Reactor-ν Oscillations

XLII Moriond-EW
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Anatael Cabrera
Marie Curie Fellow
Double Chooz
APC Laboratory (Paris)

overview:

- context
- general features
- physics channels
  - "solar"
  - θ_{13}
- reactor-ν help
- conclusions

context

Kayser's Talk
Gavela's Talk

beyond neutrino oscillations

- flavour-νs (interact) while mass-νs (propagate)

- "mechanism" causing a non-diagonal free-Hamiltonian

  => explain experimental data: (dis)appearance

- oscillations dominates experimental evidence to >10%

  (uncertainties on mixing amplitudes)

leptonic mixing

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

U must be unitary & 3x3 => PMNS: 3 angles & 1 complex phase

atmospheric ν | θ13 & dirac-δCP | solar ν

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

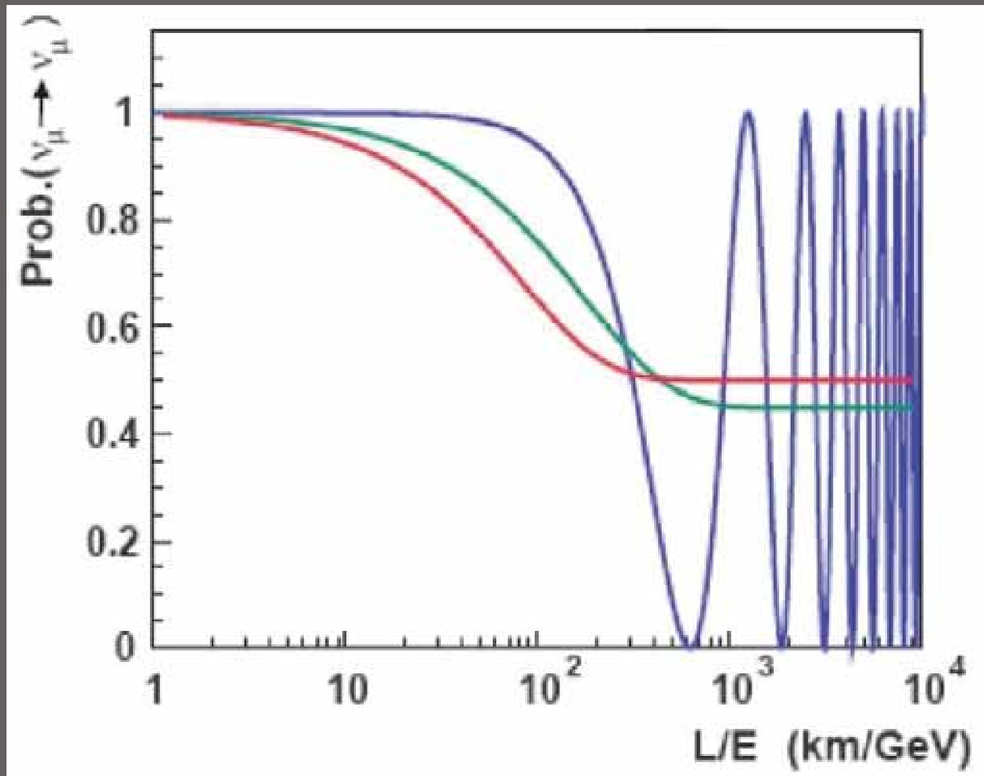
$P(\nu_\mu\rightarrow\nu_\mu)$ | $P(\text{anti-}\nu_e\rightarrow\nu_x)$ & $P(\nu_\mu\rightarrow\nu_e)$ | $P(\nu_e\rightarrow\nu_x)$

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...

E/L modulation unique feature!

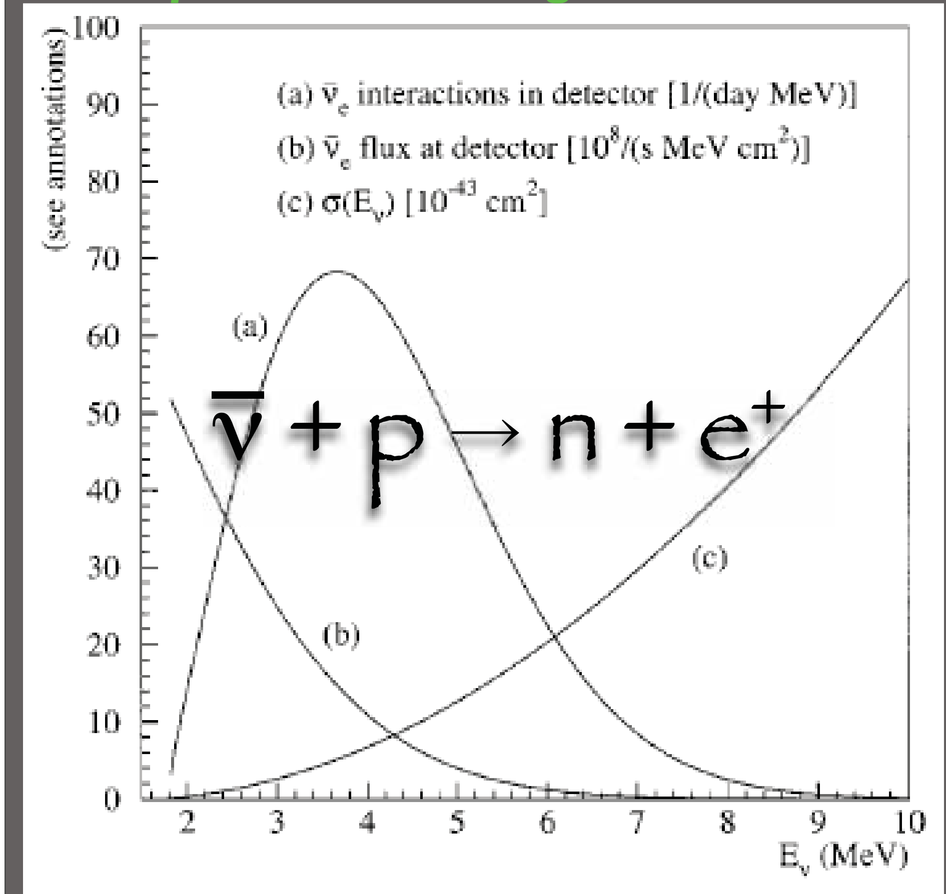


Raufer's Talk

general feature...

inverse-β reaction

Bemporad, Gratta, Vogle. RMP. 2002



- spectrum: convolution of...
  - Σ β-tails from fission debris
  - σ(E) => $E_{threshold}$=1.8MeV
- threshold: see only 1/4 νs
  - slow decays contribute little

- ν = e+ [prompt] + n-capture on H/Gd [delayed]:
  - E(ν)=E(e+) + Δ
  - E(n_{th}-Gd capture) ~ 8MeV => energy tag (away from BG)
- n-Gd capture τ~30μs (CHOOZ)

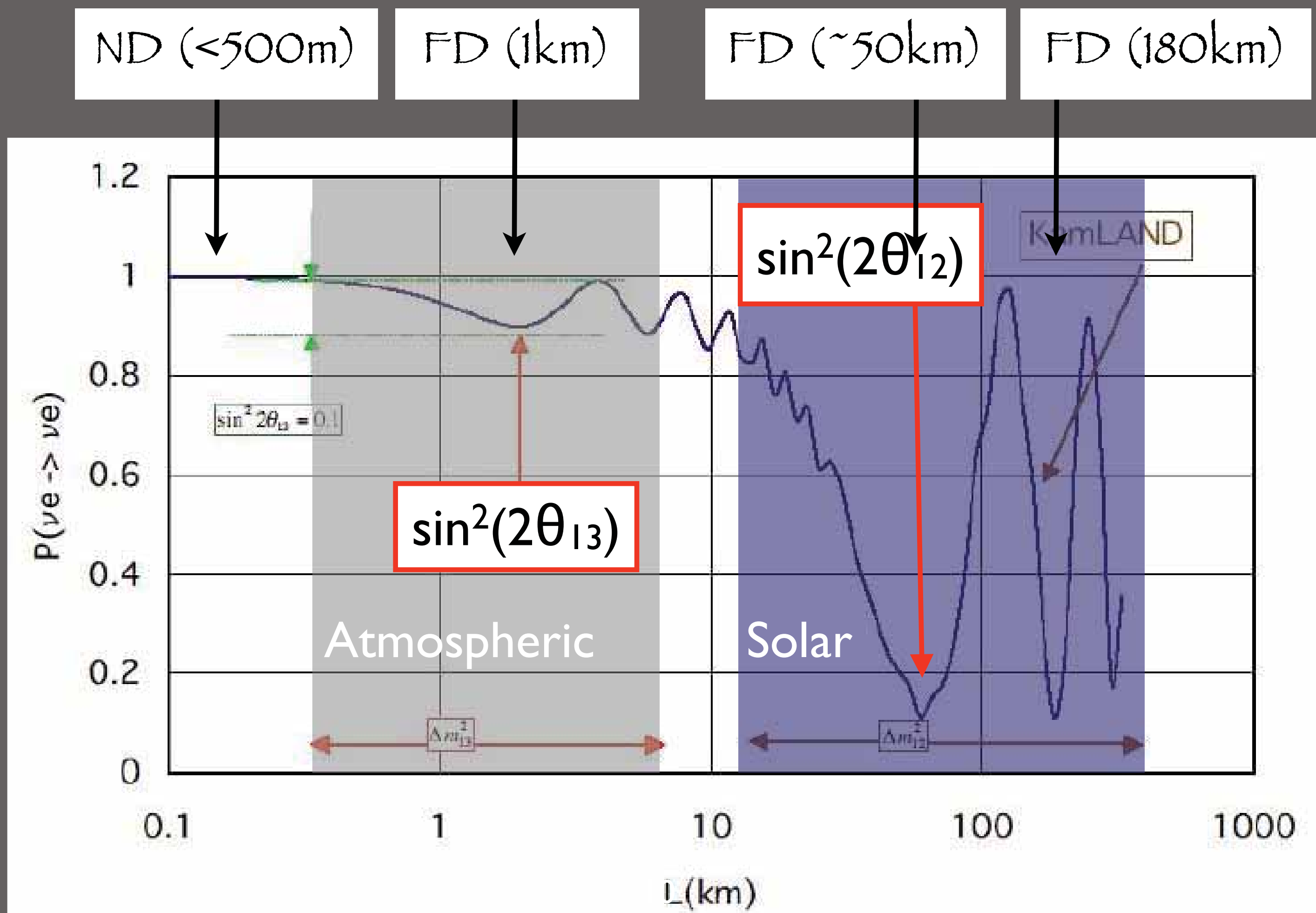
advantages of reactor-νs

- source:
  - copious, free and sometimes switchable (on/off)
  - finite size and well localised [L]
- inverse-β:
  - cross-section (±0.2%) and spectrum (±2%)
  - a few MeV plenty of calibration sources [E]
- disappearance ν-oscillation precision: high resolution E/L CC events: characterise dip
- flux uncertainty: multi-detector extrapolation ($1/L^2$)
- background: cosmogenic (overburden) (to improve)

physics potential

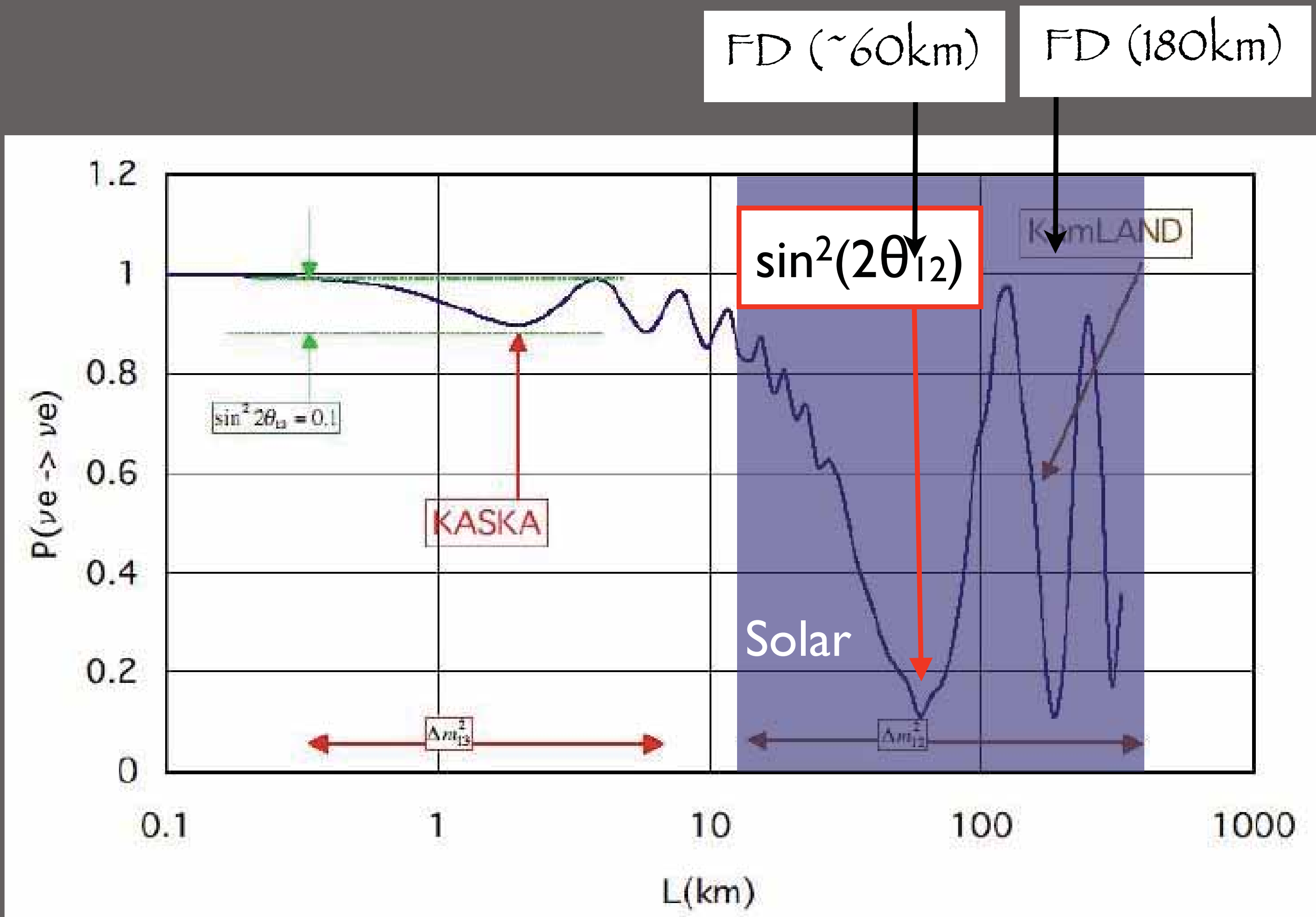
reachable oscillation physics

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - 4c_{13}^2(c_{13}^2 s_{12}^2 c_{12}^2 \sin^2\Phi_{21} + s_{13}^2 c_{12}^2 \sin^2\Phi_{31} + s_{13}^2 s_{12}^2 \sin^2\Phi_{32})$$



Δm^2_{12} & θ_{12}

KamLAND
SK+Gd
Reactor



$\delta(\sin^2\theta_{12})=9\%$
$\delta(\Delta m^2_{12})=4\%$

Vagins' Talk
hep-ph/0410283

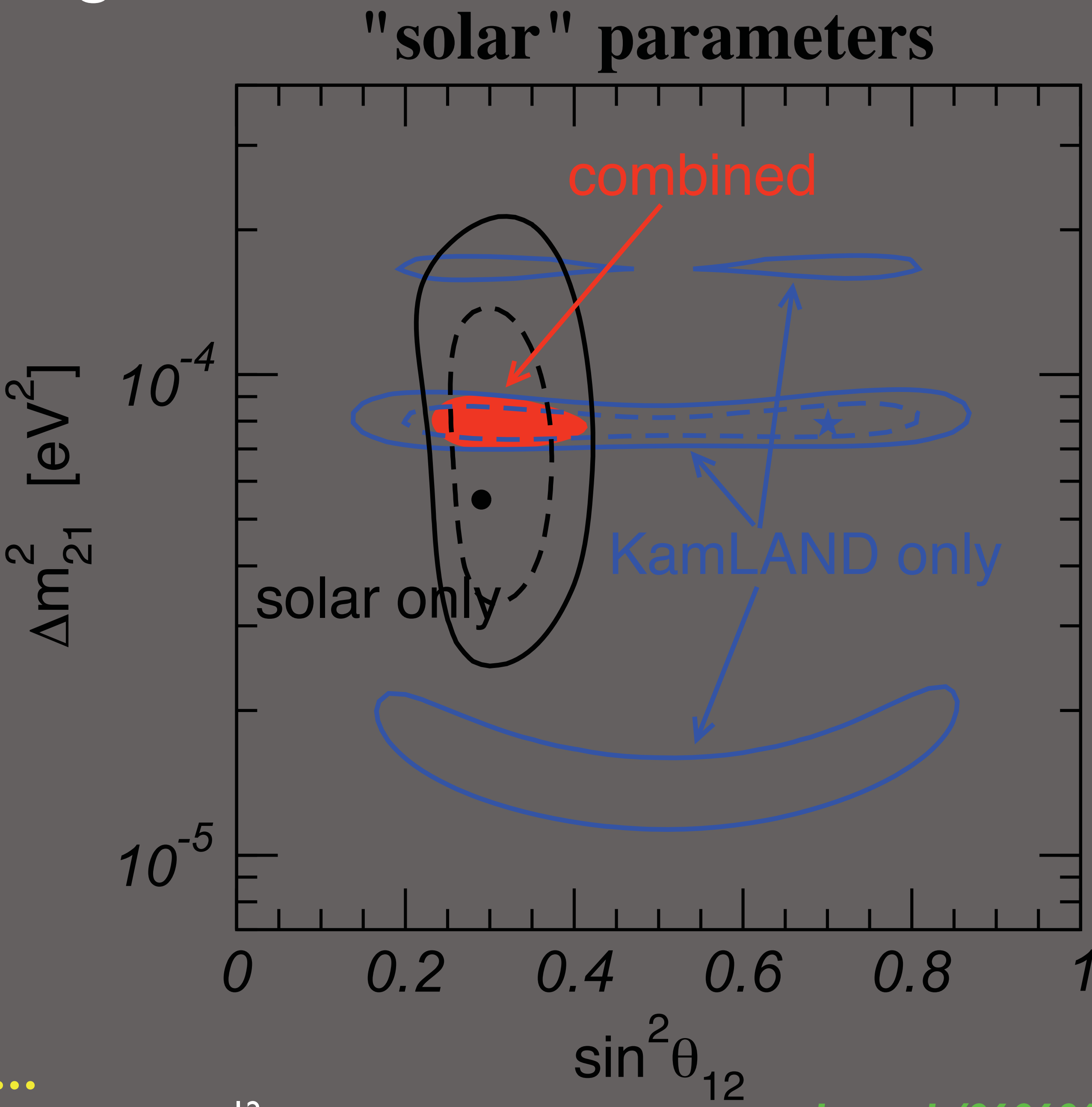
Believing in ν-oscillations?

One the most fascinating demonstration so far...

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

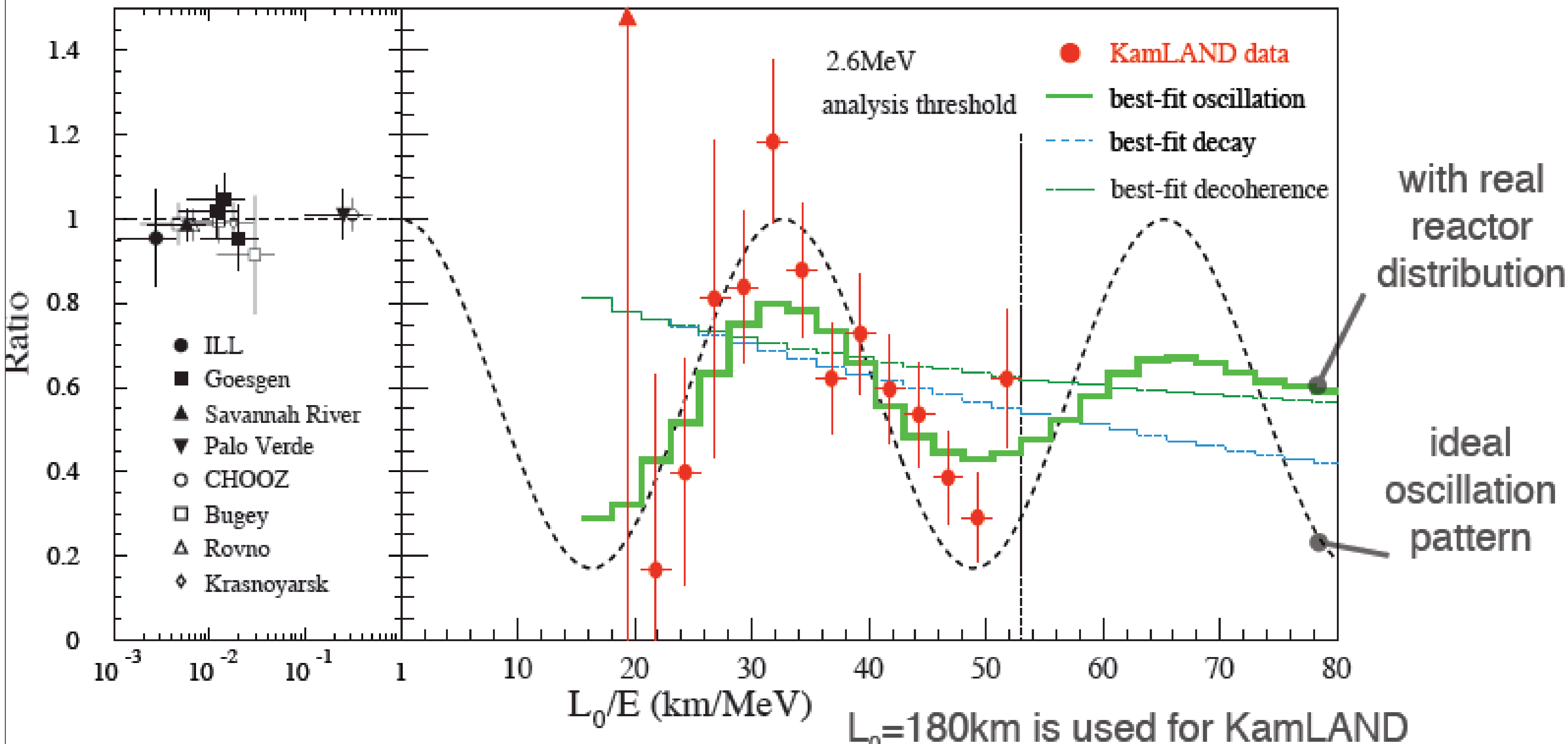
KamLAND
P=0.6 (N_{obs}/N_{exp})
(vacuum osc.)

Even E/L modulation...

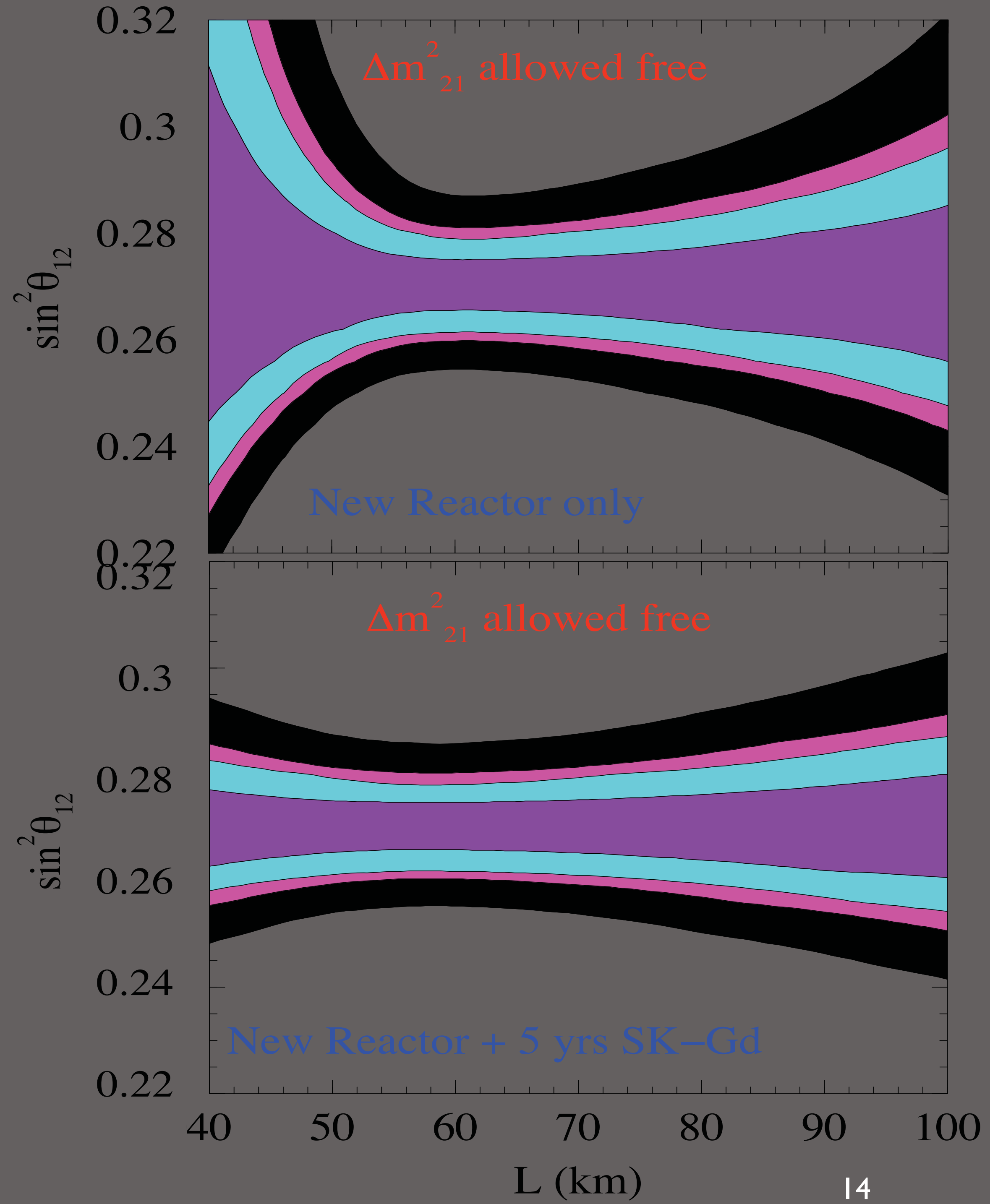


hep-ph/0606060

KamLAND spectral distortion



L_0=180km is used for KamLAND



Solar+KamLAND
$1\sigma(\sin^2\theta_{12})=9\%$

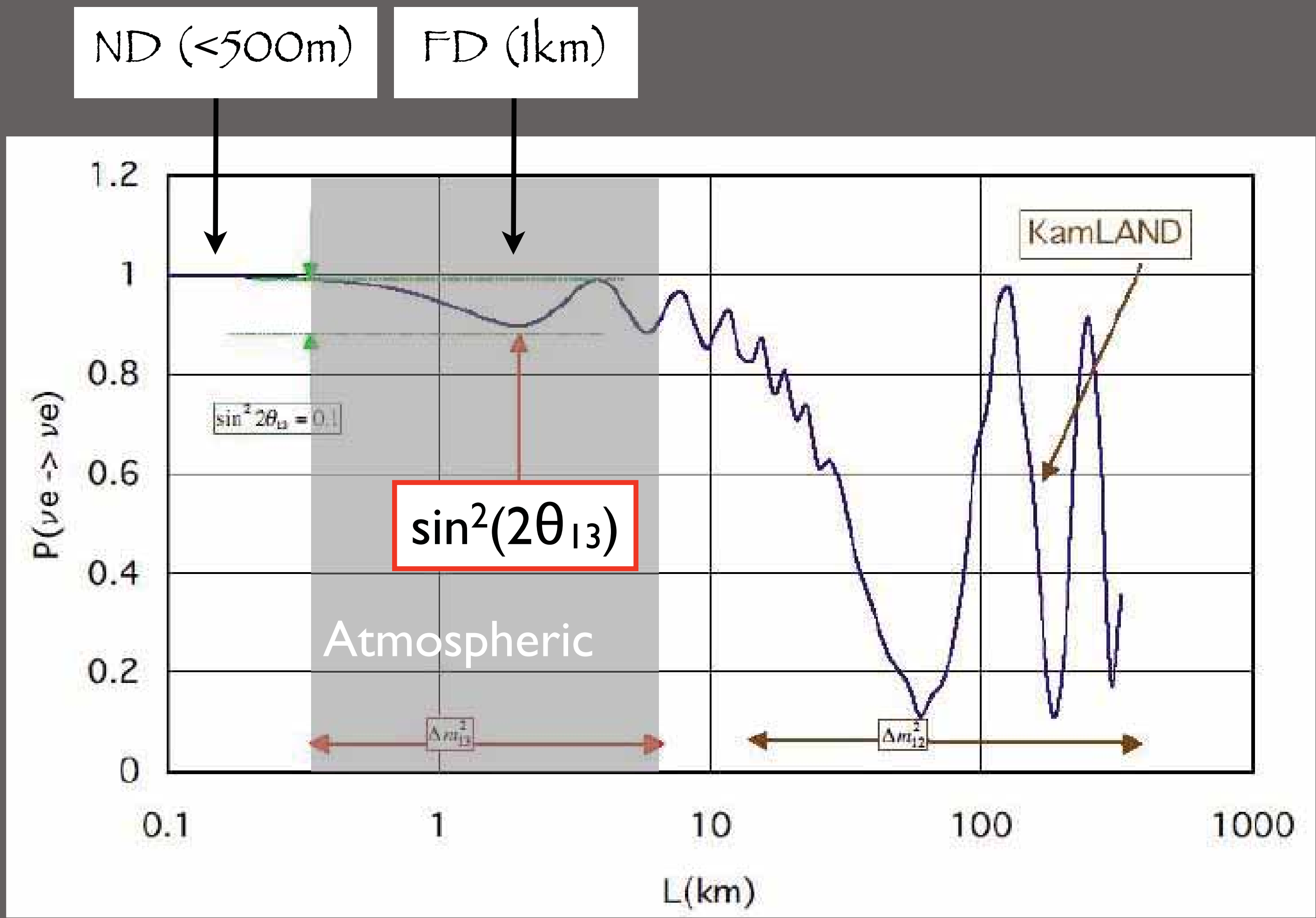
Reactor @ ~60km
(60GWkTy)
$1\sigma(\sin^2\theta_{12})<2\%$

SK+Gd (5 years)
$1\sigma(\sin^2\theta_{12})<2\%$

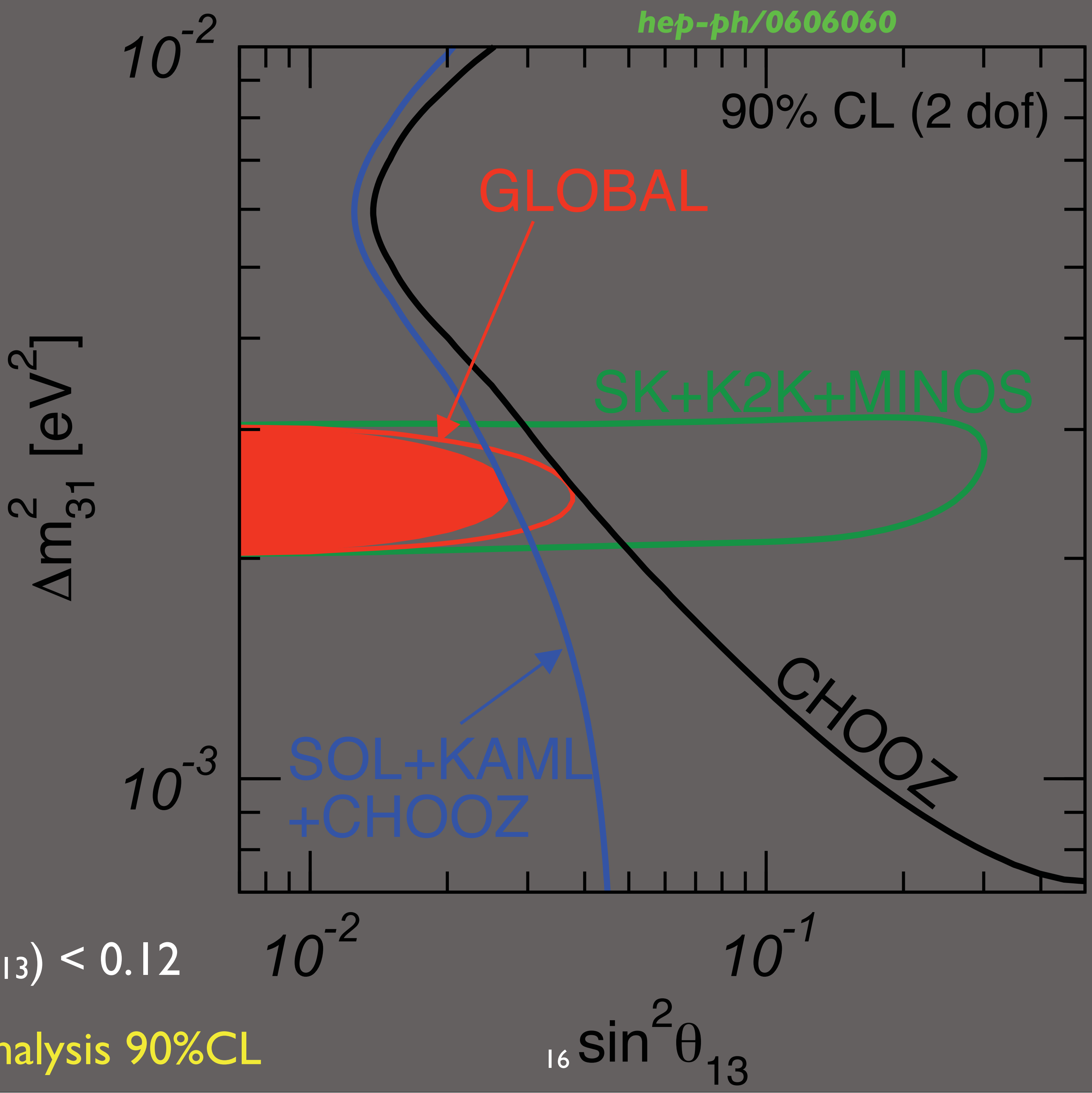
Petcov et al. hep-ph/0410283

θ13

CHOOZ
Palo Verde
Double Chooz
RENO
Daya Bay
Angra
Hanohano



KASKA: hep-ex/0607013
Daya Bay: hep-ex/0701029
RENO: NOW06
Angra: hep-ex/0511059
Hanohano: NOW06



★ $\sin^2(2\theta_{13}) < 0.12$

Global Analysis 90%CL

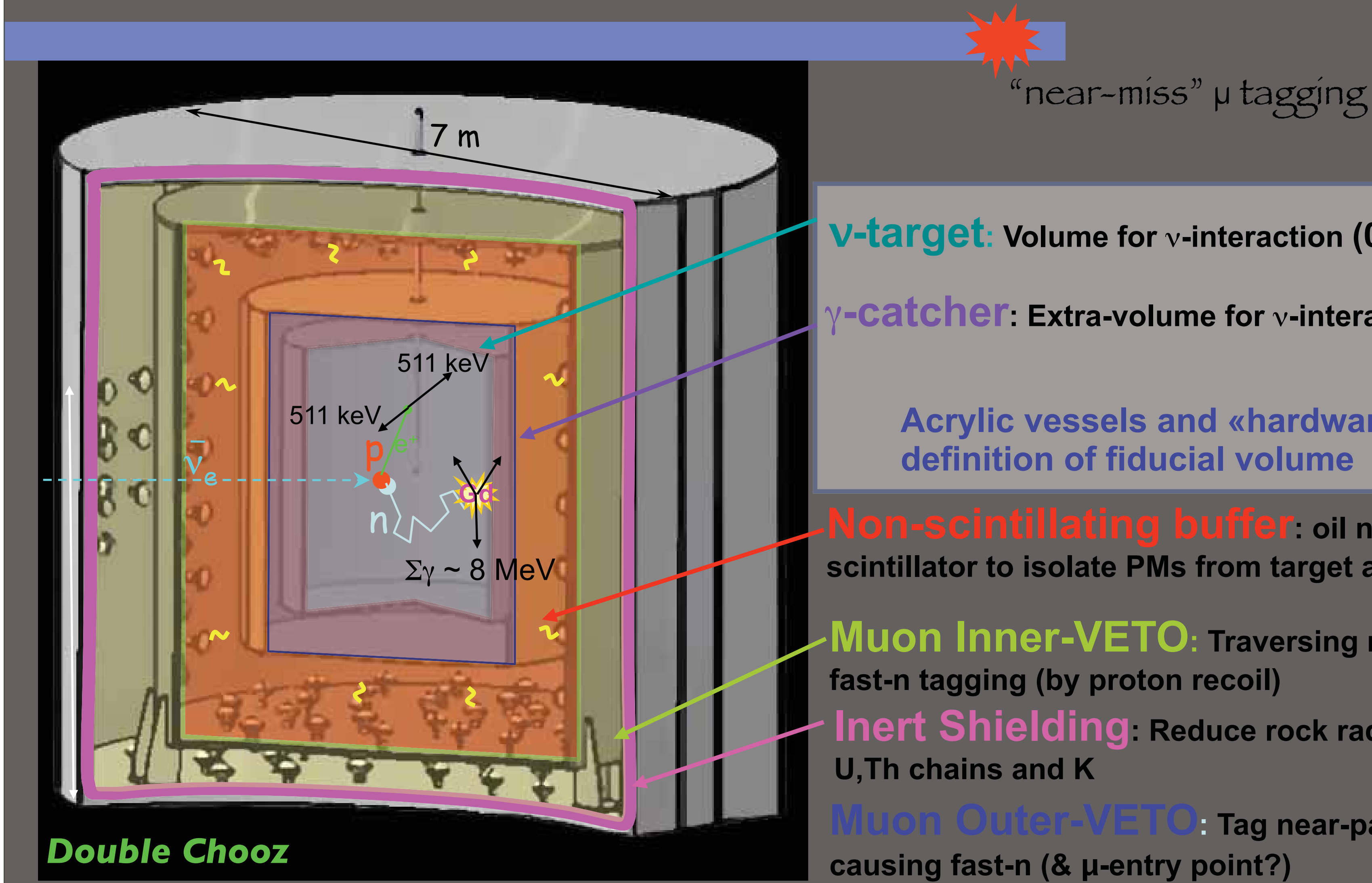
strategy

- make flux uncertainty negligible: multi-detector
- S/BG>100: huge statistical power => many reactors
  - large (or many) detectors: S/B ~ f(radius)
  - a few reactors may be nice too: "reactor off"
- reduce & understand backgrounds
  - overburden, radio-purity & detector design
- reduce & understand experimental systematics
  - inter-detector normalisation: <0.6%
  - inter-detector energy calibration: <1-2%

standard θ13-LAND

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

Input from:
CHOOZ
Borexino
KamLAND
SNO



ν-target: Volume for ν-interaction (0.1% Gd)

γ-catcher: Extra-volume for ν-interaction

Acrylic vessels and «hardware» definition of fiducial volume

Non-scintillating buffer: oil no scintillator to isolate PMs from target area

Muon Inner-VETO: Traversing muon and fast-n tagging (by proton recoil)

Inert Shielding: Reduce rock radioactivity from U,Th chains and K

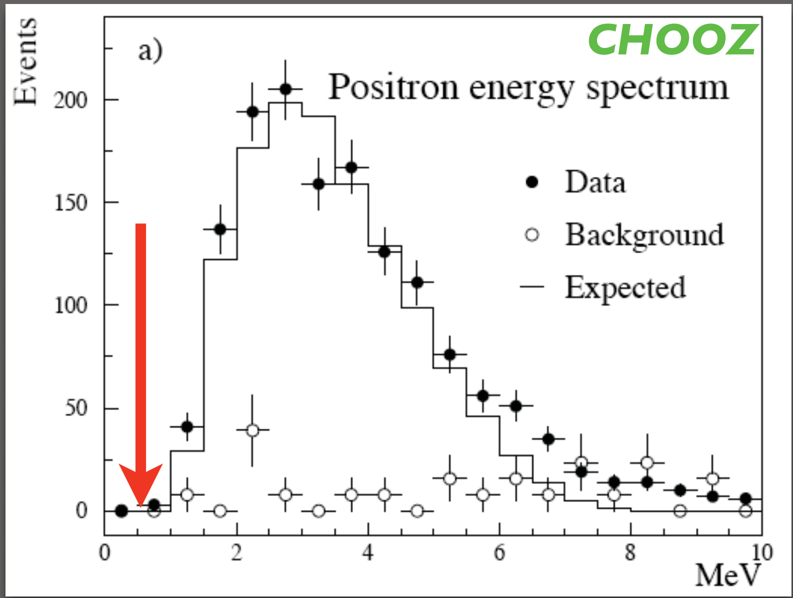
Muon Outer-VETO: Tag near-passing μs causing fast-n (& μ-entry point?)

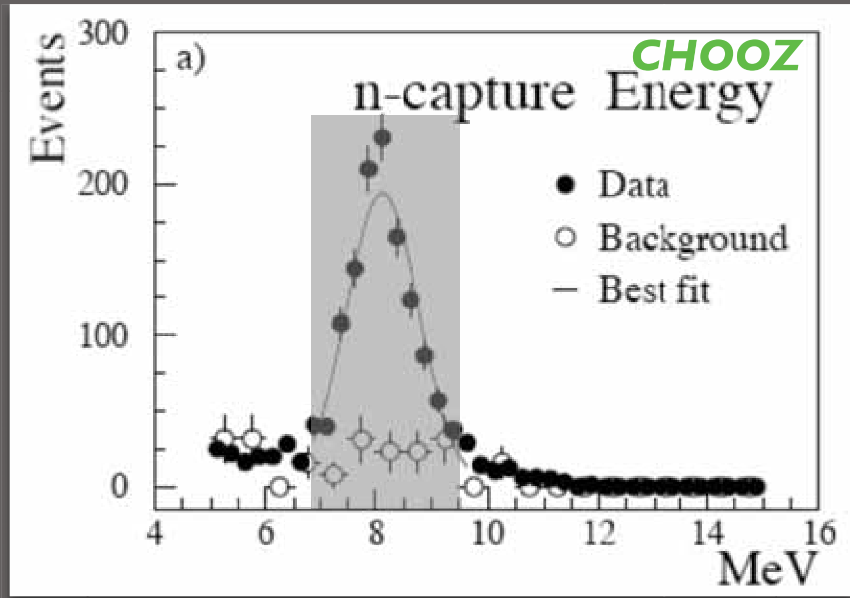
Proposal: hep-ex/0606025
LoI: hep-ex/0405032

analysis: 3 cuts (7 cuts at CHOOZ)

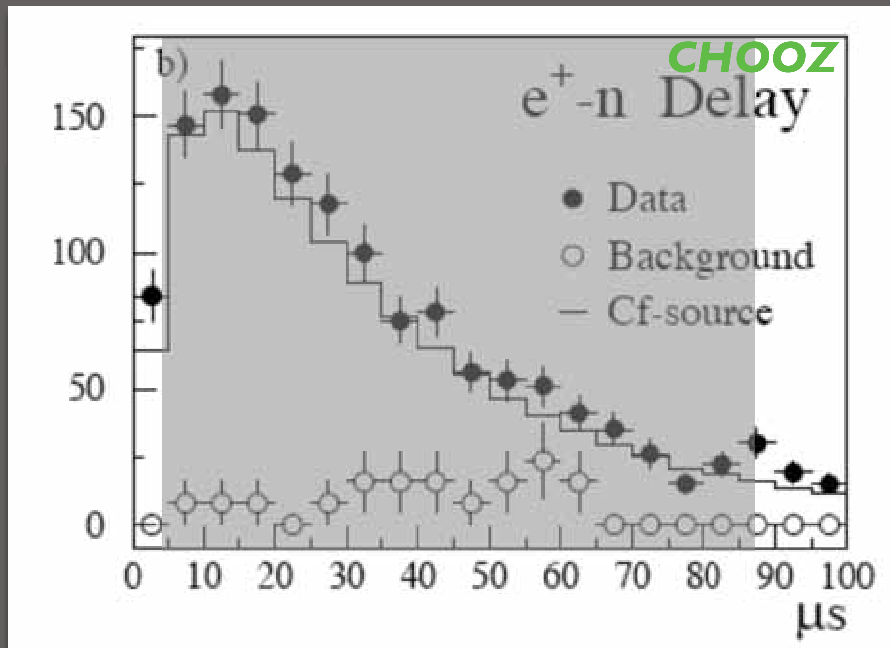
Apollonio et al. hep-ex/0301017 [CHOOZ]

e+-n energy deposited



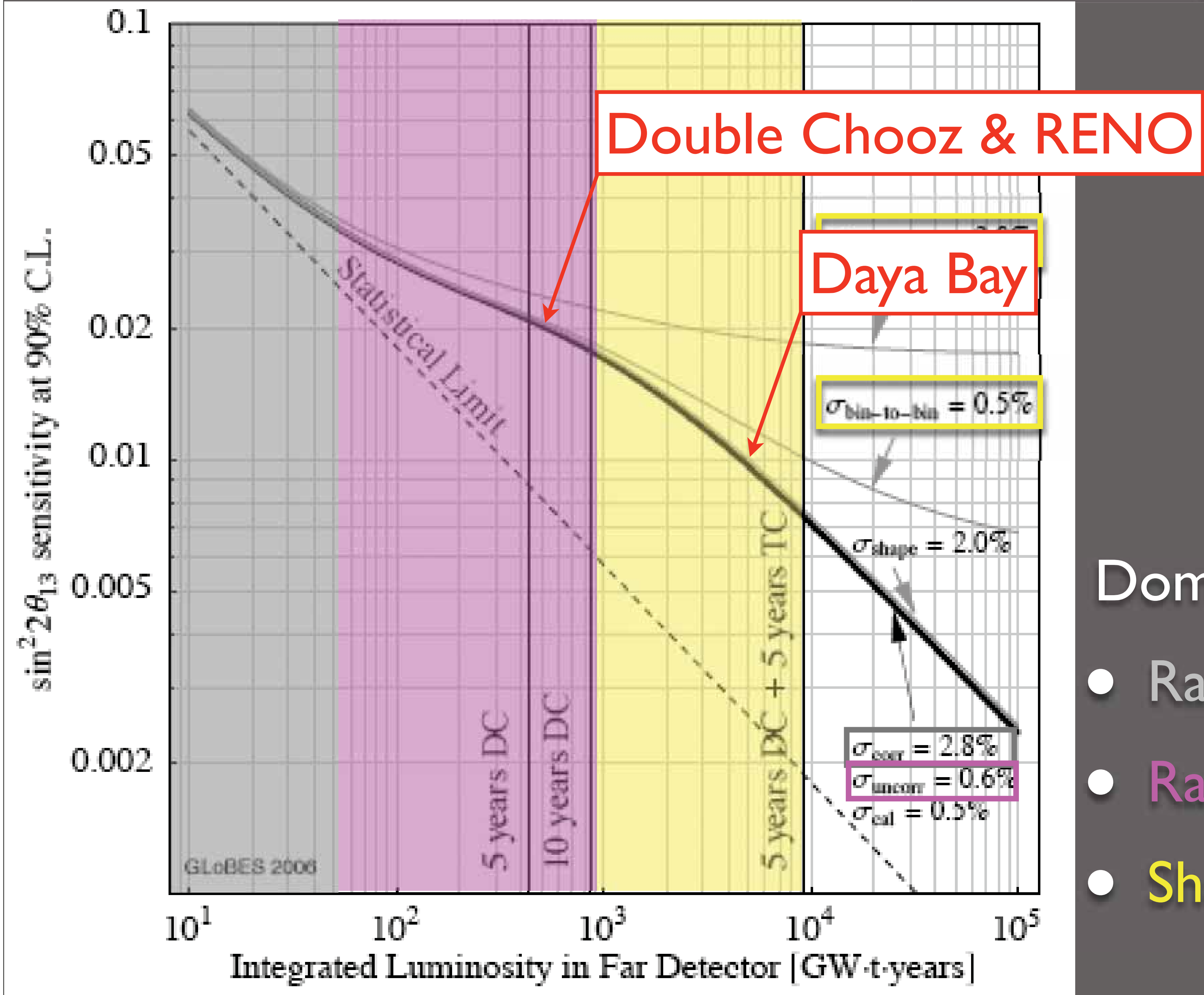


e+-n time-correlation



sensitivity regime

Huber et al. hep-ph/0601266



Domains:

- Rate
- Rate+Shape
- Shape

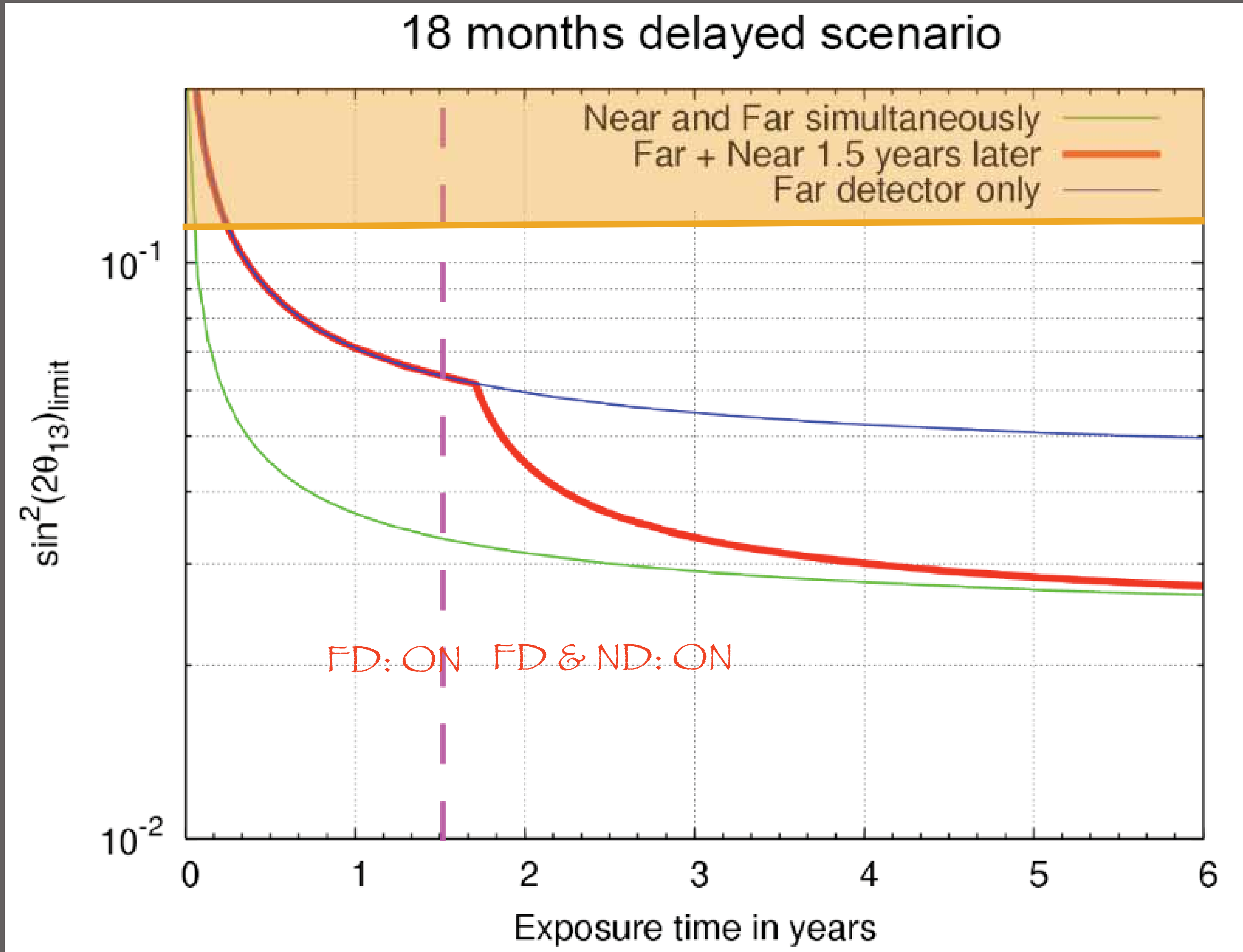
DC time-scale

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

Phases:

DC-I: FD only:
10x stat CHOOZ
=> x2 sensitivity

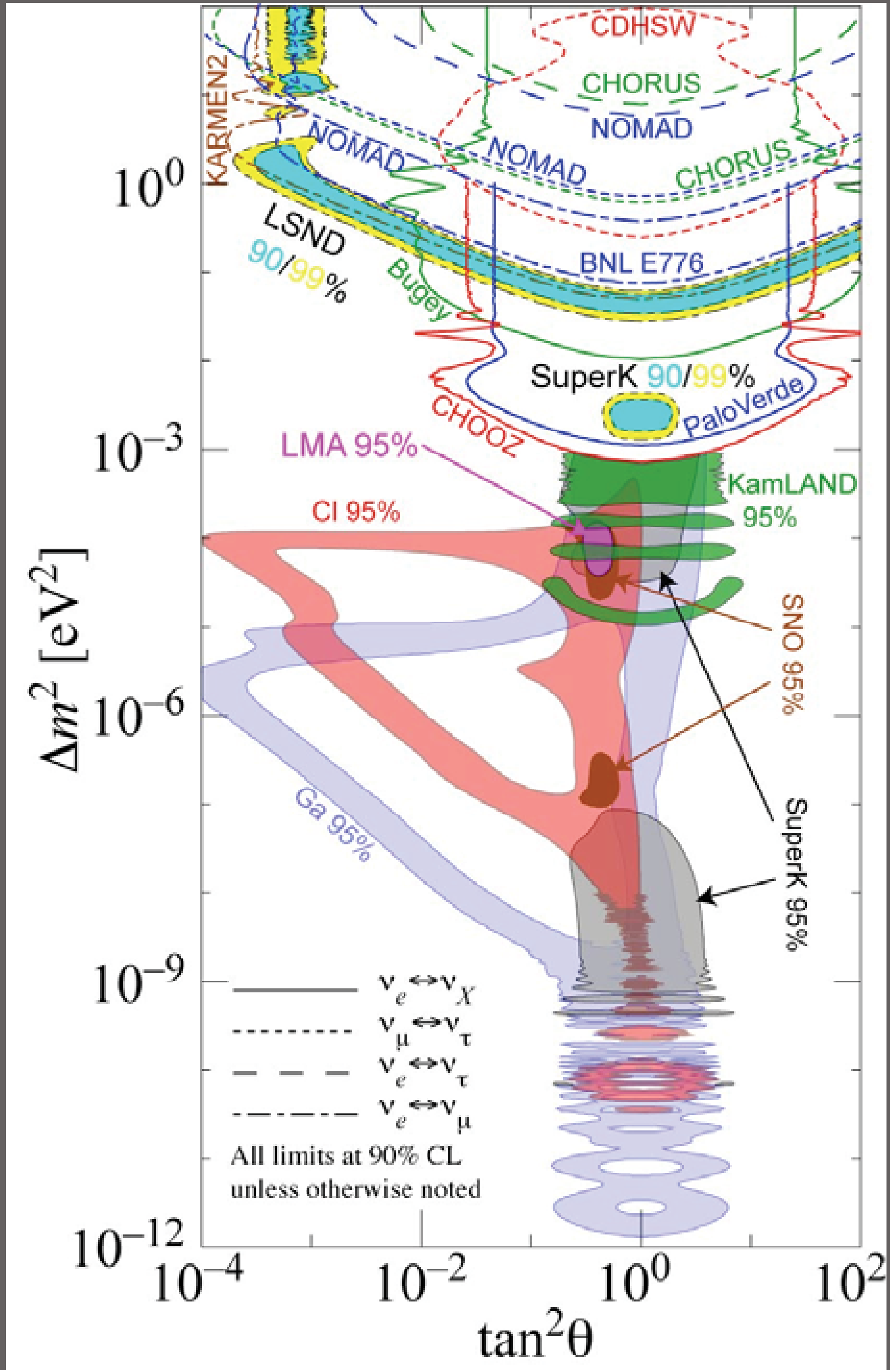
DC-II: FD+ND:
shape analysis
=> 4x sensitivity
from DC-I



And beyond their capabilities...

PDG 2004

50 years of complementarity...



two approaches

- reactor: disappearance => high statistics
  - sensitive to θ_{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 (<150νs Phase-I)
  - BG: π^0 production and beam ν_e contamination
  - correlation: δ_{CP}, θ_{13},θ_{23} degeneracy and matter effects*

Yokoyama-san's Talk

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

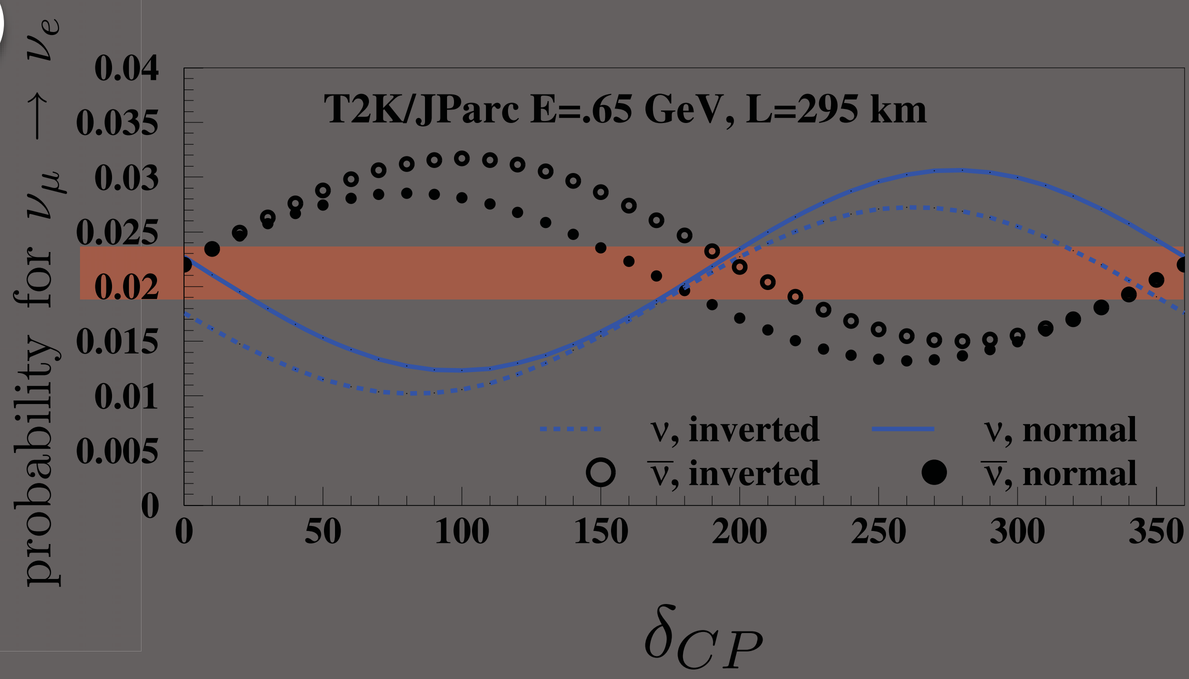
$$\Delta \equiv \Delta m^2_{31} L/(4E_\nu)$$

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

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

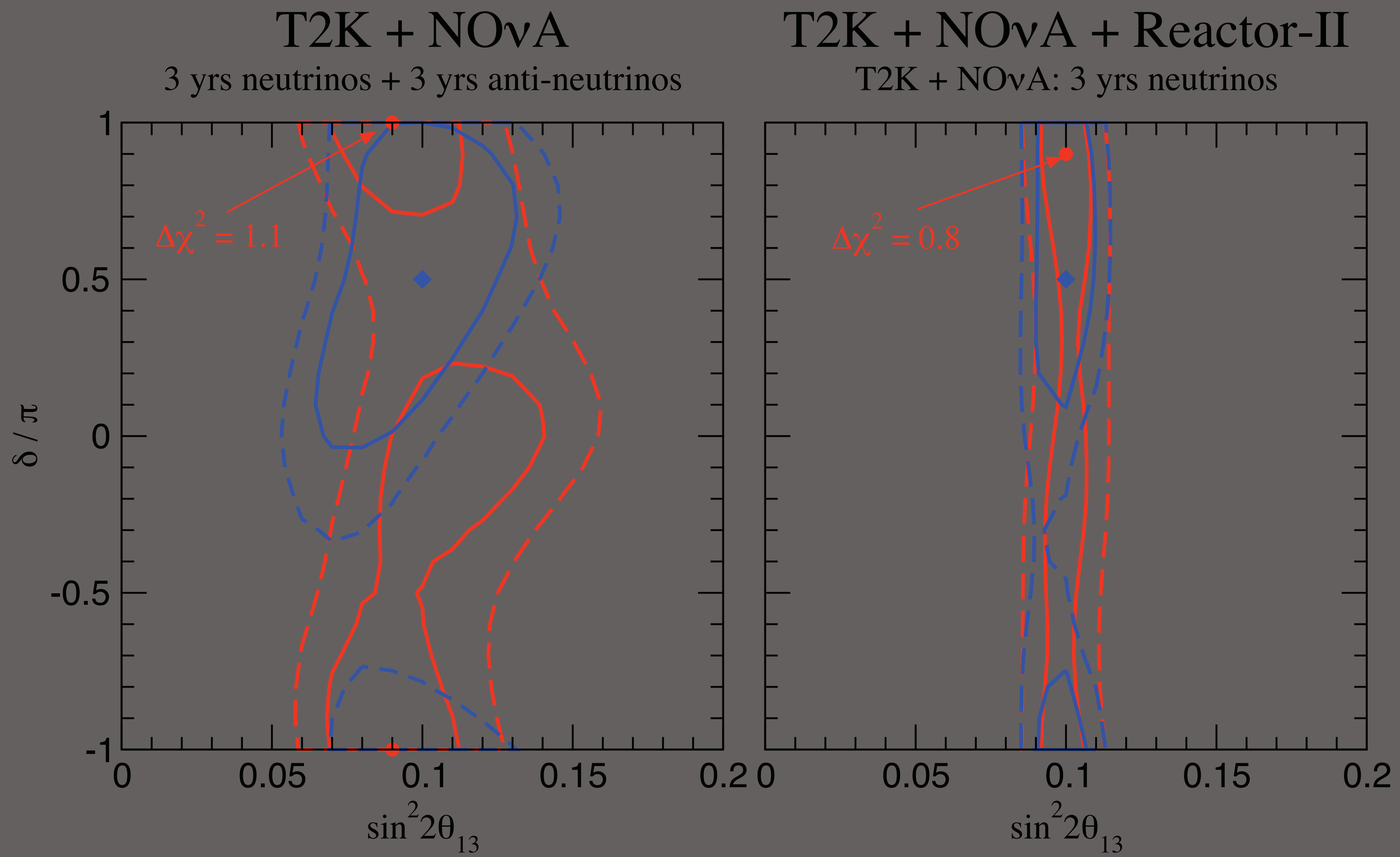
$$\Delta m^2 = 2.5 \times 10^{-3}\ \mathrm{eV}^2,\ \sin^2 2\theta_{13} = 0.05$$
$$\sin^2 2\theta_{23} = 0.95$$



hep-ex/0409028

Normal hierarchy

Inverted hierarchy

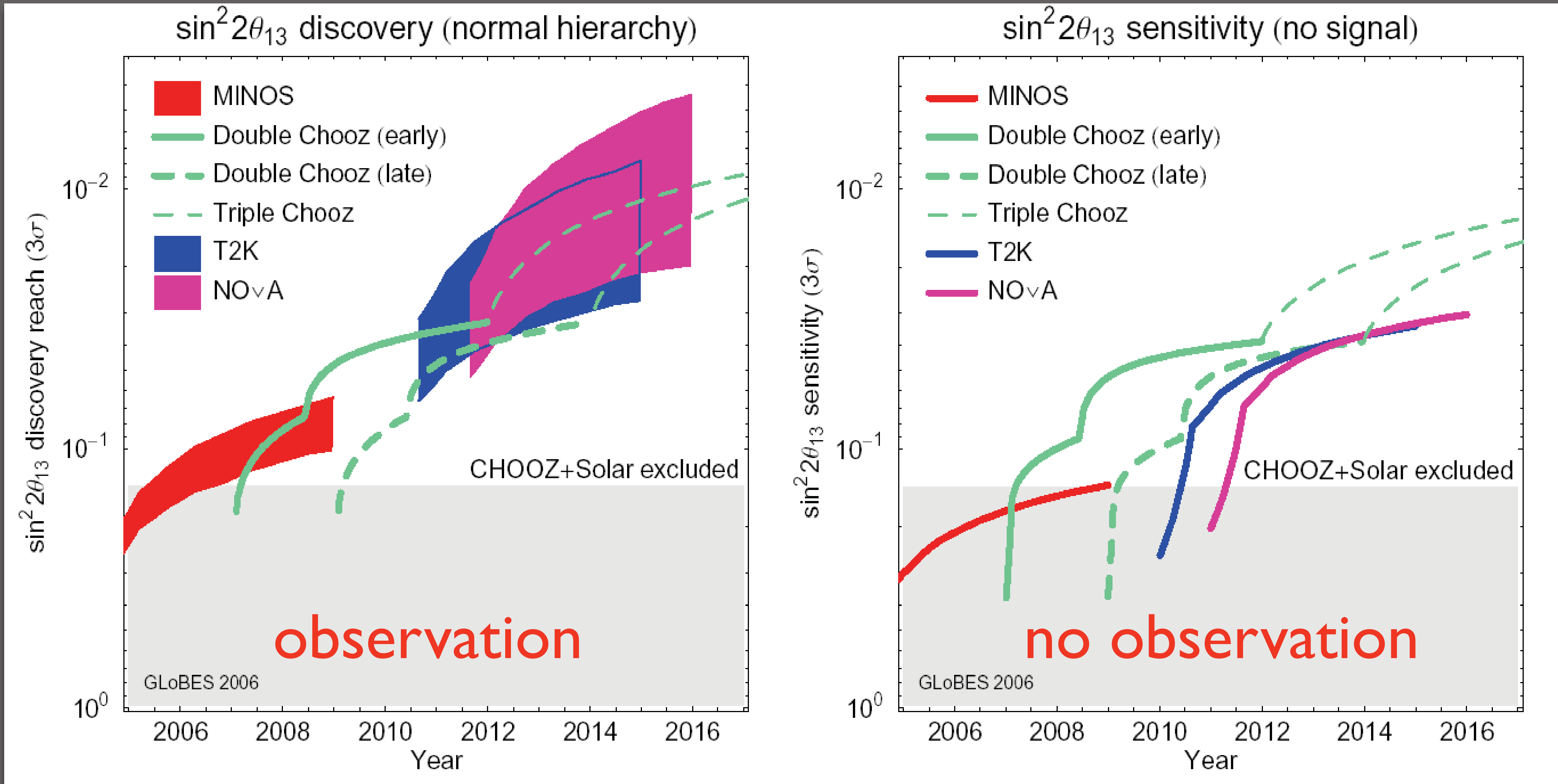


Huber et al. hep-ph/0412133

conclusions

beams + reactors = deeper insight

Competitive & overlapping coverage by both techniques!



Similar time scale

Huber et al: hep-ph/0601266