May 27, 2002
@NEUTRINO2002

Future Experiments with Super Neutrino Beams

Tsuyoshi NAKAYA
(Kyoto University)

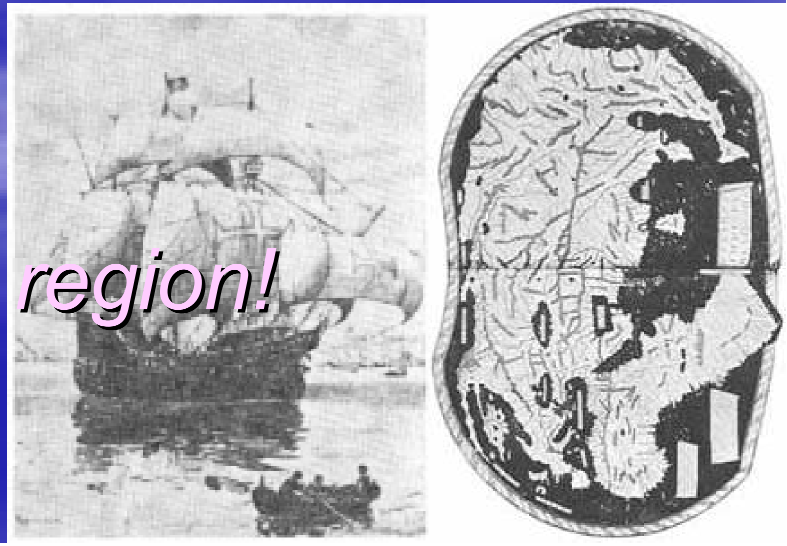
Outline

1. Introduction
2. Super Neutrino Beams
3. Experiments with a super neutrino beam
4. Physics sensitivity
5. Summary and Conclusion

1. Introduction

- A next goal of the neutrino experiments is to explore the neutrino oscillation phenomena in detail beyond the discovery phase.
  - Three generation Matrix (NMS matrix)
  - CP Violation, matter effect, the sign of Δm_{23}^2
  - May be an unexpected physics behind the oscillation phenomena.

A voyage to the unexplored region!



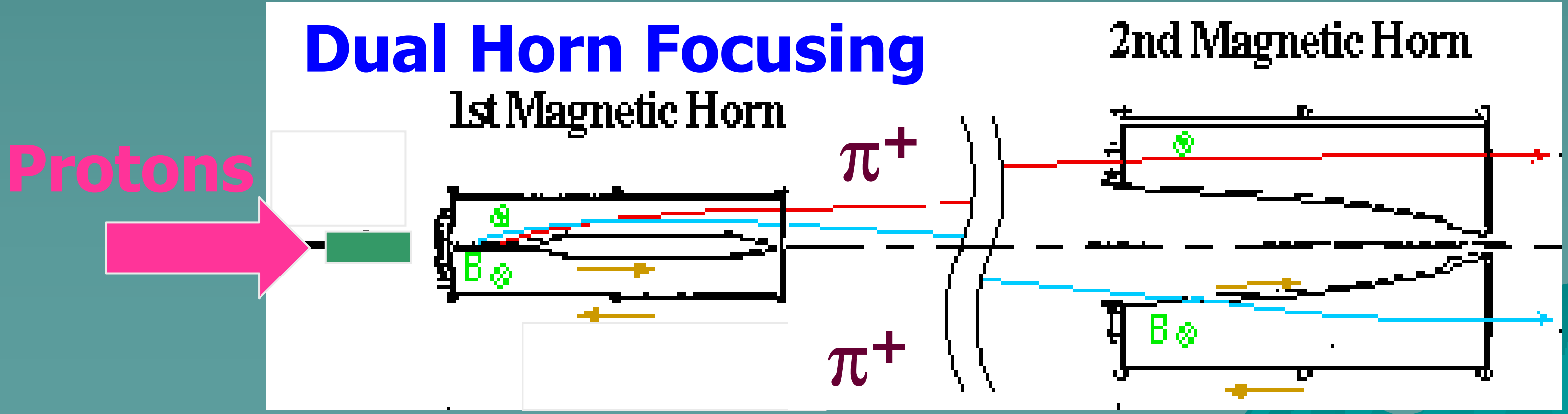
- Discovery and Confirmation.
  - Super-Kamiokande, SNO, K2K, MINOS, ICARUS, ….
  - These are good at discovering a surprise of the large effect (ν oscillation).

- , which should be followed by the more complete studies with high statistics,
  - more precision
    - θ_{23}, Δm^2_{23}, oscillation curve, non-oscillation scenario
  - sensitive to a rare process
    - θ_{13} ($\nu_\mu \rightarrow \nu_e$), CP Violation, unexpected phenomena.

to explore the underlying physics of ν oscillation.

2. Super Neutrino Beam

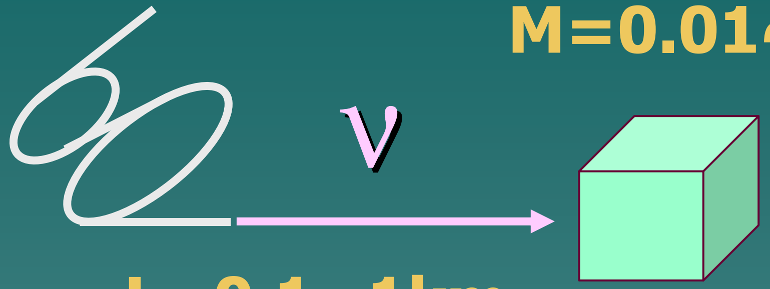
- A Super Neutrino Beam makes it possible to study ν oscillation phenomena with a great precision.
- What is the Super Neutrino Beam?
  - No Clear definition, but it is a very intense neutrino beam produced by a high power (~1MW or more) accelerator.
    - A conventional method.
    - Still technically challenging due to the high power and the high radiation environment, but not impossible.



- Past Accelerator Neutrino Experiment

P=0.01-0.1MW

M=0.01~1kton



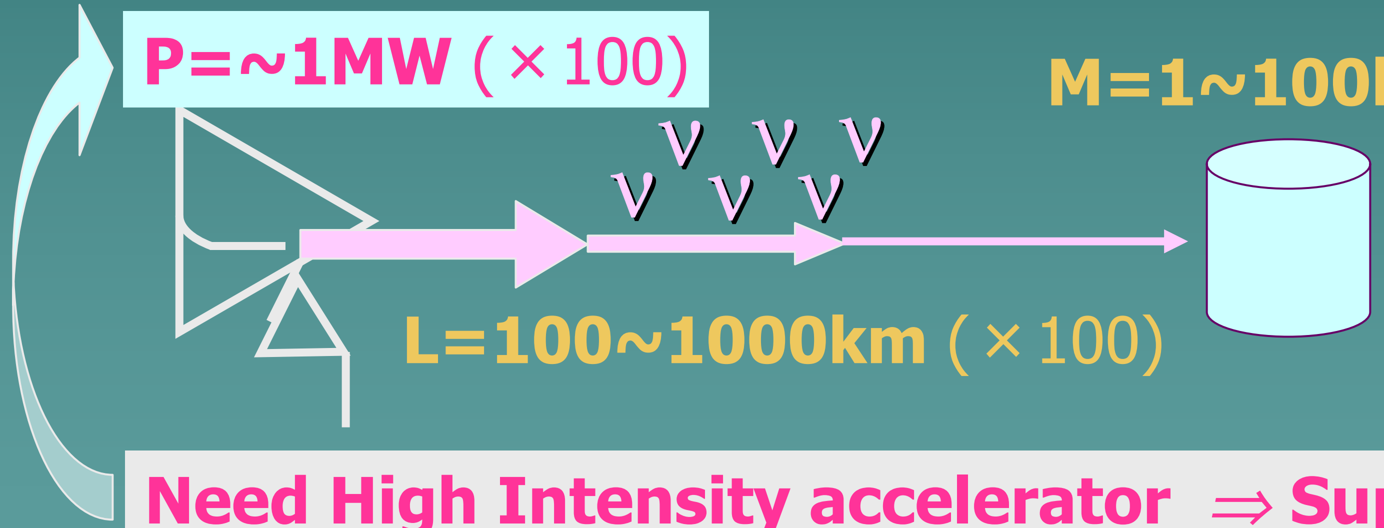
L=0.1~1km

$$\#\nu \propto P \times M / L^2$$

- Accelerator Long Baseline Neutrino Experiment

P=~1MW (×100)

M=1~100kton (×100)



L=100~1000km (×100)

Need High Intensity accelerator ⇒ Super ν Beam

NOTE: The detector size is equally important.

(High Intensity) Proton Accelerators

	Power (MW)	Energy (GeV)	Intensity (10^{12} ppp)	Rep. rate (Hz)
KEK-PS	0.005	12	6	0.45
AGS	0.14	24	60	0.6
FNAL-MI	0.41	120	40	0.53
SPS	0.3	400	35	0.16
JHF-I	0.77	50	330	0.29
Super-AGS	1.3	28	120	2.5
FNAL-proton driver-I	1.2	16	30	15
SPL	4	2.2	230	50
JHF-II	4	50		

Not the construction stage yet, but R&D stage.

(Super) Neutrino Beams

	<Eν> (GeV)	L (km)	#CC ν/kt/yr	L/Losci.*	f(νe) @peak
K2K	1.3	250	2	0.47	~1%
NuMi (High E)	15	730	3100	0.12	0.6%
NuMi (Low E)	3.5	730	469	0.51	1.2%
CNGS	17.7	732	2448	0.10	0.8%
JHF-I	0.7	295	133	1.02	0.2%
Numi off-axis	2.0	730	~80	0.89	0.5%
Super AGS	1.5	2540	11	4.1	0.5%
JHF-II	0.7	295	691	1.02	0.2%
SPL	0.26	130	16.3	1.21	0.4%
β beam**	0.58	130	84	0.54	-------

(*) $L_{osci.} = \frac{\pi}{2} \bullet \frac{\langle E_\nu \rangle}{1.27\,\Delta m_{23}^2}$ w/ $\Delta m_{23}^2 = 3 \times 10^{-3} eV^2$ (**) γ=150, ^{6}He ($\bar{\nu}_e$)

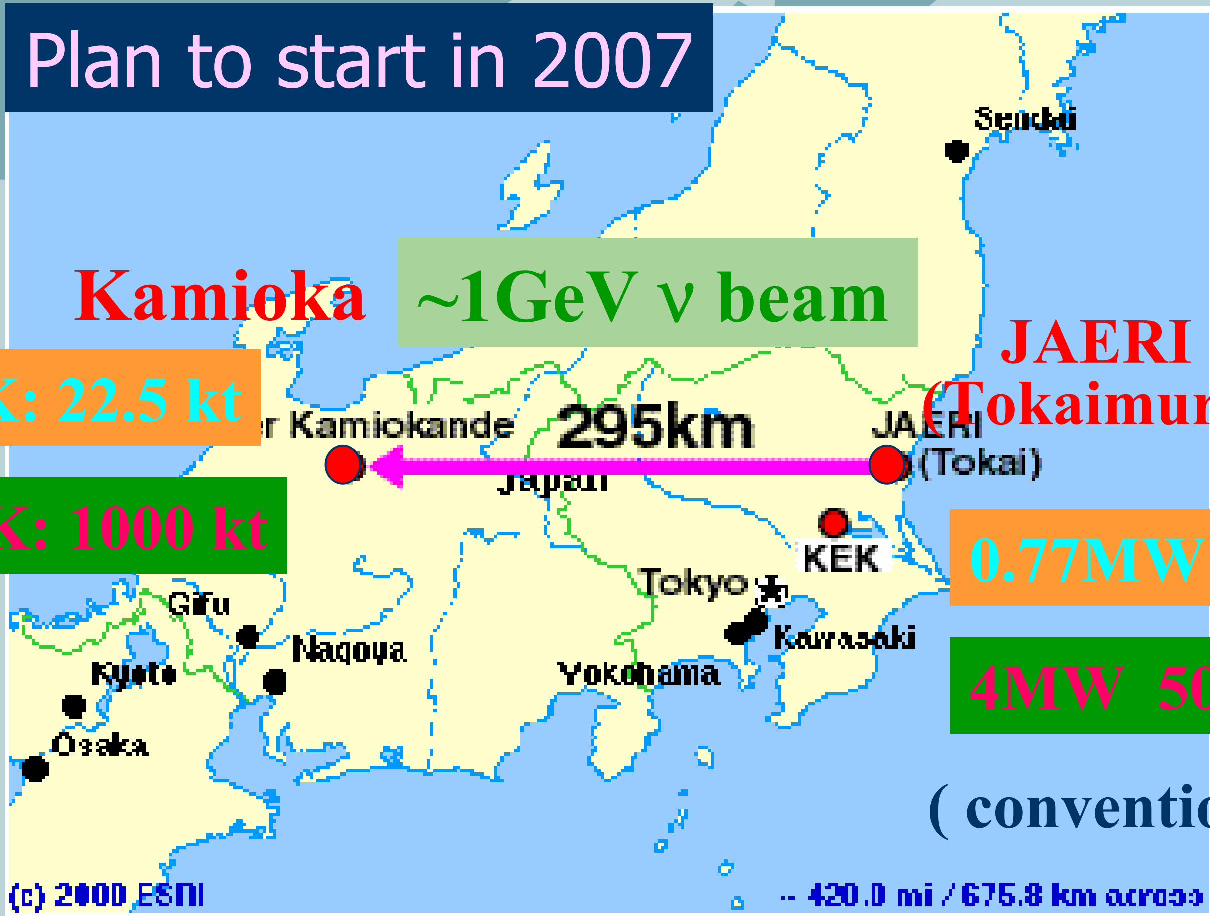
3. Experiments with the super neutrino beam

1. **Japan:** JHF-Kamioka Neutrino Project
2. **USA:** FNAL Super-NUMI w/ the proton driver upgrade and the BNL Super-AGS
3. **Europe:** SPL (or CNGS off-axis) +β beam

3.1 JHF-Kamioka Neutrino Project

(hep-ex/0106019)

Plan to start in 2007



Kamioka

~1GeV ν beam

JAERI (Tokaimura)

Super-K: 22.5 kt

Hyper-K: 1000 kt

0.77MW 50 GeV PS

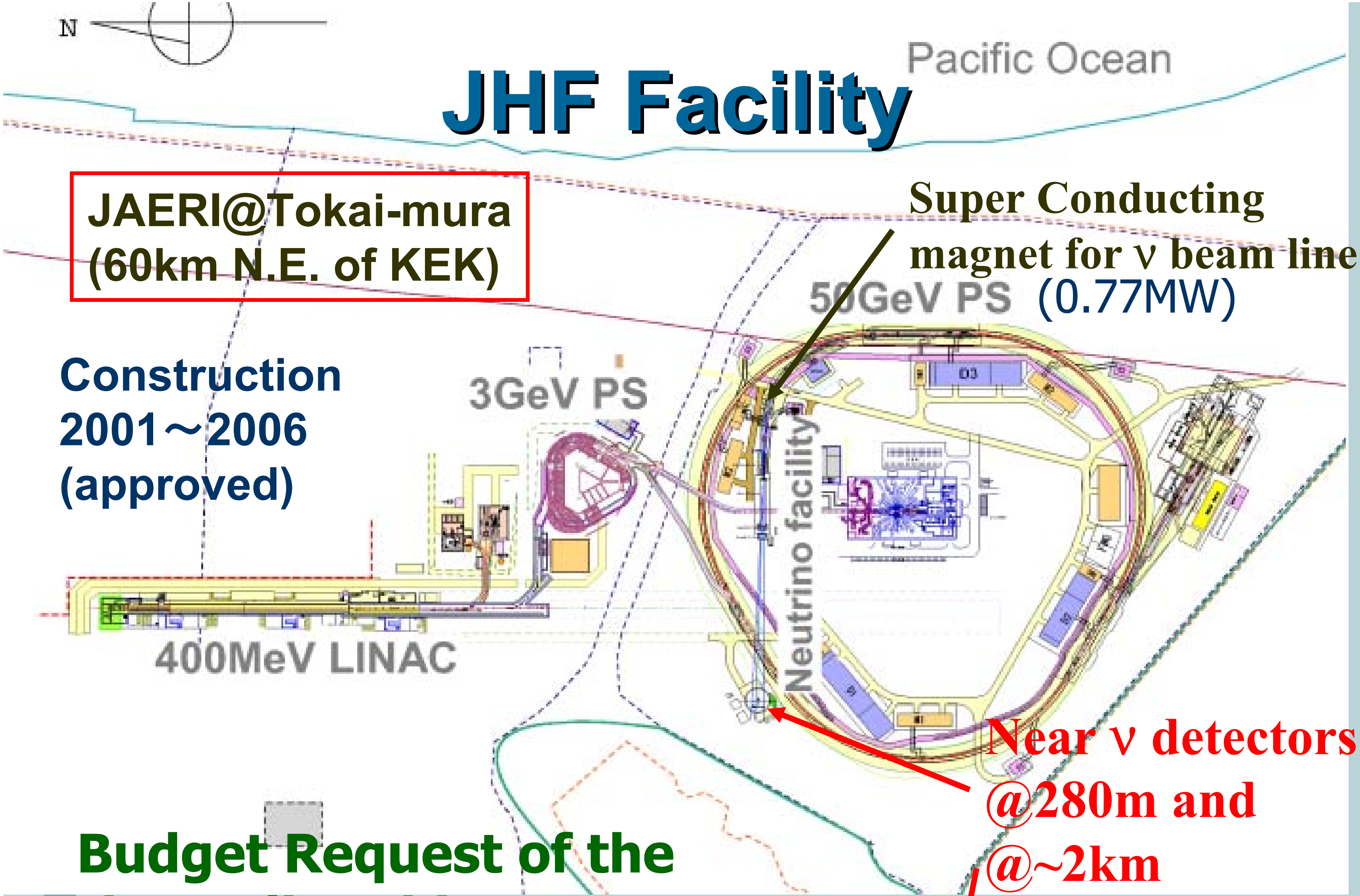
4MW 50 GeV PS

(conventional ν beam)

Phase-I (0.77MW + Super-Kamiokande)

Phase-II (4MW+Hyper-K) ~ Phase-I × 200

JHF Facility



JAERI@Tokai-mura (60km N.E. of KEK)

Construction 2001～2006 (approved)

Super Conducting magnet for ν beam line

(0.77MW)

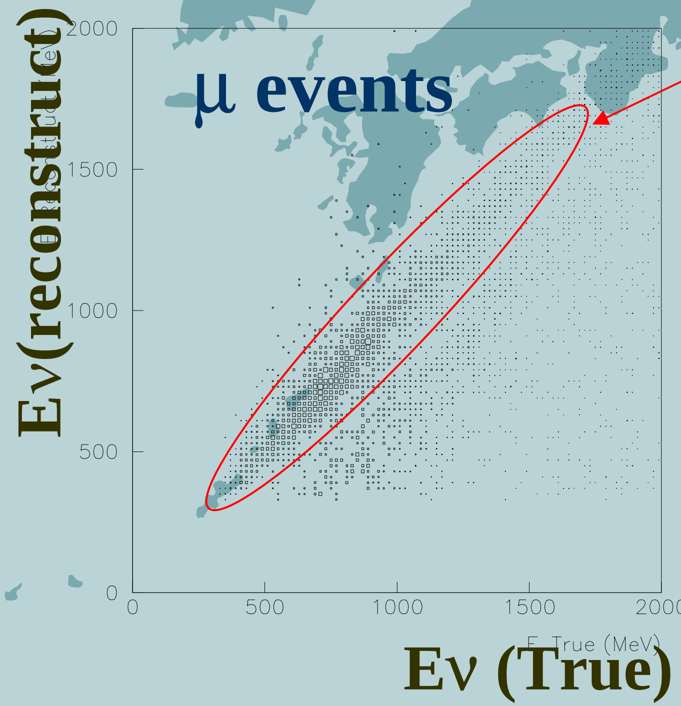
Near ν detectors @280m and @~2km

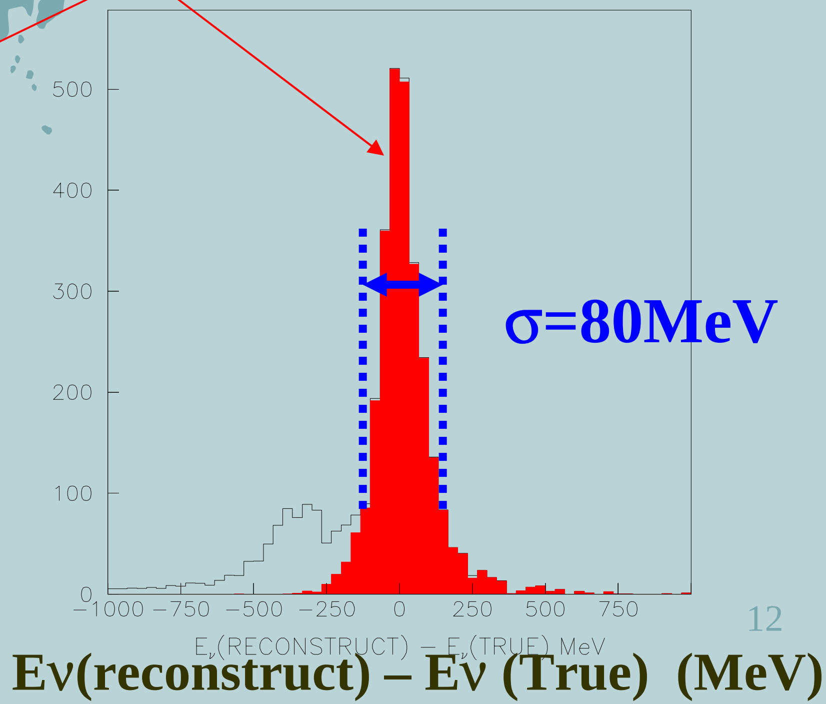
Budget Request of the ν beam line this year

10^{21}POT(130day)≡ "1 year"

ν *beam at JHF*

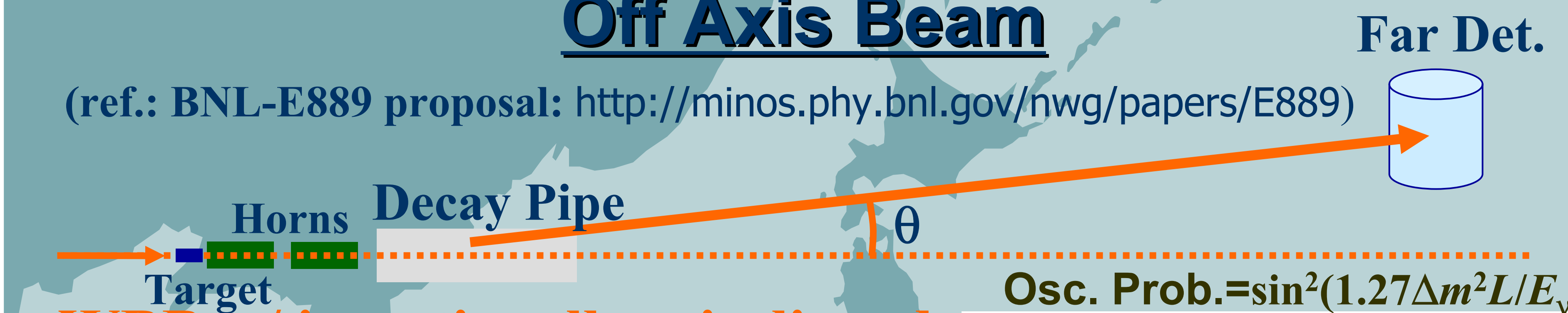
- Principle
  - Intense Narrow Band Beam by "off-axis".
  - Beam energy is at the oscillation maximum.
    - **High sensitivity, less background**
  - **~1 GeV ν beam for** Quasi-elastic **interaction.**



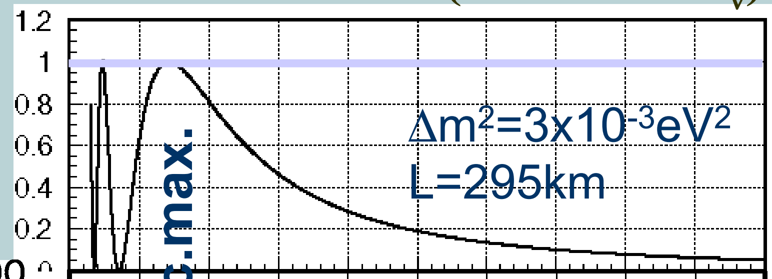


Off Axis Beam

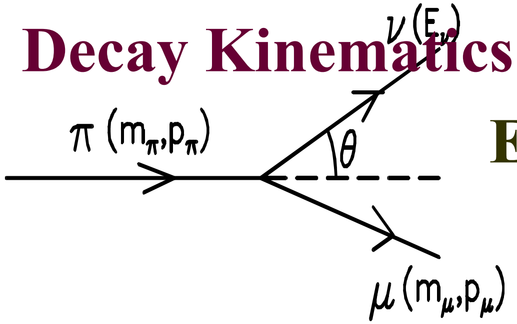
(ref.: BNL-E889 proposal: http://minos.phy.bnl.gov/nwg/papers/E889)



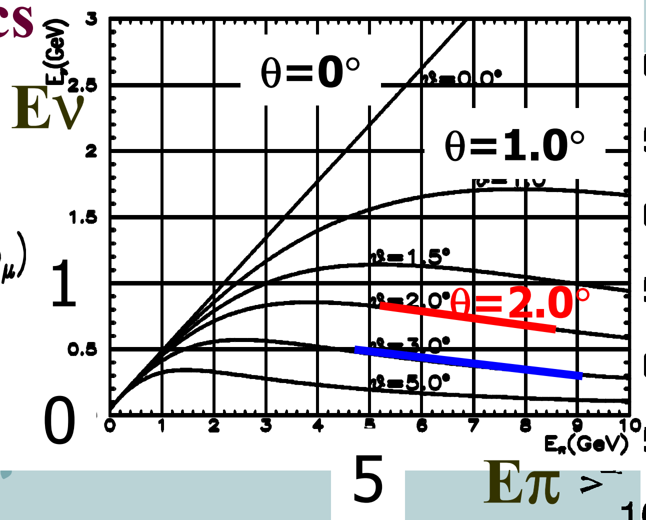
WBB w/ intentionally misaligned beam line from det. axis

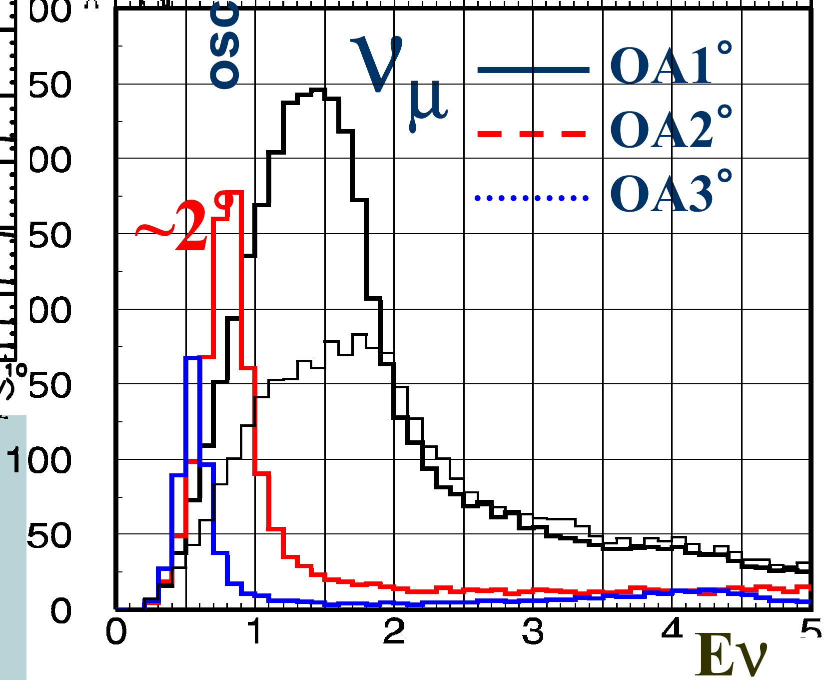


Decay Kinematics



$$E_\nu = \frac{m_\pi^{\;2} - m_\mu^{\;2}}{2(E_\pi - p_\pi \cos\theta)}$$



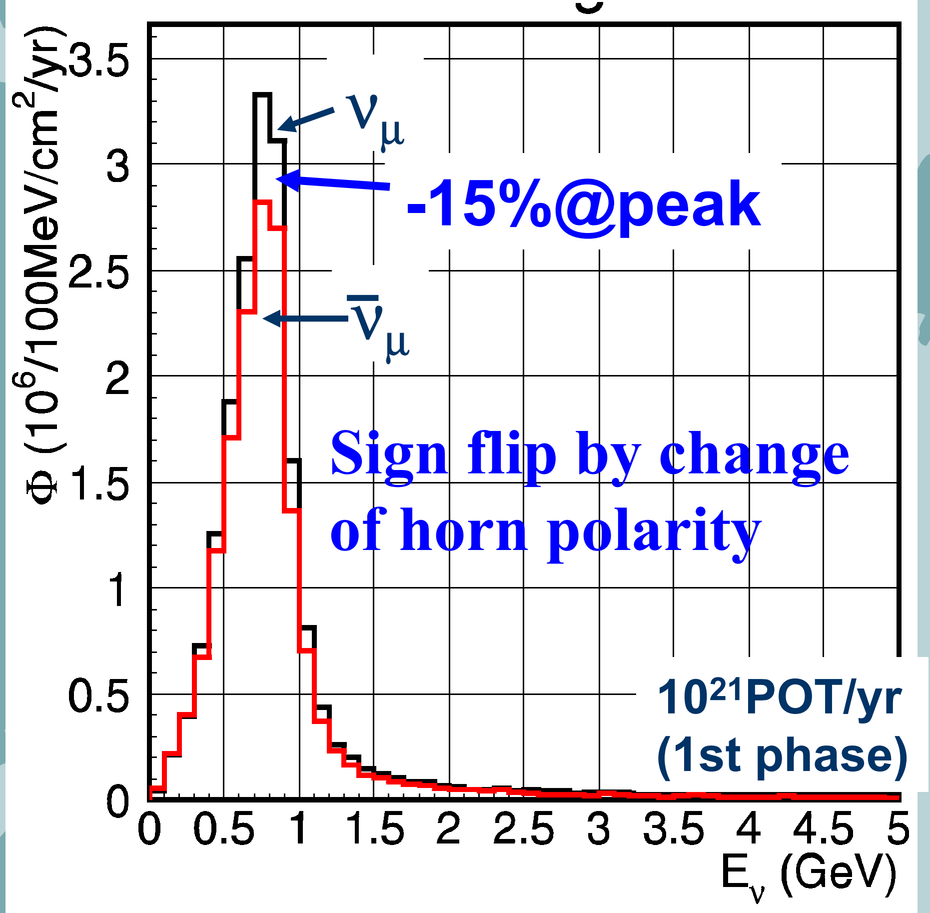


~3000 CC int./22.5kt/yr

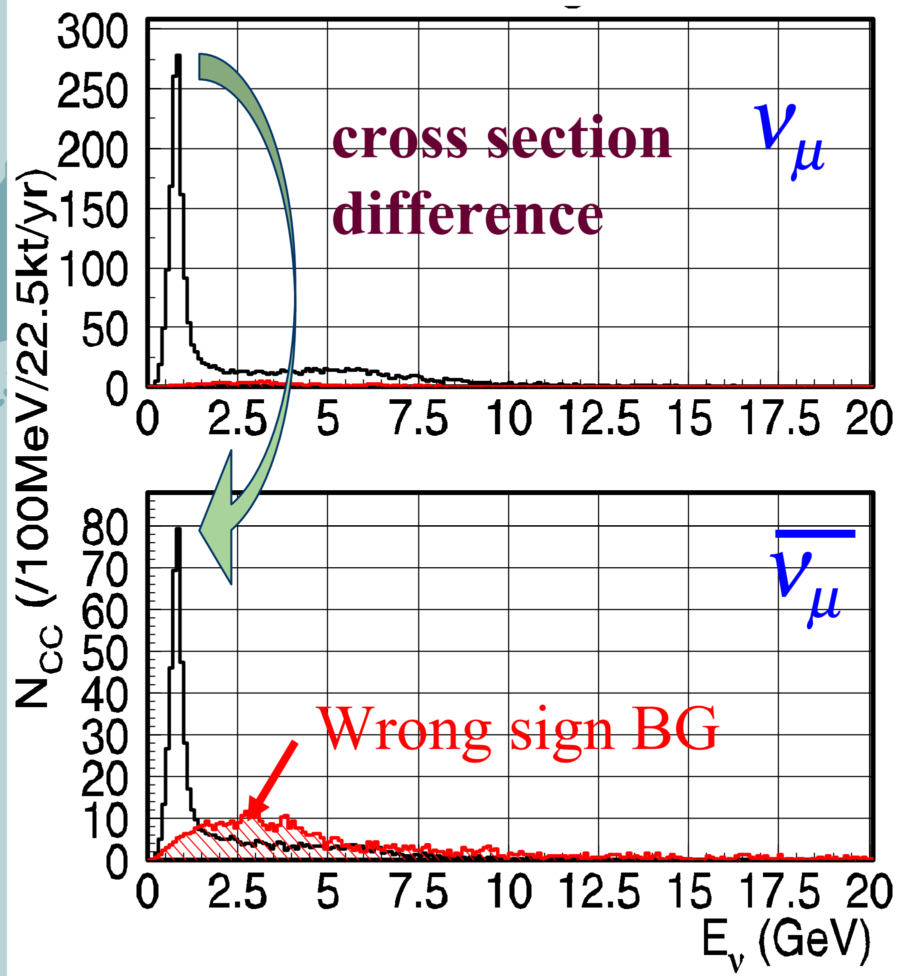
ν_e: 1.0% (0.2% @ peak);

$\overline{\nu_\mu}/\nu_\mu$ flux for CP violation search.

Flux

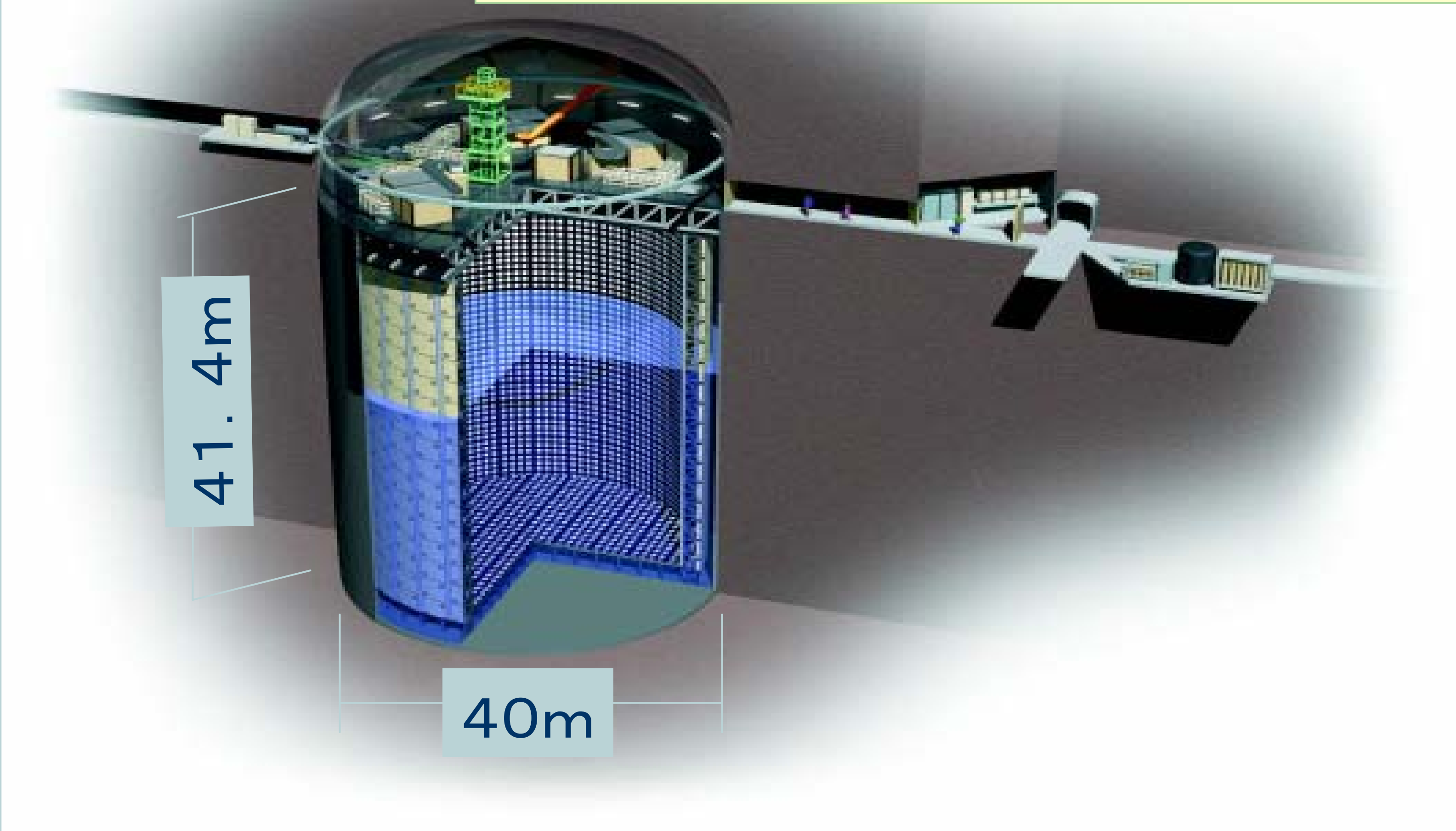


CC interaction



Super-Kamiokande

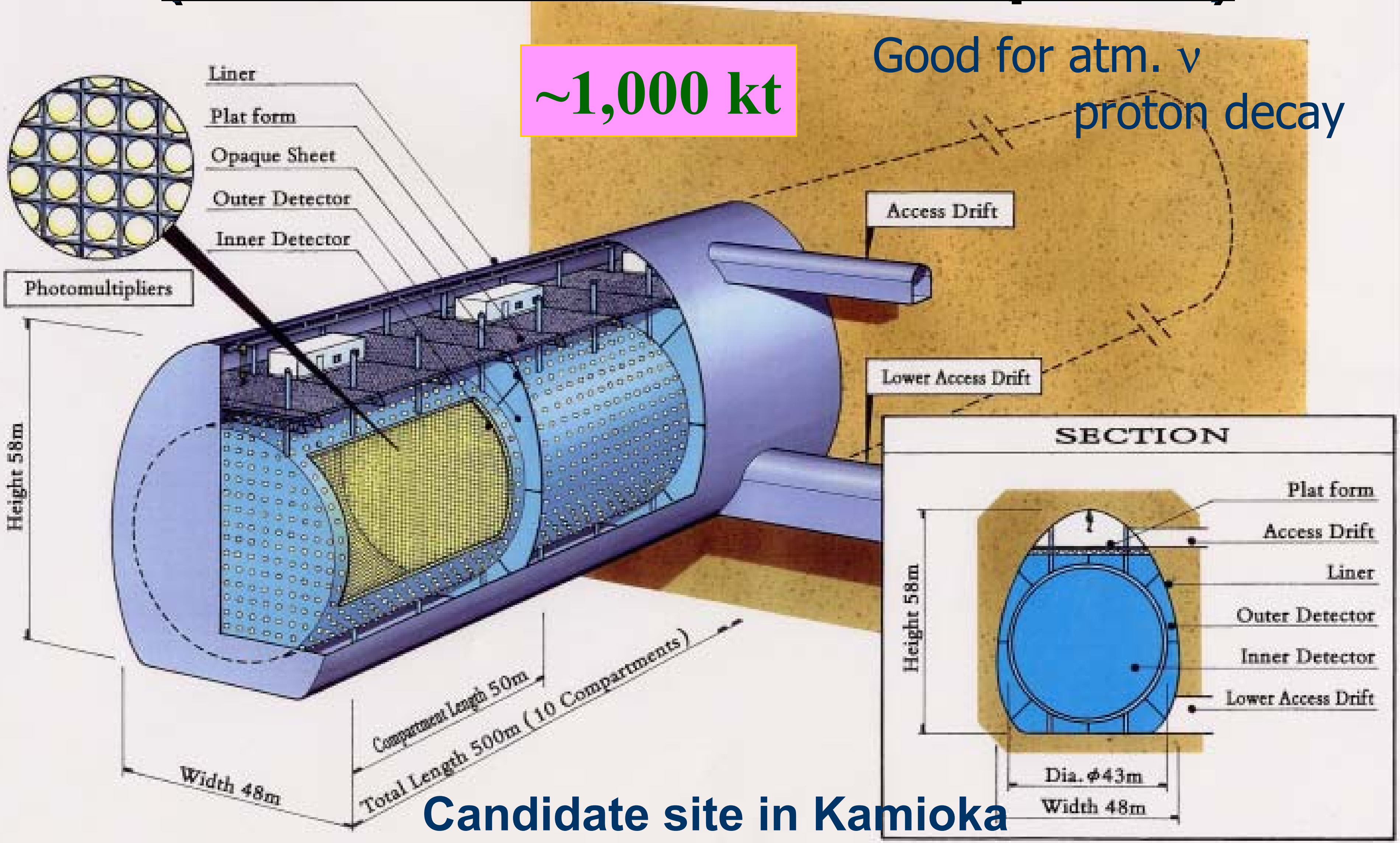
50,000 ton water Cherenkov detector (22.5 kton fiducial volume)



Hyper-Kamiokande
(a far detector in the 2nd phase)

~1,000 kt

Good for atm. ν
proton decay

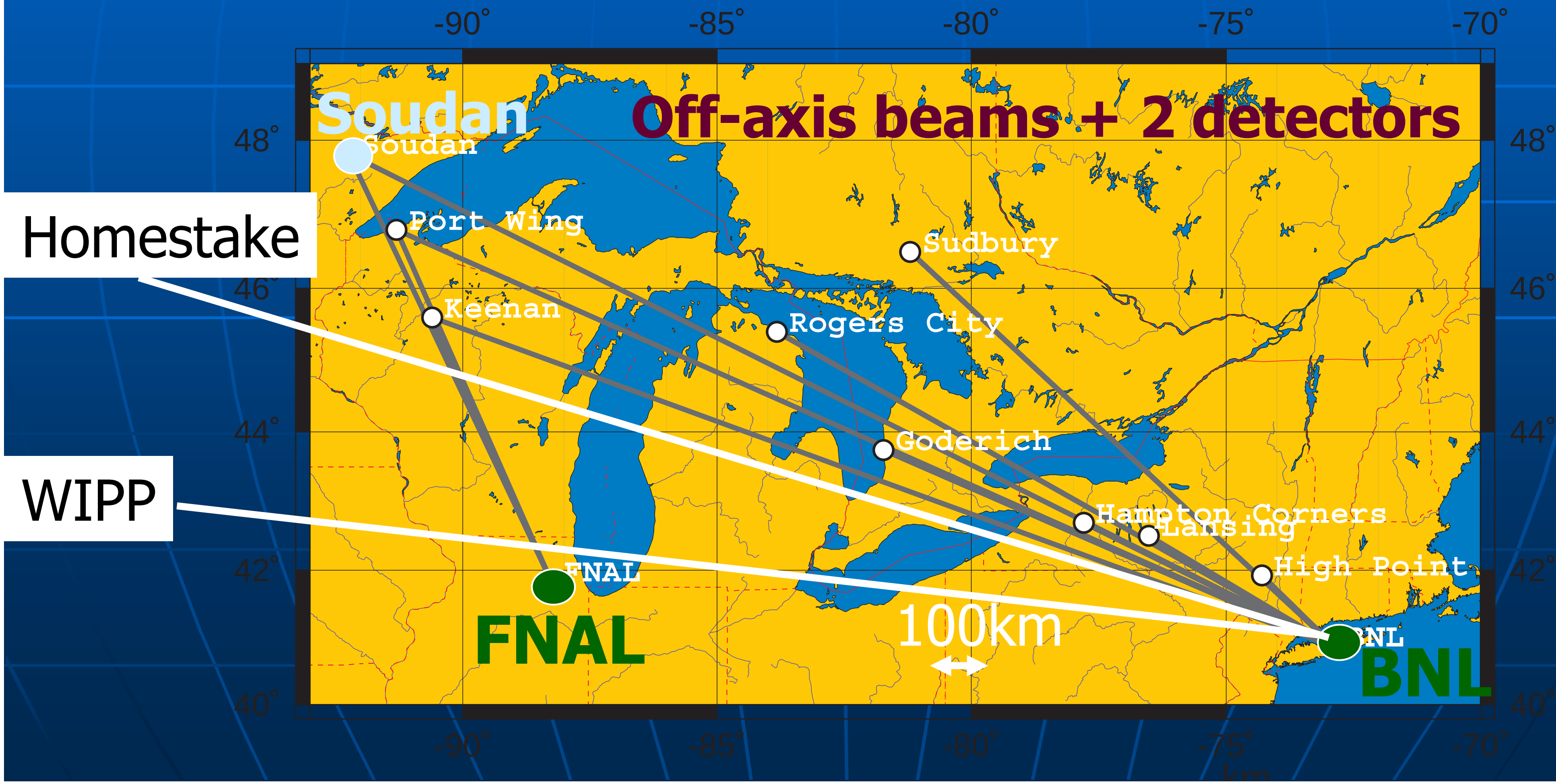


Candidate site in Kamioka

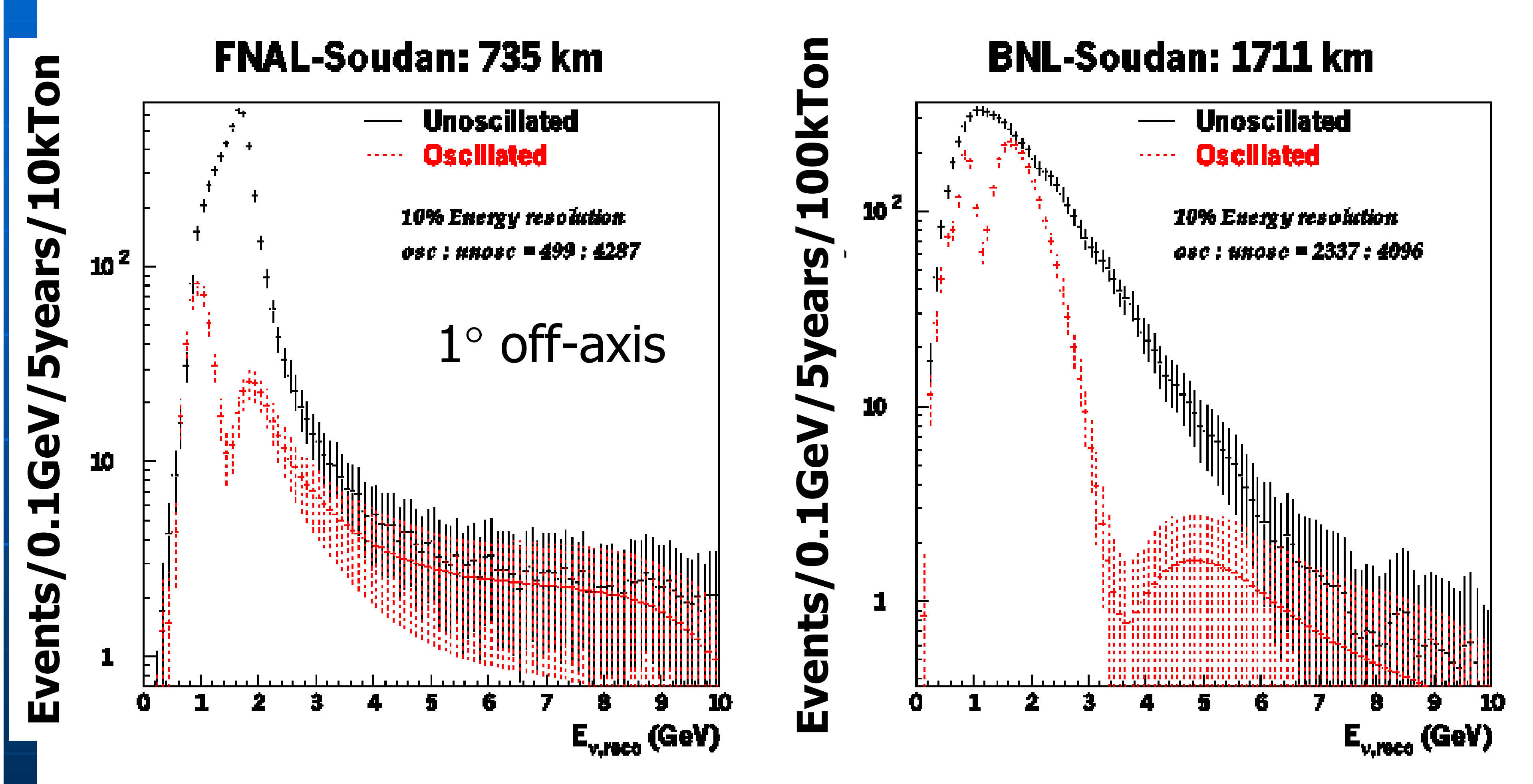
3.2 USA: FNAL and BNL plan

- BNL: Super AGS (1.3MW, LOI submitted)
- FNAL: Super NUMI (1.6 MW) or the new proton driver.

(hep-ex/0205040,0204037,hep-ph/0204208)



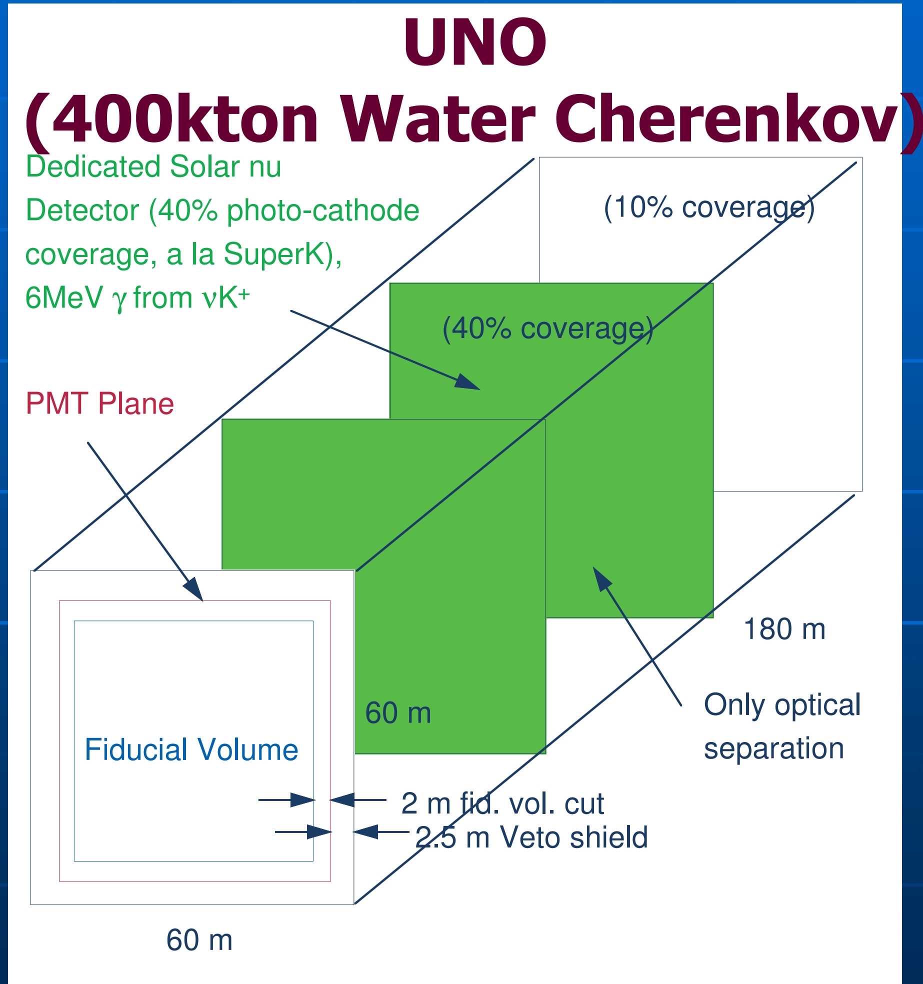
FNAL, BNL to Soudan



- Water Cherenkov like Super-K

Detectors


Liquid Ar TPC
(~100kton)
1- TOP END CAP IRON YOKE
2- BOTTOM END CAP IRON YOKE
3- BARREL IRON RETURN YOKE
4- COIL
5- CRYOSTAT
6- CATHODES (N° 5)
7- WIRE CHAMBERS (N° 4)
8- FIELD SHAPING ELECTRODES
LANNDD
Liquid Argon Neutrino and Nucleon Decay Detector


UNO
(400kton Water Cherenkov)
Dedicated Solar nu
Detector (40% photo-cathode
coverage, a la SuperK),
6MeV γ from νK+
(10% coverage)
(40% coverage)
PMT Plane
180 m
Only optical
separation
60 m
Fiducial Volume
2 m fid. vol. cut
2.5 m Veto shield
60 m

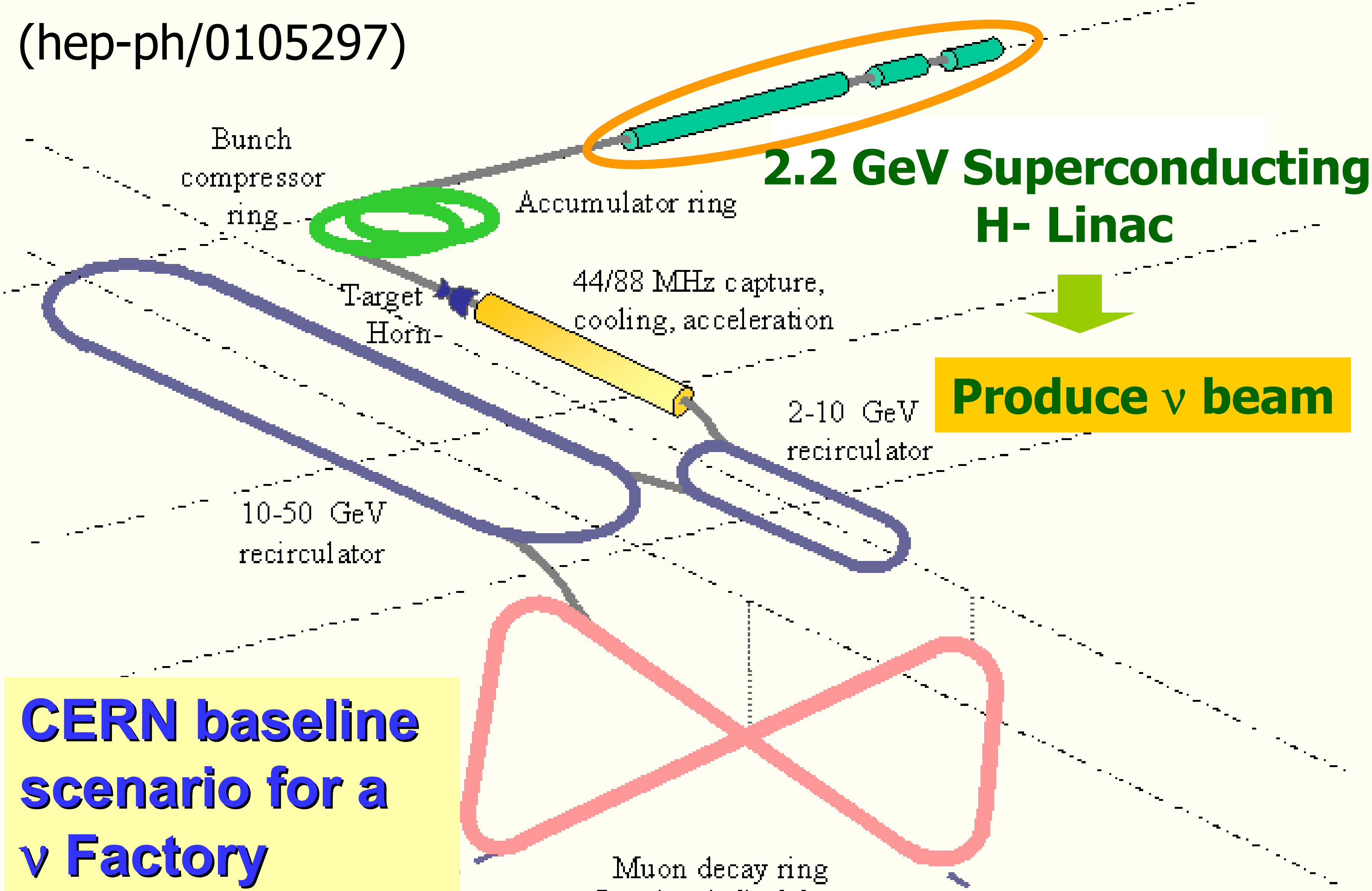
USA beams and detectors

- US neutrino physicists are investigating several combinations of detectors, beams, baseline, etc. including ν-factory.
- BNL LOI is proposed to send ν beam to Homestake at the distance of ~3000km to study matter effect and the sign of Δm_{23}^2.

  This is a unique feature of this project, which is not considered in JHF-Kamioka and CERN-SPL.
- My talk does not cover NUMI off-axis which will be presented in the later talk.

3.3 CERN: SPL + β beam

(hep-ph/0105297)

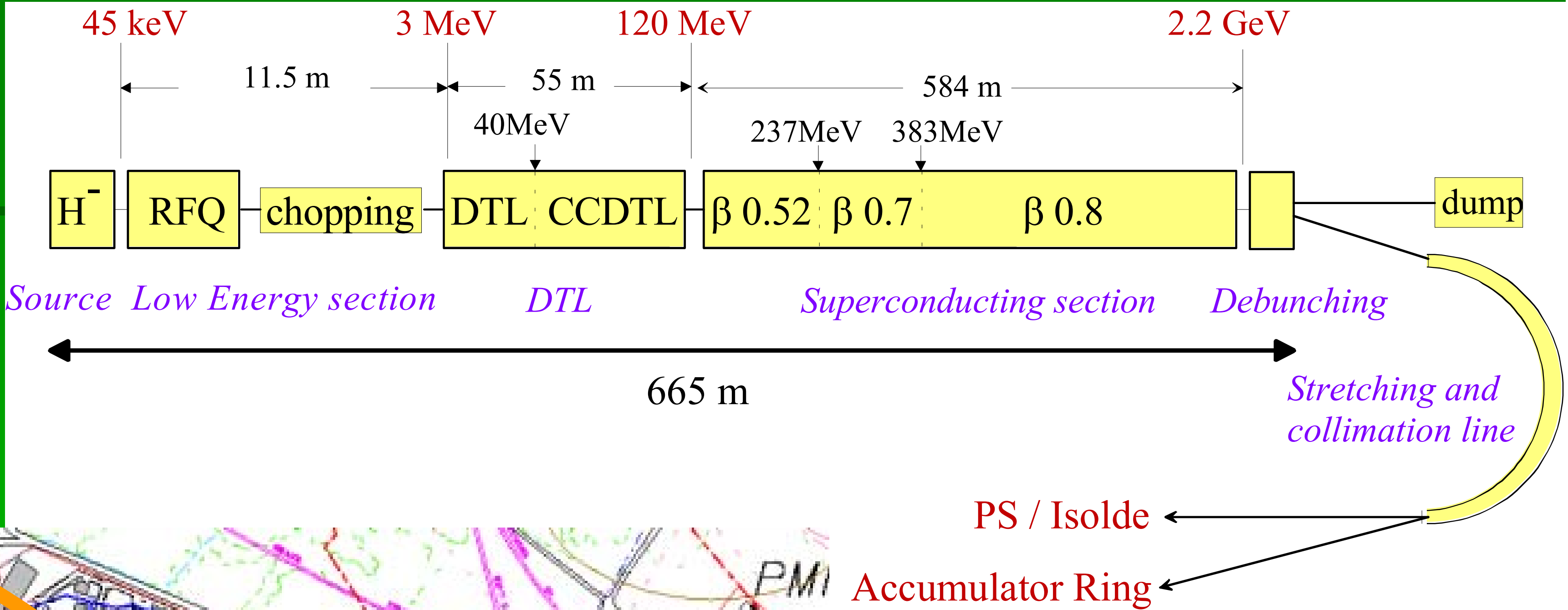


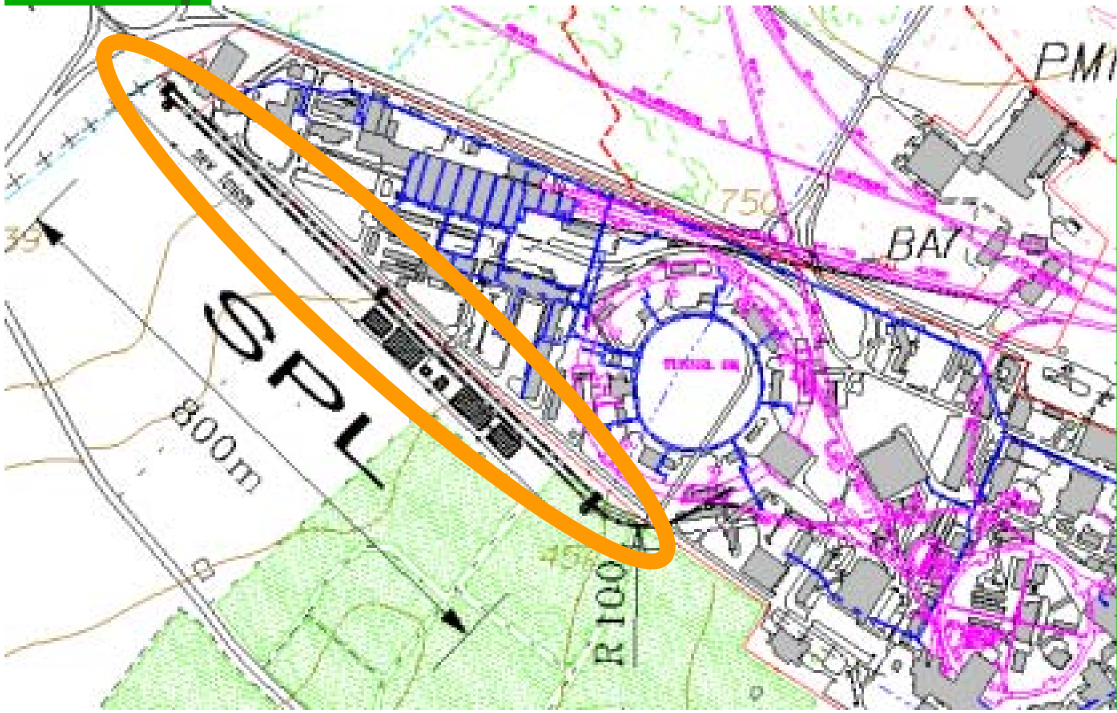
2.2 GeV Superconducting H- Linac

Produce ν beam

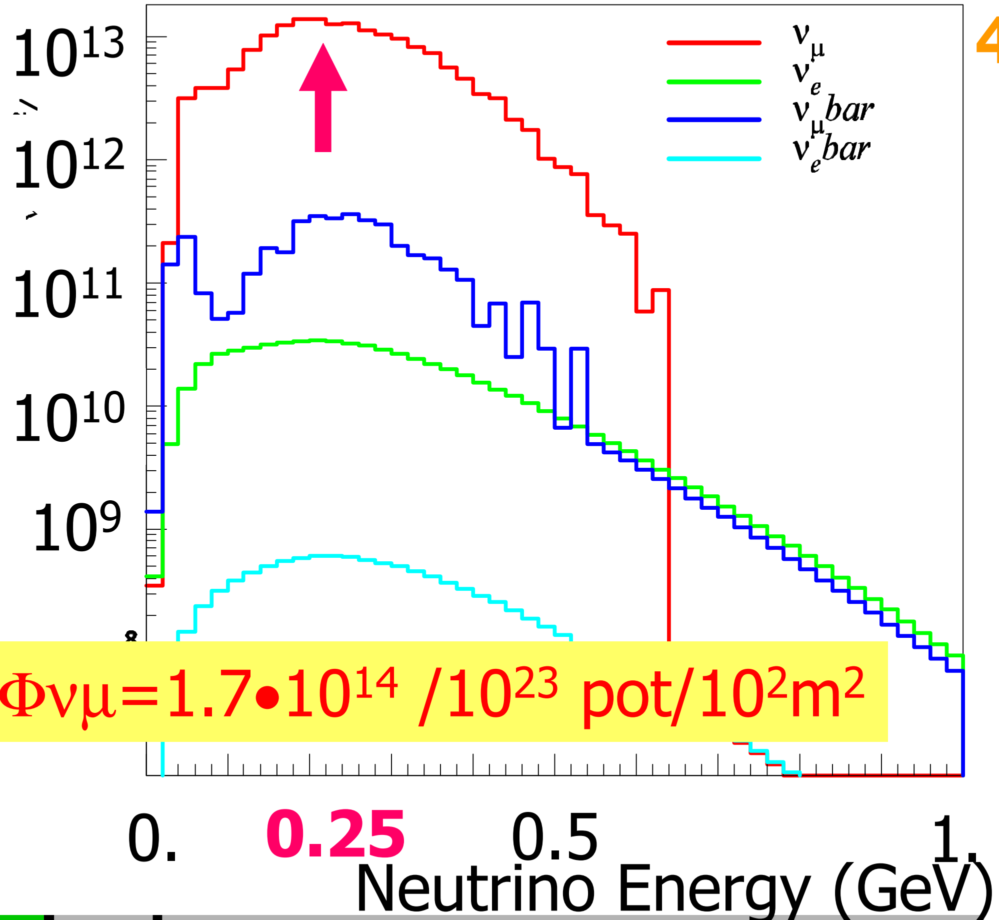
CERN baseline scenario for a ν Factory

SPL (Super Proton Linac)



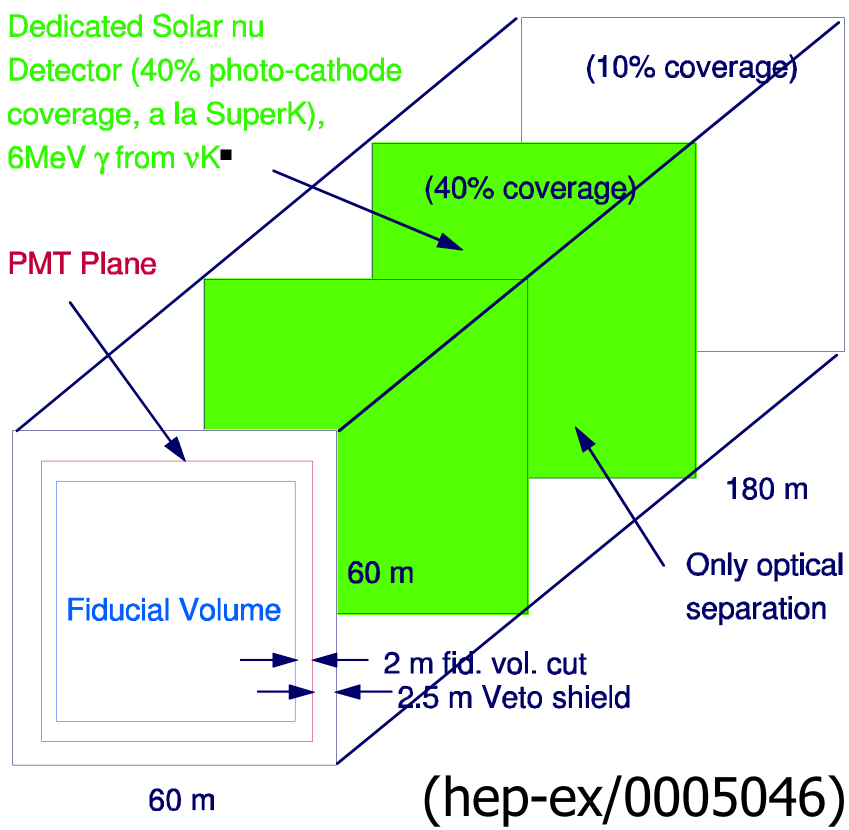


CERN SPL to UNO at Frejus



$\Phi\nu\mu = 1.7 \bullet 10^{14} / 10^{23}$ pot/$10^2 m^2$

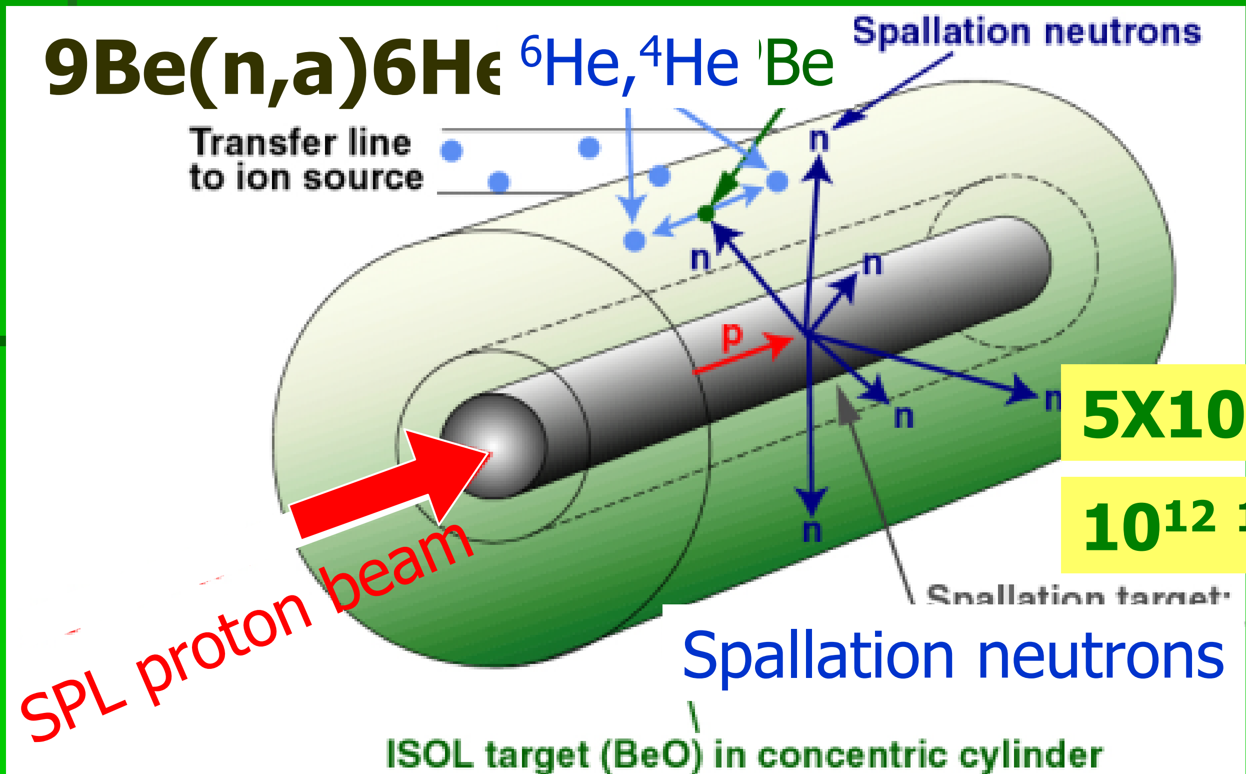
400kton Water Cherenkov



(hep-ex/0005046)

SPL β beam (ν_e and $\bar{\nu}_e$)

- A novel idea to generate a neutrino beam from accelerated radioactive irons.
  - Low energy (~2MeV) β ray in the CM frame, which can produce **the forward focused ν beam**.



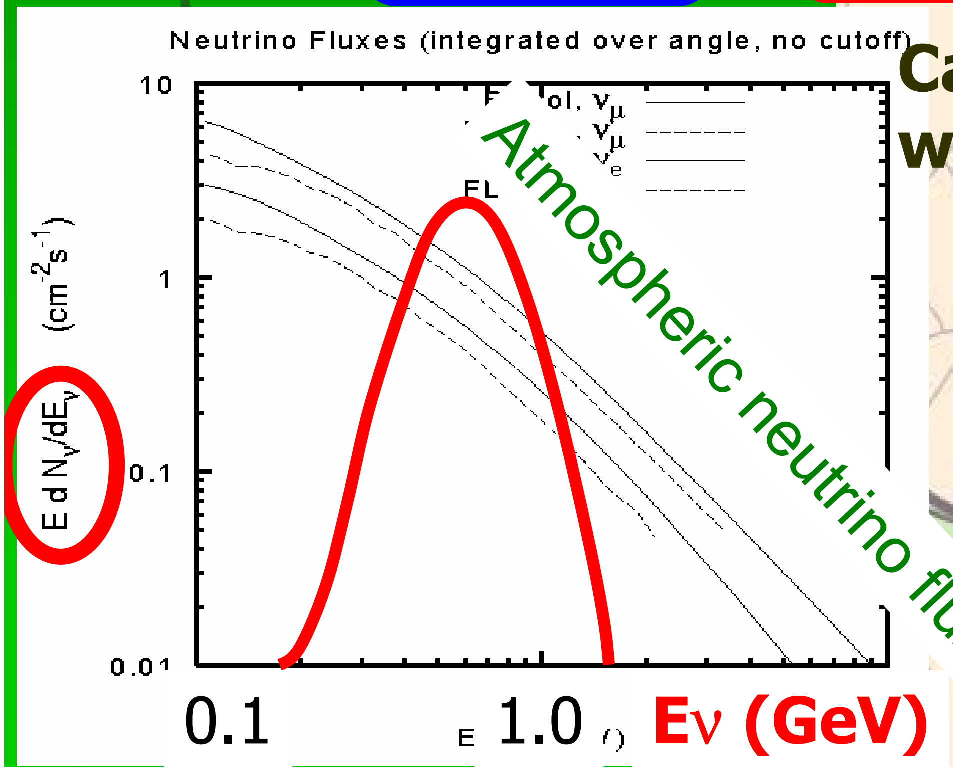
$5X10^{13}$ ^{6}He/s every 8s

10^{12} ^{18}Ne/s every 8s

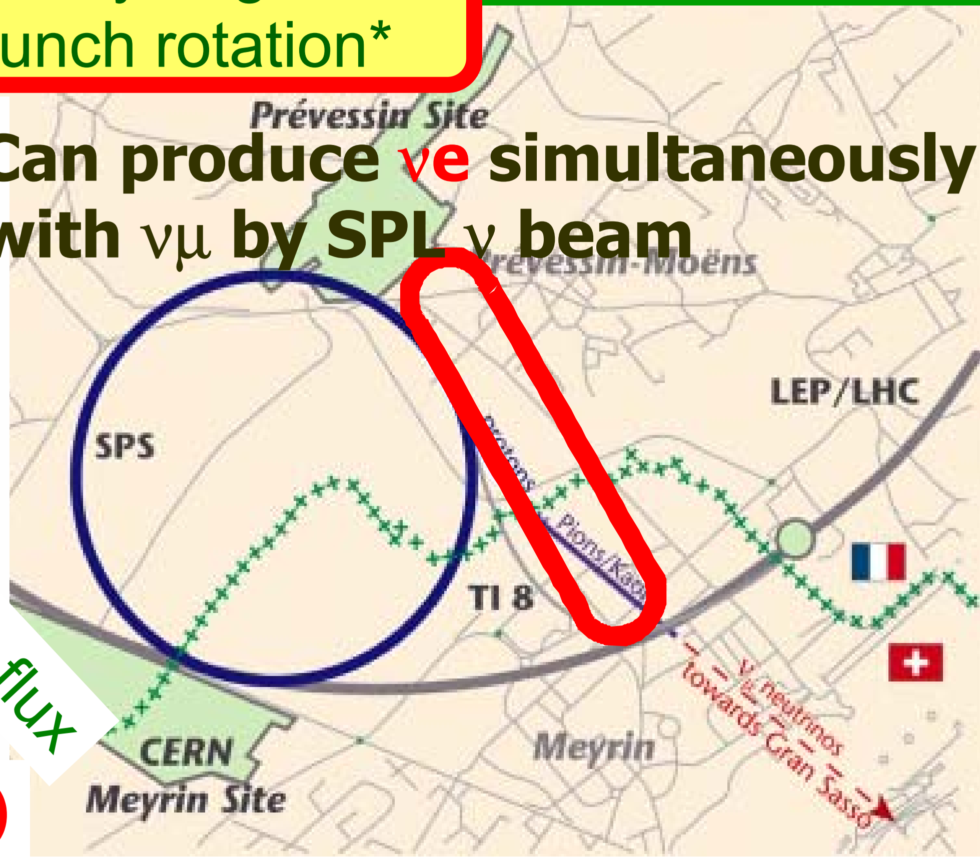
SPL β beam to Frejus

ISOL target → ECR source → Linac 20 MeV/u → Accumulator >~300 MeV/u

→ PS → SPS 450 GeV/p → Decay ring and bunch rotation*



Can produce νe simultaneously with νμ by SPL ν beam



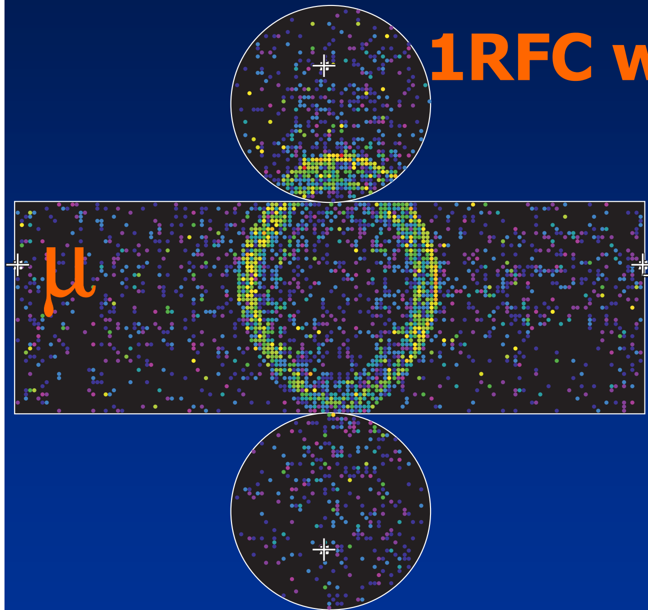
4. Physics Sensitivity

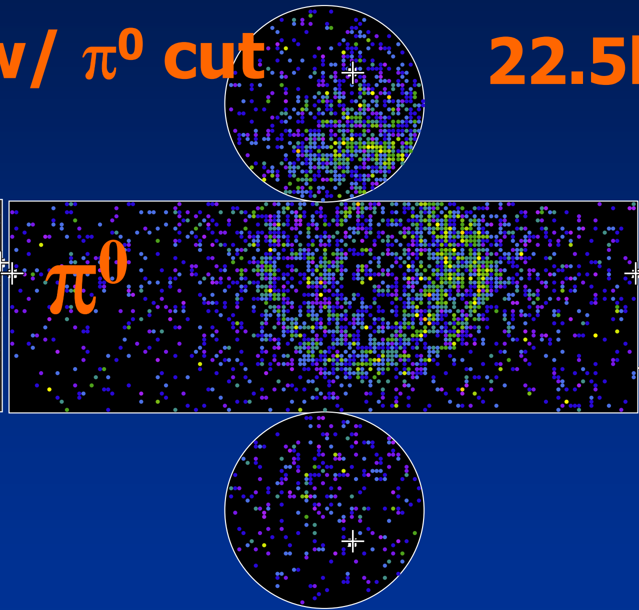
- Physics goals of most super ν-beam experiments are:
  - Discovery of $\nu_\mu \to \nu_e$ and the measurement of θ_{13}
  - CP Violation ($\nu_\mu \to \nu_e$ vs $\overline{\nu_\mu} \to \overline{\nu_e}$)
  - Sign of Δm^2 by using matter effect.
  - Precision measurement of ν oscillation parameters.

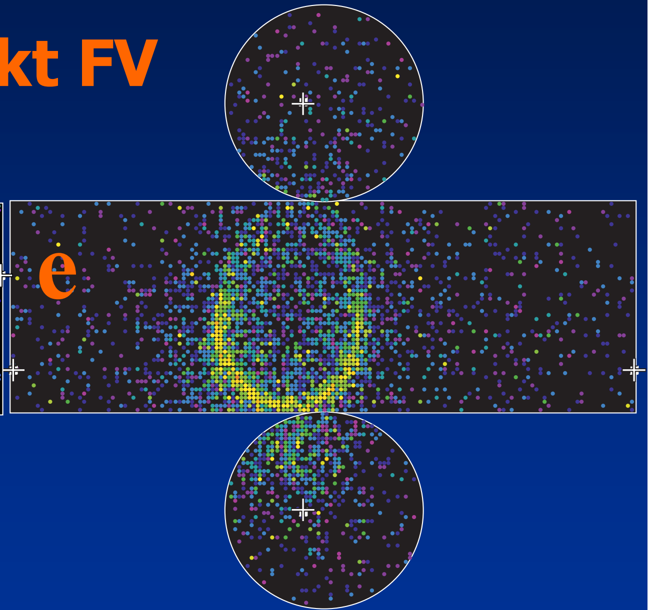
ν_e appearance in JHF-Kamioka (phase 1)

1RFC w/ π^0 cut

22.5kt FV







Backgrounds

1.8 events

9.3$^{(*)}$ events

11.1 events

Signal

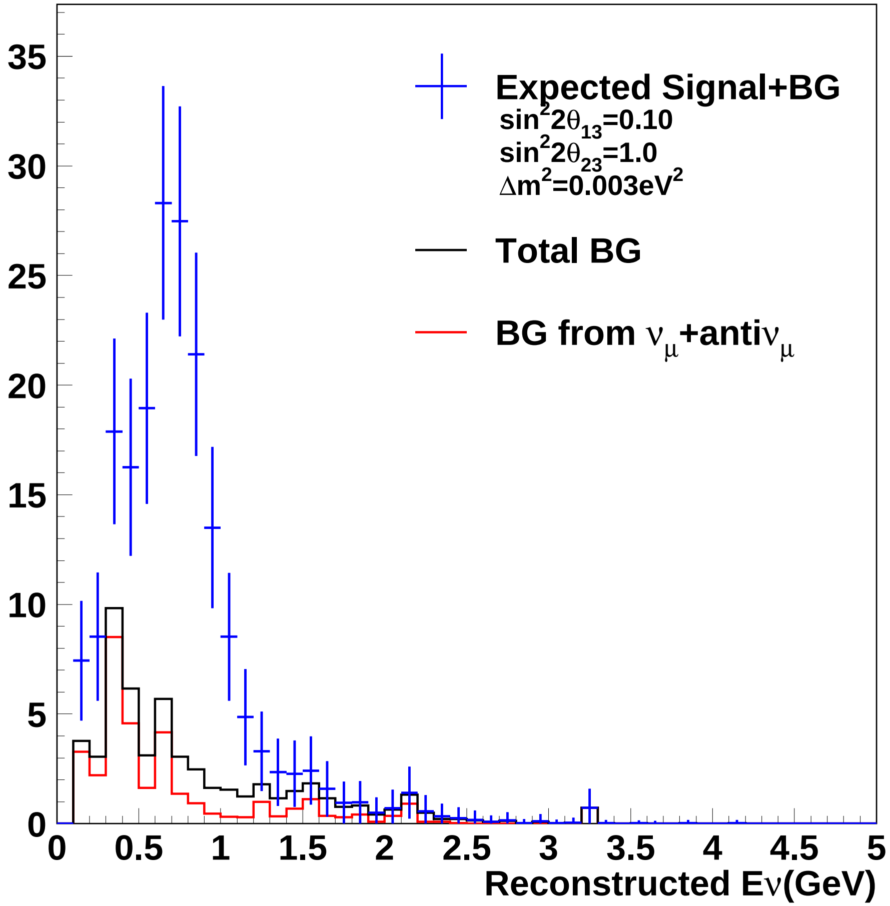
123.2 events @ $\sin^2 2\theta_{13}=0.1$, $\Delta m^2=3\times10^{-3}\text{eV}^2$

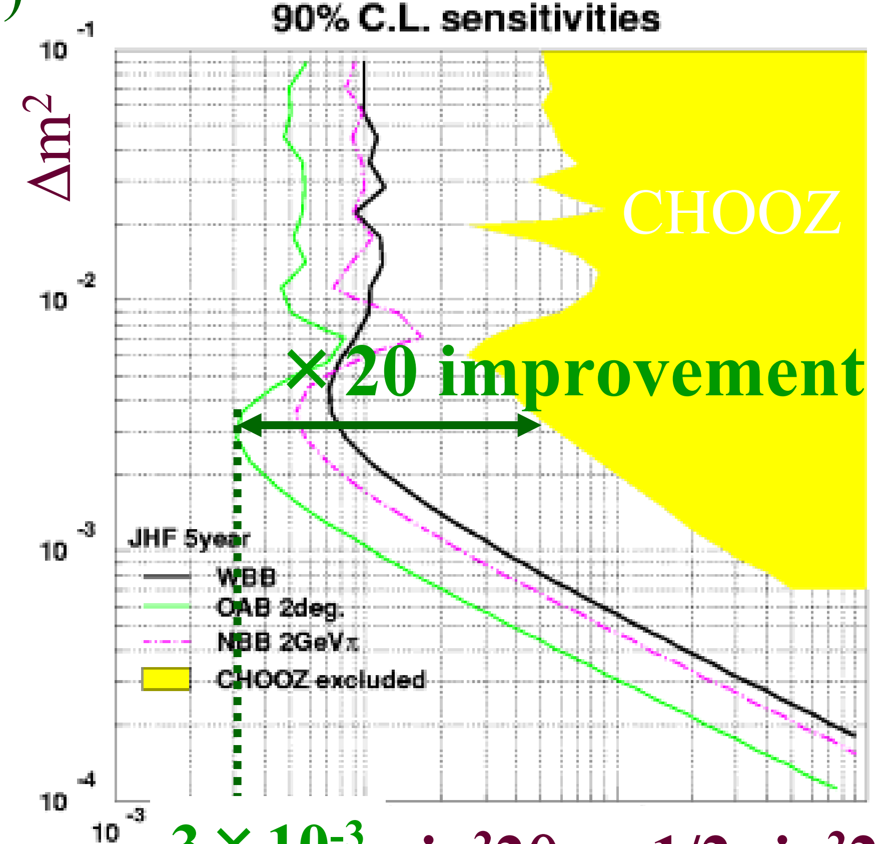
(5 years running)

(*) still can be further improved

ν_e appearance (continue)

$\sin^2 2\theta_{\mu e}=0.05$ ($\sin^2 2\theta_{\mu e} \equiv 0.5\sin^2 2\theta_{13}$)



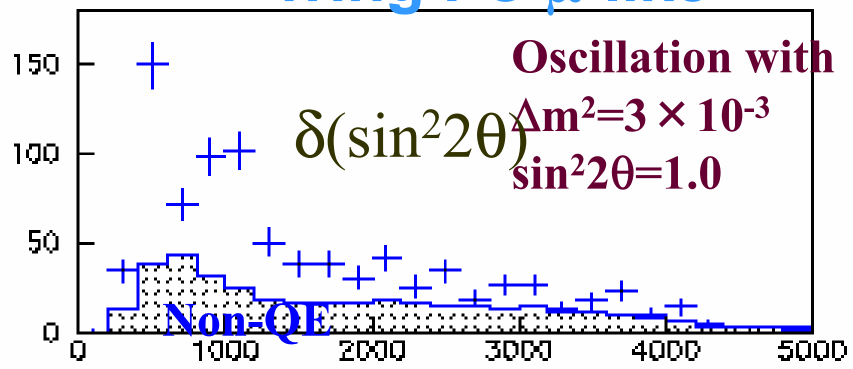


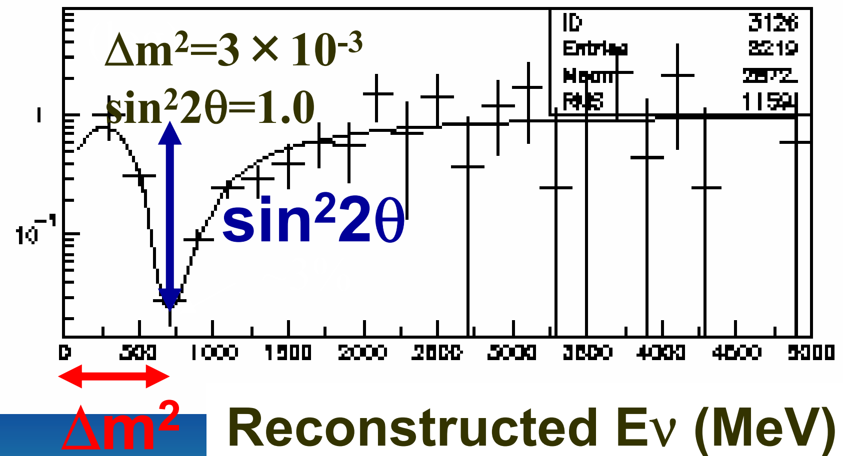
3×10^{-3}

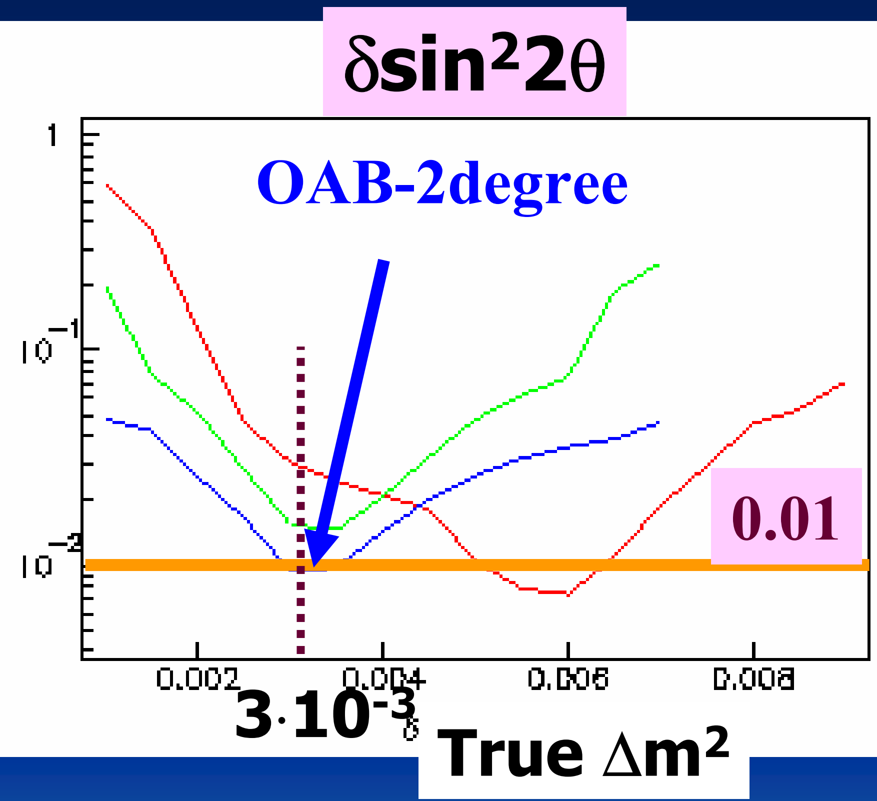
$\sin^2 2\theta_{\mu e} = 1/2\cdot\sin^2 2\theta_{13}$

$\sin^2 2\theta_{13} < 0.006$ (90% C.L.)

ν_μ disappearance







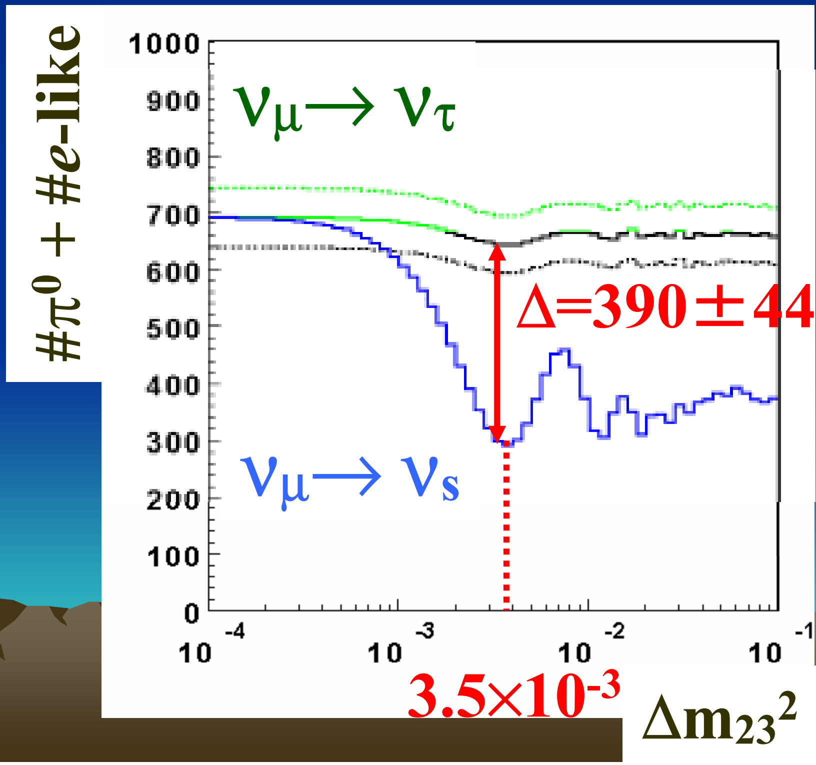
$\delta \sin^2 2\theta_{23} \sim 0.01$

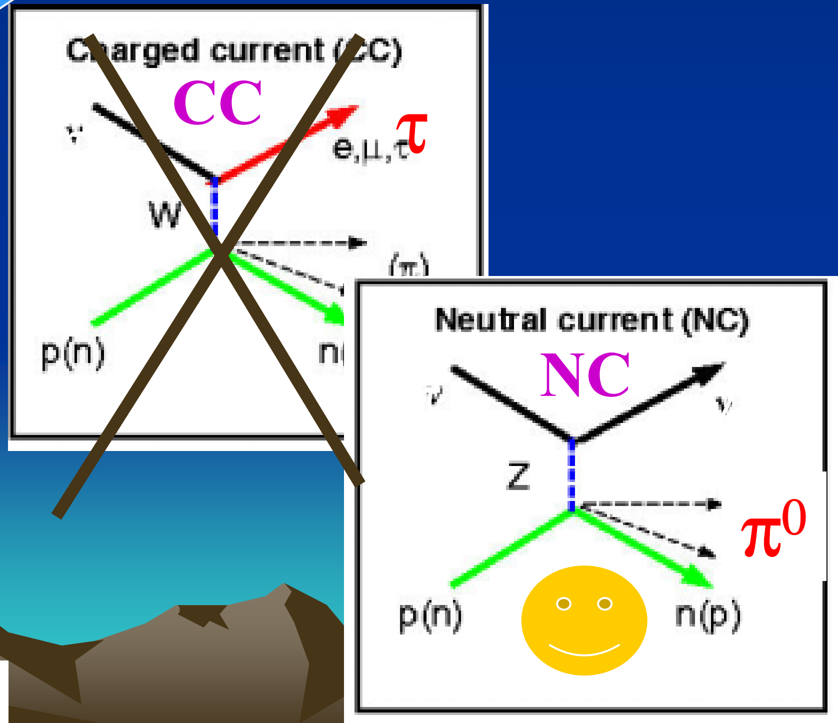
$\delta \Delta m_{23}^2 \quad < 1 \times 10^{-4} eV^2$

$\nu_\mu \rightarrow \nu_\tau$ confirmation w/ NC interaction

- NC π^0 interaction (ν + N $\rightarrow$ ν + N + π^0)
  - $\nu_\mu \rightarrow \nu_e$ CC + NC(~0.5CC) ~0 ($\sin^2 2\theta_{\mu e}$~0)
  - ν_μ CC + NC(~0.5CC) ~0 (maximum oscillation)
  - ν_τ NC

#π^0 is sensitive to ν_τ flux. ⇒ **Limit on ν_s ($\delta f(\nu_s)$~0.1)**





CP Violation Study w/ Hyper-K (Phase 2)

- Compare $\nu_\mu \to \nu_e$ (2 years) with $\overline{\nu_\mu} \to \overline{\nu_e}$ (6years)

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \approx \frac{\Delta m_{12}{}^2 L}{4E_\nu} \bullet \frac{\sin 2\theta_{12}}{\sin\theta_{13}} \bullet \sin\delta$$

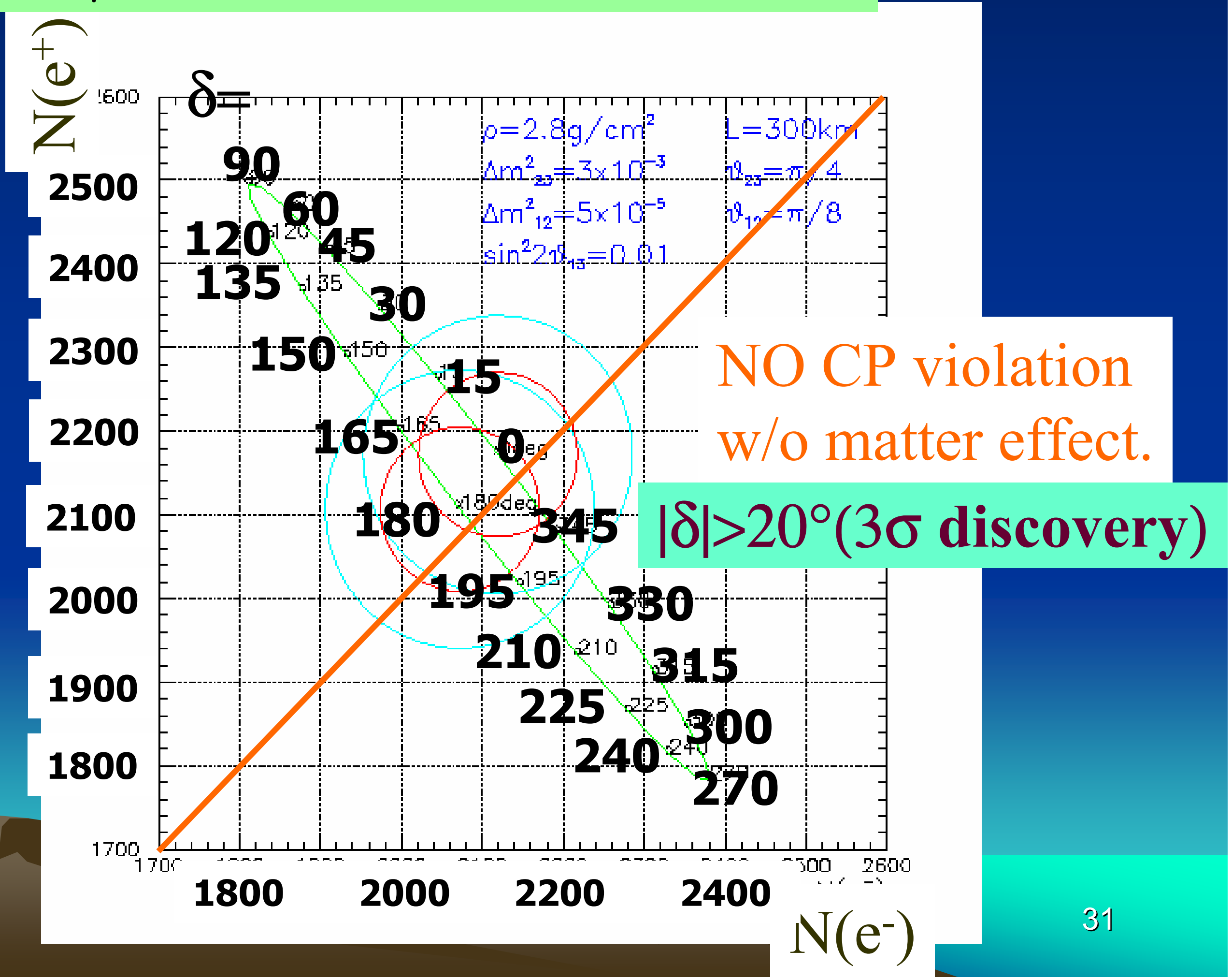
$\Delta m_{12}{}^2 = 5 \times 10^{-5}\mathrm{eV}^2$,
$\Delta m_{23}{}^2 = 3 \times 10^{-3}\mathrm{eV}^2$
$\sin^2 2\theta_{13} = 0.01$
$\theta_{23} = \pi/4$, $\theta_{12} = \pi/8$

Asymmetry

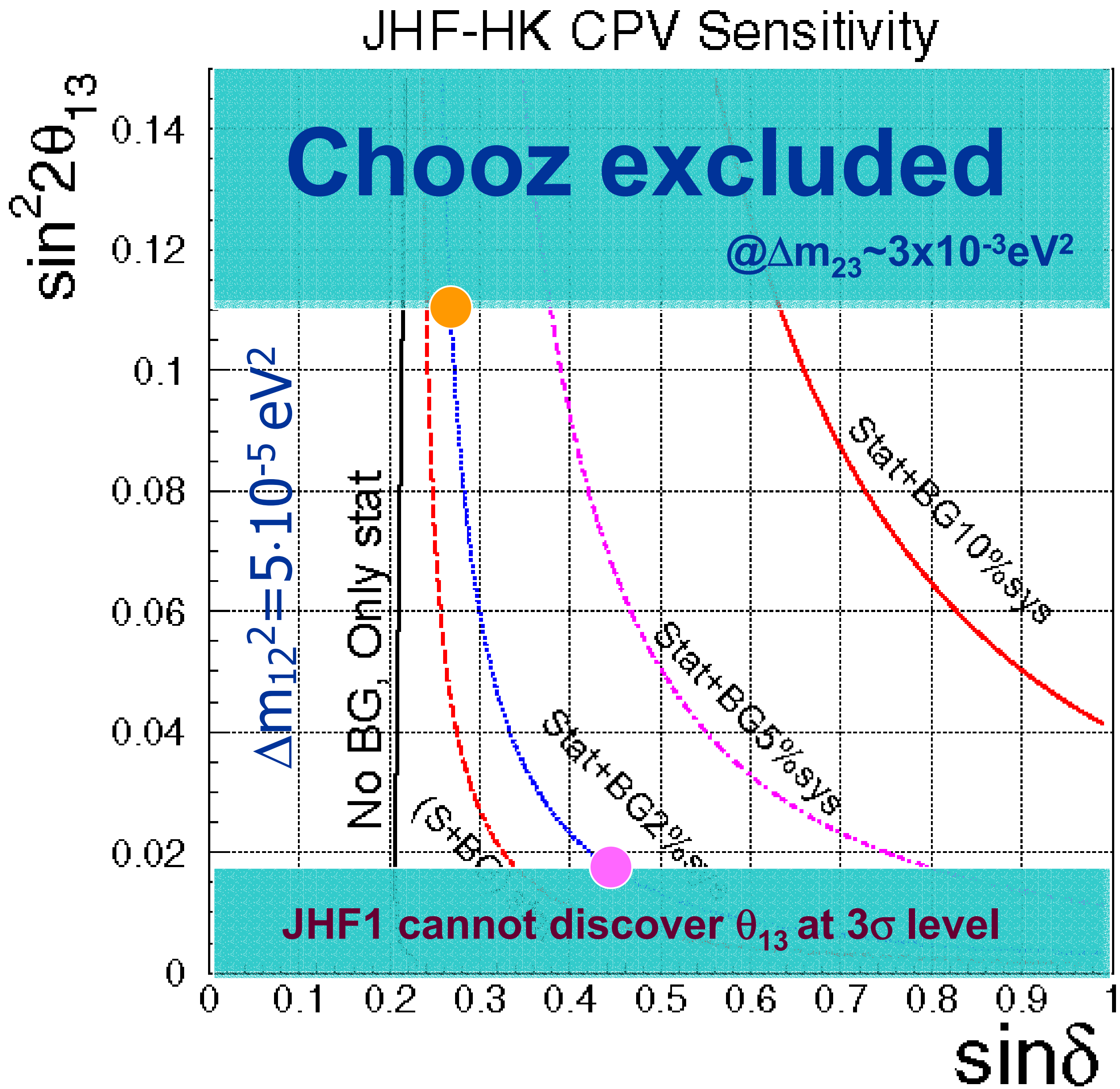
$$\equiv \frac{N(e^+) - N(e^-)}{N(e^+) + N(e^-)}$$

$$\approx \frac{\sim 2000 - \sim 2000}{\sim 2000 + \sim 2000}$$

≈ 0.02



CP Sensitivity (3σ)



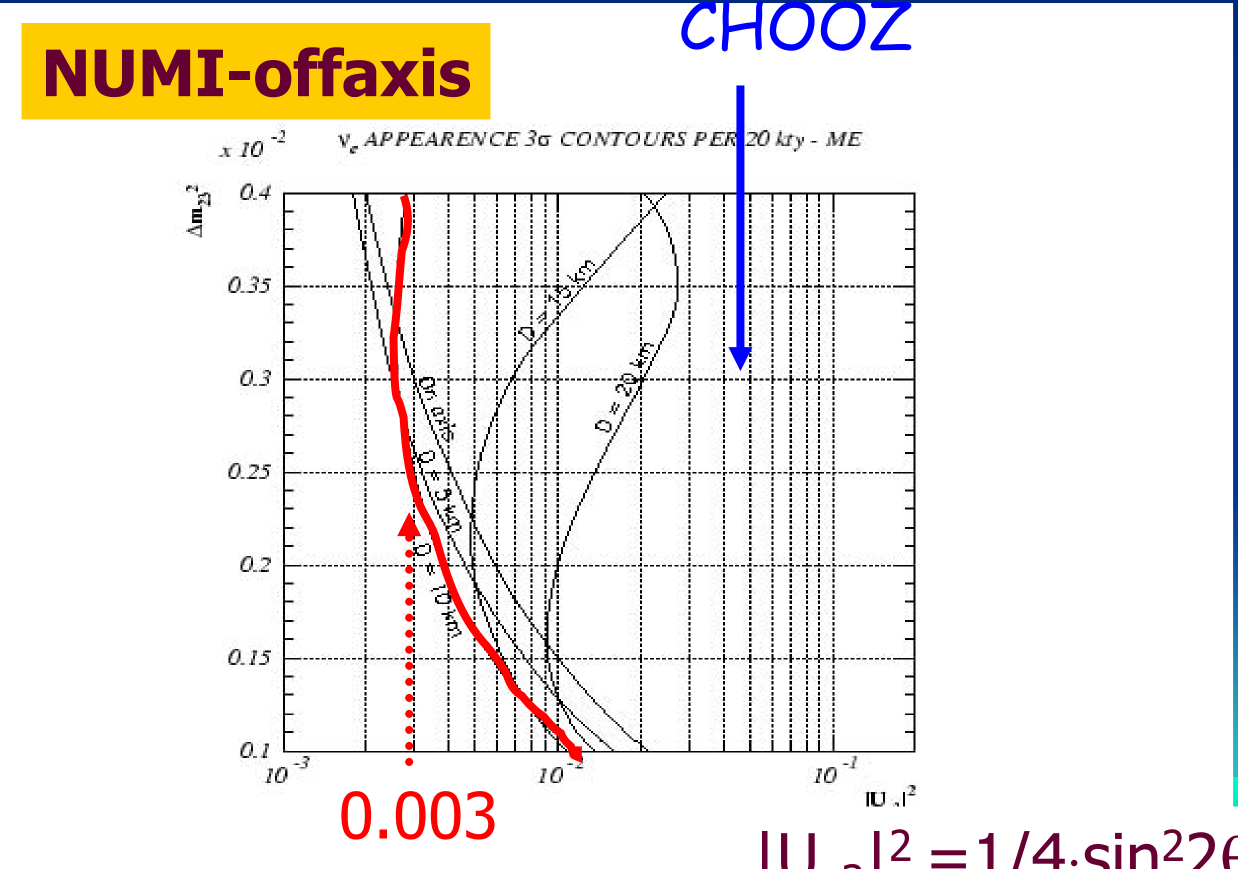
assuming 2% BG uncertainty

$\sin^2 2\theta_{13}=0.01$
→ $\sin\delta>0.44$
(26deg)

large $\sin^2 2\theta_{13}$
→ $\sin\delta>0.25$
(14deg)

US Super ν beam

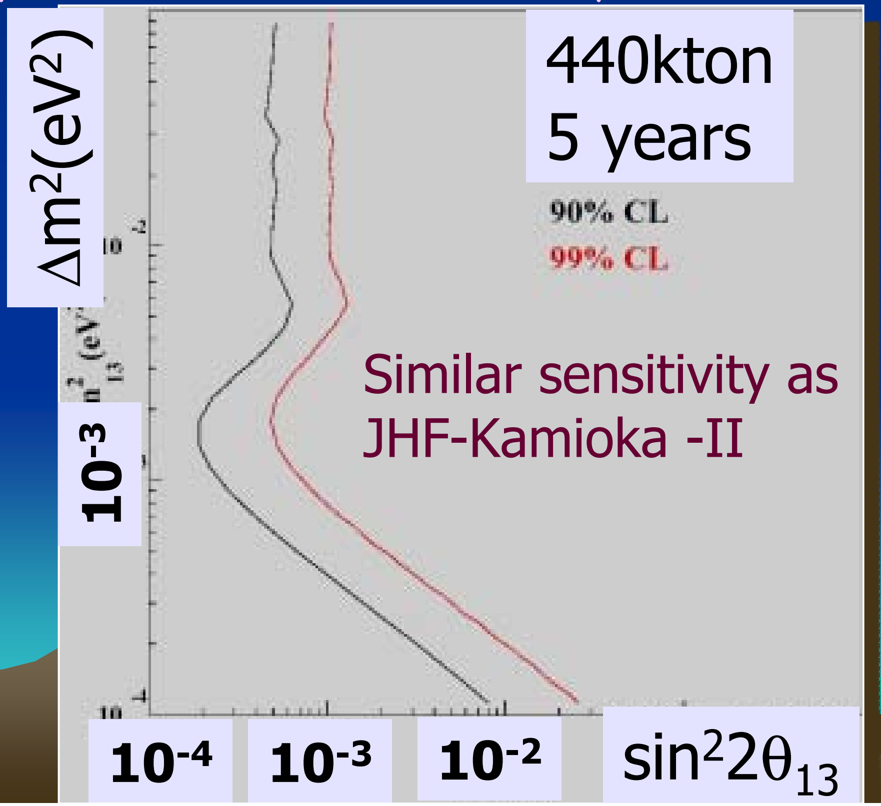
- They are studying the physics potential of several options, which are competitive to JHF-Kamioka project.



$|U_{e3}|^2 = 1/4 \cdot \sin^2 2\theta_{13}$

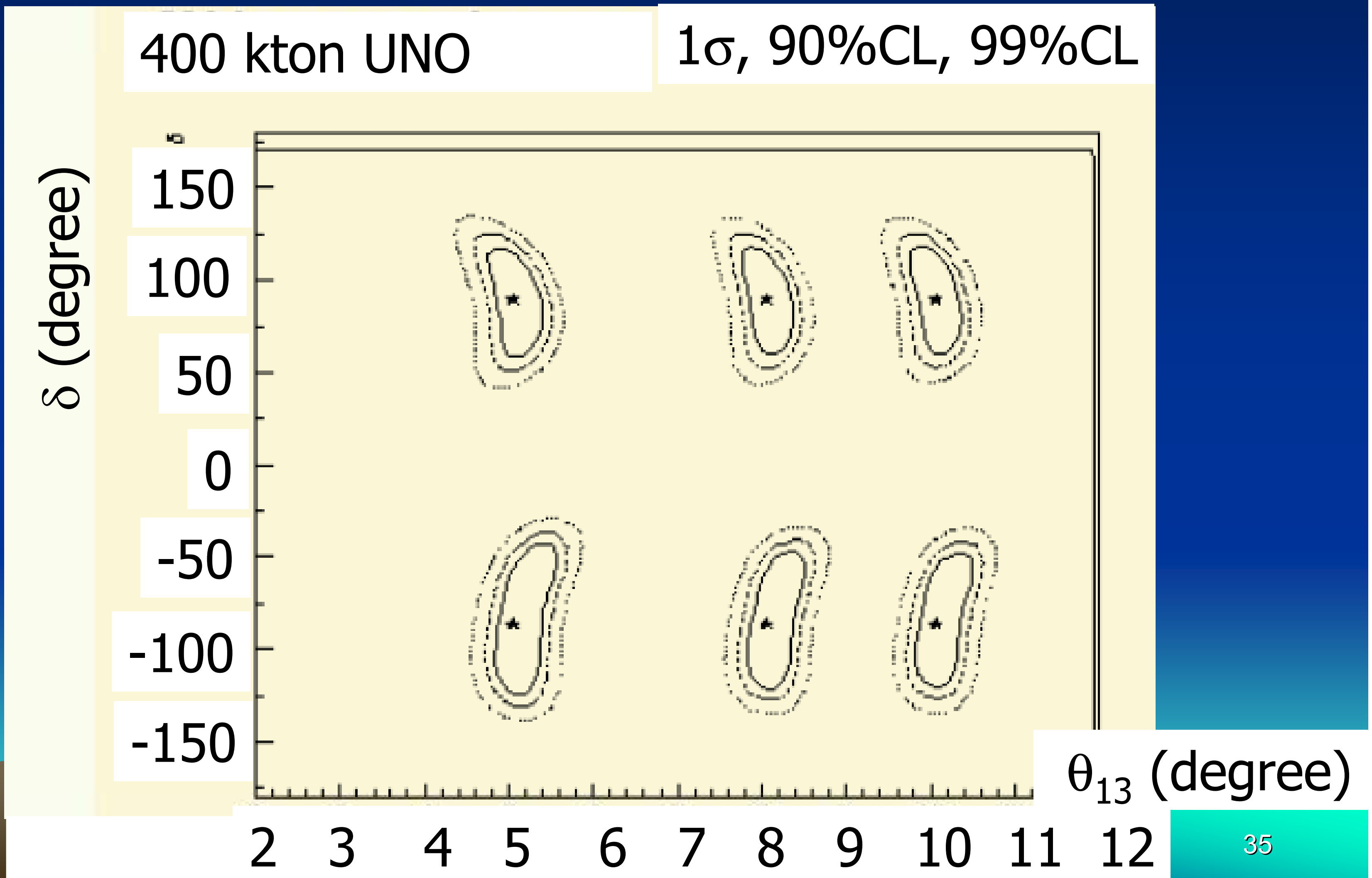
CERN: SPL+β beams to UNO@Frejus

- Search for $\nu_\mu \rightarrow \nu_e$ w/ super ν beam
- Search for $\nu_e \rightarrow \nu_\mu$ w/ β beam
- They can also study T symmetry in ν oscillation between $\nu_\mu \rightarrow \nu_e$ and $\nu_e \rightarrow \nu_\mu$.

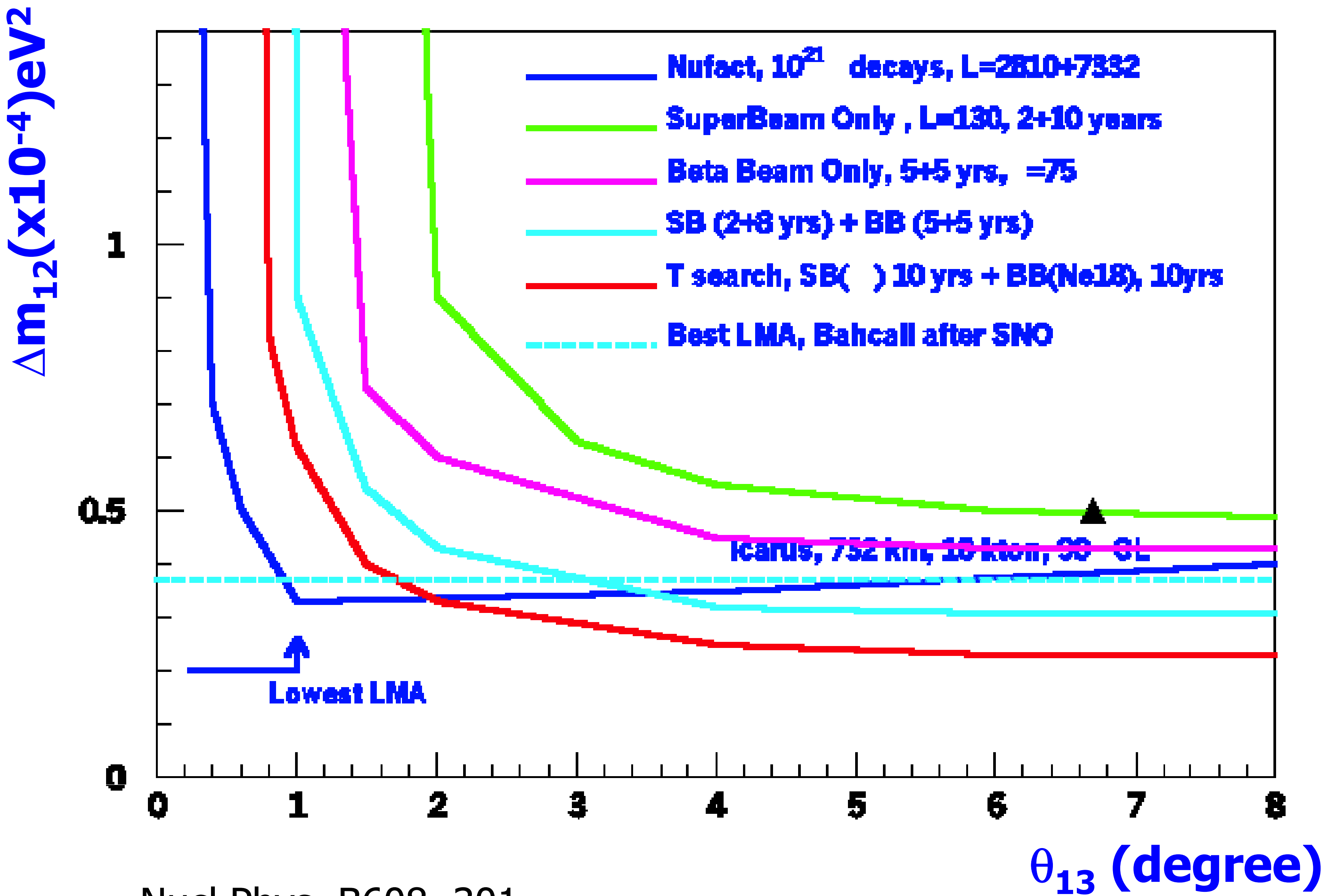


CP sensitivity (δ)

- θ_{13} and δ measurement



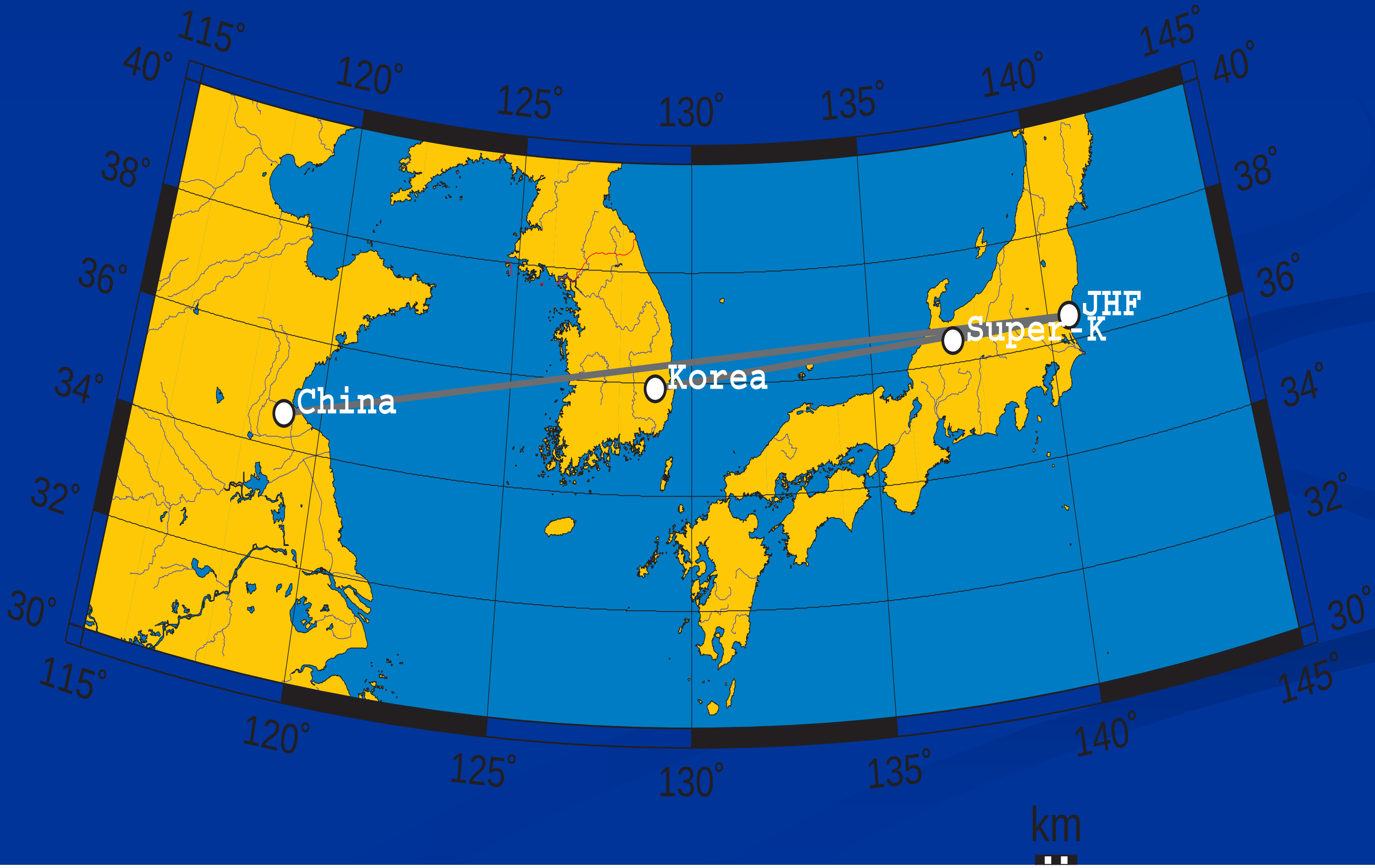
CERN: SPL+β beams to UNO@Frejus



Nucl.Phys. B608, 301

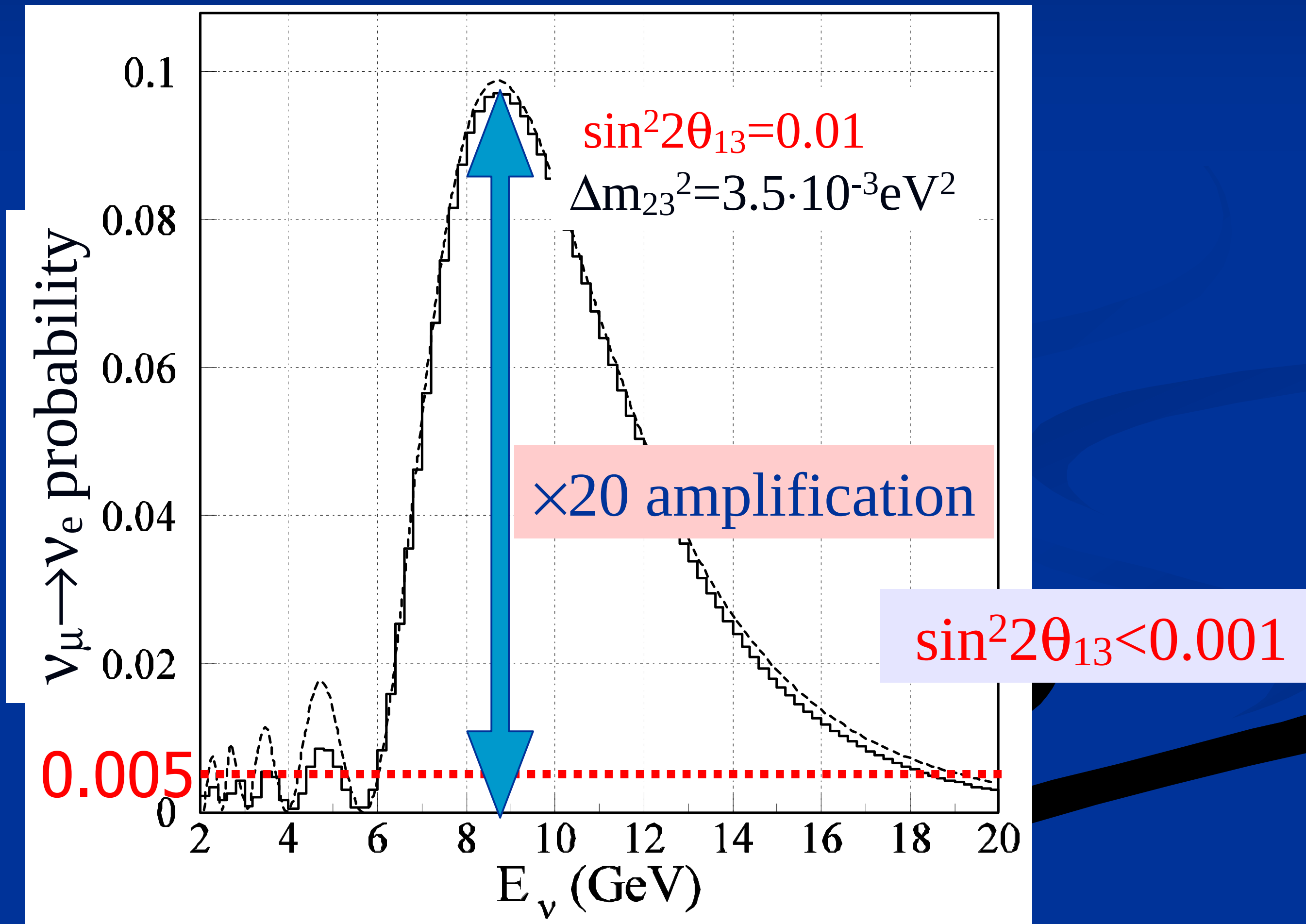
More Possibilities (1)

- Japan to Korea or China (hep-ph/0112338)
  - CP violation and the sign of Δm_{23}^2 with JHF ν beam.



More Possibilities (2)

- Fermilab to Super-Kamiokande (hep-ex/0203005)
  - Matter enhanced ν oscillation (L=9300km)



Remark: Near to Far extrapolation

A next generation LBL ν experiment requires the precise knowledge of ν spectrum at the far site based on the measurements at the near site.

- Hadron Production Experiments
  - CERN HARP(-III), FNAL E907
- A detector at the medium distance
  - JHF-Kamioka project proposes to build the near neutrino detector at 2km away from the target, which is far enough to see the neutrino production volume as a point source.

Non Oscillation Physics

- A near site detector with the super ν beam can probe LSND effect if demanded.
- Precise ν interaction and cross section study.
  - Quasi-elastic scattering; etc..
- $\nu_\mu e^-$ elastic scattering at low Q^2; the neutrino magnetic moment.

5. Summary and Conclusion

- In the next 5 years, several LBL ν experiments will provide more information on ν oscillation.

- The Super ν beam experiments will follow the trend, and further explore the physics.

  JHF-Kamioka experiment will start in 2007 earliest.
  - $\sin^2 2\theta_{13}$ sensitivity w/ super ν-beams
    - 0.01~0.001 w/ 20~50 kton detectors

      >10 times more sensitive than CHOOZ.
    - <0.001 w/ 400~1000 kton detectors

5. Summary and Conclusion (Continue)

- CP Violation sensitivity
  - Need a larger detector (400~1000 kton) when $\nu_\mu \rightarrow \nu_e$ oscillation is discovered.
  - The sensitivity of CP violation phase δ is down to 10~20 degrees if $\Delta m_{12}^2 = 5 \cdot 10^{-5} eV^2$ (LMA).
- The sign of Δm_{23}^2 and matter effect
  - The longer baseline (~1000km or more) is necessary to study it. JHF and CERN SPL has no design of the ν beam line for this purpose.
- There may be a surprise behind the ν oscillation phenomena. We should proceed the experiments with the super ν beams and the larger detectors.