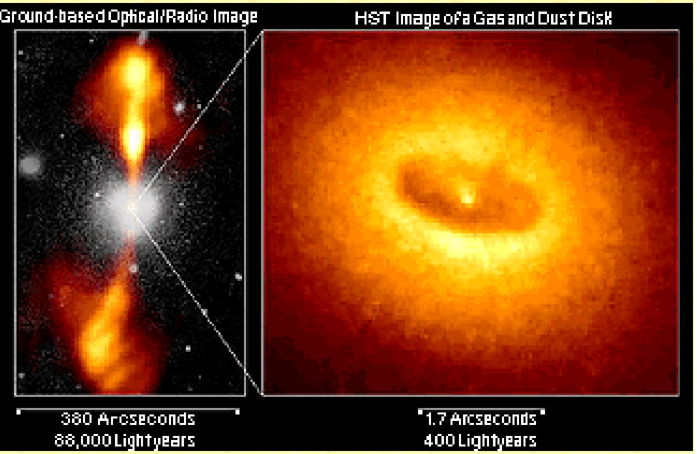
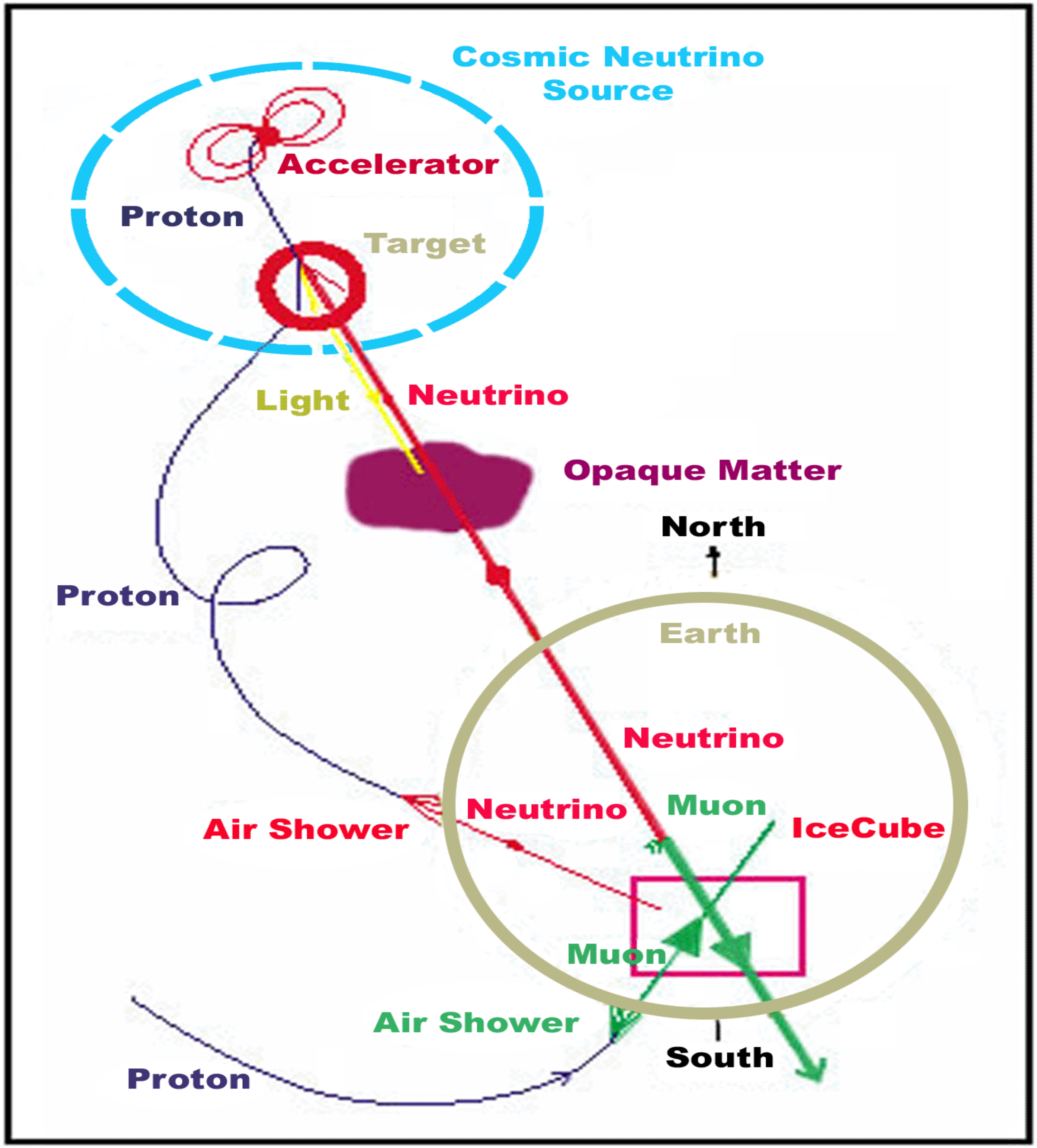
Possible sources of very energetic neutrinos





What might we learn from astrophysical neutrinos?

•Neutrinos not attenuated/absorbed

→Information about central engines of astrophysical sources

→Only window on the Universe available at E >10^{20} eV.

•Neutrinos not deflected by magnetic fields

→Their arrival direction points back to the source

• Flavor degree of freedom

→ Useful for probing neutrino properties

• Extreme energies and extreme baselines

→ Sensitivity to new physics

UHE neutrino sources

•"Cosmic beam dumps", eg, active galactic nuclei, gamma ray bursts, supernovae remnants.

→Flux limit set by the Waxman-Bahcall bound. Cosmic ray connection.

•Annihilation or decay of WIMPs, super-heavy dark matter particles, topological defects, etc.

→Fluxes related to dark matter properties and distributions.

•"Cosmogenic" or "GZK" neutrinos, produced via interaction of UHE cosmic rays with the microwave background radiation.
A "guaranteed" neutrino source.

→Flux related to the cosmic ray spectrum.

→Accompanying gamma flux also produced

Flavor Information

pp and pγ collisions produce pions → Decay to neutrinos

$$\pi^{+} \rightarrow \nu_{\mu} + \mu^{+}$$
$$\downarrow$$
$$\bar{\nu}_{\mu} + e^{+} + \nu_{e}$$

Expected flavor ratio at the source: $\nu_e : \nu_\mu : \nu_\tau = 1:2:0$

Expected flavor ratio after oscillations: $\nu_e : \nu_\mu : \nu_\tau = 1:1:1$

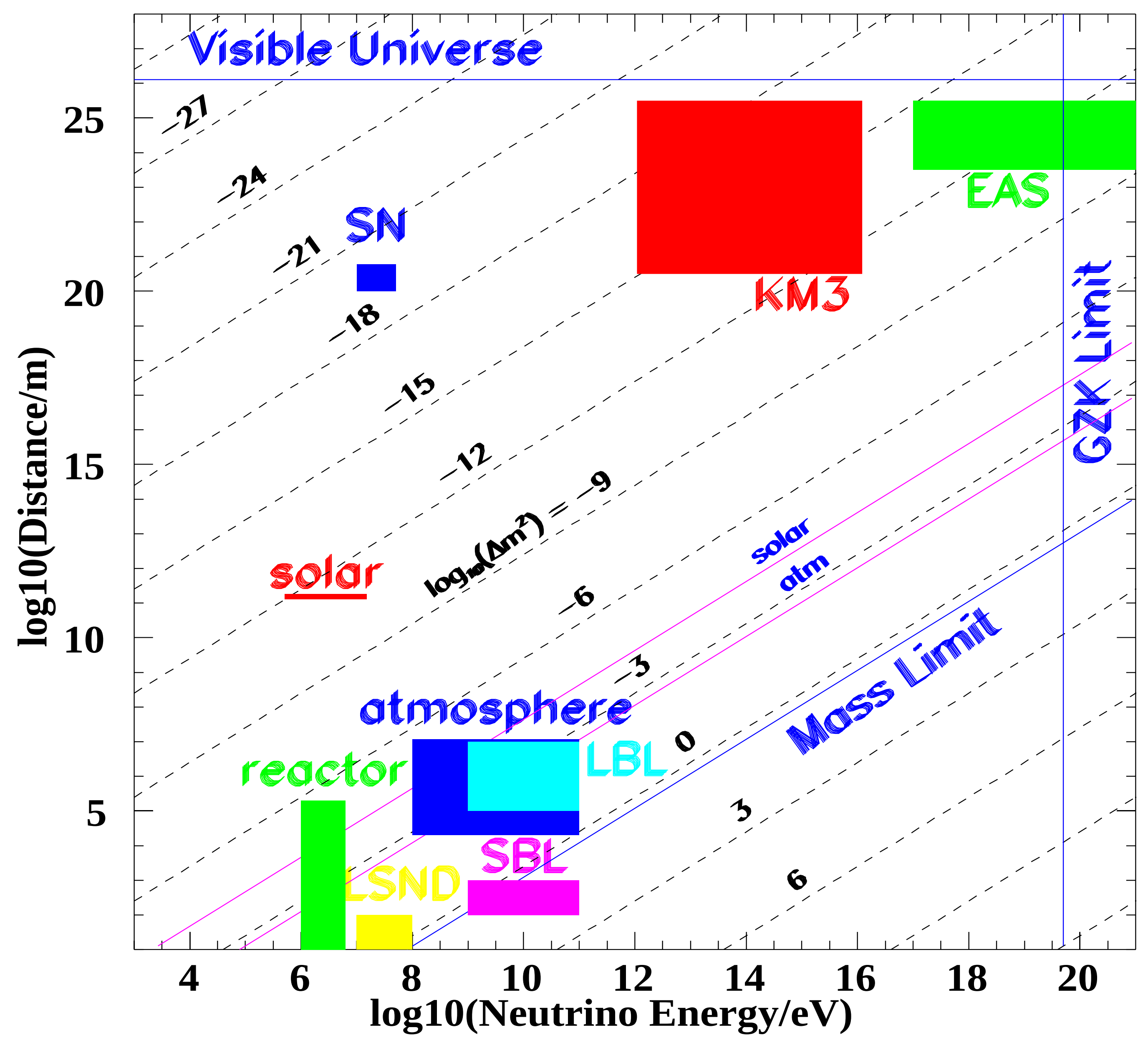
Deviation to these ratios might signal:

❖Different production mechanism at source

❖Exotic neutrino properties

➢Neutrino lifetime, CPT violation, magnetic moments, oscillations (e.g. to steriles) with tiny delta δm^2, varying mass neutrinos….

Extreme Energies and Baselines



Extreme Energies and New Physics

❖Neutrino cross-sections $\sigma_{\nu N}$ unknown for $E_\nu > 5 \times 10^{13}$ eV

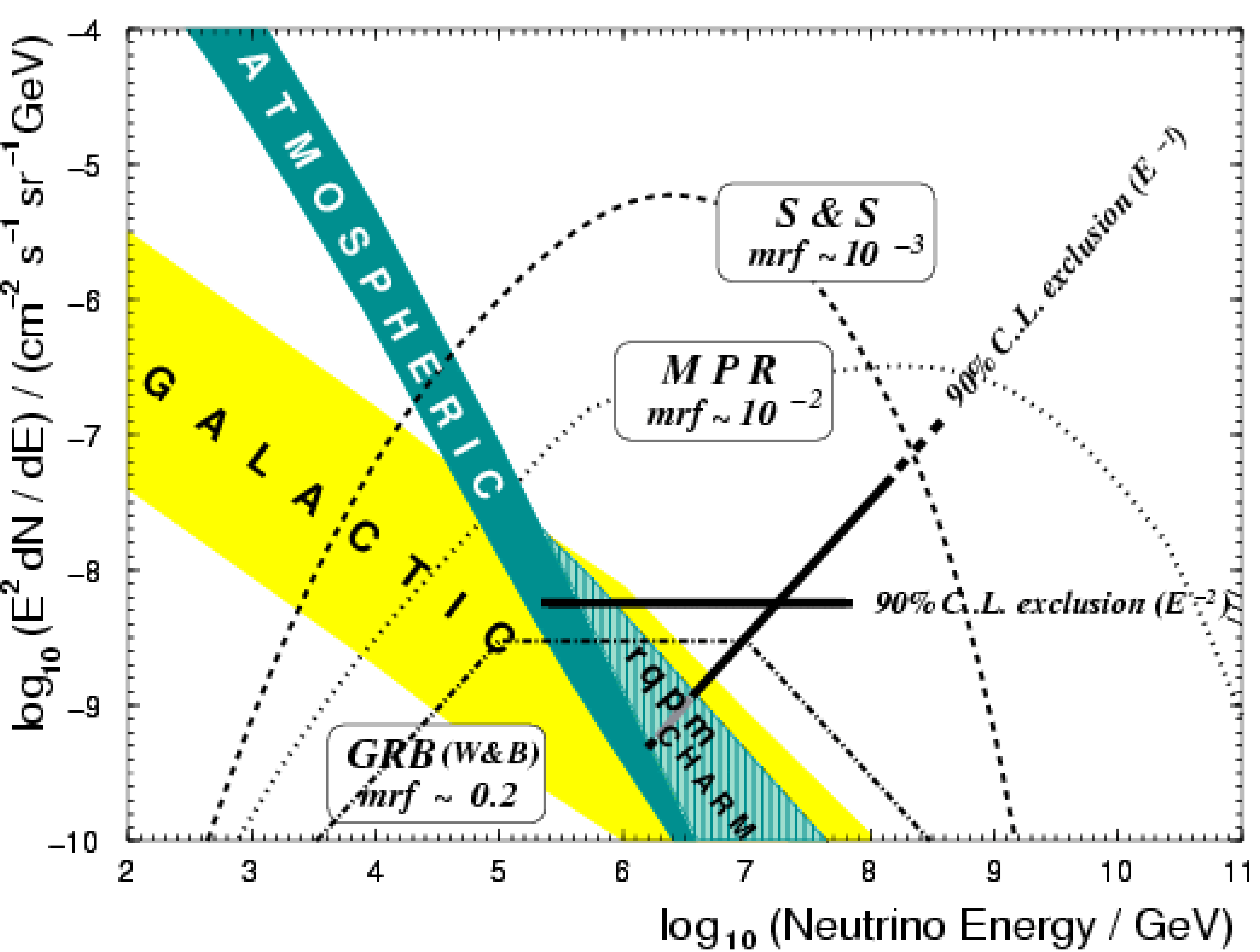
→ New physics could enhance or suppress the cross-sections, compared to Standard Model extrapolations.

Horizontal events → rate ↑ if cross-section ↑
Up-going events → rate ↑ if cross-section ↓
(because the Earth becomes opaque for E > 100 TeV)

→Probe the neutrino cross-section by comparing event rates from different directions through the Earth.

→Possible new physics: e.g. Low scale gravity, extra dimensions

IceCube (Diffuse) Sensitivity

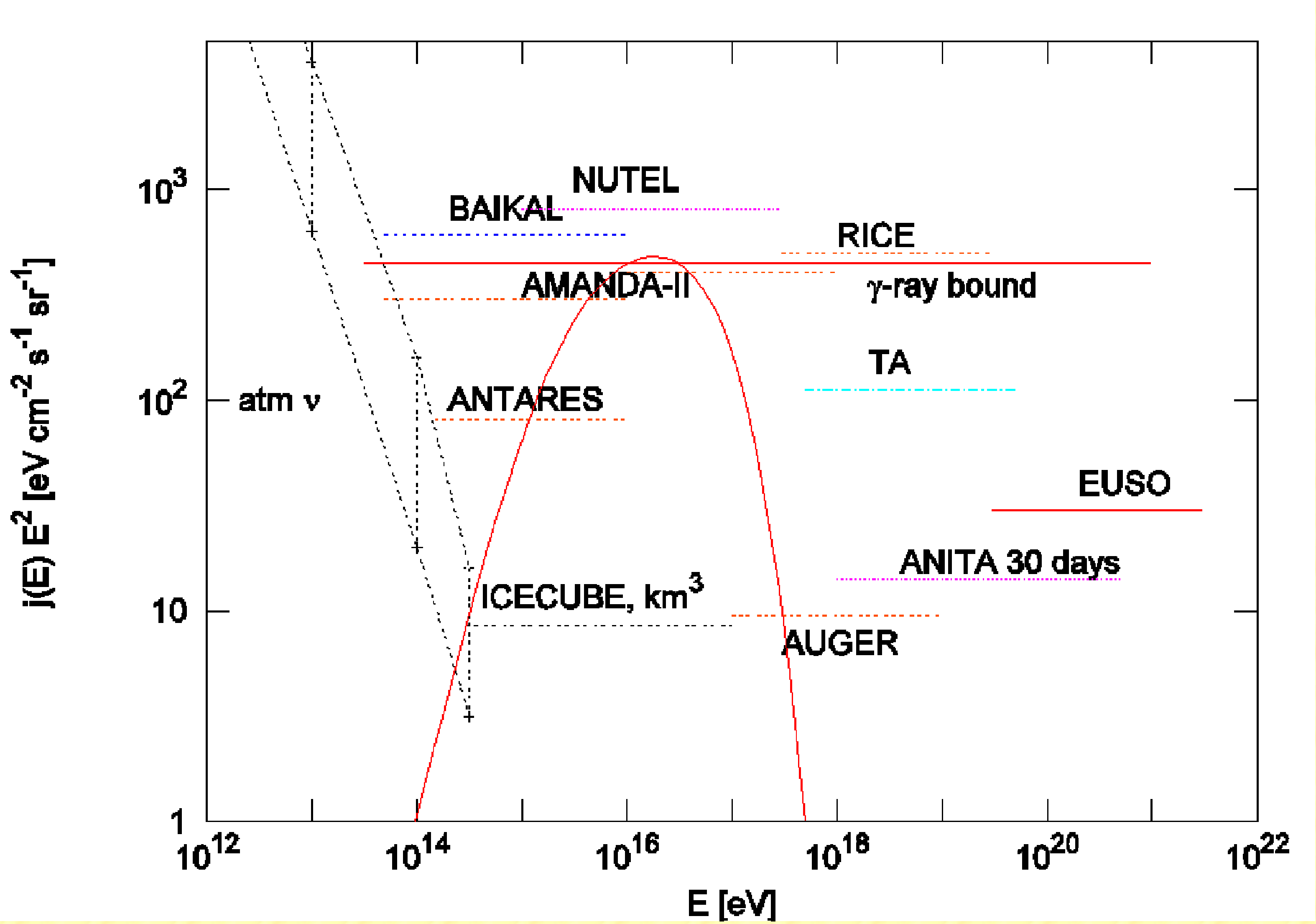


AMANDA-B10

AMANDA-II

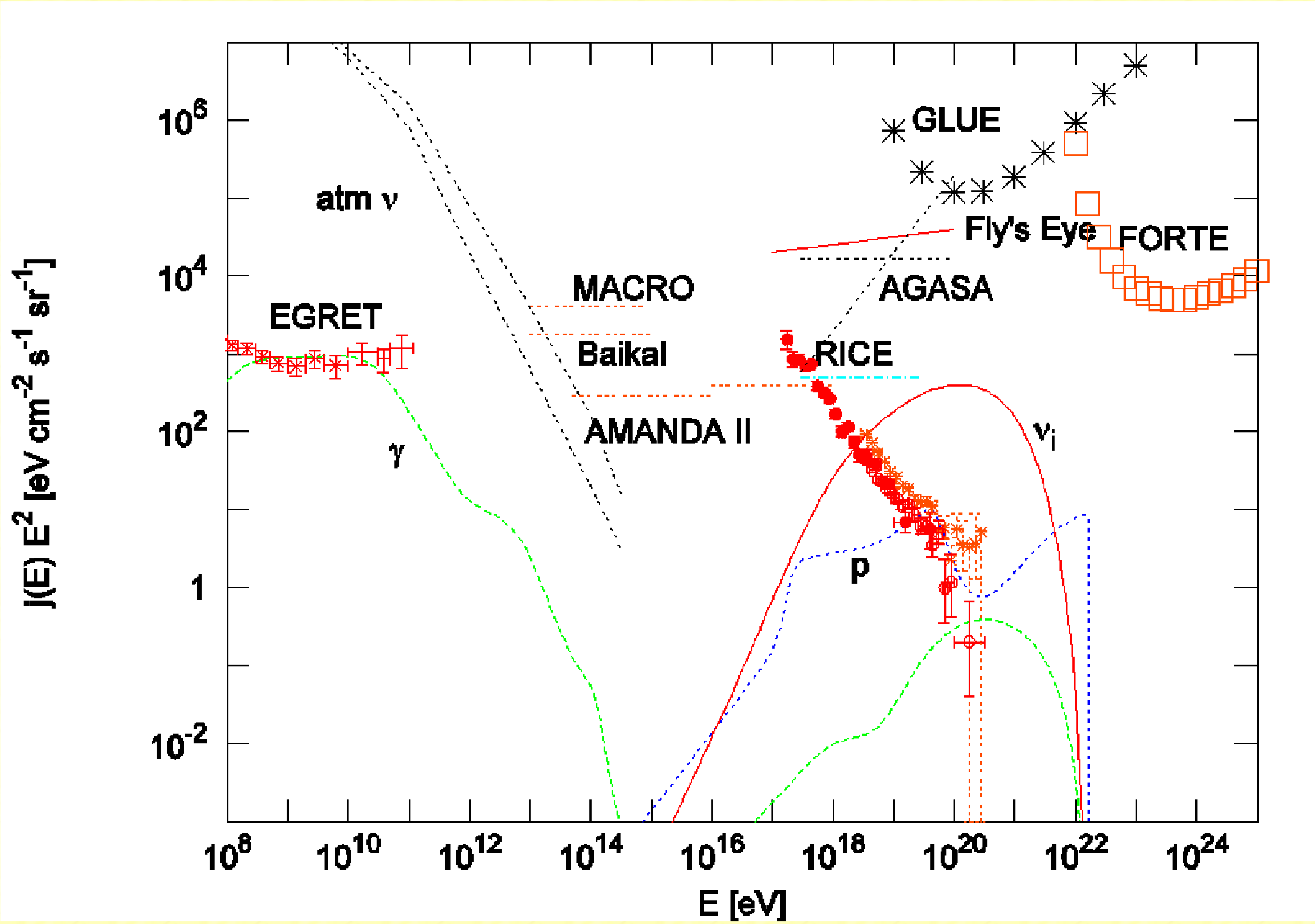
J. Ahrens et al. (IceCube), astro-ph/0305196

AGN Model



Sigl & Semikoz, JCAP 0404, 003 (2004)

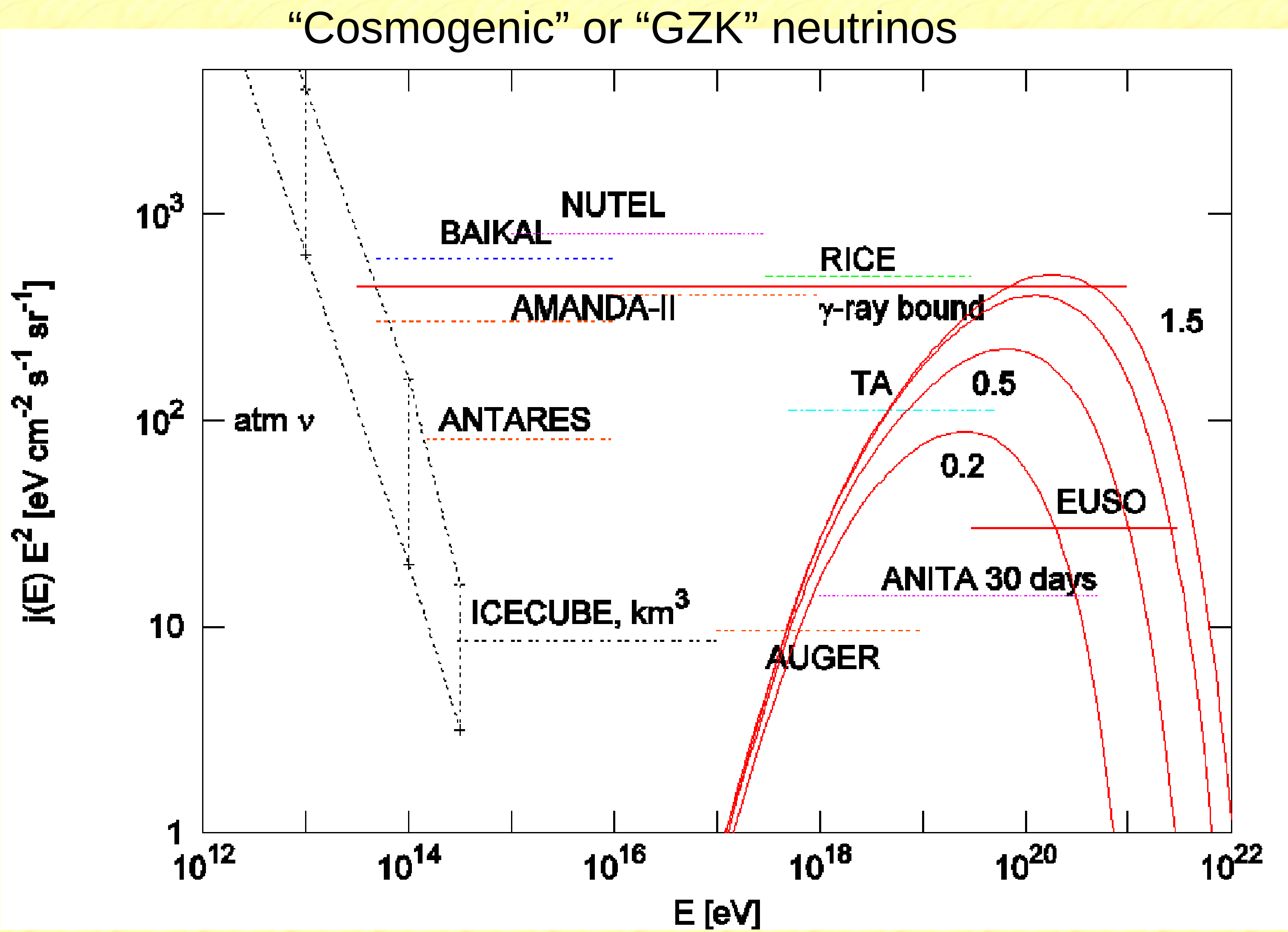
Connecting photon and (cosmogenic) neutrino fluxes:



Red – "cosmogenic" (GZK) nu flux
Green – accompanying photon flux

Sigl & Semikoz, JCAP 0404, 003 (2004)

Predicted sensitivities of future experiments



Sigl & Semikoz, JCAP 0404, 003 (2004)

Neutrinos in Cosmology

Timeline: ↓

Leptogenesis ?	~ 10^{10} GeV
Big Bang Nucleosynthesis	~ 1 MeV
Cosmic Microwave Background	~ 1 eV
Large Scale Structure	< 1 eV
Today	~ 10^{-4} eV

Neutrinos and Big Bang Nucleosynthesis

Neutron to proton ratio set by the processes:

$$n + \nu_e \leftrightarrow p + e^-$$

$$n + e^+ \leftrightarrow p + \overline{\nu}_e$$

If there were extra neutrinos

→The universe would expand faster

→Weak interaction rates would freeze out earlier

→Larger n/p ratio and hence more Helium

BBN limit: $N_\nu^{\mathrm{eff}} < 3.5$

(best fit at $N_\nu^{\mathrm{eff}} \approx 2.5$)

Also: $N(\nu) \approx N(\overline{\nu})$

Sterile Neutrinos and Cosmology

Active - sterile oscillations in the early universe:

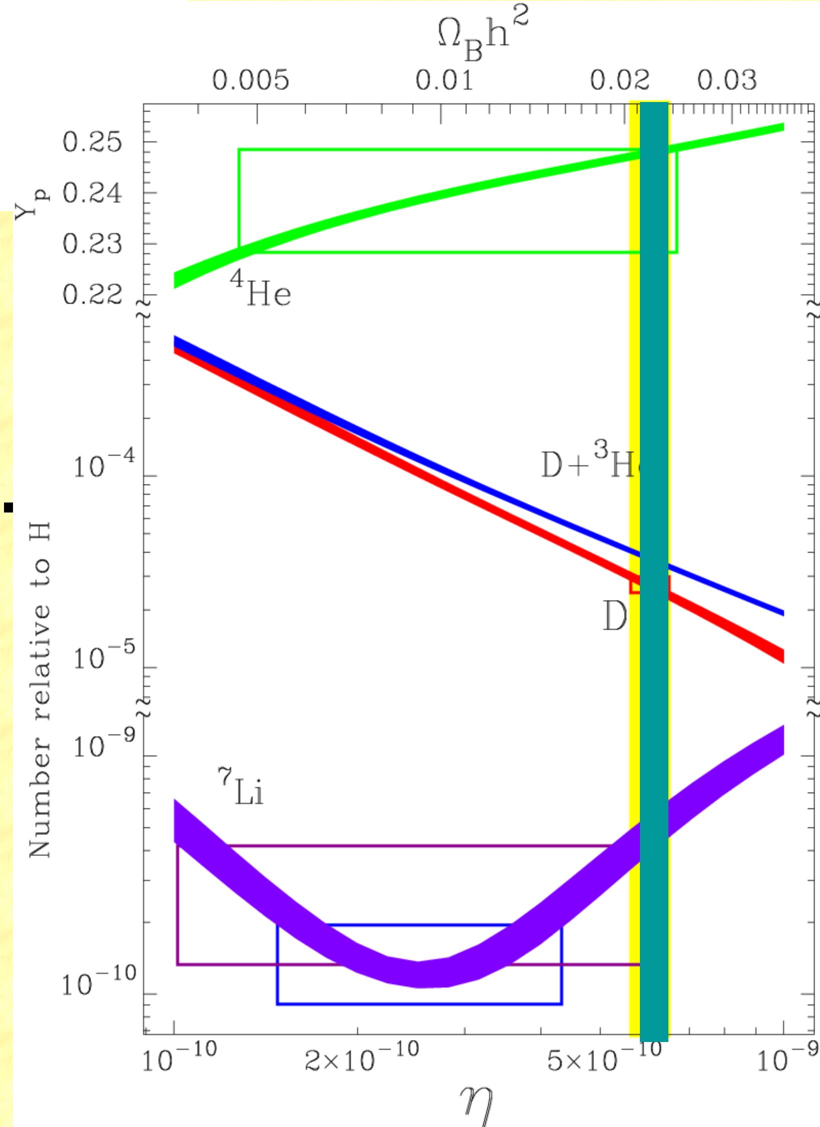
$$\nu_{\text{active}} \leftrightarrow \nu_{\text{sterile}}$$

would bring ν_s into thermal equilibrium.

But Big Bang Nucleosynthesis requires N_ν < 4 at 99% confidence.

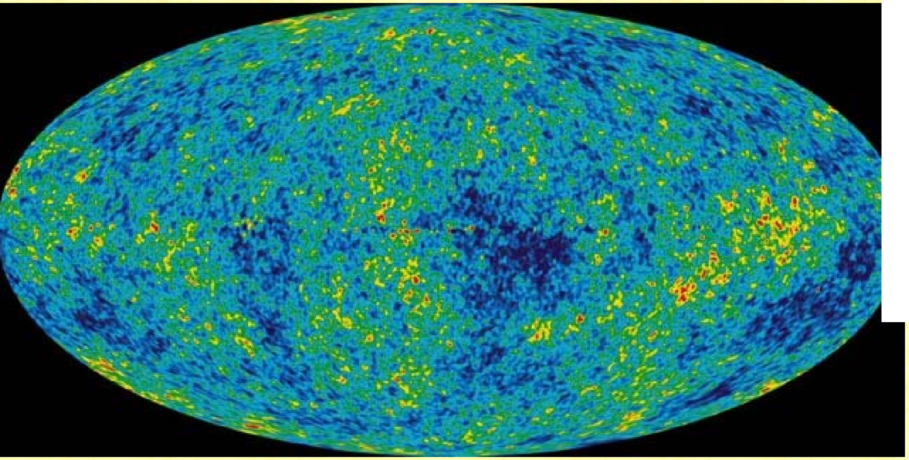
e.g. Abazajian (2003)

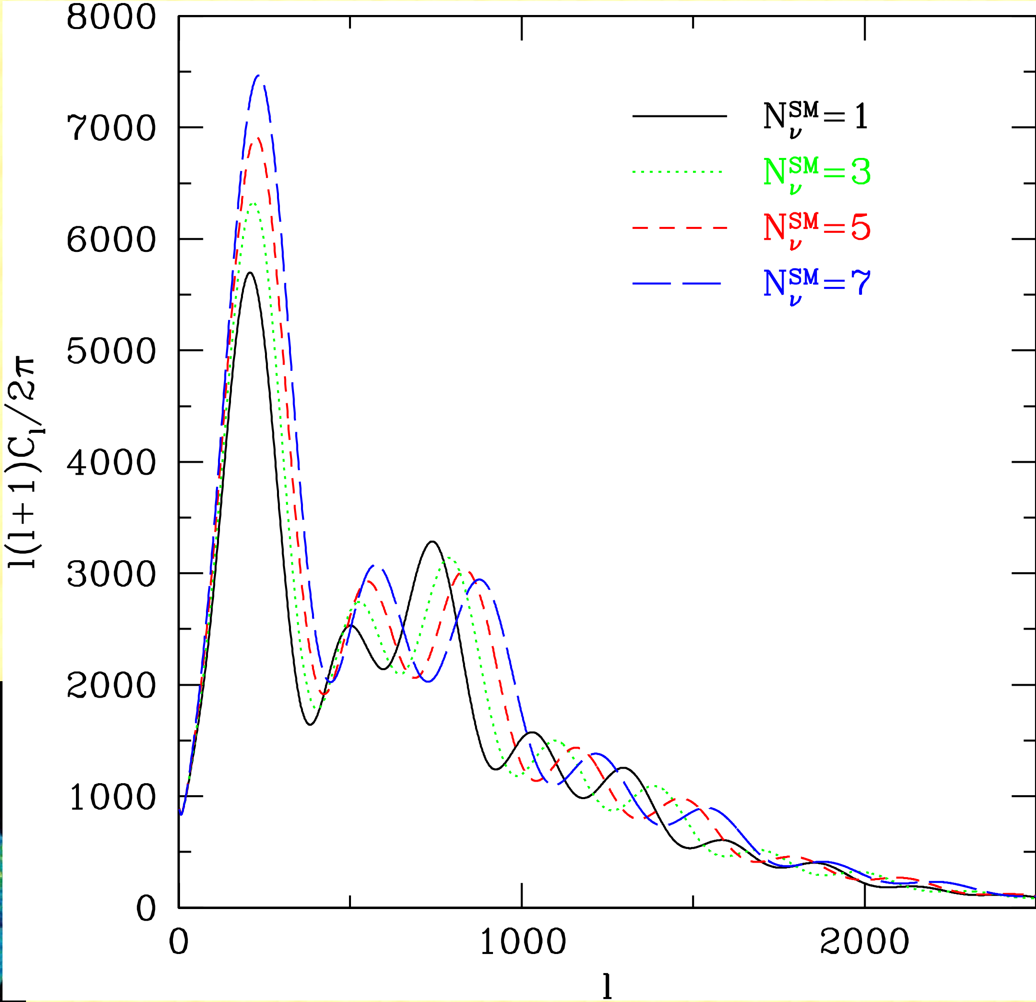
ALL sterile neutrino models which accommodate LSND are problematic.



How Many Neutrinos?

Extra neutrinos
→ Universe was less matter dominated at CMB decoupling
→Different ISW effect
→Different expansion history





Present limit (WMAP(3yr) + SDSS): $N_\nu^{\mathrm{eff}}\,(\mathrm{CMB}) < 6$

Future precision (Planck): $\Delta N_\nu^{\mathrm{eff}}\,(\mathrm{CMB}) < 0.01$

Lopez et al.

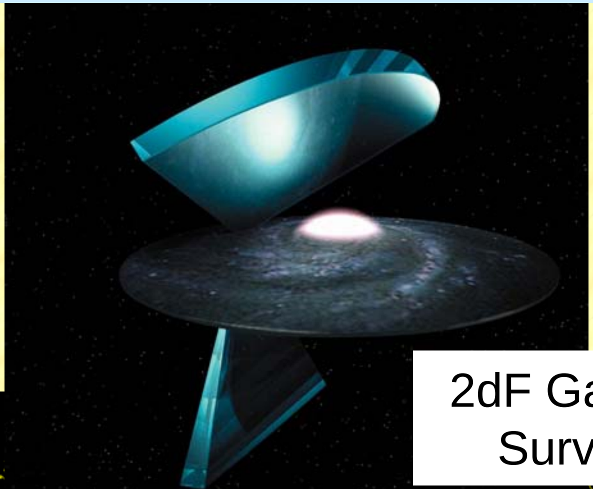
"Weighing" neutrinos with cosmology

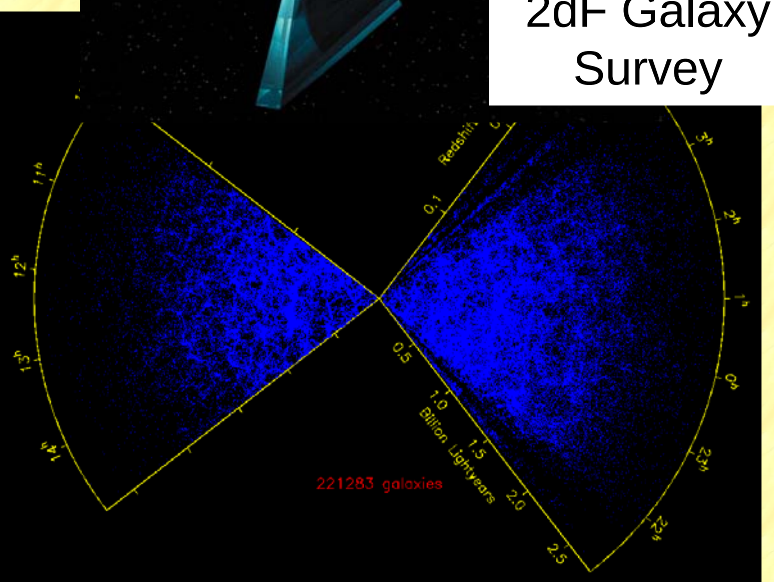
$$\sum m_\nu < 2\ \text{eV}$$

CMB alone

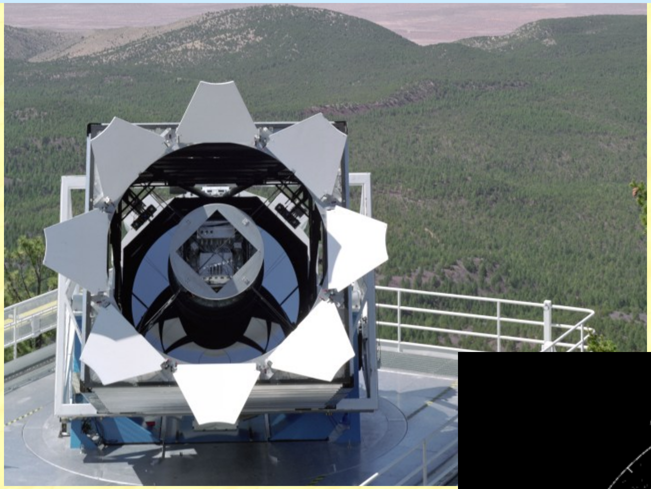
$$\sum m_\nu < 0.2\ \text{eV}$$

Lyman-alpha + CMB + Galaxy surveys

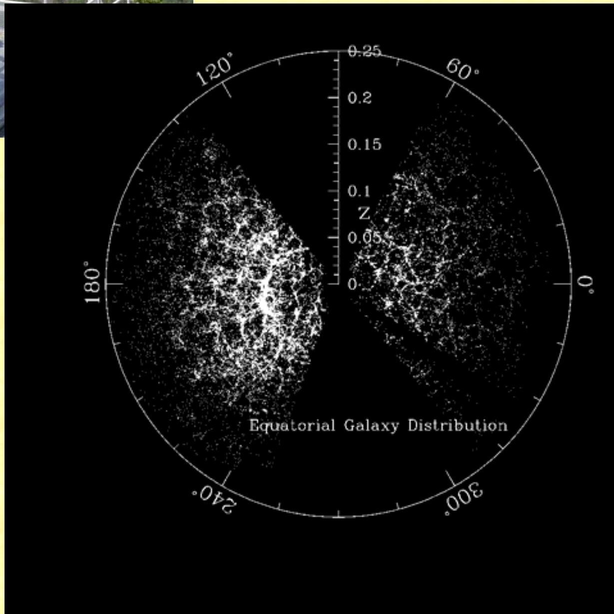




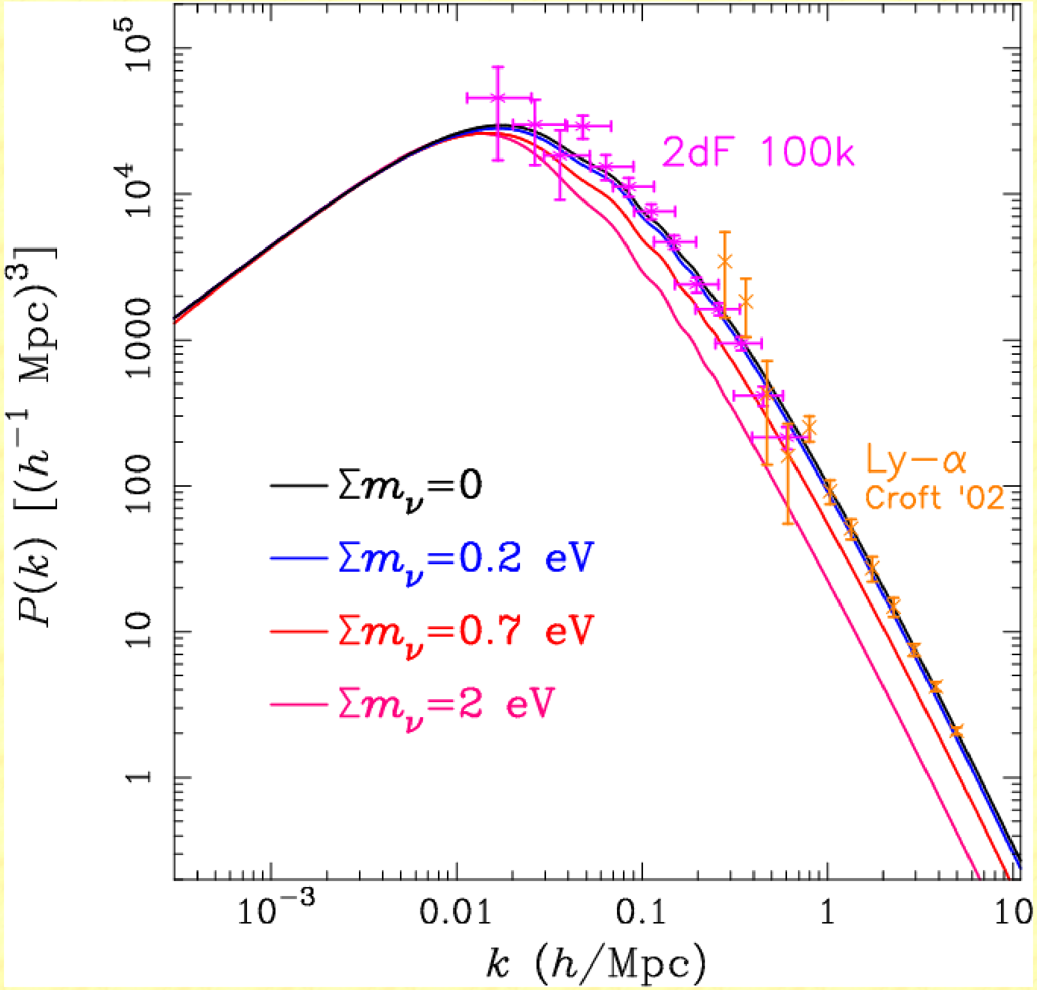
2dF Galaxy Survey



Sloan Digital Sky Survey



Neutrino Dark Matter



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

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

(from Kev Abazajian)

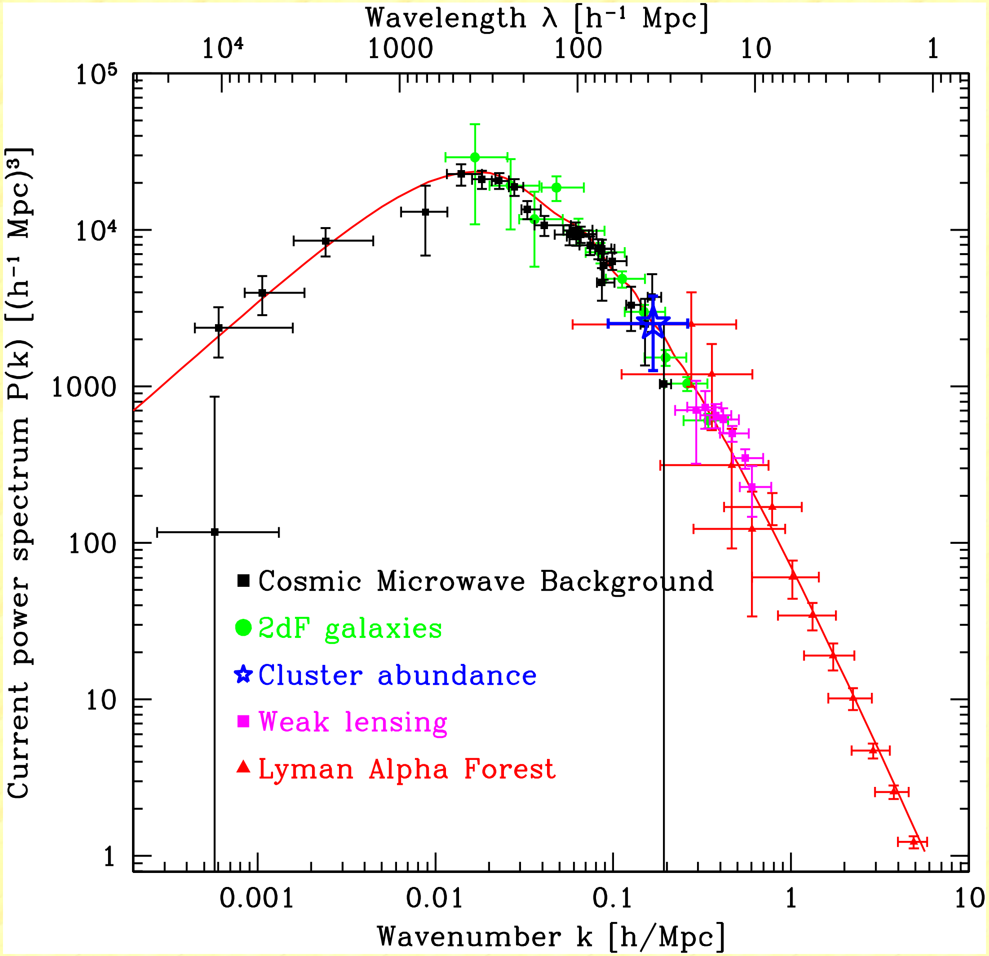
Neutrino Mass & Large Scale Structure

Neutrinos are only a small component of the dark matter ..... but the effects of the neutrino dark matter can be significant.

Neutrinos “free-stream” from density perturbations when relativistic

→Suppression of the growth of structure.

→Size of suppression proportional to m_ν



Tegmark and Zaldarriaga

Neutrino Mass Limits from Cosmology

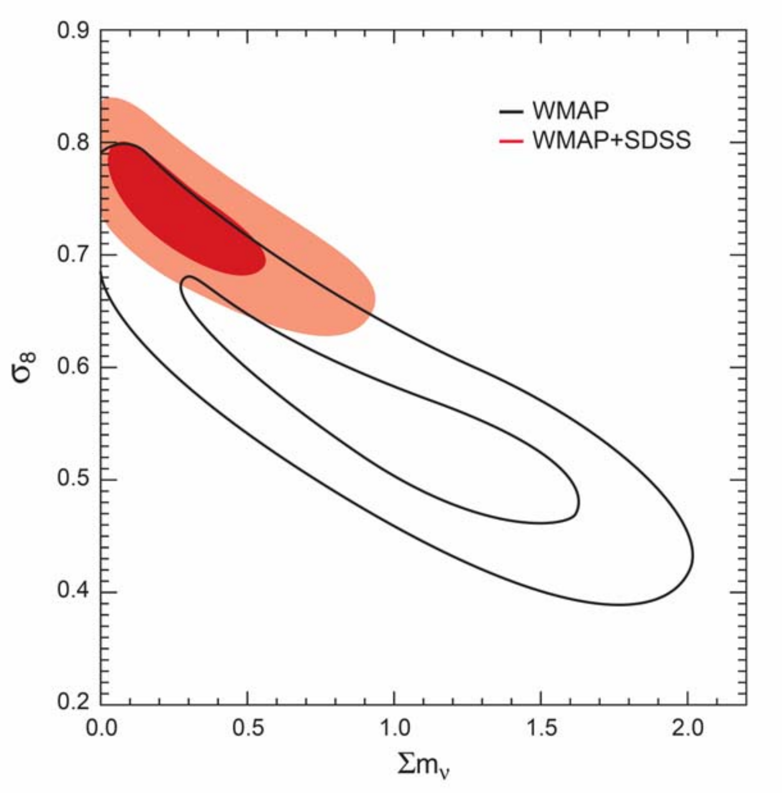
Data Set	$\sum m_\nu$ (95% limit for $N_\nu = 3.02$)
WMAP	2.0 eV(95% CL)
WMAP + SDSS	0.91 eV(95% CL)
WMAP + 2dFGRS	0.87 eV(95% CL)
CMB + LSS +SN	0.68 eV(95% CL)

Spergel et al
(WMAP collaboration)

Lyman-alpha + SDSS
+ 3yr WMAP + SN

$$\sum m_\nu < 0.17 \text{ eV}$$

Seljak, Slosar and McDonald
(astro-ph/0604335)



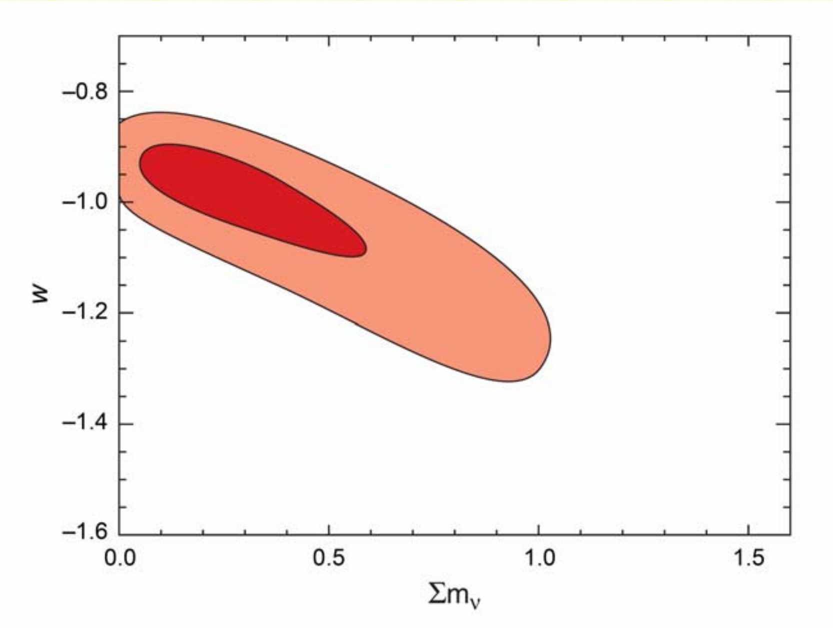
Degeneracy with sigma_8

The value of sigma_8 found from Ly-alpha is higher than that for WMAP

→Lyman-alpha biased toward lower neutrino mass.

Uncertainties in cosmological m_ν measurements:

❖Mild degeneracies with other cosmological parameters e.g. Dark energy equation of state



Spergel et al
(WMAP collaboration)

❖Non-standard (exotic) particle physics

-- Annihilating neutrinos (no neutrino dark-matter) (Beacom, Bell, Dodelson

-- Mass-varying neutrinos (Fardon, Nelson, Weiner, Kaplan)

Future Technique: Weak Lensing

Galaxy surveys (like SDSS or 2dF) are subject to bias
→how well does the distribution of luminous matter trace the distribution on dark matter?

Weak gravitational lensing of distant galaxies by intervening matter directly probes matter distribution in Universe.

Can do tomography by breaking data into redshift bins → evolution of gravitational potential as function of time.

Projected sensitivity: $\sum m_\nu < 0.05 \text{ eV}$

Summary of methods to measure neutrino masses and *projected* sensitivities:

Neutrino oscillations:
observed 10^{-3} and 10^{-5} eV^2

$$m_1^2 - m_2^2$$

Single beta decay:
0.2 eV

$$m_{\nu_e}^{2\,(eff)} = \sum_i \left|U_{ei}\right|^2 m_i^2$$

Double beta decay:
0.05 eV

$$\langle m_\nu \rangle = \left| \sum_{i=1}^{3} U_{ei}^2 m_i \, \varepsilon_i \right|$$

Cosmology:
0.05 eV

$$m_{\nu_e}^{tot} = \sum_i m_i$$