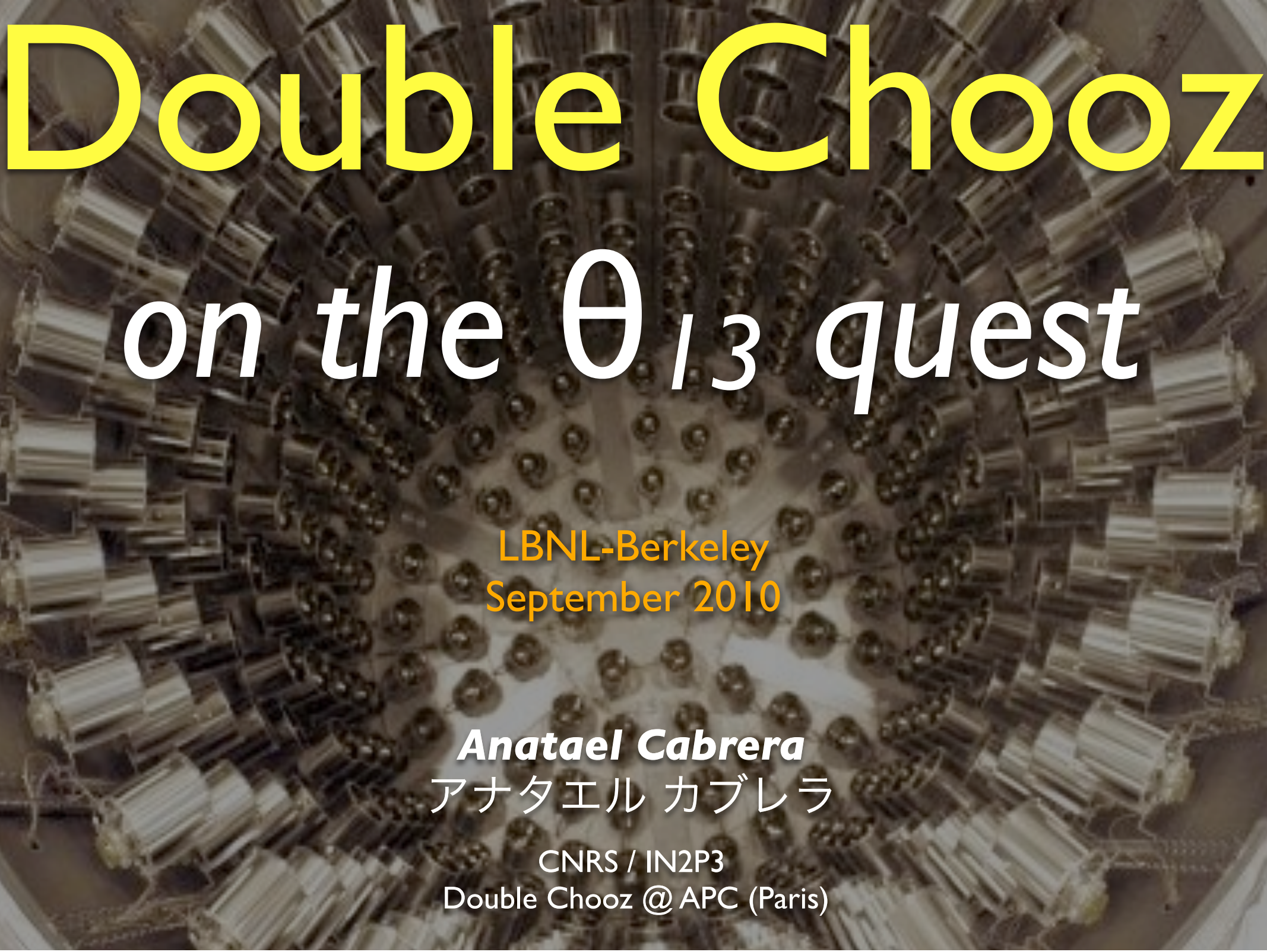


Double Chooz

on the θ_{13} quest

LBNL-Berkeley
September 2010

Anatael Cabrera
アナタエル カブレラ

CNRS / IN2P3
Double Chooz @ APC (Paris)

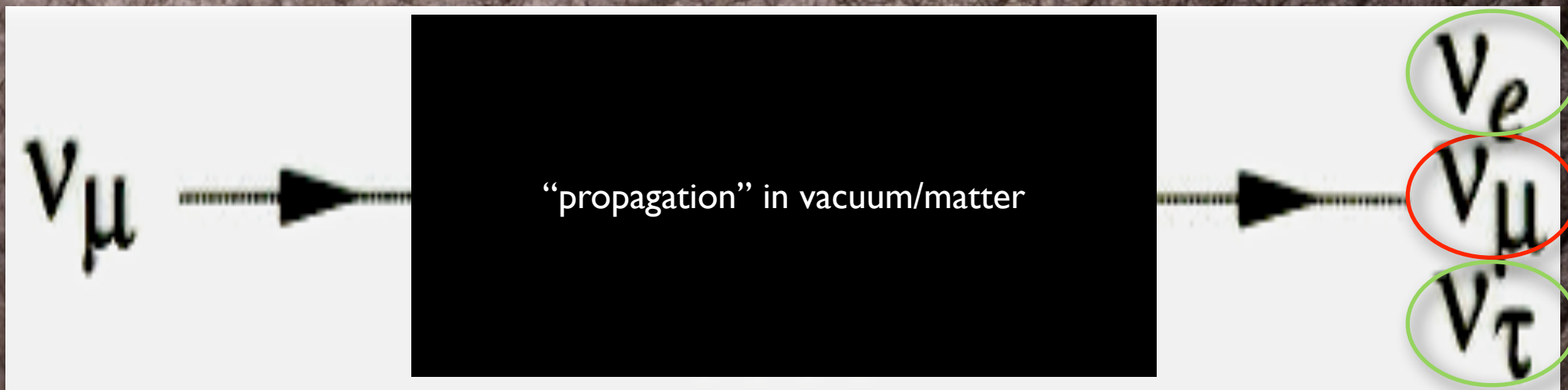
- what?
  - neutrino oscillation (a "micro-intro")
  - experimental basics
  - status of leptonic mixing sector $\Longrightarrow$ the PMNS matrix
- how?
  - reactor neutrinos
- where and when? (not inclusive)
  - Double Chooz
- concluding…

neutrino oscillations…

Anatael Cabrera (CNRS-IN2P3 & APC)

neutrino oscillations: a cartoon

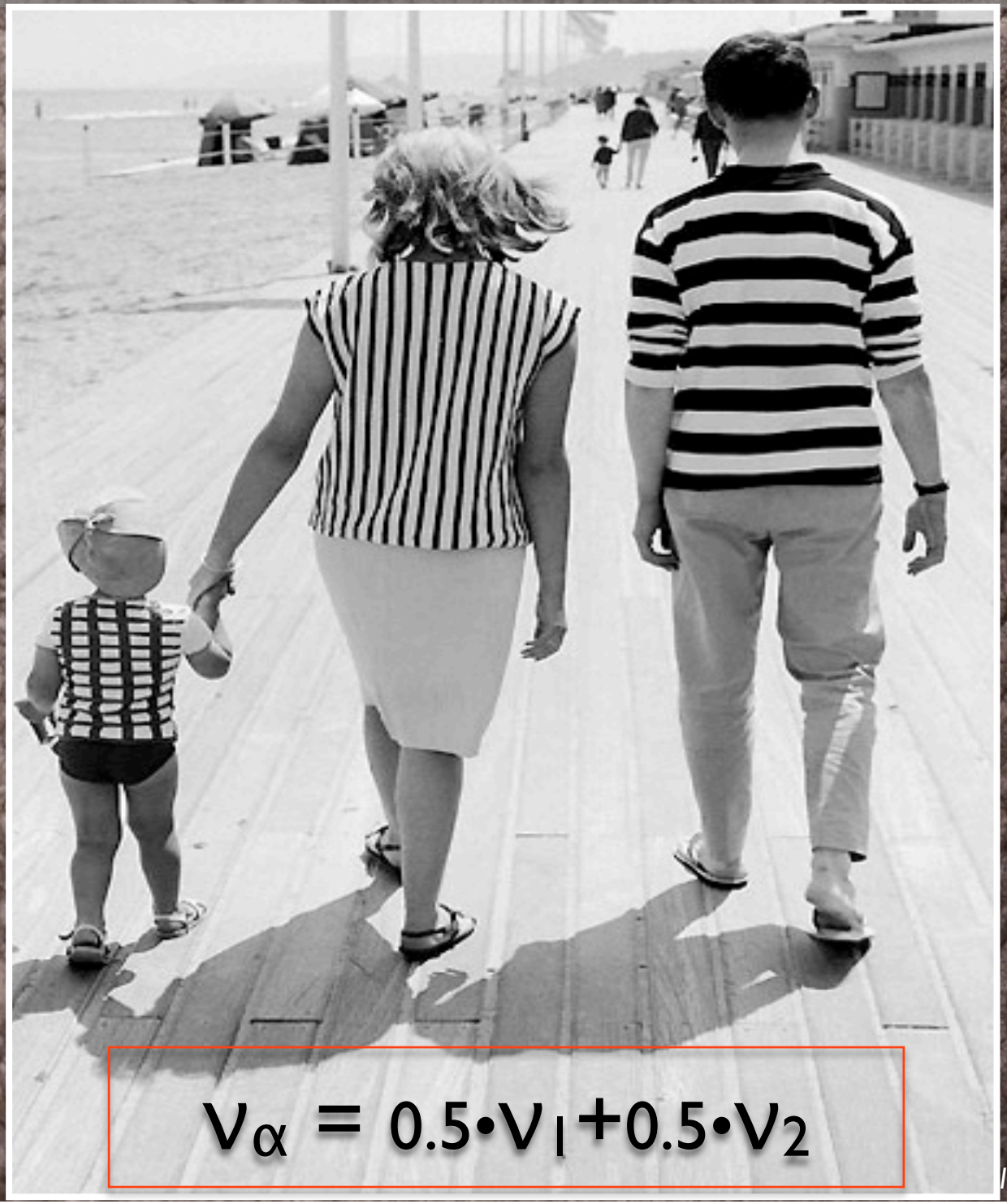
Let's take ν_μ (a good example) to start with…



disappearance experiment goal

appearance experiment goal

how about "mixing"…?



$$\nu_\alpha = 0.5 \cdot \nu_1 + 0.5 \cdot \nu_2$$

assumption:
biology likes 50% mixing

mixing 3x3 means…

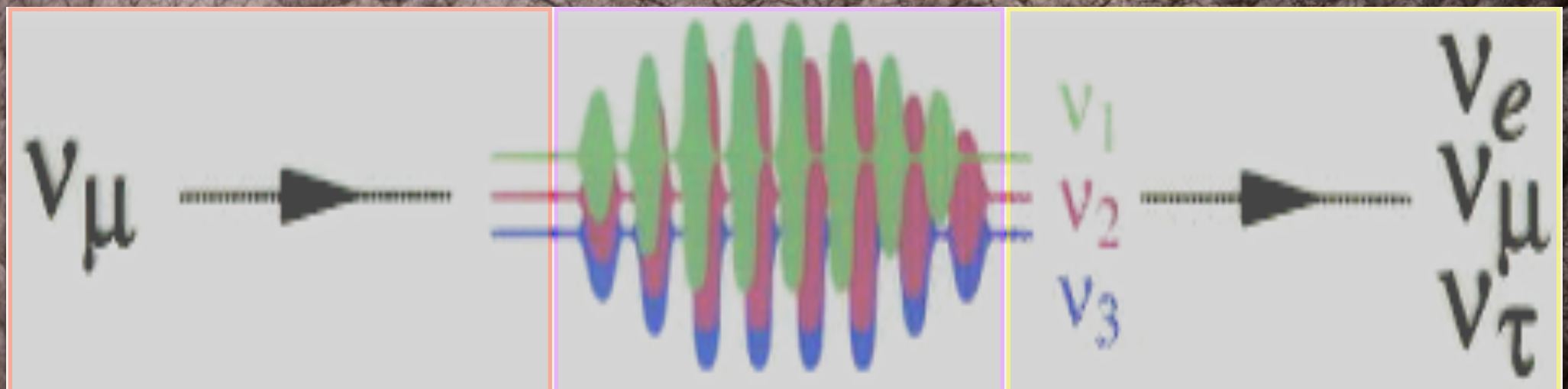
$$(\nu_e,\nu_\mu,\nu_\tau)^T = \boldsymbol{U}\,(\nu_1,\nu_2,\nu_3)^T$$

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

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}|\nu_i\rangle \qquad (\alpha = e,\ \mu,\ \tau)$$

if U = I $\Longrightarrow$ trivial mixing (i.e. no mixing)

neutrino oscillations: in a nutshell



$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}|\nu_i\rangle \qquad (\alpha = e,\ \mu,\ \tau)$$

production of ν_α
[mixing: from weak-space to mass-space]

$$|\nu_\alpha(t>0)\rangle = \sum_i e^{-iE_i t}U^*_{\alpha i}|\nu_i\rangle$$

propagation ν_i's
[Dirac/Schrödinger Eq.]

$$\mathrm{P}(\nu_\alpha \to \nu_\beta) = |\langle\nu_\beta|\nu_\alpha(t)\rangle|^2 = \left|\sum_i U_{\beta i}e^{-iE_i t}U^*_{\alpha i}\right|^2$$

detection ν_α*
[mixing: back from mass-space to mass-space]

neutrino oscillation probability…

solution for *2x2 ν case*…

$$\mathrm{P}(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

Mixing in the leptonic sector (θ) $\Longrightarrow$ ***PMNS*** matrix (*à la* ***CKM***)

Non-degenerate mass spectrum (Δm) $\Longrightarrow$ (macroscopic) *quantum interference*

L & **E** to be tuned (i.e. *experimental setup*) $\Longrightarrow$ measure **P(L$_o$,ΔE)**

neutrino oscillations facts...

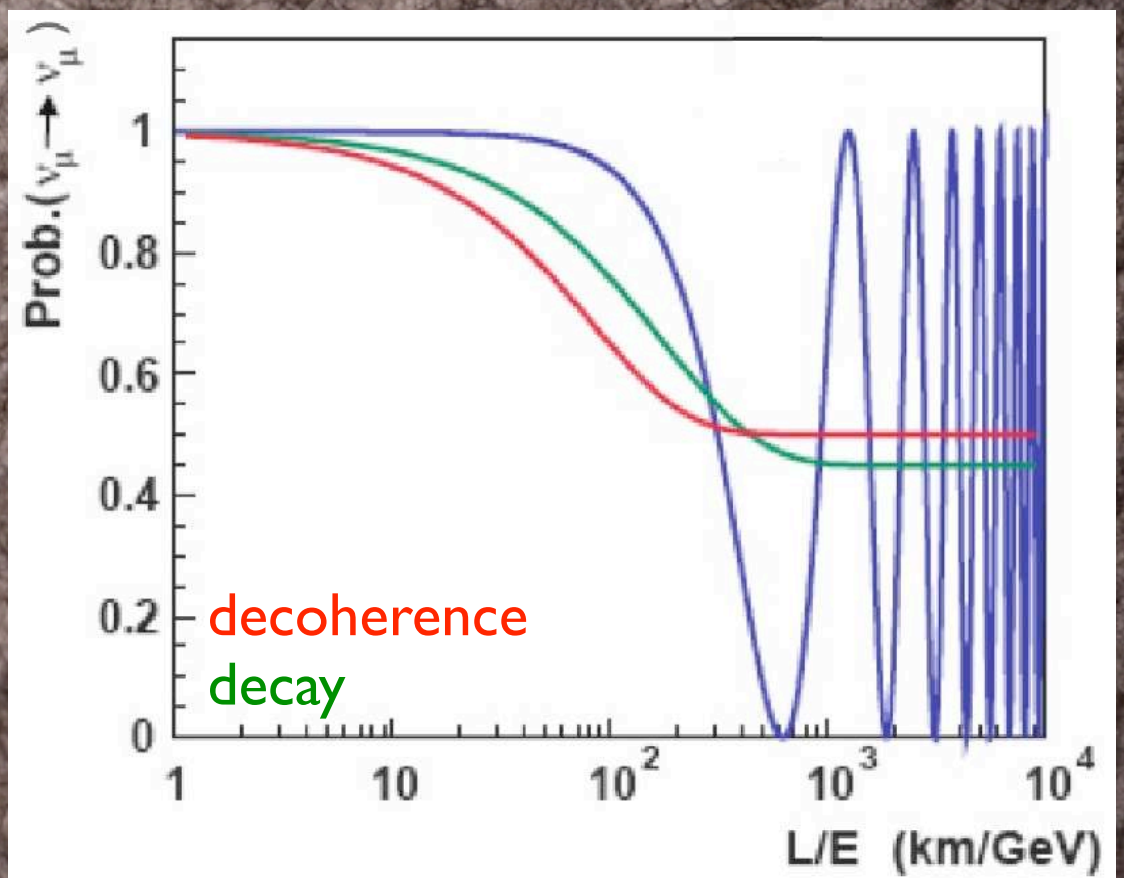
- flavour-νs (@ *interaction*) while mass-νs (during *propagation*)
- experimental observation: (dis)appearance => free-Hamiltonian causing mutation
  - physics behind? a "mechanism" causing a non-diagonal free-Hamiltonian
- high precision O(<10%)⟹ experiments sensitive to 3x3 oscillation ν formalism
- oscillations explains *most* experimental evidence to date ⟹ only physics?
- oscillation means:
  - mixing in lepton sector: PMNS matrix (*à la CKM*, for quarks)
  - prediction: leptonic CP-violation (in-built on complexity of matrix)
  - matrix must be unitary ⟹ measure number νs: 3?
  - non-degenerate mass spectrum of νs
  - no lepton-flavour number conservation on *SM*, but total-lepton number
  - "mirroring" lepton-quark mixing $\Longrightarrow^{\text{(appealing)}}\Longrightarrow$ beyond *SM*?

hunting ν-oscillations...

2x2 oscillations probability…

$$\mathrm{P}(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

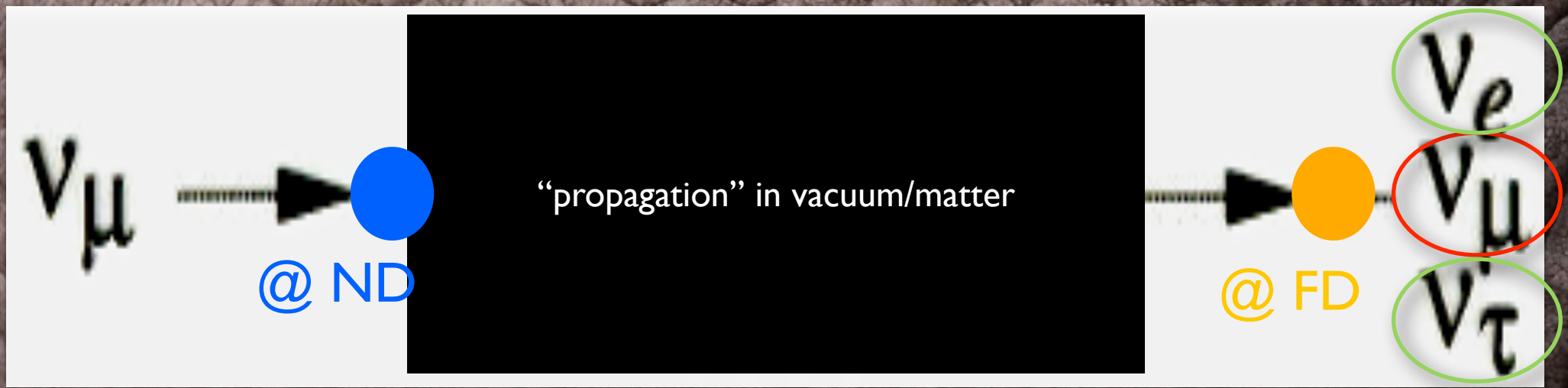
Disappearance: E/L modulation unique feature!



neutrino oscillations: a cartoon

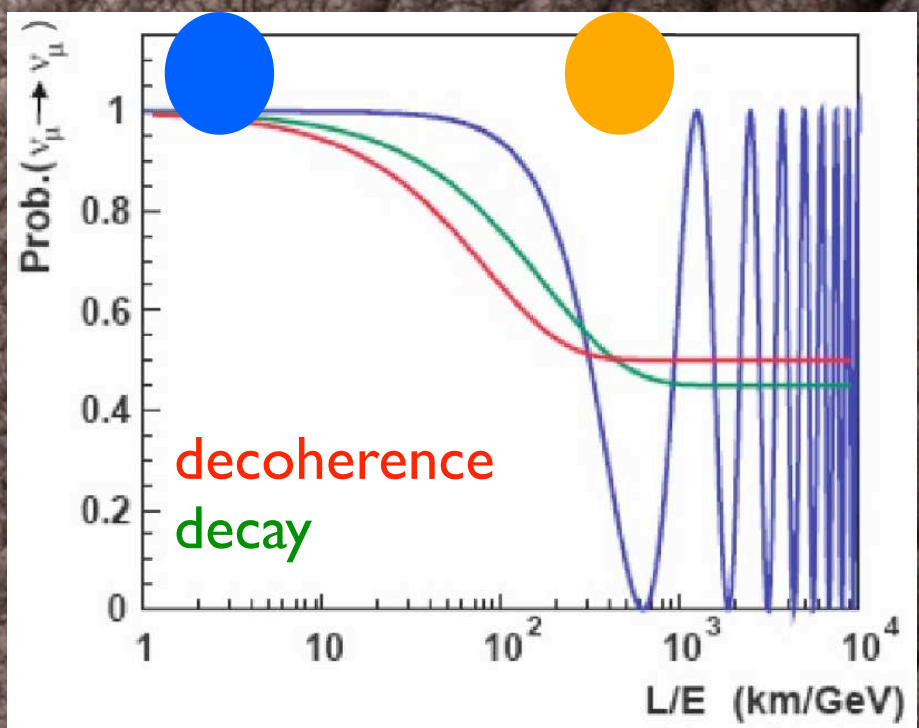
disappearance experiment goal

appearance experiment goal



L⟹ one fixed value (if one source)

E⟹ several decades in energy (spectrum)

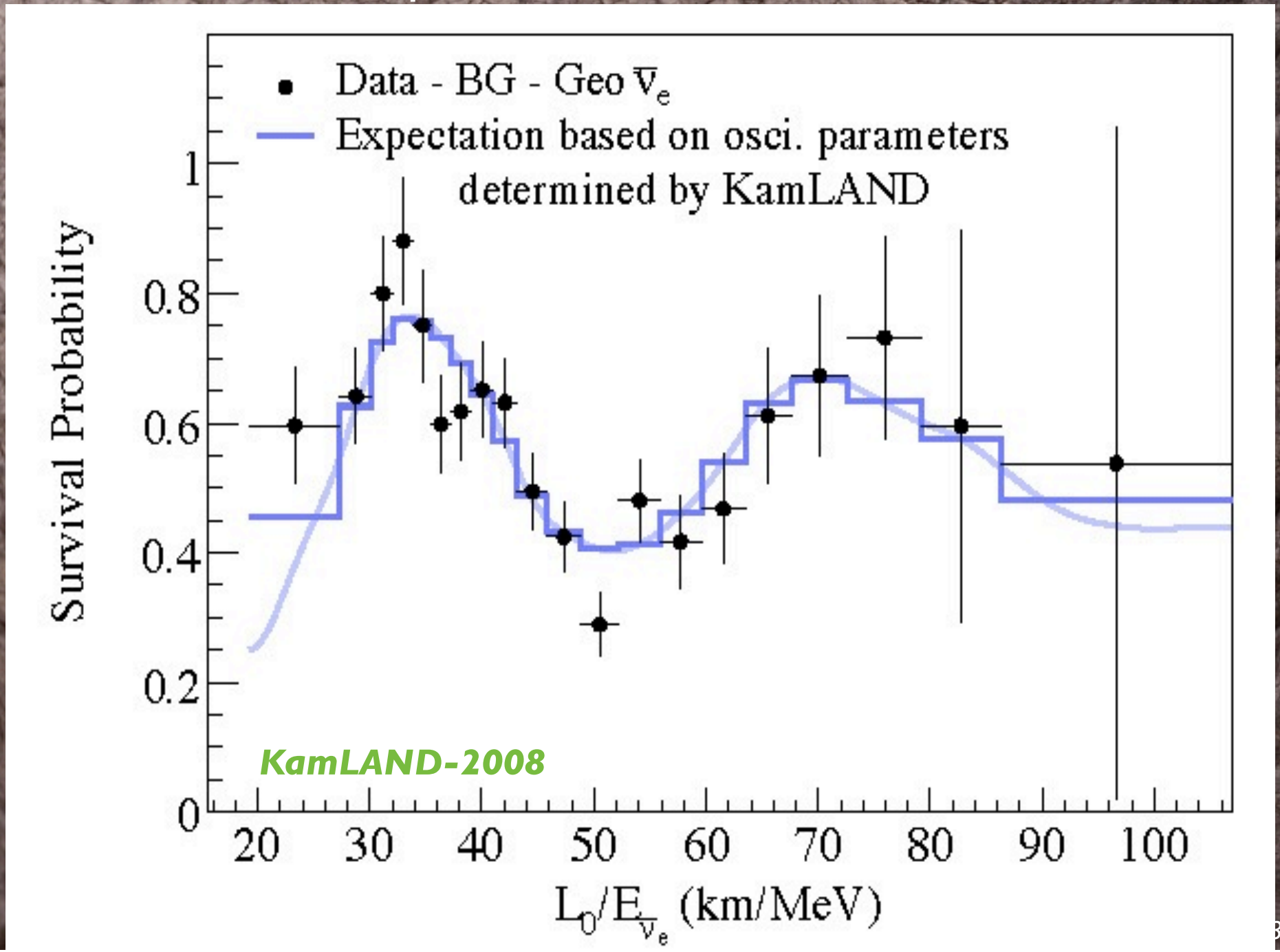


criteria

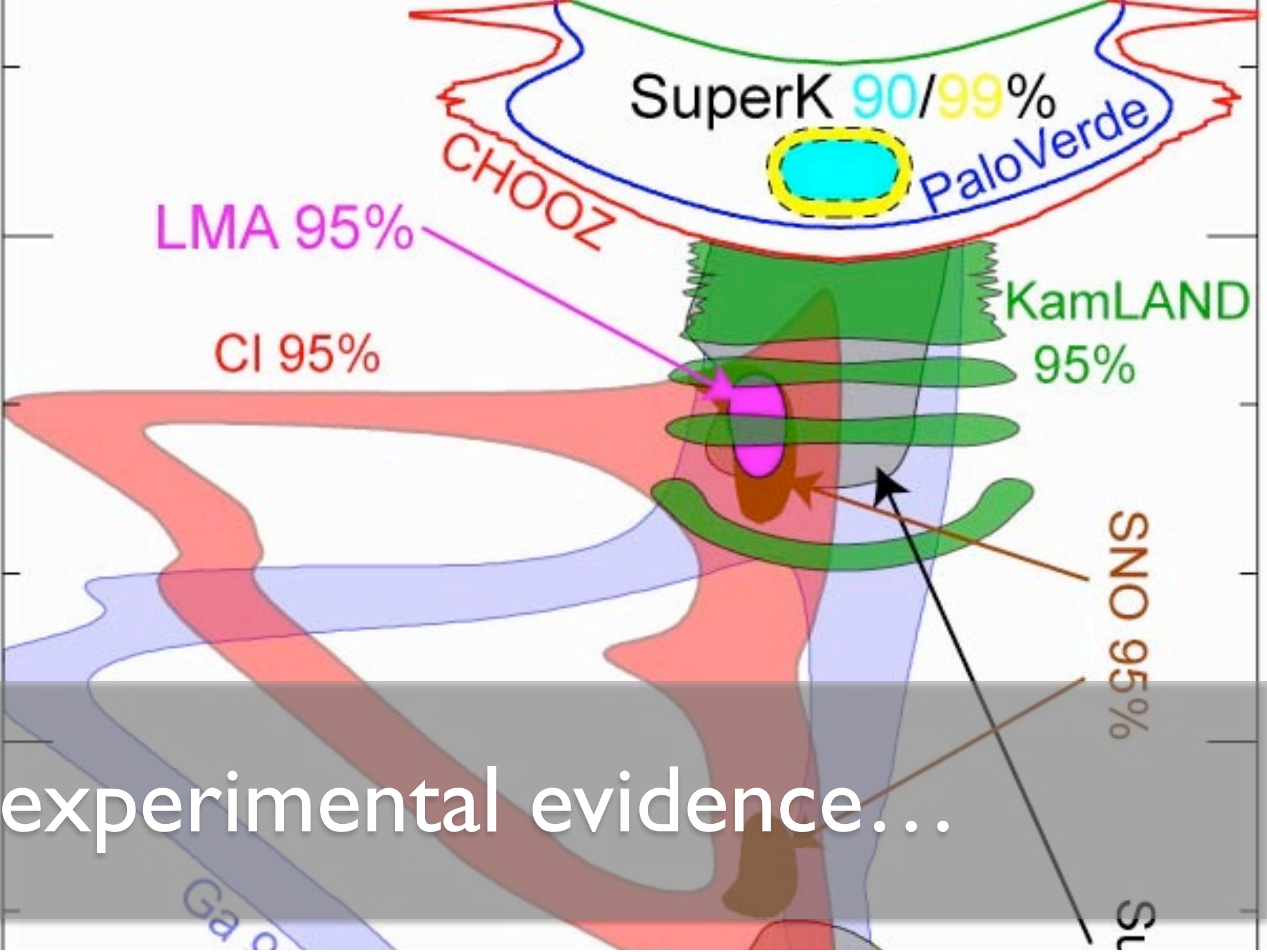
- Experimentalists control L and E $\Longrightarrow$ tune E/L ratio to maximise oscillation effect
- Length (L):
  - loss in flux ($1/L^2$)
  - longer allows to explore "Matter Effects" (or the MSW effect) or "Non-Standard-Interactions" (NSI) $\Longrightarrow$ not always desired (more observables)
- Energy (E):
  - determined by neutrino source (reactors, beams, sun, SNs, cosmic rays, etc)
  - cross-section: $\sigma(E)$ α E (linearly) [$\Longrightarrow$ statistics too]
    - cross-section regime: $\sigma(E)$ is *very rich* @ *O*(1 GeV)
  - lepton production threshold @ low energy CC interactions
  - detection efficiency: typically tailored to one lepton or even interaction type
    - example: interactions type $\Longrightarrow$ high particle multiplicities

"solar" E/L @ KamLAND (reactor-νs)

The most beautiful E/L plot so far...



& APC)



experimental evidence…

Solar & atmospheric "anomalies" appeared as *rather decoupled* problems
$\Longrightarrow$ due to very different Δm^2 & the smallness of θ_{13} (sub-leading)

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

"atmospheric" $\Longrightarrow \theta_{23}$ | θ_{13} & dirac-δ_{CP} | "solar" $\Longrightarrow \theta_{12}$

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix} \begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix} \begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

sub-leading | sub-leading

$P(\nu_\mu \to \nu_\mu)$ | $P(\nu_e \to \nu_e)$ & $P(\nu_\mu \to \nu_e)$ | $P(\nu_e \to \nu_x)$

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Double Chooz @ APC (Paris)

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

θ_{13} knowledge today

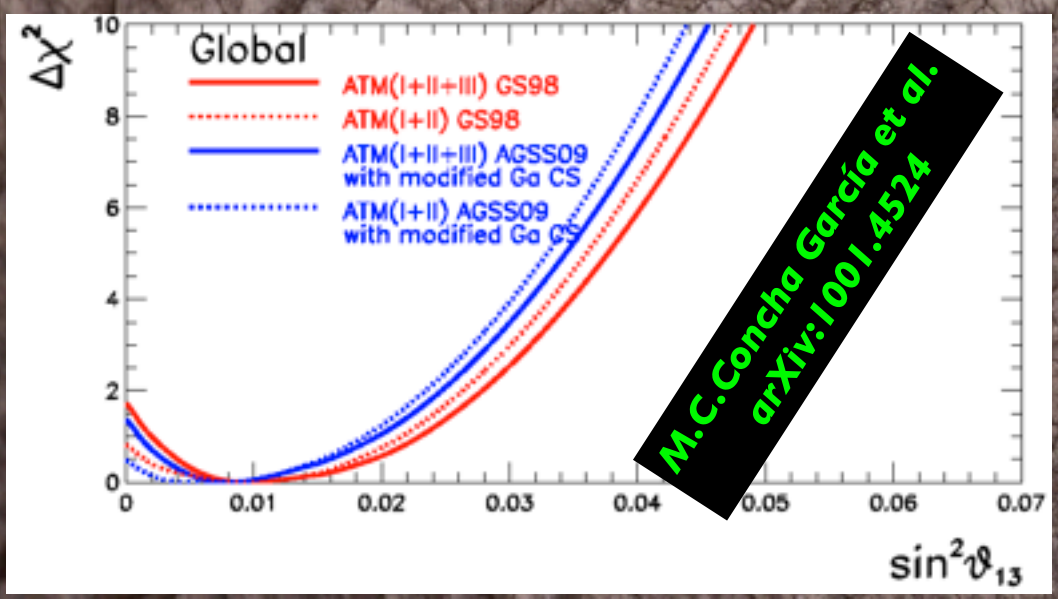
★$\sin^2(2\theta_{13}) < 0.12\text{-}0.20$

CHOOZ only @ 90%CL

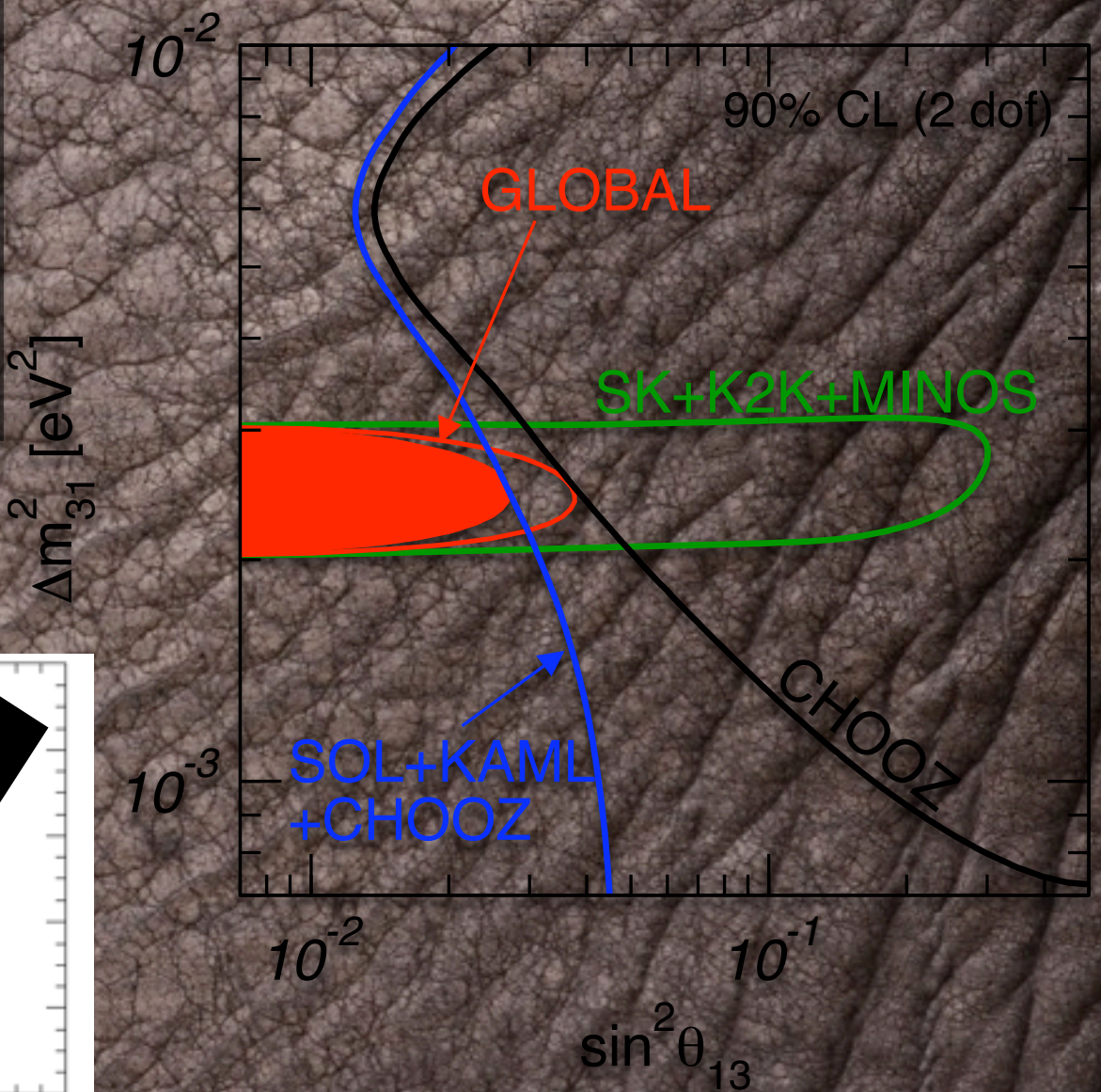
★$\sin^2(2\theta_{13}) < \sim 0.10$

Global Analysis @ 90%CL

★Global fit claims [Bari et al]⟹
"hint" for a non-zero θ_{13} @ ~1.5σ

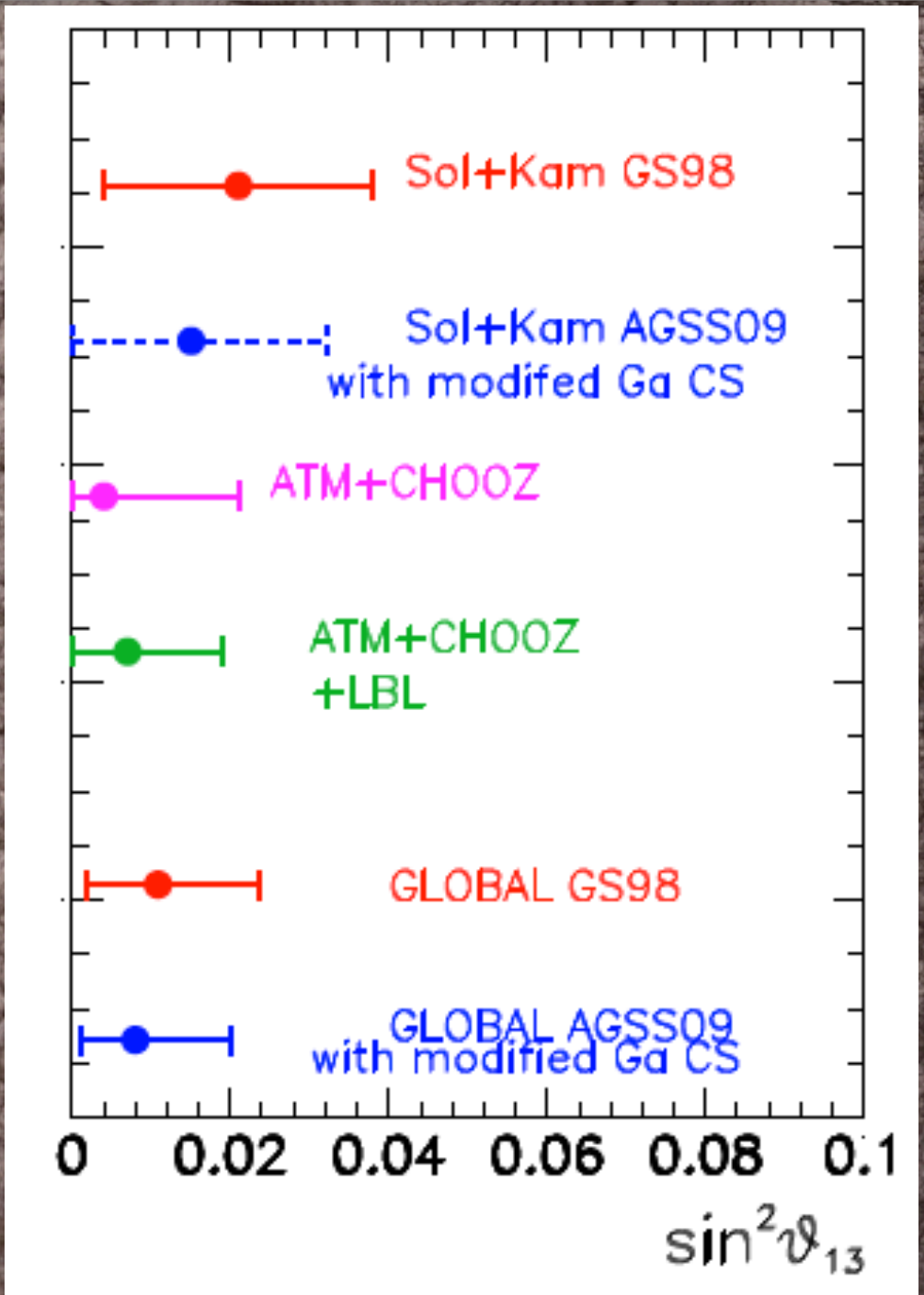


M.Concha-Garcia et al. arXiv:1001.4524
T.Schwetz et al. hep-ph/0606060



θ_{13} evidence today…

M.C.Concha García et al.
arXiv:1001.4524

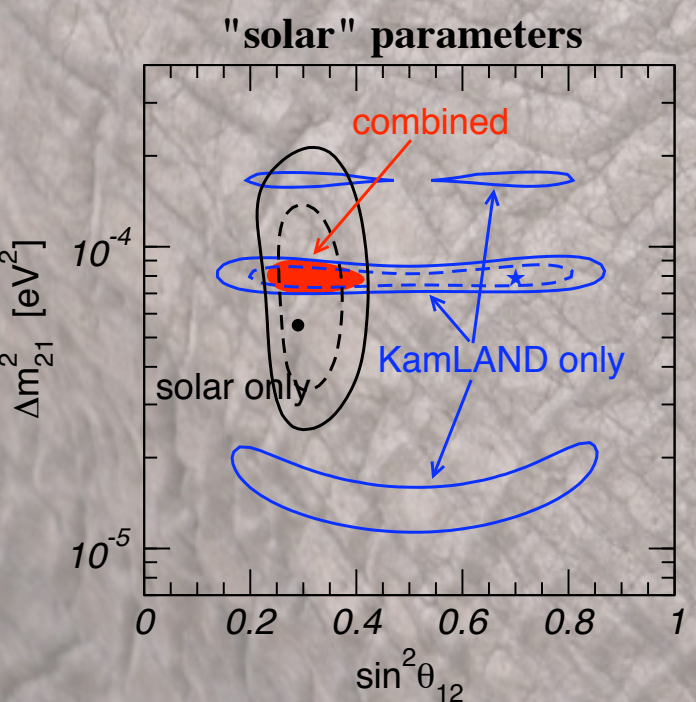


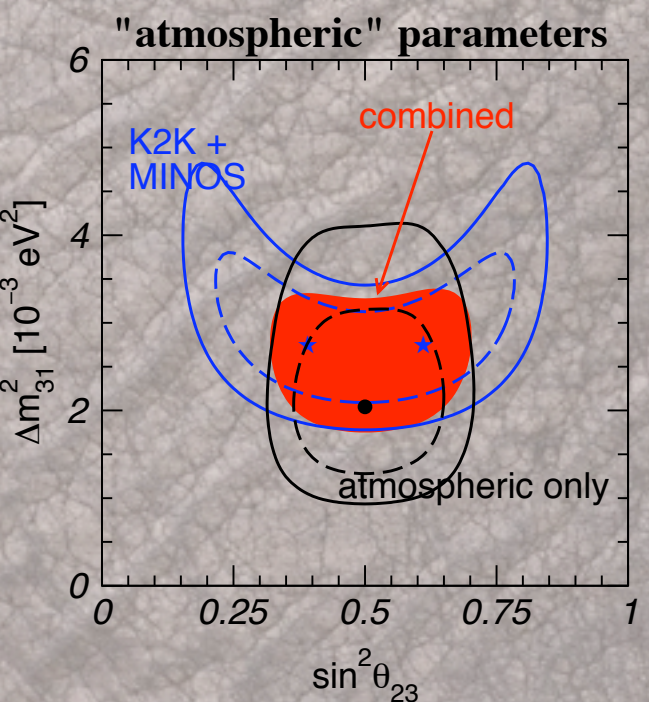
oscillations status

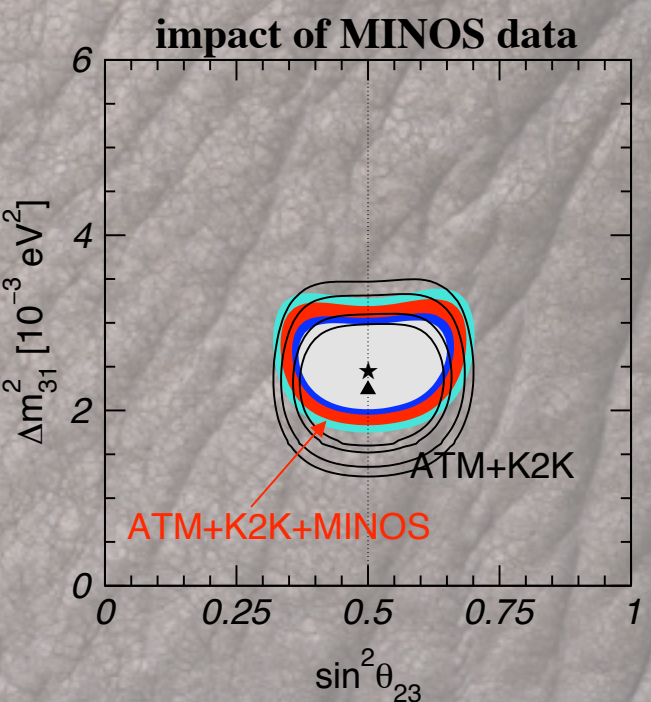
PMNS: large mixing (unlike CKM)...

T.Schwetz et al. hep-ph/0606060

parameter	bf$\pm 1\sigma$	1σ acc.	2σ range	3σ range
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	7.9 ± 0.3	4%	$7.3 - 8.5$	$7.1 - 8.9$
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$	$2.5^{+0.20}_{-0.25}$	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%	$0.38 - 0.64$	$0.34 - 0.68$
$\sin^2\theta_{13}$	–	–	≤ 0.025	≤ 0.041

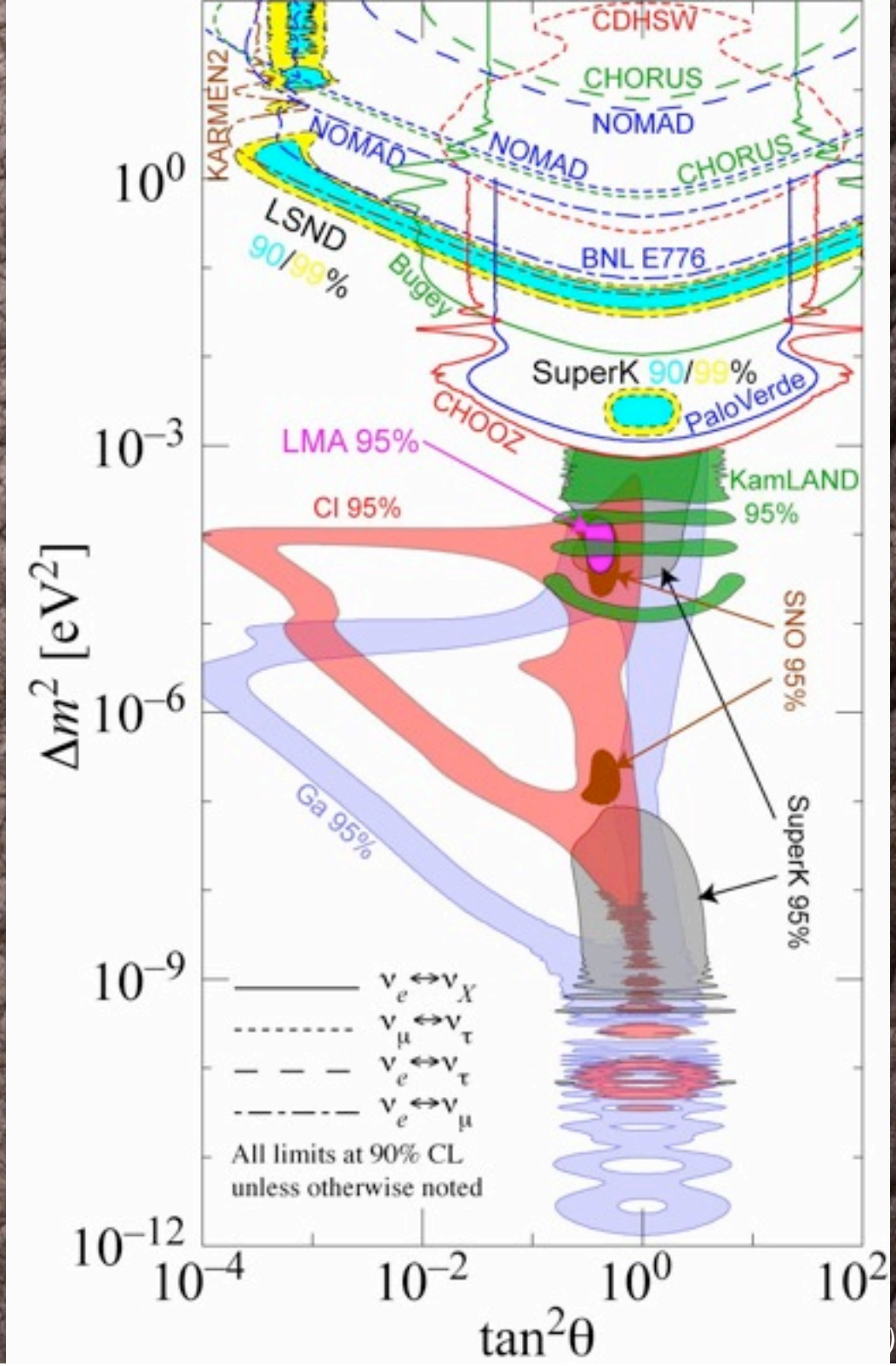


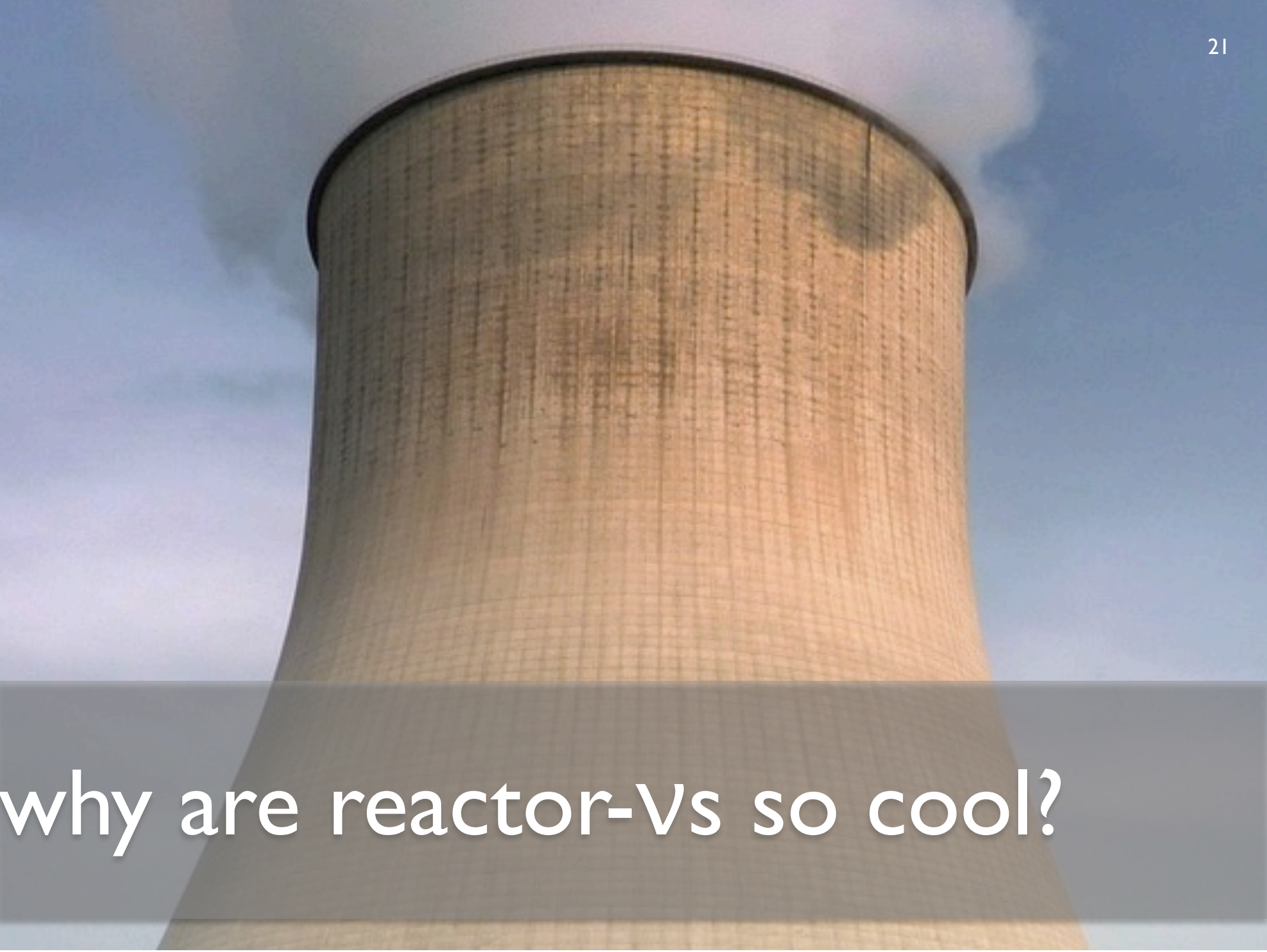




visual summary of experimental neutrino oscillations phase-space campaign…

$\theta_{12}, \theta_{23}, \Delta m^2_{12}, \Delta m^2_{23}$



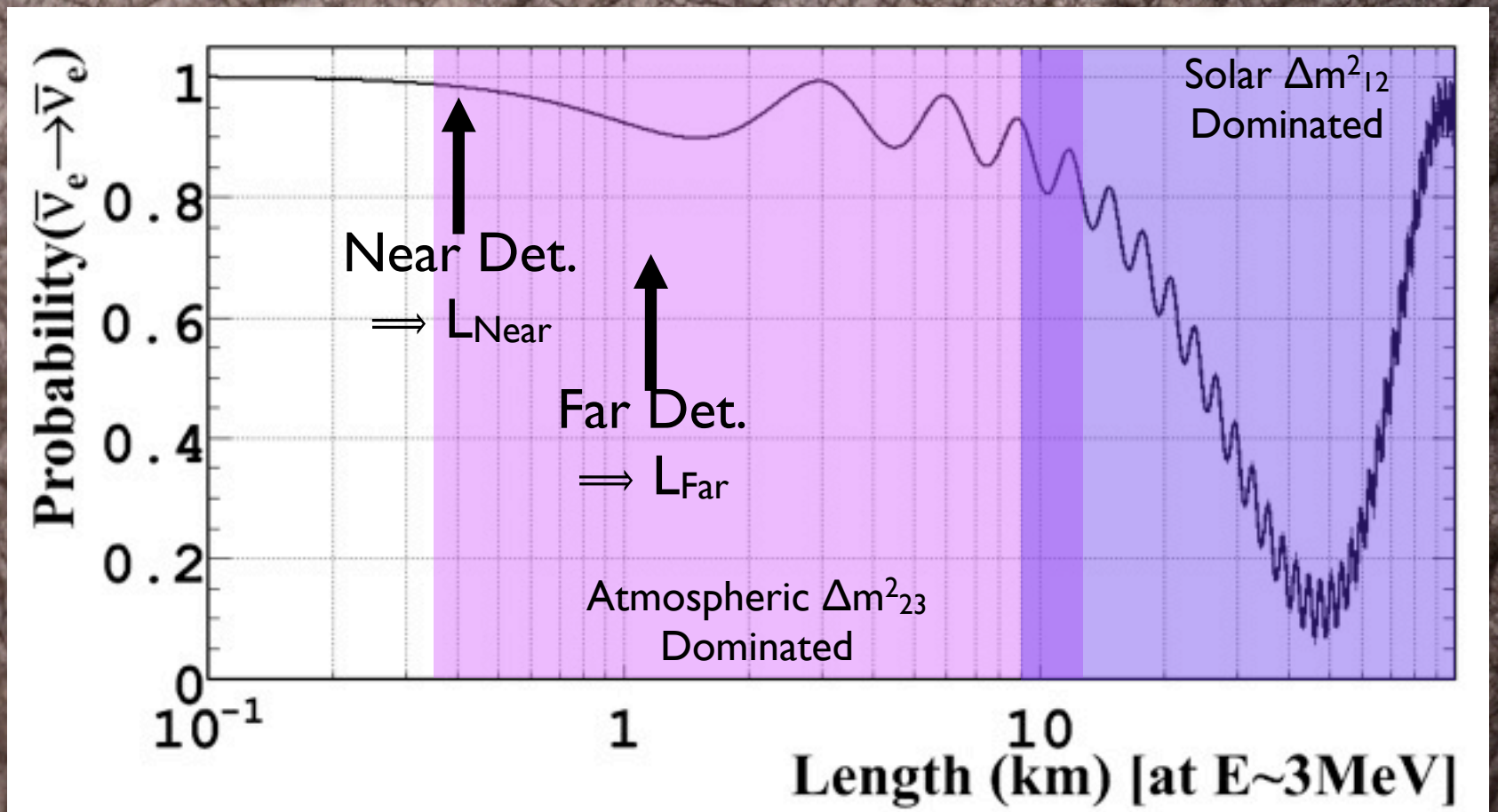


why are reactor-vs so cool?

strategy...

$$P(\nu_e \rightarrow \nu_e) \sim 1 - \sin^2(2\theta_{13}) \sin^2(\Delta m^2_{23} L_o/E)$$

[plot: E = 3MeV, $\sin^2(2\theta_{13}) = 0.1$, $\Delta m^2_{23} = 2.5 \times 10^{-3} eV^2$]



ND$\Longrightarrow$ reduce systematic uncertainties (mainly flux rate & shape) wrt FD

DC strongly involved in leading efforts to improve **reactor flux measurements**

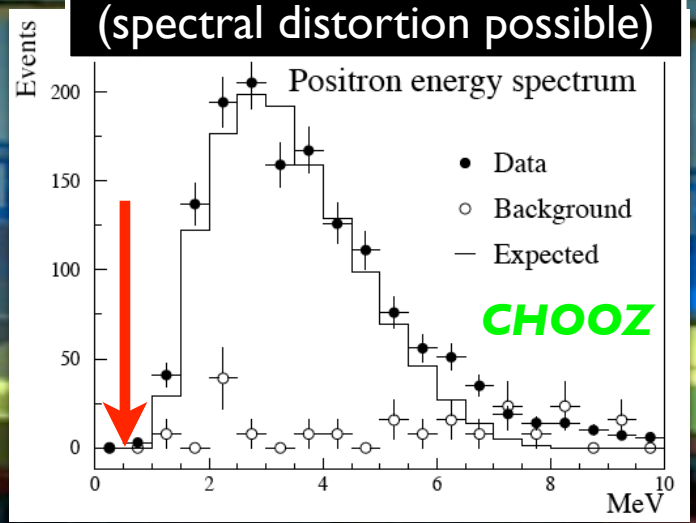
why reactors then?

- copious (high statistics) source and free νs
  - highly reliable beam $\Longrightarrow$ beam OFF cost O(1 M€/day) (strike-proof)
- excellent **δ(E/L) resolution** $\Longrightarrow$ perfect for disappearance experiment
- [for θ_{13} searches] **short baselines** $\Longrightarrow$
  - small detectors (less expensive)
  - negligible matter & "NSI" effects (useful for global analysis input)
- high & well known cross-section (no NC contamination)
- **BG** $\Longrightarrow$ overburden, shielding, radio-purity (possible "reactor OFF")
- **trivial multi-detector extrapolation**: flux scales with $1/L^2$ (isotropic)
- **rich calibration energy scale**: many radioactive sources @ few MeV
- 1 unknown & 1 observable $\Longrightarrow$ unambiguous θ_{13} signature
  - compelling *synergy wrt to beam results (several unknown's) & global picture!*

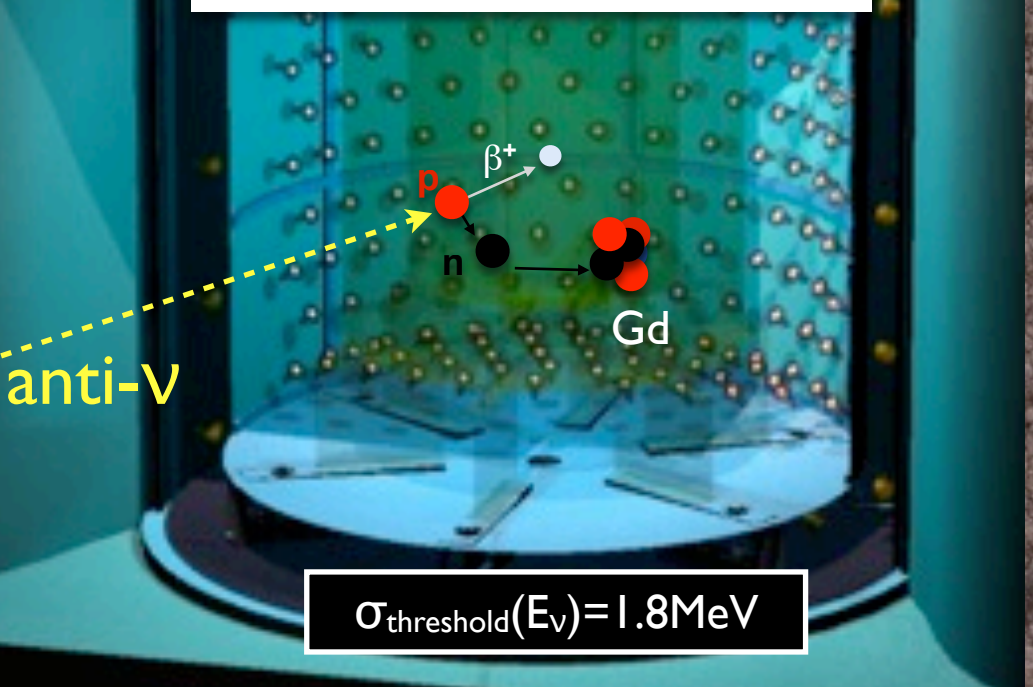

OFF
ON
Rue de l'Hayaumart
Google reactor monitor
Anatael Cabrera (CNRS-IN2P3-APC)

inverse-β reaction

β+ Energy ⟹ ν Energy (spectral distortion possible)

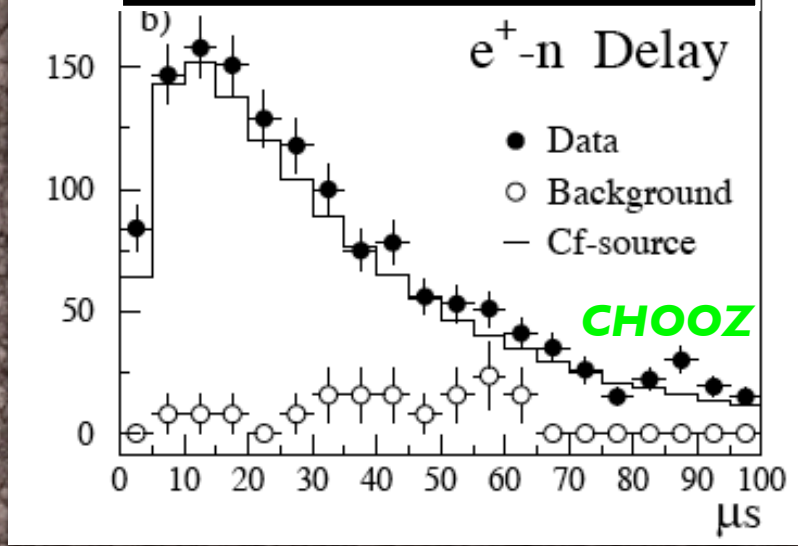


$$\bar{\nu} + p \rightarrow e^+ + n$$



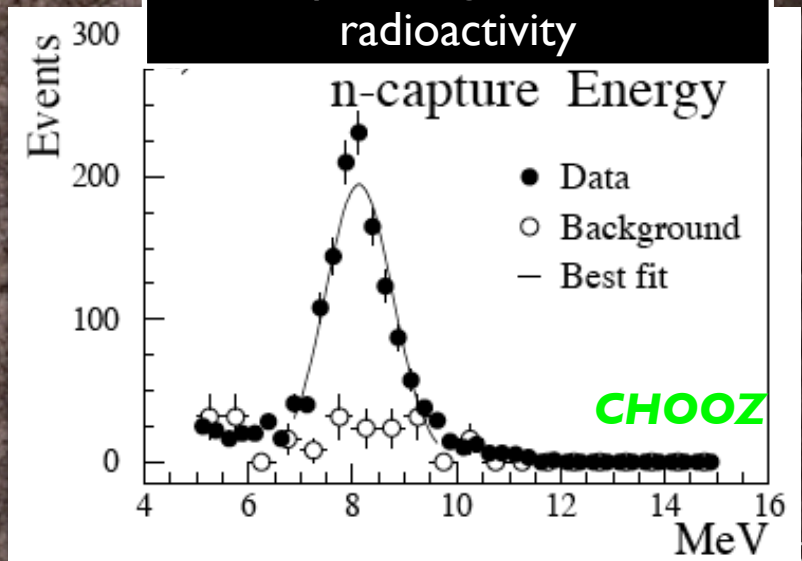
$\sigma_{threshold}(E_\nu) = 1.8\,MeV$

n is captured Δτ after β+



Coincidence Δτ depends on Gd concentration
⟹ excellent BG rejection mechanism

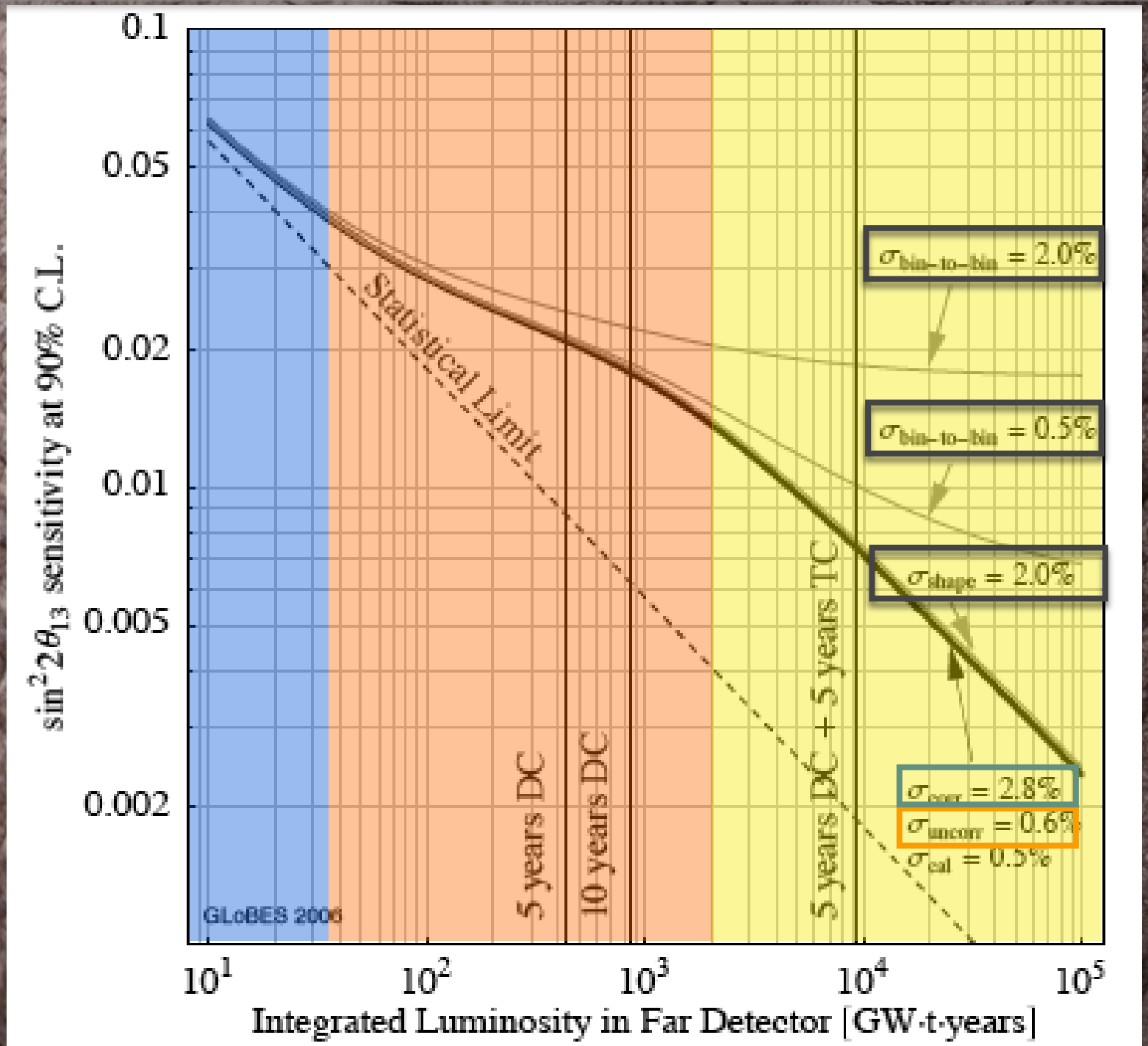
n-Gd capture signal: well above radioactivity



Apollonio et al (CHOOZ) hep-ex/0301017

...2P3 & APC)

sensitivity evolution

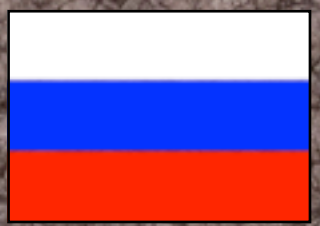


Double Chooz Collaboration





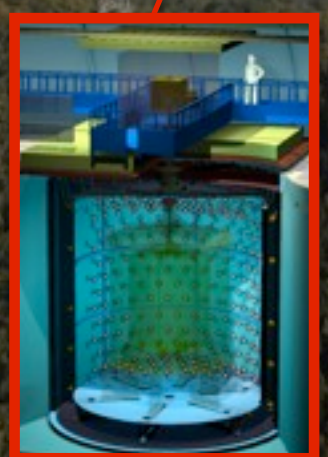




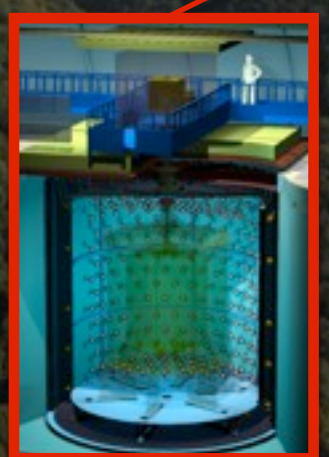
~150 physicists in 35 institutions over 9 countries in 3 continents

Our experimental setup…

Chooz Reactors
Power: 8.5GW$_{th}$
(N4s: most powerful)



Near
<L> 400m
400ν/day
120mwe
Target: 8.2t
Early 2012



Far
<L> 1050m
50ν/day
300mwe
Target: 8.2t
end of 2010

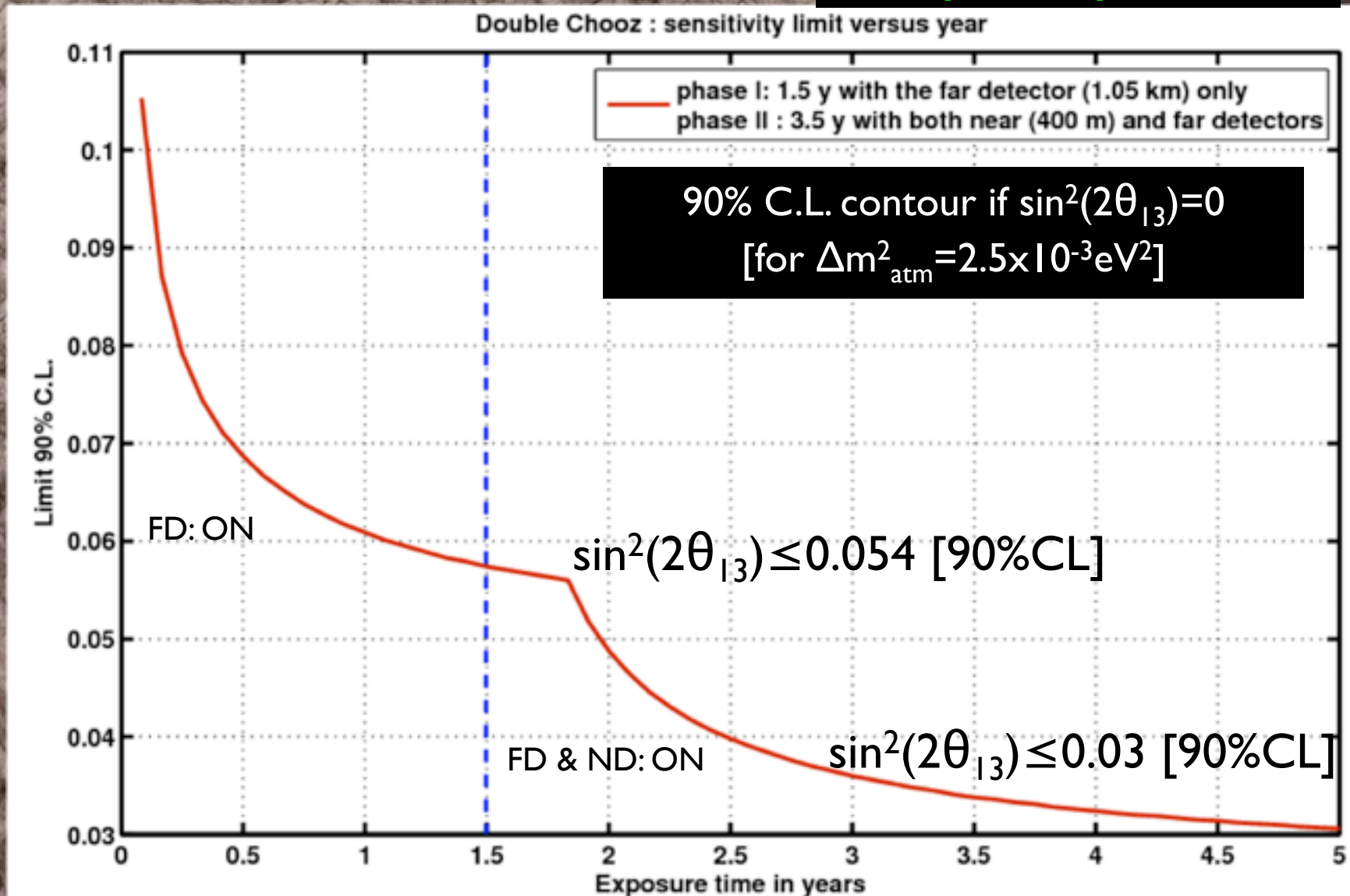
our θ_{13} knowledge versus time...

DC Proposal: hep-ex/0606025

Phases:

DC-I (FD only)
10x more statistics than CHOOZ
Limited by:
rate and shape reactor flux uncertainties (2.8%)

DC-II (FD+ND)
more robust
Limited by:
inter-detector normalisation systematic uncertainties (0.6%)

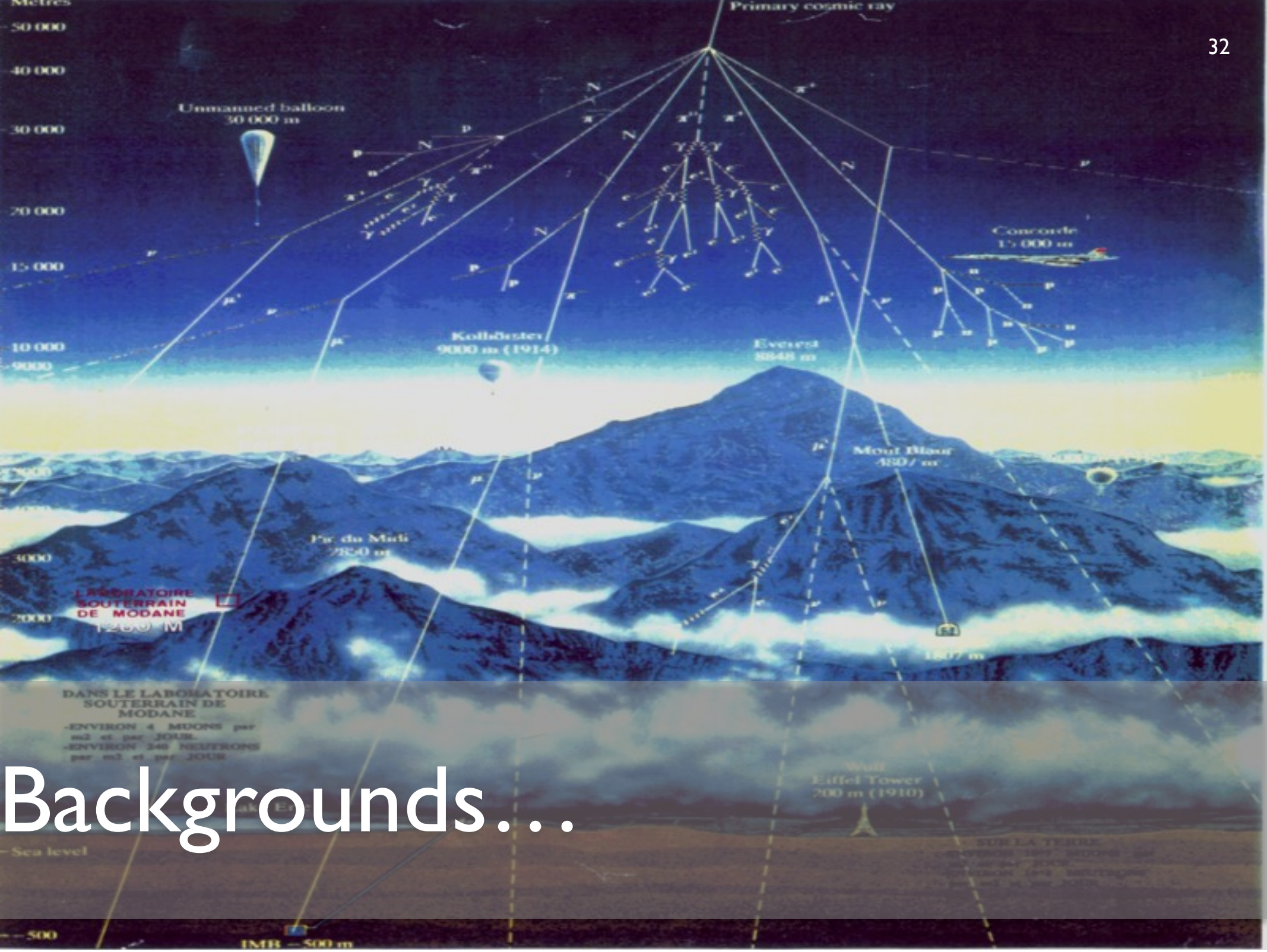


Discovery @ 3σs if $\sin^2(2\theta_{13})>0.05$

how do we do that?

our strategy

- flux uncertainty (~2%) goes negligible⟹ near Detector
- S/BG > 50⟹ huge statistical power (two most reactors in the world)
  - fewer reactors⟹ maybe "reactor-off"
  - large or many detectors? S/B often scales with radius (Volume/Surface)
- reduce & understand backgrounds in situ (even if no "reactor-off")
  - optimal detector overburden, design, shielding, radio-purity, etc…
- reduce & understand experimental systematics: design & calibration
  - inter-detector normalisation: ≤0.6%
  - inter-detector energy calibration: ≤2%

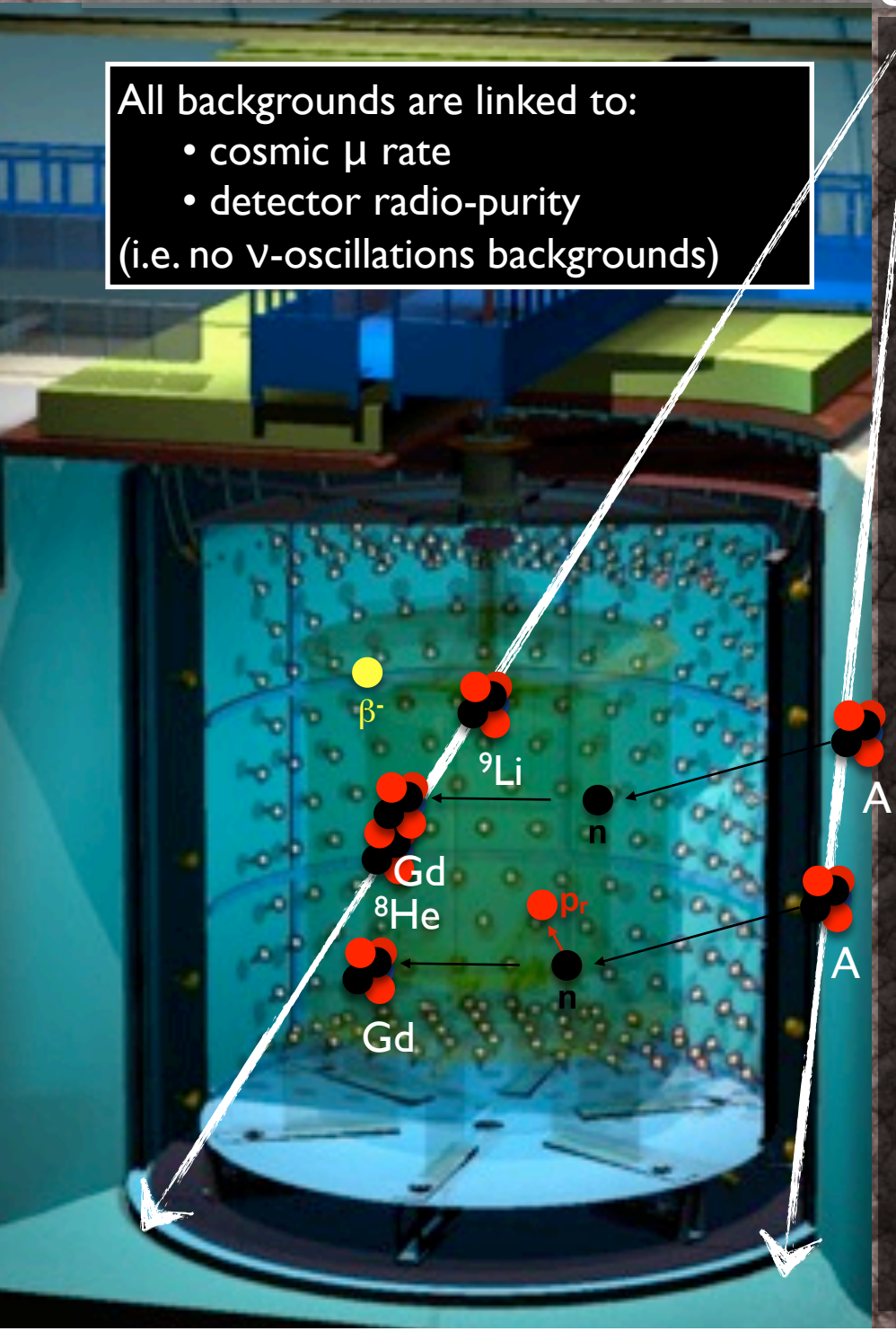


Backgrounds…

backgrounds…

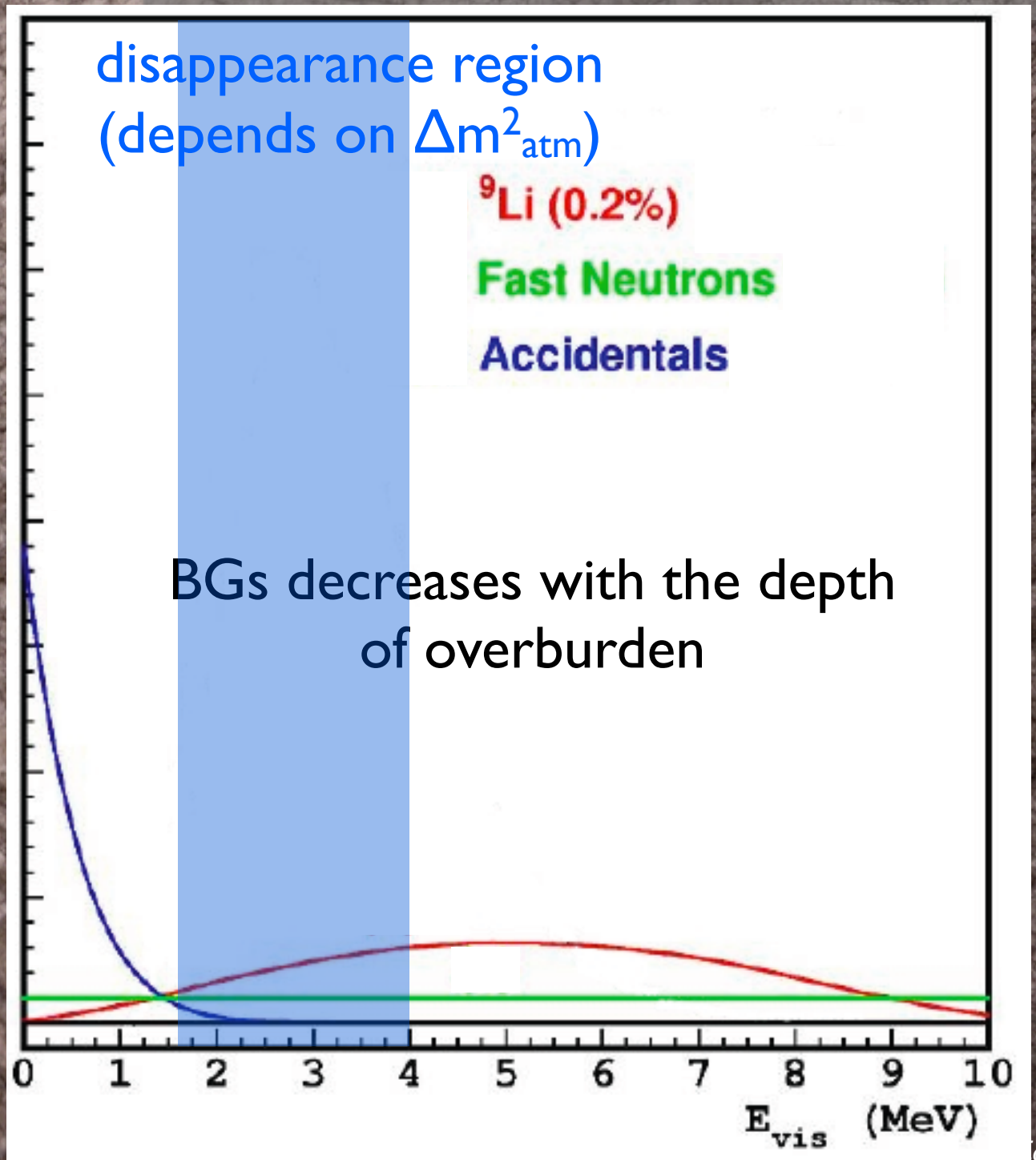
All backgrounds are linked to:
- cosmic μ rate
- detector radio-purity

(i.e. no ν-oscillations backgrounds)



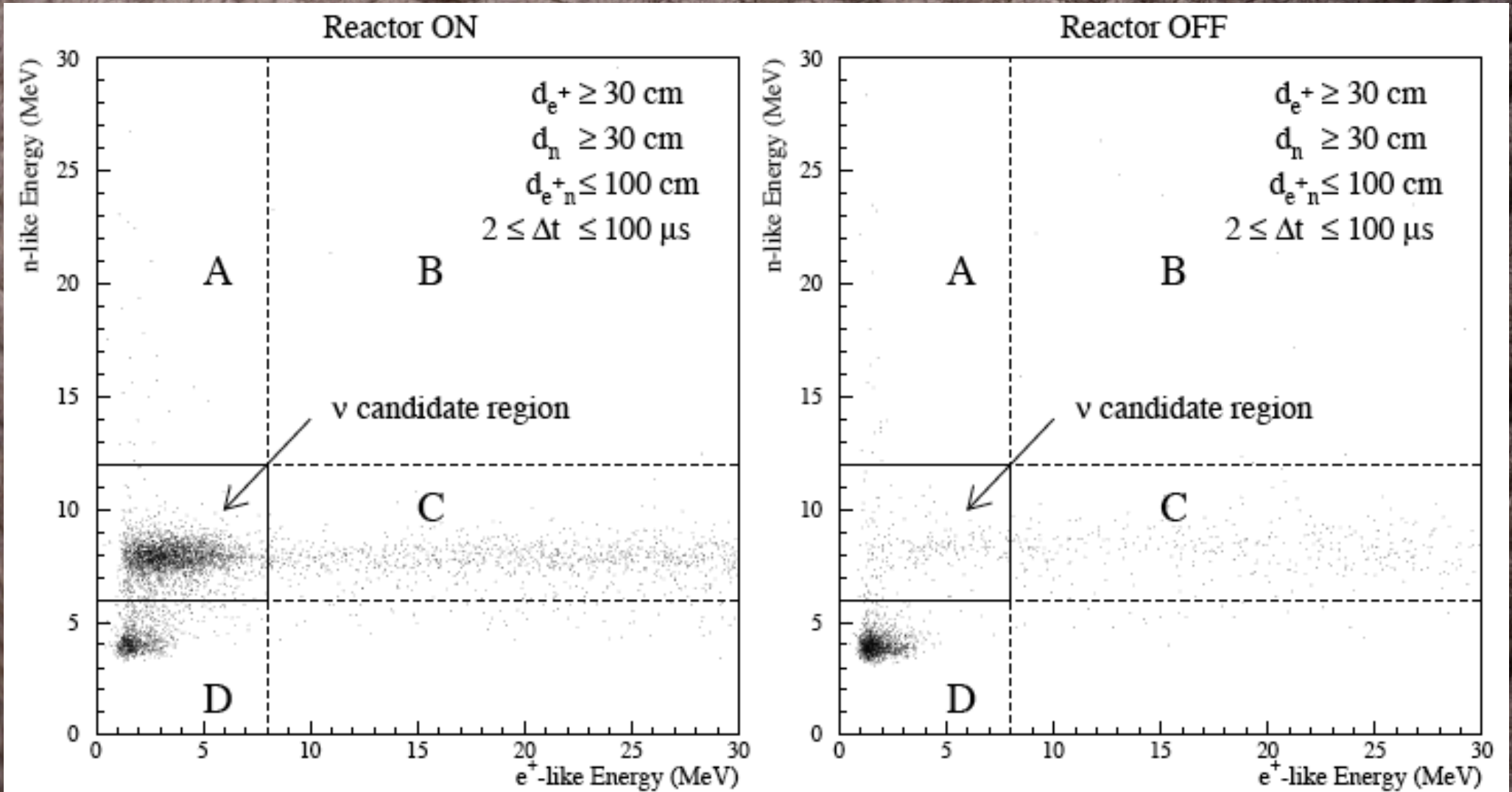
- BGs are reduced (wrt CHOOZ) ⟹ detector design & measure in situ
- μ tagging and detection ⟹ IV, OV detectors [see later] and dedicated electronics
- **Correlated BGs**
  - β-n Isotopes (half-life time ~100ms)⟹ impossible to veto (time/location)
  - Fast-n's p-recoil & Gd capture
- **Accidental BGs**
  - radio-active β^- (rate @ ID <10Bq)
    - radio-purity campaigns & all installation under cleaning environ.
  - fast-n thermalises and captures on Gd

BG spectra


disappearance region
(depends on Δm^2_{atm})
^{9}Li (0.2%)
Fast Neutrons
Accidentals
BGs decreases with the depth
of overburden
0
1
2
3
4
5
6
7
8
9
10
E_{vis} (MeV)

experimentalist's dream…

switched off signal => measure background "naked"!



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

more reactors⟹ less likely!

Anatael Cabrera (CNRS-IN2P3 & APC)

BG rates

FD ⟹ much input from CHOOZ experiment
ND⟹ extrapolation from FD/CHOOZ to new site

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

DC Proposal: hep-ex/0606025

systematics breakdown

Error Source	Error Type	Error Description	CHOOZ Absolute	DC Absolute	DC Relative
		Reactor			
Reactor		Production Cross Section	1.90%	1.90%	
		Core Powers	0.70%	0.70%	
		Energy per Fission	0.60%	0.60%	
		Solid Angle/Bary. Displct.			0.20%
		Detector			
		Detection Cross Section	0.30%	0.10%	
Detector	Free H in TG	Volume	0.30%	0.20%	0.20%
		Fiducial Volume	0.20%	0.20%	
		Density		0.10%	0.01%
		H/C (Chemical Composition)	0.80%	0.80%	0.10%
	Electronics	Dead Time	0.25%		0.00%
		Analysis			
Analysis	Particle Id				
	Positron	Escape	0.10%		
		Capture	0.00%		
		Identification Cut	0.80%	0.10%	0.10%
	Neutron	Escape	1.00%		
		Capture (% Gd)	0.85%	0.30%	0.30%
		Identification Cut	0.40%	0.10%	0.10%
	Anti-neutrino	Time Cut	0.40%	0.10%	0.10%
		Distance Cut	0.30%		
		Unicity (neutron multiplicity)	0.50%		
		Efficiency uncert due to bkg			
Total			**2.90%**	**2.31%**	**0.46%**

Upgraded to expected ND location

N2P3 & APC)

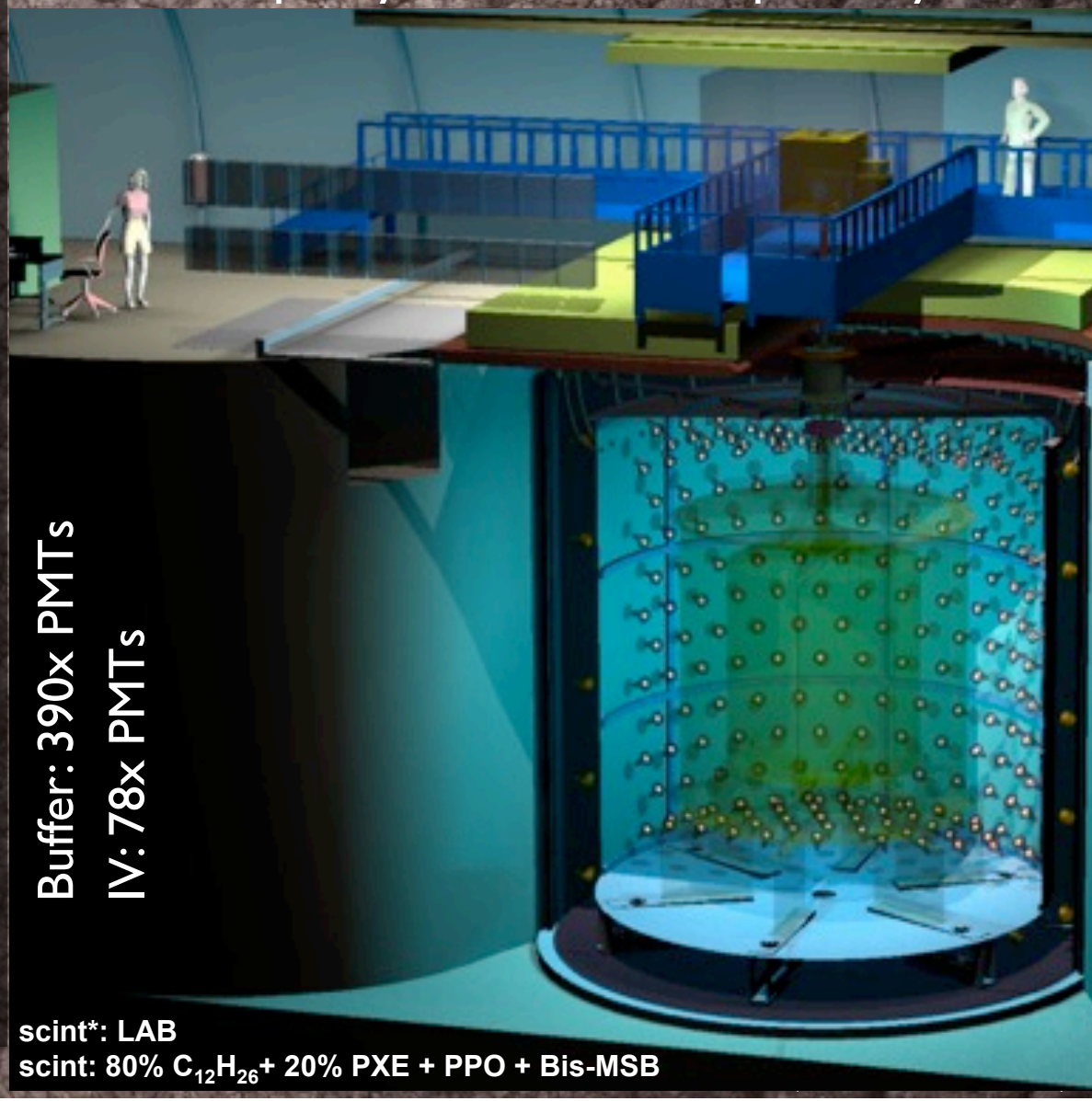
the detector: a θ_{13}-LAND

a θ_{13}-LAND…

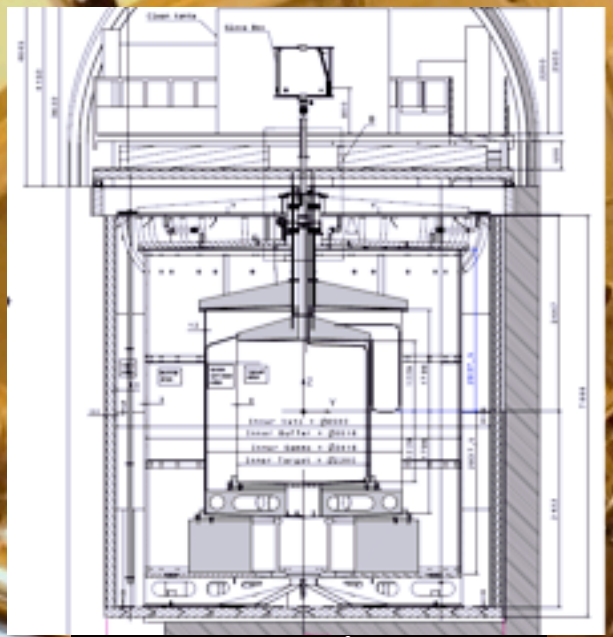
- **Pit**: 7mx7m (FD: CHOOZ lab) ⟹ max. fiducial volume cylinder
- **Inner-Detector**
  - **Target**: acrylics + scint & 0.1%Gd ⟹ n-Gd interaction region
  - **γ-Catcher**: acrylics + scint ⟹ extra calorimetry containment
  - **Buffer**: oil no scint ⟹ isolation
- **Inner-Veto**: scint* ⟹ tagged μs and fast-n
- **Outer-Veto**: scint-strips (a la MINOS) ⟹ tagged near-by μs
- **γ-Shield**: 15cm steel ⟹ reduce rock-γs (singles)
- **Glove-Box** ⟹ calibration apparatus contamination-less

θ_{13}-LAND must...

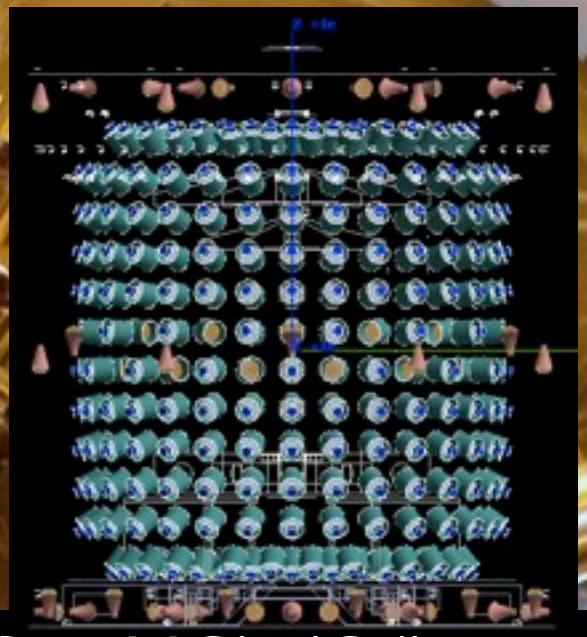
- inter-detector comparison systematic <1%
- radio-purity & material compatibility



scint*: LAB
scint: 80% $C_{12}H_{26}$+ 20% PXE + PPO + Bis-MSB



engineer's view

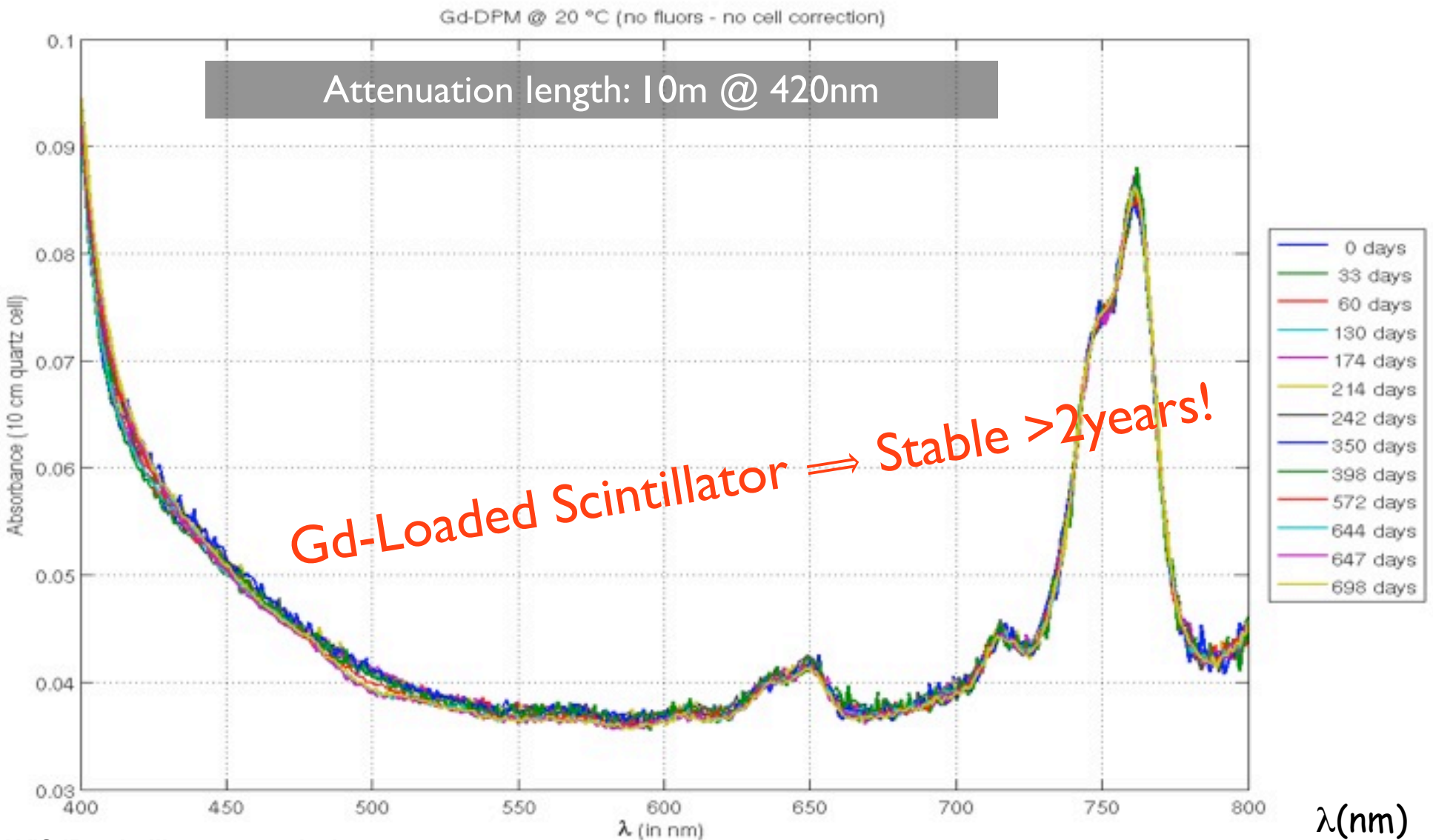


Our MC's (G4)view

our favorite's view…

Gd doped liquid scintillator

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



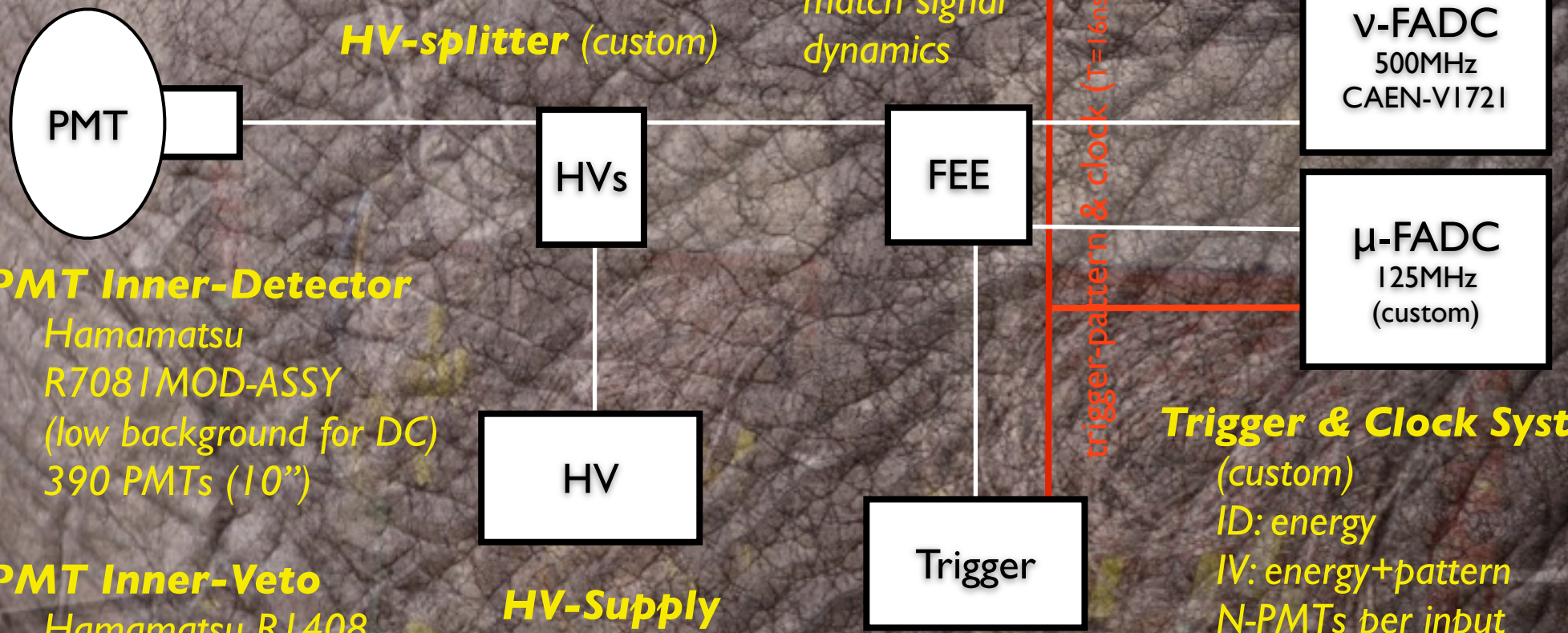
UV-VIS-IR scintillator transmission

Anatael Cabrera (CNRS-IN2P3 & APC)

readout & online

one channel

Trigger Rate <300Hz (cosmic-μs @ ND)



HV-splitter *(custom)*

FEE *(custom)*
match signal dynamics

VME-Bus
DAQ software in Ada

PMT Inner-Detector
Hamamatsu
R7081MOD-ASSY
(low background for DC)
390 PMTs (10")

PMT Inner-Veto
Hamamatsu R1408
78 PMTs (8")
(from IMB)

HV-Supply
CAEN-A1535P

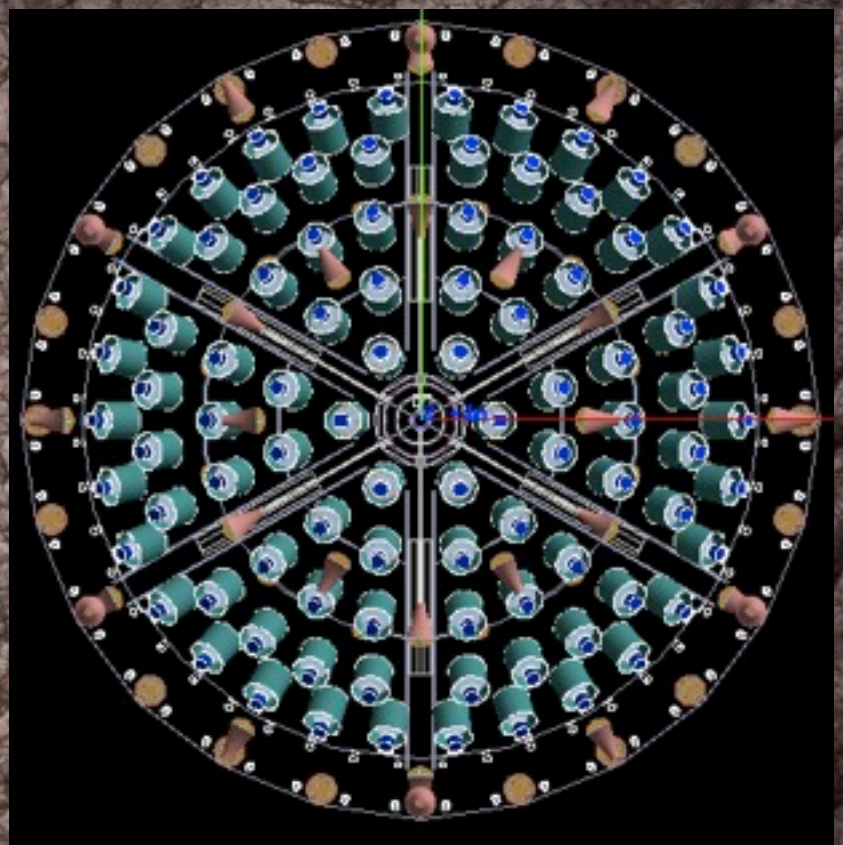
Trigger & Clock System
(custom)
ID: energy
IV: energy+pattern
N-PMTs per input

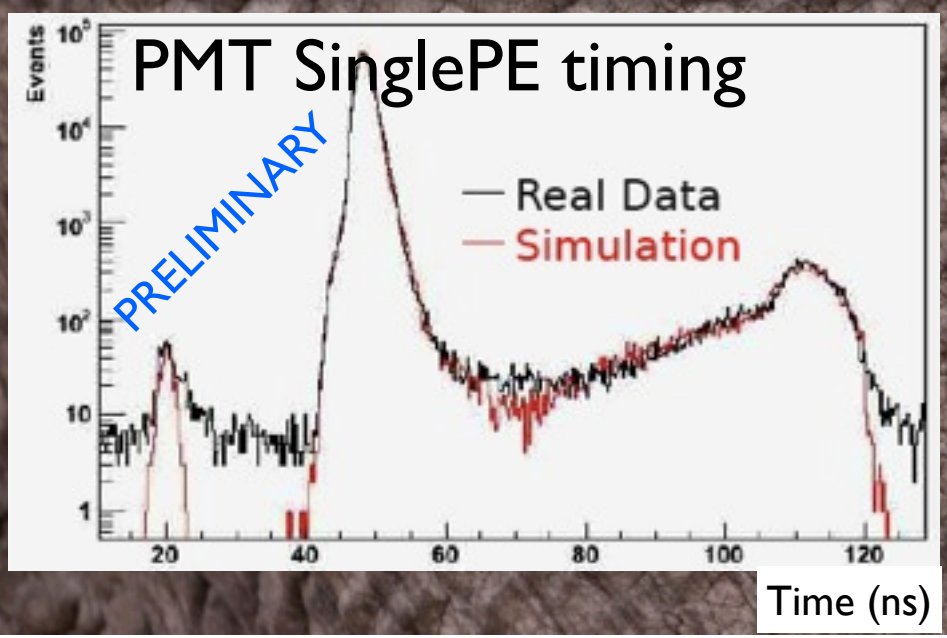
online/electronics integration benches…
"*Vertical Slice*" (1PMT) @ APC
"Super-Vertical Slice" (30 PMTs) @ MPIK

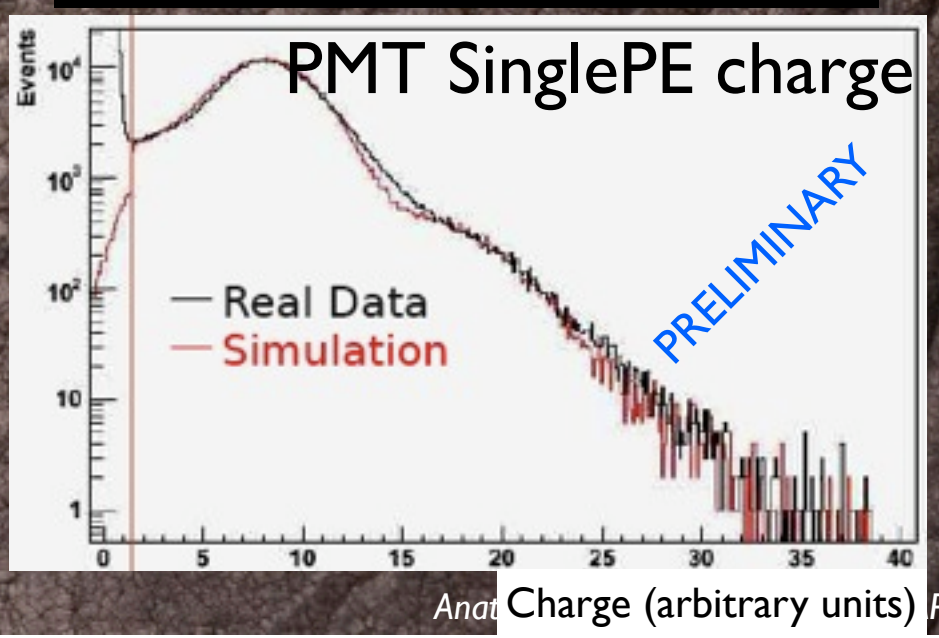
OV readout a la OPERA (Hamamatsu M64 + Maroc2-chip)

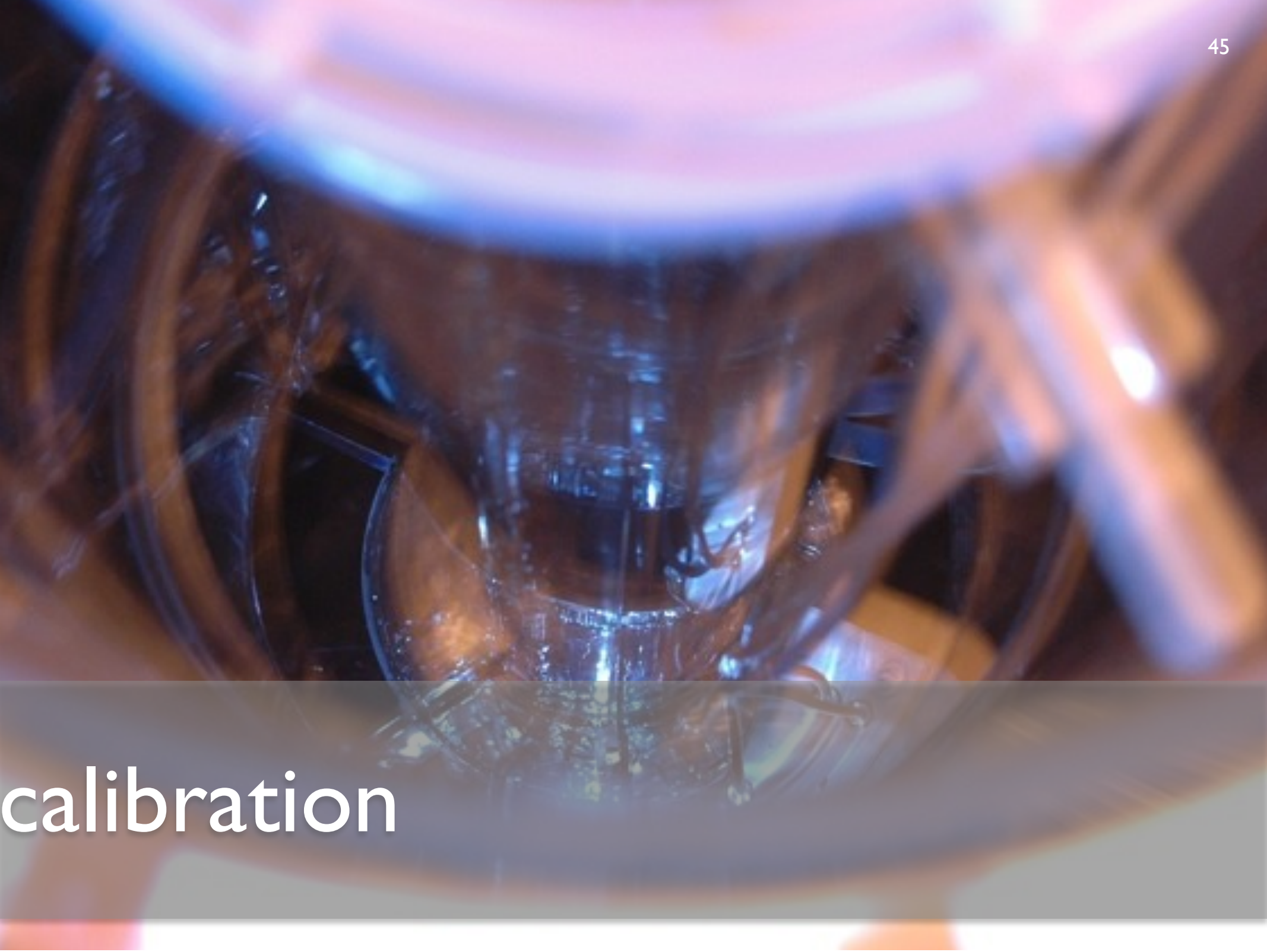
detector & readout simulation...

- Complete detector simulation...
- Physics: Geant4
- Optical Interface: Geant4
  - based on "GLG4sim"
- dedicated detector simulation (optical interface, PMT, electronics, trigger) tuned to test-bench data⟹ **understand/ evaluate systematics**





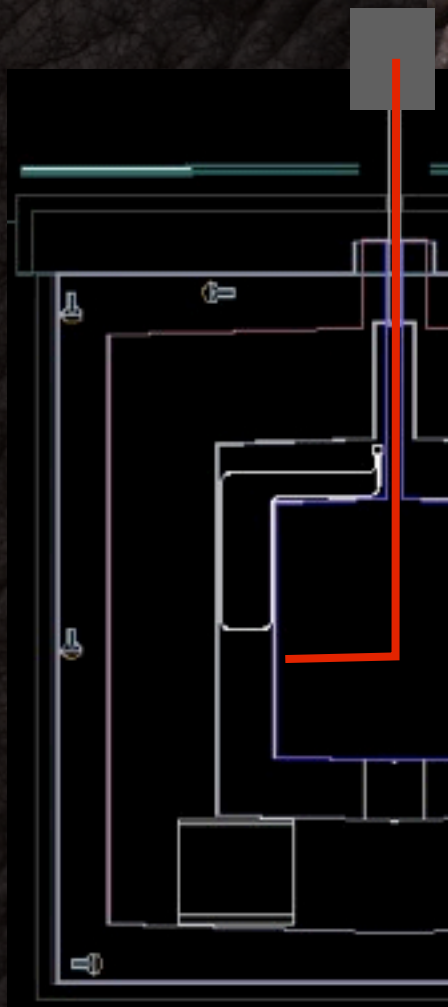




calibration

calibration…

- **Redundancy** ⟹ cross-check & understand inter-detector systematics
- light sources (embedded, i.e. non-intrusive): LEDs in ID and IV
  - monitor stability of readout (timing, gain) and scintillator
- light sources (deployed): LED, red-laser & UV-laser
  - PM gain, timing, scintillator stability & attenuation
- radioactive source: across most energy scale
  - H-capture, Cs^{137}, Na^{22}, K^{40}, Co^{60}, etc
- n-sources: n capture on Gd (study efficiencies)
  - Cf^{252}(untagged) & AmBe (light tagged)⟹ 3D deployable
- 3D calibration strategy: map full detector response
  - along z-axis, articulated arm (off z-axis), GC & Buffer tubes
- 2 detectors⟹ calibration source absolute knowledge less important
  - same source response comparison ND and FD (cancel some systematics)



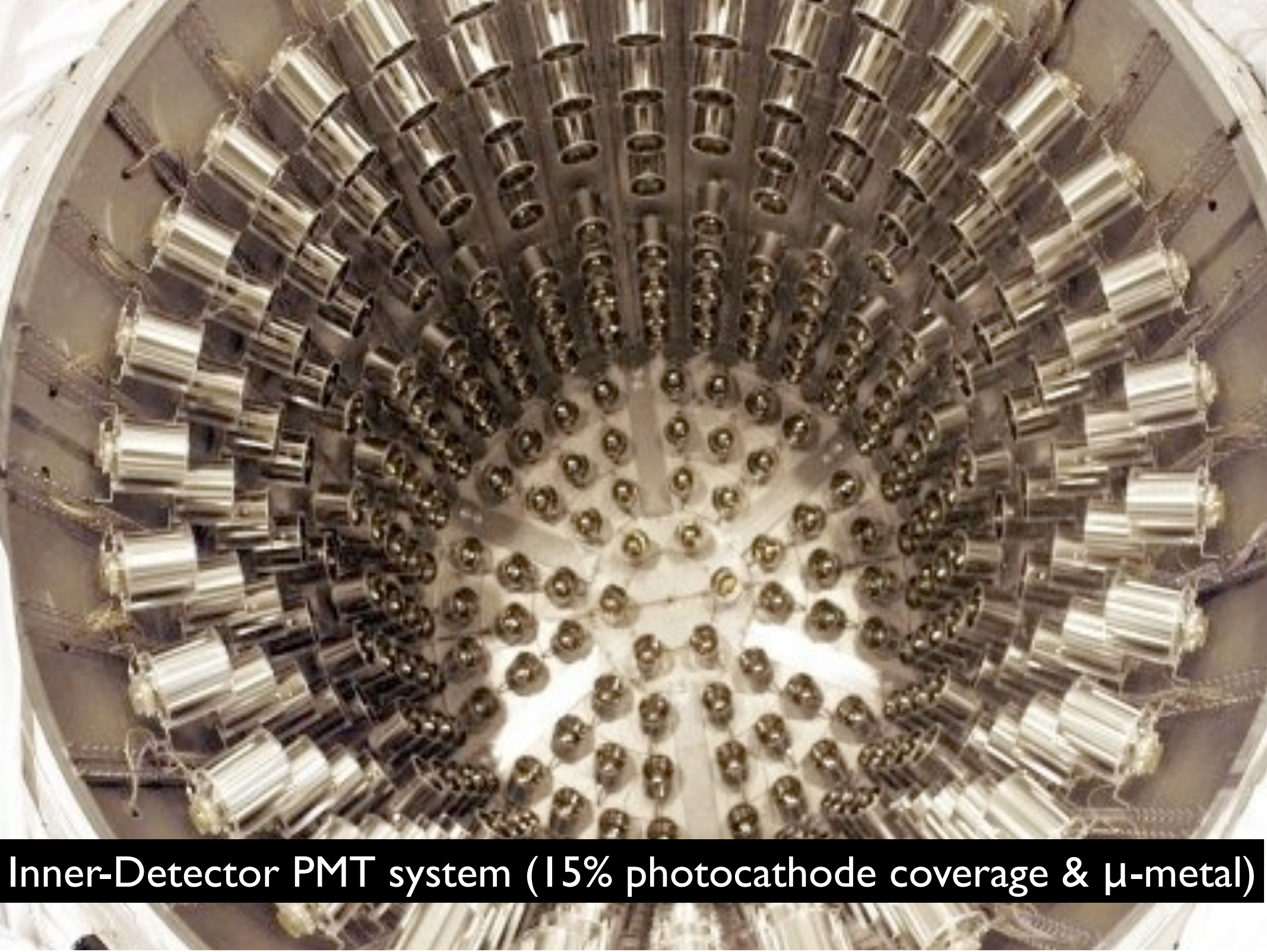
far detector status:
constructed⟹ now to be filled!


the neutrino source: 2 of the most powerful reactors in the world


FD underground lab access: 300m walk @ a small angle


Inner-Veto detector (scintillator)⟹ tag μs & possible fast-neutrons

Inner-Detector PMT installation



Inner-Detector PMT system (15% photocathode coverage & μ-metal)

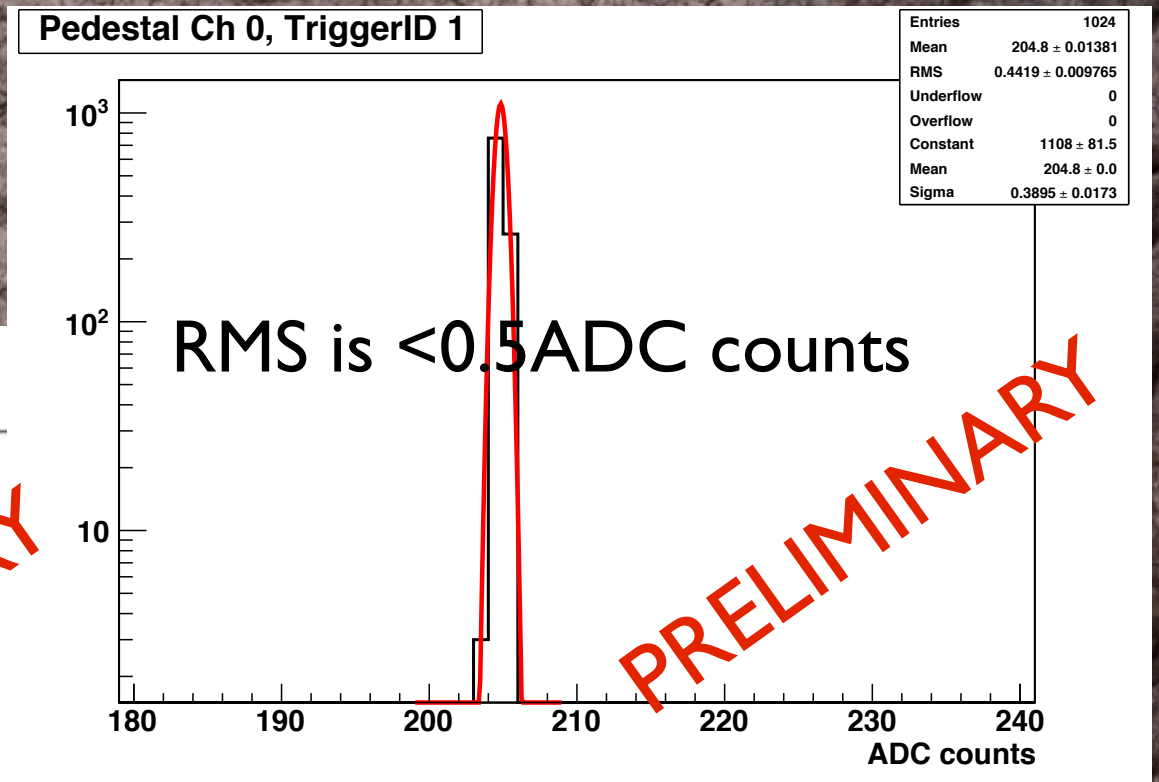

Inner-Detector Acrylics (installation)⟹ our fiducial volumes!

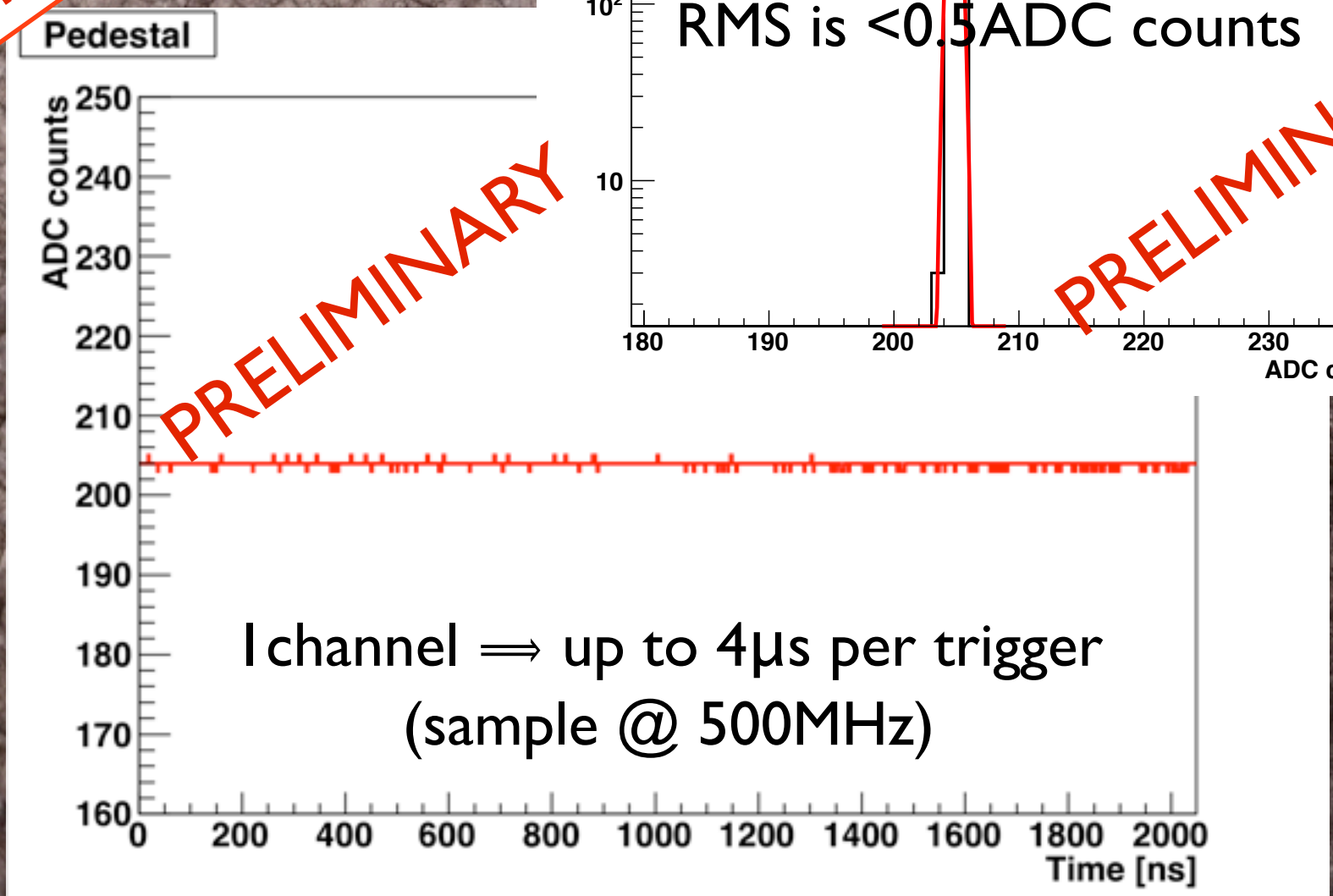
final mechanical tuning of the chimney (hyper-delicate interface)

FD “pre-commissioning”…

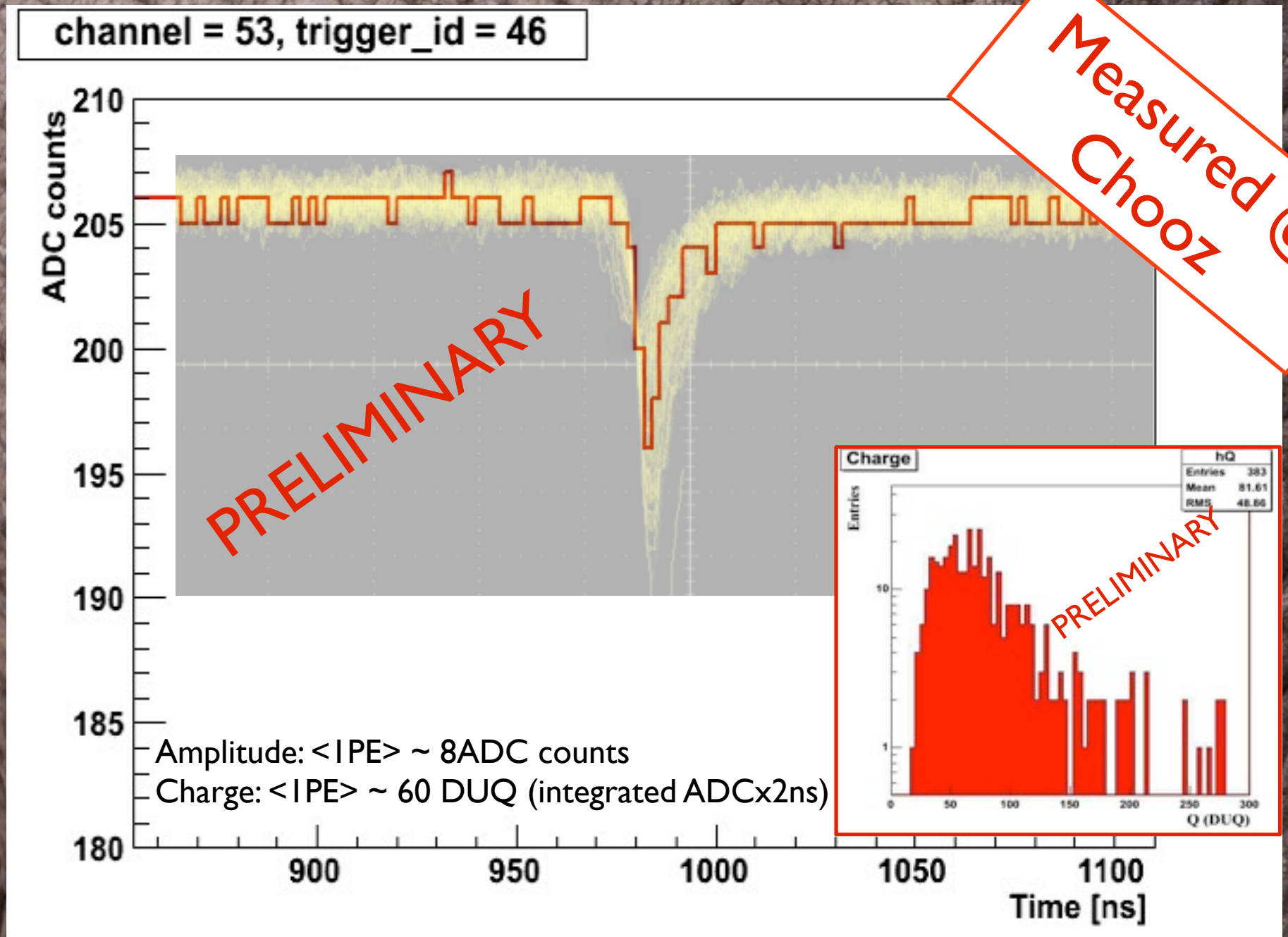
checking electronics noise with FADC…

Measured @ Chooz





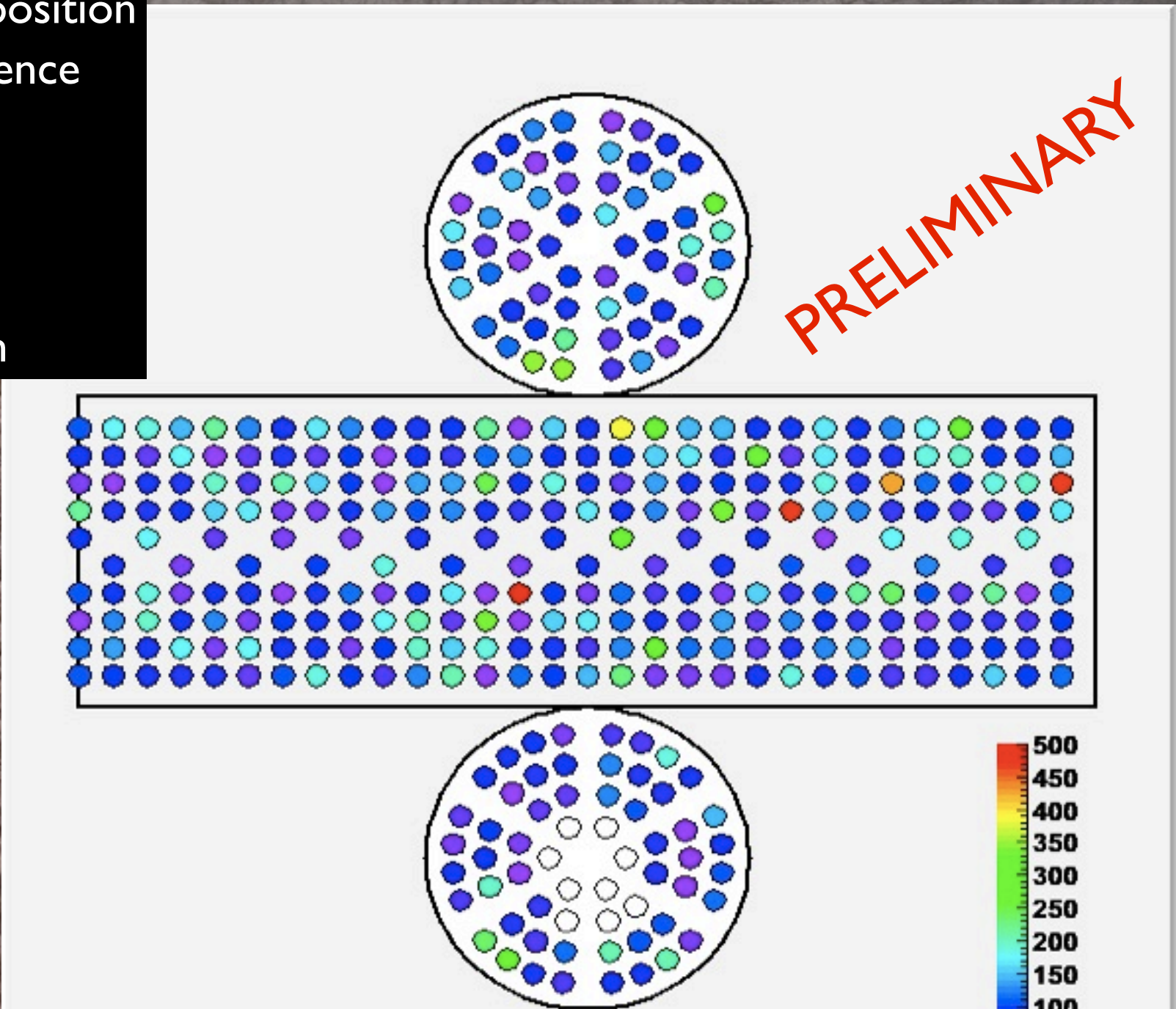
the first single-PEs detected @ FD…



first internal triggers…

First Energy-Trigger
⟹ large energy deposition over ~70ns coincidence without scintillator

No Mapping
⟹ no spatial reconstruction then



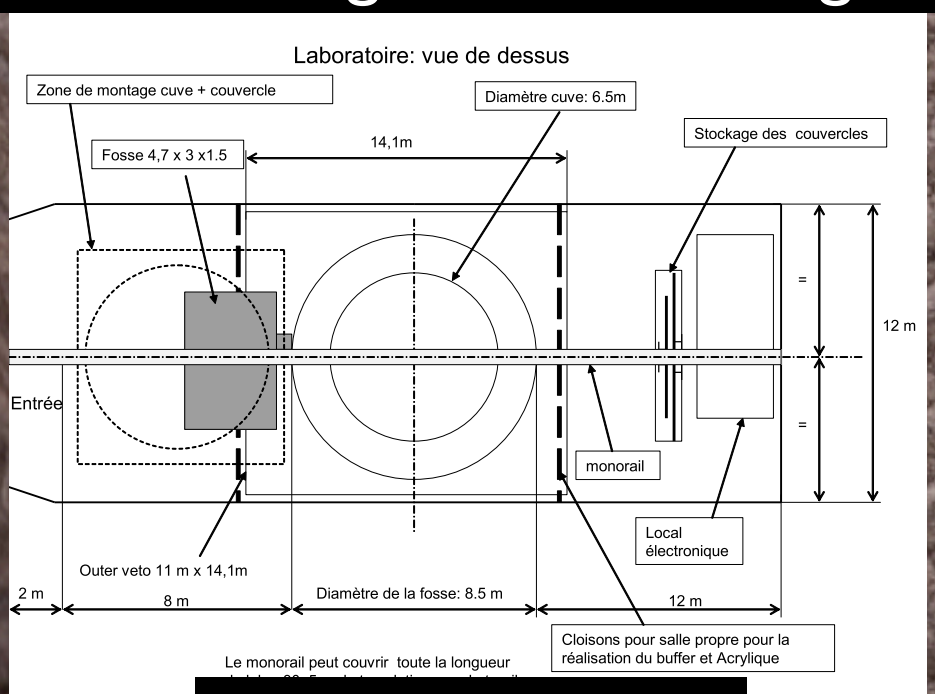
Most electronics up & running! (1FADC card missing)

near detector status…

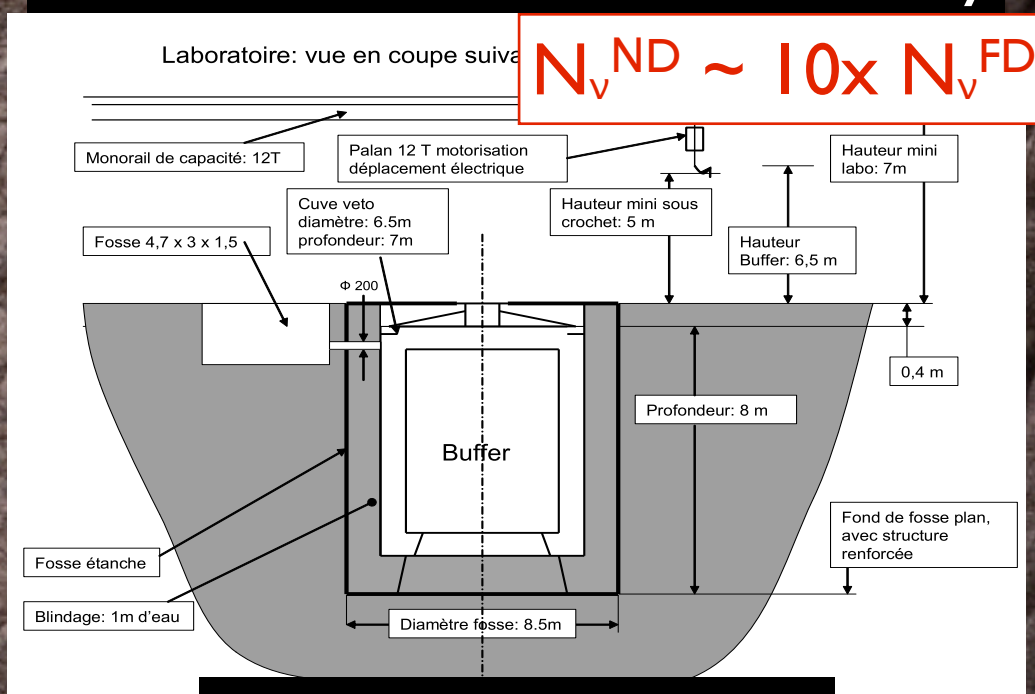
ND status…

- **all authorisations & funding secured…**
  - ground studies completed since end of 2009
  - involvement of EDF on the construction
- tendering over summer⟹ **digging from end of 2010**
- lab available by end of 2011
  - ND construction⟹ 30 weeks (many lessons learned from FD)
  - goal: **data taking by towards 2012**

ND Lab designed for building ND



1m water shield to radioactivity



3x zones concept

easier filling concept

-IN2P3 & APC)

what to remember?

…impact in the θ_{13} quest

- neutrino oscillations framework is not exhausted from physics (but harder)…
  - the "gate" to understand leptonic flavour sector $\Longrightarrow$ θ_{13} critical
  - compelling research programme: Double Chooz, Daya Bay, RENO
- we must measure θ_{13}…
  - *SM* leptonic mixing parameter $\Longrightarrow$ it must be measured
  - even a zero-value is interesting (less fortunate for experimentalist)
- Double Chooz…
  - DC has led much of the θ_{13}-LAND business "*on the shoulders of giants*" (CHOOZ, Borexino, KamLAND, SNO, etc). Its legacy is a reality…
  - DC input on θ_{13} (measurement/limit) will deepen our insight on a global perspective of the (light) neutrino flavour sector$\Longrightarrow$ critical synergies with beams (MINOS, T2K, NOvA, etc) and Solar/KamLAND results

…about Double Chooz

- **Double Chooz FD is about to start data taking…**
  - FD construction ⟹ finished!
  - FD first lights ⟹ since June ("dry" detector)
  - FD filling ⟹ ready to start…
  - FD first scintillation lights ⟹ during filling data-taking (October)
  - FD commissioning ⟹ **hoping to start by late December!**
  - FD publication on θ_{13} ⟹ soon next year (our goal)!
- DC can obtain CHOOZ worth of **signal** data ~2 months of running
  - **$\sin^2(2\theta_{13})\leq 0.054$ @ 90%CL** with FD only (about 1.5years of data)
  - **$\sin^2(2\theta_{13})\leq 0.030$ @ 90%CL** with FD & ND (about 3years of data)
- Near Detector digging end of 2010 ⟹ running by end of 2012!

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thank you…