Neutrino Astrophysics

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baryon number of universe → $$\eta \equiv \frac{n_{\mathrm{b}} - n_{\bar{\mathrm{b}}}}{n_\gamma}$$

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

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

three lepton numbers →

$$\begin{cases} L_{\nu_e} \approx \dfrac{n_{\nu_e} - n_{\bar{\nu}_e}}{n_\gamma} \\ L_{\nu_\mu} = \dfrac{n_{\nu_\mu} - n_{\bar{\nu}_\mu}}{n_\gamma} \\ L_{\nu_\tau} = \dfrac{n_{\nu_\tau} - n_{\bar{\nu}_\tau}}{n_\gamma} \end{cases}$$

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

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

A significant lepton number ($L > 10^{-4}$)
at $T > T_{\text{decoupling}}$ in the early universe
will suppress the
scattering-induced production of
light sterile neutrinos and antineutrinos

(we will see why below)

Low-Temperature Neutrino Forward Scattering Potentials

$$H(\nu_s) = 0$$

$$H(\nu_e) = \sqrt{2}G_F\left(n_e - \tfrac{1}{2}n_n\right) + \sqrt{2}G_F\left[2\left(n_{\nu_e} - n_{\bar{\nu}_e}\right) + \left(n_{\nu_\mu} - n_{\bar{\nu}_\mu}\right) + \left(n_{\nu_\tau} - n_{\bar{\nu}_\tau}\right)\right]$$

$$H(\nu_\mu) = \sqrt{2}G_F\left(-\tfrac{1}{2}n_n\right) + \sqrt{2}G_F\left[\left(n_{\nu_e} - n_{\bar{\nu}_e}\right) + 2\left(n_{\nu_\mu} - n_{\bar{\nu}_\mu}\right) + \left(n_{\nu_\tau} - n_{\bar{\nu}_\tau}\right)\right]$$

$$H(\nu_\tau) = \sqrt{2}G_F\left(-\tfrac{1}{2}n_n\right) + \sqrt{2}G_F\left[\left(n_{\nu_e} - n_{\bar{\nu}_e}\right) + \left(n_{\nu_\mu} - n_{\bar{\nu}_\mu}\right) + 2\left(n_{\nu_\tau} - n_{\bar{\nu}_\tau}\right)\right]$$

Define $\mathcal{L}_\alpha \equiv 2L_{\nu_\alpha} + \sum_{\beta\neq\alpha} L_{\nu_\beta}$

$$H(\nu_e) = \sqrt{2}G_F n_\gamma\left(\mathcal{L}_e + \left[\tfrac{3}{2}Y_e - \tfrac{1}{2}\right]\right) \approx \frac{2\sqrt{2}\zeta(3)}{\pi^2}G_F T^3\left(\mathcal{L}_e + \eta/4\right)$$

$$H(\nu_\mu) = \sqrt{2}G_F n_\gamma\left(\mathcal{L}_\mu + \left[\tfrac{1}{2}Y_e - \tfrac{1}{2}\right]\right) \approx \frac{2\sqrt{2}\zeta(3)}{\pi^2}G_F T^3\left(\mathcal{L}_\mu - \eta/4\right)$$

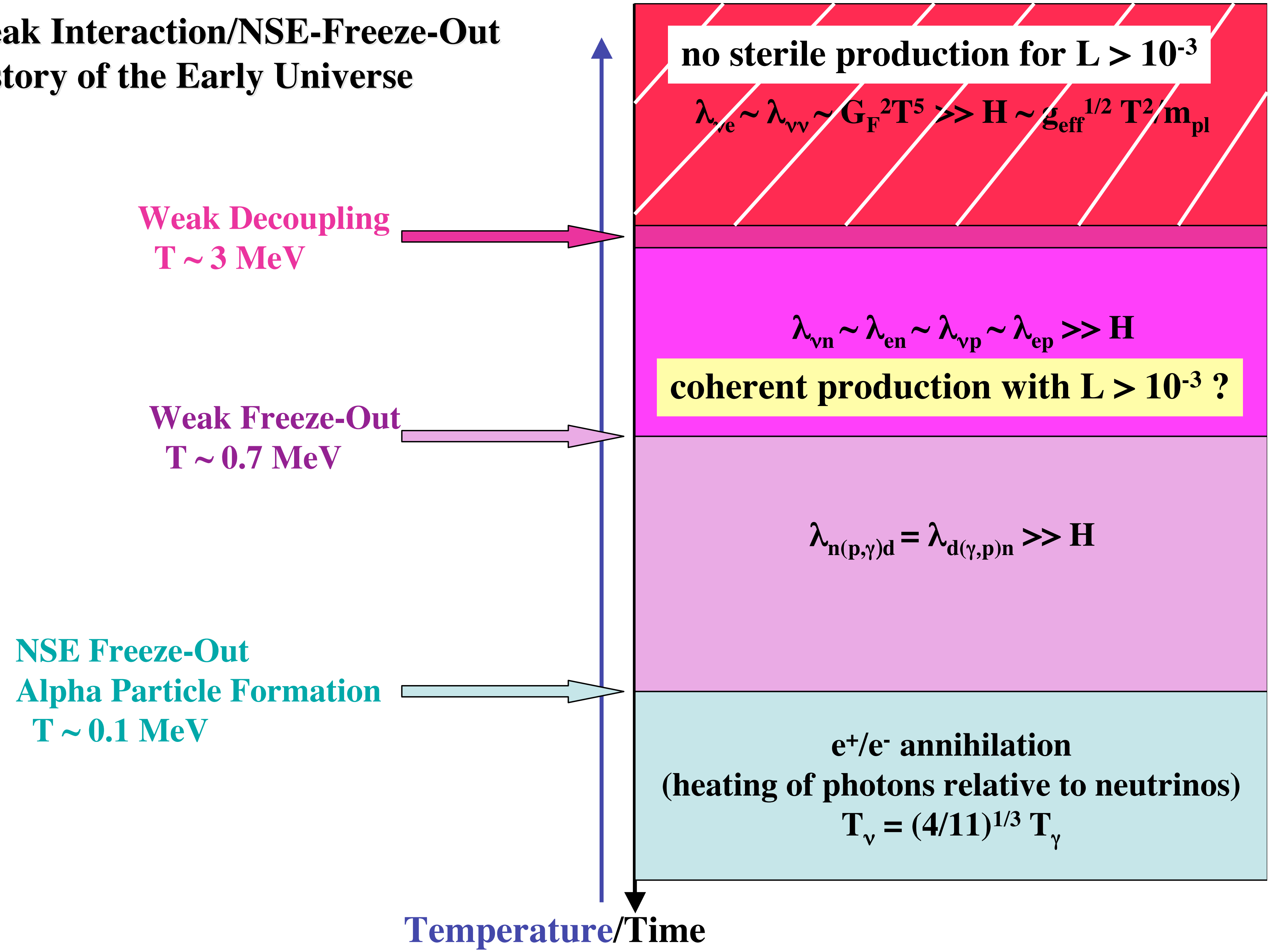
$$H(\nu_\mu) = \sqrt{2}G_F n_\gamma\left(\mathcal{L}_\tau + \left[\tfrac{1}{2}Y_e - \tfrac{1}{2}\right]\right) \approx \frac{2\sqrt{2}\zeta(3)}{\pi^2}G_F T^3\left(\mathcal{L}_\tau - \eta/4\right)$$

K. Abazajian, N. Bell, G. M. Fuller, Y. Wong

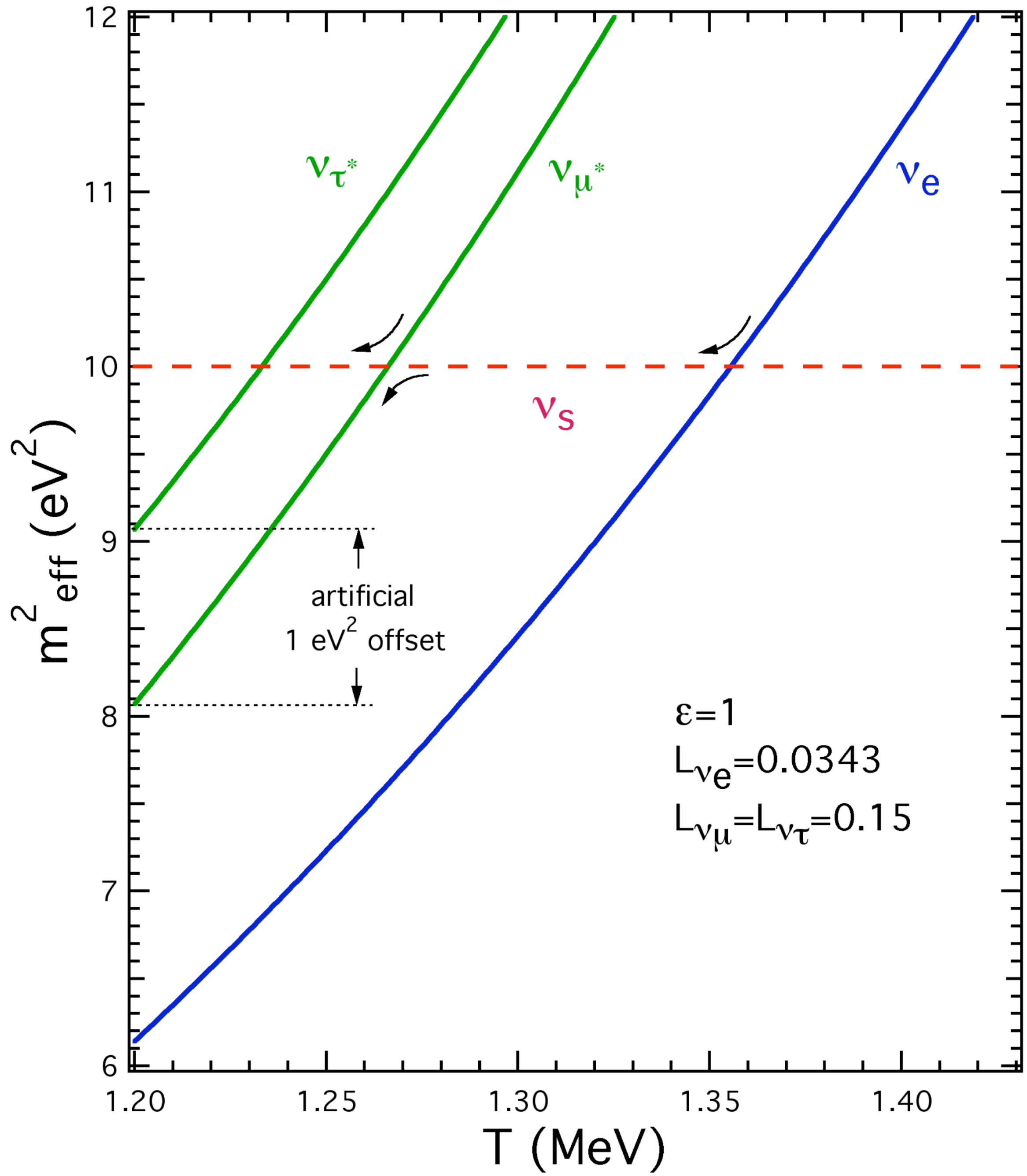
**"Cosmological Lepton Asymmetry,
Primordial Nucleosynthesis,
and Sterile Neutrinos"**
astro-ph/0410175
Phys. Rev. D72, 063004 (2005).

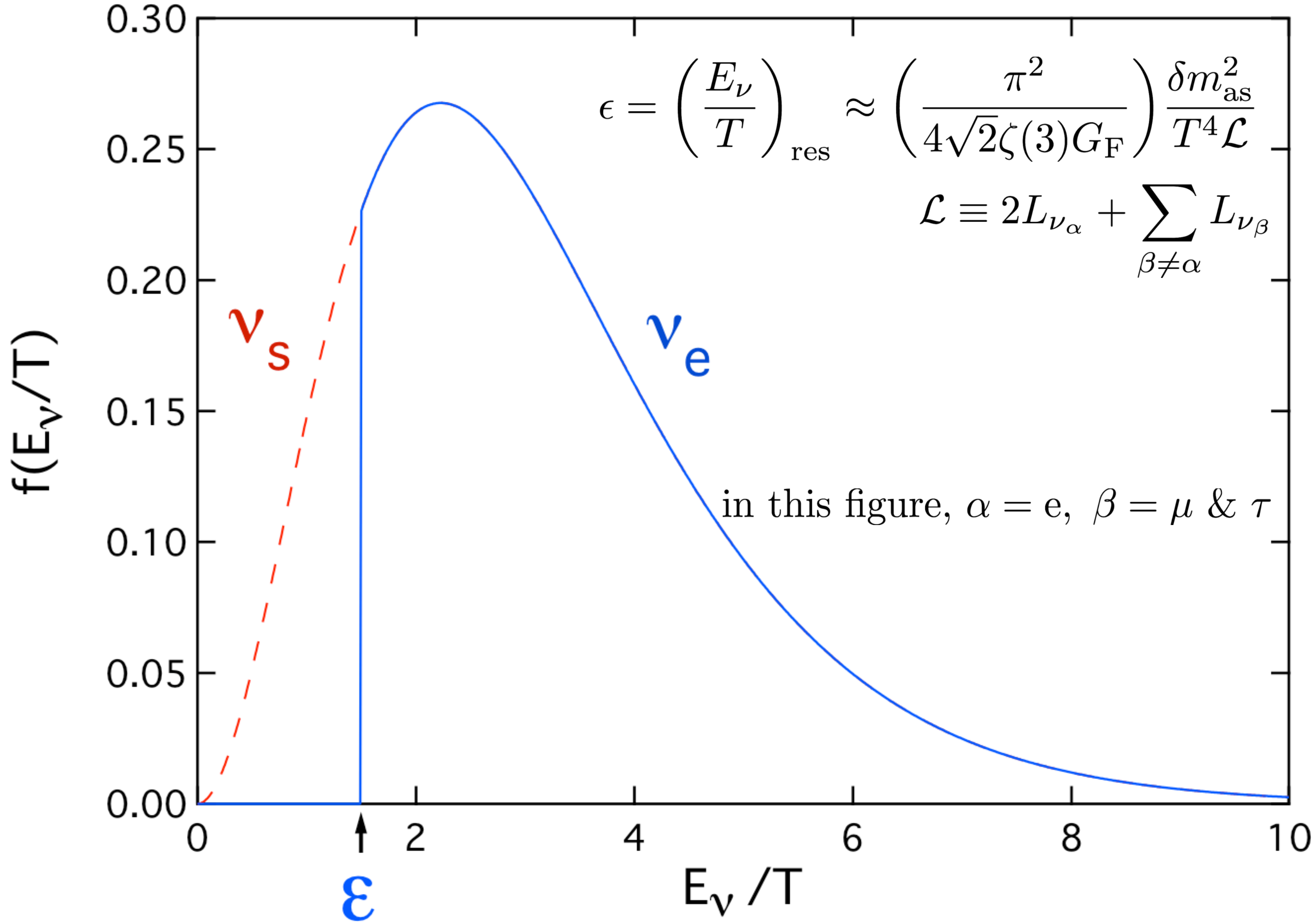
The existence of light sterile neutrinos that mix with active neutrinos could imply distorted, non-thermal energy spectra for all neutrinos and this means altered cosmolgical constraints and BBN.

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



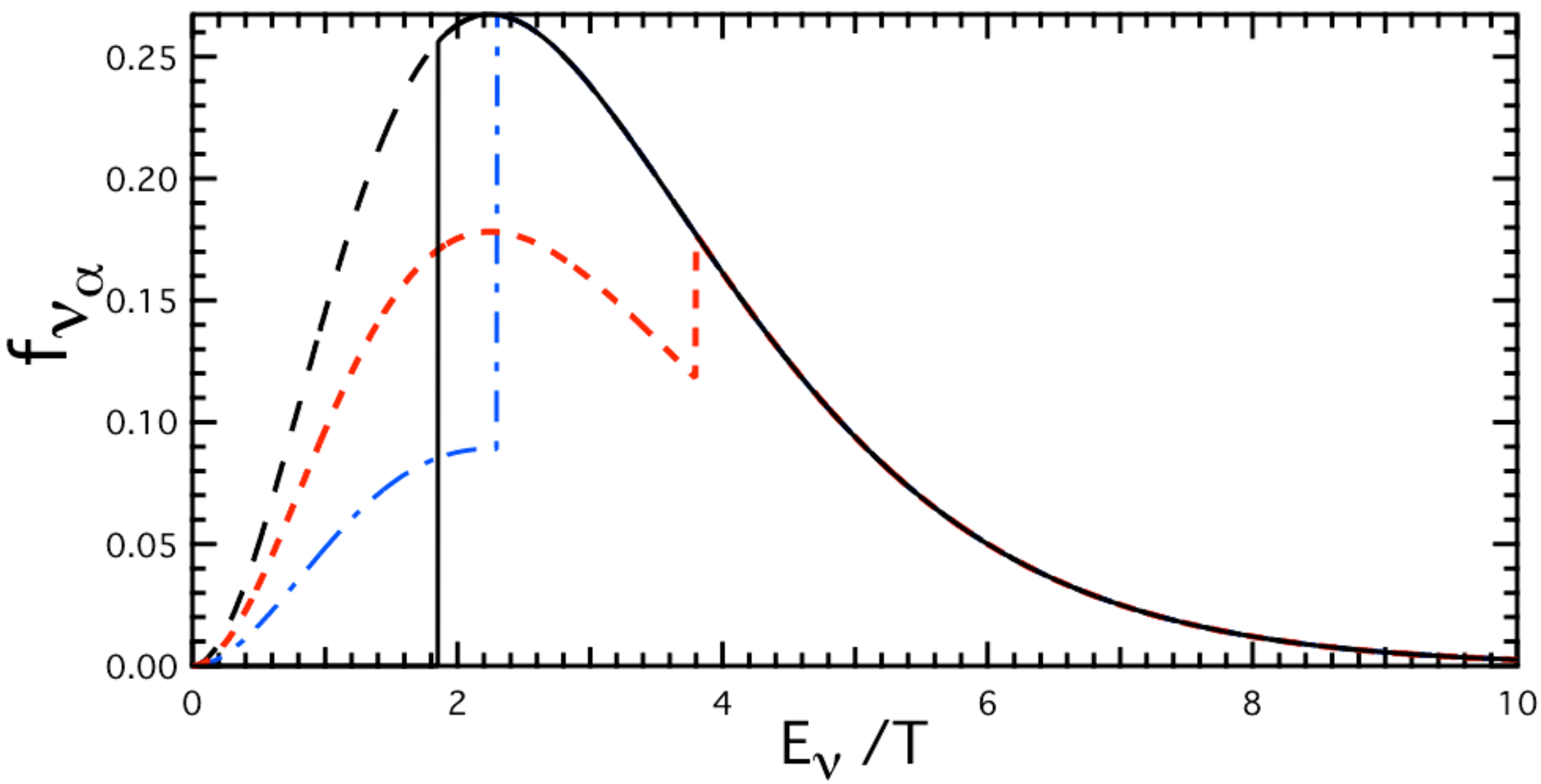
Abazajian, Bell, Fuller, Wong astro-ph/0410175 (ABFW 05)





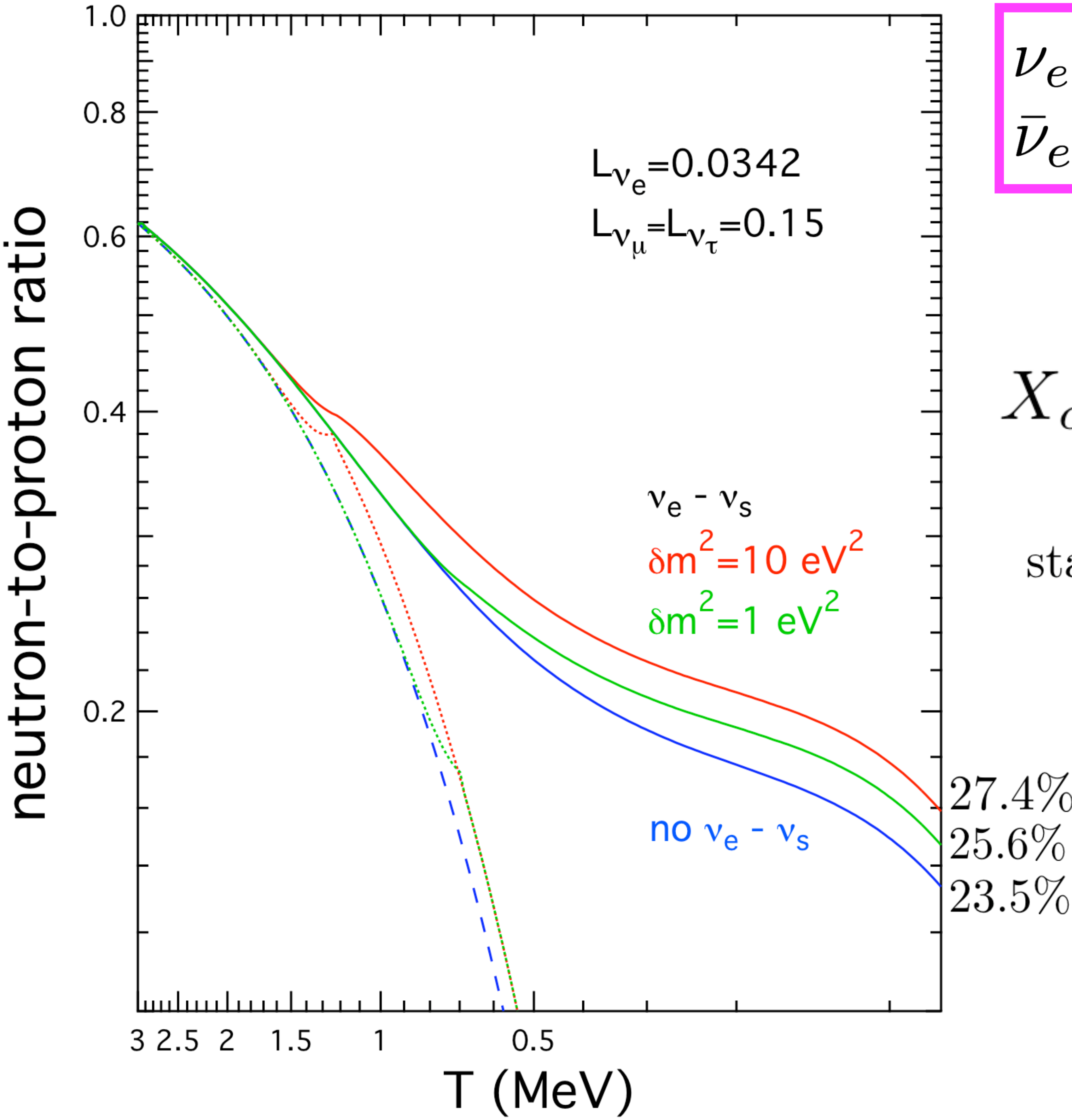
astro-ph/0410175

Conversion of active neutrinos to sterile species in the early universe leads to distorted, non-thermal energy spectra for all neutrinos and this, in turn, leads to alteration of ^4He, ^2H, and ^7Li production.



$$\nu_\alpha \rightarrow \nu_s \text{ causes spectral distortion}$$

Abazajian, Bell, Fuller, Wong, PRD, 2005.
astro-ph/0410175

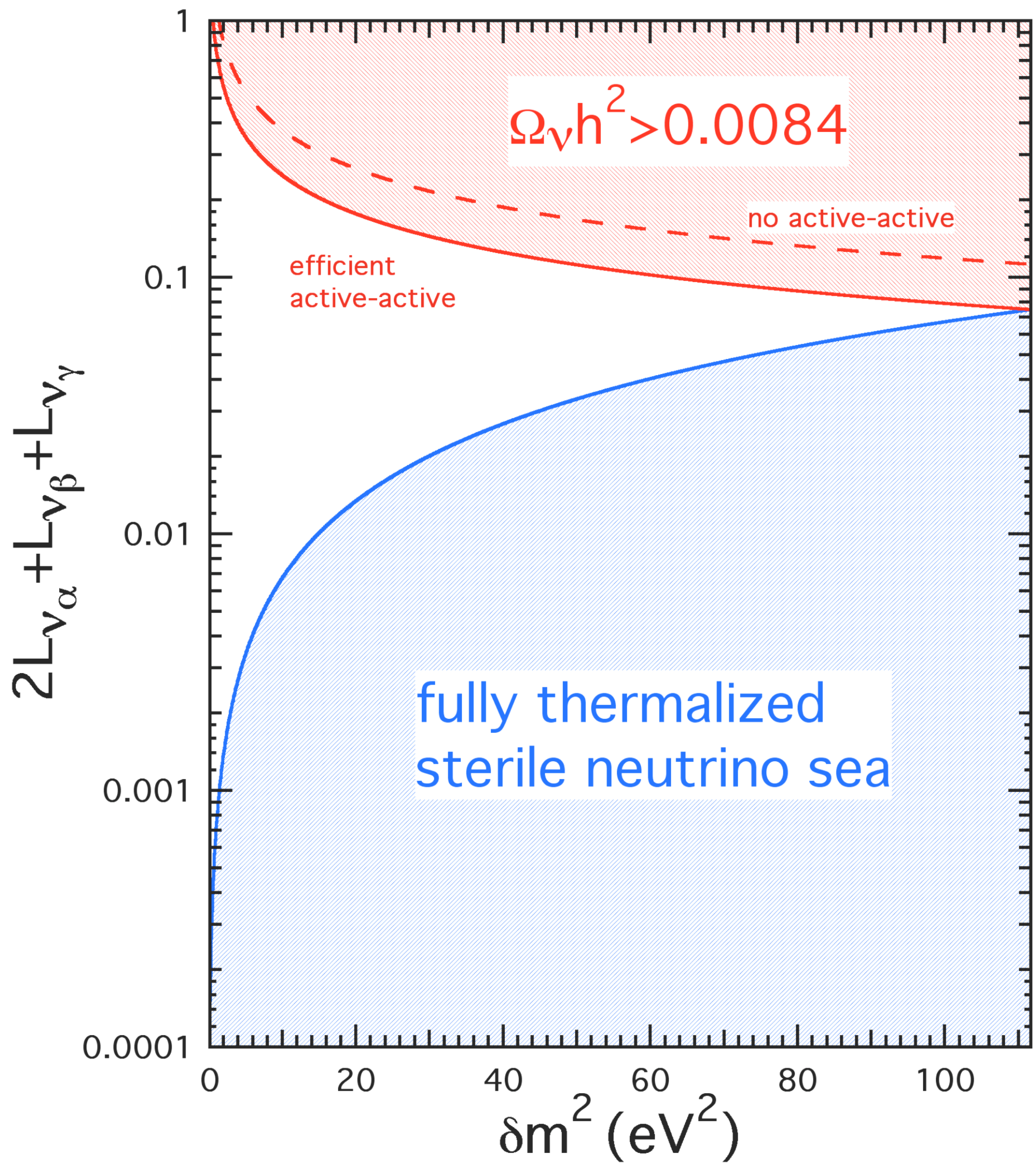


$$\nu_e + n \rightleftharpoons p + e^-$$
$$\bar{\nu}_e + p \rightleftharpoons n + e^+$$

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

standard BBN 24.7%

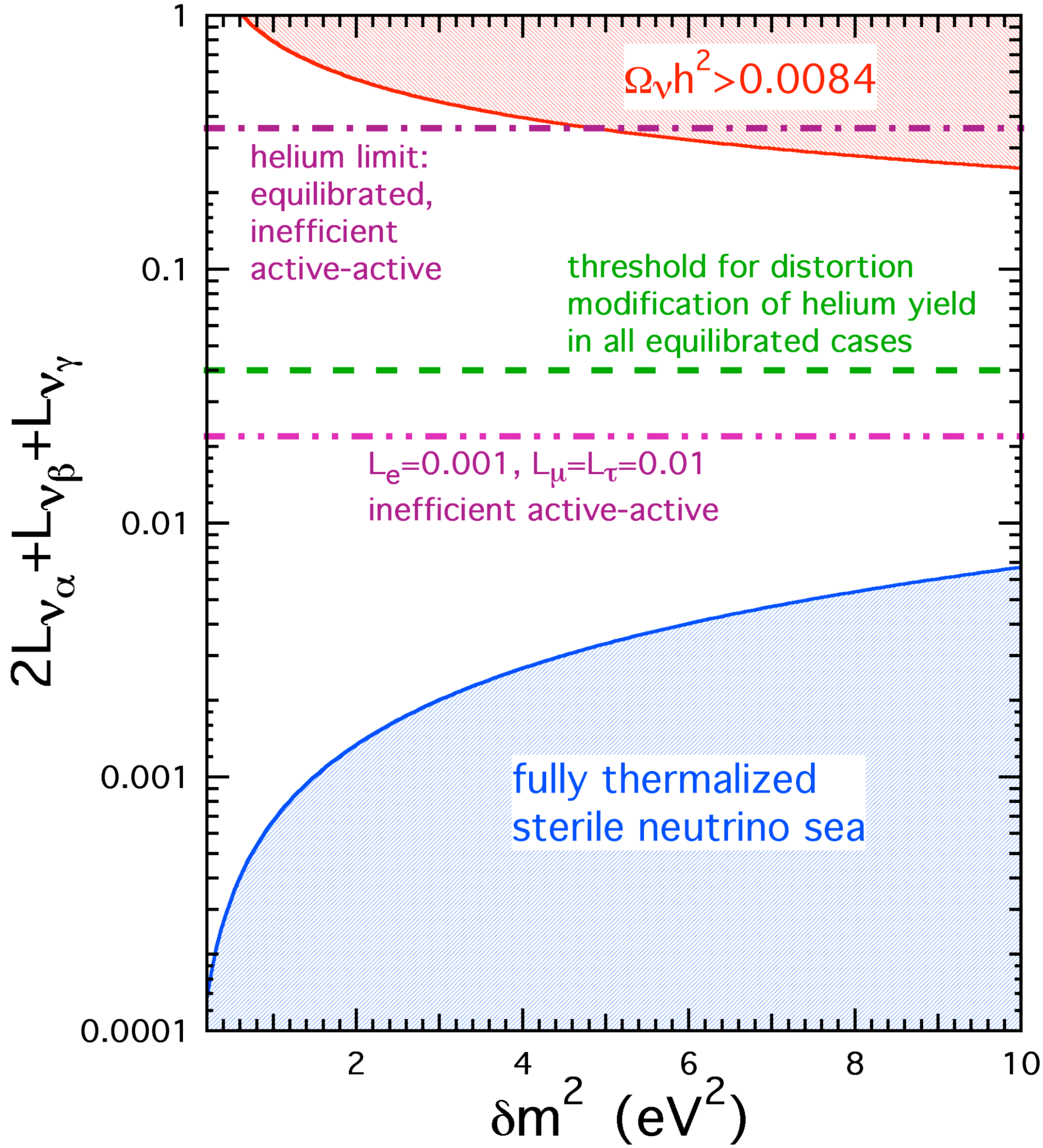
ABFW 05
astro-ph/0410175



ABFW 05

astro-ph/ 0410175

Relationship between lepton numbers and BBN yields altered by existence of sterile neutrinos.



Active-Sterile Neutrino Flavor Transformation

and

decoherence at high density in both the active-active and active-sterile channels

The forward scattering-induced potential is

$$V = A + B + C$$

$$A + B \approx \frac{2\sqrt{2}\zeta(3)}{\pi^2} G_F T^3 (\mathsf{L} \pm \eta/4)$$

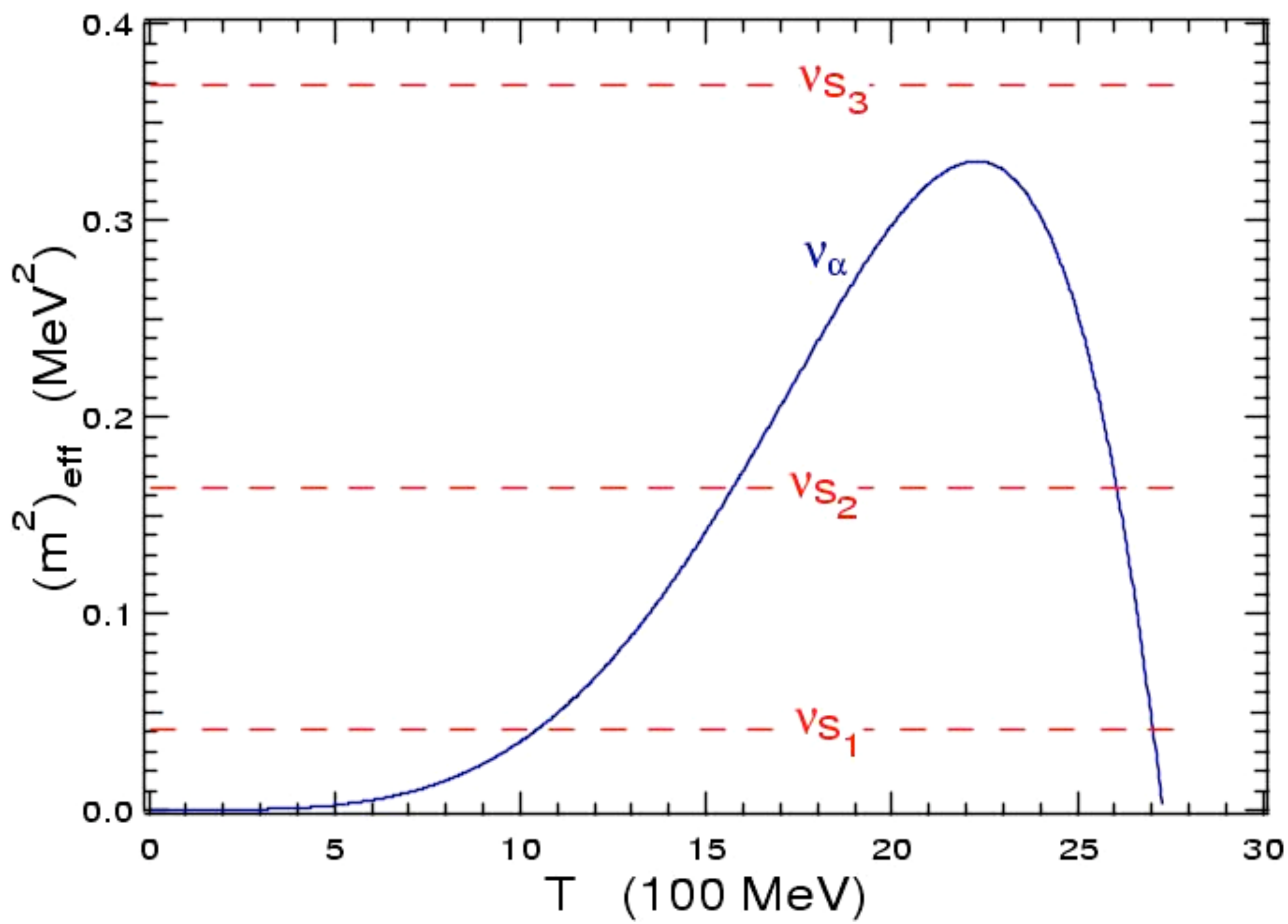
$$C \approx -\alpha_e G_F^2 \varepsilon T^5 \quad \text{the "thermal term"}$$

where we define $\varepsilon \equiv E_\nu / T$

and where the sum of the lepton numbers for each flavor enters the potential as

$$\mathsf{L} \equiv 2L_{\nu_\alpha} + \sum_{\beta \neq \alpha} L_{\nu_\beta}$$

Active neutrinos ν_α could have two *level crossings* with singlet states (sterile neutrinos) ν_s in the early universe.



Effective "matter" mixing angle

$$\sin^2 2\theta_M \approx \frac{\tan^2 2\theta}{\left(1 - E_\nu / E_R\right)^2 + \tan^2 2\theta}$$

Where the resonance energy E_R is related to the forward scattering potential V through

$$E_R = \frac{\delta m^2 \cos 2\theta}{2V}$$

Evolution of the "sterile" and active neutrino distribution functions given by the Boltzmann equation:

$\alpha = e, \mu, \tau$

$$\frac{\partial}{\partial t} f_s(p,t) - Hp\frac{\partial}{\partial p} f_s(p,t) \approx \Gamma(\nu_\alpha \rightarrow \nu_s; p,t)\left[f_\alpha(p,t) - f_s(p,t)\right]$$

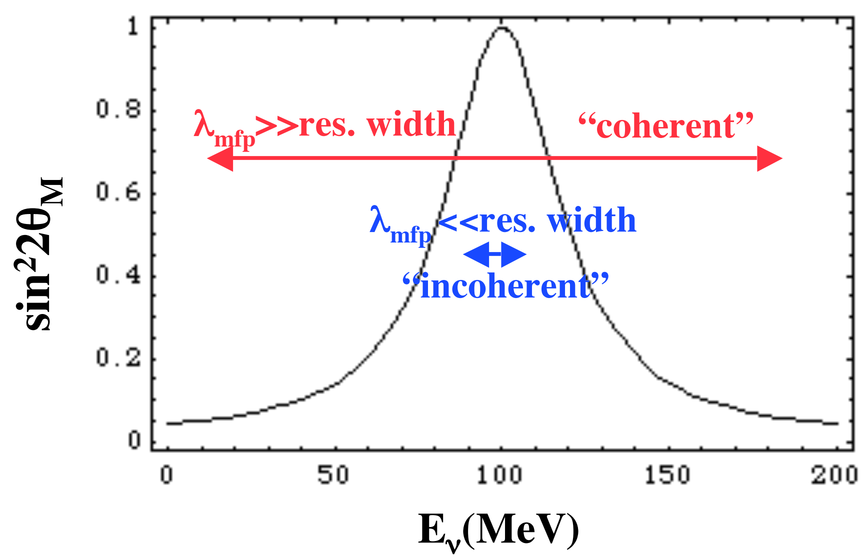
active neutrino scattering rate

Sterile neutrino production rate

$$\approx \tfrac{1}{2}\Gamma_\alpha(p)\sin^2 2\theta_M \left[1 + \left(\tfrac{1}{2}\Gamma_\alpha(p) l_M\right)^2\right]^{-1}$$

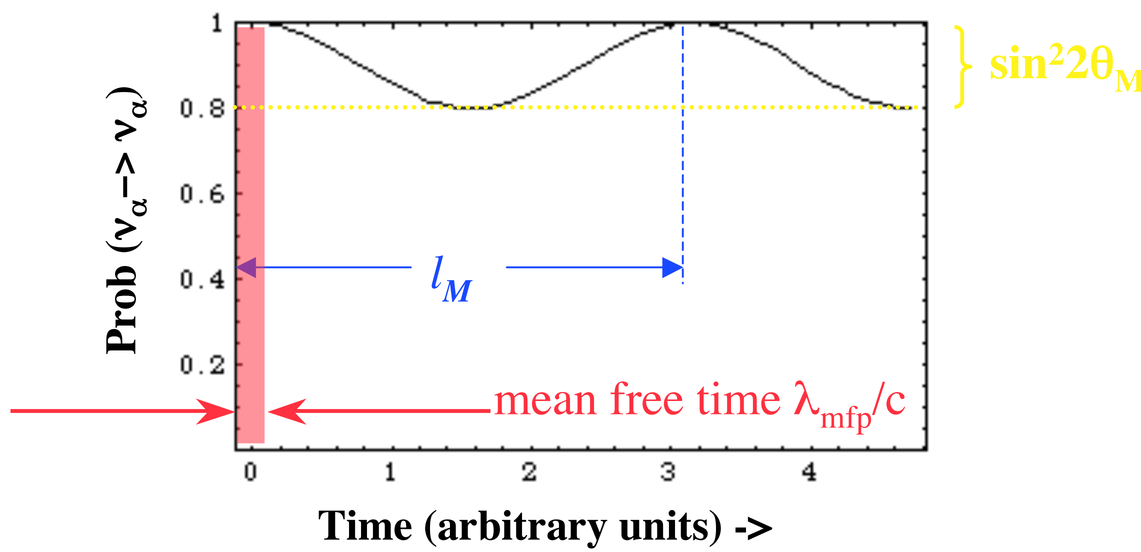
$$|\nu_\alpha\rangle = \cos\theta_M |\nu_1\rangle + \sin\theta_M |\nu_2\rangle$$

$$|\nu_s\rangle = -\sin\theta_M |\nu_1\rangle + \cos\theta_M |\nu_2\rangle$$



Quantum Zeno Effect

Phase in the neutrino oscillation begins to develop after a collision, but is reset at the next collision. If the mean free path λ_{mfp} is short compared to the oscillation length l_M, the probability of sterile neutrino production is suppressed.



Singlet Neutrino Dark Matter?

Singlet ("sterile") neutrinos which have tiny vacuum mixing with active neutrinos can be produced in the early universe and in supernova cores via coherent MSW processes and via de-coherence associated with collisions.

These singlets make interesting Warm and Cold Dark Matter candidates. They are not "WIMPS," as their interaction strengths are typically 10 to 15 orders of magnitude weaker than the Weak Interaction and they were never in equilibrium in the early universe.

However, they are eminently constrainable/detectable with existing and proposed X-Ray observatories.

The recent experimental discoveries have forced us into a corner: A positive signal in Mini-BooNE may be tantamount to the discovery of a light sterile neutrino and a large lepton number.

In this eventuality, the idea of Singlet ("Sterile") Neutrino Dark Matter becomes more than an idle curiosity.

What if there are heavier "sterile" (singlet) states which have very small vacuum mixings with active species?

$$|\nu_\alpha\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$$

$$|\nu_s\rangle = -\sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle$$

where, for example, m_2 = 1 keV to 100 keV
and where $\sin^2 2\theta \leq 10^{-10}$

Every time an active neutrino scatters in the early universe or in a supernova core there is a (usually very small) probability that the neutrino's wave function collapses into a "sterile" state. This de-coherence production process can be matter-enhanced as well.

Abazajian, Fuller, Patel, Phys. Rev. D64, 023501 (2001) follow the Boltzmann evolution of a system of active neutrinos to calculate the relic singlet neutrino density.

Singlet "Sterile" Neutrino Dark Matter

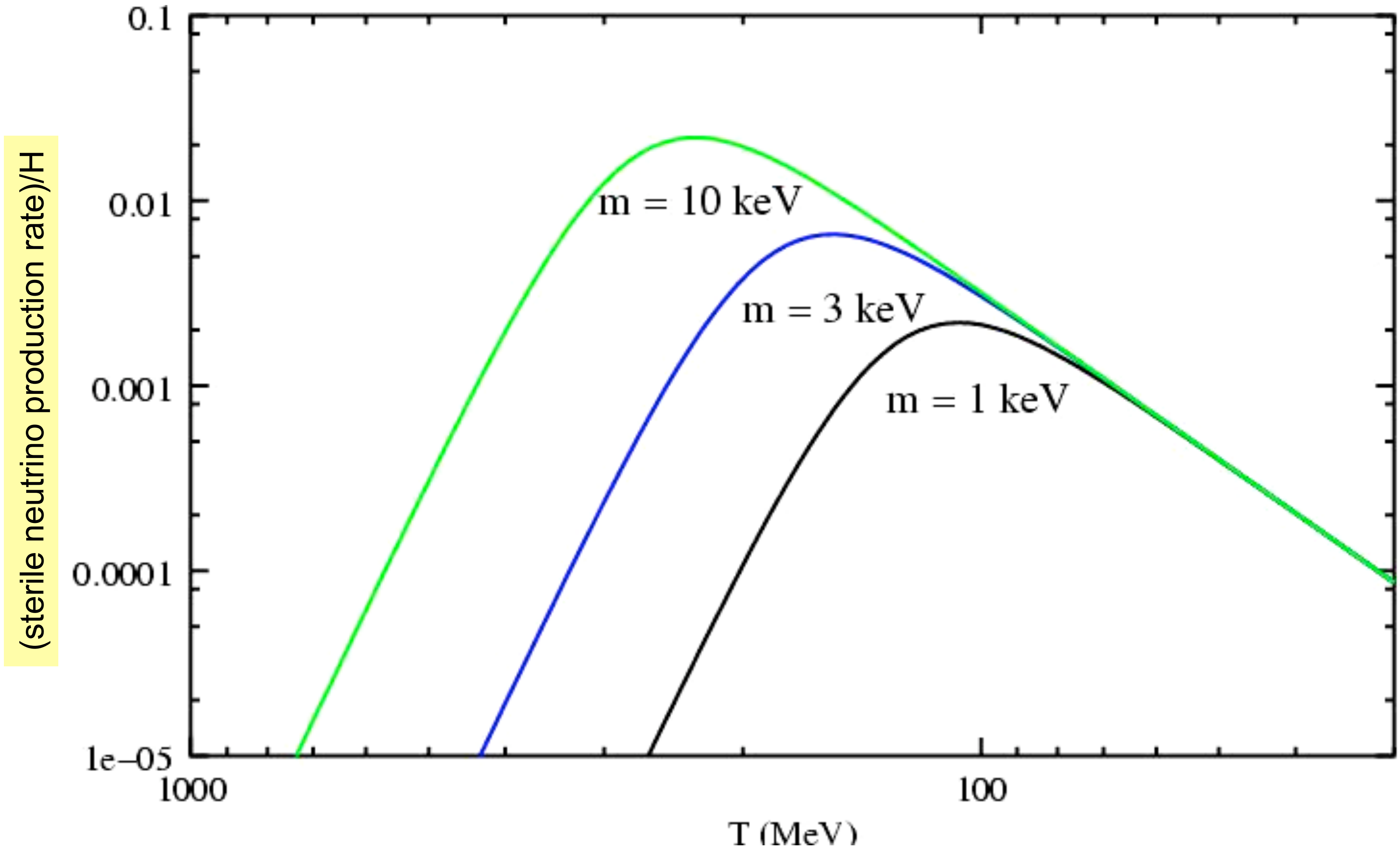
- **Scattering-induced de-coherence, matter-suppressed production**
  S. Dodelson & L. M. Widrow, Phys. Rev. Lett. 72, 17 (1994).

- **Matter-enhanced (resonant) production**
  X. Shi & G. M. Fuller, Phys. Rev. Lett. 82, 2832 (1999).

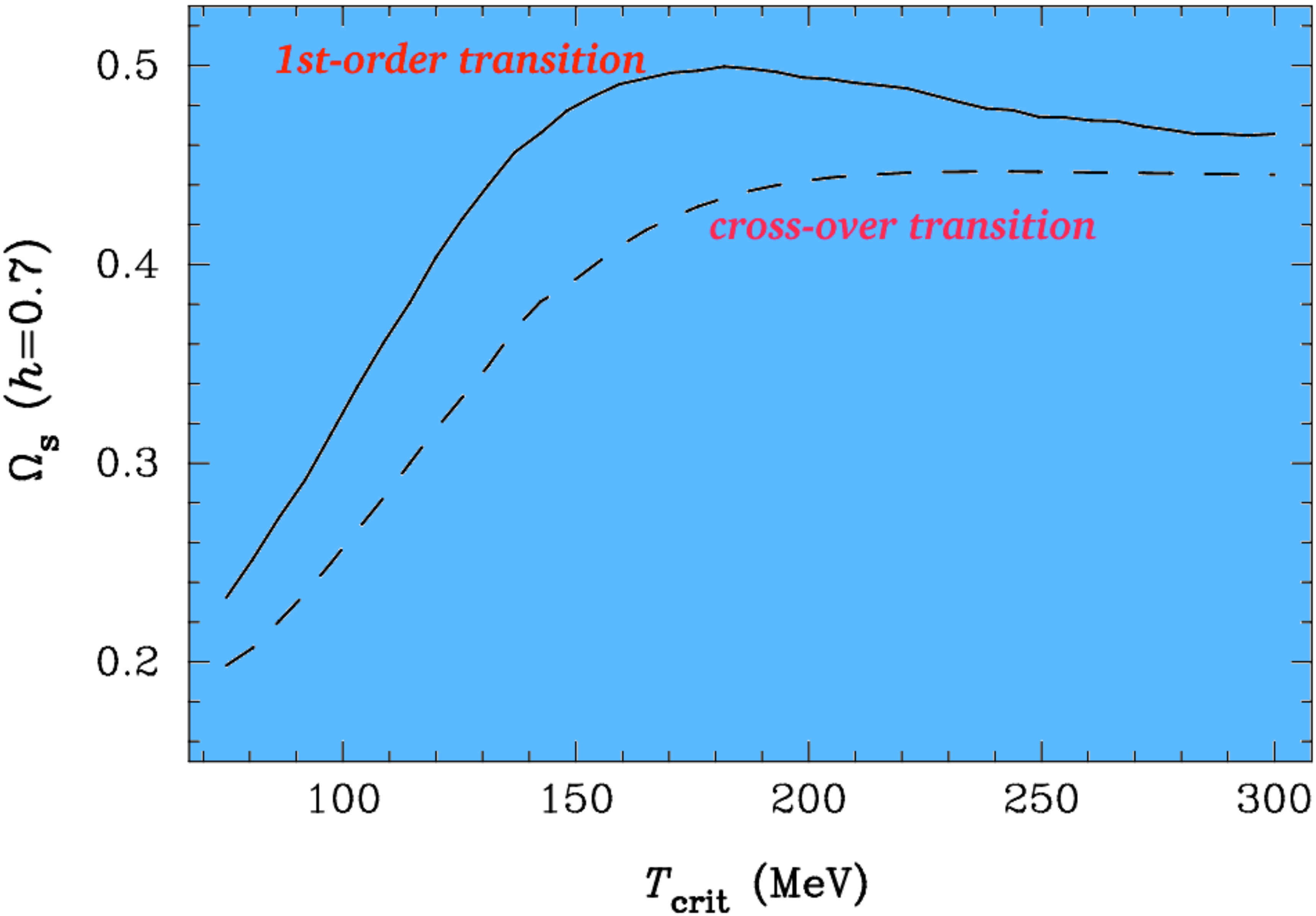
- **Re-look at scattering-induced de-coherence, matter-suppressed production**
  A. D. Dolgov and S. Hansen, Astropart. Phys. 16, 339 (2002).
  hep-ph/0009083.

- **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**
  T. Asaka, A. Kusenko, and M. Shaposhnikov (2006) hep-ph/0602150.

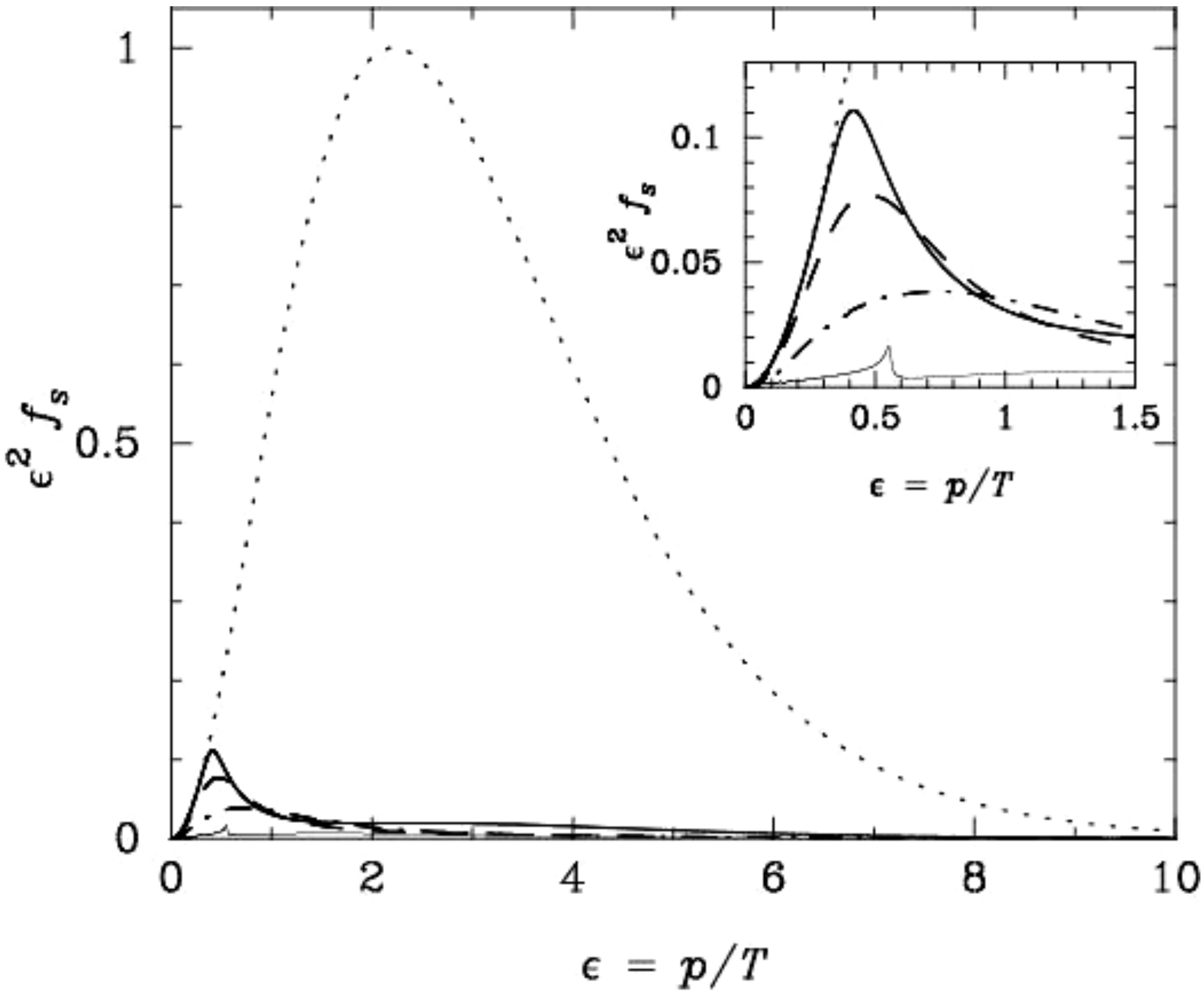


(sterile neutrino production rate)/H
0.1
0.01
0.001
0.0001
1e−05
1000
100
T (MeV)
m = 10 keV
m = 3 keV
m = 1 keV

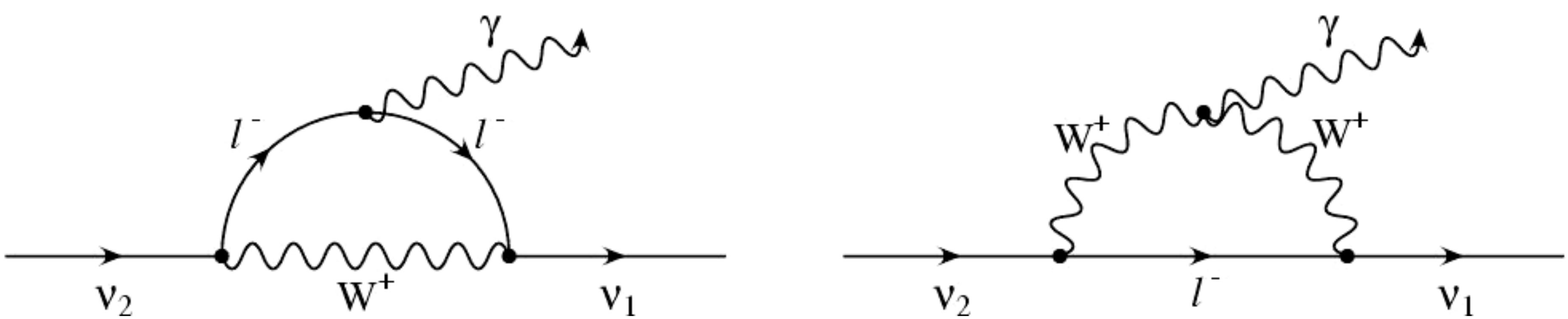


Abazajian & Fuller, astro-ph/0204293

The energy spectra of the sterile neutrinos will not be thermal, Fermi-Dirac



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

$$\Gamma_\gamma \approx \frac{\alpha G_F^2}{64\pi^4} m_2^5 \left[\sum\nolimits_\beta U_{1\beta} U_{2\beta} F(r_\beta)\right]^2$$

$$\approx 6.8 \times 10^{-33}\,\mathrm{s}^{-1} \left(\frac{\sin^2 2\theta}{10^{-10}}\right)\left(\frac{m_s}{\mathrm{keV}}\right)^5$$

no GIM suppression for sterile neutrinos

$$F(r_\beta) \approx -\tfrac{3}{2} + \tfrac{3}{4} r_\beta$$

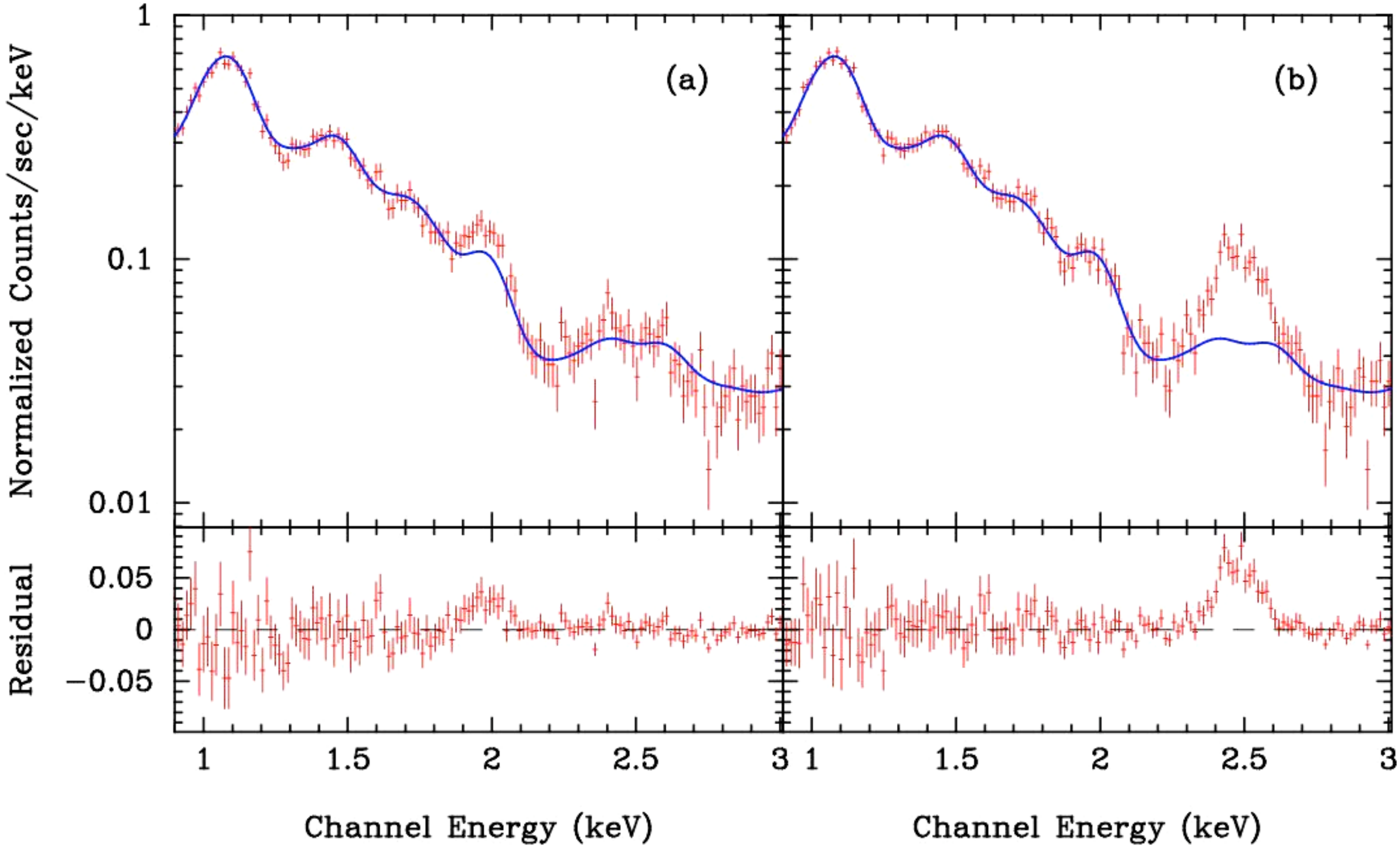
$$r_\beta = \left(M_\beta^{lep} / M_W\right)^2$$

Abazajian, Fuller, & Tucker, astro-ph/0106002 considered the radiative decays of heavy singlets and possible x-ray constraints and pointed out this serendipitous coincidence:

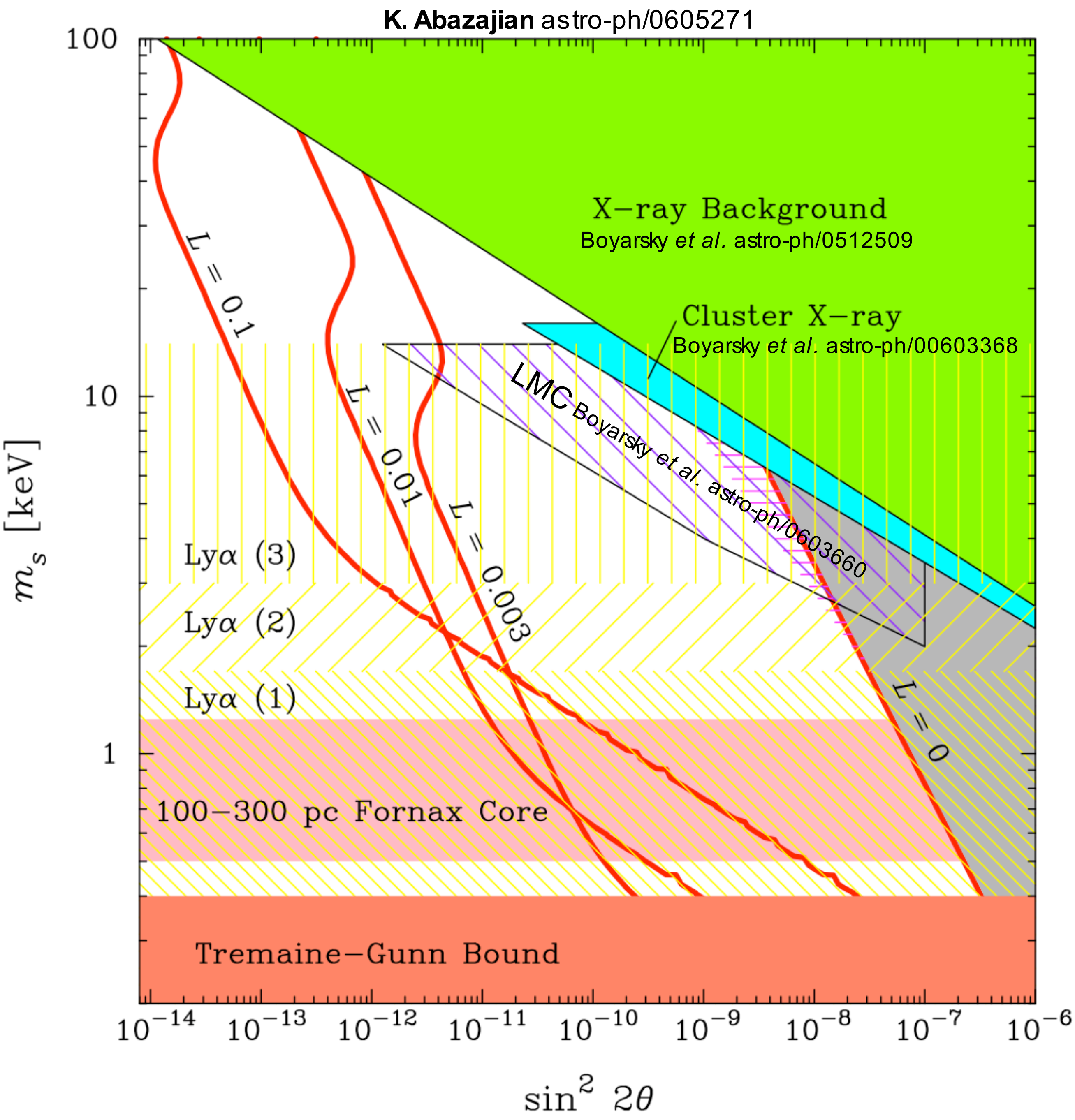
XMM-Newton and Chandra have greatest sensitivity for photons with energies between about 1 keV to 10 keV, serendipitously coincident with the expected photon energies from decaying WDM/CDM singlets.

Typical singlet lifetimes against radiative decay are some $\sim 10^{16}$ Hubble times! However, if singlets are the dark matter, then in a typical cluster of galaxies there could be $\sim 10^{79}$ of these particles.

This could allow x-ray observatories to probe physics at interaction strengths some 10-14 orders of magnitude smaller than the Weak Interaction.



Synthetic spectra for the Virgo cluster when the Dark Matter is composed of singlets with rest mass (b) m_s=5 keV and (a) m_s=4 keV.



K. Abazajian astro-ph/0605271
X−ray Background
Boyarsky et al. astro-ph/0512509
Cluster X−ray
Boyarsky et al. astro-ph/00603368
LMC Boyarsky et al. astro-ph/0603660
L = 0.1
L = 0.01
L = 0.003
L = 0
Lyα (3)
Lyα (2)
Lyα (1)
100−300 pc Fornax Core
Tremaine−Gunn Bound
m_s [keV]
sin² 2θ
100
10
1
10⁻¹⁴ 10⁻¹³ 10⁻¹² 10⁻¹¹ 10⁻¹⁰ 10⁻⁹ 10⁻⁸ 10⁻⁷ 10⁻⁶

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 feedback 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);
G. M. Fuller, A. Kusenko, I. Mocioiu, and S. Pascoli PRD 68, 103002 (2003).

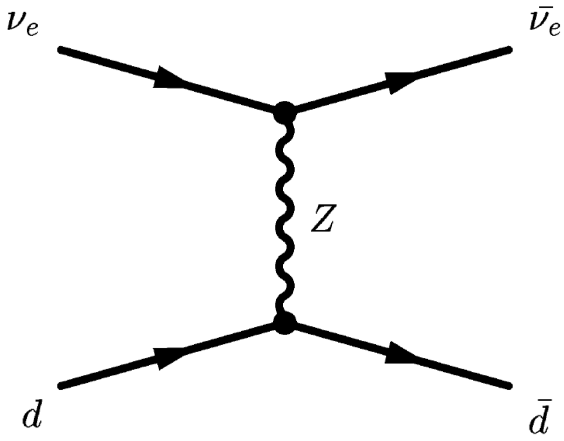
Proto-neutron star "kick"-aided hydrodynamic supernova shock enhancement
C. Fryer & A. Kusenko, Astrophys. J. (Suppl) 163, 335 (2006).

Active-sterile-active neutrino matter-enhanced alteration of collapse physics and enhanced shock re-heating
J. Hidaka & G. M. Fuller (2006)

New Neutrino Couplings
- *scattering at high density*

(flavor changing neutral currents)

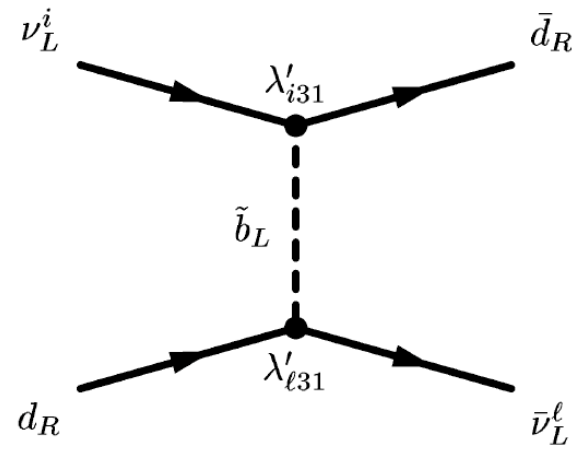
Standard Model Neutral Currents



$$\frac{G_F}{\sqrt{2}} \equiv \frac{g^2}{8m_W^2}$$

$$\sigma \sim G_F^2 E_\nu^2 A^2$$

Flavor Changing Neutral Currents



$$\frac{\lambda'\lambda'}{m_{\tilde{d}}^2}$$

$$\sigma \sim \epsilon^2 G_F^2 E_\nu^2 (2N + Z)^2$$

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

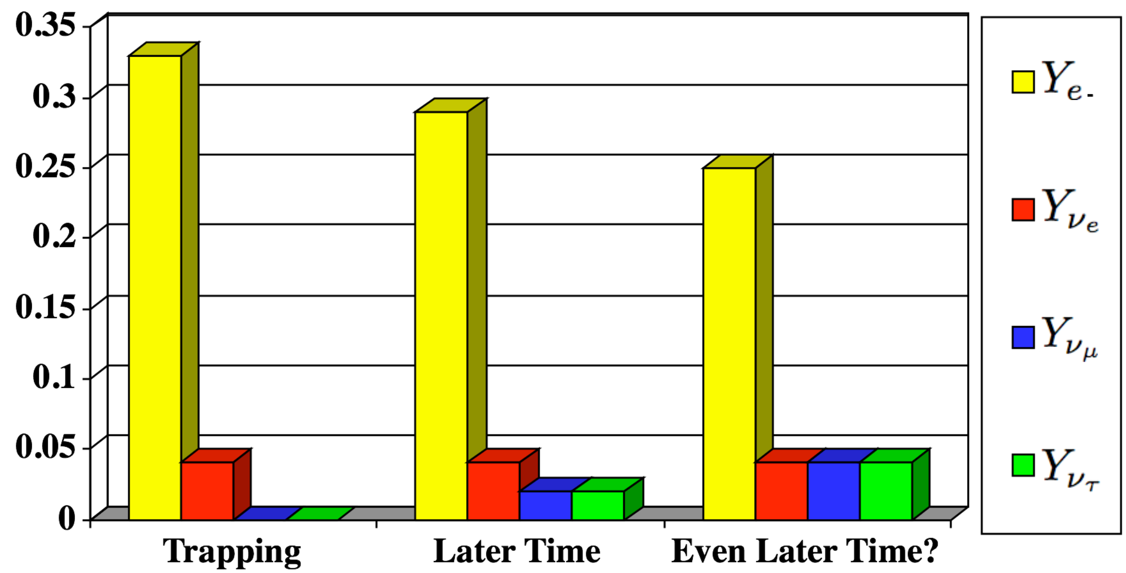
$$\Delta Y_e = -(\Delta Y_{\nu_\mu} + \Delta Y_{\nu_\tau})$$

homologous core mass smaller:

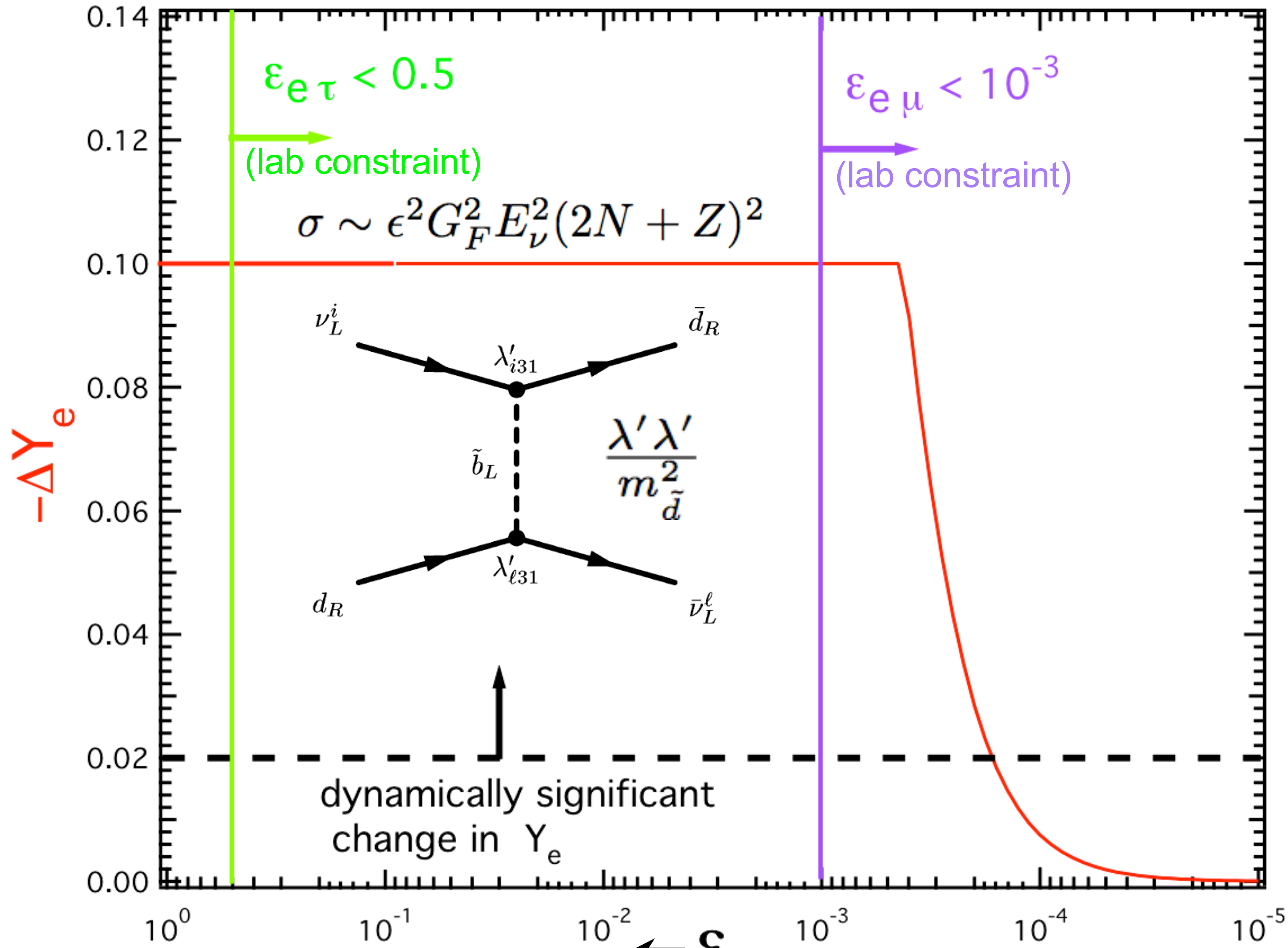
$$M_{hc} \sim 5.8 Y_e^2 M_\odot$$

initial shock energy lower:

$$E_i \sim (Y_e^f)^{10/3}$$



Supernova physics is orders of magnitude more sensitive to Flavor Changing Neutral Current couplings than the best current laboratory experiments!



Amanik & Fuller astro-ph/0606607; Amanik, Fuller, Grinstein, *Astroparticle Phys.* 24, 160 (2005).