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Recent developments on hydro-instabilities and neutrinos in 3D

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Outline

★ Supernova explosion mechanism

★ Hydrodynamical instabilities and detection perspectives

★ A new instability: Lepton number emission self-sustained asymmetry

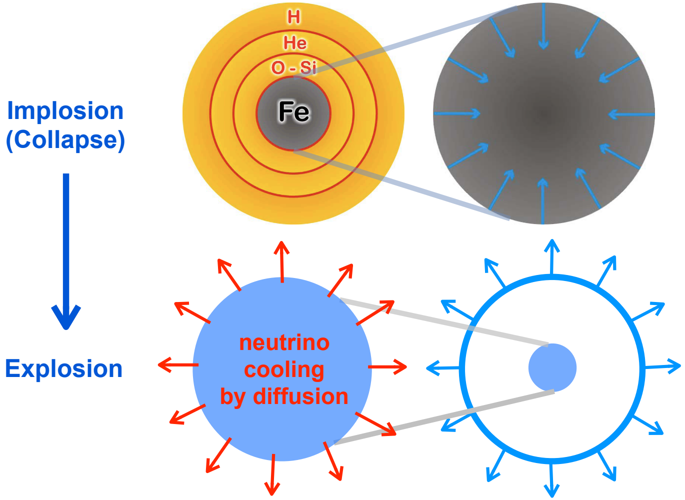
★ Conclusions

The Neutrino-driven Explosion Mechanism

Neutrinos in Supernovae

Core-collapse supernovae: Terminal phase of massive stars [$M \geq 8 M_{\odot}$].
Stars collapse ejecting the outer mantle by means of shock-wave driven explosions.

Expected rate: 1-3 SN/century in our galaxy (~ 10 kpc).



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

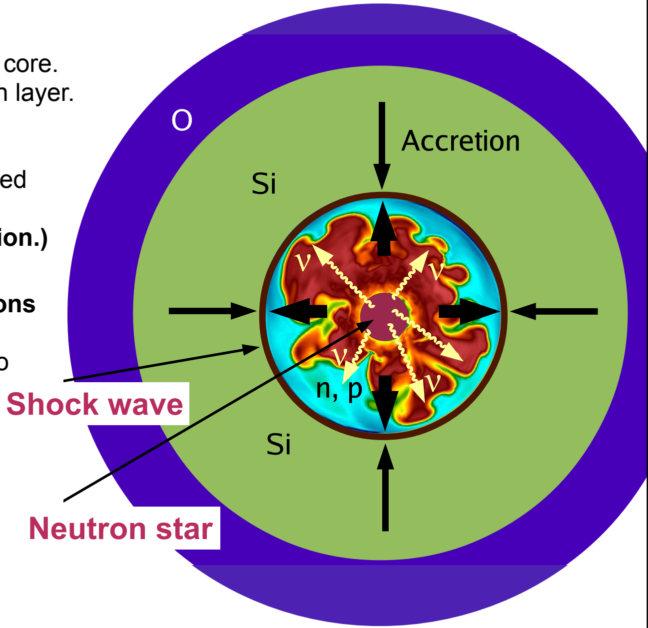
Neutrino typical energies: ~ 15 MeV.
Neutrino emission time: ~ 10 s.

Neutrinos and SN Explosion Mechanism

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

★ **Neutrinos** provide energy to stalled shock wave to start re-expansion.
(Delayed Neutrino-Driven Explosion.)

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



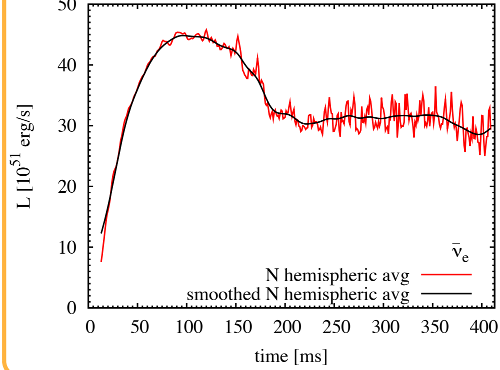
For details see Janka, Ann. Rev. Nucl. Part. Sci. 62 (2012) 407.

Fast-time Variations of SN Neutrino Signal

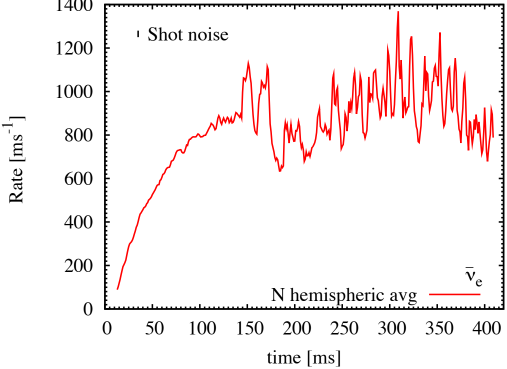
First attempts to detect large amplitude modulations of the neutrino signal:

- 2D SN simulations ➔ SASI detectable
- 3D SN simulations ➔ SASI not strong.

Neutrino luminosity (2D)



IceCube rate (2D)



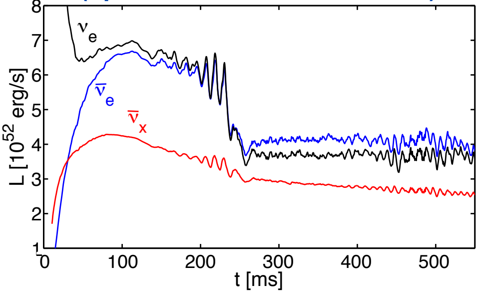
* T. Lund et al., PRD 82 (2012) 063007, PRD 86 (2012) 105031.

Directional Neutrino Signal

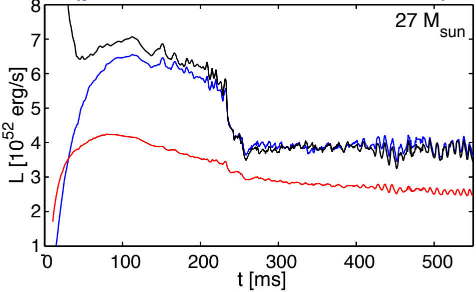
Full-scale 3D SN simulations with detailed neutrino transport performed!

SASI and convective motions leave imprints on the neutrino signal.

Close to the SASI plane (optimistic observer direction)



Perpendicularly to the SASI plane (pessimistic observer direction)



Large amplitude modulations close to the plane where spiral SASI mode develops.

Are such modulations detectable?
Are these features generic for any SN progenitor?

* Tamborra, Hanke, Mueller, Janka, Raffelt, PRL 111 (2013) 121104, PRD 90 (2014) 045032.

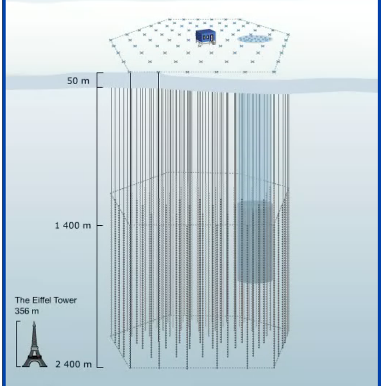
Detection Perspectives

Detection Perspectives

In IceCube and Hyper-Kamiokande, neutrinos are primarily detected by inverse beta decay

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

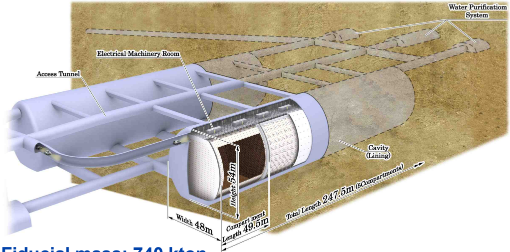
IceCube



1 km antarctic ice with 5160 PMT

R_{bkgd} = 1480 ms^{-1}

Hyper-Kamiokande



Fiducial mass: 740 kton

Background free signal + event-by-event energy information

* For details see: Abbasi et al., arXiv: 1108.0171 (IceCube), K. Abe et al., arXiv: 1109.3262 (Hyper-K).

SASI Detection Perspectives (27 M_{sun})

SASI sinusoidal modulation of the neutrino signal will be detectable by IceCube and Hyper-K.

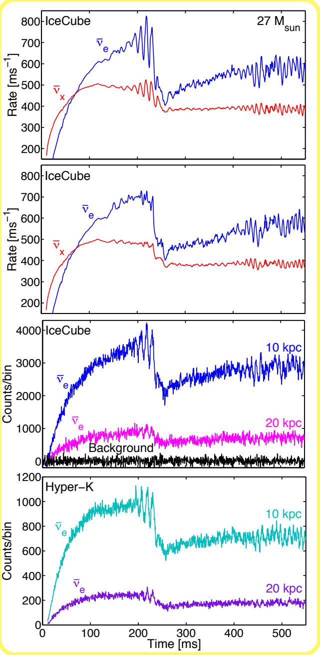
Strong signal modulation (optimistic observer direction)

Weak signal modulation (pessimistic observer direction)

Expected rate above IceCube background

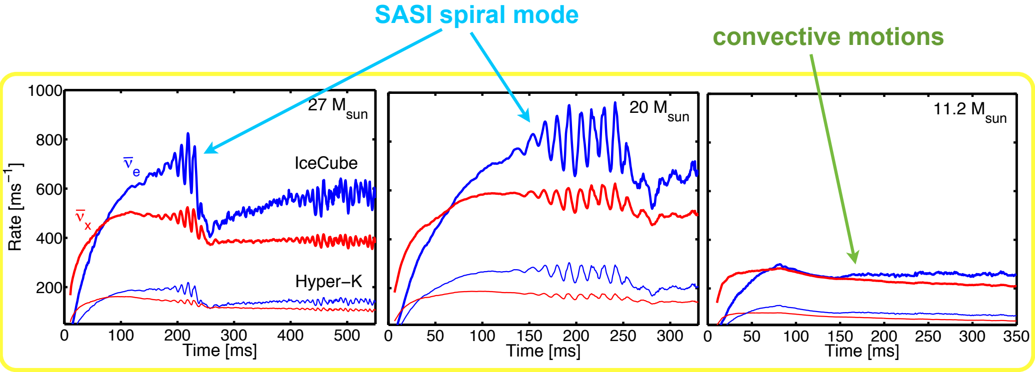
Hyper-K rate = 1/3 IceCube rate

SASI still detectable



* Tamborra et al., PRL 111 (2013) 121104.

SASI Detection Perspectives



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

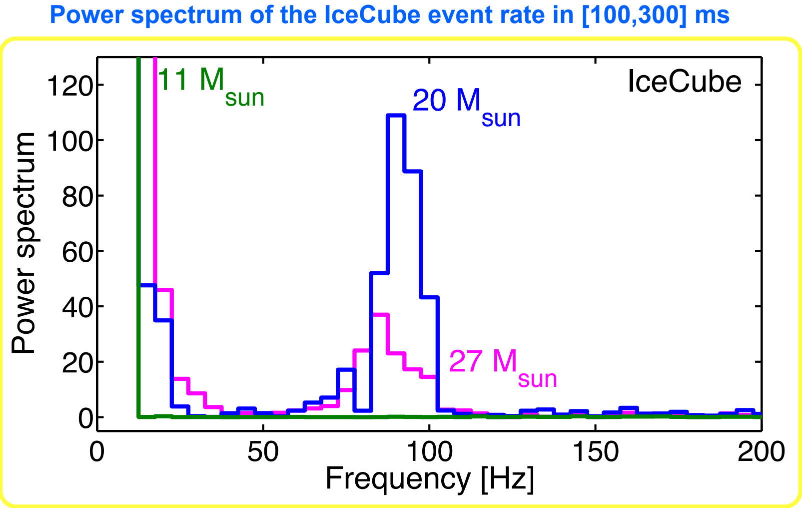
20 M_{sun} SN progenitor:
One SASI episode.

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 111 (2013) 121104, PRD 90 (2014) 045032.
See also: Melson, Janka, Marek, ApJ 801 (2015) 2, L24. Melson et al., arXiv: 1504.07631.

Power Spectrum of the Event Rate



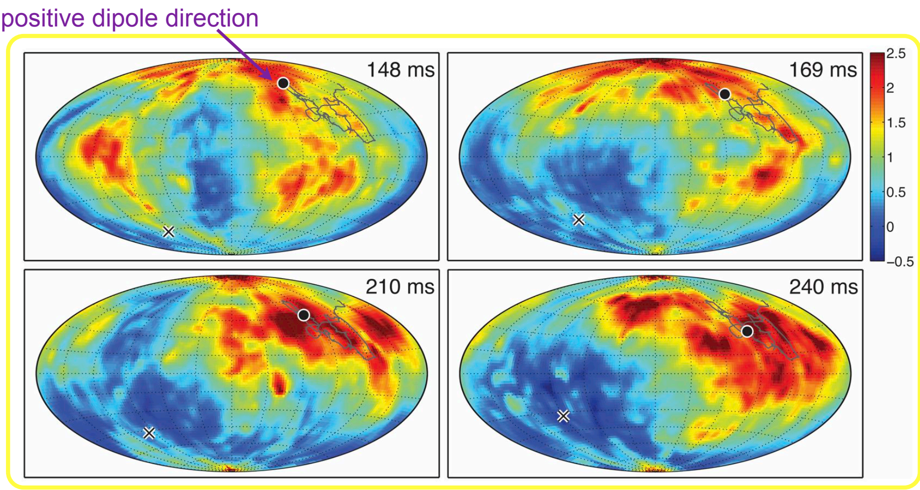
A peak appears at the SASI frequency of ~ 80 Hz for the 20 and 27 M_{sun} SN progenitors.

* Tamborra, Hanke, Mueller, Janka, Raffelt, PRL 111 (2013) 121104.

Lepton-number Emission Self-sustained Asymmetry: A new phenomenon

Lepton-number Flux Evolution

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



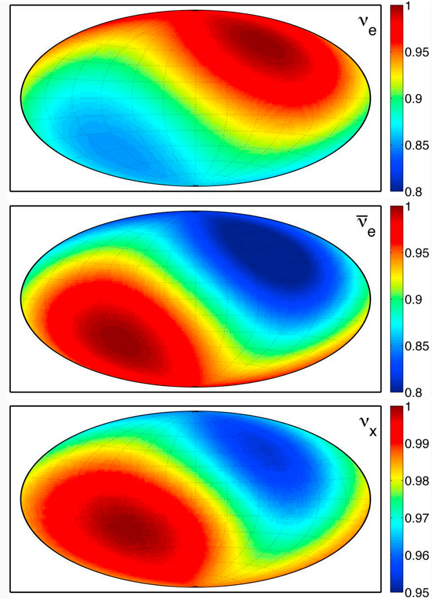
Lepton-number emission asymmetry (**LESA**) is a large-scale feature with **dipole character**.

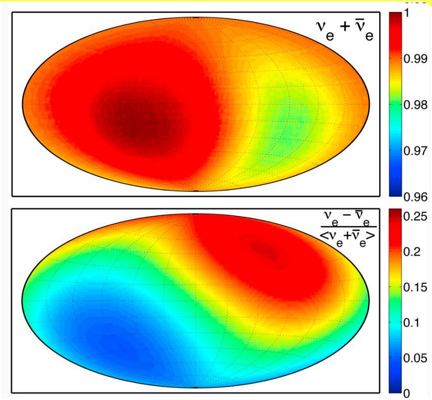
Once the dipole develops, its direction remains stable. No-correlation with numerical grid.

* Tamborra, Hanke, Janka, Mueller, Raffelt, Marek, ApJ 792 (2014) 96.

Number Flux Evolution

Number flux for the 11.2 M_{sun} progenitor, integrated over [150,250] ms.

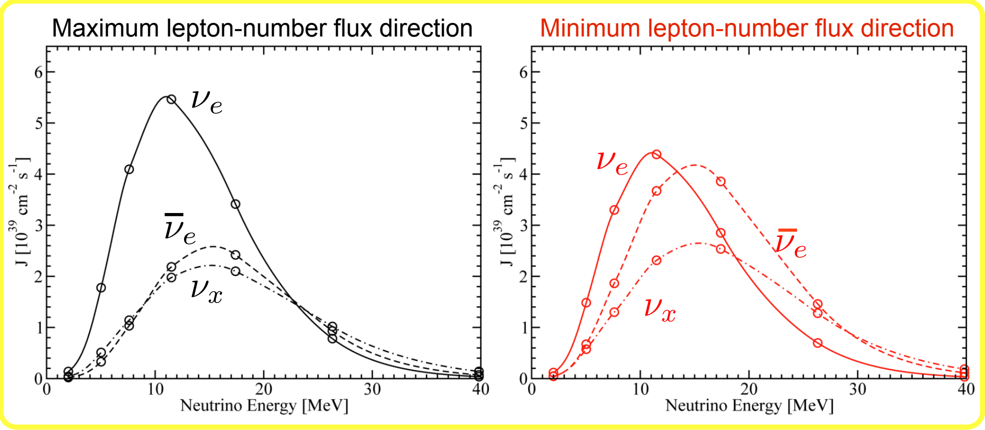




* Tamborra, Hanke, Janka, Mueller, Raffelt, Marek, ApJ 792 (2014) 96.

Neutrino energy spectra

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

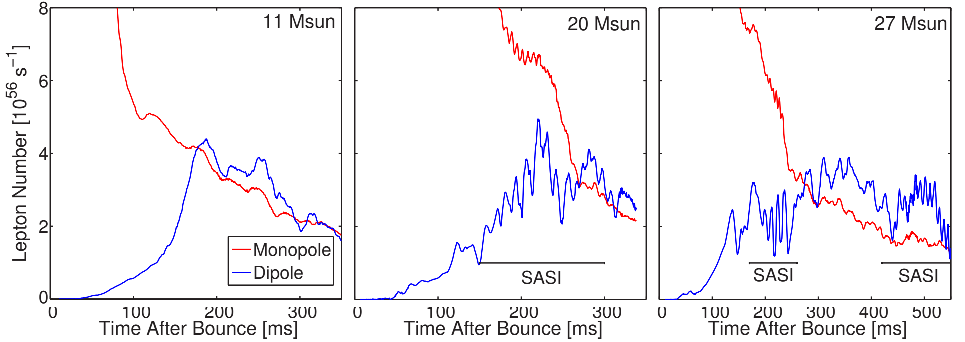


During the accretion phase, fluxes strongly vary with the observer direction.

* Tamborra, Hanke, Janka, Mueller, Raffelt, Marek, ApJ 792 (2014) 96.

Lepton-number Flux Evolution

Monopole and dipole of the lepton number flux

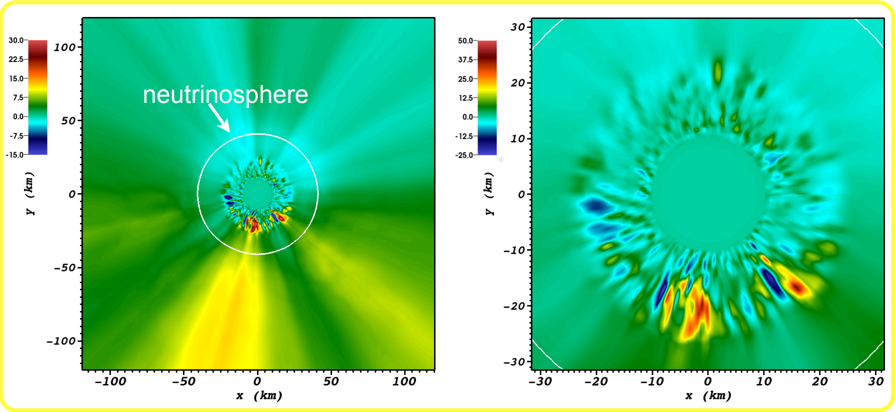


- ★ Monopole evolution strongly depends on the accretion rate and varies between models.
- ★ Maximum dipole amplitude similar in all cases.
- ★ Dipole persists during SASI activity.
- ★ Dipole direction different in each progenitor.

* Tamborra, Hanke, Janka, Mueller, Raffelt, Marek, ApJ 792 (2014) 96.

Lepton-number Flux Evolution

Radial evolution of the lepton-number flux in the the 11.2 M_{sun} progenitor at 210 ms p.b.

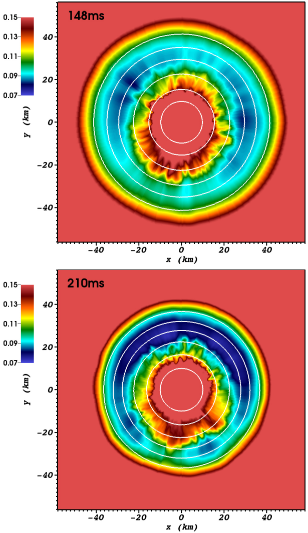


Most of the hemispheric difference builds up in the PNS mantle below the neutrinosphere.
PNS convection stronger in the hemisphere of maximal lepton-number flux (bottom direction).

* Tamborra, Hanke, Janka, Mueller, Raffelt, Marek, ApJ 792 (2014) 96.

Electron Fraction Evolution

Distribution of the electron fraction in the the 11.2 M_{sun} progenitor.



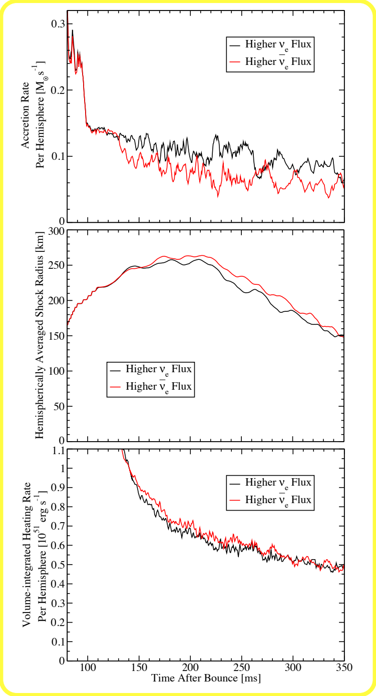
Strongly deleptonized shell in the upper hemisphere (direction of minimal lepton number flux).

* Tamborra, Hanke, Janka, Mueller, Raffelt, Marek, ApJ 792 (2014) 96.

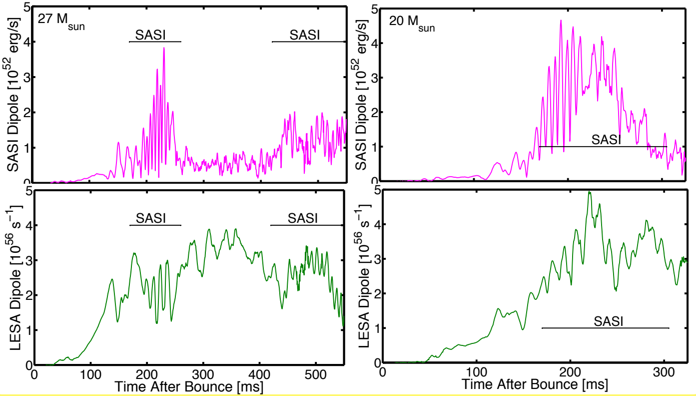
Accretion Rate and Shock Radius (11 M_{sun})

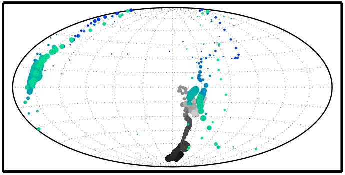
Anti-correlation between mass-accretion flow and shock-wave radius.

Neutrino heating is stronger on the side of lower lepton-number flux.

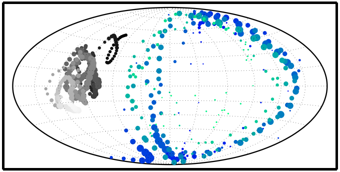


LESA-SASI Interference





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 792 (2014) 96. Tamborra et al., PRD 90 (2014) 4, 045032.

Features of the LESA Phenomenon

★ The initial spherically symmetric state is not stable. LESA grows from any perturbation.

★ LESA is the first neutrino-hydrodynamical instability in contrast to convection or SASI.

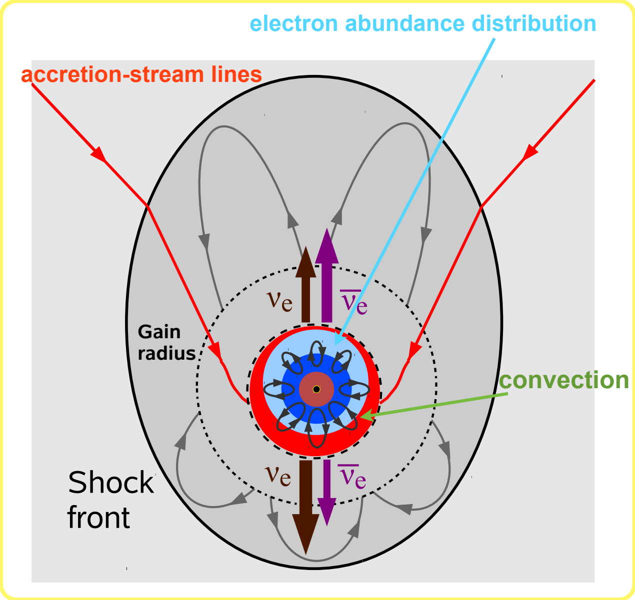
★ LESA mostly builds up below the neutrinosphere.

★ Hemispheric asymmetry of the lepton number flux reaches 20-30% of average values. Sum of neutrino fluxes nearly isotropic.

★ LESA is a self-sustained phenomenon which exists despite convection and SASI.

★ LESA is responsible for asymmetric electron fraction distribution, asymmetric accretion rate, asymmetric neutrino heating rate, and dipole deformation of the shock front.

Overall Picture of the LESA phenomenon

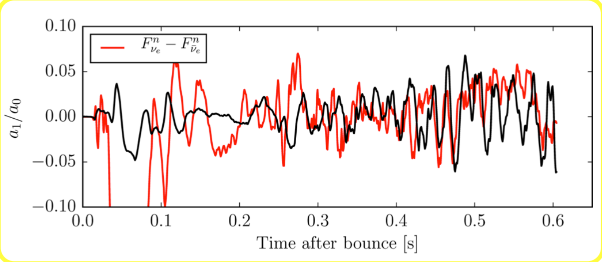


Feedback loop consisting of asymmetric accretion rate, asymmetric lepton-number flux, asymmetric neutrino heating rate, and dipole deformation of the shock front.

* Tamborra, Hanke, Janka, Mueller, Raffelt, Marek, ApJ 792 (2014) 96.

Is the LESA Phenomenon Real?

★ Couch & O'Connor (2014) do find LESA in their **3D** models.
★ Dolence, Burrows & Zhang (2015) do not find LESA in their **2D** models.



Red: Lepton-number dipole (x 5).
No evidence for lepton number dipole.

Different neutrino radiative transfer method as well as many other differences.
LESA not appearance in Dolence et al. 2D models to be understood.

★ LESA do appear in correspondent **2D** models from the Garching group.
★ Exploding **3D** models from the Garching group (2015) to be investigated.

* Couch, O'Connor, ApJ, 785 (2014) 123. Melson, Janka, Marek, ApJ 801 (2015) 2, L24. Melson et al., arXiv: 1504.07631. Dolence, Burrows, Zhang, ApJ, 800 (2015) 1, 10.

Implications of the LESA Phenomenon

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

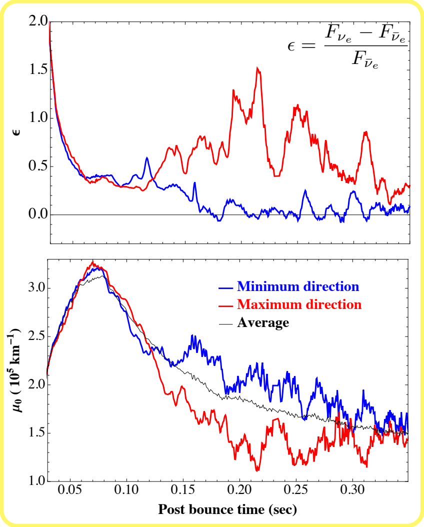
★ **Neutron star kicks**: Asymmetric neutrino emission imparts a recoil on the nascent NS.

★ 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.

LESA vs. Self-induced Flavor Conversions



Preliminary study based on stability analysis suggests that self-induced flavor conversions are suppressed below the shock front, even in presence of LESA.

Caution: Simplified setup assumed. Coexistence of LESA and SASI not yet investigated.

* Chakraborty, Raffelt, Janka, Mueller, arXiv: 1412.0670. See also: Banerjee, Dighe, Raffelt, PRD 84 (2011) 053013, Esteban-Pretel et al., PRD 78 (2008) 085012. Duan & Shalgar, arXiv: 1412.7097.

Conclusions

★ Neutrinos carry imprints of the SN explosion dynamics.

★ The SN neutrino signal can probe the nature of the hydrodynamical instability.

★ SASI modulations of the neutrino signal detectable in IceCube and Hyper-K.

★ LESA: New neutrino-hydrodynamical instability.
Lepton number flux emerges predominantly in one hemisphere.

Thank you

for your attention!