Neutrino Experiments - Can we reach a Precision Era?

Peter Dornan

Imperial College London

Why Neutrinos are important?

Brief Review of Neutrino Phenomenology

Non-Oscillation Expts

Oscillation Expts

- Active
- Near Future
- Towards a Precision Era

Summary

Why do Neutrino Physics?

- Least understood particle
  - Yet after photon most common
- Beyond the Standard Model
  - A trivial Addition?
  - The Window on the Fundamental Theory?
- Understanding the Flavour Problem
  - Understanding lepton flavour as fundamental as quark flavour (and no QCD complications)
- New Source(s) of CP Violation
  - Contributor (solution) to the anti-matter asymmetry
- Ultimate theory must relate quarks & leptons
  - Cannot do this without a full understanding of the neutrino sector
  - Cannot do this with LHC or ILC
- Neutrinos provide unique probes of Unknown Phenomena

Neutrino Production, Detection

- Neutrinos are produced in various decays
  - Beta decay $X^N > \; Y^{N+1} + e^- + \bar{\nu}_e$
  - Pion Decay $\pi^- \quad \mu^- + \bar{\nu}_\mu$
  - Muon Decay μ^- õ $e^- + \bar{\nu}_e + \nu_\mu$

Neutrino (Pauli 1930)
before discovery

- Sources of terrestrial neutrinos
  - Now
    - Nuclear reactor - Many β^- decaying nuclei
    - Accelerator produced Pion beams
  - Future?
    - Beta Decaying Ions in a Storage Ring (Beta Beam)
    - Muons Decaying in a Storage Ring (Neutrino Factory)

- Neutrinos are observed by their interactions with protons and neutrons in nuclei $\bar{\nu}_l + [p \quad n + l^+ \qquad \nu_l + n \quad p + l^- \qquad l = e, \mu, \tau$

Distinguishing Neutrinos from Antineutrinos

- Cannot use Charge
- Can always invent a new conserved Quantum Number
  - Lepton Number

$$L=+1 \ for \ \nu, e^- etc., \quad L=-1 \ for \ \bar{\nu}, e^+ etc. \quad and \ \Delta L=0$$

rather ad-hoc!

- But In The SM neutrinos only interact in a left-handed way H = -1

  and antineutrinos in a right handed way, H=+1

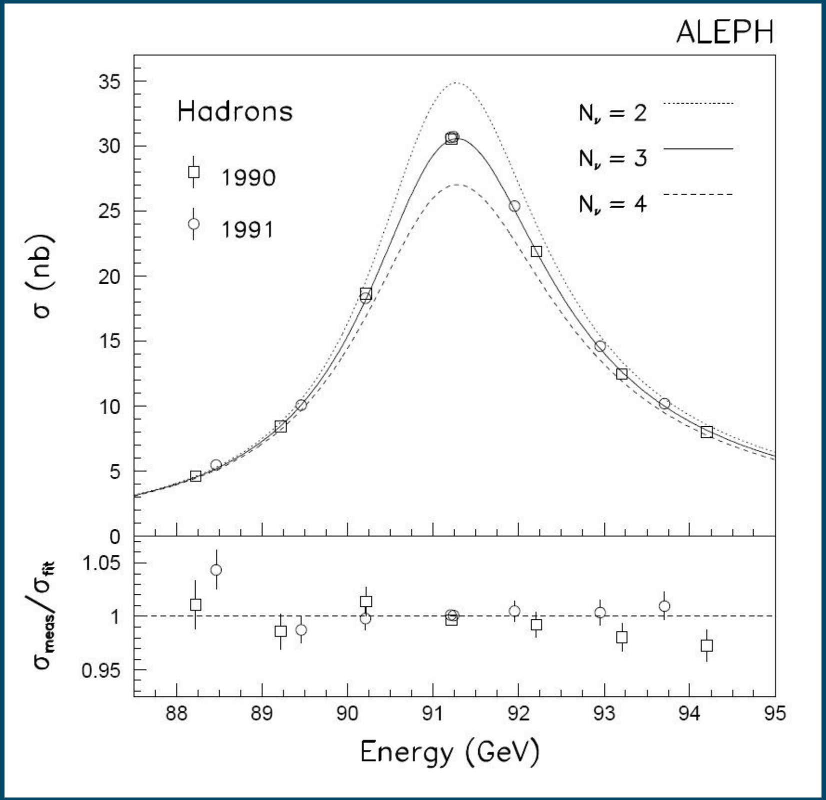
  satisfies all known ν production interactions

- So can use Helicity No need for ΔL = 0

- But then in the SM all Neutrinos have identically ZERO mass

What do we know now?

- There are three light active neutrino species (LEP/SLC)



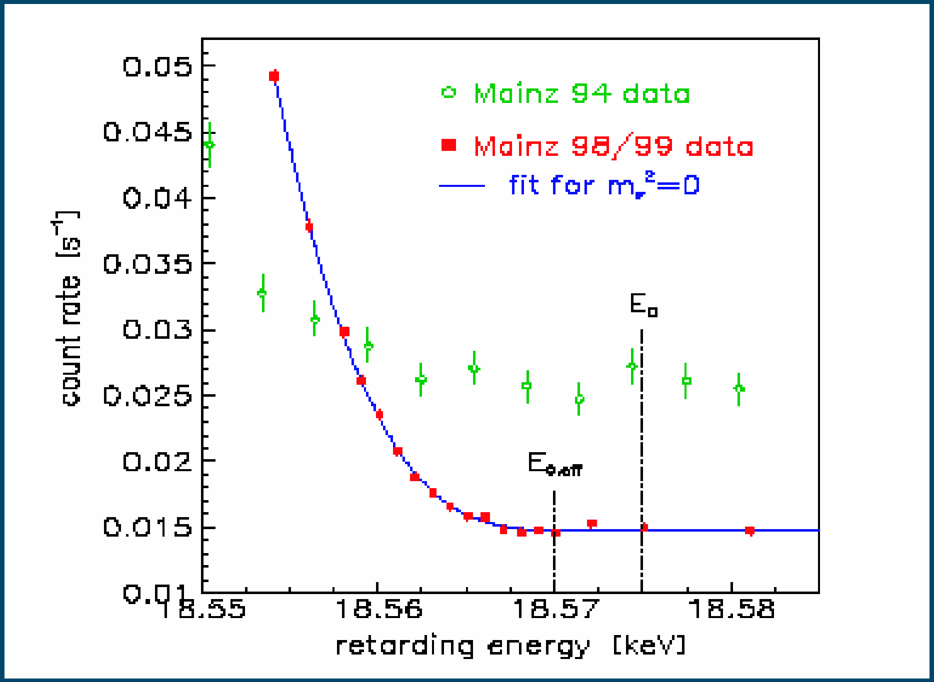
Width of the Z resonance

Only 3 generations of quarks and leptons

Unless heavy or sterile neutrinos

What do we know now?

- There are three light active neutrino species (LEP/SLC)
- Mass of electron neutrino <2.2 eV/c² from H^3 decay spectrum (Mainz)



Using the Endpoint of the Tritium beta decay electron spectrum

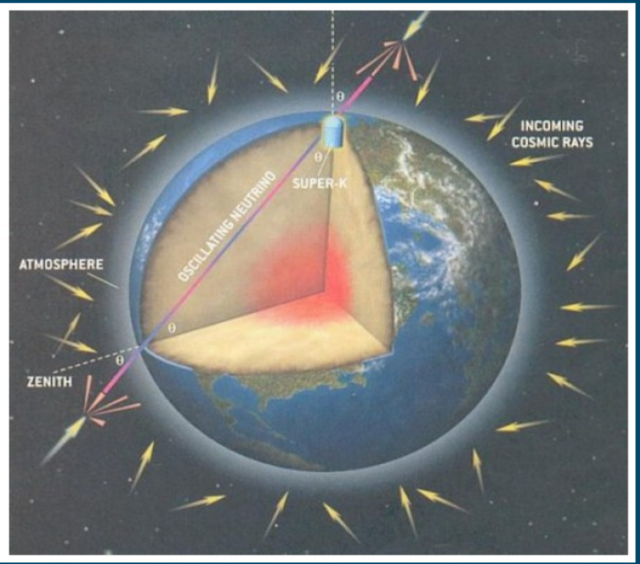
$$H^3 \rightarrow He^3 + e^- + \bar{\nu}$$

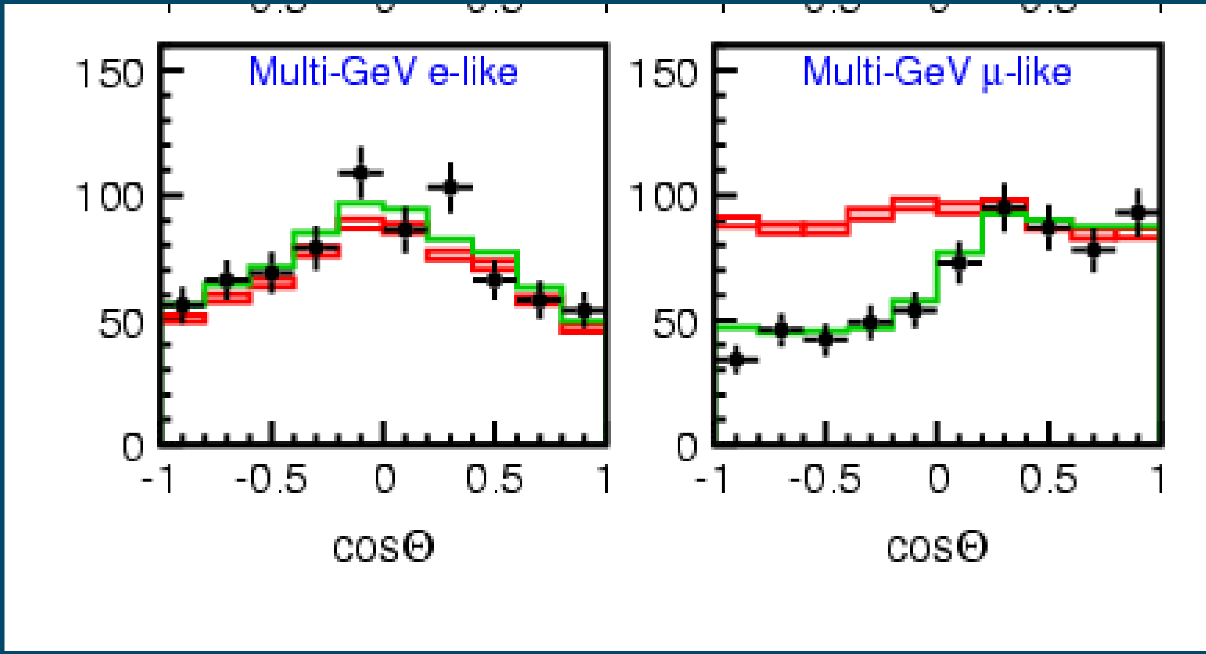
What do we know now?

- There are three light active neutrino species (LEP/SLC)
- Mass of electron neutrino <2.2 eV/c^2 from H^3 decay spectrum (Mainz)
- Muon Neutrinos produced in the upper atmosphere disappear (SuperK)

$$p + N \rightarrow N' + \pi's \qquad \pi^+ \rightarrow \mu^+ + \nu_\mu \qquad \mu^+ \rightarrow e^+ + \bar{\nu}_e + \nu_\mu$$

expect twice as many ν_μ as ν_e



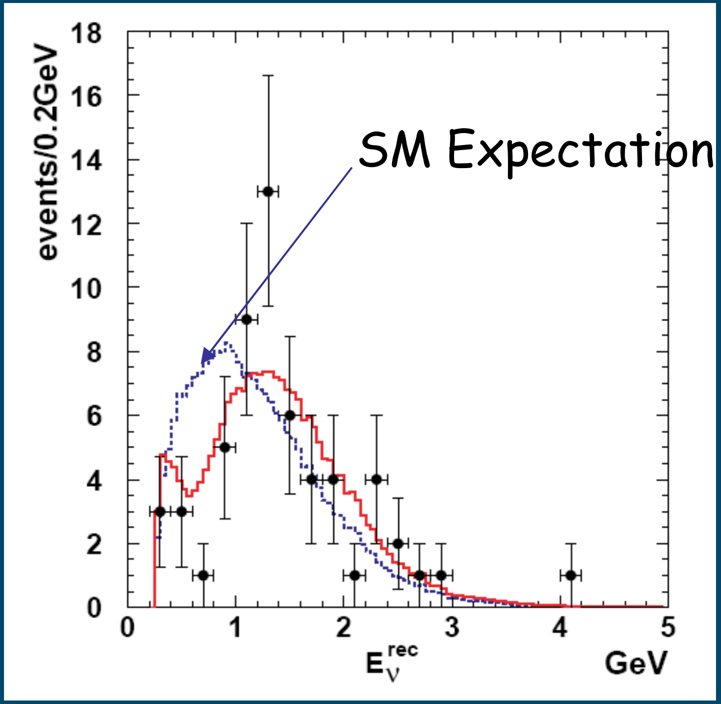


What do we know now?

- There are three light active neutrino species (LEP/SLC)
- Mass of electron neutrino <2.2 eV/c^2 from H^3 decay spectrum (Mainz)
- Muon Neutrinos produced in the upper atmosphere disappear (SuperK)
- Muon Neutrinos produced in π decay disappear (K2K, MINOS)

K2K - 1st long baseline neutrino experiment

KEK to SuperK

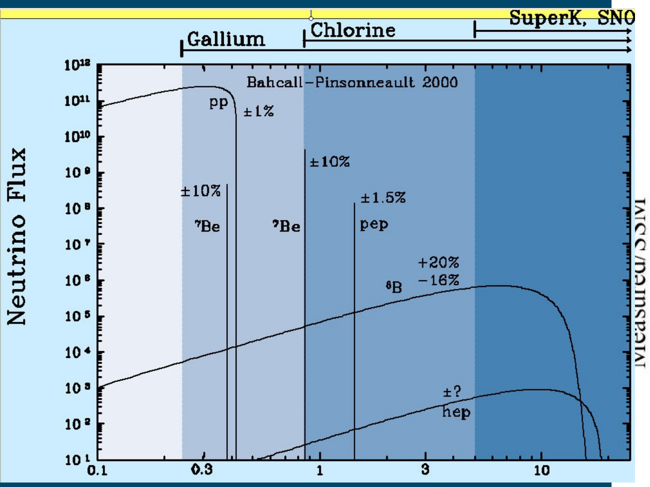


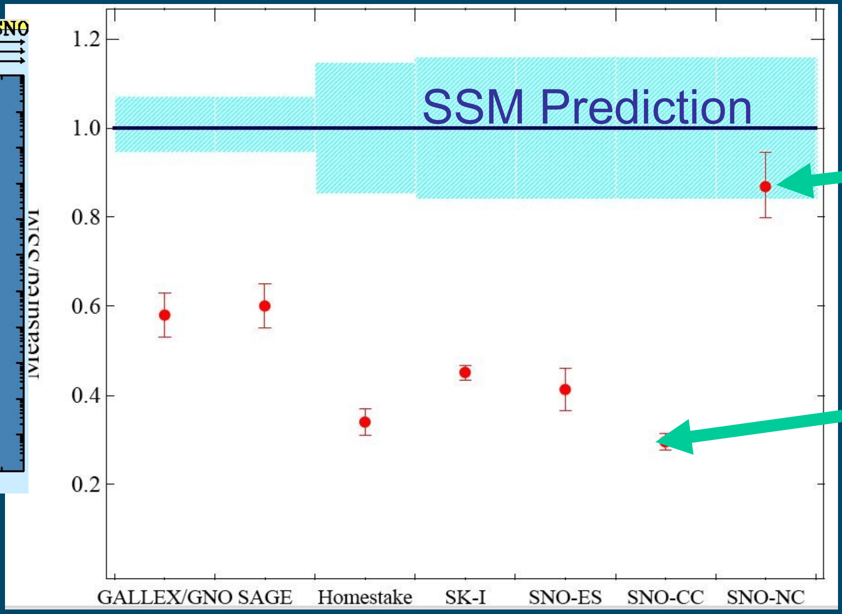
What do we know now?

- There are three light active neutrino species (LEP/SLC)
- Mass of electron neutrino <2.2 eV/c^2 from H^3 decay spectrum (Mainz)
- Muon Neutrinos produced in the upper atmosphere disappear (SuperK)
- Muon Neutrinos produced in π decay disappear (K2K, MINOS

ν

- Electron Neutrinos produced in the sun disappear (Many experiments)
- BUT The total flux of neutrinos from the sun stays constant (SNO)





SNO
Neutral Currents

$\nu_x + d \quad p + n + \nu_x$

- Detects all Neutrino

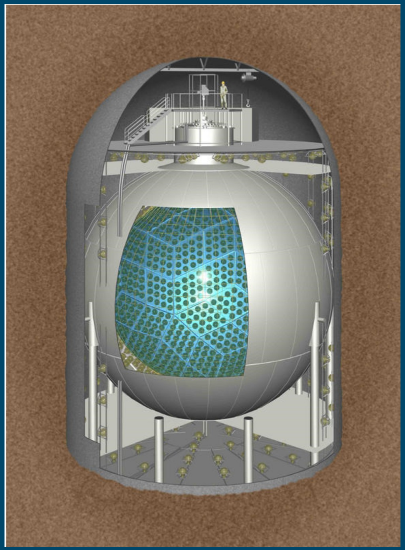
Charged Current

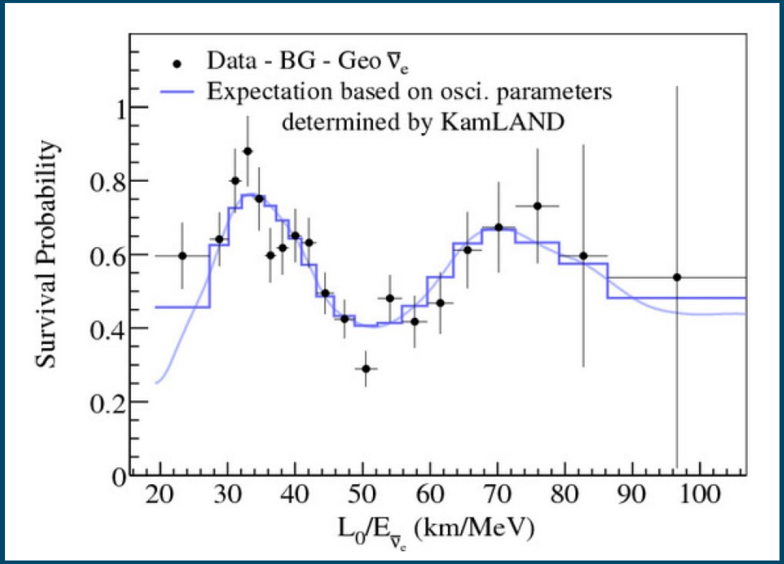
$\nu_e + d \quad e^- + p + p$

- Detects only Electron Neutrinos
insuffcient energy to produce μ or τ

What do we know now?

- There are three light active neutrino species (LEP/SLC)
- Mass of electron neutrino <2.2 eV/c^2 from H^3 decay spectrum (Mainz)
- Muon Neutrinos produced in the upper atmosphere disappear (SuperK)
- Muon Neutrinos produced in π decay disappear (K2K, MINOS
- Electron Neutrinos produced in the sun disappear (Many experiments)
- The total flux of neutrinos from the sun stays constant (SNO)
- Electron antineutrinos from reactors disappear and then reappear (Kamland)

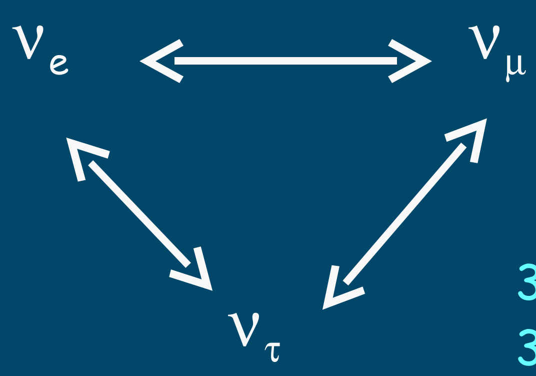




What do we know?

- There are three light active neutrino species (LEP/SLC)
- Mass of electron neutrino <2.2 eV/c^2 from H^3 decay spectrum (Mainz)
- Muon Neutrinos produced in the upper atmosphere disappear (SuperK)
- Muon Neutrinos produced in π decay disappear (K2K, MINOS
- Electron Neutrinos produced in the sun disappear (Many experiments)
- The total flux of neutrinos from the sun stays constant (SNO)
- Electron antineutrinos from reactors disappear and then reappear (Kamland)

The accepted results are well explained assuming a three family neutrino oscillation



But this means that neutrinos exist in different states when they travel than when they are produced

For this they must have mass

3 **Flavour** (production) eigenstates ν_α, α = e. μ. τ

3 **Mass** (travel) eigenstates ν_i, i =1,2,3

Oscillations

- 2 sets of eigenstates - flavour and mass
  - connected by Unitary matrix

the Maki-Nakagawa-Sakata (MNS) matrix

$$\left|\nu_\alpha\right\rangle = U_{MNS}\left|\nu_i\right\rangle \qquad \alpha = electron, muon, tau \qquad i = 1, 2, 3$$

$$U_{MNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

just like CKM matrix in quark sector

- Consequences

Neutrinos are produced in a particular flavour state, ν_e ν_μ or ν_τ

but as they move through space they change nature so that after some time there is a probability that when detected they will be detected as a different ν_e, ν_μ or ν_τ

If only 2 Generations e and μ

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

One parameter – angle θ

Gives ν_e to ν_μ transitions

$$P_{\nu_\alpha \to \nu_\alpha} = 1 - \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

$$\Delta m^2 = m_2^2 - m_1^2$$

Amplitude of Oscillations - mixing angle θ

Frequency of Oscillations - Mass Squared Differences Δm^2
and L/E

but ambiguities $\theta \Leftrightarrow \frac{\pi}{4} - \theta$ Δm^2 $-\Delta m^2$

so vacuum oscillations only give modulus of mass difference squared

No information on absolute mass or sign of mass difference (mass hierarchy)

3 Generations

- Algebra more complicated   3 angles θ_{12}, θ_{13}, θ_{23} 1 phase δ

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{1\delta} & c_{12}c_{13} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

and can be written

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{-i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

atmospheric

ν_μ disappearance

ν_μ to ν_τ

θ_{13}, δ ?

solar

ν_e disappearance

ν_e to ν_μ or ν_τ

and now many ambiguities & degeneracies from a single measurement

3 Generations

- Algebra more complicated

3 angles θ_{12}, θ_{13}, θ_{23} 1 phase δ

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{1\delta} & c_{12}c_{13} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

and can be written

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{-i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

θ_{13}, δ ?

phase δ gives the possibility of leptonic CP violation

But always multiplied by *sin*θ_{13}

Mass Hierarchy

Vacuum oscillations have terms like $\sin^2\Delta_{ij}, \quad \Delta_{ij} = \left(\frac{1.27\Delta m^2_{ij} L}{E}\right)$

and so only sensitive to $|\Delta m^2|$

but when neutrinos pass through matter flavours interact differently

and this modifies this e.g. $\sin\Delta_{13} \rightarrow \frac{\sin(\Delta_{13} - AL)}{(\Delta_{13} - AL)}\Delta_{13}, \qquad with \qquad A = \pm\frac{G_F N_e}{\sqrt{2}}$

A is the matter density factor
AL related to the amount of matter travelled through
+ for neutrinos, - for antineutrinos

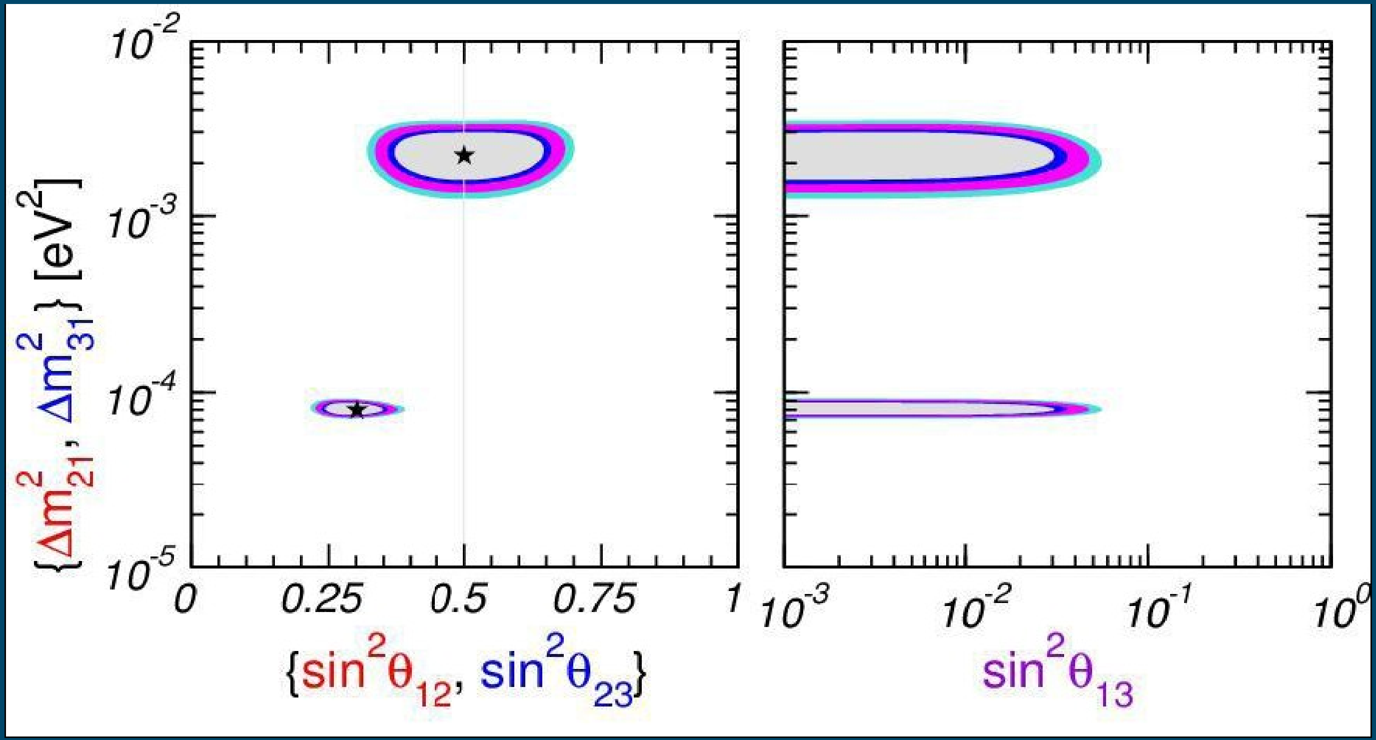
and this removes the degeneracy on the sign of Δm^2

Solar Neutrinos - travel through the sun

and this shows $m_2 > m_1$

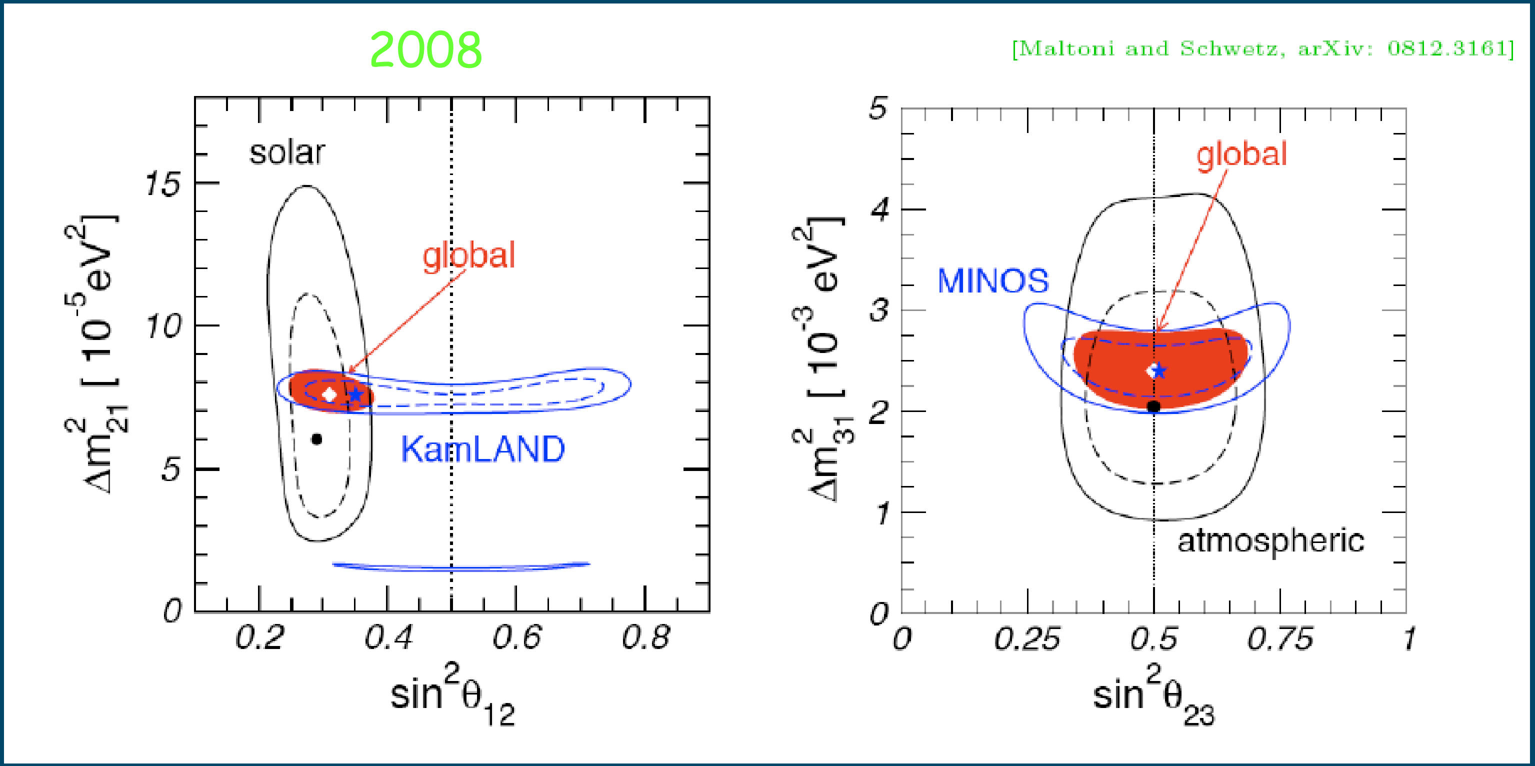
Where are we?

from: Maltoni, Schwetz, Tortola, Valle ('04)



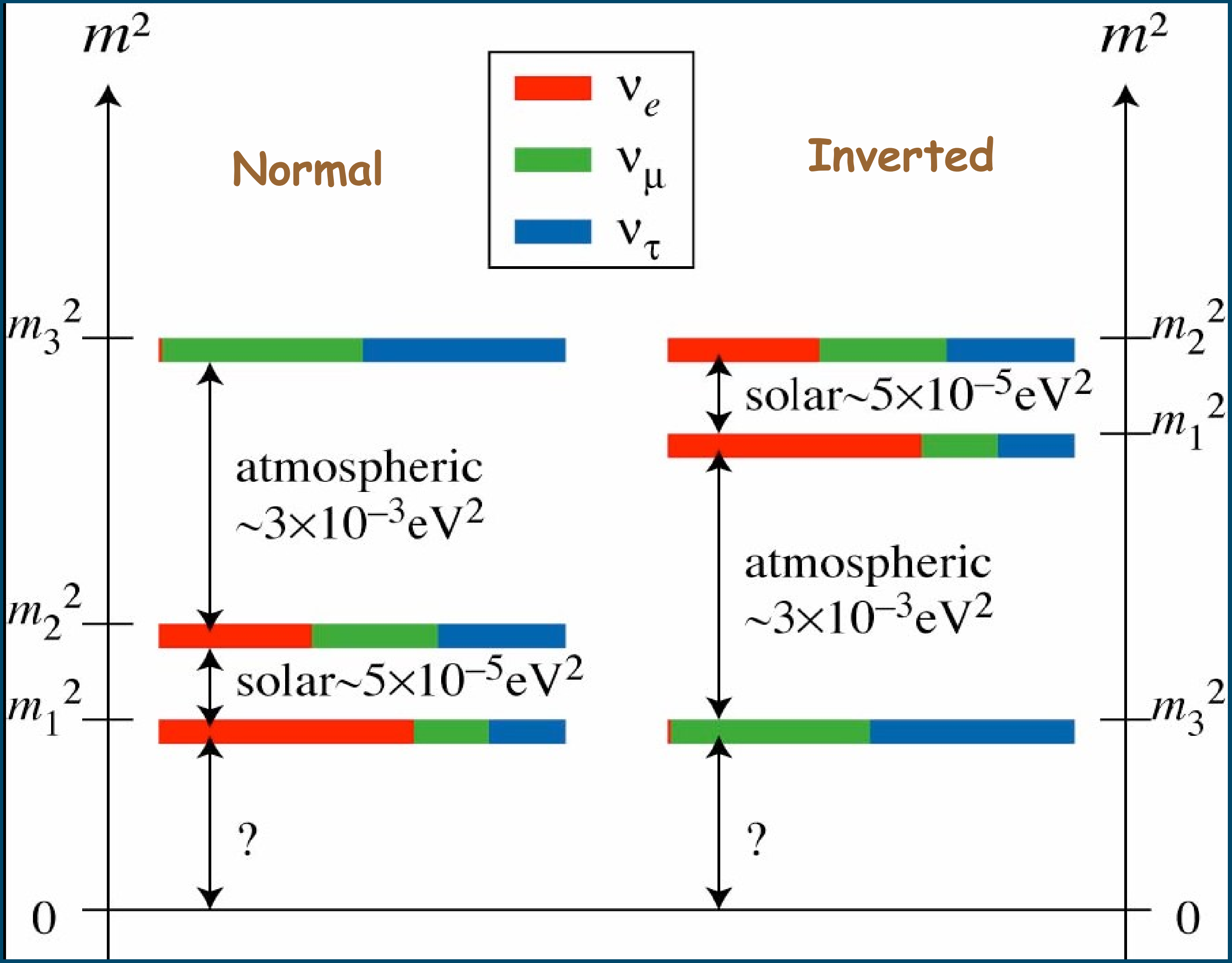
Also know $m_2 > m_1$ from matter effects in the sun

Where are we?



Updated vedrsion 2008

Mass Hierarchy?



Require matter interactions to distinguish.

Long Baseline

Nova > T2K

Leads to degeneracies in superbeam expts.

Critical for Neutrinoless double beta decay

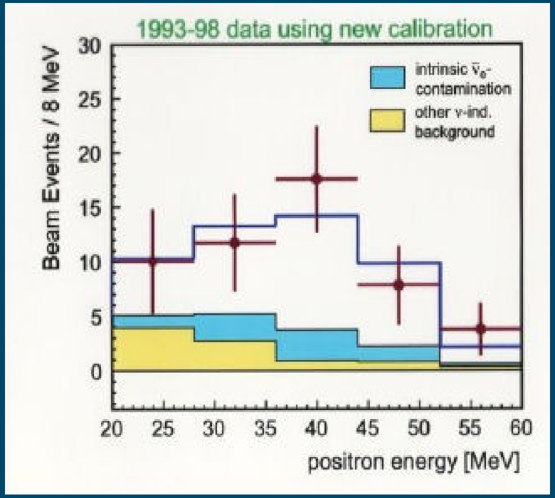
Anomalies LSND, MiniBooNe

- LSND
  - The appearance of electron antineutrinos in a muon antineutrino beam

    If true a 3-Neutrino Scenario is excluded. Either

    > 3 Flavours (with heavy lh neutrinos)

    > 1 or more sterile neutrinos



- MiniBooNe

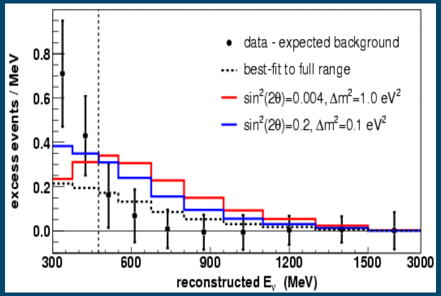
  Aim was to test LSND result – using same L/E

  but used different E and ν not anti-ν

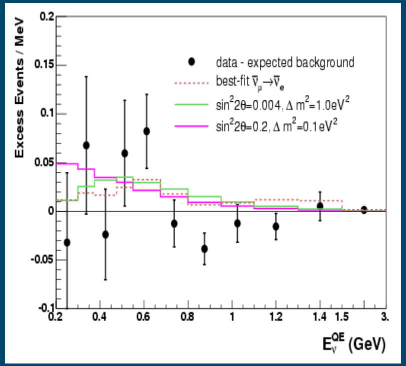
  No confirmation - but they have a new 'interesting' anomaly

  The low energy excess

  \- but not seen (yet) in anti-ν running



Neutrino Mode
5.2e20 POT
PRL **98** 231801 (2007)



Antineutrino Mode
3.4e20 POT
PRL **103** 11801 (2009)

Are Neutrinos Majorana States?

Neutrinos have mass

Although a bizarrely tiny mass

ν cannot be distinguished from $\bar{\nu}$ on the basis of Helicity

Two alternatives

L is Conserved ν and $\bar{\nu}$ are distinct Dirac Neutrino

L is NOT Conserved ν and $\bar{\nu}$ are the same Majorana Neutrino

Mass Terms

Dirac Neutrino single mass term for each neutrino - like the other particles $m(\nu) = m(\bar{\nu})$

Majorana Neutrino three possible mass terms for each neutrino

m_L, m_R Majorana mass terms

m_D Dirac mass term

Majorana Neutrino - Masses & See-Saws

For each generation

can now have two neutrinos - with different masses m_1, m_2

$$m_{1,2} = \tfrac{1}{2}\left(m_R - m_L\right) \text{m} \tfrac{1}{2}\sqrt{\left(m_R - m_L\right)^2 + 4m_D^2}$$

but we only see 1 per generation !

Can choose, m_L Q٠, m_D : $EWscale$ ١−١٠٠ GeV, m_R ? m_D

then m_1 5 $\dfrac{m_D^2}{m_R}$ See-Saw Relation

and to get m_1 small enough, ≤ 1 eV Need $m_R \sim 10^{15}$ (~ *GUT scale*)

If Neutrinos are Majorana the small mass of those observed is a consequence of very heavy ones at ~ GUT scale !

They provide a 'window' on unapproachable heavy scales

Majorana Neutrinos – Phases & CP

If Majorana - Lose two constraints on the mixing matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-id} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{-id} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha/2} & 0 & 0 \\ 0 & e^{1\beta/2} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

two more phases α and β - extra source of CP violation

and this could be critical in the understanding of the baryon- antibaryon asymmetry in the universe

but appear to be very difficult to measure

Very important to determine if neutrinos are Dirac or Majorana.

Future - Non-Oscillation Experiments

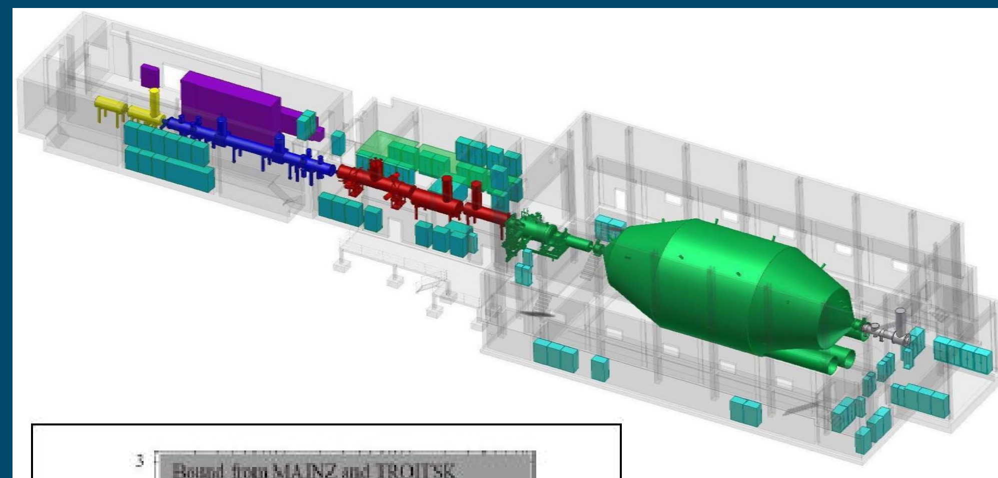
- Absolute Mass
- Majorana/Dirac

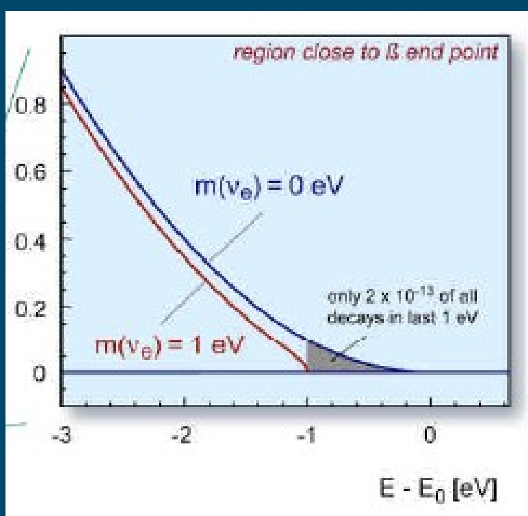
The Absolute Mass?

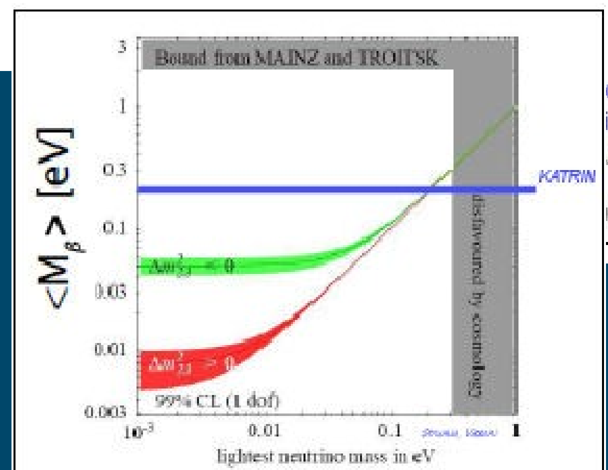
- Cosmological data
- Neutrinoless double-beta decay
- Tritium Decay Spectrum

Katrin aims for
$M(\nu_e) < 0.2$ eV

Model Dependent
Currently Σm <~ 0.7 eV
Potential Σm <~ 0.07 eV?

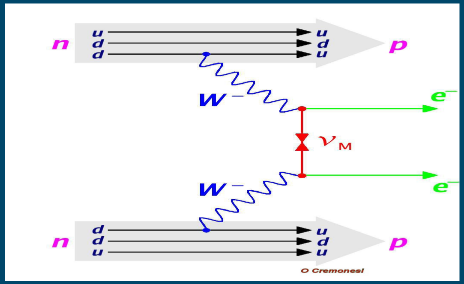






Dirac or Majorana? - 0νββ

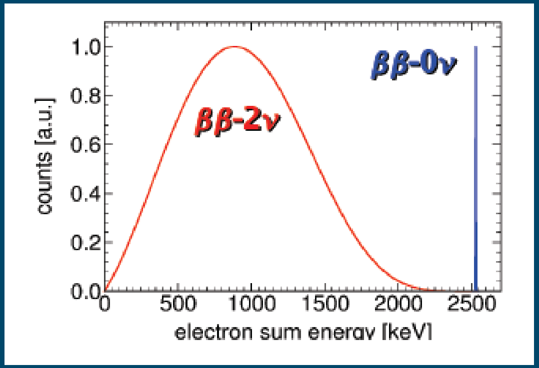
- If Dirac – lepton no. is conserved. If so - what is it?
- If Majorana
  - ΔL = 2 BSM processes, More CP violation, Seesaws possible, leptogenesis, solution to antimatter asymmetry?



- Only approach 0νββ – Rate depends on mass via

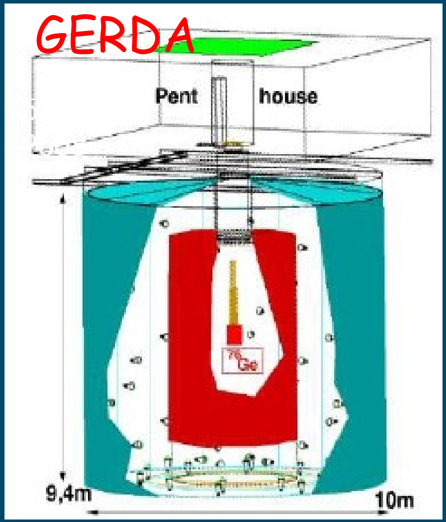
$$m_{ee} = \left|\sum U_{ei} m_i\right|^2$$

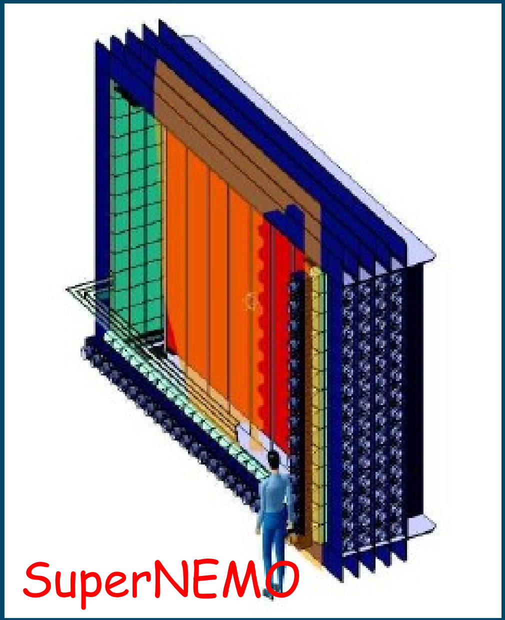
- If a Positive Result
  - ν's are Majorana
  - A measurement of the absolute Mass (subject to NME)
- If a Negative result
  - Nothing – cannot even confirm Dirac nature

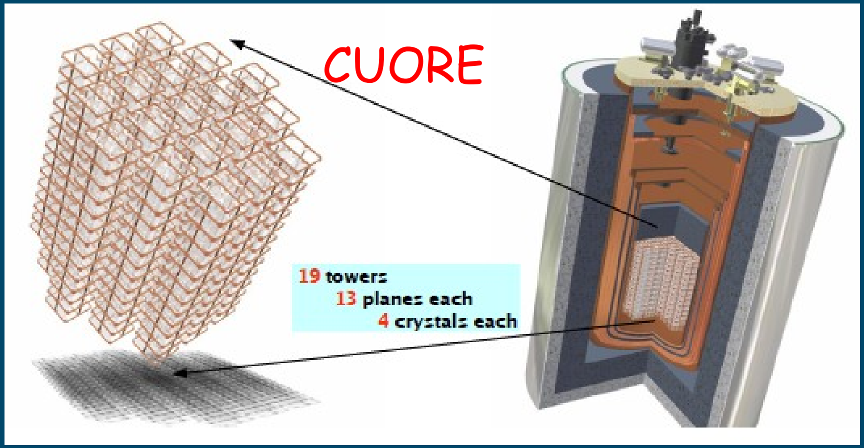


Many Experiments planned

- CUORE, GERDA, MAJORANA, SuperNEMO, EXA, XMASS, SNO+ ….
- Range of techniques: Bolometers, Scintillators, Tracking, Combinations
- Many Isotopes: Te, Ge, Se, Xe, Mo, Cd, Ca, Gd…
- Aim `for mass values down to ~ 0.02 eV

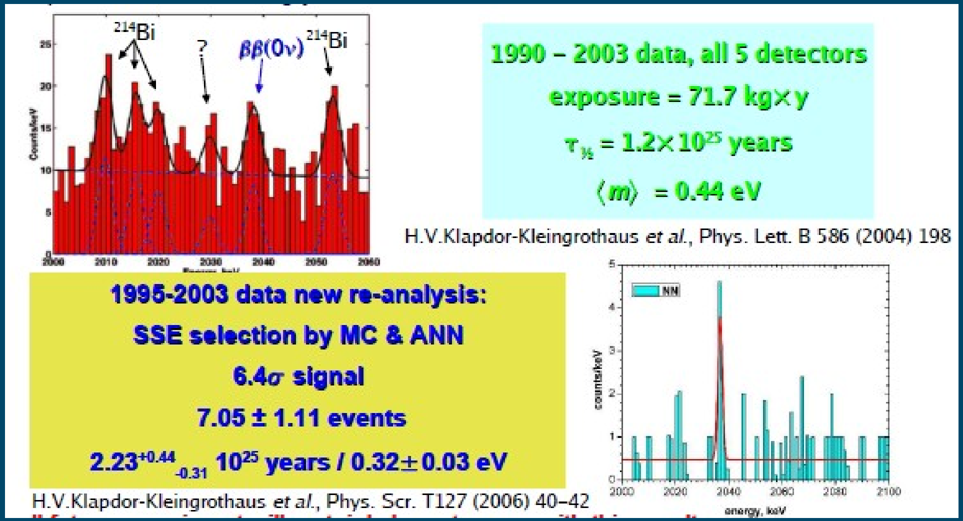


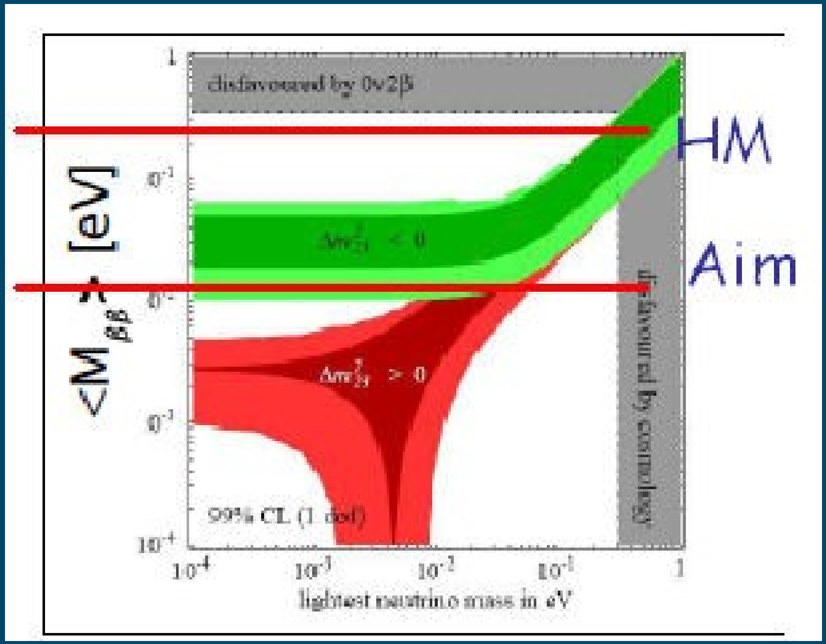




There is a published positive result

H.V.Klapdor-Kleingrothaus *et al.*, Heidelberg-Moscow Expt for ^{76}Ge , $^{76}Se + e^- + e^-$





If True - Neutrinos are Majorana – $M(\nu_e)$ = ~0.4 eV

Confirmation or otherwise urgently needed
This will be a first goal of GERDA

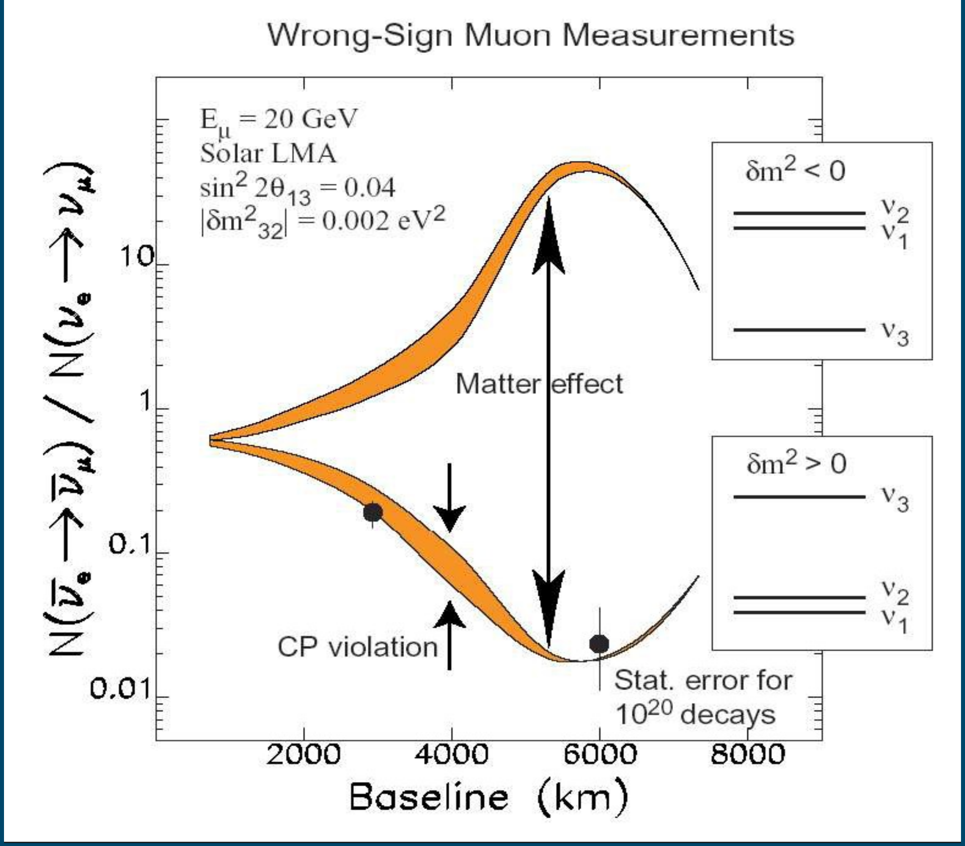
Oscillation Expts - Goals

Observe Flavour of an Oscillated ν	Identify a ν_τ or ν_e in a ν_μ Beam
How small is θ_{13}?	Critical Parameter to define future programme
Mass hierarchy?	**m_3 < or > m_2, requires $\theta_{13} \neq 0$**
Leptonic CP Violation?	Requires $\theta_{13} \neq 0$, $\delta \neq 0$
Is θ_{23} maximal? – is it > or < $\pi/4$?	Improve accuracy of atmospheric parameters
Is the MNS approach correct?	Measure parameters in as many ways – and as precisely - as possible
Are there sterile neutrinos?	Precision measurement of parameters. Repeat LSND? (MiniBooNE does not disprove LSND in exotic scenarios – different E)
CPT violation?	Measure parameters in as many ways – and as precisely - as possible
Do we have Tribimaximal mixing?	If yes presumably some underlying symmetry. Needs precision measurements

CP Violation

- Vitally important for our understanding of nature and the universe
- Arises from phases which flip sign on the change particle ←→ antiparticle

  Standard MNS matrix has one phase, δ, (like CKM)
- BUT also matter effects flip sign on the change particle ←→ antiparticle



AND, if neutrinos are Majorana additional phases and potential for substantial CP violation - but Majorana phases appear virtually unmeasurable

The Need for Precision Measurements

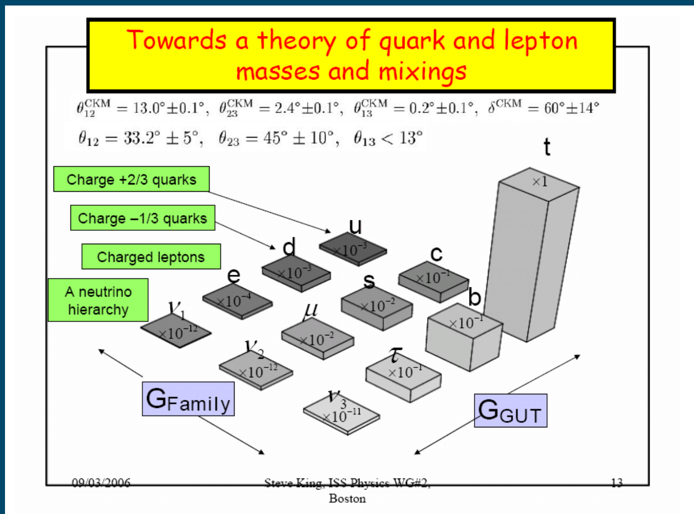
- No understanding of the underlying physics without precision measurements - as in the quark sector
  - e.g. CP violation in the neutrino sector?
    - Interesting to demonstrate this at 3σ level
    - Much more useful to know δ precisely

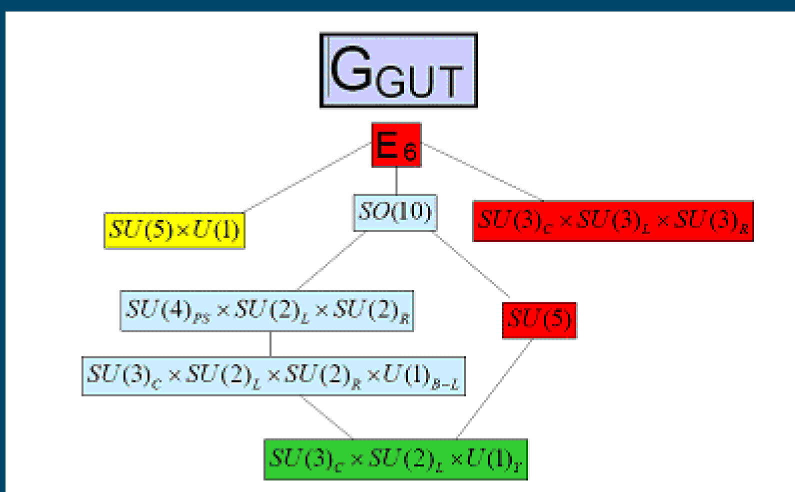
- Quark – Lepton Complementarity
  - Motivated by GUTs
  - Also by intriguing relations such as

$$\theta_{١٢}^{MNS} + \theta_{١٢}^{CKM} \cong \pi/٤$$
$$\theta_{23}^{MNS} + \theta_{23}^{CKM} \cong \pi/4$$

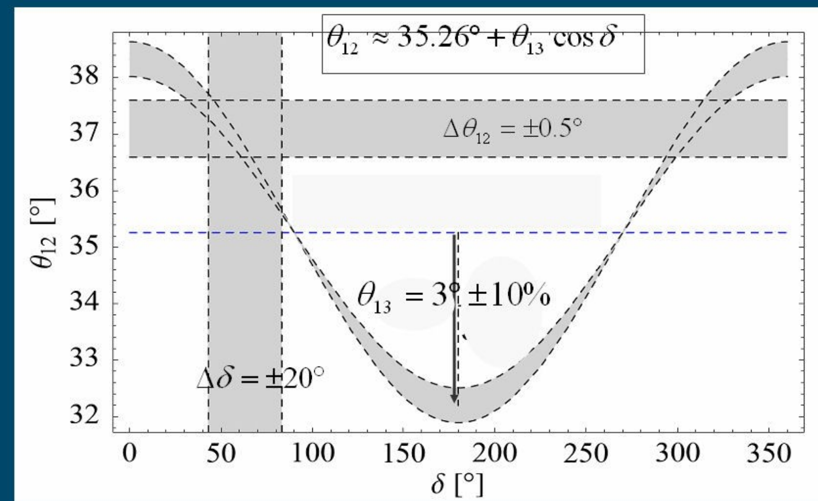
  - Improved precision of solar and atmospheric angles also needed

Ideas/Speculation





A Neutrino Sum Rule? (S King)

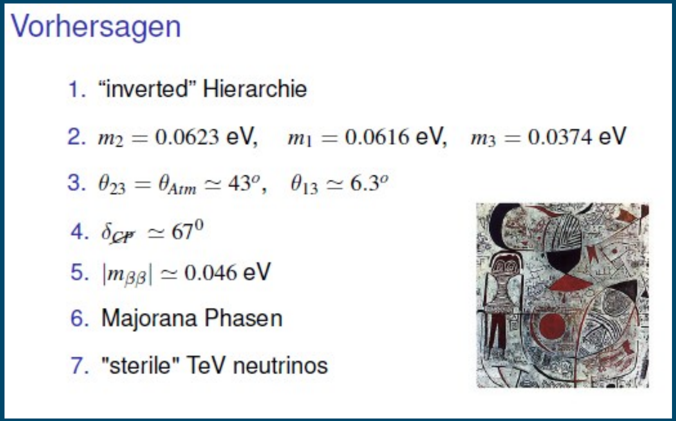


Tribimaximal Mixing? (Harrison, Perkins, Scott)

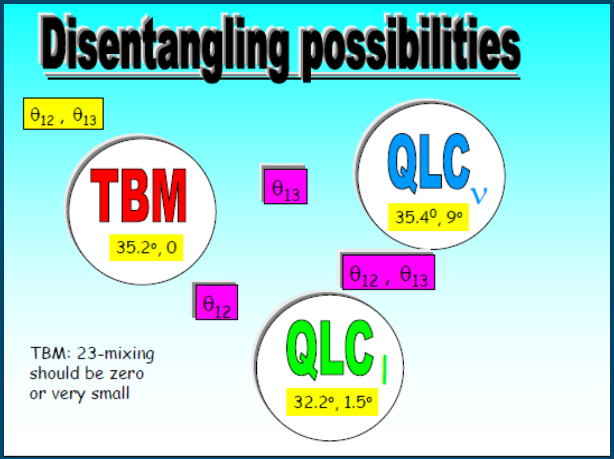
$$\begin{pmatrix} \sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & 0 \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & -\sqrt{\frac{1}{2}} \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \end{pmatrix}$$

Some (of many) Predictions from GUTs

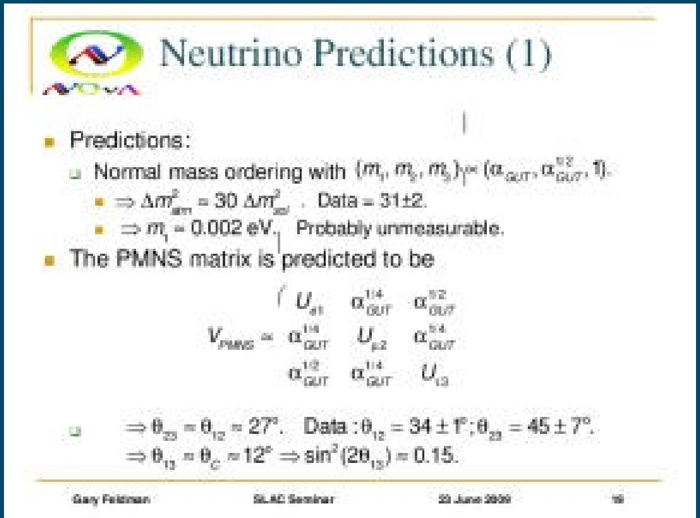
From B Stech
From an E6 GUT



From A Yu Smirnov
Neutrino 08



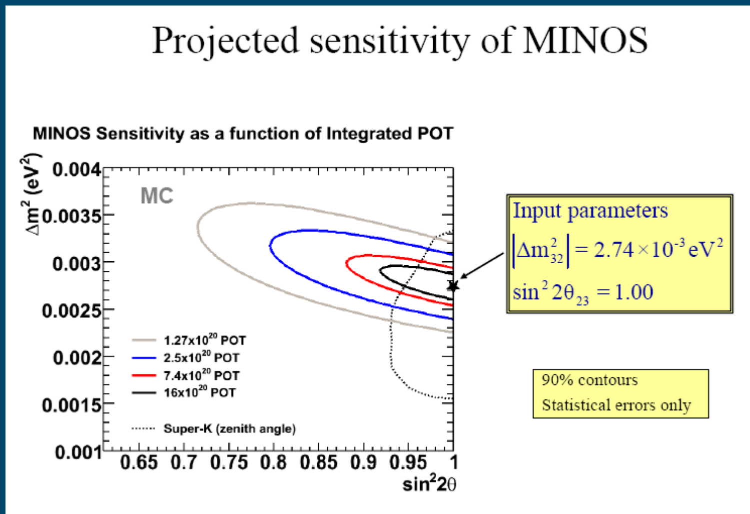
From Vafa et al
based on String theory + GUT

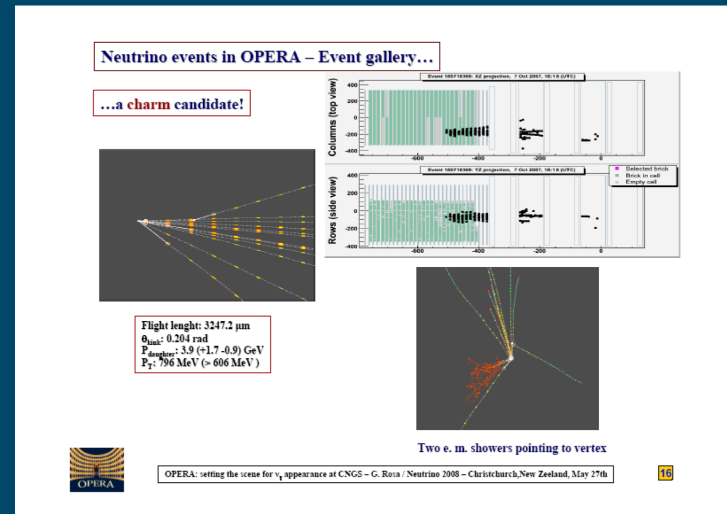


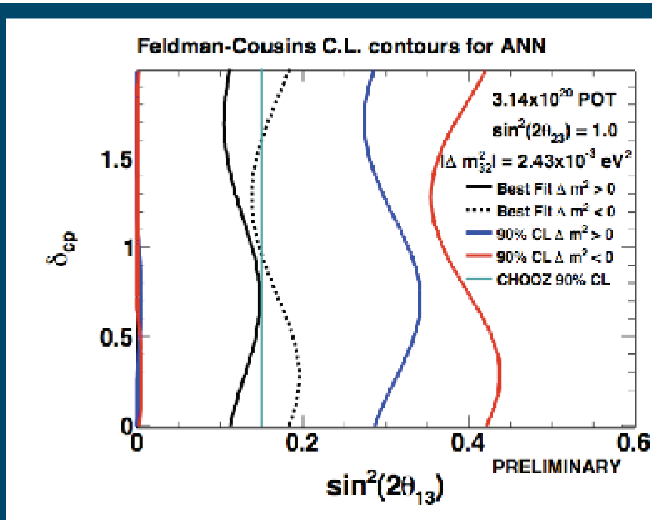
The Imminent Future

- Two long base line experiments using a ν_μ beam now taking data
- MINOS
  - Numi Beam from FNAL to Soudan 735 km
    - Two Detectors – near and far – magnetized Fe-scintillator
    - Look for ν_μ disappearance → θ_{23}, Δm^2_{23}
    - ν_e Appearance → θ_{13} (~factor 2 better than Choose)
- OPERA
  - CNGS Beam from CERN to Gran Sasso 732 km
    - One Far Detector – Emulsion
    - Look for ν_τ Appearance, now expect ~10 observed ν_τ events in 5 years

MINOS OPERA







- 5 years CNGS data taking (4.5 10^{19} pot/year)
- 1.35 ktons target mass

τ decay channels	Signal ÷ Δm^2 (Full mixing) 2.5 x 10^{-3} (eV^2)	Signal ÷ Δm^2 (Full mixing) 3.0 x 10^{-3} (eV^2)	Background
$\tau \to \mu^-$	2.9	4.2	0.17
$\tau \to e^-$	3.5	5.0	0.17
$\tau \to h^-$	3.1	4.4	0.24
$\tau \to 3h$	0.9	1.3	0.17
ALL	10.4	15.0	0.76

In the next ~4 Years - θ_{13}

- ν_e Appearance in a ν_μ Beam - SuperBeam

$$P[\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e] \cong \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2\Delta_{31}$$
$$+ \sin 2\theta_{13} \cos\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12}$$
$$\sin\Delta_{31} \sin\Delta_{21} \cos(\Delta_{32} \pm \delta)$$
$$+ \sin^2 2\theta_{12} \cos^2\theta_{23} \cos^2\theta_{13} \sin^2\Delta_{21}$$
$$(\Delta_{ij} \equiv 1.27 \Delta m_{ij}^2 (eV^2) L(km) / E(GeV))$$

ν / $\bar{\nu}$ (sign of δ); (solar)

δ leads to CP Violation

δ - θ_{13} degeneracy

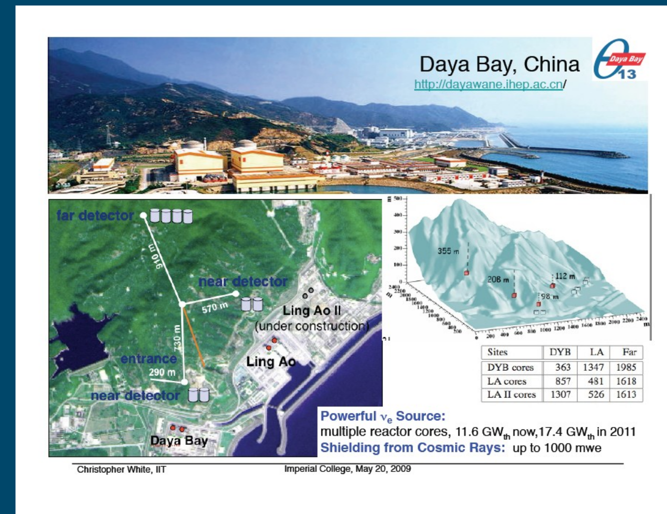
Matter effects can also be significant

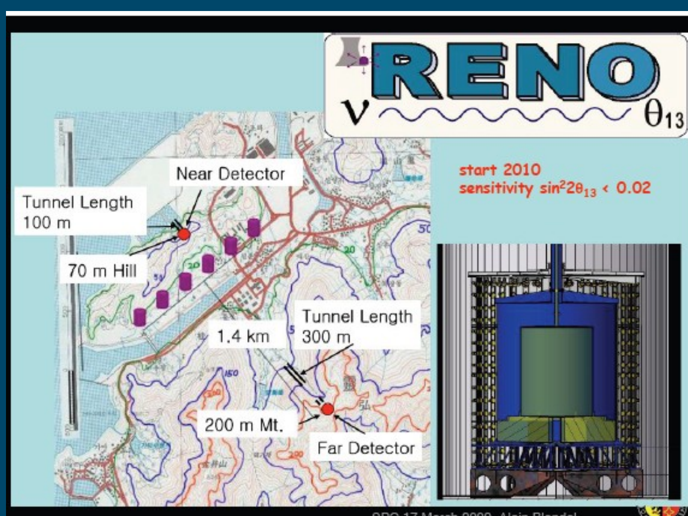
- ν_e Disappearance in a ν_e Beam - Reactor

$$P[\bar{\nu}_e \to \text{Not } \bar{\nu}_e] \cong \sin^2 2\theta_{13} \sin^2\Delta_{31} + \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\Delta_{21}$$

No δ term, no matter effect

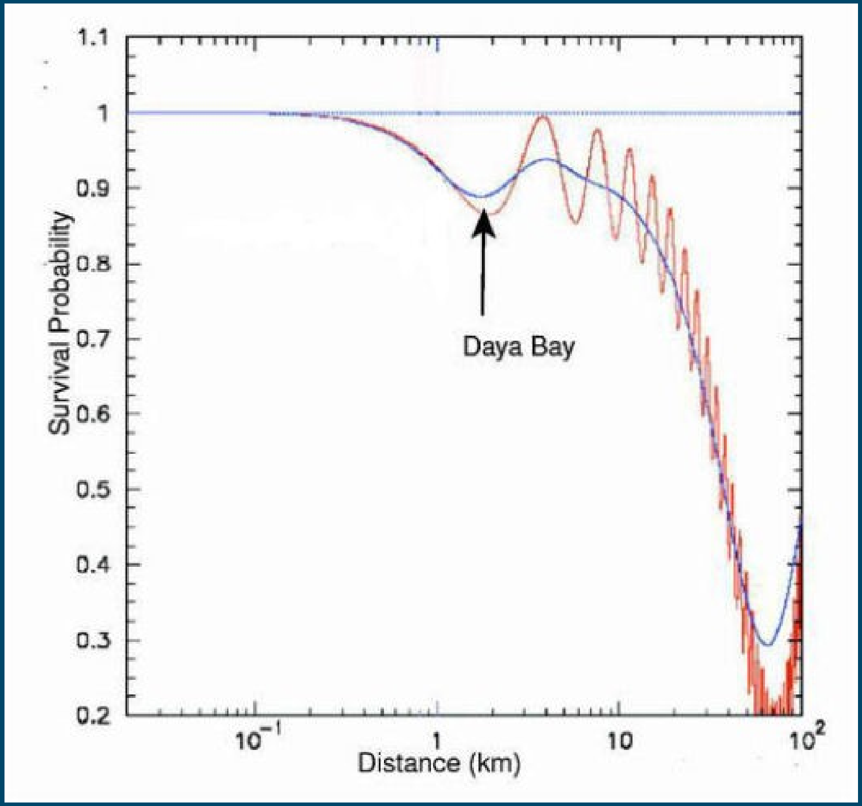
Three Reactor Expts for θ_{13}

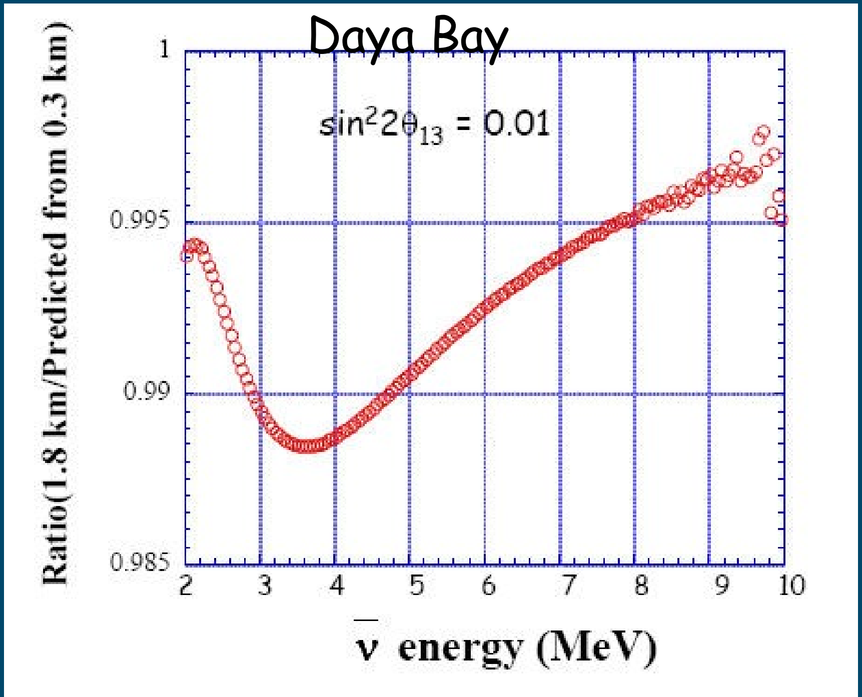




	Power Gw	Start	$\sin^2 2\theta_{13}$
Double Chooz	8.5	2009-10	>~0.02
Daya Bay	11.6 to 17.4	2011	>~0.01
RENO	16.4	2011	>~0.02

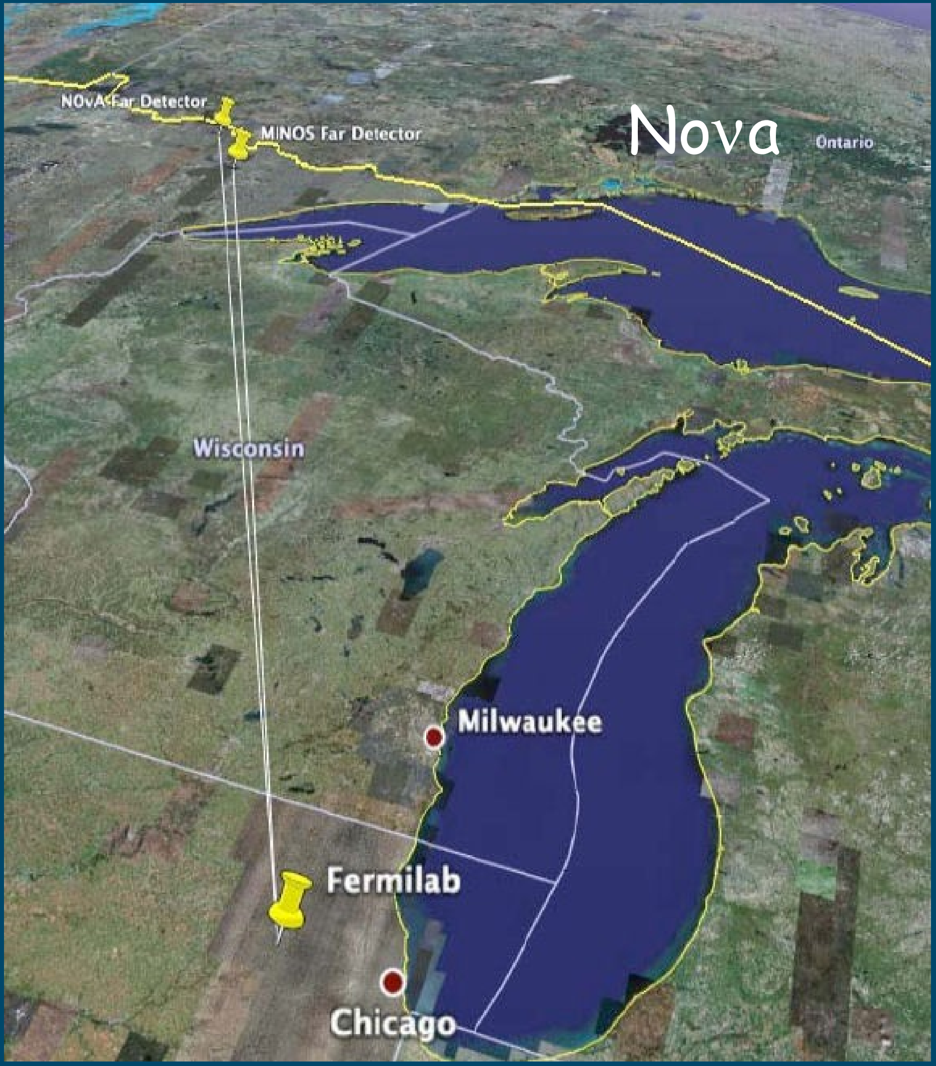
Reactor Measurement of θ_{13}





No Dependence on δ, No matter effects
But small effect and control of systematics vital.

Two Off Axis Superbeams,T2K, Nova

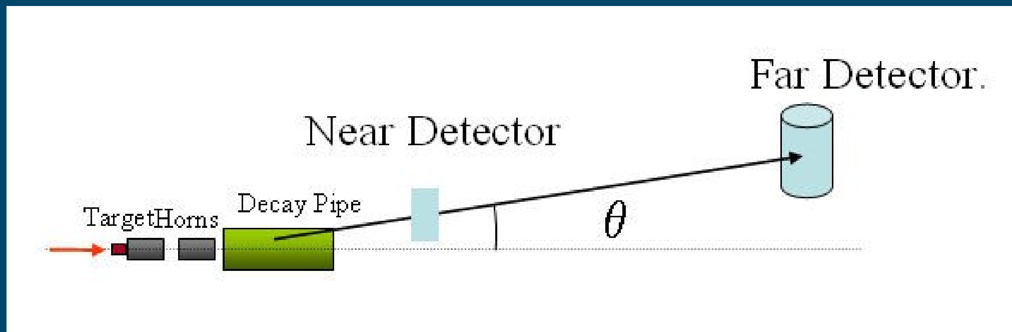


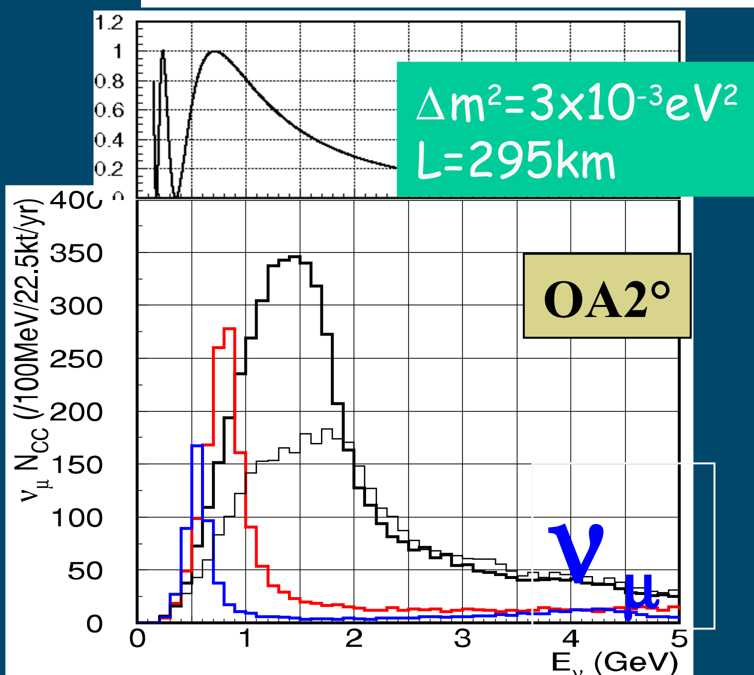
T2K, Nova

- Both use a ν_μ off-axis beam and have both e and μ detection

- Aim
  - Measurement or much better upper limit on θ_{13} using electron appearance
  - Improve accuracy of $\sin^2 2\theta_{23}$, Δm^2_{23} using muon disappearance
  - Determine mass hierarchy (Nova) – depends on θ_{13}
- T2K
  - Super-K, 50kt Water Cerenkov Detector, 295 km from J-PARC
  - A near detector but not same technique
  - J-PARC Beam
    - Just started , starts in earnest early 2010 at about 30 – 50 kW and will then steadily improve to ~1.5 MW, 30 – 50 GeV protons, 3 horns
    - Off axis beam $\langle E_\nu \rangle \sim 0.65$ GeV, better energy spread and less contamination
- Nova
  - Huge totally active scintillating detector (TASD)
  - Work on the site has recently started , first events ~2012
  - Numi Beam
    - Already available
    - Upgrade to 700 kW

Off Axis Superbeams





Much better energy resolution

More flux at oscillation max

Less ν_e Contamination

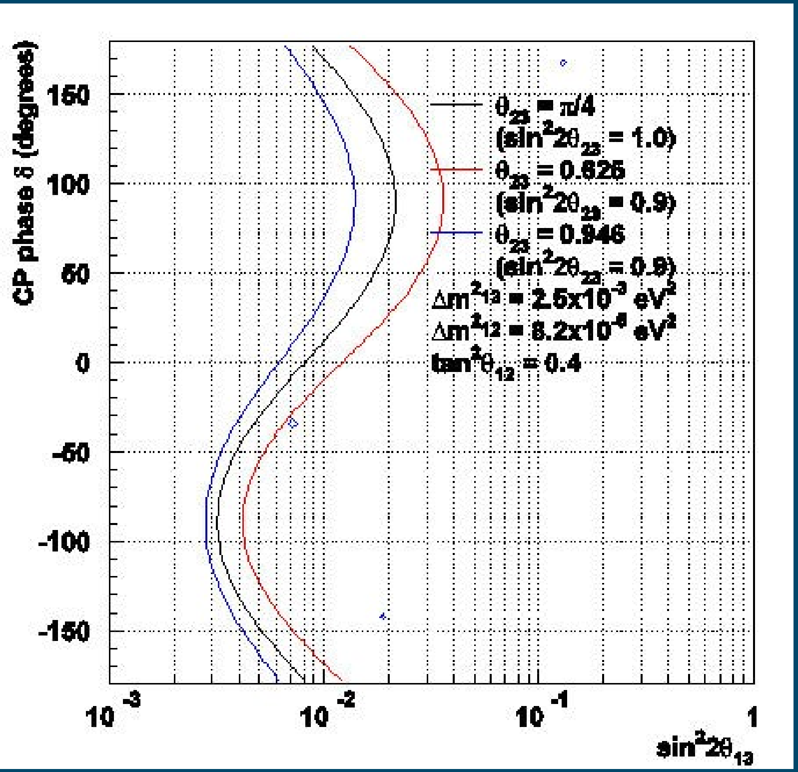
Reduces high energy tail and hence NC background

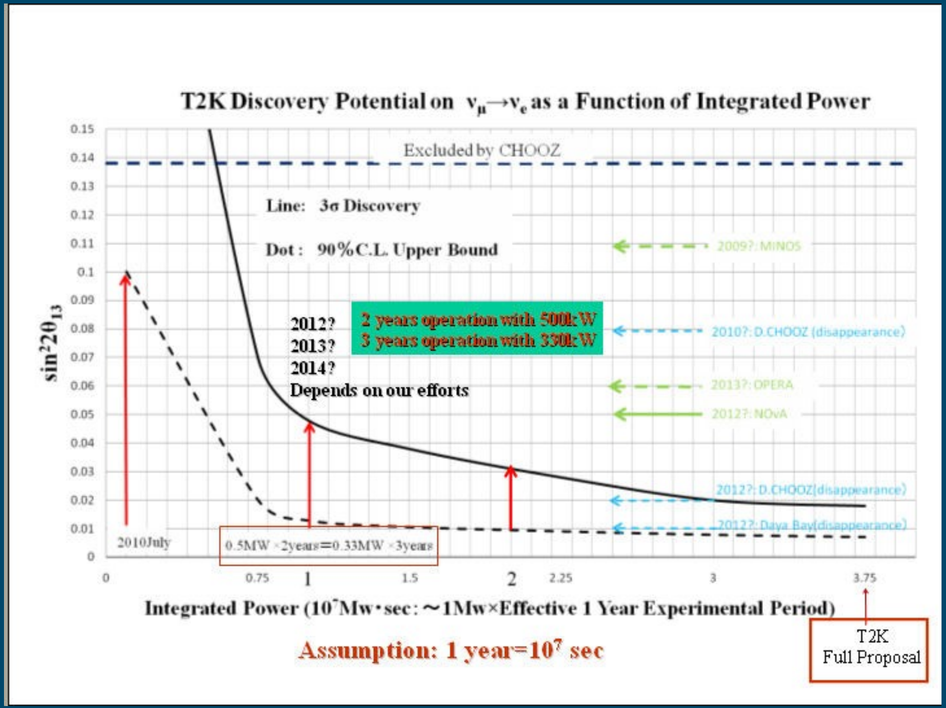
But

Increases near/far differences

Complicates disappearance

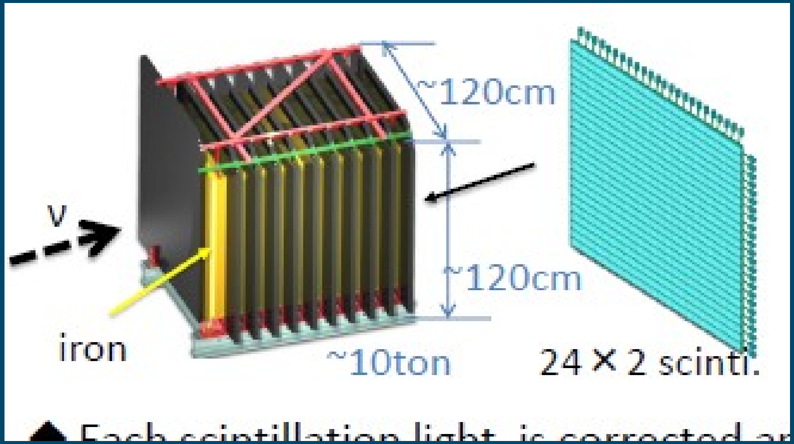
T2K Prospects

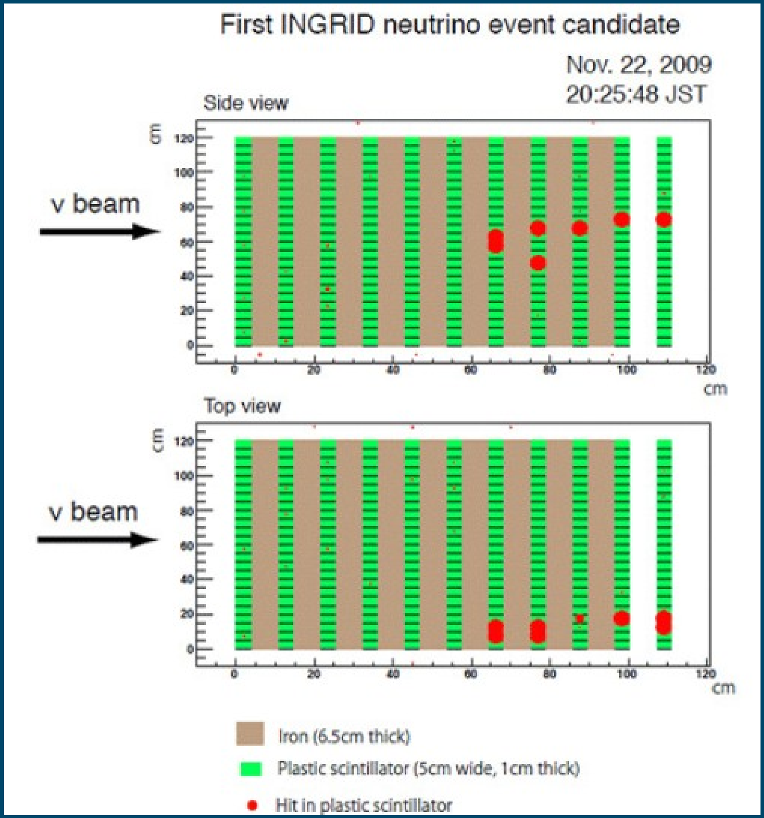




First T2K Neutrino Event

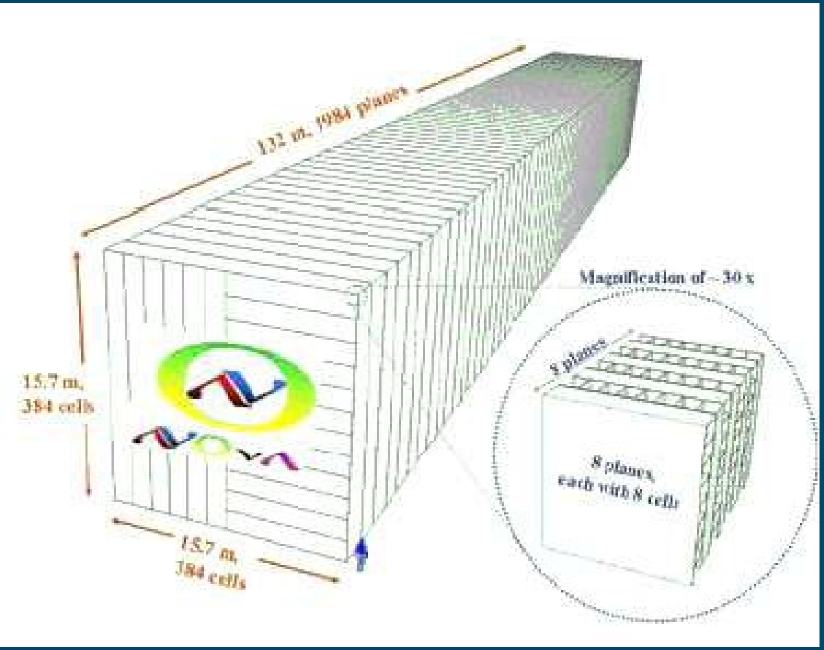
21 Nov 2009 In the INGRID Near Detector





Nova

- Upgrade of FNAL NuMi program.
- Off-axis configuration, and larger proton intensity (6.5x1020 proton/year).
- Very Long Baseline (810km) and sizeable matter effects
- Complementary to T2K program (mass hierarchy).
- <Eν> ~ 2.22GeV
- 30Kton "fully" active detector.
- Liquid scintillator.
- Data taking Expected to start 2012/13



The Precision Era - after T2K and Nova

- Around 2012 - 2015
- We shall have good measurements of
  - θ_{12}, θ_{23}, Δm^2_{12}, Δm^2_{23}
- Probably have a measurement of θ_{13}
- Possibly know the mass hierarchy

- So can now plan for the ultimate neutrino measurements
  - Refine all parameters
  - Check consistency
  - Measure CP Violation

Long Baseline Experiments

- What can be measured?
  - ν_e Beam

$\nu_e \to \nu_e$	$\bar{\nu}_e \to \bar{\nu}_e$	'disappearance'
$\nu_e \to \nu_\mu$	$\bar{\nu}_e \to \bar{\nu}_\mu$	'golden channel'
$\nu_e \to \nu_\tau$	$\bar{\nu}_e \to \bar{\nu}_\tau$	'silver channel'

  - ν_μ Beam

$\nu_\mu \to \nu_e$	$\bar{\nu}_\mu \to \bar{\nu}_e$	'platinum channel'
$\nu_\mu \to \nu_\mu$	$\bar{\nu}_\mu \to \bar{\nu}_\mu$	'disappearance'
$\nu_\mu \to \nu_\tau$	$\bar{\nu}_\mu \to \bar{\nu}_\tau$	'silver channel'

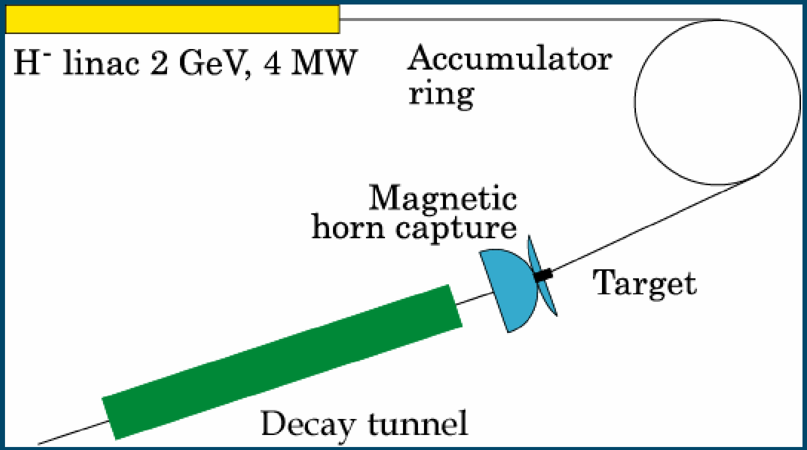
To test the Unitarity of the PMNS matrix and CPT invariance ideally measure all of these

Determining Factors

- Beam
  - Intensity, Purity, Divergence, Energy, Energy Spread?
- Detector
  - Size, energy resolution, for μ's, for e's, Detection threshold, Pictorial (τ's and e's), Magnetisable
- Near Detector
  - Crucial to understand systematics, same technology as far?
- Experiment
  - Baseline, L/E (optimum determined by Δm_{ij}^2, now reasonably known, Removal of degeneracies- More than 1 L/E, Backgrounds
- Systematics
  - Cross sections, neutrino cross sections are still not well known
  - Particle/antiparticle
  - Near/Far
- Cost

Neutrino source – options:

- Second generation super-beam
  - 'Platinum Channel'
  - ν_μ, anti-ν_μ in separate experiments. Significant ν_e contamination
  - On axis – wide band beam, Off axis - narrow band. Wide band beam can give 1st and 2nd max at same L
  - Intensity dependent on proton driver, target and horn system



Possible Next Generation Superbeams

- Typical parameters
  - Proton driver 2 – 4 Mw
  - Long Baselines
  - At least two L/E
  - Far detector very large which could also search for proton decay

- Japan
  - Boost power at JPARC to ~4 MW
  - T2HK ~1 Mton water Cerenkov or very large Liquid Argon
  - T2KK - split detector half in Japan, half in Korea
  - T2K to Okinoshima

Three Possible Scenario Studied at NP08 Workshop

1000km
1deg. Off-axis

658km
0.8deg. Off-axis

295km
2.5deg. Off-axis

NP08 is **The 4th International Workshop on Nuclear and Particle Physics at J-PARC**

http://j-parc.jp/NP08

Possible Next Generation Superbeams

- USA
  - **Project X**
    - Initially 150 kW at 8 GeV, 2 MW at 120 GeV
    - First to boost beam to Nova
    - Later to produce a new wide band beam to a new detector, Water Cerenkov or Liquid Argon at DUSEL
- CERN?
  - **Possibility using the SPL**
    - Replacement for present PS booster, part of the LHC luminosity upgrade
    - Low power and high power versions
    - High Power version, ~4 MW at 5 GeV for neutrino and ISOLDE programmes
    - Could produce a new neutrino beam to Frejus (Memphys Water Cerenkov) or possibly to Gran Sasso

NSF's proposed Underground Lab. DUSEL

1300 km

~100 kton Liquid Ar TPC

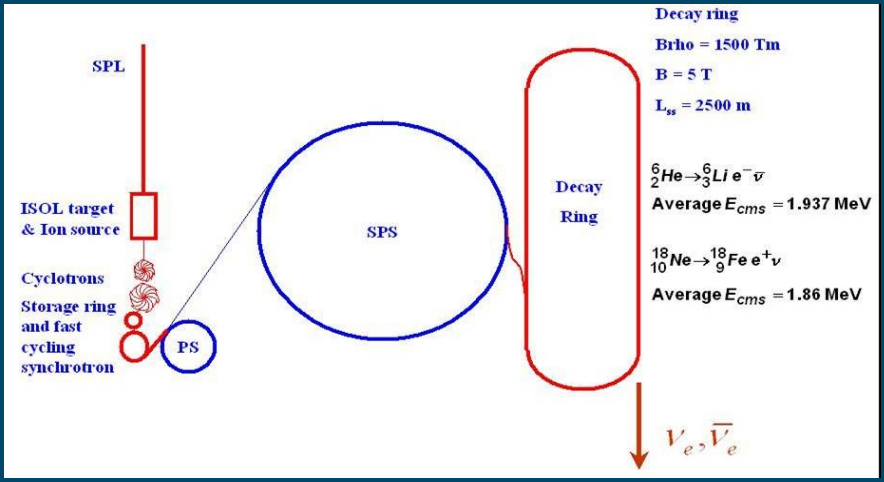
~100 kton Water Cerenkov

700 kW to 2 MW (Project X)

matter – antimatter asymmetry with neutrinos
Proton decay - Supernovae

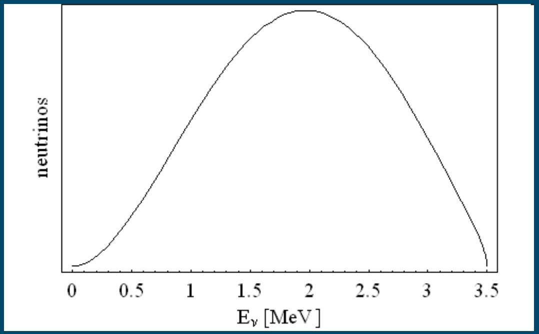
Neutrino source – options:

- Second generation super-beam
- Beta-beam
  - 'Golden Channel'
  - Very pure $\nu_e, \bar{\nu}_e$ Low Divergence beam possible
  - Intensity questionable, depends primarily on ion source. particularly for ν
  - Wide range of possible detectors

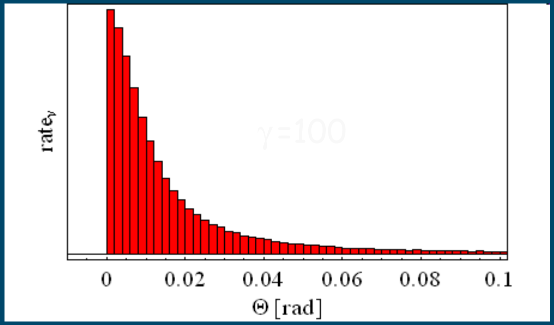


Beta Beams

- Storage ring with β-decaying ions (P Zucchelli)
  - β^- decay => anti-ν_e, β^+ decay => ν_e, Very pure beam – ideal for golden channel
- Choice of Ions
  - Lifetime ~1 sec, shorter, cannot store, longer too few ν's
  - Low Z better – lower mass/charge/ν
  - High E desired, $\sigma \propto E_\nu$, $E_\nu \propto Q_{decay}E_{ion}$, Divergence $\propto 1/E_{ion}$



  - Choices
  - Original γ_{ion} = 100 (feasible at CERN with current SPS)
    - $^6He_2$ for ν, Q = 3.5 MeV, $\langle E_\nu \rangle$ ~ 350 MeV
    - $^{18}Ne_{10}$ for ν-bar, Q = 3.0 MeV, $\langle E_\nu \rangle$ ~ 300 MeV
  - Improved γ = 350 (needs new PS and SPS at CERN)



- High - Q versions (C Rubbia)
    - Increase energy using high-Q decays rather than high γ
    - $^8Li_3$ for ν, Q = 13.0 MeV
    - $^8B_5$ for ν-bar, Q = 13.9 MeV
- Production of sufficient ions is a major challenge, $^6He_2$ OK, $^{18}Ne_{10}$, $^8Li_3$ hard, $^8B_5$ appears very difficult.

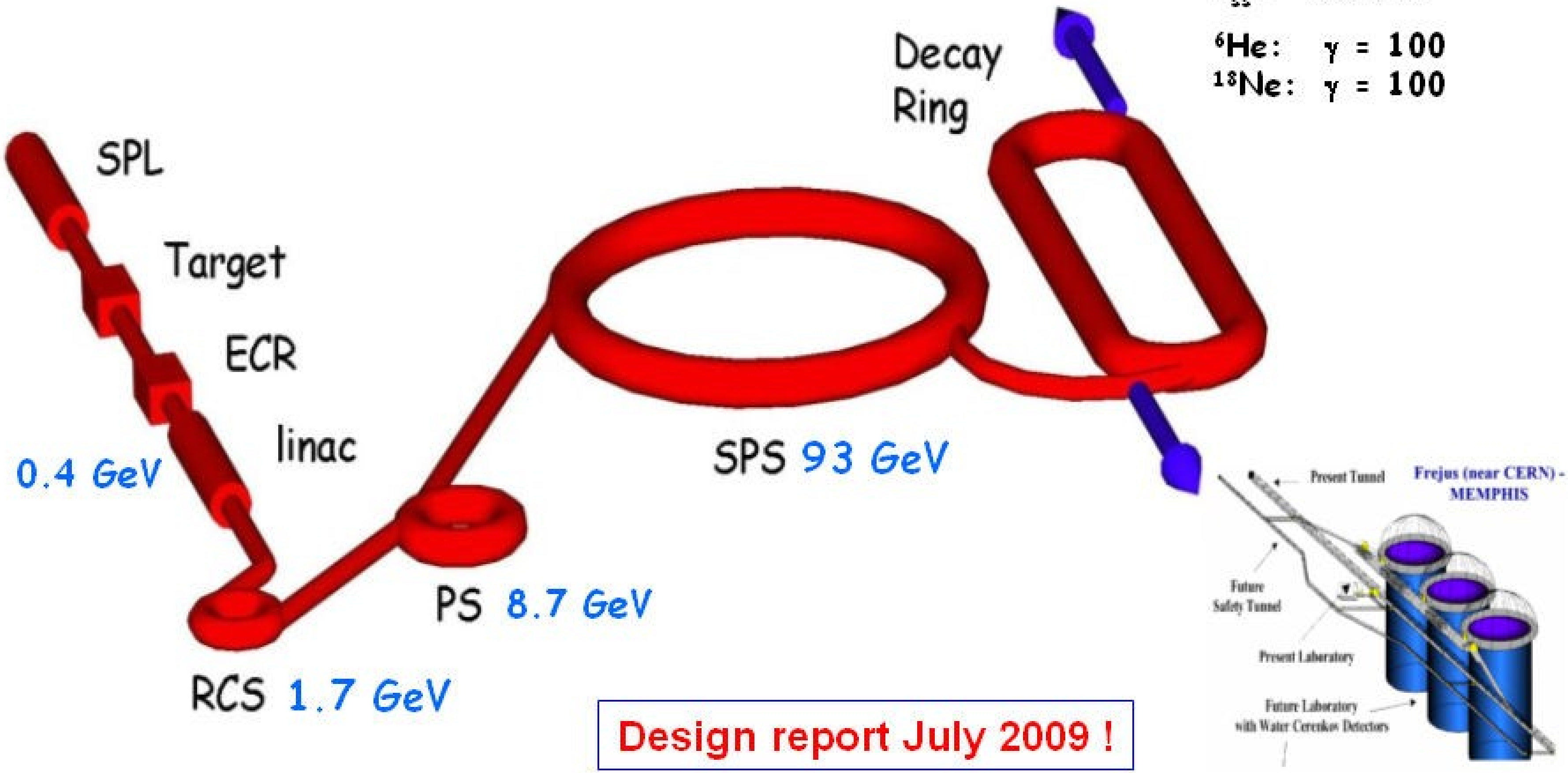
The EURISOL scenario
Design Study

Decay ring

$B\rho$ = 1500 Tm

B = ~6 T
C = ~6900 m
L_{ss} = ~2500 m

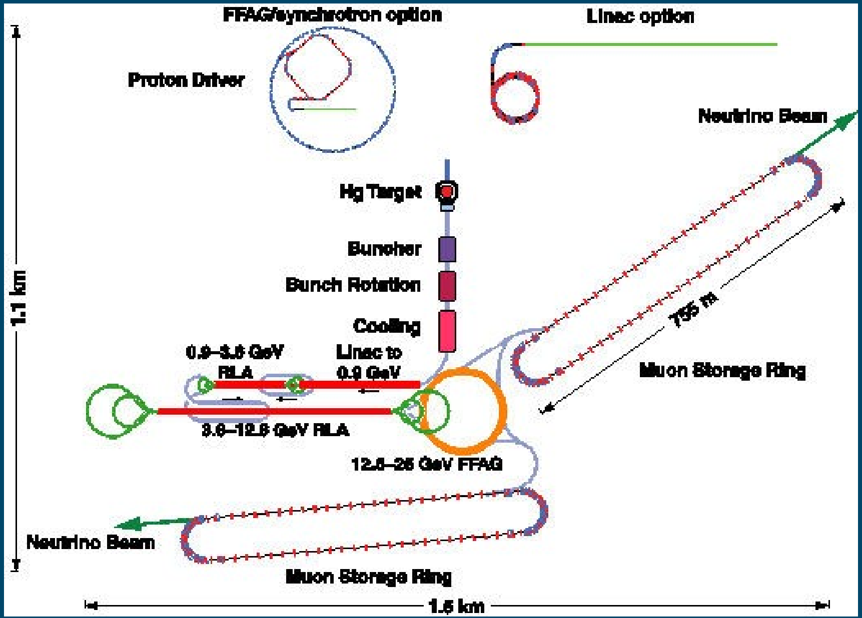
^{6}He: γ = 100
^{18}Ne: γ = 100



Design report July 2009 !

Neutrino source – options:

- Second generation super-beam
- Beta-beam
- Neutrino Factory
  - 'Golden', 'Silver' & 'Platinum'
  - High Purity, Low Divergence beam possible, can have high energy & very long baselines
  - Intensity dependent on proton driver
  - Can have alternate nu, nubar pulses
  - Requires Magnetisable Detector



Neutrino Factory

- Neutrinos from muon decay in a storage ring
- Can arrange for alternate bunches to be from μ^+ and μ^-

$$\nu_e \text{ and } \bar{\nu}_\mu \text{ from } \mu^+$$
$$\bar{\nu}_e \text{ and } \nu_\mu \text{ from } \mu^-$$

Very pure beams but must have charge identification in the detector to establish 'wrong' sign product

The performance of the detector is very important -
magnetisable,
and ideally
as low a threshold as possible for μ sign determination
electron detection sign determination
tau detection appears feasible with magnetized emulsion detector (MECC) or liquid Argon

Has the greatest potential but still technical problems requiring solution.
These are in common with mu collider R&D

NF Feasibility/Design Studies

- Several studies at the turn of the century
  - US Studies I, II, IIa
  - ECFA/CERN Study
  - NuFact-J Study

  established feasibility & R&D programme

  - MUCOOL, MICE, MERIT....
- International Scoping Study (ISS) launched in 2005
  - International integrated accelerator, detector and physics study
  - Completed in 2007 with 3 reports: Accelerator, Detectors & Physics case, (now accepted for publication) ` - include a comparison with performance of superbeams and beta-beams
  - Produced baseline design for
- International Design Study (IDS-NF) launched 2008
  - Goal to produce a CDR inc approx costing by 2012
  - Being conducted in conjunction with NFMC Collaboration in US, EuroNu Design Study in Europe, UKNF in UK + others.

Accelerator Subsystems

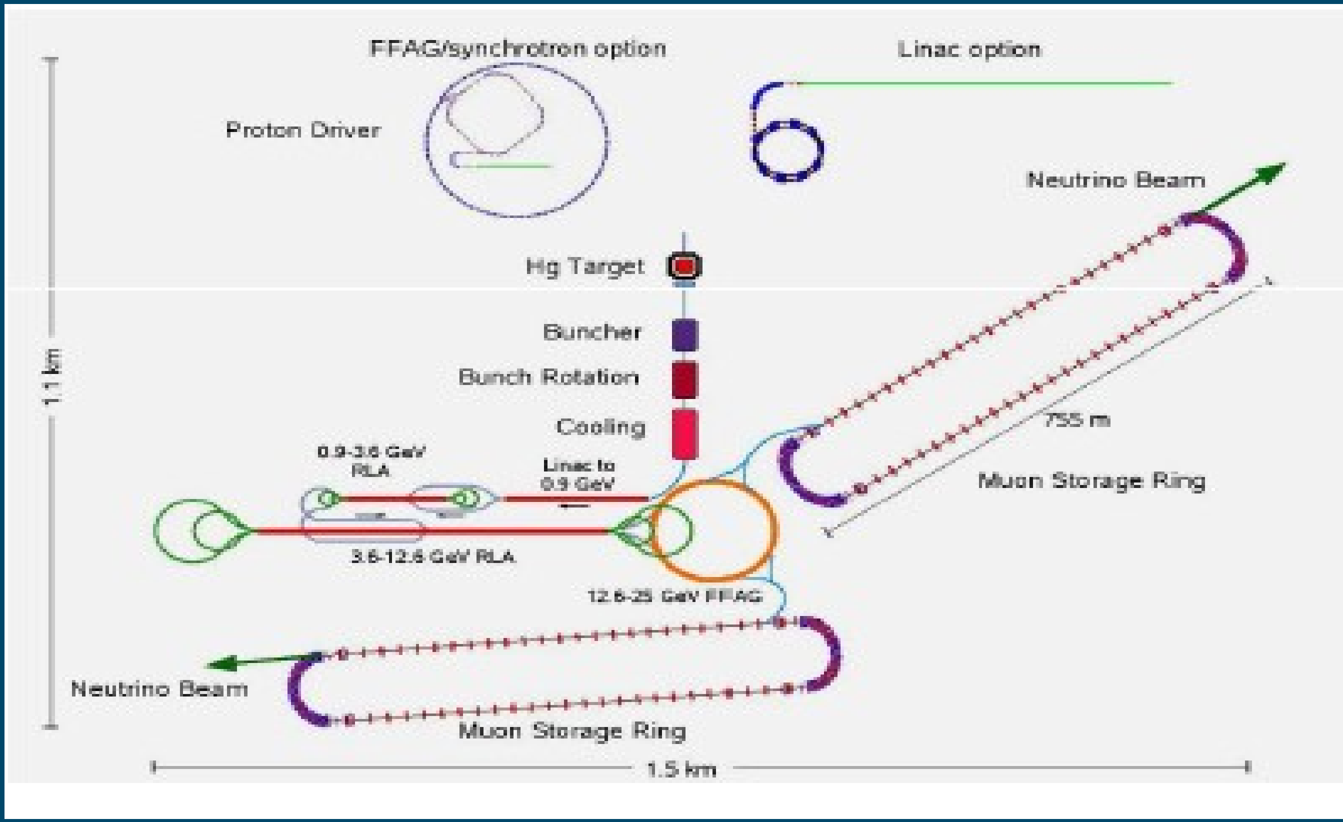
Proton driver

Target and capture

Front end
- Bunching and phase rotation
- Cooling

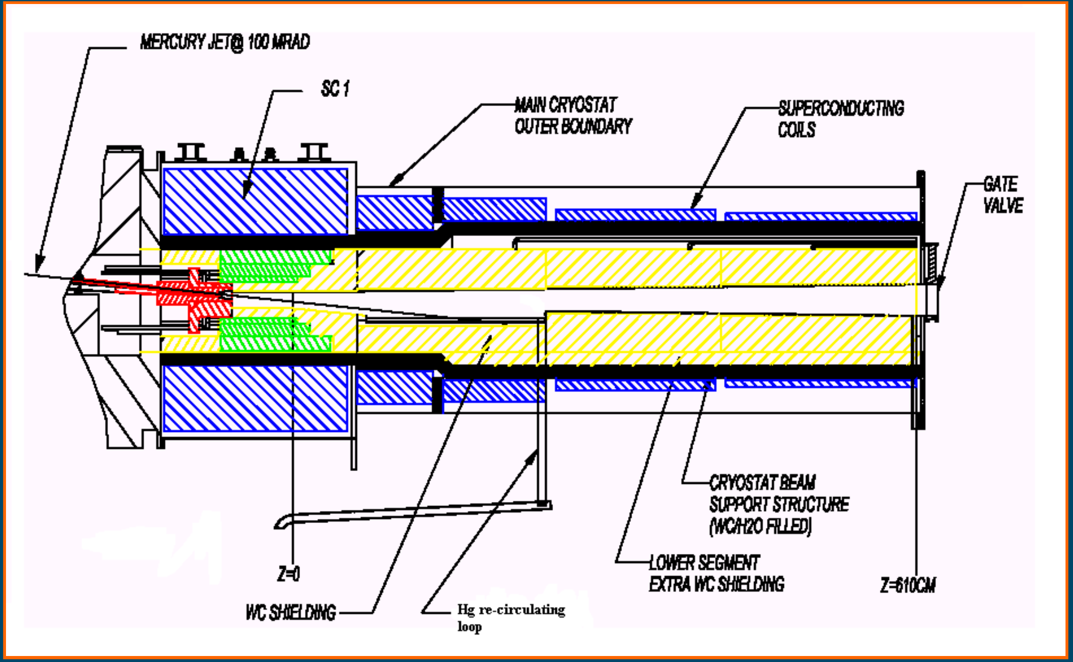
Acceleration

Decay ring



Target – Major difficulty at 4 MW

- Baseline - Mercury Jet

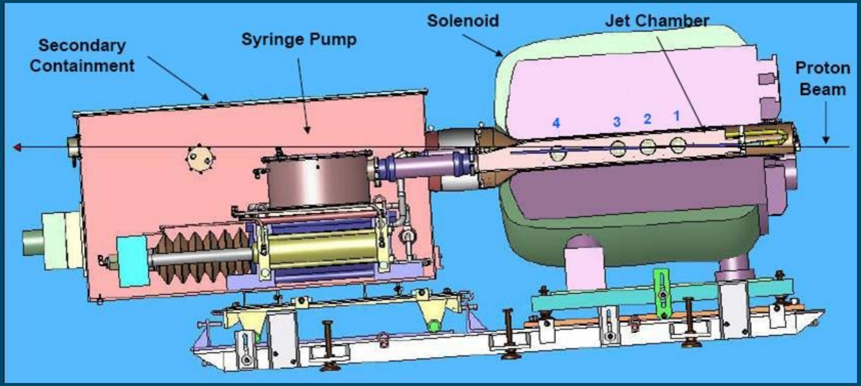


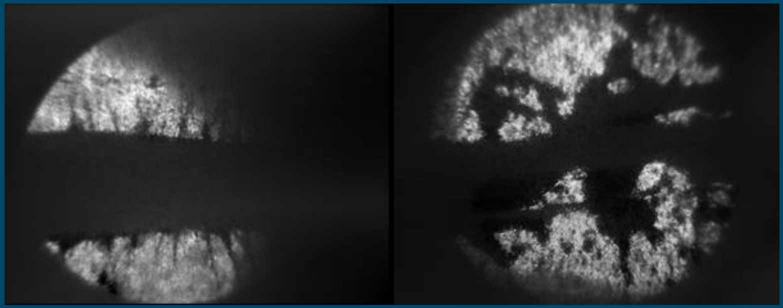
MERIT Expt serves as a satisfactory proof-of-principle of Hg-jet concept
(Ilias Efthymiopoulos)

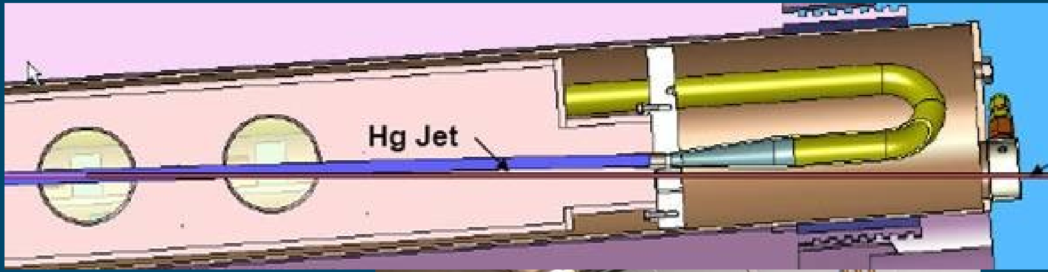
Field tapers from 20 T, 15 cm to 1.75 T, 60 cm over 20 m

MERIT expt at CERN (2008)

- High-power liquid-mercury jet target engineering demonstration







CONCLUSIONS

Power handling of target is adequate

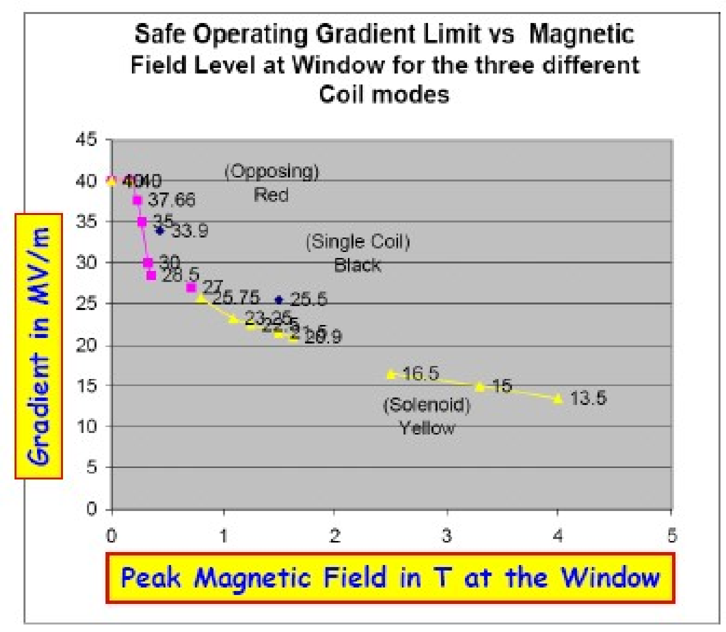
disruption length of 28 cm $\Rightarrow$ 70 Hz rep. rate at 20 m/s

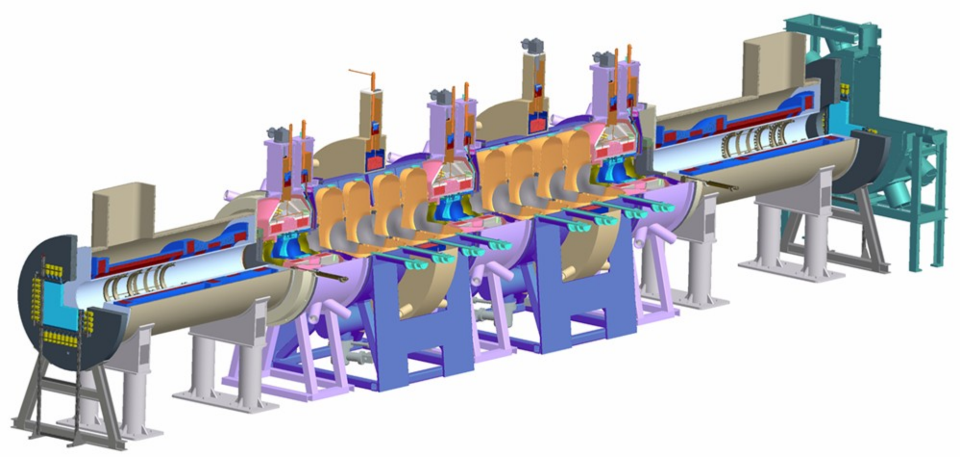
115 kJ per pulse x 70 Hz gives 8 MW of beam power

4 MW design value seems "comfortable"

Cooling: R&D programme

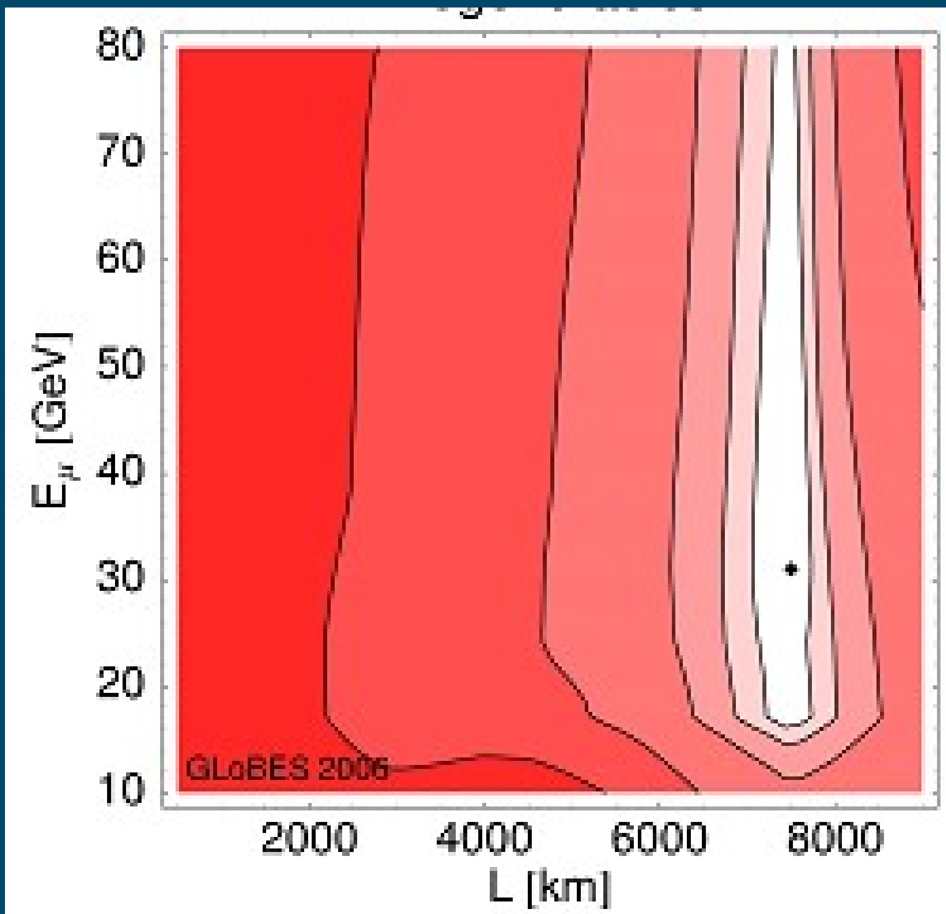
- Essentially focussing a high emittance beam
- 2 Complementary programmes:
  - MuCool: (FNAL)
    - Design, prototype, and test – using an intense proton beam – cooling channel components
  - MICE: (RAL)
    - Design, construct, commission, and operate – in a muon beam – a section of cooling channel and measure its performance in a variety of modes
- MICE results 2012-13





ISS Report - NuFact - $\sin^2 2\theta_{13}$ sensitivity

ISS Physics Report



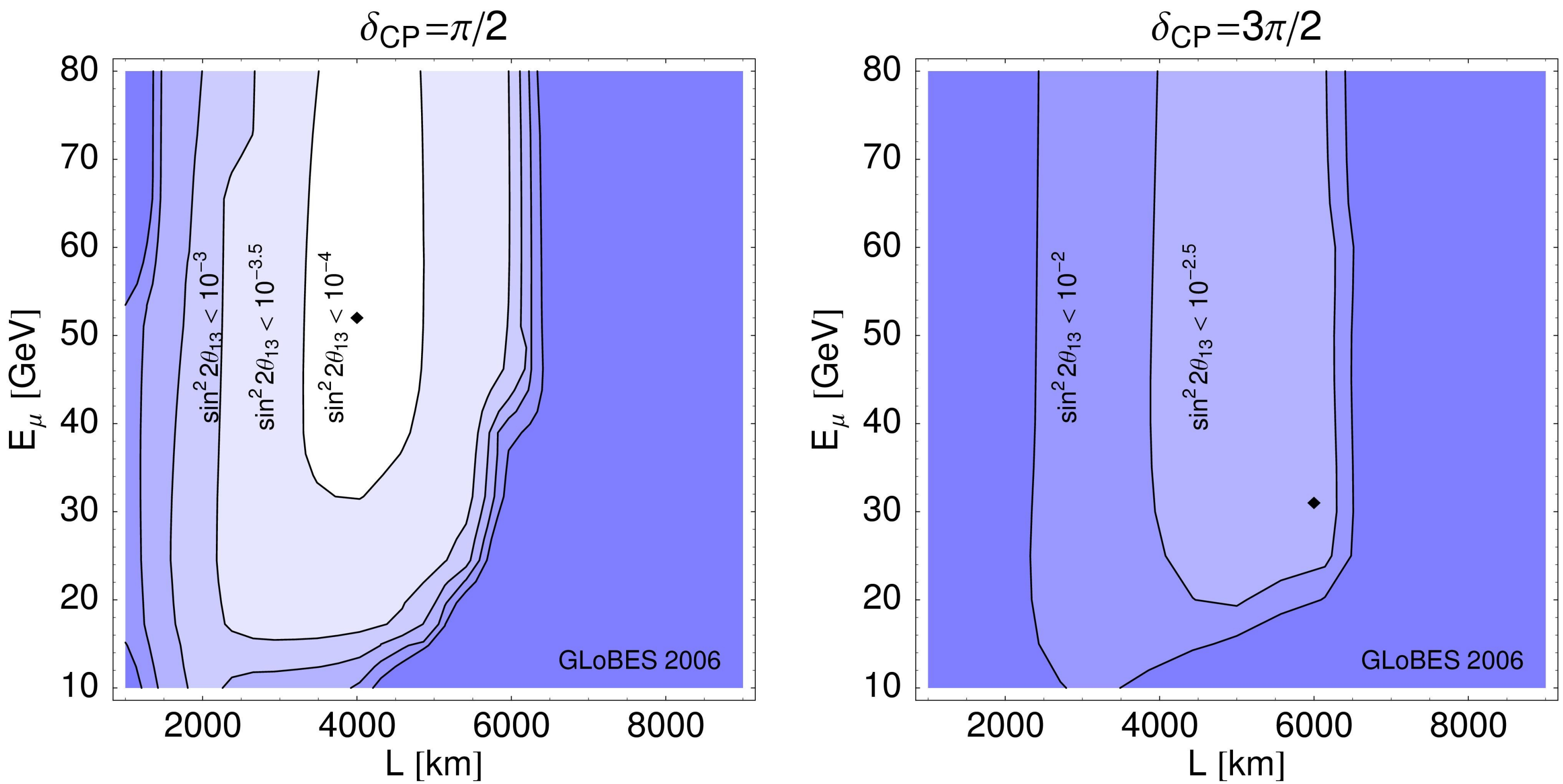
Taking into account statistics, systematics, correlations, degeneracies

Magic baseline (7500 km) good degeneracy solver

Europe to INO (India) is Ideal

Stored muon energy is 20 GeV

NuFact - CP sensitivity



Baseline: 3000 – 5000 km
Stored-muon energy > 30 GeV

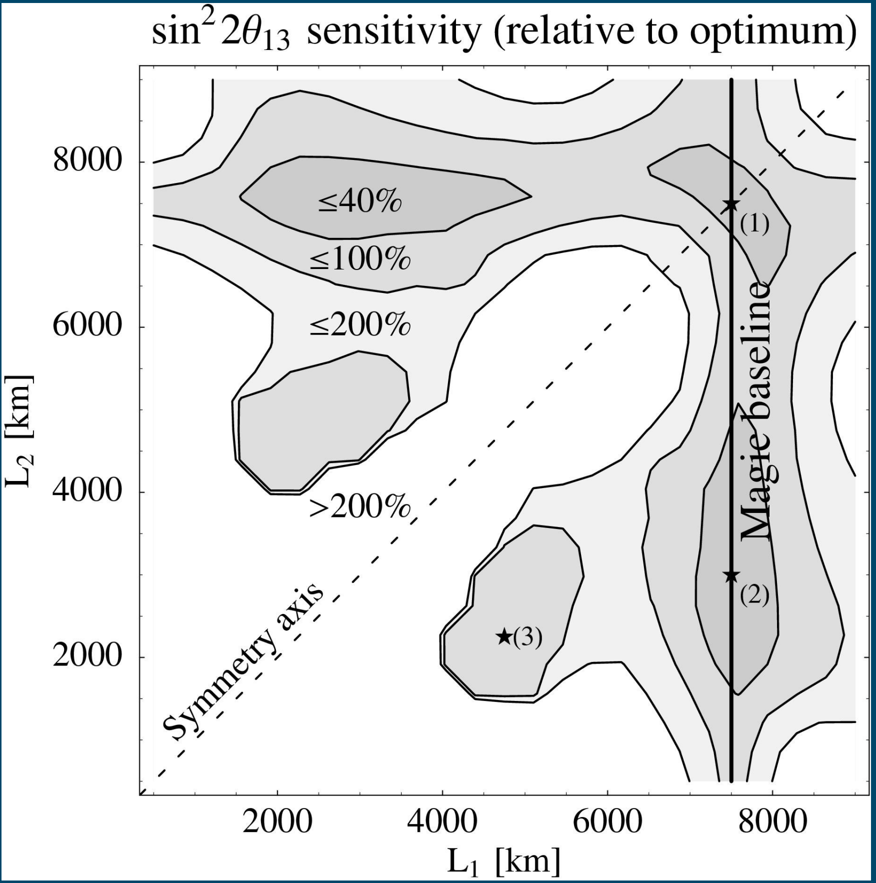
ISS Physics Report

NuFact - Multiple baselines:

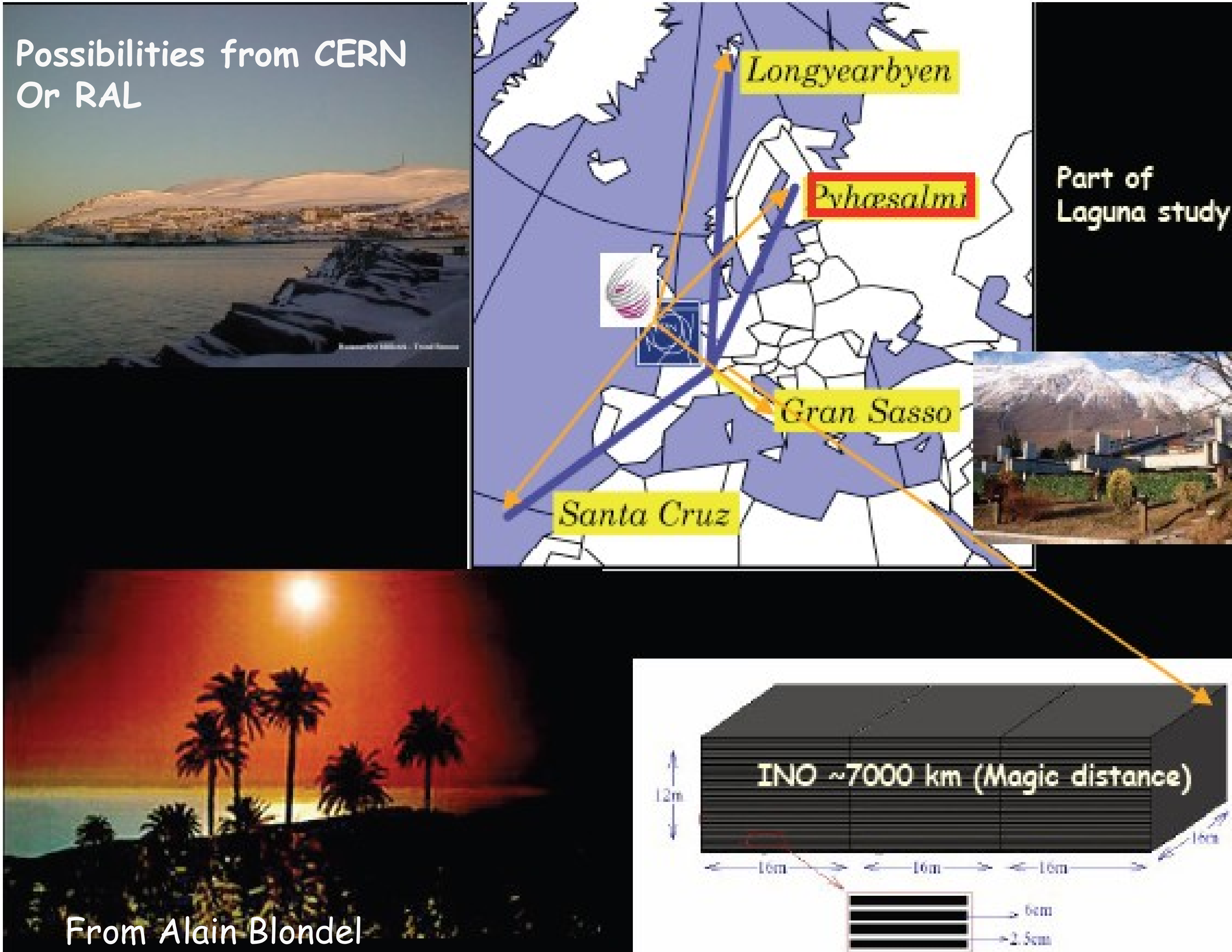
- Performance for two 25kT detectors relative to the performance for one 50 kT detector at the magic baseline

Stored muon energy 50 GeV

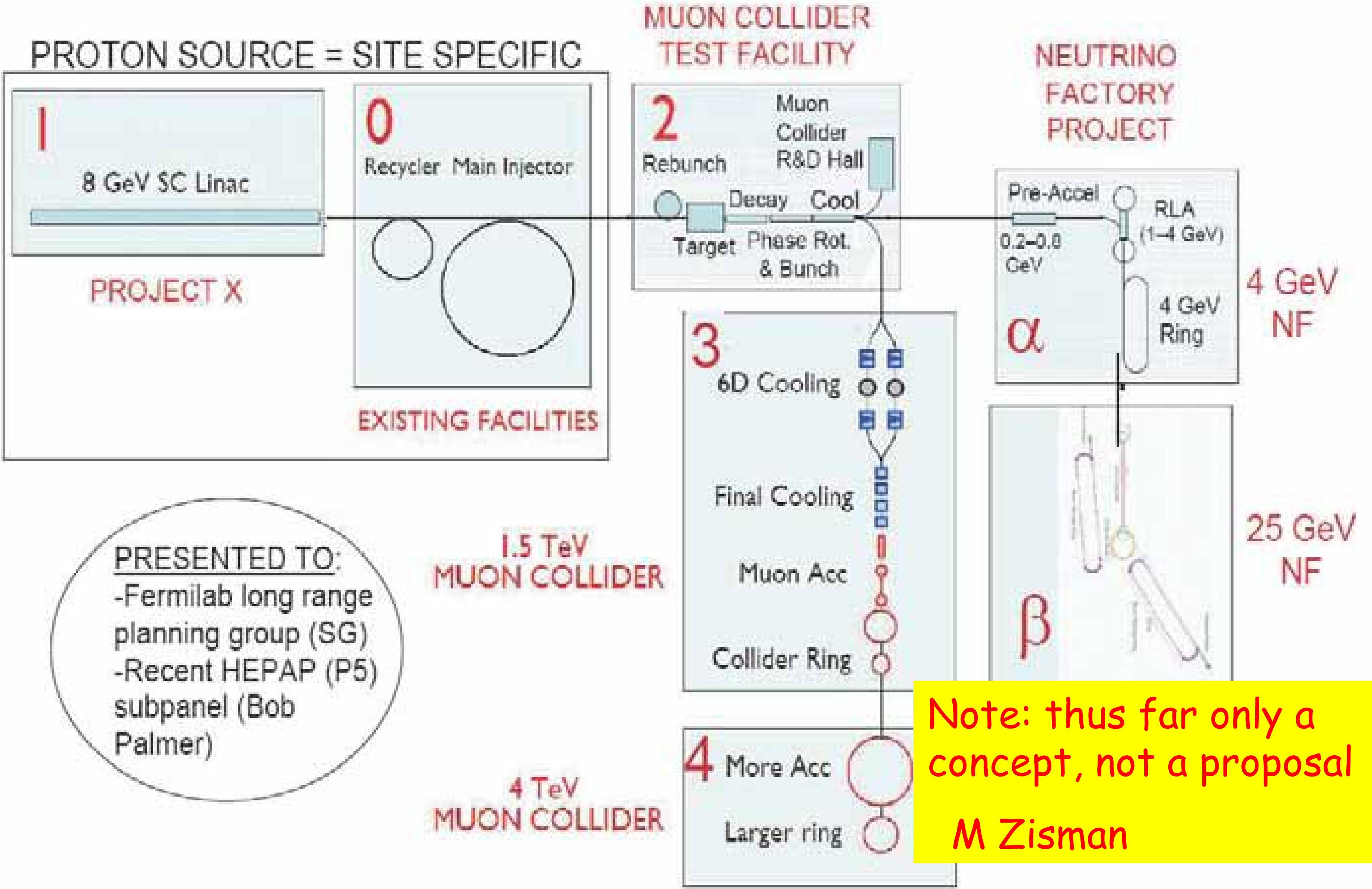
Second detector at ~3000 km is preferred



ISS Physics Report


Possibilities from CERN
Or RAL
Longyearbyen
Pyhæsalmi
Part of
Laguna study
Gran Sasso
Santa Cruz
INO ~7000 km (Magic distance)
12m
16m
16m
16m
16m
6cm
2.5cm
From Alain Blondel

A U.S. Scenario / Project X



Note: thus far only a concept, not a proposal

M Zisman

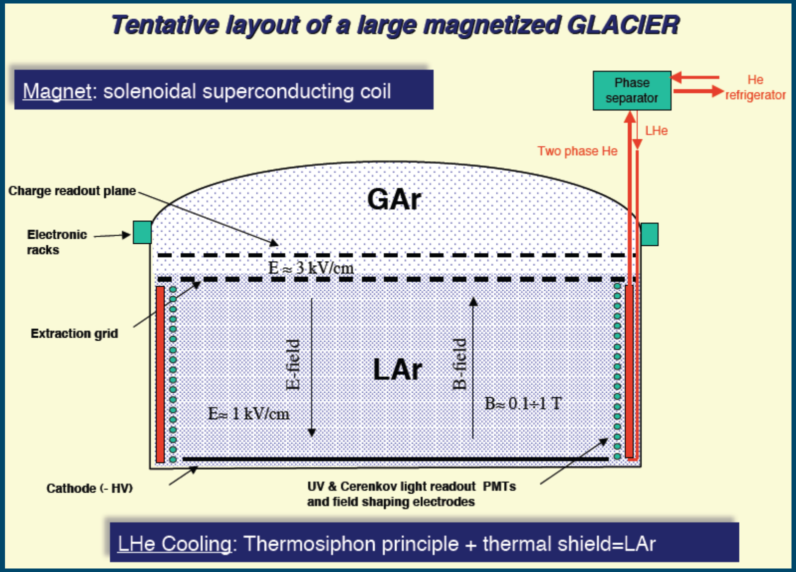
Detectors

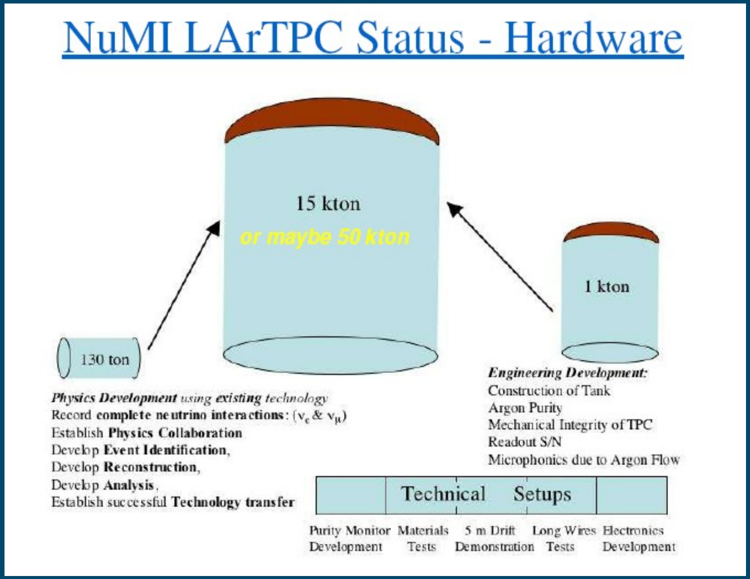
Choice & Design Critcal for precision experiments

- Water Cerenkov
  - Good for low energy SB, BB, well established, also p-decay
- Liquid Argon TPC
  - SB, BB, (NF if magnetisable), prob also p-decay
- MIND Iron / Scintillator sandwich (MINOS like)
  - NF baseline
- TASD Totally Active Scintillating Detector (Nova, Minerva like)
  - SB, BB, (NF if magnetisable), poss also p-decay
- Hybrid Emulsion Detectors
  - NF – for silver channel
- Beam Diagnostic Devices
- Near Detector
  - Vital for precision

Liquid argon

- Detector concepts





- Various configurations being studied :
  - Glacier
  - T2K-LAr (near det.)
  - NuMI LArTPC

Emulsion detector – MECC

DONUT/OPERA type target + Emulsion spectrometer + TT + **Electron/pi discriminator**

B

Stainless steel or Lead Film Rohacell 3 cm Electronic detectors/ECC

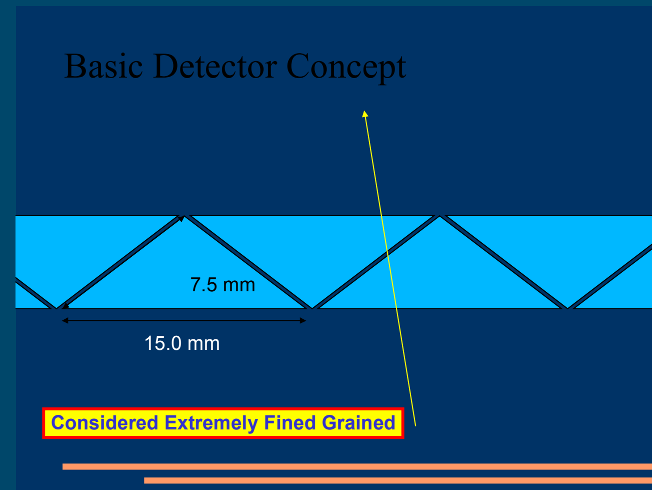
Assumption: accuracy of film by film alignment = 10 micron (conservative)

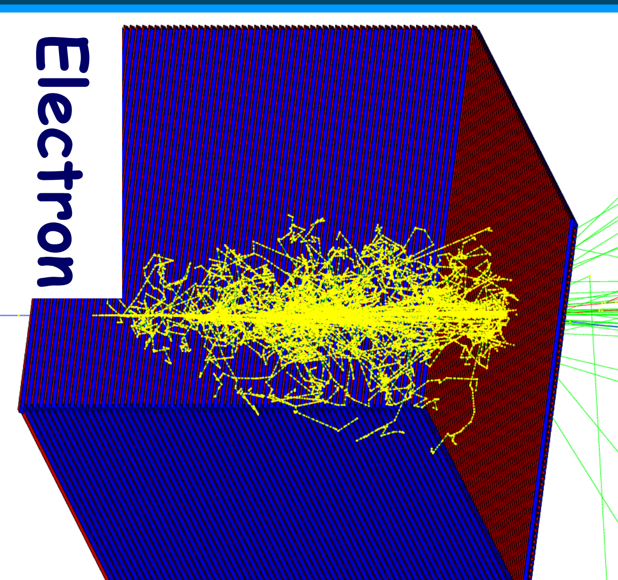
13 lead plates (~2.5 X_0) + 4 spacers (2 cm gap) (NB in the future we plan to study stainless steel as well. May be it will be the baseline solution: lighter target)

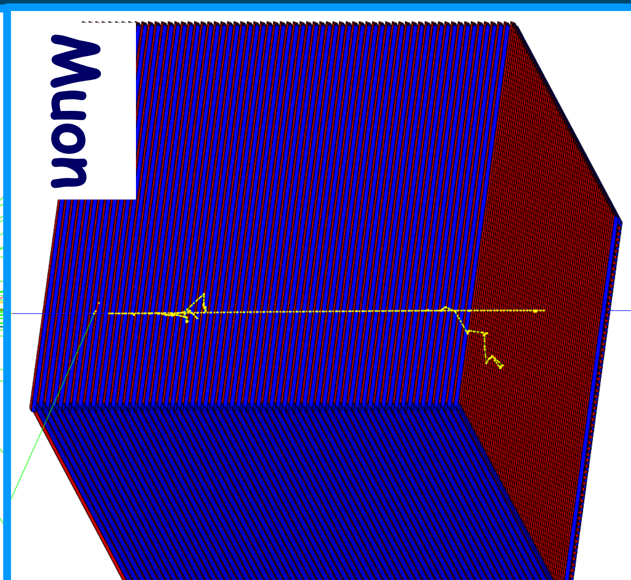
The geometry of the MECC is being optimized

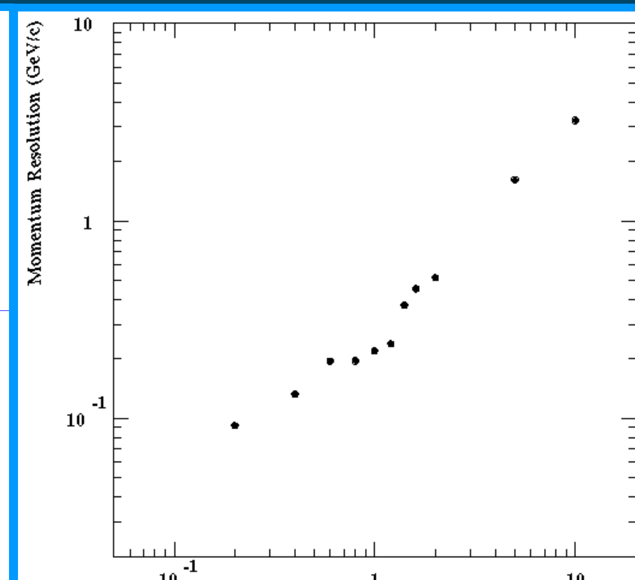
Magnetic sampling calorimeter

- Development of MINOS detector
  - Magnetised iron?
    - Sampling fraction?
  - Most easily realised magnetic detector







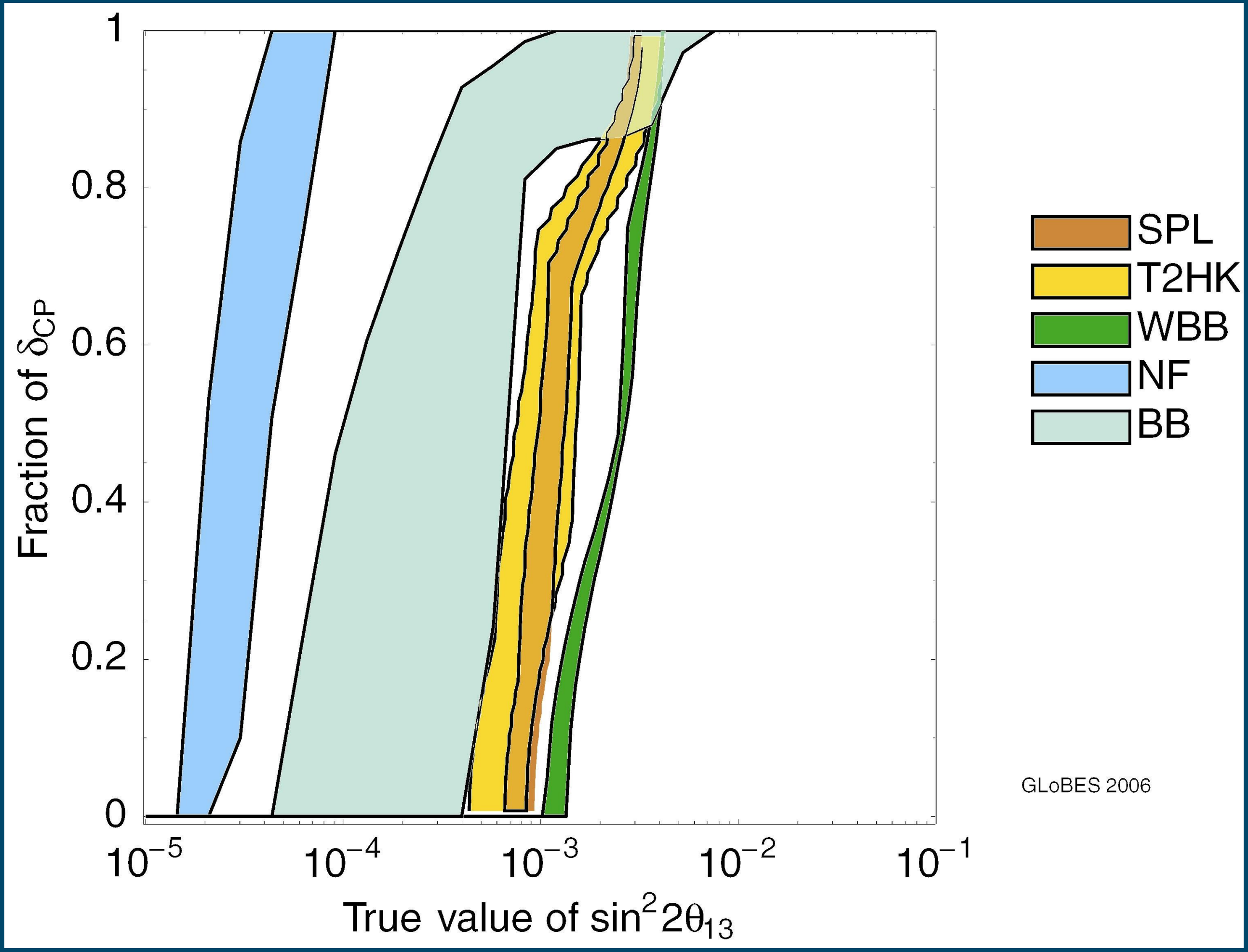


A performance comparison (ISS)

- Super-beam:
  - T2HK, SPL CERN beam to Frejus, A Long baseline Wide-band Beam such as planned for Project X
- Beta beam:
  - Low γ: γ = 100 and L = 130 km
    - Flux (~10^{18} decays per year)
  - High γ: γ = 350 and L = 700 km
    - Flux (~10^{18} decays per year)
- Neutrino Factory
  - Performance studied as a function of:
    - E and L
    - E_{thresh} and E_{Res}
- The bands correspond to basic/enhanced performance

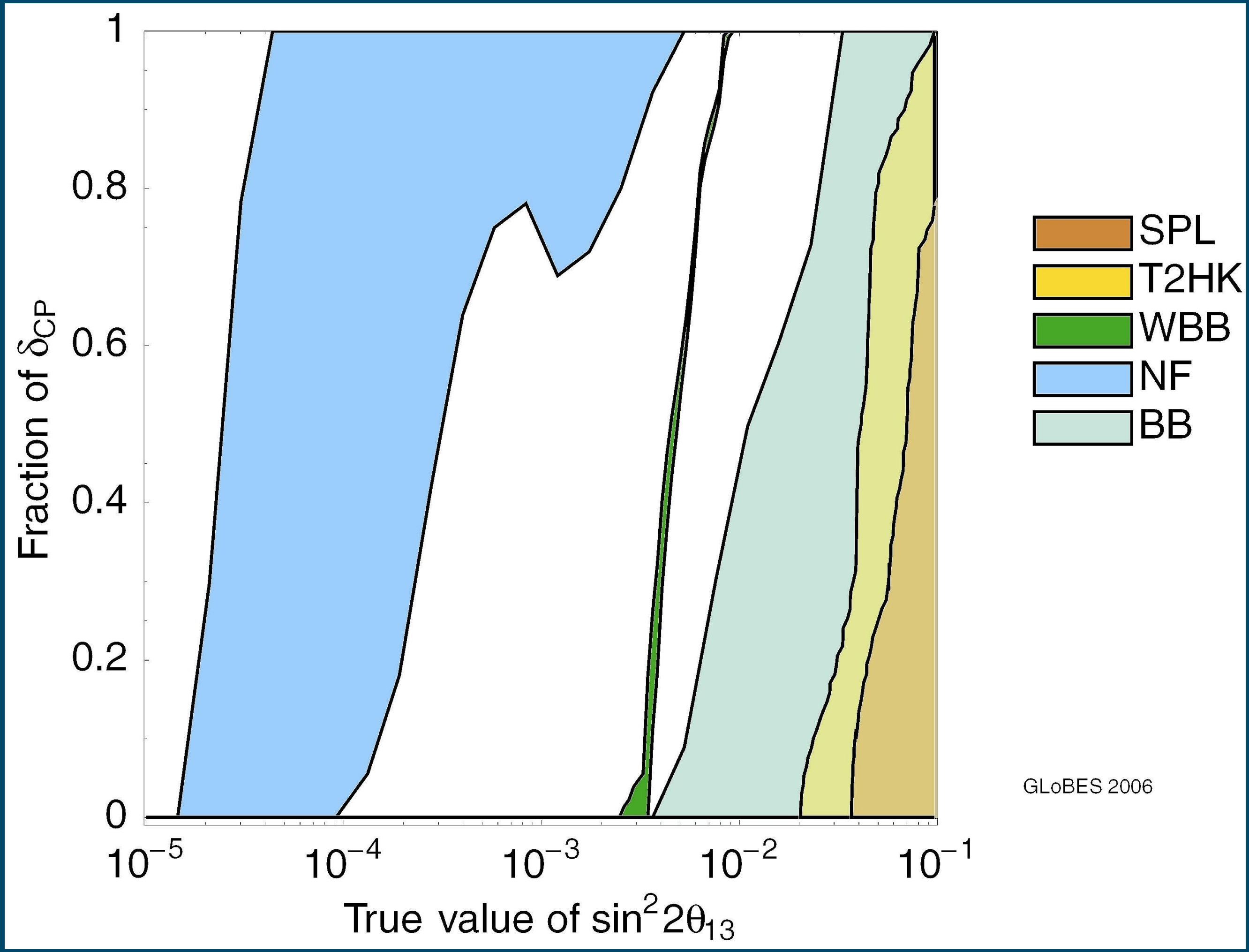
For θ_{13}

ISS Physics Report



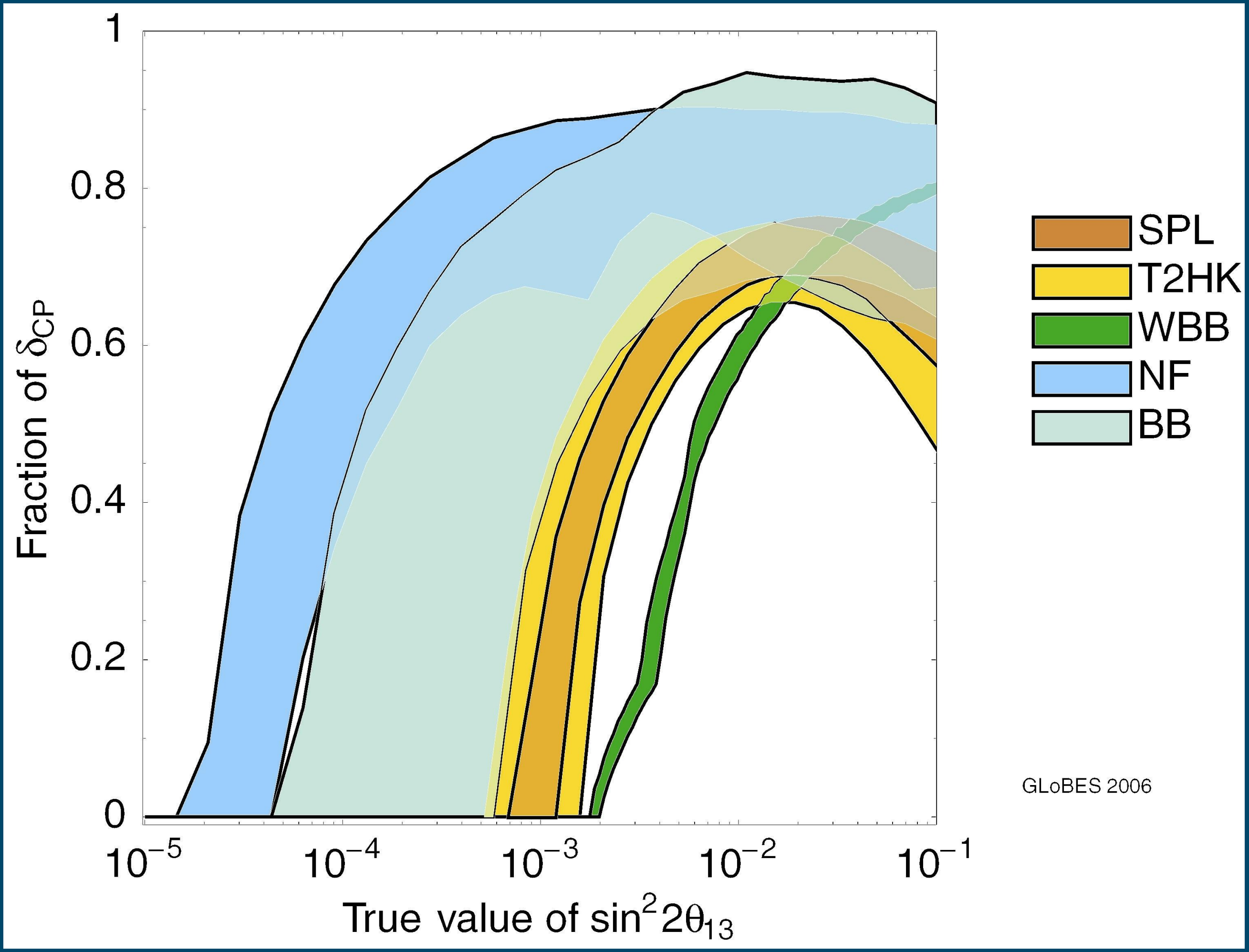
For the Mass Hierarchy

ISS Physics Report



For CP violation

ISS Physics Report



Summary

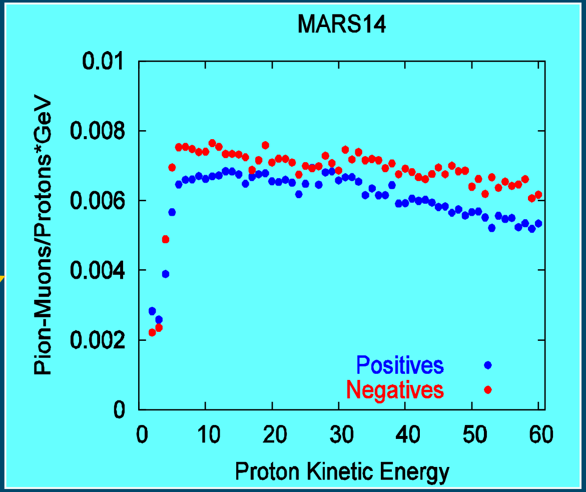
- The Lepton Sector has shown the first sign of BSM physics and may hold the key to the Flavour problem, CP violation and a viable GUT
- Progress will need precision measurements of the oscillation parameters (comparable with CKM)
- This will demand major construction beyond T2K and Nova to produce intense neutrino beams and very large detectors
- Realistic proposals exist but both beams & detectors still require R&D to show viabiliy. This is taking place now.
- By 2012 – 2014 there should be enough information, R&D results, cost estmates and crucially the value of θ_{13} to decide the best approach
- With funding, a precision era experiment could take data by 2020-25
- It would be wonderful to know if neutrinos are Majorana and what is m_1,

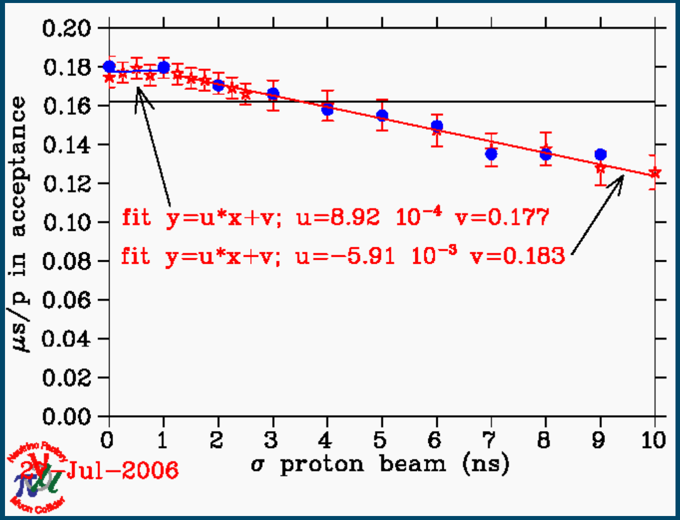
Back-up

Proton Driver

- Baseline Parameters

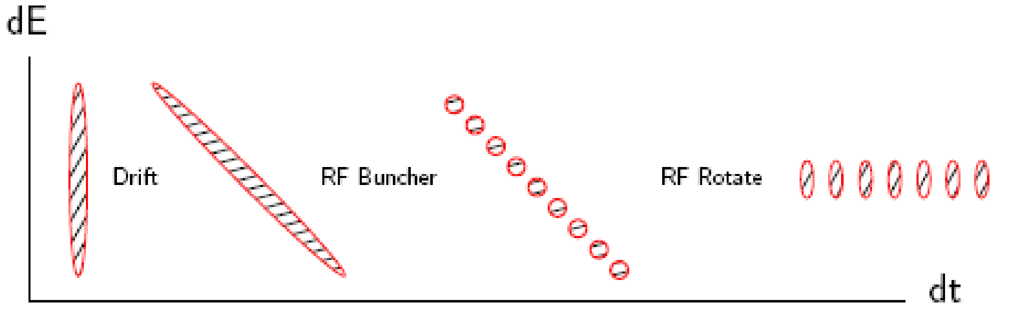
Parameter	Value
Energy (GeV)	10 ± 5
Beam power (MW)	4
Repetition rate (Hz)	≈ 50
No. of bunch trains	3,5[a)]
Bunch length, rms (ns)	2 ± 1
Beam duration[b)] (μs)	≈ 40

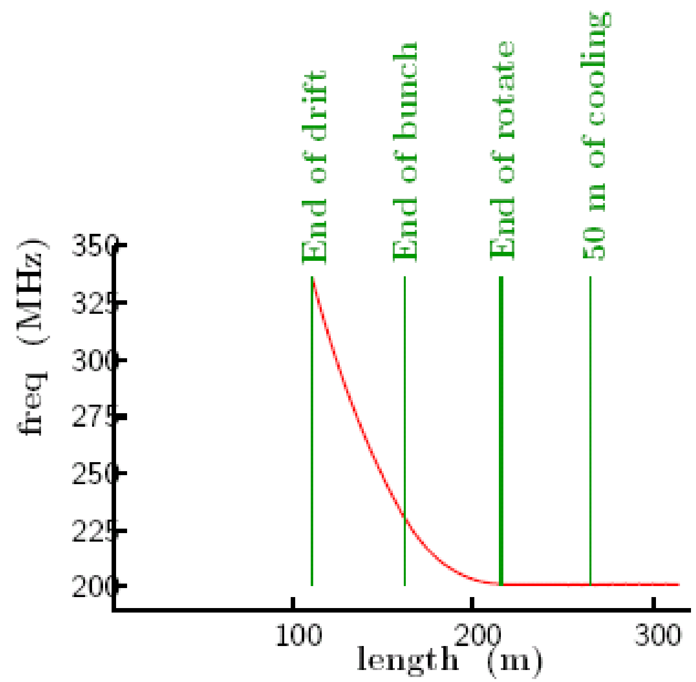




Phase Rotation & Bunching

Bunched Beam Rotation with 200 MHz RF (Neuffer)

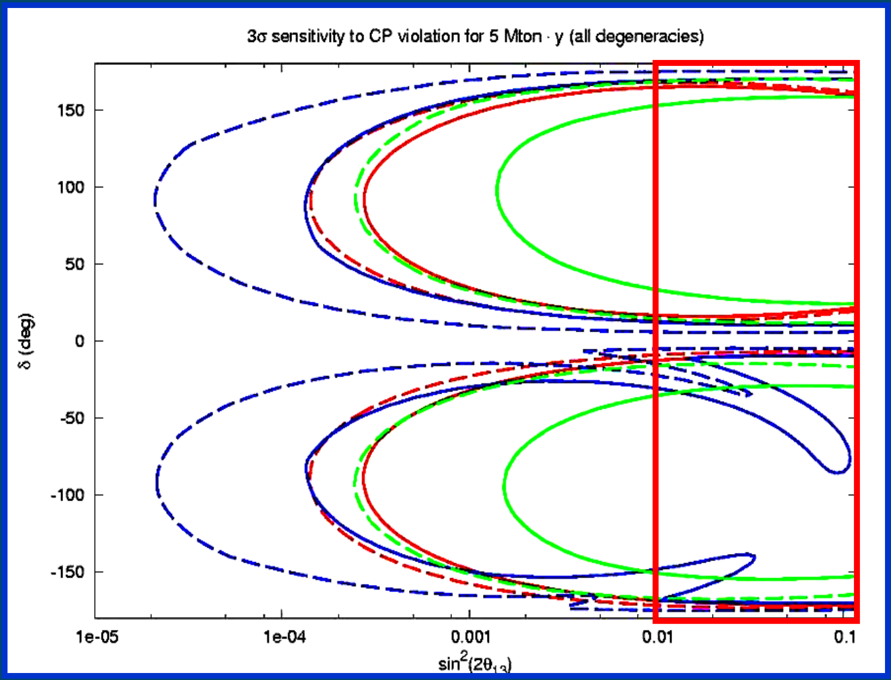




- RF frequency must vary along bunching channel (high mom. bunches move faster than low)
- Bunched Beam method captures both signs in interleaved bunches

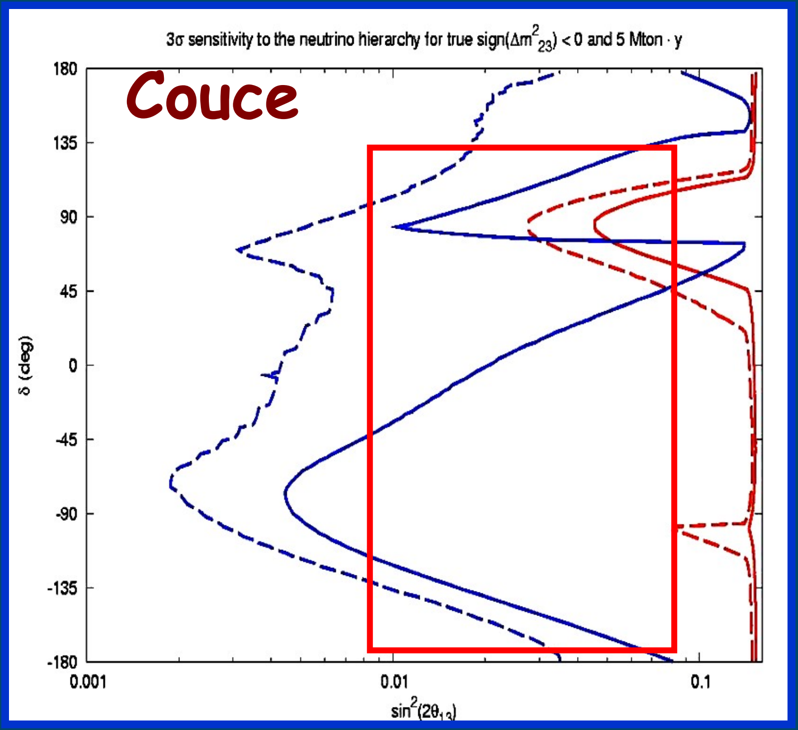
Requires R & D

Beta beam, super beam comparison



Preliminary! Need to include better treatment of background and sys. err.

T2HK	2 MW 4 MW
Low-E βB	Low Flux High Flux
High-E βB	Low Flux High Flux



- High θ_{13}:
  - Beta beam & super beam alone:
    - δ sensitivity good
    - Poor sign(Δm_{23}^2) sensitivity

Front end: new configurations

(D. Neuffer)

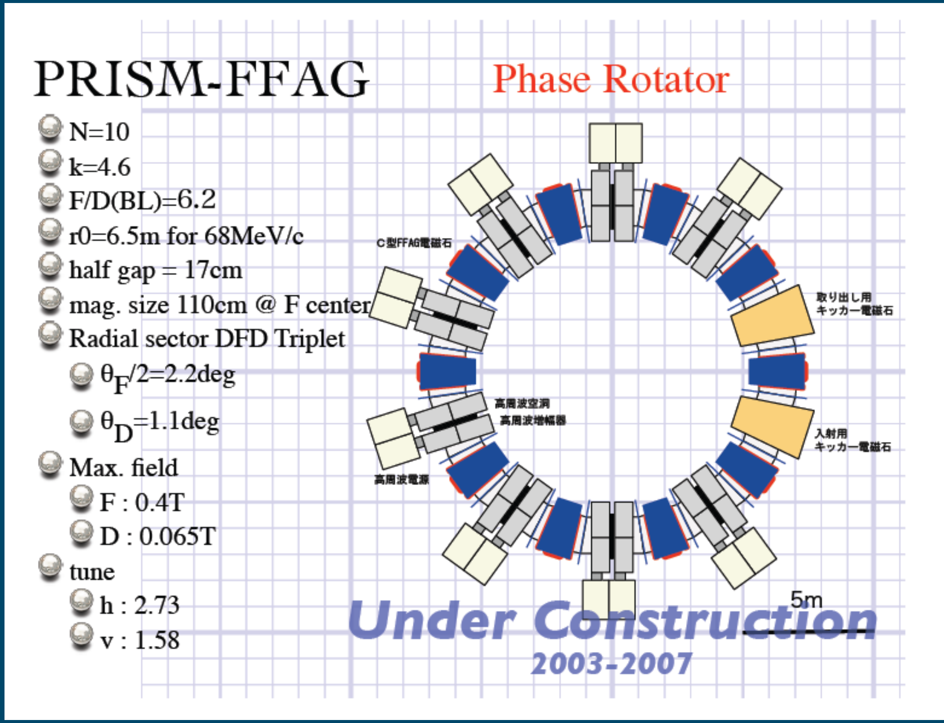
(A. Klier)

- "Guggenheim" cooling channel
- provides longitudinal cooling
- solves problems with
  injection, absorber heating
- can taper parameters

- cool while doing phase rotation
- cost savings
- 150 atm hydrogen (room temp)
- 24 MV/m RF
- performance looks promising

Acceleration: FFAG development

- Increasing effort on scaling and non-scaling FFAG
- PRISM: Phase rotated intense muon source
  - Under construction in Osaka
    Commissioning 2007



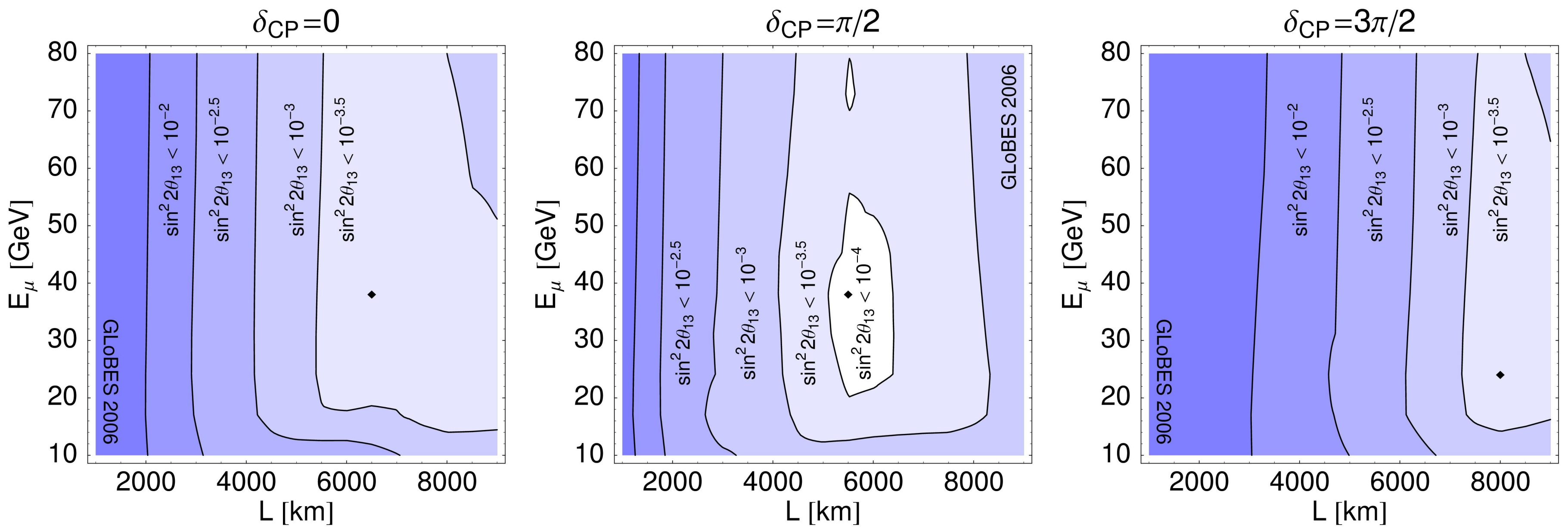
EMMA :Electron model of muon acceleration

Near detector

- Measurement of cross sections in DIS, QE and RES.
- Coherent π
- Different nuclear targets: H_2, D_2
- Nuclear effects, nuclear shadowing, reinteractions

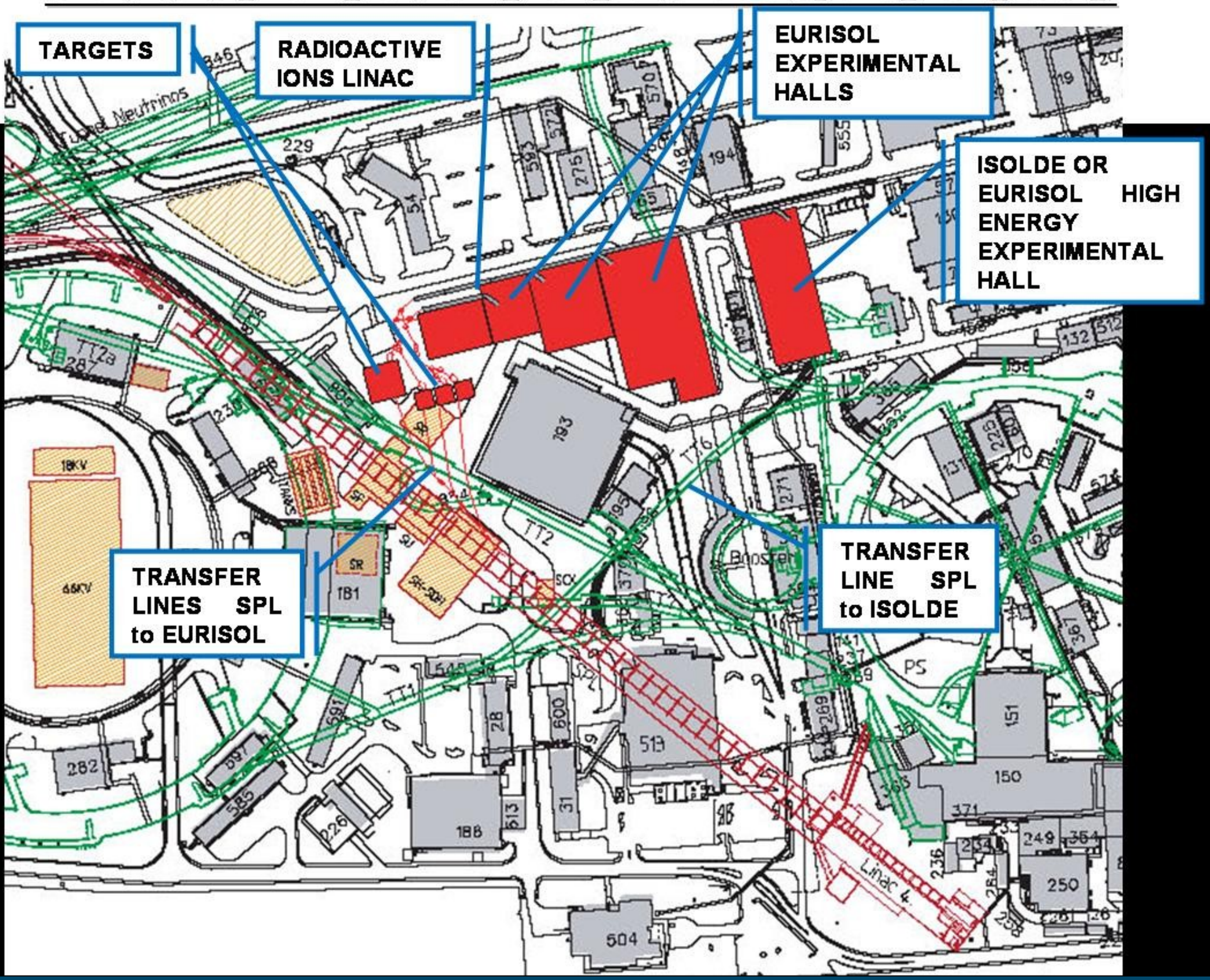
- With modest size targets can obtain very large statistics
- What is lowest energy we can achieve? E.g. with LAr can go down to ~MeV

NuFact - Mass Hierarchy sensitivity

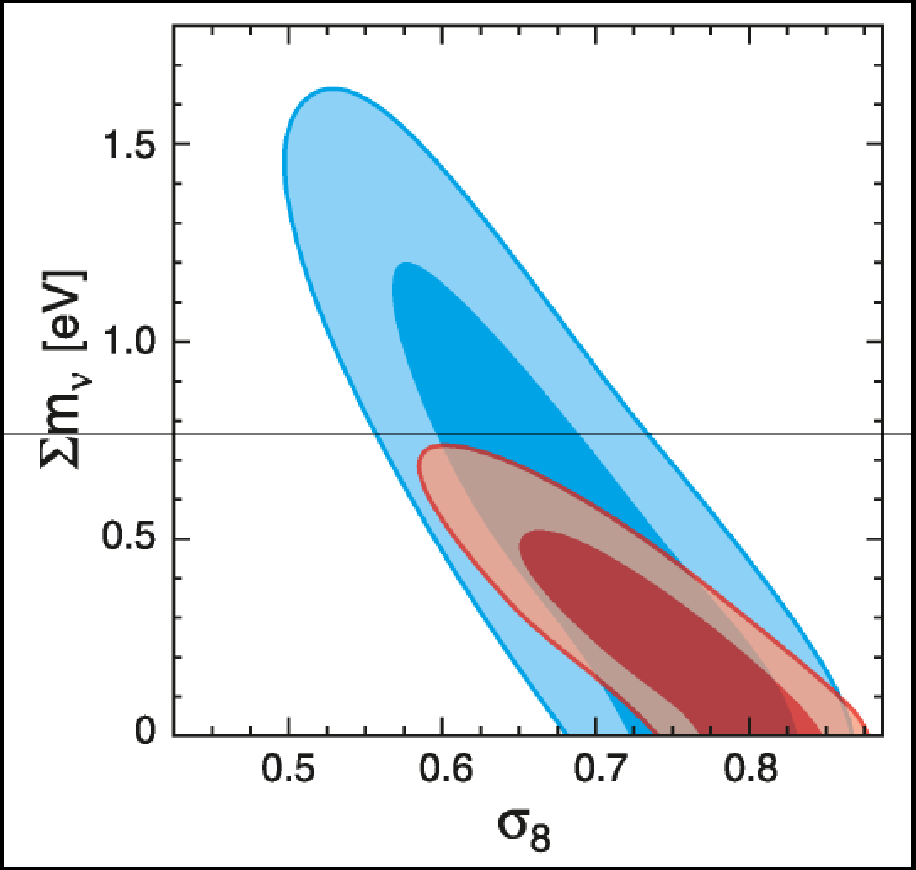


Baseline: ~7500 km
Stored muon energy 20 – 50 GeV

PLANS FOR FUTURE INJECTORS



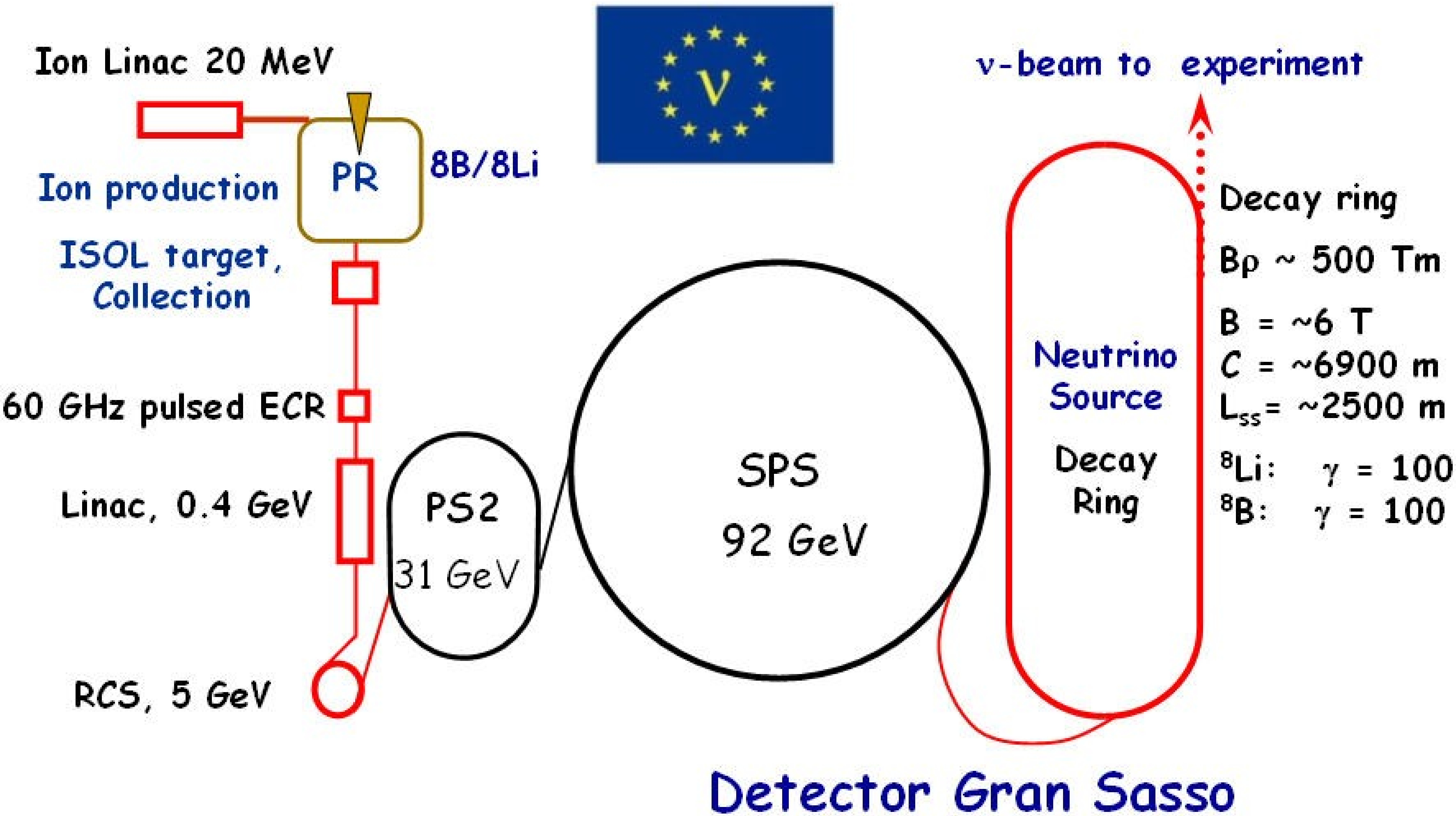
From Cosmology



WMAP-5 ONLY ~ 1.3 eV
WMAP + OTHER 0.67 eV

Komatsu et al., arXiv:0803.0547

Beta Beam scenario EUROν (FP7)



Search for $\nu_\mu \rightarrow \nu_e$ appearance T2K

- Look for excess events in 1-ring e-like sample at SK

Expected number of events at SK (0.75kW beam x 5yr)

$\sin^2 2\theta_{13}$	Backgrounds			Signal
	ν_μ induced	Beam ν_e	**Total**	
0.1	10	13	**23**	**103**
0.01				**10**

- Dominant background sources:
  - Beam ν_e contamination
    - Irreducible, but different energy spectrum from oscillated ν_e
  - ν-induced NC1π^0 events
    - one of 2γ from π^0 is missed
    - Reducible, needs knowledge of NC1π^0 interaction

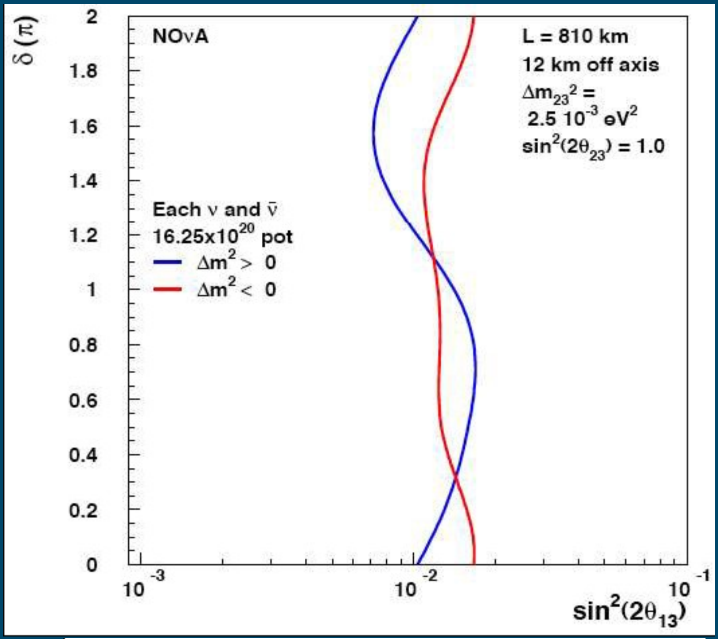
→ To be studies/estimated at near detector

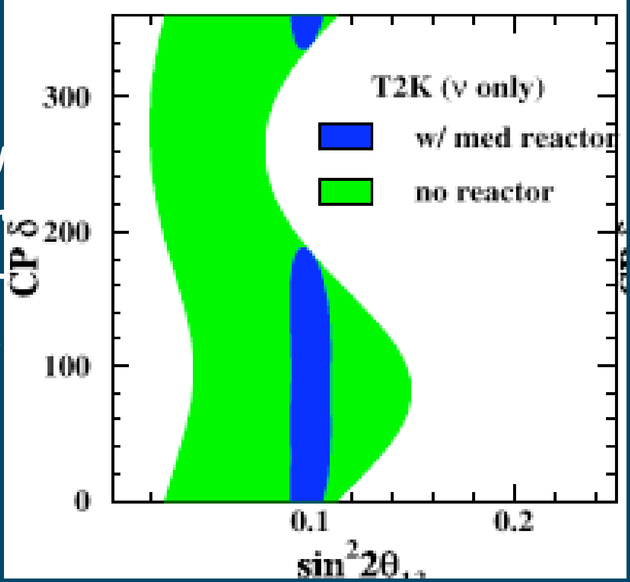
Nova

Sensitivity similar to T2K.
– improve with antineutrino run.

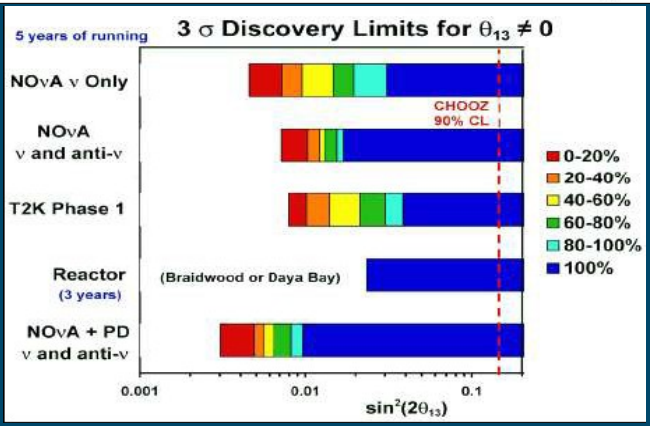
- Sensitivity to mass hierarchy.

- Synergies w
reactor exper
different mat
different deg





90% CL regions for $\sin^2 2\theta_{13}$=0.1, δ=90

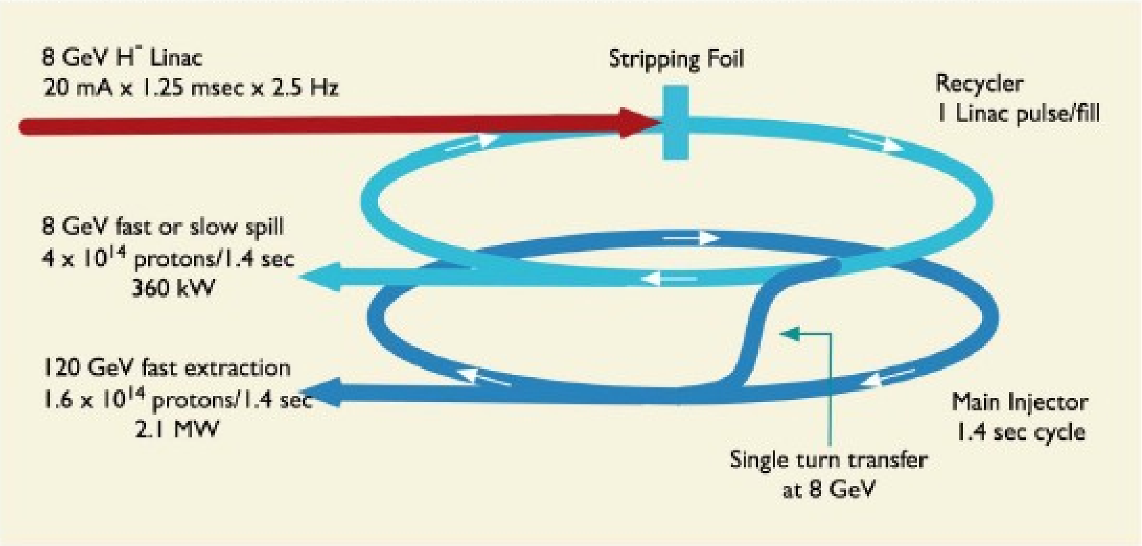


FNAL - Project X

Initial Configuration

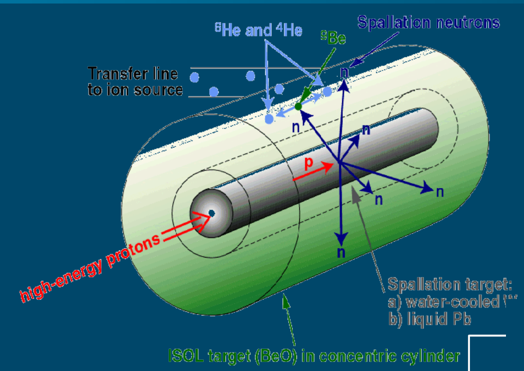
- A multi-megawatt proton source is considered a central and cohesive element for future accelerator developments needed in the exploration of both Energy and Intensity Frontiers at Fermilab

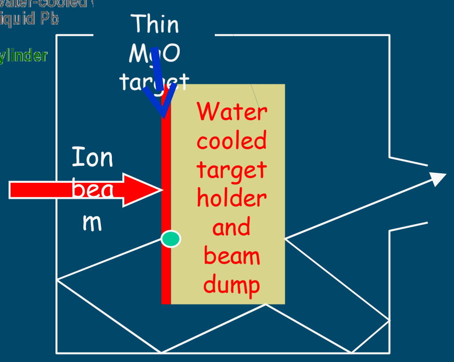
- Project X Design Criteria
  - 2 MW of beam power over the range 60 - 120 GeV;
  - Simultaneous with at least 150 kW of beam power at 8 GeV;
  - Compatibility with future upgrades to 2-4 MW at 8 GeV

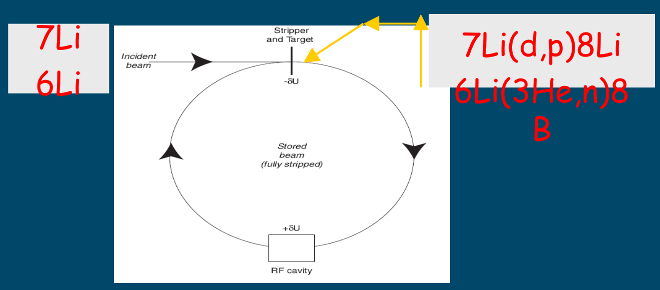


Ion production (from Elena Wildner)

- ISOL method at 1-2 GeV (200 kW)
  - >1 10^{13} ^{6}He per second
  - <8 10^{11} ^{18}Ne per second
  - Studied within EURISOL
- Direct production
  - >1 10^{13} (?) ^{6}He per second
  - 1 10^{13} ^{18}Ne per second
  - ^{8}Li ?
  - Studied at LLN, Soreq, WI and GANIL
- Production ring
  - 10^{14} (?) ^{8}Li
  - >10^{13} (?) ^{8}B
  - Will be studied within EUROν







N.B. Nuclear Physics has limited interest in those elements ->> Production rates not pushed!

E Wildner New Opportunities in the Physics Landscape at CERN May 2009

ν FACTORY

✓ The layout of the future injectors is compatible with a ν Factory at CERN.

MUON ACCELERATORS

MUON PRODUCTION TARGET

ACCUMULATOR & COMPRESSOR

SPL

MUON STORAGE RING

From Roland Garoby

Neutrinos as Probes

Neutrinos are

Not absorbed by matter
Not deflected by magnetic or electric fields

so the perfect probe
if there are enough to be able to measure them !

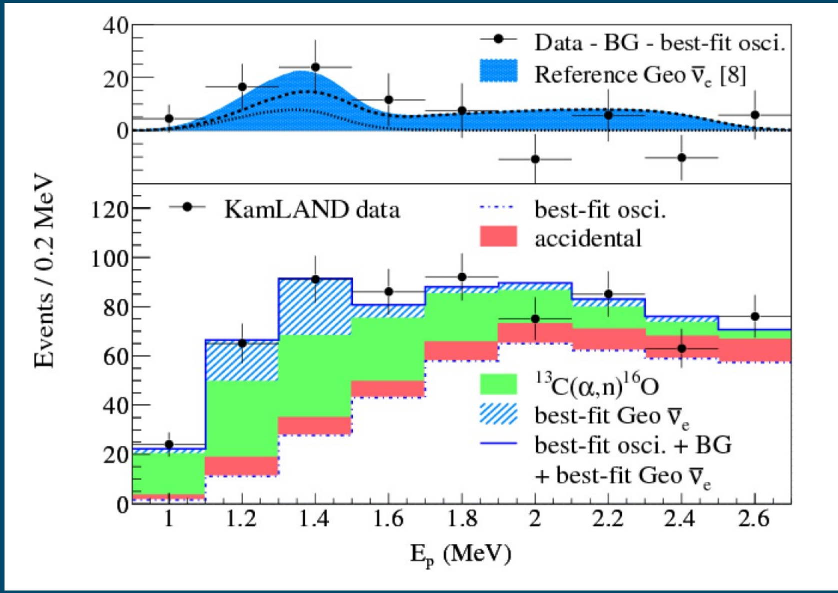
Neutrinos are produced

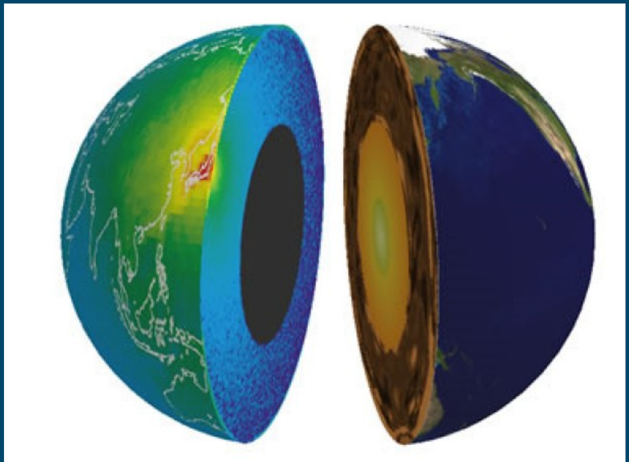
In the Big Bang
In Supernovae
In the Earth
In the Sun
Probably with HE cosmic rays
Probably with Gamma Ray Bursts

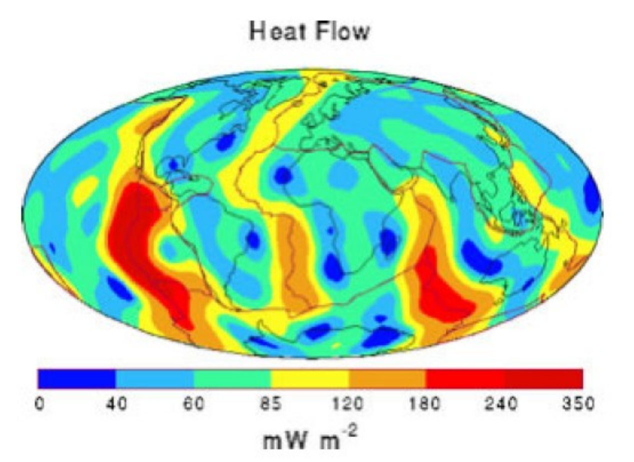
and so if they can be detected they may solve some mysteries of the universe

GeoNeutrinos

From radioactive elements in the earth
Recently detected in Kamland detector

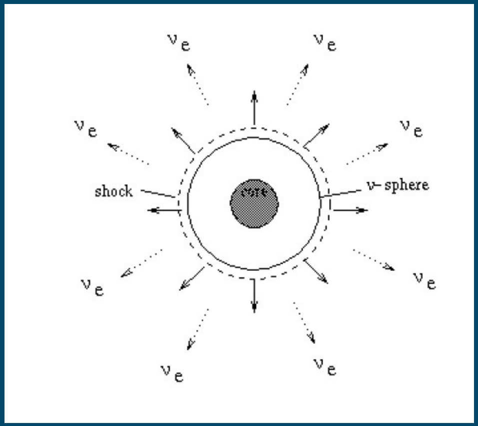






Potentially very useful for exploring the structure of the earth and the heat patterns

Supernovae – Gravitational Collapse



When a star collapses much of energy is radiated by neutrinos over a timescale of < 1 min

Neutrino luminosity believed to be 100 times optical luminosity

Neutrino signal emerges promptly
Optical signal later

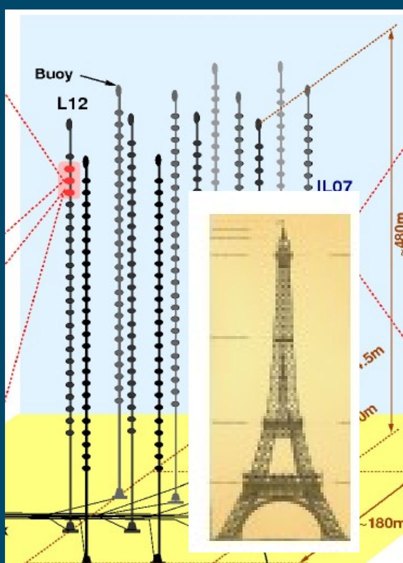
In 1987 Kamiokande detector observed neutrinos from SN1987A ~ 18 hours before optical signal

HE Cosmic Neutrinos - Neutrino telescopes

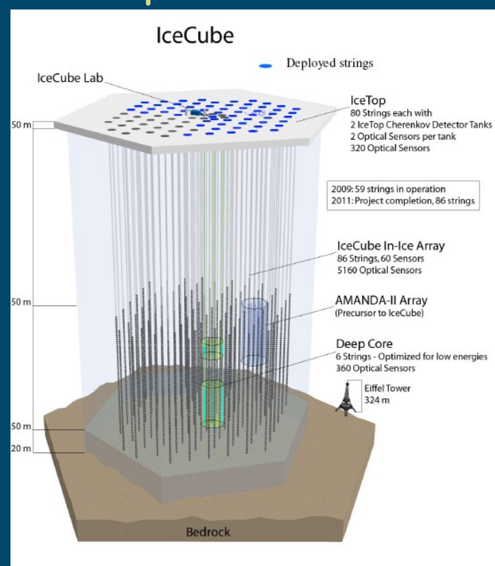
Neutrino interaction rate much lower than photons
Neutrinos not deflected by magnetic fields

HE ν's could reveal source of cosmic acceleration

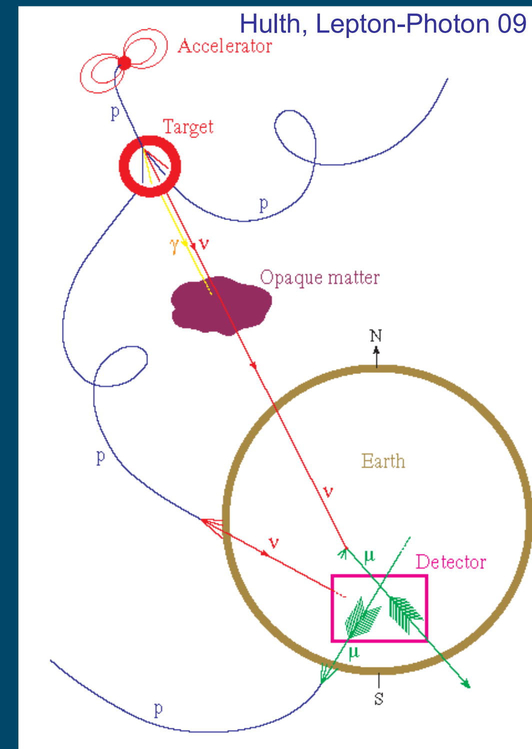
Neutrino Telescopes



Antares in Mediterranean



IceCube at South Pole



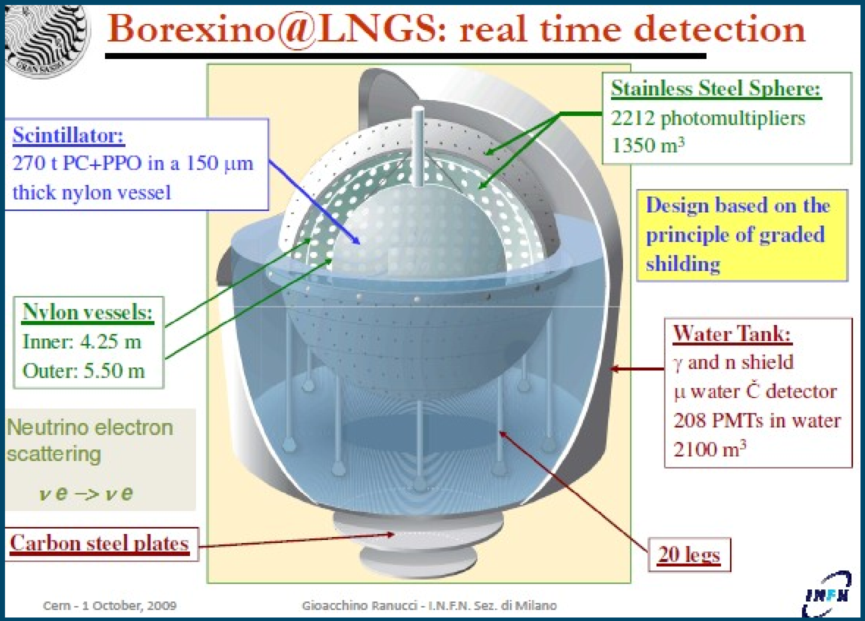
Signal – Cerenkov light from upward going muons from ν interactions in the earth

So far no unambiguous signal above background observed

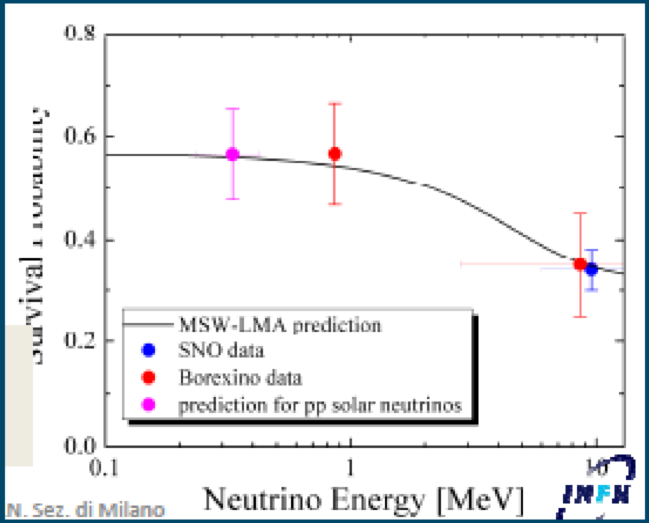
Solar Neutrinos

Testing solar standard model - most neutrinos are low energy

Need very low background detector to investigate - Borexino



Matter – Vacuum Transition



Striking first confirmation of the predicted MSW transition between vacuum and matter regimes to be improved with a future 5% measure

Big Bang - Dark Matter

Cosmic Relic Neutrinos

Believed to be cosmic relic neutrinos from the Big Bang

Many but very low energy - very difficult to detect

Dark Matter

Neutrinos are hot dark matter - a small proportion of the total

Even with mass they are conisdered too dispersed to contribujte to cold dark matter

Neutrinos produced by neutralino-neutralino annhilation???

Current Situation on the Mass

From Cremonesi CERN neutrino workshop

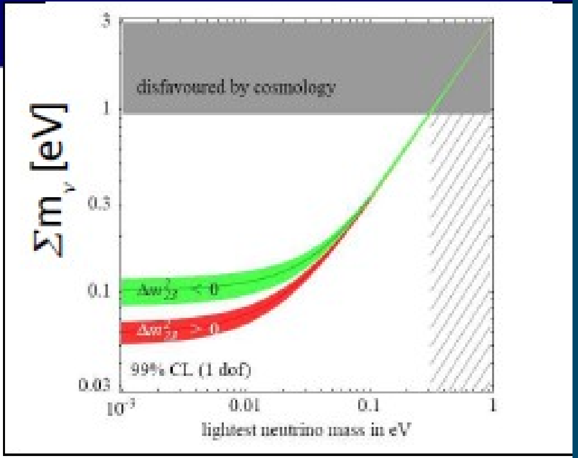
Present bounds

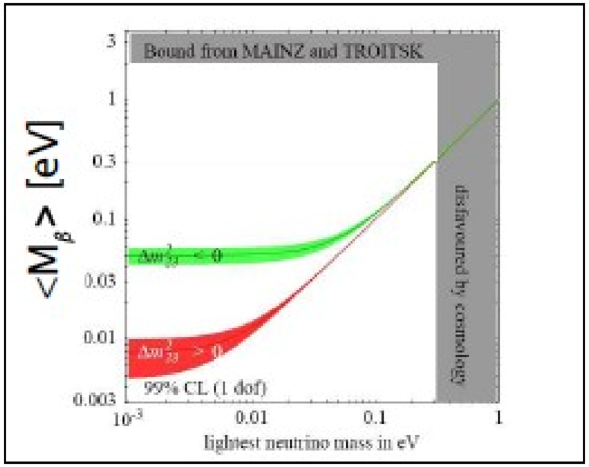
Combined informations:

- cosmology
- single β-decay
- double β-decay

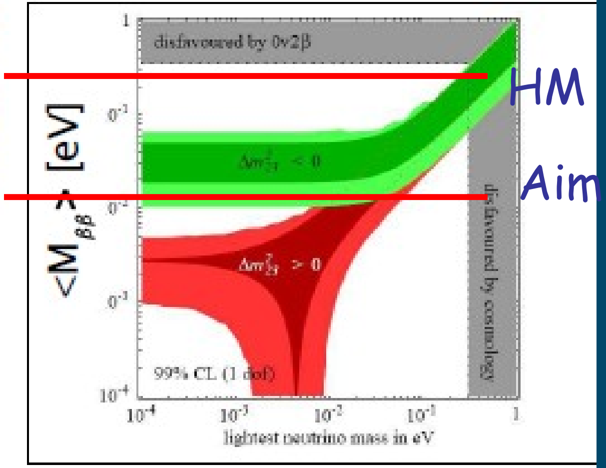
Sensitivity (eV)

Method	Present	Future
Cosmology	0.7-1.0	0.1
ββ(0ν) decay	0.5	0.05
Β-decay	2.2	0.2





Strumia-Vissani hep-ph/0503246



Strumia, Vissani

Quest for the Origin of Matter Dominated Universe

One of the Main Subject of the KEK Roadmap

T2K
(2009~)

Discovery of
the ν_e Appearance

Neutrino
Intensity Improvement

Huge Detector R&D

Establish
Huge Detector
Technology

Construction of
Huge Detector

Discovery of
Lepton CP Violation
Proton Decay