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MASS VARYING NEUTRINOS, NEUTRINO OSCILLATIONS AND DARK ENERGY

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Dark Energy from Mass Varying Neutrinos

and Neutrino Oscillations

Talk at Conference on Fundamental Symmetries and Fundamental Constants, Trieste, September 18, 2004

given by Ann Nelson, University of Washington

based on work by

Rob Fardon, A.E.N., Neal Weiner; astro-ph/0309800, JCAP

David B. Kaplan, A.E.N., Neal Weiner; hep-ph/0401099, PRL

Kathryn Zurek, hep-ph/0405141

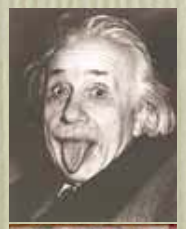
Kiyoshi Shiraishi, in progress

A.E.N., Kevin Weil, Neal Weiner, in progress

1998, First Convincing evidence for Physics Beyond the Standard Model from

SuperK, evidence for atmospheric θ_θ oscillations

But, the *"Breakthrough of the Year"* is the supernovae evidence for the acceleration of the universe



Einstein was wrong about having blundered? (Cosmological Constant?)

"Why Now" and finetuning are evidence for the Anthropic Principle?

Our Universe is mostly mysterious dark stuff

Strong Evidence for at least two kinds:

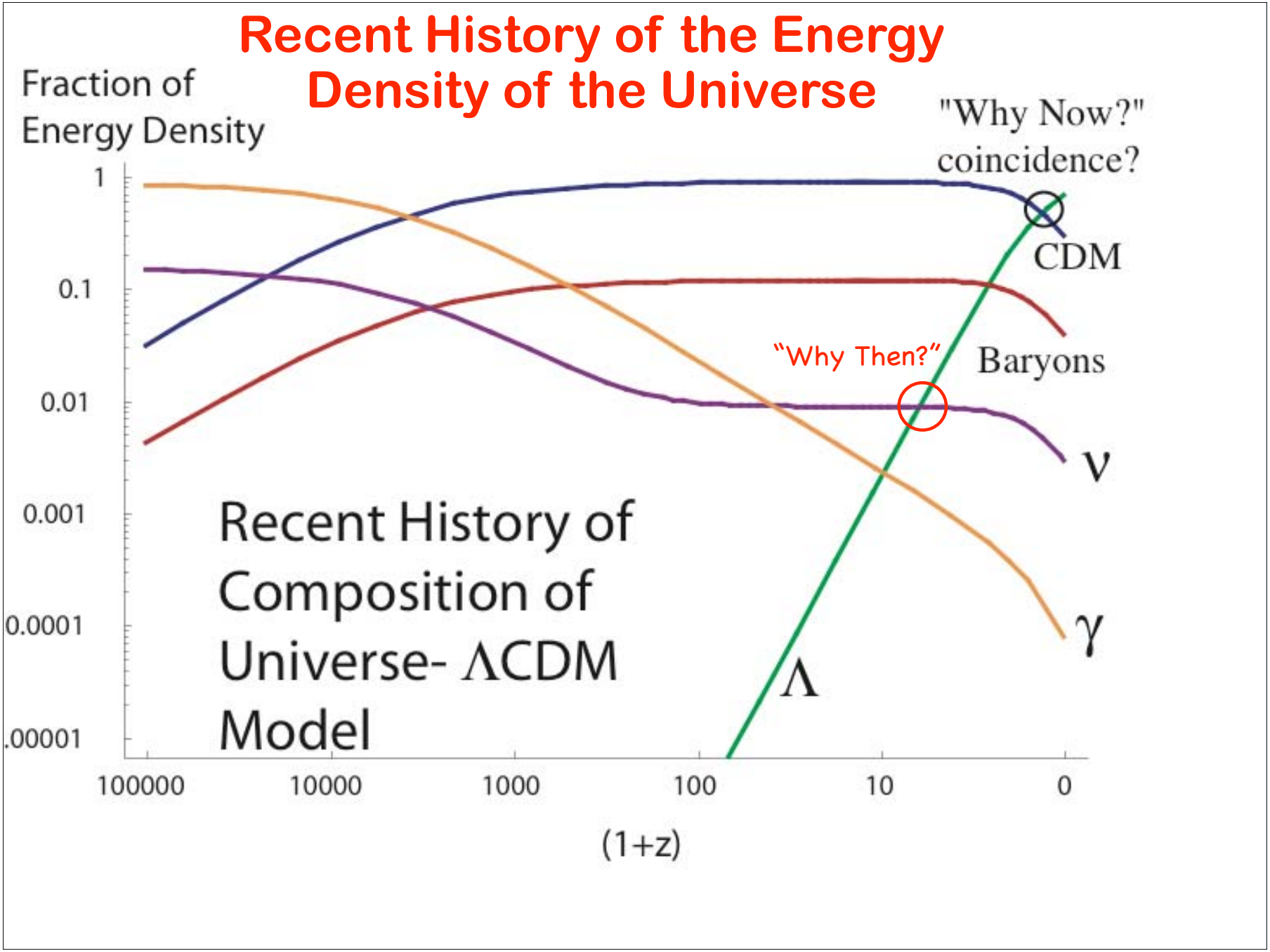
1. 23% Dark Matter β some garden variety pressureless clumpy fluid, but nonbaryonic
2. 73% "Dark Energy" β exotic negative pressure smooth substance

- ☐ usually attributed to the energy of the vacuumβ energy density which does not dilute with expansion and is therefore equivalent to Einstein's cosmological constant. I will assume this is zero.
- ☑ sometimes assumed to be some weird dynamical "quintessence" substance with equation of state parameter w near -1, which nevertheless does not clump (not your typical nonrelativistic stuff)

Hints or Red Herrings?

- Density of "Dark Energy" ~ $(2 \theta\ 10^{-3}\ \text{eV})^4$
- Solar Neutrino Mass^2 splitting ~ $(4 \theta\ 10^{-3}\ \text{eV})^2$
- Atmospheric Neutrino Mass^2 splitting ~ $(3 \theta\ 10^{-2}\ \text{eV})^2$
- Cosmological Neutrino density ~$(10^{-4}\ \text{eV})^3$
- Convincing evidence for Dark Energy found in 1998
- Convincing evidence for Neutrino Oscillations found in 1998
- Low Scale SUSY gravitino mass ~ 10^{-3} eV
- "seesaw" M_W^2/M_{Pl} ~ 10^{-5} eV

Recent History of the Energy Density of the Universe



Can dark energy be related to something we know?

- Dark Matter? We know scaling behavior of dark matter from large scale structure and CMB. Dark energy currently scales very differently. Scaling behavior of dark energy must have recently changed (Why Now?)
- Neutrinos? Could neutrino energy density scale like dark energy?
- Requires neutrino mass to increase with scale factor

Isn't varying neutrino mass crazy?

Varying 'Mass' is Everywhere!

- Index of refraction
- K_S regeneration
- Quasi particles in condensed matter
- neutrino MSW effect
- All Standard Model fermion mass terms depend on value of Higgs scalar which can vary
- All known masses depend on environment

The issue is not 'whether', but 'how much' neutrino mass should vary !

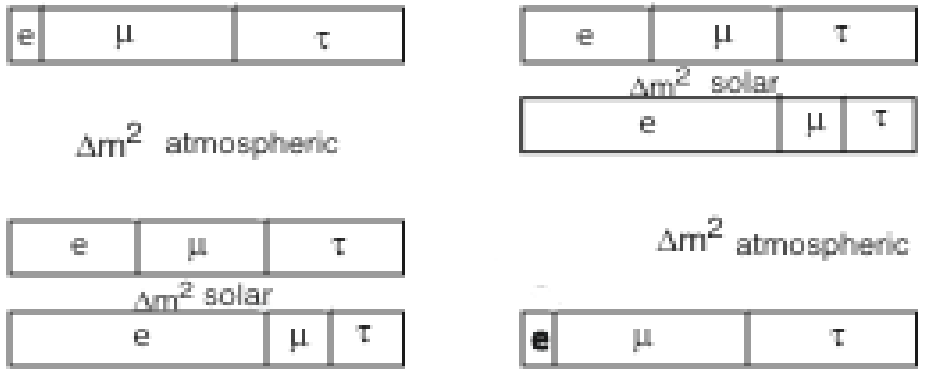
After Six Years of Surprises, Now We Almost Completely Understand Neutrinos

Neutrino mass and mixing either …

Normal Hierarchy or Inverted Hierarchy ?

β_{13} ?

Flavor Composition of ν Mass Eigenstates



β_{13} ?

LSND outlier?

Absolute mass scale? CP? Majorana or Dirac?

No more surprises?

- Visible oscillations are sensitive to tiny GUT suppressed operators (standard seesaw) and weak force(s)
- Neutrinos can mix with dark fermions
- Neutrinos can thus experience dark forces much more strongly than other particles
- Environment dependence of oscillations is sensitive to new millimeter range forces which are subgravitational strength for other particles
- Neutrinos are Special!
  Expect exotic physics to be discovered there!
  Window on the Dark Sector!

The 'mini-seesaw' MaVaN Model

Assume "Dark Sector" (= unknown particles with no standard Model charges) contains light (~10^{-3} eV)

- "Acceleron" scalar field A
- Dark fermion fields n (aka 'sterile' or 'righthanded' ν)
- Yukawa couplings $\beta A n n$
- Scalar potential $V(A)$

"Our sector" contains

- Active Neutrinos β
- Higgs Field H

Allow tiny ($y = O(10^{-11})$) Yukawa coupling $y H n \beta$

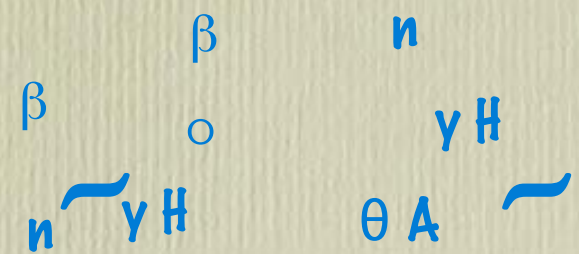
$$\begin{pmatrix} 0 & y\langle H\rangle \\ y\langle H\rangle & \beta\langle A\rangle \end{pmatrix}$$

⇨ Neutrino mass matrix

'Dirac' Mass $m_D = y\langle H\rangle \sim$ eV

⇨ 'seesaw' mass $m_D^2/\beta\langle A\rangle$

Active Neutrino Masses vary as A^{-1}



Neutrino mass matrix

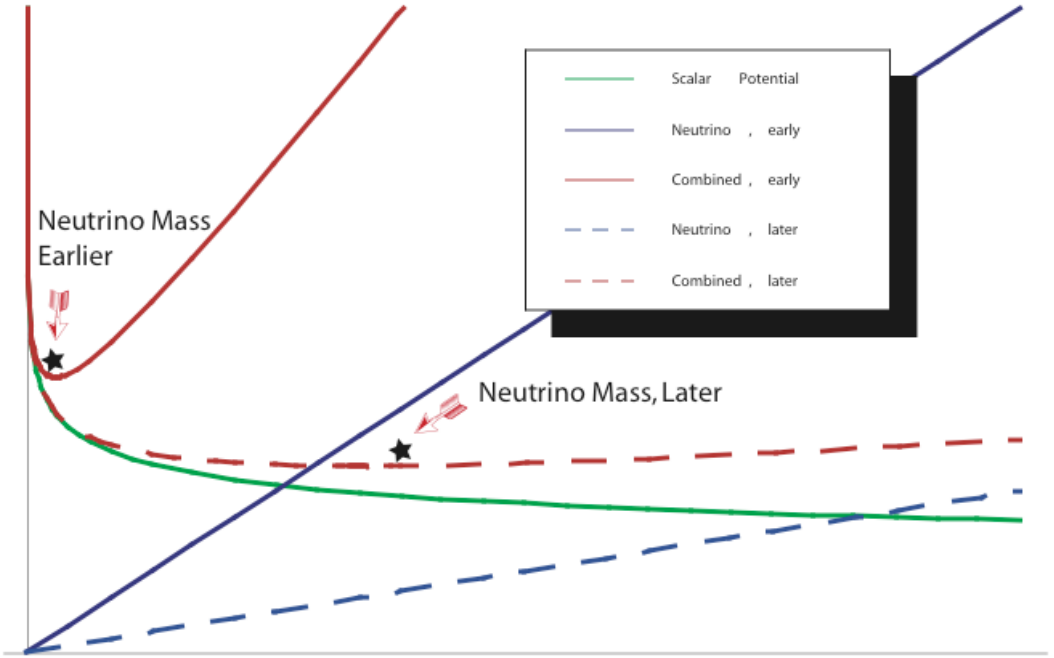
For large $\langle A \rangle$ light neutrino is mostly active, mass is $\sim (y \langle H \rangle)^2 / \theta A$

Heavier neutrino is mostly dark, mass is $\sim \theta A$

Assume $V(A)$ slowly increasing function of A.

V is then slowly decreasing function of the light neutrino mass

Energy Densities
of Scalar Potential, Neutrino Mass



- ☞ Neutrino mass increases adiabatically as neutrino density dilutes
- ☞ Combined neutrino + scalar potential energy decreases slowly

Equation of State

Shape of potential related to equation of state of neutrino+scalar fluid (for nonrelativistic MaVaNs)
Neutrino mass minimizes energy density

Neutrino density n_β dilutes as $1/a^3$

⇨ $$V = m_\nu n_\nu + V_0(m_\nu)$$

⇨ $$\mathrm{w} + 1 = -\frac{1}{3}\frac{\partial \log V}{\partial \log a}$$

$$\mathrm{w} + 1 = -\frac{m_\nu V_0'(m_\nu)}{V_0(m_\nu) + m_\nu n_\nu} = \frac{\Omega_\nu}{\Omega_\nu + \Omega_{V_0}}$$

$$V(m_\nu) \sim m_\nu^{(1+w)/w}$$

Sterile Neutrinos reconciled?

- Sterile neutrino mass increasing function of neutrino density
- Mixing with sterile neutrino decreasing function of neutrino density
- Simple to reconcile sterile neutrino with BBN ☞ sterile mass always much heavier than temperature
- May similarly evade Supernovae bounds

Can we test MaVaN Dark Energy?

- Cosmological tests of neutrino mass from large scale structure: MaVaN mass was much lighter at high redshift.
- Relation (for simple models): $m_\beta = (1+w)V/n_\beta$

  (V= dark energy density, n_β=neutrino density)
- No terrestrial sources of high scalar neutrino density (neutrino density weighted by (m/E)), relative to cosmological, other than nuclear fireball.
- Main interesting astrophysical source of high scalar neutrino density is *supernova*.

Generic tests difficult, not impossible.

Other effects of environment?

- A should have coupling to matter
- Loop suppressed and/or
- Planck/String scale suppressed
- Possible very interesting terms:

$$\frac{A}{M_{Pl}} G_{\mu\nu} G^{\mu\nu},$$

$$\frac{A}{M_{Pl}} H \bar{q}_L q_R,$$

$$\frac{A}{M_{Pl}} H \bar{\ell}_L e_R$$

Matter Dependent Neutrino Mass

e.g., in dark energy model, for $\theta m_\theta < m_\theta$, and sub gravitational strength Yukawa coupling of A to nucleons N

$$\lambda_B \frac{A}{M_{Pl}} \bar{N} N$$

the change in the neutrino mass in matter of density ρ_B is

$$\rho m_\rho \sim \frac{1\,ev}{\rho_n (w+1)} \left(\frac{\rho_B}{10^{-2}}\right) \left(\frac{\rho_B}{\bar{\rho}_B}\right) \left(\frac{m_D}{1\,ev}\right)^2,$$

where m_D is Dirac mass term connecting active and dark neutrino, $\bar{\rho}_B \equiv 3g/cm^3$

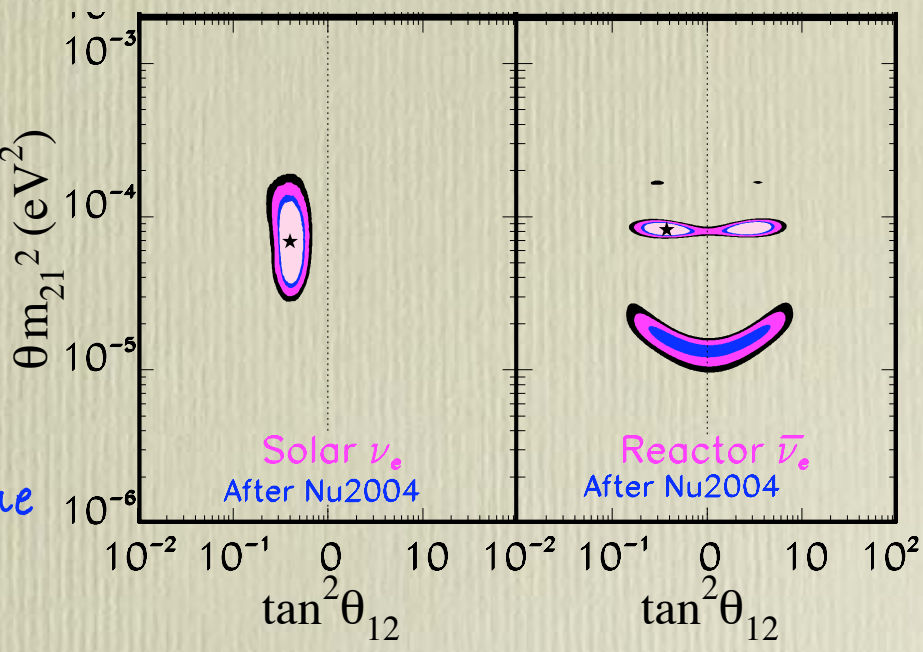
λ_n is Yukawa coupling of A to dark neutrino

Kamland/Solar Concordance

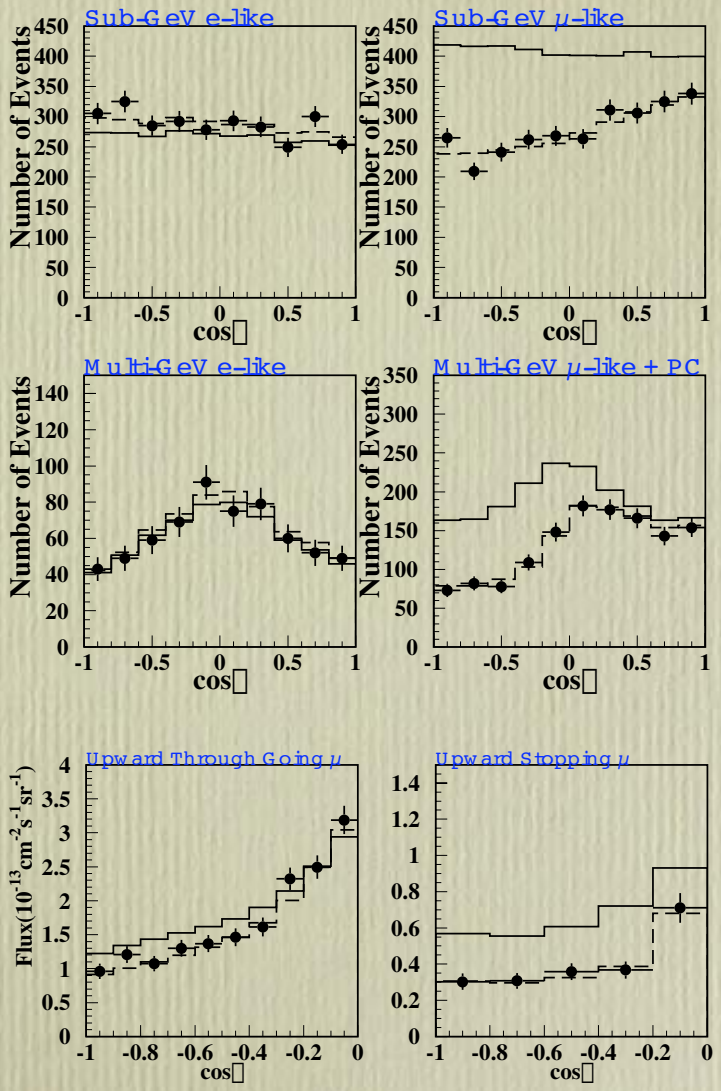
Two Neutrino Analysis of Solar Expts (particularly SNO) (Solar Interior/Space environment) and Kamland Reactor experiment (Earth's crust)

Why Concordance?

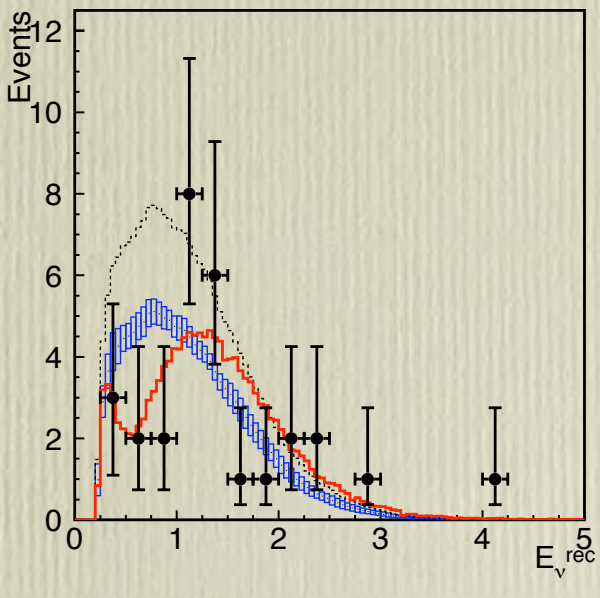
1. ν_e parameters not varying?
2. ν masses could saturate at some constant value above some maximum density
3. Weak density dependence allowed may improve fit to Chlorine, give 'anomalous' energy dependence of conversion (A.E.N. Weiner, Weil, in progress)



from Bahcall, Gonzalez-Garcia, and Peña-Garay, 2004



β_μ disapearance:SuperK and K2K Concordance



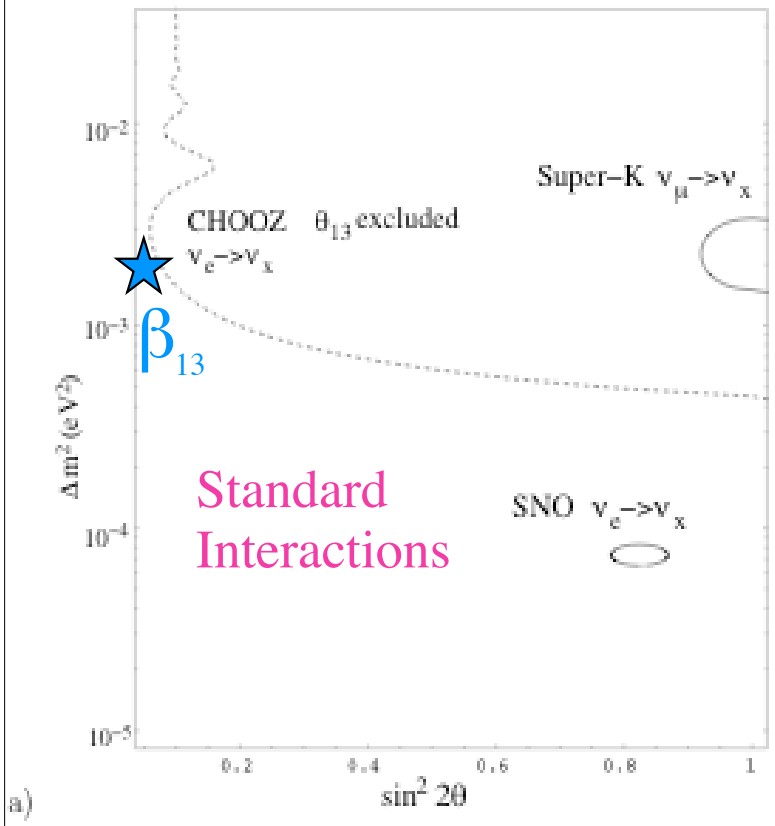
Do Neutrinos ever oscillate in air?

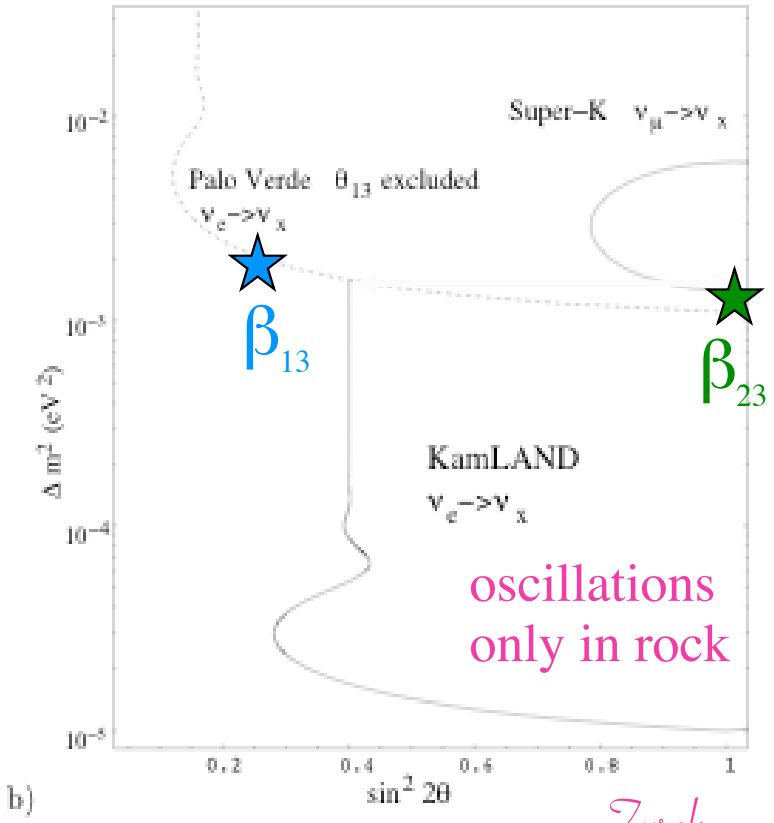
- Recent Kiyoshi Shiraishi analysis of SuperK atmospheric neutrinos assuming no oscillations in air fits all data well
- Very weak (consistent with LSND?) upper bound on mass squared difference in rock from contained, partially contained events, K2K
- reanalysis of upward through going and upward stopping muons underway, probably yields best upper bound on βm^2 in rock

Large θ_{13} in Rock? CHOOZ, Bugey baselines are in air!

Δm^2_{atm} β → | e | μ | β |

$\sin^2\beta_{13}$ $\cos^2\beta_{13}\sin^2\beta_{23}$ $\cos^2\beta_{13}\cos^2\beta_{23}$

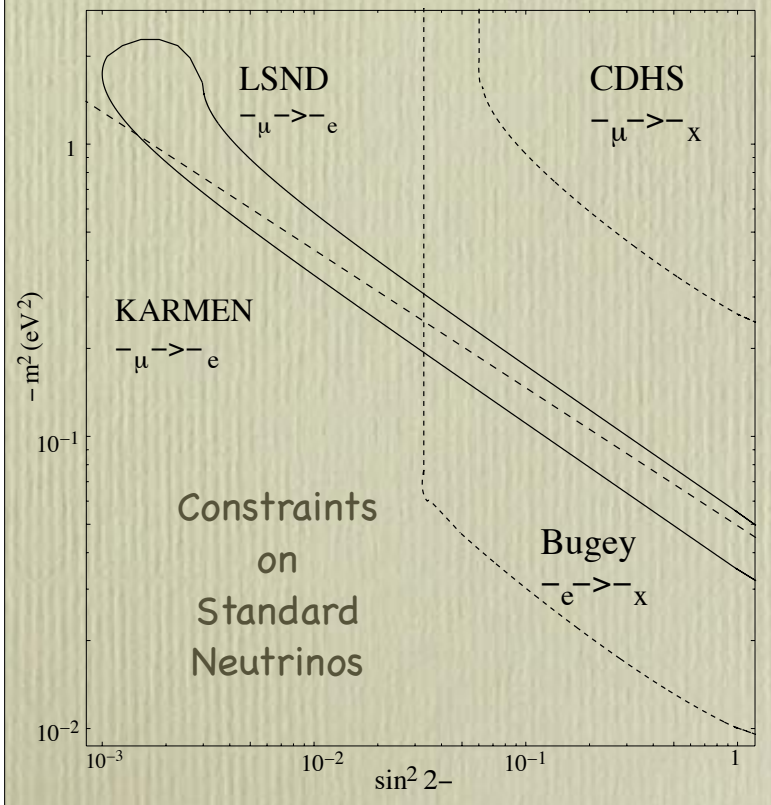




Zurek

The Outlier: LSND

Conventional Wisdom: need > 3 neutrinos to get 3 independent masses squared, and oscillations involving extra dark states constrained by Bugey, CDHS, Cosmology, and Supernova, so LSND **must** be wrong



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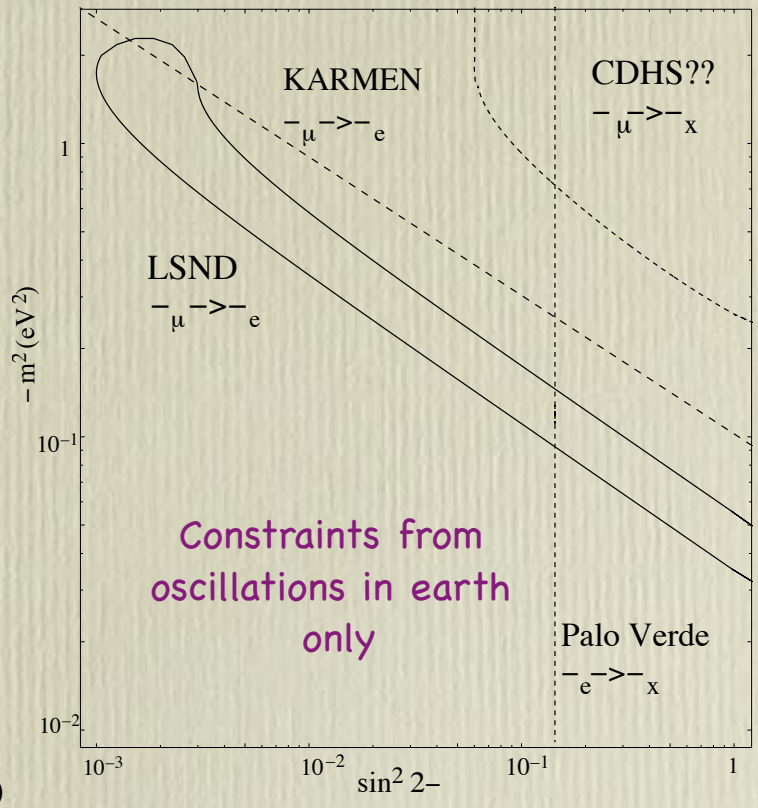

To Do: Experimentalists

- Document and consider environment of neutrino path in neutrino oscillation experiments
- Consider β_{13} measurements in reactor experiments with pathlength in air and in rock, allow for β_{13} to be larger than CHOOZ bound
- Consider environment of neutrinos in direct mass search and $0\beta\beta\beta$ measurements
- Short baseline experiments to search for heavier sterile neutrinos with small mixing angles; consider varying density of material in neutrino path

Smoking Guns for MaVaNs

- Effects of environment in neutrino oscillations?
- Tritium endpoint searches for absolute β mass depends on density of source?
- Cosmologically "impossible" sterile neutrinos?
- Cosmologically "inconsistent" neutrino masses?
- MiniBoone confirmation of LSND?
- β_{13} in matter inconsistent with CHOOZ constraint?
- Energy spectrum of solar β inconsistent with LMA?

Stay tuned

- Reanalysis of Solar neutrino expts (A.E.N., Weil, Weiner)
- Consider Supernovae constraints and phenomena
- Full 3 Flavor analysis of SuperK, upward going muons with MaVaNs (Shiraishi)
- Existence Proof of natural models (A.E.N., Weiner)
- Cosmological constraints