Future Neutrino Experiments

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Why?
Non-Oscillation Expts
Oscillation Expts
  Active
  Near Future
  More distant future

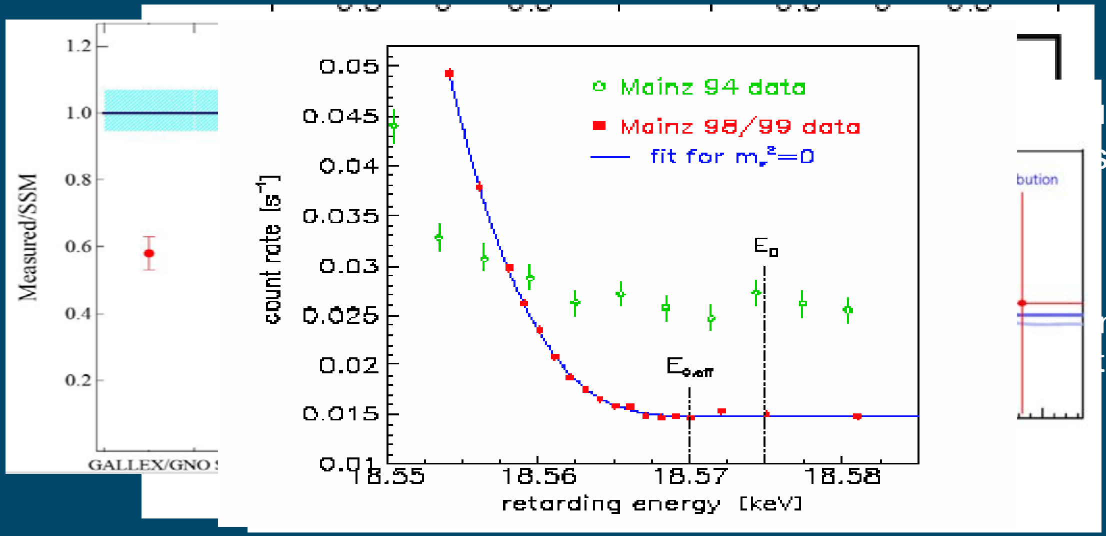
Not included
  Neutrino astroparticle Expts

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

What do we know?

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



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s all Neutrinos

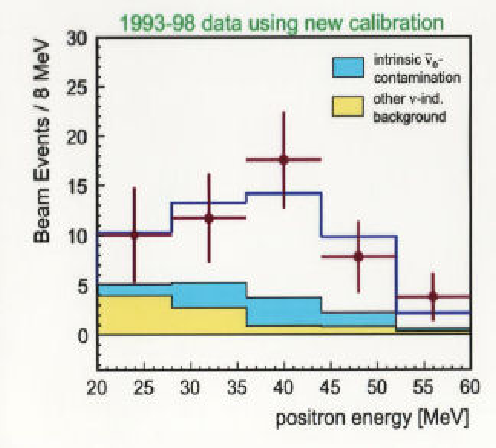
nt
tron Neutrinos

Other Results - Require Confirmation

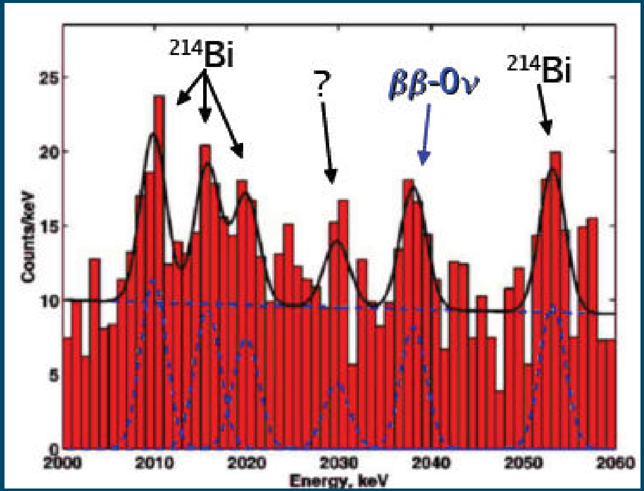
- 1. The appearance of electron antineutrinos in a muon antineutrino beam (LSND)

If true a 3-Neutrino Scenario is excluded.
Either

- > 3 Flavours (with heavy lh neutrinos)
- > 1 or more sterile neutrinos



- 2. The observation that the decay
- $^{76}Ge \rightarrow {}^{76}Se + e^{-} + e^{-}$ has a half life of
- $T^{0\nu}_{1/2} = 2.3^{+0.44}_{-0.31} . 10^{25}$ years (H.V.Klapdor-Kleingrothaus *et al*.,)
  - If True
  - Neutrinos are Majorana
  - $M(\nu_e)$ = ~0.44 eV



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

Oscillation Probability

Depends upon Mixing Angle, Mass Squared Difference, L/E

2 state (e, μ)

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

$$\text{Prob}_{\nu_e \Rightarrow \nu_\mu} = \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{E}$$

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

- but ambiguities

$$\theta \to \tfrac{\pi}{4} - \theta \qquad \Delta m^2 \to -\Delta m^2$$

3 State (e,μ,τ)

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

3 mixing angles, θ_{12}, θ_{13}, θ_{23}, 1 Dirac phase, δ
2 Majorana phases, α, β (=0 if Neutrinos are Dirac)

Vacuum Oscillations

$\theta_{12}, \theta_{13}, \theta_{23}$

δ

$|m_2^2 - m_1^2|, |m_3^2 - m_1^2|$

$$\sin \Delta_{ij}, \qquad \Delta_{ij} = \left(\frac{1.27\,\Delta m_{ij}^2 L}{E} \right)$$

In matter

$$\sin\Delta_{13} \Rightarrow \frac{\sin(\Delta_{13} - AL)}{(\Delta_{13} - AL)} \Delta_{13}, \qquad \sin\Delta_{12} \Rightarrow \frac{\sin(AL)}{(AL)} \Delta_{12}$$

$$with \;\; A = \pm \frac{G_F N_e}{\sqrt{2}}$$

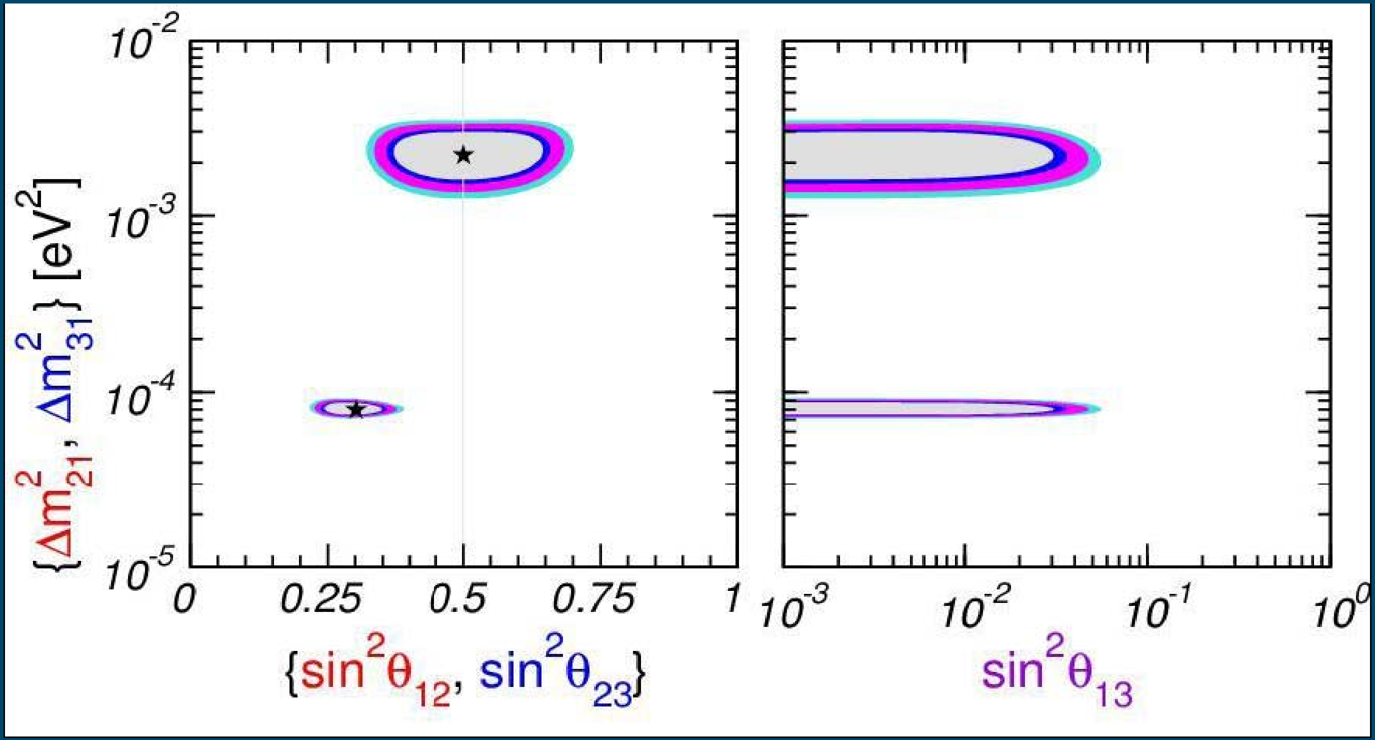
Sensitive to Sign (Δm^2)

- depends upon *AL*

i.e. density and baseline

Where are we?

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



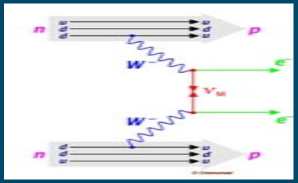
Also know $m_2 > m_1$ from matter effects in the sun

Future - Non-Oscillation Experiments

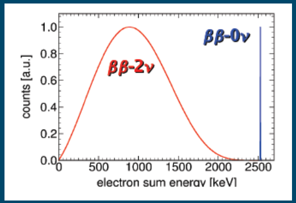
- Majorana/Dirac
- Absolute Mass

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



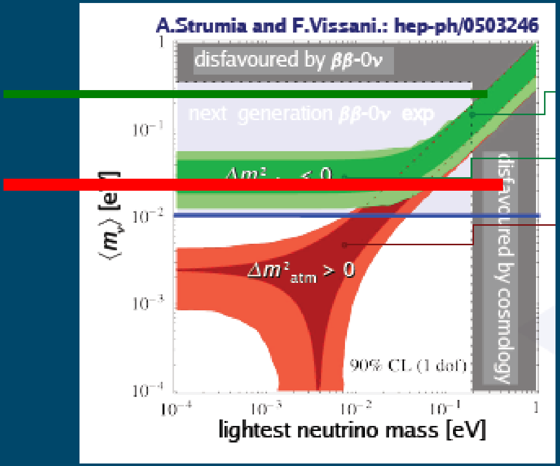
- Positive Result
  - ν's are Majorana
  - A measurement of the absolute Mass (subject to NME)



- 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

HM

Future


A.Strumia and F.Vissani.: hep-ph/0503246

The Absolute Mass?

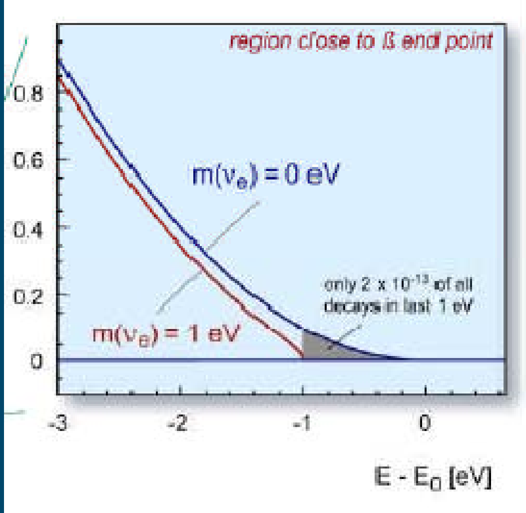
- Cosmological data
- Neutrinoless double-beta decay
- Tritium Decay Spectrum

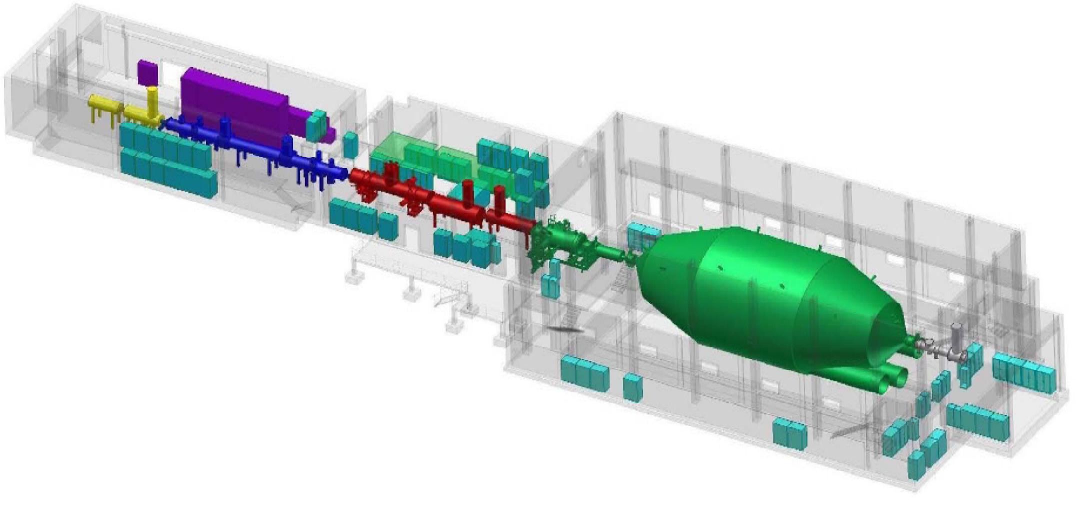
Model Dependent

Currently $\Sigma m <\sim 0.7$ eV

Potential $\Sigma m <\sim 0.07$ eV?

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

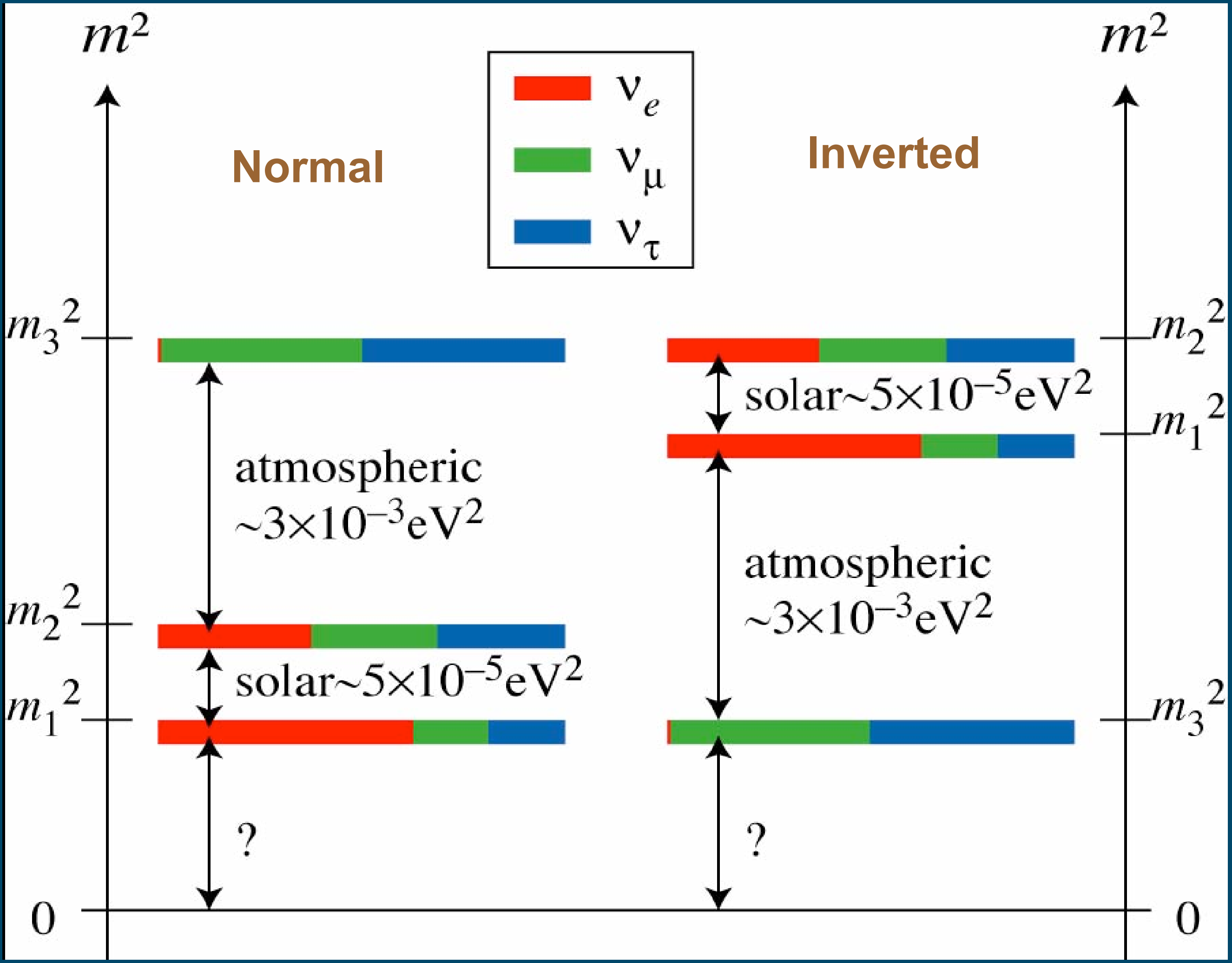




‘Standard’ Oscillation Goals

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 meaurements

Mass Hierarchy?



Require matter interactions to distinguish.

Long Baseline

Nova > T2K

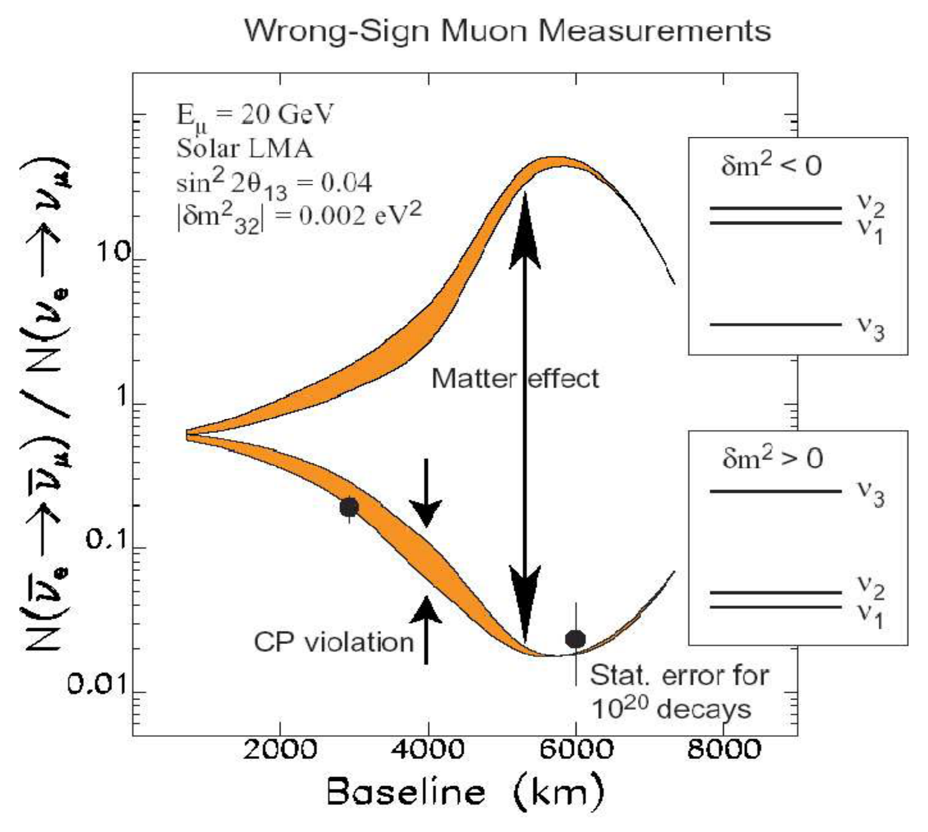
Leads to degeneracies in superbeam expts.

Critical for Neutrinoless double beta decay

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

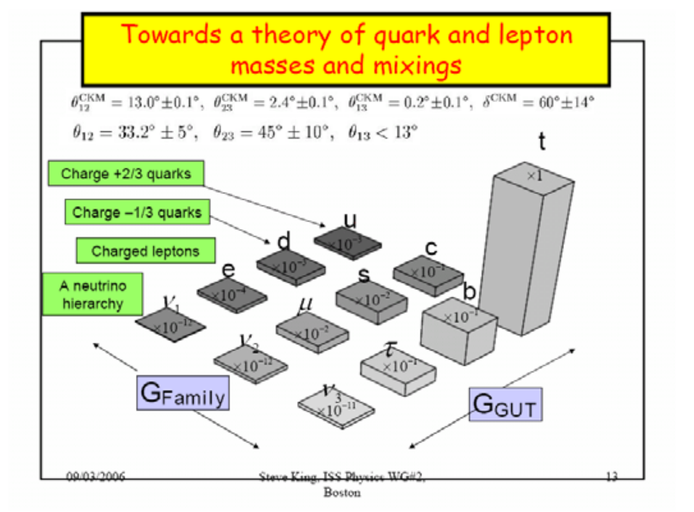
- No understanding of the underlying physics without precision measurements - as in the quark sector
  - CP violation in the neutrino sector?
    - Interesting to demonstrate this at 3σ level
    - Much more useful to know δ precisely

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

$$\theta_{12}^{MNS} + \theta_{12}^{CKM} \cong \pi/4$$
$$\theta_{23}^{MNS} + \theta_{23}^{CKM} \cong \pi/4$$

  - Improved precision of solar and atmospheric angles needed

Ideas/Speculation

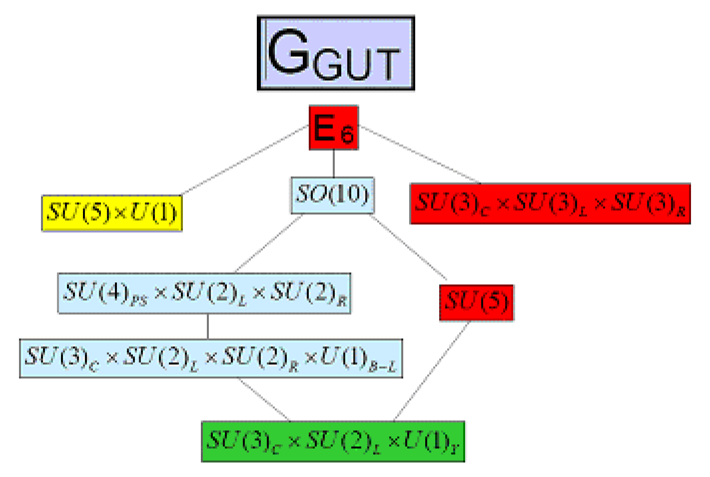


Towards a theory of quark and lepton masses and mixings

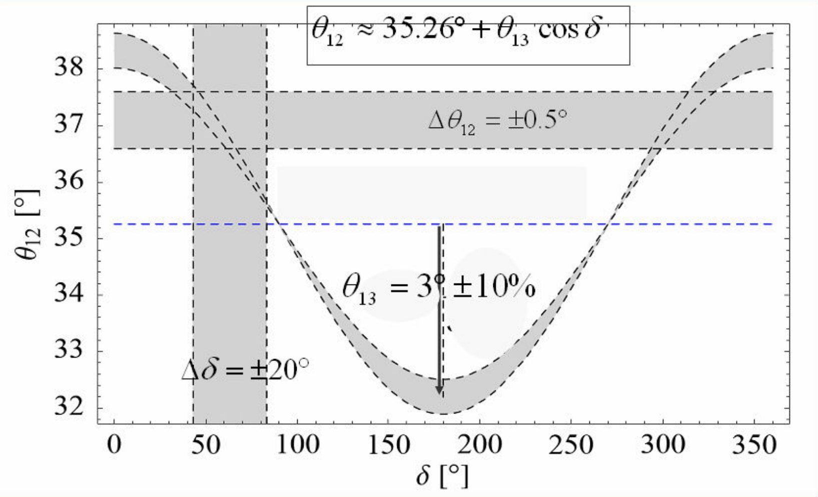
$\theta_{12}^{\rm CKM} = 13.0°\pm0.1°$, $\theta_{23}^{\rm CKM} = 2.4°\pm0.1°$, $\theta_{13}^{\rm CKM} = 0.2°\pm0.1°$, $\delta^{\rm CKM} = 60°\pm14°$

$\theta_{12} = 33.2° \pm 5°$, $\theta_{23} = 45° \pm 10°$, $\theta_{13} < 13°$

09/03/2006 Steve King, ISS Physics WG#2, Boston 13



A Neutrino Sum Rule? (S King)



Tribimaximal Mixing?
(Harrison, Perkins, Scott)

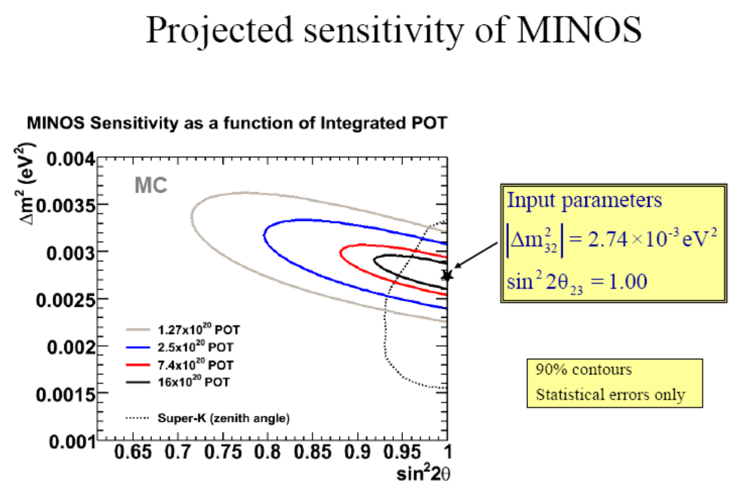
$$\begin{pmatrix} \sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & 0 \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & -\sqrt{\frac{1}{2}} \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \end{pmatrix}$$

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 Chooz)
- 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

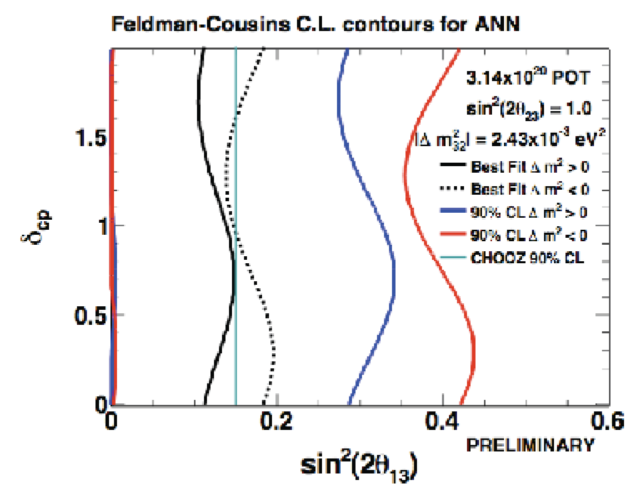

Projected sensitivity of MINOS

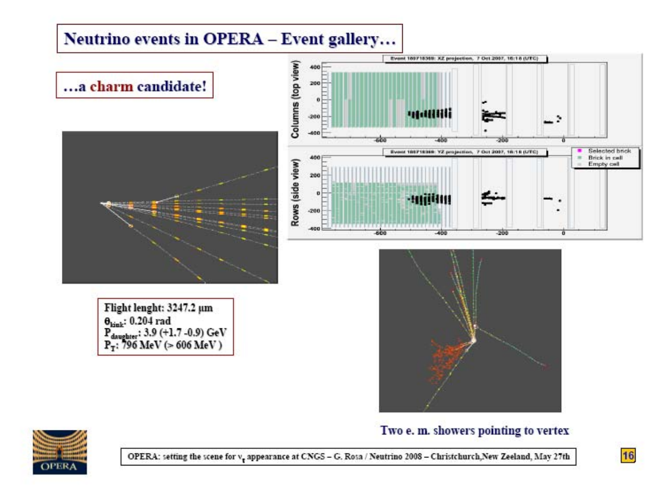
Input parameters

$$|\Delta m^2_{32}| = 2.74\times10^{-3}\,\mathrm{eV}^2$$

$$\sin^2 2\theta_{23} = 1.00$$

90% contours
Statistical errors only



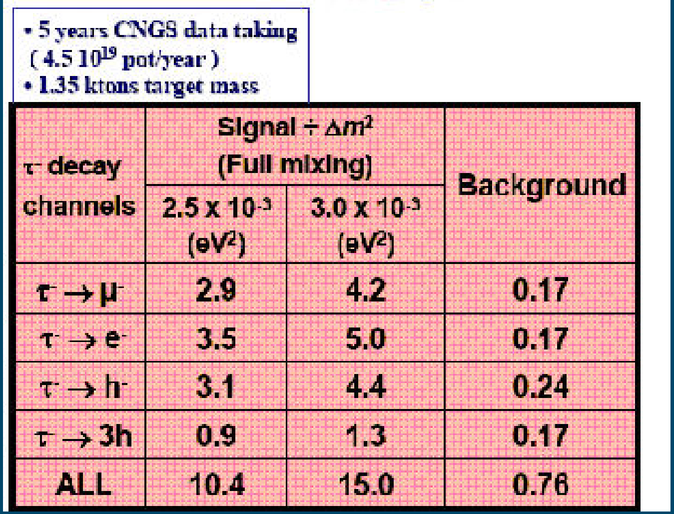

Neutrino events in OPERA – Event gallery…

…a charm candidate!

Flight lenght: 3247.2 μm
θ_{kink}: 0.204 rad
$P_{daughter}$: 3.9 (+1.7 -0.9) GeV
P_T: 796 MeV (> 606 MeV)

Two e. m. showers pointing to vertex

OPERA: setting the scene for ν_τ appearance at CNGS – G. Rosa / Neutrino 2008 – Christchurch,New Zeeland, May 27th


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

τ^- decay channels	Signal ÷ Δm^2 (Full mixing)		Background
	2.5×10^{-3} (eV^2)	3.0×10^{-3} (eV^2)	
$\tau^- \to \mu^-$	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

$$
\begin{aligned}
P[\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e] \cong {} & \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \Delta_{31} \\
& + \sin 2\theta_{13} \cos\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \\
& \sin\Delta_{31} \sin\Delta_{21} \cos(\Delta_{32} \pm \delta) \\
& + \sin^2 2\theta_{12} \cos^2 \theta_{23} \cos^2 \theta_{13} \sin^2 \Delta_{21}
\end{aligned}
$$

$$(\Delta_{ij} \equiv 1.27 \Delta m^2_{ij}(eV^2) L(km) / E(GeV))$$

ν

$\bar{\nu}$

(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

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

No δ term, no matterr effects

For θ_{13}

- Three Approved Reactor Experiments
  - Double Chooz (France)
  - Daya Bay (China)
  - RENO (Korea)

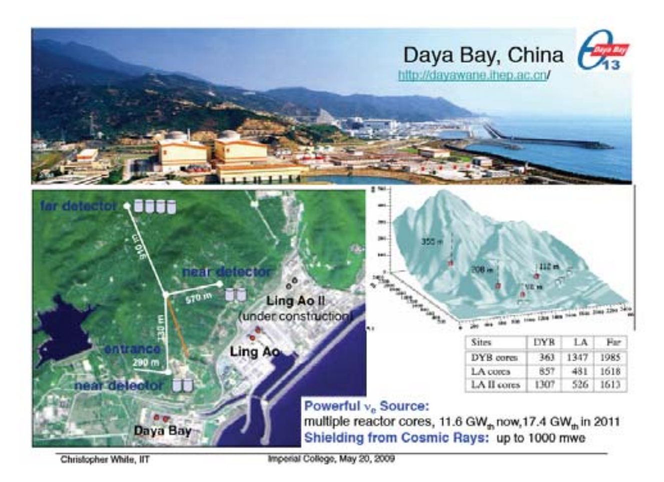
- Two off-axis Superbeam Experiments
  - Main aim is θ_{13} - but will also improve other parameters
  - T2K
  - Noνa - maybe also the mass hierarchy

Reactor Expts for θ_{13}

Double Chooz concept

- 2 reactors - 8.5 GW_{th}
- 2 identical detectors:
  - Target: 2 x 8.3 t
- Comparison of neutrino rate & energy spectrum
- Civil work:
  - 1 near lab is foreseen
  - 1 far lab is available

Chooz B nuclear power plant
Ardennes, France



Daya Bay, China

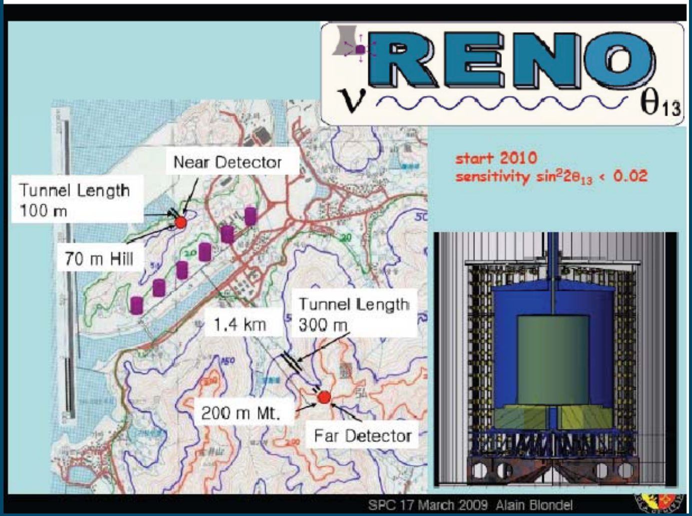
http://dayawane.ihep.ac.cn/

Sites	DYB	LA	Far
DYB cores	363	1347	1985
LA cores	857	481	1618
LA II cores	1307	526	1613

Powerful ν_e Source: multiple reactor cores, 11.6 GW_{th} now, 17.4 GW_{th} in 2011

Shielding from Cosmic Rays: up to 1000 mwe

Christopher White, IIT   Imperial College, May 20, 2009

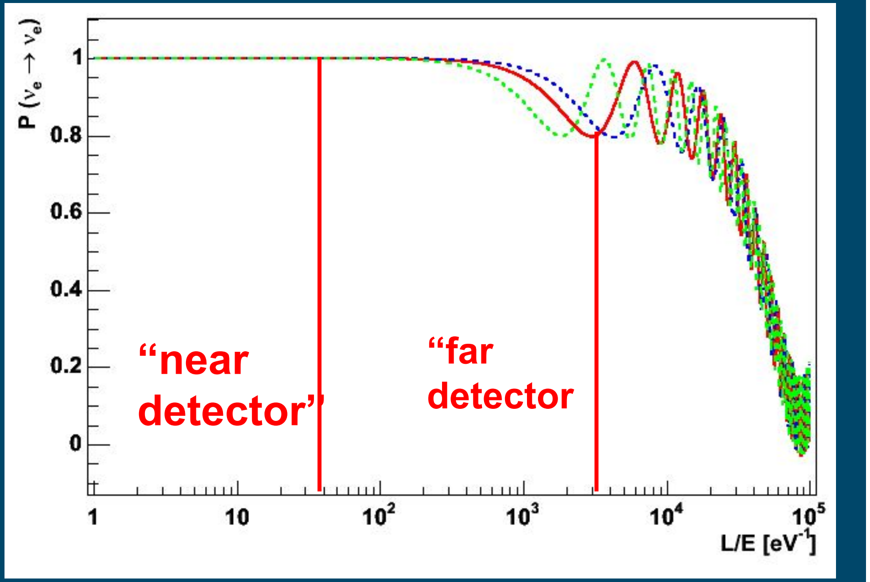


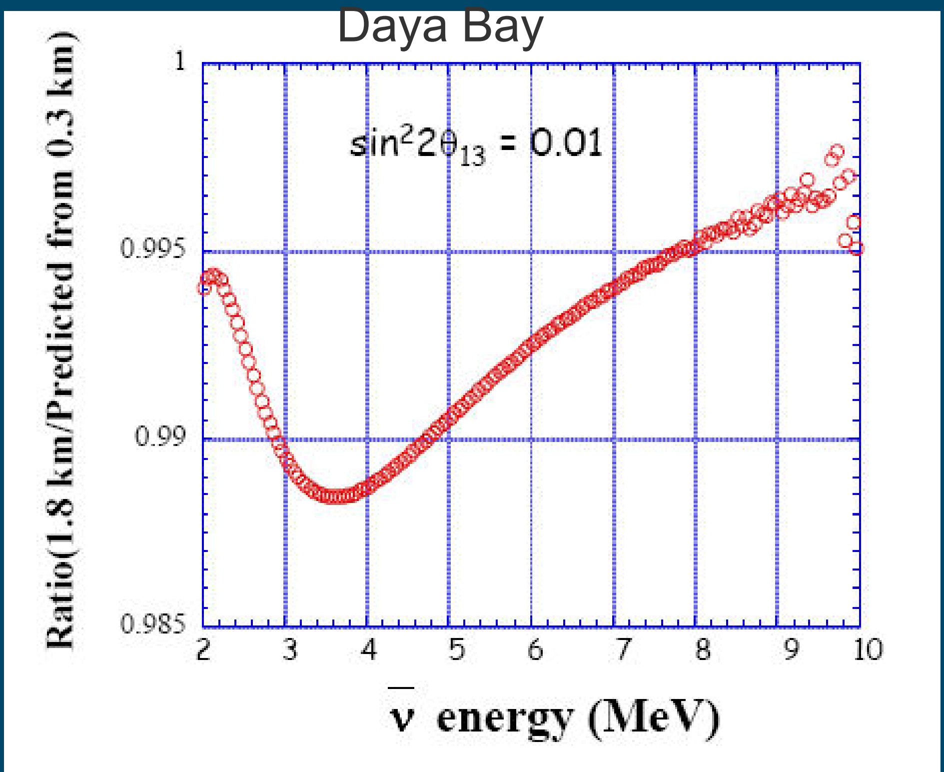
start 2010
sensitivity $\sin^2 2\theta_{13} < 0.02$

SPC 17 March 2009 Alain Blondel

	Start	$\sin^2 2\theta_{13}$
Double Chooz	2009-10	>~0.02
Daya Bay	2011	>~0.01
RENO	2011	>~0.02

Reactor Measurement of θ_{13}





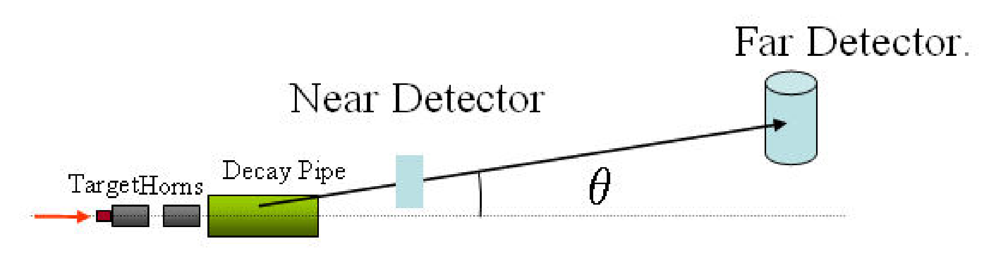
No Dependence on δ, No matter effects
But small effect and control of systematics vital.

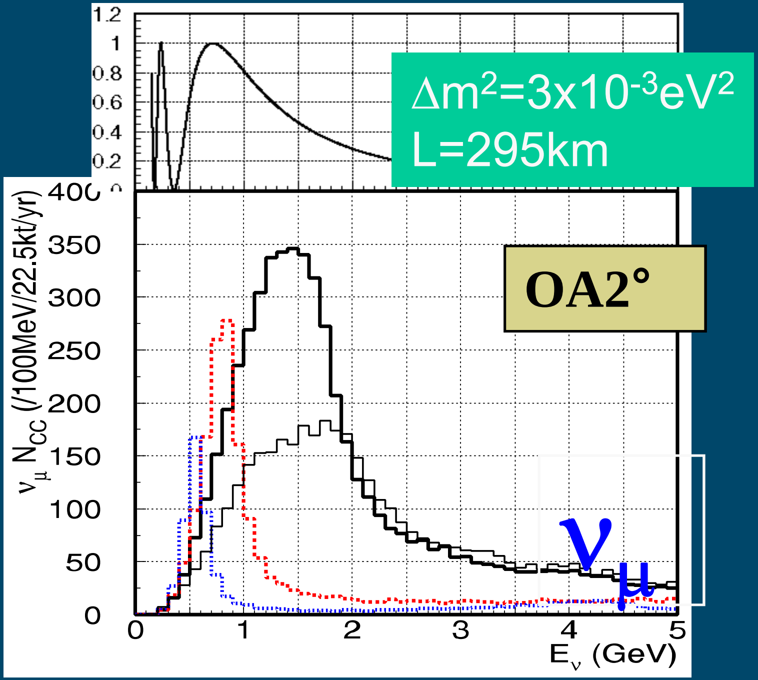
Superbeams – near future – T2K, Noνa

- 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 (Noνa) – 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 $<E_\nu>$ ~ 0.65 GeV, better enrgy spread and less contamination
- Noνa
  - 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




$\Delta m^2=3\text{x}10^{-3}\text{eV}^2$

L=295km

Much better energy resolution

More flux at oscillation max

Less ν_e Conamination

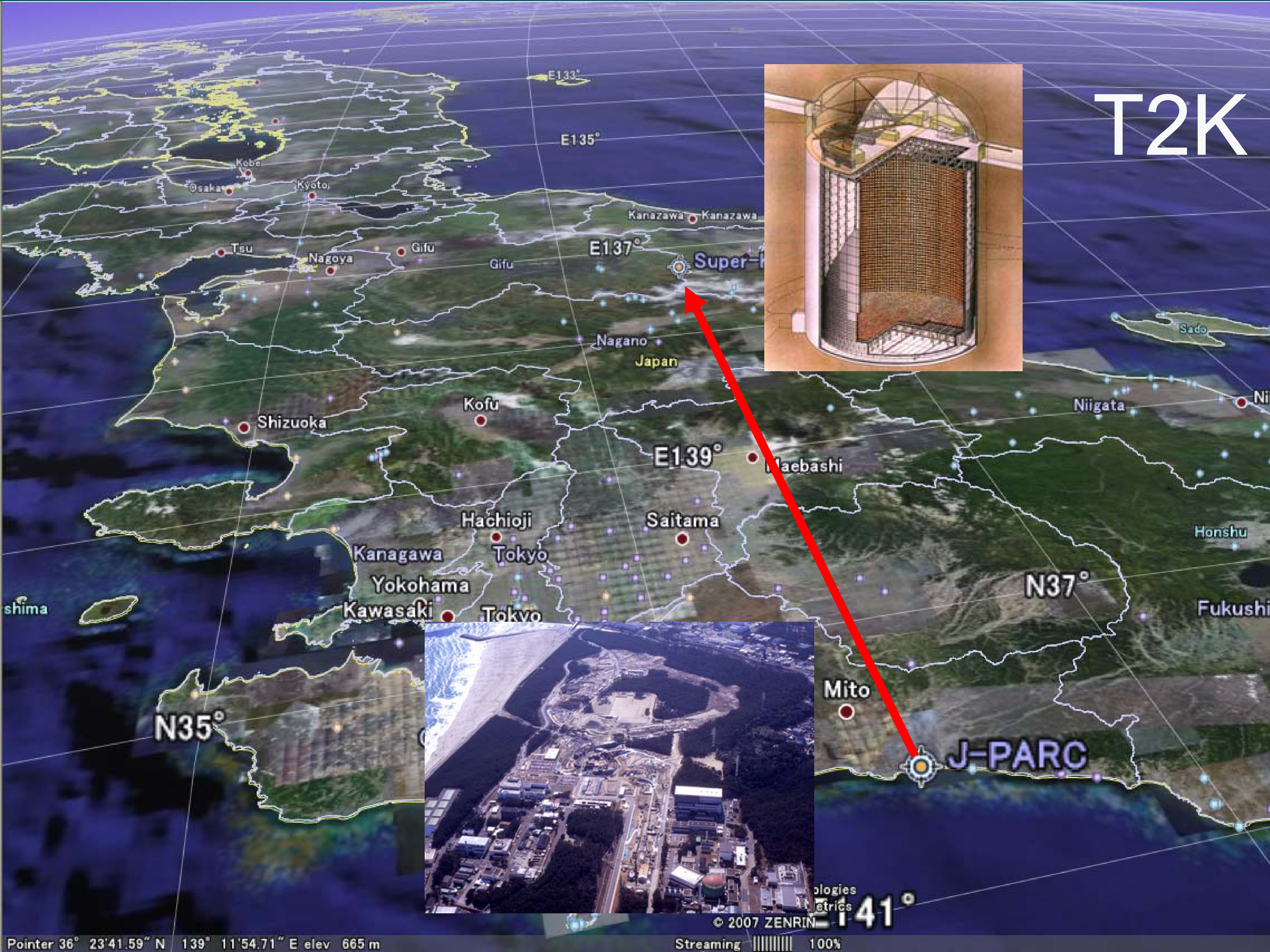
Reduces high energy tail and hence NC background

But

Increases near/far differences

Complicates disappearance

T2K


E133°
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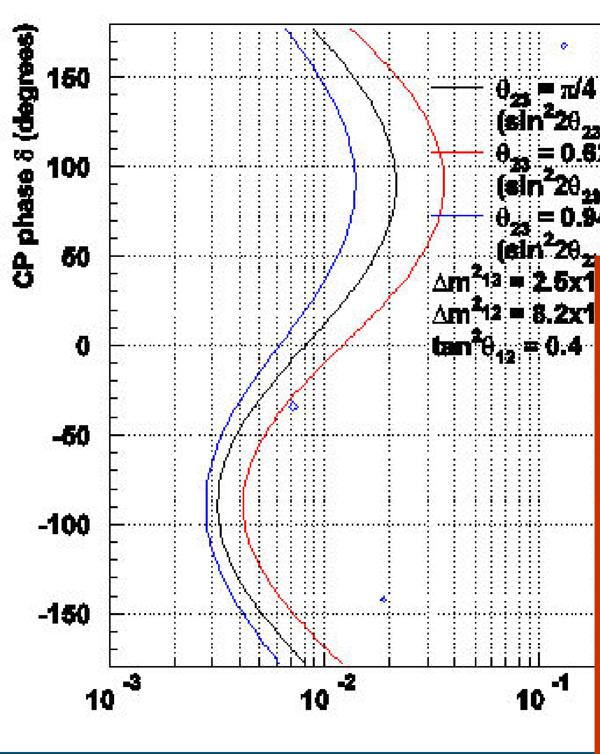
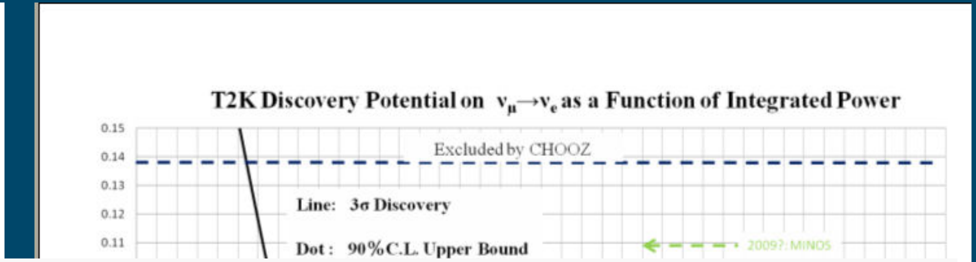
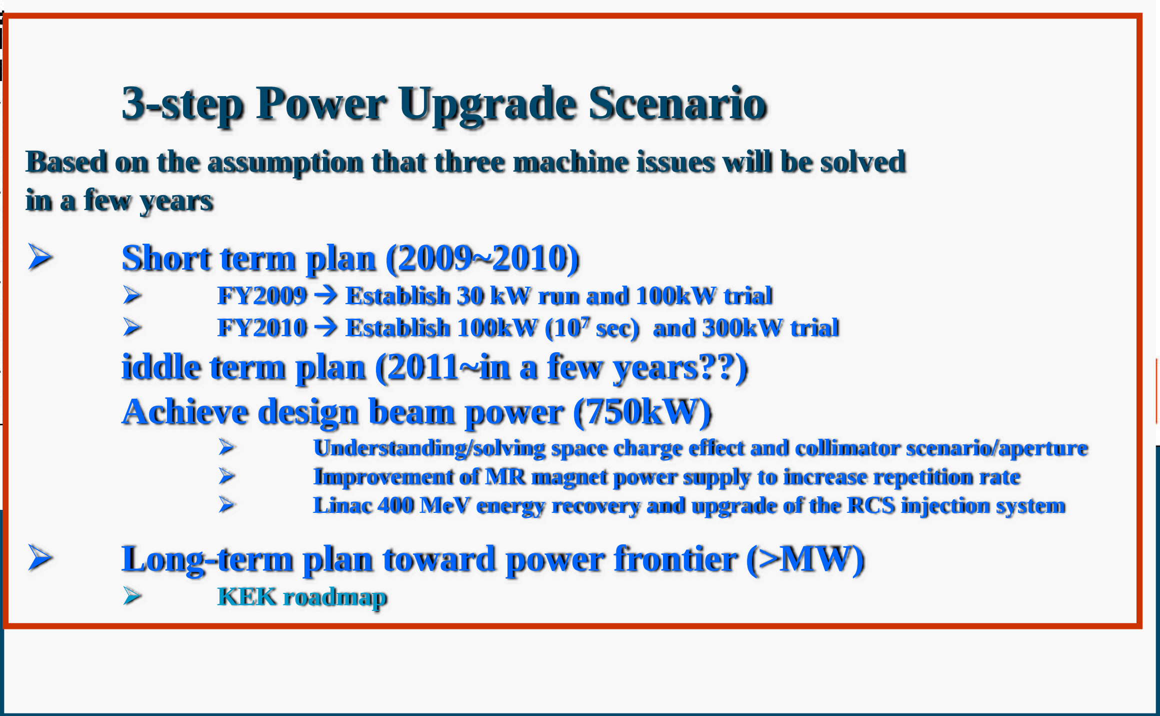
Nagano
Japan
Sado
Niigata
Kofu
Shizuoka
E139°
Maebashi
Hachioji
Saitama
Honshu
Kanagawa
Tokyo
Yokohama
N37°
shima
Kawasaki
Tokyo
Fukushi
Mito
N35°
J-PARC
E141°
© 2007 ZENRIN
Pointer 36° 23'41.59" N 139° 11'54.71" E elev 665 m
Streaming 100%

T2K Prospects







3-step Power Upgrade Scenario

Based on the assumption that three machine issues will be solved in a few years

- Short term plan (2009~2010)
  - FY2009 → Establish 30 kW run and 100kW trial
  - FY2010 → Establish 100kW (10^7 sec) and 300kW trial

iddle term plan (2011~in a few years??)

Achieve design beam power (750kW)

  - Understanding/solving space charge effect and collimator scenario/aperture
  - Improvement of MR magnet power supply to increase repetition rate
  - Linac 400 MeV energy recovery and upgrade of the RCS injection system

- Long-term plan toward power frontier (>MW)
  - KEK roadmap

Search for $\nu_\mu \to \nu_e$ 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)

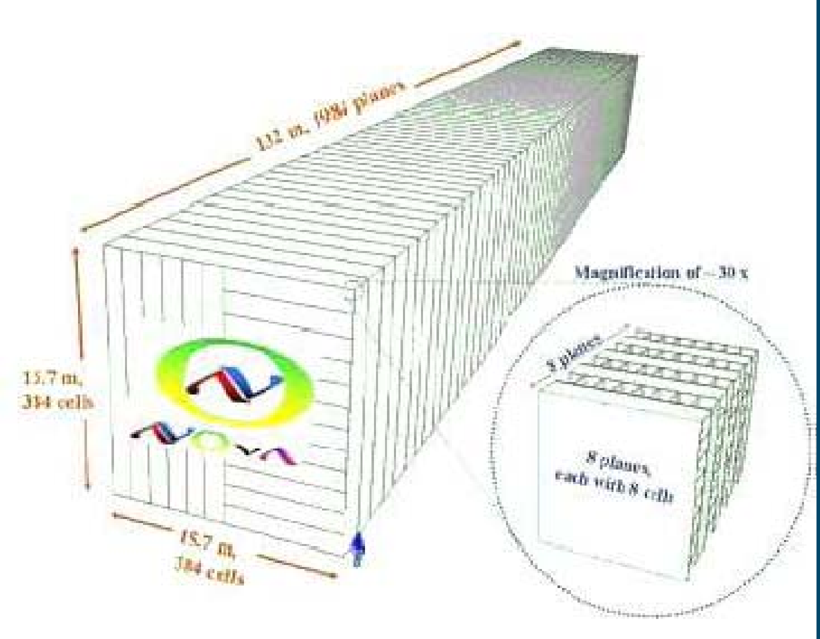
$\sin^2 2\theta_{13}$	Backgrounds			**Signal**
	ν_μ induced	Beam ν_e	**Total**	
0.1	10	13	**23**	**103**
0.01				**10**

- 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

Noνa

- 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

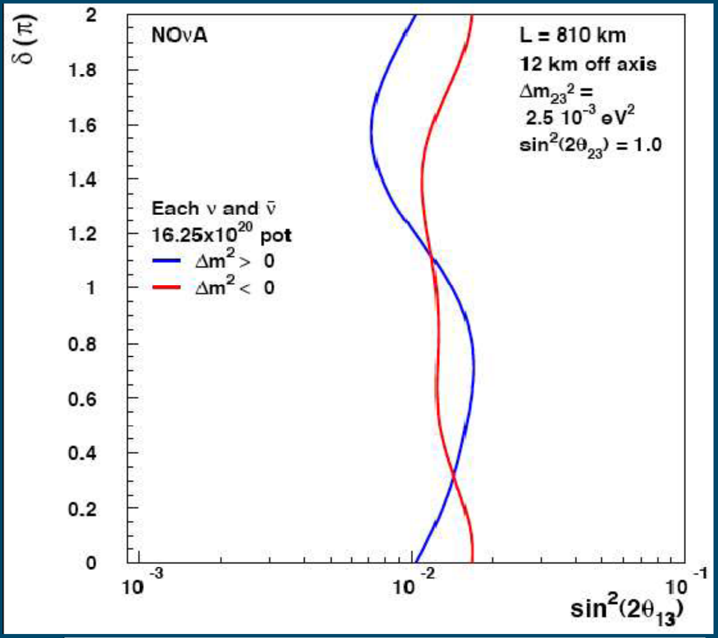


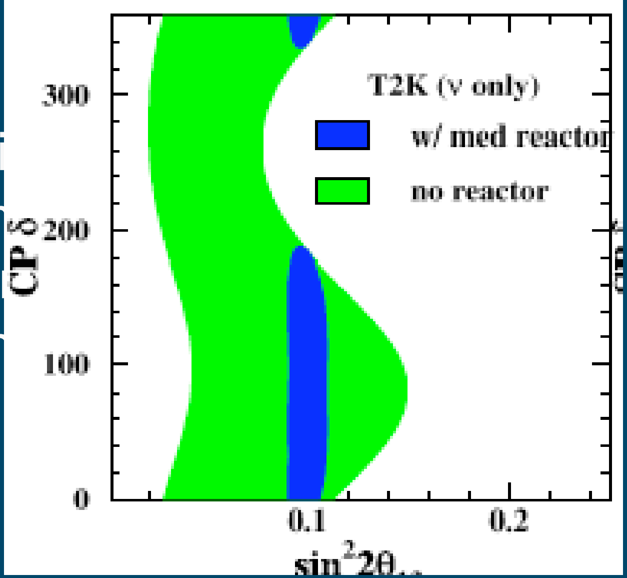
Nova

Sensitivity similar to T2K.
– improve with antineutrino run.

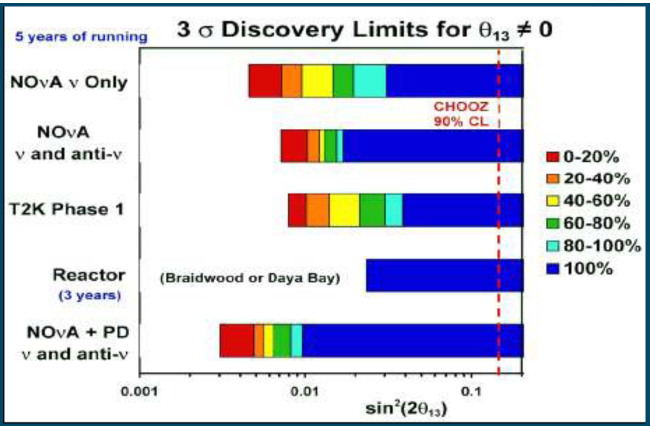
- Sensitivity to mass hierarchy.

- Synergies wi
reactor experin
different matte
different degen





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



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'

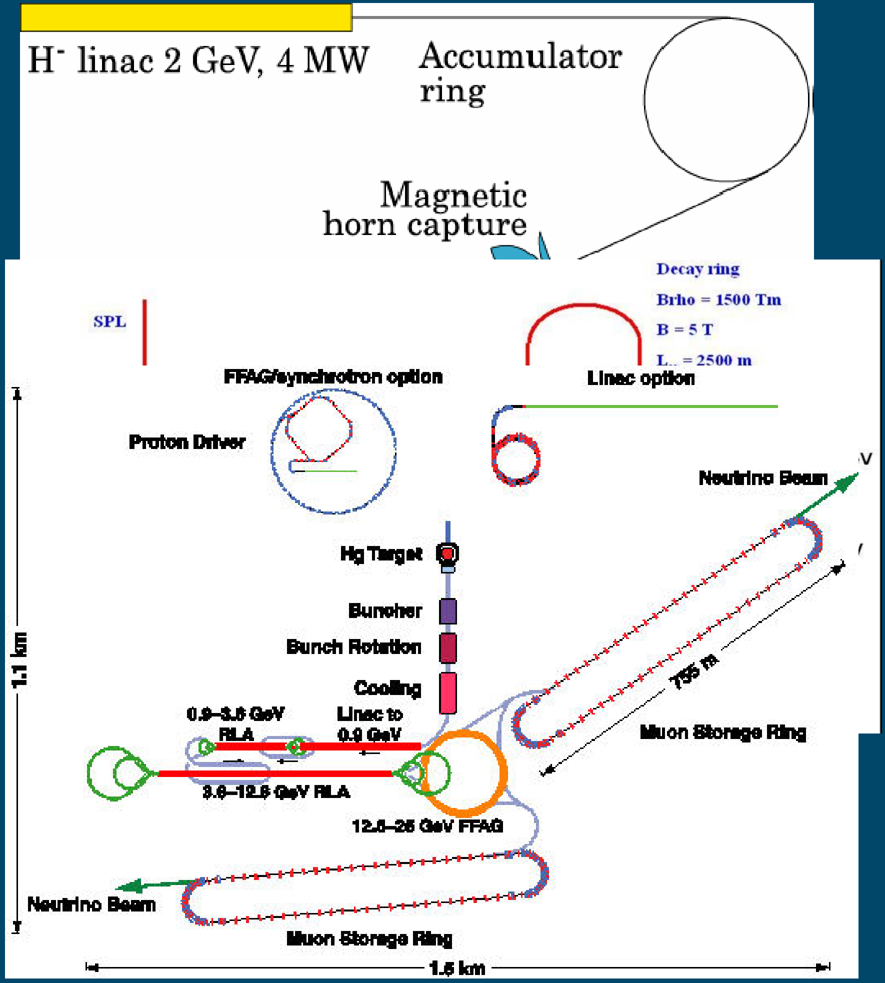
To test the Unitarity of the PMNS matrix and CPT invariance ideally measure all of these

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
  - CERN, FNAL, BNL, J-PARC II
- Beta-beam
- Neutrino Factory



$\nu_e, \bar{\nu}_e$ Beams - Golden Channel

- Reactors
  - Can only measure ν_e disappearance
  - It is hard to see reactors playing a major role after Double Chooz, Daya Bay and RENO
- Beta beams
  - High purity, Low Divergence beam possible
  - Intensity questionable, depends primarily on ion source. particularly for ν
  - Wide range of possible detectors
- Neutrino Factory
  - 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

$\nu_\mu, \bar{\nu}_\mu$ Beams - Platinum Channel

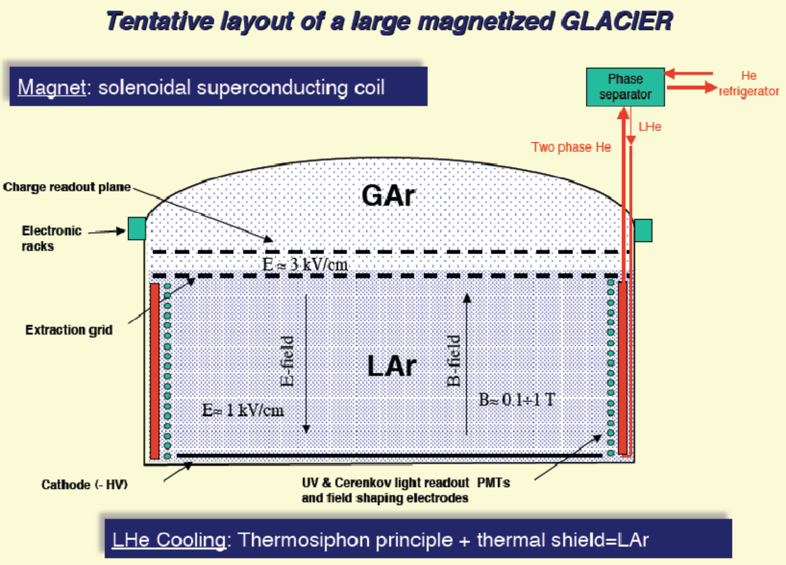
- Superbeams
  - ν, anti-ν in separate experiments. Significant ν_e contamination
  - On axis – wide band beam, Off axis - narrow band. Wide band beam can give 1st and 2nd max at same L
  - Intensity dependent on proton driver, target and horn system
- Neutrino Factory
  - High Purity, Low Divergence beam possible, can have very long baselines
  - Intensity dependent on proton driver, target
  - Can have alternate nu, nubar pulses
  - Requires Magnetisable Detector – not ideal for electron detection

Detectors

- 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 (Noνa, 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

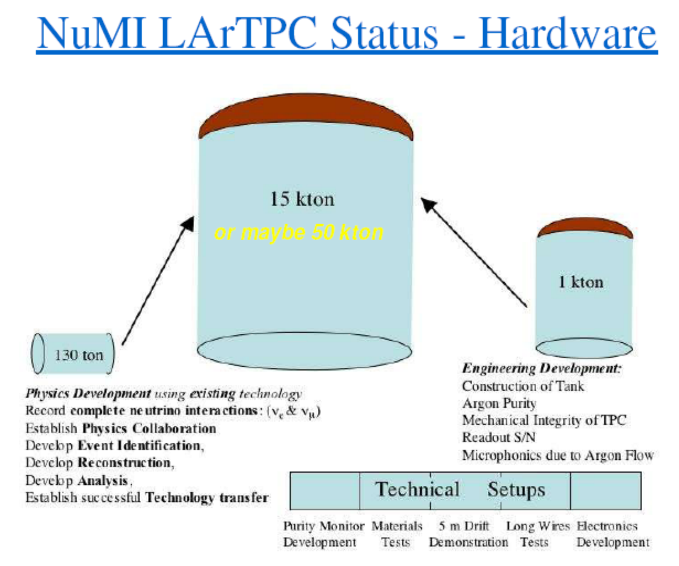
- Detector concepts



Tentative layout of a large magnetized GLACIER

Magnet: solenoidal superconducting coil

LHe Cooling: Thermosiphon principle + thermal shield=LAr



NuMI LArTPC Status - Hardware

***Physics Development** using **existing** technology*
Record **complete neutrino interactions**: (ν_e & ν_μ)
Establish **Physics Collaboration**
Develop **Event Identification**,
Develop **Reconstruction**,
Develop **Analysis**,
Establish successful **Technology transfer**

Engineering Development:
Construction of Tank
Argon Purity
Mechanical Integrity of TPC
Readout S/N
Microphonics due to Argon Flow

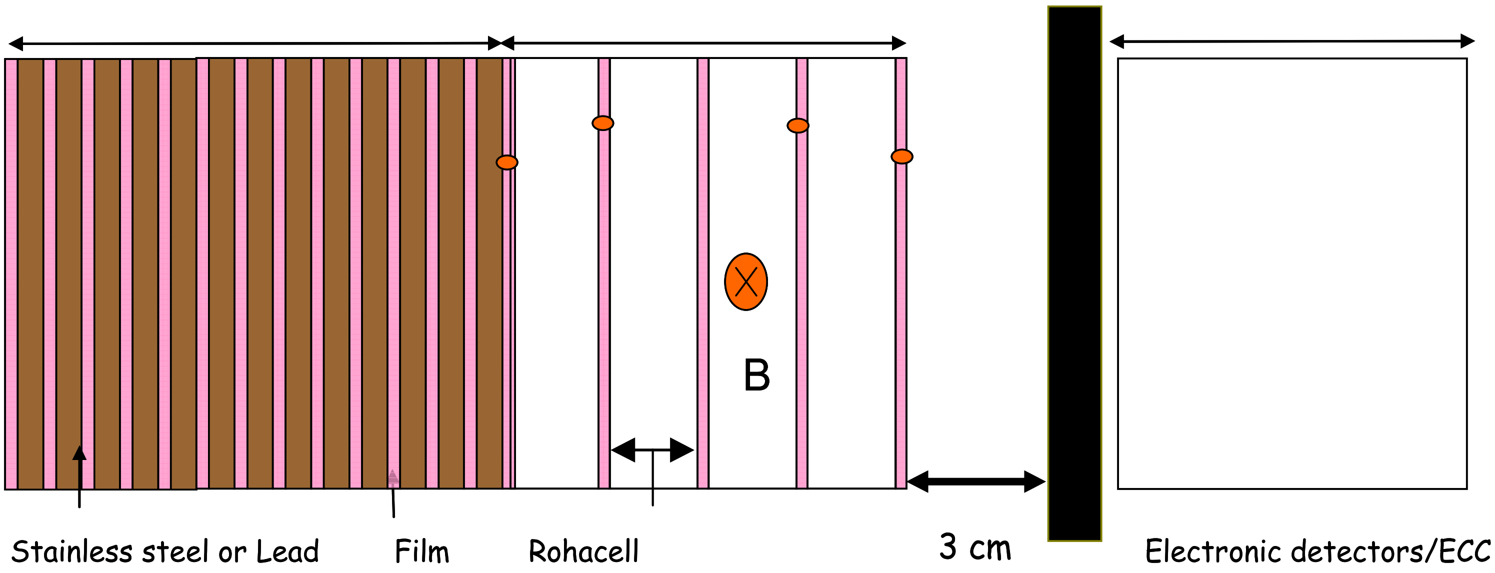
Technical Setups

Purity Monitor Development
Materials Tests
5 m Drift Demonstration
Long Wires Tests
Electronics Development

- Various configurations being studied in ISS:

Emulsion detector – MECC

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



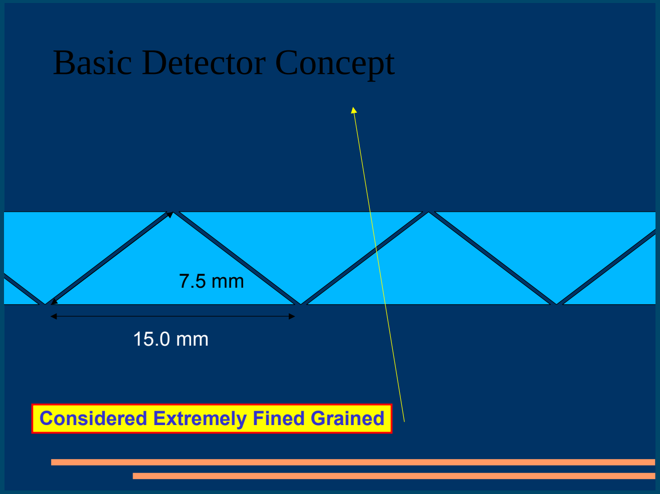
Assumption: accuracy of film by film alignment = 10 micron (conservative)

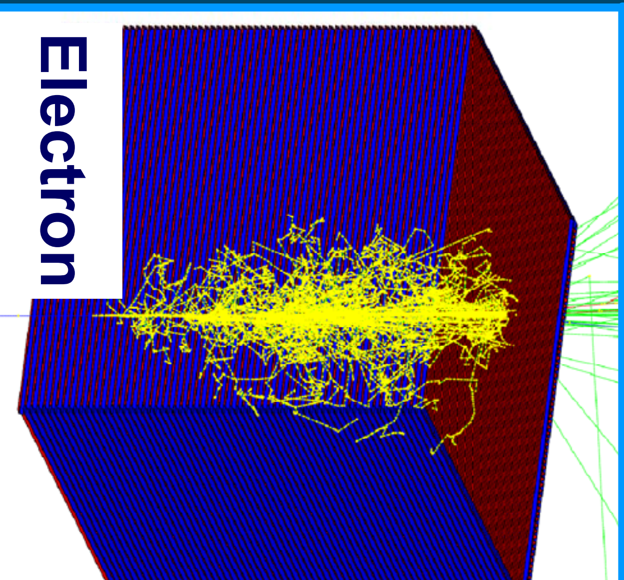
13 lead plates (~2.5 X_0) + 4 spacers (2 cm gap) (NB in the future we plan to study stainless steel as well. May be it will be the baseline solution: lighter target)

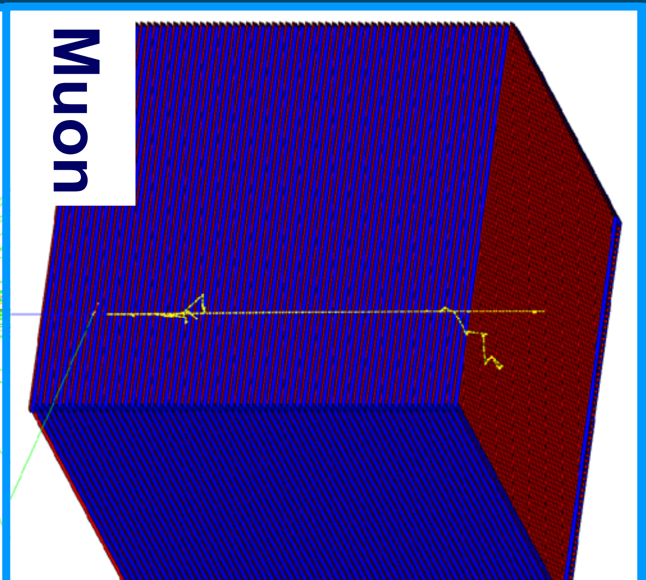
The geometry of the MECC is being optimized

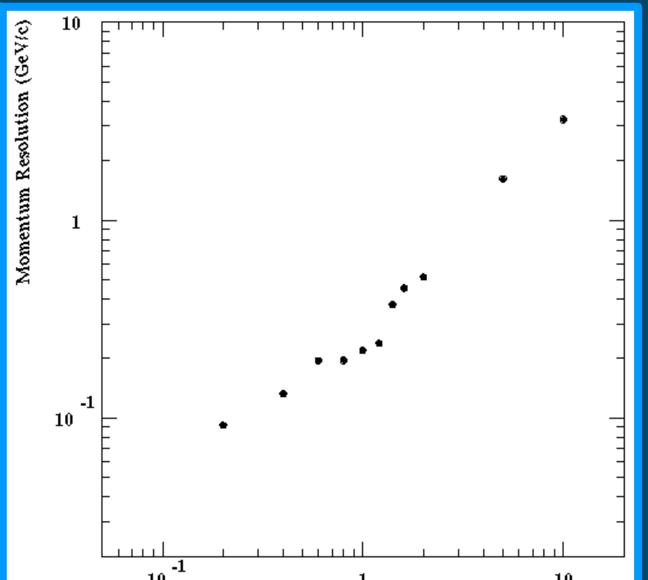
Magnetic sampling calorimeter

- Concept:
  - Magnetised iron?
    - Sampling fraction?
  - Air toroid
  - Cost
    - ~ $300M







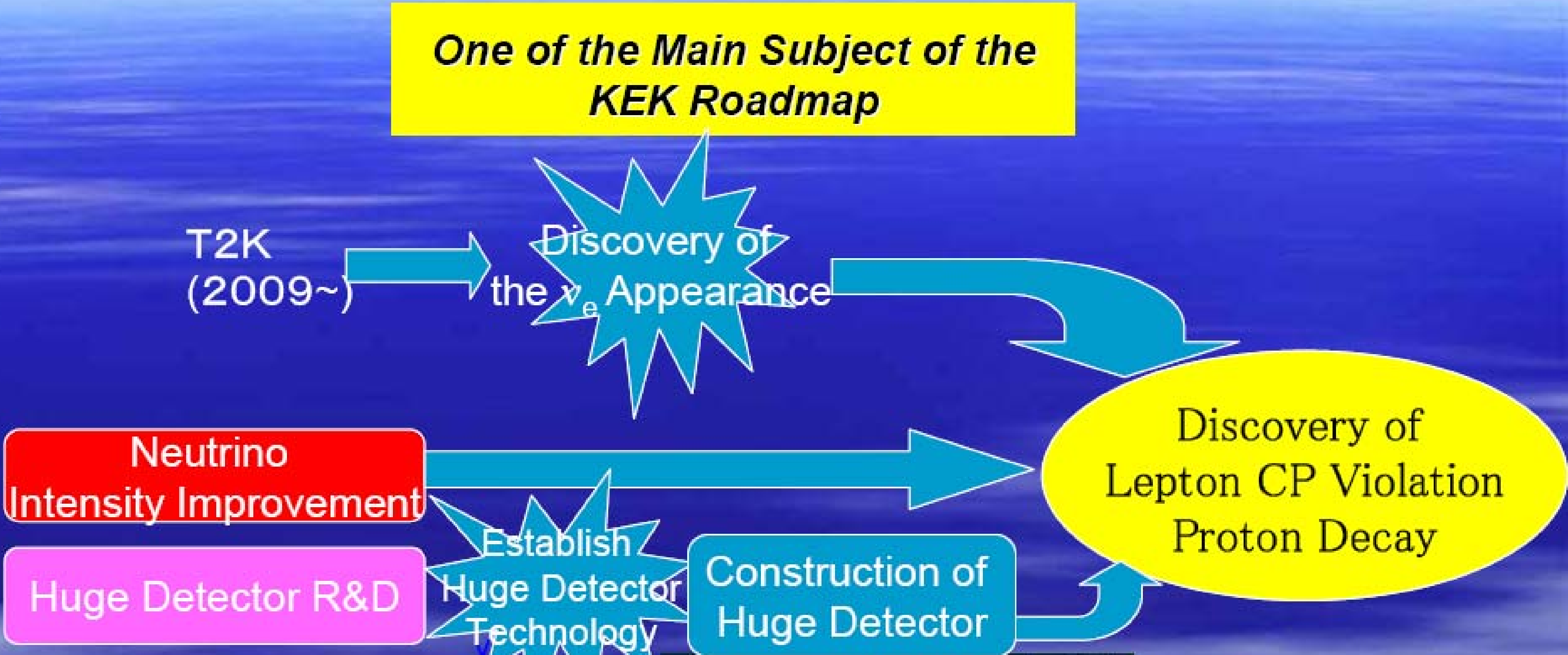


Possible Next Generation Superbeams

- 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

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

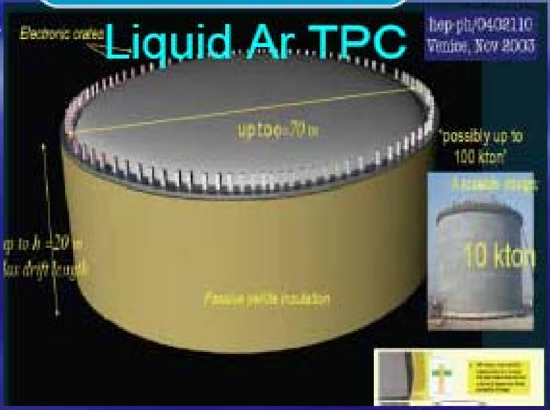
Neutrino
Intensity Improvement

Huge Detector R&D

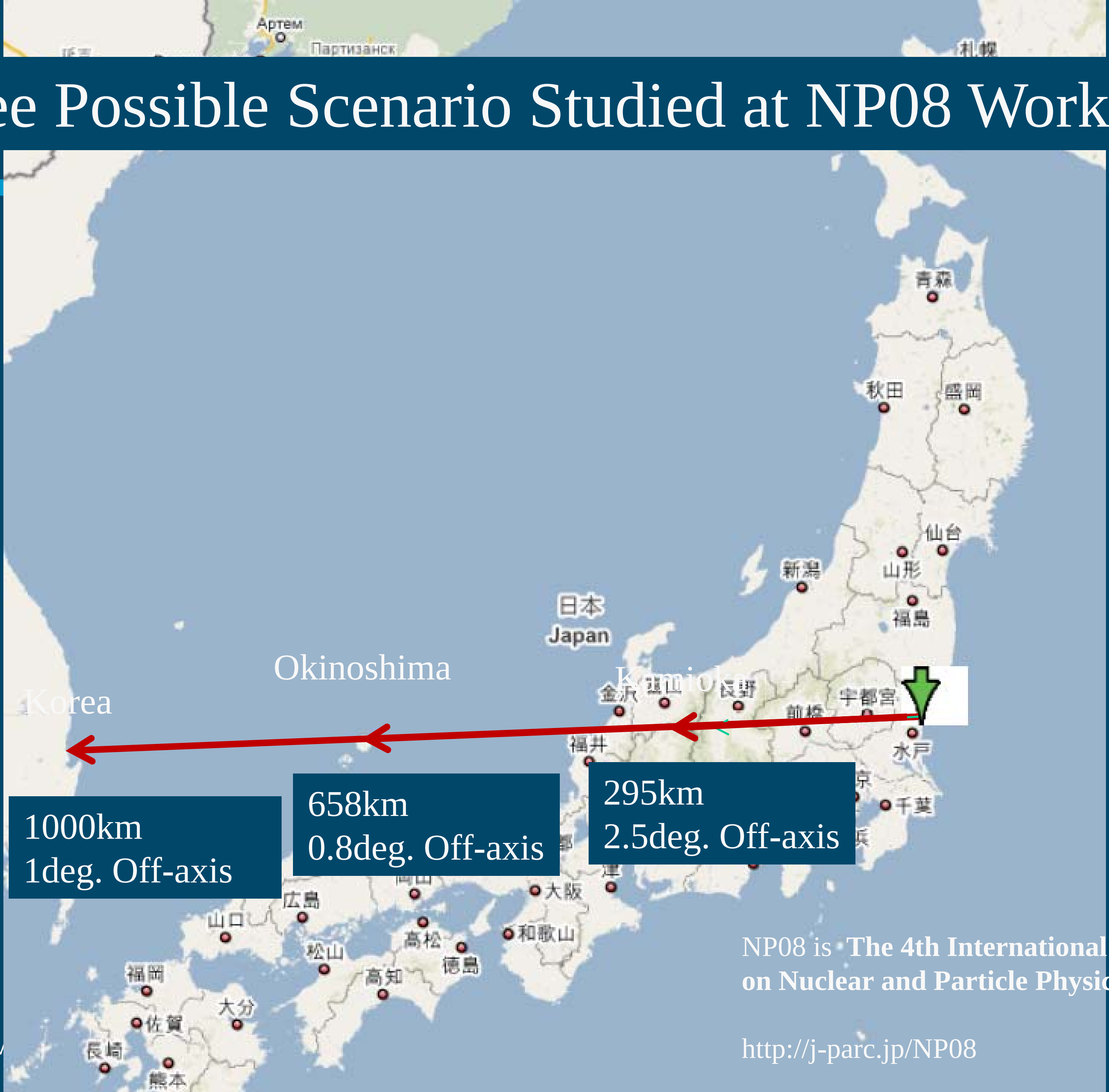
Establish
Huge Detector
Technology

Construction of
Huge Detector

Discovery of
Lepton CP Violation
Proton Decay



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 Noνa
    - Later to produce a new wide band beam to a new detector, Water Cerenkov or Liquid Argon at DUSEL
- CERN
  - 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 (Memphis Water Cerenkov) or possibly to Gran Sasso

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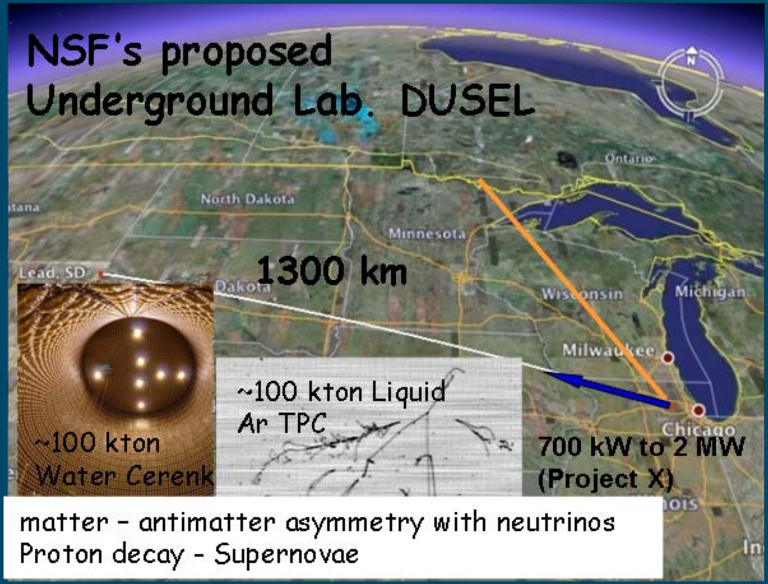

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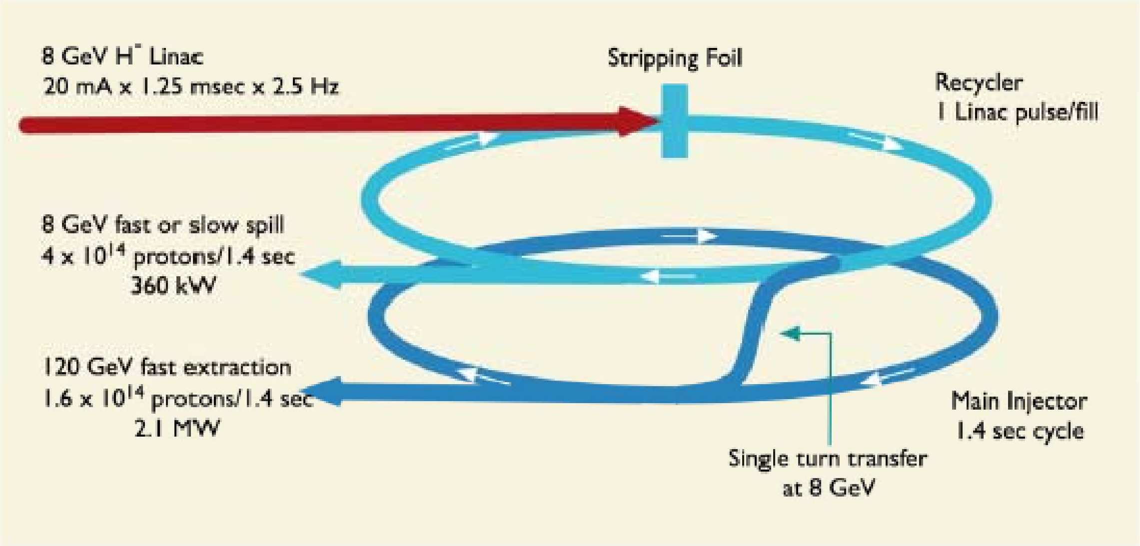
    - Replacement for present PS booster, part of the LHC luminosity upgrade
    - Low power and high power versions
    - High Power version, ~4 MW at 5 GeV for neutrino and ISOLDE programmes
    - Could produce a new neutrino beam to Frejus (Memphis Water Cerenkov) or possibly to Gran Sasso

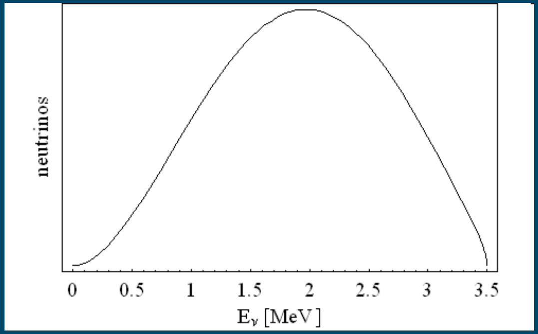
Initial Configuration

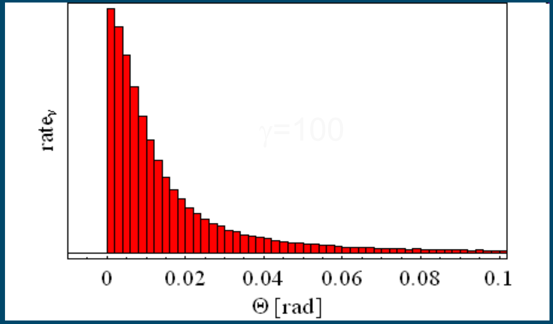
- A multi-megawatt proton source is considered a central and cohesive element for future accelerator developments needed in the exploration of both Energy and Intensity Frontiers at Fermilab
- Project X Design Criteria
  - 2 MW of beam power over the range 60 - 120 GeV;
  - Simultaneous with at least 150 kW of beam power at 8 GeV;
  - Compatibility with future upgrades to 2-4 MW at 8 GeV



Beta Beams

- Storage ring with β-decaying ions (P Zucchelli)
  - β^- decay => anti-$\nu_{e,}$ β^+ decay => $\nu_{e,}$ 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, σ α E_ν, E_ν α $Q_{decay}E_{ion}$, Divergence α $1/E_{ion}$
  - Choices
  - Original γ_{ion} = 100 (feasible at CERN with current SPS)
    - $^6He_2$ for ν, Q = 3.5 MeV, $<E_\nu>$ ~ 350 MeV
    - $^{18}Ne_{10}$ for ν-bar, Q = 3.0 MeV, $<E_\nu>$ ~ 300 MeV
  - Improved γ = 350 (needs now 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

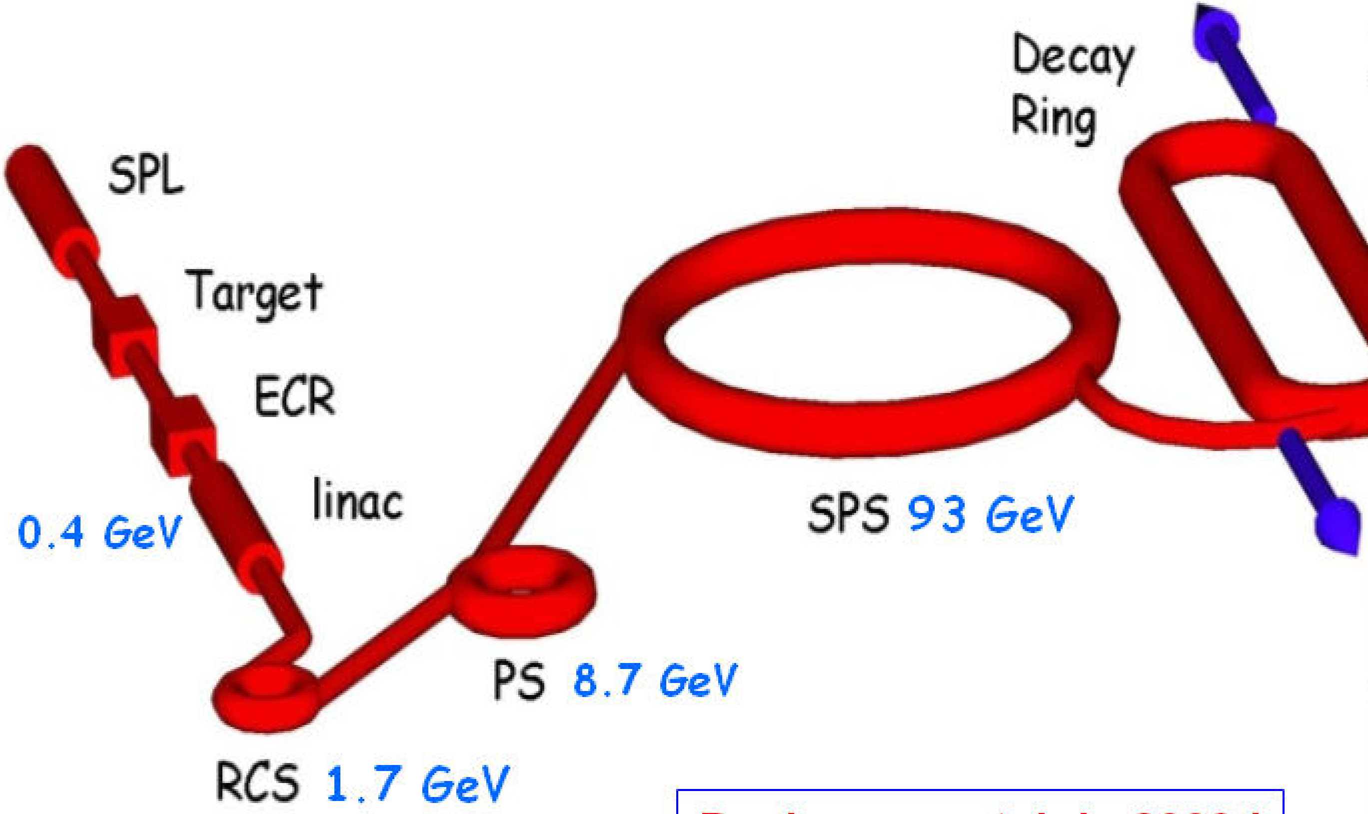
Design Study

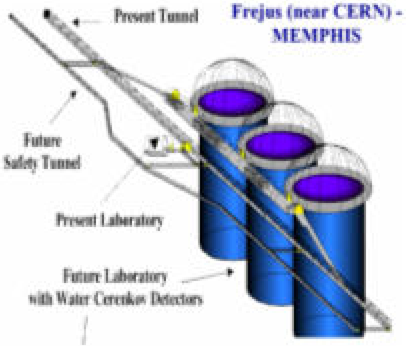
Decay ring

$B\rho$ = 1500 Tm

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

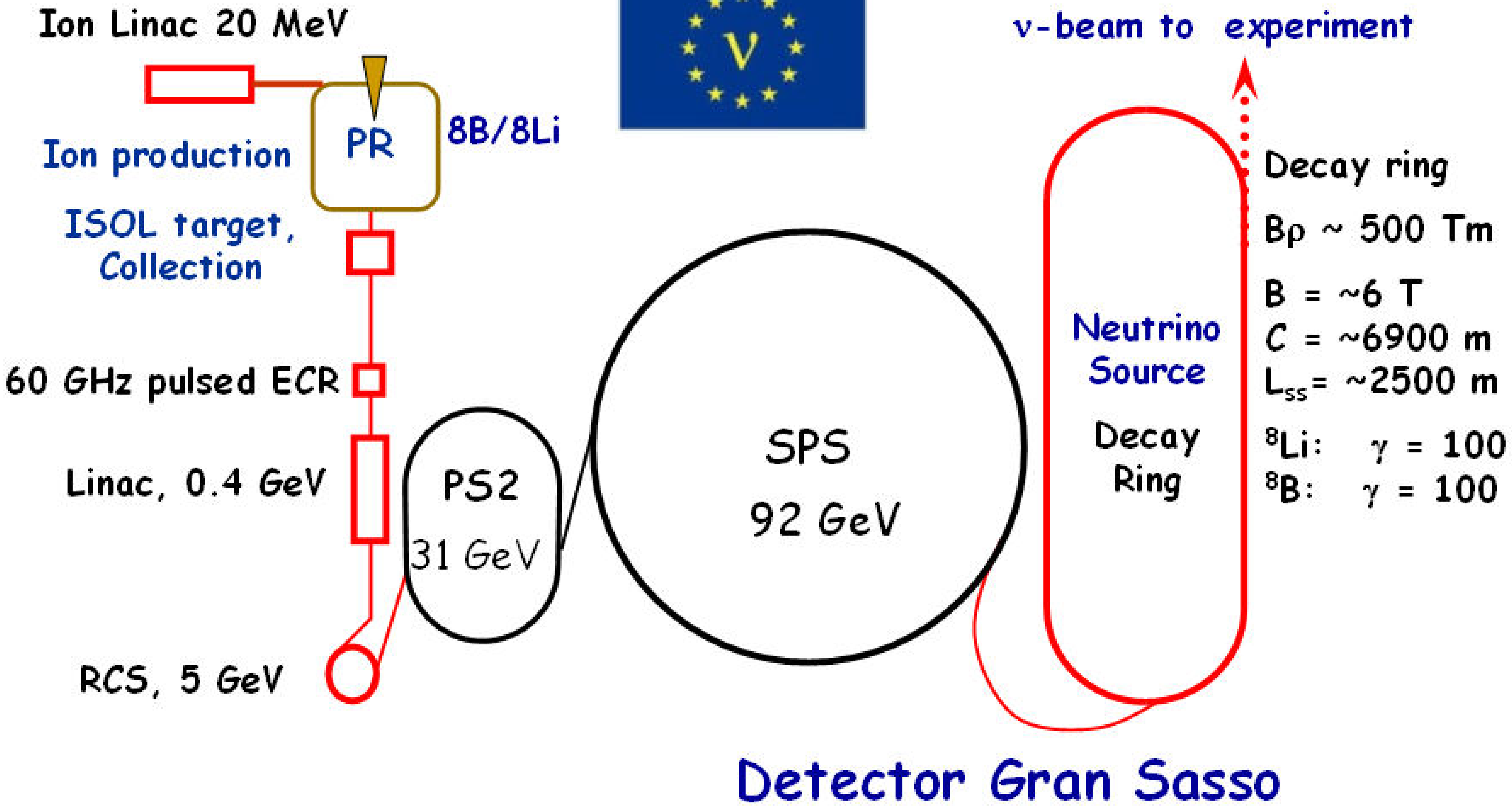
^{6}He: γ = 100
^{18}Ne: γ = 100





Design report July 2009 !

Beta Beam scenario EUROν (FP7)



Ion Linac 20 MeV

Ion production

PR

8B/8Li

ISOL target, Collection

60 GHz pulsed ECR

Linac, 0.4 GeV

RCS, 5 GeV

PS2

31 GeV

SPS

92 GeV

Neutrino Source

Decay Ring

ν-beam to experiment

Decay ring

$B\rho \sim 500$ Tm

$B = \sim 6$ T

$C = \sim 6900$ m

$L_{ss} = \sim 2500$ m

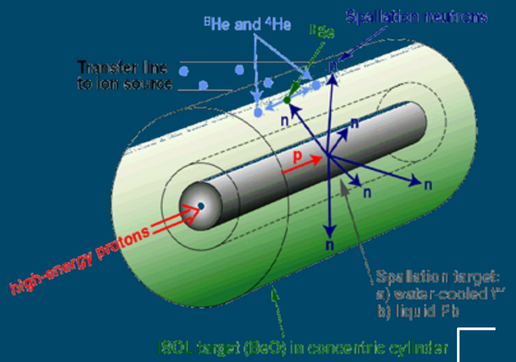
^{8}Li: $\gamma = 100$

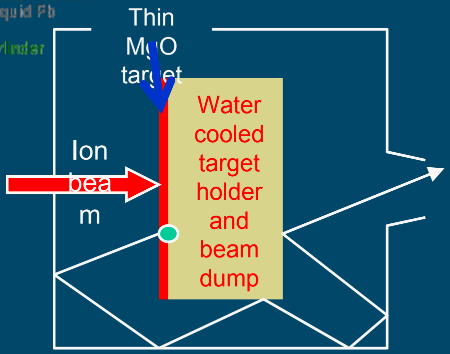
^{8}B: $\gamma = 100$

Detector Gran Sasso

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**



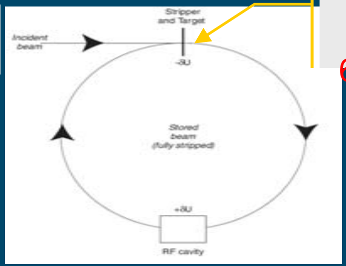

Thin MgO target

Ion beam

Water cooled target holder and beam dump

7Li

6Li



7Li(d,p)8Li

6Li(3He,n)8B

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

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

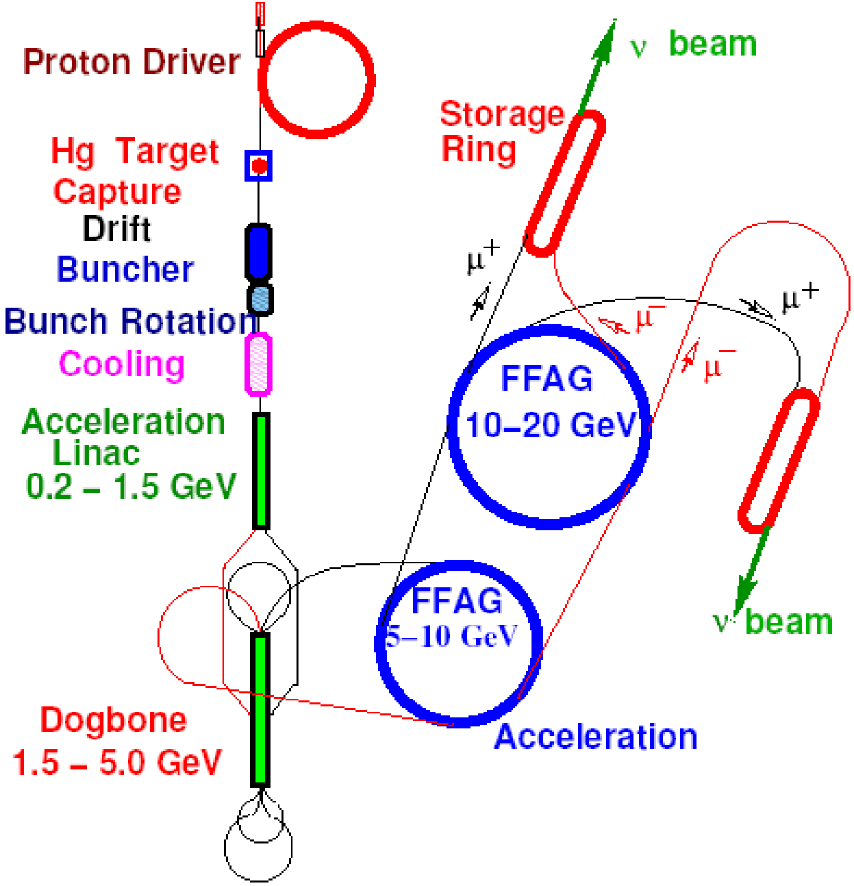
  established feasibility & R&D programme

  ○ 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.

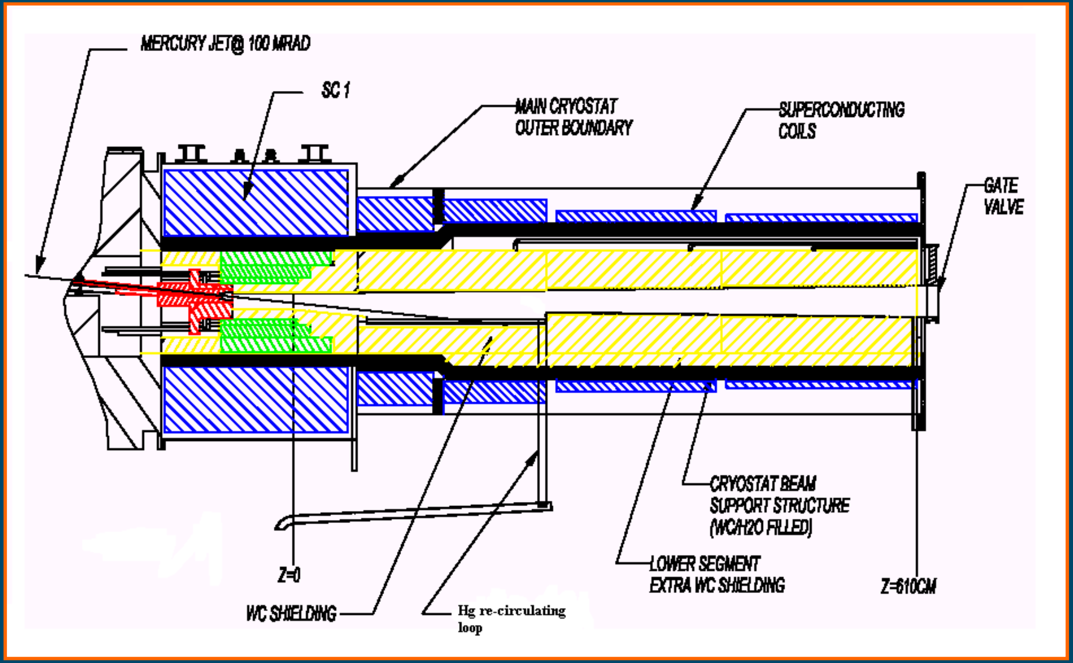
Accelerator Subsystems

- Proton driver
- Target and capture
- Front end
  - Bunching and phase rotation
  - Cooling
- Acceleration
- Decay ring



Target – Major difficulty at 4 MW

- Baseline - Mercury Jet

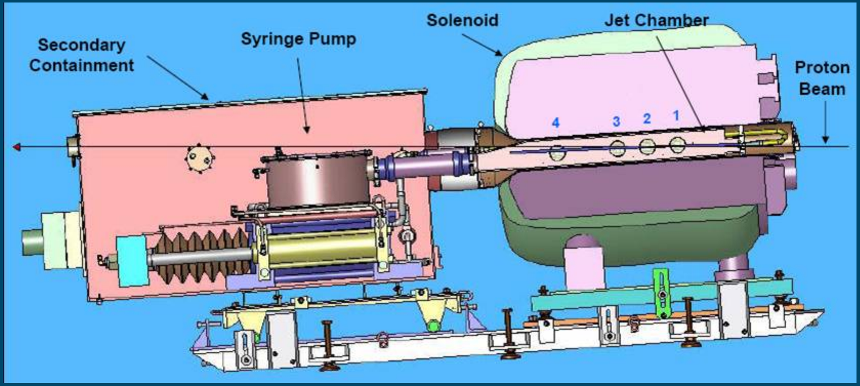


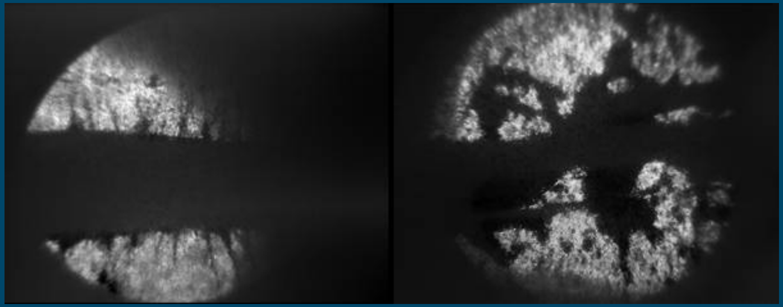
MERIT EXot serves as a satisfactory proof-of-principle of Hg-jet concept
(Ilias Efthymiopoulos)

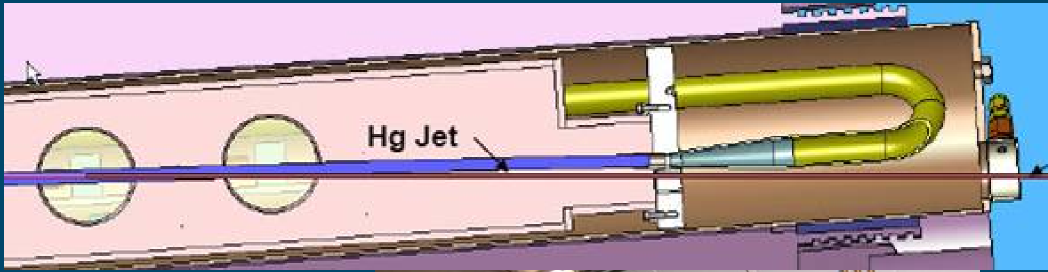
Field tapers from 20 T, 15 cm
to 1.75 T, 60 cm over 20 m

MERIT expt at CERN (2008)

- High-power liquid-mercury jet target engineering demonstration







CONCLUSIONS

Power handling of target is adequate

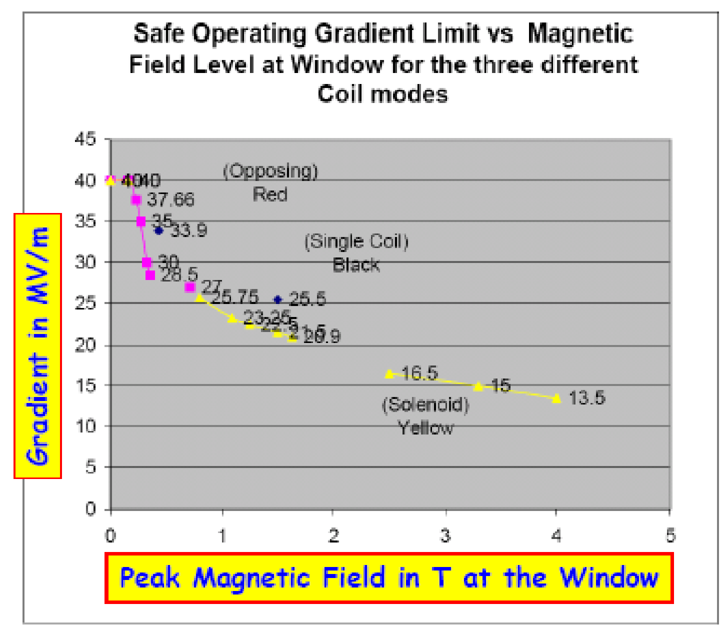
  disruption length of 28 cm ⇒ 70 Hz rep. rate at 20 m/s

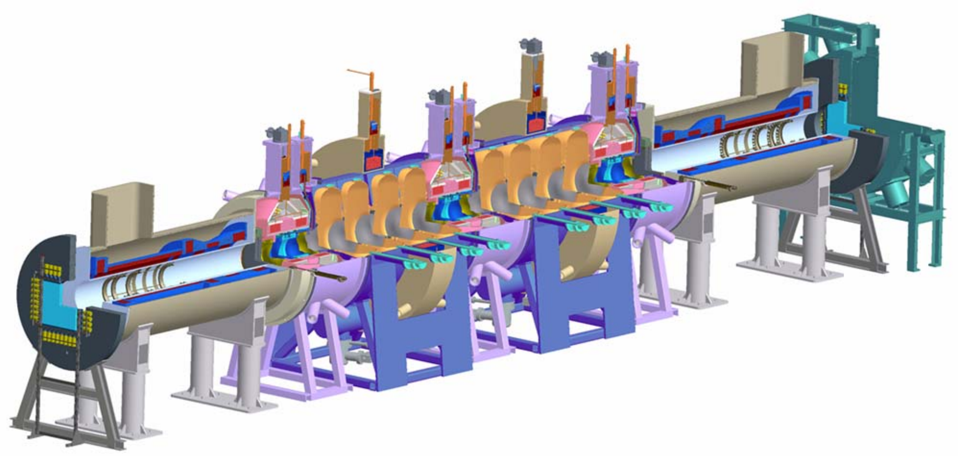
  115 kJ per pulse x 70 Hz gives 8 MW of beam power

    4 MW design value seems “comfortable”

Cooling: R&D programme

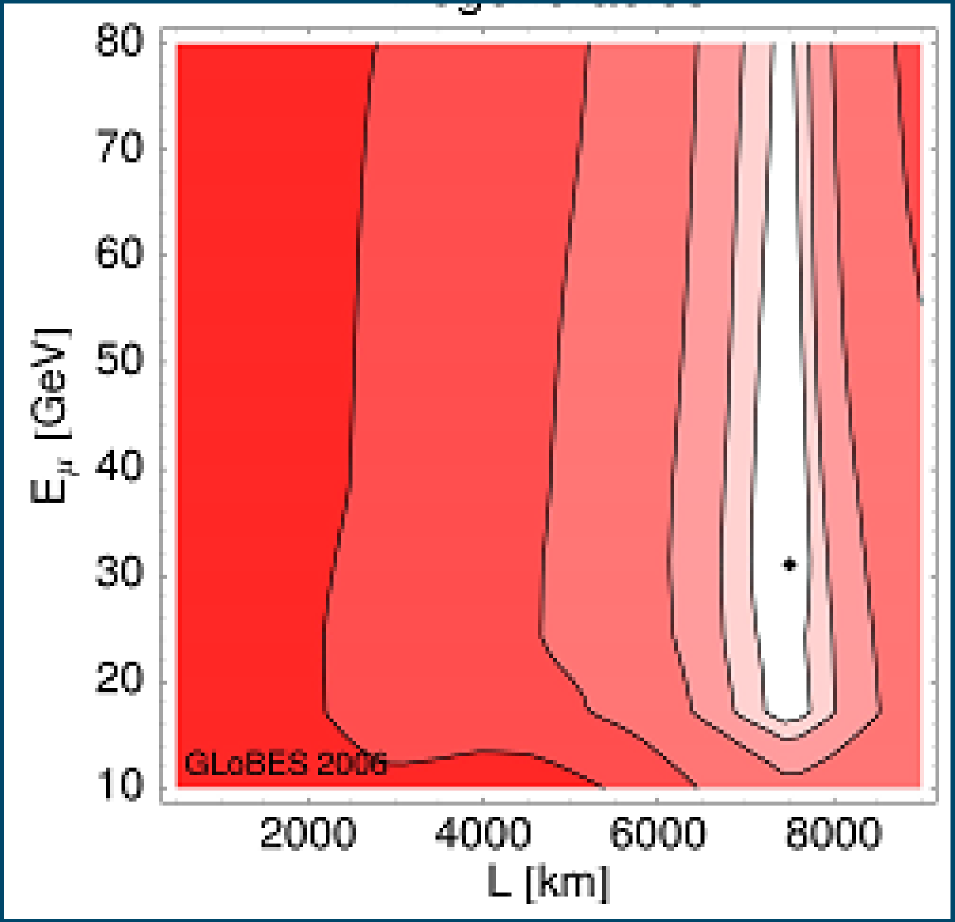
- 2 Complementary programmes:
  - MuCool: (FNAL)
    - Design, prototype, and test – using an intense proton beam – cooling channel components
  - MICE: (RAL)
    - Design, construct, commission, and operate – in a muon beam – a section of cooling channel and measure its performance in a variety of modes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





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

ISS Physics Report

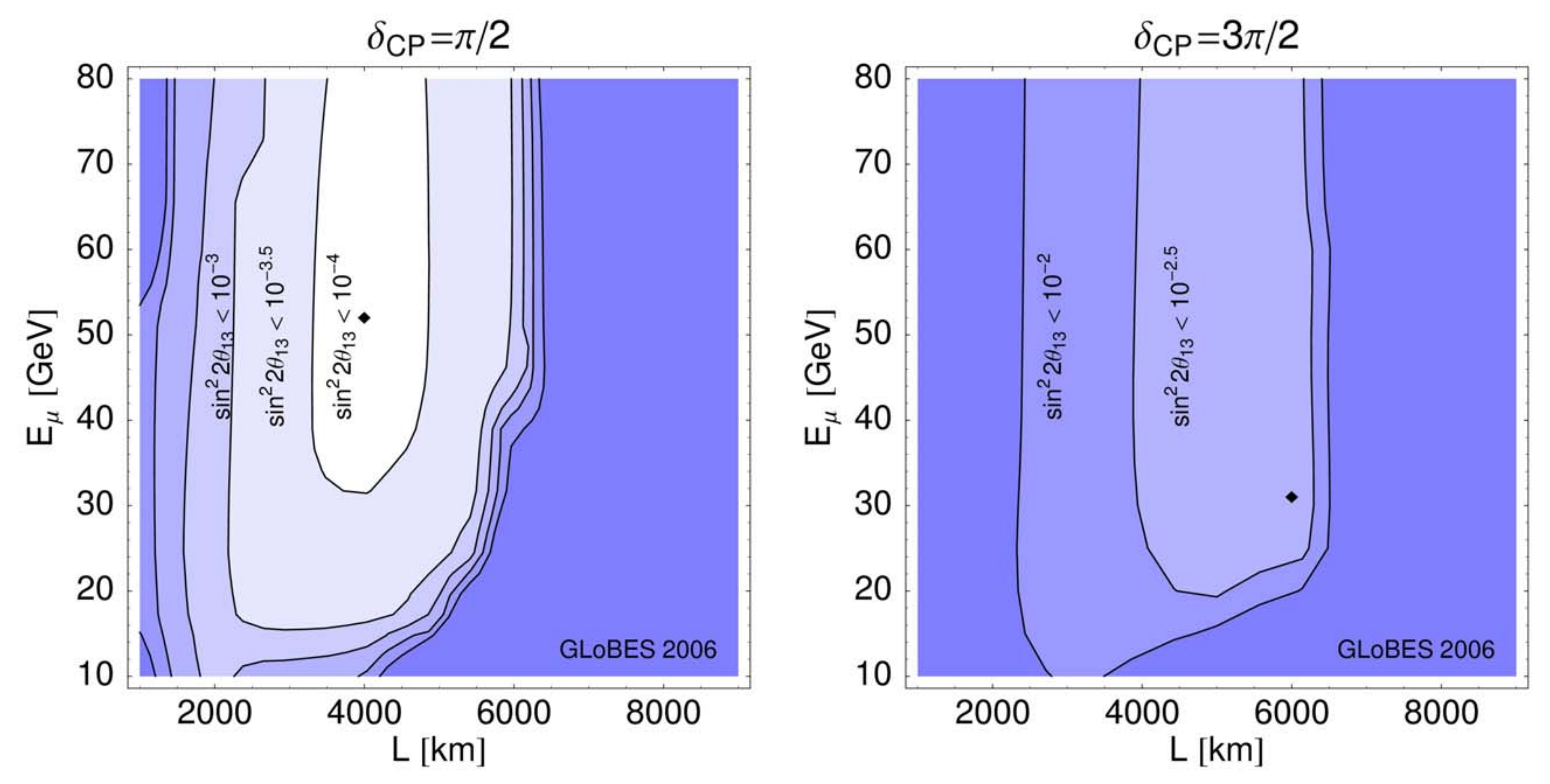


Taking into account statistics, systematics, correlations, degeneracies

Magic baseline (7500 km) good degeneracy solver

Stored muon energy > 20 GeV

NuFact - **CP sensitivity**



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

ISS Physics Report

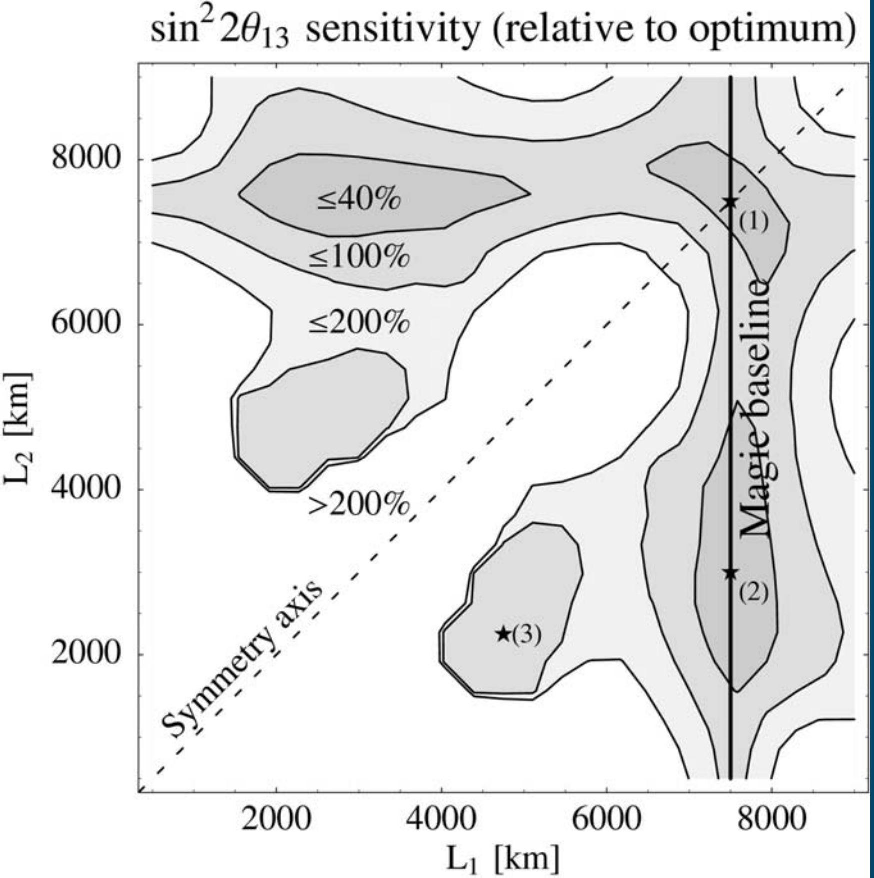
NuFact - Multiple baselines:

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

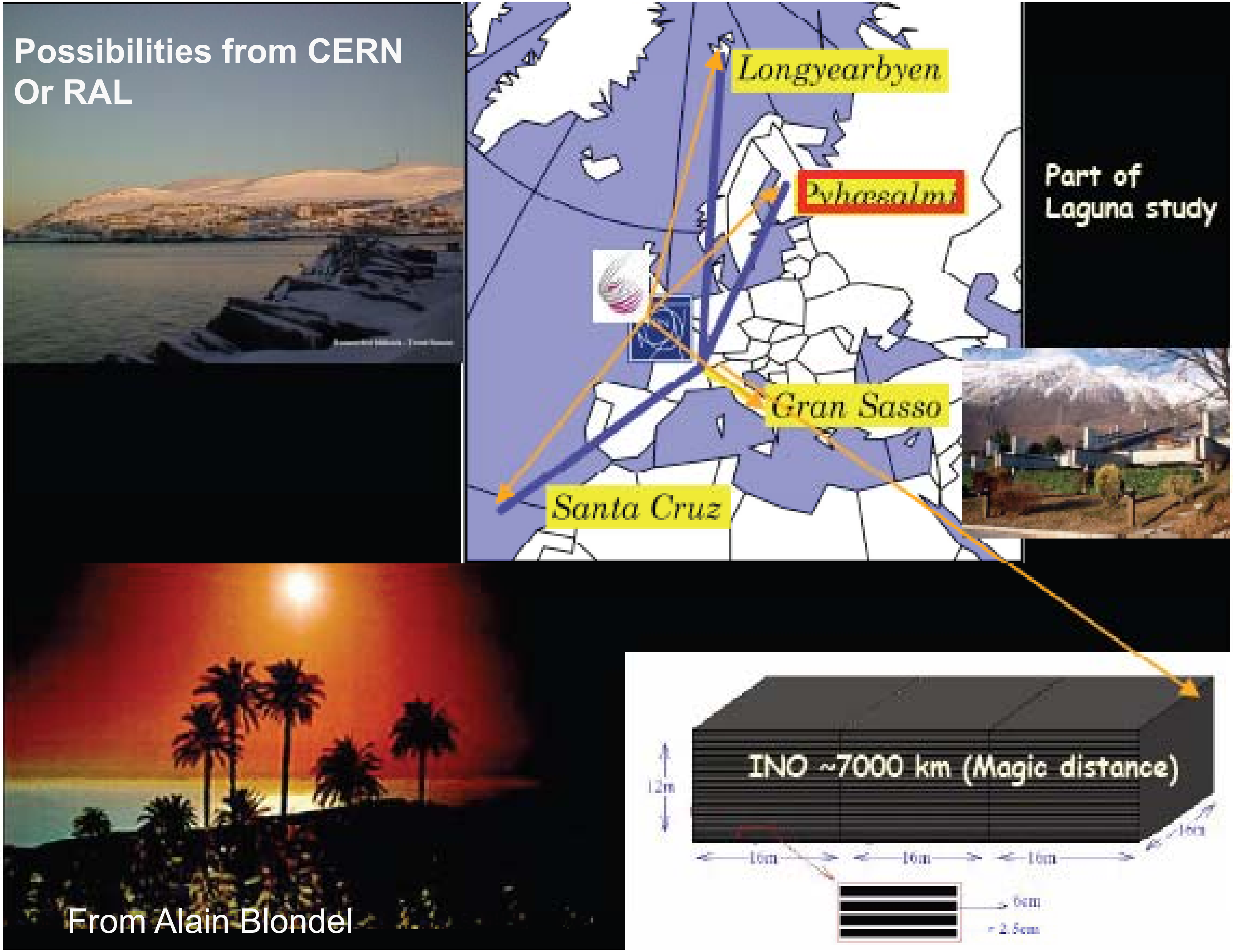
Stored muon energy 50 GeV

Second detector at ~3000 km preferred as it has sensitivity to CP violation

ISS Physics Report



Possibilities from CERN
Or RAL

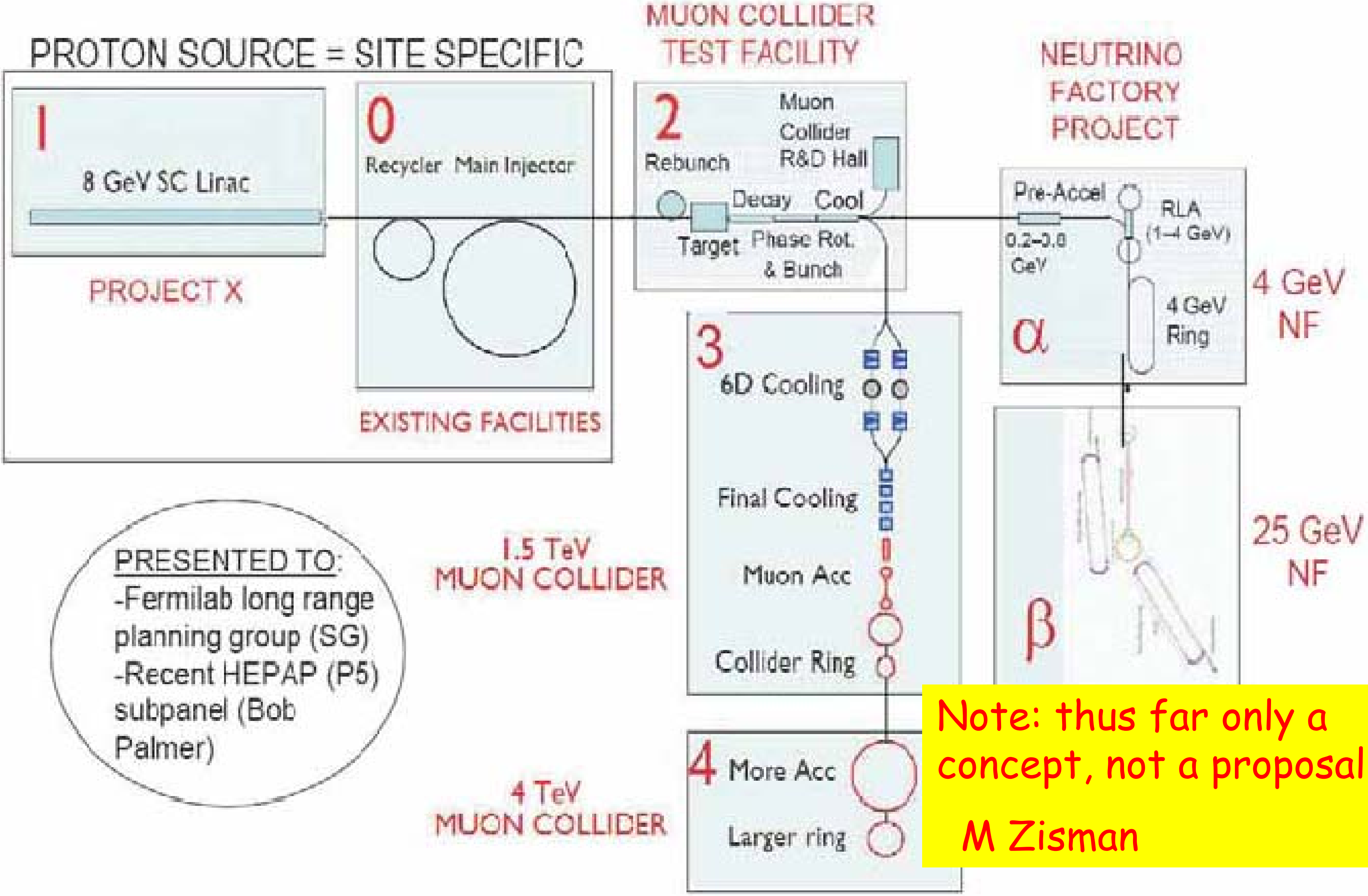


Part of
Laguna study

INO ~7000 km (Magic distance)

From Alain Blondel

A U.S. Scenario / Project X



PROTON SOURCE = SITE SPECIFIC

1

8 GeV SC Linac

PROJECT X

0

Recycler Main Injector

EXISTING FACILITIES

MUON COLLIDER TEST FACILITY

2

Rebunch

Muon Collider R&D Hall

Decay Cool

Target Phase Rot. & Bunch

3

6D Cooling

Final Cooling

Muon Acc

Collider Ring

1.5 TeV MUON COLLIDER

4

More Acc

Larger ring

4 TeV MUON COLLIDER

NEUTRINO FACTORY PROJECT

Pre-Accel

0.2–3.8 GeV

RLA (1–4 GeV)

4 GeV Ring

α

4 GeV NF

β

25 GeV NF

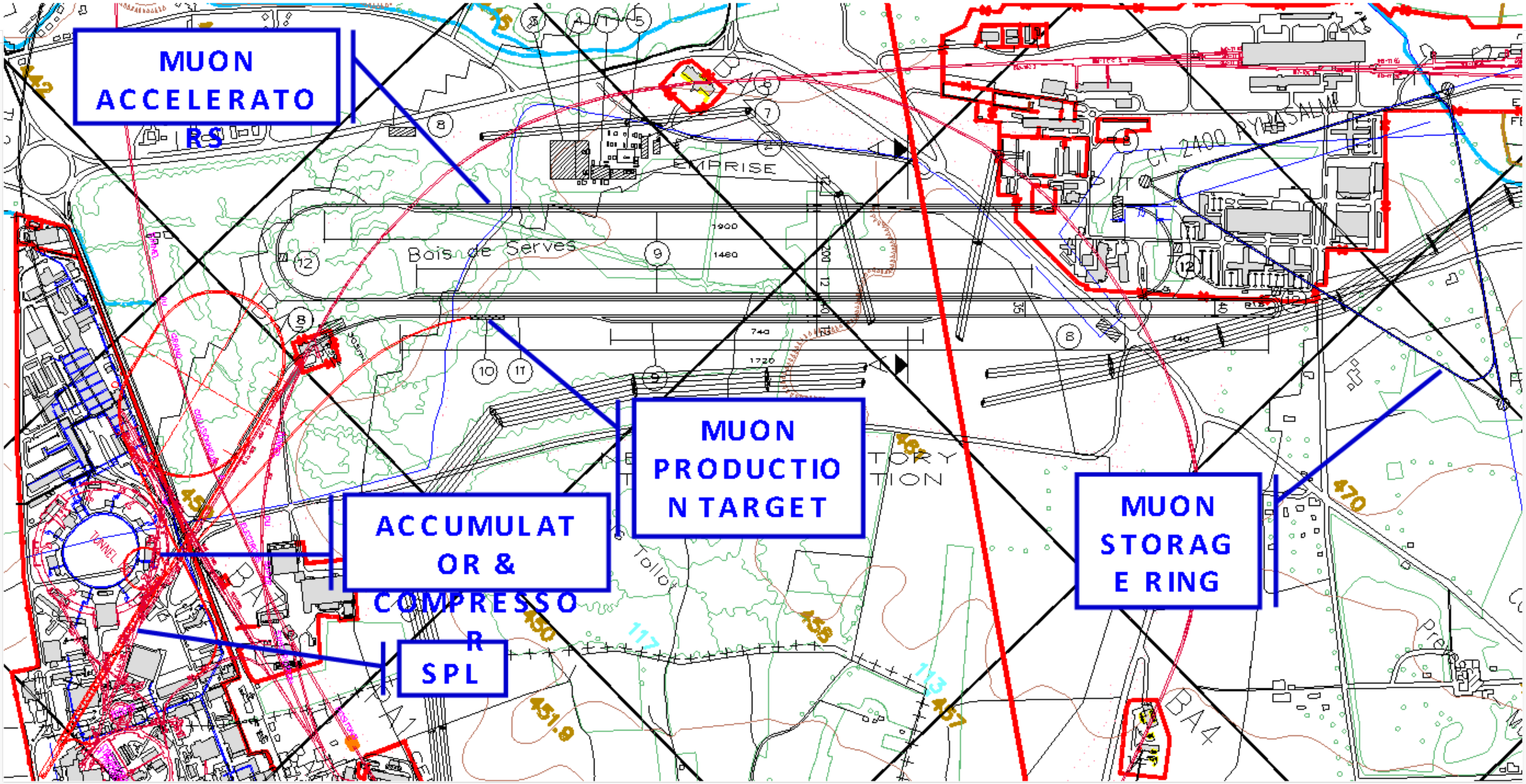
PRESENTED TO:
-Fermilab long range planning group (SG)
-Recent HEPAP (P5) subpanel (Bob Palmer)

Note: thus far only a concept, not a proposal

M Zisman

ν FACTORY

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



MUON ACCELERATORS

MUON PRODUCTION TARGET

ACCUMULATOR & COMPRESSOR

MUON STORAGE RING

SPL

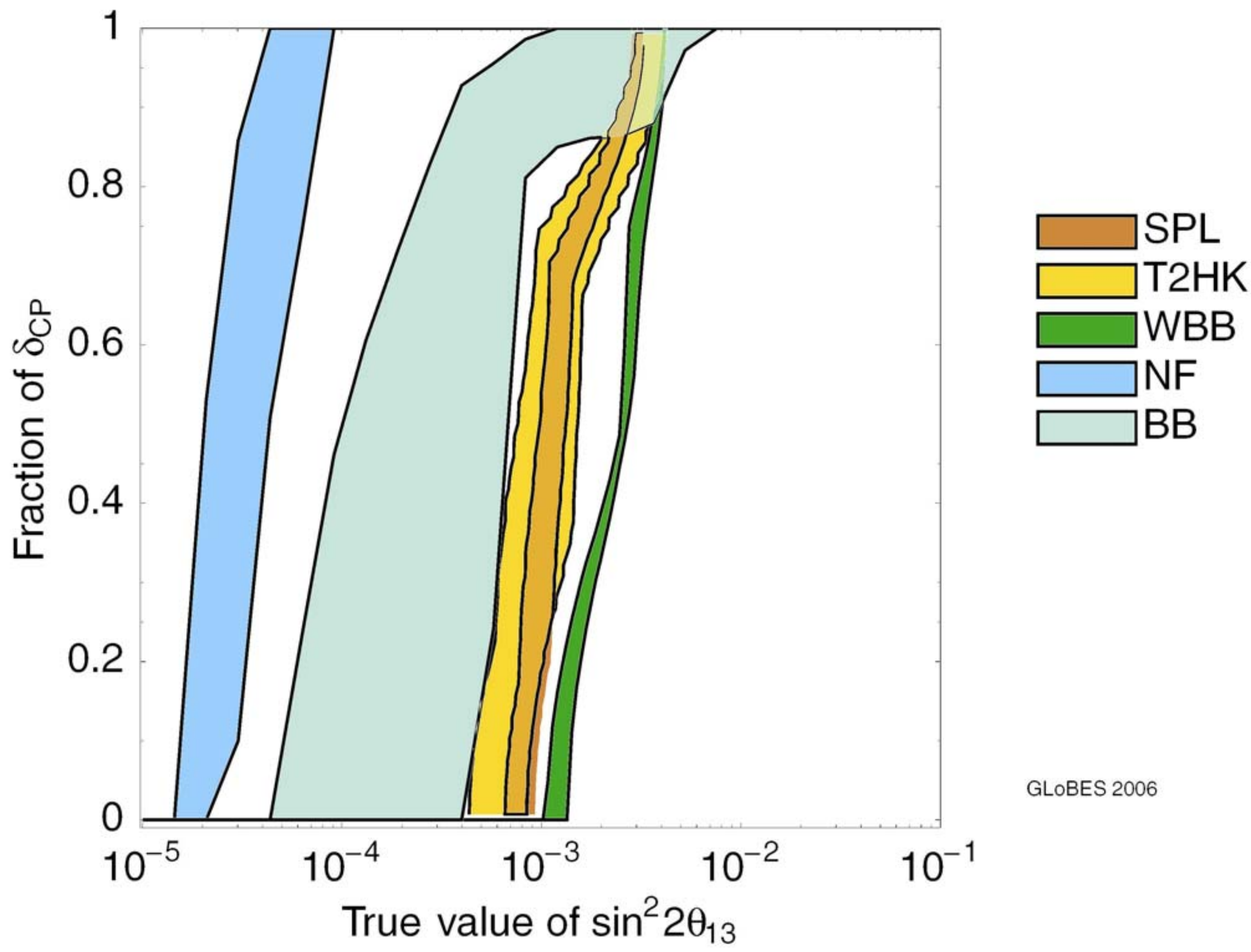
From Roland Garoby

A performance comparison (ISS)

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

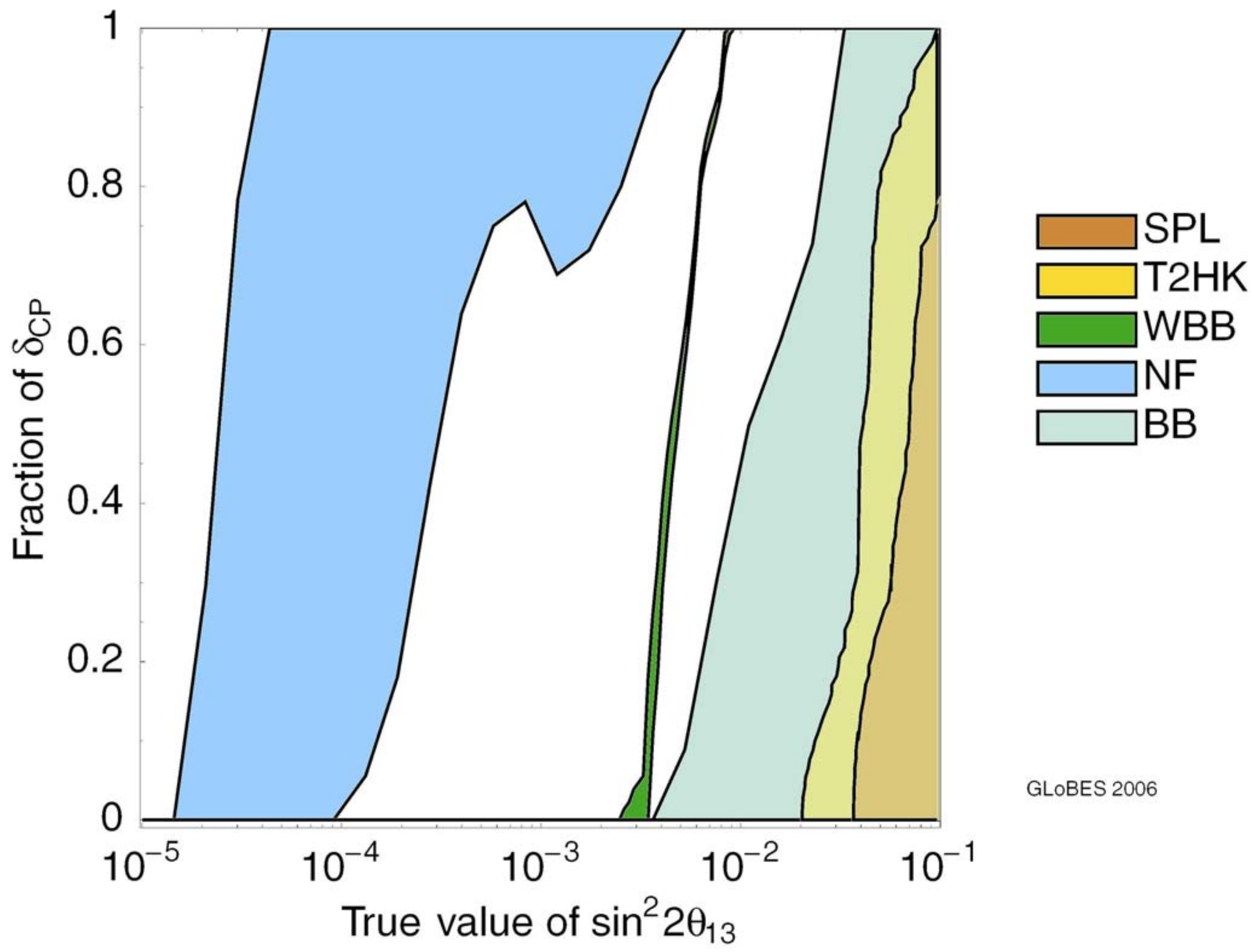
For θ_{13}

ISS Physics Report



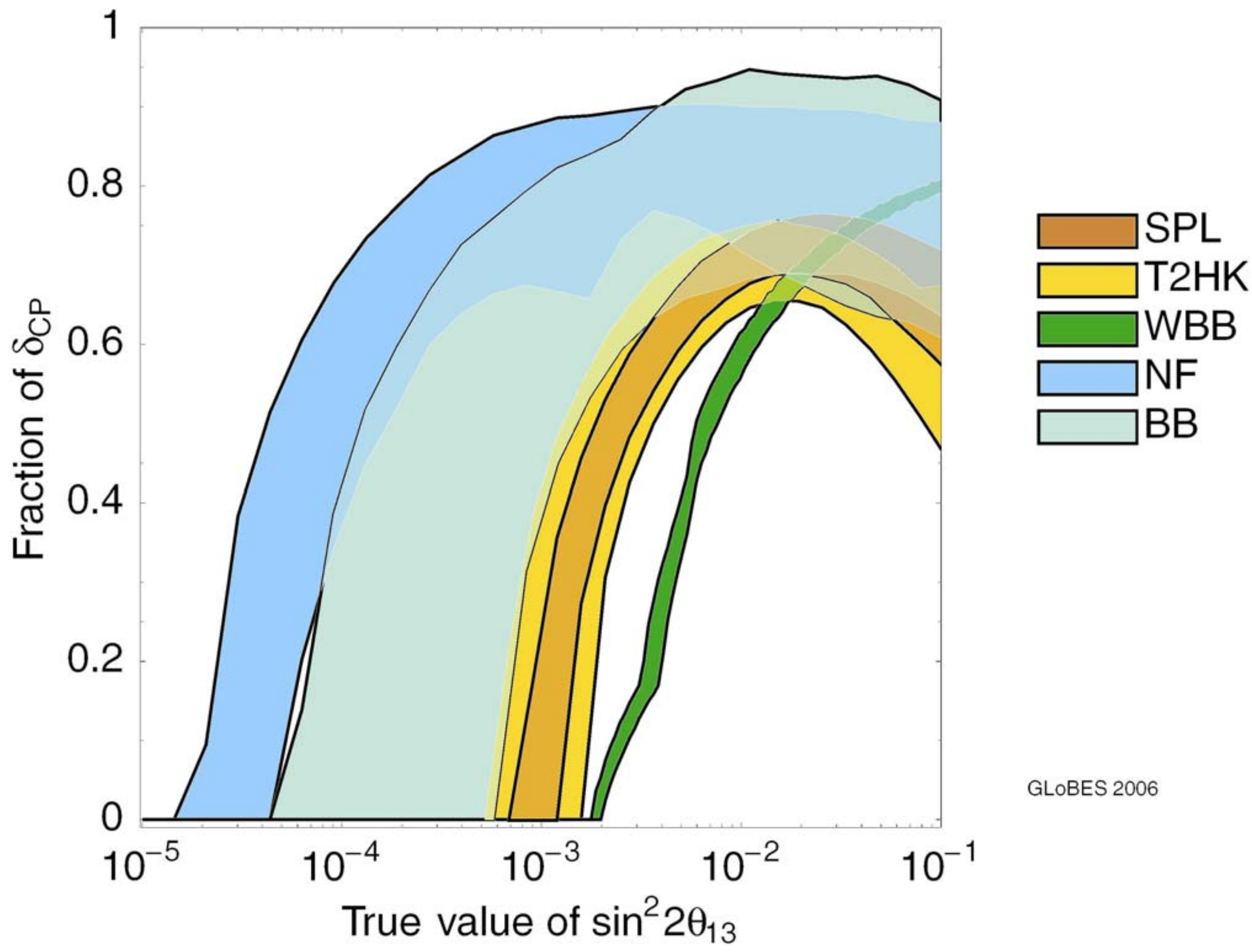
For the Mass Hierarchy

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 Noνa 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,

Advert

European Strategy for Future Neutrino Physics

- *A workshop to discuss the possibilities for future neutrino investigations in Europe and the links to CERN*

- *CERN Oct 1-3, 2009*

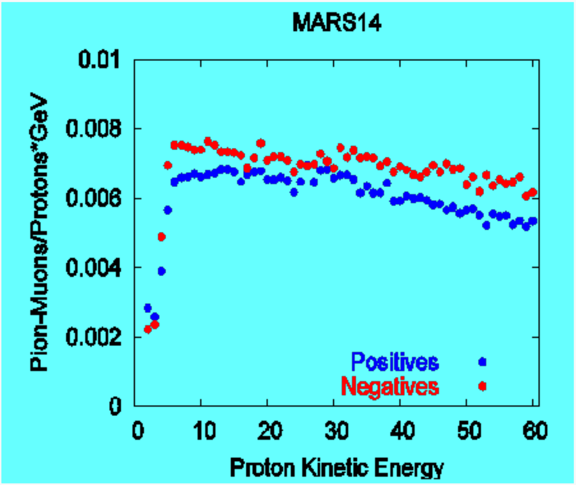
- *All Welcome*

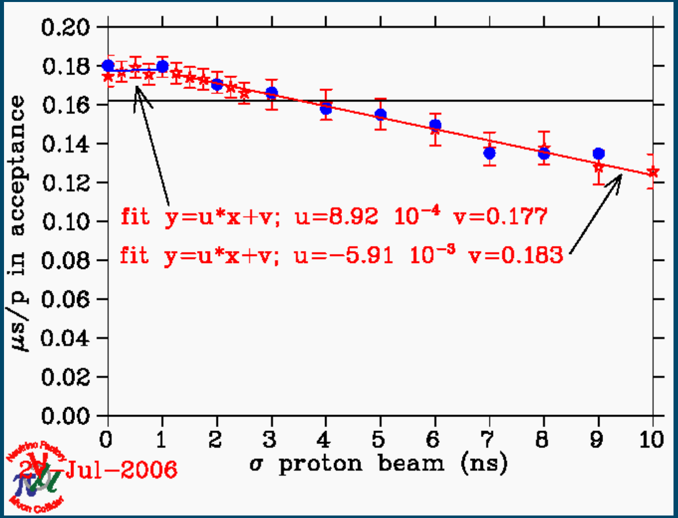
Back-up

Proton Driver

- Baseline Parameters

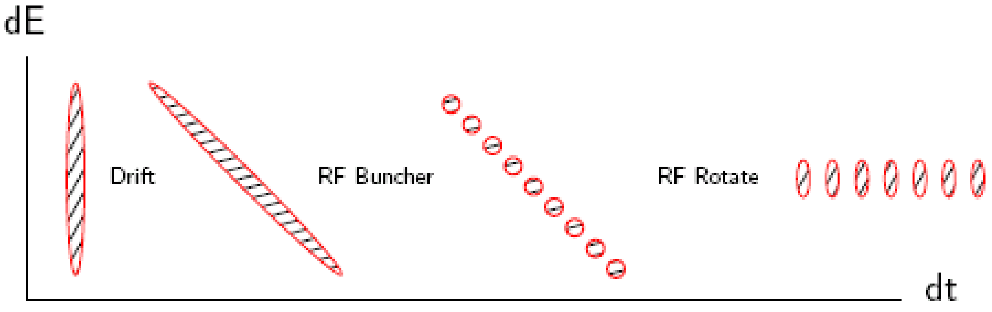
Parameter	Value
Energy (GeV)	10 ± 5
Beam power (MW)	4
Repetition rate (Hz)	≈50
No. of bunch trains	3,5[a)]
Bunch length, rms (ns)	2 ± 1
Beam duration[b)] (μs)	≈40



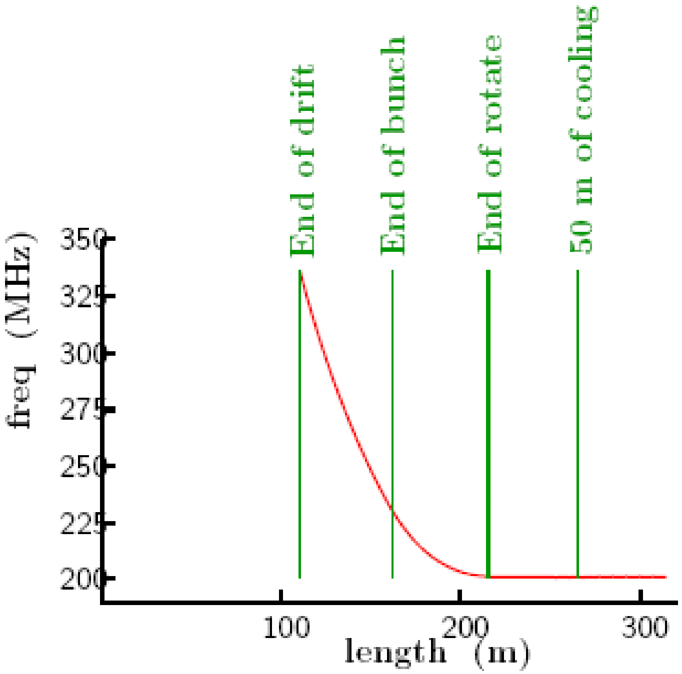


Phase Rotation & Bunching

Bunched Beam Rotation with 200 MHz RF (Neuffer)

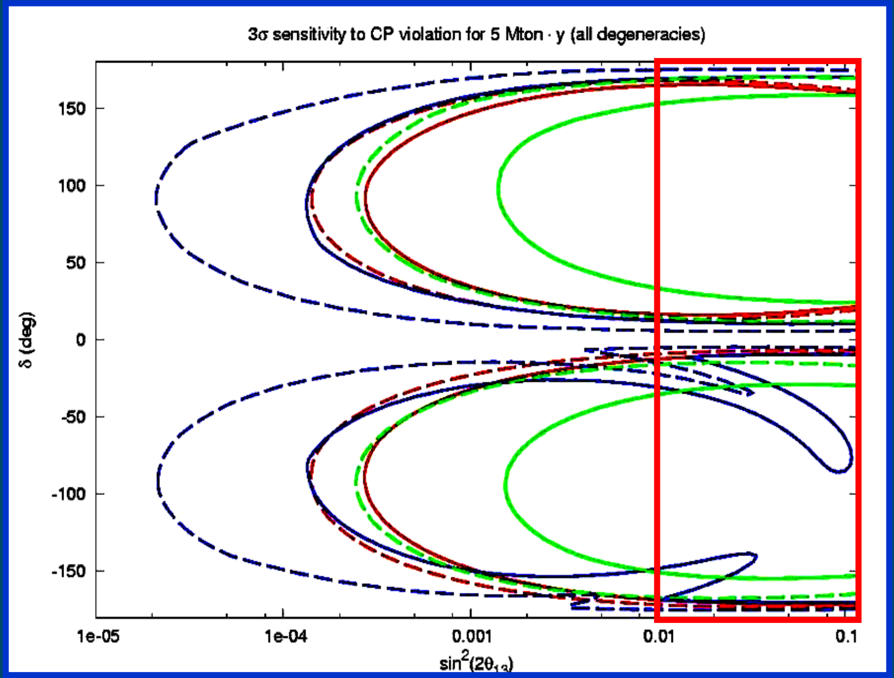


- RF frequency must vary along bunching channel (high mom. bunches move faster than low)
- Bunched Beam method captures both signs in interleaved bunches

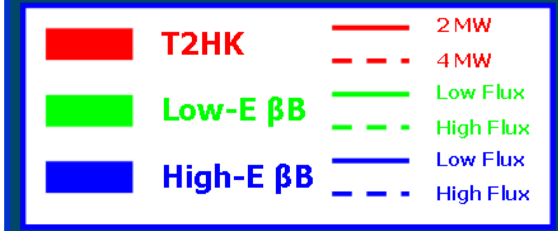


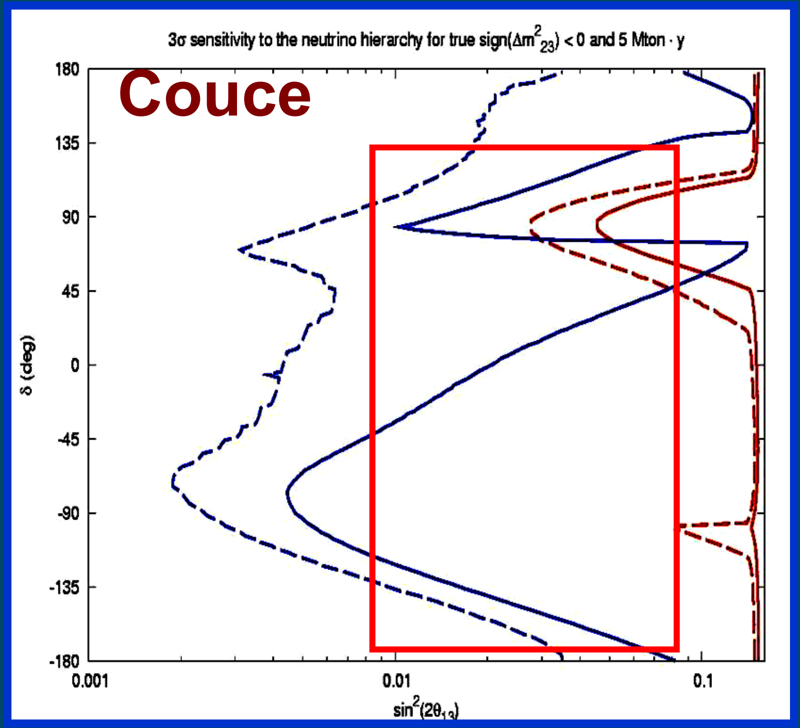
Requires R & D

Beta beam, super beam comparison



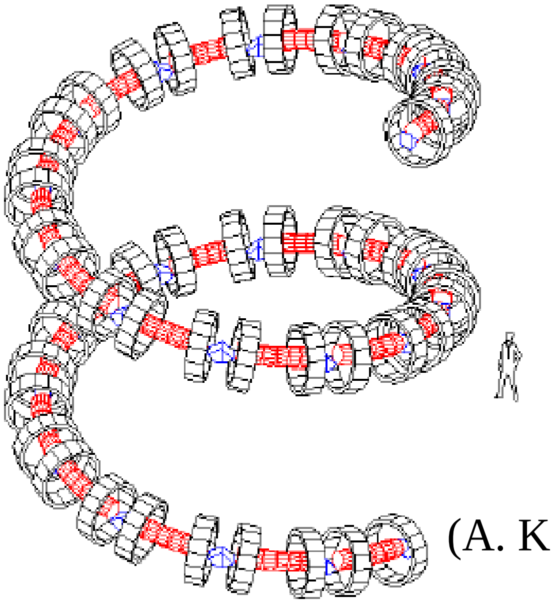
Preliminary! Need to include better treatment of background and sys. err.





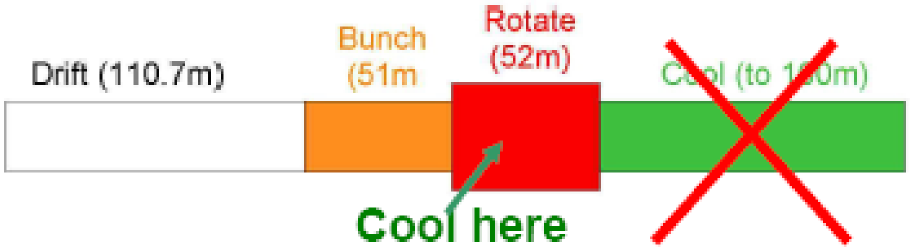
- High θ_{13}:
  - Beta beam & super beam alone:
    - δ sensitivity good
    - Poor sign(Δm_{23}^2) sensitivity

Front end: new configurations



(A. Klier)

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

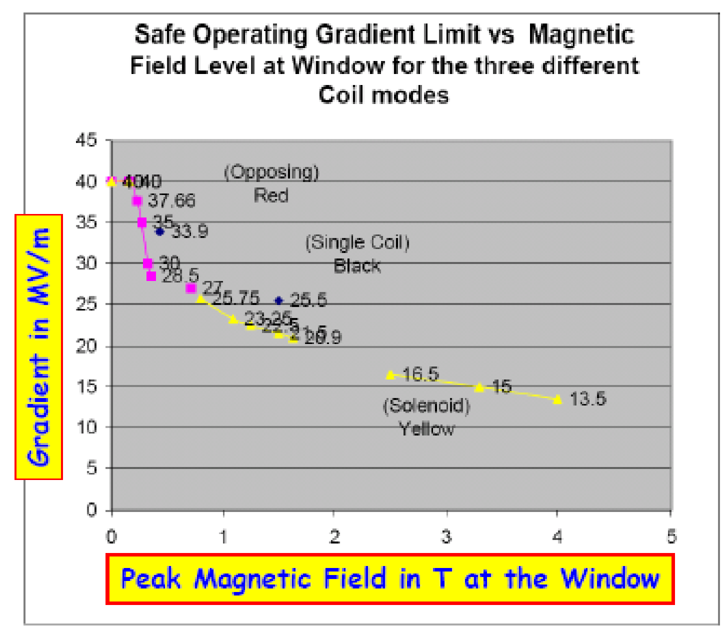


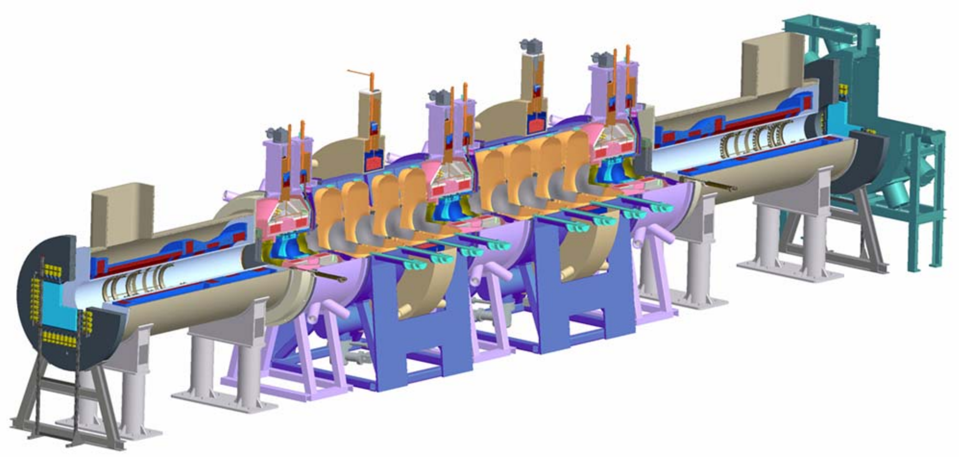
(D. Neuffer)

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

Cooling: hardware R&D programme

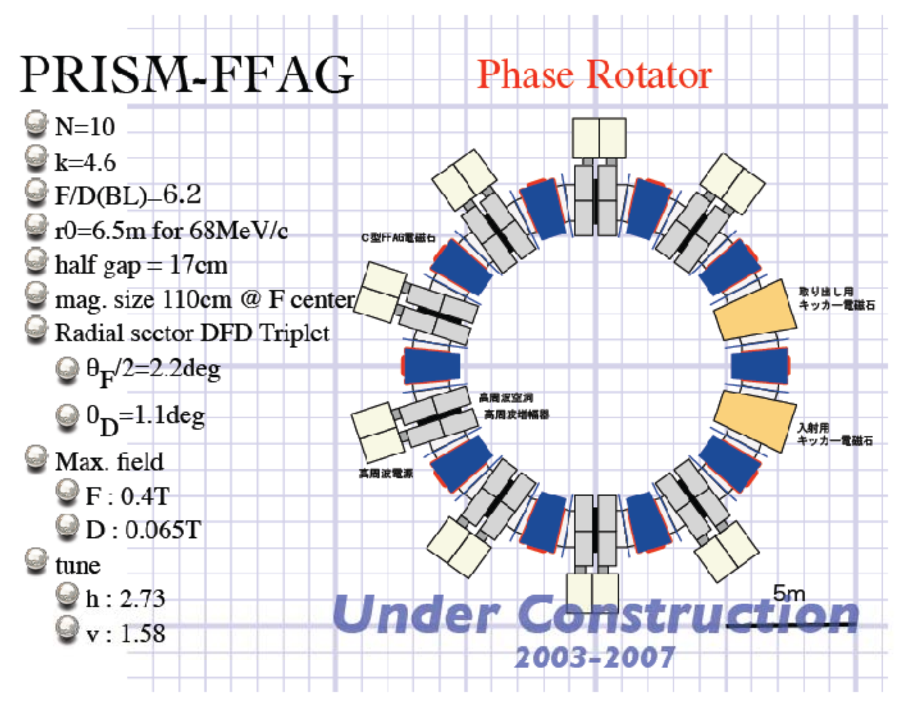
- Complementary programmes:
  - MuCool:
    - Design, prototype, and test – using an intense proton beam – cooling channel components
  - MICE:
    - Design, construct, commission, and operate – in a muon beam – a section of cooling channel and measure its performance in a variety of modes
- Both programmes well advanced


Safe Operating Gradient Limit vs Magnetic Field Level at Window for the three different Coil modes



Acceleration: FFAG development

- Increasing effort on scaling and non-scaling FFAG
- PRISM: Phase rotated intense muon source
    - Under construction in Osaka
Commissioning 2007
    - Proof of principle 'non-scaling' FFAGDecay ring



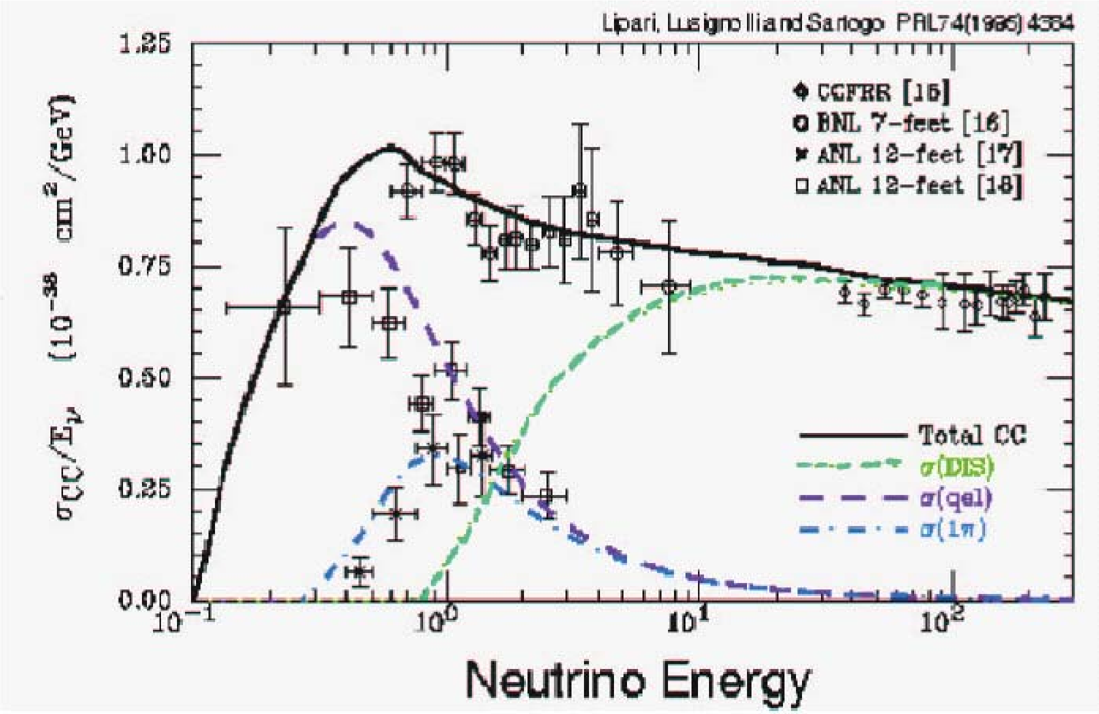
PRISM-FFAG

- N=10
- k=4.6
- F/D(BL)–6.2
- r0=6.5m for 68MeV/c
- half gap = 17cm
- mag. size 110cm @ F center
- Radial sector DFD Triplet
    - $\theta_F/2$=2.2deg
    - 0_D=1.1deg
- Max. field
    - F : 0.4T
    - D : 0.065T
- tune
    - h : 2.73
    - v : 1.58

EMMA :Electron model of muon acceleration

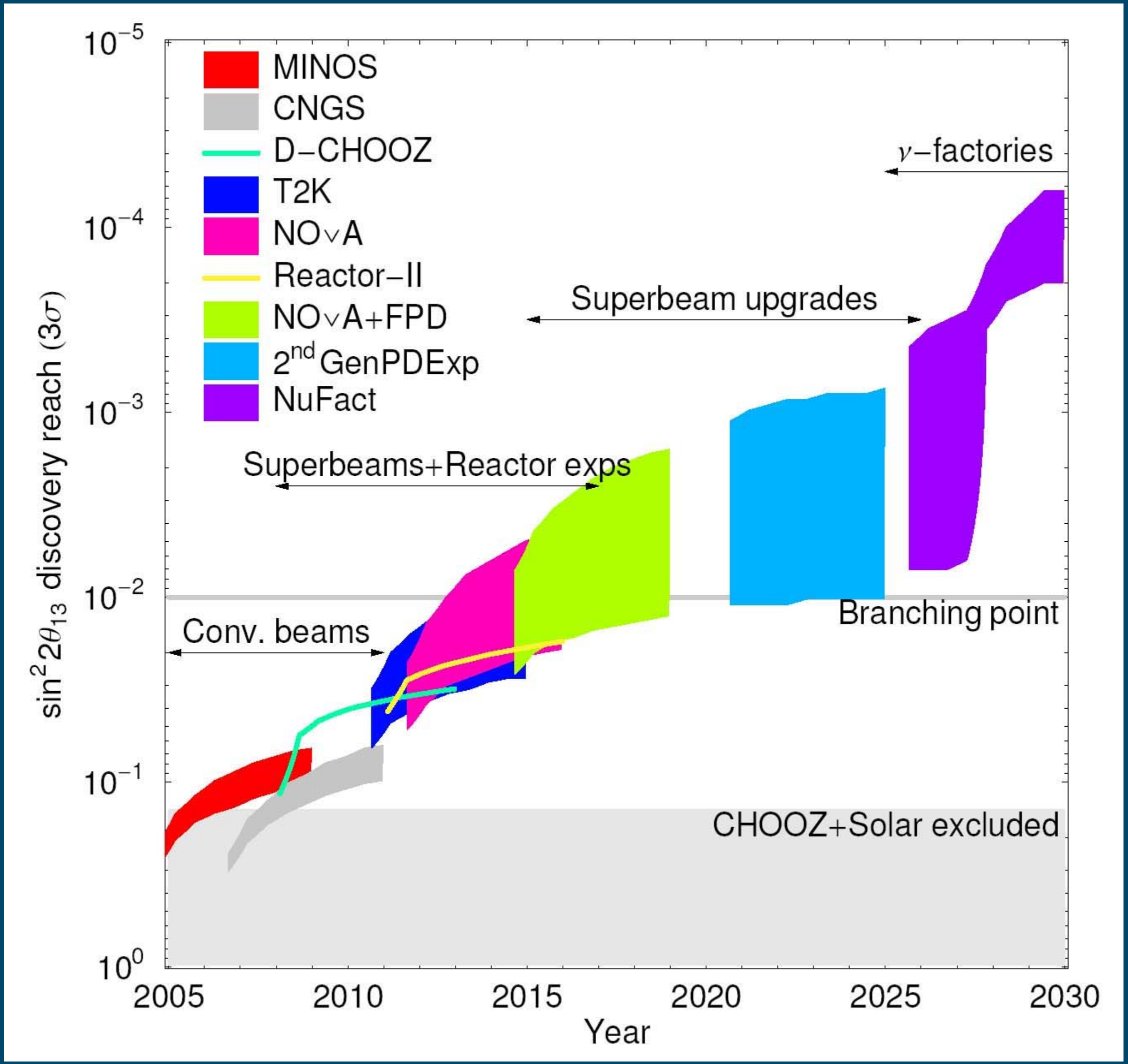
Near detector

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

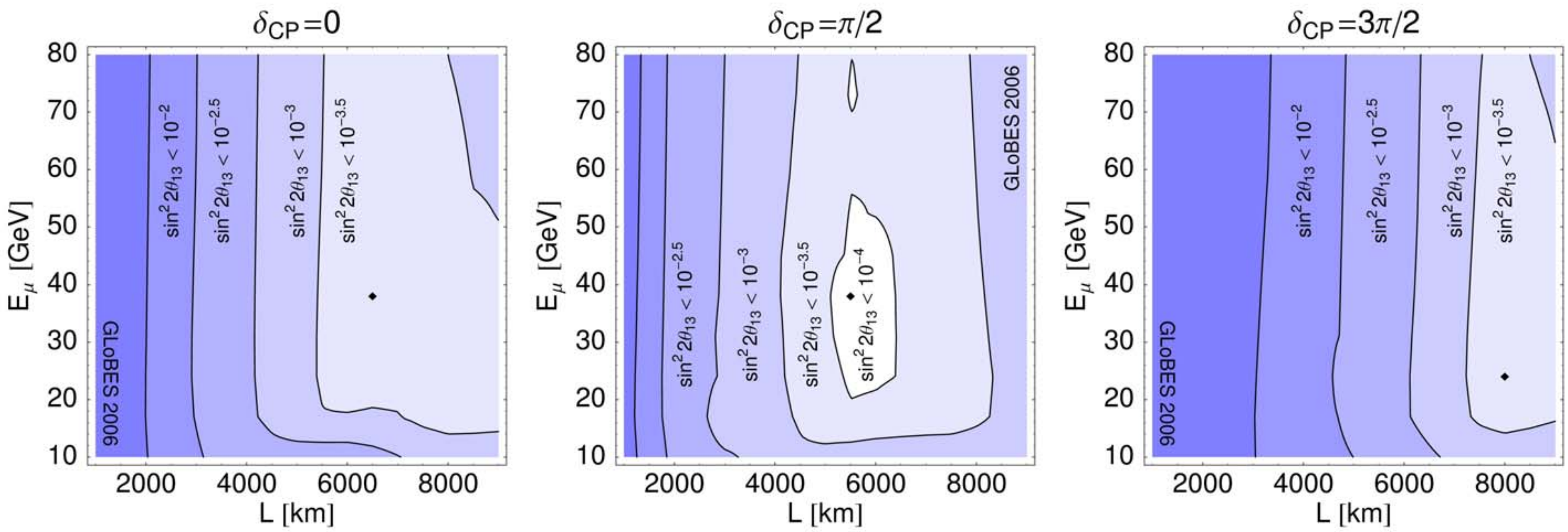

Lipari, Lusignolli and Sartogo PRL74(1995) 4384

- 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

Timescales: the challenge

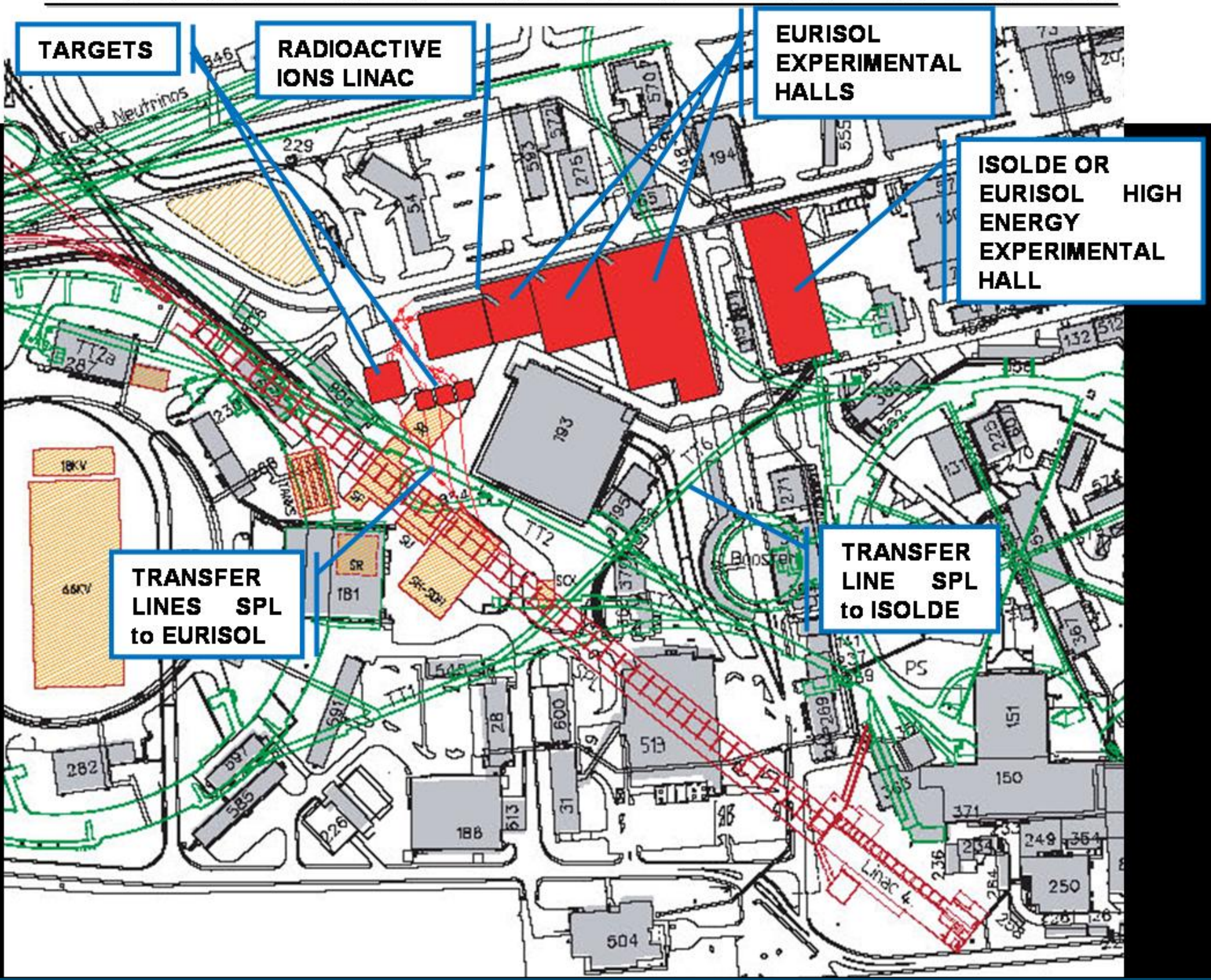


NuFact - Mass Hierarchy sensitivity



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

PLANS FOR FUTURE INJECTORS



TARGETS

RADIOACTIVE IONS LINAC

EURISOL EXPERIMENTAL HALLS

ISOLDE OR EURISOL HIGH ENERGY EXPERIMENTAL HALL

TRANSFER LINES SPL to EURISOL

TRANSFER LINE SPL to ISOLDE