

Neutrino oscillations and the Neutrino Factory

... MICE will lead the way

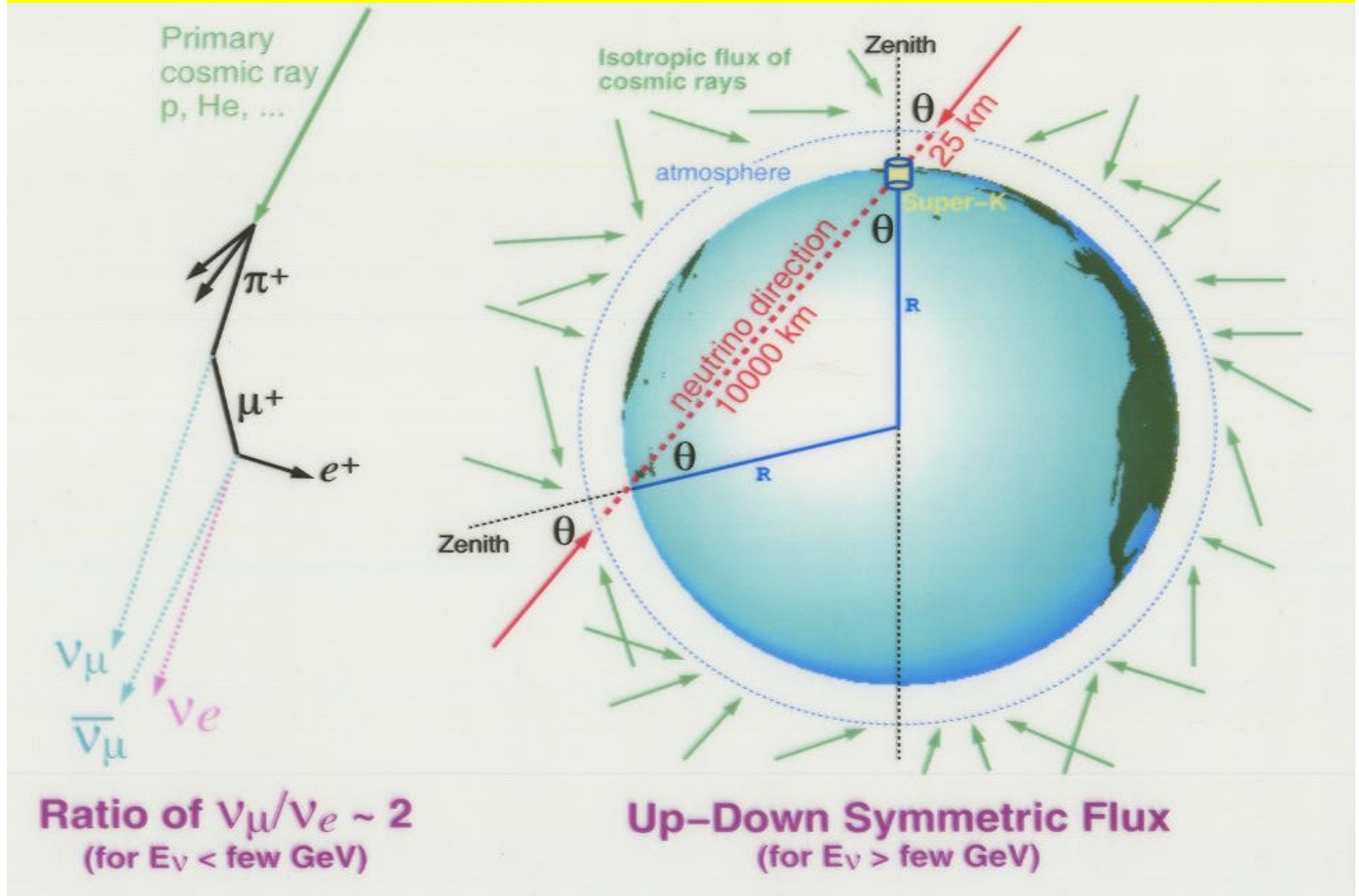
The end of the beginning?

- Neutrino oscillations – established exp^{tly}
- Implications for particle physics:
 - Neutrino mass > 0
 - Lepton number violation
 - CP violation in the lepton sector?
- Impact on astrophysics and cosmology:
 - Dark matter
 - Leptogenesis
- Require dedicated expt^l programme to:
 - Precisely measure parameters
 - Search for (and discover?) leptonic-CP violation

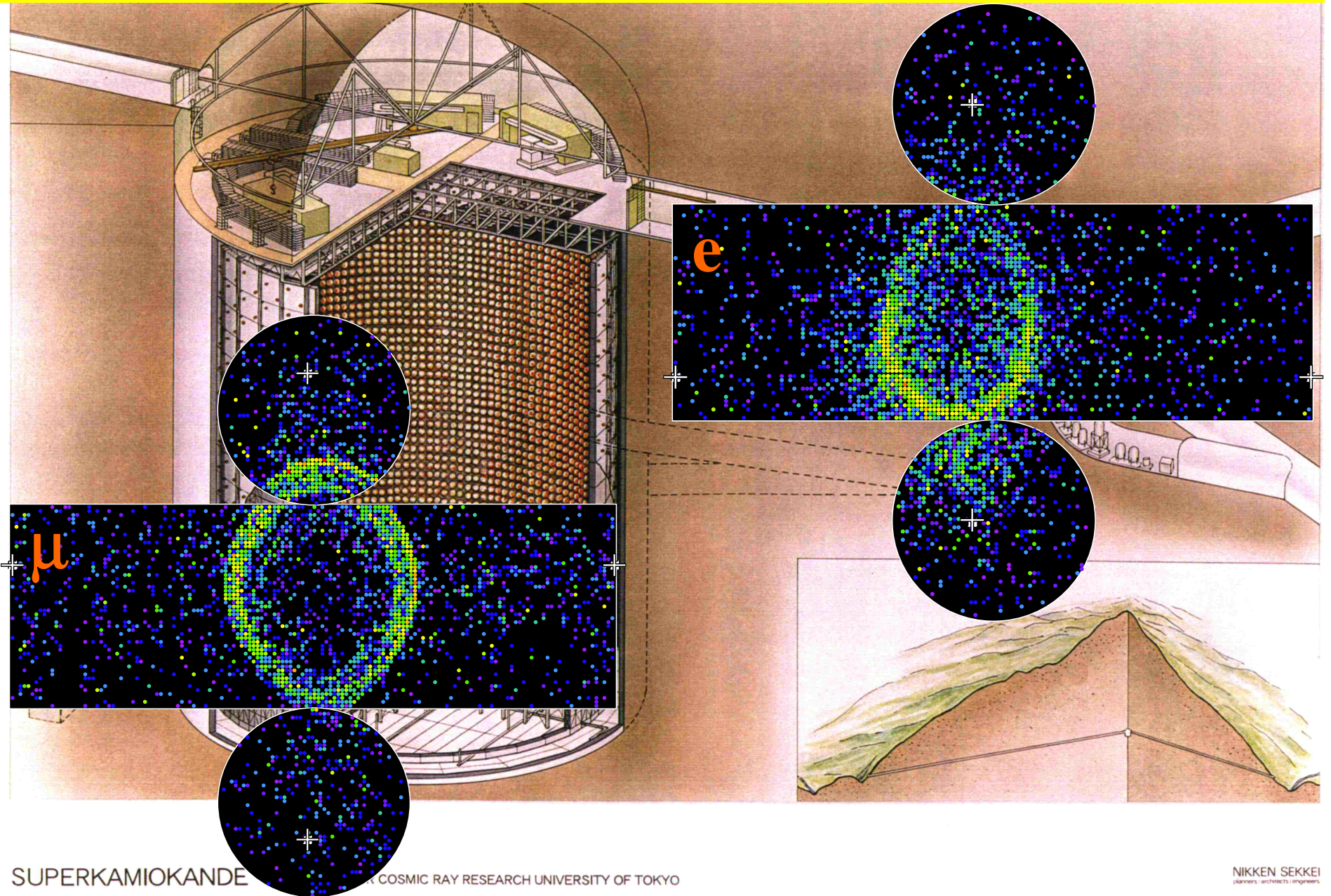
Contents

- **Neutrino oscillation – observation & status**
- **Measurements with next-generation terrestrial sources (brief)**
- **Physics reach of the Neutrino Factory**
- **Neutrino Factory accelerator R&D**
- **Conclusions**

Oscillations: atmospheric

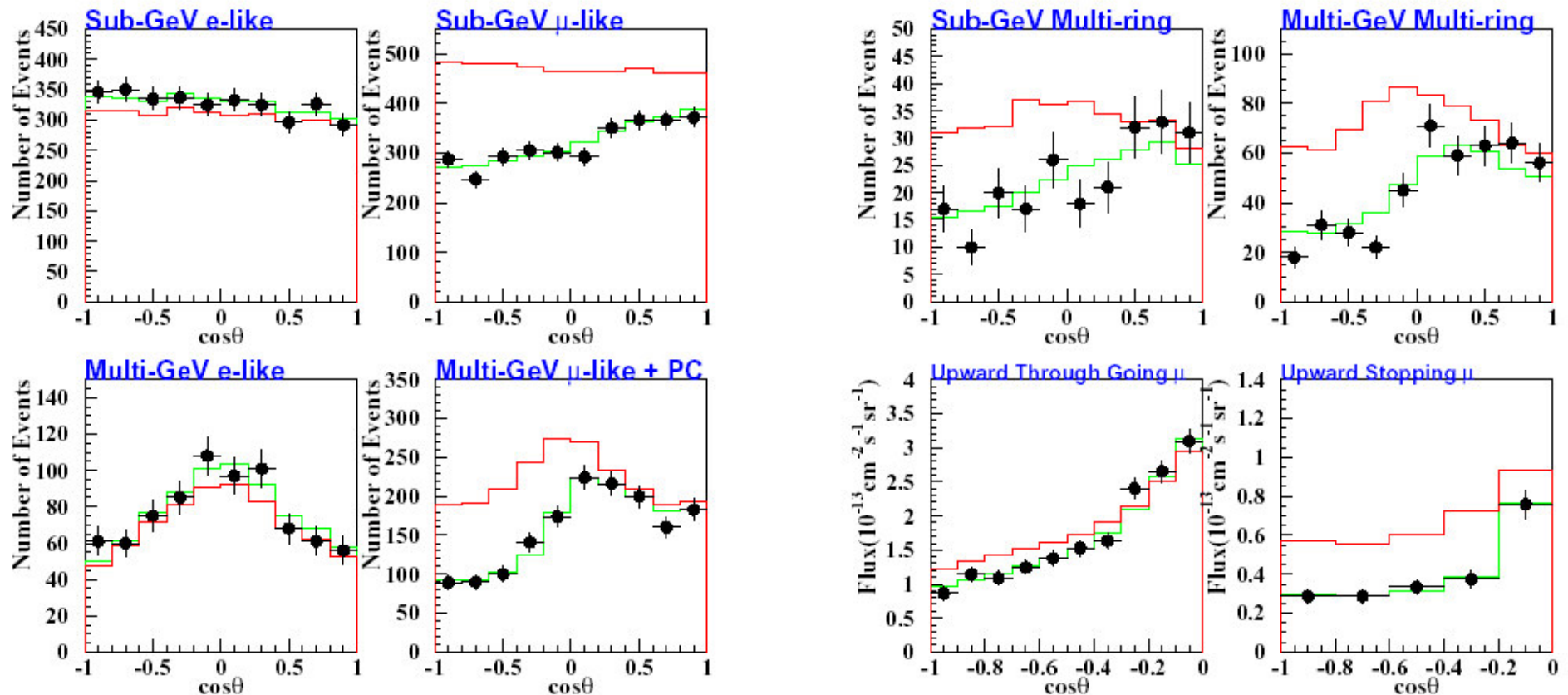


Super-Kamiokande



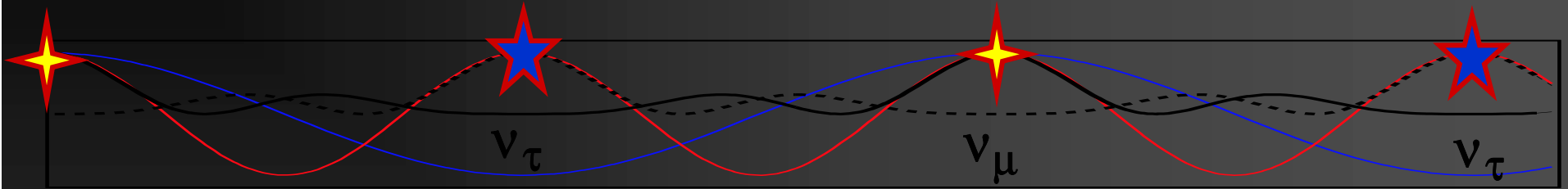
Atmospheric neutrinos: SK

- zenith angle dependence:



- Too few muon neutrinos

Neutrino oscillations: two flavour

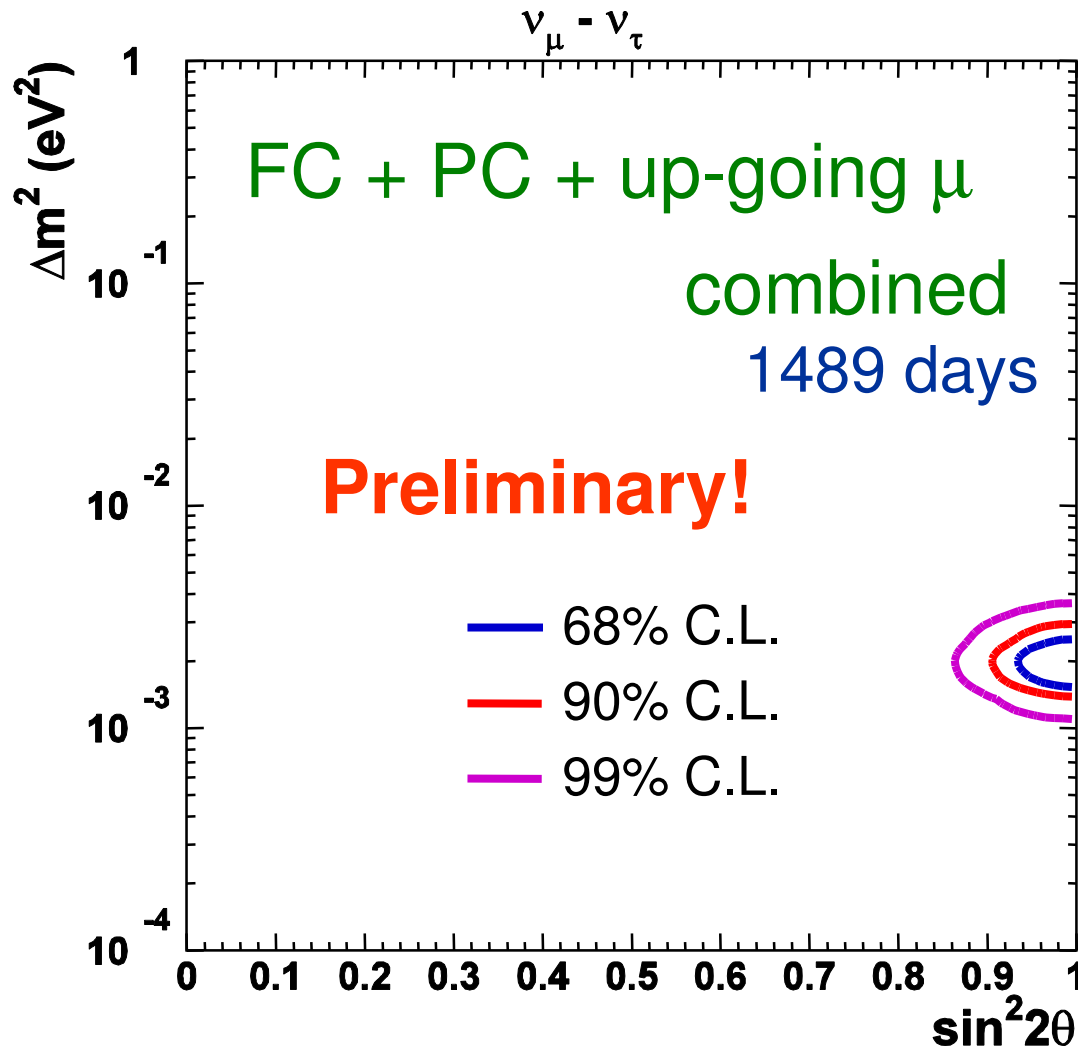


- 2 flavours (α & β) ; 2 mass eigenstates (i & j)

$$\begin{array}{ccc} \text{Flavour eigenstates} & \leftarrow & \text{Mass eigenstates} \\ \begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} & = & \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_2 \\ \nu_3 \end{pmatrix} \end{array}$$

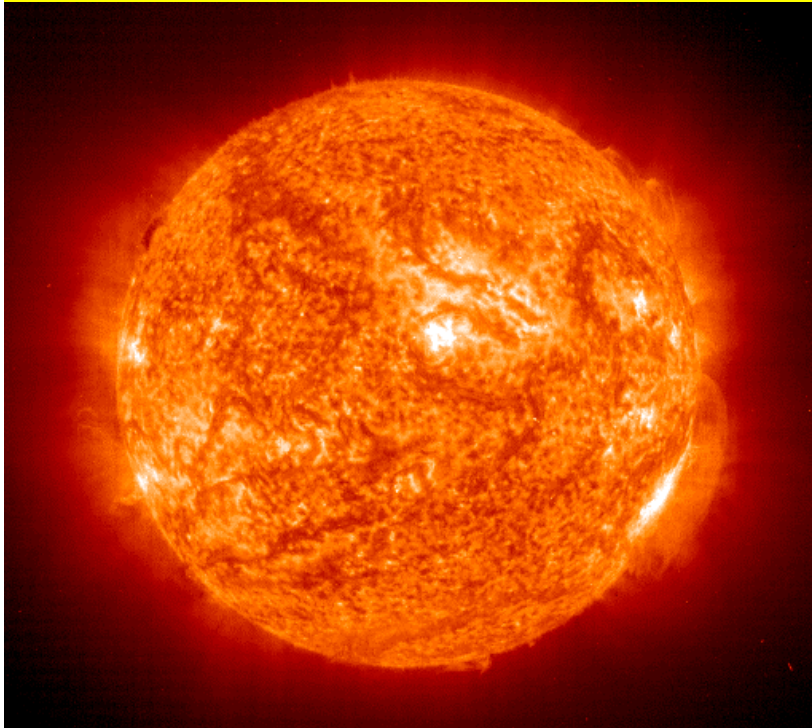
$$P(\nu_\alpha \Rightarrow \nu_\beta) = \sin^2(2\theta) \sin^2\left(\frac{\Delta m_{23}^2 L}{4E}\right)$$

'Atmospheric' parameters



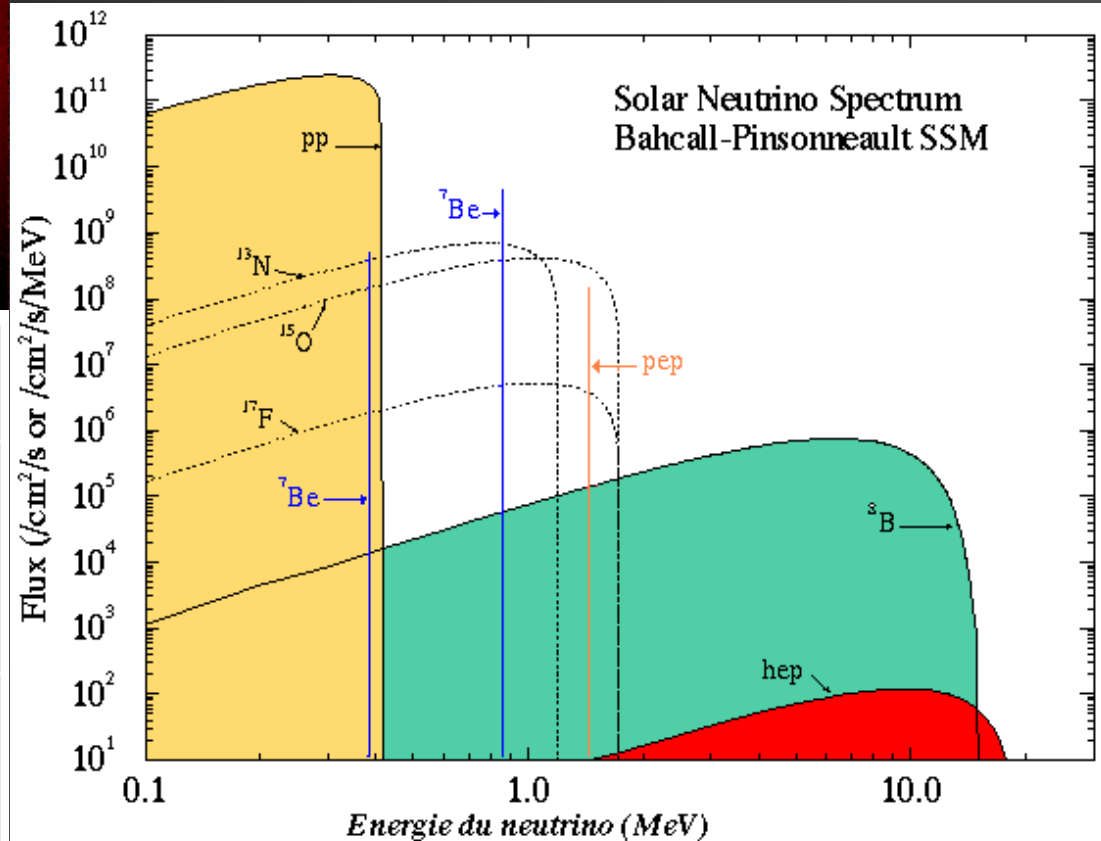
- Fit assumes $\nu_\mu \rightarrow \nu_\tau$
- $\sin^2 2\theta > 0.9$ (90%)
- $1.3 \times 10^{-3} < \Delta m^2 < 3.0 \times 10^{-3} \text{ (eV)}^2$

Oscillations: solar



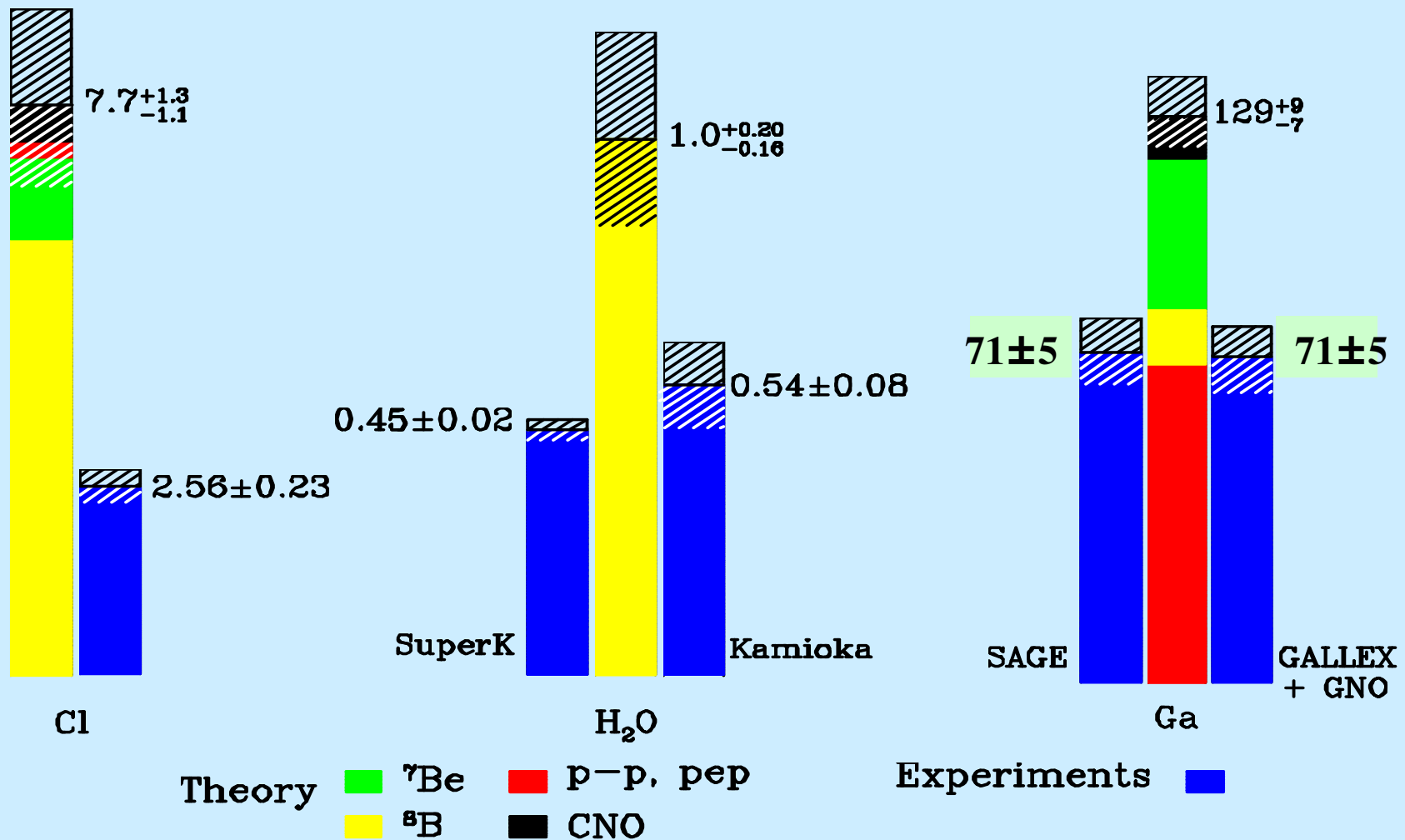
- *ONLY* ν_e produced in the sun

$pp \rightarrow {}^2\text{H} + e^+ + \nu_e$	
${}^2\text{H} + p \rightarrow {}^3\text{He} + \gamma$	
${}^3\text{He} + {}^3\text{He} \rightarrow {}^4\text{He} + 2p$	85%
${}^3\text{He} + {}^4\text{He} \rightarrow {}^7\text{Be} + \gamma$	15%
$e^- + {}^7\text{Be} \rightarrow {}^7\text{Li} + \nu_e$	
${}^7\text{Li} + p \rightarrow 2{}^4\text{He}$	
$p + {}^7\text{Be} \rightarrow {}^8\text{B} + \gamma$	0.02%
${}^8\text{B} \rightarrow {}^8\text{Be}^* + e^+ + \nu_e$	
${}^8\text{Be}^* \rightarrow 2{}^4\text{He}$	

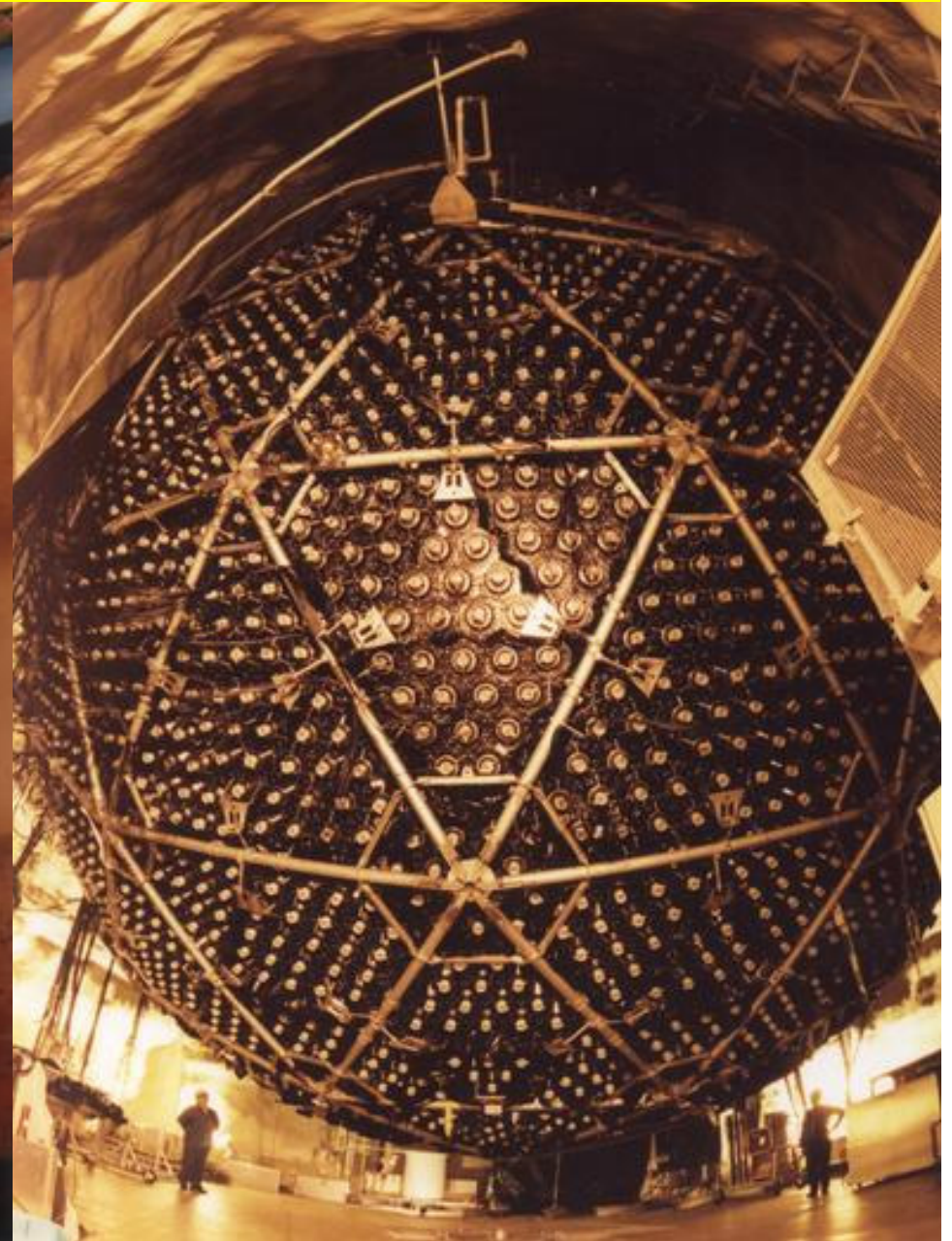


Solar neutrino rates:

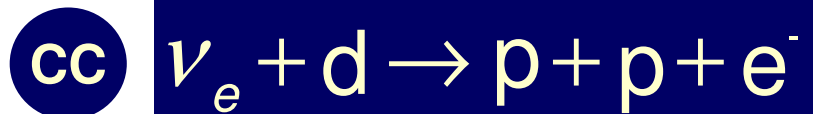
Total Rates: Standard Model vs. Experiment
Bahcall–Pinsonneault 2000



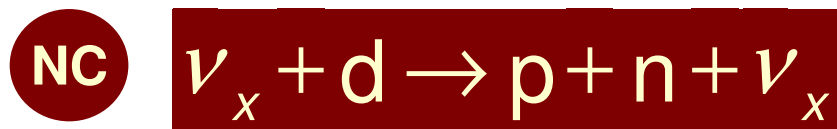
Sudbury Neutrino Observatory



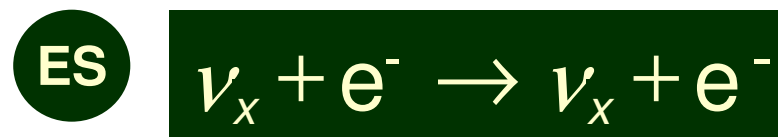
Neutrino detection at SNO



- Measurement of ν_e energy spectrum
- Weak directionality: $1 - 0.340 \cos \theta$



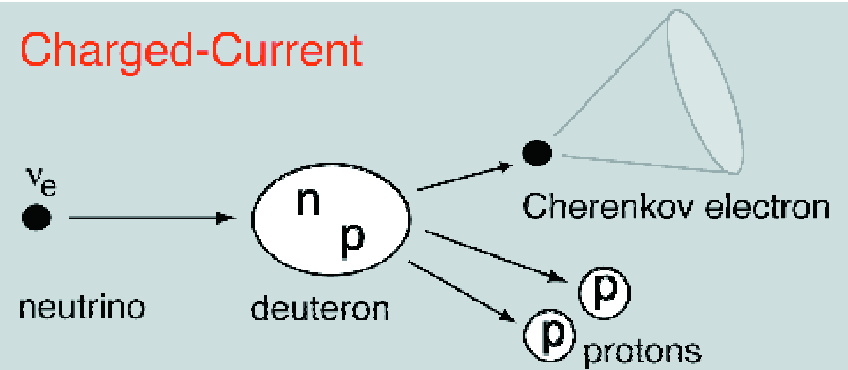
- Measure total ^8B ν flux from the sun
- $\sigma(\nu_e) = \sigma(\nu_\mu) = \sigma(\nu_\tau)$



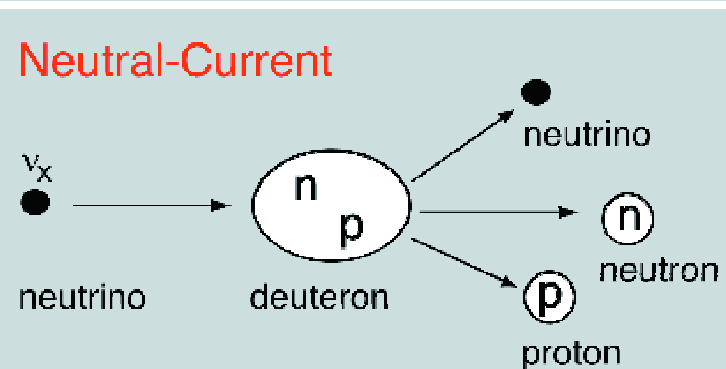
- Low Statistics
- $\sigma(\nu_e) \approx 6 \sigma(\nu_\mu) \approx 6 \sigma(\nu_\tau)$
- Strong directionality:

$$\theta_e \leq 18^\circ \quad (T_e = 10 \text{ MeV})$$

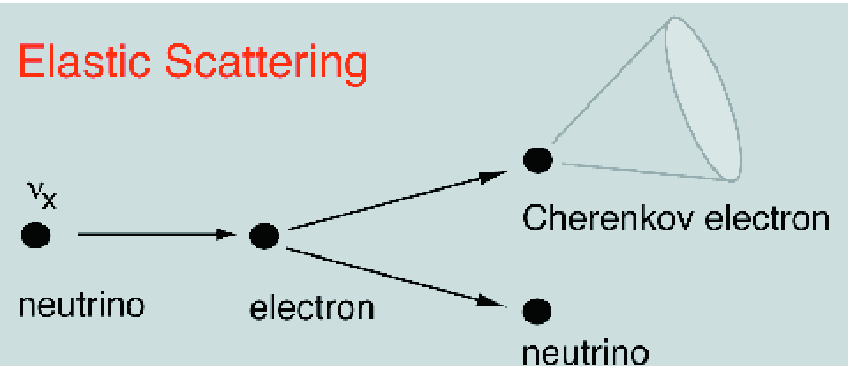
Charged-Current



Neutral-Current



Elastic Scattering

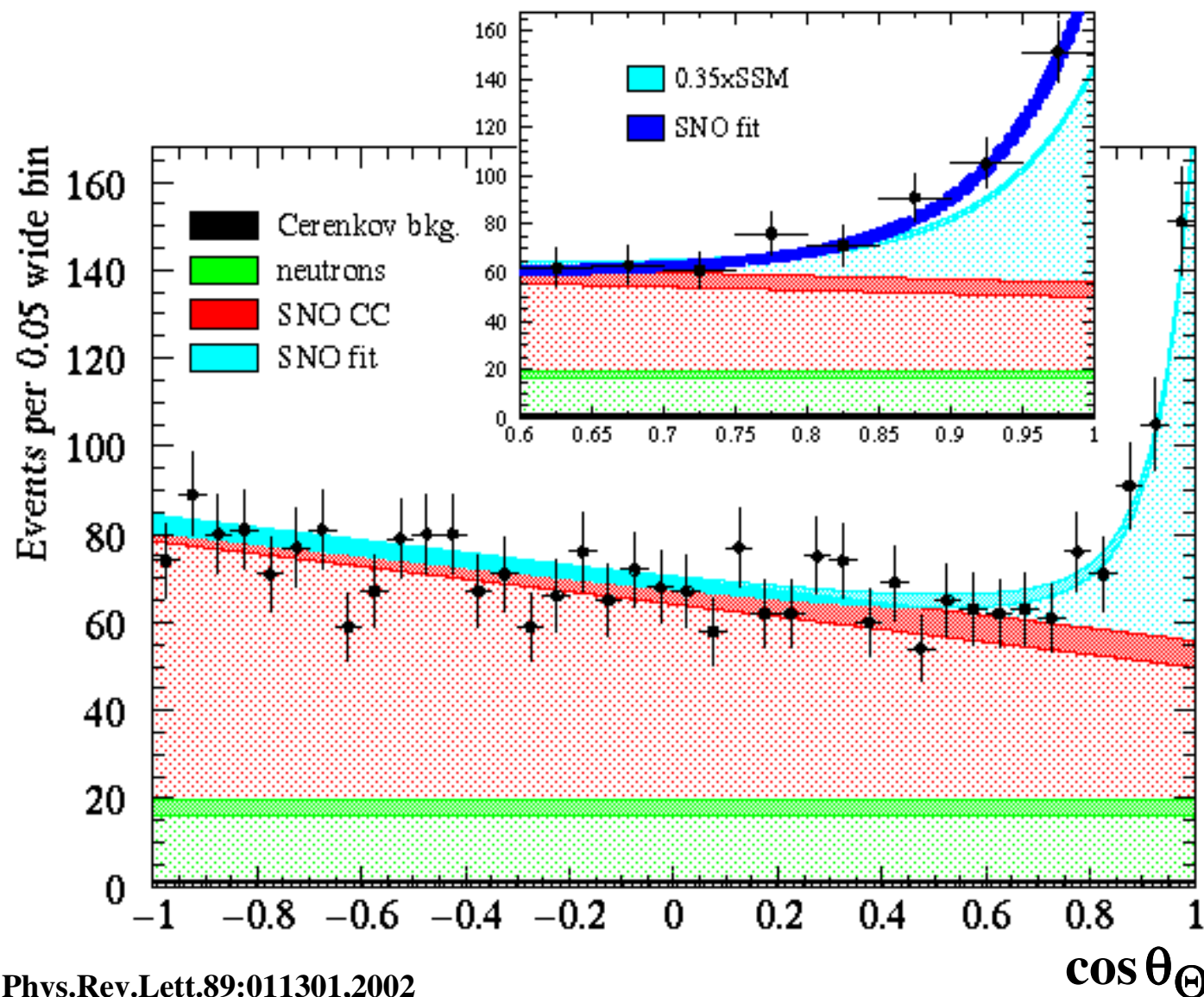


SNO: solar neutrino spectra

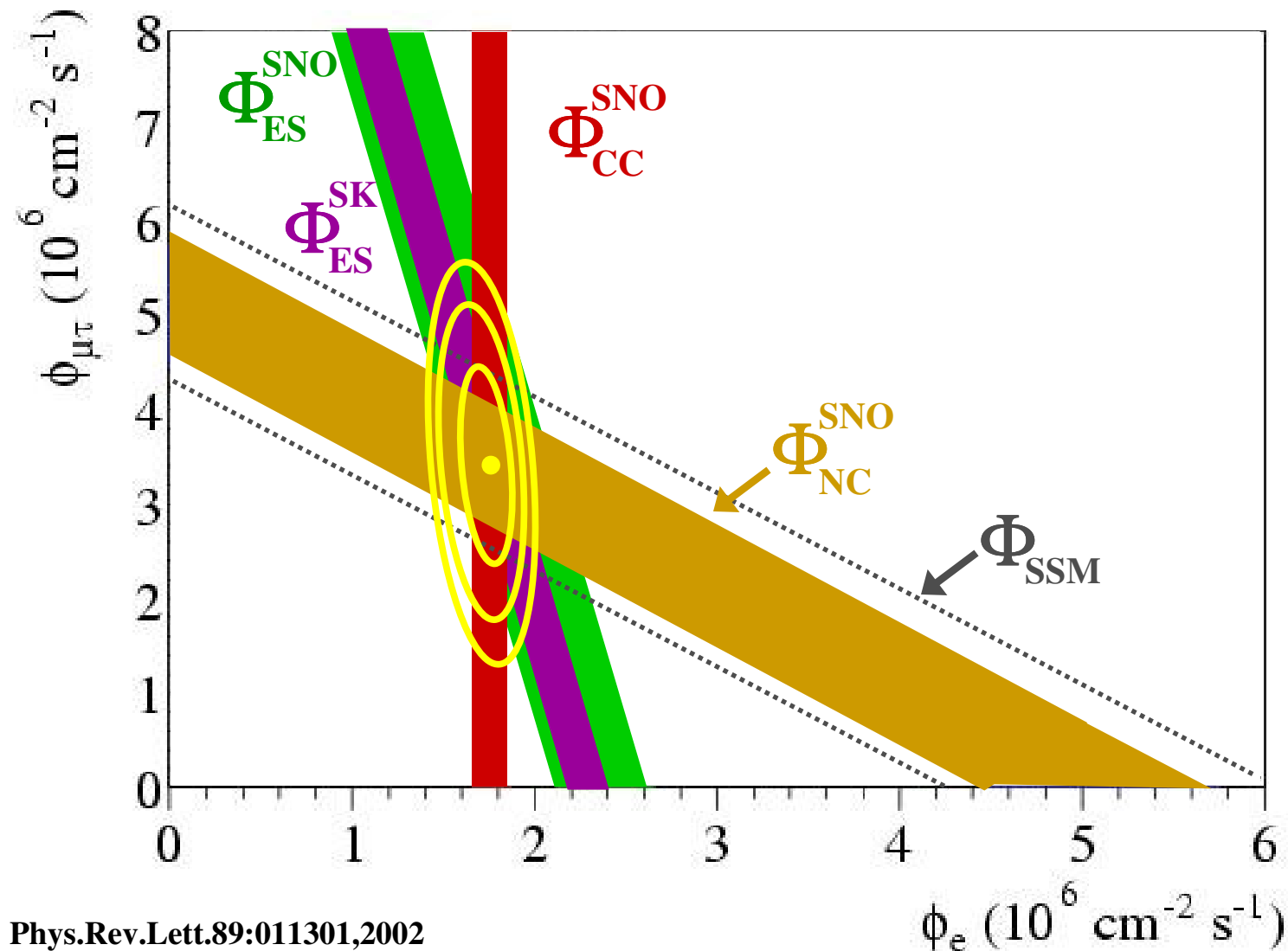
CC 1967.7^{+61.9}_{+60.9}

ES 263.6^{+26.4}_{+25.6}

NC 576.5^{+49.5}_{+48.9}



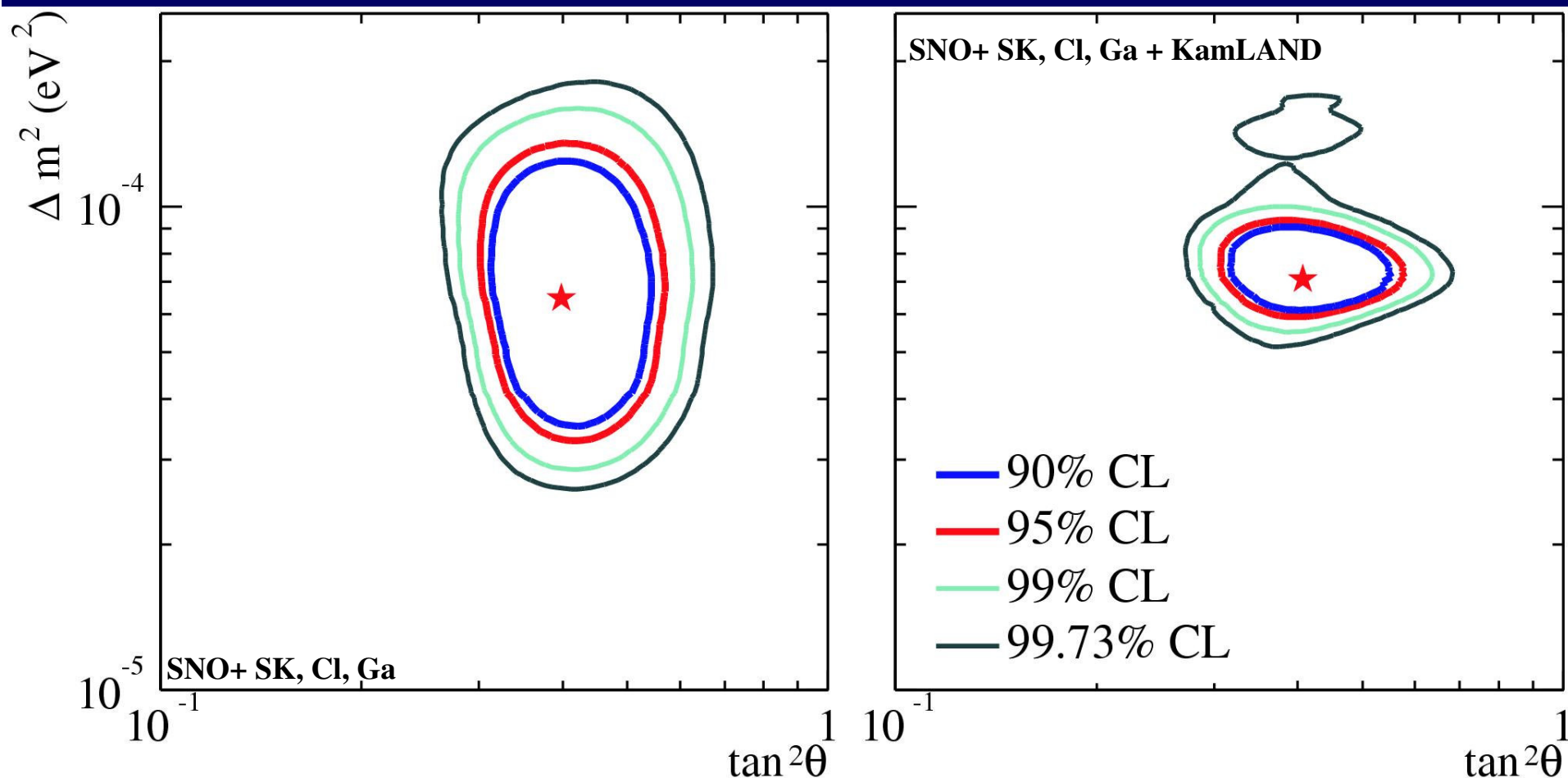
SNO: solar neutrino fluxes



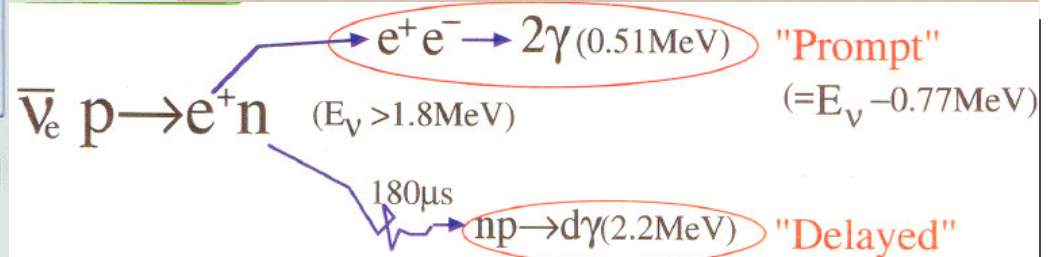
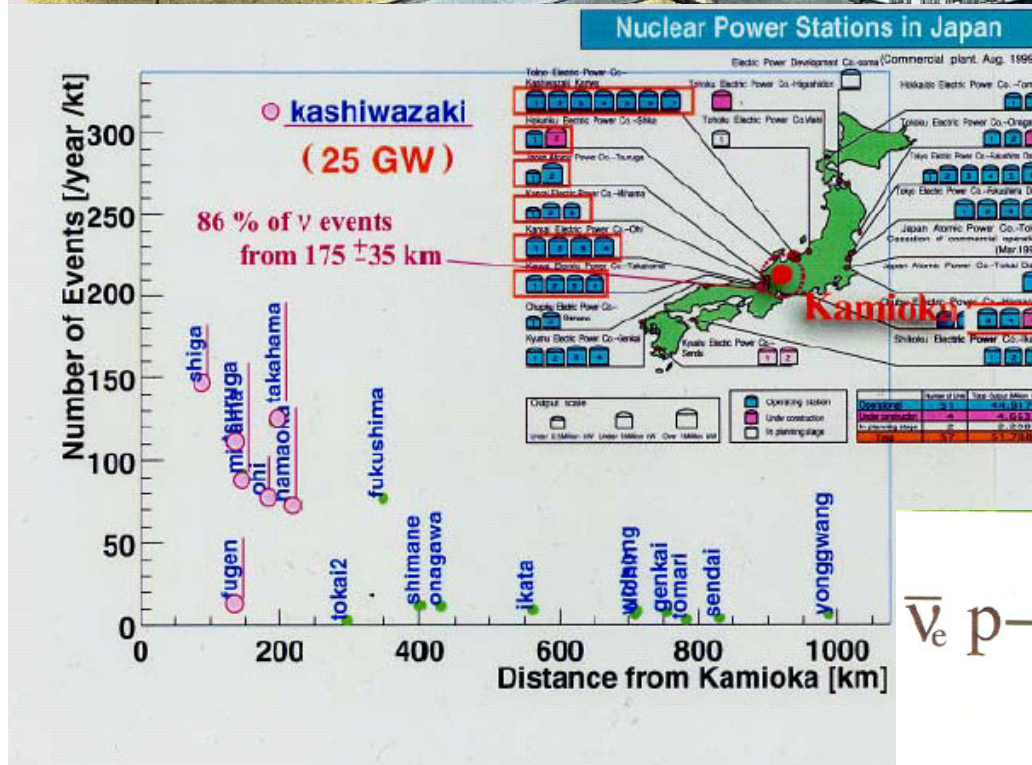
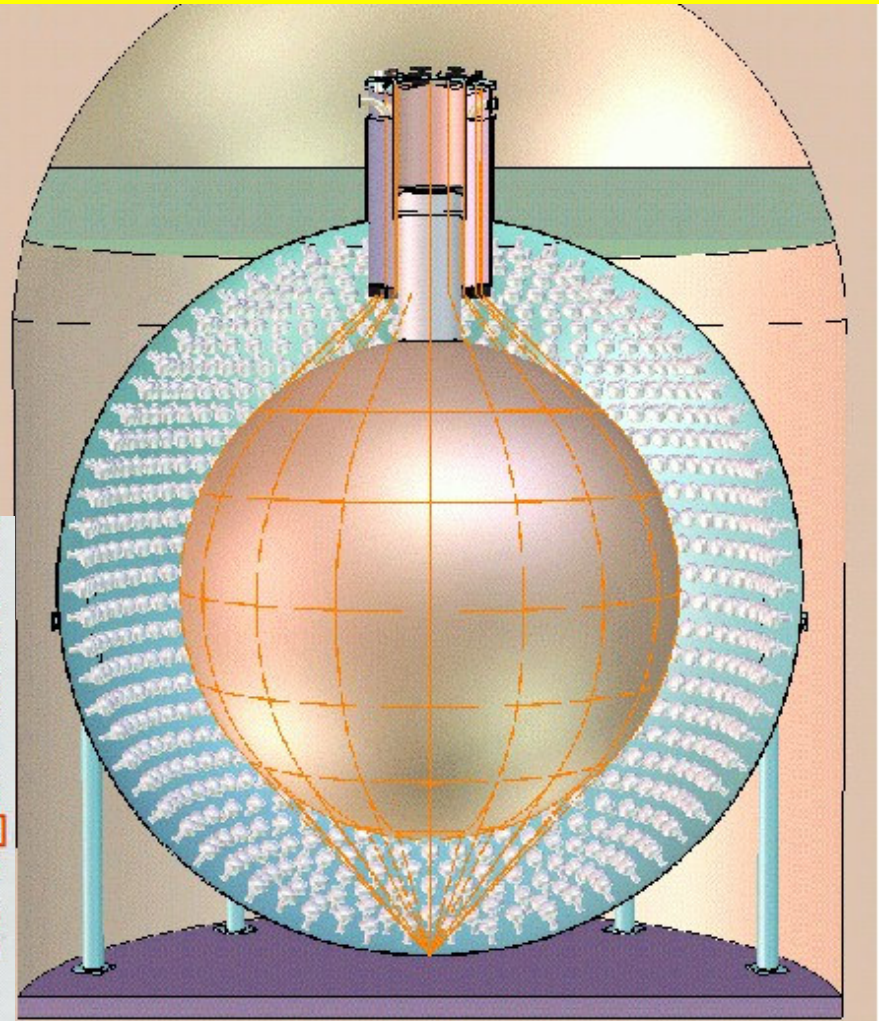
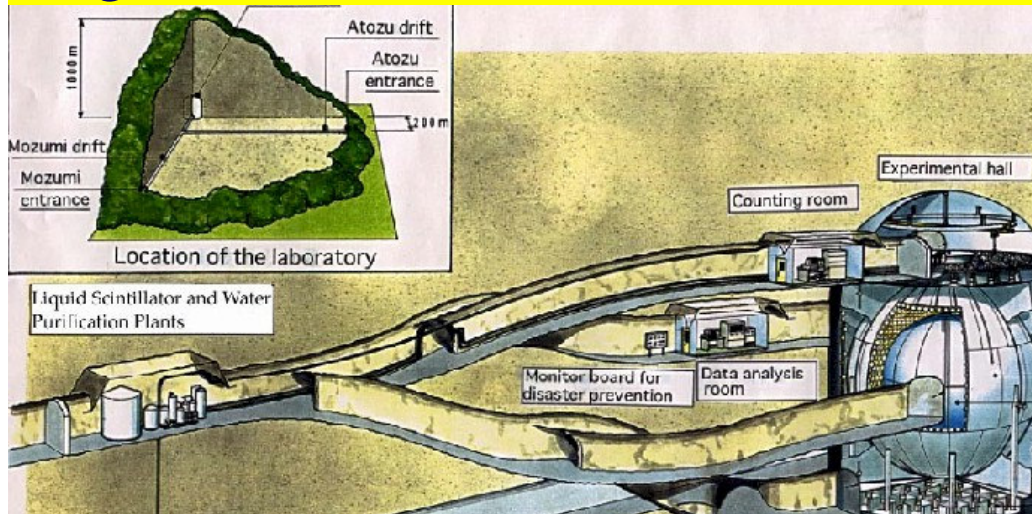
- Too few electron neutrinos (total flux OK)

Solar parameters: SNO

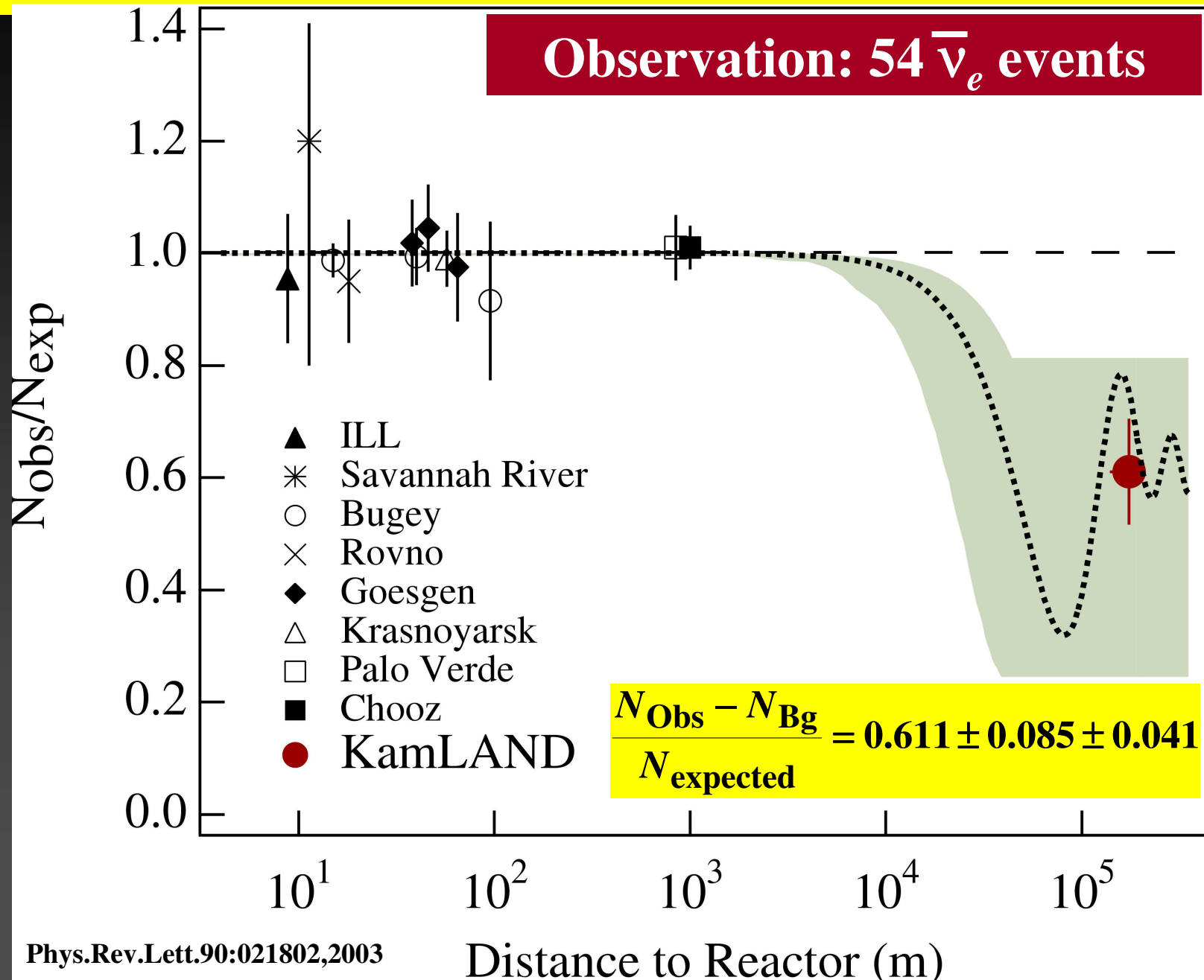
^8B flux measurement using NaCl



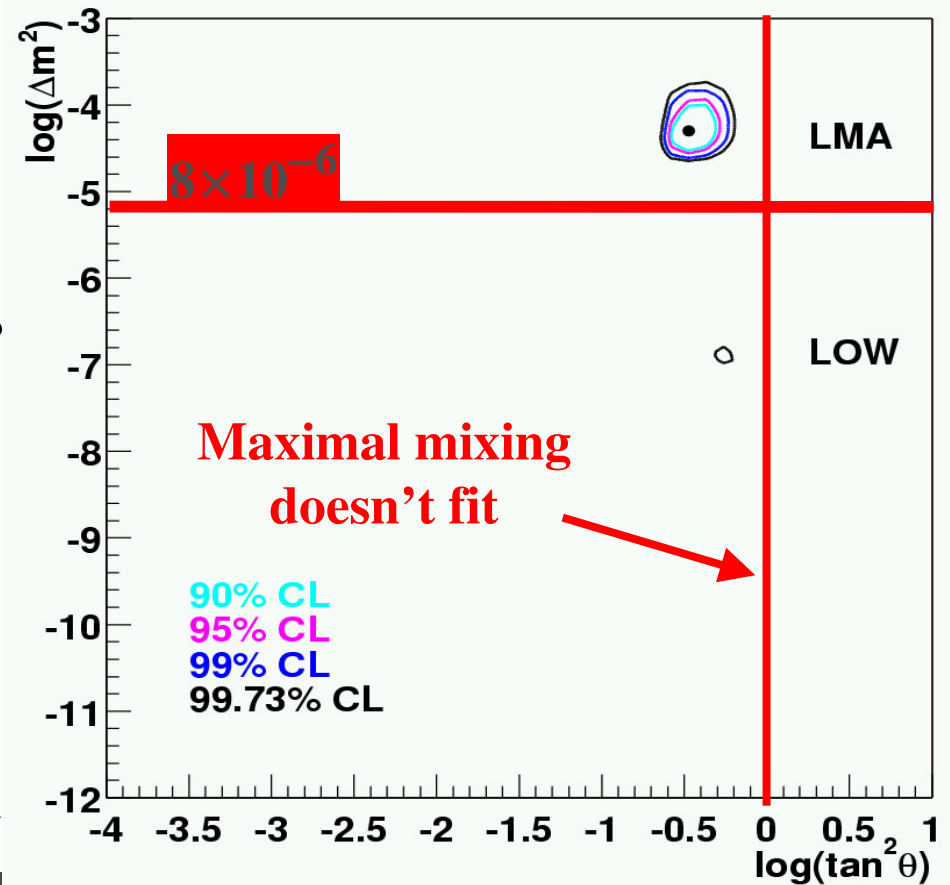
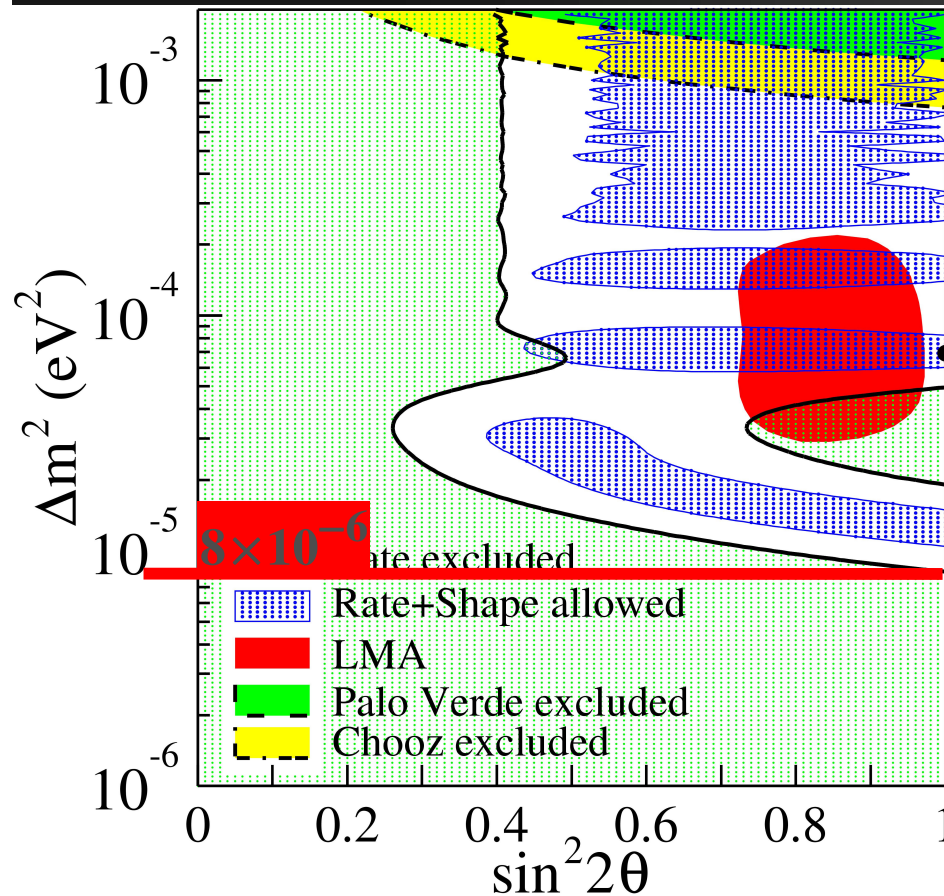
$\bar{\nu}_e$ – Kamland reactor experiment



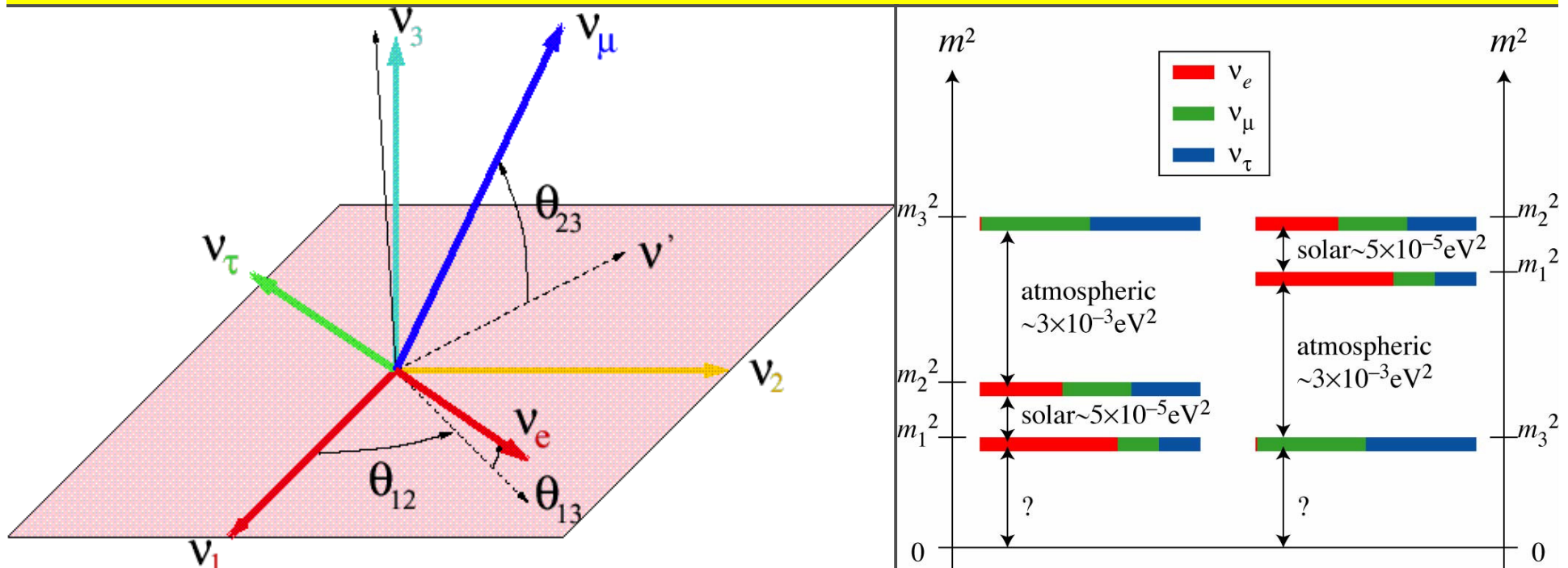
$\bar{\nu}_e$ – oscillation observation



Impact on solar parameters



Neutrino oscillation: three flavour



$$U = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{-i\delta} s_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$$

Solar

CP-violation: $\delta \neq 0$

Atmospheric

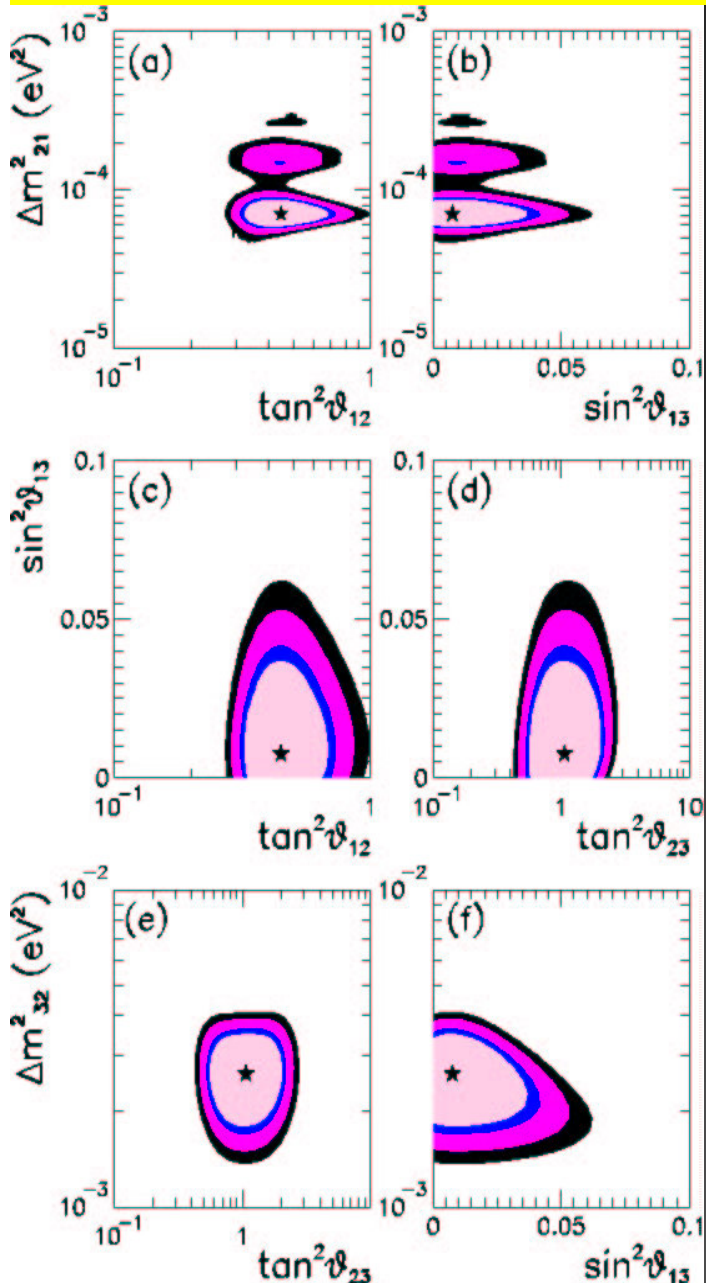
Oscillation parameters: status

Result of global fit

- Includes data from:
 - SNO, SK
 - Impacts on solar (12) params
 - SK, K2K
 - Impacts on atmos (23) params
 - Chooz, KamLAND (reactor)
 - Impacts on 12 and 13 params

Now need:

- Ever increasing precision!
 - Measure θ_{13}
 - Search for CP violation ($\delta \neq 0$)



Terrestrial sources: next generation

■ ν_μ ($\bar{\nu}_\mu$):

- Measurement: $\theta_{23}, \Delta m_{23}$ – K2K, MINOS*
- Confirmation $\nu_\mu \rightarrow \nu_\tau$ – ICARUS*, OPERA*

■ ν_e ($\bar{\nu}_e$):

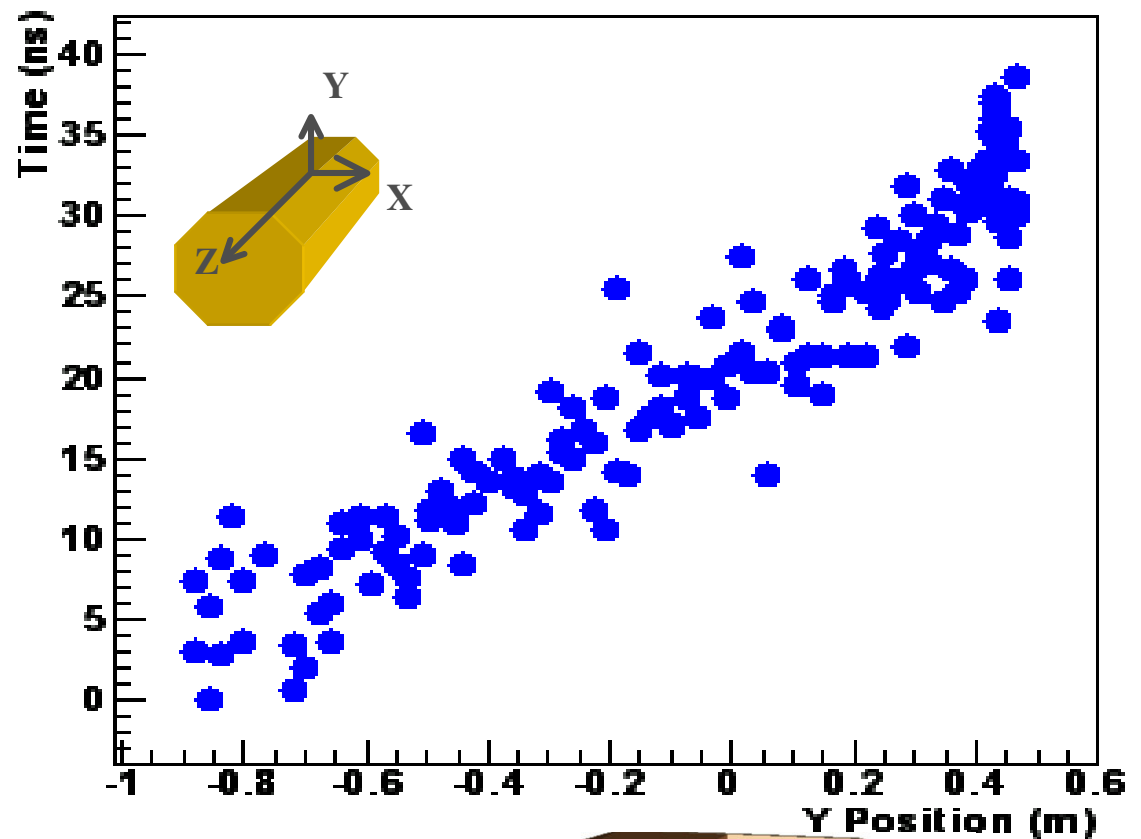
- Measurement: $\theta_{12}, \Delta m_{12}$ – SNO, KamLAND, SK, Borexino
- Measurement: θ_{13} – J-PARC $\rightarrow$ SK*
– NuMI off axis*
- Search for $\cancel{CP}$: $\delta \neq 0$ – J-PARC $\rightarrow$ SK
– NuMI off axis

■ $\nu_\mu \rightarrow \nu_{\text{sterile}} \rightarrow \nu_e$:

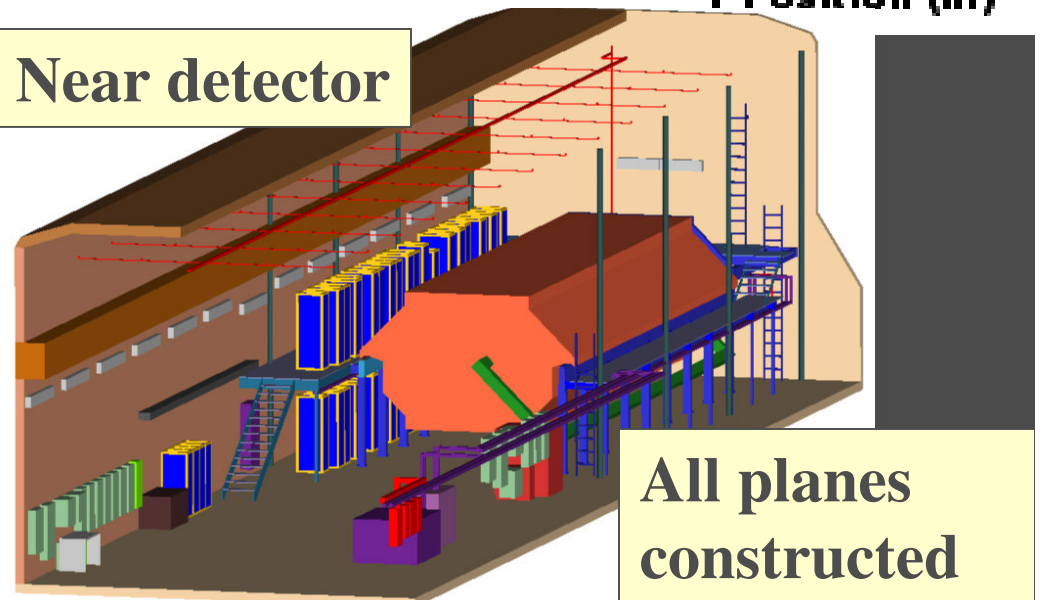
- Search! (LSND, Karmen) – MiniBOONE

MINOS

P. Shanahan,
EPS03



Near detector

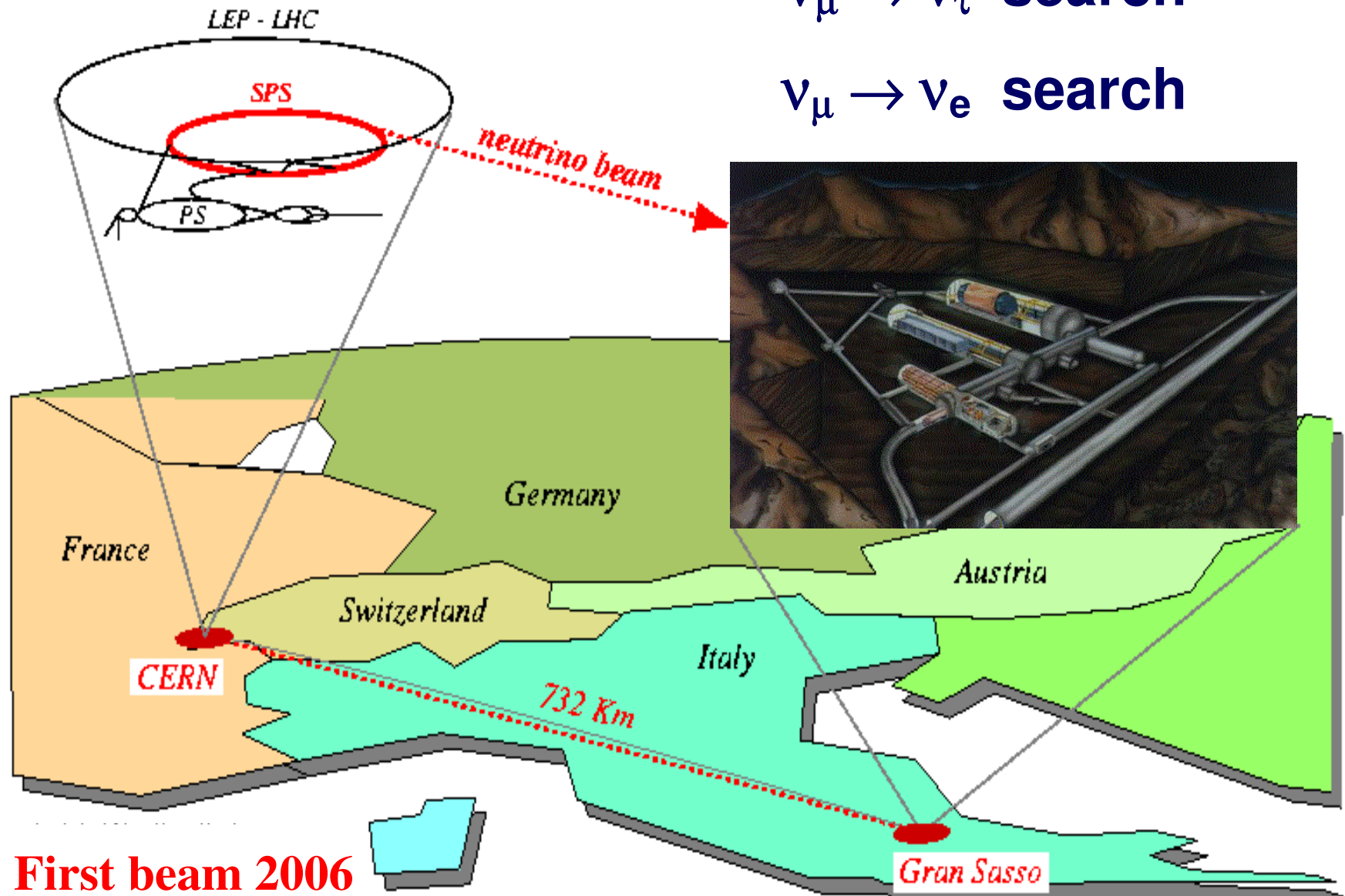


Commissioning:
December 2004

CERN to Gran Sasso

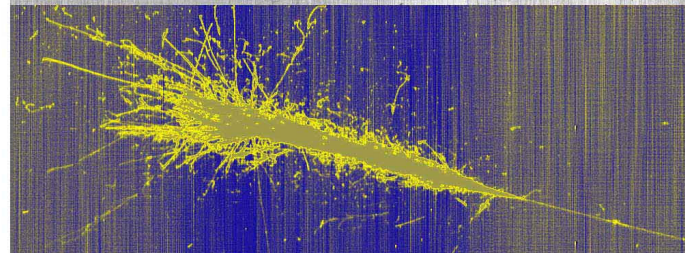
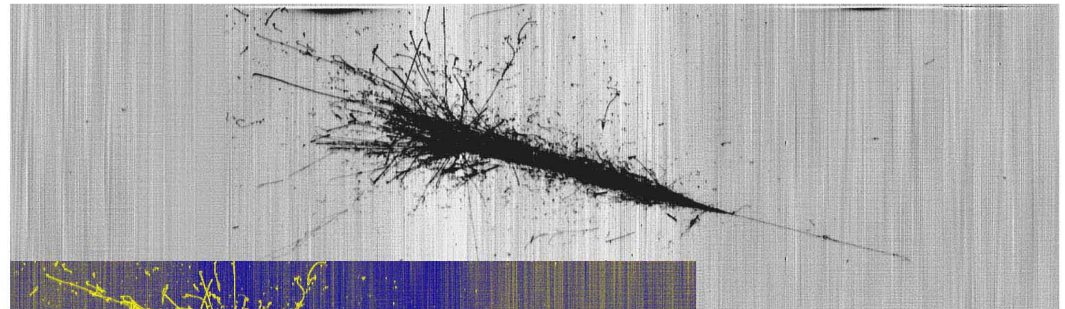
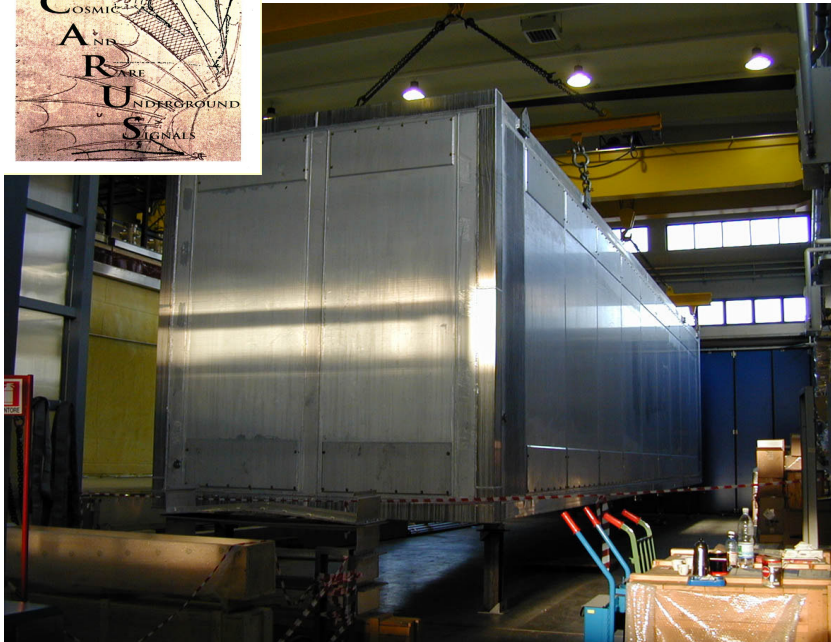
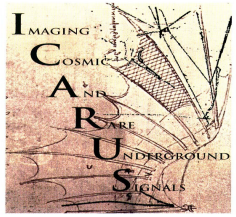
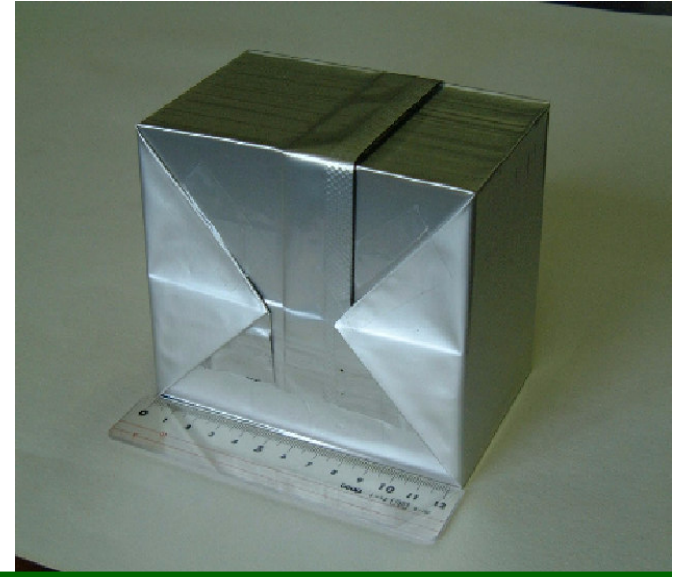
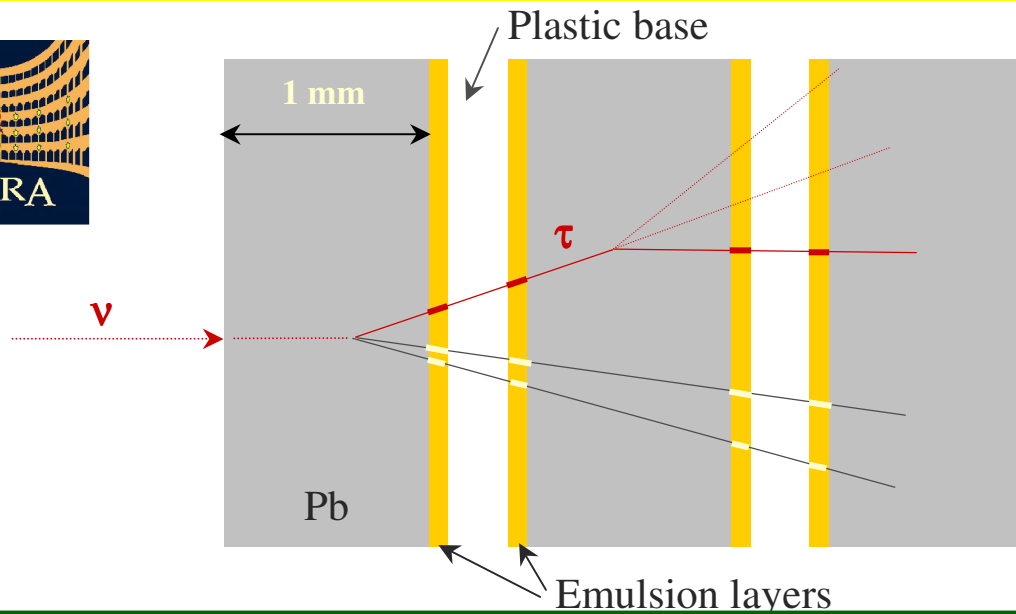
$\nu_\mu \rightarrow \nu_\tau$ search

$\nu_\mu \rightarrow \nu_e$ search

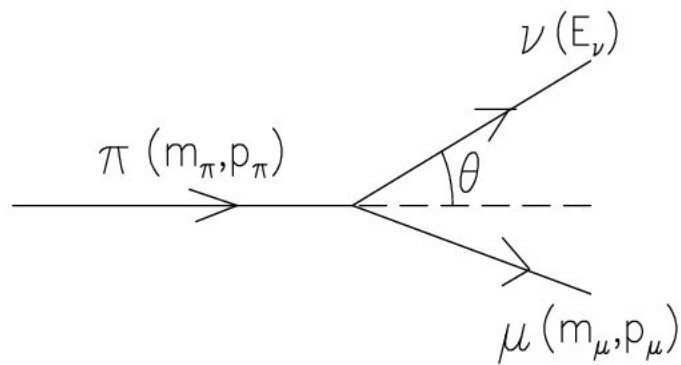
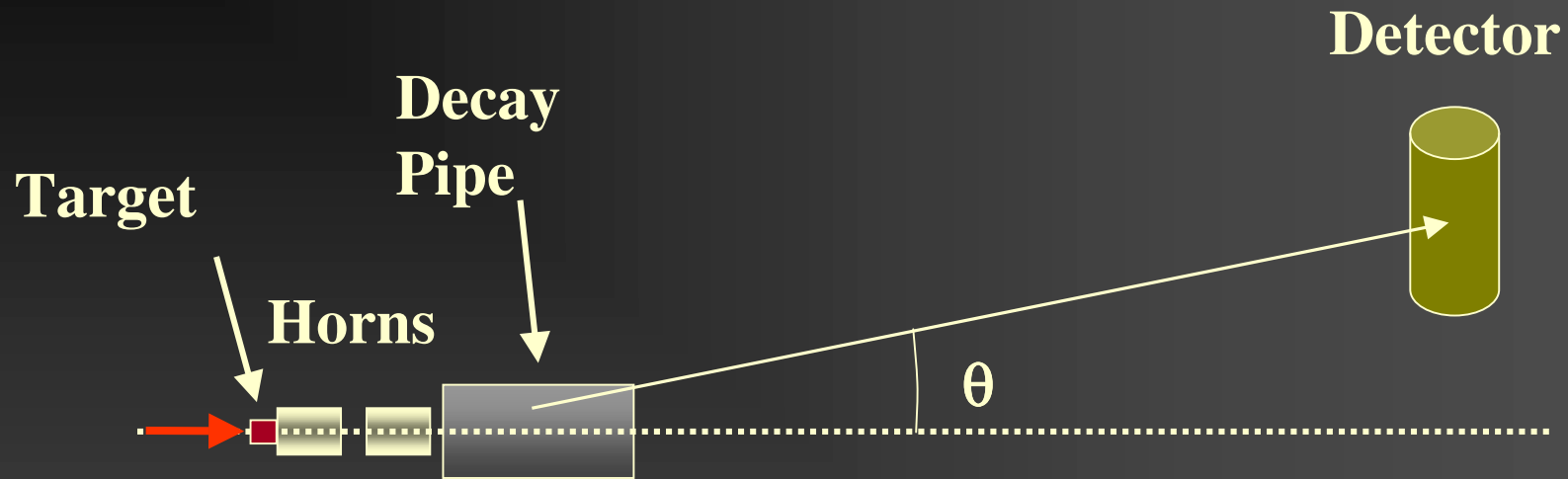


First beam 2006

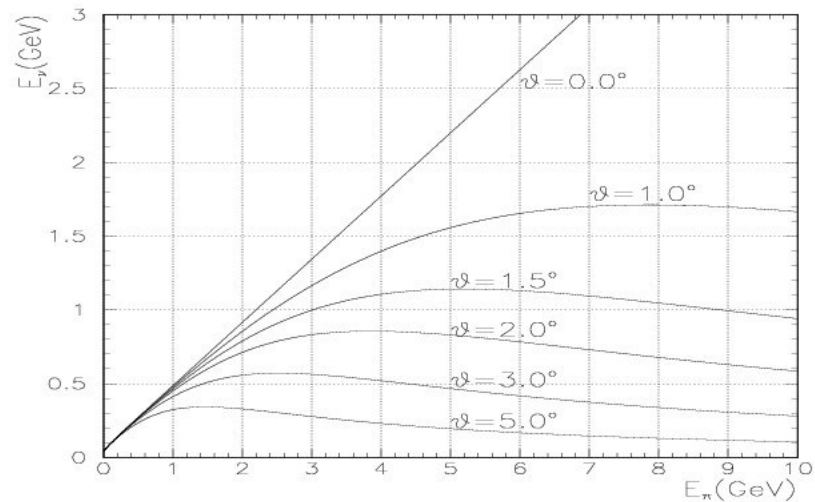
CNGS expt^s: ICARUS, OPERA



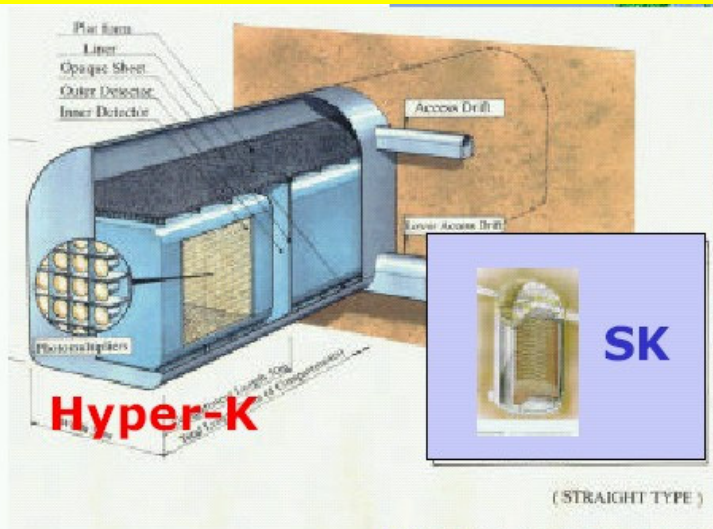
Off-axis neutrino beams



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



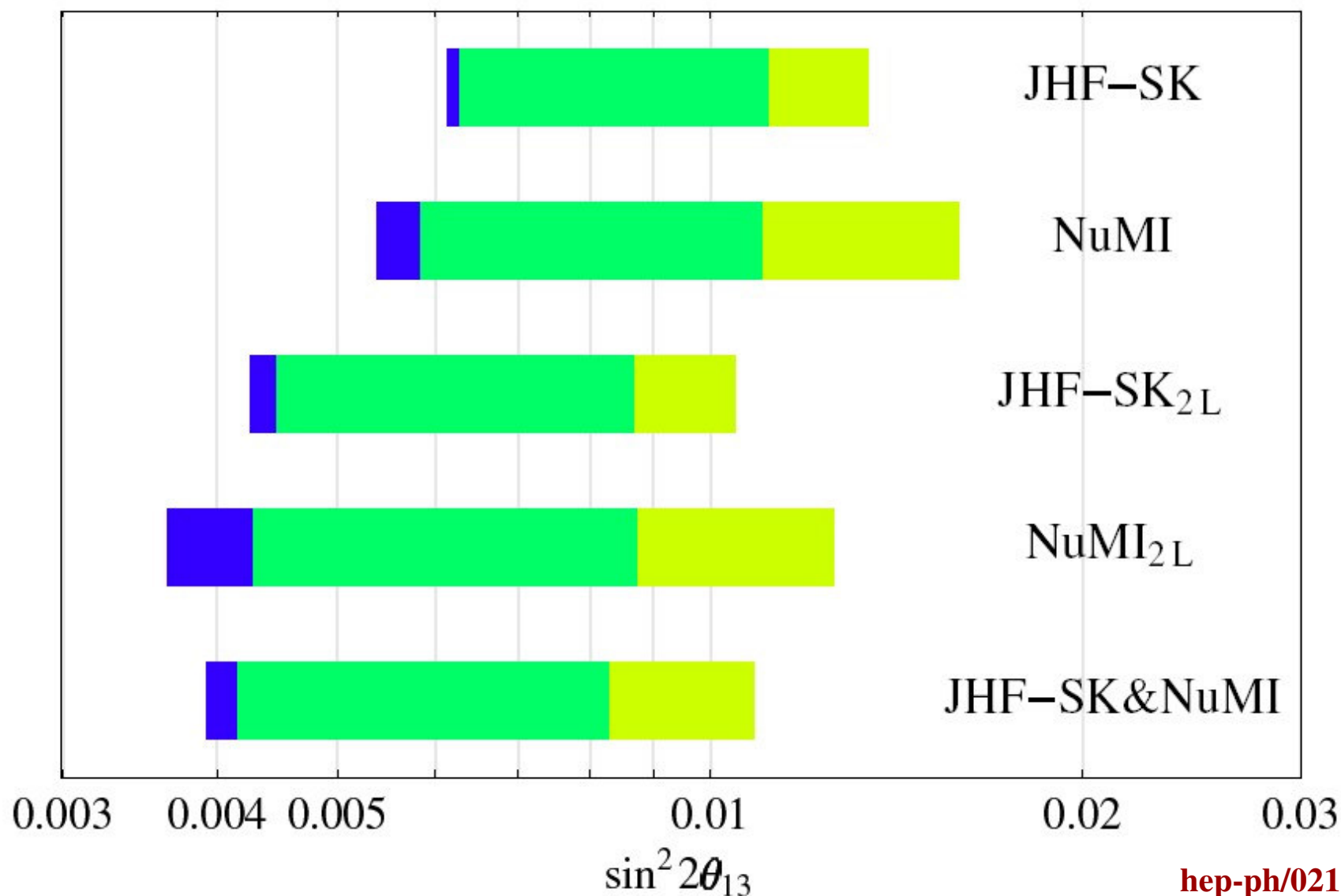
J-PARC to Super-Kamiokande



- Phase I: 2007(?)~201x
 - ~1MW 50GeV PS → 22.5kt detector (Super-Kamiokande)
 - $\nu_{\mu} \rightarrow \nu_x$ disapp., $\nu_{\mu} \rightarrow \nu_e$ app., NC measurement
- Phase II: 201x(?)~202y(??)
 - ~4MW 50GeV PS → ~1Mt detector (Hyper-Kamiokande)
 - CPV search, Proton Decay, . . .

J2K, NuMI OA sensitivity

Sensitivity to $\sin^2 2\theta_{13}$



Neutrino oscillations: summary

Atmospheric	Solar - preferred solution
$\sin^2 2\theta_{23} > 0.90$ (90% c.l.)	$\sin^2 2\theta_{12} \dots$ 'Large'
$1.3 \times 10^{-3} \text{ eV}^2 < \Delta m_{32}^2 < 3.0 \times 10^{-3} \text{ eV}^2$	$5 \times 10^{-5} \text{ eV}^2 < \Delta m_{12}^2 < 2 \times 10^{-4} \text{ eV}^2$
$\sin^2 2\theta_{13} < 0.052$ (3σ)	

Still require to:

- Measure Δm_{12}^2 and θ_{12} precisely;
- Measure Δm_{23}^2 and θ_{23} precisely;
- ❖ Sign of Δm_{23}^2 ;
- ❖ Measure θ_{13} ;
- ❖ Measure (set limits on?) δ

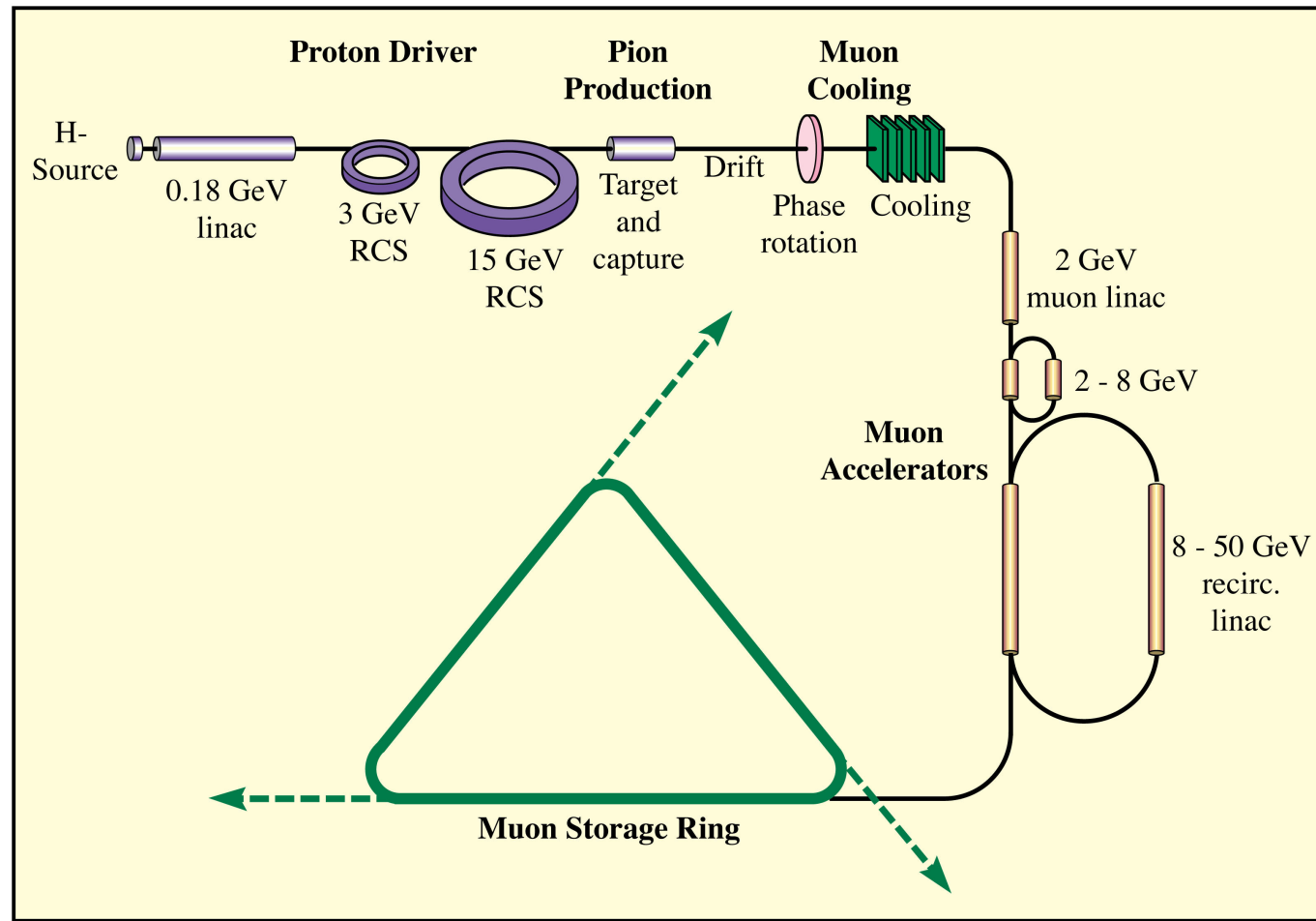
Neutrino Factory: the concept

Intense neutrino beam from decay of stored μ beam:

- Beam composition precisely known
- Neutrino energy spectrum known and tunable
- Neutrino flux precisely determined from μ current
- On paper can produce neutrino beams 1,000 times more intense than conventional beams
- Wide variety of possible oscillation channels can be studied:

$\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$	
Disappearance	Appearance
$\bar{\nu}_e \rightarrow \bar{\nu}_e \rightarrow e^+$	$\bar{\nu}_e \rightarrow \bar{\nu}_\mu \rightarrow \mu^+$ $\bar{\nu}_e \rightarrow \bar{\nu}_\tau \rightarrow \tau^+$
$\nu_\mu \rightarrow \nu_\mu \rightarrow \mu^-$	$\nu_\mu \rightarrow \nu_e \rightarrow e^-$ $\nu_\mu \rightarrow \nu_\tau \rightarrow \tau^-$

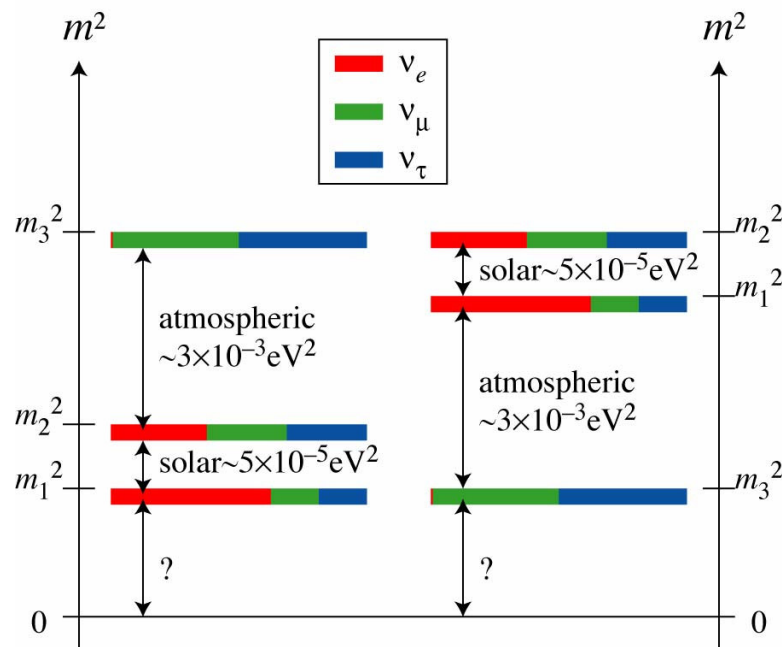
Neutrino Factory: possible layout



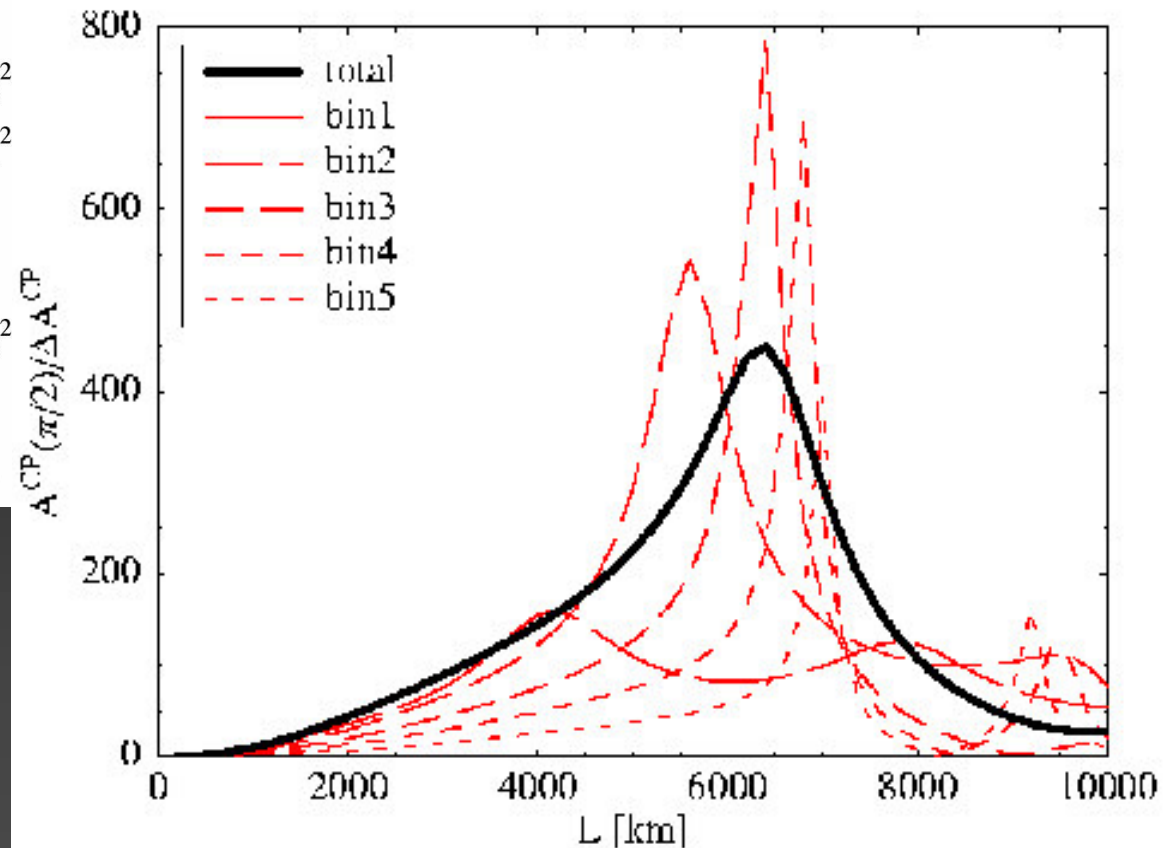
Neutrino Factory at RAL

- US, CERN schemes very similar to RAL layout
- Japanese NF based on FFAGs ... see e.g. R.Edgecock EPS03

Neutrino Factory: performance



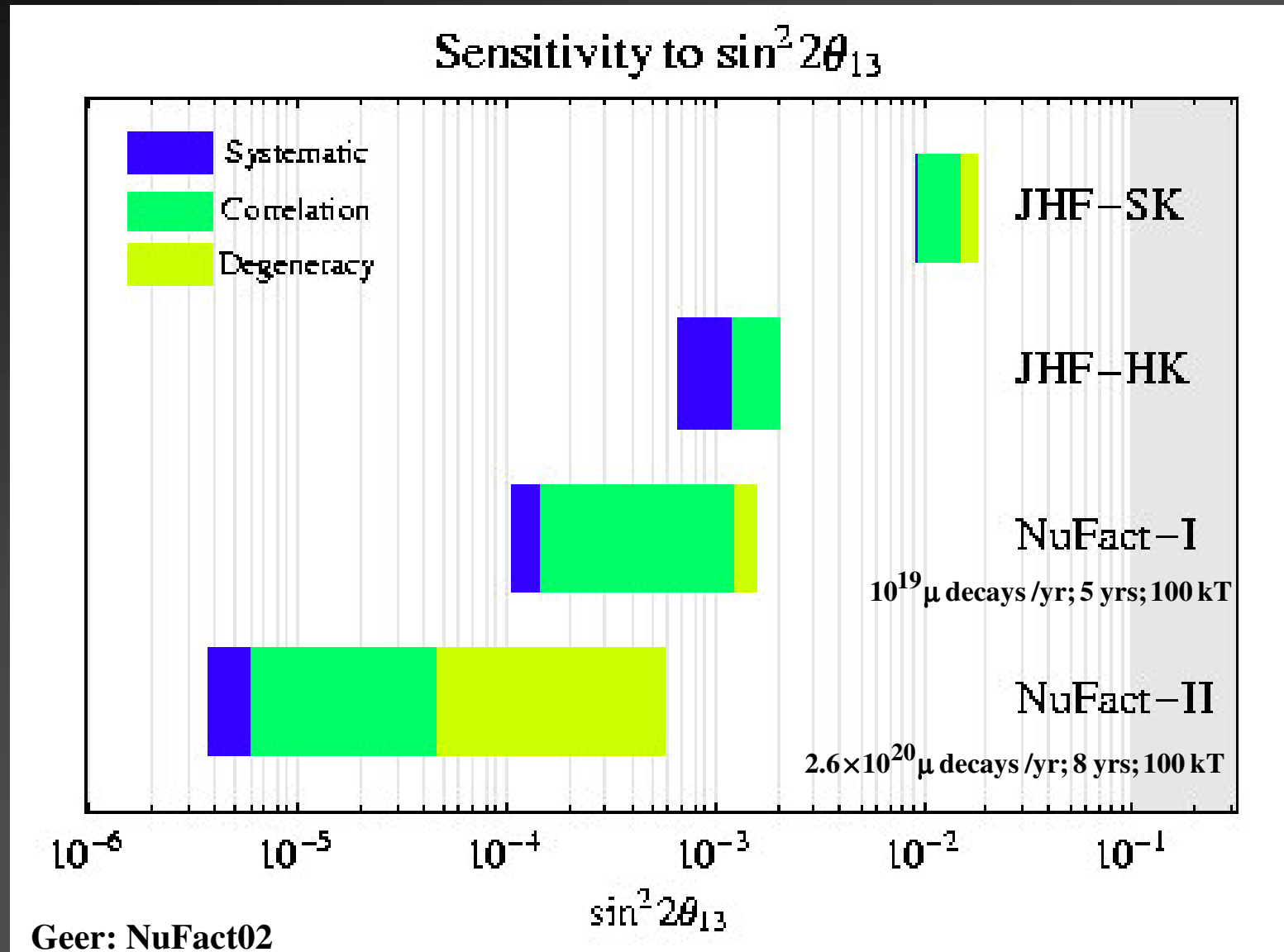
- sign of Δm_{23}^2 :



- Sign of Δm_{23}^2 measured at better than 5σ for any 'reasonable' baseline

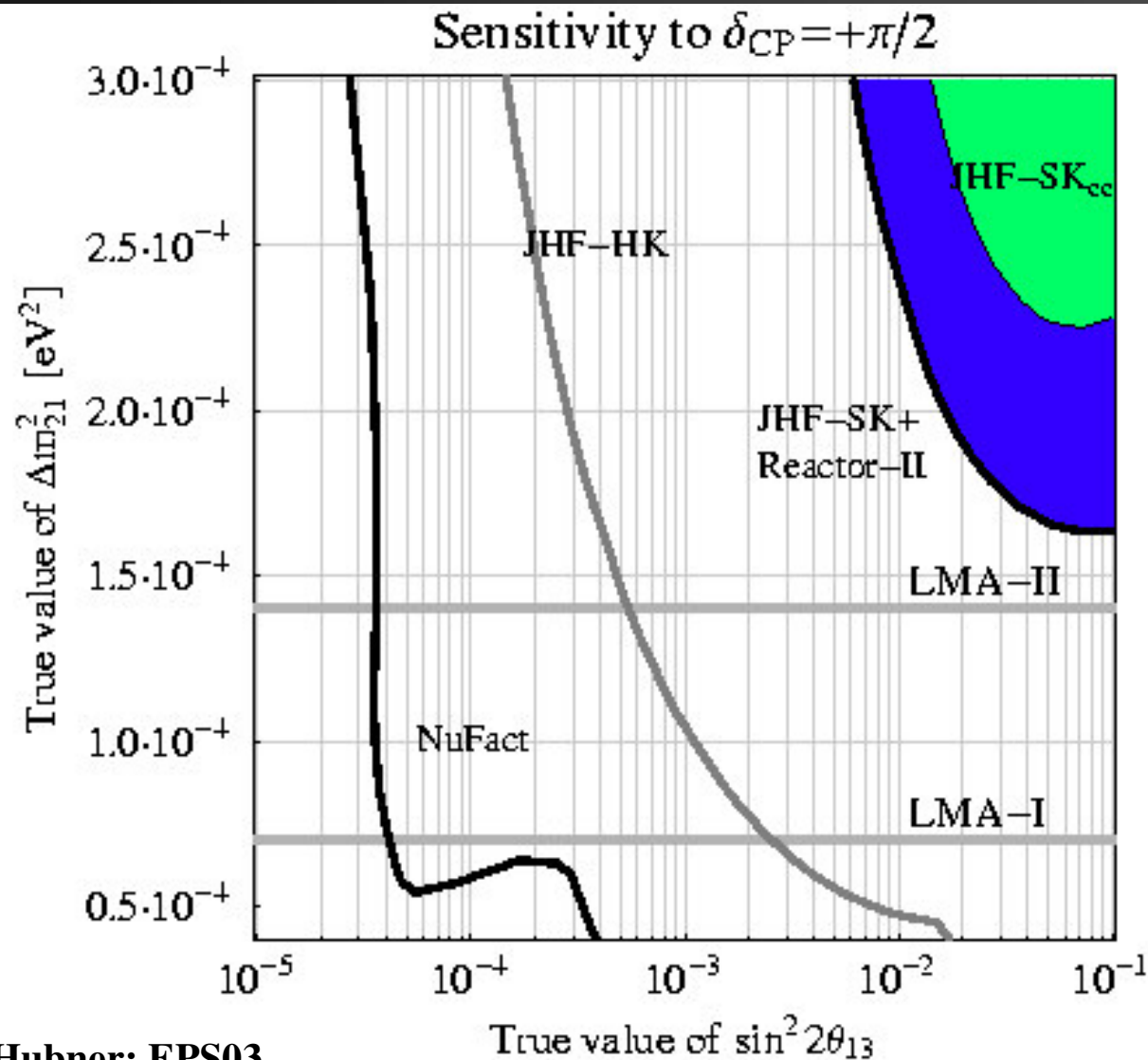
Neutrino Factory: performance

- Measurement of $\sin^2\theta_{13}$:



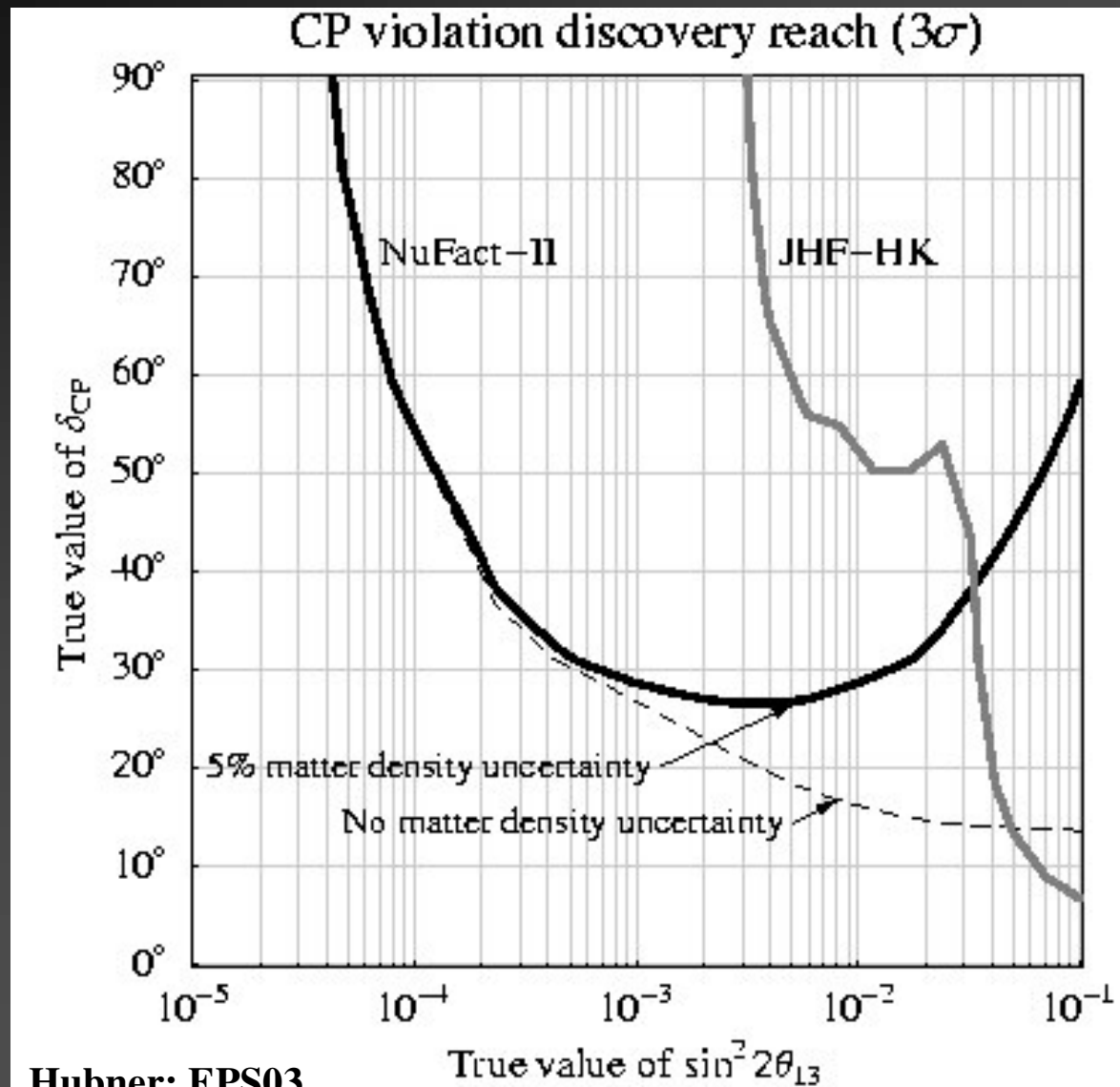
Neutrino Factory: performance

- Sensitivity to maximal CP violation – $\delta = \pi/2$:



Neutrino Factory: performance

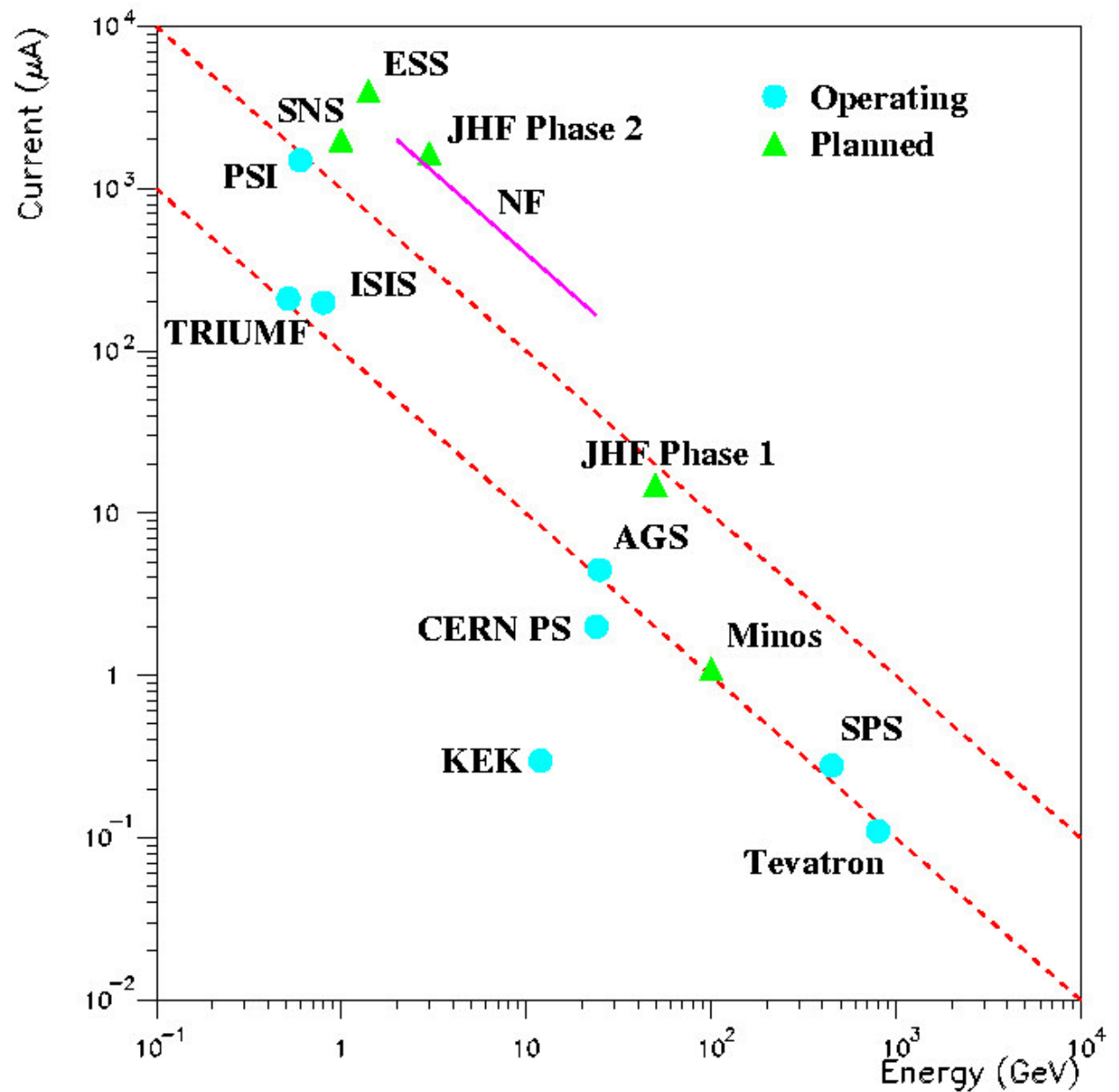
- CP violation discovery reach (3σ):



Neutrino Factory: the machine

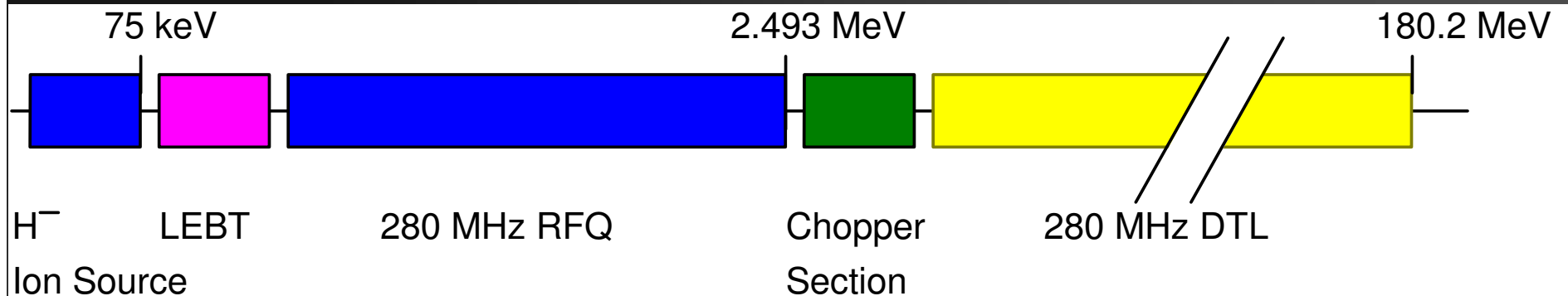
Requirements

- High power (~1-4 MW)
- Short (~ns) bunches
- Many proposals:
CERN: SPL, RCS in ISR
Japan: U/g to JHF driver
RAL: ISIS u/g

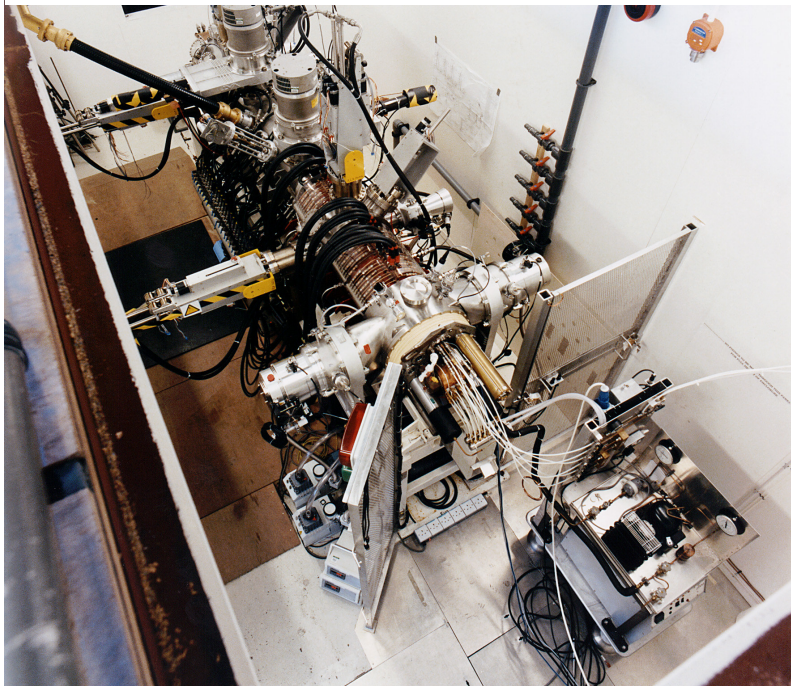


NF machine: Proton driver - front end:

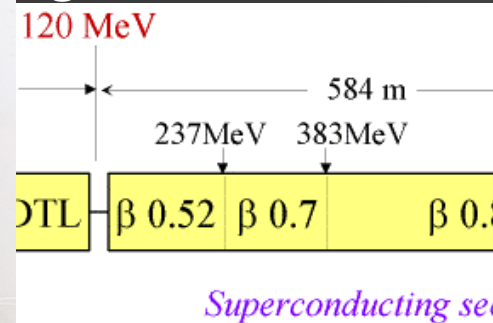
RAL: 180 MeV H⁻ linac



ISIS RFQ test stand

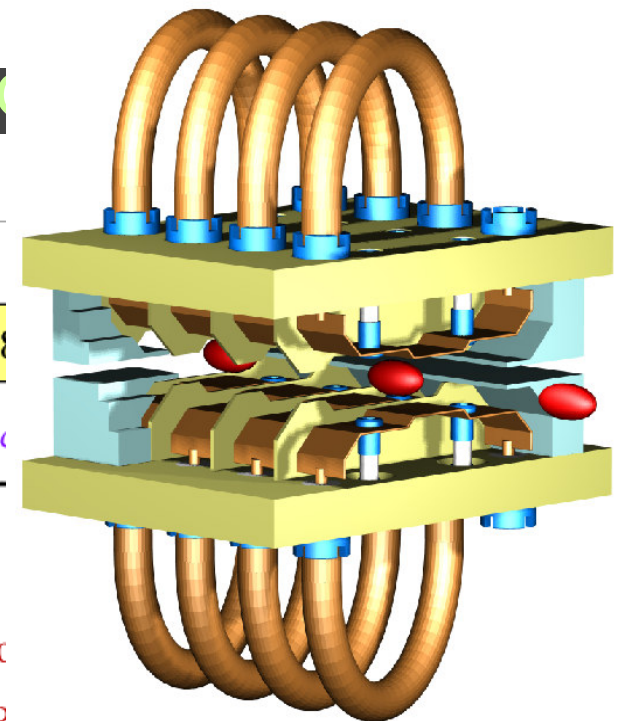


Chopper ing Proton Linac

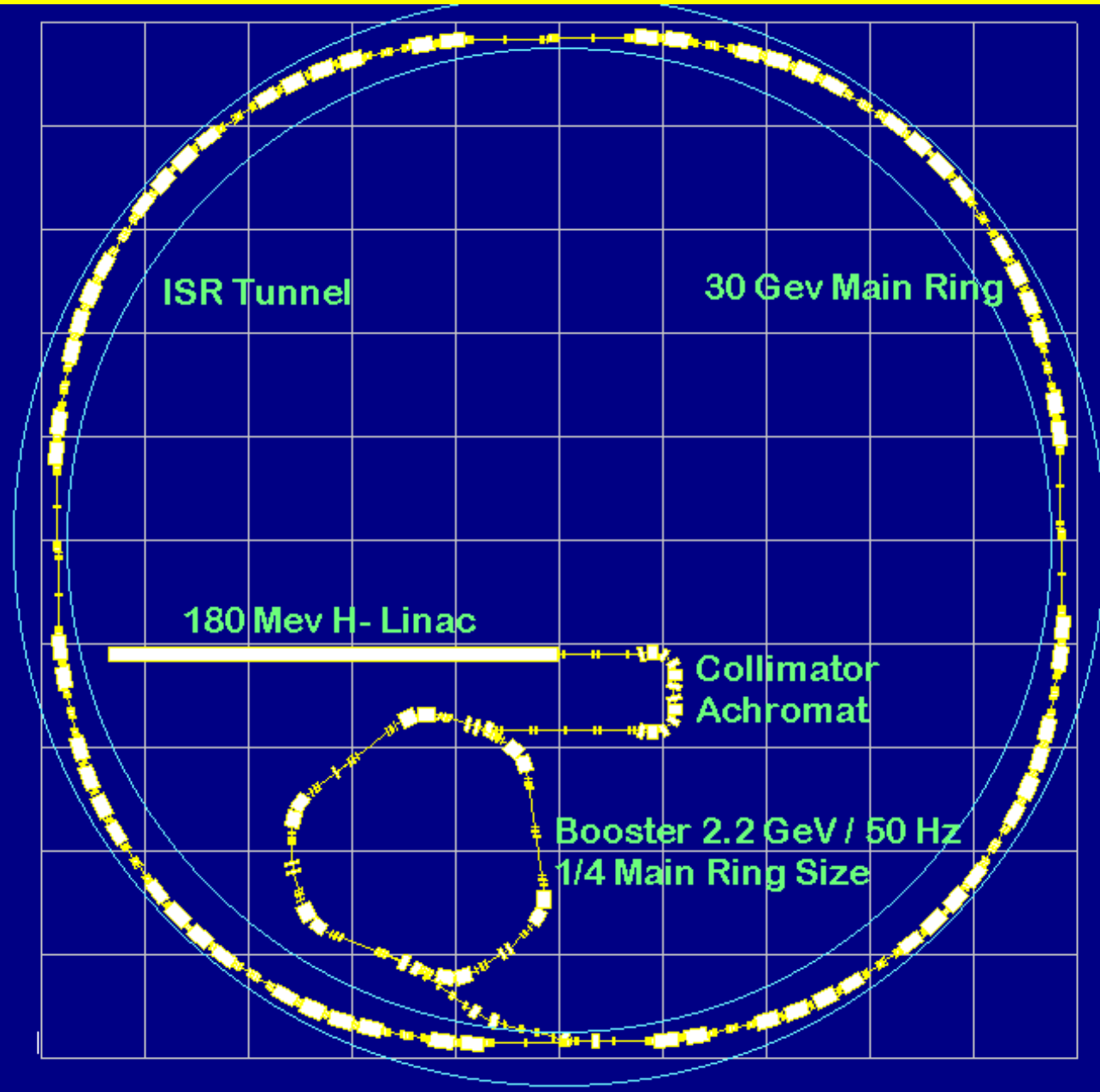


668 m

PS / Isc
Accumulator R



NF machine: Proton driver



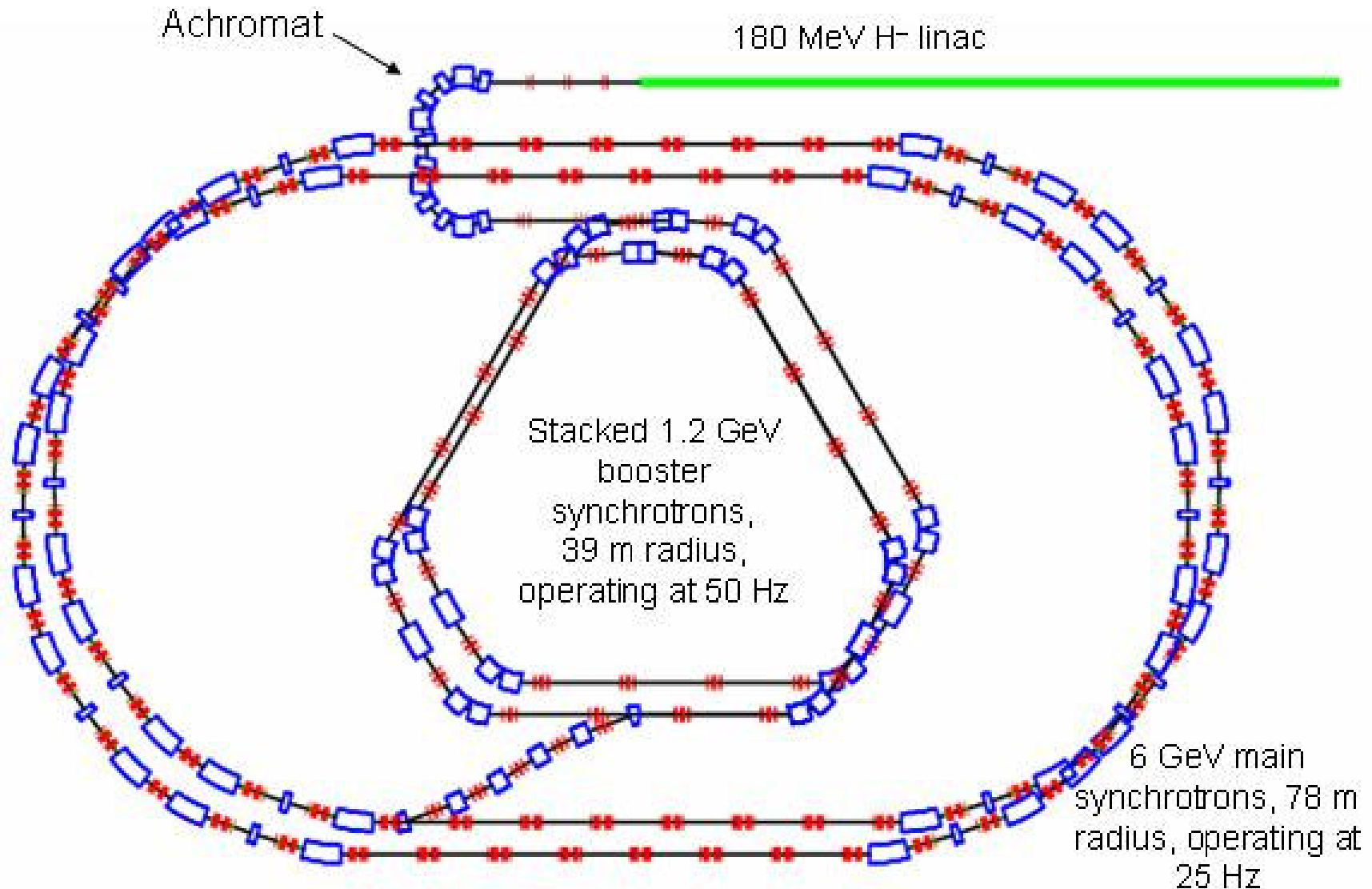
CERN:

**30 GeV rapid
cycling
synchrotron
in the ISR
tunnel**

NF machine: Proton driver

RAL

5 MW proton driver developed from ISIS synchrotron

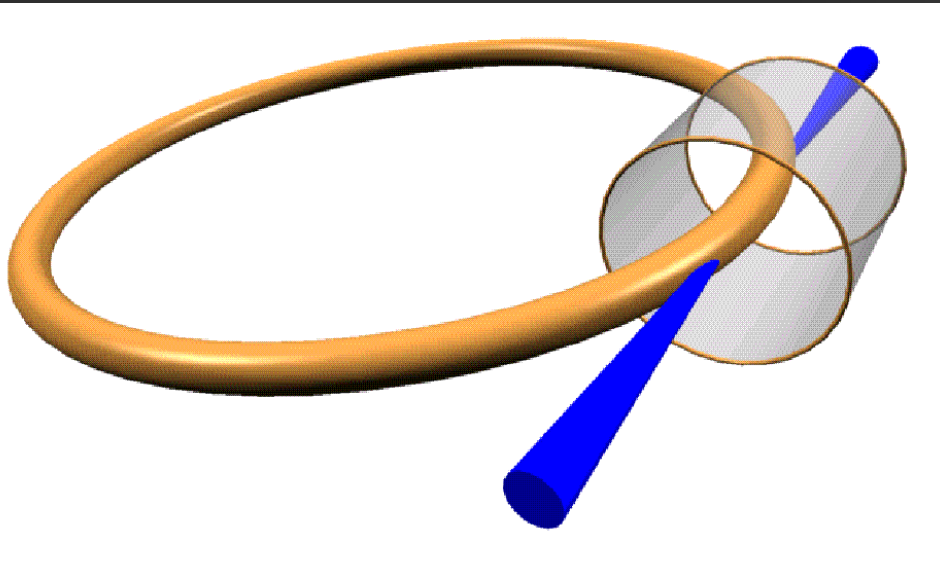


NF machine: target

Maximise pion yield:

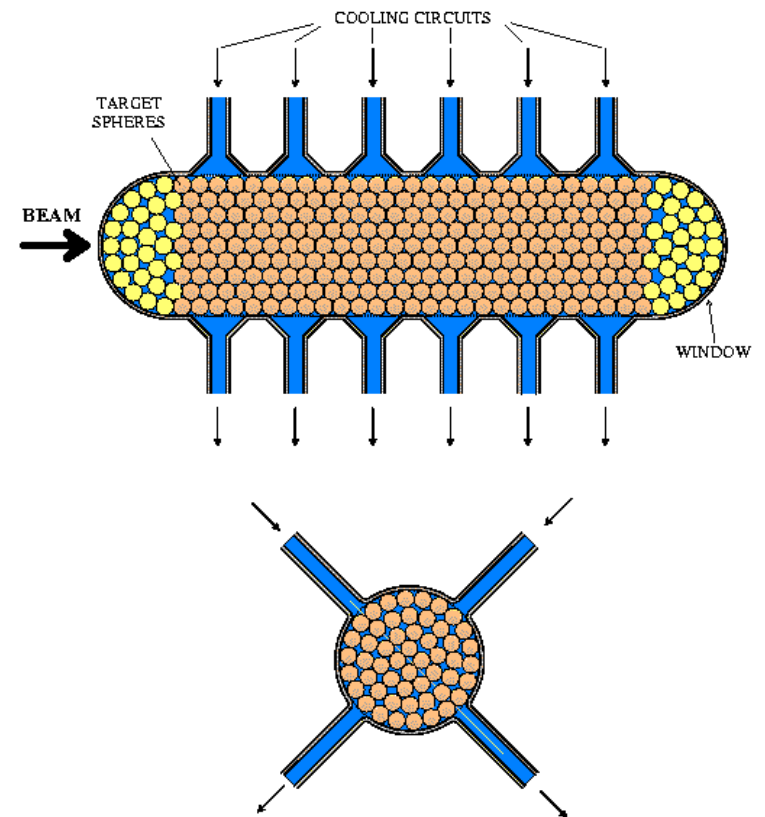
- Power density (dissipate ~ 1 MW as heat in target)

Rotating band [RAL]



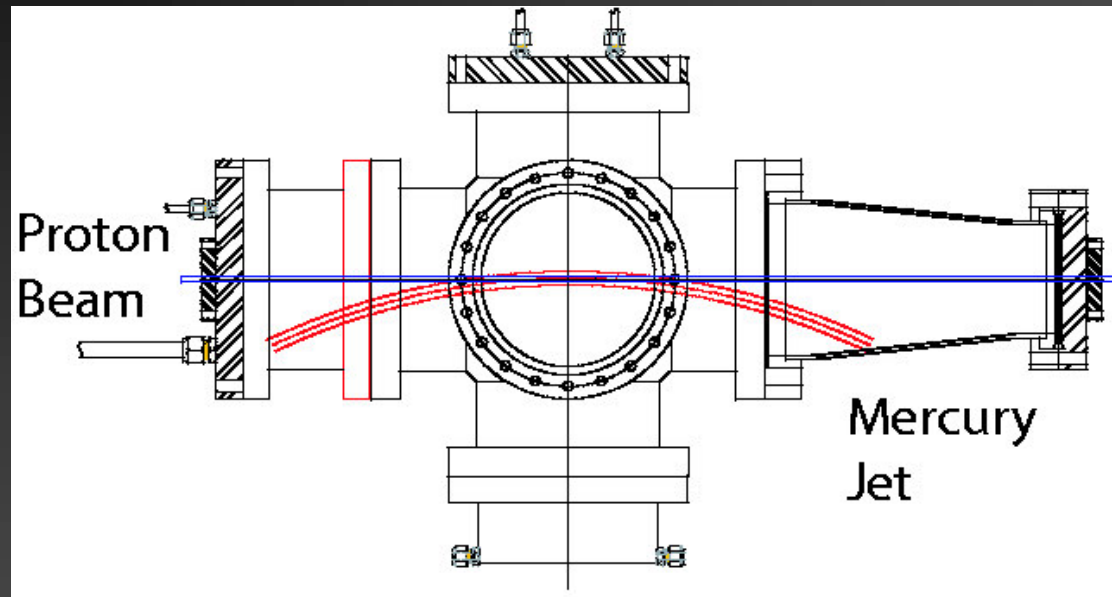
‘Replace’ target between pulses

Cooled metal beads [CERN]

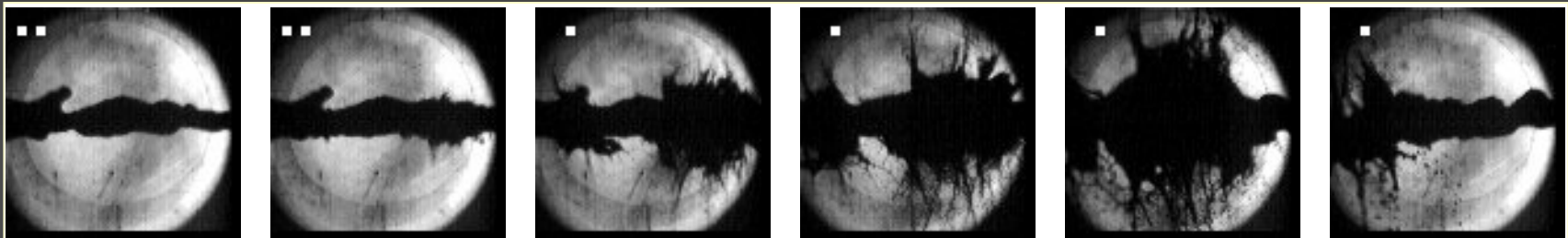


NF machine: target

Liquid mercury jet [US/CERN collaboration]



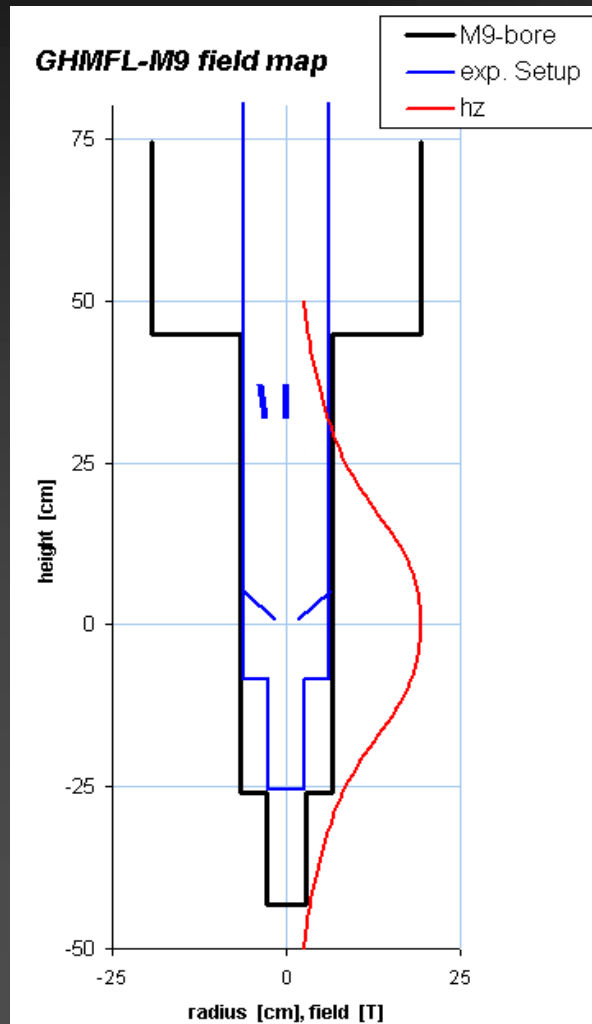
Tests with proton beam at BNL:



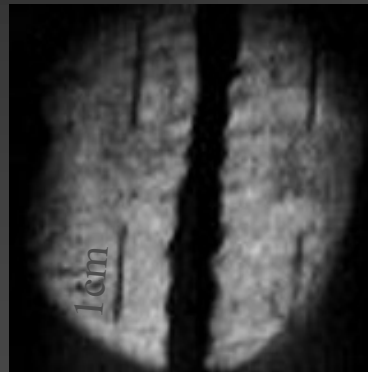
NF machine: target

Tests with a 20T magnet at Grenoble

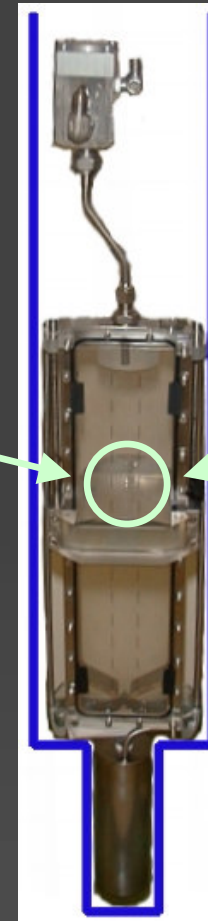
Mercury jet ($v=15$ m/s)



$B = 0\text{T}$



- Jet deflection
- Reduction in velocity
- Reduction in radius



$B = 18\text{T}$

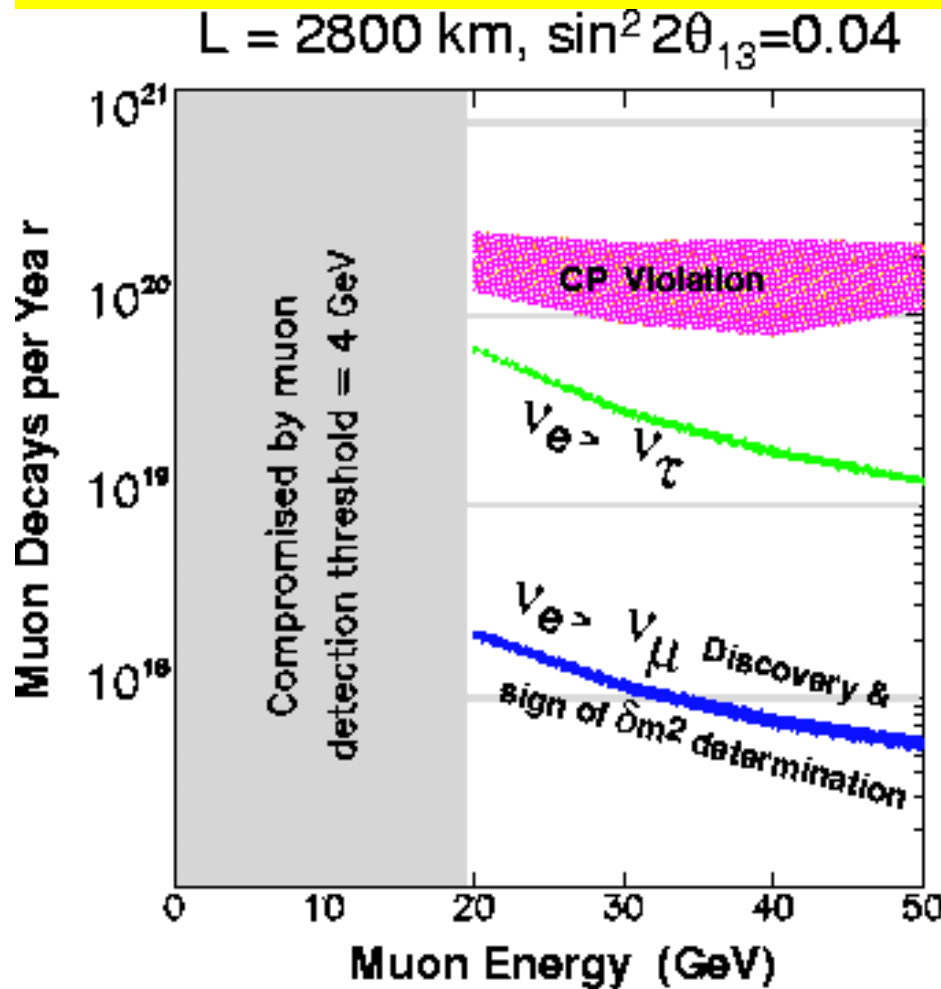


Smoothing

NF machine: π prodⁿ and capture

- Measurement of particle spectra:
 - HARP (CERN): $E_p=2-15$ GeV; range of materials
 - MIPP (FNAL): $E_p=5-120$ GeV; range of materials
- Capture schemes:
 - US: Solenoid with field falling from 20T to 1.25T
 - CERN: horn; prototype built and tested at CERN
- Pion decay/muon capture performed in a solenoidal channel
- Phase rotation and bunching: several schemes under discussion
 - Must match into cooling channel

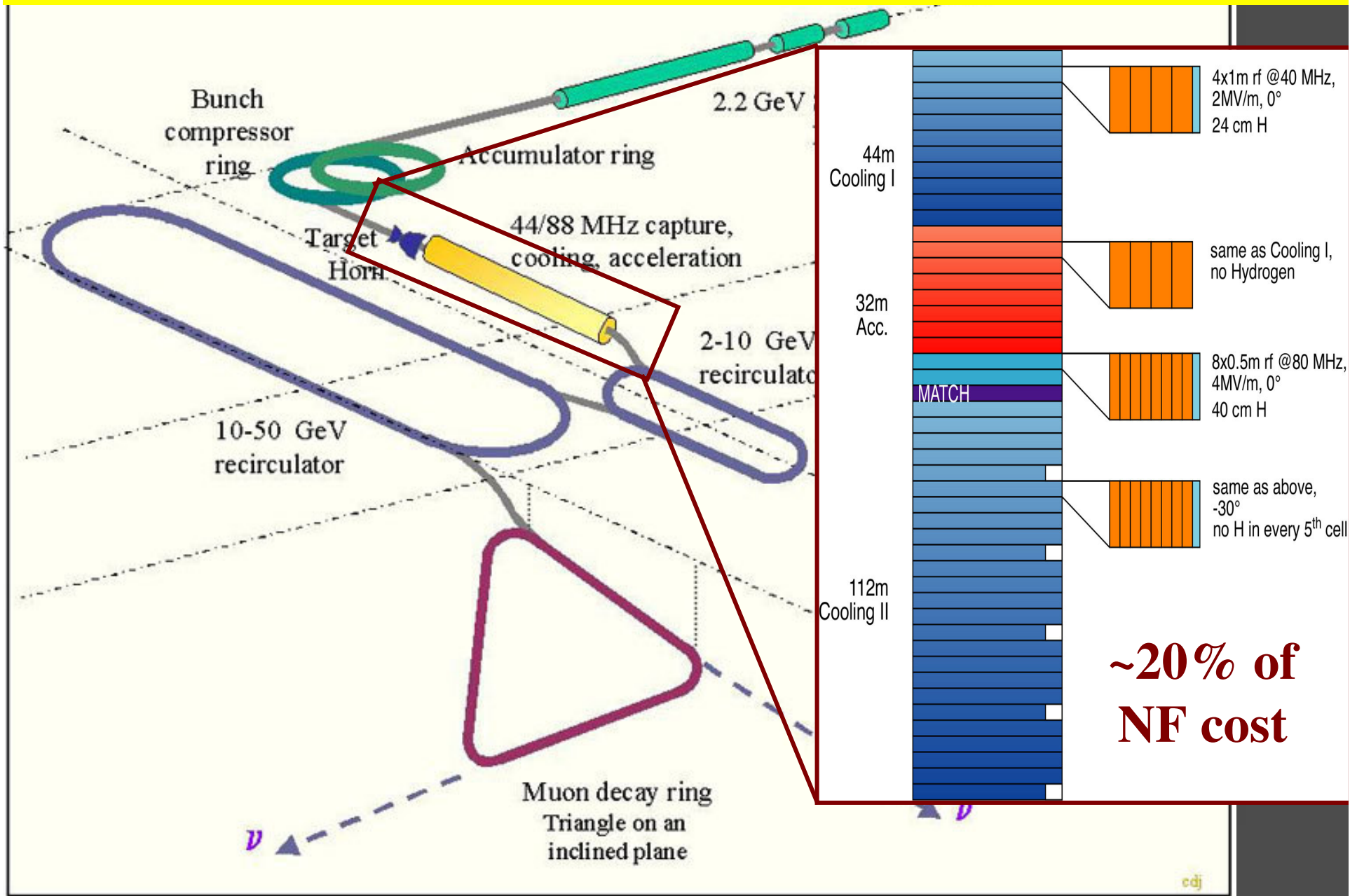
NF machine: ionisation cooling



- Physics reach increases with neutrino flux
- Maximise stored muon intensity
- Implies:
 - Require to capture and store as many of the 'decay' muons as possible
⇒ **Cool muon beam**

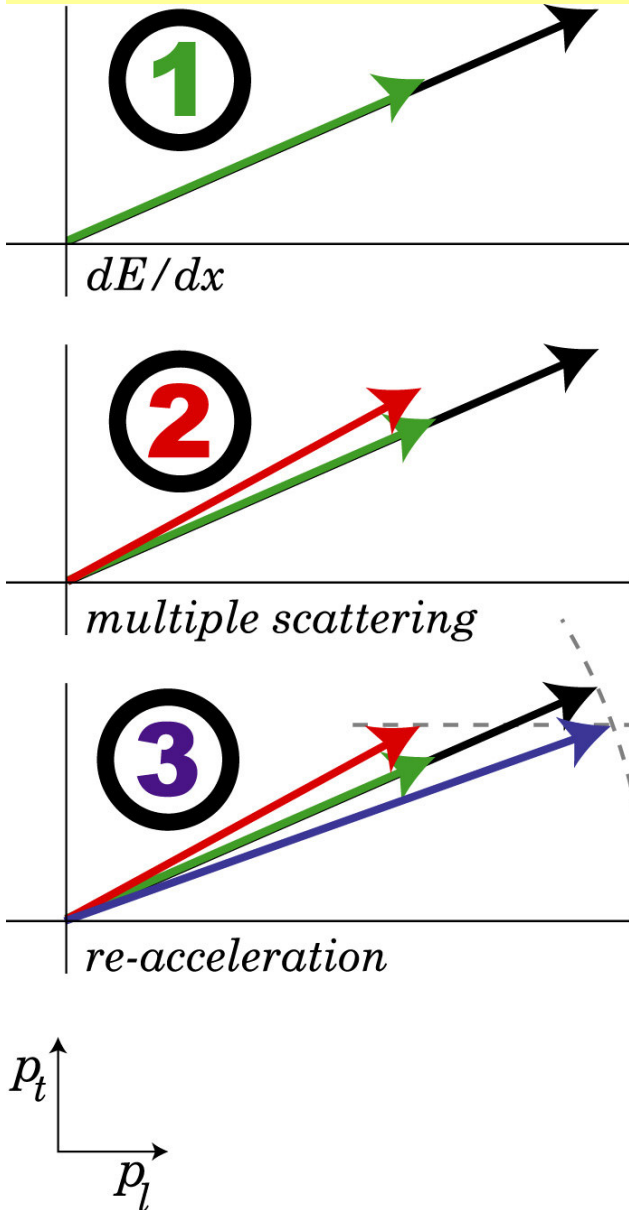
Short muon lifetime requires novel technique:
IONISATION COOLING

NF machine: ionisation cooling



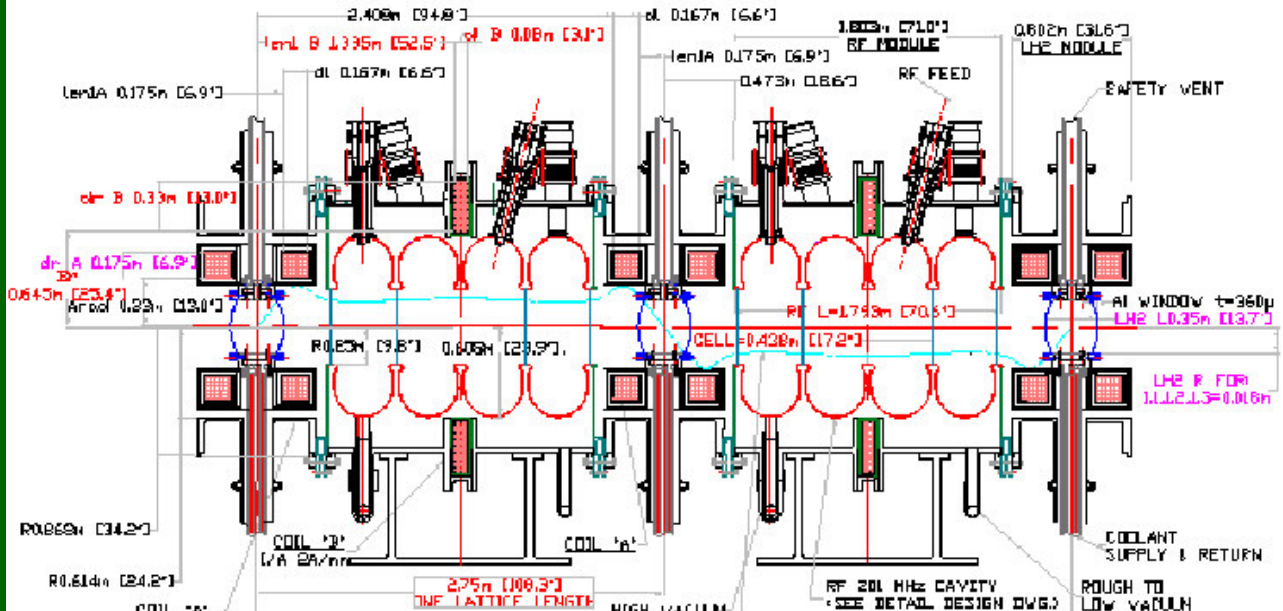
NF machine: ionisation cooling

Principle



Practice

Study II

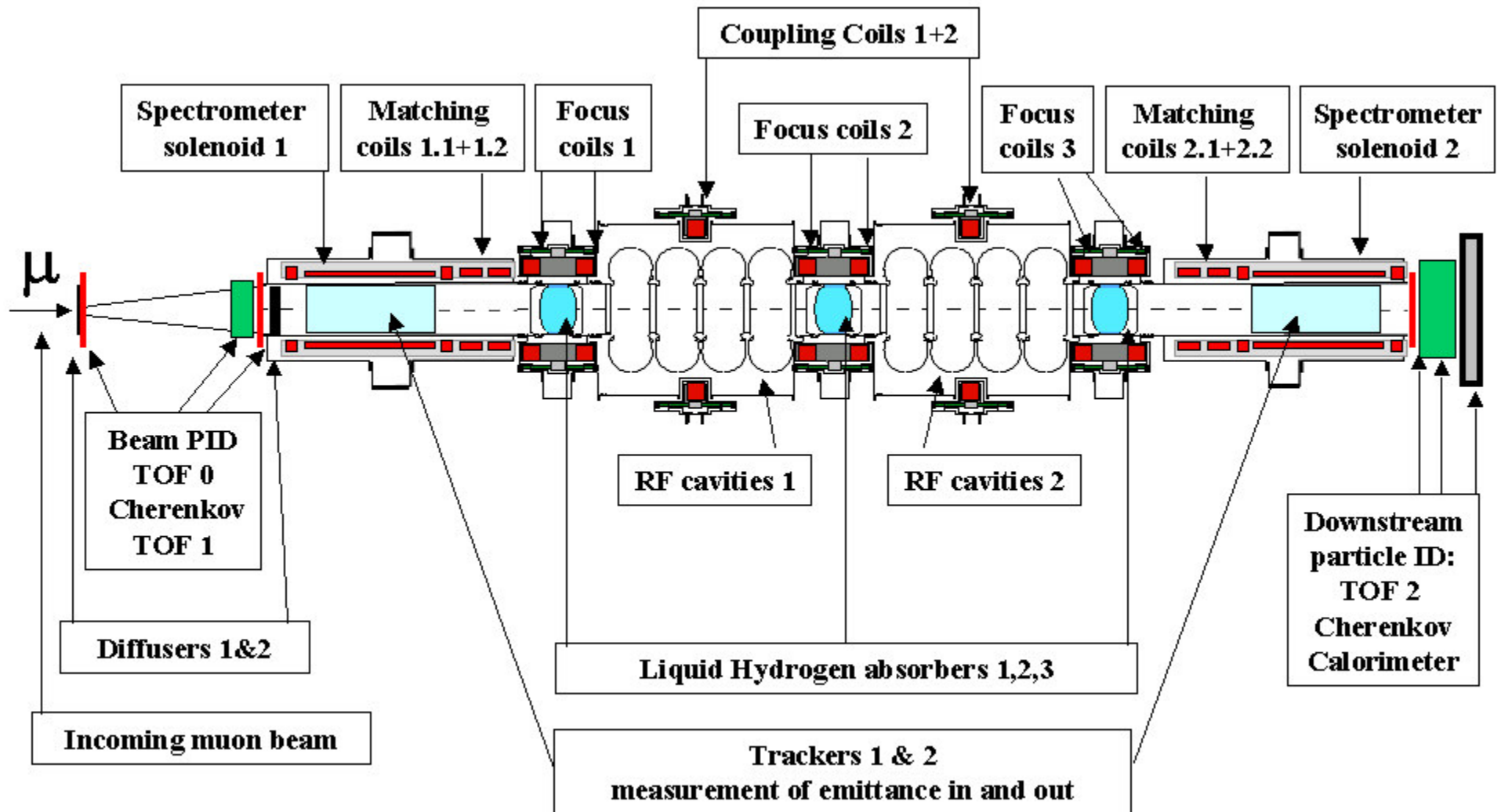


MICE:

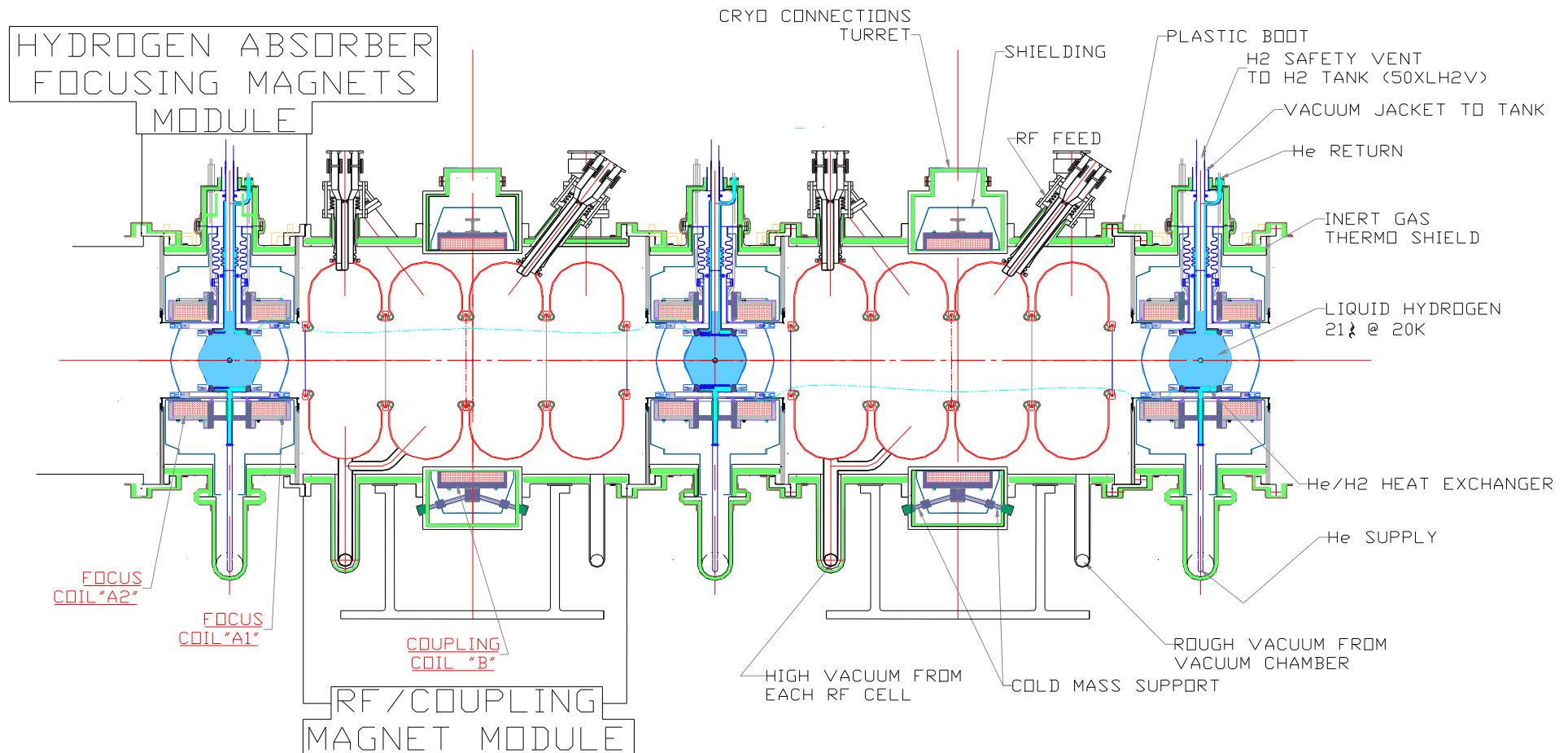
- **Design, build, commission and operate a realistic section of cooling channel**
- **Measure its performance in a variety of modes of operation and beam conditions**

i.e. results will allow NuFact complex to be optimised

Muon Ionisation Cooling Exp^t



The MICE cooling channel



Note, hydrogen safety implies:

- Two pairs of windows on absorber vessel
- Perhaps also, argon jacket for MICE

Cooling performance of MICE

Lattice

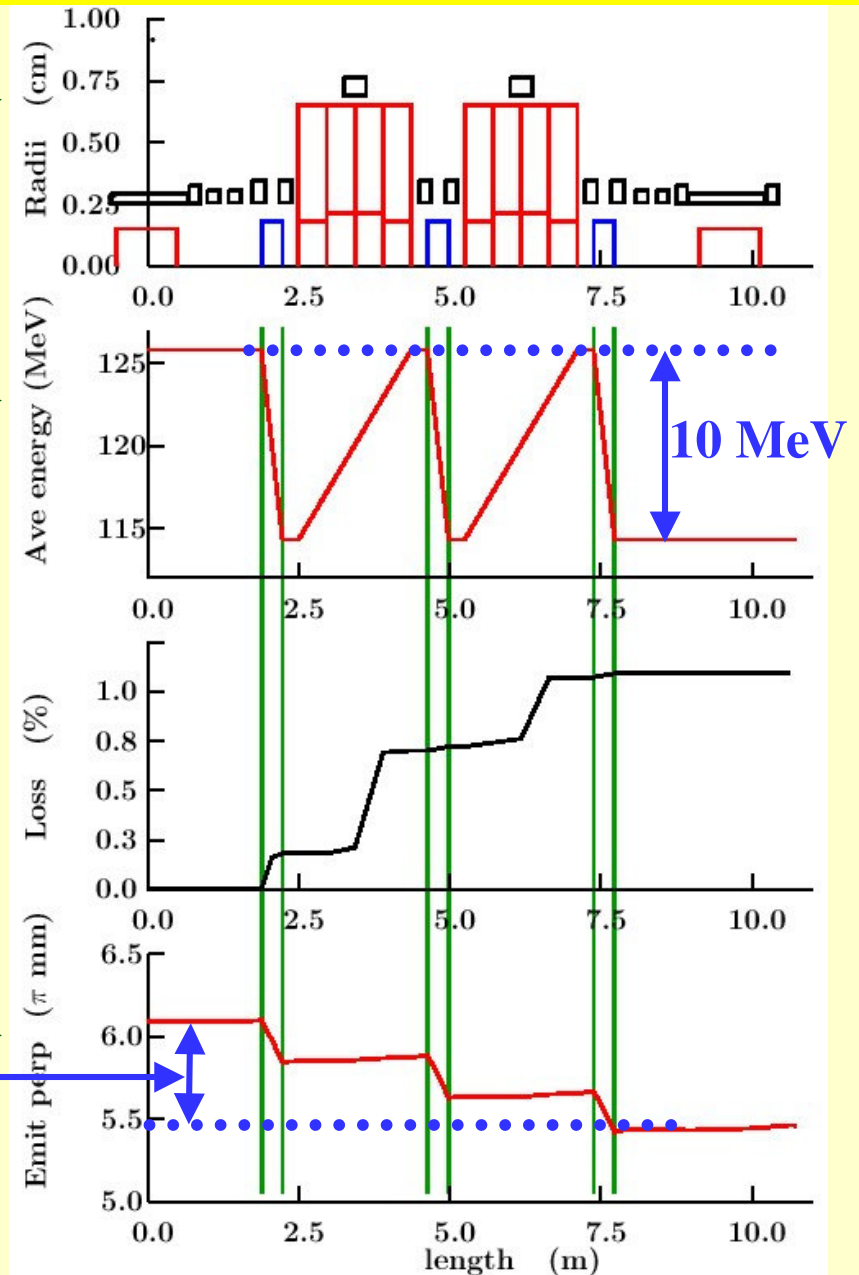
Average K.E.

~20 MV total

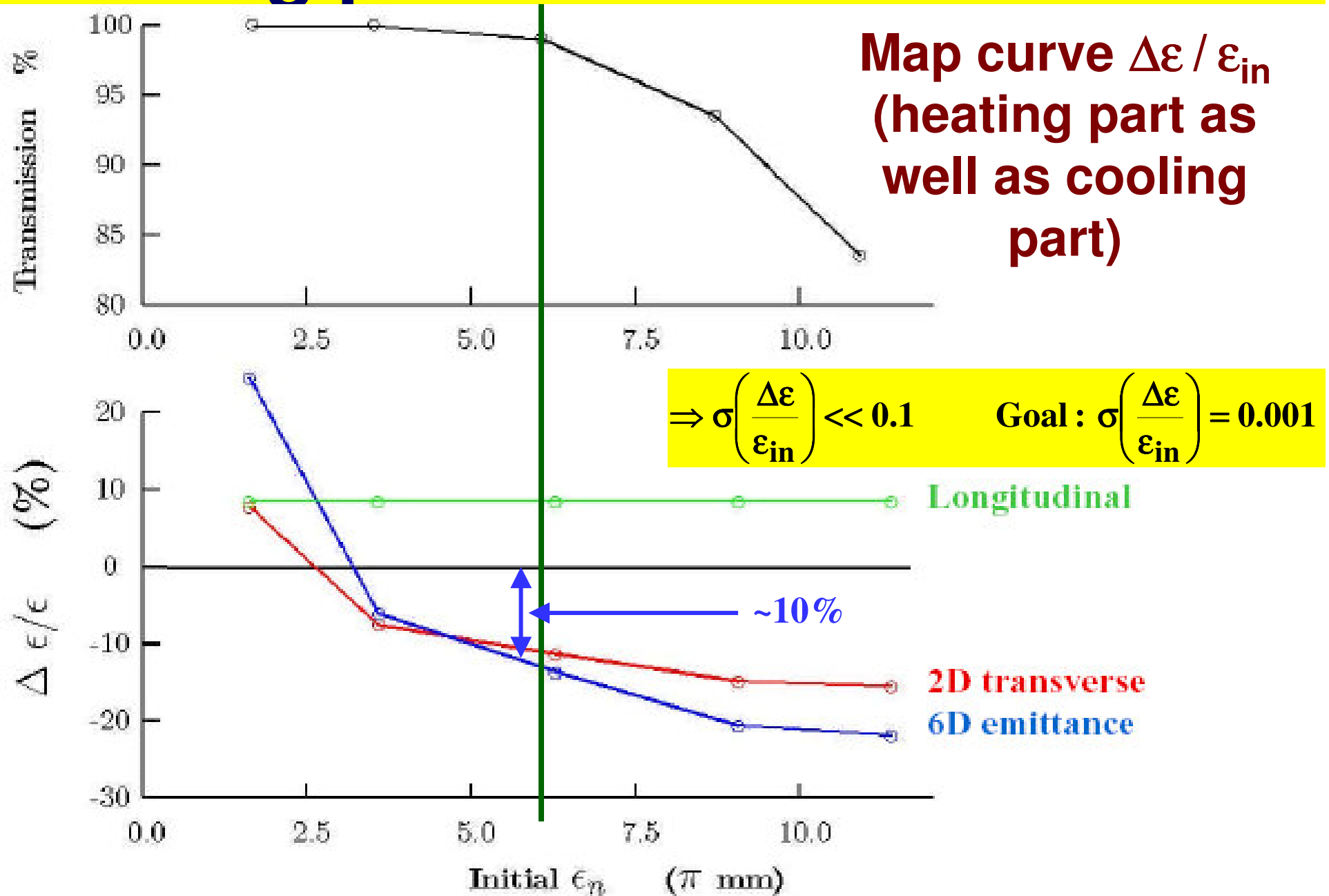
Particle loss

2D emittance

~10%



Cooling performance of MICE



MICE: precision

$$\text{Goal : } \sigma\left(\frac{\Delta\epsilon}{\epsilon_{\text{in}}}\right) = 0.001$$

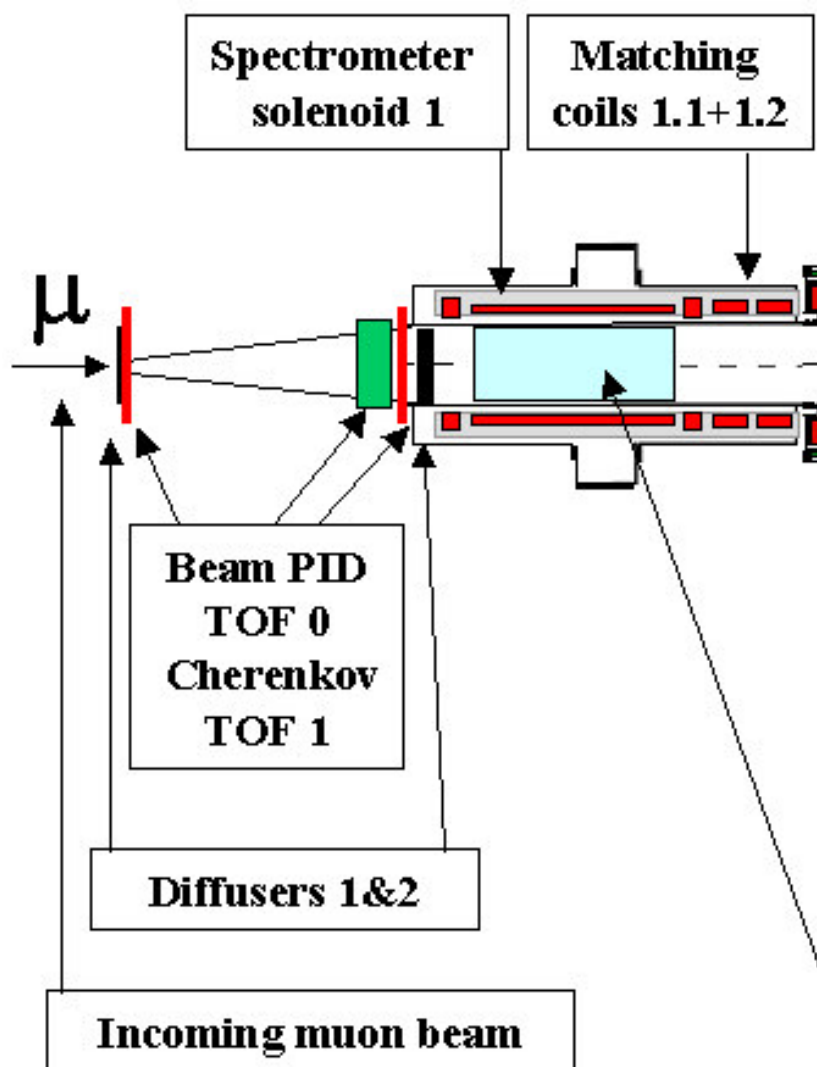
Statistical

- Take 10^6 muons to reduce statistical error to 10^{-3}

Systematic

- **Description of apparatus:**
 - Thickness/density of absorber, windows, etc.
 - Magnitude of magnetic and RF fields, phase of RF
 - Alignment
 - Beam energy scale
 - Simulation of multiple Coulomb scattering and dE/dx
- **Systematic differences between spectrometers:**
 - Efficiency, noise differences
 - Mis-alignment/mis-match
 - Different fields

MICE: upstream particle id

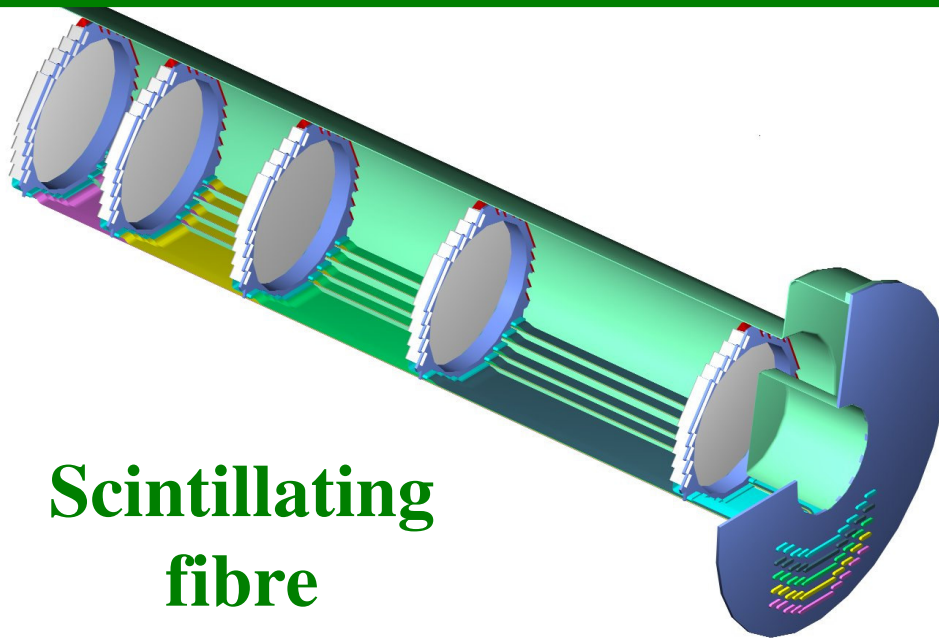


Time of flight system:

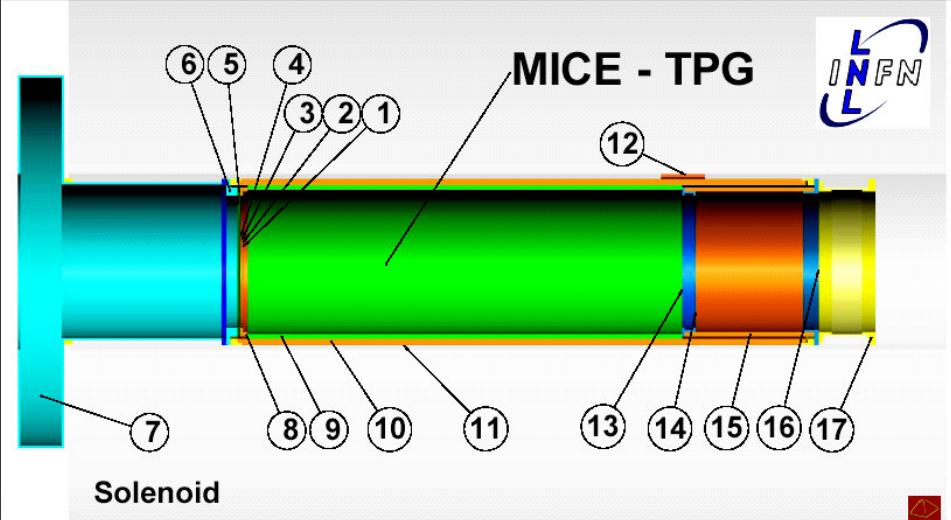
- 10 m flight path
- TOF scintillator hodoscopes with 70 ps time resolution
- Yields π/μ separation better than 1% at 300 MeV/c
- Beam already provides π/μ (10%)

MICE: tracker

Baseline



Alternative

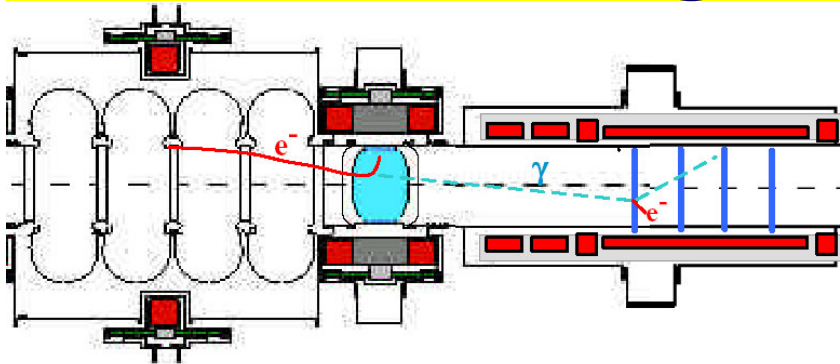


TPG – TPC with GEM readout

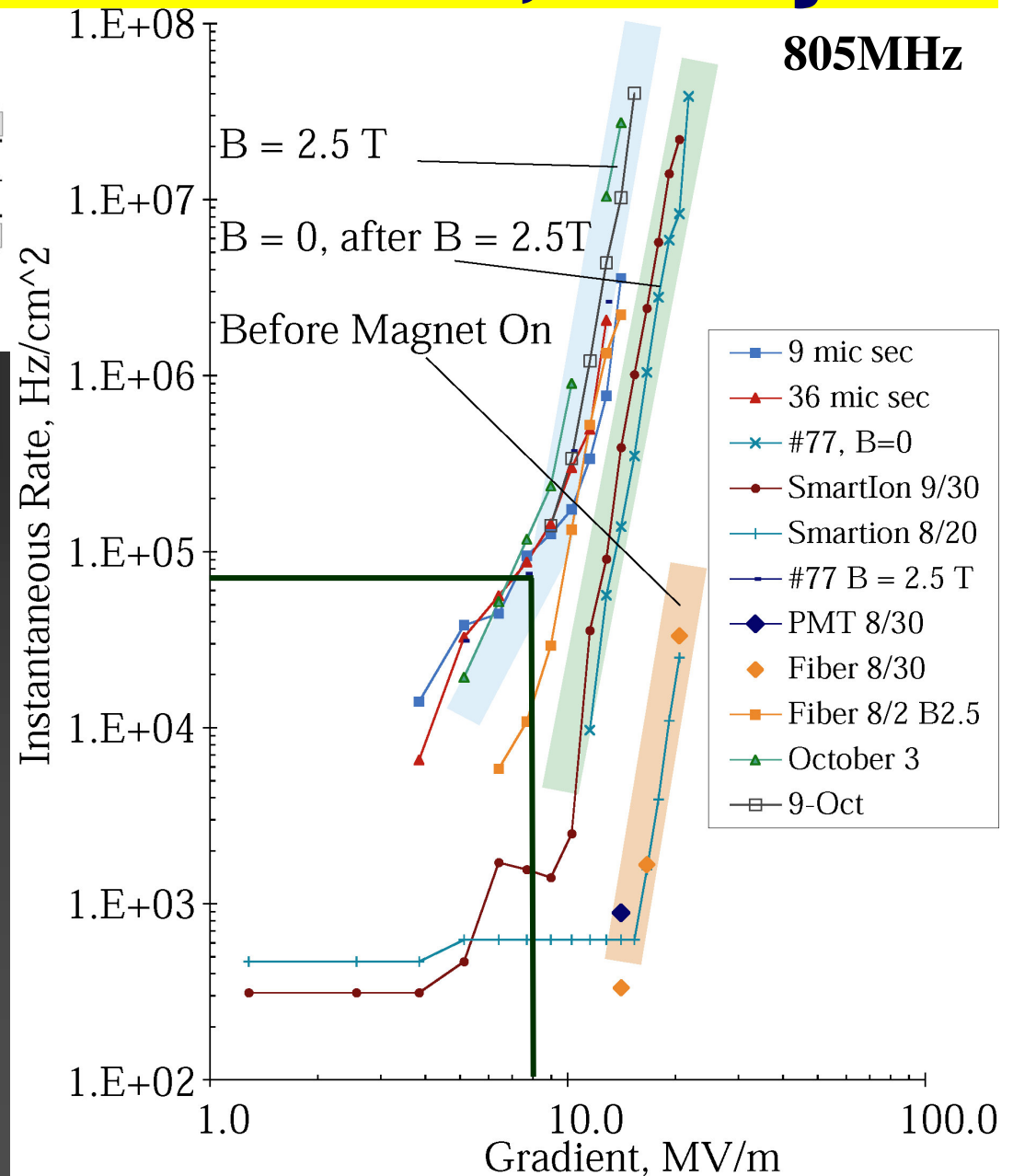
- No active electronics/HV close to liquid hydrogen absorber
- No copper close to RF (low pickup)
- 350 μ fibre: 3-fold doublet; 0.35% X_0
- VLPC read-out: high quantum-efficiency, high gain

- Light gas (0.15% X_0)
- Many points per track
- High precision track recⁿ possible
- Large integration time
- Effect of X-rays on GEMs

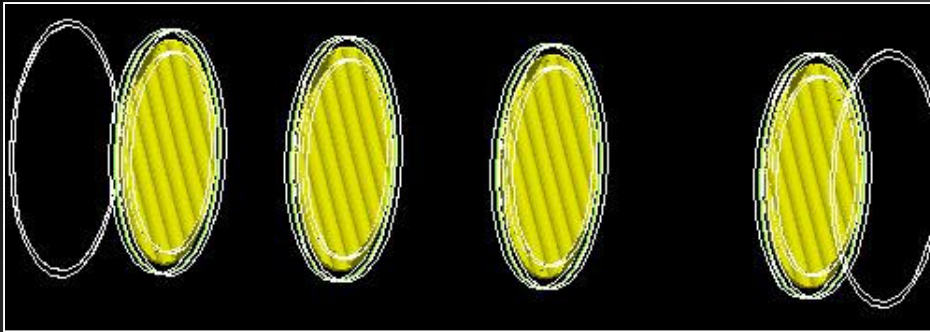
MICE: backgrounds ... e^- , X-rays



- **Instantaneous rate at 8 MV/m (201 MHz):**
 $4 \times 10^4 \text{ Hz/cm}^2$
- **Gives rate/plane = 0.5 MHz**
(rate/fibre = 116 Hz)
- **To reduce noise-hit rate:**
Trigger gate: 15 ns
On-board TDC
resolution 2 ns
(proposed u/g to board for D0)



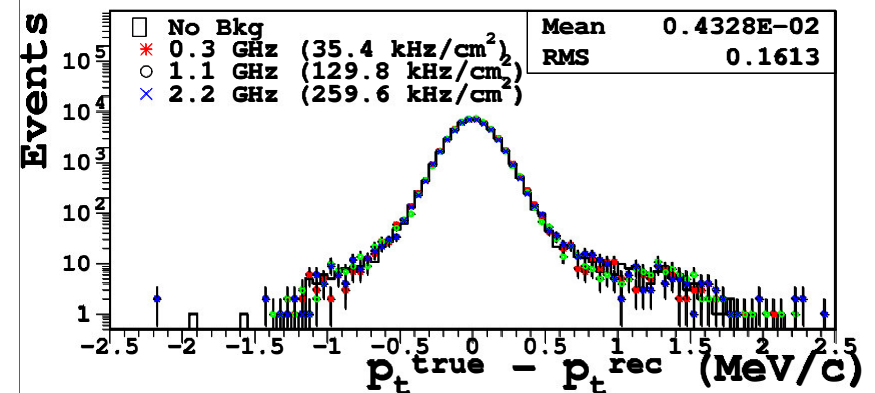
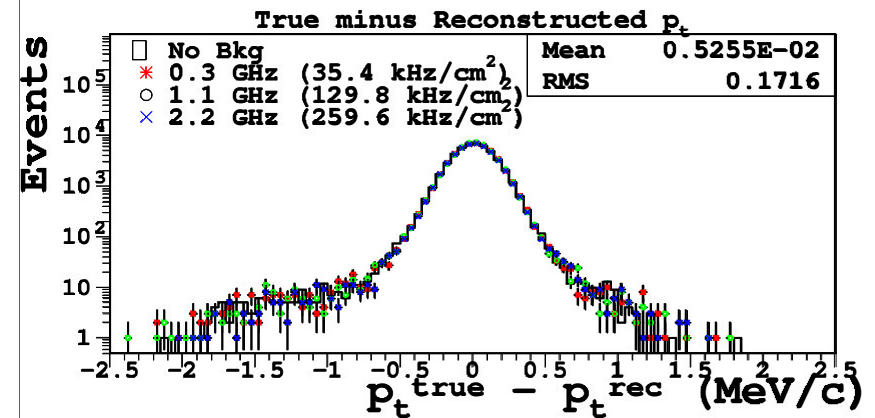
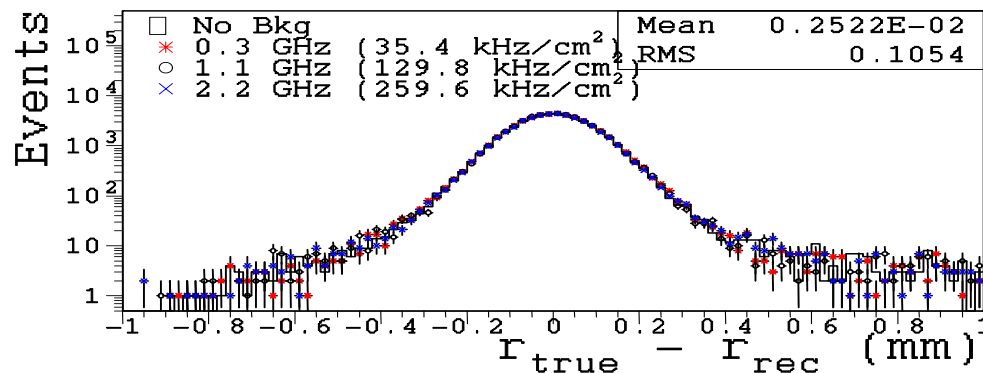
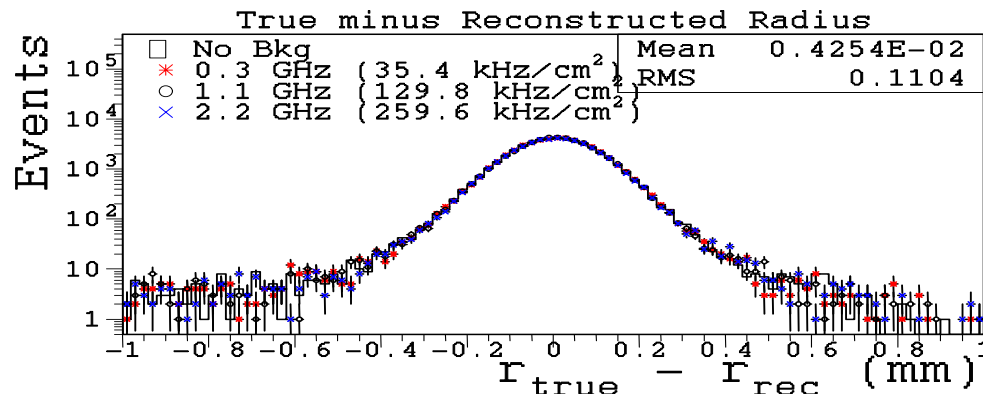
MICE: tracker sensitivity to bg



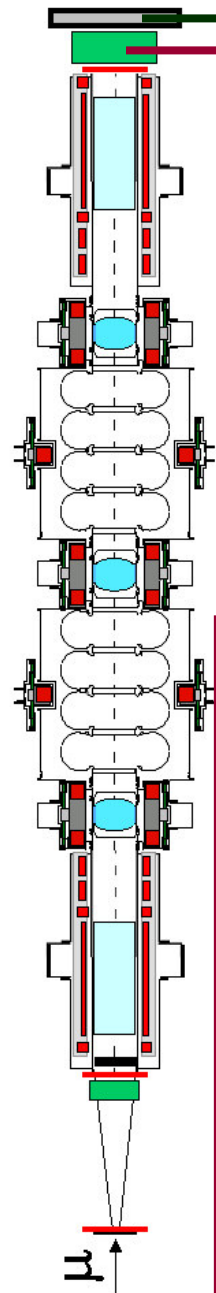
Performance OK

(require to simulate inefficiency)

× - 550 MHz/plane

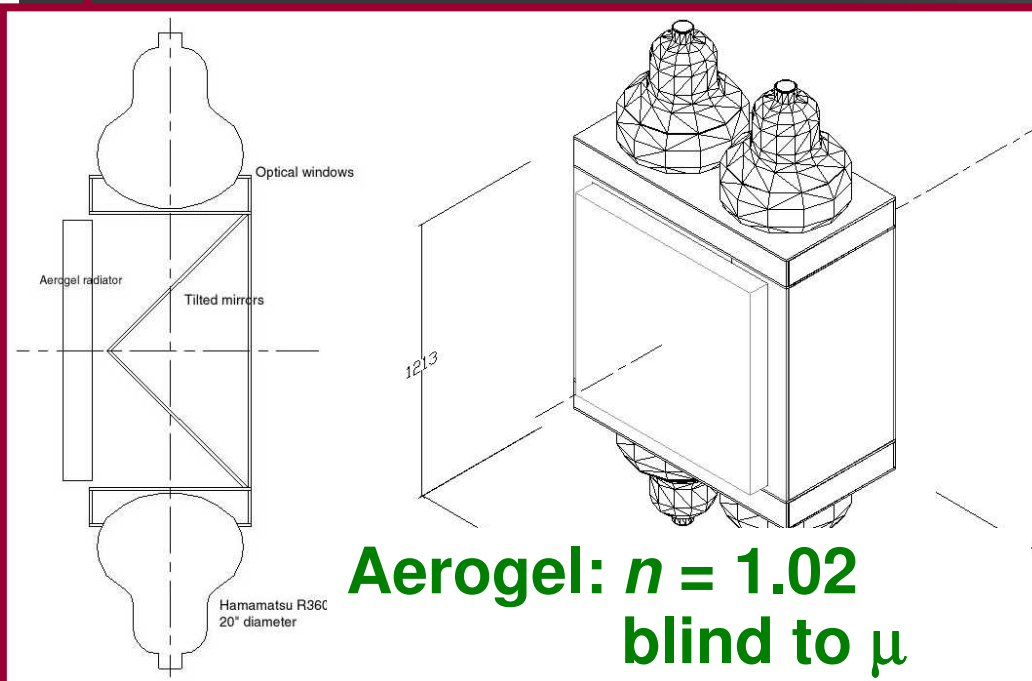
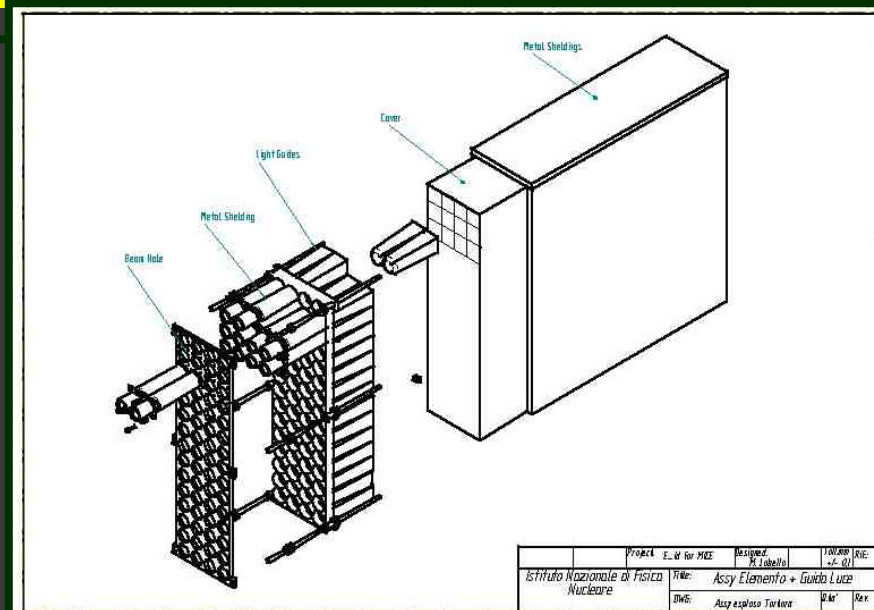


MICE: downstream particle id



0.5% of muons
decay in channel

Require to veto
electrons at
better than %
level

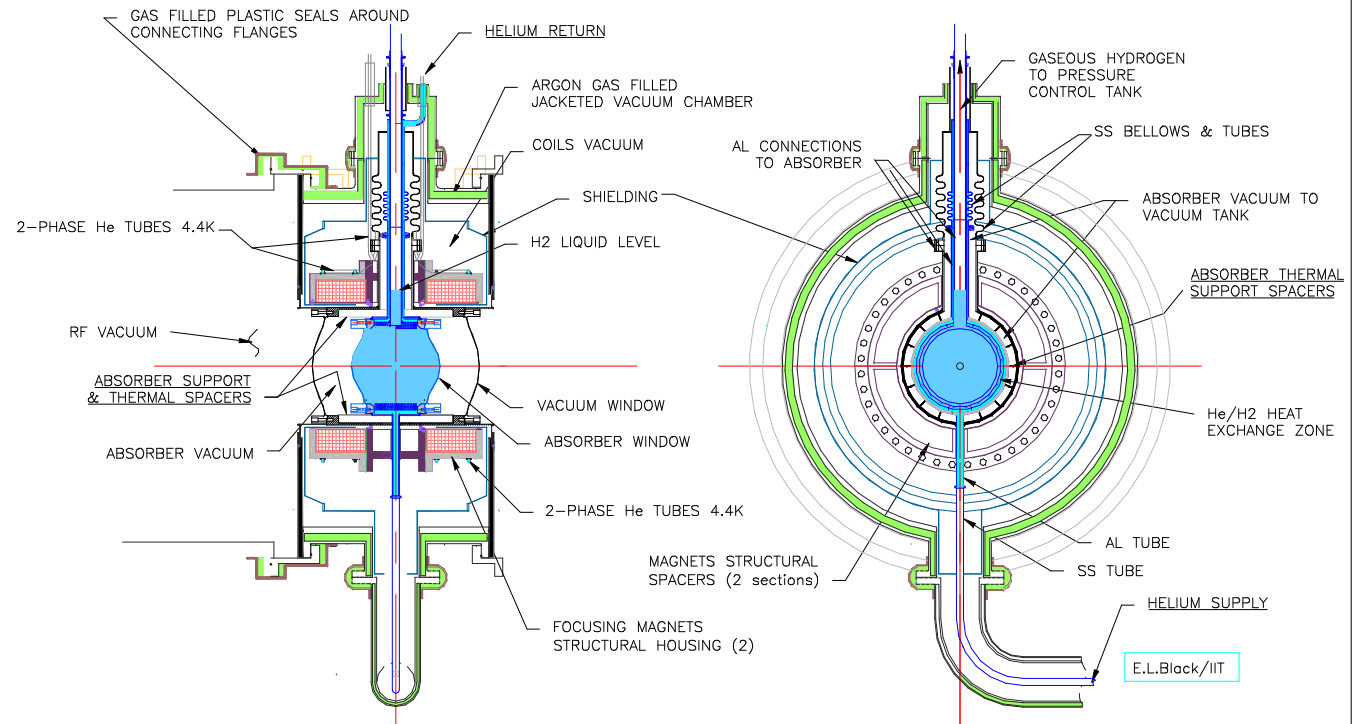
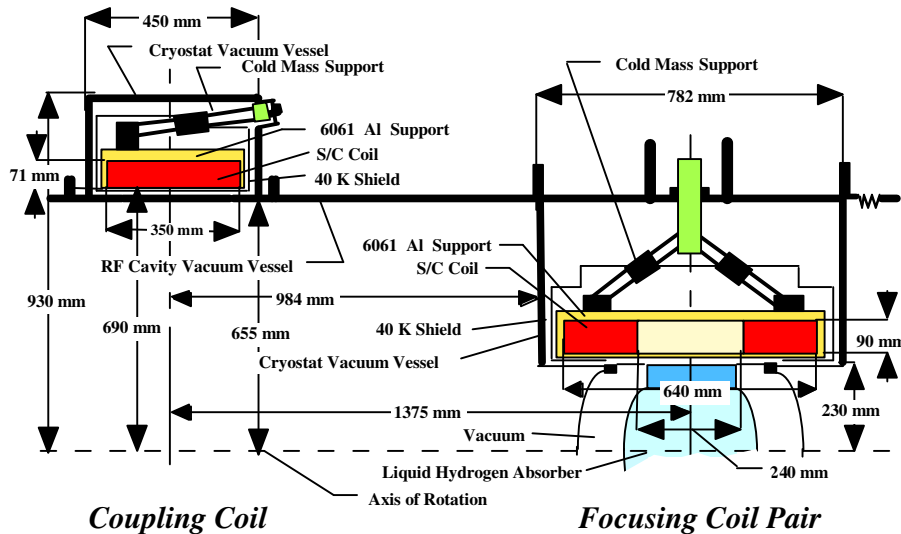


Aerogel: $n = 1.02$
blind to μ

Cherenkov
veto
EM shower
veto from CAL

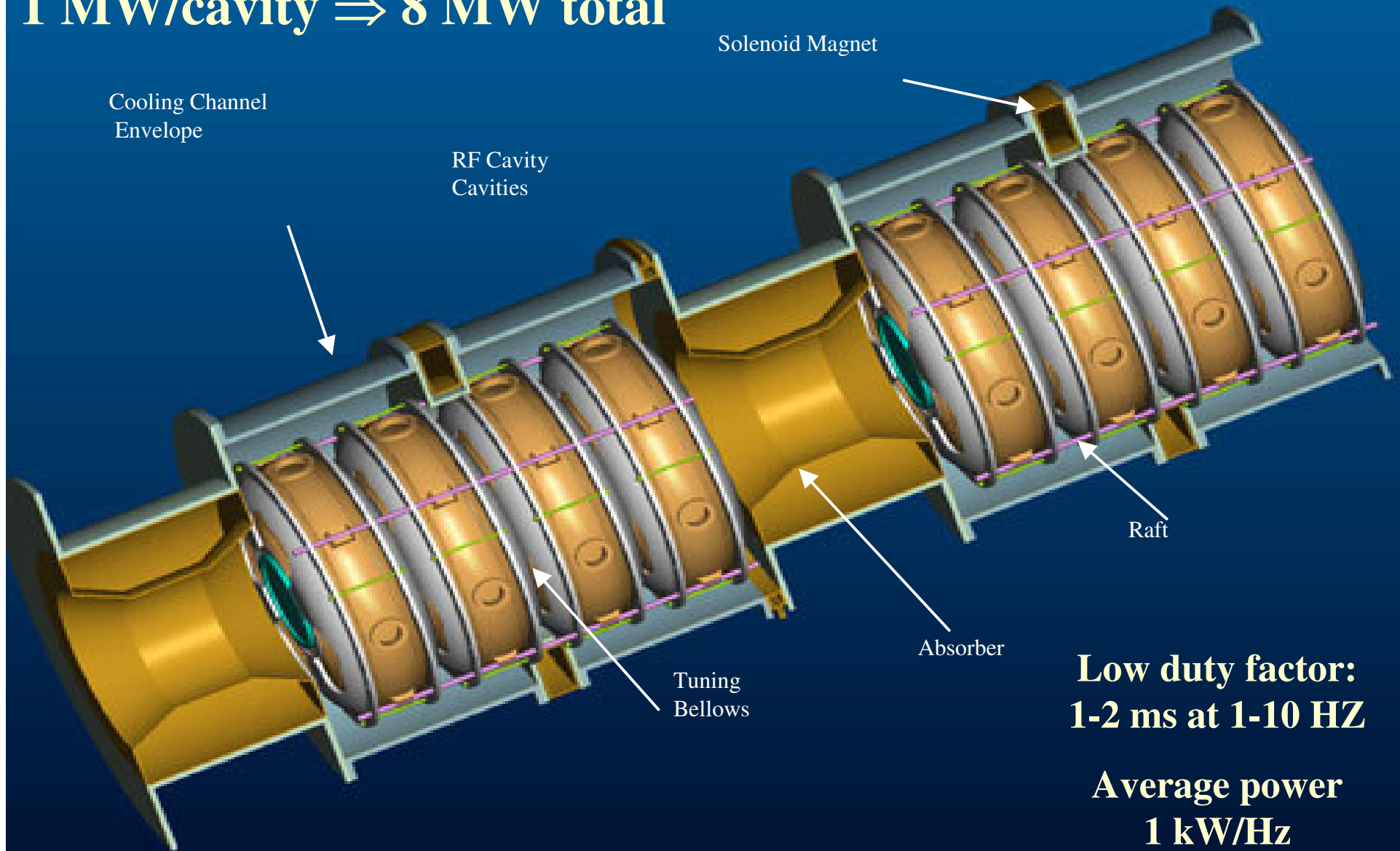
MICE: absorber and focus pair

Engineering of absorber vessel, focus pair and integration of the two to meet hydrogen safety specification a significant challenge

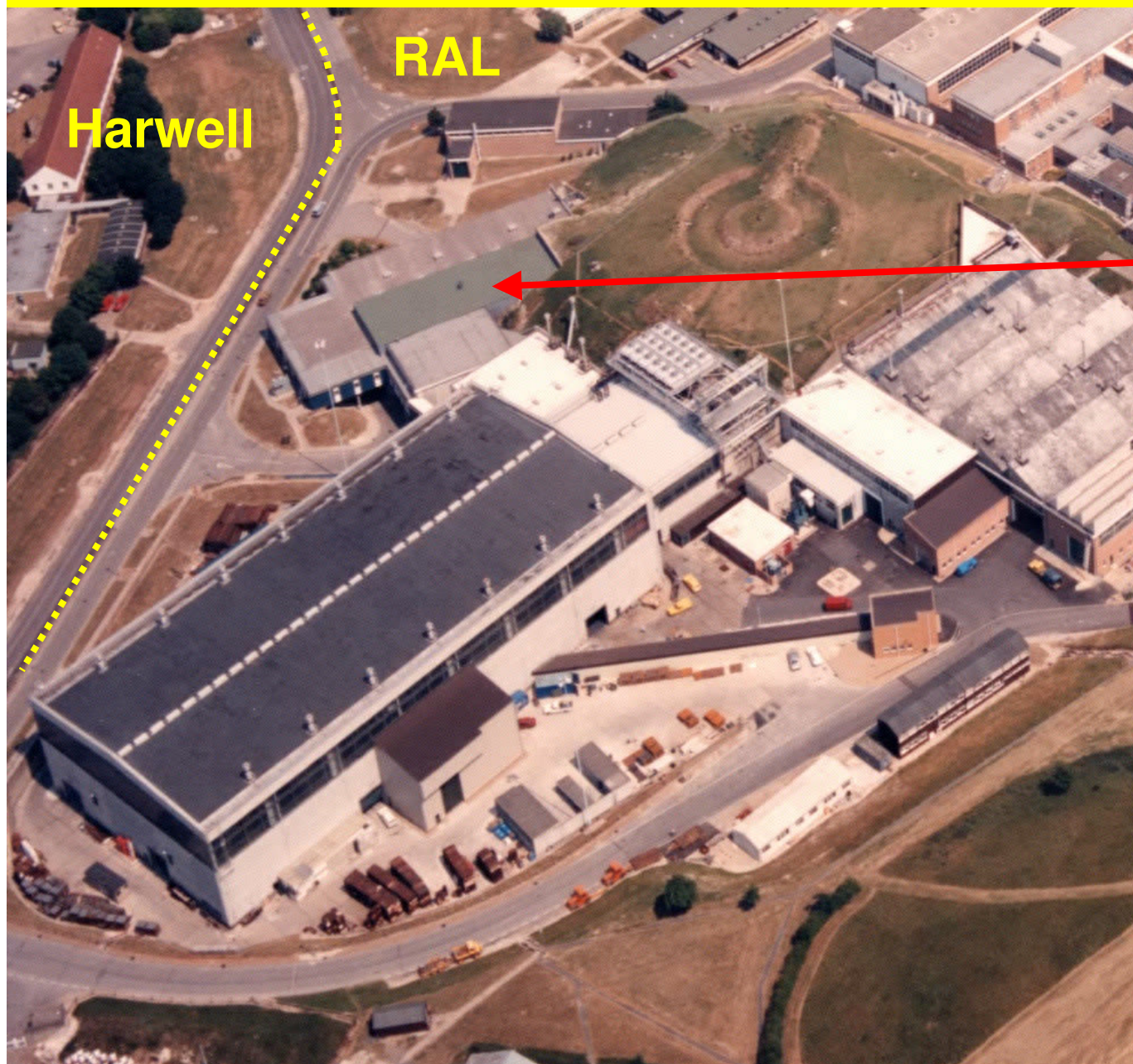


MICE: RF system

1 MW/cavity $\Rightarrow$ 8 MW total

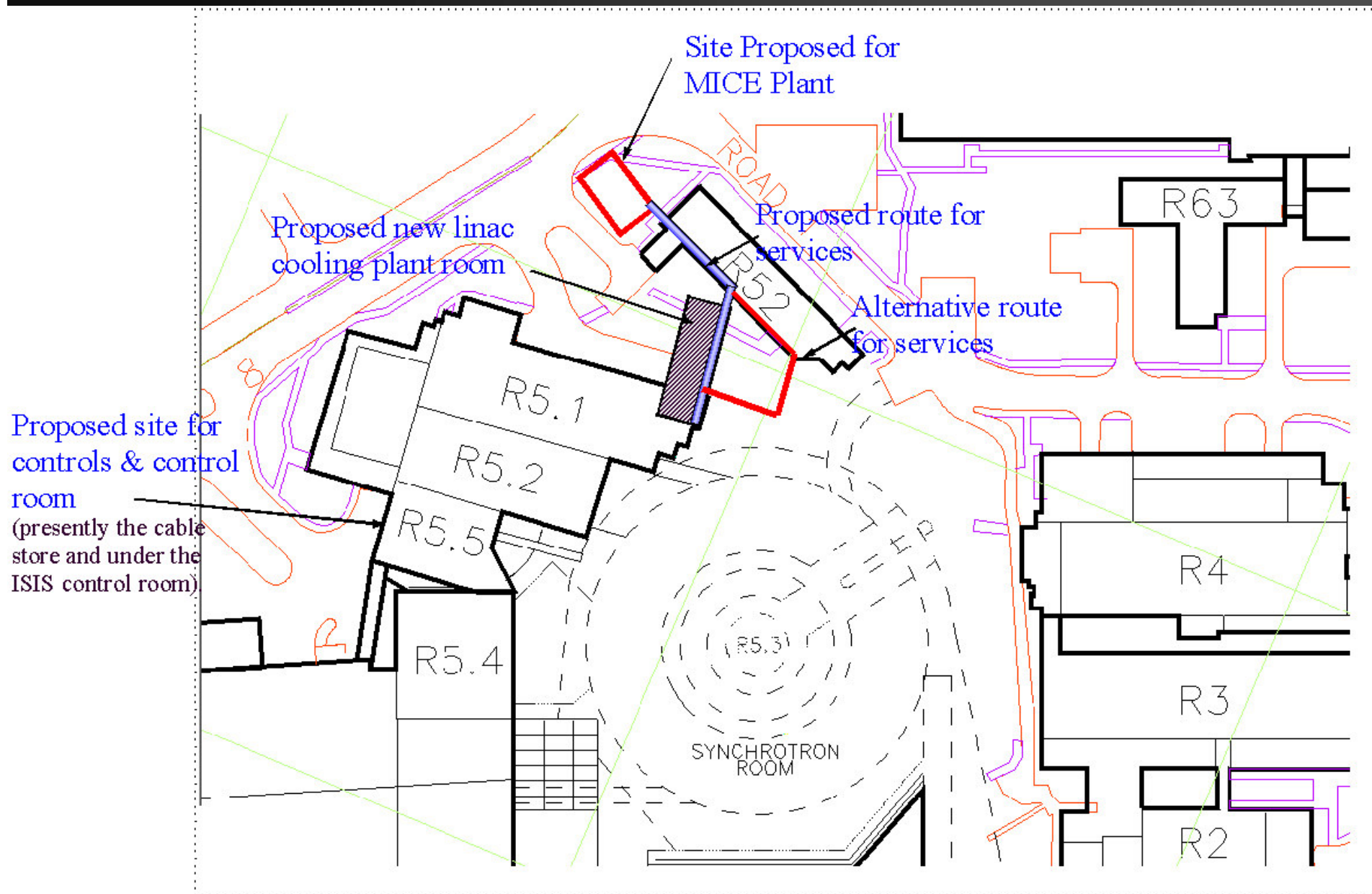


MICE: implementation at RAL

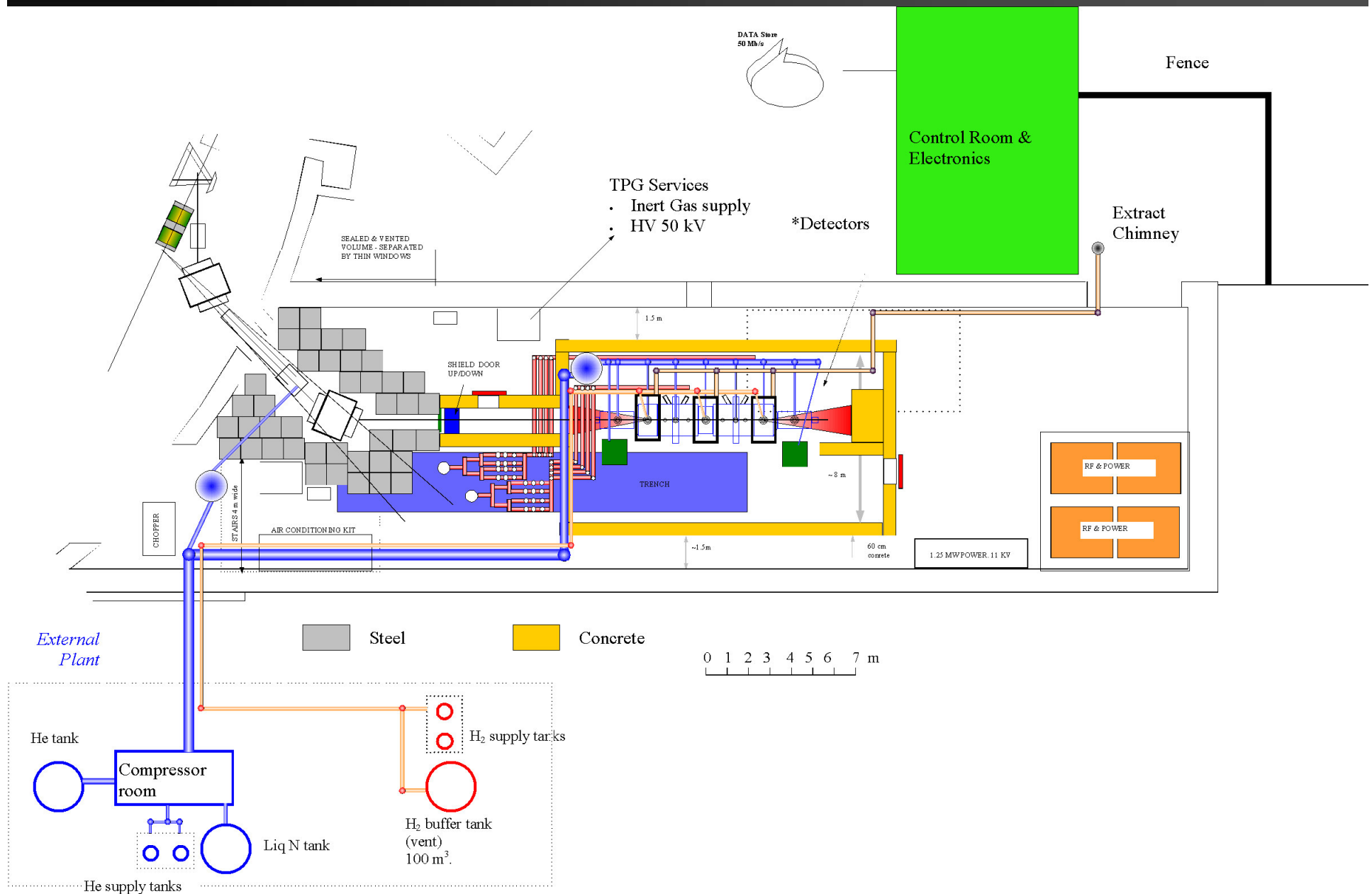


**MICE
hall**

MICE: implementation at RAL



MICE: implementation at RAL



MICE hall prep. work 2003/04

Work Plan

- Isolate Power & Water to Beam Line & Power Supplies ✓
- Re-establish power & water services to CMS test facility ✓
- Drain Water from beam line ✓
- Remove all pipe work and cable trays around magnets ✓
- Remove Beam Element to storage
- Remove old power supplies - salvage / dispose as required

MICE collaboration:

Europe

Louvain la Neuve, Saclay, Bari, LNF Frascati, Genova, Legnaro, Milano, Napoli, Padova, Roma III, Trieste, NIKHEF, Novosibirsk, CERN, Genève, ETH Zurich, PSI, Brunel, Edinburgh, Glasgow, Imperial College, Liverpool, Oxford, RAL, Sheffield

Japan

KEK, Osaka University

United States of America

ANL, BNL, FNAL, IIT, Chicago Enrico Fermi Inst., LBNL, UCLA, NIU, Mississippi, Riverside

- **IPRC: scientific approval**
- **PPRP: scientific approval**
- **UK support; funding search in the three regions**

Opportunities for new collaborators!

142 authors, 37 institutes, 3 continents!

26 institutes from Europe

Conclusions

- Window on physics ‘beyond’ SM
- Present expt^s measure ‘solar’ & ‘atmos’ parameters
- Next generation: off-axis beams to:
 - measure θ_{13}
 - preliminary search for leptonic-CP violation
- Require to plan for *precision* ν physics
 - Neutrino Factory the leading contender
 - MICE: 1st global collaboration Neutrino Factory collaboration
- Overall a first-class programme!