Telling Three from Four Neutrinos with Cosmology

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NASA/Fermilab
Theoretical Astrophysics

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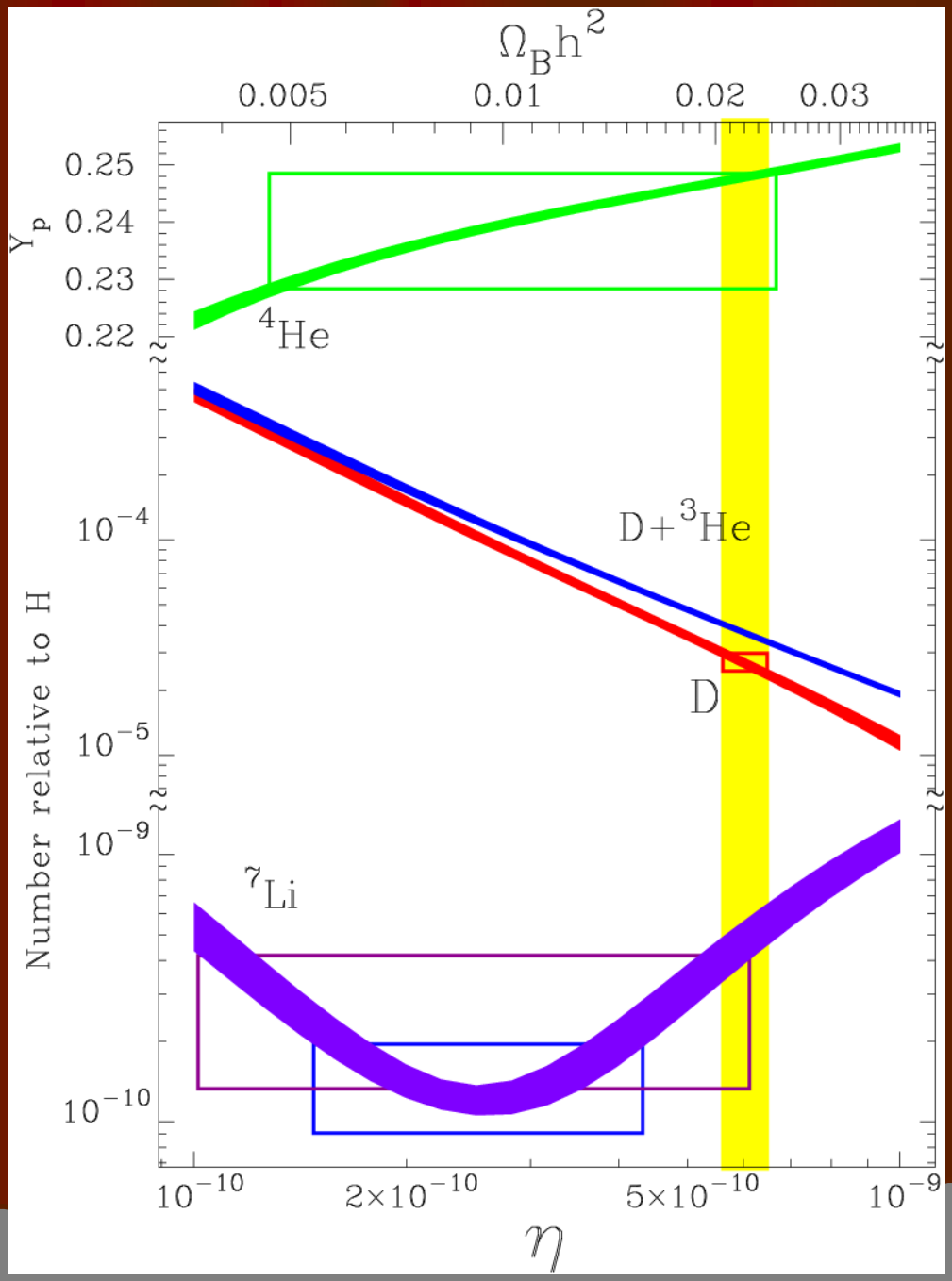
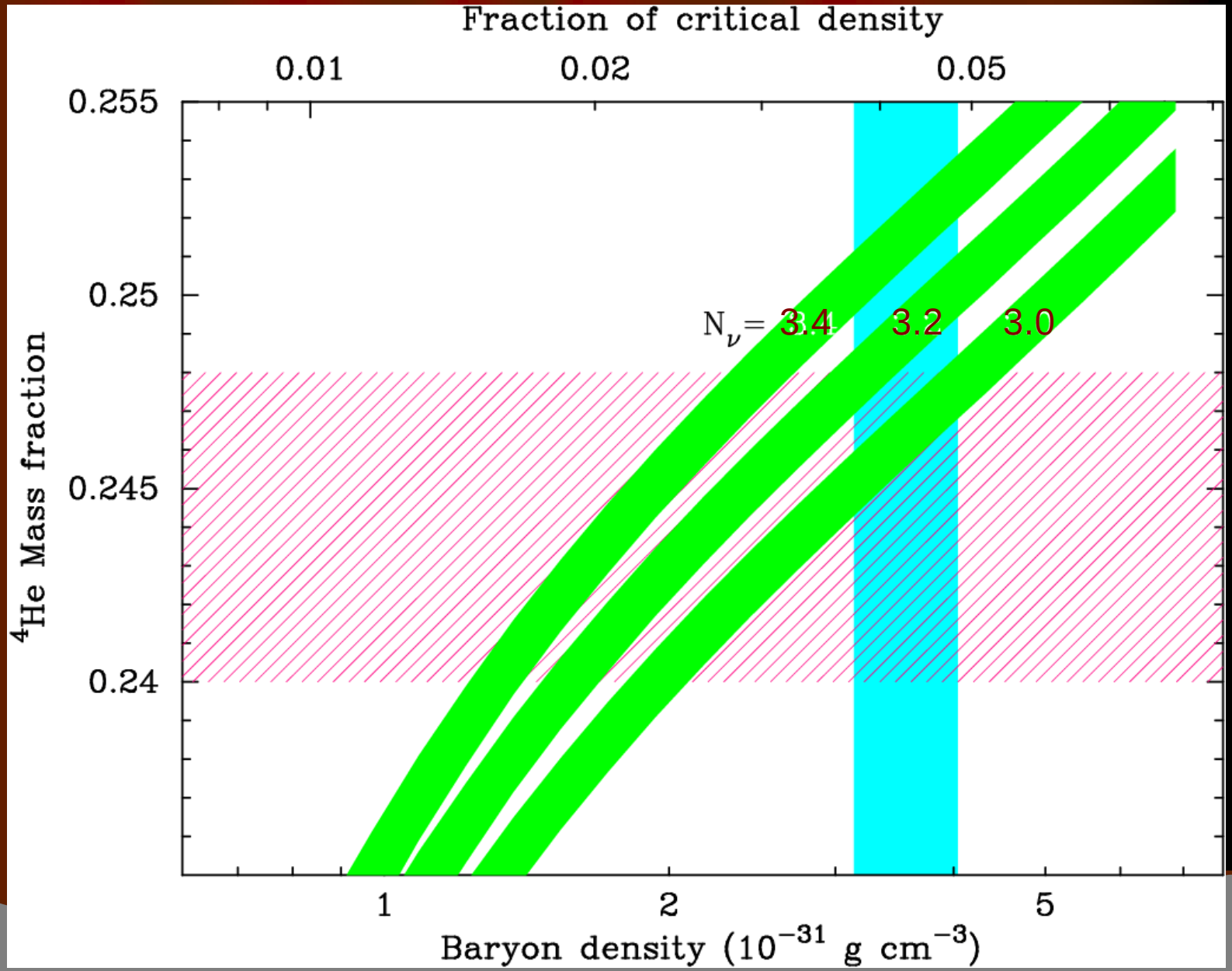
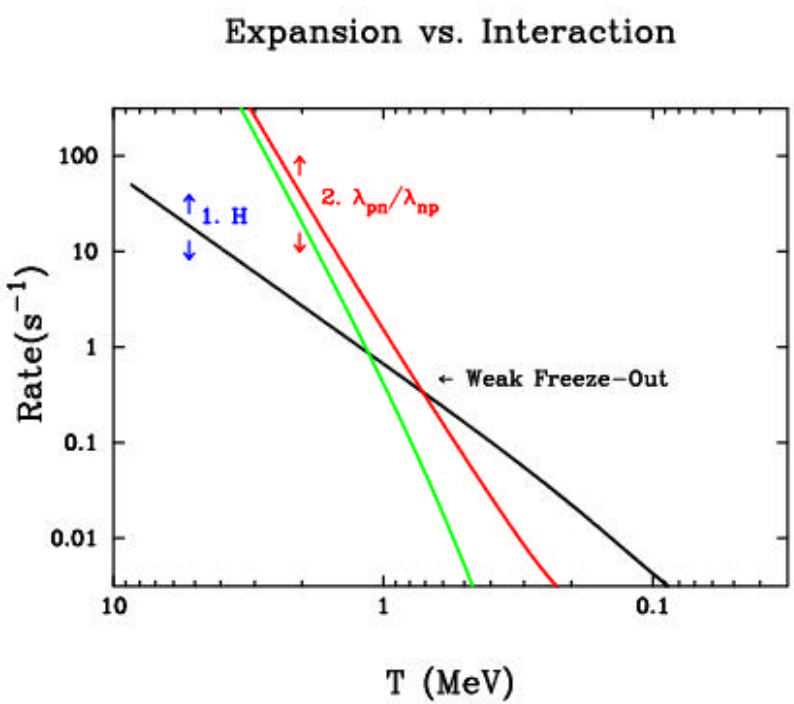

$\Omega_B h^2$
0.005
0.01
0.02
0.03
Y_p
0.25
0.24
0.23
0.22
^{4}He
10^{-4}
10^{-5}
10^{-9}
10^{-10}
D+^{3}He
D
^{7}Li
Number relative to H
10^{-10}
2×10^{-10}
5×10^{-10}
10^{-9}
η

Counting Neutrino Number...



Cosmic Helium Production:



1. **Hubble Expansion:**

$$H \propto \rho^{1/2}$$
$$H \propto (\rho_\gamma + \rho_{e^\pm} + \rho_{\nu_\alpha} + \rho_{\nu_s} + \ldots)^{1/2}$$

2. **Weak Interaction Rates:**

$$\lambda_{n\to p} \begin{cases} n + e^+ \to p + \bar{\nu}_e \\ n + \nu_e \to p + e^- \\ n \to p + e^- + \bar{\nu}_e \end{cases}$$

$$\lambda_{p\to n} \begin{cases} p + \bar{\nu}_e \to n + e^+ \\ p + e^- \to n + \nu_e \\ p + e^- + \bar{\nu}_e \to n \end{cases}$$

Assuming Standard Big Bang Nucleosynthesis

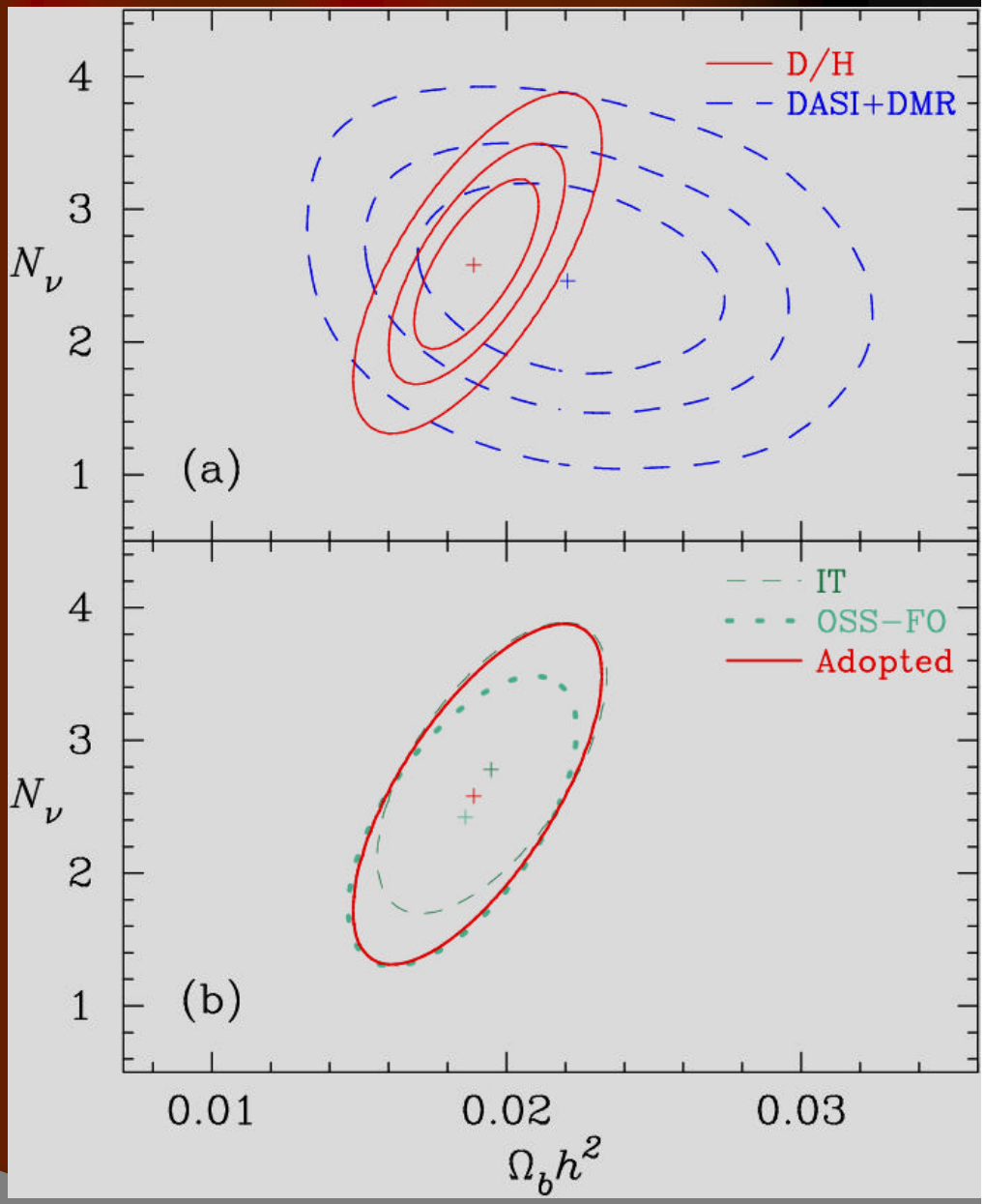
Something much more scientific than "optimistic" and "pessimistic" limits

And using only:

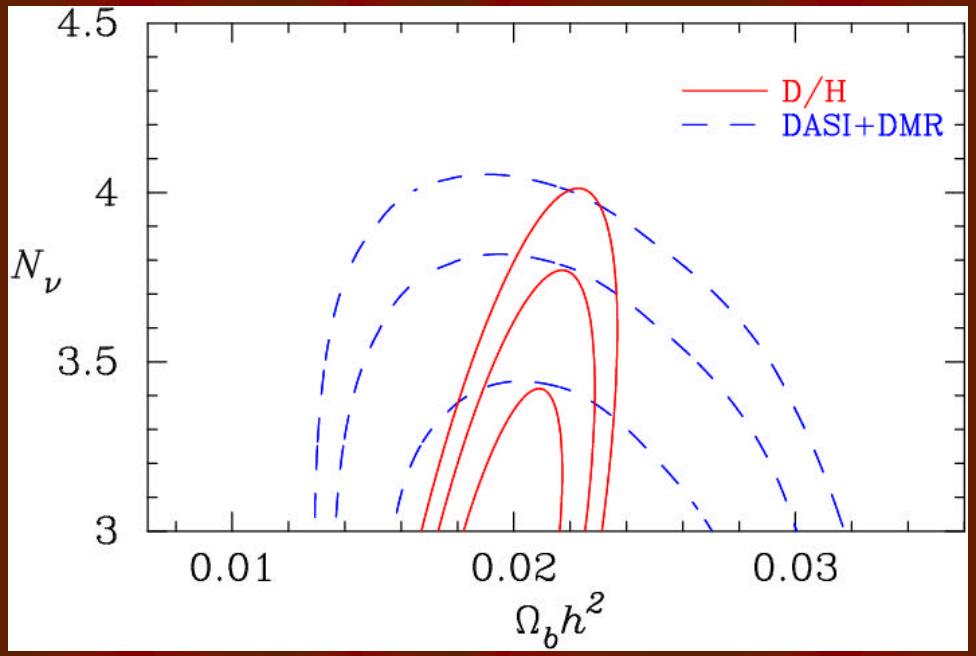
1. The cosmological baryon density from the deuterium abundance:
   D/H = (3.0 ± 0.4) x 10^{-5}
   ? $_b h^2$ = 0.020 ± 0.002 (95% CL)
   (Burles, Nollet & Turner 2000; Burles & Tytler 1998)

2. The CMB-determined baryon density:
   ? $_b h^2$ = 0.022(+0.004)(-0.003)
   (DASI+DMR)

3. The primordial helium abundance:
   Y_p = 0.238 ± 0.002 ± 0.005
   (Olive, Steigman & Skillman 1997; Fields & Olive 1998)
   Yp = 0.244 ± 0.002
   (Izotov & Thuan 1998)



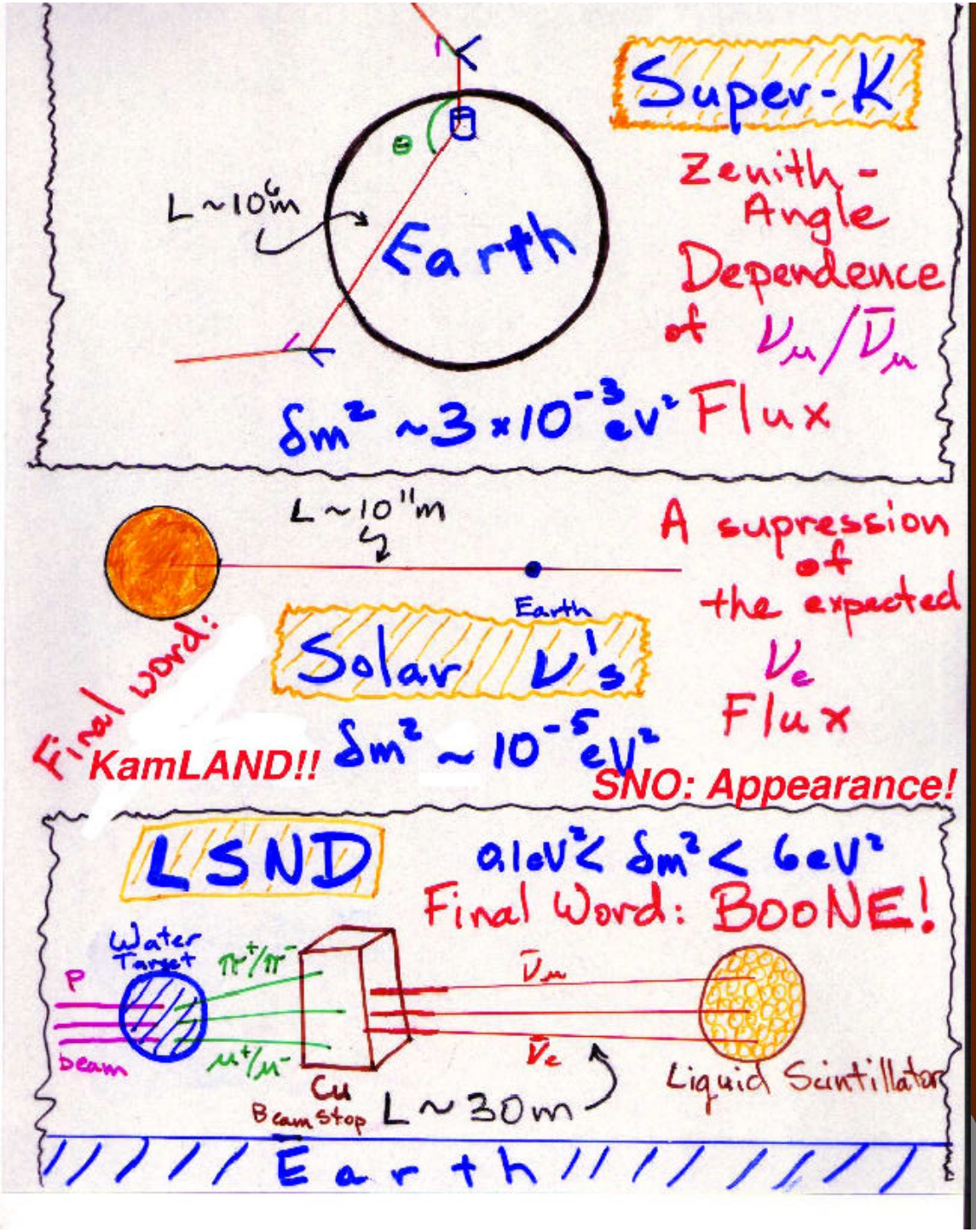
Active Neutrino Thermalization Prior: $N_? > 3$

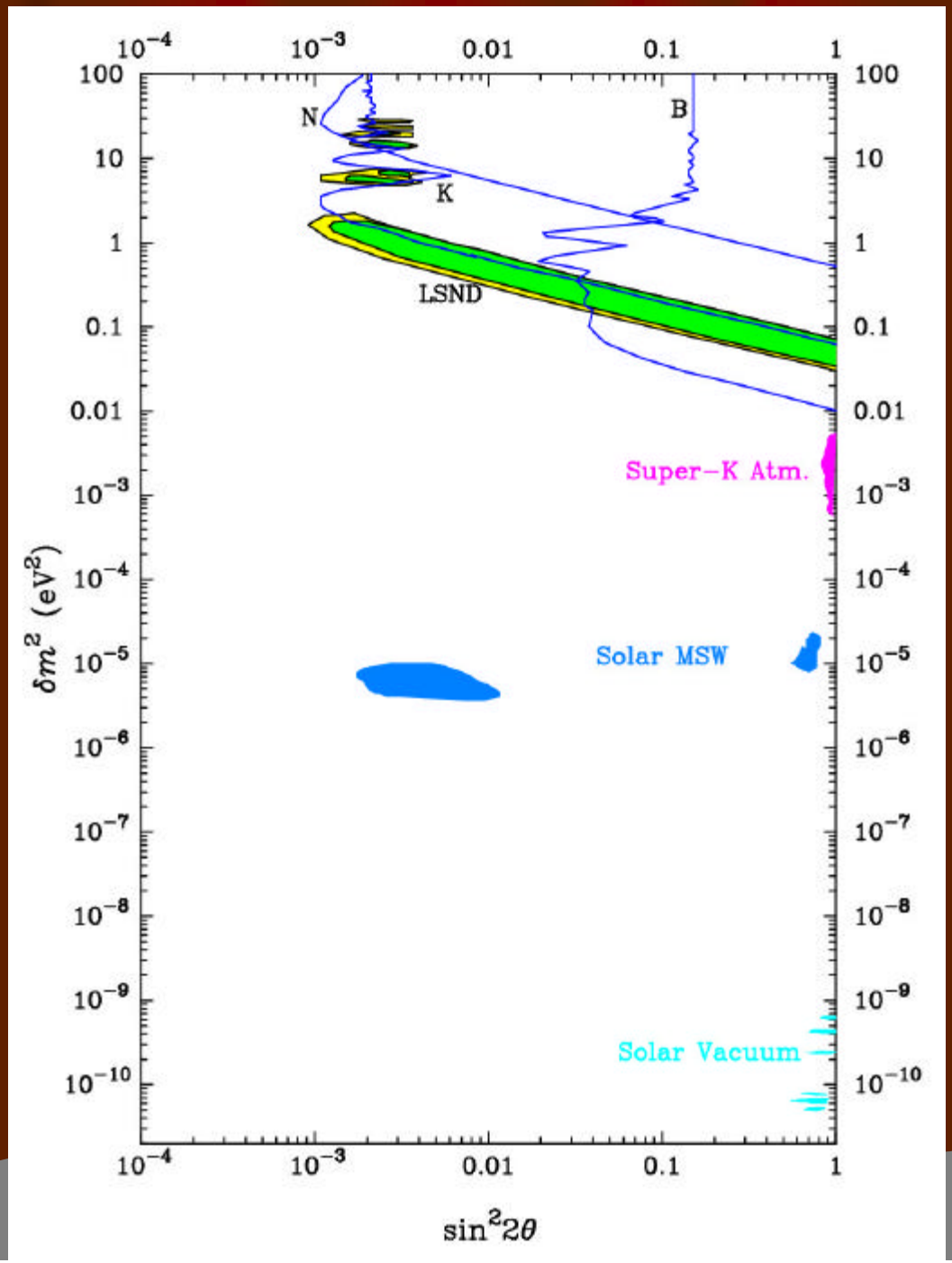


K. Abazajian, astro-ph/0205238

With a precise determination of $?_b h^2$ from MAP satellite:

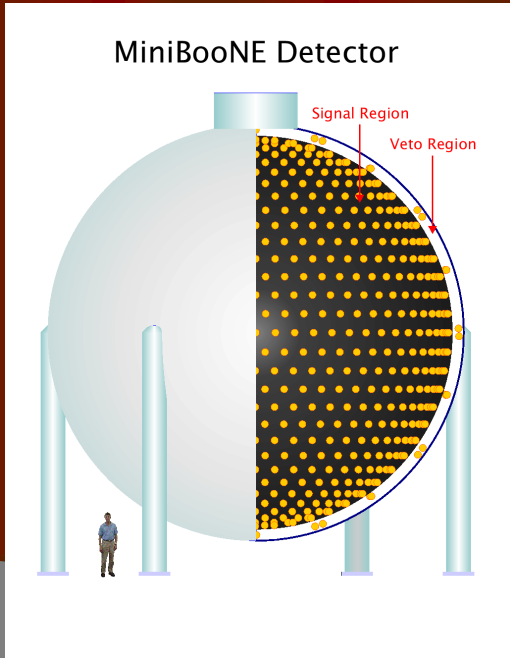
$$\mathrm{CL}(N_\nu) = \int_3^{N_\nu} p(N'_\nu | Y_p)\, dN'_\nu .$$

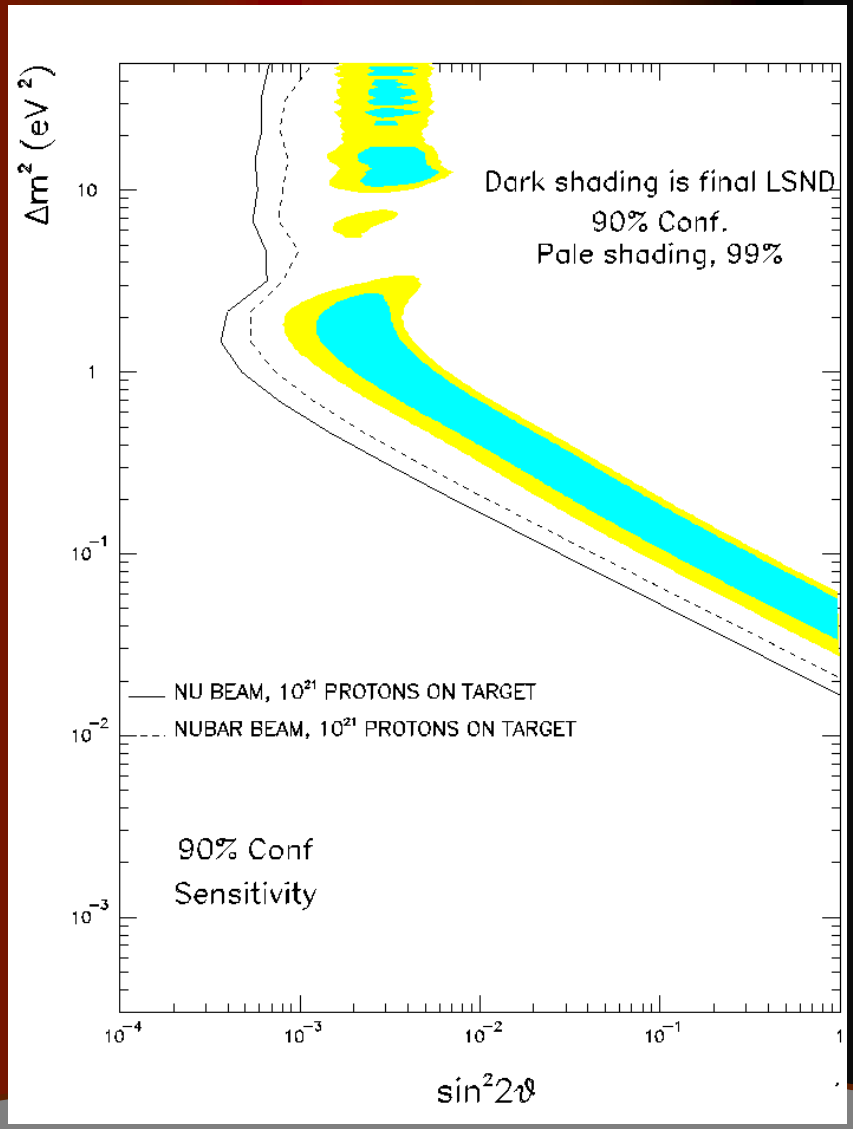

Super-K
Zenith-Angle Dependence of $\nu_\mu/\bar{\nu}_\mu$ Flux
$L \sim 10^6 m$
Earth
$\delta m^2 \sim 3 \times 10^{-3} eV^2$
$L \sim 10^{11} m$
Earth
Solar ν's
A supression of the expected ν_e Flux
Final word:
KamLAND!!
$\delta m^2 \sim 10^{-5} eV^2$
SNO: Appearance!
LSND
$0.1 eV^2 < \delta m^2 < 6 eV^2$
Final Word: BooNE!
Water Target
p
beam
π^+/π^-
μ^+/μ^-
Cu Beam Stop
$\bar{\nu}_\mu$
$\bar{\nu}_e$
$L \sim 30 m$
Liquid Scintillator
Earth


N
B
K
LSND
Super−K Atm.
Solar MSW
Solar Vacuum
δm^2 (eV^2)
$\sin^2 2\theta$

New Physics

The MiniBooNE Experiment



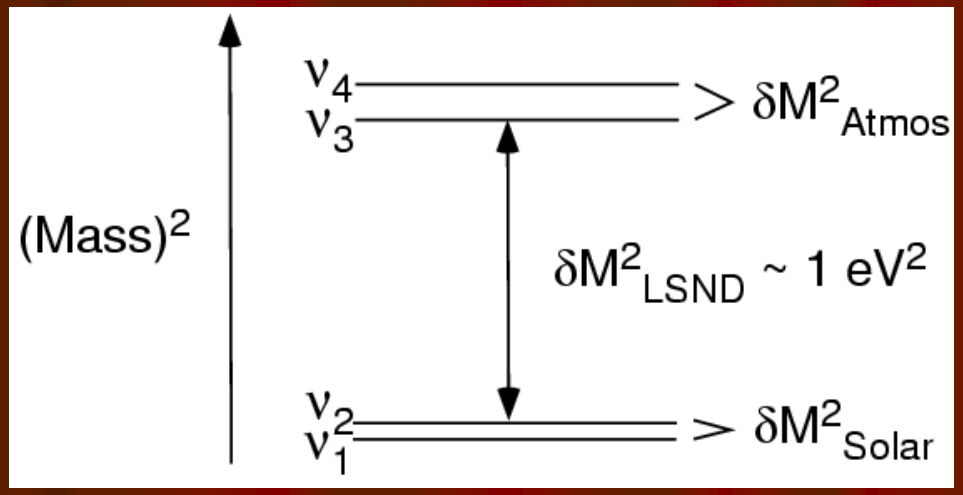


4-Neutrino Mass-modelling

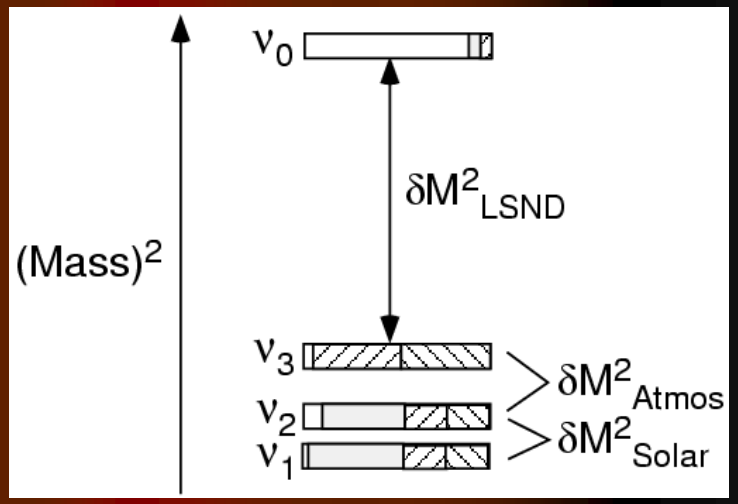
$$\nu_\alpha = \sum_i^4 U_{\alpha i}\nu_i \,,$$

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}\left(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}\right)\,\sin^2\left(\delta m^2_{ij}\frac{L}{4E}\right) + 2\sum_{i>j}\mathrm{Im}\left(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}\right)\,\sin\left(\delta m^2_{ij}\frac{L}{2E}\right),$$

"2+2"



"3+1"



Maltoni, Schwetz, & Valle 2001, 2002; Wieler 2002

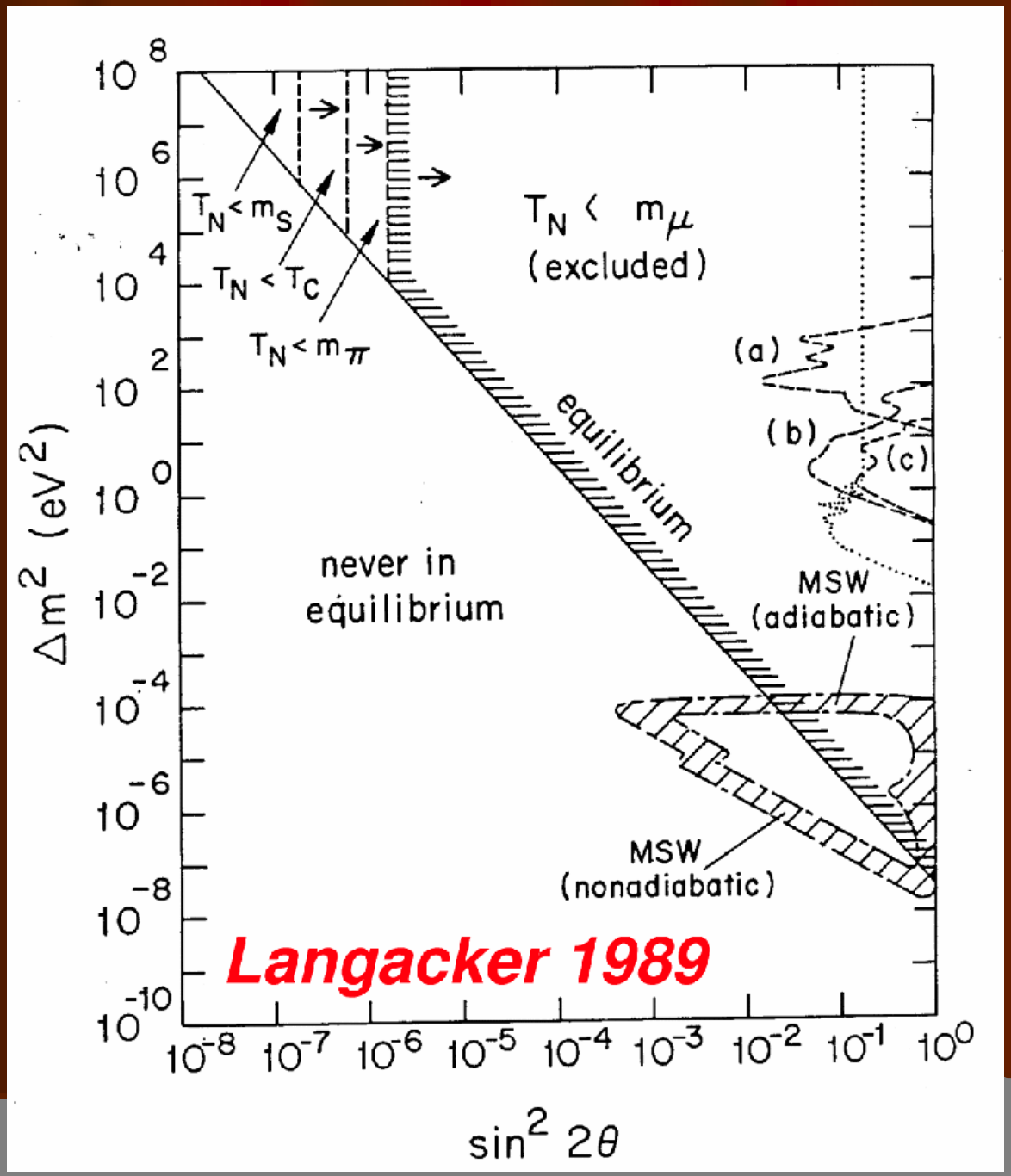
Constraining Sterile Neutrino Mixing

- Collisions decohere neutrino gas and populate sterile neutrinos
- Requiring that $?_s$ are not equilibrated ($N_? < 4$)

$$\delta m^2_{\alpha s} \sin^4 2\theta_{\rm BBN} \lesssim \begin{cases} 5 \times 10^{-6}, & \text{for } \alpha = e \\ 3 \times 10^{-6}, & \text{for } \alpha = \mu, \tau \end{cases}$$

The relevant amplitude is simply:

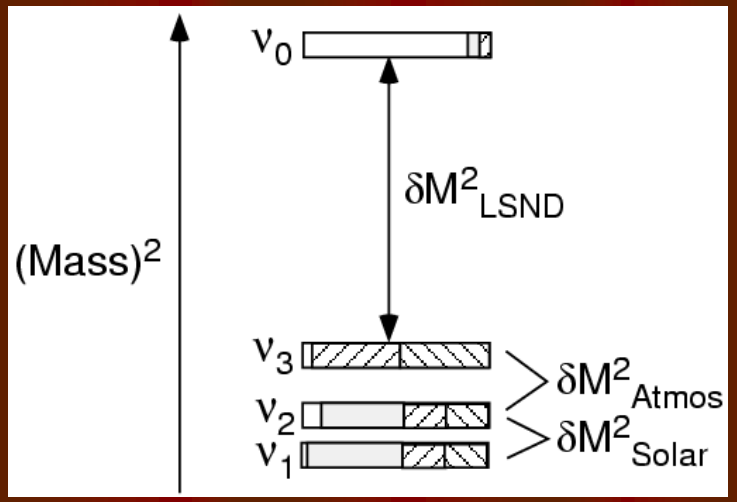
$$A_{\alpha;s} = 4|U_{\alpha 4}|^2 |U_{s4}|^2 \simeq \sin^2 2\theta_{\rm BBN} \, .$$



Original 2-neutrino limits:
Langacker 1989;
Barbieri & Dolgov 1990;
Enqvist, Kainulainen, Thomson 1992;
Shi, Schramm & Fields 1993

Application to all 4 neutrino models:
K. Abazajian, Astropart. Phys. 2002, astro-ph/0205238;
P. Di Bari, PRD **65**, 043509 (2002)

3+1

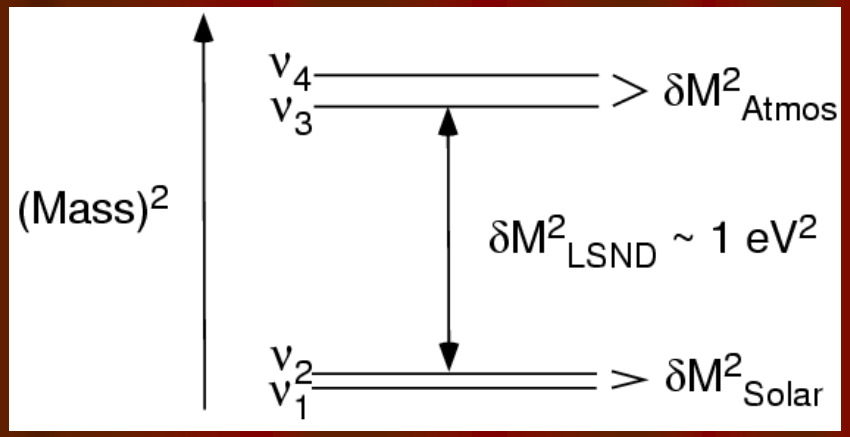


Indirect ?$_?$ -> ?$_e$

$$A_{\mu;e} = 4|U_{e4}|^2|U_{\mu 4}|^2 > 3 \times 10^{-4} \quad (99\% \text{ CL}),$$

Along with unitarity, forces large amplitude mixing with large ?m^2, violating BBN bound

2+2



Both solar (SNO) – neutral current signal of D breakup and capture

and atmospheric (Super-K) – enhanced neutral current component and matter effects

experiments are now effectively appearance experiments, and disfavor large sterile components

Sterile must be split between upper and lower doublet

$$U_{s1} = U_{s3} = 0, \text{ but by unitarity } |U_{s2}|^2 + |U_{s4}|^2 = 1,$$

$$|U_{s2}|^2 = |U_{s4}|^2 = 1/2.$$

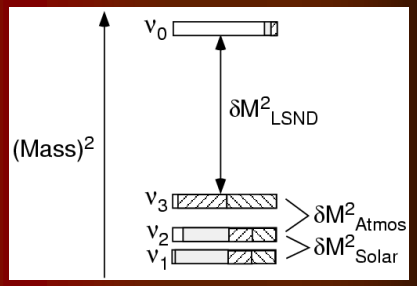
$$A_{\mu;s} = 4|U_{\mu 2}|^2|U_{s2}|^2 \text{ and } A_{e;s} = 4|U_{e4}|^2|U_{s4}|^2$$

$$|U_{e4}|^2 = |U_{e1}|^2 \tan^2\theta_{\mathrm{LMA}}$$

Constraint Evasion & New Physics

Those unafraid of further complications may choose from:

1. Pre-existing lepton number ($L \sim 10^5$ B)
2. A fifth mass eigenstate, mostly sterile



$?_5$

may dynamically generate lepton number (Foot, Thomson & Volkas, 1996) sufficiently early

3. Generation of majoron fields (Berezinsky & Bento 2001)
4. Low reheating temperature (3 active neutrinos are not thermalized)
5. Baryon-Antibaryon inhomogeneities: $N_? < 7$ (Giovannini, Kurki-Suonio & Sihvola 2002)
6. Extended quintessence ("dark radiation") (Chen, Scherrer & Steigman 2001)
7. CPT violating Neutrinos (Murayama & Yanagida 2001; Barenboim, Borrisov, Lykken & Smirnov 2001)

Conclusions

- Minimal models of the big bang and nucleosynthesis are in conflict 4 neutrino models accommodating LSND+Solar+Atm results

- If LSND is verified, will require new physics in the early universe and in particle physics