Anomalies in Neutrino Oscillation experiments and its compatibility with Cosmology

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1. Outline

- Neutrino oscillations
- Analysis of Neutrino Experimental Data
  - Gallium experiments
  - Reactor experiments
- Neutrino as CWDM
- Conclusions

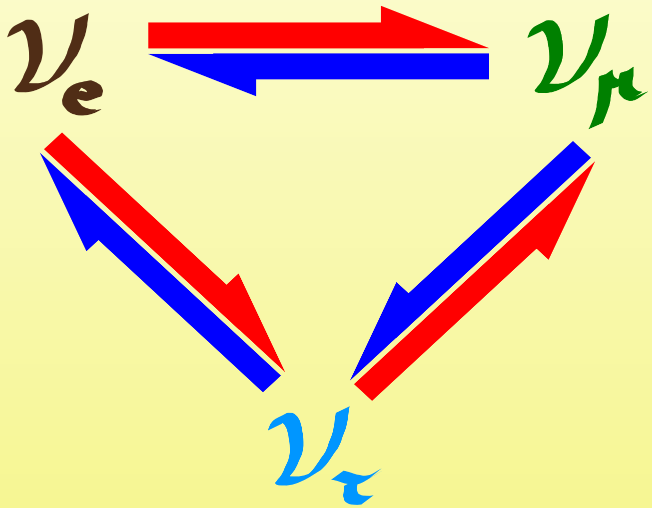
2. Neutrinos oscillations

Quantum mechanical phenomenon $\Rightarrow$ interference of different massive νs.

Oscillations between active neutrino flavors

$$\Updownarrow$$

they are **massive** and **mixed**.



We can detect νs through

- Charged- or neutral current processes ($\nu_e + {}^{71}Ga \to {}^{71}Ge + e^-$ used in gallium experiments);
- Elastic scattering $\nu + e^- \to \nu + e^-$.

Neutrinos in Cosmology $\Rightarrow$ History of the Universe and Structure formation. Particular interest in Seterile Neutrinos and the oscillation between active and sterile neutrinos.

$$\nu_\alpha \to \nu_s, \qquad \alpha = e, \mu, \tau.$$

3. Analysis of Neutrino Experimental Data

There is experimental evidence of three-neutrino mixing from solar and atmospheric neutrino experiments:

$$\Delta m^2_{\text{sol}} = (8.0^{+0.6}_{-0.4}) \times 10^{-5}\text{eV}^2 \qquad \Delta m^2_{\text{atm}} \simeq 2.74^{+0.44}_{-0.26} \times 10^{-3}\text{eV}^2$$

However... $\longrightarrow$ anomalies which can be interpreted as **exotic neutrino mixing**:

- LSND (but with MiniBOONE (low energy anomaly)...),
- Gallium radioactive source experiments $\longrightarrow$ GALLEX, SAGE.

Possible explanation: disappearance of electron neutrinos due to neutrino oscillation ($\nu_e \longrightarrow \nu_s$).

We perform the analysis of the Gallium experiment data and study the compatibility of the result with the data from other neutrino oscillation experiments: **Bugey** and **CHOOZ**

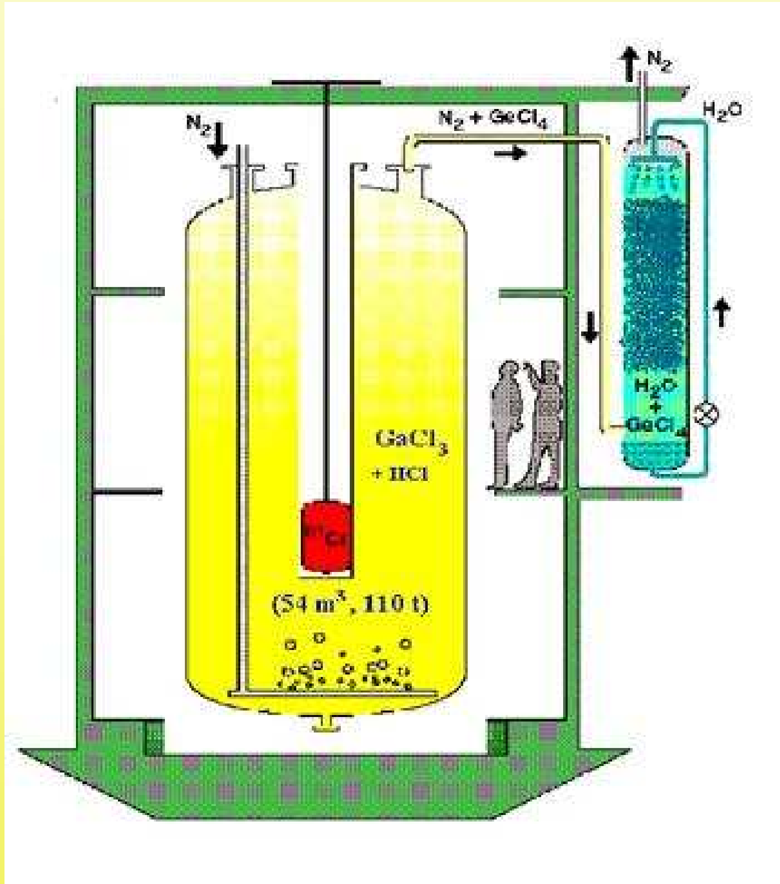
$$\Downarrow$$

Two Neutrino Mixing framework.

3.1 Ga experiments: GALLEX and SAGE

The Gallium radiactive source experiments were designed to test the GALLEX and SAGE solar neutrino detectors. Electron neutrinos come from the decay of ^{51}Cr and ^{37}Ar radioactive (placed inside the detectors) sources which decay through electron capture emiting monoenergetic ν_e detected through the reaction

$$\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + \mathrm{e}^- .$$



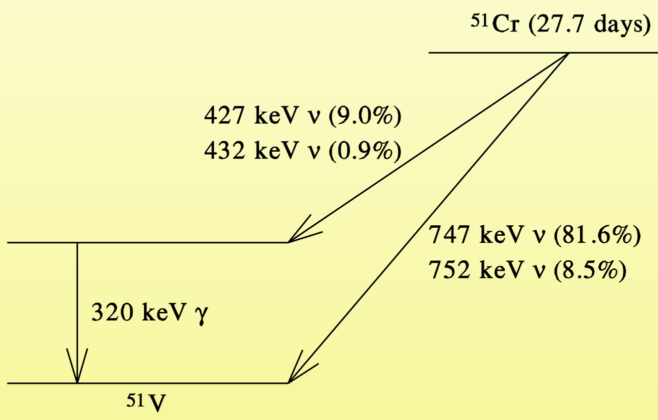
	^{51}Cr				^{37}Ar	
E(keV)	747	752	427	432	811	813
B.R. (%)	81.63	8.49	8.95	0.93	90.2	9.8

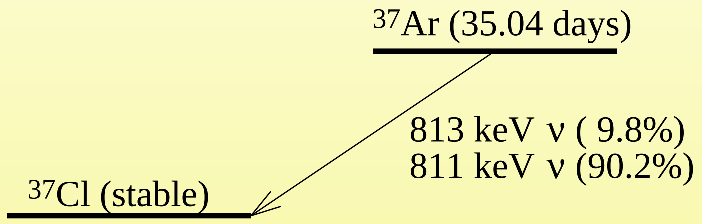
3.2 Ga experiments

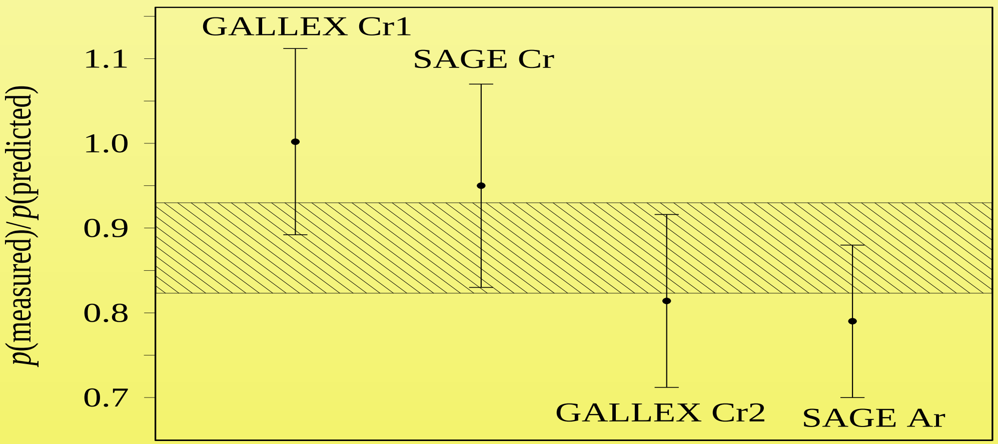
Electron capture

$$^{51}_{24}\mathbf{Cr} + \mathbf{e}^- \rightarrow \; ^{51}_{23}\mathbf{V} + \nu_e$$

$$^{37}_{18}\mathbf{Ar} + \mathbf{e}^- \rightarrow \; ^{37}_{17}\mathbf{Cl} + \nu_e$$







SAGE, PRC 73 (2006) 045805

Weighted average

$$\mathbf{R = 0.88 \pm 0.05}.$$

3.3 Ga experiments

The survival probability of electron (anti)neutrinos with energy E at a distance L from the source is

$$P_{\nu_e \to \nu_e}(L, E) = 1 - \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2(\text{eV}^2)L(\text{m})}{E(\text{MeV})}\right),$$

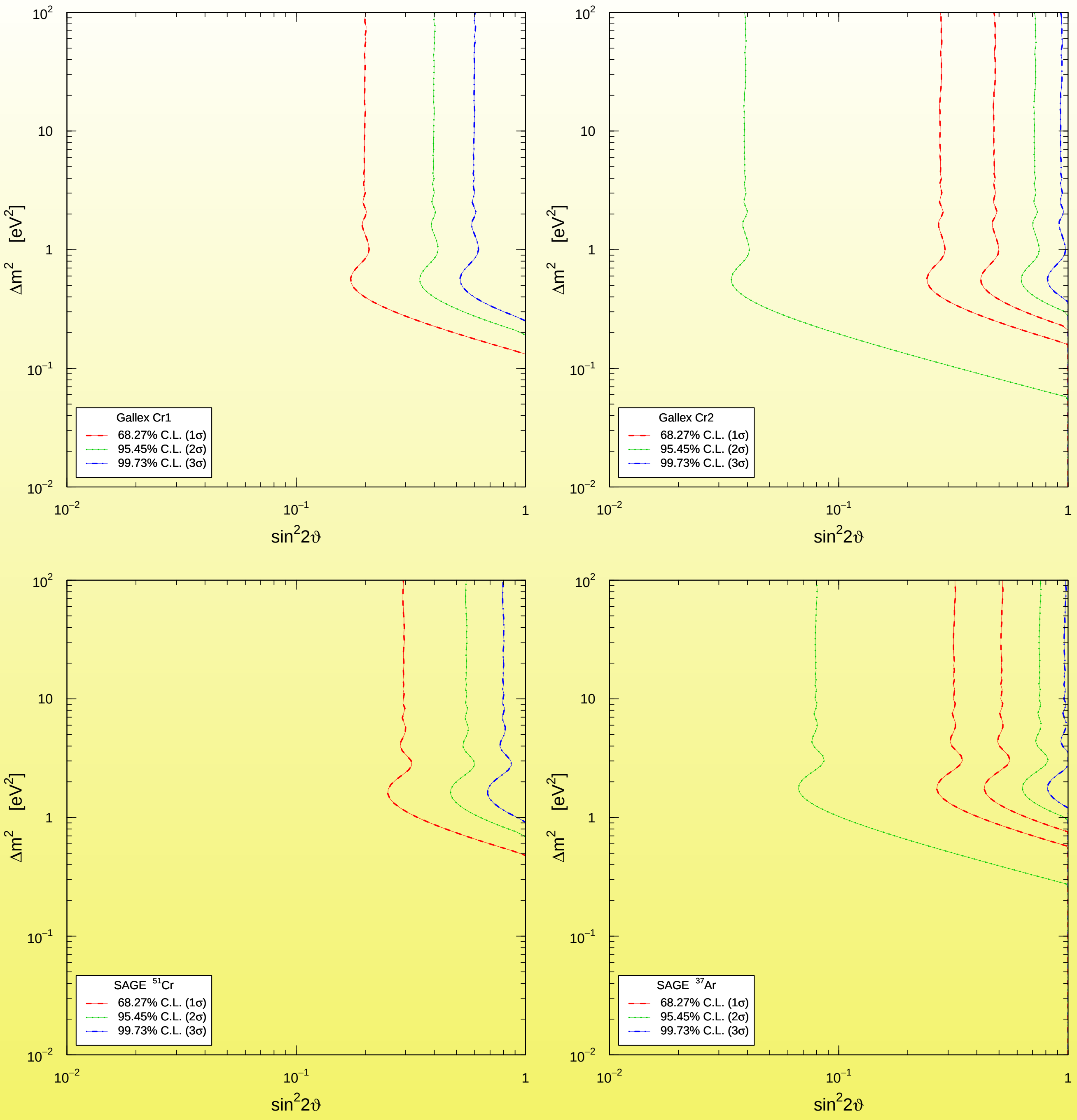
For the analysis we use the theoretical ratio, R_{th}, of the predicted ^{71}Ge production rates with and without neutrino oscillations:

$$R_{\text{th}} = \frac{\int dV\, L^{-2} \sum_i (B.R.)_i \sigma_i P_{\nu_e \to \nu_e}(L, E_i)}{\sum_i (B.R.)_i \sigma_i \int dV\, L^{-2}},$$

which is to be compared with the measured ratios.

3.4 Ga experiments

Individual analysis: 2σ allowed bands for GALLEX-Cr2 and SAGE ^{37}Ar, with $\mathbf{\Delta m^2 \gtrsim 1\,eV^2}$.



3.5 Ga experiments

Combined least-squares analysis for the Gallium experiments. It shows a 1σ allowed region, and we find

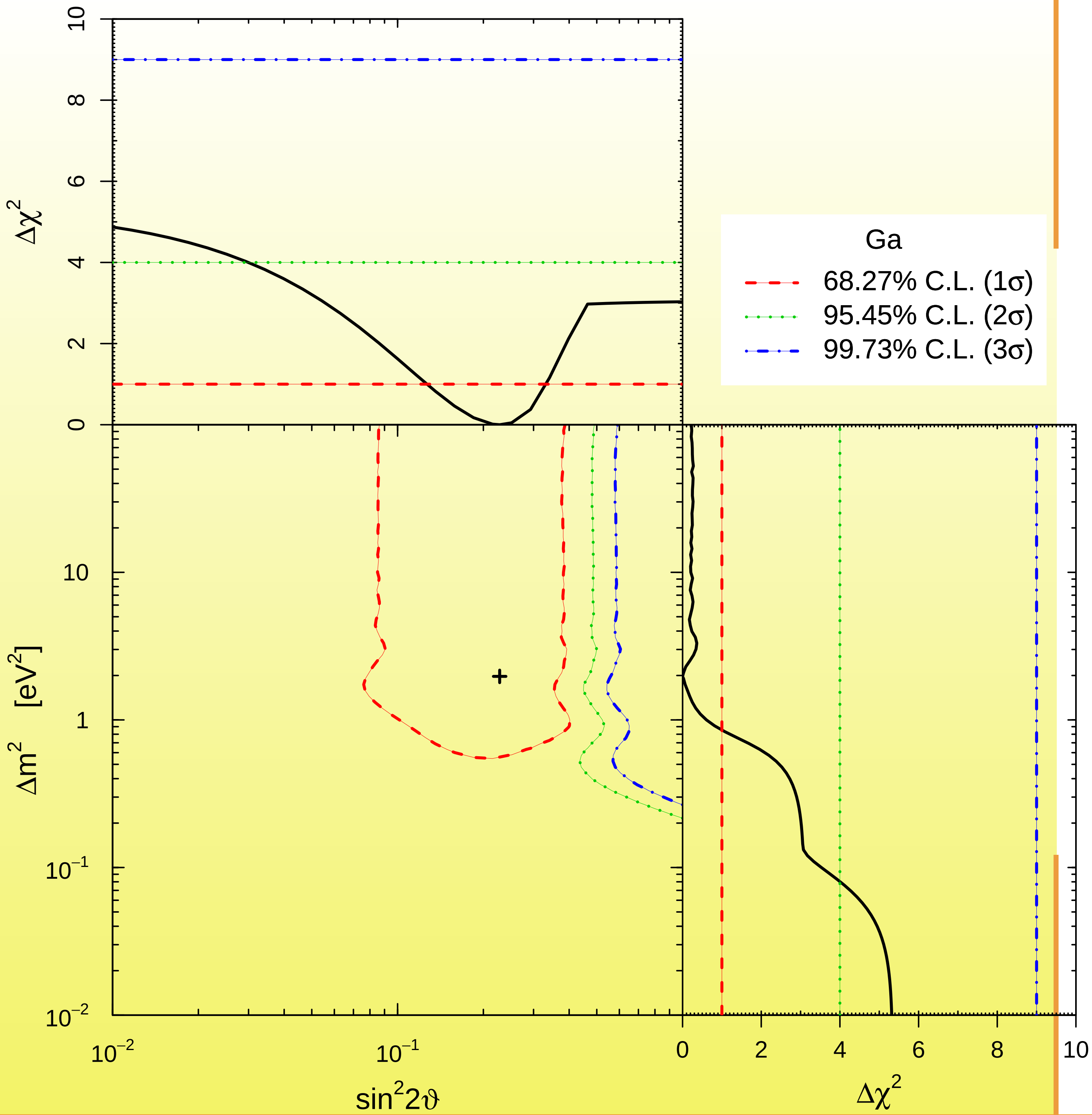
$$\mathbf{\Delta m^2_{bf} = 2.00\,eV^2}$$

$$\sin^2(2\theta)_{bf} = 0.23$$

and at 1σ (68.27 % C.L.)

$$\mathbf{\Delta m^2 > 0.90\,eV^2}$$

$$\sin^2(2\theta)_{bf} = 0.13 - 0.34$$

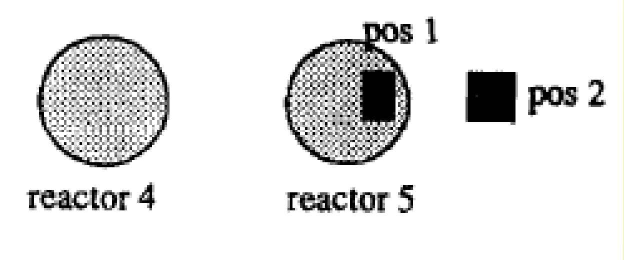


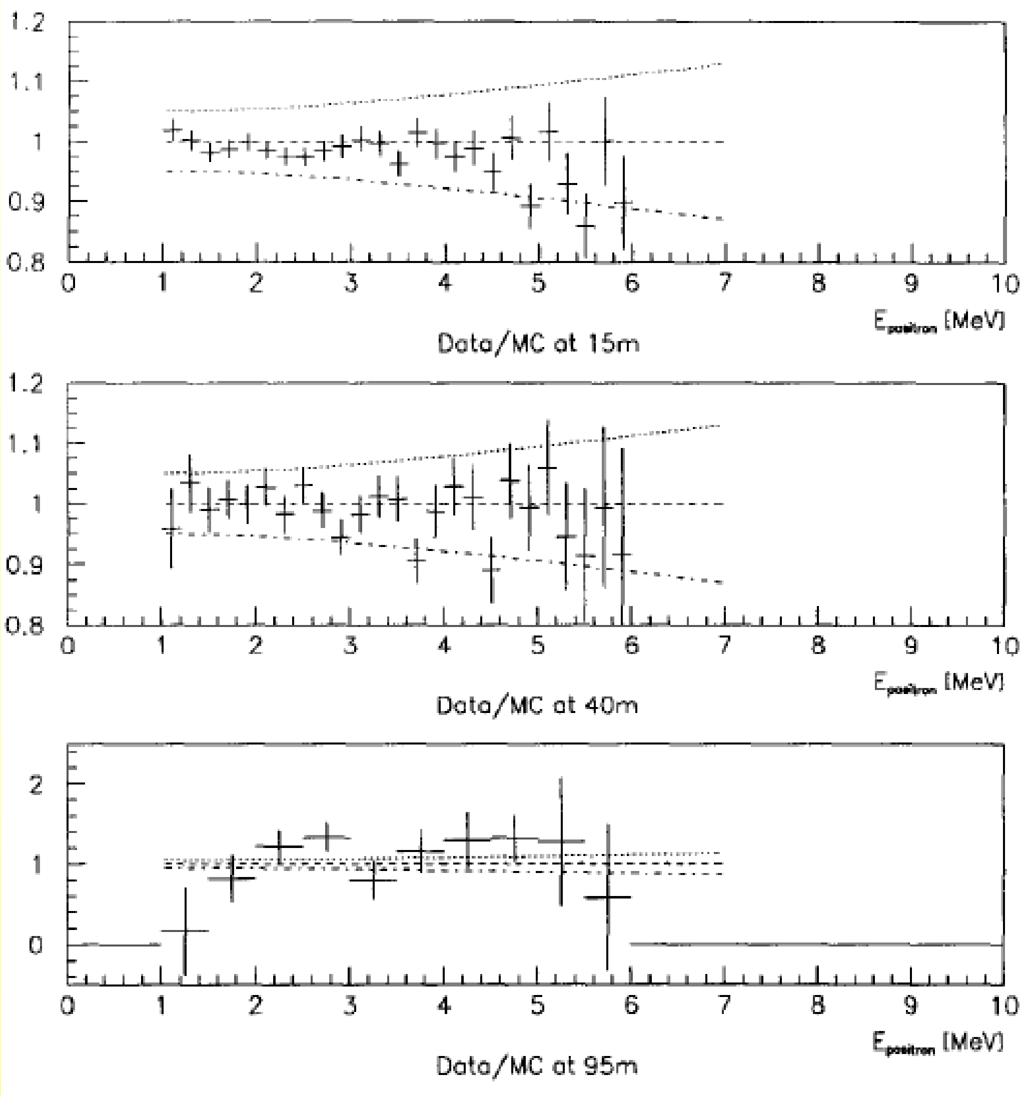
4. Reactor experiments

Electron antineutrino detected through the inverse beta decay process

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

with the energy relation $E_\nu = E_{e^+} + 1.8$MeV.
The **Bugey** experiment searches for $\bar{\nu}_e$ disappearance at the three distances ($L_j = 15, 40, 95$ m) and collected $N_j = 25, 25, 10$ (for $j = 1, 2, 3$) energy bins (data).





Bugey, NPB 434 (1995) 503

4.1 Bugey analysis

We analize the data using the χ^2 function given by

$$\chi^2 = \sum_{j=1}^{3} \left\{ \sum_{i=1}^{N_j} \frac{\left[(A a_j + b(E_{ji} - E_0)) R_{ji}^{\text{the}} - R_{ij}^{\text{exp}}\right]^2}{\sigma_{ji}^2} + \frac{(a_j - 1)^2}{\sigma_{a_j}^2} \right\} + \frac{(A-1)^2}{\sigma_A^2} + \frac{b^2}{\sigma_b^2};$$

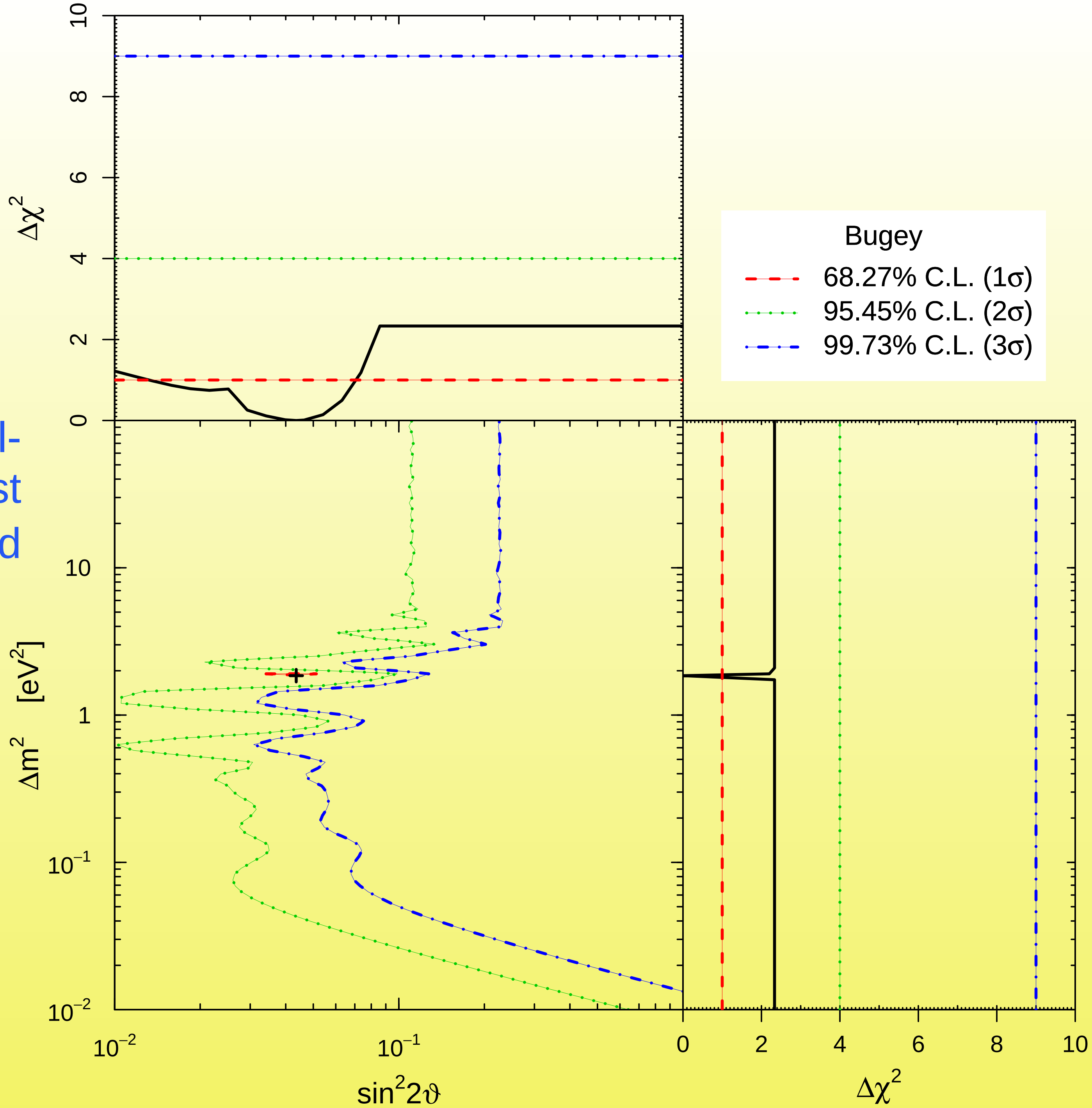
the coeficients $(A a_j + b(E_{ji} - E_0))$ are introduced to take into account the systematic uncertainty of the positron energy calibration.

$$R_{ji}^{\text{the}} = \frac{\int dL L^{-2} \int_{E_{ji}-\Delta E_j/2}^{E_{ji}+\Delta E_j/2} dE \int_{-\infty}^{+\infty} dT_e F(E, T_e) P_{\bar{\nu}_e \to \bar{\nu}_e}(L, E_\nu)}{\Delta E_j \int dL L^{-2}};$$

$F(E, T_e)$ is the energy resolution function, considered as a Gaussian function with standard deviation $0.06\sqrt{4.2\,E(\text{MeV})}$.

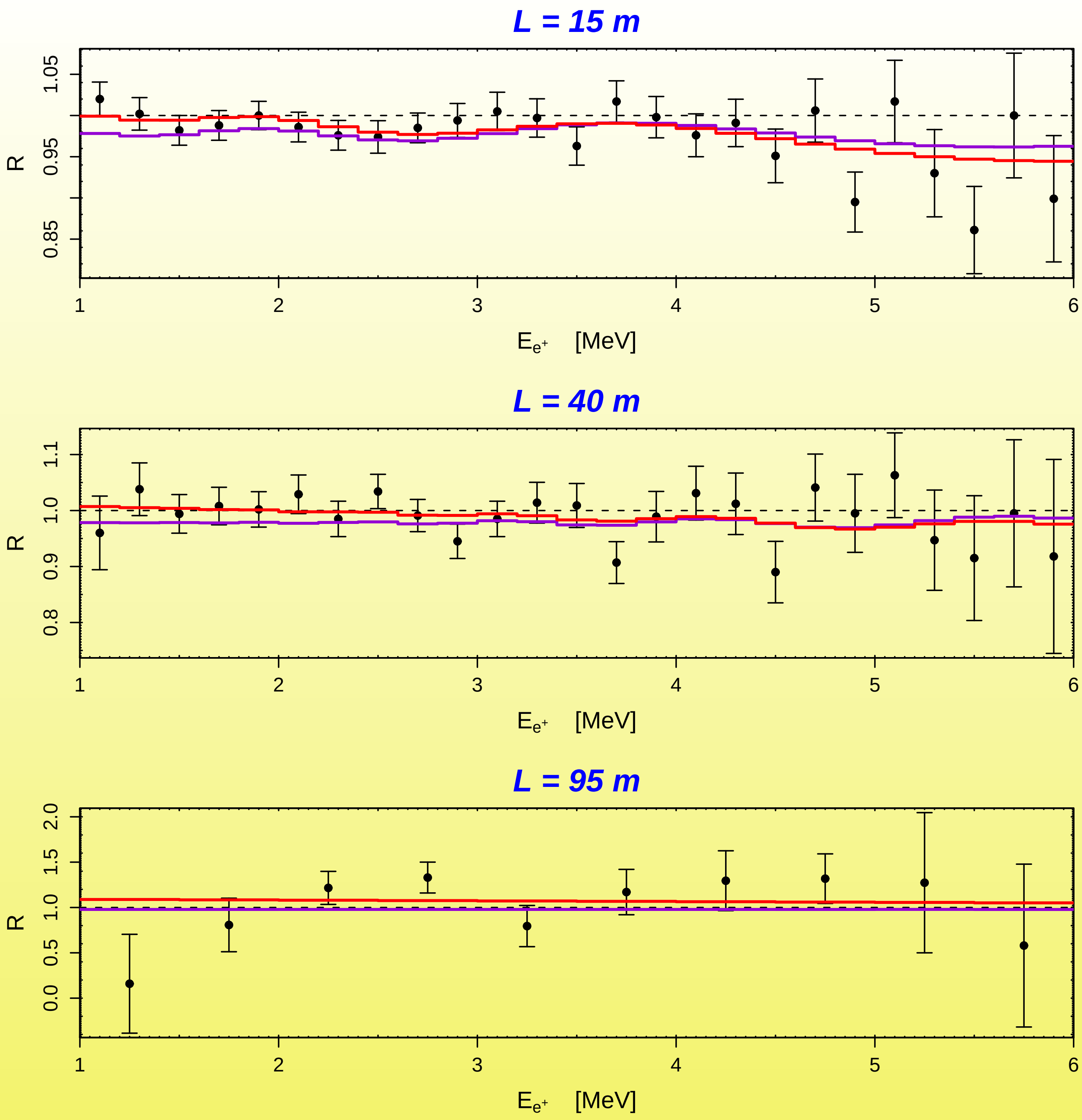
4.2 Bugey

We find a narrow 1σ allowed region with the best fit at $\Delta m^2 = 1.85 eV^2$ and $\sin^2 2\theta = 0.043$



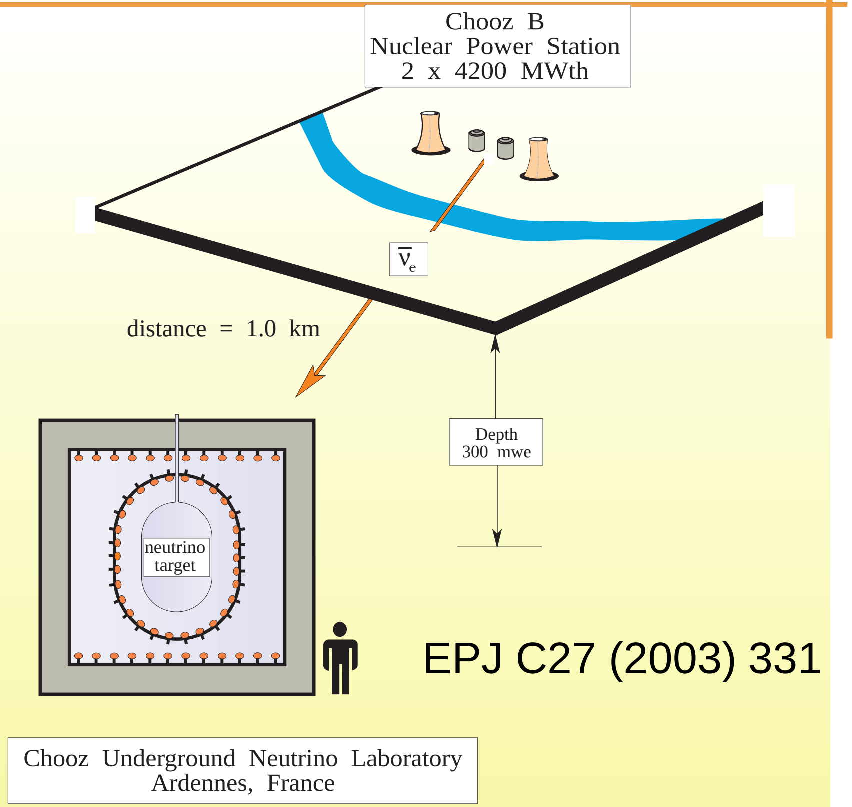
4.3 Bugey spectra

Histogram relative to the best fit against the Bugey experimental data.



4.4 Chooz

The ratio of the number of observed to the expected events (in absence of oscillations) is $R_{\text{Chooz}} = 1.01 \pm 0.04$.



EPJ C27 (2003) 331

$$P_{\nu_e\to\nu_e}(L,E) = 1-\sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2(eV^2)L(m)}{E(MeV)}\right)$$

average to

$$\langle P_{\bar{\nu}_e\to\bar{\nu}_e}\rangle = 1 - \frac{1}{2}\sin^2 2\theta,$$

Experiment	L	E	Δm^2
Bugey (SBL)	$\sim$ 10 m	$\sim$ 1 MeV	$\sim$ 0.1 eV^2
Chooz (LBL)	$\sim$ 1 km	$\sim$ 1 MeV	$\sim 10^{-3}$ eV^2

Which is then combined with the previous analysis, excluding values of $\sin^2(2\theta) \gtrsim 0.1$ for $\Delta m^2 \lesssim 3\times10^{-2}$, where Bugey is not sensitive.

4.5 Combined Fit

The combined analisys confirms the weak indication in favor of neutrino oscillations with

$$\mathbf{\Delta m^2 \simeq 1.85eV^2}$$

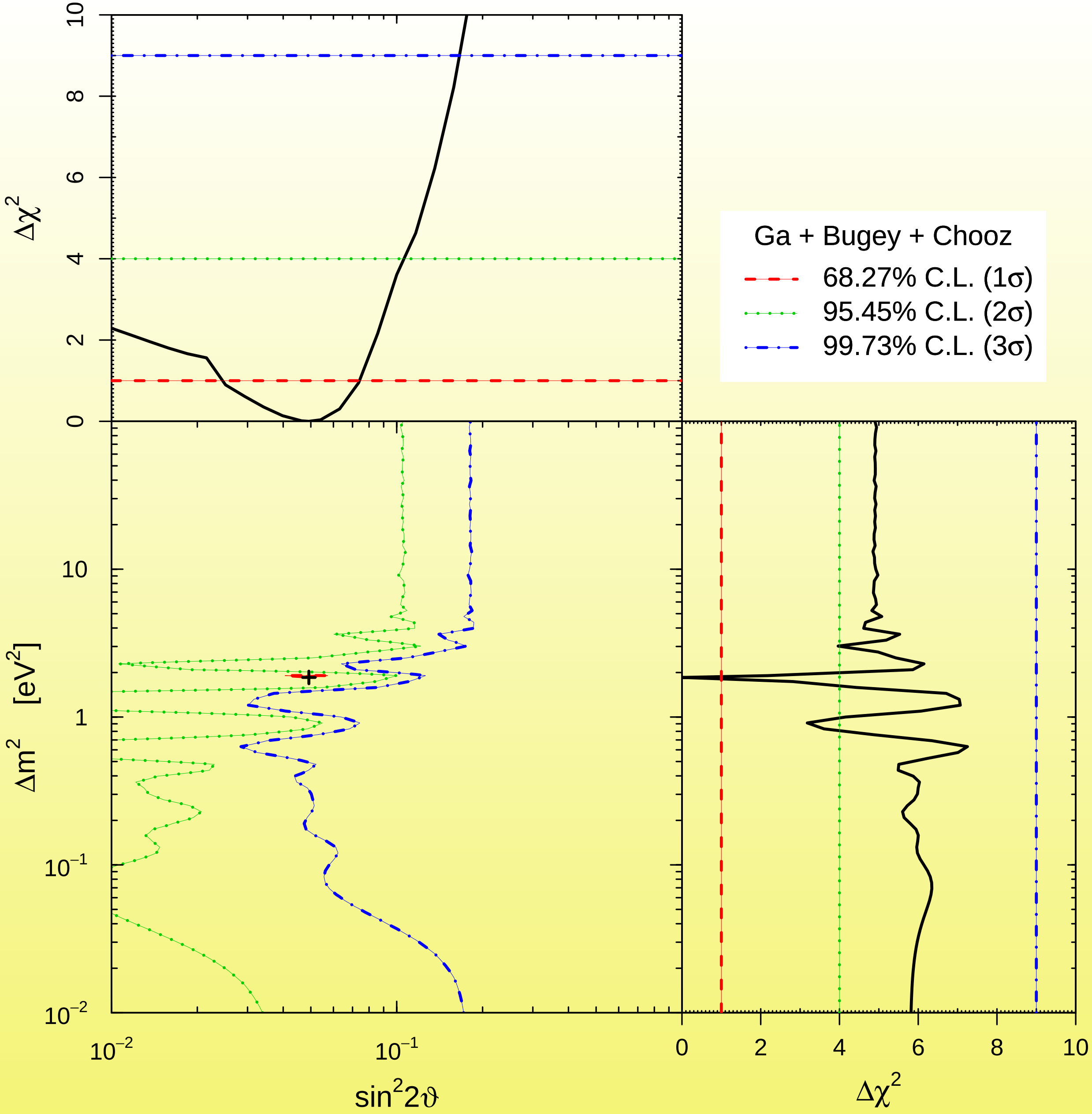
and

$$\mathbf{0.03 \lesssim \sin^2 2\theta \lesssim 0.07}.$$

Our Best Fit:

$$\chi^2_{\text{min}} = 53.40,$$

$$\sin^2 2\theta = 0.05 \quad \Delta m^2 = 1.85\text{eV}^2.$$



5. Sterile Neutrino from Cosmology

- Our results $\rightarrow \Delta m^2 \sim 1.8$ev^2
- Results from analysis of LSND+Gallium experiments $\rightarrow$ $\Delta m^2 = 20 - 30$ev^2
- Scenarios in which cosmological bounds on neutrino parameters are evaded
  - Low Reheating temperature (T_R) Universe

MOTIVATIONS

Light sterile neutrino in Cosmology: physical effects.

Analysis using cosmological experimental data with CosmoMC.

5.1 Sterile Neutrino: parameters

Parameters to study:

- ΔN_{eff}: contribution to the relativistic density,
- $\omega_s = \Omega_s h^2$: current energy density,
- $\langle v_s \rangle$: average velocity of the particles.

All of them depending on the form of the phase-space distribution function $f(p)$.

6. Conclusions

- From Gallium experiments, **we found a possible indication of $\nu_e \to \nu_s$ oscillation** with $\sin^2 2\theta \gtrsim 0.03$ and $\Delta m^2 \gtrsim 0.1$ eV^2.
- The Bugey data present a **weak indication in favor of neutrino oscillations** with $0.01 \lesssim \sin^2 2\theta \lesssim 0.07$ and $1.8 \lesssim \Delta m^2 \lesssim 1.9$ eV^2.
- The combined analysis of the Gallium, Bugey and CHOOZ data, the **weak indication persists**, with **compatible results** with the Bugey and CHOOZ reactor experiments.

Work published:
M.A.A., C. Giunti, M. Laveder, ***Limits on ν_e and $\bar{\nu}_e$ disappearance from Gallium and reactor experiments***, `arXiv:0711.4222`.

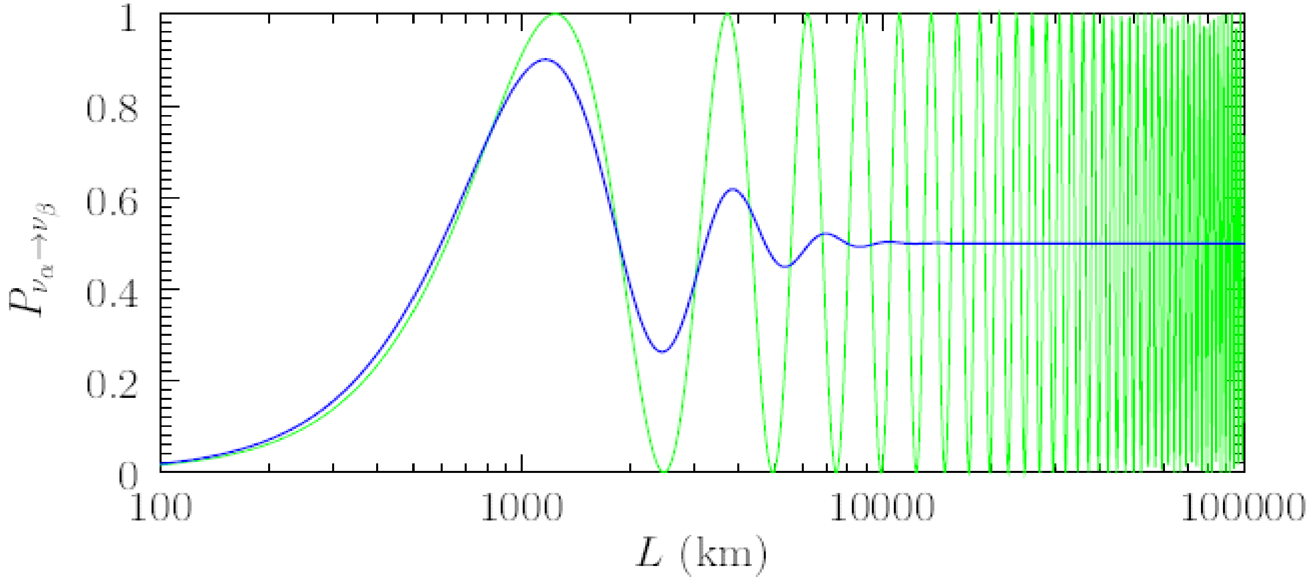
Future work

- Extending the data analysis including some other reactor experiments:
  - Chooz (complete analysis)
  - Savannah River Site (S.R.S.)
  - Institute Laue Langevin (I.L.L.)
  - Gösgen
- Concluding (and publishing) work on sterile neutrinos

Thanks!

Average over Energy Resolution of the Detector

$$P_{\nu_\alpha \to \nu_\beta}(L,E) = \sin^2 2\vartheta \sin^2\left(\frac{\Delta m^2 L}{4E}\right) = \frac{1}{2}\sin^2 2\vartheta \left[1 - \cos\left(\frac{\Delta m^2 L}{2E}\right)\right]$$



$\Delta m^2 = 10^{-3}\,\text{eV}$ $\quad \sin^2 2\vartheta = 1$ $\quad \langle E \rangle = 1\,\text{GeV}$ $\quad \Delta E = 0.2\,\text{GeV}$

$$\langle P_{\nu_\alpha \to \nu_\beta}(L,E)\rangle = \frac{1}{2}\sin^2 2\vartheta \left[1 - \int \cos\left(\frac{\Delta m^2 L}{2E}\right)\phi(E)\,dE\right] \qquad (\alpha \neq \beta)$$

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