Present status and perspectives of neutrino oscillation phenomenology

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I. Present status of neutrino oscillations

- *Interpretation of the experimental data*
- *Global analysis in a 3ν scenario*

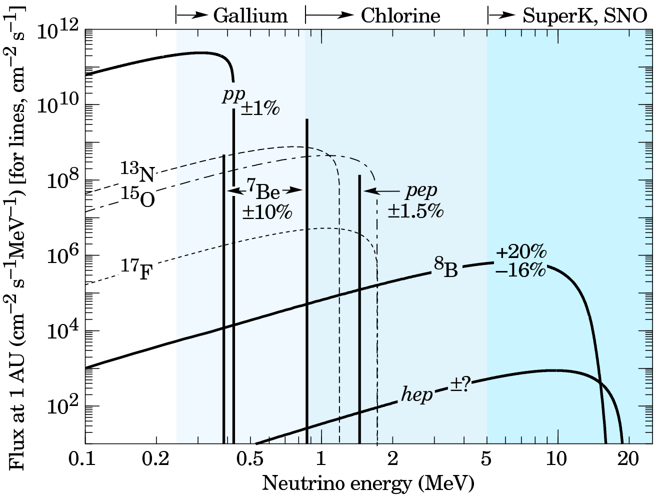
II. Potentialities of future experiments

- *Man-made neutrino experiments*
- *Natural-source neutrino detectors*
- *The role of New Physics*

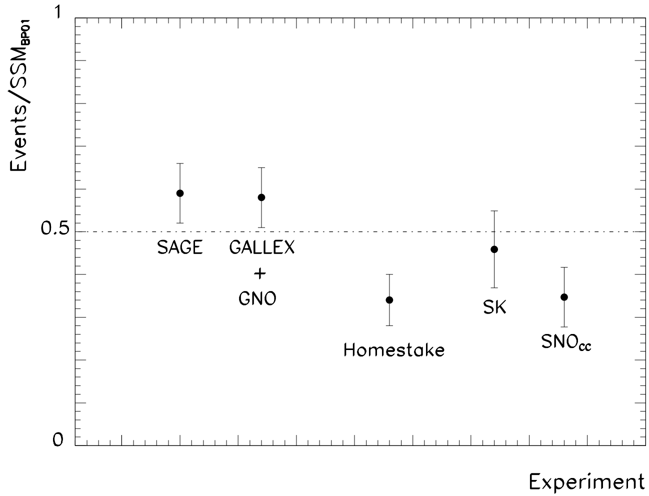
Conclusions

Solar Neutrino Oscillations

- **Problem**: disagreement between **expected** and **observed** fluxes of ν_e from the Sun:



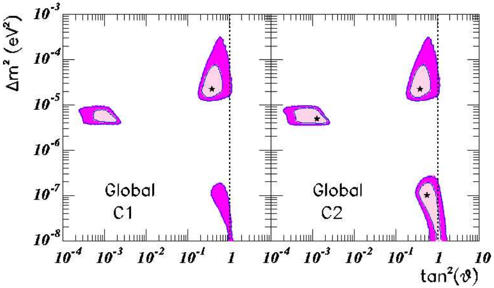
$\not\Leftrightarrow$



- **Solution**: flavor conversion ($\nu_e \to \nu_{\mu,\tau}$) during the flight from **source** to **detector**:

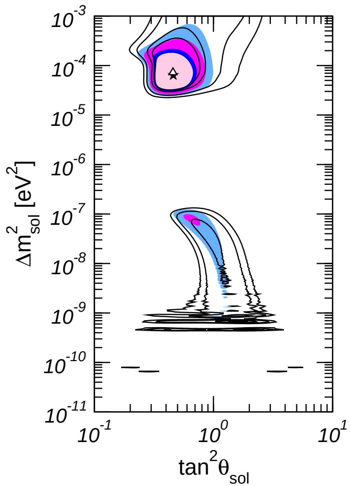
$$i\frac{d\vec{\nu}}{dt} = \left[\frac{\Delta m^2}{4E_\nu} \begin{pmatrix} -\cos 2\theta & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{pmatrix} \pm \sqrt{2}G_F \begin{pmatrix} N_e & 0 \\ 0 & 0 \end{pmatrix} \right] \vec{\nu}, \quad \text{with} \quad \vec{\nu} = \begin{pmatrix} \nu_e \\ \nu_a \end{pmatrix}.$$

Solar neutrinos: keystones in the new millennium

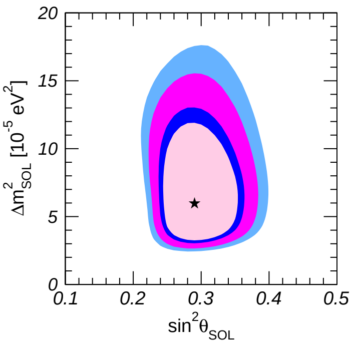


- **April 2000**: **LMA**, **SMA**, **LOW**, **VAC**, sterile, . . .
  [Gonzalez-Garcia, Peña-Garay, hep-ph/0002186]

- **June 2001**: SNO-I data (241 days, CC only, no spectrum):
  - ⇒ **Flavor conversion established**;
  - ⇒ **SMA** and sterile disfavored.



- **April 2002**: SNO-I data (306 days, CC/NC/ES spectrum+DN):
  - ⇒ **SMA** and sterile disappear.

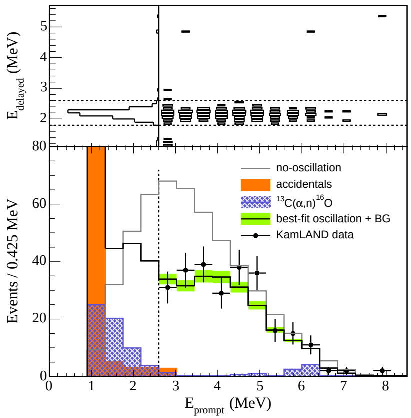


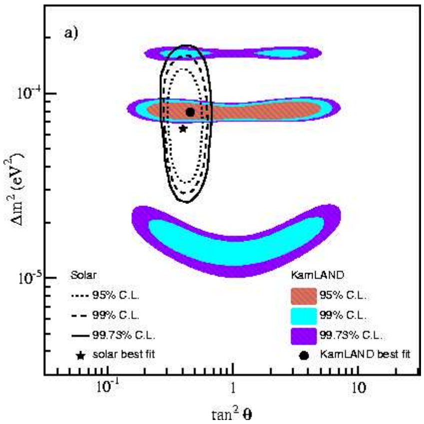
- **September 2003**: SNO-II data (CC/NC/ES):
  - ⇒ **Solar neutrino problem solved**;
  - ⇒ **LMA** singled out (by solar data alone);
  - ⇒ maximal mixing ($\theta_{sol} = 45^\circ$) excluded;

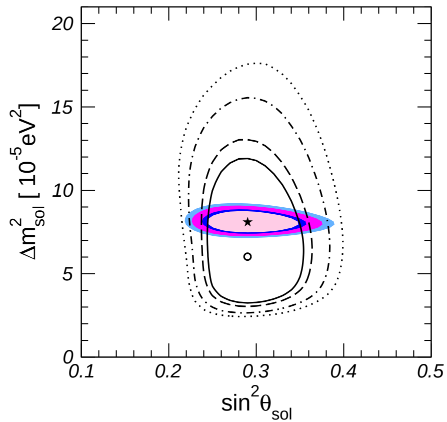
- **February 2005**: SNO-II data (CC/NC/ES spectrum+DN):
  - ⇒ solar solution stable; new data have no significant impact.

The KamLAND experiment

- *Evidence* of $\bar{\nu}_e$ disappearance ($E_{\text{vis}} > 2.6$ MeV, average length ≈ 180 km);
  CPT conservation $\Rightarrow$ same osc. channel as solar data $\Rightarrow$ same parameters (Δm^2_{sol}, θ_{sol}).
- **December 2002**: first data release (86.8 events expected, 54 observed):
  $\Rightarrow$ **LMA solution singled out**, and split into **LMA-I** and **LMA-II**;
- **June 2004**: second data release (365.2 events expected, 258 observed):
  $\Rightarrow$ **LMA-II** disappears, only one solution remains.

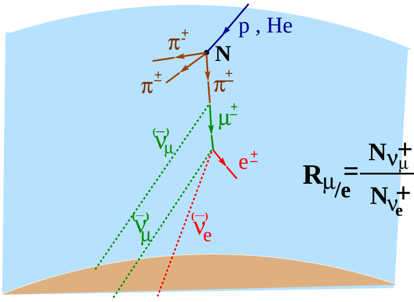




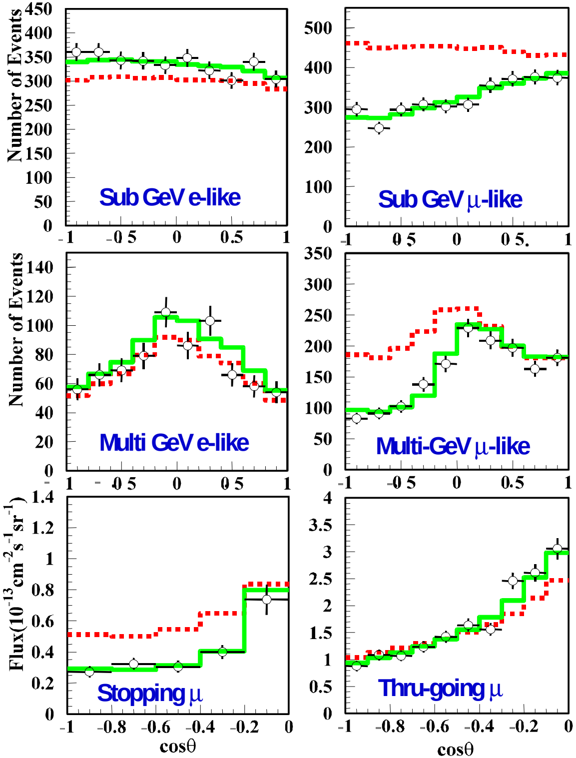


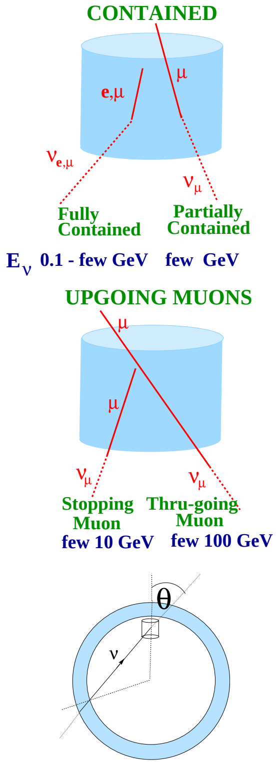
Atmospheric neutrino oscillations

- **Problem**: disagreement between **expected** and **observed** fluxes of atmospheric ν_μ:



$$R_{\mu/e} = \frac{N_{\nu_\mu} + N_{\bar\nu_\mu}}{N_{\nu_e} + N_{\bar\nu_e}} \sim 2 \quad \not\approx$$



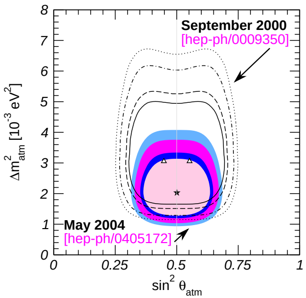


- **Solution**: flavor conversion ($\nu_\mu \to \nu_\tau$) during the flight from **source** to **detector**:

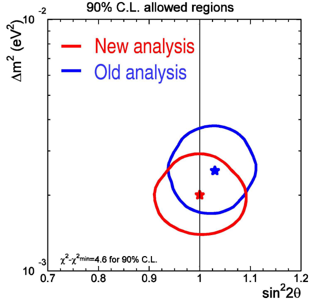
$$i\frac{d\vec{\nu}}{dt} = \frac{\Delta m^2}{4E_\nu}\begin{pmatrix} -\cos 2\theta & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{pmatrix}\vec{\nu},$$

with $\vec{\nu} = \begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix}$.

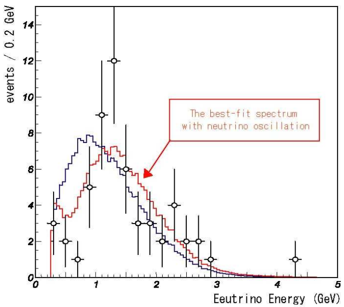
Progress in ATM & K2K data

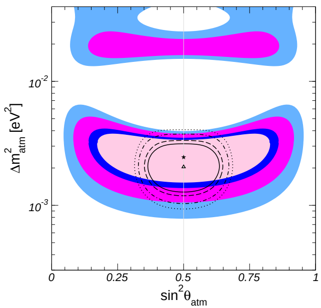


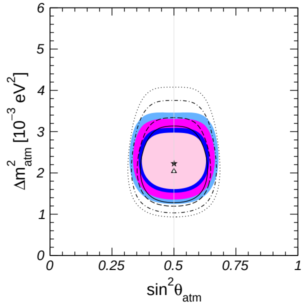
- Progress in ATM neutrinos mostly limited to increase in statistics; shift in Δm^2_{atm} due to improved calculation of ATM fluxes (1D $\longrightarrow$ 3D);
- K2K: accelerator experiment (length ≈ 250 km, $\langle E_\nu \rangle \approx 1.3$ GeV); search for ν_μ disappearance:
  - **release I**: 44 single-ring μ-like events expected, 29 observed;
  - **release II**: 88 single-ring μ-like events expected, 56 observed;



$\Rightarrow$ same osc. channel as ATM data $\Rightarrow$ same param. (Δm^2_{atm}, θ_{atm}).







Three neutrino oscillations

- $2\nu \to 3\nu$: $(\Delta m^2_{\rm sol}, \theta_{\rm sol}) \to (\Delta m^2_{21}, \theta_{12})$, $(\Delta m^2_{\rm atm}, \theta_{\rm atm}) \to (\Delta m^2_{32}, \theta_{21})$, $\theta_{\rm rea} \to \theta_{13}$, new $\delta_{\rm CP}$:

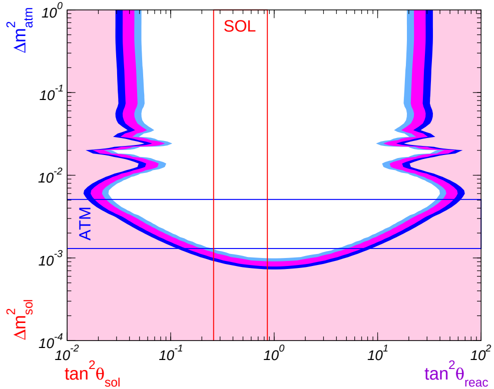
$$i\frac{d\vec{\nu}}{dt} = \mathbf{H}\vec{\nu}; \qquad \mathbf{H} = \mathbf{O}\cdot\mathbf{H}_0^d\cdot\mathbf{O}^\dagger + \mathbf{V};$$

$$\mathbf{O} = \begin{pmatrix} c_{12}\,c_{13} & s_{12}\,c_{13} & s_{13}\,e^{-i\delta_{\rm CP}} \\ -s_{12}\,c_{23} - c_{12}\,s_{13}\,s_{23}\,e^{i\delta_{\rm CP}} & c_{12}\,c_{23} - s_{12}\,s_{13}\,s_{23}\,e^{i\delta_{\rm CP}} & c_{13}\,s_{23} \\ s_{12}\,s_{23} - c_{12}\,s_{13}\,c_{23}\,e^{i\delta_{\rm CP}} & -c_{12}\,s_{23} - s_{12}\,s_{13}\,c_{23}\,e^{i\delta_{\rm CP}} & c_{13}\,c_{23} \end{pmatrix}, \qquad \vec{\nu} = \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix};$$

$$\mathbf{H}_0^d = \frac{1}{2E_\nu}\mathbf{diag}\left(-\Delta m^2_{21}, 0, \Delta m^2_{32}\right); \qquad \mathbf{V} = \mathbf{diag}\left(\pm\sqrt{2}G_F N_e, 0, 0\right).$$

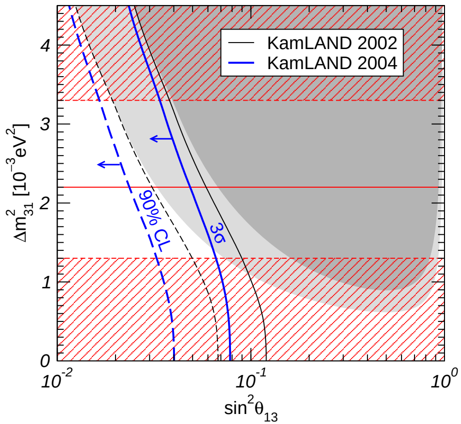
The hierarchy approximation

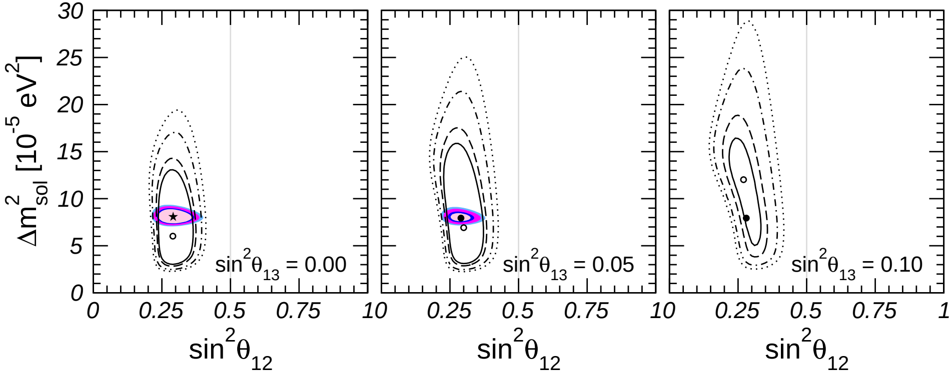
- From SOL and ATM data, we have $\Delta m^2_{21} \ll \Delta m^2_{32}$;
- **SOL**: $\Delta m^2_{32} \approx \infty \Rightarrow$ only **3** parameters: Δm^2_{21}, θ_{12}, θ_{13};
- **ATM**: $\Delta m^2_{21} \approx 0 \Rightarrow$ only **3** parameters: Δm^2_{32}, θ_{23}, θ_{13};
- From Chooz: $\theta_{13} \approx 0 \Rightarrow$ **SOL** and **ATM** decoupled.

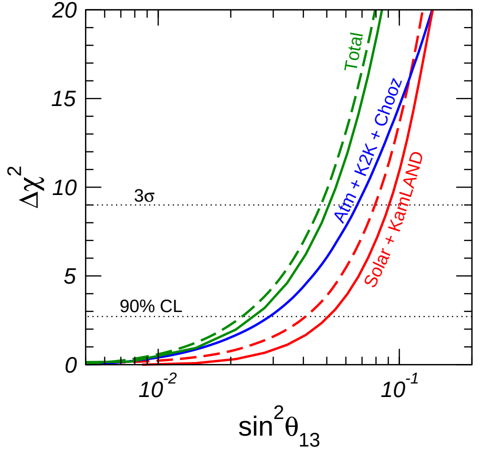


Bound on θ_{13}

- $\theta_{13} \neq 0$: { *solar* region moves to larger values of Δm^2_{21}; *KamLAND* region only weakly affected.
- bounds on θ_{13}: { from Chooz+atmospheric data (best); from Solar+KamLAND data (good).
- 3σ range: $\sin^2\theta_{13} \leq 0.051$.

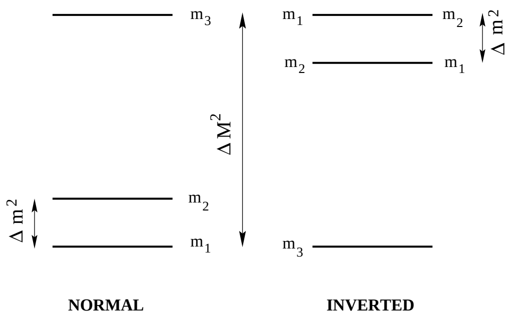




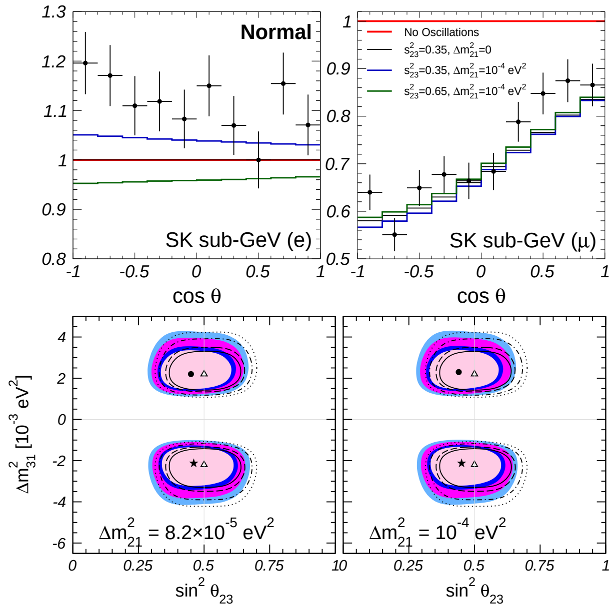


Intrinsic features of the three-neutrino scenario

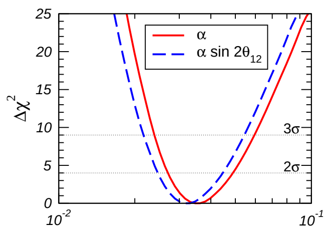
- In addition to 2ν parameters, we have:
  1. Two mass spectra: **normal** and **inverted**:



  2. Sub-leading oscillations due to Δm^2_{21};
  3. $\nu_\mu \to \nu_e$ conversion if θ_{13} is non-zero;
  4. CP violation due to complex phase δ_{CP}.

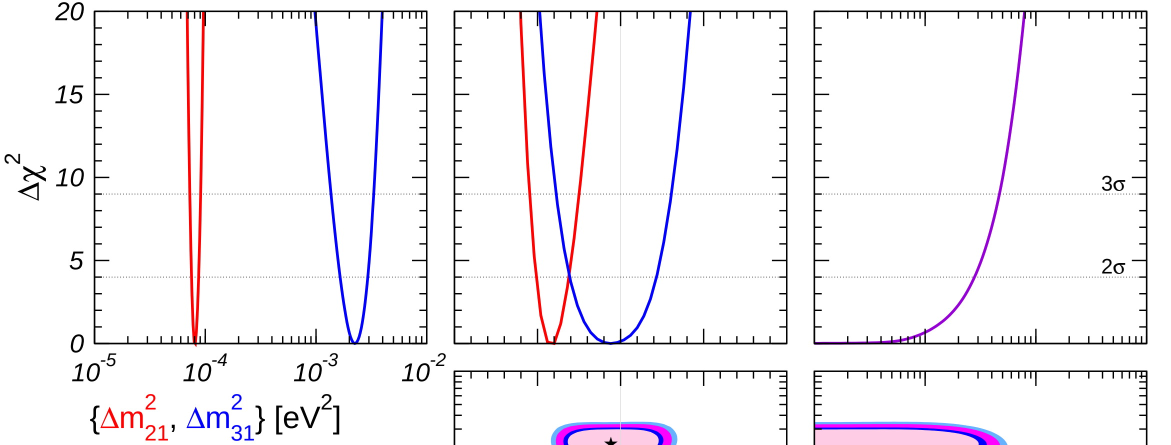


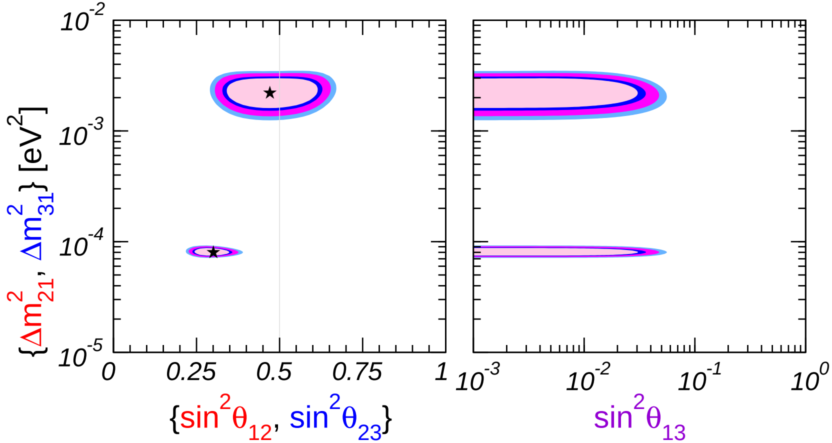
- Present ATM data: $\left\{ \begin{array}{l} \text{are sensitive to subleading } \Delta m^2_{21} \text{ effects;} \\ \text{cast no light on the } \nu \text{ mass hierarchy.} \end{array} \right.$



- $\alpha = |\Delta m^2_{21} / \Delta m^2_{31}| \Rightarrow \alpha \in [0.024,\ 0.060]$ at 3σ, best $= 0.035$.

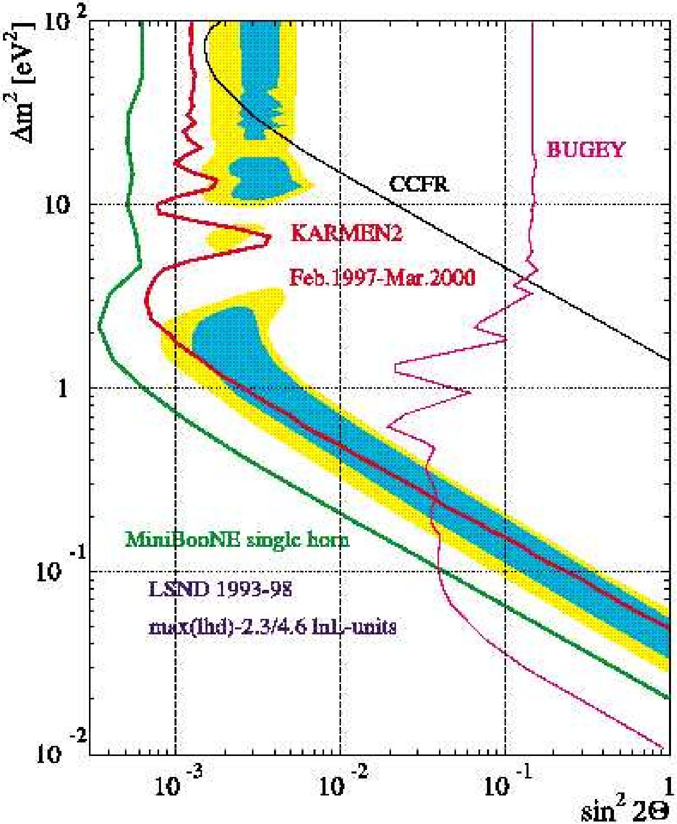
Global analysis (SOL + ATM + Reactor + K2K)





parameter	best fit	2σ	3σ
Δm^2_{21} $[10^{-5}\text{eV}^2]$	7.9	7.3–8.5	7.1–8.9
Δm^2_{31} $[10^{-3}\text{eV}^2]$	2.2	1.7–2.9	1.4–3.3
$\sin^2\theta_{12}$	0.30	0.25–0.34	0.23–0.38
$\sin^2\theta_{23}$	0.47	0.35–0.61	0.31–0.65
$\sin^2\theta_{13}$	0.000	≤ 0.031	≤ 0.051
δ_{CP}, hier, m_1, ϕ_i	undetermined		

Anything left out?



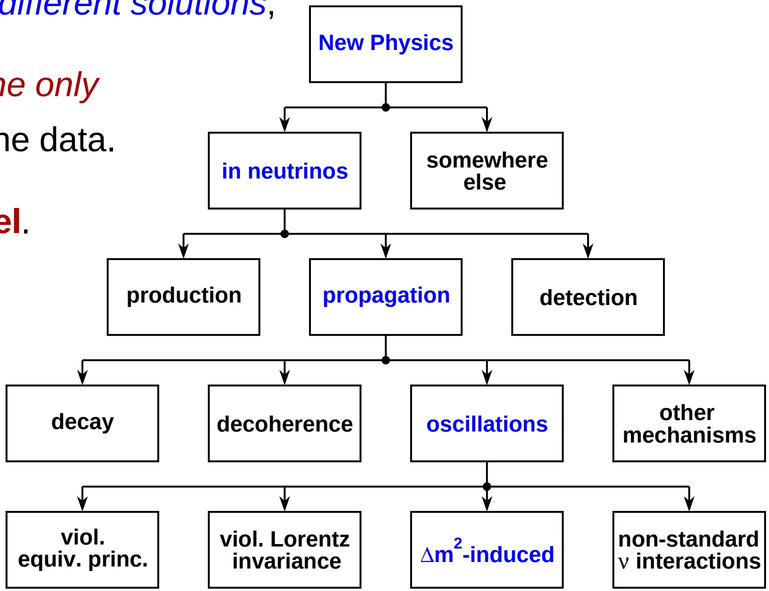
- LSND claimed *evidence* of $\bar{\nu}_\mu \to \bar{\nu}_e$ conversion ($L = 30$ m, $\langle E_\nu \rangle \sim 30$ MeV);
- ν-oscillations: need $\Delta m^2 \gtrsim 0.1$ eV^2 $\Rightarrow$ *incompatible* with SOL+ATM data in a 3ν scenario;
- proposed solutions:
  - ~~four-neutrino oscillations~~;
  - ~~3ν osc. with CPT violation~~;
  - 4ν osc. with CPT violation;
  - 4ν with neutrino decay;
  - …
- MiniBOONE data expected soon.

Why mass-induced neutrino oscillations?

- Theoretically, many different mechanisms have been proposed;
- some anomalies (*e.g.*, solar) can be perfectly explained also by alternative mechanisms;
- however, *different experiments require different solutions*;

$\Rightarrow$ mass-induced neutrino oscillations is *the only* mechanism which can account for **all** the data.

$\Rightarrow$ **Δm^2-oscillations is the Minimal Model**.



What about other mechanisms?

- Still theoretically acceptable, but *must coexist with oscillations*;
- should not spoil the good description of Δm^2-oscillations $\Rightarrow$ **bounded**!

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Future perspectives of neutrino physics

Man-made neutrinos

- **Long-baseline, reactor, $0\nu\beta\beta$, ...**

Main goal: accurate reconstruction of the neutrino mass matrix.

MINOS, ICARUS, OPERA, T2K, NEMO3, KATRIN, ...

⇔

Natural-source neutrinos

- **Solar, ATM, SN, HEν, cosmo-ν, ...**

Main goal: Use neutrinos as a tool to study other aspects of Physics.

ANTARES, ICECUBE, BOREXINO, WMAP, PLANCK...

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New Physics

Whatever the outcome, we will learn a lot about **Physics Beyond the Standard Model**:

- If data **disagree** with the expectations $\Rightarrow$ New Physics beyond 3ν oscillations;
- If data **agree** with the expectations $\Rightarrow$ Strong bounds on New Physics.

Potentialities and limitations of long-baseline experiments

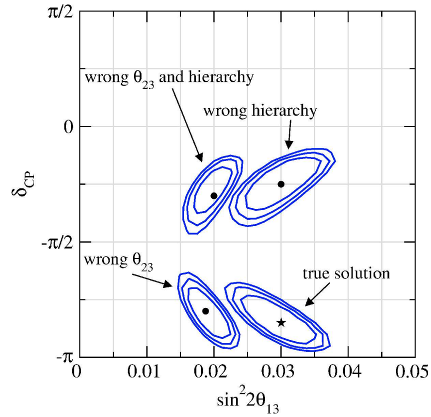
- Goal of LBL experiments is precision but challenged by *parameter degeneracies*:
  - *intrinsic* or $(\delta_{CP}, \theta_{13})$: $P_{\nu_e\nu_\mu}(\theta_{13}, \delta_{CP}) = P_{\nu_e\nu_\mu}(\theta'_{13}, \delta'_{CP})$
  - *hierarchy* or $\text{sgn}(\Delta m^2_{31})$: $P_{\nu_e\nu_\mu}(\Delta m^2_{31}, \delta_{CP}) = P_{\nu_e\nu_\mu}(-\Delta m^2_{31}, \delta'_{CP})$
  - *octant* or θ_{23}: $P_{\nu_\mu\nu_\mu} \propto \sin^2 2\theta_{23}$, $P_{\nu_e\nu_\mu}(\theta_{23}, \theta_{13}, \delta_{CP}) = P_{\nu_e\nu_\mu}(\pi/2 - \theta_{23}, \theta'_{13}, \delta'_{CP})$

$\Rightarrow$ if only total number of $\nu_{e,\mu}$ and $\bar{\nu}_{e,\mu}$ at a given L/E are measured $\Rightarrow$ 8-fold degeneracy;

- Solutions:
  - use "silver" channels $\nu_e \to \nu_\tau$ and $\nu_\mu \to \nu_\tau$;
  - use wide-band superbeams for E_ν spectrum;
  - combine measurements at different L;
  - combine LBL with other data (ATM, reactor);

$\Rightarrow$ single experiment: not enough (even with E_ν spectrum);

$\Rightarrow$ **combined analyses of different data sets required**.



Example: solving parameter degeneracies with ATM+LBL data

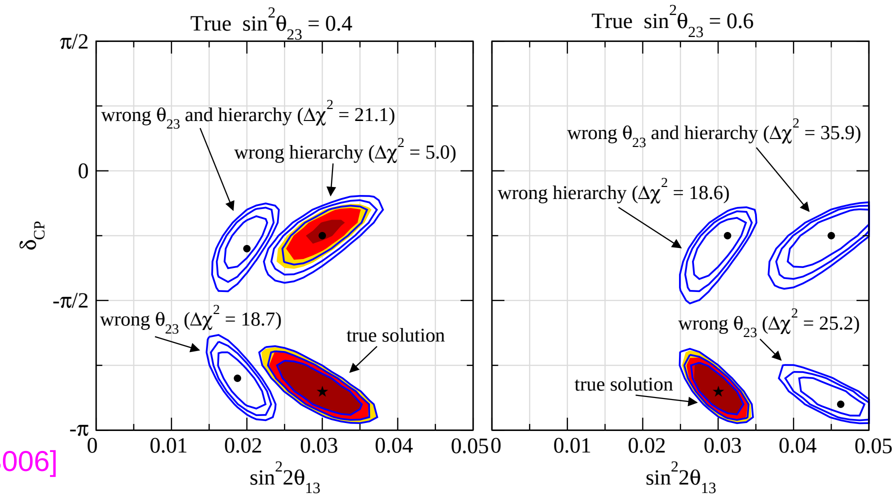
Why atmospheric neutrinos?

- Contrary to LBL, ATM data naturally span a very large range of energies and distances;
- future LBL experiments ⇒ huge ($\sim$ Mton) detectors ⇒ **lots of ATM ν events for free!**

Combined analysis of LBL and ATM data

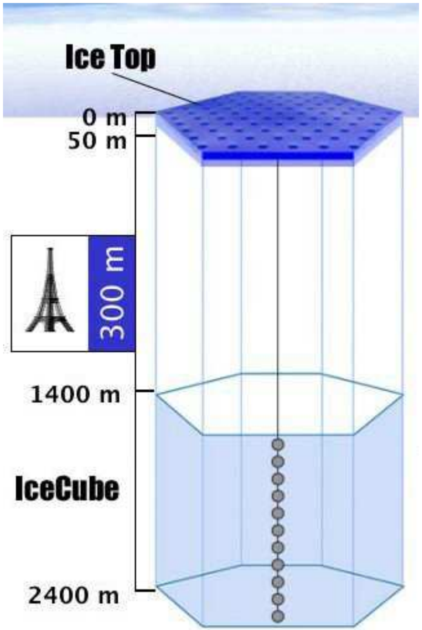
- 4 MW superbeam at JPARC;
- $\langle E_\nu \rangle \approx 0.76$ GeV, 2° off-axis;
- baseline: 295 km;
- 1 Mton Cerenkov at Kamioka;
- runtime: 2 years ν, 6 years $\bar{\nu}$.

[Huber, MM, Schwetz, PRD 71 (2005) 053006]



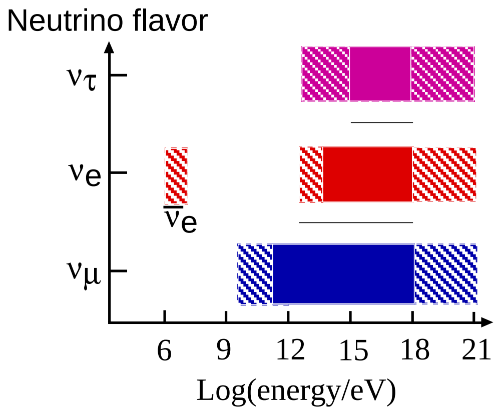
Neutrino telescopes: the IceCube detector

- Geometry: hexagon of 80 strings (separation: 125 m), each carrying 60 photo-multipliers (distance: 17 m). Total size: $\sim 1\ \text{km}^3$ (20000 times bigger than Super-Kamiokande).



[http://icecube.wisc.edu/gallery/]

- Detection technique: observation of *Cerenkov light*;
- Threshold: ~ 80 GeV for ν_μ, ~ 10 TeV for ν_e and ν_τ;
  [Halzen & Hooper, Rept. Prog. Phys. 65 (2002) 1025]
- Resolution (μ): angular $\lesssim 1^\circ$, energy $\lesssim 30\%$ in logarithm;
  [Astropart. Phys. 20 (2004) 507]
- Status: *under construction*;
- Physics reach:
  - atmospheric ν's;
  - astrophysical ν's;
  - ultra-high energy ν's;
  - ...



Example: bound on New Physics from IceCube data

Viol. of Lorentz Invariance

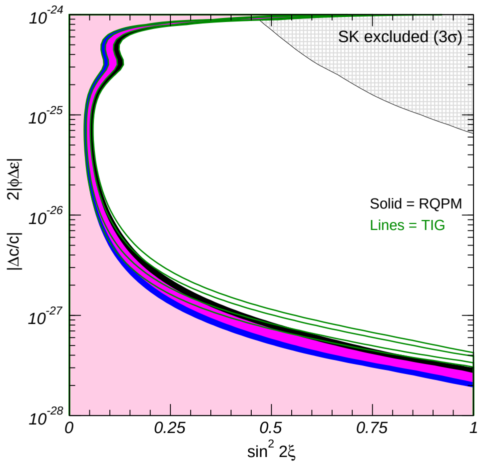
$$\vec{\nu} = (\nu_\mu, \nu_\tau)^t,$$

$$i\frac{d\vec{\nu}}{dt} = \left[\frac{\Delta m^2}{4E_\nu}\begin{pmatrix} -\cos 2\theta & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{pmatrix} + \frac{\Delta c}{c}\frac{E_\nu}{2}\begin{pmatrix} -\cos 2\xi & \sin 2\xi \\ \sin 2\xi & \cos 2\xi \end{pmatrix}\right]\vec{\nu};$$

- from SK atmospheric data: $|\Delta c/c| \leq 1.6 \times 10^{-24}$ (3σ);
- after 10 yr of IceCube: $|\Delta c/c| \leq 2 \times 10^{-28}$ (3σ, $\xi = 45°$);

$\Rightarrow$ SK bound improved by 4 order of magnitude.

[Halzen, Gonzalez-Garcia & MM, PRD 71 (2005) 093010]



Quantum decoherence

- Expected flux of TeV anti-ν from Cygnus OB2;
- $P_{\bar{\nu}_\alpha\to\bar{\nu}_\beta} = \frac{1}{3} + e^{-\bar{\gamma}L} f_{\bar{\nu}_\alpha\to\bar{\nu}_\beta}, \quad \bar{\gamma} = \kappa_n \left(\frac{E_\nu}{[\text{GeV}]}\right)^n;$
- bounds in table are for 15 yr of IceCube data.

	SK-atm [GeV]	IceCube [GeV]
κ_{-1}	2.0×10^{-21}	1.0×10^{-34}
κ_0	3.5×10^{-23}	3.2×10^{-36}
κ_1	—	1.6×10^{-40}
κ_2	9.0×10^{-28}	2.0×10^{-44}
κ_3	—	3.0×10^{-47}

SK: [Lisi, Marrone & Montanino, PRL 85 (2000) 1166] IceCube: [Anchordoqui *et al.*, hep-ph/0506168]

Conclusions

- **Solar**, **Atmospheric**, **Reactor**, **Accelerator** (except LSND) data are perfectly compatible:
  - solar & KamLAND favor $\Delta m^2_{sol} \approx 8 \times 10^{-5}$ eV^2 and *large but non-maximal* mixing;
  - atmospheric & K2K data favor $\Delta m^2_{atm} \approx 2 \times 10^{-3}$ eV^2 and *nearly maximal* mixing; subleading effects start being visible;
  - all data sets indicate $\theta_{rea} \approx 0$;
- MiniBOONE is running to test LSND; results expected soon (by the end of the year?)
- Future experiments will:
  - improve out knowledge of the neutrino mass matrix;
  - use neutrinos as a tool to study other aspects of physics;
  - open a unique door on Physics Beyond the SM.

Man-made neutrinos

- **Long-baseline, reactor, $0\nu\beta\beta$, . . .**

Main goal: accurate reconstruction of the neutrino mass matrix.

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$\Leftrightarrow$

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$\Updownarrow$ $\Updownarrow$

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