The HLMA project

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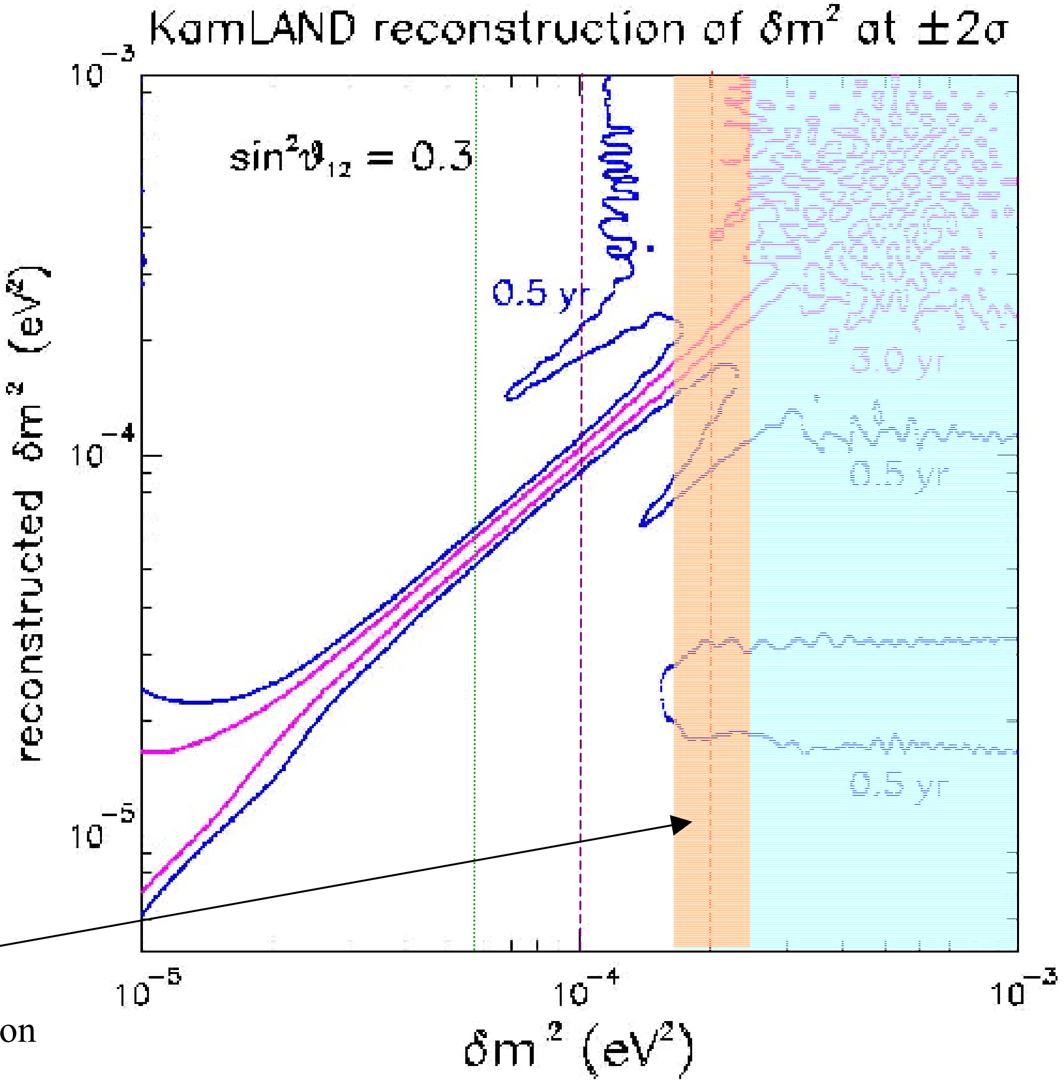
In collaboration avec S. Schönert (MPIK) & L. Oberauer (TUM)

December 11th 2002, CERN

KamLAND sensitivity study



Will depend on the achieved energy resolution

Fogli, Lettera, Lisi, Marrone, Palazzo, Rotunno, hep-ph/0208026

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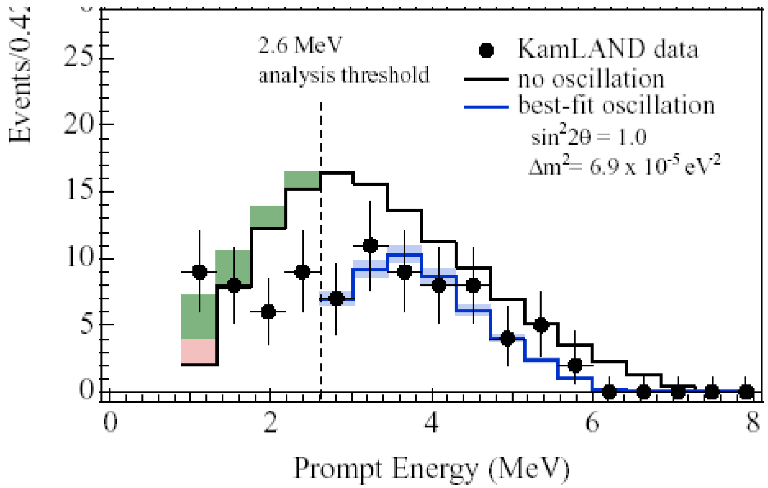
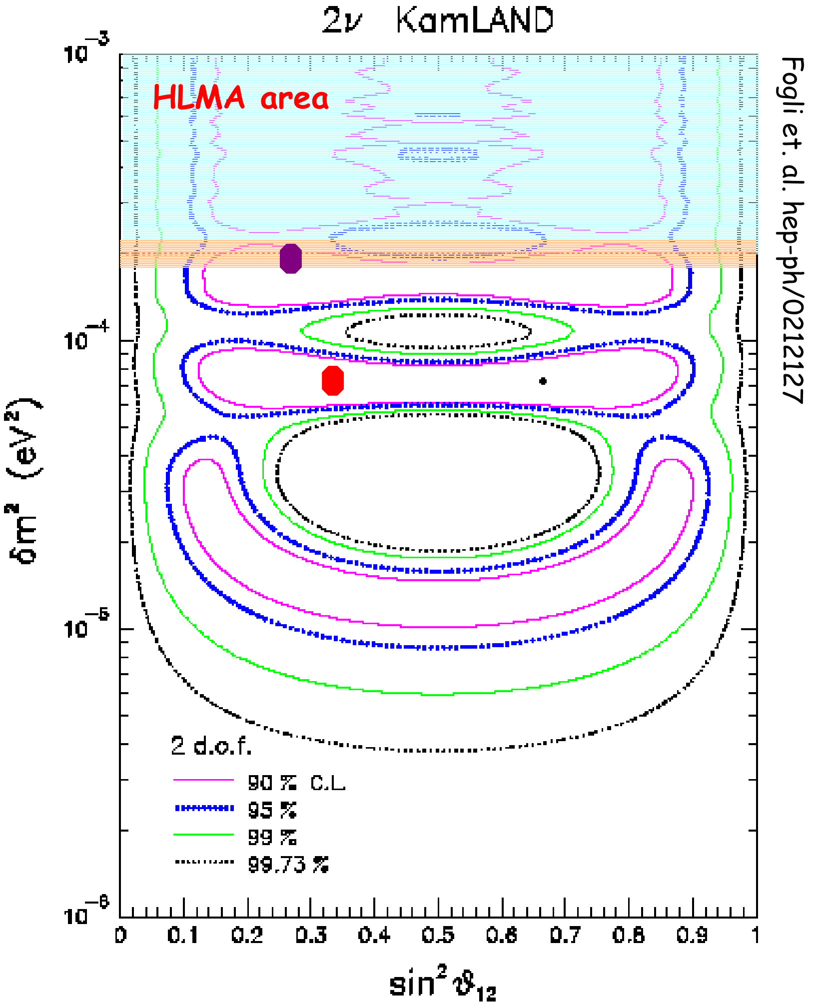
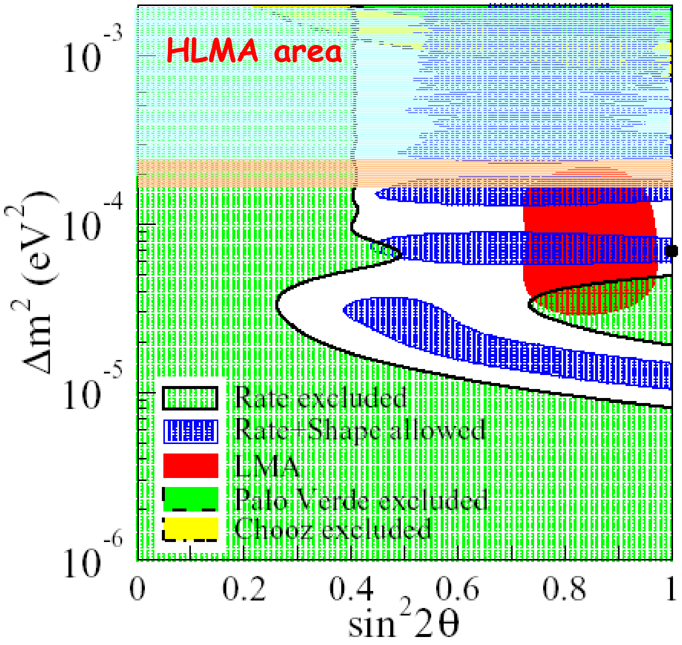
The Post-KamLAND world: HLMA is among the possible solutions





Fogli et. al. hep-ph/0212127



KamLAND alone:
2 bset solutions

No. of data	Best fit point(s)[a]	$\chi^2_{\min}$
13	🔴 (7.3, 0.335)	6.1
13	🟣 (18.0, 0.270)	7.9

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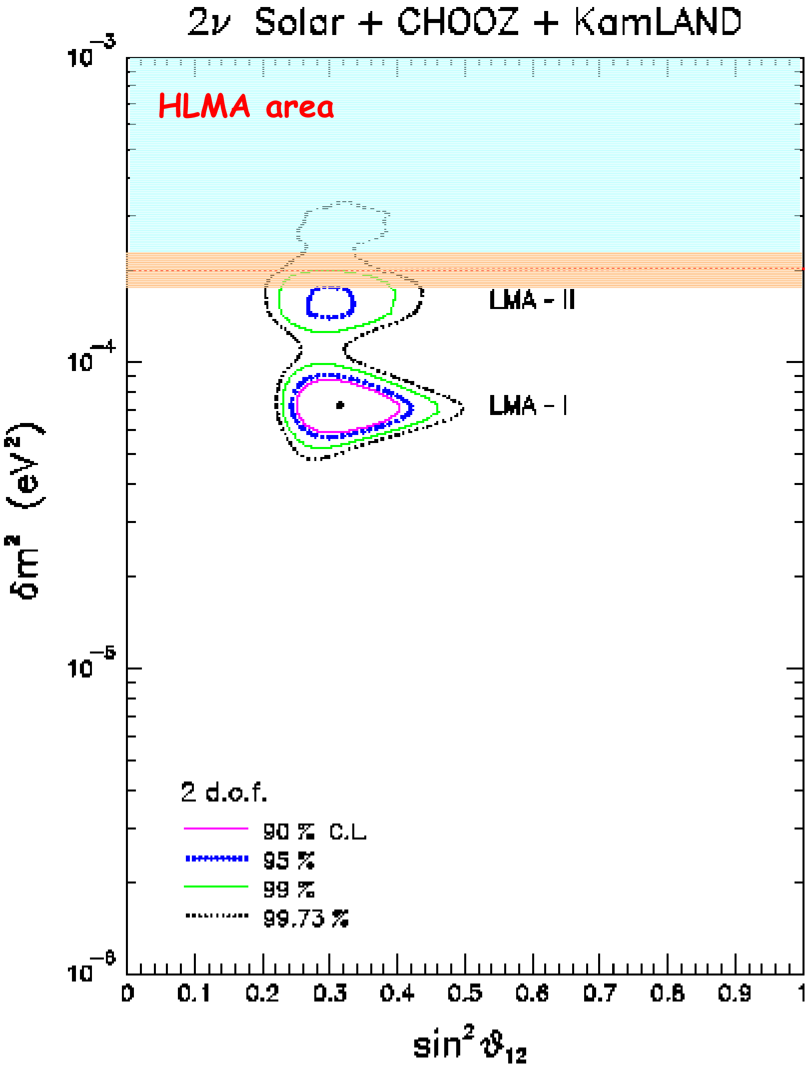
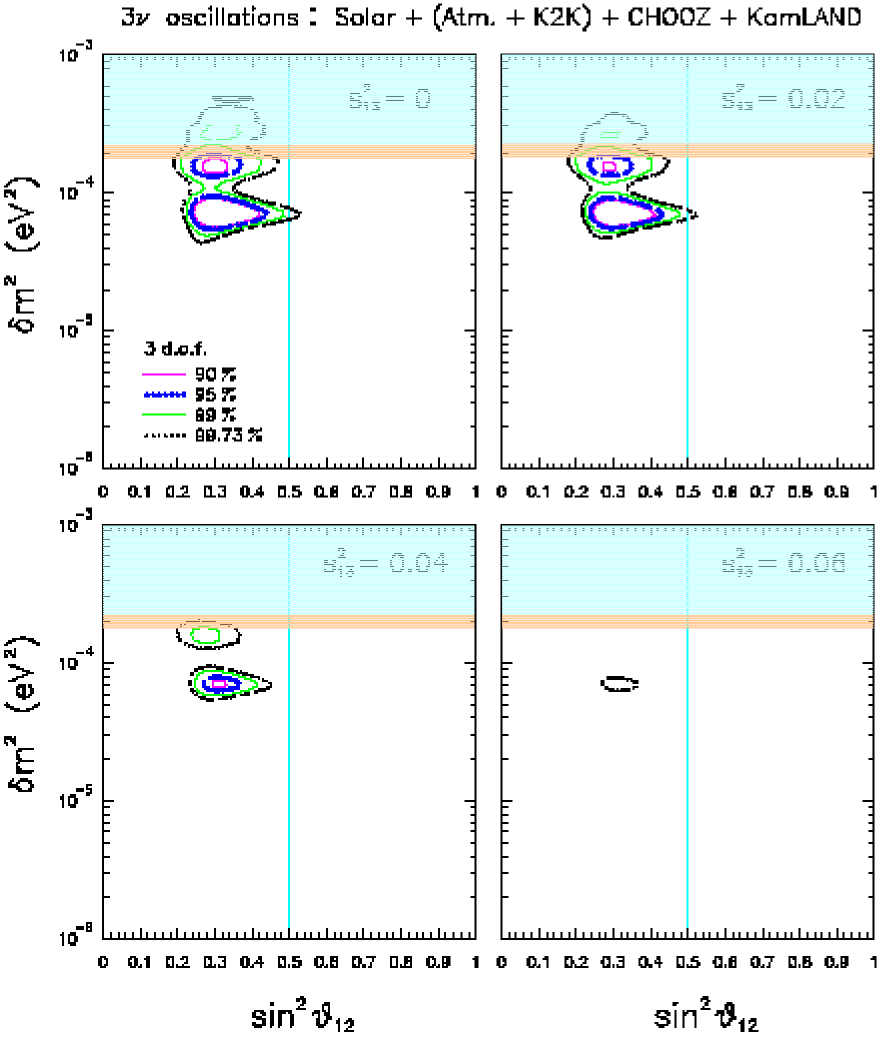
Post-SNO global analysis + KamLAND: HLMA disfavoured



Fogli et. al. hep-ph/0212127

Solar+CHOOZ+KamLAND	81+14+13	$(7.3,\ 0.315)^b$	85.2
	81+14+13	$(15.4,\ 0.300)^c$	90.6



Fogli et. al. hep-ph/0212127

LMA-II (~HLMA) disfavoured
BUT statistically acceptable
➔ Should not be neglected a priori !

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The HLMA Facility

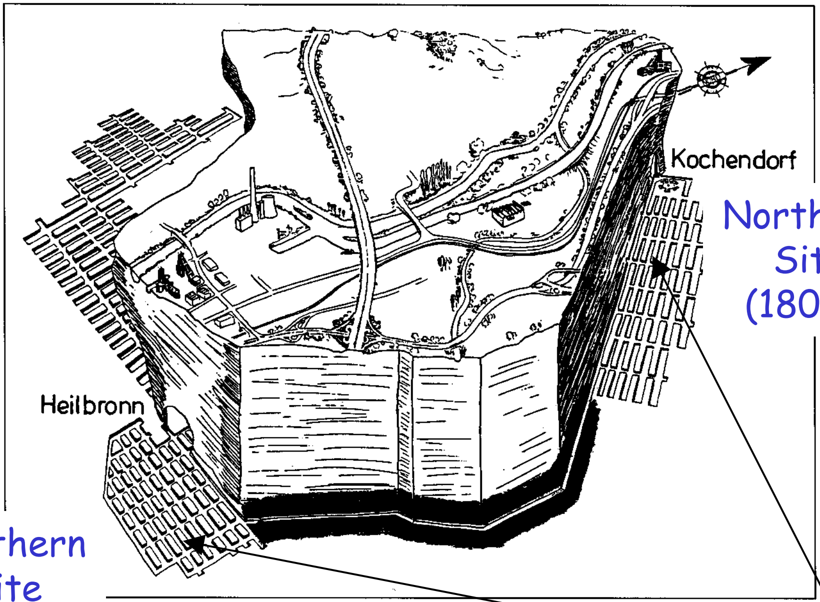
Dedicated reactor neutrino experiment to probe the HLMA region: $\mathbf{2\ 10^{-4} < \Delta m^2}$ $(< 9\ 10^{-4}\ eV^2)$

Specifications:

- Physics: One dominant baseline ~ 20 km
- Facility: Underground site with large cavities
- Politics: Reactors operating more than 10 years

Current Best Choice

The Heilbronn salt mine



Northern Site (180m)

Southern Site (240m)

~ 2000 caverns,
Each of similar size to Gran Sasso halls: 15m (width) x 10-20m (height) x 100-200m

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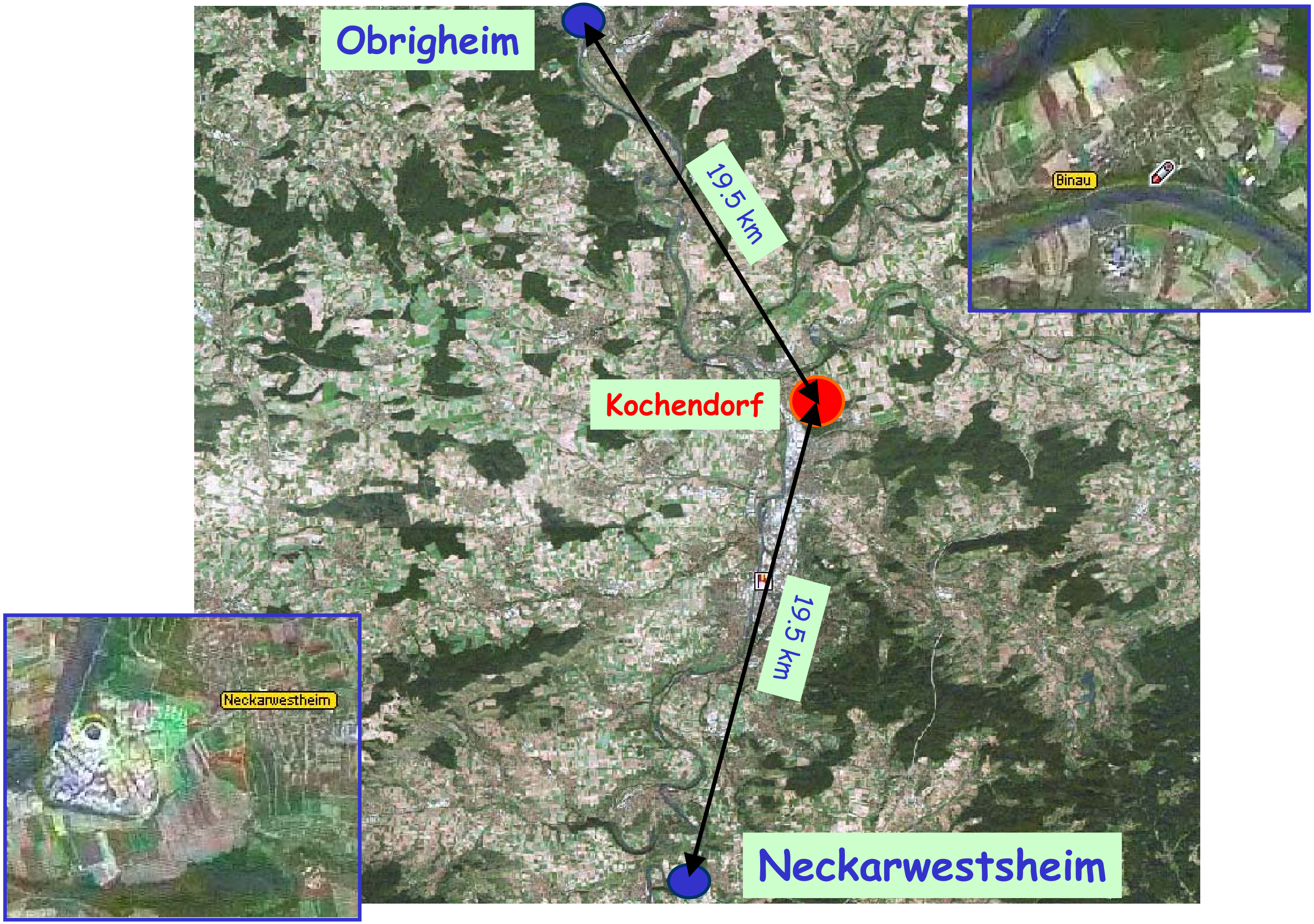
Detector site: Aerial view



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Anti-ν_e interaction rate at Heilbronn

- >300 GW_{th} European power plants included
- Average typical fuel composition (U, Pu)

$$\nu_e + p \rightarrow e^+ + n$$

➔ $\langle\sigma\rangle$/fission = 5.825×10^{-43} cm²

- For 10^{31} protons, 194 tons PXE ($C_{16}H_{18}$)
- Load factor: 80% to 90%
- Expected rate ~ 1150/year (100% eff.)
- 77% of the rate @ 20km baseline

Reactor	Distance [km]	Power [GW_{th}]	R_L	R_L/R_0
Neckarwestheim	19.5	6.388	754	66%
Obrigheim	19.5	1.057	125	11%
Philipsburg	54	6.842	107	9%
Biblis	80	7.420	52	4%
Grundremmingen	117	7.986	26	2%
Others (Europe)	> 100	~ 293	86	8%

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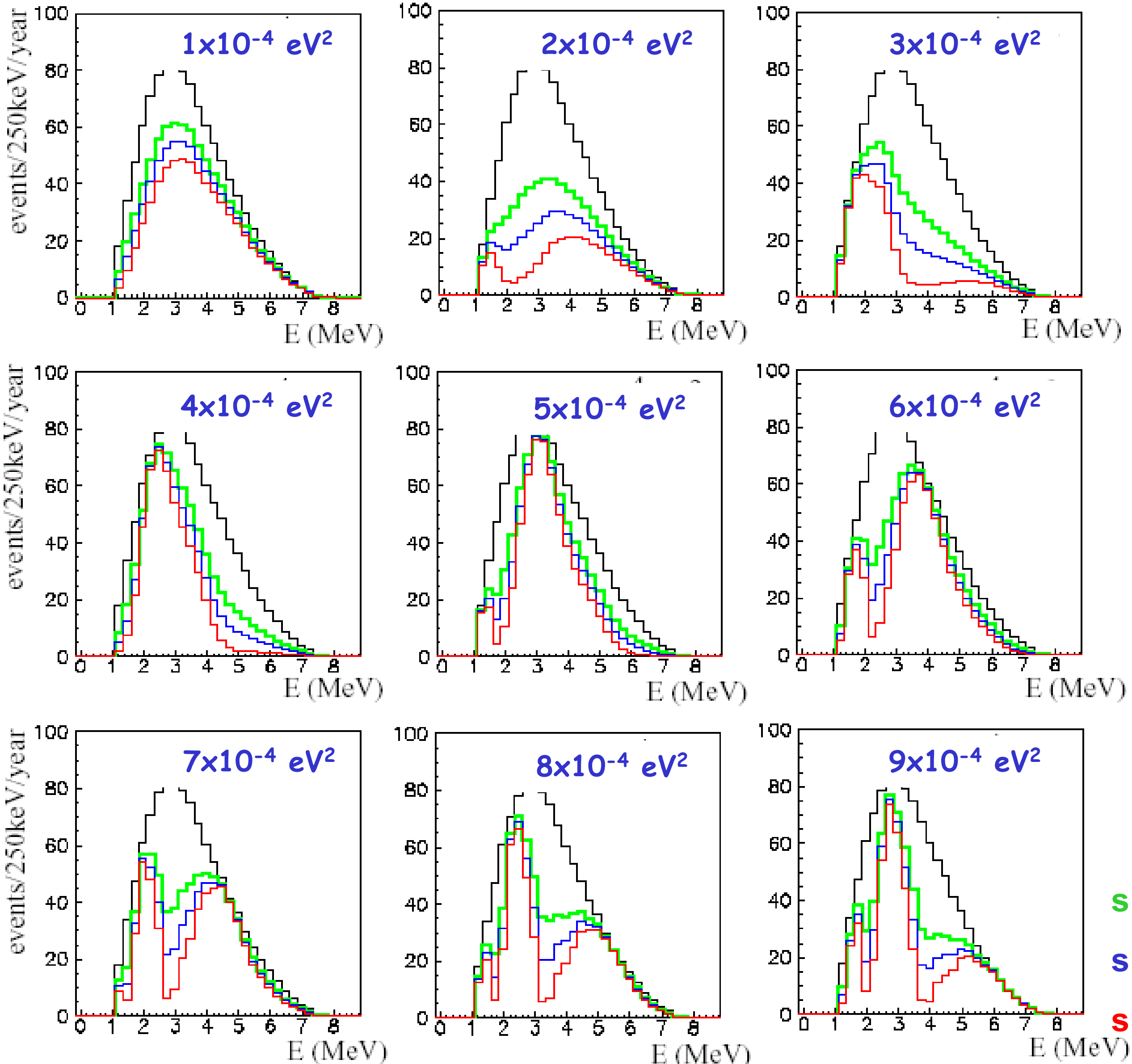
HLMA Focus: Solar mixing parameters



$\sin^2 2\theta=0.6$

$\sin^2 2\theta=0.8$

$\sin^2 2\theta=1.0$

- 2 neutrino mixing
- 10^{31} protons
- No energy resolution
- 250 keV bins
- $\Delta m^2 < 10^4$ eV^2 only rate suppr.
- Optimised for HLMA region
- High sensitivty to Δm^2

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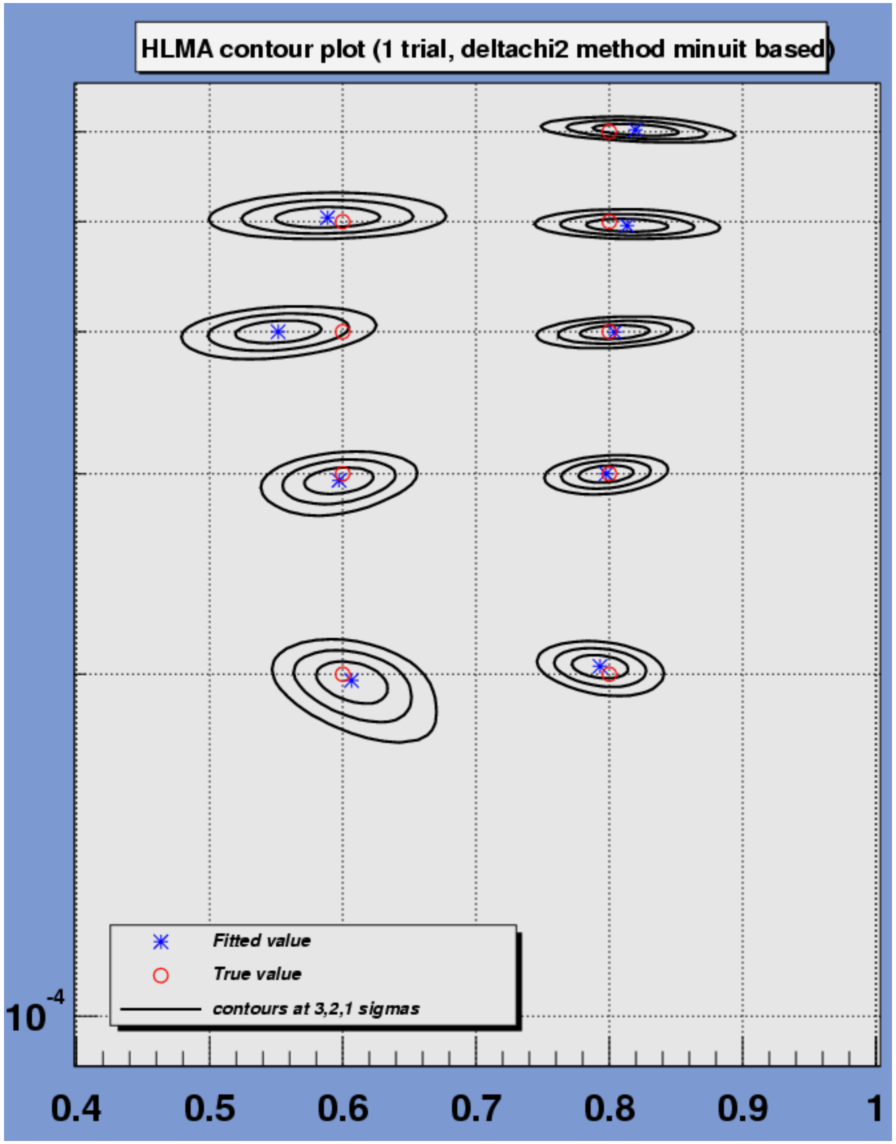
Reconstruction of $[\Delta m^2_{sol}, \sin^2 2\theta_{sol}]$



Simulation of HLMA @Heilbronn (kochendorf)

For a fix choice of $[\Delta m^2_{sol}, \sin^2 2\theta_{sol}]$

- 1 HLMA simulated - 3 years of data
- No background included
- 250 keV bins
- 100% efficiency
- 10^{31} free protons target
- 2 neutrino mixing scenario

MINUIT fit – MINOS contours
($\Delta\chi 2$, 2 parameters & 1, 2, 3 σ)

Δm^2_{sol} eV^2	$\sin^2 2\theta_{sol}$	$\delta(\Delta m^2_{sol})$ 1σ	$\delta(\sin^2 2\theta_{sol})$ 1σ
2×10^{-4}	0.8	1.8 %	1.8 %
3×10^{-4}	0.8	1.2 %	1.7 %
4×10^{-4}	0.8	1 %	2.3 %
6×10^{-4}	0.8	-	-

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3 neutrino oscillation analysis

$$
\begin{aligned}
P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - & 2|U_{e3}|^2(1-|U_{e3}|^2)\left(1-\cos\frac{\Delta m^2_{31}L}{2E}\right) && \text{Atmospheric} \qquad (4.1)\\
& -\frac{1}{2}(1-|U_{e3}|^2)^2\sin^2 2\Theta_{12}\left(1-\cos\frac{\Delta m^2_{21}L}{2E}\right) && \text{Solar}\\
\text{Interference} \quad & +2|U_{e3}|^2(1-|U_{e3}|^2)\sin^2\Theta_{12}\left(\cos\left(\frac{\Delta m^2_{31}L}{2E}-\frac{\Delta m^2_{21}L}{2E}\right)-\cos\frac{\Delta m^2_{31}L}{2E}\right).
\end{aligned}
$$

- $|U_{e3}|2 << 1$ ➔ atmospheric and solar neutrinos decoupled
- $|U_{e3}|2 \geqslant$ 0.01 and $\Delta m^2_{sol} \lesssim \Delta m^2_{atm}$:
  BOTH atmospheric and solar oscillations develop without being averaged
- HLMA: Optimal baseline ~ 20km
- 2 by-products of the HLMA : constraint on $|U_{e3}|$ and probe of the ν mass hierarchy
  (Petcov & Piai)

Constaint on $|U_{e3}|$:

- CHOOZ bound: $|U_{e3}|^2 < 0.036$ (95% C.L), $\Delta m^2_{atm}=2.5\ 10^{-3}$ eV^2, $\sin^2(2\theta)=0.89$ (*Bilenky, Nicolo, Petcov*)
- HLMA: down to $|U_{e3}|^2 \sim 0.01$ (estimation)
- Detector size scale: 10^{32} protons-year
- Effect independent of the $(\Delta m^2_{sol})_{LMA}$ value

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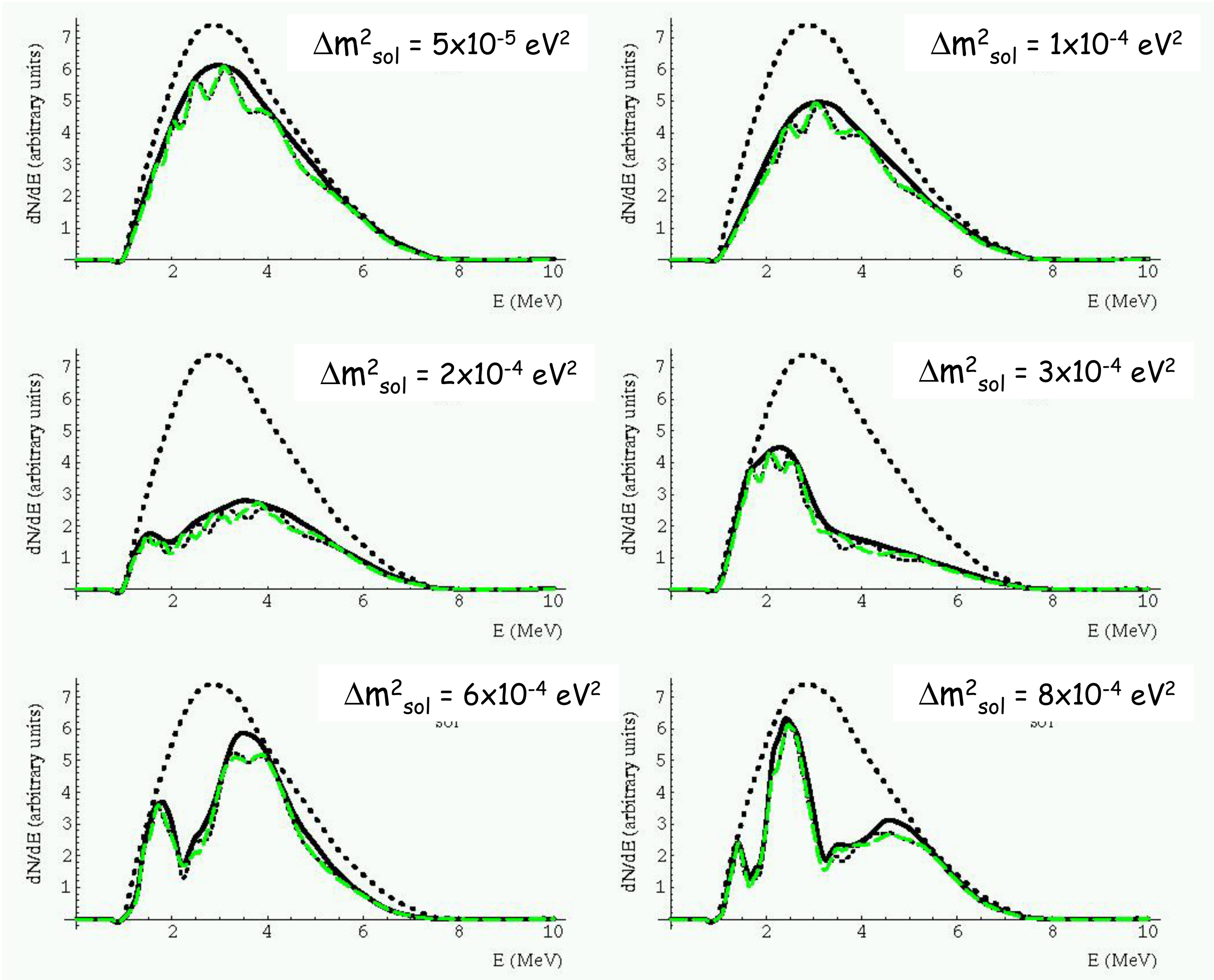
By-product 1: constraint on $|U_{e3}|$



- Visible energy
- Unbinned spectra
- No energy resolution
- Δm^2_{atm}=2.5 10^{-3} eV^2
- $\sin^2 2\theta_{sol}$=0.8
- $|U_{e3}|^2$ = 0.04
- HLMA ➔ $|U_{e3}|^2$ ~ 0.01
- 10^{32} p-year

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By-product 2: ν mass hierarchy (1)

Normal Hierarchy (NH)

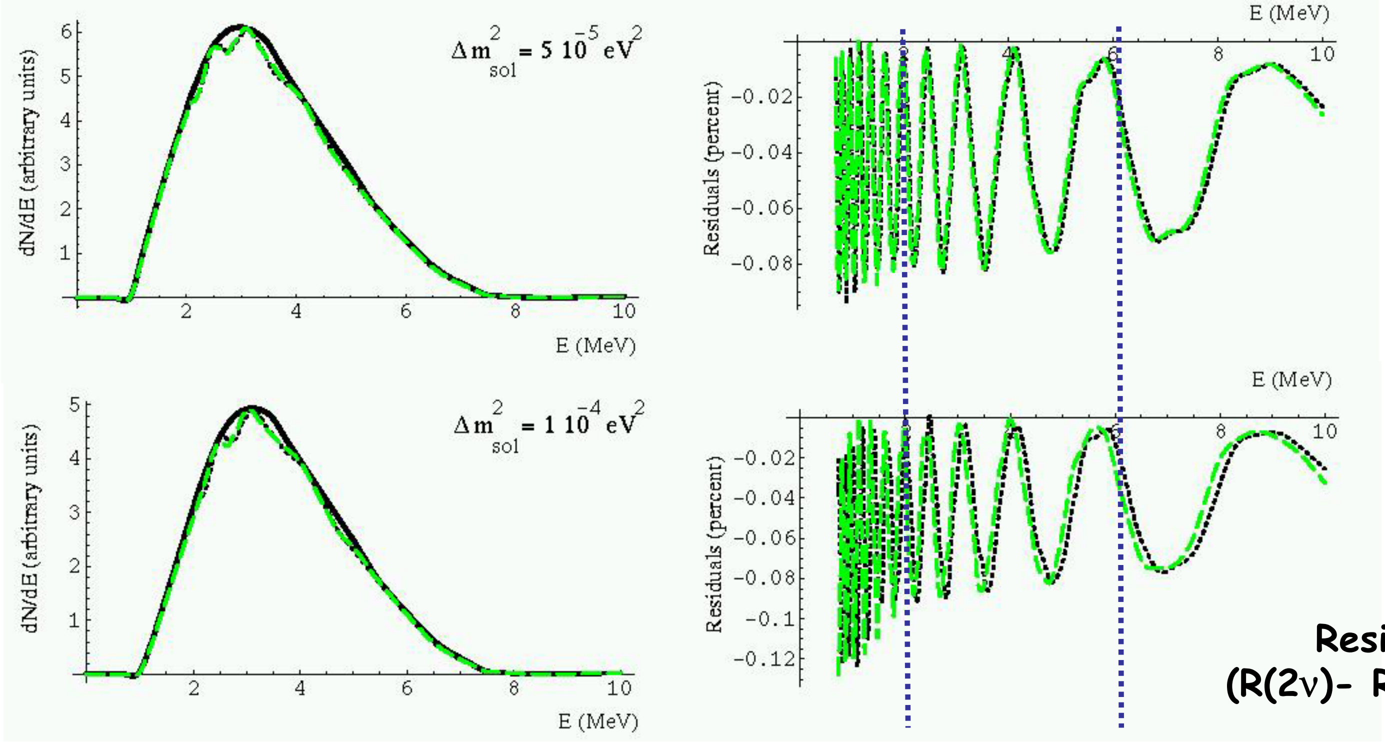
- $m_1<m_2<m_3$
- Interference term: $\sin^2(\theta_{sol})$
- constraint on $|U_{e3}|$

Inverted Hierarchy (IH)

- $m_3<m_1<m_2$
- Permutation 3→1 , 2→3, 1→2
- Interference term: $\cos^2(\theta_{sol})$
- constraint on $|U_{e1}|$

$$+2|U_{e3}|^2(1-|U_{e3}|^2)\ \begin{matrix}\sin^2(\theta_{sol})\\ \cos^2(\theta_{sol})\end{matrix}\left(\cos\left(\frac{\Delta m^2_{atm}L}{2E}-\frac{\Delta m^2_{sol}L}{2E}\right)-\cos\frac{\Delta m^2_{atm}L}{2E}\right)$$

$|U_{e3/1}|^2 = 0.04$



Residuals:
(R(2ν)- R(3ν)) / R(2ν)

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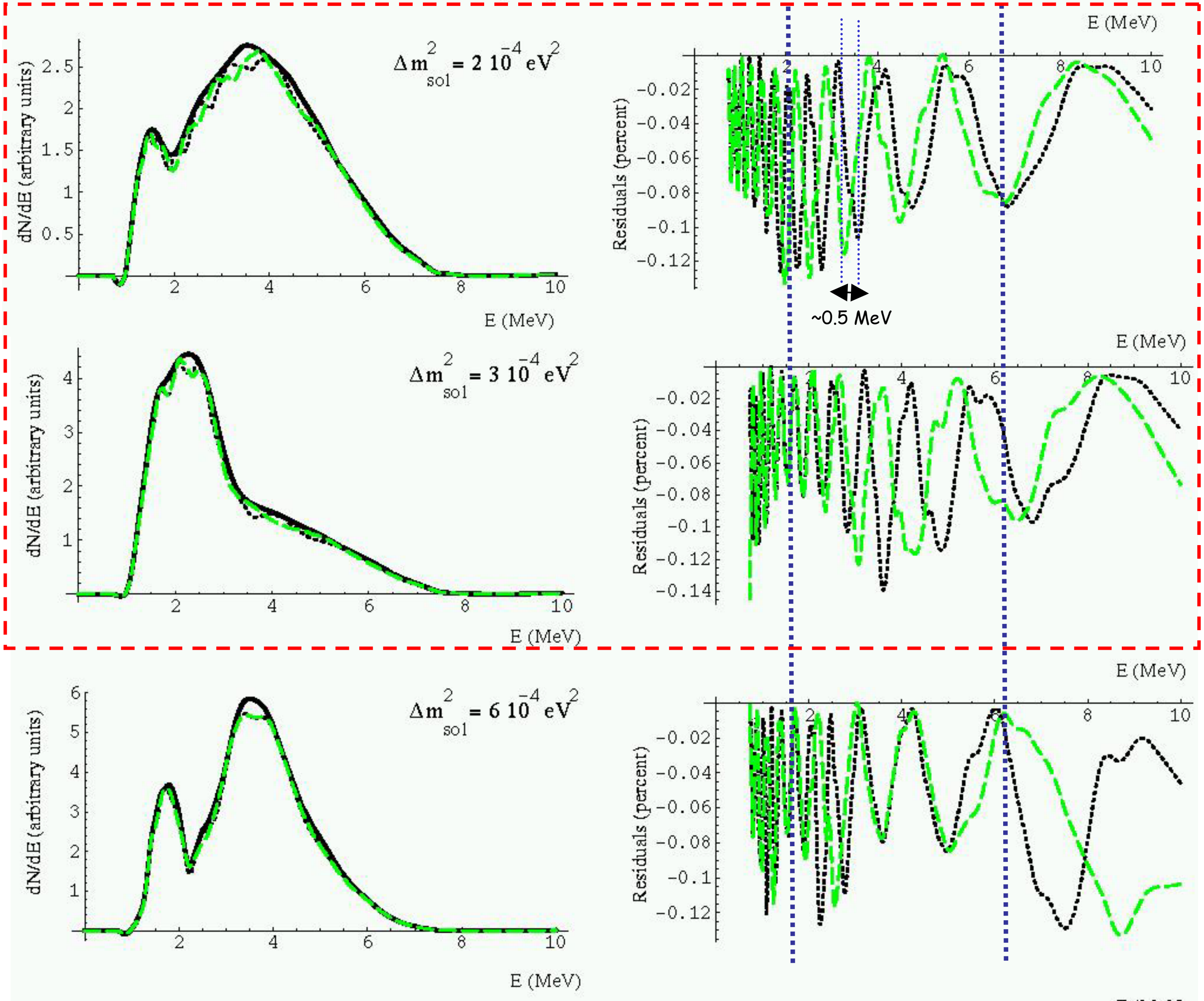
By-product 2: ν mass hierarchy (2)

Sensitive to hierarchy: ~2-4 x 10^{-4} eV²



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Physics goals & detector design

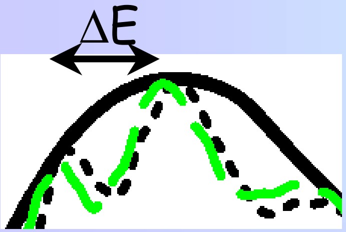
I) Accurate measurement of the solar mixing parameters

- Target size scale: ~ 5×10^{30} protons-year (~100t PXE)
- $\delta(\Delta m^2) < 5\%$ & $\delta(\sin^2 2\theta) < 5\%$ (2 sigmas)

II) By-product 1: Constraint on $|U_{e3}|$

By-product 2: Sensitivity to ν mass hierarchy ?

- Target size scale: 10^{32} protons-year for $|U_{e3}|^2$~0.01 (KamLAND scale)
- Resolve Δm^2_{atm} driven oscillations ➔ Energy resolution δE



$$\delta E < \Delta(E) = \left(\frac{a \cdot E^2_{\bar{\nu}_e}[MeV]}{1 - a \cdot E[MeV]}\right)$$

$$2\pi/a = 2.54 \cdot \Delta m^2_{atm}[eV^2] \cdot L[m]$$

@20 km

@3MeV ➔ $\delta E<0.5$ MeV
@4MeV ➔ $\delta E<1.0$ MeV
@5MeV ➔ $\delta E<1.7$ MeV

- Energy Resolution ➔ 400 pe/MeV, ~7% σ (1MeV)

***) Anti-neutrino detection free of background !

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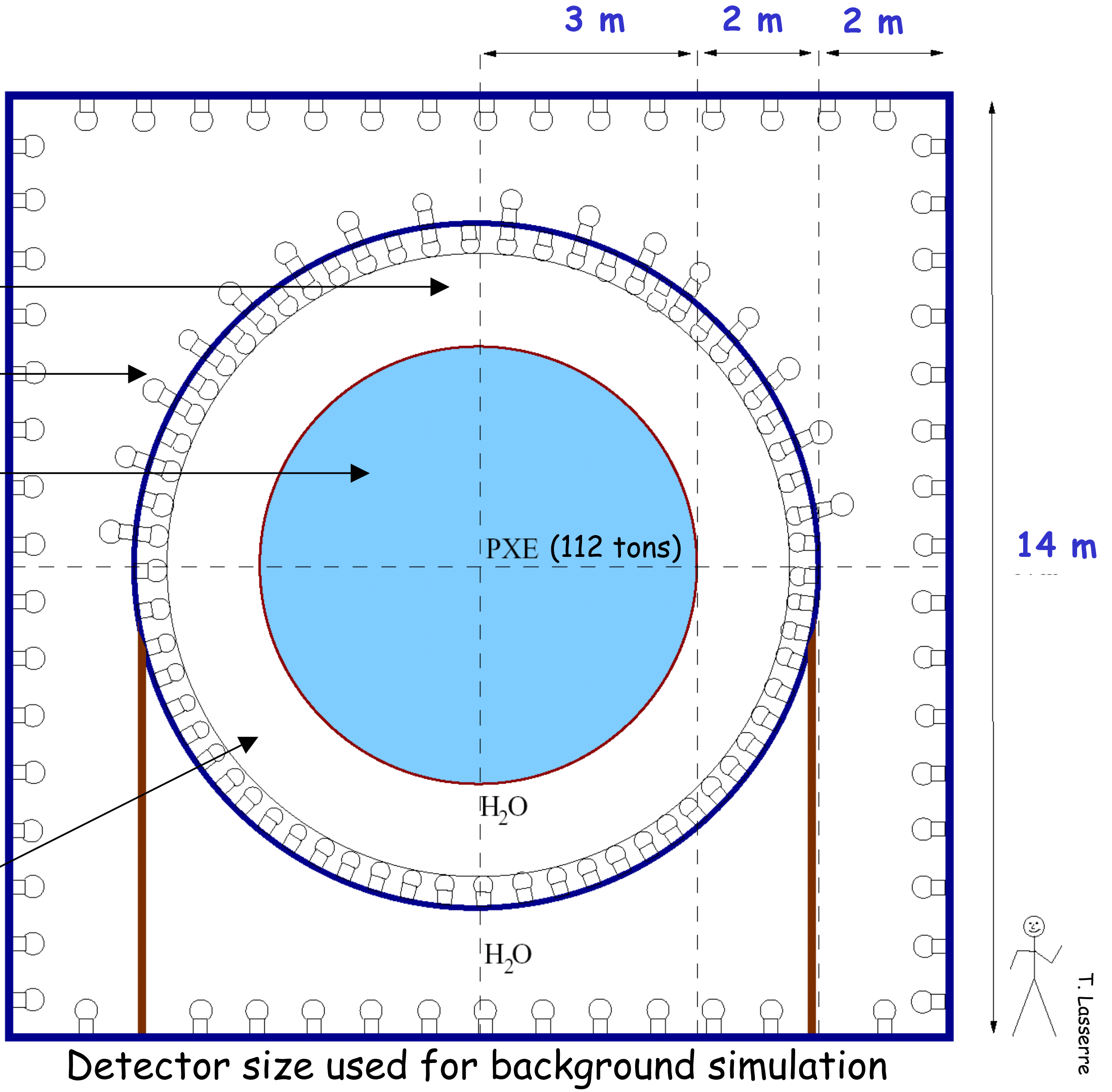
Schematic view of the detector

- **"CTF" like design**
- **Water Buffer**
- **Muon Veto**
- **Pure PXE scintillator**
  - d= 0.99 g/cm^3
  - P_{vapor}=1.4 10^{-5} kPa @20°C
  - Flash point = 149 °C
  - High LY (no Gadolinium)
  - Stable
  - Excellent PSD
  - < 10^{-17} gU/g
  - No fiducial volume
- **PMTs coverage ~30%**
  - 400 pe/MeV



Detector size used for background simulation

$\overline{\nu}_e$ detection free of background

Anti-ν_e tag: $\overline{\nu}_e + p \rightarrow e^+ + n$, ~1.8 MeV Threshold

- Prompt e+, E_P=1-8 MeV, visible energy
- Delayed neutron capture on H, E_D=2.2 MeV

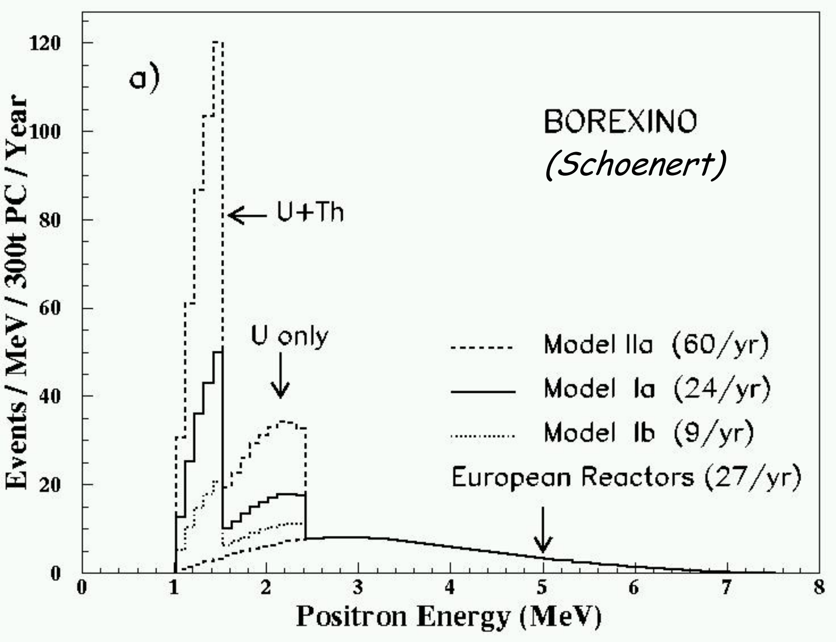
} Time correlation: $\tau \sim 200\mu$sec

Space correlation: < $1m^3$

- Prompt(β/γ) - Delayed(β/γ) → pulse shape discrimination

backgrounds

- **Geophysical anti-ν_e**
  From ^{238}U, ^{232}Th daughters
  from continental crust, mantle
  Characteristic spectrum – E_ν < 2.4 MeV
  Rate: 5-33/year/10^{31} protons (<3% reactor rate)
  Measurement @ KamLAND & BOREXINO



- **Background induced by cosmic rays** (radioactive nuclei, neutrons)
- **Background from radioactivity** (rocks, detector material, water shielding, scintillator)

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Measurement of $|U_{e3}|^2$ with an optimum reactor neutrino experiment

Working Group: S. Schönert (MPIK), K. Knoepfle (MPIK), T. Lasserre (CEA/Saclay), L. Oberauer (TUM), F. Von Feilitzch (TUM), L. Mikaelyan (RRC), V. Martemyanov (RCC), …

December 11th 2002, CERN

Current Status on $|U_{e3}|^2$ constraints

Experiment	$\sin^2(2\theta_{13})$	$\|U_{e3}\|^2$	θ_{13} (deg)	Physics
CHOOZ (95%C.L.)	<0.14	<0.036	<11	-
MINOS	<0.06	<0.015	<7.1	?
ICARUS 5 years	<0.04	<0.010	<5.8	2013 ?
OPERA 5 years	<0.06	<0.015	<7.1	2013 ?
JHF2K 3years ?	<0.006	<0.0015	<2.3	2011 ?
Kr2Det	<0.016	<0.004	<4?	?
Kashiwasaki	>0.02	>0.05	>4	?
XXX (95% C.L) *Without a near detector*	**<0.04(0.05)**	**<0.01(0.012)**	**<5.7**	**2008 ?**
XXX (95% C.L) *With a near detector*	**<0.02(0.025)**	**<0.005(0.007)**	**<2.9**	**2009 ?**

- When the C.L. are not given, upper limits correspond to 90% C.L
- $\Delta m^2_{atm} = 2.5\ 10^{-3}$ eV^2 and $\sin^2(2\theta_{atm}) = 1$
- $\sin^2(2\theta_{13}) = 4\ |U_{e3}|^2 (1 - |U_{e3}|^2)$

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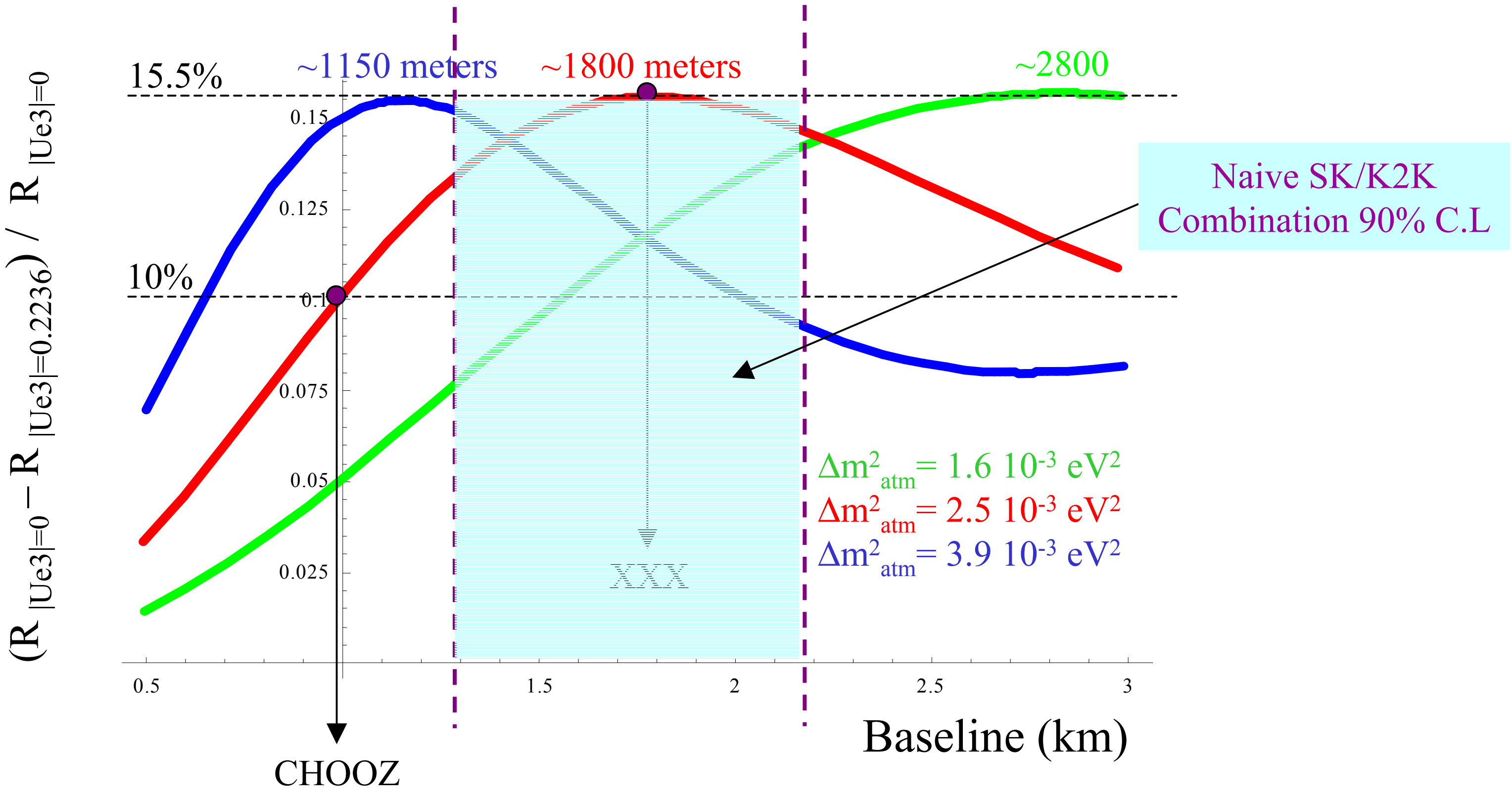
Working group meeting 1

- **Working Group:** S. Schönert (MPIK), K. Knoepfle (MPIK), T. Lasserre (CEA/Saclay), L. Oberauer (TUM), F. Von Feilitzch (TUM), L. Mikaelyan (RRC), V. Martemyanov (RCC), …

- **First Meeting:** Max-Planck Institut fuer Kernphysisk Heidelberg, 05-06 December 2002

- **Discussion:**
  - The optimum reactor experiment for $|U_{e3}|^2$ measurement
  - Sensitivity to $|U_{e3}|^2$ shape analysis & rate analysis
  - Advantages of reactor experiments & Complementarity with long baseline
  - Outline of the experimental issues ()
  - Discussion of the Kr2Det project at Krasnoyarsk (Russia)

Optimum baseline VS Δm^2_{atm}



If $\Delta m^2_{atm} = 3.9\ 10^{-3}\ eV^2$ (SK/K2K upper bound at 90% C.L) then the optimum baseline is at ~1150 meters. It shows that CHOOZ was optimised for higher Δm^2_{atm} values since Kamiokande preferred higher Δm^2_{atm} values than Super-Kamiokande? If $\Delta m^2_{atm} = 1.6\ 10^{-3}\ eV^2$ (SK/K2K lower bound at 90% C.L) then the optimum baseline is at ~2800 meters. If $\Delta m^2_{atm} = 2.5\ 10^{-3}\ eV^2$ (SK/K2K best fit value) then the optimum baseline is at ~1800 meters

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Advantages / Disavantages of a reactor experiment

- **Few MeV ν_e ➔ disappearance experiments**
  ➔ $P(\nu_e \rightarrow \nu_e)$ measurement

- **Few MeV ν_e + very short baseline**
  ➔ No matter effect contribution
  ➔ $|U_{e3}|^2$ measurement independent of sign(Δm^2_{13})

- **$|U_{e3}|^2$ measurement rather insensitive to precise values Δm^2_{12} - $|U_{e2}|^2$ (if not in the HLMA region ! or solar driven oscillation to be included – not a problem)**

- **$|U_{e3}|^2$ measurement independent of the δ-CP phase**

CLEAN constraint on $|U_{e3}|$ *independent of: sign(Δm^2_{13}) - θ_{23} - δ - Δm^2_{12} - θ_{12}*

➔ complementary with long baseline experiments

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Parameter degeneracy in LBL experiments

LBL ν_μ disappearance gives: $\sin^2(2\theta_{23}) \Rightarrow$ 2 solutions : θ_{23} & $\pi/2-\theta_{23}$
$|\Delta m^2_{13}| \Rightarrow$ 2 solutions $m_1>m_3$ or $m_3>m_1$

LBL appearance probability given by:

$$
\begin{aligned}
P(\text{anti-}\nu_\mu(\nu_\mu)\rightarrow\text{anti-}\nu_e\,(\nu_e)) \sim \;& K_1 \sin^2(\theta_{23}) \sin^2(2\,\theta_{13}) \\
& + K_2 \sin(2\theta_{23}) \sin(\theta_{13}) \,\mathrm{sign}(\Delta m^2_{31}) \cos(\delta) \\
& \pm K_3 \sin(2\theta_{23}) \sin(\theta_{13}) \sin(\delta)
\end{aligned}
$$

- K_1,K_2,K_3: known constants (within experimental error)
- dependence on $\sin(2\theta_{23})$, $\sin(\theta_{23}) \Rightarrow$ 2 solutions
- dependence on $\mathrm{sign}(\Delta m^2_{31}) \Rightarrow$ 2 solutions
- δ-CP phase can run in $[0,2\pi] \Rightarrow$ panel of solutions in general
  $\Rightarrow$ A least 2 solutions with optimal LBL, ν_μ & anti-ν_μ

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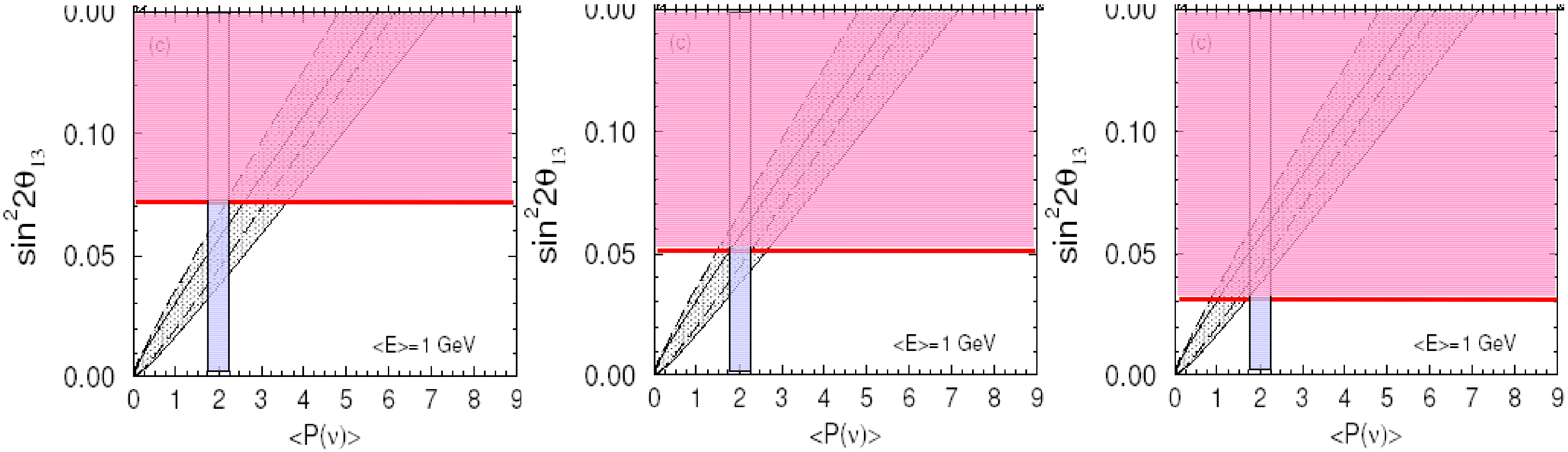
Complementarity of LBL appearance and reactor disappearance experiments

▨ Excluded by an optimal
reactor experiment (95% C.L.)

Reactor negative
LBL Positive



Reactor provides confirmation

Improvement of the upper bound

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The dream site …

- **Reactor Complex requirement:**
  - As less reactor cores as possible (or compact group of cores) ➔ only 1 near detector
  - (But) high thermal power ➔ a lots of statistics in a short time
  - With a underground cavern ~ few hundreds meters from the reactor (near detector)
  - ON/OFF cycle for efficient background suppression

- **Detector Site:**
  - Optimum baseline ➔ 1.8 km for $\Delta m^2_{atm} = 2.5\ 10^{-3}\ eV^2$
  - Underground cavern:
    - → ~ 600 mwe overburned) ➔ S/R ratio (muon background, cosmogenics, neutrons, …)
    - → Extended cavern (late baseline optimisation)
    - → Easily accessible – Existing infrastructure
  - Detector design: Low target mass (smaller → cheaper, and easier: cavity may be dig for the near detector 50t max). 2 identical detectors

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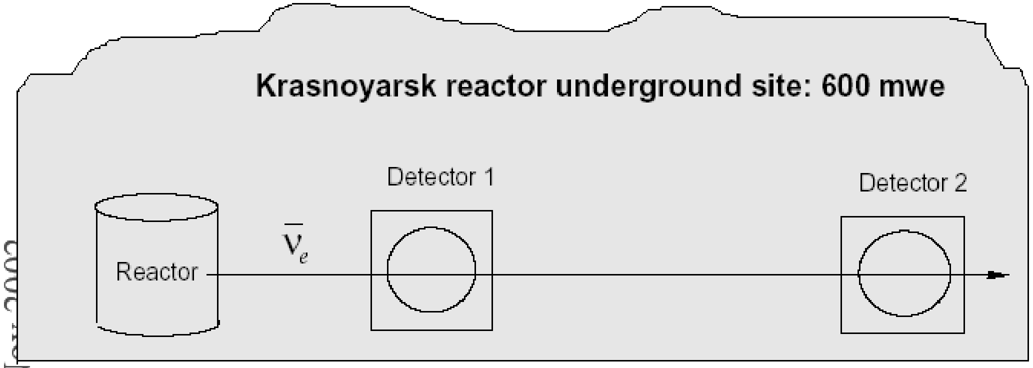
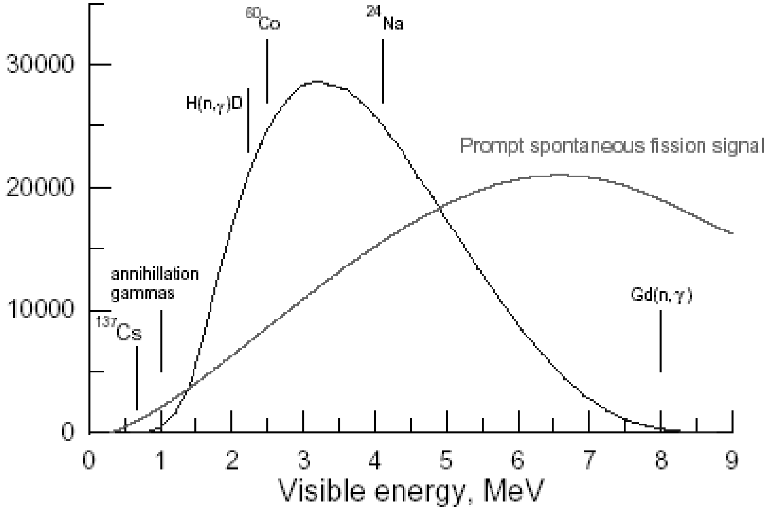
Current best site: Krasnoyarsk (Kr2Det)

V. Martemyanov, L. Mikaelyan, V. Sinev, V. Kopeikin, Y. Kozlov, Russian Research Center “Kurchatov Institute”



	115 m	**1000 m**
Target:	**46 t**	**46 t**
Rate:	**4200/day**	**55 /day**
S:B	**>>1**	**~ 10:1**



Parameter	Distance, m	Target, mass, ton	$N(e^+,n)$, day^{-1}	$N(e^+,n)$, year^{-1*}	Backgr., day^{-1}	
					correl.	accid.**
Far detector	1000	46	55	$16.5 \cdot 10^3$	5	~0.3
Near detector	115	46	4200	$12.5 \cdot 10^5$	5	~0.3

* 300 days/year at full power.

** due to internal radioactivity of the detector materials only.

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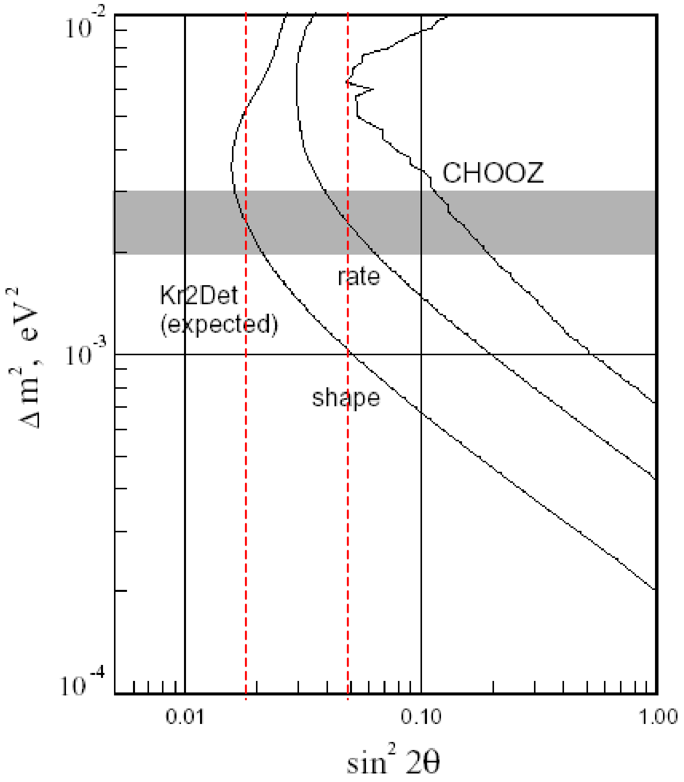
Current best site: Krasnoyarsk



$$X_{shape} = C \cdot \frac{1 - \sin^2 2\theta \cdot \sin^2\left(\frac{1.27\Delta m^2 L_{far}}{E}\right)}{1 - \sin^2 2\theta \cdot \sin^2\left(\frac{1.27\Delta m^2 L_{near}}{E}\right)}$$

$$X_{rate}(\sin^2 2\theta, \Delta m^2) = \left(\frac{L_{far}}{L_{near}}\right)^2 \cdot \left(\frac{V_{near}}{V_{far}}\right) \cdot \left(\frac{\epsilon_{near}}{\epsilon_{far}}\right) \cdot \left(\frac{N_{far}}{N_{near}}\right)$$

- **Advantages:**
  - 1 core
  - Underground reactor
  - Underground cavern (600 mwe) with 2 sites at ~100m and ~1000m
  - ON/OFF cycle for efficient background suppression: [50d/ON & 7d/OFF] cycle
  - 2 identical detectors (same overburned)
  - Available now

- **Weak points:**
  - Far detector @1000m ➔ probably not optimal
  - Only 1.6 GWth ➔ 50tons detector for 15kevents/year
  - Siberian Taiga (2x5h plane, + 2h drive …)

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Experimental challenge: reduce the systematics

Reactor experiment could be the *cheapest & fastest* only
if one demonstrates that one can reduce the systematics

σ_{sys}

- Number of protons in target ➔ few R&D effort (Balloon !) ?
- Energy scale
  - Energy scale D_{near}/D_{far}
  - Energy resolution D_{near}/D_{far}
  - Differences D_{near}/D_{far}
  - ➔ Calibration/Design
- Neutrino flux calculation
  - Reactor power
  - Fuel composition
  - Fission spectra
  - ➔ near/far detectors

Important question: which systematical error is realistically achievable ?

- CHOOZ ➔ 2.8 %
- Bugey ➔ 3.5 %
- Kr2Det ➔ 0.5 % (shape) 0.8% (rate) with a near detector
- Kashiwasaki ➔ 0.8 % with a near detector (Bugey Scaling)

Needs justification

NOT straightforward to decreadse systematics to 1% - Investigation -

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