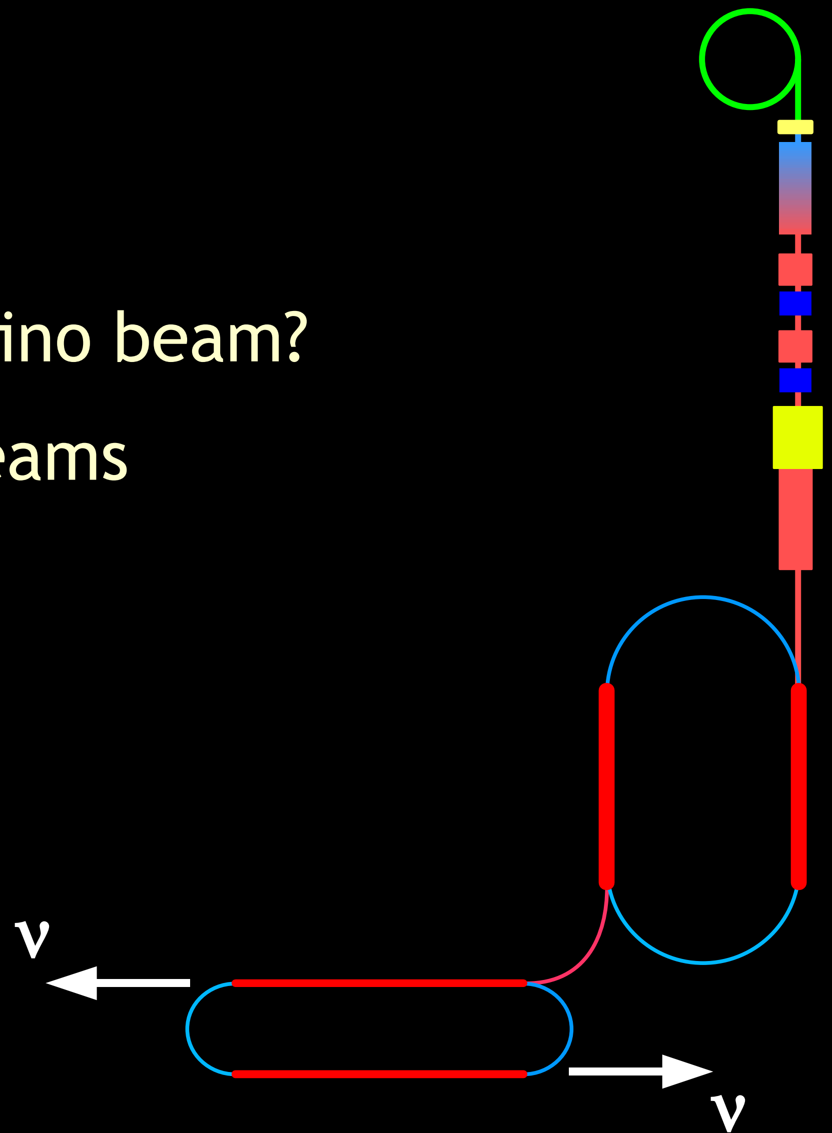
# Neutrino Beams – A Machine Overview

Neutrino beams for Long Baseline oscillation experiments

**by Daniel Kollar**

MPI, 09.06.2006

- why do you need a neutrino beam?
- conventional neutrino beams
- superbeams
- neutrino factory
- beta beams
  - EC beams



# Why do you need a neutrino beam?

We know:

- neutrinos oscillate and have masses — $\Delta m^2_{atm}$, $\Delta m^2_{sol}$, $\theta_{12}$, $\theta_{23}$, limit on $\theta_{13}$

$\Rightarrow$ from **natural neutrino sources** — solar & atmospheric neutrinos (and from reactor neutrinos)

We **DON'T** know:

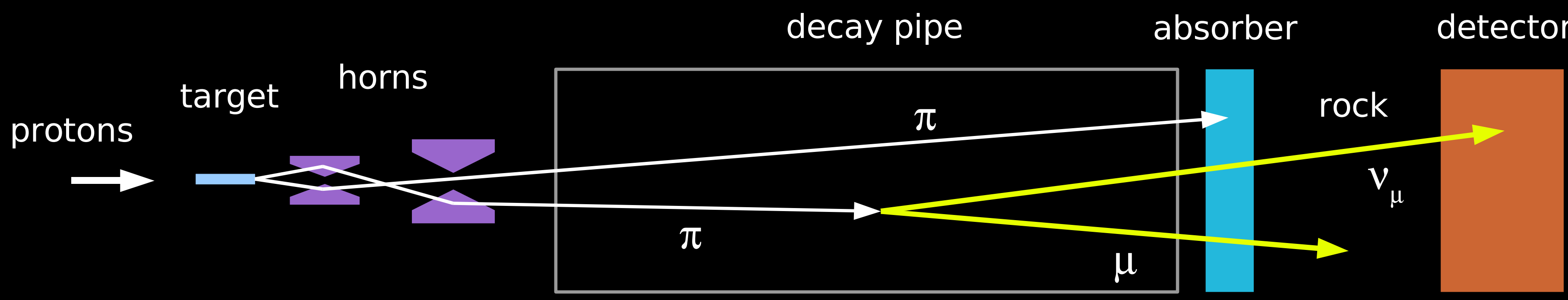
- what is the absolute mass scale?
- what is the size of $\theta_{13}$, is it non-zero?
- CP violation?
- ...

Large improvement in precision of measurements can be achieved if one exactly knows

→ flavour composition
→ flux density
→ energy

} **NEUTRINO BEAMS**

# Neutrino beam

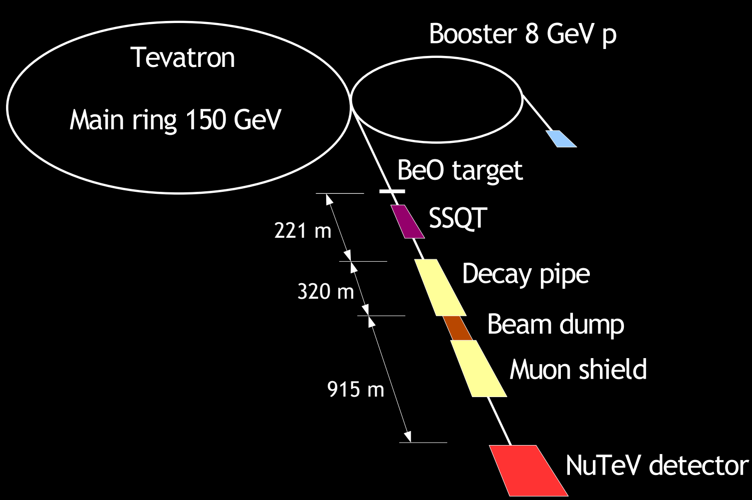



Generic features:
- produce weakly decaying relativistic particles
- focus them towards detector
- allow them to decay
- shield the detector from unwanted particles

Types:
- conventional — $\pi^+, K^+ \rightarrow \mu^+ \nu_\mu$
- muon source — $\mu^+ \rightarrow e^+ \nu_e \nu_\mu$
- beta source — ${}^{A}Z \rightarrow {}^{A}(Z+1)\, e^- \nu_e$

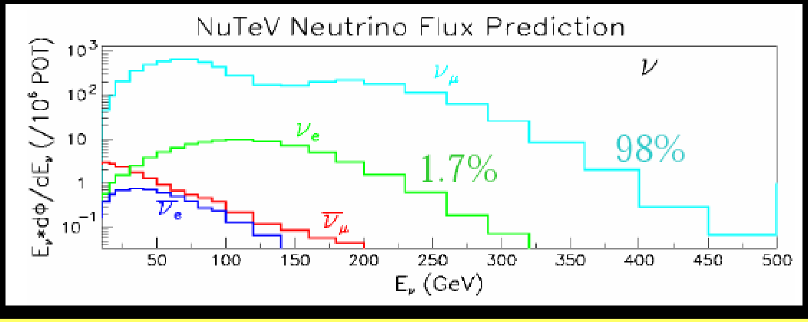
# Conventional beams

- use existing multi-GeV proton beams (small intensity)
- $\pi$ and **K** mesons primarily decay to muon neutrinos or anti-neutrinos
  - selection using meson charge sign, e.g. $\pi^+ \to \mu^+\nu_\mu$ , $\pi^- \to \mu^-\nu_\mu$
- flavour backgrounds come from
  - muon decay
  - $K_{e3}$ decay ($K \to \pi^0 e \nu_e$, ~7% of $K \to \mu\nu_\mu$ decay rate)
  - charm decay (to $eD_s$ with $D_s \to \tau\nu_\tau$)




Example: **NuTeV**

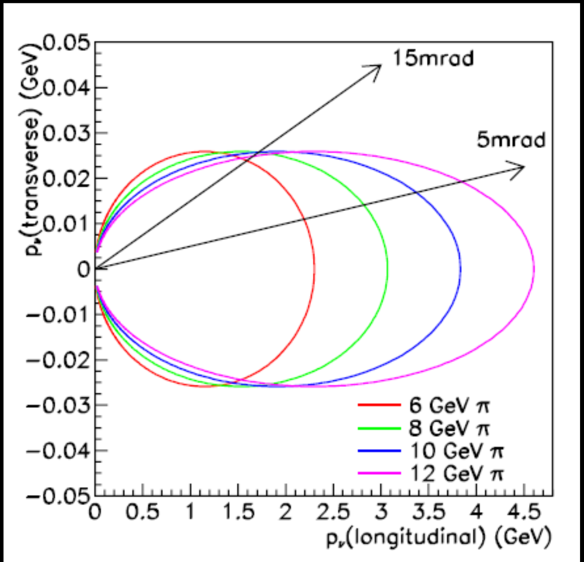
- $10^{13}$ p $\to$ $2\times10^{12}$ $\pi$/K $\to$ $3\times10^{10}$ $\nu$ $\to$ 30 interactions in detector
- very pure beam
- broad energy spectrum



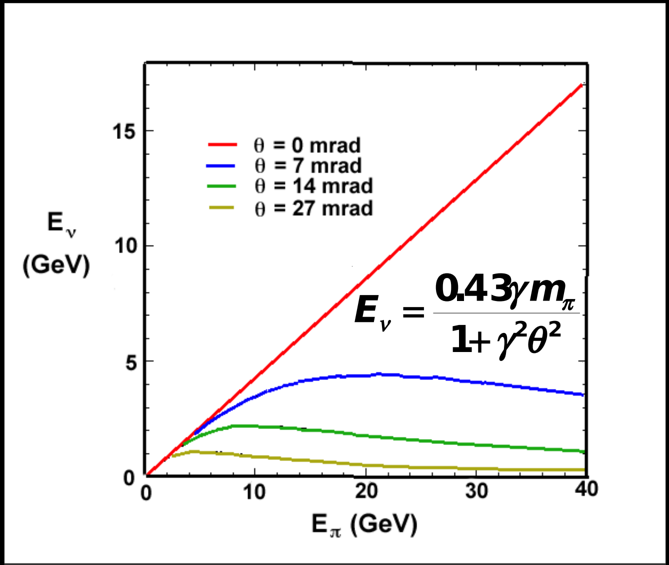
# "Off-axis" beams

Purposeful misalignment of beam with detector → **WHY?**

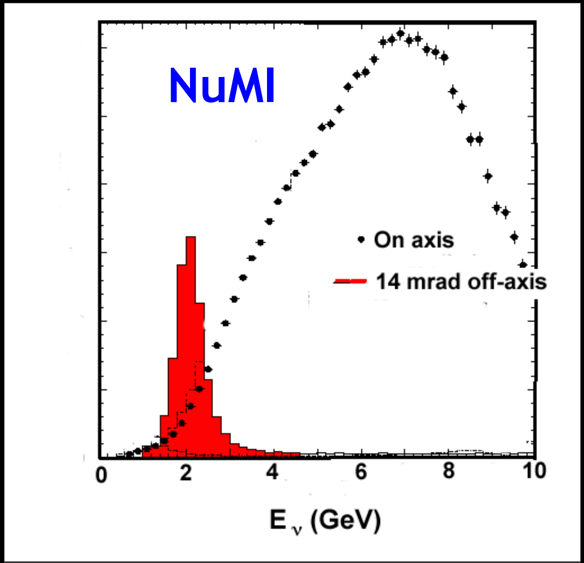
- considering two-body decay $\pi \rightarrow \mu \nu_\mu$
- **neutrino momentum at a small angle from the meson direction is nearly independent of parent meson energy !!!**
- at 15 mrad $E_\nu \approx$ 1.5-2.0 GeV for all pion energies
- higher low energy flux, smaller total flux




neutrino momentum ($p_t$ vs. $p_l$) for different π energies

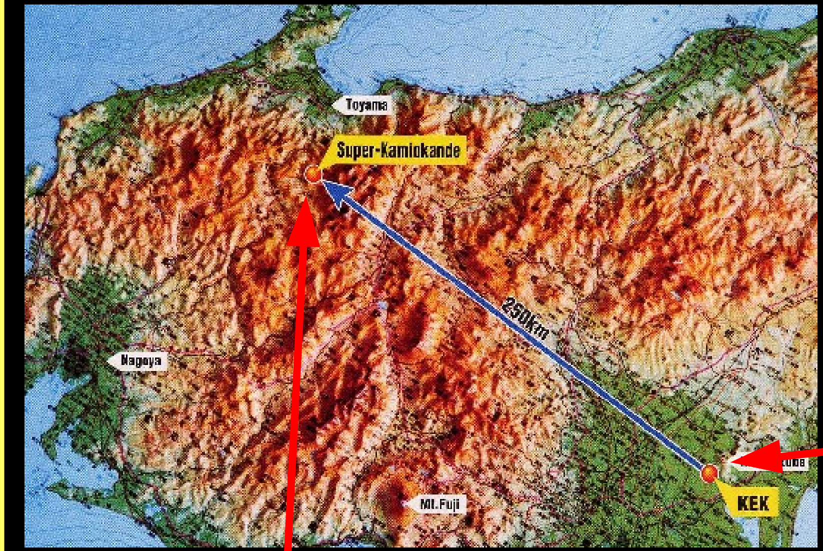


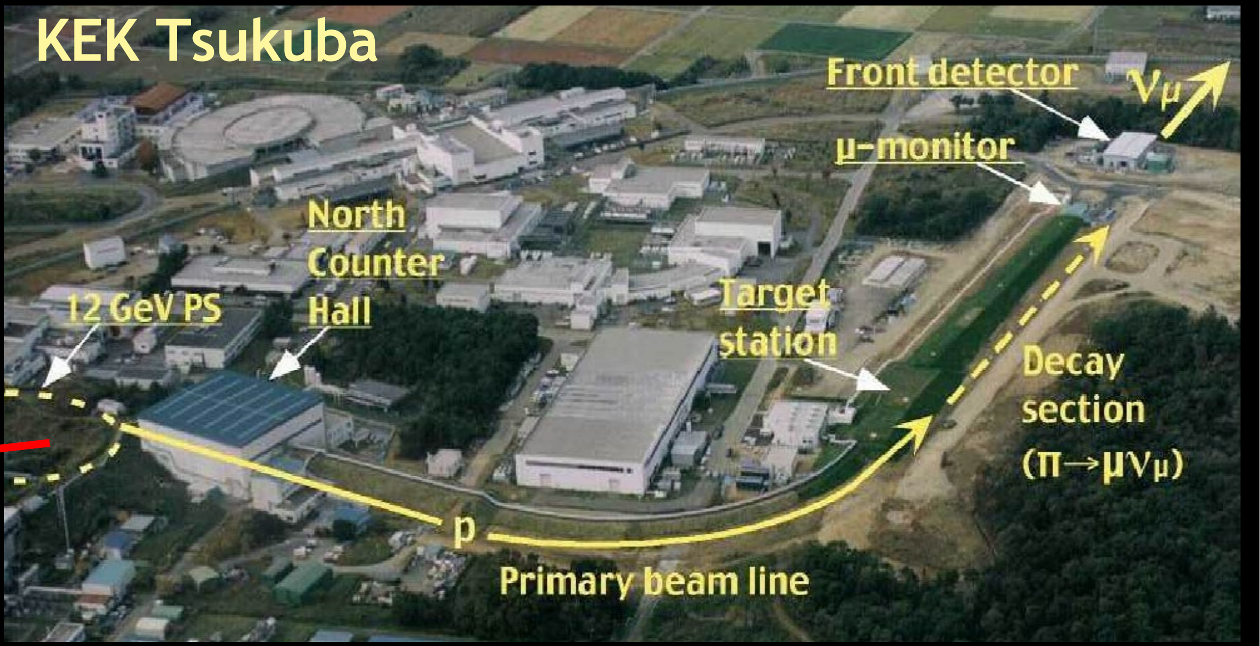

neutrino energy as a function of π energy for different angles

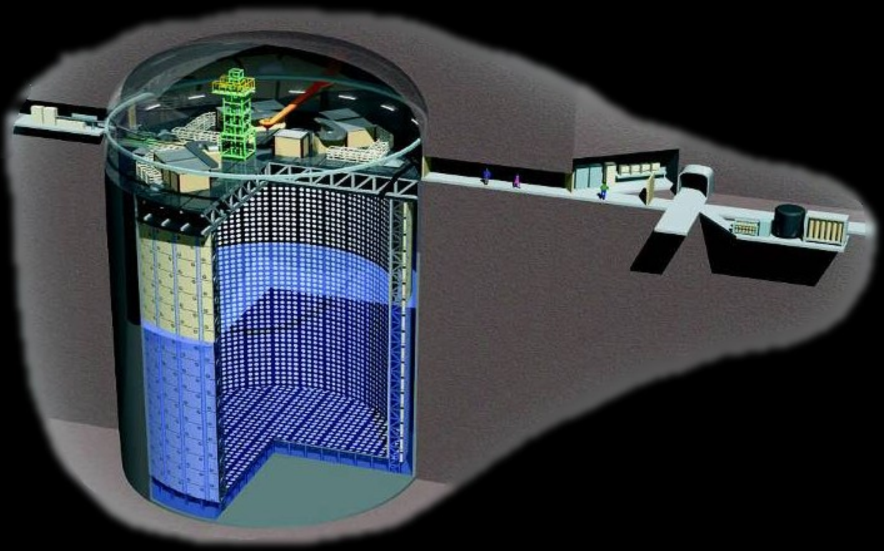



on-axis anf off-axis neutrino spectra from MuMI beam

# K2K



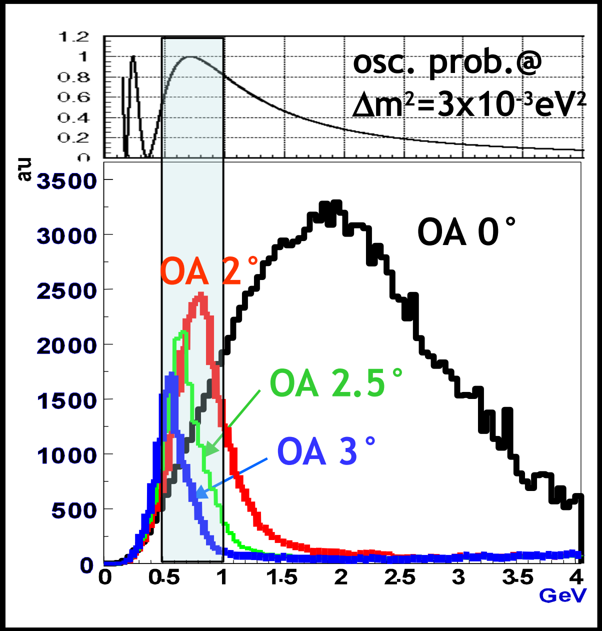



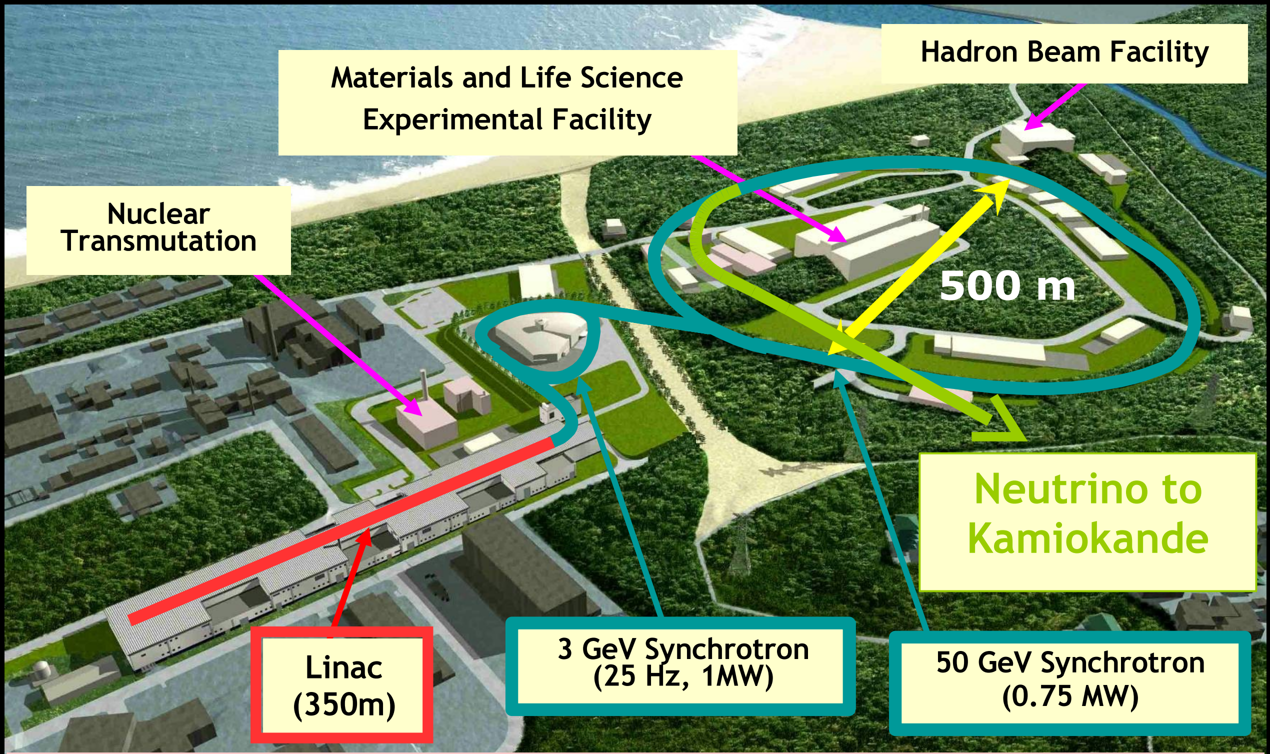



## Neutrino beam from KEK to Kamioka

- 250 km to SUPERKAMIOKANDE experiment (50 kt water Čerenkov)
- 1 kt water Čerenkov near detector
- running from 1999 to 2004

# T2K

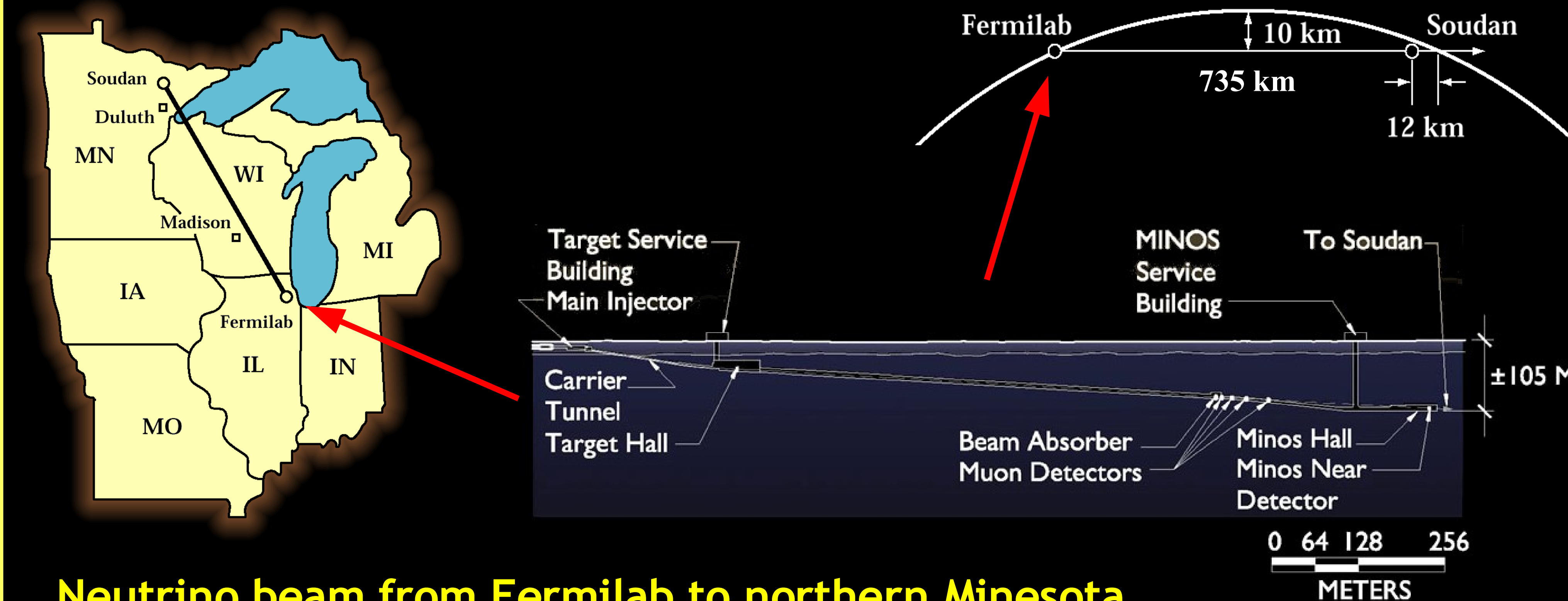




J-PARC = Japan Proton Accelerator Research Complex

## Neutrino beam from Tokai to Kamioka

- 295 km to SUPERKAMIOKANDE experiment
- 2.5° off-axis to increase oscillation sensitivity
- J-PARC under construction since 2004
- start of experiment in 2009
- proton driver with 0.75 MW at 50 GeV

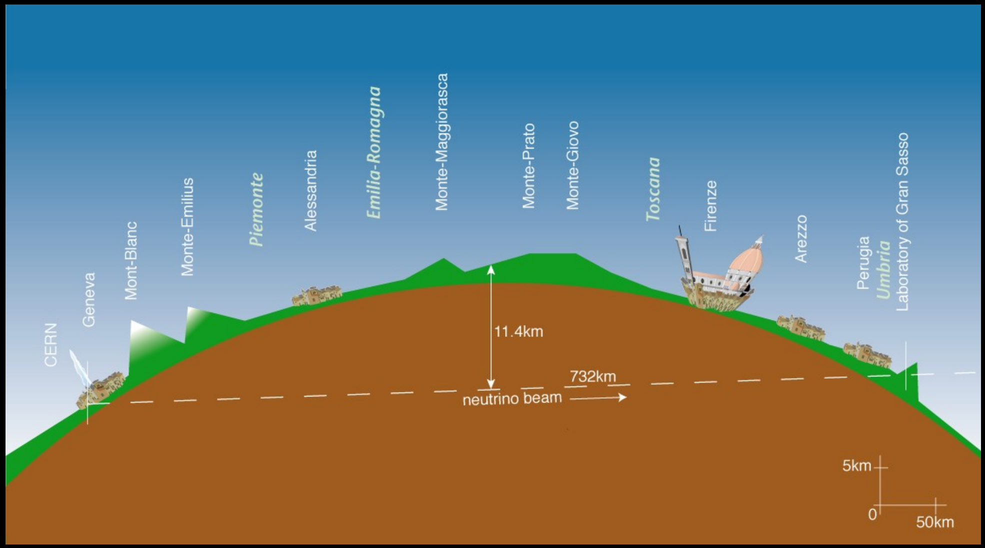
# NuMI

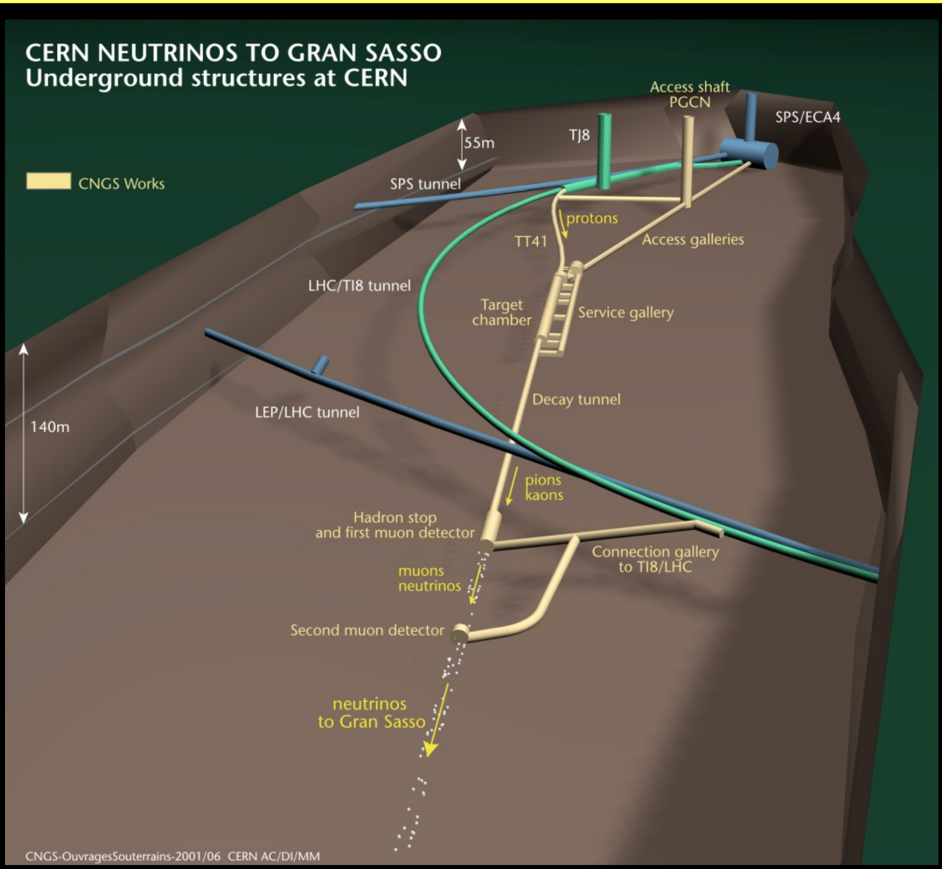


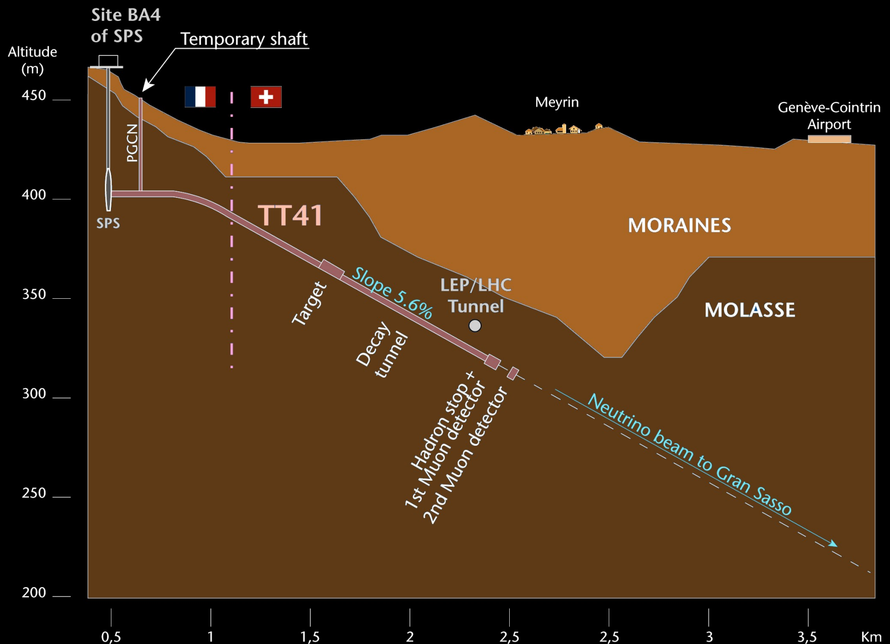

## Neutrino beam from Fermilab to northern Minesota

- on-axis over 735 km to Soudan mine → MINOS experiment
- 15 mrad off-axis over 810 km to Ash River → NOνA experiment
- large **Near Hall** at 1 km from the target
  - MINOS near detector, MINERνA, PEANUT (exposure of opera bricks)
- facility design up to 0.4 MW (120 GeV protons)
- running since 2005

# CNGS




## Neutrino beam from CERN to LNGS

- 732 km to OPERA and ICARUS detectors
- first beam in July this year
- proton beam with 0.5 MW at 400 GeV
- optimized for $\nu_\tau \rightarrow \nu_\mu$

# SuperBeams

New beams should be optimized for sensitive measurement of $\theta_{13}$ , $\Delta m^2_{23}$ & $\delta$

This requires:
- new higher power proton driver (multi MW)
- tunable $L/E_\nu$
- narrow band beams with $E_\nu$ = 1.5 – 2 GeV
- lower contamination with $\nu_e$

**SUPERBEAM ≡ Conventional beam + High power proton driver**

Plans for SuperBeams:

- NuMI upgrade to 1 MW → SNuMI + NOνA
- T2K PS upgrade to 4 MW + HYPERKAMIOKANDE
  - goal $\theta_{13} \geq 2.2°$
  - plans for another HK-like detector in Korea (off axis, BL > 1000 km)
- CERN-SPL SuperBeam (Superconductiong Proton Linac) with 4 MW + MEMPHYS (MEgaton Mass PHYSics) in Frejus (130 km away from CERN)
  - goal $\theta_{13} \geq 1.4°$

# Targetry

**High intensity proton beams require new technologies for targets**

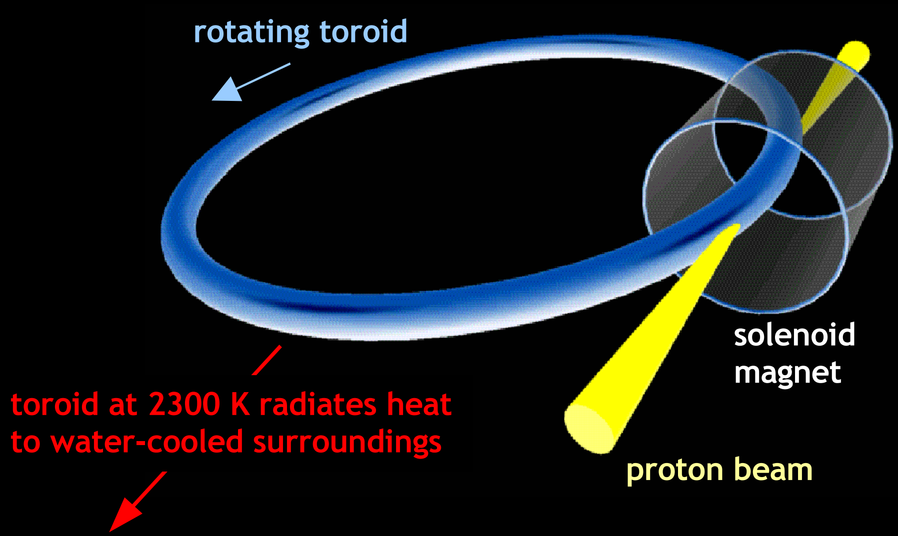
**π production targets have to balance many competing needs:**

- longer target ⇒ higher probability for proton to interact ← **GOOD**
- longer target ⇒ higher probability of meson scattering ← **NOT GOOD**
- the more protons interact, the hotter the target will be ← **VERY BAD**

**Target heating is the main issue**

→ proton pulse hitting the target leads to thermal shock waves
→ can easily result in material collapse
→ lot of R&D going on
→ proposed solutions

- Rotating toroidal ring
- Mercury jet target



# Neutrino Factory

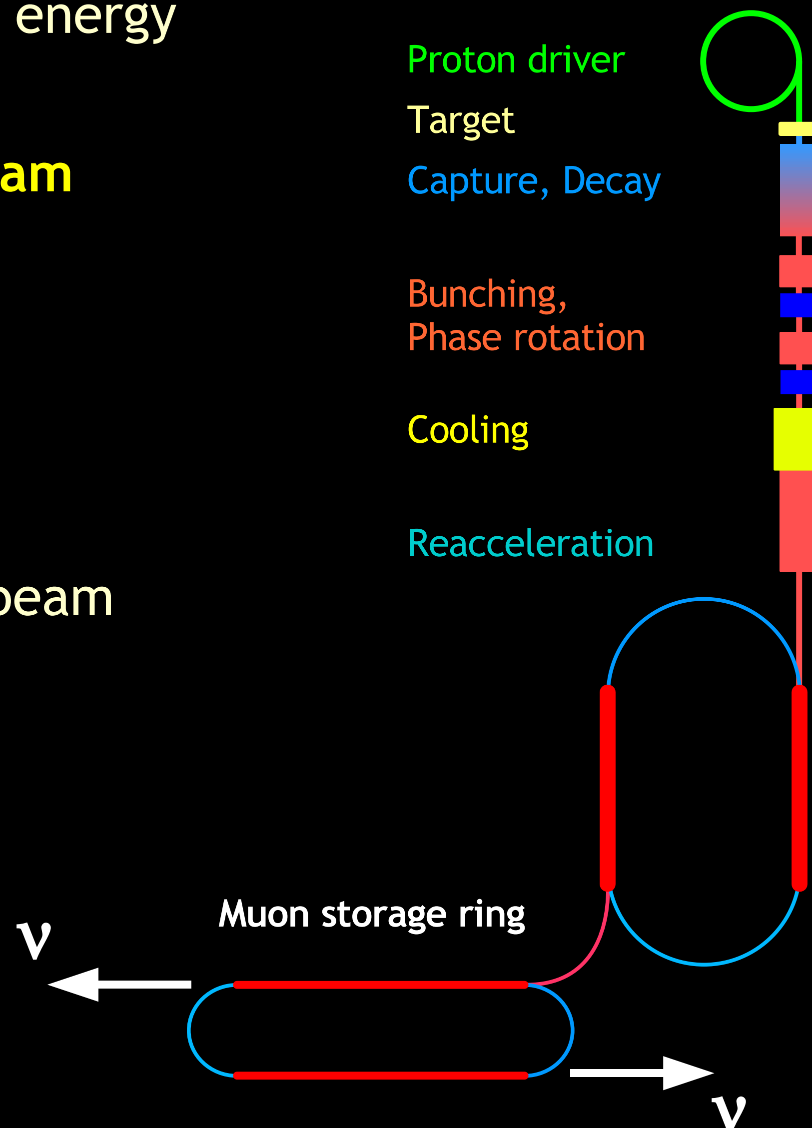
Ideally: → select beam parent

→ collimate and accelerate it to given energy

Decay then results in

**pure and perfectly predictable neutrino beam**

ideal for high precision measurements




## Neutrino Factory:

- front-end same as for SuperBeam
- now capture muons and prepare pure muon beam
  - $\mu^+ \rightarrow e^+ \nu_e \nu_\mu$ and $\mu^- \rightarrow e^- \nu_e \nu_\mu$
- however, **muon lifetime is only 2.2 μs**
  - new issues — preparing the beam in extremely short time while loosing as little muons as possible
  - ionization cooling considered

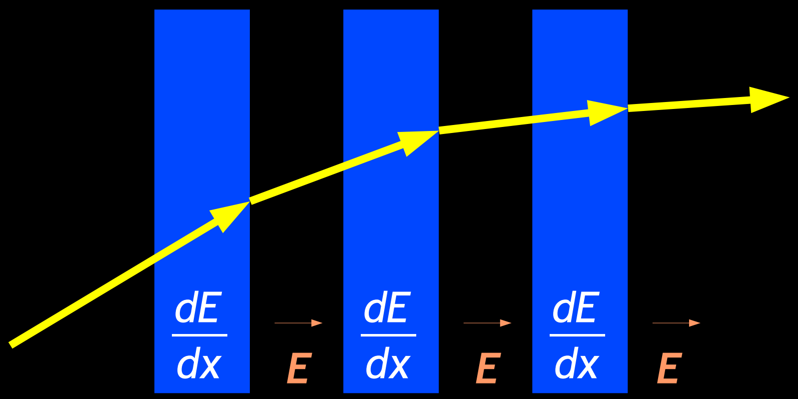
# Ionization Cooling

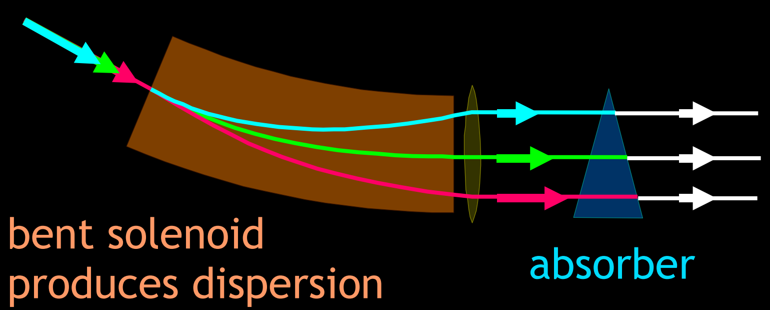
- produced muon beam occupies large phase space — large spatial and momentum spread
  - needs to be reduced before reacceleration ← **COOLING**
- standard cooling schemes used for electrons and protons too slow
- cooling scheme proposed for Neutrino factory → **Ionization Cooling**

**The Idea:**

→ muons are maintained at ≈200 MeV while passed successively through a slowing down medium and an accelerating stage

→ transverse cooling only



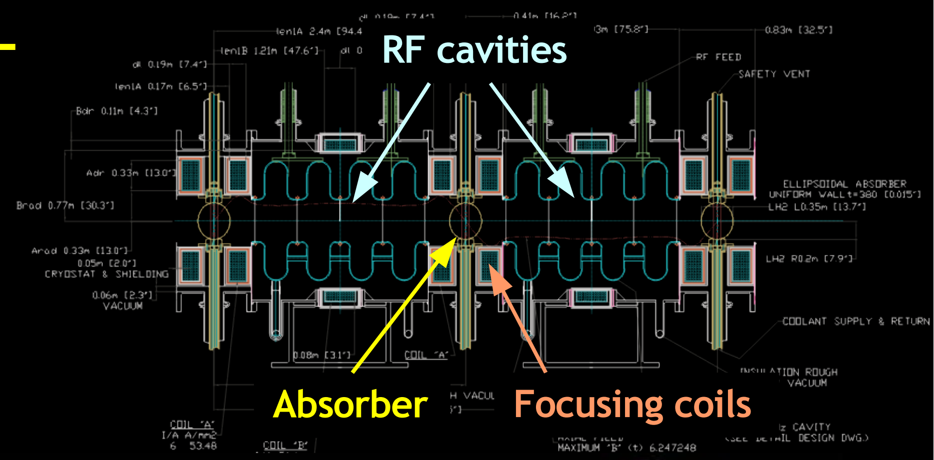



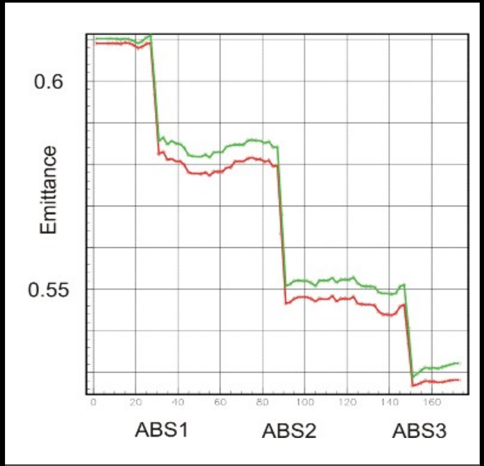

→ longitudinal cooling possible via phase rotation

# MICE

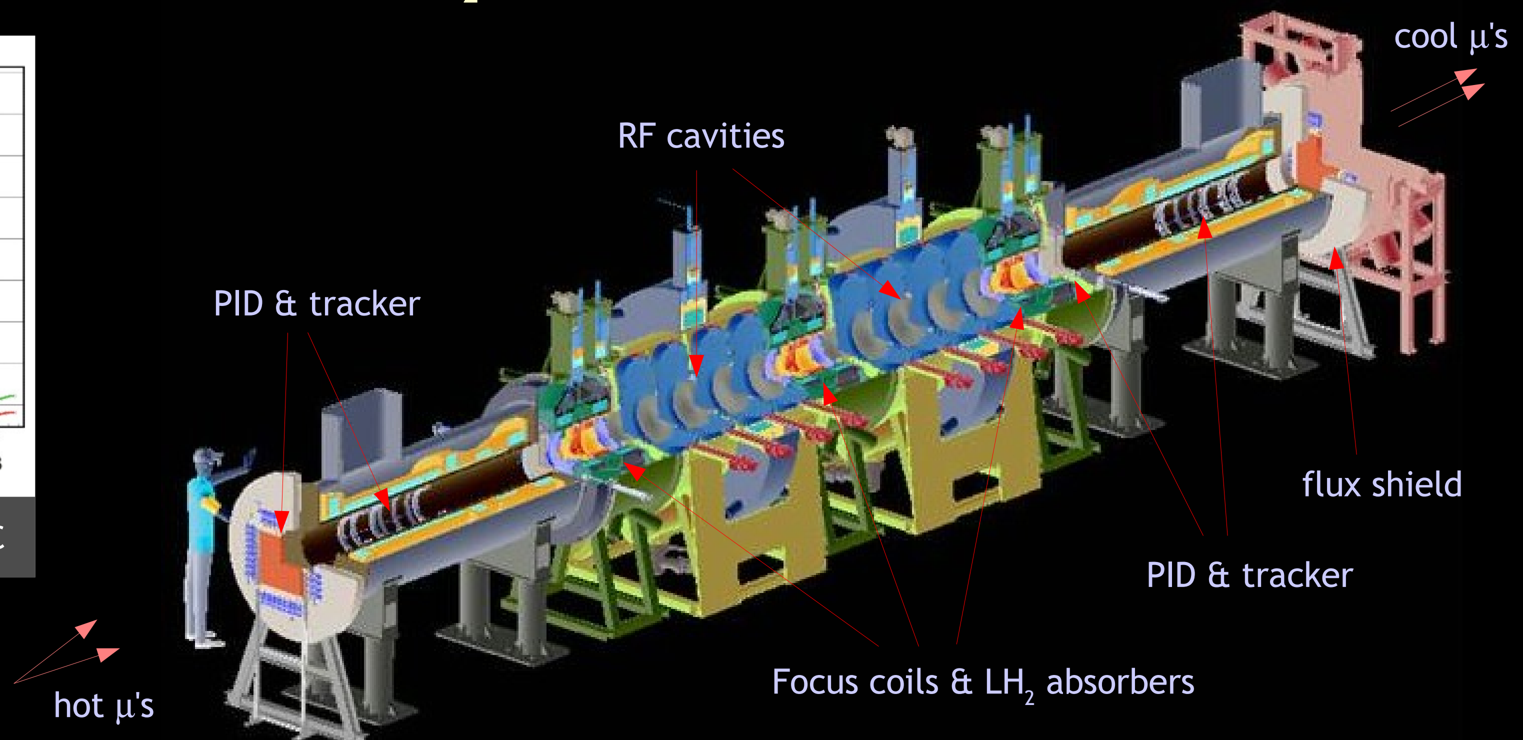
**Muon Ionization Cooling Experiment at RAL**

- demonstrate the ionization cooling of μ's
- in construction phase since 2005
- **Phase I** without acceleration should be running in 2008
- considered absorber materials: $LH_2$, LiH




emittance reduction from MC



## FFAG — Fixed Field Alternating Gradient

- unlike synchrotron, the magnetic field is fixed
  - do not have to change the strength of the ***B*** field with increasing energy
  - instead the beam naturally moves to region with higher field intensity

<u>Consequently:</u>

→ very fast acceleration
(150 MeV proton FFAG at KEK
with 100 Hz repetition rate)

→ **acceleration of large acceptance beam possible**


**Japanese Neutrino factory design with FFAG's but without Phase rotators and Cooling channel**

# Neutrino Factory revised

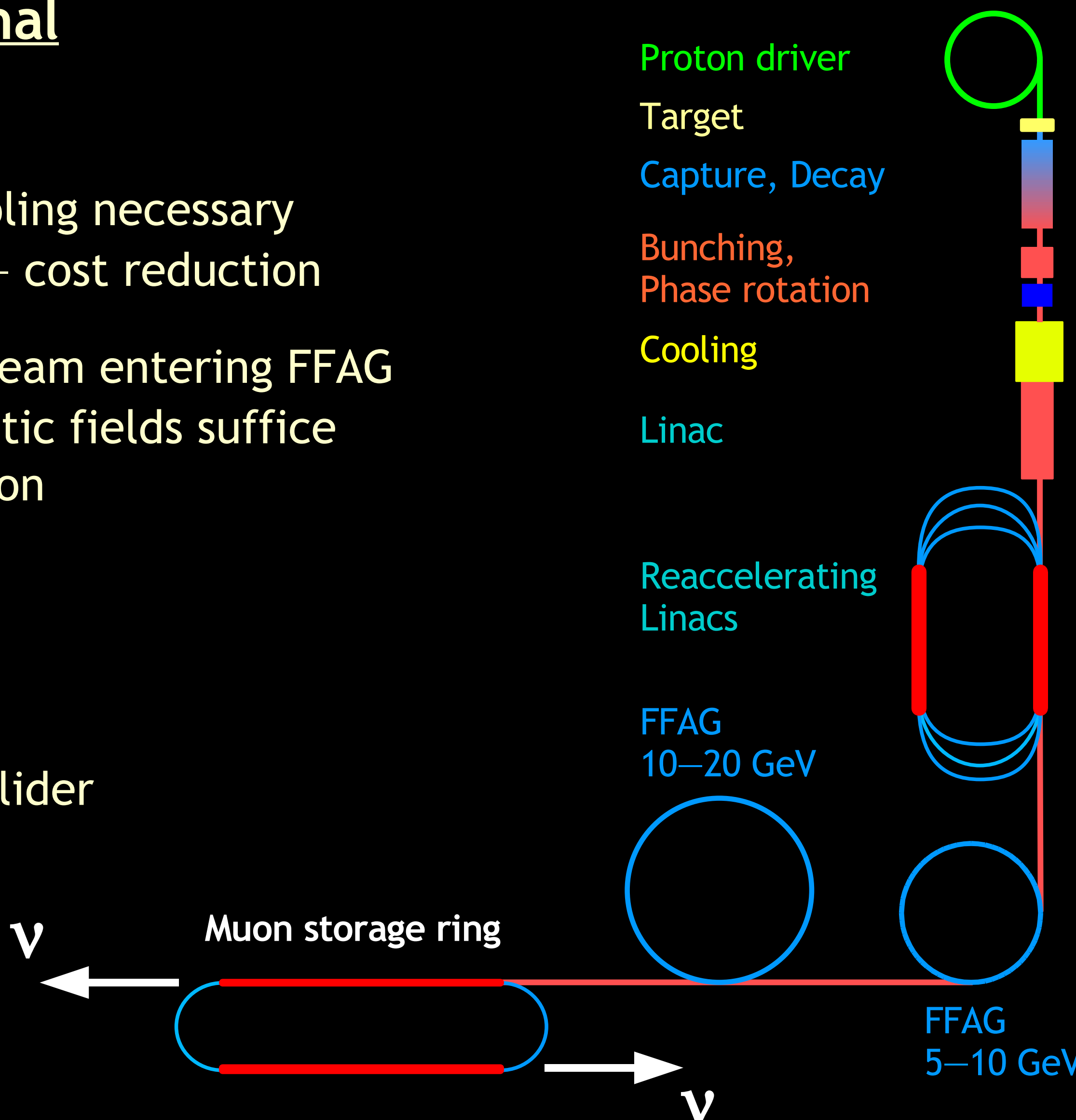
## Optimal solution — international

- use both Cooling and FFAG's
- use of FFAG ⇒ not so strong cooling necessary
  ⇒ less RF cavities — cost reduction
- use of cooling ⇒ cooler muon beam entering FFAG
  ⇒ weaker magnetic fields suffice
  — cost reduction

→ better chance to ever be built

## Related R&D:

- muon cooling studies for Muon Collider
  - frictional cooling, ...
- target R&D for
  Spallation neutron source



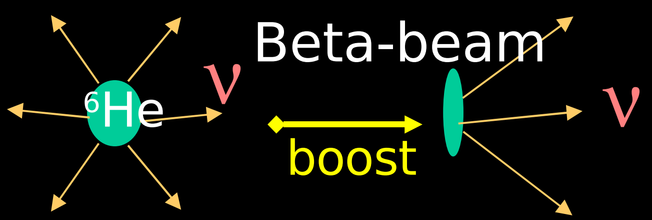
# Beta beams

Use beta-unstable nuclides for neutrino production as: ${}^{A}Z \rightarrow {}^{A}(Z \mp 1) + e^{\pm} + \nu_e(\bar{\nu}_e)$

**What's necessary:**

- radionuclides with short lifetime that can easily be produced
- not too short lifetime otherwise low intensity
- not too long lifetime otherwise no decay at high energy
- rare gases are preferred – easy ion extraction
- best options: ${}^{6}_{2}He \rightarrow {}^{6}_{3}Li + e^{-} + \bar{\nu}_e$ ${}^{18}_{10}Ne \rightarrow {}^{18}_{9}F + e^{+} + \nu_e$

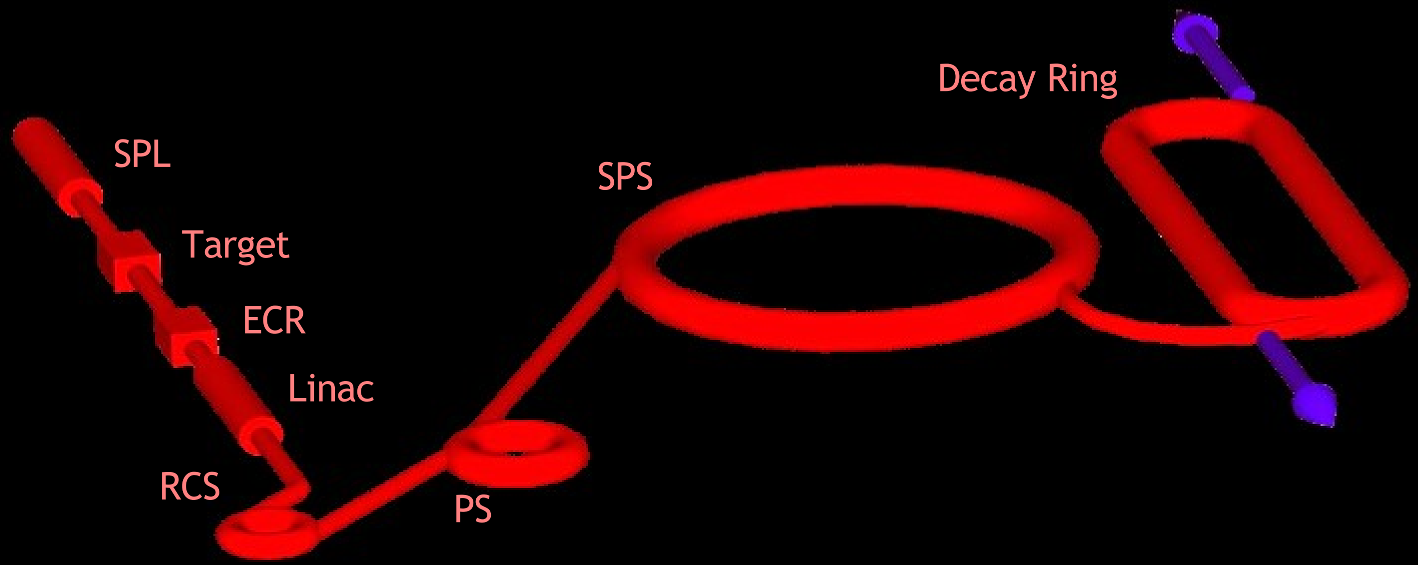
→ accelerate selected heavy ions and store them to high energy (γ~100) storage ring for decay – get pure electron (anti-)neutrino beam



# Beta beams cont.

Beta beam is European initiative (CERN)

- trying to make maximum use of existing infrastructure (PS, SPS)




- front-end R&D and construction to be shared with EURISOL (European Radioactive Ion Beam Facility)
- neutrino beam to Frejus

# EC beams

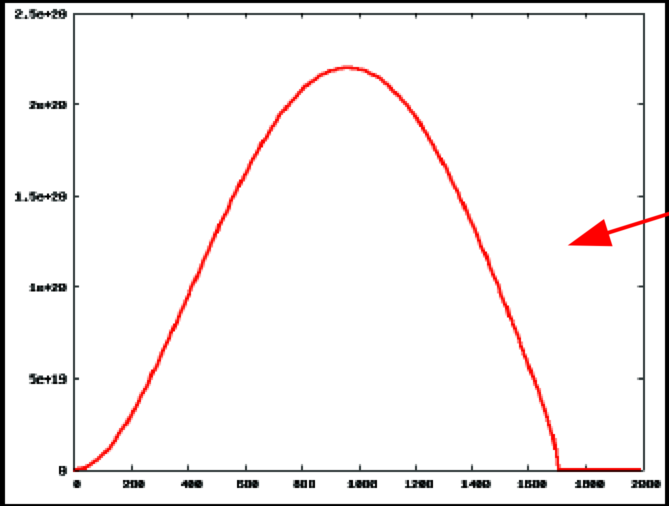
**Use Electron Capture unstable nuclei to produce neutrinos**

$^{A}Z + e^{-} \rightarrow {}^{A}(Z-1) + \nu_e$

The "breakthrough" thanks to recent discovery of short-living isotopes which decay mainly through EC to a single resonance in a super-allowed transition

Best candidate $^{150}$**Dy** $\rightarrow$ $^{150}$**Tb** (Dysprosium, Terbium)

$\rightarrow$ $t_{1/2}$ = 7.17 m, EC 99.9%, $E_\nu$ = 1.4 GeV

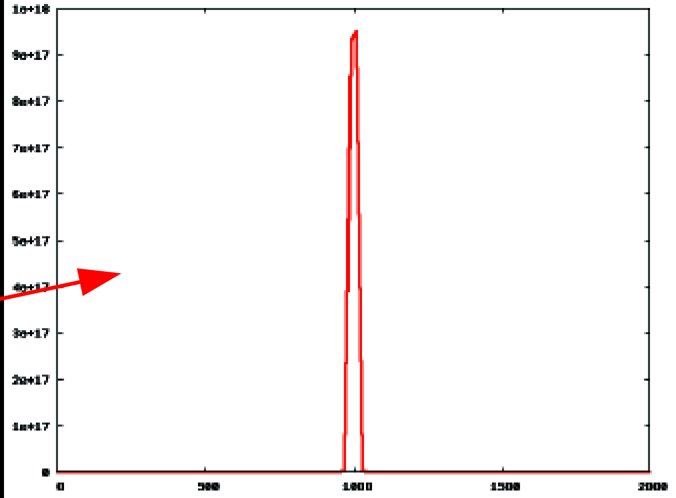



**ν flux**

Beta beam

vs.

EC beam

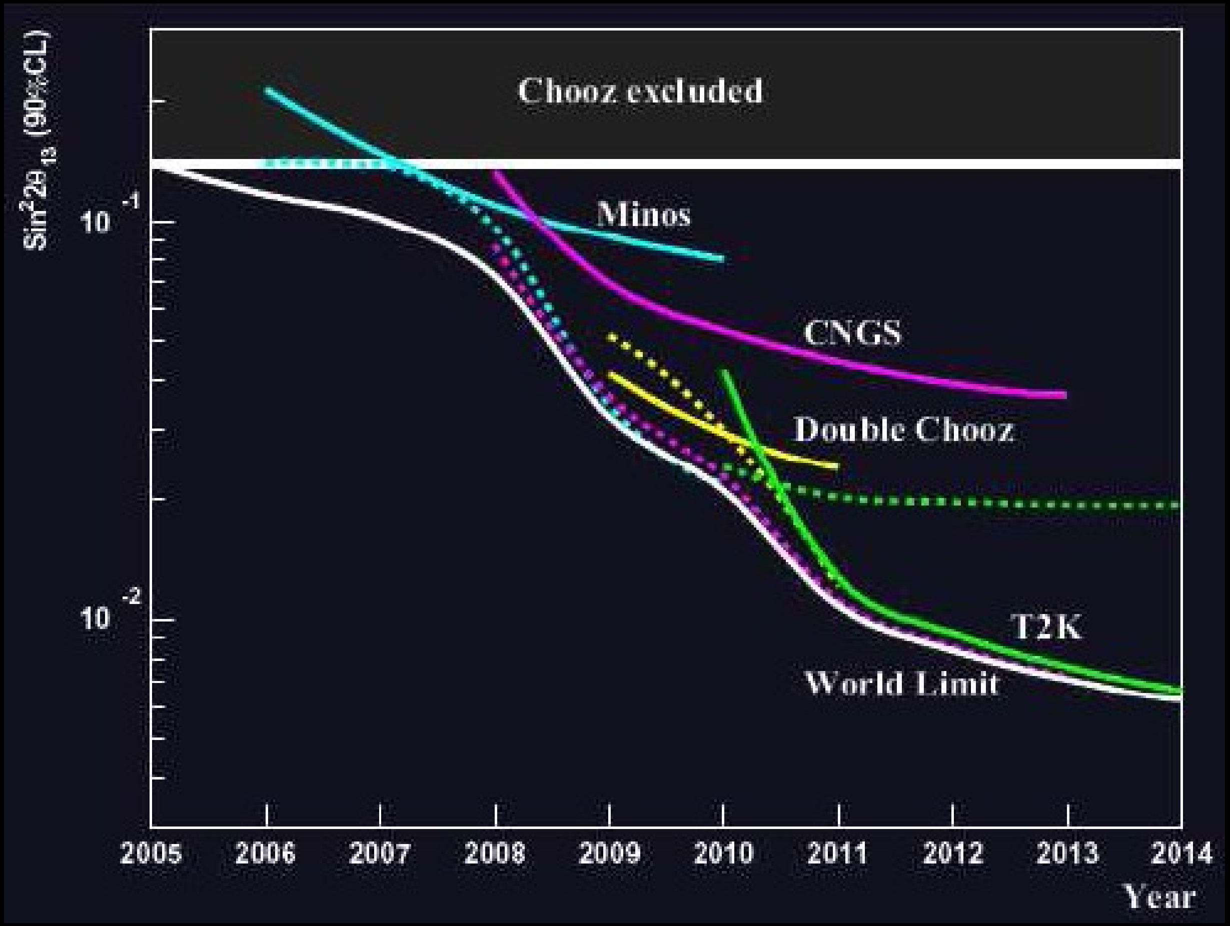



However, EC beam can produce **only neutrinos, no anti-neutrinos**

**⇒ measurement of δ is only possible in combination with other type beam**

# Sensitivity

Just one plot — sensitivity of different approved experiments to $\sin^2(2\theta_{13})$ vs. time




Not really a fair comparison as not all experiments are optimized for $\sin^2(2\theta_{13})$ measurement (CNGS)

Two lines for each experiment:

- solid — sensitivity of the experiment,
- dashed — world sensitivity with experiment excluded

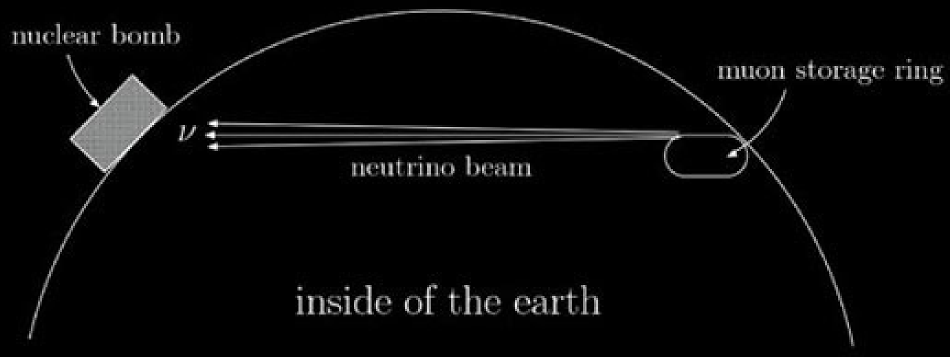
# Summary

- a couple of Conventional neutrino beams is running or being under construction
- sensitive measurement of missing parameters only with off-axis SuperBeams
- Neutrino Factory is still far away with several issues to resolve
  - probably one large international collaboration

- other applications of neutrino beams exist: (hep-ph/0305062)

"*A super-powered neutrino generator could in theory be used to instantly destroy nuclear weapons anywhere on the planet, according to a team of Japanese scientists.*"

*newscientist.com*




(Sorry if I didn't mention your favorite neutrino beam... Go go grillin'...)