Living in a (massive) ν-World

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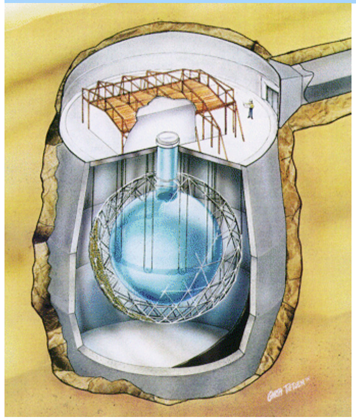
National Nuclear Physics Summer School

Bloomington, IN
July 23rd-26th, 2006

Neutrino mass continued...

Neutrino Oscillations



Probe mass differences

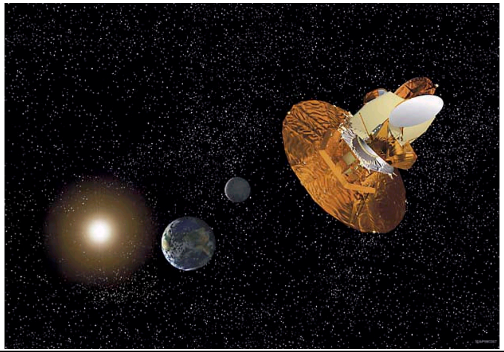
Use quantum mechanical effects

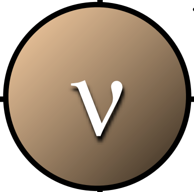
Sources: Reactor, solar, atmospheric, beams

Cosmology

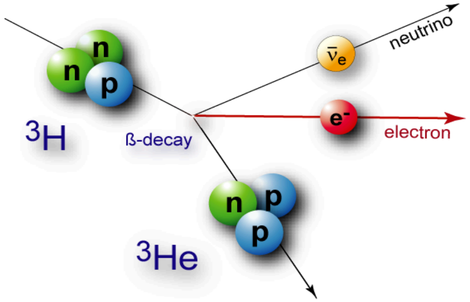
Probe total neutrino mass
Use Gen. relativity

Satellites & ground observatories





Single Beta Decay



Probe absolute mass scale

Use conservation of energy

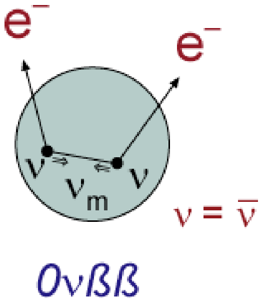
Model-independent

0ν Double Beta Decay

Probe Majorana masses

Use rarest decays on Earth

Probe identity of neutrinos




Neutrinos?
The Sudbury Neutrino
Observatory
(surface view)

The Sudbury Neutrino Observatory

2092 m underneath the surface
(6800 ft level)

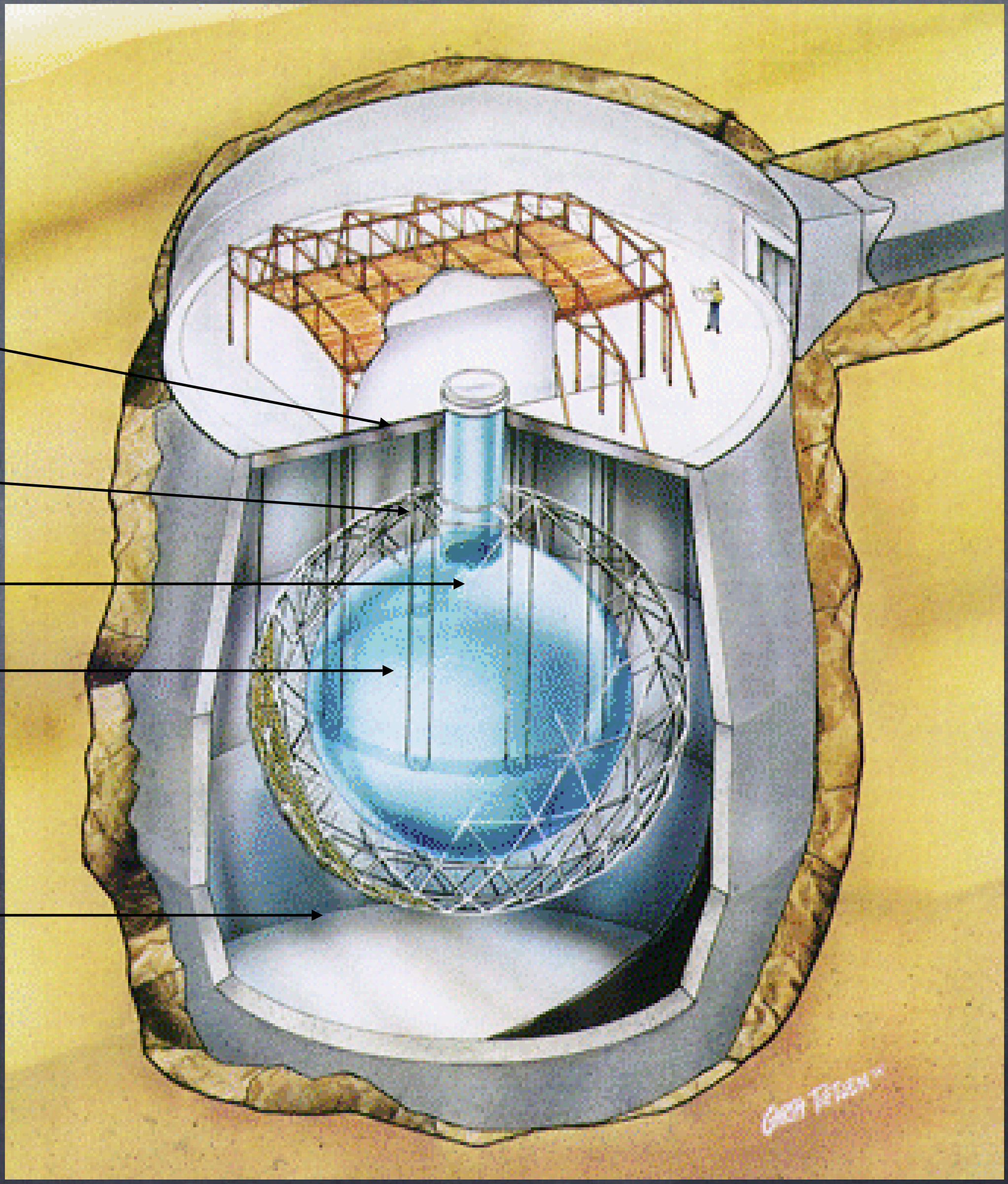
Almost 10,000 phototubes to detect light emitted when neutrinos interact.

Acrylic vessel 12 meter diameter

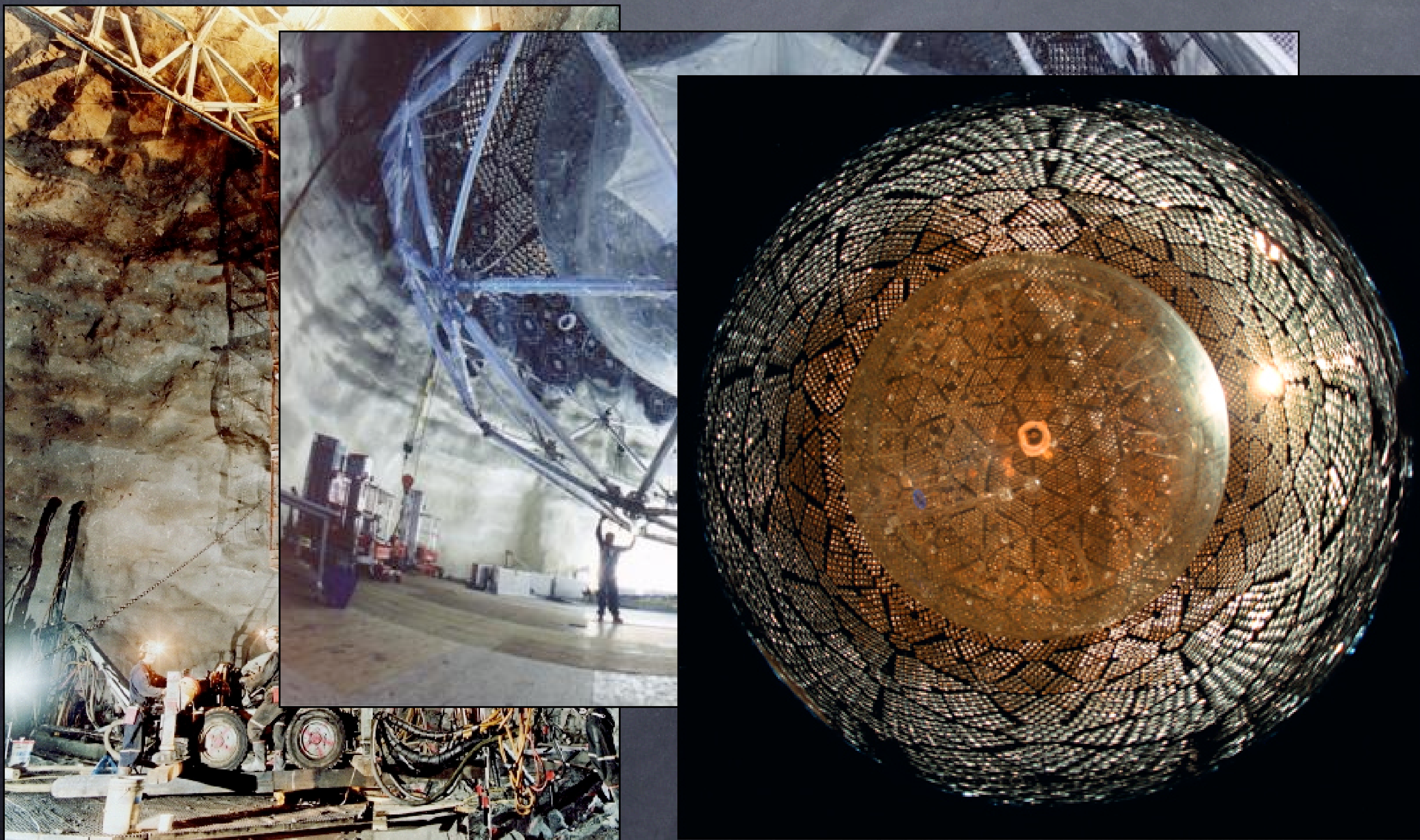
1000 Tonnes heavy water

7000 Tonnes of ultra clean water, as a shield.

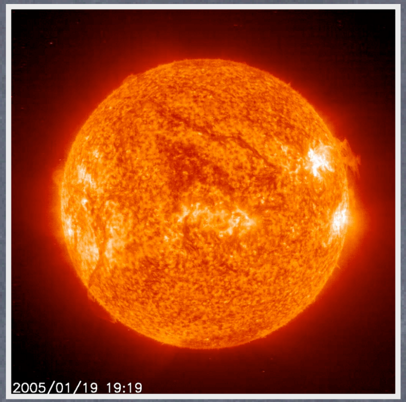
Urylon Liner and Radon Seal



SNO during Construction



Mixing Established



= Oscillations

If one looks only
at electron neutrinos, only 1/3
are seen

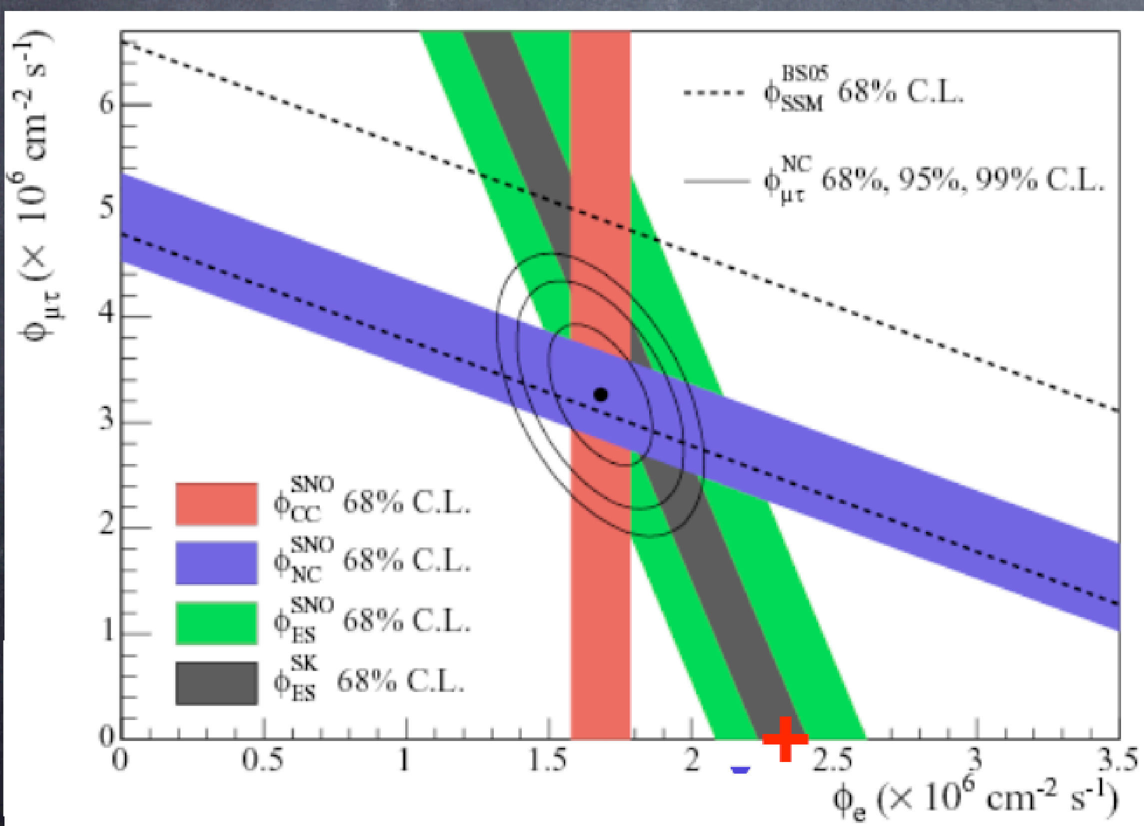
ν_e

However, if one looks at all
neutrino flavors, we see the
number expected

ν_e ν_τ ν_μ

Neutrino Mixing Confirmed

- Neutrino mixing established (non-electron flavors coming from the sun).
- Original ^8B fluxes confirmed.
- Solar core temperature known to 1%.



Fluxes

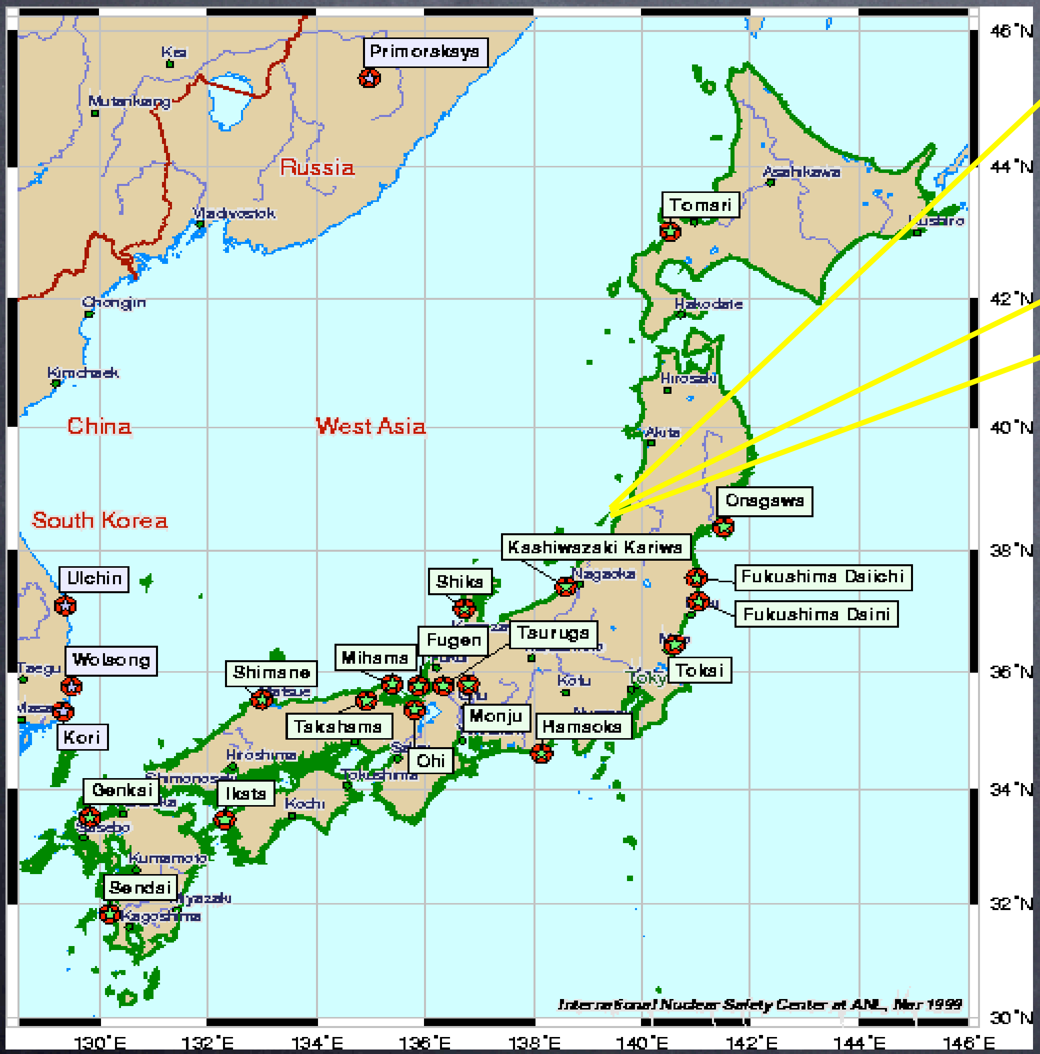
(10^6 cm^{-2} s^{-1})

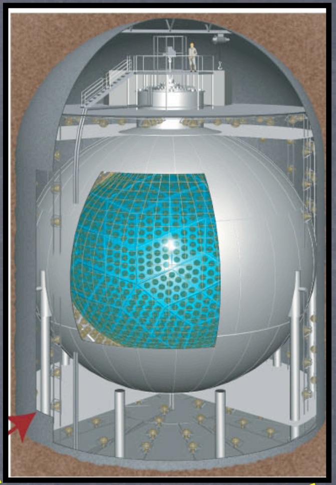
ν_e:	1.68(11)
$\nu_{\mu\tau}$:	3.26(47)
ν_{total}:	4.94(43)
ν_{SSM}:	5.69

KamLAND

- Using reactor neutrinos to match the sun...

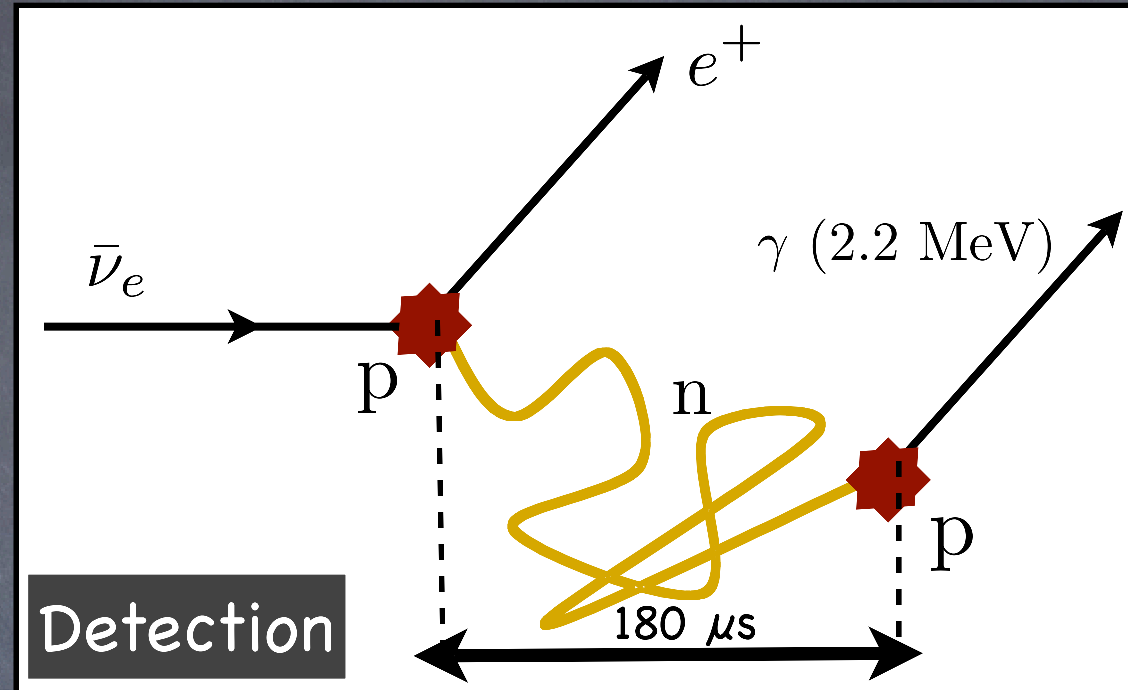
KamLAND



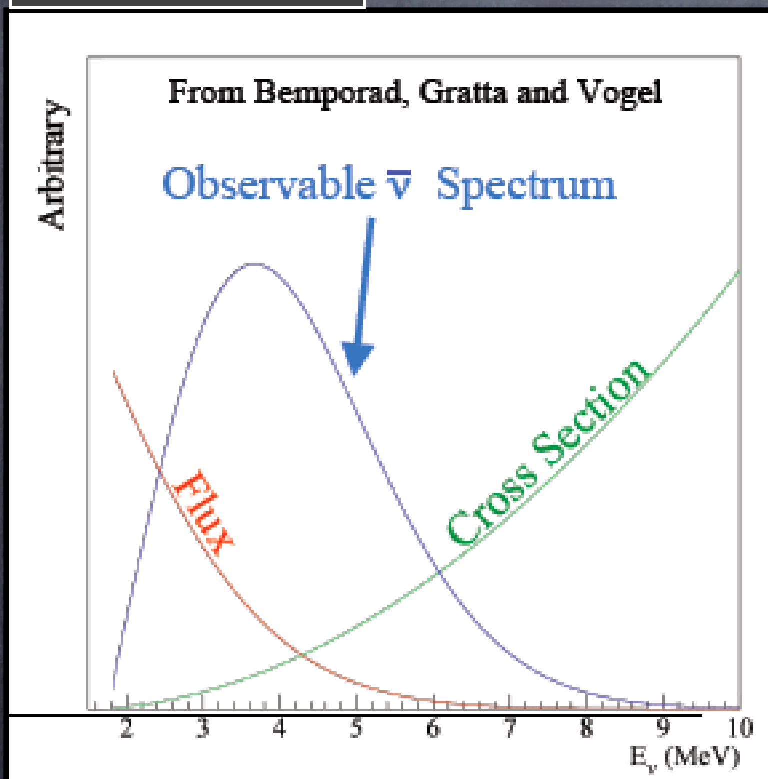


- Located approximately 180 km (average) from strongest reactors
- Distance is selected so as to probe same oscillation length as solar experiments.

Reactor Flux & Interactions



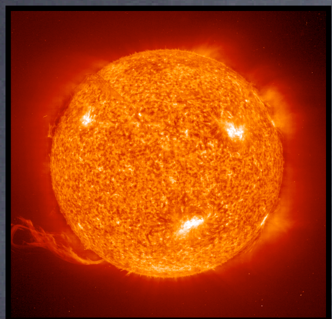
Production



- Combination of falling flux and rising cross-section yields average energy ≈ 4 MeV.
- Sensitive to both q13 and q12.

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}{}^2 L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}{}^2 L}{4E_\nu}\right)$$

Solar vs. KamLAND



Produced in the sun (fusion).

MSW/matter effects.

Neutrinos.

Baseline ≈ 10^{11} km

Nuclear reactors (fission)

No matter effects

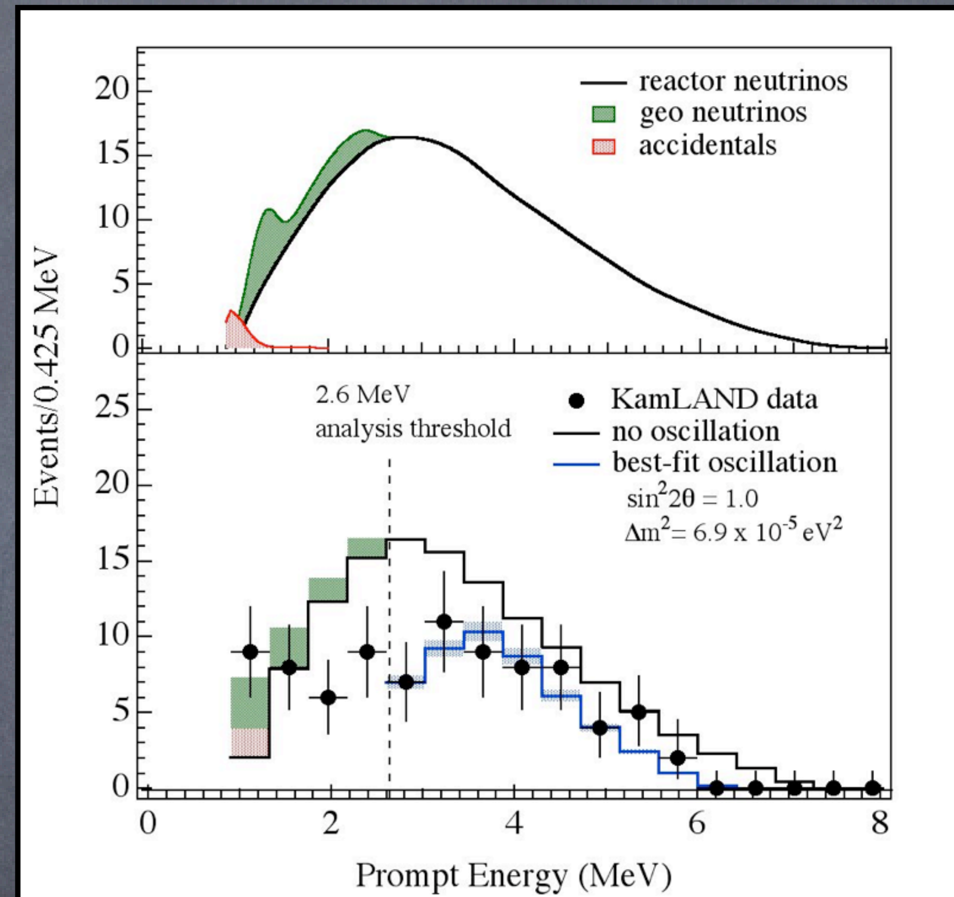
Anti-neutrinos.

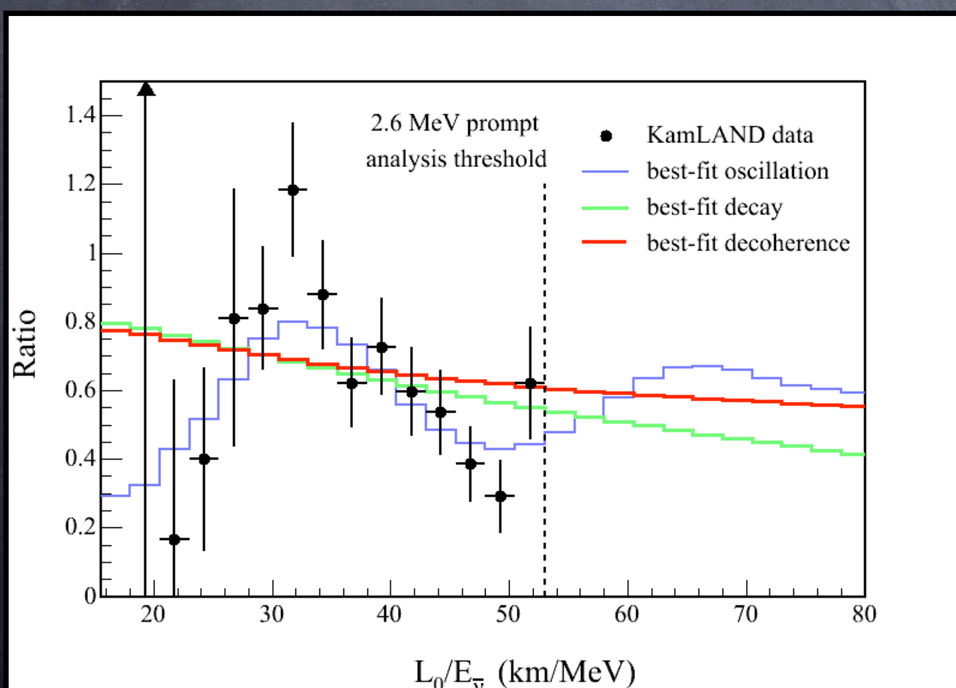
Baseline ≈ 10^{3} km

No common systematics!

Confirmation!

- Can look at deficit in neutrinos OR L/E behavior.
- Both consistent with solar neutrino oscillations (in vacuum)

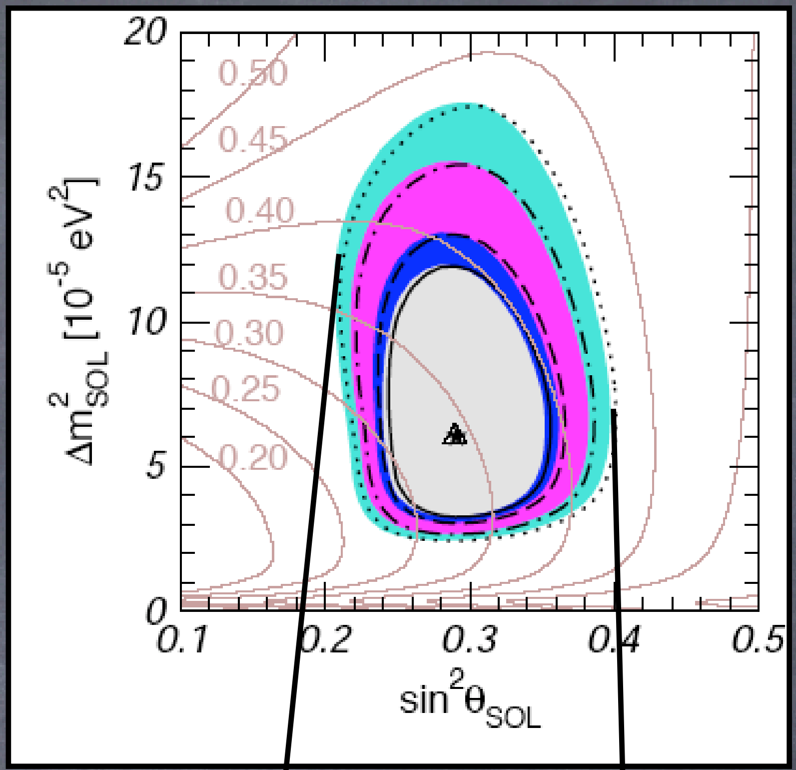


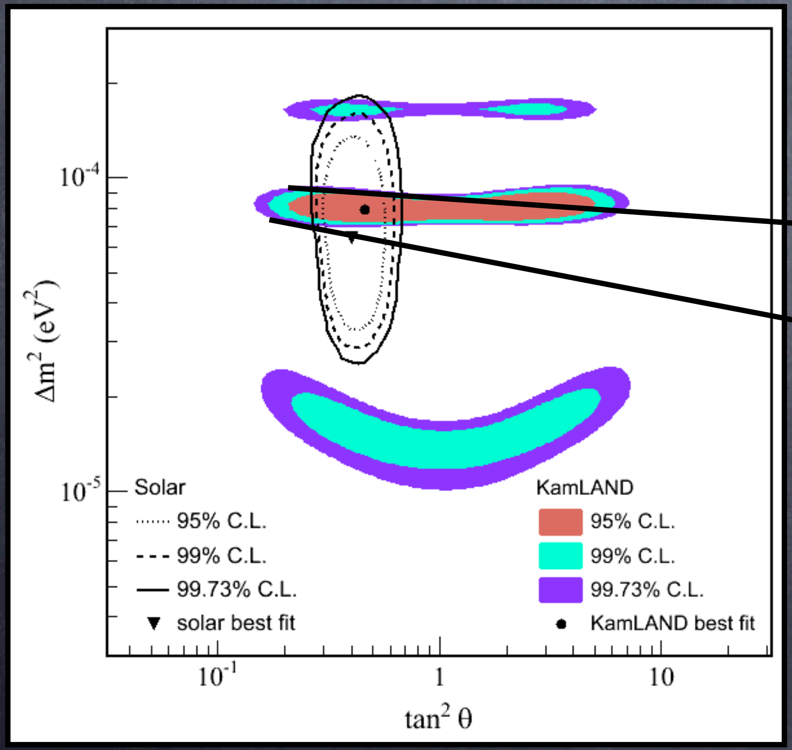


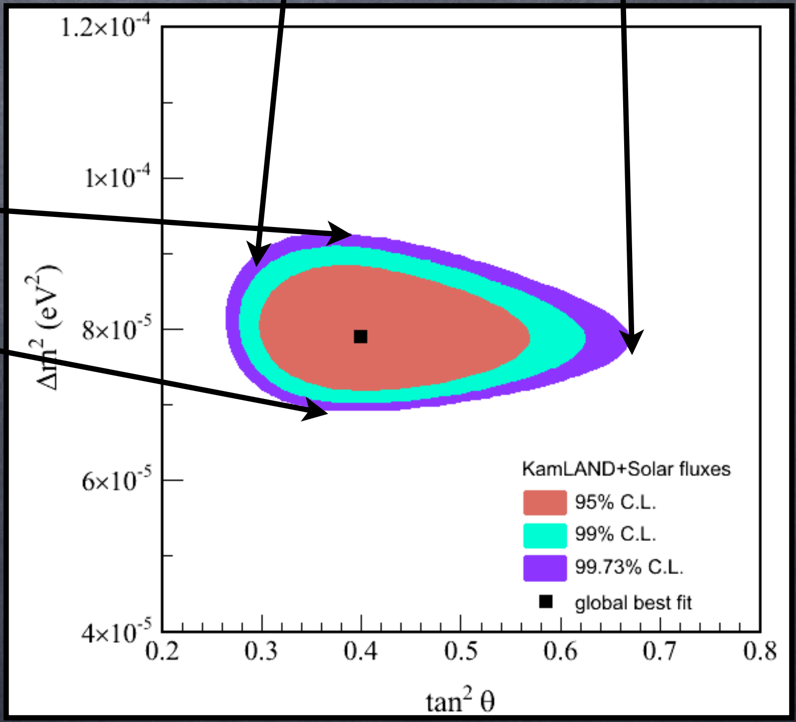
$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}{}^2 L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}{}^2 L}{4E_\nu}\right)$$

Confirmation

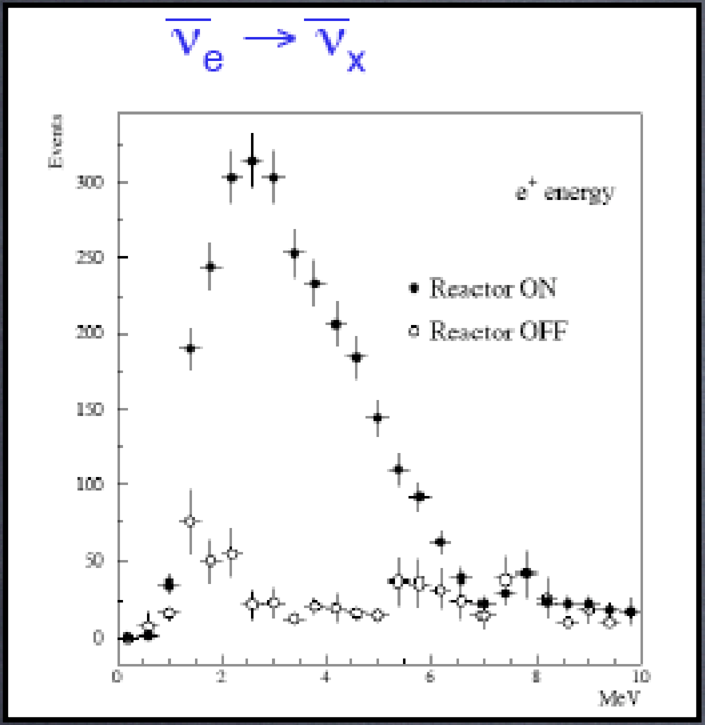
- Combination of reactor and solar data confirms oscillation mechanism.
- Rule out various exotic explanations (CPT violation, etc.)

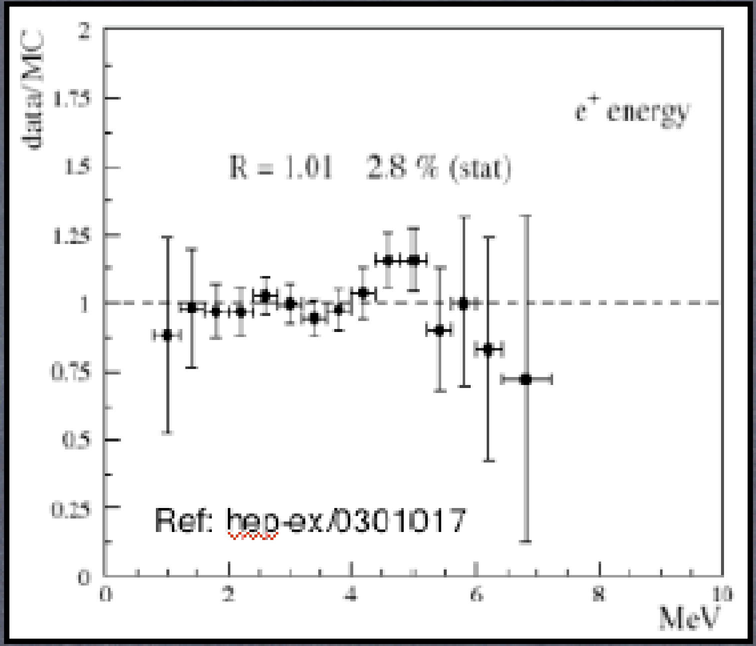






Reactor Experiments



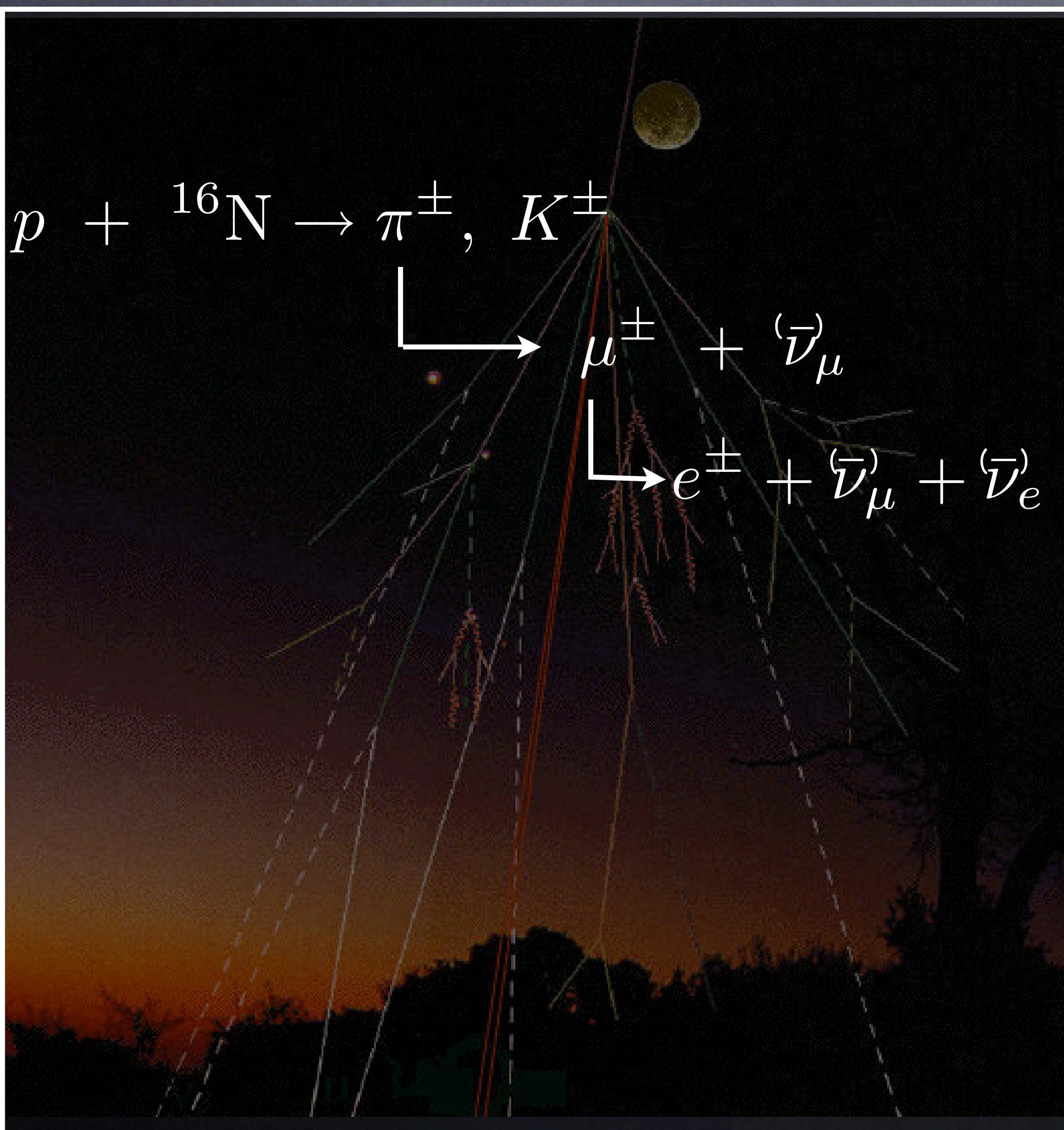


$\theta_{13} < 9.5^0$ (90% C.L).

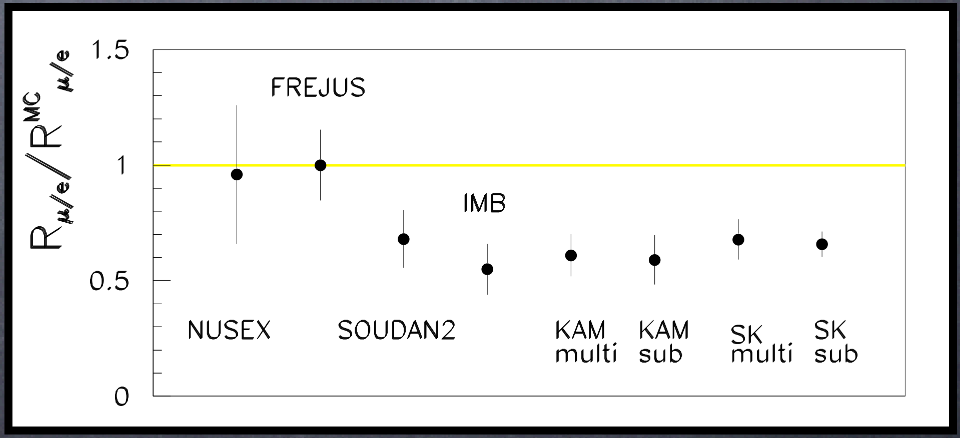
- Chooz also probes reactor neutrinos, but different mixing angles.

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}{}^2 L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}{}^2 L}{4E_\nu}\right)$$

Atmospheric Neutrinos

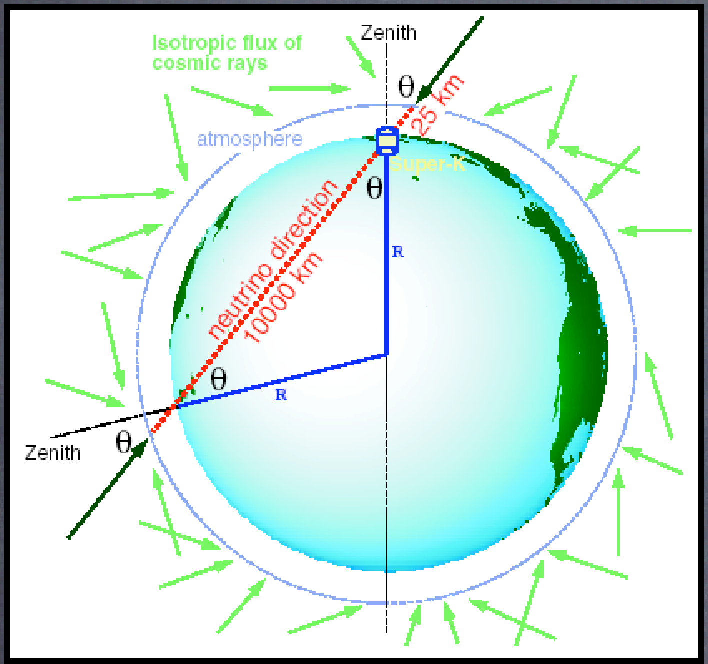


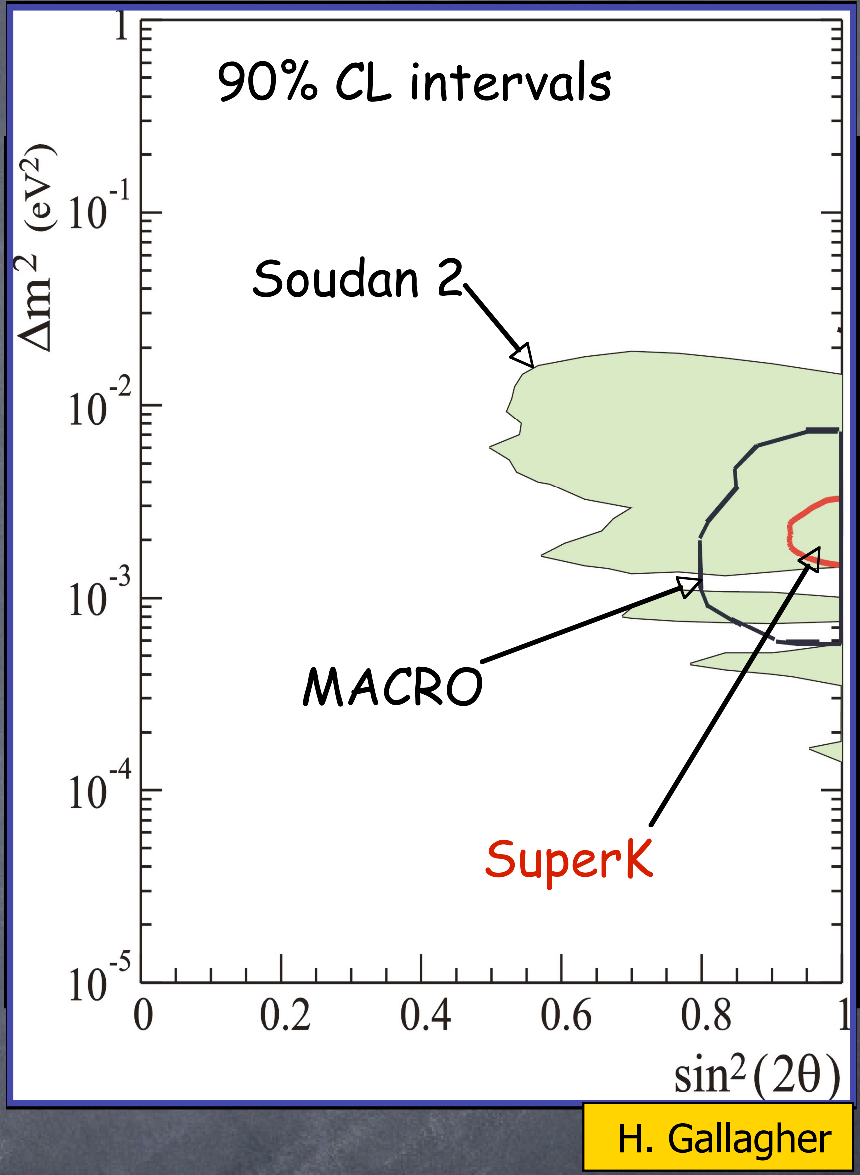
- Measurements of the absolute and electron/muon ratio also show deficit of muon neutrinos.
- Ratio consistent with neutrino oscillations.



- Insufficient proof at this point.

The Clincher

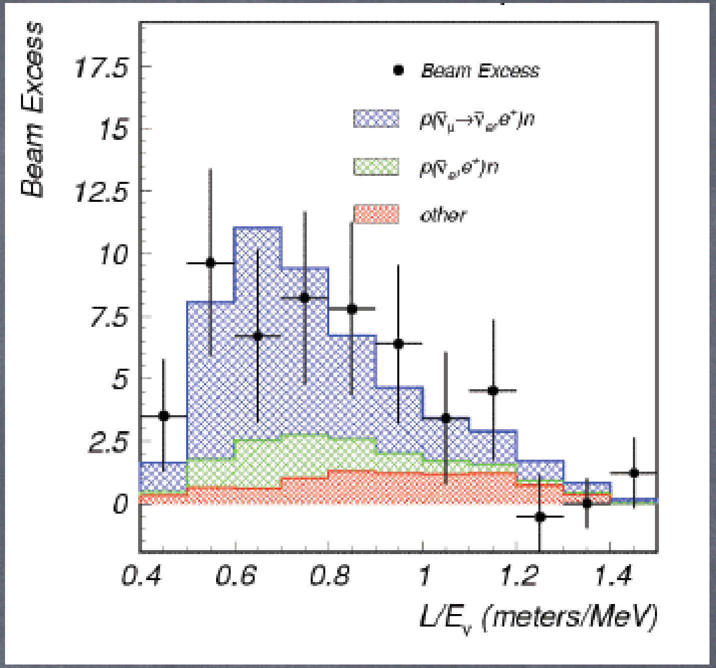


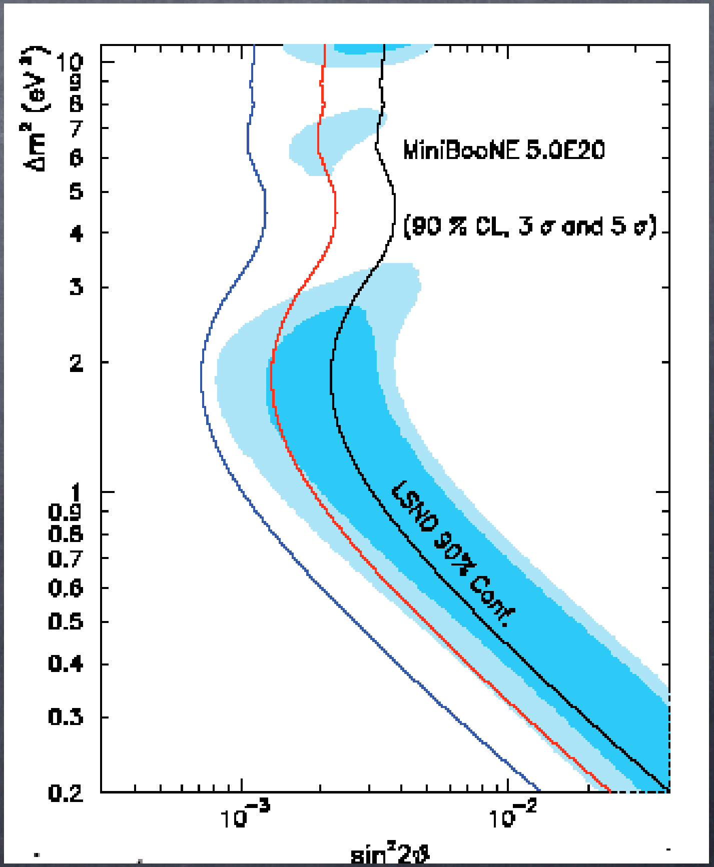


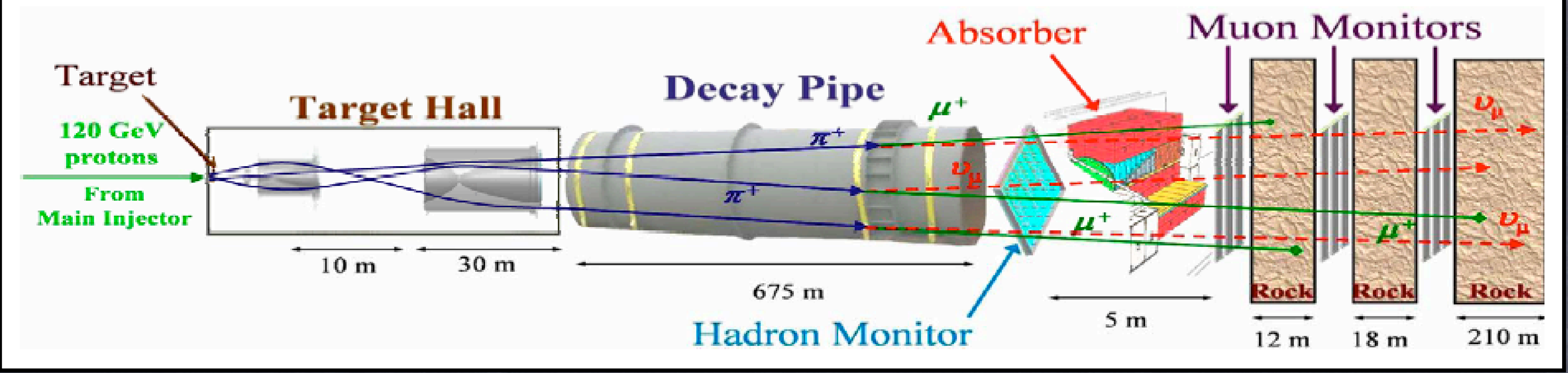
- Super-K illustrates the distance-dependence of oscillations by showing deficit changes as a function of zenith angle.
- Firmly established the phenomena of neutrino oscillations for the atmospheric sector.

One too many?

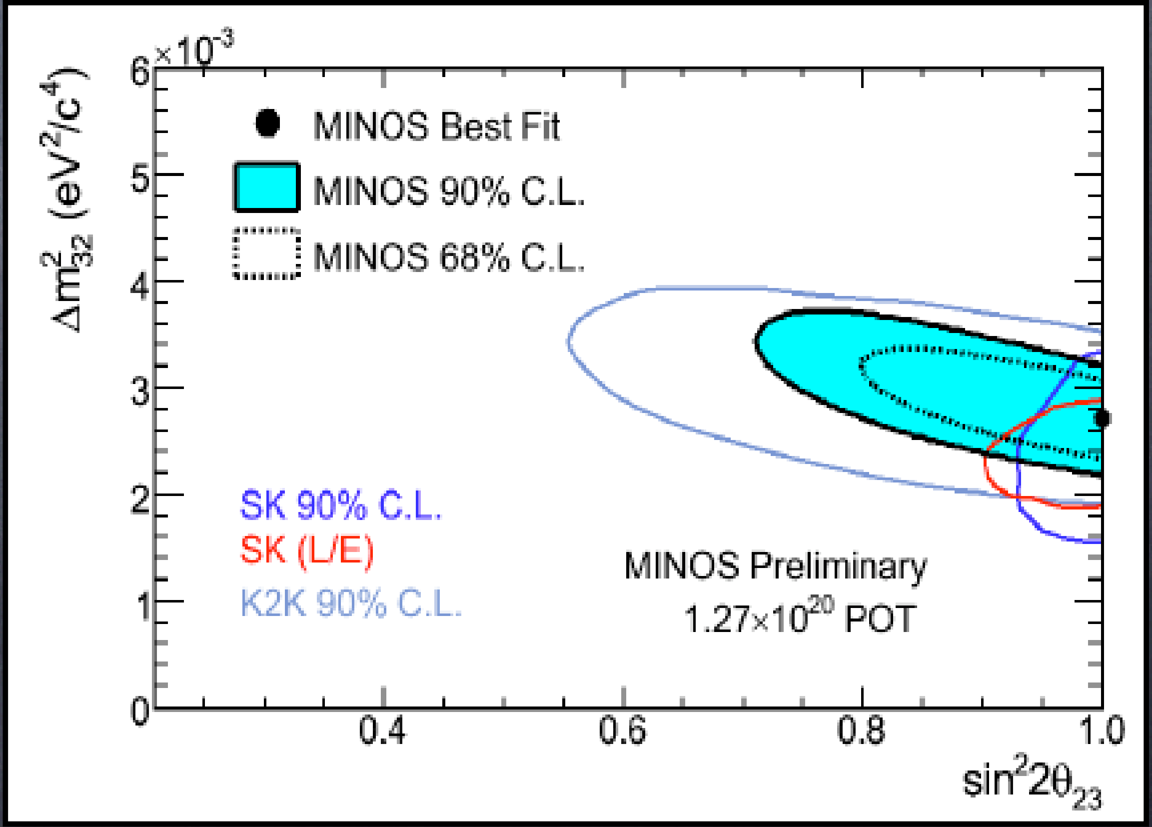
- The LSND experiment also sees events consistent with neutrino oscillations.
- Excess of electron neutrinos from a pure muon neutrino beam.
- In combination with other experiment, may indicate additional (light sterile) neutrinos.
- To be confirmed by the MiniBooNE experiment.







- Further verification from beams:
  - MINOS (new!) results
  - K2K (with smaller statistics).
- Maximal mixing established.



Neutrino Mass Established

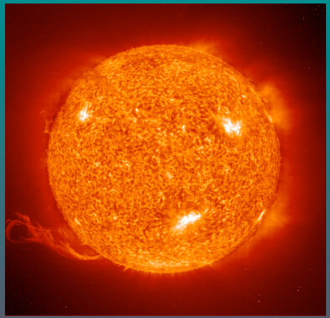
Solar/reactor neutrino experiments:

(SNO, KamLAND, Super-K, GNO, etc)

Limit solar mixing parameters:

$$\theta_{12} = 37^0 \pm 3^0$$

$$\Delta m^2_{12} = (8.0 \pm 0.5) \times 10^{-5} \mathrm{eV}^2$$



Atmospheric neutrino experiments:

Super-K, Soudan, Kamiodande, new MINOS results)

Limit atmospheric mixing parameters:

$$\theta_{23} = 45^o \pm 15^o$$

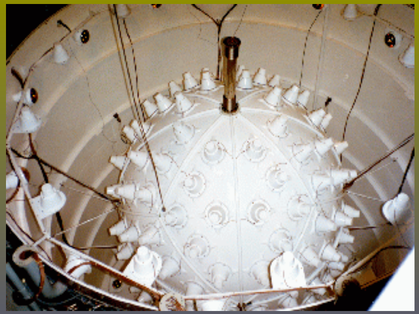
$$\Delta m^2_{23} = (2.72 \pm 0.25) \times 10^{-2} \mathrm{eV}^2$$

Short baseline & reactors experiments:

(LSND, CHOOZ, Palo Verde, etc...)

Limits on last mixing angle; hints of sterile ν's?:

$$\theta_{13} < 9.5^0 \ (90\% \ \mathrm{C.L}).$$



A Revolution

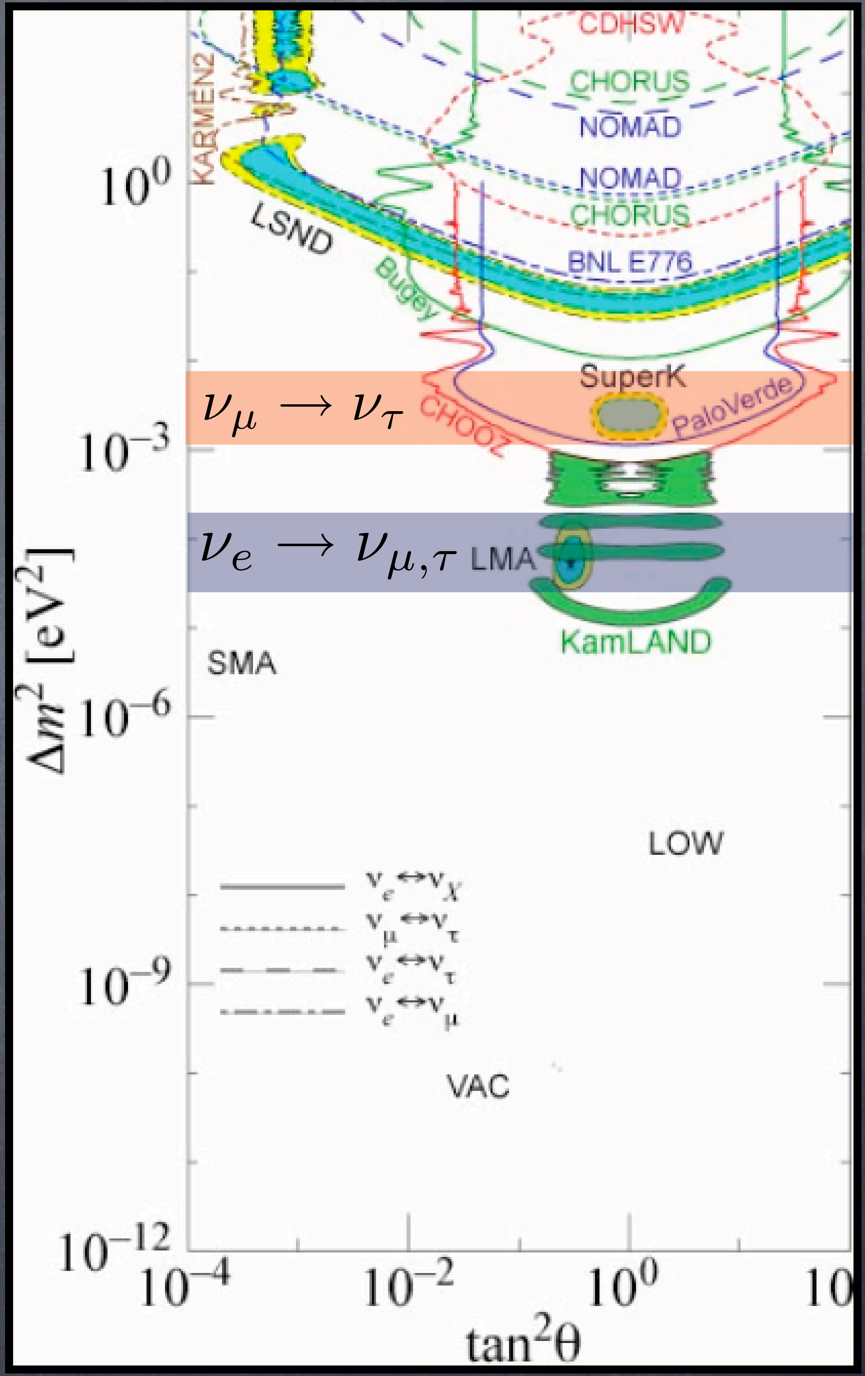
- Neutrino physics has provided a new framework in understanding electroweak interactions and particle masses.
- The culmination of forty years of data now indicates that neutrinos have mass and oscillate from one flavor to the other.
- Redundancy has been a key component in being able to make this claim:

Atmospheric

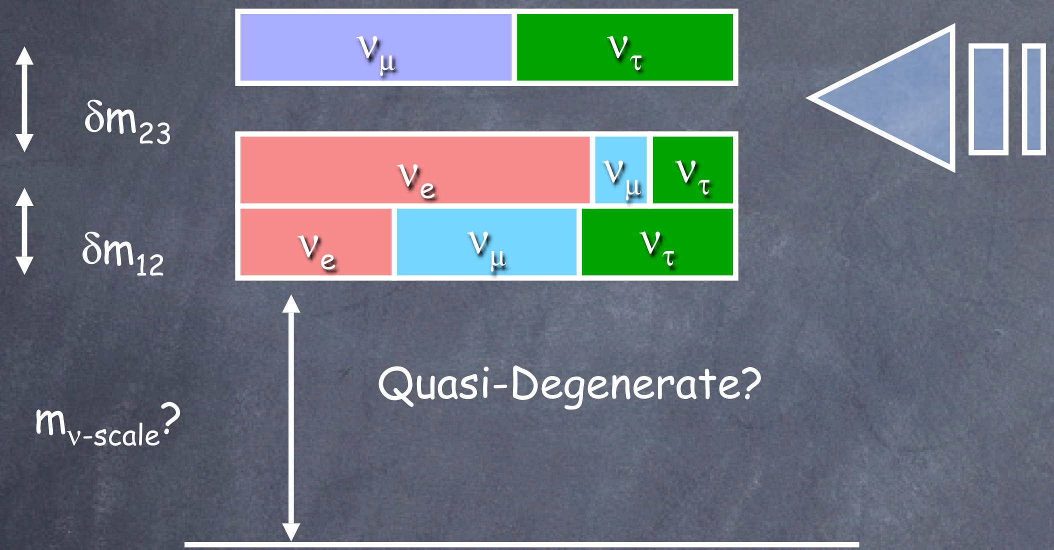
Reactor

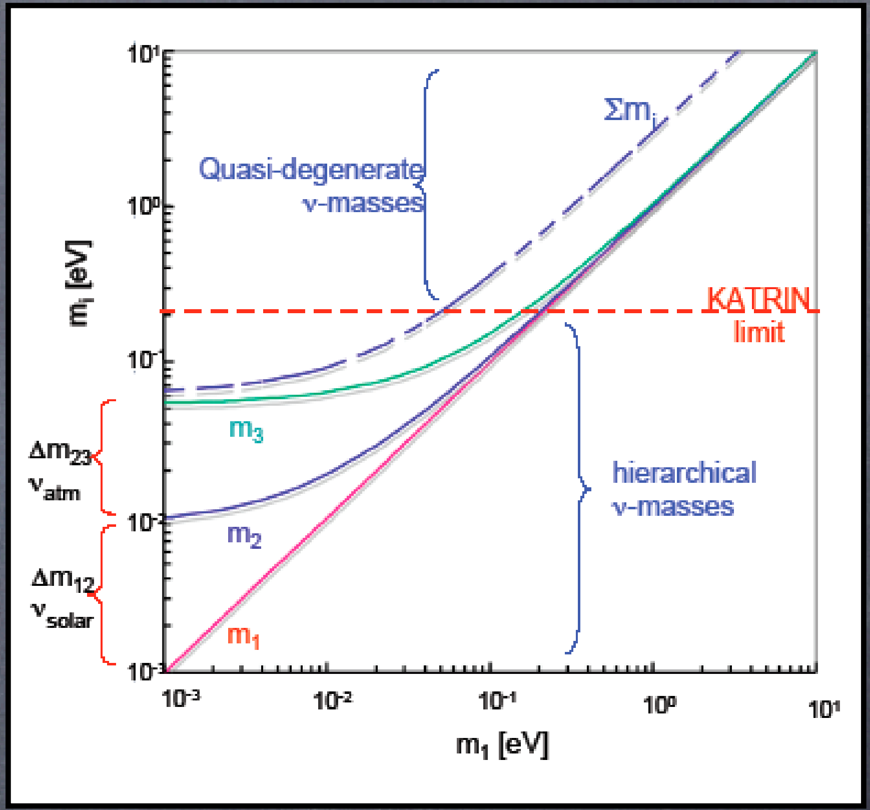
Solar

Neutrino beams



Open Questions in Neutrino Physics



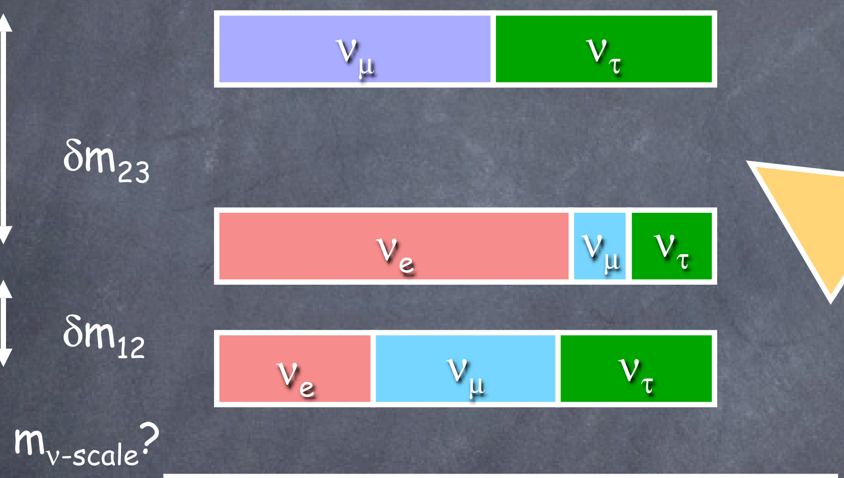


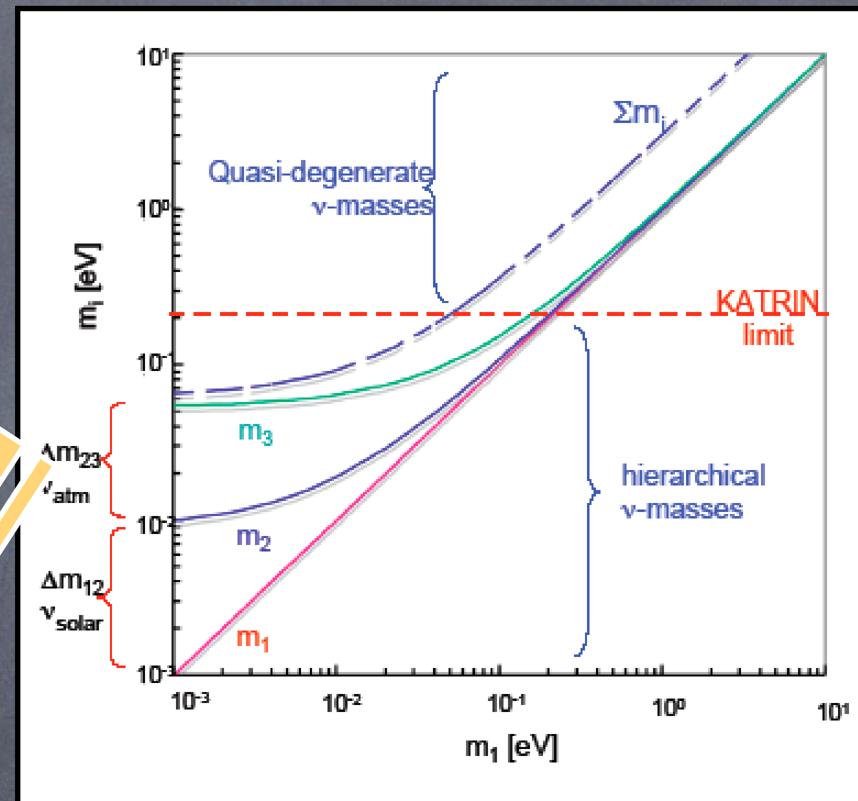
Searching for the mass scale:

- Oscillation experiments place limit on m_ν > 50 meV
  - What is the absolute mass scale?
  - Quasi-degenerate (m_1~m_2~m_3)...?

Open Questions in Neutrino Physics

Hierarchical?





Searching for the mass scale:

- Oscillation experiments place limit on m_ν > 50 meV
  - What is the absolute mass scale?
  - ...or hierarchical ($m_1 \ll m_2 \ll m_3$)?

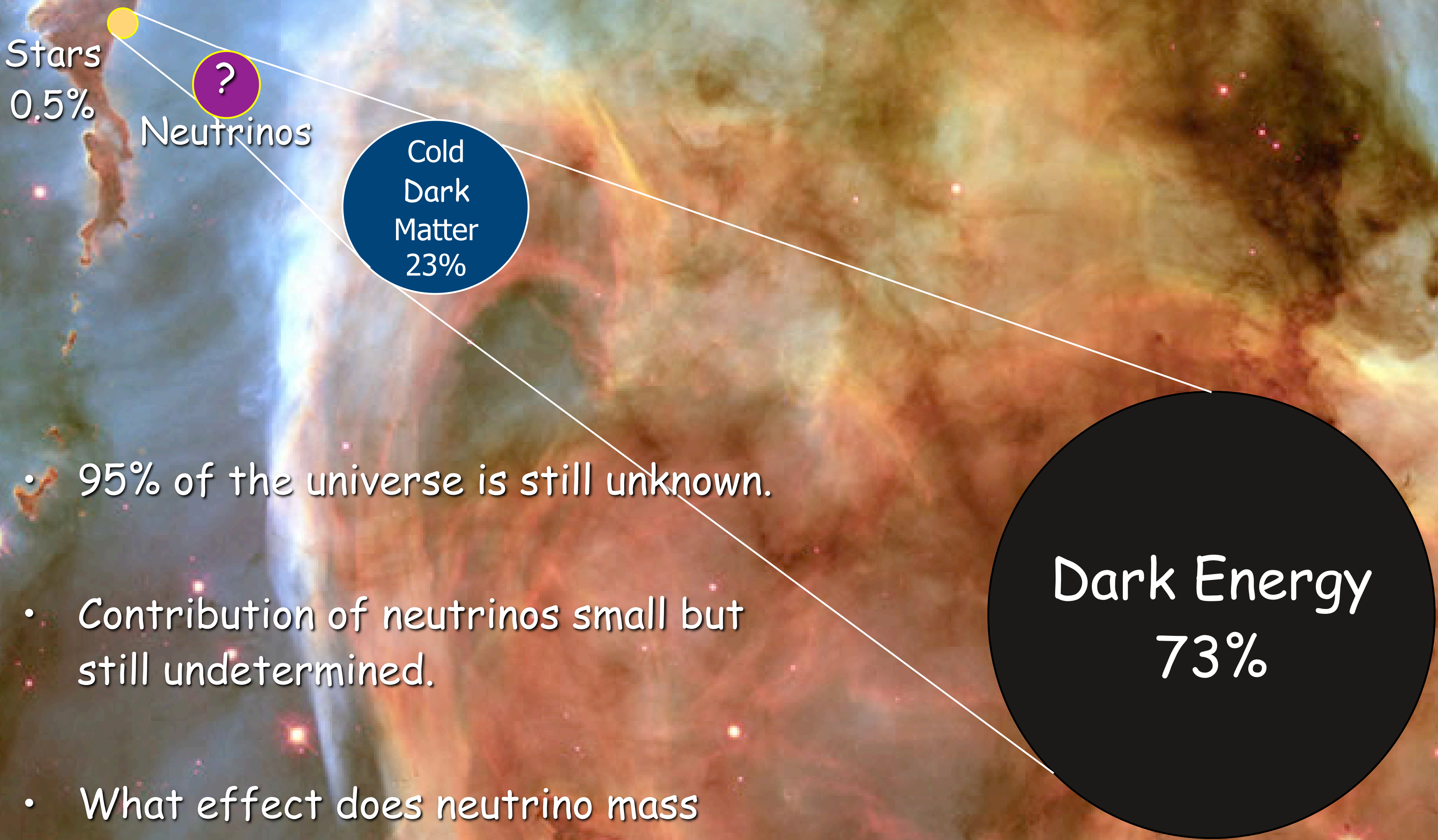
Lesson #2

m_ν is everywhere

Neutrinos and Cosmology

- Neutrinos are the second-most abundant particle in the universe (second only to photons).
- Any neutrino mass, even if small, shows up in the cosmic "scale"
- Neutrinos are "hot" dark matter, and, as such, influence the structure and clustering of galaxies...

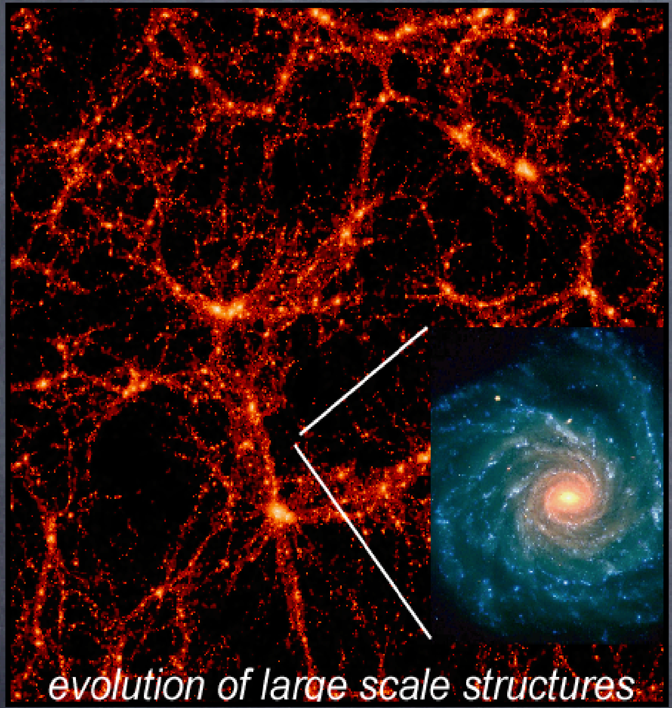
The Known (and Unknown) Universe



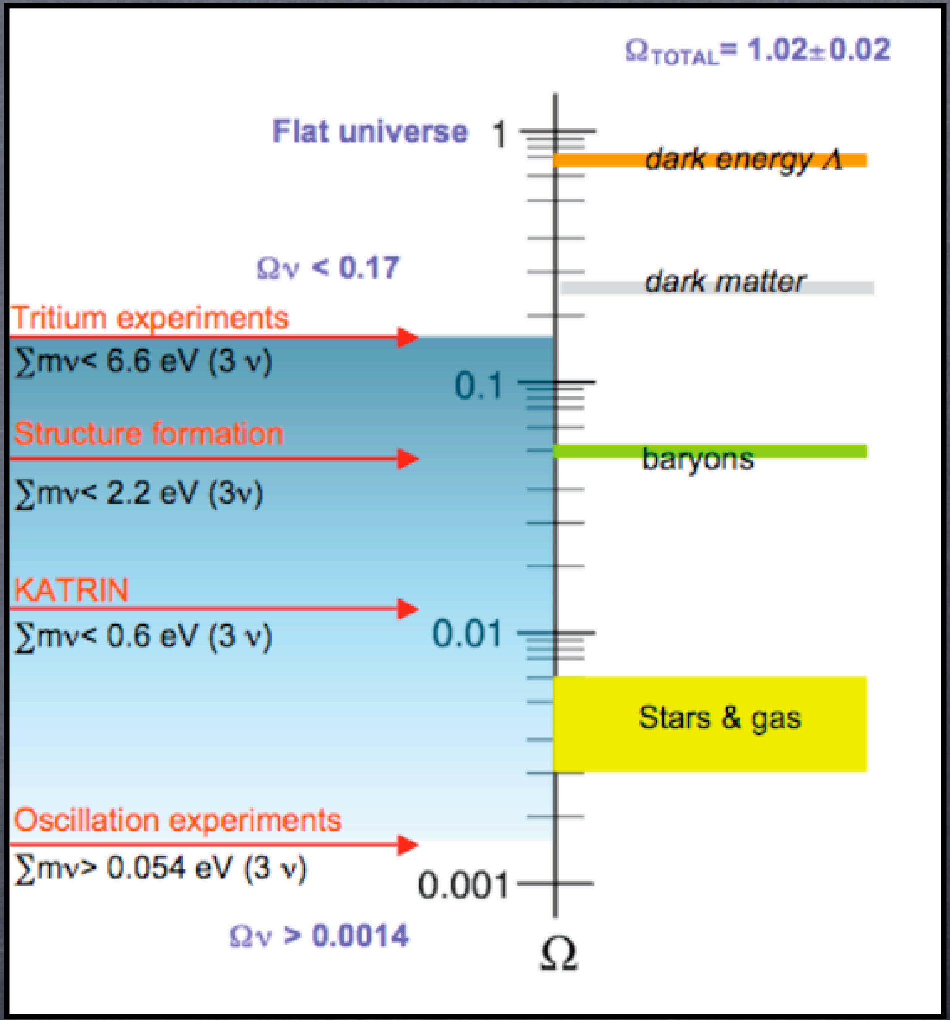
- 95% of the universe is still unknown.
- Contribution of neutrinos small but still undetermined.
- What effect does neutrino mass have on cosmology?

Connections with Cosmology

$$\Omega_\nu h^2 = \Sigma\, m_\nu / 92\ \text{eV}$$

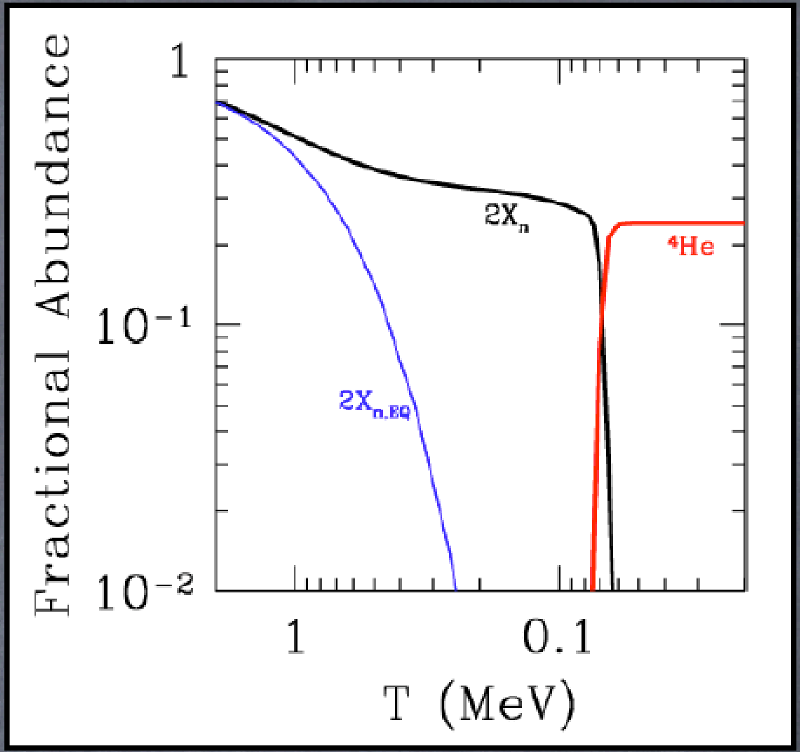


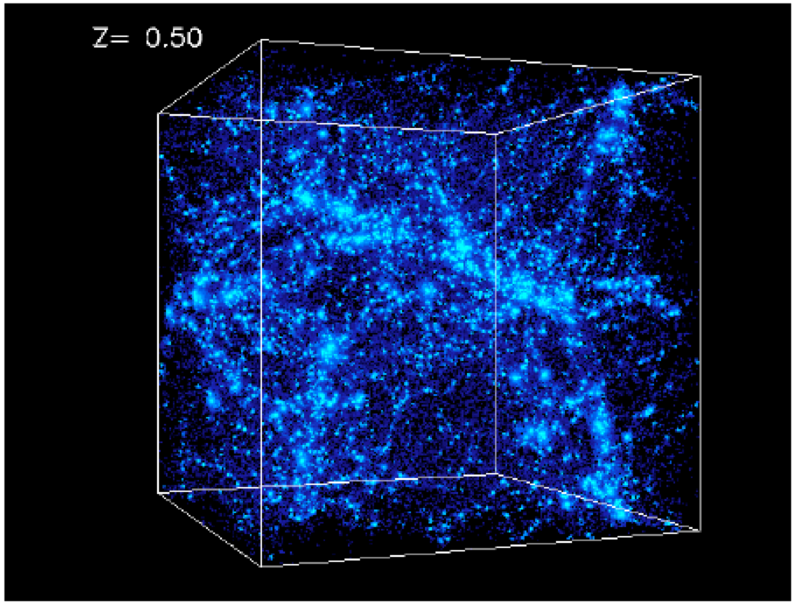
- Large scale structure
- CMB
- Lyman-alpha lines
- Weak gravitational lensing



Neutrinos in the Cosmos

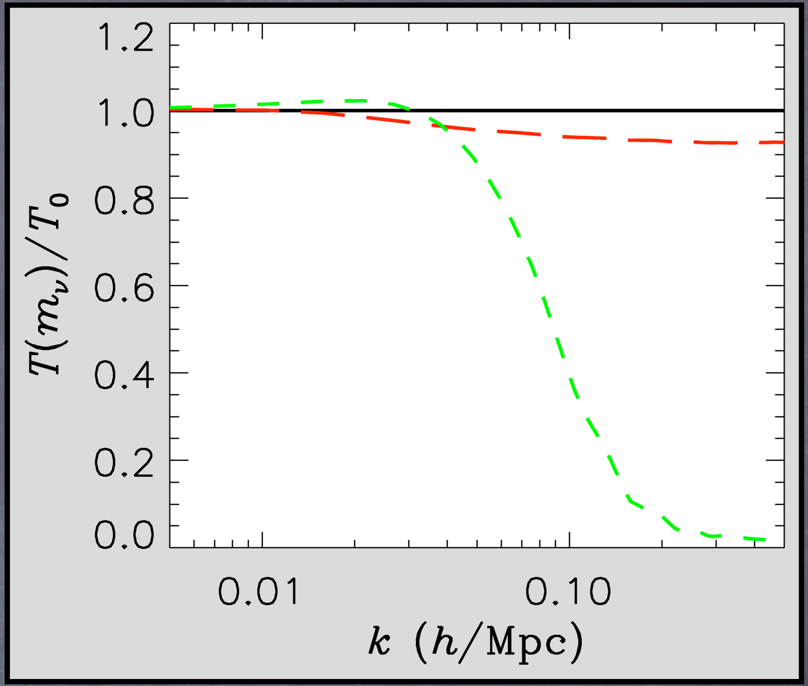
- Neutrinos produced at high energies/temperatures before freeze-out takes place.
- Evidence for neutrinos in the cosmos:
  - Big bang nucleosynthesis (^{4}He would increase if neutrinos energy density higher)
  - Large scale structure also dependent on neutrino energy density

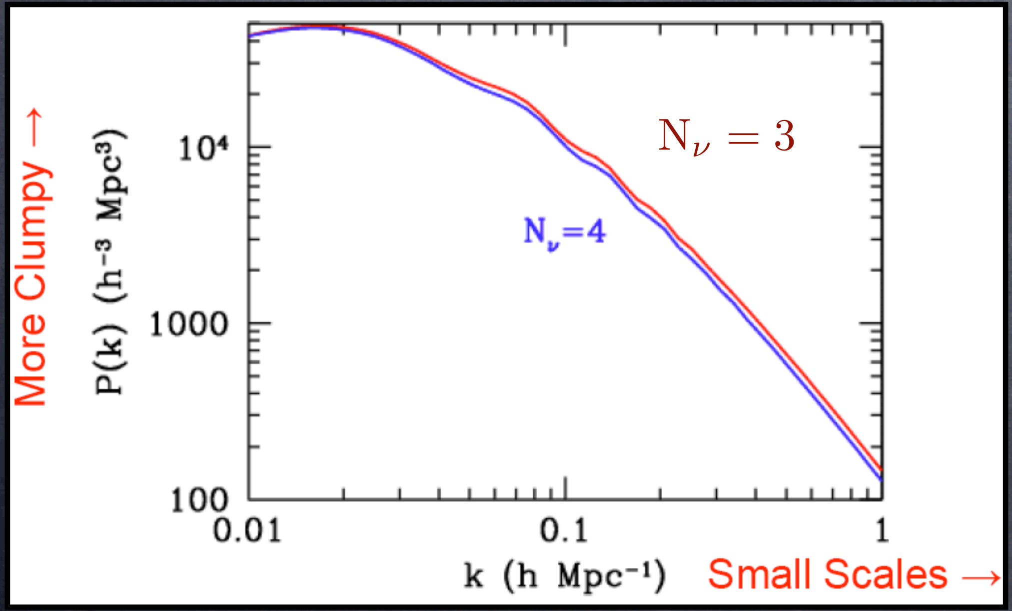


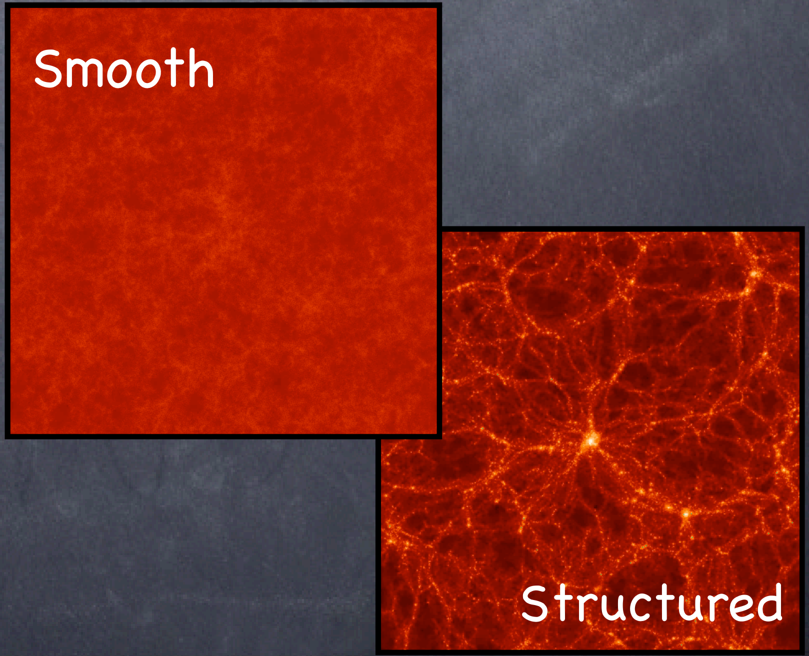


Power Spectra

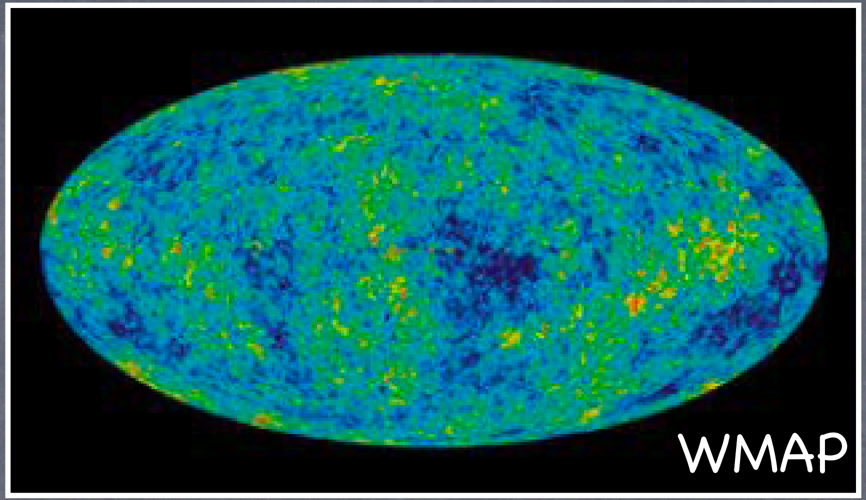
- Power spectra measures the structure as a function of scale length.
- Sensitive to neutrino mass more than neutrino number.



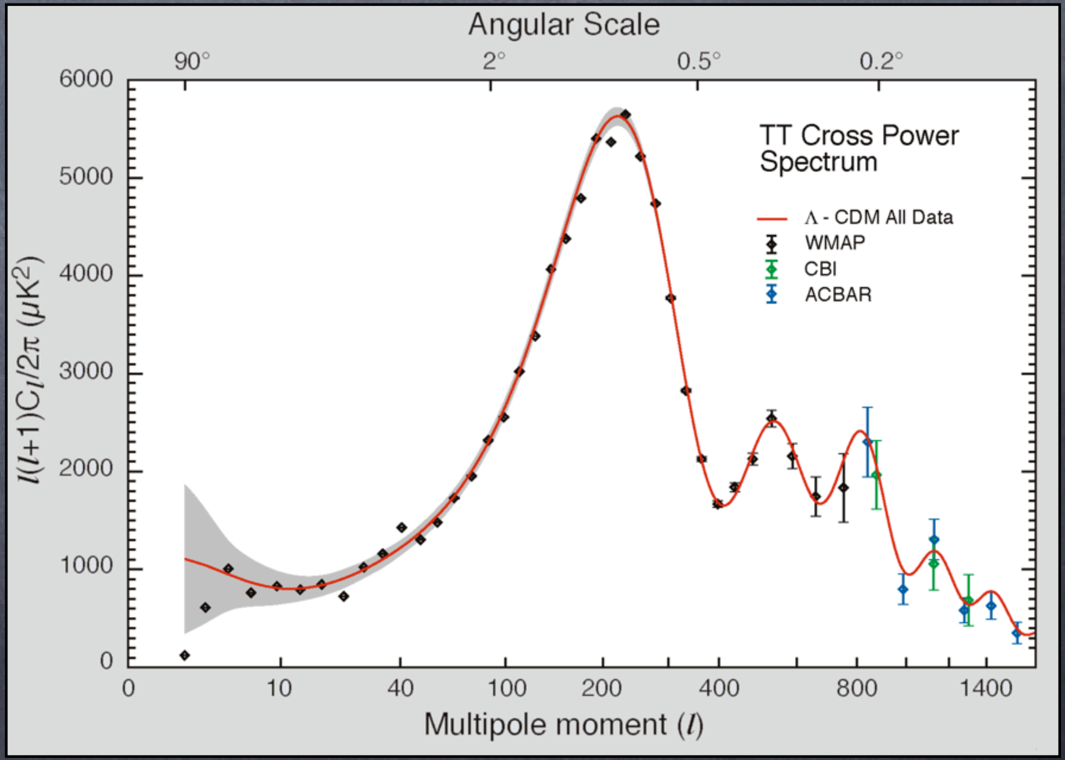


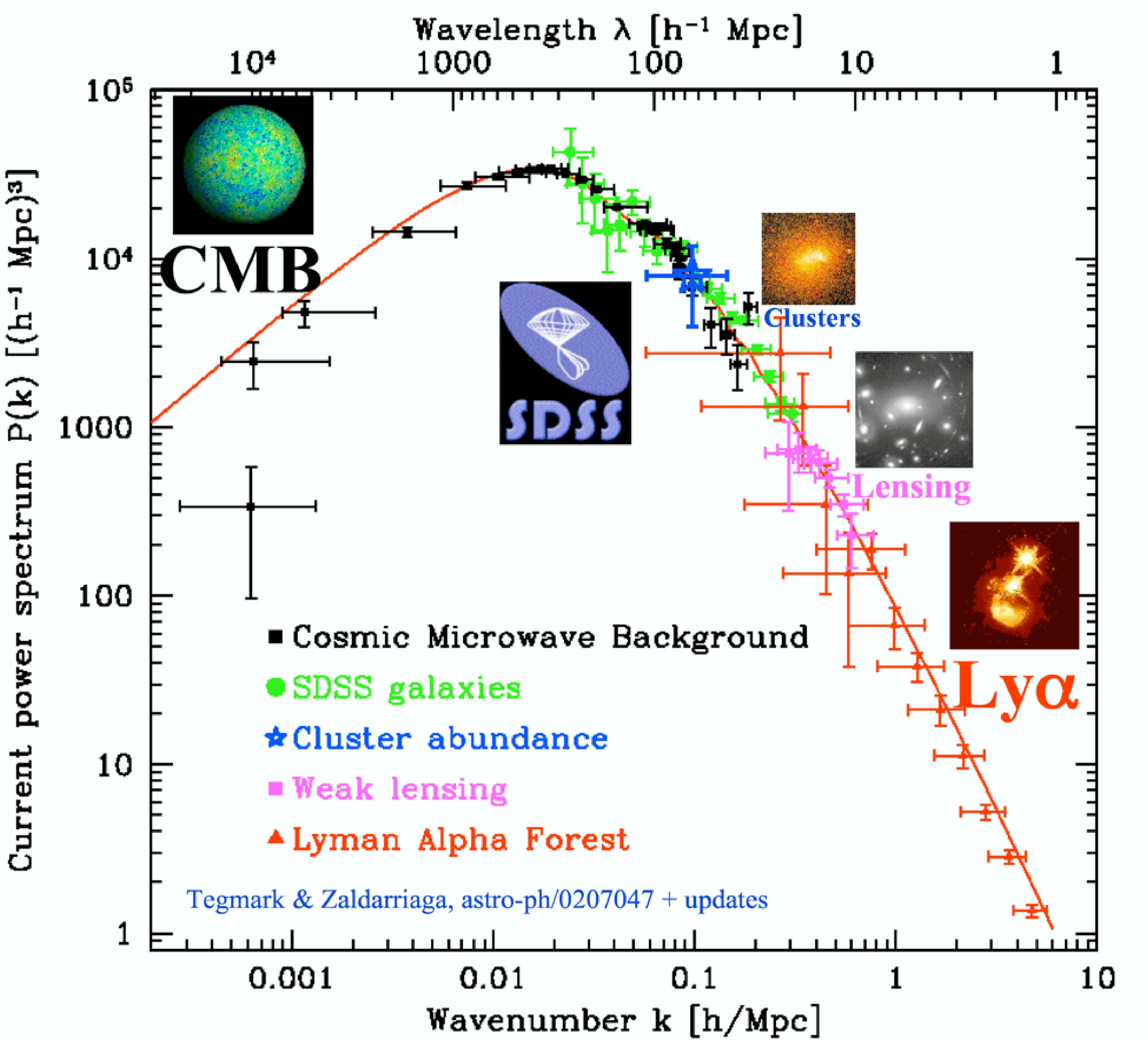


Cosmic Microwave Background



- WMAP data reveals structure of microwave background and temperature fluctuations at small angular scales.
- Provides a normalization constraint on the power spectrum.
- Complimentary information to power spectrum.

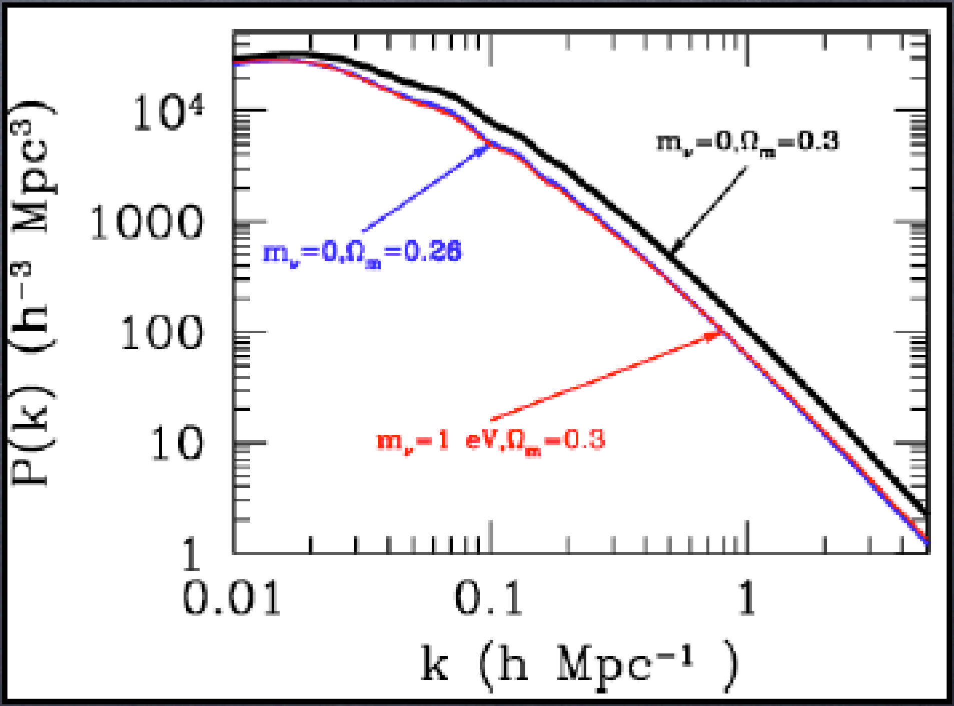



Wavelength λ [h⁻¹ Mpc]
10⁴
1000
100
10
1
10⁵
10⁴
1000
100
10
1
Current power spectrum P(k) [(h⁻¹ Mpc)³]
CMB
SDSS
Clusters
Lensing
Lyα
Cosmic Microwave Background
SDSS galaxies
Cluster abundance
Weak lensing
Lyman Alpha Forest
Tegmark & Zaldarriaga, astro-ph/0207047 + updates
0.001
0.01
0.1
1
10
Wavenumber k [h/Mpc]

Biases/Dependencies

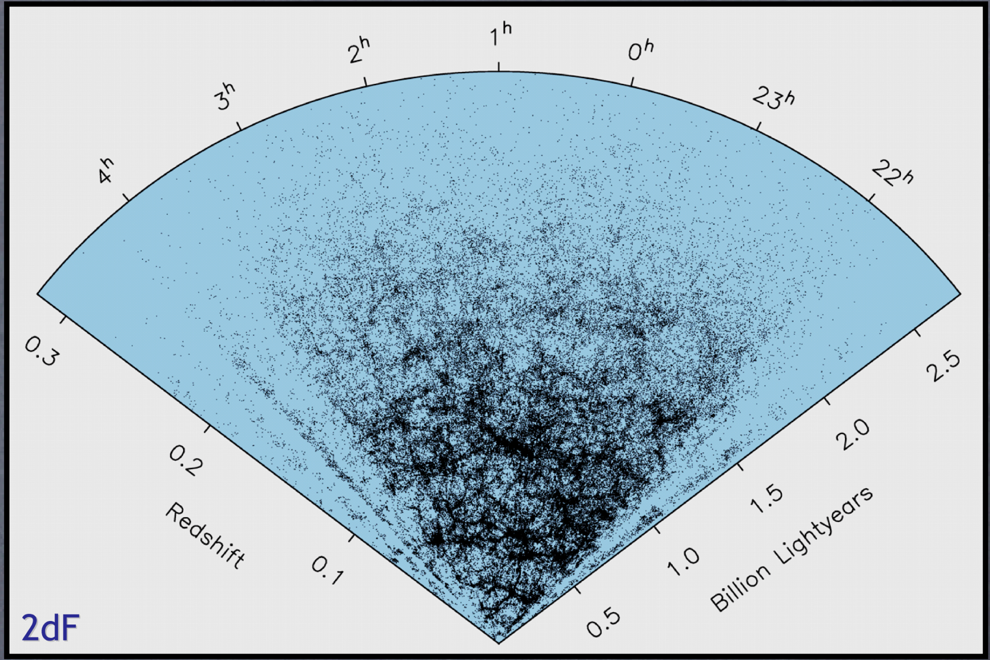
Author	WMAP	CMB	SDSS	2dF	Other Data	Σm_ν[eV]
Bar'03	X	X	X	X	h(HST)	<0.75
Teg'03	X	X	X		SNIa	<1.7
ASB'03	X	X		X	XLF	=0.36-1.03
WMAP	X	X		X	Lyman a, h	<0.7
Bla'03	X			X	Ω_m=1	= 2.4
Han'03	X	X		X	h(HST), SNIa	<1.01
Han'03	X	X		X		<1.2
Han'03	X			X		<2.12

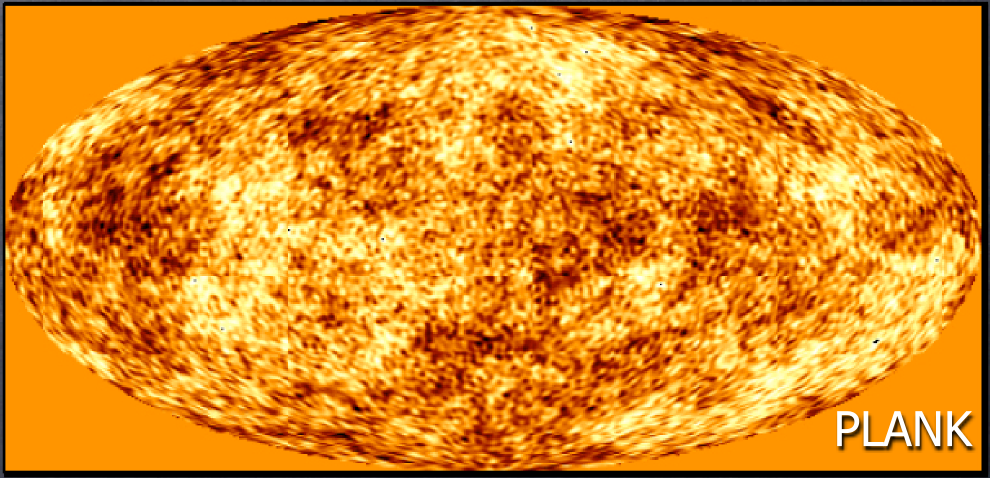
- Despite advances, system is still prone to priors and degeneracies between various parameters.
- Test of model parameters or search for new physics.



Increasing Precision...

- Further surveys of the matter density of the universe will provide stronger tests of the matter composition of the universe.
- Future satellites (e.g. PLANK) will probe in greater detail the role of neutrinos in the universe.
- Greater precision expected, but model dependencies will remain.





Closing in...

$$50 \text{ meV} < m_\nu < 2.2 \ (350) \text{ eV}$$

- The culmination of different experiments and experimental techniques have shown that neutrinos are massive particles.
- The absolute (and nature) of neutrino mass presents itself as the next challenge in neutrino physics.
- New experiments will shed light on the nature and scale of neutrino mass.