

Title: Mass Varying Neutrinos and Dark Energy

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Abstract:

Mass Varying Neutrinos and Dark Energy

Neal Weiner

Perimeter Institute Workshop: In Search of
Variation of Fundamental Couplings and Mass Scales

Center for Cosmology and Particle Physics

New York University

July 18, 2008

"Don't you mean neutrinos and dark matter?"

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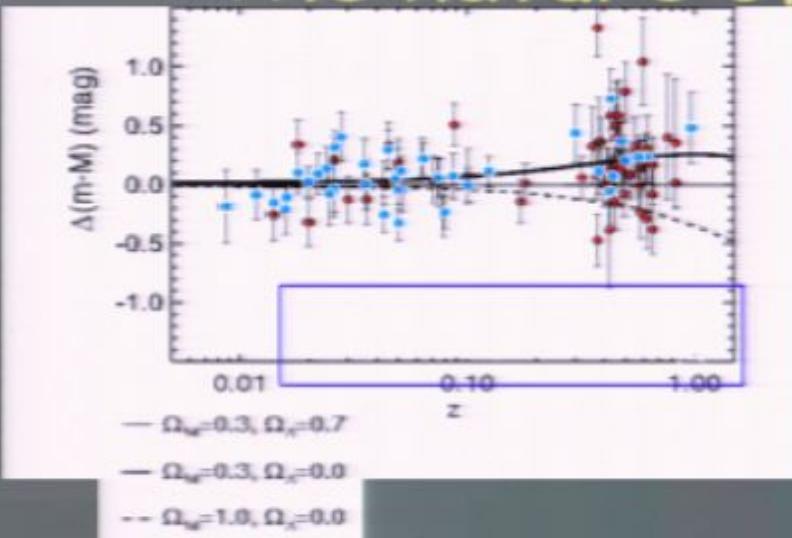
"Don't you mean neutrinos and dark matter?"

- Exciting proposal: connect neutrinos and neutrino mass to cosmic acceleration
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- Questions:
 - How would a scenario like this arise?
 - Theoretical/dynamical issues?
 - Experimental tests

"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?
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 - Experimental tests
- Will find:
 - General cosmologically mass varying neutrino exciting but hard to test
 - New matter dependence in neutrino mass
 - Possible signals in DM power spectrum (if phase transition)

The nature of acceleration

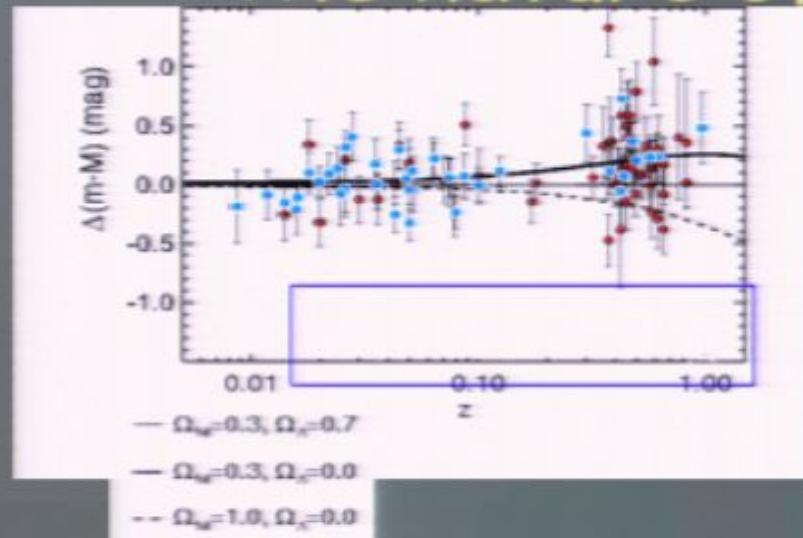


$$\Lambda^4 = 7 \times 10^{-30} \text{ g/cm}^3$$
$$\sim (10^{-2.5} \text{ eV})^4$$

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



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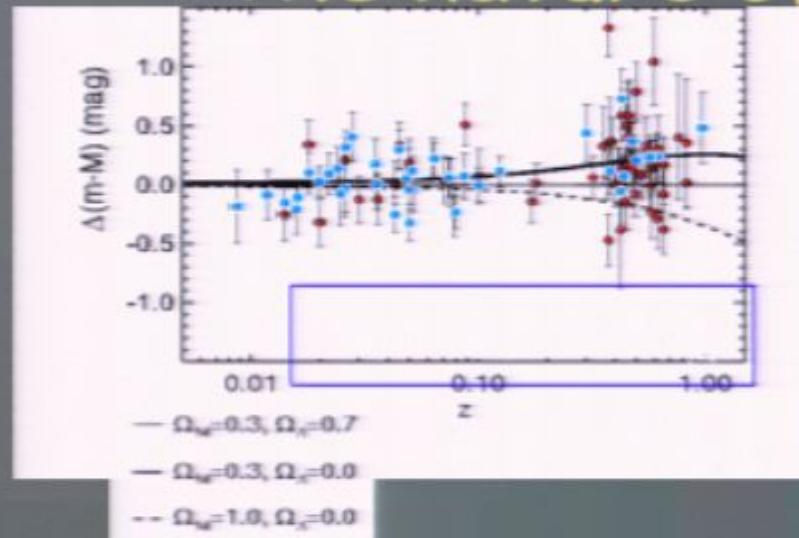
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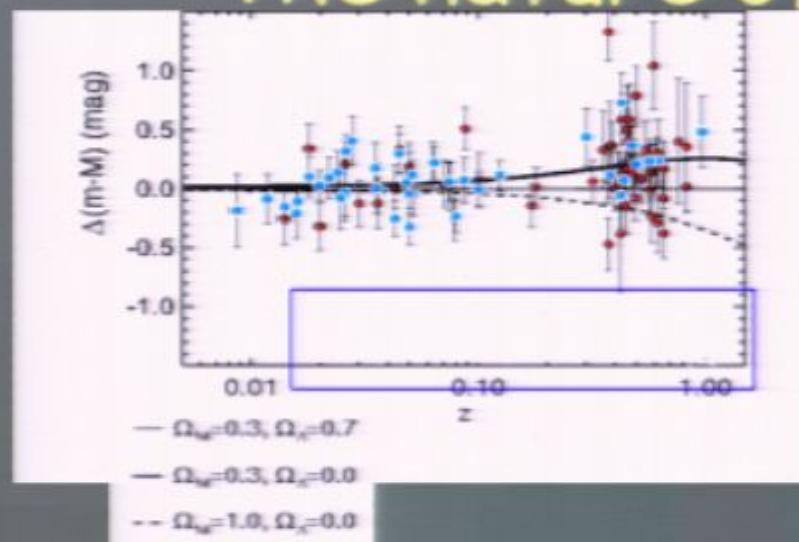
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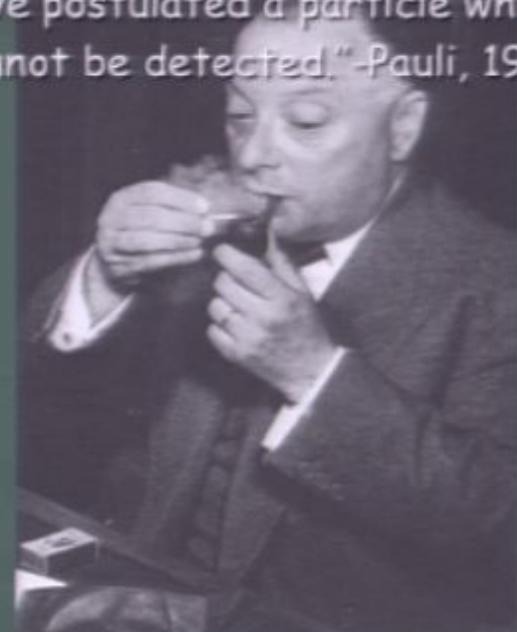


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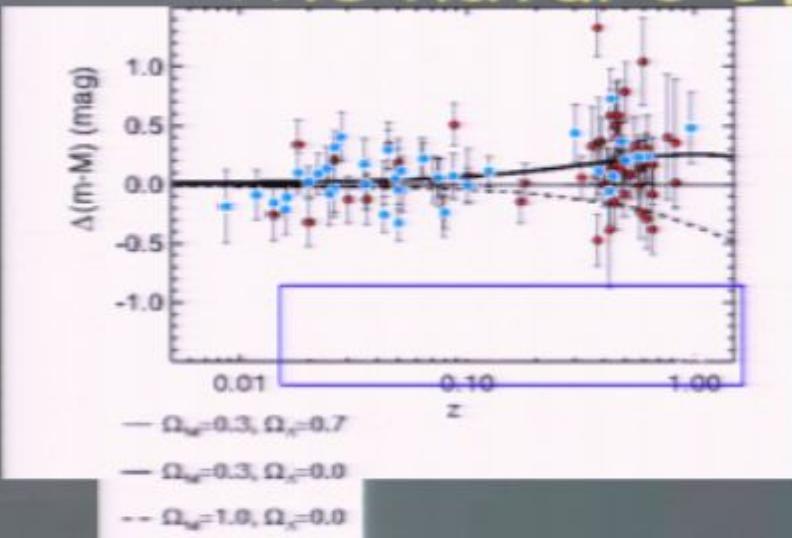
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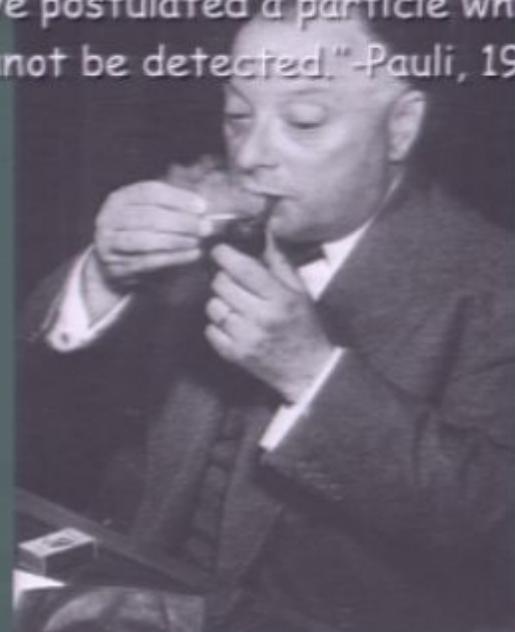
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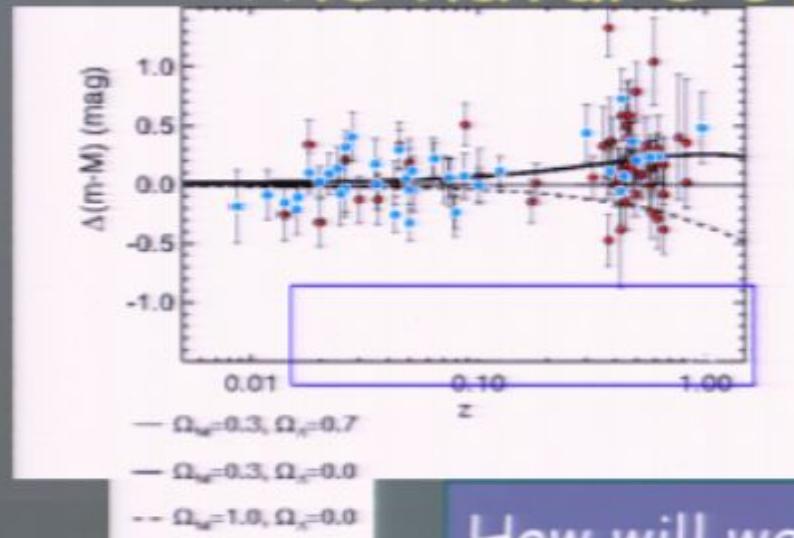
07/17/2008

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N. Weiner CCPP

The nature of acceleration



How will we ever know?

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A Cosmic Coincidence? Neutrino mass and dark energy

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THE ASTRONOMICAL JOURNAL, 116: 1009–1038, 1998 September
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Preprint: May 15, 1998

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

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ABSTRACT

We present spectral and photometric observations of 10 Type Ia supernovae (SNe Ia) in the redshift range $0.16 \leq z \leq 0.62$. The luminosity distances of these objects are determined by methods that employ relations between SN Ia luminosity and light curve shape. Combined with previous data from our High- z Supernova Search Team and recent results by Riess et al., this expanded set of 16 high-redshift supernovae and a set of 34 nearby supernovae are used to place constraints on the following cosmological parameters: the Hubble constant (H_0), the mass density (Ω_M), the cosmological constant (i.e., the vacuum energy density, Ω_Λ), the deceleration parameter (q_0), and the dynamical age of the universe (t_0). The distances of the high-redshift SNe Ia are, on average, 10%–15% farther than expected in a low mass density ($\Omega_M = 0.2$) universe without a cosmological constant. Different light curve fitting methods, SN Ia subsamples, and prior constraints unanimously favor eternally expanding models with positive cosmological constant (i.e., $\Omega_\Lambda > 0$) and a current acceleration of the expansion (i.e., $q_0 < 0$). With no prior constraint on mass density other than $\Omega_M \geq 0$, the spectroscopically confirmed SNe Ia are statistically consistent with $q_0 < 0$ at the 2.8σ and 3.9σ confidence levels, and with $\Omega_\Lambda > 0$ at the 3.0σ and 4.0σ confidence levels, for two different fitting methods, respectively. Fixing a “minimal” mass density, $\Omega_M = 0.2$, results in the weakest detection, $\Omega_\Lambda > 0$ at the 3.0σ confidence level from one of the two methods. For a flat universe prior ($\Omega_M + \Omega_\Lambda = 1$), the spectroscopically confirmed SNe Ia require $\Omega_\Lambda > 0$ at 7σ and 9σ formal statistical significance for the two different fitting methods. A universe closed by ordinary matter (i.e., $\Omega_M = 1$) is formally ruled out at the 7σ to 8σ confidence level for the two different fitting methods. We estimate the dynamical age of the universe to be 14.2 ± 1.7 Gyr including systematic uncertainties in the current Cepheid distance scale. We estimate the likely effect of several sources of systematic error, including progenitor and metallicity evolution, extinction, sample selection bias, local perturbations in the expansion rate, gravitational lensing, and sample contamination. Presently, none of these effects appear to reconcile the data with $\Omega_\Lambda = 0$ and $q_0 \geq 0$.

Key words: cosmology: observations — supernovae: general

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MEASUREMENTS OF Ω AND Λ FROM 42 HIGH-REDSHIFT SUPERNOVAE

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ABSTRACT

We report measurements of the mass density, Ω_m , and cosmological-constant energy density, Ω_Λ , of the universe based on the analysis of 42 type Ia supernovae discovered by the Supernova Cosmology Project. The magnitude-redshift data for these supernovae, at redshifts between 0.18 and 0.83, are fitted jointly with a set of supernovae from the Calán/Tololo Supernova Survey, at redshifts below 0.1, to yield

We present spectral and photometric observations for 42 supernovae with redshifts in the range $0.16 \leq z \leq 0.62$. The luminosity distances and relations between SN Ia luminosity and light curve width are derived from the High-z Supernova Search Team and recent results for supernovae and a set of 34 nearby supernovae. The cosmological parameters: the Hubble constant (H_0), the vacuum energy density, Ω_Λ , the deceleration parameter q_0 , and the distances of the high-redshift SNe Ia, are, on a flat density ($\Omega_M = 0.2$) universe without a cosmological constant, and prior constraints unambiguously favored. The prior constraints on the cosmological constant (i.e., $\Omega_\Lambda > 0$) and a current constraint on mass density other than $\Omega_M \geq 0$, are consistent with $q_0 < 0$ at the 2.8σ and 3.9σ confidence levels, for two different fitting methods. The result in the weakest detection, $\Omega_\Lambda > 0$ at 1.2σ . For a flat universe prior ($\Omega_M + \Omega_\Lambda = 1$), the one- and 9σ formal statistical significance for the two matter (i.e., $\Omega_M = 1$) is formally ruled out at the 1.2σ level. We estimate the dynamical age of the universe and the uncertainties in the current Cepheid distance scale. Within the systematic error, including progenitor and metallicity perturbations in the expansion rate, gravitational lensing, and these effects appear to reconcile the data with $\Omega_\Lambda = 0$.

Key words: cosmology: observations — supernovae: individual: 1IzW 1991, 1IzW 1994, 1IzW 1995, 1IzW 1996, 1IzW 1997, 1IzW 1998, 1IzW 1999, 1IzW 2000, 1IzW 2001, 1IzW 2002, 1IzW 2003, 1IzW 2004, 1IzW 2005, 1IzW 2006, 1IzW 2007, 1IzW 2008, 1IzW 2009, 1IzW 2010, 1IzW 2011, 1IzW 2012, 1IzW 2013, 1IzW 2014, 1IzW 2015, 1IzW 2016, 1IzW 2017, 1IzW 2018, 1IzW 2019, 1IzW 2020, 1IzW 2021, 1IzW 2022, 1IzW 2023, 1IzW 2024, 1IzW 2025, 1IzW 2026, 1IzW 2027, 1IzW 2028, 1IzW 2029, 1IzW 2030, 1IzW 2031, 1IzW 2032, 1IzW 2033, 1IzW 2034, 1IzW 2035, 1IzW 2036, 1IzW 2037, 1IzW 2038, 1IzW 2039, 1IzW 2040, 1IzW 2041, 1IzW 2042, 1IzW 2043, 1IzW 2044, 1IzW 2045, 1IzW 2046, 1IzW 2047, 1IzW 2048, 1IzW 2049, 1IzW 2050, 1IzW 2051, 1IzW 2052, 1IzW 2053, 1IzW 2054, 1IzW 2055, 1IzW 2056, 1IzW 2057, 1IzW 2058, 1IzW 2059, 1IzW 2060, 1IzW 2061, 1IzW 2062, 1IzW 2063, 1IzW 2064, 1IzW 2065, 1IzW 2066, 1IzW 2067, 1IzW 2068, 1IzW 2069, 1IzW 2070, 1IzW 2071, 1IzW 2072, 1IzW 2073, 1IzW 2074, 1IzW 2075, 1IzW 2076, 1IzW 2077, 1IzW 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A Cosmic Coincidence? Neutrino mass and dark energy

THE ASTRONOMICAL JOURNAL, 116: 1009–1038, 1998 September
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Preprint: May 15, 1998

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

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MEASUREMENTS OF Ω_m AND Λ FROM 42 HIGH-REDSHIFT SUPERNOVAE:
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Submitted: Sept 8, 1998

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PHYSICAL REVIEW LETTERS

24 AUGUST 1998

Evidence for Oscillation of Atmospheric Neutrinos

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COSMOLOGY PROJECT
PR accepted 1998 December 17

STRACT

Ω_m , and cosmological-constant energy density, Ω_Λ , of a supernovae discovered by the Supernova Cosmology Project, at redshifts between 0.38 and 0.83; are fitted: the CfA Supernova Survey, at redshifts below 0.1, to yield

Preprint: July 3, 1998

How far down does the milli-eV scale go?

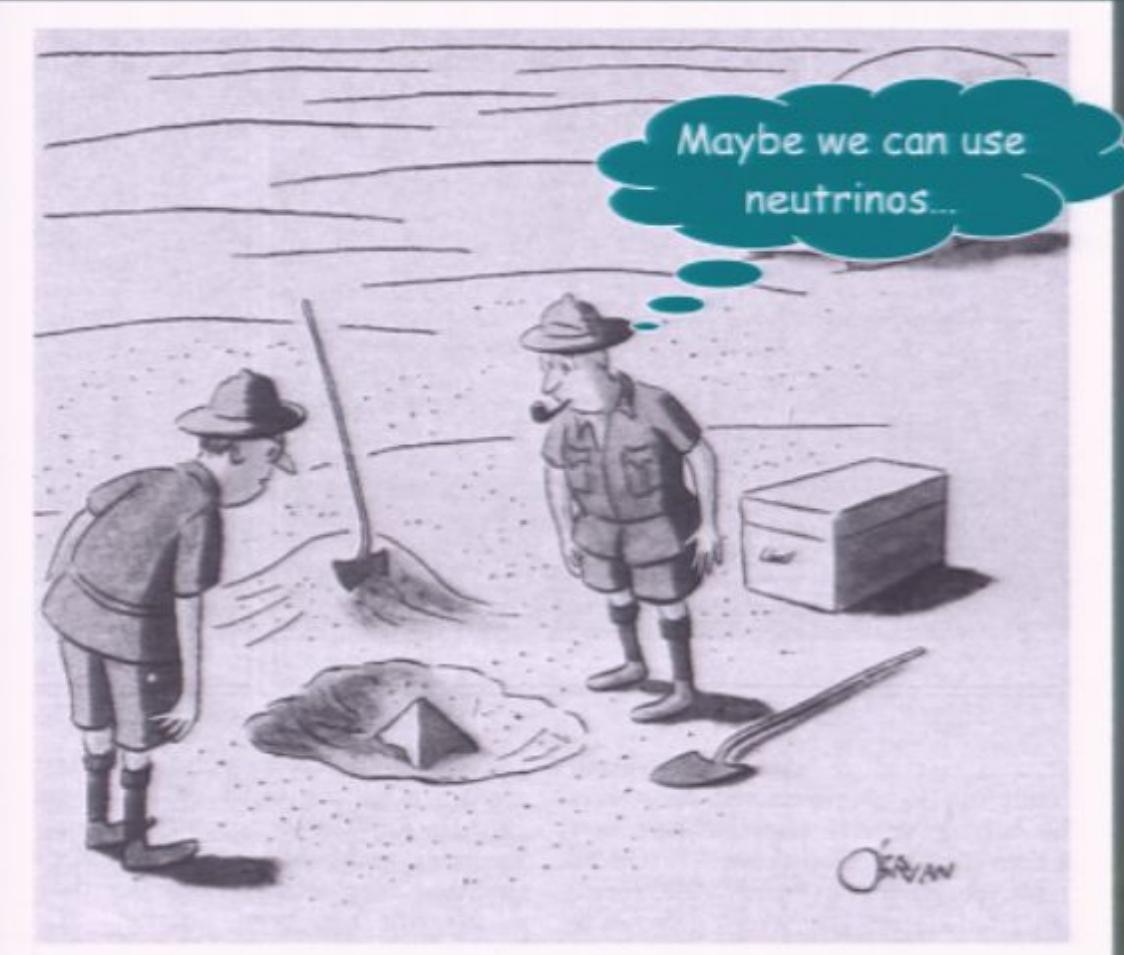


"This could be the discovery of the century. Depending, of course, on how far down it goes."

07/17/2008

N. Weiner CCPP

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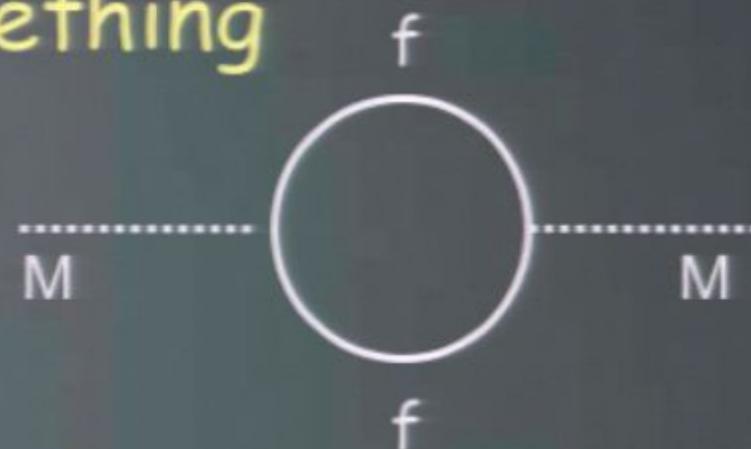
"This could be the discovery of the century. Depending

So you want a mass to vary?

- All known masses vary
 - proton/hadrons (QCD scale)
 - quarks/leptons (Higgs vev)
 - W/Z bosons (Higgs vev)
- At sufficiently high densities, all masses will vary
 - how much?

Mass varying... something

If M is the mass of a field f , it will acquire a mass from the Coleman-Weinberg potential...



$$\delta V \sim \frac{1}{16\pi^2} M^2 \Lambda^2 + \frac{1}{16\pi^2} M^4 \log(\Lambda^2/M^2)$$

Even if you ignore the quadratic piece, the flattest potential possible is $\sim M^4$

For NR matter, the energy density
in the universe is max $O((10^{-3} \text{eV})^4)$

$$V \sim (10^{-3} eV)^4 \frac{M}{M_0} + \frac{1}{16\pi^2} M^4$$
$$\rightarrow \delta M \sim \rho^{1/3} M_0^{1/3}$$

if this is $O(1)$ then

$$M_0 \sim \rho^{1/4} \sim 10^{-3} eV$$

neutrinos are singled out as natural candidates for
varying mass...

Why neutrinos? Why neutrino mass?

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- Scales are appropriate
 - $10^{-2.5} \text{ eV} \sim m_\nu$
- Relic neutrinos form smooth background, like DE
 - Bad for dark matter, good for dark energy

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 - $10^{-2.5} \text{ eV} \sim m_\nu$
- Relic neutrinos form smooth background, like DE
 - Bad for dark matter, good for dark energy
- Neutral in low energy theory, can mix with dark sector \rightarrow new forces
 - Poorly constrained

Dependencies of neutrino mass

- Expect neutrino mass to be dynamical

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

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Suppose $\langle A \rangle$ is small and $m_A \sim m_\nu$.

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Suppose $\langle A \rangle$ is small and $m_A \sim m_\nu$.

What happens to neutrinos at finite density?

Mass Varying Neutrinos

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

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Mass Varying Neutrinos

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

drives A to
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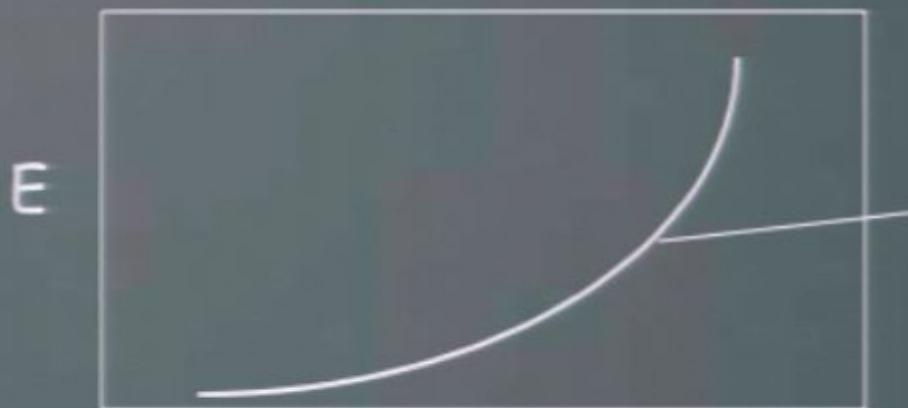
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from scalar
potential

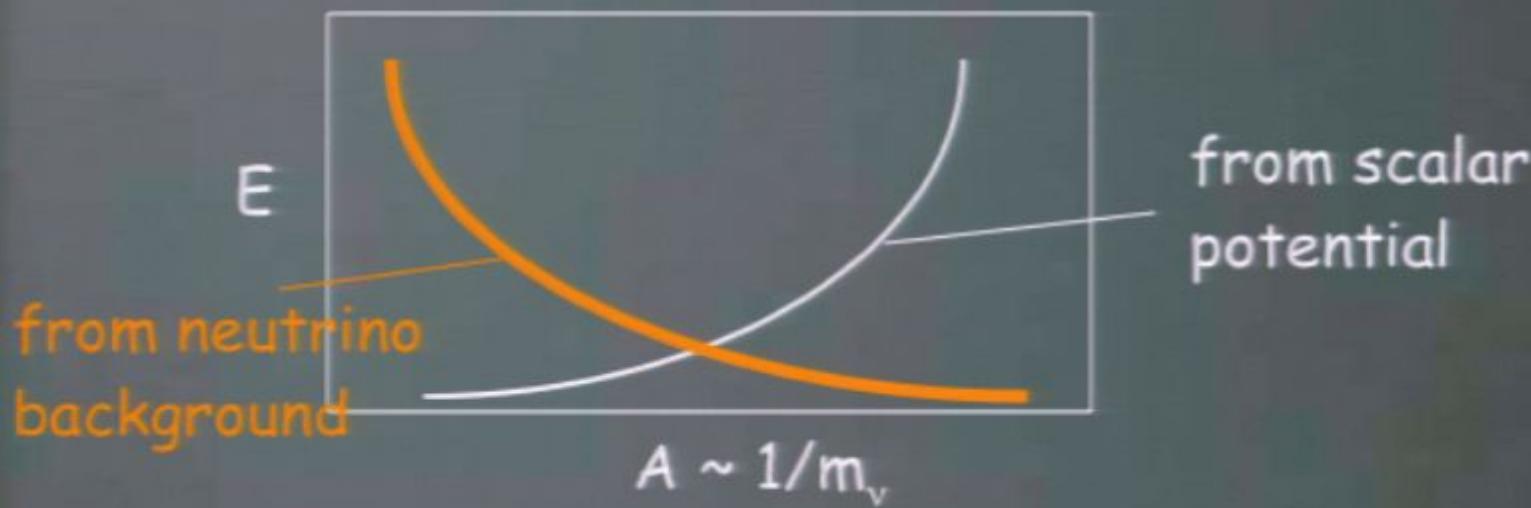
$$A \sim 1/m_\nu$$

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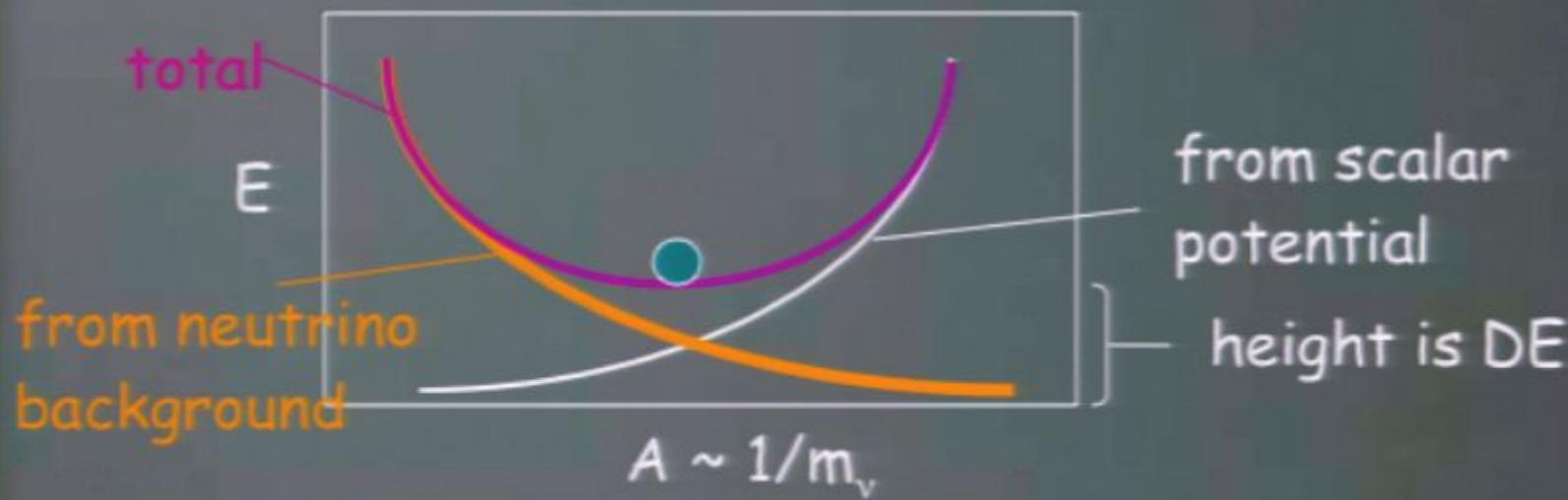


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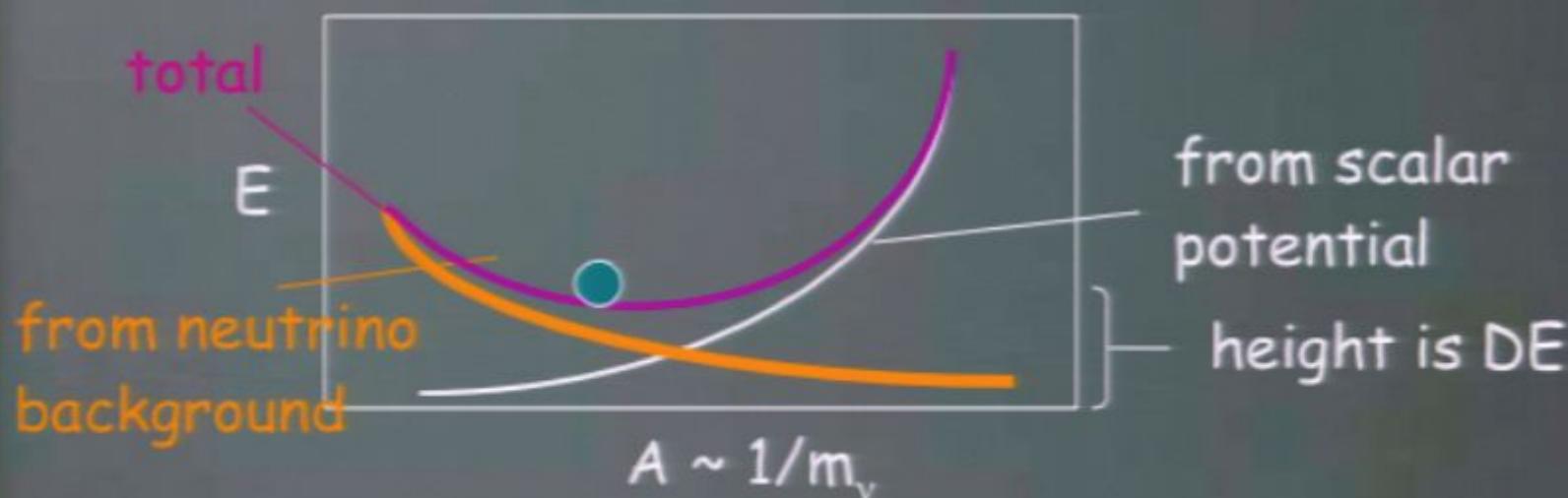


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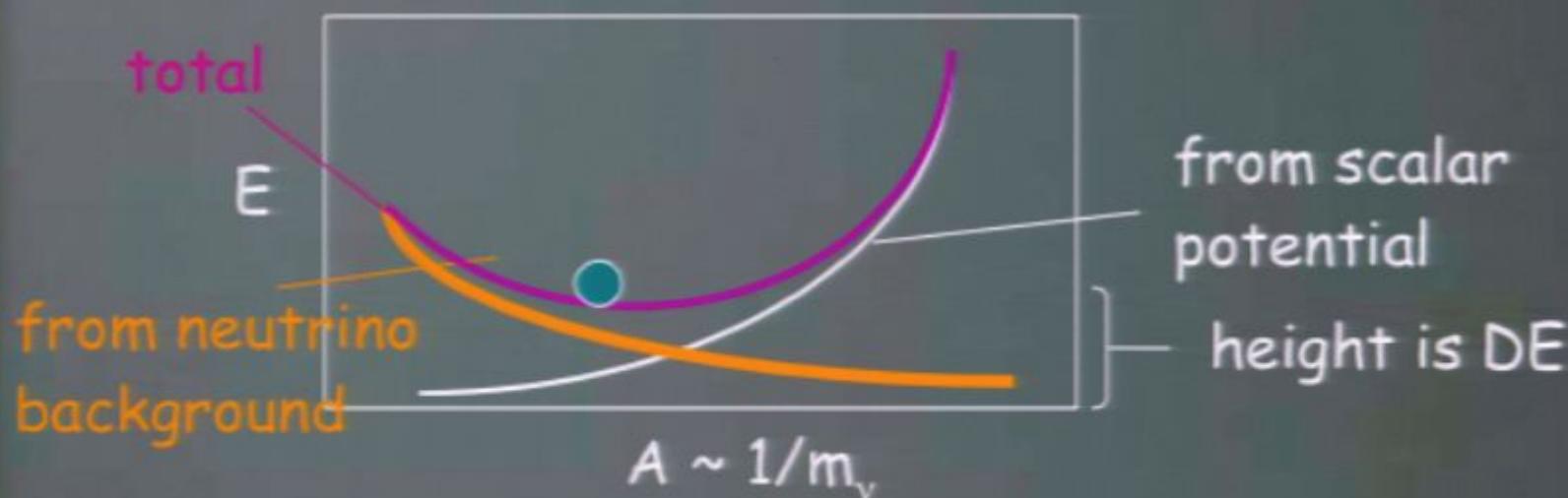


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Neutrino mass changes; total energy redshifts slowly

Theoretical Questions

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- Equation of state, forms of potentials

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(Fardon, Nelson, NW '03; Peccei '04)

- Radiative stability?

- Scalar forces generally not long range
 - SUSY models => "Hybrid" Models

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Theoretical Questions

- Equation of state, forms of potentials

(Fardon, Nelson, NW '03; Peccei '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
(Fardon, Nelson, NW '05)
 - Addit'l const mass: OK
(Takahashi & Tanimoto, '05, '06)

Generic Features of MaVaNs (Mass Varying Neutrinos)

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Generic Features of MaVaN_s (Mass Varying Neutrinos)

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 - Possible exception: Ma & Sarkar '06 (Higgs triplet)

Generic Features of MaVaN_s (Mass Varying Neutrinos)

- Few truly model independent consequences
 - Cosmological Variation of Neutrino Masses
 - Sterile Neutrinos (\sim 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

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

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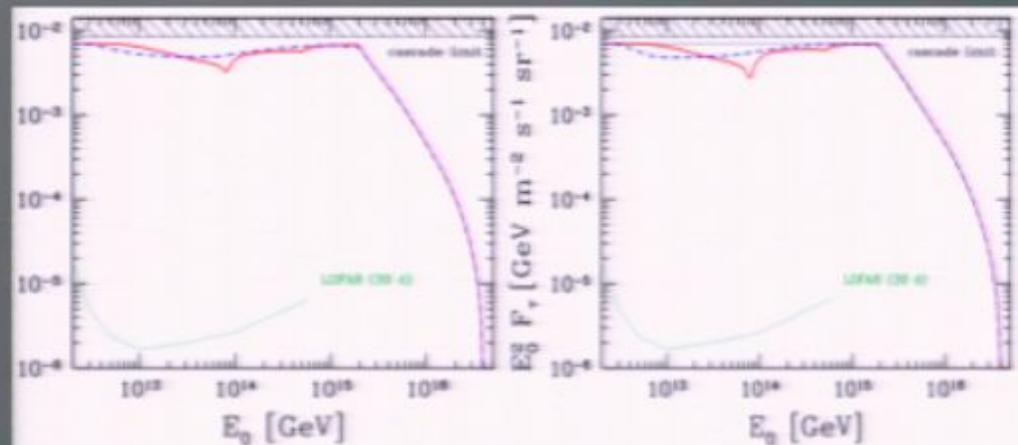


Figure 6. Projected sensitivity of LOFAR [48] expressed in terms of the diffuse neutrino flux per flavor, corresponding to one event per energy decade and indicated duration, together with $E_0^2 F$ with $F = \sum F_{\nu_e} + \sum F_{\nu_\mu}$ (left column) and $E_0^2 F_r$ with $F_r = F_{\nu_e} + F_{\nu_\mu}$ (right column) for varying (solid lines) and constant (dashed lines) neutrino masses and for $x_{\max} = 20$, assuming a normal neutrino mass hierarchy with $m_{\nu_{\alpha_1}} = 10^{-5} \text{ eV}$, $n = 4$ and $\alpha = 2$ as well as $E_{\max} = 4 \times 10^{16} \text{ GeV}$.

Ringwald & Schrempp
(June 13, '06)

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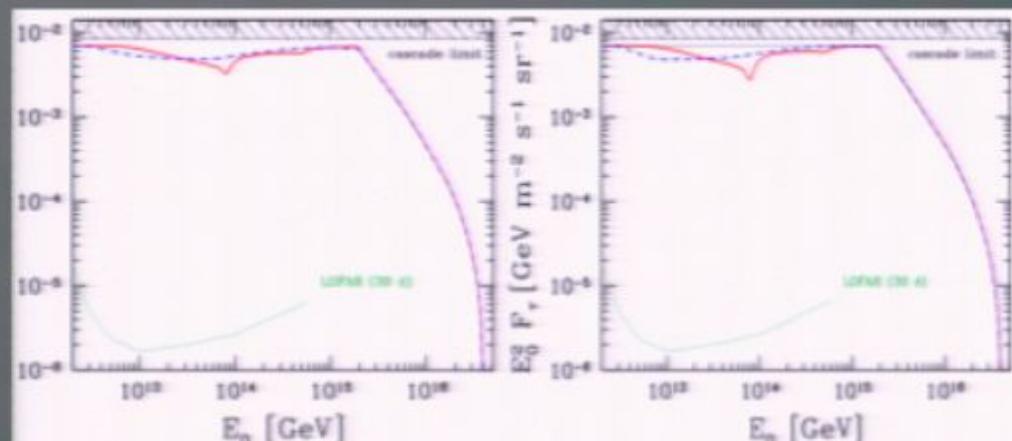


Figure 6. Projected sensitivity of LOFAR [48] expressed in terms of the diffuse neutrino flux per flavor, corresponding to one event per energy decade and indicated duration, together with $E_0^2 F$ with $F = \sum F_{\nu_e} + \sum F_{\bar{\nu}_e}$ (left column) and $E_0^2 F_r$ with $F_r = F_{\nu_e} + F_{\bar{\nu}_e}$ (right column) for varying (solid lines) and constant (dashed lines) neutrino masses and for $z_{\max} = 20$, assuming a normal neutrino mass hierarchy with $m_{\nu_{\text{light}}} = 10^{-5}$ 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

Matter effects

- Same game, but with ordinary matter
 $(O(3g/cm^3) \sim O(10^{19} eV^4))$

$$m_p = \bar{m}_p \left(1 + \frac{m_\nu}{\Lambda}\right)$$

$$V \sim (10^{19} eV^4) \left(1 + \frac{m_\nu}{\Lambda}\right) + (10^{-4} eV)^2 m_\nu^2$$

$$\Lambda = M_{Pl} \rightarrow \delta m_\nu \sim 0.1 eV$$

We already knew this!

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- Lesson of seesaw is that incredibly weak forces can be dominant effect in neutrino propagation (MSW)

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PHYSICAL REVIEW D

VOLUME 17, NUMBER 9

1 MAY 1978

Neutrino oscillations in matter

L. Wolfenstein

Carnegie-Mellon University, Pittsburgh, Pennsylvania 15213

(Received 6 October 1977; revised manuscript received 5 December 1977)

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.

We already knew this!

- 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
(Wolfenstein '78; Barger, Phillips, Whisnant '91; Bergmann '97; Friedland, Lunardini, Pena-Garay '04)
 - New Scalar Forces
(Kawasaki, Murayama, Yanagida, '91 (kpc scale); Sawyer '98 (mm scale); Hung '00 (Hubble scale))
- Scalar forces modify neutrino mass

New matter effects

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New matter effects

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 - 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,

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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
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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	$\nu_e \rightarrow \nu_e, \nu_\mu, \nu_\tau$	solar-interior	6.5×10^{-5}	8.2×10^{-5}	Unknown
Super-K(solar)	$\nu_e \rightarrow \nu_e, \nu_\mu$	solar-interior	3×10^{-5}	1.9×10^{-4}	Unknown
Super-K(atm)	$\nu_\mu \rightarrow \nu_\tau$	air/HDM	1.9×10^{-3}	3.0×10^{-3}	1.5×10^{-3}
KamLAND	$\nu_e \rightarrow \nu_\tau$	HDM	10^{-5}	7×10^{-4}	10^{-5}
K2K	$\nu_\mu \rightarrow \nu_\tau$	HDM	10^{-3}	no limit	10^{-3}
LSND	$\nu_\mu \rightarrow \nu_e$	HDM	4×10^{-2}	1.2	4×10^{-2}
Null Search			SI Δm^2_{min} (eV ²)	Medium Δm^2_{min} (eV ²)	Ref.
KARMEN	$\nu_\mu \rightarrow \nu_e$	~ 50% air	5×10^{-2}	0.1	[19]
Bugey	$\nu_e \rightarrow \nu_\tau$	air	10^{-2}	N/A	[21, 22]
CHOOZ	$\nu_e \rightarrow \nu_\tau$	~ 80 – 90% air	7×10^{-4}	4×10^{-3}	[23, 24]
Palo Verde	$\nu_e \rightarrow \nu_\tau$	~ 95% HDM	2×10^{-3}	2×10^{-3}	[25, 26]
CDHS	$\nu_\mu \rightarrow \nu_\tau$	Unknown	0.25	Unknown	[27]
NOMAD	$\nu_\mu \rightarrow \nu_\tau$	~ 60% HDM	0.7	1.2	[28, 29]
	$\nu_e \rightarrow \nu_\tau$		5.9	9.8	
CHORUS	$\nu_\mu \rightarrow \nu_\tau$	~ 60% HDM	0.6	1	[29, 30]
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Future Exptn.	Channel	Environment	SI Δm^2_{min} (eV ²)	Medium Δm^2_{min} (eV ²)	Ref.
MiniBooNE	$\nu_\mu \rightarrow \nu_e$	HDM	2×10^{-2}	2×10^{-2}	[31]
OPERA	$\nu_\mu \rightarrow \nu_\tau$	HDM	10^{-3}	10^{-3}	[32]
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Zurek '04

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Zurek '04

Only experimental evidence for m_{ν} in air:

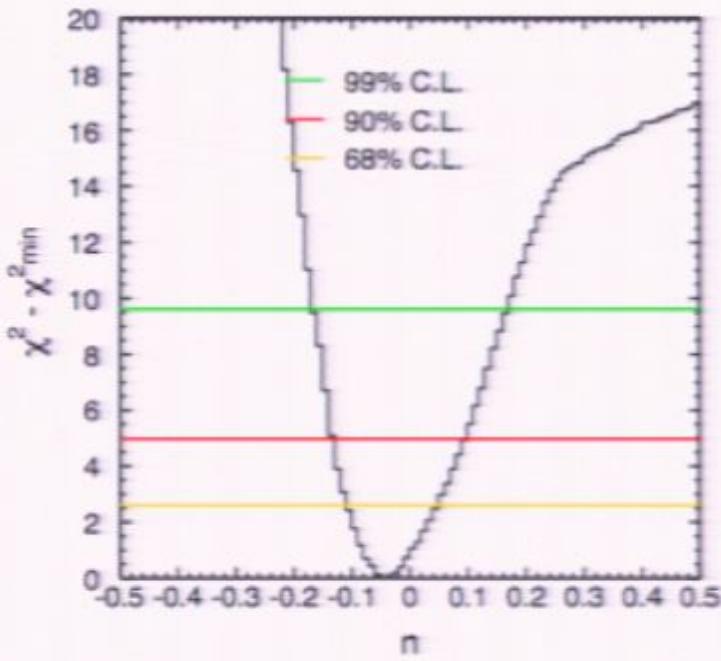
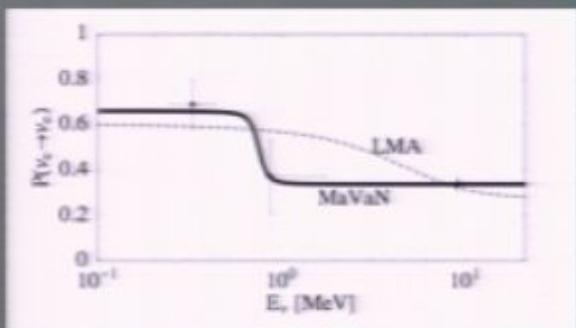


FIG. 1: $\Delta m^2 \rightarrow \Delta m^2 \times \left(\frac{\rho_c}{\rho_o}\right)^n$ (including air path length). Upper plot shows relative- χ^2 confidence level contours on the Δm^2 versus n plane, obtained when taking into account both high and low density matter path lengths. The lower plots display the $\chi^2 - \chi^2_{\min}$ contours, with confidence levels shown, at the best-fit parameter values.

Abe et al, '08

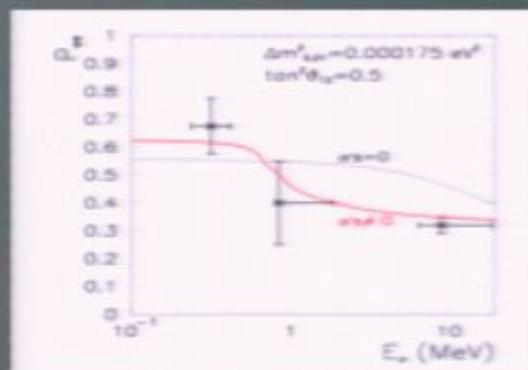
Signals: Solar Neutrinos

- New matter effects can modify solar neutrino signals



Barger, Huber, Marfatia '05

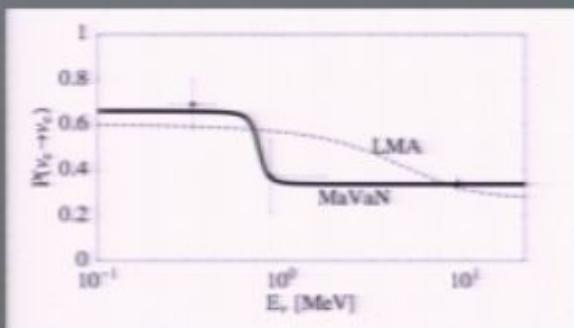
improve fit / modify spectrum
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Gonzalez-Garcia,
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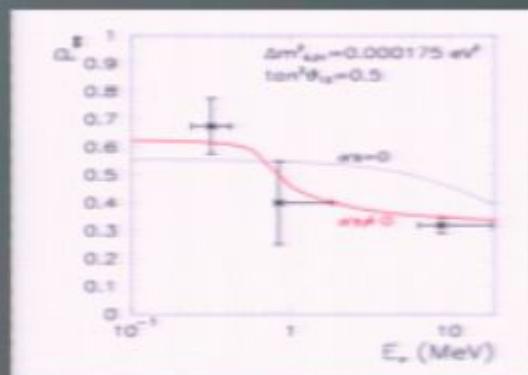
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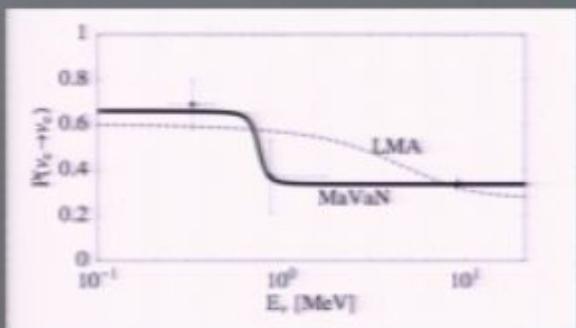


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- All comparisons are in given model
- Provides important comparison for standard MSW

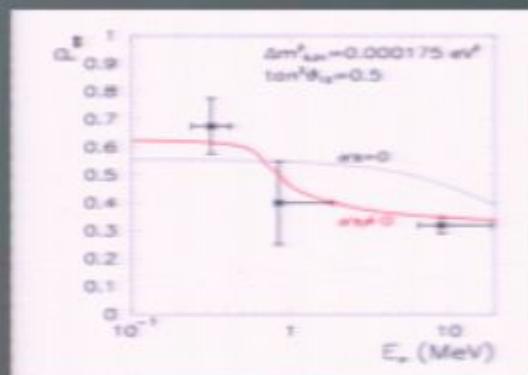
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- Extracting Be neutrino flux key for testing new forces

Reactor Neutrino Experiments

07/17/2008

N. Weiner CCPP

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- Short baseline experiments offer strong possibility of constraining new matter effects (Schwetz & Winter '05)

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 - Different path environments in same exp (Daya Bay)
 - Movable detector remove systematics (Schwetz & Winter)
- Simple modification: change shielding for near detector

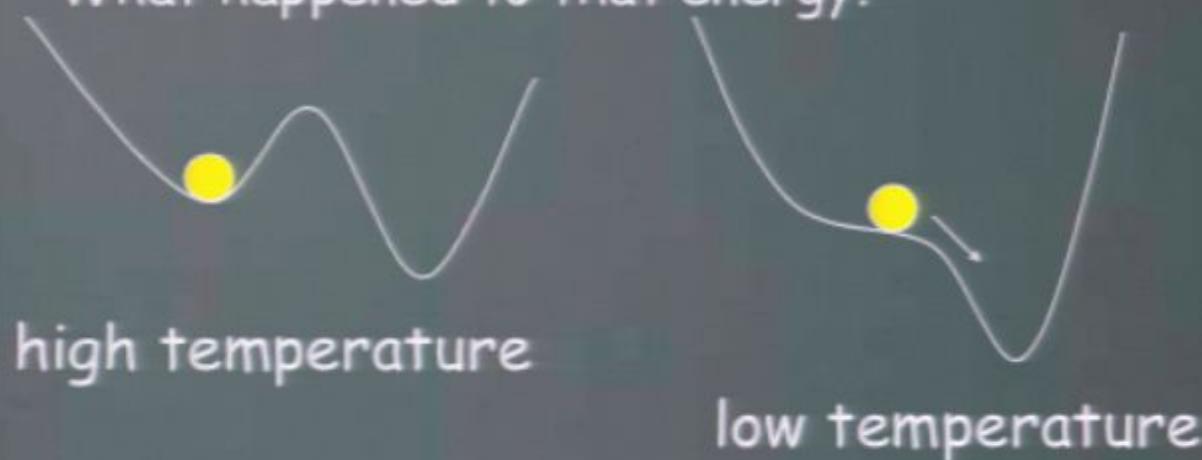
Cosmo Consequences: Late Forming Dark Matter (S.Das, NW '06)

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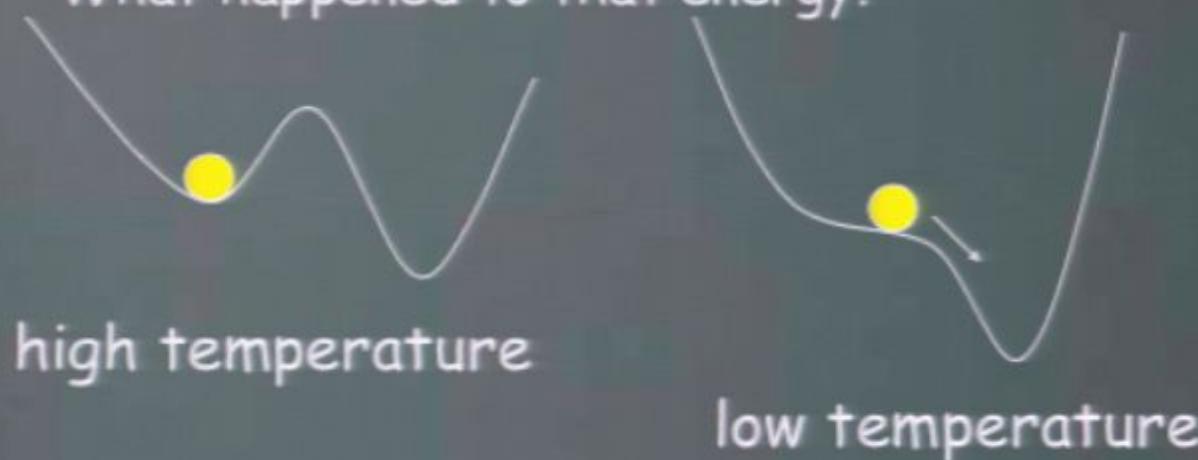
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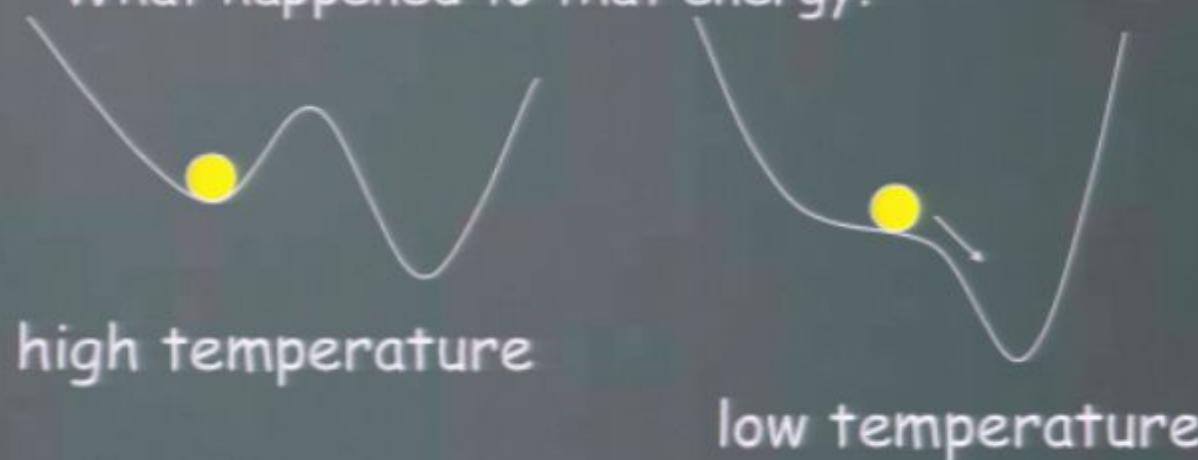
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- Phase transition should occur at $T \sim m_{\text{neu}}/g^2$
- Should appear as dark matter today!

Power at small scales

07/17/2008

N. Weiner CCPP

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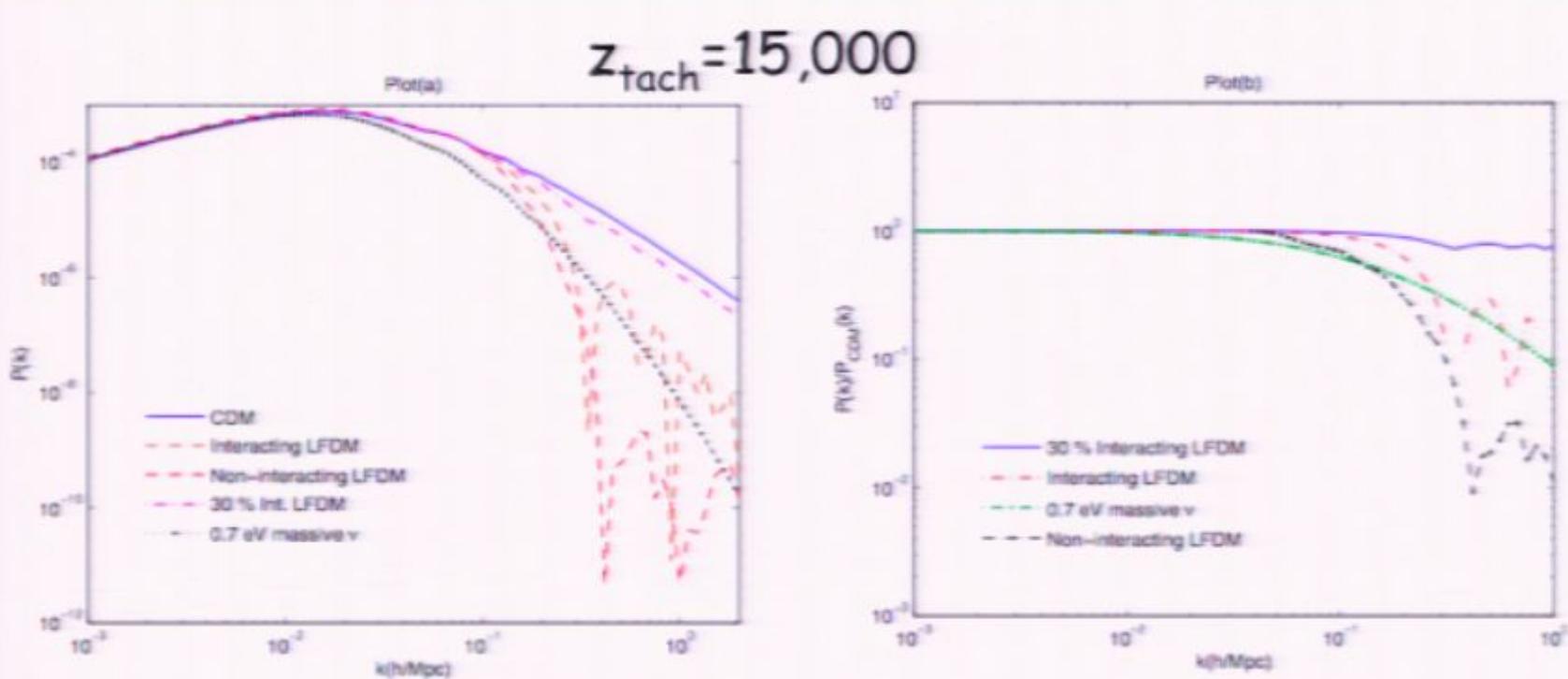
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$$\delta\rho_{DM}(x, z_{\text{tach}}) \propto \delta T_\nu(x, z_{\text{tach}})$$

CDM $P(k)$ gives snapshot of universe at z_{tach}



estimate $10^{-3} > k_{\text{tach}} > 10^2$

logically separate from, but motivated by, neutrino
dark energy theories

Stability of late-forming dark matter

Bjølle, Das, NW

- Oscillating neutrino mass field = DM can decay into neutrinos, filling the Fermi sea
- Leads to a modified equation of state for dark matter, redshifting slightly faster than a^{-3}
- “Preheating dark matter”
 - could be constrained from tilt in power spectrum, or modification to ISW effect

Summary

07/17/2008

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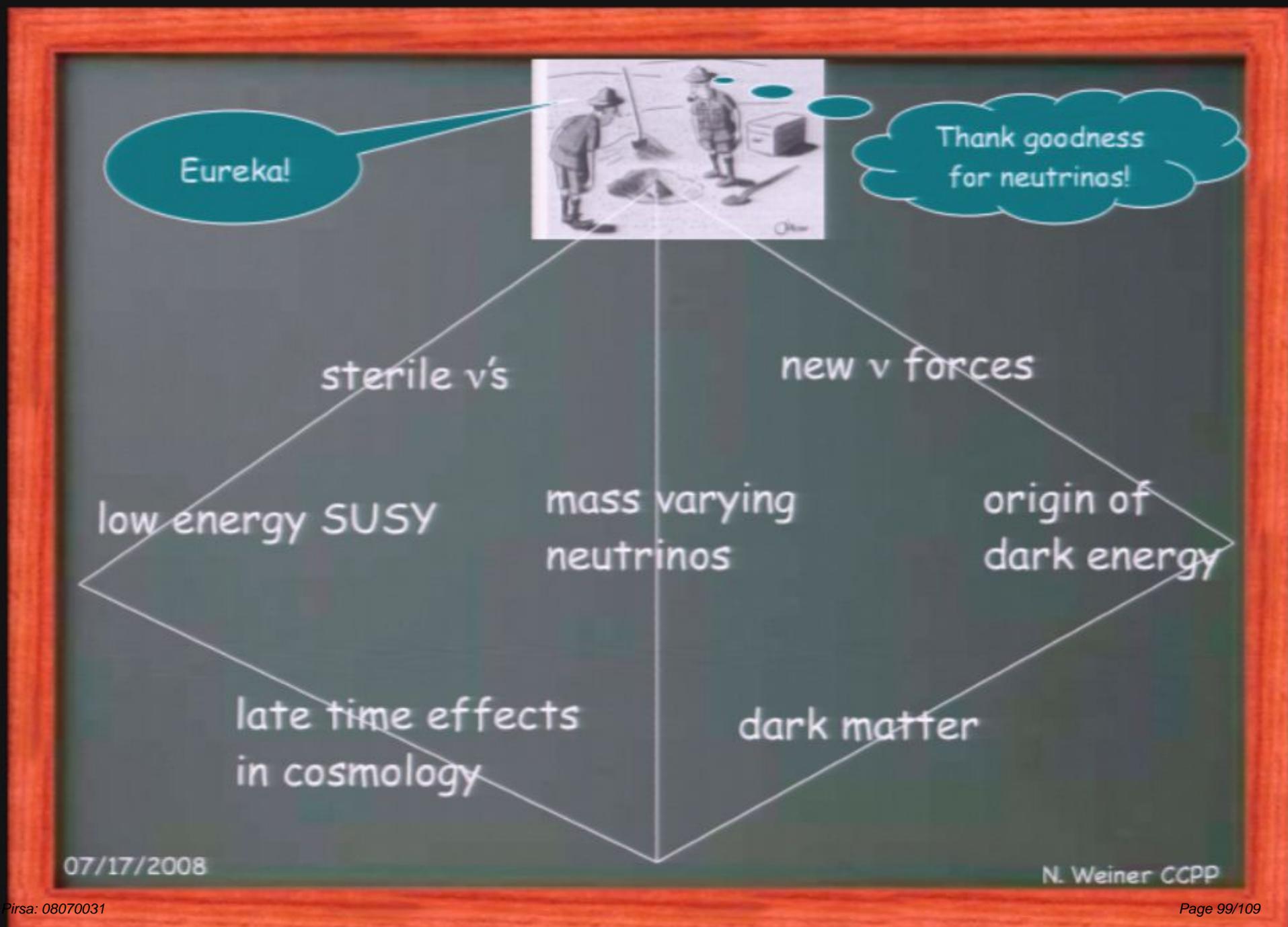
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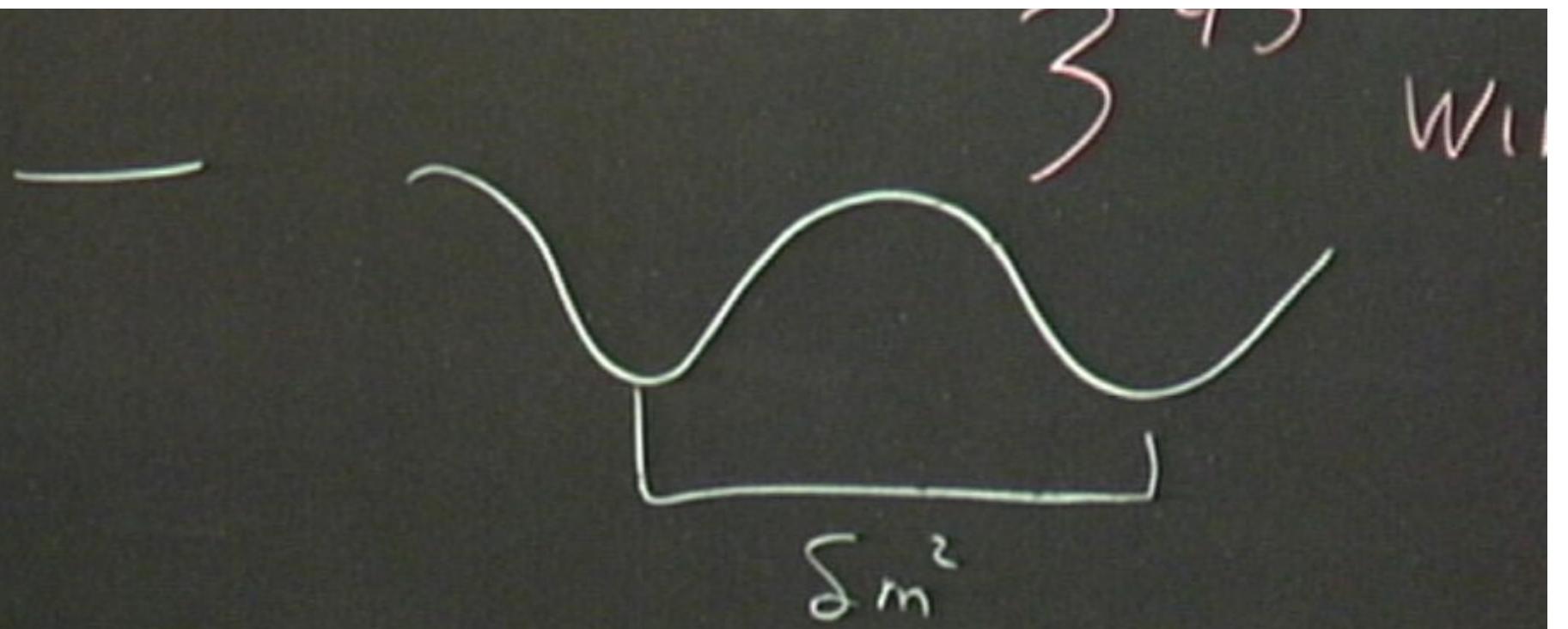
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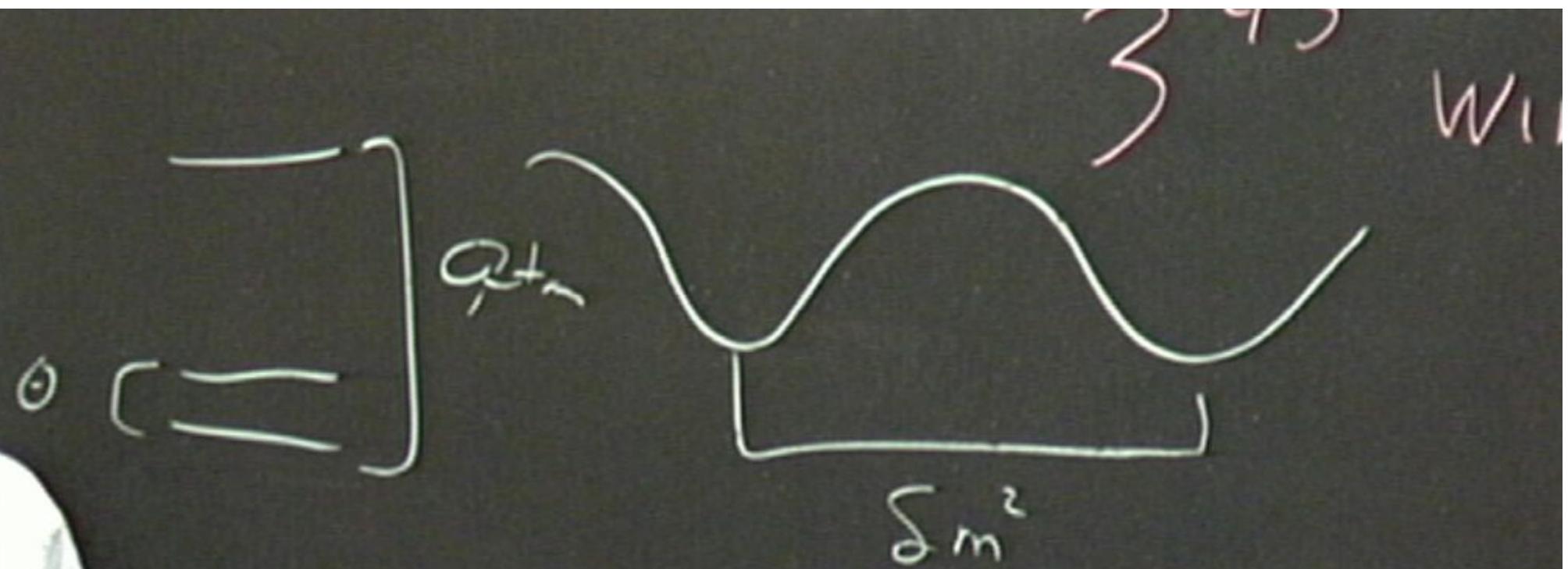
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- All these things may point to a new scale of physics at 10^{-3} eV

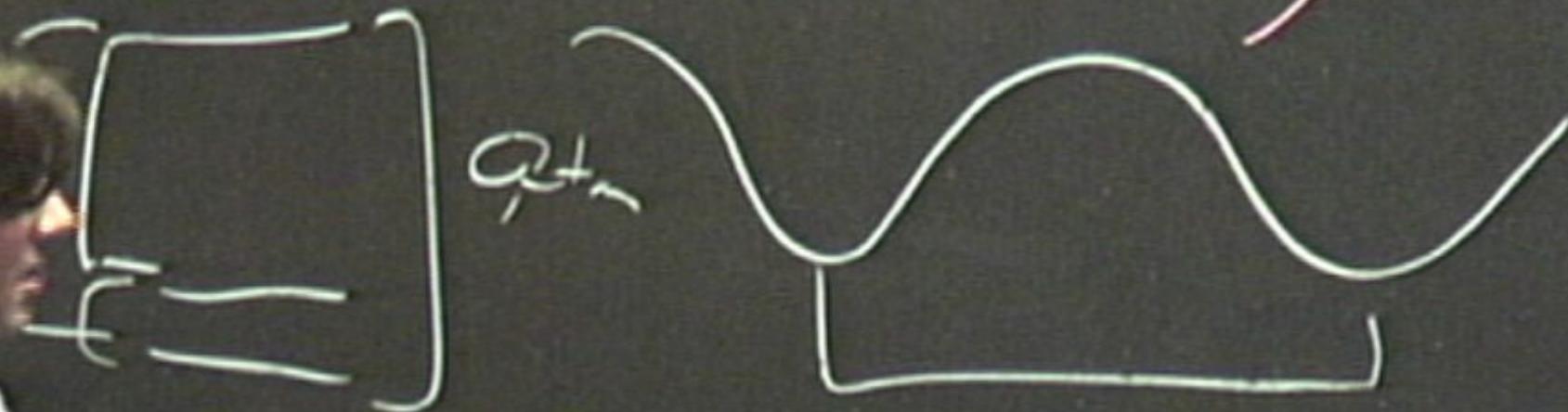


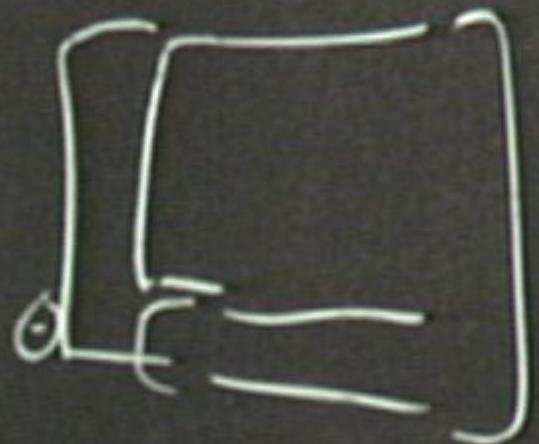




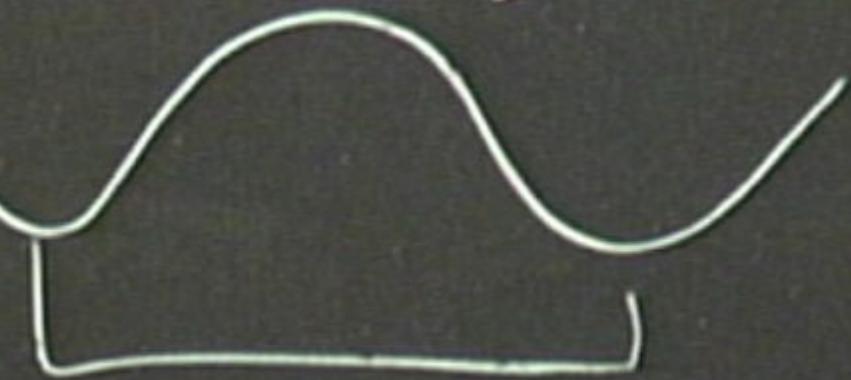
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WIL

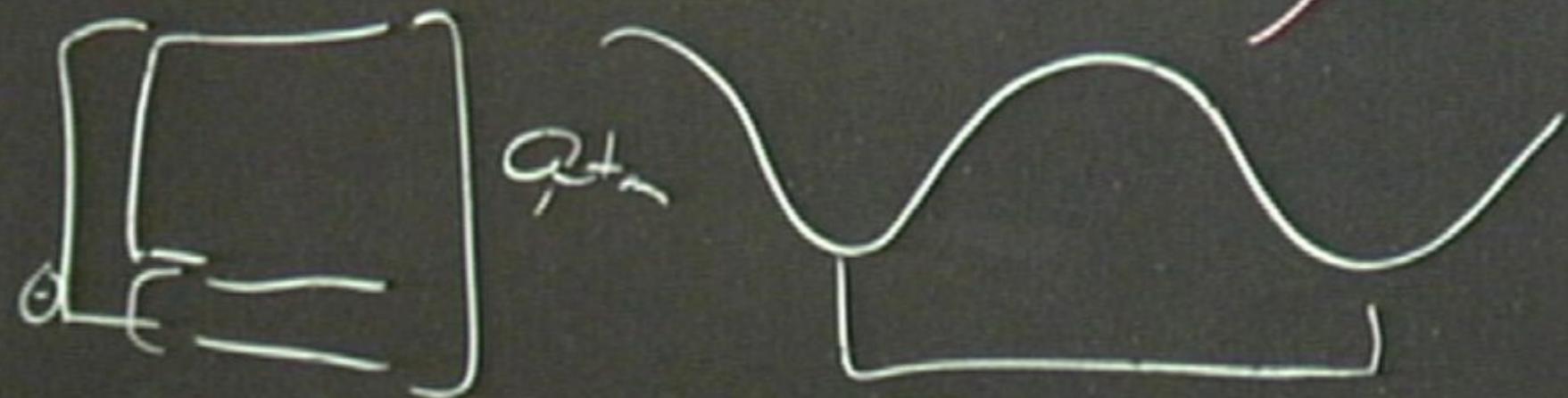




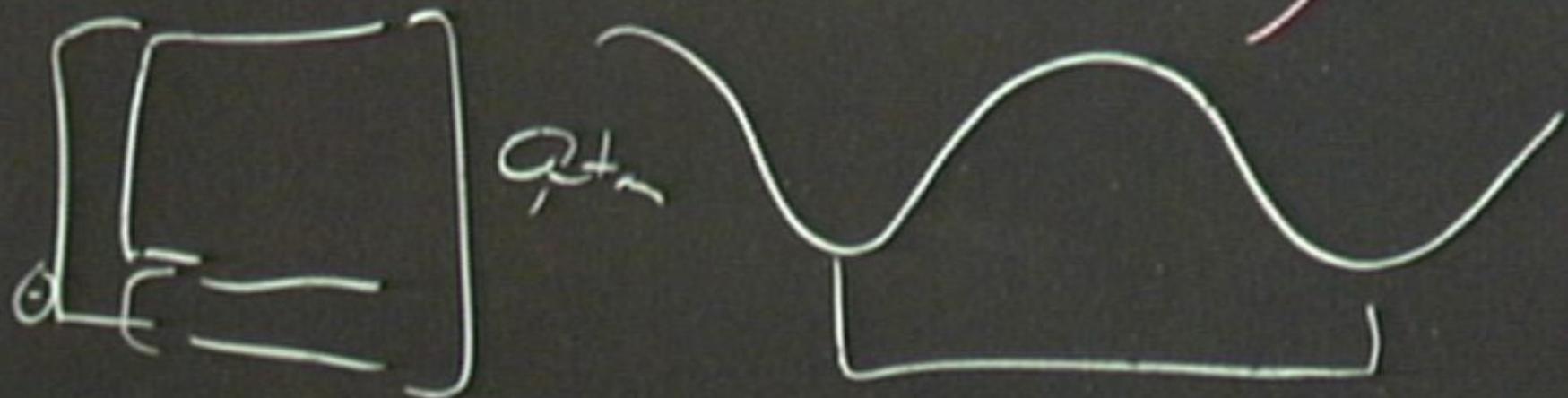
$a +$



(m_D)



$$\begin{pmatrix} m_1 \\ m_D \end{pmatrix}$$



$$\begin{pmatrix} m_1 \\ m_2 \\ M \end{pmatrix} \Rightarrow \begin{pmatrix} \frac{m_1^2}{M} & \delta m^2 \\ 0 & 0 \\ 0 & M \end{pmatrix}$$

Dependencies of neutrino mass

- Expect neutrino mass to be dynamical

depends on
Higgs vev

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

Depends on
other vev
“acceleron”

Suppose $\langle A \rangle$ is small and $m_A \sim m_\nu$.

What happens to neutrinos at finite density?

Mass Varying Neutrinos

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

drives A to
large values (m_ν to small values)

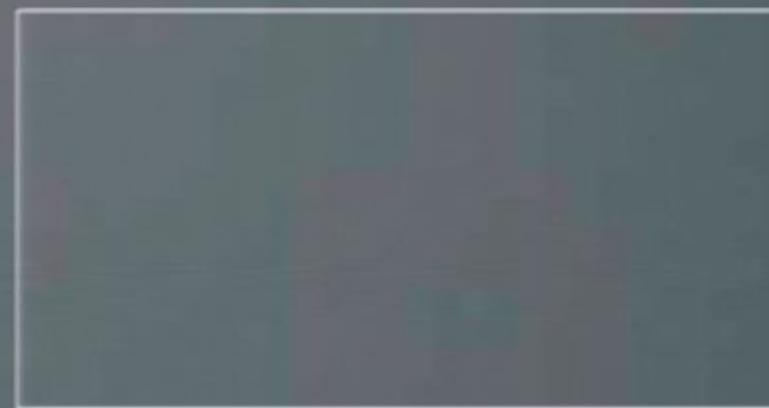
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from scalar
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