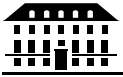

The Niels Bohr
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SFB 1258 | Neutrinos Dark Matter Messengers

Neutrino Signatures from 3D Models of Core-Collapse Supernovae

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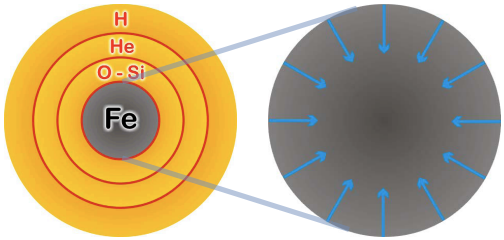
nuEclipse
Knoxville, August 20, 2017

Outline

- Supernova explosion mechanism
- Hydrodynamical instabilities and detection perspectives
- Lepton number emission self-sustained asymmetry
- Consequences on neutrino flavor conversions
- Conclusions

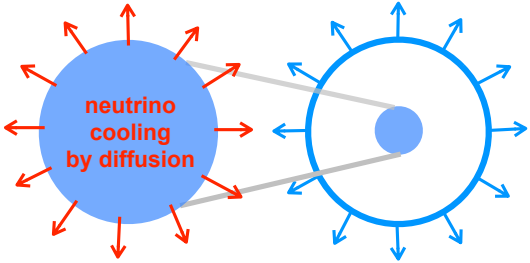
Core-Collapse Supernova Explosion



Implosion (Collapse)

Neutrinos carry 99% of the released energy (~ 10^{53} erg).

Explosion



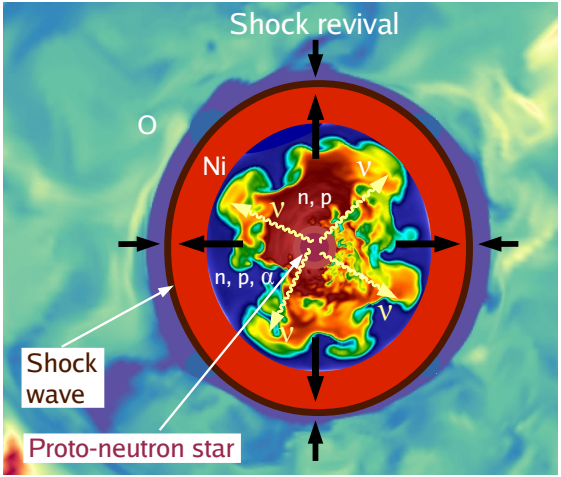
Neutrino energies: ~ 10 MeV.
Neutrino emission time: ~ 10 s.

Delayed Neutrino-Driven Explosion

- Shock wave forms within the iron core. It dissipates energy dissociating iron layer.

- **Neutrinos** provide energy to stalled shock wave to start re-expansion.

- **Convection** and **shock oscillations** (standing accretion shock instability, **SASI**) enhance efficiency of neutrino heating and revive the shock.



Recent review papers: Janka (2017). Mirizzi, Tamborra et al. (2016).

SASI Detection Perspectives (27 M_{sun})

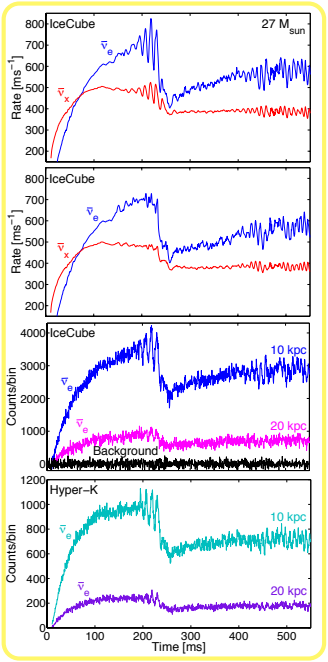
Strong signal modulation
(optimistic observer direction)

Weak signal modulation
(pessimistic observer direction)

Expected rate above IceCube background

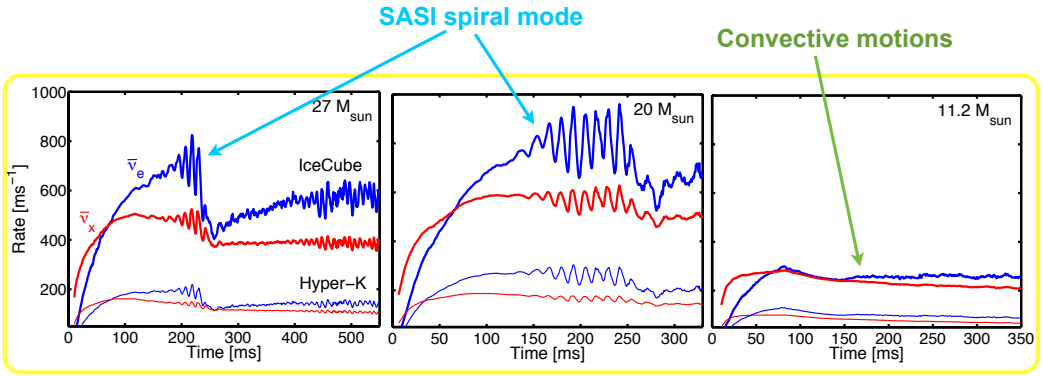
Hyper-K rate = 1/3 IceCube rate

SASI still detectable



Tamborra et al., PRL (2013). Tamborra et al., PRD (2014).

SASI Detection Perspectives



27 M_{sun} SN progenitor:
Two SASI episodes with convective phase in between.

20 M_{sun} SN progenitor:
One SASI episode.

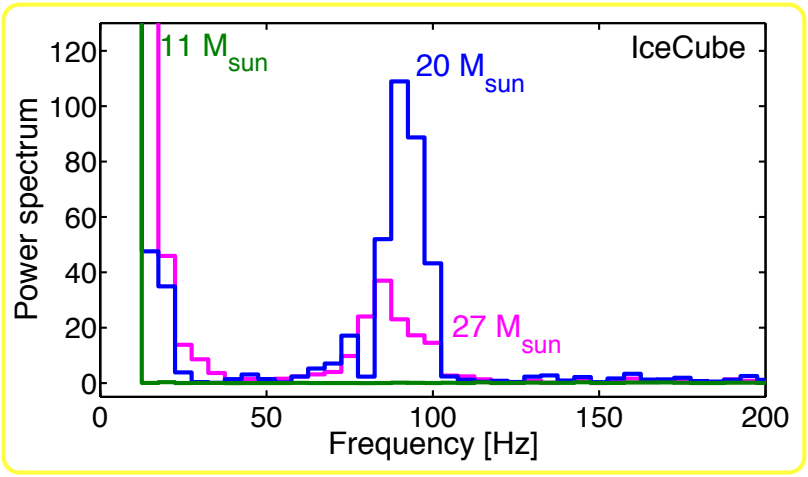
11.2 M_{sun} SN progenitor:
Large scale convection.

SASI seems to occur for the heavier SN progenitors only.

Tamborra, Hanke, Mueller, Janka, Raffelt, PRL (2013), PRD (2014). See also: Melson, Janka, Marek, ApJ (2015).

Power Spectrum of the Event Rate

Power spectrum of the IceCube event rate in [100,300] ms



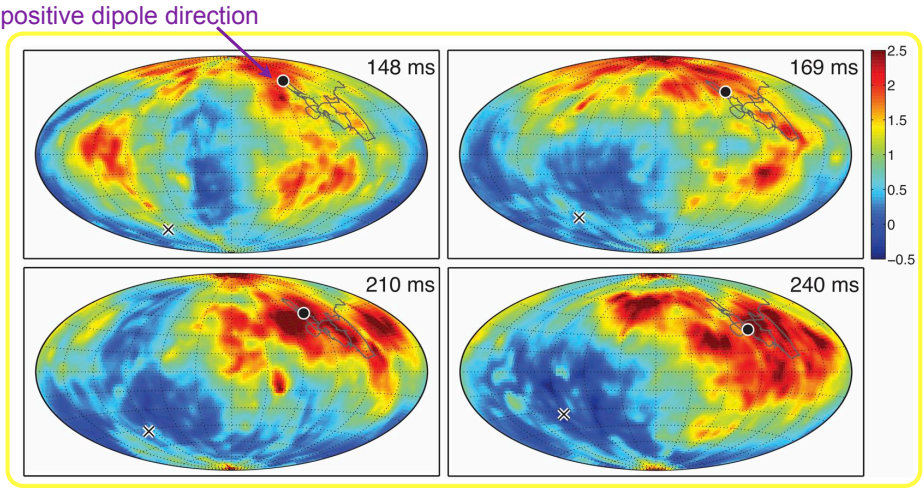
A peak appears at the SASI frequency of ~ 80 Hz for the 20 and 27 M_{sun} SN progenitors.

Tamborra, Hanke, Mueller, Janka, Raffelt, PRL (2013).

LESA Instability

Lepton Number Flux Evolution

Lepton-number flux for the 11.2 M_{sun} progenitor [$(F_{\nu_e} - F_{\bar{\nu}_e})/\langle F_{\nu_e} - F_{\bar{\nu}_e}\rangle$].



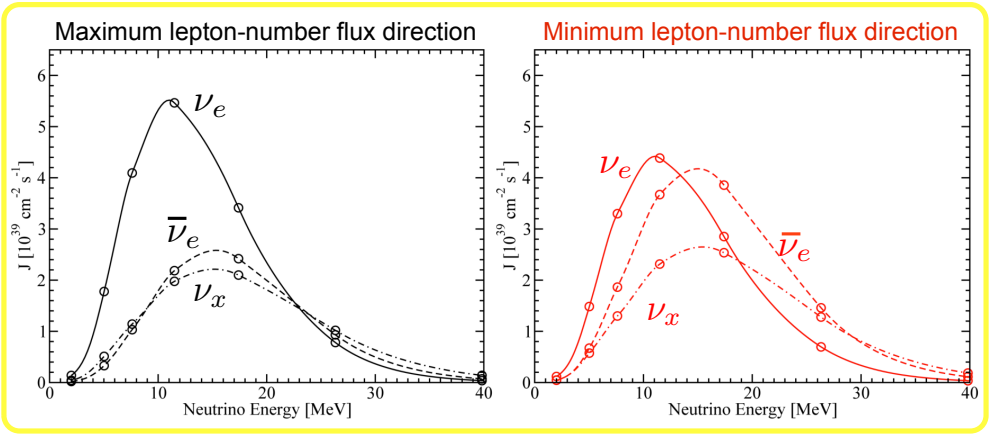
Lepton-number emission asymmetry (**LESA**) is a large-scale feature with **dipole character**.

Once the dipole develops, its direction remains stable. No-correlation with numerical grid.

Tamborra, Hanke, Janka, Mueller, Raffelt, Marek, ApJ (2014).

Neutrino Energy Spectra

Neutrino flux spectra in opposite LESA directions (11.2 Msun, t = 210 ms)

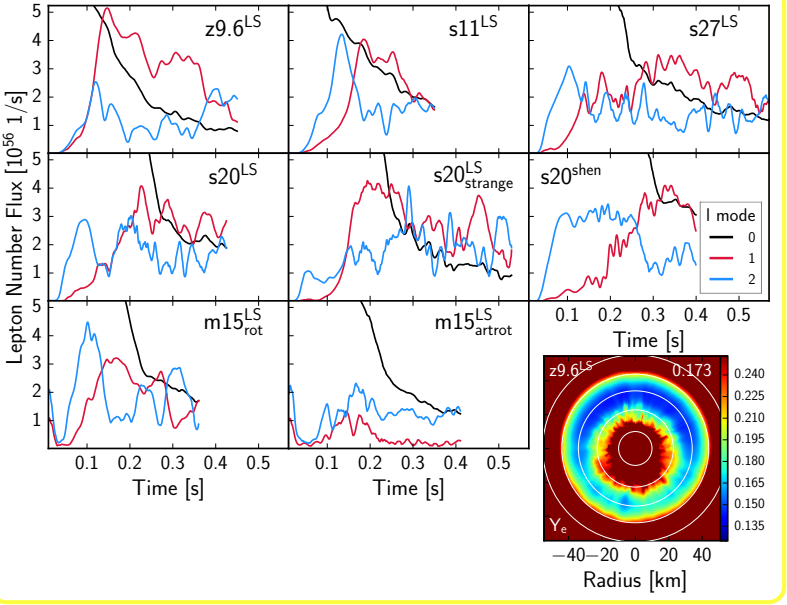


During the accretion phase, fluxes strongly vary with the observer direction.

Tamborra, Hanke, Janka, Mueller, Raffelt, Marek, ApJ (2014).

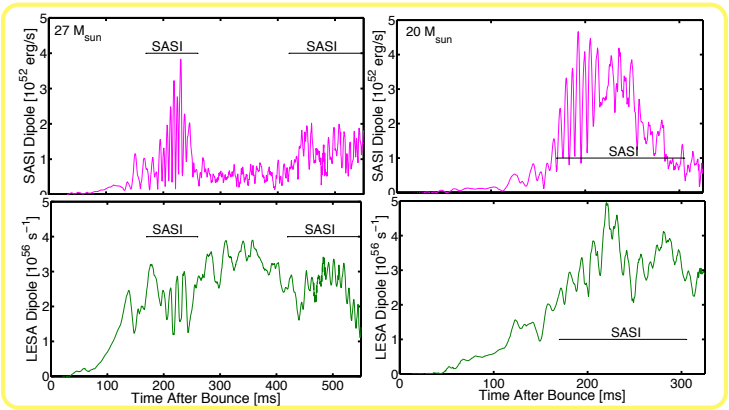
Lepton Number Flux Evolution

Monopole, dipole and quadrupole of the lepton number flux



Janka, Melson, Summa, ARNPS (2016). Tamborra, Hanke, Janka, Mueller, Raffelt, Marek, ApJ (2014).

LESA-SASI Interference



LESA dipole close to SASI plane

LESA dipole perp. to SASI plane

No clear correlation between LESA and SASI.
Interplay dependent on relative orientations of SASI plane and LESA dipole.

Tamborra et al., ApJ (2014). Tamborra et al., PRD (2014).

Implications of the LESA Phenomenon

★ **Nucleosynthesis in the neutrino heated ejecta**: Considerable hemispheric asymmetry of the electron fraction in the neutrino ejecta.

★ **Neutron star kicks**: Asymmetric neutrino emission imparts a recoil on the nascent NS.

★ LESA responsible for **angular momentum transfer**, i.e. spin-up of the nascent NS.

★ **Neutrino-flavor conversions:**

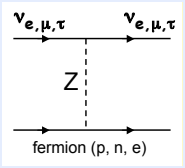
- LESA depends on hemispheric asymmetry of neutrino heating rates (modified by oscillations).
- Flavor conversions modify the n/p ratio in the context of nucleosynthesis.
- Directional neutrino-neutrino refraction index.

Consequences on Flavor Conversions

Neutrino Interactions

Neutrinos in supernovae interact with matter and among each other.

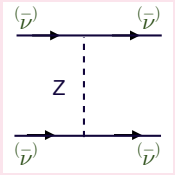
Understood phenomenon.



Neutrinos interact with neutrons, protons and electrons.

Wolfenstein, PRD 17 (1978) 2369

We still need to learn a lot!

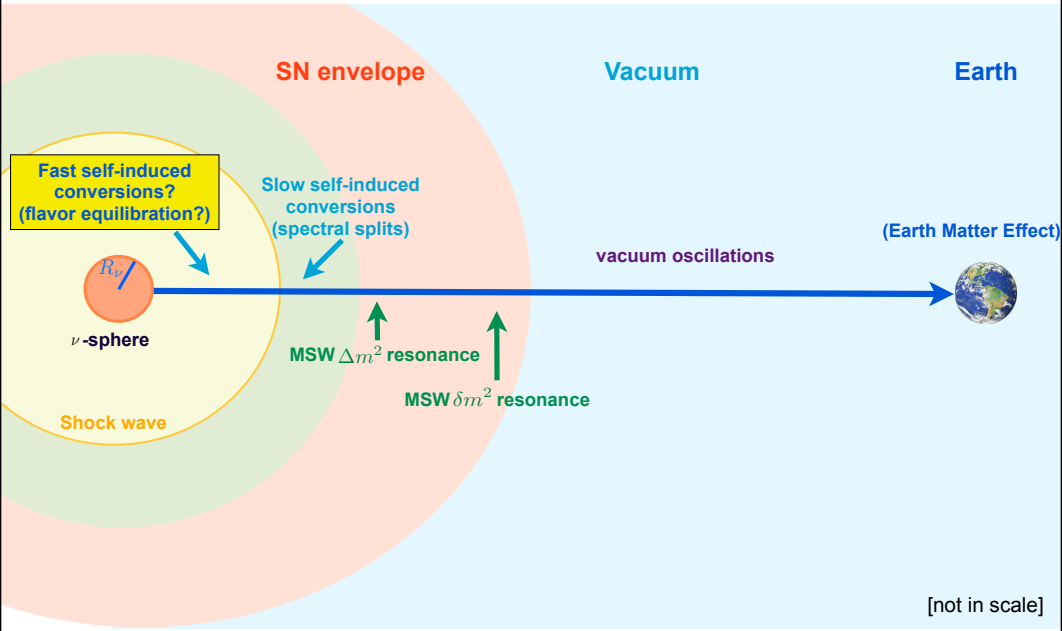


$\nu - \nu$ interactions

Non-linear phenomenon

Pantaleone, PLB 287 (1992) 128

Simplified Picture of Flavor Conversions



Fast Pairwise Neutrino Conversions

Flavor conversion (vacuum or MSW): $\nu_e(p) \to \nu_\mu(p)$.

Lepton flavor violation by mass and mixing.

Pairwise flavor exchange by $\nu - \nu$ scattering: $\nu_e(p) + \bar{\nu}_e(k) \to \nu_\mu(p) + \bar{\nu}_\mu(k)$
$\nu_e(p) + \nu_\mu(k) \to \nu_\mu(p) + \nu_e(k)$

Can occur **without masses/mixing**. No net lepton flavor change.

Growth rate: $\sqrt{2} G_F (n_{\nu_e} - n_{\bar{\nu}_e}) \simeq 6.42 \text{ m}^{-1}$ vs. $\dfrac{\Delta m^2}{2E} \simeq 0.5 \text{ km}^{-1}$ ⇨ **"Fast" conversions**

⇧

Neutrino angular distributions **crucial**.

Sawyer, PRD (2005), Sawyer, PRL (2016), Chakraborty et al., JCAP (2016).

Fast Pairwise Conversion of Supernova Neutrinos: A Dispersion Relation Approach

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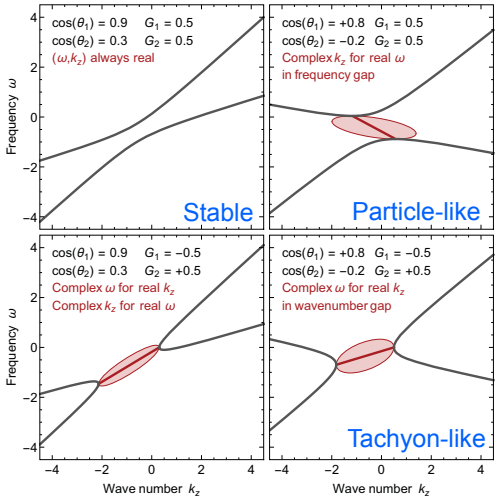
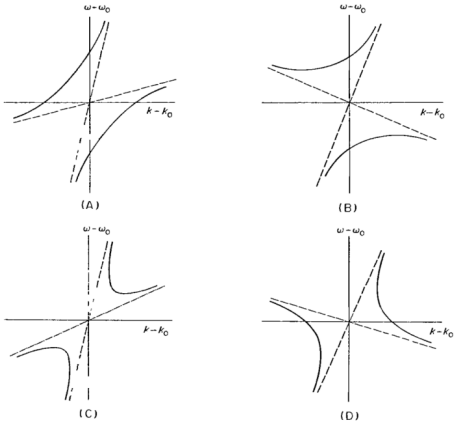
(Received 10 October 2016; published 10 January 2017)

Instabilities of "flavor waves"



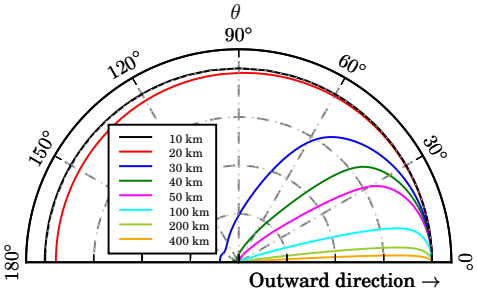
Instabilities of "plasma waves"



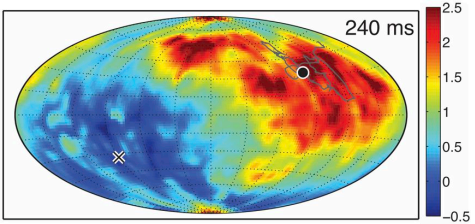
[Landau&Lifshitz, Vol. 10, Physical Kinetics, Chapter VI, Instability Theory]

Izaguirre, Raffelt, Tamborra, PRL (2017).

Fast Pairwise Neutrino Conversions



Non-negligible inward neutrino flux may induce fast conversions.



LESA may induce fast conversions.

Flavor equipartition might occur close to neutrino decoupling region. Explosion affected?

Existing investigations are simplified case studies. Further work needed.

Tamborra et al., ApJ (2017). Izaguirre, Raffelt, Tamborra, PRL (2017). Capozzi et al. 2017.

Conclusions

- Neutrinos play a fundamental role in supernovae.
- Intriguing neutrino features from 3D SN simulations.
- The SN neutrino signal can probe the nature of the hydrodynamical instability.
- Nu-nu interactions may potentially affect the explosion and LESA.

Thank you

for your attention!