Neutrinos Probe Supernova Dynamics

Irene Tamborra

GRAPPA Institute, University of Amsterdam

Rencontres de Moriond, EW Interactions and Unified Theories
La Thuile, March 18, 2014

Outline

★ Supernova explosion mechanism and hydrodynamical instabilities

★ Detection perspectives adopting first full-scale 3D SN simulations

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

★ Conclusions

This talk is mainly based on:

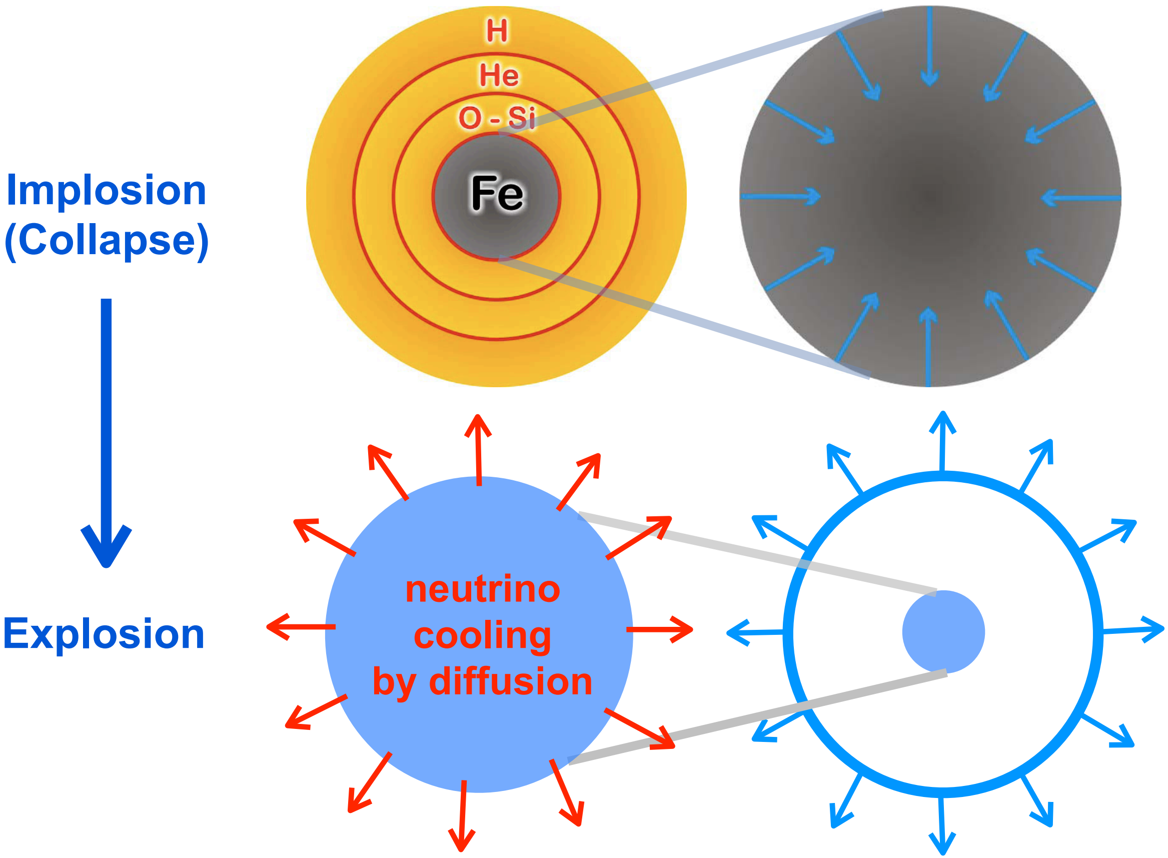
- I. Tamborra, F. Hanke, B. Mueller, H.-T. Janka, and G. Raffelt, PRL 111 (2013) 121104.
- I. Tamborra, F. Hanke, H.-T. Janka, B. Mueller, G. Raffelt, A. Marek, arXiv: 1402.5418.

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).

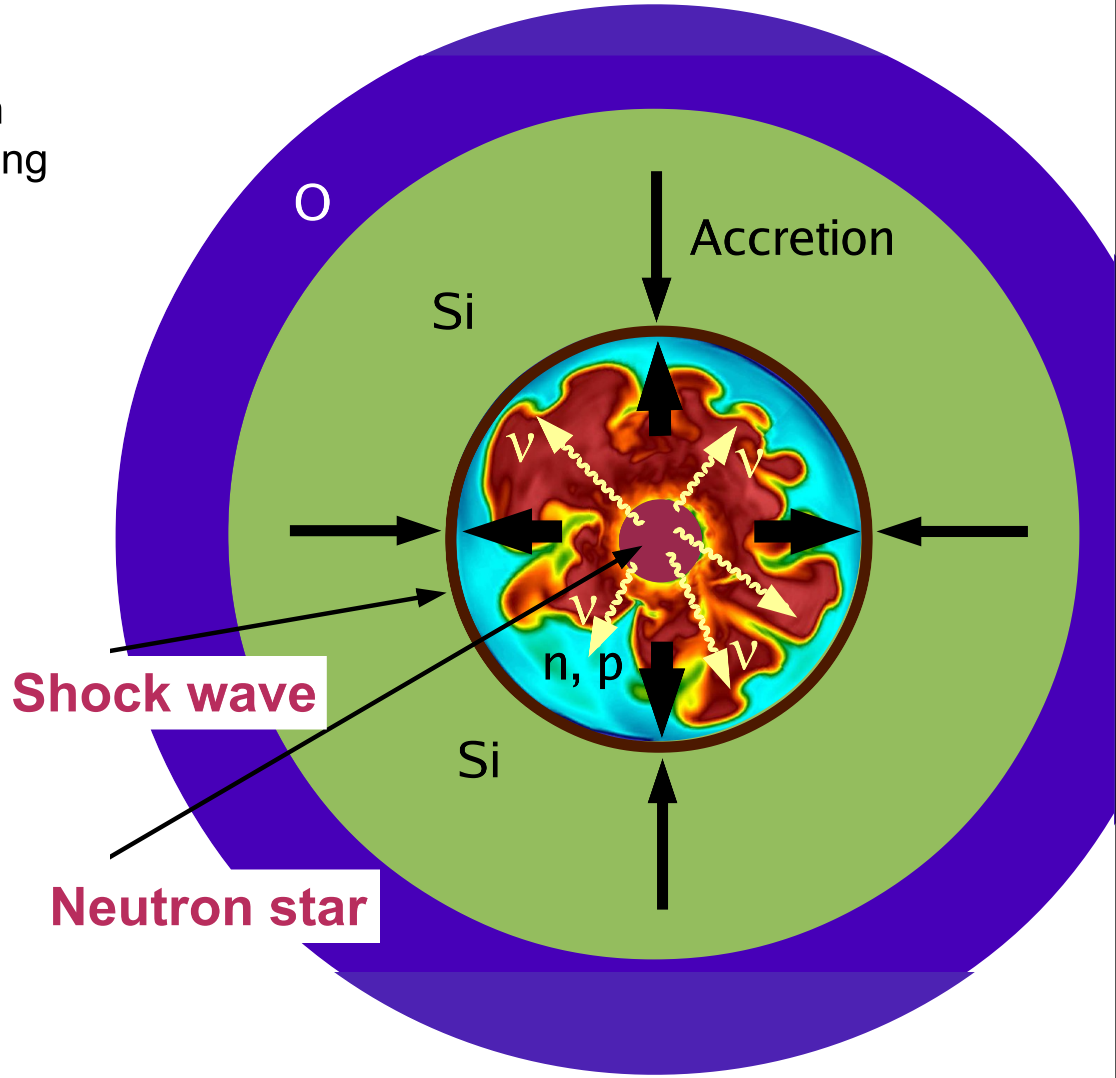
Neutrino typical energies: ~ 15 MeV.
Neutrino emission time: ~ 10 s.

Neutrinos and SN Explosion Mechanism

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

★ Stalled shock wave receives energy from **neutrinos** to start re-expansion against ram pressure of in-falling stellar matter.
(Delayed Neutrino-Driven Explosion.)

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

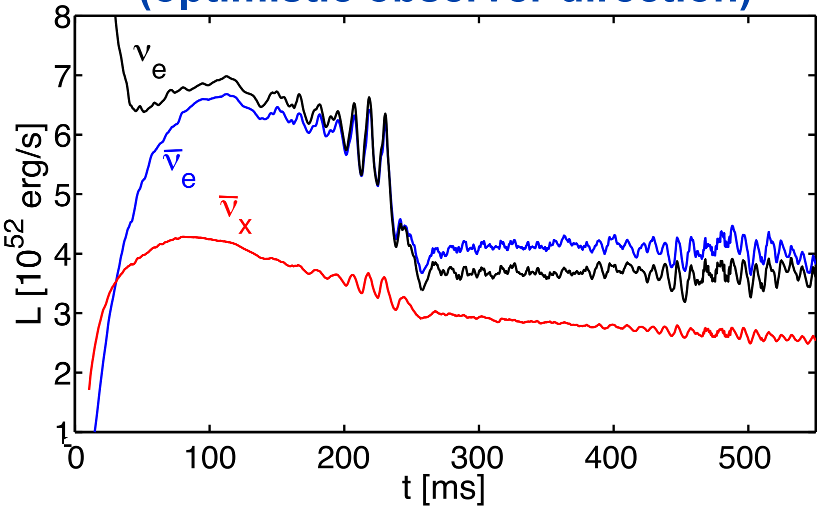


* For more details see H.-T. Janka, arXiv: 1206.2503, H.-T. Janka et al., arXiv: 1211.1378.

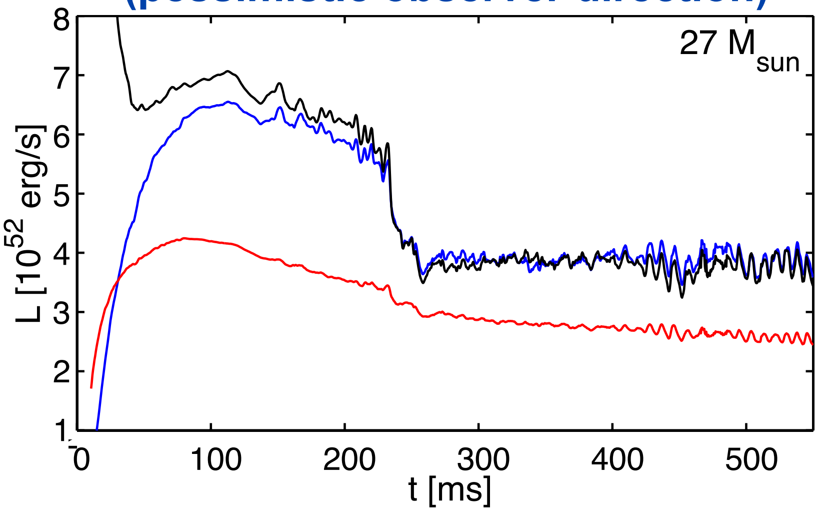
Directional Neutrino Signal

First world-wide 3D SN simulations with detailed neutrino transport available.
SASI and convective motions leave an imprint 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?

For more details see also: F. Hanke et al., APJ 770 (2013) 66. T. Lund et al., arXiv: 1006.1889, arXiv: 1208.0043.

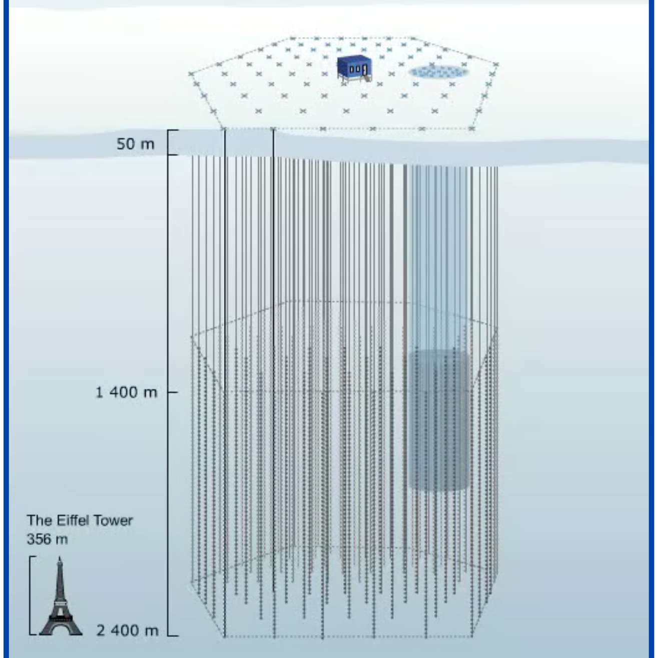
Detection Perspectives

Detection Perspectives

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

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

IceCube

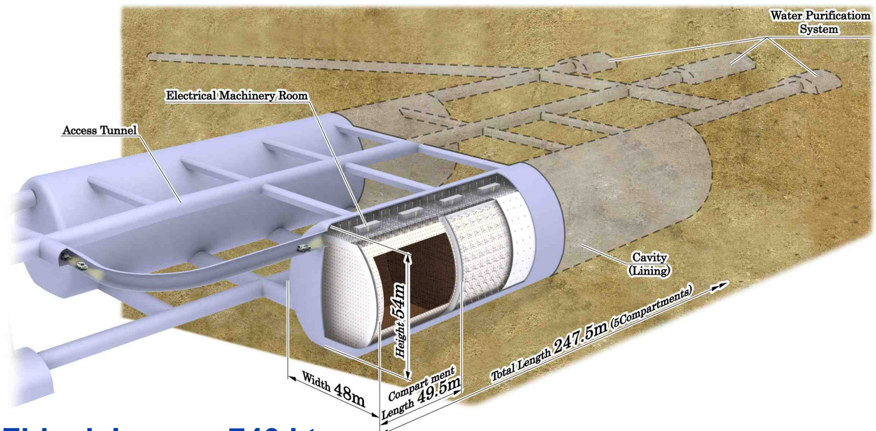


Atom

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})

Our 3D 27 M_{sun} SN progenitor shows pronounced SASI.
SASI sinusoidal modulation of the neutrino signal will be detectable by IceCube and Hyper-K.

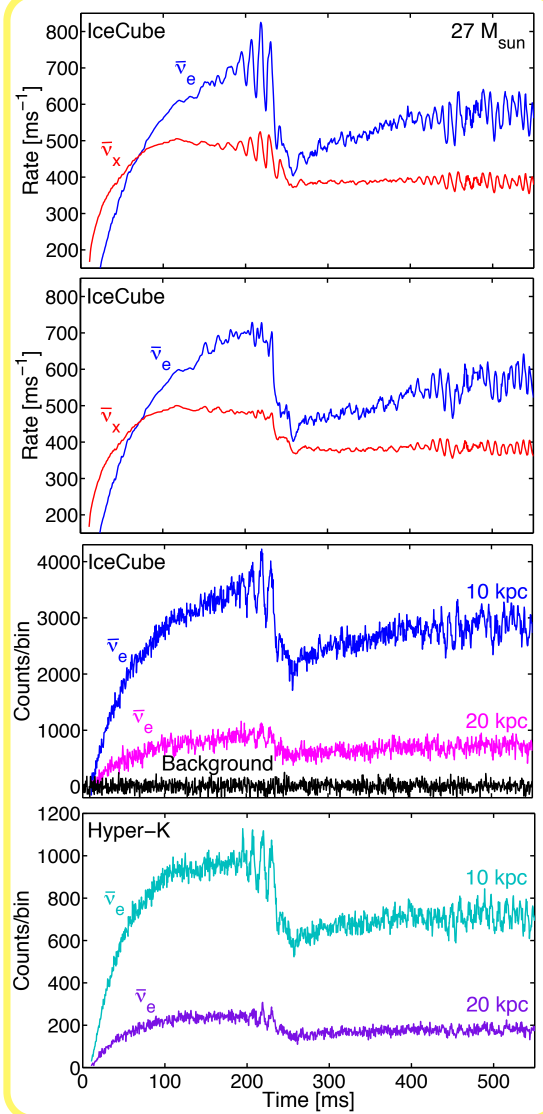
Strong signal modulation (optimistic observer direction)

Weak signal modulation (pessimistic observer direction)

Expected rate above IceCube background

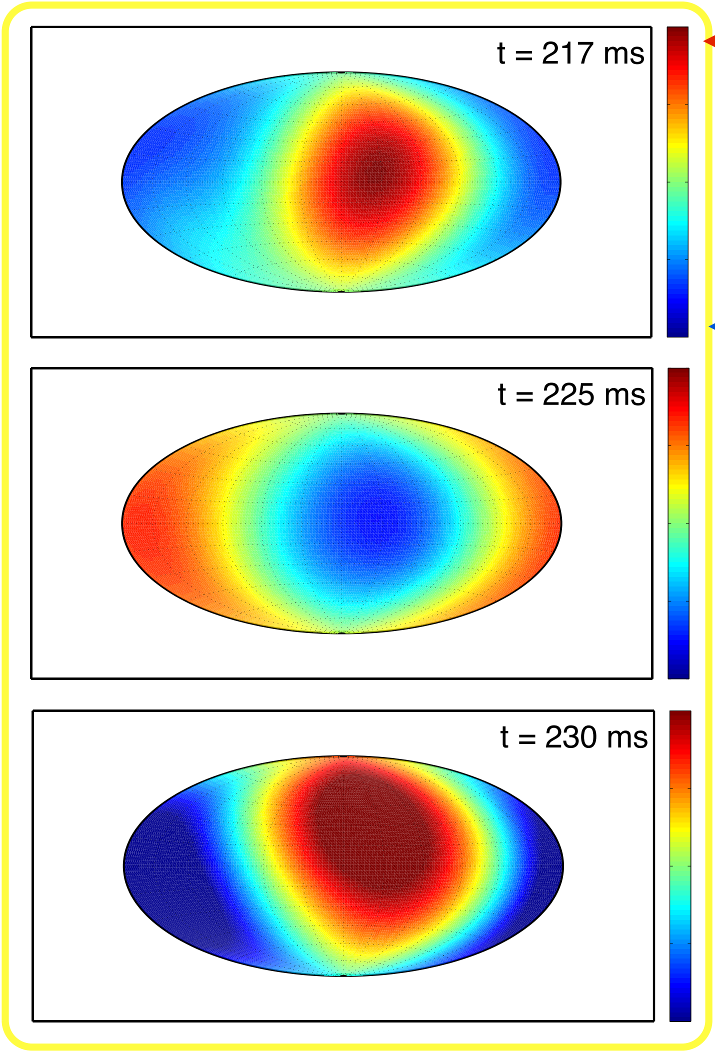
Hyper-K rate = 1/3 IceCube rate

SASI still detectable



SASI Detection Perspectives (27 M_{sun})

Time evolution of the IceCube detection rate on a sky-plot of observer directions.



high detection rate

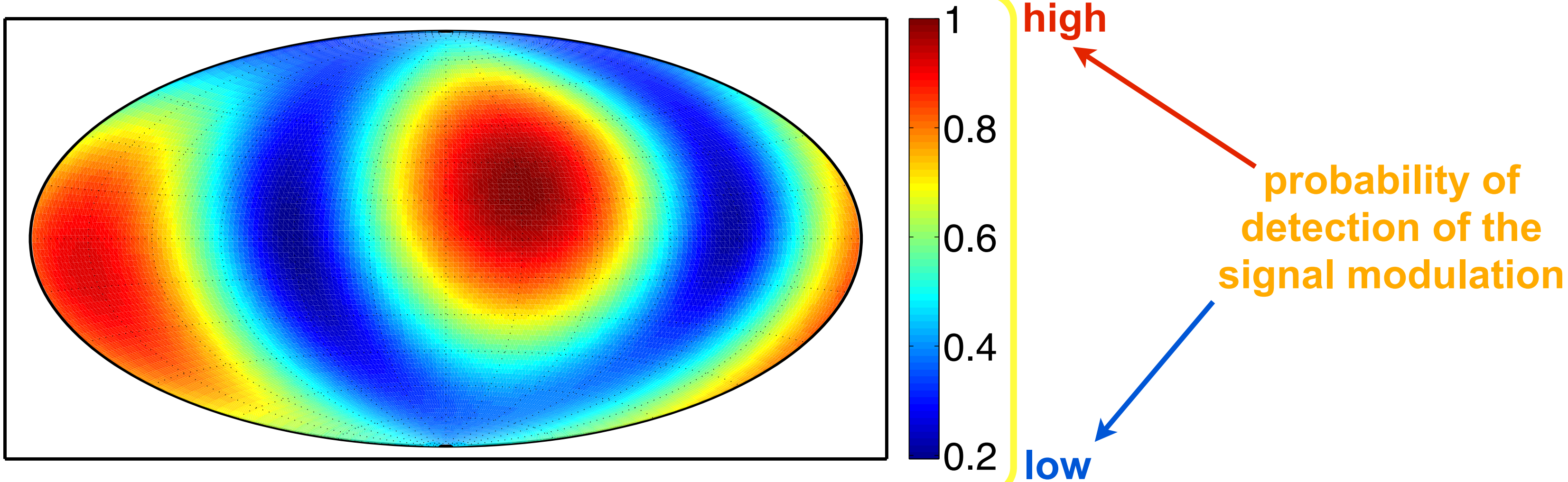
low detection rate

Animated visualization available at:
http://www.mpa-garching.mpg.de/ccsnarchive/data/Hanke2013_movie/index.html

SASI Detection Perspectives (27 M_{sun})

$$\sigma \equiv \left(\int_{t_1}^{t_2} dt \left[\frac{R - \langle R \rangle}{\langle R \rangle} \right]^2 \right)^{1/2}$$

$$[t_1, t_2] = [120, 250] \text{ ms}$$



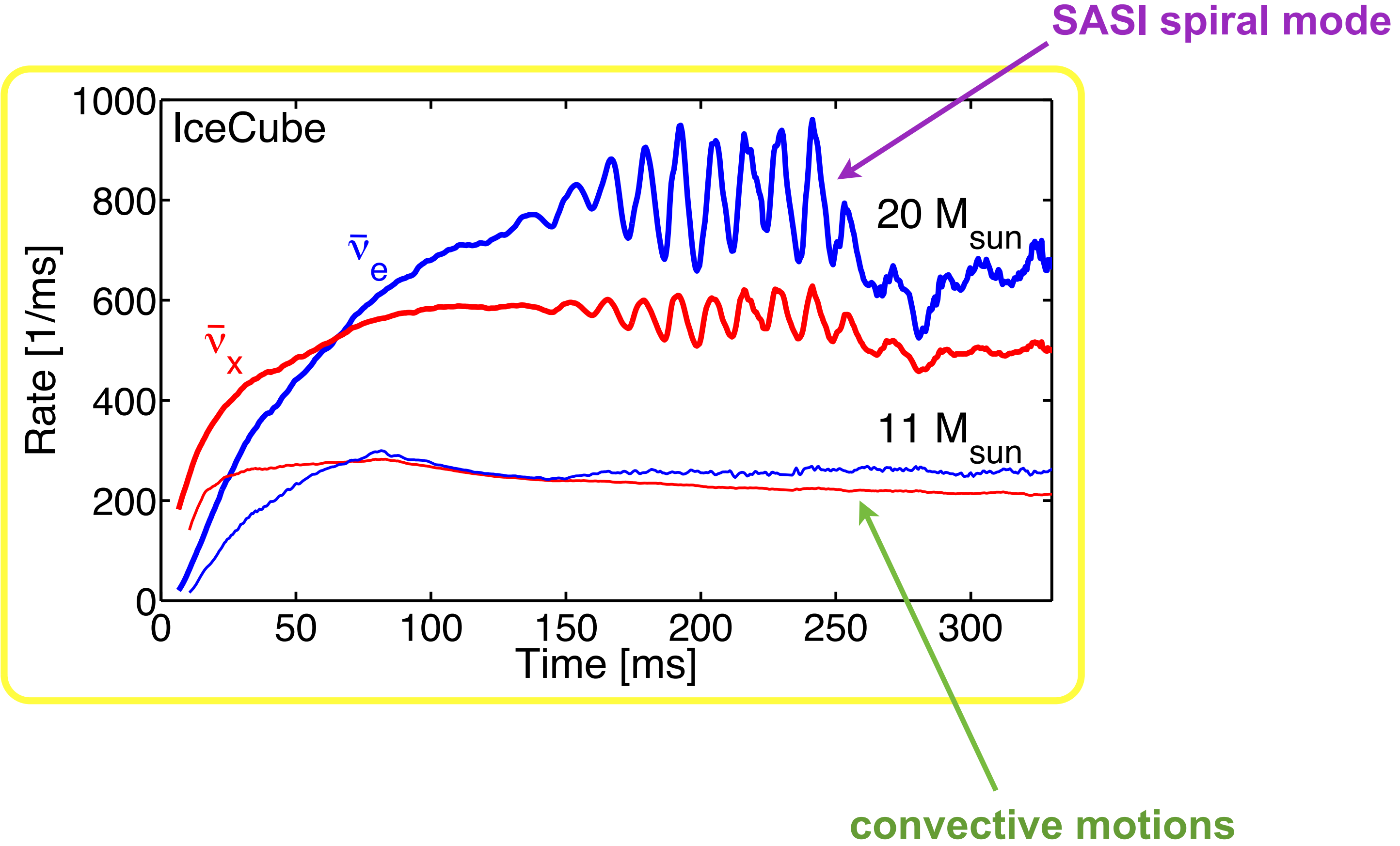
On average, the fraction of sky where good observation chances apply is significant (> 50%).

SASI Detection Perspectives

For the 27 M_{sun} SN progenitor, two SASI episodes occur with a convective phase in between.
For the 20 M_{sun} SN progenitor, only one SASI episode occurs.

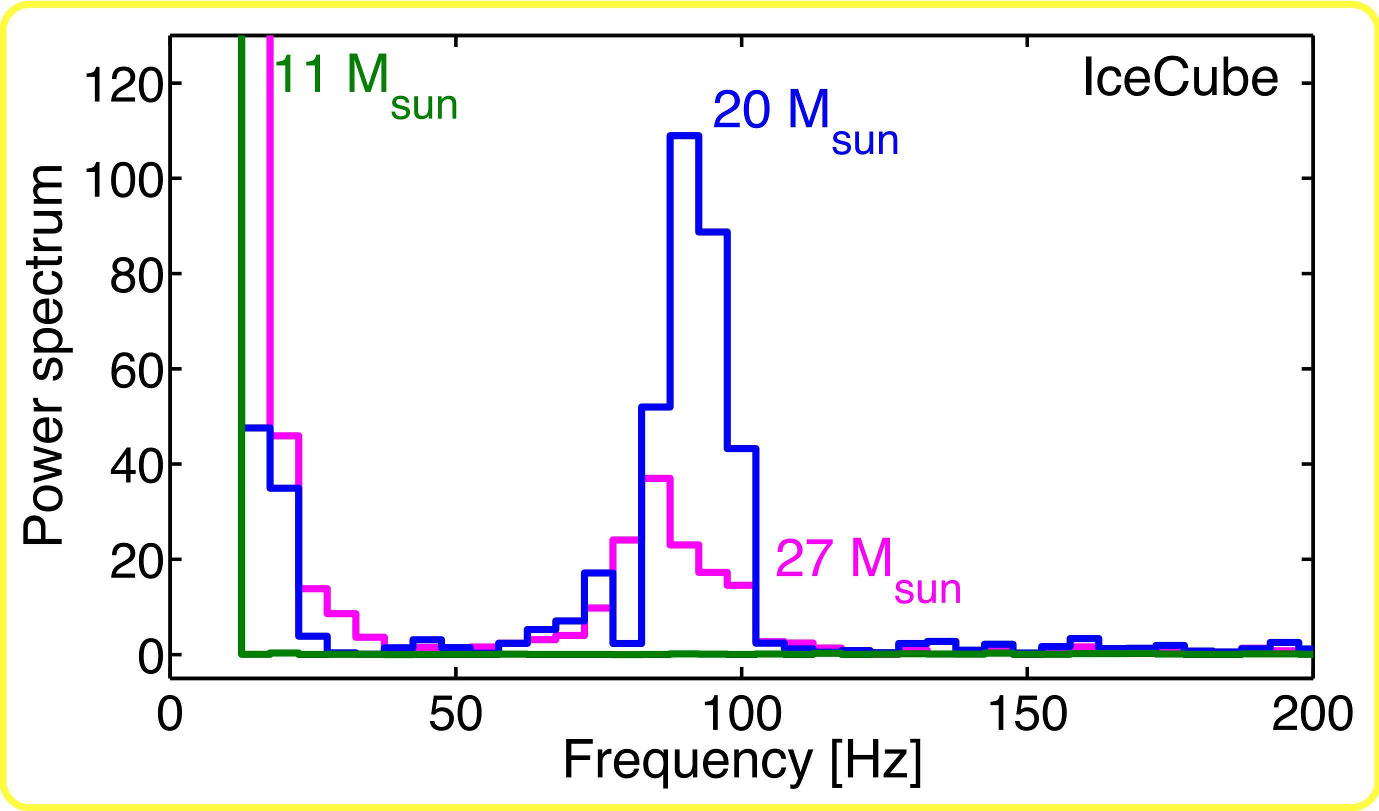
SASI does not occur for any progenitor.

Large scale convection is the dominant hydrodynamic instability in the 11.2 M_{sun} progenitor.



Power Spectrum of the Event Rate

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

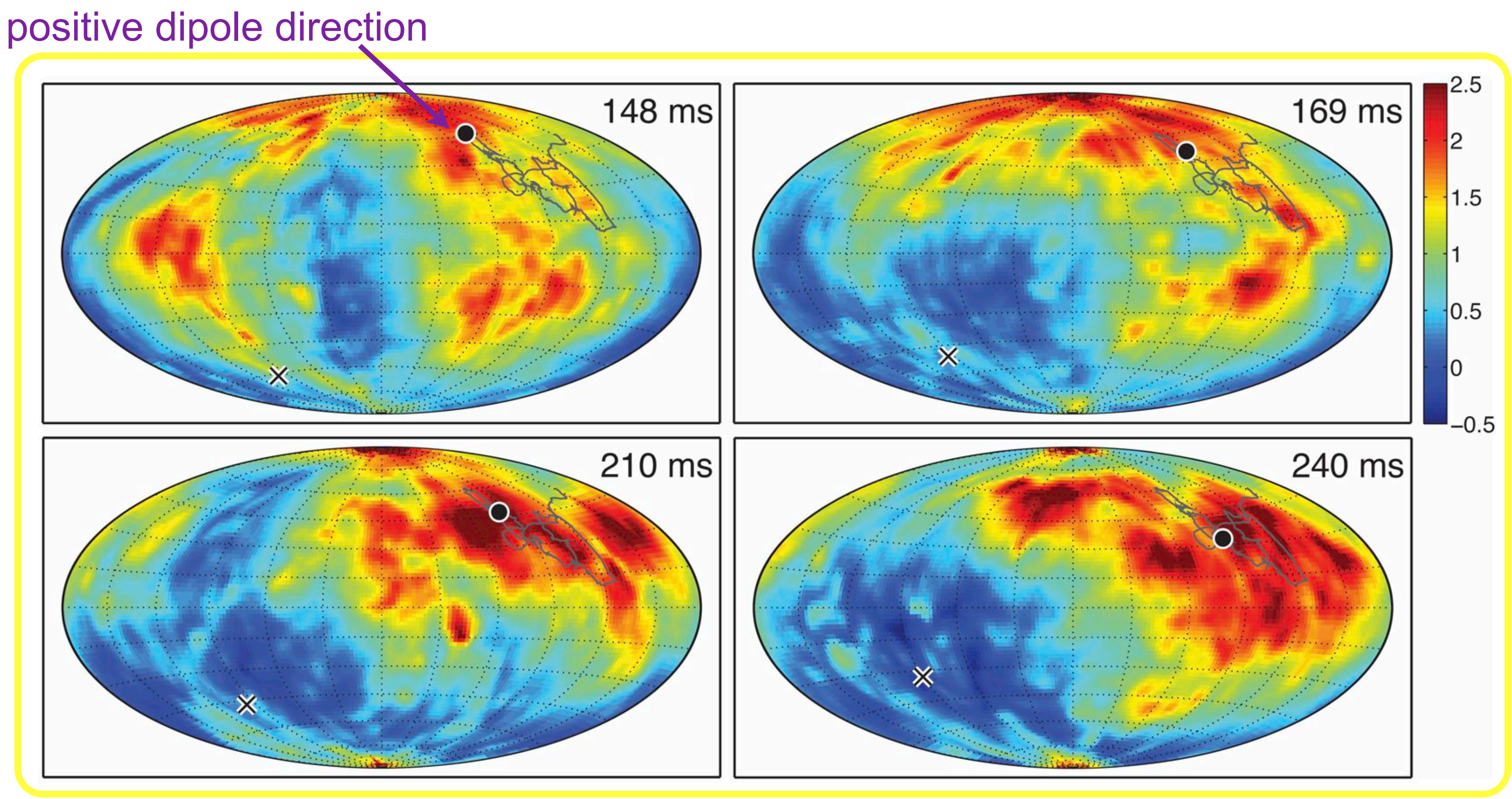


A peak appears at the SASI frequency of ~ 80 Hz for the 20 and 27 M_{sun} SN progenitors.

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

Lepton-number Flux Evolution

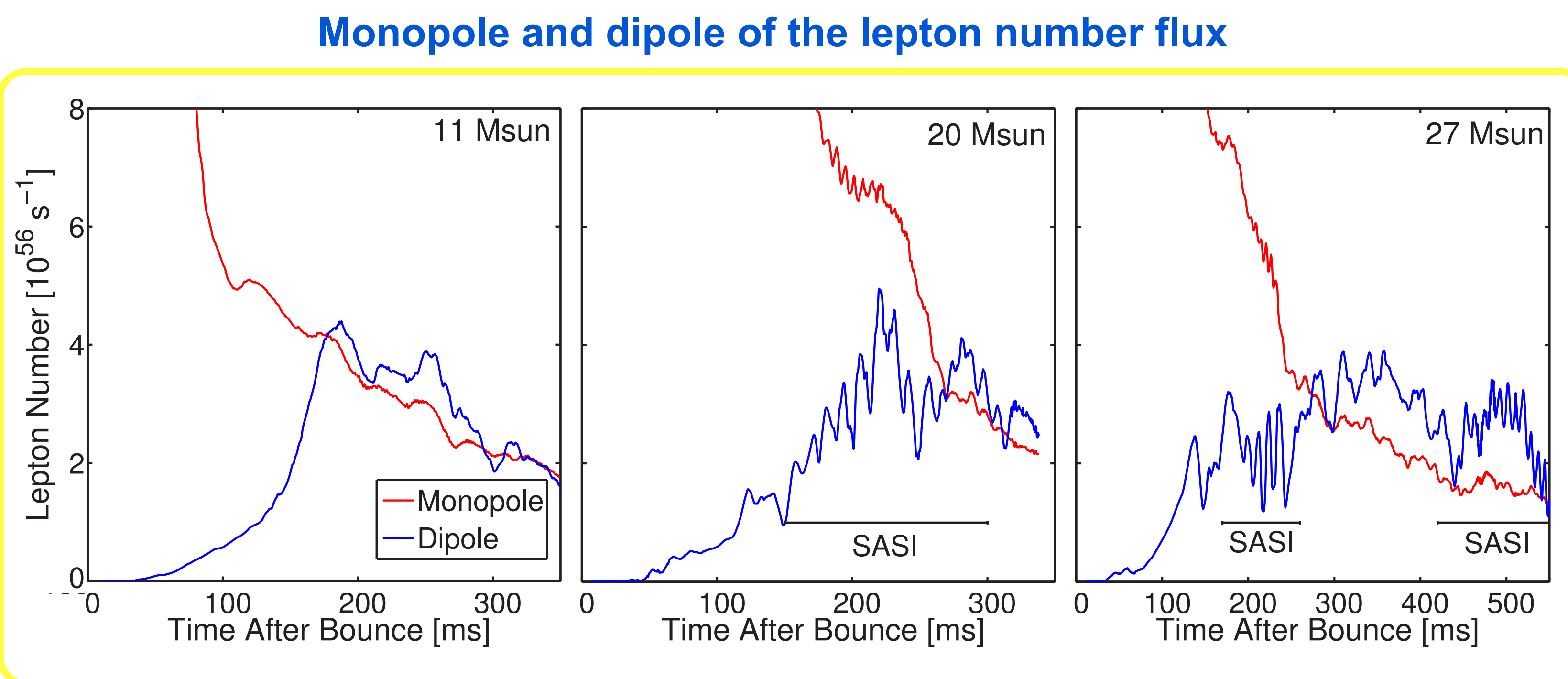
Lepton-number flux for the 11.2 M_{sun} progenitor [$(F_{\nu_e} - F_{\bar{\nu}_e})/\langle F_{\nu_e} - F_{\bar{\nu}_e}\rangle$].



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

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

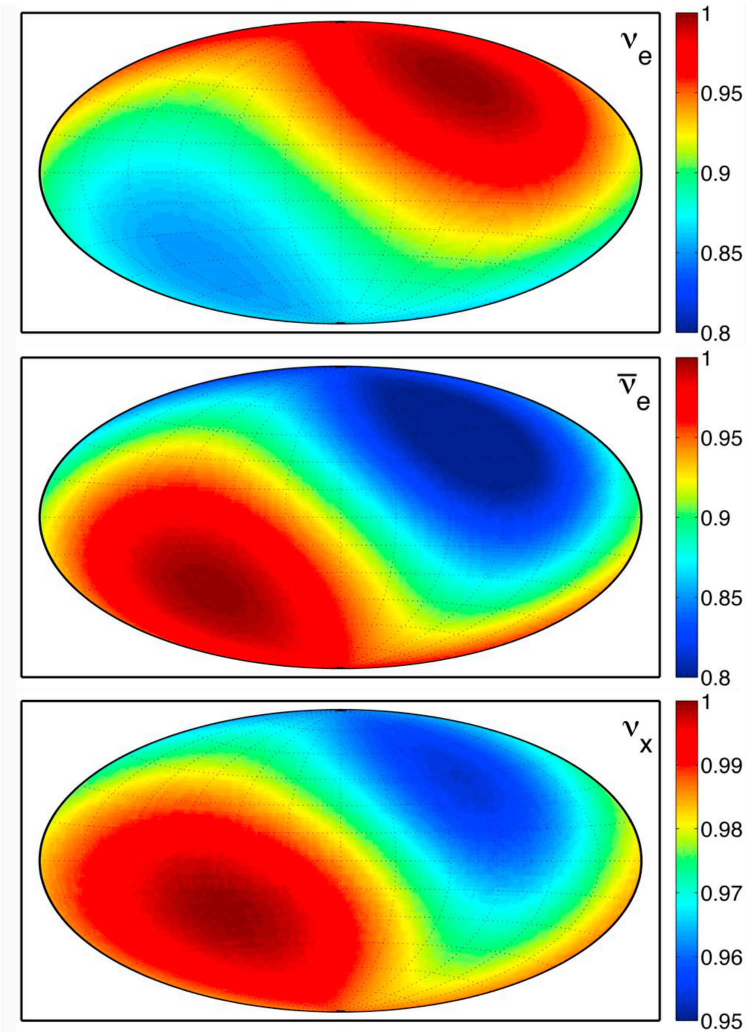
Lepton-number Flux Evolution

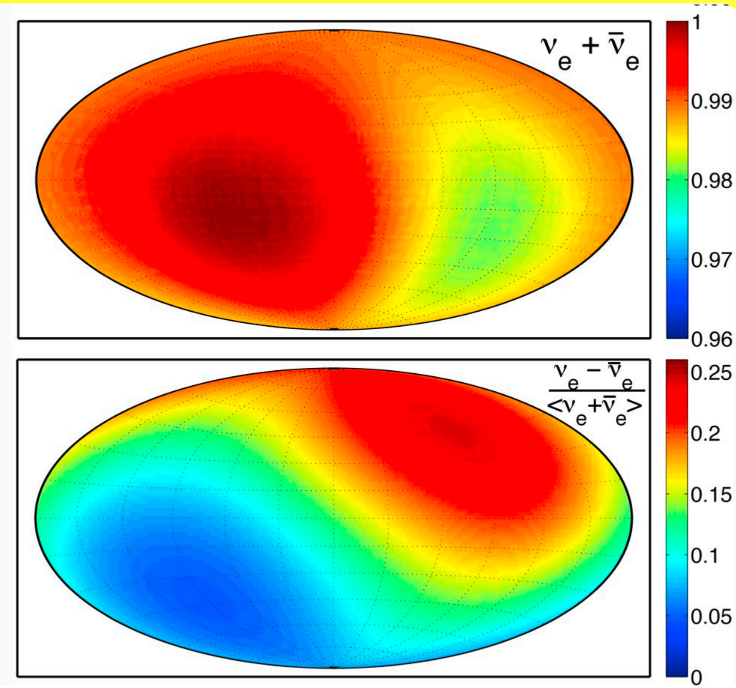


★ Monopole evolution strongly depends on the accretion rate and varies between models.
★ Maximum dipole amplitude similar in all cases.
★ Dipole persists during SASI activity.
★ Dipole directions different in all cases. They drift slowly even during SASI phases.

Number Flux Evolution

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





Features of the LESA Phenomenon

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

★ LESA is not simply hydrodynamical, but a neutrino-hydrodynamical instability in contrast to convection or SASI. First of its kind identified in the SN context.

★ 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 activity.

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

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 as major source for NS kicks unluckily.

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

★ **Neutrino-flavor conversion:**

- 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.

Conclusions

★ World-wide first 3D SN simulations with detailed neutrino transport available.

★ Neutrinos carry imprints of the explosion dynamics.

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

★ SASI modulation of the neutrino signal will be clearly detectable in IceCube and Hyper-K.

★ LESA: new neutrino-hydrodynamical instability. The lepton number flux emerges predominantly in one hemisphere.

Thank you

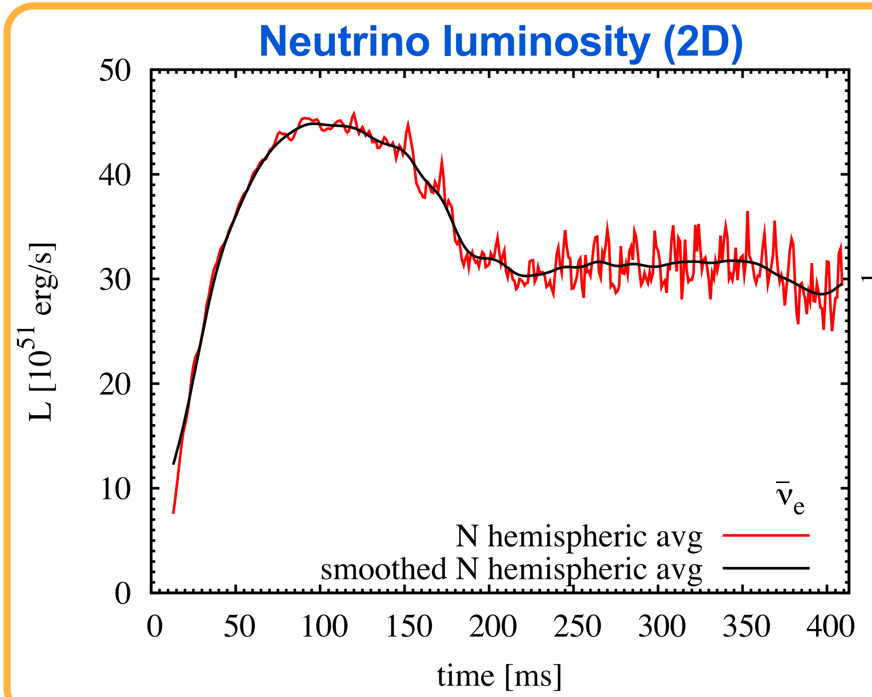
for your attention!

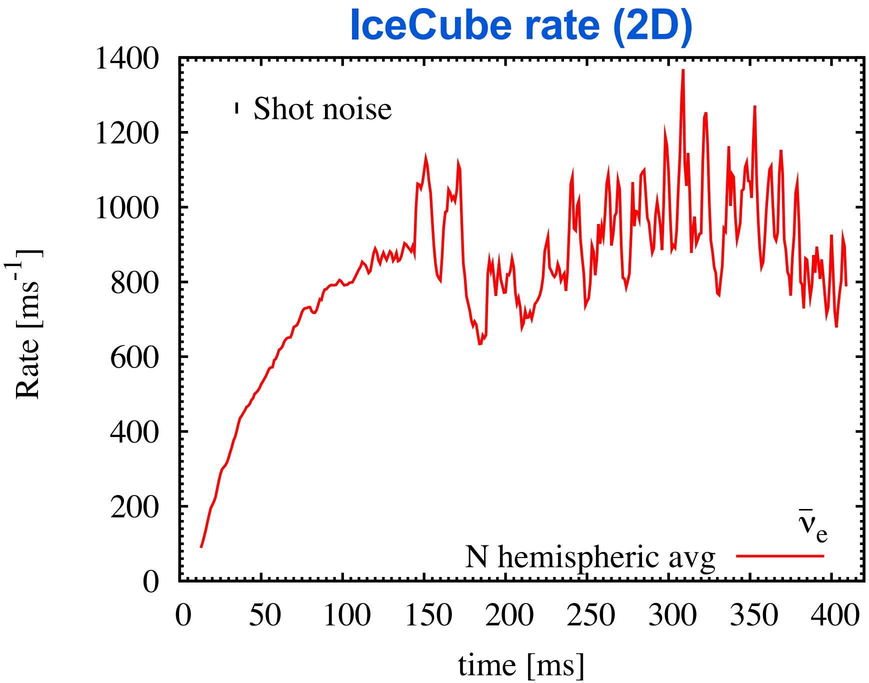
Back-up Slides

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.



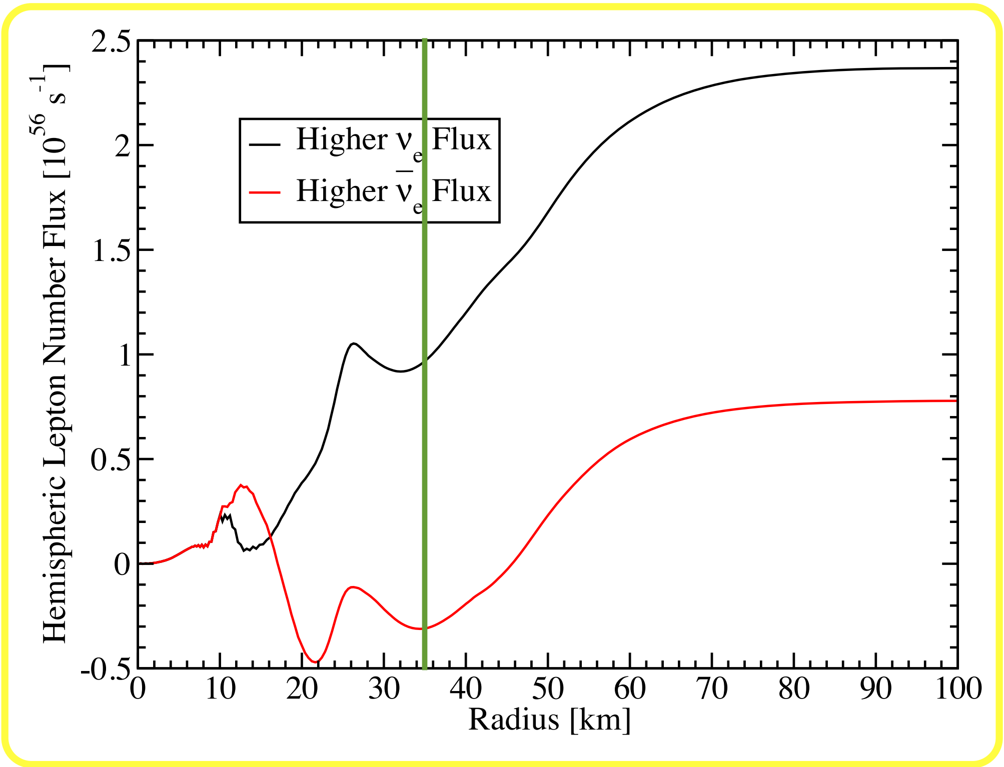


Are these features generic for any SN progenitor, 3D SN models?

First full-scale 3D SN simulations with detailed neutrino transport being performed!

* T. Lund et al., arXiv: 1006.1889, arXiv: 1208.0043.

Lepton-number Flux Radial Evolution

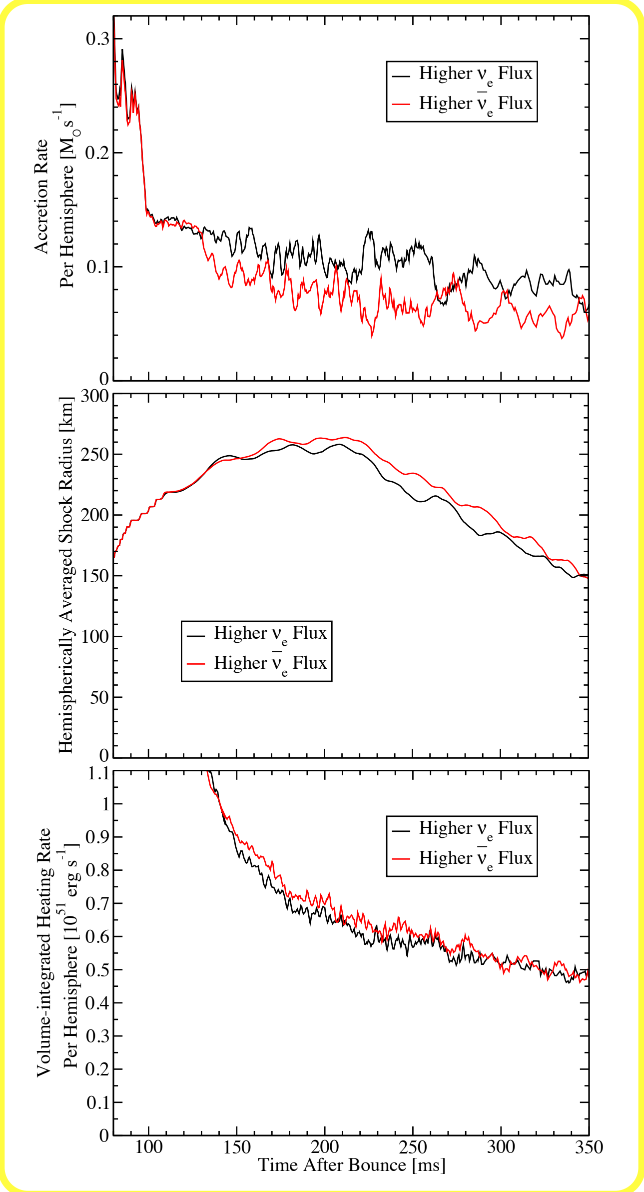


Most of the hemispheric difference builds up in the PNS mantle below the neutrinosphere. Only 20-25% arise at larger radii ans are therefore more directly associated with the hemispheric asymmetry of the accretion flow.

Accretion Rate and Shock Radius

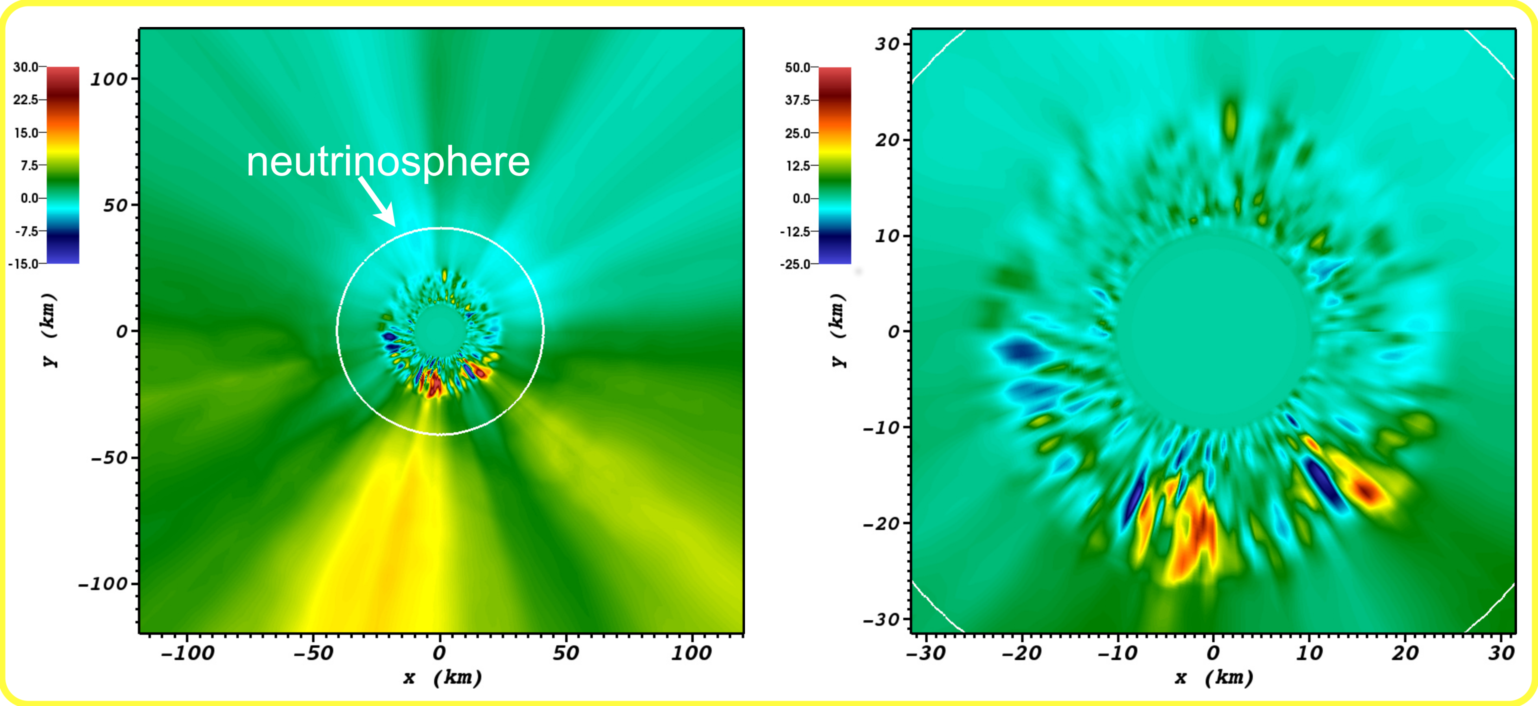
Anti-correlation between mass-accretion flow and shock-wave radius.

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



Lepton-number Flux Evolution

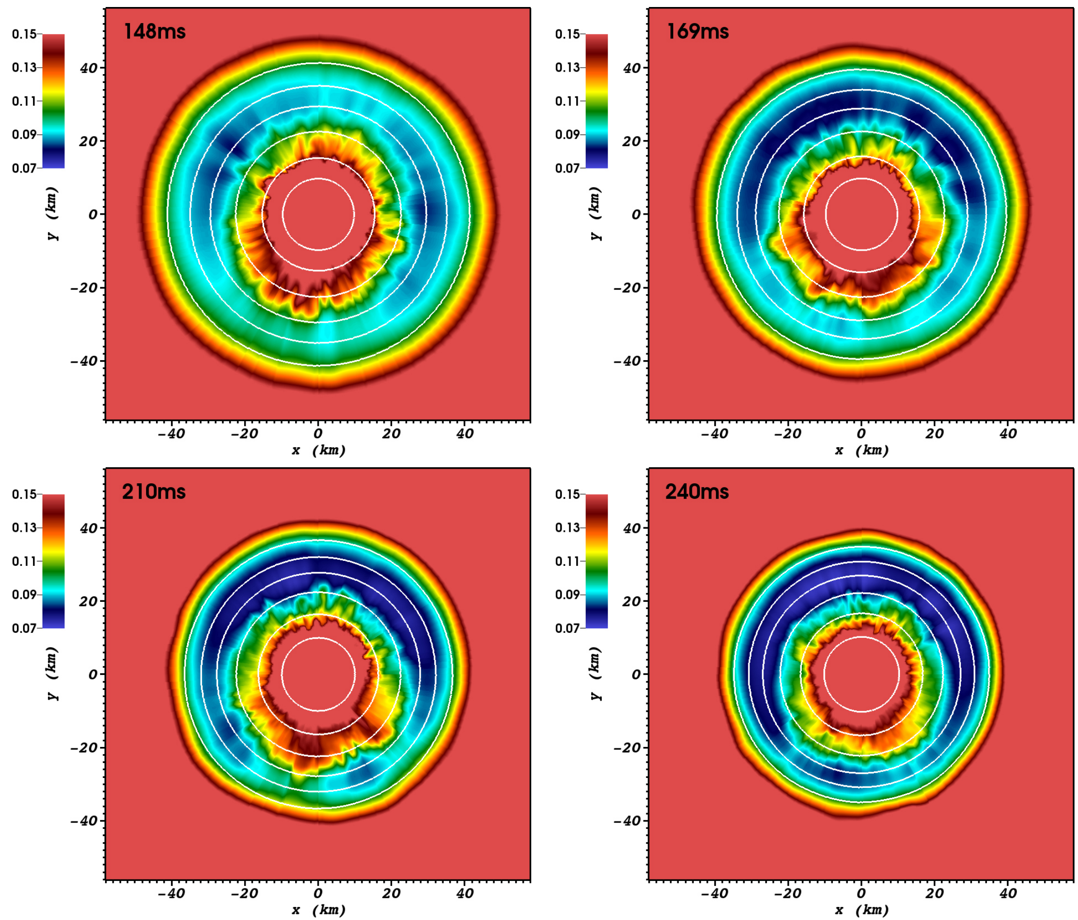
Radial evolution of the lepton-number flux in the the 11.2 M_{sun} progenitor at 210 ms p.b.



PNS convection stronger in the hemisphere of maximal lepton-number flux (bottom direction).

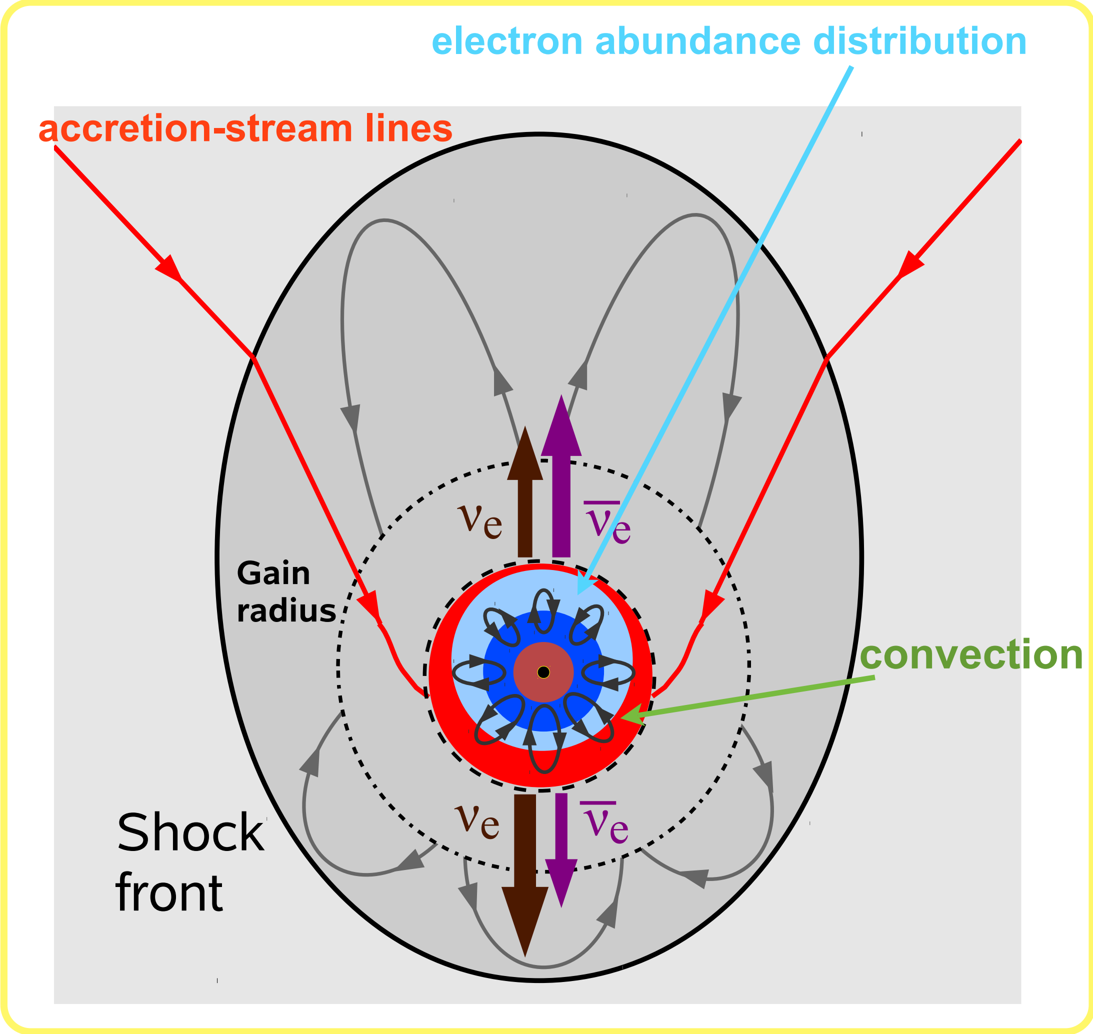
Electron Fraction Evolution

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).

Overall Picture of LESA



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