Particle Physics aspects of a MW machine

- **Long-range programme in neutrino physics:**
  superbeam, β beam, neutrino factory
- **Complementary programme in μ physics:**
  rare μ decays, μ properties, μ colliders?
- ***Next-generation facility for nuclear physics***
  also tests of SM, nuclear astrophysics
  (next talk)

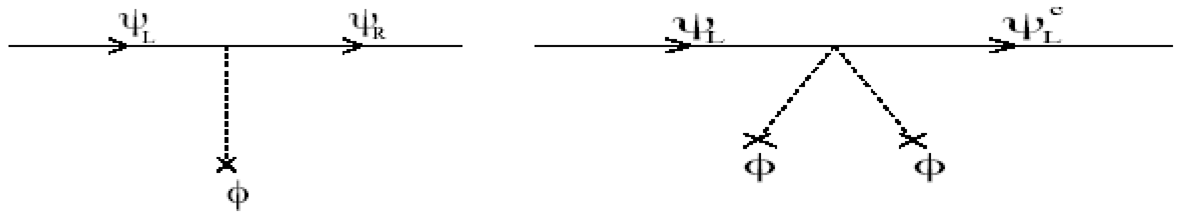
- ***Synergy with CERN programme:***
  LHC, CNGS ν, ISOLDE, heavy ions, β beam
  (next talk + J.Ellis talk)

M.Spiro

See also talks by Migliozzi and Ceccucci for SBL and higher energy options

The primary Physics motivation:

Neutrino masses and mixings



$$\lambda_\nu \, \bar{\psi}_R \, \Phi \, \psi_L + h.c. \qquad \frac{\alpha_\nu}{M} \nu_L^T C \, \tilde{\Phi}^T \, \tilde{\Phi} \, \nu_L + h.c.$$

$$m_f = \lambda_f \, v \qquad m_\nu = \alpha_\nu \frac{v^2}{M}$$

$$L \qquad \not{L}$$

Hernandez

Why so small?

Why mixing angles so large?

Possible connection with GUT theories at high mass M

and with Lepto & Baryo-genesis

The homework

After the next generation of neutrino experiments we will probably be far from having the complete picture:

1. Measure better $(\Delta m^2_{23}, \theta_{23})$ and $(\Delta m^2_{12}, \theta_{12})$
   $\theta_{23} = \pi/4$ fundamental symmetry ?
2. Establish 3 family mixing: θ_{13}, δ
3. Establish if CP violation occurs: ie. $\sin\delta \neq 0$
4. Find the correct spectrum: ie. $\Delta m^2_{atmos} >$ or < 0

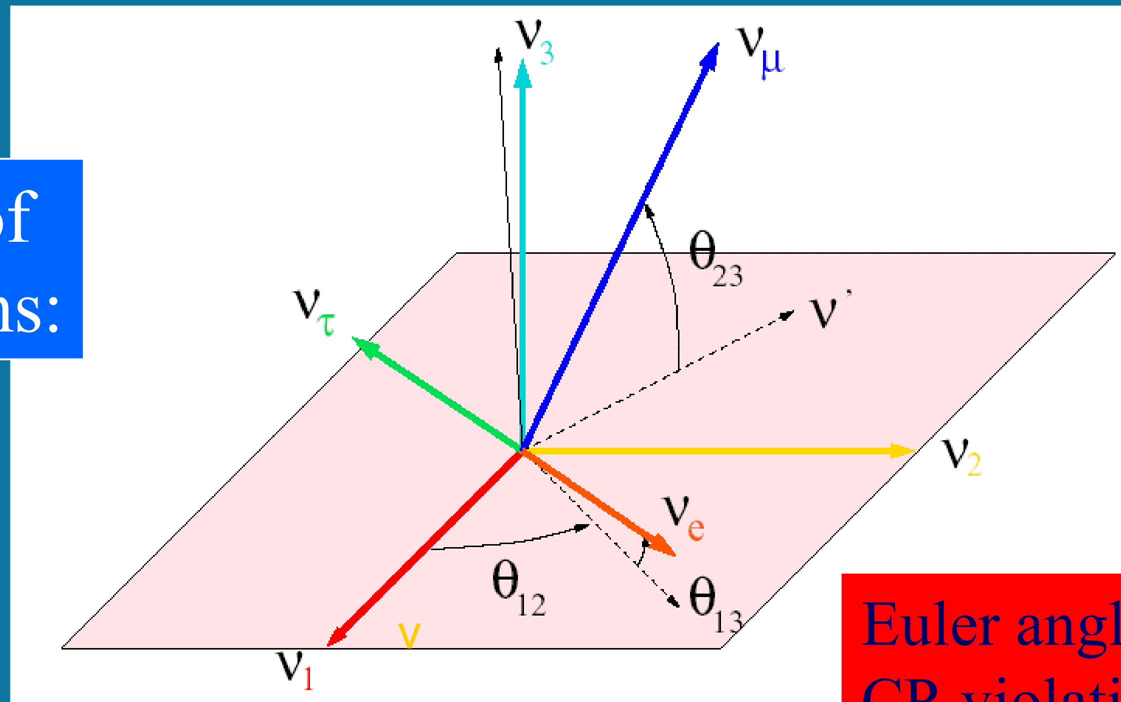
} Precision ν osc. experiments $@\langle E_\nu \rangle / L \sim \Delta m^2_{atmos}$

5. Establish Majorananess and phases α_1, α_2
6. Find absolute ν mass scale $\leftrightarrow$ new physics scale

} End-point of tritium β-decay
Rare $\not{L}$ violating decays: $0\nu\beta\beta$ decay

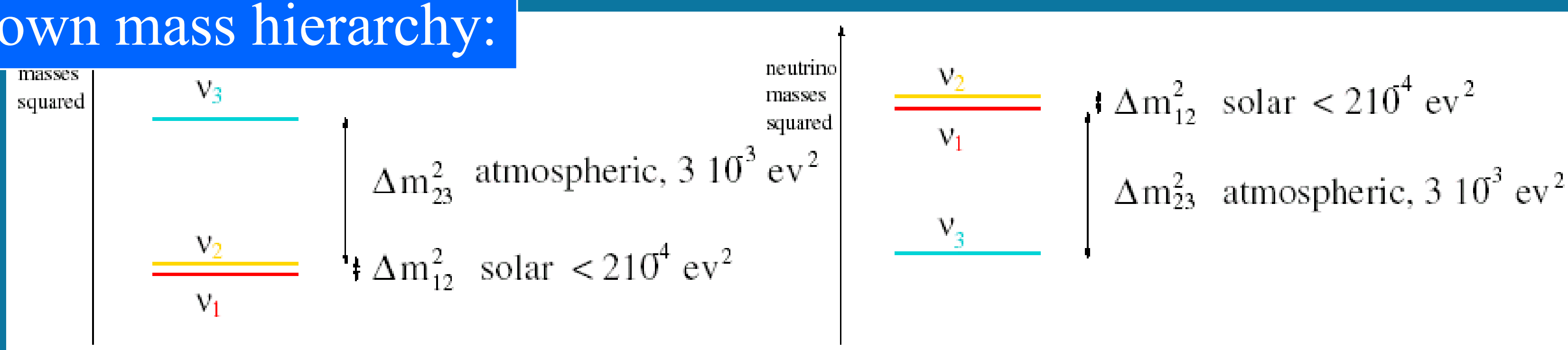
ν Oscillation Parameters

Geometry of ν oscillations:



Euler angles + CP-violating phase

Unknown mass hierarchy:



Neutrino Oscillations

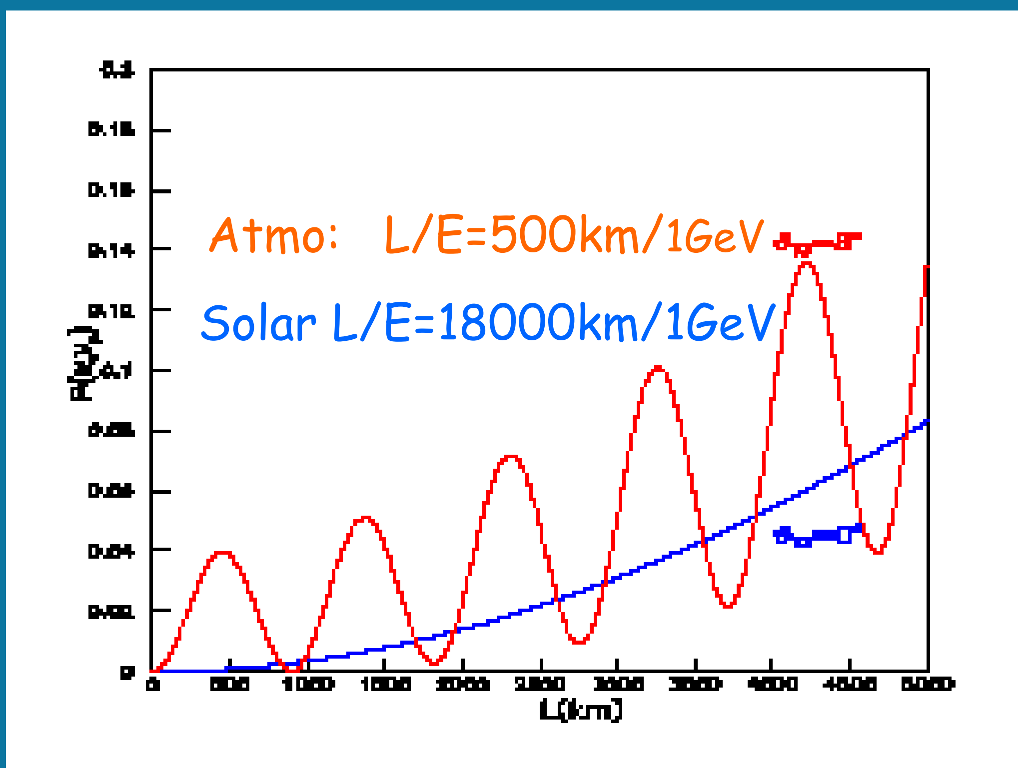
$$\begin{aligned} P_{\nu_e\nu_\mu(\bar\nu_e\bar\nu_\mu)} = \; & c_{23}^2 \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta_{12}L}{2}\right) \\ & + s_{23}^2 \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta_{23}L}{2}\right) \\ & + \tilde{J} \cos\left(\pm\delta - \frac{\Delta_{23}L}{2}\right) \frac{\Delta_{12}L}{2} \sin\left(\frac{\Delta_{23}L}{2}\right) \end{aligned}$$

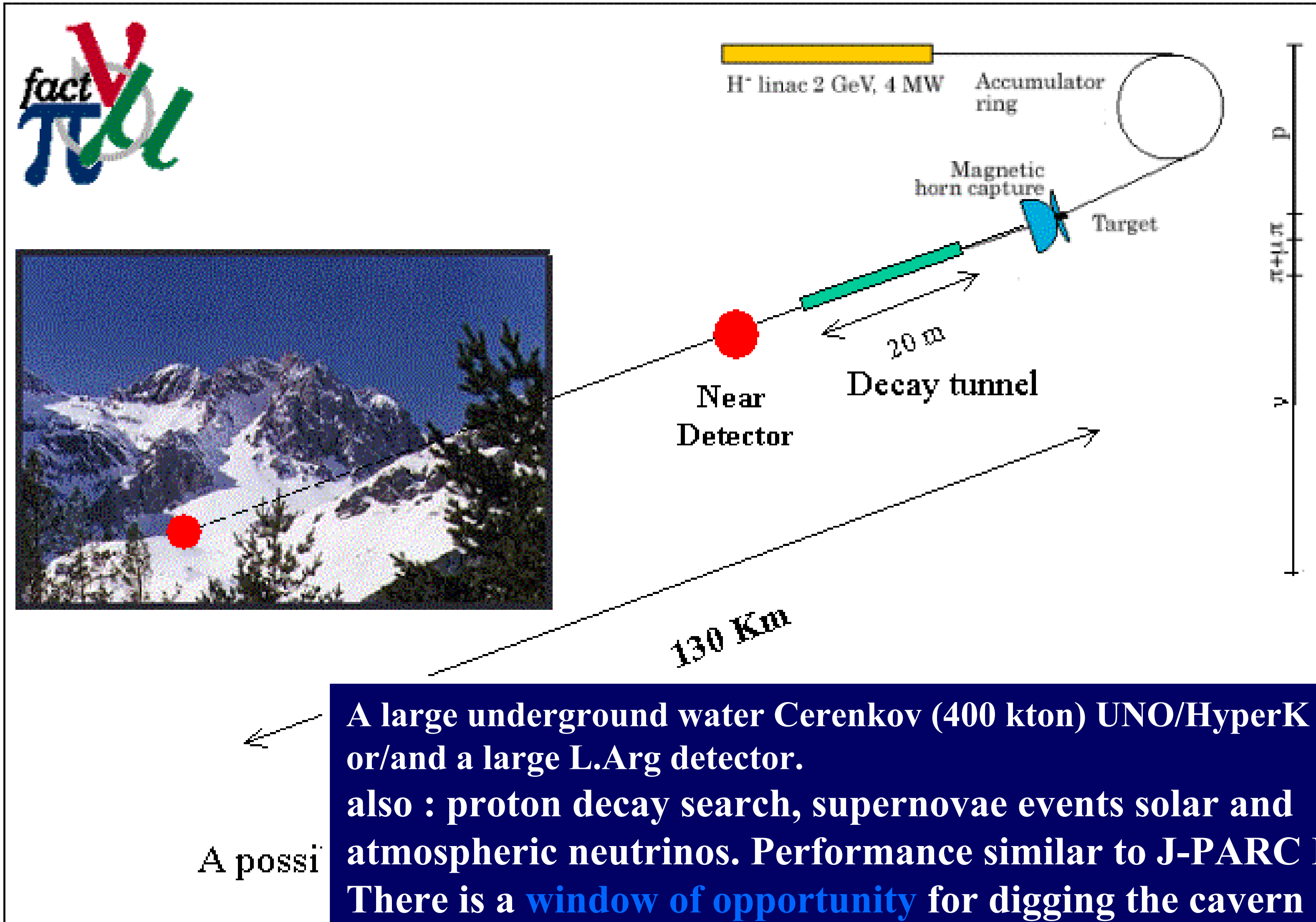
Solar

Atmospheric

Interference, responsible for

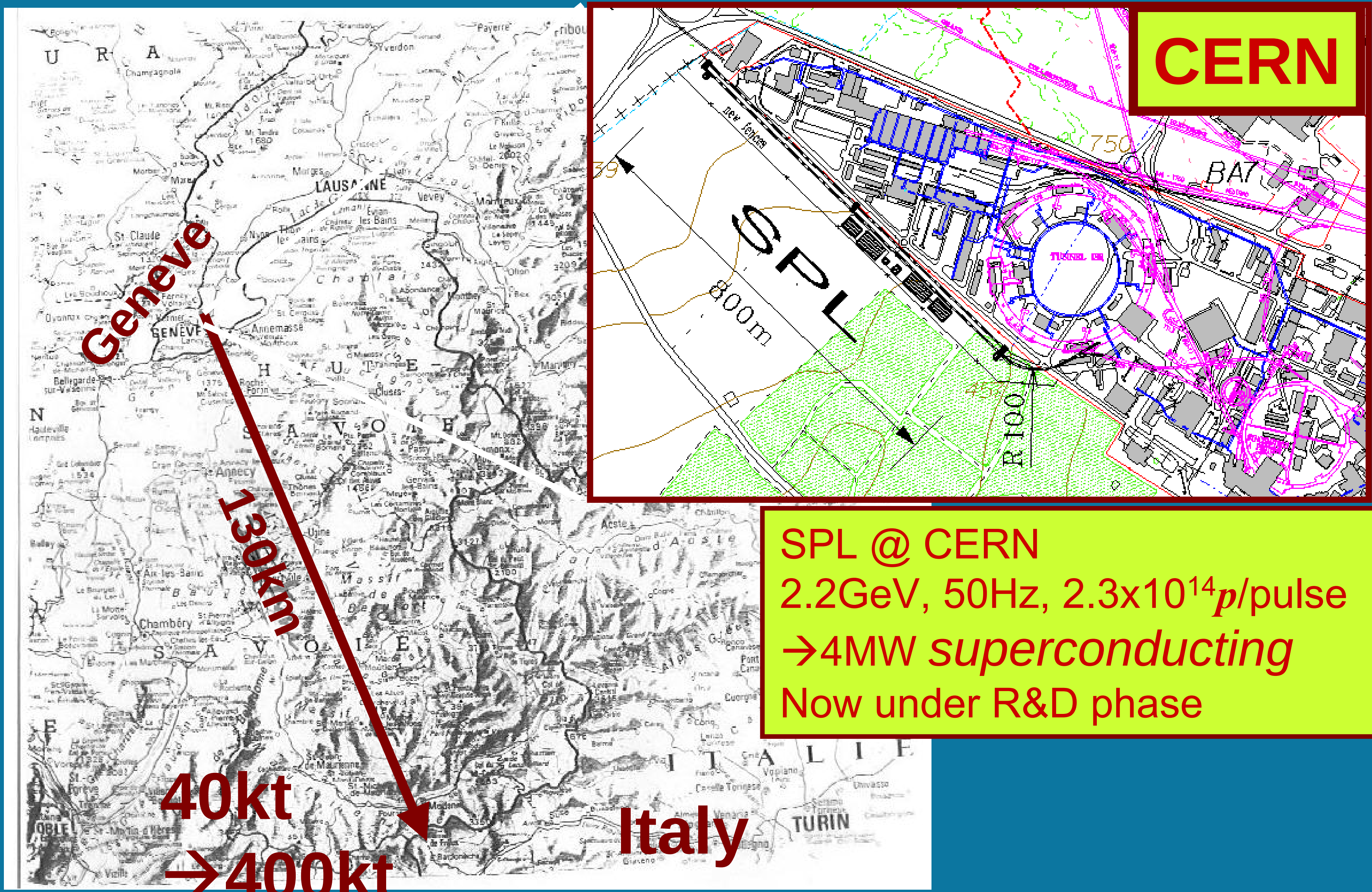
CP, T violation





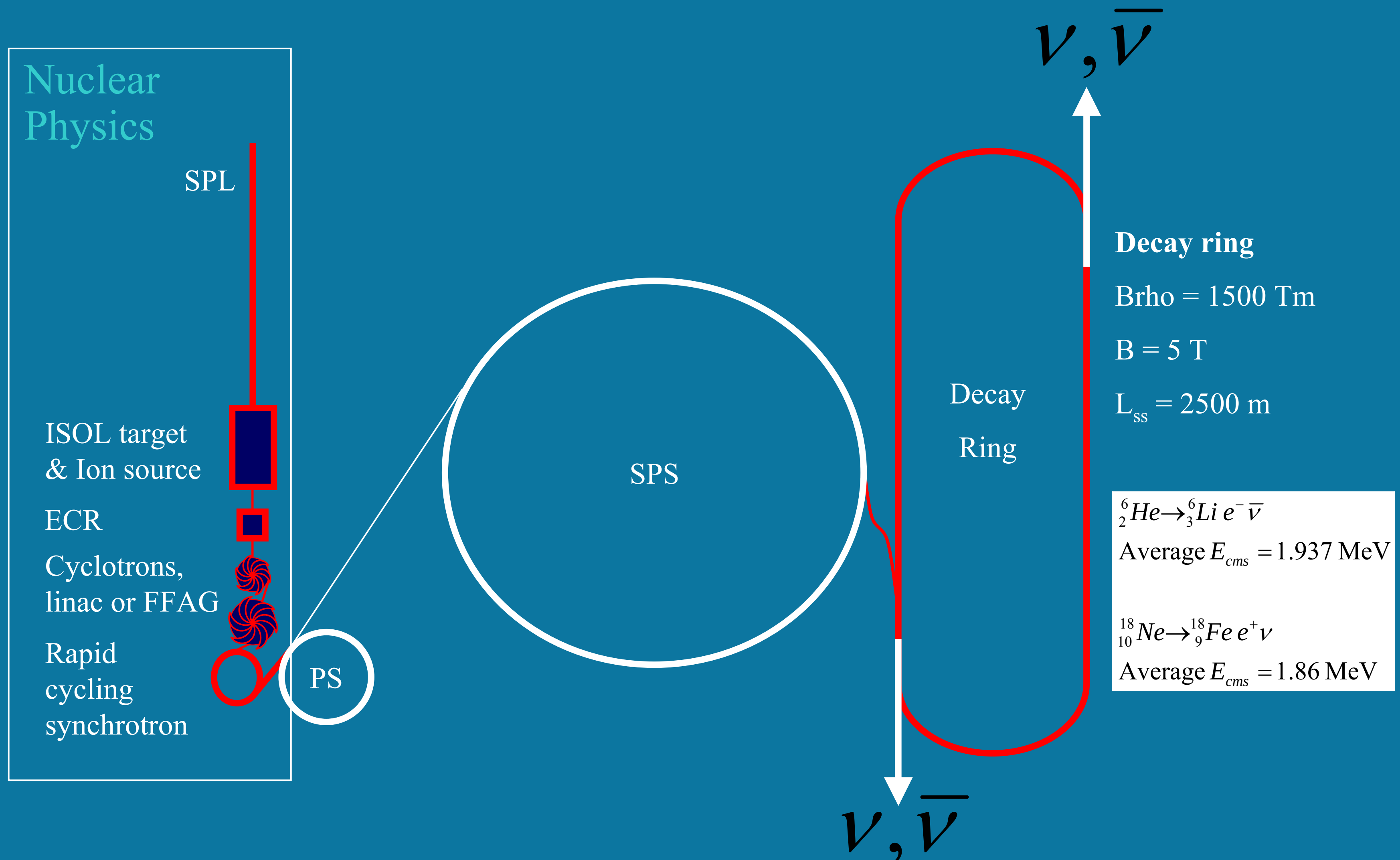
A large underground water Cerenkov (400 kton) UNO/HyperK or/and a large L.Arg detector.
also : proton decay search, supernovae events solar and atmospheric neutrinos. Performance similar to J-PARC II
There is a window of opportunity for digging the cavern starting in 2008 (safety tunnel in Frejus or TGV test gallery)

Europe: SPL→Frejus

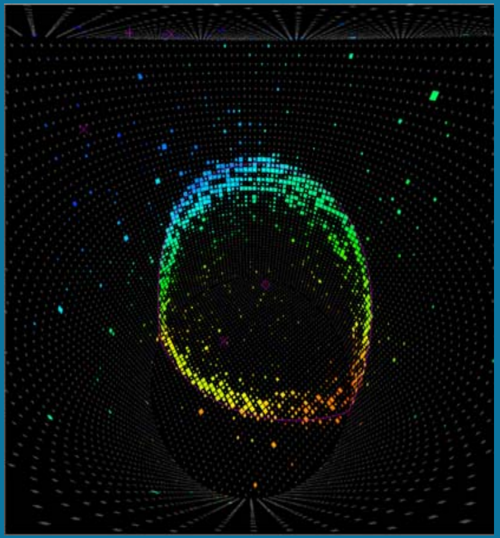


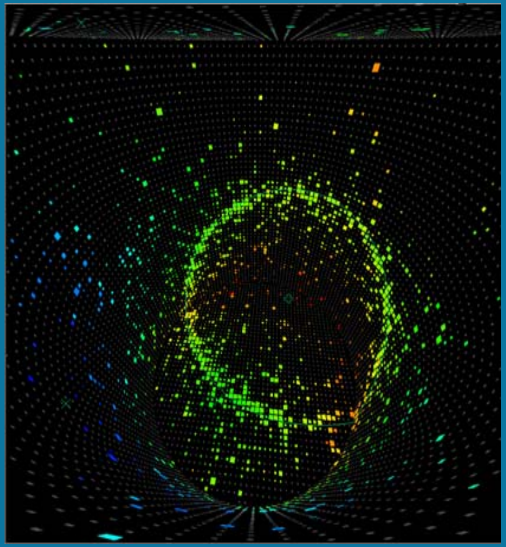
SPL @ CERN
2.2GeV, 50Hz, 2.3x10^{14} p/pulse
→4MW *superconducting*
Now under R&D phase

CERN: β-beam baseline scenario



Combination of beta beam with low energy super beam





Unique **to CERN- based scenario**

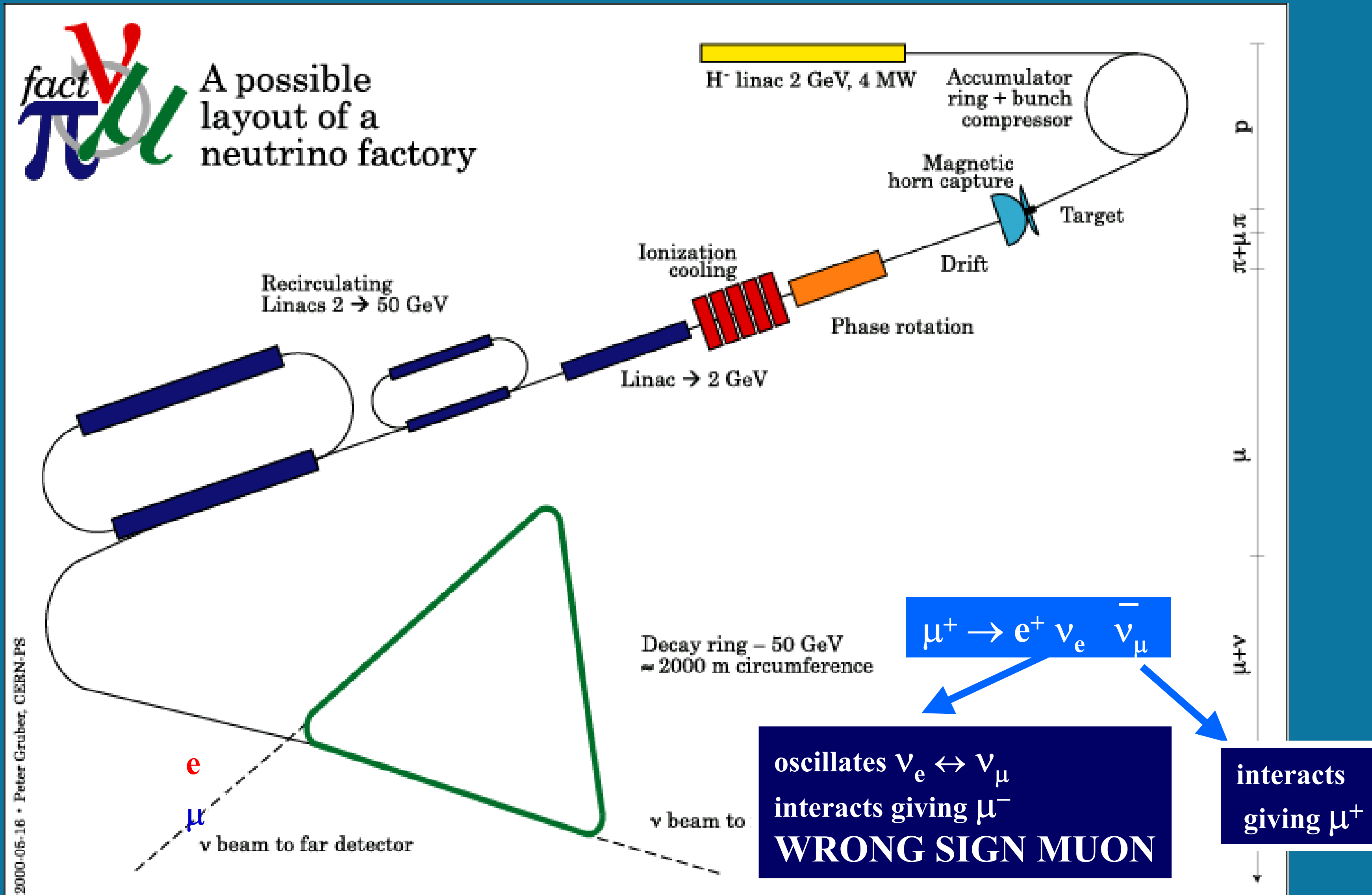
combines CP and T violation tests

$\nu_e \rightarrow \nu_\mu$ $(\beta+)$ **(T)** $\nu_\mu \rightarrow \nu_e$ (π^+)

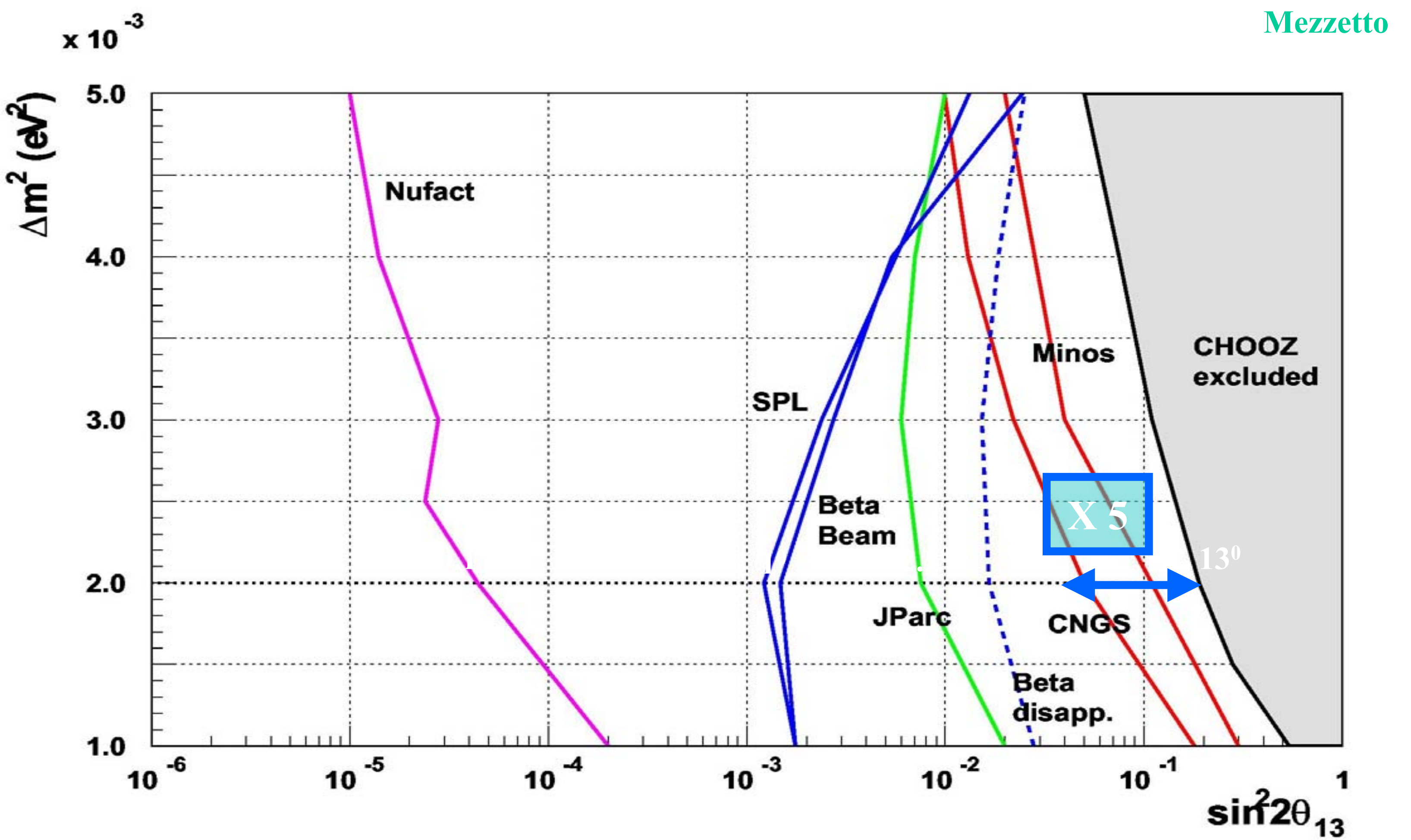
(CP)

$\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ $(\beta-)$ **(T)** $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ (π^-)

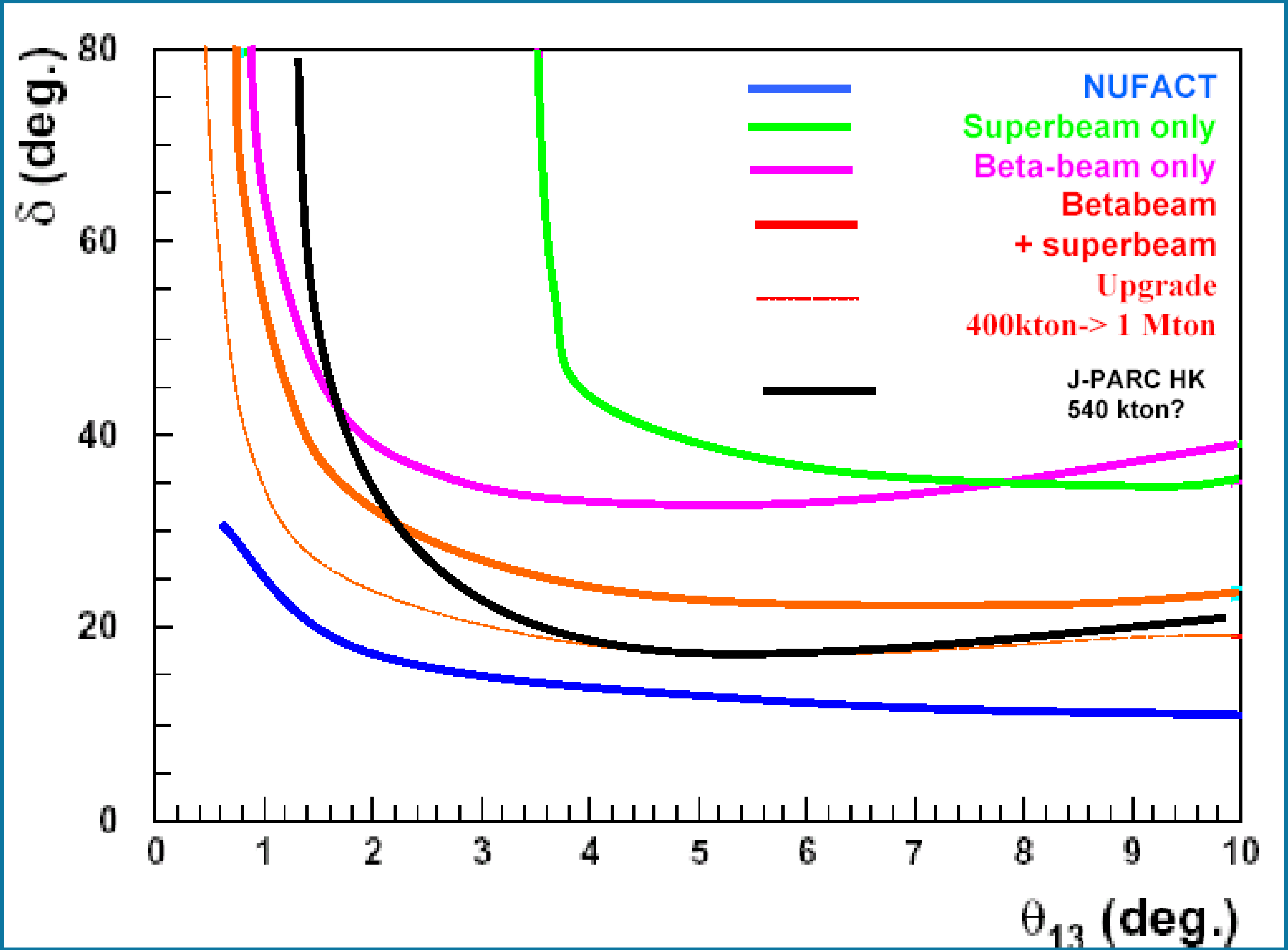
-- Neutrino Factory --
CERN layout



Where will this get us…

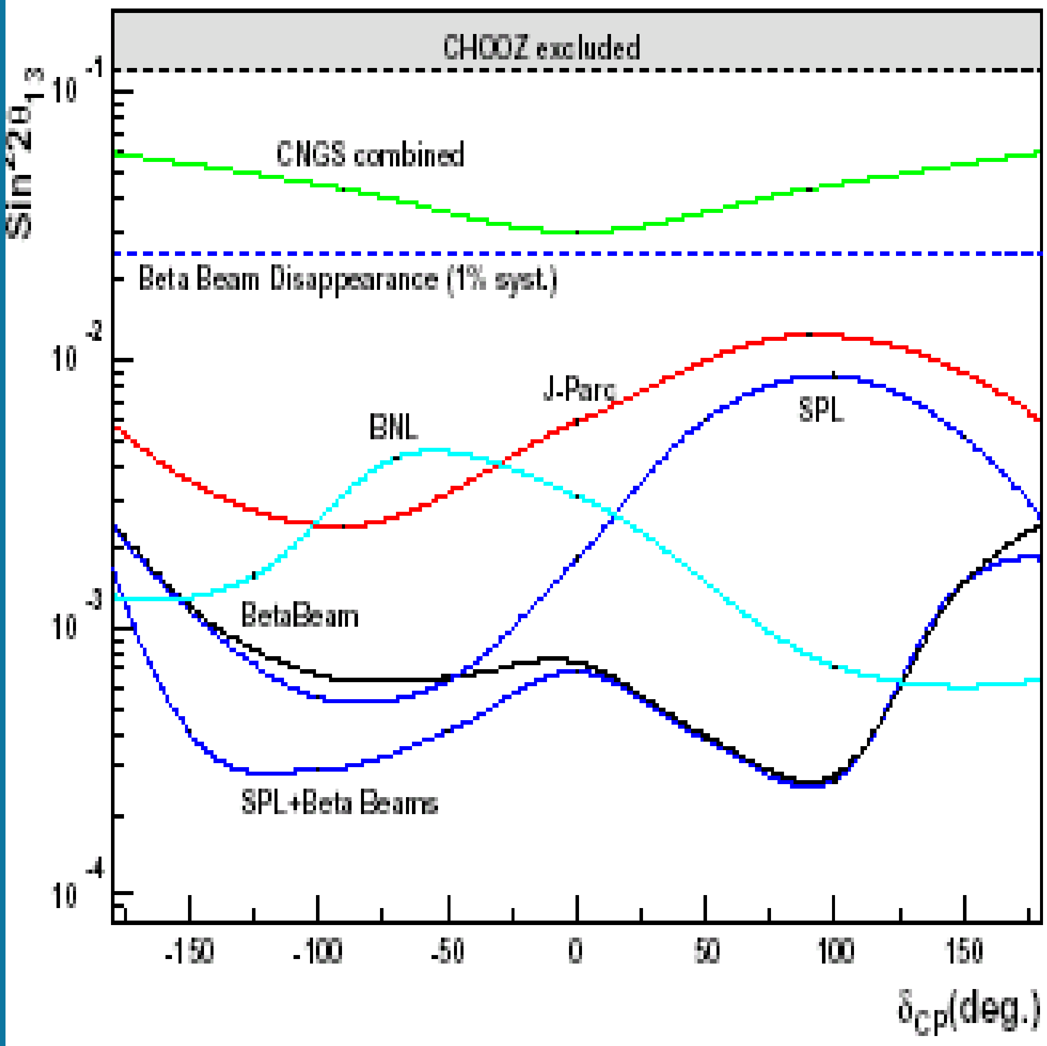


comparison of reach in the oscillations; right to left:
present limit from the CHOOZ experiment,
expected sensitivity from the MINOS experiment, CNGS (OPERA+ICARUS)
0.75 MW JHF to super Kamiokande with an off-axis narrow-band beam,
Superbeam: 4 MW CERN-SPL to a 400 kton water Cerenkov in Fréjus (J-PARC phase II similar)
from a Neutrino Factory with 40 kton large magnetic detector.


NUFACT
Superbeam only
Beta-beam only
Betabeam
+ superbeam
Upgrade
400kton-> 1 Mton
J-PARC HK
540 kton?
δ (deg.)
80
60
40
20
0
0
1
2
3
4
5
6
7
8
9
10
θ13 (deg.)

The « Venice » 4 phase program for θ_{13} and δ

1) CNGS/MINOS (2005-2010)
2) JPARC/Reactor(?) (2008-2013)
3) Superbeam/betabeam or NUMI off axis or 4MW JPARC (2014-)
4) Neutrino factory (>2020)



A MW machine is central

The Neutrino Road Map

Experiments to find θ_{13} :

1. search for $\nu_\mu \rightarrow \nu_e$ in conventional ν_μ beam (MINOS, ICARUS/OPERA) ==> 2005-2010
   limitations: NC π^0 background, intrinsic ν_e component in beam
2. Off-axis beam (JParc-SK, off axis NUMI, off axis CNGS) (~2008-2013) or reactor experiments
3. Low Energy Superbeam (BNL → Homestake, SPL →Fréjus or J-Parc-HyperK) (~2014-2020)

Precision experiments to find CP violation

-- or to search further if θ_{13} is too small

1. beta-beam $^6He^{++} \rightarrow {}^6Li^{+++}\ \bar{\nu}_e\ e^-$ and $^{18}Ne^{10+} \rightarrow {}^{18}F^{9+}\ \nu_e\ e^+$
   (also 2014-2020?)
2. Neutrino factory with muon storage ring (>2020)

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

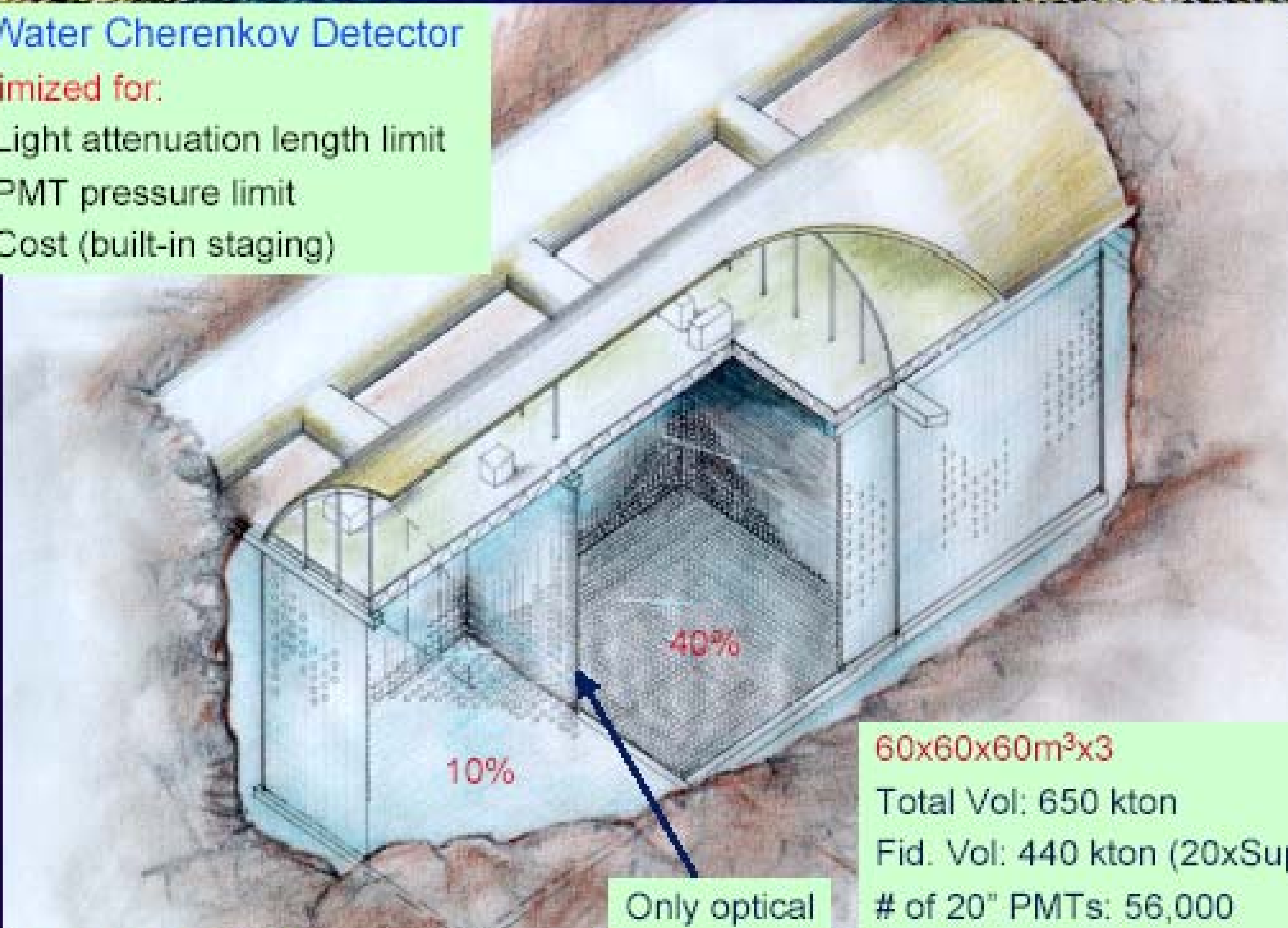
fraction thereof will exist .

UNO Detector Conceptual Design

A Water Cherenkov Detector

optimized for:

- Light attenuation length limit
- PMT pressure limit
- Cost (built-in staging)



$60x60x60m^3x3$

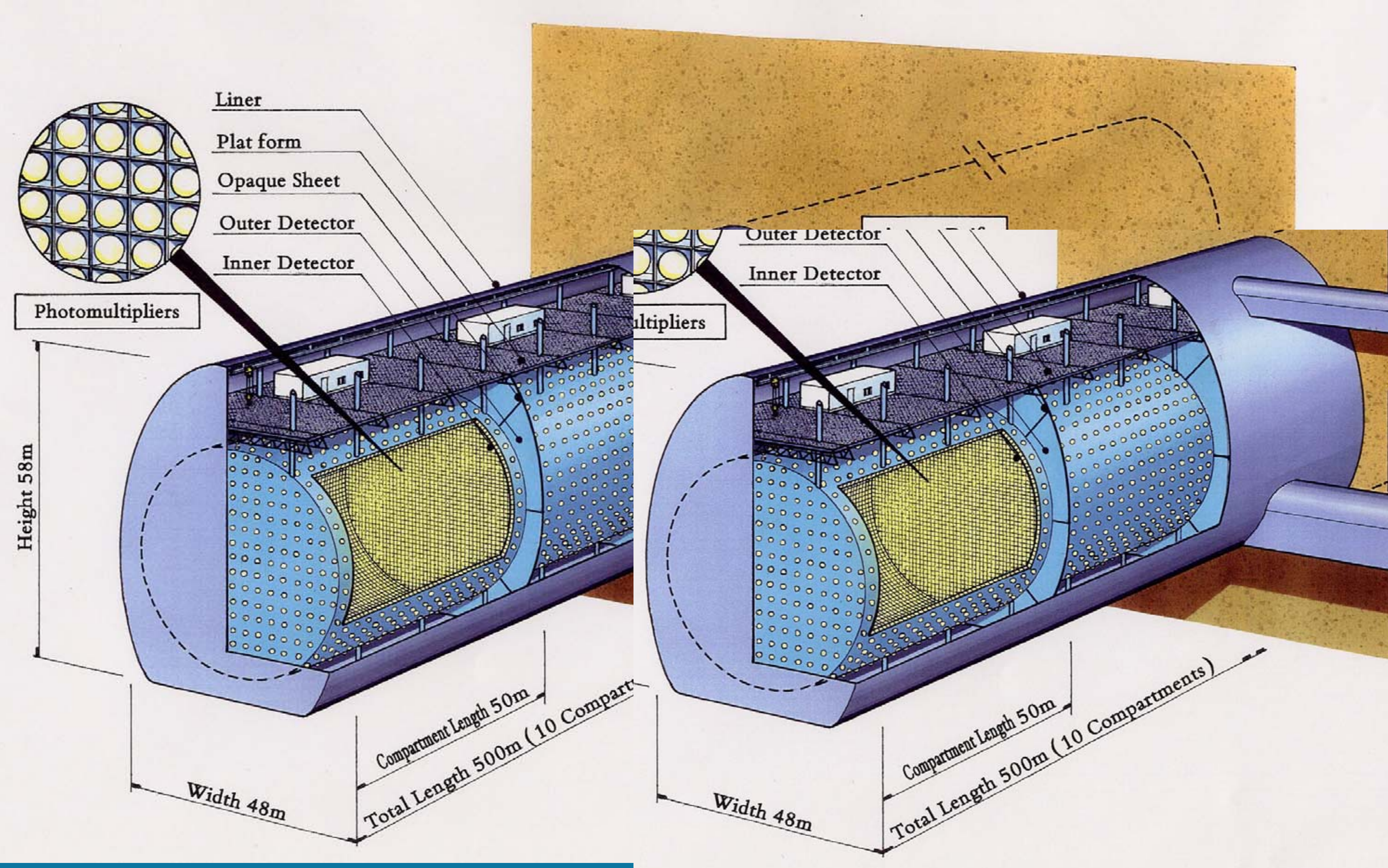
Total Vol: 650 kton

Fid. Vol: 440 kton (20xSuperK)

# of 20" PMTs: 56,000

# of 8" PMTs: 14,900

2 Detector Hyper-Kamiokande



2 detectors×48m × 50m ×250m, Total mass = 1 Mton

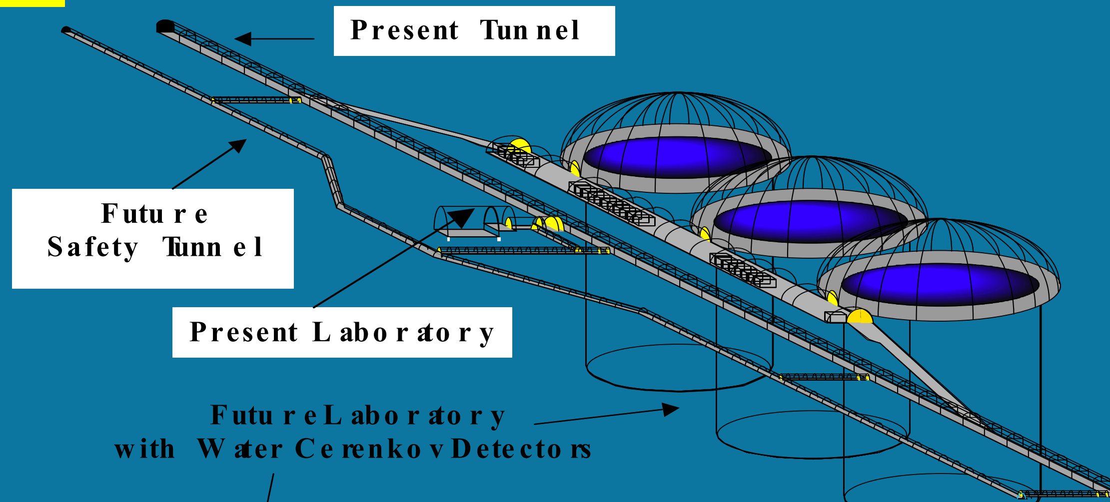
The 'Baseline' European Project: in the Franco-Italian tunnel Fréjus

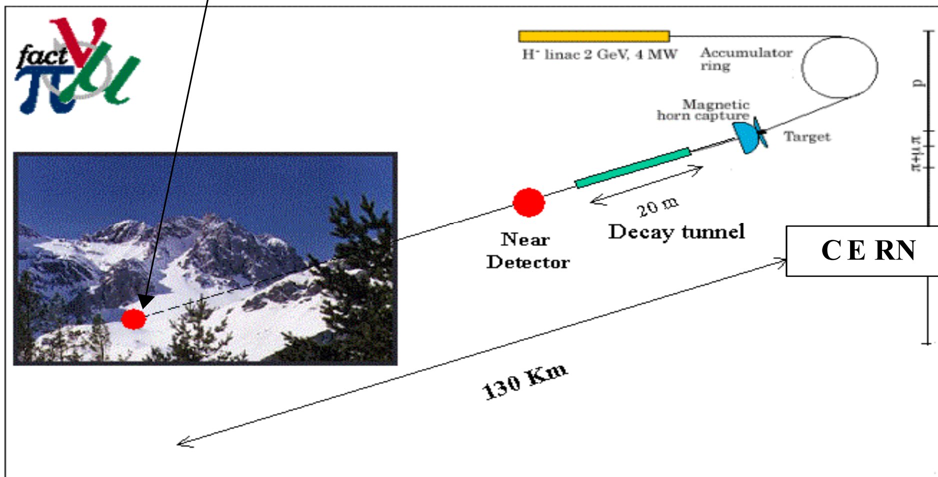
Components of the Project

MoU CEA/IN2P3/INFN

Main advantages:

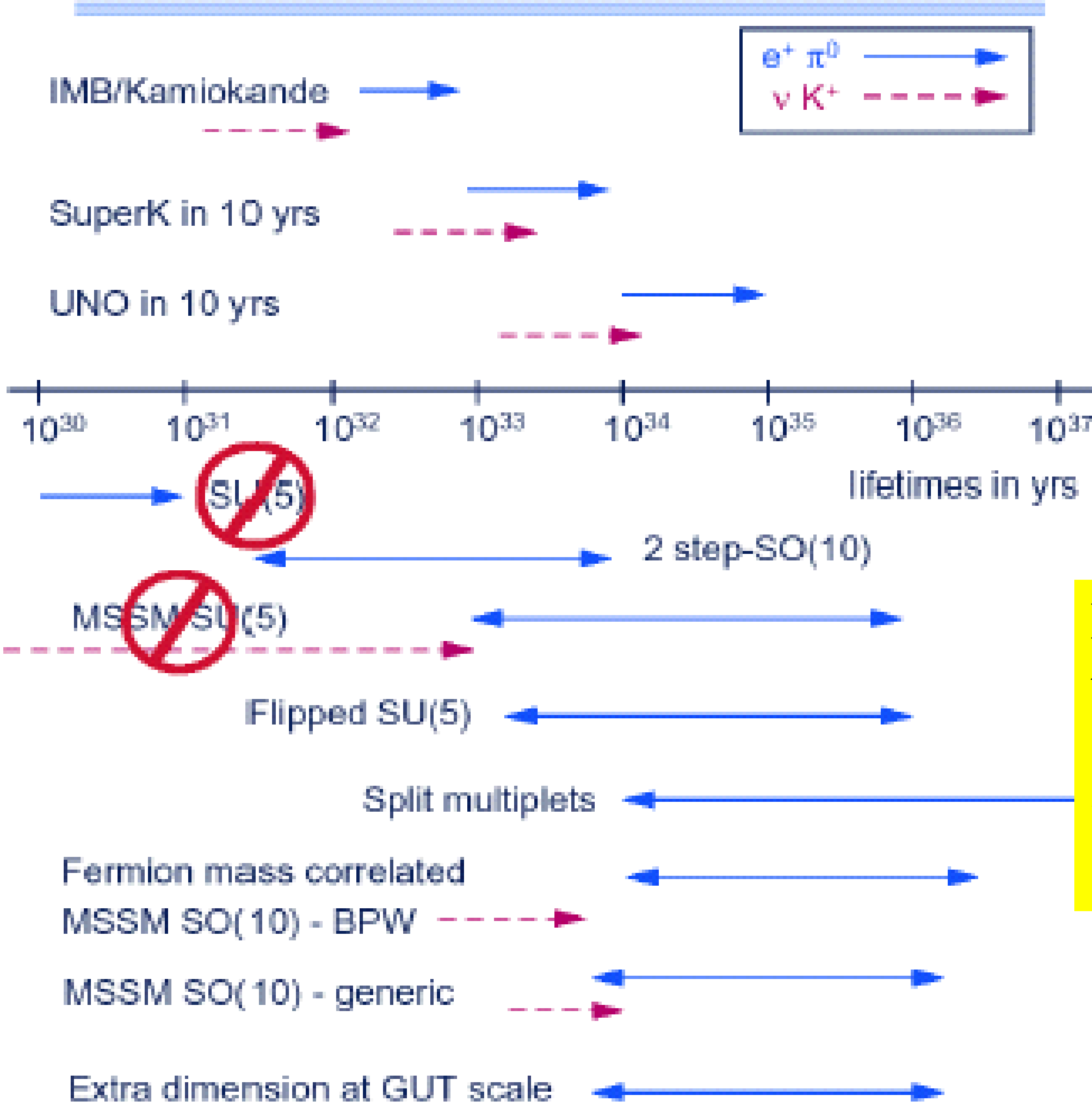
1) Large depth (>4800 mwe)
2) Beam at the right distance
3) Easy access, central european position
4) Support from local autorities, governments





A possible layout of a Low Energy Neutrino Super Beam

Proton decay



Do we need more theoretical effort for really model independent limits and guidance?

Supernova Reach
~ 1 Mpc
(local group of galaxies)

Supernova Rate
~ 1/10 or 15 yrs

SK is a factor of 3 in sensibility below models
A Megaton detector in a deep site (<4000 mwe) could exclude all models or discover SNR in3-5 years

Supernova

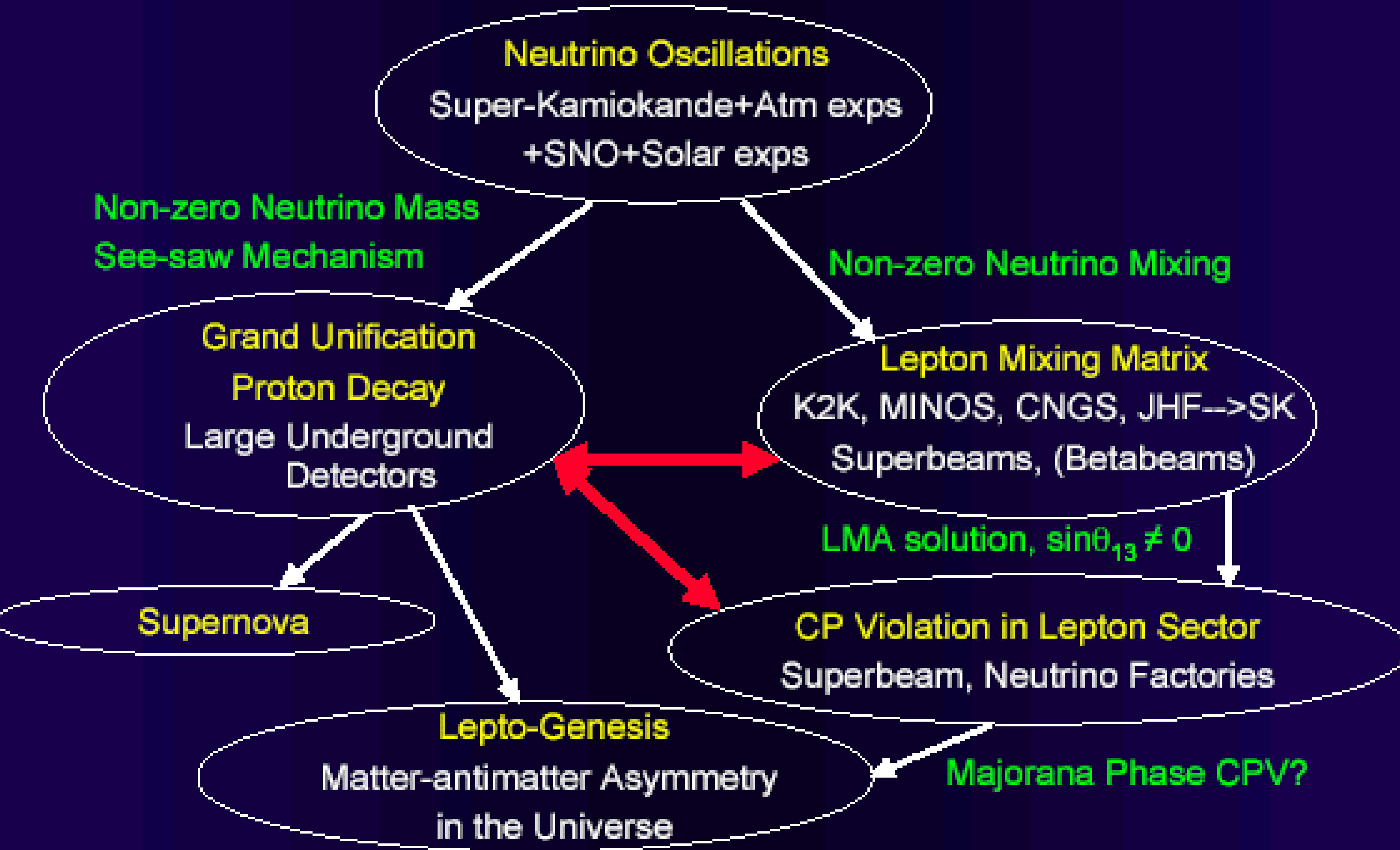
Theory Model	SK SRN Rate Limit (Efficiency Corrected)	SK SRN Flux Limit (18 MeV < Ee < 82 MeV)	SK SRN Flux Limit (Full Spectrum)	Predicted SRN Flux (Full Spectrum)
Galaxy evolution (Totani et al., 1996)	$3.2 \frac{\text{events}}{\text{year 22.5 kton}}$	$< 1.2 \frac{\bar{\nu}_e}{\text{cm}^2\ \text{sec}}$	$< 130 \frac{\bar{\nu}_e}{\text{cm}^2\ \text{sec}}$	$44 \frac{\bar{\nu}_e}{\text{cm}^2\ \text{sec}}$
Heavy metal abundance (Kaplinghat et al.,2000)	$3.0 \frac{\text{events}}{\text{year 22.5 kton}}$	$< 1.2 \frac{\bar{\nu}_e}{\text{cm}^2\ \text{sec}}$	$< 29 \frac{\bar{\nu}_e}{\text{cm}^2\ \text{sec}}$	$< 54 \frac{\bar{\nu}_e}{\text{cm}^2\ \text{sec}}$
Constant supernova rate (Totani et al., 1996)	$3.4 \frac{\text{events}}{\text{year 22.5 kton}}$	$< 1.2 \frac{\bar{\nu}_e}{\text{cm}^2\ \text{sec}}$	$< 20 \frac{\bar{\nu}_e}{\text{cm}^2\ \text{sec}}$	$52 \frac{\bar{\nu}_e}{\text{cm}^2\ \text{sec}}$
LMA neutrino oscillation (Ando et al., 2002)	$3.5 \frac{\text{events}}{\text{year 22.5 kton}}$	$< 1.2 \frac{\bar{\nu}_e}{\text{cm}^2\ \text{sec}}$	$< 31 \frac{\bar{\nu}_e}{\text{cm}^2\ \text{sec}}$	$11 \frac{\bar{\nu}_e}{\text{cm}^2\ \text{sec}}$

M.S. Malek et. al, Phys. Rev. Lett. 90, E-ID 061101 (2003)

Megaton physics goals

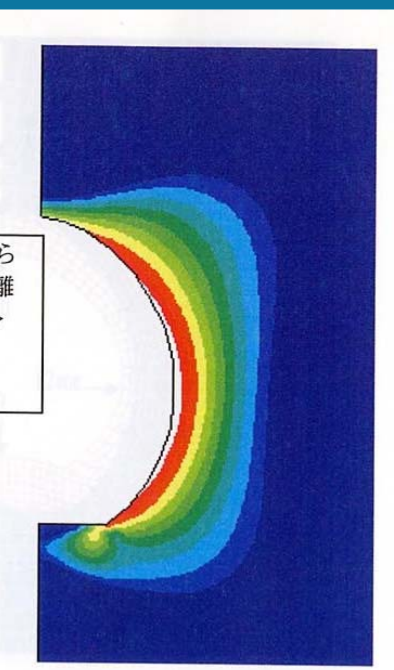
- Proton decay and GUT theories
- Neutrino parameters
  - superbeam/betabeam
  - atmospheric/solar
- Astroparticle
  - **Supernova explosion and relic**
  - **Other astrophysical sources**
- **Synergy**
  - **accelerator and astroparticle physics**
  - **and nuclear physics (EURISOL)**

1998 Neutrino Revolution and Physics Goals for NNN Experiments

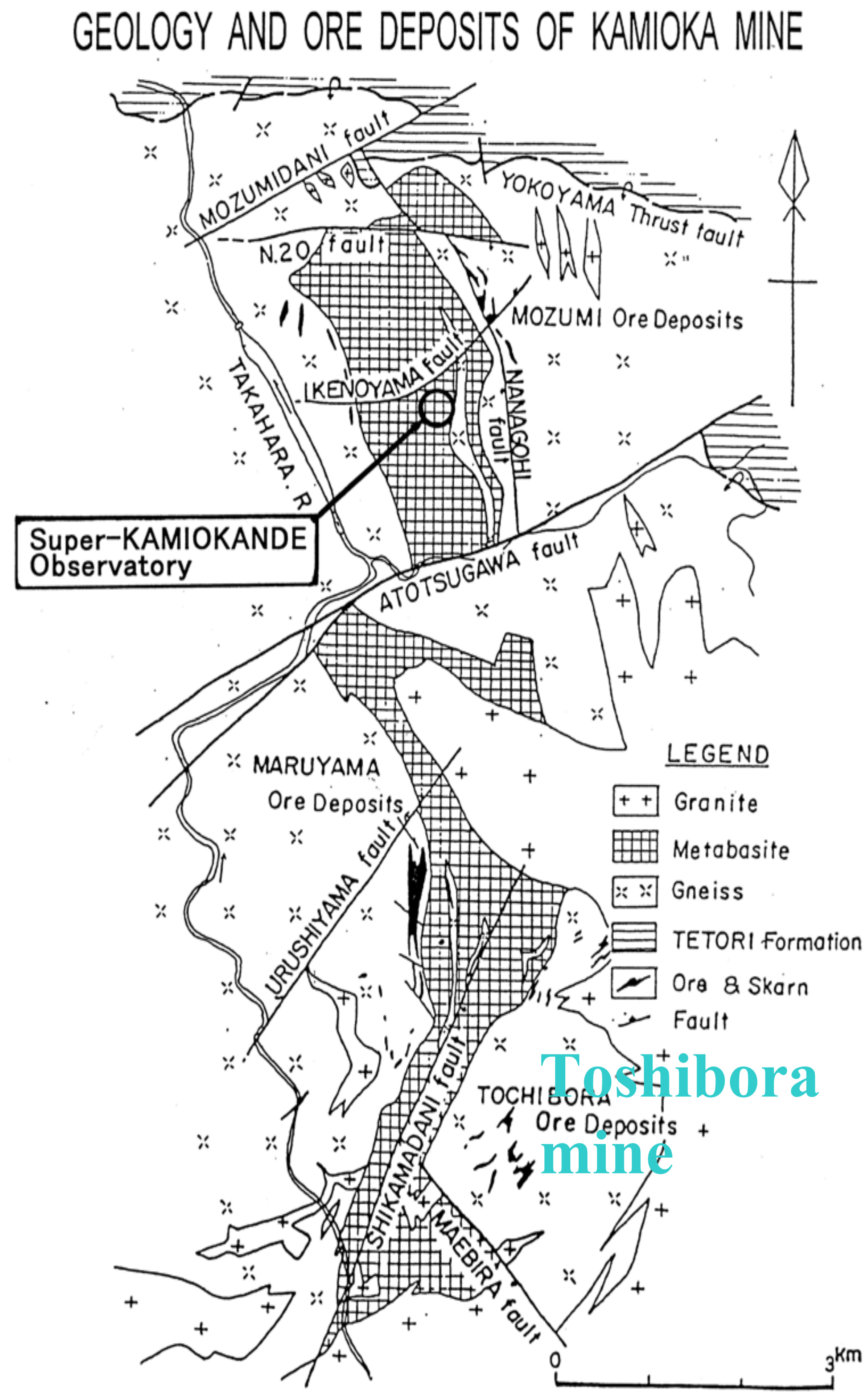


2 critical elements for the megaton detectors:

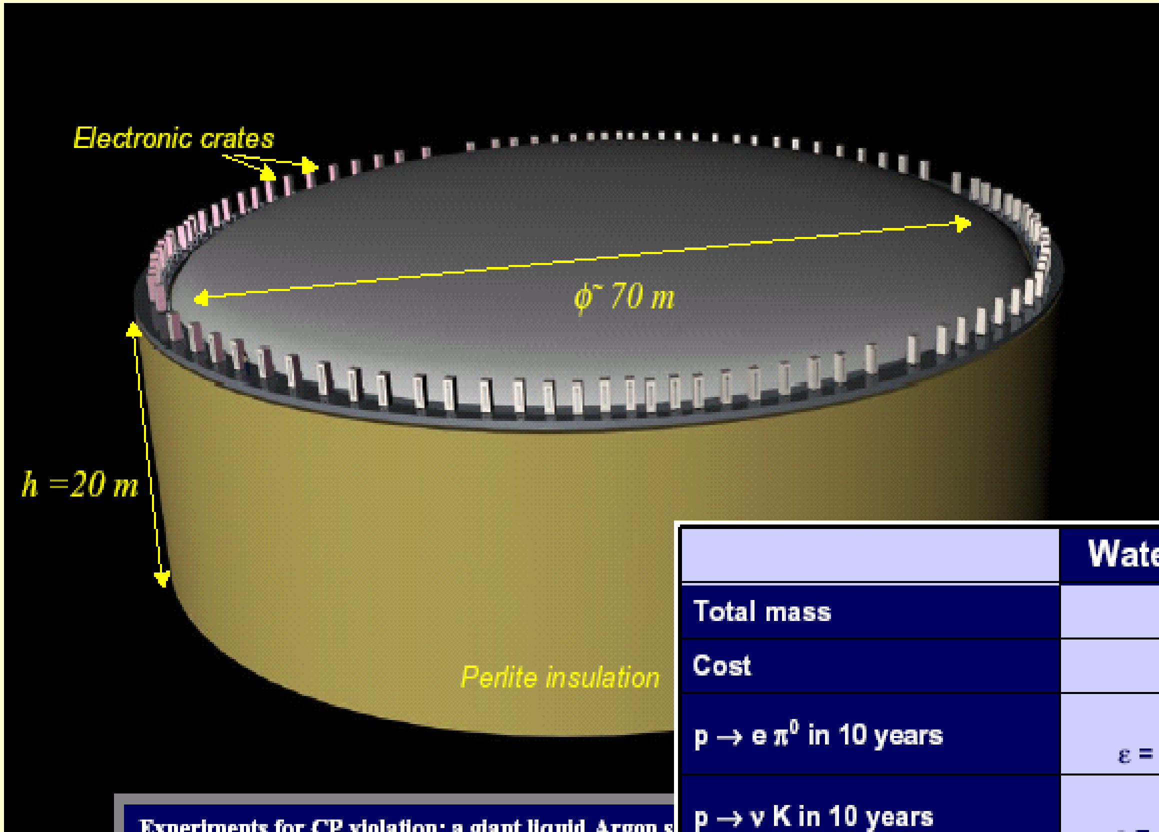
1) Excavation
2) cost of photodetectors



Design studies should include these two topics



100 kton liquid Argon TPC detector



Experiments for CP violation: a giant liquid Argon s
A.Rubbia, Proc. II Int. Workshop on Neutrinos in

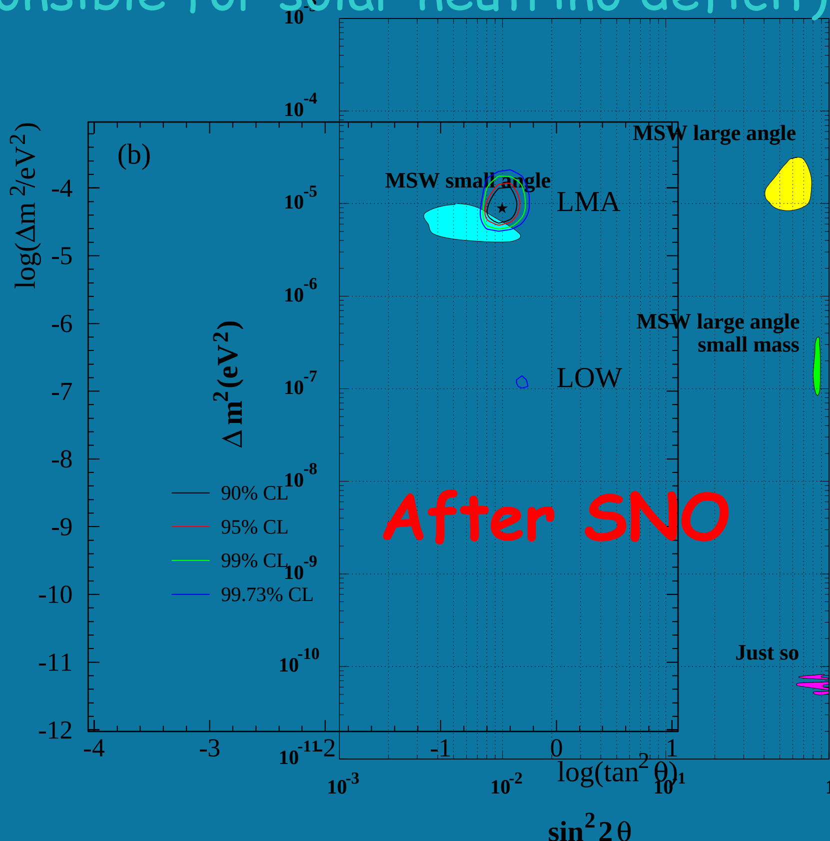
	Water Cerenkov (UNO)	Liquid Argon TPC
Total mass	650 kton	100 kton
Cost	~ 500 M$	Under evaluation
$p \to e\,\pi^0$ in 10 years	10^{35} years ε = 43%, ~ 30 BG events	3×10^{34} years ε = 45%, 1 BG event
$p \to \nu\, K$ in 10 years	2×10^{34} years ε = 8.6%, ~ 57 BG events	8×10^{34} years ε = 97%, 1 BG event
$p \to \mu\,\pi\, K$ in 10 years	No	8×10^{34} years ε = 98%, 1 BG event
SN cool off @ 10 kpc	194000 (mostly $\overline{\nu}_e p \to e^+ n$)	38500 (all flavors) (64000 if NH-L mixing)
SN in Andromeda	40 events	7 (12 if NH-L mixing)
SN burst @ 10 kpc	~ 330 ν-e elastic scattering	380 ν_e CC (flavor sensitive)
SN relic	Yes	Yes
Atmospheric neutrinos	60000 events/year	10000 events/year
Solar neutrinos	E_e > 7 MeV (central module)	324000 events/year E_e > 5 MeV

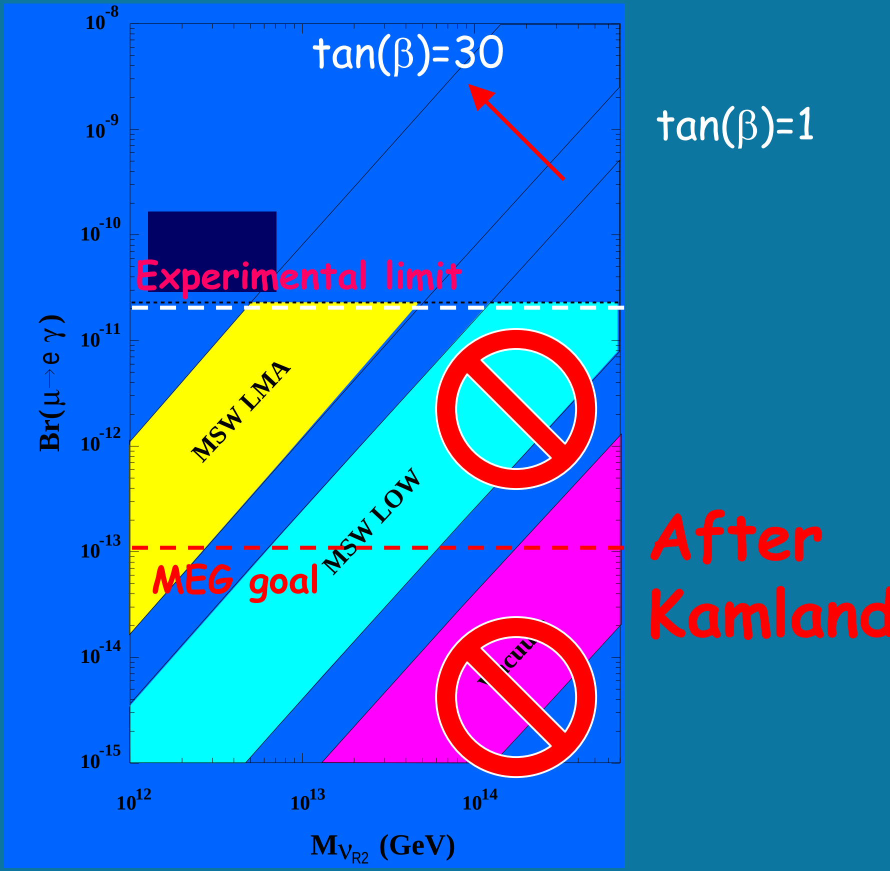

An example to follow
JPARC start of construction
KEK side
JAERI side

rare muon decays -- connection with ν-oscillations

Additional contribution to slepton mixing from V_{21} (the matrix element responsible for solar neutrino deficit)

J. Hisano, N. Nomura, Phys. Rev. D59 (1999)



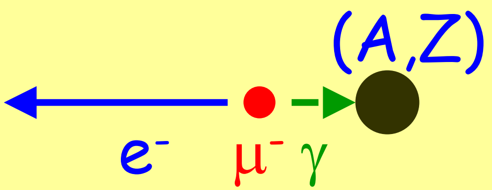


$R \approx 10^{-54}$ in the Standard Model !!

$\mu^- \to e^-$ conversion

signal

$\mu\ (A,Z) \to e\ (A,Z)$



$E_e = m_\mu - E_B$

main backgrounds

MIO

$\mu\ (A,Z) \to e\ \nu\ \nu\ (A,Z)$

RPC

$\pi\ (A,Z) \to \gamma\ (A,Z\text{-}1)$

Beam related background

Requires a BUNCHED beam

Illustration of the beam needs for the different kinds of experiments

Experiment	q_μ	$\int I_\mu dt$	I_0/I_m	δT [ns]	ΔT [μs]	E_μ [MeV]	$\Delta p_\mu / p_\mu$ [%]
$\mu^- N \to e^- N^\dagger$	$-$	10^{21}	$< 10^{-10}$	≤ 100	≥ 1	< 20	< 10
$\mu^- N \to e^- N^\ddagger$	$-$	10^{20}	n/a	n/a	n/a	< 20	< 10
$\mu \to e\gamma$	$+$	10^{17}	n/a	n/a	n/a	1...4	< 10
$\mu \to eee$	$+$	10^{17}	n/a	n/a	n/a	1...4	< 10
$\mu^+ e^- \to \mu^- e^+$	$+$	10^{16}	$< 10^{-4}$	< 1000	≥ 20	1...4	1...2
τ_μ	$+$	10^{14}	$< 10^{-4}$	< 100	≥ 20	4	1...10
transvers. polariz.	$+$	10^{16}	$< 10^{-4}$	< 0.5	> 0.02	30-40	1...3
$g_\mu - 2$	$\pm$	10^{15}	$< 10^{-7}$	≤ 50	$\geq 10^3$	3100	10^{-2}
edm_μ	$\pm$	10^{16}	$< 10^{-6}$	≤ 50	$\geq 10^3$	≤ 1000	$\leq 10^{-3}$

Conclusions

Neutrino physics (masses, mixings and CP violation) meet proton decay physics at GUT scales

This physics is just as important as the exploration of the electroweak scale.

Megawatt beams coupled with Megaton detectors are the natural aim at the 2015 horizon.

Conclusions (Euro-centered)

Unique opportunities exist in Europe:

1. Unique LHC upgraded+ Superbeam + betabeam + rare μ decays synergies *at CERN*

(accelerator complex + Isolde/Eurisol Expertise and physics)

2. The Superconducting proton Linac option has more potential for ultimate intensities

3. Deep underground megaton laboratory opportunities in Europe at adequate distance

(Fréjus…)

4. these are first steps towards Neutrino Factories and muon colliders.