Neutrino masses and mixings

Solar and atmospheric **evidences**

Completing **oscillations**.

Discovering neutrino **masses** (Majorana or Dirac?).

Connection with cosmology?

Alessandro Strumia, Cosmo 03

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Present status

Anomaly	Solar	Atmospheric
first hint	1968	1986
confirmed	2002	1998
evidence	9σ	17σ
for	$\nu_e \longrightarrow \nu_{\mu,\tau}$	$\nu_\mu \longrightarrow \nu_\tau$
seen by	Cl,2Ga,SK,SNO,KL	SK,Macro, K2K
disappearance	seen	seen
appearance	seen	partly seen
oscillations	not yet	partly seen
$\sin^2 2\theta$	0.86 ± 0.04	1.00 ± 0.04
Δm^2	$(7.1 \pm 0.6)10^{-5}\,\text{eV}^2$	$(2.0^* \pm 0.4)10^{-3}\,\text{eV}^2$
sterile?	5σ disfavoured	7σ disfavoured

* recently revised by SK

Unconfirmed anomalies

- A reanalysis of **Heidelberg-Moscow** data claims $|m_{ee}| \sim$ eV.

  Problems: 1.5σ at most

- **NuTeV** claims NC/CC ratio between ν_μ/iron couplings $\sim$ 1% below SM

  Could be a QCD effect e.g. strange momentum asymmetry

- ◦ Events above the **GZK** could arise from $\nu_{\text{UHE}}\nu_{\text{CMB}} \to Z$ with $m_\nu \sim$ eV

  Energy calibration? Wait Auger.

- **LSND** claims $\bar{\nu}_\mu \to \bar{\nu}_e$ with small θ and $\Delta m^2 \sim$ eV^2

  Hard to analyze ($3 \div 7$ σ) and hard to explain: best solution is 3+1, disfavoured by Bugey/SK, BBN and LSS (4 too heavy ν). Wait MiniBoone.

Interpretation(s)

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 ($\Delta L = 2$),
maybe induced by new physics **around 10^{14} GeV** (see-saw?)...

Assuming oscillations

$$\begin{aligned} |\Delta m^2_{\rm atm}| &= (2.0 \pm 0.4) 10^{-3}\,{\rm eV}^2 \\ \sin^2 2\theta_{\rm atm} &= 1.00 \pm 0.04 \\ \Delta m^2_{\rm sun} &= (7.1 \pm 0.6) 10^{-5}\,{\rm eV}^2 \\ \tan^2 \theta_{\rm sun} &= 0.45 \pm 0.06 \end{aligned}$$

Assuming flat ΛCDM and cte n_s

$$\begin{aligned} h &= 0.71 \pm 0.04 \\ \Omega_m h^2 &= 0.135 \pm 0.01 \\ \Omega_b h^2 &= 0.022 \pm 0.001 \\ n_s &= 0.98 \pm 0.04 \end{aligned}$$

Scenario must be tested (doable) and concrete theory behind found (hard)

SK ~100 億¥   WMAP ~100 M$ LHC ~2000 M€   (億¥ ≈ M$ ≈ M€)

Oscillations

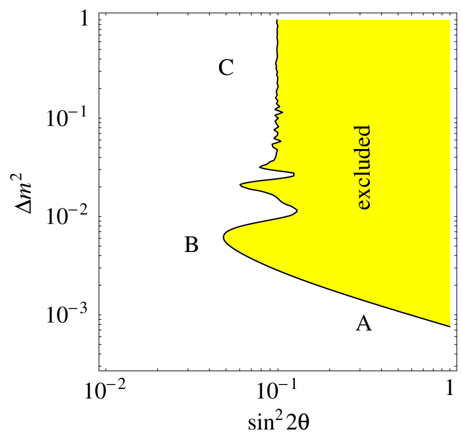
Vacuum oscillations

Present evidences can be understood knowing vacuum oscillations of 2 ν:

$$P(\nu_e \to \nu_e) = 1 - S \sin^2 2\theta \qquad S = \sin^2 \frac{c^3}{\hbar}\frac{\Delta m^2 L}{4E} = \sin^2 1.27 \frac{\Delta m^2}{\text{eV}^2}\frac{L}{\text{Km}}\frac{\text{GeV}}{E}.$$

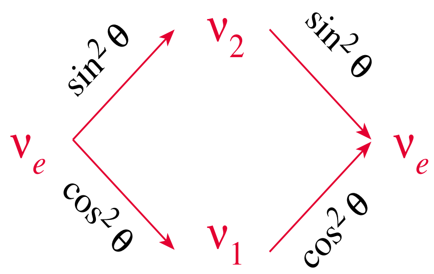
Need **low** E **and big** L to see this macroscopic quantum phenomenon

A **Oscillations with short base-line**:
$S \ll 1$, reduces to Fermi golden rule

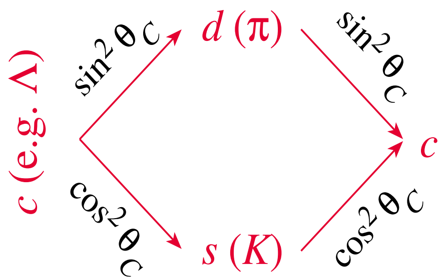


C **ΔE, ΔL averaged oscillations**: $\langle S \rangle = 1/2$

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



like



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

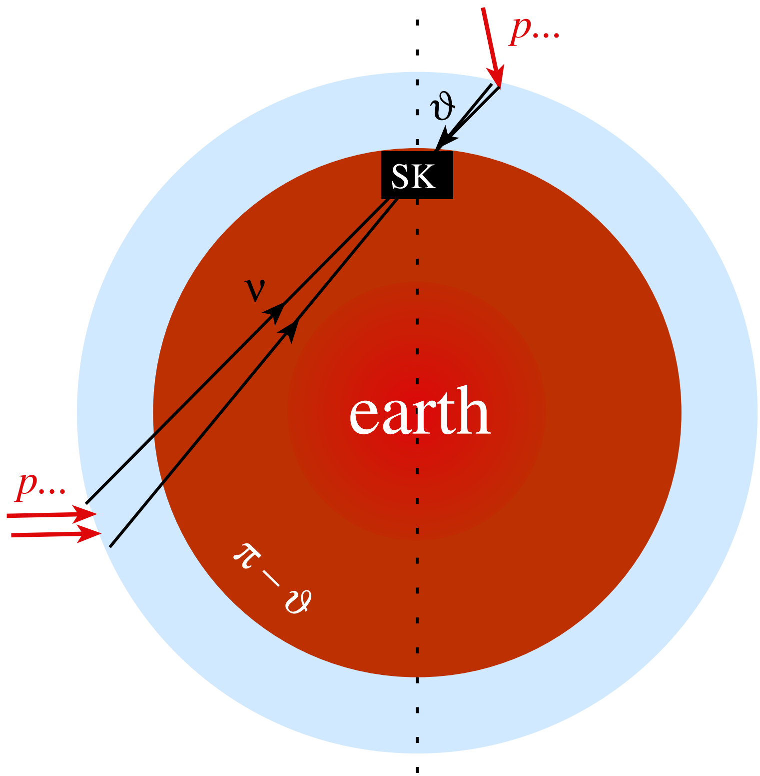
The atmospheric anomaly

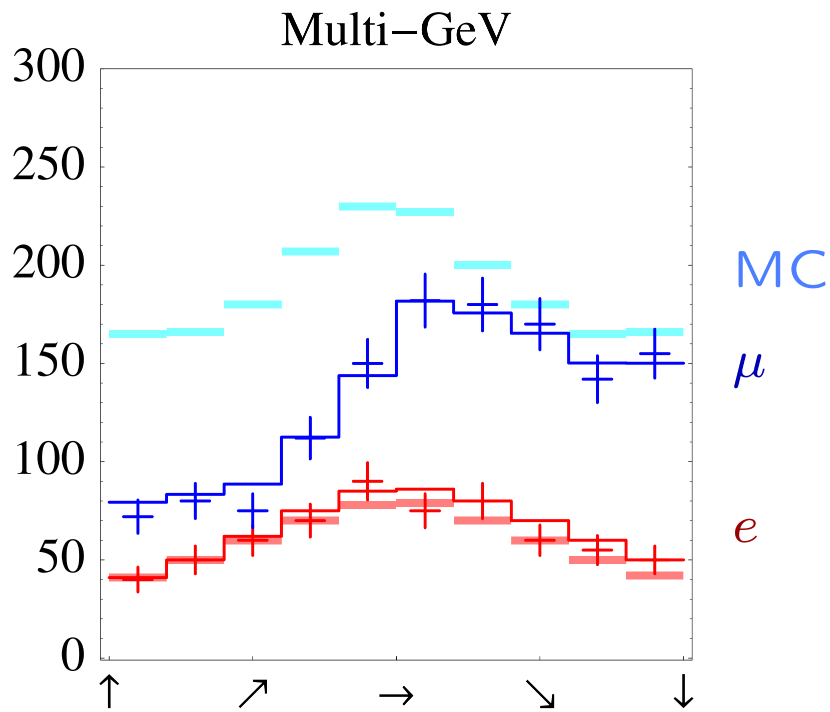
The atmospheric anomaly

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

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

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





No doubt that there is an anomaly

Atmospheric oscillations?

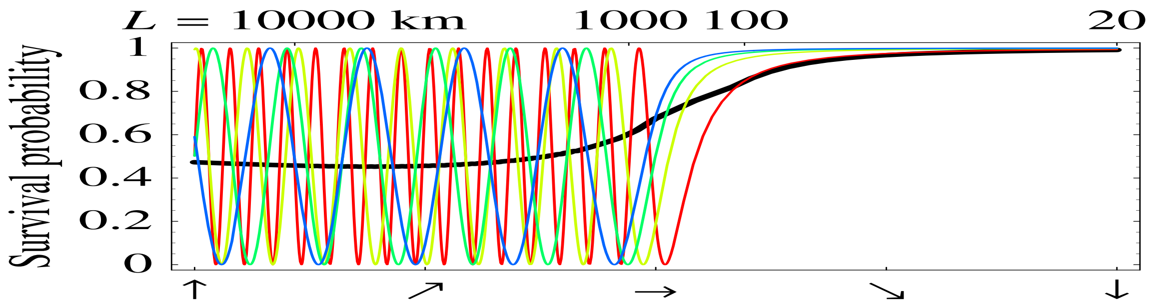
$$P_{ee} = 1 \qquad P_{e\mu} = 0 \qquad P_{\mu\mu} = 1 - \sin^2 2\theta_{\text{atm}} \;\; \sin^2 \frac{\Delta m^2_{\text{atm}} L}{4E_\nu}$$

- $\sin^2 2\theta_{\text{atm}} = 2\frac{N_\uparrow}{N_\downarrow} = 1 \pm 0.1$ i.e. $\theta_{\text{atm}} \sim 45$

- oscillatations begin around the horizontal $L \sim 1000\,\text{km}$:

$$\Delta m^2_{\text{atm}} \sim \frac{E_\nu}{L} \sim 3\ 10^{-3}\,\text{eV}^2$$

$P_{\mu\mu}(L)$: at SK $\sigma_{E_\nu} \sim E_\nu$:
oscillation dip averaged out
(ν_μ decay disfavoured at 4σ)

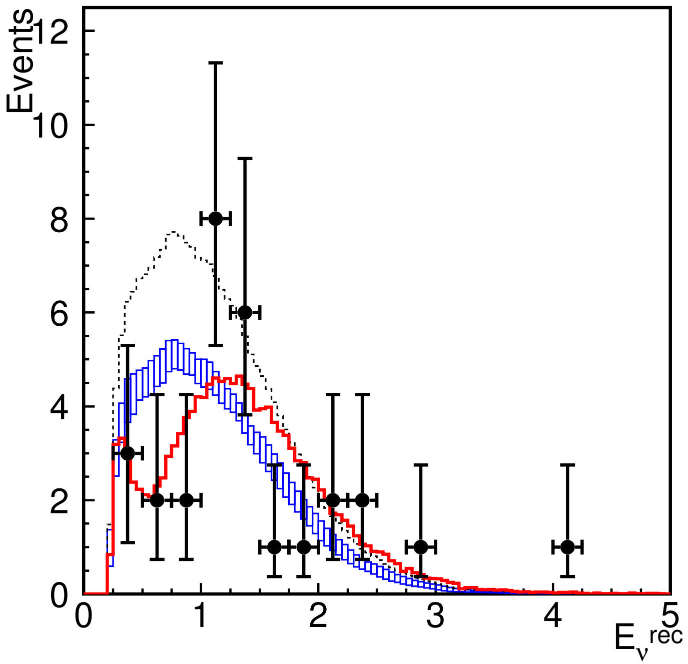


$P_{\mu\mu}(E_\nu)$: The anomaly disappears at high energy, as predicted by oscillations.

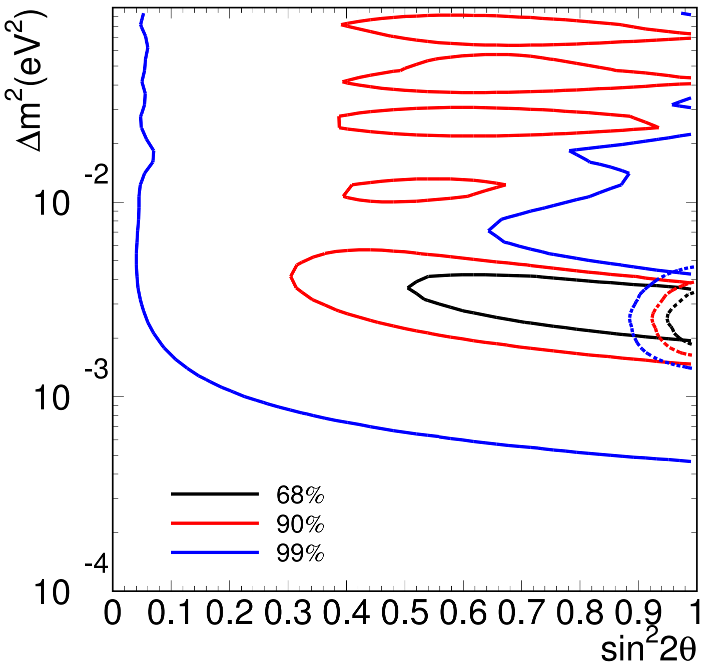
K2K

ν_μ beam sent from KEK to Kamioka ($L = 250\,\mathrm{km}$, $E \sim 1.3\,\mathrm{GeV} \sim m_p$).
80±6 events expected without oscillations (fiducial volume, forward/near ratio)
56 observed. Hint of spectral distortion. Fit consistent with SK atmospheric

K2K data



K2K vs SK fit



The solar anomaly

The solar ν anomaly

6 Dec: KamLAND confirms the solar anomaly with reactor $\bar{\nu}_e$. Few days later...

Creminelli, Signorelli, Strumia	hep-ph/0102234	9 Dec 2002 17.27.35
Barger, Marfatia	hep-ph/0212126	9 Dec 2002 20:30:41
Fogli, Lisi, Marrone, Montanino, Palazzo	hep-ph/0212127	9 Dec 2002 20:35:18
Maltoni, Schwetz, Valle	hep-ph/0212129	9 Dec 2002 20:53:09
Bandyopadhyay, Choubey, Gandhi, Goswami, Kar, Roy	hep-ph/0212146	10 Dec 2002 20:24:04
Bahcall, Gonzalez-Garcia, Peña-Garay	hep-ph/0212147	11 Dec 2002 20:33:29
Aliani, Antonelli, Picariello, Torrente-Lujan	hep-ph/0212212	15 Dec 2002 18:25:26
Nunokawa, Teves, Zukanovich Funchal	hep-ph/0212202	16 Dec 2002 18:16:34
de Holanda, Smirnov	hep-ph/0212270	18 Dec 2002 19:25:22
Balantekin, Yuksel	hep-ph/0301072	10 Jan 2003 20:17:38

In the near future main results will follow from simple arguments:

- $\Delta m^2_{\rm sun}$ from KamLAND: $P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{\rm sun} \ \sin^2 \dfrac{\Delta m^2_{\rm sun} L}{4E}$
- $\theta_{\rm sun}$ from SNO/SK: $P(\nu_e \to \nu_e) \simeq \sin^2 \theta_{\rm sun}$ and from KamLAND

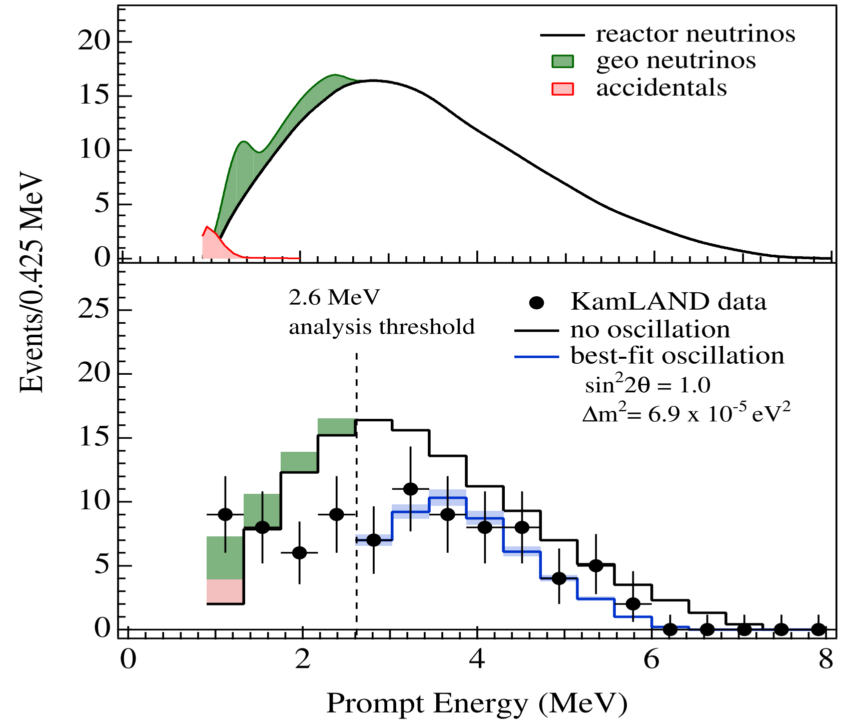
KamLAND

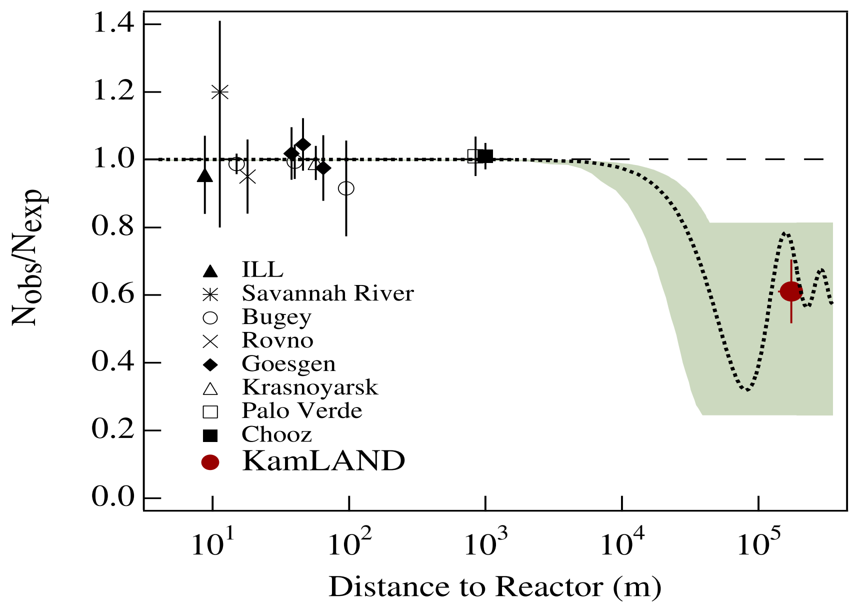
Čerenkov scintillator that detects $\bar{\nu}_e$ from terrestrial (japanese) reactors using $\bar{\nu}_e p \to e^+ n$

- Delayed $e^+ + n$ coincidence: $\sim$ no bck (geo neutrinos at $E_e < 2.6\,\mathrm{MeV}$)
- $\Phi\cdot\sigma$ known at $\sim 3\%$: $E_{\bar{\nu}} \sim$ few MeV $\ll m_p$
- $E_{\bar{\nu}} \approx E_e + m_n - m_p$: **can see spectral distortion typical of oscillations**
- Most reactors at $L \sim$180 km

- First data: 54 events seen, 86.8 expected **effect seen at 99.95% CL**
- Errors will decrease to $(3 \div 4)\%$

素晴らしい 結果

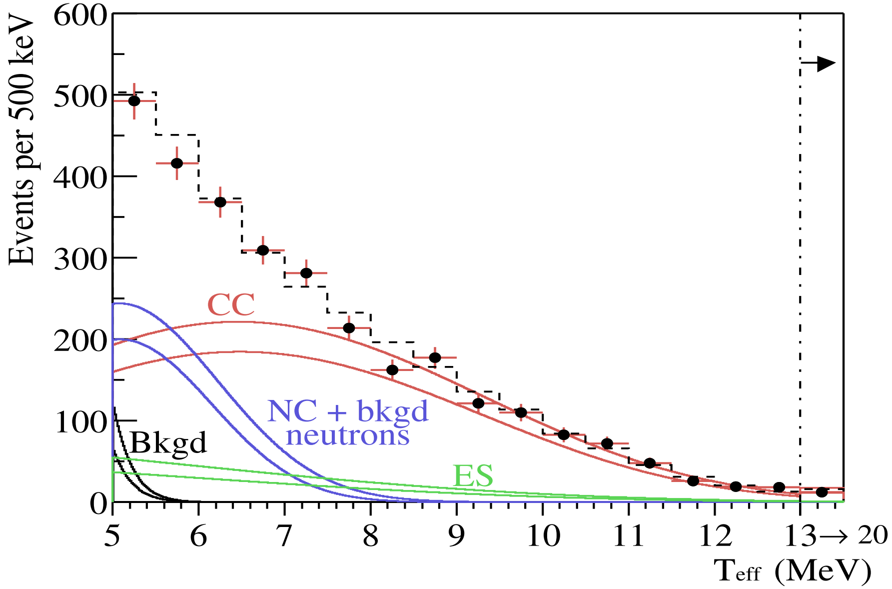


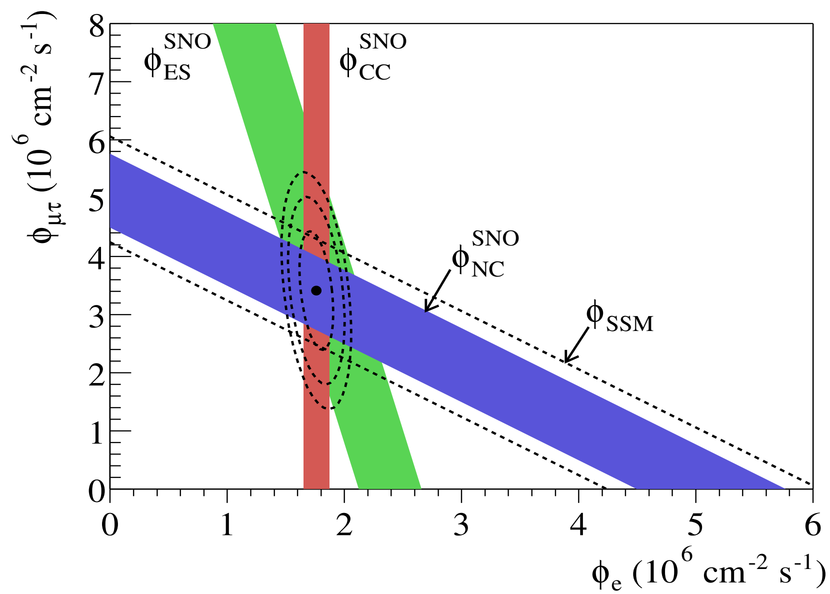


SNO

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

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

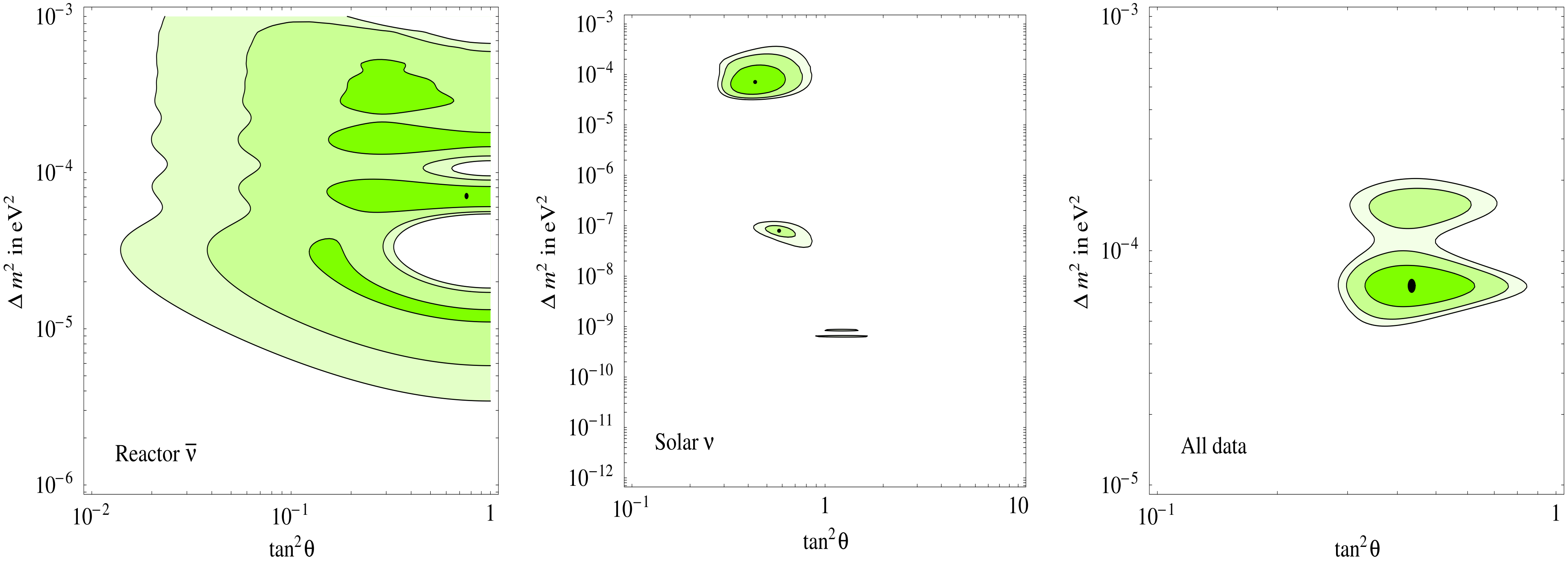




- 1st phase (2001): only e detected: distribution in ϑ_e gives CC. Confirms no spectral distortion.
- 2nd phase (2002): D captures n giving a 6.25 MeV γ ($\epsilon \sim 20\%$): CC/NC mainly distinguished by energy spectrum
- 3rd phase (2003): salt heavy water: Cl captures n giving a 8 MeV γ ($\epsilon \sim 80\%$). CC/NC mainly distinguished by zenith-angle spectrum

Reactor $\bar{\nu}$ + solar ν

Fits at 90, 99, 99.73% CL



More oscillations?

What do we know?

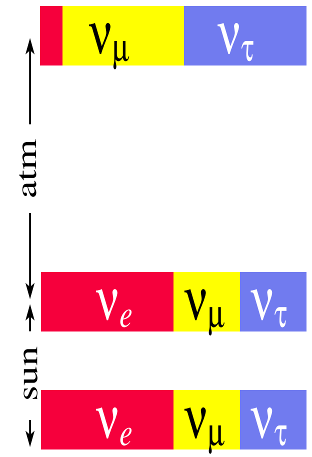
Assuming **oscillations** of **3 massive Majorana** neutrinos, we know

$$|\Delta m^2_{23}| \qquad \sin^2 2\theta_{23} \qquad \Delta m^2_{12} \qquad \theta_{12}$$

We do we not know

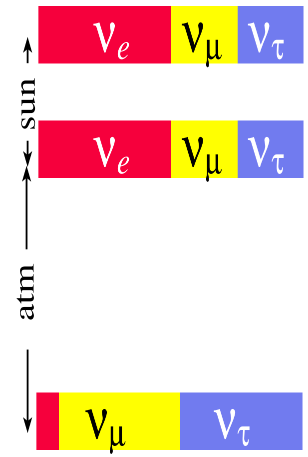
$$\theta_{13} \qquad \theta_{23} - \pi/4 \qquad \text{sign}\Delta m^2_{23} \qquad \text{overall scale} \qquad \text{CP phases } \varphi, \alpha, \beta$$

¿



'normal'

or



'inverted'

?

Future plans

Up to unexpected surprises (LSND?) future plans are:

1) Discover θ_{13}. I guess: either $\theta_{13} \approx \sqrt{\Delta m^2_{\rm sun}/\Delta m^2_{\rm atm}} \approx 4.5^\circ$
or around its bound $\theta_{13} \lesssim 15^\circ$ (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 (sun, atm, terrestrial, reactor) maybe all done.
   Beam experiments: $\theta_{13} \gtrsim 7^\circ$ 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) $\not{C}\not{P}$ from superbeam or ν-factory

Oscillations $\leftrightarrow$ astronomy

from cosmic rays: mostly done (atmospheric anomaly).

from the sun: partly done (solar anomaly). Sun shines by pp not CNO.

from the earth: KamLAND is measuring MeV $\bar{\nu}_e$ from U, Th radioactivity

from galactic core collapse supernovæ: 20 $\bar{\nu}_e$ in 1987 roughly confirmed SN picture. At the next explosion $\sim 10^3$ ν will teach us about SN and maybe θ_{13}. SK sensitivity close to expected *relic* SN $\bar{\nu}_e$ flux (might see if loaded with Gd).

from WIMP annihilations in the earth, sun... (ANTARES, IceCube, NEMO)

from other cosmic sources. If ν produced as $\pi^+ \to \mu^+\nu_\mu \to e^+\nu_e\bar{\nu}_\mu\nu_\mu$ the standard fraction $1:2:0$ gets converted by atmospheric oscillations into $1:1:1$, unaltered by extra oscillations, possibly by surprises (ν decay, $\cancel{CP}T$). Oscillation-generated ν_τ cross the earth even at high E_ν simplifying detection.

Oscillations $\leftrightarrow$ cosmology

According to SM, many things happened at $T \sim$ MeV $=$

- $(G_\mathrm{F}^2 M_\mathrm{Pl})^{-1/3}$: ν decoupling
- $m_n - m_p$: BBN
- m_e: $e\bar{e}$ heating
- max of Γ_osc/H

Formalism: evolve 3×3 density matrices $\rho_\nu, \rho_{\bar{\nu}}$ taking into account MSW effect at 1st ($\propto G_\mathrm{F}(N_e - N_{\bar{e}})$) and 2nd order ($\propto G_\mathrm{F}^2(N_e + N_{\bar{e}}) =$ thermal ν masses)

Actually ν decoupling happened a bit earlier, so

observable	naïve	$+\ e\bar{e} \to \nu\bar{\nu}$	+ oscillations	exp
^{4}He abundancy	0.246	$+0.0001$	$+0.0001$	0.24 ± 0.01
$(\rho_\nu/\rho_\gamma)/(\rho_\nu^0/\rho_\gamma^0)$ at CMB	3	$+0.04$	$+0.001$	2 ± 1

Counting neutrinos: $N_\nu = 3$ in the SM

LEP told $N_\nu = 2.984 \pm 0.008$ ($N_\nu =$ light invisible species coupled to the Z)

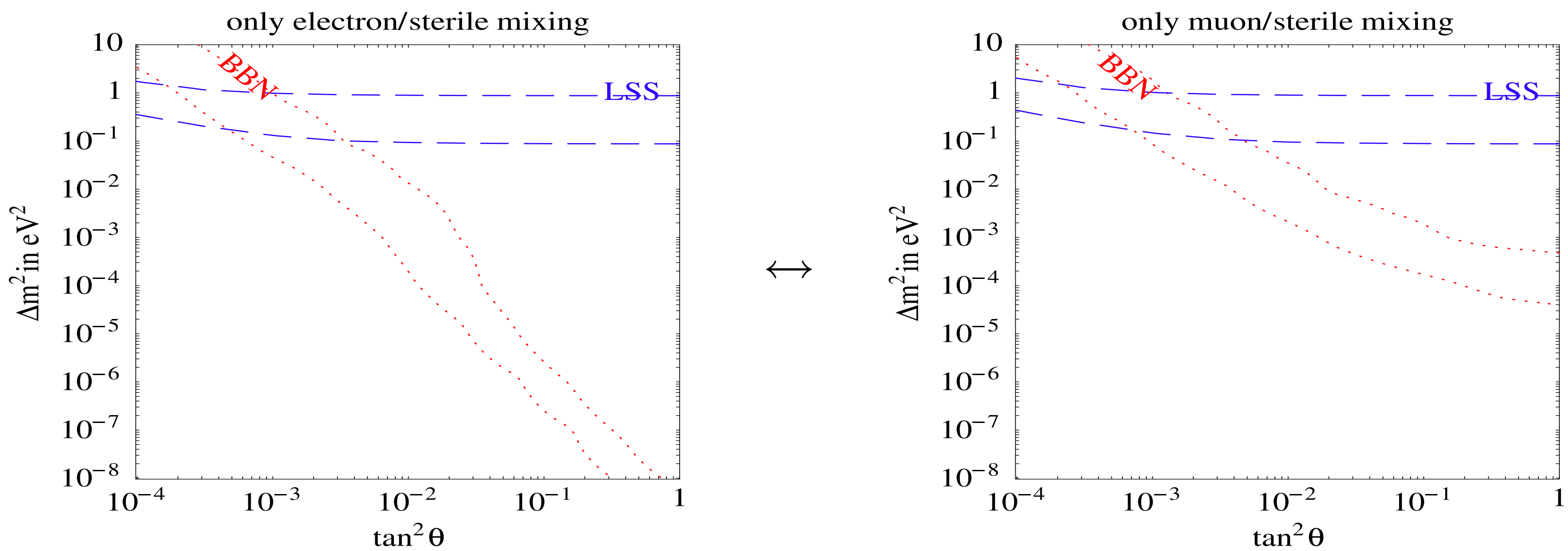
CMB starts seeing $N_\nu \gtrsim 0$ ($N_\nu =$ thermalized relativistic species at $T \sim$ eV)

BBN tells $N_\nu = 2.6 \overset{???}{\pm} 0.5$ ($N_\nu =$ thermalized relativistic species at $T \sim$ MeV)

Non-standard neutrinos in standard cosmology

'Standard' cosmology gives significant bounds on chemical ν potentials and on mixings with extra sterile neutrinos (e.g. LSND).

These bounds are affected by observed $\nu_e \leftrightarrow \nu_\mu$ oscillations...



...but can be evaded with non standard cosmology.

Summary: unsafe bounds on unseen new physics.

Cosmology might enter in causal contact with neutrinos detecting their masses

Neutrino masses

Paths to neutrino masses

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

Astrophysics. Time delay from galactic SN: $m_\nu < 20\,\mathrm{eV}$, improvable to eV. 0.05 eV if intense source of MeV $\bar\nu_e$ from cosmological distance with ms timing.

β **decay**. Mainz, Troitsk imply $m_{\nu_e} \lesssim 2\,\mathrm{eV}$, improvable to 0.2 eV.

$\mathbf{0\nu2\beta}$ **decay**. HM tells $|m_{ee}|/h \lesssim 0.4$ eV (if ν have Majorana masses implies $m_\nu/h < 1\,\mathrm{eV}$), improvable to few 0.01 eV.

Cosmology. LSS + CMB + standard cosmology imply $m_\nu < (0.23 \div 1)\,\mathrm{eV}$.

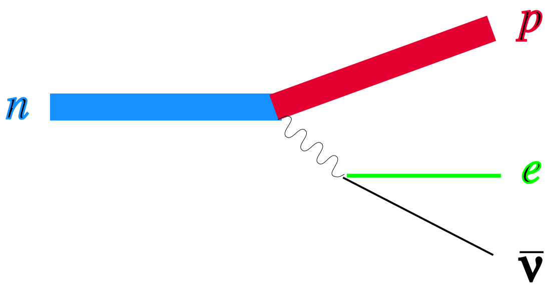
β decay

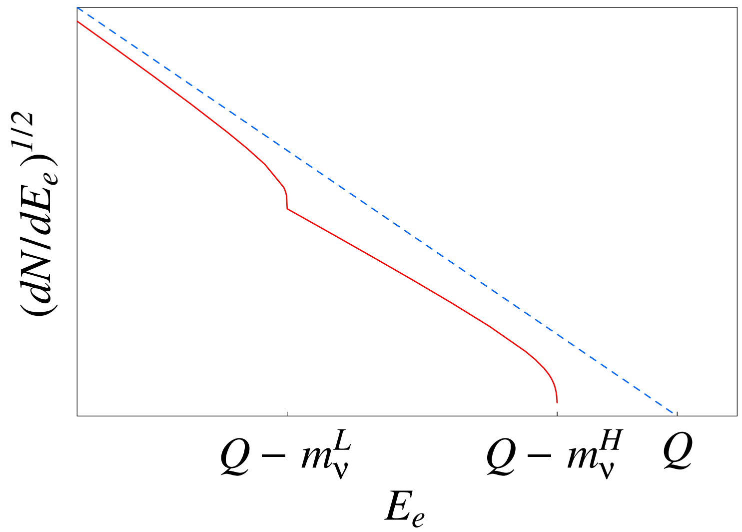
Neutrino masses affect end-point e energy spectrum in β decays, $E_e \simeq Q - E_\nu$

$$^3\text{H} \to {}^3\text{He}\ e\ \bar{\nu}_e \qquad \frac{dN}{dE_e} \propto \text{Re}\sum_i |V_{ei}^2|\, E_\nu \sqrt{E_\nu^2 - {m_i}^2}$$

$$Q = 18.6\,\text{keV}$$

In principle sensitive to all masses and all ν_e mixings:





Mainz implies $m_\nu \lesssim 2\,\text{eV}$ at 95% CL (Troitsk has a similar sensitivity)

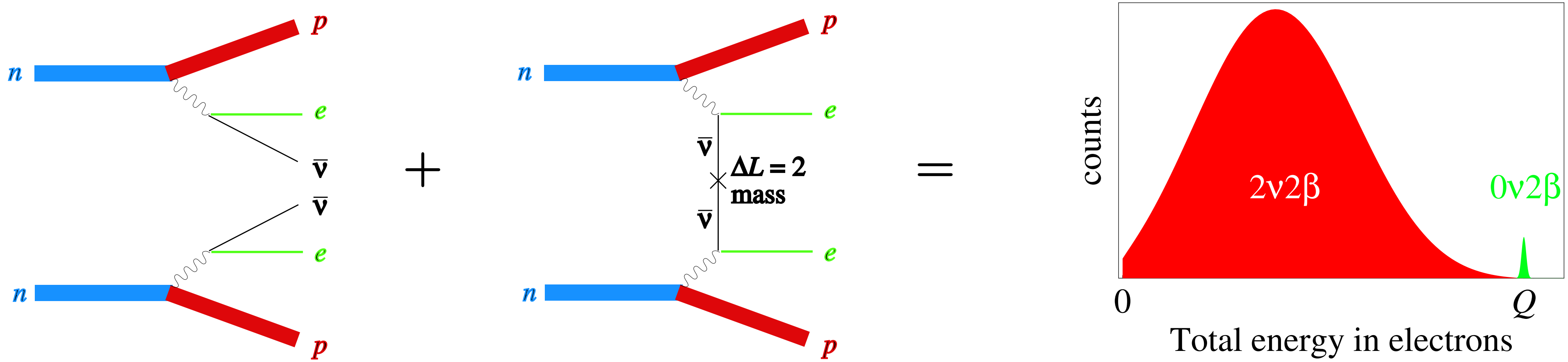
Katrin aims at reaching a $0.2\,\text{eV}$ sensitivity in 2010.
Further improvements require new ideas.

$0\nu 2\beta$

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

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

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

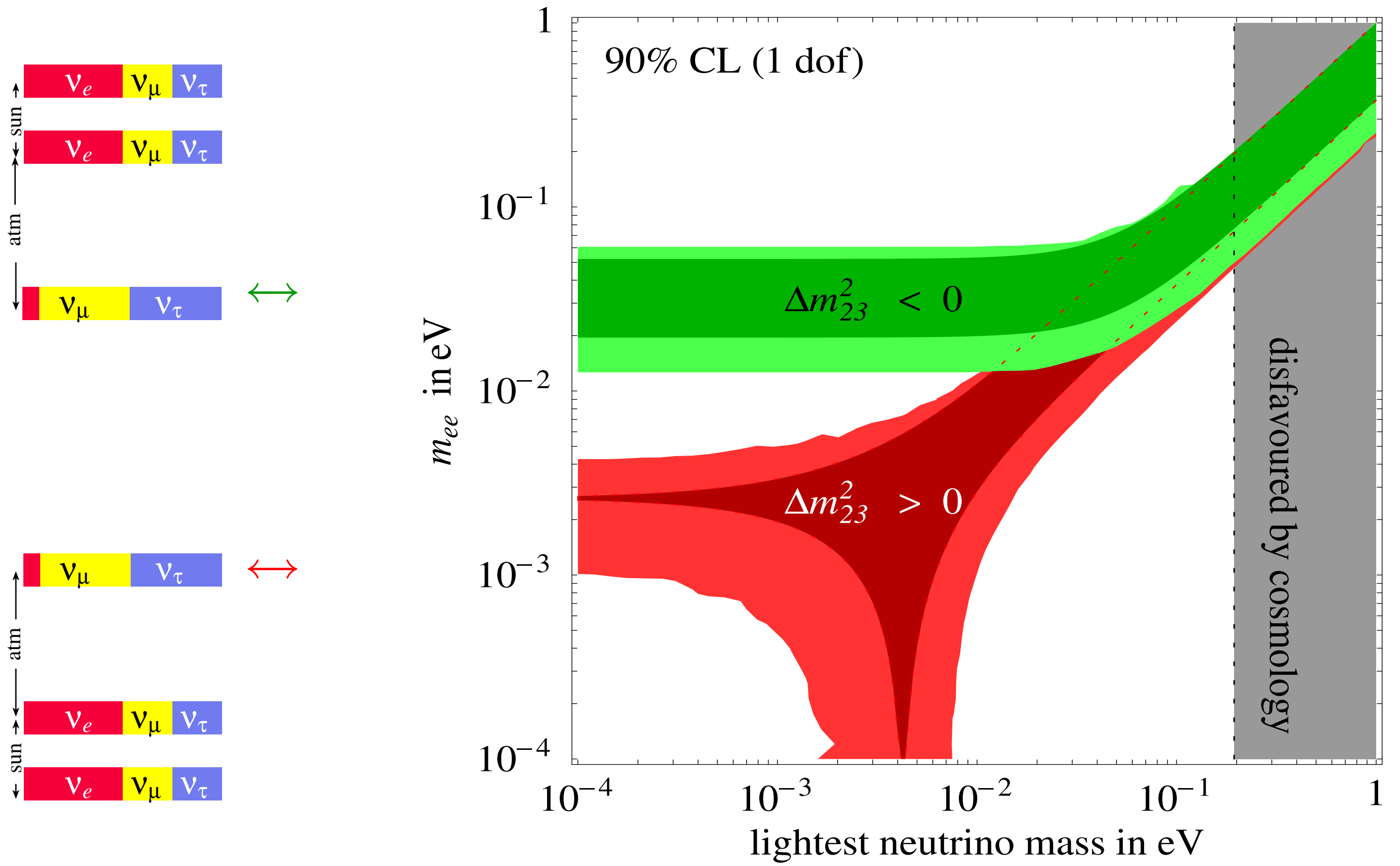


Neutrino-less double β decay $\propto |m_{ee}|^2$ implies (...) $|m_{ee}| < 0.4\ h$ eV

- $h \sim 1$ is a $\sim 50\%$ uncertain nuclear matrix element.
- Many proposals with different nuclei and experimental techniques.
- Next experiment must suppress background ($2\nu 2\beta$, cosmic, U, Th,...), improve energy resolution, be **big**. 100 M€ in steps?
- Some proposals also for detection of WIMP CDM and/or pp solar ν.

Oscillation 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.

Cosmology

Since 3 K° $< m_\nu < T_{\rm rec}$ cosmology is a powerful probe of neutrino masses.

Neutrinos reduce clustering on scales smaller than $R_U/z_{\rm nr}$, becoming non-relativistic at $z_{\rm nr} = m_\nu/3\,{\rm K} \approx 100$. Assuming 'standard cosmological models' (e.g. ΛCDM + cte n_s) large scale structures combined with CMB data imply

$$m_\nu < (0.23 \div 1)\,{\rm eV} \qquad \text{(bias? Lyman-}\alpha\text{? Priors?)}$$

If cosmology is minimal (ΛCDM with $n_s = 1$), can see $m_\nu = 0.05$ eV with CMB, galaxy power spectrum, gravitational lensing of CMB?

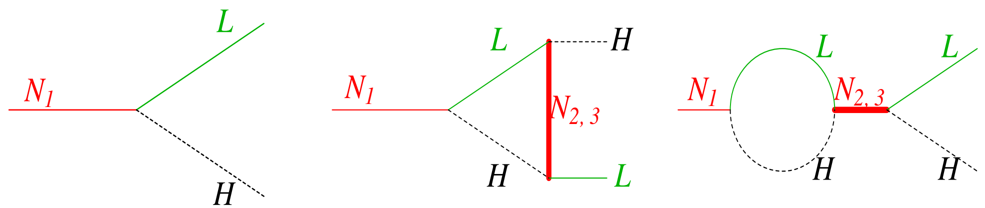
Leptogenesis

Thermal leptogenesis

$N_{1,2,3} = \nu_R$ of see-saw with Yukawa $\lambda_{1,2,3}$ and masses $M_1 \ll M_2 < M_3$
$\tilde{m}_i \equiv \lambda_i^2 v^2/M_i =$ 'N_i contribution to ν_L masses' $= \{m_{\rm atm}$ or $\gtrsim m_{\rm sun}$ or $< m_{\rm sun}\}$

Out of equilibrium (η) $N_1 \to HL$ decays violate CP (ϵ): $\boxed{6\ 10^{-10} = \frac{n_B}{n_\gamma} \approx \frac{\epsilon\eta}{100}}$

$\epsilon(M_1, \tilde{m}_{2,3}, \ldots)$

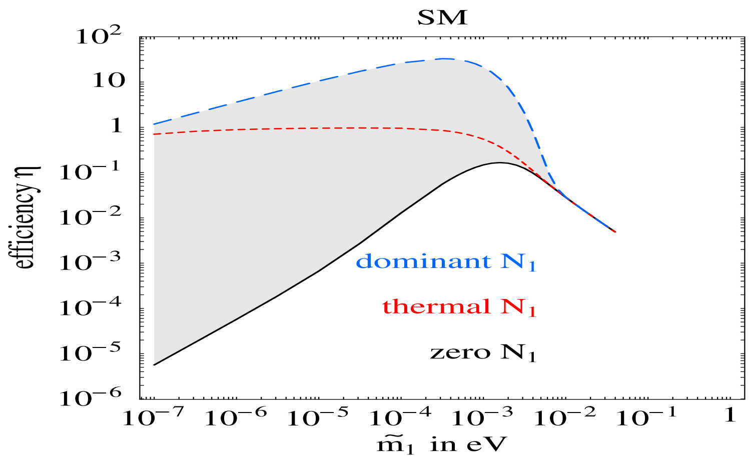


$$\epsilon \simeq \frac{3}{16\pi}\frac{M_1}{M_{2,3}}{\rm Im}\,\lambda_{2,3}^2 = \frac{3}{16\pi}\frac{\tilde{m}_{2,3}M_1}{v^2}\sin\delta =$$

$$= 10^{-6}\frac{\tilde{m}_{2,3}}{0.05\,{\rm eV}}\frac{M_1}{10^{10}\,{\rm GeV}}\sin\delta$$

$\eta(\tilde{m}_1, \ldots)$ if $\tilde{m}_1 \gg 10^{-3}\,$eV

$$\eta \sim \frac{H}{\Gamma} \sim \frac{10^{-3}\,{\rm eV}}{\tilde{m}_1} \sim 0.01 \div 0.1$$



Thermal leptogenesis: results

Smells right: as in BBN perform 'state of the art' computation adding • all sub-leading λ_t^2 and $g_{1,2}^2$ effects • thermal corrections • correct Boltzmann equations. Result changes by several $\mathcal{O}(1)$ factors.

But see-saw 'predicts' 9 Majorana ν parameters in terms of 18 parameters.

Results: 'typically' $M_1 \sim 10^{10}\,\mathrm{GeV}$. With assumptions ($M_1 \ll M_{2,3}...$) get
– Lower bound on M_1. Conflicts with gravitino over-production in SUSY?
– Upper bound on ν masses (valid if ν_L are quasi-degenerate but ν_R are not)
– No prediction neither in minimal models with a single CP phase.

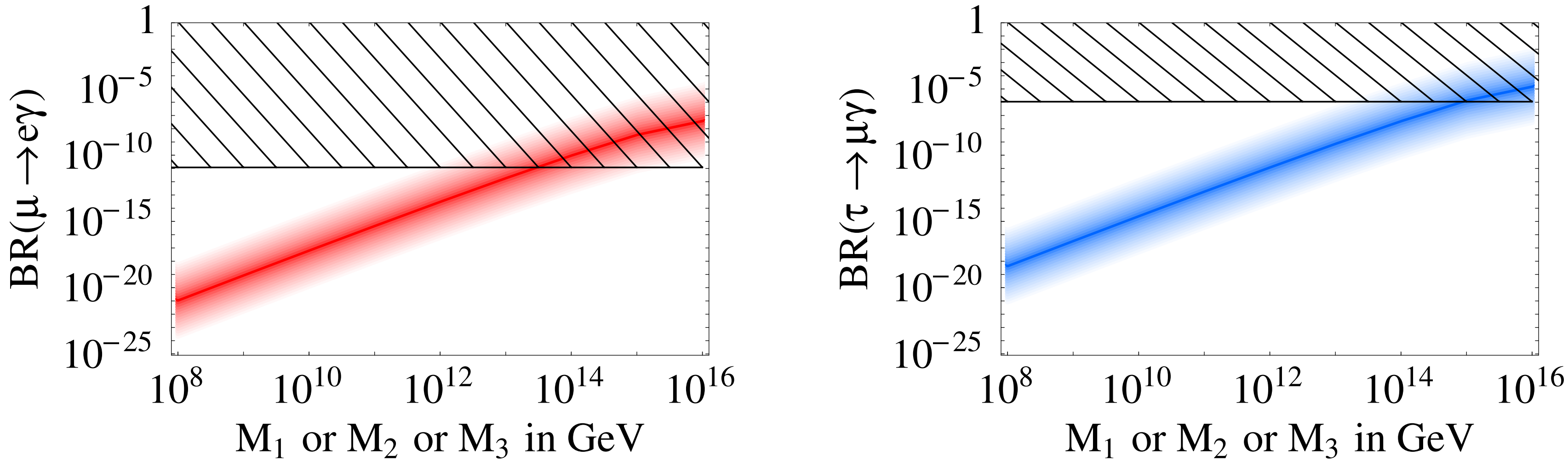
True goal is: test if leptogenesis is right, wrong or 'not even wrong':
1) understand flavour (many attempts without results), or
2) discover SUSY, $\mu \to e\gamma$, $\tau \to \mu\gamma$, δ and do archeology
3) or give up.

$\mu \to e\gamma$ 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 $M_{\rm GUT}$

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

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.