

# **Frontiers of Neutrino Physics in the Cosmos**

**INFO 2007**

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**Neutrino physics/astrophysics** is rife with new opportunities.

Exploiting these will require synergistic applications of conventional particle/nuclear experiments plus novel new astronomical and astrophysical probes.

The stakes are high. Lurking in the weakly interacting and sub-weakly interacting neutrino sectors may lie keys to understanding the Dark Matter and the origin of core collapse supernova explosions and the synthesis of the heavy nuclei.

My philosophy is as follows: (1) what we already know about neutrino mass/mixing has big implications for astrophysics; (2) working out those implications may allow, e.g., a supernova neutrino signal to help us get some of the unmeasured parameters; and . . .

(3) We remain largely ignorant of the mass/mixing scales in the **right-handed/sterile neutrino** sector. Particle astrophysicists can map out the regimes of astrophysical interest where experimenters/observers should look.

## The current neutrino physics situation has been summed up nicely.

There are known knowns.

These are things we know that we know.

There are known unknowns.

That is to say, there are things that we know we don't know.

But there are also unknown unknowns.

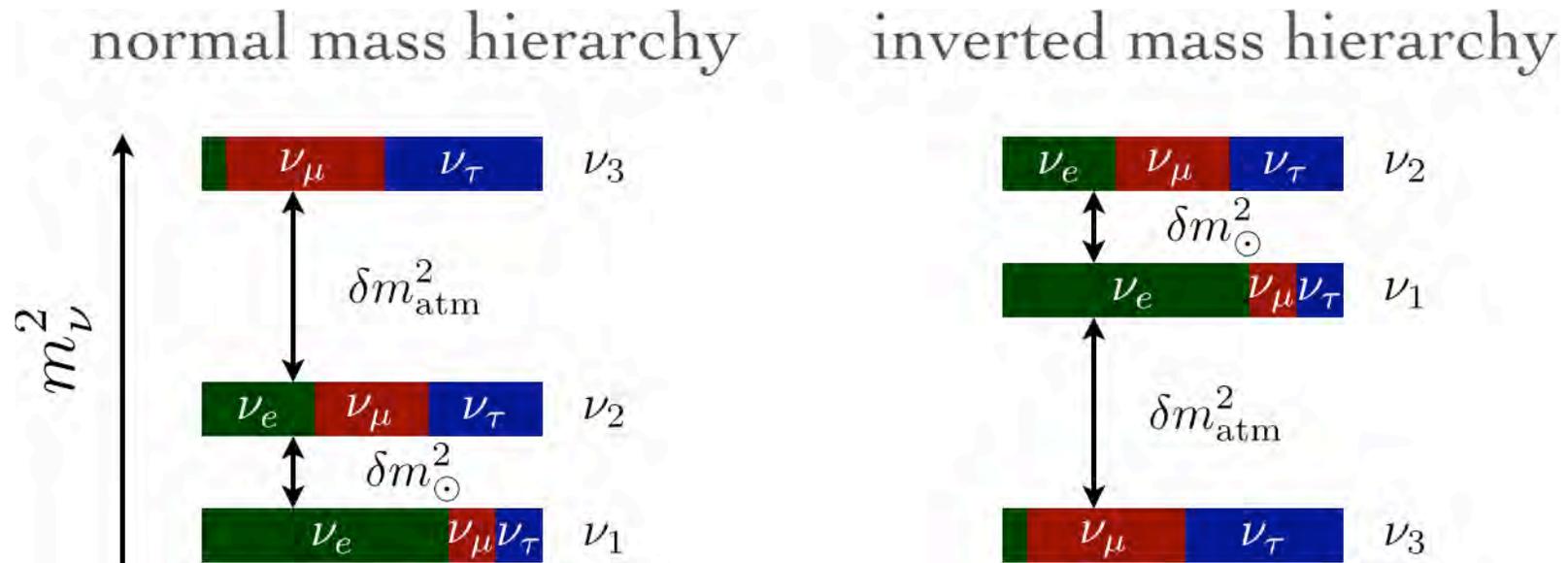
There are things we don't know we don't know.

**Donald Rumsfeld**

## some known knowns & some known unknowns

We know the *mass-squared* differences:  $\left\{ \begin{array}{l} \delta m_{\odot}^2 \approx 8 \times 10^{-5} \text{ eV}^2 \\ \delta m_{\text{atm}}^2 \approx 3 \times 10^{-3} \text{ eV}^2 \end{array} \right.$

We *do not* know the *absolute masses* or the *mass hierarchy*:



**We know 2 of the 4 vacuum 3X3 mixing parameters and we have a good upper limit on a third.**

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = U_m \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

$$U_m = U_{23}U_{13}U_{12}$$

$$U_{23} \equiv \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & \sin \theta_{23} \\ 0 & -\sin \theta_{23} & \cos \theta_{23} \end{pmatrix}$$

$$U_{13} \equiv \begin{pmatrix} \cos \theta_{13} & 0 & e^{i\delta} \sin \theta_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta} \sin \theta_{13} & 0 & \cos \theta_{13} \end{pmatrix}$$

$$U_{12} \equiv \begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ -\sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

**4 parameters**

## Atmospheric Neutrinos

$$\delta m_{23}^2 \approx 2.5 \times 10^{-3} \text{ eV}^2$$

$$\sin^2 2\theta_{23} \approx 1.0$$

## “Solar”/KamLaND Neutrinos

$$\delta m_{\text{sol}}^2 \approx 8 \times 10^{-5} \text{ eV}^2$$

$$\tan^2 \theta_{12} \approx 0.42 \Leftrightarrow 0.45$$

## Chooz

Chooz limit on  $\theta_{13} \Rightarrow$

$$|U_{e3}|^2 < 2.5\% \text{ or } \sin^2 2\theta_{13} < 0.1 \quad (\theta_{13} < \frac{\pi}{20} \approx 9^\circ)$$

plus KamLaND  $\Rightarrow$

$$\sin^2 2\theta_{13} < 6.65 \times 10^{-2} \quad (< 0.2 \text{ at } 3\sigma)$$

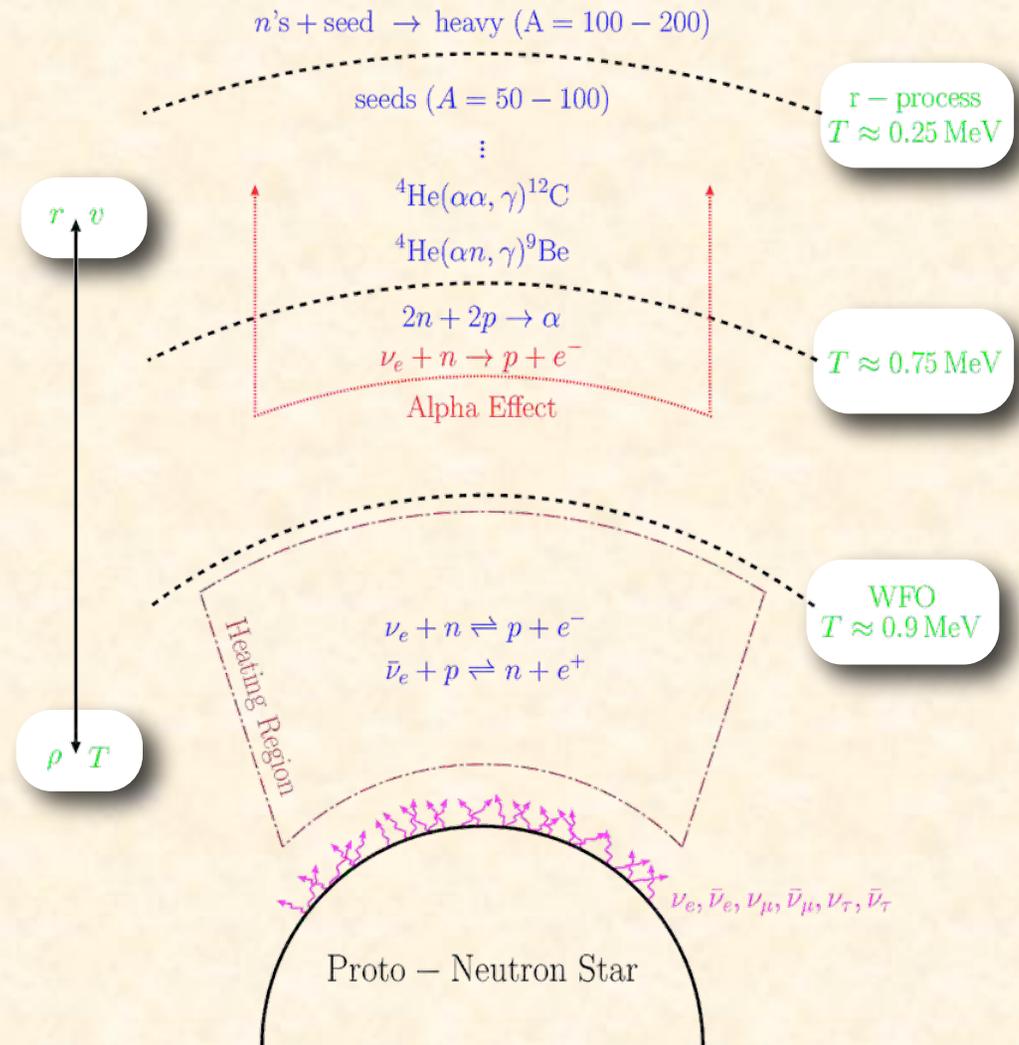
# SN environment

Supernova neutrino signals might be used to determine neutrino mixing parameters.

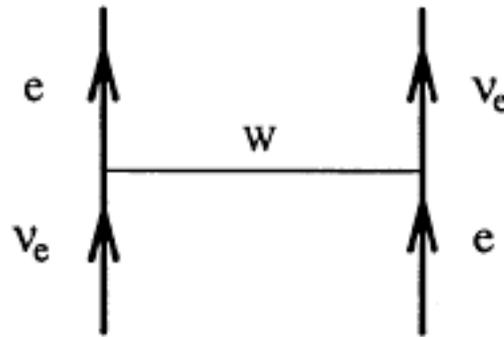
Neutrino flavor transformation in the “right” regions can help or hinder the r-process nucleosynthesis and explosion.  
**Active-sterile still only r-Process solution.**

Charge current neutrino interactions set the composition (n/p ratio) and can be instrumental in energetics.

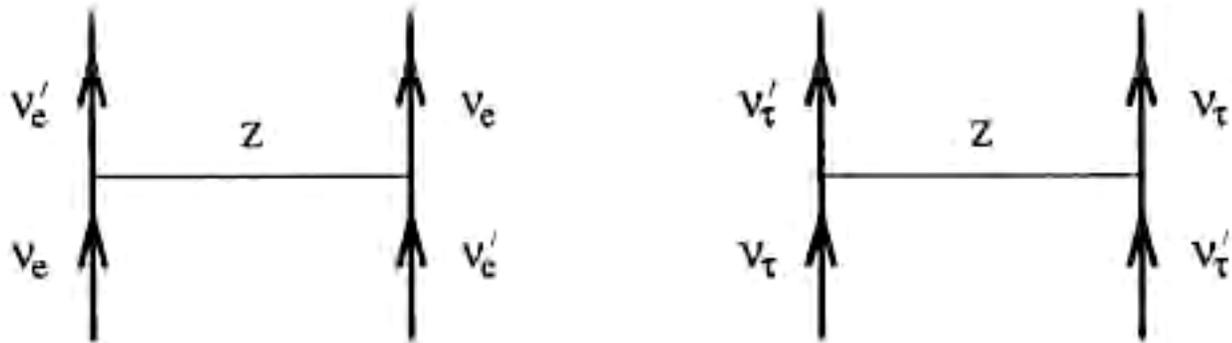
- Most of the gravitational binding energy (99%) is released in the form of neutrinos of all kinds.



The **A** potential arises from charged current forward exchange



The neutrino “background” potentials arise from neutral current forward exchange scattering, e.g.,



flavor diagonal potential **B**

flavor off-diagonal potential **B**<sub>eτ</sub>

# Neutrino Self Coupling

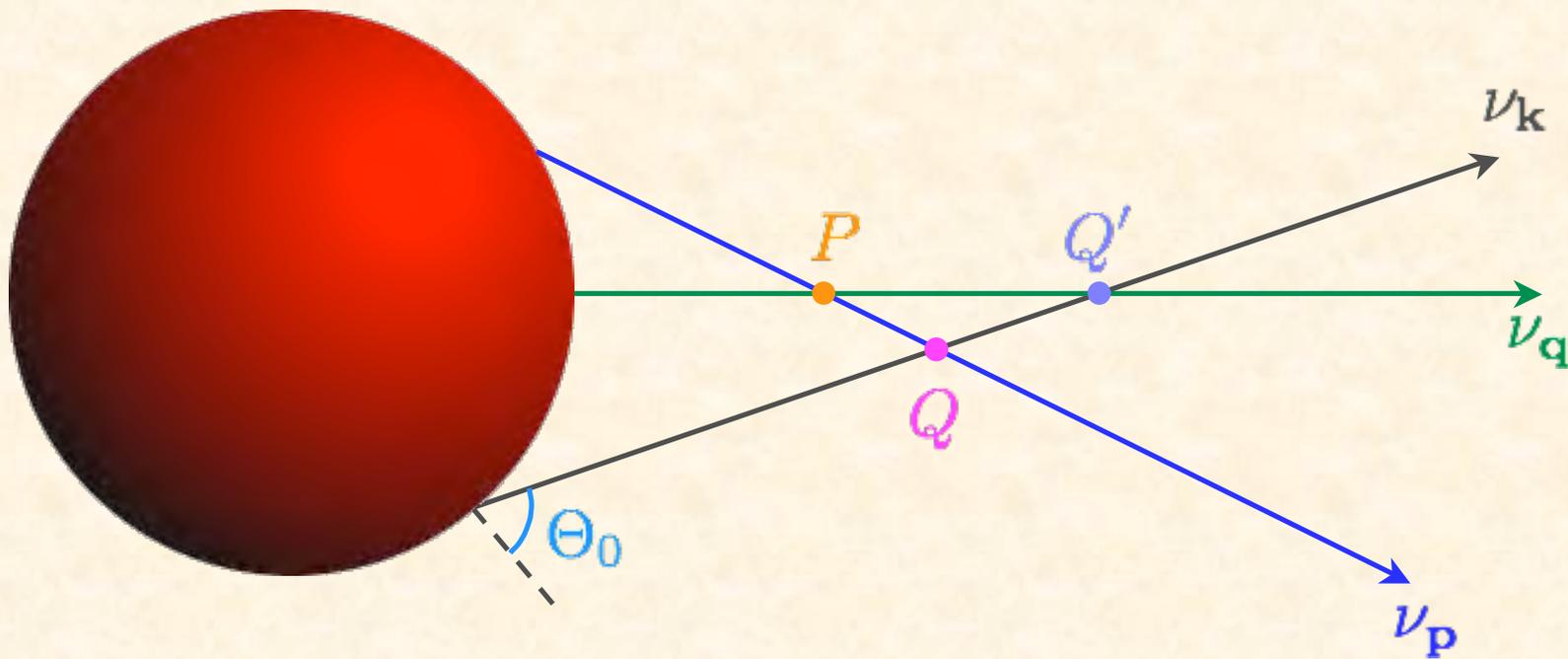
- Neutrino-neutrino forward scattering

$$i \frac{d}{dt} \psi_{\nu,i} = (\mathcal{H}_{\text{vac},i} + \mathcal{H}_e + \mathcal{H}_{\nu\nu,i}) \psi_{\nu,i}$$

$$\begin{aligned} \mathcal{H}_{\nu\nu,i} \equiv & \sqrt{2}G_F \sum_j (1 - \hat{\mathbf{k}}_i \cdot \hat{\mathbf{k}}_j) n_{\nu,j} \psi_{\nu,j} \psi_{\nu,j}^\dagger \\ & - \sqrt{2}G_F \sum_j (1 - \hat{\mathbf{k}}_i \cdot \hat{\mathbf{k}}_j) n_{\bar{\nu},j} (\psi_{\bar{\nu},j} \psi_{\bar{\nu},j}^\dagger)^* \end{aligned}$$

# The complication . . .

- Anisotropic, nonlinear coupling of all neutrino flavor evolution histories



On *each* trajectory we must solve

$$i \frac{d}{dt} \begin{pmatrix} a_{e\alpha} \\ a_{\tau\alpha} \end{pmatrix} = \hat{H}_f \begin{pmatrix} a_{e\alpha} \\ a_{\tau\alpha} \end{pmatrix}$$

$$\hat{H}_f = \begin{pmatrix} A + B - \Delta \cos 2\theta & \Delta \sin 2\theta + B_{e\tau} \\ \Delta \sin 2\theta + B_{e\tau}^* & \Delta \cos 2\theta - A - B \end{pmatrix}$$

$$\Delta = \frac{\delta m^2}{2E_\nu}$$



# Neutrino flavor evolution in core collapse supernovae

(including large-scale numerical simulations  
with coupled trajectories)

Huaiyu Duan (UCSD)

George M. Fuller (UCSD)

Joseph A. Carlson (LANL)

Yong-Zhong Qian (U. Minn.)



“Coherent Development of Neutrino Flavor in the Supernova Environment,”  
H. Duan, G.M. Fuller, J. Carlson, Y.-Z. Qian, Phys. Rev. Lett. **97**, 241101 (2006)

“Simulation of coherent nonlinear neutrino flavor transformation in the supernova environment:  
Correlated neutrino trajectories,”  
H. Duan, G.M. Fuller, J. Carlson, Y.-Z. Qian, Phys. Rev. D **74**, 105014 (2006)

“Analysis of Collective Neutrino Flavor Transformation in Supernovae,”  
H. Duan, G.M. Fuller, J. Carlson, Y.-Z. Qian, Phys. Rev. D **75**, 125005 (2007)

“Neutrino Mass Hierarchy and Stepwise Spectral Swapping of Supernova Neutrino Flavors,”  
H. Duan, G.M. Fuller, J. Carlson, Y.-Z. Qian, astro-ph/0707.0290

# Recent analyses of neutrino flavor evolution in core collapse supernovae

“A Simple Picture for Neutrino Flavor Transformation in Supernovae,”

H. Duan, G.M. Fuller, & Y.-Z. Qian, [astro-ph/0706.4293](#)

“Collective neutrino flavor transformation in supernovae,”

H. Duan, G.M. Fuller, & Y.-Z. Qian, *Phys. Rev. D* **74**, 123004 (2006)

“Simultaneous flavor transformation of neutrinos and antineutrinos with dominant potentials from neutrino-neutrino forward scattering,”

G.M. Fuller & Y.-Z. Qian, *Phys. Rev. D* **73**, 023004 (2006)

G.C. Raffelt & A.Y. Smirnov, [hep-ph/0705.1830](#)

S. Hannestad, G.C. Raffelt, G. Sigl, & Y.Y.Y. Wong, *Phys. Rev. D* **74**, 105010 (2006)  
[astro-ph/0608695](#) (the “**flavor pendulum**”)

G.C. Raffelt & G. Sigl [astro-ph/0608695](#)

A.B. Balantekin & H. Yuksel, *New J. Phys.* **7**, 51 (2005)

S. Pastor & G.C. Raffelt, *Phys. Rev. Lett.* **89**, 191101 (2002)

A. Dolgov, S. Hansen, S. Pastor, S. Petcov, G. Raffelt, P. Semikoz [hep-ph/0201287](#)

K. Abazajian, J. Beacom, N. Bell [astro-ph/0203442](#)

# Results of Large-Scale Numerical Calculations

In the sample numerical calculations that follow we have taken:

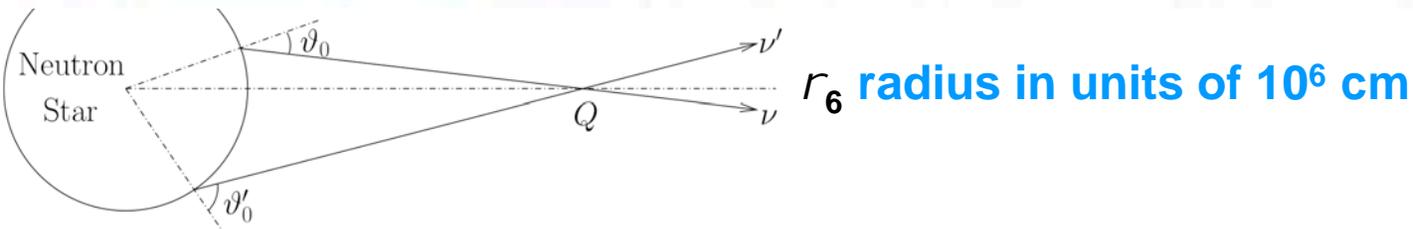
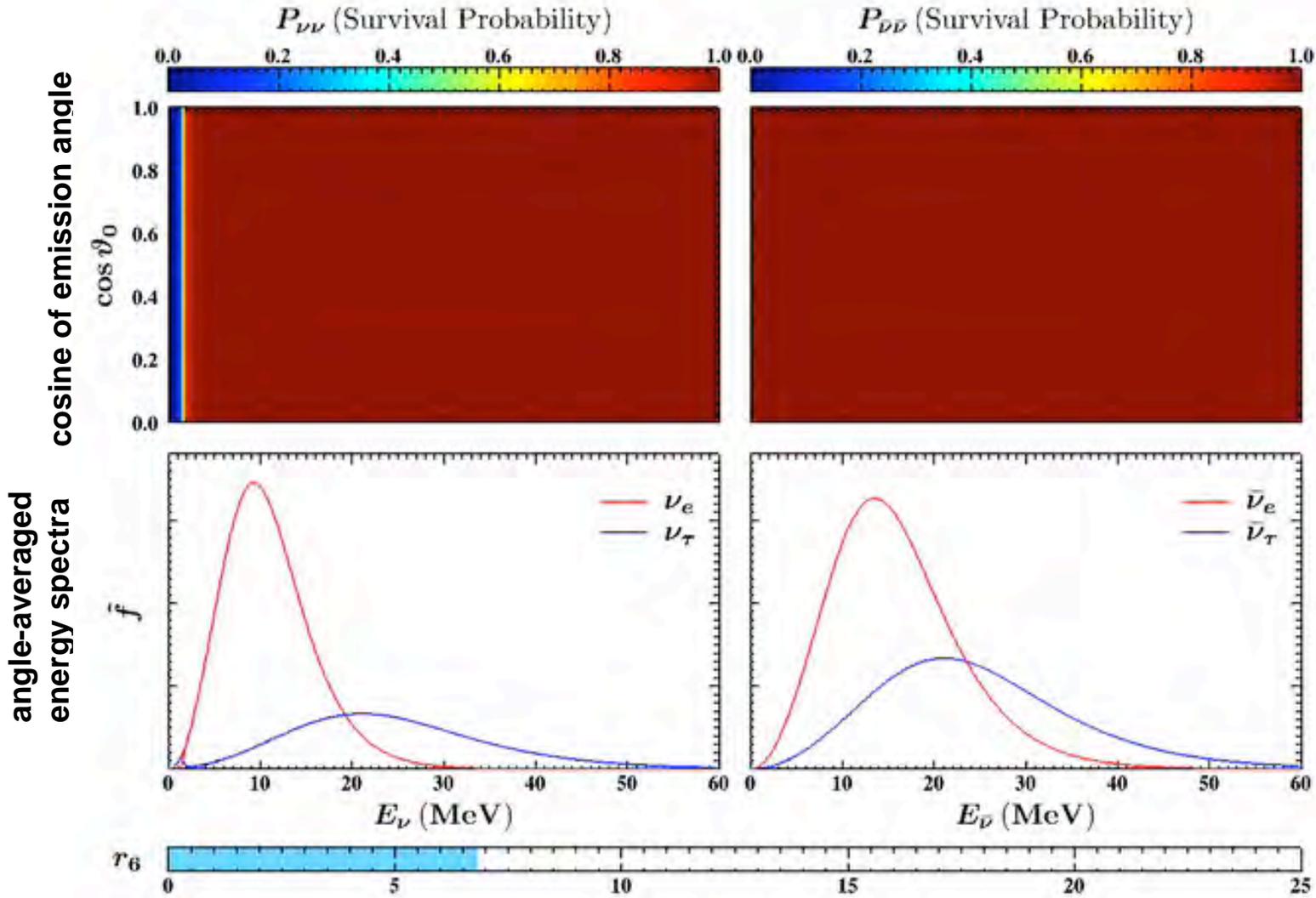
- The neutrino mass-squared difference to be  $\delta m^2 = 3 \times 10^{-3} \text{ eV}^2$
- The effective 2 X 2 vacuum mixing angle to be either
$$\theta_V = 0.1 \quad \text{for the } \mathbf{NORMAL\ MASS\ HIERARCHY}$$
$$\theta_V = \frac{\pi}{2} - 0.1 \quad \text{for the } \mathbf{INVERTED\ MASS\ HIERARCHY}$$
- The neutrino energy luminosities to be the same for all species and either
$$L_\nu \equiv L_{\nu_e} = L_{\bar{\nu}_e} = L_{\nu_\mu} = L_{\bar{\nu}_\mu} = L_{\nu_\tau} = L_{\bar{\nu}_\tau} = 10^{51} \text{ erg s}^{-1}$$
**or**
$$L_\nu = 0 \quad \text{as indicated.}$$

neutrinos  $\nu_e \rightleftharpoons \nu_\tau$

antineutrinos  $\bar{\nu}_e \rightleftharpoons \bar{\nu}_\tau$

NORMAL MASS HIERARCHY

$$I_{\nu} = 0$$

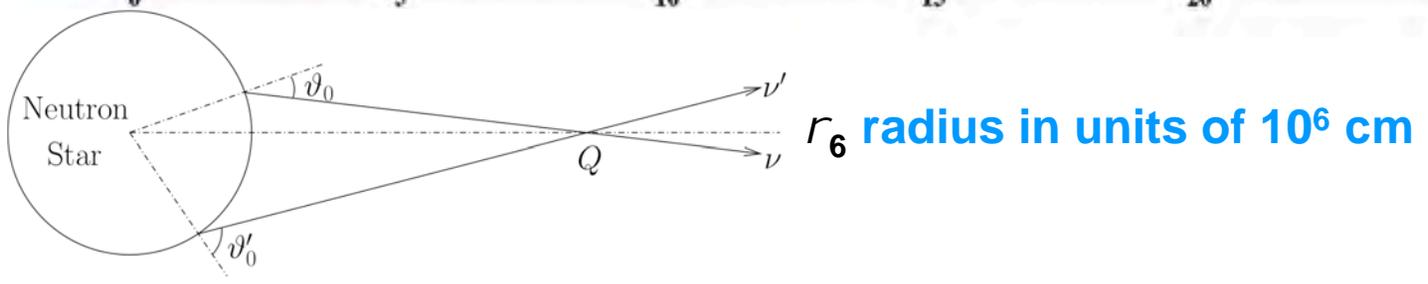
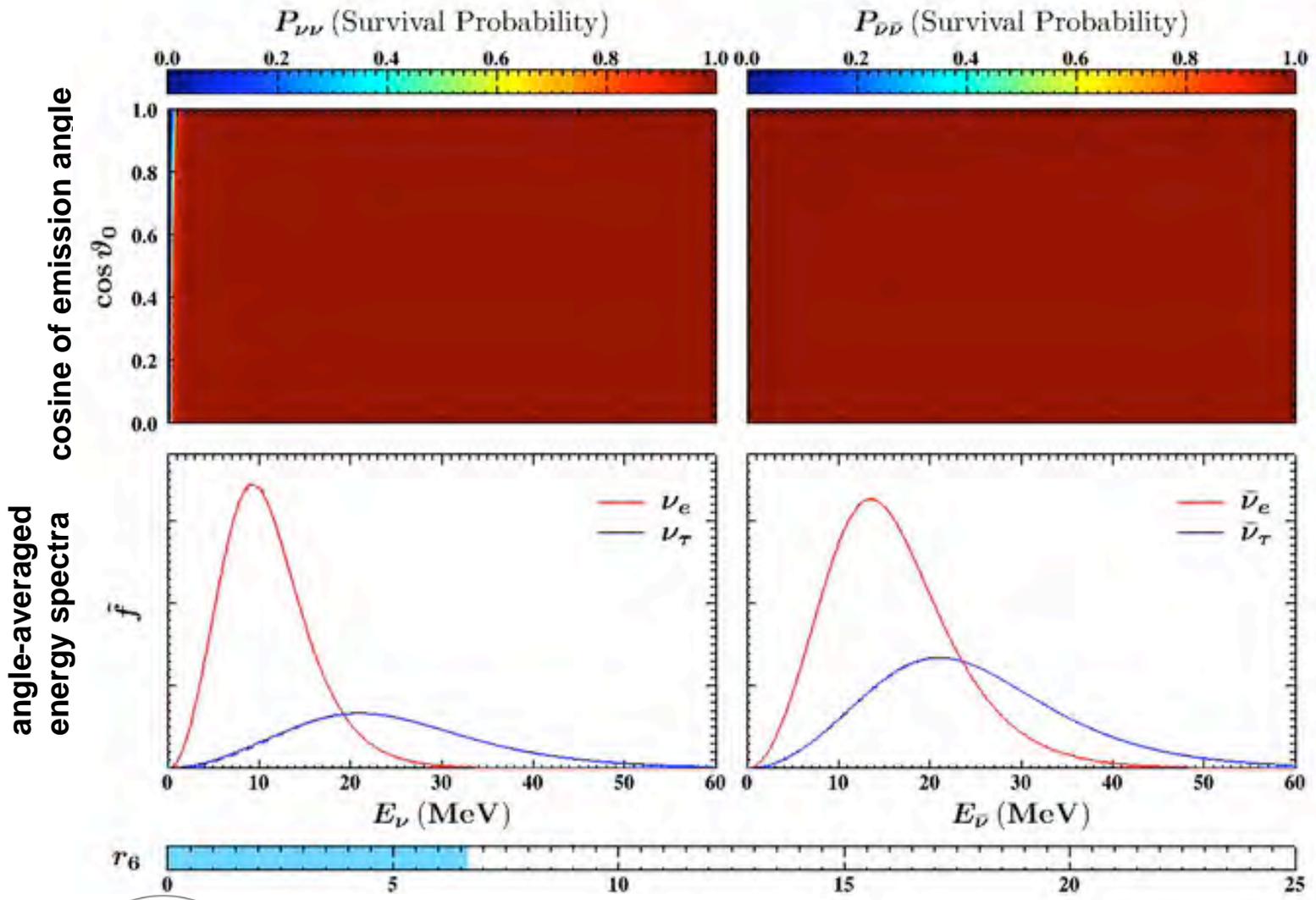


$$L_\nu = 10^{51} \text{ erg s}^{-1}$$

**NORMAL MASS HIERARCHY**

neutrinos  $\nu_e \rightleftharpoons \nu_\tau$

antineutrinos  $\bar{\nu}_e \rightleftharpoons \bar{\nu}_\tau$

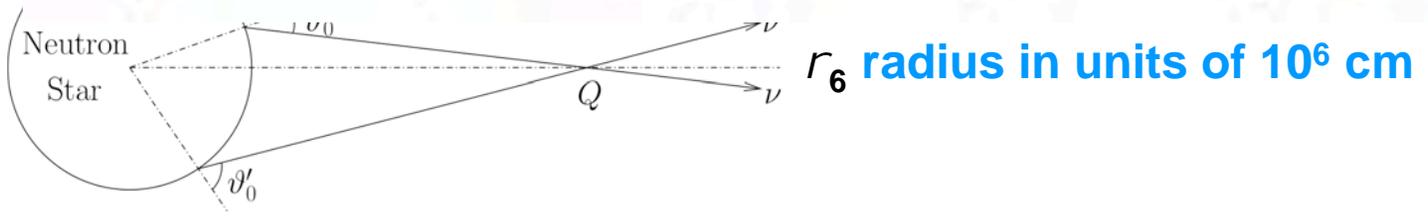
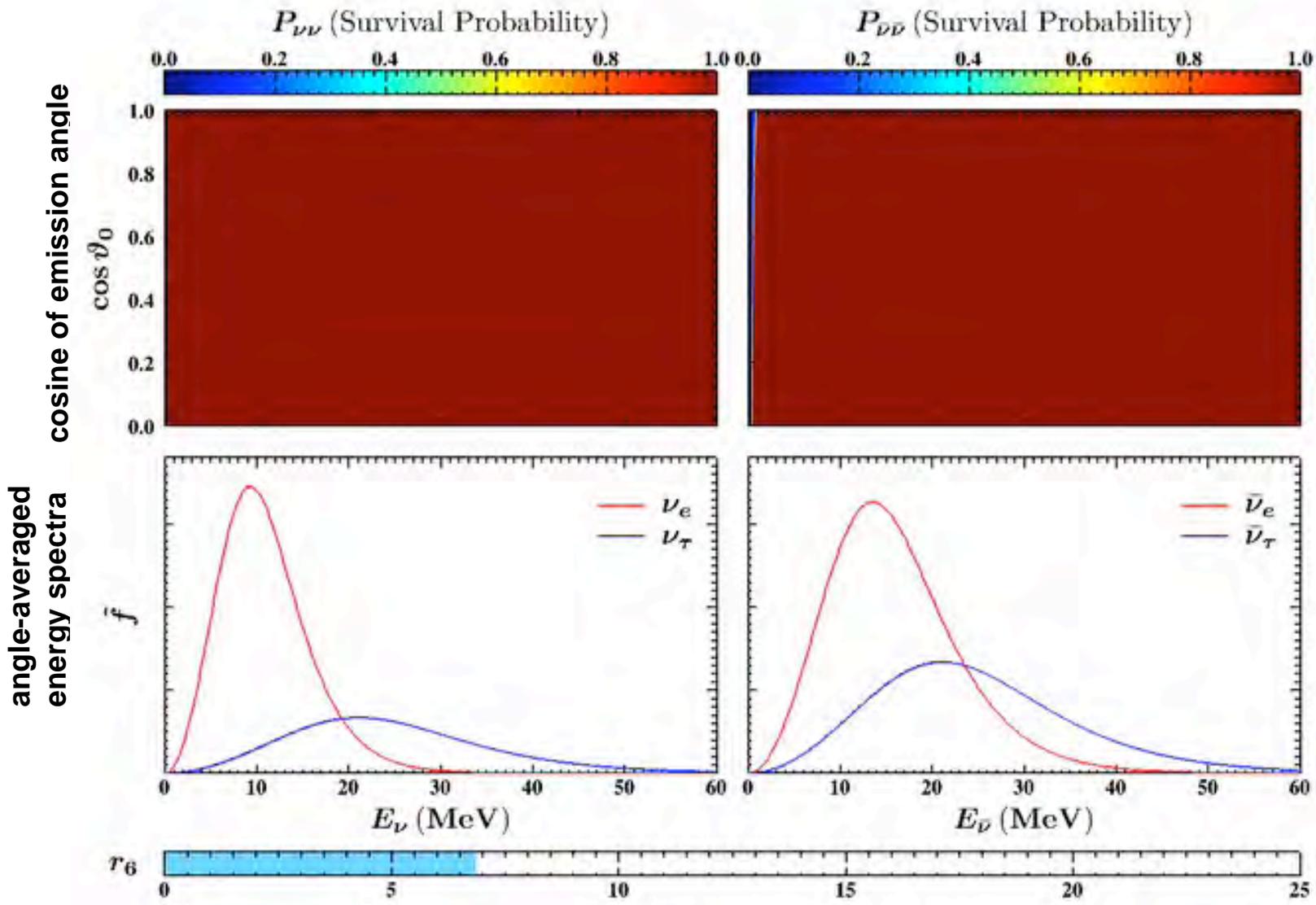


$$L_\nu = 10^{51} \text{ erg s}^{-1}$$

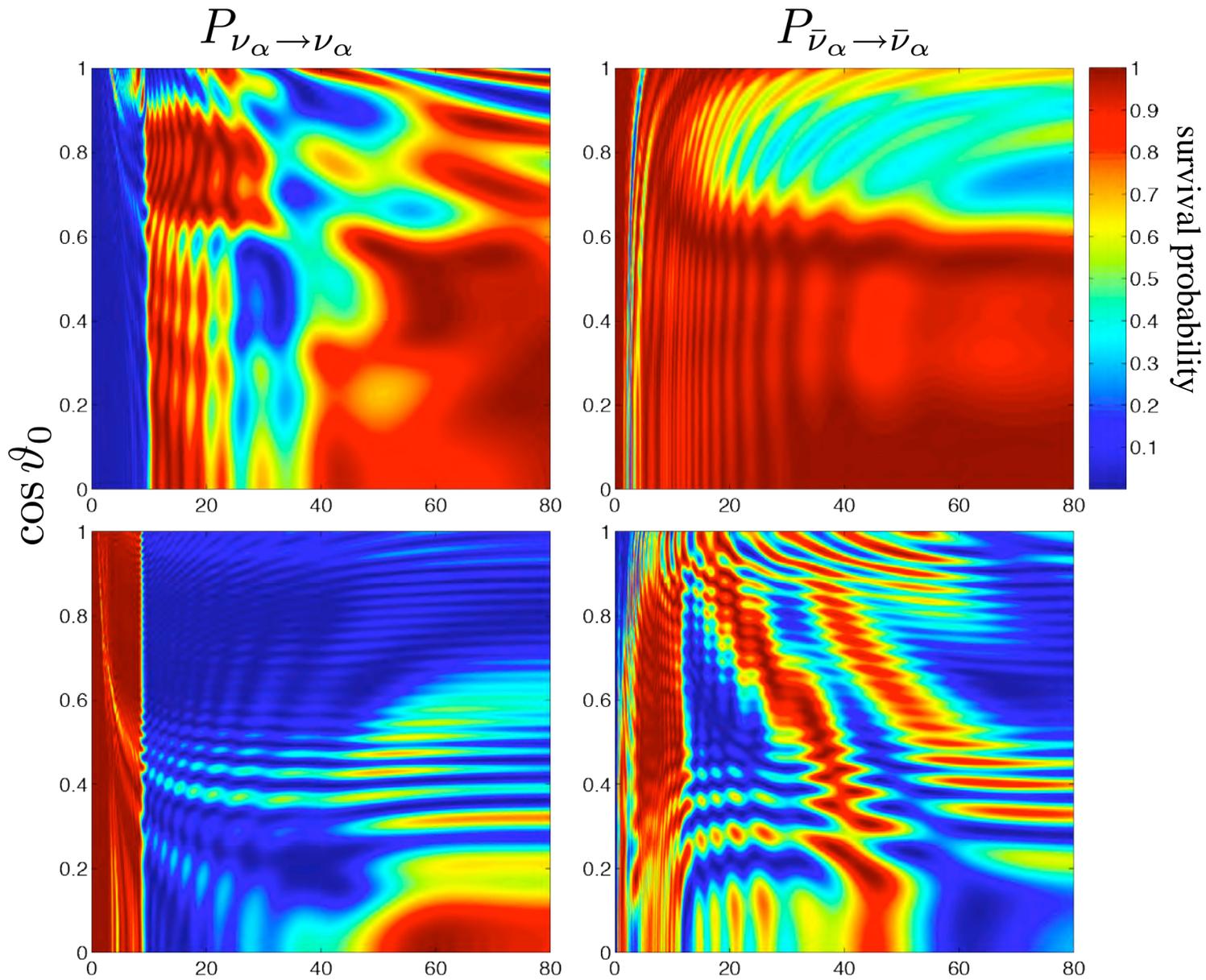
**INVERTED MASS HIERARCHY**

**neutrinos**  $\nu_e \rightleftharpoons \nu_\tau$

**antineutrinos**  $\bar{\nu}_e \rightleftharpoons \bar{\nu}_\tau$



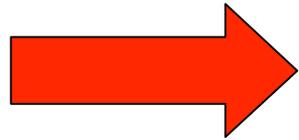
cosine of  $\nu$  trajectory angle wrt. normal to n.s. surface



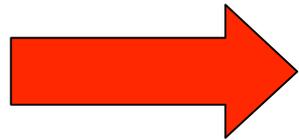
$E_\nu$  (MeV)  
**macroscopic quantum coherence in neutrino/antineutrino fields**

H. Duan, G. M. Fuller, J. Carlson, Y.-Z. Qian, astro-ph/0606616

# So, what happens when the active neutrinos transform among themselves ?



**Shock re-heating *may* be enhanced,  
neutrino nucleosynthesis and signal affected.**  
(nu-process affected by mixing but NOT like in ordinary MSW!)



**R-Process/Alpha-Effect problems may  
or may not get worse.**

# CONCLUSIONS

- The experimental revolution in neutrino physics has given us some of the mass/mixing properties of the neutrinos.  
We must include this physics in models for core collapse supernova physics.
- Neutrino self coupling can alter neutrino flavor evolution in SN, ultimately causing large-scale flavor conversion deep in the supernova envelope, despite the small measured neutrino mass-squared differences.  
MSW-based analyses are inadequate.  
This could affect neutrino-heated nucleosynthesis and the neutrino signal.
- These collective modes may produce distinctive signatures that could allow a supernova neutrino signal to give us the mass hierarchy and  $\theta_{13}$

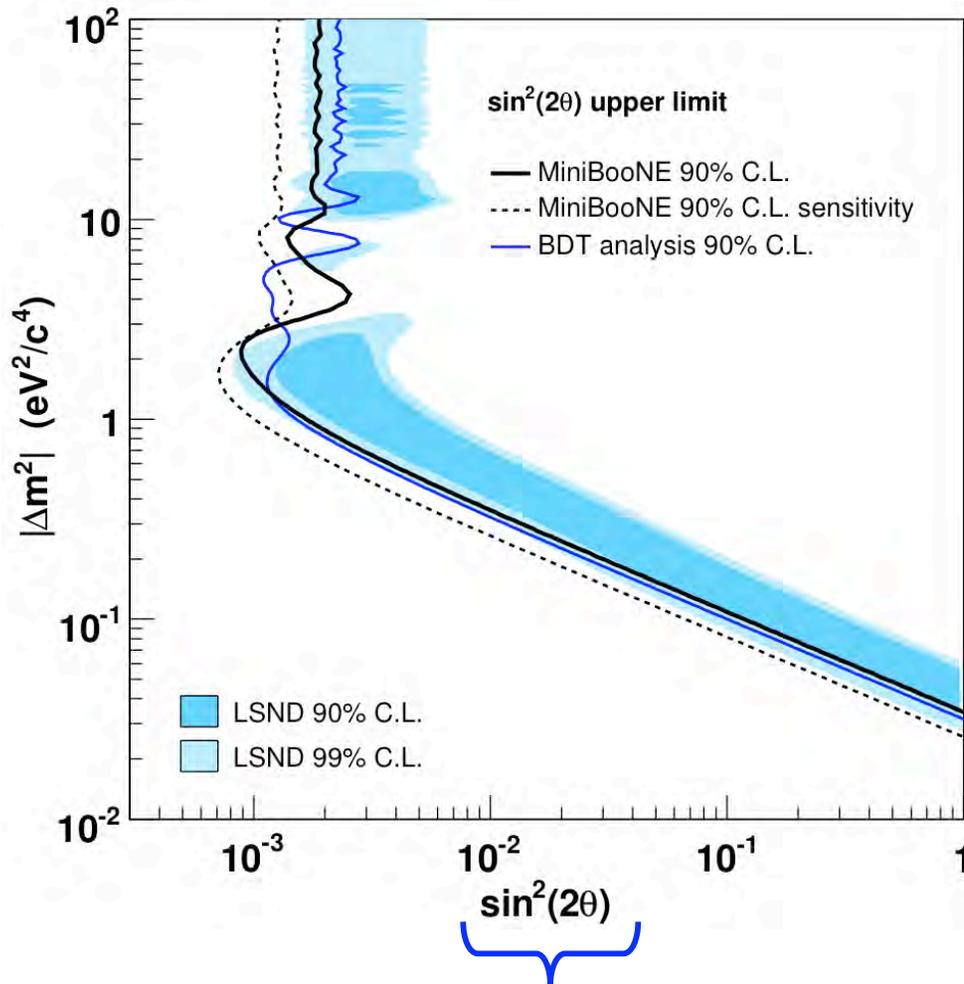
## Unknown unknowns: **right-handed/sterile** neutrino sector

Experiment tells us that neutrinos have mass.  
This fact begs the questions:

Are there right-handed or “sterile” neutrino states?

What are their mass scales?

# MiniBooNE



Inconsistent with the LSND signal.

I take this as a constraint on active-sterile mixing. It does not eliminate much of the astrophysically interesting parameter space.

Why?

Watch out! This refers to an effective 2X2 vacuum mixing angle satisfying (for, e.g., “3+1”)

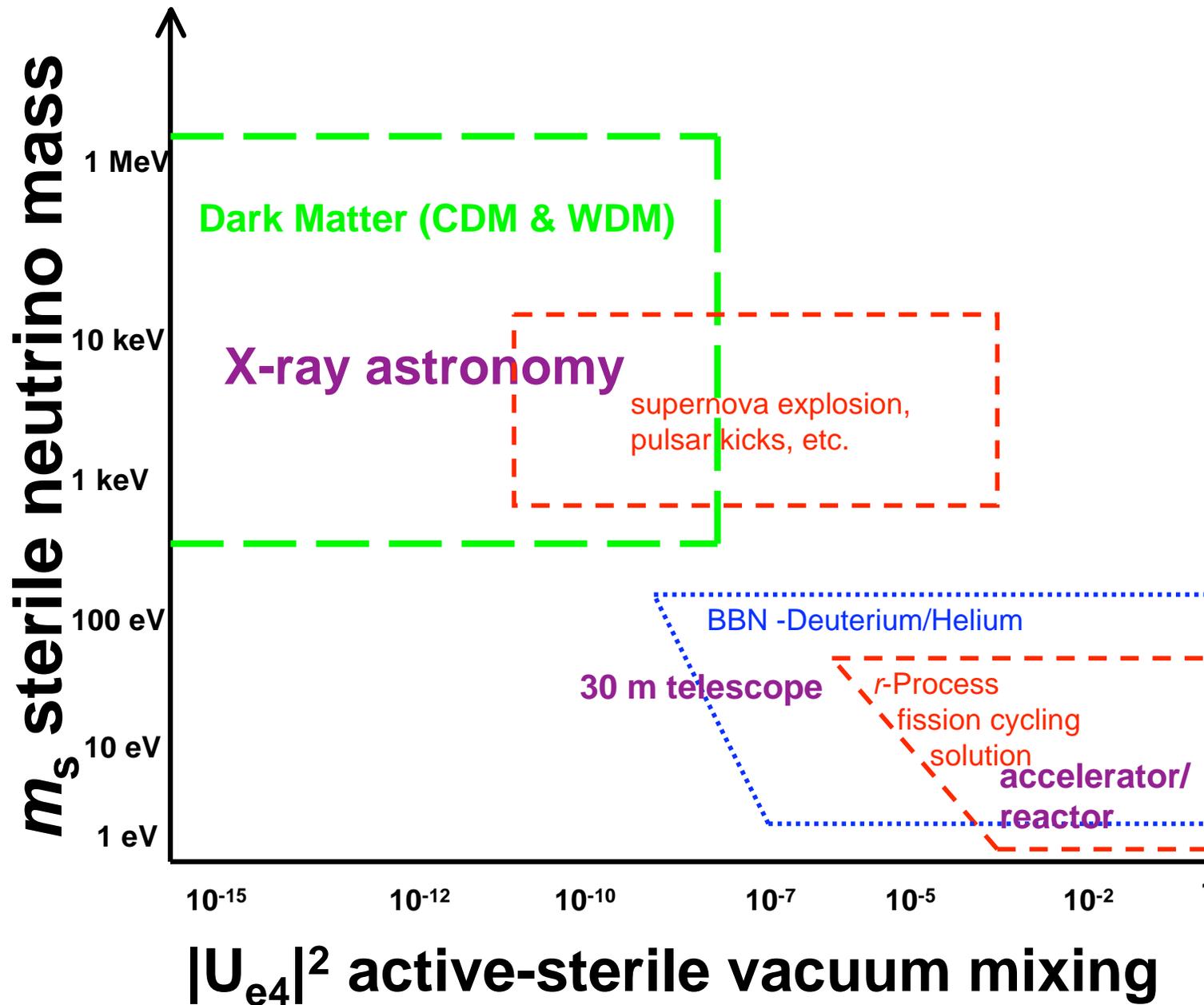
$$\sin^2 2\theta \approx 4|U_{e4}|^2|U_{\mu4}|^2$$

$$\nu_\mu \rightarrow \nu_s \rightarrow \nu_e$$

But for astrophysics we want , e.g., just

$$\nu_e \rightarrow \nu_s \quad \& \quad |U_{e4}|^2$$

# Sterile Neutrino Mass/Mixing of Interest in Astro.

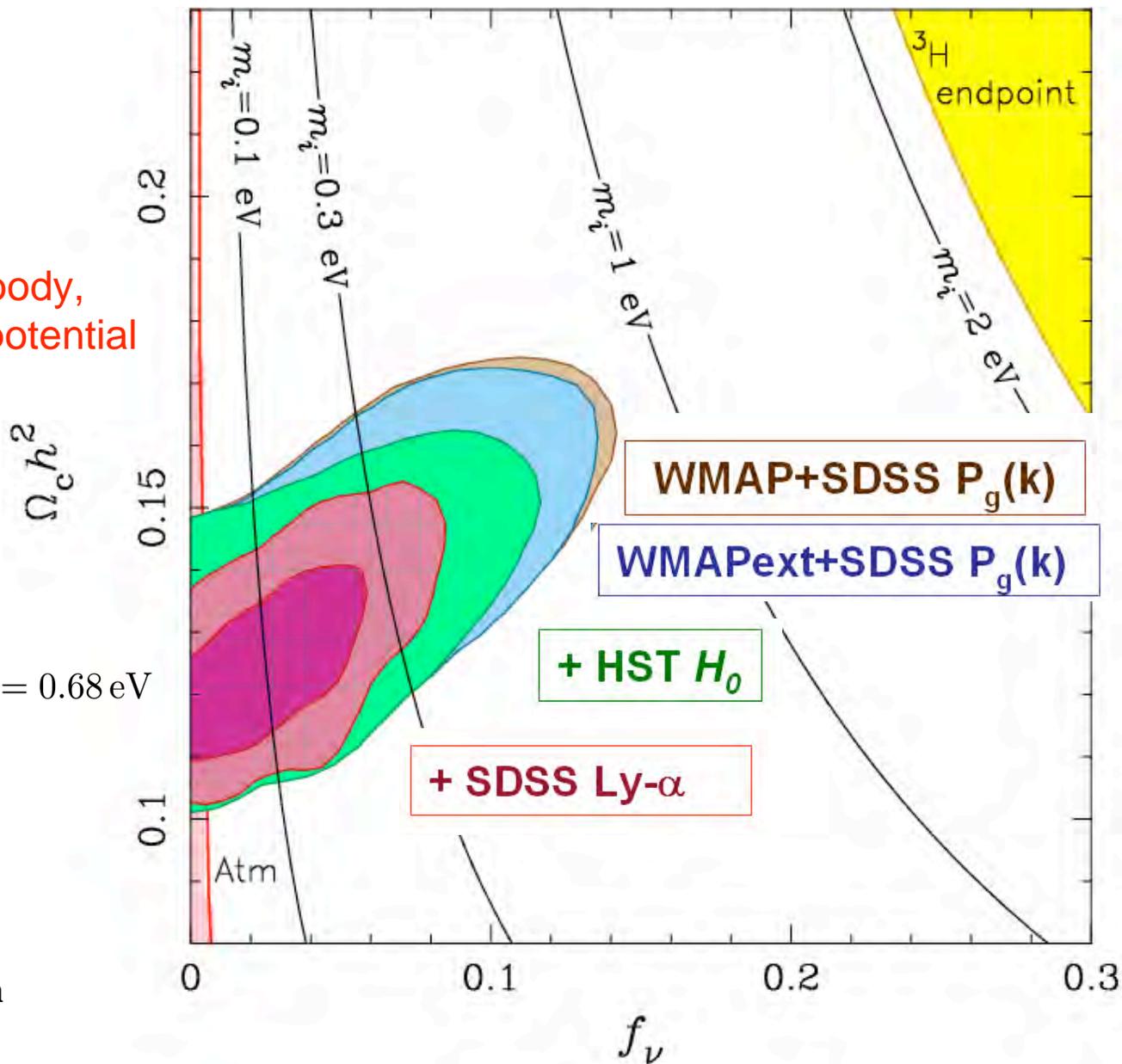


## cosmological constraints on neutrino rest mass

# WMAP<sub>+ACBAR+CBI</sub> + SDSS + HST: $\nu$ Dark Matter

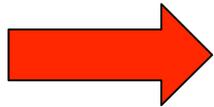
assumes that  
neutrinos have  
thermal, black body,  
zero chemical potential  
energy spectra

$$\text{WMAP } \sum m_\nu = 0.68 \text{ eV}$$



K. Abazajian

# How to avoid full scattering-induced population of sterile neutrino & antineutrino seas



Neutrinos have no mass/mixing at  $T > T_{\text{Decoupling}}$



Low re-heat temperature for inflation ( $T_{\text{re-heat}} \sim T_{\text{decoupling}}$ )  
Gelmini, Palomares-Ruiz, Pascoli, Phys. Rev. Lett 93, 081302 (2004)



Posit a pre-existing lepton number

$$|L_{\nu_\alpha}| > 10^{-3} \text{ for } m_s \sim 1 \text{ eV}$$

Foot & Volkas, Phys. Rev. Lett. 75, 4350 (1995)

Abazajian, Bell, Fuller, Wong, Phys. Rev. D72, 063004 (2005)

**baryon number of universe**  $\longrightarrow \eta \equiv \frac{n_b - n_{\bar{b}}}{n_\gamma}$

From CMB acoustic peaks, and/or  
observationally-inferred primordial D/H:

$$\eta \approx 6 \times 10^{-10}$$

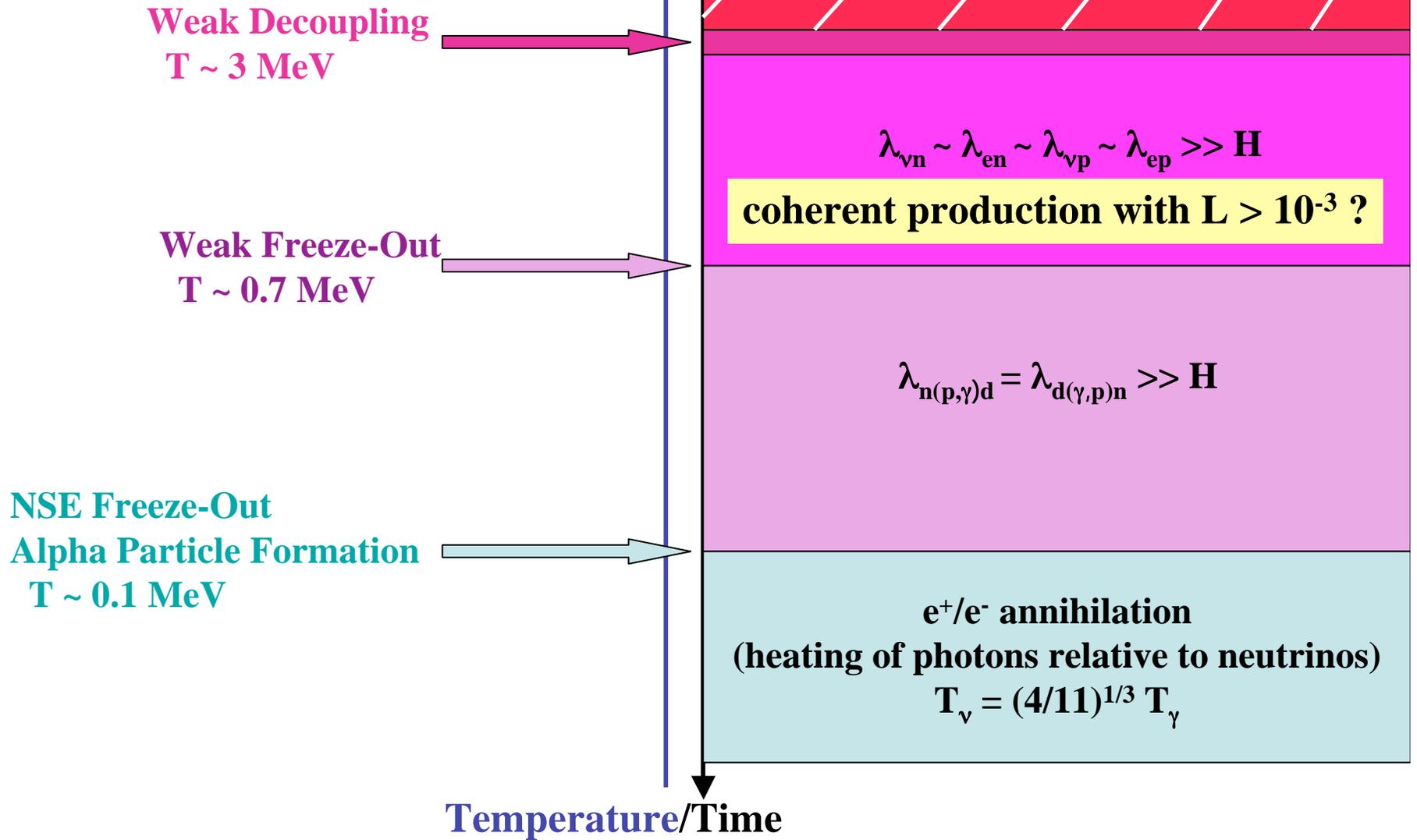
**three lepton numbers**  $\longrightarrow$

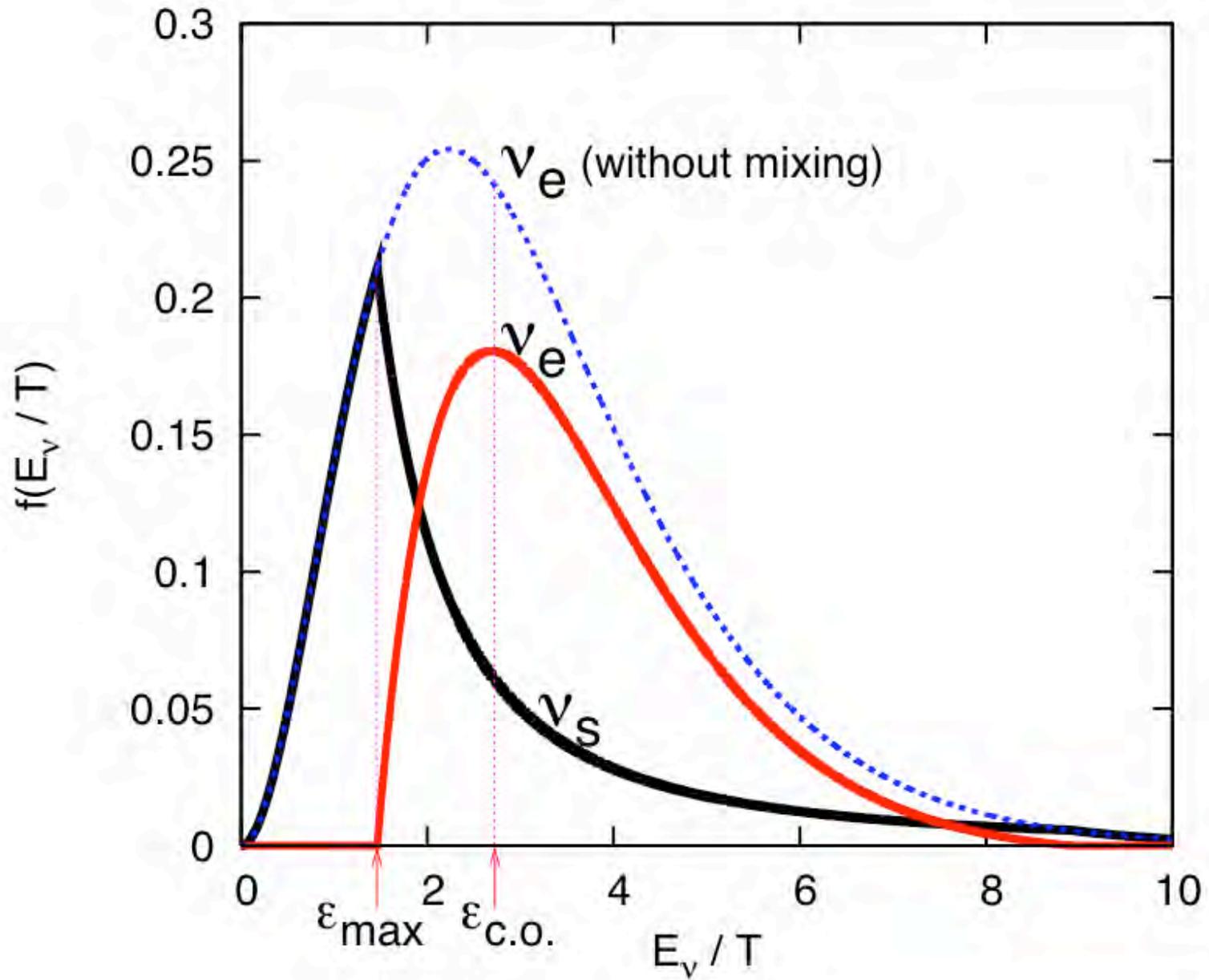
$$\left\{ \begin{array}{l} L_{\nu_e} \approx \frac{n_{\nu_e} - n_{\bar{\nu}_e}}{n_\gamma} \\ L_{\nu_\mu} = \frac{n_{\nu_\mu} - n_{\bar{\nu}_\mu}}{n_\gamma} \\ L_{\nu_\tau} = \frac{n_{\nu_\tau} - n_{\bar{\nu}_\tau}}{n_\gamma} \end{array} \right.$$

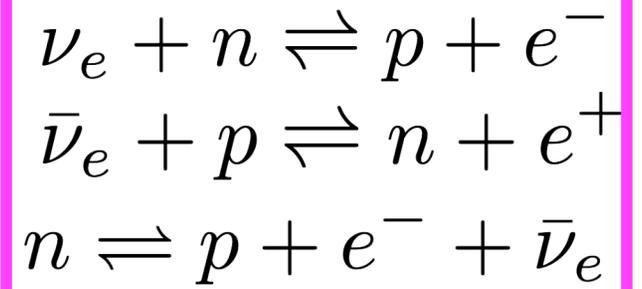
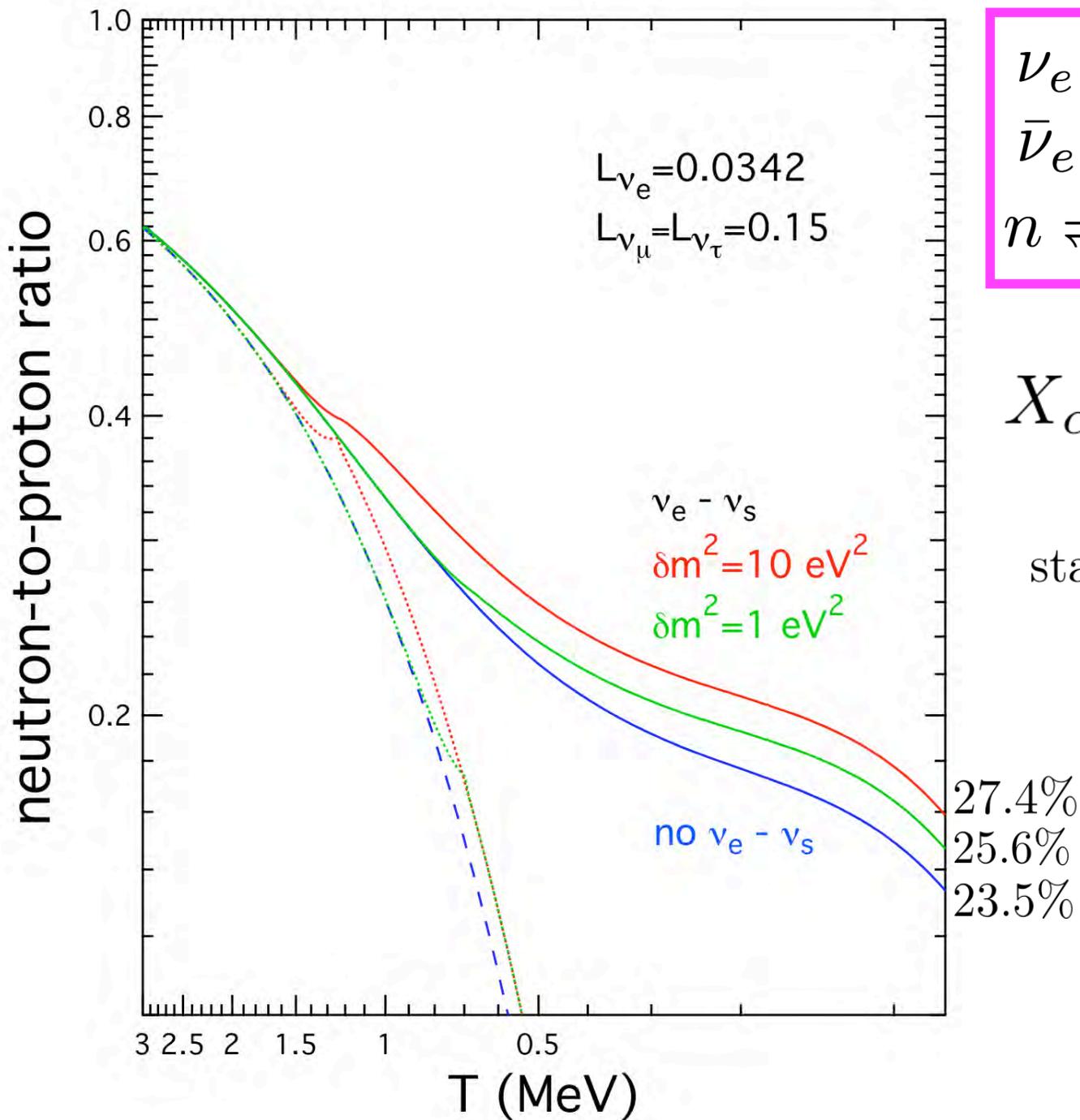
From observationally-inferred  $^4\text{He}$  and large scale structure  
and using *collective active-active neutrino oscillations*  
(Abazajian, Beacom, Bell 03; Dolgov et al. 03):

$$|L_{\nu_{\mu,\tau}}| \sim L_{\nu_e} < 0.15$$

# Weak Interaction/NSE-Freeze-Out History of the Early Universe



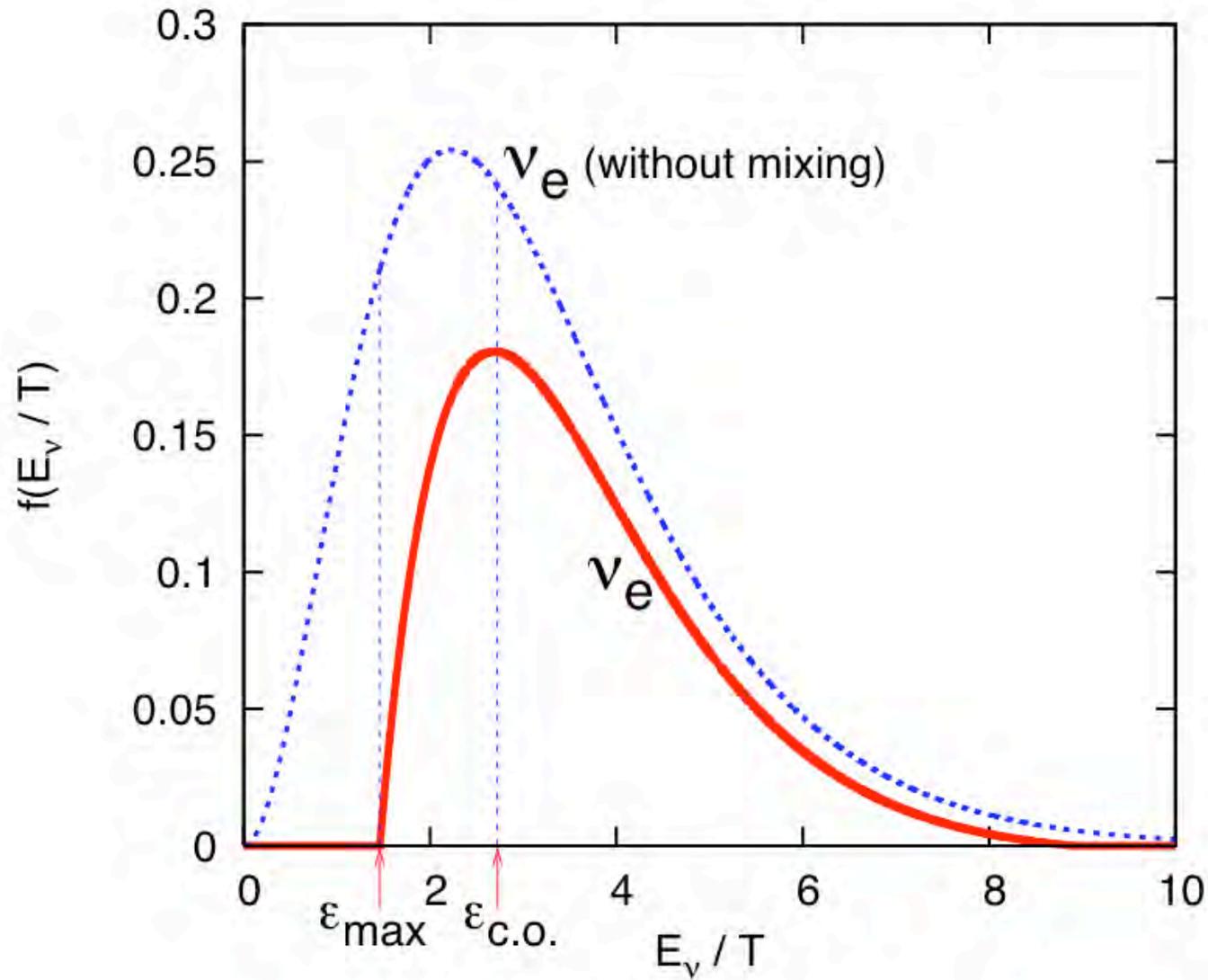




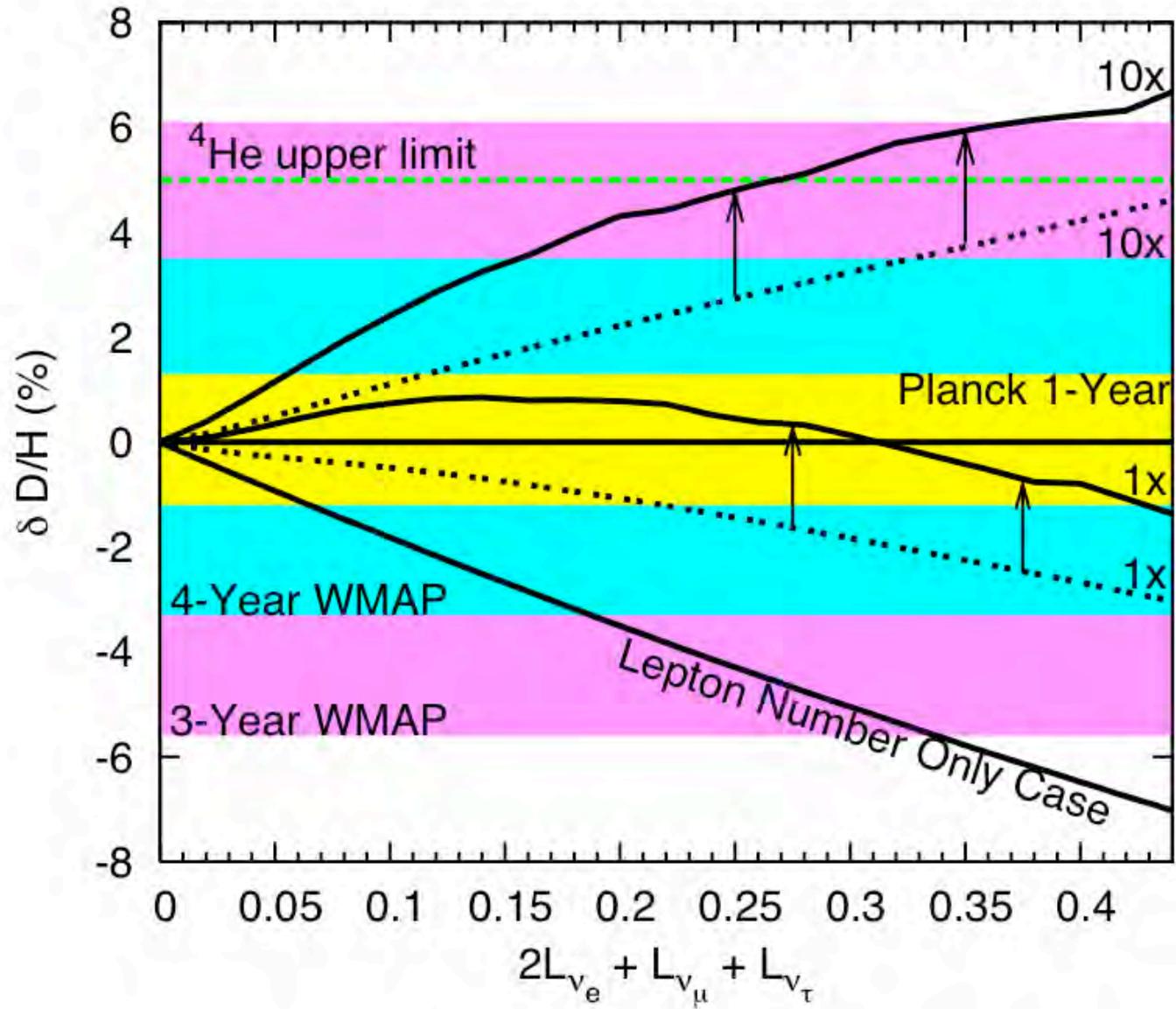
$$X_\alpha \approx \frac{2(n/p)}{1 + (n/p)}$$

standard BBN 24.7%

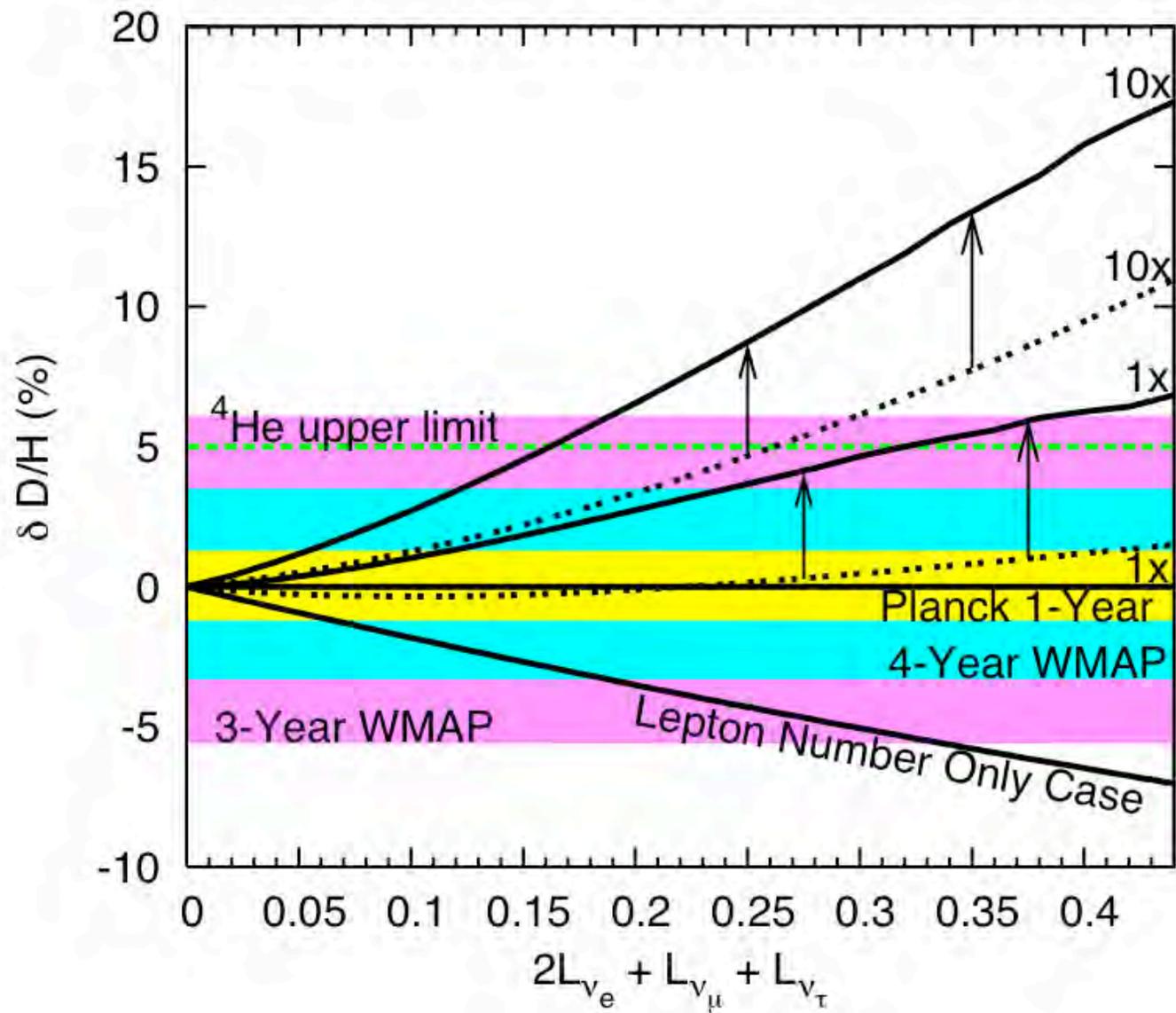
# full solution



$$\delta m^2 = 1 \text{ eV}^2$$

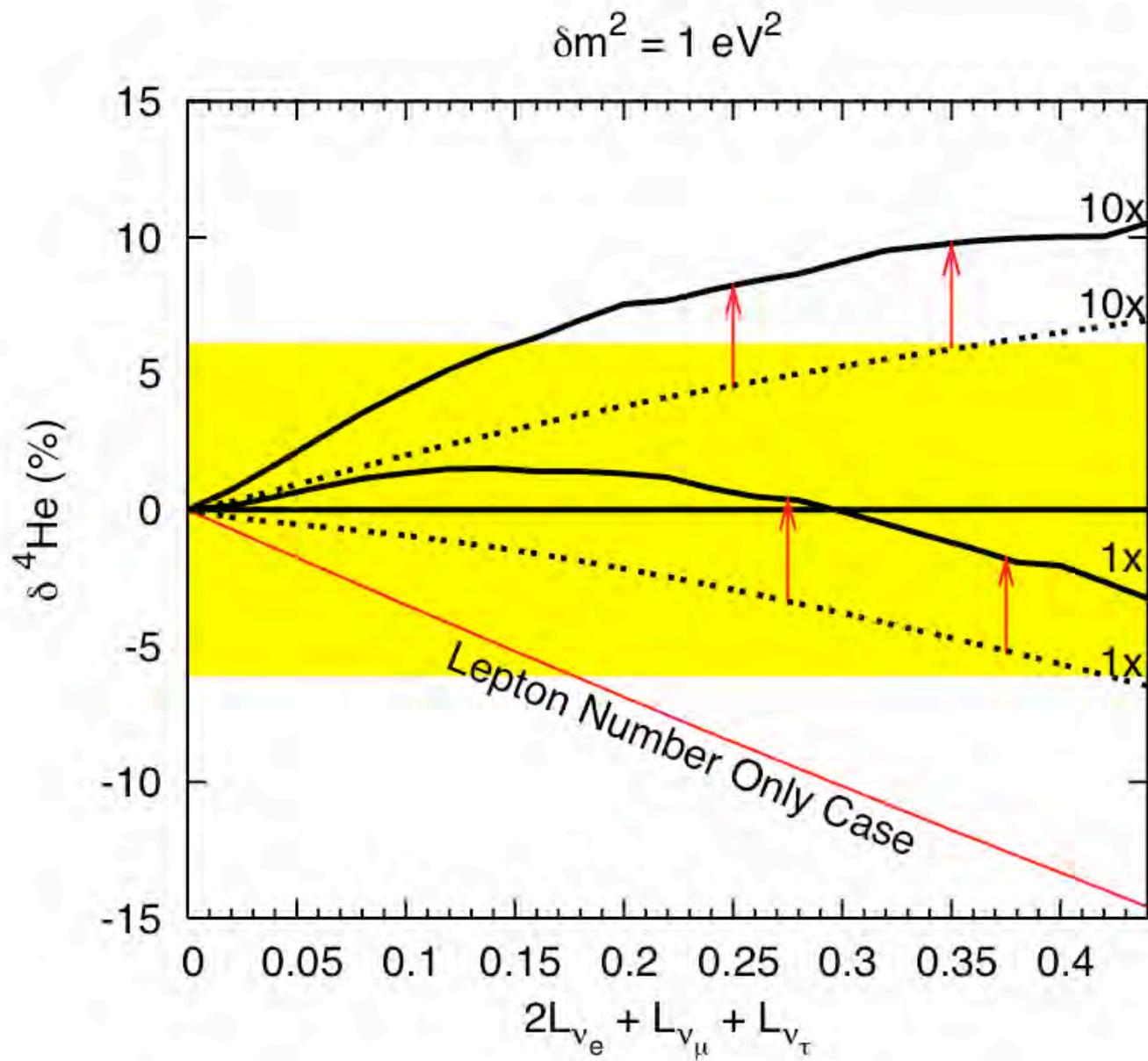


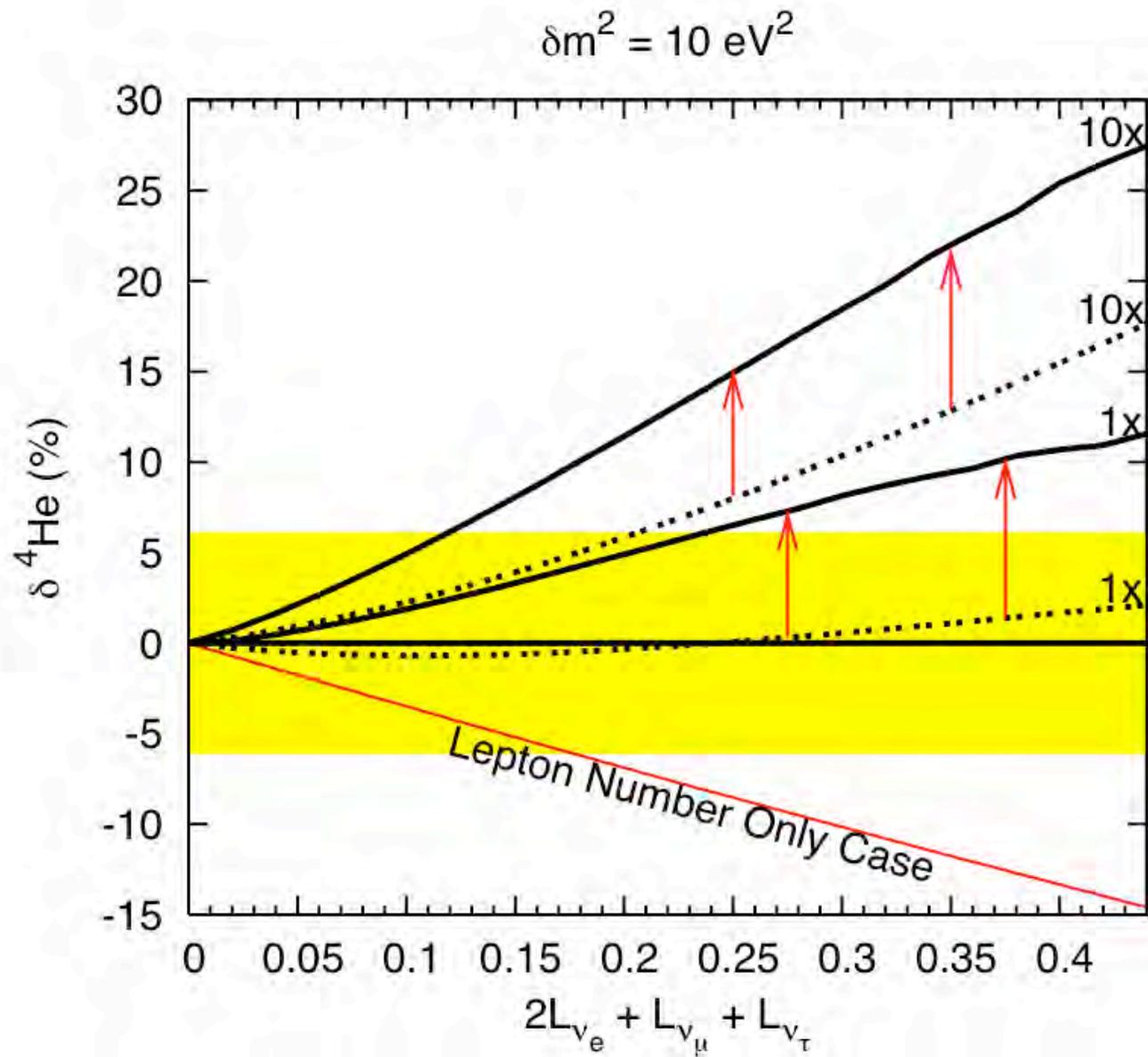
$$\delta m^2 = 10 \text{ eV}^2$$



$$\text{factor} \equiv \frac{L_{\nu_{\mu}} + L_{\nu_{\tau}}}{2L_{\nu_e}}$$

e.g., factor = “1X” and “10X”, etc. on the plots



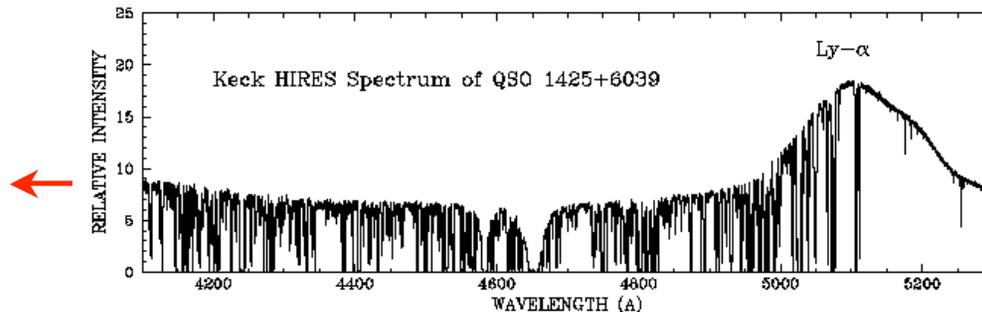


# Primordial Deuterium Abundance

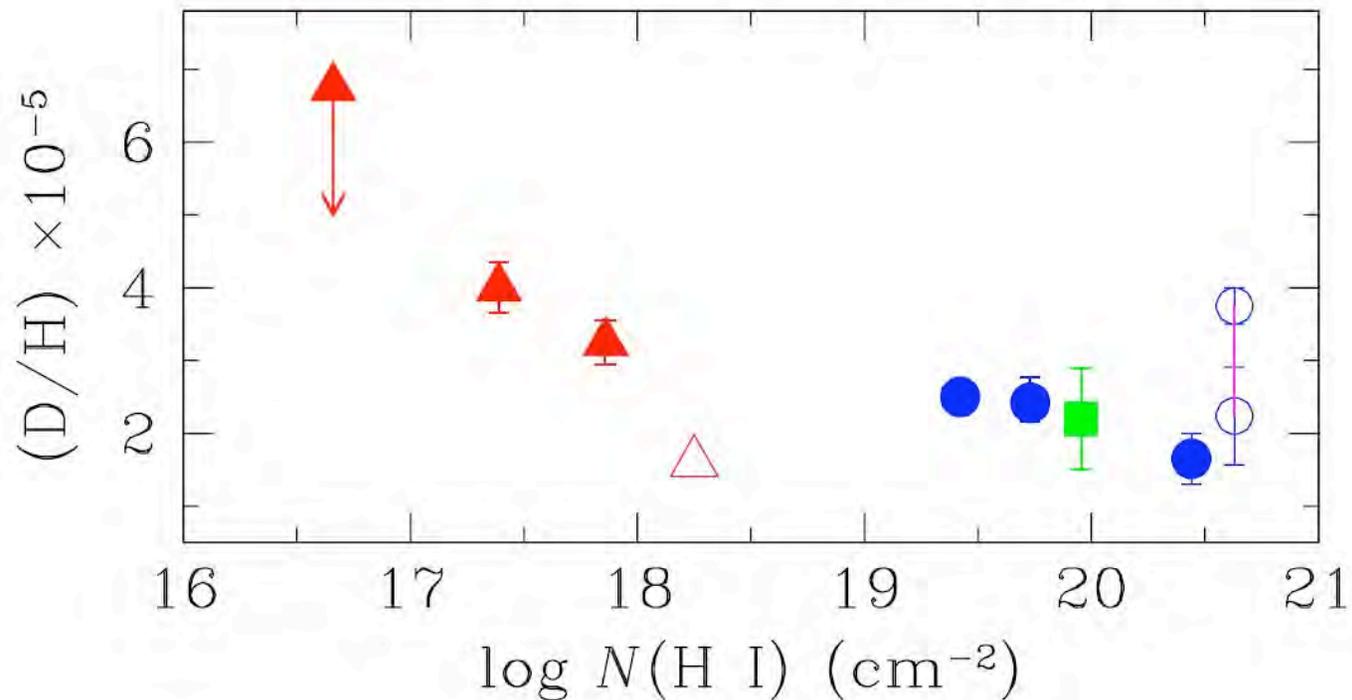
From observations of isotope-shifted Lyman lines in the spectra of high redshift QSO's.

See for example: J.M. O'Meara, D. Tytler, D. Kirkman, N. Suzuki, J.X. Prochaska, D. Lubin, & A.M. Wolfe  
*Astrophys. J.* **552**, 718 (2001)

D. Kirkman, D. Tytler, N. Suzuki, J.M. O'Meara, & D. Lubin  
*Astrophys. J. Suppl. Ser.* **149**, 1 (2003)



## (D/H) in LLS and DLAs



**M. Petini** in *Astrophysics in the Far UV: five years of discovery with FUSE*  
ed. G. Sonneborn, H. Moos, B.G. Andersson, ASP Conf. Ser. **348**, pg. 19

## Uncertainty in Primordial Deuterium Abundance

arguably ~15% to ~30% with current data

With the advent of 30m class telescopes ([hence, many more “clean” QSO absorption systems](#)), we might get the uncertainty down to ~5% or lower.

# Conclusions

**The existence of light sterile neutrinos which mix with actives could result in distorted, non-thermal energy spectra for both active and sterile neutrinos. This, in turn, could allow sterile neutrinos to escape cosmological mass bounds and could alter significantly the relationship between primordial lepton numbers and the light element BBN abundances yields.**

Improvement in the CMB-derived baryon-to-photon ratio leaves the principal uncertainties in BBN in the leptonic sector.

If the uncertainty in the observationally-inferred  $^2\text{H}$  and/or  $^4\text{He}$  could be reduced significantly, then we can use BBN to provide constraints on, or signatures of, e.g., sterile neutrinos.

# Dark Matter

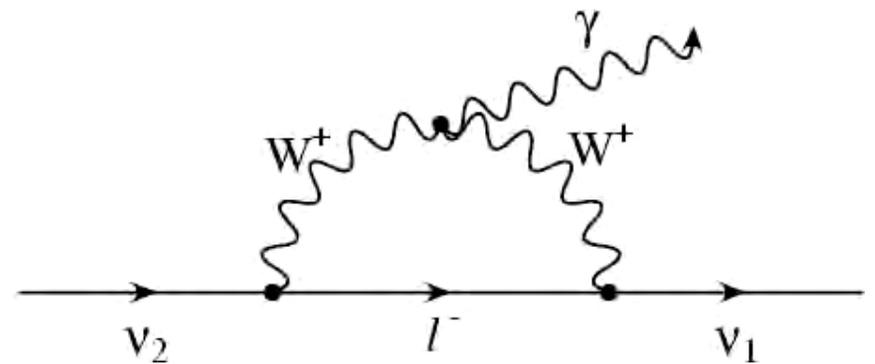
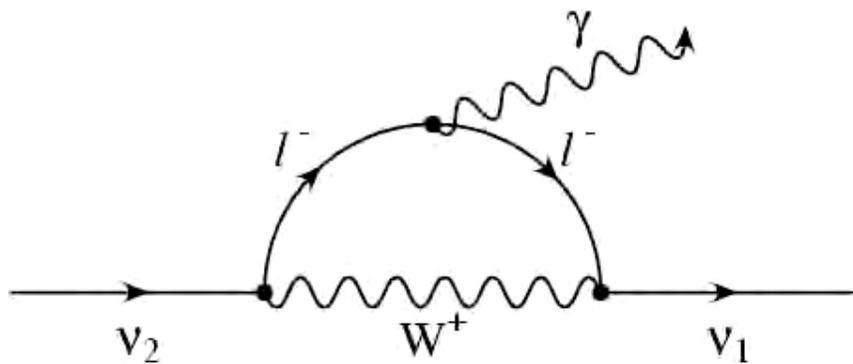
**Sterile neutrinos with rest masses in the  $\sim$  keV to  $\sim$  MeV range and with tiny vacuum mixing with active species could make viable Warm or Cold Dark Matter candidates.**

The best probe of this sector of particle physics is X-ray astronomy.

# Singlet “Sterile” Neutrino Dark Matter

- ➔ **Scattering-induced de-coherence, matter-suppressed production**  
[S. Dodelson & L. M. Widrow, Phys. Rev. Lett. 72, 17 \(1994\).](#)
- ➔ **Matter-enhanced (resonant) production**  
[X. Shi & G. M. Fuller, Phys. Rev. Lett. 82, 2832 \(1999\).](#)
- ➔ **Re-look at scattering-induced de-coherence, matter-suppressed production**  
[A. D. Dolgov and S. Hansen, Astropart. Phys. 16, 339 \(2002\).](#)  
[hep-ph/0009083.](#)
- ➔ **Matter-enhanced (resonant) plus matter-suppressed production with proper attention to disappearance of relativistic degrees of freedom**  
[K. Abazajian, G. M. Fuller, M. Patel, Phys. Rev. D64, 023501 \(2001\).](#)  
[astro-ph/0101524; Abazajian & Fuller, Phys. Rev. D66, 023526 \(2002\).](#)
- ➔ **De-coherence plus dilution/production during inflation**  
[T. Asaka, A. Kusenko, and M. Shaposhnikov \(2006\) hep-ph/0602150.](#)

**Radiative decay graphs for heavy singlets.**  
**The final state neutrino and the photon**  
**equally share the rest mass energy of the singlet.**



## Singlet Neutrino Radiative Decay Rate

$$\Gamma_\gamma \approx \frac{\alpha G_F^2}{64\pi^4} m_2^5 \left[ \sum_\beta U_{1\beta} U_{2\beta} F(r_\beta) \right]^2$$
$$\approx 6.8 \times 10^{-33} \text{ s}^{-1} \left( \frac{\sin^2 2\theta}{10^{-10}} \right) \left( \frac{m_s}{\text{keV}} \right)^5$$

no GIM suppression  
for sterile neutrinos

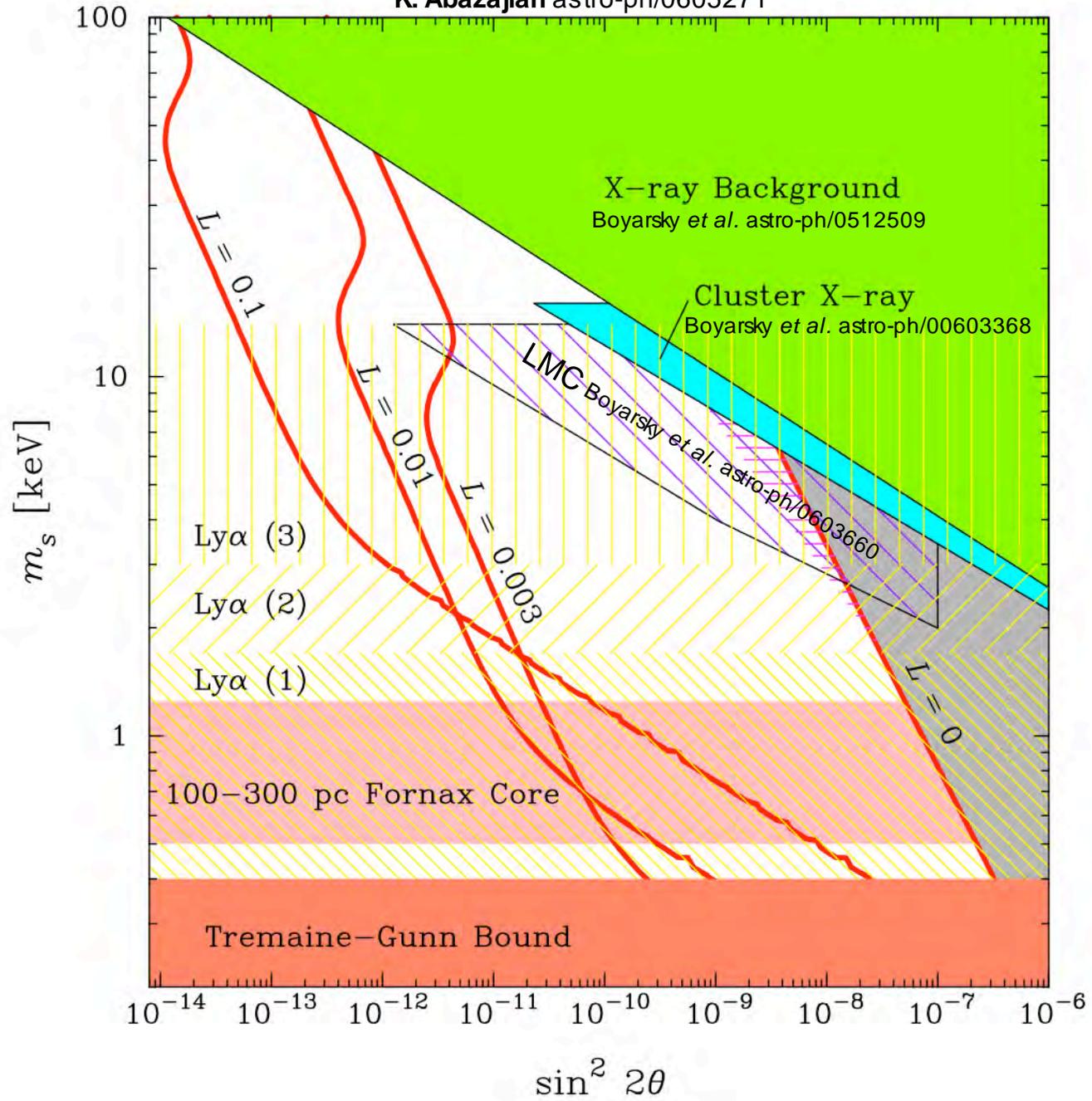
$$F(r_\beta) \approx -\frac{3}{2} + \frac{3}{4} r_\beta$$
$$r_\beta = \left( M_\beta^{\text{lep}} / M_W \right)^2$$



Chandra X-Ray Observatory

# Constellation X





Constraints based on SDSS plus Lyman alpha forest plus high resolution structure formation considerations could provide exceptionally stringent constraints on models with Warm Dark Matter ([Seljak, Makarov, McDonald, & Trac, astro-ph/0602430](#)).

However, these constraints may be altered for sterile neutrinos because, as [Biermann & Kusenko PRL 96, 091301 \(2006\)](#) point out, the x-rays from the radiative decays of these neutrinos can feed back on structure formation by catalyzing the production of molecular hydrogen at early epochs, thereby altering the thermal and ionization history of the universe.

# Fun with **Compact Objects** and ~ keV Rest Mass **Sterile Neutrinos**



## **Pulsar “Kicks”**

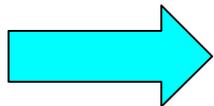
A. Kusenko & G. Segre, PRD 59, 061302 (1999);

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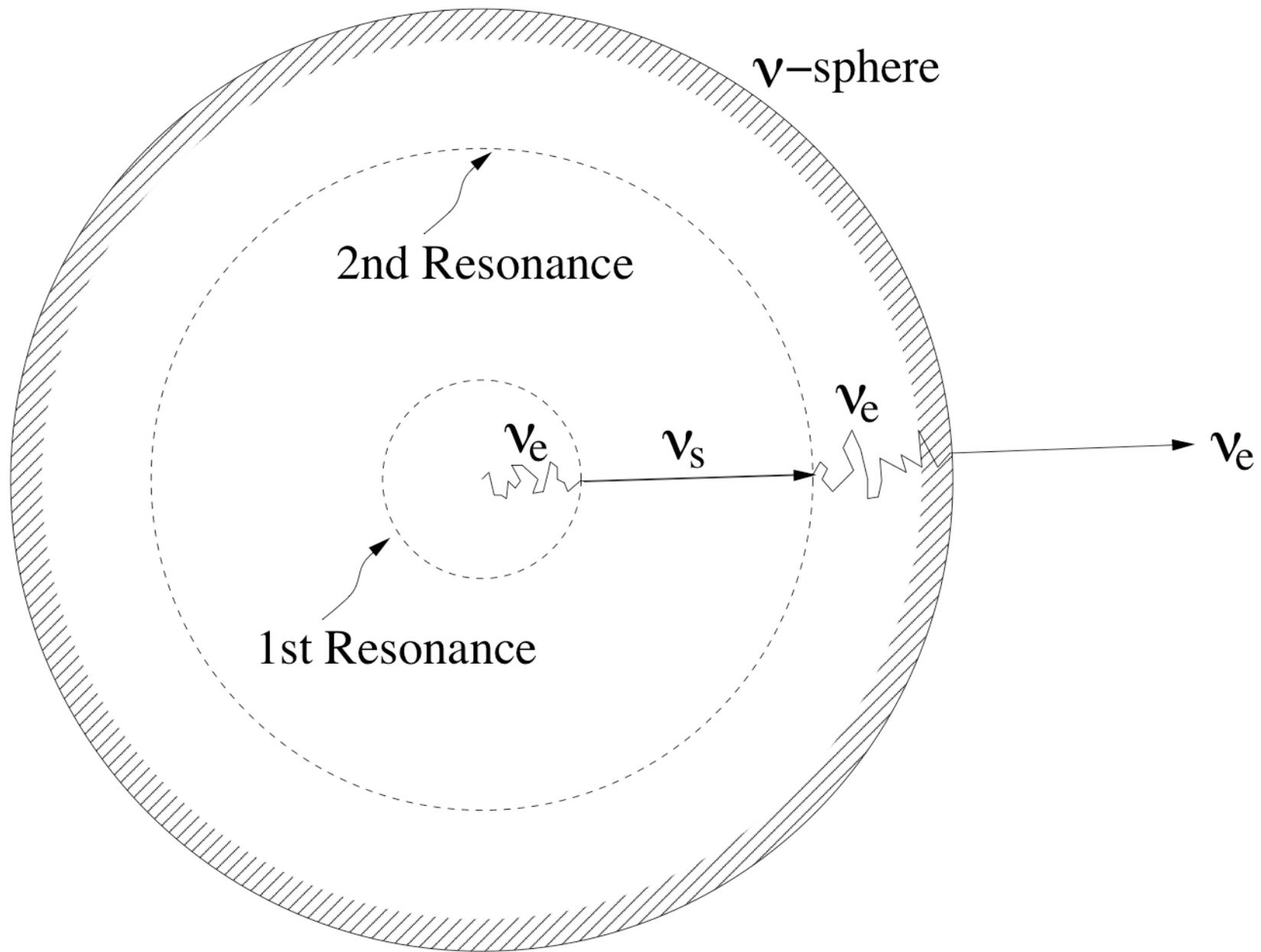
## **Proto-neutron star “kick”-aided hydrodynamic supernova shock enhancement**

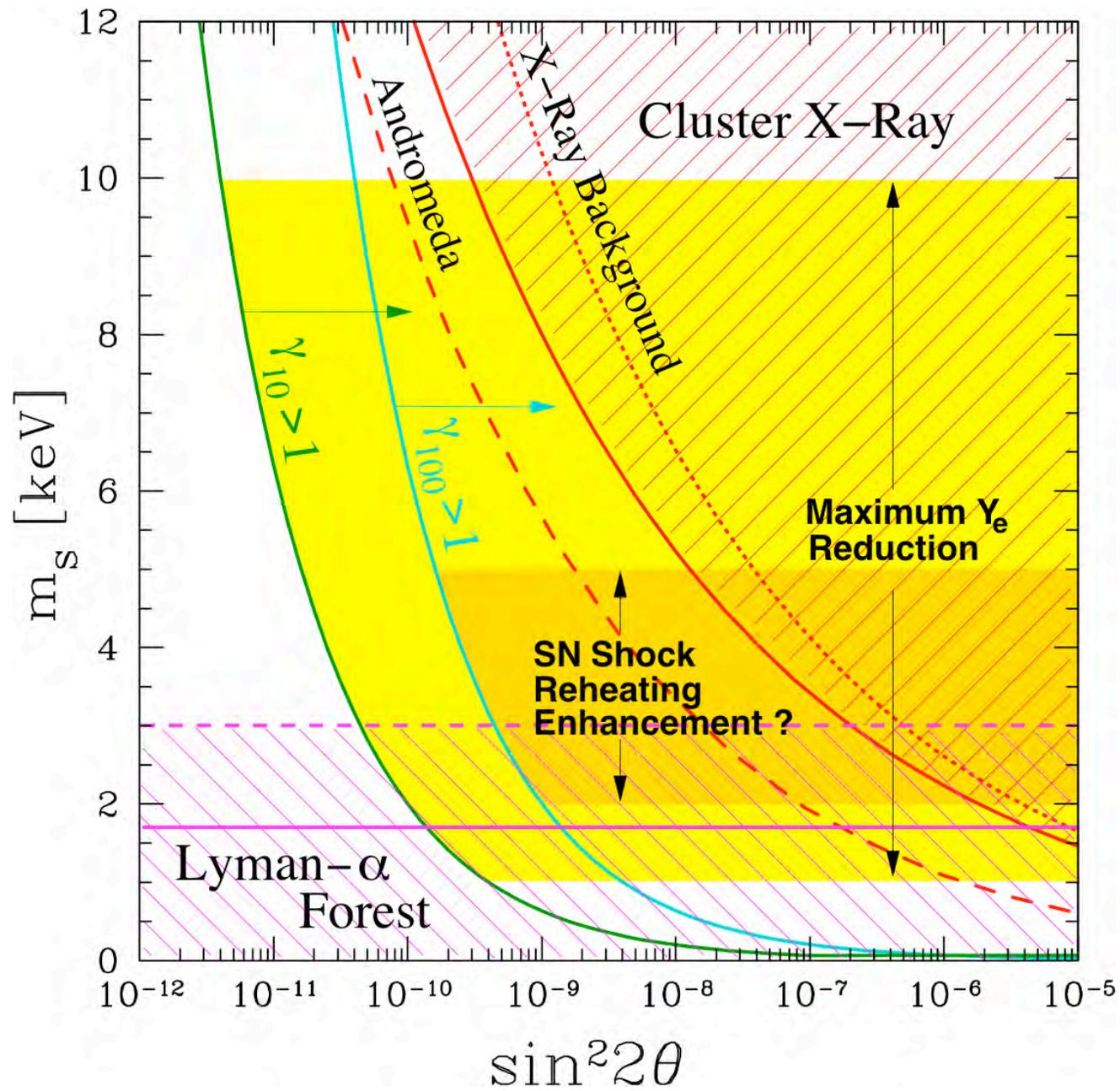
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## More unknown unknowns:

Flavor Changing Neutral Currents??

Electromagnetic properties of neutrinos, e.g.,  
magnetic moment??



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See talks by M. Giannotti and D. Caldwell