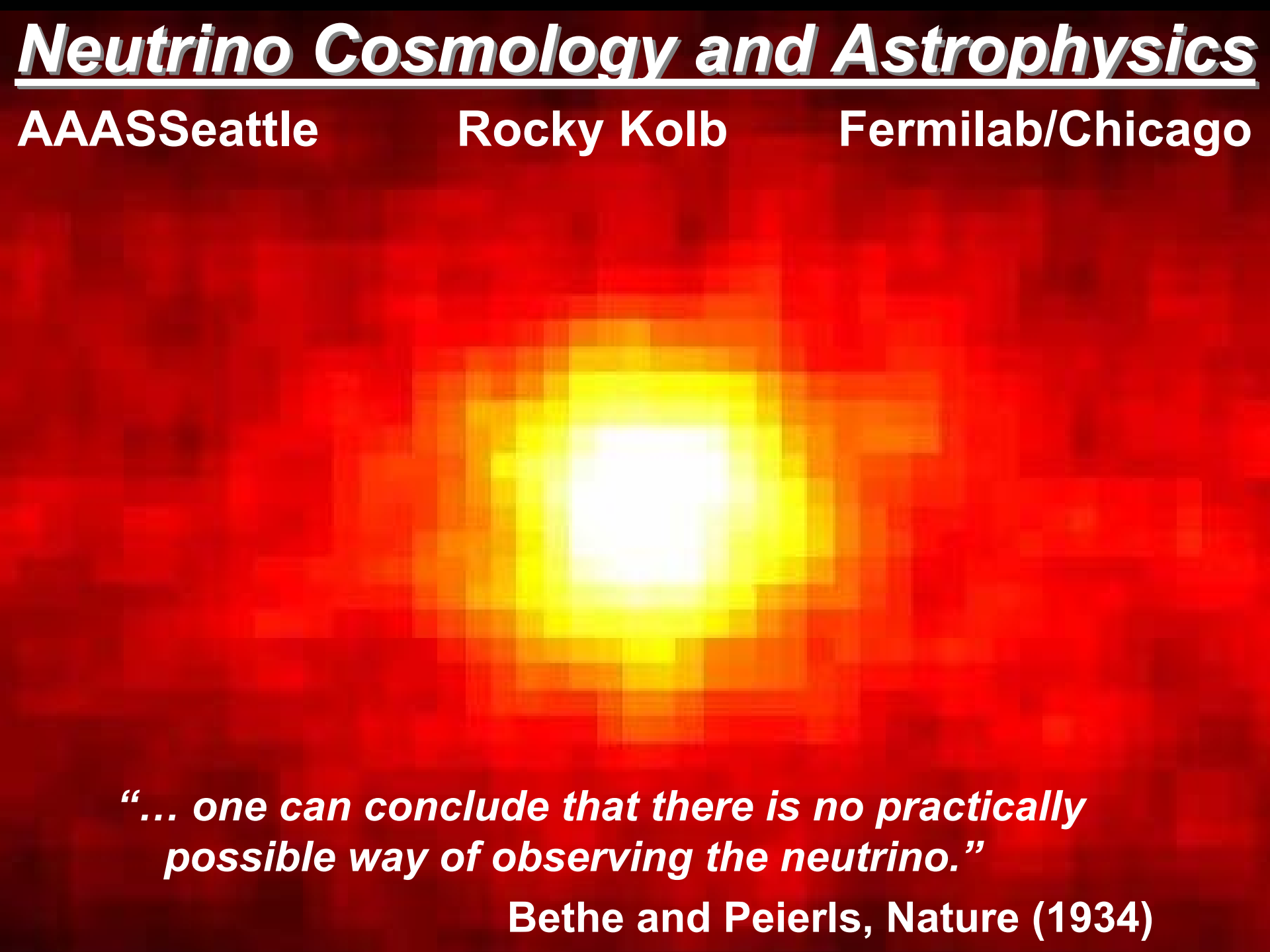
Neutrino Cosmology and Astrophysics

AAASSeattle Rocky Kolb Fermilab/Chicago

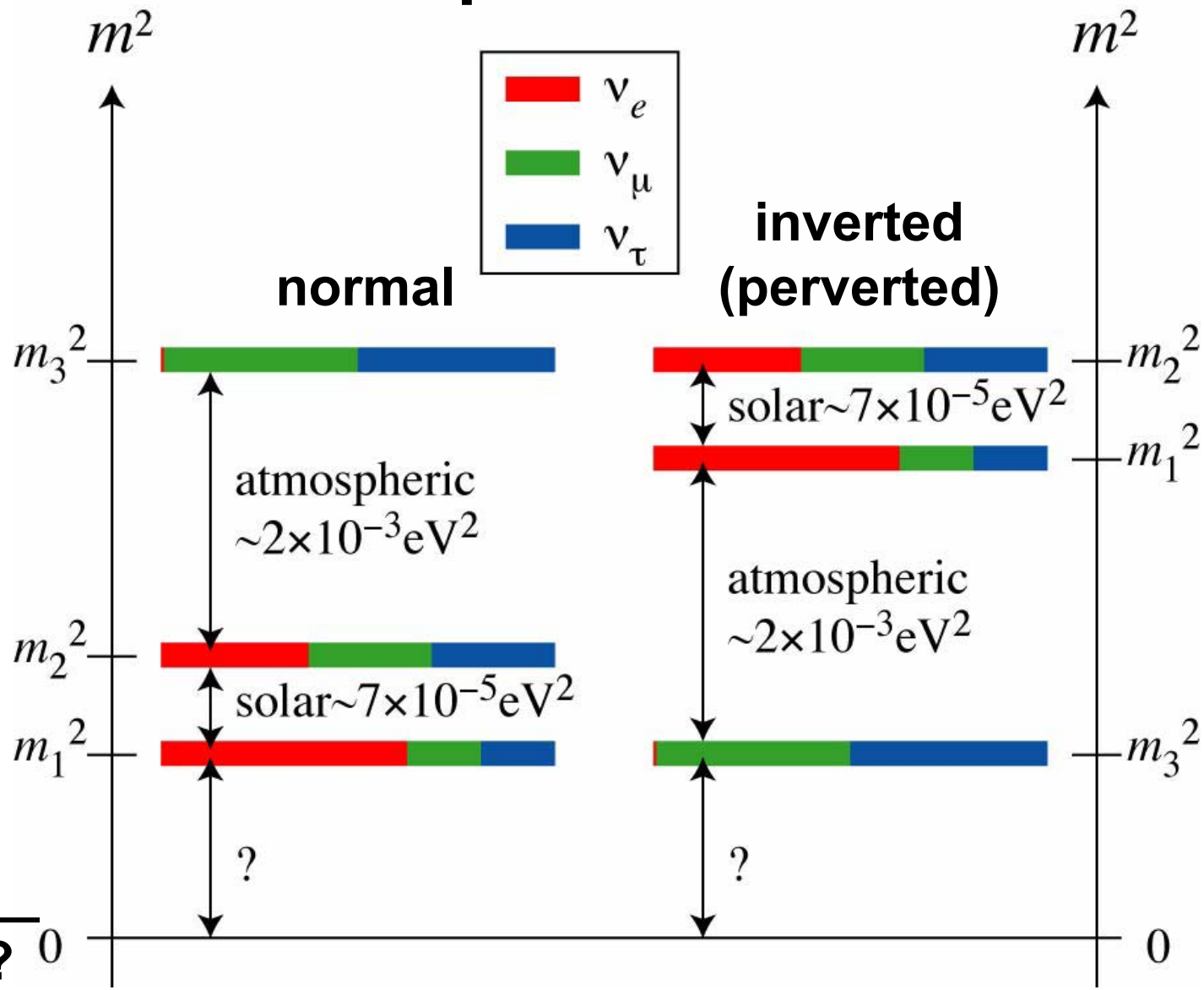


"… one can conclude that there is no practically possible way of observing the neutrino."

Bethe and Peierls, Nature (1934)

Neutrino mass differences*

Solar – Atmospheric – K2K/Kamland



*LSND?

Neutrinos all mixed up

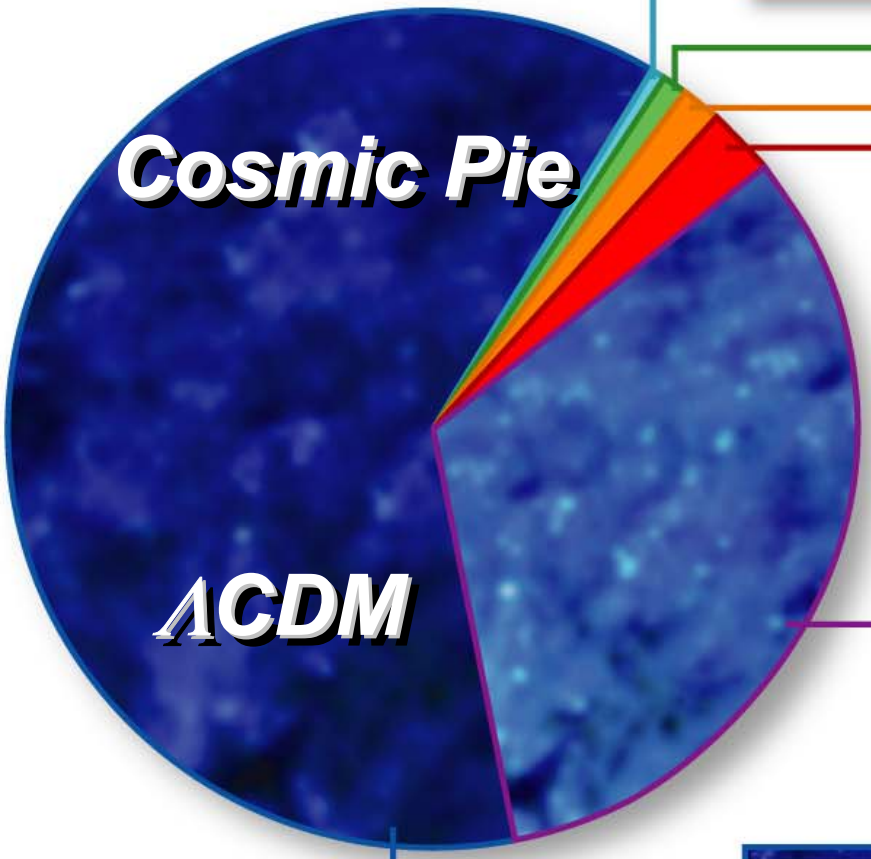
$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} \\ U_{\alpha j} \\ \\ \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

$$[U] \simeq \begin{bmatrix} \cos\theta_{solar} & \sin\theta_{solar} & \sin\theta_{13} \\ -\sin\theta_{solar}/\sqrt{2} & \cos\theta_{solar}/\sqrt{2} & 1/\sqrt{2} \\ \sin\theta_{solar}/\sqrt{2} & -\cos\theta_{solar}/\sqrt{2} & 1/\sqrt{2} \end{bmatrix}$$

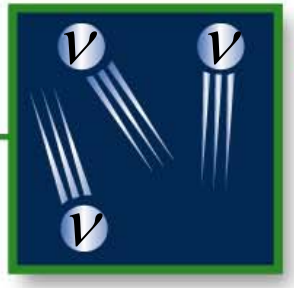
$$\theta_{atm} \simeq 45^\circ, \qquad \theta_{solar} \simeq 35^\circ, \qquad \theta_{13} \leq 10^\circ$$

$$\Omega_i \equiv \rho_i / \rho_{\text{CRITICAL}}$$

$$\Omega_{\text{TOTAL}} = 1$$

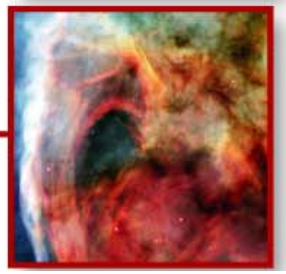


Heavy Elements:
Ω=0.0003

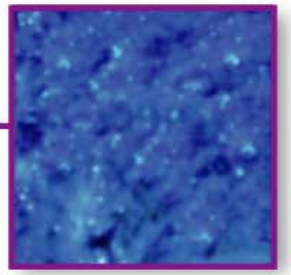


Massive Neutrino:
Ω=0.0047

Stars:
Ω=0.005



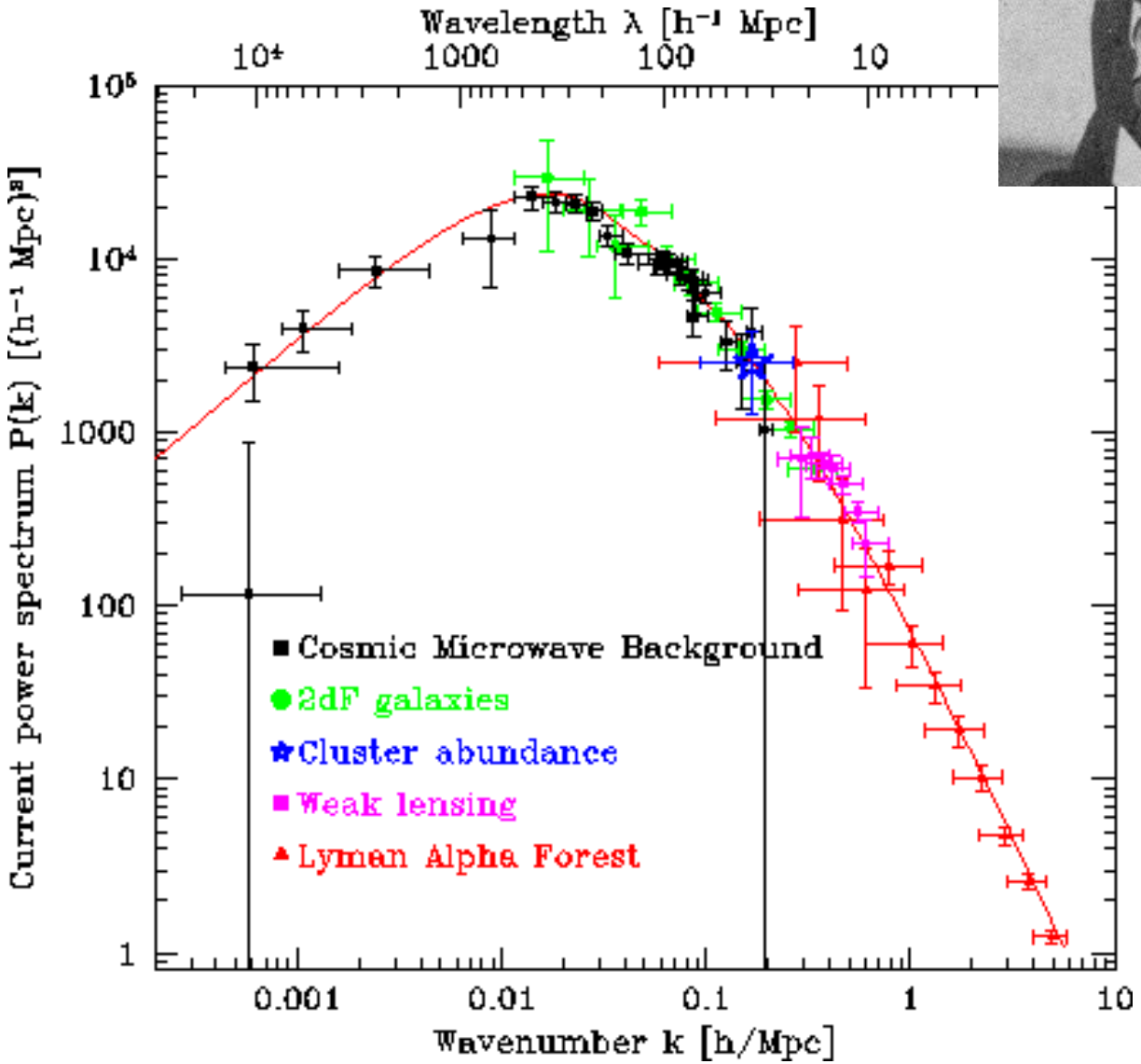
Free H & He:
Ω=0.04



Dark Matter:
Ω=0.25
Massive neutrinos?

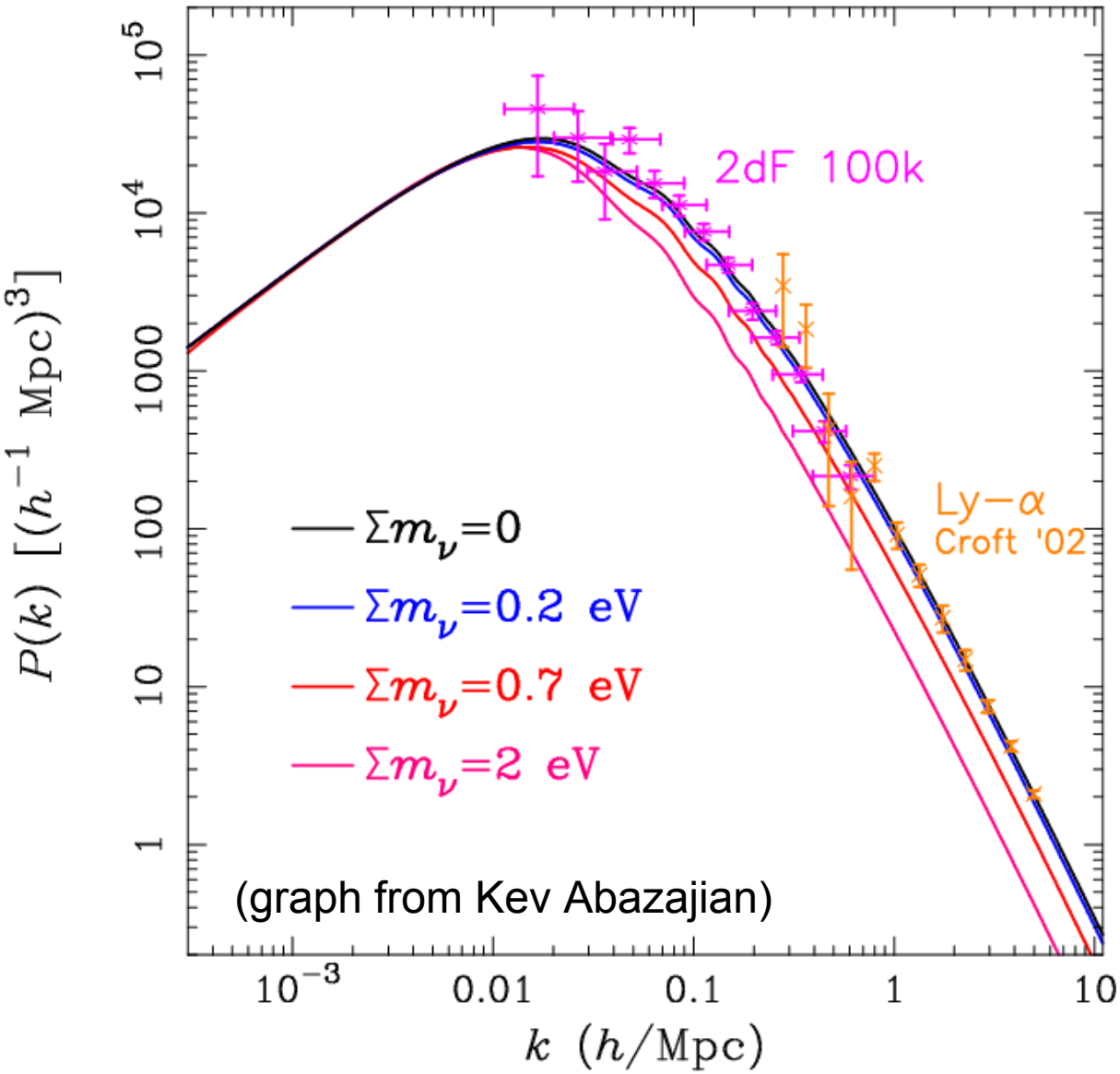
Dark Energy (Λ):
Ω=0.70

Harrison-Zel'dovich Spectrum - ΛCDM



Tegmark

Hot dark matter



(graph from Kev Abazajian)

Present limit:

few eV

(2DF, SDSS, Ly-α …)

Future discovery range:

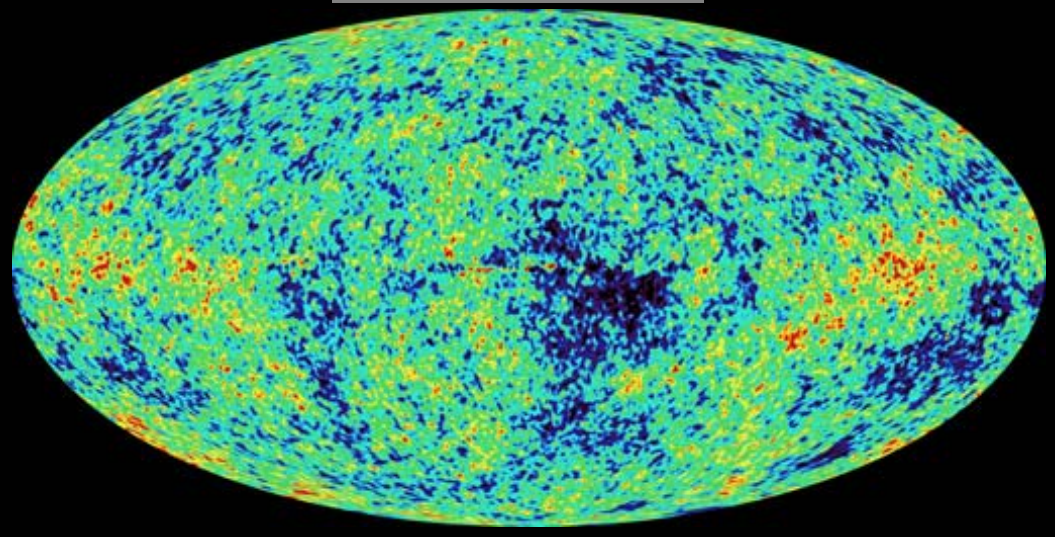
better than 0.1 eV

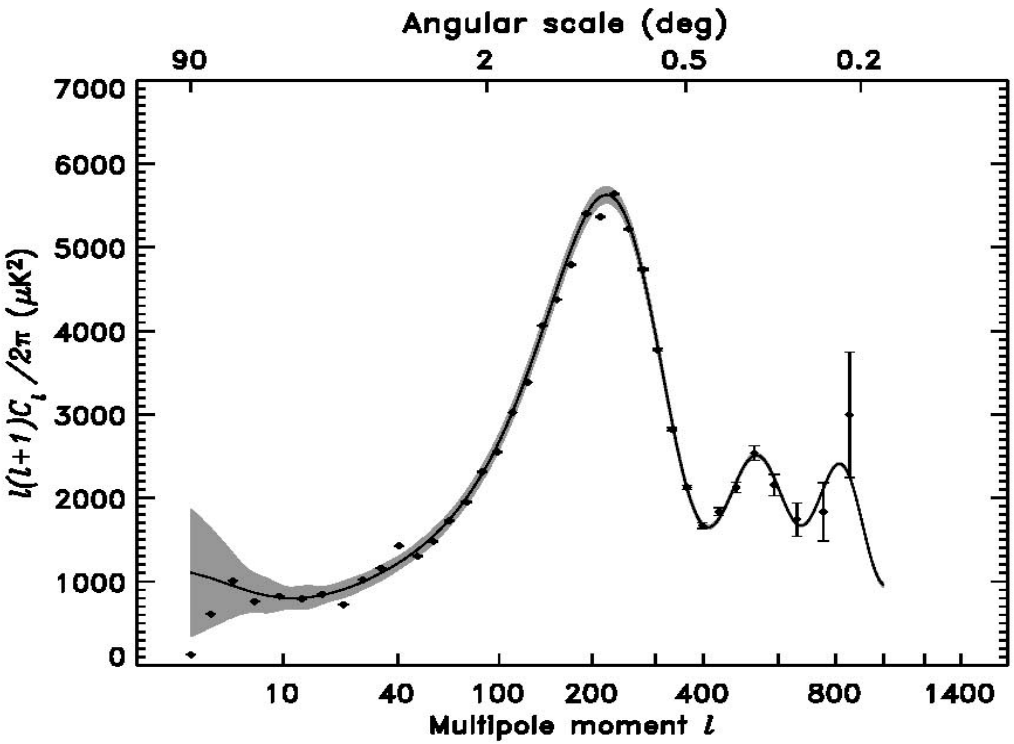
(lensing, SDSS, Ly-α WMAP, Planck, …)

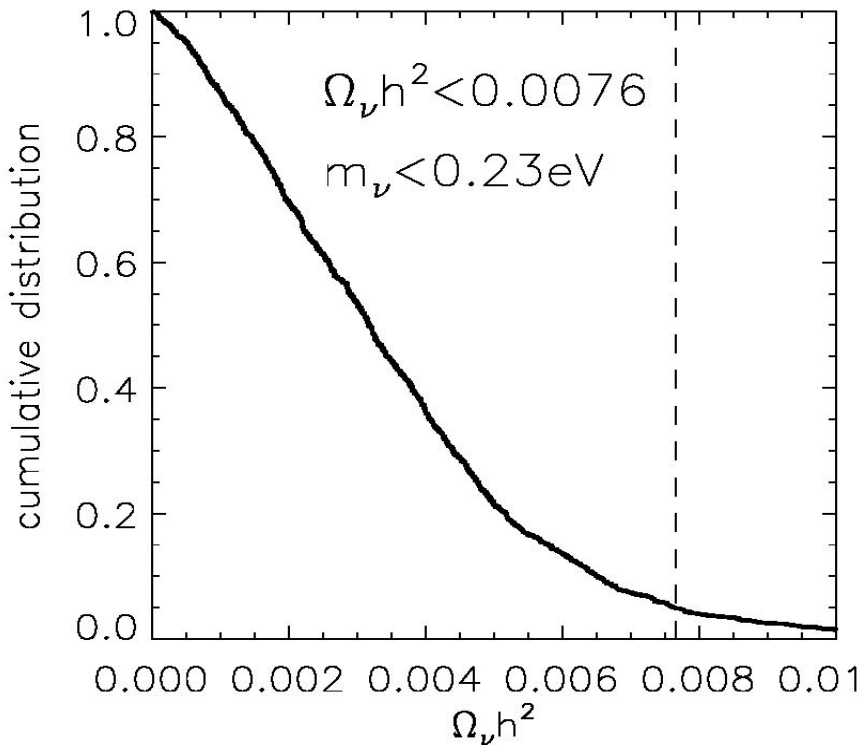
Abazajian & Dodelson, PRL 91, 041301 (2003)

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

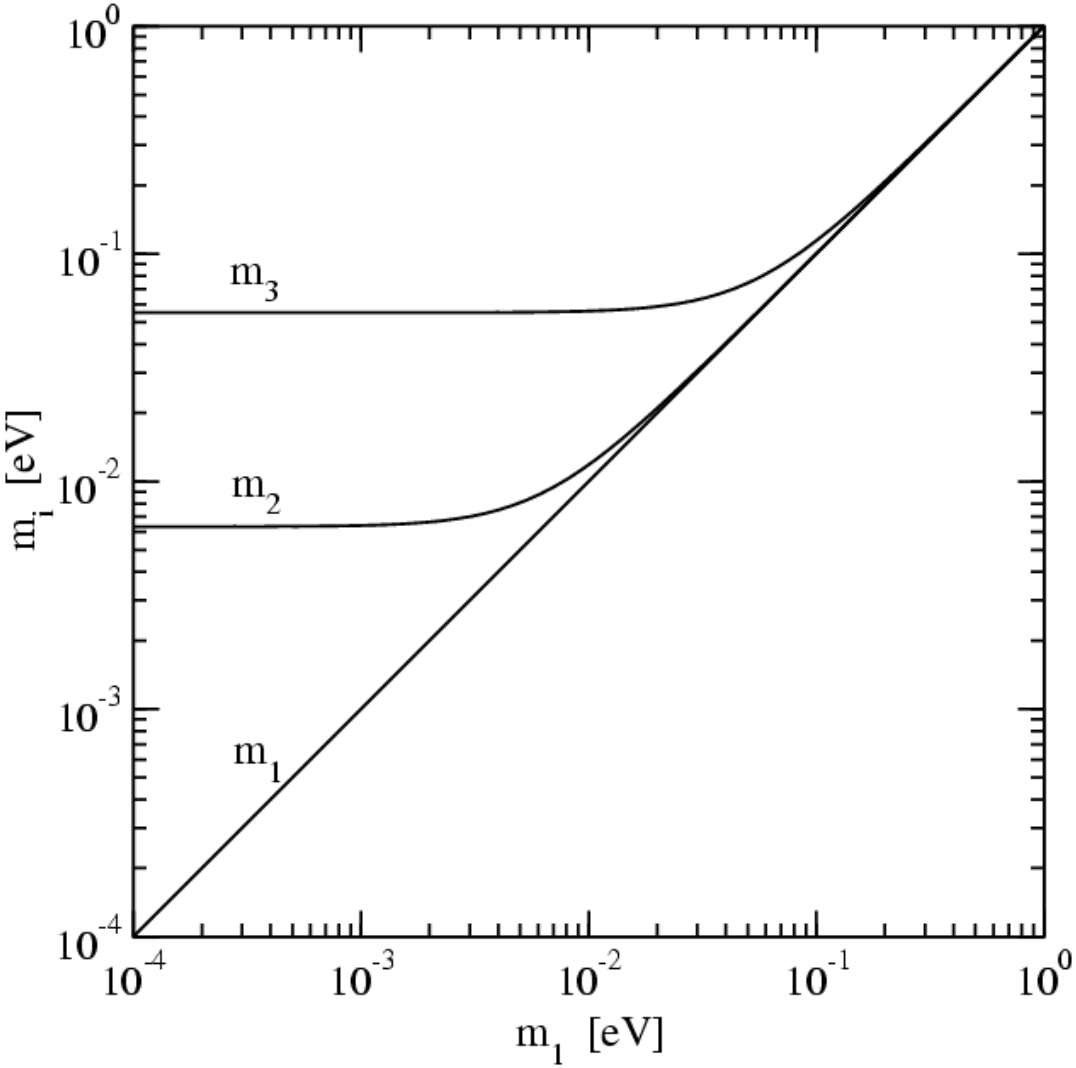
WMAP

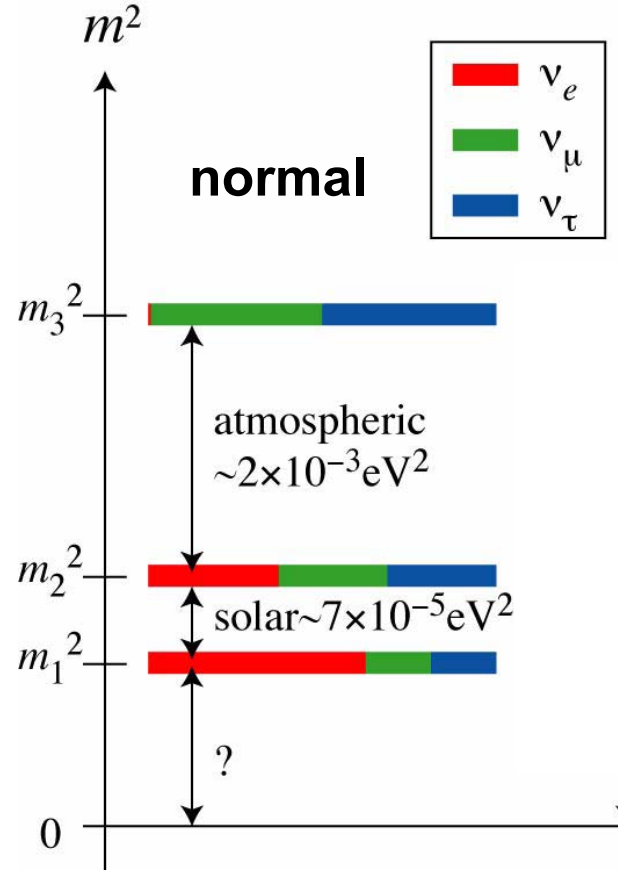



Angular scale (deg)
90
2
0.5
0.2
7000
6000
5000
4000
3000
2000
1000
0
$l(l+1)C_l/2\pi$ (μK^2)
10
40
100
200
400
800
1400
Multipole moment l


$\Omega_\nu h^2 < 0.0076$
$m_\nu < 0.23$eV
cumulative distribution
1.0
0.8
0.6
0.4
0.2
0.0
0.000
0.002
0.004
0.006
0.008
0.01
$\Omega_\nu h^2$

Neutrino masses





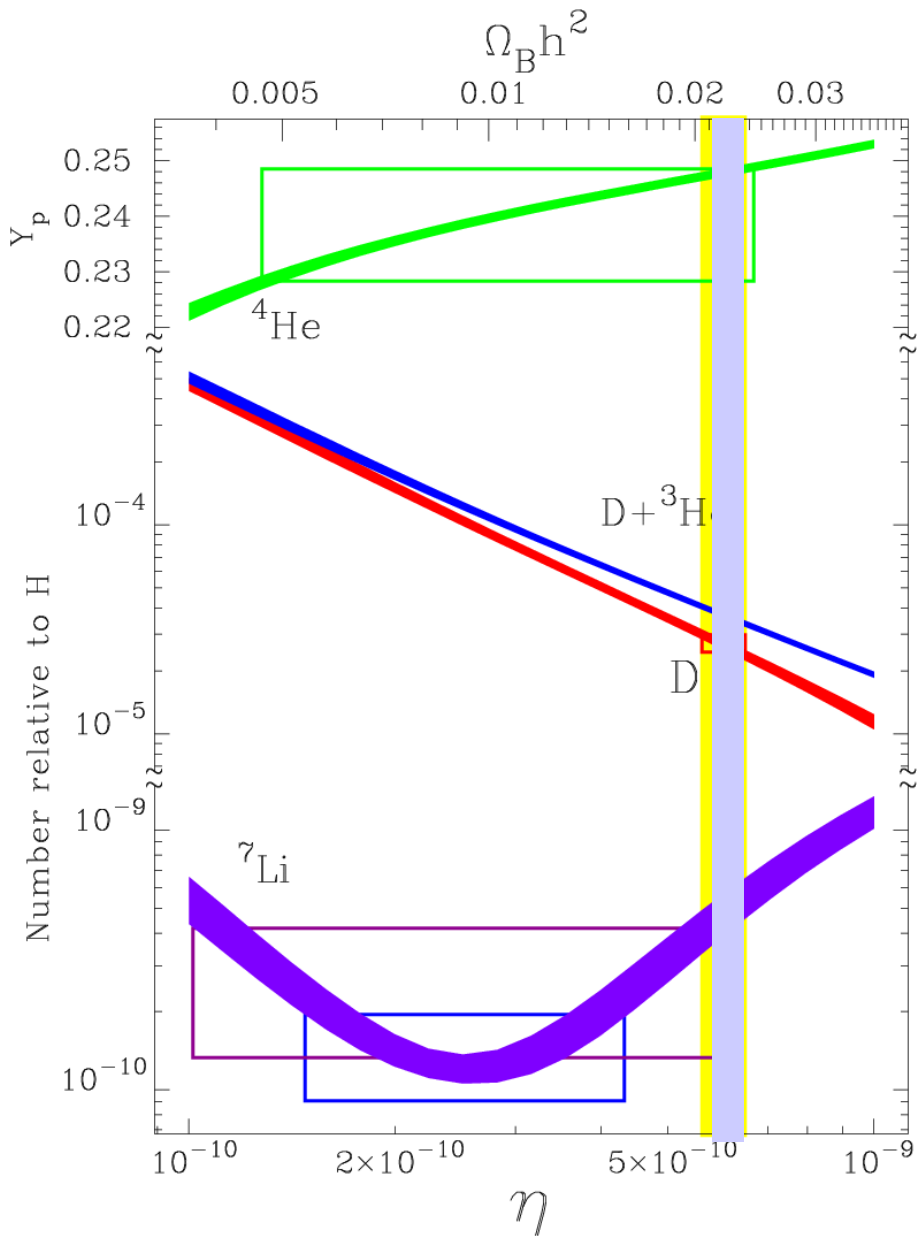
$$m_1 = m_1$$

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

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

Beacom and Bell, PRD 65, 113009 (2002)

Number of neutrino species



$$N_\nu < 4\,(99\%\mathrm{CL})$$

Abazajian, Astropart. 19, 303 (2003)

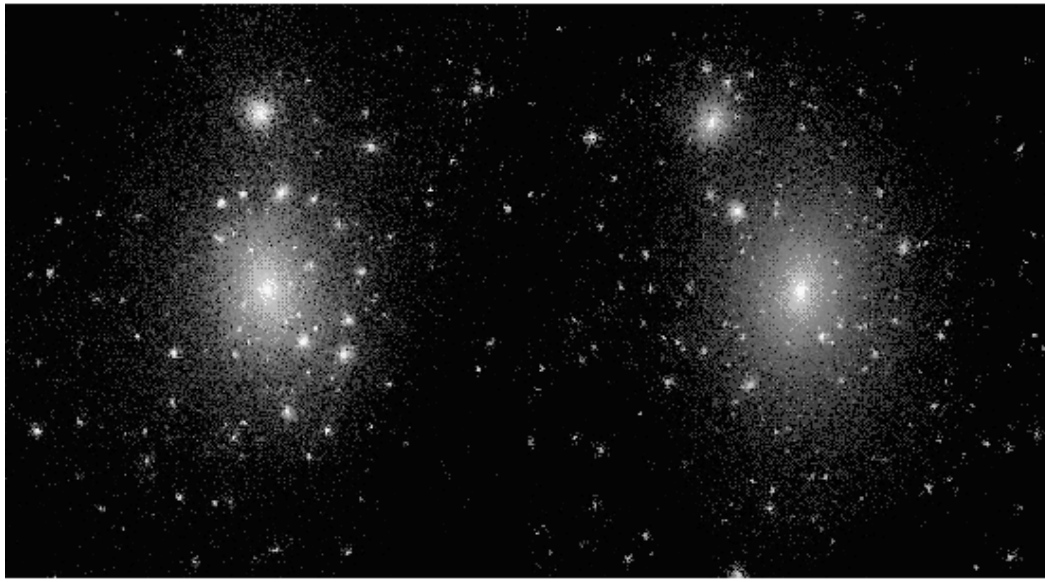
$$1.5 \le N_\nu \le 7.2 \quad (\mathrm{WMAP})$$

Crotty, Lesgourgues, 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, Bell,
PRD 66, 013008 (2002)

Sterile neutrinos

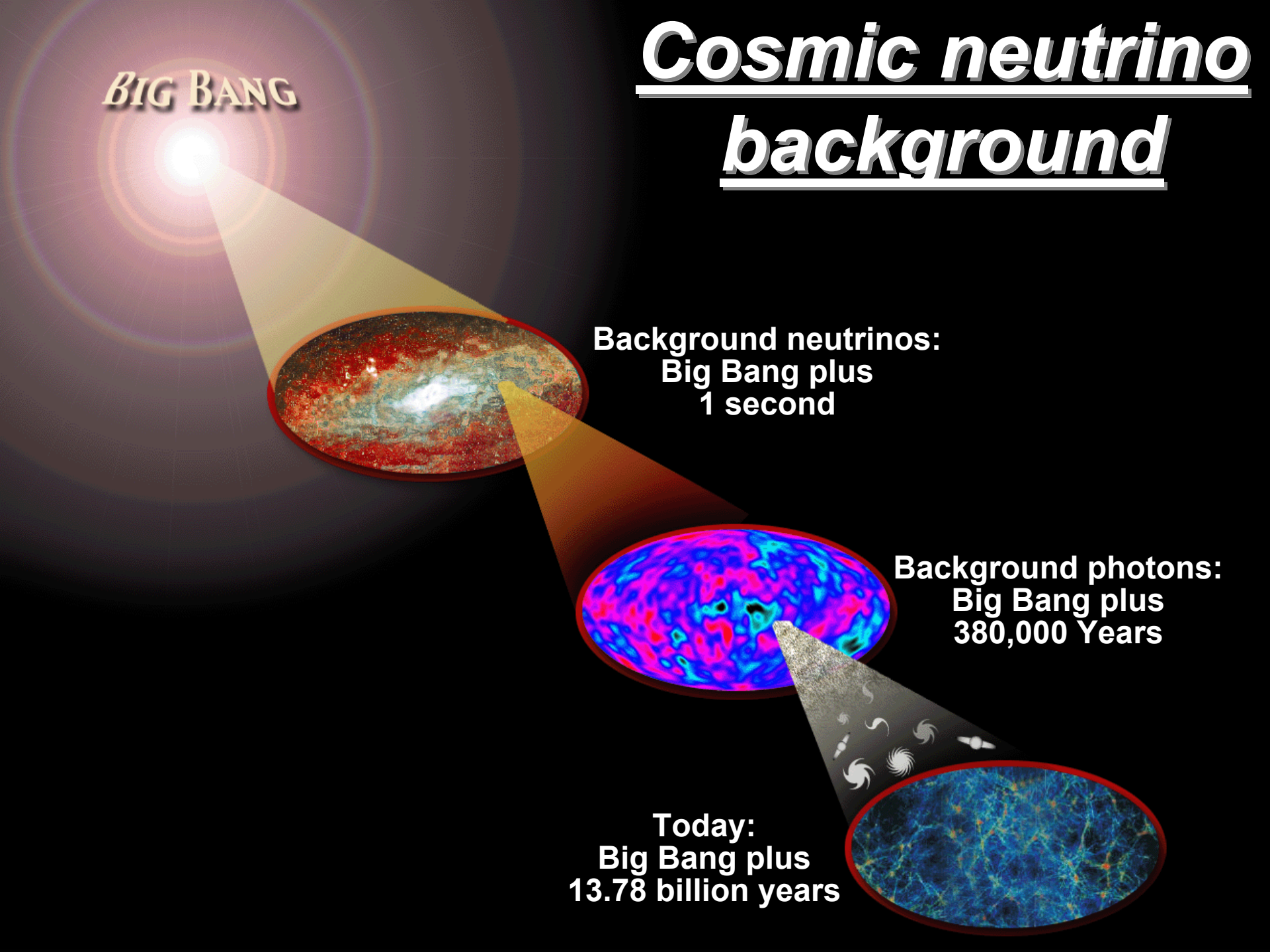


- weaker interactions
- decouple earlier
- diluted more
- can have larger mass
- smaller velocity
- “warm”
- satellite & cusp problem?

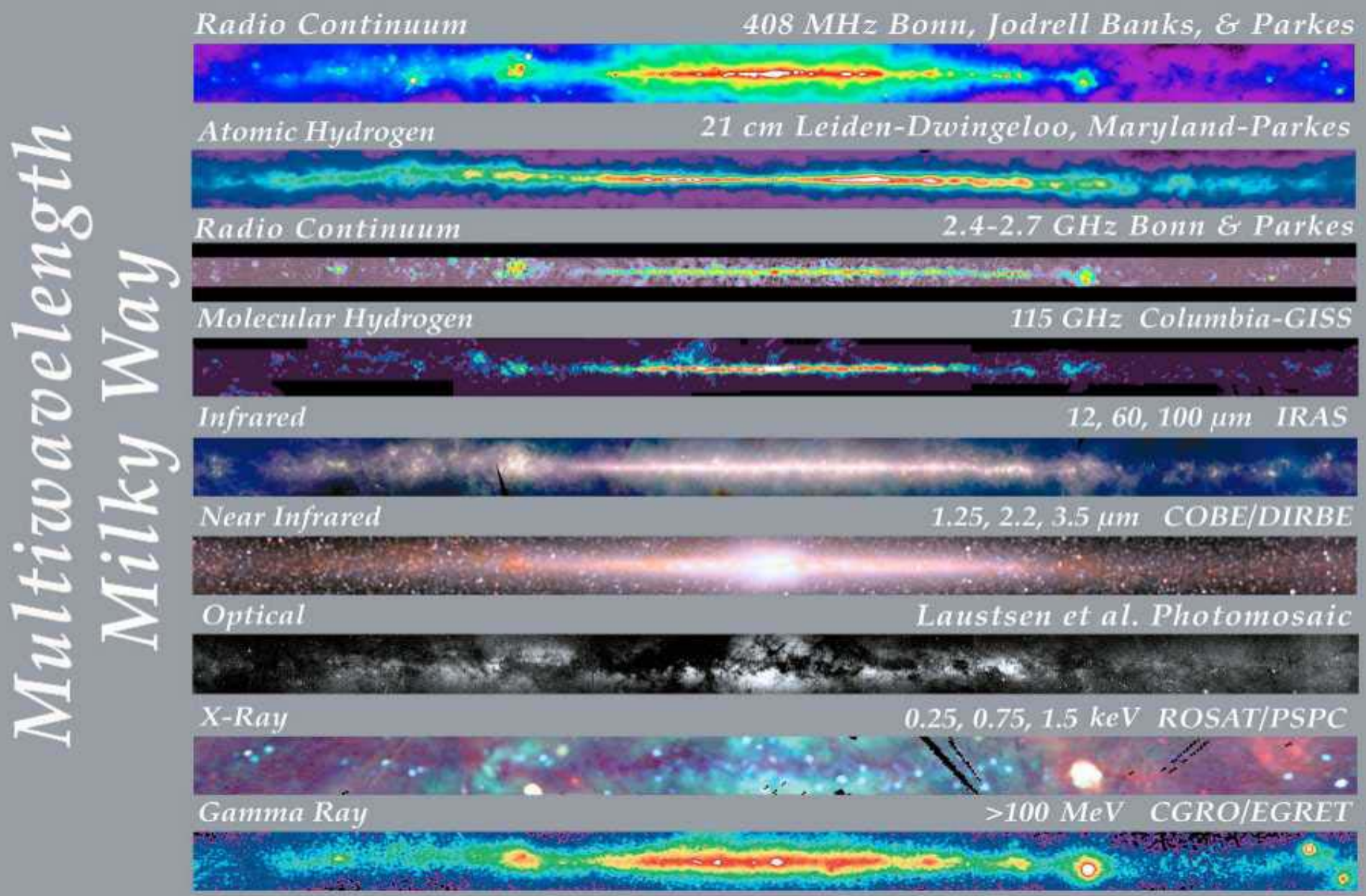
Particle models with sterile neutrino in desired mass range are “unfashionable” (and observationally challenged).

Warm Dark Matter

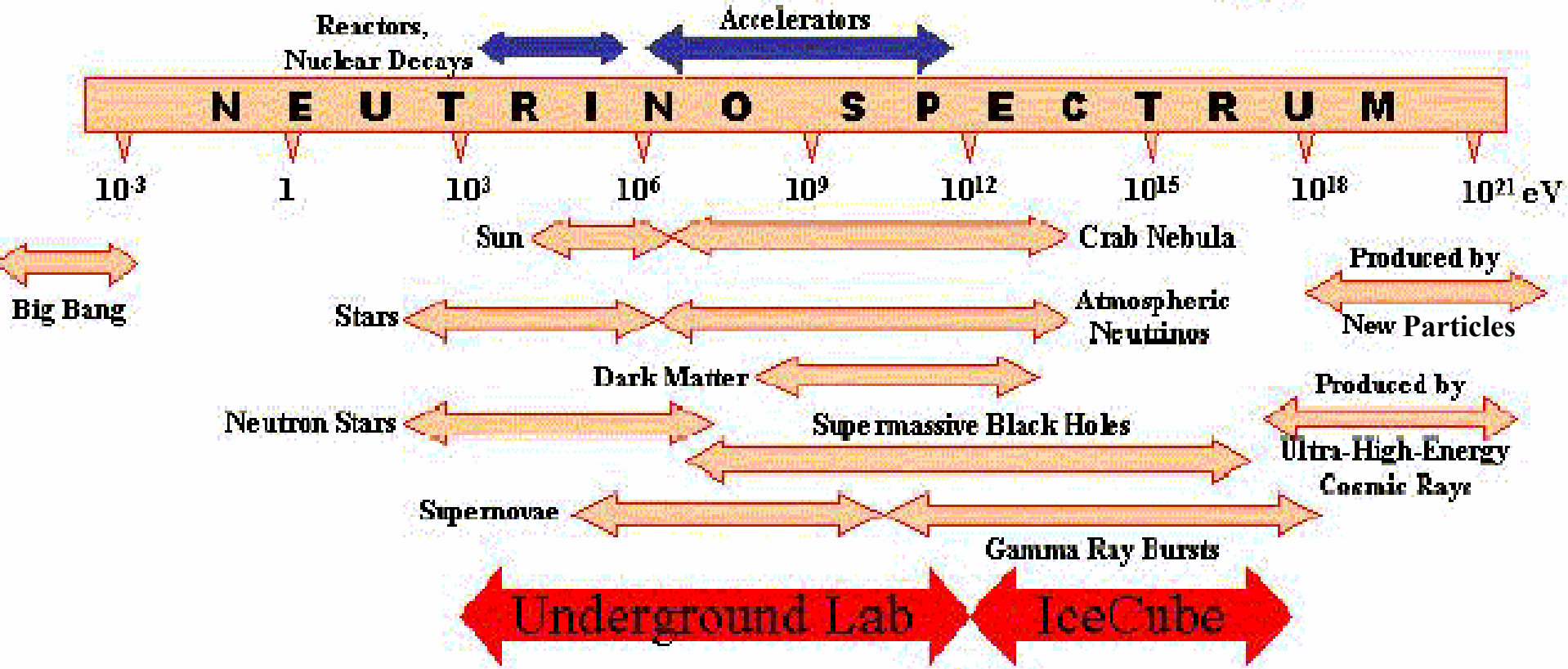
Cosmic neutrino background



The photon sky (data)

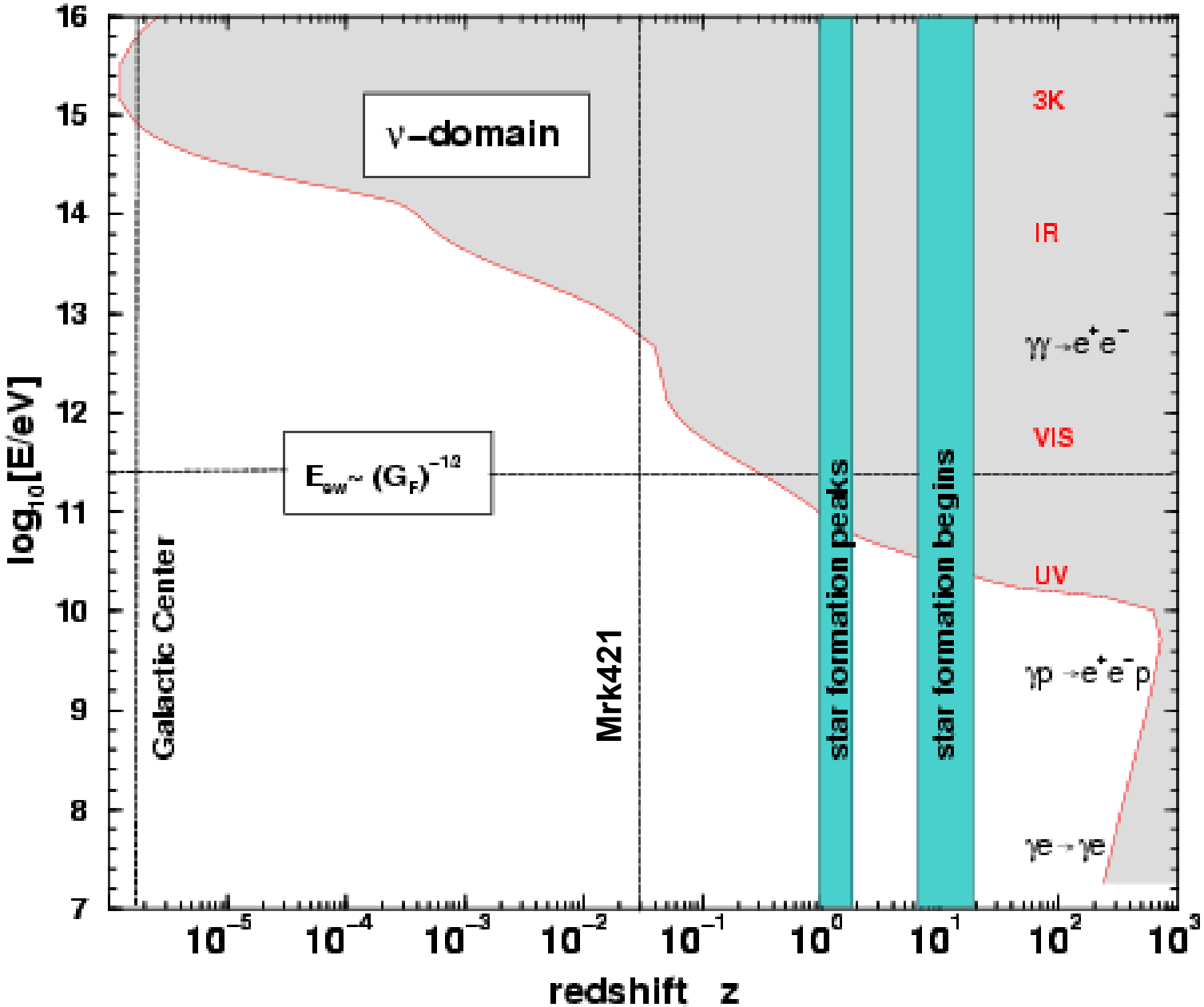


The neutrino sky (committee)



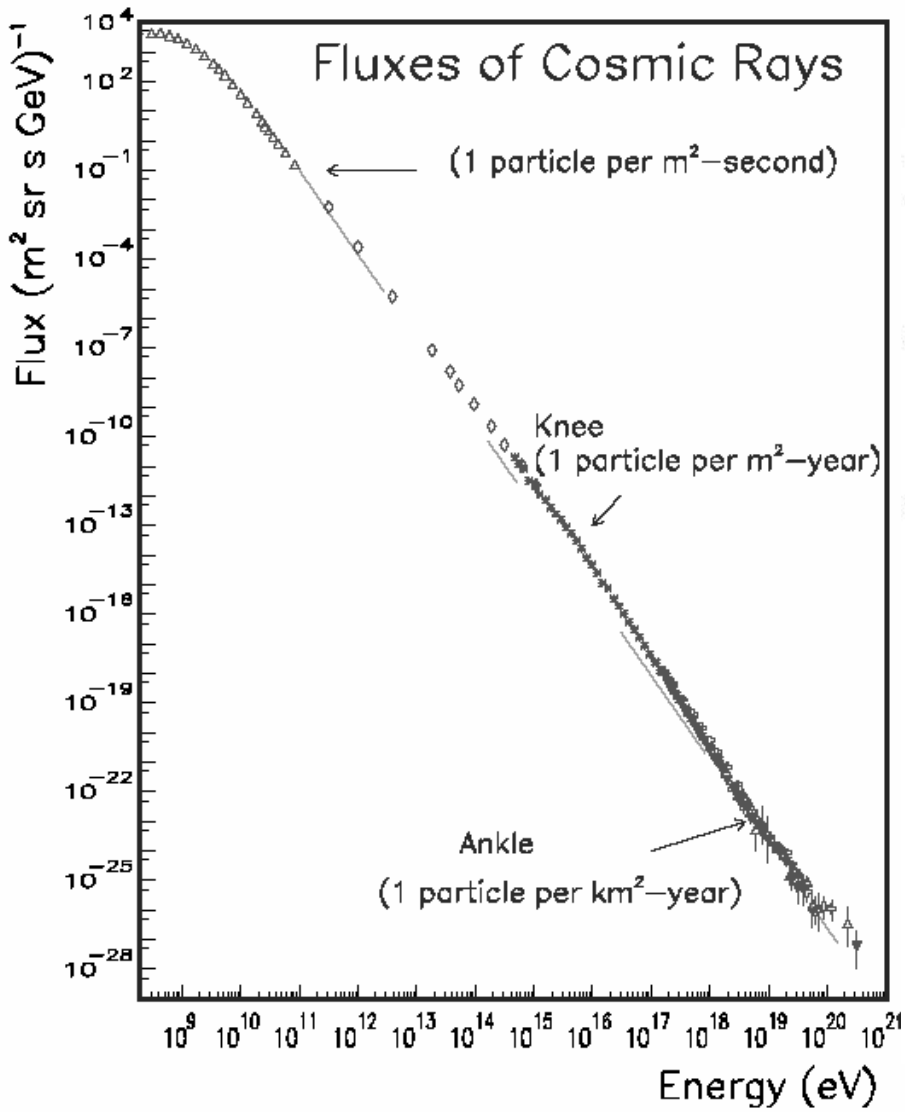
Neutrino Facilities Assessment Committee, NAS (2002)

Neutrinos see where photons can't



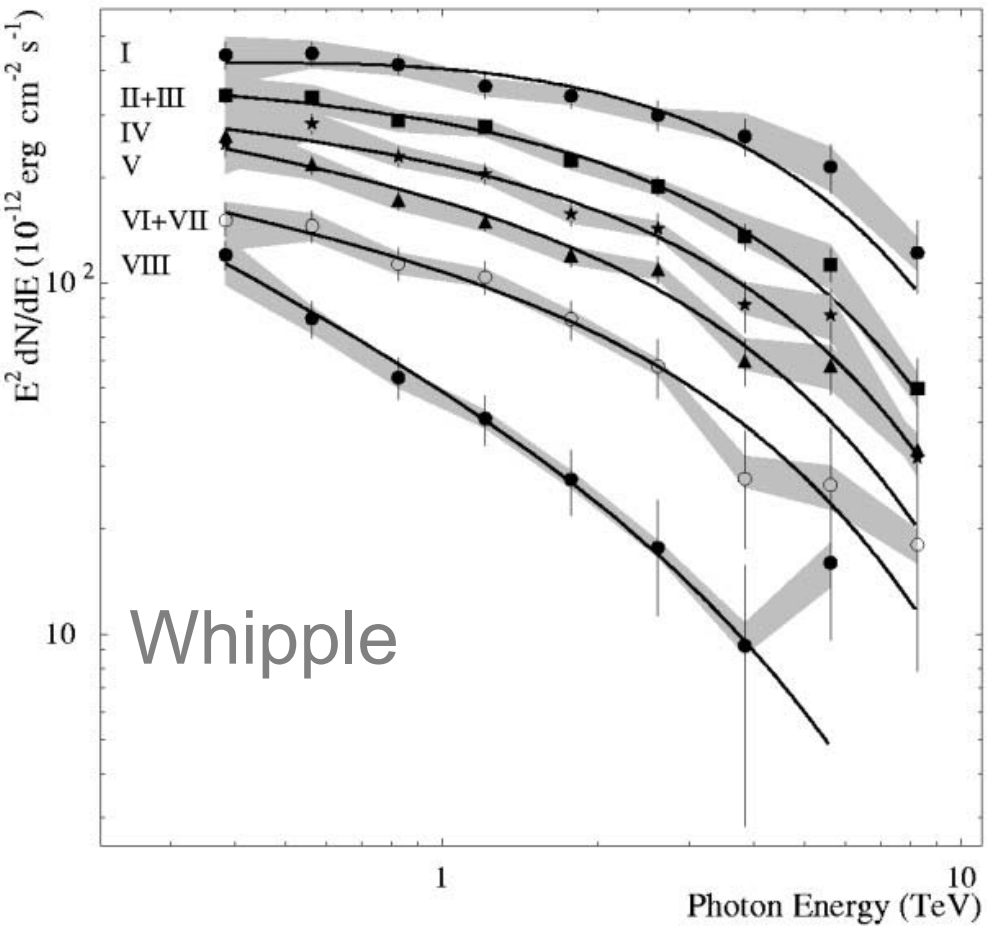
Learned and Mannheim,
Ann.Rev.Nucl.Part.Sci 50, 679 (2000)

High-energy neutrino sources



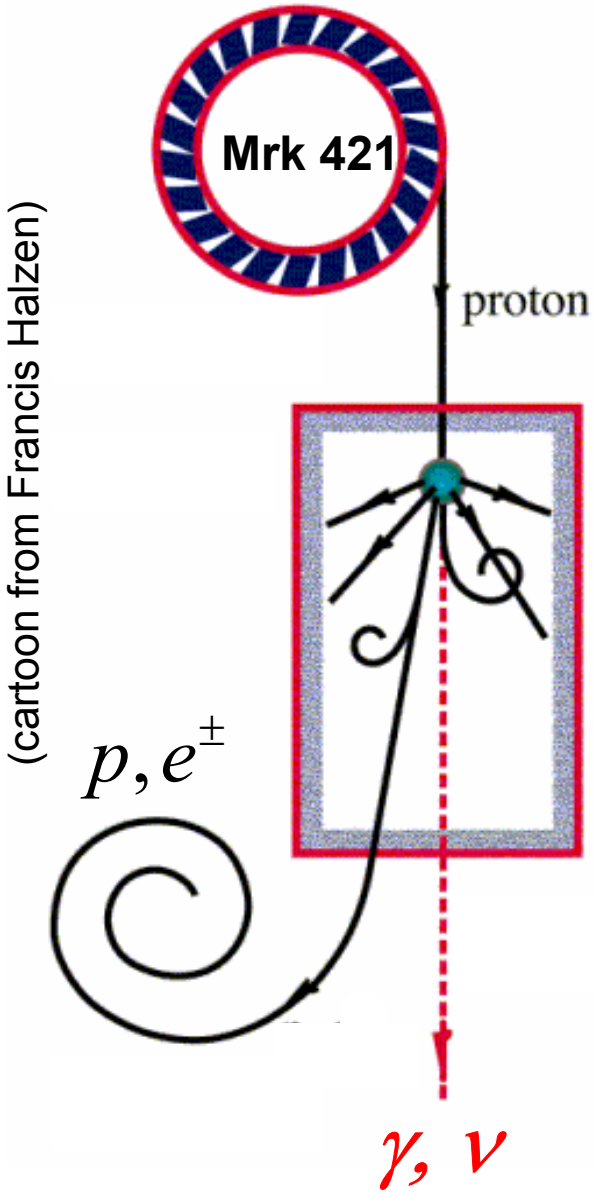
Protons (diffuse)

F. Krennrich et al., ApJ 575, L9 (2002)



Photons (Markarian 421)

Cosmic accelerator



(cartoon from Francis Halzen)

$$p + \text{target} \rightarrow \ldots + \pi\text{'s}$$

$$\pi^0 \rightarrow \gamma\gamma$$

$$\pi^{\pm} \rightarrow \mu^{\pm}\nu_{\mu}$$

$$\hookrightarrow e^{\pm}\nu_e\nu_{\mu}$$

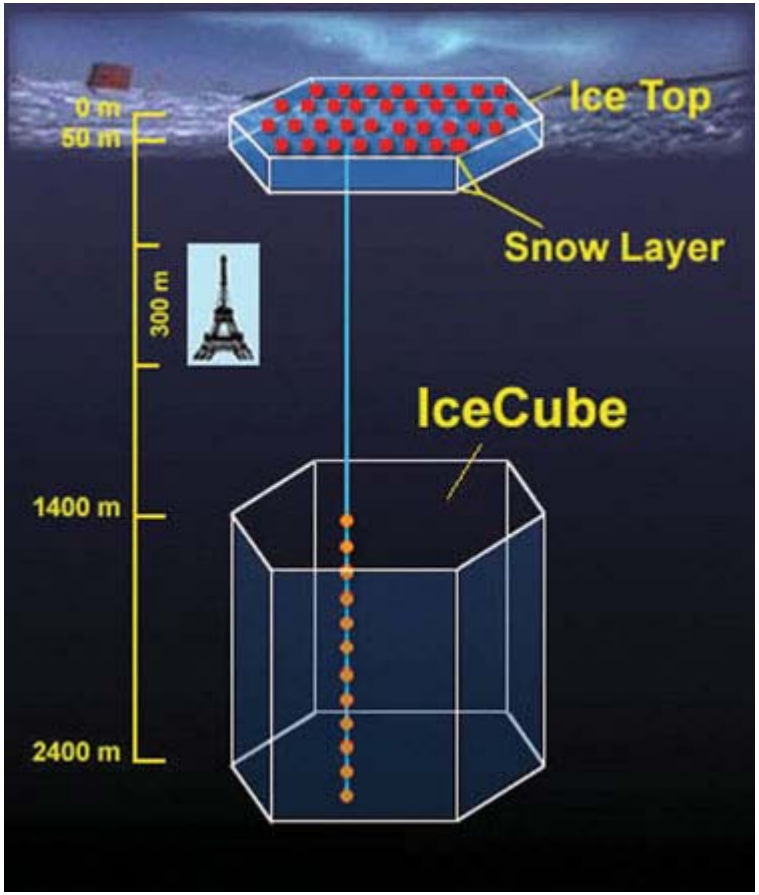
when produced:

$$\gamma : \nu_e : \nu_{\mu} : \nu_{\tau} = 2 : 1 : 2 : 0$$

after oscillations:

$$\gamma : \nu_e : \nu_{\mu} : \nu_{\tau} = 2 : 1 : 1 : 1$$

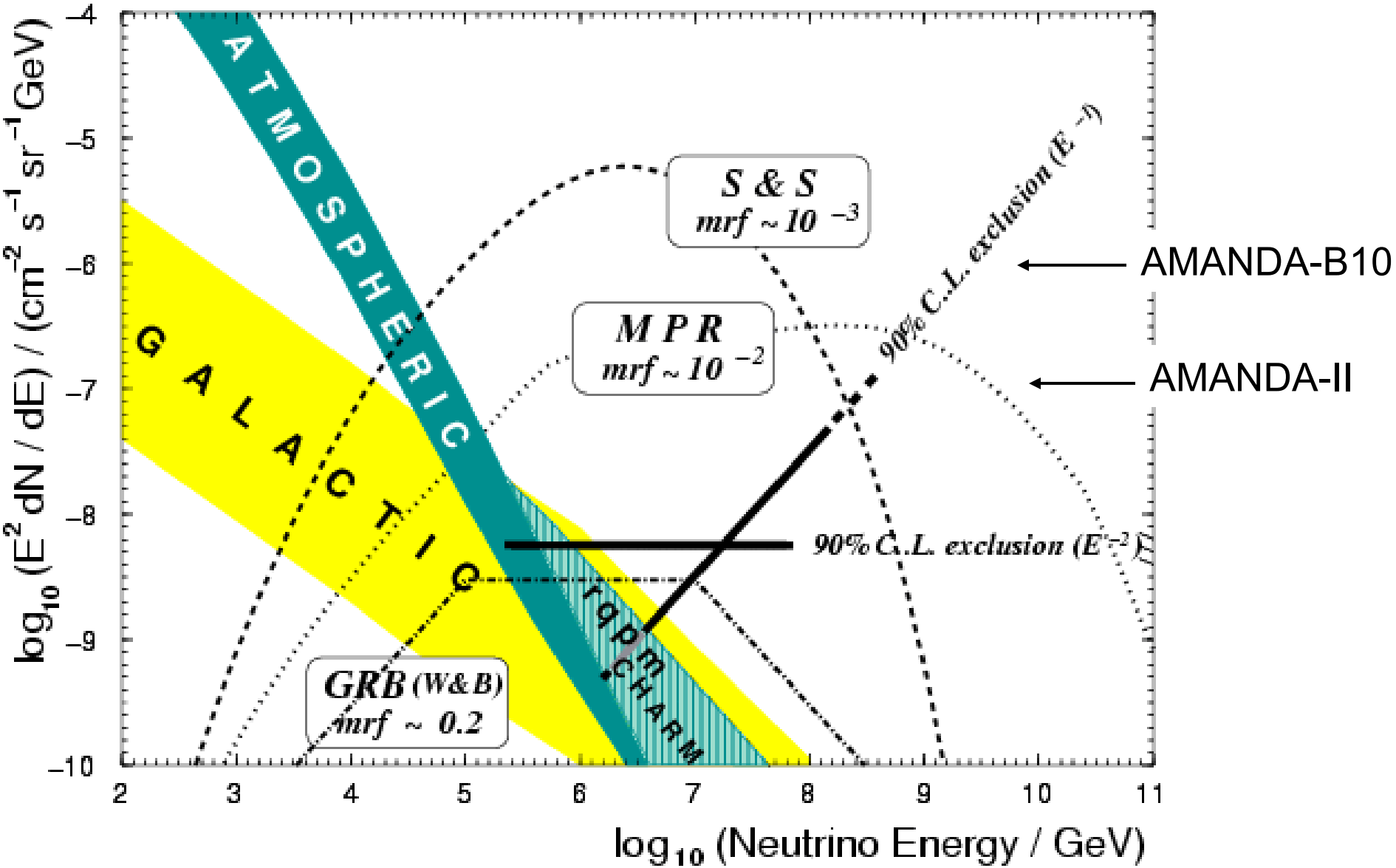
Undersea/Underground/Underice



AMANDA/IceCube

Amanda/IceCube (diffuse) limits

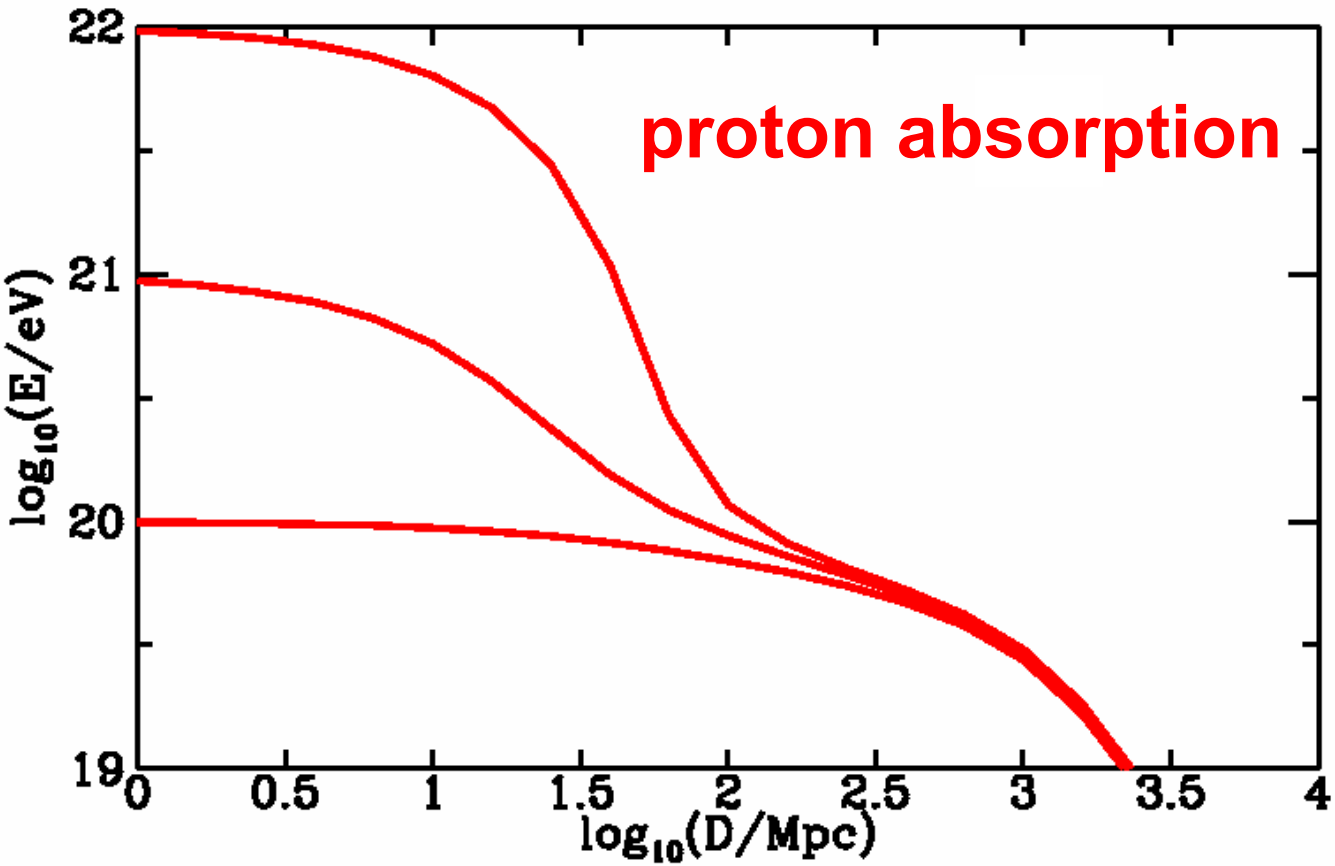
J. Ahrens et al. (IceCube), astro-ph/0305196



GZK Neutrinos

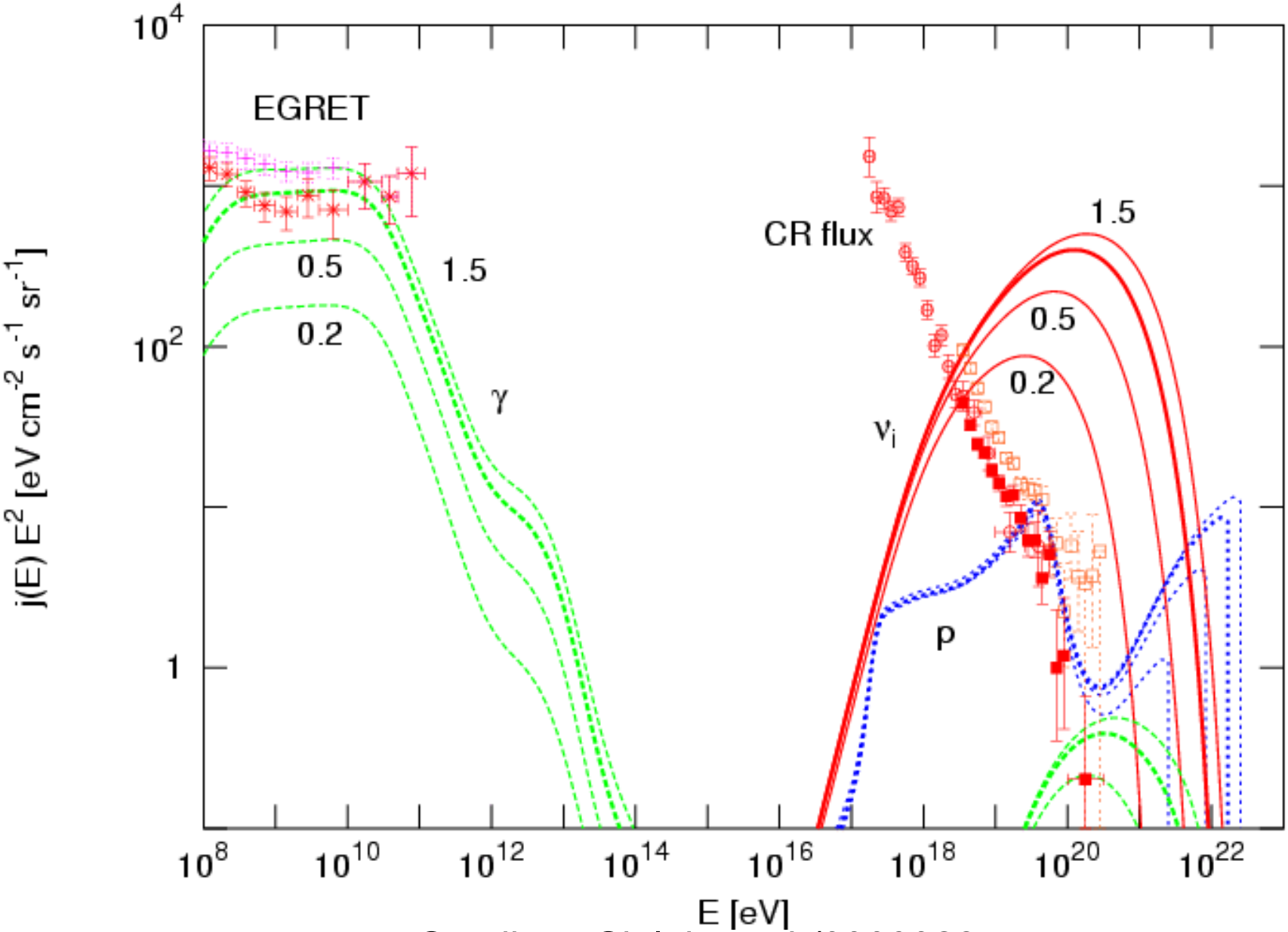
$$p_{CR} + \gamma_{CMB} \rightarrow \Delta^{+} \rightarrow \begin{cases} p\,\pi^{0} & \pi^{0} \rightarrow \gamma\,\gamma \\ n\,\pi^{+} & \pi^{+} \rightarrow \mu^{+}\,\nu_{\mu} \end{cases}$$

$$\hookrightarrow e^{+}\nu_{e}\nu_{\mu}$$



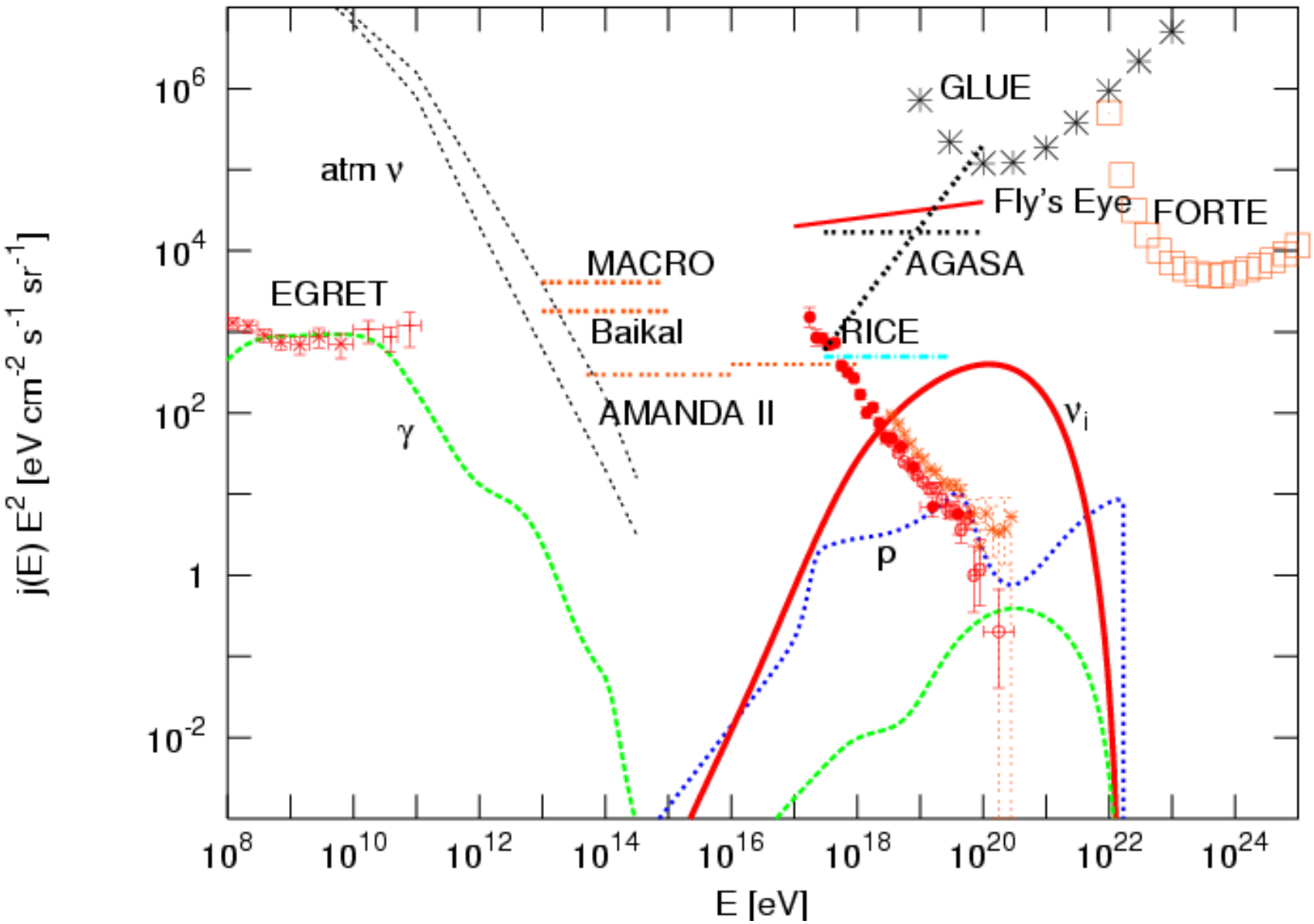
observables:
protons,
photons,
neutrinos

Protons, Photons, and Neutrinos



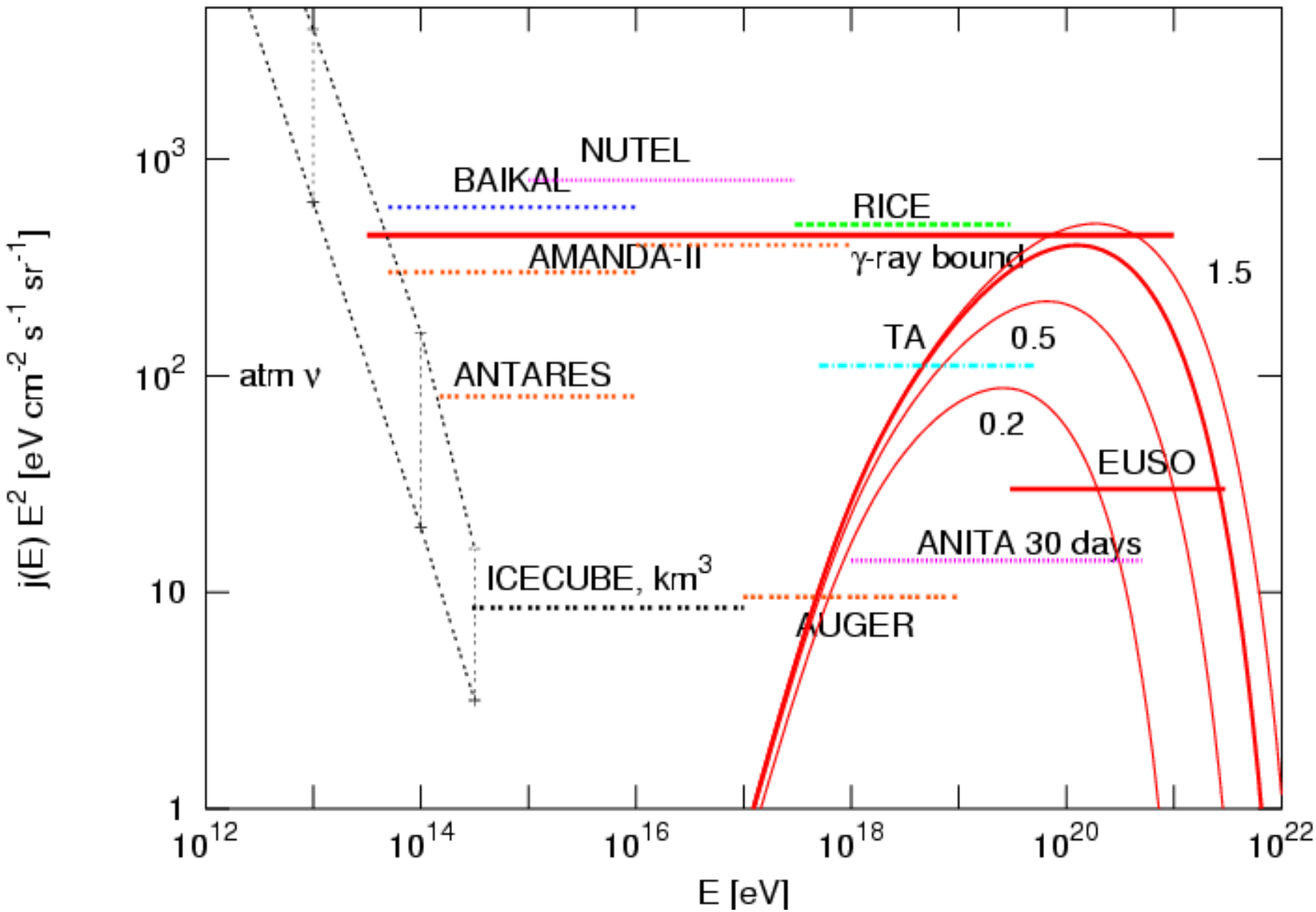
Semikoz, Sigl, hep-ph/0309328

Existing neutrino limits



Semikoz, Sigl, hep-ph/0309328

Future neutrino sensitivity



Semikoz, Sigl, hep-ph/0309328

Major connections

Cosmo/Astro		Particle
• Leptogenesis • BBN • Dark energy • Dark matter • WIMP detection • UHE neutrinos • SN neutrinos	⟷	• Number of flavors • Sterile neutrinos • Dirac vs. Majorana • Mass scale • Mixing parameters • Cross sections • Exotic properties

Neutrinos are a key to

New physics in the universe

New physics beyond the Standard Model