

# Double Chooz

11<sup>th</sup> Pisa Meeting (a l'Isola d'Elba)  
May 2009

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アナタエル カブレラ

CNRS / IN2P3  
Double Chooz @ APC (Paris)

- Why  $\theta_{13}$  matters?
- Why to use reactor vs?
- Double Chooz
- DC strategy...
- DC detector...
- DC readout...
- DC online system...
- What to remember?

Why  $\theta_{13}$ ?

## Neutrino Oscillations means...

- + **Non-degenerate mass spectrum**  $\Rightarrow$  quantum interference
- + **Mixing** in the leptonic sector  $\Rightarrow$  **PMNS** matrix (a la **CKM**)

$$(\nu_e, \nu_\mu, \nu_\tau)^T = \mathbf{U} (\nu_1, \nu_2, \nu_3)^T$$

$$\begin{array}{c}
 \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{array}{c} \text{atmospheric-}\nu: \theta_{23} \\ \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \\ \text{P}(\nu_\mu \rightarrow \nu_\mu) \end{array} \begin{array}{c} \theta_{13} \text{ \& \; dirac-}\delta_{\text{CP}} \\ \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta} & 0 & c_{13} \end{pmatrix} \\ \text{P}(\text{anti-}\nu_e \rightarrow \nu_x) \text{ \& \; P}(\nu_\mu \rightarrow \nu_e) \end{array} \begin{array}{c} \text{solar-}\nu: \theta_{12} \\ \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \\ \text{P}(\nu_e \rightarrow \nu_x) \end{array} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}
 \end{array}$$

PMNS (Unitary & 3x3)  $\Rightarrow$  3 angles & 1 complex phase  $\Rightarrow$  **leptonic CP violation**

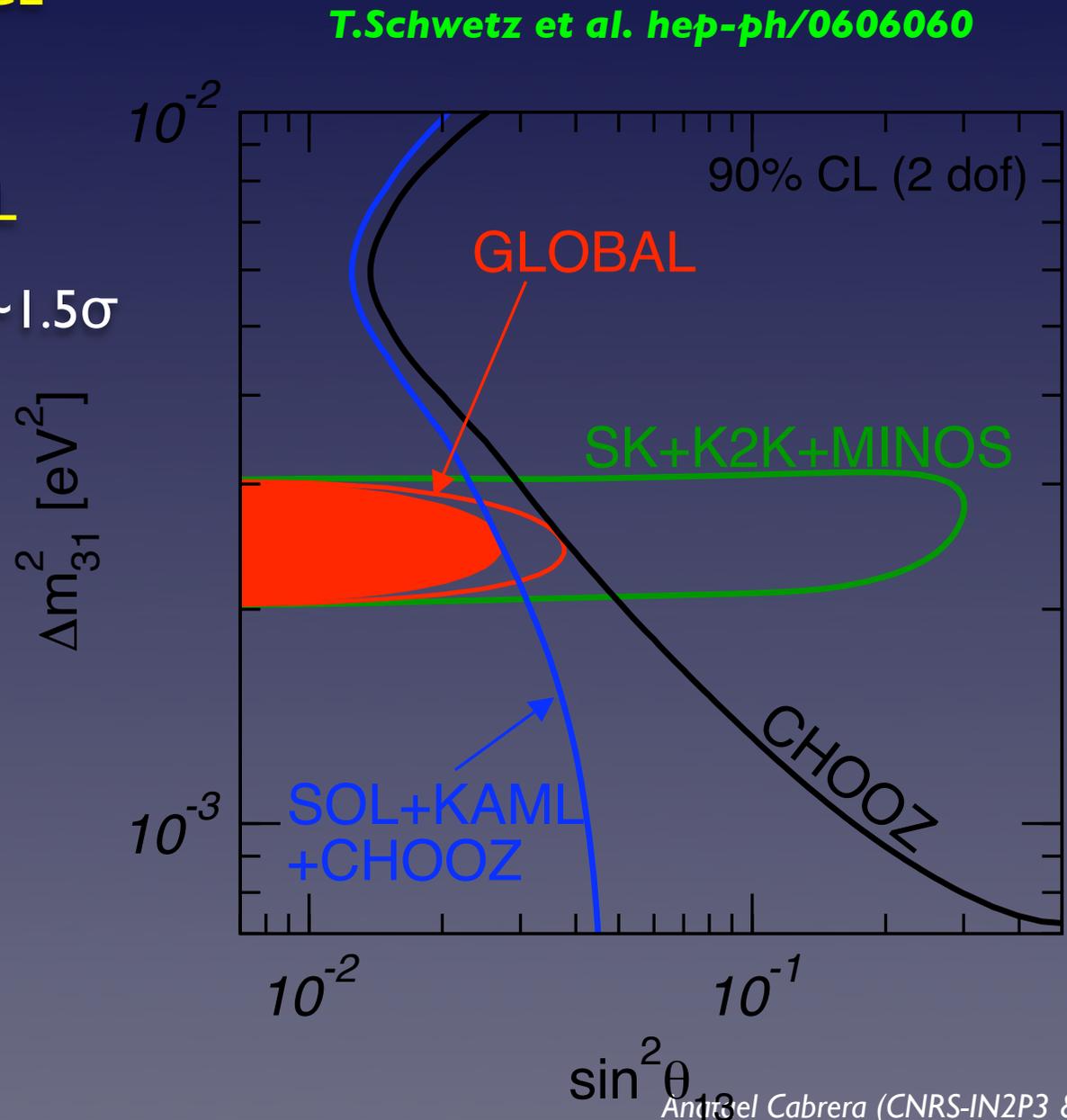
★  $\sin^2(2\theta_{13}) < 0.12-0.20$

CHOOZ only @ 90%CL

★  $\sin^2(2\theta_{13}) < 0.12$

Global Analysis @ 90%CL

★ Bari group Global fit claims  $\sim 1.5\sigma$   
for a non-zero  $\theta_{13}$



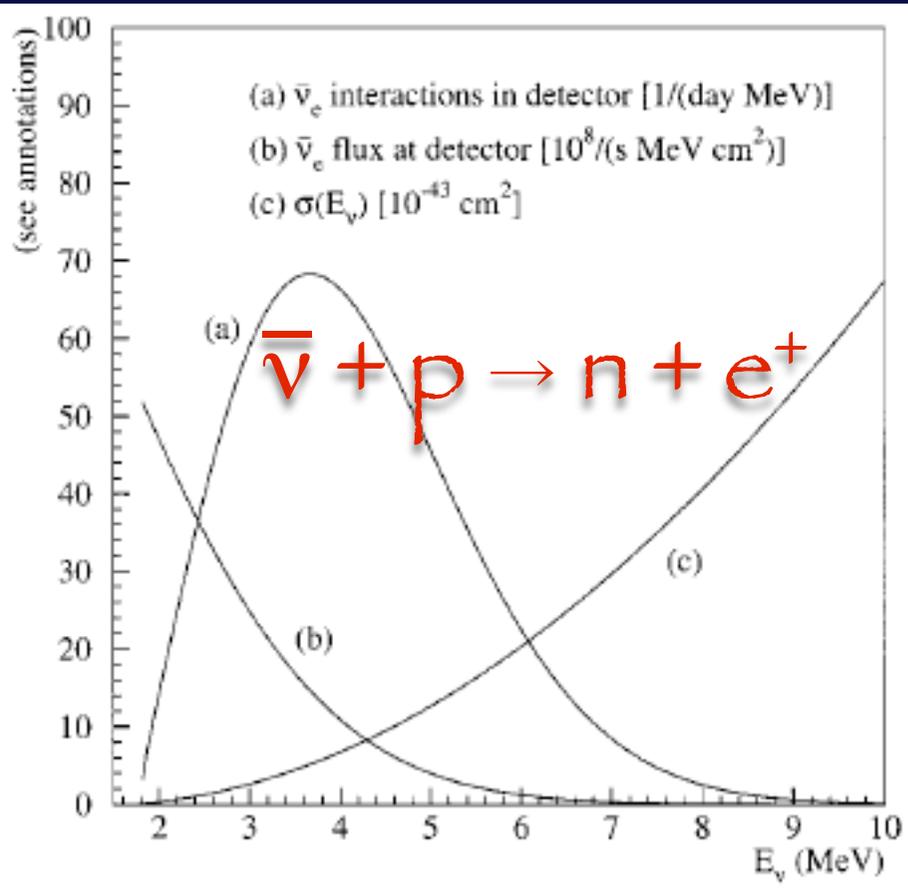
# Why reactors?

Beyond the first observation of neutrinos...

See also talks by...

Marco Battaglieri (INFN-Genova)

Raffaella De Vita (INFN - Genova)

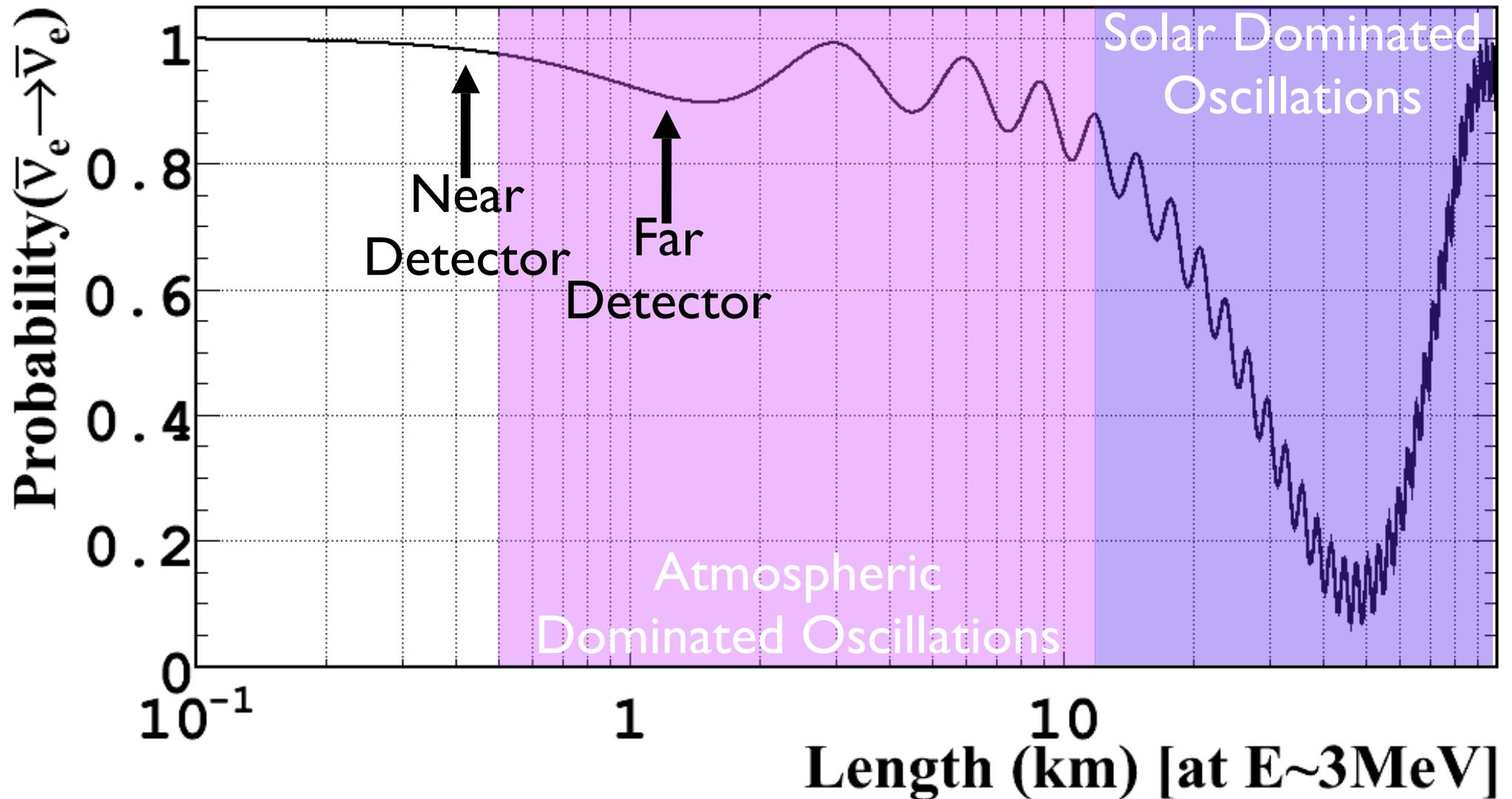


Bemporad, Gratta, Vogl. RMP. 2002

- Spectrum (observable): Flux(E)  $\times$   $\sigma$ (E)
- $\sigma$ (E) highest available within few MeV
- $\sigma$ (E):  $E_{th}=1.8\text{MeV}$  (see only 1/4 vs)
  - slow decays contribute very little
  - low E  $\nu$ : harder for oscillations!
- Flux:  $\Sigma$   $\beta$ -tails from fission debris (many)

- $\nu = e^+$  [prompt] + n-capture on H/Gd [delayed]:
  - $E(\nu)=E(e^+) + \Delta$
  - $E(n_{th}\text{-Gd capture}) \sim 8\text{MeV} \Rightarrow$  energy tag (away from natural radioactivity)
- n-Gd capture  $\tau \sim 30\mu\text{s}$  (CHOOZ)

$$P(\nu_e \rightarrow \nu_e) \sim 1 - \sin^2\theta_{13} \sin^2(\Delta m_{13}^2 L/E) @ E=3\text{MeV}$$



- **copious** (high statistics) and for **free!**
- **excellent  $\delta(E/L)$  resolution** => perfect for  $\nu$ -oscillations
- **short baselines** => no matter effects
- well known  $\sigma(E)$  & no NC contamination
- **BG is oscillation independent** (overburden & radio-purity)
- **trivial multi-detector extrapolation** (scales  $1/L^2$ )
- **many calibration sources @ few MeV** regime
- beams has **richer physics program**: 3x3 neutrino oscillations...
  - **one neutrino oscillation observable**: only  $\theta_{13}$ !!
  - => input from both (if possible) is compelling: synergy

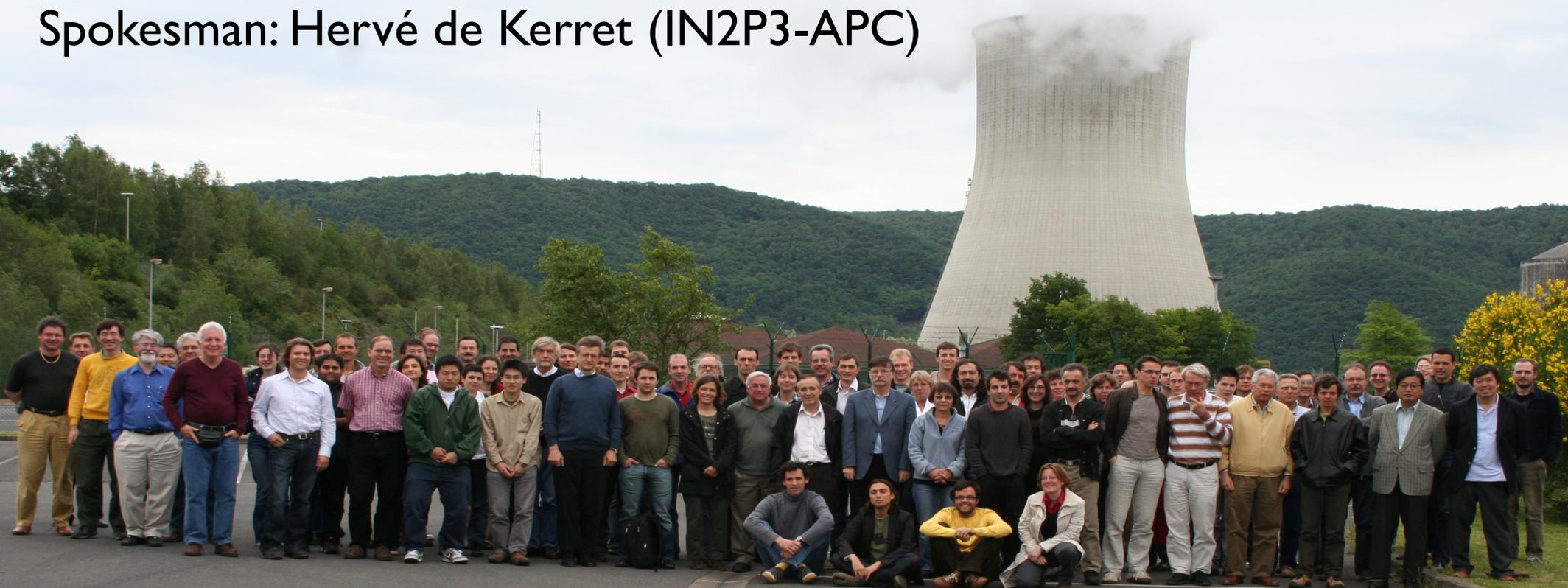
# Double Chooz

# Collaboration



~180 physicists - 35 institutes/universities

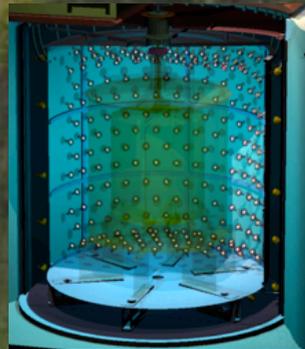
Spokesman: Hervé de Kerret (IN2P3-APC)



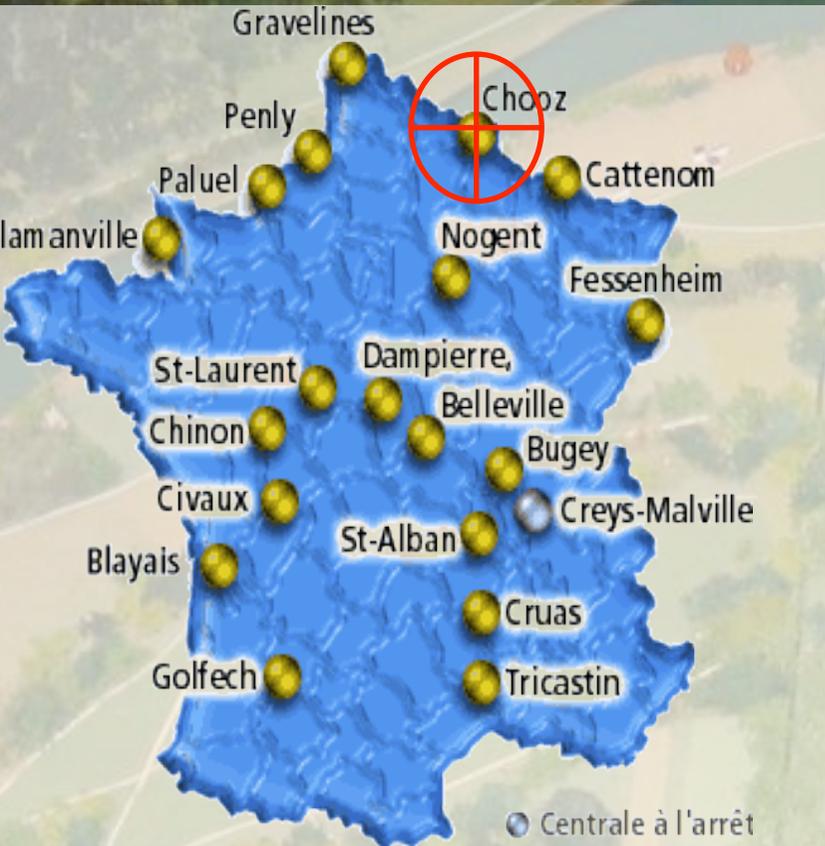
# Designed and R&D completed



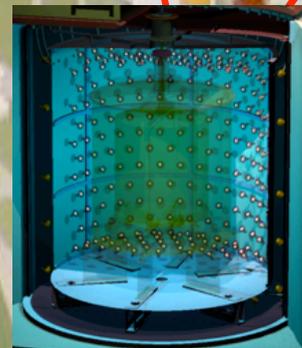
**Far** (1050m)  
50v/day  
1000mwe  
8.2tonnes



Power: 8.5GW<sub>th</sub>



**Near** (400m)  
500v/day  
120mwe  
8.2tonnes



**Building...**



90% C.L. contour if  $\sin^2(2\theta_{13})=0$  &  $\Delta m_{\text{atm}}^2 \approx 2.5 \times 10^{-3} \text{ eV}^2$

## Phases:

DC-I (FD only)

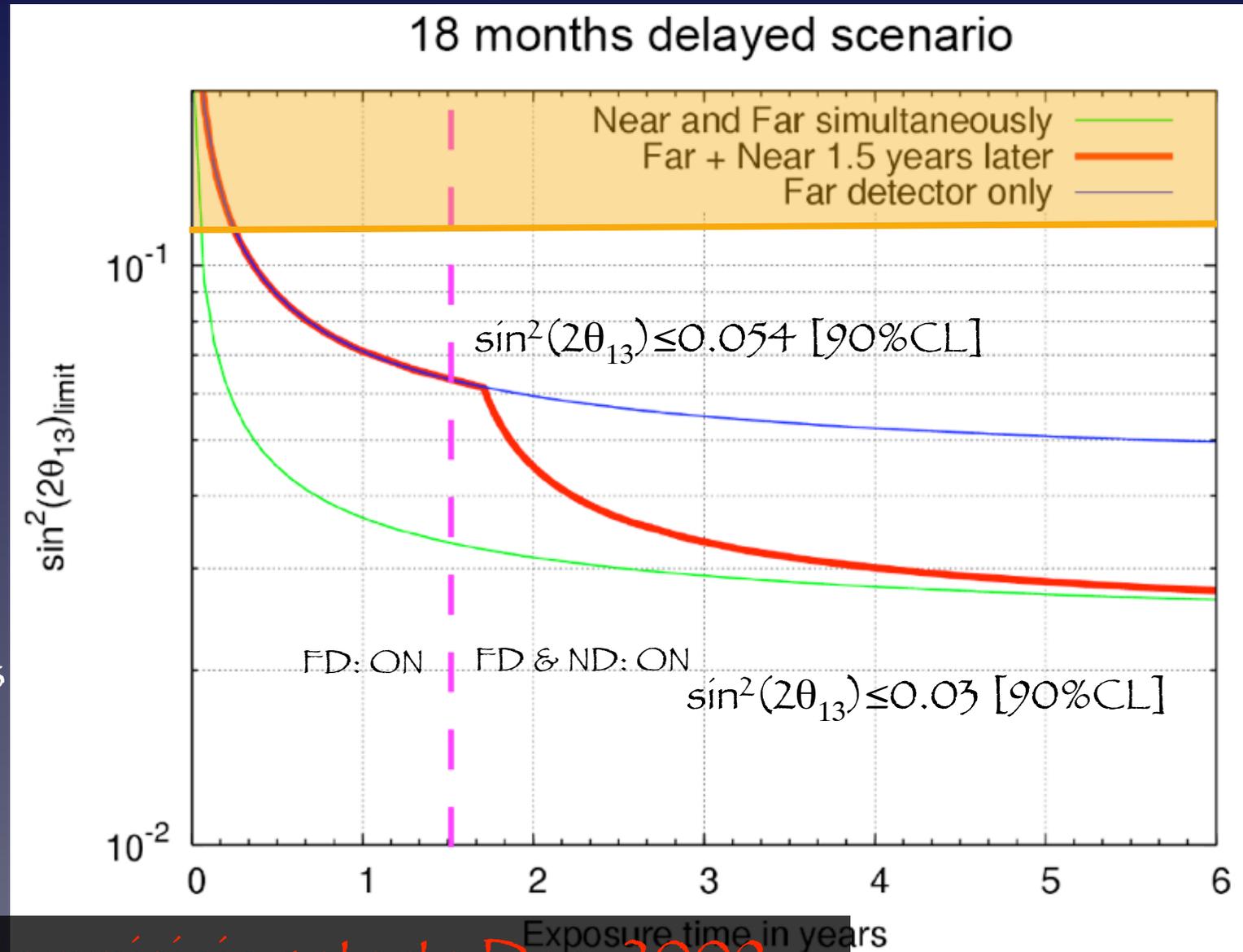
10x stat CHOOZ

(limited by flux  
uncertainty)

DC-II (FD+ND)

rate + shape analysis

(systematics limited)



Commissioning starts Dec. 2009....

**How do we achieve this?**

- flux uncertainty ( $\sim 2\%$ ) goes negligible  $\Rightarrow$  Near Detector
- $S/BG \sim 100$ : huge statistical power  $\Rightarrow$  many reactors
  - large or many? detector  $S/B$  often scales with radius (Volume/Surface)
  - a few reactors may be nice too  $\Rightarrow$  maybe “reactor-off”
- reduce & understand backgrounds in situ (reactor-off is unlikely)
  - optimal detector design, overburden, radio-purity, etc
- reduce & understand experimental systematics: design & calibration
  - inter-detector normalisation:  $\leq 0.6\%$
  - inter-detector energy calibration:  $\leq 2\%$

# $\nu$ candidates...

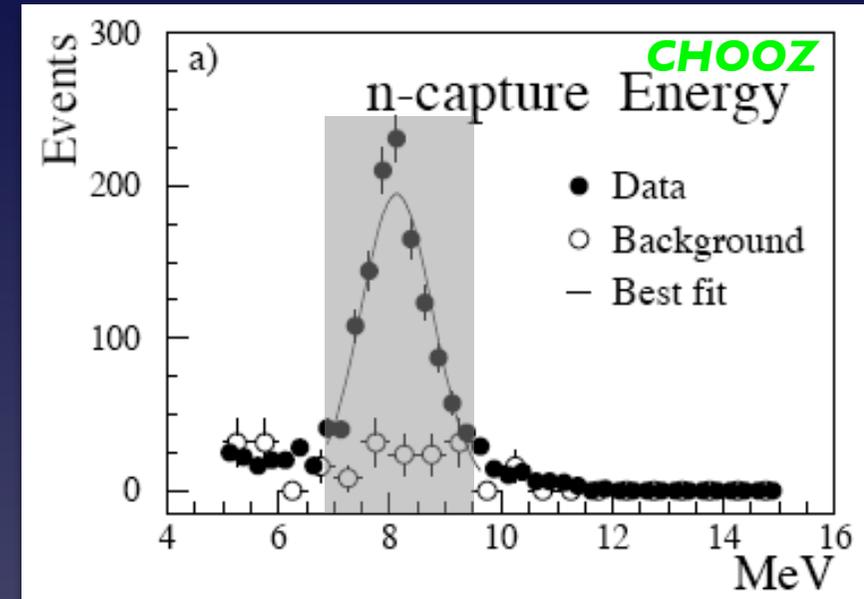
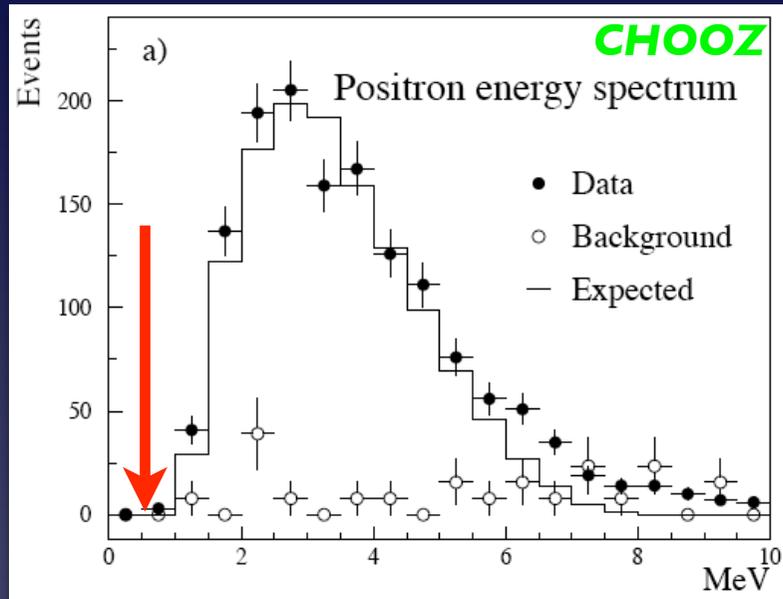
*Not all neutrinos are “useful” for our analysis...*

*...but those that can understand well (low BG and low systematics) and have high precision information about E/L*

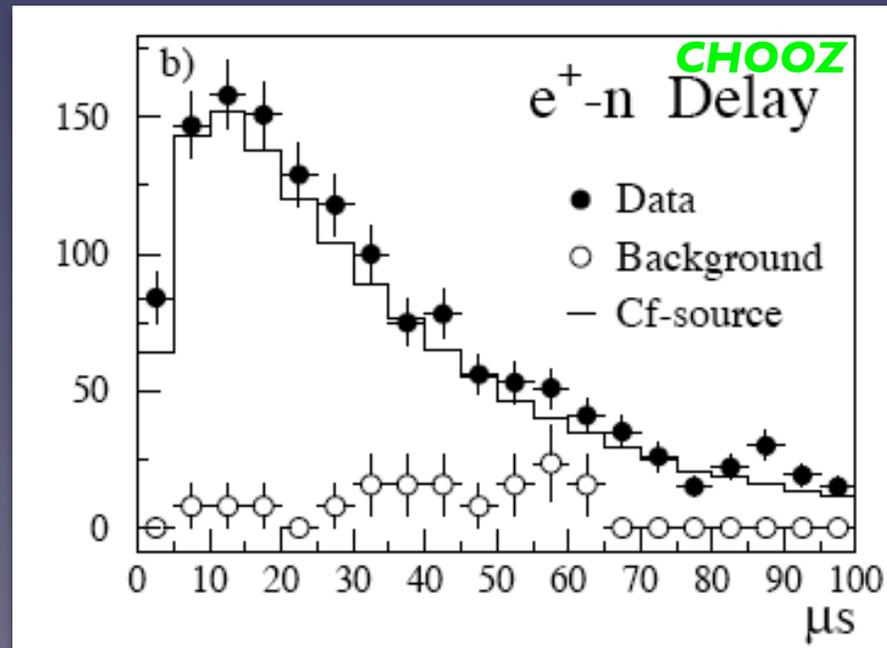
# analysis: 3 cuts (7 cuts at CHOOZ)

e<sup>+</sup> & n energy spectra

Apollonio et al (CHOOZ): hep-ex/0301017



e<sup>+</sup>-n time-correlation



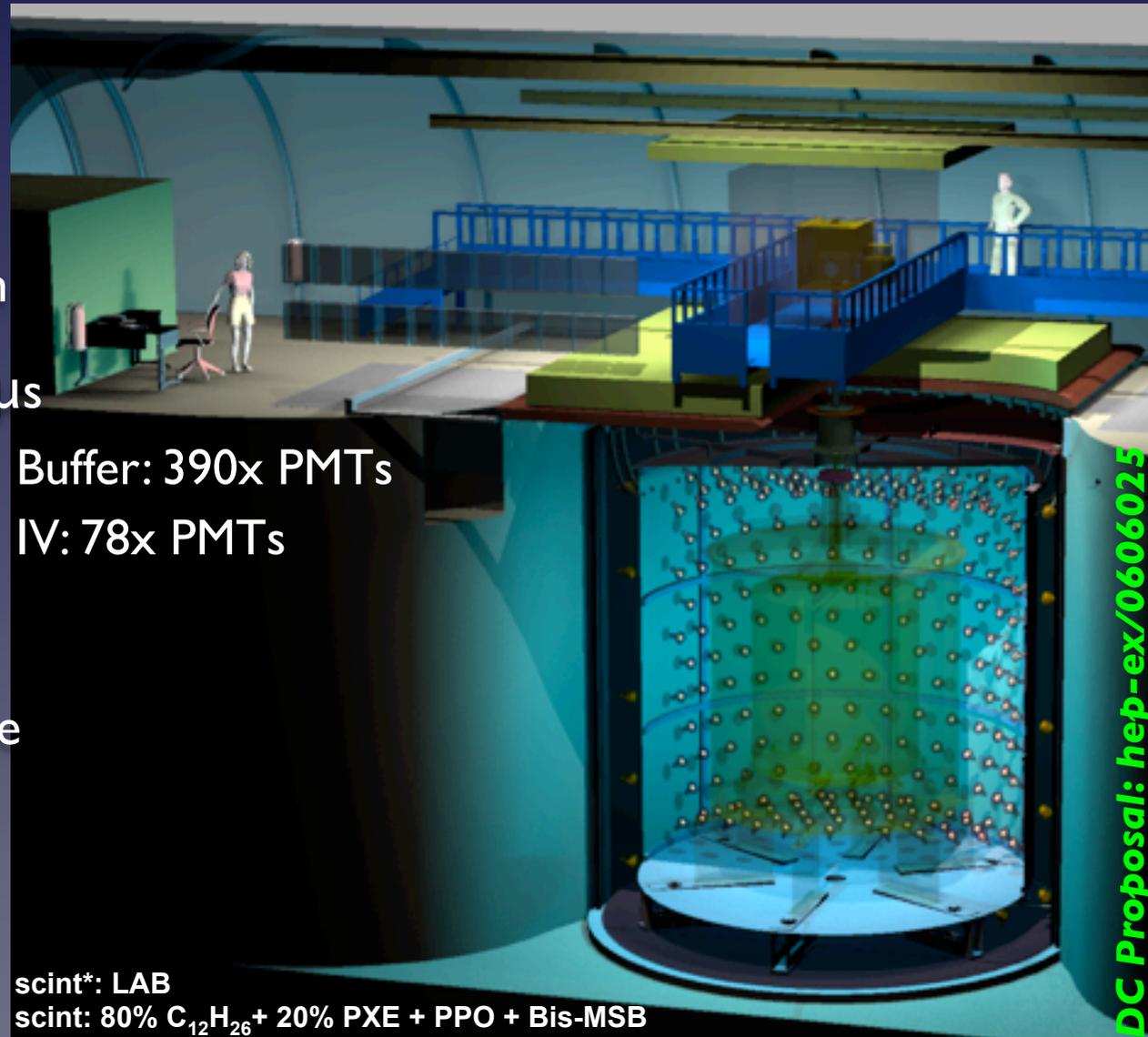
# Background

# BG: any resembling coincidence

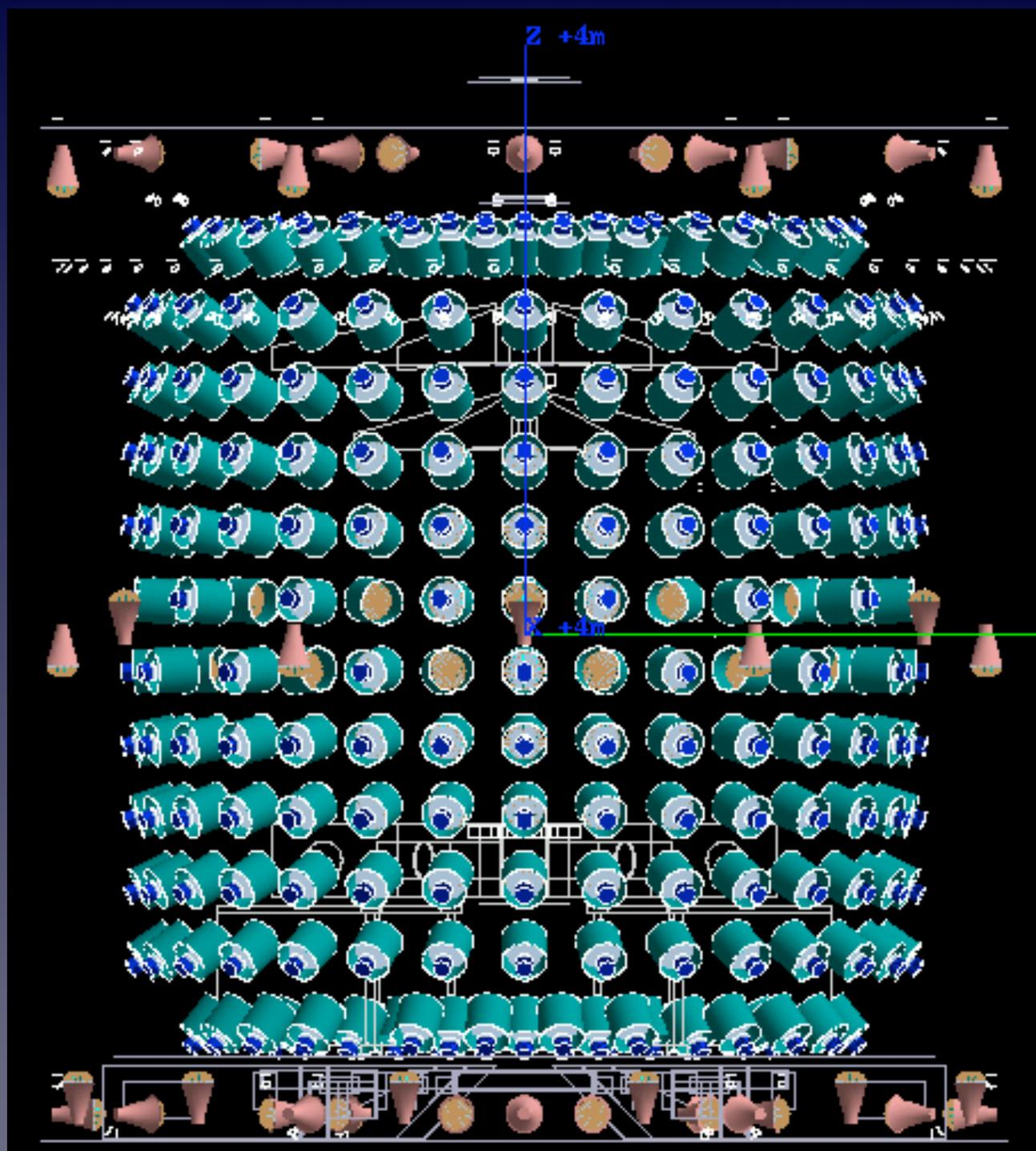
- backgrounds estimates use CHOOZ data
- accidentals BG [measurable in situ to <10%]:
  - e<sup>+</sup>-like: natural radioactivity  $E \leq 2.5 \text{ MeV}$  ( $^{208}\text{Tl}$ )
    - singles: DC <10Hz thanks to shield (CHOOZ: ~130Hz)
  - n-like (from  $\mu$ s):  $\sim 0.01 \text{ Hz}^{\text{DC-FD}} \rightarrow < 1 \text{ Hz}^{\text{DC-ND}}$
- correlated BG [measurable in situ]:
  - fast-n (from  $\mu$ ): reduce by cuts upon  $\mu$  incidence
    - recoil-p<sup>+</sup> (mimic e<sup>+</sup>) & Gd-n upon thermalisation
- cosmogenic BG [KamLAND]:
  - long-lived (~order ms)  $\beta$ -n decaying isotopes: Li & He (spallation products)

$\theta_{13}$ -LAND

- **Pit:** 7m x 7m (FD: CHOOZ lab) =>  $\theta_{13}$ -**LAND must...**  
max. fiducial volume cylinder
  - \* inter-detector comparison systematic < 1%
  - \* radio-purity (>> Borexino though)
- **Target:** acrylics + scint & Gd (1%)  
=> n-Gd interaction region
- **$\gamma$ -Catcher:** acrylics + scint => calorimetry containment
- **Buffer:** oil no scint => isolation
- **Inner-Veto:** scint\* => tagged  $\mu$ s and fast-n
- **Outer-Veto:** scint-strips (a la MINOS) => tagged near-by  $\mu$ s
- **$\gamma$ -Shield:** 15cm steel => reduce rock- $\gamma$ s (singles)
- **Glove-Box** => calibration apparatus contamination-less



## DC “naked”... (MC’s view)

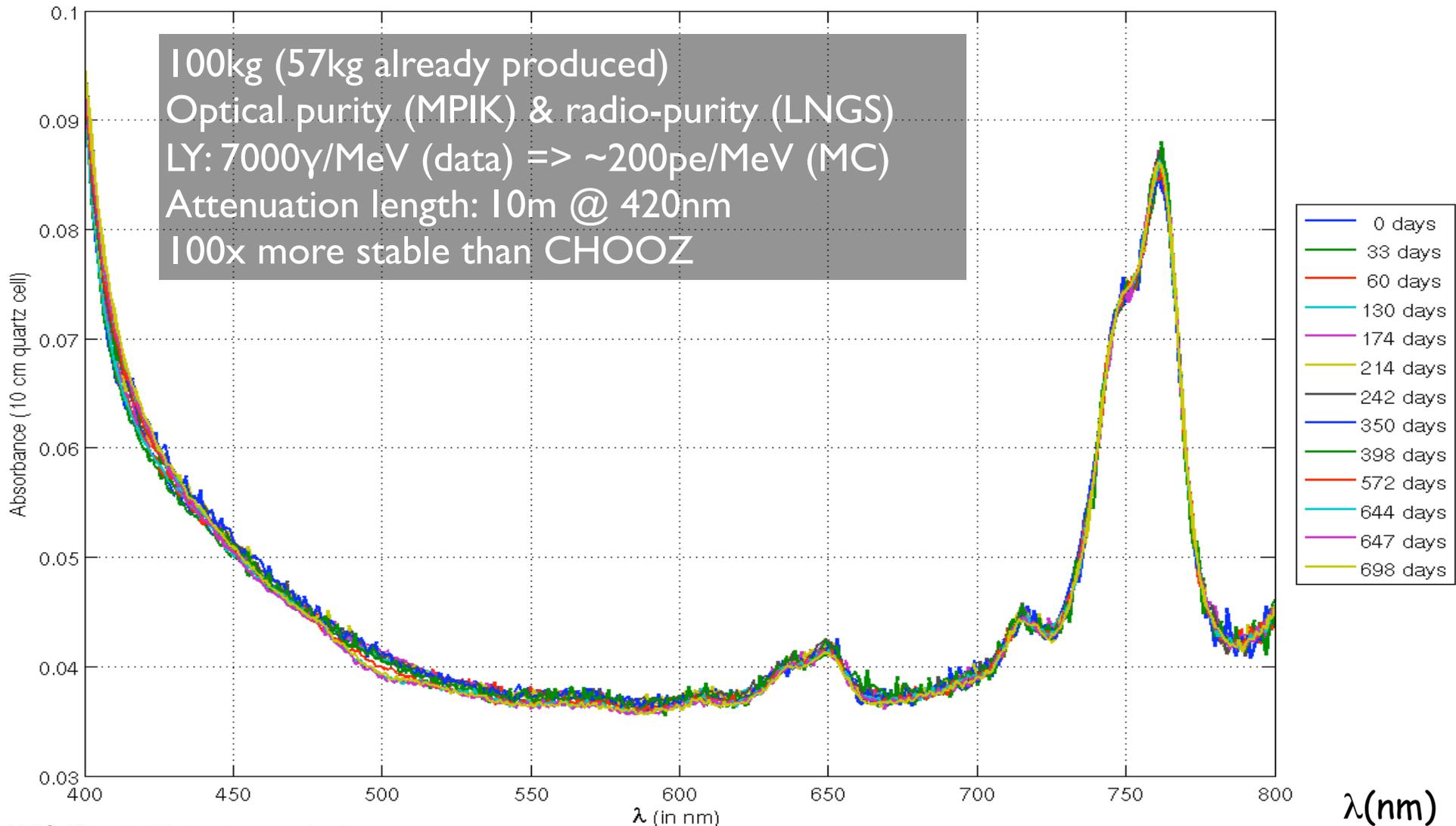


- **Multi-Identical detectors:**
  - relative comparisons of detectors: reduce systematics (flux & detector)
- **Good energy measurement:**  $e^+$  and  $n$  (signal & BG)
  - selection relies on energy cuts to identify  $n$ -Gd capture candidates
  - resolution enough to spectral analysis
- **Good timing:**
  - resolution enough to reconstruct position (ToF):  $O(1\text{ns})$  level
  - help the quality of the energy calibration
- **Good lifetime** (no deadtime DAQ):
  - study detector activity after muon (huge energy deposition)
- **Stability** (detector should run for long time):
  - stable scintillator (limiting factor for CHOOZ)
  - good calibration: characterise time evolution (readout & mechanics)

# Gd doped liquid scintillator

## Liquid Scintillator: 80% Dodecane + PXE 20% + 0.1%Gd

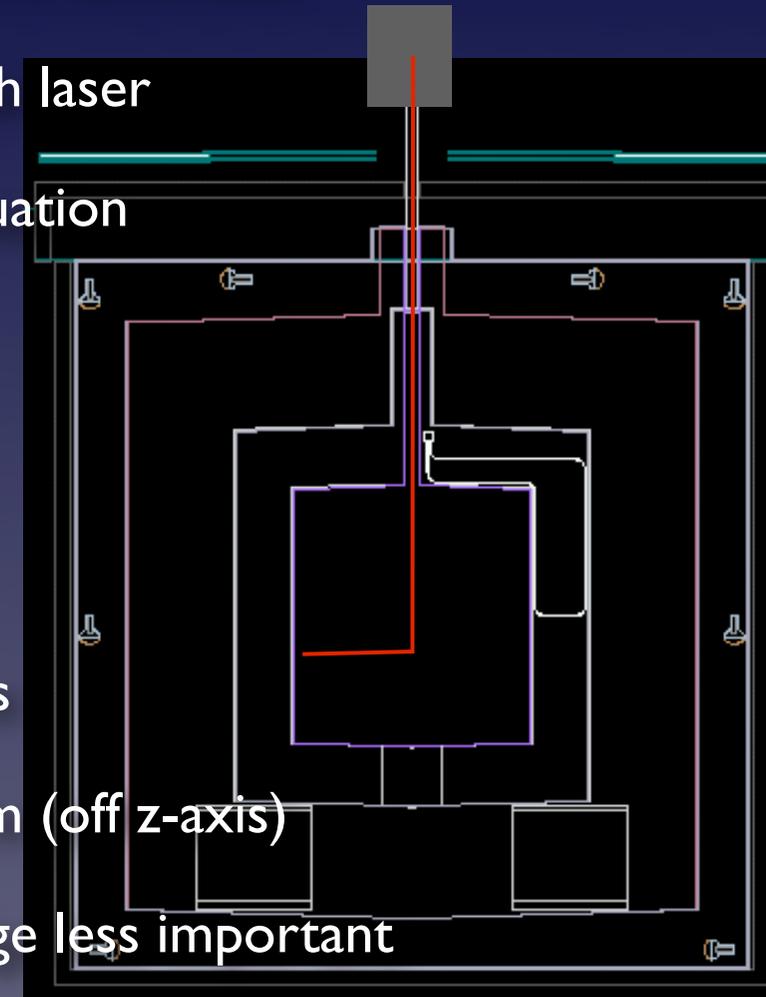
Gd-DPM @ 20 °C (no fluors - no cell correction)



# calibration

# calibration (a few words)

- **light sources (embedded: non-intrusive):** LED in ID and IV
  - monitor stability of readout (timing, gain) and scintillator
- **light sources (deployed):** LED, Red-ish laser & Blue-ish laser
  - PM gain, timing, scintillator stability & attenuation
- **radioactive source:** energy scale
  - $\text{Cs}^{137}$ ,  $\text{Na}^{22}$ ,  $\text{K}^{40}$ ,  $\text{Co}^{60}$ , etc
- **n-sources:** n capture on Gd (study efficiencies)
  - Cf(252), AmBe => untagged/tagged sources
- **3D calibration strategy:** along z-axis & articulated arm (off z-axis)
- 2 detectors => calibration source absolute knowledge less important
  - same source response comparison ND and FD (cancel some systematics)
- MC-calibration interplay critical for systematic estimation



**readout & online**

# readout: one channel

Integration validation system  
(Vertical Slice @ APC)

## Trigger Rate

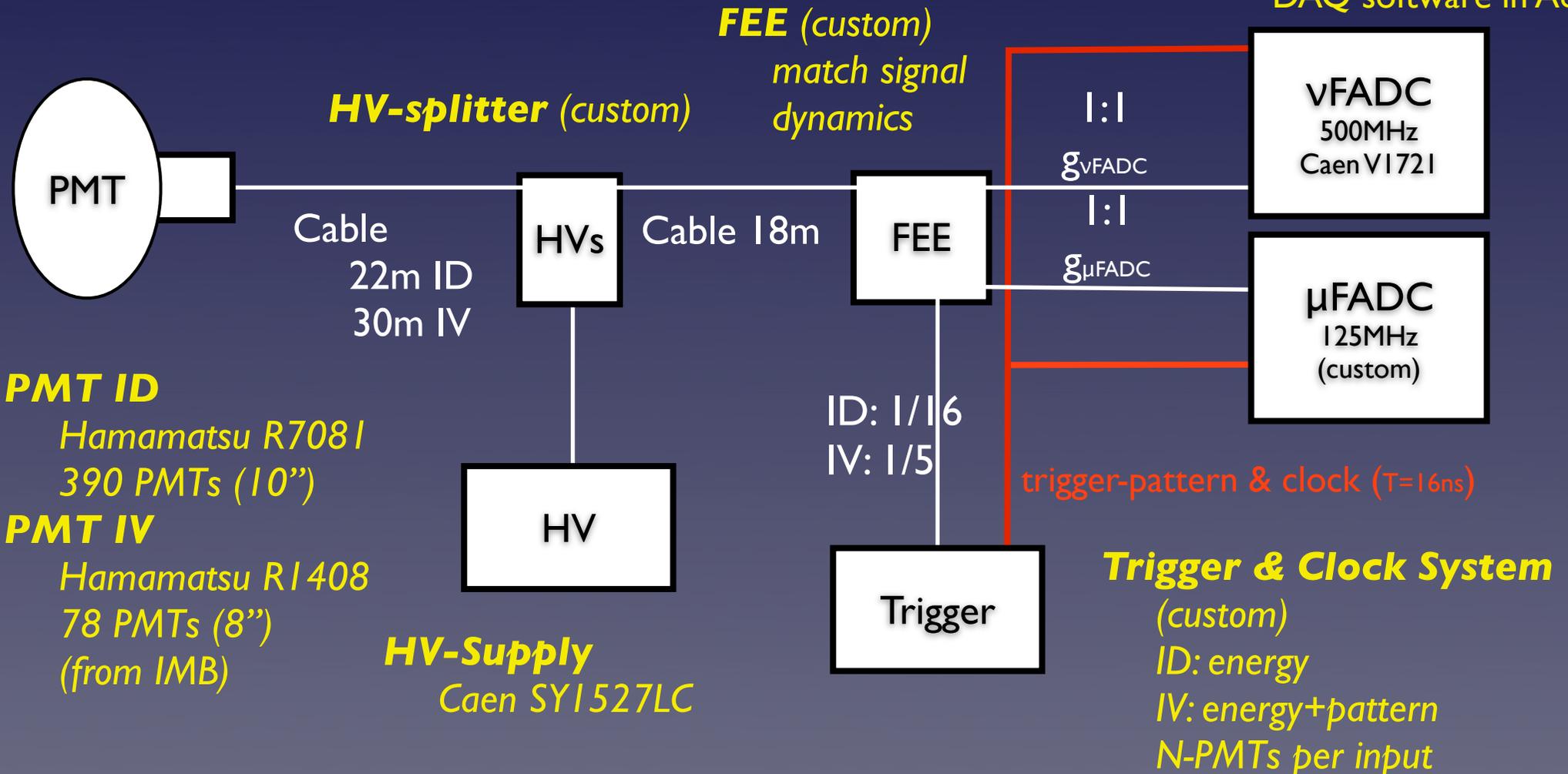
<300Hz (cosmic muons @ ND)  
<500Hz (calibration)

## Event data size per trigger

max: 1kB per ch (2 $\mu$ s worth)  
min: 32B per ch (time stamp)

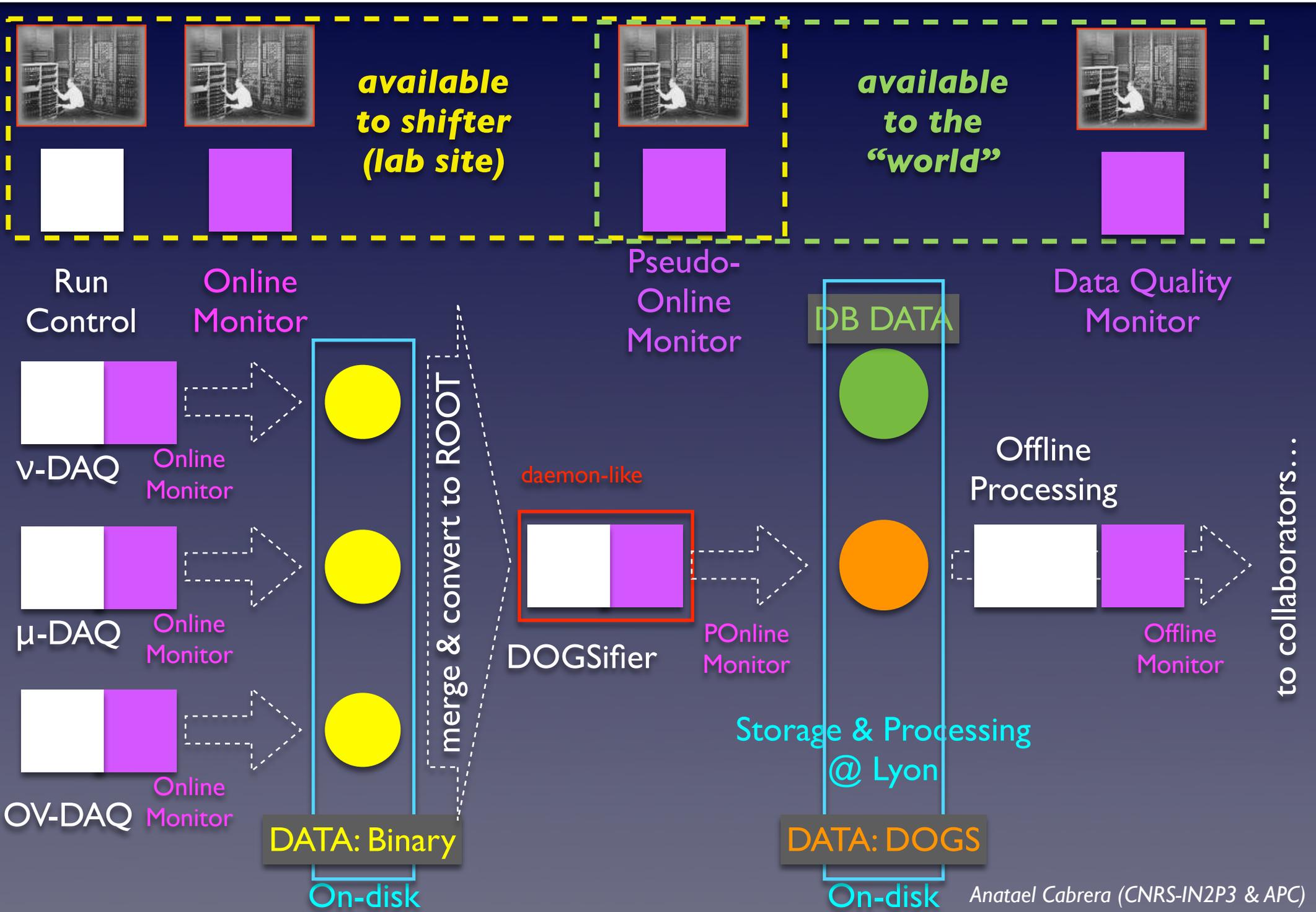
## VME Crate (U6)

~16 FADC cards  
DAQ software in Ada

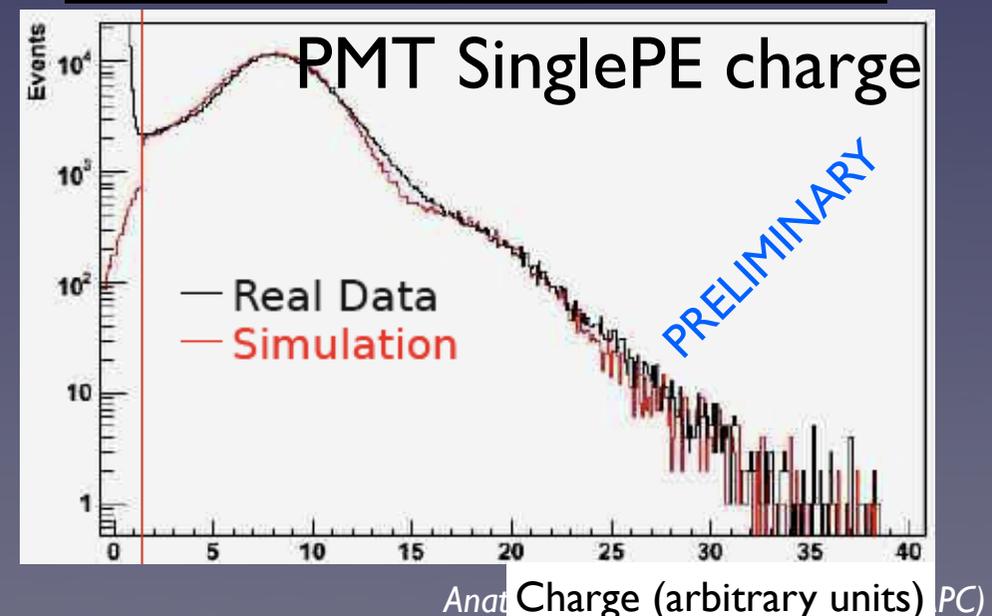
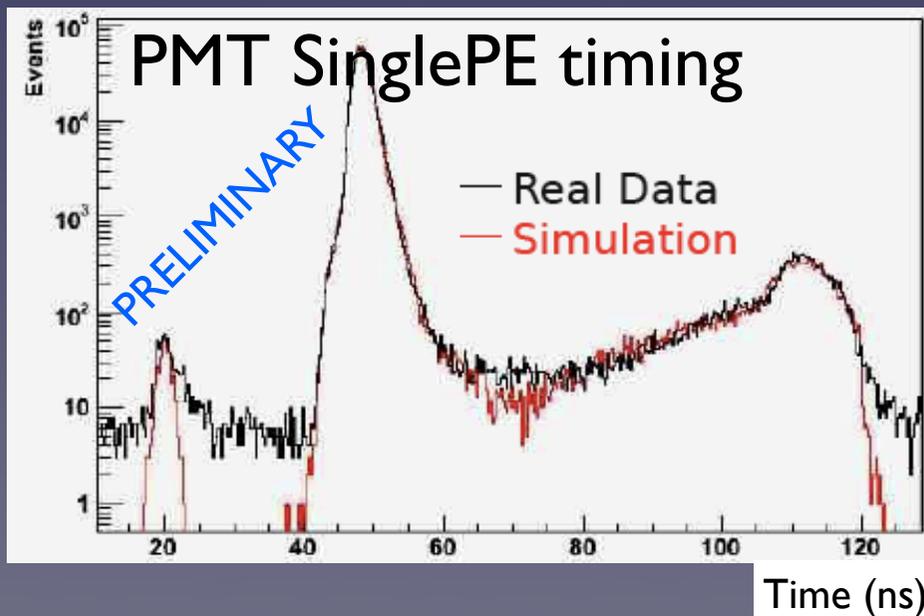
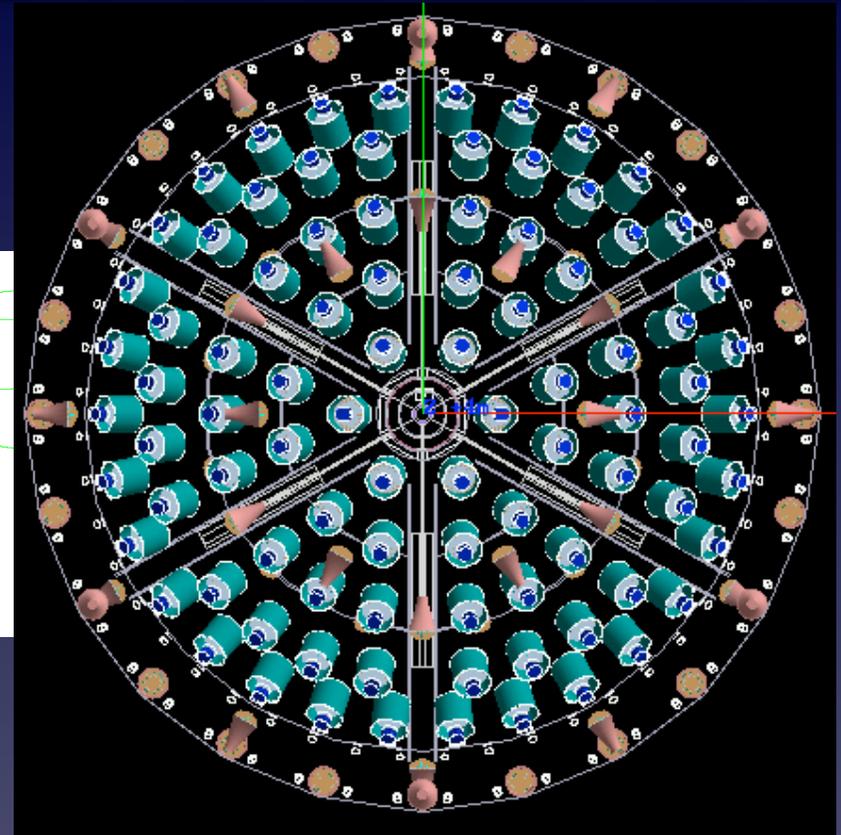
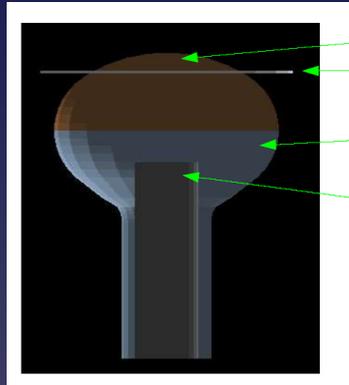


Missing: OV readout (Hamamatsu M64 + Maroc2-chip based)

# online (DAQ+monitor) system



- Complete detector simulation...
- Physics: Geant4
- Optical Interface: Geant4
  - based on “GLG4sim”
- Readout Interface (PMT, electronics, trigger) tuned to data



# DC status

- FAR DETECTOR
  - rock-gamma shield: **built!**
  - Inner-Veto detector (including PMTs and calibration system): **built!**
  - Inner Detector (within Buffer):
    - Buffer: **built!**
    - ID-PMT installation: **on-going!** (~200 PMTs tested & installed)
    - **Next:** acrylics for Target &  $\gamma$ -Catcher
    - **Commissioning start by end of the year**
- NEAR DETECTOR...

# la dépêche

du groupe EDF

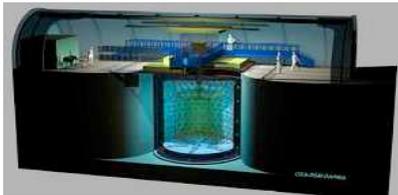
n° 3117  
25 mai 2009

DIFFUSION INTERNE

NUCLEAIRE

## Chooz : coup double pour la recherche

Le 20 mai 2009, EDF a signé une convention avec le CEA et le CNRS pour engager l'expérience « Double Chooz ». Deux laboratoires souterrains de recherche sur la matière seront aménagés sur le site nucléaire de Chooz. La mise en place de ce dispositif constitue une première mondiale, dans un domaine où les précédentes découvertes ont déjà été couronnées par cinq prix Nobel.



Vue du futur détecteur Chooz B situé à 45 m sous terre et relié à la surface par un tunnel de 155 m de long

Ces deux laboratoires permettront de mieux comprendre le neutrino - une des quatre particules élémentaires - et sa faculté de changer d'état lors de sa propagation dans l'espace.

Une première expérience sur le site de Chooz A avait permis de lever en partie le voile sur ce phénomène énigmatique. Le programme « Double Chooz » prolonge l'expérimentation par la comparaison des flux de neutrinos à deux distances différentes des réacteurs de la centrale.

Lancé en partenariat avec le Conseil Régional de Champagne-Ardenne, le Conseil Général des Ardennes, le CEA et le CNRS, le programme nécessite la construction de deux détecteurs identiques, enterrés pour les protéger des rayonnements cosmiques et de la radioactivité naturelle. Le premier (détecteur proche) sera situé à proximité de Chooz B dans un nouveau laboratoire à 45 mètres sous terre. Le second (détecteur lointain) sera construit dans la colline de Chooz A, sur le site de la première expérience.

### EDF, acteur majeur du projet

Outre la mise à disposition d'une partie de l'installation de Chooz A, EDF a fortement mobilisé son ingénierie : le Centre national d'équipement nucléaire pour l'étude de faisabilité du détecteur proche, le Centre d'ingénierie hydraulique pour la maîtrise d'œuvre du génie civil, le Centre d'ingénierie de déconstruction et environnement nucléaire pour la logistique journalière. La coordination générale est réalisée par les équipes de la centrale.

### Une collaboration internationale à la hauteur des enjeux

Huit pays (Japon, Etats-Unis, Brésil, Russie, Grande-Bretagne, Allemagne, Espagne et France) coopèrent financièrement à la construction des détecteurs. 140 physiciens de 30 universités dans le monde participent à cette expérience. Le détecteur lointain sera opérationnel fin 2009, le détecteur proche fin 2011.

### L'énigme neutrino

Très abondant dans l'univers, le neutrino est produit par les étoiles, le rayonnement cosmique ou encore par le cœur des centrales nucléaires. L'une des énigmes de cette particule réside dans sa faculté à se métamorphoser en trois états distincts : c'est le phénomène d'oscillation, dont seuls deux des trois paramètres ont pu être complètement mesurés à ce jour. Le neutrino est la baguette magique capable de changer un élément en un autre. Il pourrait expliquer la différence entre matière et anti-matière.

#### POUR EN SAVOIR +

• Olivier Lamarre, CNPE de Chooz, 03 24 36 30 01

RETROUVEZ LA DÉPÊCHE SUR  **e-toile** ÉDITÉE PAR la direction de la Communication interne – Pauline Sergent

122-30, avenue de Wagram – 75382 Paris cedex 08 – [www.edf.com](http://www.edf.com)  
SA au capital de 911085545 euros – 552081317R.C.S.Paris – Le groupe EDF est certifié ISO 14001



# Major milestone!

## Signature few days ago!!

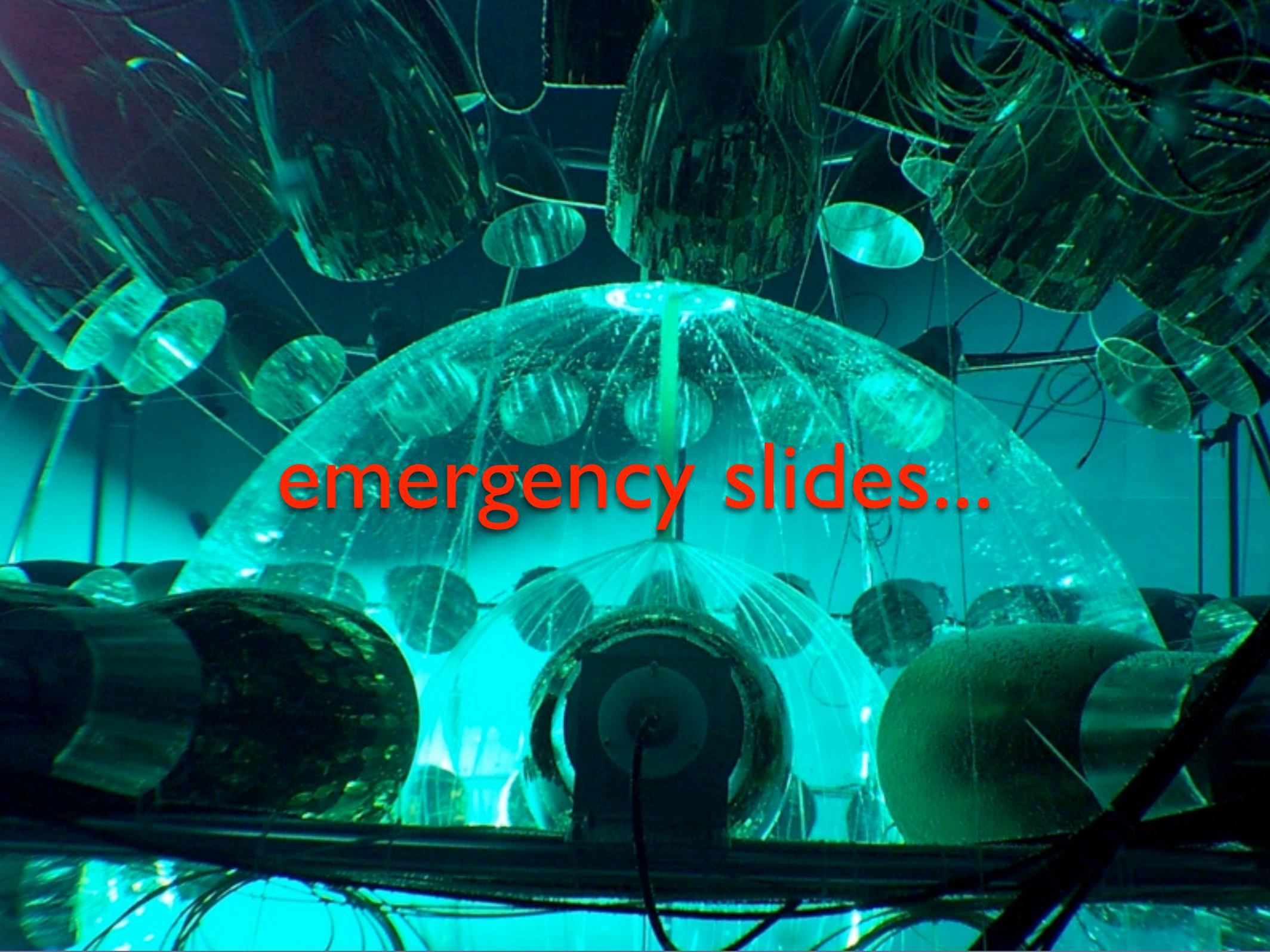
=> civil-construction of ND laboratory starts by early 2010

=> first Vs in 2011!

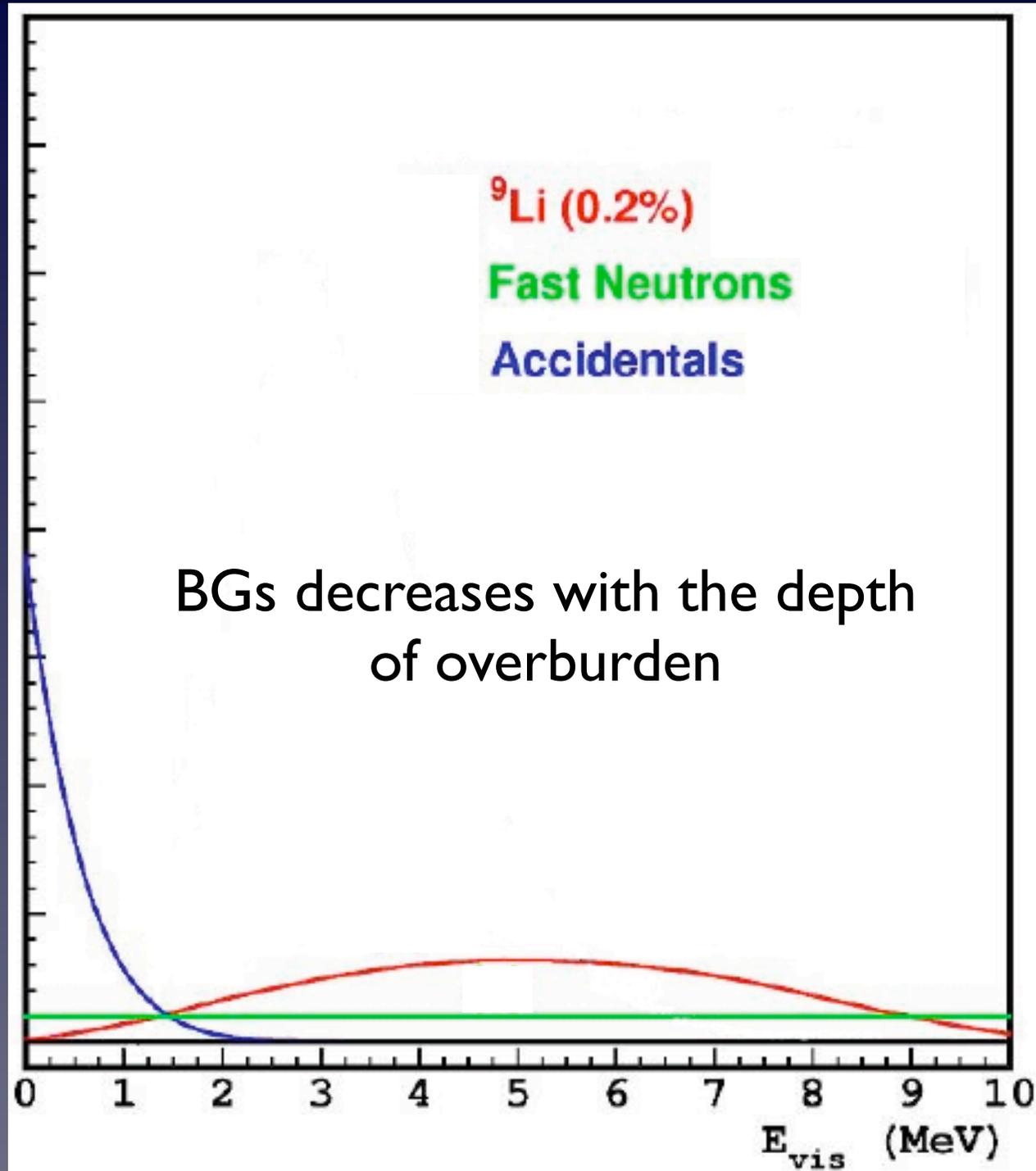
Anatael Cabrera (CNRS-IN2P3 & APC)

# What to remember?

- Neutrino Oscillations framework is not exhausted from physics...
  - gate locking (*with current technology*) is  $\theta_{13}$
- We must measure  $\theta_{13}$ ...
  - interesting by itself: SM leptonic mixing parameter
  - even a zero value is interesting (but unfortunate for us!)
  - reactors (& beams) will try measure it within next 5 years...
- DC detector...
  - DC has led much of the  $\theta_{13}$ -LAND approach. Its legacy is already visible... (*“on the shoulders of giants”*... CHOOZ, Borexino, KamLAND, etc)
  - DC likely the first to go beyond CHOOZ... **beam is waiting for us!**



emergency slides...

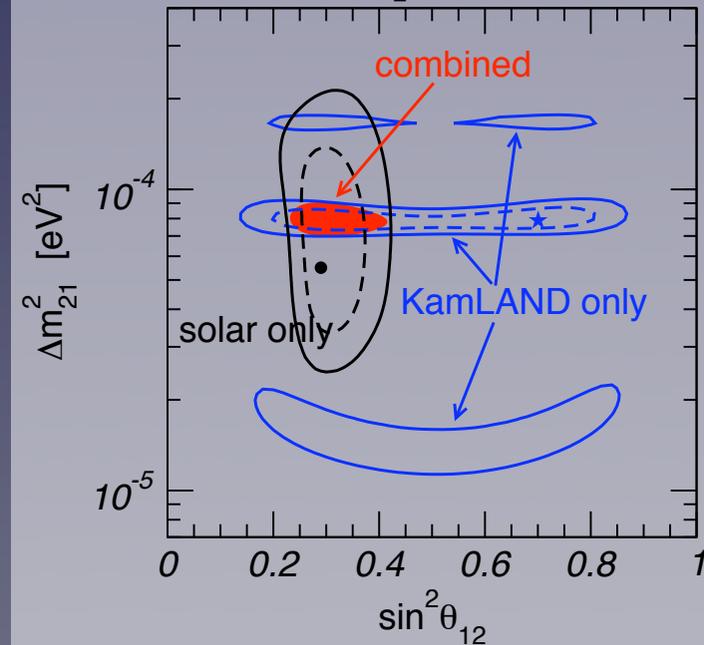


## MNS: large mixing (unlike CKM)...

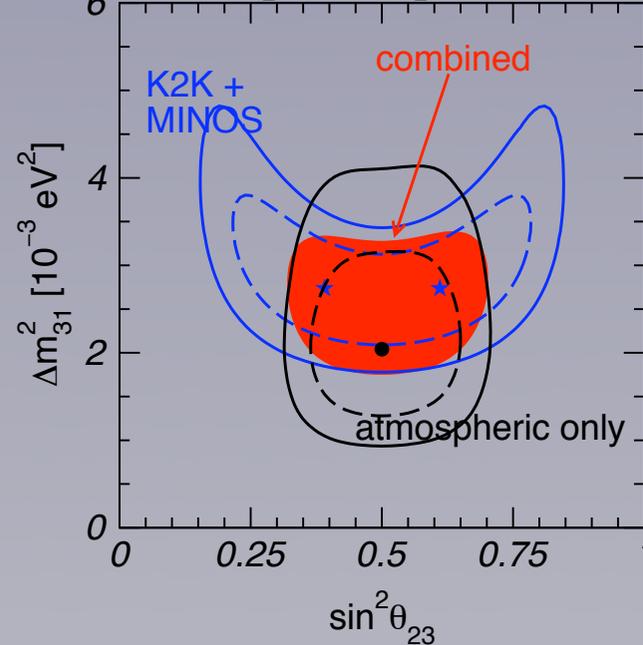
T.Schwetz et al. hep-ph/0606060

parameter	bf $\pm 1\sigma$	1 $\sigma$ acc.	2 $\sigma$ range	3 $\sigma$ range
$\Delta m_{21}^2$ [ $10^{-5} \text{eV}^2$ ]	$7.9 \pm 0.3$	4%	7.3 – 8.5	7.1 – 8.9
$ \Delta m_{31}^2 $ [ $10^{-3} \text{eV}^2$ ]	$2.5^{+0.20}_{-0.25}$	10%	2.1 – 3.0	1.9 – 3.2
$\sin^2 \theta_{12}$	$0.30^{+0.02}_{-0.03}$	9%	0.26 – 0.36	0.24 – 0.40
$\sin^2 \theta_{23}$	$0.50^{+0.08}_{-0.07}$	16%	0.38 – 0.64	0.34 – 0.68
$\sin^2 \theta_{13}$	—	—	$\leq 0.025$	$\leq 0.041$

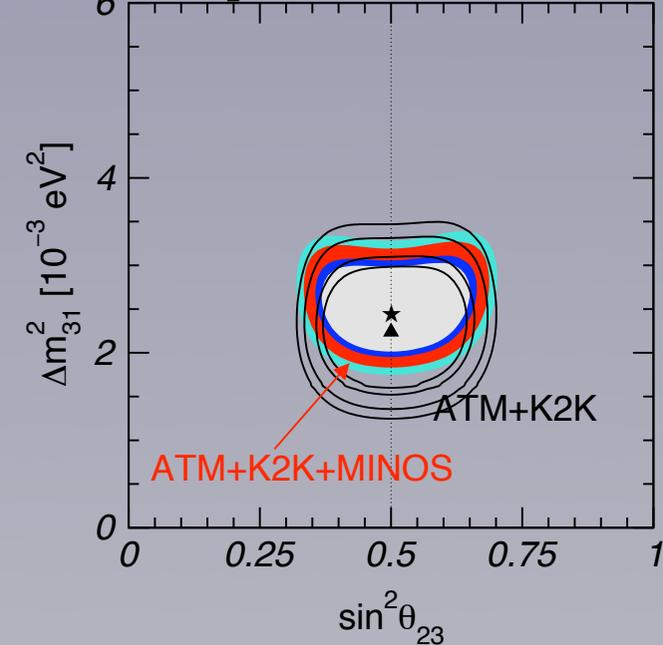
"solar" parameters

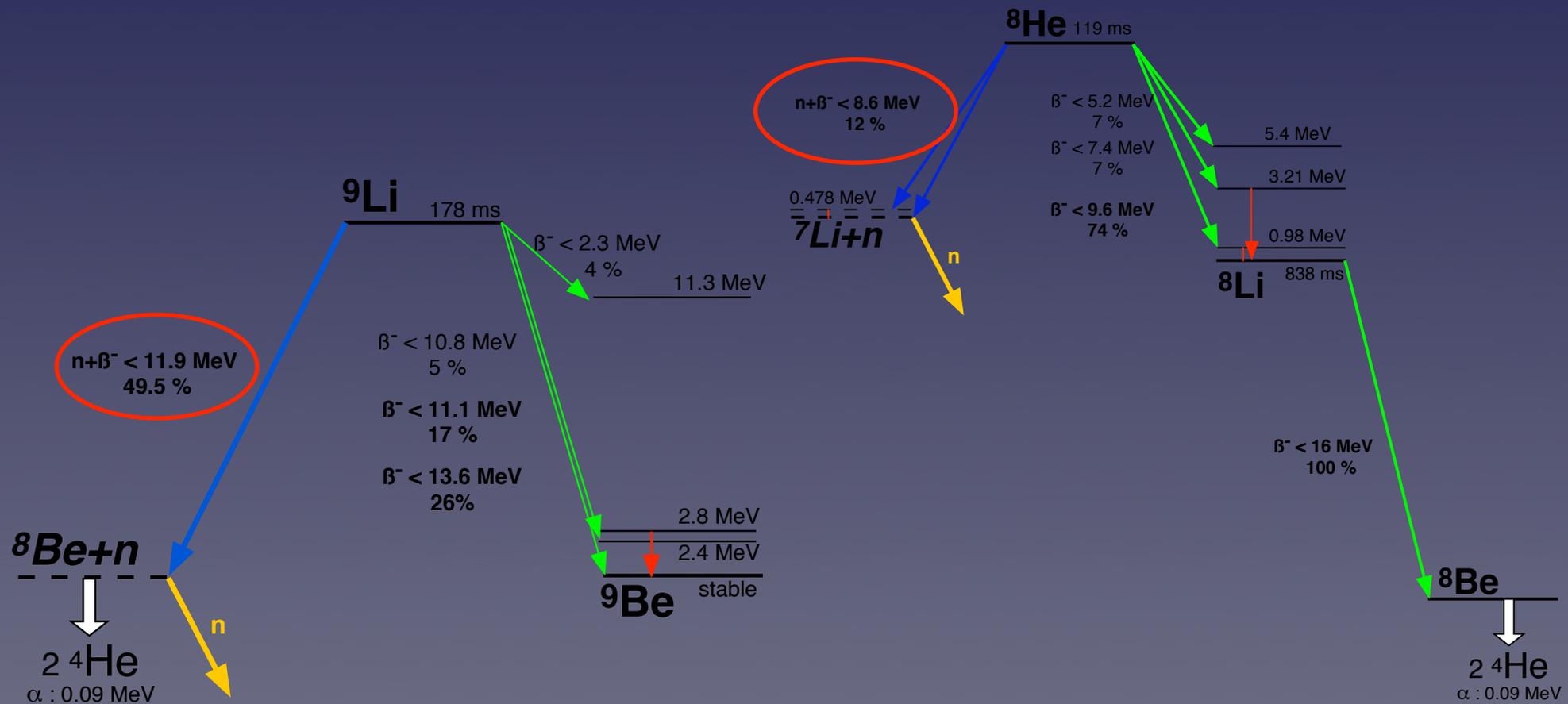


"atmospheric" parameters

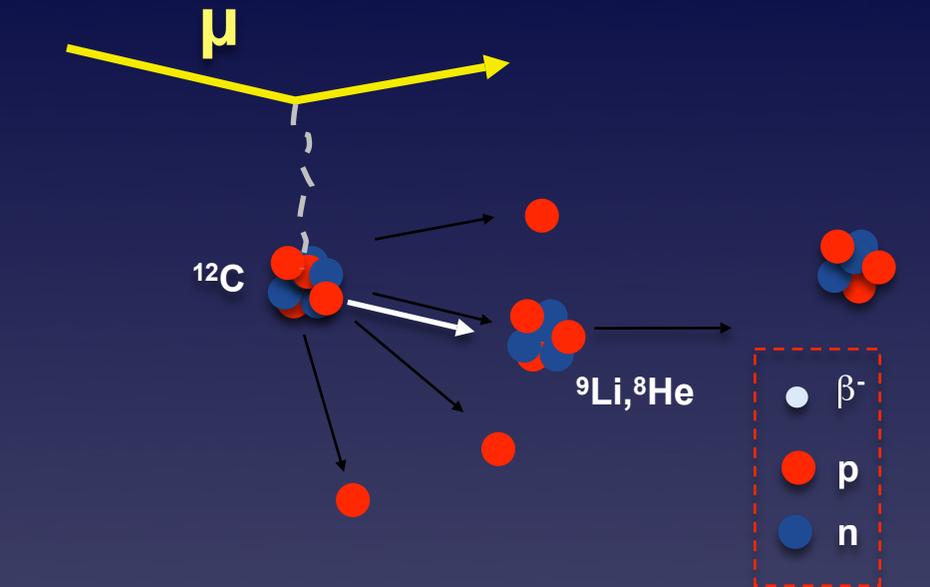


impact of MINOS data

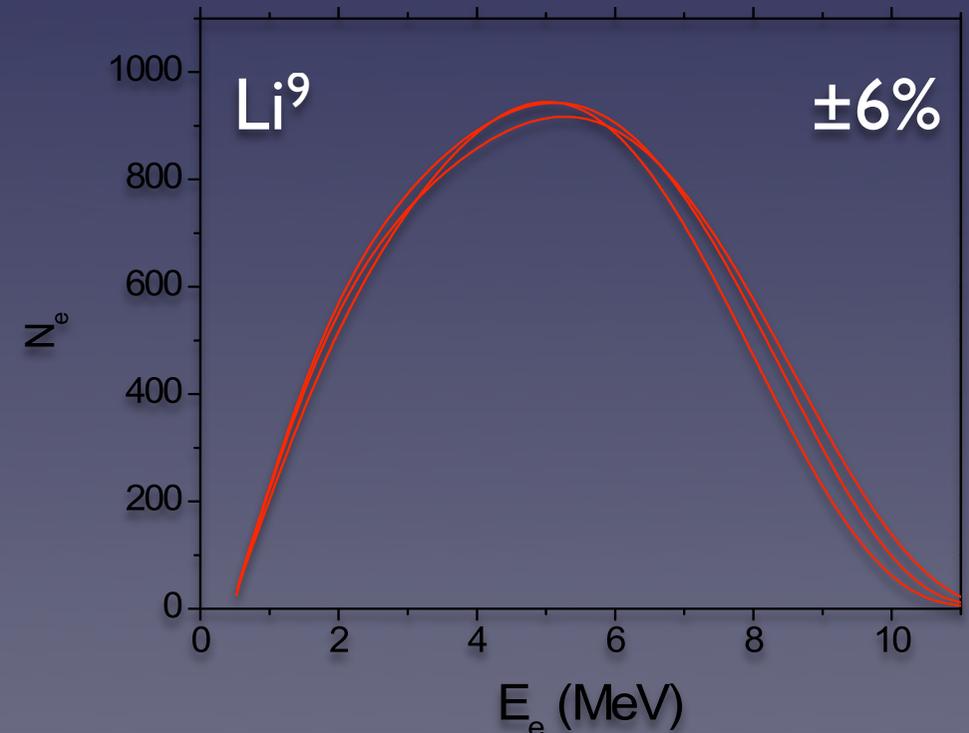
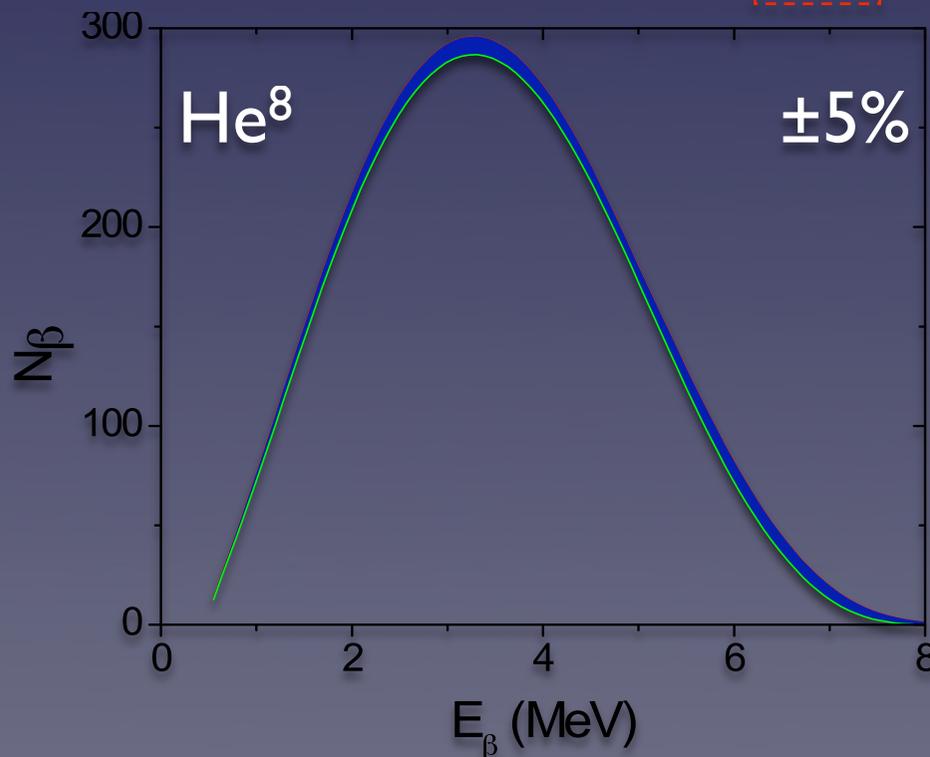


long lived  $\beta$ -n sources...

## Shape Estimations by R. Lazaukas &amp; L. Grigorenko

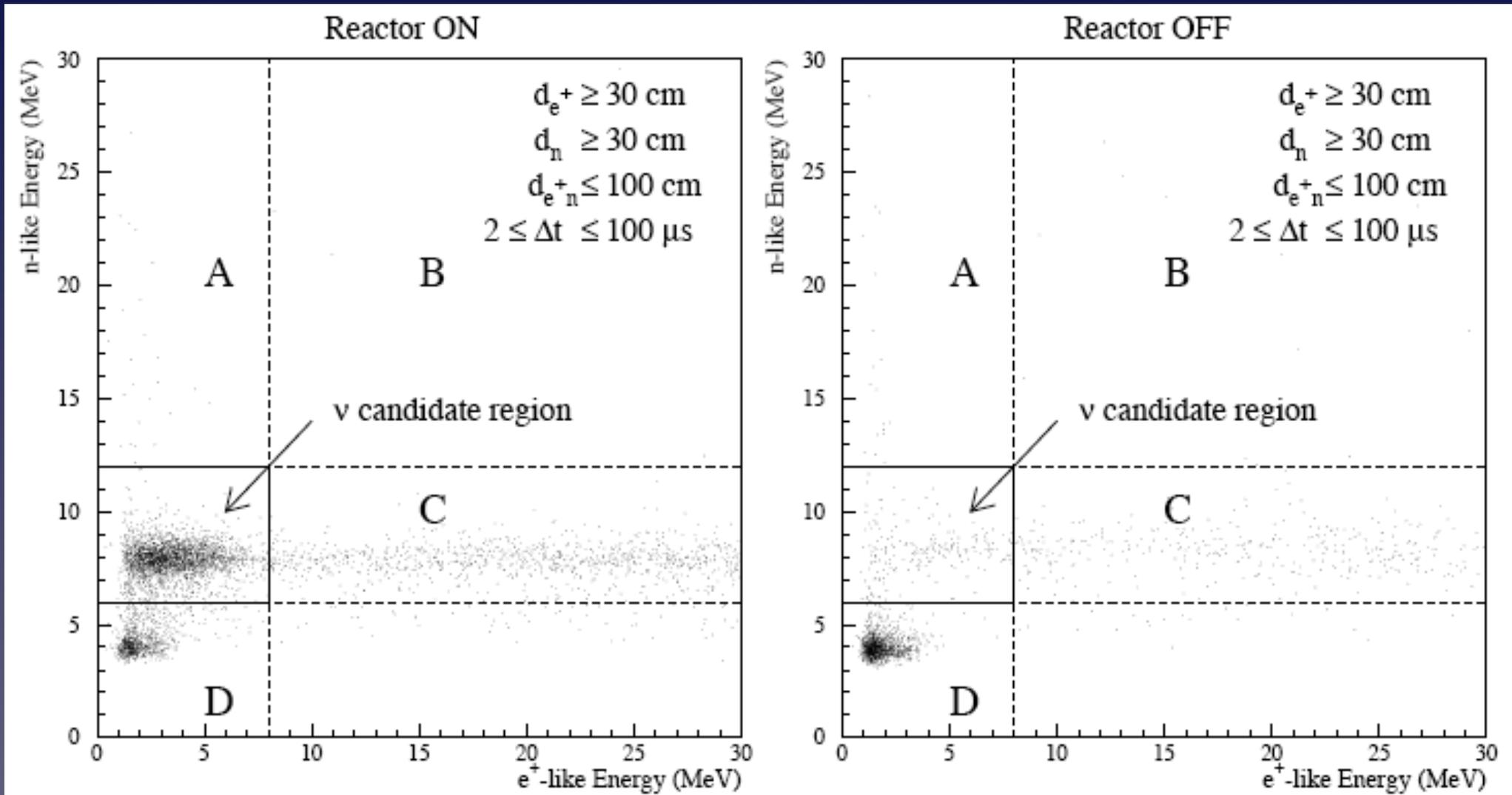


- $\mu$  induced ( $\beta$ -n) BGs
- rate  $\propto$  overburden of detector
- @ FD:  $\sim 1.4 \pm 0.9$  per day (CHOOZ)
- long decay  $\beta$ : cannot veto!
- introduced in fit for BG estimation
- knowing shape is very useful...



# an experimentalist's dream

switched off signal => measure background "naked"!



Apollonio et al (CHOOZ): [hep-ex/0301017](https://arxiv.org/abs/hep-ex/0301017)

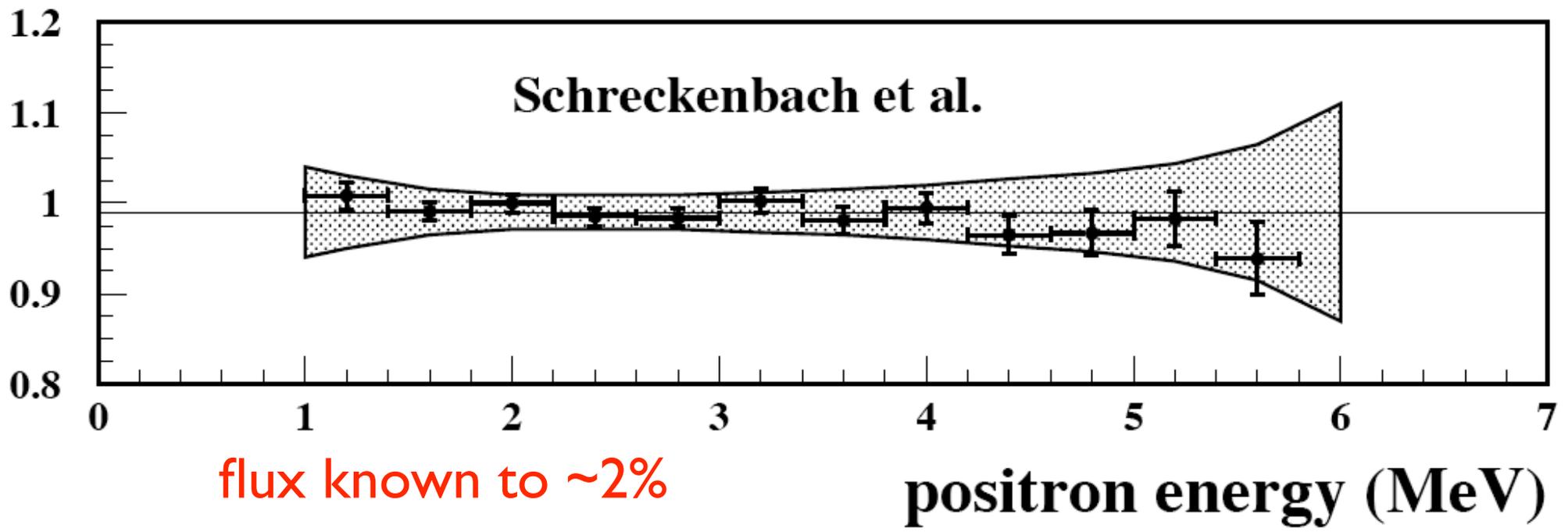
multi-reactor-core experiments => less likely to happen

Table 12: Summary of the background subtraction error at the Far and Near detector (preliminary). Background rate and shape with their corresponding uncertainties are used for the calculation of the sensitivity. The systematics correspond to our best estimate of the error associated with each particular background (this can be used as a “background systematic error”).

Detector	Site		Background				
			Accidental Materials	PMTs	Fast n	Correlated $\mu$ -Capture	$^9\text{Li}$
CHOOZ (24 $\nu$ /d)	Far	Rate ( $d^{-1}$ )	—	—	—	—	$0.6 \pm 0.4$
		Rate ( $d^{-1}$ )	$0.42 \pm 0.05$		$1.01 \pm 0.04$	$(stat) \pm 0.1$	$(sys)$
		bkg/ $\nu$	1.6%			4%	
		Systematics	0.2%			0.4%	
Double Chooz (69 $\nu$ /d)	Far	Rate ( $d^{-1}$ )	$1 \pm 0.1$	$1 \pm 0.1$	$0.15 \pm 0.15$	$0.42 \pm 0.2$	$1 \pm 0.5$
		bkg/ $\nu$	1.4%	1.4%	0.2%	0.6%	1.4%
		Systematics	0.2%	0.2%	0.2%	0.3%	0.7%
Double Chooz (990 $\nu$ /d)	Near	Rate ( $d^{-1}$ )	$7.2 \pm 1.0$	$7.2 \pm 1.0$	$1.4 \pm 0.14$	$2.6 \pm 1.2$	$5.2 \pm 3.2$
		bkg/ $\nu$	0.7%	0.7%	0.14%	0.26%	0.6%
		Systematics	0.1%	0.1%	0.2%	0.1%	0.3%

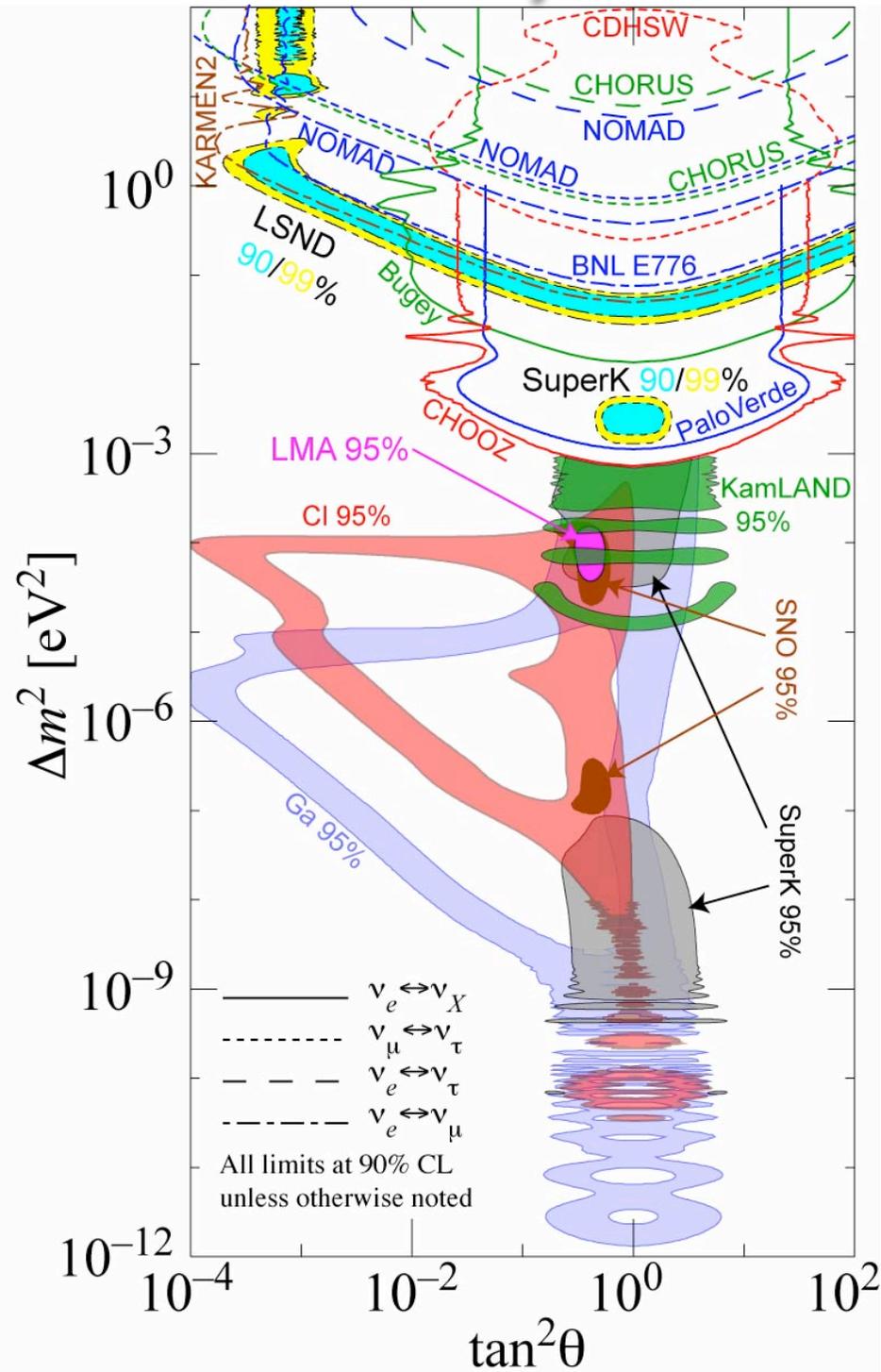
# eliminate flux uncertainty

Bugey (3 & 4) vs Schreckenbach *et al* (1985)



Apollonio *et al* (CHOOZ): [hep-ex/0301017](https://arxiv.org/abs/hep-ex/0301017)

# half-century of complementarity



- reactor: disappearance => high statistics

- no NC BG or matter effects
- sensitive to  $\theta_{13}$  only:

$$1 - P_{\bar{e}\bar{e}} \simeq \sin^2 2\theta_{13} \sin^2 \Delta + \alpha^2 \Delta^2 \cos^4 \theta_{13} \sin^2 2\theta_{12}.$$

- beams: appearance => low statistics (<150vs T2K Phase-I)

- BG:  $\pi^0$  production and beam  $\nu_e$  contamination
- correlation:  $\delta_{CP}, \theta_{13}, \theta_{23}$  degeneracy and matter effects\*

$$\begin{aligned}
 P(\nu_\mu \rightarrow \nu_e) &\simeq \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \Delta \\
 &\mp \alpha \sin 2\theta_{13} \sin \delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \Delta \sin^2 \Delta \\
 &+ \alpha \sin 2\theta_{13} \cos \delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \Delta \cos \Delta \sin \Delta \\
 &+ \alpha^2 \cos^2 \theta_{23} \sin^2 2\theta_{12} \Delta^2
 \end{aligned}$$

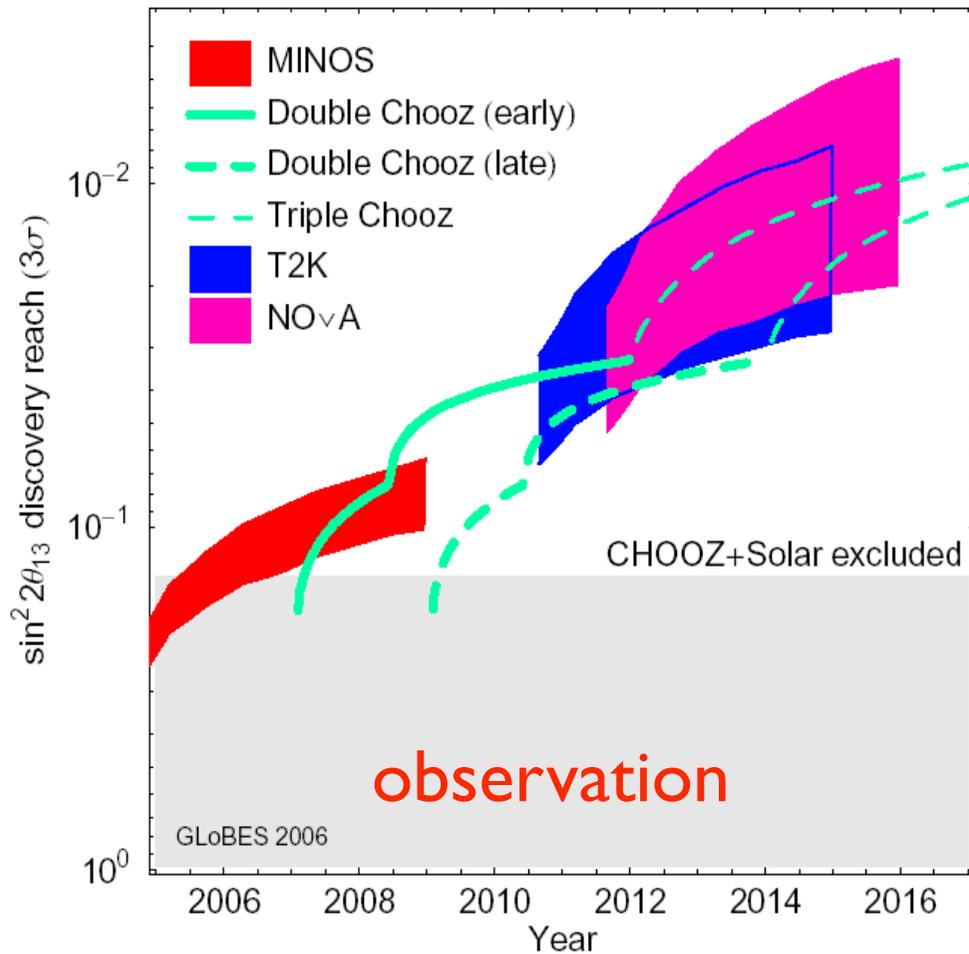
$$\Delta \equiv \Delta m_{31}^2 L / (4E_\nu)$$

$$\alpha \equiv \Delta m_{21}^2 / \Delta m_{31}^2$$

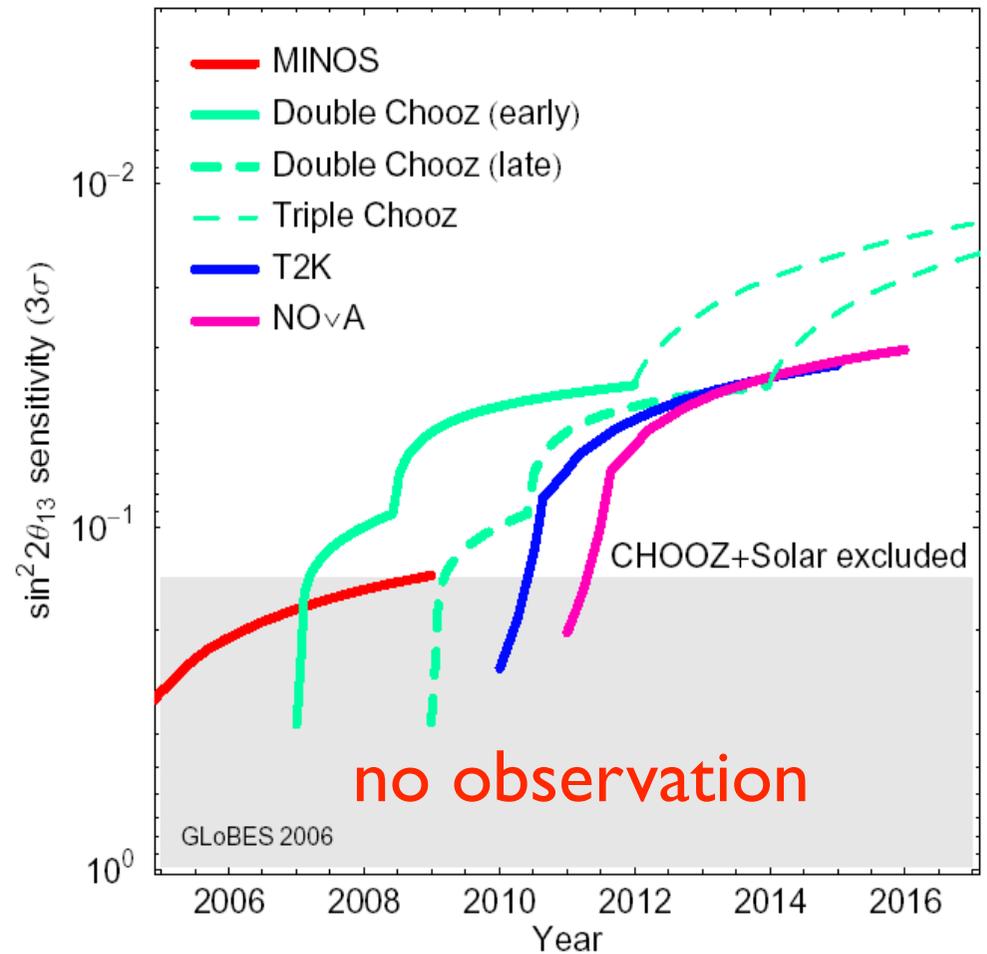
# beams + reactors = deeper insight

## Competitive & overlapping coverage by both techniques!

$\sin^2 2\theta_{13}$  discovery (normal hierarchy)

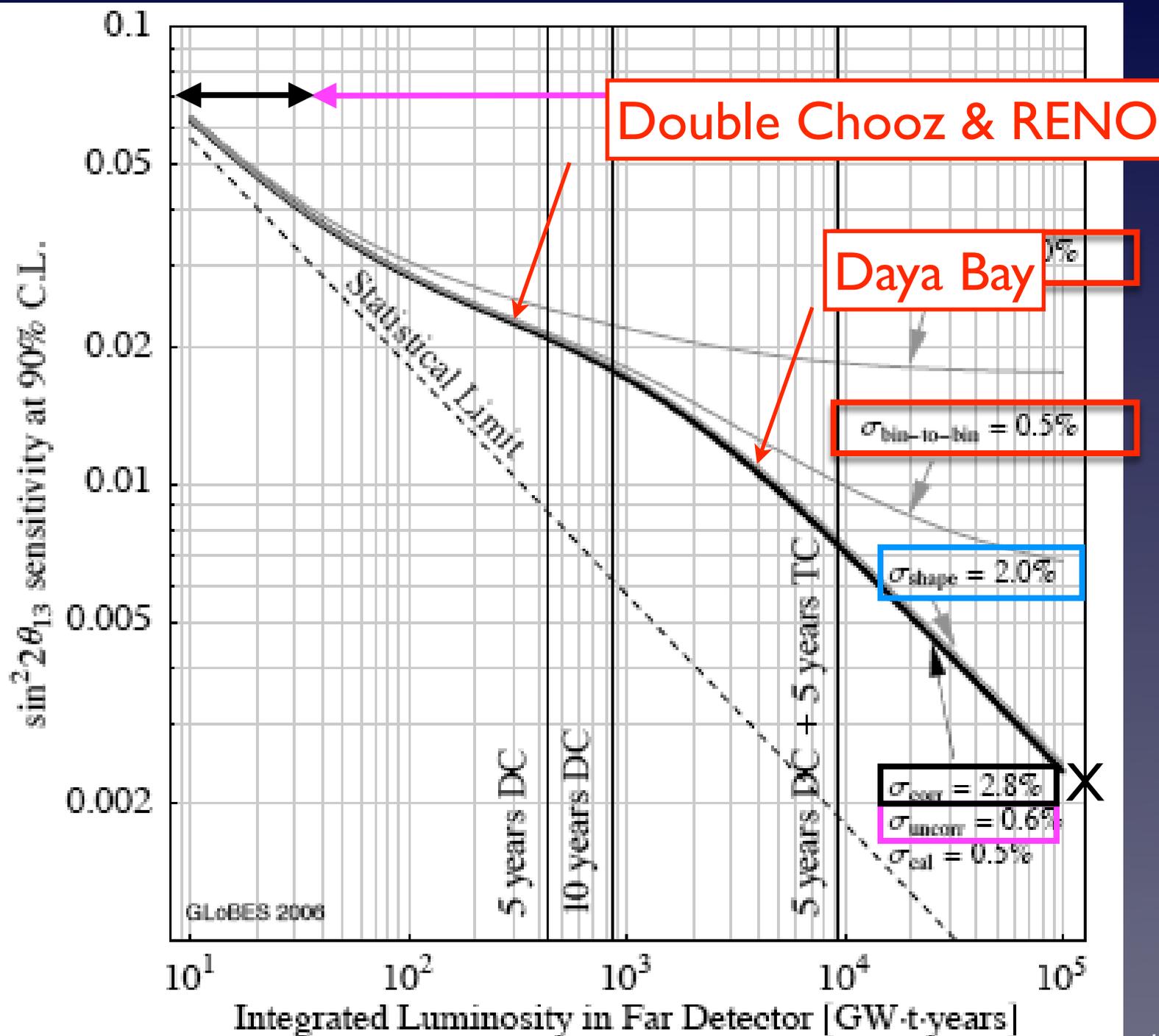


$\sin^2 2\theta_{13}$  sensitivity (no signal)

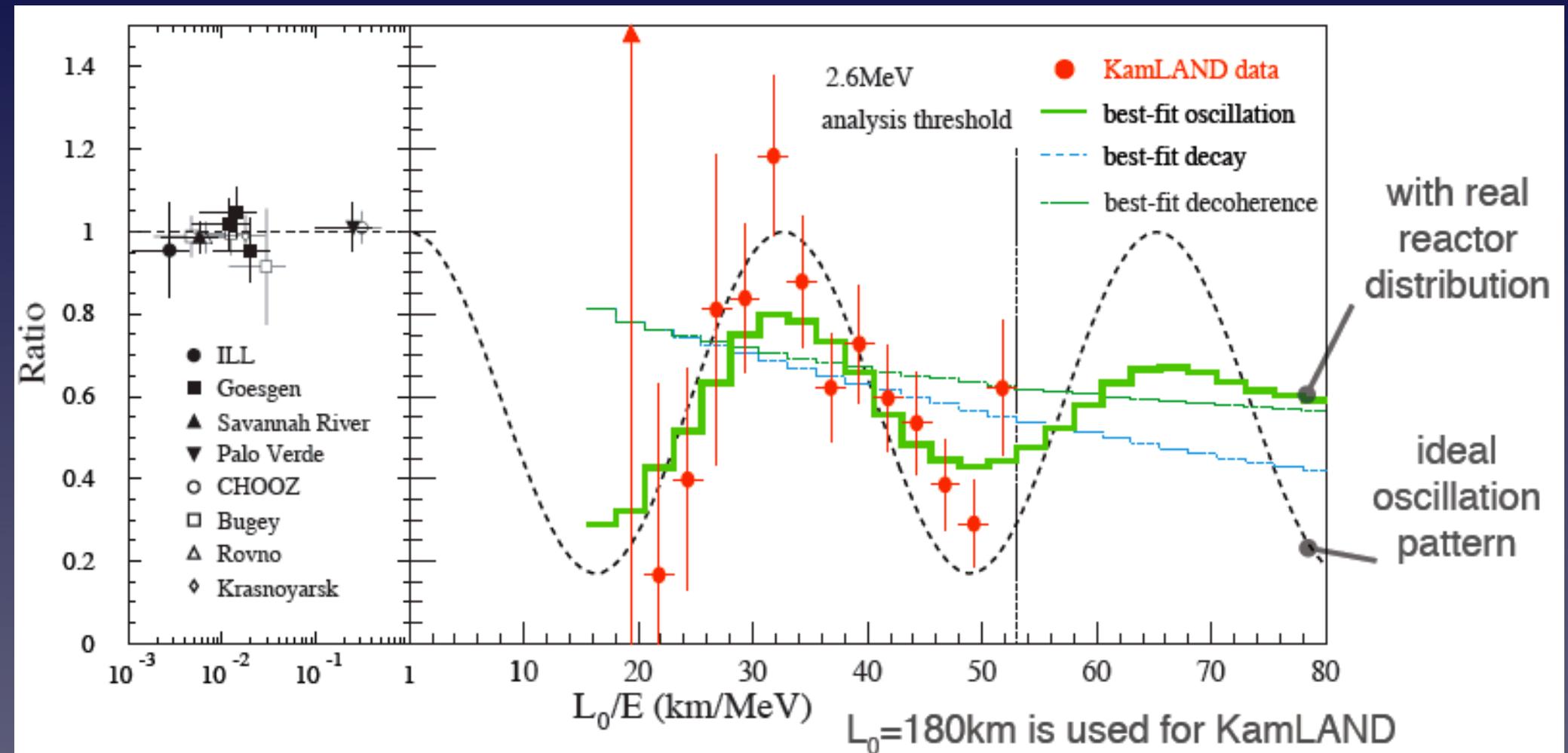


Similar time scale

Huber et al: [hep-ph/0501266](https://arxiv.org/abs/hep-ph/0501266)



systematics  
 &  
 BG shape  
 ignorance



- **Angra (reactor):**  $\theta_{13}$  [hep-ex/0511059]
- **KASKA (reactor):**  $\theta_{13}, \theta_{12}, \Delta m^2(\text{atm})$  [hep-ex/0607013]
- **$\beta$ -beam (beam):**  $\theta_{13}, \Delta m^2(\text{atm})$  [hep-ph/0605033]
- **NuFact (beam):**  $\theta_{13}, \Delta m^2(\text{atm})$  [hep-ph/0210192]
- **Hanohano (reactor):**  $\theta_{13}, \Delta m^2(\text{atm})$  [hep-ex/0612022]
- And more...