Neutrino oscillations and nucleosynthesis of elements

Meng-Ru Wu (TU Darmstadt)

In collaboration with Tobias Fischer (U of Wroclaw), Lutz Huther (TU Darmstadt),
Gabriel Martinez-Pinedo (TU Darmstadt GSI), Yong-Zhong Qian (U of Minnesota)

Nuclear structure and reactions: weak, strange and exotic
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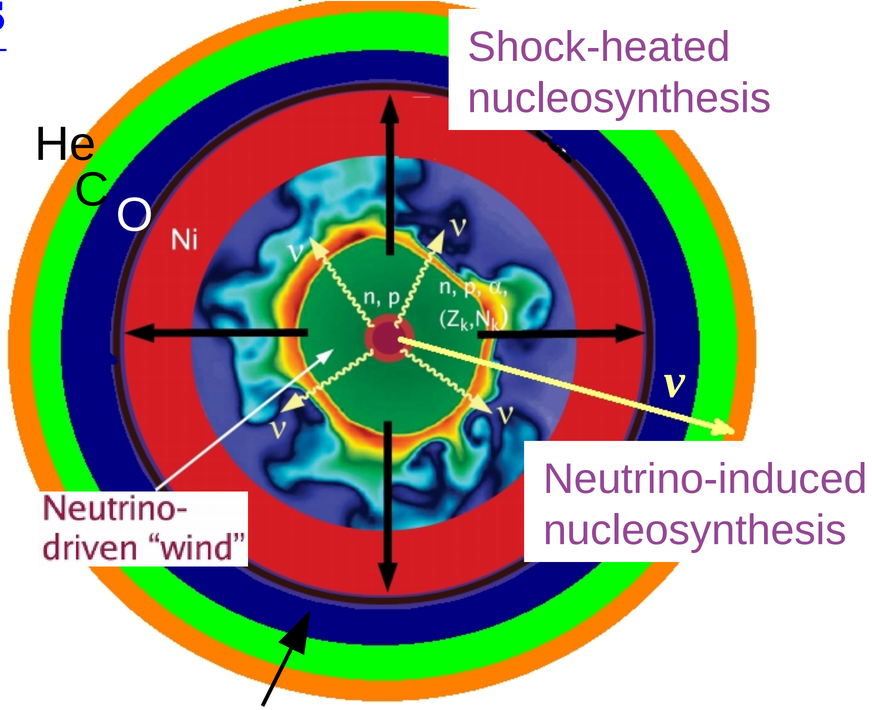
Neutrinos and nucleosynthesis

(1) Core-collapse supernovae:

- shock-heated nucleosynthesis
  → elements below Fe group
  from nuclear burning
- neutrino-driven wind
  → nuclei with $A \lesssim 130$
- neutrino (induced) nucelsynthesis
  → light elements : Li, Be, B, F
  rare isotopes : ^{138}La, ^{180}Ta
  r-process in He shell

(Modified from Janka+, PTEP 01A309, 2012)



Shock-heated nucleosynthesis

Neutrino-driven “wind”

Neutrino-induced nucleosynthesis

Shockwave (revived mainly by neutrino-heating)

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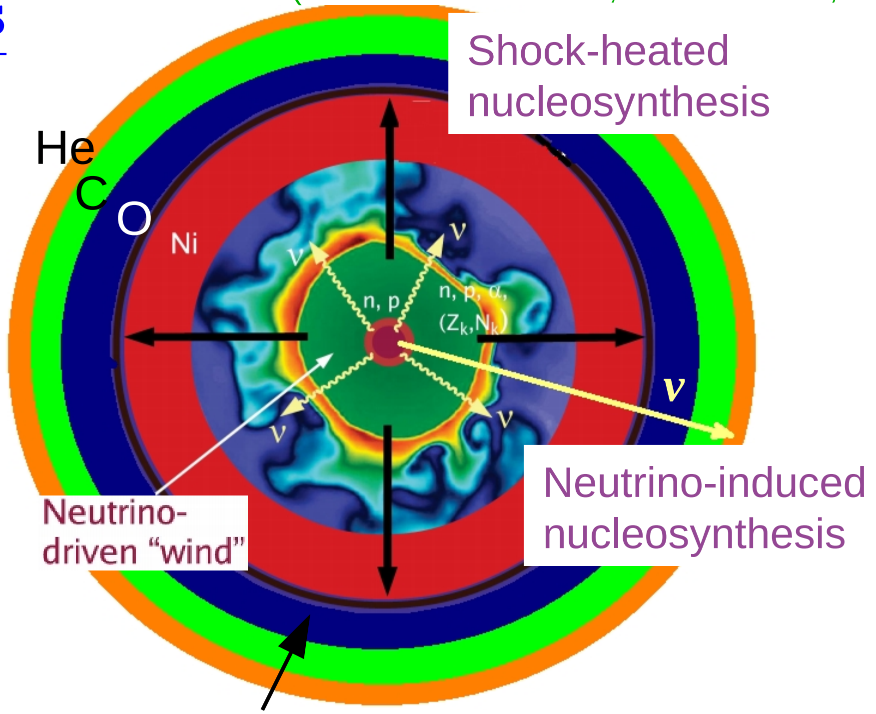

Shock-heated nucleosynthesis

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Shockwave (revived mainly by neutrino-heating)

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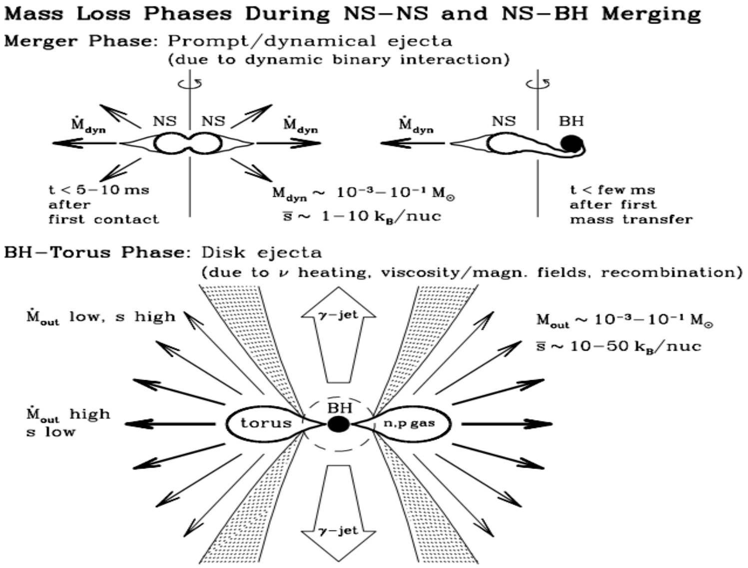
(2) NS-NS or NS-BH mergers:

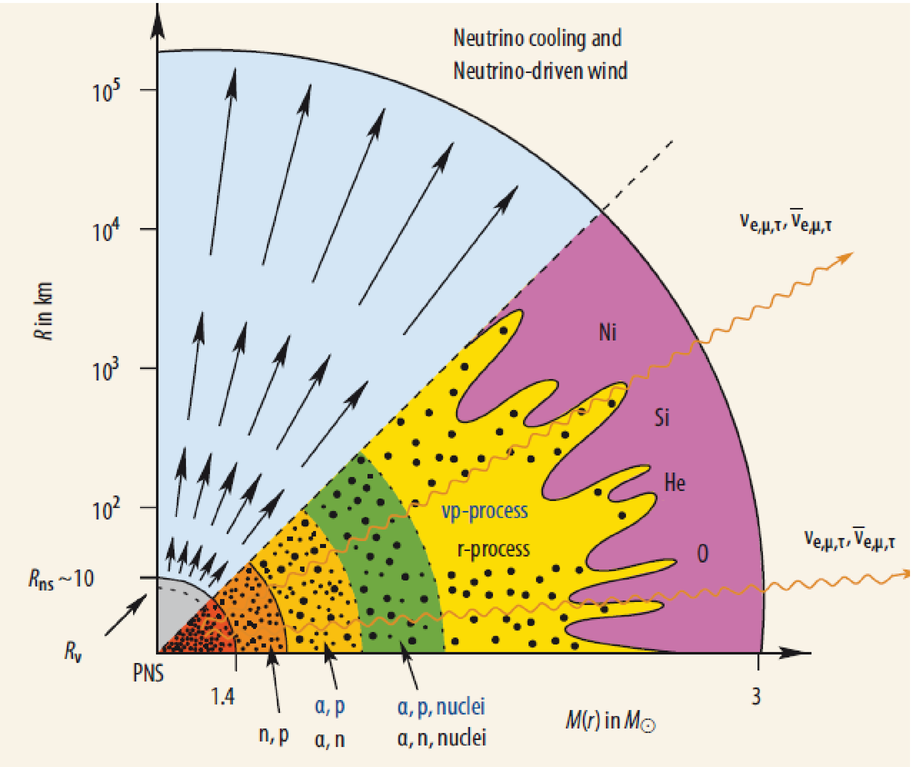
- dynamical ejecta
  → heavy $(A > 130)$ r-process nuclei
  light $(A < 130)$ r-process nuclei?
- viscously-driven ejecta
  → depends on the BH mass, viscousity
- neutrino-driven wind
  → mostly nuclei with $A \lesssim 130$



Neutrino interactions

$$\boxed{\begin{array}{l}\nu_e + n \rightarrow p + e^- \\ \bar{\nu}_e + p \rightarrow n + e^+\end{array}}$$

→ determine the neutron-to-proton ratio (or equivalently, the electron fraction, Y_e) of the ejecta
→ for νp process, neutrons created via the $\bar{\nu}_e$ capture leads to subsequent (n,p) reactions to pass over the waiting point nuclei



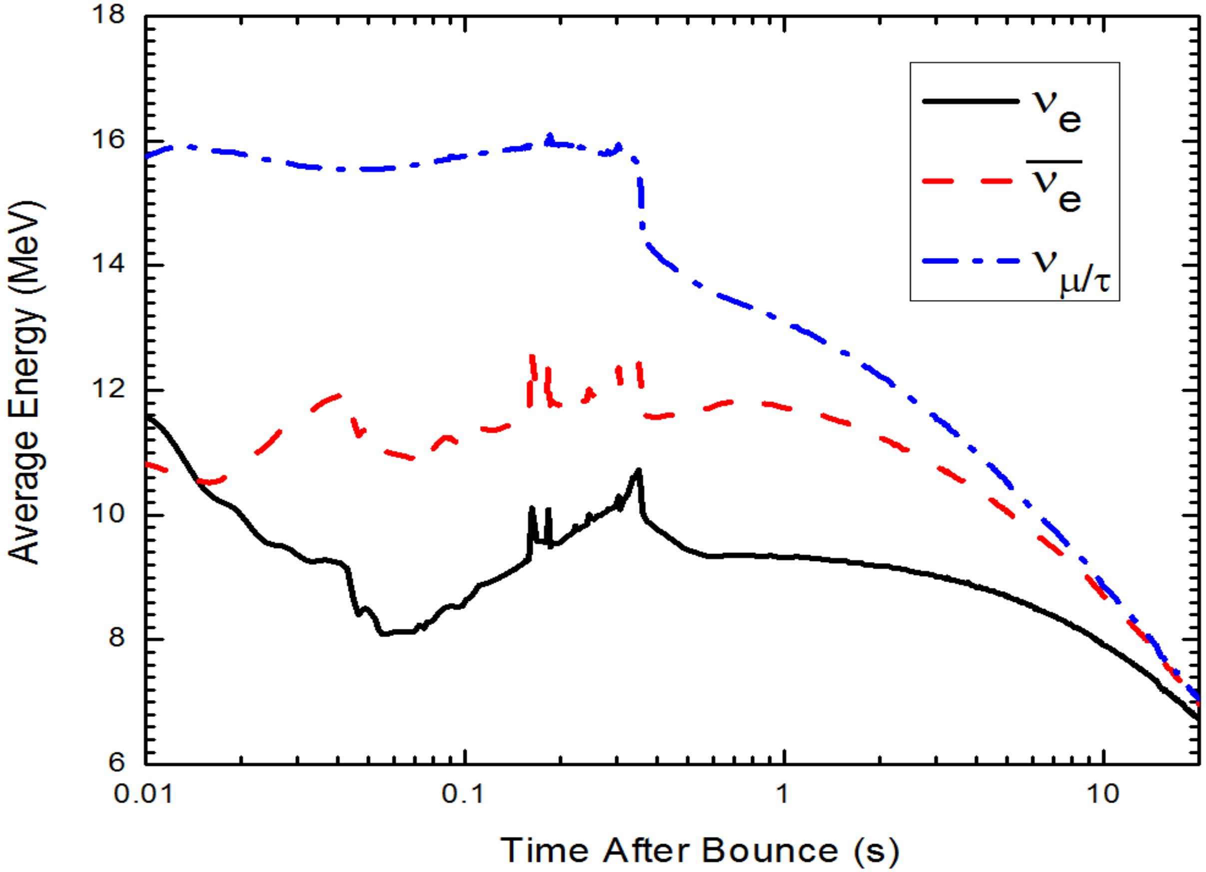
$$\boxed{\begin{array}{l}{}^4\mathrm{He}(\nu_e, e^- p)^3\mathrm{He},\ {}^4\mathrm{He}(\bar{\nu}_e, e^+ n)^3\mathrm{H}, \\ {}^4\mathrm{He}(\nu, \nu' p)^3\mathrm{H},\ {}^4\mathrm{He}(\nu, \nu' n)^3\mathrm{He}\end{array}}$$

→ subsequent ^{3}He$(\alpha,\gamma)^7$Be$(,e^+\nu_e)^7$Li and ^{3}H$(\alpha,\gamma)^7$Li$(\alpha,\gamma)^{11}$B producing Li and B
→ released neutrons may help a slow r-process to occur in the He shell

$$\boxed{{}^{138}\mathrm{Ba}(\nu_e, e^-)^{138}\mathrm{La},\ {}^{180}\mathrm{Hf}(\nu_e, e^-)^{180}\mathrm{Ta}}$$

→ dominant channel to produce these rare isotopes in the O/Ne shell

production of these nuclei are sensitive to the charged-current ν interaction rates



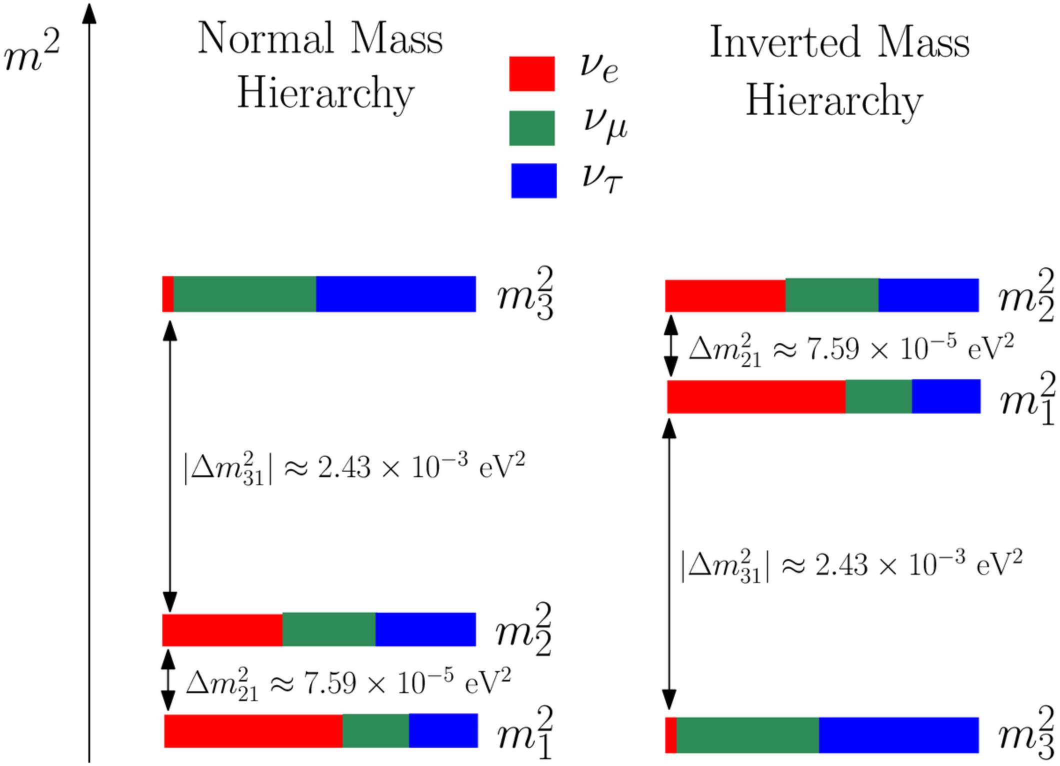
Energy hierarchy of supernova neutrinos :

$$\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_{\mu,\tau}} \rangle$$

charged-current interaction rates may be strongly enhanced by neutrino oscillations

Neutrinos do oscillate

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2}|\nu_1\rangle \\ e^{i\alpha_2/2}|\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$



mixing angles:
$\theta_{12} \approx 34°$
$\theta_{13} \approx 9°$
$\theta_{23} \approx 45°$

mass hierarchy?
CP phases?
absolute neutrino mass?
sterile neutrinos?

Neutrino oscillations in medium

With the mean-field approximation, up to the leading-order contribution of forward-scattering potential: [Sigl & Raffelt 1992, Volpe+ 2013]

$$\boxed{i\frac{d}{dt}\rho_{\nu,\vec{p}} = [H_{\rm vac} + H_m + H_\nu, \rho_{\nu,\vec{p}}], \qquad \begin{array}{l} \rho_\nu = |\nu\rangle\langle\nu| \\ |\nu\rangle = [a_e, a'_\mu, a'_\tau]^\dagger \end{array}}$$

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(1) vacuum Hamiltonian:

$$H_{\rm vac} \approx \frac{\Delta m^2_{31}}{4E_\nu}\begin{bmatrix} -\cos 2\theta_{13} & 0 & \sin 2\theta_{13} \\ 0 & 1 & 0 \\ \sin 2\theta_{13} & 0 & \cos 2\theta_{13} \end{bmatrix} + \frac{\Delta m^2_{21}}{4E_\nu}\begin{bmatrix} -\cos 2\theta_{12} & \sin 2\theta_{12} & 0 \\ \sin 2\theta_{12} & \cos 2\theta_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

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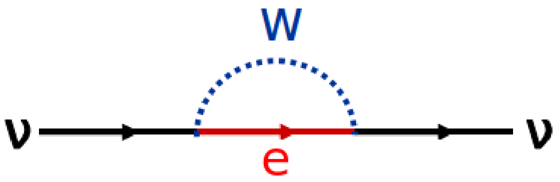
(2) MSW Hamiltonian: [Wolfenstein 1978, Mikheyev & Smirnov, 1985]

$$H_m = \pm\sqrt{2}G_F n_e \times {\rm diag}(1,0,0)$$



→ MSW resonances: $\pm\sqrt{2}G_F n_e = \frac{\Delta m^2_{ji}}{2E_\nu}\cos 2\theta_{ij}$

for Δm^2_{31}, $\rho_{\rm res} \sim O(10^3)$ g/cm^3

for Δm^2_{21}, $\rho_{\rm res} \sim O(10)$ g/cm^3

Neutrino oscillations in medium

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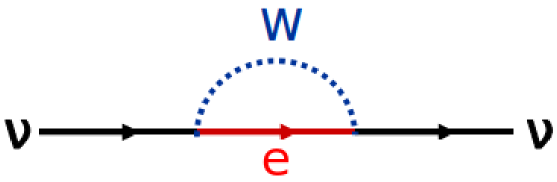

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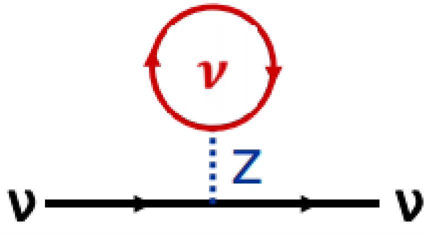
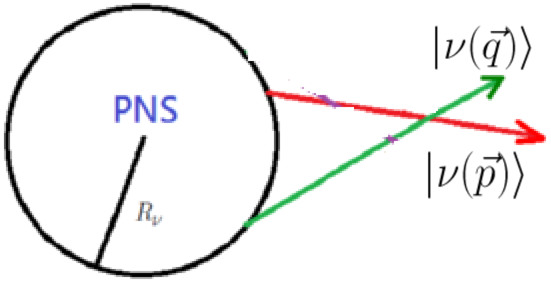
for Δm^2_{21}, $\rho_{\rm res} \sim O(10)$ g/cm^3

---

(3) ν-ν Hamiltonian: [Fuller+ 1987, Pantaleone 1992, Sigl & Raffelt, 1992]

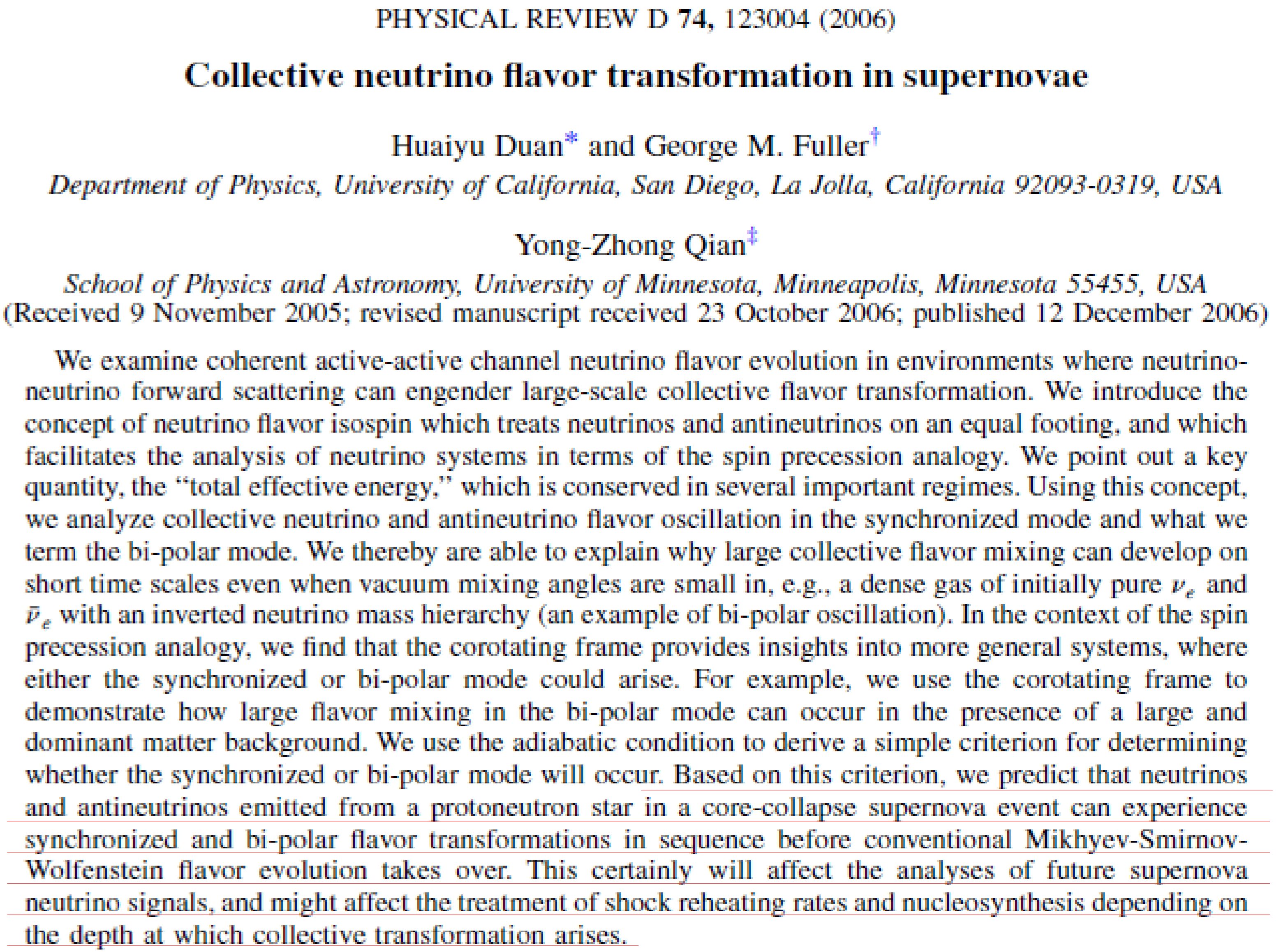
$$H_\nu = \sqrt{2}G_F \int (1 - \hat{p}\cdot\hat{q})(\rho_{\nu,\vec{q}} - \bar{\rho}^*_{\nu,\vec{q}})dn_{\nu,\vec{q}}$$





→ coupled non-linear equations

→ $\pm\sqrt{2}G_F(n_{\nu_e} - n_{\bar{\nu}_e})\frac{R_\nu^2}{r^2} \approx \frac{\Delta m^2_{ji}}{2E_\nu}\cos 2\theta_{ij}$



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Collective neutrino flavor transformation in supernovae

Huaiyu Duan[*] and George M. Fuller[†]
Department of Physics, University of California, San Diego, La Jolla, California 92093-0319, USA

Yong-Zhong Qian[‡]
School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota 55455, USA

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We examine coherent active-active channel neutrino flavor evolution in environments where neutrino-neutrino forward scattering can engender large-scale collective flavor transformation. We introduce the concept of neutrino flavor isospin which treats neutrinos and antineutrinos on an equal footing, and which facilitates the analysis of neutrino systems in terms of the spin precession analogy. We point out a key quantity, the "total effective energy," which is conserved in several important regimes. Using this concept, we analyze collective neutrino and antineutrino flavor oscillation in the synchronized mode and what we term the bi-polar mode. We thereby are able to explain why large collective flavor mixing can develop on short time scales even when vacuum mixing angles are small in, e.g., a dense gas of initially pure ν_e and $\bar{\nu}_e$ with an inverted neutrino mass hierarchy (an example of bi-polar oscillation). In the context of the spin precession analogy, we find that the corotating frame provides insights into more general systems, where either the synchronized or bi-polar mode could arise. For example, we use the corotating frame to demonstrate how large flavor mixing in the bi-polar mode can occur in the presence of a large and dominant matter background. We use the adiabatic condition to derive a simple criterion for determining whether the synchronized or bi-polar mode will occur. Based on this criterion, we predict that neutrinos and antineutrinos emitted from a protoneutron star in a core-collapse supernova event can experience synchronized and bi-polar flavor transformations in sequence before conventional Mikhyev-Smirnov-Wolfenstein flavor evolution takes over. This certainly will affect the analyses of future supernova neutrino signals, and might affect the treatment of shock reheating rates and nucleosynthesis depending on the depth at which collective transformation arises.

neutrinos with different E_ν nearly oscillate with a uniform collective frequency

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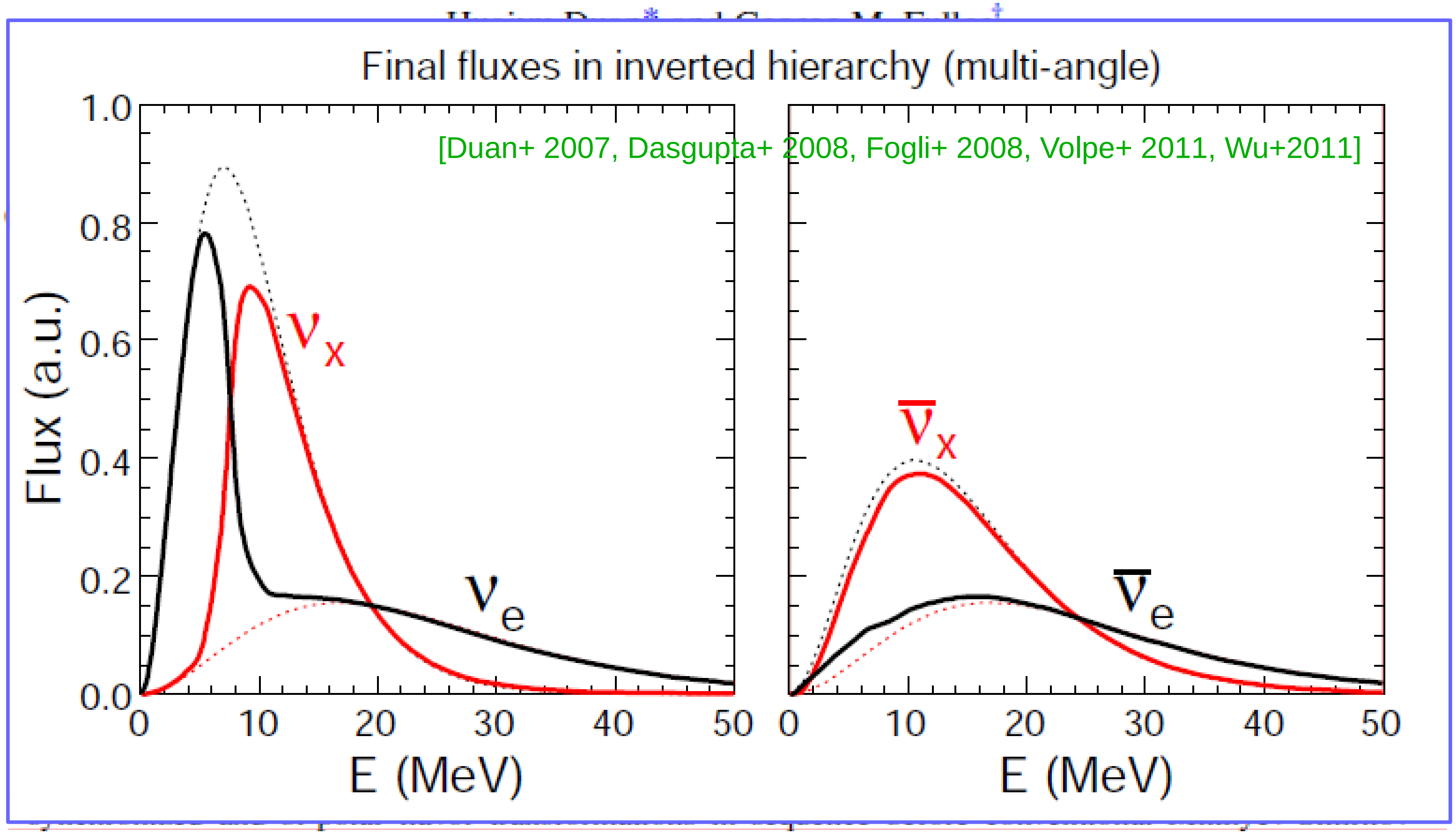

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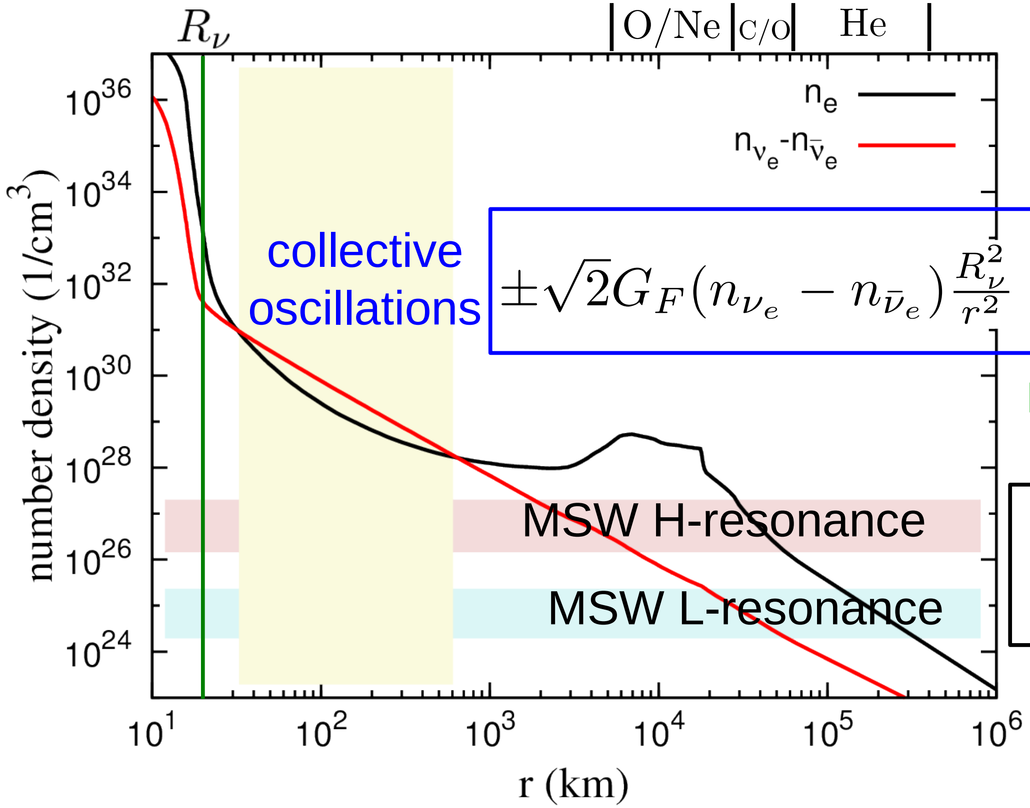

$$\pm\sqrt{2}G_F(n_{\nu_e}-n_{\bar\nu_e})\frac{R_\nu^2}{r^2}\approx\frac{\Delta m_{ji}^2}{2E_\nu}\cos 2\theta_{ij},\; n_e\lesssim n_{\nu_e}-n_{\bar\nu_e}$$

[Duan et. al, 2006-2013, Raffelt et. al., 2006-2013, …]

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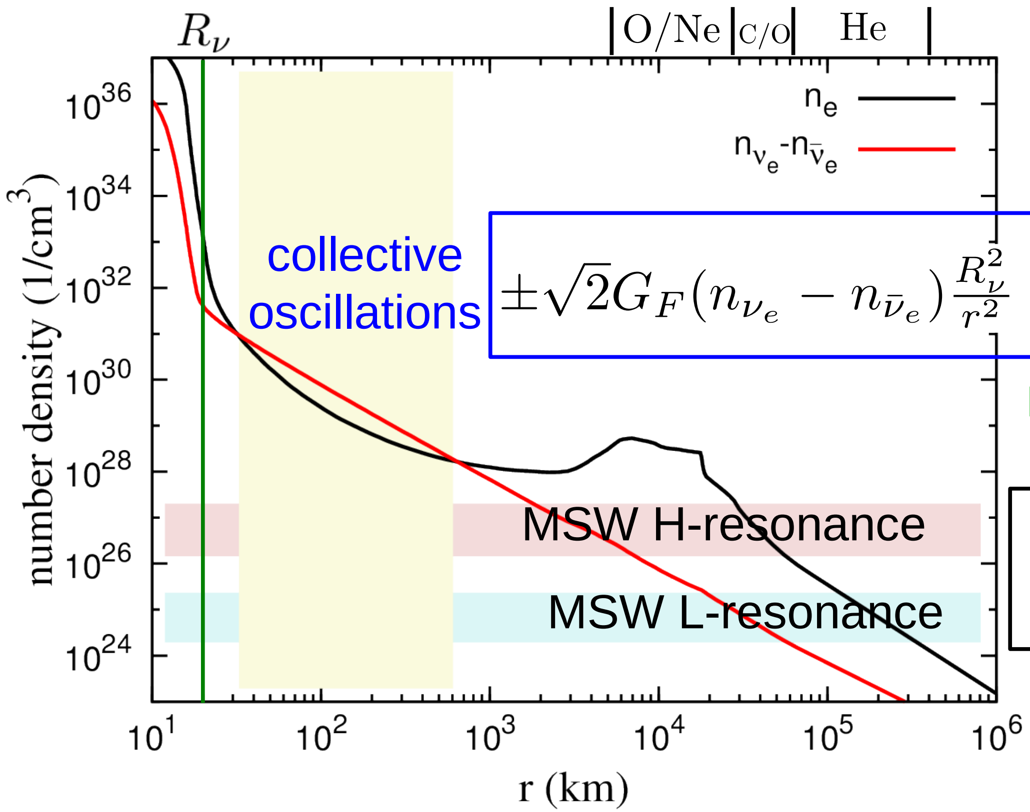

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[Duan et. al, 2006-2013, Raffelt et. al., 2006-2013, …]

$$\pm\sqrt{2}G_F n_e=\frac{\Delta m_{ji}^2}{2E_\nu}\cos 2\theta_{ij}$$

	Shock Revival ~O(10^2 km)	ν-driven Wind ~O(10^3 km)	ν-induced nucleosynthesis in outer shells ~O(10^5 km)	Neutrino signals
Collective Oscillations	no (?) (Chakraborty + 2011 Dasgupta + 2012)	possible (Martinez-Pinedo + 2011, Duan + 2012)	possible	possible (Gava + 2009 Dighe + 2000 Tomas+ 2004 ……… ……..)
MSW H-resonance	no	no	yes (Yoshida + 2006, Banerjee + 2011, 2012)	yes
MSW L-resonance	no	no	very little	yes

However, a calculation consistent with the supernova model is lacking...

Collective oscillations with inputs from supernova model

[MRW, Qian, Martinez-Pinedo, Fischer, Huther, arXiv:1412.8587, 2014]

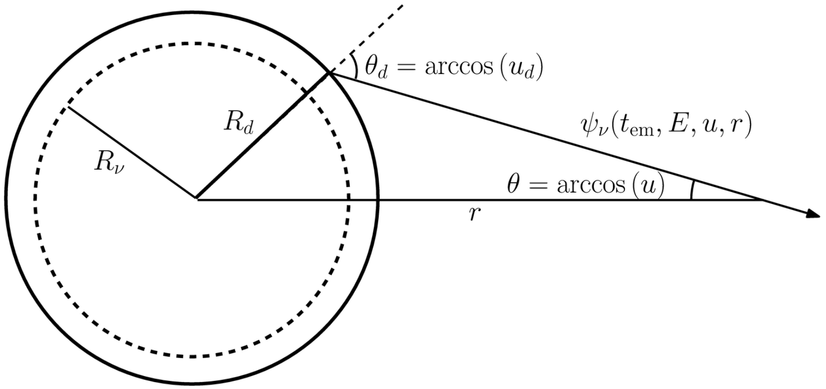
Supernova model: [Fischer+, A&A 517A, 80F, 2010]

- 18 $M_\odot$, spherically symmetric + Boltzmman ν transport
- axial symmetric ν distribution, $f_\nu(t, r, E_\nu, \theta)$
- proton-rich ν-driven wind, possible νp process site

Model of Neutrino Oscillations:

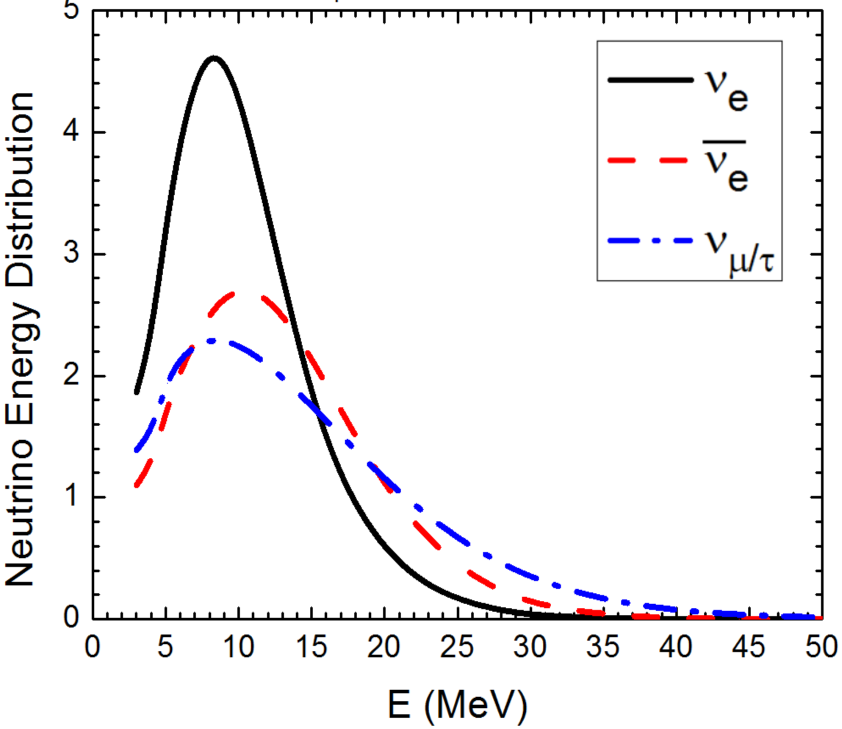
- a sharp ν-decoupling spheres, R_d
- all neutrinos in pure flavor eigenstate at R_d
- axial-symmetry of ν flavor evolution being maintained

$$i\frac{d}{dr}\rho_\nu(t_{\rm em}, r, E_\nu, \theta) = \left[\frac{H_{\rm vac}(E_\nu) + H_m(t_{\rm em}, r)}{\cos\theta} + H'_\nu(t_{\rm em}, \theta, r), \rho_\nu\right]$$

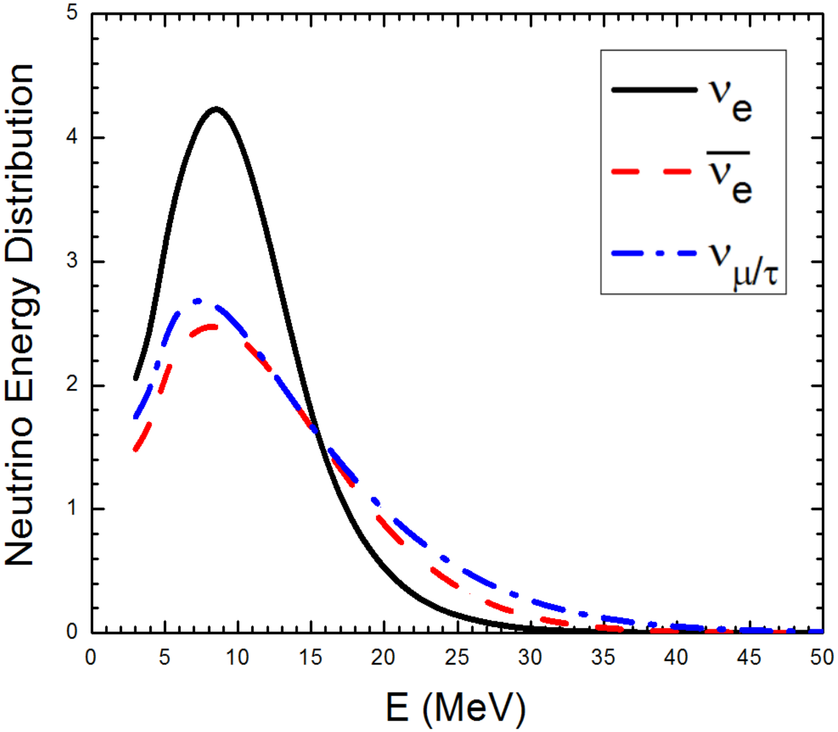


→ numerically ∼ millions of coupled ODEs to solve for each $t_{\rm em}$

Collective oscillations : time-evolution of ν spectra



$t_{\rm pb} = 1.0$ s



$t_{\rm pb} = 3.0$ s

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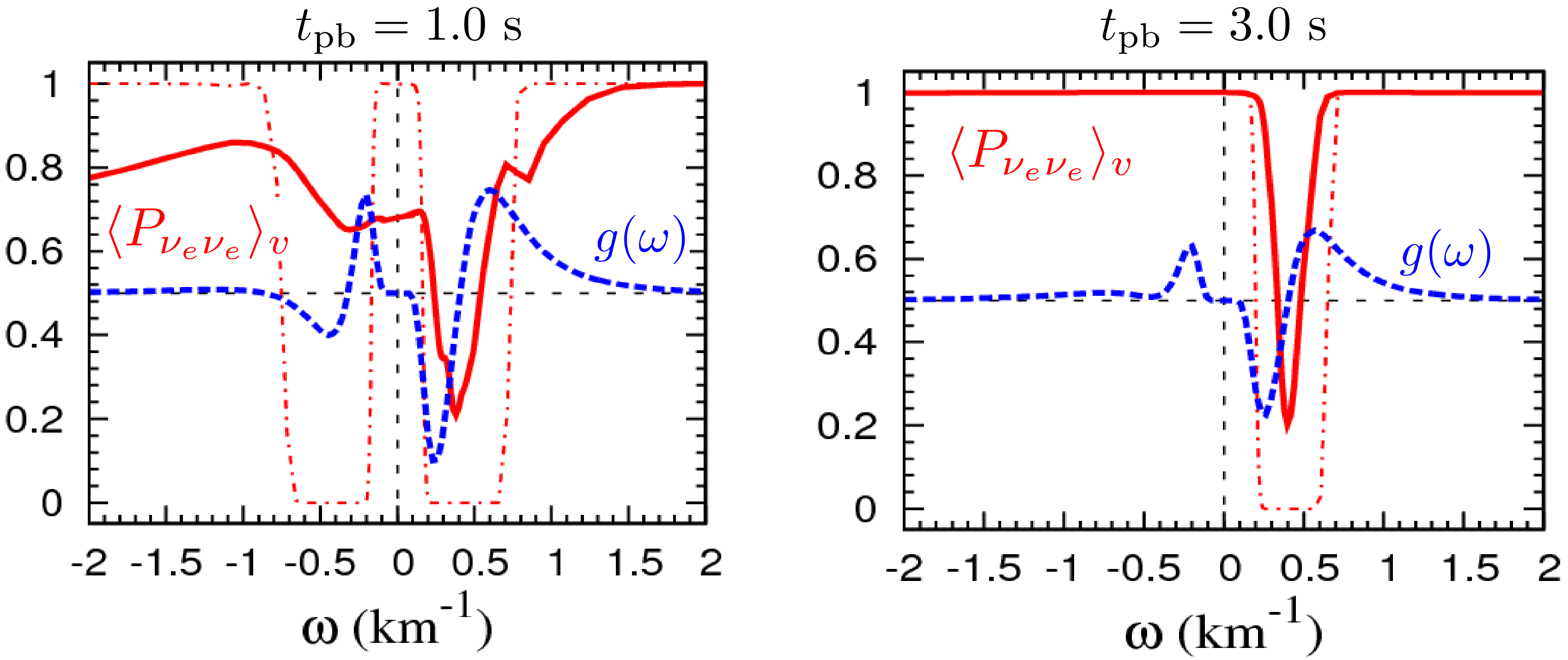


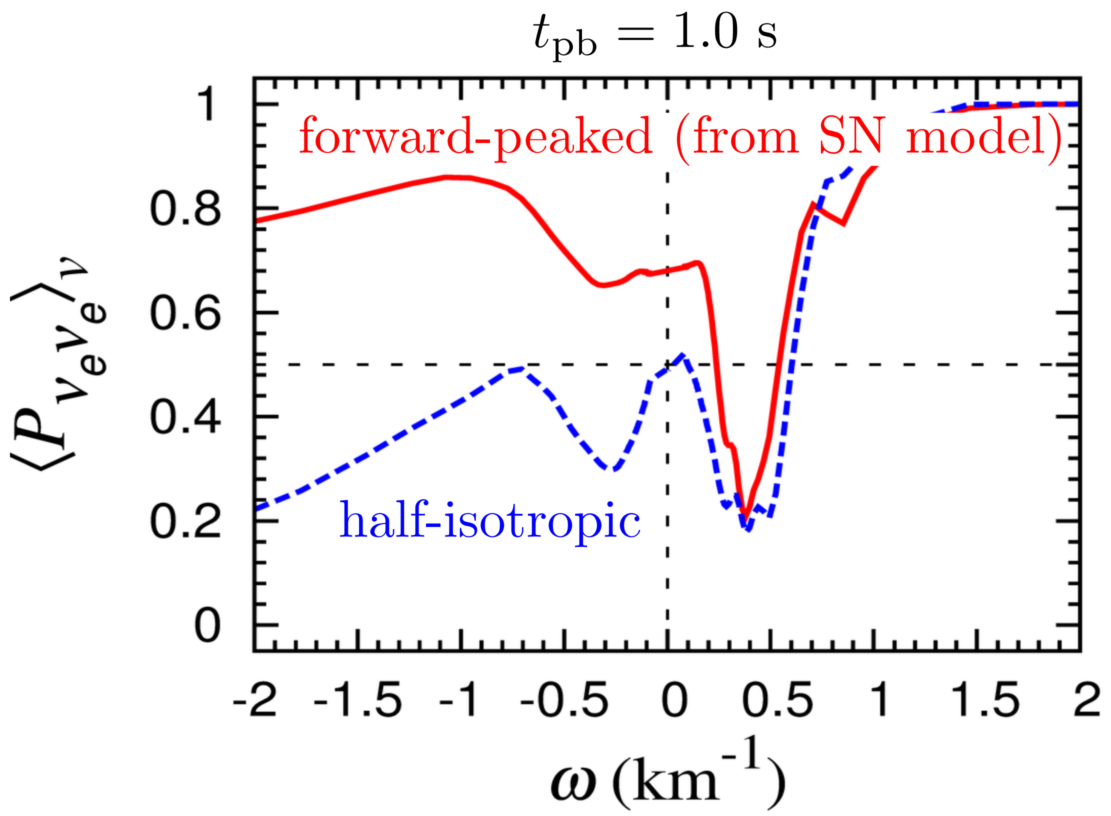
$t_{\text{pb}} = 1.0$ s

$t_{\text{pb}} = 3.0$ s

$$\omega = \pm\frac{|\Delta m^2_{31}|}{2E_\nu} = \pm 0.616\times\left(\frac{10\text{MeV}}{E_\nu}\right)\text{km}^{-1}, \begin{cases}\omega > 0, \nu_{e,x}\\ \omega < 0, \bar{\nu}_{e,x}\end{cases}$$

$$g(\omega) \propto \omega^{-2}\begin{cases} f_{\nu_e}(\omega) - f_{\nu_x}(\omega), \omega > 0\\ f_{\bar{\nu}_x}(\omega) - f_{\bar{\nu}_e}(\omega), \omega < 0\end{cases}$$

Collective oscillations : ν angular distribution



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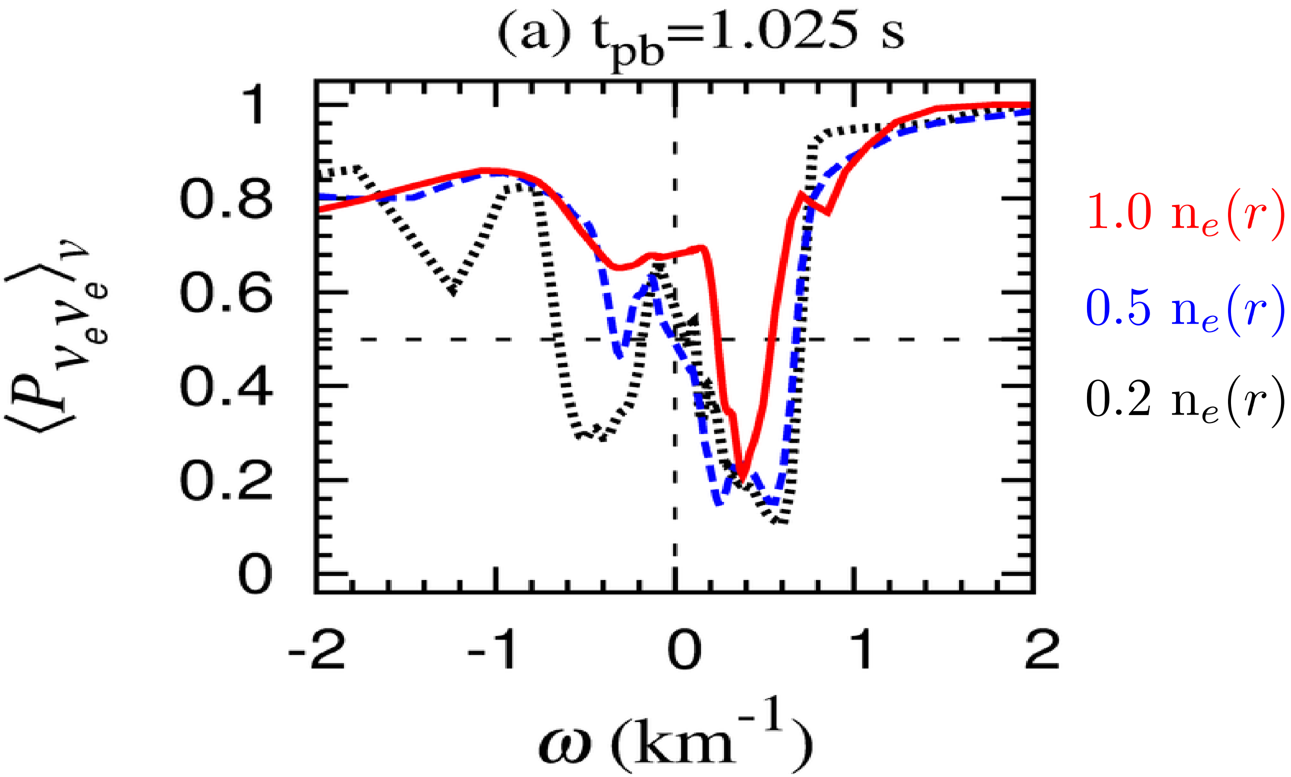
Collective oscillations : electron number density



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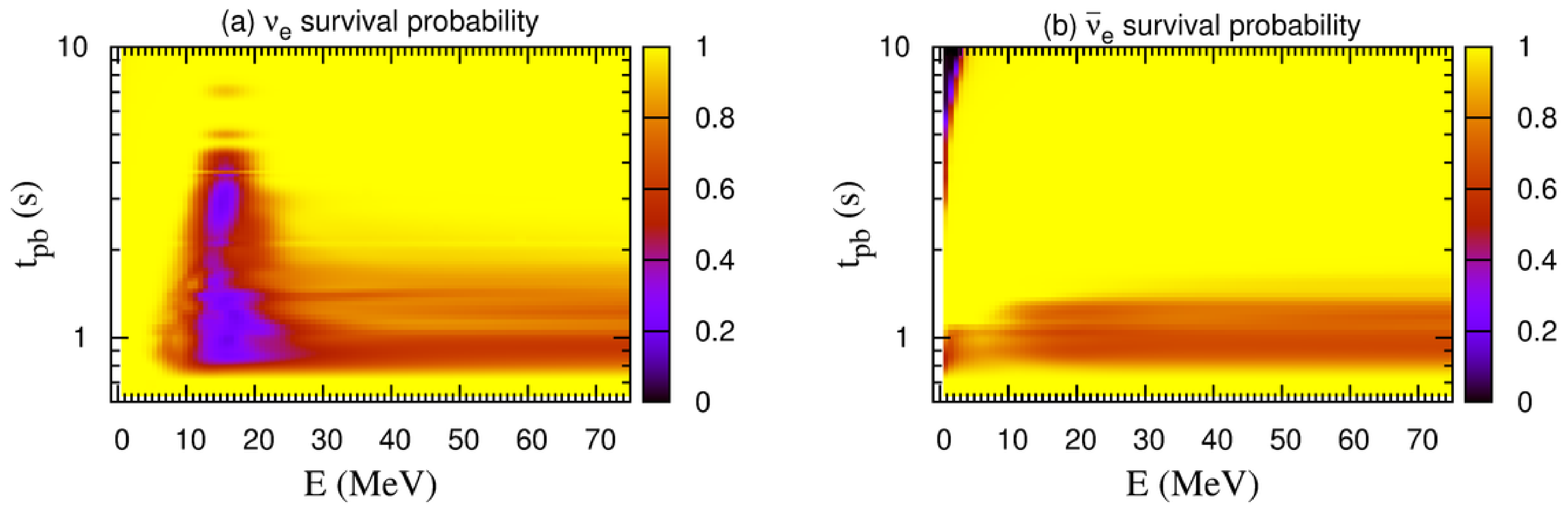
Result: collective ν oscillations

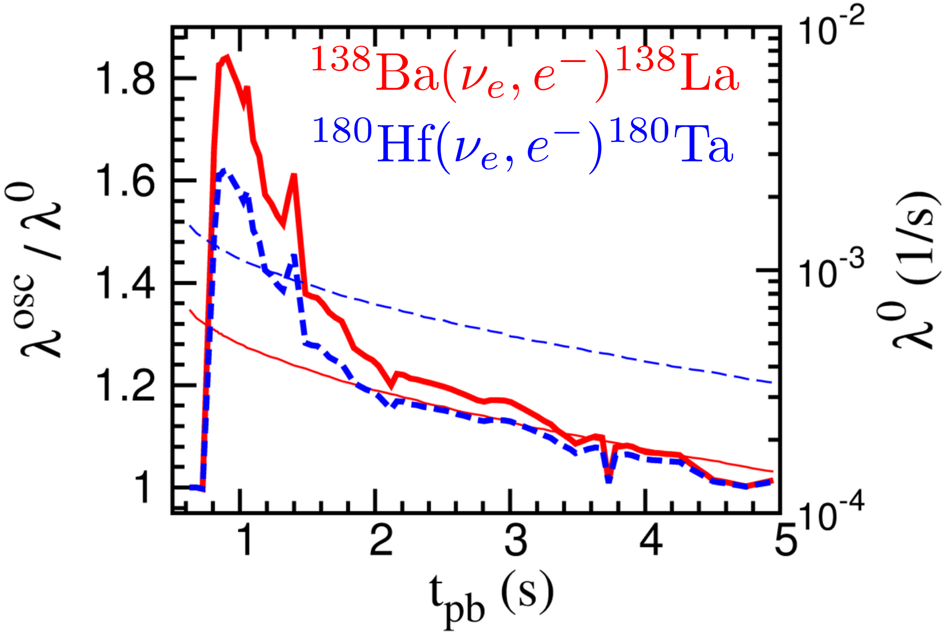
after the collective oscillations (at $r = 500$ km):



- collective oscillations only occur for inverted ν mass hierarchy
- forward-peaked ν angular distribution → reduces the ν-ν strength
- dominant $\bar{\nu}_x$ over $\bar{\nu}_e$ spectra → no flavor conversion for $\bar{\nu}_e$ for $t_{\rm pb} \gtrsim 1.5$ s
- realistic n_e profiles → strongly supress ν_e flavor conversion for for $t_{\rm pb} \gtrsim 5$ s

→ no effect on the νp process

Effect on ^{138}La and ^{180}Ta production



^{138}La and ^{180}Ta production may be enhanced by $\sim$ 11.5% and 8.5%

Adiabatic MSW ν oscillations

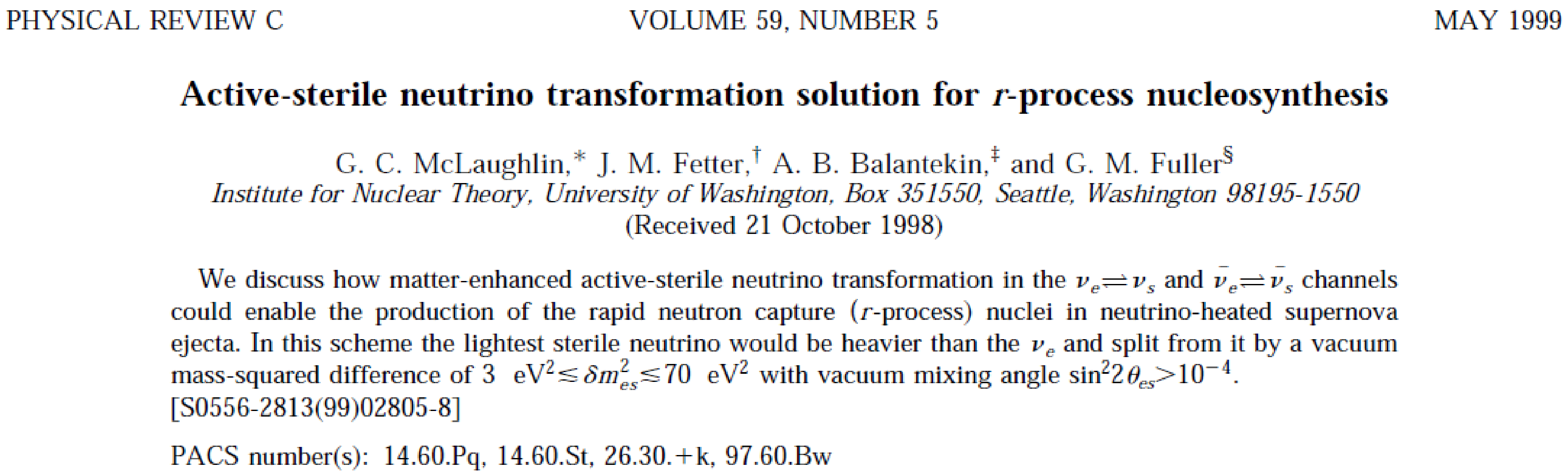
		$f_{\nu_e}(r)$	$f_{\bar{\nu}_e}(r)$
NH	$n^{31}_{\mathrm{e,res}} \gtrsim n_e \gtrsim n^{21}_{\mathrm{e,res}}$	$f^c_{\nu_x}$	$f^c_{\bar{\nu}_e}$
	$n_e \gtrsim n^{21}_{\mathrm{e,res}}$	$f^c_{\nu_x}$	$0.7 f^c_{\bar{\nu}_e} + 0.3 f^c_{\bar{\nu}_x}$
IH	$n^{31}_{\mathrm{e,res}} \gtrsim n_e \gtrsim n^{21}_{\mathrm{e,res}}$	$f^c_{\nu_e}$	$f^c_{\bar{\nu}_x}$
	$n_e \gtrsim n^{21}_{\mathrm{e,res}}$	$0.3 f^c_{\nu_e} + 0.7 f^c_{\nu_x}$	$f^c_{\bar{\nu}_x}$

^{4}He$(\nu_e, e^- p)^3$He rates boosted by a factor of ~ 32 larger in NH
$\rightarrow$ enhances ^{7}Li production

^{4}He$(\bar{\nu}_e, e^+ n)^3$H boosted by a factor of ~ 17 larger in IH
$\rightarrow$ enhances ^{11}B production

similar enhancement as in Yoshida et. al. 2006
full calculation of ν-nucleosynthesis needs to be further studied

What if there are light (eV) sterile neutrinos?



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Active-sterile neutrino transformation solution for *r*-process nucleosynthesis

G. C. McLaughlin,* J. M. Fetter,† A. B. Balantekin,‡ and G. M. Fuller§
Institute for Nuclear Theory, University of Washington, Box 351550, Seattle, Washington 98195-1550

(Received 21 October 1998)

We discuss how matter-enhanced active-sterile neutrino transformation in the $\nu_e \rightleftharpoons \nu_s$ and $\bar{\nu}_e \rightleftharpoons \bar{\nu}_s$ channels could enable the production of the rapid neutron capture (*r*-process) nuclei in neutrino-heated supernova ejecta. In this scheme the lightest sterile neutrino would be heavier than the ν_e and split from it by a vacuum mass-squared difference of $3\ \mathrm{eV}^2 \lesssim \delta m^2_{es} \lesssim 70\ \mathrm{eV}^2$ with vacuum mixing angle $\sin^2 2\theta_{es} > 10^{-4}$. [S0556-2813(99)02805-8]

PACS number(s): 14.60.Pq, 14.60.St, 26.30.+k, 97.60.Bw

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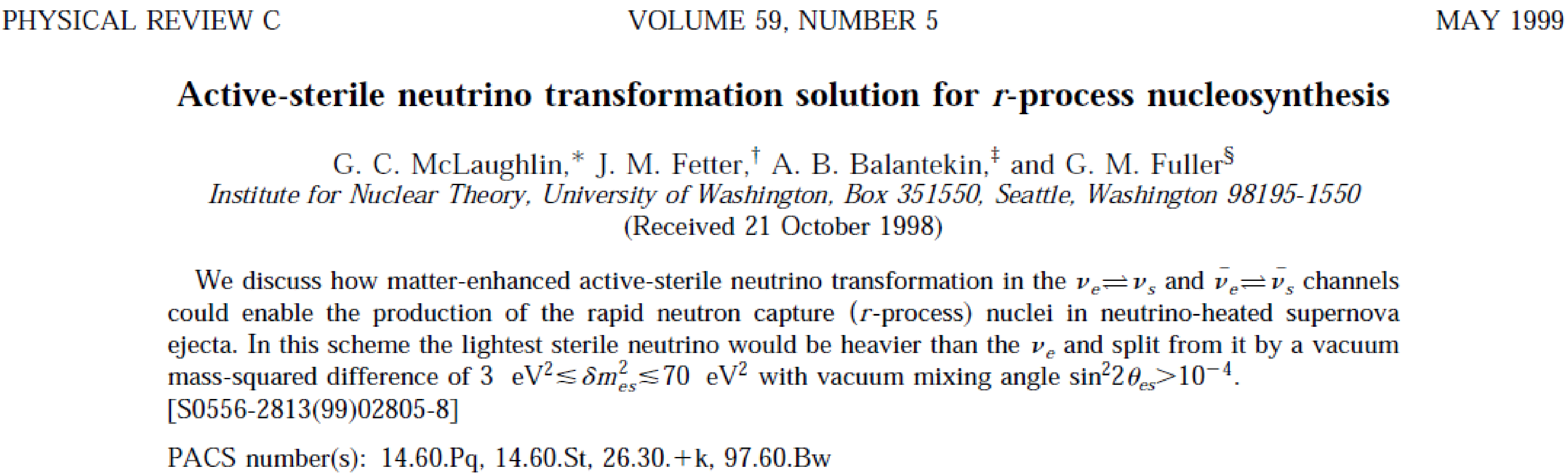

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Active-sterile neutrino transformation solution for *r*-process nucleosynthesis

G. C. McLaughlin,[*] J. M. Fetter,[†] A. B. Balantekin,[‡] and G. M. Fuller[§]
Institute for Nuclear Theory, University of Washington, Box 351550, Seattle, Washington 98195-1550

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We discuss how matter-enhanced active-sterile neutrino transformation in the $\nu_e \rightleftharpoons \nu_s$ and $\bar{\nu}_e \rightleftharpoons \bar{\nu}_s$ channels could enable the production of the rapid neutron capture (*r*-process) nuclei in neutrino-heated supernova ejecta. In this scheme the lightest sterile neutrino would be heavier than the ν_e and split from it by a vacuum mass-squared difference of $3\ \mathrm{eV}^2 \lesssim \delta m^2_{es} \lesssim 70\ \mathrm{eV}^2$ with vacuum mixing angle $\sin^2 2\theta_{es} > 10^{-4}$. [S0556-2813(99)02805-8]

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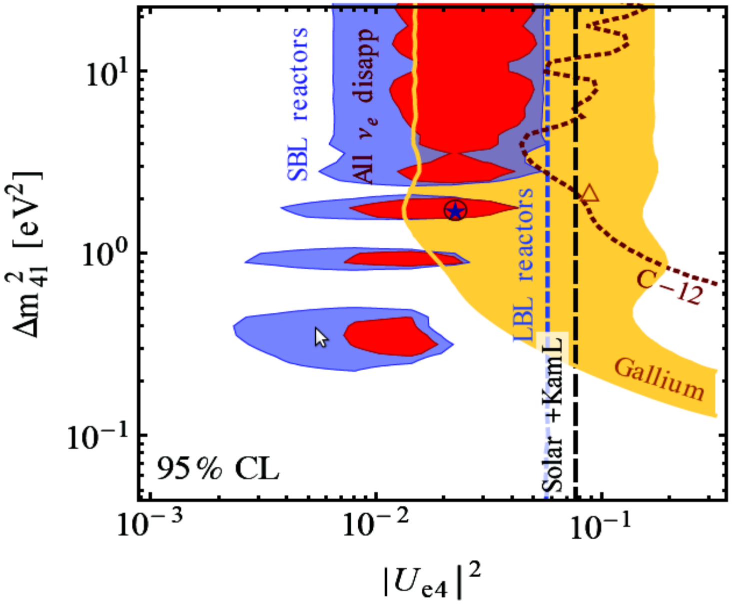
Reactor ν anomaly + Gallium anomaly:

(Mention+ 2011) (Giunti+ 2011-2013)

$$\Delta m^2_{41} \sim O(\mathrm{eV}^2)$$
$$\sin^2 2\theta_{14} = \sin^2 2\theta_{ee} \sim 0.1$$

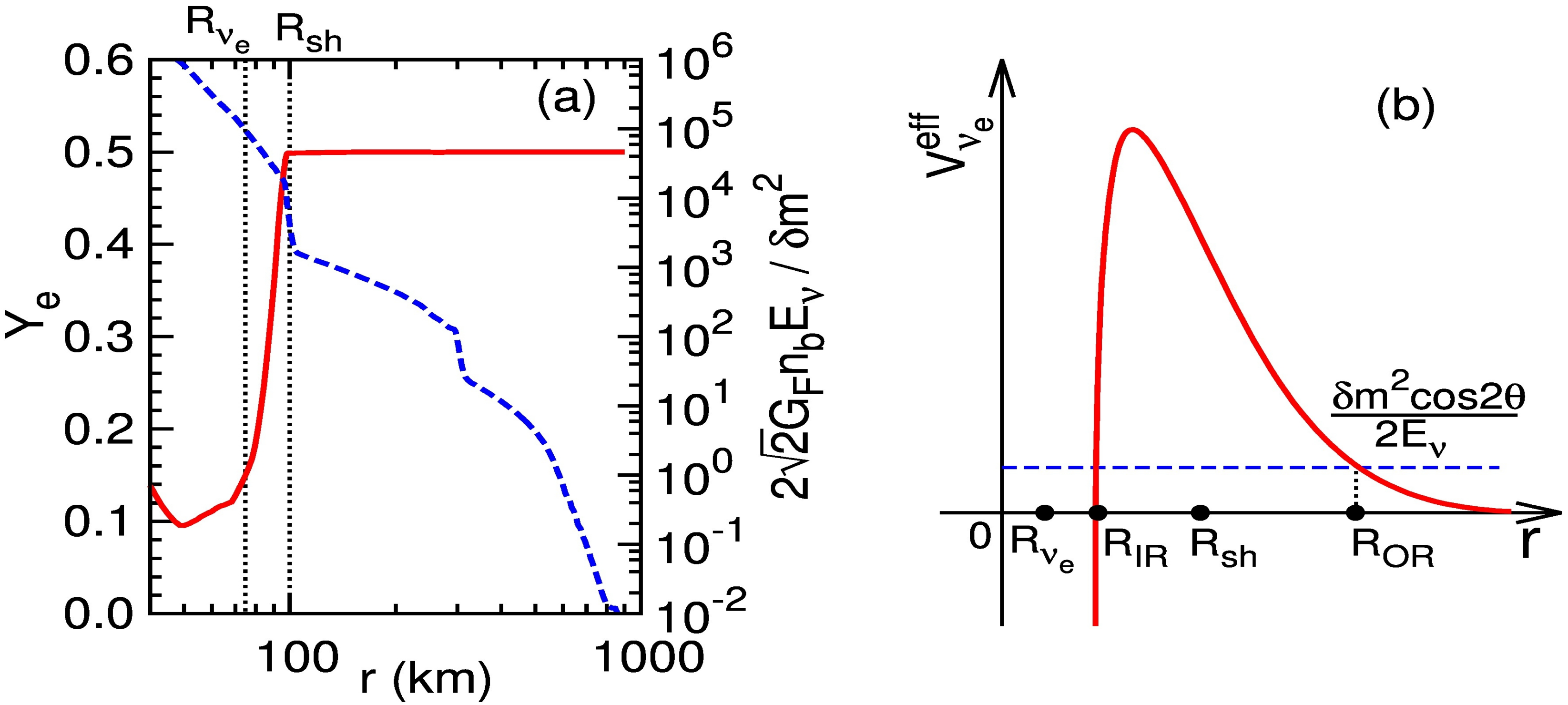
(Kopp et.al, JHEP05 (2013) 050)



Recent studies from Tamborra et. al. suggest that the impact on nucleosynthesis in the ν-driven wind is small

What if there are light (eV) sterile neutrinos?

$$\pm\frac{3\sqrt{2}}{2}G_F n_b\left(Y_e-\frac{1}{3}\right)\approx\frac{\Delta m_{41}^2}{2E_\nu}\cos 2\theta_{14}$$



Inner resonance: both ν_e-ν_s and $\bar{\nu}_e$-$\bar{\nu}_s$, non-adiabatic?

$$\left|Y_e-\tfrac{1}{3}\right|\approx 7.7\times10^{-4}\left(\frac{10^9\mathrm{g/cm^3}}{\rho}\right)\left(\frac{10\mathrm{MeV}}{E_\nu}\right)\left(\frac{\Delta m_{41}^2}{1.75\mathrm{eV}^2}\right)\cos 2\theta_{14}$$

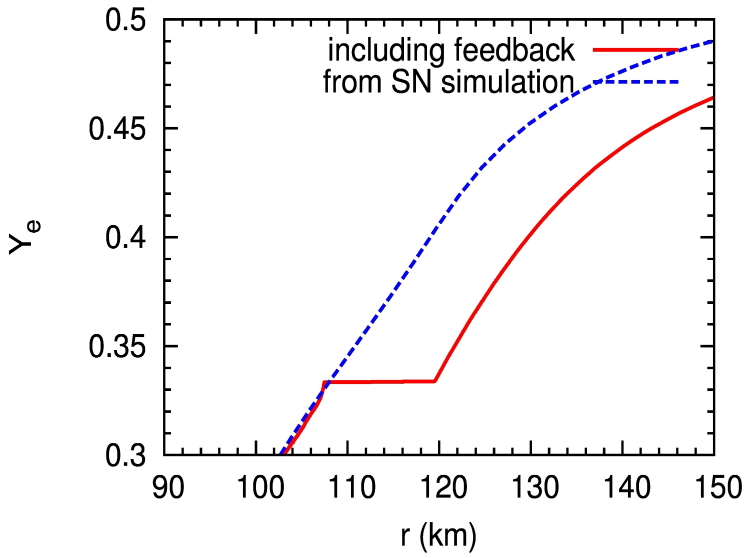
Onner resonance: only ν_e-ν_s

$$\rho\sim 10^6\ \mathrm{g/cm^3},\ Y_e\approx 0.5$$

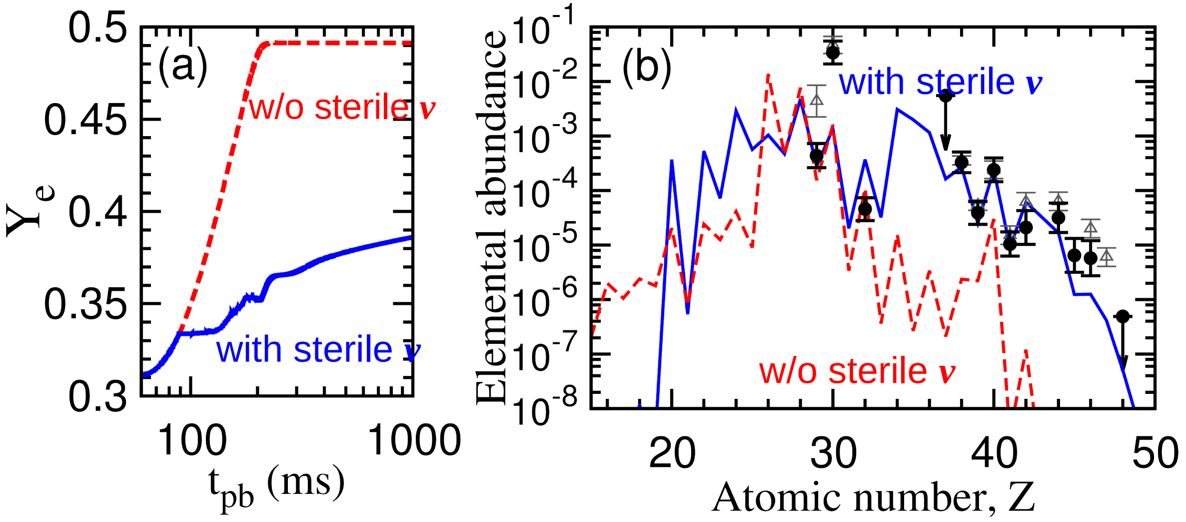
What if there are light (eV) sterile neutrinos?

- a $Y_e \gtrsim 1/3$ plateau forms when the feedback of $\nu_e(\bar{\nu}_e) \to \nu_s(\bar{\nu}_s)$ is taken into account immediately after the core-bounce
- more ν_e can be converted to ν_s than $\bar{\nu}_e$ to $\bar{\nu}_s$ at the $Y_e \approx 1/3$ plateau

$\to$ neutron-richness of the ejecta may be largely increased



$$\boxed{\nu_e + n \to p + e^-, \bar{\nu}_e + p \to n + e^+}$$

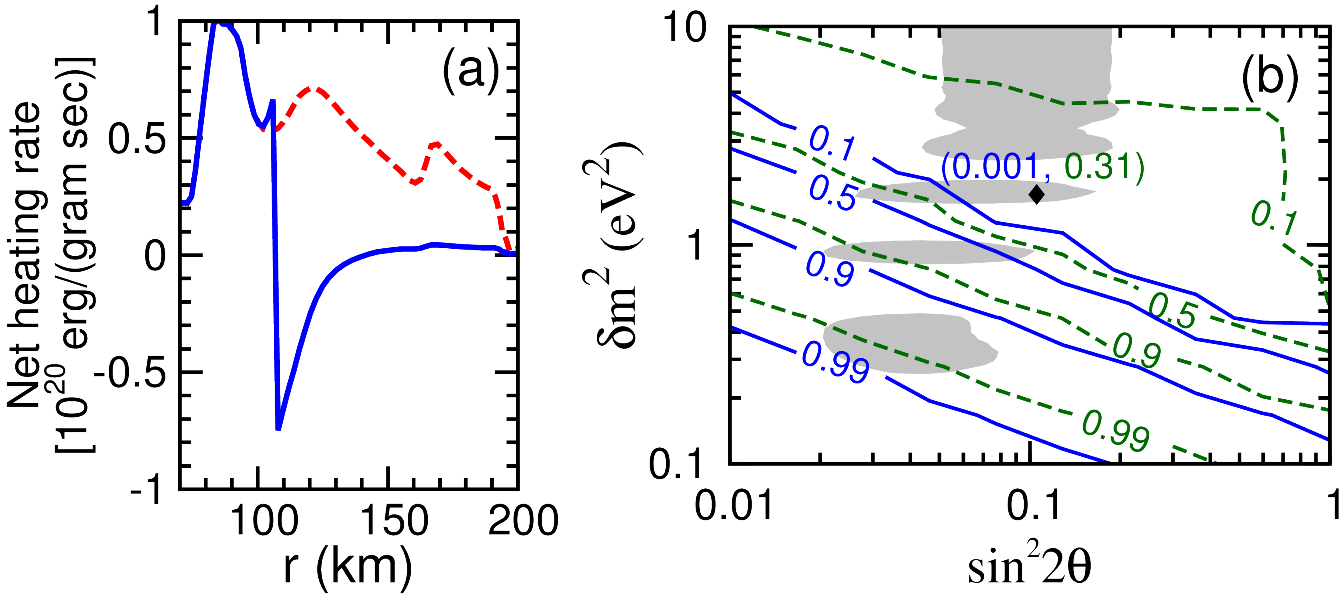


a viable option for the weak-r process IF eV sterile ν really exist?

[MRW, Fischer, Huther, Martinez-Pinedo, Qian, PRD 89, 061303, 2014]

Are light sterile ν consistent with SN explosion?

The reduction of heating rate around the shock break-out :



Summary

- Neutrino oscillations may significantly alter the outcome of nucleosynthesis in supernovae and/or in NS-NS(BH) mergers.
- Collective neutrino oscillations sensitively depend on :
    - ν energy and angular distributions
    - n_e profiles
    - the time evolution of both
- For an $18\ M_\odot$ SN model, we find that collective ν oscillations have no impact on the νp process, but may enhance the production of ^{138}La and ^{180}Ta.
- MSW flavor transformation strongly boosts the charged-current ν reaction rates on ^{4}He and will alter the production of ^{7}Li and ^{11}B.
- eV mass sterile neutrino may enable the formation of heavy elements in supernovae when the feedback of oscillations and Y_e evolution is carefully treated at the position of the inner resonance.

Future works (challenges)

- Modelling of neutrino oscillations:
  - breaking of the axial-symmetry? [Raffelt+ 2013]
  - finite (small) size of the neutrin wave-packets? [Akhmedov+ 2014]
  - H_ν contribution from scattered neutrinos? [Cherry+ 2012]
  - beyond the mean-field? [Volpe+ 2013, Vlasenko+ 2013]
- Astrophysical input:
  - ν distribution from improved weak rates?
  - effect of turbulence?
- convoluted feedback between ν oscillations and hydrodynamics?
- complicated geometry in the case of mergers [Malkus+ 2013]
- possible observational constraint?

Neutrino signals and mass hierarchy

In the accretion phase of Fe-core SN, collective oscillations are expected to be suppressed by the large matter potential.

→ possibility of using SN signal to distinguish the neutrino mass hierarchy by comparing the event rates and spectra using multiple detection channels.