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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- Exciting proposal: connect neutrinos and neutrino mass to cosmic acceleration

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- Exciting proposal: connect neutrinos and neutrino mass to cosmic acceleration
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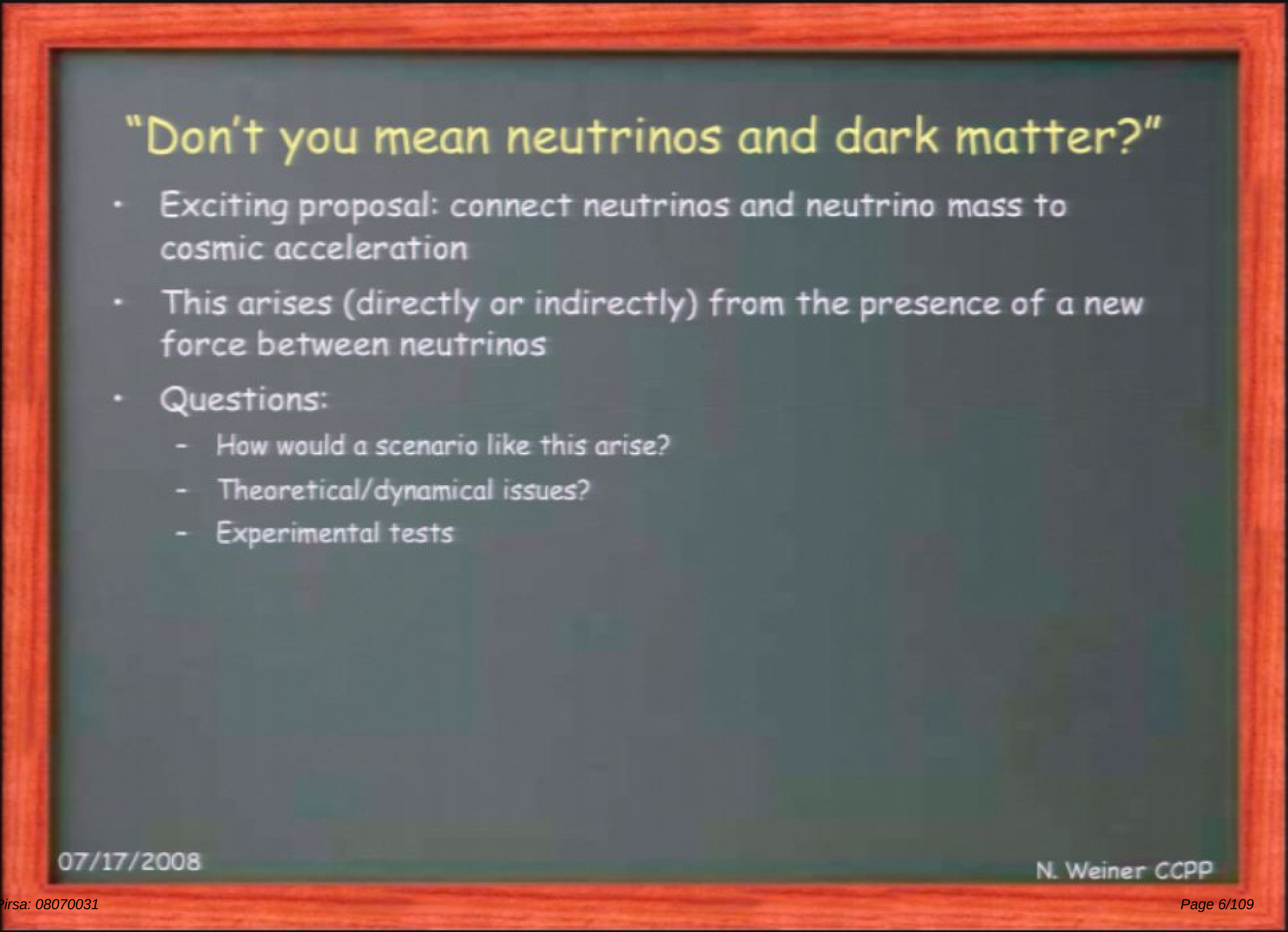

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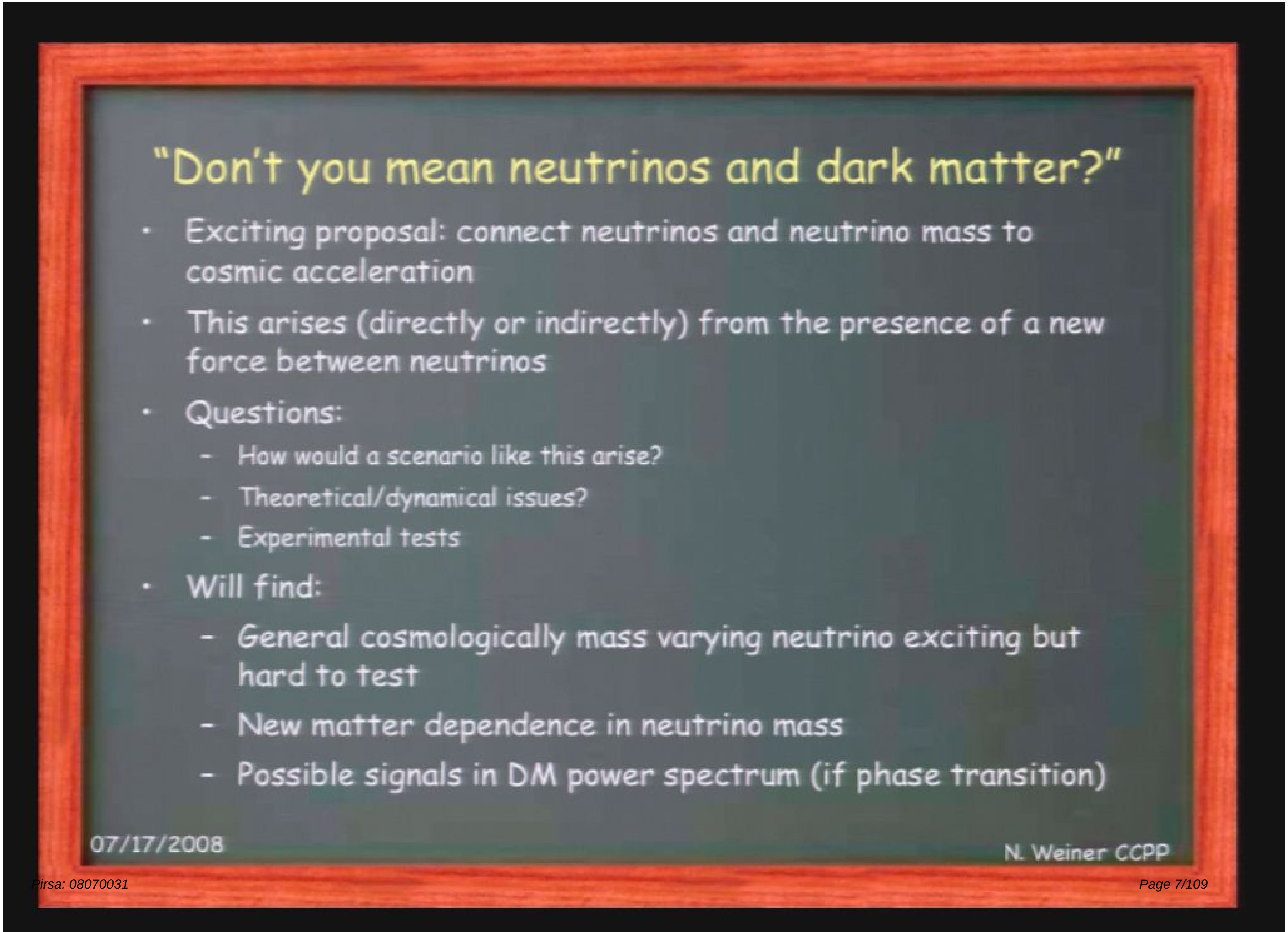
- Questions:
  - How would a scenario like this arise?
  - Theoretical/dynamical issues?
  - Experimental tests



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

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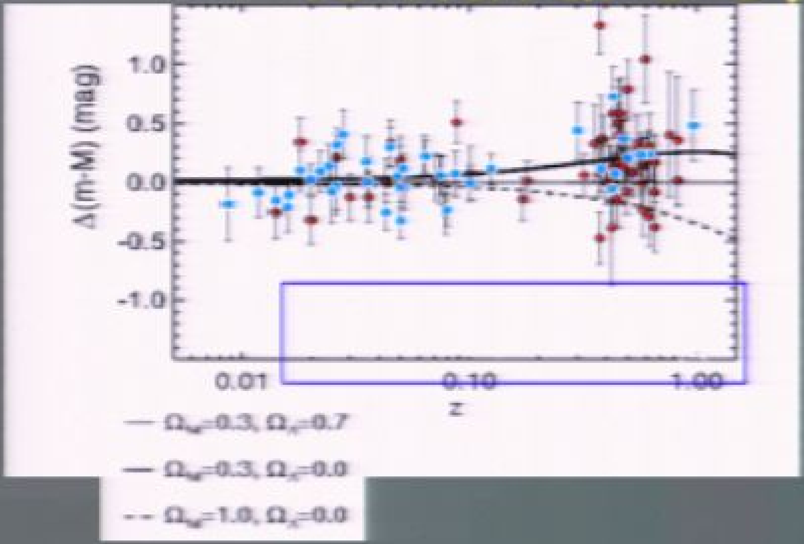
- This arises (directly or indirectly) from the presence of a new force between neutrinos
- Questions:
  - How would a scenario like this arise?
  - Theoretical/dynamical issues?
  - Experimental tests
- Will find:
  - General cosmologically mass varying neutrino exciting but hard to test
  - New matter dependence in neutrino mass
  - Possible signals in DM power spectrum (if phase transition)

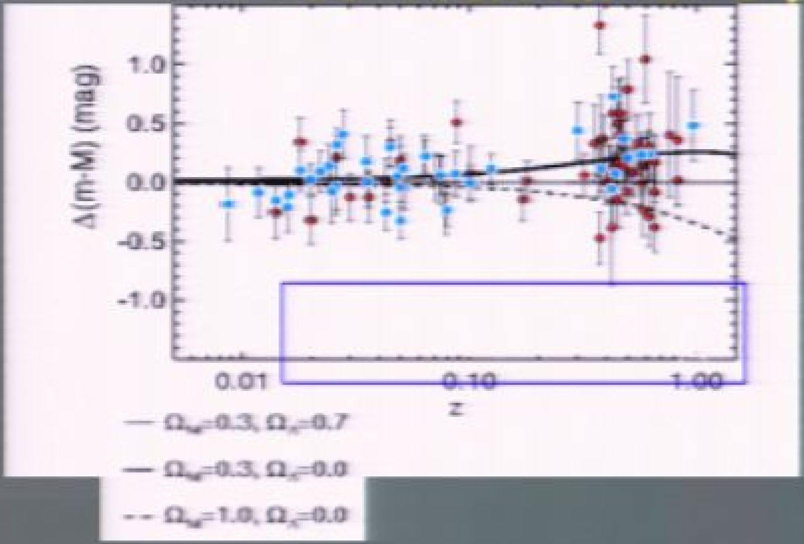
The nature of acceleration



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

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

The nature of acceleration



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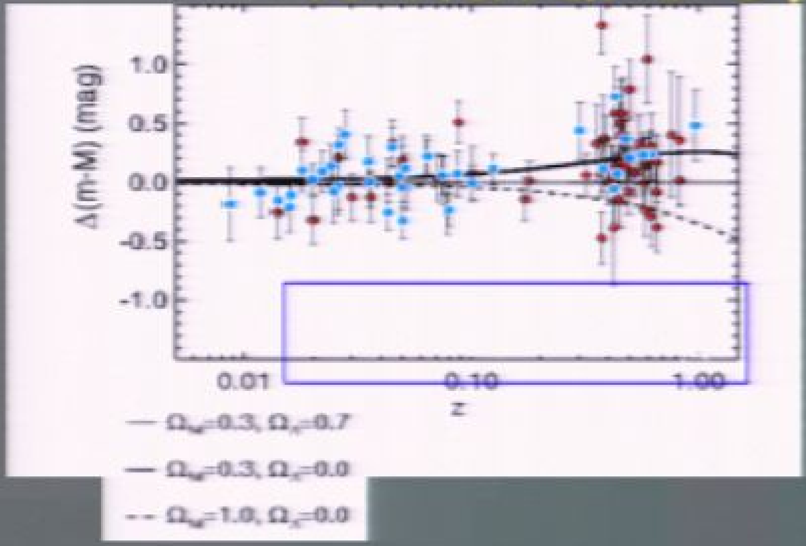

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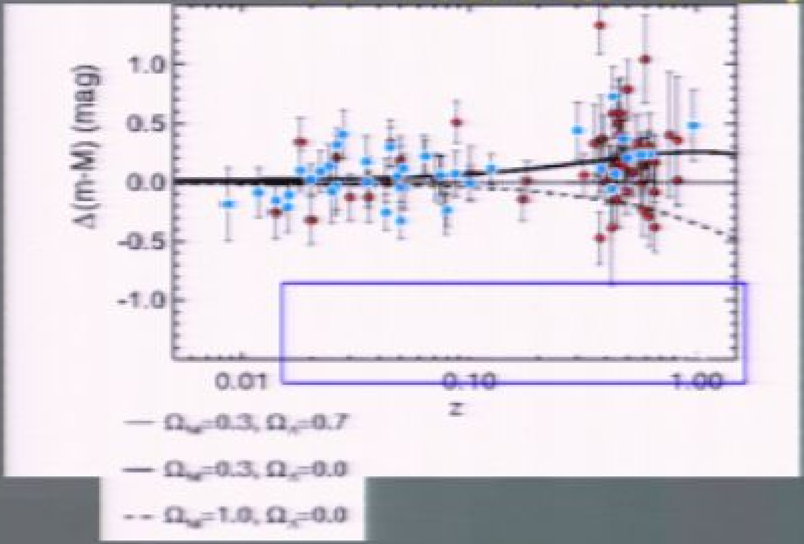

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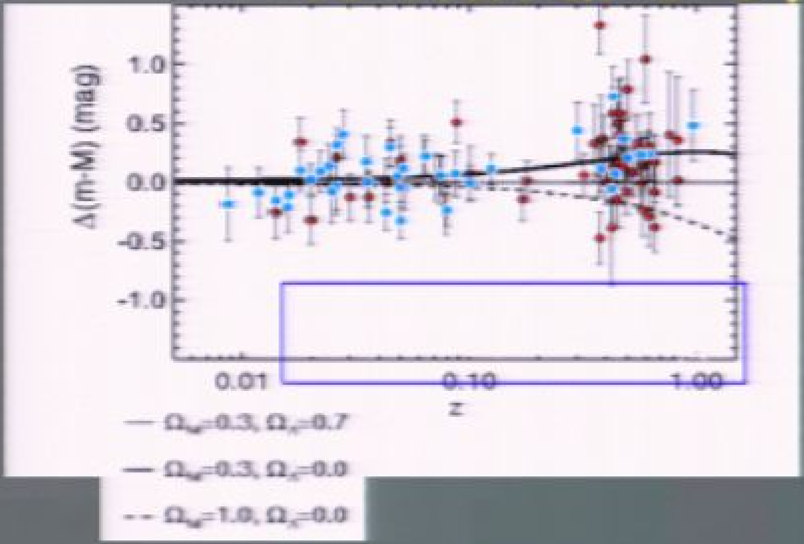

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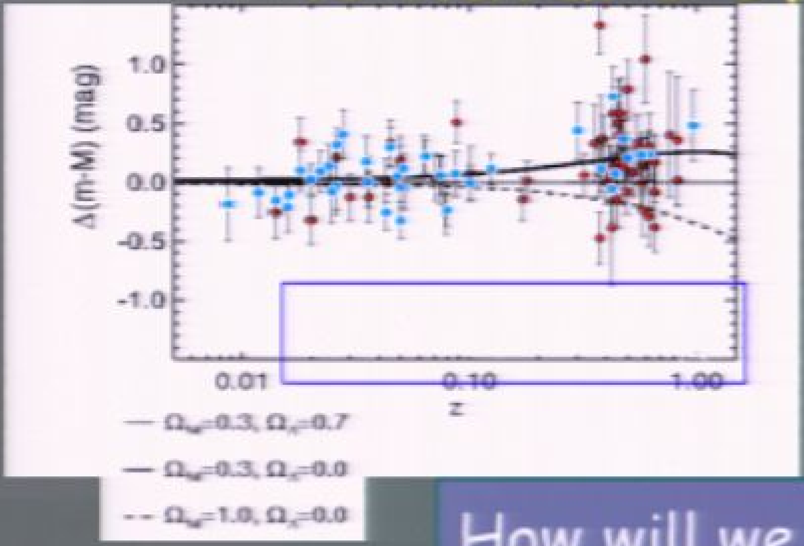

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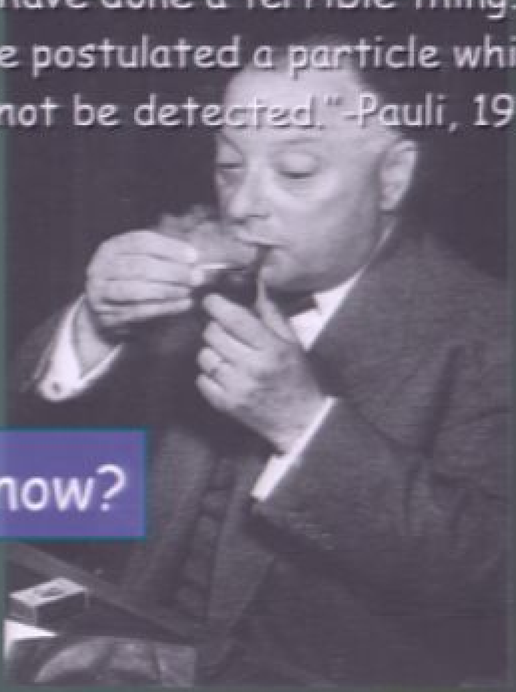

How will we ever know?

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A Cosmic Coincidence? Neutrino mass and dark energy

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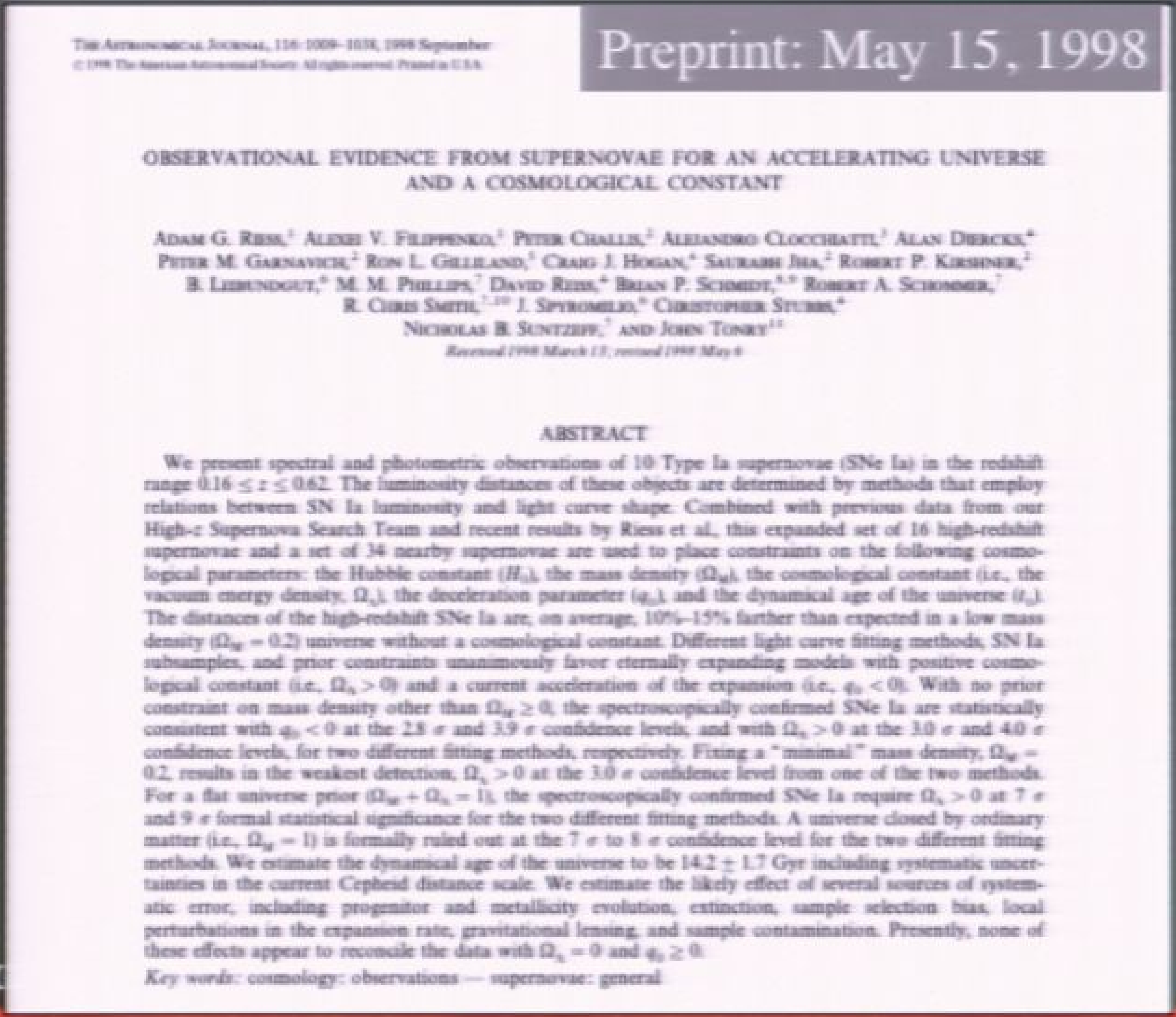


THE ASTRONOMICAL JOURNAL, 116:1009–1038, 1998 September

Preprint: May 15, 1998

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

ADAM G. RIESS,[1] ALEXEI V. FILIPPENKO,[1] PETER CHALLIS,[2] ALEJANDRO CLOCCHIATTI,[3] ALAN DIERCKS,[4]
PETER M. GARNAVICH,[2] RON L. GILLILAND,[5] CRAIG J. HOGAN,[4] SAURABH JHA,[2] ROBERT P. KIRSHNER,[2]
B. LEIBUNDGUT,[6] M. M. PHILLIPS,[7] DAVID REISS,[4] BRIAN P. SCHMIDT,[8,9] ROBERT A. SCHOMMER,[7]
R. CHRIS SMITH,[7,10] J. SPYROMILIO,[6] CHRISTOPHER STUBBS,[4]
NICHOLAS B. SUNTZEFF,[7] AND JOHN TONRY[11]

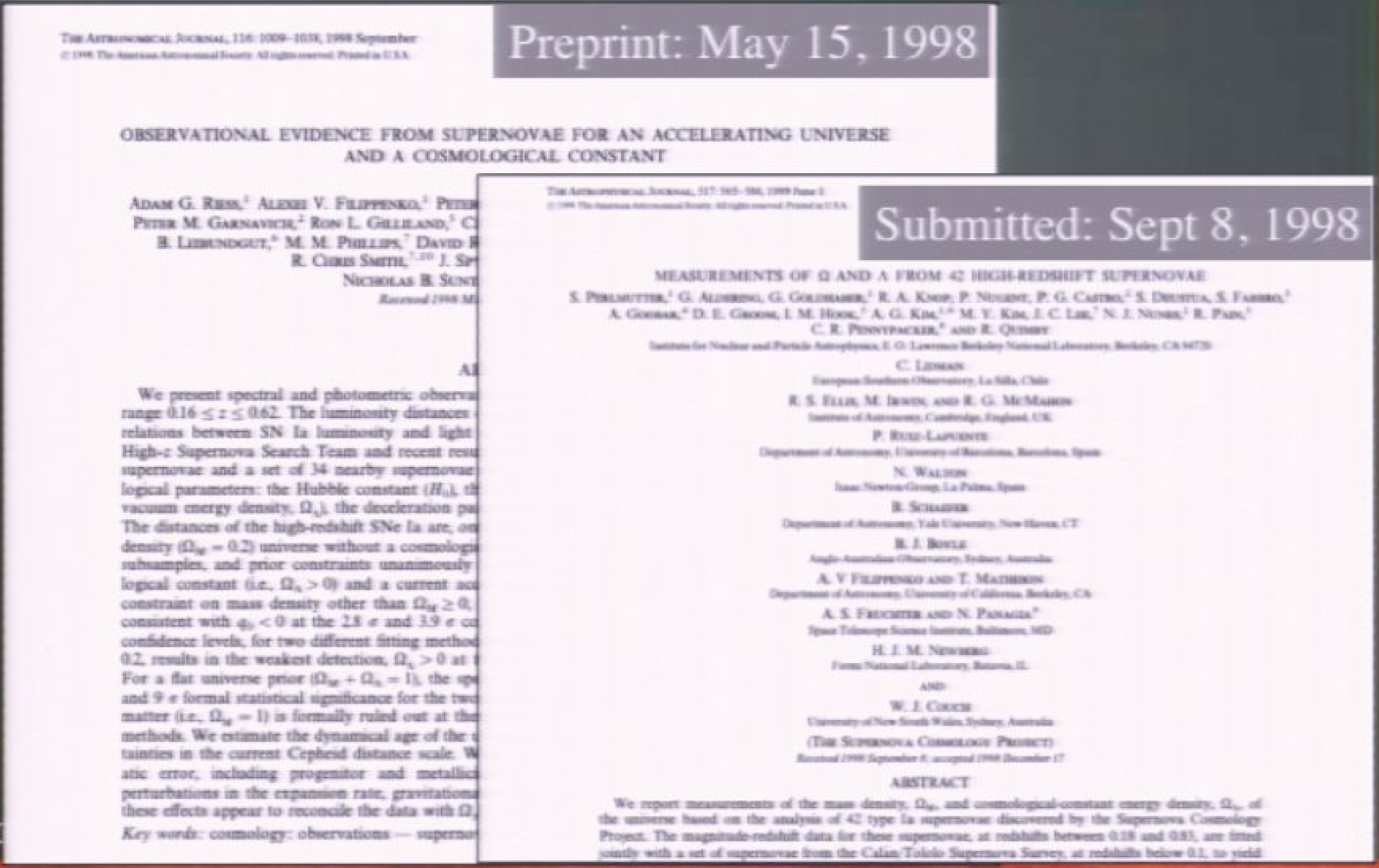
Received 1998 March 13; revised 1998 May 6

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 2.8 σ and 3.9 σ confidence levels, and with $\Omega_\Lambda > 0$ at the 3.0 σ and 4.0 σ 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 3.0 σ 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 7 σ and 9 σ 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 7 σ to 8 σ 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

A Cosmic Coincidence? Neutrino mass and dark energy



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Adam G. Riess,[1] Alexei V. Filippenko,[2] Peter
Peter M. Garnavich,[2] Ron L. Gilliland,[3] C
B. Leibundgut,[6] M. M. Phillips,[7] David R
R. Chris Smith,[7,10] J. Sp
Nicholas B. Sunt

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The Astrophysical Journal, 517:565–586, 1999 June 1

Submitted: Sept 8, 1998

MEASUREMENTS OF Ω AND Λ FROM 42 HIGH-REDSHIFT SUPERNOVAE

S. Perlmutter,[1] G. Aldering, G. Goldhaber,[1] R. A. Knop, P. Nugent, P. G. Castro,[2] S. Deustua, S. Fabbro,[3]
A. Goobar,[4] D. E. Groom, I. M. Hook,[5] A. G. Kim,[1,6] M. Y. Kim, J. C. Lee,[7] N. J. Nunes,[2] R. Pain,[3]
C. R. Pennypacker,[8] and R. Quimby
Institute for Nuclear and Particle Astrophysics, E. O. Lawrence Berkeley National Laboratory, Berkeley, CA 94720

C. Lidman
European Southern Observatory, La Silla, Chile

R. S. Ellis, M. Irwin, and R. G. McMahon
Institute of Astronomy, Cambridge, England, UK

P. Ruiz-Lapuente
Department of Astronomy, University of Barcelona, Barcelona, Spain

N. Walton
Isaac Newton Group, La Palma, Spain

B. Schaefer
Department of Astronomy, Yale University, New Haven, CT

B. J. Boyle
Anglo-Australian Observatory, Sydney, Australia

A. V Filippenko and T. Matheson
Department of Astronomy, University of California, Berkeley, CA

A. S. Fruchter and N. Panagia[9]
Space Telescope Science Institute, Baltimore, MD

H. J. M. Newberg
Fermi National Laboratory, Batavia, IL

and

W. J. Couch
University of New South Wales, Sydney, Australia

(The Supernova Cosmology Project)

Received 1998 September 8; accepted 1998 December 17

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

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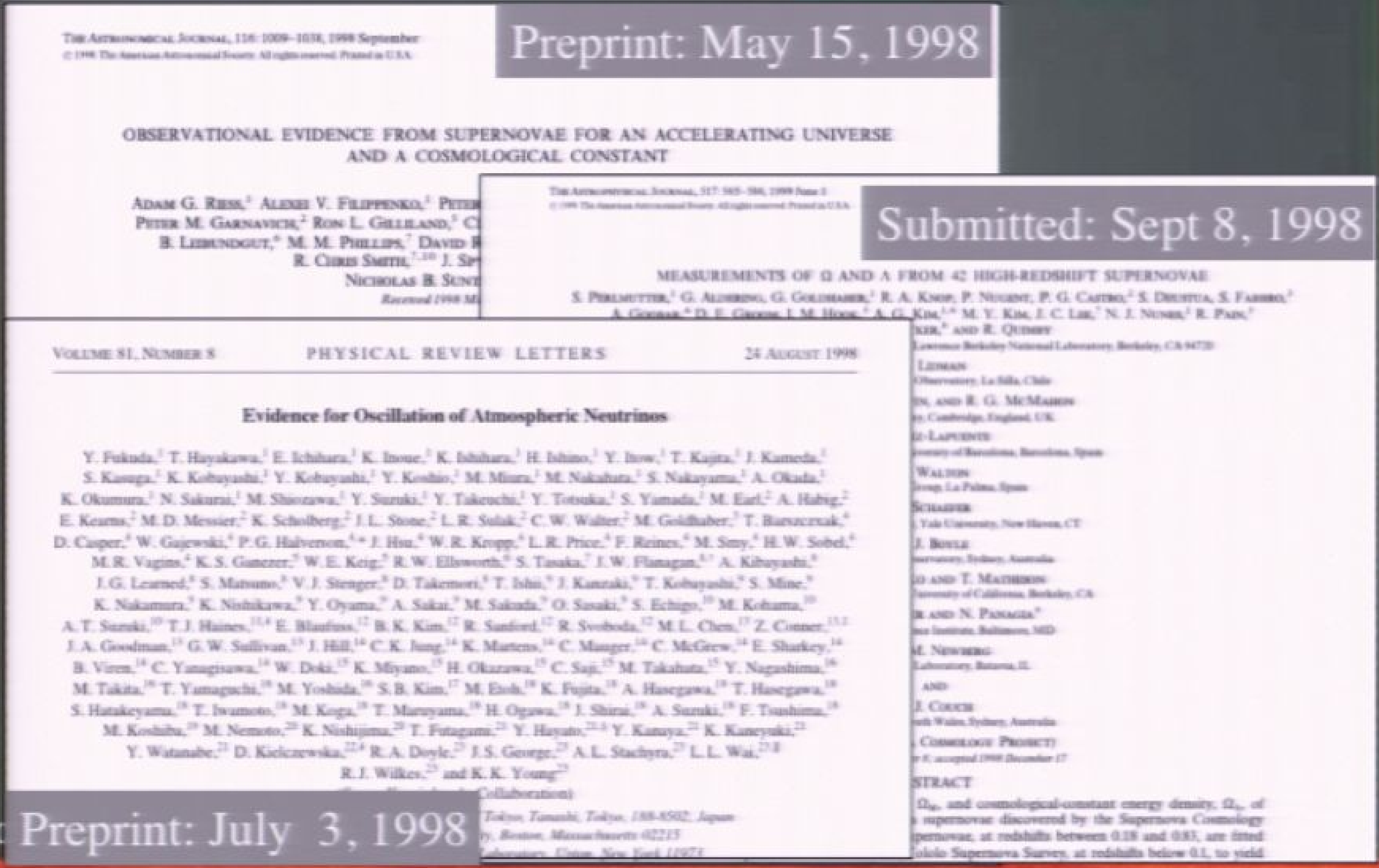

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AND R. G. MCMAHON

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VOLUME 81, NUMBER 8 PHYSICAL REVIEW LETTERS 24 AUGUST 1998

Evidence for Oscillation of Atmospheric Neutrinos

Y. Fukuda,[1] T. Hayakawa,[1] E. Ichihara,[1] K. Inoue,[1] K. Ishihara,[1] H. Ishino,[1] Y. Itow,[1] T. Kajita,[1] J. Kameda,[1]
S. Kasuga,[1] K. Kobayashi,[1] Y. Kobayashi,[1] Y. Koshio,[1] M. Miura,[1] M. Nakahata,[1] S. Nakayama,[1] A. Okada,[1]
K. Okumura,[1] N. Sakurai,[1] M. Shiozawa,[1] Y. Suzuki,[1] Y. Takeuchi,[1] Y. Totsuka,[1] S. Yamada,[1] M. Earl,[2] A. Habig,[2]
E. Kearns,[2] M. D. Messier,[2] K. Scholberg,[2] J. L. Stone,[2] L. R. Sulak,[2] C. W. Walter,[2] M. Goldhaber,[3] T. Barszczak,[4]
D. Casper,[4] W. Gajewski,[4] P. G. Halverson,[4,*] J. Hsu,[4] W. R. Kropp,[4] L. R. Price,[4] F. Reines,[4] M. Smy,[4] H. W. Sobel,[4]
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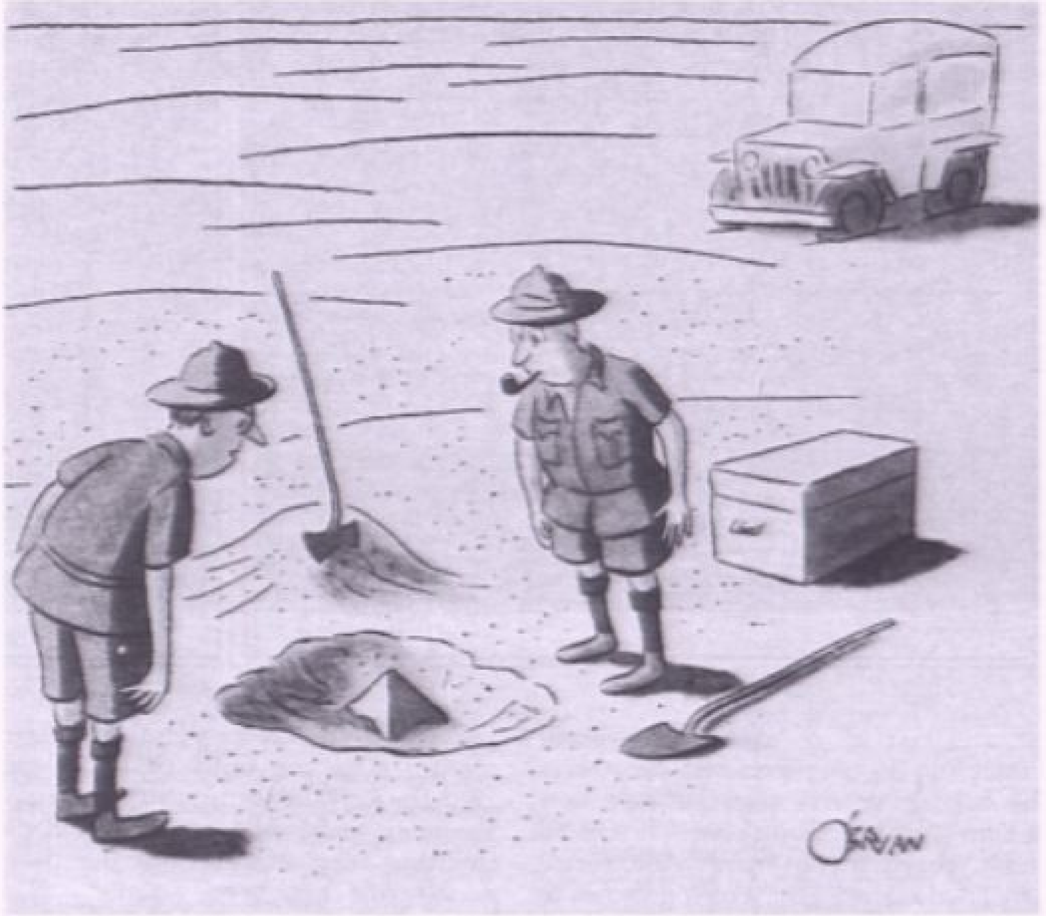
R. J. Wilkes,[23] and K. K. Young[23]

Collaboration)

Tokyo, Tanashi, Tokyo, 188-8502, Japan

Boston, Massachusetts 02215

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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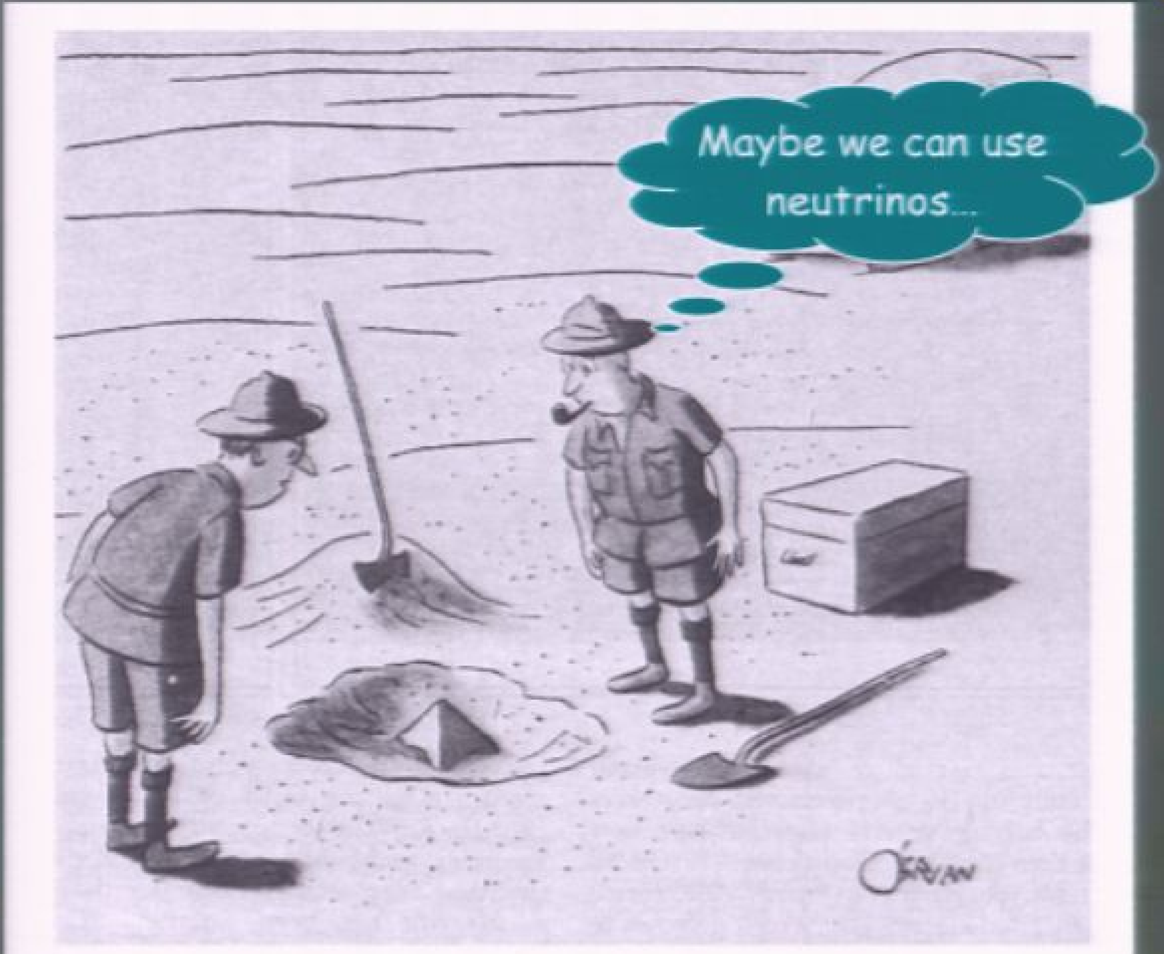

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So you want a mass to vary?

- 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 ~M^4

07/17/2008

N. Weiner CCPP

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

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

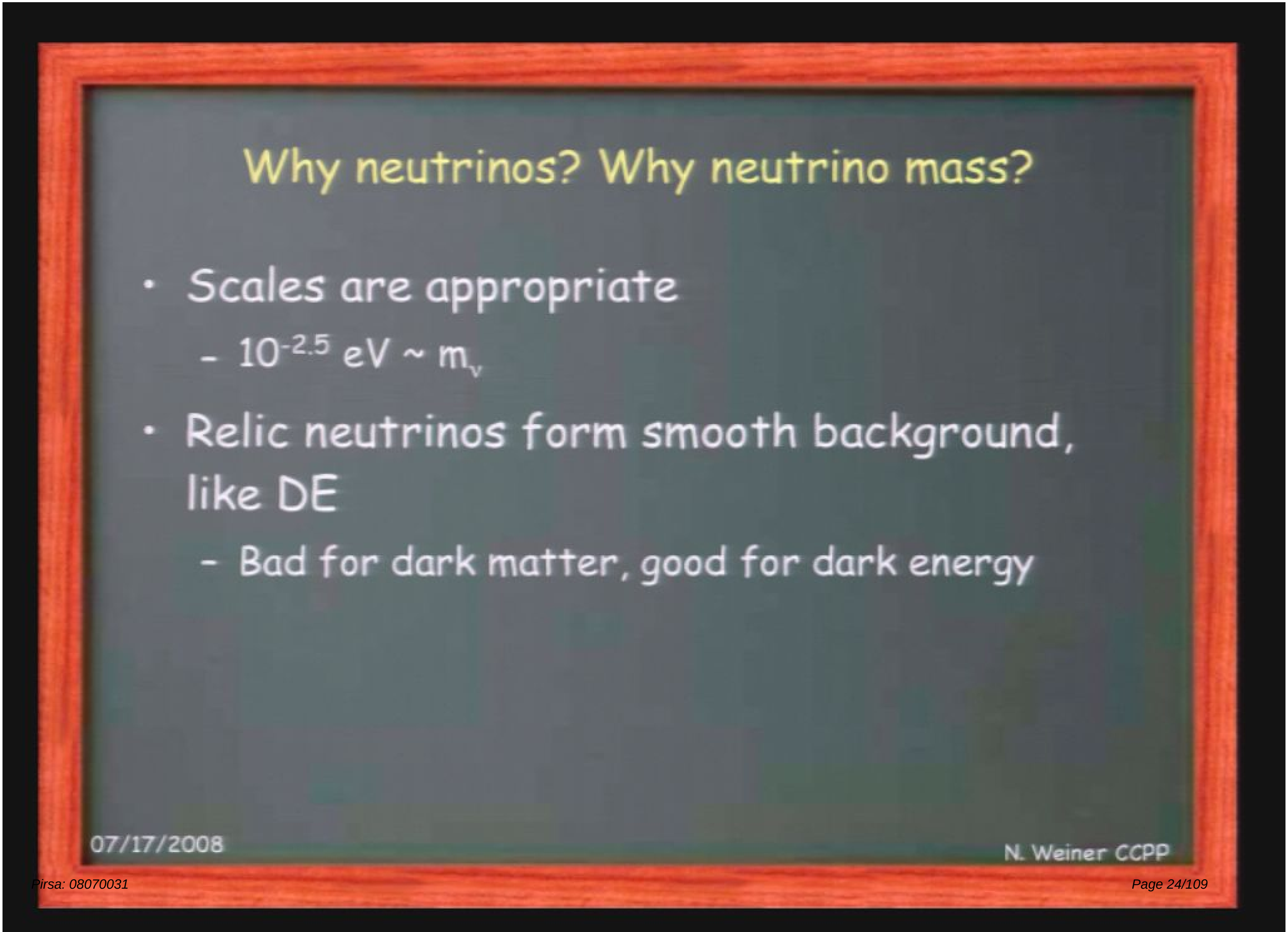
$$\rightarrow \delta M \sim \rho^{1/3} M_0^{1/3}$$

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?



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

07/17/2008

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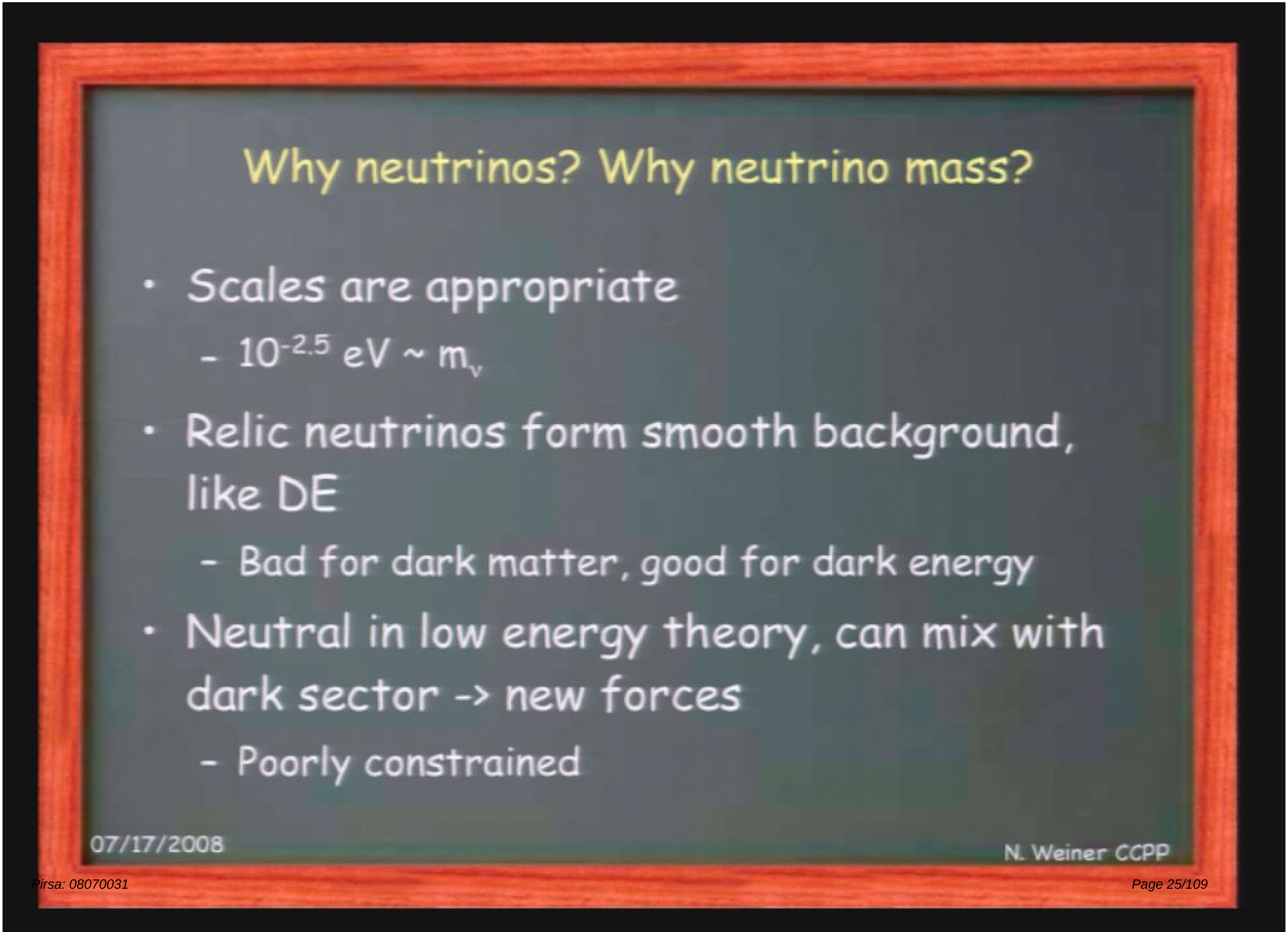

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- Scales are appropriate
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- Relic neutrinos form smooth background, like DE
  - Bad for dark matter, good for dark energy
- Neutral in low energy theory, can mix with dark sector -> new forces
  - Poorly constrained

Dependencies of neutrino mass

- Expect neutrino mass to be dynamical

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

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depends on
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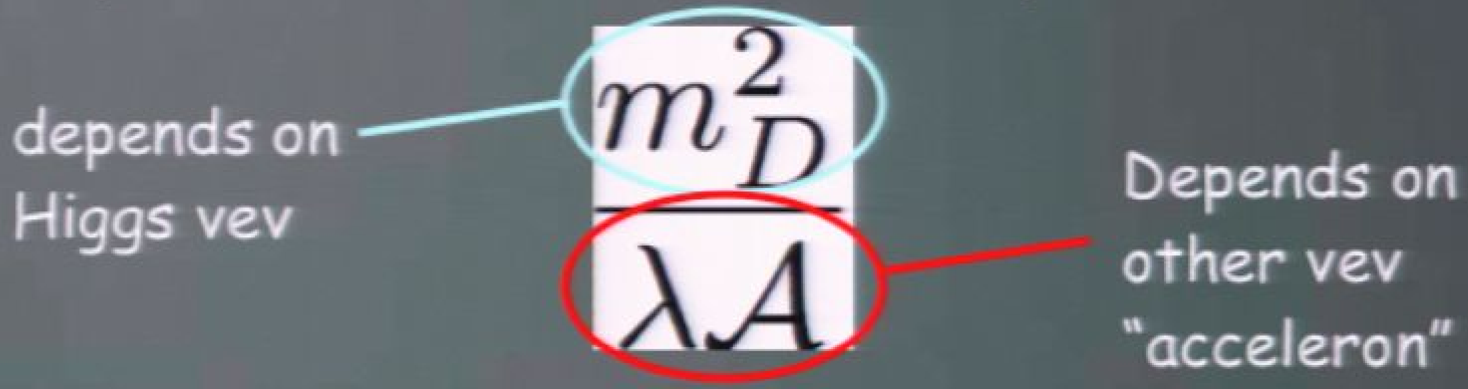

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Suppose <A> is small and $m_A \sim m_\nu$.

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depends on Higgs vev

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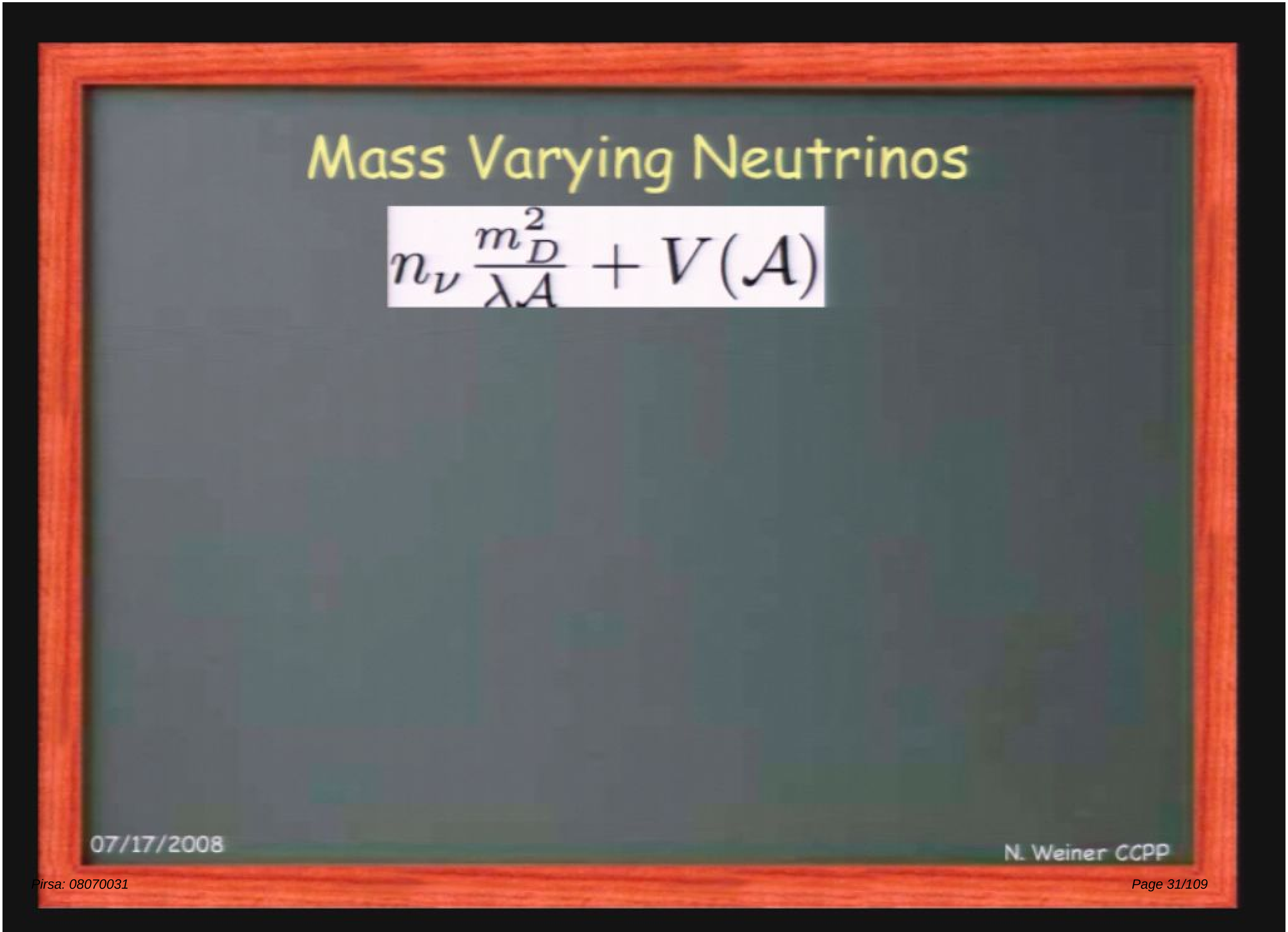
Suppose <A> is small and $m_A \sim m_\nu$.

What happens to neutrinos at finite density?



Mass Varying Neutrinos

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

07/17/2008

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drives A to
large values (m_ν to small values)

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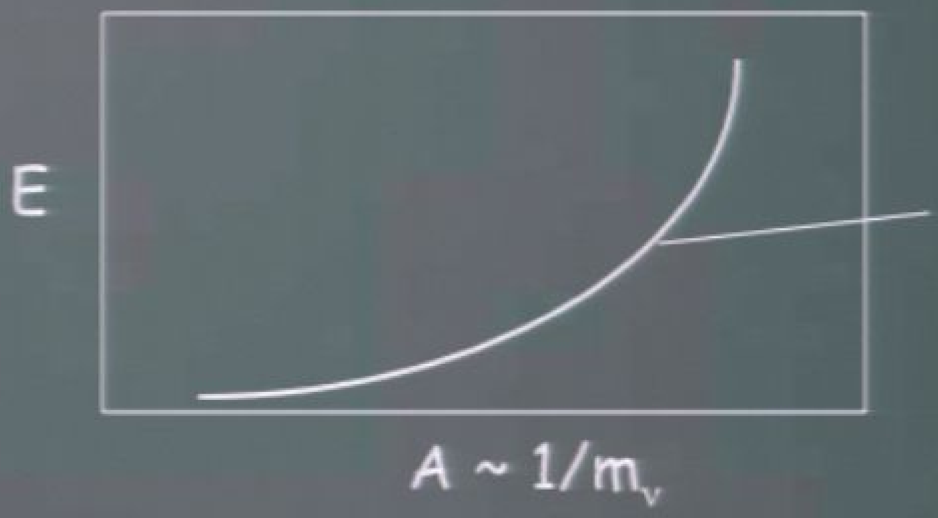

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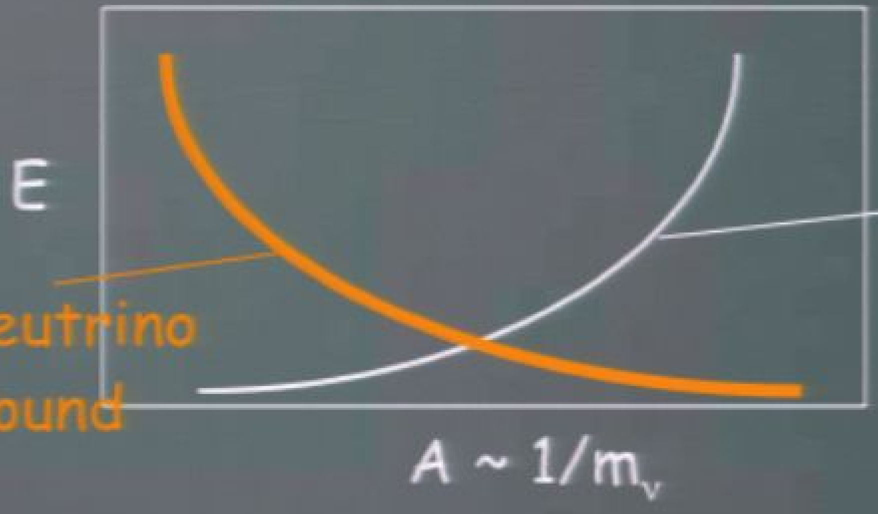

from neutrino background

from scalar potential

07/17/2008

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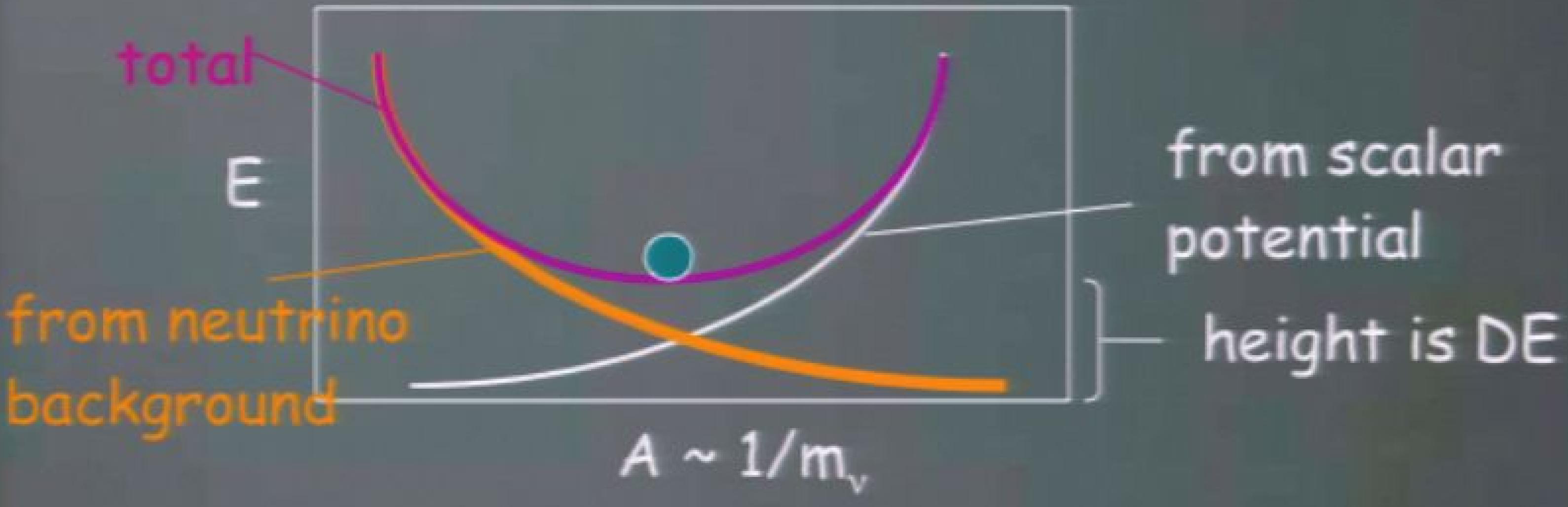

total

E

from neutrino background

from scalar potential

height is DE

A ~ $1/m_\nu$

07/17/2008

N. Weiner CCPP

Mass Varying Neutrinos

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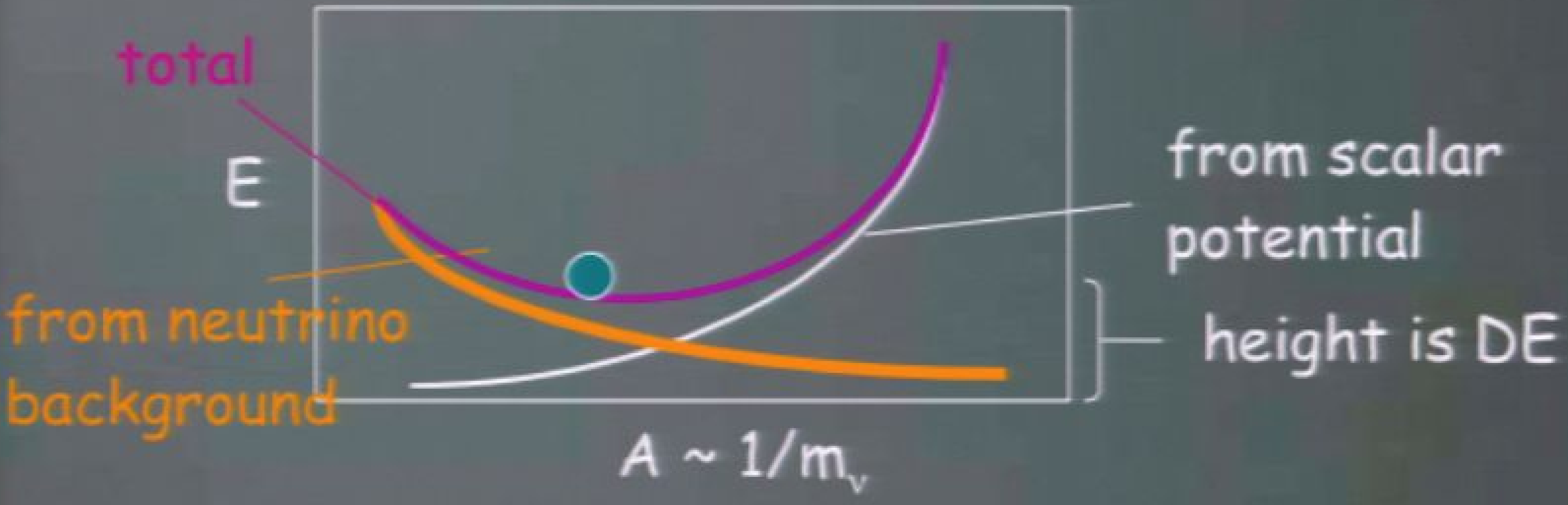
drives A to large values (m_ν to small values)

drives A to small values (m_ν to large values)



total

E

from neutrino background

from scalar potential

height is DE

A ~ 1/m_ν

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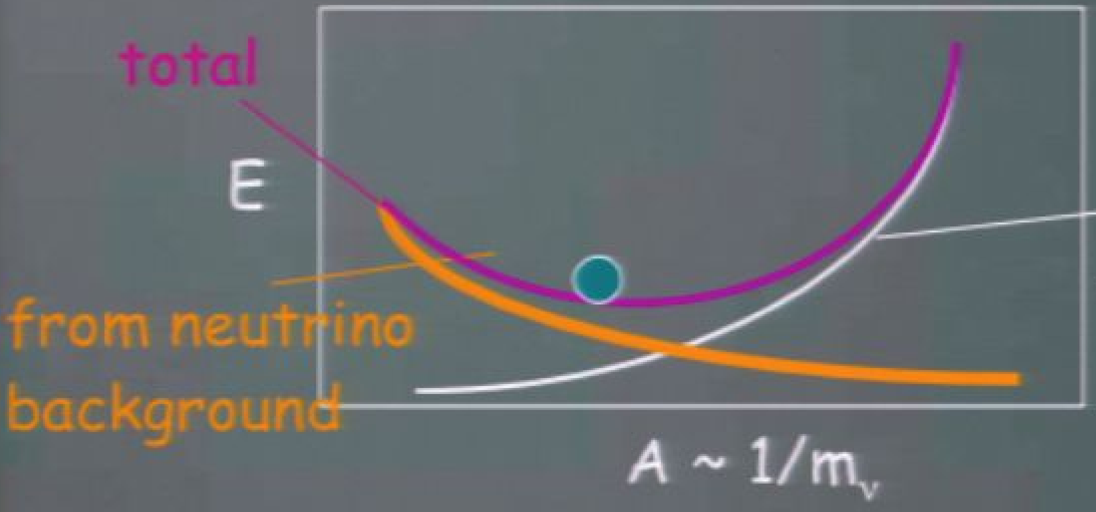

from scalar potential

height is DE

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)

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(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)

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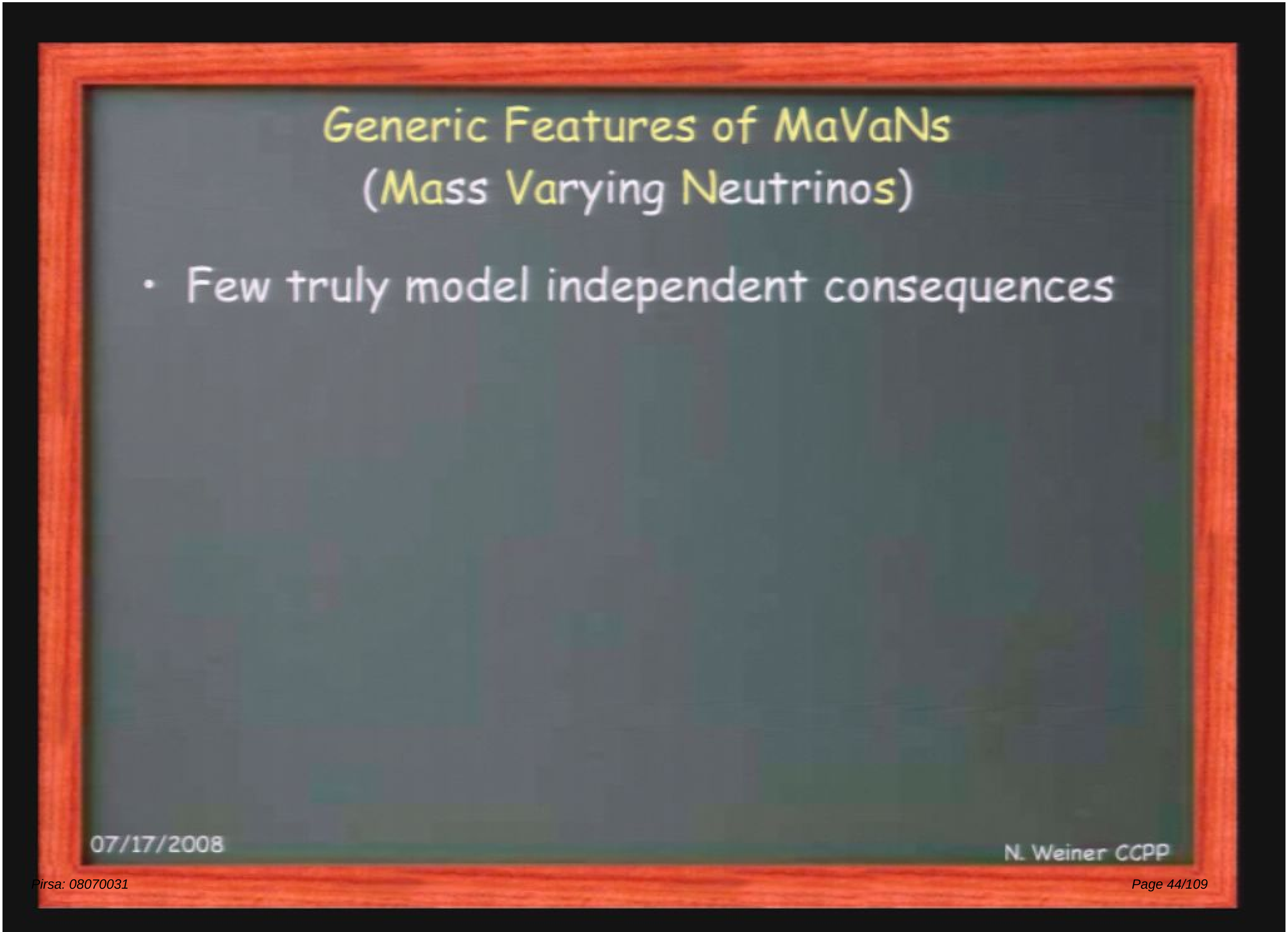
Generic Features of MaVaNs
(Mass Varying Neutrinos)



Generic Features of MaVaNs (Mass Varying Neutrinos)

- Few truly model independent consequences

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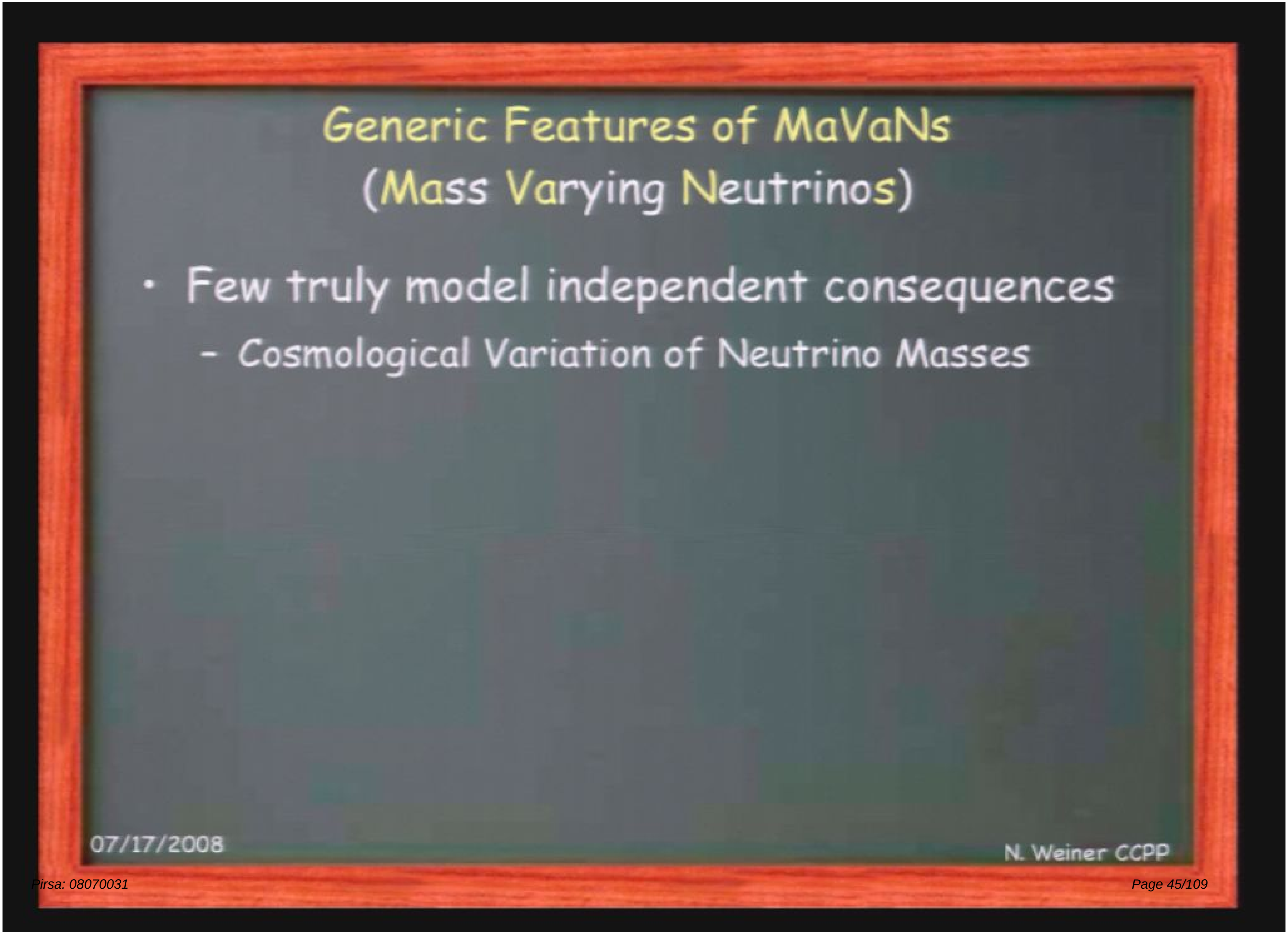

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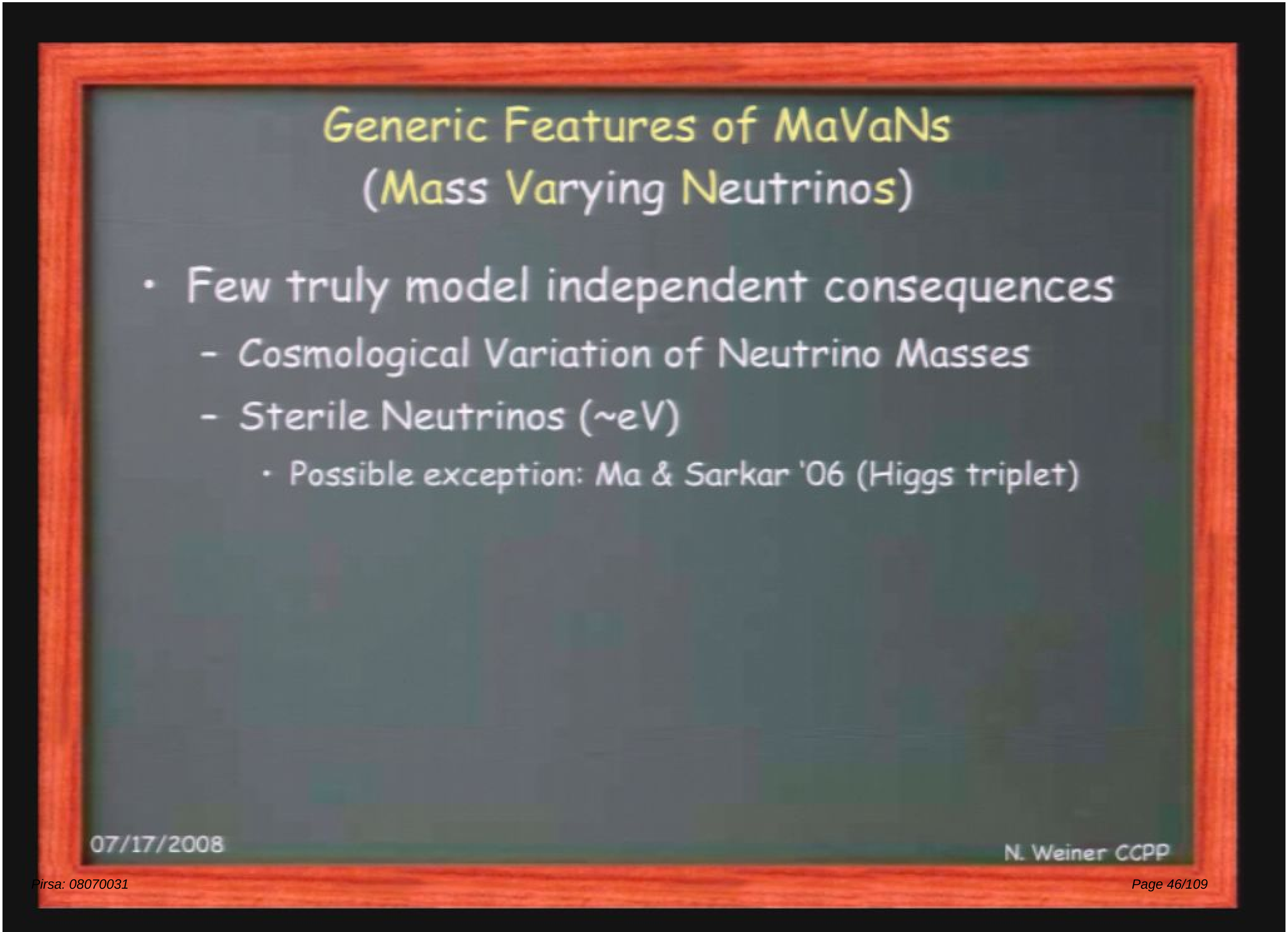

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  - Strong motivation to consider new matter effects
    - New scalar should couple to ordinary matter at least through gravitational-strength couplings

Cosmological Consequences

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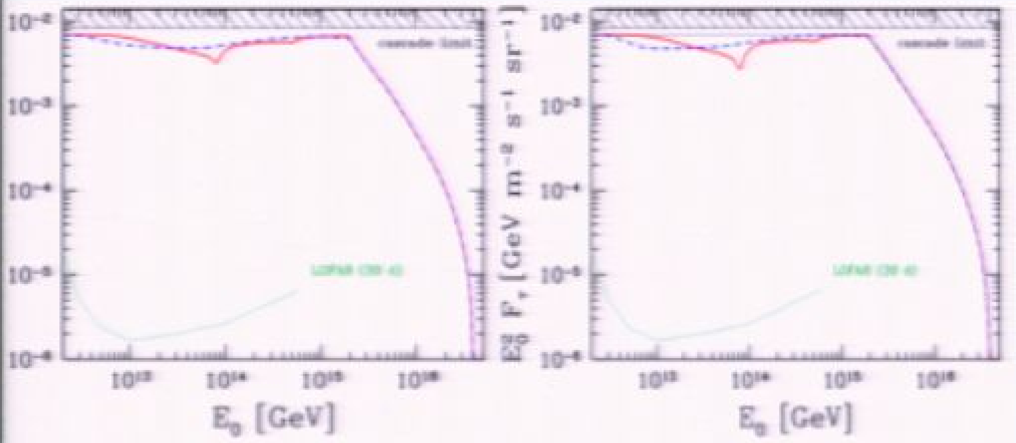

Figure 6. Projected sensitivity of LOFAR [48] expressed in terms of the diffuse neutrino flux per flavor, corresponding to one event per energy decade and indicated duration, together with $E_0^2 F$ with $F = \sum F_{\nu_\alpha} + \sum F_{\bar{\nu}_\alpha}$ (left column) and $E_0^2 F_\tau$ with $F_\tau = F_{\nu_\tau} + F_{\bar{\nu}_\tau}$ (right column) for varying (solid lines) and constant (dashed lines) neutrino masses and for $z_{\max} = 20$, assuming a normal neutrino mass hierarchy with $m_{\nu_1} = 10^{-5}$ eV, $n = 4$ and $\alpha = 2$ as well as $E_{\max} = 4 \times 10^{16}$ GeV.

Ringwald & Schrempp
(June 13, '06)

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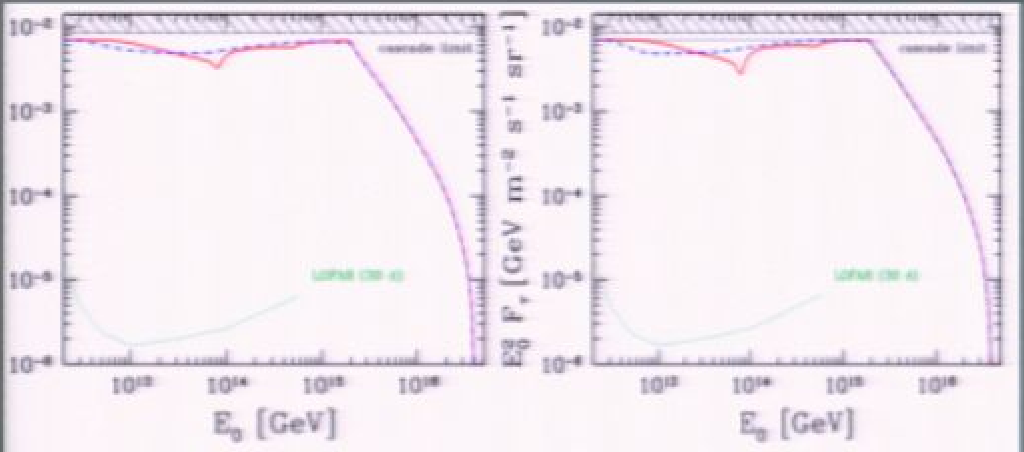

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Flavor changing effects: Hung & Pas '03

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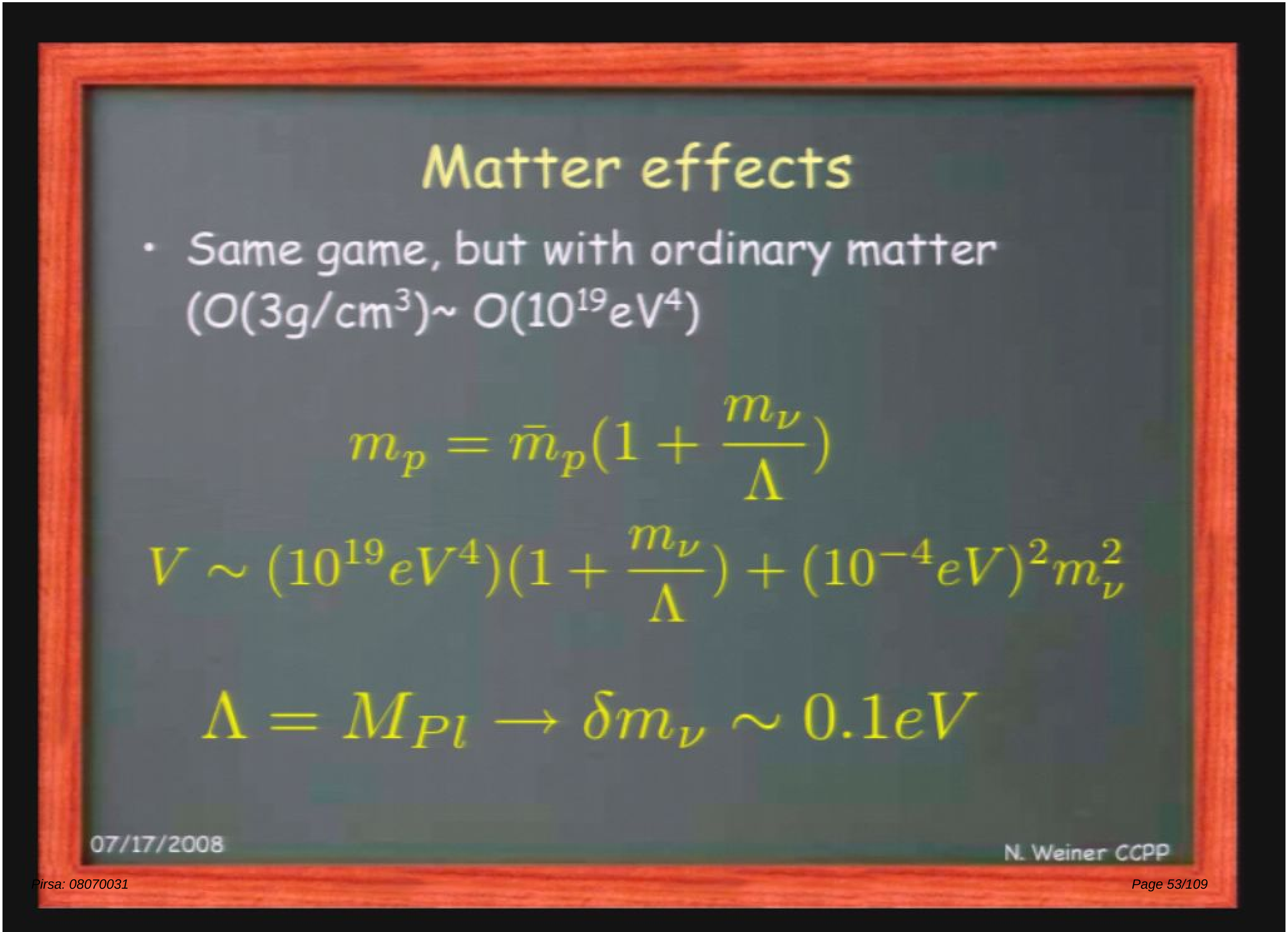

Matter effects

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

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

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

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

We already knew this!

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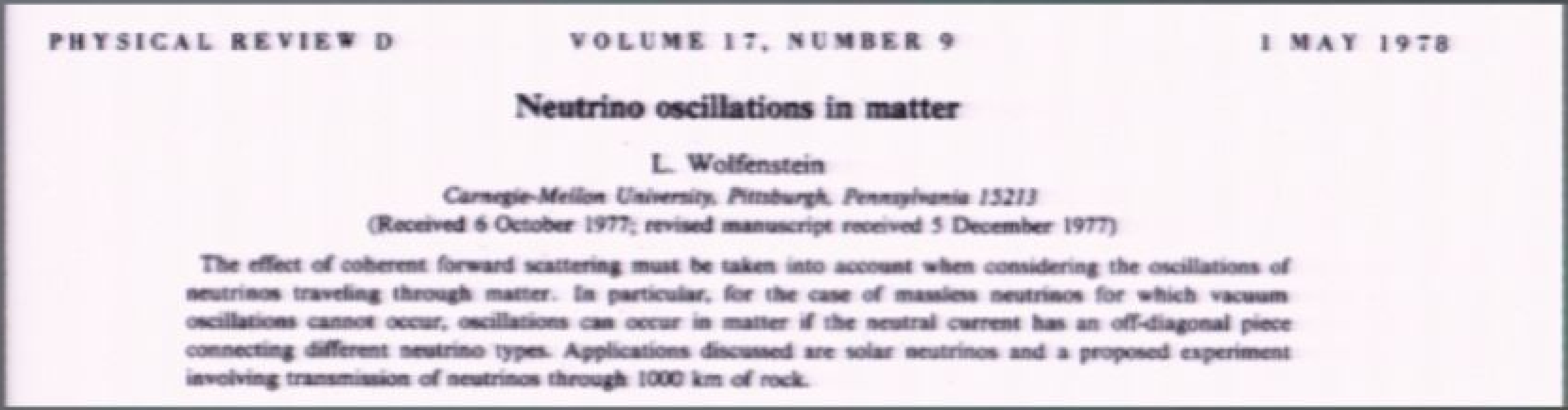

PHYSICAL REVIEW D VOLUME 17, NUMBER 9 1 MAY 1978

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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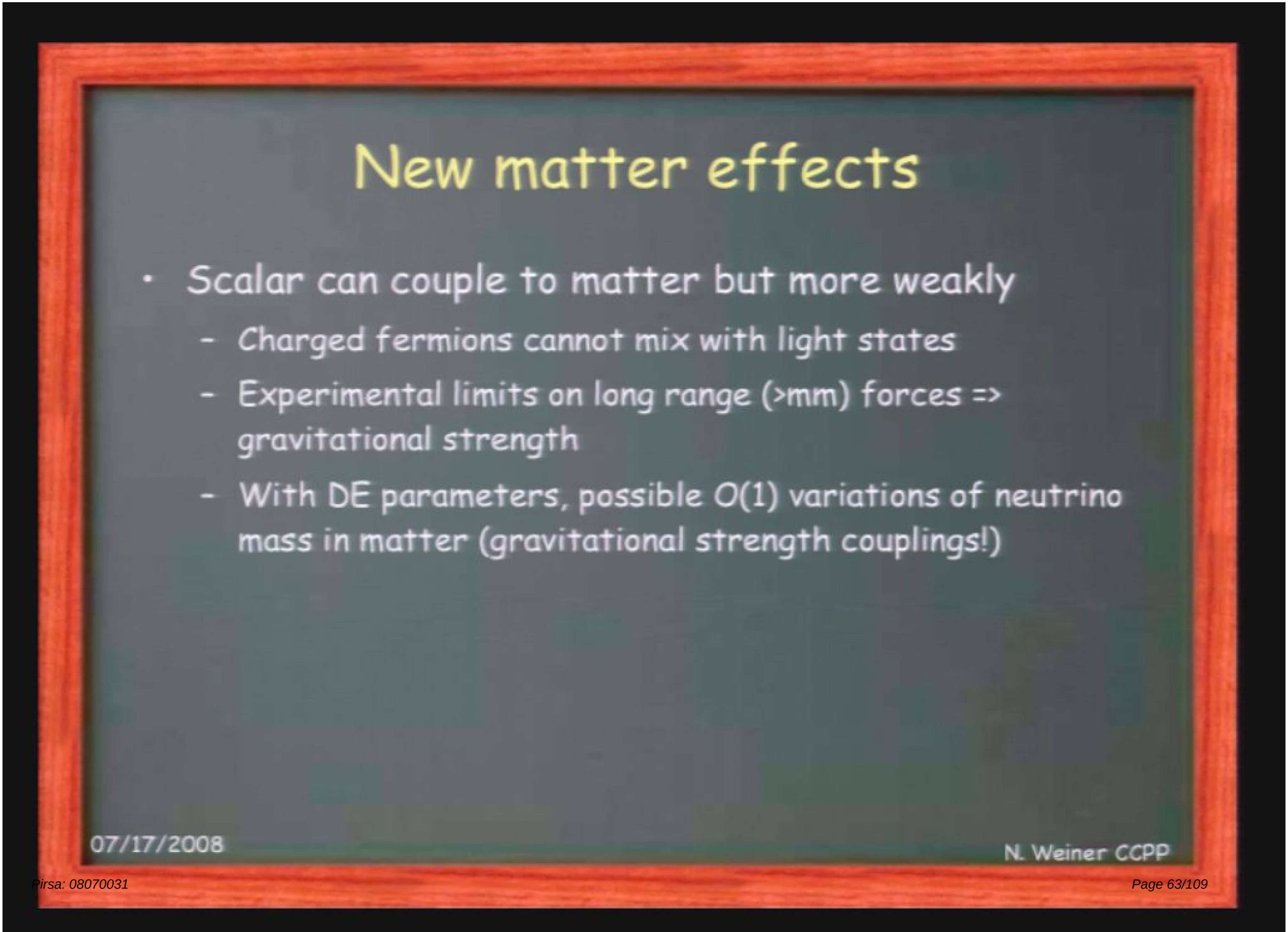

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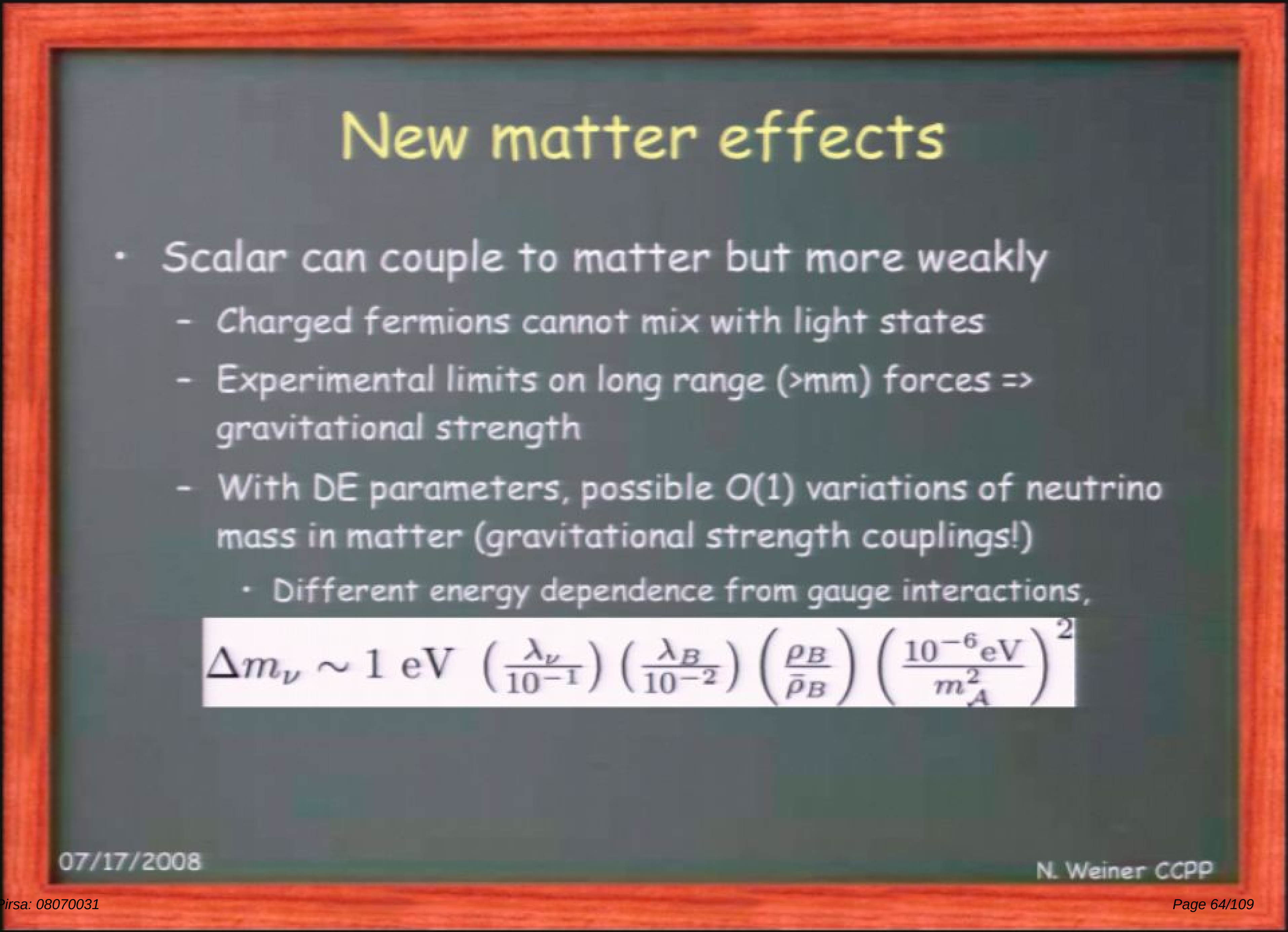

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    - Different energy dependence from gauge interactions,

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

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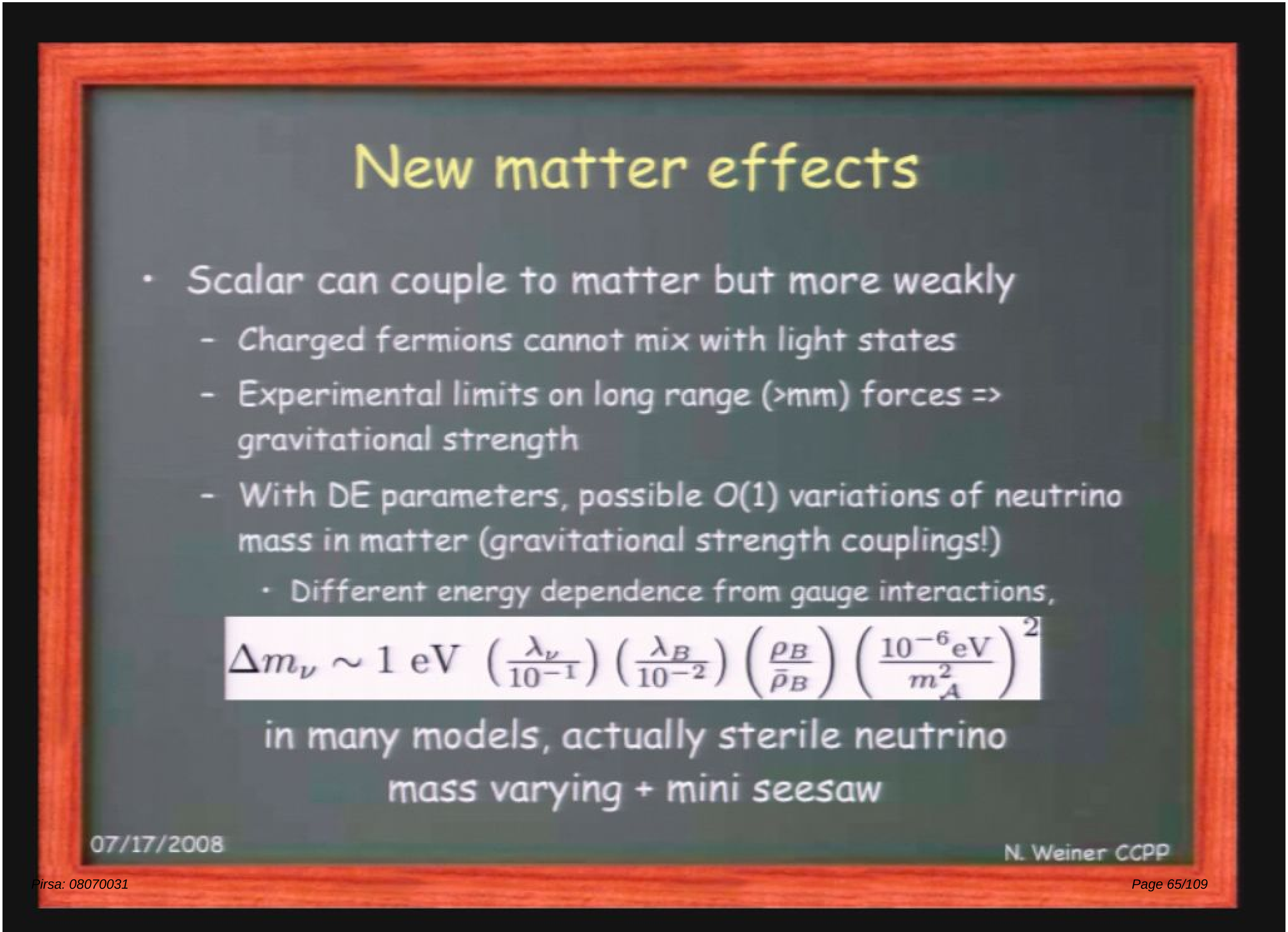

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in many models, actually sterile neutrino mass varying + mini seesaw

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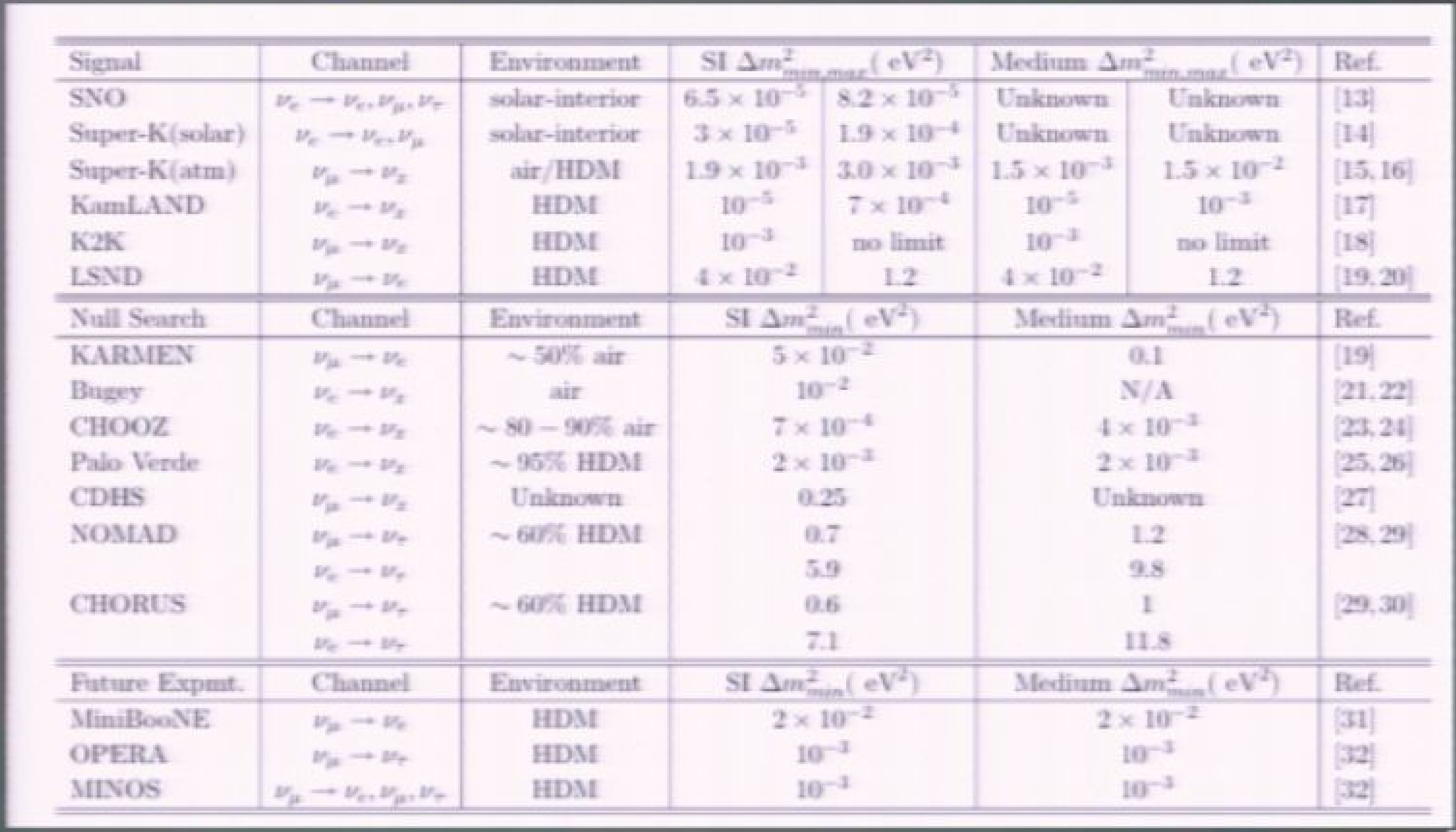
Comparing experiments considering matter effects



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	$\nu_\mu \to \nu_e$	$\sim 50\%$ air	5×10^{-2}		0.1		[19]
Bugey	$\nu_e \to \nu_x$	air	10^{-2}		N/A		[21, 22]
CHOOZ	$\nu_e \to \nu_x$	$\sim 80 - 90\%$ air	7×10^{-4}		4×10^{-3}		[23, 24]
Palo Verde	$\nu_e \to \nu_x$	$\sim 95\%$ HDM	2×10^{-3}		2×10^{-3}		[25, 26]
CDHS	$\nu_\mu \to \nu_x$	Unknown	0.25		Unknown		[27]
NOMAD	$\nu_\mu \to \nu_\tau$	$\sim 60\%$ HDM	0.7		1.2		[28, 29]
	$\nu_e \to \nu_\tau$		5.9		9.8		
CHORUS	$\nu_\mu \to \nu_\tau$	$\sim 60\%$ 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

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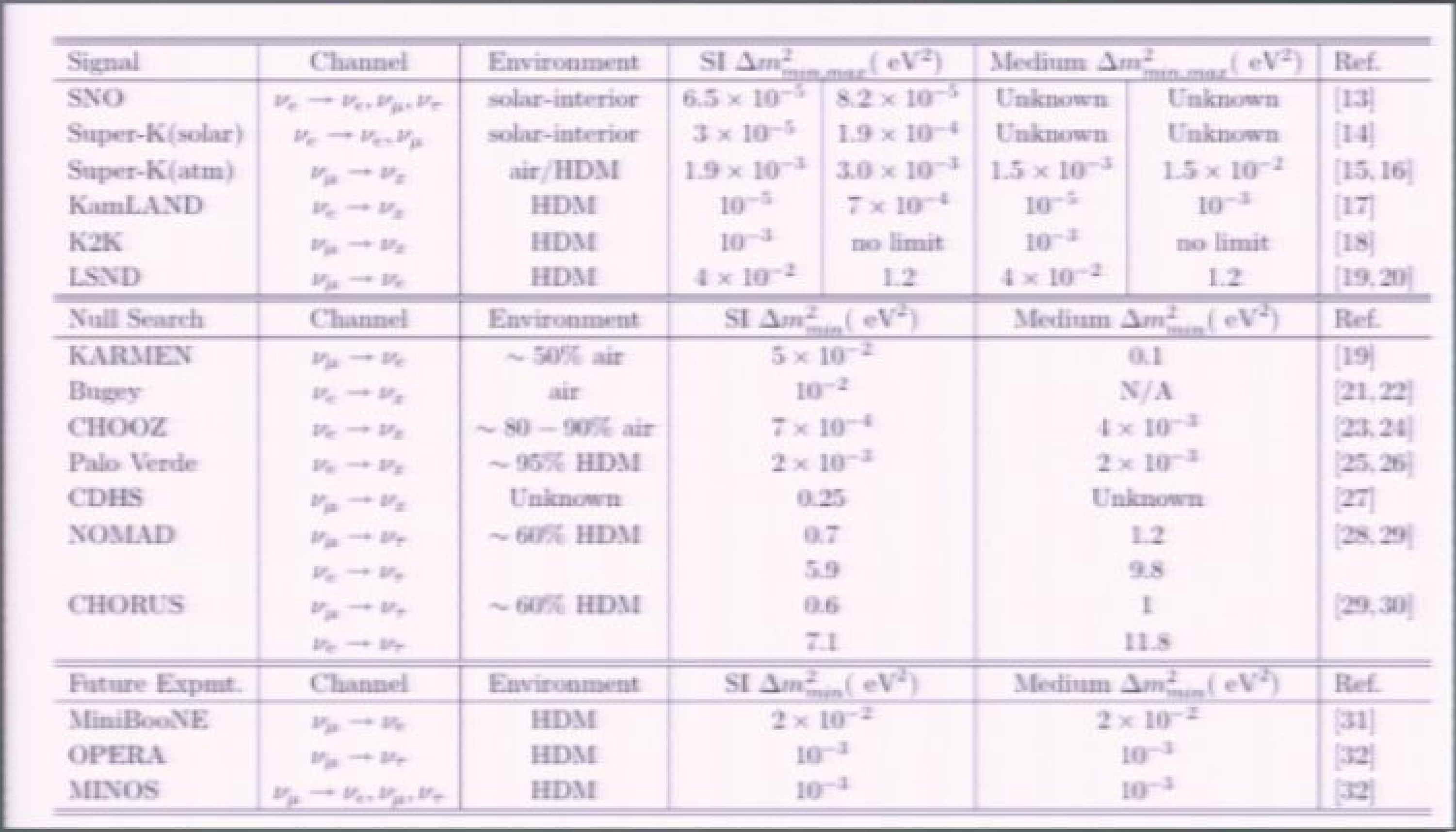
Comparing experiments considering matter effects



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Zurek '04

Only experimental evidence for m_ν in air:

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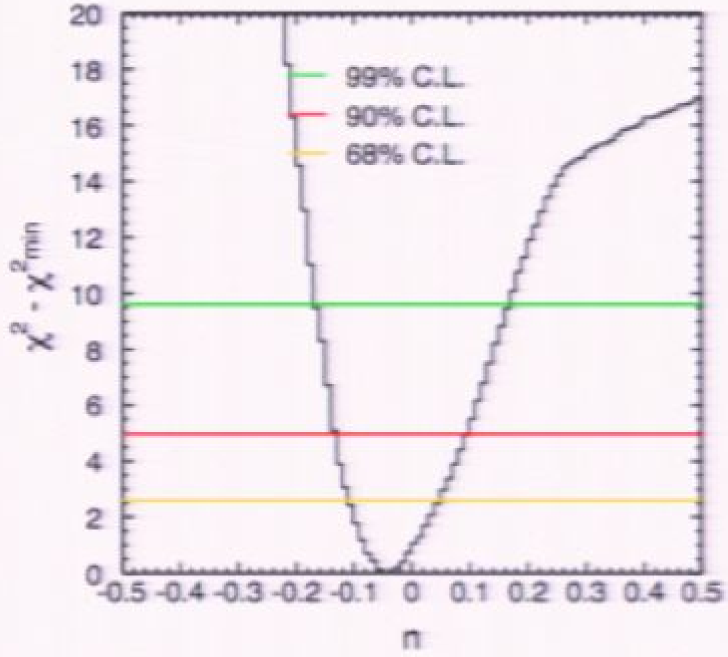
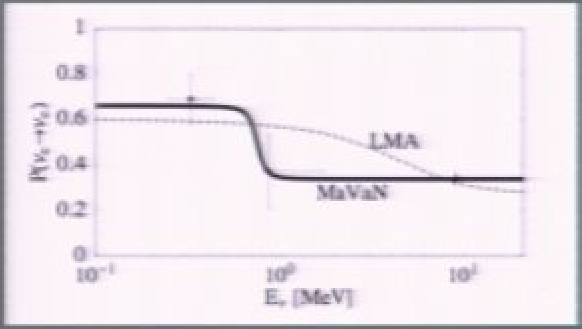


FIG. 1: $\Delta m^2 \rightarrow \Delta m^2 \times \left(\frac{\rho_c}{\rho_o}\right)^n$ (including air path length). Upper plot shows relative-χ^2 confidence level contours on the Δm^2 versus n plane, obtained when taking into account both high and low density matter path lengths. The lower plots display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

Abe et al, '08

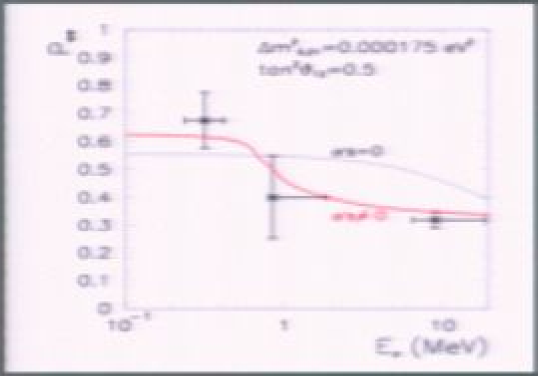
Signals: Solar Neutrinos

- New matter effects can modify solar neutrino signals



Barger, Huber, Marfatia '05

improve fit / modify spectrum of neutrino survival probability



Gonzalez-Garcia,
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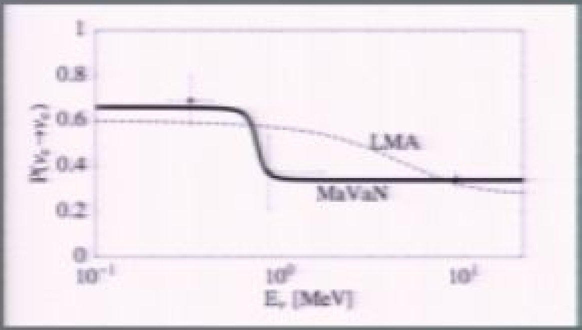

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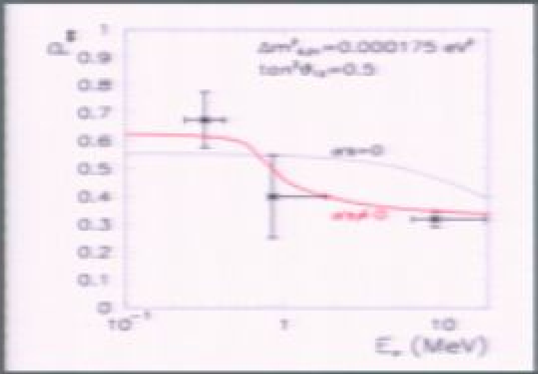

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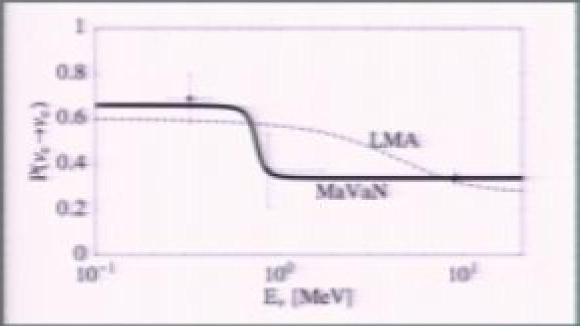

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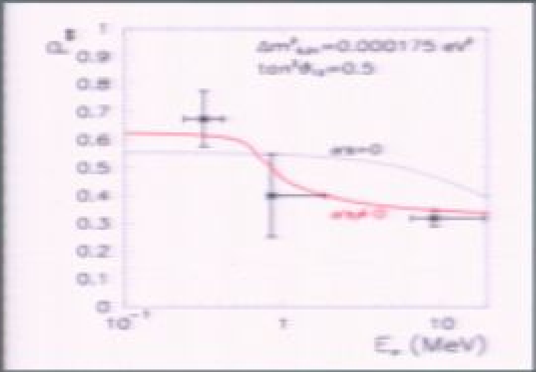

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- All comparisons are in given model
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- Extracting Be neutrino flux key for testing new forces

Reactor Neutrino Experiments

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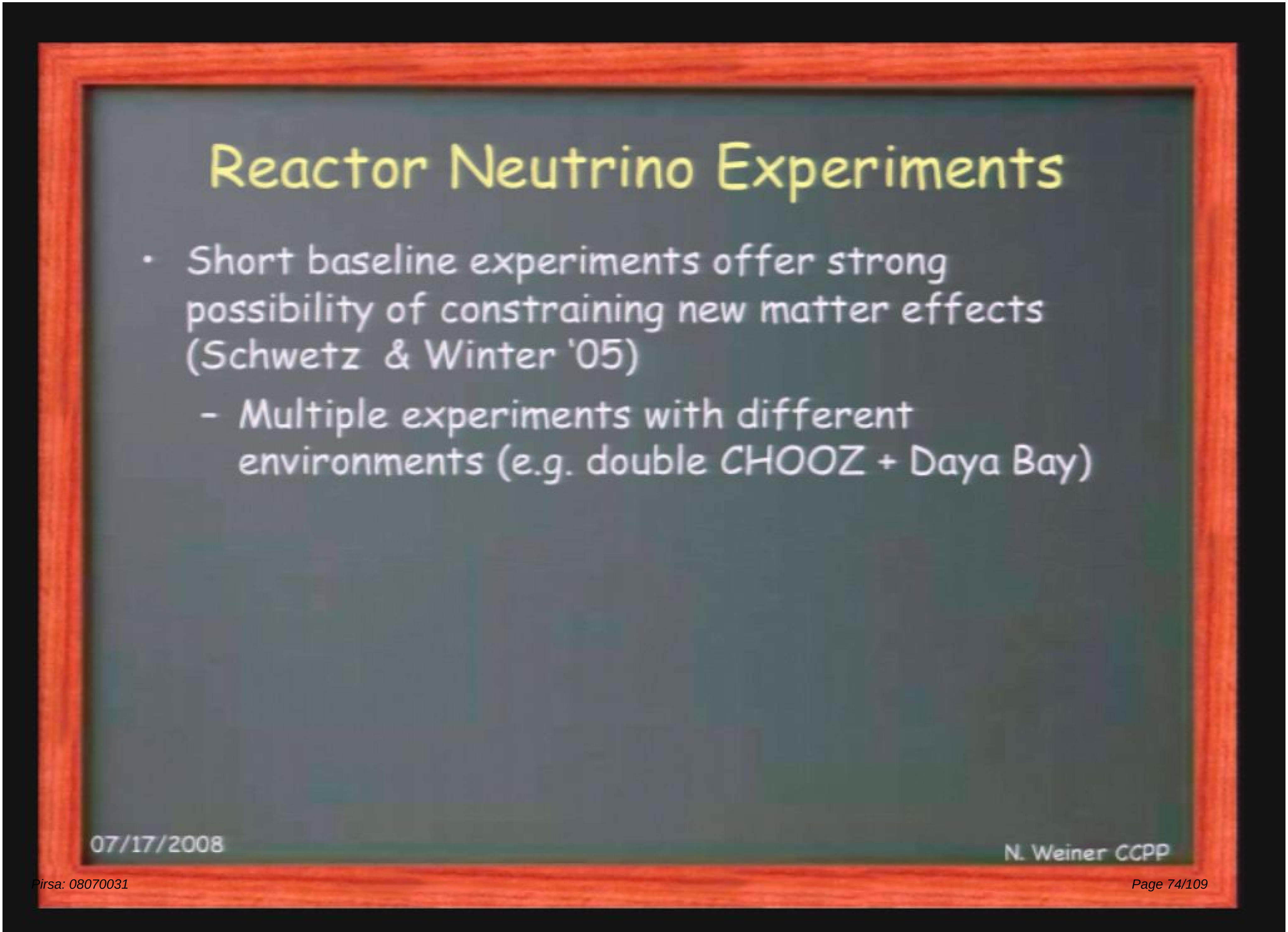
- Short baseline experiments offer strong possibility of constraining new matter effects (Schwetz & Winter '05)



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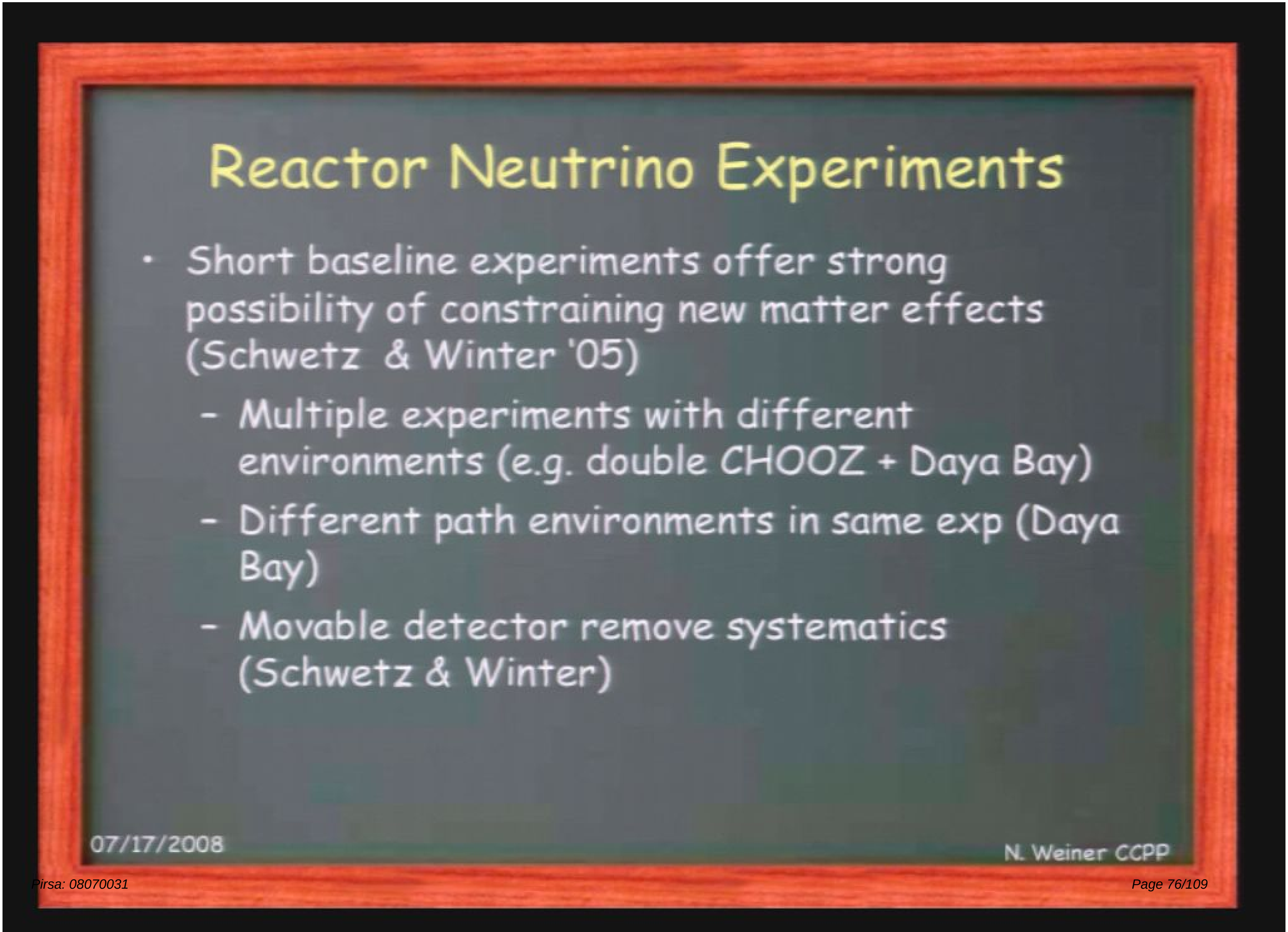

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  - Movable detector remove systematics (Schwetz & Winter)
- Simple modification: change shielding for near detector

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

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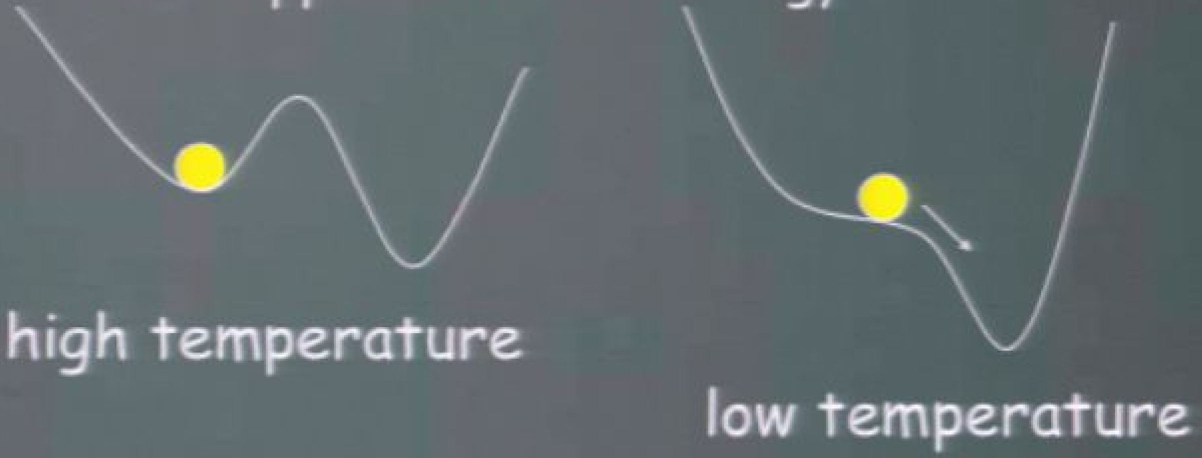
- Very exciting possibility - neutrino mass associated with phase transition
  - What happened to that energy?



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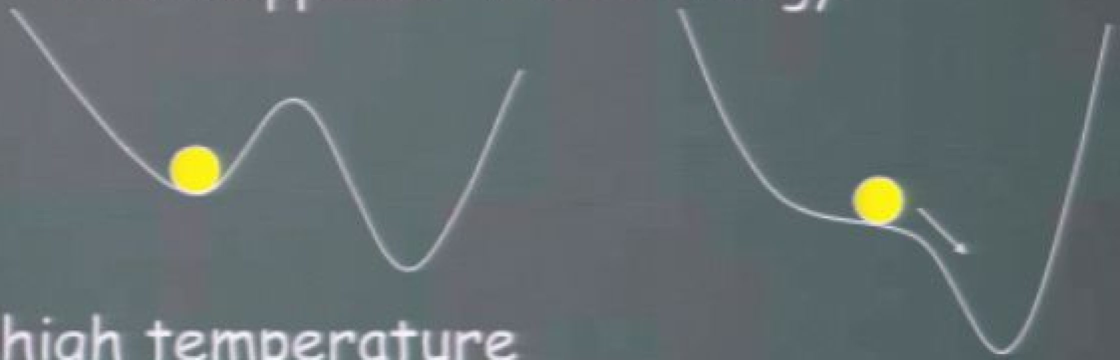

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  - What happened to that energy?

high temperature

low temperature

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

Power at small scales

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

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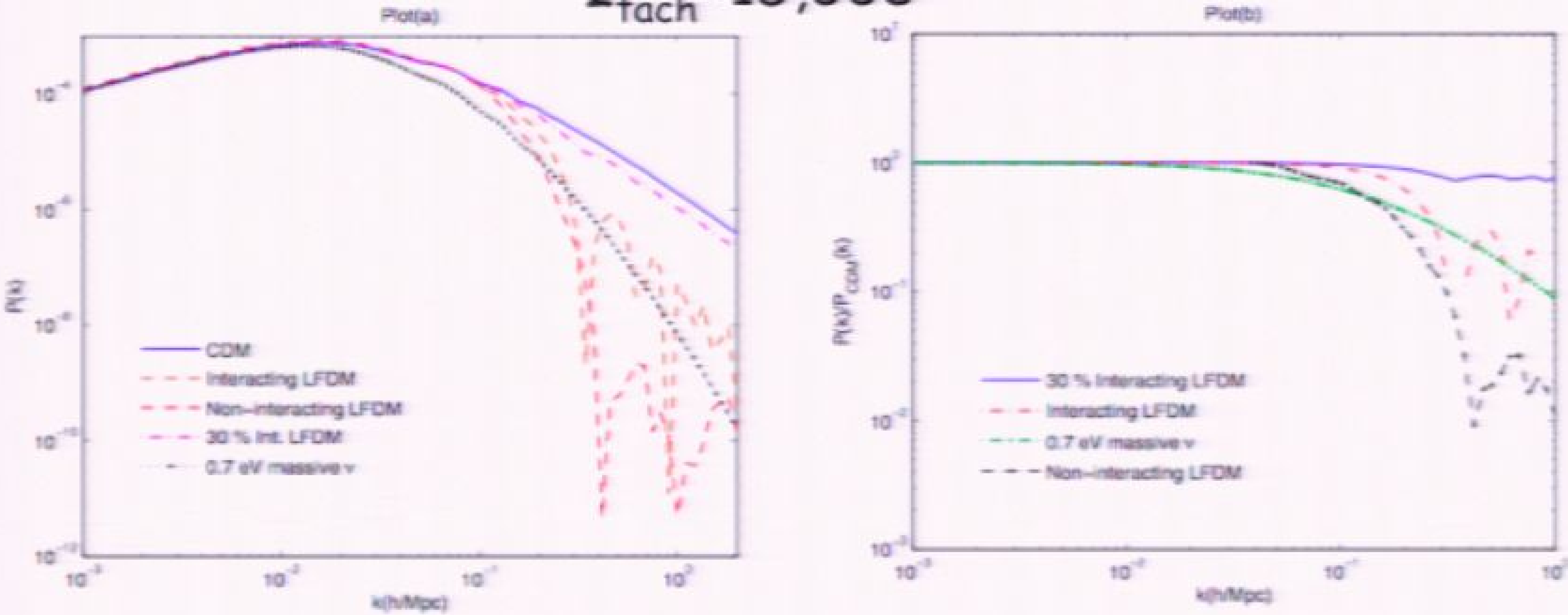
- Power spectrum determined by power of thermal species (i.e., neutrinos)

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

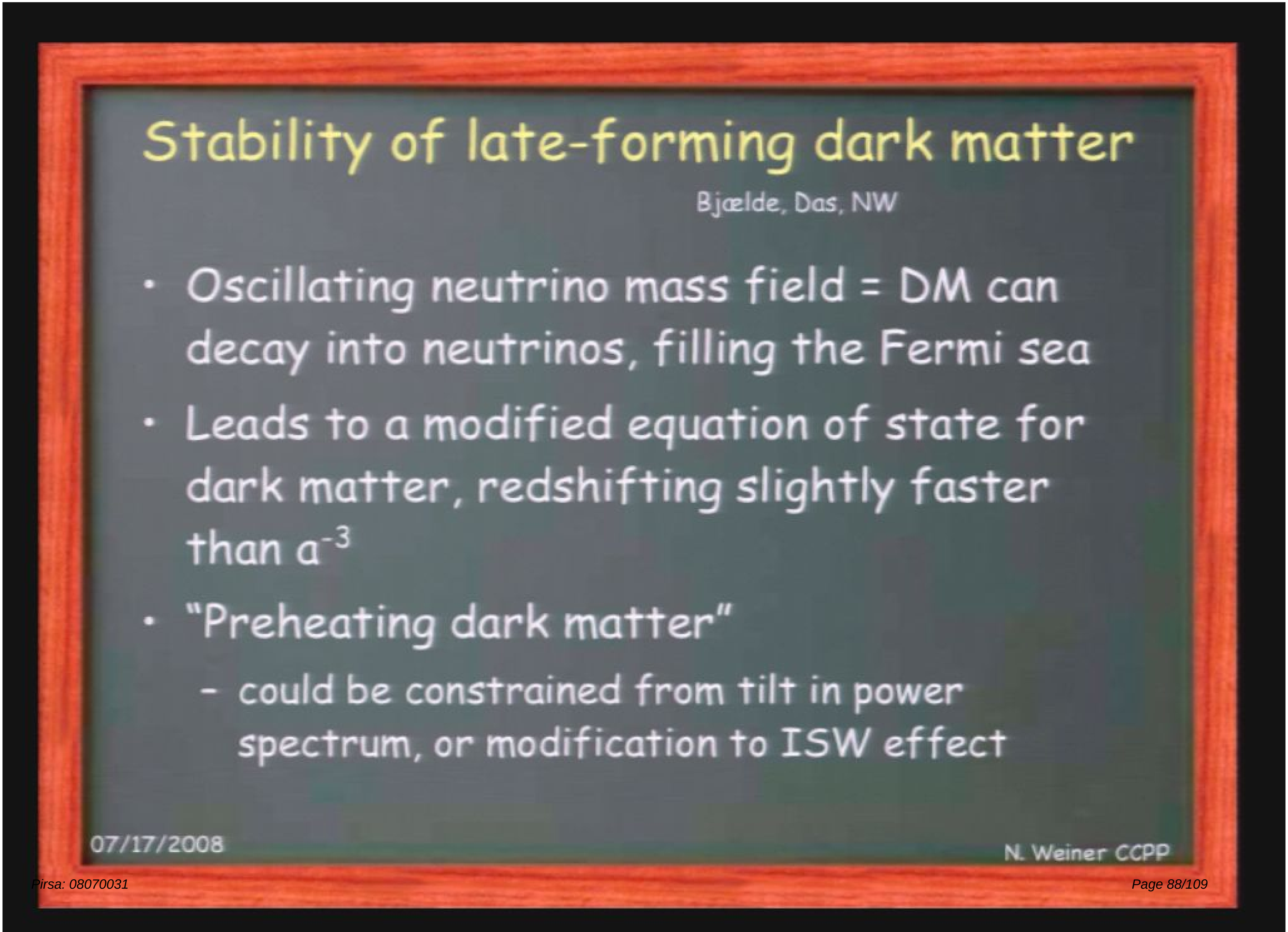
CDM P(k) gives snapshot of universe at z_{tach}

z_{tach}=15,000



estimate $10^{-3} \gtrsim k_{\rm tach} \gtrsim 10^{2}$

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



Stability of late-forming dark matter

Bjælde, 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

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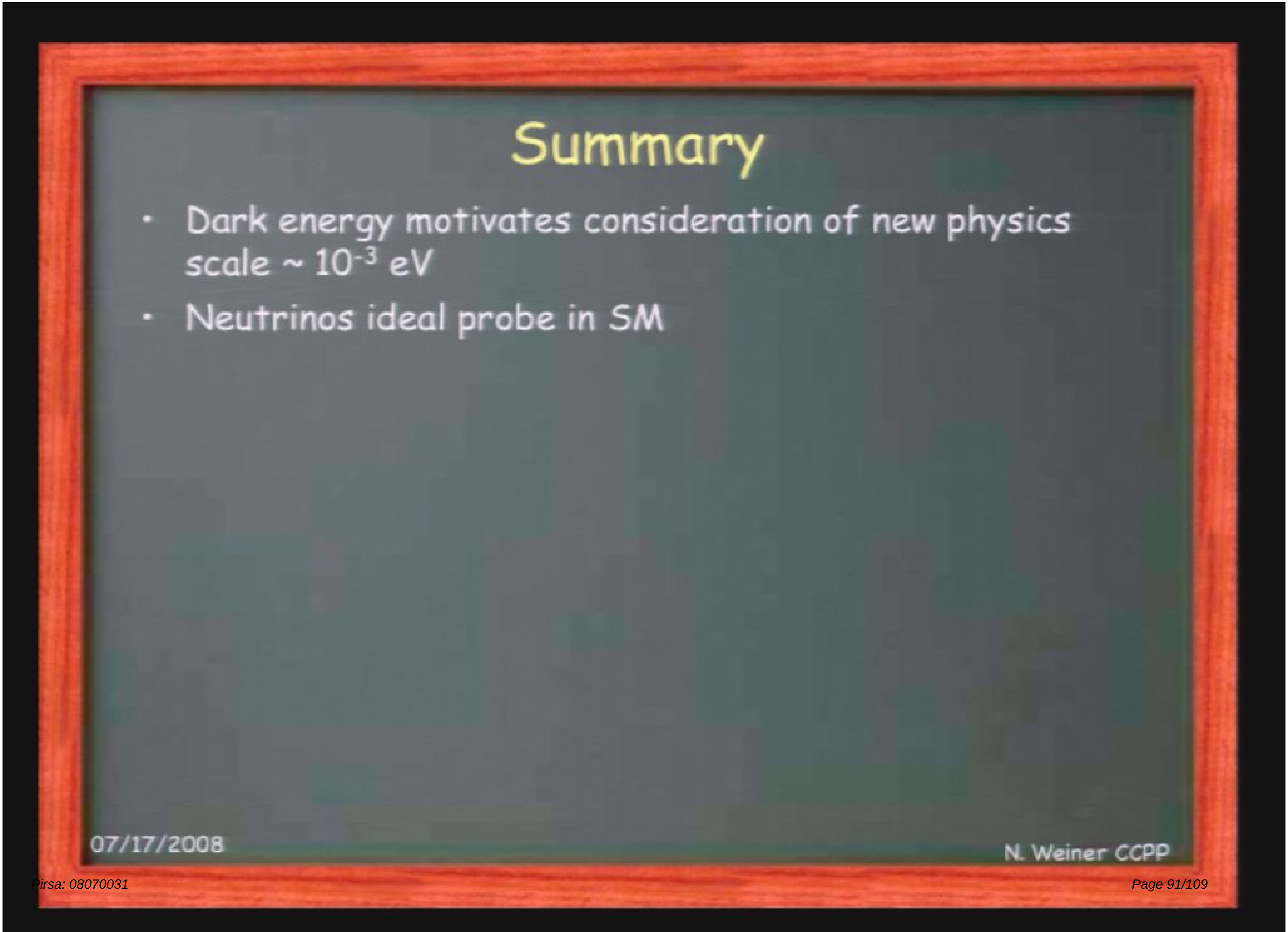

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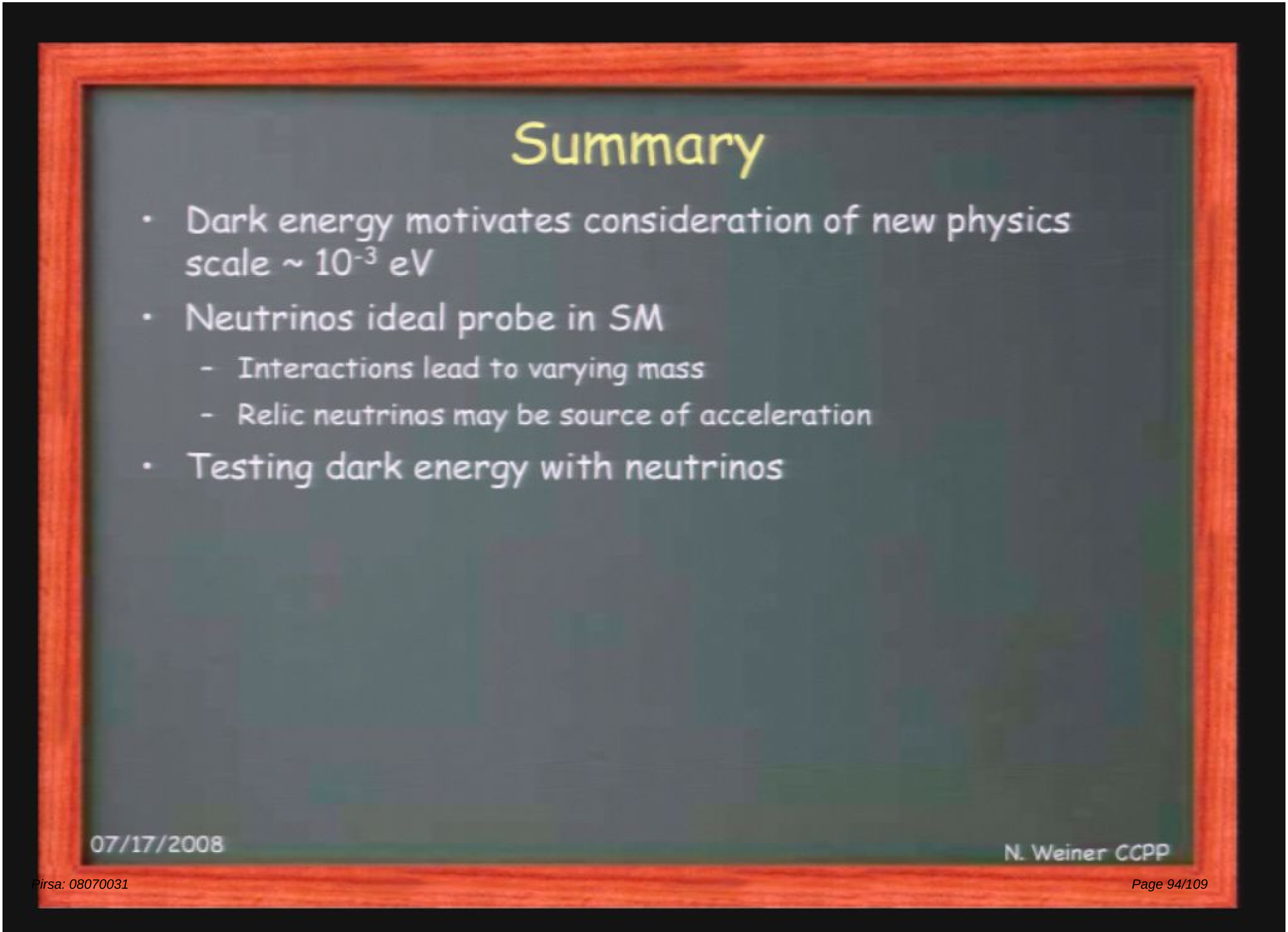

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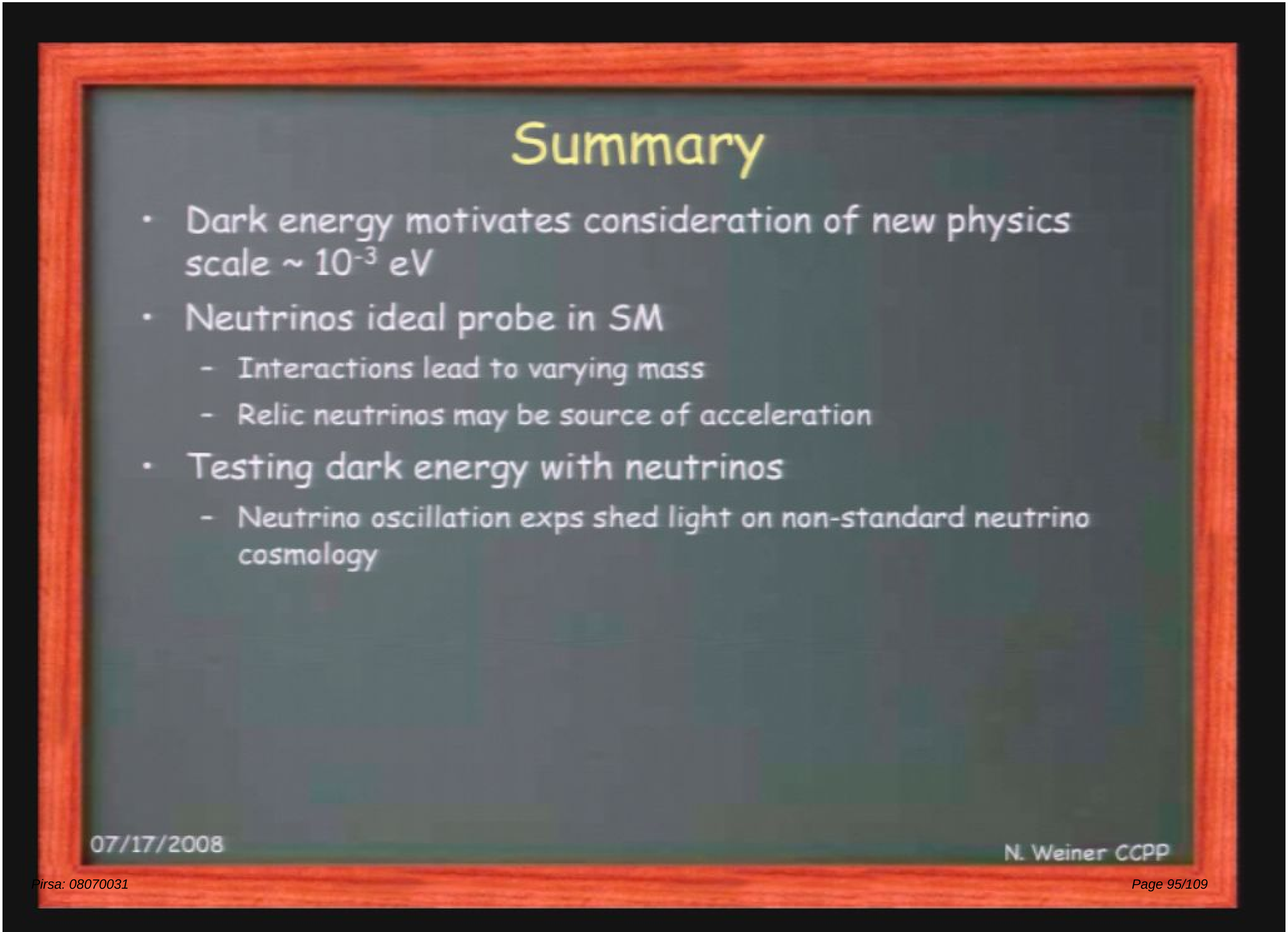

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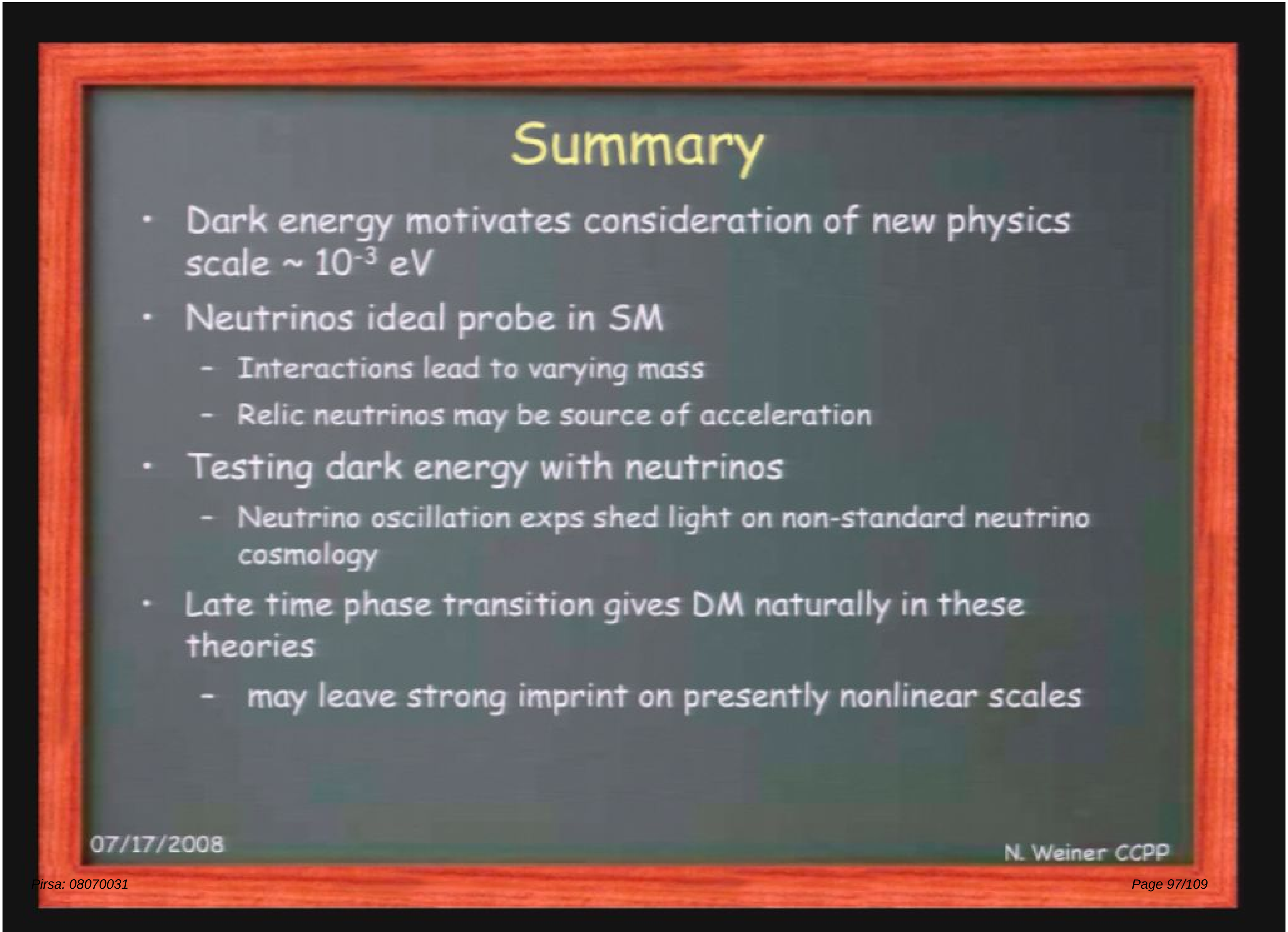

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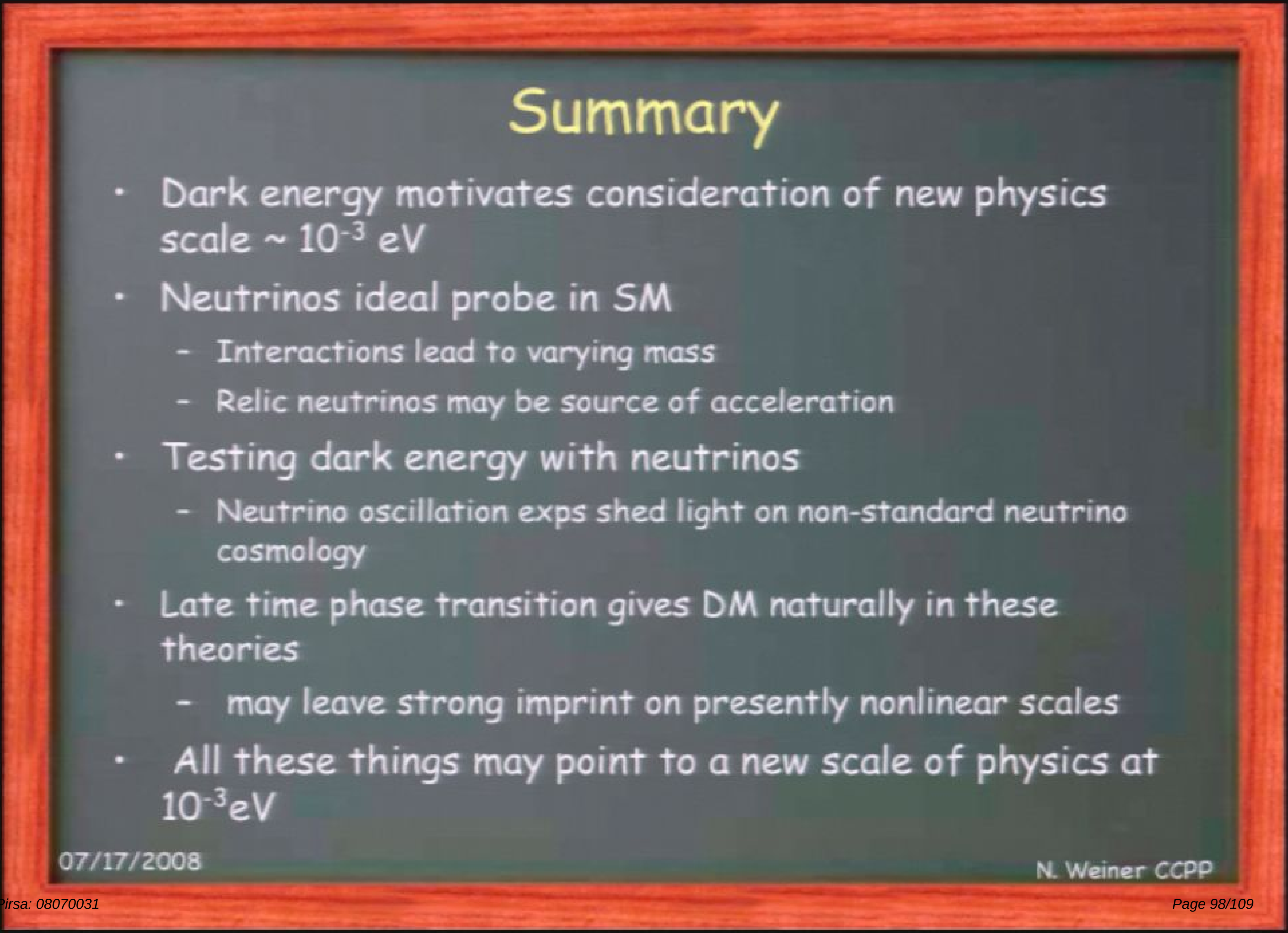

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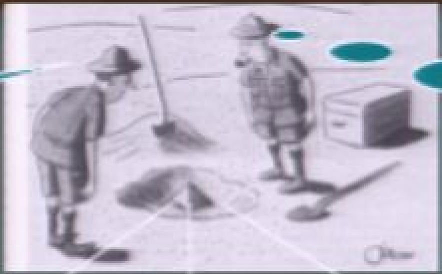
- All these things may point to a new scale of physics at 10^{-3}eV

07/17/2008

N. Weiner CCPP

Eureka!



Thank goodness for neutrinos!

sterile ν's

new ν forces

low energy SUSY

mass varying neutrinos

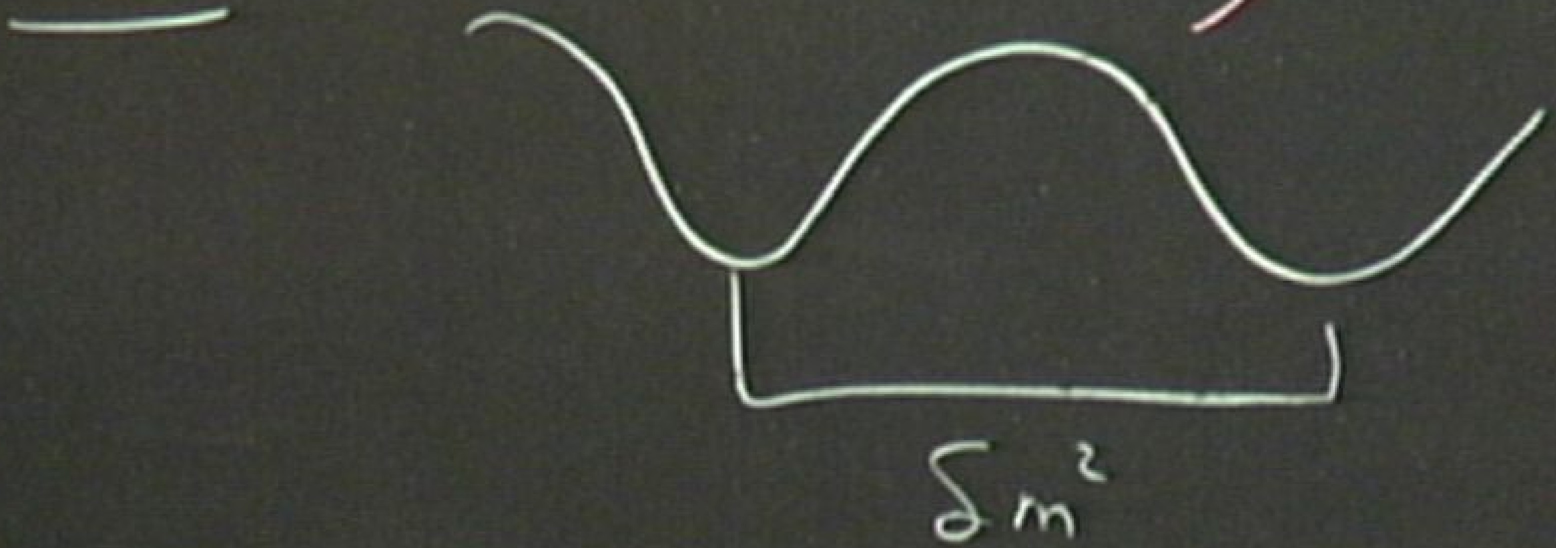
origin of dark energy

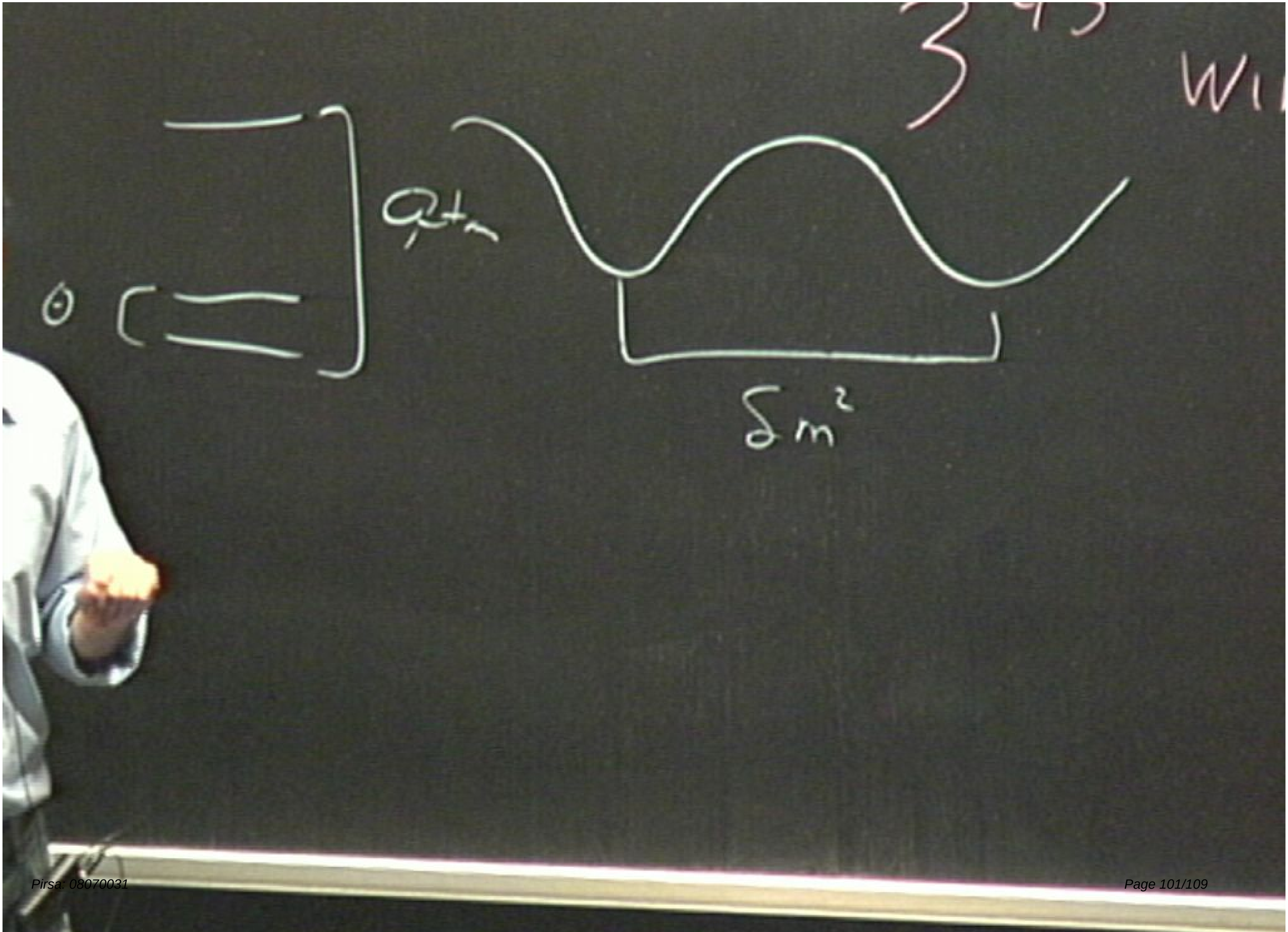
late time effects in cosmology

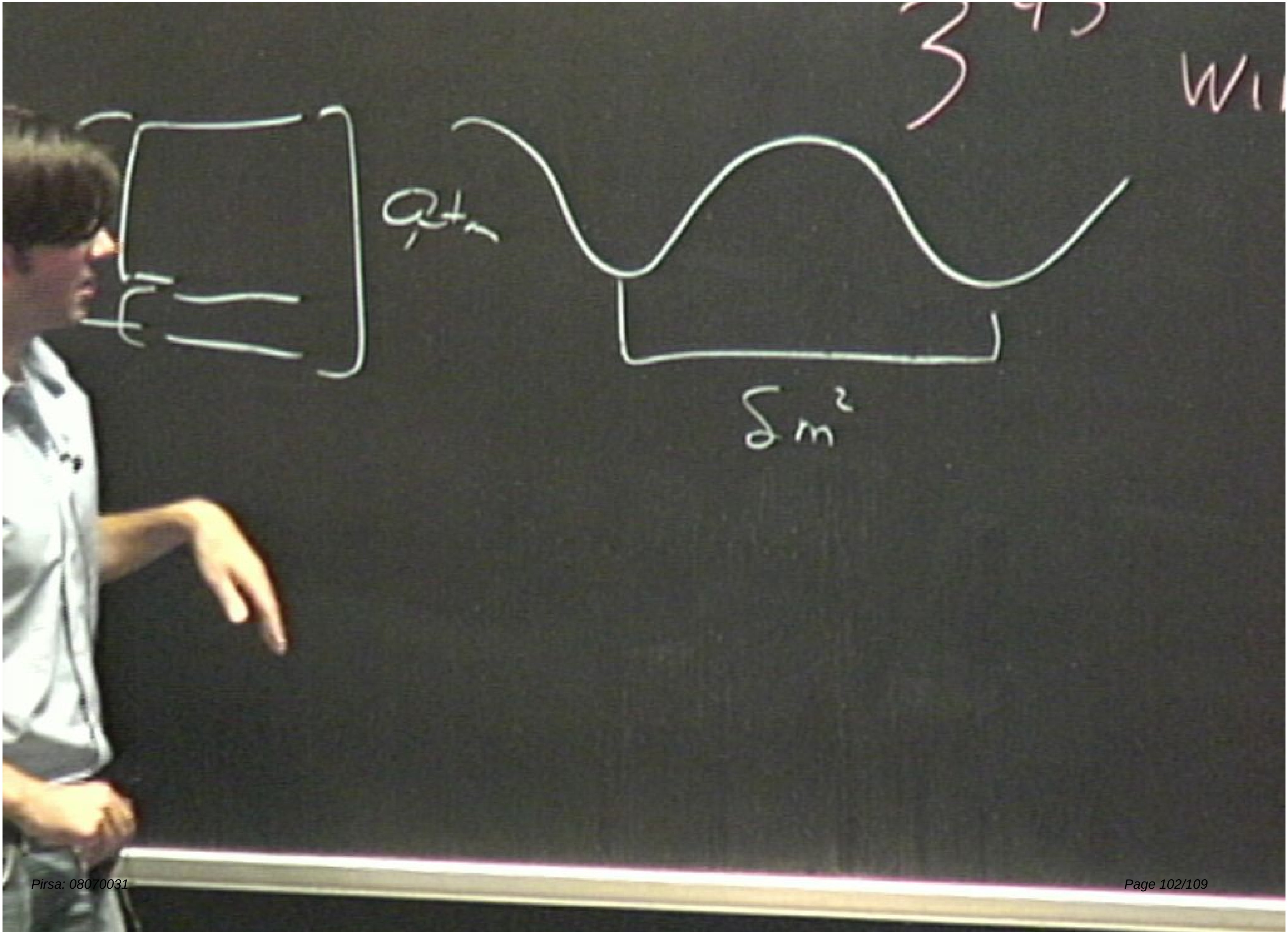
dark matter

3 45

Wi




3
45
Wi
atm
⊙
δm^2


3
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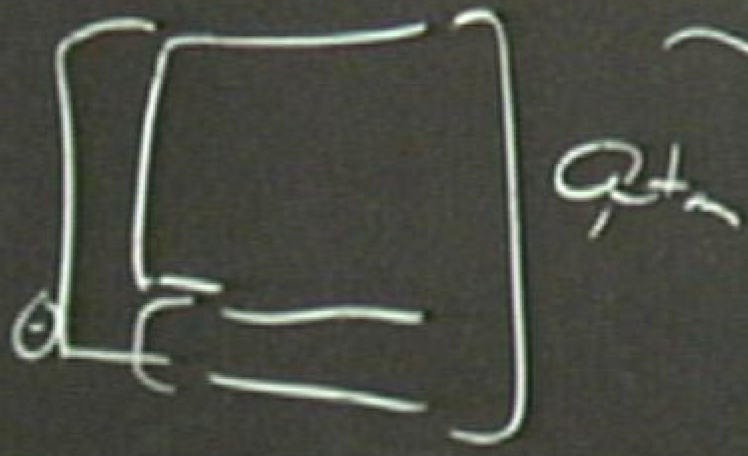
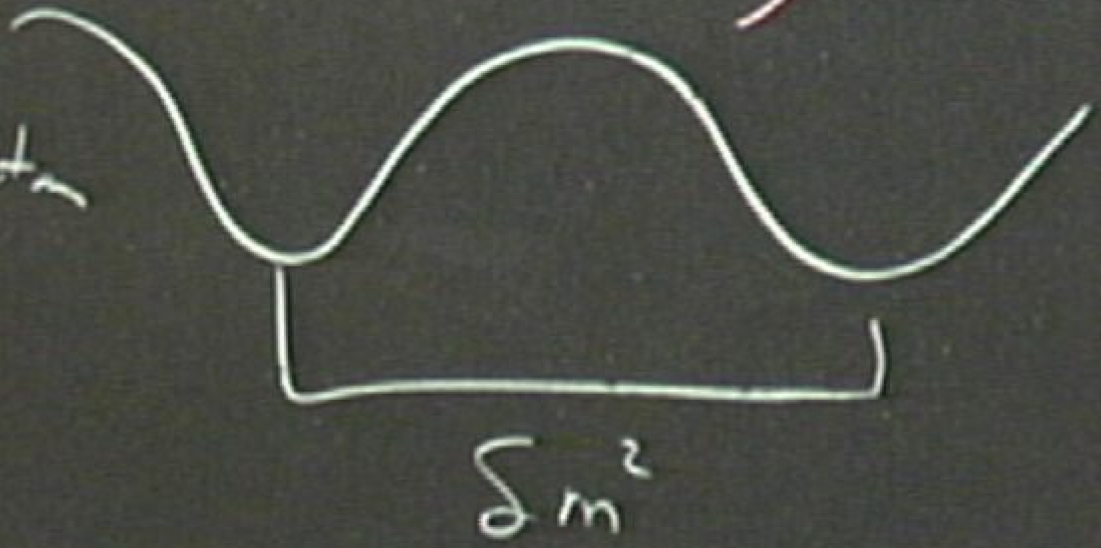
Wi

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

Wi





$$\begin{pmatrix} & m_D \\ m_D & M \end{pmatrix}$$

3 45

Wi

$$\begin{pmatrix} & m_D \\ m_D & M \end{pmatrix} \Rightarrow \begin{pmatrix} \frac{m_D^2}{M} & 0 \\ 0 & M \end{pmatrix}$$

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 <A> is small and $m_A \sim m_\nu$.

What happens to neutrinos at finite density?

Mass Varying Neutrinos

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

drives A to
large values (m_ν to small values)

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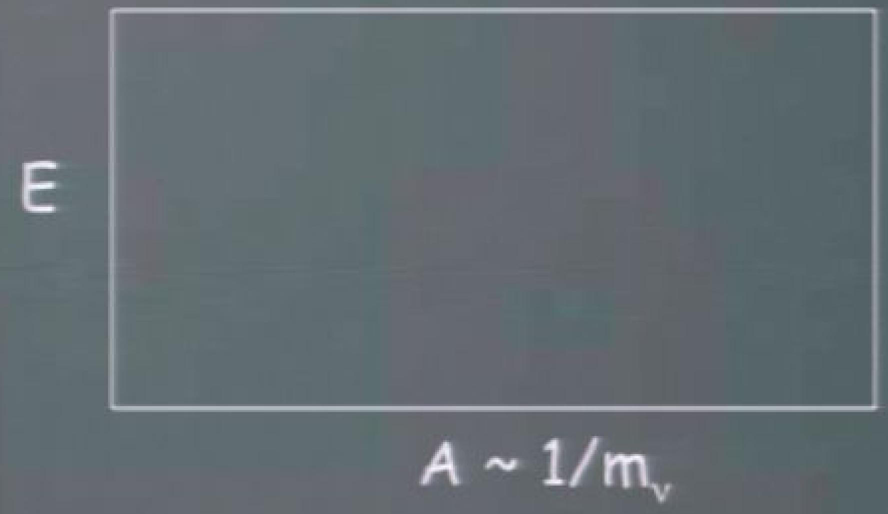

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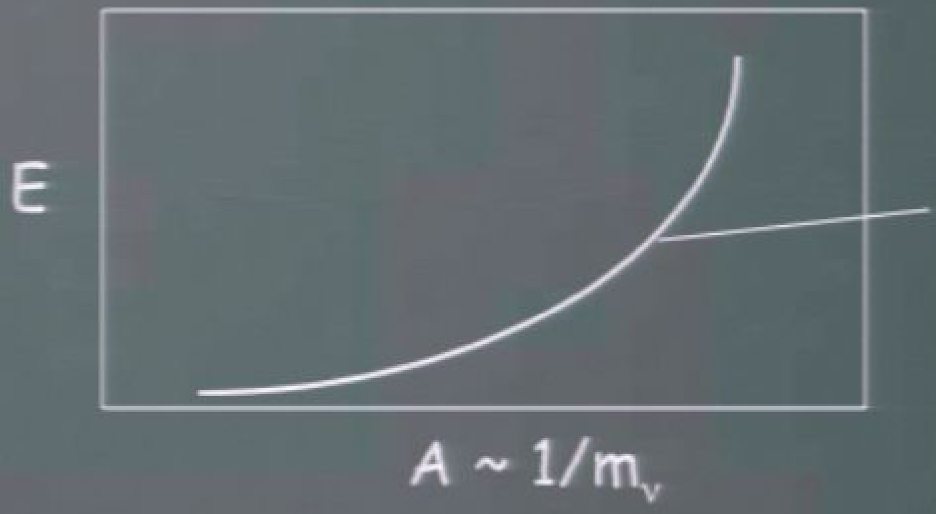

from scalar potential