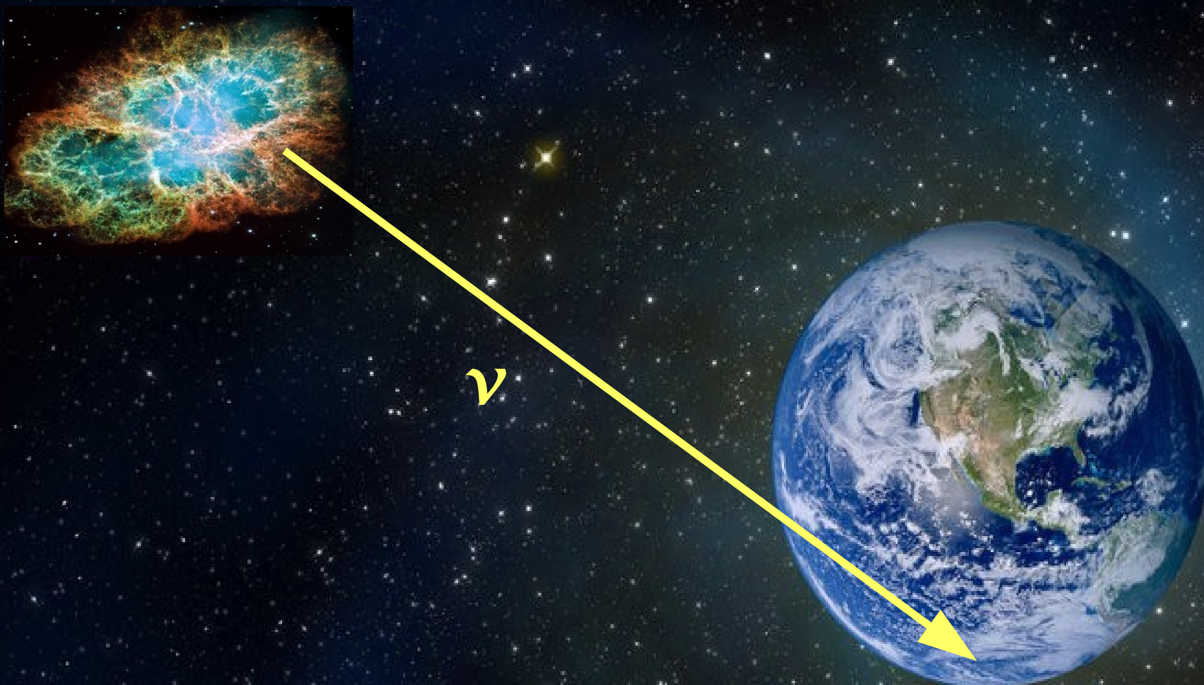
Neutrino Signatures of Supernova SASI

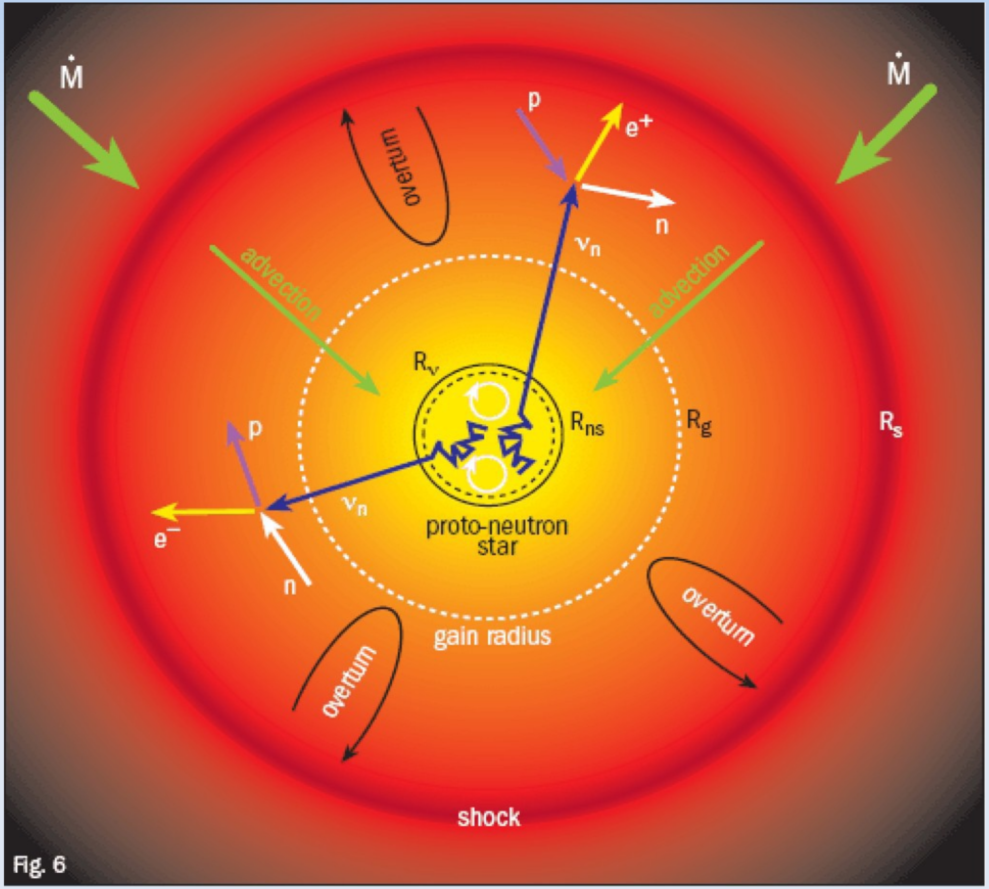


Collaborators: H.-Th. Janka, G. Raffelt, A. Wongwathanarat, A. Marek, C. Lunardini, E. Müller

INT 12-2a "Core-Collapse Supernova: Models and observable signals"
July 23rd, 2012

Tina Lund

Standing Accretion Shock Instability



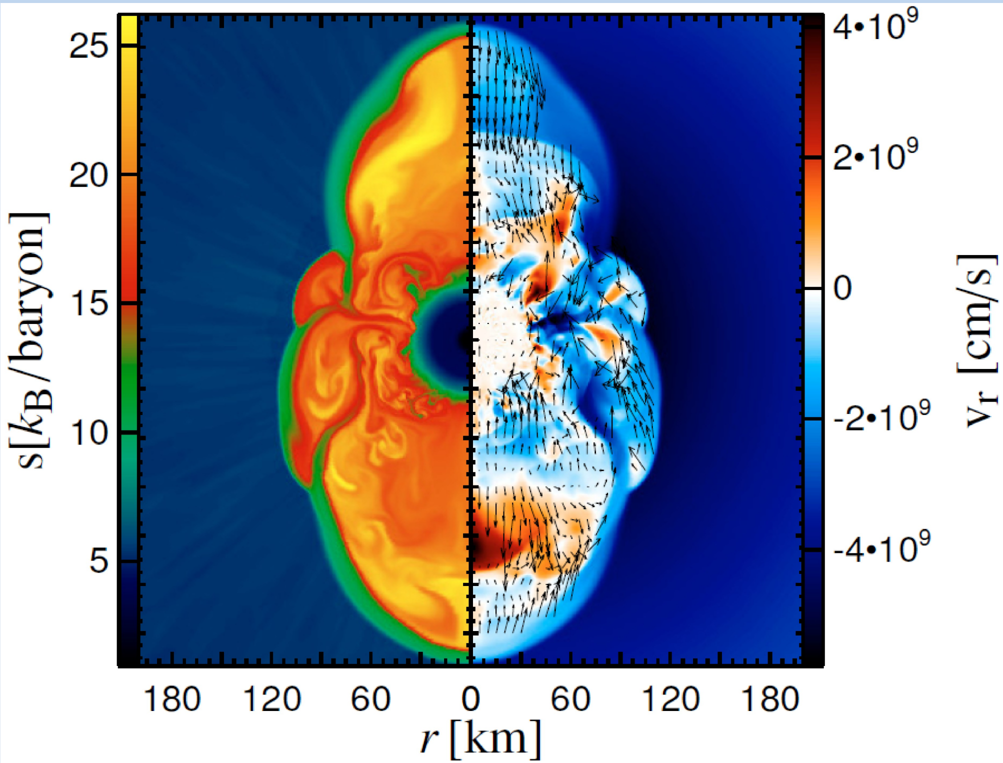
- Shock stalls.
- Neutrino heating to revive.
- Aid needed.
- SASI → infalling material longer time in heating area → more energy → shock wave revived → final explosion.
- SASI:
  - time scales.
  - spherical harmonics.

Movie of 11.2 M_{sun} 2D simulation

[R.Buras, A.Marek, H.Th.Janka]

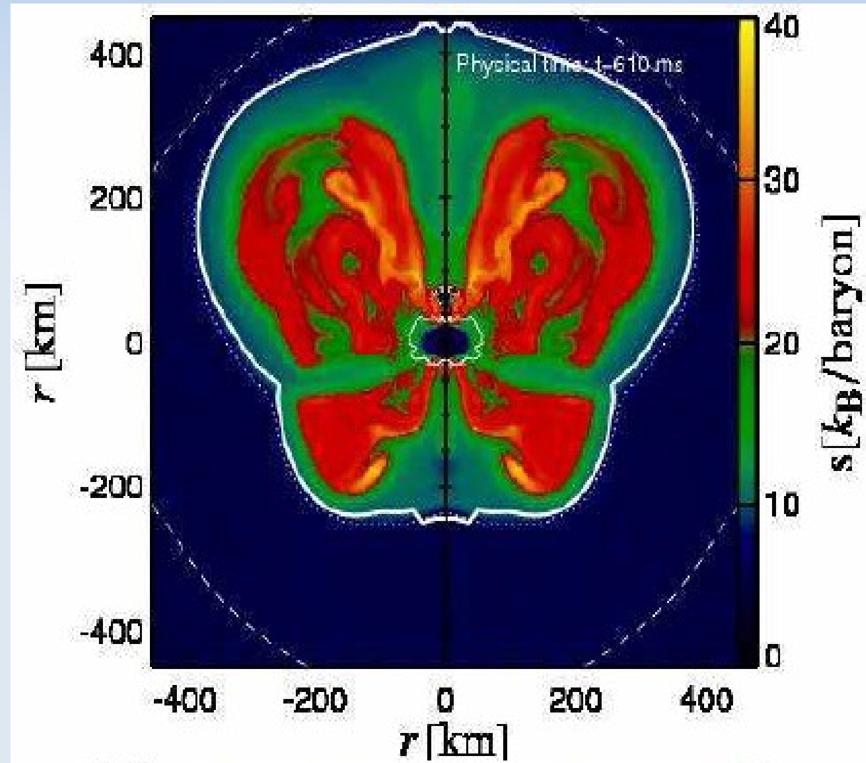
SASI – in 2D

Non-rotating 15 M_{sun}



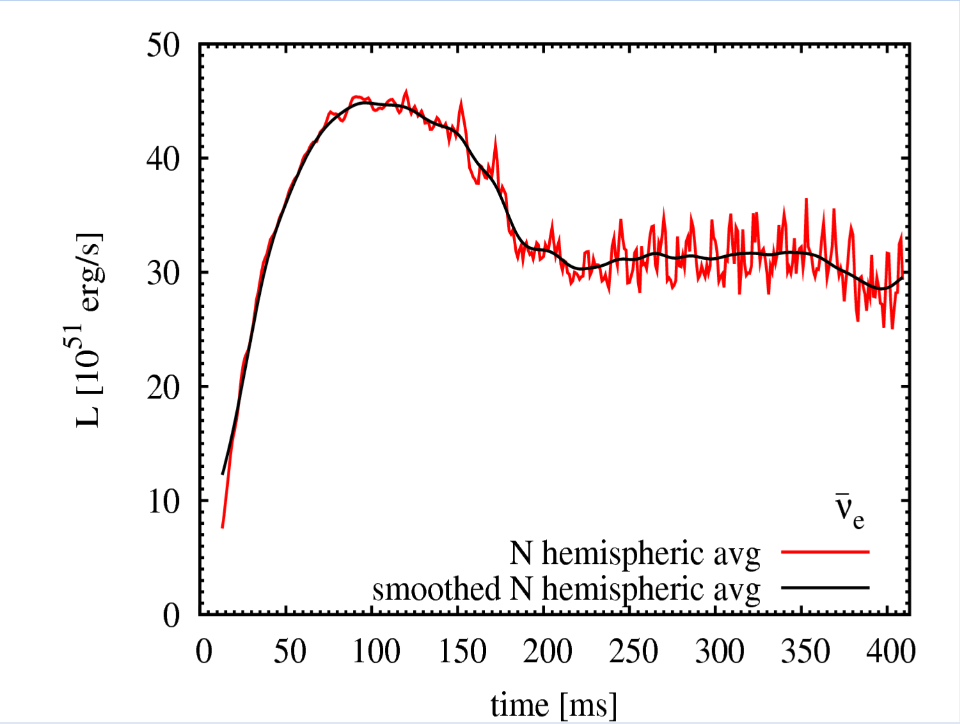
[A. Marek, H.-Th. Janka & E. Müller, 2009]

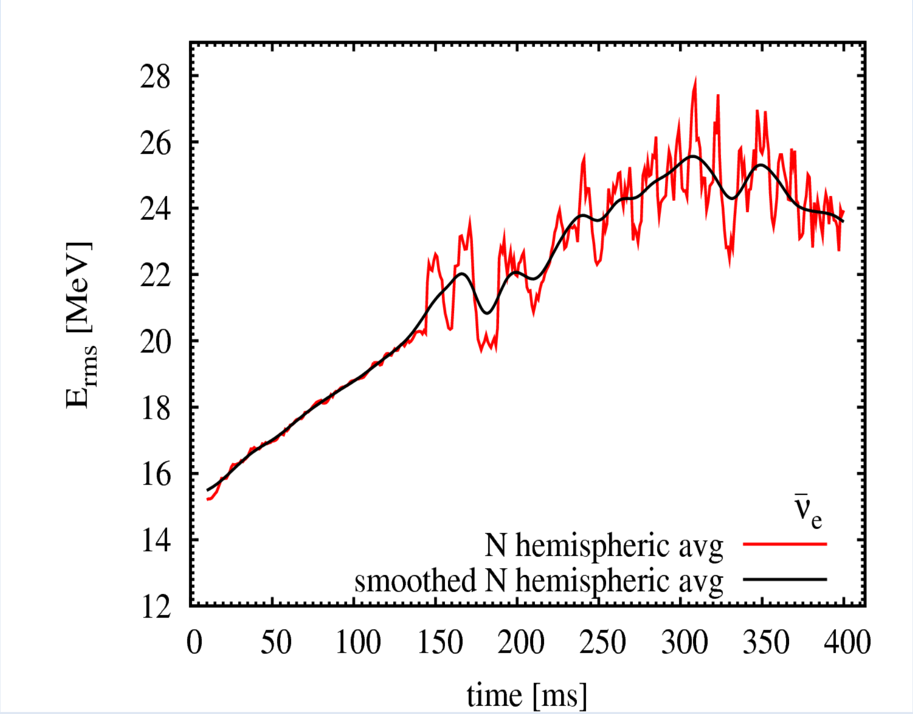
Rotating 15 M_{sun}



[A. Marek & H.-Th. Janka, 2008]

Effects of SASI





Non-rotating 15 M_{sun}

[Lund et al., 2010]

IceCube – Cherenkov telescope

- Digital Optical Modules with photo-multiplier tubes.

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

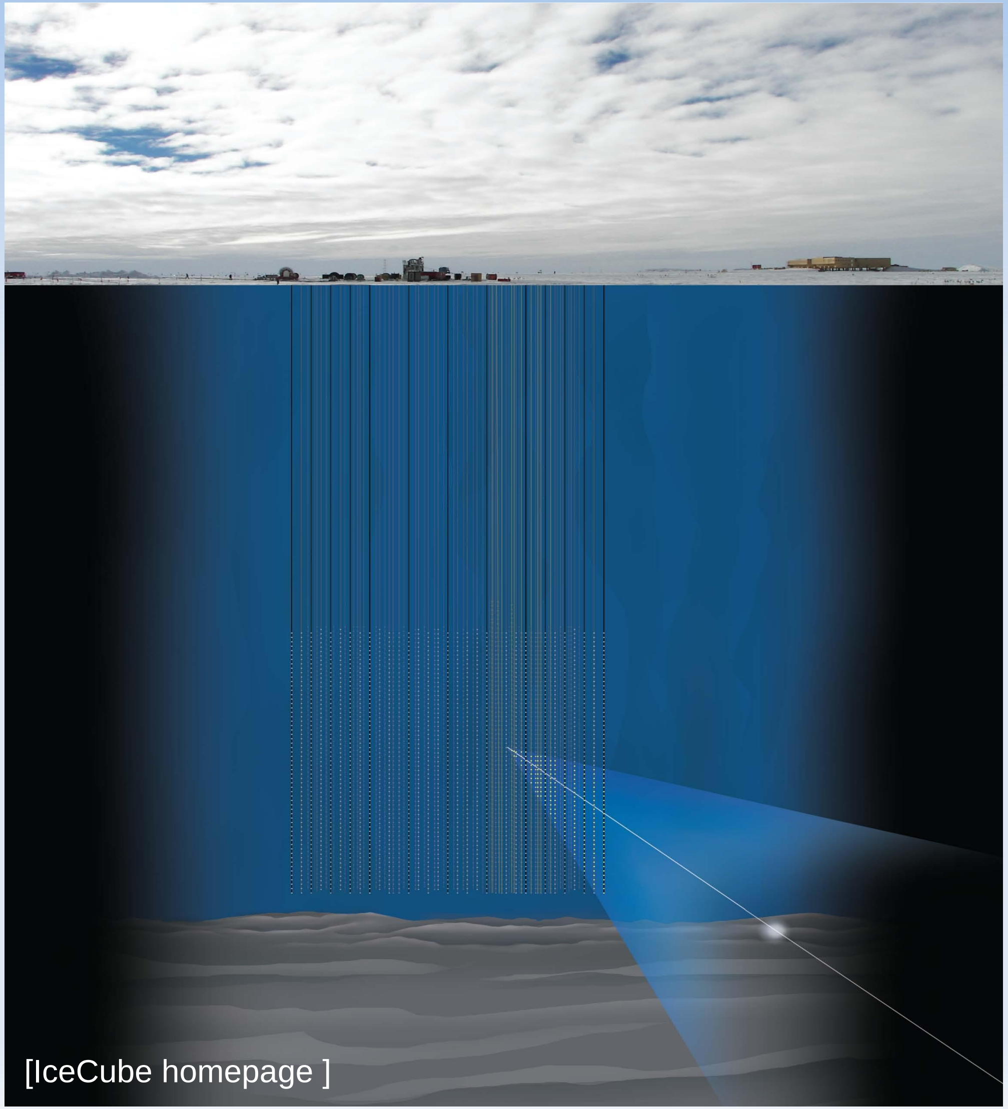
- Optimized for energy range:

  1 TeV ≤ E ≤ 1 PeV

- SN $\bar{\nu}_e$ energy:

  E ~ 12 – 18 MeV

- Not entire Cherenkov cone only one photon per interaction → diffuse blue glow of the ice.



IceCube – superiority

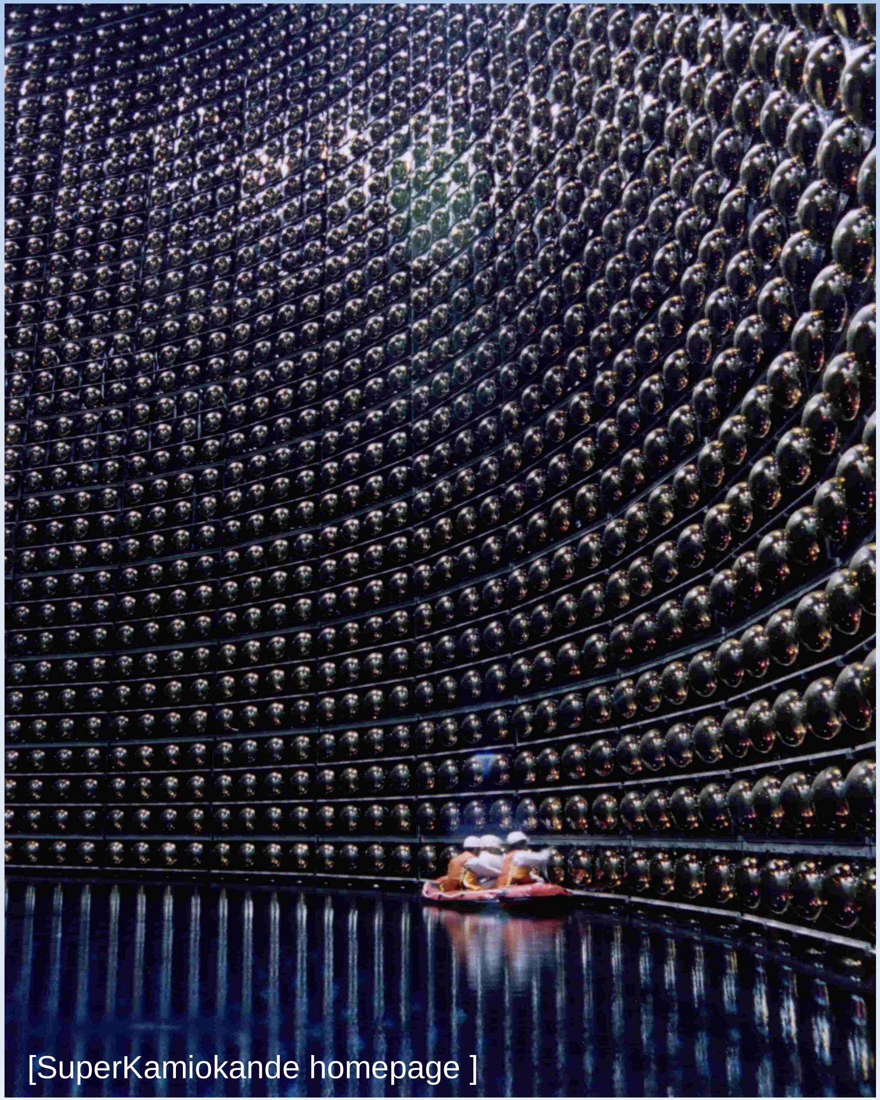
- For entire duration (t~10 s) of SN we expect ~10^6 events.
- Factor of 100 more than expected in SuperKamiokande.
- Instantaneous rate for 2D:

$$\Gamma_{SN} \sim 900\ \mathrm{ms}^{-1}$$

- Dark Current noise in IceCube:

$$\Gamma_{noise} \approx 1340\ \mathrm{ms}^{-1}$$

- Looking at time structure of the increased noise.



Calculations

Expected eventrate in IceCube:

$$R_{\bar{\nu}_e} = 114 \text{ ms}^{-1} \frac{L_{\bar{\nu}_e}}{10^{52} \text{ erg s}^{-1}} \left(\frac{10 \text{ kpc}}{D}\right)^2 \left(\frac{E_{\text{rms}}}{15 \text{ MeV}}\right)^2$$

$$E_{\text{rms}}^2 = \frac{\langle E^3 \rangle}{\langle E \rangle}$$

- Energy and luminosity data from numerical simulations by A. Marek and H.-Th. Janka.

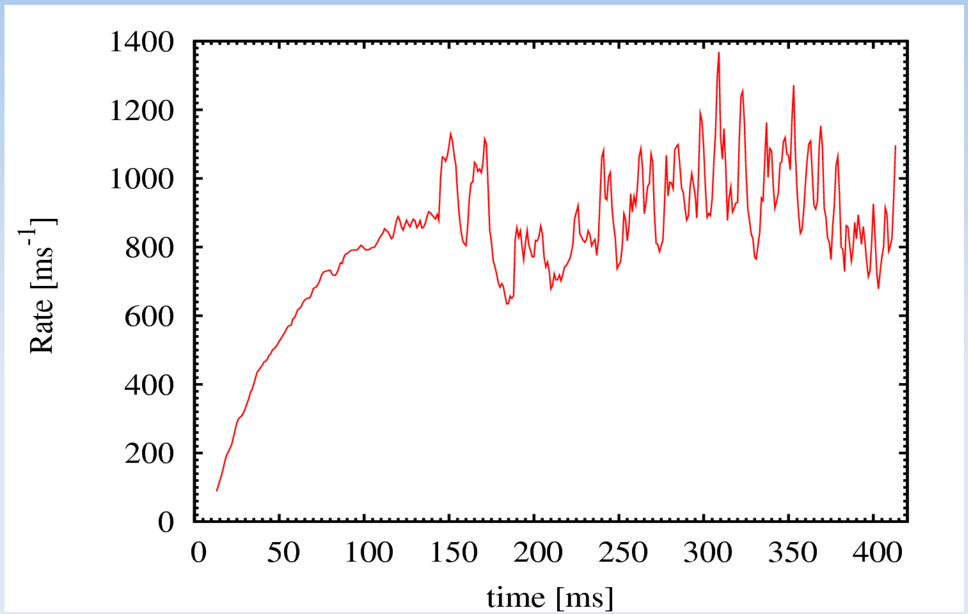
2D:

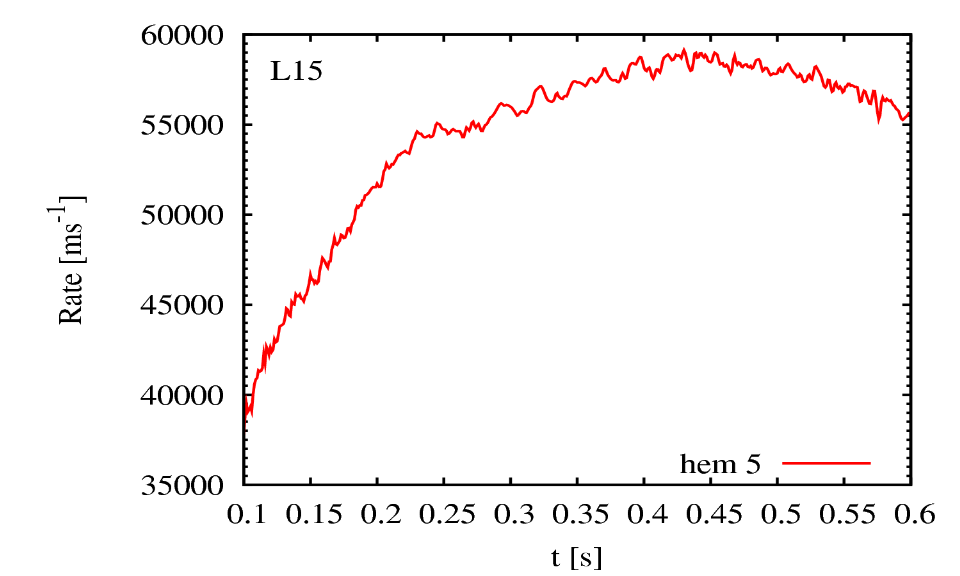
- Progenitor star; 15 $M_\odot$, non-rotating, soft and stiff EoS.
- Progenitor star; 11.2 $M_\odot$, non-rotating, 3 EoS.

3D:

- Progenitor star: non-rotating, 2 models with 15 $M_\odot$, and 1 model with 20 $M_\odot$.

IceCube event rates





[Lund et al., 2010.]

[Lund et al., 2012, *in preparation*.]

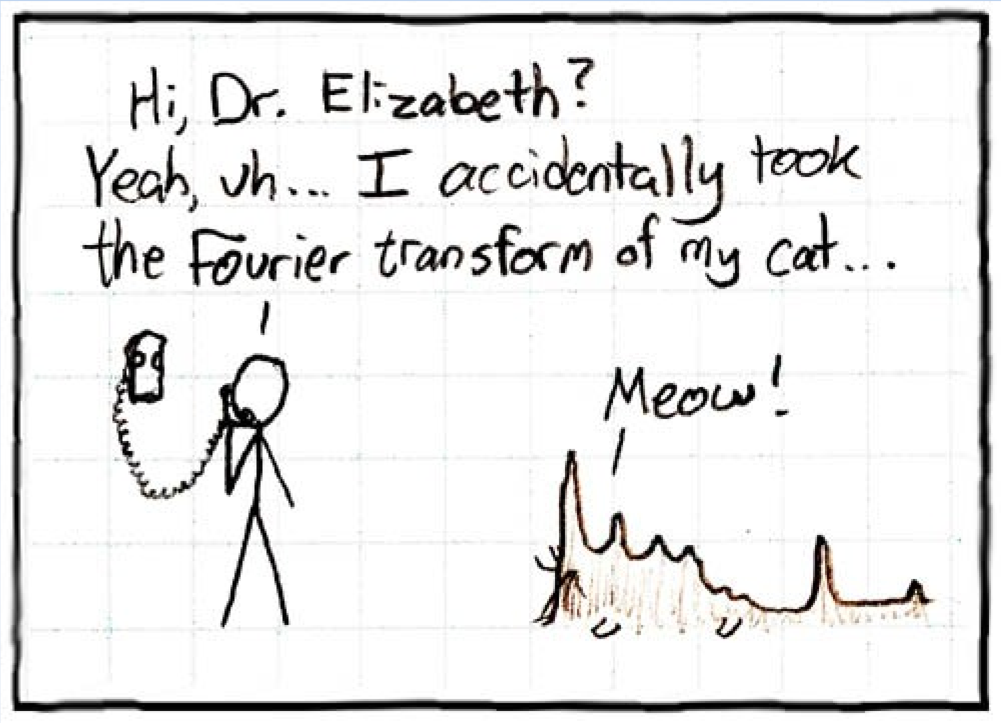
- Instantaneous rate for 2D at 10 kpc:

$$\Gamma_{\mathrm{SN,\,2D}} \sim 900\ \mathrm{ms}^{-1}$$

- Instantaneous rate for 3D at 1 kpc:

$$\Gamma_{\mathrm{SN,\,3D}} \sim 55000\ \mathrm{ms}^{-1}$$

Power spectrum



[xkcd.com]

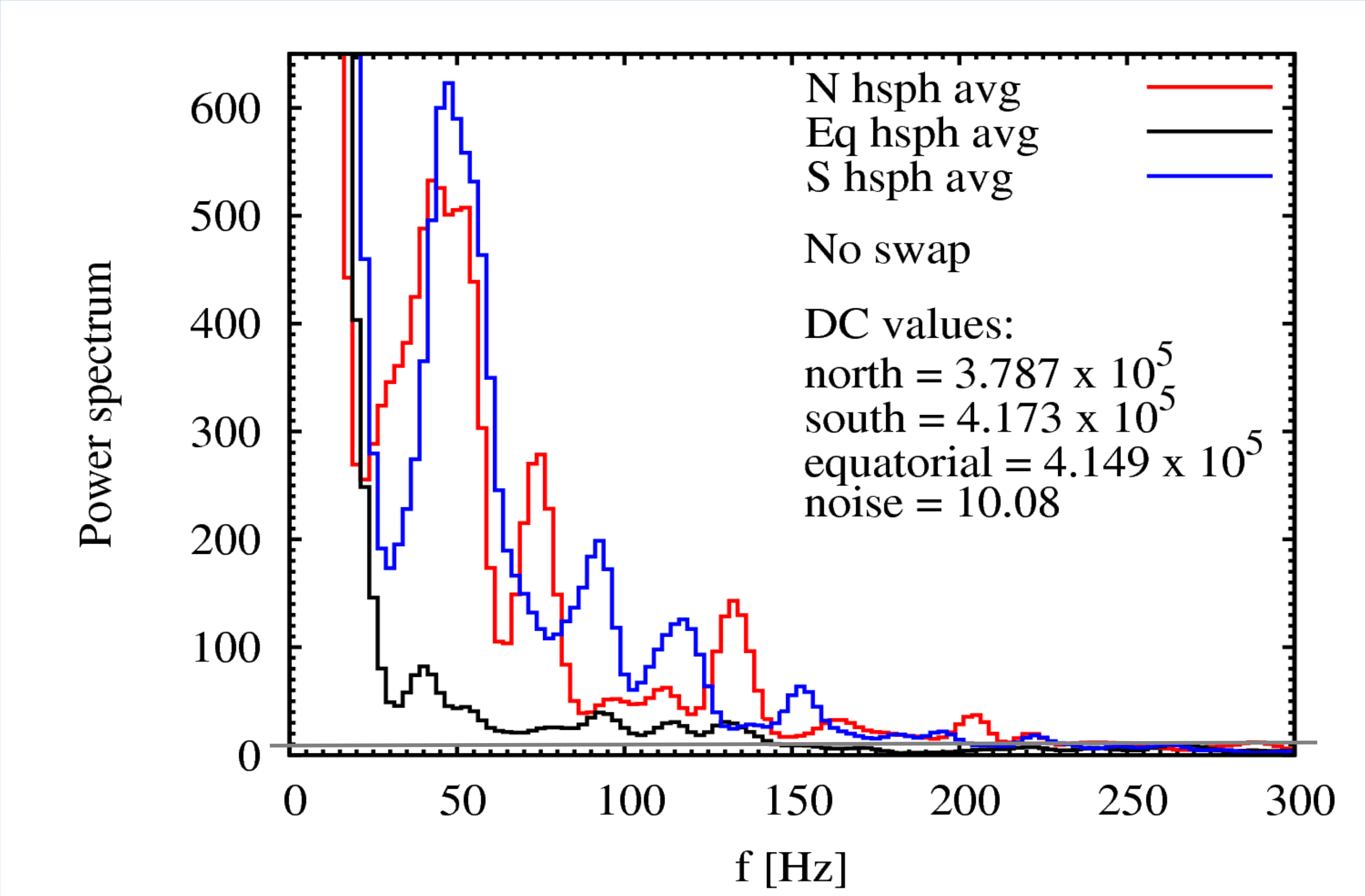
- Fourier transform to investigate features in the time signal.
- Nyquist frequency is 300 Hz due to IceCube binning.
- Used Hann window to avoid edge effects.

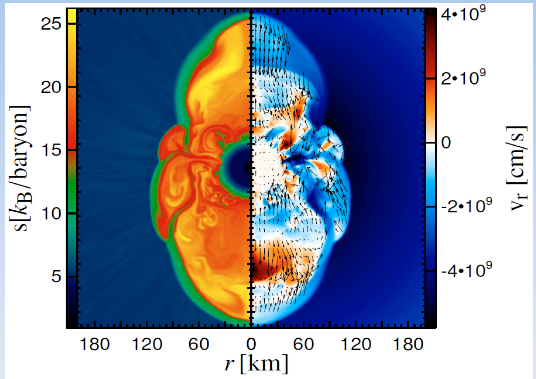
Restating our question before we answer it:

Are SASI imprints observable in IceCube?

Results - 2D

Non-rotating 15 M_{sun}



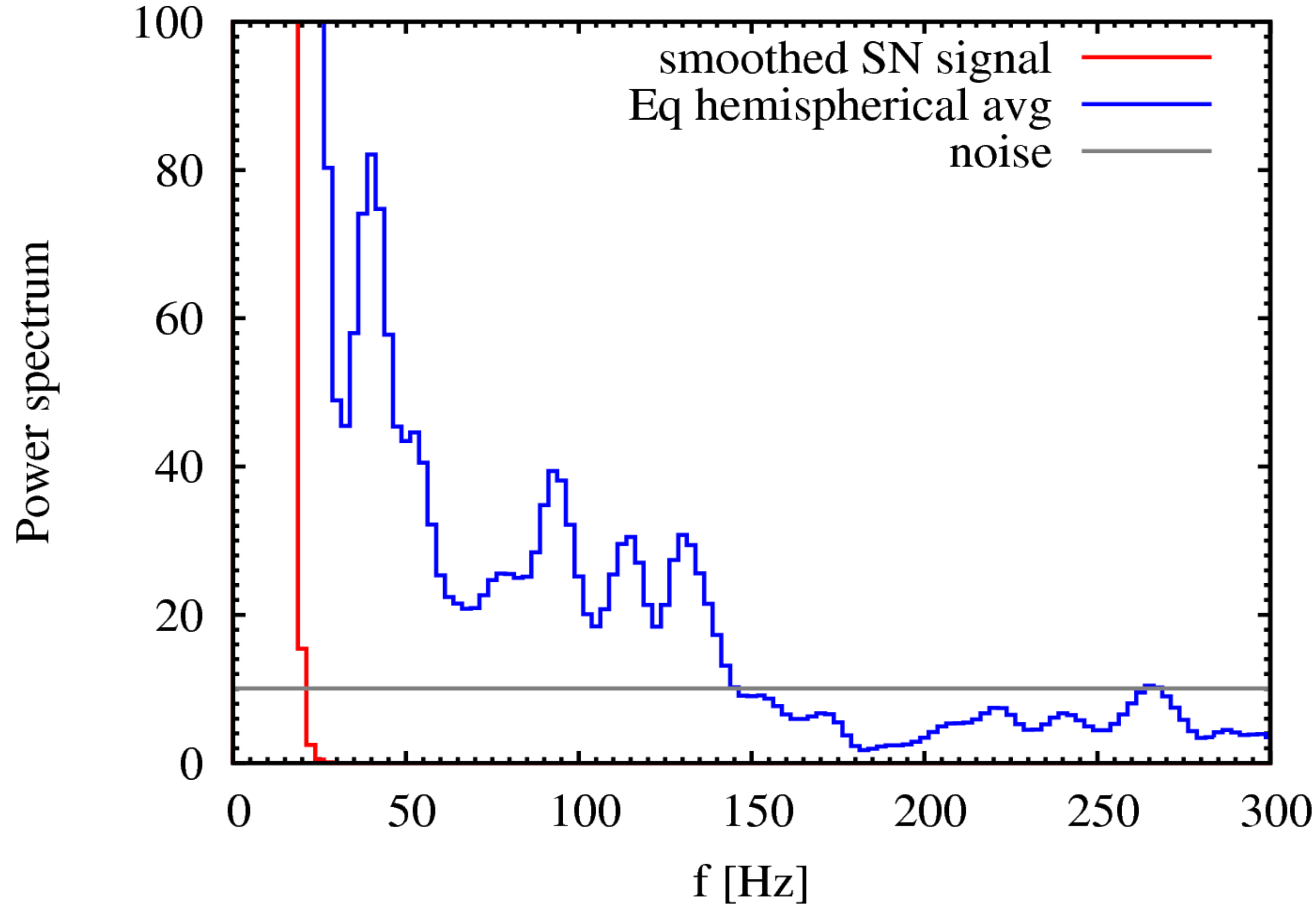


- Hemispherical differences.
- SASI modes:

  50 Hz is l = 1

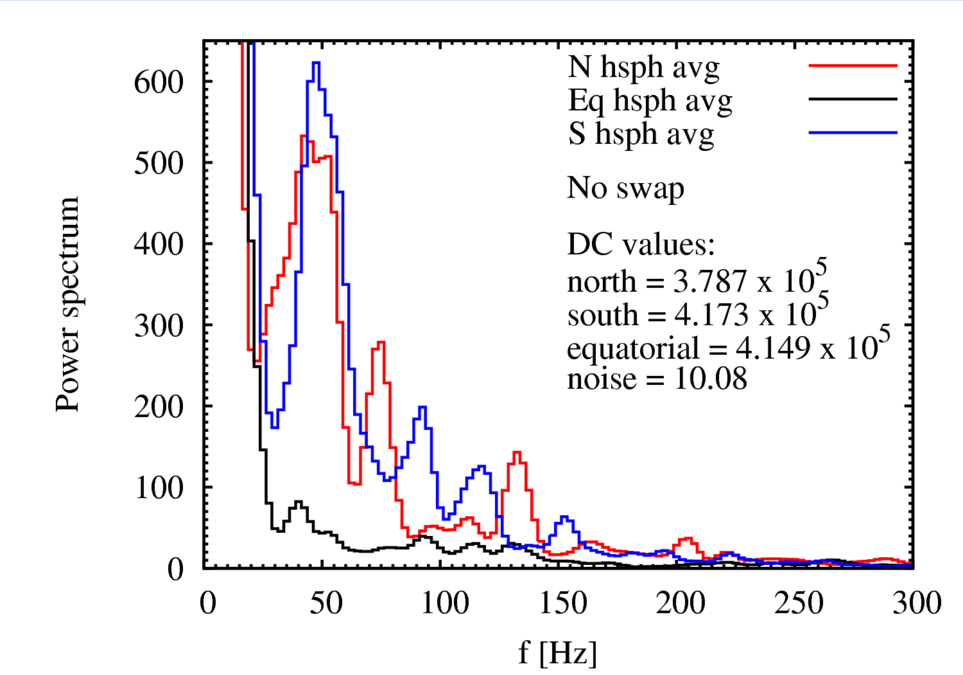
  70 Hz is l = 2

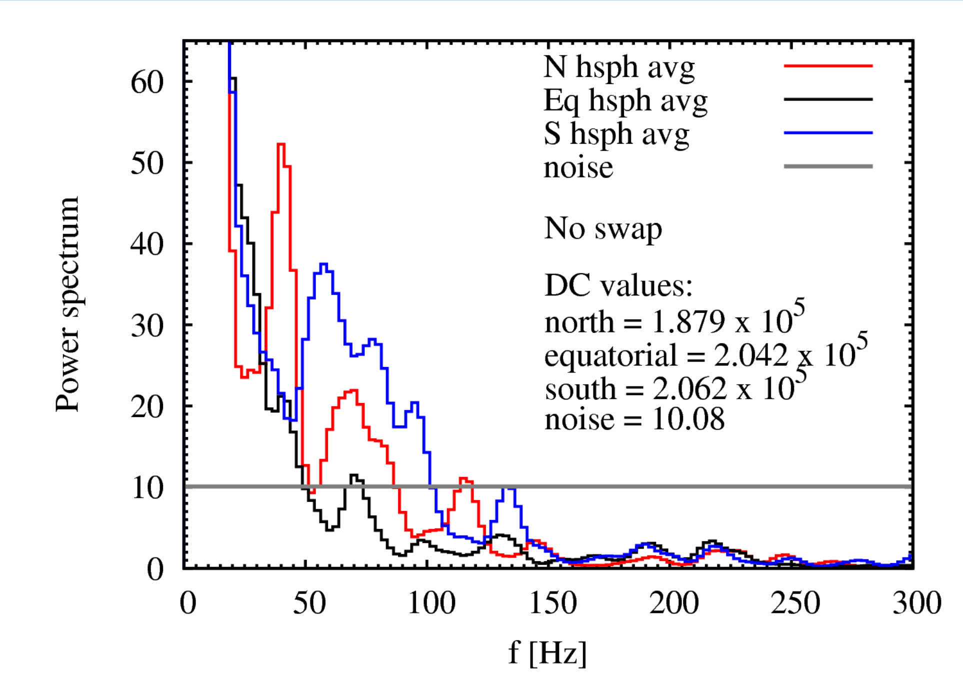
Results – 2D



smoothed SN signal
Eq hemispherical avg
noise
Power spectrum
f [Hz]
0
20
40
60
80
100
0
50
100
150
200
250
300

Equation of State dependence





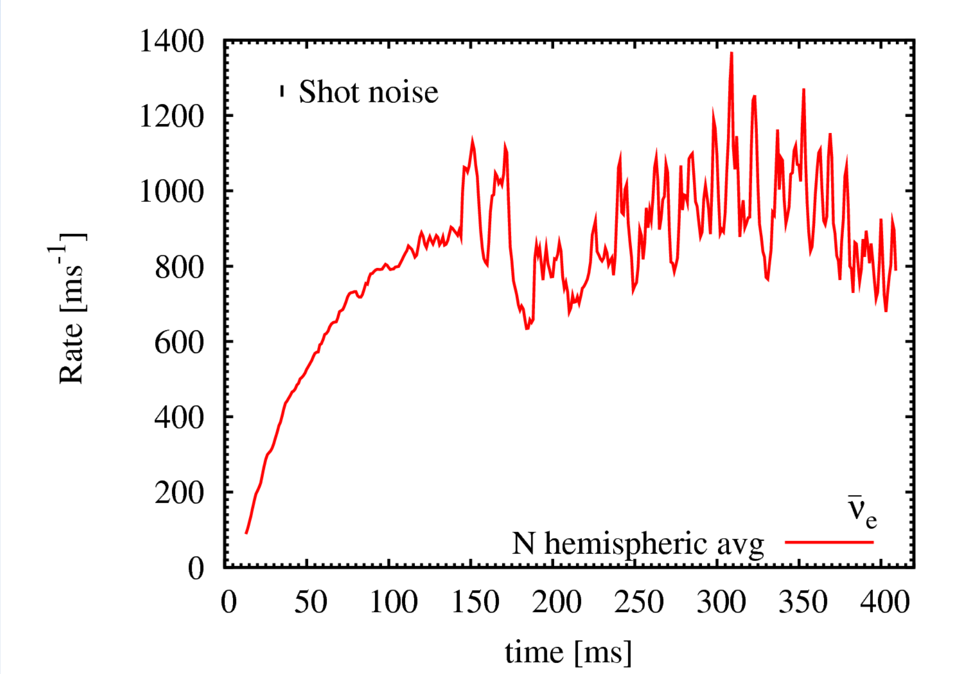
Lattimer & Swesty EoS:

- More compact NS: R = 12 km
- Larger envelope

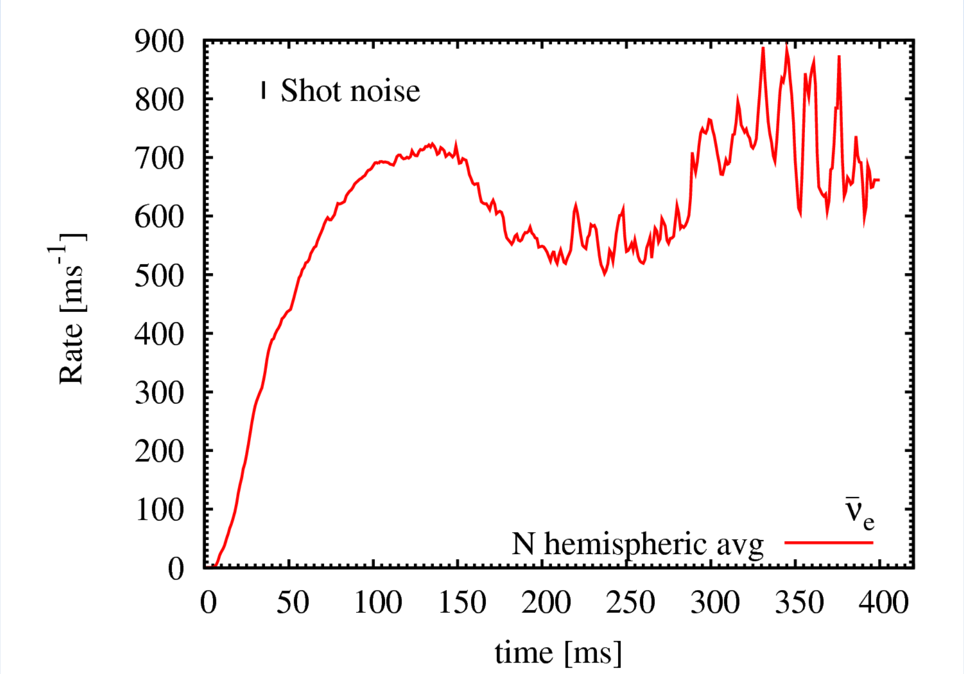
Hillebrandt & Wolff EoS:

- Less compact NS: R = 14 km
- Smaller envelope

EoS dependence II



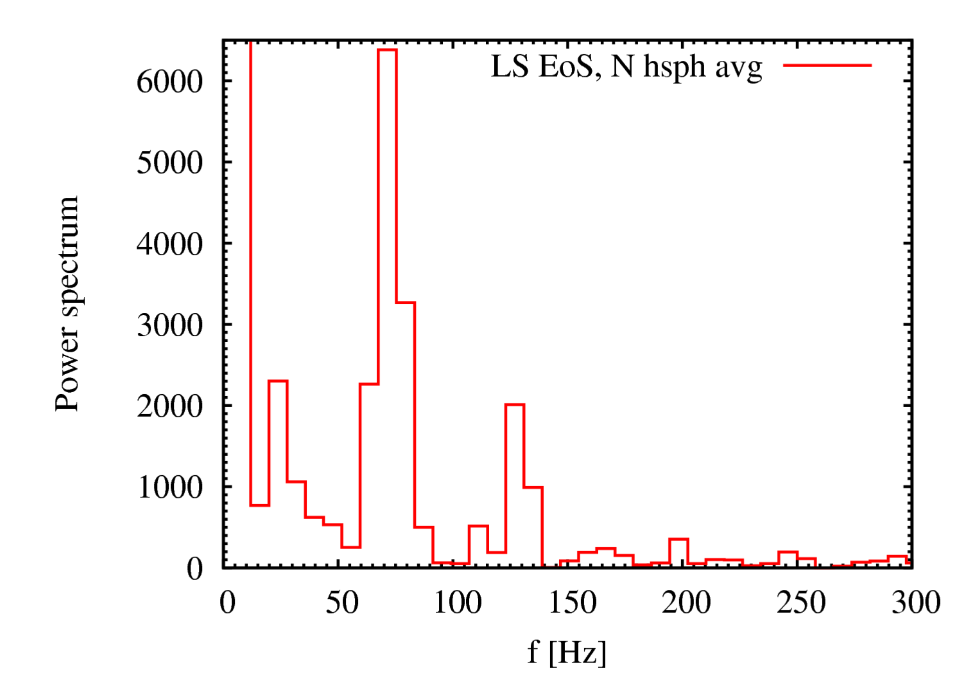
Lattimer & Swesty EoS



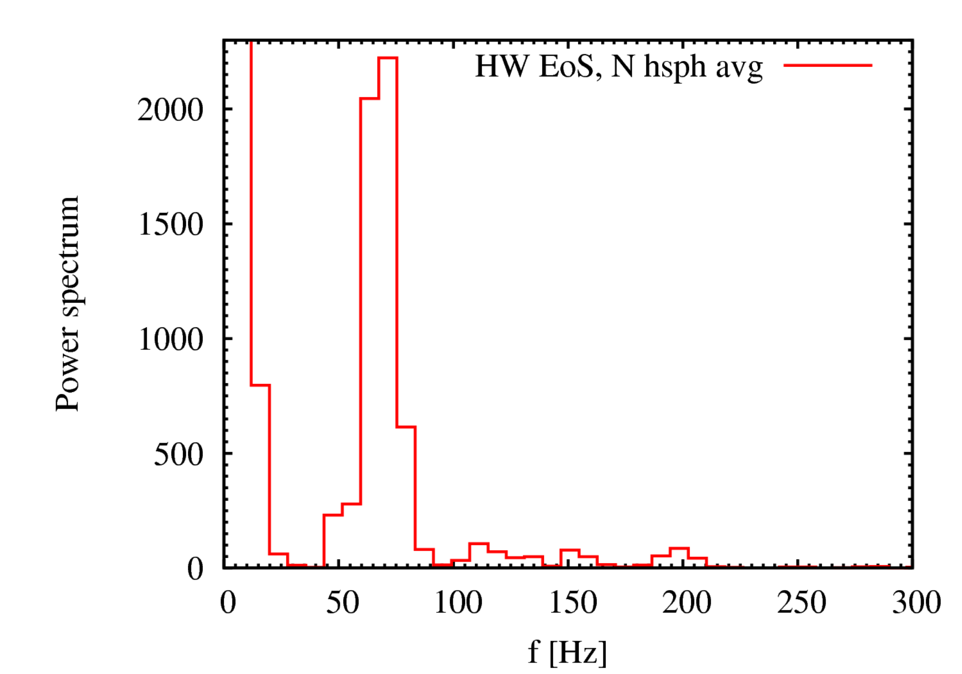
Hillebrandt & Wolff EoS

EoS dependence III

- Windows of 126 ms length.



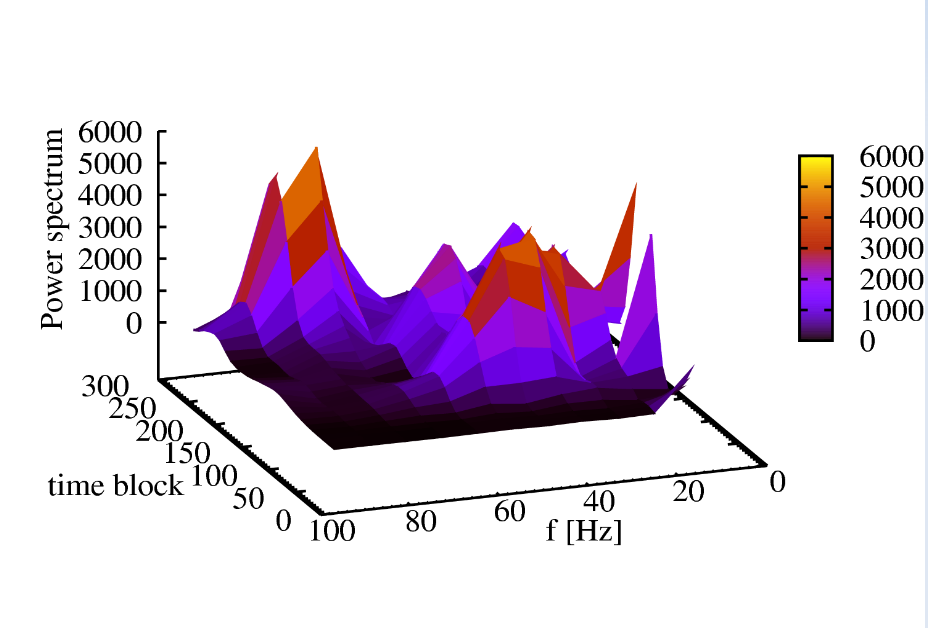
Lattimer & Swesty EoS



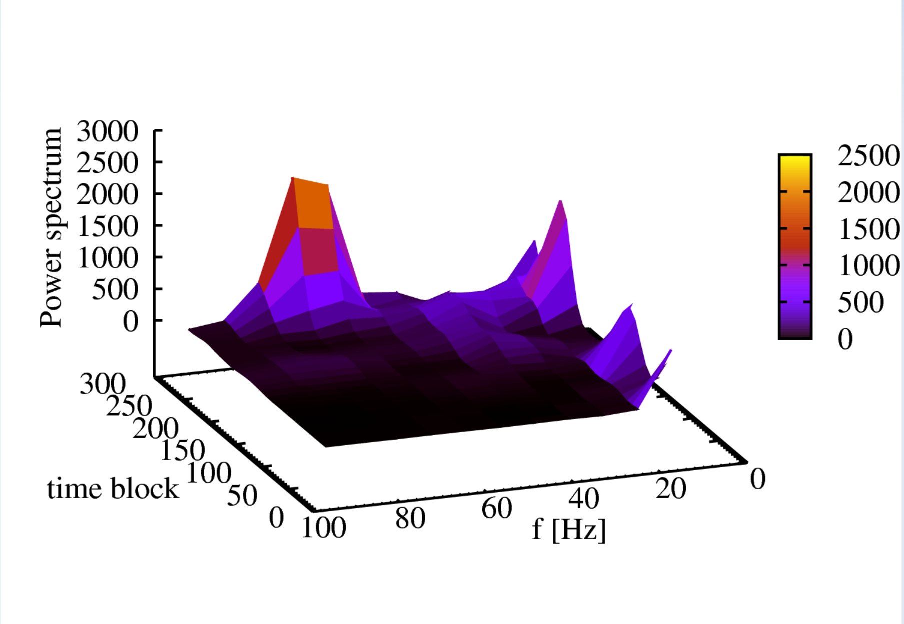
Hillebrandt & Wolff EoS

Time evolution of frequencies

Non-rotating 15 M_{sun}

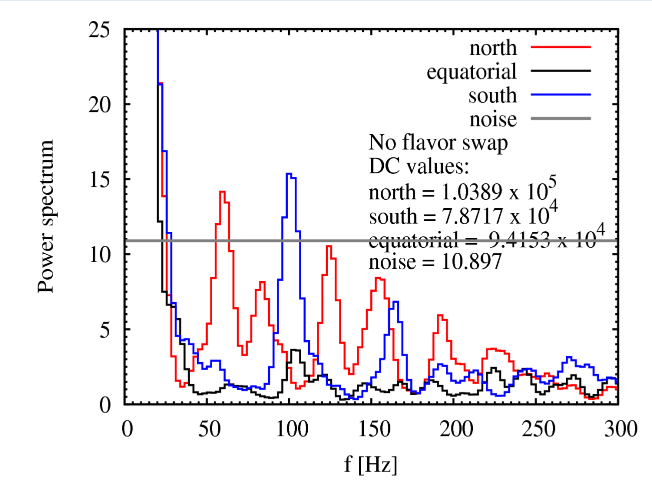


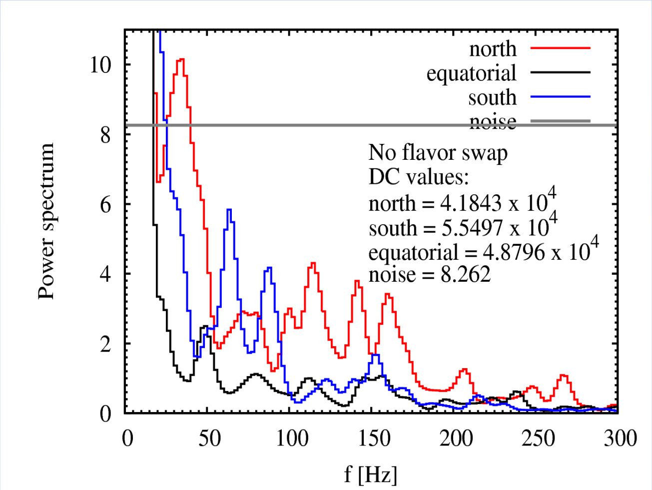
LS EoS

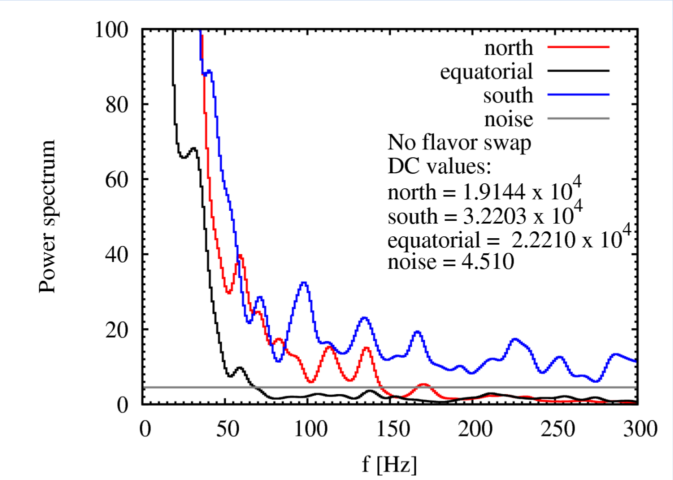


HW EoS

11.2 M_{sun} model







LS EoS, 10 kpc

explodes quickly

weak SASI

HW EoS, 10 kpc

non - exploding

Shen EoS, 5 kpc

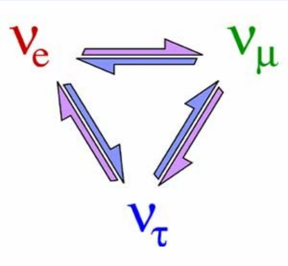
explodes quickly

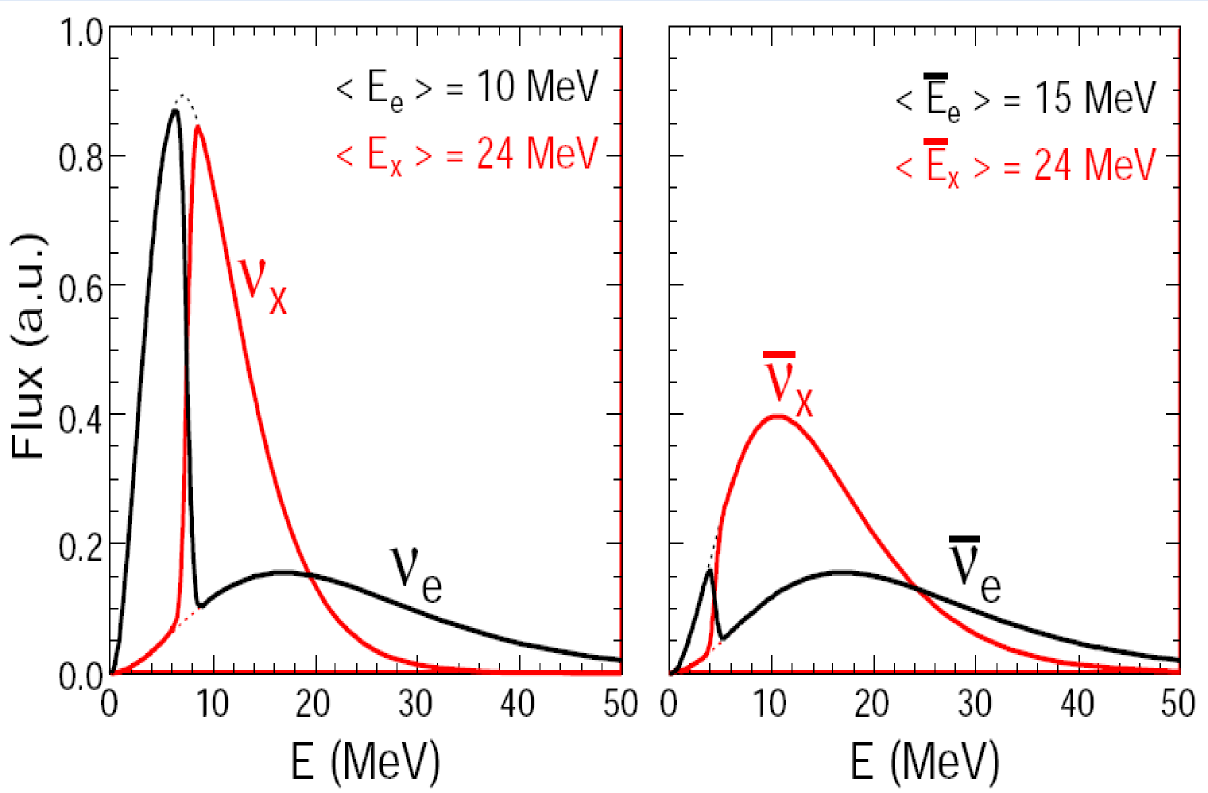
weak SASI

long time run

Caveat

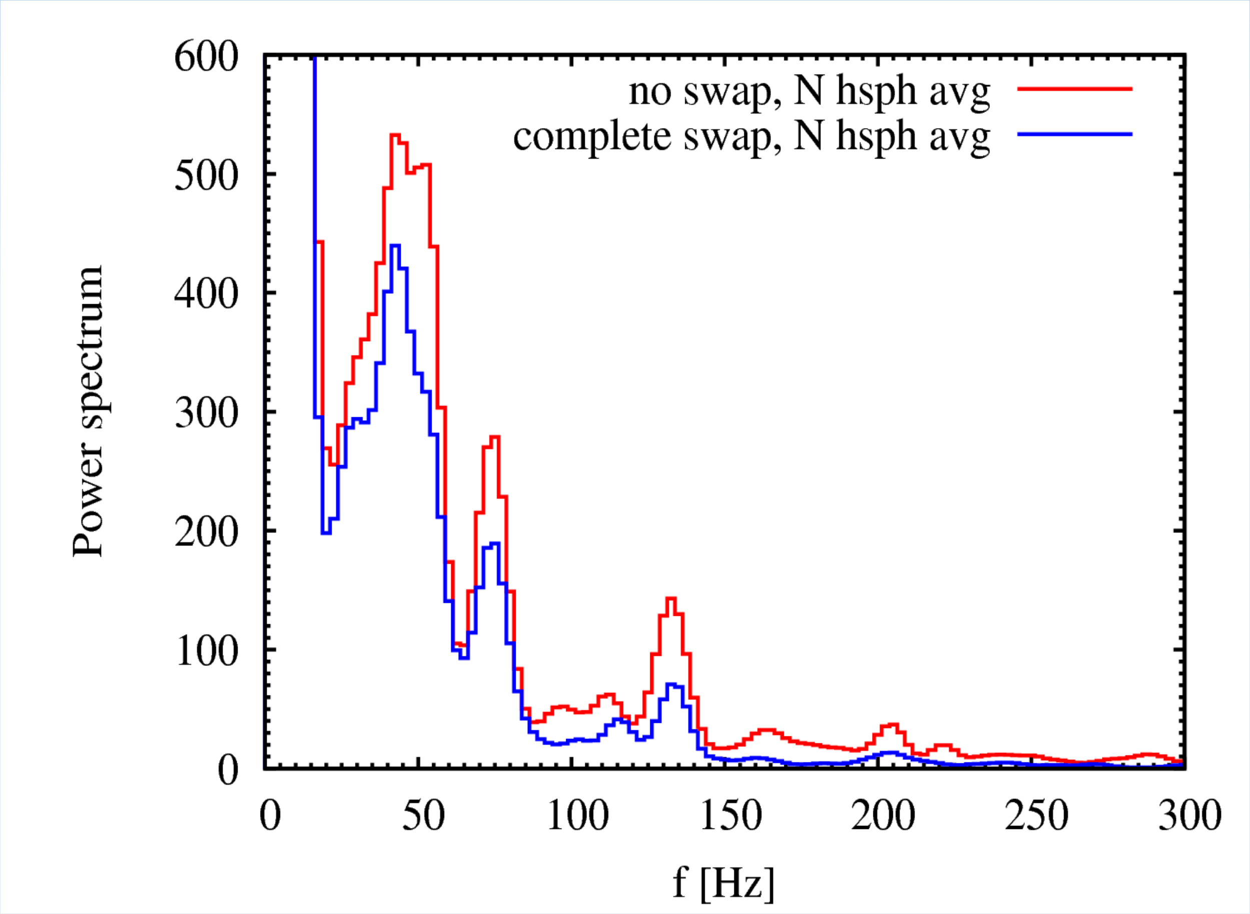
- Collective flavor oscillations not included.
- May swap the energy spectra of $\bar{\nu}_e$ and $\bar{\nu}_x$ flavors.





[Fogli et al., 2006]

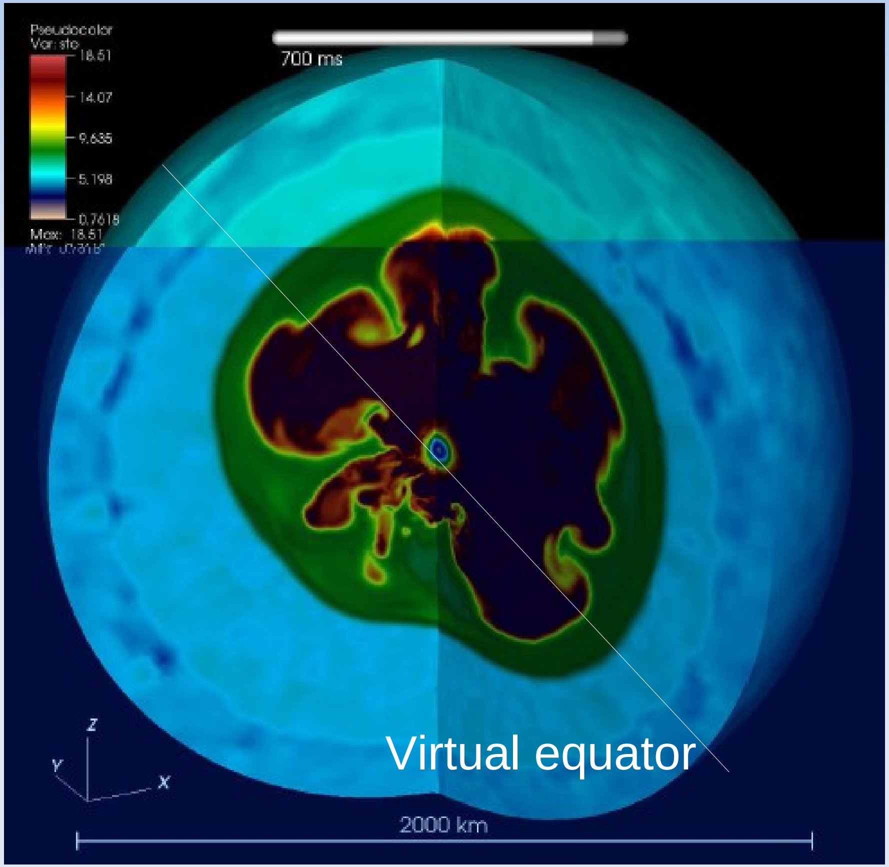
Flavor comparison



Summary of 2D

- SASI imprints on neutrino signal observable in IceCube.
- Beneficial to investigate both long and short time segments.
- Power spectrum features depend on EoS, rotation, mass and viewing direction.

SASI - 3D



11.2 M_{sun}, illustrational pupose only.

[Hanke et al, 2011]

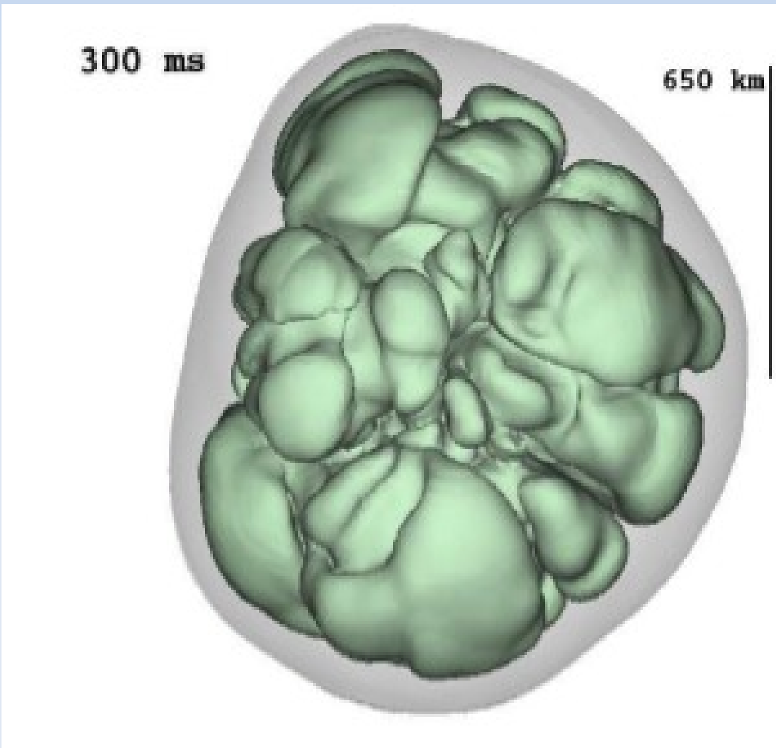
- SASI not as strong.

Our models:

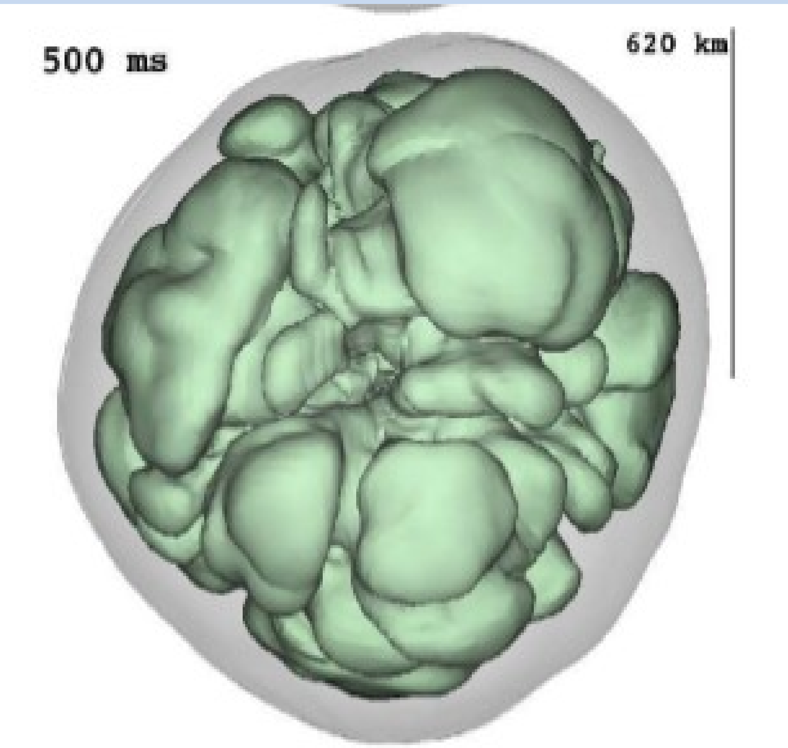
- Yin-Yang grid.
- PNS excised.
- 15 M_{sun}, Woosley & Weaver.
- 15 M_{sun}, Limongi et al.
- 20 M_{sun}, Nomoto et al.

SASI – 3D

W15-4

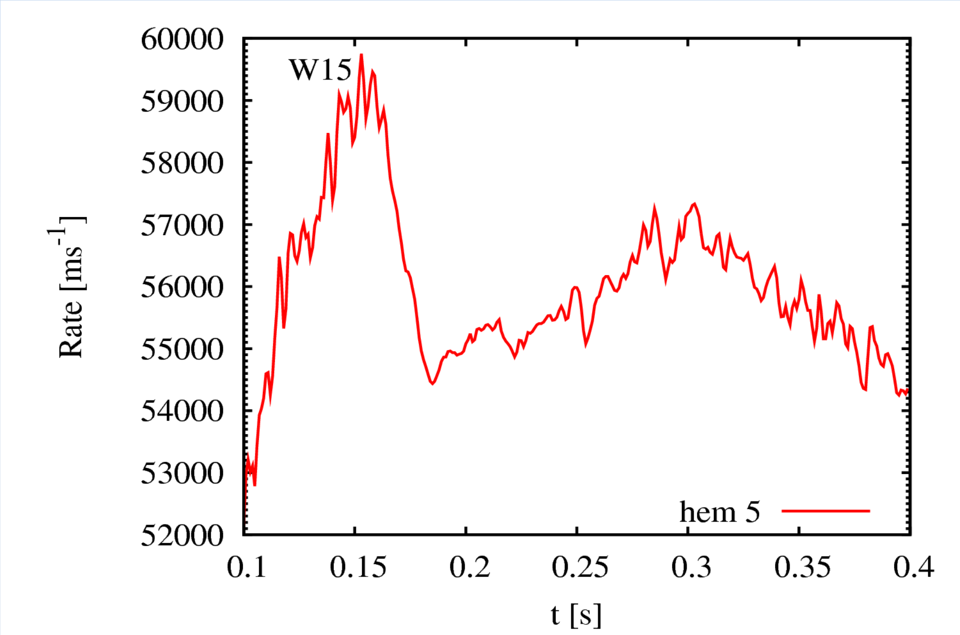


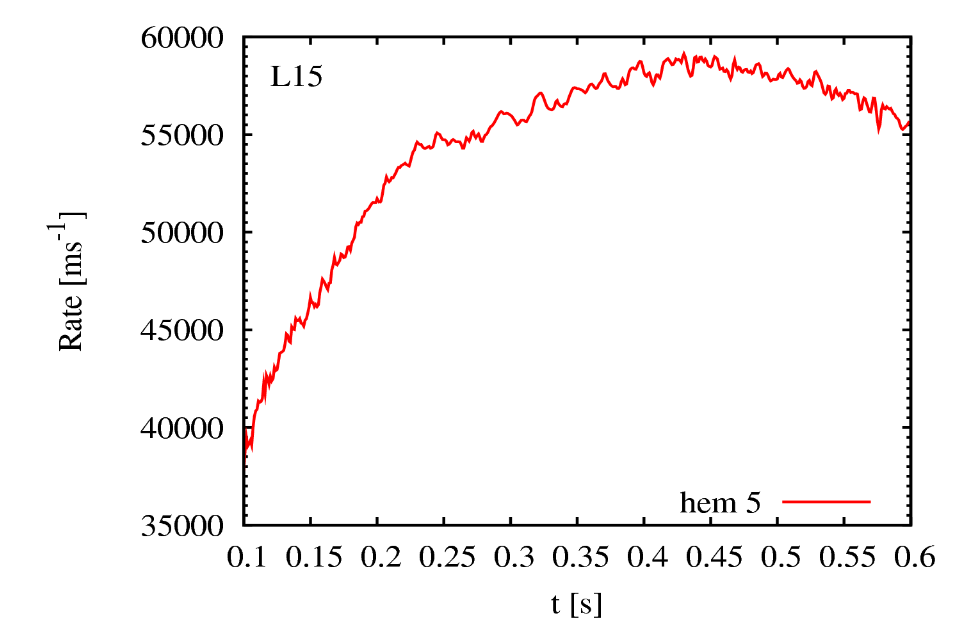
L15-3



[E. Müller, H.-Th. Janka & A. Wongwathanarat, 2011]

Rates in 3D

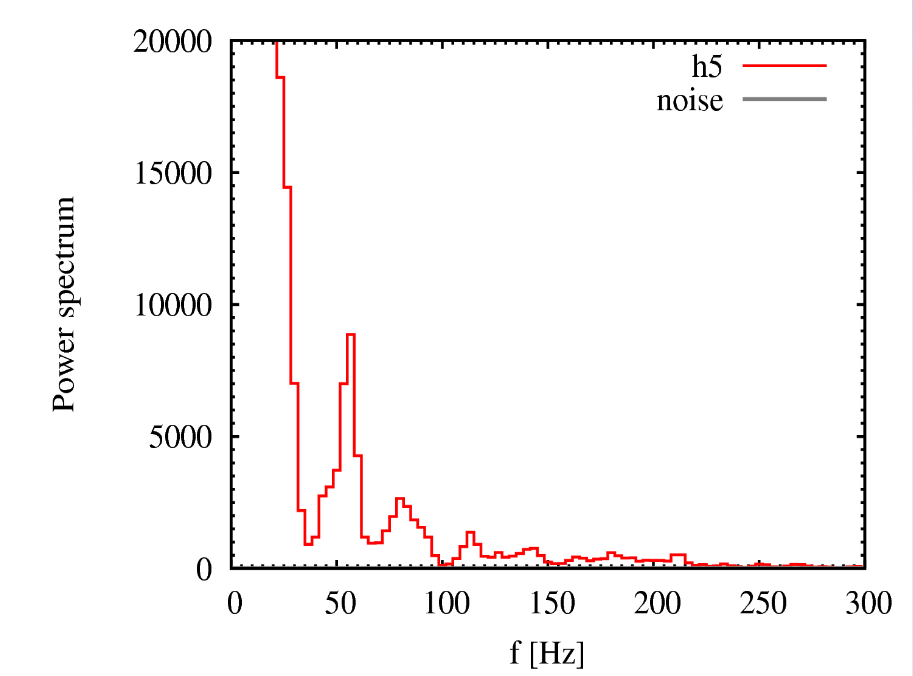




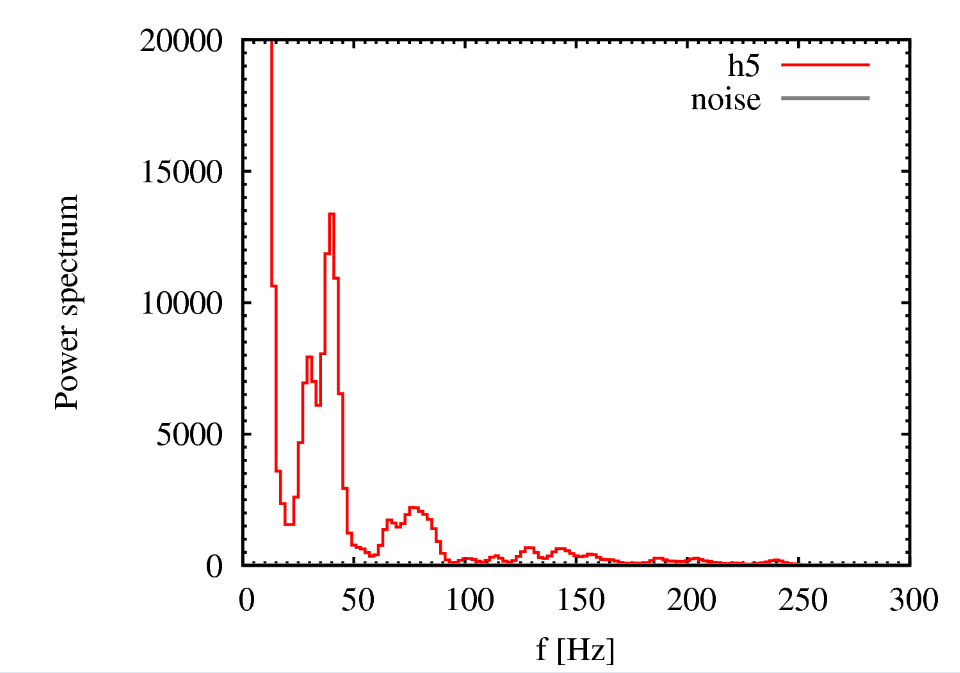
At 1 kpc

Results - 3D

W15-4



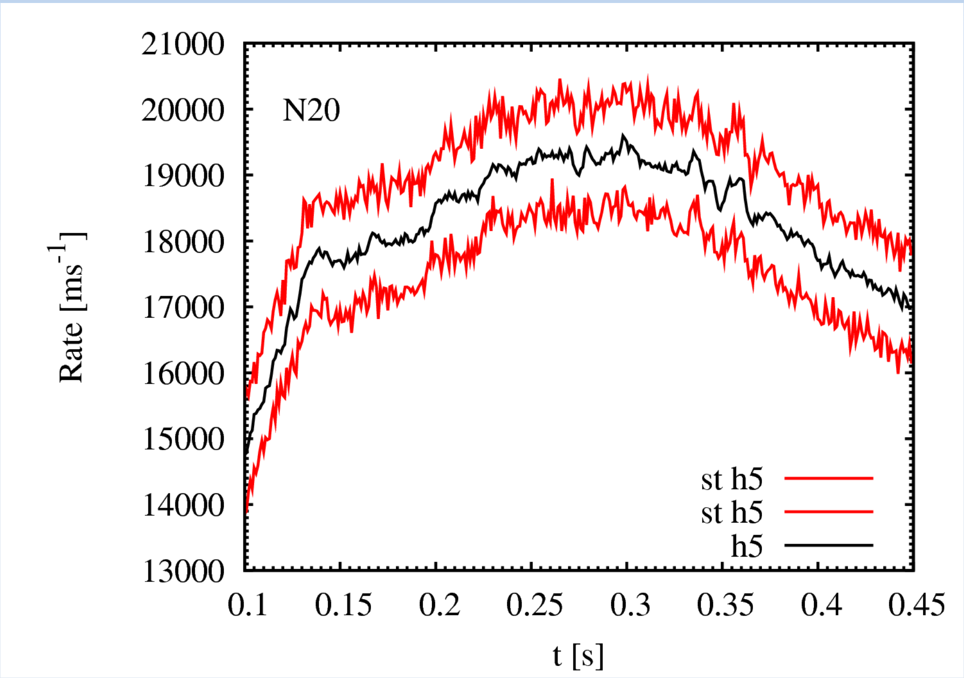
L15-3



At 1 kpc

[Lund et al, 2012, *in preparation*.]

Stastistical effects



N20 at 2 kpc

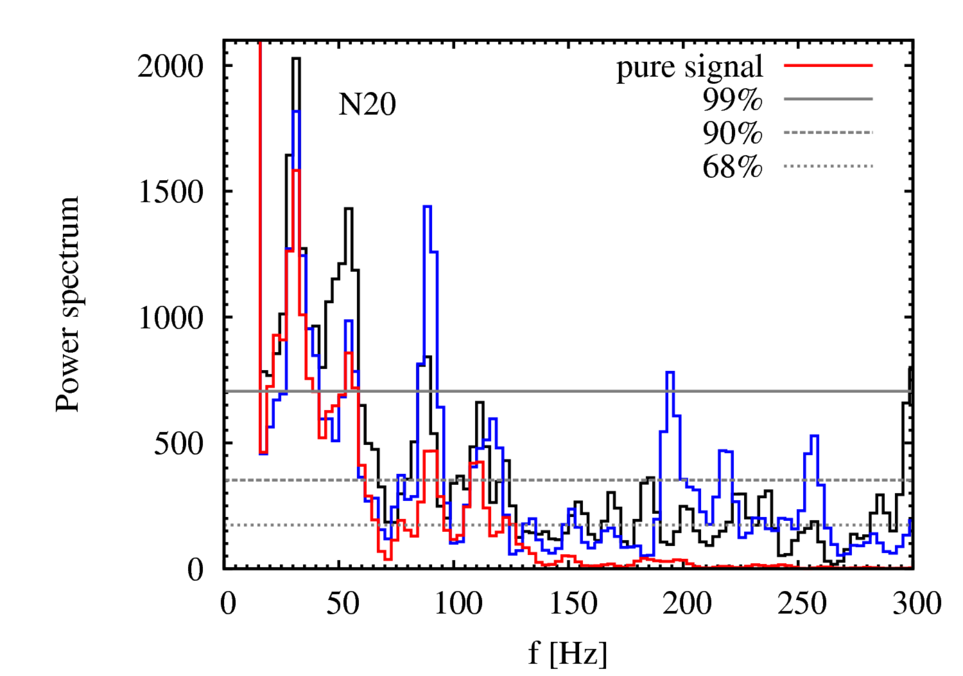
- Statistical fluctuations of the observed signal:

  $N = \sqrt{R}$

- Was ~ 3 % in 2D, compared to 18 % for SASI induced.
- At 10 kpc for 3D would have been ~ 4 %, compared to 1-2% for SASI induced.
- Scales with 1/D, thus less than 1 % at 2 kpc.

Stastistical effects

- With given probilities a peak caused purely by statistical fluctuations will fall below gray line levels.
- Peaks reaching above cannot be caused purely by statistics.



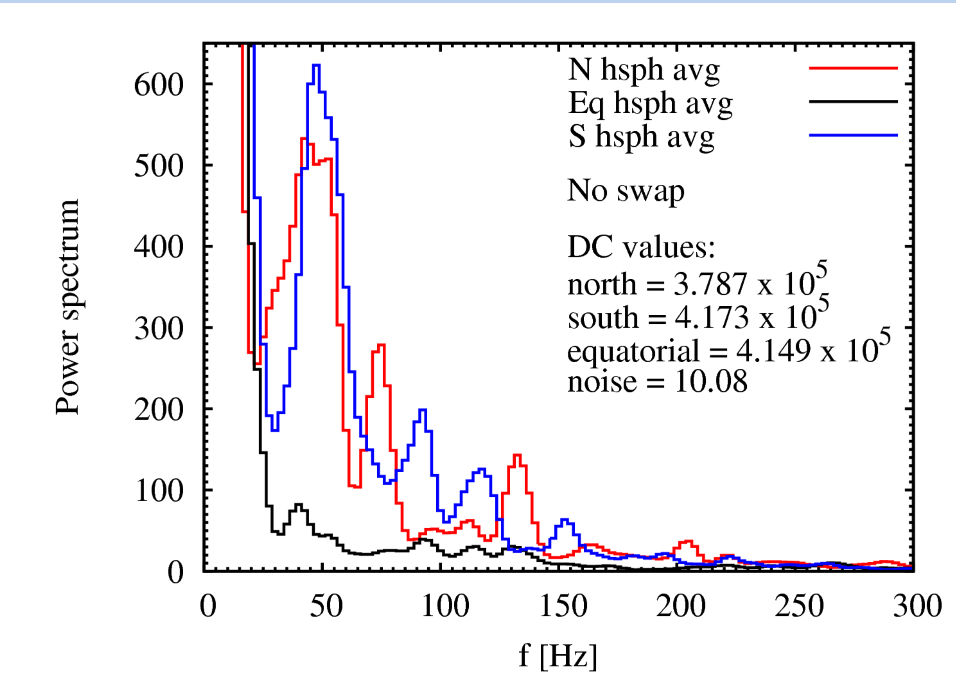
[Lund et al, 2012, *in preparation*.]

Conclusions

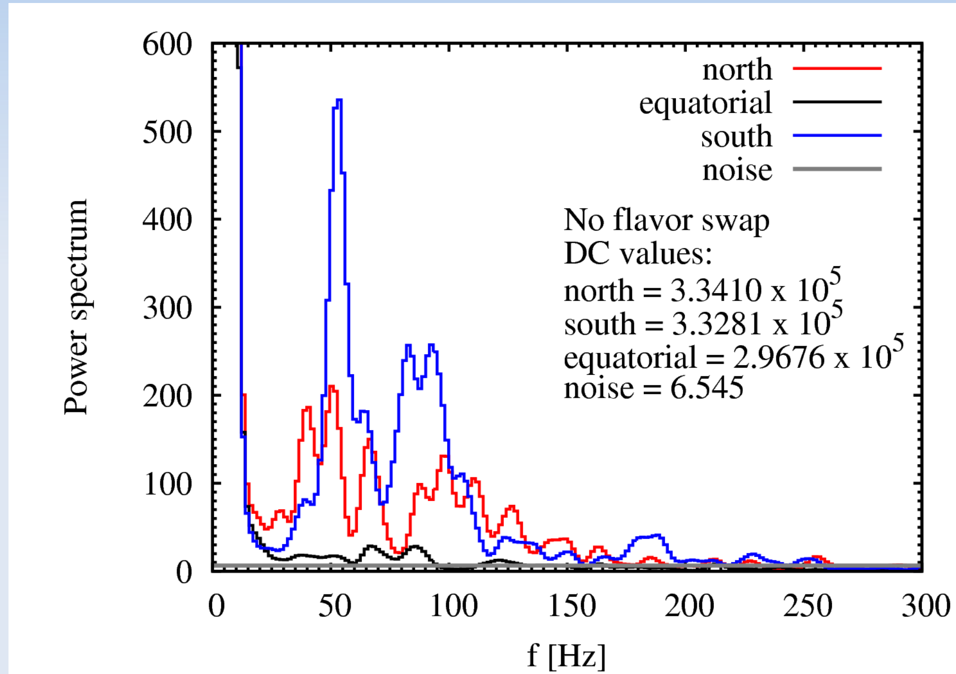
- IceCube usefull despite lacking energy information.
- SASI effects observable in IceCube → better understanding of SN.
- If observed short-lived mechanisms ruled out.
- Signal depends on mass, EoS, rotation, viewing direction and flavor.
- Weaker SASI in 3D models.

Need new Milky Way SN.

Rotating 15 M_{sun} model



non-rotating, LS EoS



rotating, LS EoS