The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific
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International Atomic
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SMR.1663- 11

SUMMER SCHOOL ON PARTICLE PHYSICS

13 - 24 June 2005

Neutrino Physics - Part 1

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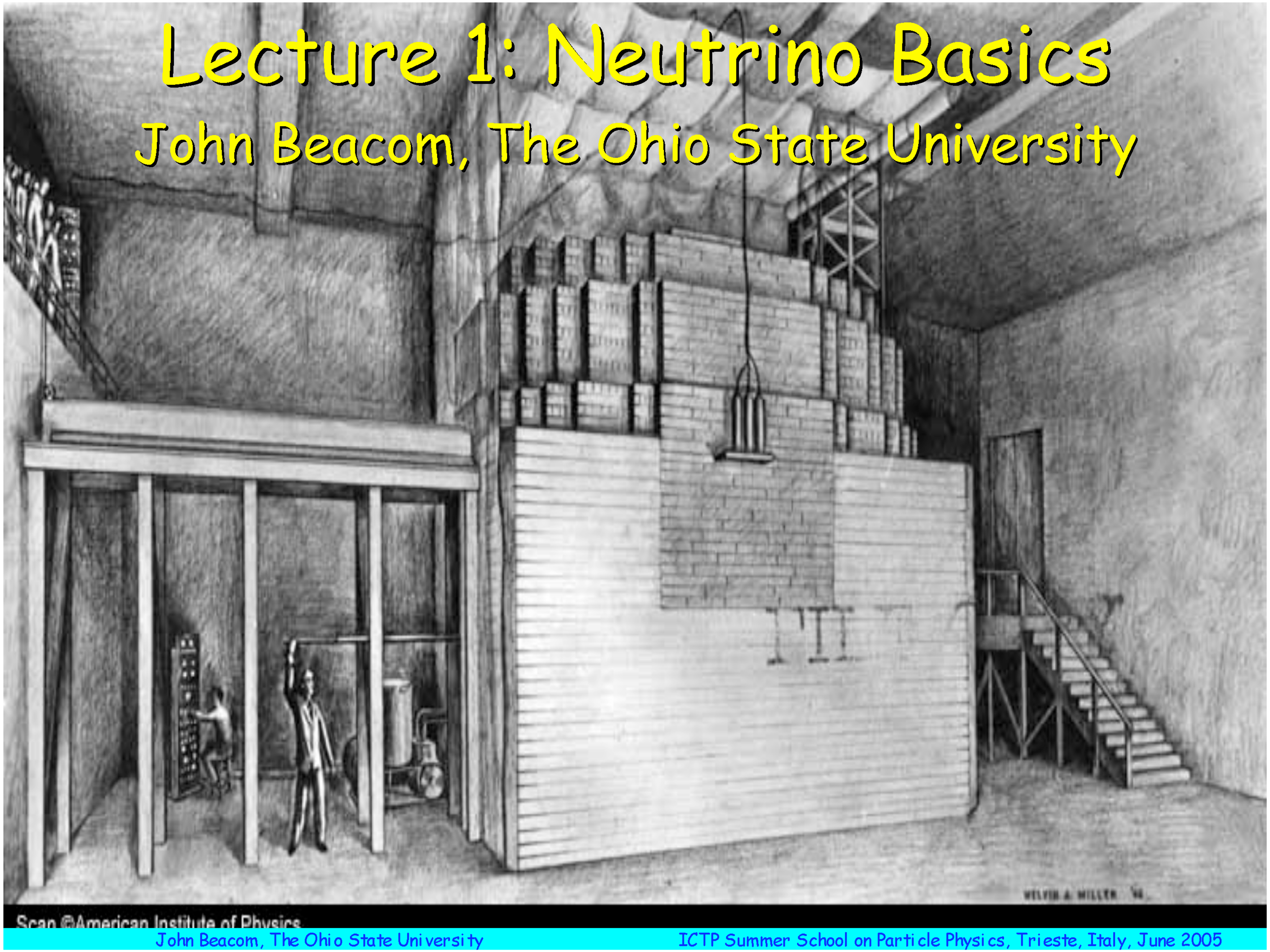
Lecture 1: Neutrino Basics

John Beacom, The Ohio State University



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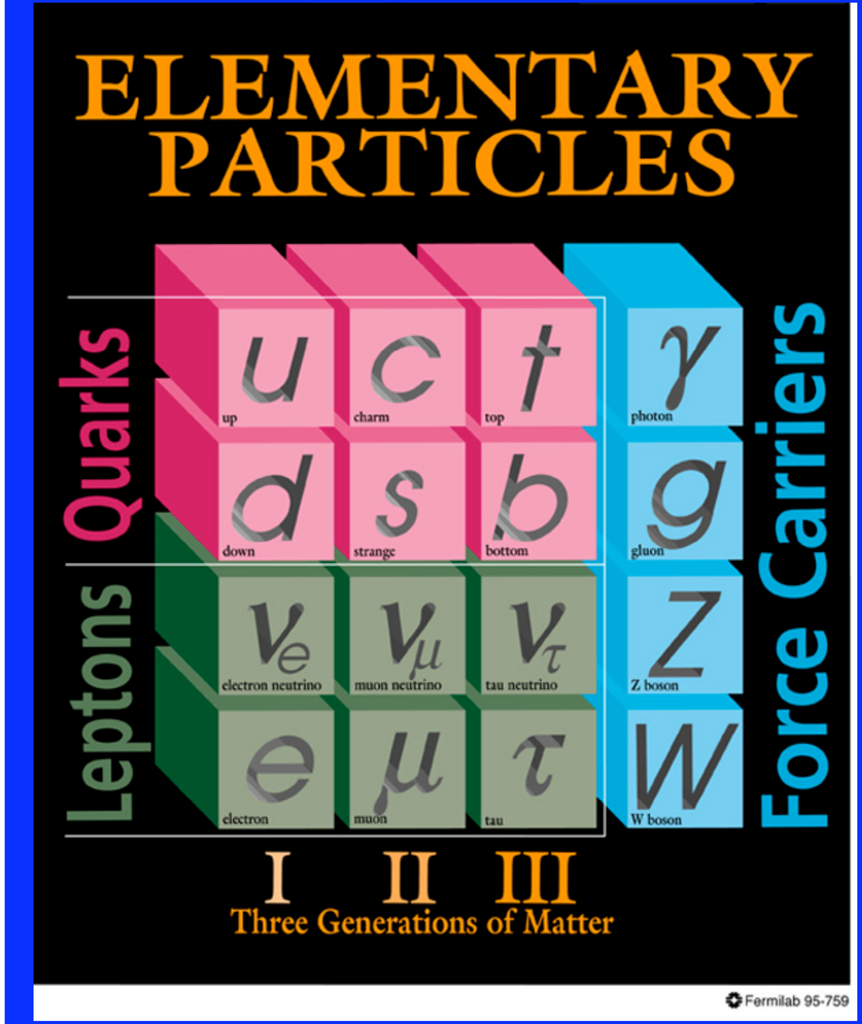
Elevator Pitch

- Neutrino interactions are “weak”
- Thus it is very hard to measure them
- But which makes it much important to do so:
- Any interactions beyond weak revealing BSM?
- Any special properties revealing BSM?
- What is deep within astrophysical objects?

Lucky Neutrinos



The Nobel Prize in Physics 2002

"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"

"for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources"

Raymond Davis Jr.	**Masatoshi Koshiba**	**Riccardo Giacconi**
◔ 1/4 of the prize	◔ 1/4 of the prize	◑ 1/2 of the prize
USA	Japan	USA
University of Pennsylvania Philadelphia, PA, USA	University of Tokyo Tokyo, Japan	Associated Universities Inc. Washington, DC, USA
b. 1914	b. 1926	b. 1931 (in Genoa, Italy)

Perspective

> *"If [there are no new forces] ---- one can conclude that there is no practically possible way of observing the neutrino."* Bethe and Peierls, Nature (1934)

- 10 years ago

Solar neutrino problem?

Atmospheric neutrino problem?

Large neutrino masses?

Nonzero magnetic moments, decay, etc.?

Key Observational Results

Cosmological

- Big-bang nucleosynthesis consistency
- Neutrino hot dark matter models ruled out

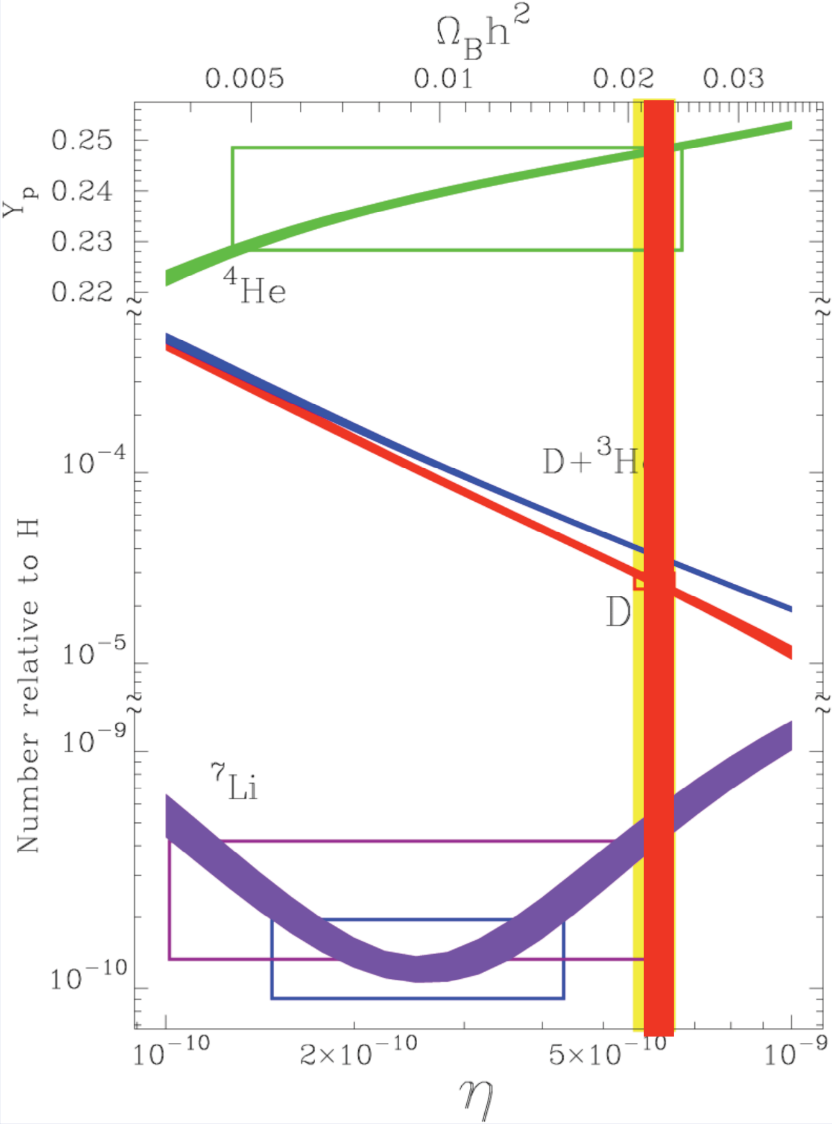
Astrophysical

- Neutrinos from SN 1987A observed
- The solution of the solar neutrino problem

Fundamental

- Neutrinos have mass and mixing
- Non-discovery of all manner of exotica

Neutrino Number Densities



$$\boxed{\rho_\nu = \sum m_\nu n_\nu}$$

$N_\nu < 4$ (99% CL)   BBN

Abazajian, Astropart. 19, 303 (2003)

$1.5 \le N_\nu \le 7.2$ WMAP++

Crotty, Lesgourgues, and Pastor,
PRD 67, 123005 (2003)

$n_\nu \simeq n_{\bar\nu}$

Dolgov et al., NPB 632, 363 (2002);
Wong, PRD 66, 025015 (2002);
Abazajian, Beacom, and Bell,
PRD 66, 013008 (2002)

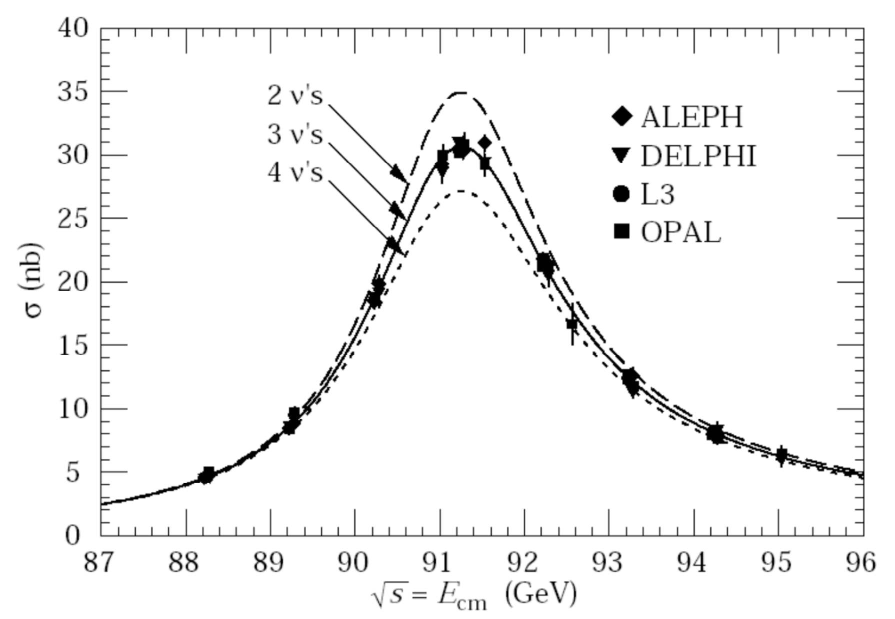
Three Weak Pieces

$\nu_e, \nu_\mu, \nu_\tau,$

defined by $W^+ \to e^+\nu_e, \mu^+\nu_\mu, \tau^+\nu_\tau$

and neutral couplings $Z^0 \to \nu_e\bar{\nu}_e, \nu_\mu\bar{\nu}_\mu, \nu_\tau\bar{\nu}_\tau$

- Three (2.984 +/- 0.008)
- Weak
- Massless in SM
- Lepton number?



Neutrino Interactions

(On the blackboard)

Neutrino Mass from Theory

Google: "Simon Says scratch your head like a monkey!"

- Big? Zero? Medium? Small? Zero? Tiny?
- Mass splittings?
- Dirac or Majorana?

Neutrino Mass from β Decay

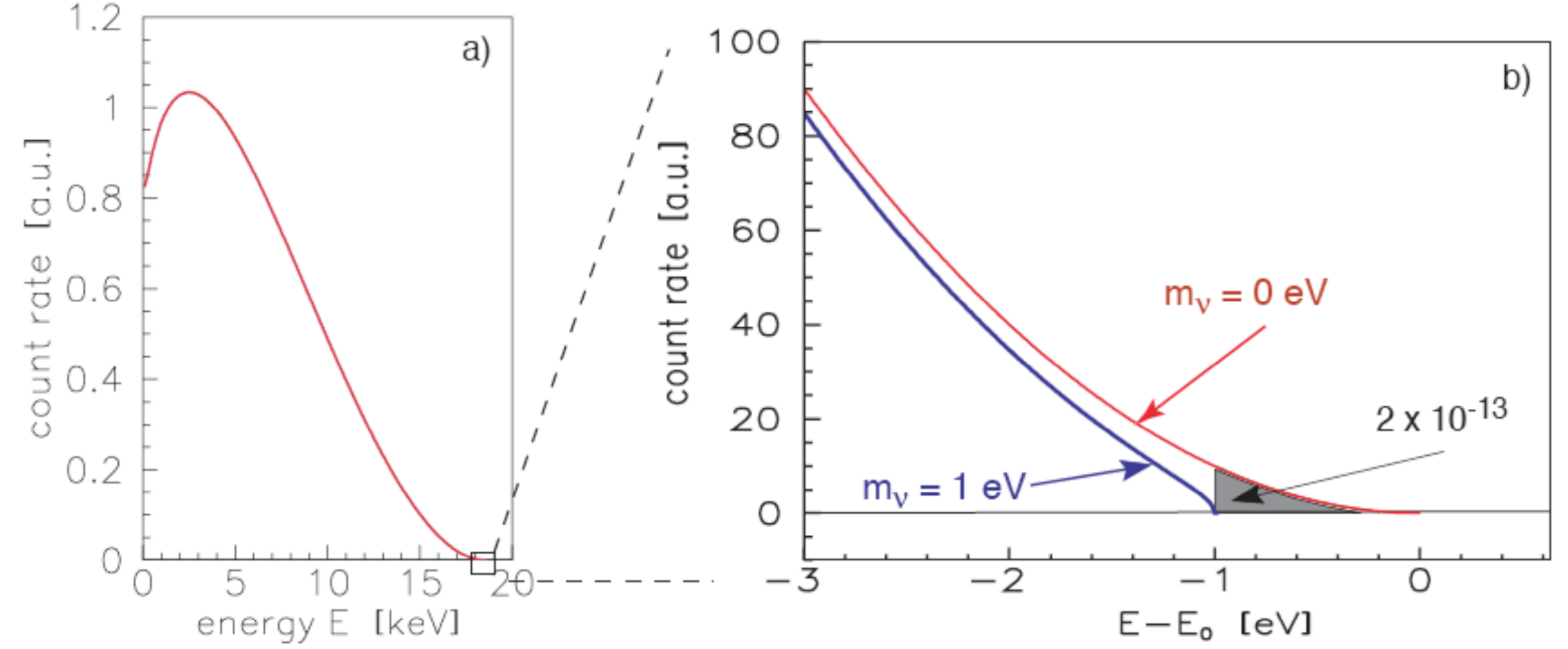
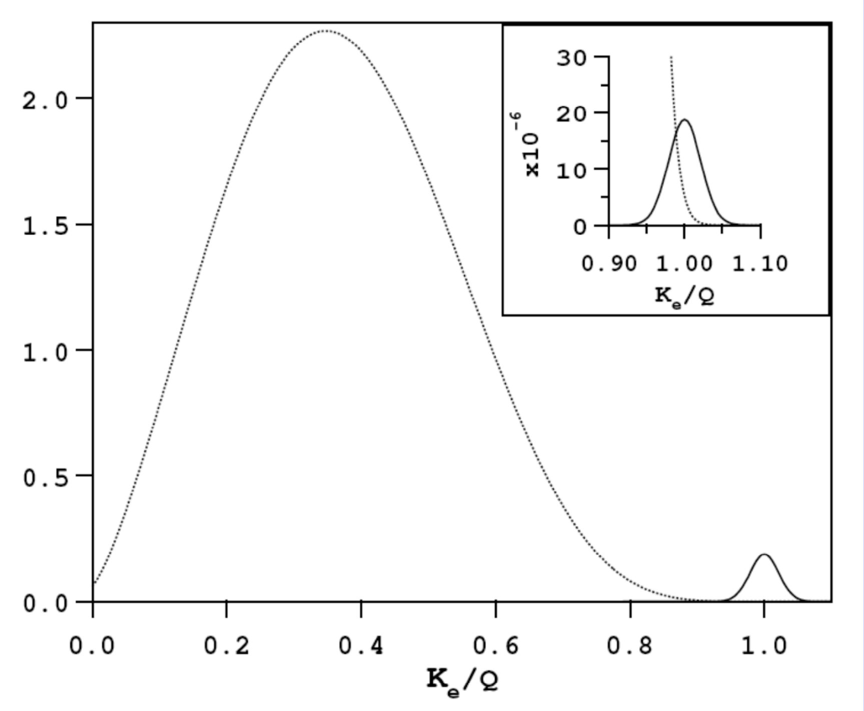


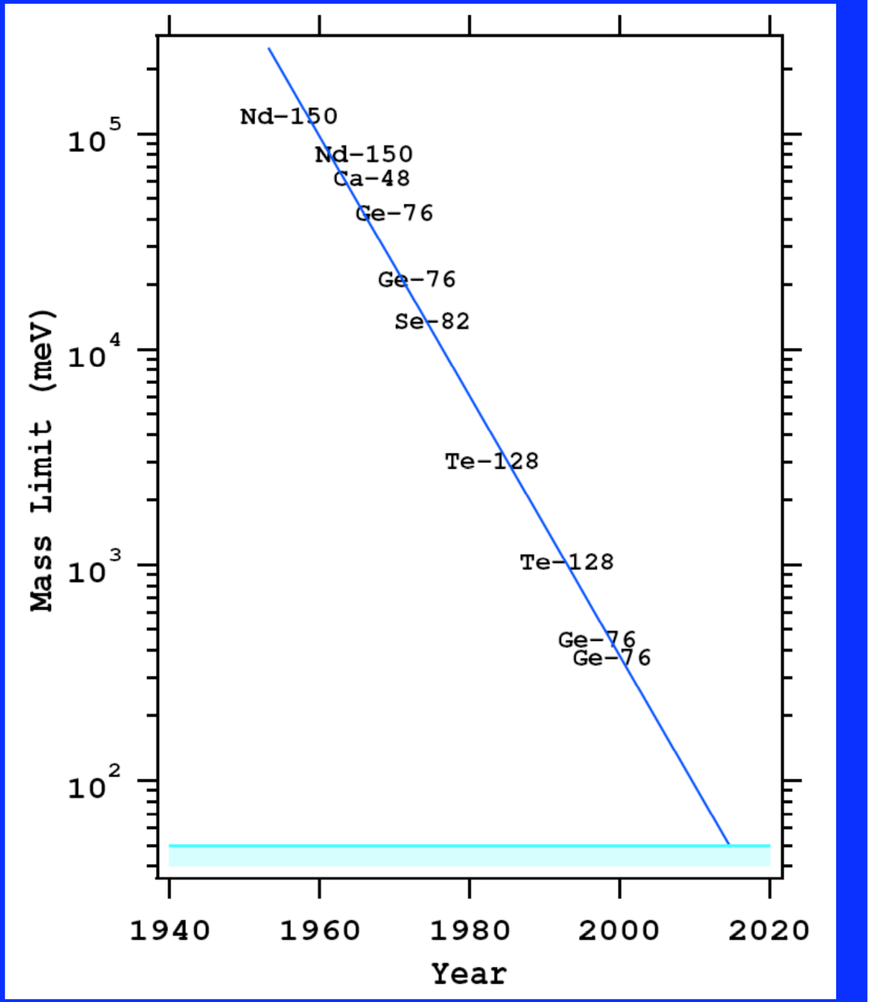
Figure 2: The electron energy spectrum of tritium β decay: (a) complete and (b) narrow region around endpoint E_0. The β spectrum is shown for neutrino masses of 0 and 1 eV.

Osipowicz et al., hep-ex/0109033

KATRIN will have sensitivity down to 0.2 eV

Neutrino Mass from ββ Decay

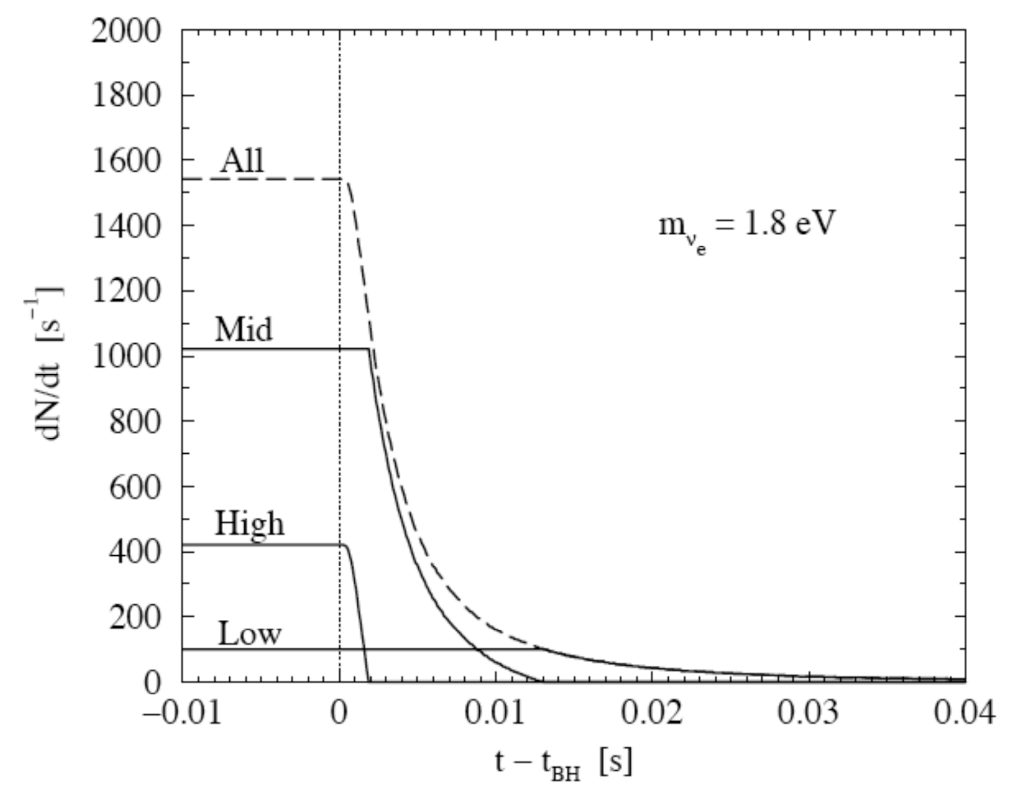




Elliott and Vogel, Ann. Rev. Nucl. Part. Sci. 52, 115 (2002)

Neutrino Mass from Supernova

Old idea due to Zatsepin, others

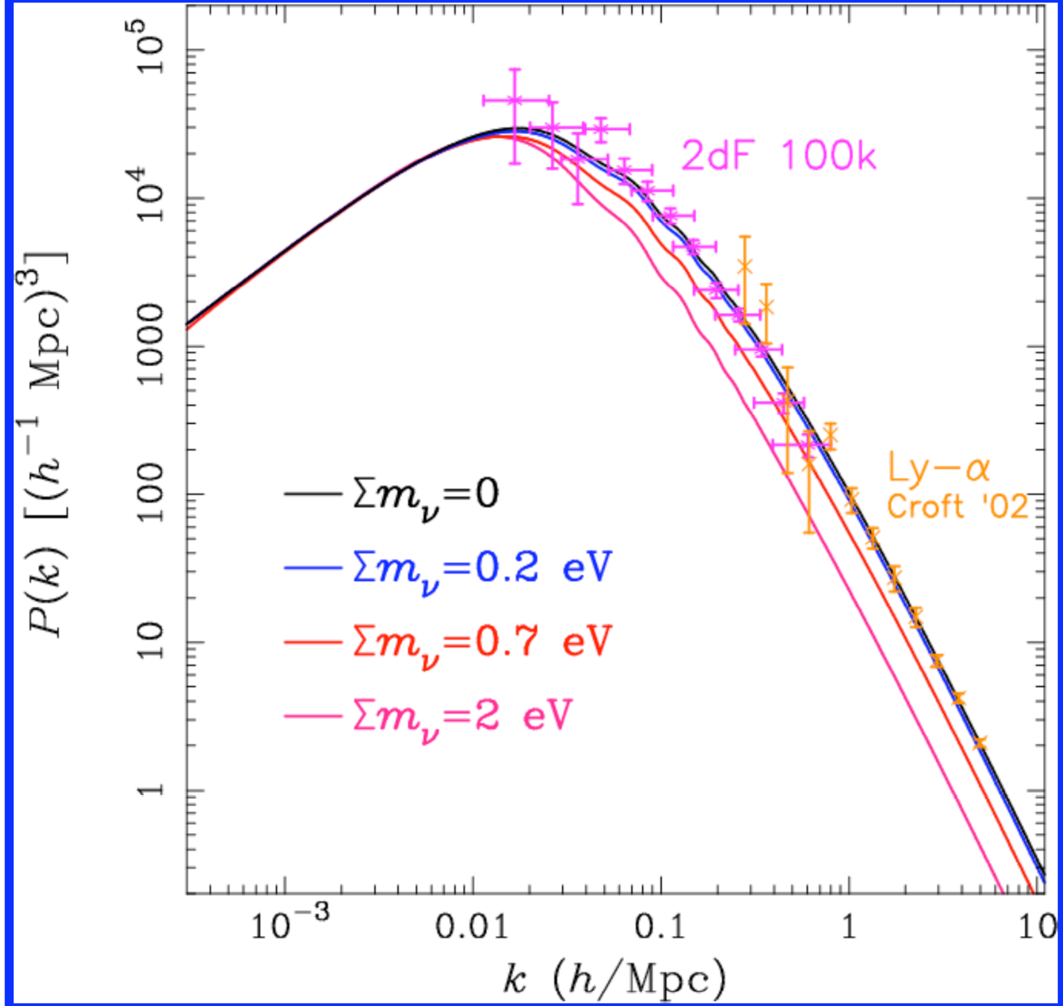


Best (?) case:
prompt BH formation

$$\Delta t(E) = 0.515 \left(\frac{m}{E}\right)^2 D$$

Beacom, Boyd, and Mezzacappa, PRL 85, 3568 (2000)

Neutrino Mass from Cosmology



(graphic from Kev Abazajian)

$$\rho_{\mathrm{matter}} = \rho_{\mathrm{CDM}} + \rho_{\mathrm{baryons}} + \rho_{\mathrm{neutrinos}}$$

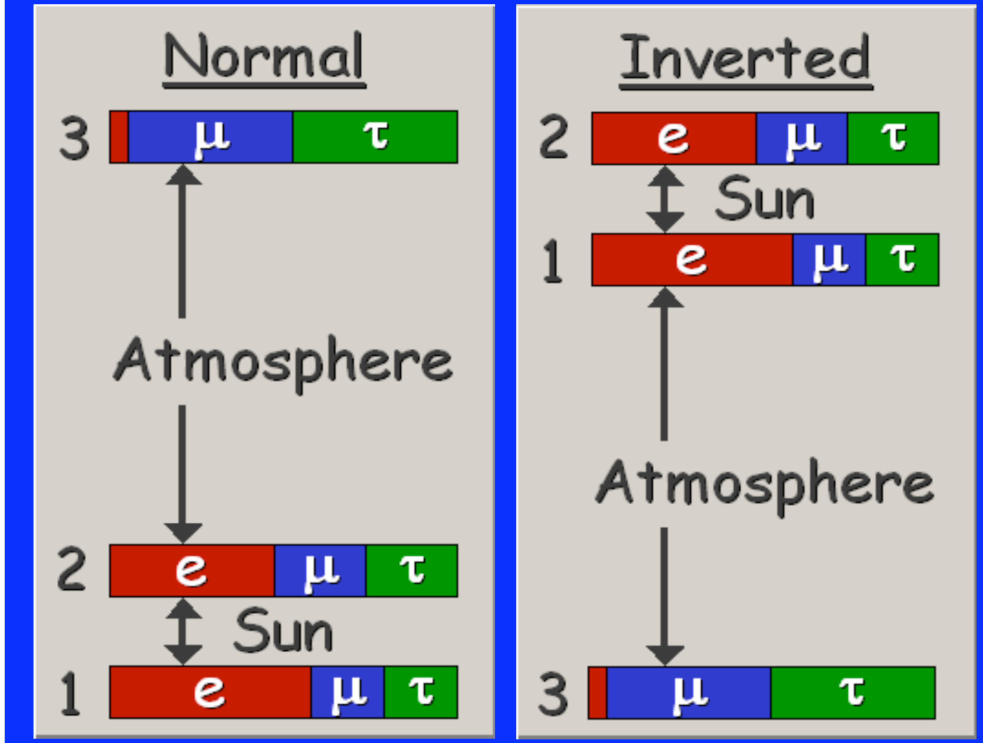
$$\rho_\nu = m_\nu n_\nu$$

Latest limits:

$\Sigma\, m_\nu < 0.42$ eV

Seljak et al. (SDSS), astro-ph/0407372

Neutrino Mixing



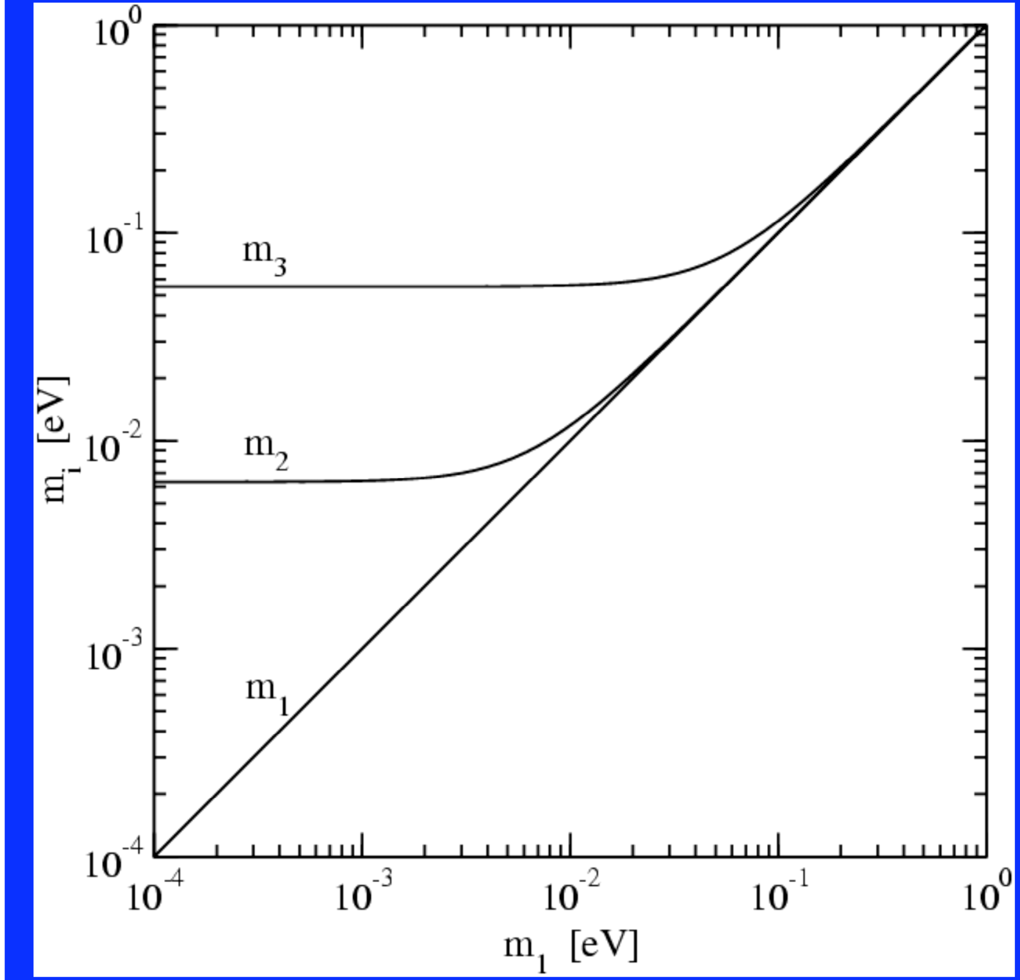
(graphic from Georg Raffelt)

$$\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix} = \begin{bmatrix} U_{\alpha j} \end{bmatrix} \begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix}$$

$$U \simeq \begin{bmatrix} c_\odot & s_\odot & s_{13}e^{-i\delta} \\ -s_\odot/\sqrt{2} & c_\odot/\sqrt{2} & 1/\sqrt{2} \\ s_\odot/\sqrt{2} & -c_\odot/\sqrt{2} & 1/\sqrt{2} \end{bmatrix}$$

$$\theta_{atm} \simeq 45^\circ, \quad \theta_{solar} \simeq 35^\circ, \quad \theta_{13} \leq 10^\circ$$

Neutrino Mass Splittings



Beacom and Bell, PRD 65, 113009 (2002)

Normal Hierarchy

$$m_1 = m_1$$

$$m_2 = \sqrt{m_1^2 + \delta m^2_{solar}}$$

$$m_3 = \sqrt{m_1^2 + \delta m^2_{solar} + \delta m^2_{atm}}$$

$$\frac{m_3}{m_2} \leq \frac{\sqrt{\delta m^2_{atm}}}{\sqrt{\delta m^2_{solar}}} \leq 10$$

Conclusions

- Neutrinos are very hard to measure
- They are also very important to measure
- Neutrino oscillations have been detected:
- Thus neutrino masses are nonzero
- Mixing matrix tells us how to interpret mass tests
- The mass scale is well below 1 eV!

Further Reading

- Kayser in the RPP: http://pdg.lbl.gov/2004/reviews/numixrpp.pdf
  Waltham, arXiv:physics/0303116

- Goodman's page: http://www.neutrinooscillation.org/
  Giunti's page: http://www.to.infn.it/~giunti/NU/

- Bahcall, Neutrino Astrophysics
  Boehm and Vogel, Physics of Massive Neutrinos
  Kayser, The Physics of Massive Neutrinos
  Raffelt, Stars as Laboratories for Fundamental Physics

- Kolb and Turner, The Early Universe
  Dodelson, Modern Cosmology

- Inverse beta cross section:

$$\sigma = \frac{G_F^2 \cos^2\theta_c}{\pi} (g_V^2 + 3g_A^2) E_e p_e$$

$$E_e \simeq E_\nu - \Delta$$

$$G_F \simeq \frac{10^{-5}}{\text{GeV}^2}$$, factors of $\hbar c$

Role of M_p/M_n, m_e, m_ν; neglect since large or small

$$\Gamma_n \sim G_F^2 m_e^5 \qquad G_F^2 \sim \frac{\Gamma_n}{m_e^5} \sim \frac{1}{\tau_n m_e^5}$$

$$\sigma = \frac{2\pi^2}{f_{ps} \tau_n m_e^5} E_e p_e$$

- Neutrino-electron scattering: $\sigma \sim G_F^2 E_\nu m_e$

Need weak interaction theory, not just crossing, to get this. Specifically, need NC too.

- Compare at UHE (quarks, inelastic, propagators)

- Mean free path:

$$\lambda = \frac{1}{n\sigma}$$

n = target number density
get from ρ

$$\mu = \frac{L}{\lambda} = L n \sigma$$

optical depth, typically tiny

number of expected scatterings

$$P_n = \frac{\mu^n e^{-\mu}}{n!}$$

note 1 bn ~ 1 cm for $\rho = 1$ nucleon

- Neutrinos in Sun, scattering from p or e^-:

$$\rho(r) \simeq \frac{150\,g}{cm^3} \cdot \exp\left(\frac{-r}{0.1 R_\odot}\right)$$

$$n(r) \simeq \frac{150\,N_A}{cm^3} \cdot \exp\left(\frac{-r}{0.1 R_\odot}\right)$$

$$\text{column depth} = \int dr\, n(r) \simeq 0.1 R_\odot \cdot \frac{150\,N_A}{cm^3}$$

$$\simeq 0.1\,(7\times10^{10}\,cm)\,\frac{150\,N_A}{cm^3}$$

$$\sim 0.1 \cdot 10^{11} \cdot 10^{2} \cdot 10^{24}\ cm^{-2}$$

$$\sim 10^{36}\ cm^{-2}$$

compare to sigma

- Neutrinos in Earth:

$$\text{column depth} \sim \frac{10 N_A}{\text{cm}^3} \cdot 10^4 \cdot 10^5 \text{ cm}$$

$$\sim 10^{34} \text{ cm}^{-2}$$

$$\text{Scale sigma from } 1 \text{ MeV}^2 \longrightarrow 1 \text{ GeV} \cdot 100 \text{ TeV}$$

$$\sim 10^3 \cdot 10^8$$

$$\sim 10^{11}$$

$$\sigma \sim 10^{-43} \cdot 10^{11} \sim 10^{32} \text{ cm}^2$$

a bit too big, but in the right neighborhood

- In a NS:

$$\text{shrink solar radius, density} \sim \frac{1}{R^3}$$