Neutrino masses and mixings and

light particles,
Dark Matter, Dark Energy,
SuperSplit SuperSymmetry

Alessandro Strumia, GGI, Firenze 21/9/2005

Present

Two direct evidences for violation of lepton flavour.

Anomaly	Solar	Atmospheric
first hint	1968	1986
confirmed	2002	1998
evidence	12σ	17σ
for	$\nu_e \to \nu_{\mu,\tau}$	$\nu_\mu \to \nu_\tau$
seen by	Cl,2Ga,SK,SNO,KL	SK,Macro, K2K
disappearance	seen	seen
appearance	seen	partly seen
oscillations	almost seen	almost seen
$\sin^2 2\theta$	0.85 ± 0.03	1.02 ± 0.04
Δm^2	$(8.0 \pm 0.3)10^{-5}\,\mathrm{eV}^2$	$(2.5 \pm 0.3)10^{-3}\,\mathrm{eV}^2$
sterile?	6σ disfavoured	7σ disfavoured

Theory

Neutrino oscillations

Ultrarelativistic neutrinos with 3 × 3 mass matrix:

$$m_\nu = V^* \,\mathrm{diag}(m_1 e^{-2i\beta}, m_2 e^{-2i\alpha}, m_3) V^\dagger$$

where

$$V = R_{23}(\theta_{23}) \cdot R_{13}(\theta_{13}) \cdot \mathrm{diag}\,(1, e^{i\phi}, 1) \cdot R_{12}(\theta_{12})$$

is the neutrino mixing matrix, oscillate in normal matter as dictated by

$$i\frac{d}{dx}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = H\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}, \qquad \text{where} \qquad H = \frac{m_\nu^\dagger m_\nu}{2E} + \sqrt{2} G_{\mathrm{F}} N_e \,\mathrm{diag}(1,0,0)$$

Main facts can be understood in terms of 2ν vacuum oscillations.

2ν vacuum oscillations

(Derivation as simple as the well-known $e^{iE_i t}$ hand-waving, and correct)
Oscillations from interference between states with different mass and same E
Often stationary fluxes. Always energy resolution $\Delta E \gg 1/\Delta t$: $\langle e^{i\Delta E\cdot t}\rangle = 0$

At the production region $x \approx 0$

$$|\nu(x\approx 0)\rangle = |\nu_\mu\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$$

At a generic x

$$|\nu(x)\rangle = e^{ip_1 x}\cos\theta|\nu_1\rangle + e^{ip_2 x}\sin\theta|\nu_2\rangle.$$

Since $p_i^2 = \sqrt{E^2 + m_i^2} \simeq E - m_i^2/2E$ at the detection region $x \approx L$

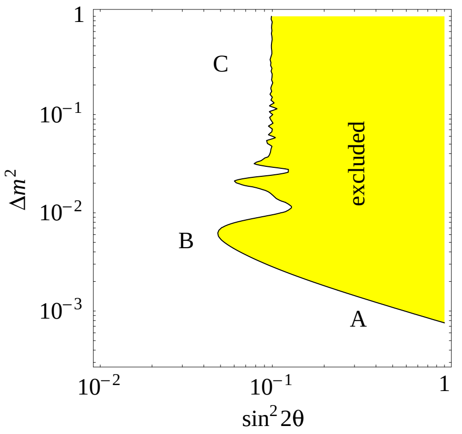
$$P(\nu_\mu \to \nu_\mu) = |\langle\nu_\mu|\nu(L)\rangle|^2 \simeq 1 - S_{12}\sin^2 2\theta$$

$$S_{ij} \equiv \sin^2 \frac{c^3}{\hbar}\frac{\Delta m_{ij}^2 L}{4E} = \sin^2 1.27 \frac{\Delta m_{ij}^2}{\text{eV}^2}\frac{L}{\text{Km}}\frac{\text{GeV}}{E}.$$

Need low E and big L to see this macroscopic quantum phenomenon

Limiting cases

A **Oscillations with short base-line**: $S \ll 1$, reduces to perturbation theory $P(\nu_e \to \nu_\mu) \propto L^2$: enough to fix factor-2 ambiguity!



C ΔE, ΔL **averaged oscillations**: $\langle S \rangle = 1/2$

$$P(\nu_e \to \nu_e) = 1 - \frac{1}{2}\sin^2 2\theta = \sin^4\theta + \cos^4\theta =$$

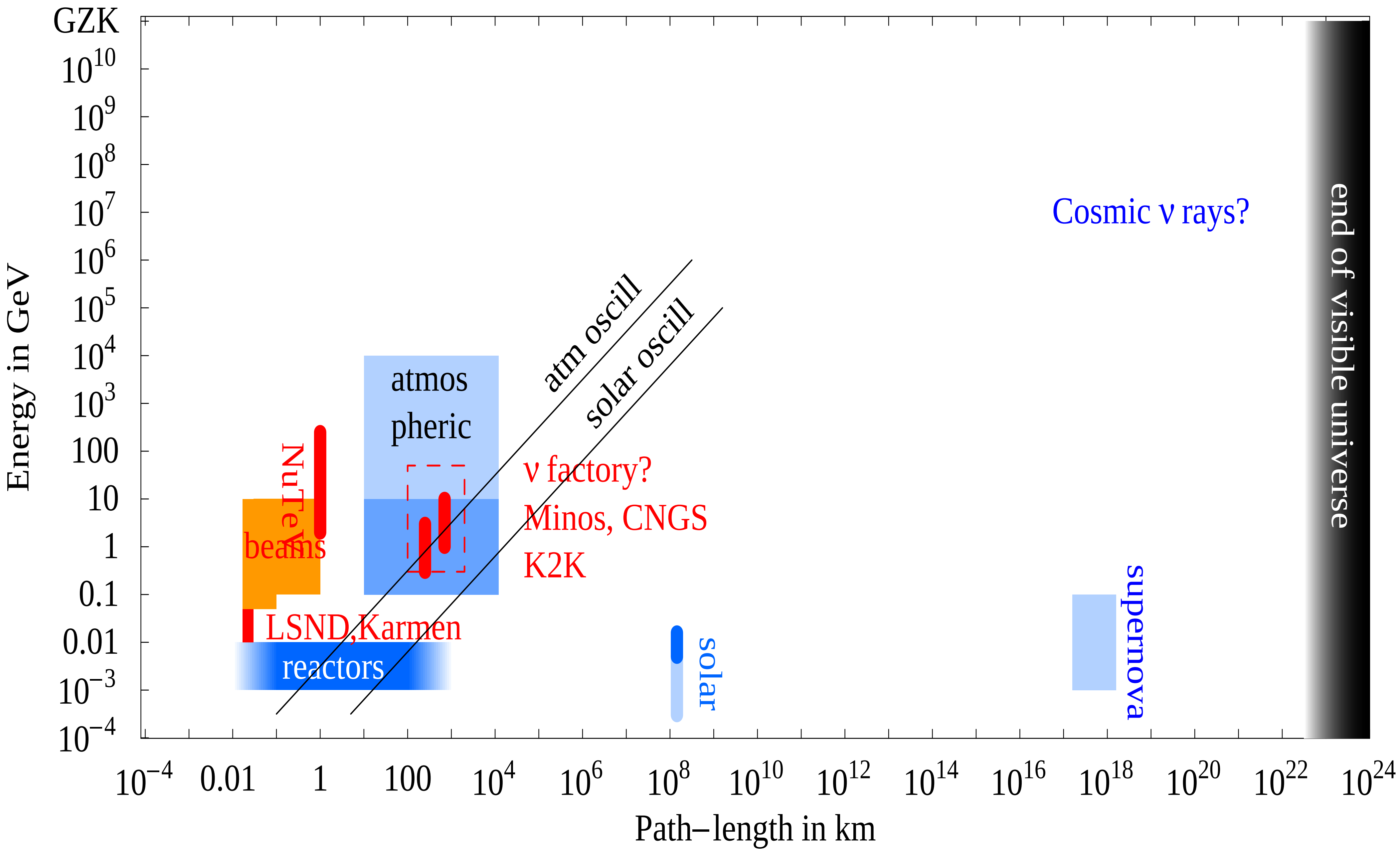
$$\begin{tikzcd}
 & \nu_2 \arrow[dr, "\sin^2\theta"] & \\
\nu_e \arrow[ur, "\sin^2\theta"] \arrow[dr, "\cos^2\theta"'] & & \nu_e \\
 & \nu_1 \arrow[ur, "\cos^2\theta"'] &
\end{tikzcd}$$

like

$$\begin{tikzcd}
 & d\ (\pi) \arrow[dr, "\sin^2\theta_C"] & \\
c\ (\text{e.g. } \Lambda) \arrow[ur, "\sin^2\theta_C"] \arrow[dr, "\cos^2\theta_C"'] & & c \\
 & s\ (K) \arrow[ur, "\cos^2\theta_C"'] &
\end{tikzcd}$$

The information on the phase is lost: combine probabilities, not amplitudes

B **The intermediate region**. Coherence is lost when neutrinos with different E have too different oscillation phases $\phi \sim \Delta m^2 L/E$, i.e. when $\Delta\phi \approx n\phi \gtrsim 1$. With energy resolution ΔE one can see $n \sim E/\Delta E$ oscillations (zero so far).



Atmospheric and solar discoveries based on careful study of natural ν sources

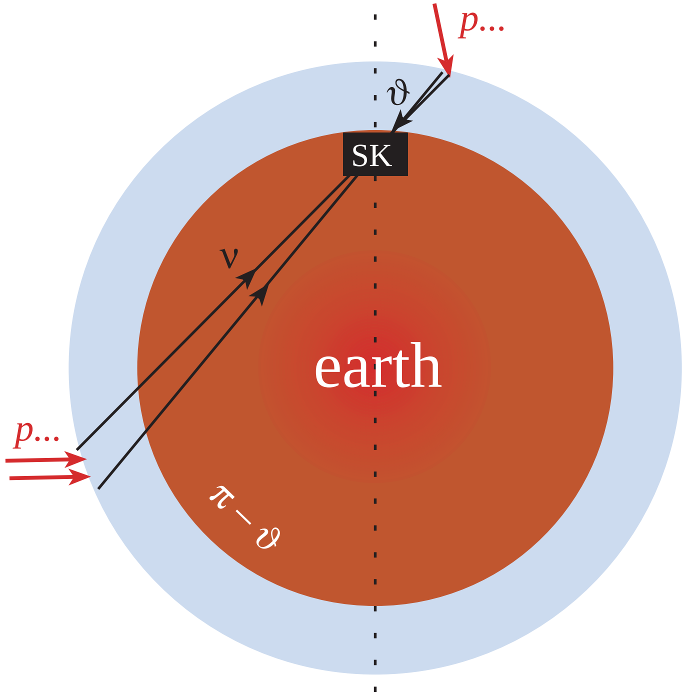
The atmospheric anomaly

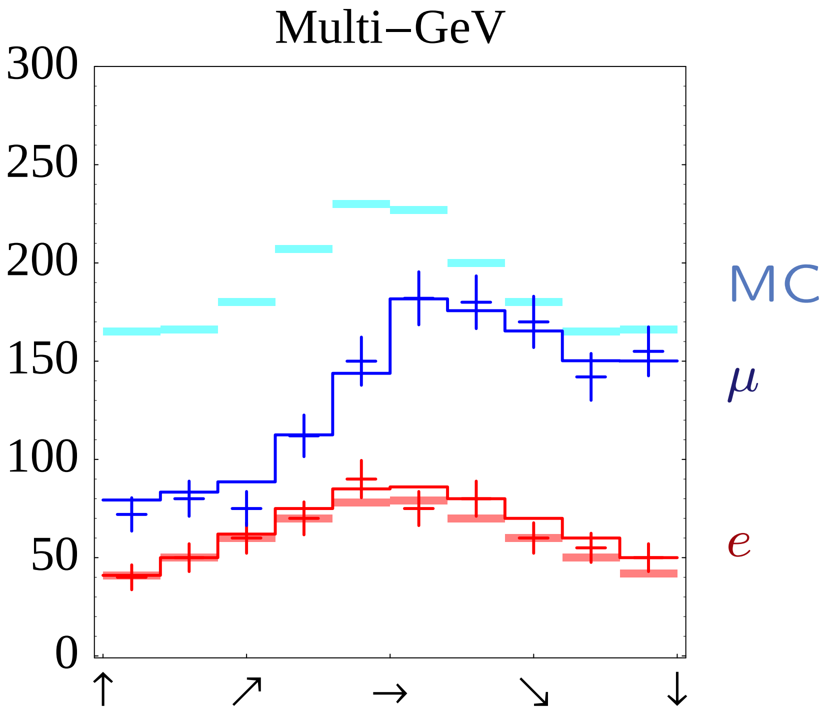
The atmospheric anomaly

SK detects $\nu_\ell N \to \ell N$ distinguishing μ from e. In the multi-GeV sample

$$E_\ell \lesssim E_\nu \sim 3\,\text{GeV}, \qquad \vartheta_\ell \sim \vartheta_\nu \pm 10^\circ$$

Without oscillations $N(\cos\vartheta_{\text{zenith}})$ is up/down symmetric





No doubt that there is an anomaly

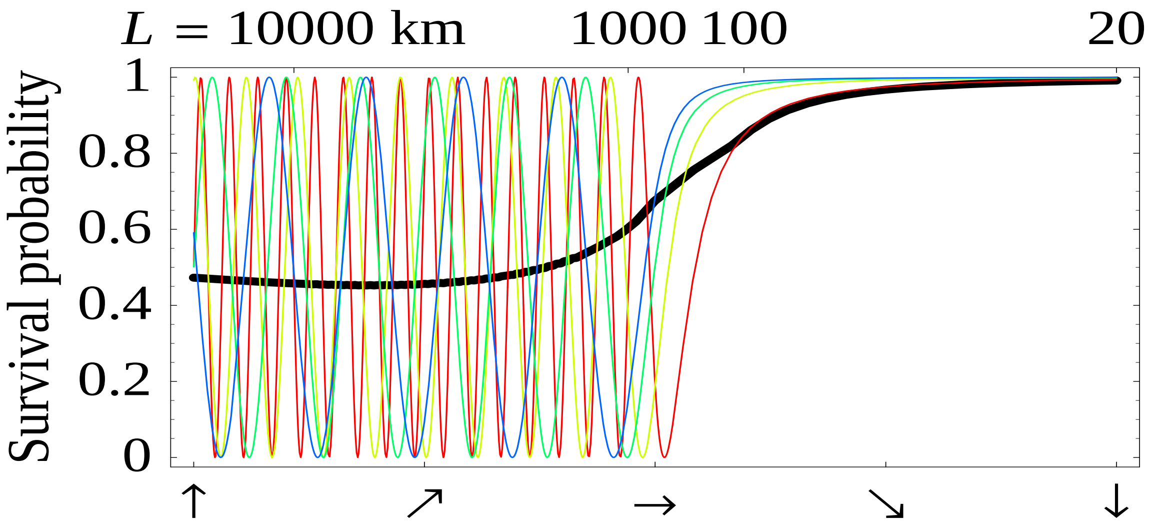
Atmospheric oscillations?

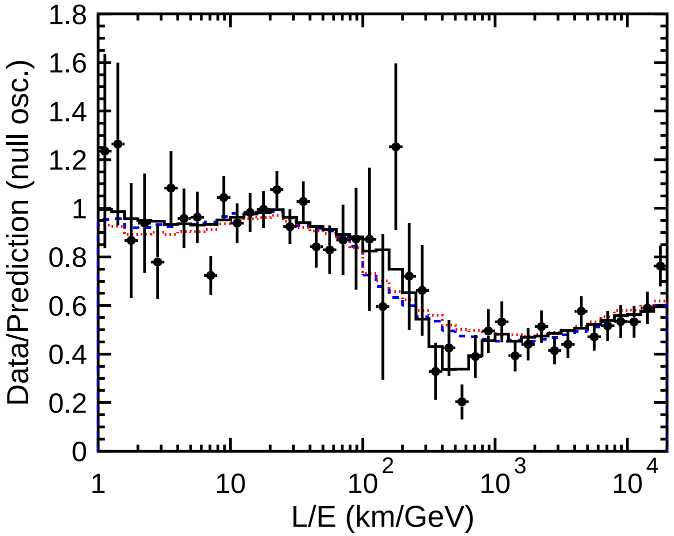
$$P_{ee}=1 \qquad P_{e\mu}=0 \qquad P_{\mu\mu}=1-\sin^2 2\theta_{\rm atm}\ \sin^2\frac{\Delta m^2_{\rm atm}L}{4E_\nu}$$

- $\sin^2 2\theta_{\rm atm} = 2-2\frac{N_\uparrow}{N_\downarrow} = 1\pm 0.1$ i.e. $\theta_{\rm atm}\sim 45$
- oscillatations start 'horizontal', $L\sim 1000\,$km: $\Delta m^2_{\rm atm}\sim\frac{E_\nu}{L}\sim 3\ 10^{-3}\,{\rm eV}^2$

$P_{\mu\mu}(E_\nu)$: the anomaly disappears at high energy, as predicted by oscillatons.

$P_{\mu\mu}(L)$: at SK $\sigma_{E_\nu}\sim E_\nu$: **oscillation dip** averaged out (ν_μ decay, decoeherence disfavoured at 4σ). Restricting to cleanest events, SK sees a hint





K2K

ν_μ beam sent from KEK to Kamioka. Gosplan:

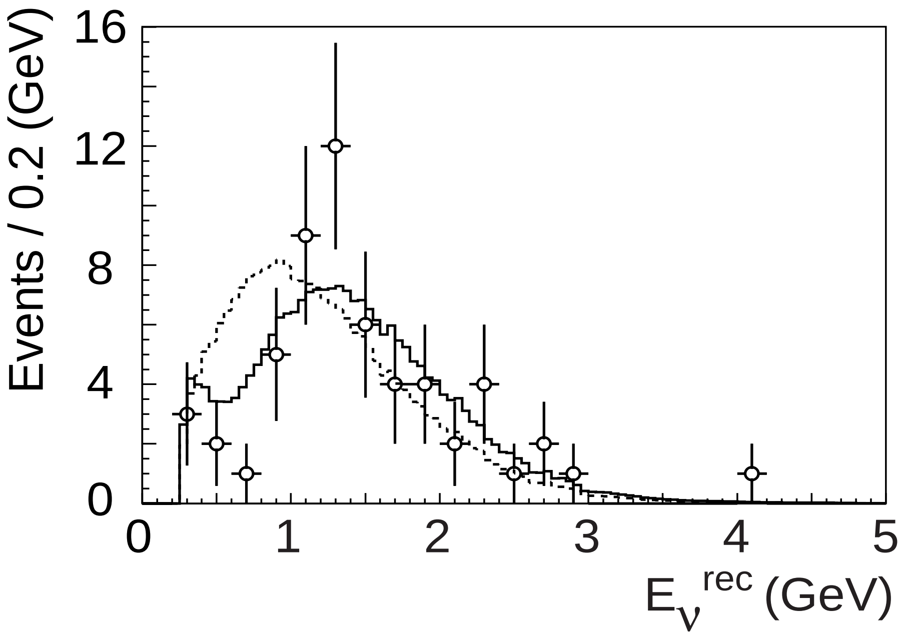
- Energy $E_\nu \sim 1.3\,\text{GeV} \sim m_p$ chosen such that $\vartheta_\mu \sim 1$.
- Distance $L = 250\,\text{km}$ chosen such that $\Delta m^2_{\text{atm}} L/E_\nu \sim 1$.

⋆ $\boldsymbol{E_\nu}$ **reconstructed** from E_μ, ϑ_μ since ν source known.

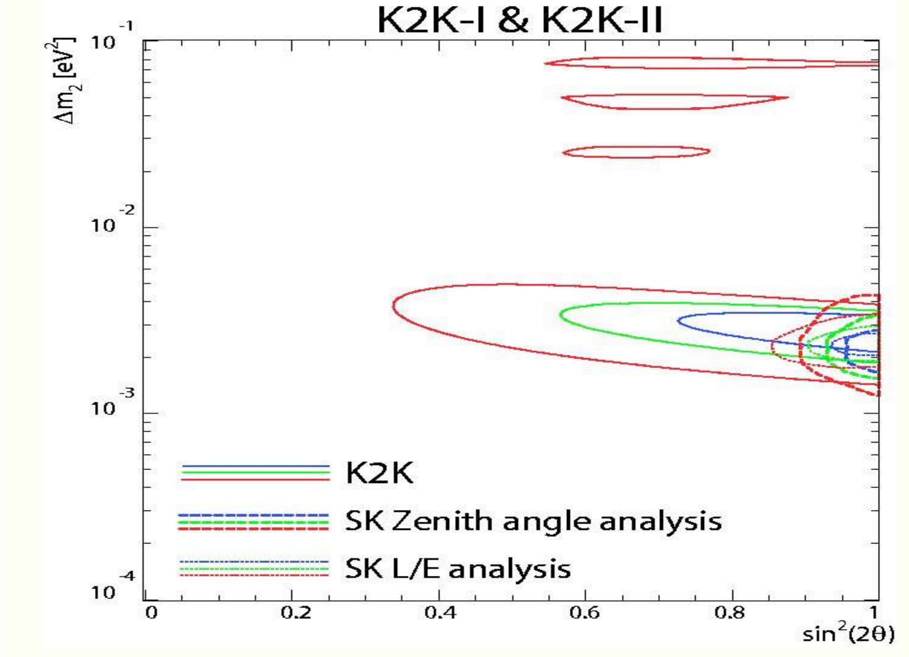
○ SK broken after beam started to really work.

151 ± 12 events without oscillations (± fiducial volume ± forward/near ratio) 107 observed. Hint of spectral distortion. Fit consistent with SK atmospheric

K2K data



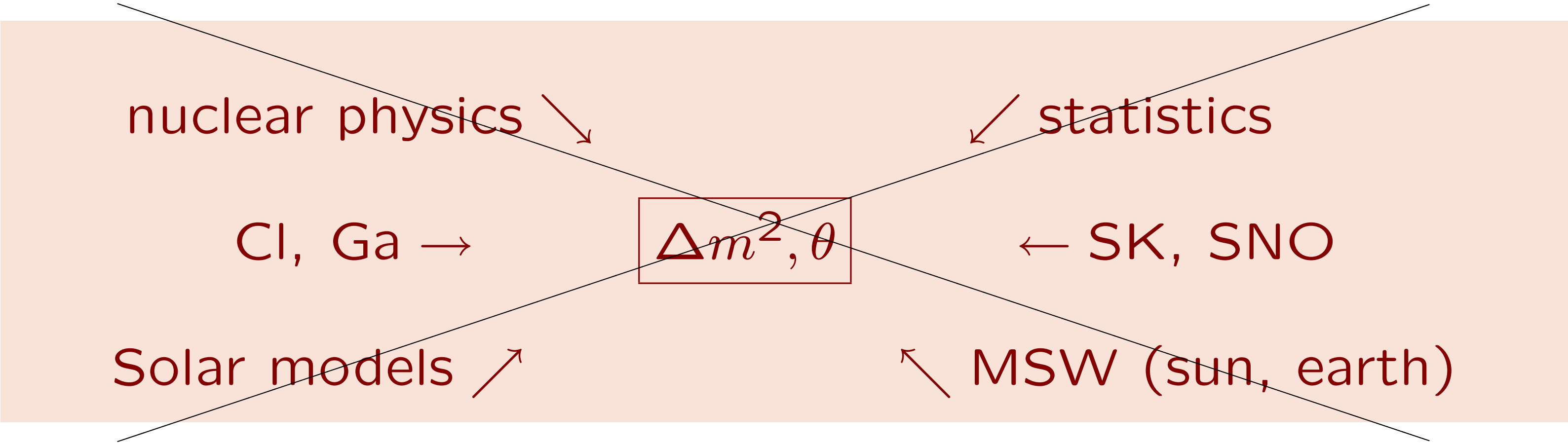
K2K vs SK fit



The solar anomaly

The solar ν anomaly

Previously based on global fits of many ingredients:



nuclear physics $\searrow$ $\swarrow$ statistics

Cl, Ga $\rightarrow$ $\boxed{\Delta m^2, \theta}$ $\leftarrow$ SK, SNO

Solar models $\nearrow$ $\nwarrow$ MSW (sun, earth)

Today we can choose best and simpler pieces of data

KamLAND confirms the solar anomaly with reactor $\bar{\nu}_e$.

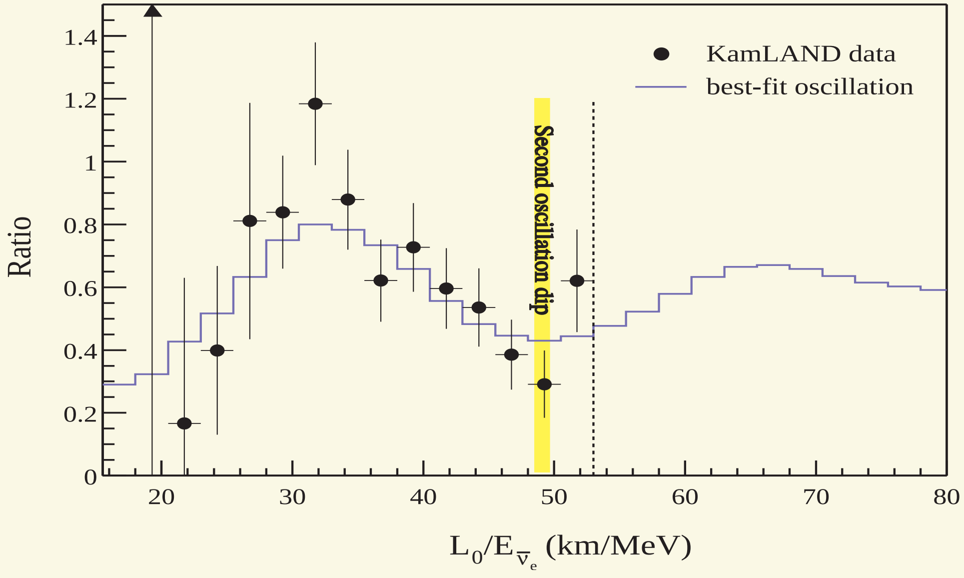
SNO measures ν_e and $\nu_{\mu,\tau}$ solar rates at $E_\nu \sim 10$ MeV.

Simple arguments allow to extract results quantitatively.

Fit without fit

Solar mass splitting

Data dominated by KamLAND:



Theory: II dip of vacuum oscillations:

$$\Delta m^2 = 6\pi \left.\frac{E}{L}\right|_{\text{dip}} = (8.0 \pm 0.3)10^{-5}\,\text{eV}^2$$

Solar mixing angle

Data dominated by SNO:

$$\langle P(\nu_e \to \nu_e)\rangle = 0.357 \pm 0.030.$$

Theory: at largest energies

$$P(\nu_e \to \nu_e) \simeq |\langle \nu_2 | \nu_e \rangle|^2 = \sin^2\theta.$$

Small correction due to

$$\nu_e(\text{center of sun}) \neq \nu_2 :$$

$$\langle P(\nu_e \to \nu_e)\rangle \approx 1.15\sin^2\theta$$

So:

$$\tan^2\theta = 0.45 \pm 0.05$$

Global fits needed to check if all the rest is consistent... and for movies

KamLAND

Čerenkov scintillator that detects $\bar{\nu}_e$ from terrestrial (japanese) reactors using $\bar{\nu}_e p \to \bar{e} n$

- Delayed $\bar{e}n$ coincidence: ~ no bck (geo$\bar{\nu}_e$ background at $E_{\text{vis}} < 2.6\,\text{MeV}$)

- 258 events seen, 365 ± 24 expected

  Deficit seen at 4σ

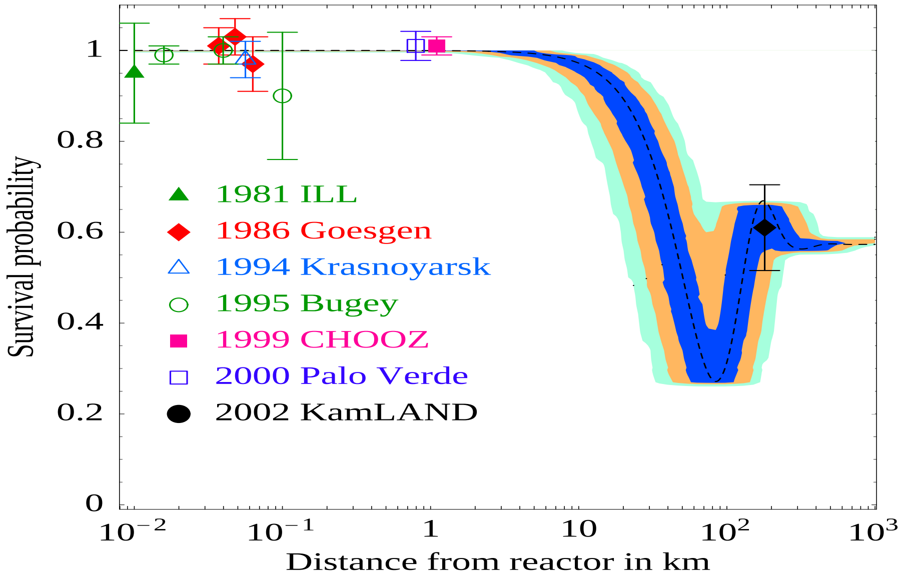
  Errors will decrease to $(3 \div 4)\%$

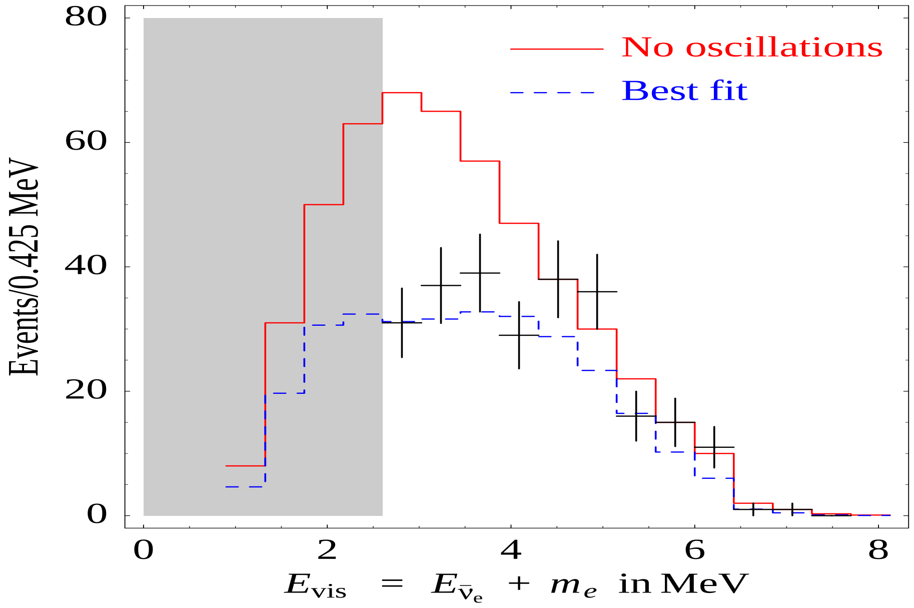
- Most reactors at $L \sim 180$ km.

  $E_{\bar{\nu}} \ll m_p$: $E_{\bar{\nu}} \approx E_e + m_n - m_p$:

  L/E distortion seen at 3σ

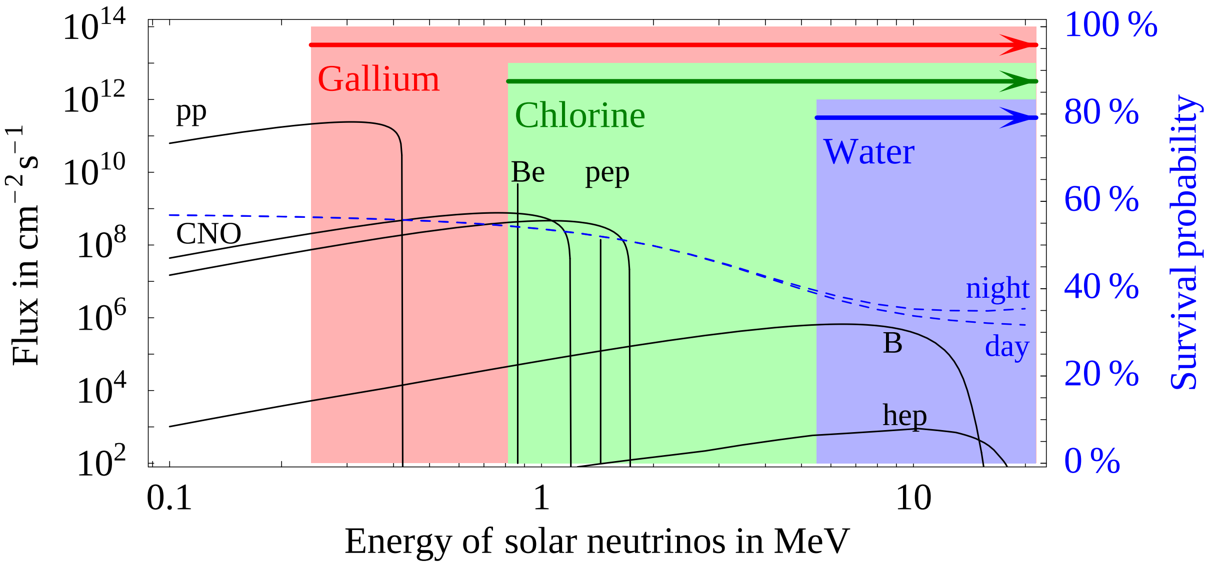
素晴らしい 結果

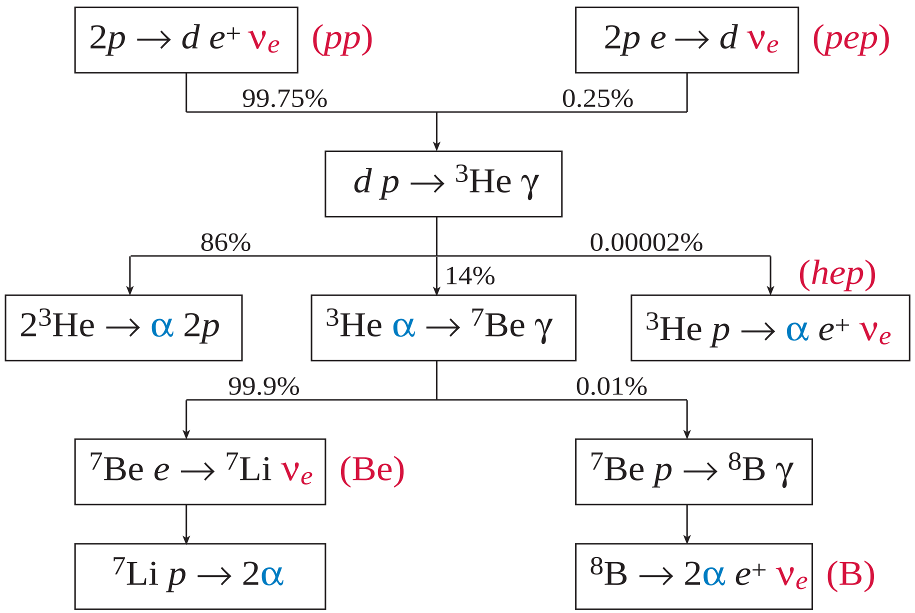




Solar ν fluxes

The sun shines as $4p + 2e \to {}^4\text{He} + 2\nu_e$ ($Q = 26.7\,\text{MeV}$).
Proceeds in steps giving a complex ν spectrum





$2p \to d\, e^+ \nu_e$ (*pp*)

$2p\, e \to d\, \nu_e$ (*pep*)

99.75%

0.25%

$d\, p \to {}^3\text{He}\, \gamma$

86%

14%

0.00002%

$2\,{}^3\text{He} \to \alpha\, 2p$

${}^3\text{He}\, \alpha \to {}^7\text{Be}\, \gamma$

${}^3\text{He}\, p \to \alpha\, e^+ \nu_e$ (*hep*)

99.9%

0.01%

${}^7\text{Be}\, e \to {}^7\text{Li}\, \nu_e$ (Be)

${}^7\text{Be}\, p \to {}^8\text{B}\, \gamma$

${}^7\text{Li}\, p \to 2\alpha$

${}^8\text{B} \to 2\alpha\, e^+ \nu_e$ (B)

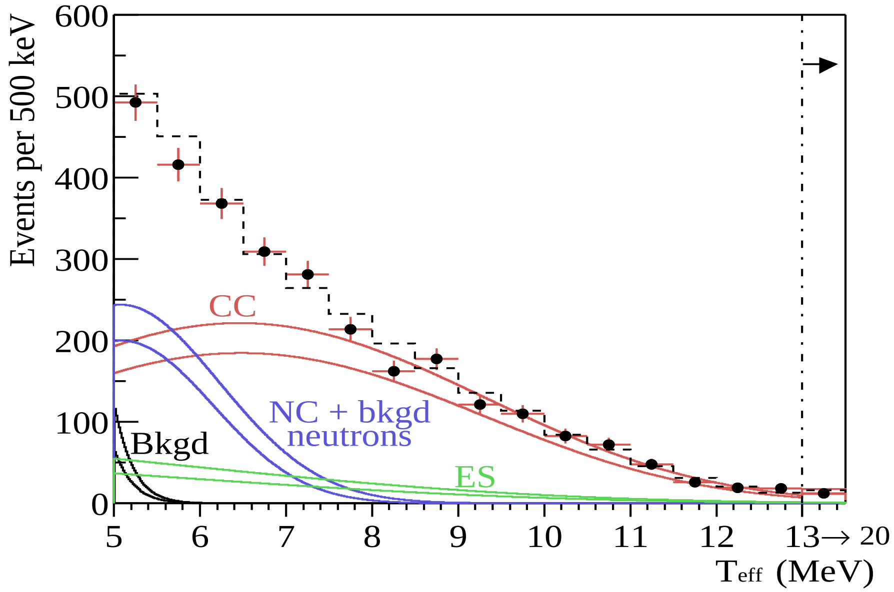
- pp: energy $< 0.42\,\text{MeV} \sim 2m_p - m_d - m_e$: too small for most expriments.
  Precisly known flux $\Phi \sim 2K_\odot/Q \sim 6.5 \cdot 10^{10}/\text{cm}^2\text{s}$.
  Vacuum oscillations: $P(\nu_e \to \nu_e) = 1 - \frac{1}{2}\sin^2 2\theta$.

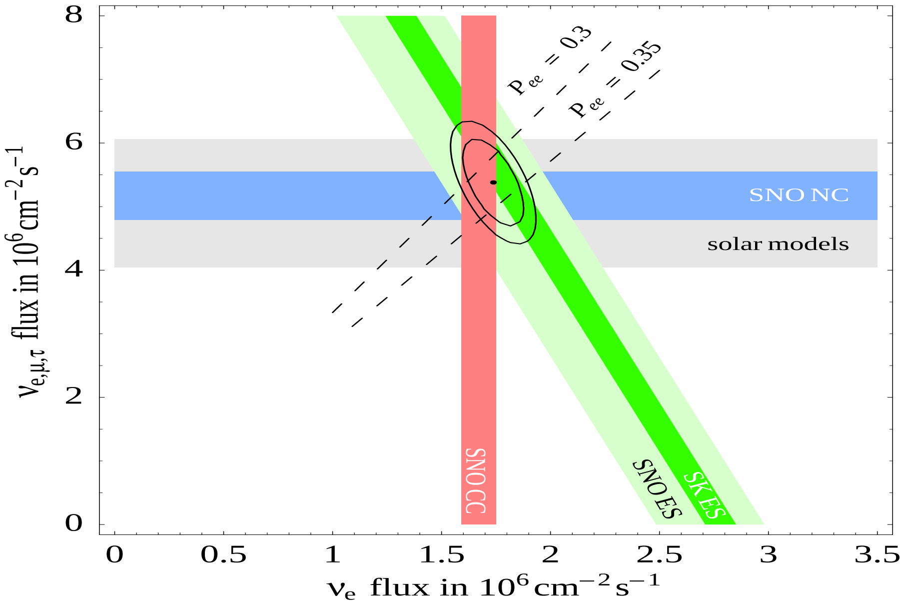
- B: highest energy, small flux predicted to $\pm 20\%$.
  Adiabatic MSW resonance: $P(\nu_e \to \nu_e) = \sin^2\theta$.

SNO

Čerenkov detector similar to SK (smaller, cleaner) with $H_2O \to D_2O$

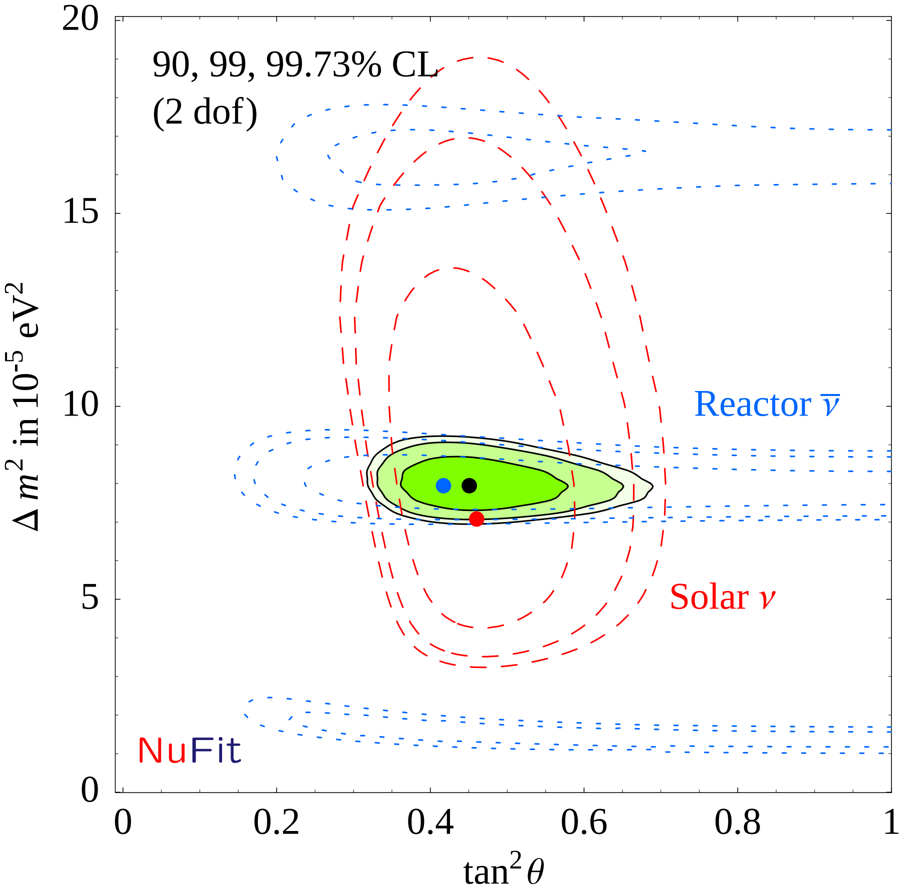
$$\mathrm{CC} + \frac{1}{6}\mathrm{NC}: \ \nu e \to \nu e \qquad \mathrm{CC}: \ \nu_e d \to ppe \qquad \mathrm{NC}: \ \nu d \to \nu pn$$





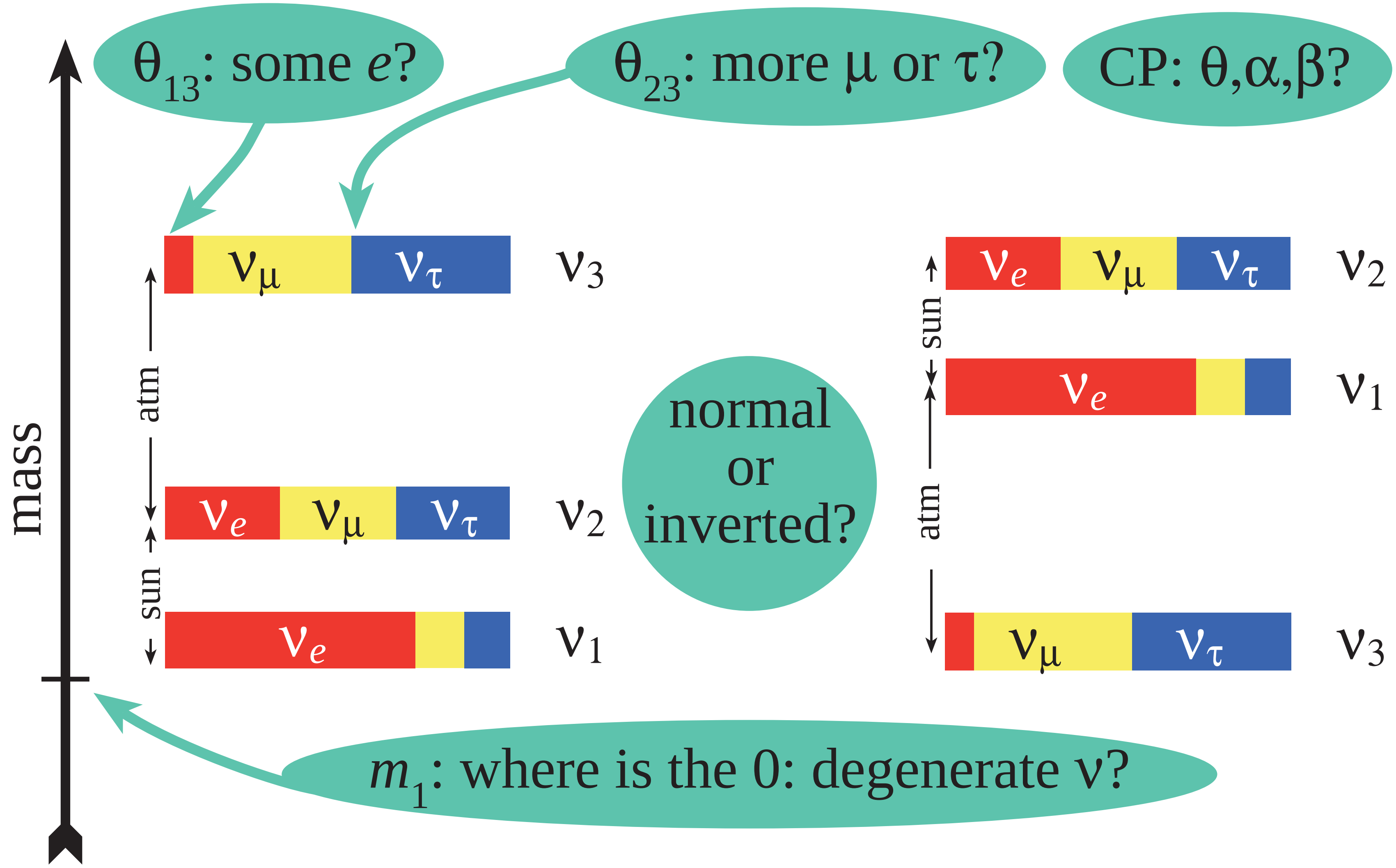
- 1st phase (2001): only e detected: distribution in ϑ_e gives CC. Confirms no spectral distortion.
- 2nd phase (2002): D captures n giving a 6.25 MeV γ ($\epsilon \sim 20\%$): CC/NC mainly distinguished by energy spectrum
- 3rd phase (2003): salt heavy water: Cl captures n giving multiple γ's ($\epsilon \sim 80\%$). CC/NC mainly distinguished by event shapee

Global fit


90, 99, 99.73% CL
(2 dof)
Reactor $\bar{\nu}$
Solar ν
NuFit
Δm^2 in 10^{-5} eV^2
$\tan^2\theta$
0
5
10
15
20
0
0.2
0.4
0.6
0.8
1

More oscillations?

Remaining questions



θ_{13}: some e?

θ_{23}: more μ or τ?

CP: θ,α,β?

normal or inverted?

m_1: where is the 0: degenerate ν?

Missing oscillations

If there will be no unexpected surprises:

1) Discover $\theta_{13} \lesssim 15^\circ$ now (from the CHOOZ **reactor**)
   - $\theta_{13} \gtrsim 3^\circ$ with detector at few km from a **reactor**
   - $\theta_{13} \gtrsim \sqrt{E_\nu/\Delta m^2_{\rm atm}\,\text{km}} \approx 2^\circ$ if inverted spectrum and if **supernovæ** will be understood and detected
   - Discoveries with natural ν (solar, atmospheric, terrestrial, reactor) maybe all done.

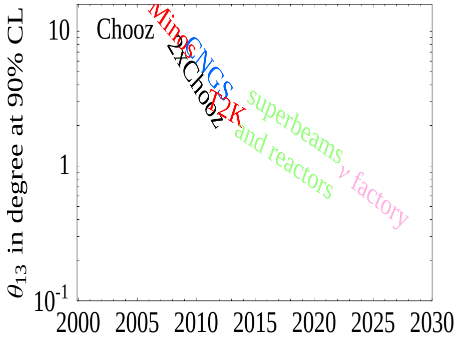
     LBL experiments: $\theta_{13} \gtrsim 10^\circ$ at K2K, Minos, CNGS.

     Off axis/superbeam could reach 2° in 2010.

     ν-factory can go below 1° in 2020 (price: G€)
2) then earth or SN matter effects tell the sign of $\Delta m^2_{\rm atm}$ (i.e. normal or inverted spectrum?)
3) Sign of $\theta_{23} - \pi/4$ (i.e. more ν_μ or ν_τ in ν_3?) from

$$P(\nu_\mu \to \nu_e) = \sin^2\theta_{23} \cdot [1 - P(\nu_e \to \nu_e)]$$

4) $\cancel{CP}$ from superbeam or ν-factory



Neutrino masses

How to detect $m_\nu \gtrsim \sqrt{\Delta m^2_{\rm atm}} \approx$ 0.05 eV?

4 techniques are close to sensitivity; in all cases improvements are hard

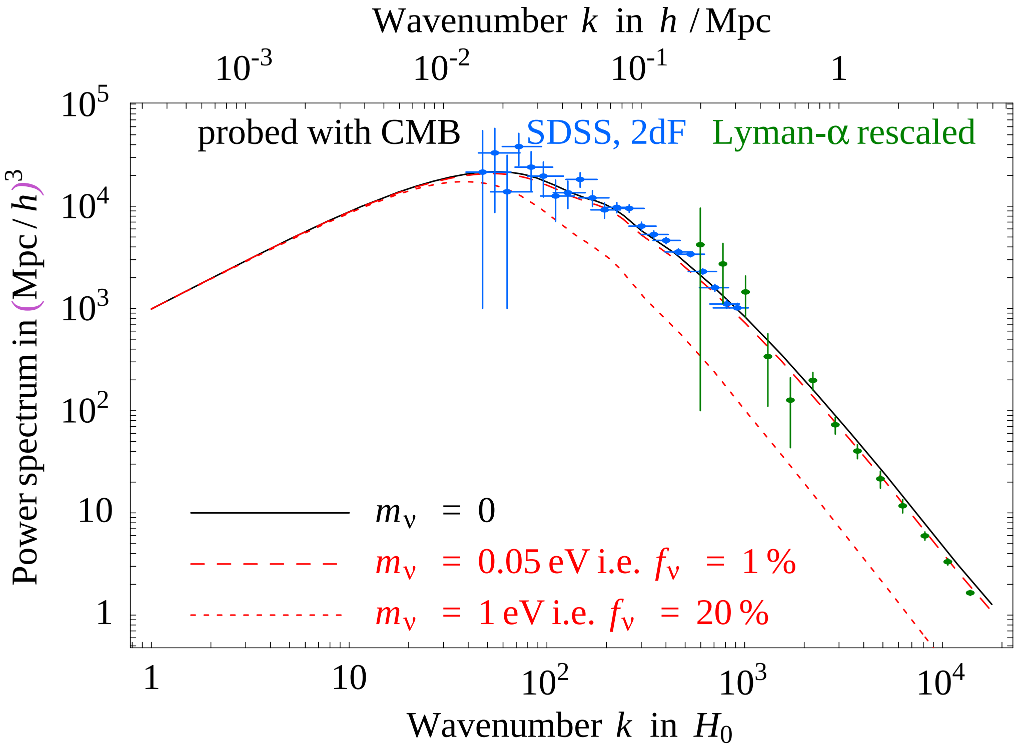
	Astrophysics	**Cosmology**	β **decay**	$0\nu2\beta$
Signal	Time delay from supernova	LSS and CMB: reduced $P(k)$	End-point spectrum	Electrons with $E_{ee} = Q$-value
Needs	—	Simple cosmology	—	Majorana
Measures	Δm_ν	$\sum m_\nu$	$(m^\dagger m)^{1/2}_{ee}$	m_{ee}
Today	$<$ 20 eV	$<$ 1 eV	$<$ 2 eV	$<$ 0.4h eV
From	SN1987A	MAP,SDSS,2dF	Mainz, Troitsk	HM,Igex,Cuoric
Implies	$m_\nu <$ 20 eV	$m_\nu \lesssim$ 0.3 eV	$m_\nu \lesssim$ 2 eV	$m_\nu/h \lesssim$ 1 eV
Future	eV	0.03 eV	0.2 eV	0.05 eV
If normal	too small	$(51 \div 66)$ meV	$(4.6 \div 10)$ meV	$(1.1 \div 4.5)$ meV
If inverted	too small	$(83 \div 114)$ meV	$(42 \div 57)$ meV	$(12 \div 57)$ meV

Constraints and predictions at 99% C.L.

Cosmology

Neutrinos suppress clustering $P(k)$ in way which depends on m_ν because:
1) Heavier neutrinos contribute more: $\Omega_\nu \sim m_\nu/94\,\mathrm{eV}$.
2) Lighter neutrinos travel more: ν non-relativistic at $z_{\mathrm{NR}} \sim m_\nu/3\,\mathrm{K} \sim 100$.

CMB starts seeing that $N_\nu > 0$ exist. Main probe is LSS: $m_\nu < (0.23 \div 1)\,\mathrm{eV}$, improvable to $0.05\,\mathrm{eV}$ with (10^7 galaxies, weak lensing)



Analytic approximation:

$$\frac{P(m_\nu,k)}{P(0,k)} \approx \begin{cases} 1 & k \lesssim k_{\mathrm{NR}} \\ (k_{\mathrm{NR}}/k)^p & k_{\mathrm{NR}} \lesssim k \lesssim k_0 \\ (k_{\mathrm{NR}}/k_0)^p & k \gtrsim k_0 \end{cases}$$

where $p \approx 5\Omega_\nu/2\Omega_{\mathrm{DM}}$

$$k_{\mathrm{NR}} = k_{\mathrm{Jeans}}(a_{\mathrm{NR}}) \approx 60 H_0 \sqrt{m_\nu/\,\mathrm{eV}}$$

$$k_0 = k_{\mathrm{Jeans}}(a=1) \approx 5000 H_0\,(m_\nu/\,\mathrm{eV})$$

β and $0\nu2\beta$ decay

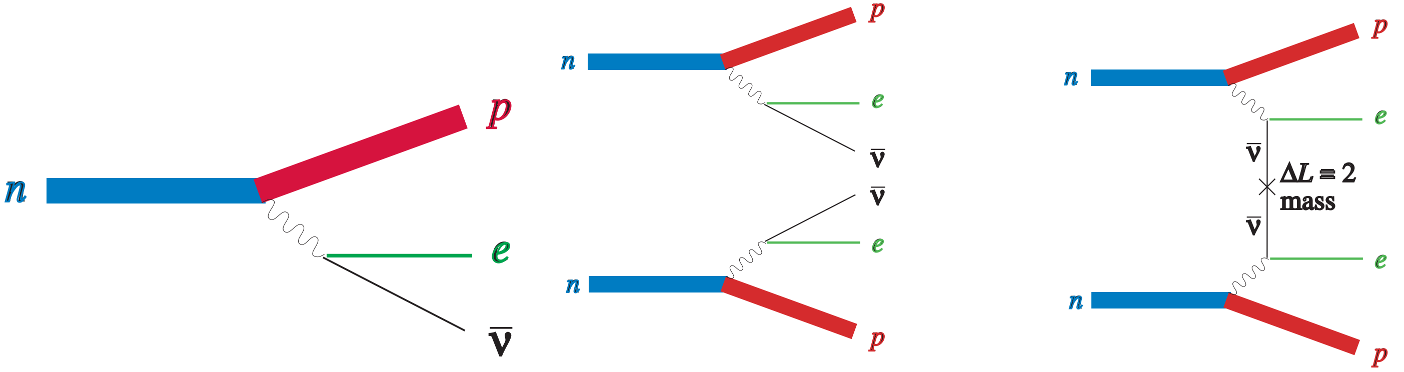
Normal β decay: m_ν affects end-point of

$$^3\text{H} \to {}^3\text{He}\ e\ \bar{\nu}_e \qquad (Q = 18.6\,\text{keV})$$

Double β decay: ${}^{76}_{32}$Ge cannot β-decay to ${}^{76}_{33}$As that is heavier, so it $\beta\beta$ decays

$${}^{76}_{32}\text{Ge} \to {}^{76}_{34}\text{Se}\ e\ e\ \bar{\nu}_e\ \bar{\nu}_e \qquad (Q = 2038.6\,\text{keV})$$

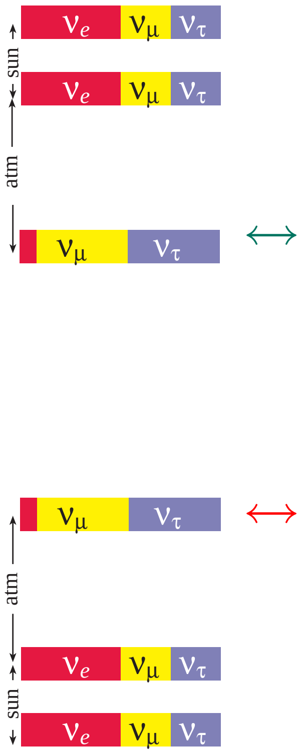
Heidelberg-Moscow, Igex, etc find $\tau \sim 10^{21}\,$yr.

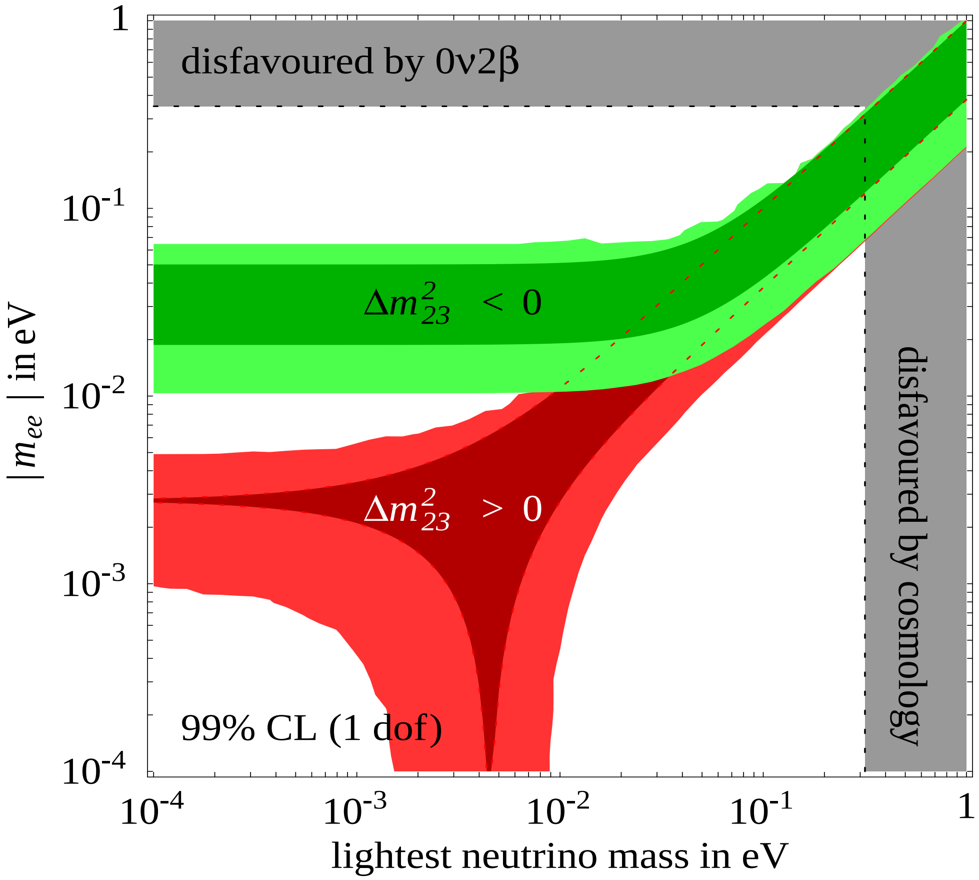


Neutrino-less double β decay: $\propto |m_{\nu_{e_L}\nu_{e_L}}|^2$. $\tau \gtrsim 10^{25}\,$yr.

Predictions for $0\nu2\beta$

$$|m_{ee}| = |\sum_i V_{ei}^2\, m_i| = |\cos^2\theta_{13}(m_1\cos^2\theta_{12} + m_2 e^{i\alpha}\sin^2\theta_{12}) + m_3 e^{i\beta}\sin^2\theta_{13}|$$





The $|m_{ee}|$ range restricts to the darker regions if we assume present best-fit values of $\Delta m^2, \theta$ with zero errors ($\theta_{13} = 0$).

Future $0\nu2\beta$ experiments should test degenerate and inverted neutrinos.

Testing origin of ν masses

Behind neutrinos

Surely we saw violation of **lepton flavour** (absent in SM),
likely due to **oscillations** induced by **neutrino masses** (absent in SM),
presumably of **Majorana** type ($\Delta L = 2$: $\mathscr{L} = \mathscr{L}_{\rm SM} + (LH)^2/\Lambda_L$),
maybe induced by new physics **around 10^{14} GeV** (see-saw?)...

first manifestation of a new scale in nature, $\Lambda_L \sim 10^{14}$ GeV?

History: operators suppressed by the EW scale $\mathscr{L} = \mathscr{L}_{\rm QED} + (\bar{e}\nu)(\bar{p}n)/\Lambda^2_{\rm EW}$ first seen as β radioactivity by Rutherford in 1896. The SM, guessed in 1968, predicts operators in terms of 2 parameters, directly probed now at LEP, LHC.

Back to neutrinos: in next few × 10 yrs the 1st mostly experimental stage might be completed, seeing all 9 $(L_iH)(L_jH)$ operators accessible at low energy.

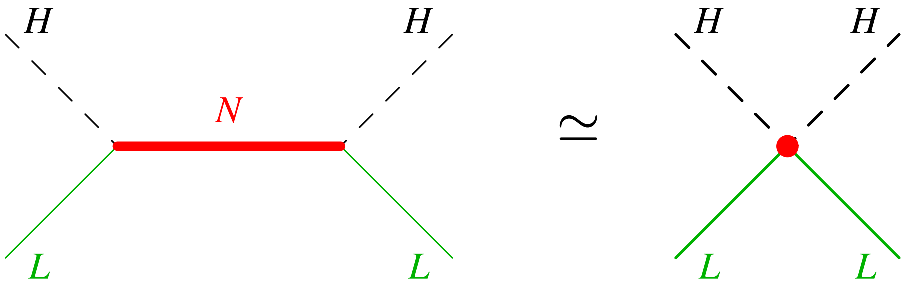
See-saw 'predicts' 9 Majorana ν parameters in terms of 18 parameters. bad
The physics behind m_ν seems either too heavy or too weakly coupled. worse
Leptogenesis or $\boldsymbol{\mu \to e\gamma}$ in SUSY-see-saw might give extra hints? hope...

See-saw

Add neutral ‘right-handed neutrinos’ N. The generic Lagrangian becomes

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \bar{N}\partial\!\!\!/ N + M\frac{N^2}{2} + \lambda\, H L N$$

Exchange of heavy N gives the dimension-5 neutrino mass operator:



$$= \frac{\lambda^2}{M}\frac{(LH)^2}{2} \to \frac{(\lambda v)^2}{M}\frac{\nu^2}{2}$$

More explicit: the neutrino mass matrix is

$$\begin{array}{c c} & \begin{array}{cc} \nu & N \end{array} \\ \begin{array}{c} \nu \\ N \end{array} & \begin{pmatrix} 0 & \lambda v \\ \lambda v & M \end{pmatrix} \end{array}$$

for $M \gg \lambda v$ the eigenvalues are $\simeq M$ and $m_\nu \simeq (\lambda v)^2/M$.

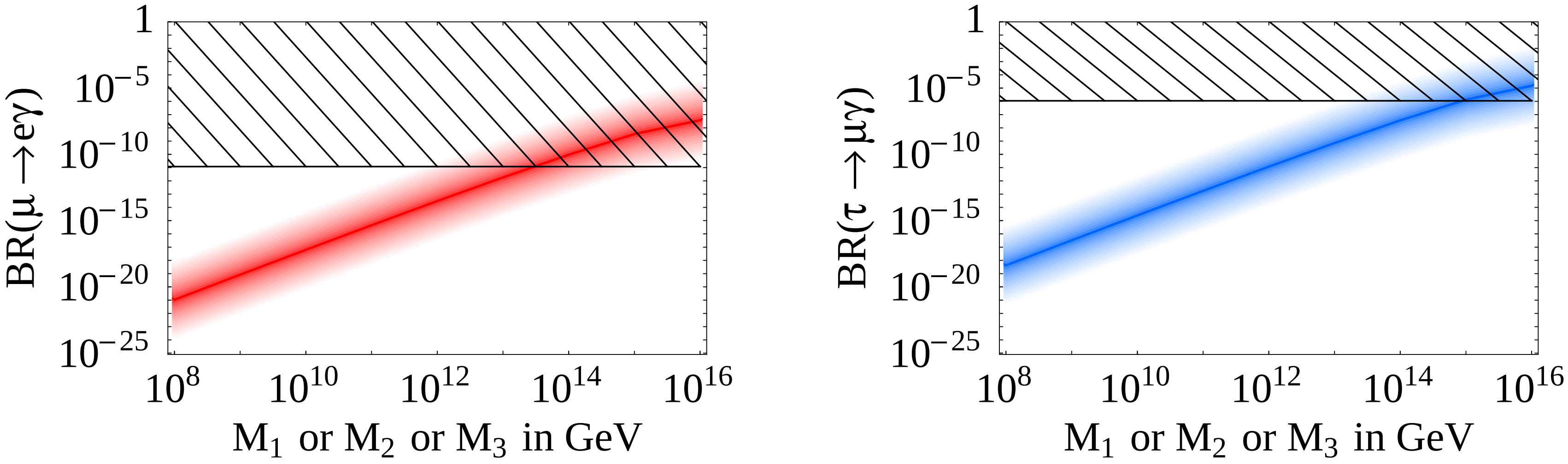
[P. Minkowski, Phys. Lett. B 67 (1977) 421]

$\mu \to e\gamma$ from SUSY λ_ν

In the SM BR$(\mu \to e\gamma) \sim (m_\mu/\Lambda_L)^2 \sim 10^{-40}$. **In SUSY see-saw quantum effects imprint LFV in slepton masses.** Starting from universal m_0^2 at $M_{\rm GUT}$

$$\boldsymbol{m}_{\tilde{L}}^2 = m_0^2 \mathbb{1} - \frac{3m_0^2}{(4\pi)^2} \boldsymbol{\lambda}_\nu^\dagger \ln(\frac{M_{\rm GUT}^2}{\boldsymbol{M}\boldsymbol{M}^\dagger}) \boldsymbol{\lambda}_\nu + \cdots$$

Even assuming large ν mixings also in λ_ν one gets loose predictions



because BR$(\mu \to e\gamma) \sim 10^{-8}\lambda_\nu^4$ while $m_\nu = \lambda_\nu^2 v^2/M$ is measured.

Baryogenesis

The universe contains γ, e, baryons (p, Helium, Deuterium, ...), likely ν.
We understand why $n_e = n_p$, why $n_{^4\text{He}}/n_p \approx 0.25$, why $n_\text{D}/n_p \approx 3\ 10^{-5}$, ...
We do not understand $n_B/n_\gamma \sim 6\ 10^{-10}$ i.e. why at $T \approx m_p$ we survived as

$$1000000001\ \frac{\text{protons}}{\text{pico-m}^3} \qquad - \qquad 1000000000\ \frac{\text{anti-protons}}{\text{pico-m}^3}$$

Might be the initial condition, but suspiciously small or large (in inflation).

Can a $p/\bar{p}$ asymmetry can be generated dynamically from nothing?

Yes, if 3 trivial Sacharov conditions are satisfied
(his big achivement was realizing that it is an interesting question).

1. Baryon number B is violated
2. C and CP are violated
   (otherwise p and $\bar{p}$ behave in the same way)
3. At some epoch the universe went out of equilibrium
   (CPT implies $m_p = m_{\bar{p}}$ so that in thermal equilibrium $n_p = n_{\bar{p}}$)

Leptogenesis

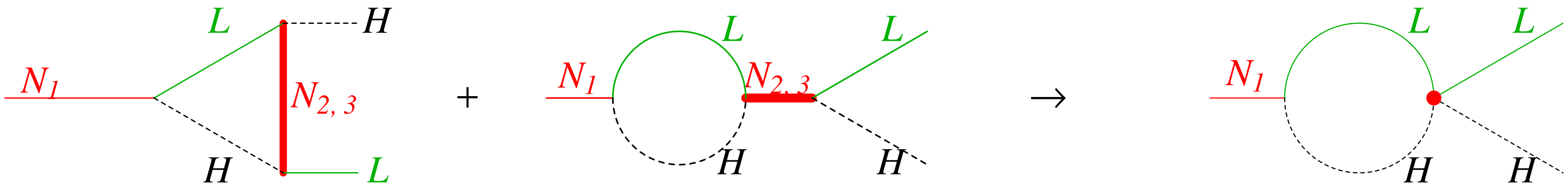
The trivial ν_R produce not only m_ν but also n_B.

See-saw with ν_R: $N_{1,2,3}$ with Yukawa $\lambda_{1,2,3}$ and masses $M_1 < M_2 < M_3$.
$m_1 < m_2 < m_3$: ν_L masses. $\tilde{m}_i \equiv \lambda_i^2 v^2 / M_i$ = 'N_i contribution to ν_L masses'.
Maybe $\tilde{m}_1 = m_{\rm atm}$ or $\gtrsim m_{\rm sun}$ or $< m_{\rm sun}$ or anywhere between 0 and ∞.

$N_1 \to HL$ decays violate CP (ε) and proceed out of equilibrium (η) generating

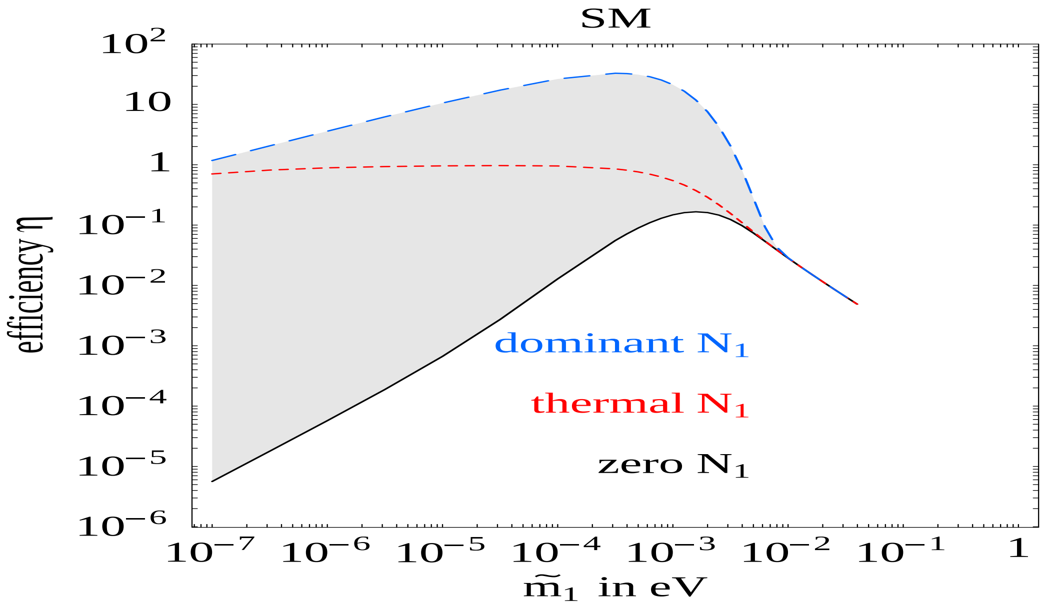
$$(6.15 \pm 0.25)\ 10^{-10} = \frac{n_B}{n_\gamma} \approx \frac{\varepsilon\eta}{100}$$

$$\varepsilon \simeq \frac{3}{16\pi}\frac{\tilde{m}_{2,3}M_1}{v^2}\sin\delta = 10^{-6}\frac{\tilde{m}_{2,3}}{0.05\,\text{eV}}\frac{M_1}{10^{10}\,\text{GeV}}\sin\delta \qquad M_{2,3} \gg M_1$$



$$\eta \text{ related to } \frac{H}{\Gamma_N} \sim \frac{m^*}{\tilde{m}_1} \text{ where } m^* \equiv \frac{256\sqrt{g_*}v^2}{3M_{\rm Pl}} = 2.2\ 10^{-3}\,\text{eV}$$

Leptogenesis



Result: ‘optimal’ at $M_1 \sim 10^{10}$ GeV (gravitino over-production in SUSY?)

But no real bound or prediction. Not even in models with a single CP phase.

Too many flavour parameters. Hard to proceed without understanding it.

Understanding flavour?

Pattern looks see-saw-like and SU(5)-like. But remind that...

Before experiments

Theory (expectation from GUT, see-saw, ...)

1. MSW enhanced small solar mixing: $\theta_{e\mu} \sim (m_e/m_\mu)^{1/2}$.
2. $m_{\nu_\ell} \underset{\sim}{\propto} m_\ell^2$: $m_{\nu_\tau} \sim$ eV is hot dark matter with small mixing
3. KamiokaNDE (‘NDE’ = Nucleon Decay Experiment).

Experiment

1. Large solar mixing
2. Nothing at Nomad and Chorus. (LSND?)
3. KamiokANDE (‘ANDE’ = Atmospheric Neutrino Detector Experiment): large mixing at $\Delta m^2_{\text{atm}} \ll \text{eV}^2$

Which pattern?

First obvious interpretation: a random mass matrix reproduces observations

$$\theta_{12} \sim \theta_{23} \sim 1 \qquad \theta_{13} < 0.2 \qquad R \equiv \Delta m^2_{\rm sun}/\Delta m^2_{\rm atm} \approx 0.03$$

with probability $\sim 3 \cdot 2\theta_{13}^{2} \cdot R^{\frac{1}{2}\div\frac{1}{4}} \sim$ few %: 2 is U(3) Haar measure; $\frac{1}{4}$ in see-saw.

The present situation is ambiguous

If not accidental the smallness of R and θ_{13} has strong implications, as only two mass matrices naturally give mass hierarchy between largely mixed states

Hierarchical: see-saw with dominant ν_R mainly coupled to ν_μ, ν_τ

$$\boldsymbol{m}_\nu \simeq \begin{pmatrix} 0 & 0 & 0 \\ 0 & s^2 & sc \\ 0 & sc & c^2 \end{pmatrix}$$

accomodates small θ_{13}, but gives no prediction

Inverted: pseudo-Dirac $L_e - L_\mu - L_\tau$ (see-saw not needed but possible)

$$\boldsymbol{m}_\nu \simeq \begin{pmatrix} 0 & s & c \\ s & 0 & 0 \\ c & 0 & 0 \end{pmatrix}$$

predicts $\theta_{13} \ll 1$ and $\theta_{12} \approx \pi/4$: excluded. Downgradable to $\theta_{13} + \theta_{12} \approx \pi/4$ i.e. $\theta_{13} \approx 0.2$.

Predictions from symmetries?

neutrinos: large mixing angles, small mass hierarchy
quarks: small mixing angles, large mass hierarchy

Is this compatible with unification?

SU(5): yes, if flavour physics acts more on $10 = (Q, U, E)$ than on $\bar{5} = (L, D)$.

$$\lambda_N \propto \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix} \qquad \lambda_E \sim \lambda_D \propto \begin{pmatrix} \epsilon^2 & \epsilon^2 & \epsilon^2 \\ \epsilon & \epsilon & \epsilon \\ 1 & 1 & 1 \end{pmatrix} \qquad \lambda_U \propto \begin{pmatrix} \epsilon^4 & \epsilon^3 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & \epsilon \\ \epsilon^2 & \epsilon & 1 \end{pmatrix}$$

CKM mixing is among left-handed quarks, not unified with left-handed leptons.
Pattern resembles lepton and quark masses: $m_e/m_\mu \sim m_d/m_s \sim (m_u/m_c)^2$.

SO(10): alive only with epicycles, because all fermions unified in 16.

Flavour symmetries: ν_3 hints at $\mu \rightleftharpoons \tau$. ν_2 at $e \rightleftharpoons \mu \rightleftharpoons \tau$.
Models of tri-bi-maximal mixing from thetrahedral A_4 symmetry. Predictions?

Predictions from numerology?

$$\theta_{12} + \theta_C = \pi/4$$

Predictions from zerology?

I ignore • elegant postdictions • predictions up to $\mathcal{O}(1)$ factors • predictions involving $\theta_{23}-\pi/4$ and $\cancel{CP}$ because hard to test precisely • small fine-tunings

1) 'Most minimal see-saw' (texture 0 can be motivated in a decent way)

$$\lambda_N = \begin{array}{c|ccc} & L_e & L_\mu & L_\tau \\ \hline N_1 & * & * & 0 \\ N_2 & 0 & * & * \end{array} \qquad M_N = \begin{pmatrix} * & 0 \\ 0 & * \end{pmatrix} \qquad \lambda_E = \begin{pmatrix} * & 0 & 0 \\ 0 & * & 0 \\ 0 & 0 & * \end{pmatrix}$$

gives $\theta_{13} \simeq \frac{1}{2}\sqrt{R}\sin 2\theta_{12}\tan\theta_{23} = 0.075 \pm 0.011$

2) $\theta_{13} \simeq \frac{1}{2}\tan 2\theta_{12}(R\cos 2\theta_{12})^{3/4} = 0.038 \pm 0.005$

3) $\theta_{13} \simeq \frac{1}{2}\tan 2\theta_{12}\tan\theta_{23}(R\cos 2\theta_{12})^{1/2} = 0.12 \pm 0.02$

4) $\theta_{13} \simeq R^{1/4}\sin\theta_{12} = 0.224 \pm 0.013$ (disfavoured)

Super-Split-Super-Symmetry

Proposed as a 1 April joke, can be a new source of neutrino masses: suppose that at low energy there is only SM, but we ‘know’ that high-energy is SUSY.

L, B violation suppressed by $1/m_{\mathsf{SUSY}}$.

Neutrino masses open a (little) window on high-energy; maybe we can build a predictive enough high-energy model. Most Minimal SUSY SM:

$\lambda_{ijk} L_i L_k E_k$ with $\tilde{L}_i = v_i$.

- If $m_{\mathsf{SUSY}} \sim 10^{12}$ GeV slepton can be higgs and R-parity not needed.
- v fine-tuned to be small (antrophic...bla bla...string landscape...bla bla)

$$m_{e,\mu,\tau} \sim \lambda v, \qquad m_{\nu_{1,2,3}} \sim \frac{v^2 A_0}{m^2_{\mathsf{SUSY}}} \frac{\lambda^4}{(4\pi)^2}$$

Neutrino masses unified with charged lepton masses.

5 parameters → many **predictions** → **excluded** after 2002 + hours.

Non-minimal models seem “not even wrong”.

(One can write a paper about typical phenomena, $\langle \tilde{\nu}_R \rangle \sim M_{\mathsf{GUT}} \gg m_{\mathsf{SUSY}}$).

. . .and. . .

What else?

Cosmology and neutrino experiments discovered something new.
New experiments will test minimal theories and search for the
unseen effects that they suggest: $\theta_{13}, \delta, m_{ee}, w, n-1, \ldots.$

What else could these experiments discover? **New light particles**

ν are not the best probe of heavy particles: high energy is SU$(2)_L$ invariant and it is easier to deal with e. Being light, $\gamma, \nu, g_{\mu\nu}$ are sensitive to light particles, which can be searched for with cosmology, astrophysics, experiments.

Colliders search for new heavy particles. Better if they have fundamental importance for theory or cosmo or astro or... E.g. neutralino: SUSY + CDM

Any light new particle would be a key discovery:

- Presumably lightness follows from some Deep Principle.
- Presumably a light particle is stable enough for affecting cosmo, astro.

(True for known light particles: $\gamma, \nu, g_{\mu\nu}$).

New light particles

ν interact with new light particles in different ways, according to their spin:

Neutral **fermion** can couple to ν as $m\ \nu\nu_{\rm s}$

Theory: ‘sterile neutrinos’ are the simplest extension of the massive ν scenario: **A**xino, **B**ranino, **C**omposite, **D**ilatino, **E**xtra-d ν_R, **F**amilino, **G**oldstino,...

Signals: more oscillations (solar, supernovæ, atmospheric, beams,... LSND); more neutrinos in BBN, CMB, LSS; warm dark matter...

Neutral **boson** can couple as $g\ \nu\nu\varphi$ or $g\ \bar{\nu}A_\mu\nu$.

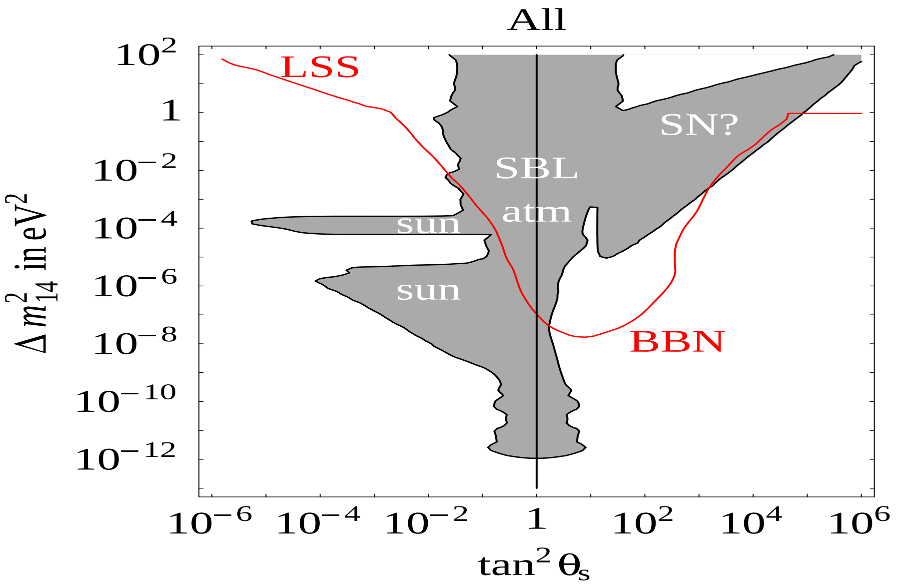
Theory: φ could be light because Goldston boson; light $\nu_{\rm s}$ needed to get $\nu\nu\varphi$:

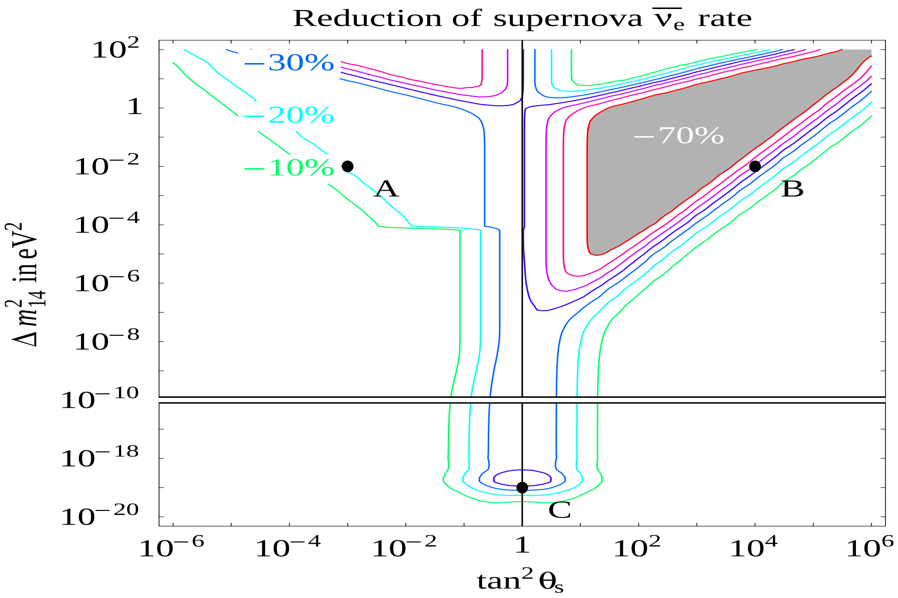
$$\mathscr{L} = \mathscr{L}_{\rm SM} + |\partial_\mu\varphi|^2 + \bar{\nu}_{\rm s}\partial\!\!\!/\nu_{\rm s} + LH\nu_{\rm s} + \varphi\nu_{\rm s}\nu_{\rm s} + (|\varphi|^2 - f^2)^2$$

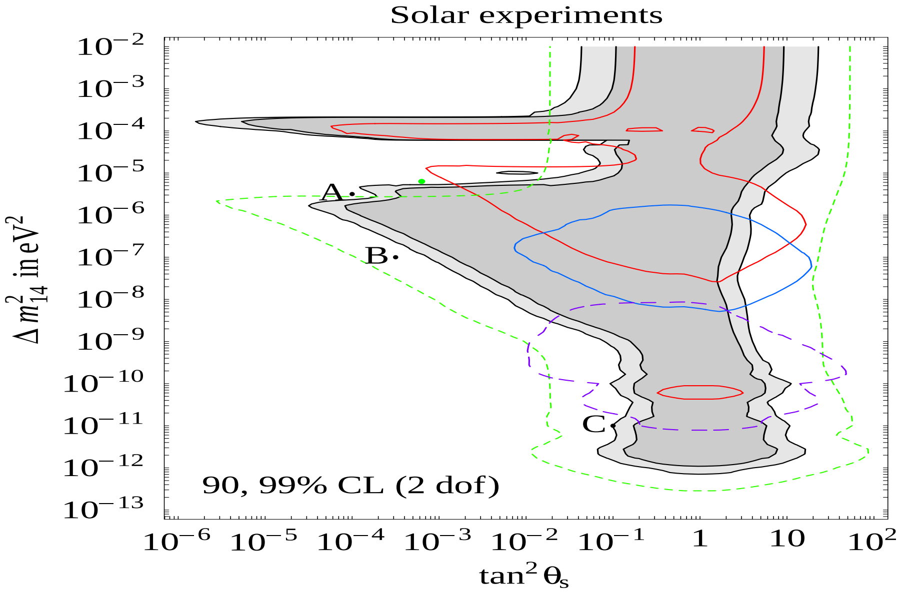
Signals: $K, \pi \to \ell\nu G$ decays; anomalous matter interactions (g^2/m^2 even if $m < E_\nu$!); more radiation and reduced free-streaming in CMB, LSS; ν decay...

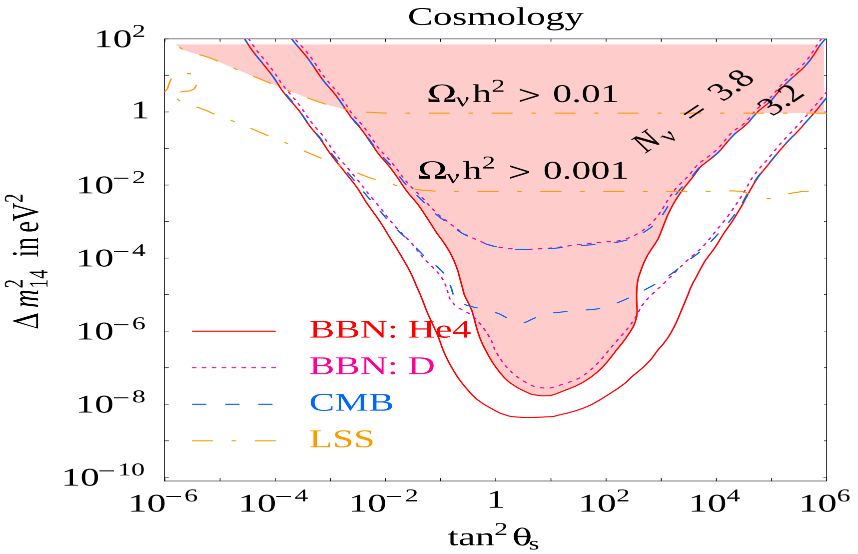
Some experimental anomalies: LSND, NuTeV, pulsar kicks, r-nucleosynthesys, low Chlorine rate, upturn in solar spectrum, solar time dependence, warm dark matter, reionization, galactic $\bar{\varepsilon}$, lower Gallium rates,...

Status of ν_s/ν_1 mixing


All


Reduction of supernova $\overline{\nu}_e$ rate

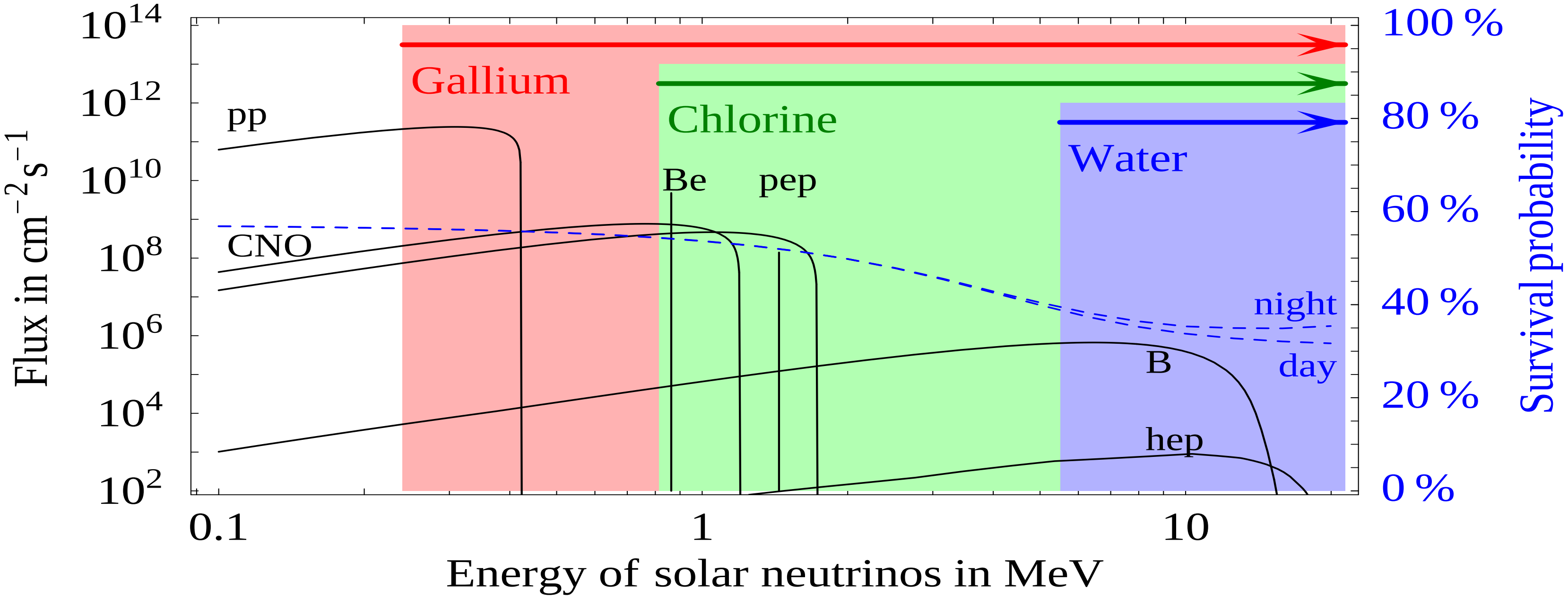

Solar experiments


Cosmology

Low energy solar ν as $\nu_{\rm s}$ signals

Are solar ν still a good signal of $\nu_{\rm s}$? Apparently SNO closed the issue: assuming energy-independent $\nu_e \to \eta\nu_{\rm s} + \sqrt{1-\eta^2}\nu_{\mu,\tau}$ data tell $\eta = 0 \pm 0.1$.

But things can be qualitatively different:



Averaged vacuum oscillations

$$P(\nu_e \to \nu_e) = 1 - \frac{1}{2}\sin^2 2\theta$$

Sun emits mostly ν_1

Critical energy

$$\frac{\Delta m^2_{\rm sun}}{G_{\rm F} N_e} \sim \text{few MeV}$$

Adiabatic MSW resonance

$$P(\nu_e \to \nu_e) = \sin^2\theta$$

Sun emits only ν_2

A sterile neutrino could mix or make a MSW resonance only with ν_1 affecting almost only the less measured sub-MeV solar neutrinos

Signals of $\nu_{\rm s}/\nu_1$ mixing

$\nu_{\rm s}$ heavier than ν_1 manifests in the sun *at sub-MeV energy*, explored only by Gallium exp.s. SK and SNO explored $E_\nu \gtrsim 5\,\mathrm{MeV}$, where the sun emits ν_2. **Measure pp neutrinos. Borexino(t) can partly explore.**

$\nu_{\rm s}$ lighter than ν_1 manifests in $\bar\nu_e$ **supernova** rates. Is a 70% reduction in SN1987A excluded? **SN20XX: better data (and better predictions?)**

In both cases BBN (^{4}He, Deuterium) and CMB (free-streaming) are sensitive probes. **Is $N_\nu = 4$ already excluded by ^{4}He? More BBN, Planck.**

Can also be studied by reactor $\bar\nu_e$, if mixing angles and Δm^2 are large enough.

Neutrinos as Dark Matter

Minimal model for m_ν and DM: **right handed neutrinos with keV masses.** (If lighter is excluded because not cold enough. If heavier decays too fast).

Needed DM sterile abundancy:

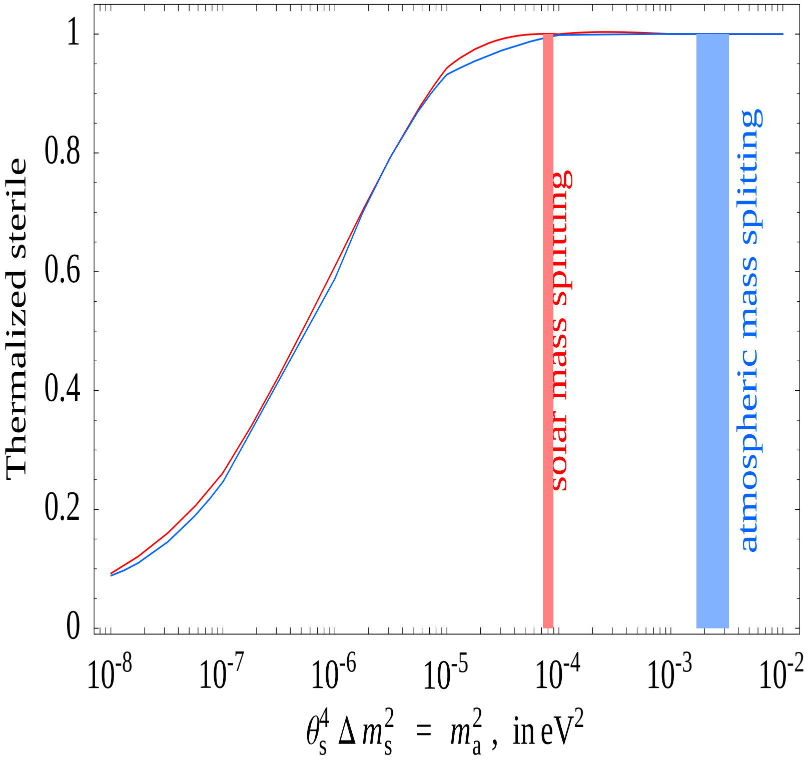
$$N_{\rm s} \sim T_{\rm eq}/m_{RR} \sim 10^{-3}.$$

Thermalization of $N_{\rm s}$ is controlled by

$$m_\nu \sim m_{LR}^2/m_{RR}:$$

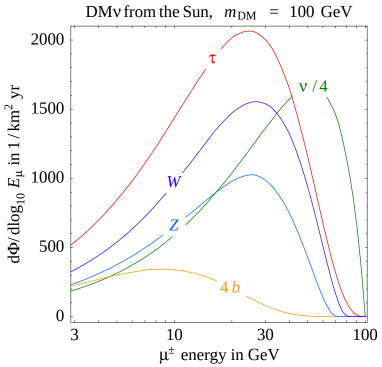
the $N_{\rm sun}$ and $N_{\rm atm}$ needed to mediate solar and atmospheric masses must be thermalized. The last $N_?$ can be DM if

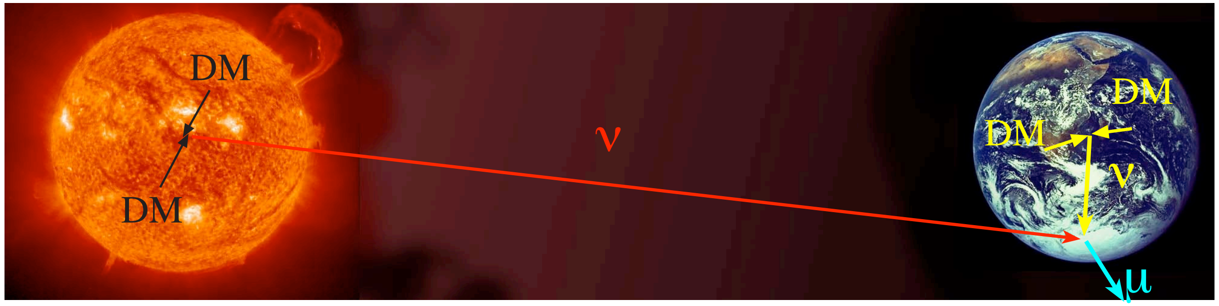
$$m_{\nu_1} \sim 10^{-6}\,{\rm eV} \ll m_{\rm sun,atm}$$

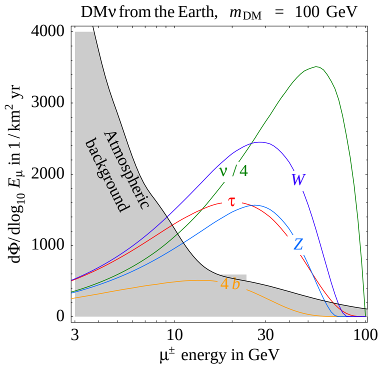


Neutrinos as signals of Dark Matter

DM accumulate in the sun and earth and annihilate into SM particles; ν exit



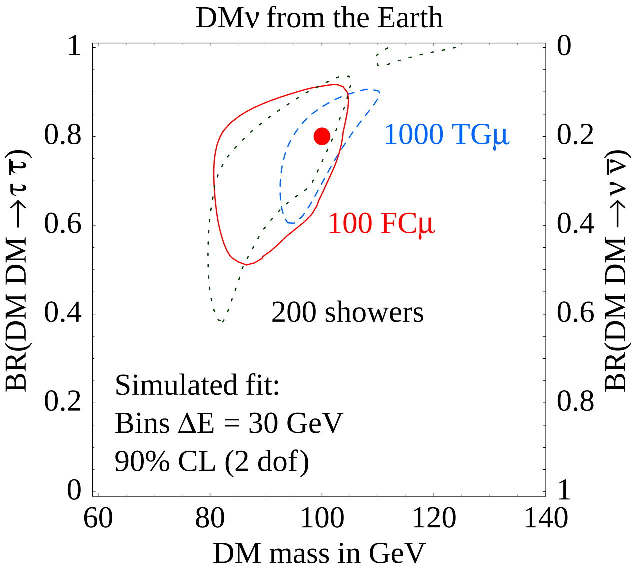




Signals: $\mu^\pm$ and showers. This DM signal allows to **reconstruct DM mass and annihilation channels**

$$\mathrm{DM\ DM} \to \nu\bar\nu, \tau\bar\tau, W^+W^-, ZZ, \ldots$$

that give characteristic spectra with $E_\nu \le m_{\rm DM}$, affected by absorption and oscillations.



Projects like IceCUBE are poor at 100 GeV. Needs **big granular** detector.

Neutrino masses and Dark Energy

Numerological connection: both around **meV**, both discovered around 2000.

DE might be the potential energy of a 'quintessence' field G. How to test? Couplings to SM seem 1) exp. problematic 2) th. unnatural: $m_G \sim H \sim 10^{-40} M_Z$.

Common solution:

G as PGBs with **small renormalizable** couplings to **light** ν_R and $m_{\nu_L \nu_L} = 0$

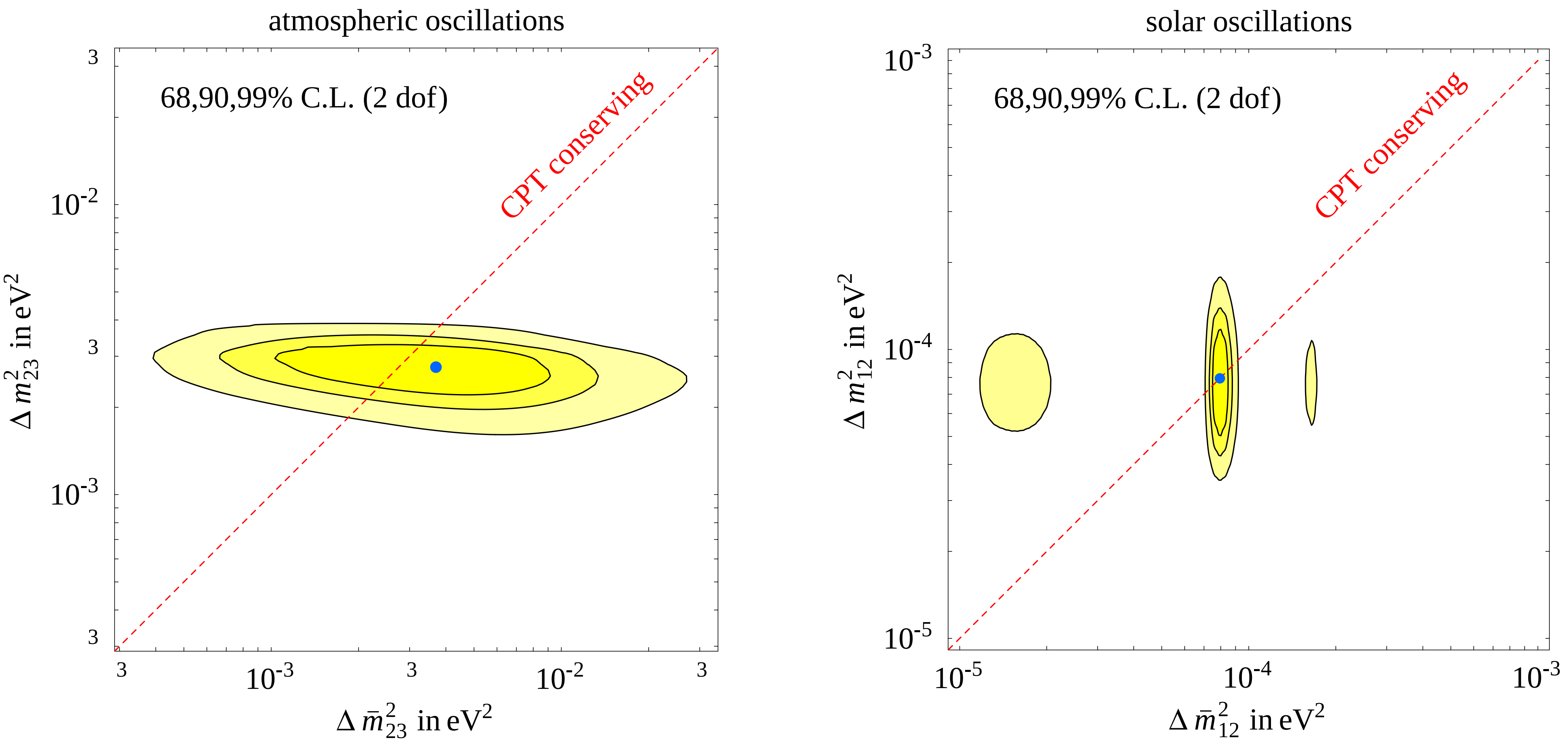
$$\mathscr{L} = \mathscr{L}_{\mathsf{SM}} + \varepsilon H L_i \nu_R^j + \varepsilon^2 \Phi_{ij} \nu_R^i \nu_R^j \qquad \Phi = M_{\mathsf{Pl}} e^{iG/M_{\mathsf{Pl}}} \qquad \varepsilon \sim \frac{M_Z}{M_{\mathsf{Pl}}} \text{ by hand}$$

2) Loop corrections give $V \sim m_\nu^4$ and $m_G \sim m_\nu^2 / M_{\mathsf{Pl}}$, as desired.
1) Steriles ν_R with mixings $\theta_{\mathsf{s}} = \sqrt{m_{\nu_L}/m_{\nu_R}}$. Constrained but still allowed.

(MaVaF..: Mass Varying Fermions: abandoning 2) one can get big cosmological variations of neutrino masses. Still alive only if very similar to Λ?)

CPT violation

Solar and atmospheric data favor equal ν and $\bar{\nu}$ mass splittings.



experiment	status	name	start	cost in 億¥ $\approx$ M\$ $\approx$ M€
WČ (3 kton)	terminated	Kamiokande	1983	5
WČ (50 kton)	running	SuperKamiokande	1996	100
WČ (1000 kton)	proposals	HyperK, UNO?	2015?	500?
Solar B	running	SNO	2001	$100+500$ (target)
Solar Be	construction	Borexino	2004?	25
Solar pp	running	Gallex $\approx$ SAGE/2	1991	$1+15$ (target)
Solar pp	proposals	many or none	2010??	100??
Reactor	terminated	CHOOZ	1997	1.5
Reactor	running	KamLAND	2002	20
Long baseline	construction	CNGS	2006	50 (beam) + 80
Long baseline	construction	NuMI	2005	110 (beam) + 60
Long baseline	approved	T2K	2008?	130
Long baseline	discussions	ν factory	2020??	2000??
β decay at 0.2 eV	approved	Katrin	2007?	25
$0\nu2\beta$ at 0.01 eV	proposals		2010??	$20\div100$
$e\bar{e}$ collider (0.2 TeV)	terminated	LEP	1989	1200
$e\bar{e}$ collider (0.5 TeV)	proposals	ILC	2020??	5000?
pp collider (7 TeV)	construction	LHC	2007?	3000?
pp collider (20 TeV)	not approved	SSC		11000
Satellite	flying	WMAP	2003	150
Space Station	flying	ISS		50000?

Conclusions

Solar and atmospheric anomalies **established**, oscillations almost seen.
Future experiments will give redundancy, testing minimal theory.
First possible surprise: MiniBoone 2006.

Progress driven by 300M€ of experiments, simple theory, nice phenomenology.

"a piece of 20th century physics that fell by chance into the 21th century"

Unexplained fundamental parameters increased from 17 to 21.
Probably bigger experiments will access a few more in next years.
Probably a window to physics at 10^{14} GeV: how to reconstruct it?

(with thanks to my $23+4$ ν collaborators, F. Vissani, R. Barbieri, C. Cattadori, M. Cirelli, P. Creminelli, S. Davidson, N. Ferrari, F. Feruglio, N. Fornengo, S. Forte, P. Gambino, G. Giudice, T. Hambye, M. Kachelrieβ, Yin Lin, G. Marandella, T. Montaruli, A. Notari, M. Papucci, M. Raidal, A. Riotto, N. Rius, G. Signorelli, I. Sokalski, R. Tomas, K. Turzynski, J.W.F. Valle)