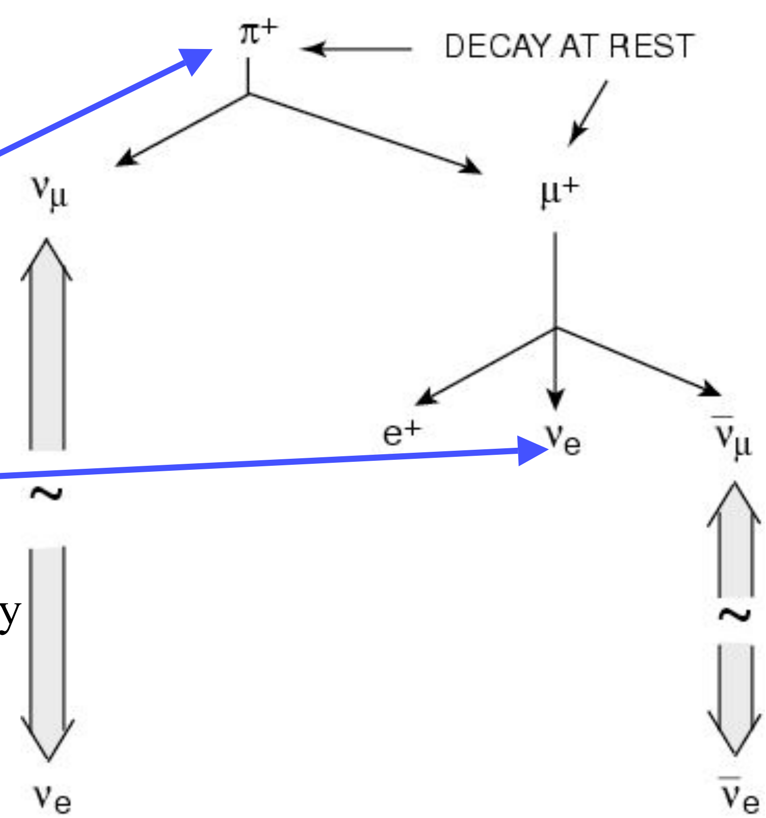
LSND

- 800 MeV protons in a dump.
- Positive Pions and then muons coming to rest
- and then decaying
- Look for $\overline{\nu}_\mu$ to $\overline{\nu}_e$ oscillations
- Through the reaction: $\overline{\nu}_e + p \rightarrow e^+ + n$
- Observe e^+ + photons from neutron capture in the scintillator
- Delayed coincidence
- Why not $\overline{\nu}_e$ from $\pi^- \rightarrow \mu^- \rightarrow \overline{\nu}_e$ decay chain ?
  - π^-/π^+ production 1/8
  - π- coming to rest in dump captured before decay
  - Only decays in flight contribute 1/20
  - Most μ^- captured before decay 1/8
- Overall reduction **7.5 x 10 $^{-4}$**.



LSND

- They also searched for ν_μ to ν_e oscillations using decay in flight
- π to μ ν_μ.
- They looked for ν_e + C (scintillator) --> e^- + X
- Searched for events in the 40-200 MeV electron energy range
- (Above the energy range of $\overline{\nu_e}$ in the decay at rest search)
- Found 40 events expected 26.

What's needed next?

- **What is the value of θ_{13} ?**
  Plans for several experiments using reactors, accelerators, etc…

- **What is the mass hierarchy ?**
  Some of these experiments, especially if extended through the use of upgraded accelerators, could begin to address this.

- **Any CP violation in the neutrino sector?**
  A new neutrino facility would be the only way to address this problem.

Compare $\nu_\mu \leftrightarrow \nu_e$ to $\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e$ oscillations
At the Atmospheric $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2

⇓

CP violation, (and θ_{13}, mass hierarchy)

Origin of Neutrino Masses

- The Higgs mechanism generates a mass term for neutrinos:

- For a single family: $\mathcal{L}^D = - m_D \bar{\nu}\nu$

(with m_D depending on a coupling and the Higgs vacuum expectation value,vev)

- And assuming the existence of both left-handed and right-handed neutrinos:

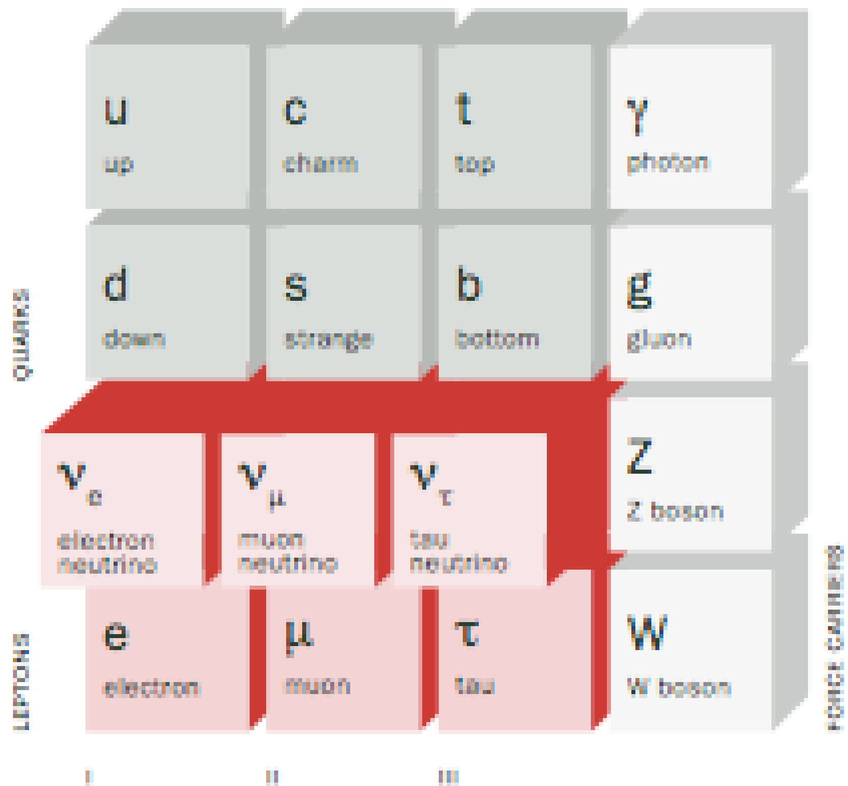
- $\mathcal{L}^D = - m_D (\bar{\nu}_L \nu_R + \bar{\nu}_R \nu_L)$

- So far we know that the neutrino is left-handed and the antineutrino right-handed.

- Do the other two states exist in nature?

- Why are the neutrino masses so much smaller than the charged lepton masses, even in the same generation?

Generations



Majorana mass terms

- In 1937 Majorana discovered that a massive neutral fermion can be described by a spinor ν with only two independent components
- if $\nu = \nu^c$ (charge conjugation)
- Then, the neutrino is its own anti-particle
  (--> importance of neutrinoless double beta decay) and
- $\nu_R = \nu^c_L \qquad \nu_L = \nu^c_R$
- $L^D = - m_D (\overline{\nu_L}\nu_R + \overline{\nu_R}\nu_L)$ ----> $L^M_L = -(1/2)\, m_M (\nu^c_L \overline{\nu_L} + \nu_L \overline{\nu^c_L})$
- Can have a mass term without additional right-handed neutrinos.
- Just need one helicity state for the neutrino, and the opposite one for the antineutrino.
- If a right-handed neutrino, **n**, exists can treat it in the same way
- $L^M_R = -(1/2)\, m_R (\overline{n_R} n^c_R + \overline{n^c_R} n_R)$

General masses

The general mass term can then be written as:

$$L^{\text{Mass}} = L^{\mathbf{D}} + L^{\mathbf{M}}_{\mathbf{L}} + L^{\mathbf{M}}_{\mathbf{R}}$$

$$L^{\text{Mass}} = -\mathbf{m_D}(\overline{\nu}_{\mathbf{L}}\nu_{\mathbf{R}} + \overline{\nu}_{\mathbf{R}}\nu_{\mathbf{L}}) - \frac{\mathbf{1}}{\mathbf{2}}(\overline{\nu}^{\mathbf{c}}_{\mathbf{L}}\nu_{\mathbf{L}} + \overline{\nu}_{\mathbf{L}}\nu^{\mathbf{c}}_{\mathbf{L}})$$

$$-\frac{\mathbf{1}}{\mathbf{2}}(\overline{\mathbf{n}}_{\mathbf{R}}\mathbf{n}^{\mathbf{c}}_{\mathbf{R}} + \overline{\mathbf{n}}^{\mathbf{c}}_{\mathbf{R}}\mathbf{n}_{\mathbf{R}})$$

$$L^{\text{Mass}} = -\frac{\mathbf{1}}{\mathbf{2}}\begin{pmatrix} \overline{\nu}^c_L & \overline{n}_R \end{pmatrix}\begin{pmatrix} m_L & m_D \\ m_D & m_R \end{pmatrix}\begin{pmatrix} \nu_L \\ n^c_R \end{pmatrix} + \mathbf{h.c.}$$

To find the definite masses of the neutrinos we have to diagonalize with a unitary transformation to end up with:

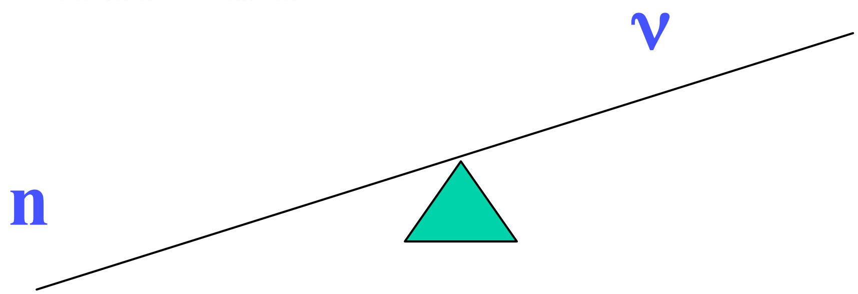
$$\begin{pmatrix} m_1 & 0 \\ 0 & m_2 \end{pmatrix}$$

See-saw mechanism

$$m_{2,1} = \frac{1}{2}\sqrt{4m_D^2 + (m_R - m_L)} \pm \frac{m_R + m_L}{2}$$

If $m_R >> m_D \quad and \quad m_L \sim 0$:

$$m_1 = \frac{m_D^2}{m_R - m_L} - m_L \quad \text{and} \quad m_2 = m_R$$



- The larger m_R the smaller m_1 ----> See-saw mechanism.
- Usually one assumes m_D to be of the order of the quark or charged lepton masses.
- m_R is assumed to be of the order of some unification scale.
- For a large m_R, m_1 and m_2 are quite different.
- m_2, the right-handed neutrino, then becomes very heavy and plays no role in our present energy range.

Estimate of Heavy neutrino mass

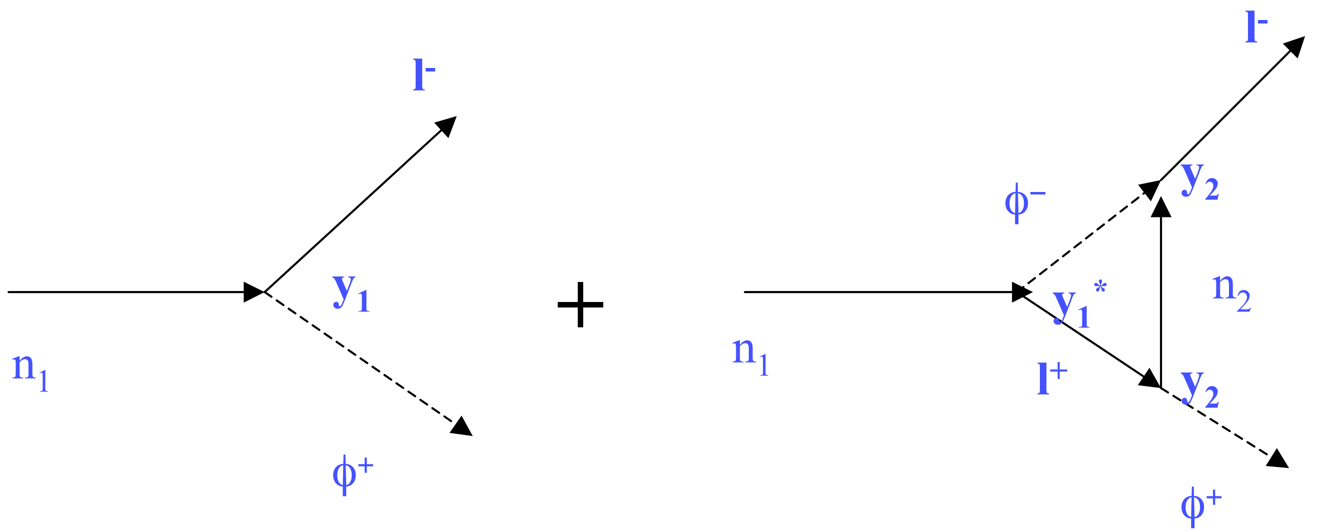
- Reverse the argument.
- Use the lower limit on at least one $m_\nu = 0.05$ eV
- Set $m_1 = m_\nu = m_D^2/m_n$
- $m_n = m_D^2/m_1 = m_{(top)}^2/ m_\nu = (170 \text{ GeV})^2/(0.05 \times 10^{-9})$
- 0.6×10^{15} GeV
- Near GUT scale

Matter-Antimatter asymmetry

- We assume that at “the beginning” the universe was matter/antimatter symmetric
- Why is the universe that we know now overwhelmingly matter ?
- This can only be explained by CP violation.
- The CP violation observed in quarks is too small.
- Can it be in the leptons?
- In the see-saw mechanism the Heavy and light neutrinos are Majorana.
- So in early Universe **n** can decay to
- **n** ---> $l^+ \phi^-$ or **n** ---> $l^- \phi^+$ ϕ : Higgs particles
- If $\Gamma\,(l^+ \phi^-) \neq \Gamma\,(l^- \phi^+)$ ------> Unequal leptonic matter and antimatter.
  Through further interactions this can be transferred to baryons.

Can CP violation occur?

- Need two diagrams leading to same final state



Direct **and via an** **additional interaction**

Amp(n_1 --> $l^+ + \phi^-$) = Amp (n_1 --> $l^- + \phi^+$, with y --> y*)

Complex y_i results in CP violation

Can CP violation occur?

- $\Gamma(n_1 \text{ --> } l^- + \phi^+) = |ay_1 + by_1^* y_2^2|^2$
- $\Gamma(n_1 \text{ --> } l^+ + \phi^-) = |ay_1^* + by_1 y_2^{*2}|^2$
- **Different if imaginary part is ≠ 0**
- **This produces different amounts of charged l^+ and l^-.**
- **CP violation.**
- **This transforms to baryon asymmetry via lepton - hadron interactions**
- **Leptogenesis**

CP in light neutrinos

- To explain the baryon asymmetry via leptogenesis we need CP violation in Heavy neutrinos.
- But we cannot access them
- The best we can do is study CP violation in light neutrinos.
- If we DO find it it **DOES NOT** guarantee that there is also CP violation for the Heavier states.

Choices for a new neutrino complex

- A new super-intense "standard" ν beam

- A beta-beam:

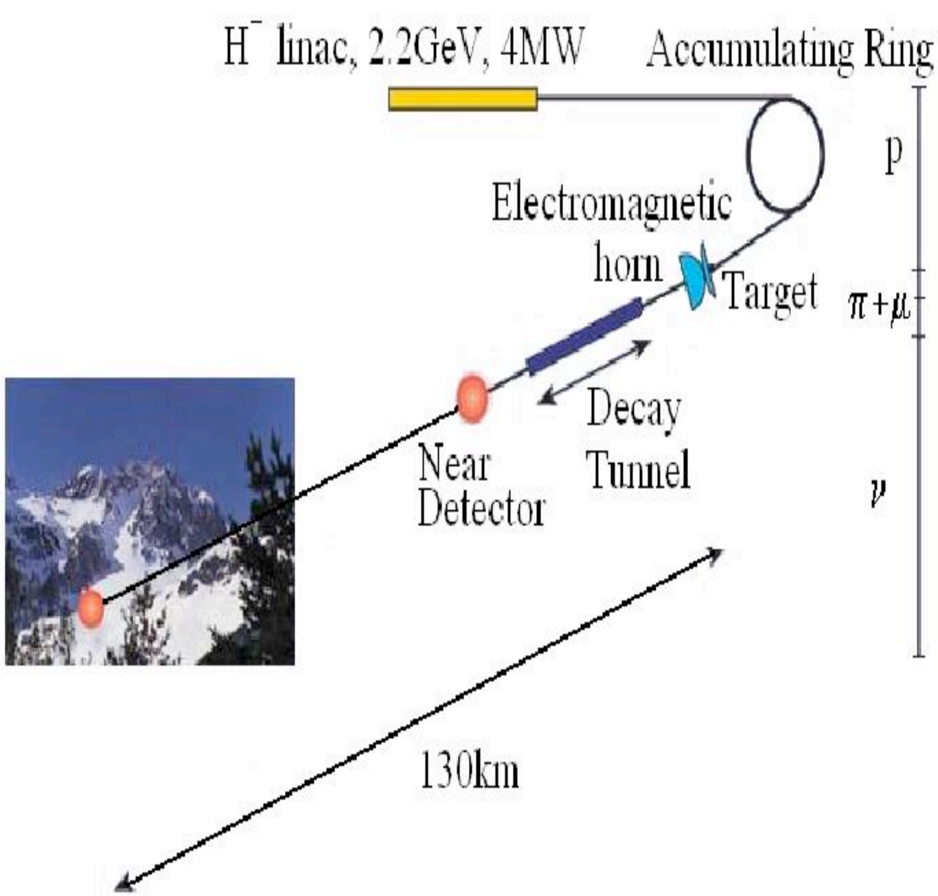
  ν beam produced by the β-decay of radioactive ions.

- A neutrino factory:

  ν beam produced through the decay of stored muons.

Superconducting Proton Linac: ν_μ beam.

Classic accelerator ν_μ beam. Intrinsic ν_e component results in a background.



- Power : **4 MW**
- Kin. Ener. : **Up to 5 GeV**.
- Shorten pulse length. (Reduce atmospheric **ν**'s contam.)
- Target: **Liquid Mercury Jet** to cope with stress due to high flux.
- Focusing: **Horn and Reflector**
- Detector: New lab in **Fréjus** tunnel
- (Safety gallery approved April 2006: **opportunity**)
- Distance: **130km**
- Neutrino energy to be at oscillation maximum for $\Delta m_{23}^2 = 2.4 \times 10^{-3}\ eV^2$ **260 MeV → 350 MeV more sensitive**

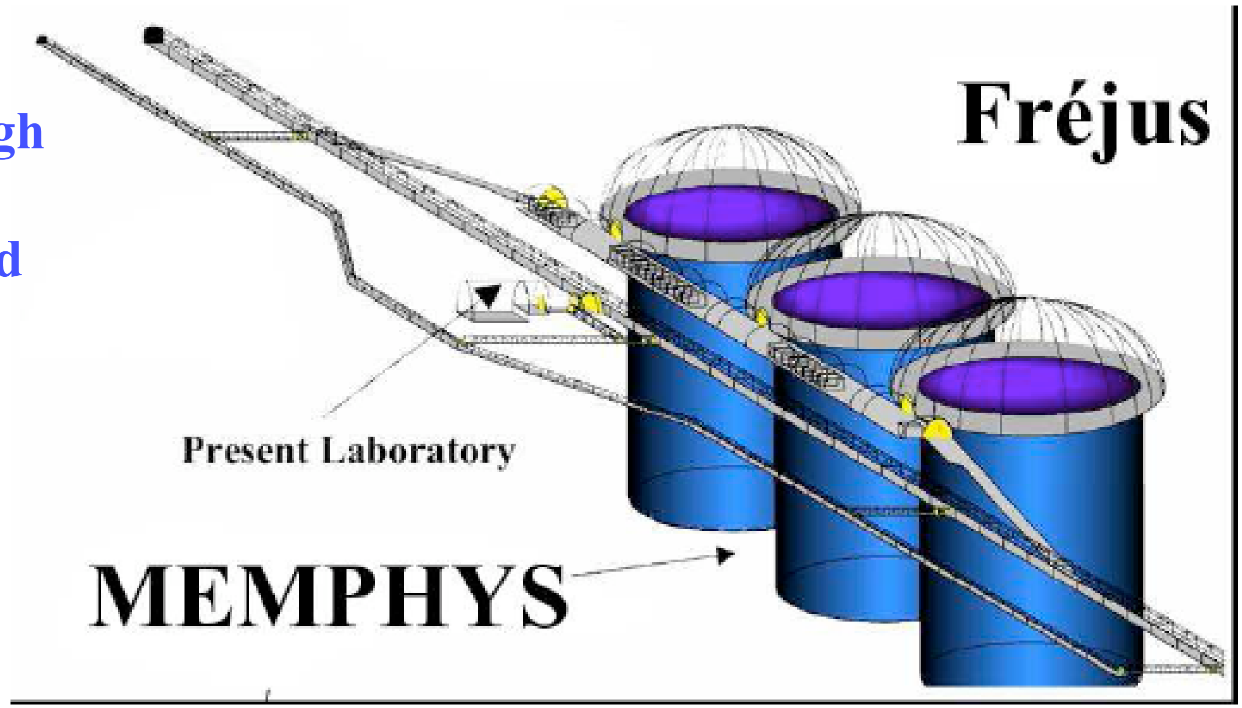
Near detector also needed, as in all schemes.

MEMPHYS at Fréjus

Up to 5 shafts possible
Each 57m diam., 57m high

For most studies assumed
3 x 145 ktons.
Water Cerenkov

Depth: 4800 m.w.e



Per shaft: 81,000 12” PMT’s → 80 M€ including electronics
+80 M€ for civil engineering.

Standard scenario: mix neutrino and antineutrino running

- 3.5 and 4.5 GeV proton beam
- 260 and 350 MeV options

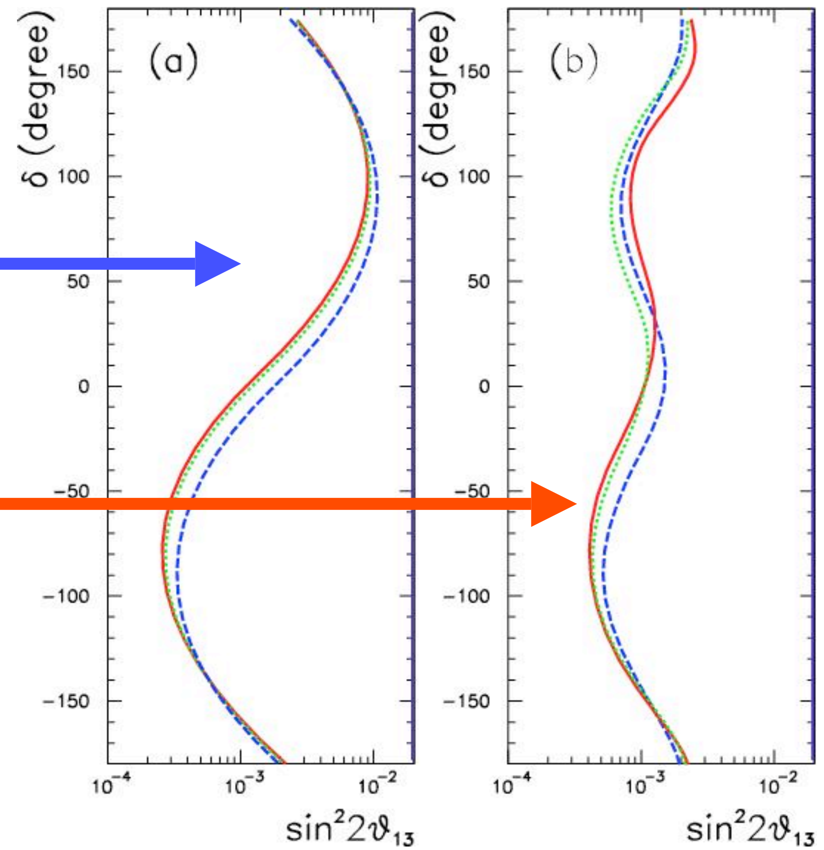
- 5 years of ν running.

- 2 years of ν running and

  8 years of $\bar{\nu}$ running

The curves flatten

90% CL Limit on $\sin^2 2\theta_{13}$ → **about 0.001.**



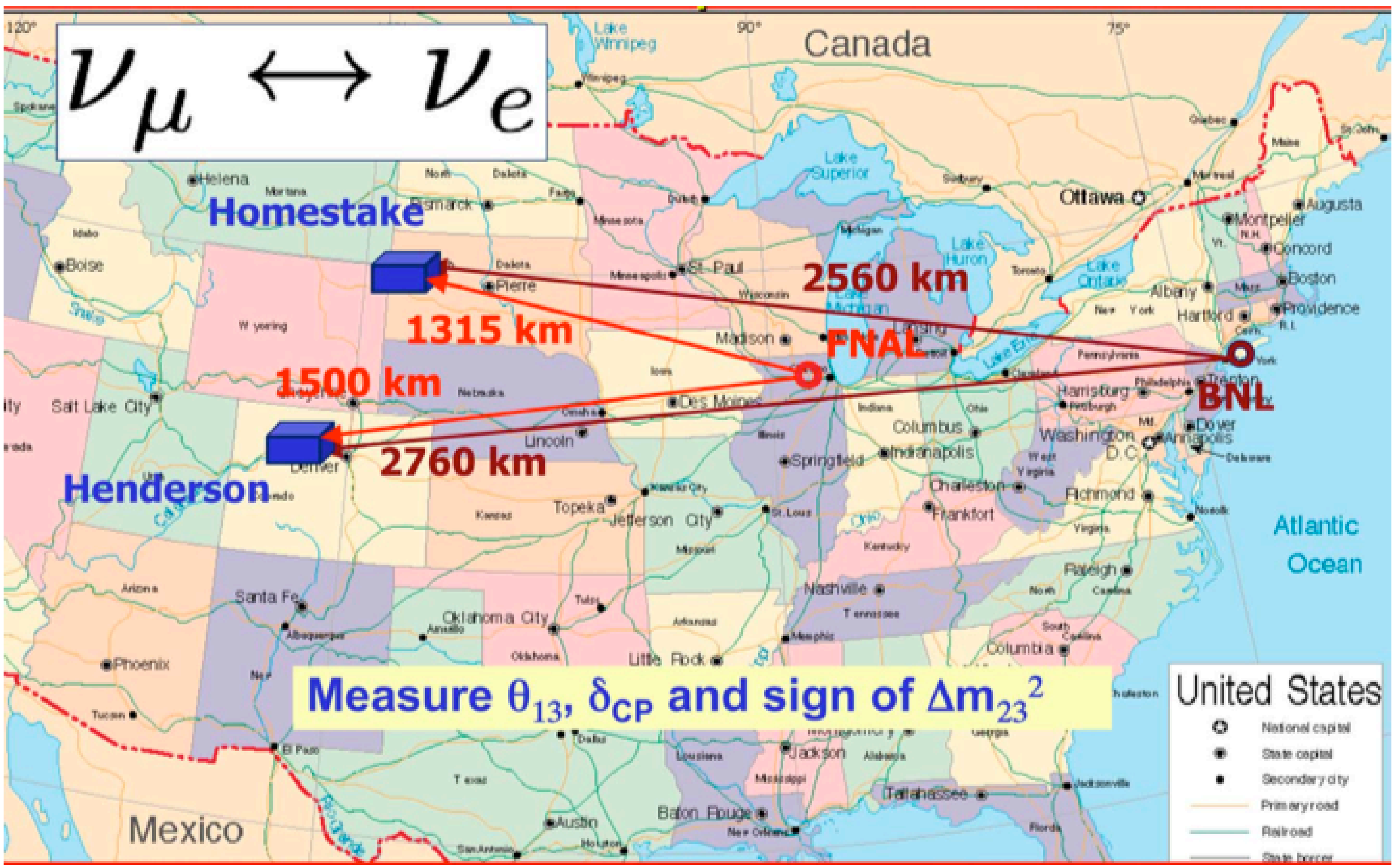
Characteristics

- Limit on **$\sin^2 2\theta_{13}$ about 0.001.**

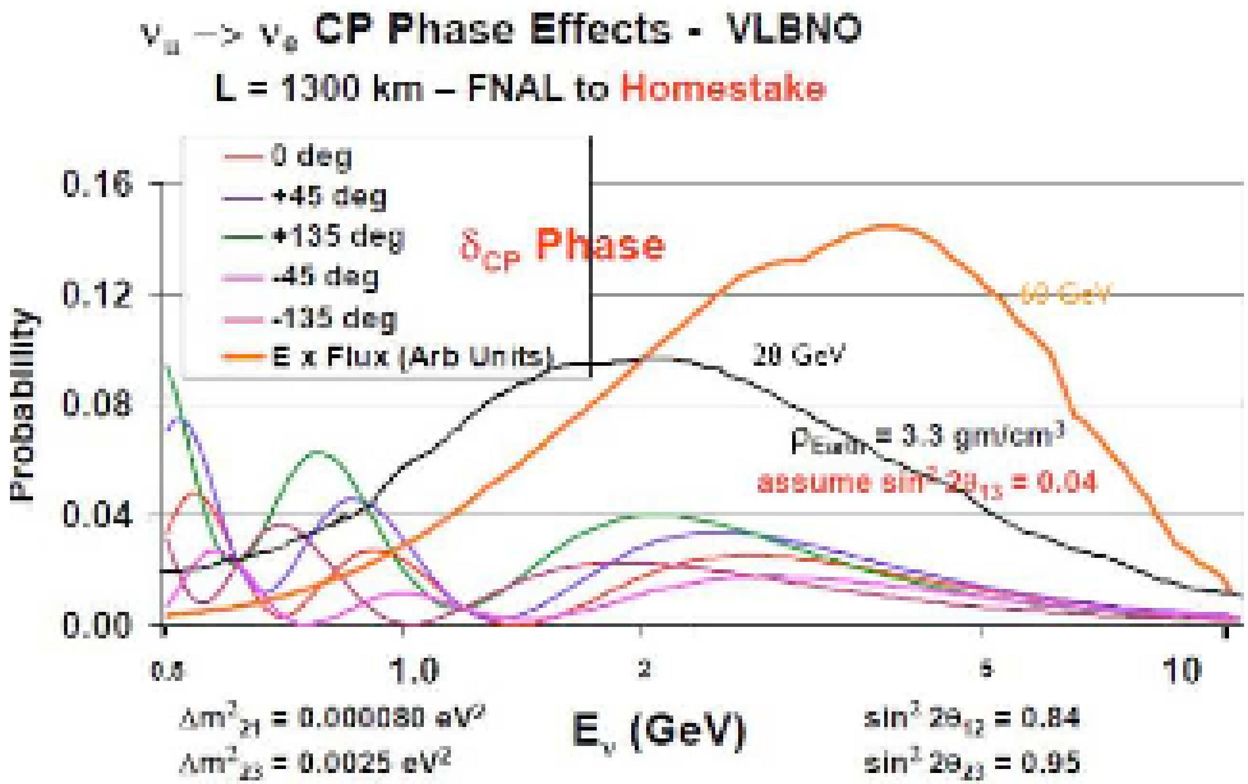
  Note this is an order of magnitude more sensitive than presently planned experiments.

- Short baseline and low energy excludes studying the mass hierarchy.

Very long baseline beam in the US.

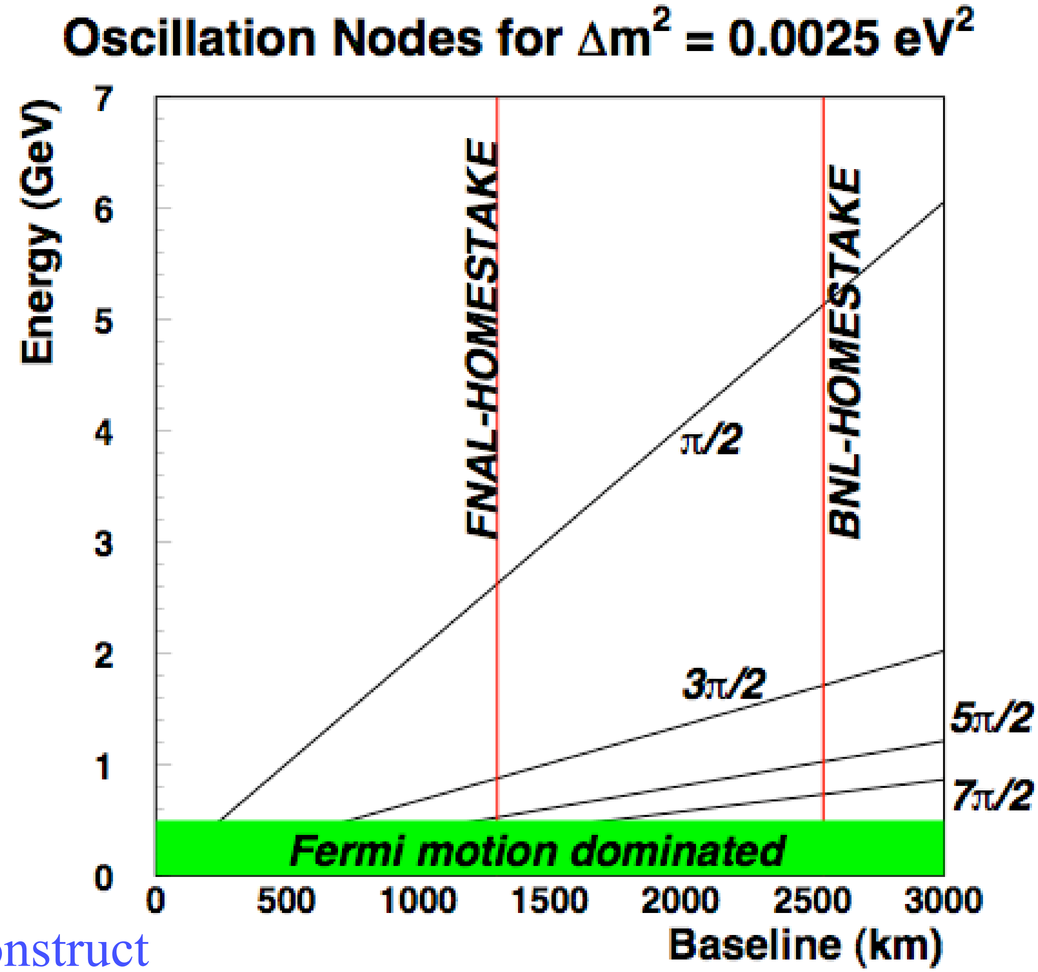


Many oscillation maxima

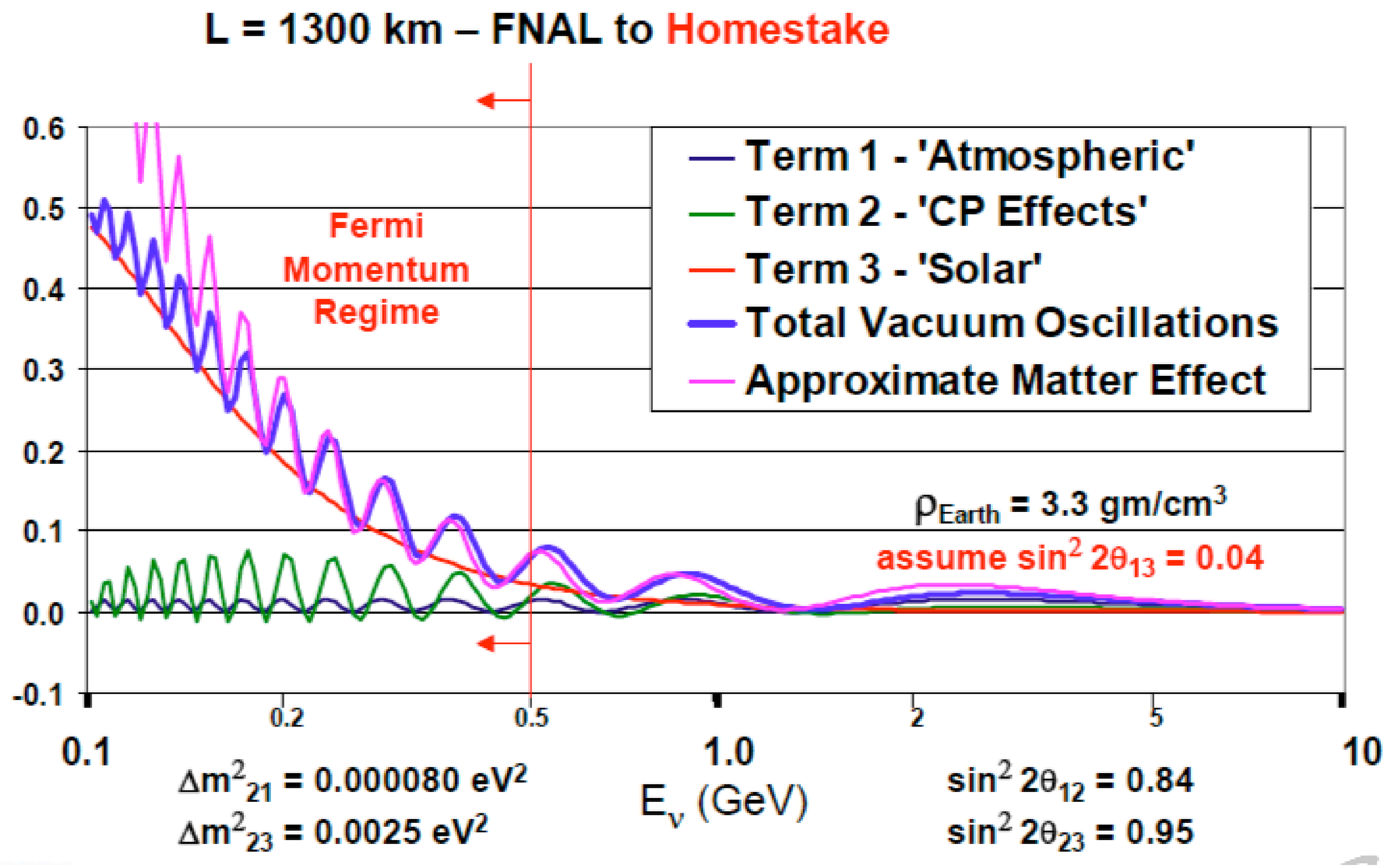


- The patern of oscillation differs from one maximum to the next
- For different values of δ_{CP}.
- Measuring over many maxima resolves ambiguities.

How many oscillations can we see?

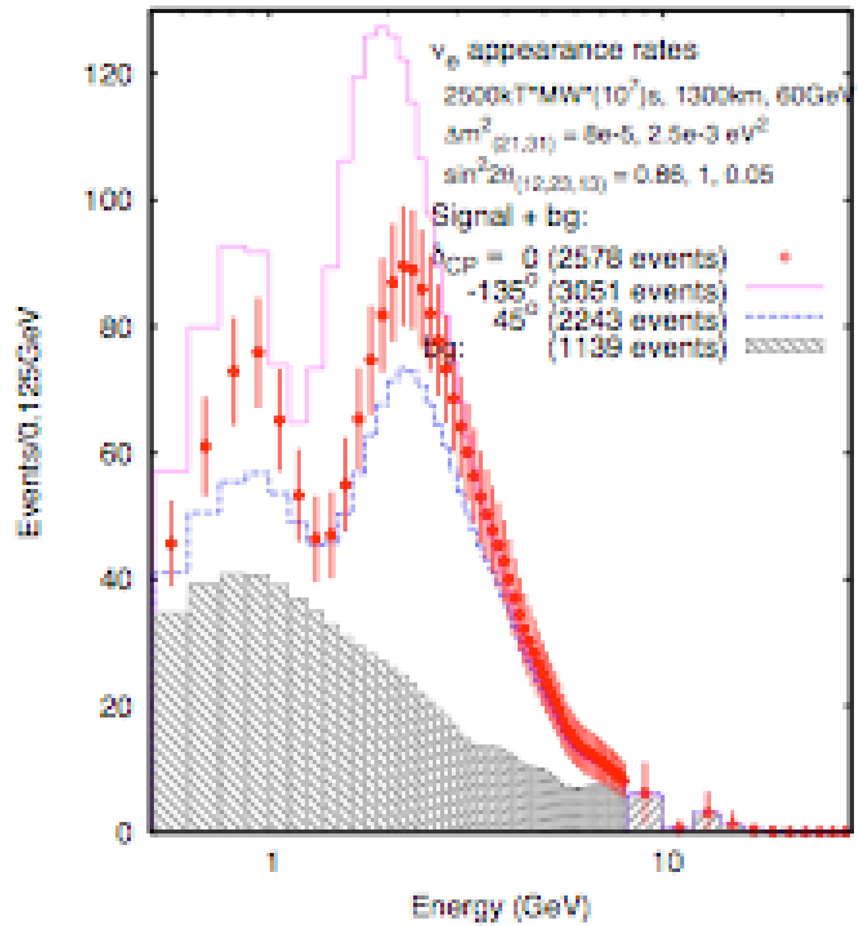


At Low energy difficult to reconstruct
Incoming neutrino energy
Because of motion of target nucleon
In Fermi sea.

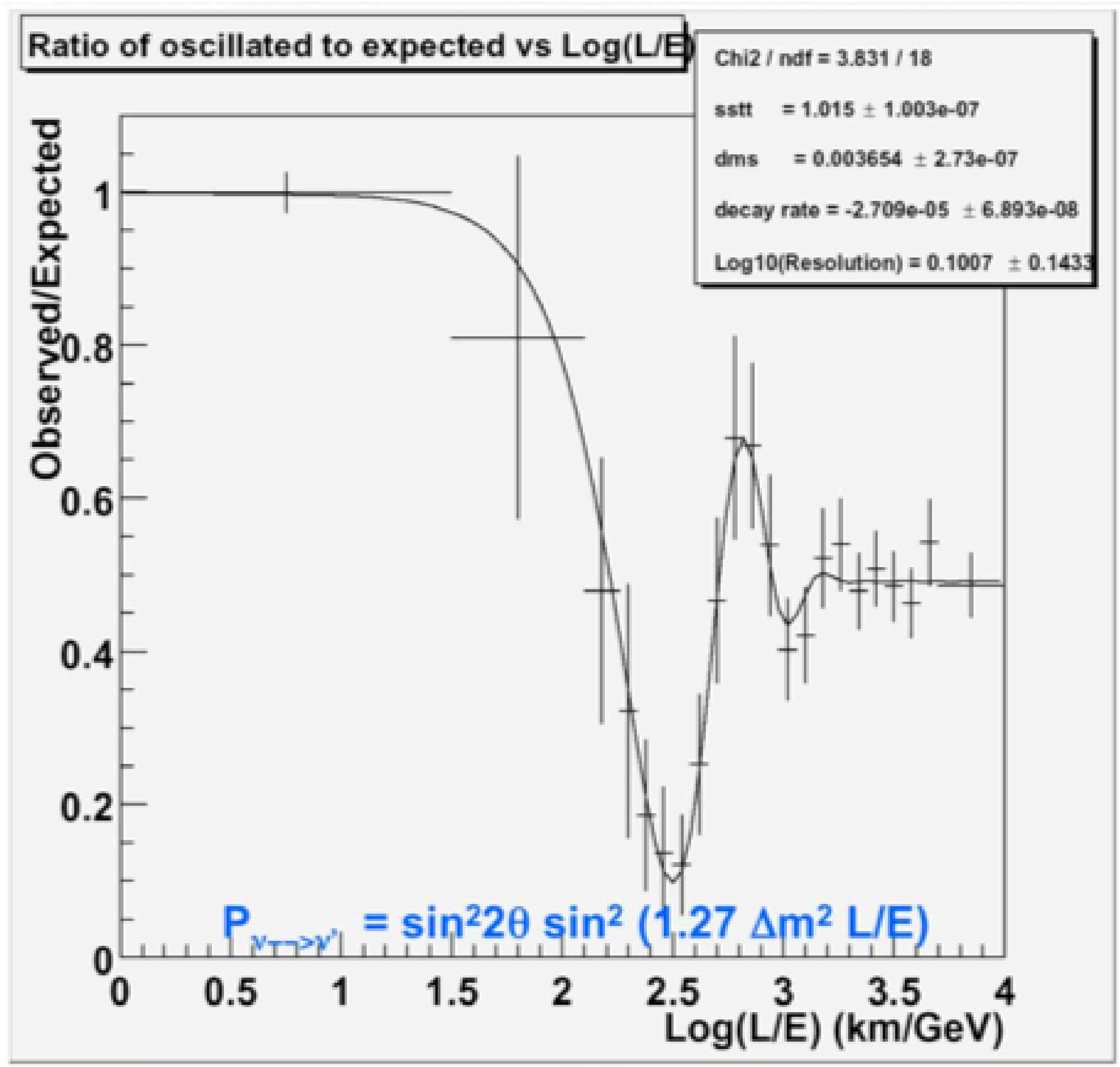


L = 1300 km – FNAL to Homestake
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
Fermi
Momentum
Regime
Term 1 - 'Atmospheric'
Term 2 - 'CP Effects'
Term 3 - 'Solar'
Total Vacuum Oscillations
Approximate Matter Effect
ρEarth = 3.3 gm/cm3
assume sin2 2θ13 = 0.04
0.2
0.5
2
5
0.1
1.0
10
Δm2 21 = 0.000080 eV2
Δm2 23 = 0.0025 eV2
Eν (GeV)
sin2 2θ12 = 0.84
sin2 2θ23 = 0.95

ν_e appearance rates



ν_μ disappearance

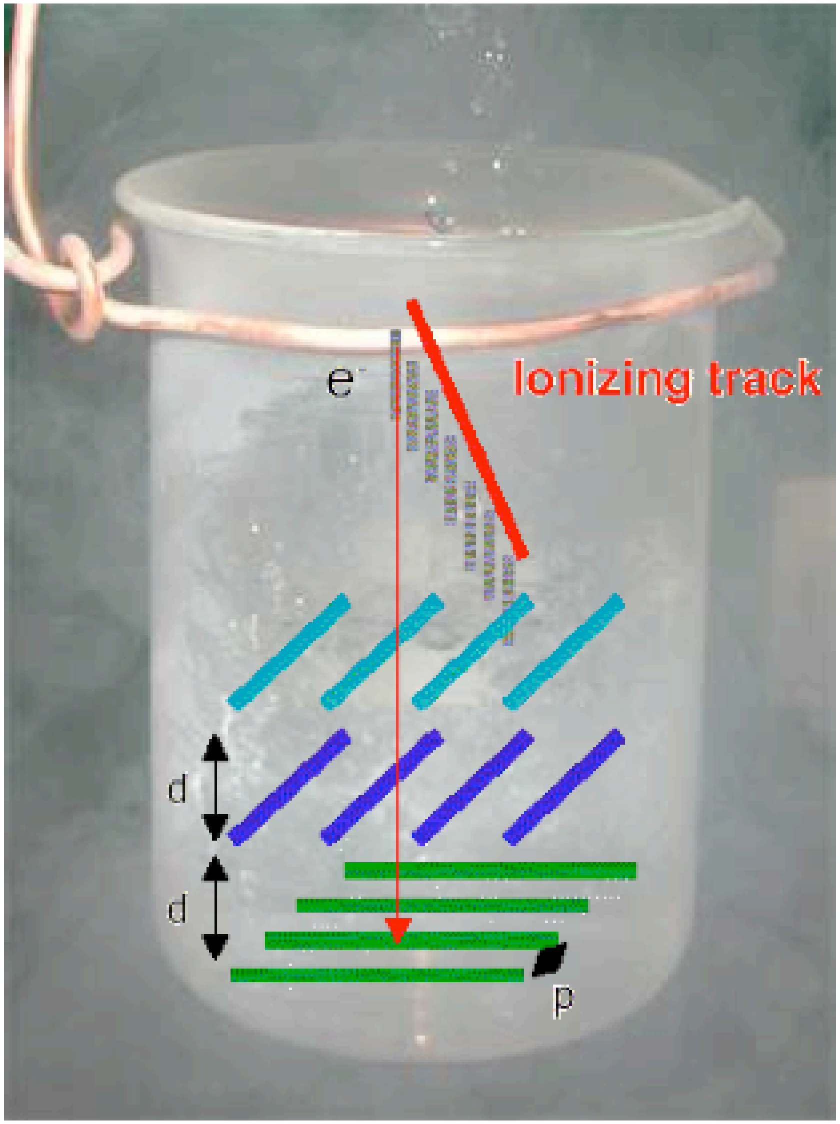


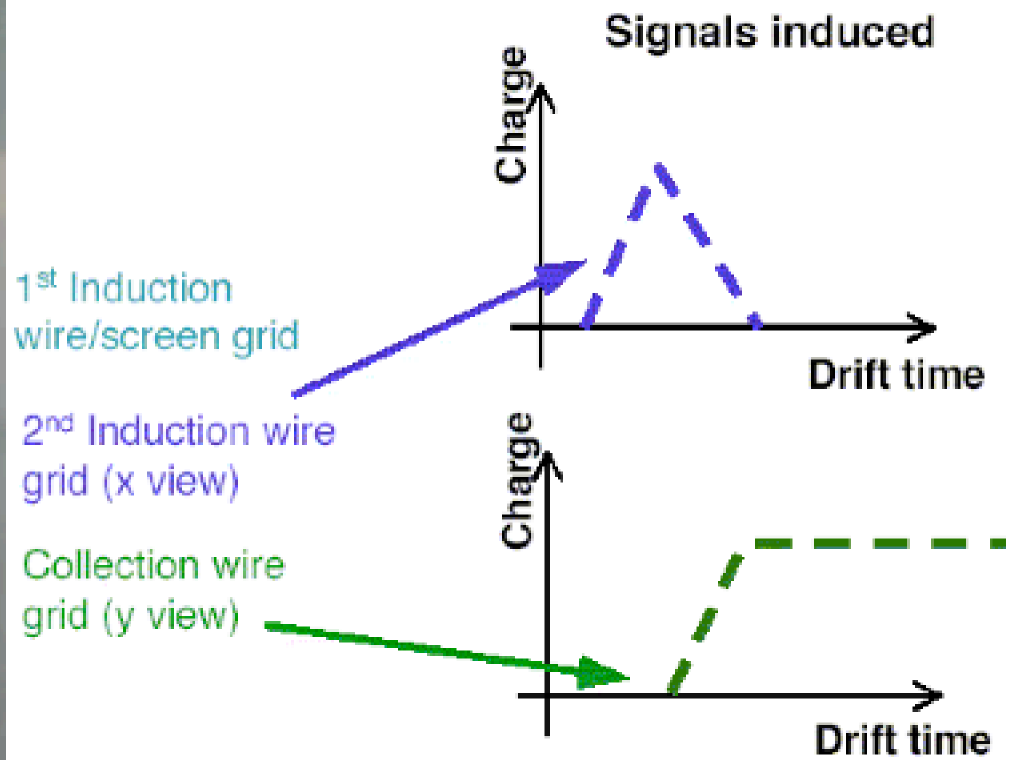
~7 years of UNO exposure

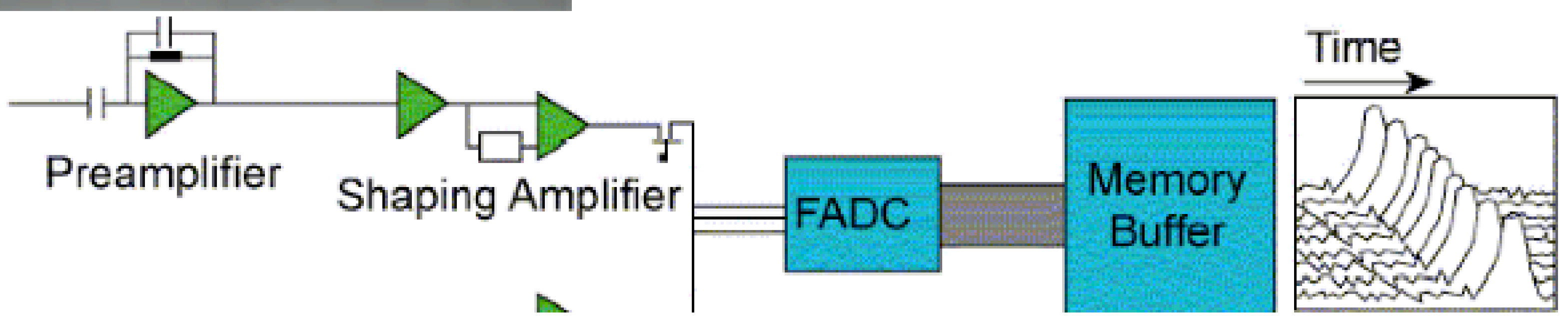
(Δm^2 = 0.003 eV^2, $\sin^2 2\theta$ = 1.0)

- 1 muon w/ E > 1GeV or
- E_{vis} (μ) > 0.5 E_{vis} (total)
- removal of horizontal events

Liquid Argon TPC

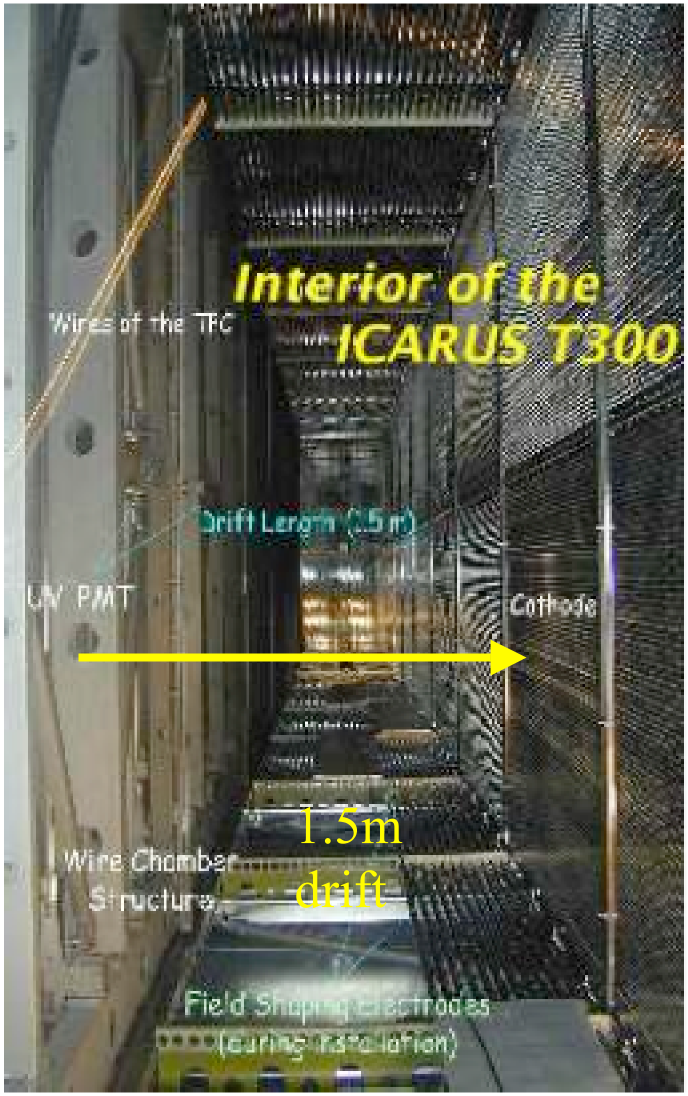




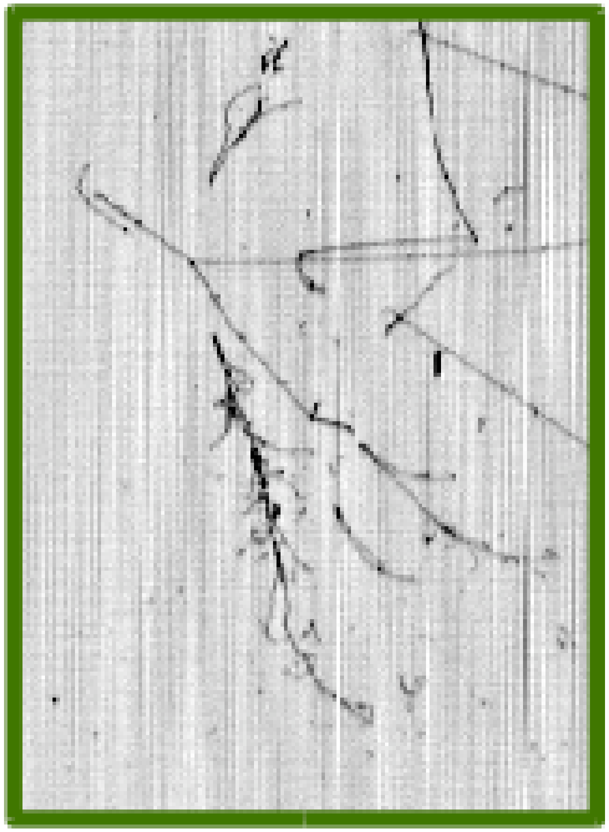


Liquid Argon Time Projection Chamber (TPC)

- Charged particle ionizes Argon
- Electrons drift over 1.5m.
- Need very pure Argon. If not electrons recombine and never reach electrodes.
- Light emitted by ionization recorded by photmultipliers
- Provides a "T0". Event time



Very detailed information



VLBL beam in the US: Expectations

- Liquid argon or water Cerenkov?
- Liquid argon can reject π^o's because it recognizes them well by observing that there are 2 photons and that these 2 photons do not come from main vertex.
- 100 ktons Liquid Argon detector favoured because of high efficiency.
- 3σ sigma sensitivity to $\sin^2 2\theta_{13} = 0.002$
- 3σ sensitivity to non-zero δ_{CP} down to $\sin^2 2\theta_{13} = 0.005$.
- Resolution of mass hierarchy down to $\sin^2 2\theta_{13} = 0.006$.

Beta beams

- Idea introduced by Piero Zucchelli.
- Accelerate radioactive ions decaying via β^+ (^{18}Ne) or β^- (^{6}He).

- $^{18}Ne \rightarrow {}^{18}F + e^+ + \bar{\nu}_e$
- $^{6}He \rightarrow {}^{6}Li + e^- + \nu_e$

- Because of Lorentz boost, the decay electron neutrinos or antineutrinos will be focused forward into a narrow beam.
- Look for: Appearance of $\bar{\nu}_\mu$ or ν_μ using CC interactions → μ^+ **or** μ^-
- Advantages:
- "Clean" beams with no intrinsic ν_μ component.
- Energy of beam tunable through acceleration of ions.

Beta beams

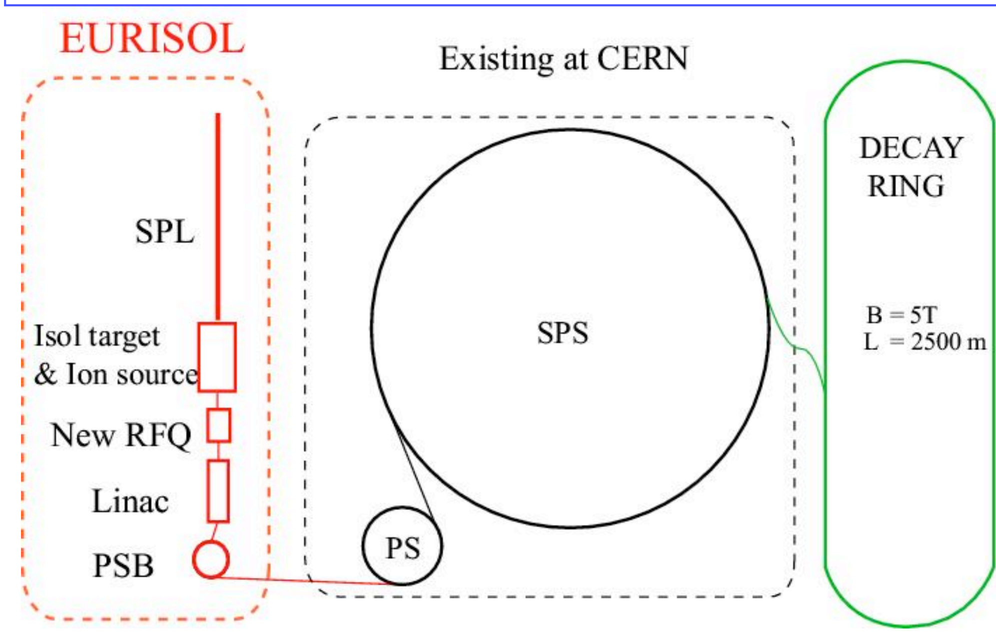
- Accelerate protons in SPL
- Impinge on appropriate source.
- Bunch resulting ions (atmospheric **ν's** !)
- Accelerate ions in CERN PS and SPS.
- Store in decay ring. 8 bunches.
- $^{6}He \rightarrow \, ^{6}Li + e^{-} + \nu_e$
- $^{18}Ne \rightarrow \, ^{18}F + e^{+} + \bar{\nu}_e$

Production rate
Still 20 times too low. Potential solution in sight

Stored together if $\gamma(^{18}Ne) = 1.67 \, \gamma(^{6}He)$.

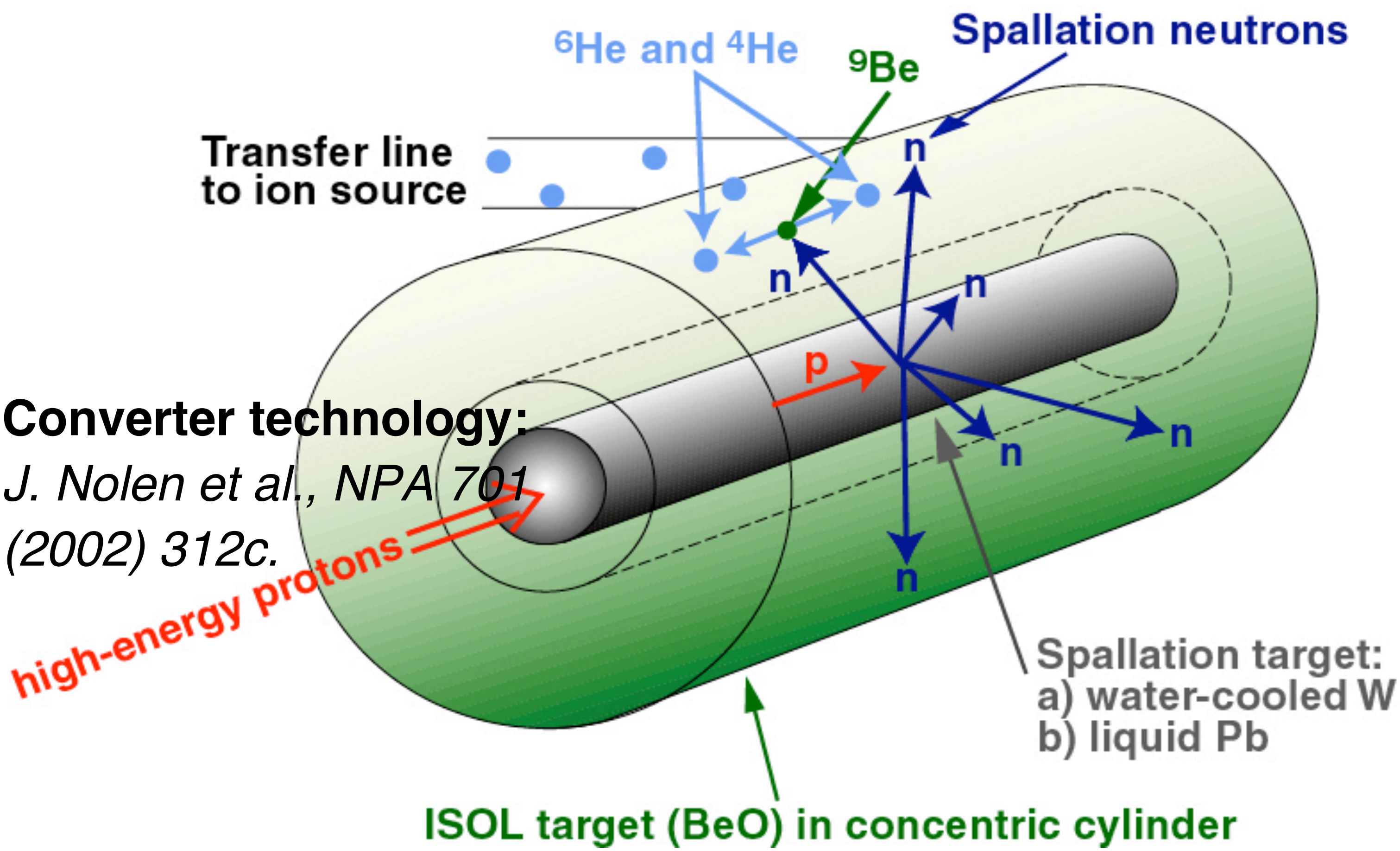
But could also be stored separately

Detector: Same as for SPL (Frejus)



Very attractive because:
- Front end → Eurisol
- PS and SPS exist.

^{6}He production by ^{9}Be(n,α)



Converter technology:

J. Nolen et al., NPA 701 (2002) 312c.

need 100μA at 2.0 GeV for needed beta-beam flux

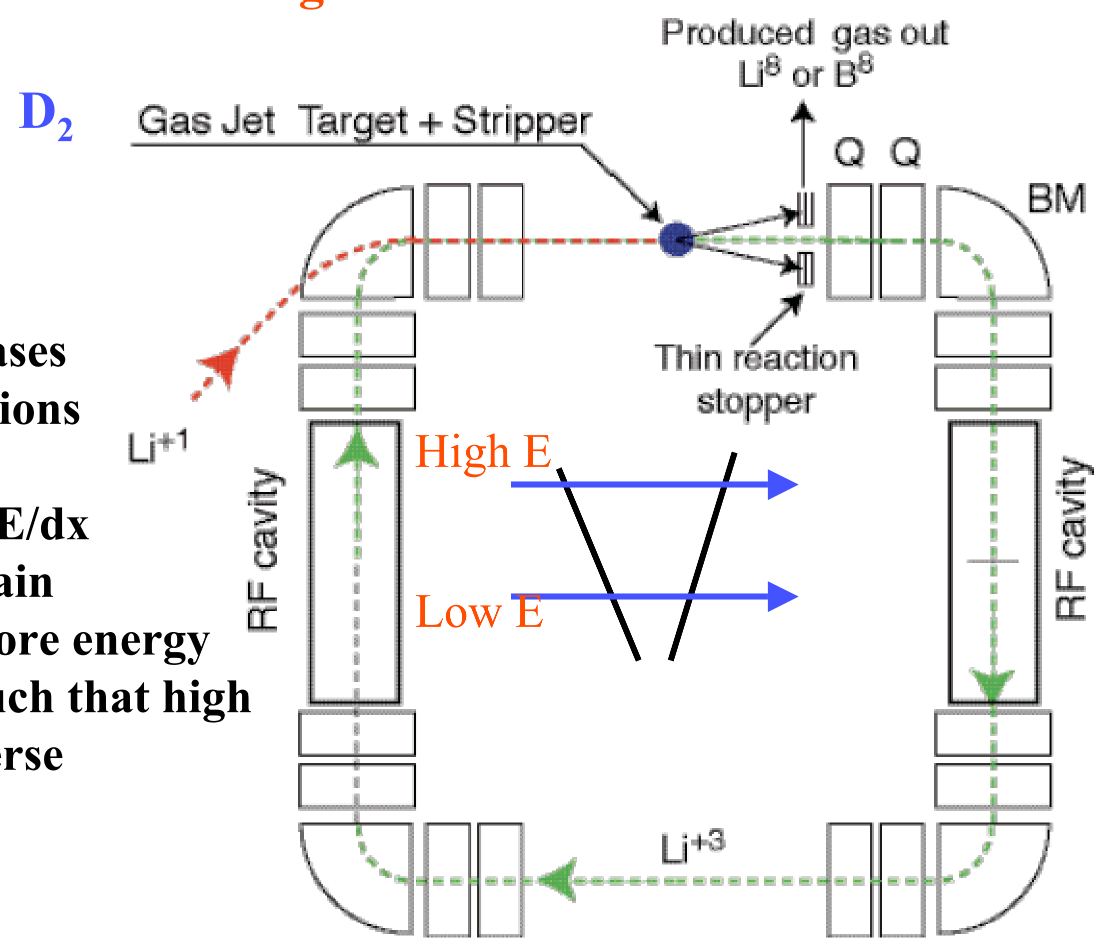
For ^{18}Ne: Proton beam into Magnesium oxide: Produce ^{18}Ne directly by spallation
Source must be hot for ^{18}Ne to diffuse out. Cannot cool it. Limits beam and rate.

Production

	Nominal production rate [ions/s]	Required production rate [ions/s]	Missing factor
6He	2×10^{13}	2×10^{13}	1
18Ne	8×10^{11}	1.9×10^{13}	24

•Major challenge for ^{18}Ne But new production method: C. Rubbia et al.
Production ring with ionization cooling

- D_2 gas jet in storage ring.
- Inject ions (^{19}F) and store
- Go through jet repeatedly increases probability to form radioactive ions
- Regain energy loss with RF
- High energy ions have smaller dE/dx than low energy ones. But will gain same amount from RF→even more energy
- To compensate shape jet (fan) such that high energy ions (larger radius) traverse more material.
- → **Longitudinal cooling.**



CP δ sensitivity for γ = 60,100

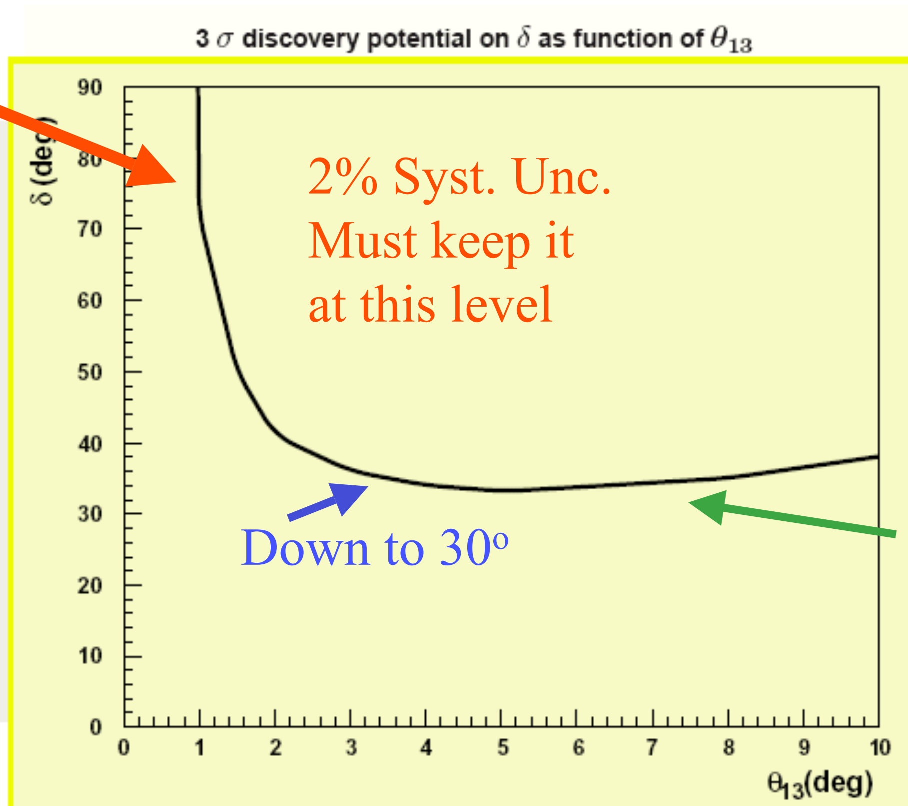
E_ν= (3 MeV) x γ = 200 – 500 MeV

M. Mezzetto SPSC Villars

Beta Beam leptonic CP violation discovery potential

Statistics limited

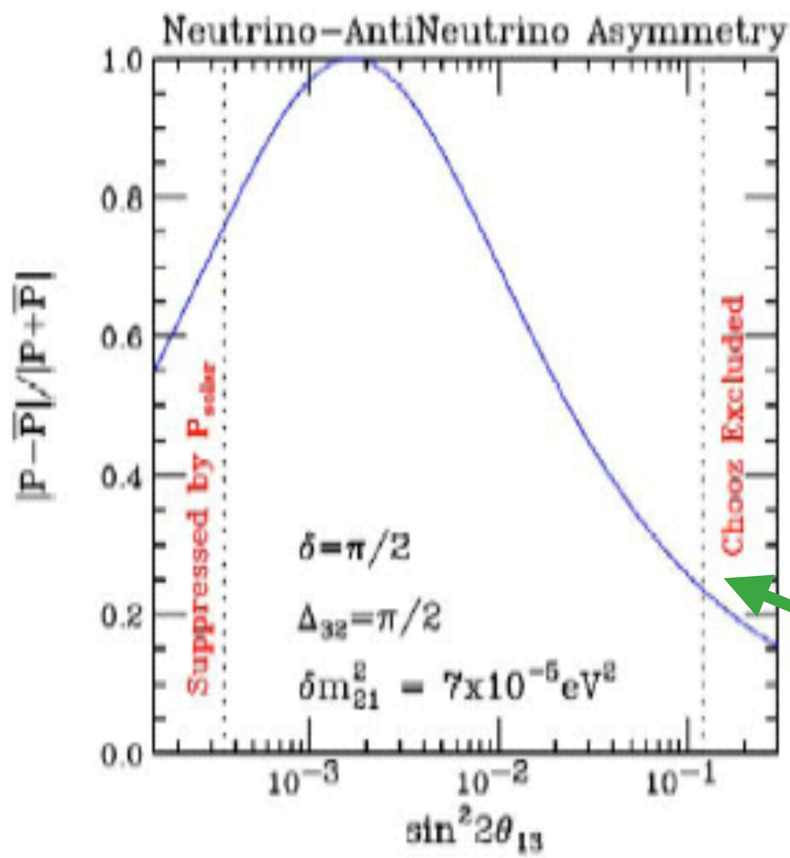
Computed with:
$\gamma(^6\mathrm{He}) = 60$
4400 kton/year exposure
Systematic Err. = 2%
$\Delta m^2_{23} = 2.5 \cdot 10^{-3} eV^2$
$\Delta m^2_{12} = 7.1 \cdot 10^{-5} eV^2$
$\sin^2 2\theta_{23} = 1$
$\sin^2 2\theta_{12} = 0.8$
sign(Δ m^2) = +1
$\sigma(\Delta m^2_{23}) = 10^{-4} eV^2$
$\sigma(\Delta m^2_{12}) = 10\%$
$\sigma(\sin^2 2\theta_{23}) = 1\%$
$\sigma(\sin^2 2\theta_{12}) = 10\%$
θ_{13}-δ degeneracy accounted for
Octant and sign(Δ m^2) degeneracies not accounted for.



Why doesn't the sensitivity Continue to decrease with increasing θ_{13}?

2.9 x 10^{18} ^{6}He ions and 1.2 x 10^{18} ^{18}Ne ions per year decaying in straight sections

Flat sensitivity?



CP violation Asymmetry decreases with increasing θ_{13}

Optimize to higher energies

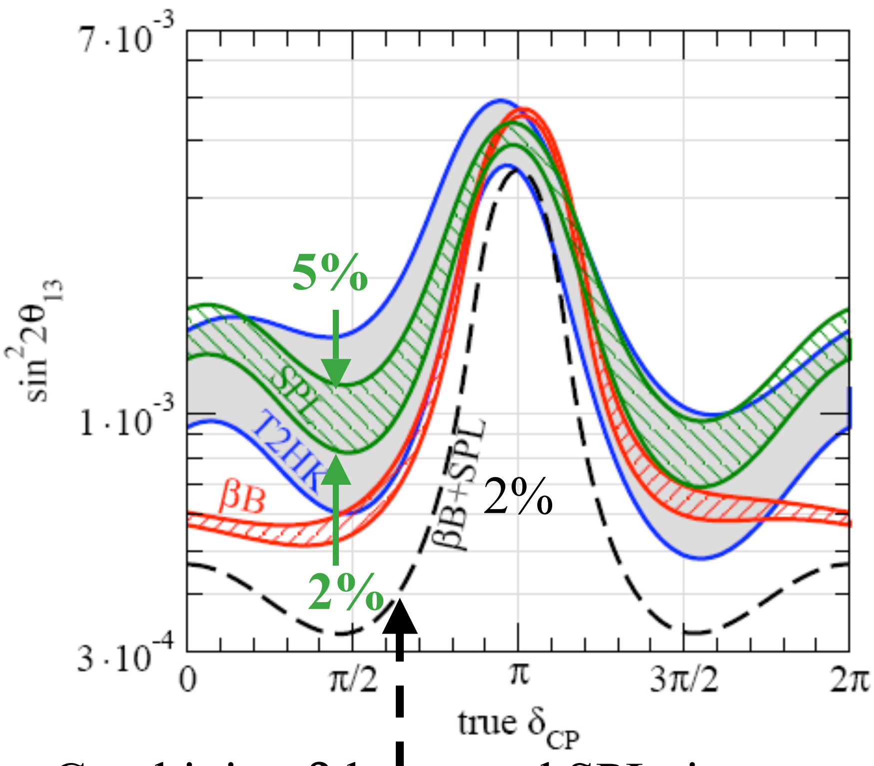
hep/ph/0503021 and M. Mezetto.

- Store ions separately.
- Optimize γ for a detector at Fréjus (**130km**). **γ (60,100) → γ (100-120,100-120)**
- **Minimum δ for which CP violation can be observed at 3σ goes down to 15^o.**
- The SPL is used only a fraction of its time to produce radioactive ions.
- Can be used the rest of the time to directly produce a neutrino beam.
- The same detector can be exposed to both

SPL, βbeam (γ=100), SPL+βbeam comparisons

- Mass: Each detector: 440 ktons ,
- Running time: SPL: 2 yrs **ν** + 8 yrs $\bar{\nu}$ **.** Beta-beam: 5 yrs + 5 yrs.
- Systematics: 2% - 5%.

3σ discovery potential for $\sin^2 2\theta_{13}$



J-E. Campagne et al hep/ph0603172 v1

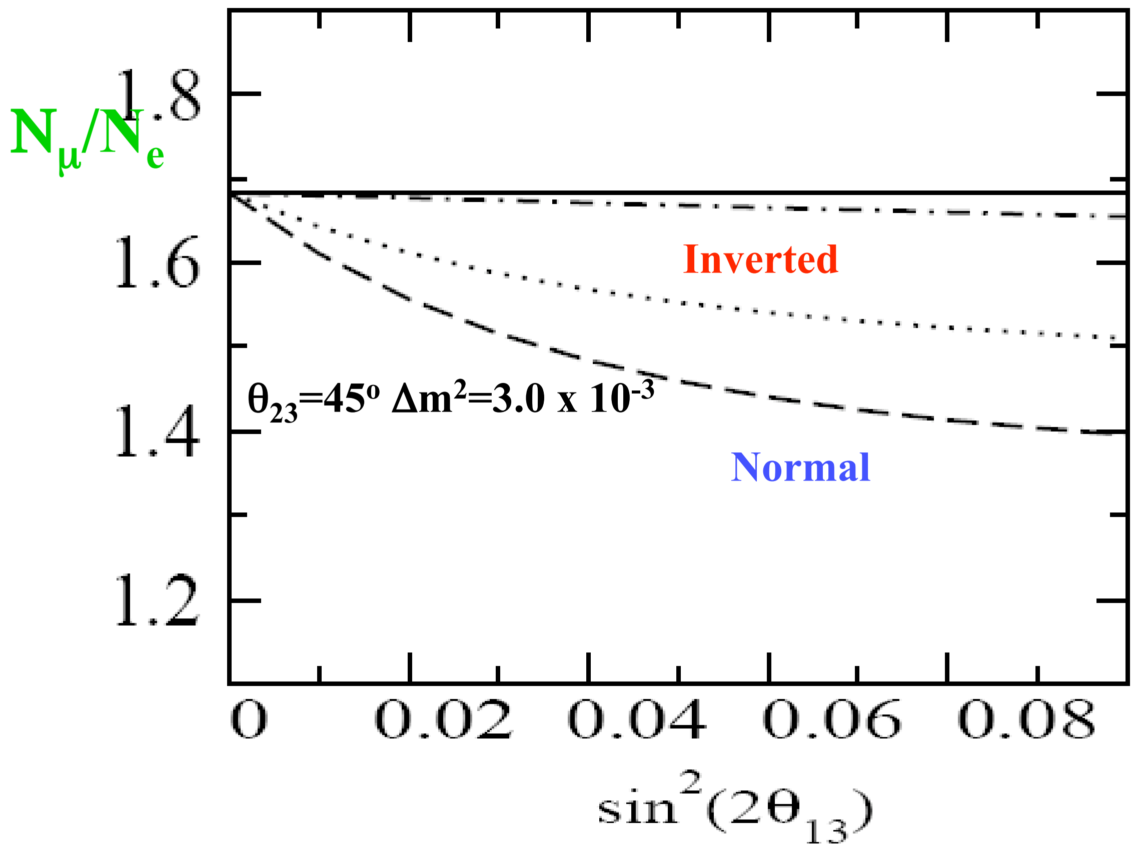
Combining **β** beam and SPL, in same detector
Improves sensitivity

Can the Mass Hierarchy be determined with SPL or β beams?

hep-ph/0305152
hep-ph/0603172

Too short a baseline, but…..

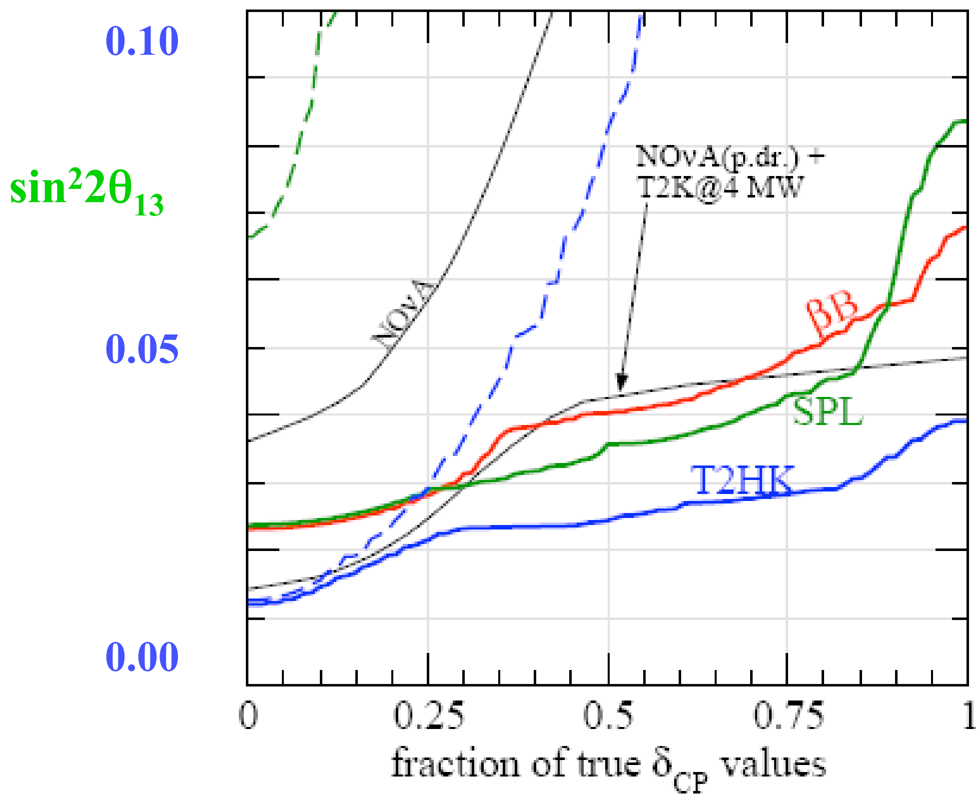
Multi-GeV (2-10 GeV) Atmospheric neutrinos going through the core of the Earth (cos θ: 0.4-1.0) are particularly affected by Matter effects And are therefore sensitive to the Mass hierarchy.



Use Atmospheric observed in MEMPHYS, HK (huge increase in mass and statistics) in conjunction with SPL, beta and T2HK beams. Makes up for small matter effects due to low energy of **β** beams.

Can the Mass Hierarchy be determined with SPL or β beams?

hep-ph/0305152
hep-ph/0603172



With Atmospheric

Use ATM observed in MEMPHYS, HK
in conjunction with SPL, beta and T2HK beams.
Makes up for small matter effects
due to short baseline of **β** beams.

Improves the fraction of δ_{CP} over which the mass hierarchy can be determined at 2 σ

New idea: Electron capture in ^{150}Dy

J. Bernabeu et al hep-ph/0605132

Instead of beta decays use:
Atomic electron captured by proton in nucleus

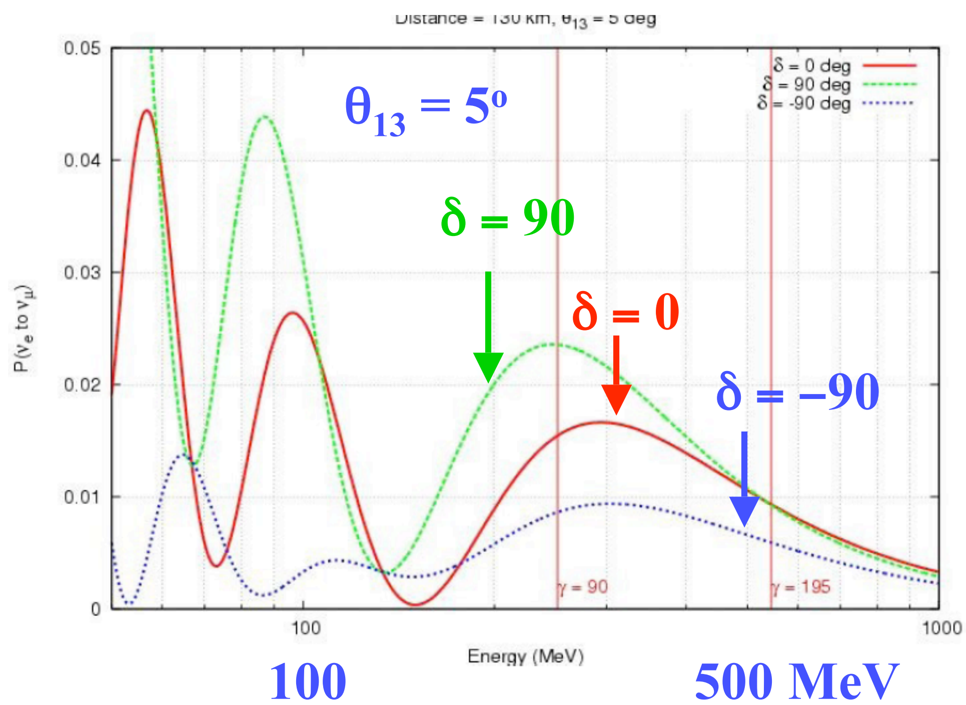
$(A,Z) + e^- \rightarrow (A,Z-1) + \nu_e$ **For instance: Dysprosium.**

Advantage: 2-body final state: monochromatic ν_e beam

CP dependence of $\nu_e \rightarrow \nu_\mu$ oscillation probability

Run at 2 or more energies to resolve ambiguities.

Problem: Intensity of Dy.



New idea: Electron capture in ^{150}Dy

J. Bernabeu et al hep-ph/0605132

Atomic electron captured by proton in nucleus

$(A,Z) + e^- \rightarrow (A,Z-1) + \nu_e$ **For instance: Dysprosium.**

Advantage: monochromatic ν_e beam

- Partly stripped ions: The loss due to stripping smaller than 5% per minute in the decay ring
- Possible to produce 1 10^{11} ^{150}Dy atoms/second (1+) with 50 microAmps proton beam with existing technology (TRIUMF).
- Problem: long lived 7 minutes.
- An annual rate of 10^{18} decays along one straight section seems a challenging target value for a design study
- Beyond EURISOL Design Study: Who will do the design?
- Is ^{150}Dy the best isotope?

Neutrino Factory

Being studied in context of International Scoping Study

Report by August 2006→ Basis for Conceptual Design Study →2010

Store muons, look for $\nu_e \rightarrow \nu_\mu$ oscillations using ν's from their decay

$$\mu^+ \rightarrow e^+ \ \bar{\nu}_\mu \ \nu_e$$

interact giving μ^+

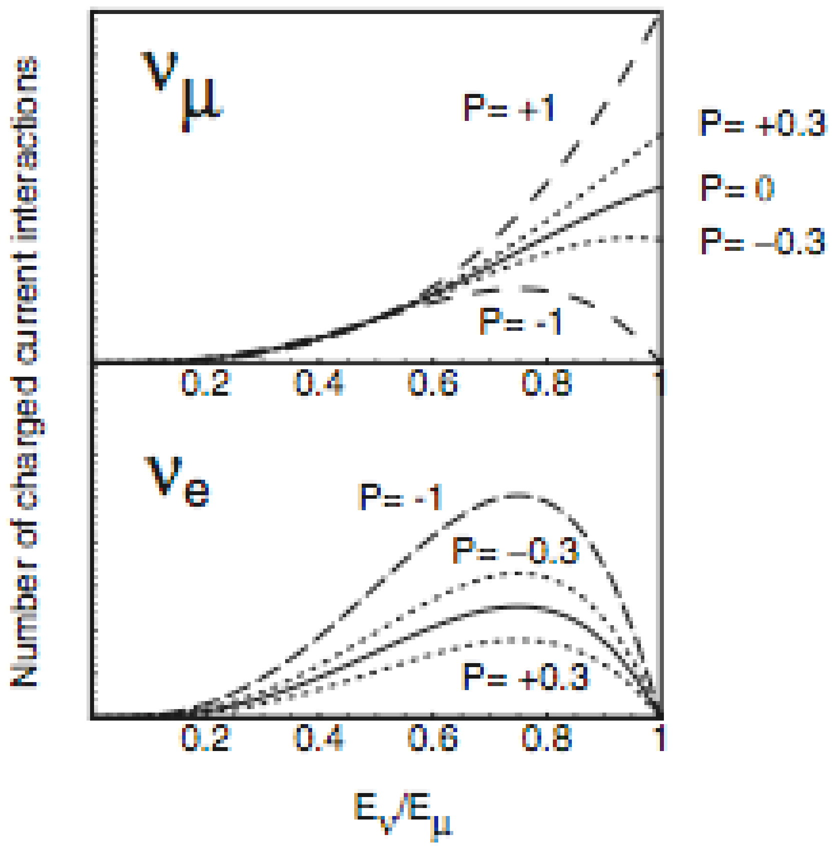
oscillate $\nu_e \rightarrow \nu_\mu$ interact giving μ^- WRONG SIGN MUON → **Golden channel**

Need to measure μ charge →Magnetic detector

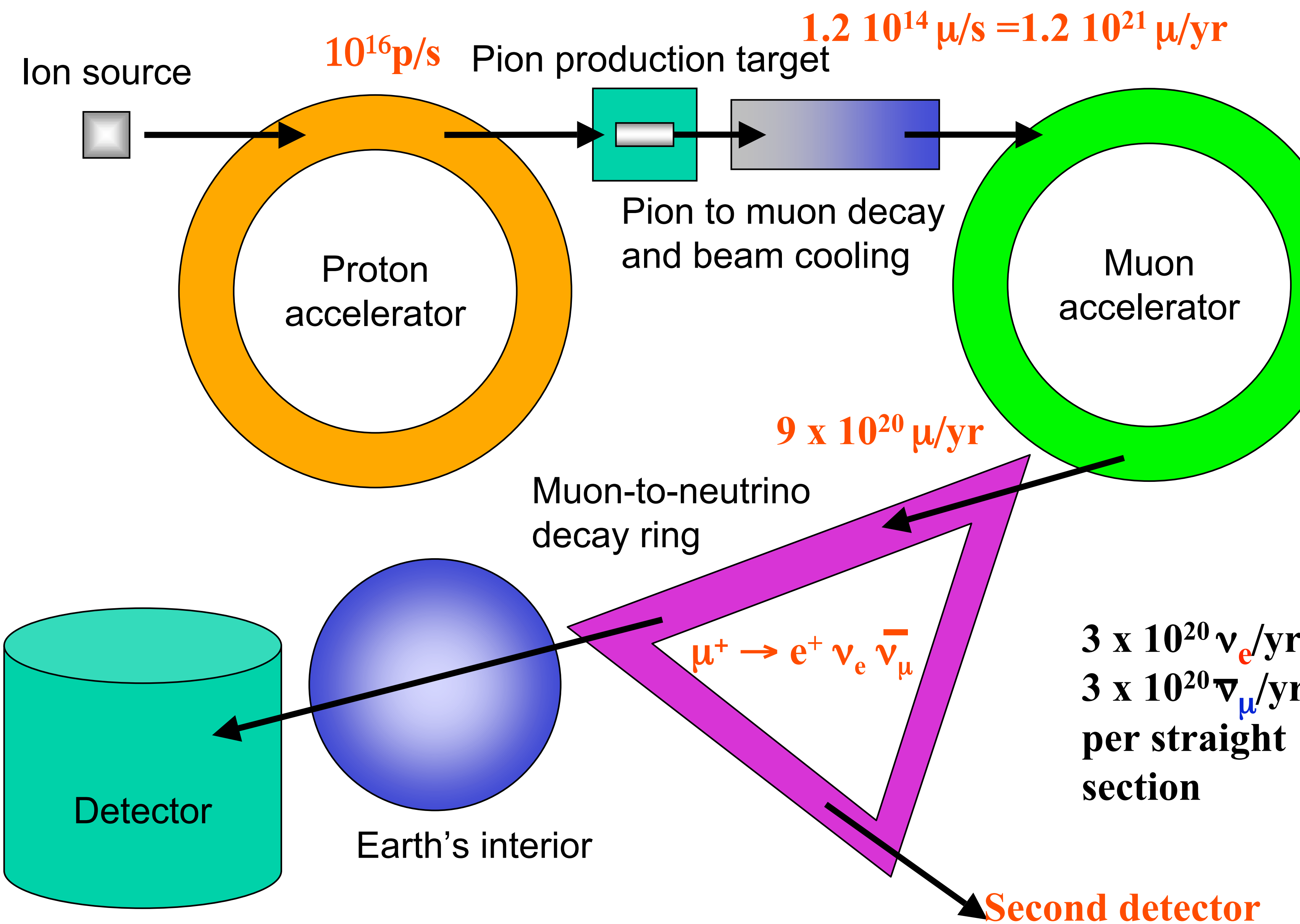
Other channels:

- **Platinum channel: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ T violation.**
- **Silver channel: $\nu_e \rightarrow \nu_\tau$ Resolve ambiguities.**

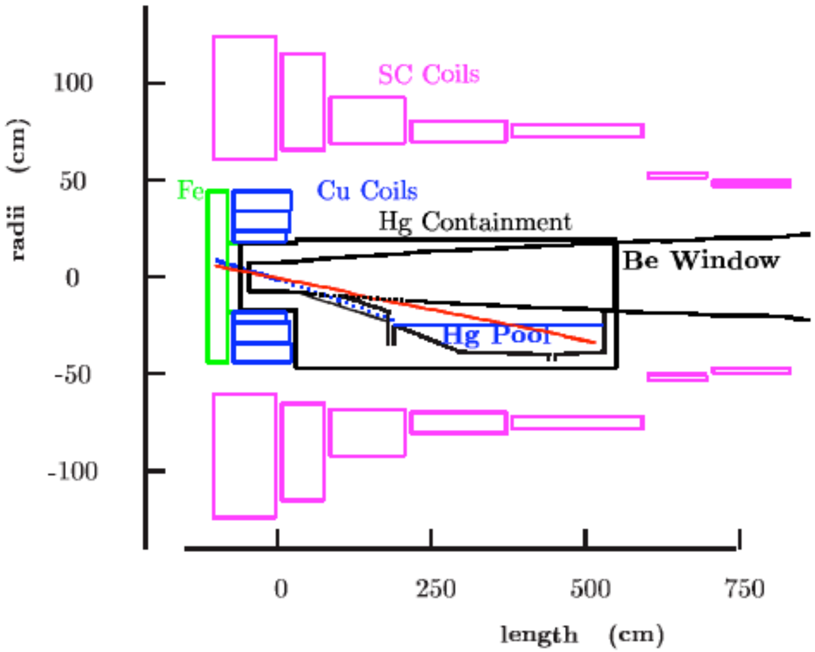
Neutrino spectra in muon decay



Simplified Neutrino Factory

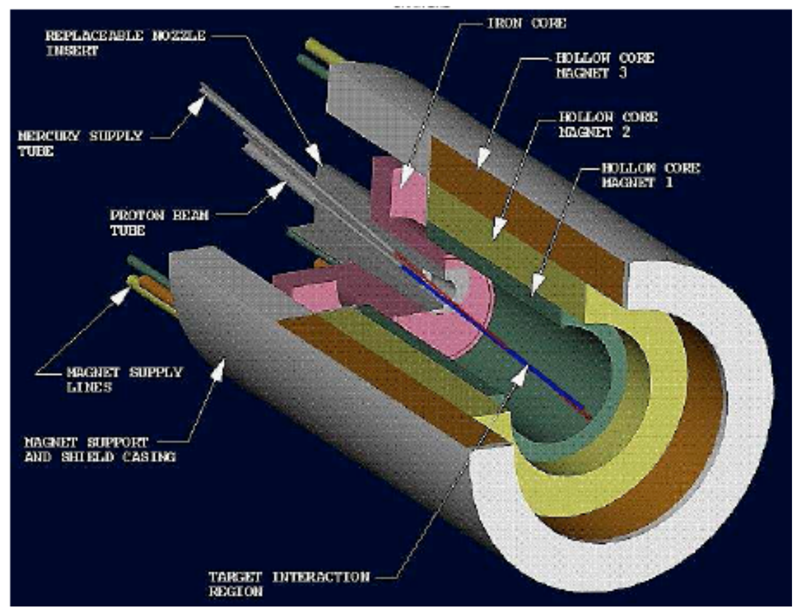


MERIT: Hg jet target tests at CERN PS



Test performed in magnetic field (15T)
To simulate actual conditions:
π collection solenoid

Proton intensity: 2 x 10^{13} protons/pulse at 24 GeV

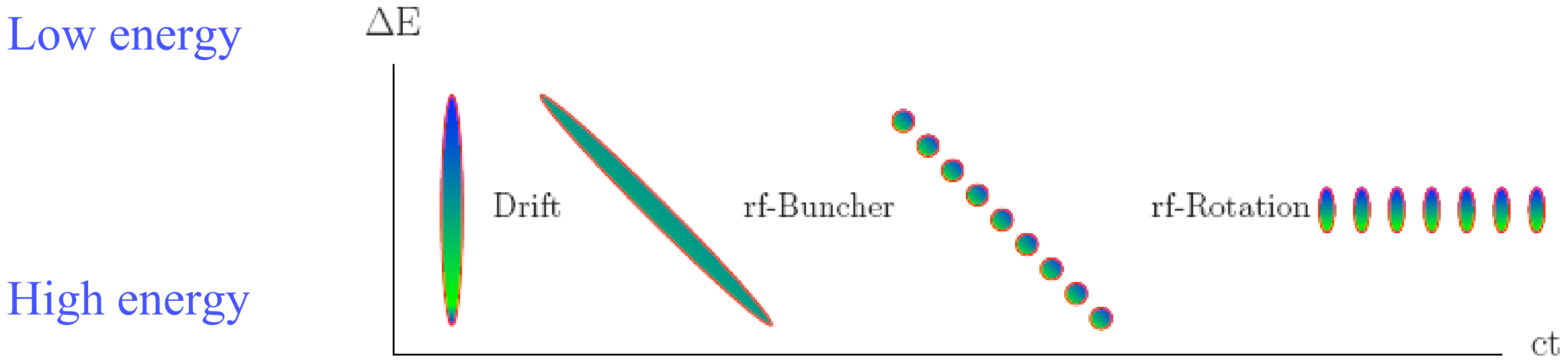


1cm diameter jet at small angle(40 mrad) to beam to maximize overlap: 2 inter. lengths.

Aims: Proof of principle.
Jet dispersal.
Effect of field on jet flow and dispersal.

Longitudinal Cooling

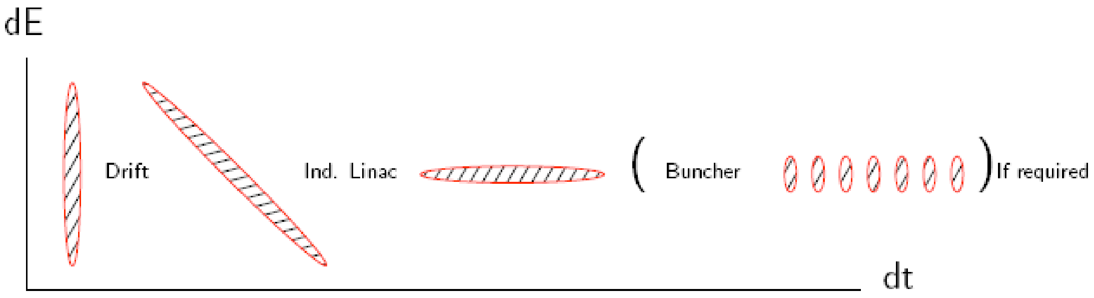
- All particles produced at same point.
- Let them drift to separate them according to velocity (energy)
- This gives you the possibility to accelerate or decelerate selectively the particles.



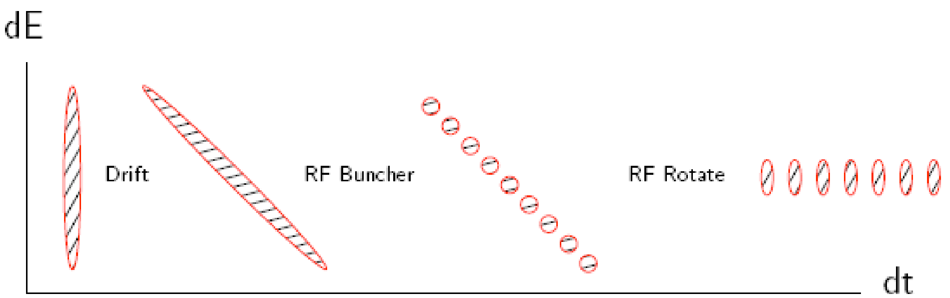
- Longitudinal Cooling. → Phase rotation Neuffer scheme.
  Capture multibunches in very high freq. RF.
  Rotate with RF frequency decreasing along tunnel

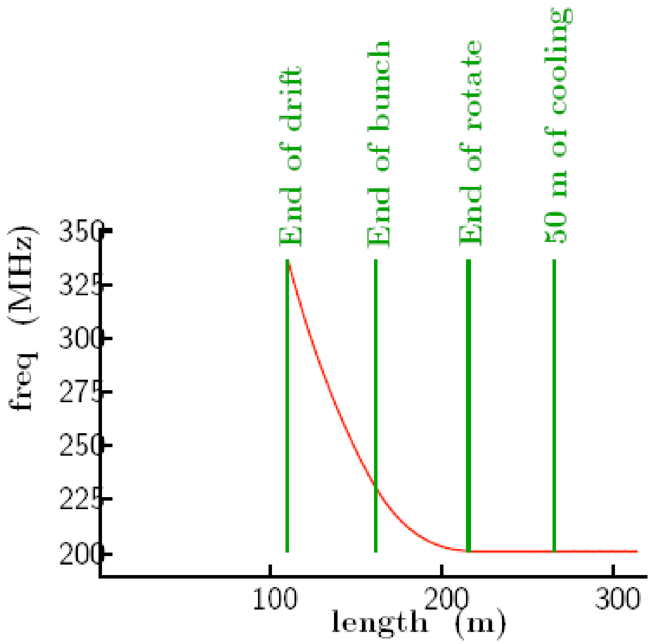
2) Matching into RF: "Phase Rotation"

Conventional with LF RF or Induction Linacs



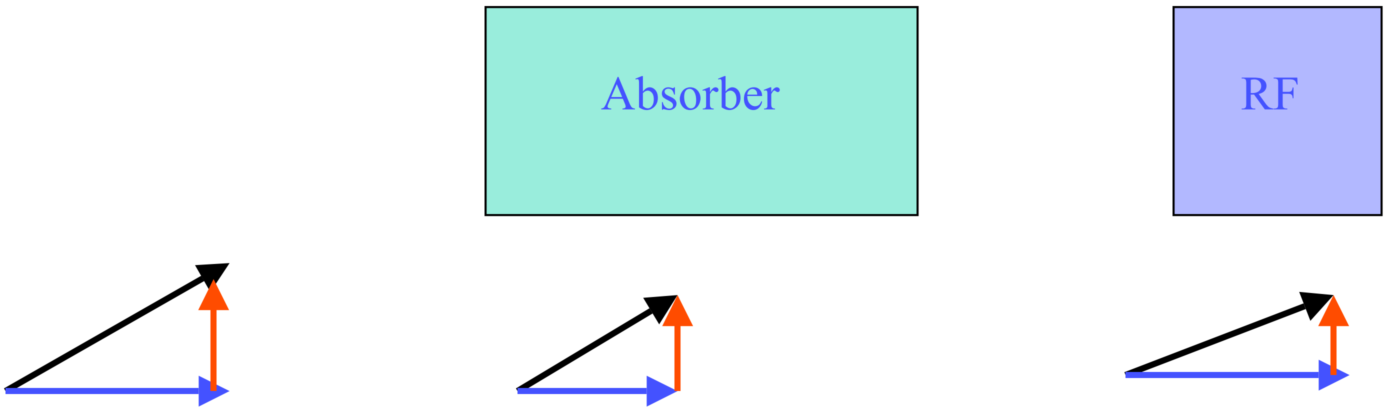
Bunched Beam Rotation with 200 MHz RF (Neuffer)





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

Transverse Cooling



Lose energy in both longitudinal and transverse direction

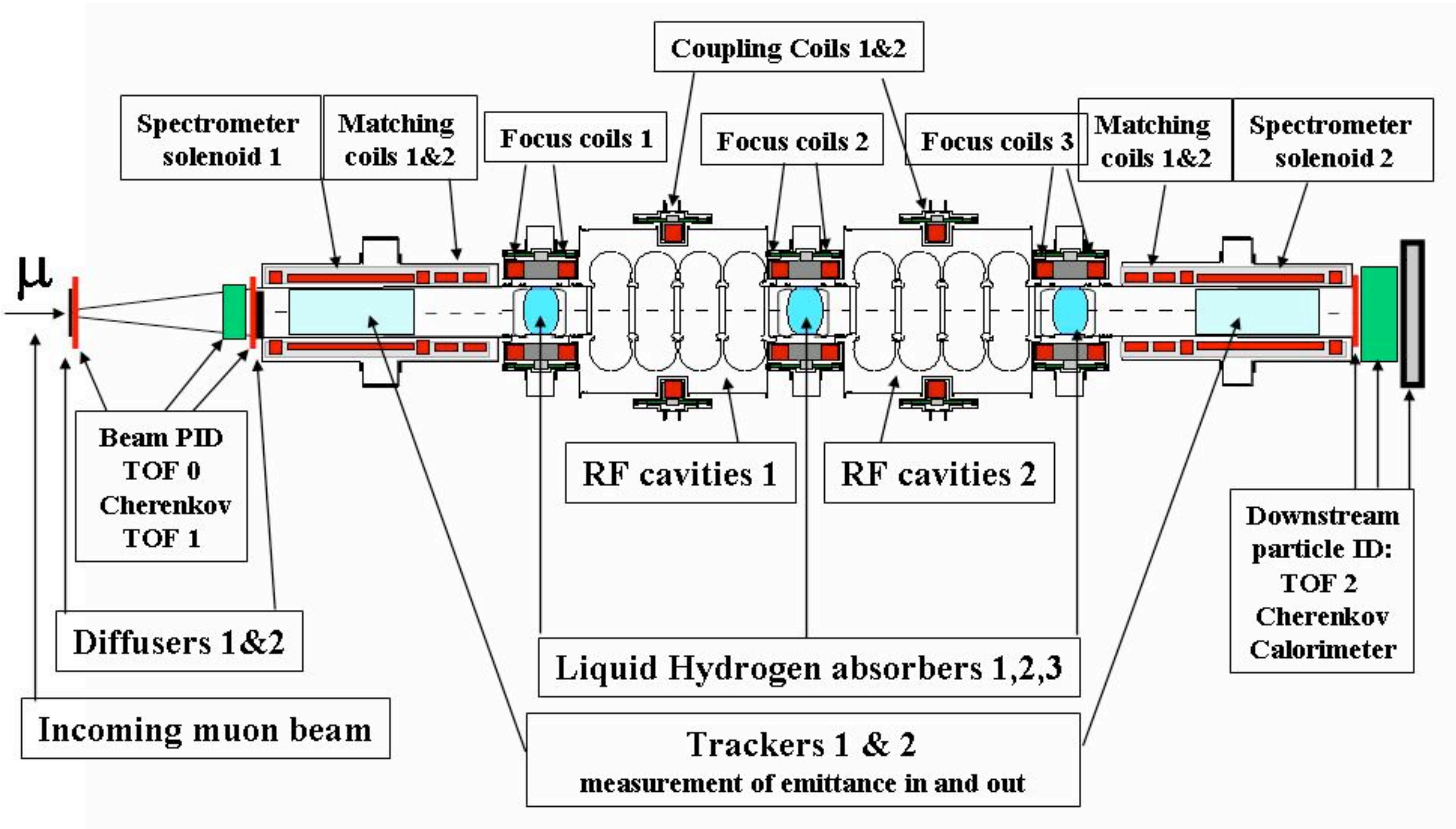
Accelerate in longitudinal direction only

Net relative reduction of transverse momentum

Low Z absorber to minimize multiple scattering that would blow up the beam

MICE: Muon cooling experiment at RAL

Prove the feasibility of ionization cooling. Strong synergy with MUCOOL.

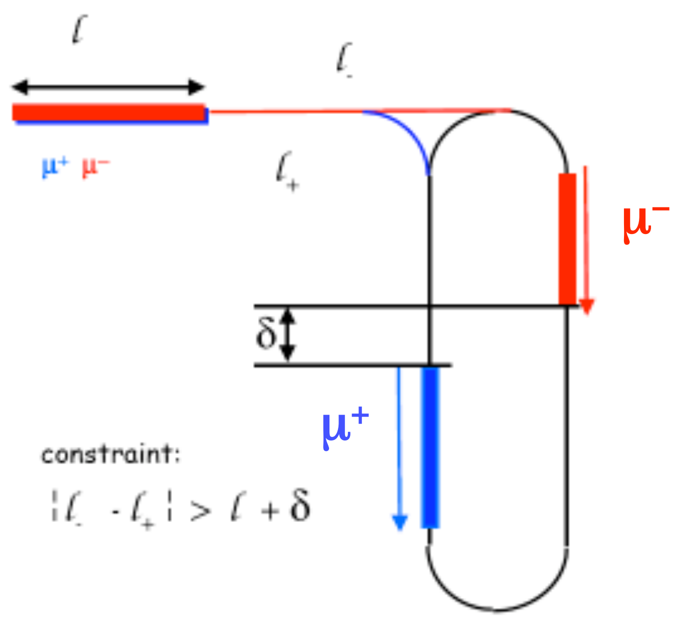


Start Spring 2007. Complete by 2009.

Storage Ring Geometry

- **Race Track**

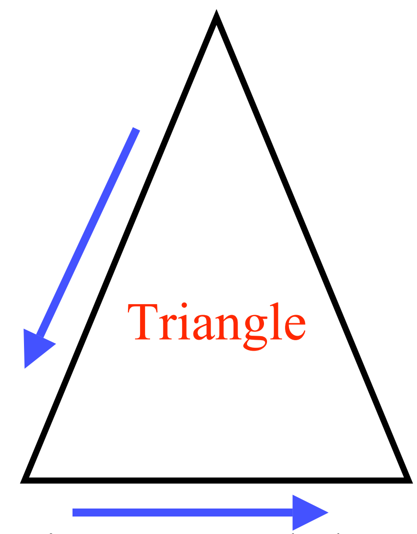
  One ring can supply one detector
  With both signs stored in opposite directions and separated by timing gaps.



If **two** detectors are active at once in two directions need **two** rings.

- **Triangle**

  One ring can supply same sign to two detectors at different locations using two arms of the triangle.



If **both** signs are needed at once need **two** rings, again separating the two signs by timing.

Baseline → Mass hierarchy

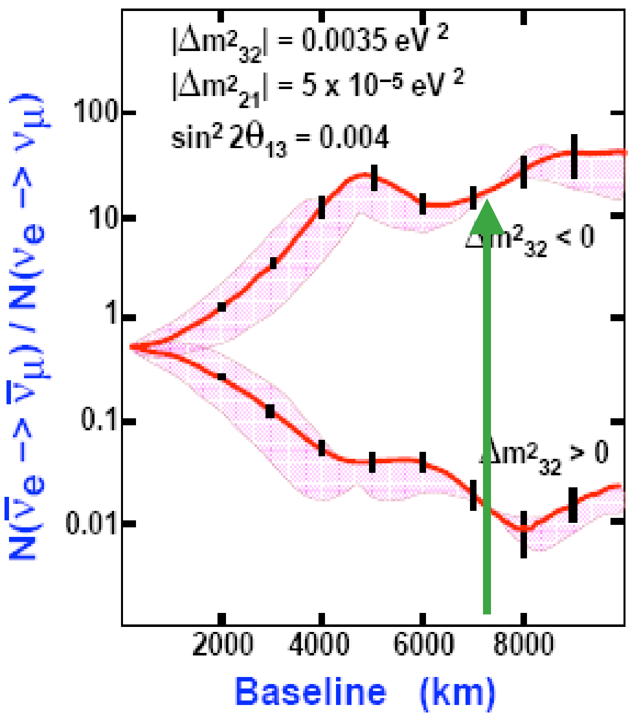
Introducing matter effects, at the first oscillation maximum:

$P(\nu_\mu - \nu_e)_{mat} = [1 \pm (2E/E_R)]\, P(\nu_\mu - \nu_e)_{vac}$ +- depends on the mass hierarchy.

with $E_R = [12\ \text{GeV}][\Delta m^2_{32}/(2.5\times10^{-3})][2.8\ \text{gm.cm}^{-3}/\rho] \sim$ **12 GeV**

Matter effects **grow** with energy.

The higher the energy, the longer the baseline needed to be at oscillation maximum.



- The difference between the two hierarchies grows with distance.
- At 7000 km the CP phase has no influence. (width of pink band shrinks to zero)

Magic distance

Correlations in Oscillation Probability

From M. Lindner:

- $\Delta = \Delta m^2_{31} L/4E$
- qualitative understanding $\Rightarrow$ expand in $\alpha = \Delta m^2_{21}/\Delta m^2_{31}$ and $\sin^2 2\theta_{13}$
- matter effects $\hat{A} = A/\Delta m^2_{31} = 2VE/\Delta m^2_{31}$; $V = \sqrt{2} G_F n_e$

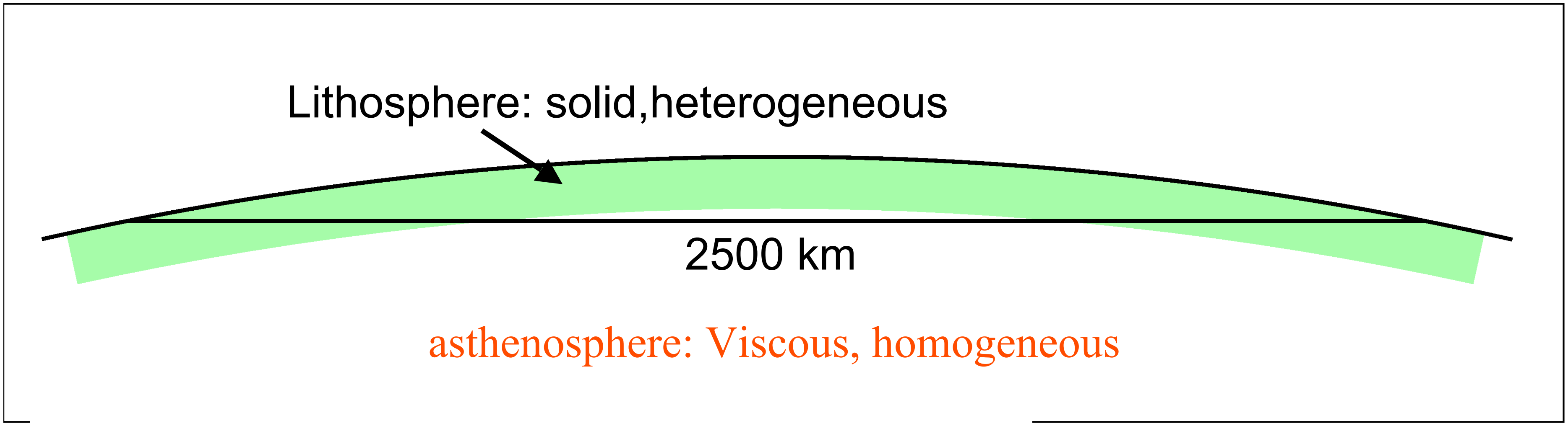
$$
\begin{aligned}
P(\nu_e \to \nu_\mu) \approx\; & \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2((1-\hat{A})\Delta)}{(1-\hat{A})^2} \\
\pm\; & \sin\delta_{CP}\, \alpha \sin 2\theta_{12} \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \sin(\Delta) \frac{\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})} \\
+\; & \cos\delta_{CP}\, \alpha \sin 2\theta_{12} \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \cos(\Delta) \frac{\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})} \\
+\; & \alpha^2 \sin^2 2\theta_{12} \cos^2\theta_{23} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}
\end{aligned}
$$

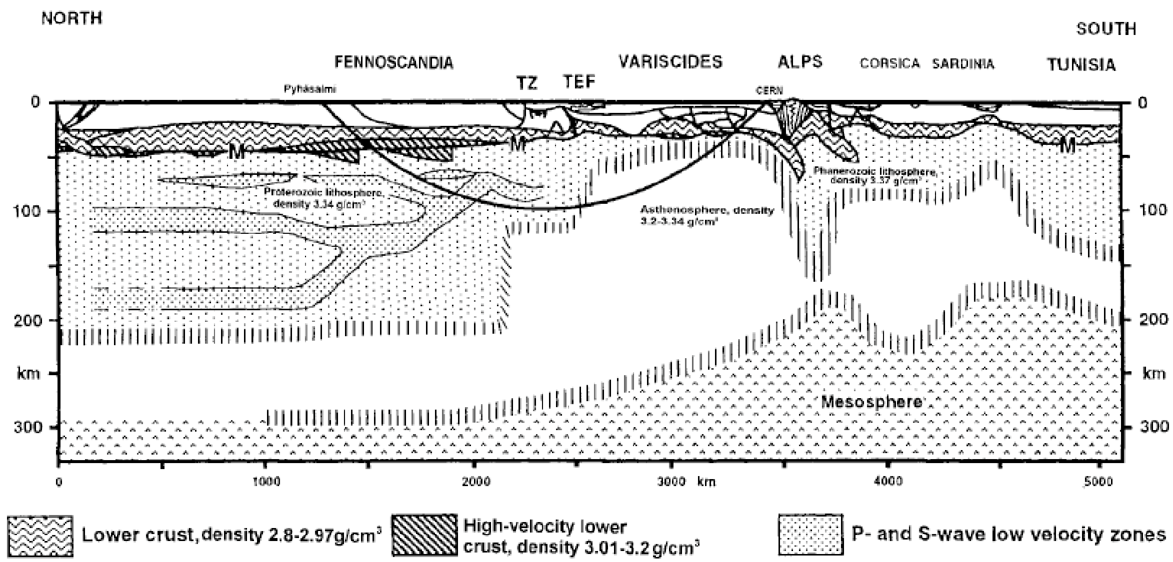
Measuring P ($\nu_\mu \sim \nu_e$) does NOT yield a UNIQUE value of θ_{13} .
Because of correlations between θ_{13}, δ_{CP} and the mass hierarchy (sign of Δm^2_{31})

CP violation: Difference between Neutrino and Antineutrino Oscillations

Mass hierarchy accessible through Matter effects :
$1 - \hat{A}$ depends on sign of Δm_{31}^2

Knowledge of Matter density along ν path





"Best" 2σ errors 1.5-3%

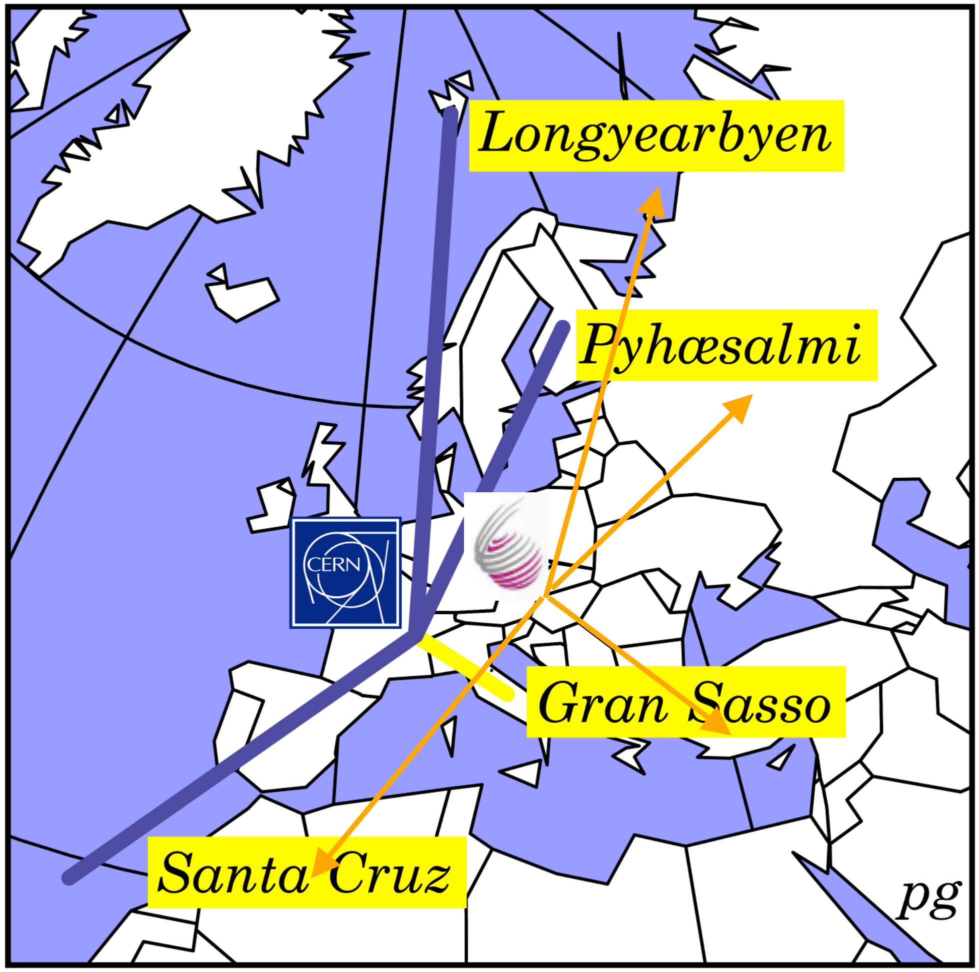
Avoid: Alps, Central Europe

Favour: Western Europe to US
Atlantic Islands

Oceans: simpler, more accurate.

Continents: more complicated, less accurate.

Possible long baseline beams in Europe



How many baselines?

Single baseline, say 3000km, ν and $\bar{\nu}$ together
Yields true value +clone: Not enough.

3000km

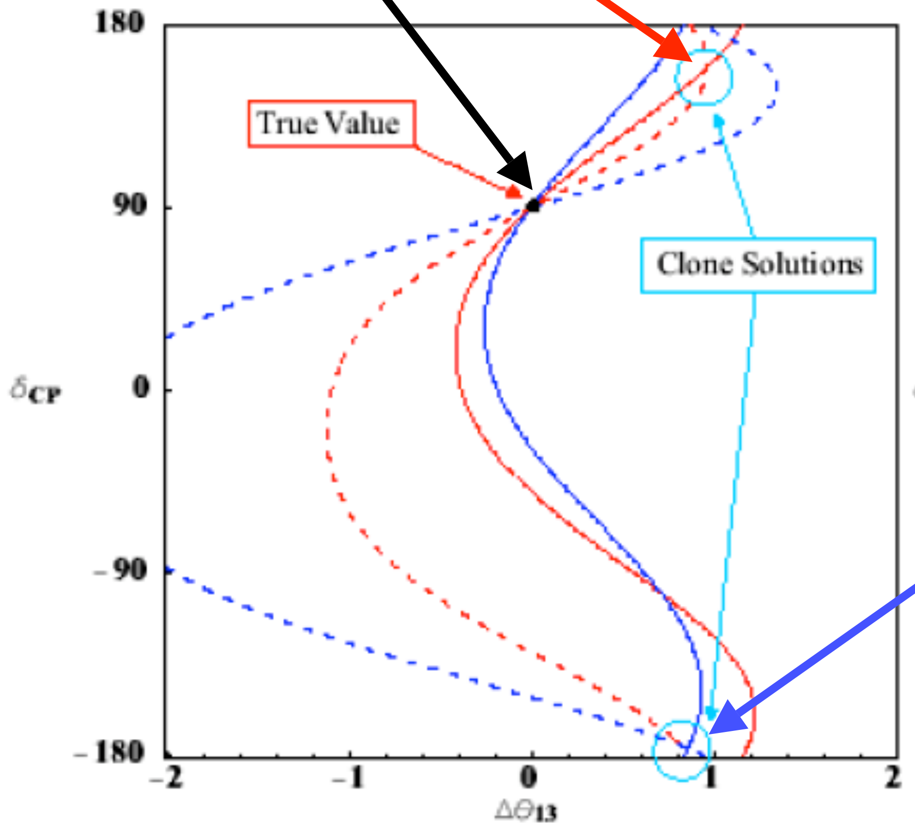
—— ν

- - - $\bar{\nu}$

730km

—— ν

- - - $\bar{\nu}$



Second baseline,
Say 730km,
Clone in different
position

2 baselines together resolve ambiguity

Usefulness of the silver channel: $\nu_e \rightarrow \nu_\tau$

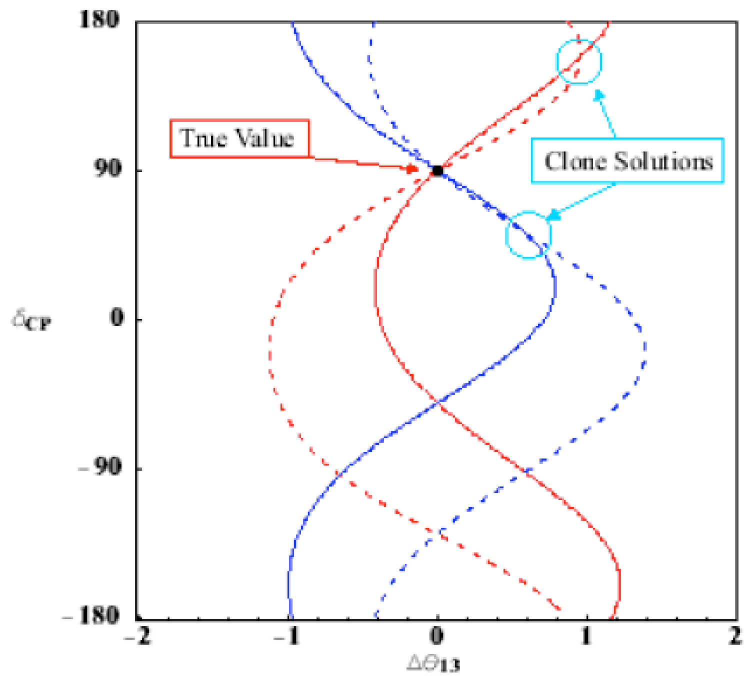
S. Rigolin, hep-ph/0407009 **D. Autiero et al. hep-ph/0305185**

$\nu_e \rightarrow \nu_\tau$ and $\nu_e \rightarrow \nu_\mu$ channels have "opposite" sign CP violation.

$\nu_e \rightarrow \nu_\mu$

ν (solid line)

$\bar{\nu}$ (dashed line)



$\nu_e \rightarrow \nu_\tau$

ν (solid line)

$\bar{\nu}$ (dashed line)

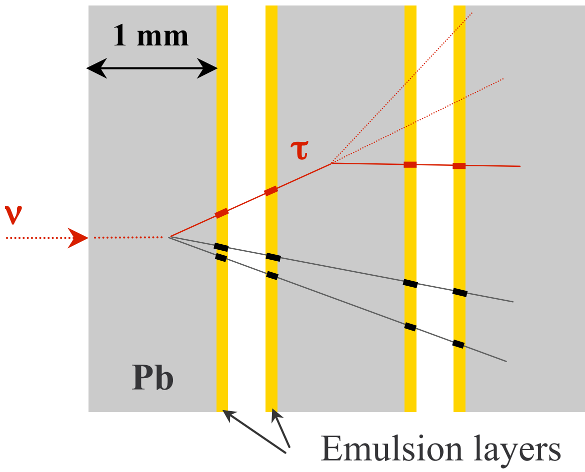
Clones for 2 reactions are also at different positions.

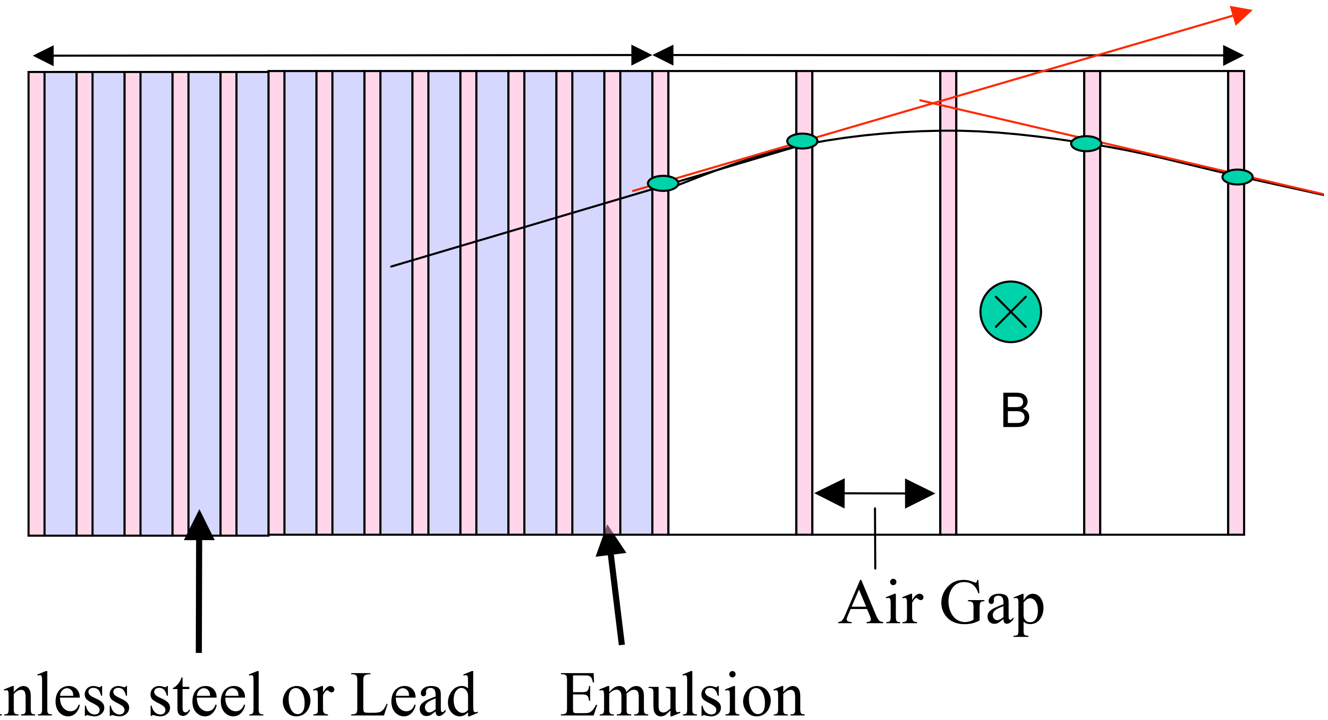
Alternative to 2 baselines

Needs fine grained detector for τ secondary vertex or kink: DONUT/OPERA technology

DONUT/OPERA type target + Emulsion spectrometer

Must be placed in a magnet





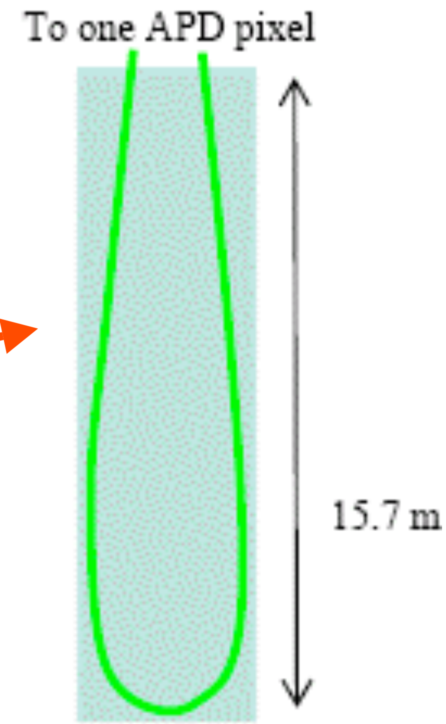
Can measure momentum of muons
and of some fraction of electrons
Identify τ using topology à la OPERA

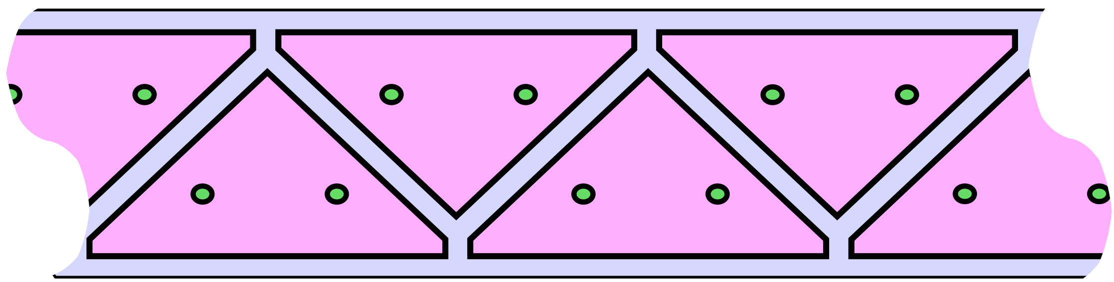
A Strawman Concept for a Nufact Magnetized Iron Tracker Detector

- 1 cm Iron sheets magnetized à la MINOS alternating with
- Planes of triangular

  4cm x 6 cm PVC tubes à la MINERVA.
- Filled with liquid scintillator
- Read by looped WLS fibres

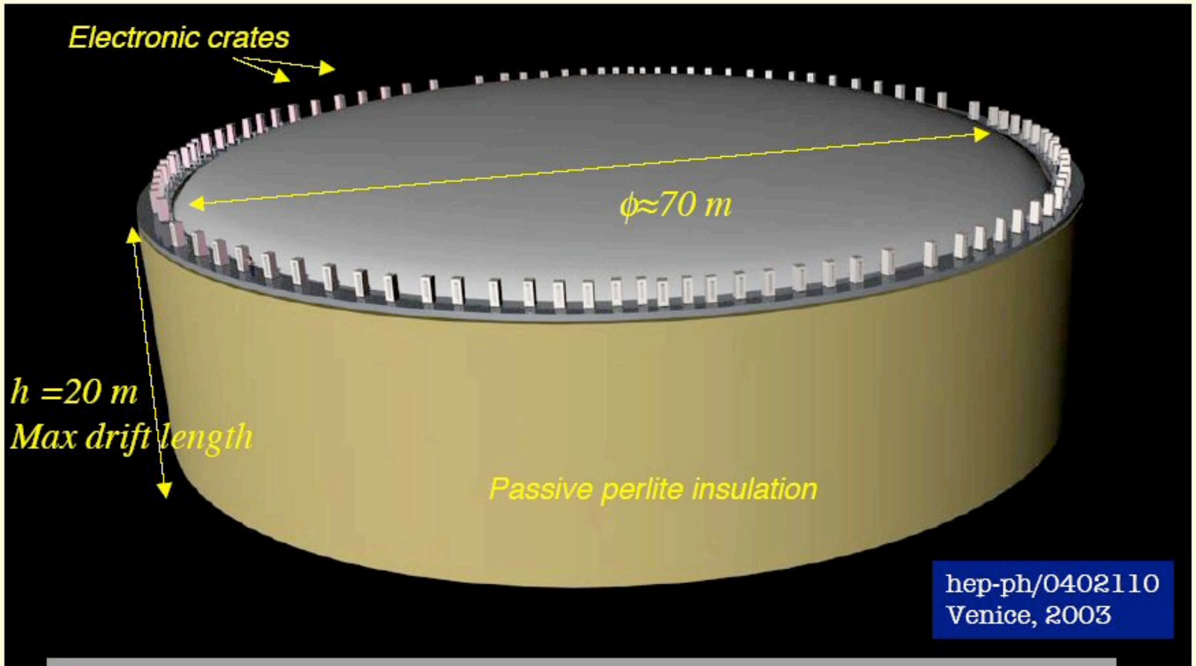
  connected to APD's à la NOvA





Giant Liquid Argon Charge Imaging Experiment

A 100 kton liquid Argon TPC detector



Single module cryo-tanker based on industrial LNG technology

A "general-purpose" detector for superbeams, beta-beams and neutrino factories with broad non-accelerator physics program (SN ν, p-decay, atm ν, …)

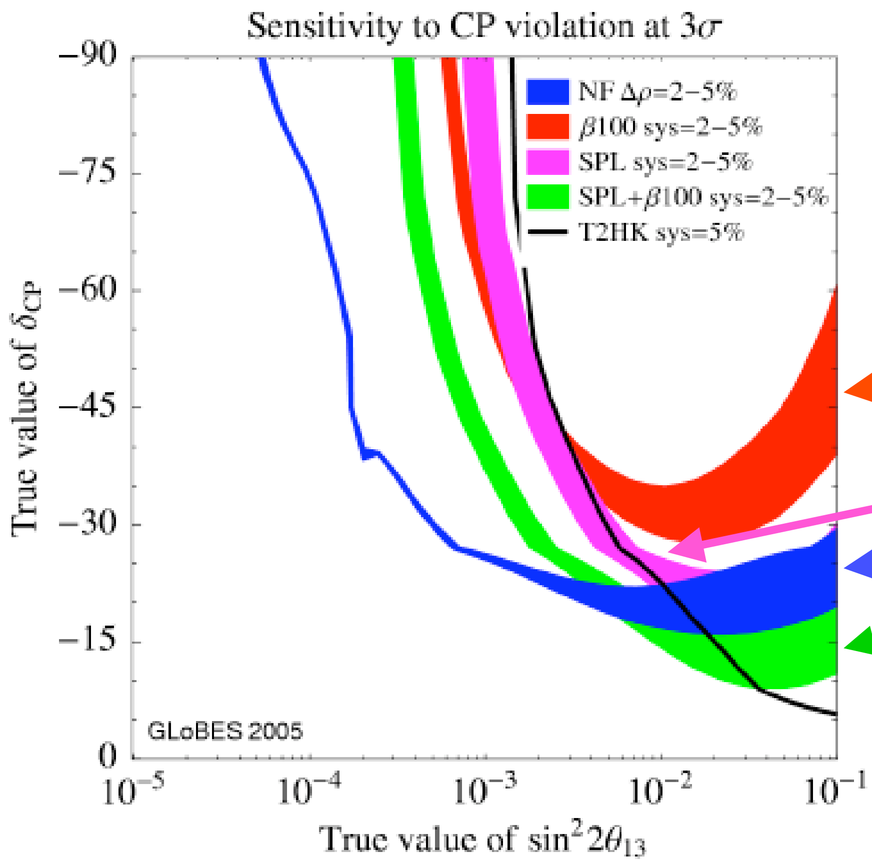
High efficiency Compared to Scintillators: x 2-3.

US-Europe Synergy ?

Impression was that magnet limited detector mass to 15 ktons.

A. Rubbia

Reach of beta-beams and ν Factory



Globes analysis shown for 1 quadrant
About the same for other
3 quadrants of CP phase.
Systematics: 2-5%. T2HK: 5%

β-beams + SPL are more sensitive for $\sin^2 2\theta_{13} > 0.01$.
(needs confirmation: cuts used in analysis $E_\mu > 5$ GeV)

But below this value ν factory is more sensitive.

Comparison of beta-beam and ν factory

Beta-beam advantages.

- Synergy with Eurisol + existing PS,SPS (if at CERN)
- Clean ν_e and $\bar{\nu}_e$ beams.
- No need for analyzing magnet.
- Negligible matter effects.

Beta-beam disadvantages

- Low energy:
  - Cross sections not so well known,
  - Fermi motion
  - Atmospheric neutrinos background
- Silver channel energetically impossible
- Need of SPL:
  - Improve sensitivity
  - Measure ν_μ cross-sections

Comparison of beta-beam and ν factory II

Advantages of Neutrino Factory

- Ultimate reach
- Presence of both $\boldsymbol{\nu}_\mu$ and $\boldsymbol{\nu}_e$ in beam allows measurement of cross-sections in near detector
- Higher energies: better measured cross sections, no atmospheric neutrinos background

Disadvantages of Neutrino Factory.

- Technically more challenging
- Matter effects must be well understood.
- Need for a magnetic detector to separate signal from background

Time line

2010: A critical year in many ways.

- Possible ILC decision.
- CLIC possibilities.
- LHC results.
- Decision on LHC upgrades.
- Eurisol siting. CERN ?
- Possible first measurement of θ_{13}: MINOS, Double CHOOZ

It is essential to know which Neutrino Facility is favoured by that date.

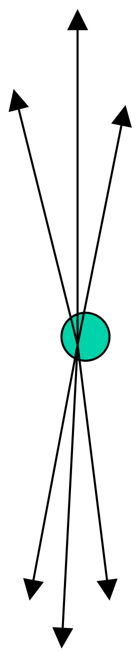
Decision process and construction will take another 8-10years.

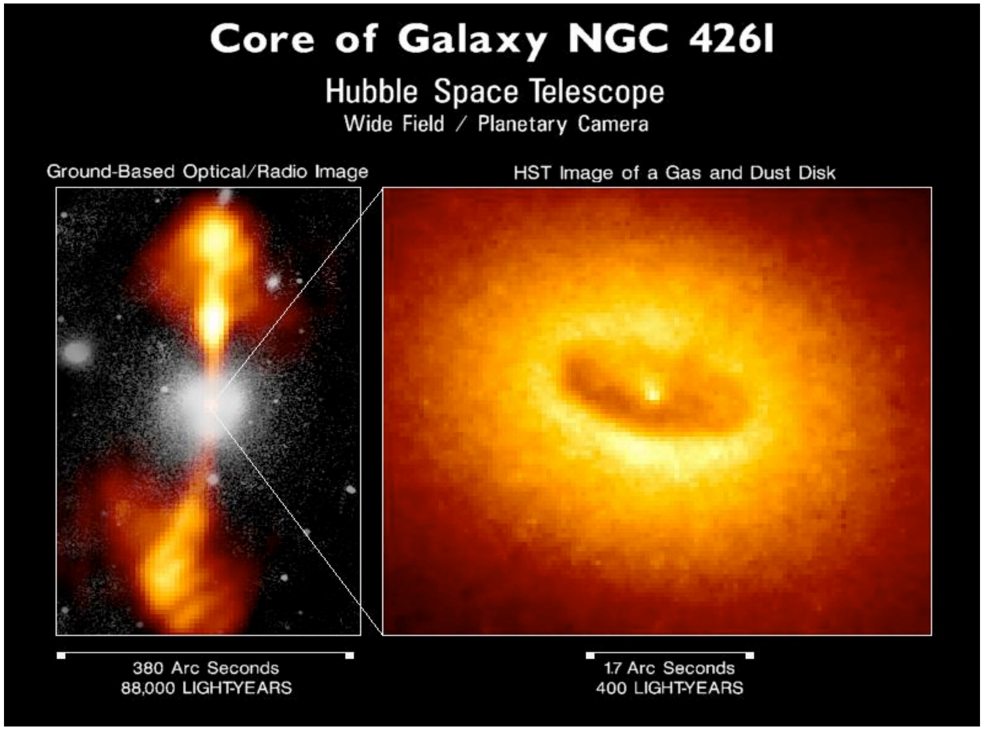
Its approval in this international context will be difficult. But it's definitely worth fighting for…!

ν's from Outer Space

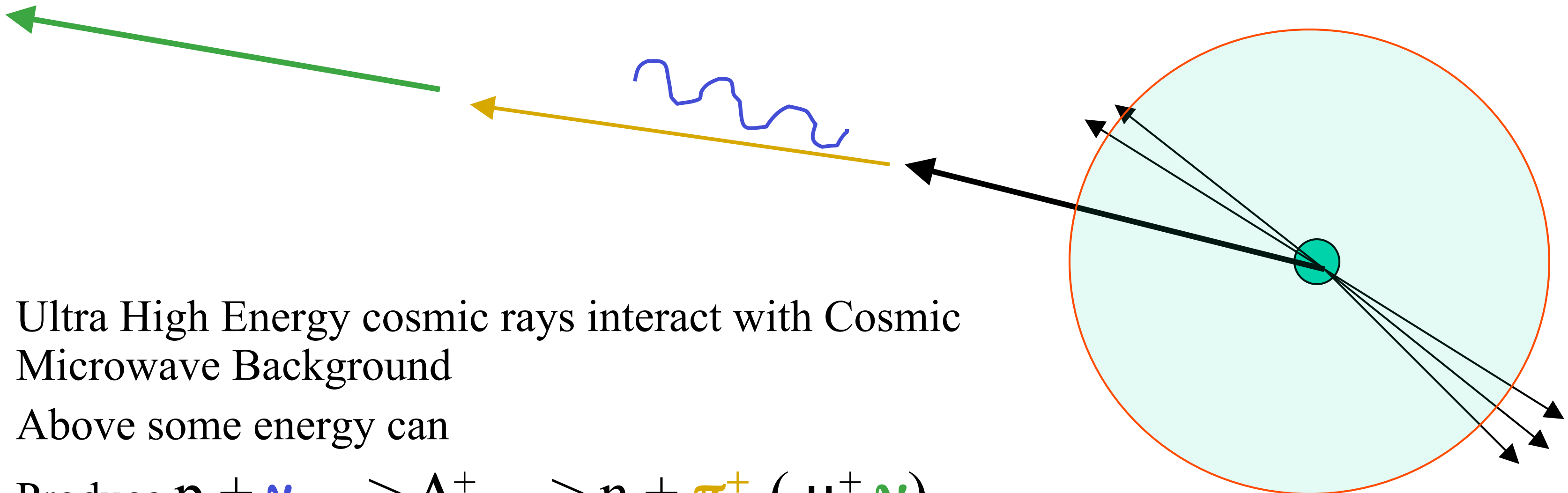
- Sources: Anything violent. Black holes, AGN's, Gamma-ray bursts…
- How: Through $\pi \dashrightarrow \mu\, \nu_\mu \quad \dashrightarrow e\, \nu_\mu\, \nu_e$
- And then oscillations probably end up with $\nu_e:\nu_\mu:\nu_\tau = 1:1:1$

Violent phenomenon !





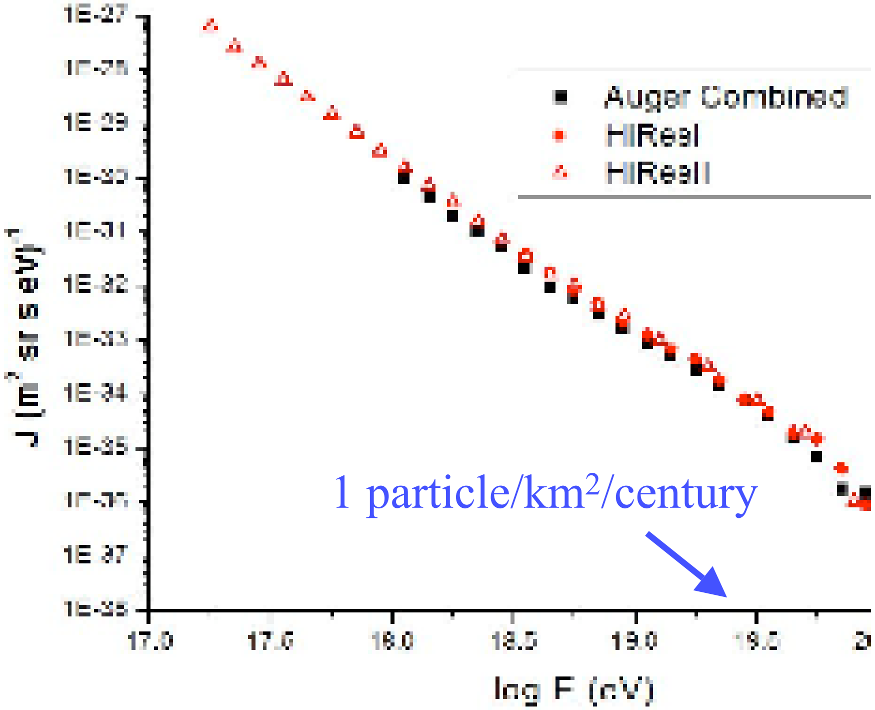
Greisen-Zatsepin-Kuzmin **GZK Cut off**

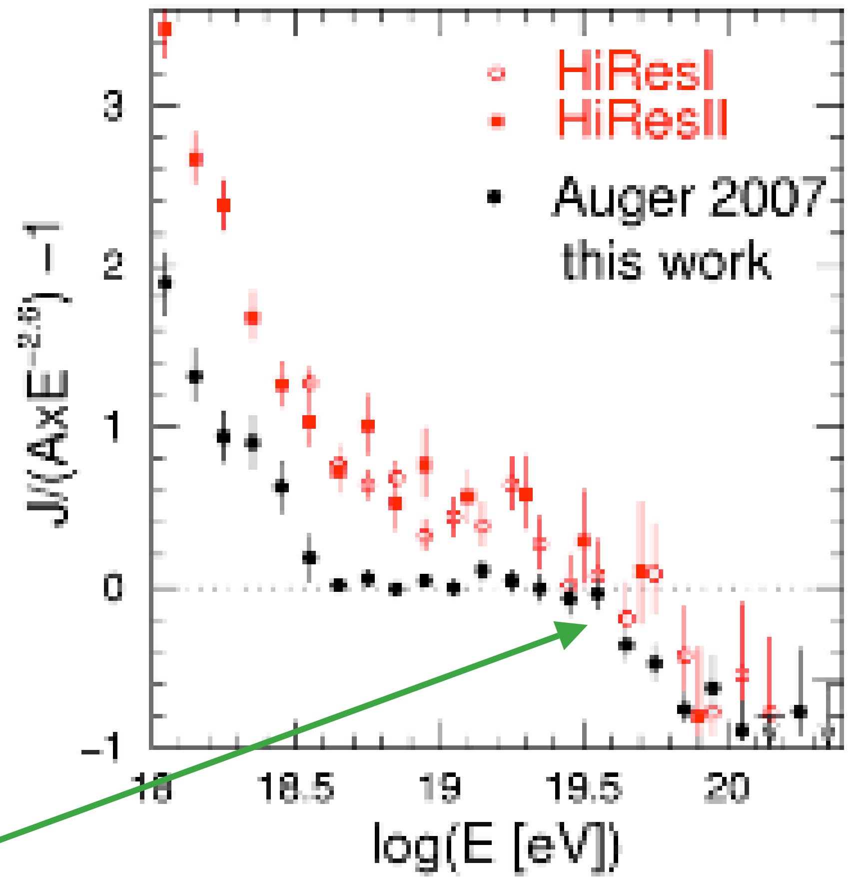


- Ultra High Energy cosmic rays interact with Cosmic Microwave Background
- Above some energy can

  Produce $p + \gamma$ ---> Δ^{+} ---> $n + \pi^{+}$ (μ^{+} ν)
- Cross section is such that cosmic rays of high enough energy to undergo this process CANNOT come from > than 50 Mpc away (mean free path).

GZK Cut off





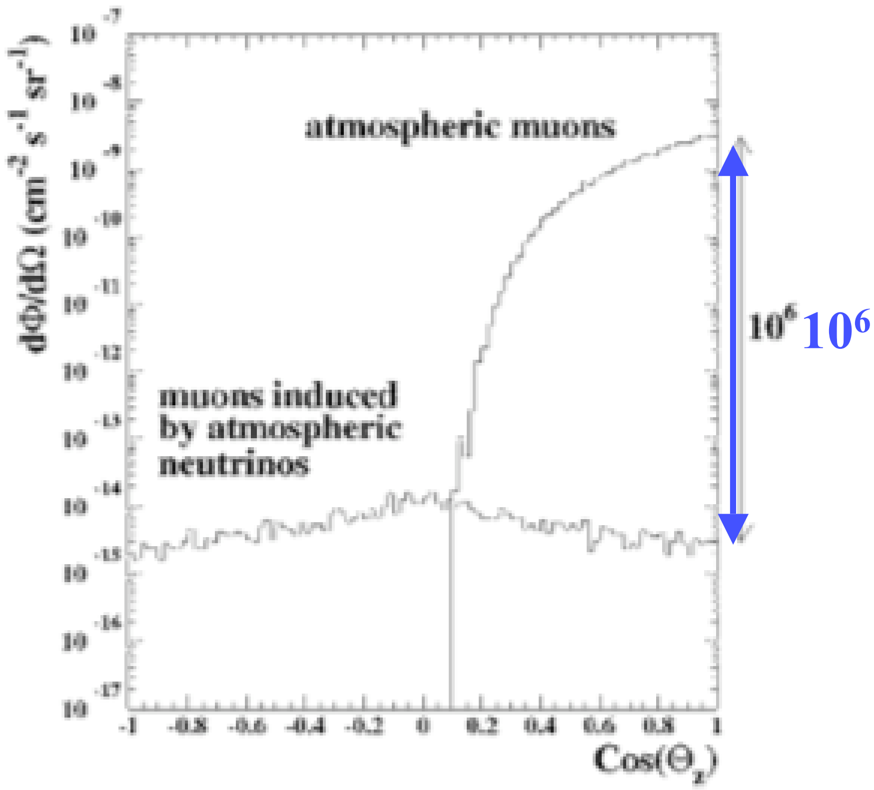
- We DO see a cut-off.
- UHECR come from FAR AWAY.
- The produced π^+ can also be a source of ν's.

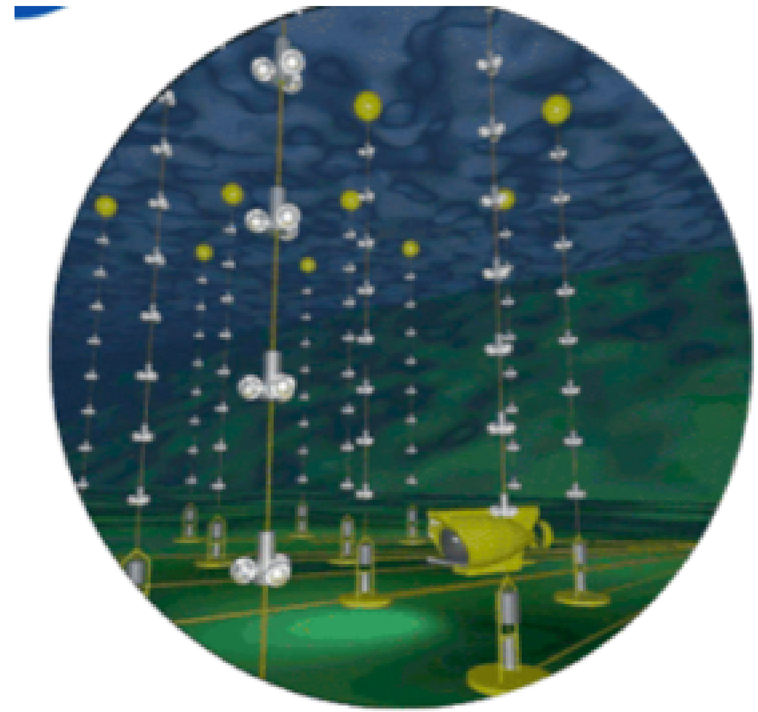
Observation of VHE neutrinos

- Why do we want to observe them? Any more info than cosmic rays?
- Yes. Neutral. Not deflected by galactic magnetic fields. Point to source.
- How do we observe them? Through CC interaction in detector.
- Easiest: ν_μ interactions ---> μ.
- Go underground to reduce ‘standard” cosmic rays background.
- Still overwhelming.
- Concentrate on ν’s coming from below: through the earth.
- To reduce background from cosmic ray muons.
- So need to have the source being studied ON THE OTHER SIDE of the Earth.
- Above 40 TeV the neutrino interaction length becomes smaller than the earth diameter. Must look for horizontal cosmic rays.

How do we detect them? Sea.

- ANTARES in the Mediterranean
- 20 km off Toulon
- 10 lines deployed: 0.1 km^2.
- 12 planned
- Cerenkov light in water



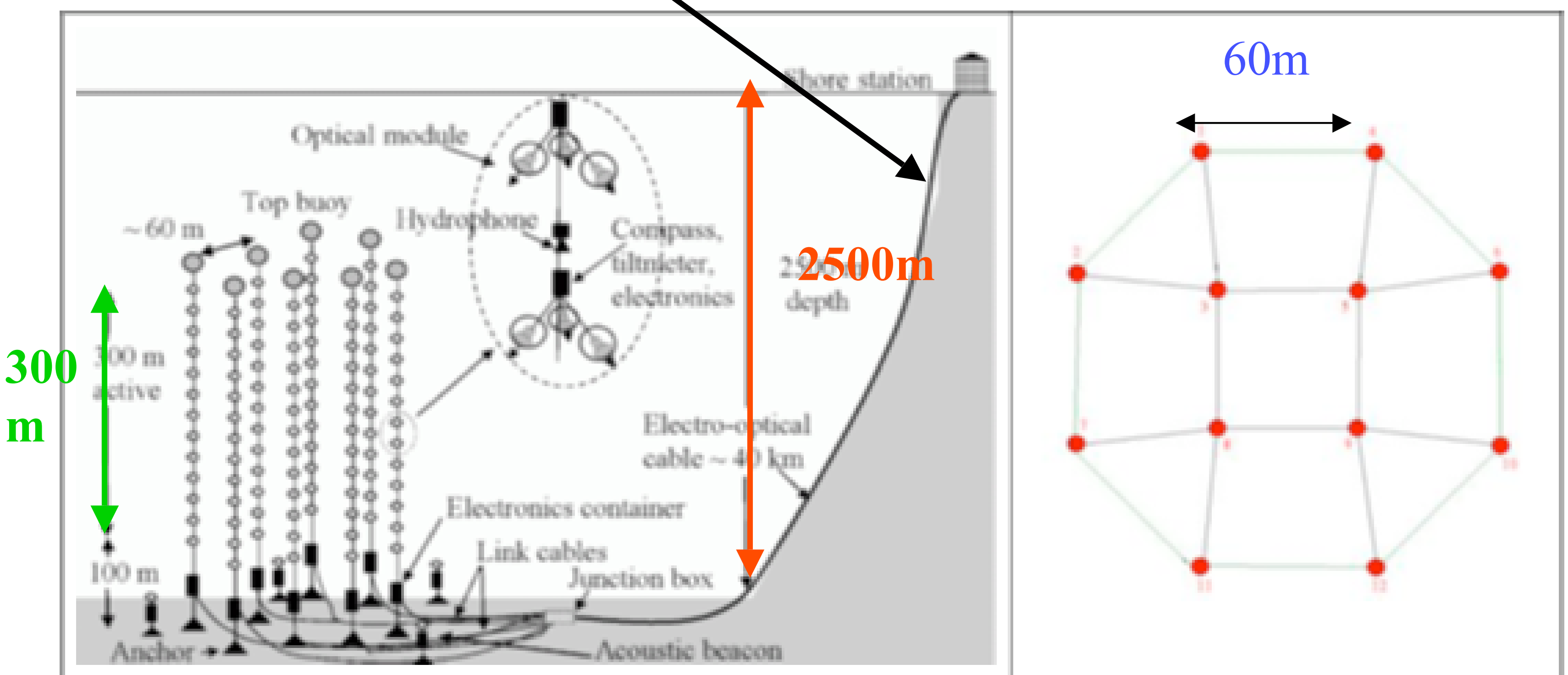


ANTARES

Benthos spheres made of glass: 600 atm. = 6000m water

Contain pm and electronics.

Data sent to shore on cable

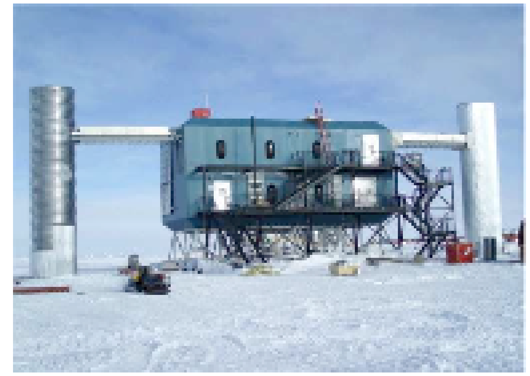


Schematic of the detector at the Antares site

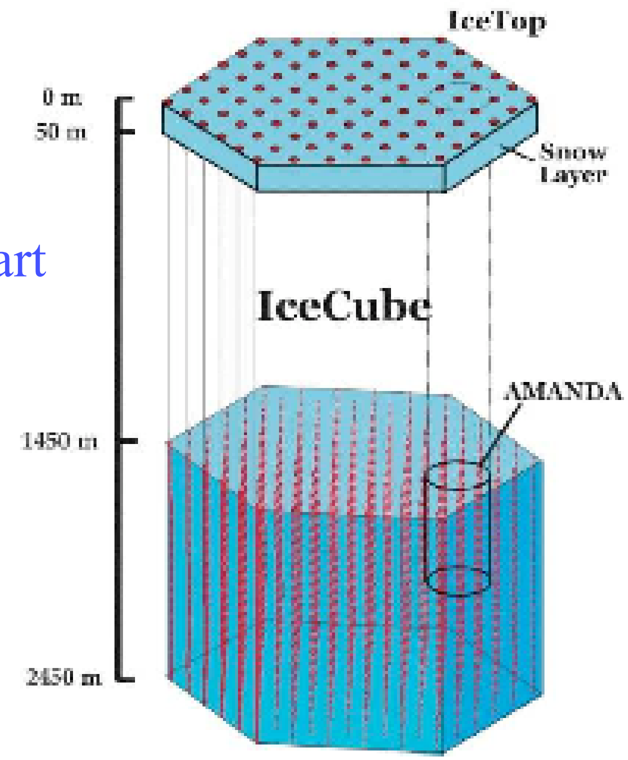
Arrangement of the twelve lines on the sea bed

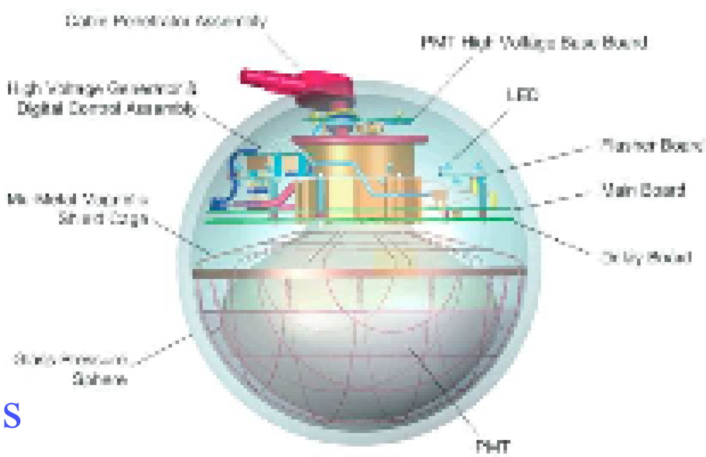
How do we detect them? Ice.

- Need exceedingly large mass and area: km^3.
- Must use naturally occuring detector.
- **Antarctic ice** (ICECUBE)
- Melt holes in ice .
- Lower strings of photomultipliers about 1 km long!
- Use Cerenkov light emitted
- In ice by charged particles



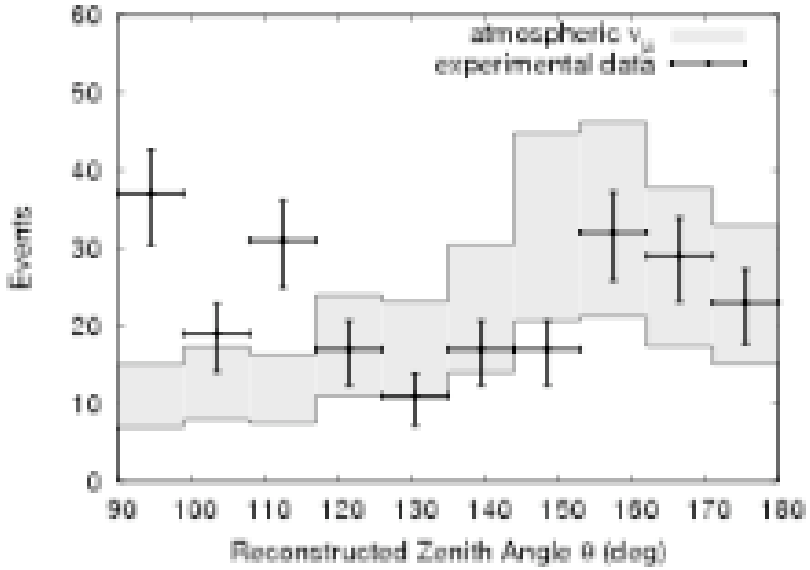
Strings
125m apart





4200
optical modules

IceCube first atmospheric neutrino data



234 events in 2006

No strong evidence for point sources of cosmic origin yet

Ice cube can identify neutrino flavours because of its large size

In particular it can identify ν_τ CC interactions: ν_τ + X ---> τ + X'

"Double bang"

Above 1 PeV the τ travels 100m.

Light from X' and light from hadronic decay of τ separated by 100m

Clear signature

SuperNovae

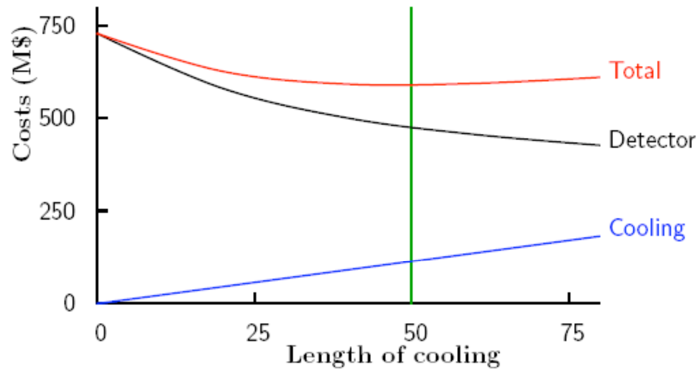
- These experiments are only sensitive to multi TeV neutrinos.
- Much higher energy than SuperNovae neutrinos
- But they will have triggers that allows them to observe a very large number of low energy neutrinos in a short burst

Crab nebula remnant of 1054 AD SN

Back up slides

- **Optimization of Cooling vs Detector Size**

- Assume base detector costs (two detectors) is 500 unloaded M$
- Scale detector sizes (and costs) for same number of events with different cooling lengths



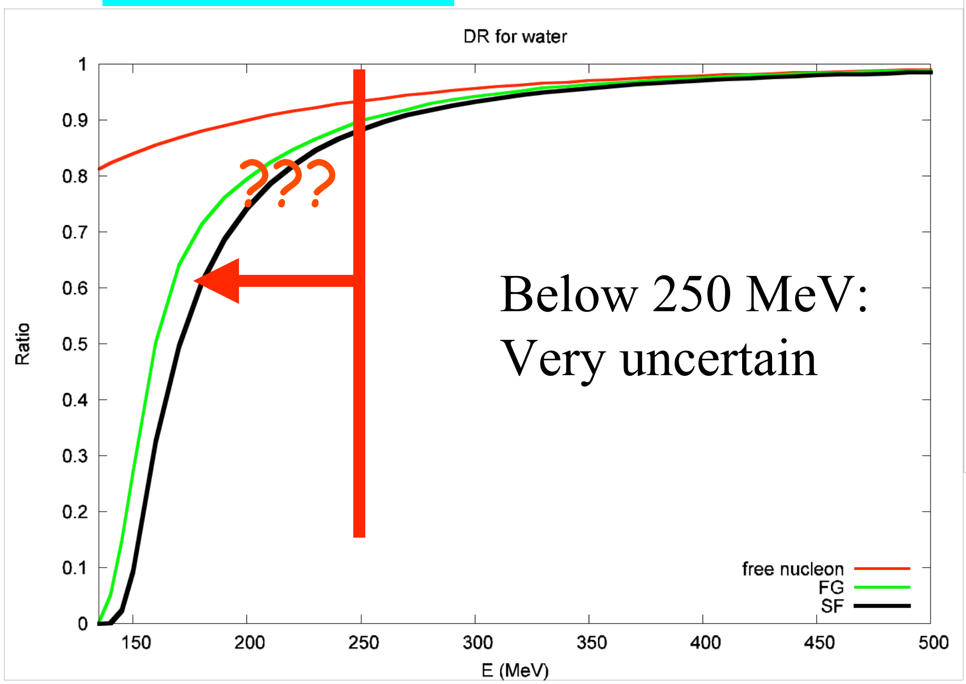
- Minimum total cost minimum at 50 m (vs. 80 m)
- Saving for Factory of 70 M$
- Saving for Factory and Detector 17 M$
- Saving at minimum relative to no cooling and larger detectors: 136 M$

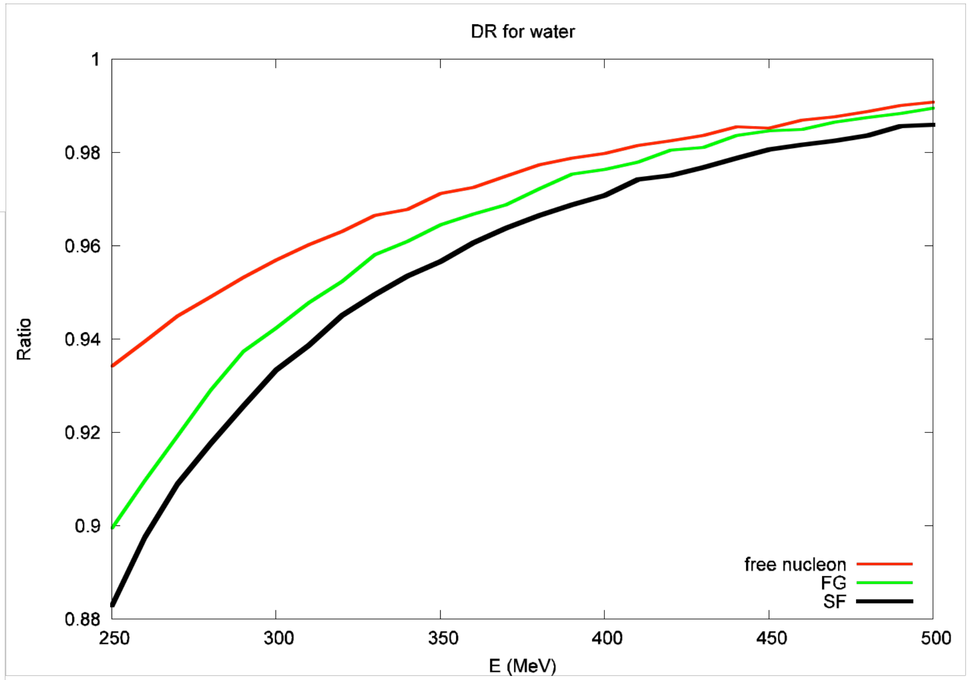
- **Chosen Baseline is ≈ 50 m of Cooling**

Uncertainty on ν cross-sections.

$$DR \equiv \frac{\dfrac{\sigma(\nu_\mu)}{\sigma(\nu_e)}}{\dfrac{\sigma(\bar{\nu}_\mu)}{\sigma(\bar{\nu}_e)}}$$

Targets: free nucleons and water





At 250 MeV:
Double ratio ~ 0.9
Nuclear effects ~ 5%
How well do we know these?

Triangle or Race-track?

- **Storage Ring**

1. Triangles
   - More usable decays than racetrack (up to 48 %)
   - Two rings in a single tunnel
   - But only works for detectors within constrained relative angles
   - Requires more difficult construction (curving up to near vertical)
   - Requires greater total depth and not possible at some sites
   - Only efficient if two detectors up and running
2. Racetracks
   - Fewer useful decays (up to 38%)
   - Two tunnels: twice total tunnel length
   - But same bend and beam length as triangle
   - No constraint on detector angles
   - Can use less total depth
   - Either ring can be filled in both directions if only one detector is up, or to respond to physics needs

Or else too many decays In 3rd "useless" leg.

Minimum length of 3rd leg for given angle is when ring is vertical

~ 400m. Limited by geology

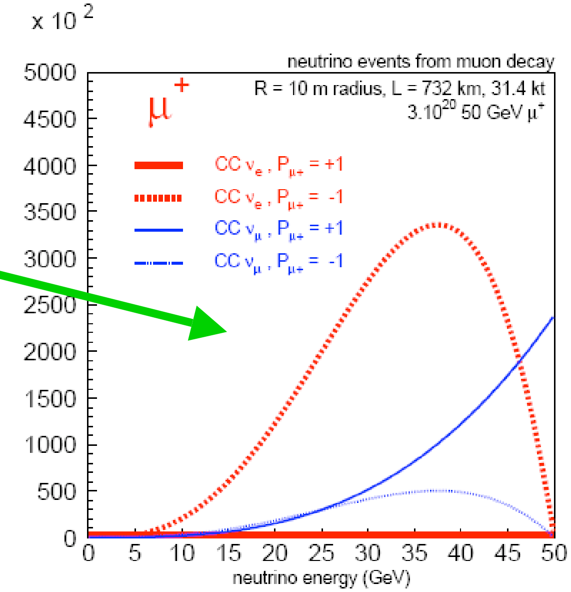
If two far sites needed

Energy spectra- Polarization

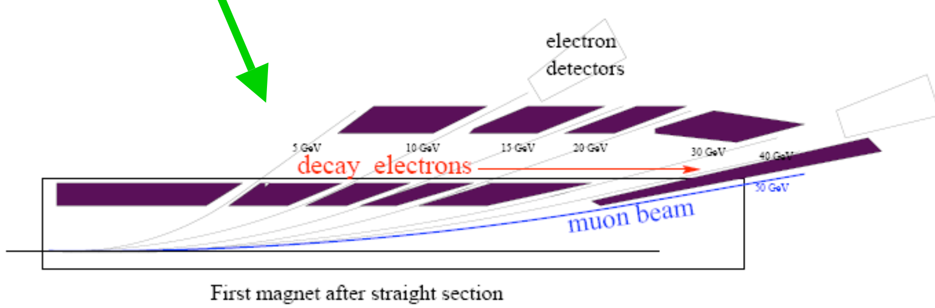
The neutrino energy spectrum
Depends on the μ polarization.

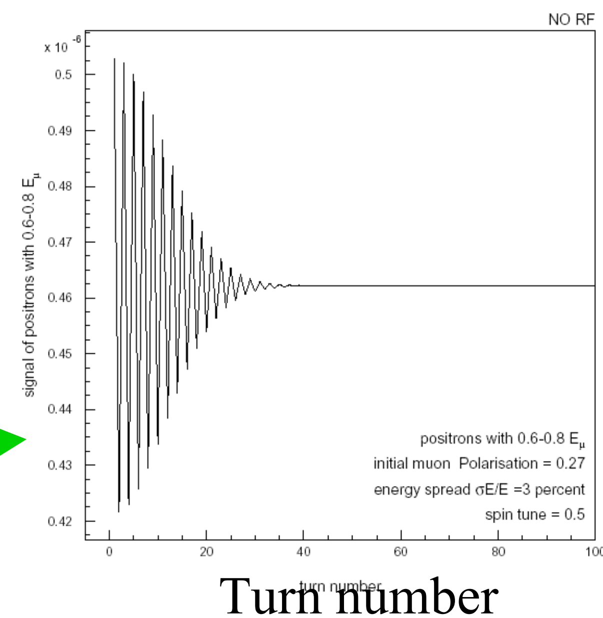
This will precess in the storage ring
and average out.

Must be monitored.



muon polarimeter





Number of decay positrons with [0.6-0.8] E_μ
gives the polarization, energy, and energy spread
of beam

Preliminary conclusions reached at April ISS meeting

Summary

- RF Frequency: Baseline is 201 MHz
- Phase Rotation: Baseline is Neuffer bunched beam rotation
- Phase Rotation: Baseline RMS bunch length ≈ 2 ns
- Amount of Cooling: Baseline is 50 m
- Target: Baseline is Liquid Mercury instead of solid
- Pion Collection: 20 T Solenoid instead of horn
- Repetition Rate: ≈ 50 (Hz)
- Proton bunch structure: ≈ 4 bunches spaced by ≈16 μsec
- Proton energy: 5-15 (GeV)
- Final acceleration: No decision yet
- Storage Ring: Choice is site dependent

Allows simultaneous collection of μ^+ and μ^-. Bunches separated by 400 ns → distinguish them through timing.

10^{21} ($\mu^+ + \mu^-$) decays per year
Half per straight section