Double Chooz: θ_{13} with Reactor-νs

May 2007 @ CPP Marseille

Anatael Cabrera
Marie Curie Fellow
Double Chooz @ APC

- ν-oscillations (reminder)
- the reactor strategy
    - Double Chooz
    - Daya Bay
- the world strategy
- what to remember?

ν-oscillations (reminder)

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  - suggestive "mirroring" to quark sector mixing

oscillations = leptonic mixing

$(\nu_e, \nu_\mu, \nu_\tau)^T = \boldsymbol{U}\,(\nu_1, \nu_2, \nu_3)^T$ where U must be unitary & 3x3...

atmospheric-ν: θ_{23} | θ_{13} & dirac-δ_{CP} | solar-ν: θ_{12}

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

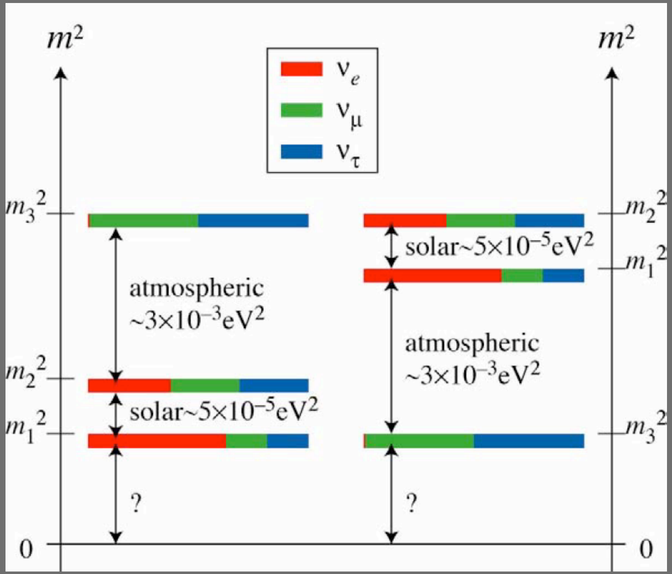
$P(\nu_\mu \to \nu_\mu)$ | $P(\text{anti-}\nu_e \to \nu_x)$ & $P(\nu_\mu \to \nu_e)$ | $P(\nu_e \to \nu_x)$

PMNS: 3 angles & 1 complex phase => leptonic CP violation

$\Delta m^2(atm) \approx 3x10^{-3}$ (large)

$\Delta m^2(solar) \approx 8x10^{-5}$ (small)

[m_0 beyond reach of oscillations]

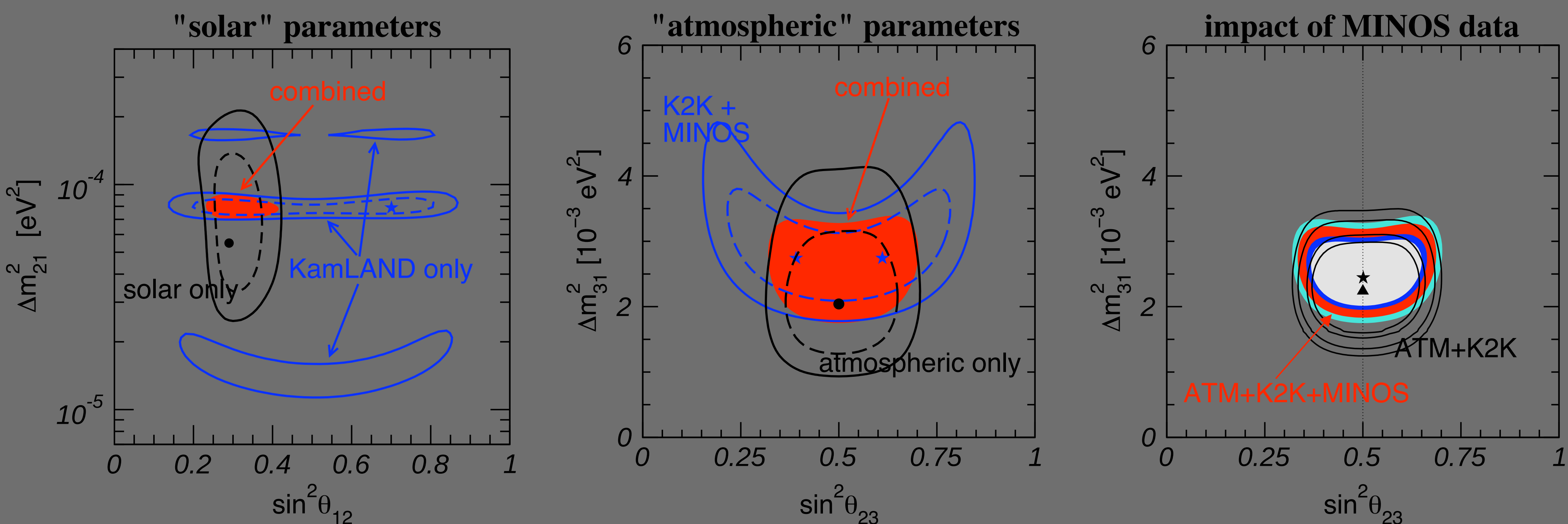


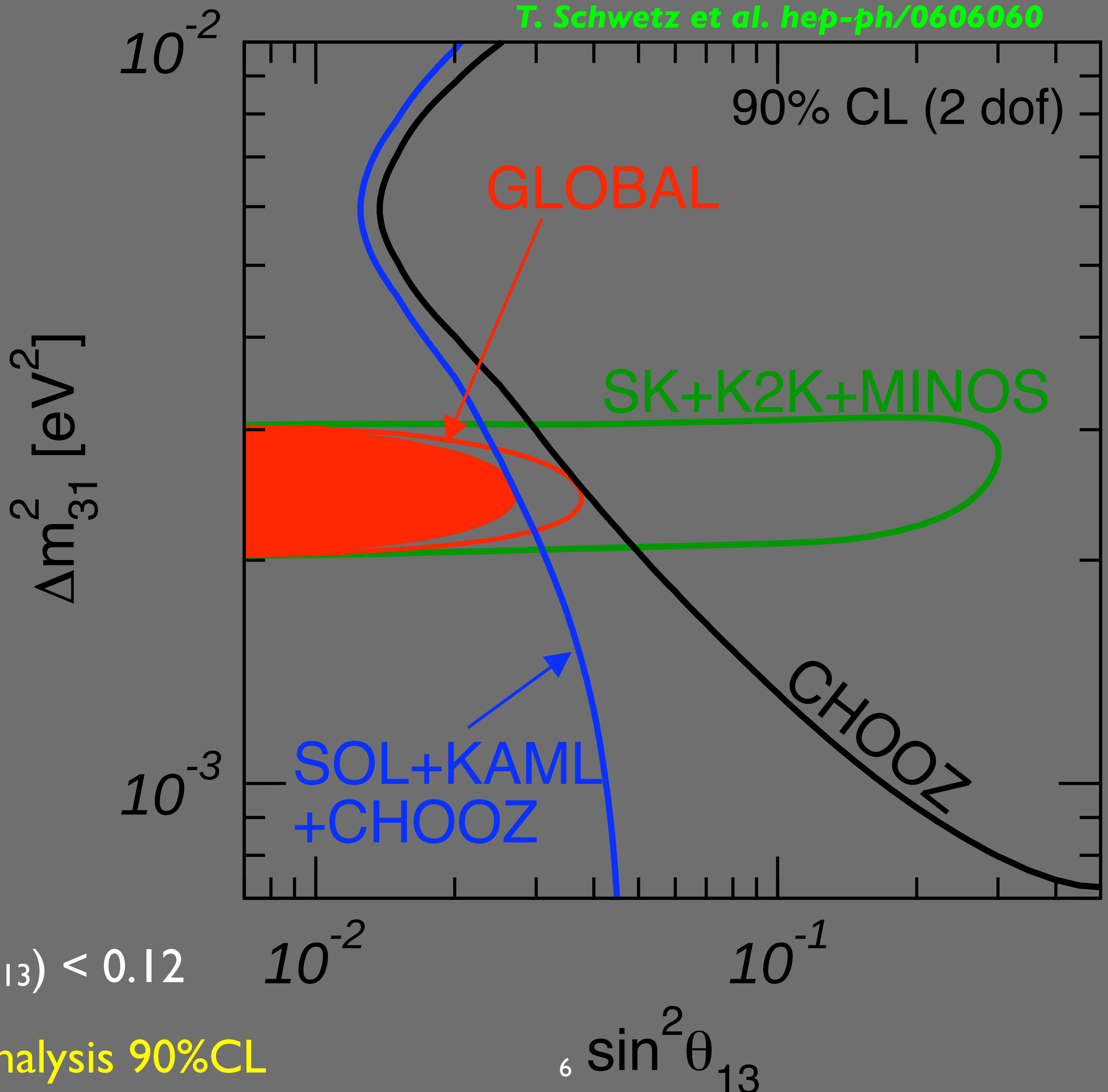
summary

PMNS: large mixing (unlike CKM)...

T.Schwetz hep-ph/0606060

parameter	bf±1σ	1σ acc.	2σ range	3σ range
$\Delta m^2_{21}\ [10^{-5}\mathrm{eV}^2]$	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%	$0.38 - 0.64$	$0.34 - 0.68$
$\sin^2\theta_{13}$	–	–	$\lesssim 0.025$	$\lesssim 0.041$





★ $\sin^2(2\theta_{13}) < 0.12$

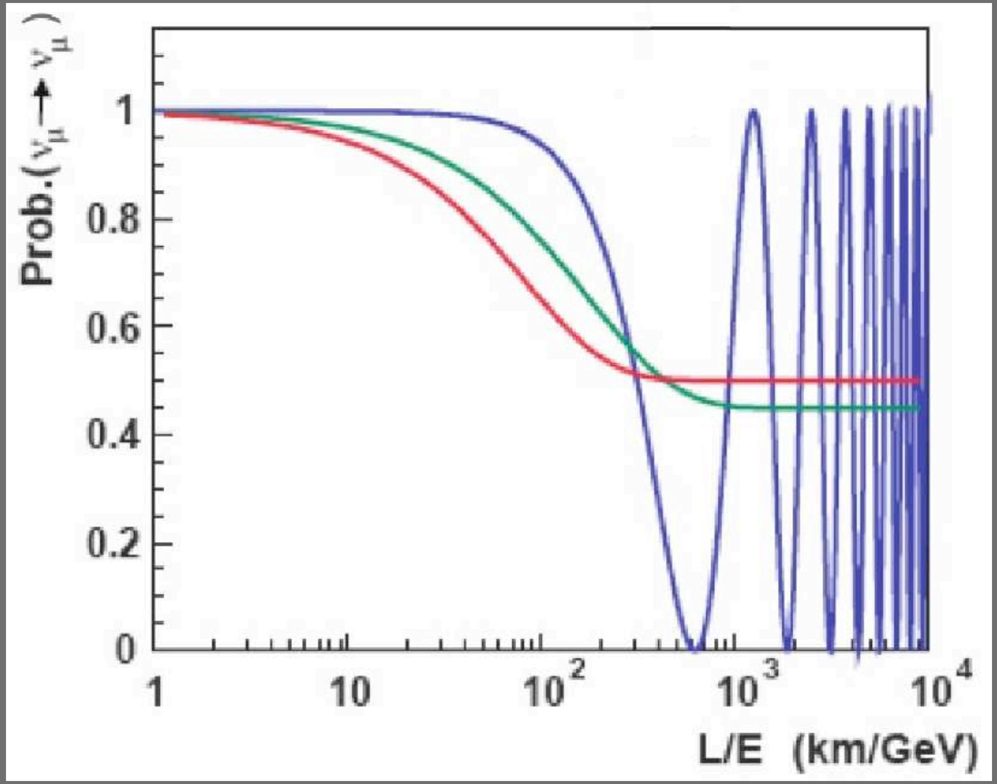
Global Analysis 90%CL

disappearance experiments...

2ν oscillation probability equation:

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

Disappearance...



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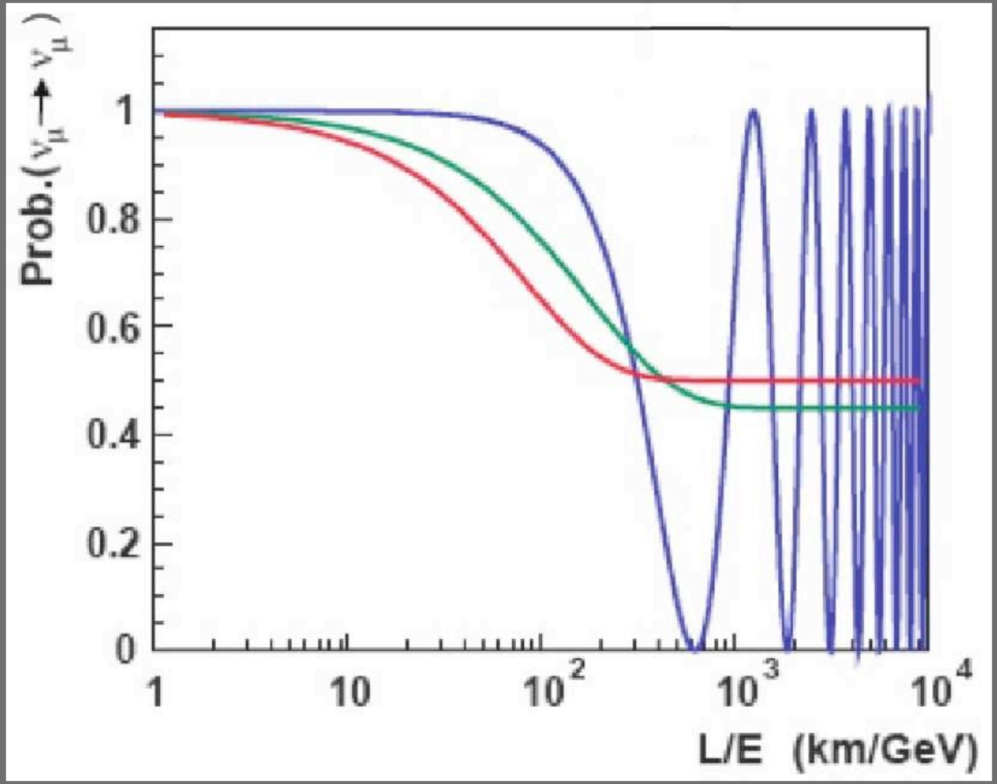

E/L modulation discriminating feature!

hep-ph/0607088

MINOS Δm^2 measurement...

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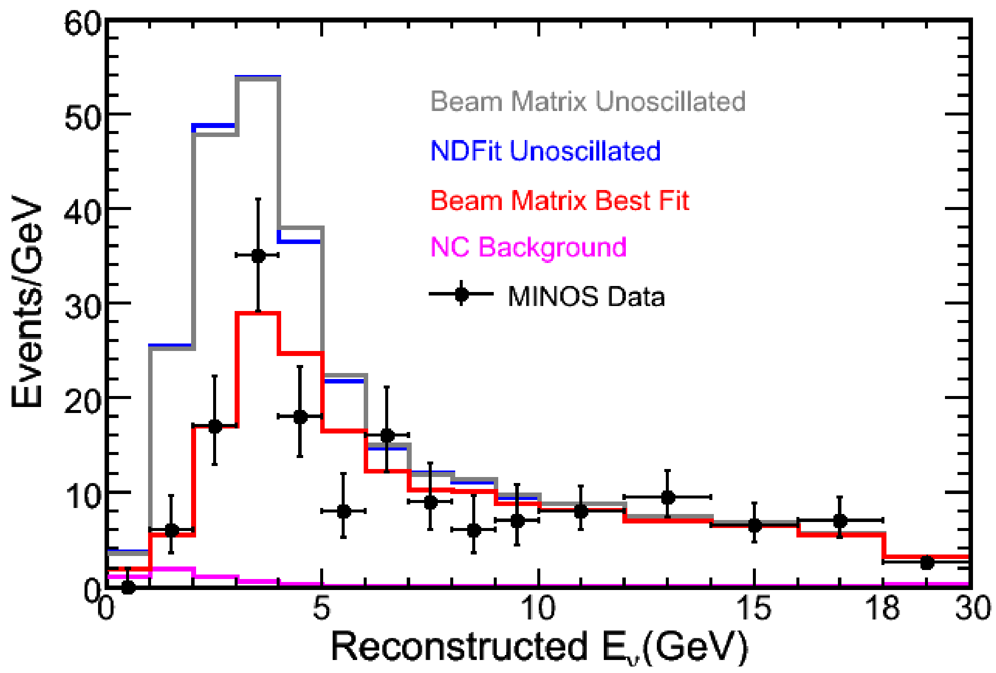

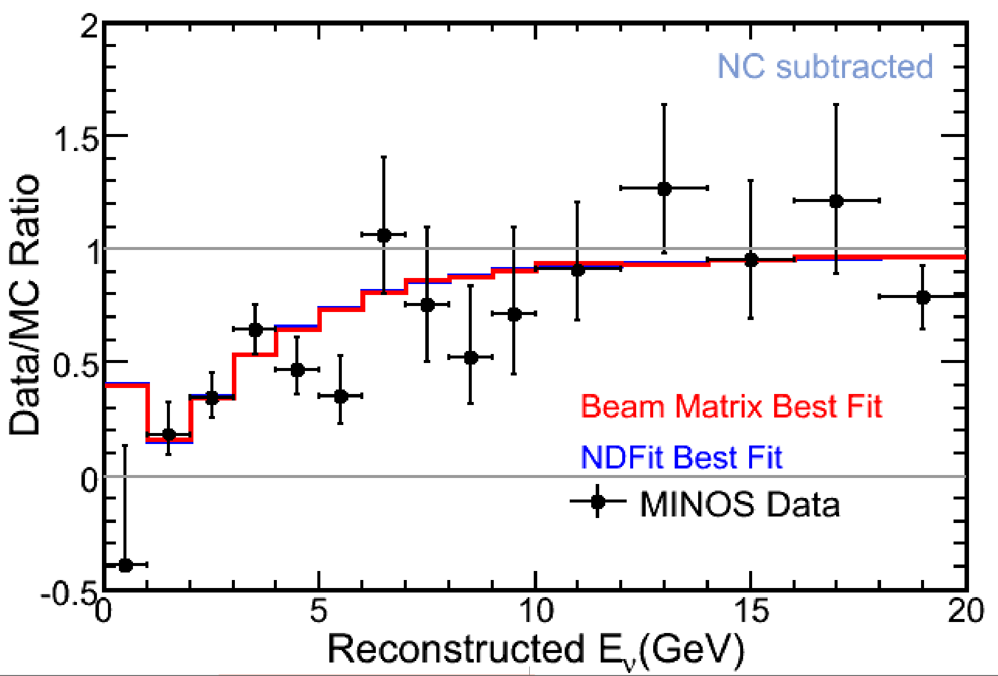

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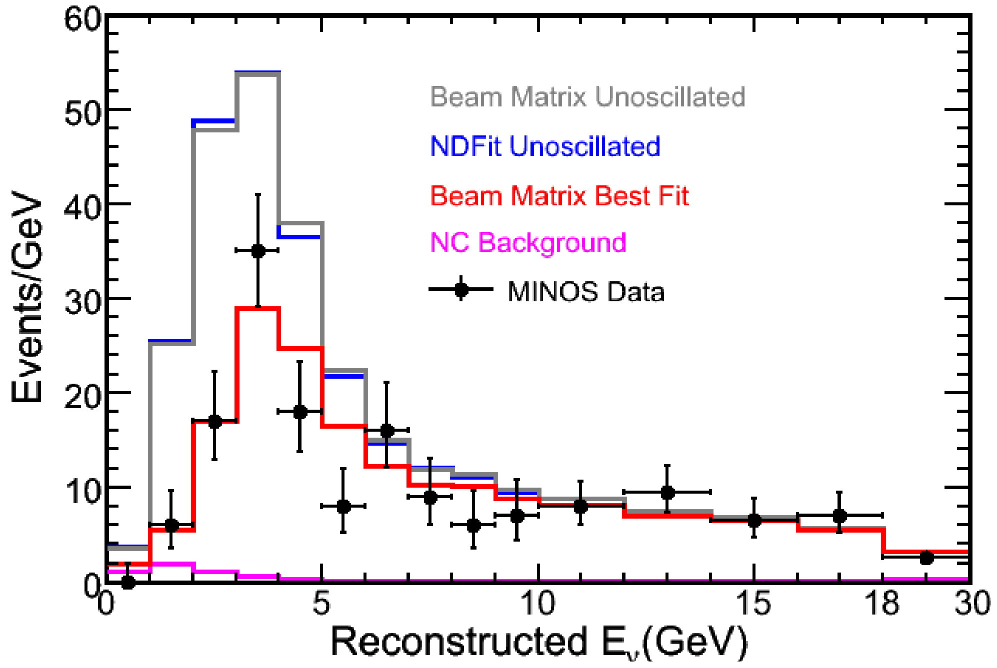

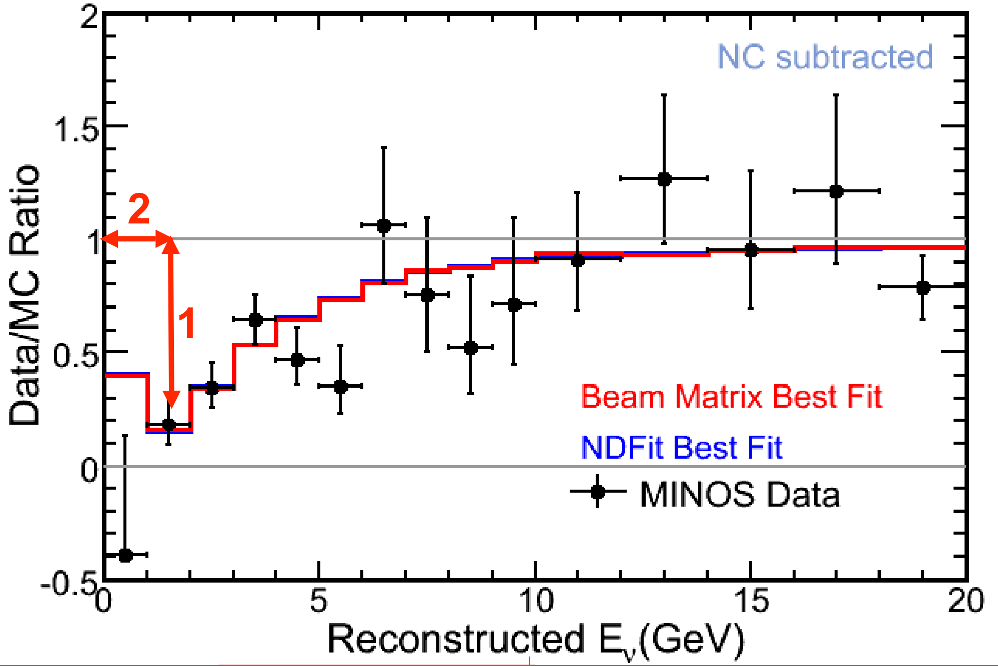

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the reactor strategy...

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- background: cosmogenic dominated => overburden

reactor oscillation physics...

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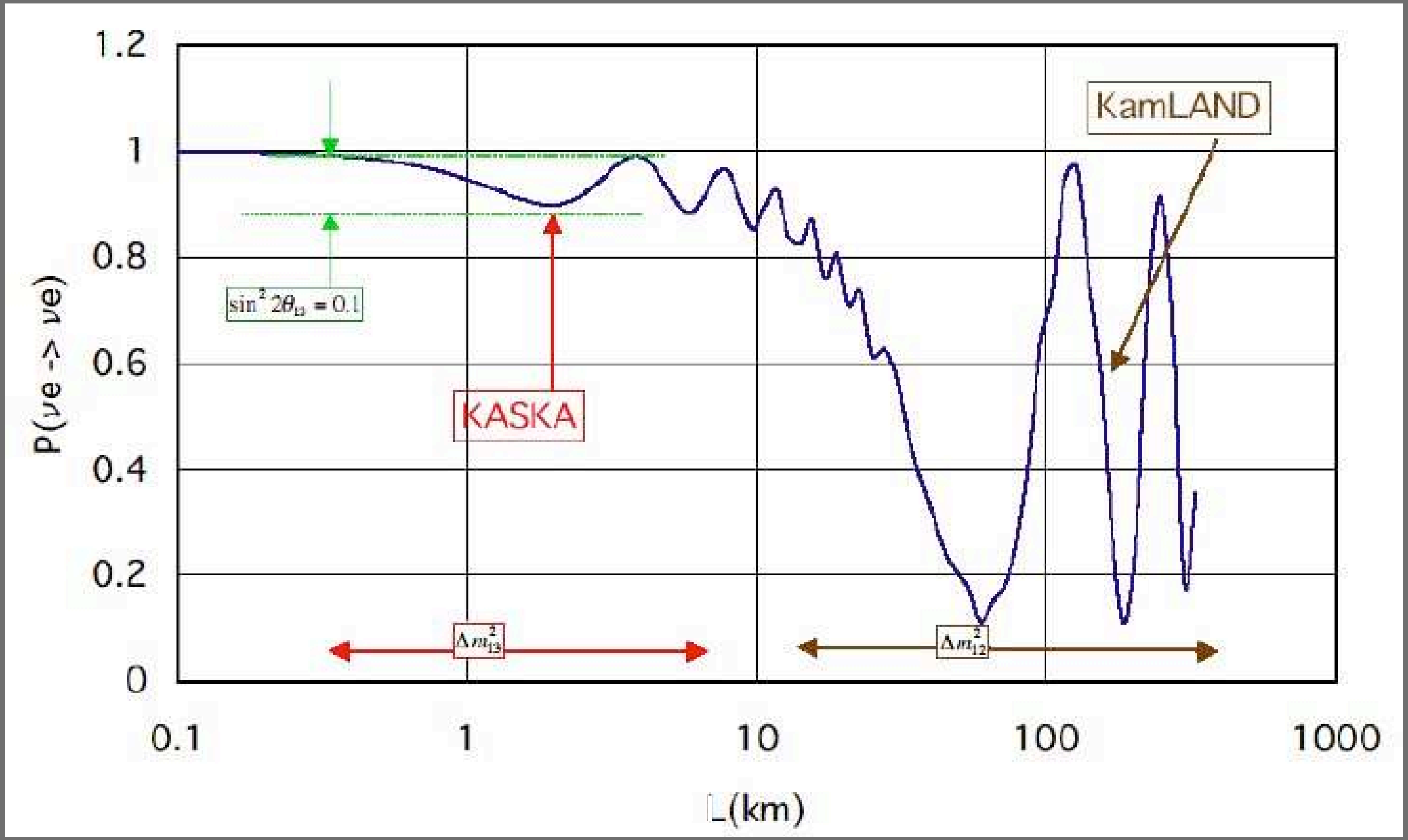

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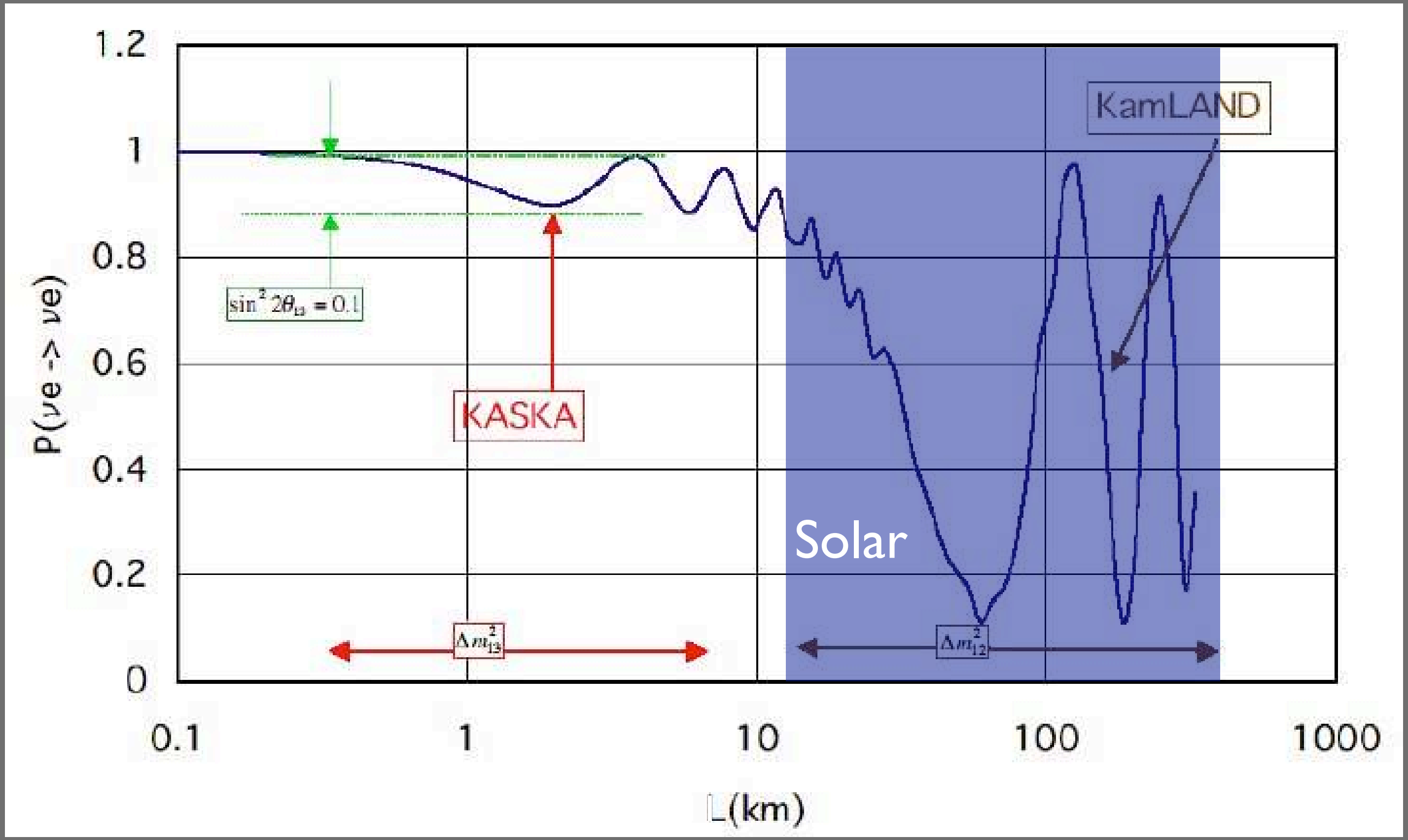

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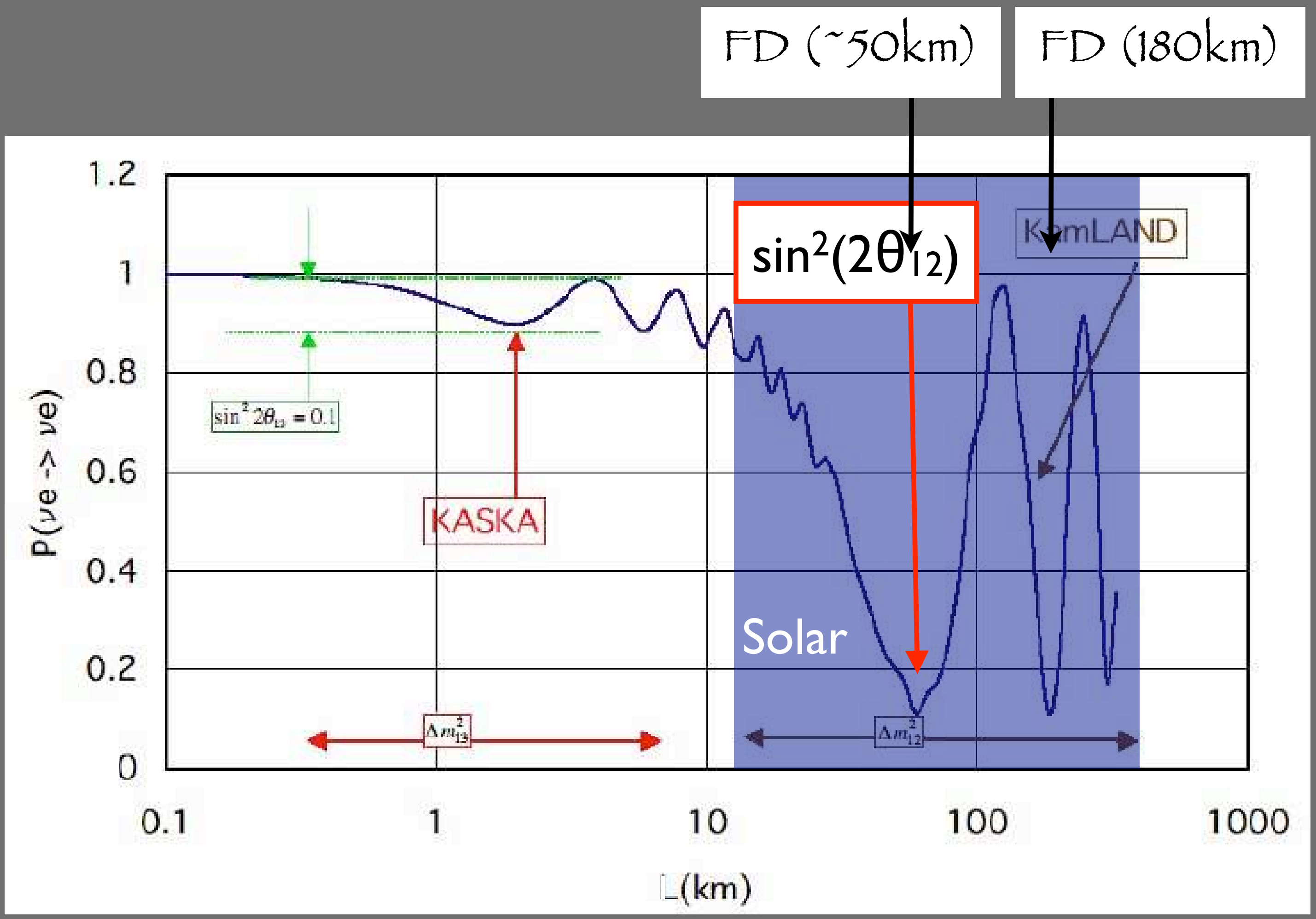

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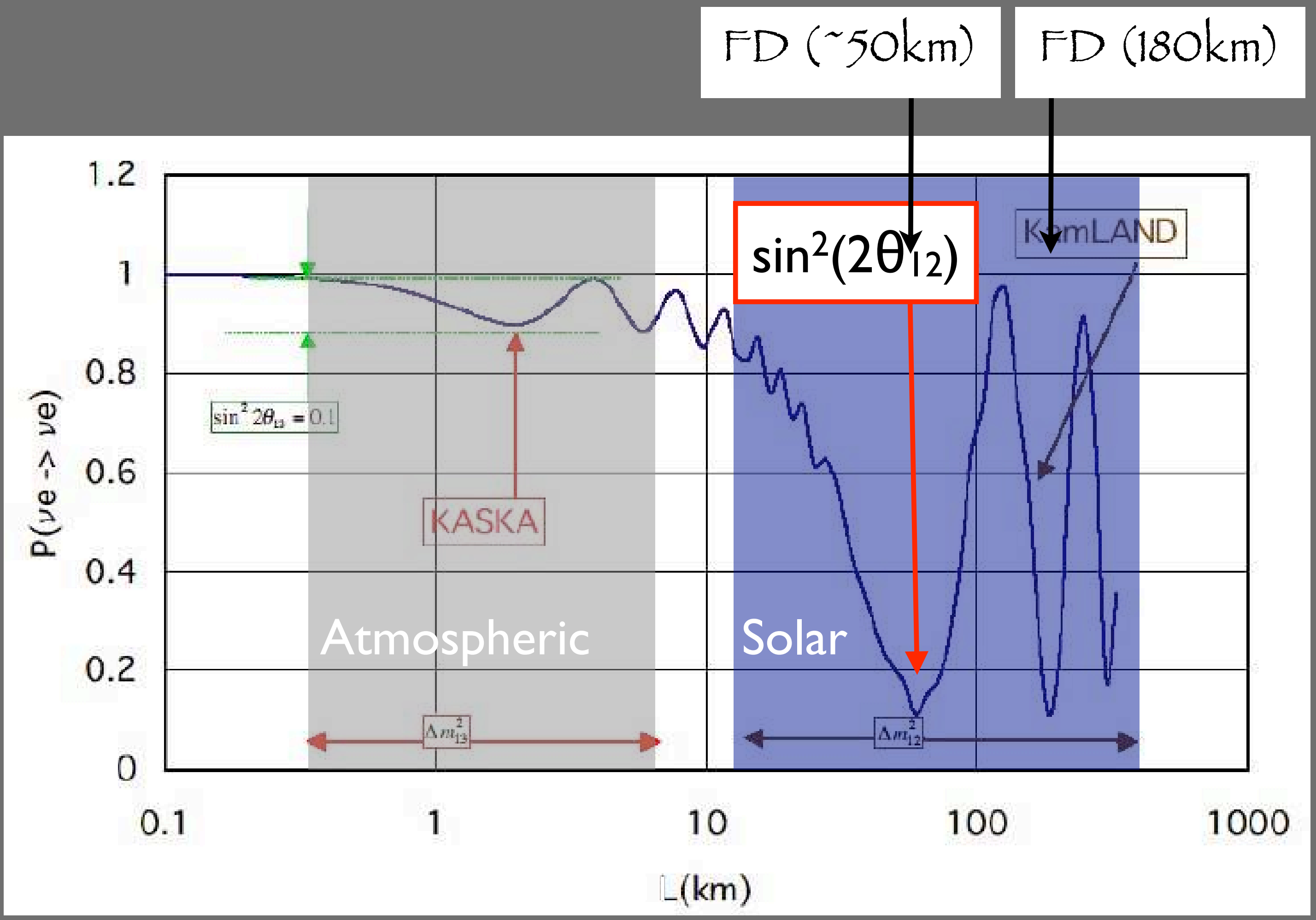

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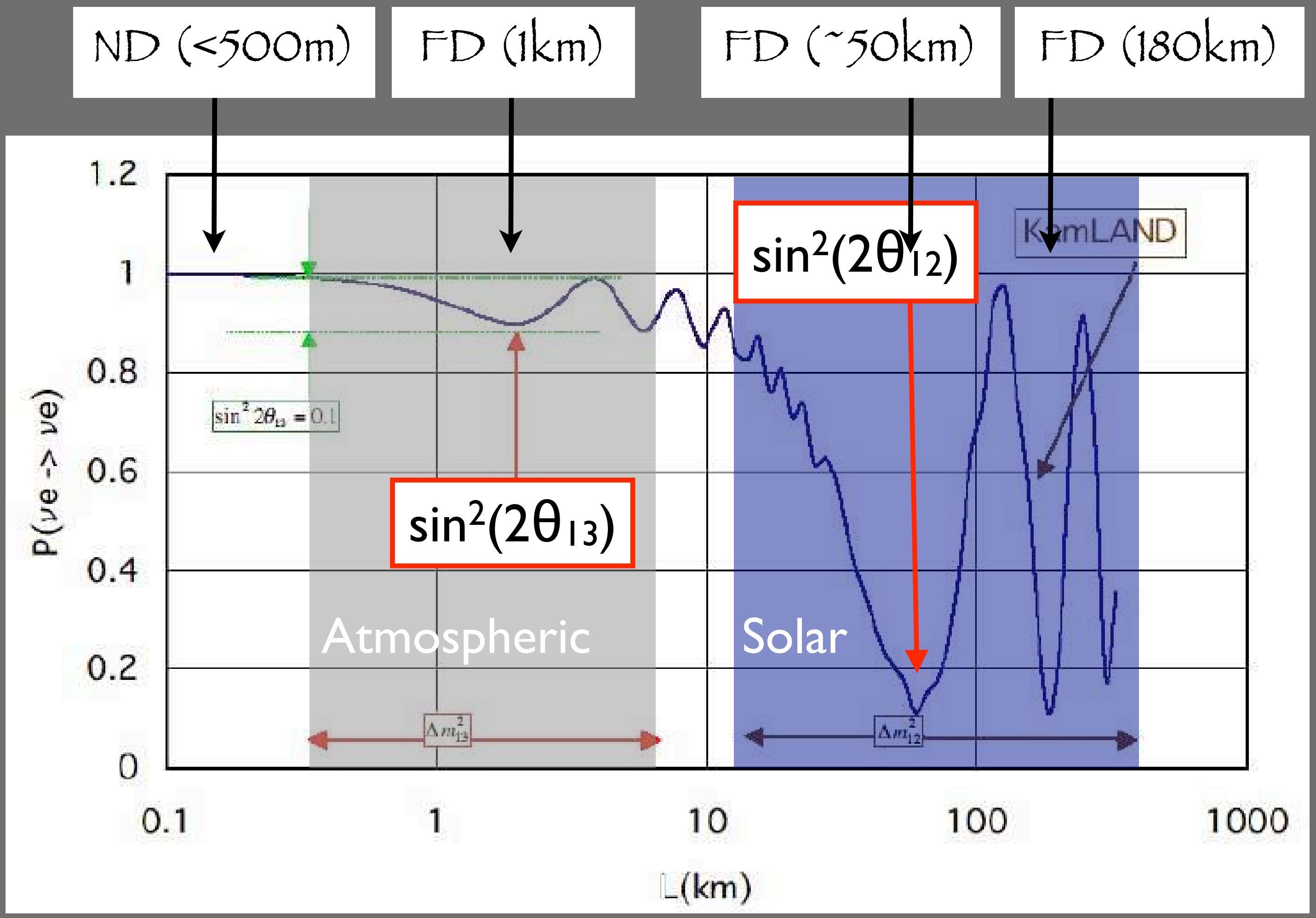

θ_{13} strategy...

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Martemianov et al: hep-ph/0211070

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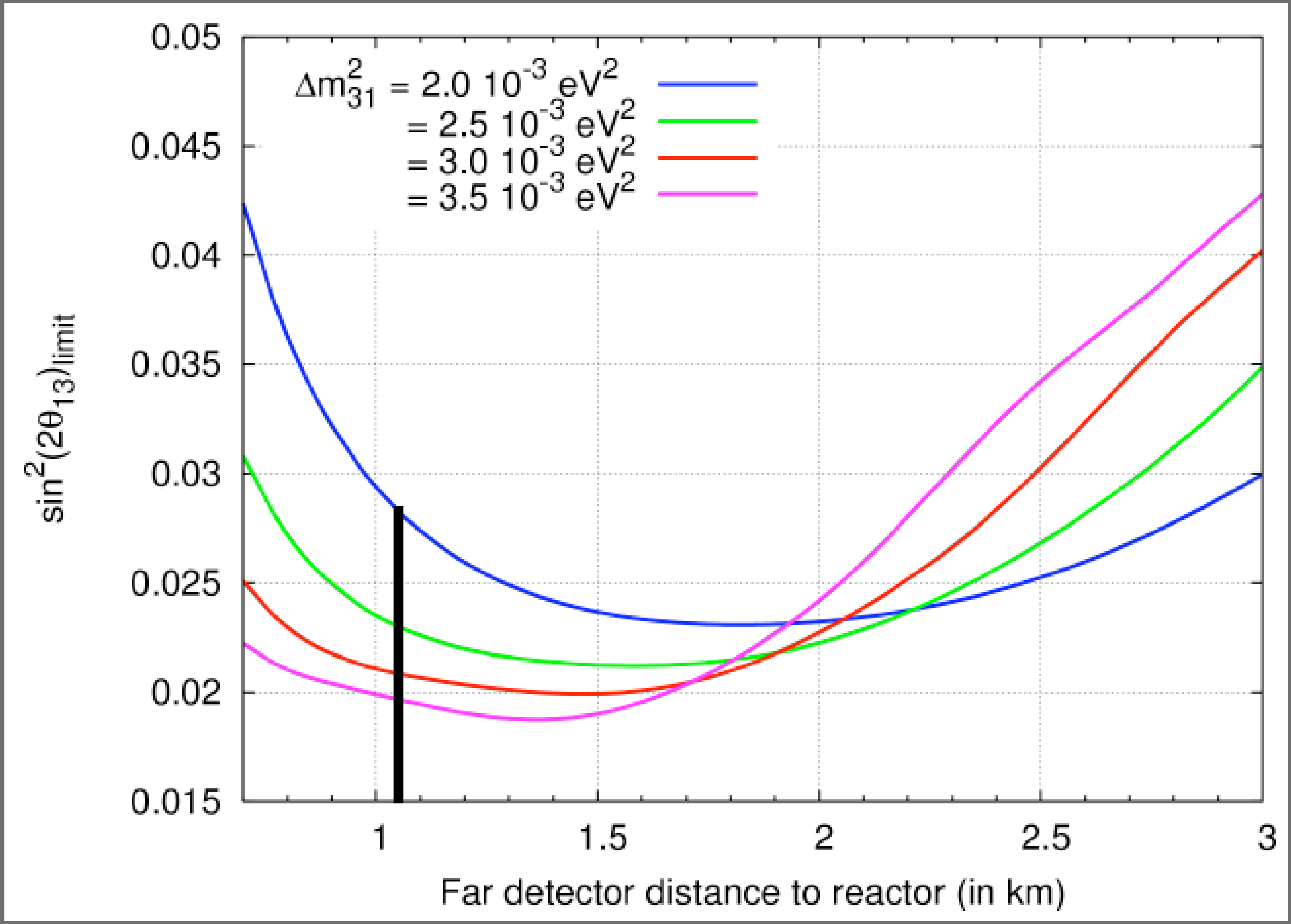

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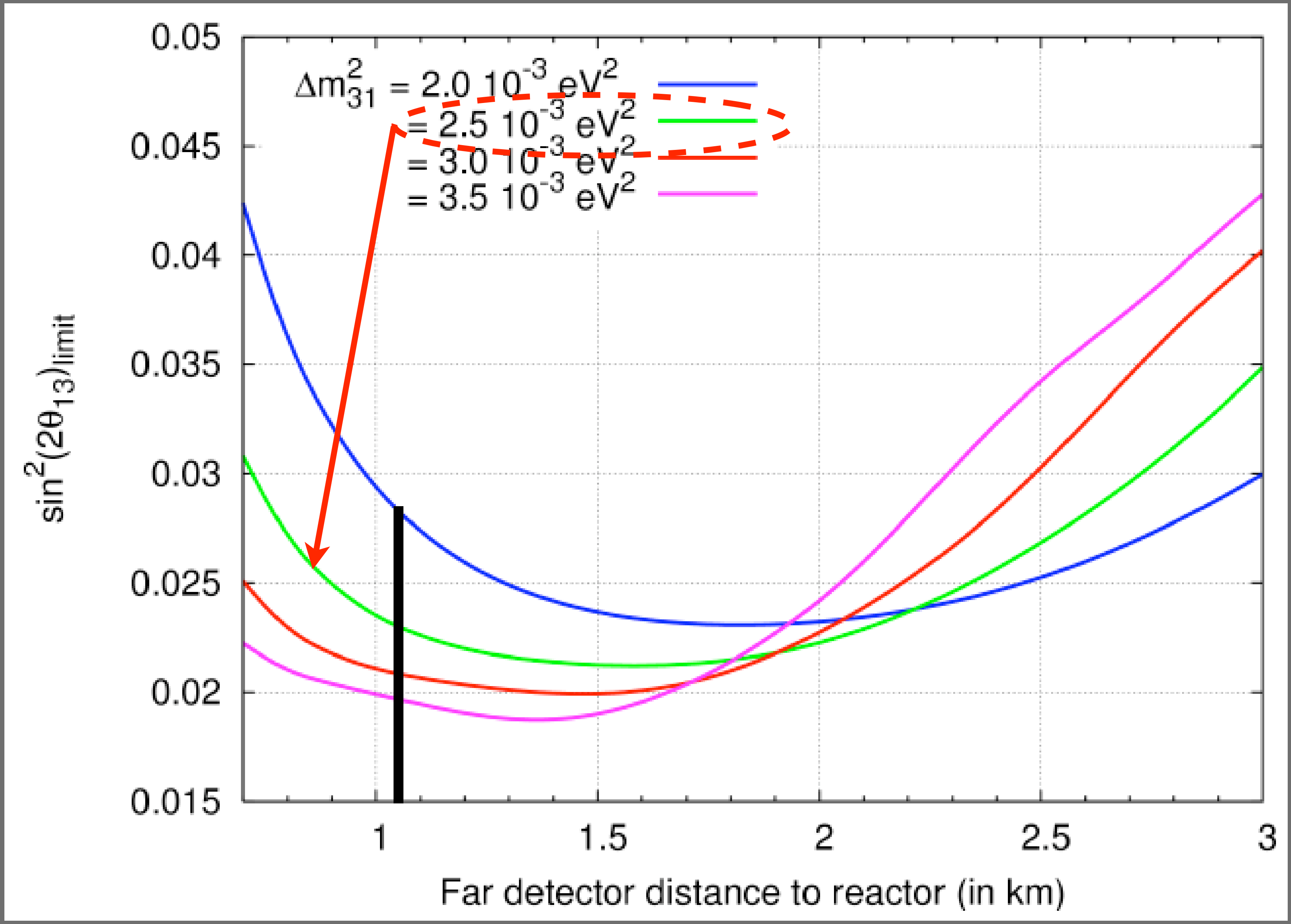


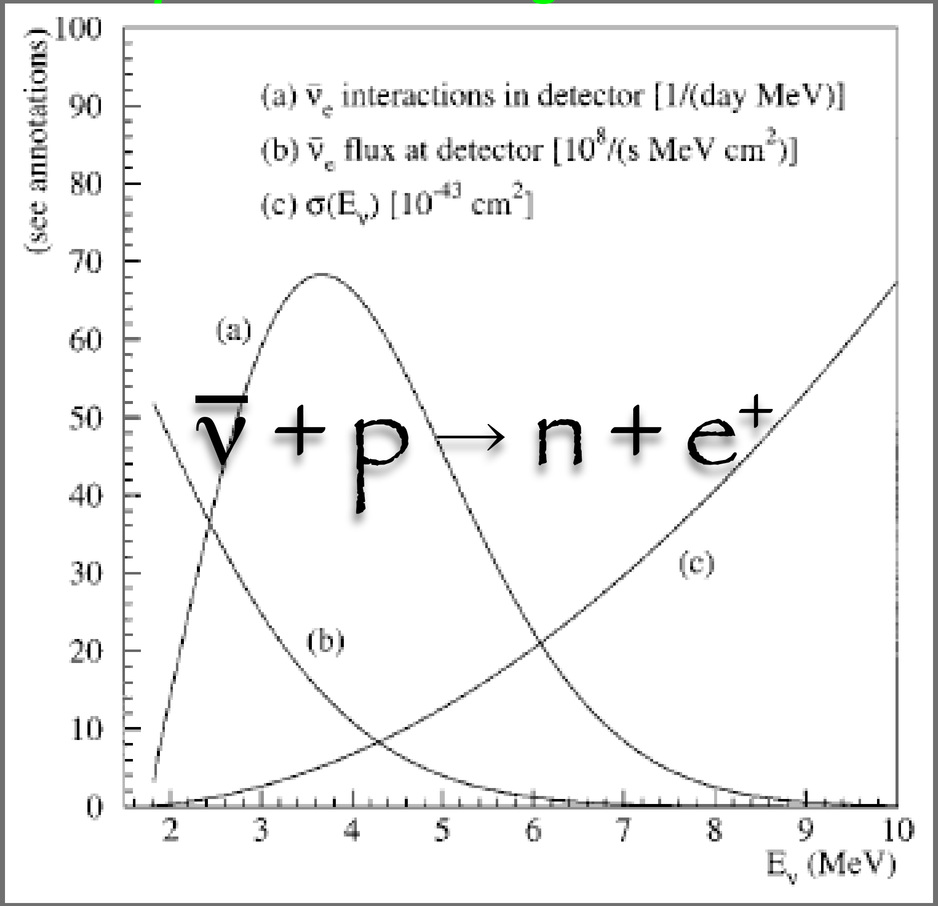
Double Chooz

detection:

magic reaction...

inverse-β reaction

Bemporad, Gratta, Vogle. RMP. 2002



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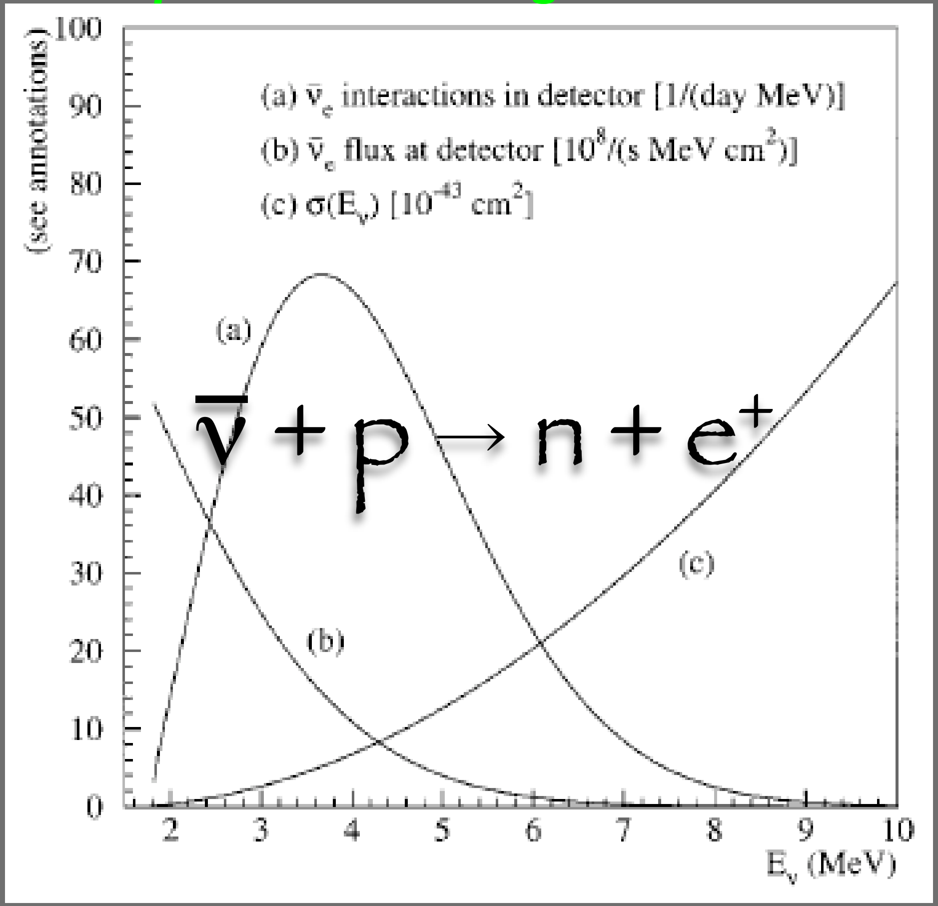

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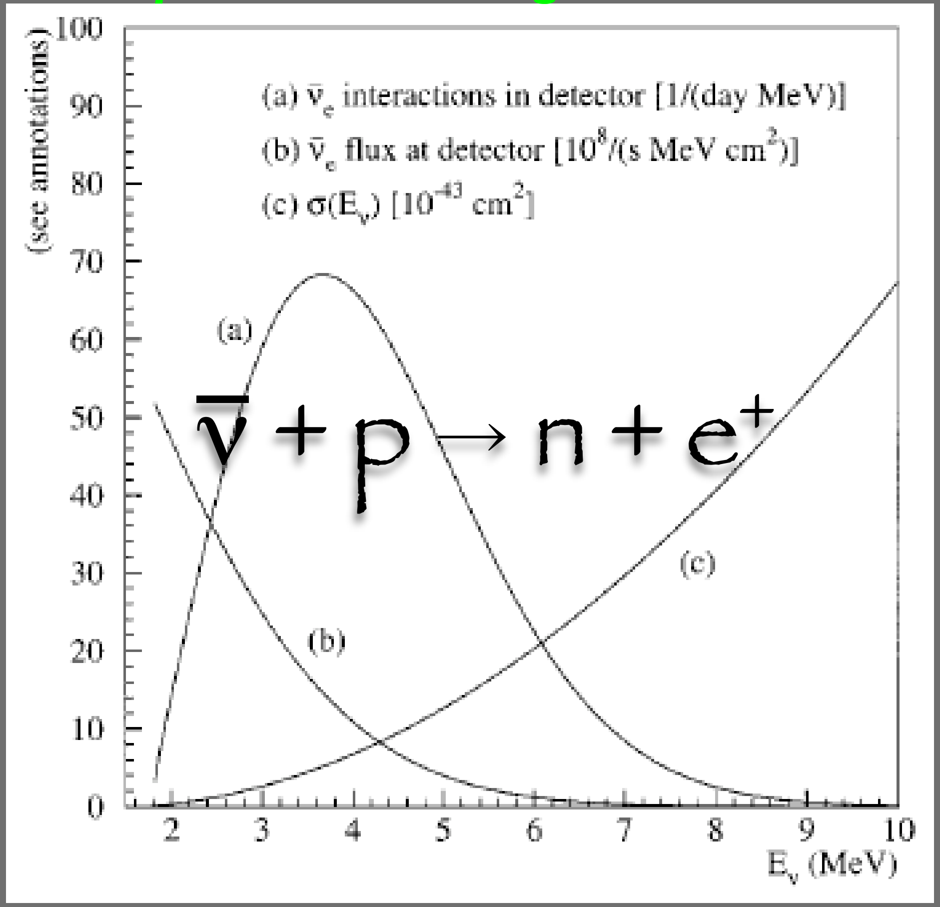

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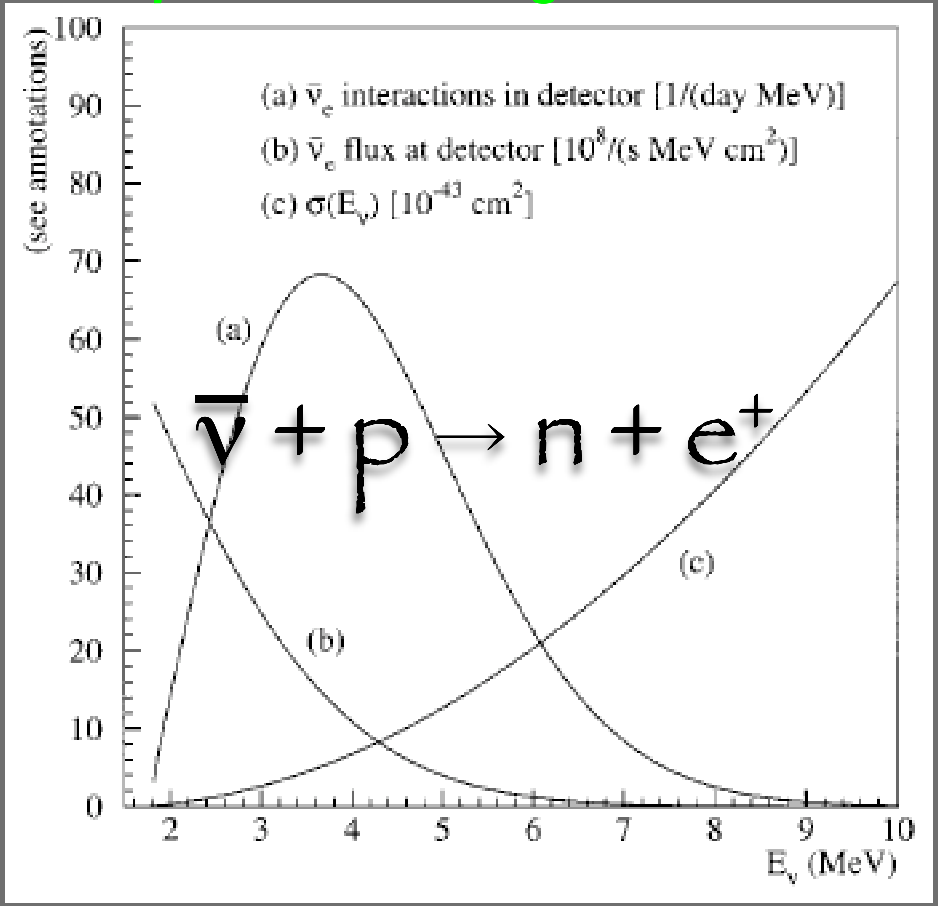

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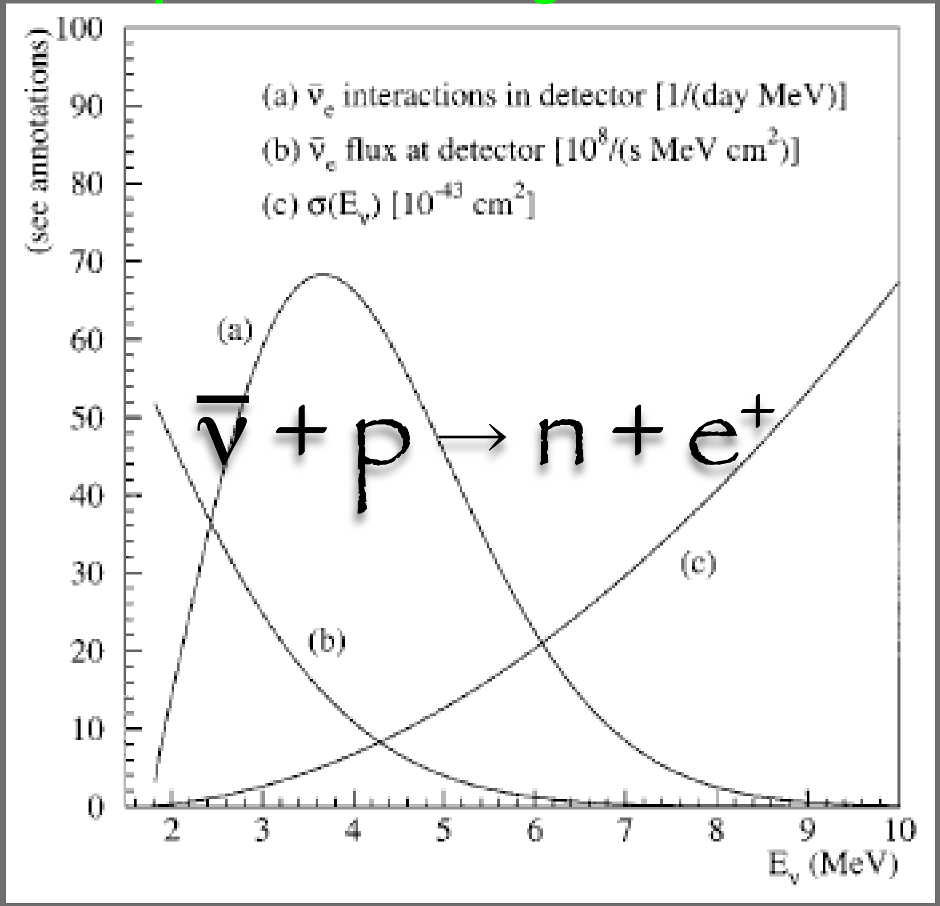

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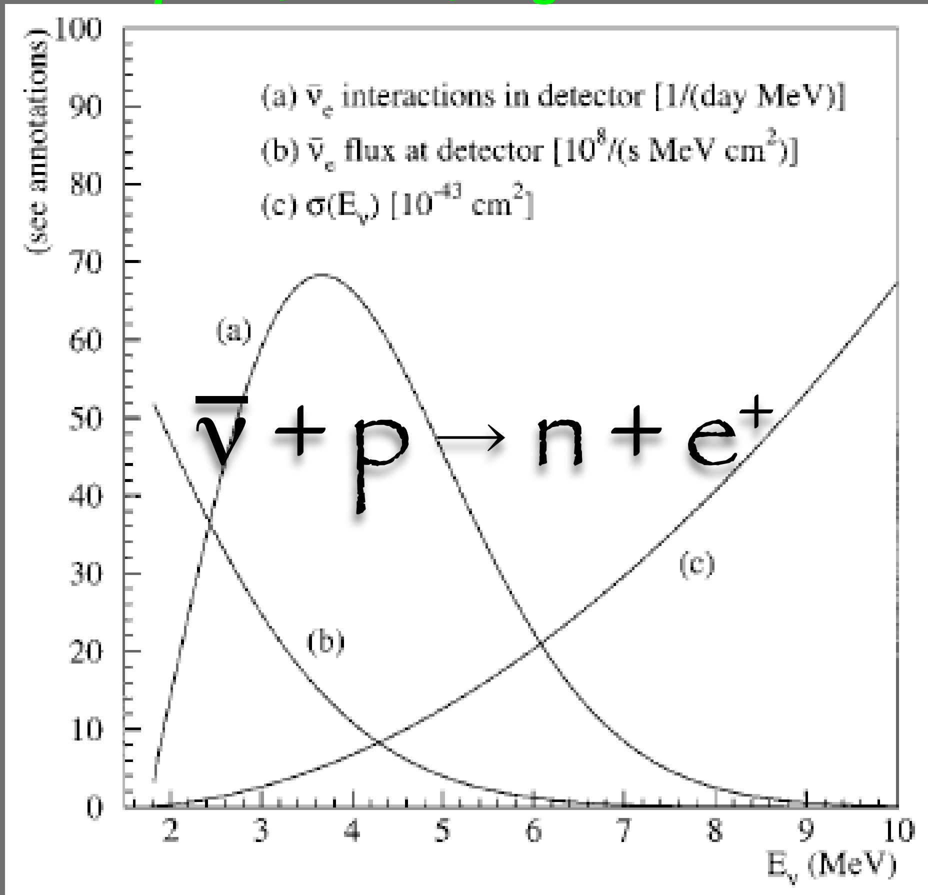

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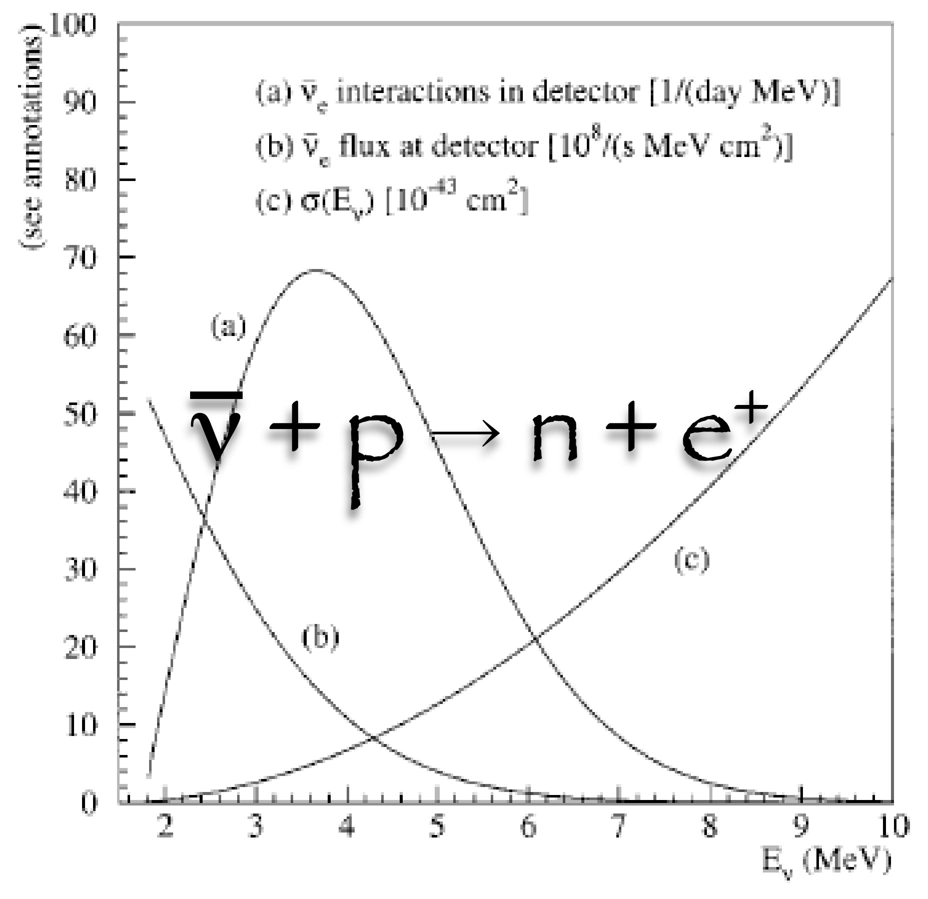

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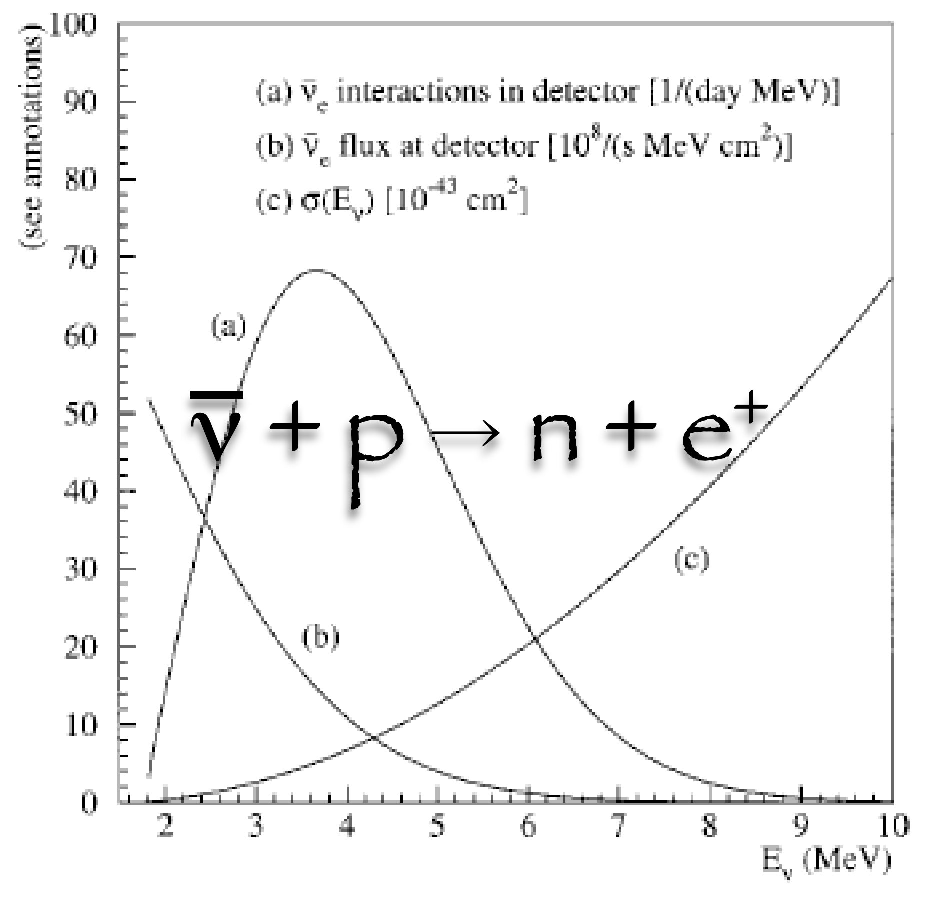

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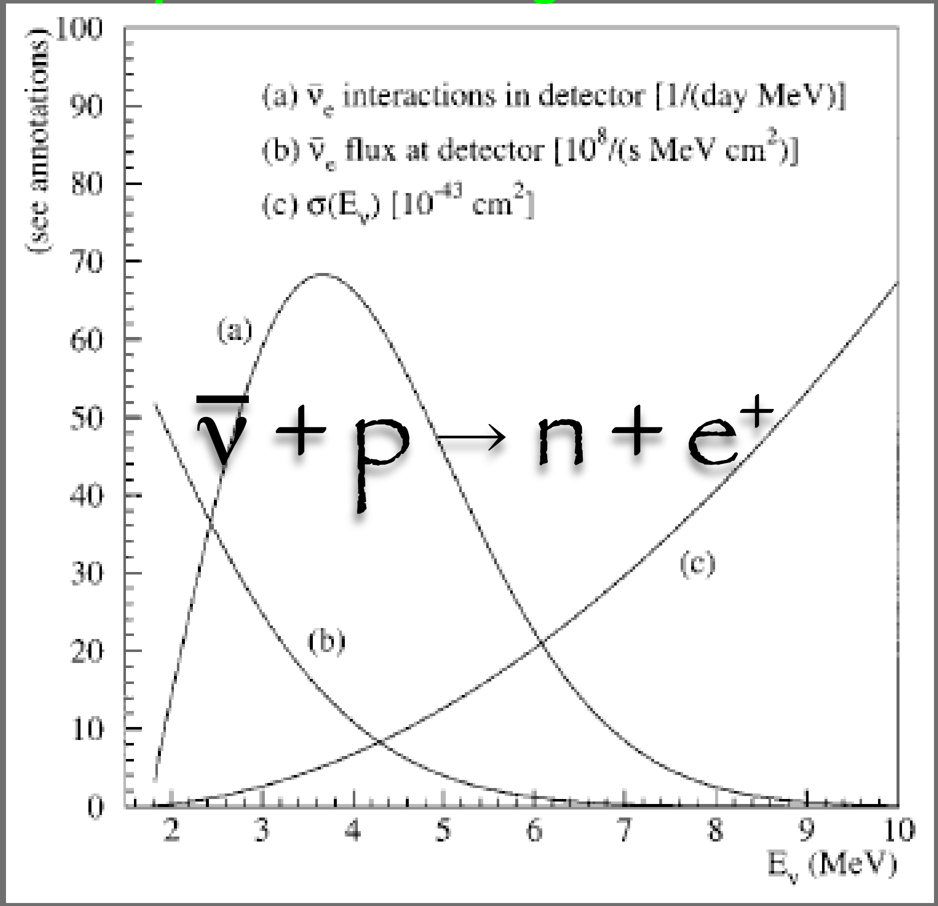

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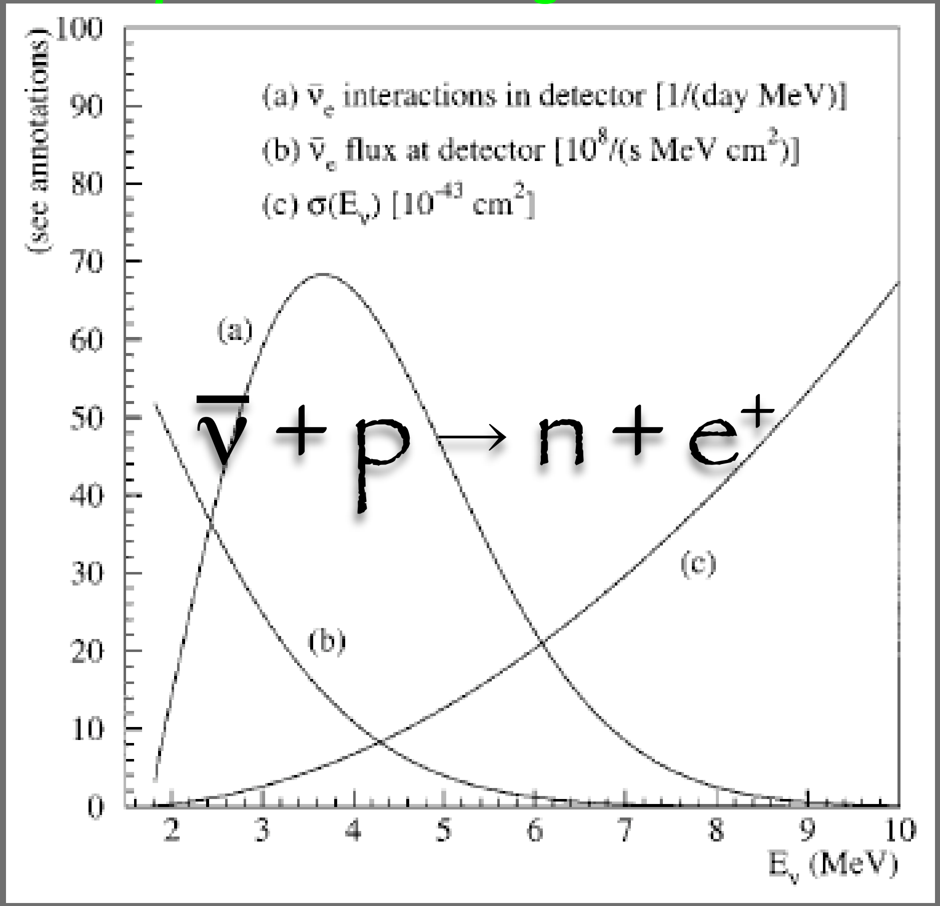

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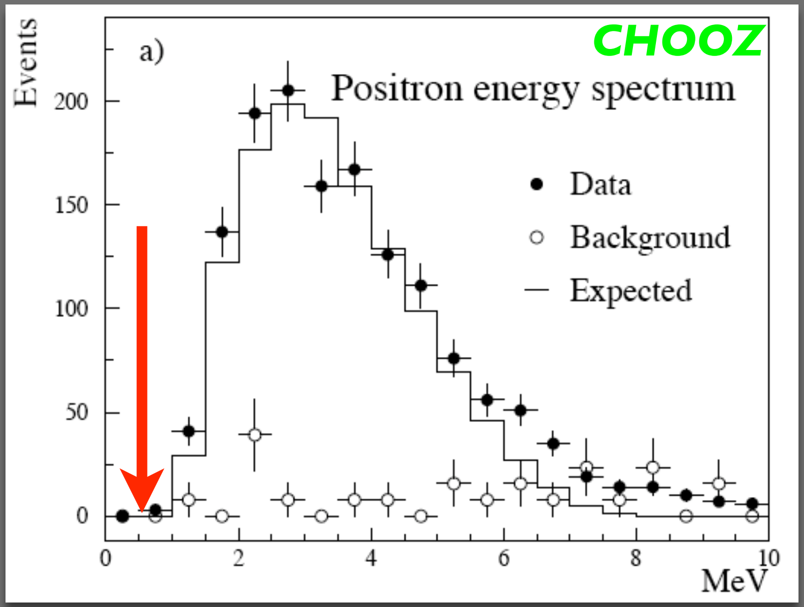

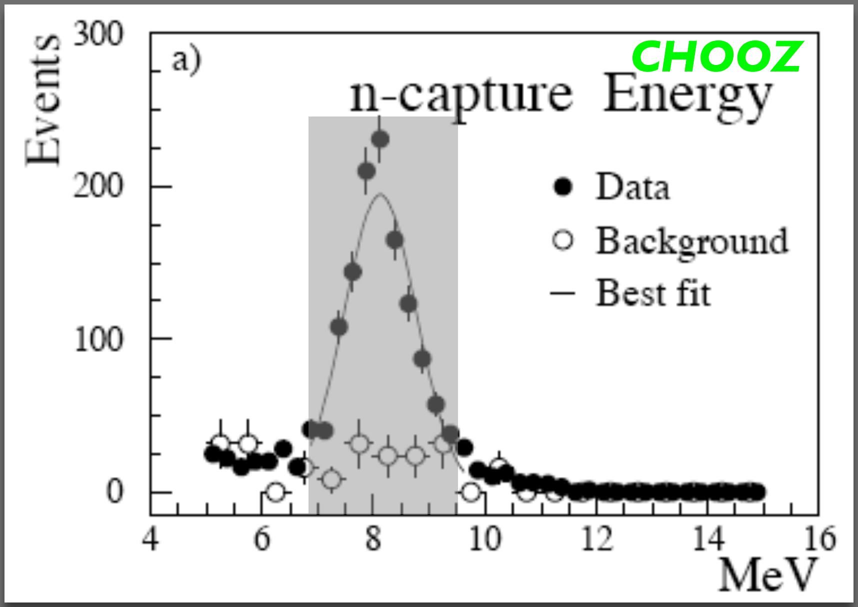

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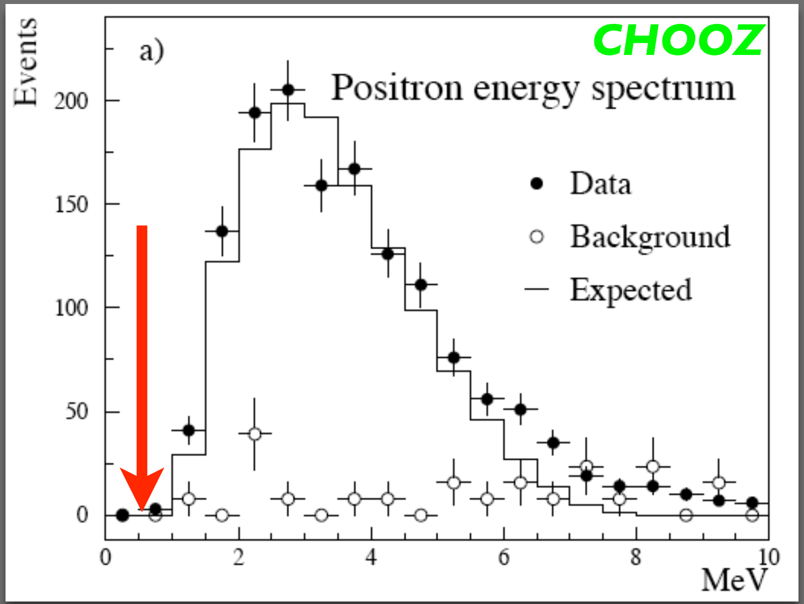
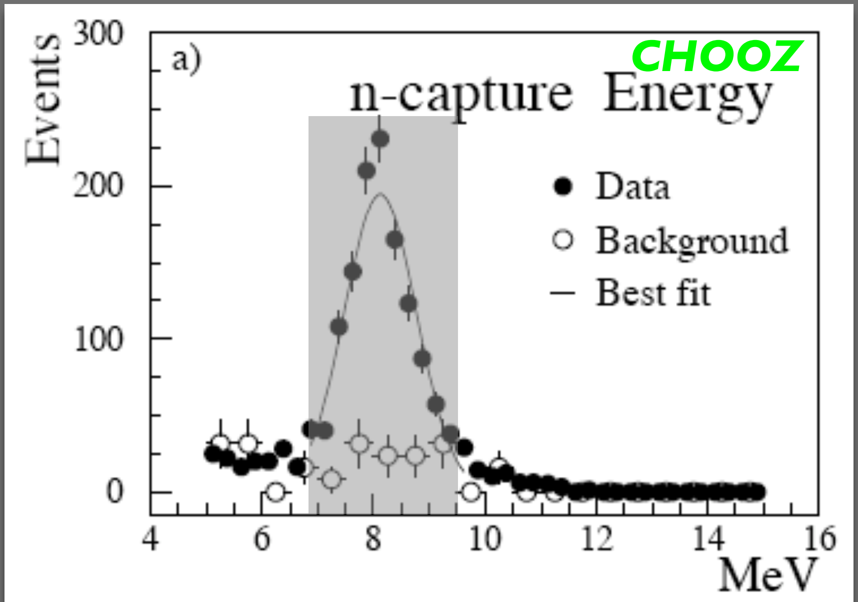
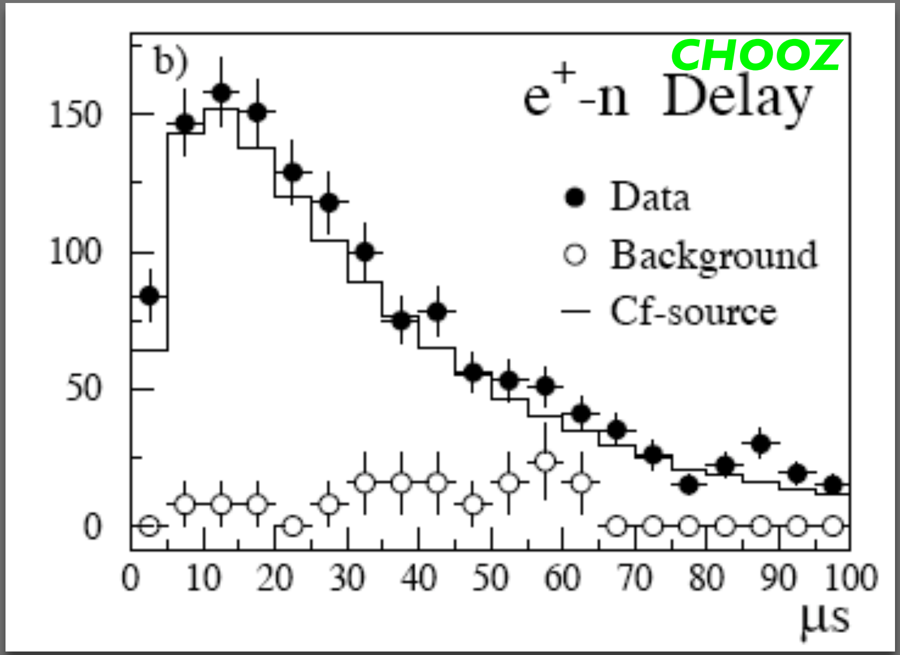




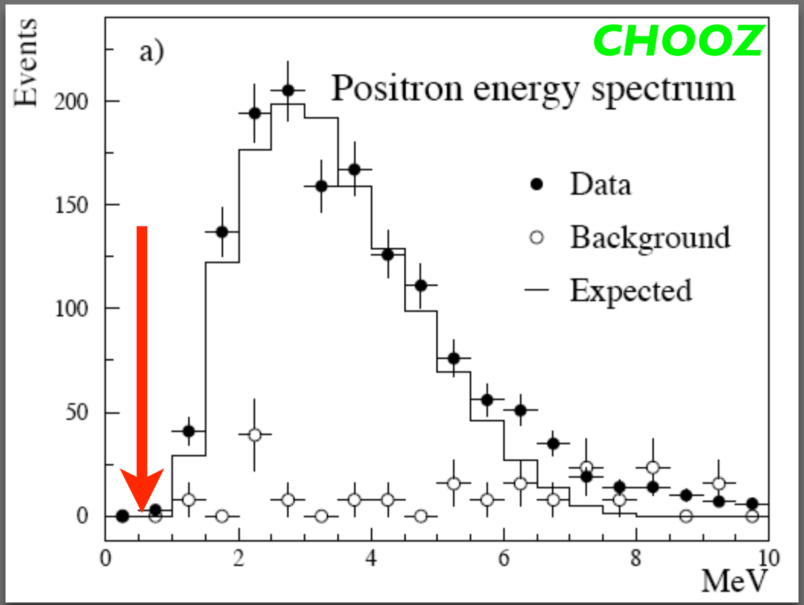
e+-n time-correlation

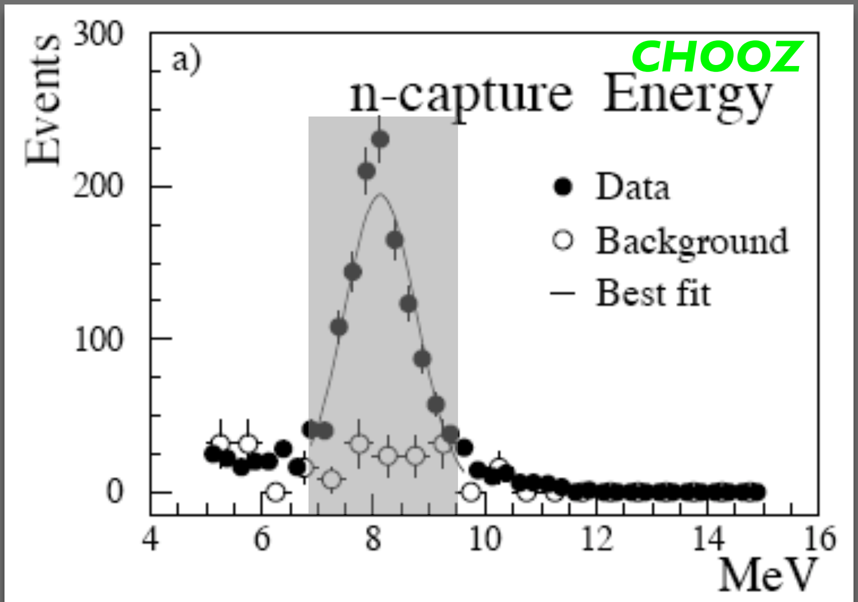


analysis: 3 cuts (7 cuts at CHOOZ)

e+-n energy deposited

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





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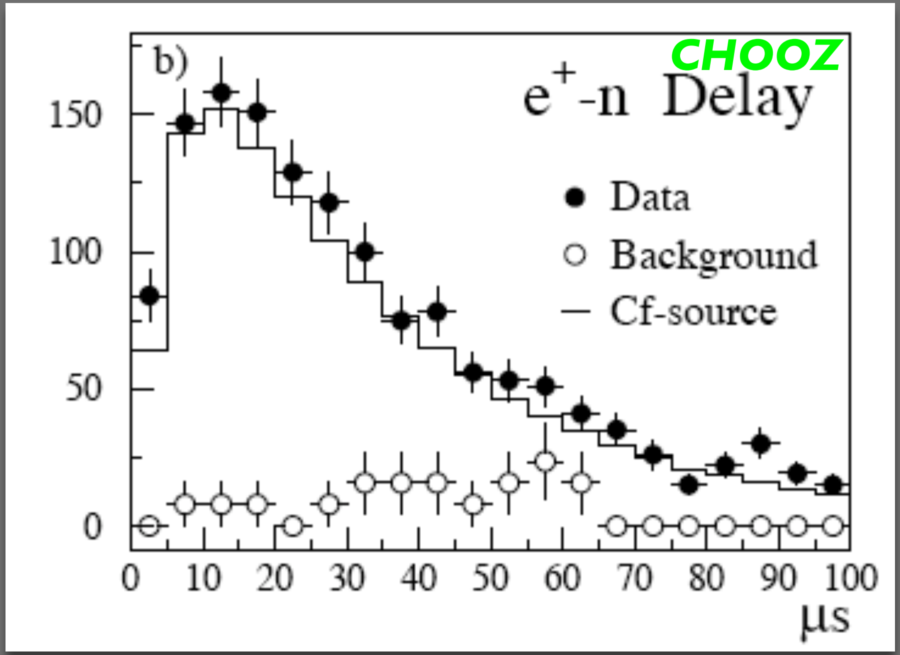
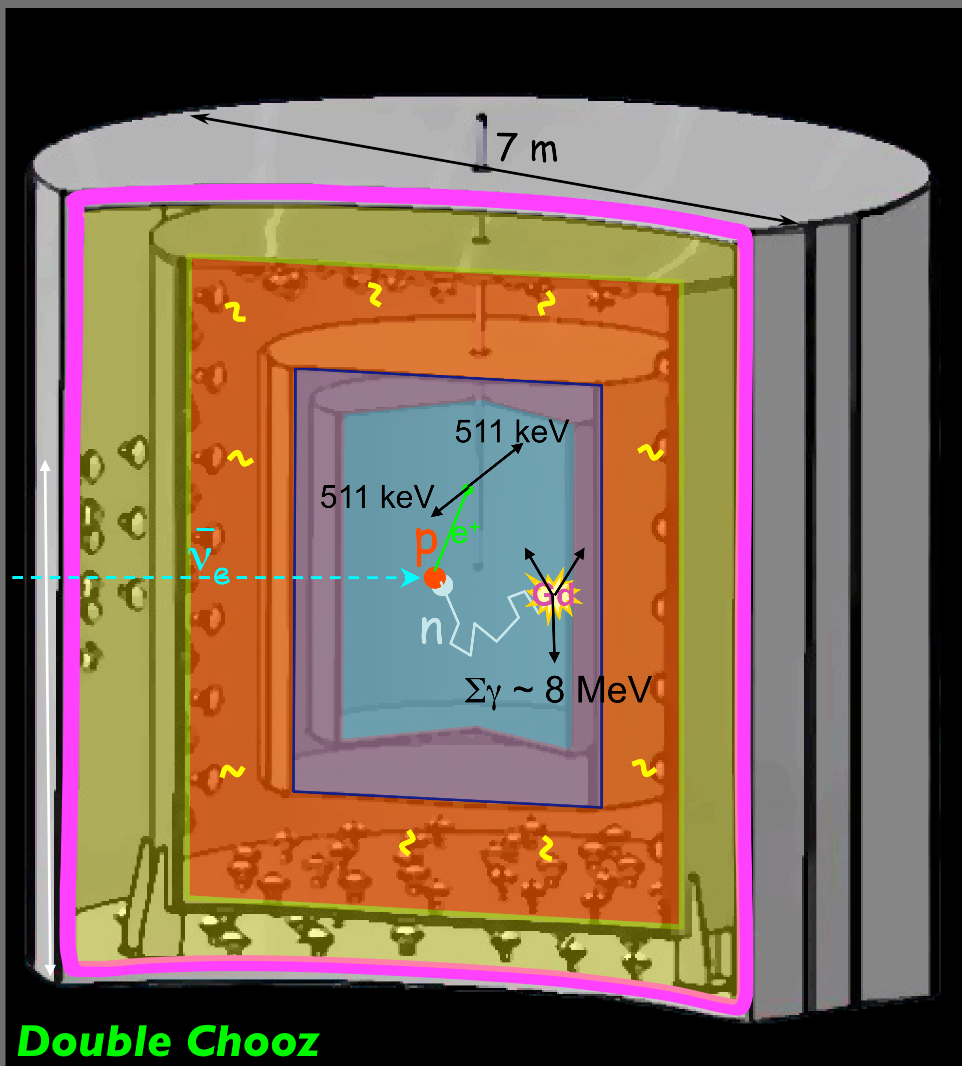


standard LAND

standard θ_{13}-LAND

θ_{13} dedicated detector => systematics <1%

Input from:
CHOOZ
Borexino
KamLAND
SNO



Proposal: hep-ex/0606025
LoI: hep-ex/0405032

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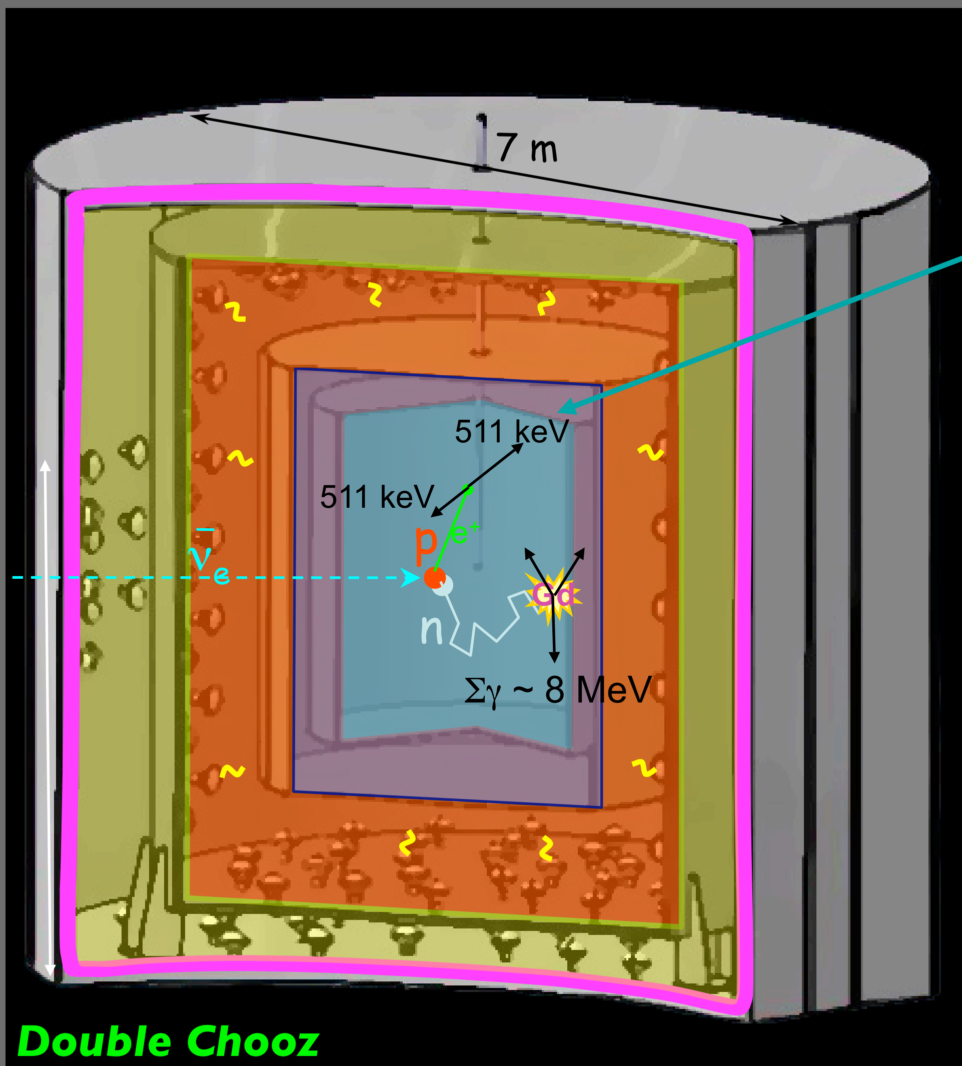

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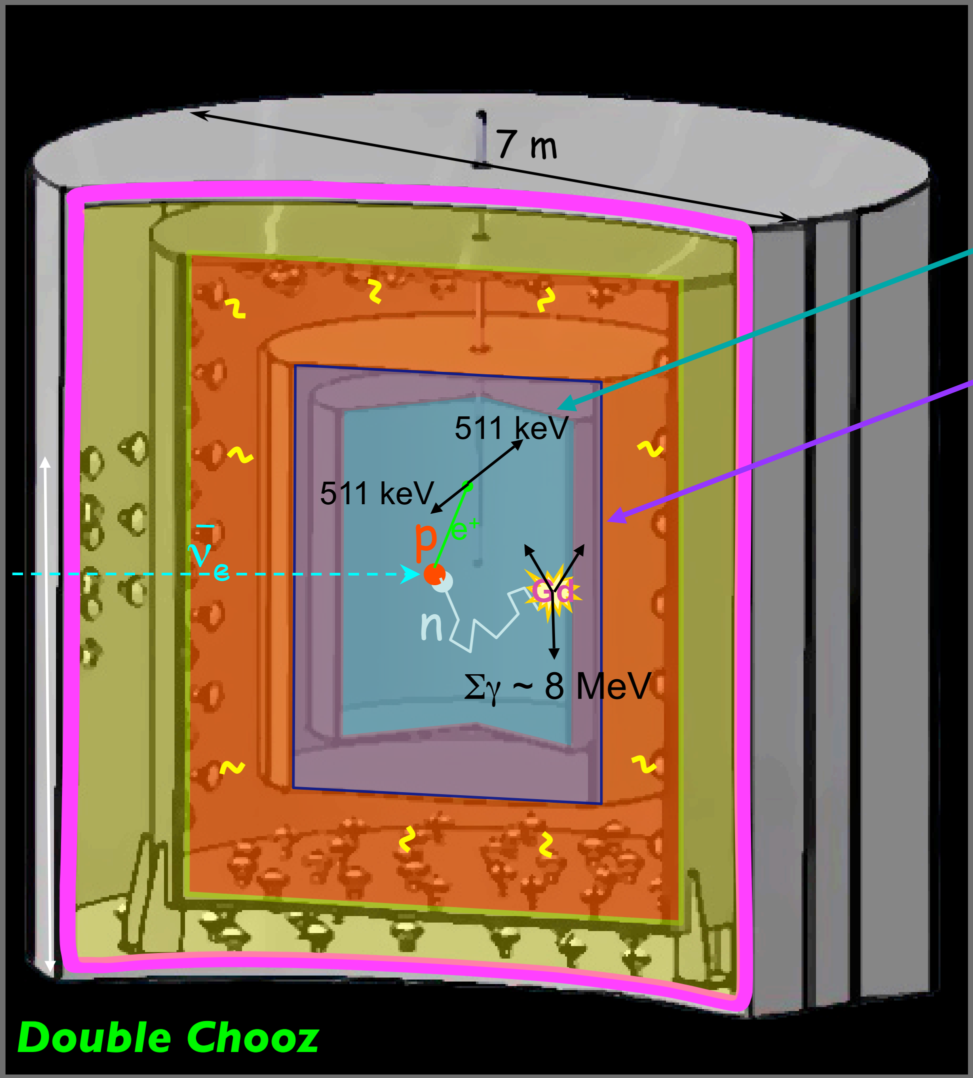

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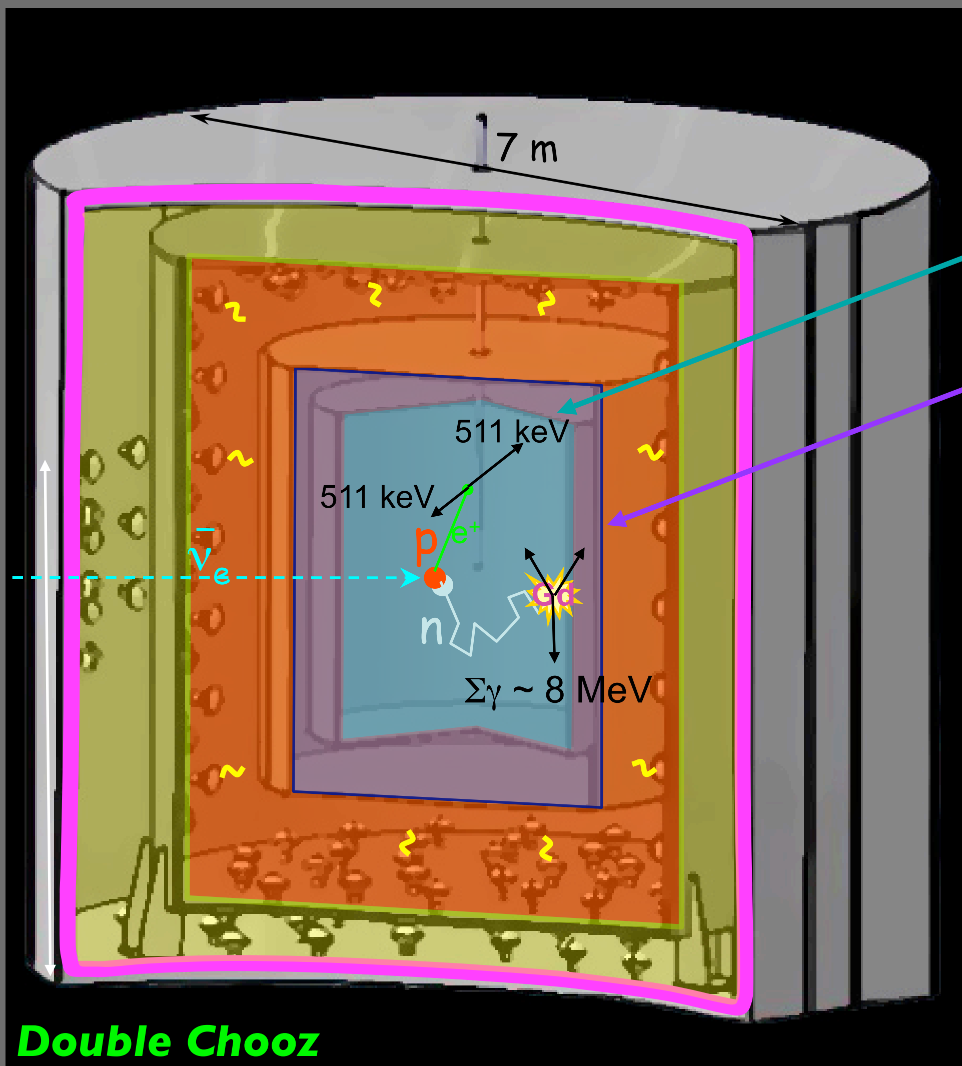

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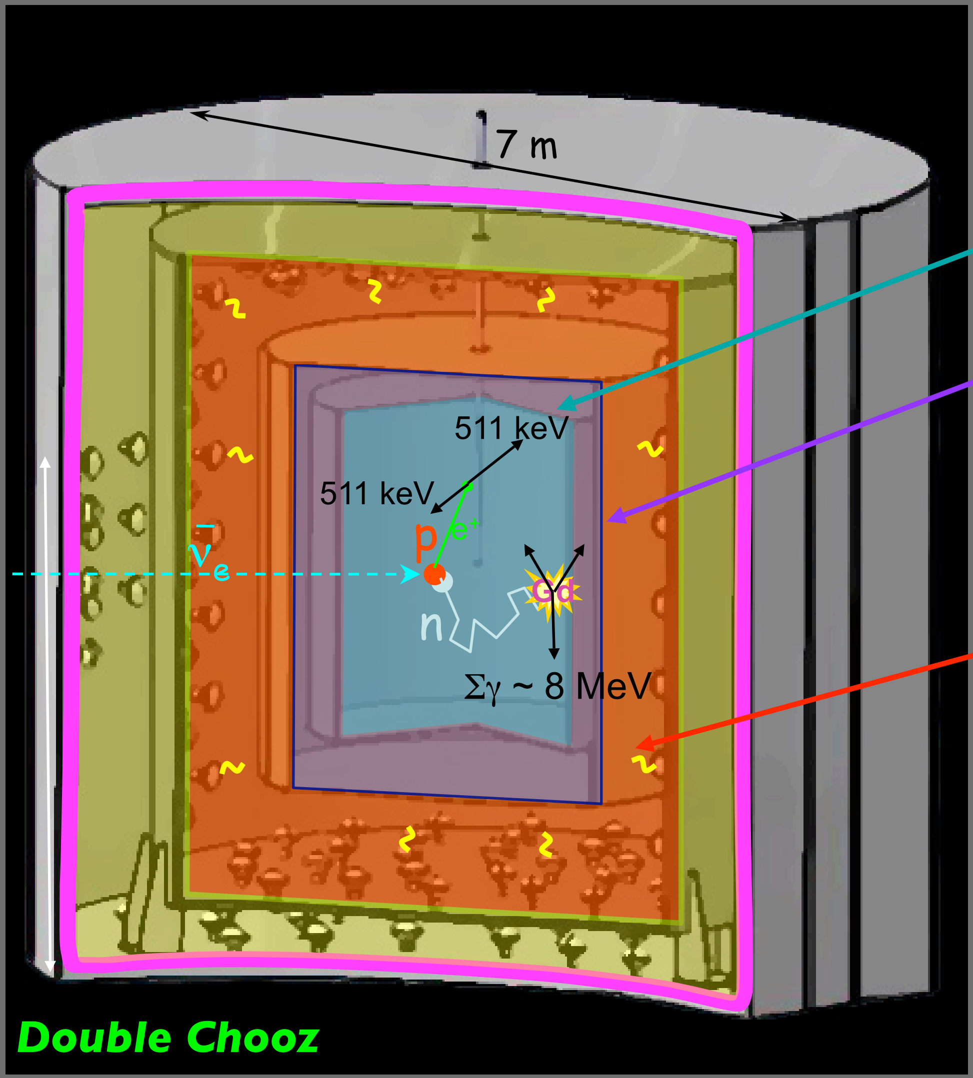

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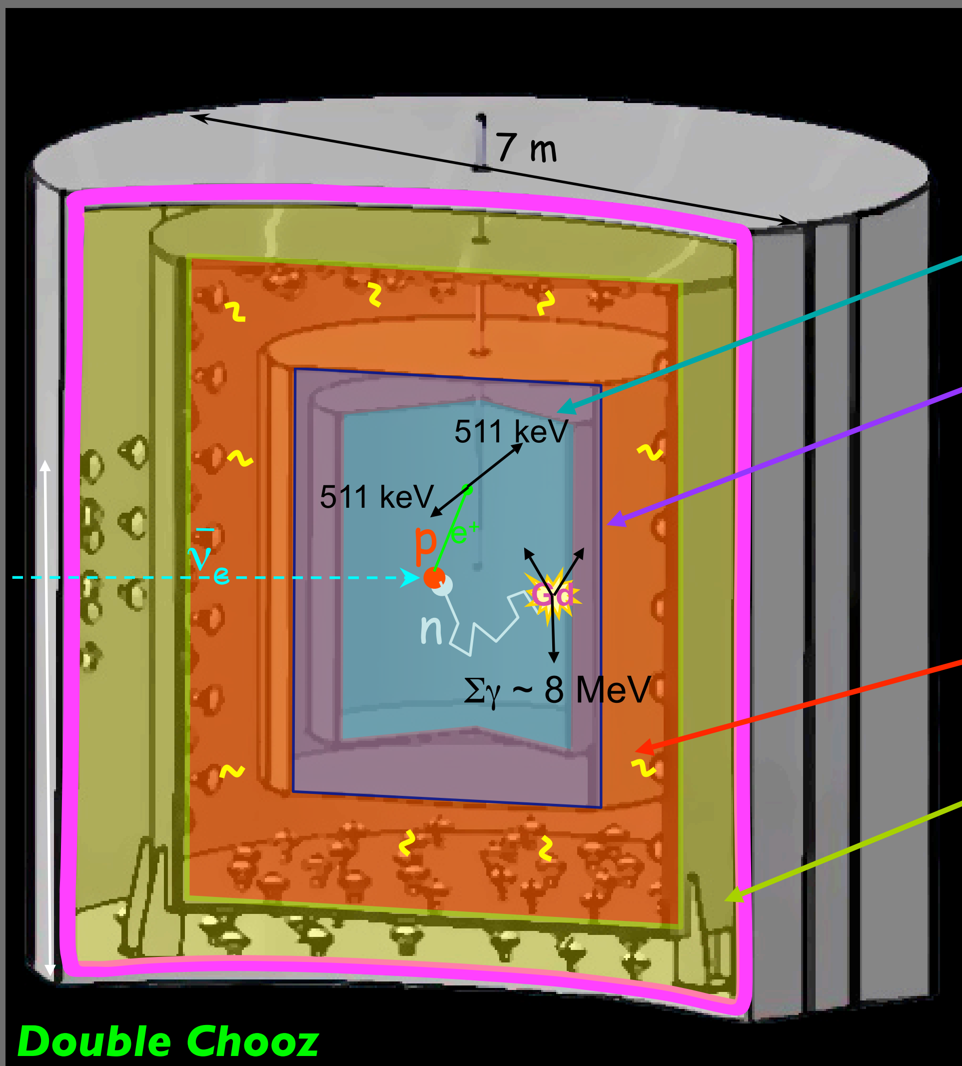

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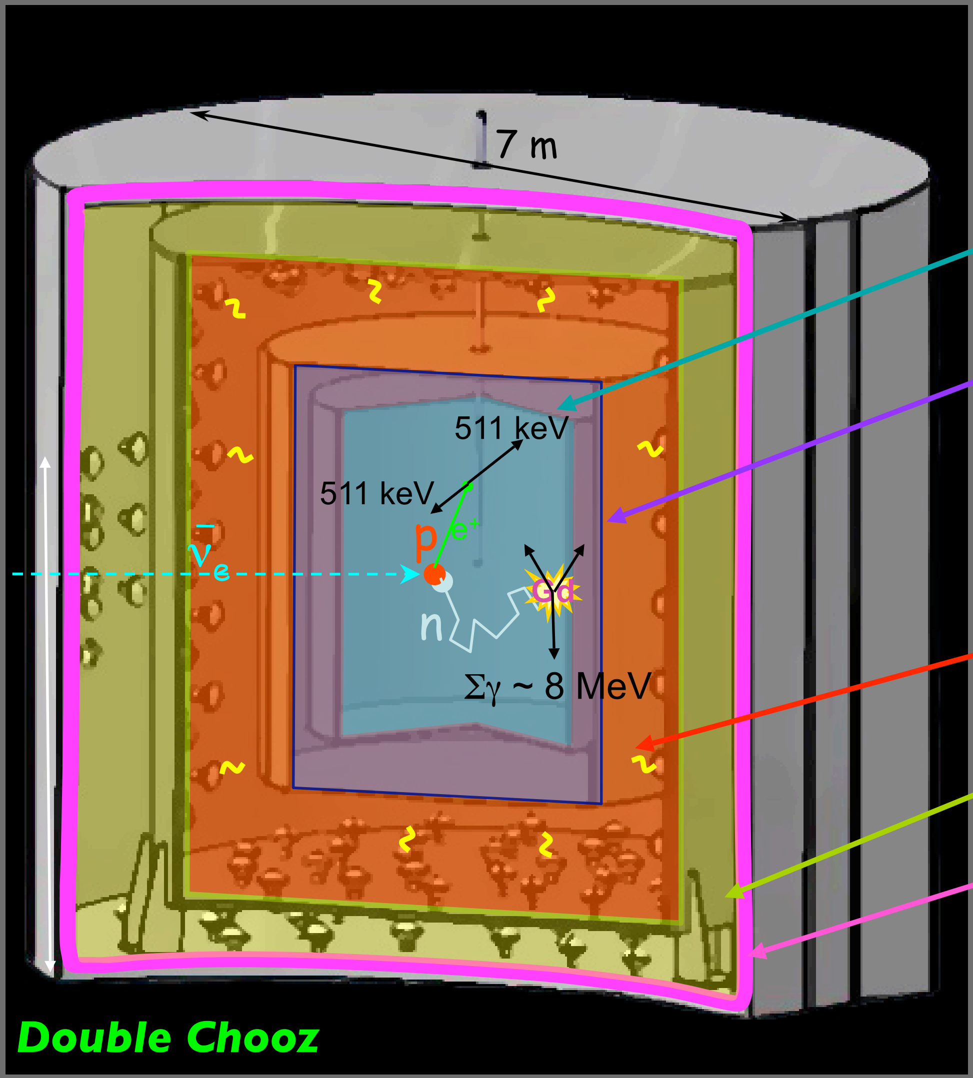

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LoI: hep-ex/0405032

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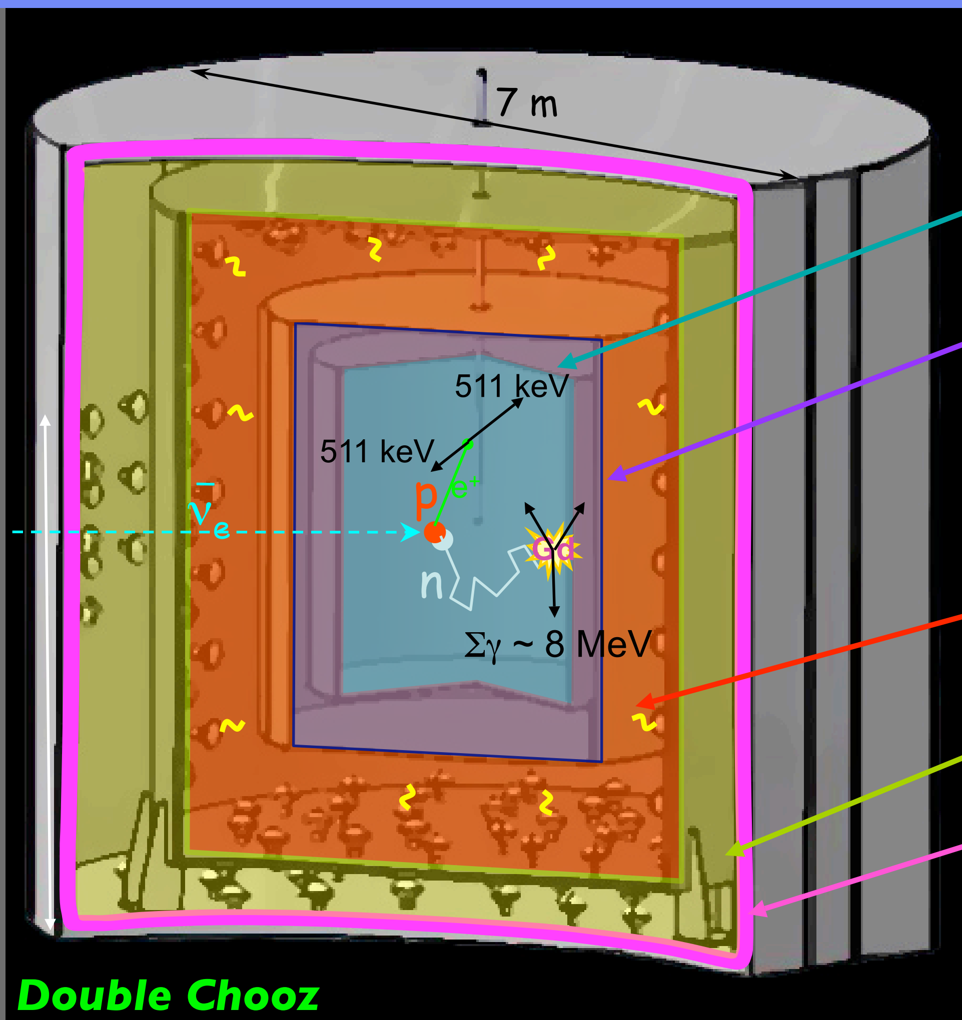

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Proposal: hep-ex/0606025
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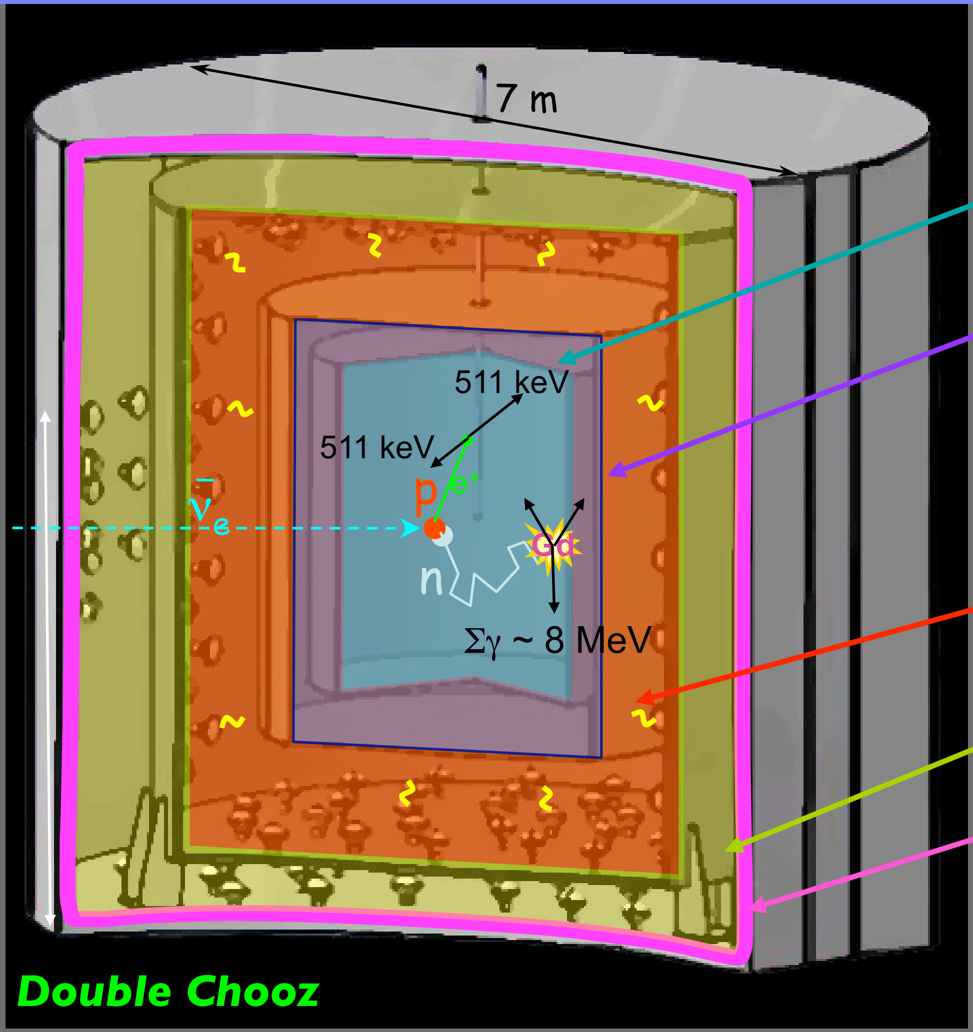
"near-miss" μ tagging



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    - ^{40}K(natural) & ^{137}Cs(calibration)

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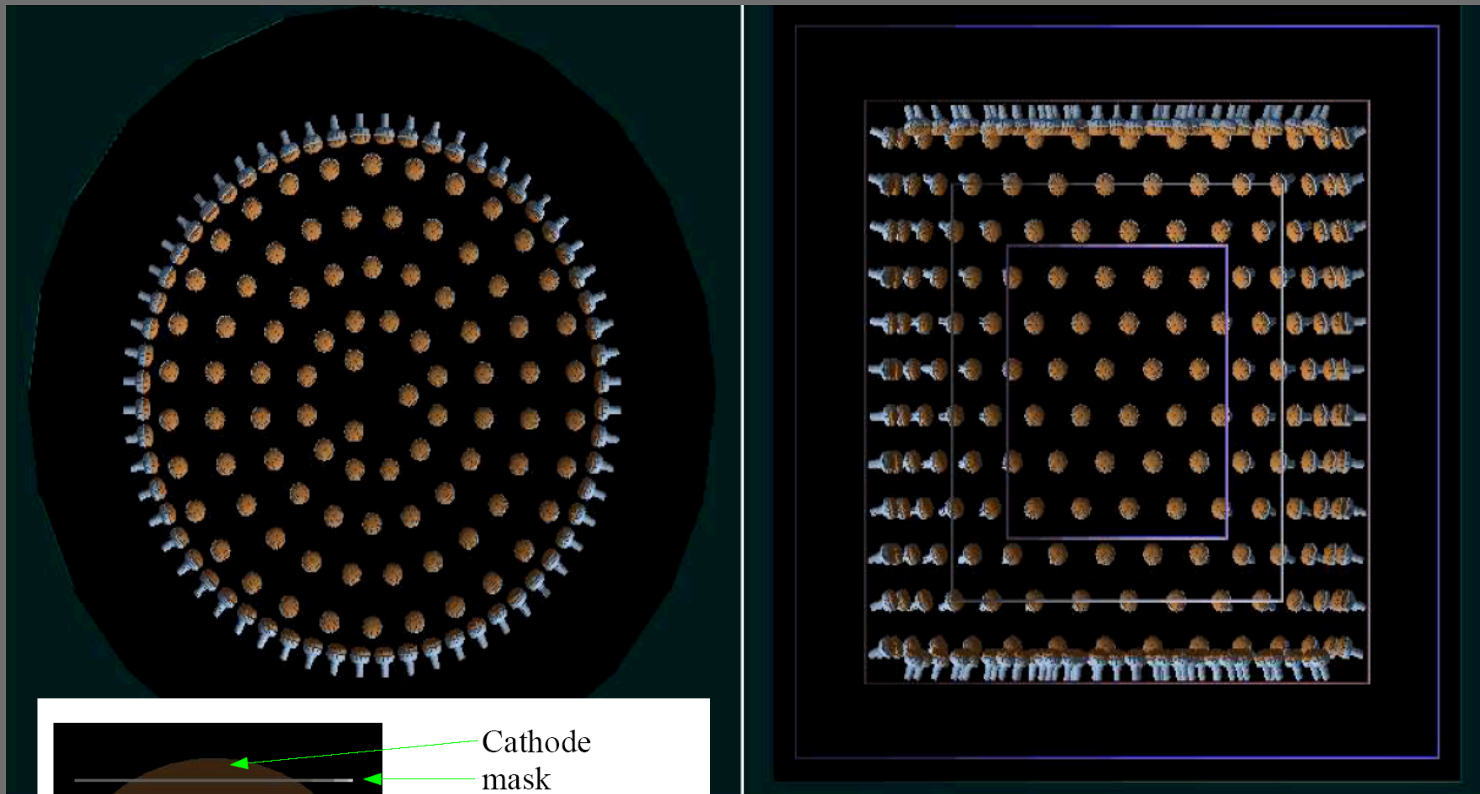
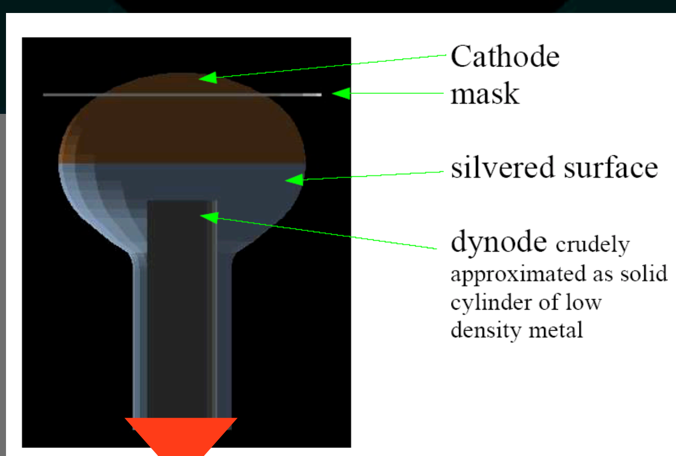
  - same source response comparison ND and FD

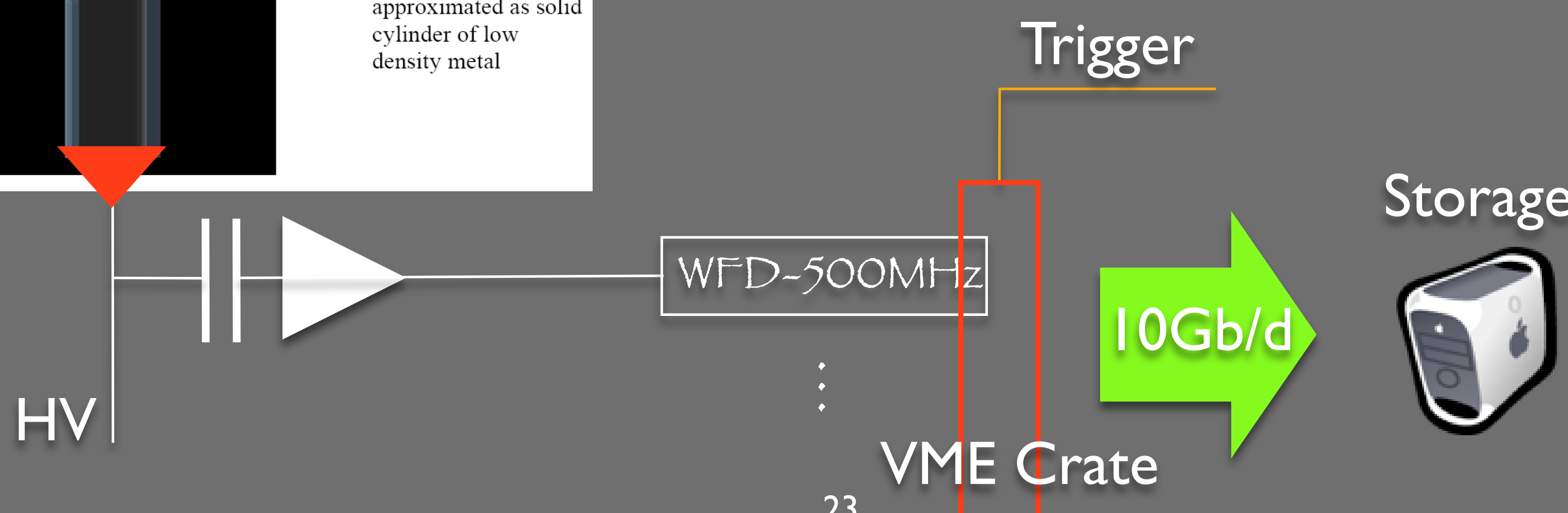
readout





8"/10" PMs

FADC-WFD
FADC



backgrounds...

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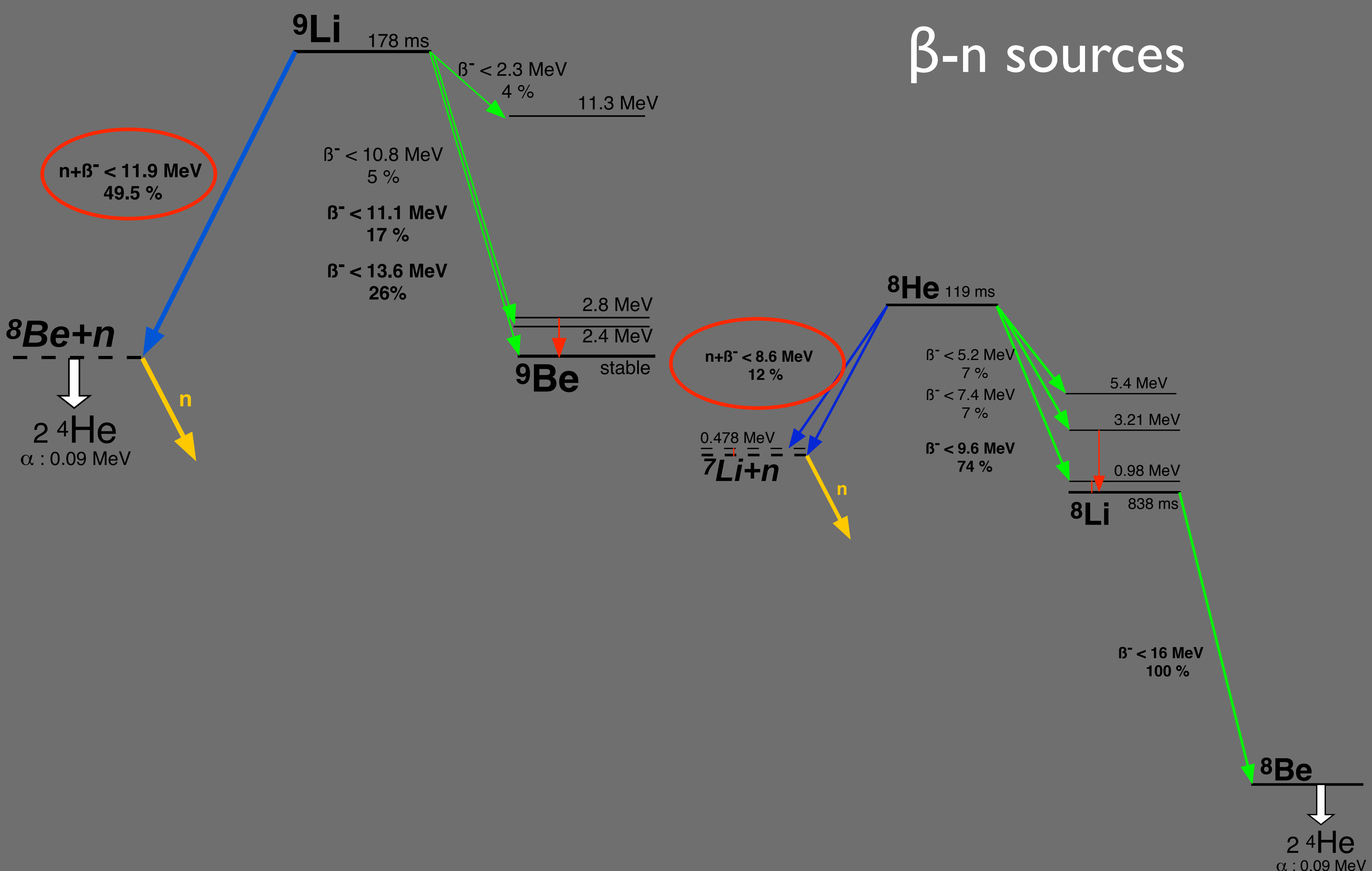
  - long-lived (~ms) β-n decaying spallation products on C: Li & He

cosmogenic BG



(s)

BG spectra

important for spectral distortion analysis

approaches...

- $BG_{ND} = BG_{FD}$
- BG/S <1% (per bin)

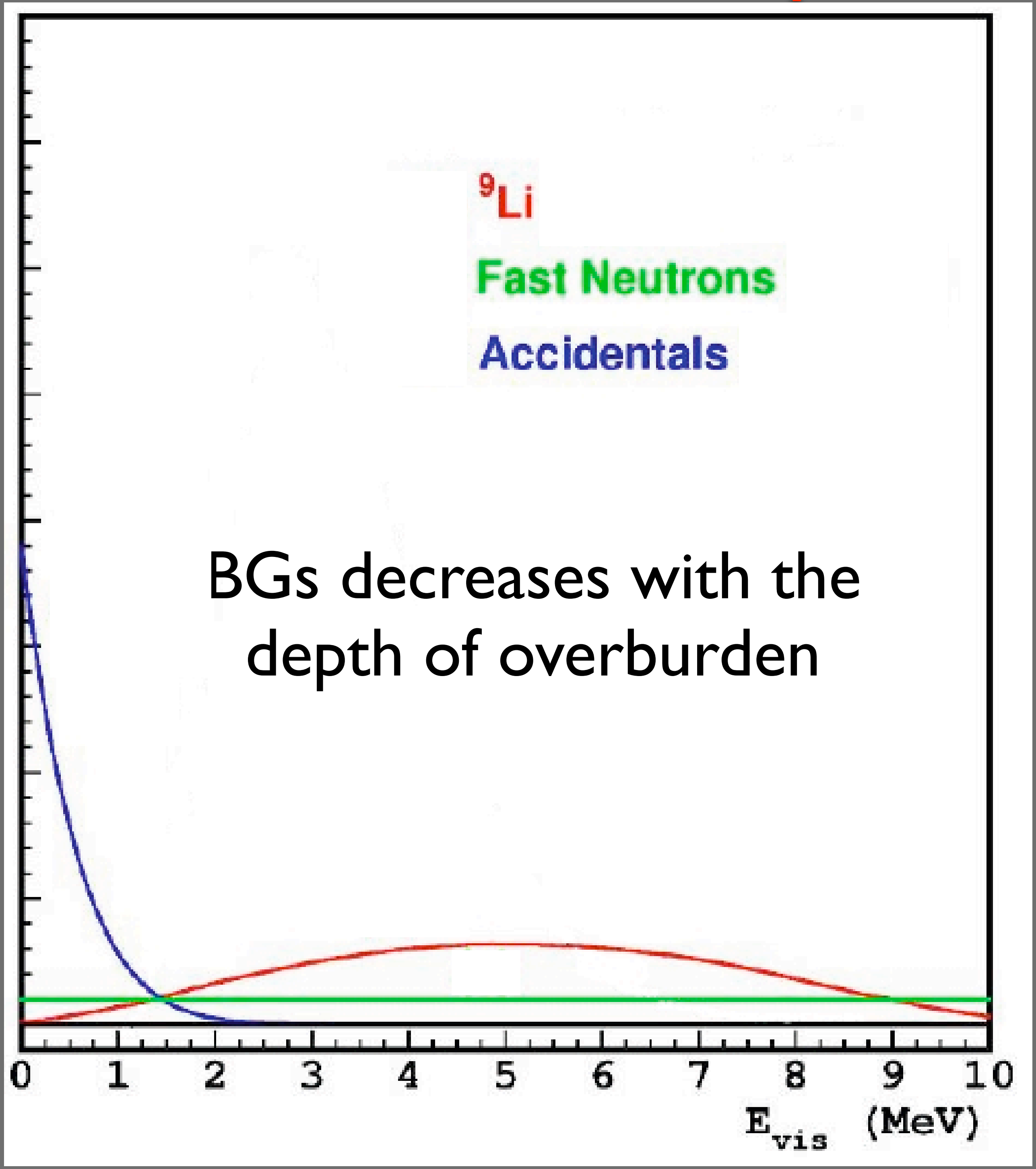
good detector design

- S/√BG (per bin) for

both ND & FD

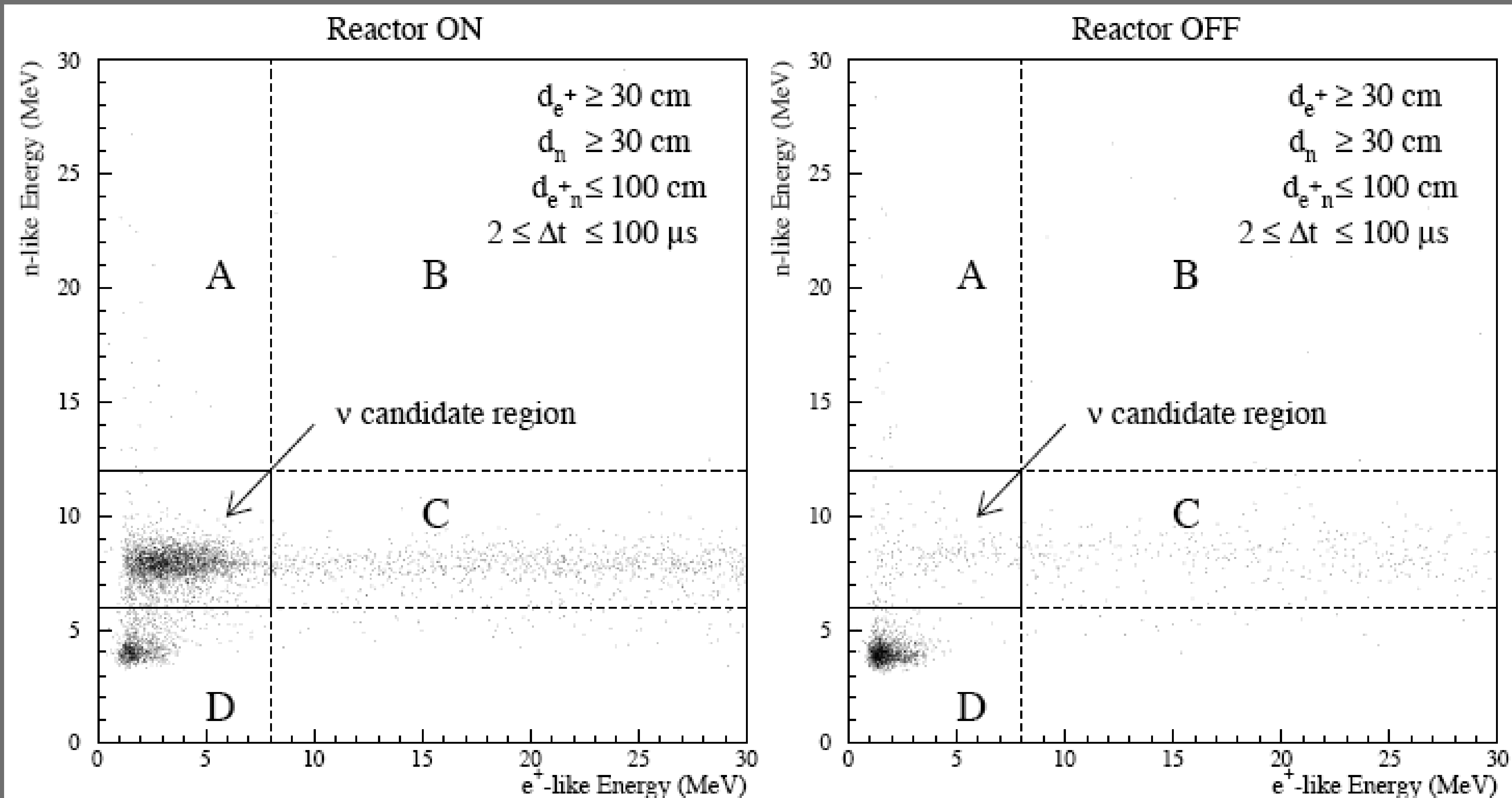
- BG knowledge is

difficult (n-flux)



an experimentalist's dream

switched off signal => measure background "naked"!



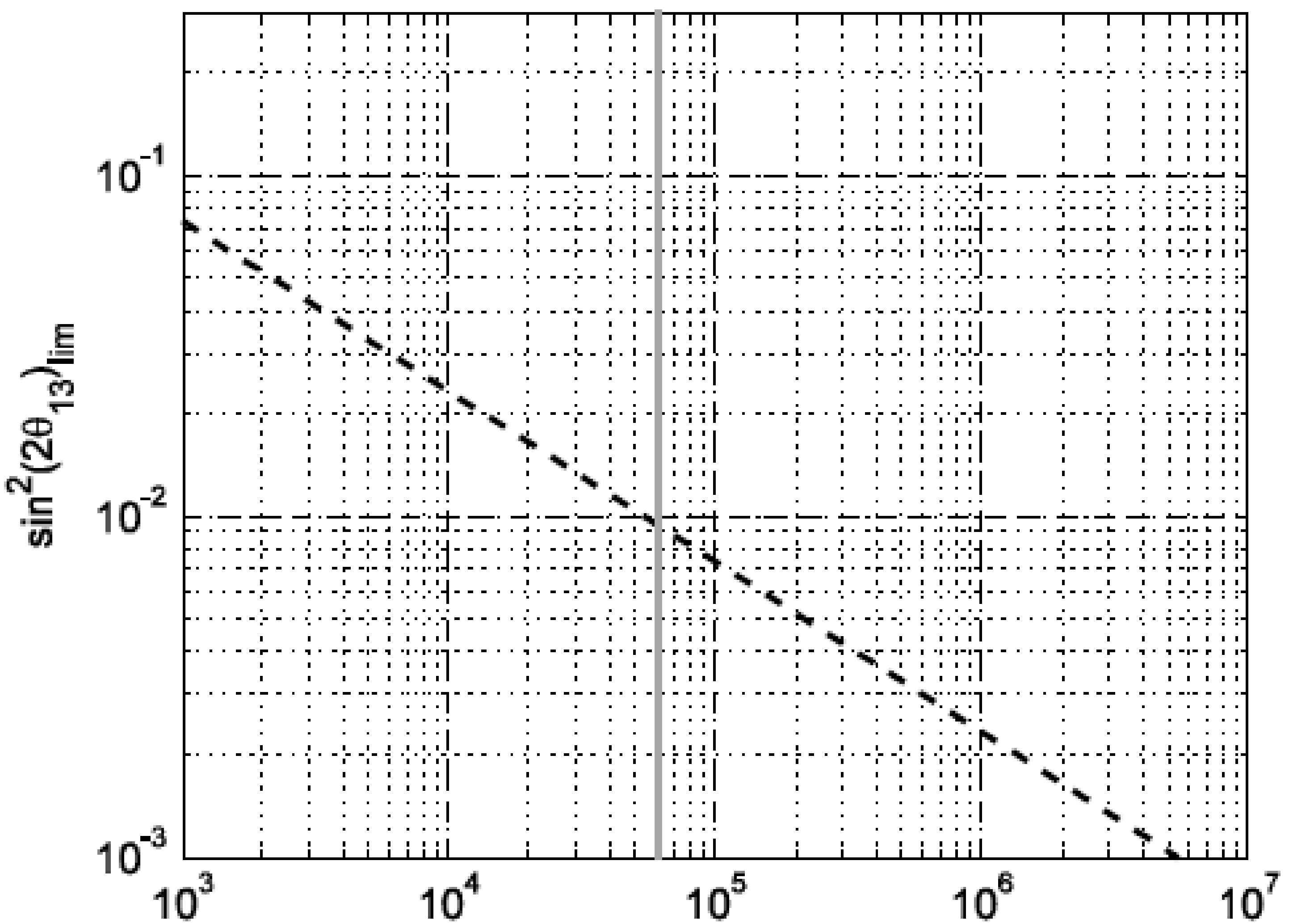
Apollonio et al (CHOOZ): hep-ex/0301017

multi-reactor-core experiments => less likely to happen sensitivity evolution...

Sensitivity Evolution

$$\chi^2 = \sum_{i=1}^{N} \frac{\left(O_i - T_i - aT_i\right)^2}{O_i} + \left(\frac{a}{\sigma_{norm}}\right)^2$$

once the flux-uncertainties are eliminated, by near detector



Ideal case:

sensitivity scales with √N

i.e. no syst. uncertainties

σ_{norm} = 0 %

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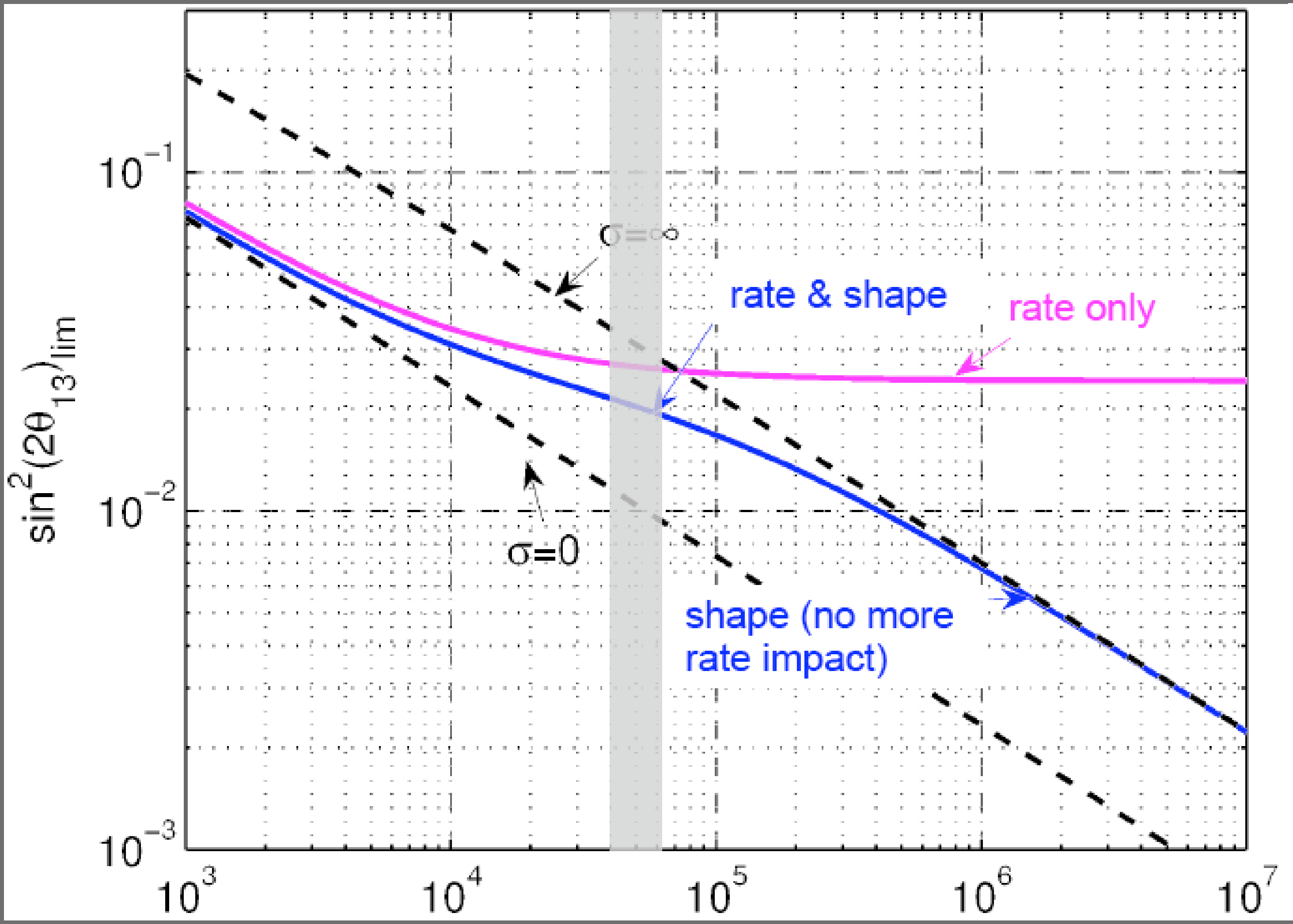
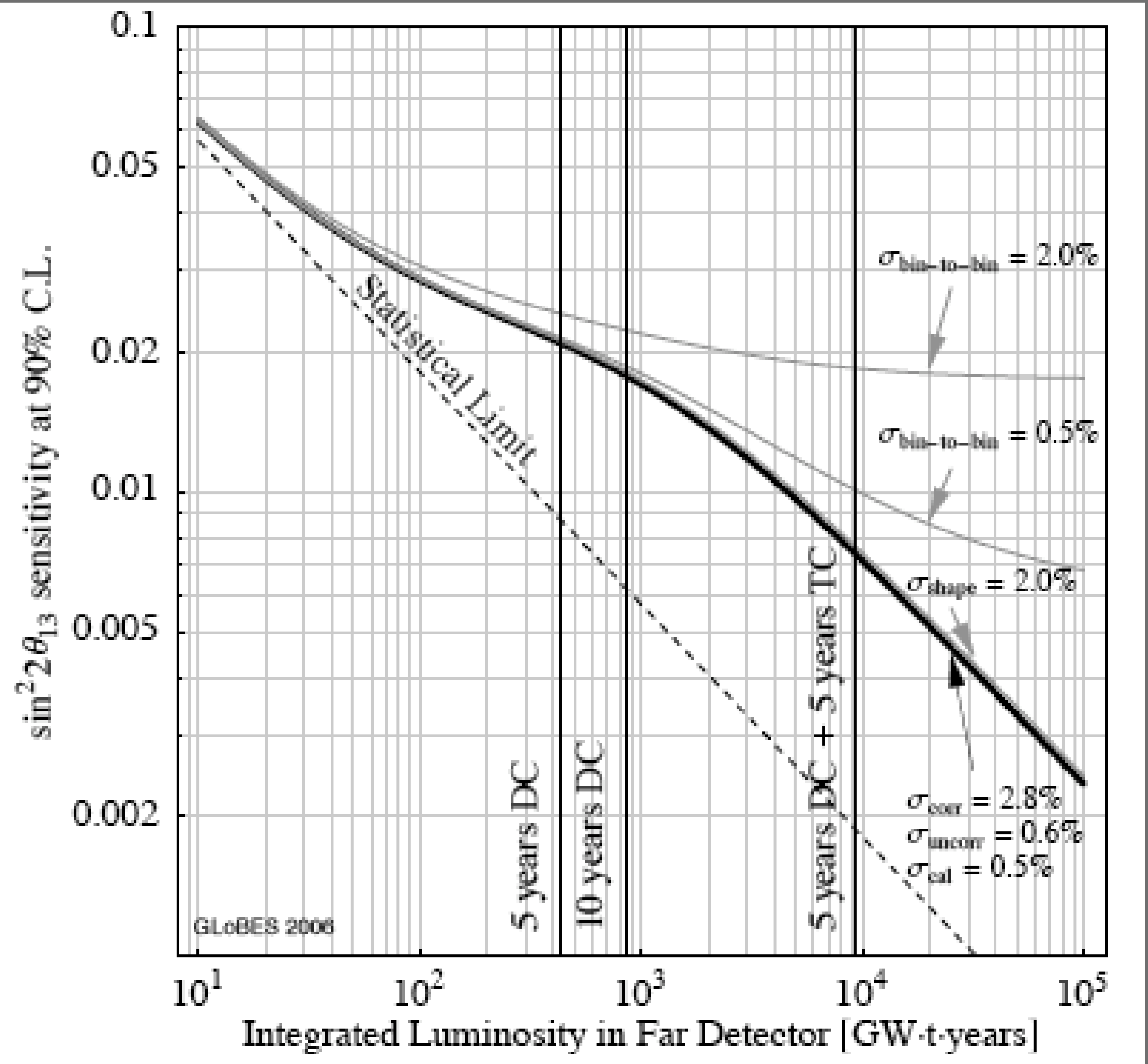


Sensitivity Break Down:

- Rate: systamics dominated
- Shape: statistics dominated

Huber et al. hep-ph/0601266

sensitivity regime



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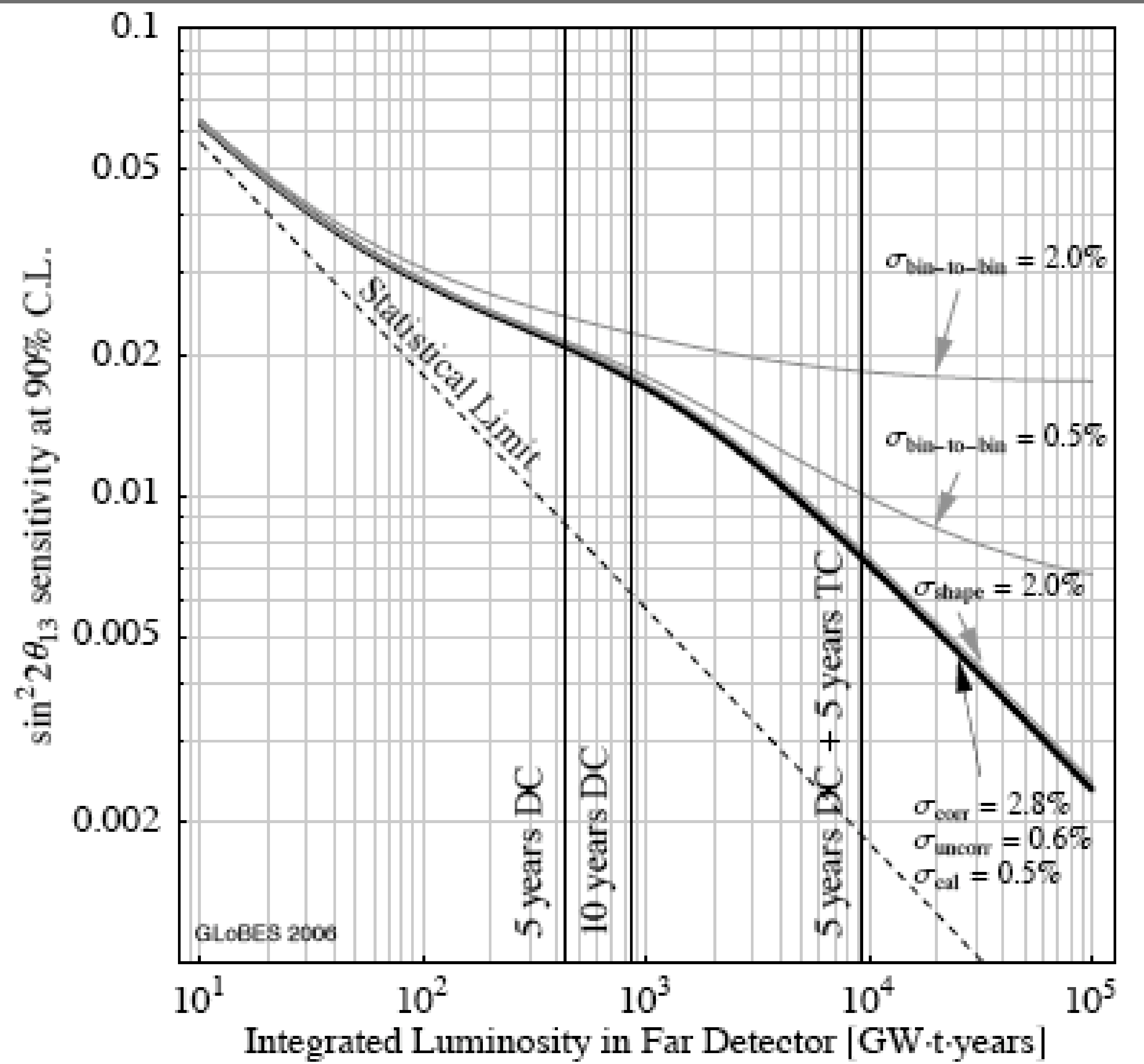

Domains:

Huber et al. hep-ph/0601266

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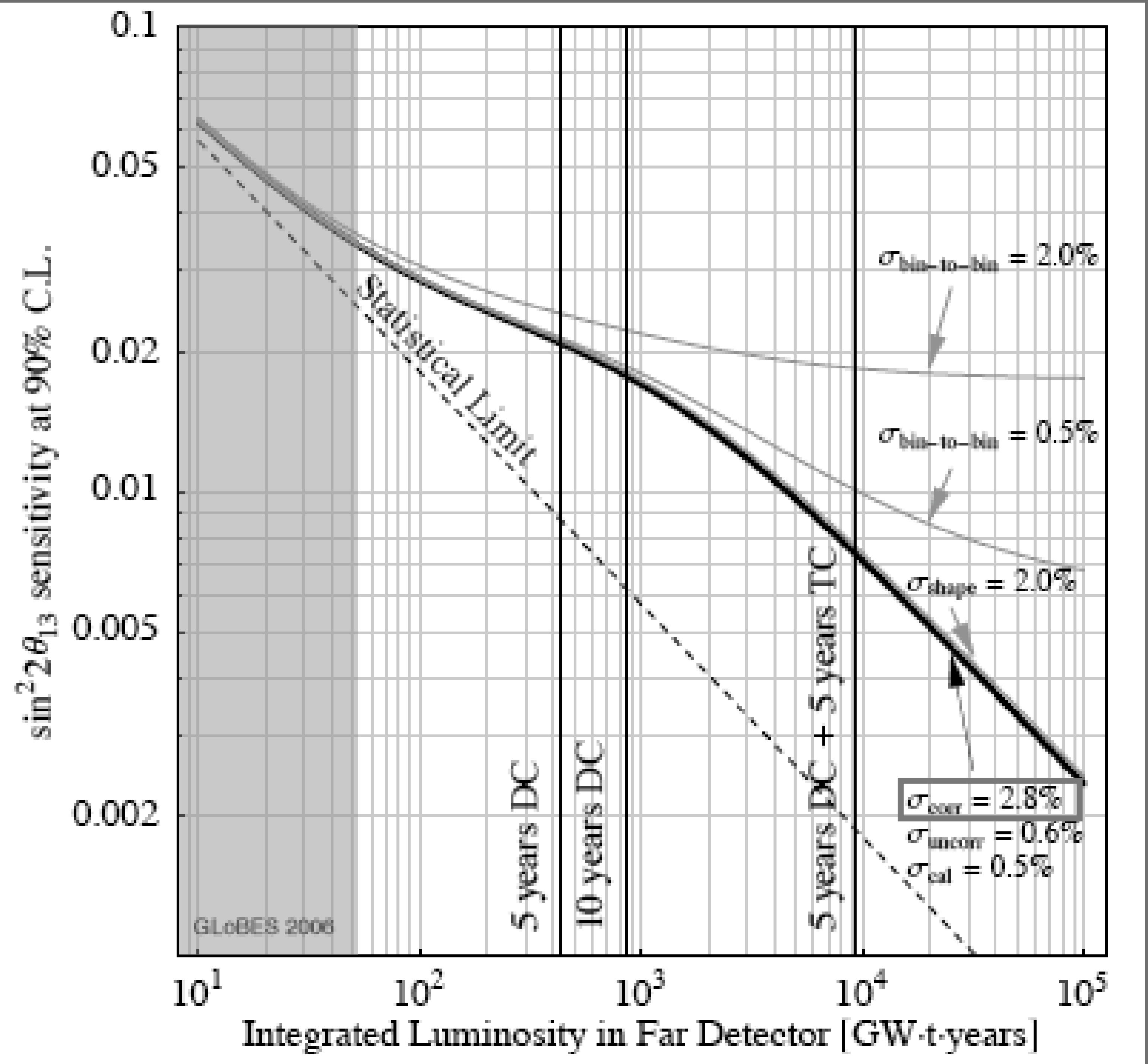

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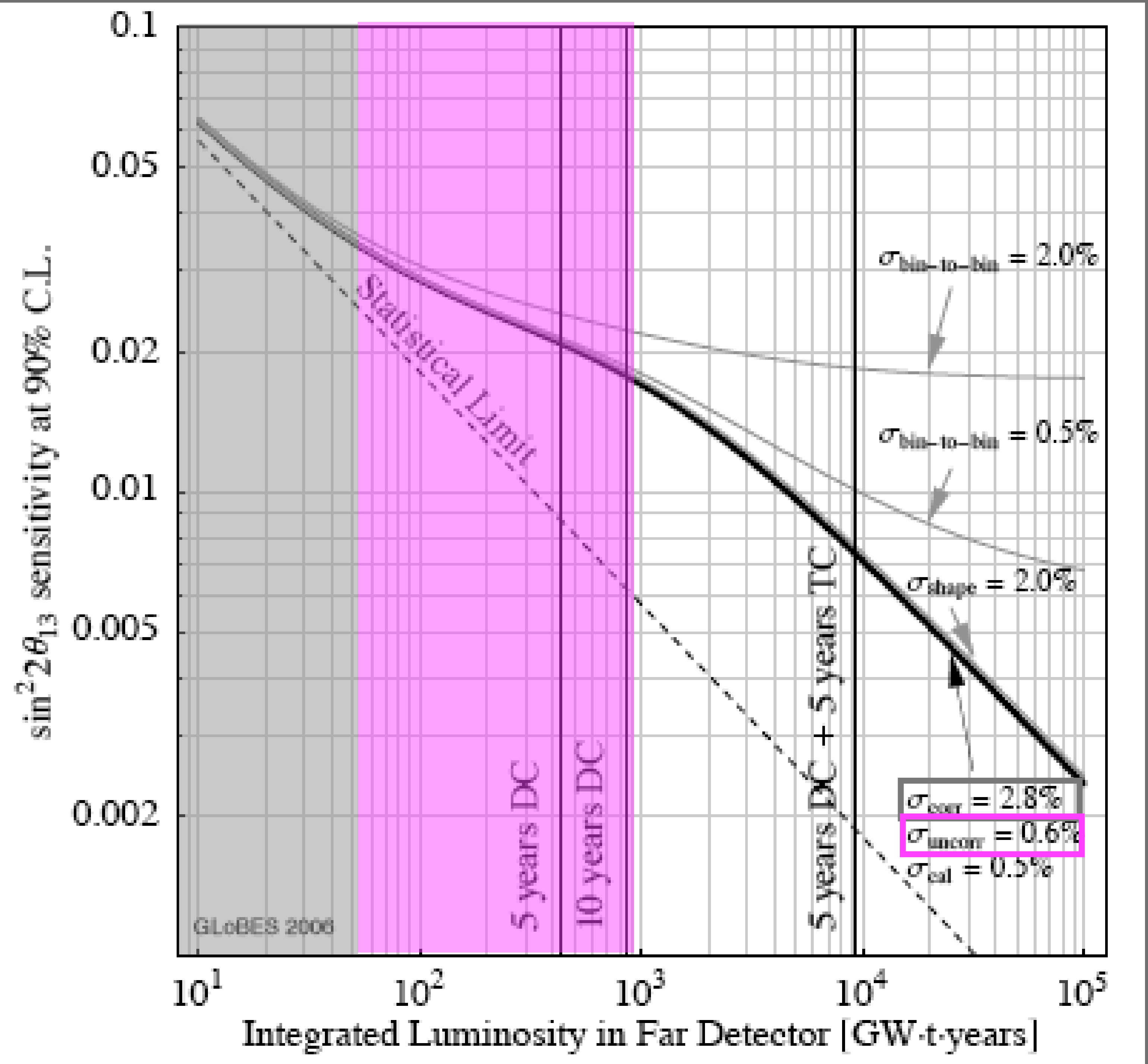

Domains:

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Huber et al. hep-ph/0601266

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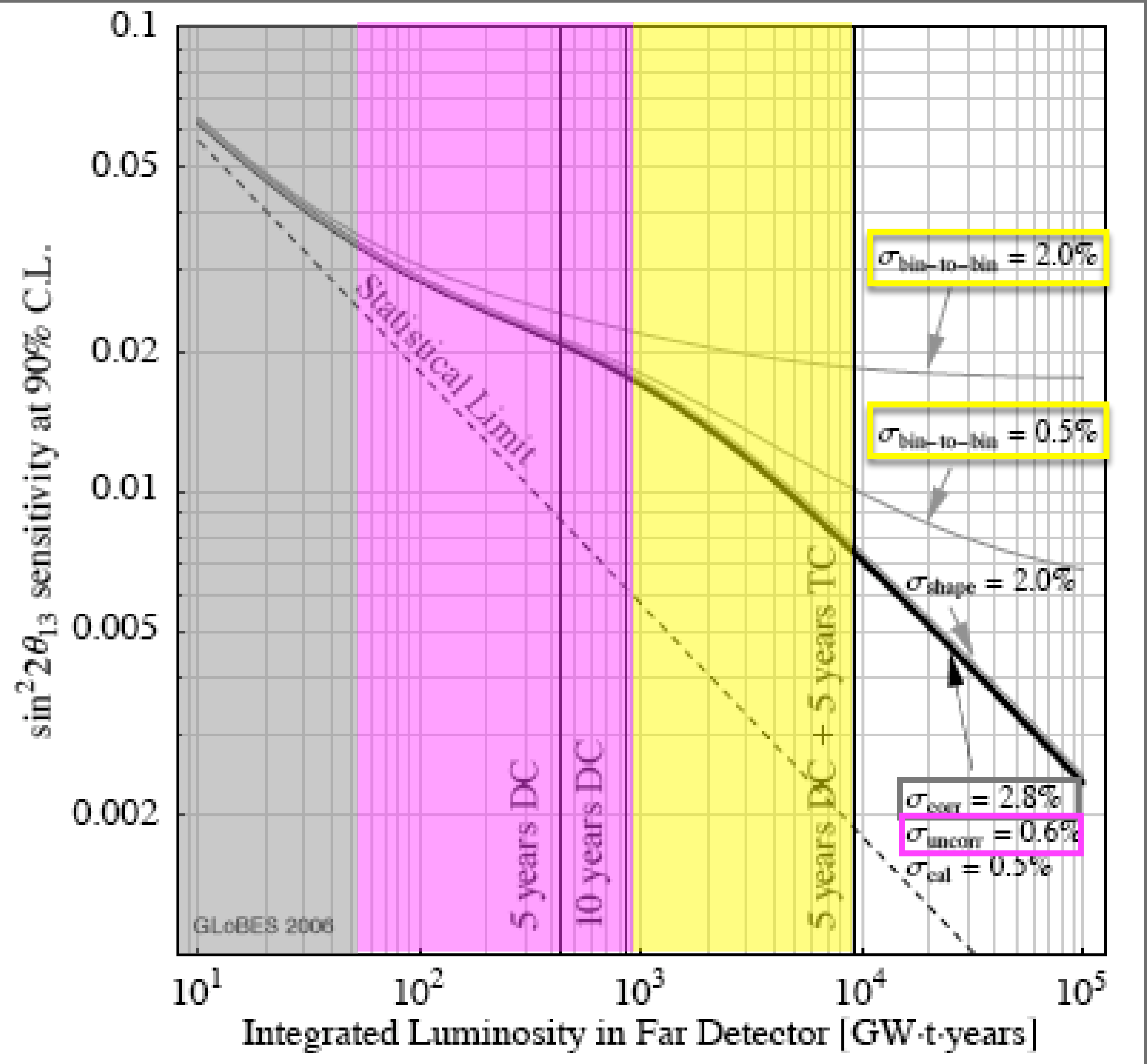

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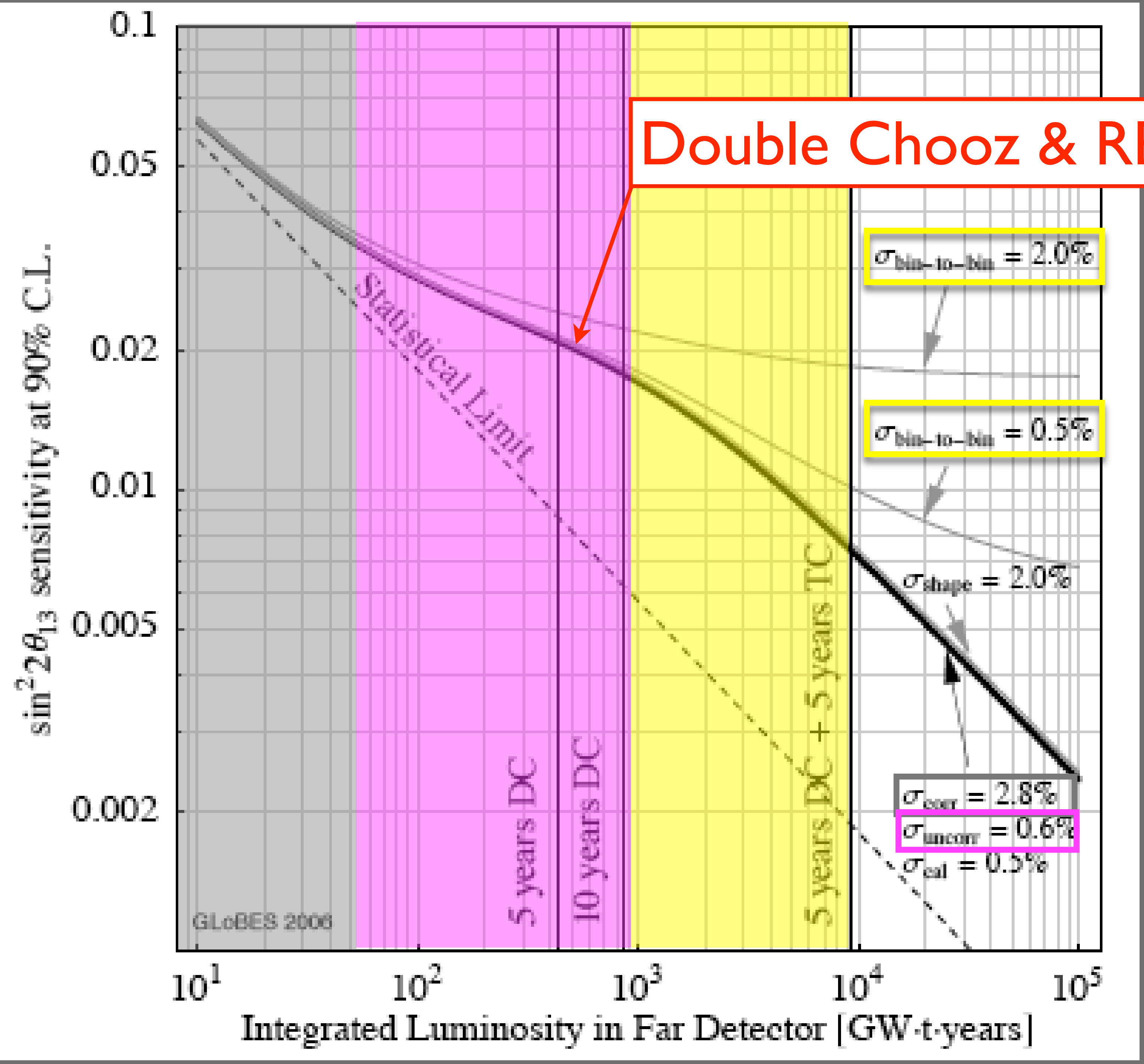

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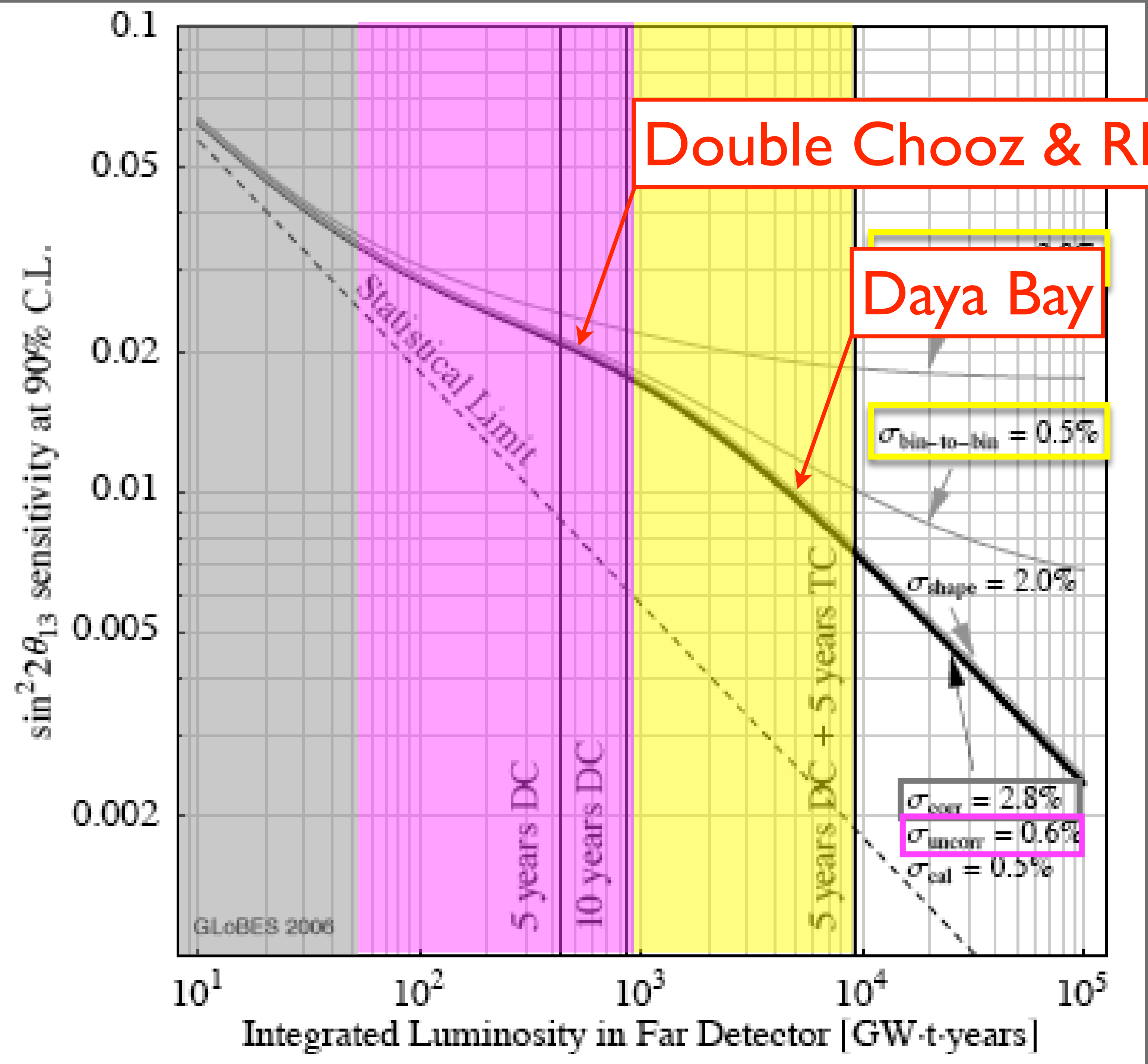

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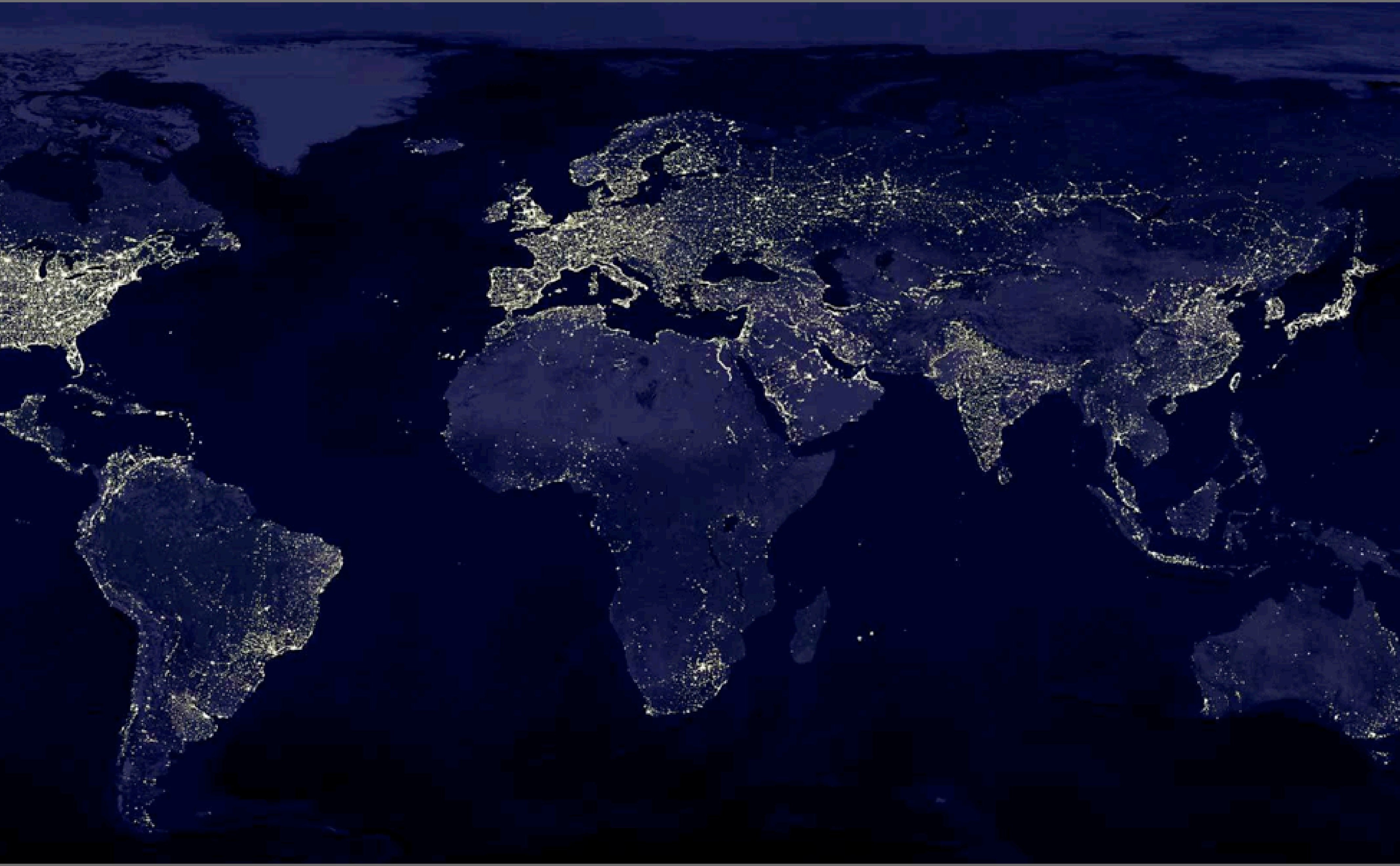
Proposed experiments...



hep-ex/0704.0498

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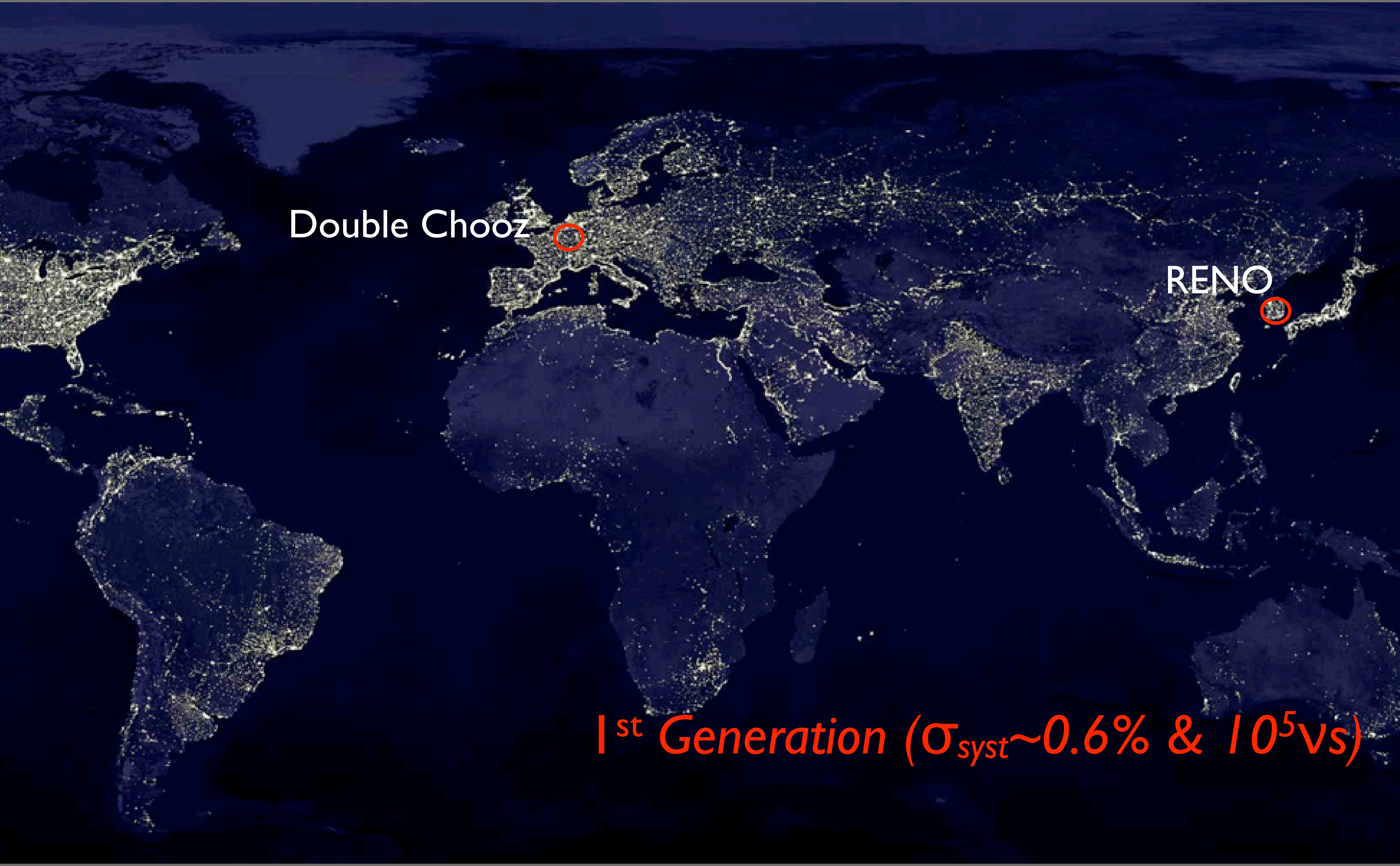

1st *Generation* (σ_{syst}~0.6% & 10^5νs)

hep-ex/0704.0498

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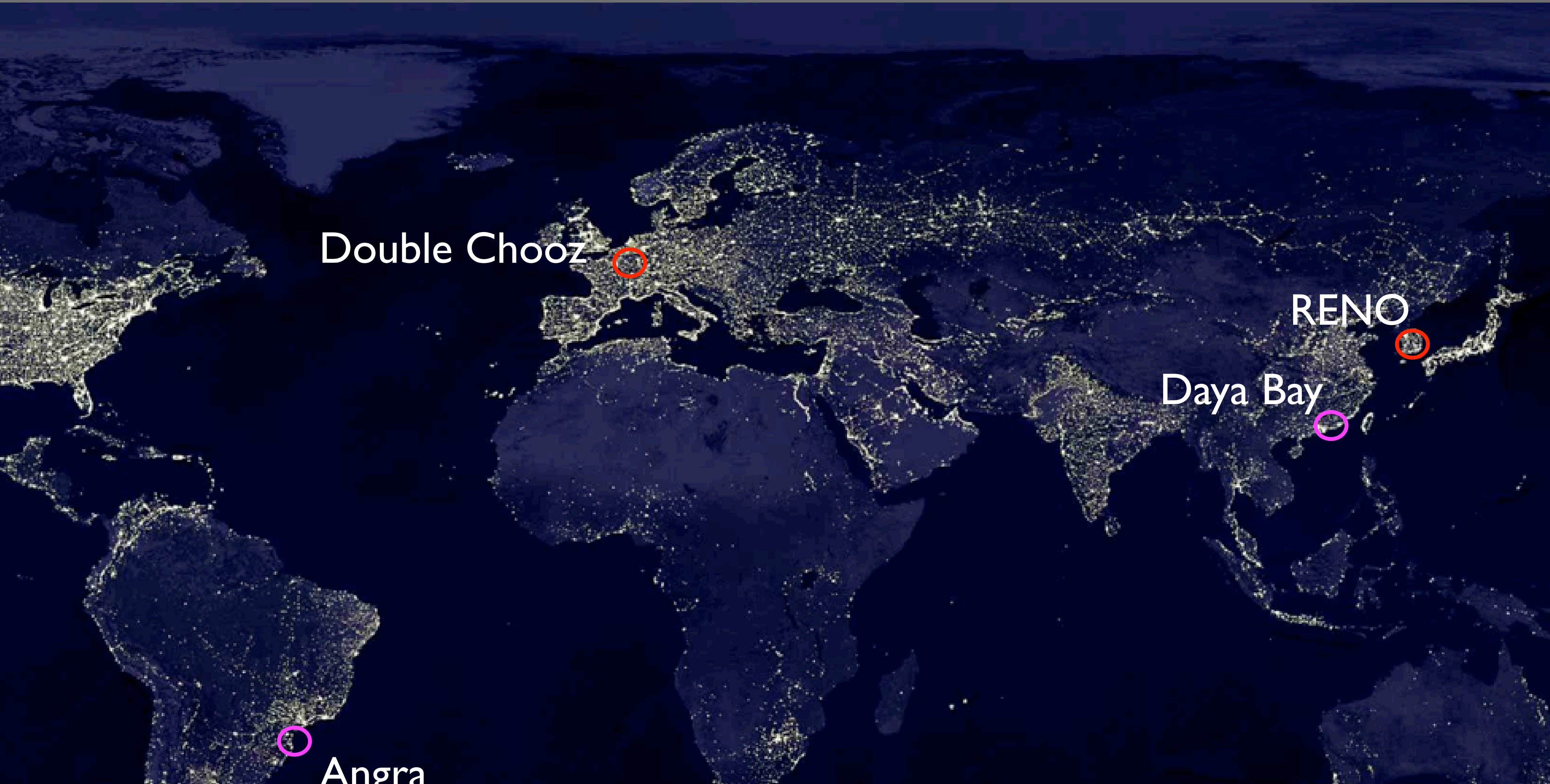

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2nd *Generation* (σ_{syst}~0.1% & $10^6\nu$s)

hep-ex/0704.0498

Double Chooz: A Search for the Neutrino Mixing Angle θ_{13}

F. Ardellier[19] I. Barabanov[10] J. C. Barrière[19] F. Beißel[1]
S. Berridge[23] L. Bezrukov[10] A. Bernstein[14] T. Bolton[12]
N.S. Bowden[20] Ch. Buck[16] B. Bugg[23] J. Busenitz[2] A. Cabrera[4]
E. Caden[6] C. Cattadori[7,17] S. Cazaux[19] M. Cerrada[5] B. Chevis[23]
H. Cohn[23] J. Coleman[15] S. Cormon[21] B. Courty[4] A. Cucoanes[1]
M. Cribier[4,19] N. Danilov[11] S. Dazeley[15] A. Di Vacri[7]
Y. Efremenko[23] A. Etenko[13] M. Fallot[21] C. Fernández-Bedoya[5]
F. von Feilitzsch[22] Y. Foucher[21] T. Gabriel[23] P. Ghislain[4]
I. Gil Botella[5] G. Giurgiu[3] M. Goeger-Neff[22] M. Goodman[3*]
D. Greiner[24] Ch. Grieb[22] V. Guarino[3] A. Guertin[21] P. Guillouet[4]
C. Hagner[8] W. Hampel[16] T. Handler[23] F. X. Hartmann[16]
G. Horton-Smith[12] P. Huber[22†] J. Jochum[24] Y. Kamyshkov[23]
D. M. Kaplan[9] H. de Kerret[4] T. Kirchner[21] V. Kopeikin[13]
J. Kopp[22] A. Kozlov[23] T. Kutter[15] Yu. S. Krylov[11] D. Kryn[4]
T. Lachenmaier[24] C. Lane[6] T. Lasserre[4,19*] C. Lendvai[22] Y. Liu[2]
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F. Meigner[19] G. Mention[19] W. Metcalf[15] L. Mikaelyan[13]
A. Milsztajn[19] J. P. Meyer[19] D. Motta[19] L. Oberauer[22]
M. Obolensky[4] C. Palomares[5] P. Perrin[19] W. Potzel[22]
J. Reichenbacher[3] B. Reinhold[1] D. Reyna[3] M. Rolinec[22]
L. Romero[5] S. Roth[1] S. Schoenert[16] U. Schwan[16] T. Schwetz[22]
L. Scola[19] V. Sinev[13,19] M. Skorokhvatov[13] A. Stahl[1] I. Stancu[2]
N. Stanton[12] S. Sukhotin[4,13] R. Svoboda[14,15] A. Tang[12]
A. Tonazzo[4] D. Underwood[3] F.J. Valdivia[5] D. Vignaud[4]
D. Vincent[4] W. Winter[22‡] K. Zbiri[21] R. Zimmermann[8]

9th June 2006

i

Proposal: hep-ex/0606025
LoI: hep-ex/0405032

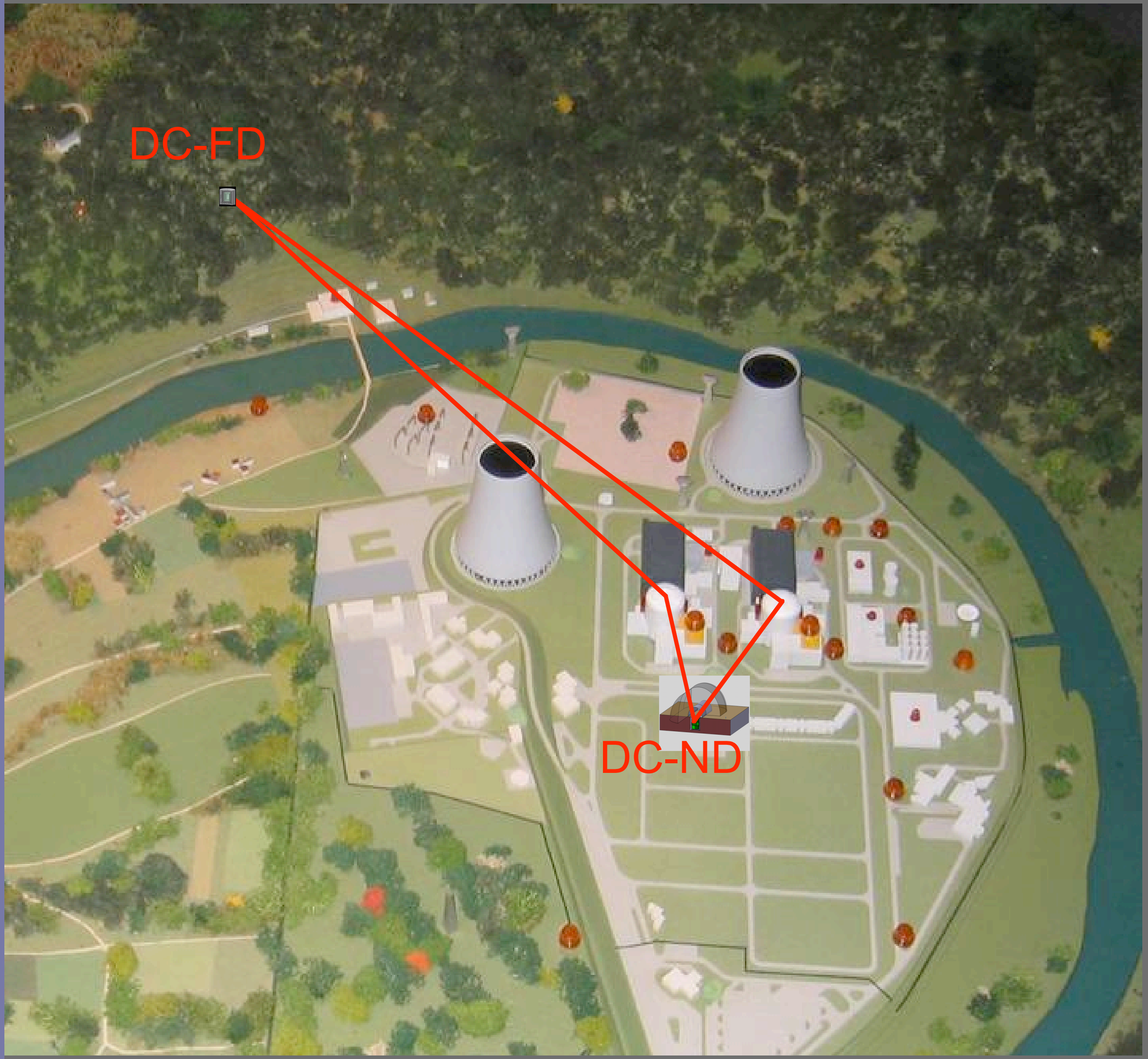
- Largest fraction of funding is secured, i.e.

  the experiment is happening...

- 120 physics (30 labs): England, France, Japan, Germany, Russia, Spain, US & Italy
- France: approved CNRS & CEA
- Germany: approved MPI & BMBF
- Japan (KASKA): all PMs => 10" PMs
- Spain: approved CIEMAT
- US: NSF + pending DoE
- England: PPARC R&D, more...
- Italy: private but important contributions

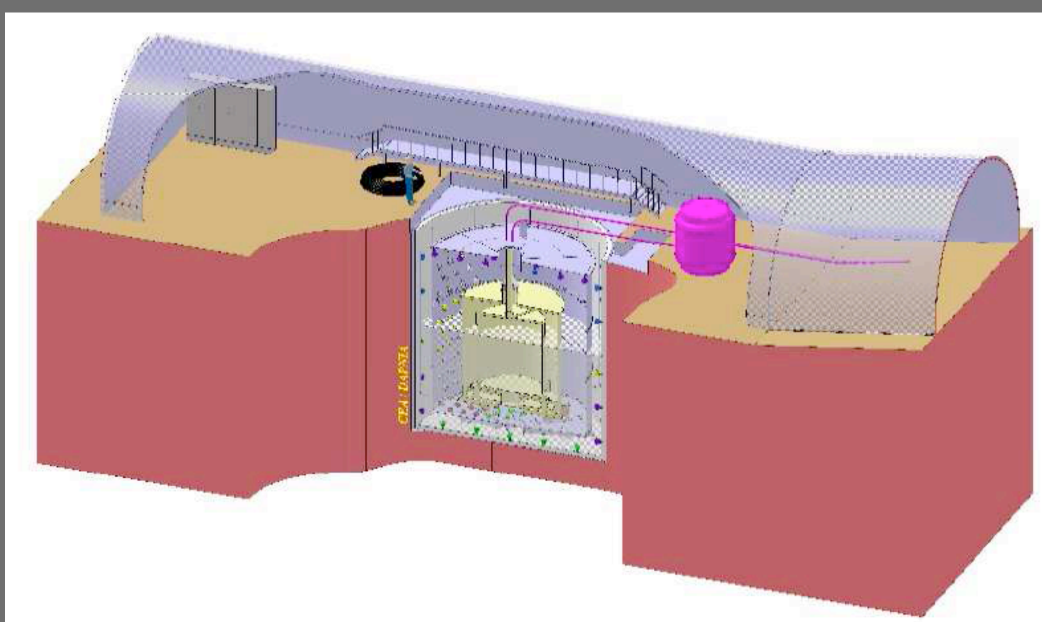
Designed and R&D completed

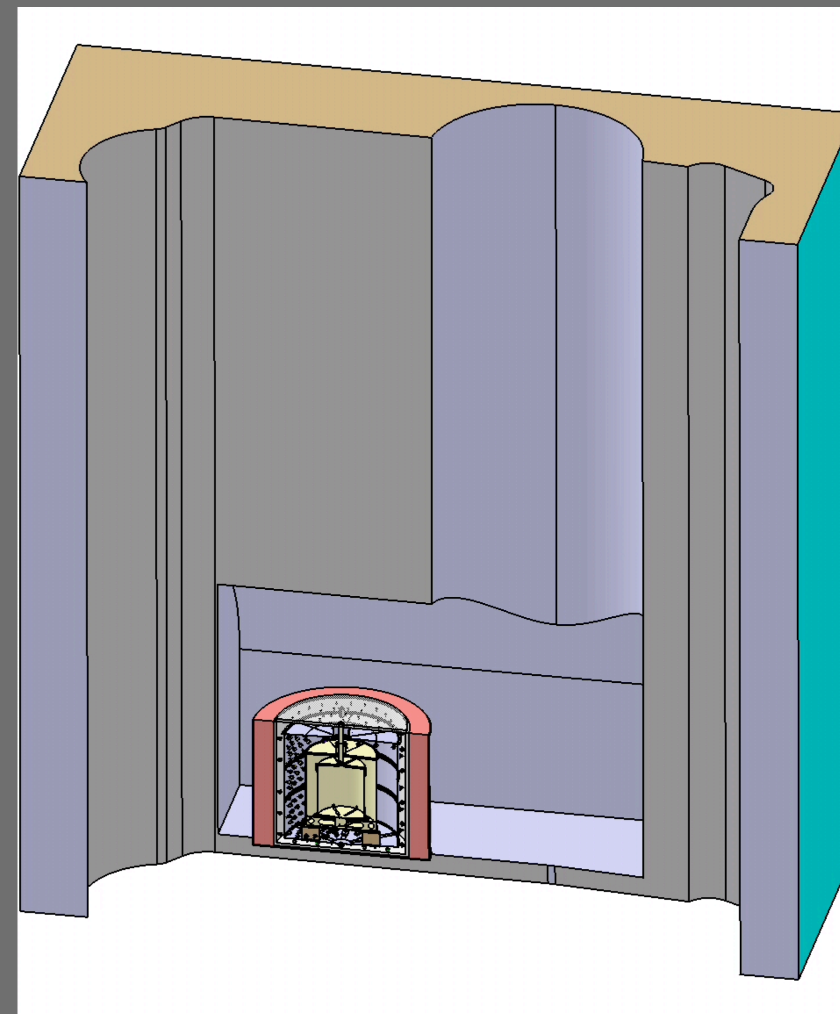
- 2 cores – 1 site – 8.5 GW_{th}
- 1 near, 1 far position (the latter available!)
  - 2x8.2t target masses
- Civil constructions
  - 1 near shaft ~ 40 m, Ø 6m
  - 1 laboratory
- Statistics (including ϵ)
  - far: ~ 50 events/day
  - near: ~ 550 events/day
- Systematics
  - reactor: ~ 0.2%
  - detector: ~ 0.5%
- Backgrounds
  - $\sigma_{bin-bin}$ at far site: ≲ 1%
  - $\sigma_{bin-bin}$ at near site: ≲ 0.5%
- Planning
  1. Far detector only
     - 2008–2009
     - Sensitivity (1.5 years) ~ 0.06
  2. Far + Near detector
     - from 2010
     - Sensitivity (3 year) ≲ 0.03



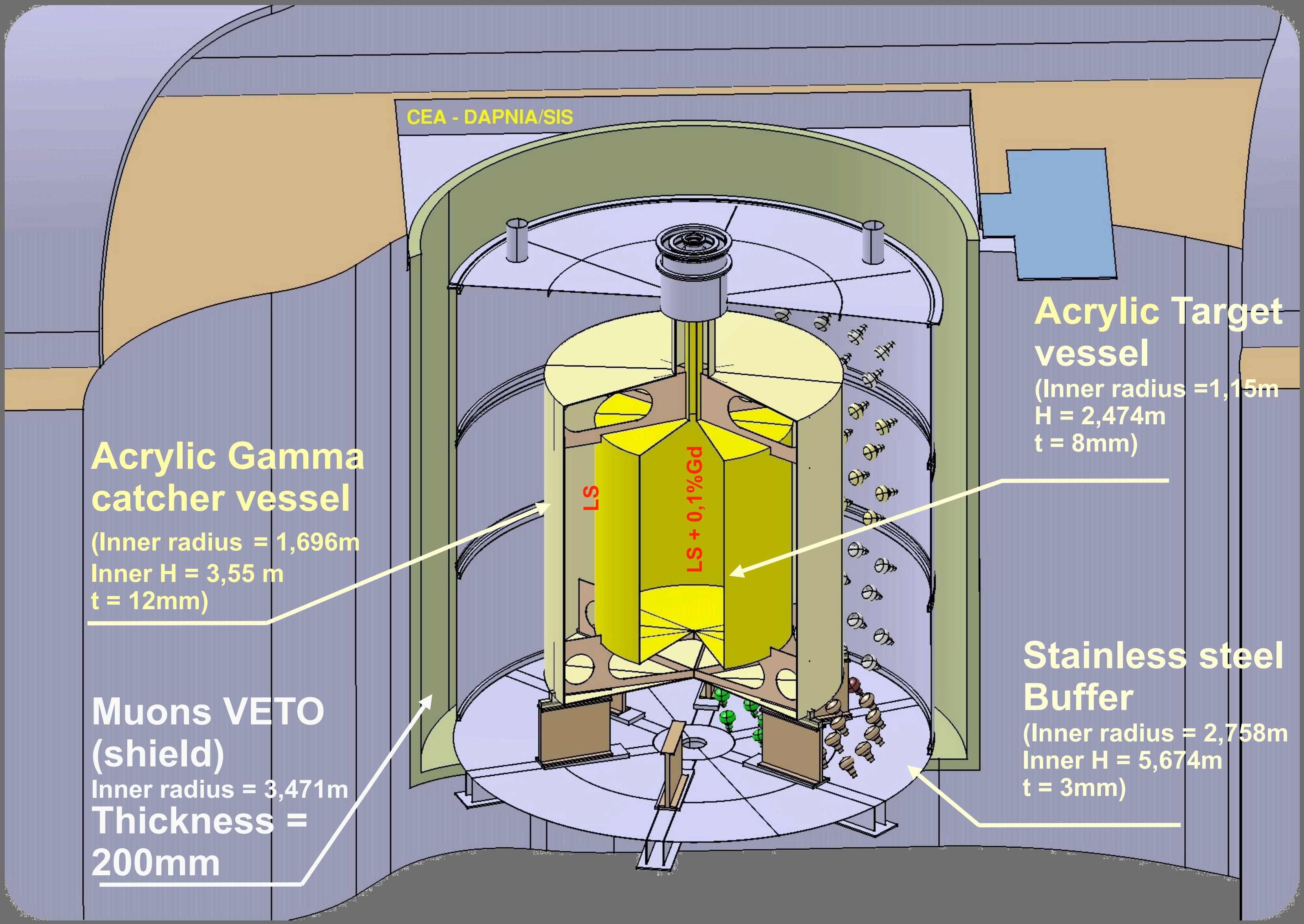
Ready for building...

FD & ND labs

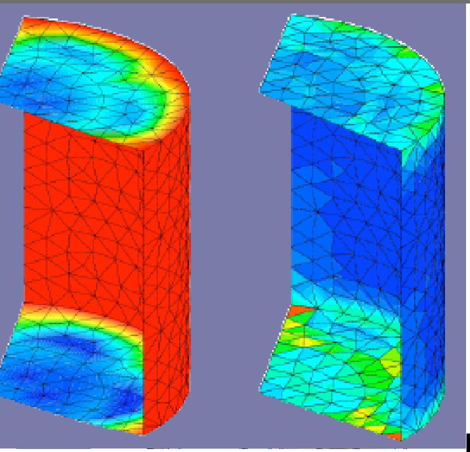


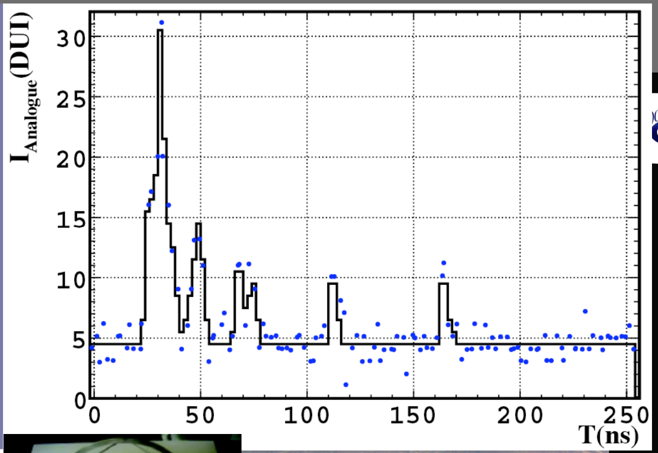


engineers' perspective

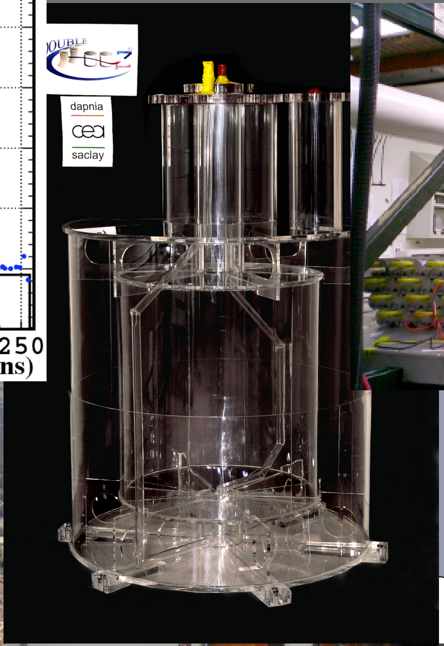


DC R&D



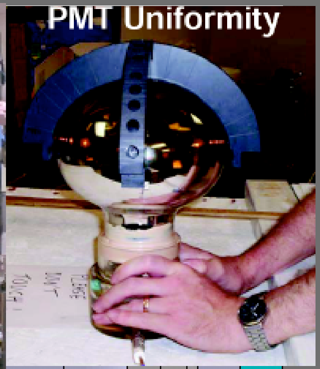


$I_{Analogue}$(DUI)
0
5
10
15
20
25
30
0
50
100
150
200
250
T(ns)

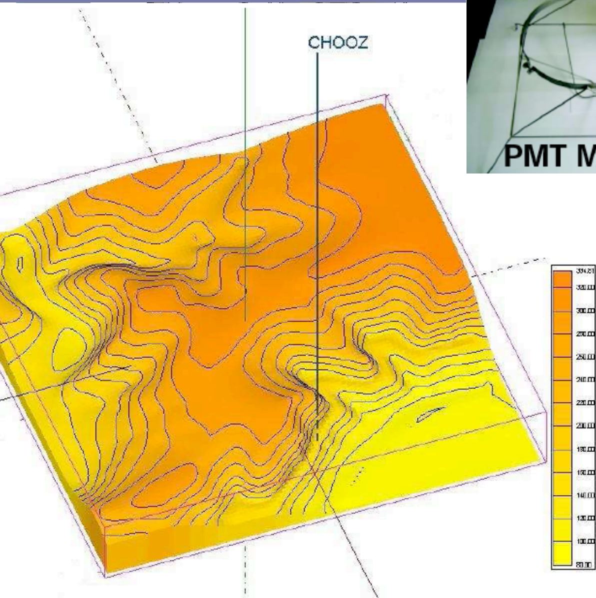


dapnia
saclay

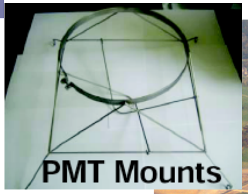
Outer Veto



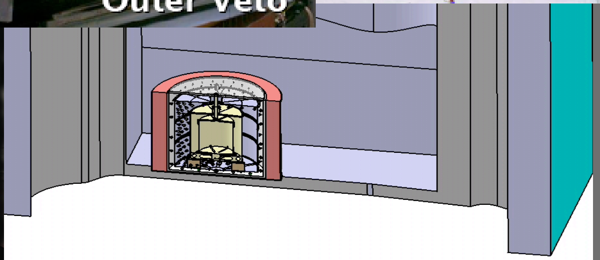
PMT Uniformity



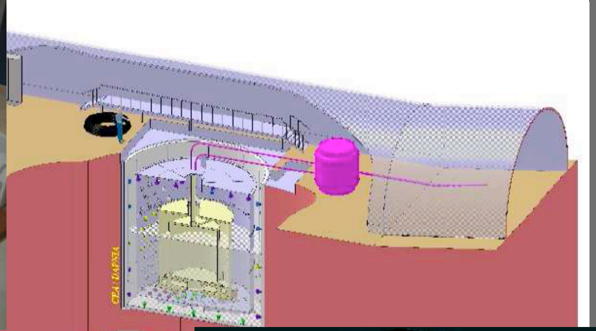
CHOOZ

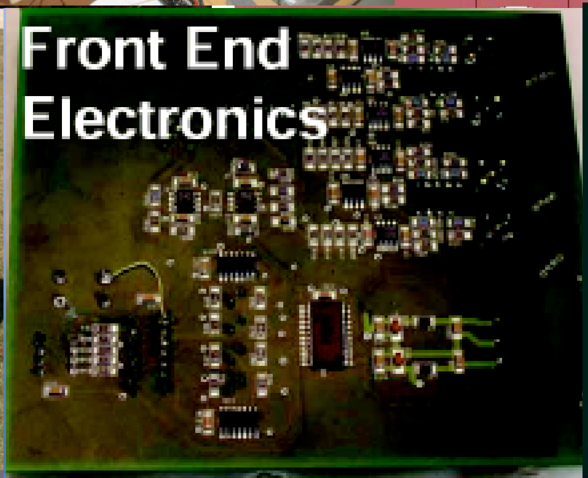


PMT Mounts

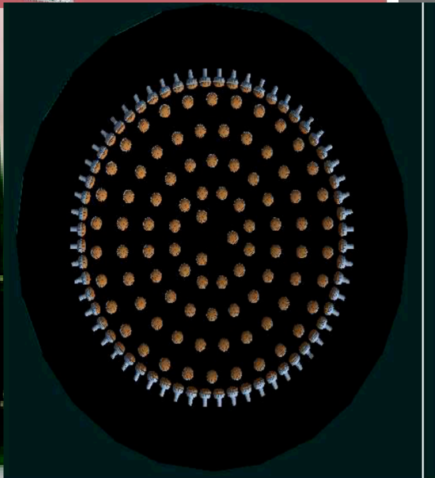


Scintillation
measurements

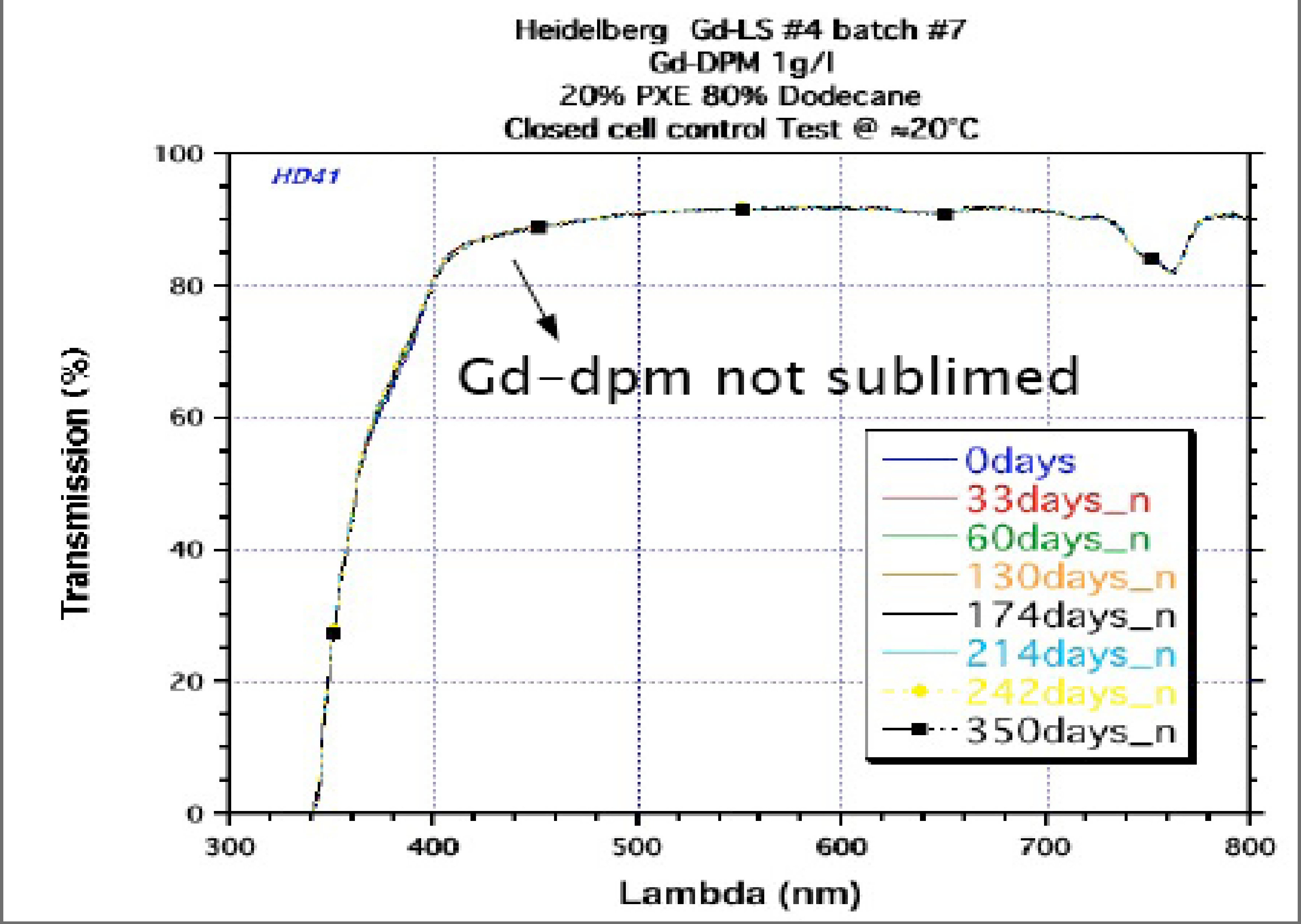




Front End
Electronics



Liquid Scintillator Stability R&D



knowledge versus time...

Phases:

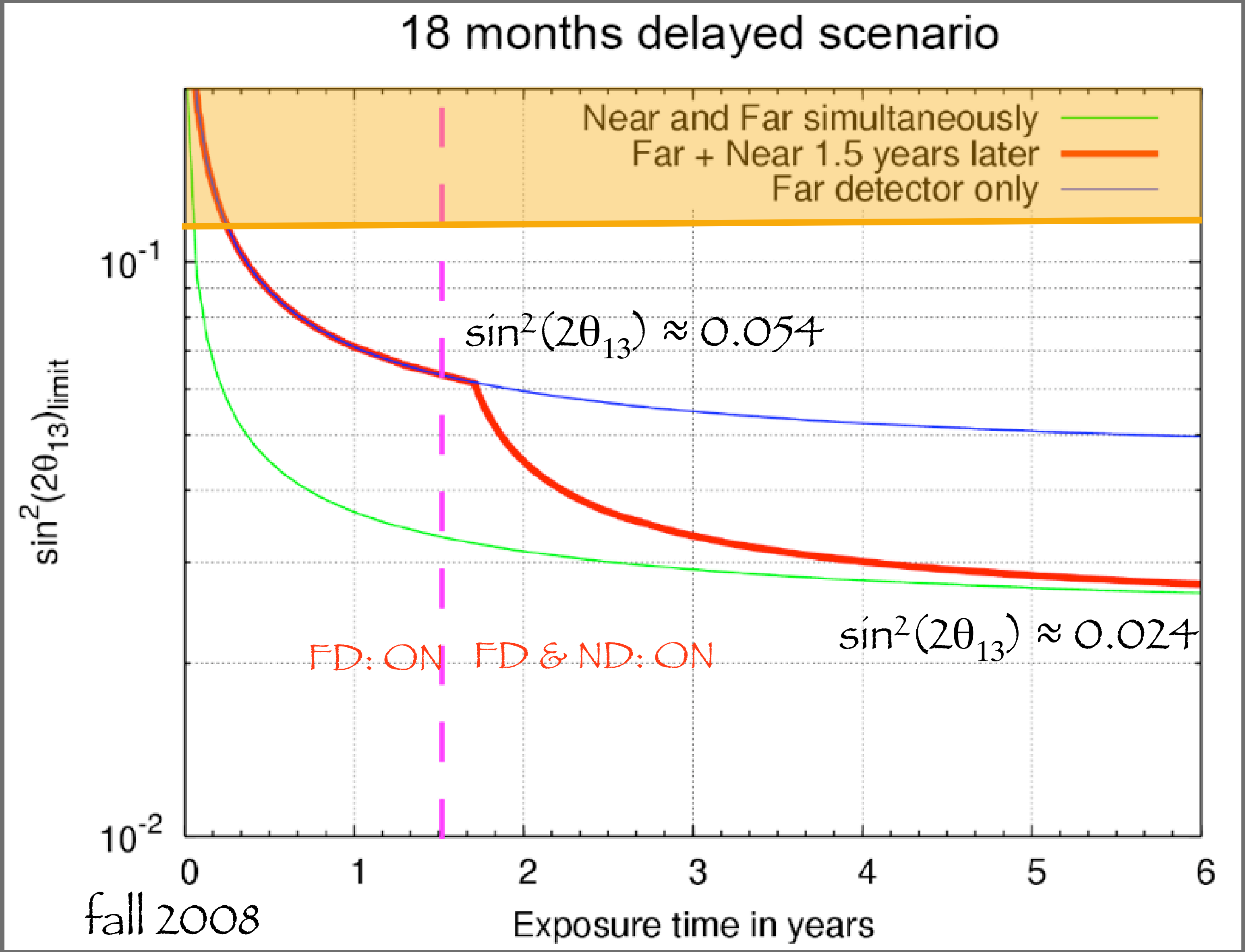
90% C.L. contour if $\sin^2(2\theta_{13}) = 0$ & $\Delta m^2_{atm} = 2.5 \times 10^{-3}$ eV^2

DC-I: FD only:

10x stat CHOOZ (limited by flux uncertainties)

DC-II: FD+ND:

rate + shape analysis (limited by relative calibration)



hep-ex/0704.0498

systematics break down

		CHOOZ	Double-Chooz	
Reactor-induced	ν flux and σ	1.9 %	<0.1 %	Two ''identical'' detectors & Low background
	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 %	mass measurements to 0.2%
	Density	0.3 %	<0.1 %	T control: ND & FD
	H/C ratio & Gd concentration	1.2 %	<0.1 %	mass measurements + same scintillator batch + stability R&D
	Spatial effects	1.0 %	<0.1 %	calibration
	Deadtime	negligible	0.25 %	dedicated measurements & calibration
Analysis	From 7 to 3 cuts	1.5 %	0.2 - 0.3 %	(see later)
	Total	**2.7 %**	**< 0.6 %**	

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σ^{abs}_{norm}

$\sigma^{relative}_{norm}$

$\sigma^{analysis}_{norm}$

Daya Bay

- Project approved in China
- R&D funding: China & DoE
- Power Plant approved project
- 100 physics (China, US, Russia)
- Proposal under preparation
- Schedule: start data taking by 2008

Proposal: hep-ex/0701029

characteristics

Complicated and deep site:

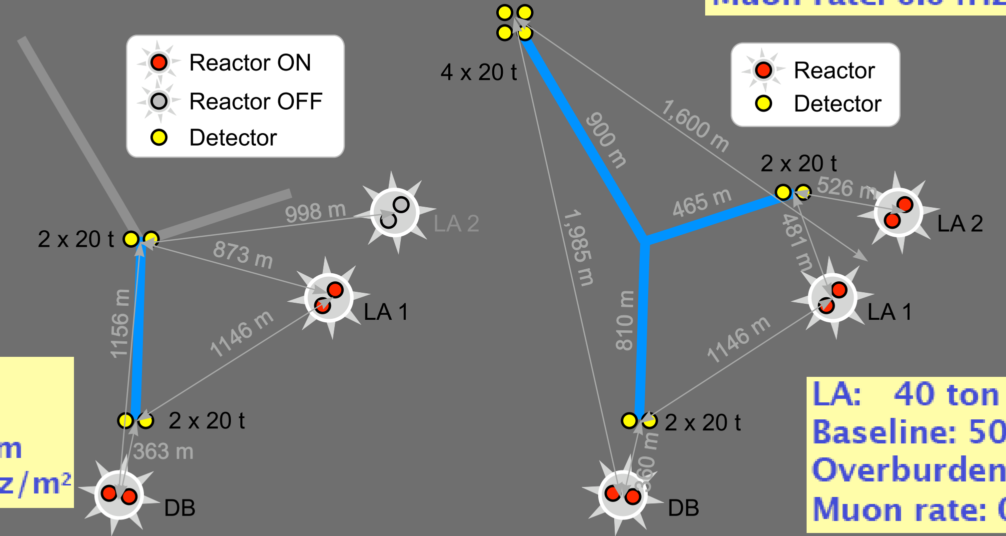
- **4 cores – 2 sites – 11.6 GW_{th}**
  -> 6 – 3 in 2011, 17.4 GW_{th}
- **2 near, 1 mid, 1 far position**
  - far: 4x20t modules
  - near: 2 x 2 x 20t
- **Civil constructions**
  - ~ 3.4 km galleries
  - 4 laboratories
- **Statistics**
  - far: 80 events/day
  - near: 560 events/day
- **Movable modules -> swap**
- **Systematics**
  - reactor: ~ 0.1%
  - detector: ~ 0.2%
- **Backgrounds**
  - B/S at near site: ~ 0.5%
  - B/S at far site: ~ 0.2%

Mid:
Baseline: ~1000m
Overburden: 208m

Far: 80 ton
1600m to LA, 1900m to DYB
Overburden: 350m
Muon rate: 0.04Hz/m²

DYB: 40 ton
Baseline: 360m
Overburden: 98m
Muon rate: 1.2Hz/m²

LA: 40 ton
Baseline: 500m
Overburden: 112m
Muon rate: 0.73Hz/m²

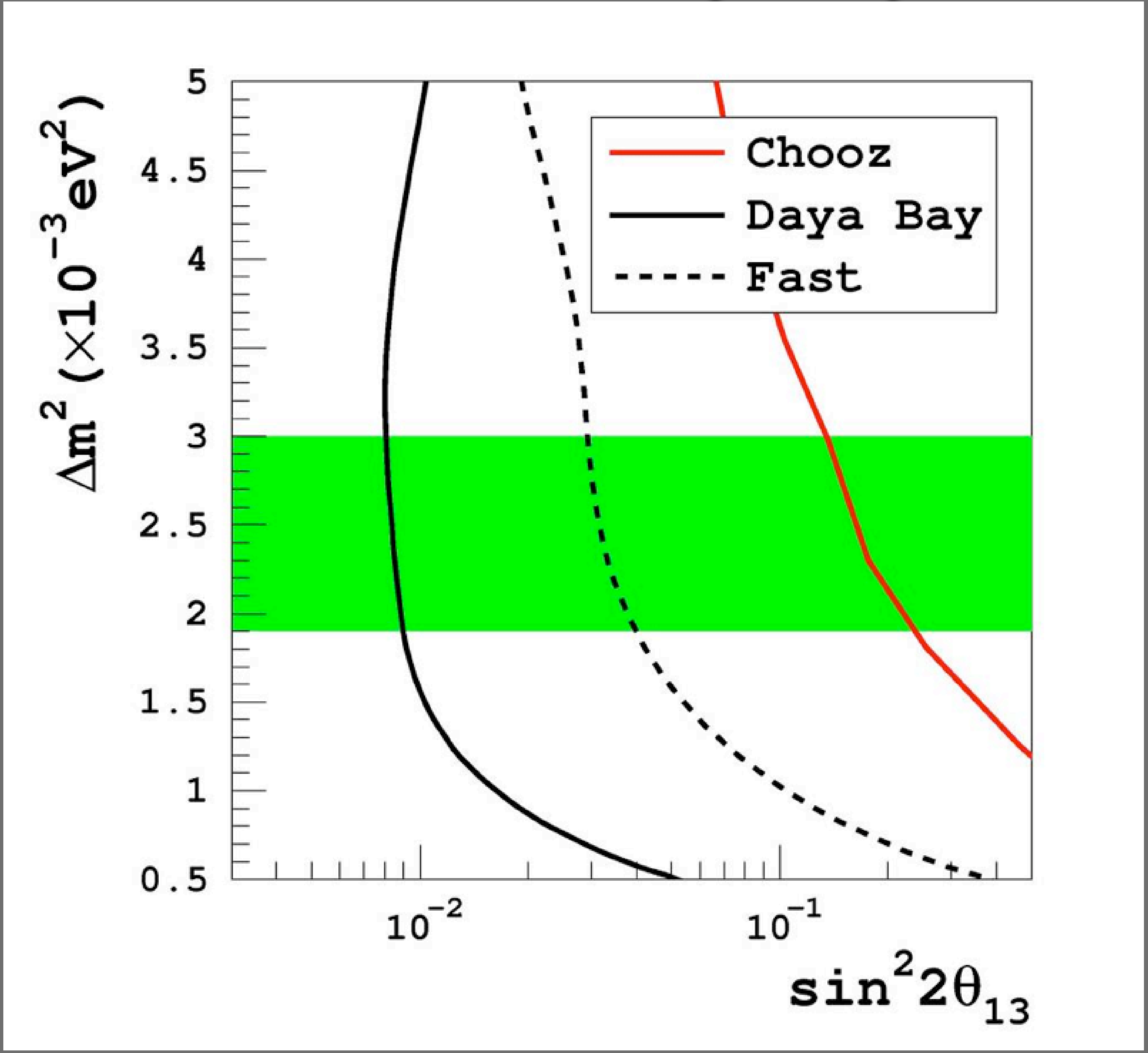


- Sensitivity in steps:
  - Mid: $\sin^2(2\theta_{13})_{limit}=0.041$
  - Mid+LA2: $\sin^2(2\theta_{13})_{limit}=0.038$
  - Far(full): $\sin^2(2\theta_{13})_{limit}=0.011$

hep-ex/0704.0498

Proposal: hep-ex/0701029

Daya Bay's sensitivity



the world strategy...

two pseudo-parallel roads...

two pseudo-parallel roads...

- reactor: disappearance => high statistics

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  - sensitive to θ_{13} only:

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

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

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- beams: appearance => low statistics (<150νs T2K-I)
  - BG: π^0 production and beam νe contamination
  - correlation: δ_{CP}, θ_{13},θ_{23} degeneracy and matter effects [neglected in equation]

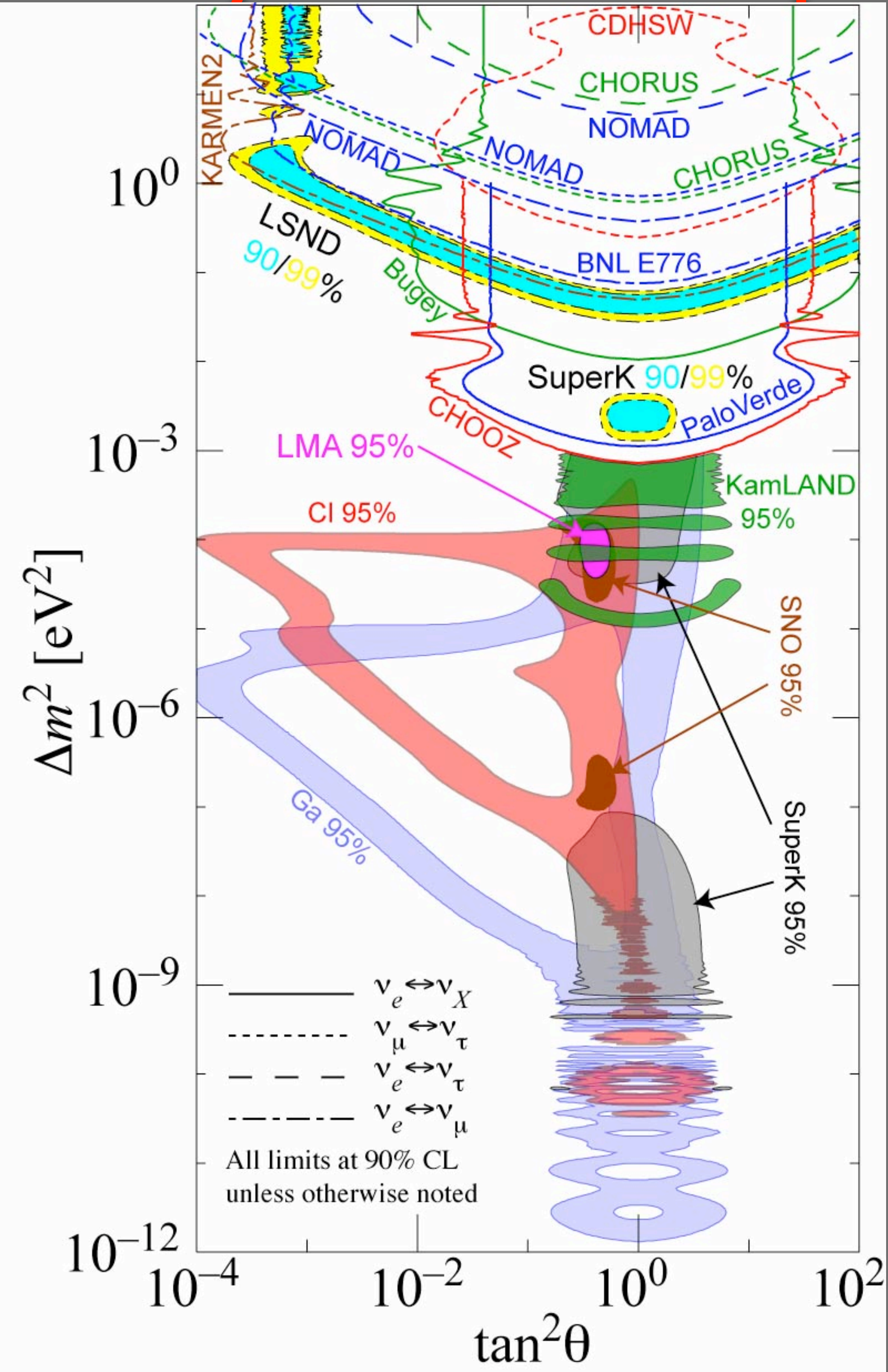
$$\begin{aligned} P(\nu_\mu \to \nu_e) \simeq\ & \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \Delta \\ \mp\ & \alpha \sin 2\theta_{13} \sin \delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \Delta \sin^2 \Delta \\ +\ & \alpha \sin 2\theta_{13} \cos \delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \Delta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

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

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

complementarity...

50 years of complementarity...

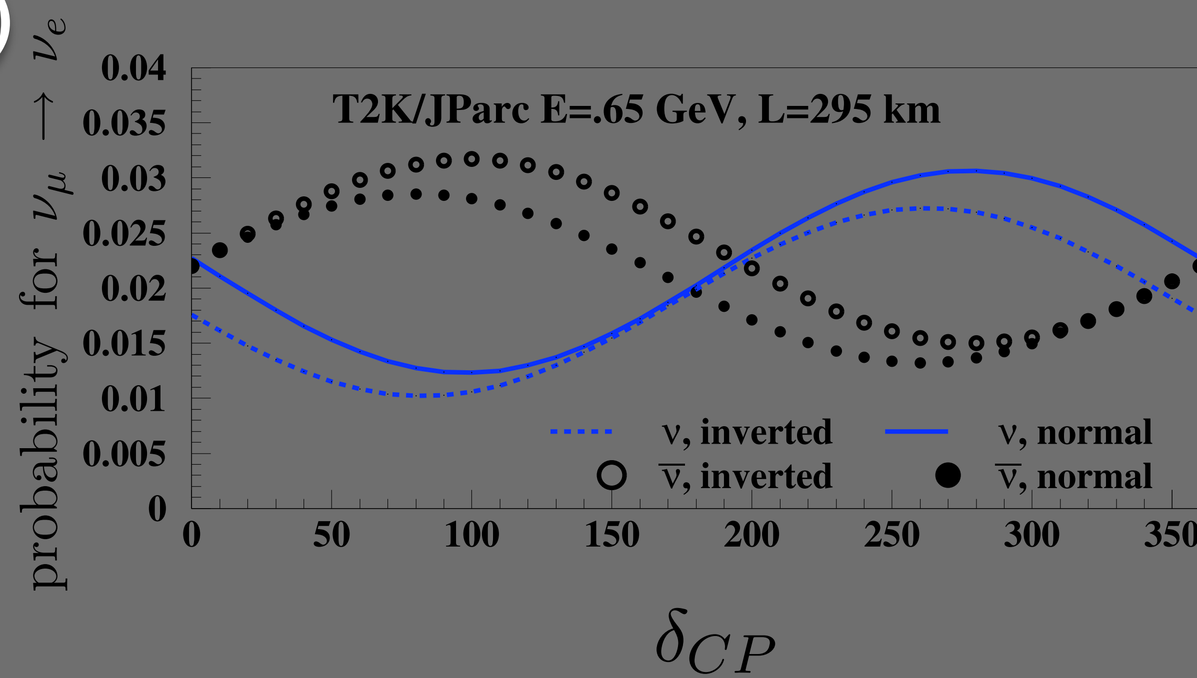


PDG 2004

beam sensitivity illustration

- beam: appearance
- $p_{osc} \propto \sin^2(2\theta_{13})$ [<10%]
  - $p_{osc} \propto$ signal (statistics)
  - BG ~ constant(E/L)
- δ_{CP}: modulates p_{osc}
  - anti-ν/ν: -π phase
  - $\sin^2(2\theta_{13})$ reactor

$$\Delta m^2 = 2.5 \times 10^{-3}\ \mathrm{eV}^2,\ \sin^2 2\theta_{13} = 0.05$$
$$\sin^2 2\theta_{23} = 0.95$$



hep-ex/0409028

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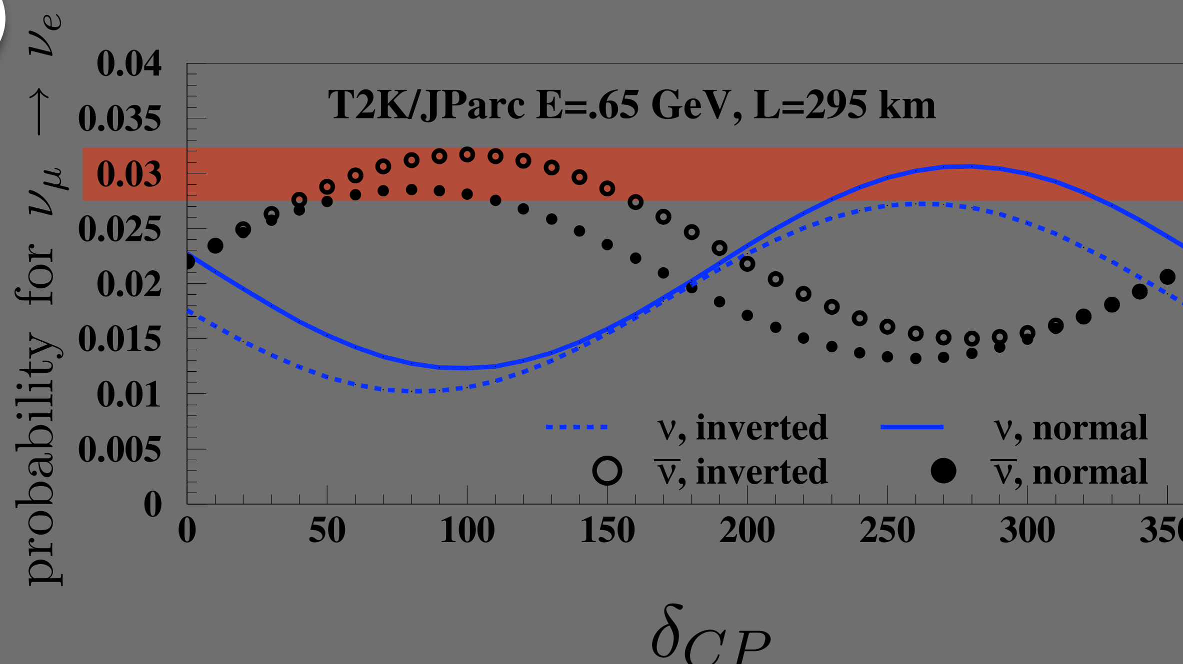
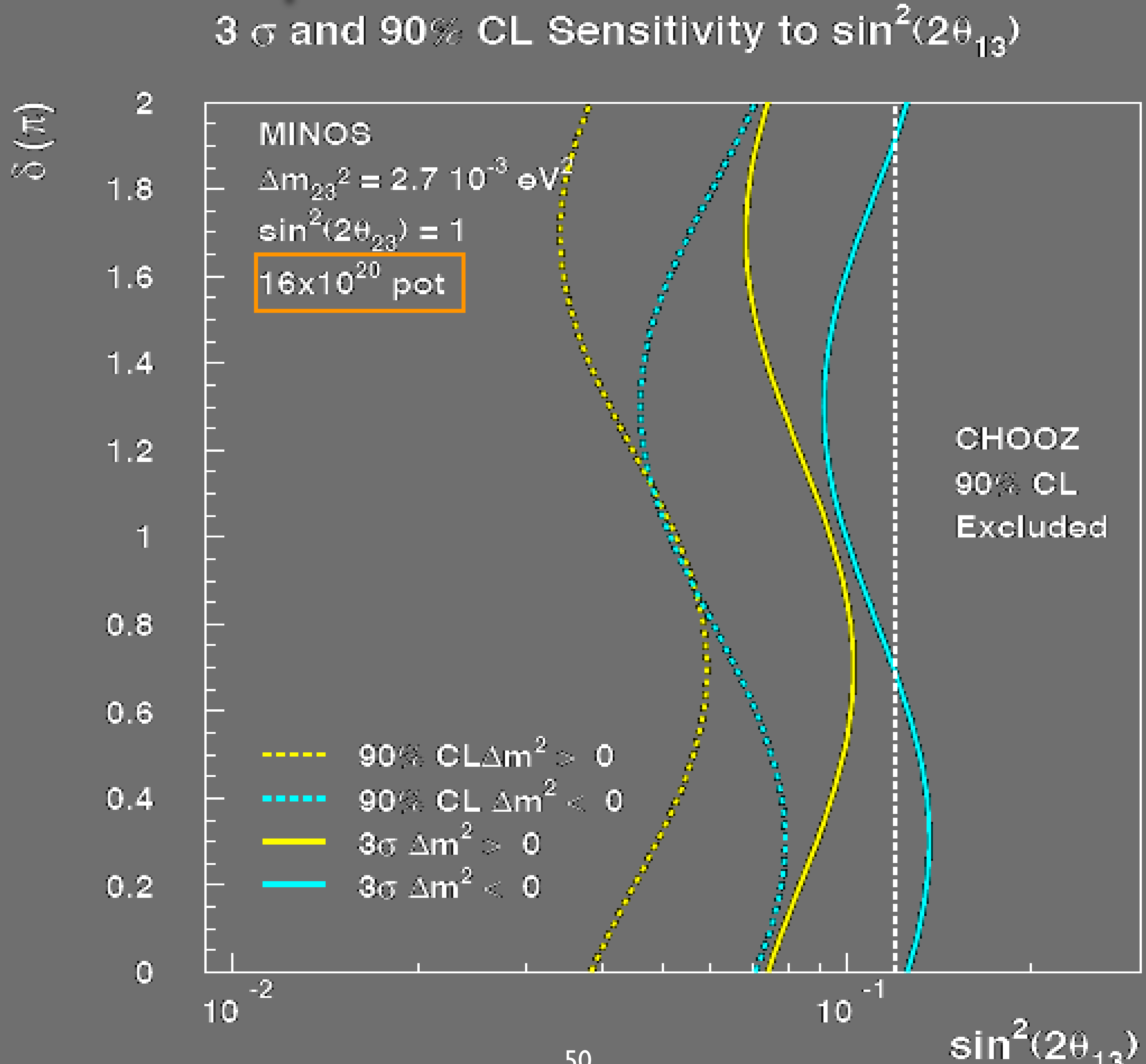


hep-ex/0409028

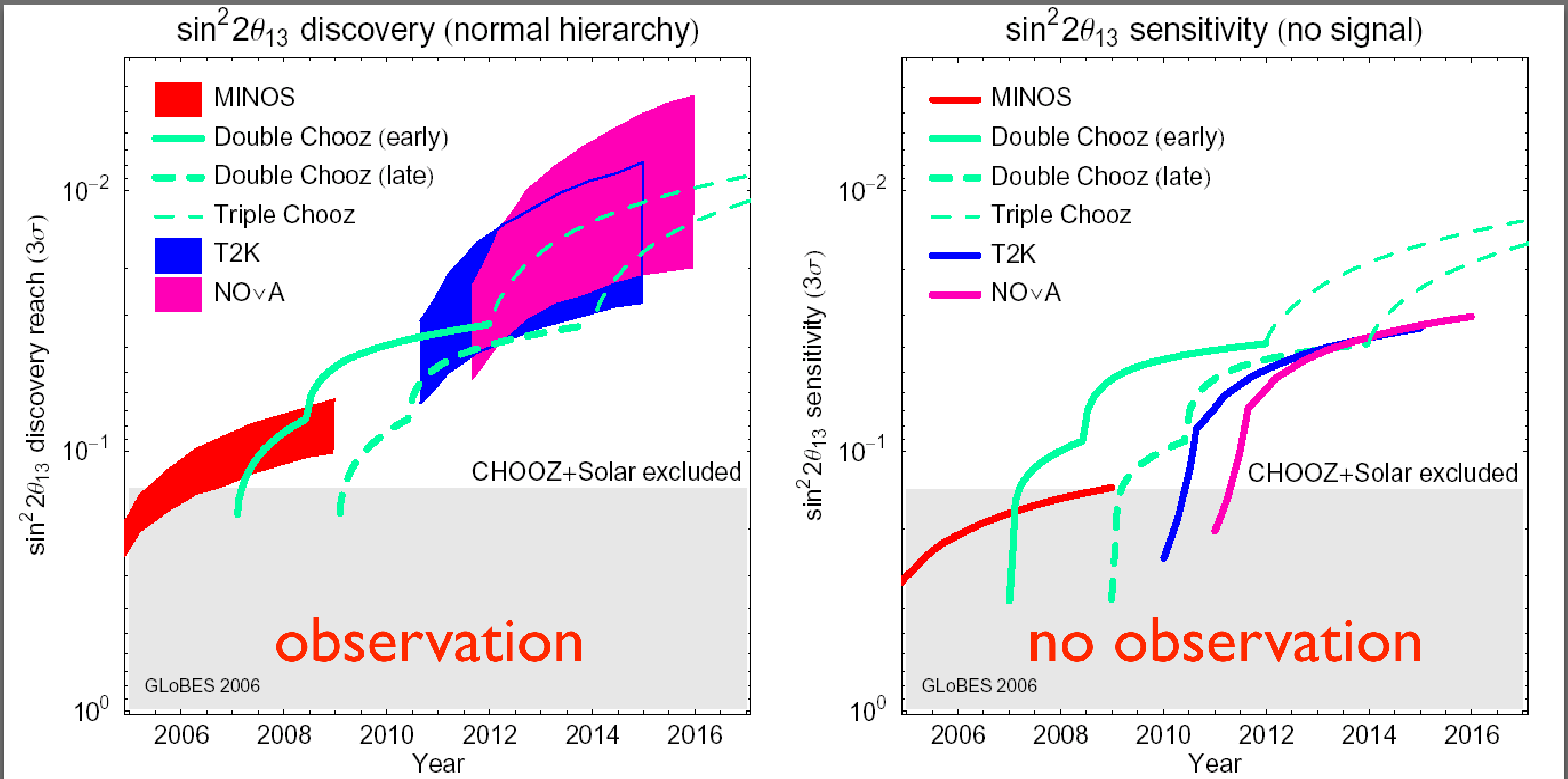
what to expect from conventional beams?



what to remember?

beams + reactors = deeper insight

Competitive & overlapping coverage by both techniques!

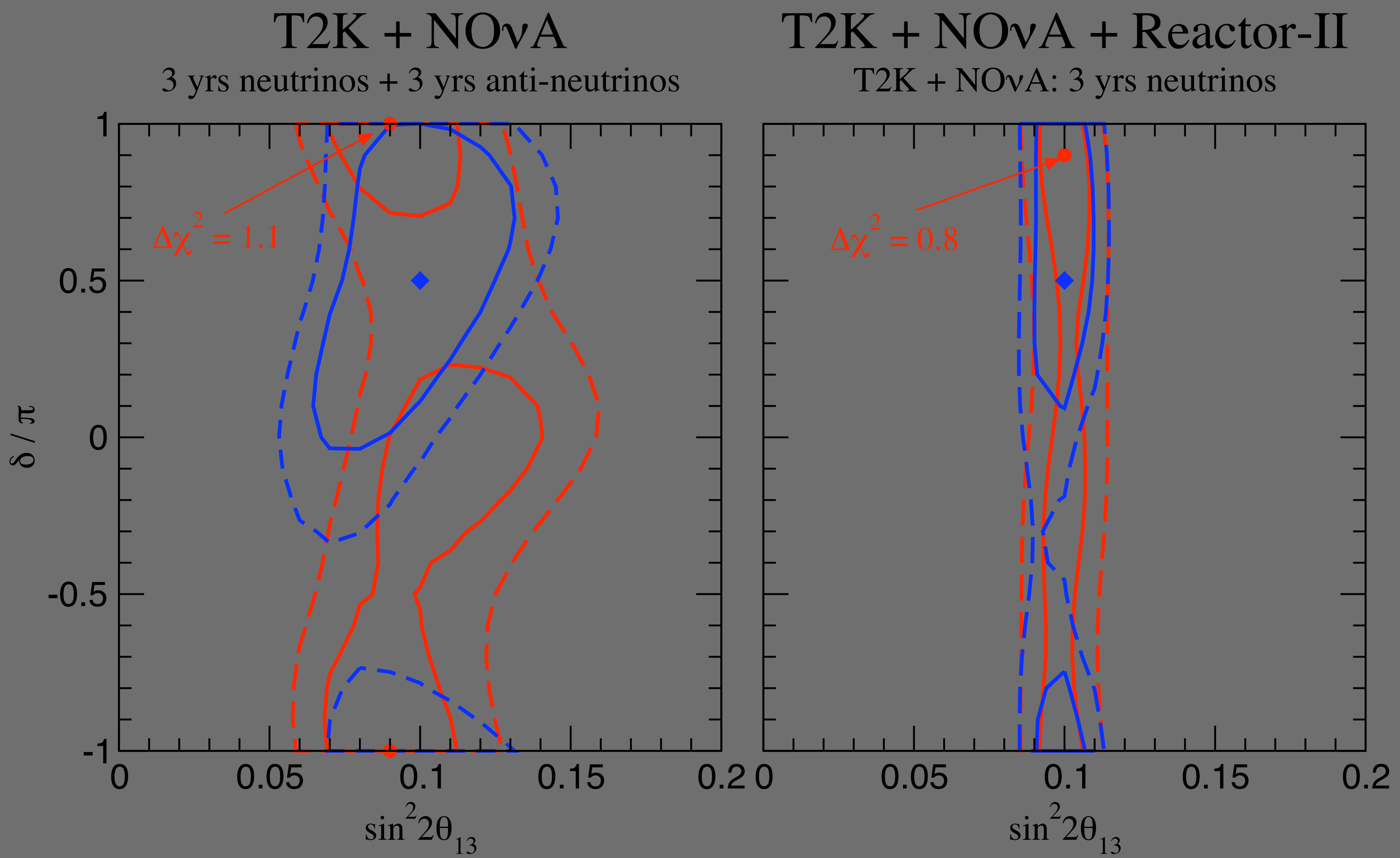


Similar time scale

Huber et al: hep-ph/0601266

emergency slides…

Normal hierarchy
Inverted hierarchy



Huber et al. hep-ph/0412133

Matter effects in a nut-shell

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- Earth made of matter (no anti-matter): e^-, p^+, n

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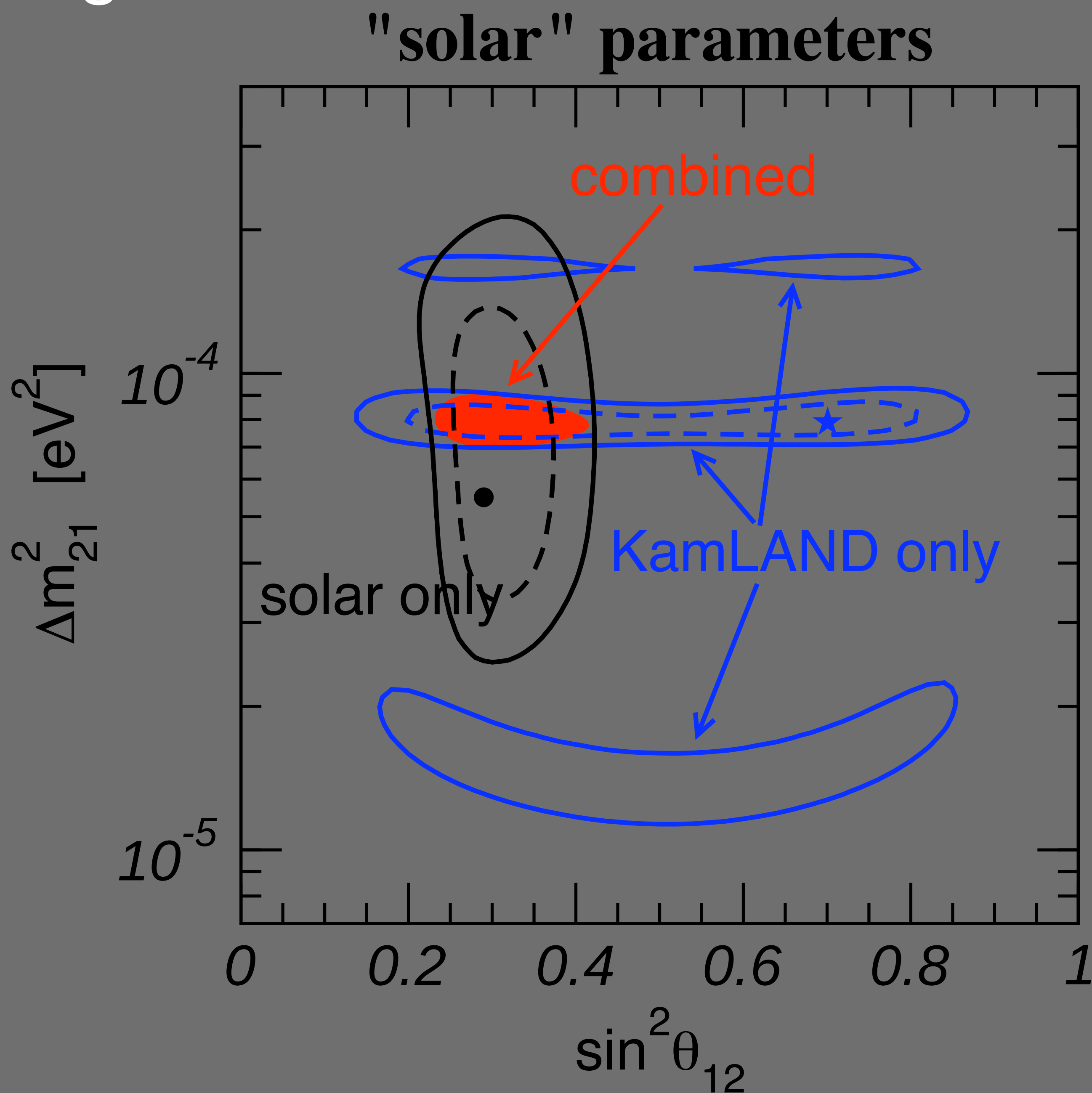
  - break degeneracy (CPT) between anti-ν/ν
  - new effective masses
  - new effective mixing angles
  - modify oscillation equations
  - explicit "L" dependence (not only E/L)

Believing in ν-oscillations?

One the most fascinating demonstration so far...

SOLAR (ALL)
P=0.3 (N_{obs}/N_{exp})
(matter effects)

KamLAND
P=0.6 (N_{obs}/N_{exp})
(vacuum osc.)



hep-ph/0606060

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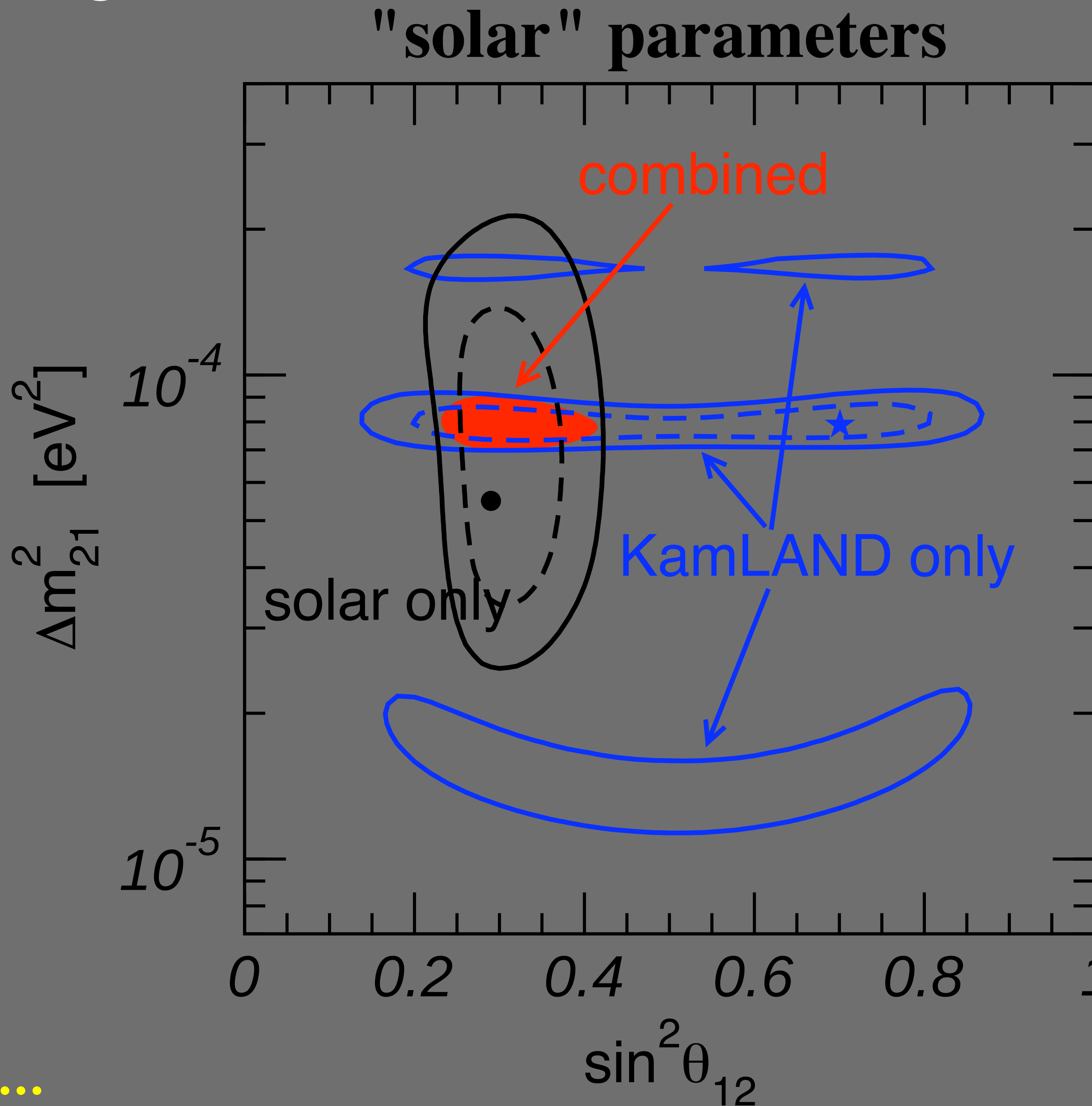
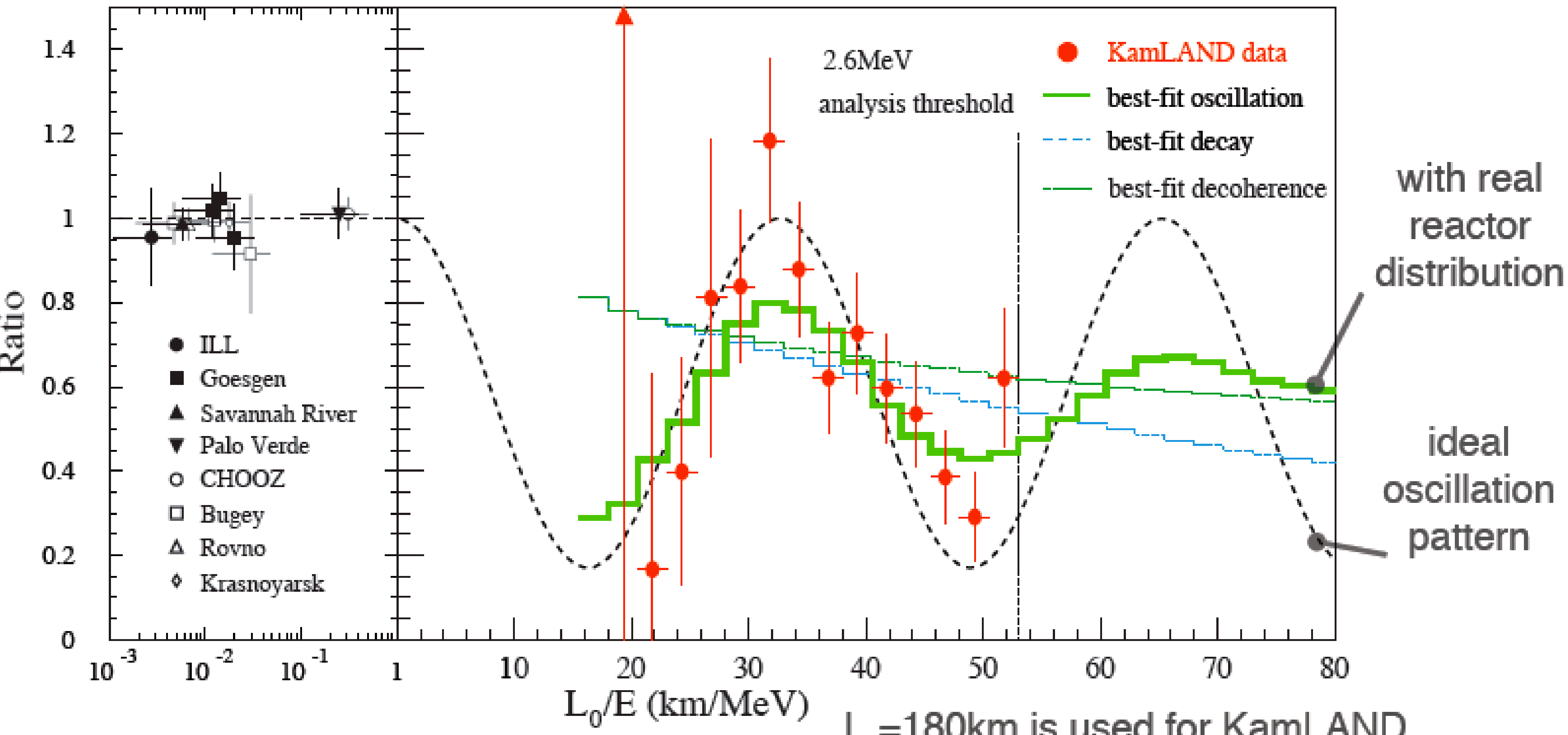


Even E/L modulation...

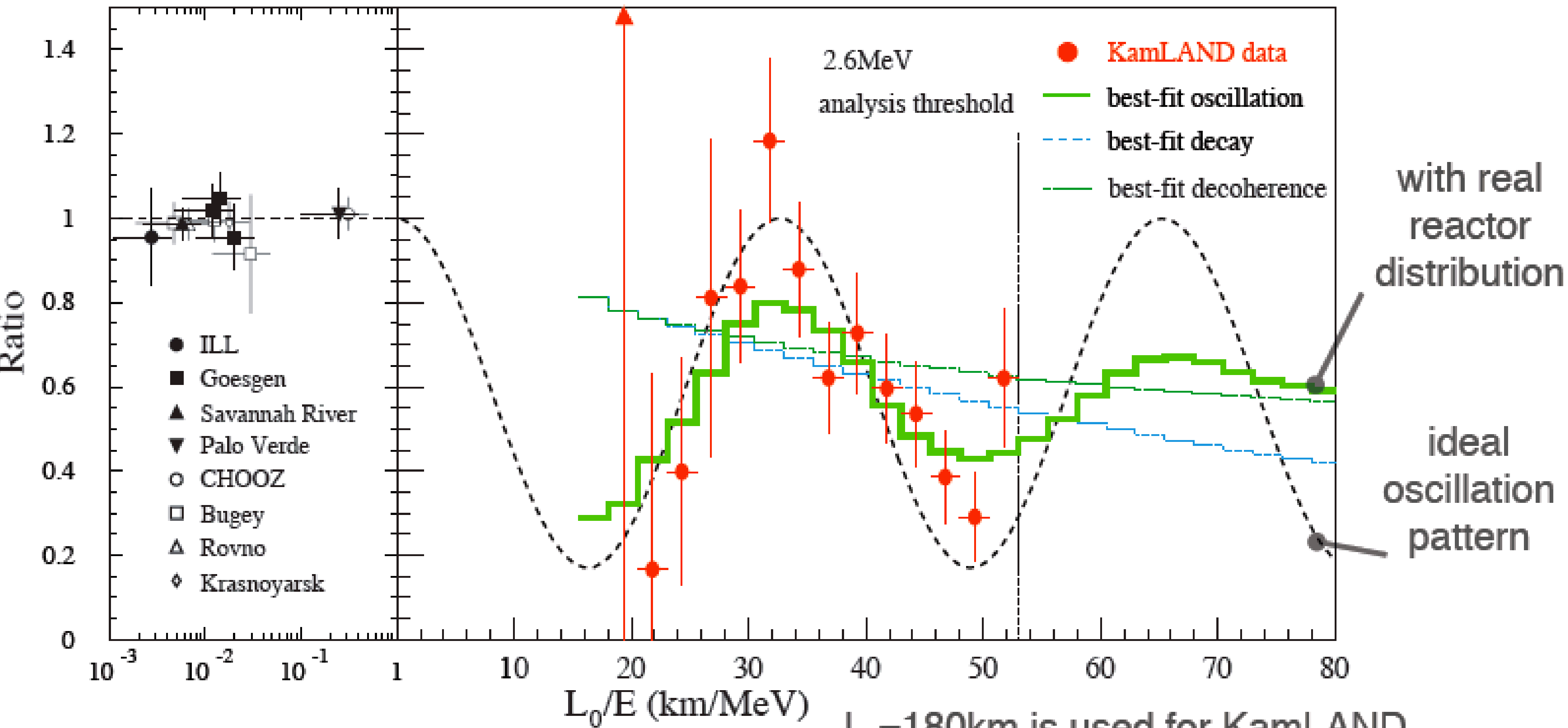
hep-ph/0606060

KamLAND spectral distortion



L_0=180km is used for KamLAND

KamLAND spectral distortion



L_0=180km is used for KamLAND

BD rates

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%

(s)

eliminate flux uncertainty

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Bugey (3 & 4)
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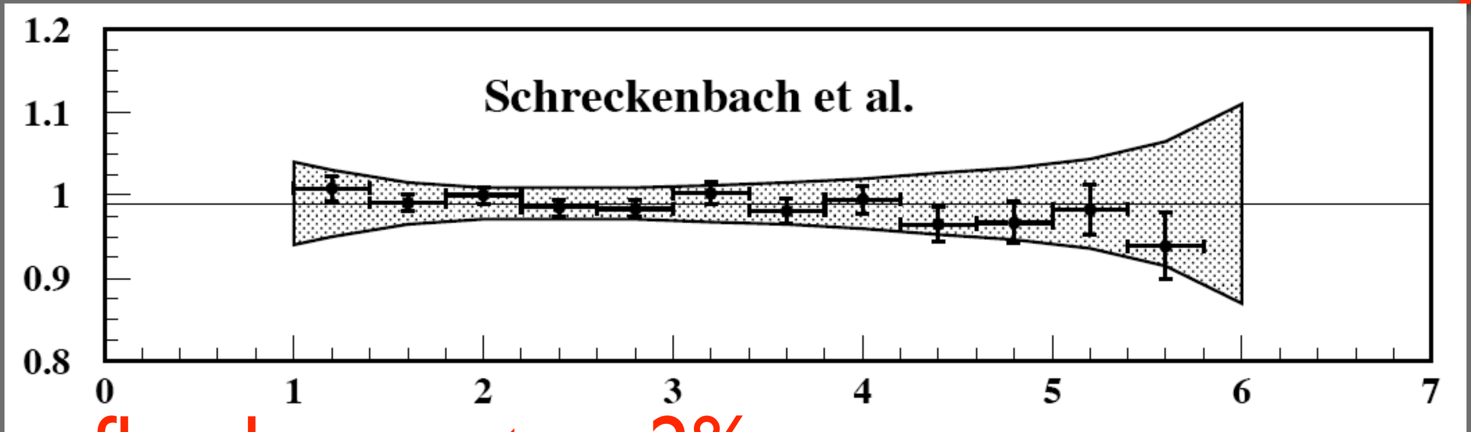

flux known to ~2%

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

(s)

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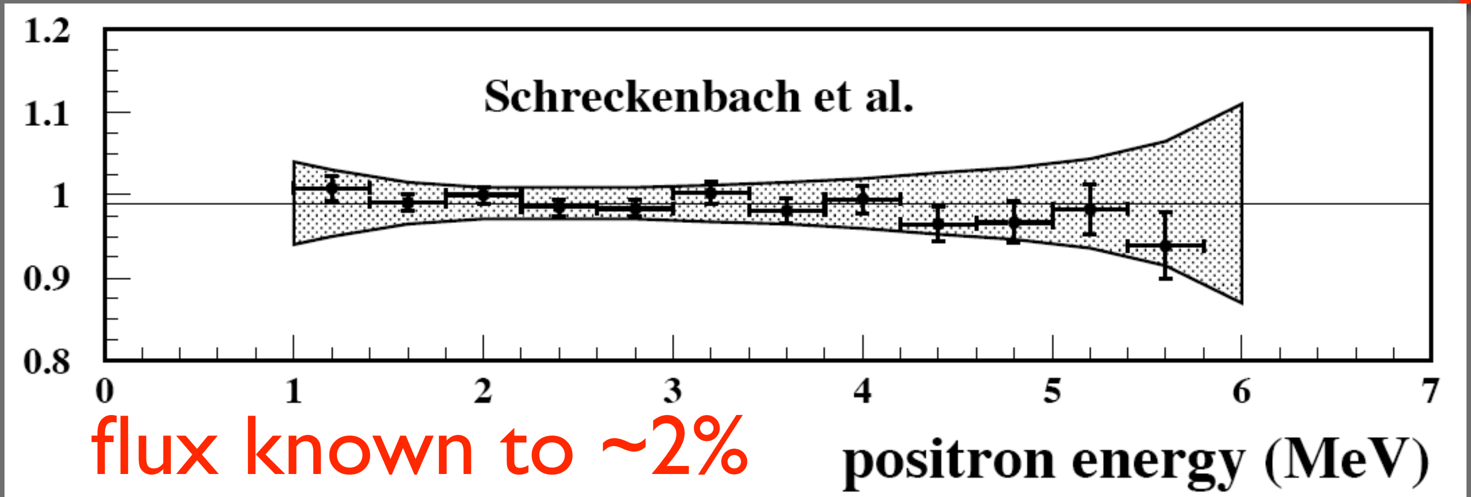

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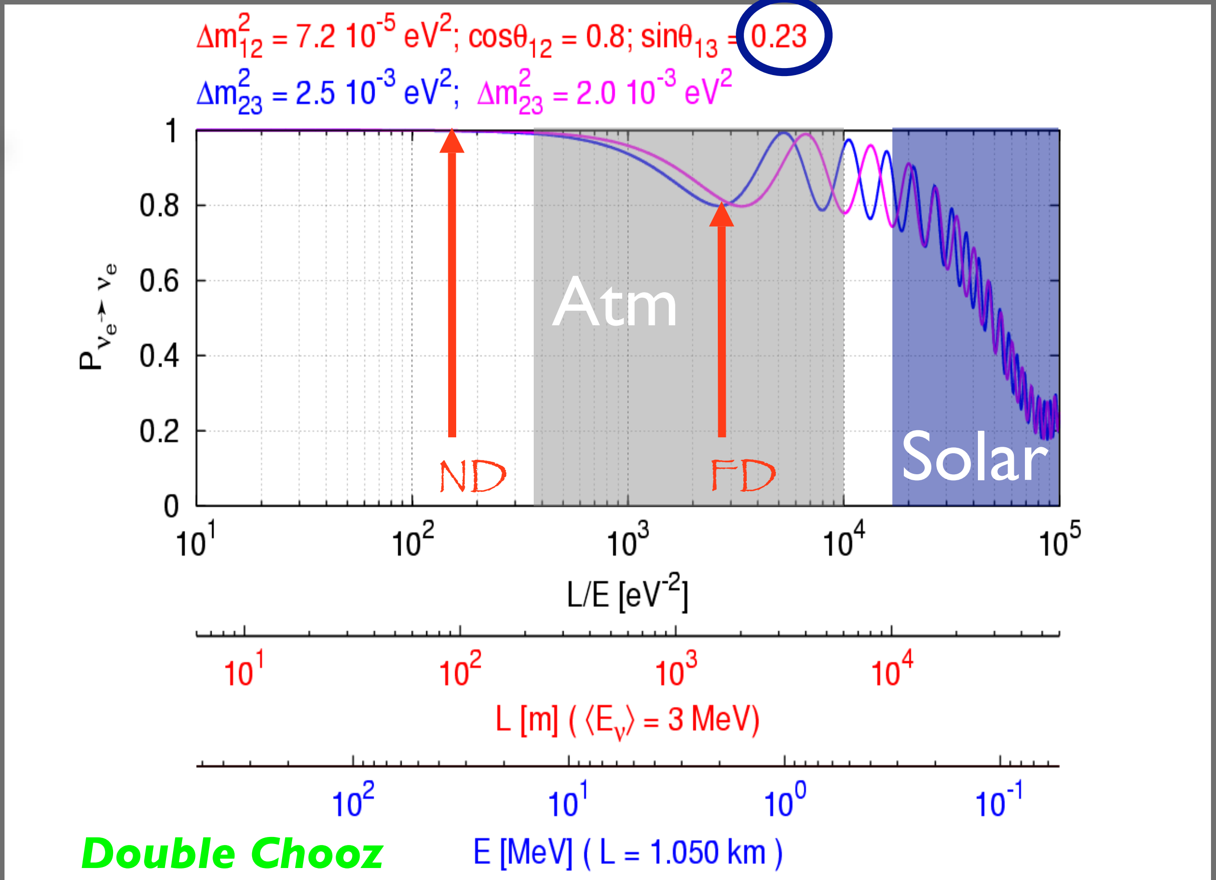
$P(\nu_e \rightarrow \nu_e) \sim$
$\sim 1 - \sin^2\theta_{13} \sin^2(\Delta m^2_{13}\, L/4E) + \ldots$



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  - radioactive sources too

DC deadtime measurements

- faked-ν injection by light system:
    - 2 flashes with $\tau \sim 30\mu s$ and correct light level
    - deadtime of full system (FEE, DAQ,etc)
    - monitor deadtime of system regularly vs time
    - dedicated system by Heidelberg group
- calibration source in both detector: "inter-calibrate"
- deadtime-less electronics with WFD (256ns window)
- (typical) pulse generation injection: DAQ deadtime