Cosmic neutrino oscillations driven by dark energy

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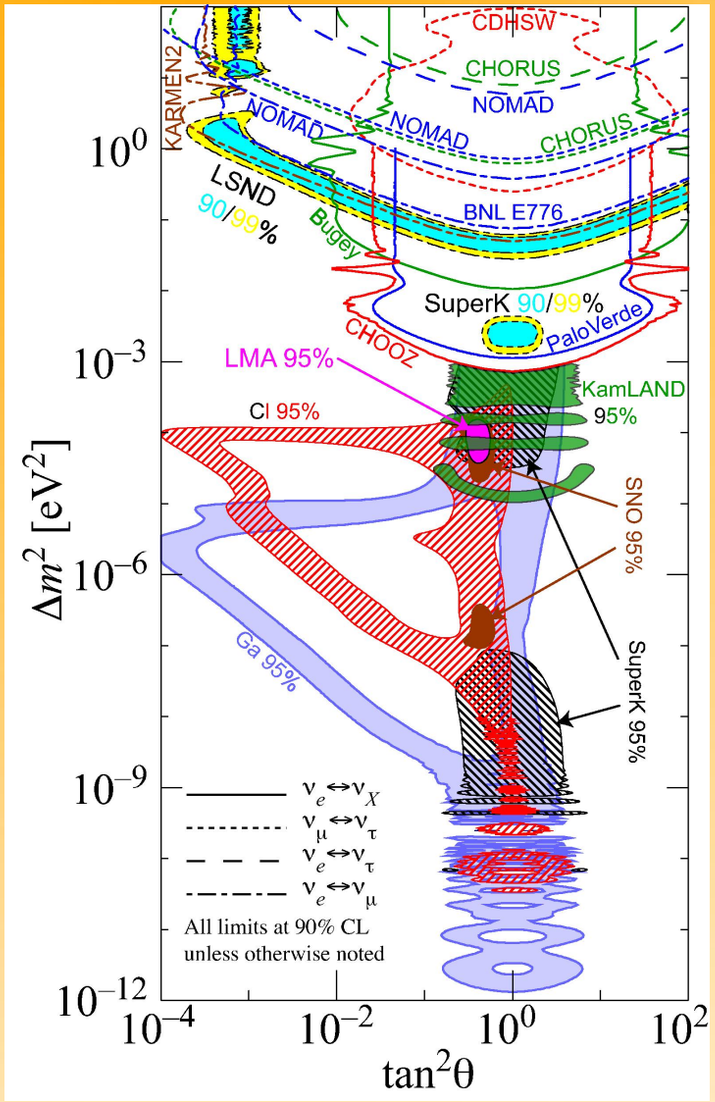
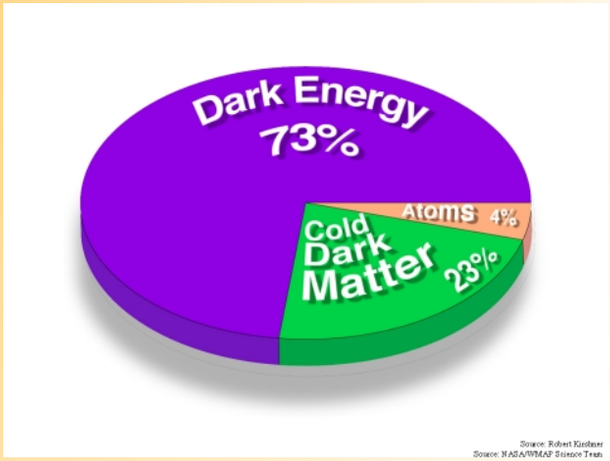
- “Numerology”
- Varying neutrino masses
- A cosmo MSW effect
- Flavor ratios of Astroneutrinos
- Conclusions

Based on:

Pham Quang Hung, Heinrich Päs:
Cosmo MSW effect for mass varying neutrinos
astro-ph/0311131





$$m_\nu = (10^{-2} - 1)\ \text{eV}$$
$$\rho_V \approx (10^{-3}\ \text{eV})^4$$

Astonishing coincidence!

Deeper connection?

Why is $\rho_\nu \propto \rho_\Lambda$?

Sterile neutrinos couple to acceleron potential

P.Q. Hung, hep-ph/0010126
A. Singh, PRD 52 (1995) 6700

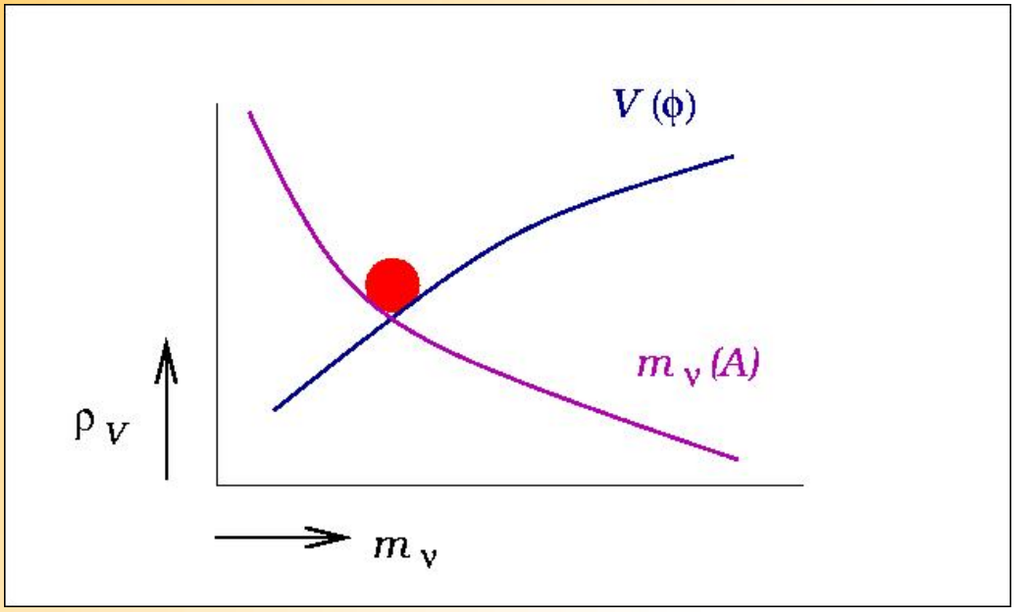
Presence of (non-relativistic) cosmologically uniform neutrino background:

effective potential which prevents m_ν from becoming too large

$\Rightarrow$ Negative pressure fluid
$\Rightarrow$ Mass varying neutrinos

Minimum of effective potential: $m_\nu \propto n_\nu^w$

$$m_\nu(z) = (1+z)^{3w} m_{\nu 0} \rightarrow (1+z)^{-3} m_{\nu 0}$$



R.Fardon, A.E. Nelson, N. Weiner, astro-ph/0309800

HOW TO TEST THESE MODELS???

MASS VARYING NEUTRINOS!

RESONANT FLAVOR TRANSITIONS?

Assume a seesaw-like matrix + extra sterile

$$\mathcal{M} = \begin{pmatrix} 0 & m_D & \epsilon \\ m_D & M_s & 0 \\ \epsilon & 0 & m_s \end{pmatrix}$$

Integrating out M_s:

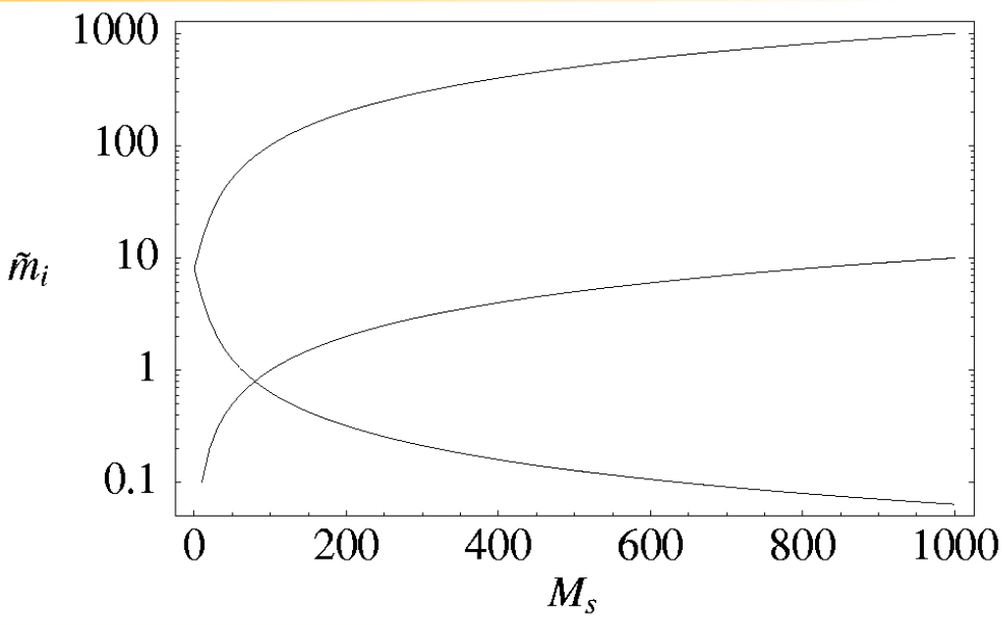
$$\mathcal{M} \to \begin{pmatrix} -m_D^2/M_s & \epsilon \\ \epsilon & m_s \end{pmatrix}$$

- Sterile neutrinos loose mass $\propto (1+z)^{-3}$

- $\to$ Active states acquire mass $\propto (1+z)^3$!

Level crossing for $-m_D^2/M_s = m_s$!

$\to$ Cosmo MSW effect in vacuo!



Evolution equation in flavor space:

- ν_s: varying mass
- ν_a: constant mass

$$i\frac{d}{dt}\begin{pmatrix}\nu_s(t)\\ \nu_a(t)\end{pmatrix} = \tilde{H}\begin{pmatrix}\nu_s(t)\\ \nu_a(t)\end{pmatrix}$$

with

$$\tilde{H} = E + \frac{m_1^2+m_2^2}{4E} + \begin{pmatrix}(-\frac{\delta m^2}{4E}\cos 2\theta + \frac{\delta m^2_{\rm cosm}}{2E}) & \frac{\delta m^2}{4E}\sin 2\theta\\ \frac{\delta m^2}{4E}\sin 2\theta & \frac{\delta m^2}{4E}\cos 2\theta\end{pmatrix}$$

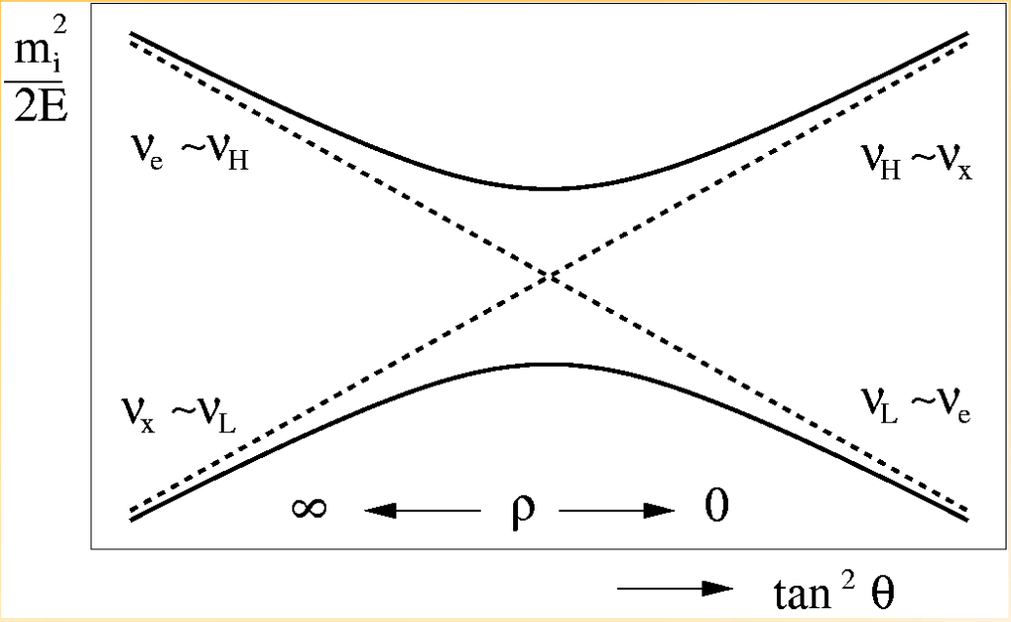
- $\theta = \left(\frac{\epsilon}{2(m_1-m_2)}\right)$: parametrizes $z=0$ mixing matrix
- $\delta m^2 = |m_2^2 - m_1^2|$
- $\delta m^2_{\rm cosm} = m^2_{s0}\left[(1+z)^6 - 1\right]$

Diagonalization of $\tilde{H}$:

$$\tan 2\tilde{\theta} = \frac{\delta m^2 \sin 2\theta}{\delta m^2 \cos 2\theta - \delta m^2_{\rm cosm}}.$$

A resonance occurs for

$$\delta m^2_{\rm cosm} = \delta m^2 \cos 2\theta$$



Strong conversion occurs for:

- Level crossing
- Adiabaticity
- Small mixing

For an adiabatic transition, the adiabaticity parameter, evaluated at the resonance, has to be large:

$$\gamma = \frac{\delta m^2 \sin^2 2\theta}{E \cos 2\theta} \left| \frac{H_0}{\delta m^2_{\rm cosm}} f(z) \, \frac{d}{dz} \, \delta m^2_{\rm cosm} \right|^{-1}_{z_{\rm res}} \gg 1$$

with Hubble relation $z = H_0 \cdot f(z) \cdot d$ and

$$f(z) = \sqrt{\Omega_M (1+z)^3 + \Omega_\Lambda} \qquad (\Omega_{\rm total} = 1)$$

Cosmological parameters: $H_0 = 70$ km/(s Mpc), $\Omega_\Lambda = 0.73$ and $\Omega_M = 0.27$

$\rightarrow f(z) \simeq 1$ for $z \ll 1$ and $f(z) \simeq 0.5 \, z^{3/2}$ for large $z \gg 1$.

Since $H_0 \simeq 10^{-33}$ eV, adiabaticity is easily fulfilled, even for PeV neutrinos!

$\rightarrow$ Jump probability $P^{LZS} = \exp\left(-\frac{\pi}{4}\gamma\right) \simeq 0$

$$P(\nu_a \to \nu_s) = \frac{1}{2}(1 - \cos 2\theta \cos 2\tilde{\theta})$$

- Contrary to the common MSW effect: depends on both z and m_{s0}
- $\to$ information on absolute neutrino masses!

Active galactic nuclei: Distances 1000 Mpc ($z = 0.3$)

Energies $\sim$ PeV

Effect on the absolute neutrino mass:

$\left(\frac{m_s(z)}{m_{s0}}\right)^2 = 4.8 \quad \to \quad \delta m^2_{\rm cosm} \gg m^2_{\rm atm}$

(assuming large neutrino masses)

Neutrino conversion over $\Delta m^2 \simeq 3 \cdot 10^{-3}$ eV^2, $\sin\theta \simeq 0.1$, $m_{s0} \simeq 0.04$ eV:

$$P(\nu_a \to \nu_b) = 0.984 \quad (\text{AGN})$$

One mass eigenstate exchanges population with sterile state:
$\longrightarrow$ vanishes

- Flavor ratios $\nu_e : \nu_\mu : \nu_\tau$
  - Normal hierarchy 1:2:0:0 $\longrightarrow$ 1:1:1:0 $\longrightarrow$ $1 \ : \ \frac{1}{2} \ : \ \frac{1}{2} \ : \ 1$
    Muon to shower ratio: 5 (at ν telescopes ala IceCube)
  - Inverse hierarchy: 1:2:0:0 $\longrightarrow$ 1:1:1:0 $\longrightarrow$ 0.3 : 0.85 : 0.85 : 1
    Muon to shower ratio: 20
- Compared to 1:2:0:0 $\longrightarrow$ 1:1:1:0 due to decoherence
  Muon to shower ratio: 9
- or 6:1:1 (normal hierarchy) and 0:1:1 (inverted hierarchy) due to neutrino decay
  Muon to shower ratio: 1.5 or 40

Beacom, Bell, Hooper, Pakvasa, Weiler, hep-ph/0307025

Local sources such as SN87A in the LMC: no effect!

- strong evidence for neutrino mass variation
- possibility to acceleron potential
- Fake effect due to Neutrino overdensity at sources?

Conservative estimate:

- $\mathcal{O}(\Delta \ln \delta m^2_{\rm cosm}) \simeq 1$
- $\Delta t \sim r_{\rm s} = 3 \cdot 10^{12}$ m (Schwarzschild radius of 10^9 solar mass black hole)

$$\gamma = \frac{\delta m^2 \sin^2 2\theta}{E \cos 2\theta} \left| \frac{d(\ln \delta m^2_{\rm cosm})}{dt} \right|^{-1}_{t_{\rm res}} \simeq 1,$$

Non-adiabatic in for multi-PeV ν energies!
Non-adiabaticity is even stronger for a Gamma Ray Burst source:
$\Delta t \sim$1 light-second $\simeq 10^9$ m

- Dark energy may be related to the neutrino mass
- Time dependent neutrino masses from interactions with rolling scalar field
- Cosmo MSW effects in vacuo are possible
- Flavor ratios of astrophysical neutrinos can be changed dramatically
- Possibility to trace back the mass variation