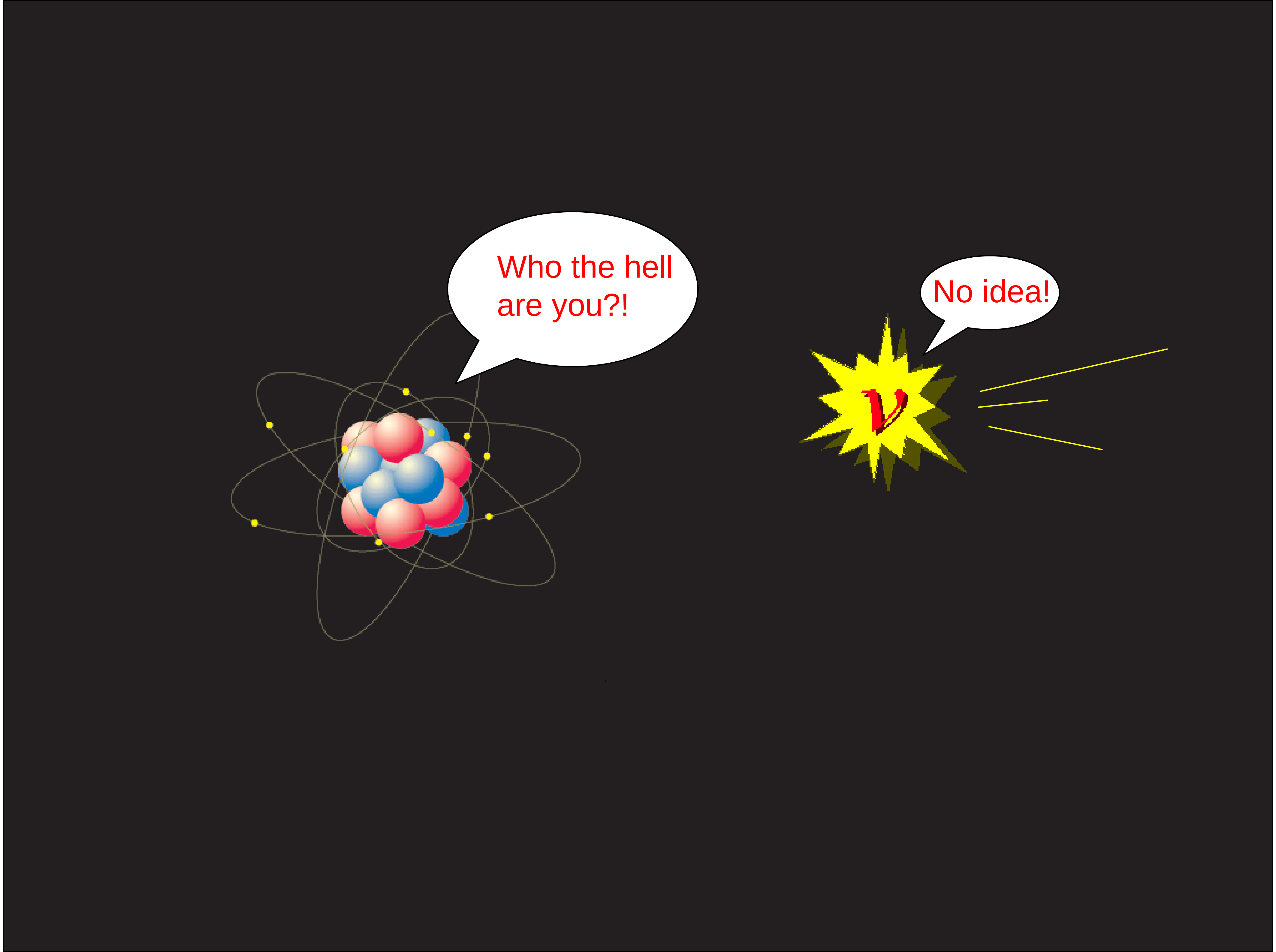
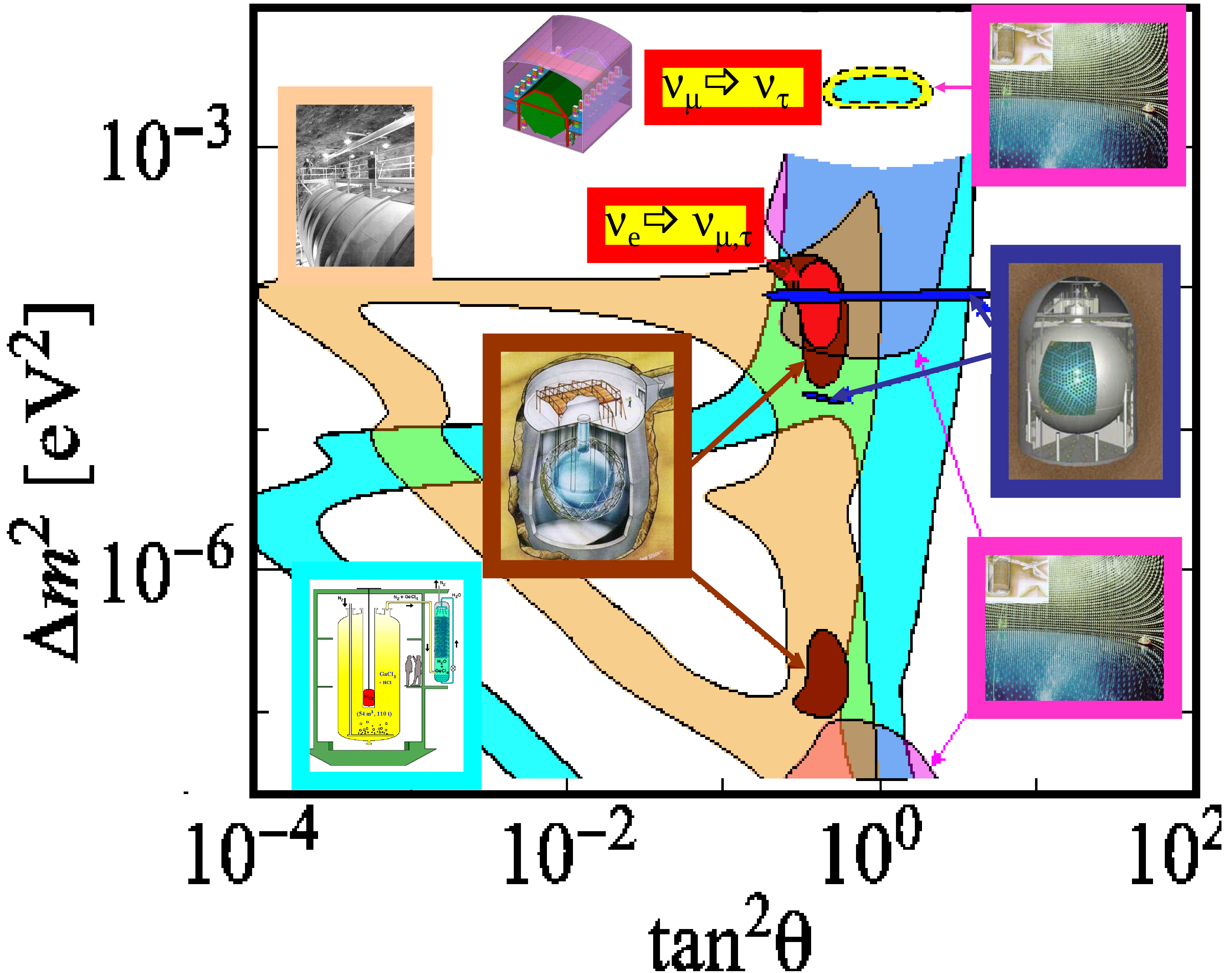
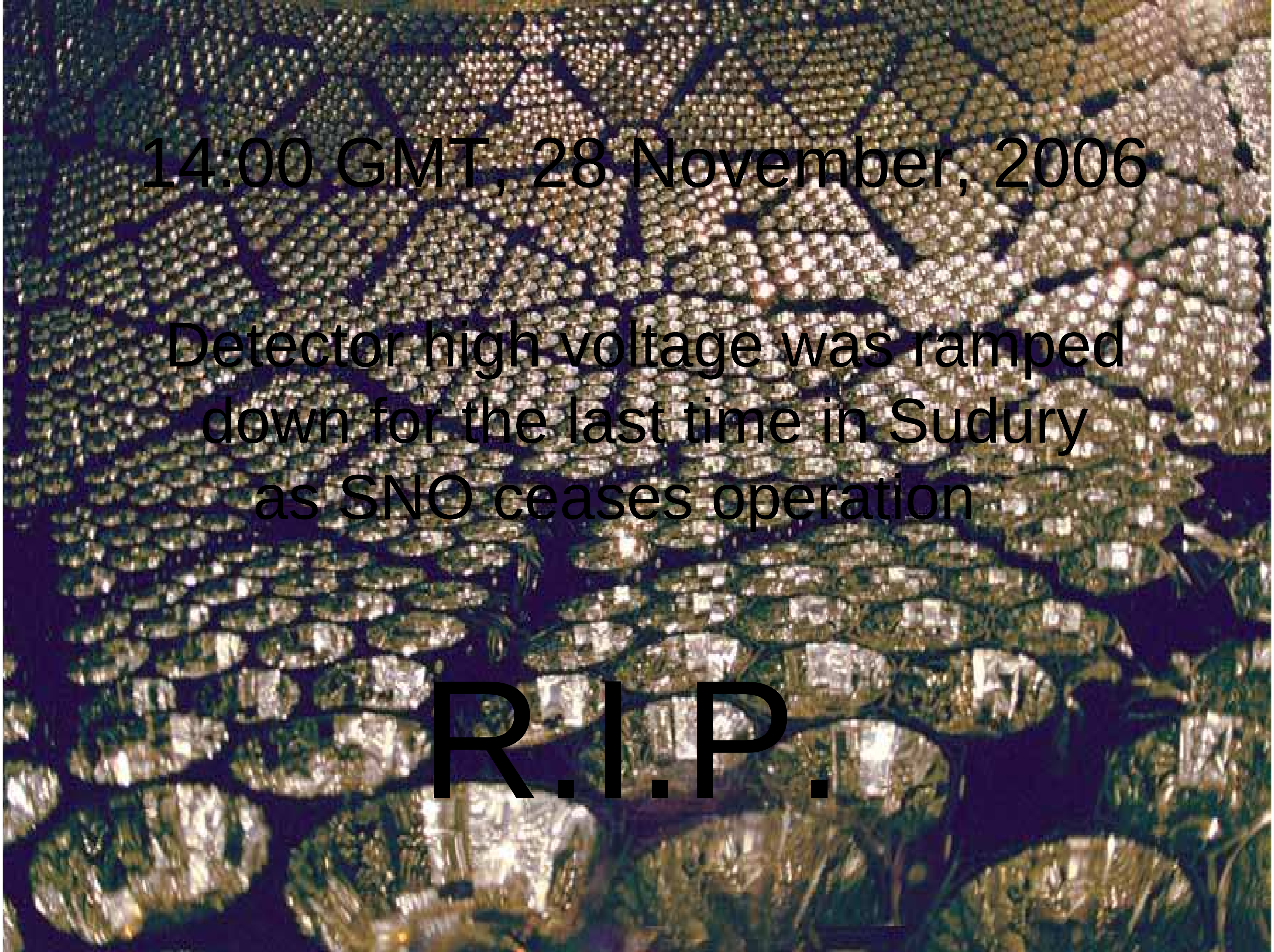
A Third Mix-Up For Experimentalists

Steve Biller, Oxford


Who the hell are you?!
No idea!
ν



$\nu_\mu \Rightarrow \nu_\tau$
$\nu_e \Rightarrow \nu_{\mu,\tau}$
10^{-3}
10^{-6}
Δm^2 [eV^2]
10^{-4}
10^{-2}
10^{0}
10^{2}
$\tan^2\theta$



14:00 GMT, 28 November, 2006

Detector high voltage was ramped down for the last time in Sudury as SNO ceases operation

R.I.P.

PMNS Neutrino Mixing Matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

CKM Quark Mixing Matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} U_{ud} & U_{us} & U_{ub} \\ U_{cd} & U_{cs} & U_{cb} \\ U_{td} & U_{ts} & U_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

PMNS Neutrino Mixing Matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\begin{pmatrix} 0.7 & 0.7 & < 0.2 e^{i\delta} ? \\ -0.5 & 0.5 & 0.7 \\ 0.5 & -0.5 & 0.7 \end{pmatrix}$$

$$\begin{pmatrix} big & big & small? \\ big & big & big \\ big & big & big \end{pmatrix}$$

GUTs? See-Saw?

IF $\theta_{13} > 0.05$

$(\sin^2 2\theta_{13} > 0.01)$

Otherwise → New symmetry?

CKM Quark Mixing Matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} U_{ud} & U_{us} & U_{ub} \\ U_{cd} & U_{cs} & U_{cb} \\ U_{td} & U_{ts} & U_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$\begin{pmatrix} 0.97 & 0.22 & 0.003 e^{i\delta} \\ -0.22 & 0.97 & 0.04 \\ 0.01 & -0.04 & 0.999 \end{pmatrix}$$

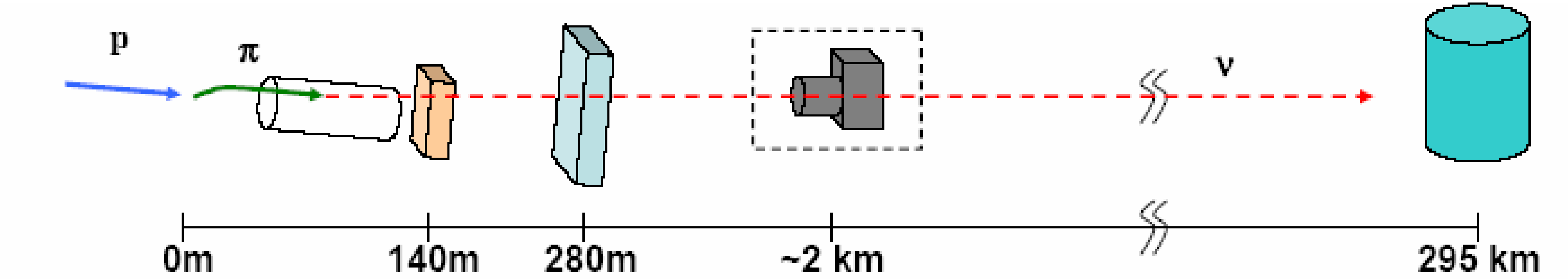
$$\begin{pmatrix} big & small & very\ tiny \\ small & big & tiny \\ tiny & tiny & big \end{pmatrix}$$

The relationship between neutrinos and quarks in GUTs may be the source of the matter-antimatter asymmetry in the Universe **(CP violation)**

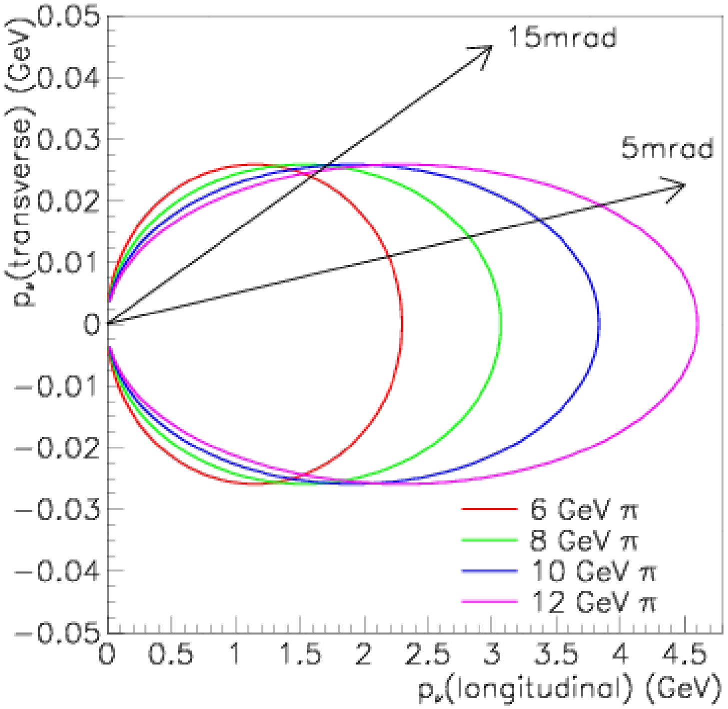
Leptogenesis

Knowing the size of $\sin\theta_{13}$ is the next step and will set the roadmap for how to proceed

“Off Axis” ν Beams



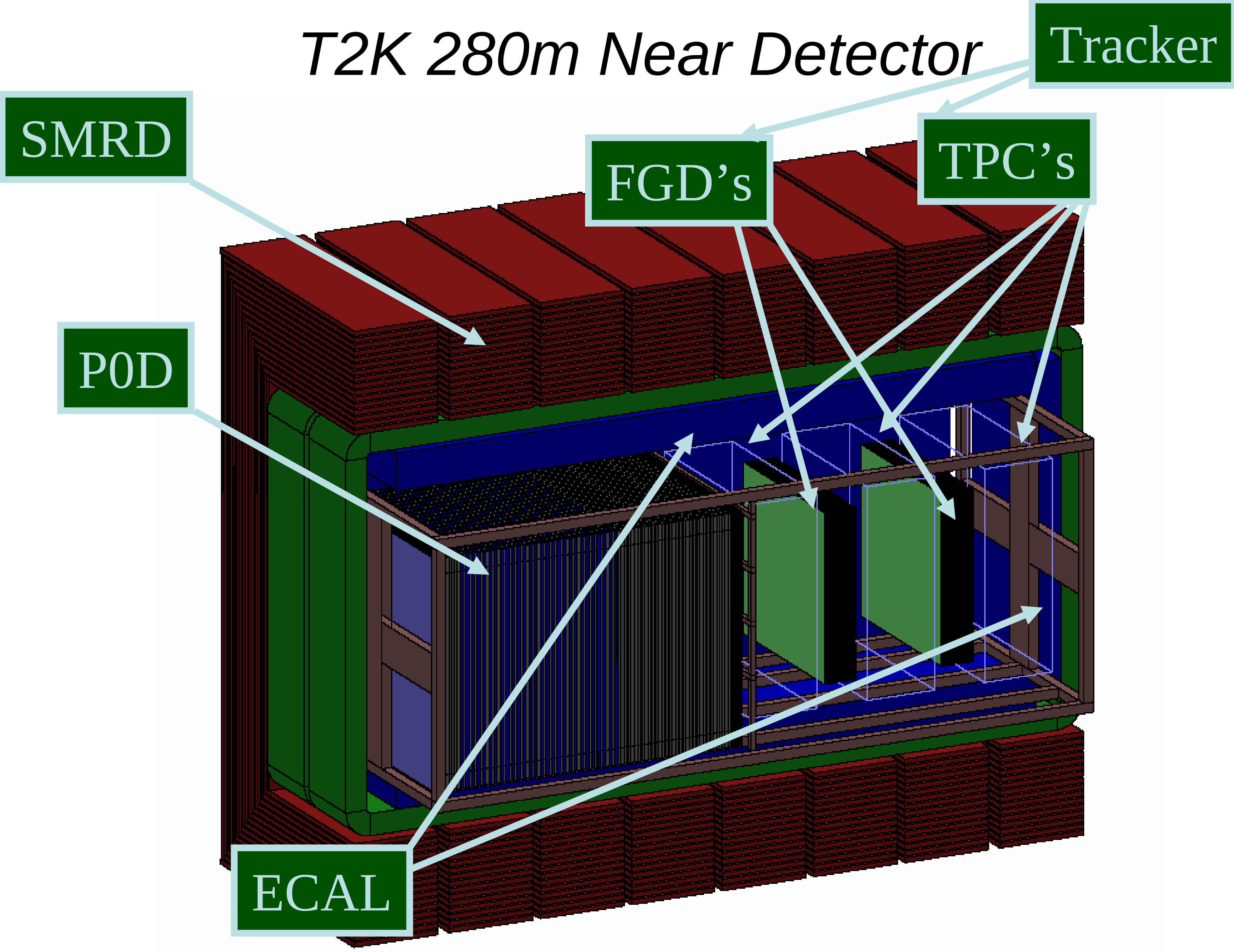
- Take advantage of Lorentz Boost and 2-body decays
- Concentrate ν_μ flux at one energy
- Lower NC and ν_e backgrounds at that energy (3-body decays)



$\nu_\mu \rightarrow \nu_e$ Appearance

T2K & NOVA

T2K 280m Near Detector



Oscillation Probability: $\mathbf{P(\nu_\mu \rightarrow \nu_e) = P_1 + P_2 + P_3 + P_4}$

where

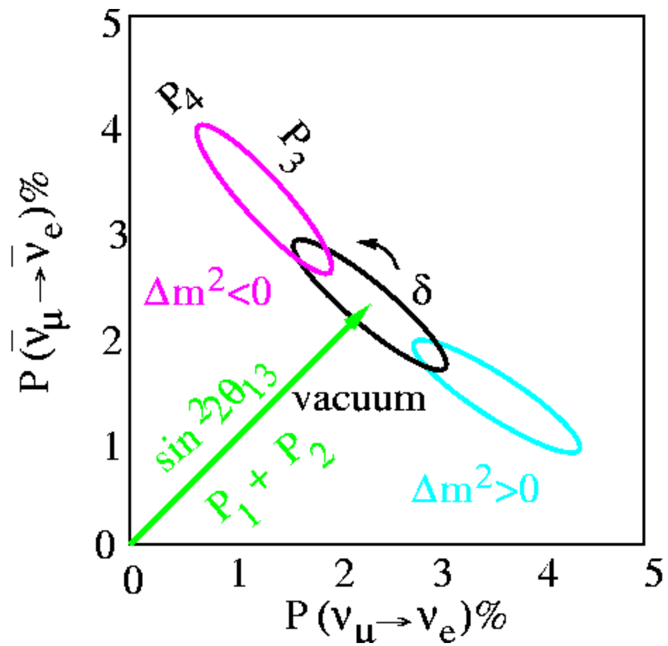
$$P_1 = \sin^2\theta_{23}\sin^2 2\theta_{13}\left(\frac{\Delta_{13}}{B_\pm}\right)^2 \sin^2\frac{B_\pm L}{2}$$

$$P_2 = \cos^2\theta_{23}\sin^2 2\theta_{12}\left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\frac{AL}{2}$$

$$P_3 = J\cos\delta\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\cos\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2}$$

$$P_4 = \mp J\sin\delta\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\sin\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2}$$

- dependence in $\sin(2\theta_{23})$, $\sin(\theta_{23})$ ➔ 2 solutions
- dependence in $\mathrm{sign}(\Delta m^2_{13})$ ➔ 2 solutions
- δ-CP phase ± [0,2π] ➔ interval of solutions



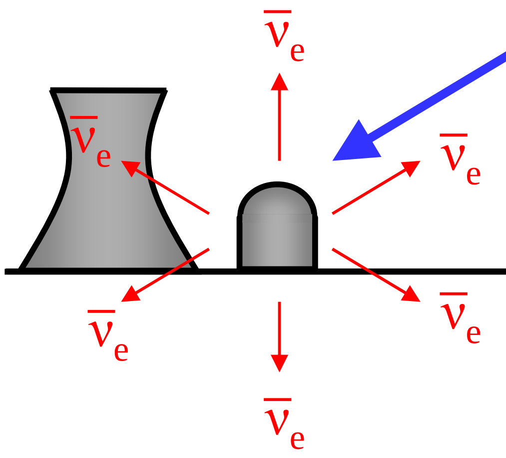
$$P(\nu_\mu \rightarrow \nu_\varepsilon) \sim \tfrac{1}{2}\left(\sin^2 2\theta_{13} - {}^{1}/_{10} \sin 2\theta_{13} \sin\delta\right)$$

$$\alpha \rightleftharpoons 5 \times \sin 2\theta_{13}$$

$$P(\nu_\mu \rightarrow \nu_\varepsilon) \sim \frac{\alpha}{50}\left(\alpha - \tfrac{1}{2} \sin\delta\right)$$

$$\left(\begin{array}{c} 0 < \alpha < 2 \\ 0 < \sin\delta < 1 \end{array}\right)$$

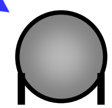
Reactor Neutrinos

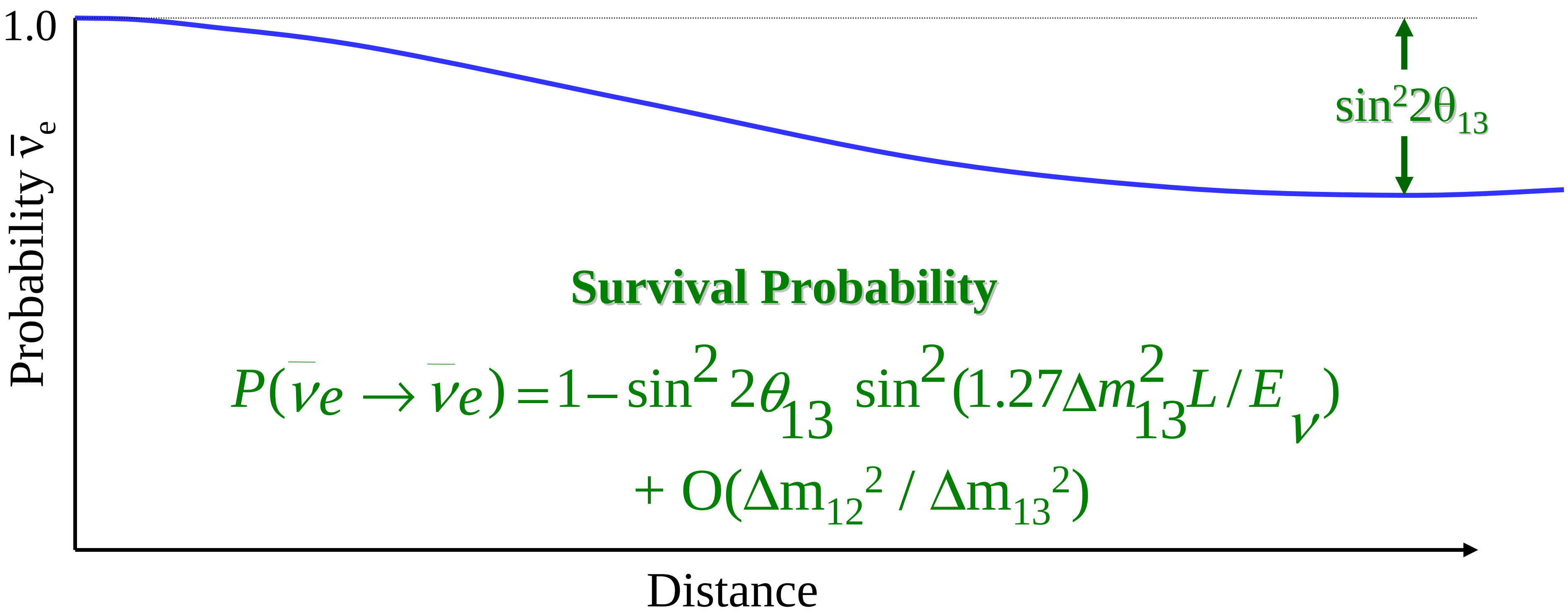


Well understood, isotropic source of electron anti-neutrinos

$E_\nu \leq 8$ MeV

Oscillations observed as **disappearance** of $\bar{\nu}_e$



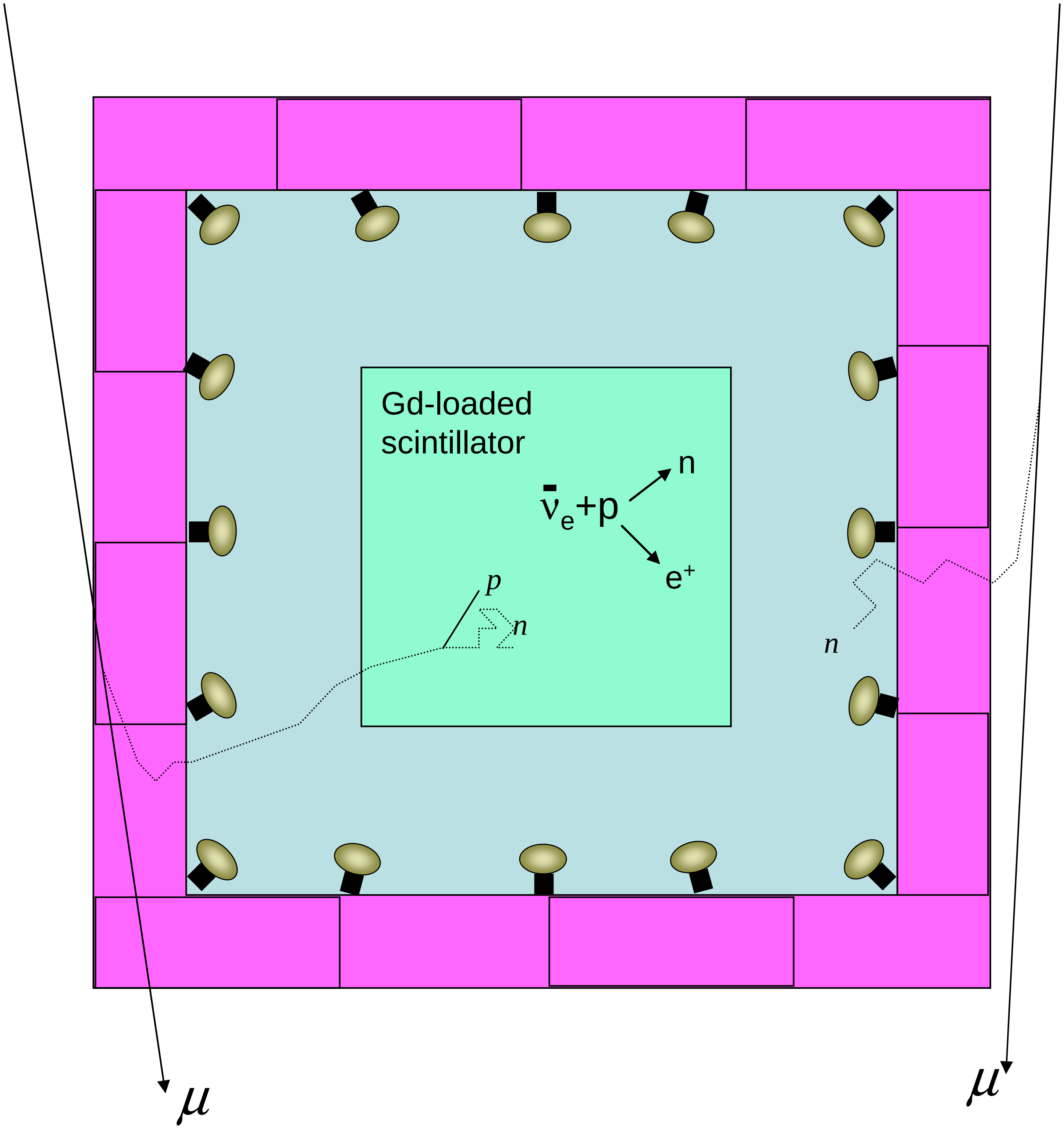


Survival Probability

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2(1.27 \Delta m^2_{13} L / E_\nu)$$

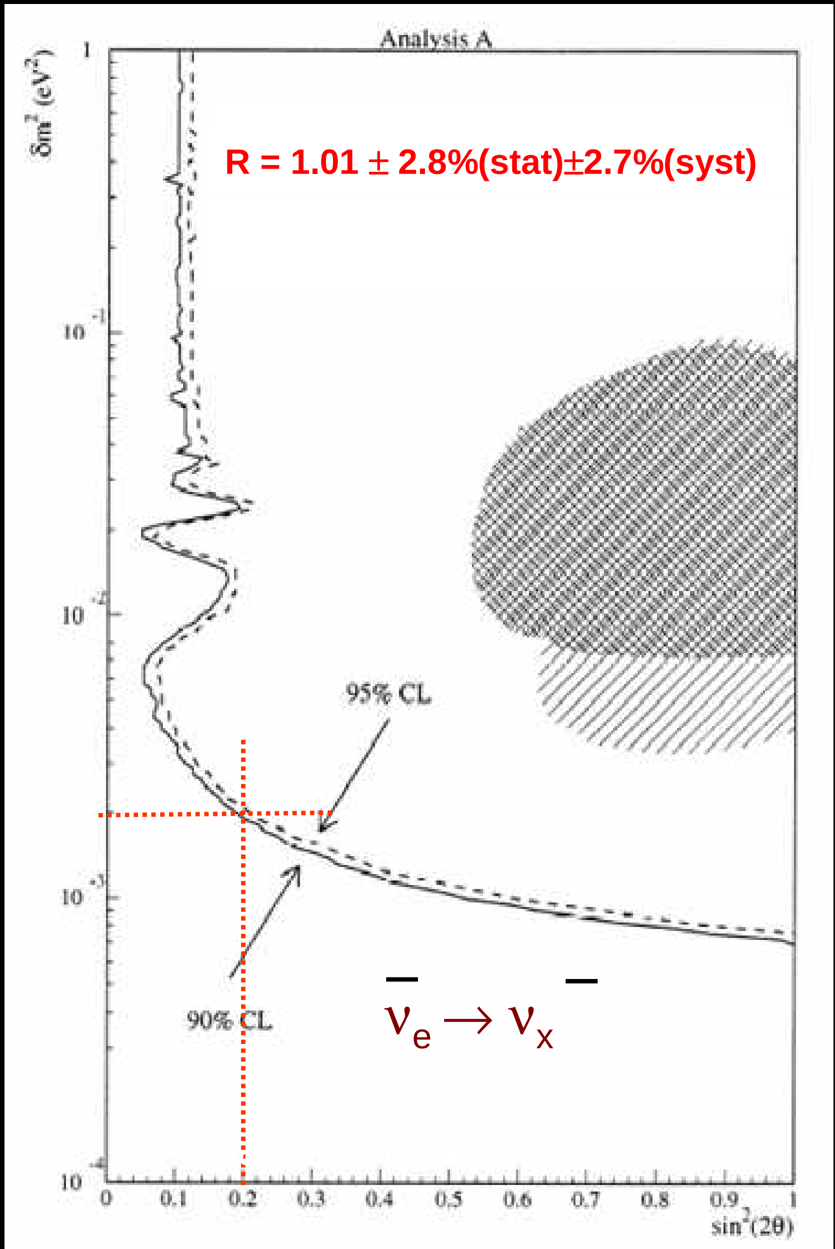
$$+ O(\Delta m_{12}^2 / \Delta m_{13}^2)$$

No θ_{23} ambiquity; No δ–CP effects; No matter effects; Minimal dependence on Δm_{12}^2



Gd-loaded scintillator
$\bar{\nu}_e + p$
n
e^+
p
n
n
μ
μ

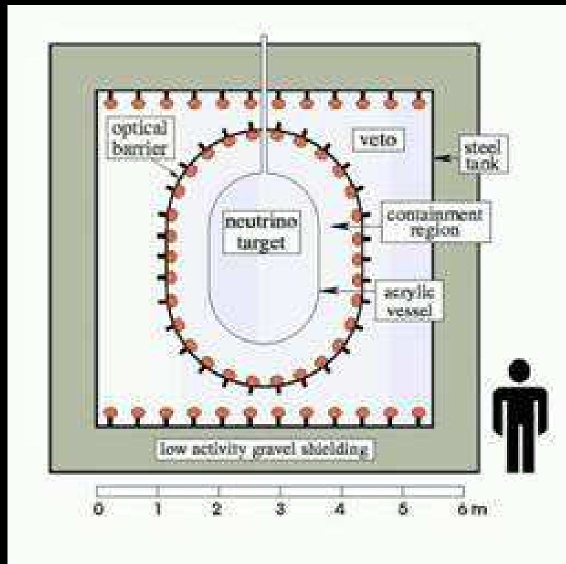
Best current constraint: Chooz



$\bar{\nu}_e \rightarrow \bar{\nu}_e$ (disappearance experiment)

P_{th} = 8.4 GW_{th}, L = 1.050 km, M = 5 t

overburden: 300 mwe

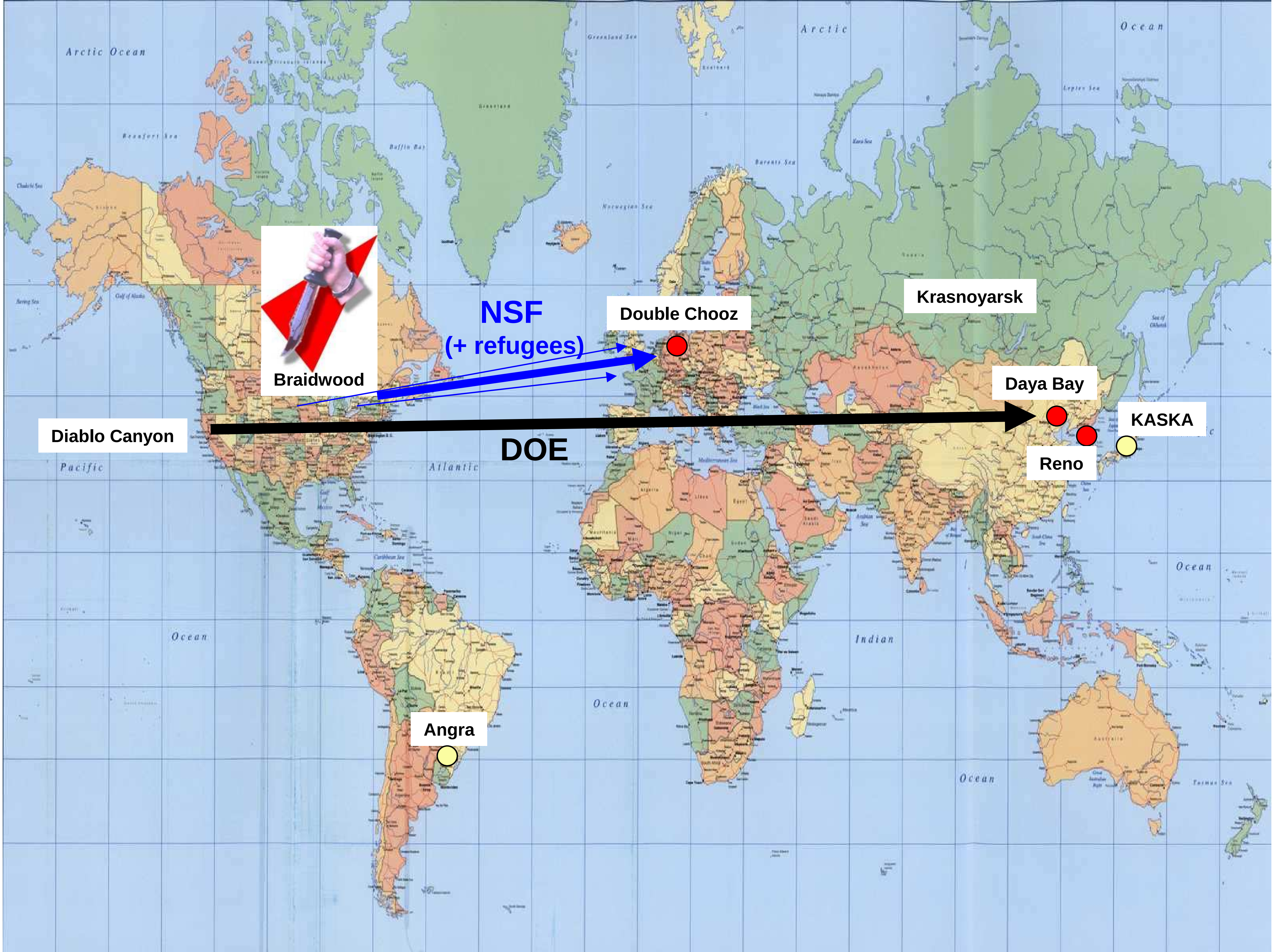


for $\Delta m^2_{atm} = 2\ 10^{-3}\ eV^2$

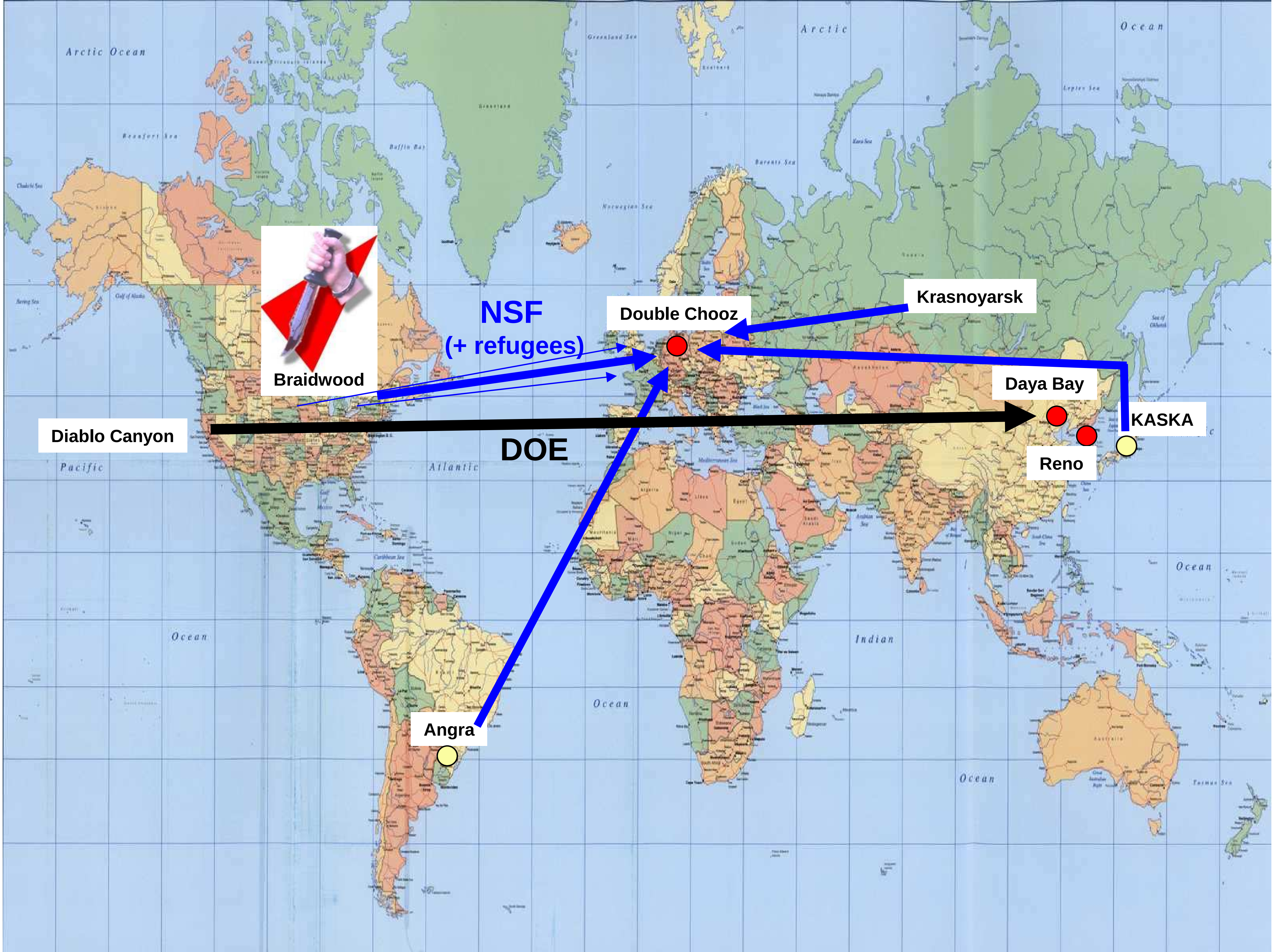
$\sin^2(2\theta_{13}) < 0.2$

(90% C.L)


Krasnoyarsk
Double Chooz
Braidwood
Daya Bay
KASKA
Diablo Canyon
Reno
Angra



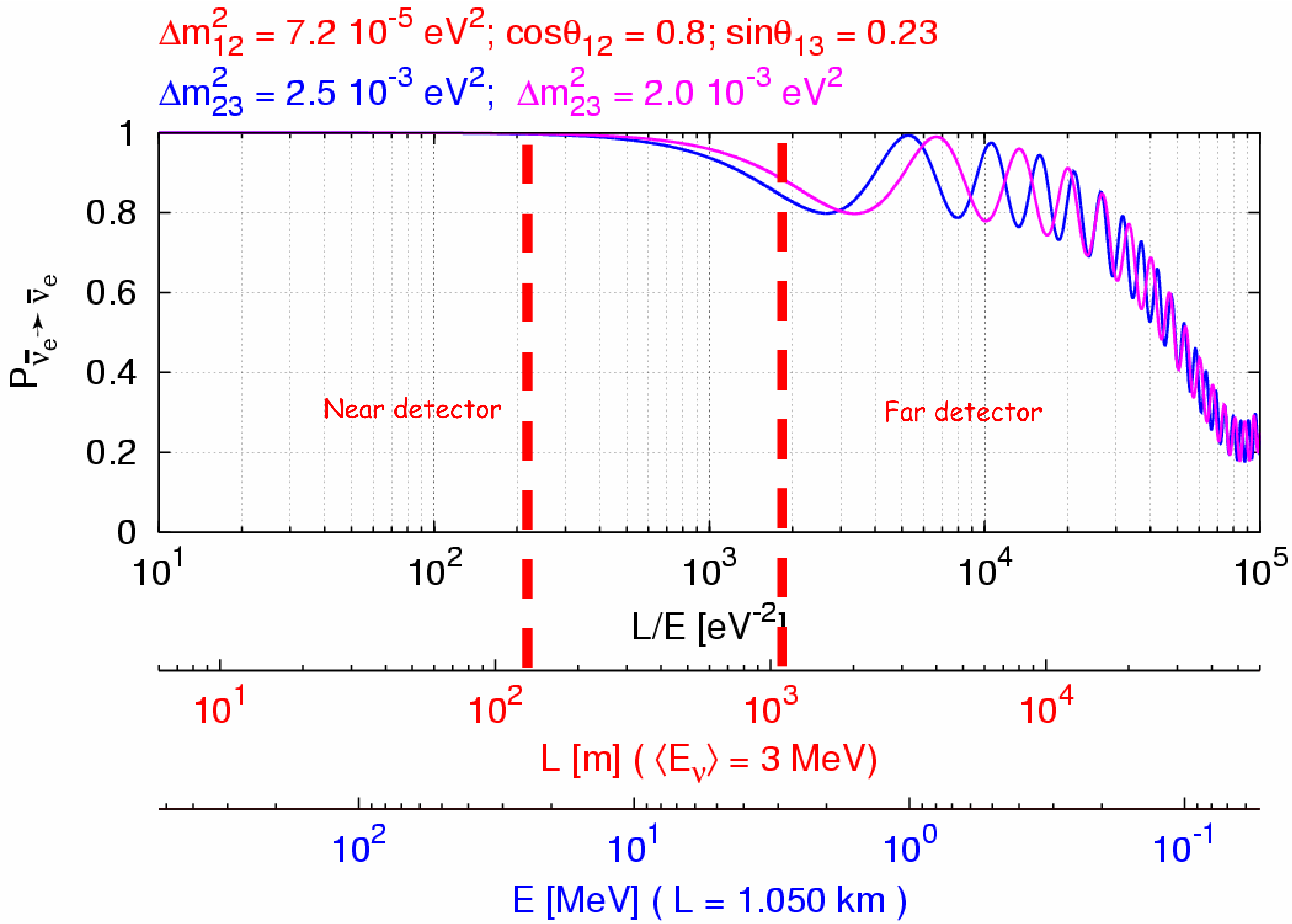
Braidwood
NSF
(+ refugees)
Double Chooz
Krasnoyarsk
Daya Bay
KASKA
Reno
Diablo Canyon
DOE
Angra



NSF
(+ refugees)
Double Chooz
Krasnoyarsk
Braidwood
Daya Bay
KASKA
Diablo Canyon
DOE
Reno
Angra

- France
  - Detector Mechanics
  - Digitization/DAQ
  - Near and Far Laboratory Infrastructure
  - Technical Coordination and detector integration
- Germany
  - Scintillators
  - Purification and fluid handling systems
  - Inner muon veto
  - Level 1 trigger System
- UK (Oxford & Sussex)
  - PMT Concentrators
  - LED Calibration System
- Japan
  - PMTs
- Spain
  - Inner detector Photo detection and mechanics
- Russia
  - Simulation and Calibration
  - Scintillator Development
- USA
  - Front End Electronics
  - Calibration system
  - Slow control system
  - Outer Muon Veto system

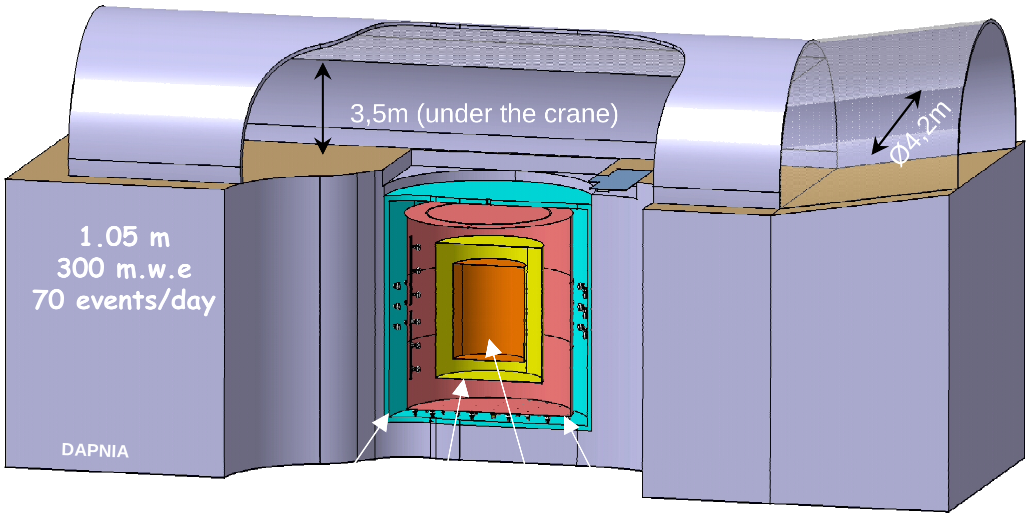
Site in Ardennes, France



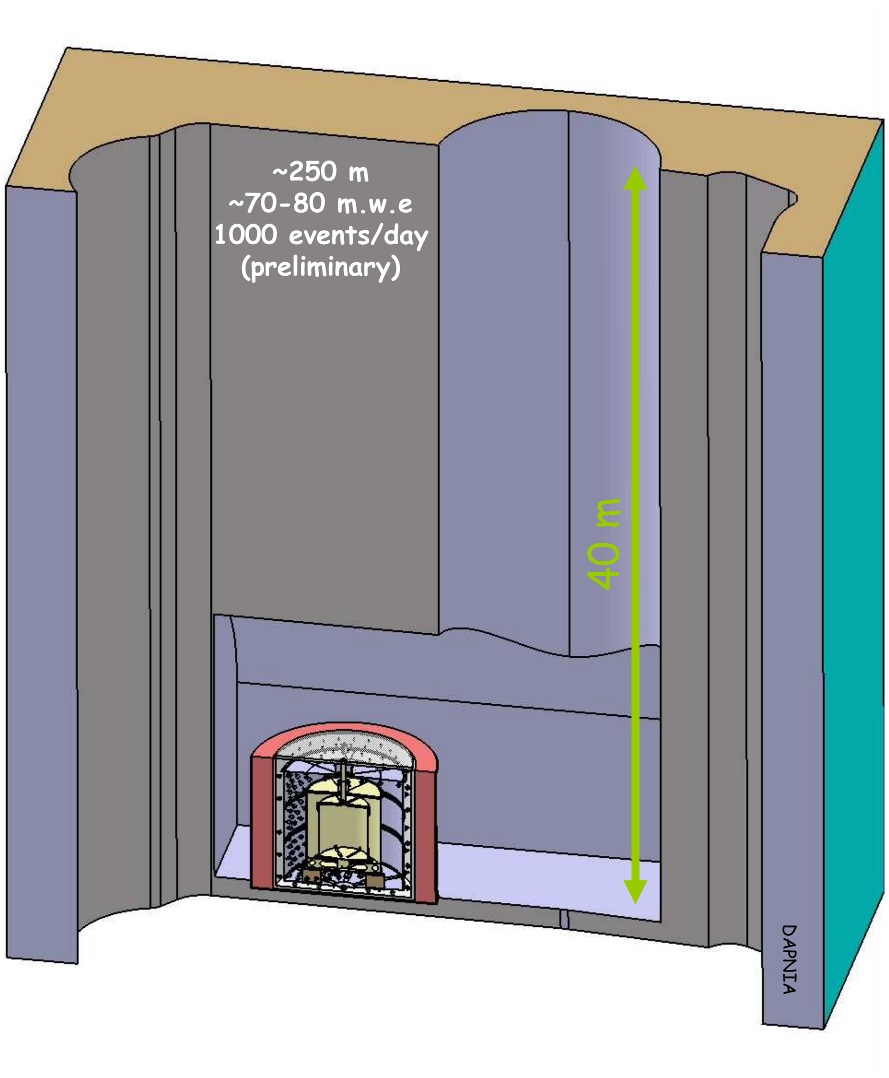
Δm²₁₂ = 7.2 10⁻⁵ eV²; cosθ₁₂ = 0.8; sinθ₁₃ = 0.23
Δm²₂₃ = 2.5 10⁻³ eV²; Δm²₂₃ = 2.0 10⁻³ eV²
Near detector
Far detector
L/E [eV⁻²]
L [m] (⟨E_ν⟩ = 3 MeV)
E [MeV] (L = 1.050 km)

Far site

Start of integration 2006



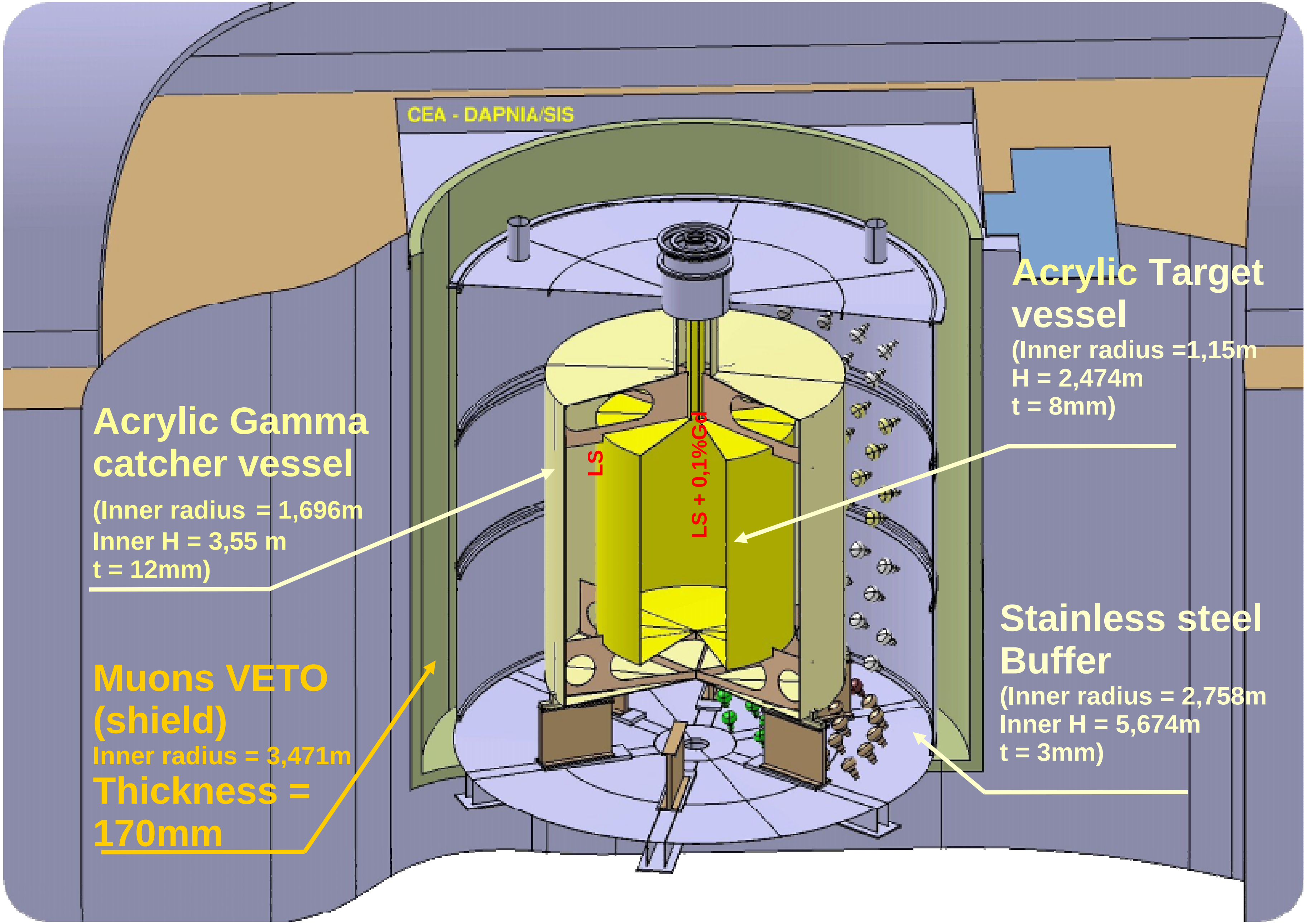
Near site

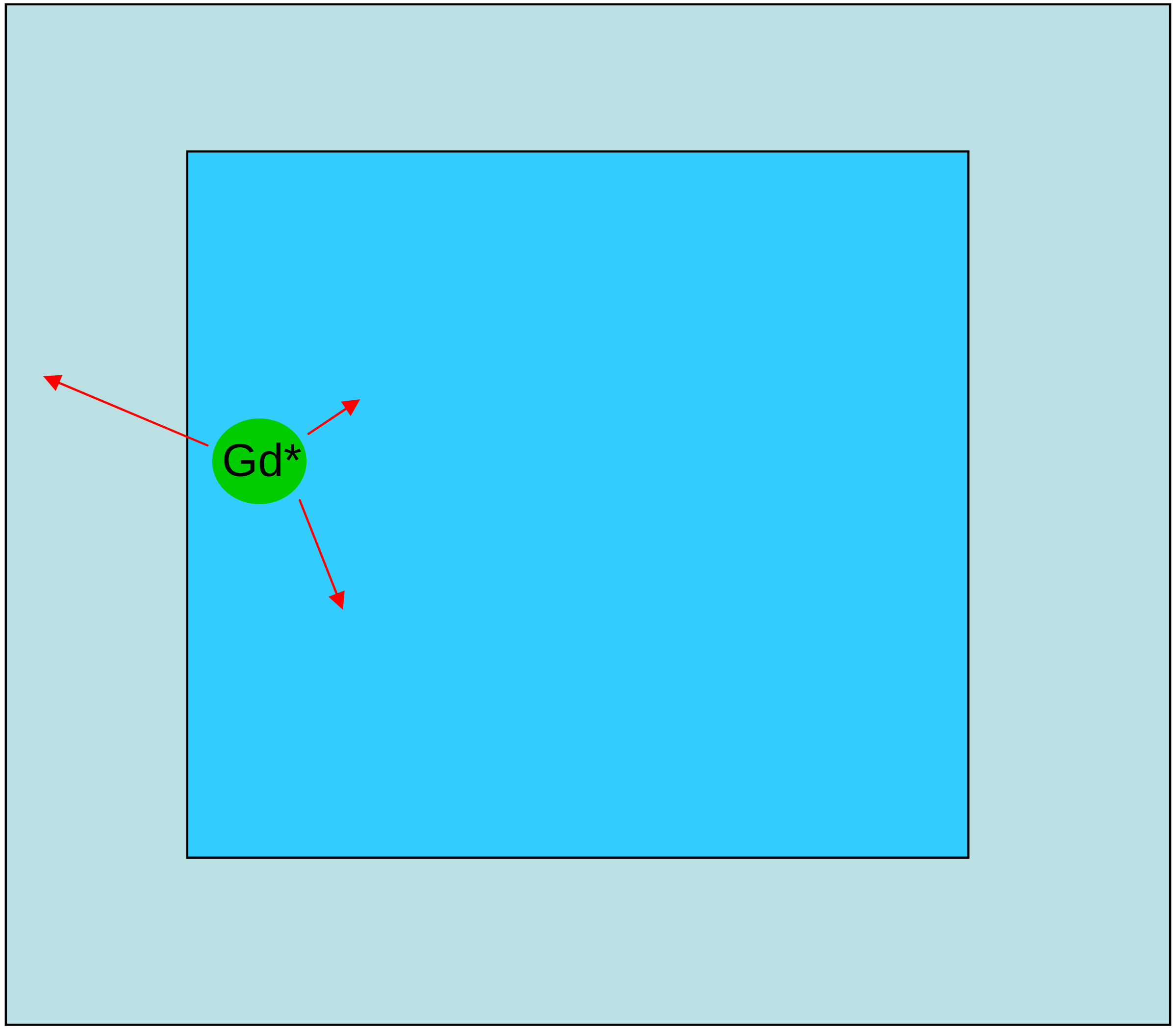


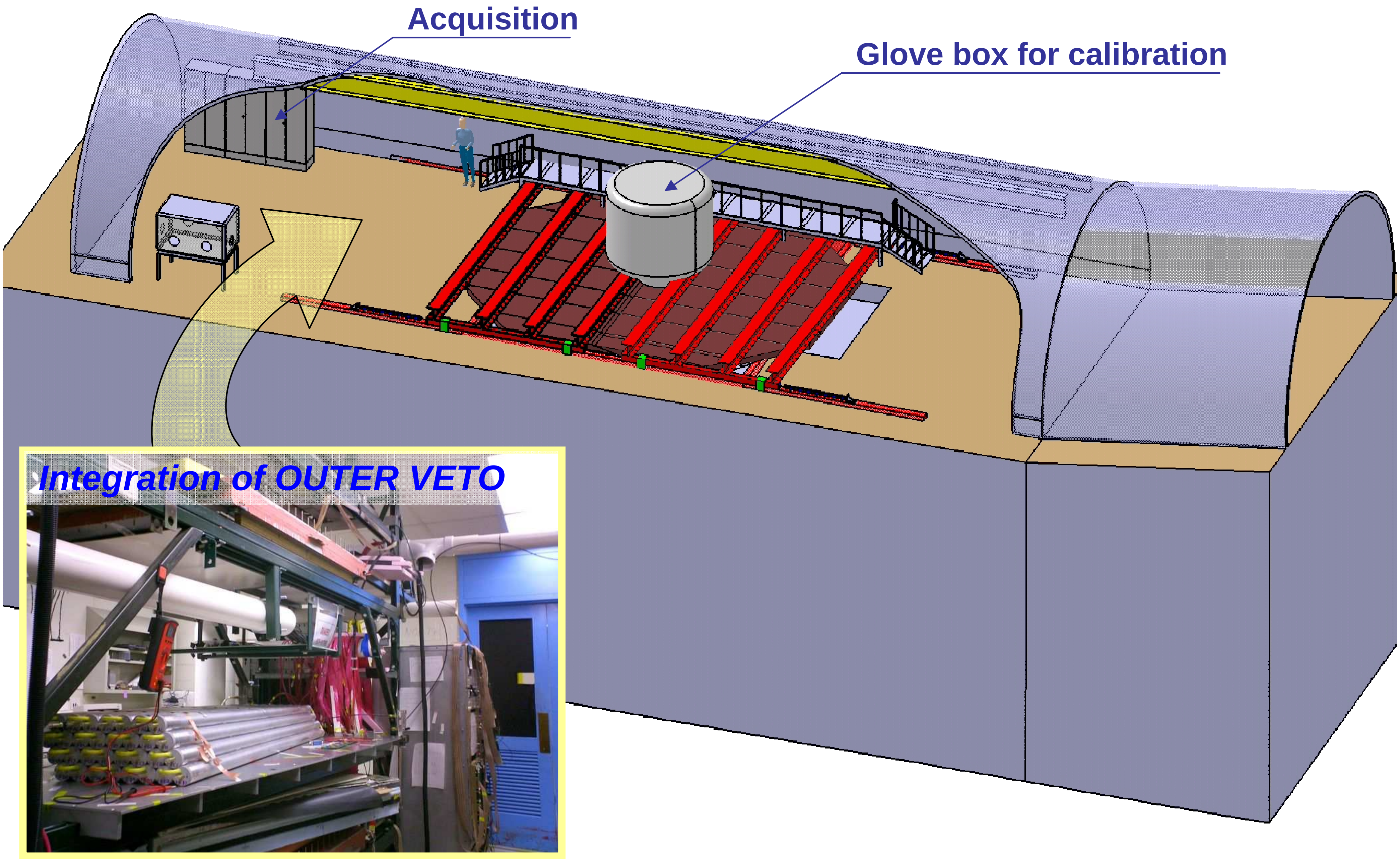
Available end of 2008

Detector layout

Detector dimensions have been frozen

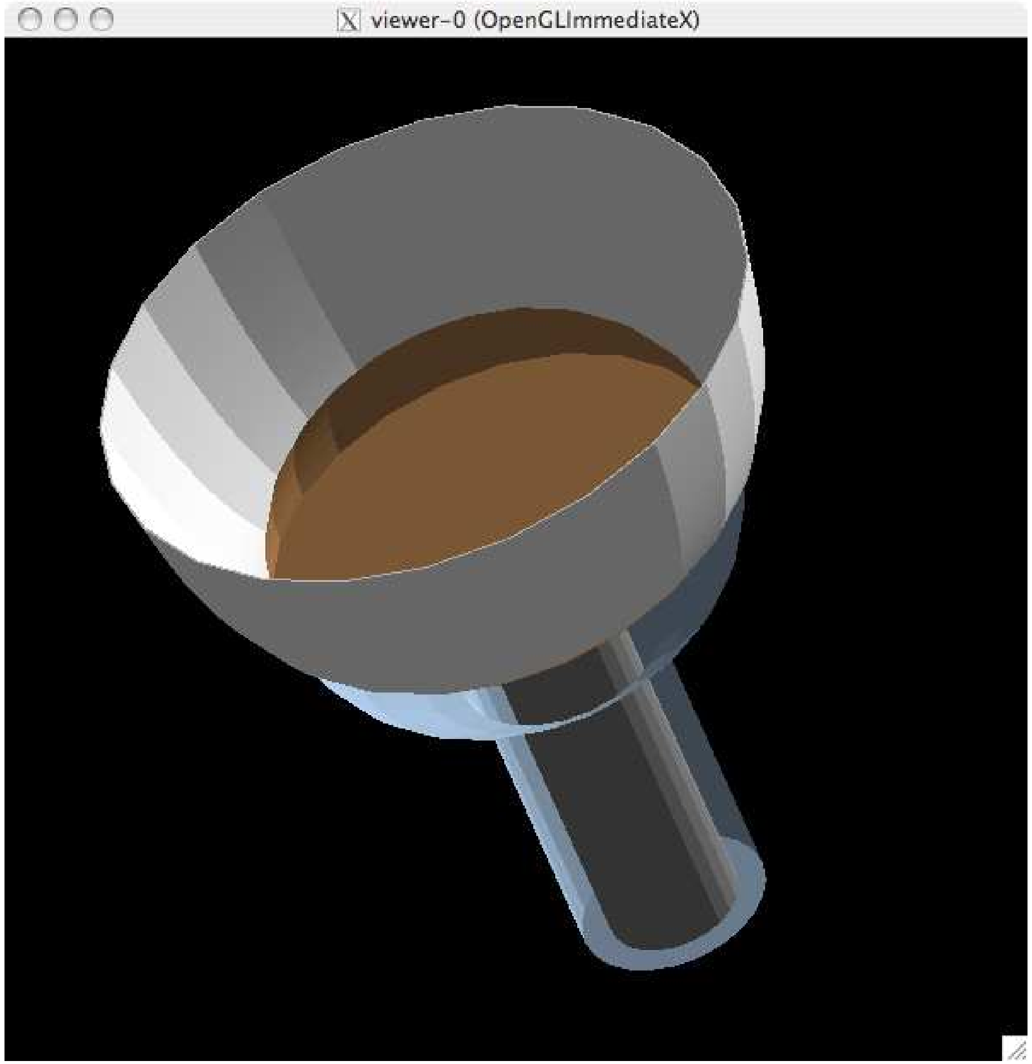


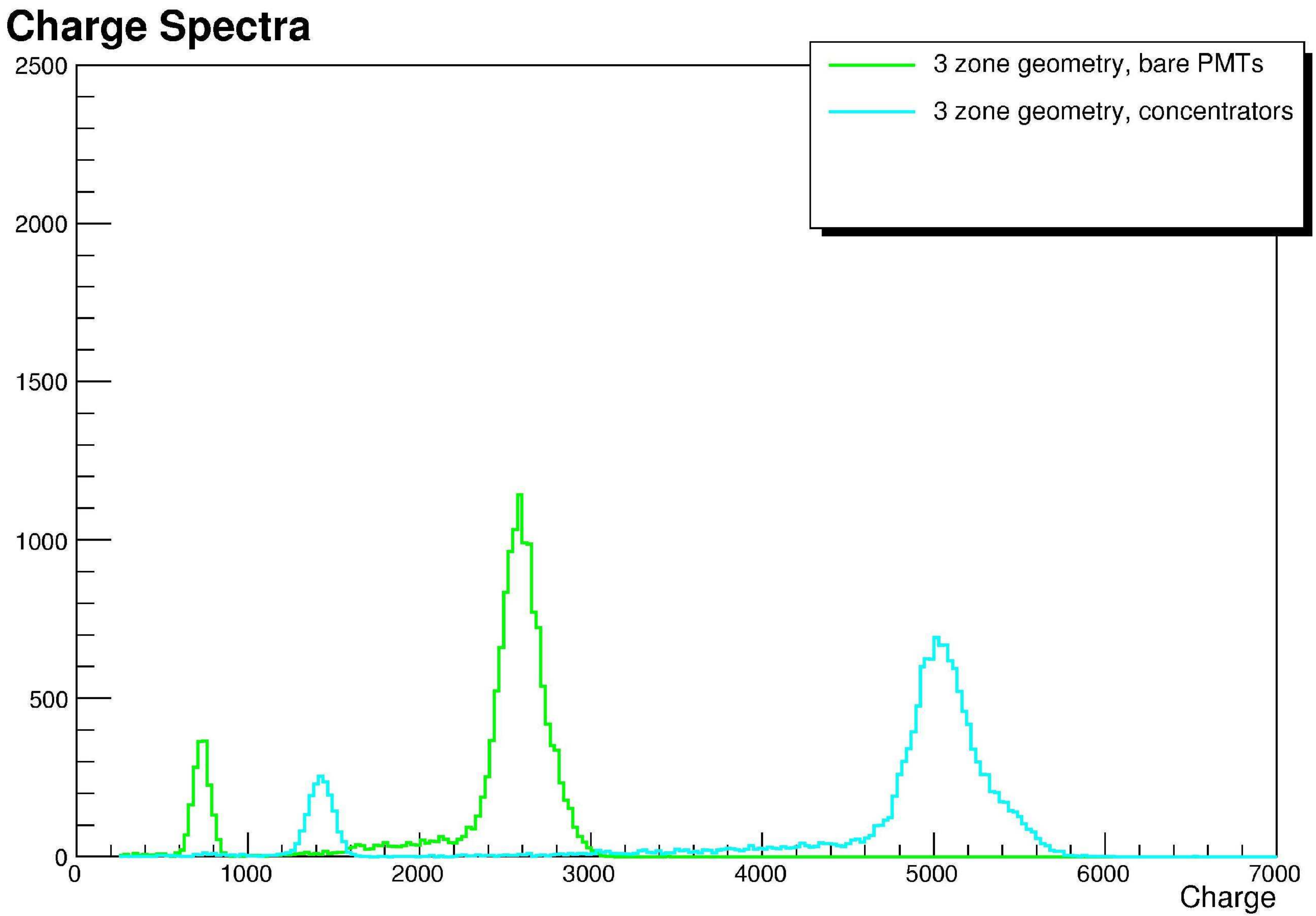

Gd*

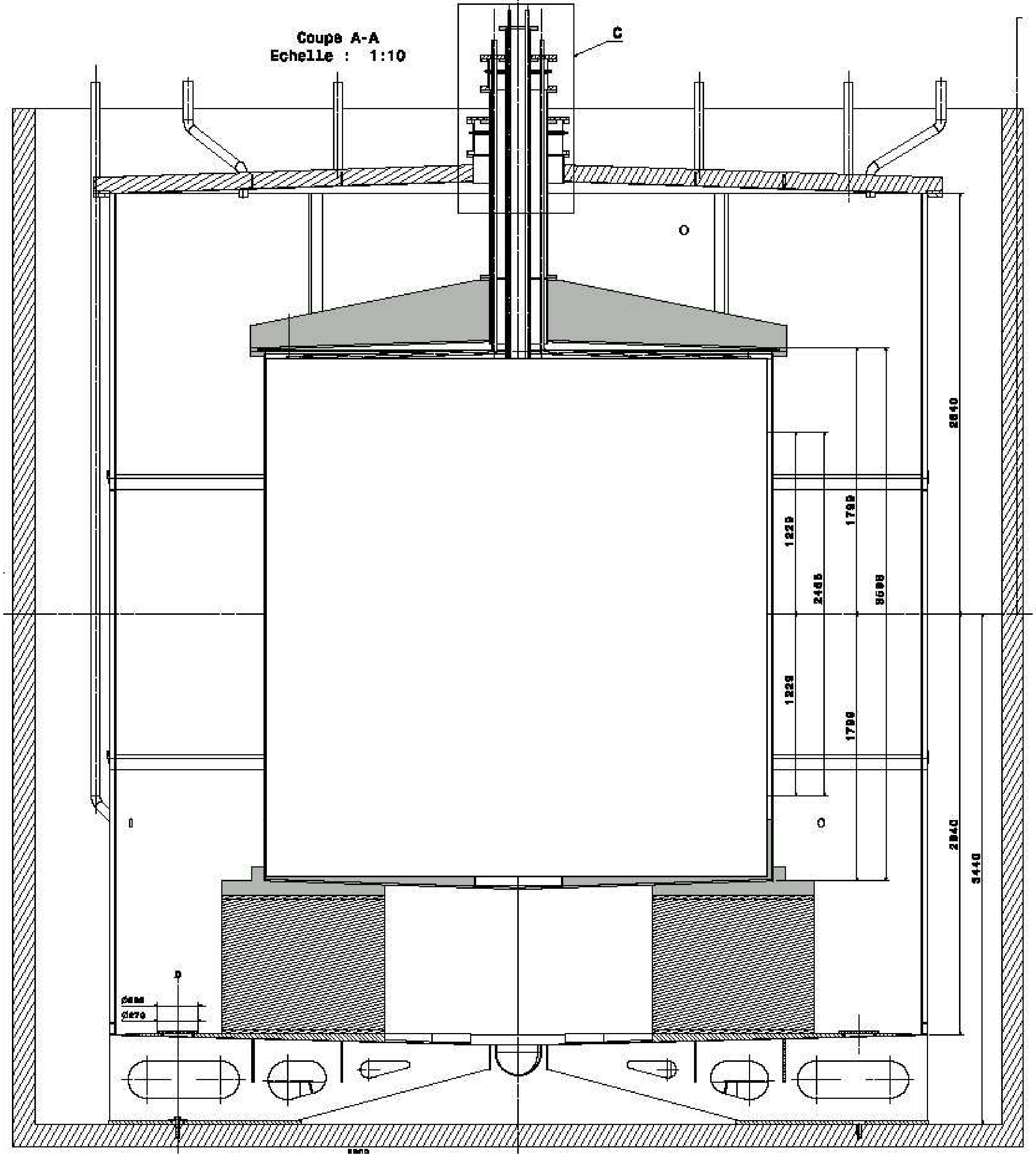

Acquisition
Glove box for calibration
Integration of OUTER VETO

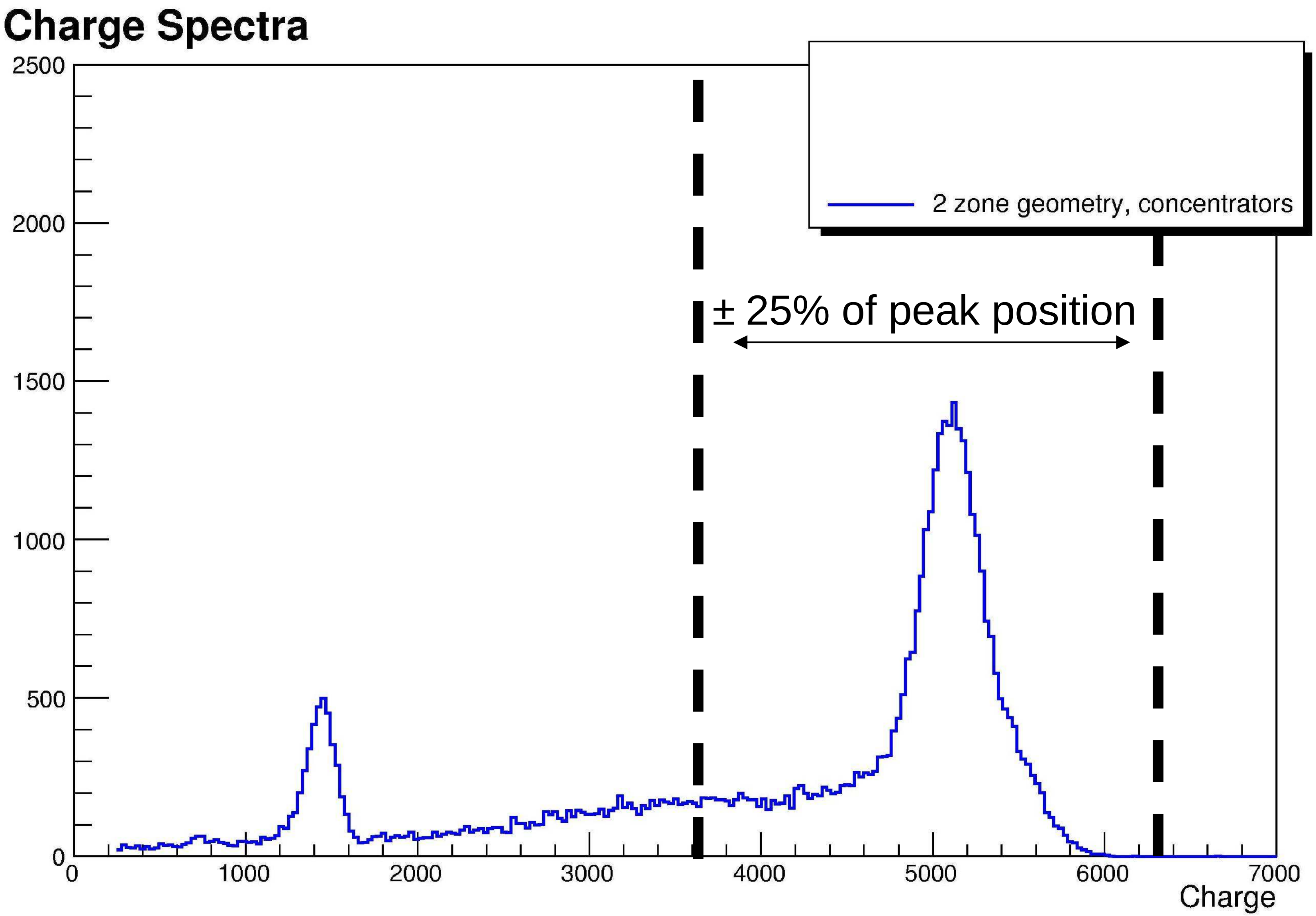
Systematic Errors

		Chooz	Double Chooz	
Reactor-induced	ν flux and σ	1.9 %	<0.1 %	Two "identical" detectors, Low bkg
	Reactor power	0.7 %	<0.1 %	
	Energy per fission	0.6 %	<0.1 %	
Detector - induced	Solid angle	0.3 %	<0.1 %	Distance measured @ 10 cm + monitor core barycenter
	Volume	0.3 %	0.2 %	Same weight sensor for both det.
	Density	0.3 %	<0.1 %	Accurate T control (near/far)
	H/C ratio & Gd concentration	1.2 %	<0.1 %	Same scintillator batch + Stability
	Spatial effects	1.0 %	<0.1 %	"identical" Target geometry & LS
	Live time	few %	0.25 %	Measured with several methods
Analysis	From 7 to 3 cuts	1.5 %	0.2 - 0.3 %	
	Total	**2.7 %**	**< 0.6 %**	


viewer-0 (OpenGLImmediateX)

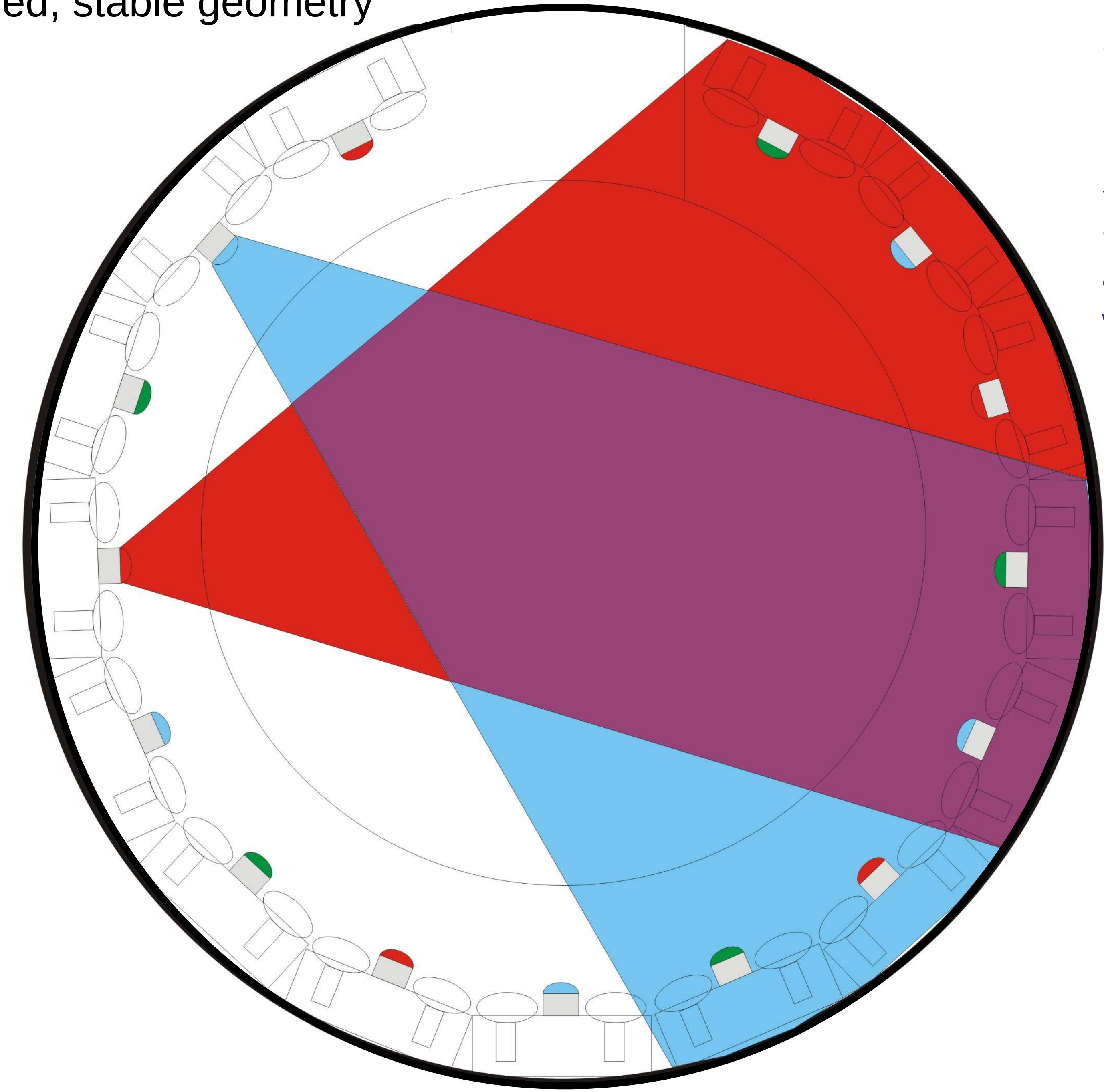

Charge Spectra
3 zone geometry, bare PMTs
3 zone geometry, concentrators
2500
2000
1500
1000
500
0
0
1000
2000
3000
4000
5000
6000
7000
Charge


Coupe A-A
Echelle : 1:10
C
2840
1799
1229
2465
1229
1799
2840
3440
D



Charge Spectra
2 zone geometry, concentrators
± 25% of peak position
0
500
1000
1500
2000
2500
0
1000
2000
3000
4000
5000
6000
7000
Charge

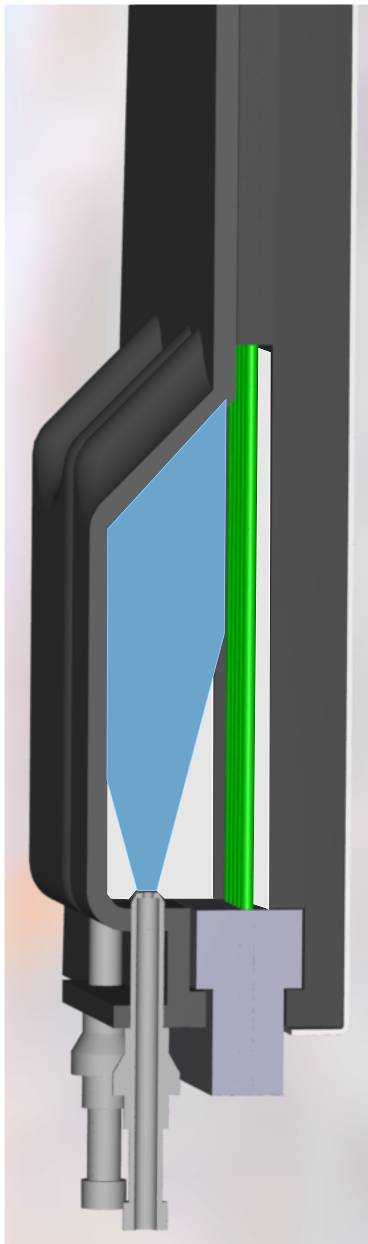
Provides a simple, adaptable system for non-intrusive, *in situ* calibration with elements fixed in a well-defined, stable geometry



Continuously monitor detector stability

Calibrate relative PMT timing

Study optical characteristics at different wavelengths



Expected Milestones

- 2007: assembly of far detector on site
- 2008: data taking with far detector
  - Start of Near lab building
- 2009: assembly of near detector
- 2010: data taking with 2 detectors

Limit @ 90% C.L. for $\sin^2(2\theta)=0$

$\Delta m^2_{atm} = 2.5\ 10^{-3}\ eV^2$ (with 20% uncertainty)