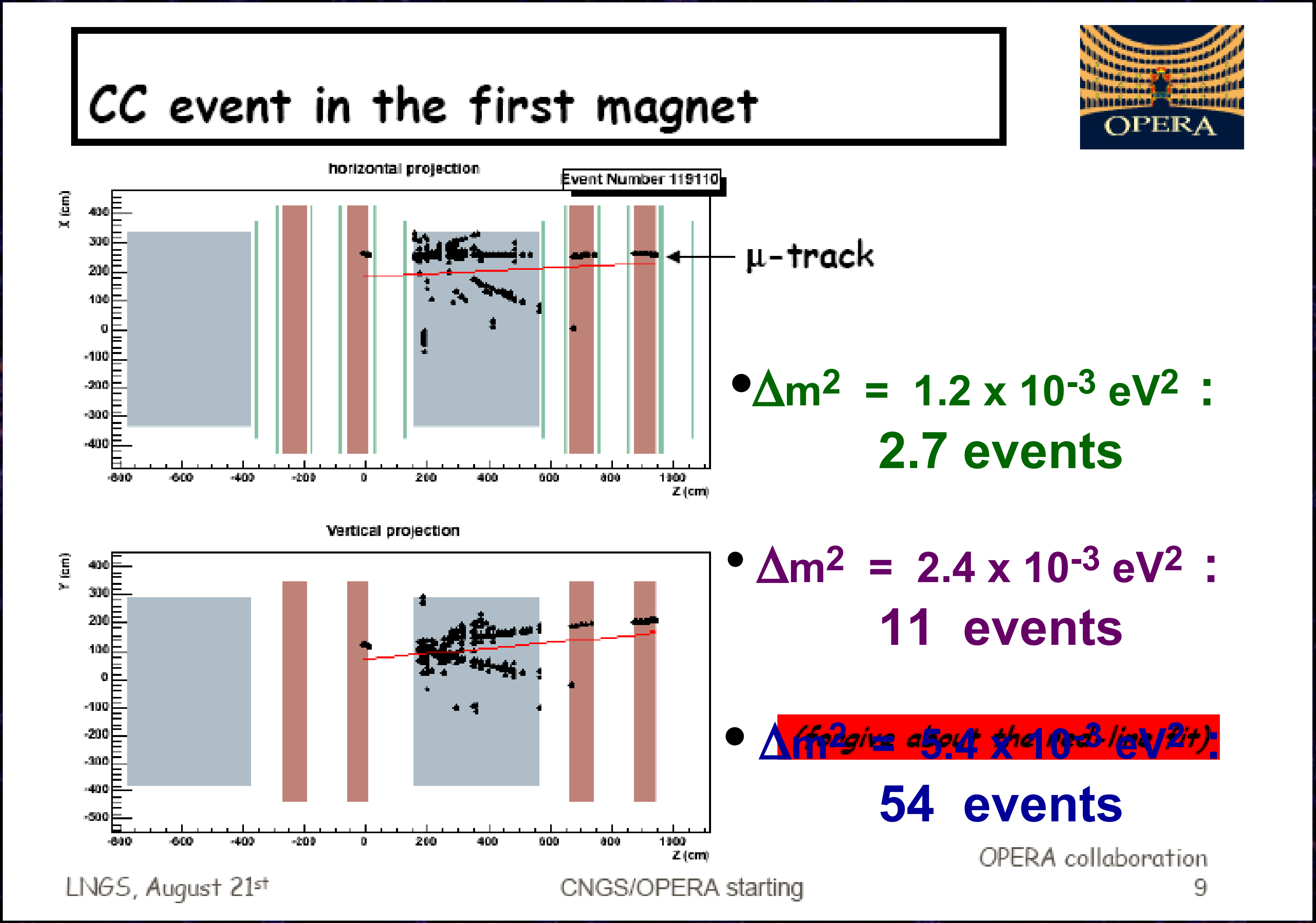
First Running has begun!





Beam event

CC event originated
from material in front of the
detector (BOREXINO, rocks)



CC event in the first magnet

- $\Delta m^2 = 1.2 \times 10^{-3}\ \mathrm{eV}^2$:
  2.7 events
- $\Delta m^2 = 2.4 \times 10^{-3}\ \mathrm{eV}^2$:
  11 events
- $\Delta m^2 = 5.4 \times 10^{-3}\ \mathrm{eV}^2$:
  (forgive about the red-line fit)
  54 events

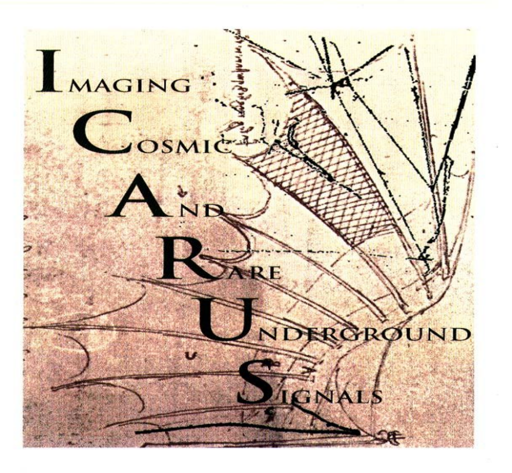
OPERA collaboration

LNGS, August 21st

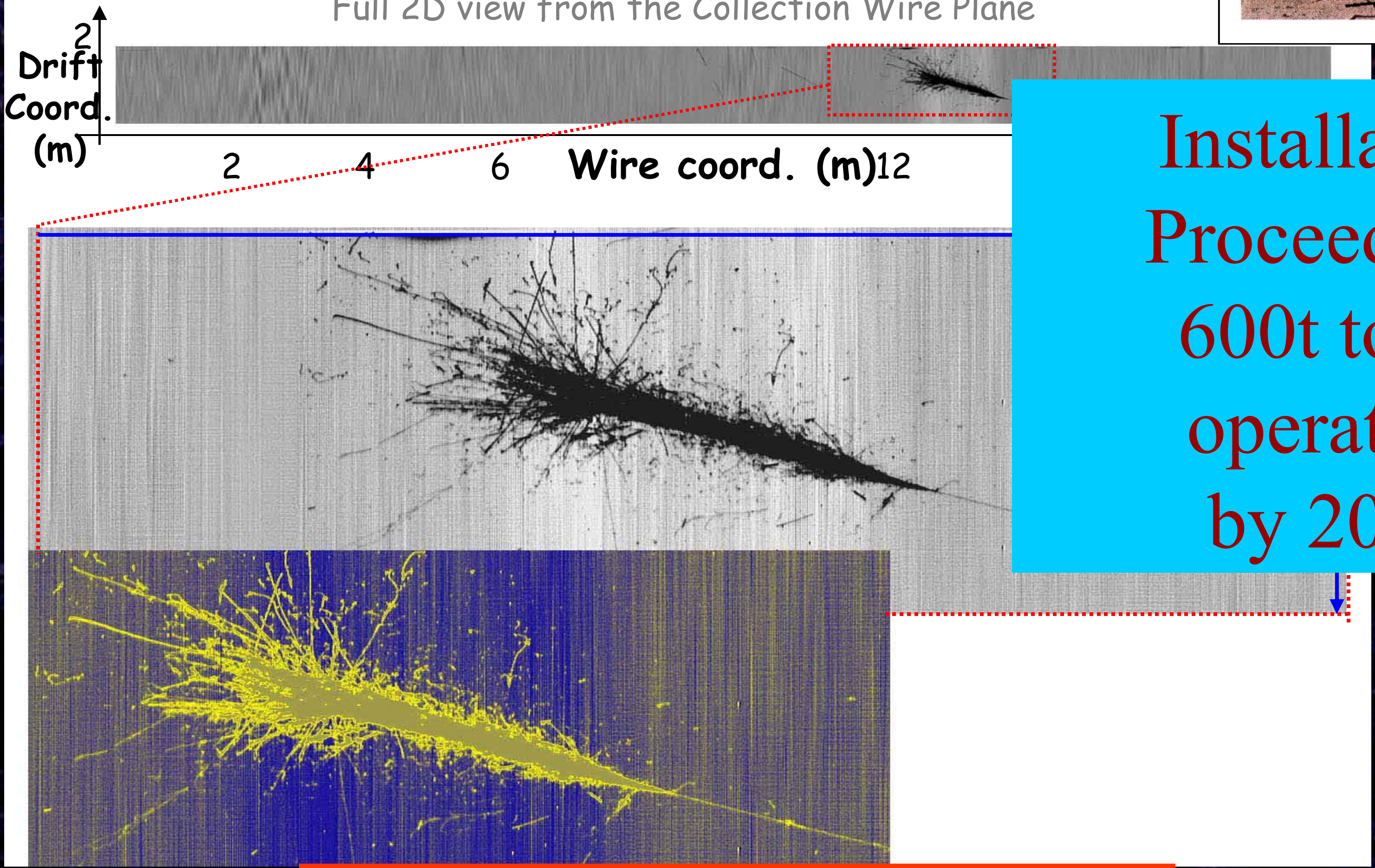
CNGS/OPERA starting

9

Slides from Yves Declais



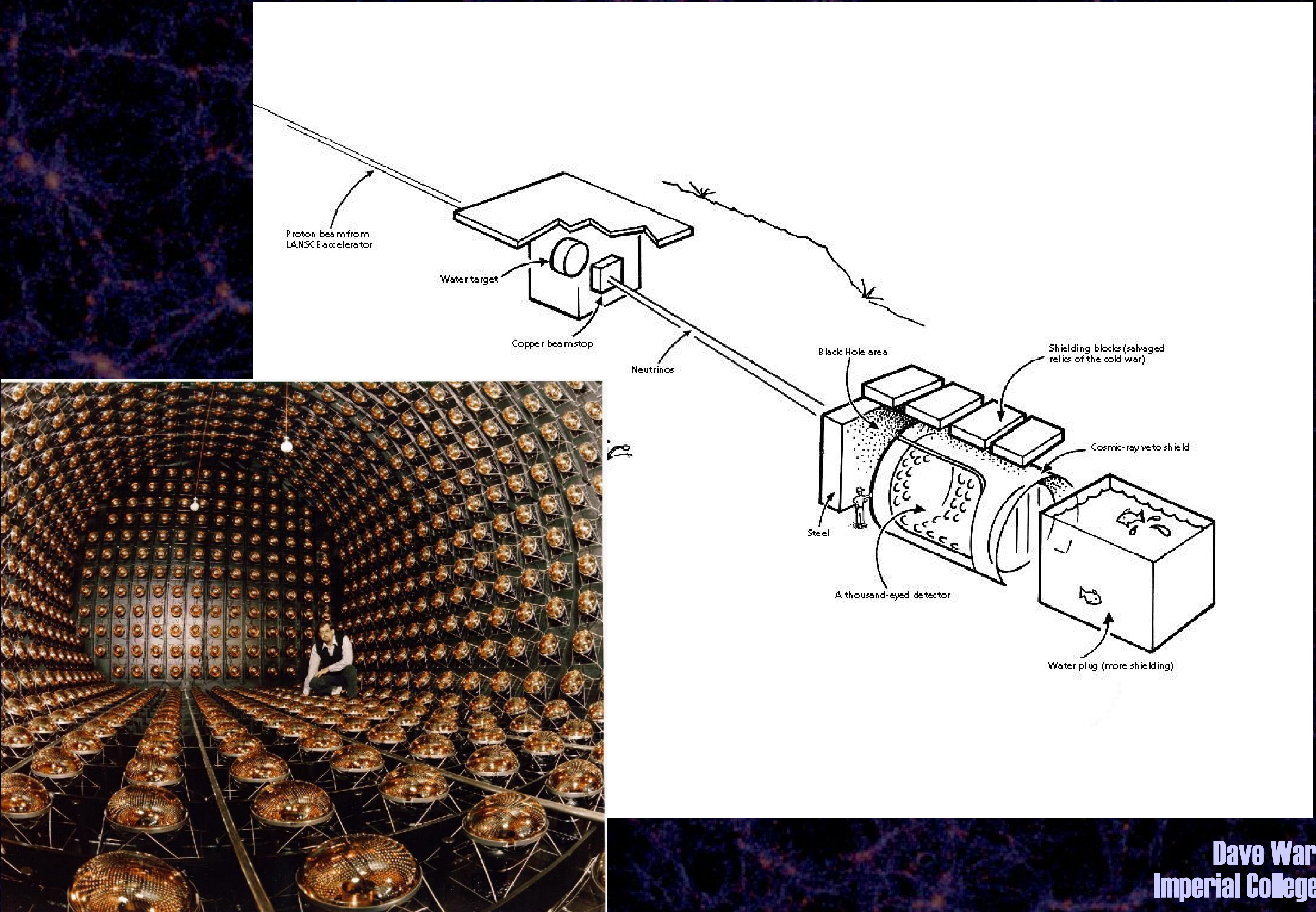
Full 2D view from the Collection Wire Plane



Installation Proceeding!
600t to be operating by 2008

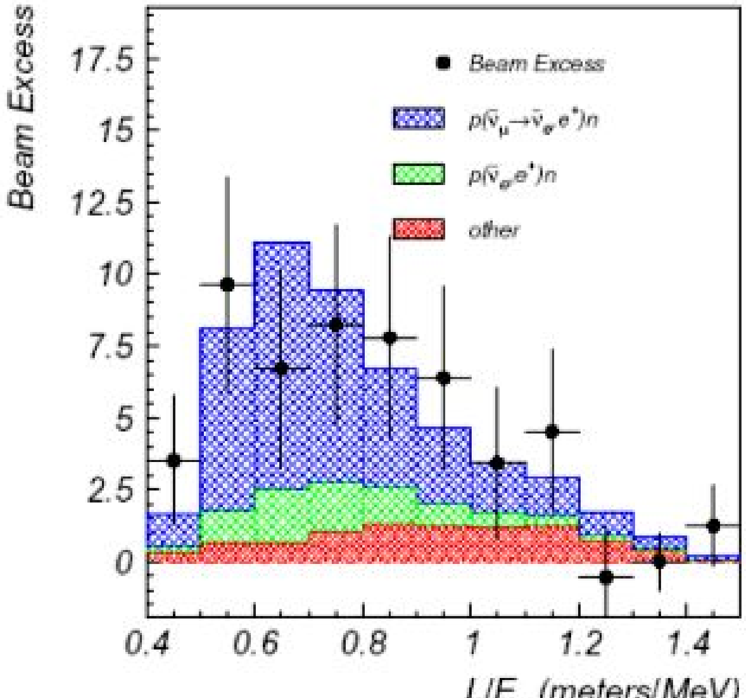
T600 test @ Pv: Run 308 - Evt 7

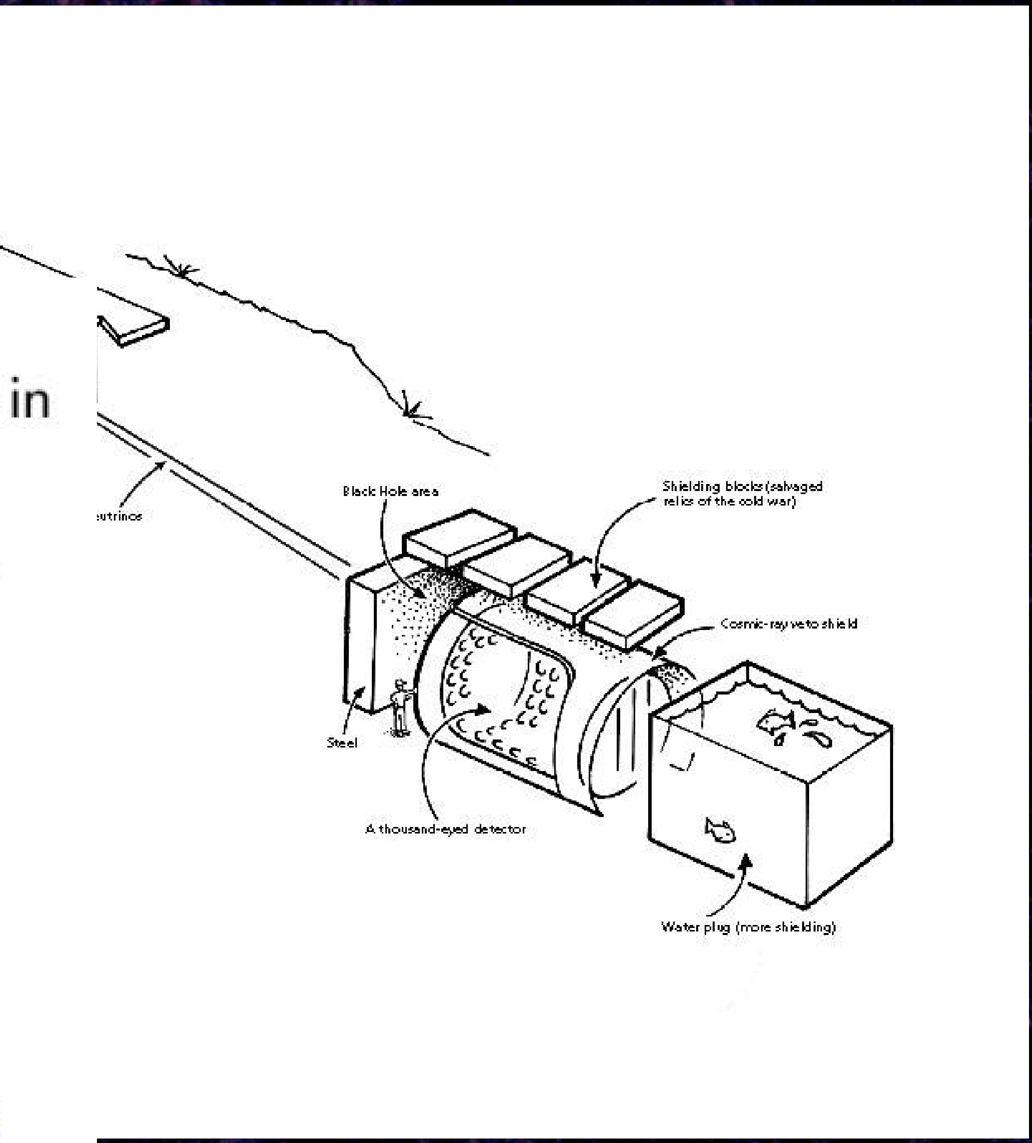
A smoking gun too many – LSND



A smoking gun too many – LSND

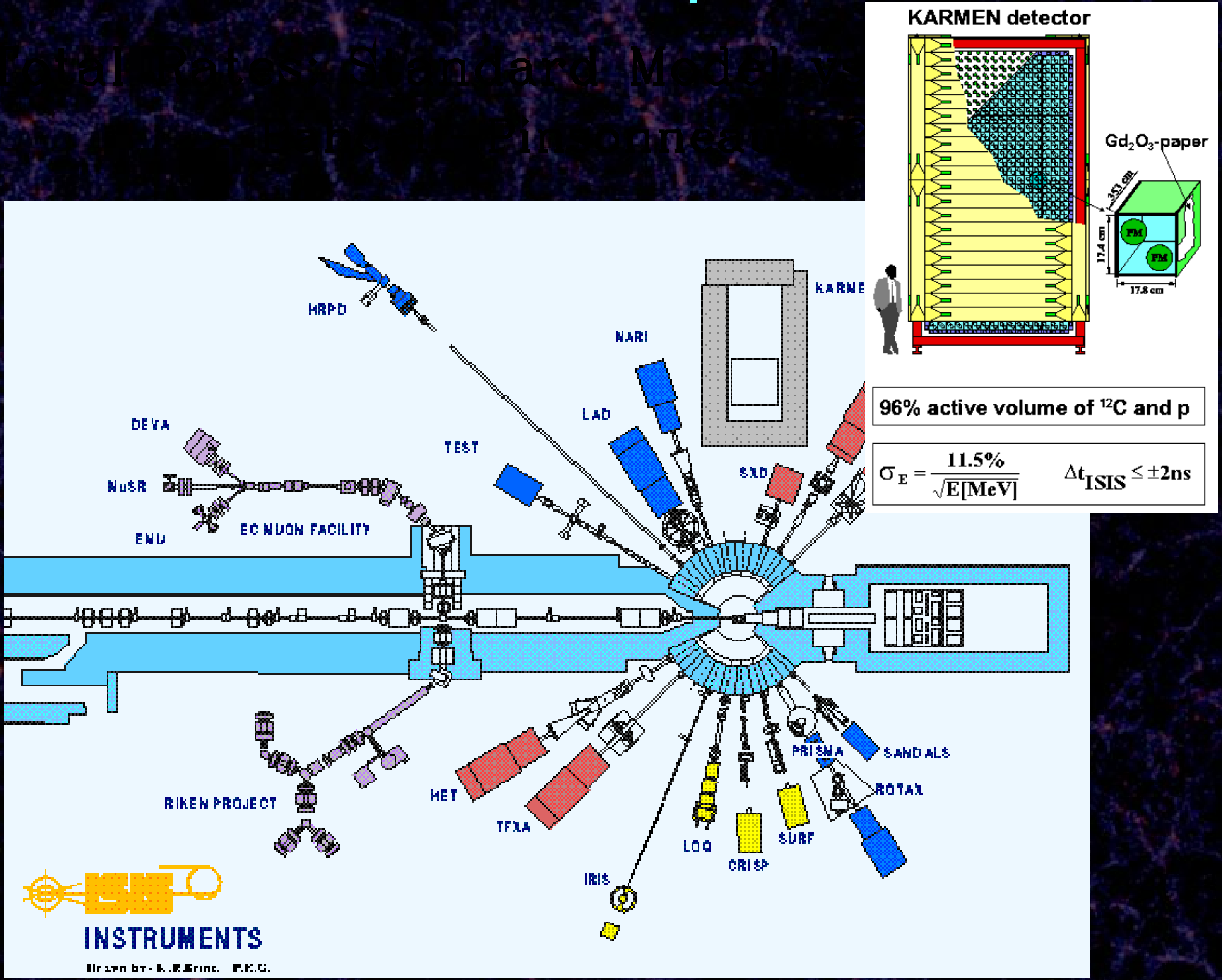
- Backgrounds in green,red
- Fit to oscillation hypothesis in blue





A second experiment…

Total Rates: Standard Model v

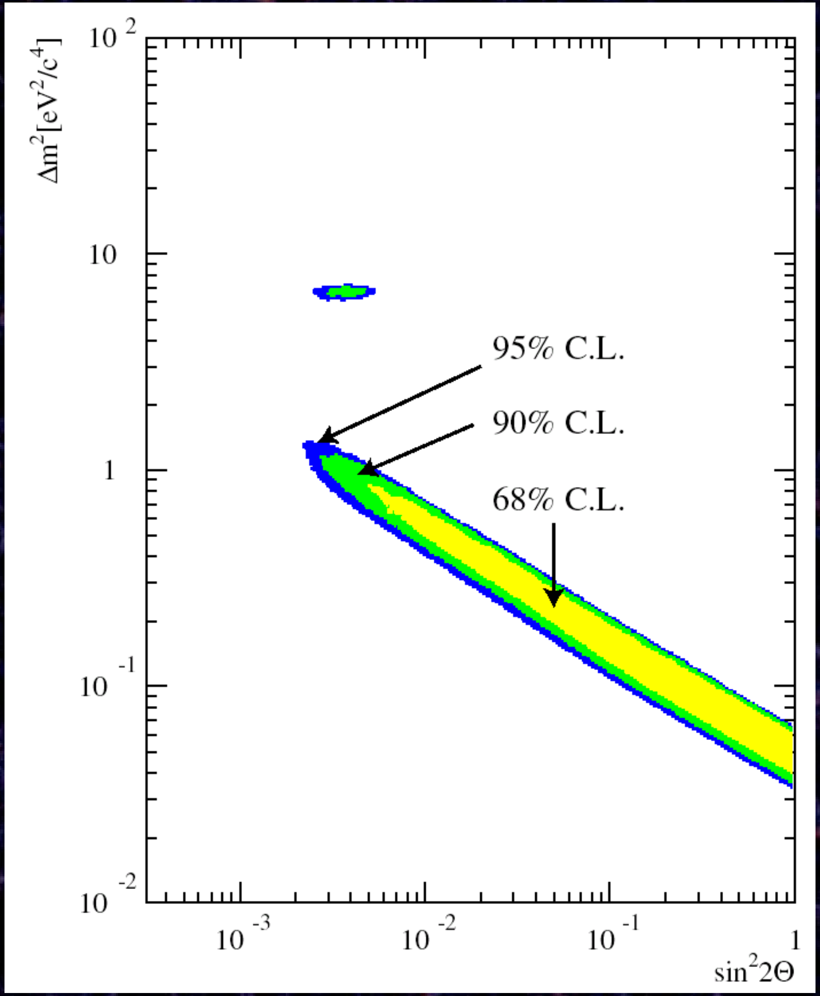


96% active volume of ^{12}C and p

$\sigma_E = \frac{11.5\%}{\sqrt{E[\text{MeV}]}}$ $\Delta t_{\text{ISIS}} \leq \pm 2\text{ns}$

…KARMEN saw no effect.

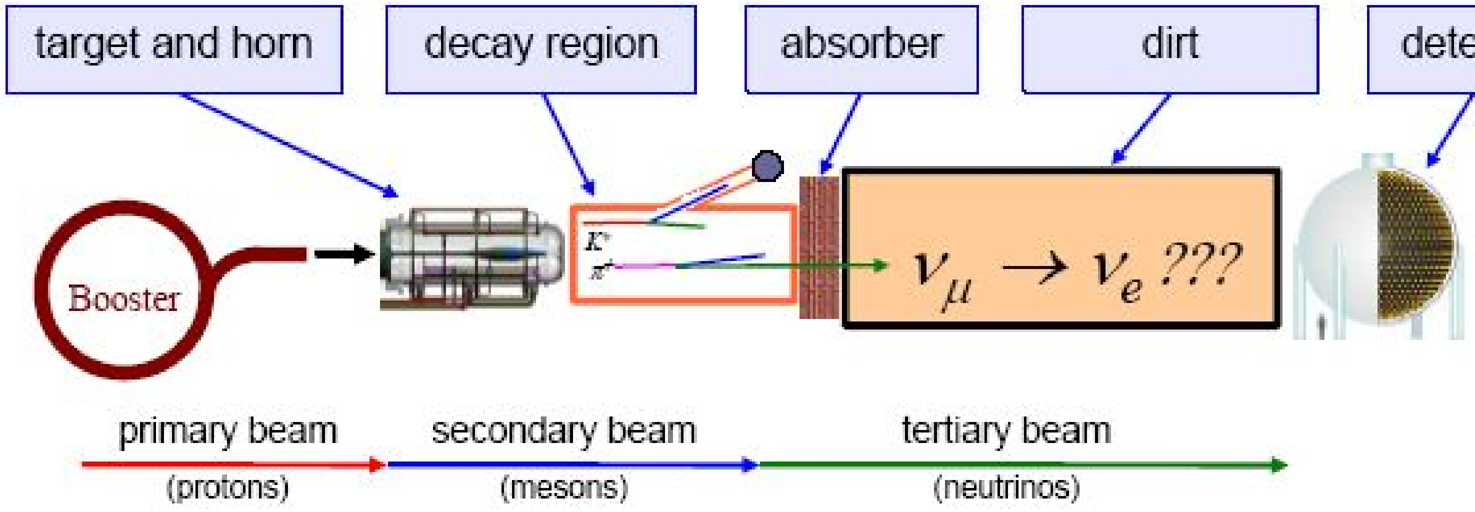
LSND and KARMEN not inconsistent with each other - just with everything else (assuming 3 neutrinos).



Joint LSND/Karmen analysis gives restricted region (Church et al. hep-ex/0203023)

MiniBooNE Design

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta \, \sin^2(1.27\Delta m^2 L/E)$$



target and horn

decay region

absorber

dirt

detector

Booster

K^+

π^+

$\nu_\mu \to \nu_e$???

primary beam

(protons)

secondary beam

(mesons)

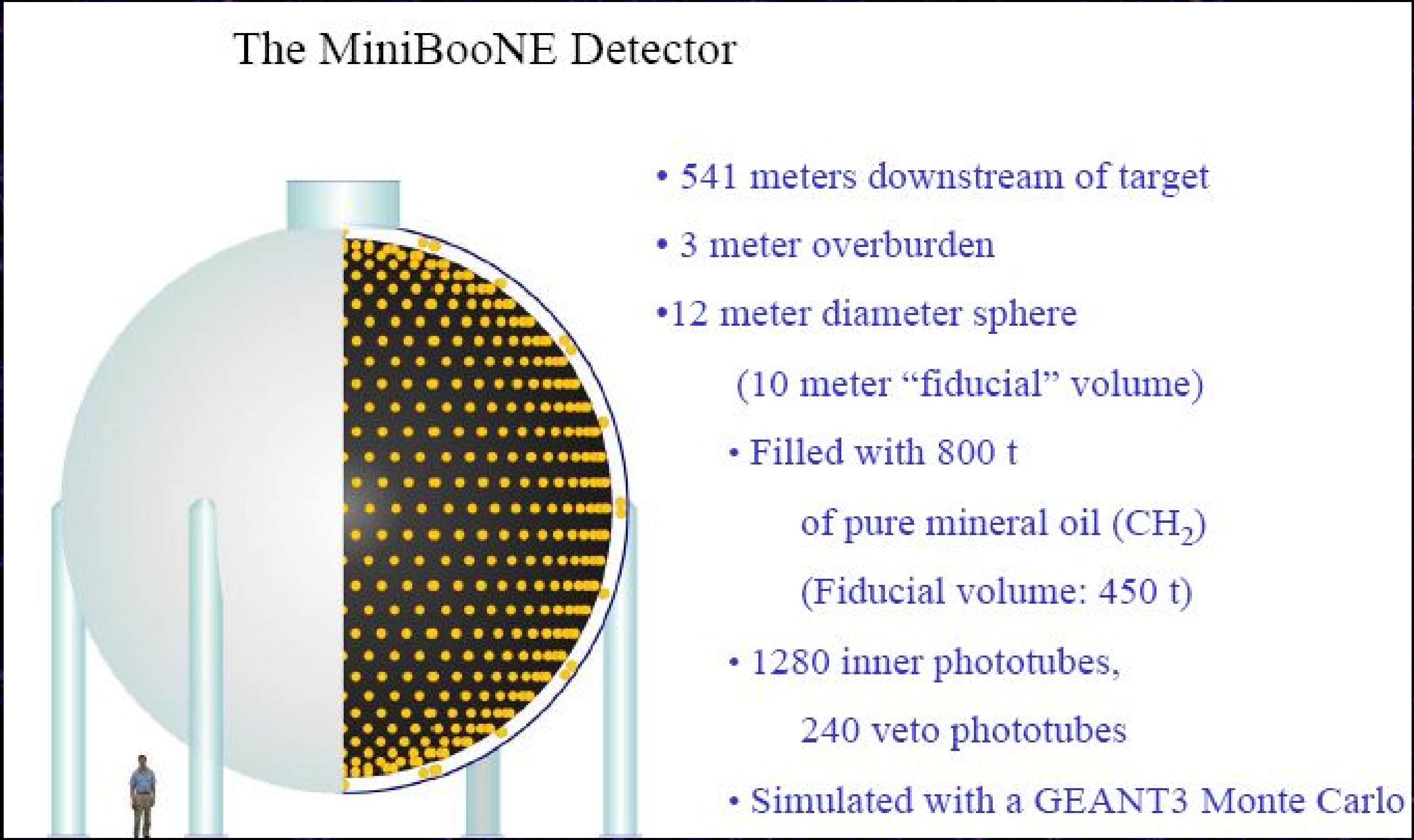
tertiary beam

(neutrinos)

Order of magnitude
higher energy (~500 MeV)
than LSND (~30 MeV)

Order of magnitude
longer baseline (~500 m)
than LSND (~30 m)

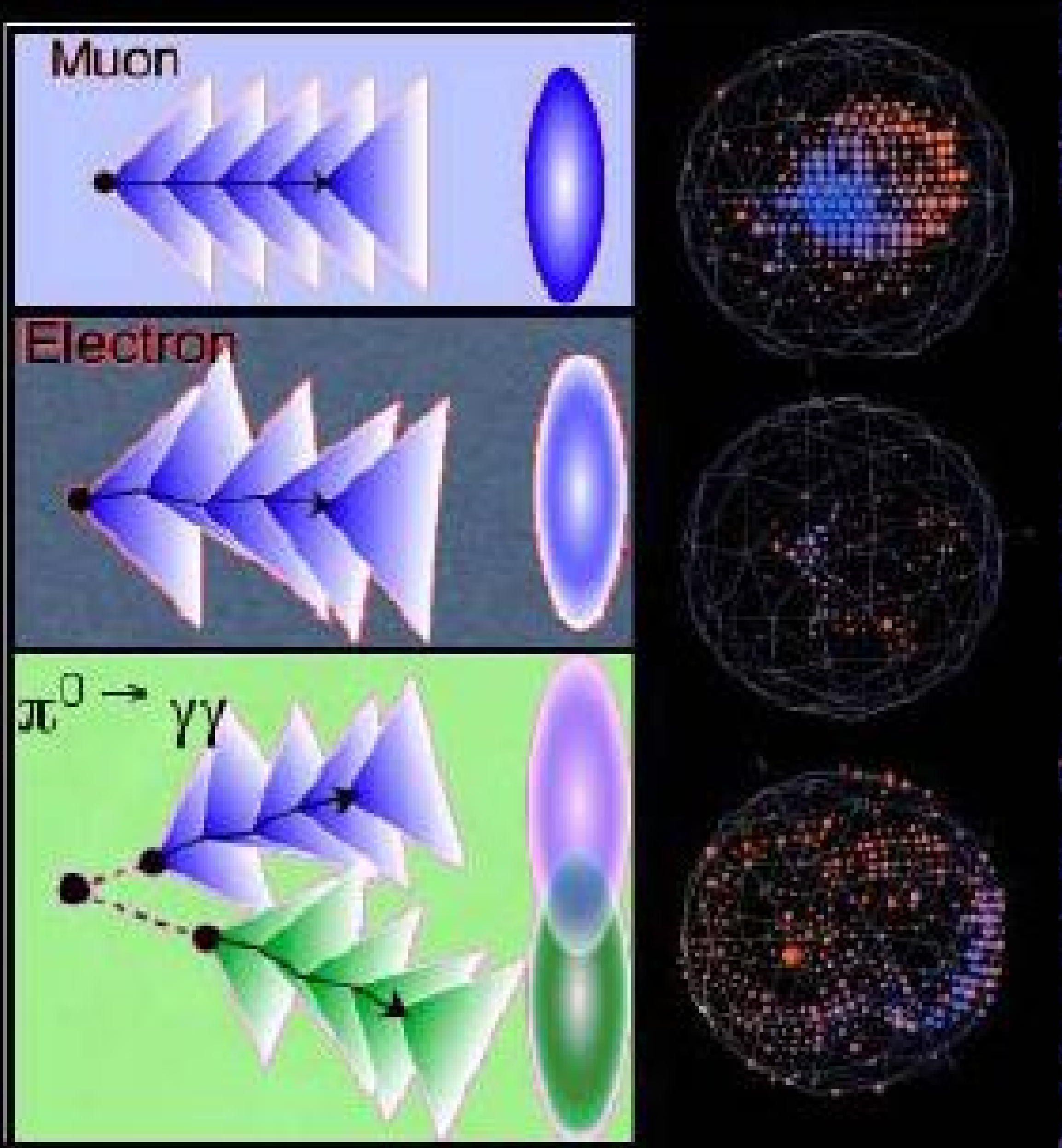
MiniBooNE Detector



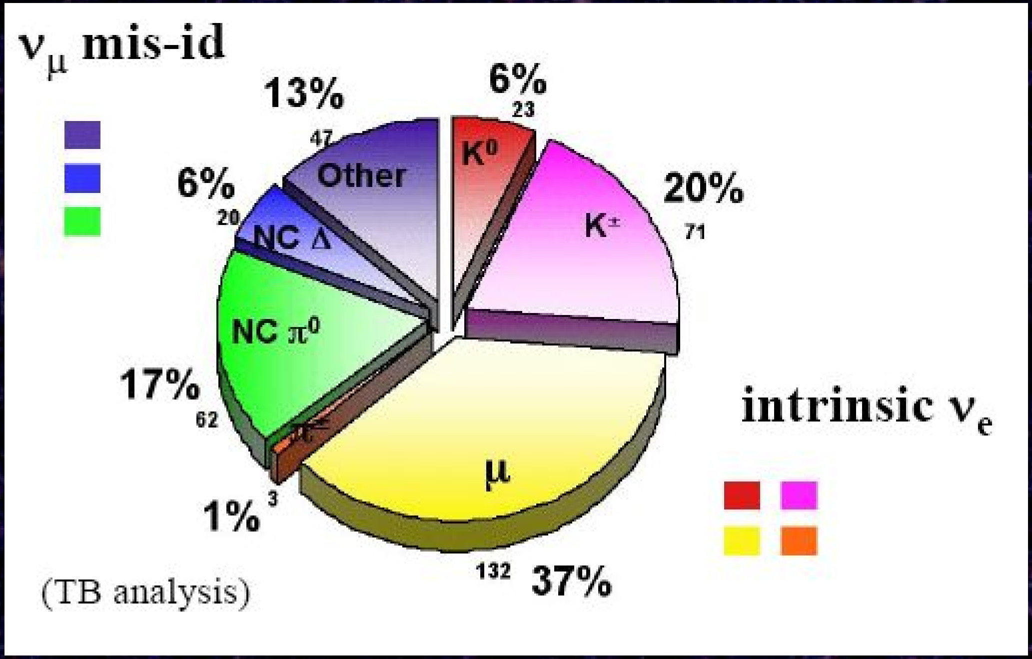
The MiniBooNE Detector

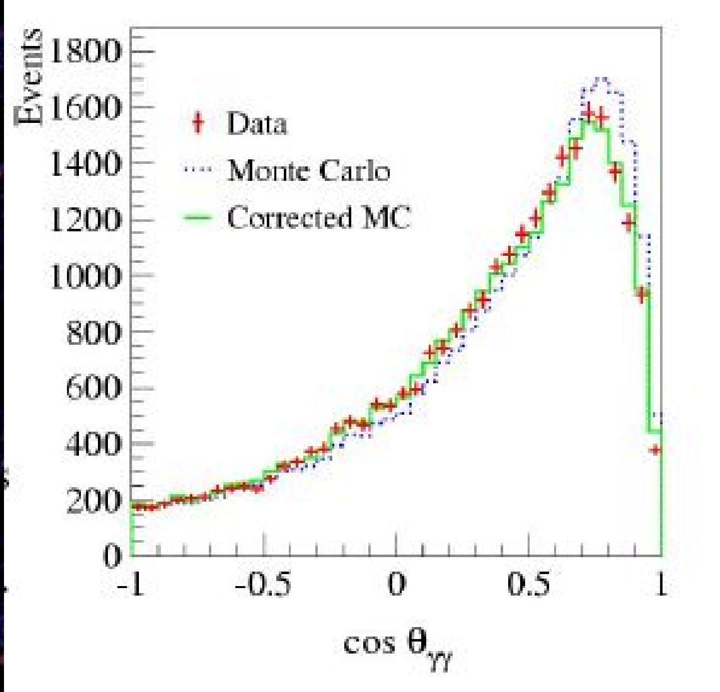
- 541 meters downstream of target
- 3 meter overburden
- 12 meter diameter sphere
  (10 meter "fiducial" volume)
  - Filled with 800 t
    of pure mineral oil (CH_2)
    (Fiducial volume: 450 t)
  - 1280 inner phototubes,
    240 veto phototubes
  - Simulated with a GEANT3 Monte Carlo

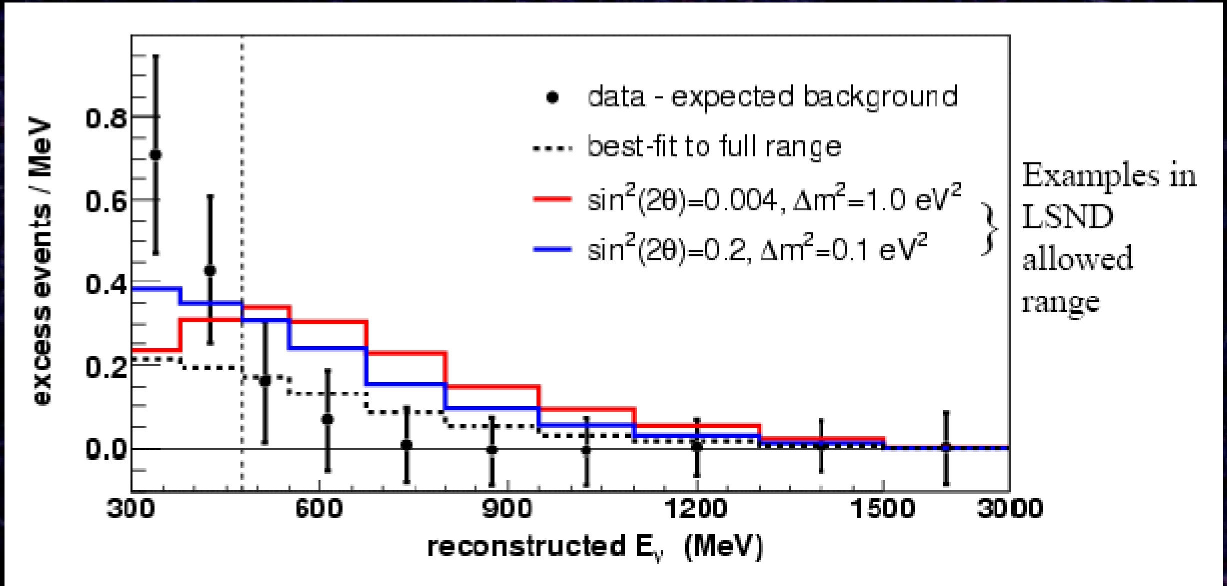
MiniBooNE Detector



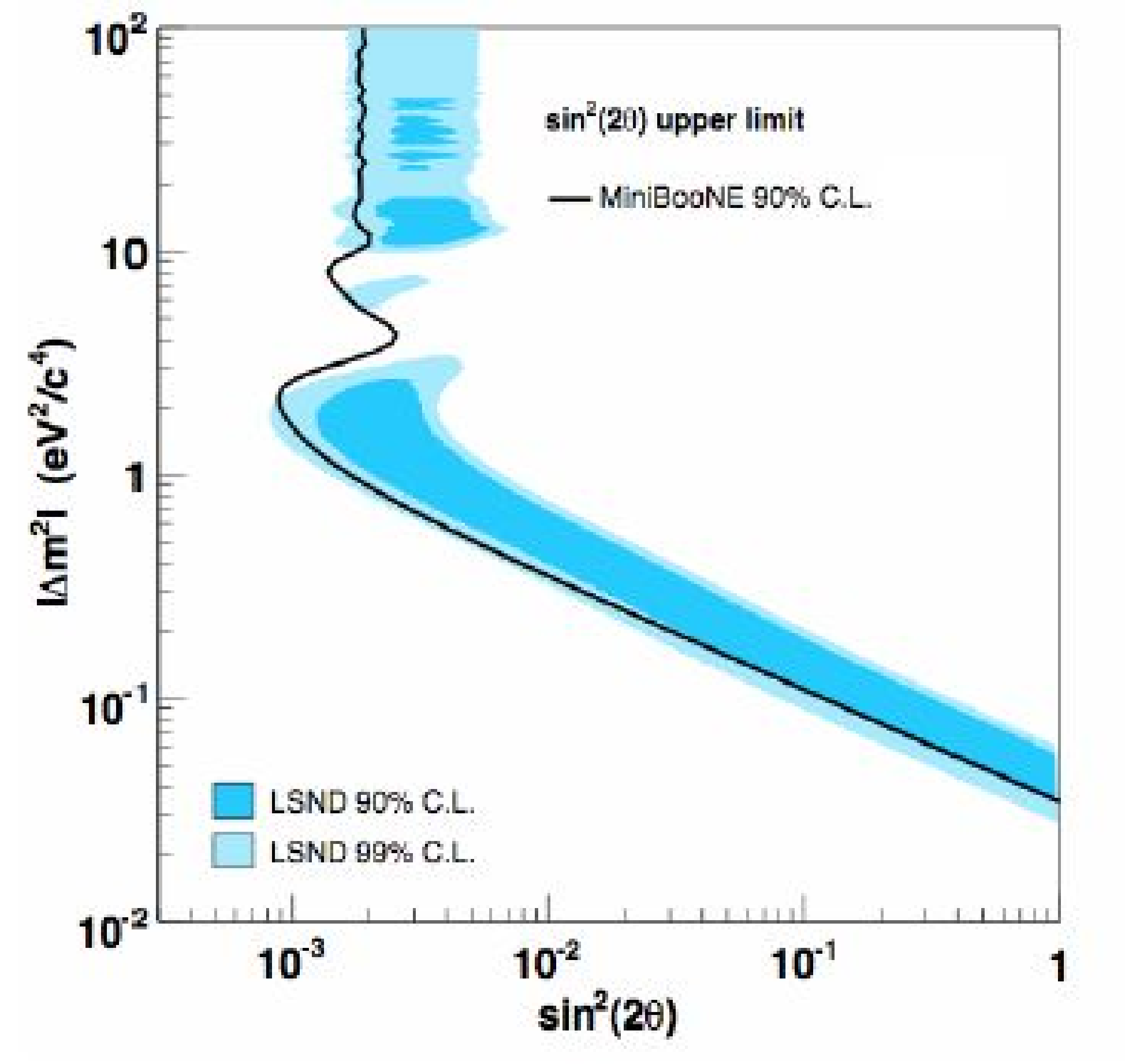
MiniBooNE Analysis







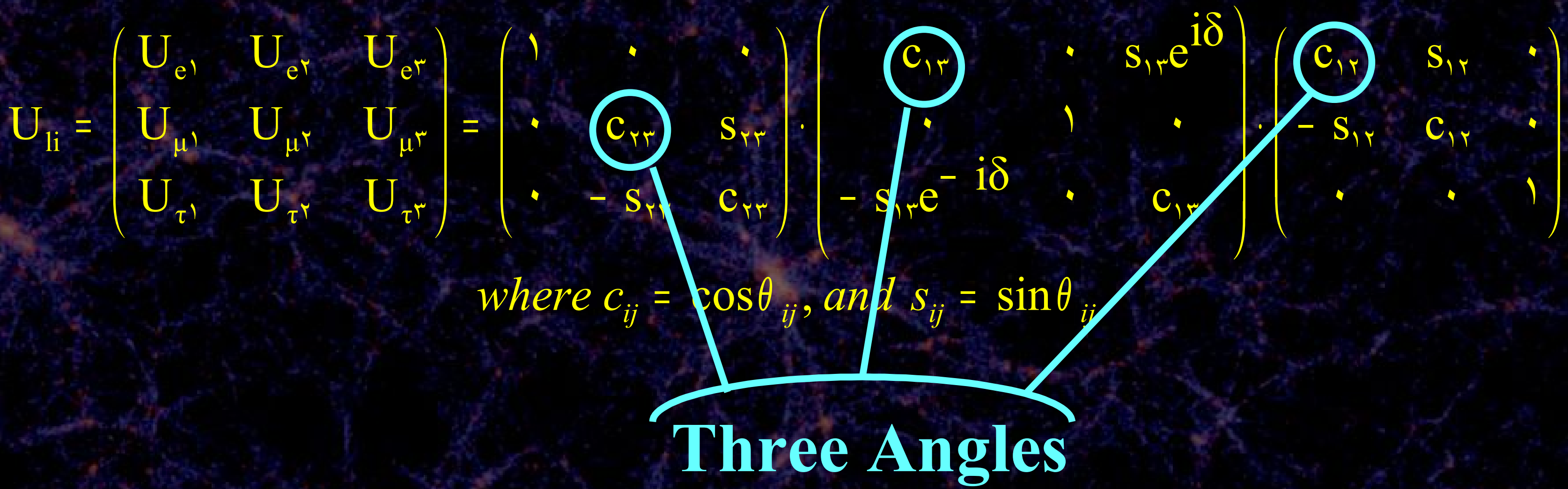
MiniBooNE Results



LSND 2ν oscillation ruled out at 98% c.l.

If neutrinos have mass: $|\nu_l\rangle = \sum U_{li}|\nu_i\rangle$

For three neutrinos:



$$U_{li} = \begin{pmatrix} U_{e١} & U_{e٢} & U_{e٣} \\ U_{\mu١} & U_{\mu٢} & U_{\mu٣} \\ U_{\tau١} & U_{\tau٢} & U_{\tau٣} \end{pmatrix} = \begin{pmatrix} ١ & ٠ & ٠ \\ ٠ & c_{٢٣} & s_{٢٣} \\ ٠ & -s_{٢٣} & c_{٢٣} \end{pmatrix} \cdot \begin{pmatrix} c_{١٣} & ٠ & s_{١٣}e^{i\delta} \\ ٠ & ١ & ٠ \\ -s_{١٣}e^{-i\delta} & ٠ & c_{١٣} \end{pmatrix} \cdot \begin{pmatrix} c_{١٢} & s_{١٢} & ٠ \\ -s_{١٢} & c_{١٢} & ٠ \\ ٠ & ٠ & ١ \end{pmatrix}$$

where $c_{ij} = \cos\theta_{ij}$, and $s_{ij} = \sin\theta_{ij}$

Three Angles

$$P(\nu_\mu \rightarrow \nu_e) = \sin^٢ ٢\theta \sin^٢(١.٢٧\frac{\Delta m^٢ L}{E})$$

If neutrinos have mass: $$|\nu_l\rangle = \sum U_{li}|\nu_i\rangle$$

For three neutrinos:

$$U_{li} = \begin{pmatrix} U_{e١} & U_{e٢} & U_{e٣} \\ U_{\mu١} & U_{\mu٢} & U_{\mu٣} \\ U_{\tau١} & U_{\tau٢} & U_{\tau٣} \end{pmatrix} = \begin{pmatrix} ١ & ٠ & ٠ \\ ٠ & c_{٢٣} & s_{٢٣} \\ ٠ & -s_{٢٣} & c_{٢٣} \end{pmatrix} \cdot \begin{pmatrix} c_{١٣} & ٠ & s_{١٣}e^{i\delta} \\ ٠ & ١ & ٠ \\ -s_{١٣}e^{-i\delta} & ٠ & c_{١٣} \end{pmatrix} \cdot \begin{pmatrix} c_{١٢} & s_{١٢} & ٠ \\ -s_{١٢} & c_{١٢} & ٠ \\ ٠ & ٠ & ١ \end{pmatrix}$$

where $c_{ij} = \cos\theta_{ij}$, *and* $s_{ij} = \sin\theta_{ij}$

Two mass differences - each has a sign

$$P(\nu_\mu \to \nu_e) = \sin^٢ ٢\theta \sin^٢ (١.٢٧ \frac{\Delta m^٢ L}{E})$$

$$\sin^٢ ٢\theta_m = \frac{\sin^٢ ٢\theta}{(\omega - \cos ٢\theta)^٢ + \sin^٢ ٢\theta}$$

$$\omega = -٢\sqrt{٢} G_F N_e E / \Delta m^٢$$

If neutrinos have mass: $$|\nu_l\rangle = \sum U_{li}|\nu_i\rangle$$

For three neutrinos:

$$U_{li} = \begin{pmatrix} U_{e١} & U_{e٢} & U_{e٣} \\ U_{\mu١} & U_{\mu٢} & U_{\mu٣} \\ U_{\tau١} & U_{\tau٢} & U_{\tau٣} \end{pmatrix} = \begin{pmatrix} ١ & ٠ & ٠ \\ ٠ & c_{٢٣} & s_{٢٣} \\ ٠ & -s_{٢٣} & c_{٢٣} \end{pmatrix} \cdot \begin{pmatrix} c_{١٣} & ٠ & s_{١٣}e^{i\delta} \\ ٠ & ١ & ٠ \\ -s_{١٣}e^{-i\delta} & ٠ & c_{١٣} \end{pmatrix} \cdot \begin{pmatrix} c_{١٢} & s_{١٢} & ٠ \\ -s_{١٢} & c_{١٢} & ٠ \\ ٠ & ٠ & ١ \end{pmatrix}$$

where $c_{ij} = \cos\theta_{ij}$, *and* $s_{ij} = \sin\theta_{ij}$

CP violating phase δ

$$P(\nu_\mu \rightarrow \nu_e) = \sin^٢ ٢\theta \sin^٢(١.٢٧\frac{\Delta m^٢ L}{E})$$

What are the experimental targets now?

- More accurate determinations of already measured parameters (better than CKM?) – is $\theta_{23} = 45°$?
  - Existing experiments offer (modest) improvements
  - Next-generation long baseline and reactor experiments (T2K will improve on MINOS by ~10x).
- Other signatures of oscillations – ν_τ appearance.
- θ_{13} – either $\nu_\mu \rightarrow \nu_e$, or $\bar{\nu}_e$ disappearance.
- The sign of Δm_{23}^2 (or Δm_{13}^2)
- The CP-violating phase δ
- The absolute mass scale.
- Are neutrinos Majorana or Dirac?
- Are there more than 3 – neuterinos?
- Surprises?

Three neutrino mixing.

If neutrinos have mass: $|\nu_l\rangle = \sum U_{li}|\nu_i\rangle$

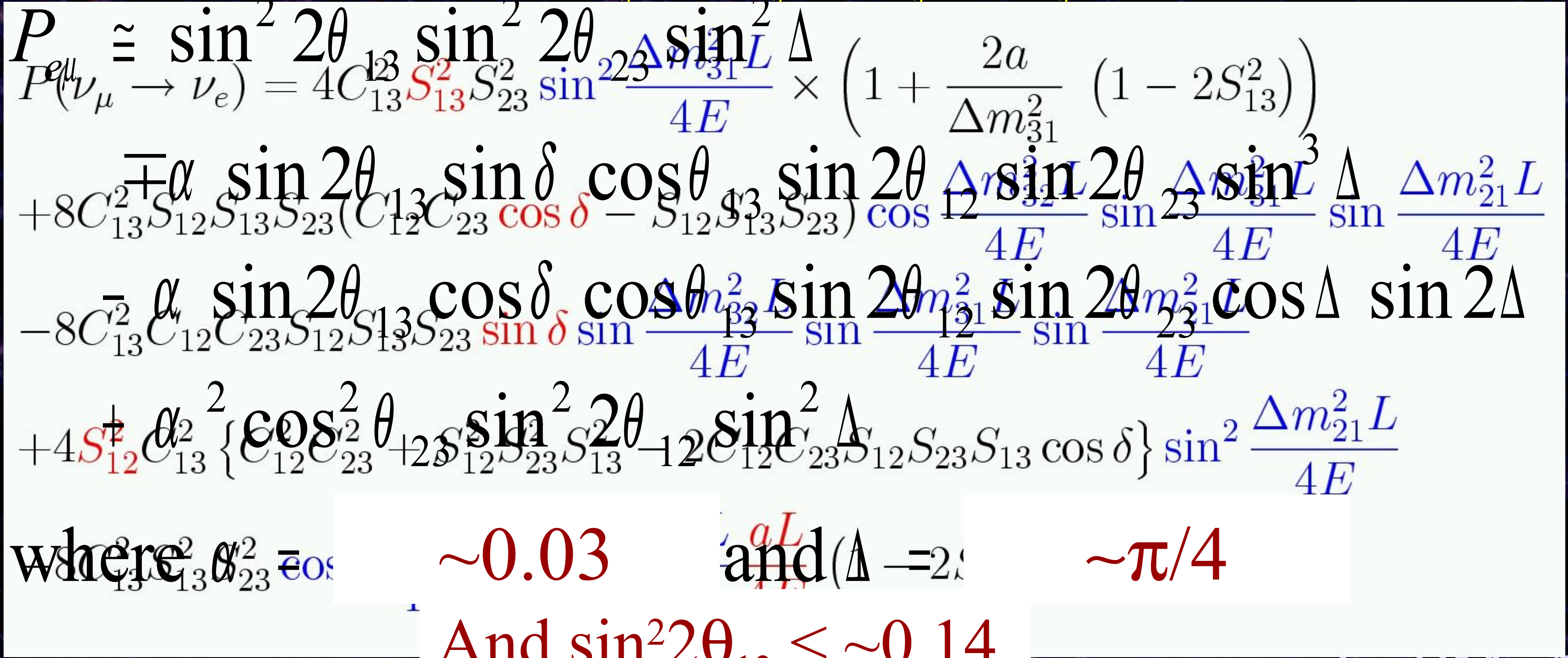
$$U_{li} = \begin{pmatrix} U_{e١} & U_{e٢} & U_{e٣} \\ U_{\mu١} & U_{\mu٢} & U_{\mu٣} \\ U_{\tau١} & U_{\tau٢} & U_{\tau٣} \end{pmatrix} = \begin{pmatrix} ١ & ٠ & ٠ \\ ٠ & c_{٢٣} & s_{٢٣} \\ ٠ & -s_{٢٣} & c_{٢٣} \end{pmatrix} \cdot \begin{pmatrix} c_{١٣} & ٠ & s_{١٣}e^{i\delta} \\ ٠ & ١ & ٠ \\ -s_{١٣}e^{-i\delta} & ٠ & c_{١٣} \end{pmatrix} \cdot \begin{pmatrix} c_{١٢} & s_{١٢} & ٠ \\ -s_{١٢} & c_{١٢} & ٠ \\ ٠ & ٠ & ١ \end{pmatrix}$$

where $c_{ij} = \cos\theta_{ij}$, *and* $s_{ij} = \sin\theta_{ij}$

$$P_{e\mu} \cong \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2 \Delta$$
$$\mp \alpha \sin 2\theta_{13} \sin\delta \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin^3 \Delta$$
$$- \alpha \sin 2\theta_{13} \cos\delta \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos\Delta \sin 2\Delta$$
$$+ \alpha^2 \cos^2\theta_{23} \sin^2 2\theta_{12} \sin^2 \Delta$$

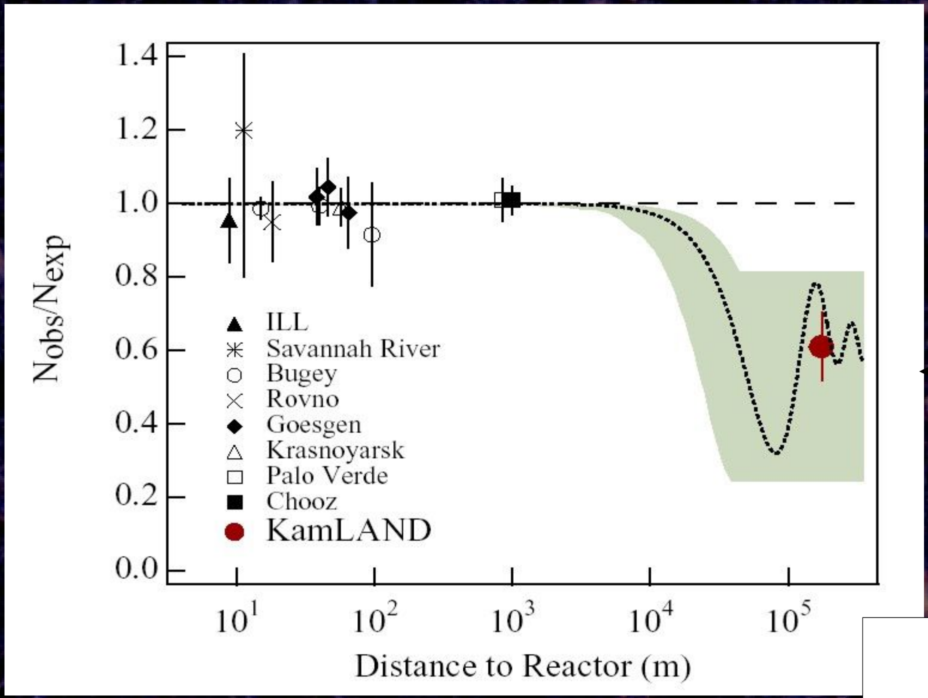
where $\alpha =$ ~0.03 and $\Delta =$ ~π/4

And $\sin^2 2\theta_{13} < \sim 0.14$



$$P(\nu_\mu \to \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} \times \left(1 + \frac{2a}{\Delta m_{31}^2}(1 - 2S_{13}^2)\right)$$
$$+8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos\frac{\Delta m_{32}^2 L}{4E} \sin\frac{\Delta m_{31}^2 L}{4E} \sin\frac{\Delta m_{21}^2 L}{4E}$$
$$-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin\frac{\Delta m_{32}^2 L}{4E} \sin\frac{\Delta m_{31}^2 L}{4E} \sin\frac{\Delta m_{21}^2 L}{4E}$$
$$+4S_{12}^2 C_{13}^2 \{C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta\} \sin^2 \frac{\Delta m_{21}^2 L}{4E}$$
$$-8C_{13}^2 S_{13}^2 S_{23}^2 \cos \quad \frac{aL}{4E}$$

Effect of 3ν on reactor disappearance



Disappearance on very short baselines – no MSW, no CP viol

$\sin^2 2\theta_{13}$

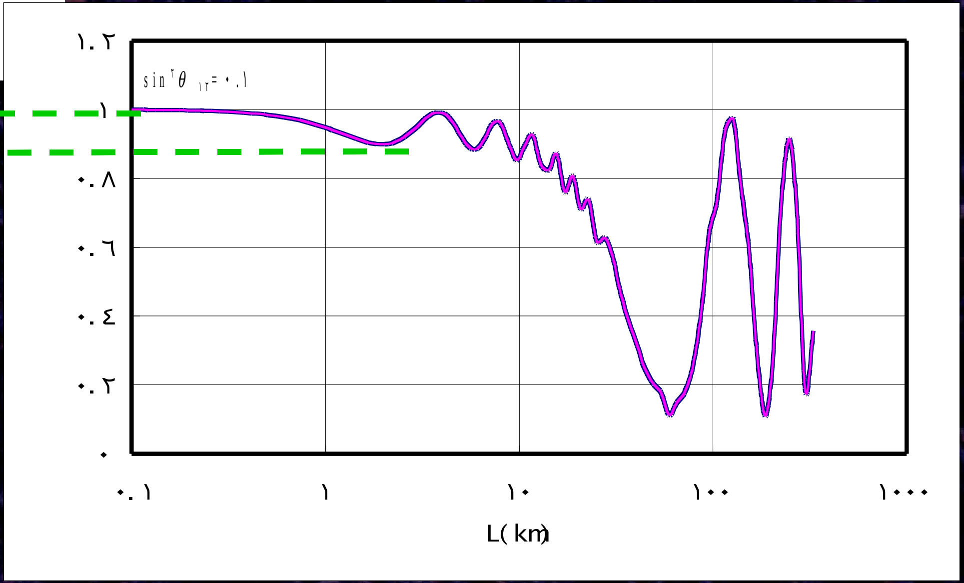
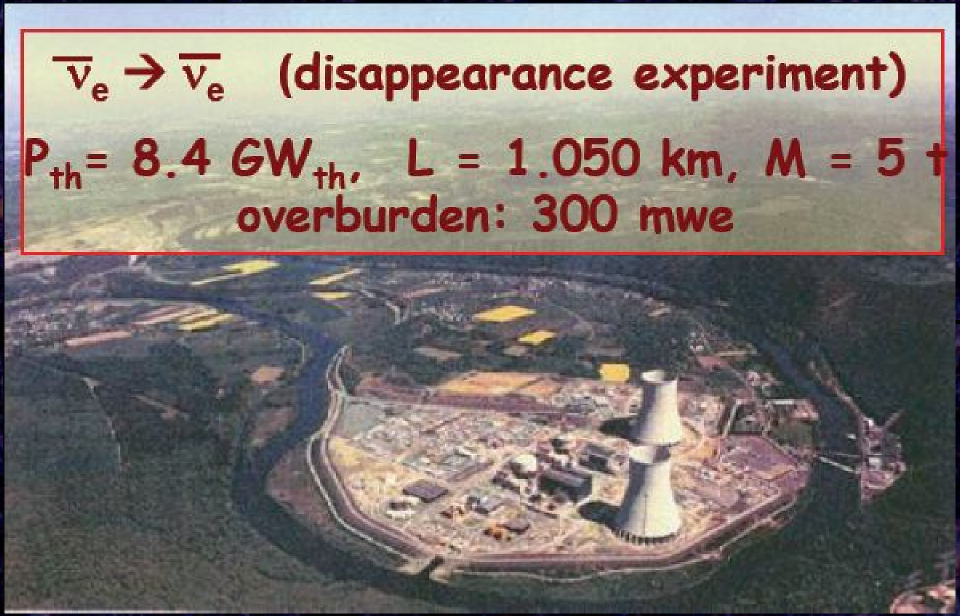


Figure from Josh Klein

Measure this small deficit. Due to $\Delta m^2_{12}<\Delta m^2_{23(13)}$, this is almost pure θ_{13} measurement

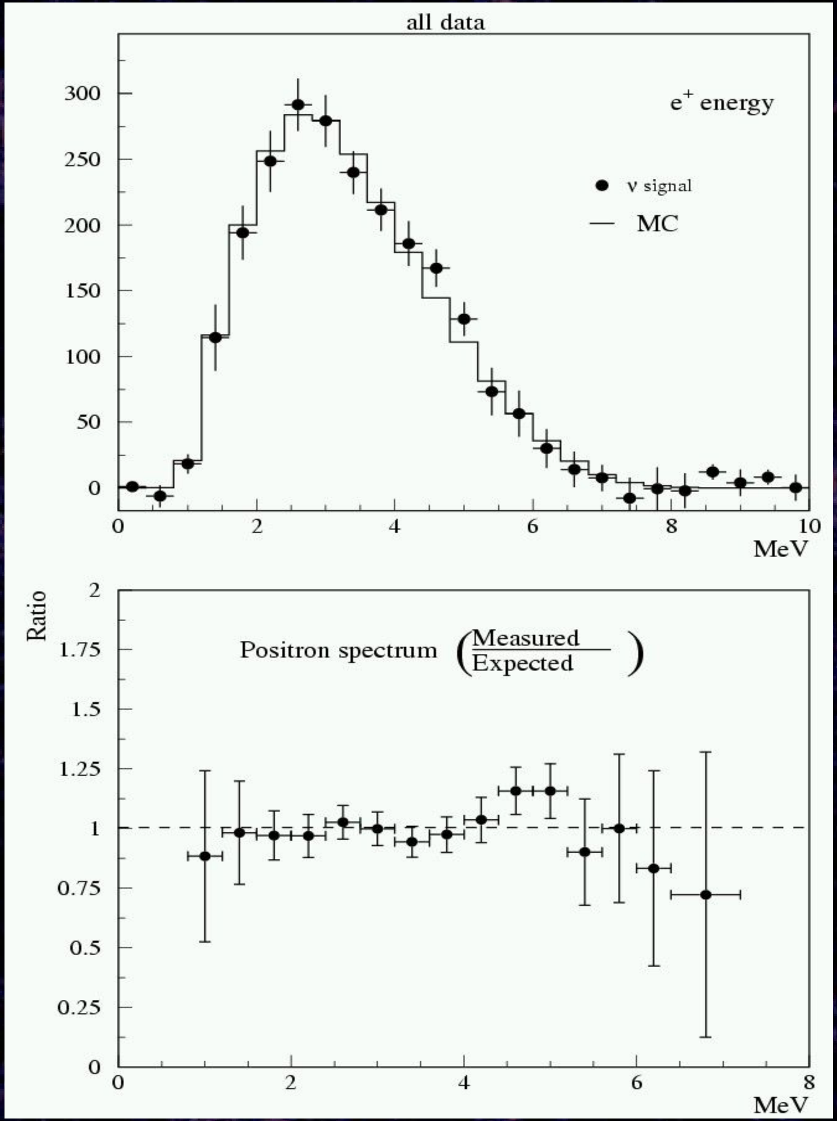
Chooz Reactor Experiment

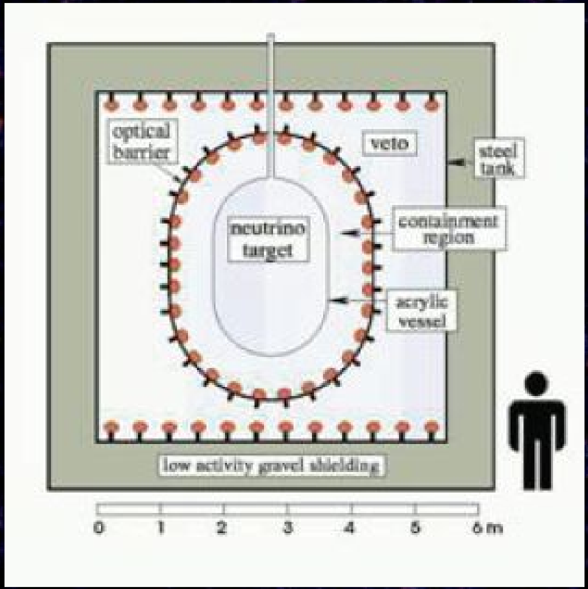


$\overline{\nu}_e \rightarrow \overline{\nu}_e$ (disappearance experiment)

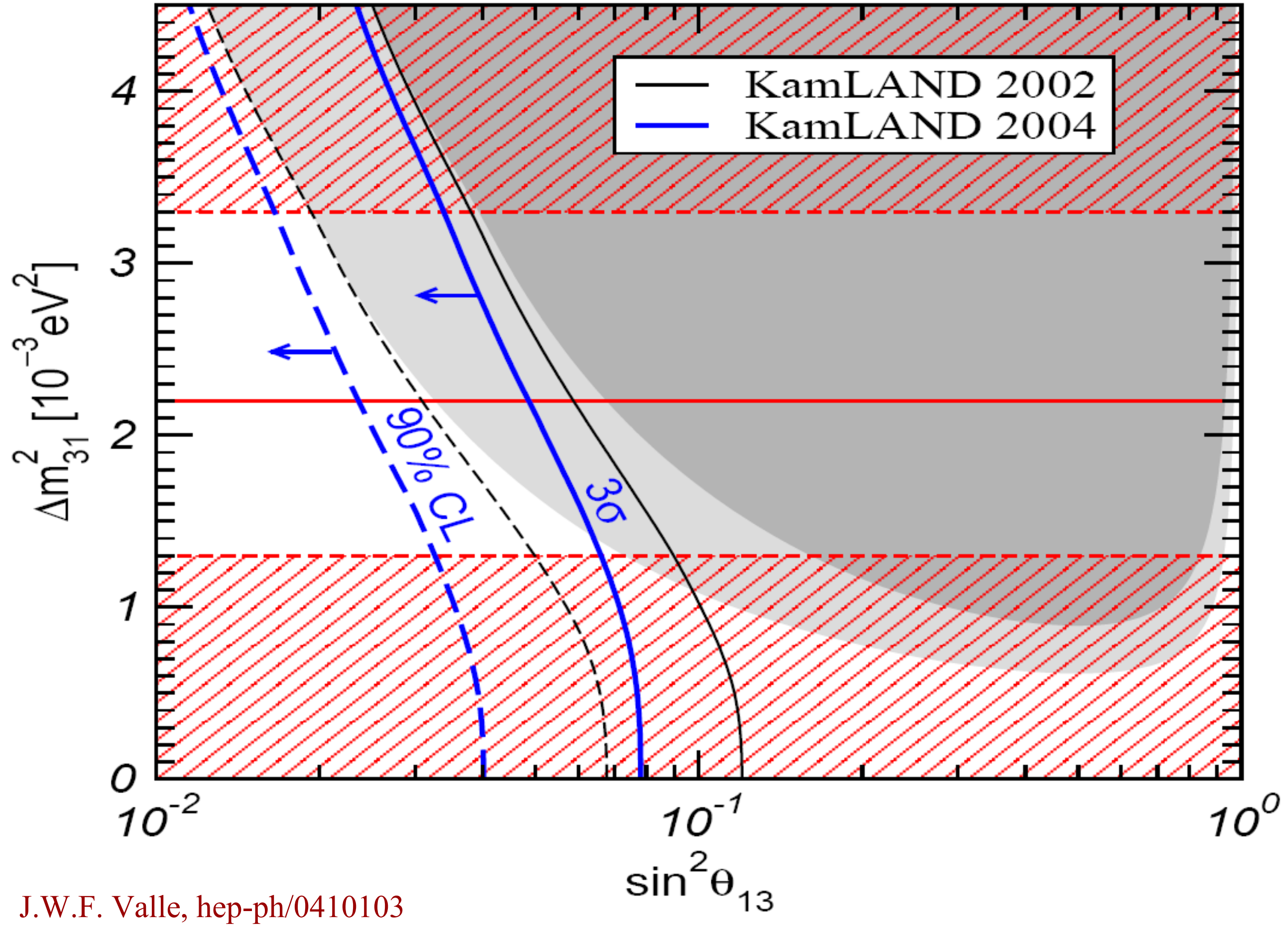
$P_{th} = 8.4\ GW_{th}$, $L = 1.050$ km, $M = 5$ t

overburden: 300 mwe





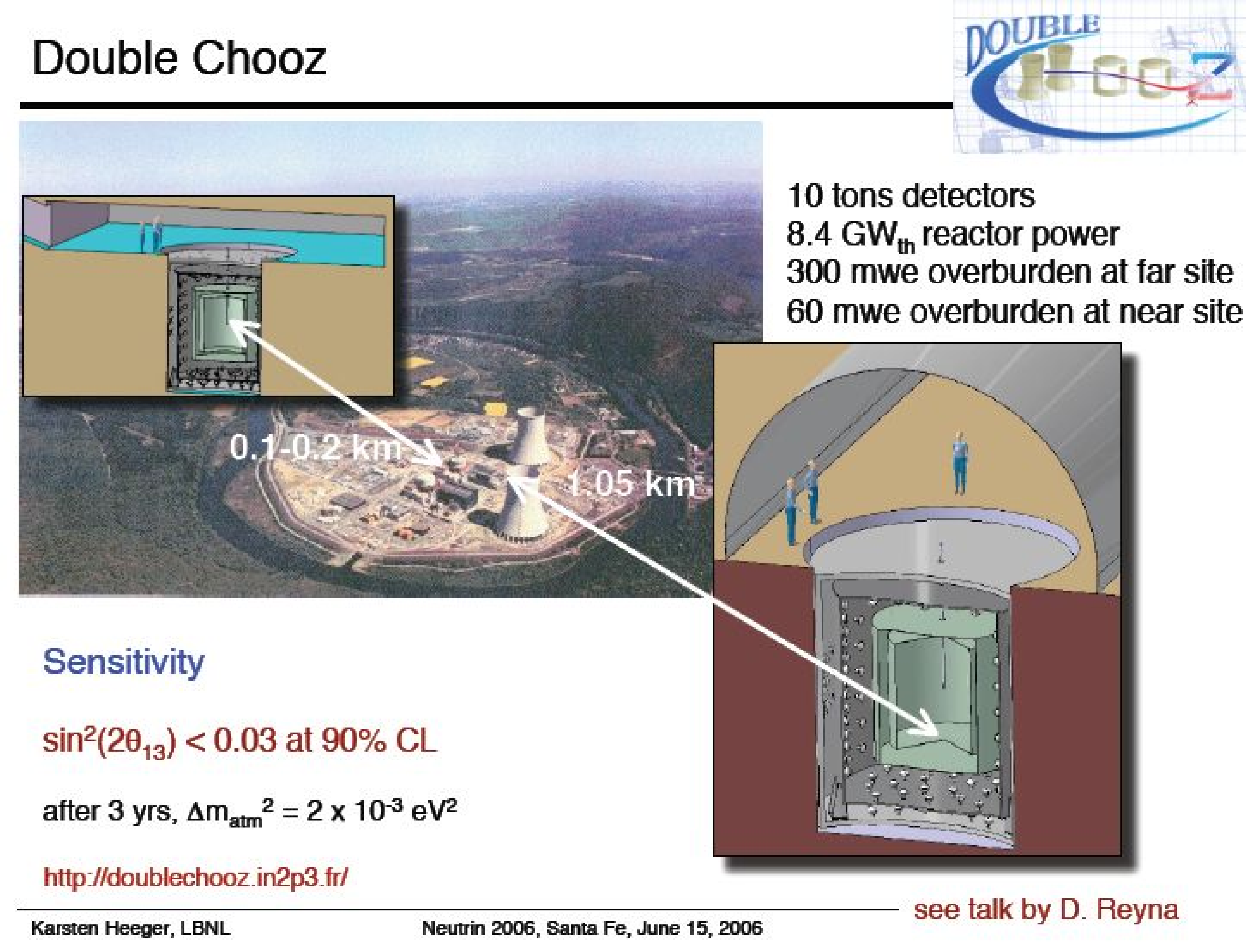
Current limits on θ_{13}



J.W.F. Valle, hep-ph/0410103

Can we improve on Chooz?

- More optimal baseline.
- Two detectors, near and far, to control normalization.
- Much larger detectors (tens or hundreds of tons).



Double Chooz

10 tons detectors
8.4 GW_{th} reactor power
300 mwe overburden at far site
60 mwe overburden at near site

Sensitivity

$\sin^2(2\theta_{13}) < 0.03$ at 90% CL

after 3 yrs, $\Delta m_{atm}^2 = 2 \times 10^{-3}$ eV^2

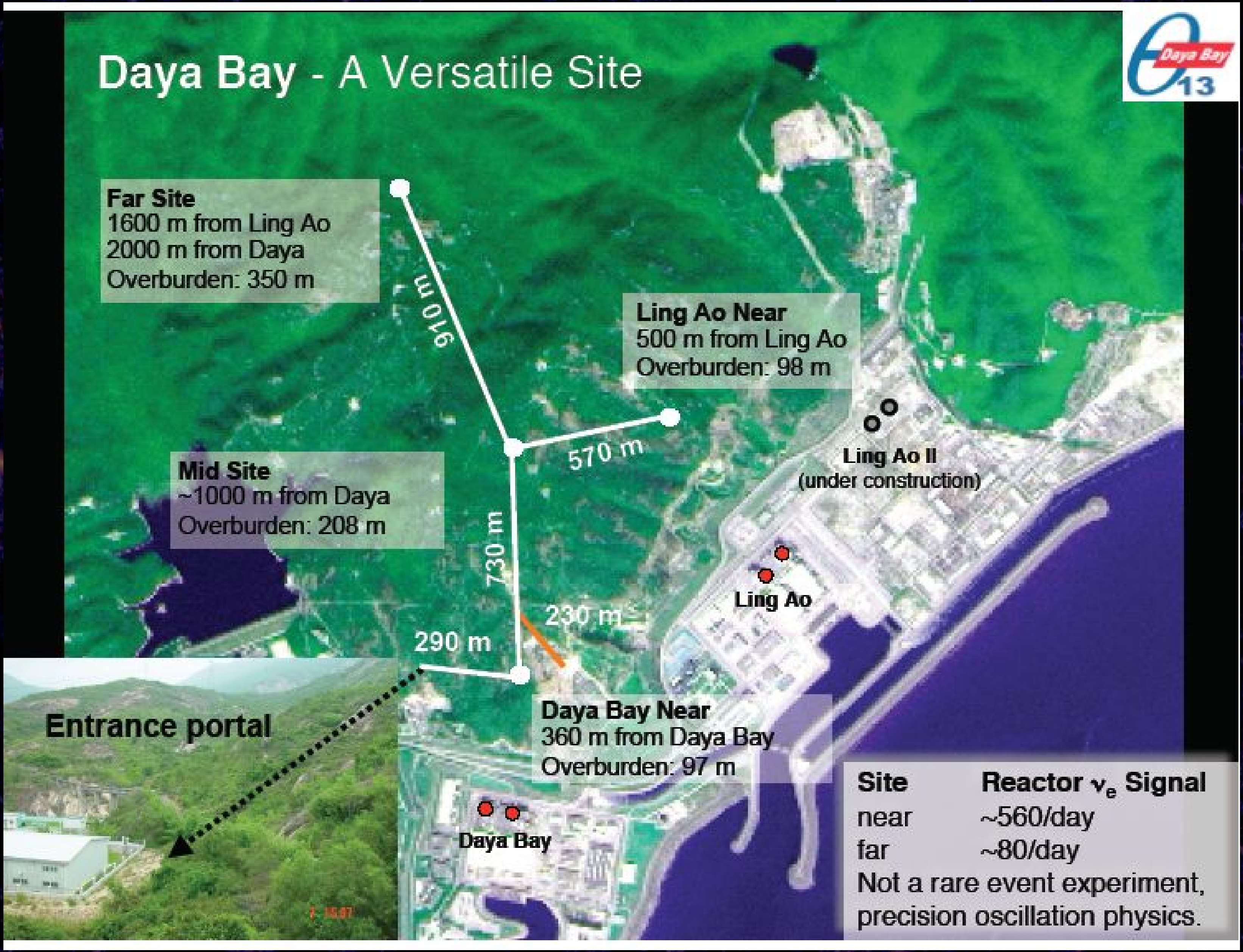
http://doublechooz.in2p3.fr/

see talk by D. Reyna

Karsten Heeger, LBNL

Neutrin 2006, Santa Fe, June 15, 2006

Daya Bay - A Versatile Site



Far Site
1600 m from Ling Ao
2000 m from Daya
Overburden: 350 m

Ling Ao Near
500 m from Ling Ao
Overburden: 98 m

Mid Site
~1000 m from Daya
Overburden: 208 m

Daya Bay Near
360 m from Daya Bay
Overburden: 97 m

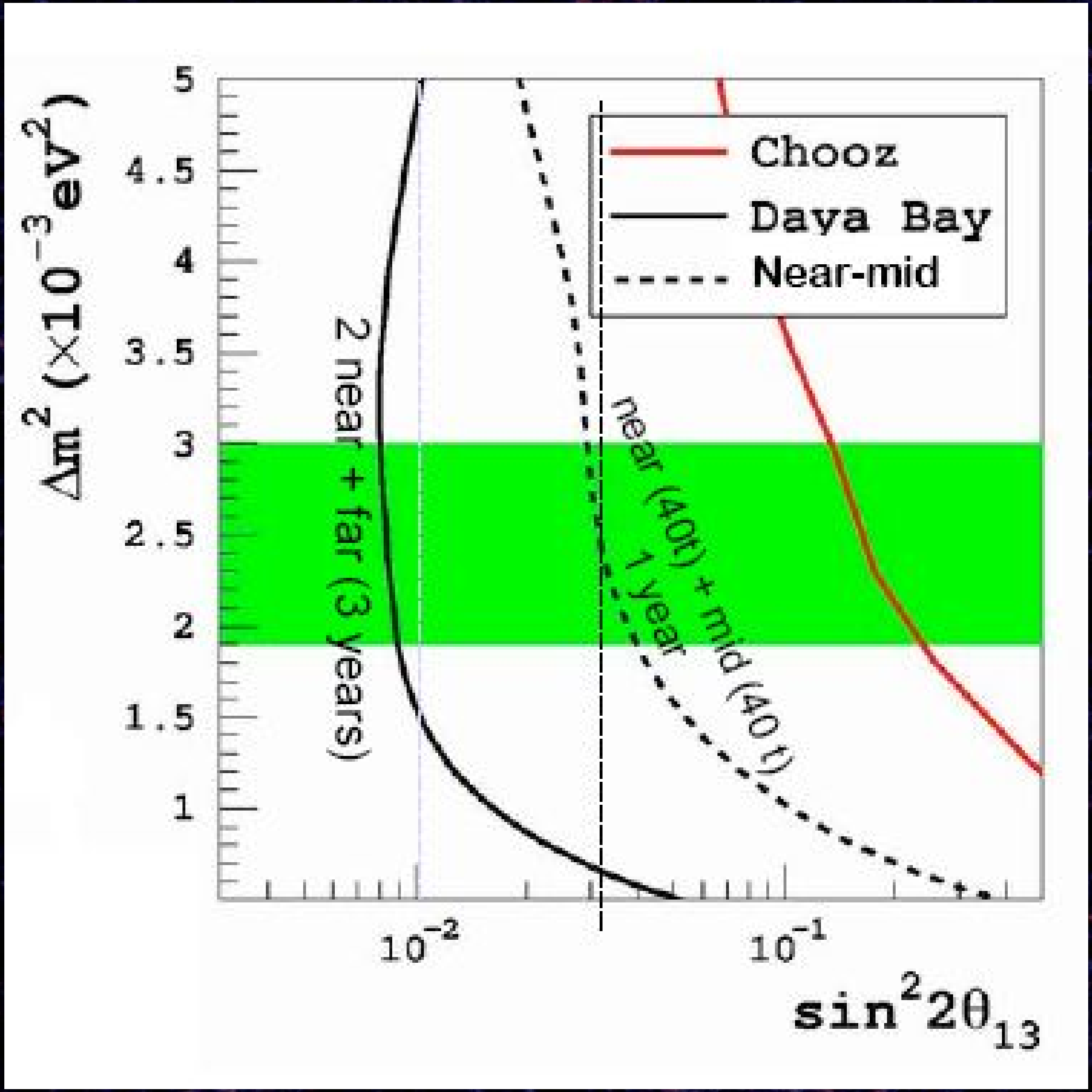
Site	Reactor ν_e Signal
near	~560/day
far	~80/day

Not a rare event experiment, precision oscillation physics.

Can we improve on Chooz?

- More optimal baseline.
- Two detectors, near and far, to control normalization.
- Much larger detectors (tens or hundreds of tons).
- Extremely challenging experiments – systematic error budget on relative rates ~ 1-2%.
- Must understand relative energy scale and linearity even better.
- Must correct for any differences in backgrounds.
- These are extremely challenging experiments, and should be treated as such.

Daya Bay planned sensitivity



Long Baseline $\nu_\mu \Leftrightarrow \nu_e$ Appearance

- *Modest improvements available from MINOS and OPERA*
- *Major improvements in sensitivity will require major new dedicated experiments.*
- *Superbeams – ν derived from π decay:*
  - *T2K*
  - *NOvA*
  - *CERN → Modanne or LNGS or…*
  - *BNL → Homestake or Henderson*
  - *FNAL → various sites*
- *β Beams – ν_e derived from β-decaying nucleus:*
  - *CERN*
  - *FNAL*
  - *EC beams? – produces "monoenergetic" neutrinos*
- *Neutrino Factories – ν_e/ν_μ derived from μ decay:*
  - *CERN*
  - *RAL*
  - *FNAL*
  - *JPARC*

Three neutrino mixing.

If neutrinos have mass: $$|\nu_l\rangle = \sum U_{li}|\nu_i\rangle$$

$$U_{li} = \begin{pmatrix} U_{e١} & U_{e٢} & U_{e٣} \\ U_{\mu١} & U_{\mu٢} & U_{\mu٣} \\ U_{\tau١} & U_{\tau٢} & U_{\tau٣} \end{pmatrix} = \begin{pmatrix} ١ & ٠ & ٠ \\ ٠ & c_{٢٣} & s_{٢٣} \\ ٠ & -s_{٢٣} & c_{٢٣} \end{pmatrix} \cdot \begin{pmatrix} c_{١٣} & ٠ & s_{١٣}e^{i\delta} \\ ٠ & ١ & ٠ \\ -s_{١٣}e^{-i\delta} & ٠ & c_{١٣} \end{pmatrix} \cdot \begin{pmatrix} c_{١٢} & s_{١٢} & ٠ \\ -s_{١٢} & c_{١٢} & ٠ \\ ٠ & ٠ & ١ \end{pmatrix}$$

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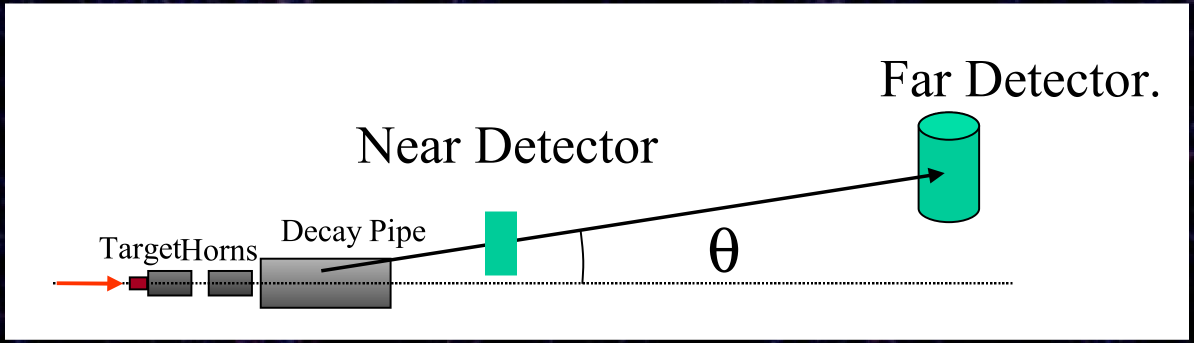
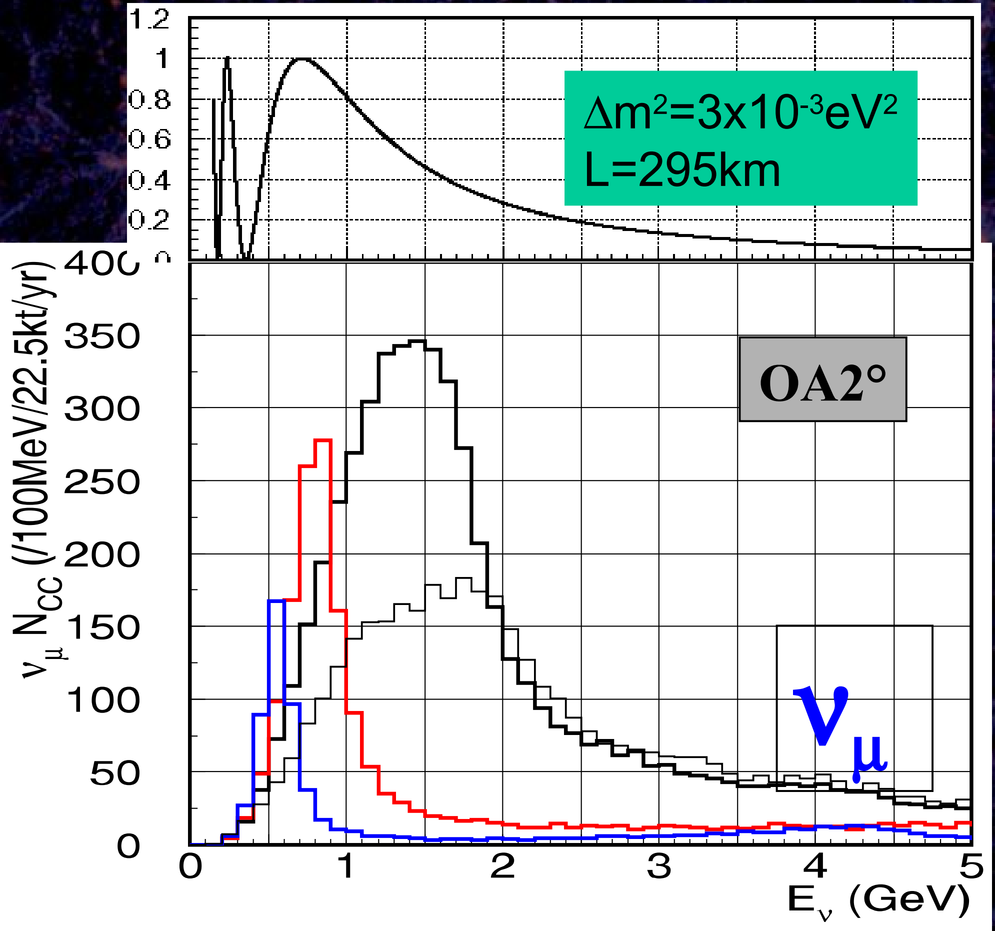
$$+8C_{13}^2 S_{12}S_{13}S_{23}(C_{12}C_{23}\cos\delta - S_{12}S_{13}S_{23}) \cos\frac{\Delta m_{32}^2 L}{4E} \sin\frac{\Delta m_{31}^2 L}{4E} \sin\frac{\Delta m_{21}^2 L}{4E}$$
$$-8C_{13}^2 C_{12}C_{23}S_{12}S_{13}S_{23} \sin\delta \sin\frac{\Delta m_{32}^2 L}{4E} \sin\frac{\Delta m_{31}^2 L}{4E} \sin\frac{\Delta m_{21}^2 L}{4E}$$
$$+4S_{12}^2 C_{13}^2 \left\{C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12}C_{23}S_{12}S_{23}S_{13}\cos\delta\right\} \sin^2\frac{\Delta m_{21}^2 L}{4E}$$
$$-8C_{13}^2 S_{13}^2 S_{23}^2 \cos\frac{\Delta m_{32}^2 L}{4E} \sin\frac{\Delta m_{31}^2 L}{4E} \frac{aL}{4E}\left(1 - 2S_{13}^2\right)$$

Common Features - Off-Axis Beams





- *Pros –*
  - *Increases flux on osc. max.*
  - *Reduces high-E tail, and thus NC backgrounds*
  - *Reduces ν_e contamination from K and μ decay*
- *Cons –*
  - *Complicates disappearance measurement*
  - *Increases near/far differences*
  - *Have to know angle!*

Common Features – Targetry is hard.

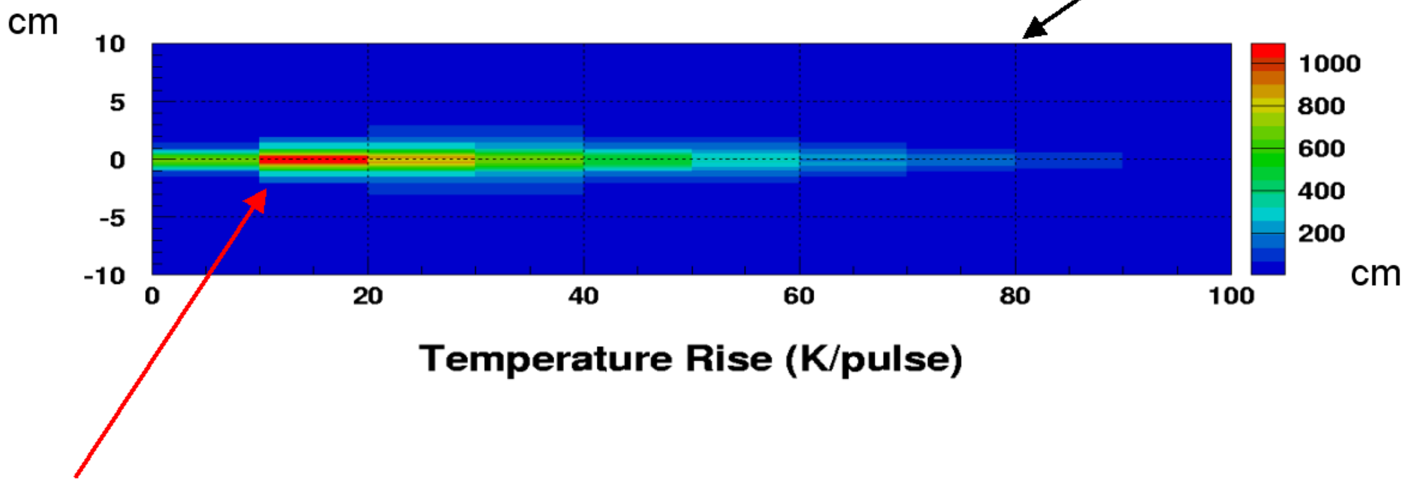
50 GeV 0.75 MW beam !

3.3E14 ppp w/ 5μs pulse

When this beam hits an iron block,

Residual
dose rate

> 1000Sv/h



Temperature Rise (K/pulse)

1100°

(cf. melting point 1536°)

- ✓ Material heavier than iron would melt.
- ✓ Thermal shock stress ≈ $E\alpha\Delta T \approx 3GPa$

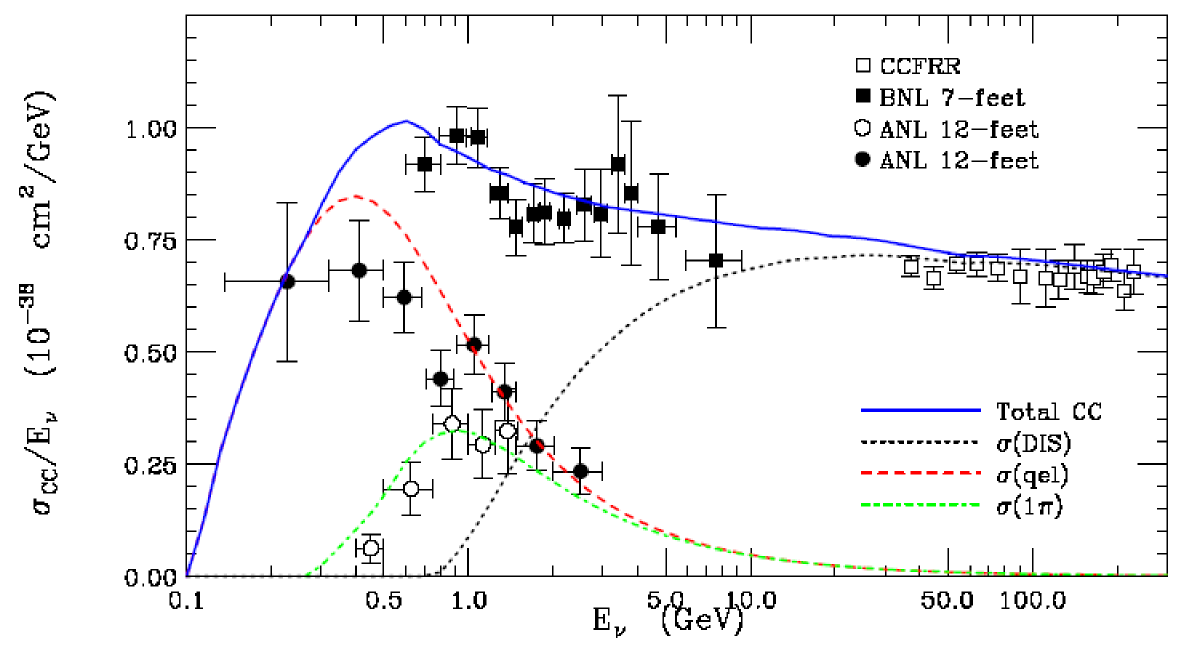
  (cf. 耐力 ~300 MPa)

  Material heavier than Ti might be destroyed.
- ✓ Cooling power and radiation shield 12GeV PS x 100

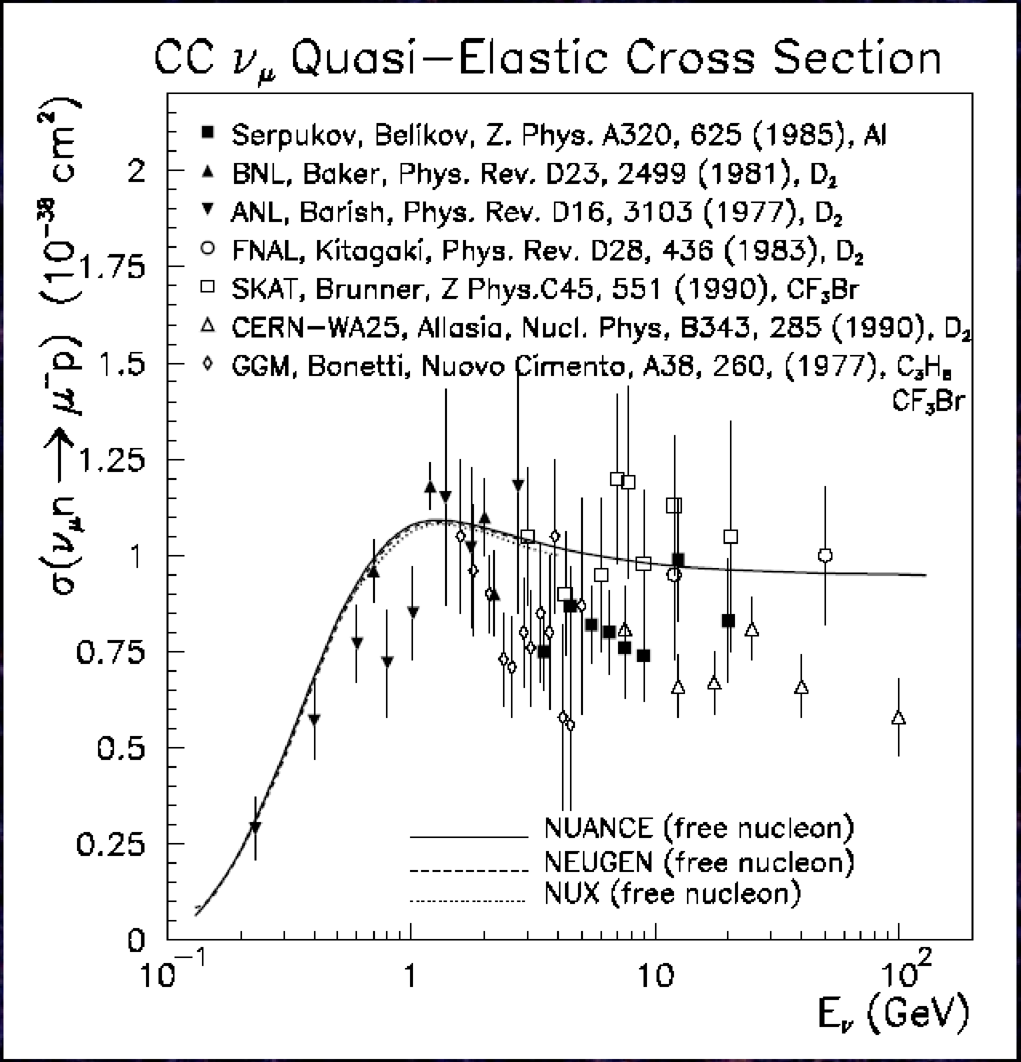
Common Features – Cross sections are poorly known in range 0.1-10 GeV

Data compiled by G.Zeller, hep-ex/0312061

Total ν_μ CC cross section

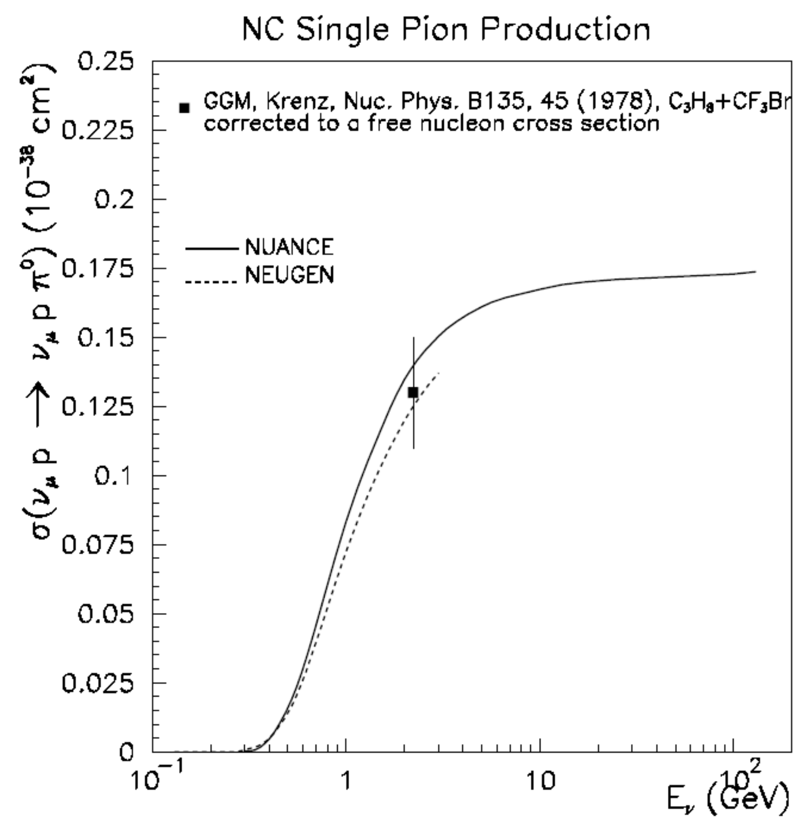


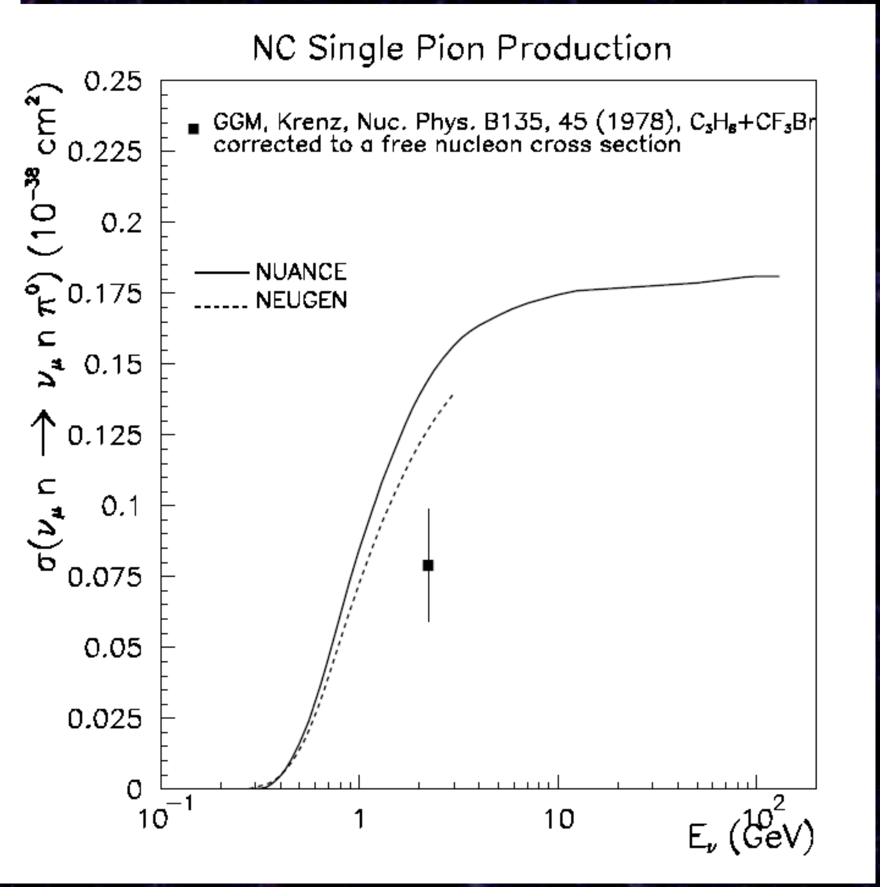
Common Features – Cross sections are poorly known in range 0.1-10 GeV



Data compiled by G.Zeller, hep-ex/0312061

Some are worse than others…

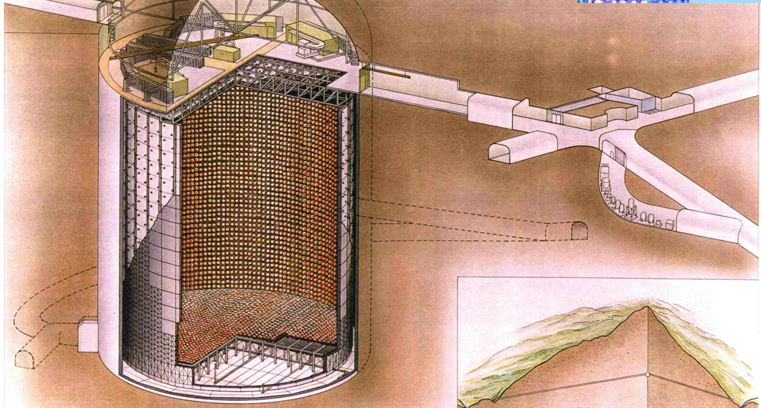




Data compiled by G.Zeller, hep-ex/0312061

JPARC – SuperK, aka T2K

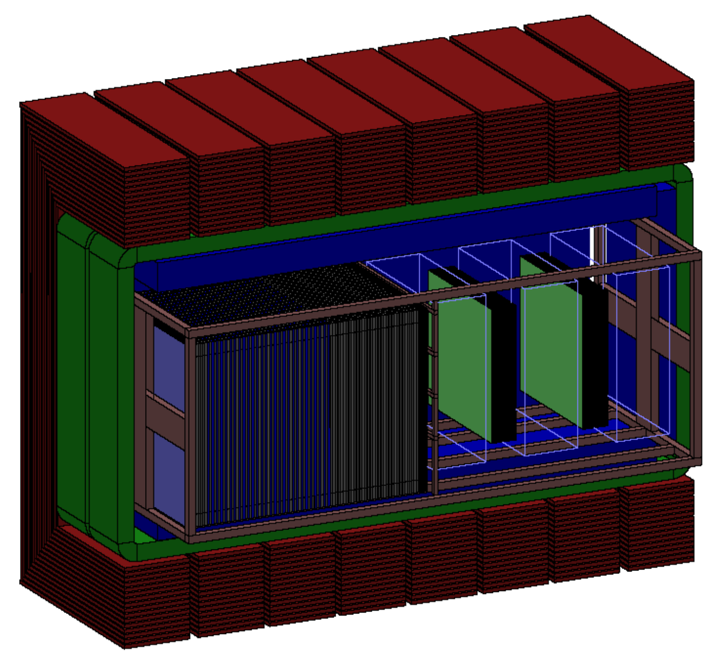
- *JPARC Accelerator –*
  - *Phase I, 0.75 MW @ 50 GeV*
  - *Phase II, raise power to 4 MW*
  - *PI Turn on 2009, but not full power till 2012?*
  - *Approved*
  - *Under const.*

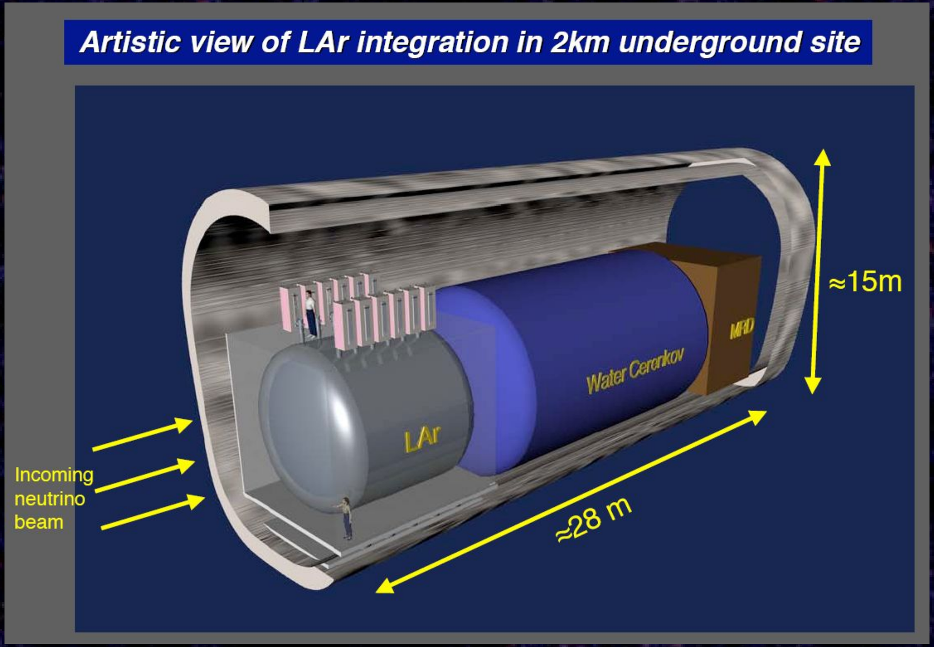


- *Far Detector – Super Kamiokande*
- *Rebuilding completed!*

T2K

- *Near Detector @ 280m*
  - *Built inside UA1/NOMAD magnet for p_μ measurement*
  - *Sandwich calorimeters/trackers and TPCs for precision beam spectrum and composition measurement.*

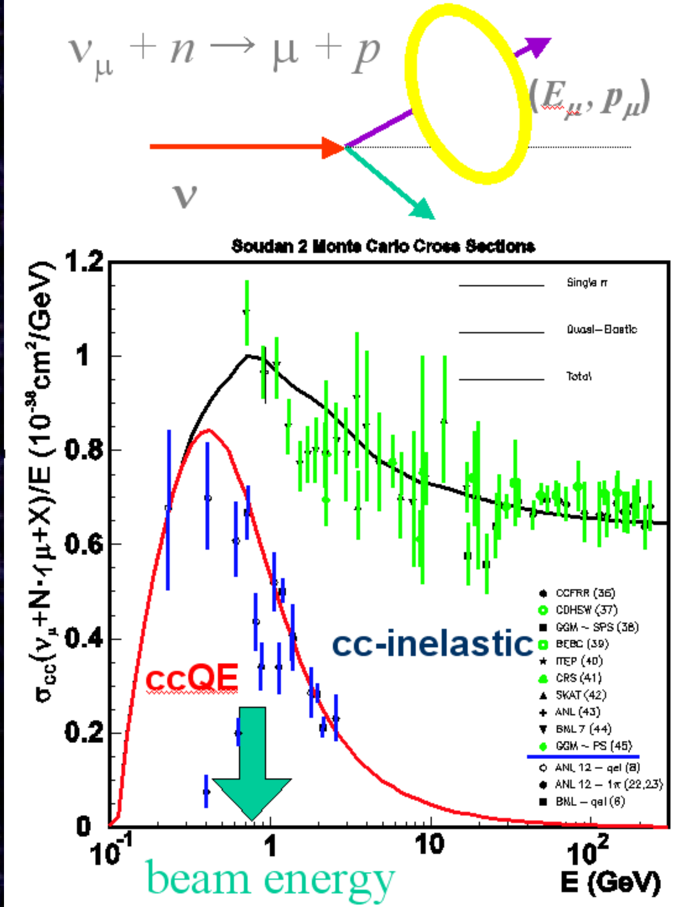


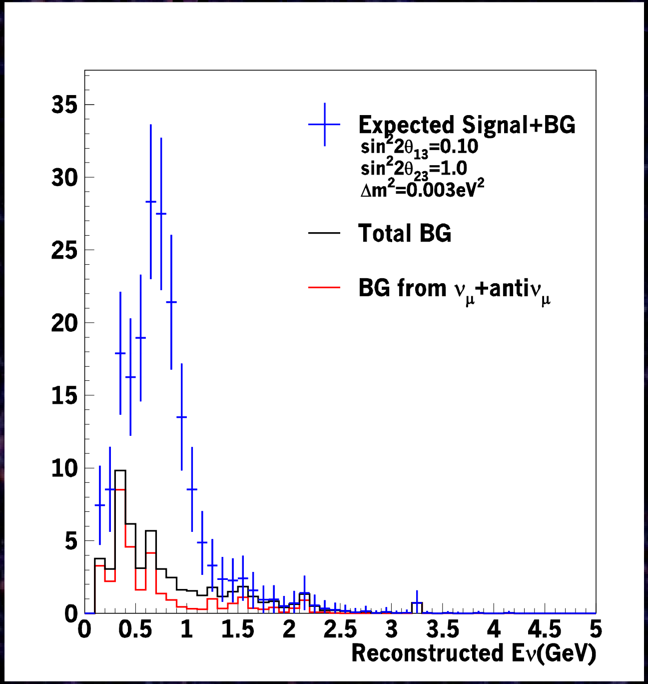


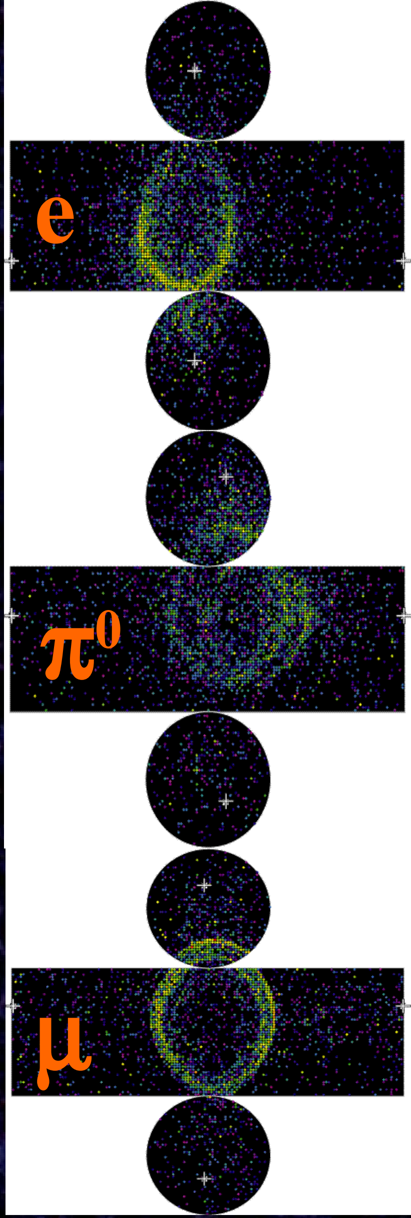
- *Near Detector @ 2km*
  - *Near/far spectral*
  - *uncertainties negligible*
  - *Water Cerenkov, MRD, and LAr*

T2K

L/E well-tuned to CCQE,
Critical for untangling
Beam ⊗ Σσ ⊗ detector



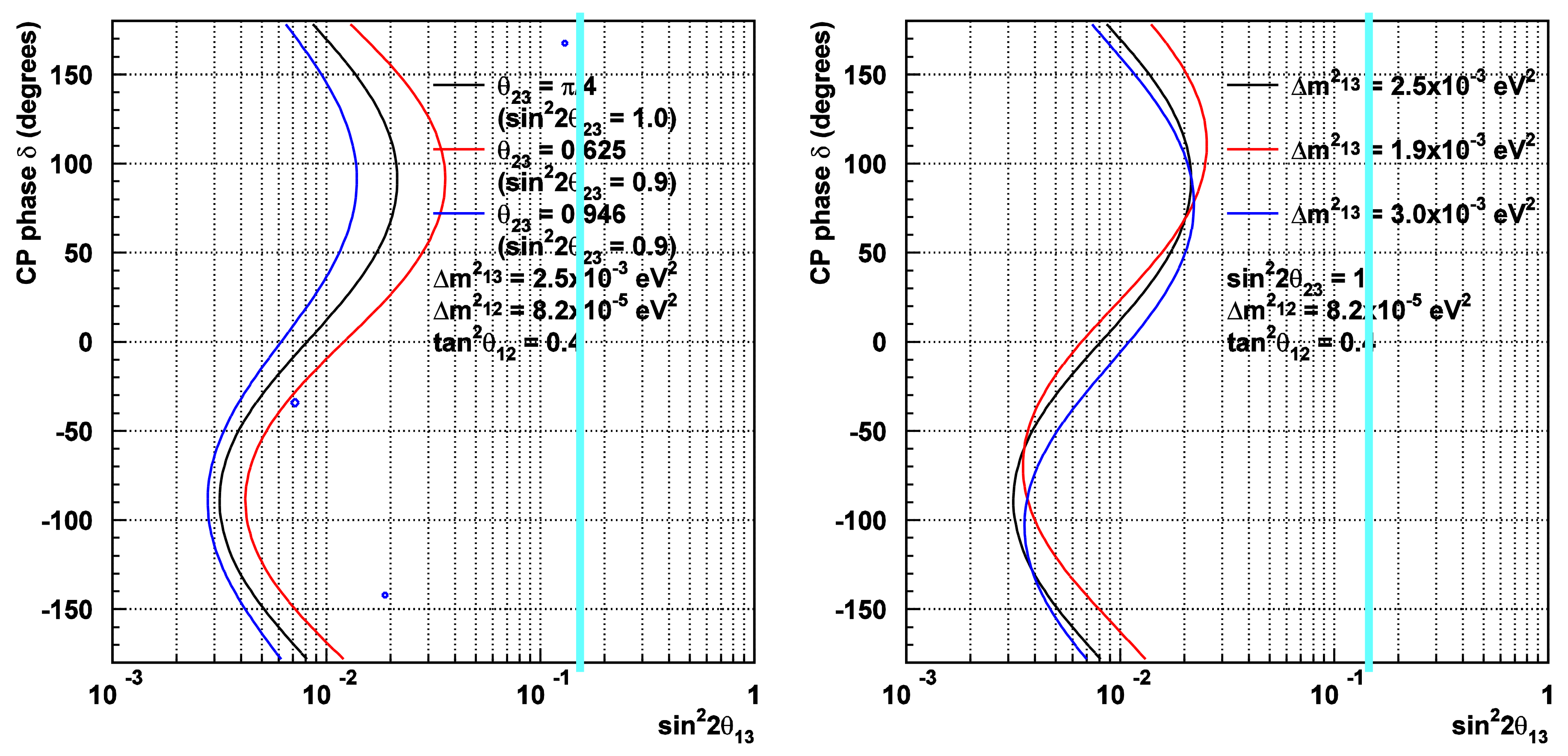




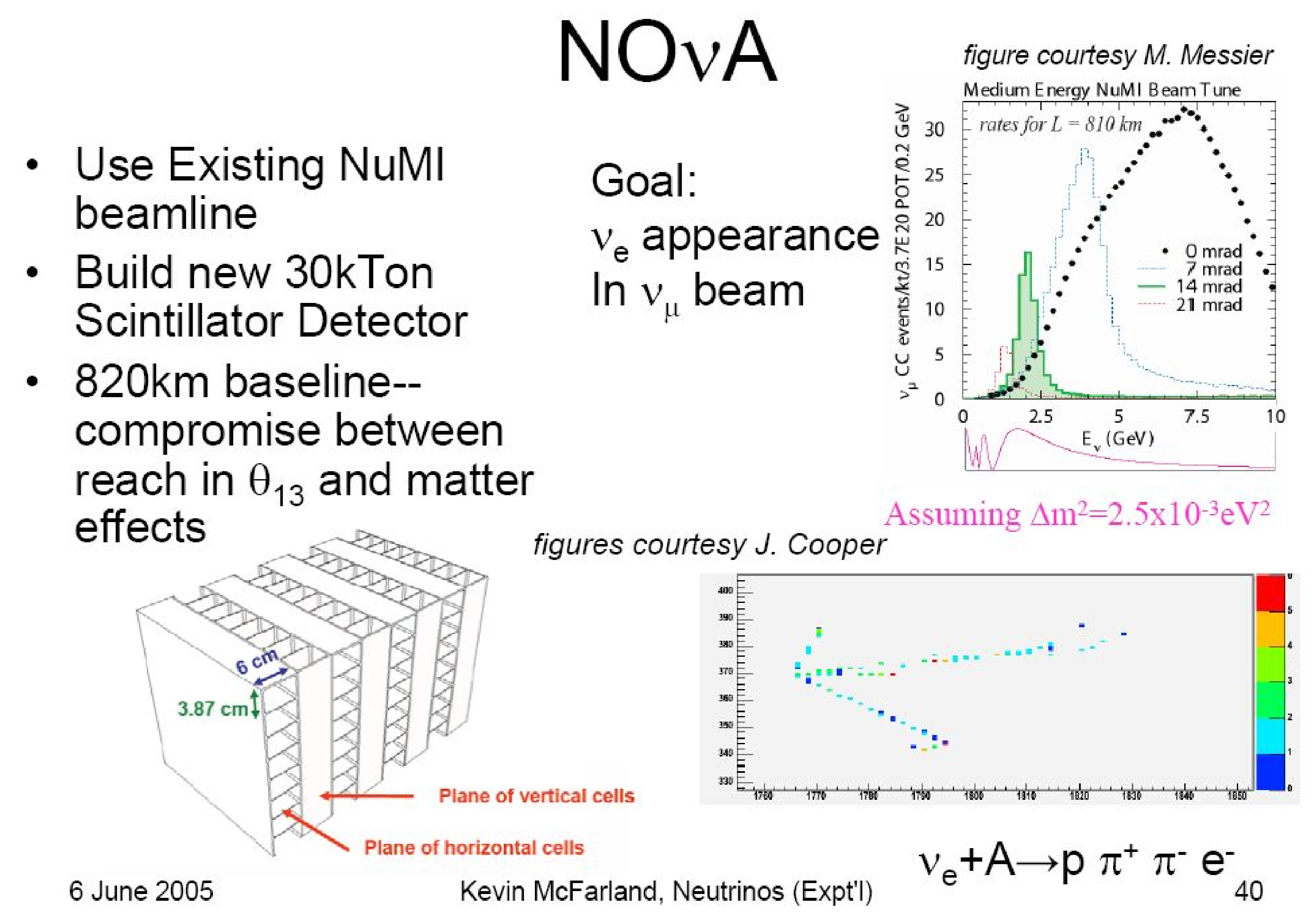
Super Kamiokande
well understood,
Ideal for separating
Electrons, μ, π^0

T2K Sensitivity

Total Rates: Standard Model vs. Experim



Plot from I. Kato/T2K



NOνA

- Use Existing NuMI beamline
- Build new 30kTon Scintillator Detector
- 820km baseline--compromise between reach in θ_{13} and matter effects

Goal:
ν_e appearance
In ν_μ beam

figure courtesy M. Messier

Assuming $\Delta m^2 = 2.5 \times 10^{-3} eV^2$

figures courtesy J. Cooper

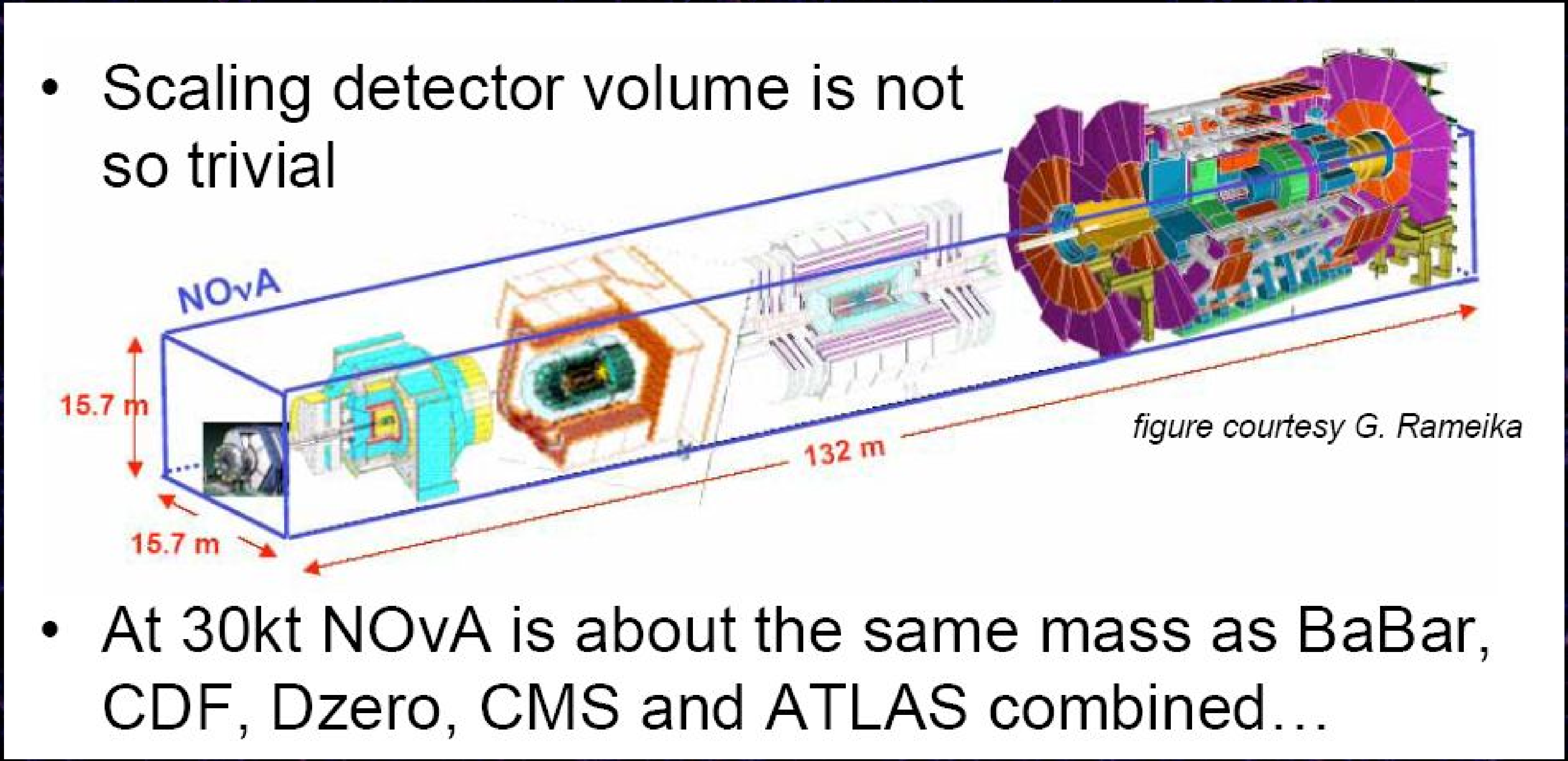
$\nu_e + A \rightarrow p\ \pi^+\ \pi^-\ e^-$

6 June 2005

Kevin McFarland, Neutrinos (Expt'l)

40

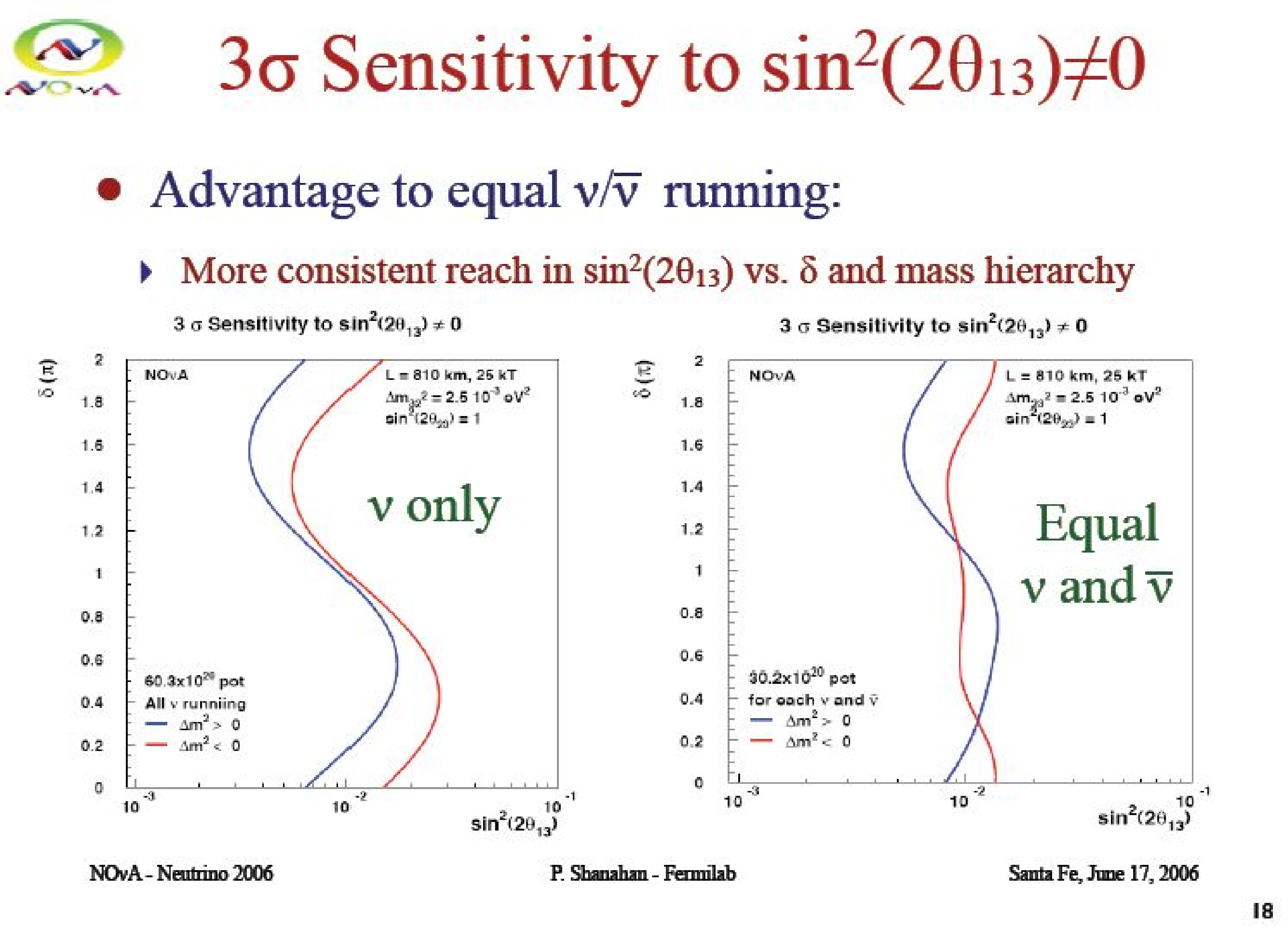
NOvA



- Scaling detector volume is not so trivial

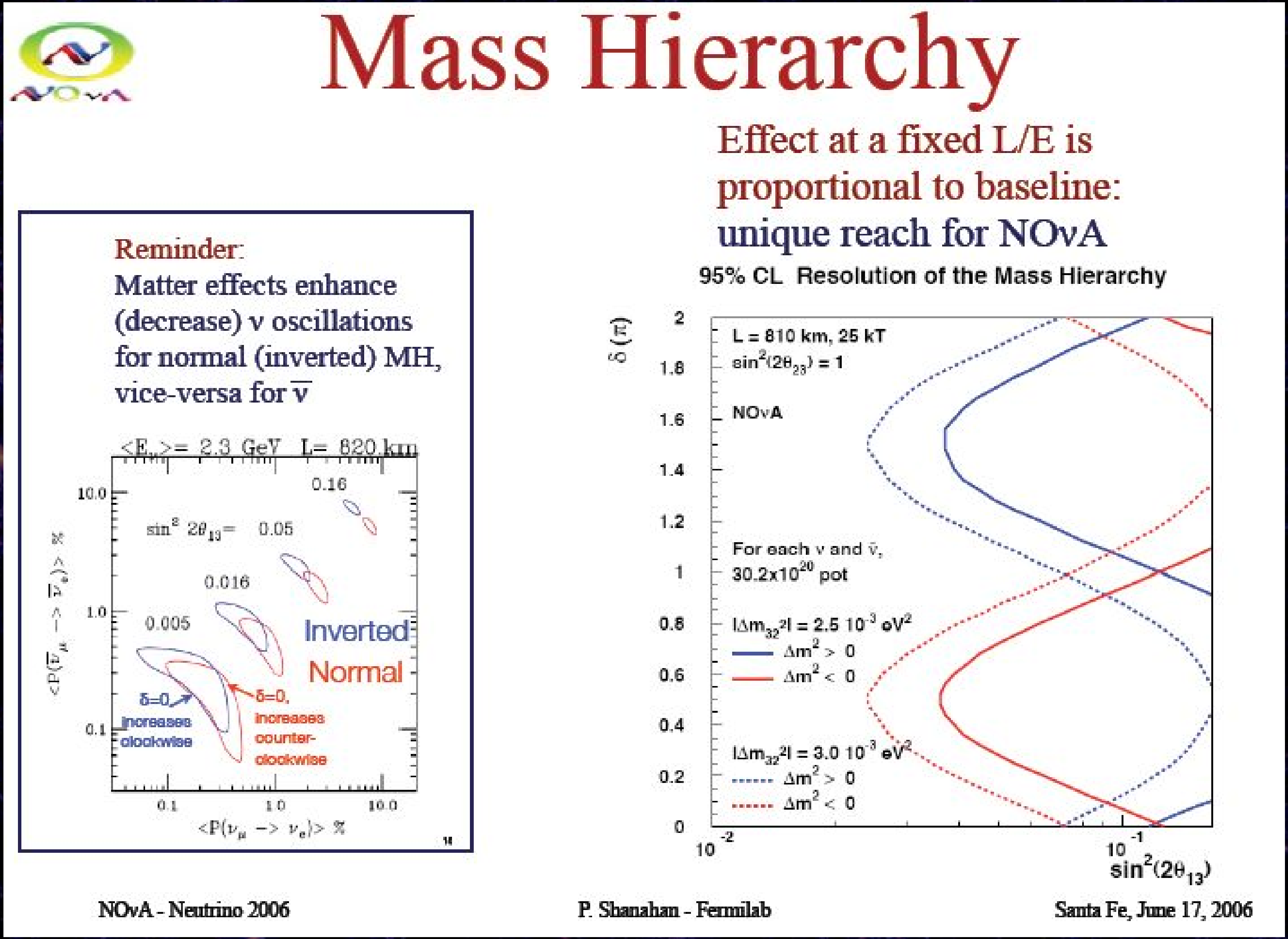
figure courtesy G. Rameika

- At 30kt NOvA is about the same mass as BaBar, CDF, Dzero, CMS and ATLAS combined…



3σ Sensitivity to $\sin^2(2\theta_{13})\neq 0$

- Advantage to equal $\nu/\bar{\nu}$ running:
  - More consistent reach in $\sin^2(2\theta_{13})$ vs. δ and mass hierarchy



Mass Hierarchy

Effect at a fixed L/E is proportional to baseline: unique reach for NOνA

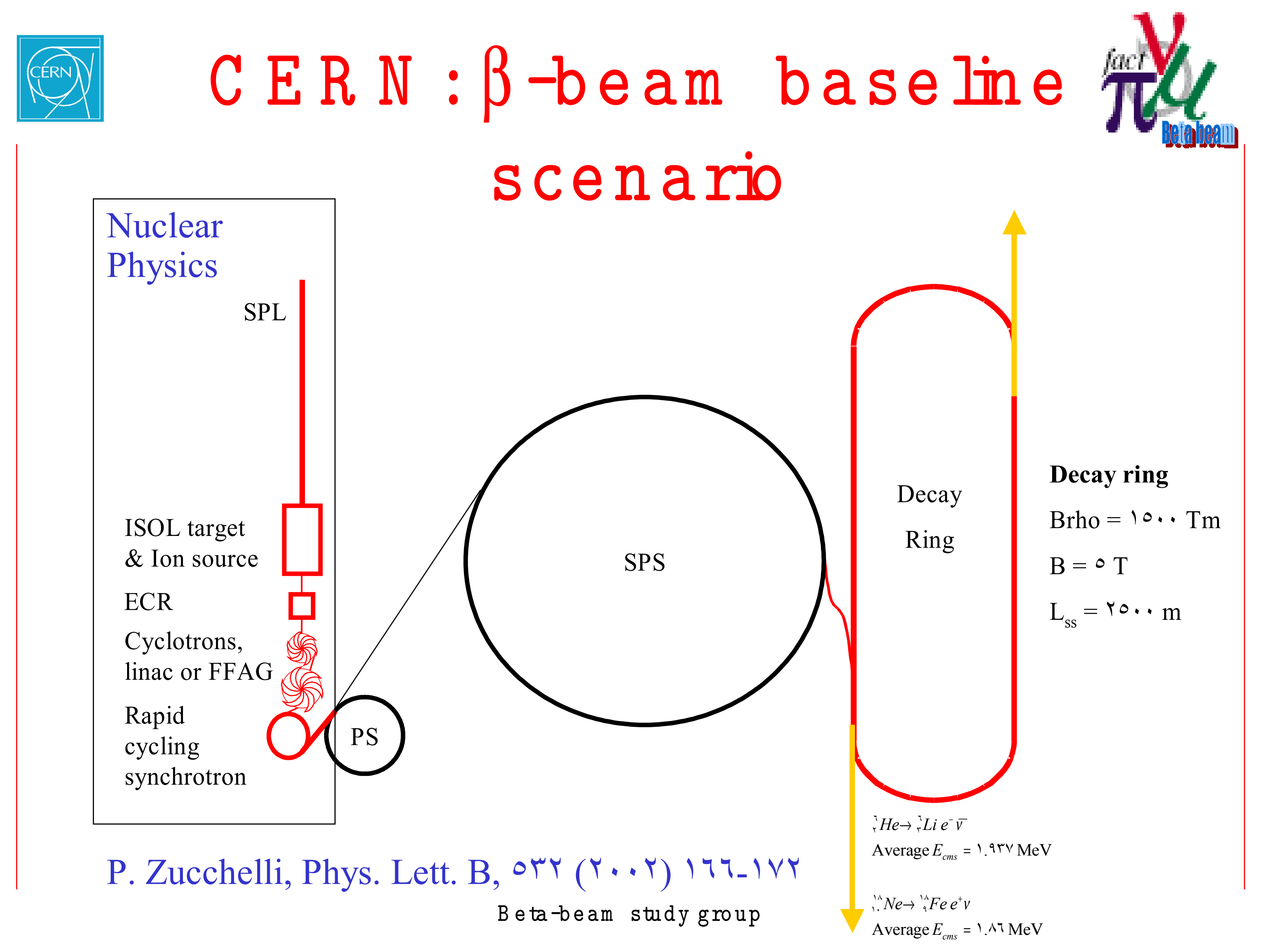
Reminder:
Matter effects enhance (decrease) ν oscillations for normal (inverted) MH, vice-versa for $\overline{\nu}$

NOvA - Neutrino 2006

P. Shanahan - Fermilab

Santa Fe, June 17, 2006

β Beams



CERN : β-beam baseline scenario

Decay ring

Brho = ١٥٠٠ Tm

B = ٥ T

L_{ss} = ٢٥٠٠ m

${}^{٦}_{٢}He \rightarrow {}^{٦}_{٣}Li\, e^{-} \bar{\nu}$

Average E_{cms} = ١.٩٣٧ MeV

${}^{١٨}_{١٠}Ne \rightarrow {}^{١٨}_{٩}Fe\, e^{+} \nu$

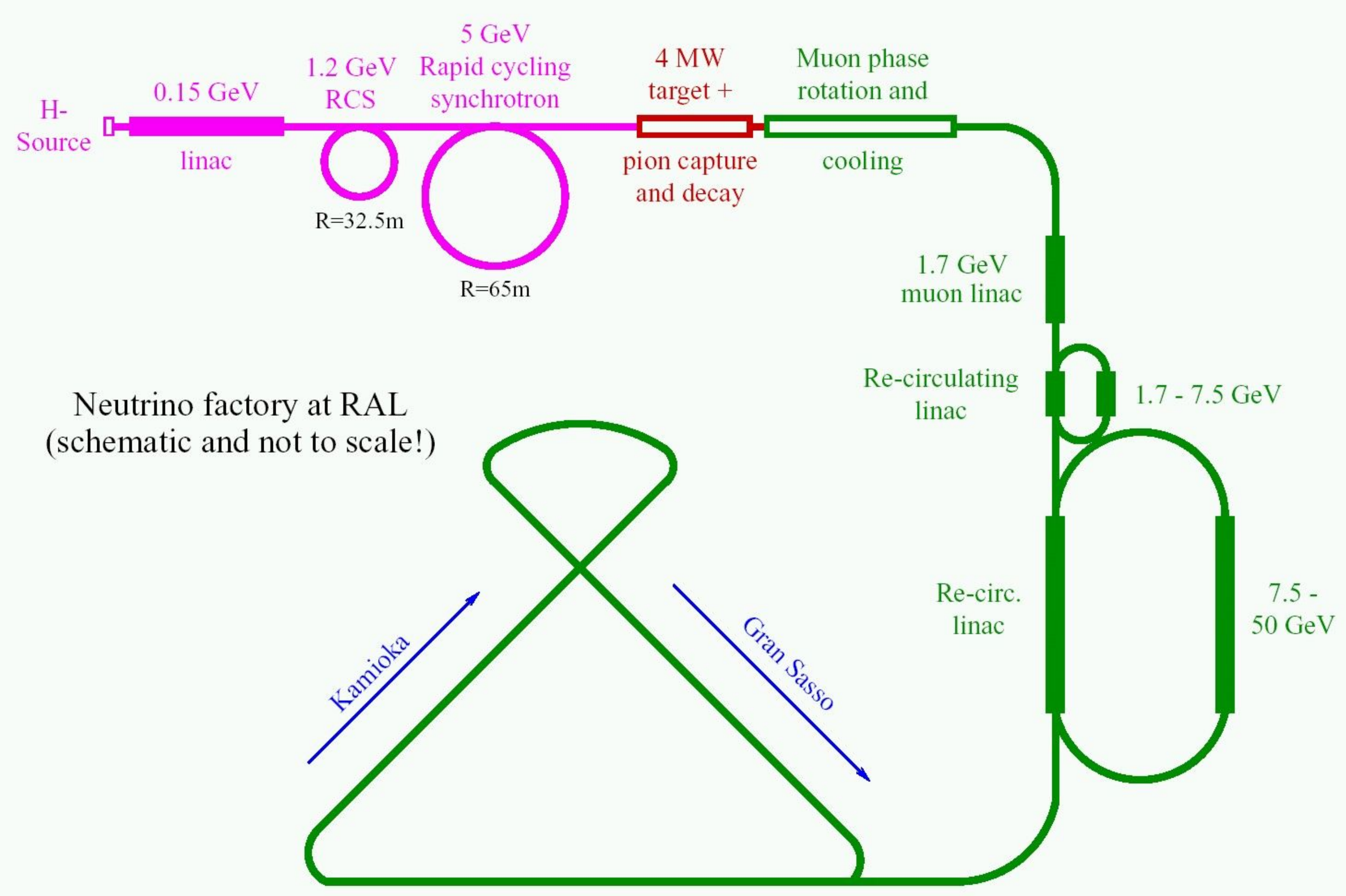
Average E_{cms} = ١.٨٦ MeV

P. Zucchelli, Phys. Lett. B, ٥٣٢ (٢٠٠٢) ١٦٦-١٧٢

Beta-beam study group

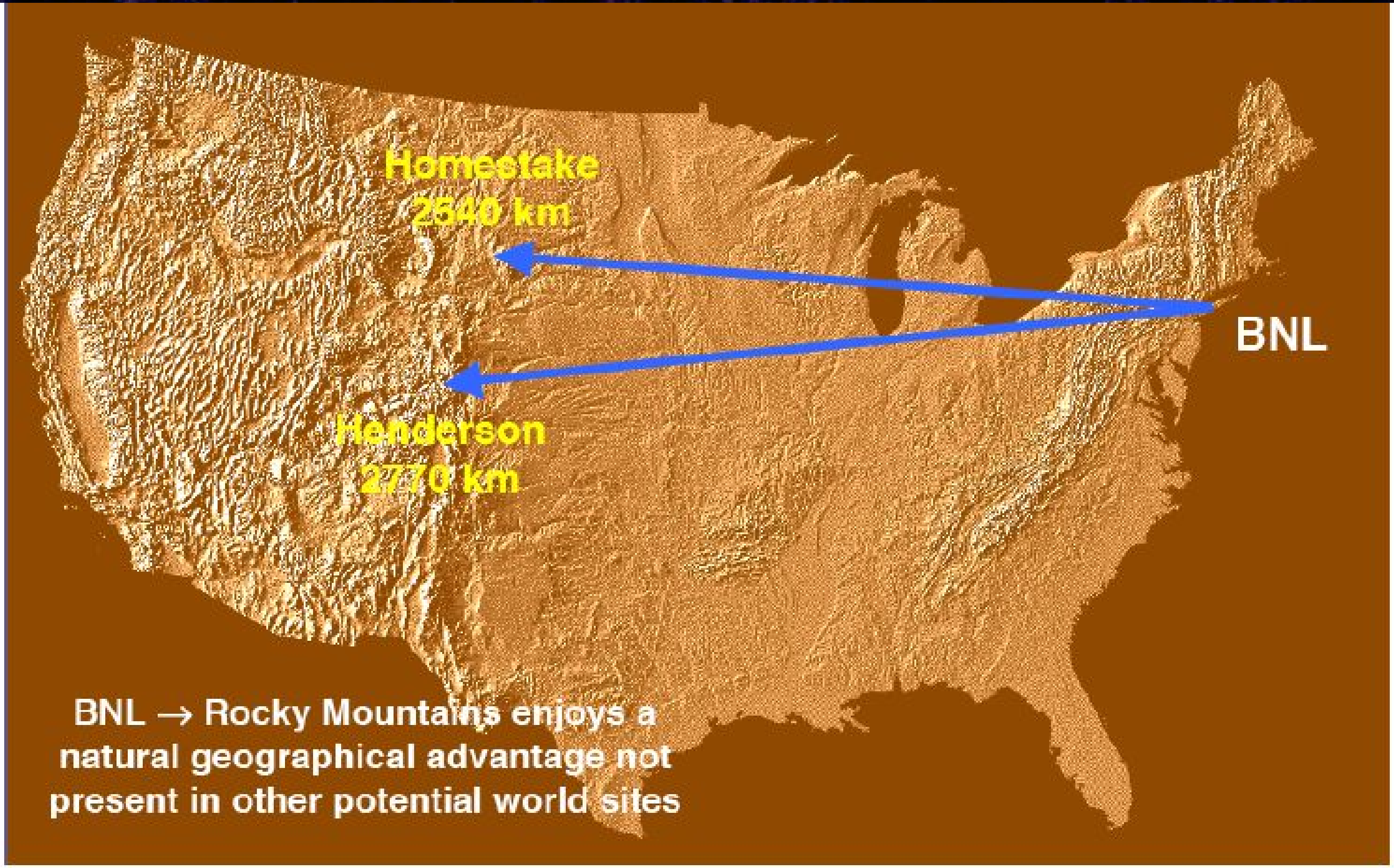
Slide from M. Lindroos

A Neutrino Factory



Neutrino factory at RAL
(schematic and not to scale!)

Further Ideas – the Wide Band Beam (WBB)

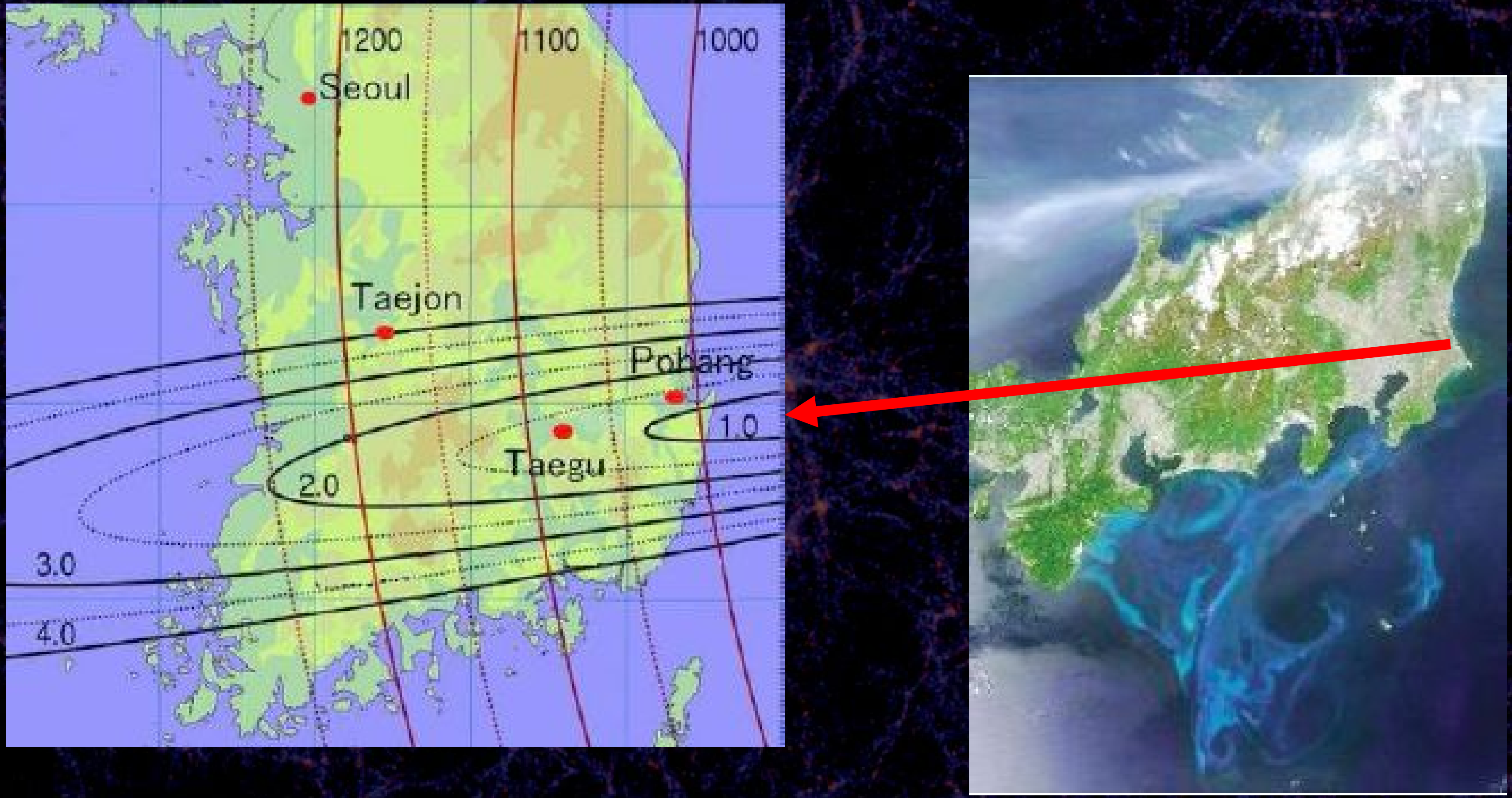


BNL → Rocky Mountains enjoys a natural geographical advantage not present in other potential world sites

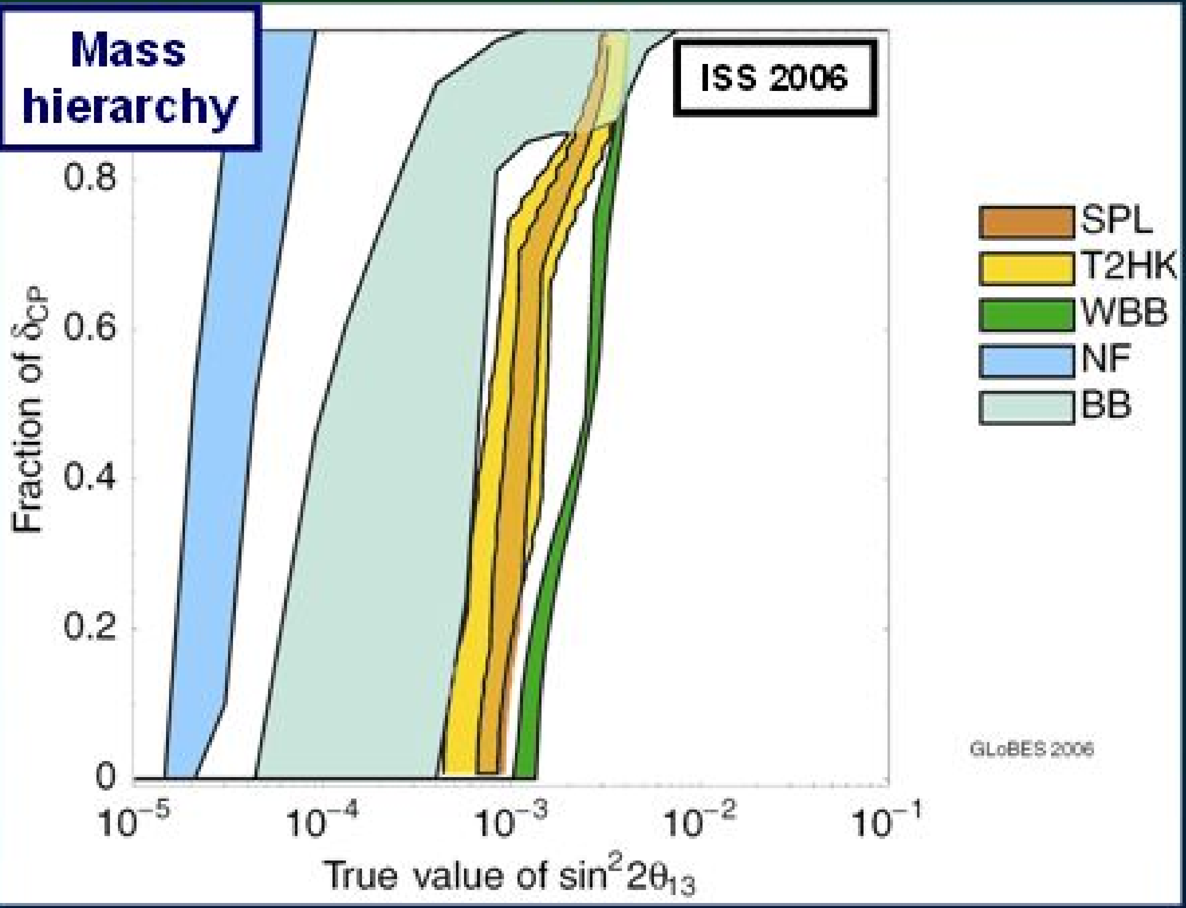
- 28 GeV protons. 1 MW beam power. Horn focussed
- 500 kT water Cherenkov detector stationed in a new DUSEL.
- baseline > 2500 km. WIPP, Henderson, Homestake

Further Ideas – the second maximum

T2KK: Tohuku→Kamioka→Korea with 2 ½-HyperKamiokandes



Comparison: mass hierarchy



SPL
Systematics: 2% – 5%

T2HK
Systematics: 2% – 5%

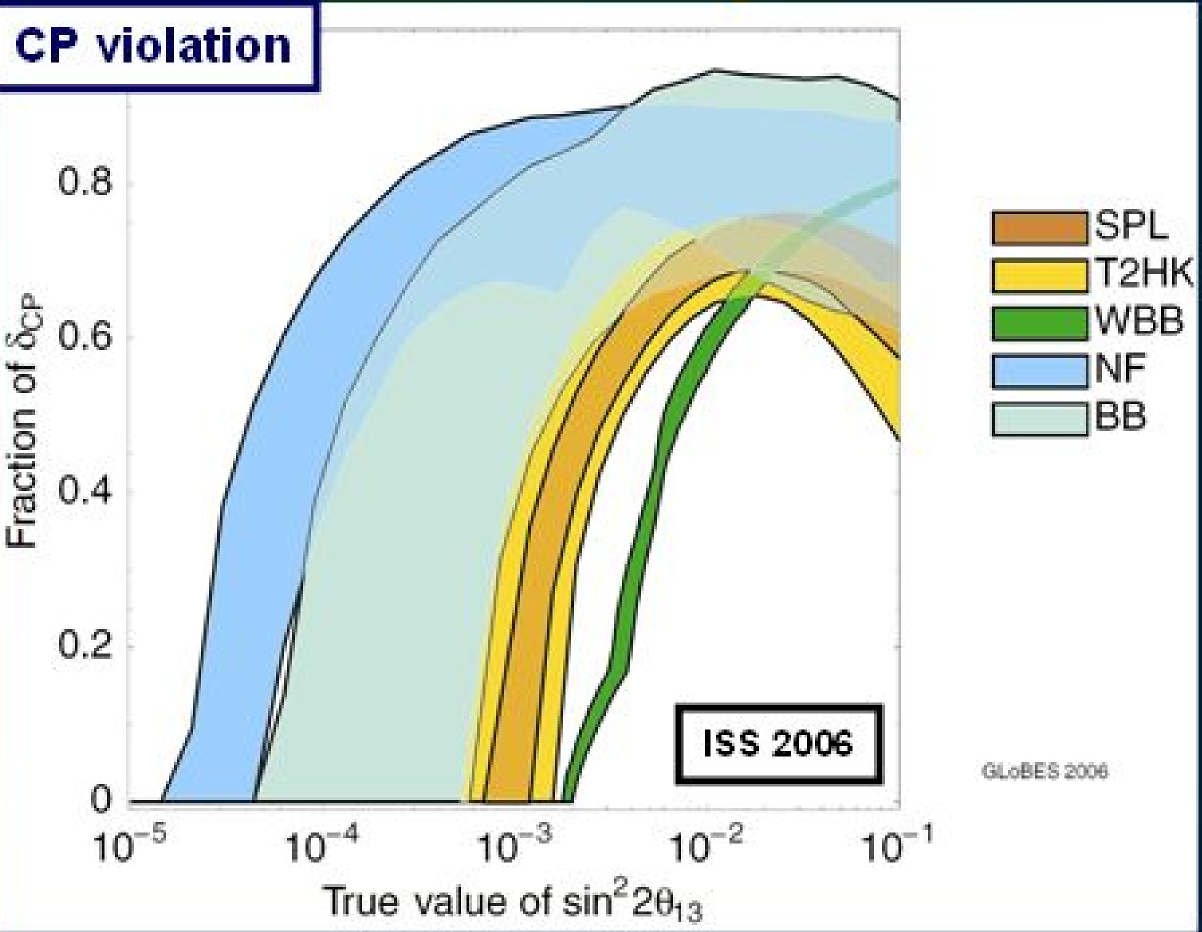
WBB
Systematics from proposal

Beta beam
$\gamma = 100$
500 kT H_2O Ç (130 km)

$\gamma = 350$
500 kT H_2O Ç (730 km)

Neutrino Factory
Golden, 4000,
$E_\mu = 50$ GeV
Golden* (4000 km), Golden* (7500 km)
$E_\mu = 20$ GeV

Comparison: CP violation



SPL

Systematics: 2% – 5%

T2HK

Systematics: 2% – 5%

WBB

Systematics from proposal

Beta beam

$\gamma = 100$

500 kT H_2O Ç (130 km)

$\gamma = 350$

500 kT H_2O Ç (730 km)

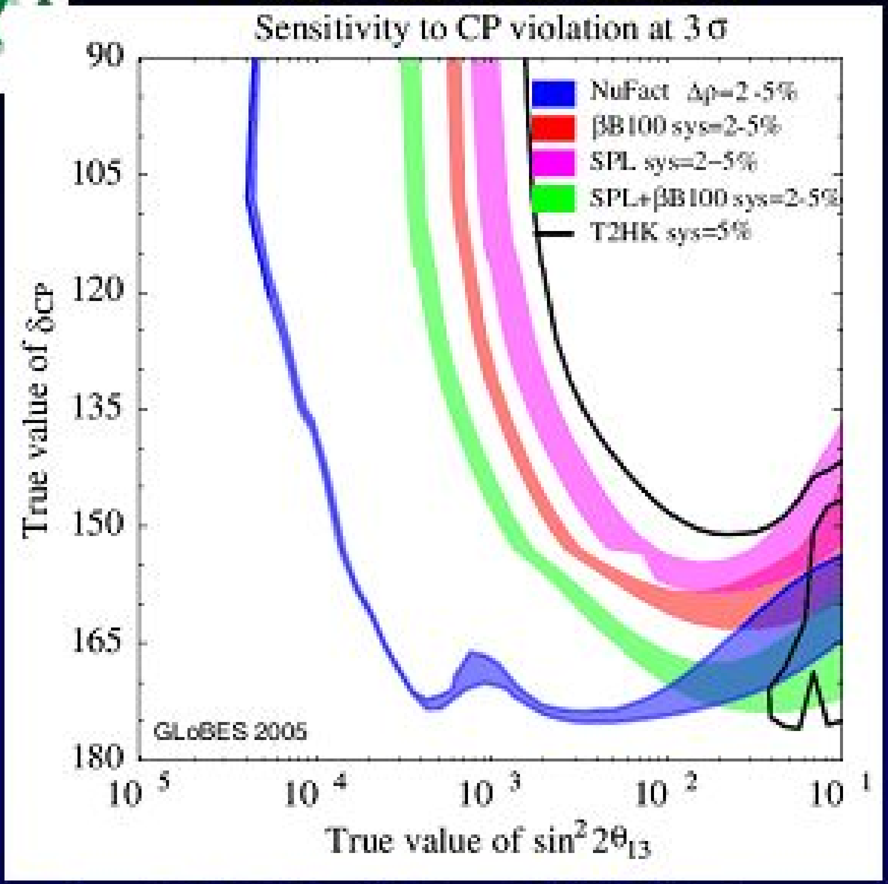
Neutrino Factory

Golden, 4000, $E_\mu = 50$ GeV

Golden* (4000 km), Golden* (7500 km)

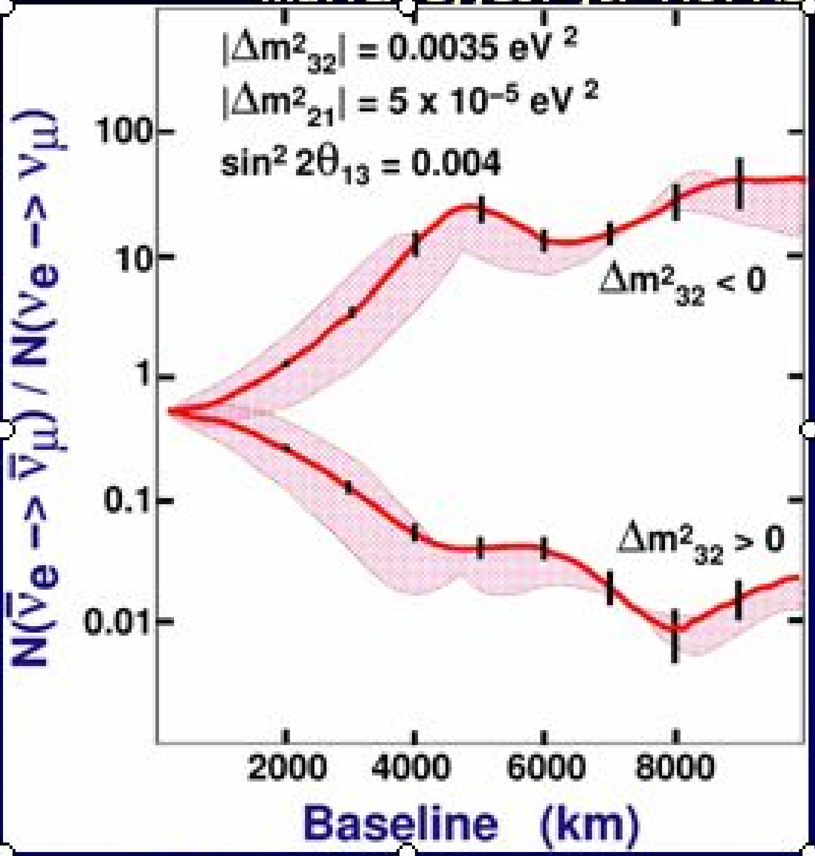
$E_\mu = 20$ GeV

What do we learn?



Sensitivity to CP violation at 3 σ

matter effect for NUFACT



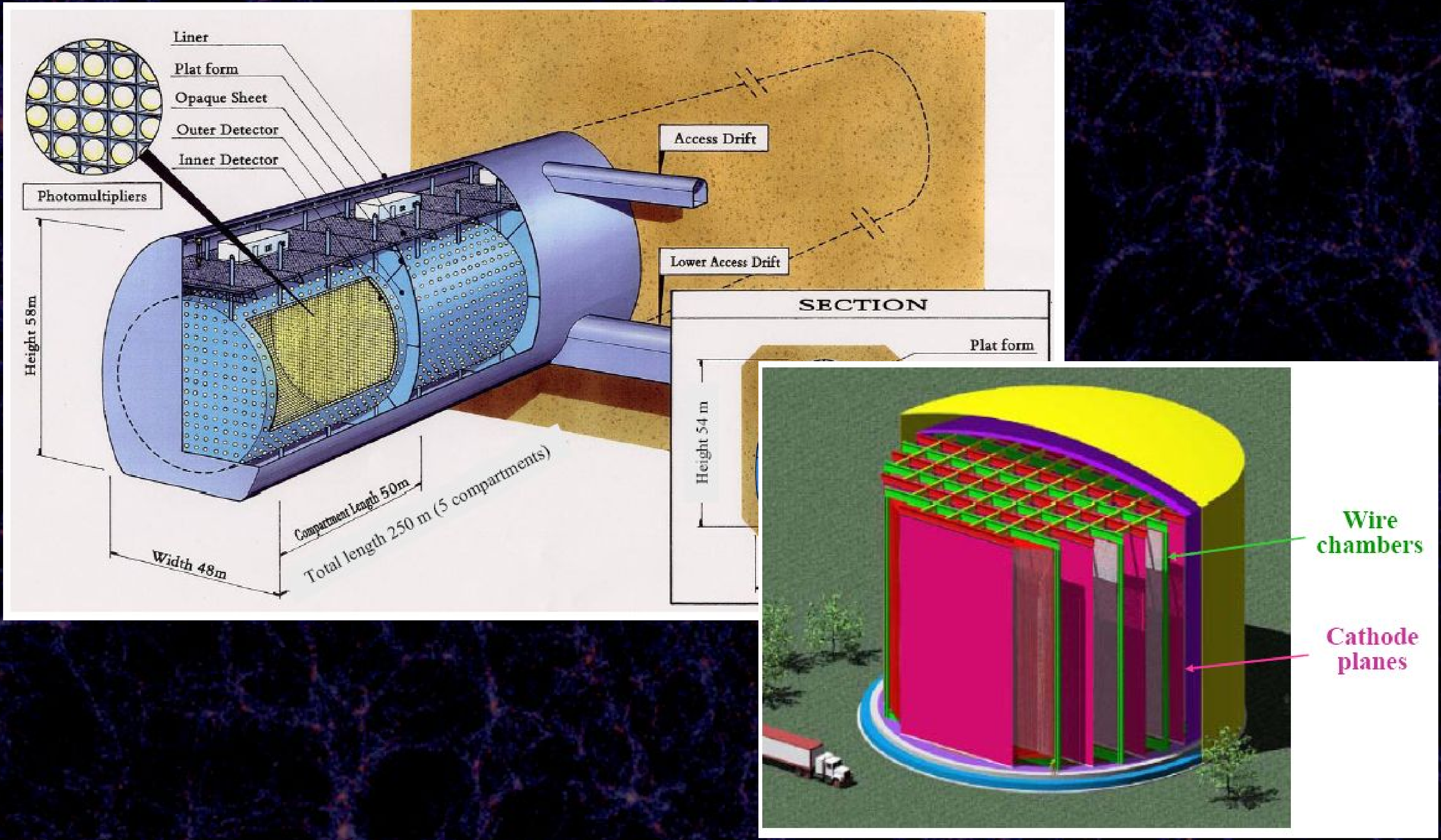
1. Both (BB+SB+MD) and NUFACT outperform e.g. T2HK on most cases.

2. combination of BB+SB is really powerful.

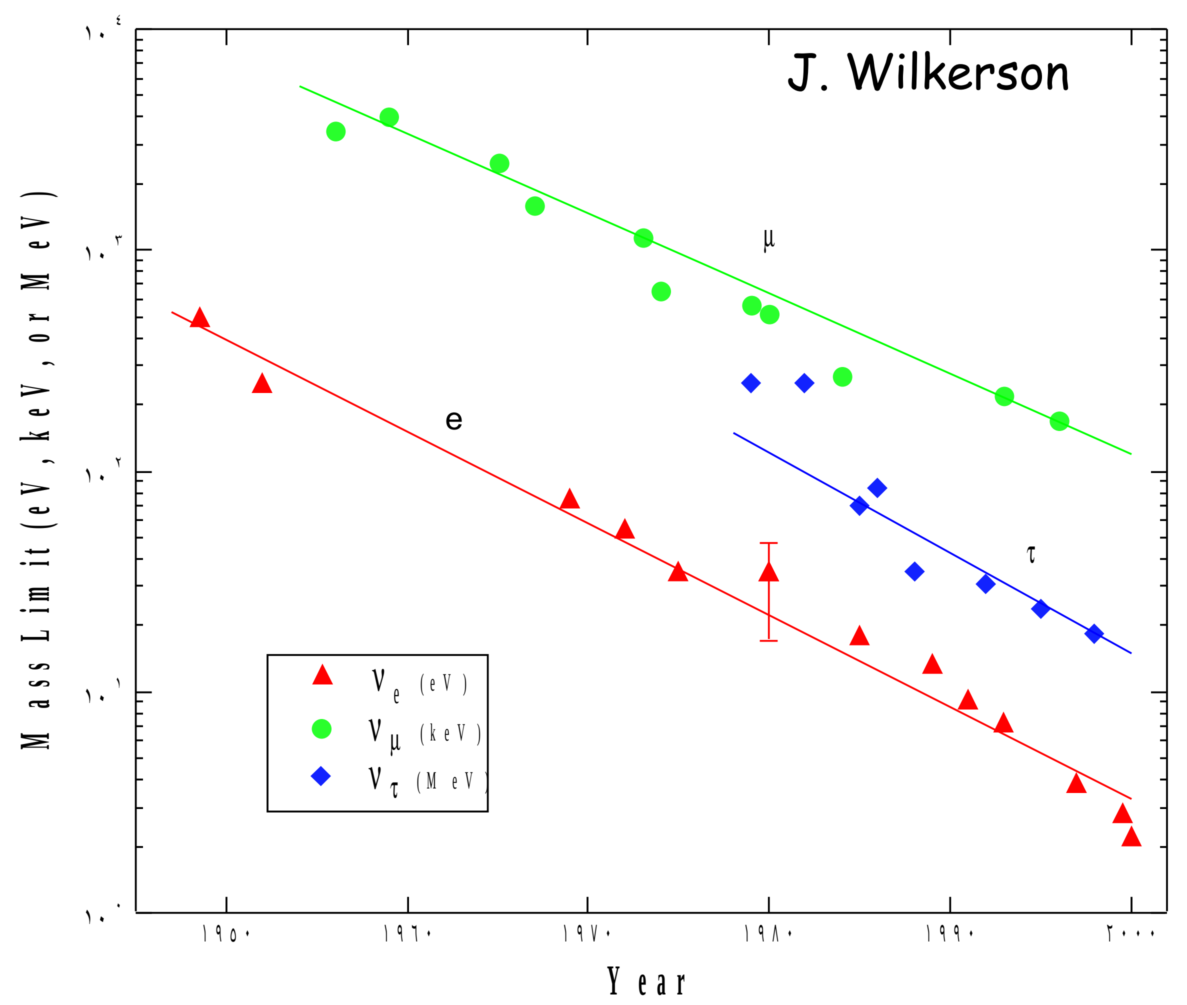
3. for $\sin^2 2\theta_{13}$ below 0.01 NUFACT as such outperforms anyone

4. for large values of θ_{13} systematic errors dominate:
Matter effects for NUFACT, cross-sections for low energy beams.
This is because we are at first maximum or above, → CP asymmetry is small!

All ideas beyond T2K/NOvA require <u>HUGE</u> detectors

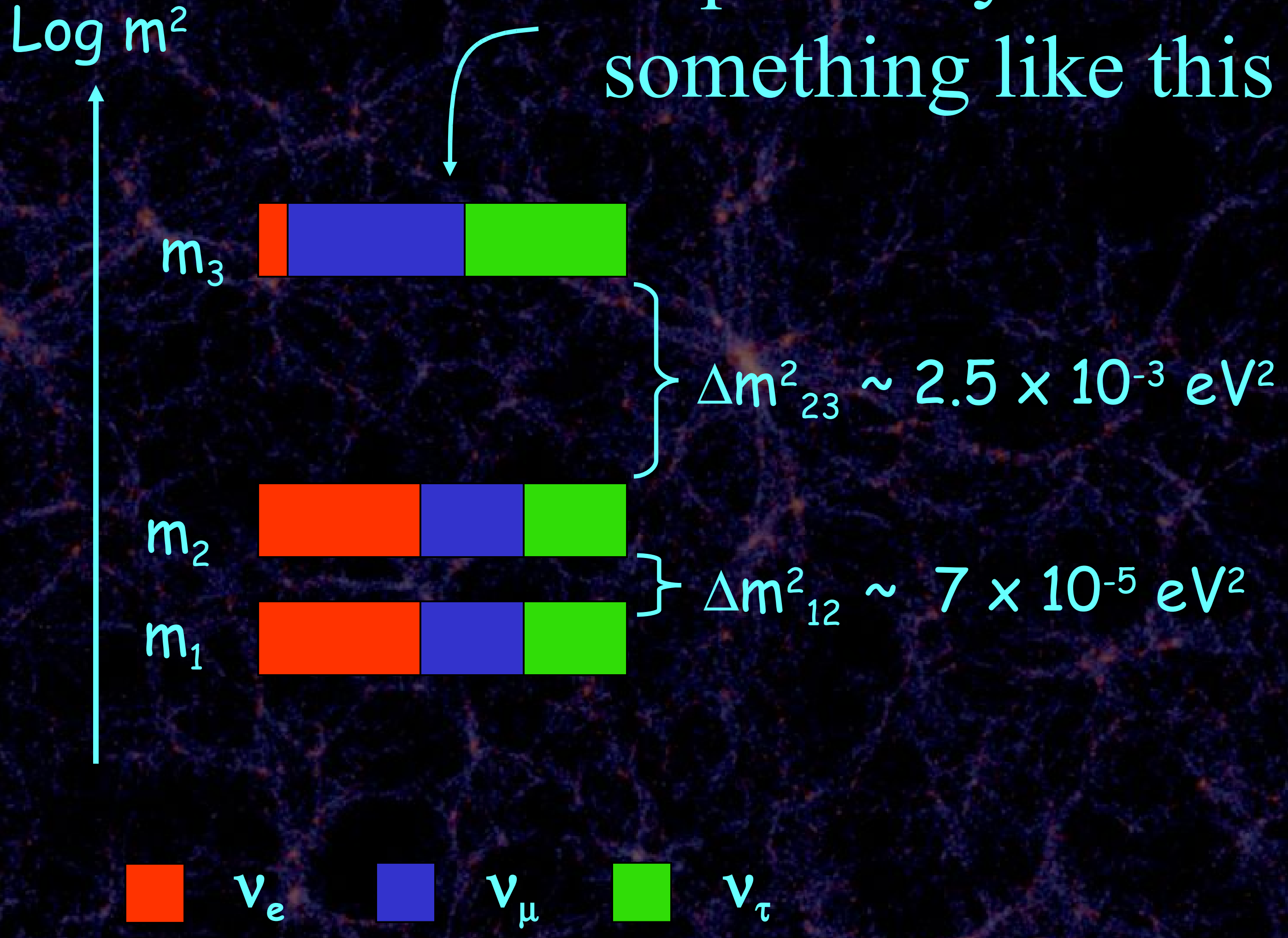


Absolute Neutrino Masses



So what does this all mean about neutrino mass?

It “probably” looks something like this



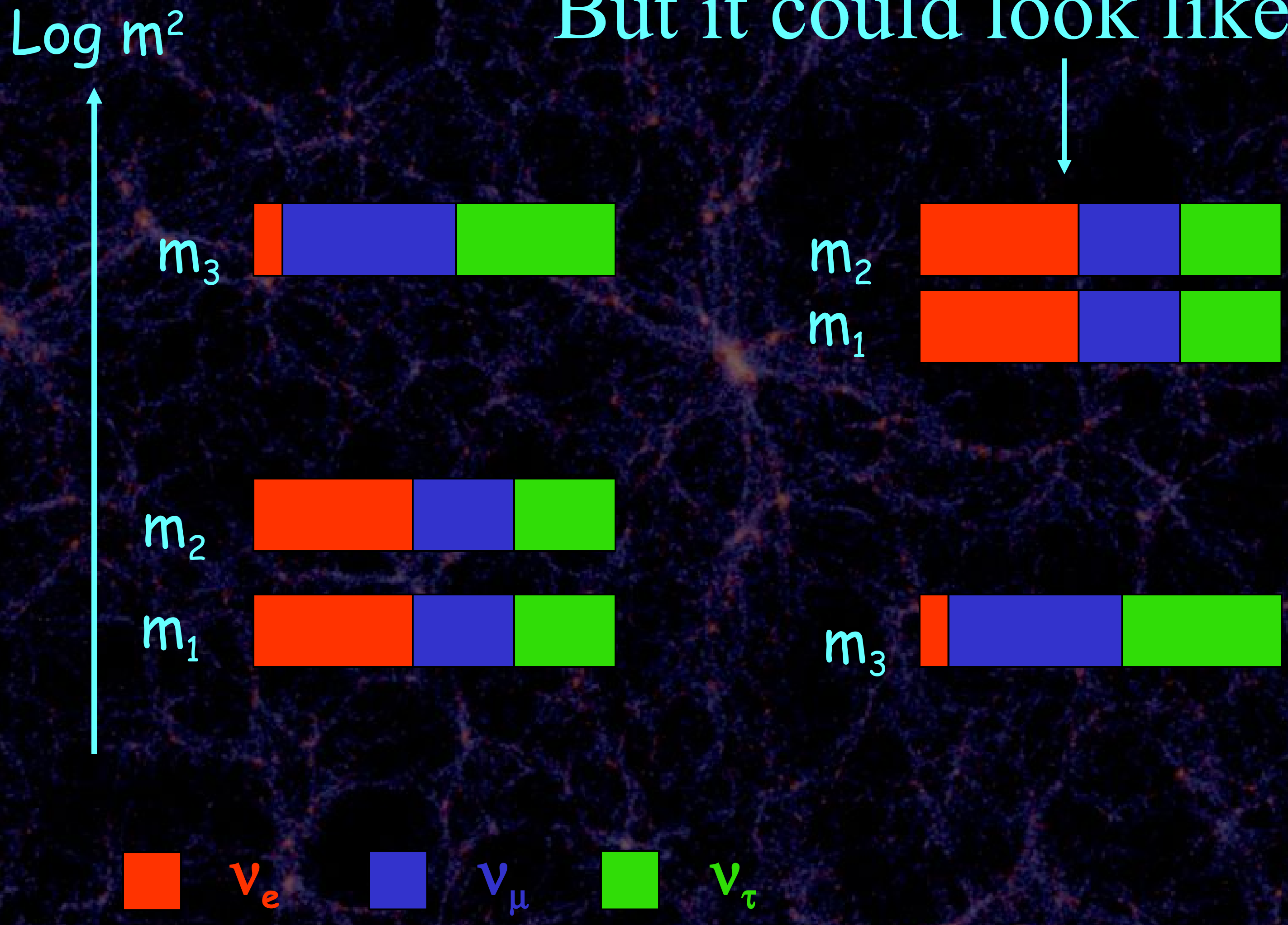
$\Delta m^2_{23} \sim 2.5 \times 10^{-3}$ eV^2

$\Delta m^2_{12} \sim 7 \times 10^{-5}$ eV^2

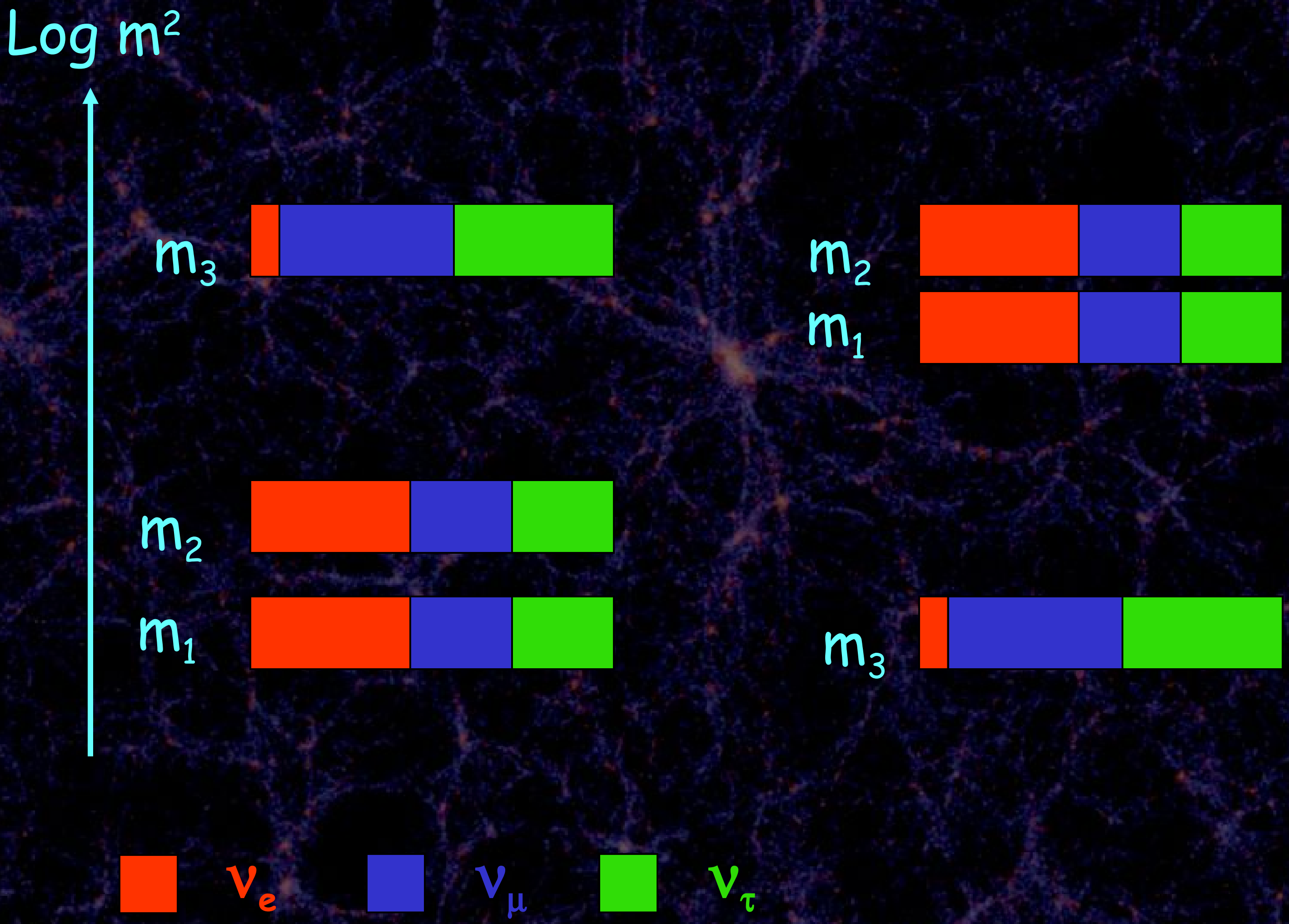
🟥 ν_e 🟦 ν_μ 🟩 ν_τ

So what does this all mean about neutrino mass?

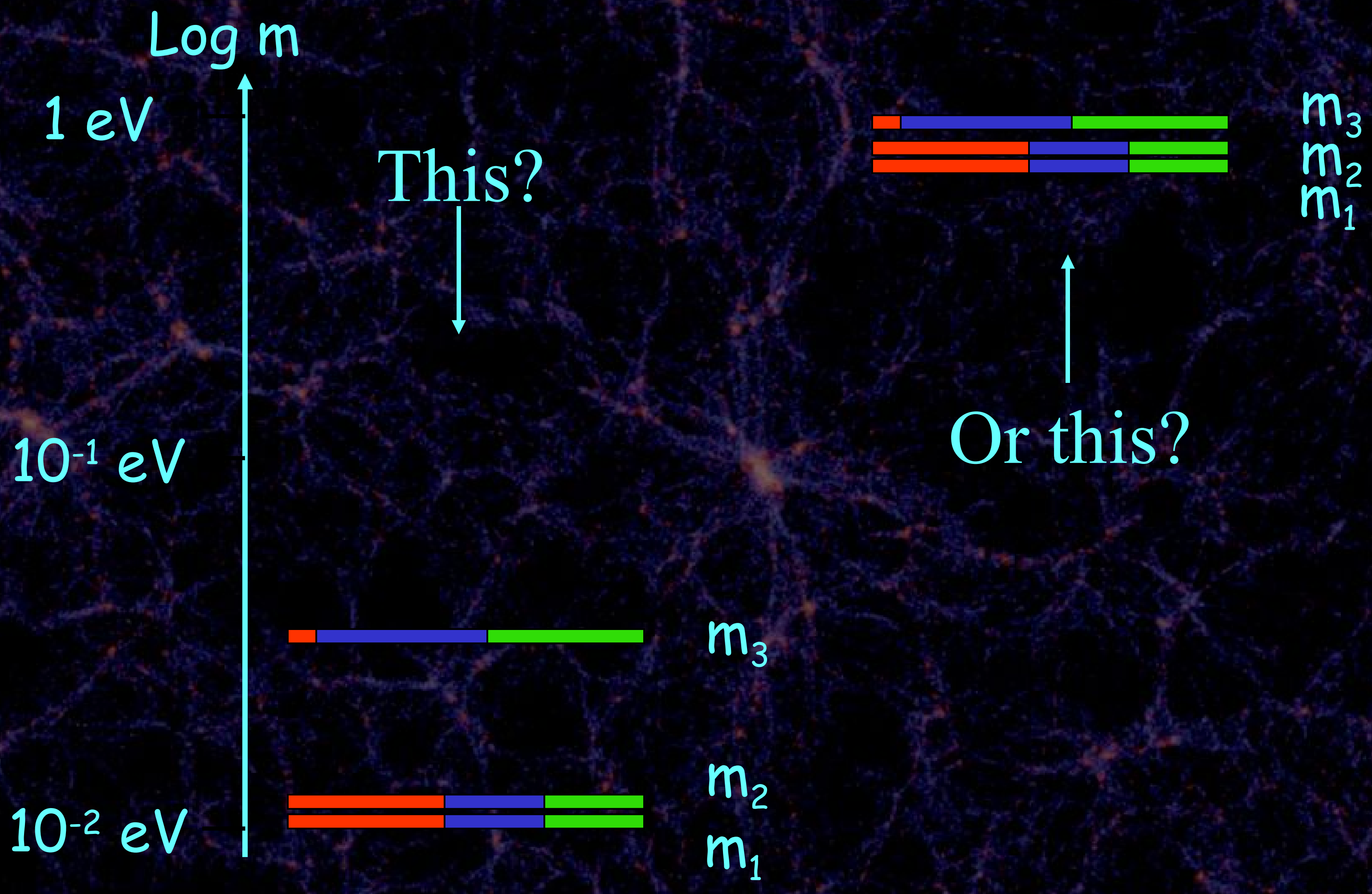
But it could look like this



This makes a factor of two difference in the cosmological contribution, but a factor of two on what?



Even more significant is the absolute scale.



🟥 ν_e 🟦 ν_μ 🟩 ν_τ

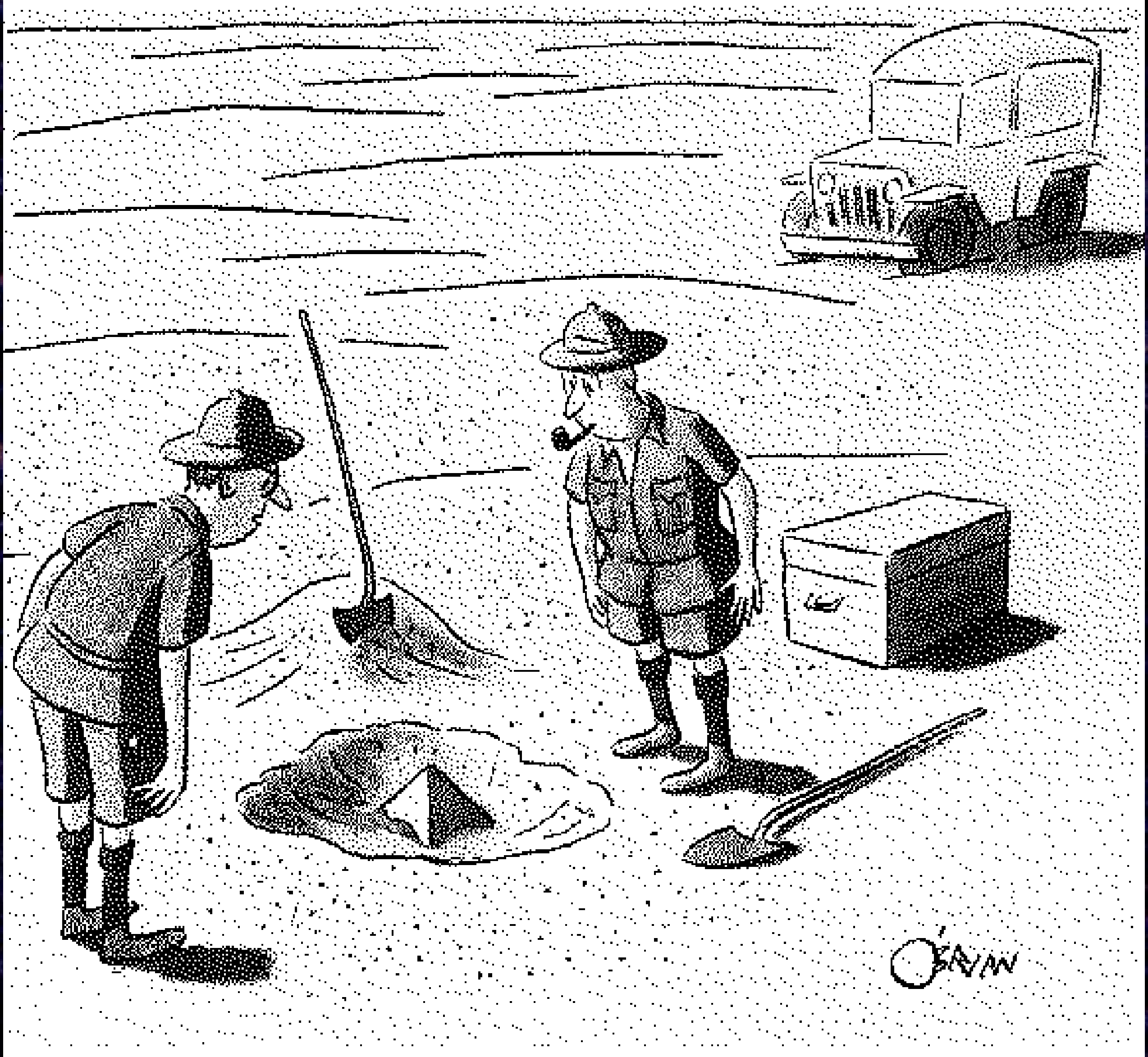
Does this look natural?

Measuring absolute m_ν

- Supernovae – Prodigious producers of neutrinos, and measuring time shifts can in principle measure neutrino masses, $m_\nu < \sim 30$ eV.
- Kinematic limits: If you believe the oscillation results, all $\Delta m^2 \ll 1$ eV, therefore only ν_e measurements have useful sensitivity → current best is Tritium Beta Decay, $m_\nu < 2.2$ eV.
- If neutrinos have Marjorana masses, then zero-neutrino double-beta decay is allowed → observation of $0\nu\beta\beta$ δεχαψ would be direct evidence for neutrino mass, $\langle m_\nu \rangle < \sim 1.3$ eV.
- Neutrinos are the second most numerous particle in the Universe → even a tiny neutrino mass could have astrophysical implications, $\Sigma m_\nu < 0.23$ eV(?)

Conclusions

- Neutrino masses and mixings give the first confirmed physics beyond the Standard Model.
- MiniBooNE results remove the last inconsistent result from a picture of three massive, mixing neutrinos.
- More accurate determinations of already seen parameters will probe symmetries of the theory.
- We must now push to see the three sines – $\sin^2 2\theta_{13}$, sign(Δm_{23}^2), $\sin \delta$. The first target is to see $\nu_\mu \rightarrow \nu_e$, which is the target of T2K and NOvA, and/or reactor disappearance on ~ 1km baseline.
- There are a number of options for the steps beyond that – β beams, EC beams, Supererbeams, Neutrino Factory – a vigorous discussion is taking place to select the optimal programme (join in!).
- All of these next steps have substantial experimental challenges, but a large, coherent, and strongly interacting world community exists which is making excellent progress in understanding the opportunities and constraints – a world scoping study for the NF is approaching completion.
- The absolute mass problem is just as interesting, and a vigorous experimental community is attacking there as well.
- There are also HE astrophysical neutrinos, SN and relic SN neutrinos, etc.
- There is plenty of work for everybody. Join in!



"This could be the discovery of the century. Depending, of course, on how far down it goes."