Symmetry, Cosmology, Nuclear Astrophysics, the Neutrino Mass and Mixing Spectrum, and the Structure of Spacetime

(Is there really any relation between these topics,
or this this just **HYPE**?)

Workshop on Low Energy Neutrino Physics
Institute for Nuclear Theory
University of Washington
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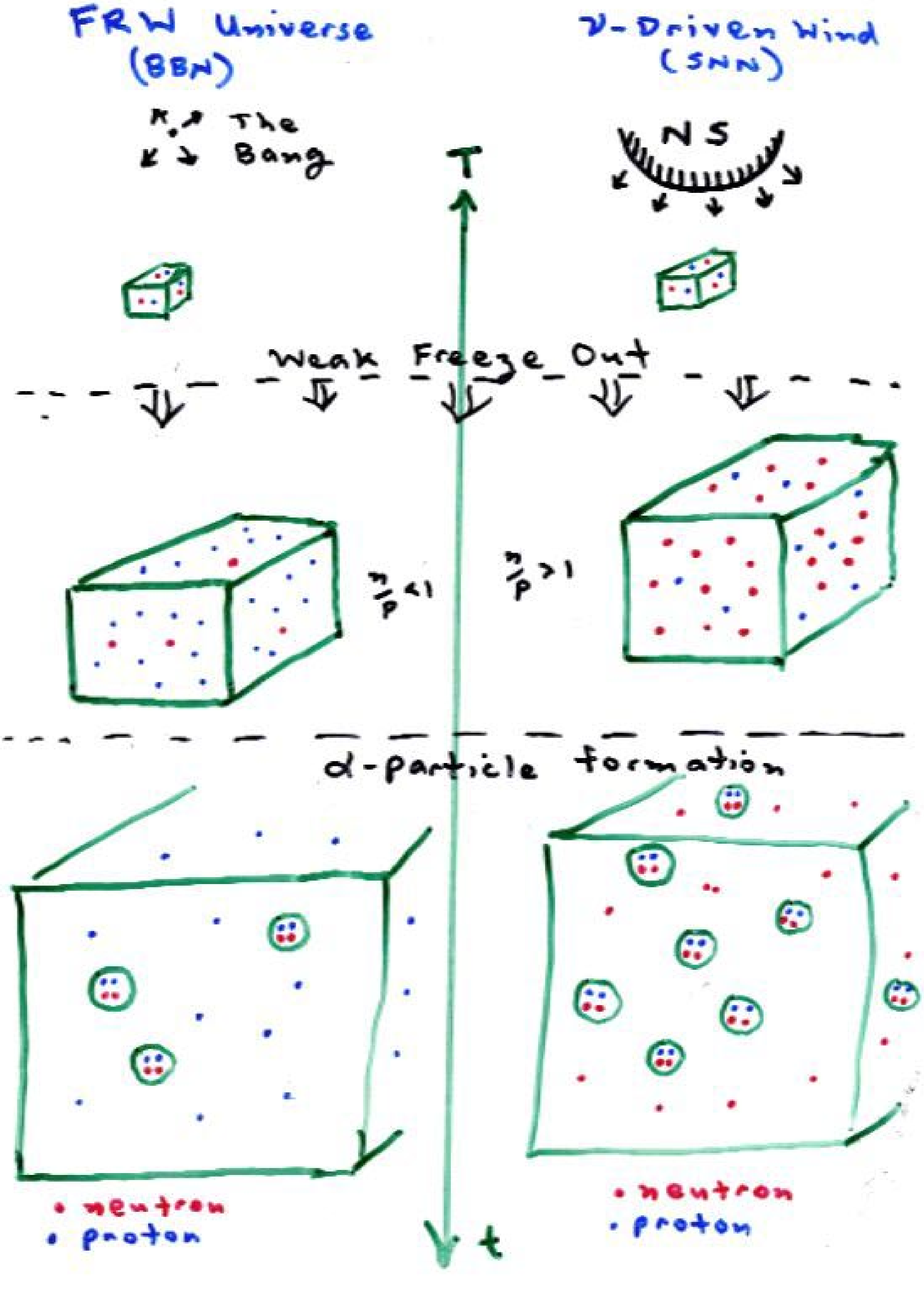

FRW Universe
(BBN)
ν-Driven Wind
(SNN)
The Bang
NS
T
Weak Freeze Out
$\frac{n}{p} < 1$
$\frac{n}{p} > 1$
α-particle formation
• neutron
• proton
• neutron
• proton
t

Neutrino Transformation in BBN

(1.) Active-Sterile Only

$\nu_{\mu,\tau} \rightleftharpoons \nu_S$ **and** $\bar{\nu}_{\mu,\tau} \rightleftharpoons \bar{\nu}_S$

c.f., Shi, Schramm, & Fields 1995, 93
Shi 1996

general constraints $\left\{ \right.$ Barbieri & Dolgov '91
Enqvist, Kainulainen, Thomson '92
J.M. Cline '92
Foot, Thomson, Volkas 96

(2.) Active-Active Only $\nu_\alpha \rightleftharpoons \nu_\beta$

$\nu_\alpha, \nu_\beta = \nu_e, \nu_\mu, \nu_\tau$

c.f., Savage, Malaney, & Fuller 1992

⇒ can "hide" an initially large lepton number in neutrinos

⇒ can relax Helium abundance limits on neutrino degeneracy

(3.) Active-Sterile Plus Active-Active

c.f., Foot & Volkas 1997; 1998
Shi & Fuller 1998

(a.) $\bar{\nu}_\mu \rightleftharpoons \bar{\nu}_S$ **creates "large" net mu lepton number**
$L_{\nu_\mu} > 0$

(b.) $\bar{\nu}_\mu \rightleftharpoons \bar{\nu}_e$ **re-distributes lepton number to create a net electron lepton number** $L_{\nu_e} > 0$

Note that in both steps (a.) and (b.) we could employ tau rather than mu neutrinos (or both)

The Paradox of Neutrino-Heated r-Process Nucleosynthesis

- Require neutrino interactions,

$$\bar{\nu}_e + p \rightarrow n + e^+$$

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

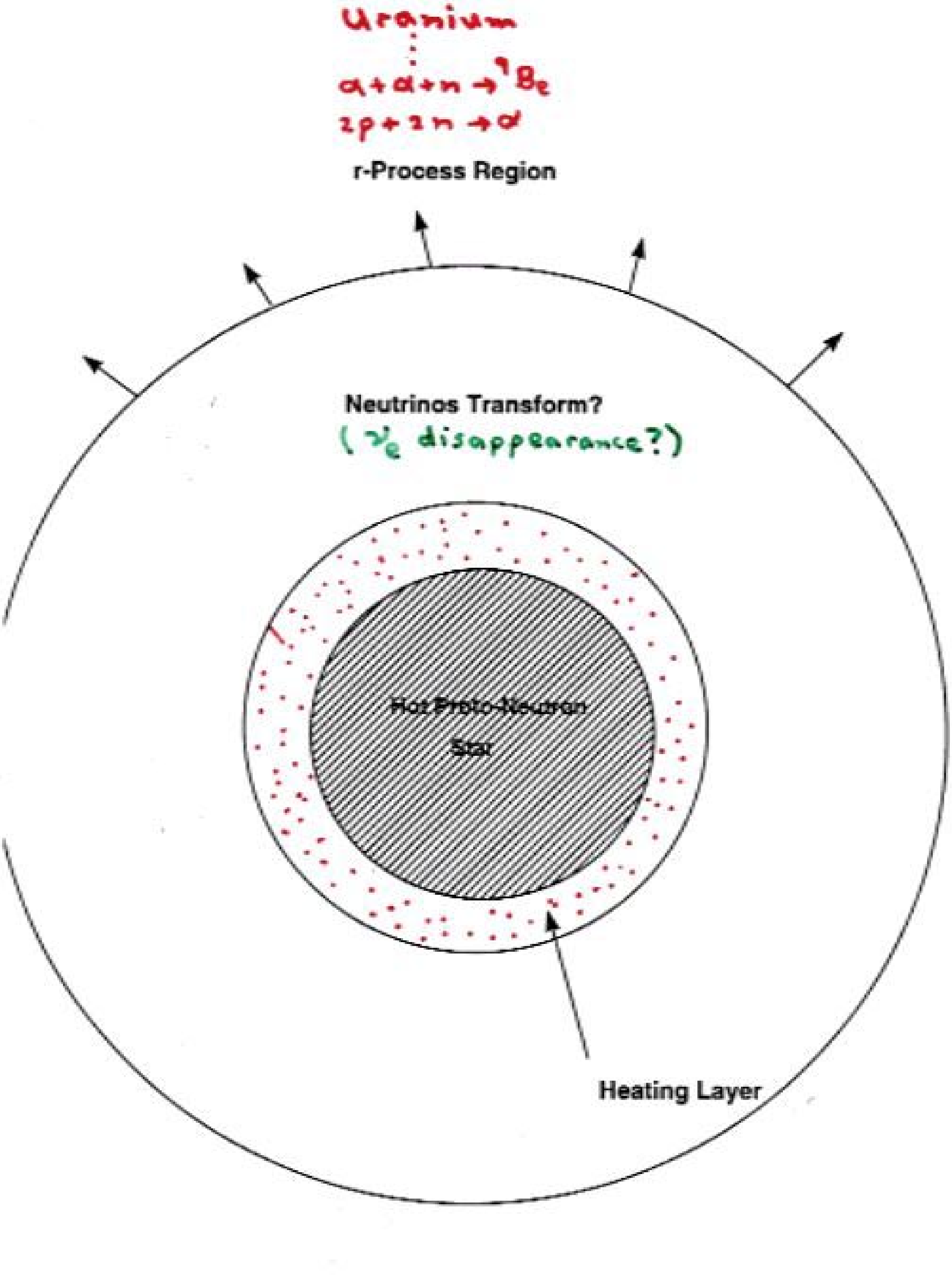
to inpart energy to baryons, so that baryons can overcome gravitational binding energy near the neutron star, $E_{\mathrm{GRAV}} \sim$ 100 MeV per baryon. Since the average energies of neutrinos are $\sim 10\,\mathrm{MeV}$, we therefore require some ~ 10 neutrino and antineutrino captures per nucleon to ensure ejection. If material is ejected by this neutrino heating process, its neutron-to-proton ratio will be set by these reactions.

- **However**, if we have an intense flux of ν_e's then there will be a **ferocious** increase in Y_e (decrease in the number of available neutrons) accompanying the formation of alpha particles at $T \lesssim 0.75\,\mathrm{MeV}$:

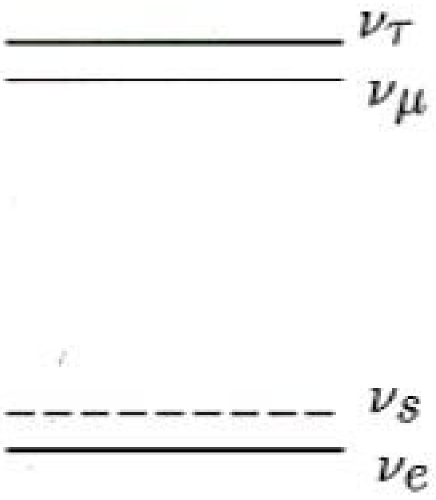
⇒ All protons incorporated into alpha particles, leaving a sea of neutrons.

⇒ Some of these neutrons will be converted to protons via $\nu_e + n \rightarrow p + e^-$.

This is the "alpha effect,"
G. M. Fuller & B. S. Meyer ApJ **453**, 202 (1995)
G. McLaughlin, B. S. Meyer, & G. M. Fuller, PRC, in press (1998).


Uranium
⋮
$\alpha+\alpha+n \to {}^9Be$
$2p+2n \to \alpha$
r-Process Region
Neutrinos Transform?
(ν_e disappearance?)
Hot Proto-Neutron Star
Heating Layer

Caldwell, Fuller, and Qian 1998



$\delta m^2_{\mu\tau} \sim 10^{-2}\,\mathrm{eV}^2$

$\delta m^2_{\mu e} \sim 6\,\mathrm{eV}^2$ (0.2eV^2 - 8eV^2)

$\delta m^2_{es} \sim 10^{-5}\,\mathrm{eV}^2$

(like old C.& Mohapatra scheme for masses)

BBN: **OK**

SNN: **Enables r-Process in neutrino-heated supernova ejecta; removes ν_e flux.**

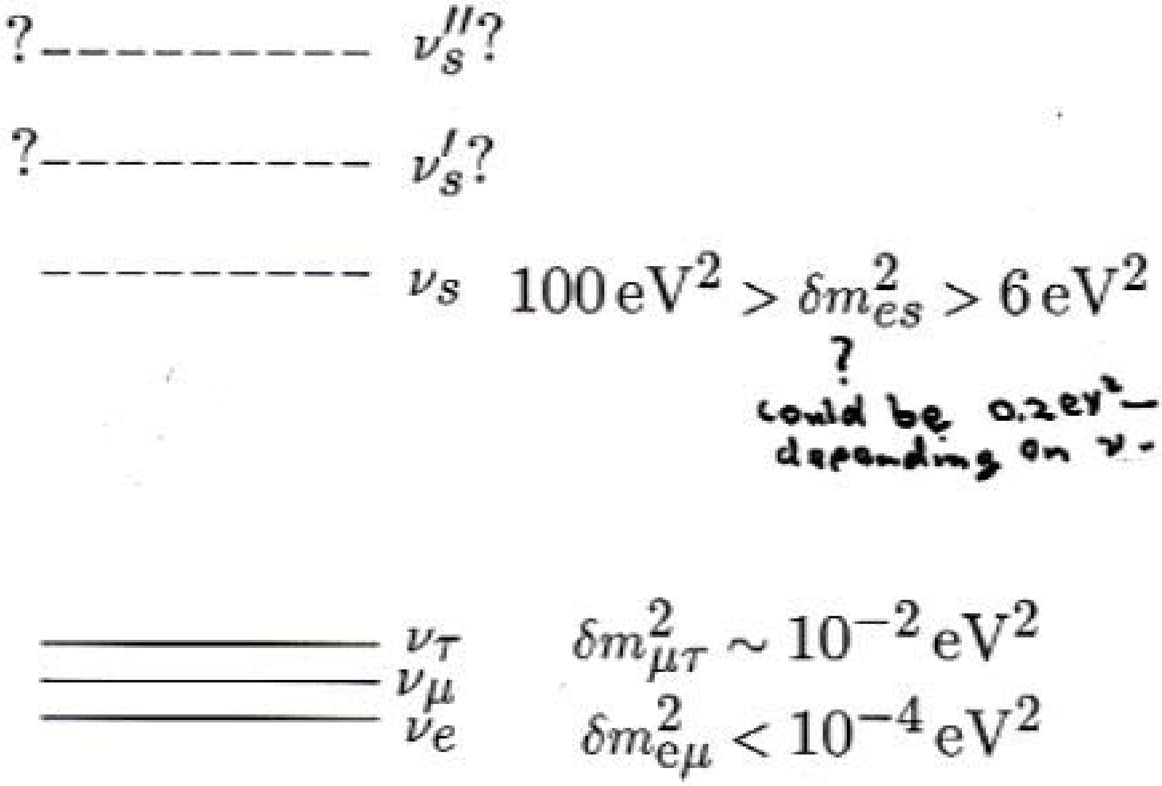
SuperK: $\nu_\mu \rightleftharpoons \nu_\tau$ **maximal vacuum mixing**

Solar Neutrinos: $\nu_e \rightleftharpoons \nu_s$ **matter-enhanced**
(or $\nu_e \rightleftharpoons \nu_s$ "just so" $\delta m^2 \sim 10^{-10}$ eV^2)

LSND: $\nu_\mu \rightleftharpoons \nu_e$ **vacuum oscillations**

McLaughlin, Fetter, Balantekin, GMF (MFBF), ~~submitted PRD~~
PRC

Balantekin, Fetter, Fuller,
McLaughlin 1998



? ν_s''?

? ν_s'?

ν_s $100\,\mathrm{eV}^2 > \delta m^2_{es} > 6\,\mathrm{eV}^2$

?
could be $0.2\mathrm{eV}^2 - 200\mathrm{eV}^2$
depending on ν-spectra

ν_τ $\delta m^2_{\mu\tau} \sim 10^{-2}\,\mathrm{eV}^2$

ν_μ

ν_e $\delta m^2_{e\mu} < 10^{-4}\,\mathrm{eV}^2$

BBN: OK ? , may give interesting CMBR signal

SNN: Enables r-Process in neutrino-heated ejecta
"removes" ν_e flux

SuperK: $\nu_\mu \rightleftharpoons \nu_\tau$ **maximal vacuum mixing**

Solar Neutrinos: $\nu_e \rightleftharpoons \nu_{\mu,\tau}$ matter-enhanced or vacuum oscillations

LSND: $\nu_\mu \rightarrow \nu_s \rightarrow \nu_e$ Indirect vacuum oscillations
(but note that oscillation channel
proceeds through sterile state)

troubled:

can effective two-ν mixing
be big enough? also BBN?

Active-Sterile Neutrino Transformation & BBN

- X. Shi, K. Abazajian, & G.M.F. : First semi-self consistant calculation of the evolution of all neutrino energy distribution functions and nuclear reaction rates through the BBN epoch. Two cases were considered:

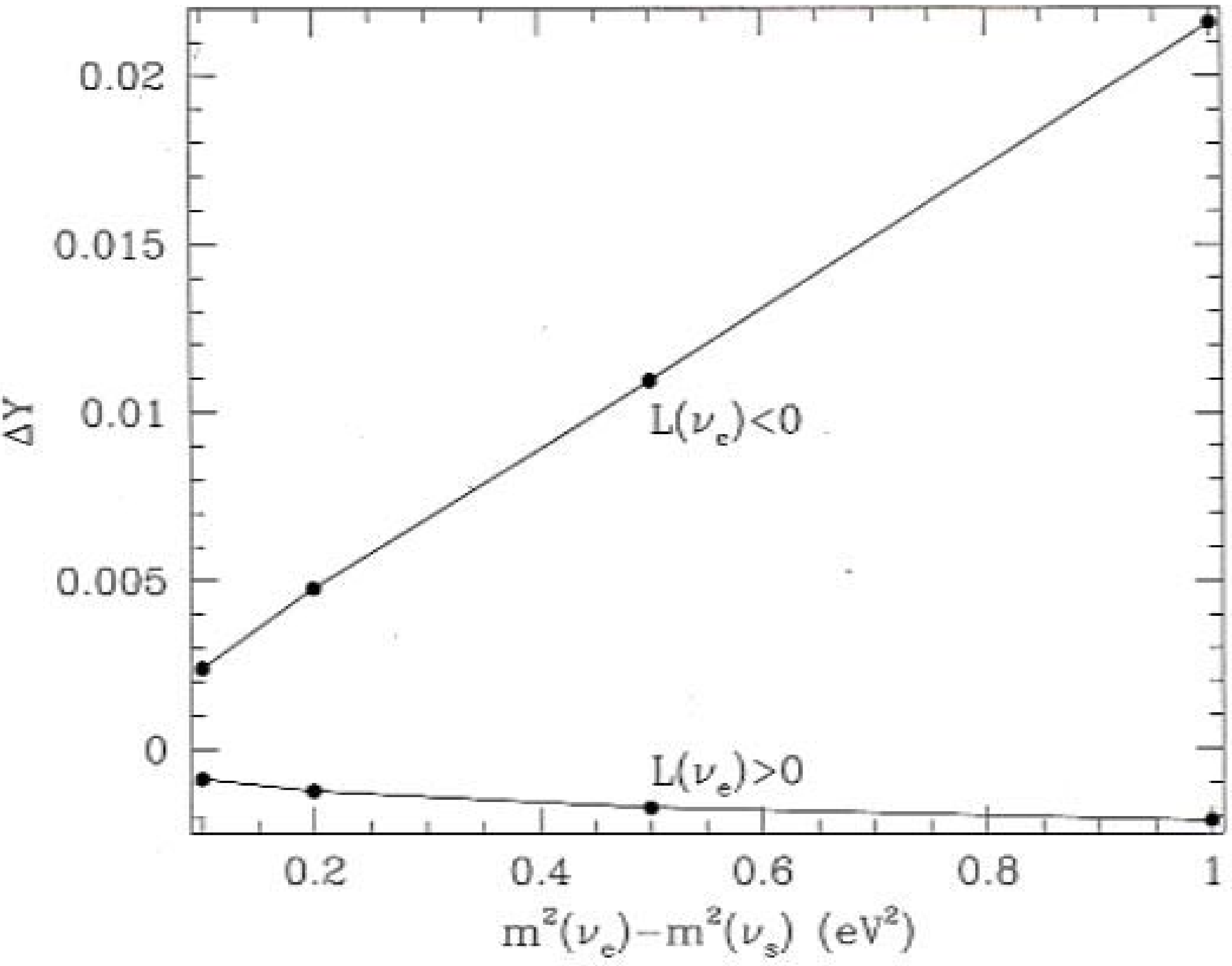
- (1) Lepton Number generation via direct $\nu_e \rightleftharpoons \nu_s$.

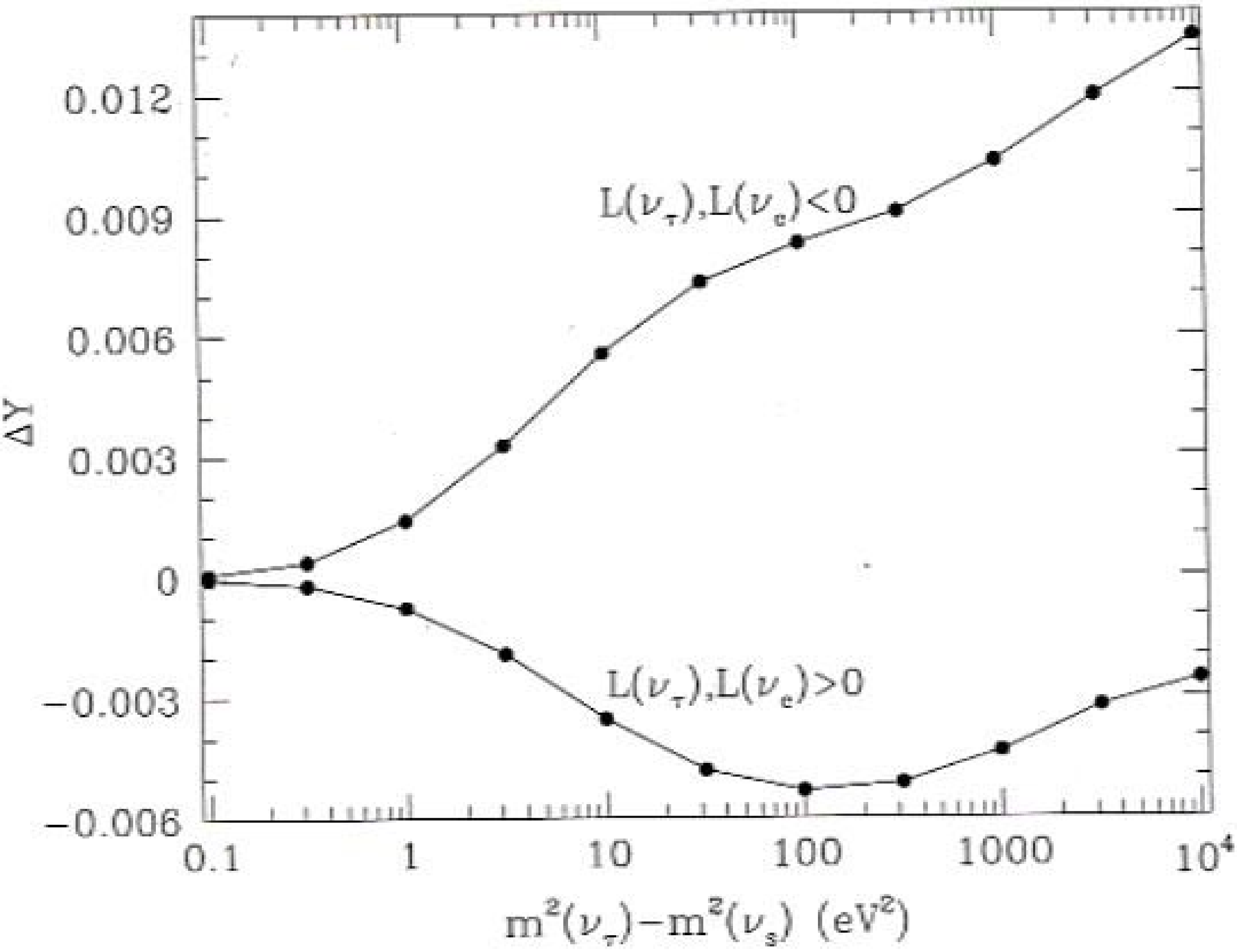
⇒ Find that change in primordial ^{4}He relative to SBBN is $\Delta Y \approx -1\%$ to $+9\%$, with the sign depending on sign of Lepton Number.

- (2) Examine Lepton Number Asymmetry in the mu and/or tau sector generated via $\nu_{\mu,\tau} \rightleftharpoons \nu_s$ followed by partial transfer of this Lepton Number to the $\nu_e\bar{\nu}_e$-sector via matter-enhanced active-active transformation.

⇒ Find that maximal reduction of ^{4}He relative to SBBN is $\sim 2\%$ if the Lepton Number in neutrinos is positive. Otherwise the increase in Y is $\lesssim 5\%$ for $m^2_{\nu_\mu,\nu_\tau} - m^2_{\nu_s} \lesssim 10^4\,\mathrm{eV}^2$.

$*$ **Overall Conclusion:** Change in ^{4}He yield induced by neutrino-mixing-generated lepton number asymmetry can be large in the upward direction, but is quite limited in the downward direction (the direction for ameliorating the "Crisis").


0.02
0.015
0.01
0.005
0
ΔY
L(ν_e)<0
L(ν_e)>0
0.2
0.4
0.6
0.8
1
m²(ν_e)−m²(ν_s) (eV²)



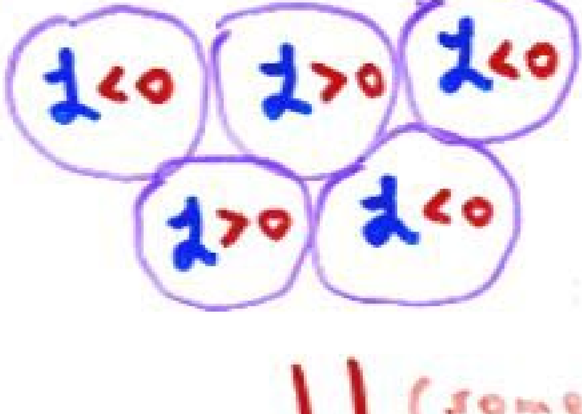
ΔY
0.012
0.009
0.006
0.003
0
−0.003
−0.006
$L(\nu_\tau),L(\nu_e)<0$
$L(\nu_\tau),L(\nu_e)>0$
0.1
1
10
100
1000
10^4
$m^2(\nu_\tau)-m^2(\nu_s)$ (eV^2)

Lepton Number Generation and The Causal Structure of Spacetime

X. Shi & G.M.F
PRL (in press '99)

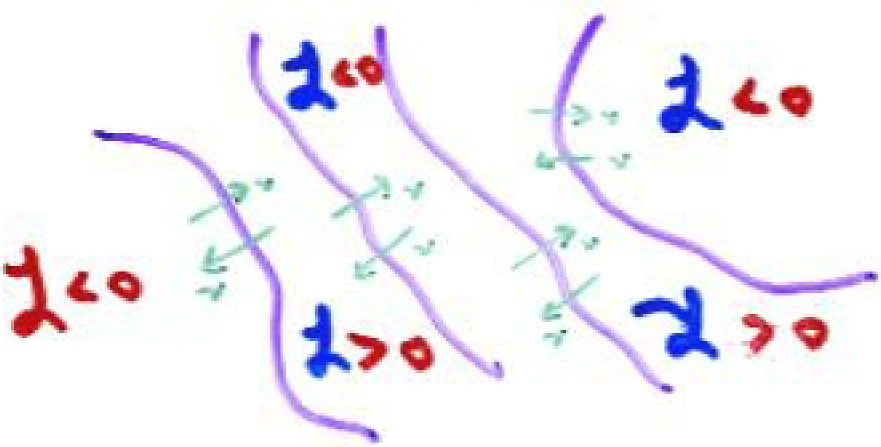
X. Shi (1996) has shown that the lepton number generation process is **chaotic**

$\Rightarrow$ **will create domains of lepton number which are bounded by the particle horizon size**



lepton no. generation epoch

$\Downarrow$ (some complicated percolation process)

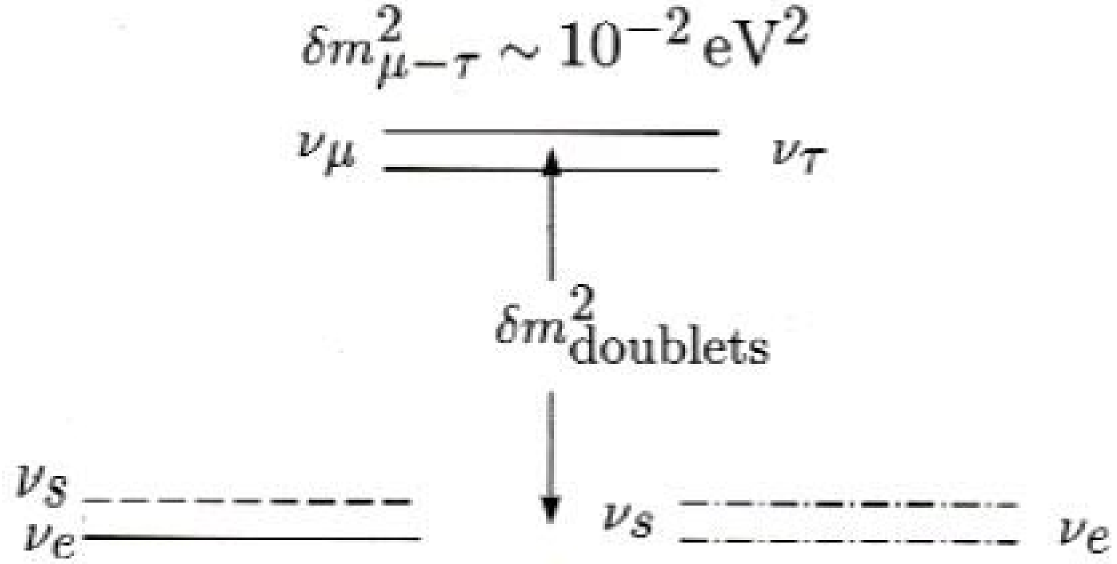


(just prior to...) BBN epoch

$\mathcal{L}$ gradients drive ν_s production

BBN, CFQ, LSND and all PDQ

X. Shi, G.M.F., K. Abazajian, PRD (submitted)



$\delta m^2_{\mathrm{se}} \le 10^{-5}\,\mathrm{eV}^2$

MSW in ⊙

BBN ⇒

$\sin^2 2\theta_{\mu s} \lesssim 10^{-10}$

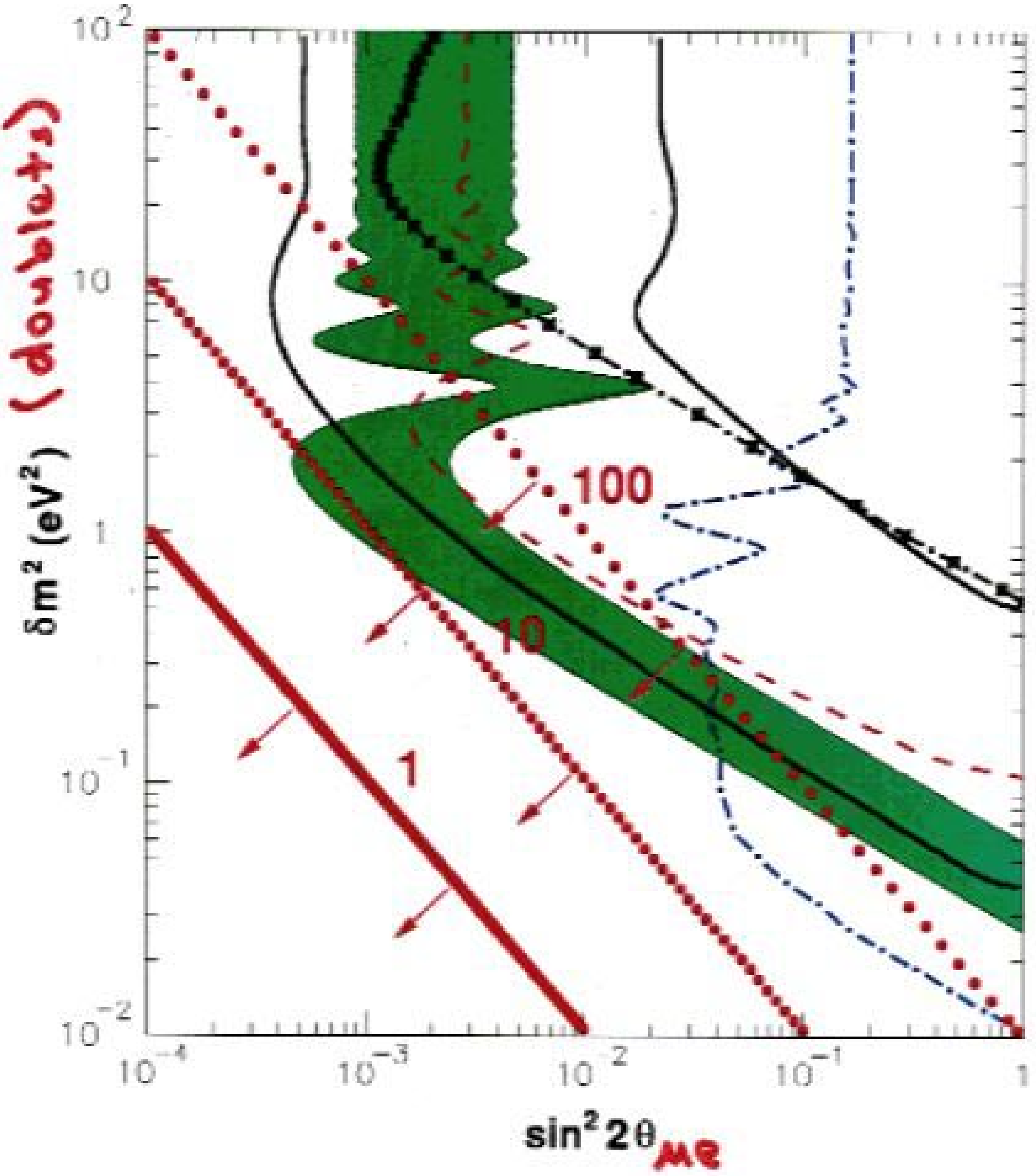
[all active↔sterile level crossings at domain boundaries must be **nonadiabatic**]

$\delta m^2_{\mathrm{e-s}} \sim 10^{-10}\,\mathrm{eV}^2$

"just so" for ⊙

BBN ⇒

$$F \equiv \frac{\sin^2 2``\theta_{\mu e}"}{\sin^2 2``\theta_{\mu s}"}$$


δm² (eV²) (doublets)
10²
10
1
10⁻¹
10⁻²
10⁻⁴
10⁻³
10⁻²
10⁻¹
1
100
10
1
sin² 2θ$_{\mu e}$

etc.