Astrophysics and Cosmology: Impact of Neutrino Oscillation Measurements

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1. New experiments in neutrino astrophysics

2. Added value to cosmological observations

3. Key role of theory in making connections

4. Strong connections to other working groups and nuclear/particle laboratory data

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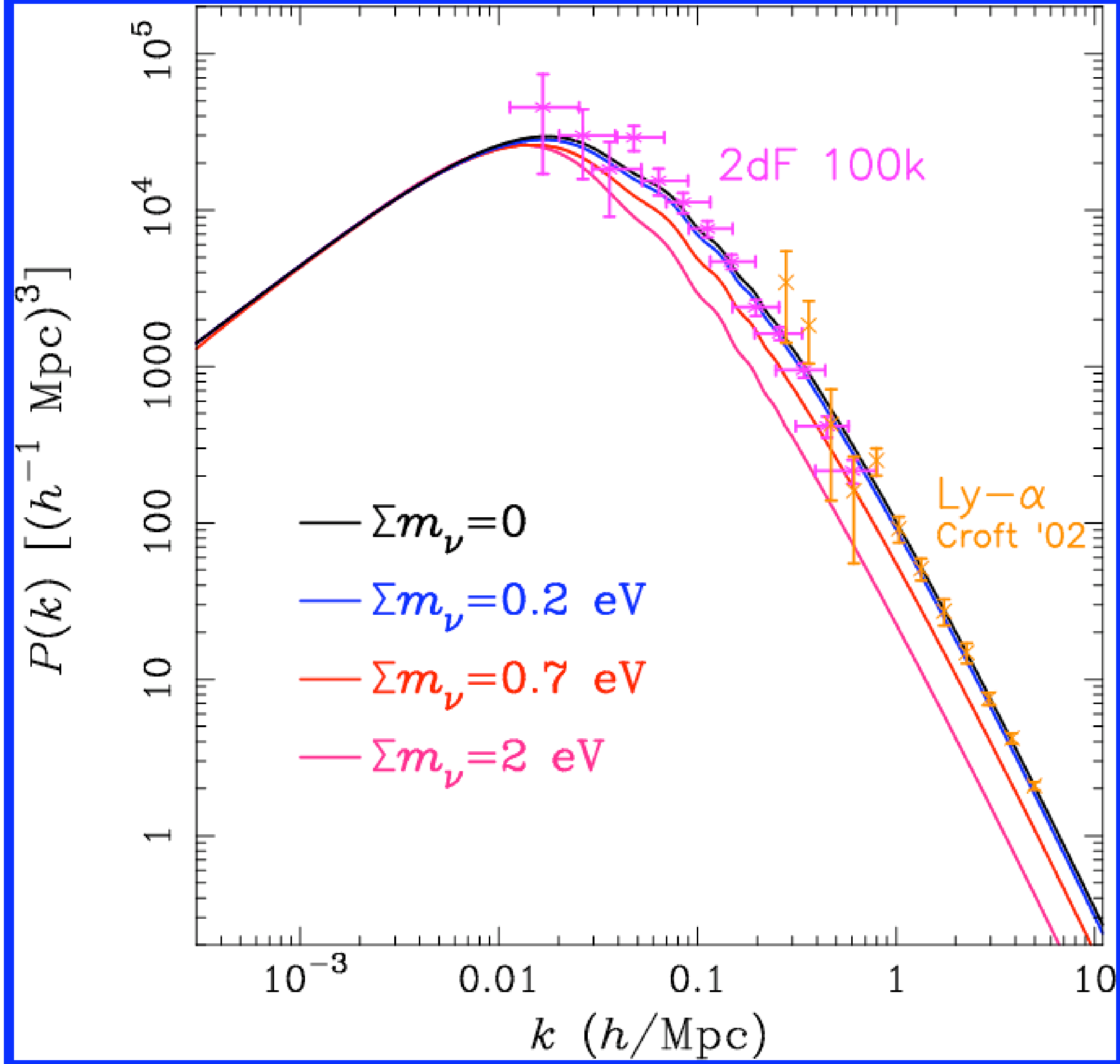
Selected Key Opportunities

- Discovery of neutrino mass using cosmological data
  - Key hint for model-building
  - Guide and foil for beta / double beta experiments

- Discovery of astrophysical neutrinos
  - Unique probe of extreme environments
  - Unique probe of neutrino properties, energy frontier

- Connections to new astrophysical/cosmological data
  - Detailed astrophysical models
  - Quest for identifying the particle dark matter
  - Fundamental theory towards the GUT scale

Neutrino Dark Matter



(graphic from Kev Abazajian)

$\rho_{matter} = \rho_{CDM}$

$+ \rho_{baryons}$

$+ \rho_{neutrinos}$

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

Future discovery range:
Abazajian & Dodelson, PRL 91, 041301 (2003)

Kaplinghat, Knox & Song, PRL 91, 241301 (2003)

The Big Question

Are improved measurements of neutrino mixing parameters important for astrophysics/cosmology?

Conventional wisdom would be: *Of course not!*

Why not? Survey says…

Neutrinos, schmeutrinos

Cosmology, cosmetology

Astrophysics/Cosmology ok to factors ~ 10

Neutrino mixing irrelevant for cosmology, ρ_ν

Can't detect astrophysical neutrinos

Short Rebuttal

- We have a reasonable working picture of the neutrino sector, but it is not complete

- Precision cosmology is here, with much more detailed cosmological/astrophysical data on the way

- Detection of neutrinos from various astrophysical sources is very promising (see my WIN03 talk)

- Connections between astrophysics/cosmology and fundamental physics are now *inescapable*

Key Observational Results

Cosmological

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

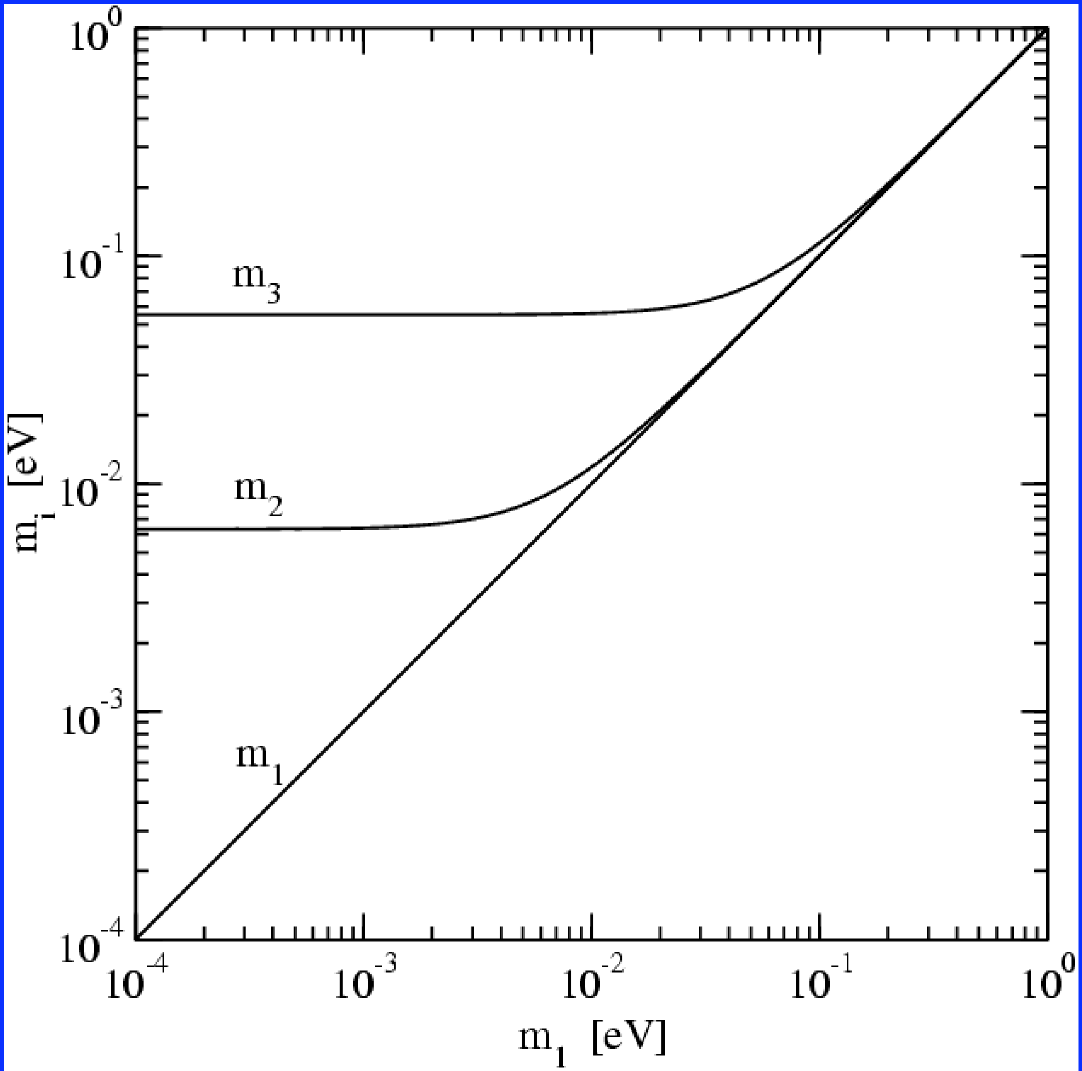
Astrophysical

- 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 Masses



Beacom and Bell, PRD 65, 113009 (2002)

Normal Hierarchy

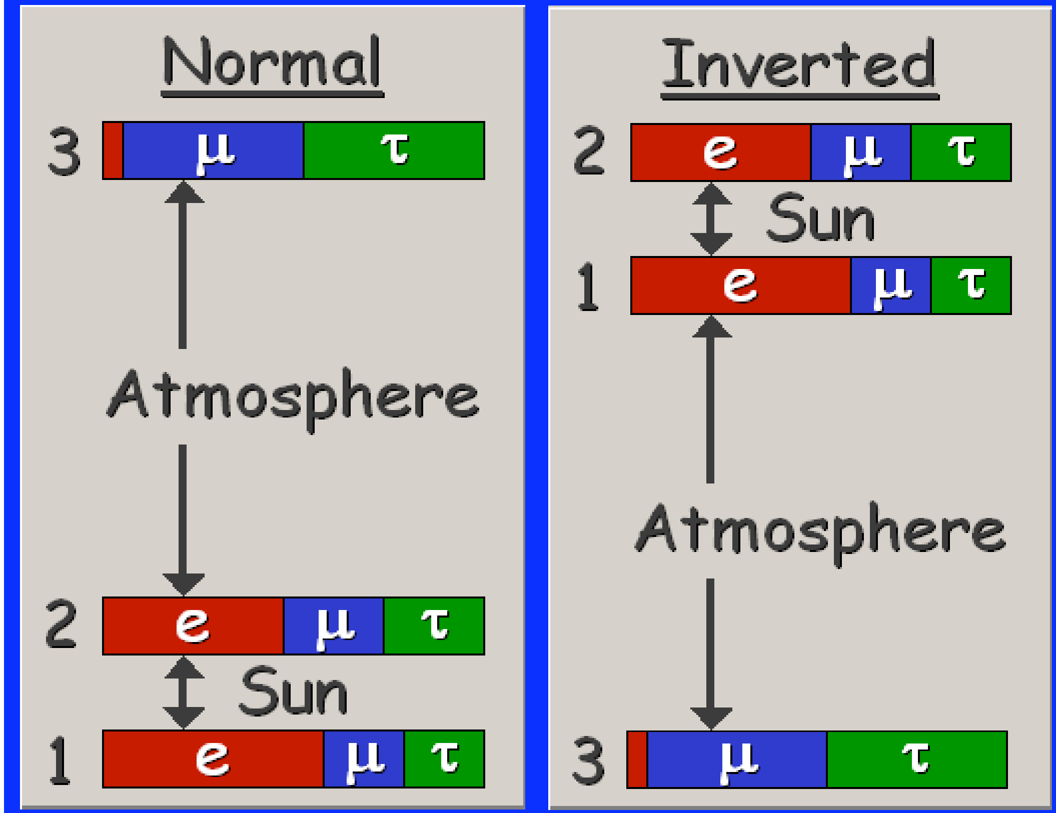
$$m_1 = m_1$$

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

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

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

Neutrino Mixing



(graphic from Georg Raffelt)

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

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

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

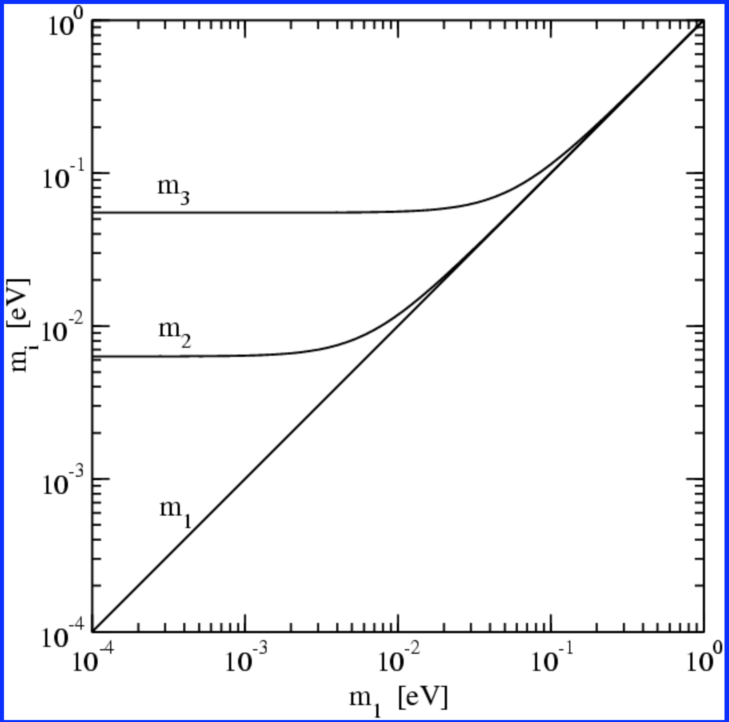
Precise δm^2 Values

- m_3/m_2 bound is an important constraint on mass models now

- δm^2 uncertainty matters for cosmological measurement of neutrino masses

- normal vs. inverted matters even more for both

- absolute masses the ultimate issue; depends on δm^2 values



Precise Mixing Angles

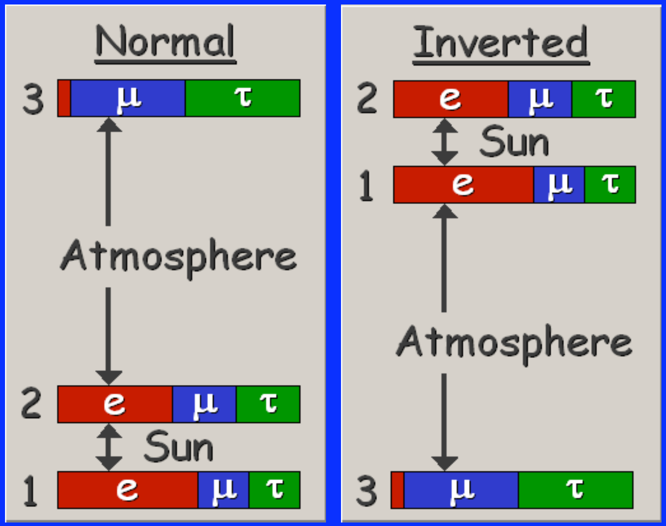
- Specific values may be more than just numerology

- θ_{12} seems "large" but not special

- θ_{23} is large and maybe maximal

- θ_{13} is large but maybe vanishing

- Is there a mu-tau symmetry?
(Balantekin/Fuller, Harrison/Scott)

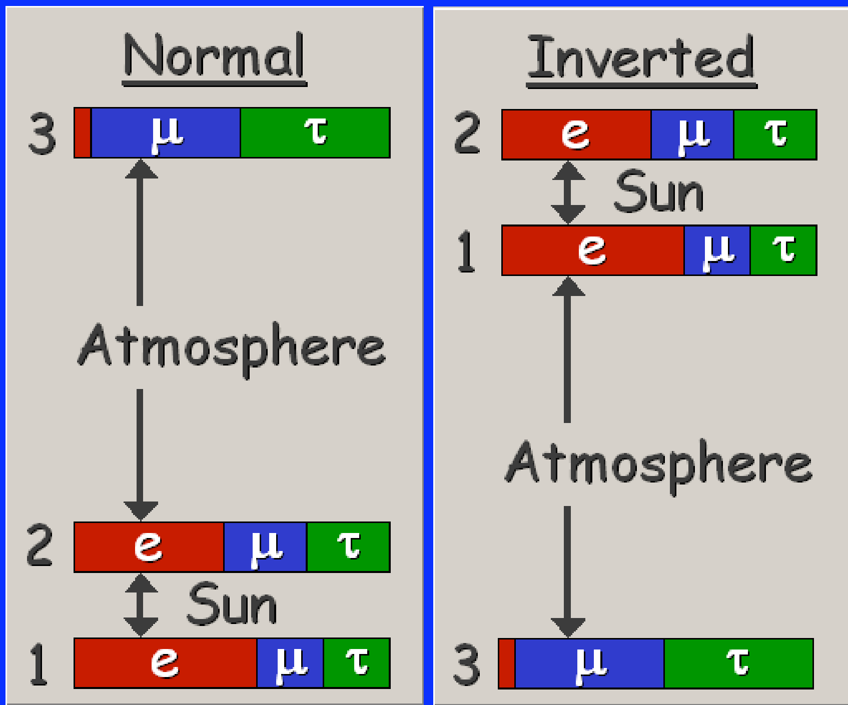


Precise Outside the Box

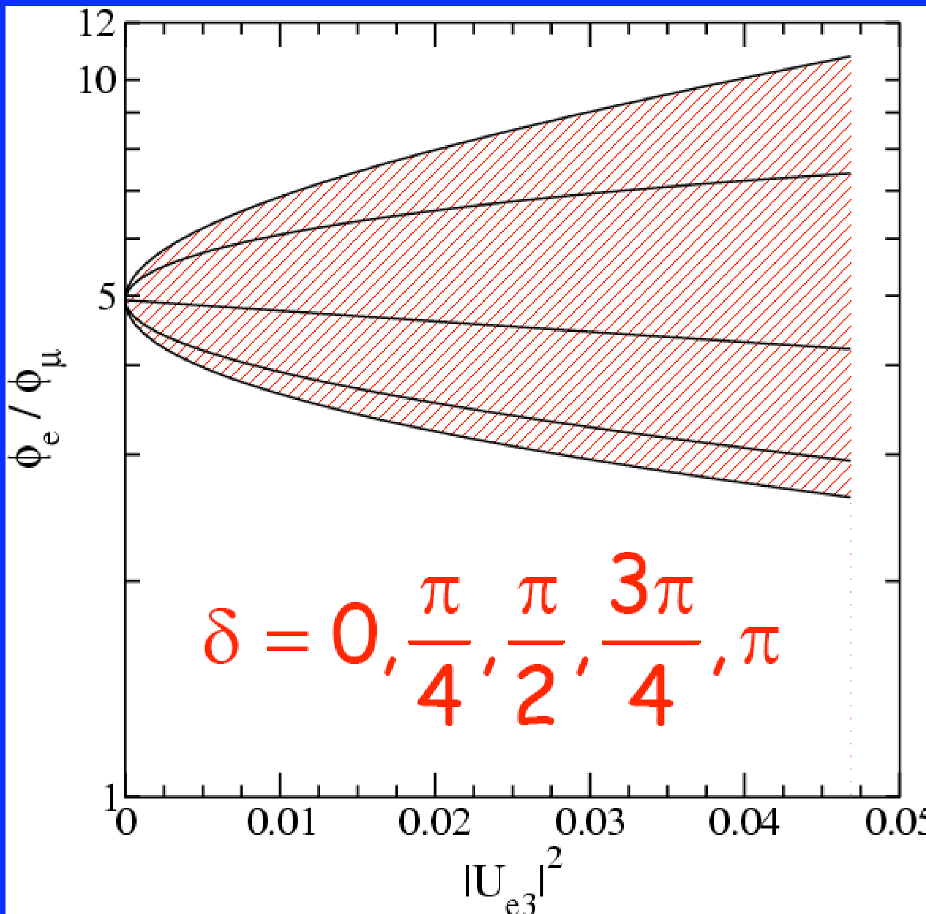
Essential open questions outside this framework:

- Is the LSND signal right?
- Is the 3x3 mixing matrix unitary? (Whisnant talk)
- Is there subdominant mixing to light steriles?
- Are there signs of other exotica?

Neutrino Decay



~ 5:1:1 ~ 0:1:1



Possible direct measurement of CP phase δ too!

Beacom, Bell, Hooper, Pakvasa, Weiler, PRL 90, 181301 (2003);
Beacom, Bell, Hooper, Pakvasa, Weiler, hep-ph/0309267

Why the Emphasis on Models?

- Required by theorist's union rules (Albright talk)

- Anything beyond the simple picture would be very important for understanding the neutrino sector and Beyond the Standard Model physics

- Sterile neutrinos could be very important to big bang nucleosynthesis and supernova modeling, and these are crucial to testing general new physics

- Necessary but not sufficient for leptogenesis

Supernova Neutrinos

- SN 1987A one of the most powerful new physics tests, based on limiting novel energy loss channels. Next time, ~ 10% tests instead of ~ 100% tests

- Oscillations with θ_{13} are especially important, and change character for small values, due to matter effects

- Something similar happens for neutrinos from WIMP annihilation in the solar core (Crotty)

Leptogenesis

• Where did the baryon-antibaryon asymmetry of the universe come from? Great unsolved mystery.

• $A_{baryon} \sim 10^{-9}$ (BBN, CMB)
$A_{lepton} < 10^{-1}$ (BBN, depends on neutrino mixing)

• Maybe neutrino masses are light due to the seesaw mechanism (heavy right-handed Majorana masses)? Maybe those heavy neutrino decays are CP violating, and this will convert to a baryon asymmetry? Low energy neutrino data necessary but not sufficient

Conclusions

1. For understanding sun and atmospherics, high precision is not needed
2. Large scale structure and cosmological parameters depend on neutrino mass pattern
3. BBN and new physics tests depend on steriles
4. Understanding supernovae very sensitive to θ_{13}
5. Unknown details of the neutrino sector are essential inputs to GUT scale model building and cosmology
6. Better tests of assumed framework essential, since anything new would be radically important