Neutrinos and Dark Energy

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Neutrino 2006
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"Don't you mean neutrinos and *dark matter?*"

- Exciting proposal: connect neutrinos and neutrino mass to cosmic acceleration
- This arises (directly or indirectly) from the presence of a new *force* between neutrinos
- Questions:
  - How would a scenario like this arise?
  - Theoretical/dynamical issues?
  - *Experimental tests*

New Forces and Neutrinos

- Lesson of seesaw is that *incredibly weak* forces can be *dominant* effect in neutrino propagation (MSW)
  - Neutrinos *best* probe of *weak* forces
- Long History:
  - New Gauge Interactions

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Neutrino oscillations in matter

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The effect of coherent forward scattering must be taken into account when considering the oscillations of neutrinos traveling through matter. In particular, for the case of massless neutrinos for which vacuum oscillations cannot occur, oscillations can occur in matter if the neutral current has an off-diagonal piece connecting different neutrino types. Applications discussed are solar neutrinos and a proposed experiment involving transmission of neutrinos through 1000 km of rock.

  - Neutrino mass becomes ideal testing ground for new forces - but what motivation?

A Cosmic Coincidence? Neutrino mass and dark energy

Preprint: May 15, 1998

THE ASTRONOMICAL JOURNAL, 116:1009–1038, 1998 September

OBSERVATIONAL EVIDENCE FROM SUPERNOVAE FOR AN ACCELERATING UNIVERSE AND A COSMOLOGICAL CONSTANT

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Submitted: Sept 8, 1998

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MEASUREMENTS OF Ω AND Λ FROM 42 HIGH-REDSHIFT SUPERNOVAE

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r 8; accepted 1998 December 17

STRACT

Ω_M, and cosmological-constant energy density, Ω_Λ, of
supernovae discovered by the Supernova Cosmology
pernovae, at redshifts between 0.18 and 0.83, are fitted
olo Supernova Survey, at redshifts below 0.1, to yield

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Evidence for Oscillation of Atmospheric Neutrinos

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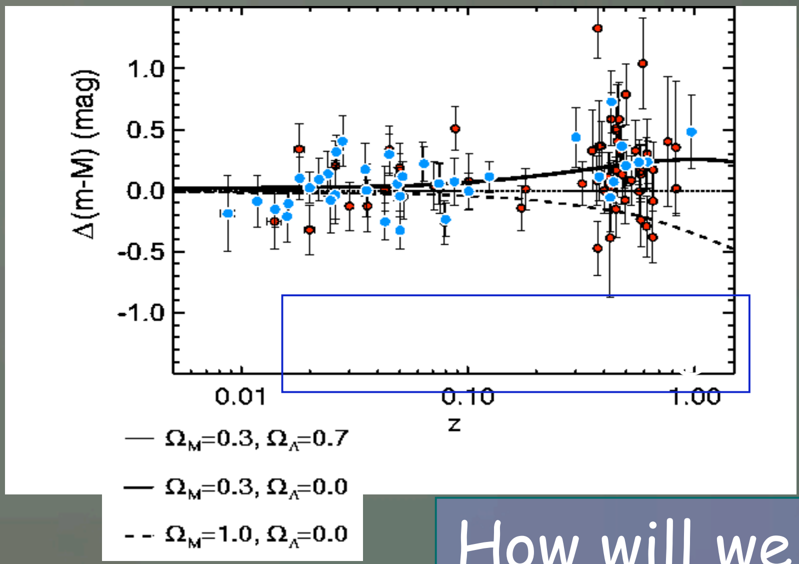
The nature of acceleration



- "I have done a terrible thing. I have postulated a particle which cannot be detected."-Pauli, 1930

How will we ever know?

$\Lambda^4 = 7 \times 10^{-30}$ g/cm^3

$\sim (10^{-2.5}$ eV$)^4$

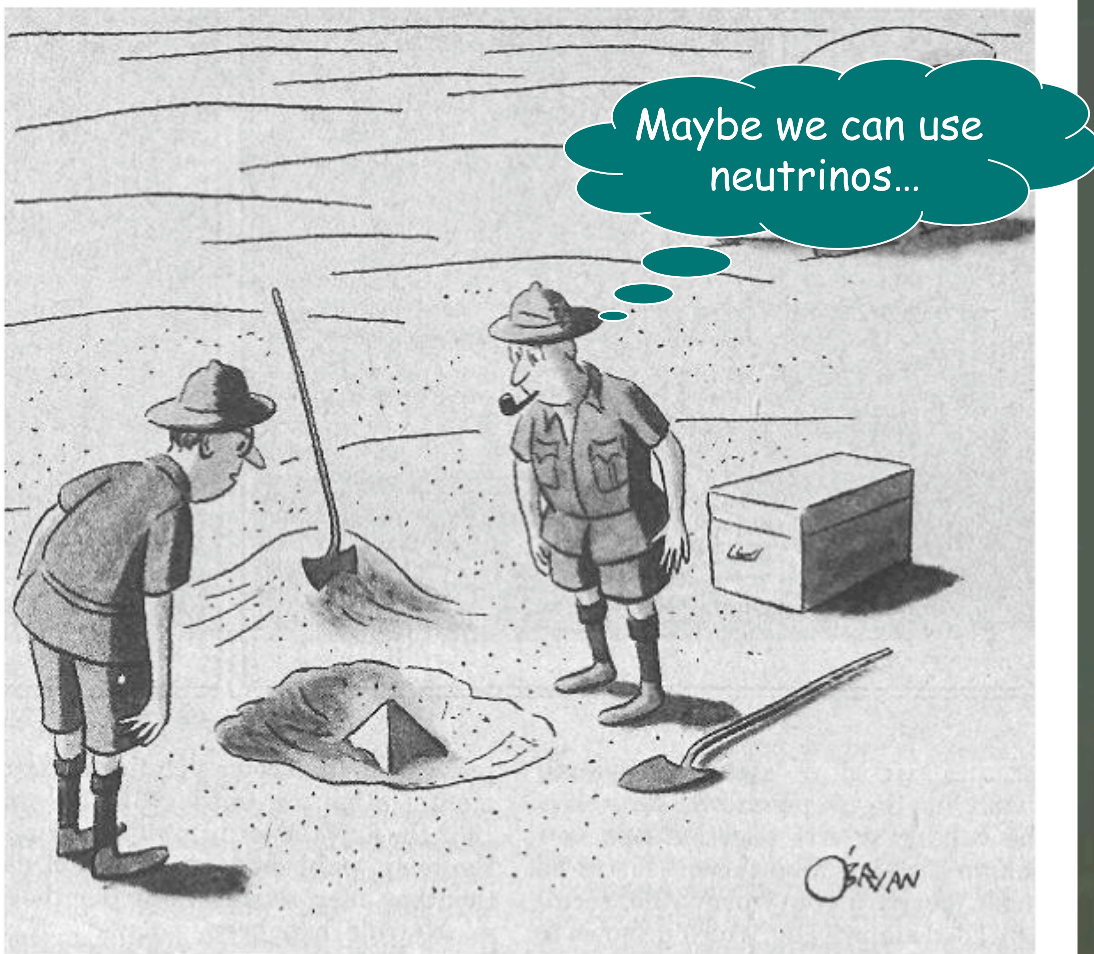
What is this stuff?

- *Anthropically selected CC from the string landscape?*
- Slowly rolling scalar field (inflation take 2?)
- Modification of gravity at the Hubble scale?
- New dynamics at the milli-eV scale?

6/19/06

N. Weiner CCPP

How far down does the milli-eV scale go?



"This could be the discovery of the century. Depending, of course, on how far down it goes."

Why neutrinos? Why neutrino mass?

- Scales are appropriate
  - $10^{-2.5}$ eV ~ m_ν
- Relic neutrinos form smooth background, like DE
  - Bad for dark matter, good for dark energy
- Neutral in low energy theory, can mix with fermions in dark sector -> new forces
  - Poorly constrained

Dependencies of neutrino mass

- Expect neutrino mass to be dynamical

$$\frac{m_D^2}{\lambda A}$$

depends on Higgs vev (m_D^2)

Depends on other vev "acceleron" (λA)

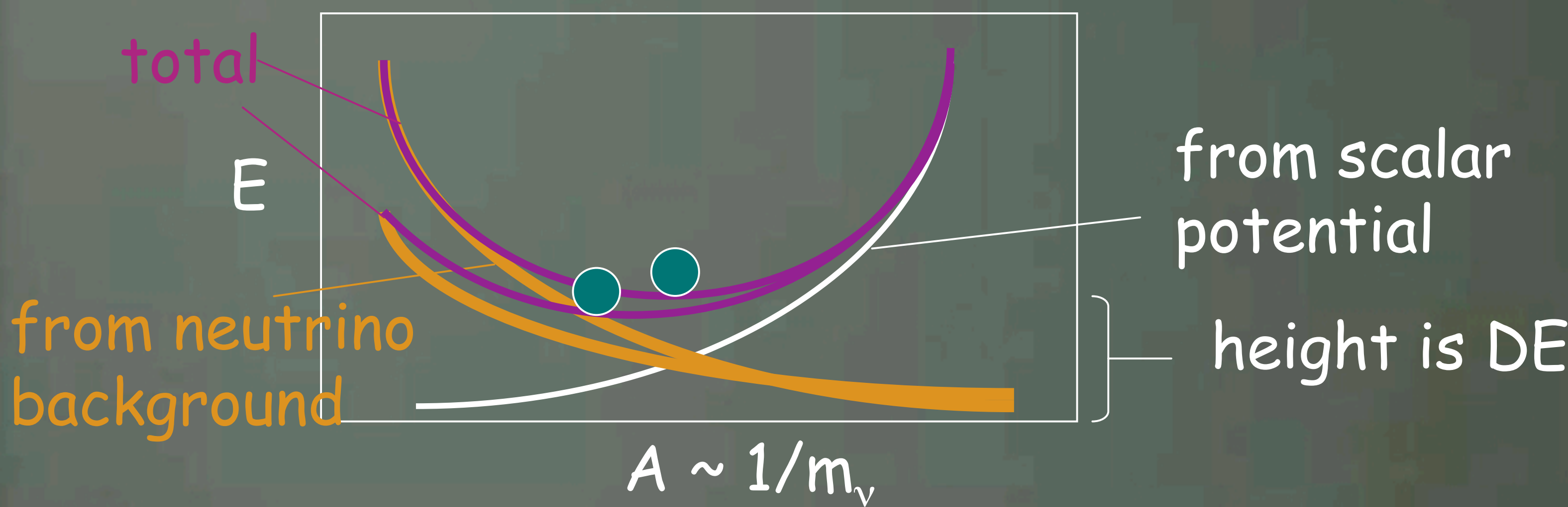
If $m_A \sim m_\nu$, what happens to neutrinos at finite density?

Mass Varying Neutrinos

$$n_\nu \frac{m_D^2}{\lambda \mathcal{A}} + V(\mathcal{A})$$

drives A to large values (m_ν to small values)

drives A to small values (m_ν to large values)



Neutrino mass changes; total energy redshifts slowly

Theoretical Questions

- Equation of state, forms of potentials - what kind of dark energy?
  - Typically indistinguishable from CC
    (Fardon, Nelson, NW '03; Peccei '04; Bi, Feng, Li, Zhang, ' 04))
- Radiative stability?
  - Scalar forces generally not long range
  - SUSY models => "Hybrid" Models
    (Fardon, Nelson, NW '05)
- Cosmological dynamics
  - Attraction between neutrinos form "neutrino nuggets"? (Afshordi, Zaldarriaga, Kohri, '05)
  - Hybrid models: OK
  - Addit'l const mass: OK (Takahashi & Tanimoto, '05, '06)
  - No present theoretical or cosmological problems

Generic Features of MaVaNs (Mass Varying Neutrinos)

- Few truly model independent consequences
  - Cosmological Variation of Neutrino Masses
  - Sterile Neutrinos (~eV)
    - Possible exception: Ma & Sarkar '06 (Higgs triplet)
  - Strong motivation to consider new matter effects
    - New scalar should couple to ordinary matter at least through gravitational-strength couplings

Cosmological Consequences

- Varying neutrino mass: suppressed imprint from massive neutrinos in power spectrum (must measure mass terrestrially)
- Cosmic ray neutrinos - dips in EHECN

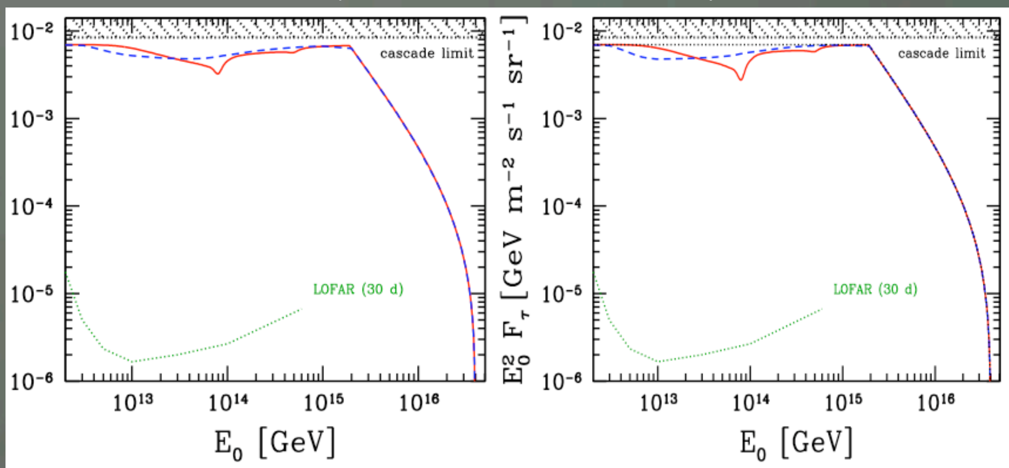


Figure 6. Projected sensitivity of LOFAR [48] expressed in terms of the diffuse neutrino flux per flavor, corresponding to one event per energy decade and indicated duration, together with $E_0^2 F$ with $F = \sum F_{\nu_\alpha} + \sum F_{\bar{\nu}_\alpha}$ (left column) and $E_0^2 F_\tau$ with $F_\tau = F_{\nu_\tau} + F_{\bar{\nu}_\tau}$ (right column) for varying (solid lines) and constant (dashed lines) neutrino masses and for $z_{\max} = 20$, assuming a normal neutrino mass hierarchy with $m_{\nu_{0,1}} = 10^{-5}$ eV, $n = 4$ and $\alpha = 2$ as well as $E_{\max} = 4 \times 10^{16}$ GeV.

Ringwald & Schrempp (June 13, '06)

Flavor changing effects: Hung & Pas '03

New matter effects

- Scalar can couple to matter but more weakly
  - Charged fermions cannot mix with light states
  - Experimental limits on long range (>mm) forces => gravitational strength
  - With DE parameters, possible O(1) variations of neutrino mass in matter (gravitational strength couplings!)
    - Different energy dependence from gauge interactions, really varying mass

$$\Delta m_\nu \sim 1 \text{ eV} \left(\frac{\lambda_\nu}{10^{-1}}\right)\left(\frac{\lambda_B}{10^{-2}}\right)\left(\frac{\rho_B}{\bar{\rho}_B}\right)\left(\frac{10^{-6}\text{eV}}{m_A^2}\right)^2$$

in many models, actually sterile neutrino mass varying + mini seesaw

Comparing experiments considering matter effects

Signal	Channel	Environment	SI $\Delta m^2_{min,max}$(eV^2)		Medium $\Delta m^2_{min,max}$(eV^2)		Ref.
SNO	$\nu_e \to \nu_e, \nu_\mu, \nu_\tau$	solar-interior	6.5×10^{-5}	8.2×10^{-5}	Unknown	Unknown	[13]
Super-K(solar)	$\nu_e \to \nu_e, \nu_\mu$	solar-interior	3×10^{-5}	1.9×10^{-4}	Unknown	Unknown	[14]
Super-K(atm)	$\nu_\mu \to \nu_x$	air/HDM	1.9×10^{-3}	3.0×10^{-3}	1.5×10^{-3}	1.5×10^{-2}	[15, 16]
KamLAND	$\nu_e \to \nu_x$	HDM	10^{-5}	7×10^{-4}	10^{-5}	10^{-3}	[17]
K2K	$\nu_\mu \to \nu_x$	HDM	10^{-3}	no limit	10^{-3}	no limit	[18]
LSND	$\nu_\mu \to \nu_e$	HDM	4×10^{-2}	1.2	4×10^{-2}	1.2	[19, 20]

Null Search	Channel	Environment	SI Δm^2_{min}(eV^2)	Medium Δm^2_{min}(eV^2)	Ref.
KARMEN	$\nu_\mu \to \nu_e$	~ 50% air	5×10^{-2}	0.1	[19]
Bugey	$\nu_e \to \nu_x$	air	10^{-2}	N/A	[21, 22]
CHOOZ	$\nu_e \to \nu_x$	~ 80 – 90% air	7×10^{-4}	4×10^{-3}	[23, 24]
Palo Verde	$\nu_e \to \nu_x$	~ 95% HDM	2×10^{-3}	2×10^{-3}	[25, 26]
CDHS	$\nu_\mu \to \nu_x$	Unknown	0.25	Unknown	[27]
NOMAD	$\nu_\mu \to \nu_\tau$	~ 60% HDM	0.7	1.2	[28, 29]
	$\nu_e \to \nu_\tau$		5.9	9.8	
CHORUS	$\nu_\mu \to \nu_\tau$	~ 60% HDM	0.6	1	[29, 30]
	$\nu_e \to \nu_\tau$		7.1	11.8	

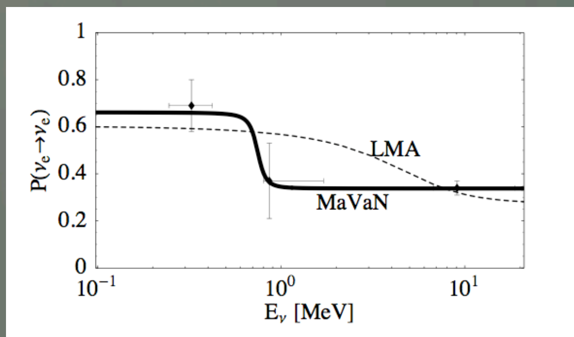
Future Expmt.	Channel	Environment	SI Δm^2_{min}(eV^2)	Medium Δm^2_{min}(eV^2)	Ref.
MiniBooNE	$\nu_\mu \to \nu_e$	HDM	2×10^{-2}	2×10^{-2}	[31]
OPERA	$\nu_\mu \to \nu_\tau$	HDM	10^{-3}	10^{-3}	[32]
MINOS	$\nu_\mu \to \nu_e, \nu_\mu, \nu_\tau$	HDM	10^{-3}	10^{-3}	[32]

Zurek '04

Only experimental evidence for m_ν in air:
SK atm - poster by K. Shiraishi

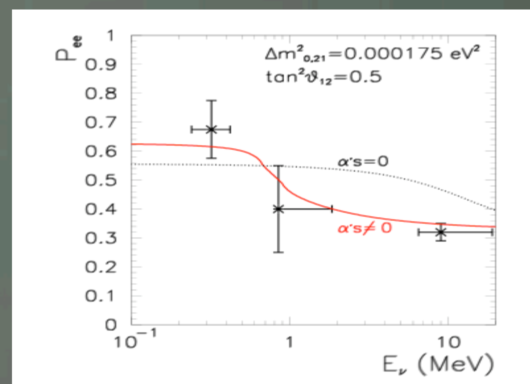
Signals: Solar Neutrinos

- New matter effects can modify solar neutrino signals



Barger, Huber, Marfatia '05

improve fit / modify spectrum of neutrino survival probability



Gonzalez-Garcia, de Holanda, Funcal '05

- All comparisons are in given model (nb Blennow, Ohlsson, Winter '05)
- Provides important comparison for standard MSW
- Extracting Be neutrino flux key for testing new forces

Neutrino Beam Experiments

- What to expect for MiniBooNE?
  - How to interpret LSND?
    - Mostly matter path
    - KARMEN mixed; Palo Verde-matter; CHOOZ-matter(?); Bugey-air; CDHS-matter
    - High mass region less constrained
      - Still need 4th mass eigenstate (Zurek '04)
      - New interactions improve fit
      - No good reason for sterile to be sterile
  - Scenarios proposed: Kaplan, Nelson, NW '04; Barger, Marfatia, Whisnant '05
    - indirect: expect change in Δm^2_{23}

$$\delta \Delta m^2_{23} > 3\ 10^{-4} \mathrm{eV}^2$$

precision key!

Reactor Neutrino Experiments

- Short baseline experiments offer strong possibility of constraining new matter effects (Schwetz & Winter '05)
  - Multiple experiments with different environments (e.g. double CHOOZ + Daya Bay)
  - Different path environments in same exp (Daya Bay)
  - Movable detector remove systematics (Schwetz & Winter)
- Simple modification: change shielding for near detector

Summary

- Neutrinos sensitive to new forces, dark energy motivates existence of new forces at m_ν
- Neutrinos best (only?) probe in SM
  - Interactions lead to varying mass
  - Relic neutrinos may be source of acceleration
- Testing dark energy with neutrinos - still model dependent
  - MiniBooNE
  - Be neutrinos
  - High statistics SBL *with known neutrino paths*
  - Precision in Δm^2_{23}, δ_{cp}, θ_{13} very important!
- New physics search very complementary with collider physics!

Eureka!

Thank goodness
for neutrinos!

new ν forces

sterile ν's

mass varying
neutrinos

low energy SUSY

origin of
dark energy

dark matter?

new gauge fields

Team USA
world cup
offense