Neutrino Oscillation Studies with Core-Collapse Supernovae

INT 12-2a Core-Collapse Supernovae: Models and Observable Signals

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Collective Flavor Oscillations

Motivation

- Matter suppresses ν-oscillations in inner region of SN during accretion phase
- Largest difference in $\bar{\nu}_e - \bar{\nu}_{\mu,\tau}$ flux
- Could allow to decide Mass Hierarchy of ν
- Collective neutrino effects can trigger self-induced flavor conversions
- Would destroy signal
- Previous work not using full $I(\varepsilon, \theta)$
- But matter effect $\propto$ path $\leftrightarrow \theta$

Paper

Suppression of Self-Induced Flavor Conversion in the Supernova Accretion Phase
Srdjan Sarikas, Georg G. Raffelt, Lorenz Hüdepohl, and Hans-Thomas Janka
Phys. Rev. Lett. 108, 061101 (2012)

Flavor mixing

Flavor eigenstates ν_e, ν_μ, ν_τ
Mass eigenstates ν_1, ν_2, ν_3

$$\nu_l = U_{li}\nu_i \quad l = e, \mu, \tau \quad i = 1, 2, 3$$

- Propagation → phase difference due to different masses
- $\Delta\phi \approx \frac{\Delta m^2}{2E} \cdot t$ → Vacuum oscillations
- Interactions with matter: Potential V
- Different for $\nu_e, \bar{\nu}_e, \overset{\leftrightarrow}{\bar{\nu}}_{\mu,\tau}$
- Additional phase $\Delta\phi = (V_i - V_j) \cdot t$ → MSW effect
- Interactions with other ν: Collective oscillations

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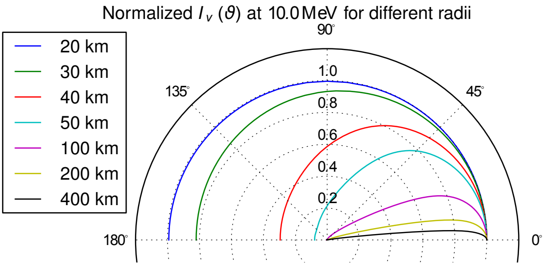
Setup

- Simulation of a 15 $M_\odot$ CC SN in spherical symmetry
- ~ 500 ms of accretion
- Snapshots of $I(\varepsilon, \theta)$ at radius outside ν-spheres
- Multi-energy, multi-angle 3 flavor oscillation evolution
- Linearized analysis: Growth rate κ of collective oscillations



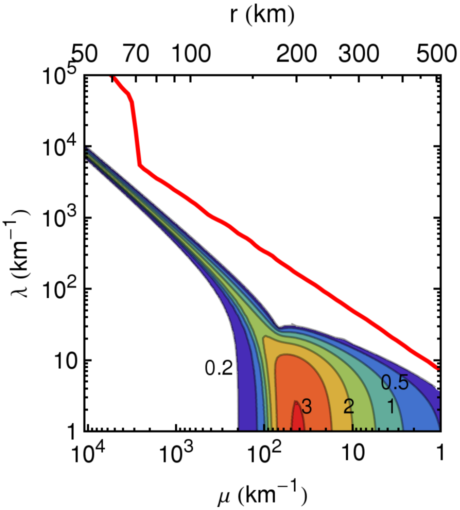


Fig. 4 from Sarikas et al., Contour of growth rate κ for one particular snapshot

$$\lambda = \sqrt{2} G_F \left[n_e(r) - n_{\bar{e}}(r) \right] \frac{R^2}{2r^2} \sim \rho$$

$$\mu = \sqrt{2} G_F \frac{F_{\bar{\nu}_e}(R) - F_{\bar{\nu}_x}(R)}{4\pi r^2} \frac{R^2}{2r^2} \sim r^{-4}$$

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Result

- Suppression of ν-induced flavor conversions
- Usual MSW effect at low densities
- With sufficiently large $\theta_{13} \rightarrow$ Mass hierarchy could be probed
- Agreement with previous work (e.g. Chakraborty et al., 2011)

Possible enhancements

- Progenitor dependence
- Deviations from spherical symmetric neutrino transport
- Halo neutrinos with large θ (Cherry et al., 2012)

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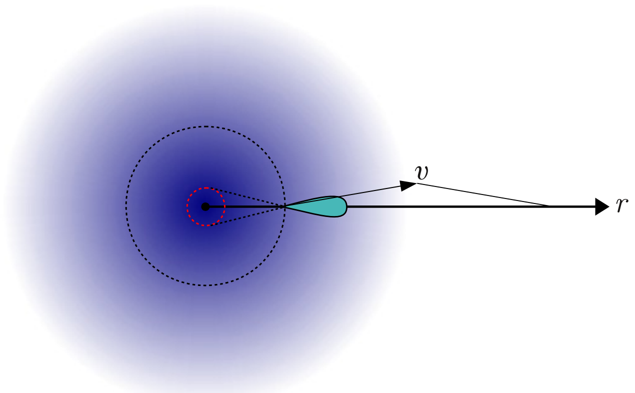
Halo Neutrinos



Paper

Supernova neutrino halo and the suppression of self-induced flavor conversion
Srdjan Sarikas, Irene Tamborra, Georg Raffelt, Lorenz Hüdepohl, Hans-Thomas Janka
Phys. Rev. D 85, 113007 (2012)

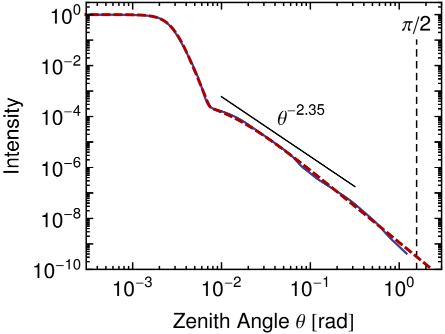


Fig. 2 from paper, neutrino intensity at 10000 km

- Light-bulb
- Tail due to halo scattering

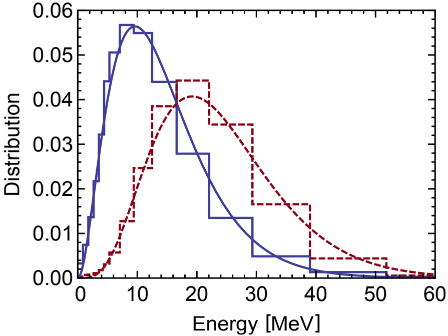


Fig. 3 from paper, $\bar{\nu}_e$ neutrino spectrum of core and halo component

- Blue: spectrum in forward direction, thermal ($T \approx 5MeV$)
- Red: of halo component (i.e. for some large θ)
- ν-scattering on nuclei $\propto E^2$
- Halo arises from high energy neutrinos
- Additional factor of E^2 in halo spectrum
- Excellent agreement with simulation

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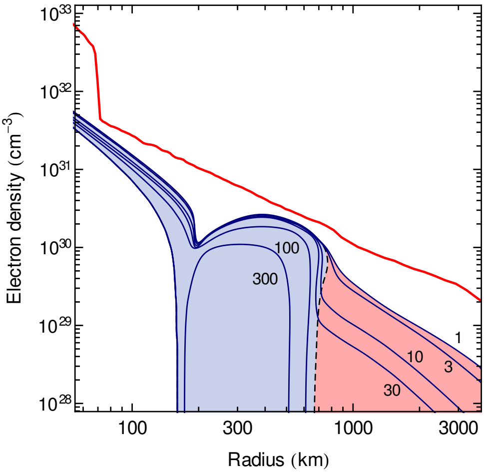

Fig. 6 from paper, contours for selected values of κr

- Blue component as in previous section
- Red area due to halo neutrinos

Result

- Still a Suppression of ν-induced flavor conversions
- Reason: Stabilizing multi-angle matter effect also gains with increasing θ, still dominating over collective instability
- Relevant quantities: electron and neutrino number densities:
  - $n_\nu \propto r^{-2}$
  - $n_e \propto r^{-1.35}$
- Matter effect still dominant

Neutrino Mass Hierarchy

Motivation

- Large flux differences during accretion phase
- MSW effect (outer layers)
- Collective effects suppressed
- Rather robust modelling of the first $\sim 200\mathrm{ms}$
- ν_e-burst difficult to detect, short-lived
- Model neutrino lightcurve in IceCube

Paper

Probing the neutrino mass hierarchy with the rise time of a supernova burst
Pasquale Dario Serpico, Sovan Chakraborty, Tobias Fischer, Lorenz Hüdepohl, Hans-Thomas Janka, Alessandro Mirizzi
Phys. Rev. D 85, 085031 (2012)

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Reaction			References
$\nu\, e^{\pm}$	$\rightleftharpoons$	$\nu\, e^{\pm}$	Mezzacappa and Bruenn (1993a)
			Cernohorsky (1994)
$\nu\, A$	$\rightleftharpoons$	$\nu\, A$	Horowitz (1997)
			Bruenn and Mezzacappa (1997)
$\nu\, N$	$\rightleftharpoons$	$\nu\, N$	Bruenn (1985), Mezzacappa and Bruenn (1993b),
			Burrows and Sawyer (1998)
$\nu_e\, n$	$\rightleftharpoons$	$e^-\, p$	Bruenn (1985), Mezzacappa and Bruenn (1993b),
			Burrows and Sawyer (1999)
$\bar{\nu}_e\, p$	$\rightleftharpoons$	$e^+\, n$	Bruenn (1985), Mezzacappa and Bruenn (1993b),
			Burrows and Sawyer (1999)
$\nu_e\, A'$	$\rightleftharpoons$	$e^-\, A$	Bruenn (1985), Mezzacappa and Bruenn (1993b)
			Langanke et al. (2003)
$\nu\, \bar{\nu}$	$\rightleftharpoons$	$e^-\, e^+$	Bruenn (1985), Pons et al. (1998)
$\nu\bar{\nu}\, N N$	$\rightleftharpoons$	$N N$	Hannestad and Raffelt (1998)
νA	$\rightleftharpoons$	νA^*	Langanke et al. (2008)
$\nu_{\mu,\tau}\bar{\nu}_{\mu,\tau}$	$\rightleftharpoons$	$\nu_e\bar{\nu}_e$	Buras et al. (2003)
$\overset{(-)}{\nu}_{\mu,\tau}\, \overset{(-)}{\nu}_e$	$\rightleftharpoons$	$\overset{(-)}{\nu}_{\mu,\tau}\, \overset{(-)}{\nu}_e$	Buras et al. (2003)

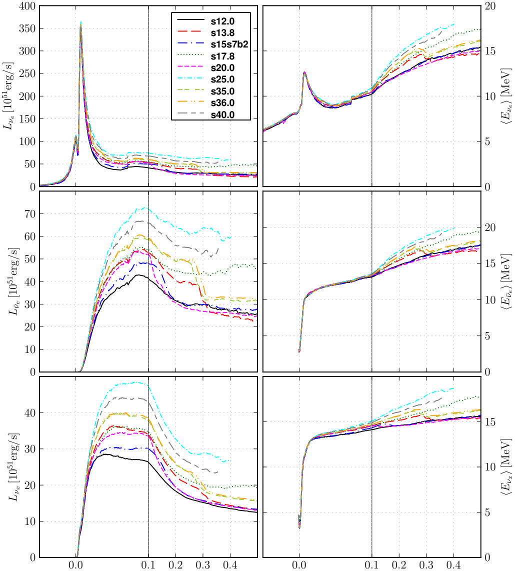

Fig. 1 from paper,
Unoscillated neutrino signal

- $\bar{\nu}_e$ rise more slowly, peak higher
- ν_x rise faster, peak lower
- Oscillations mix these curves
- Differently for NH, IH
- IceCube sensitive to $\bar{\nu}_e$
- Rise-time of lightcurve

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These (and similar) data files are available at our webpage:
`http://www.mpa-garching.mpg.de/ccsnarchive`

NH	$F_{\bar{\nu}_e} = \cos^2\theta_{12} F^0_{\bar{\nu}_e} + \sin^2\theta_{12} F^0_{\bar{\nu}_x}$
IH (for $\sin^2(\theta_{13}) \gtrsim 10^{-3}$)	$F_{\bar{\nu}_e} = F^0_{\bar{\nu}_x}$
IH (for $\sin^2(\theta_{13}) \lesssim 10^{-5}$)	$F_{\bar{\nu}_e} = \cos^2\theta_{12} F^0_{\bar{\nu}_e} + \sin^2\theta_{12} F^0_{\bar{\nu}_x}$

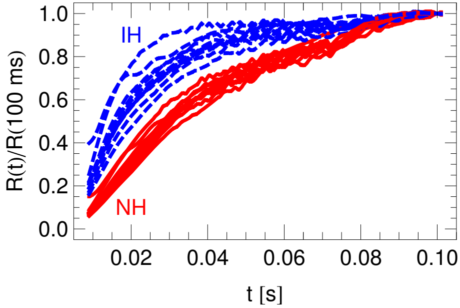

Fig. 4a from paper, neutrino signals in IceCube, normalized to 100ms

- IH case shows fast rise
- NH case slower

Result

- Neutrino lightcurve might hint at Mass Hierarchy
- Novel approach: Rise-time
- Complementary to other methods

Difficulties

- Demonstration of clear separability (detector noise..)
- Especially for unknown progenitor

Sterile Neutrinos

Motivation

- Reactor Anomaly $\rightarrow$ Sterile Neutrinos?
- Would have impact on ν-driven wind Y_e
- Analysis with PNS cooling models
- Including collective flavor oscillations
- Using $\Delta m^2, \theta_{14}$ compatible with reactor data

Paper

Impact of eV-mass sterile neutrinos on neutrino-driven supernova outflows
Irene Tamborra, Georg G. Raffelt, Lorenz Hüdepohl, Hans-Thomas Janka
JCAP01(2012)013

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Setup

- Existing EC Supernova Simulation, PNS cooling
- 3 snapshots
- Postprocessing assuming steady state
- Assume 1 sterile neutrino in eV scale
- Oscillations of ν_e, ν_x, and ν_s
- Neutrino parameters from Reactor Anomaly

Influence on Y_e

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

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

- Change in $\overset{(-)}{\nu}_e$ flux $\to$ change in Y_e
- Backreaction on mixing
- Influence due to "ordinary" oscillations
- + Sterile

The early, 0.5s snapshot

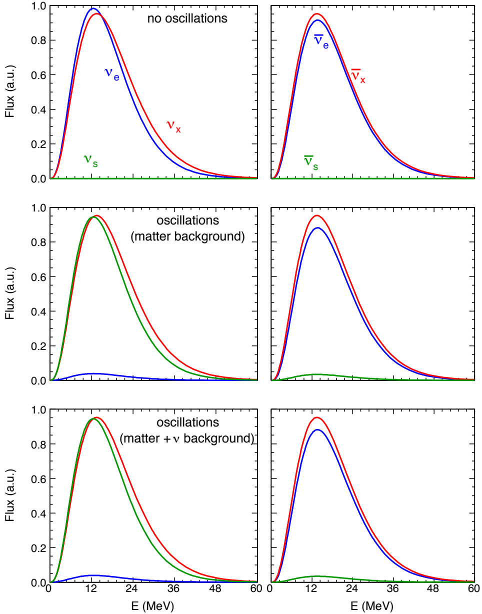

Fig. 4 from Tamborra et al., Neutrino spectra at 1000km

- Swap of ν_e and ν_s
- Little effect on $\bar{\nu}_e$ and $\bar{\nu}_s$
- $\nu - \nu$ processes have little influence

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The early, 0.5s snapshot

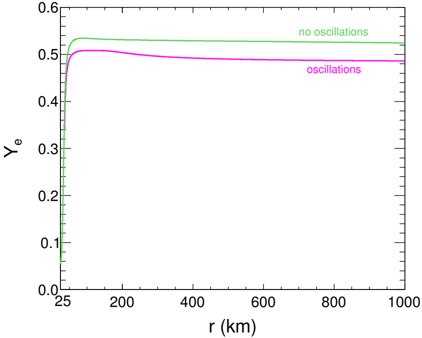

Fig. 5 from Tamborra et al., self consistent Y_e profile

- Strong reduction of ν_e flux
- $\rightarrow$ reduction in Y_e
- No influence by collective effects
- Not enough change in Y_e for an r-process

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The intermediate, 2.9s snapshot during PNS cooling

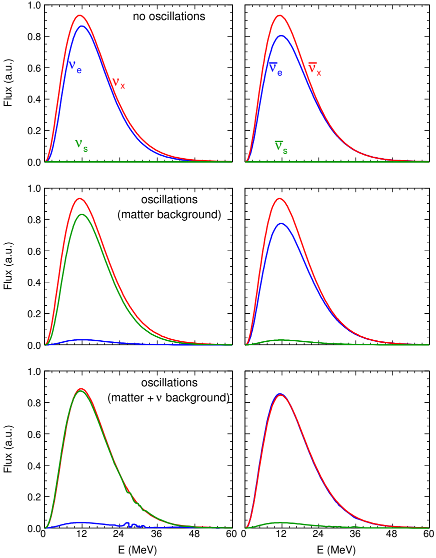

Fig. 8 from Tamborra et al.

- Stronger influence of ν background
- Averaging of $\bar{\nu}_x$ and $\bar{\nu}_e$

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The intermediate, 2.9s snapshot during PNS cooling

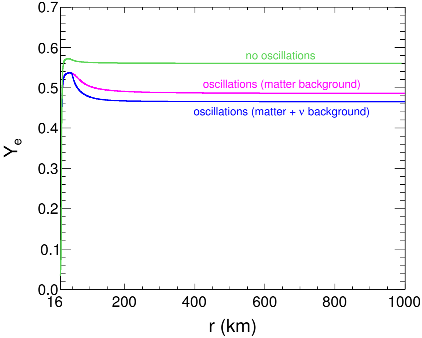

Fig. 10 from Tamborra et al.

- Strong reduction of ν_e flux
- Enhancement of $\bar{\nu}_e$ flux
- $\rightarrow Y_e$ even more reduced

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The late, 6.5s snapshot

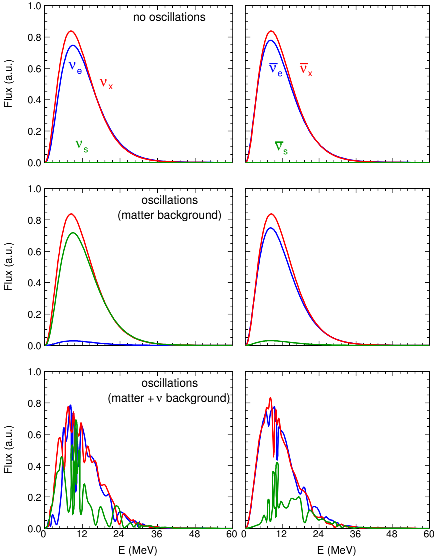

Fig. 13 from Tamborra et al.

- Strong E dependence
- Much of ν_e flux survives
- Due to ν background

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The late, 6.5s snapshot

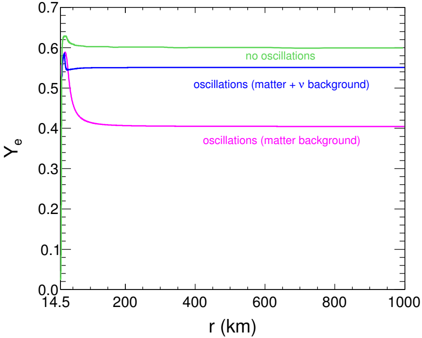

Fig. 14 from Tamborra et al.

- Moderate reduction of ν_e flux
- ν background leads to $Y_e > 0.5$ again

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Result

- Oscillations with sterile neutrino reduce Y_e in ν-driven wind
- Here, still not sufficient for viable r-process
- Collective effects important
- Result strongly sensitive to detailed matter profiles, fluxes, spectra
- If they exist, oscillations with sterile neutrinos have to be taken into account, potential influence on nucleosynthesis

Thank you for your attention

Conclusion

- Neutrino oscillations in SN might reveal a lot of information about neutrino physics
- Possibly even influence nucleosynthesis
- Complicated business

Have a look at the webpage

http://www.mpa-garching.mpg.de/ccsnarchive

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Literature

Chakraborty, S., Fischer, T., Mirizzi, A., Saviano, N., Tomàs, R. (2011). Analysis of matter suppression in collective neutrino oscillations during the supernova accretion phase. *Phys. Rev. D* **84**, *025002; Phys. Rev. Lett.* **107**, *151101.*

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