The GW and Neutrino Signatures of Stellar Core Collapse

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Motivation

Stellar Collapse!

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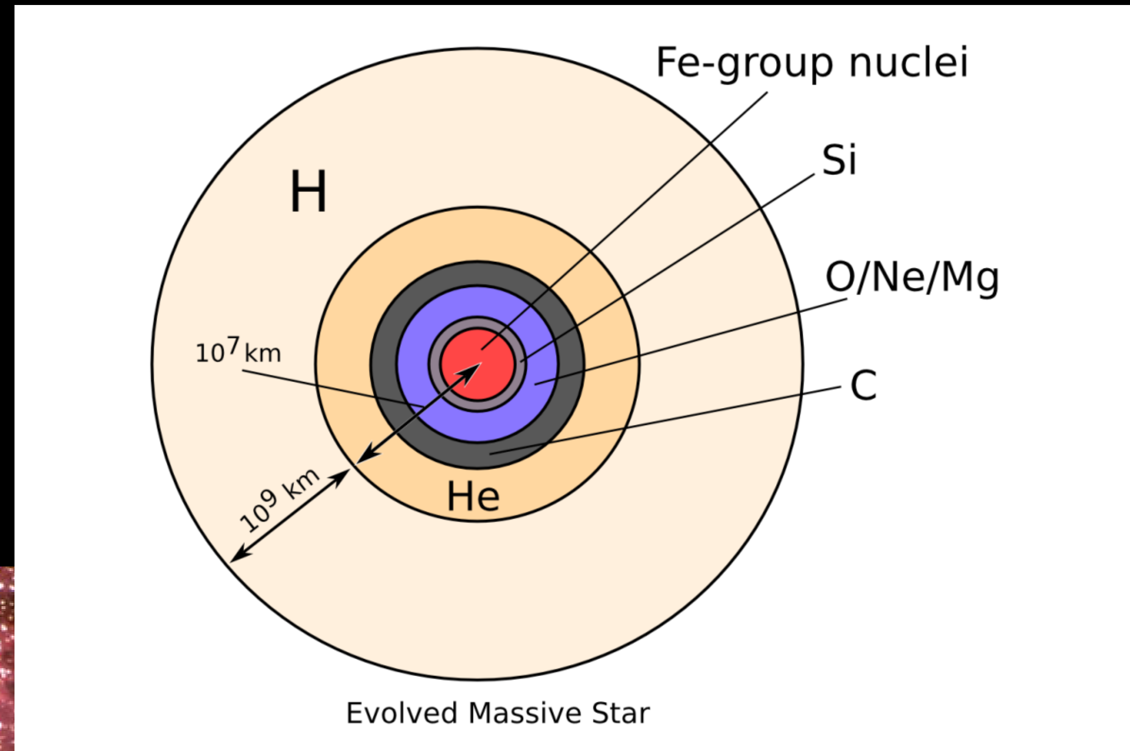
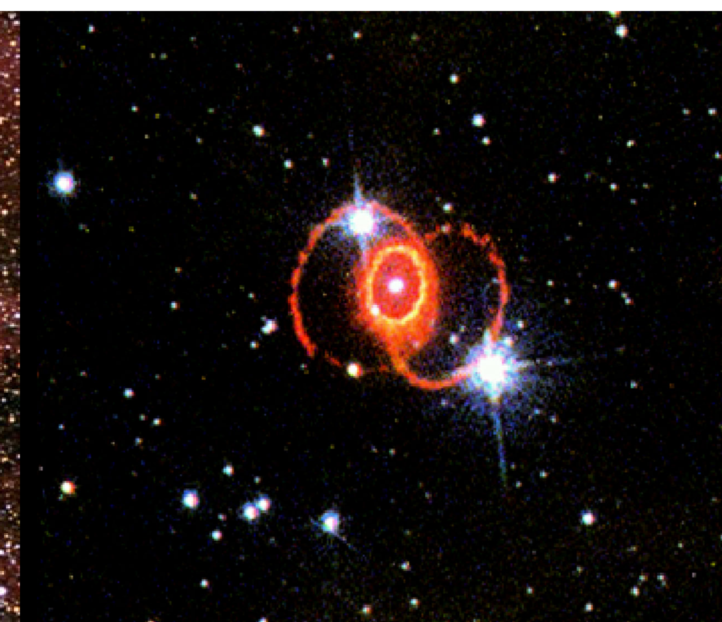
- Core-collapse supernovae (Type II, Ib/c)
- Neutron stars
- Stellar mass black holes
- Long gamma-ray bursts



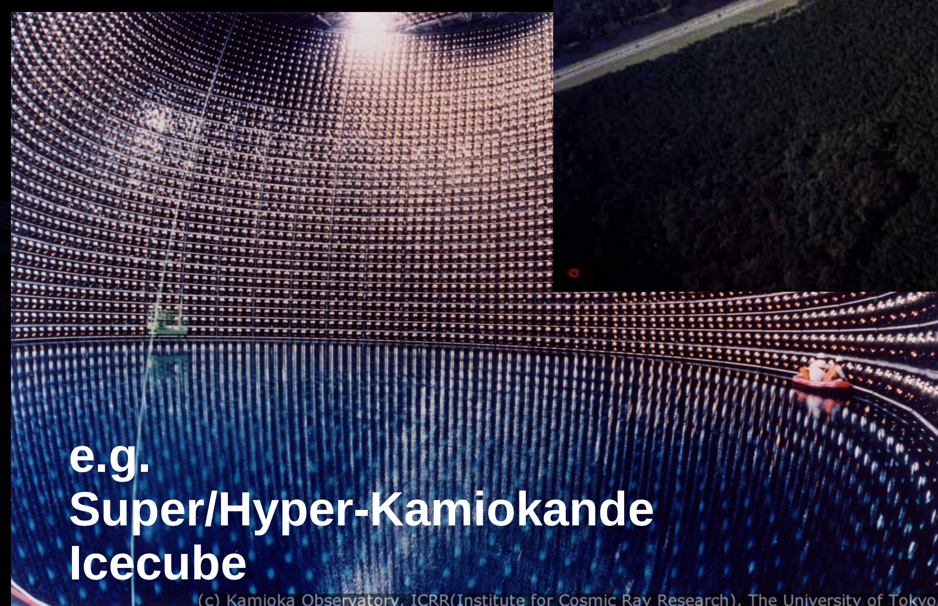


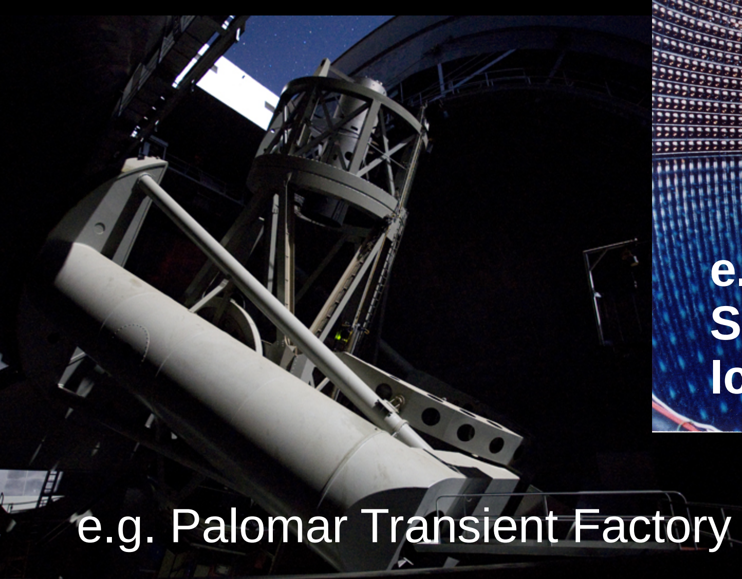
Motivation

Multimessenger Astronomy:

~100 B = 10^53 ergs liberated in

- Electromagnetic Waves (<1%)
- Neutrinos (~99%)
- Gravitational Waves (<10^-6%)





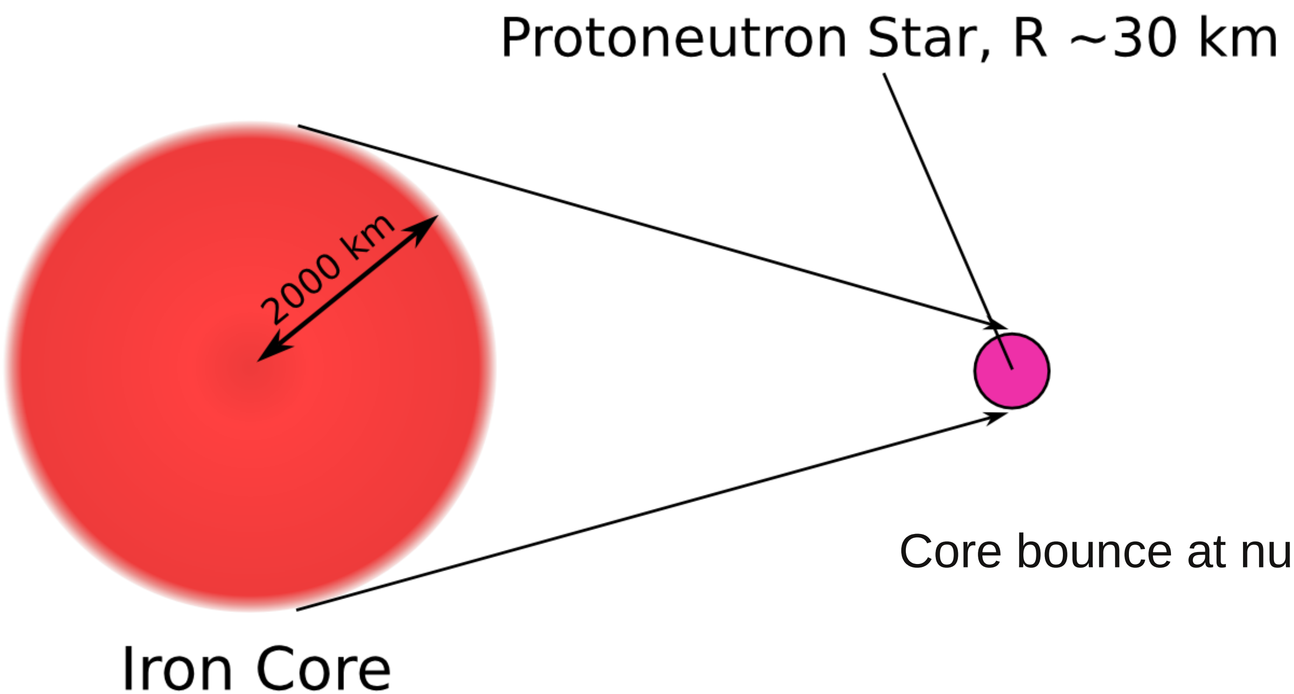
Motivation

- GWs encode dynamics of inner core
- Neutrinos encode thermodynamics / structure of inner core

- This is much more direct information than what is available from electromagnetic waves!

Stellar Collapse

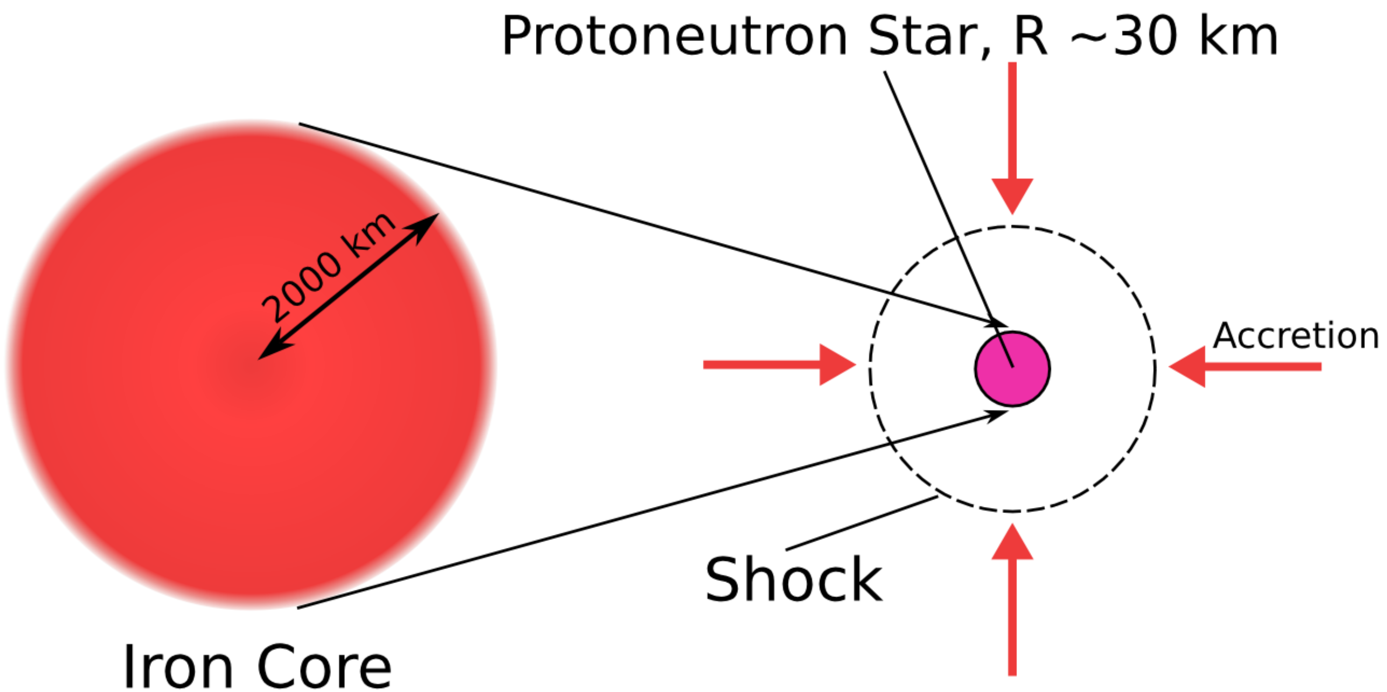
Above ~1.5 Msol, electron degeneracy pressure fails to stabilize core



Core bounce at nuclear densities

Collapse accelerated by electron capture on protons
and
dissociation of Fe group nuclei

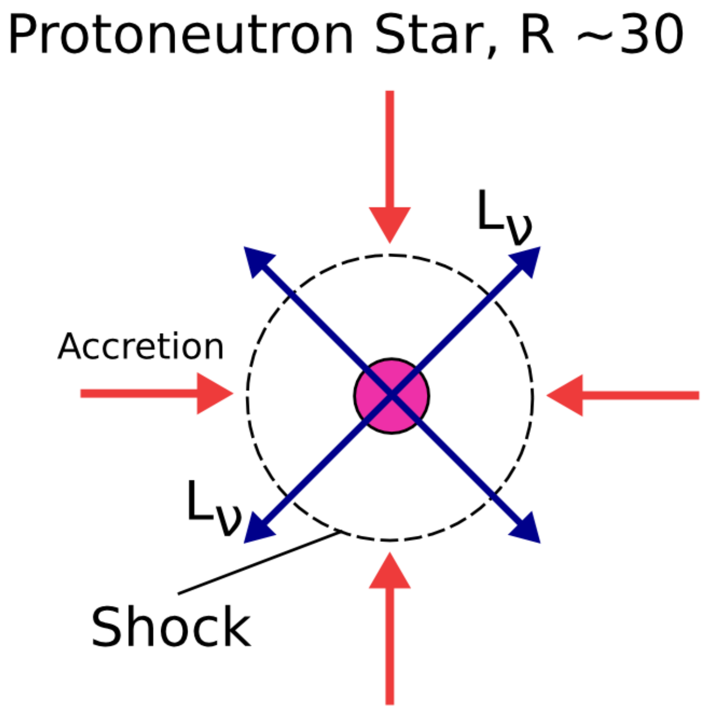
Stellar Collapse



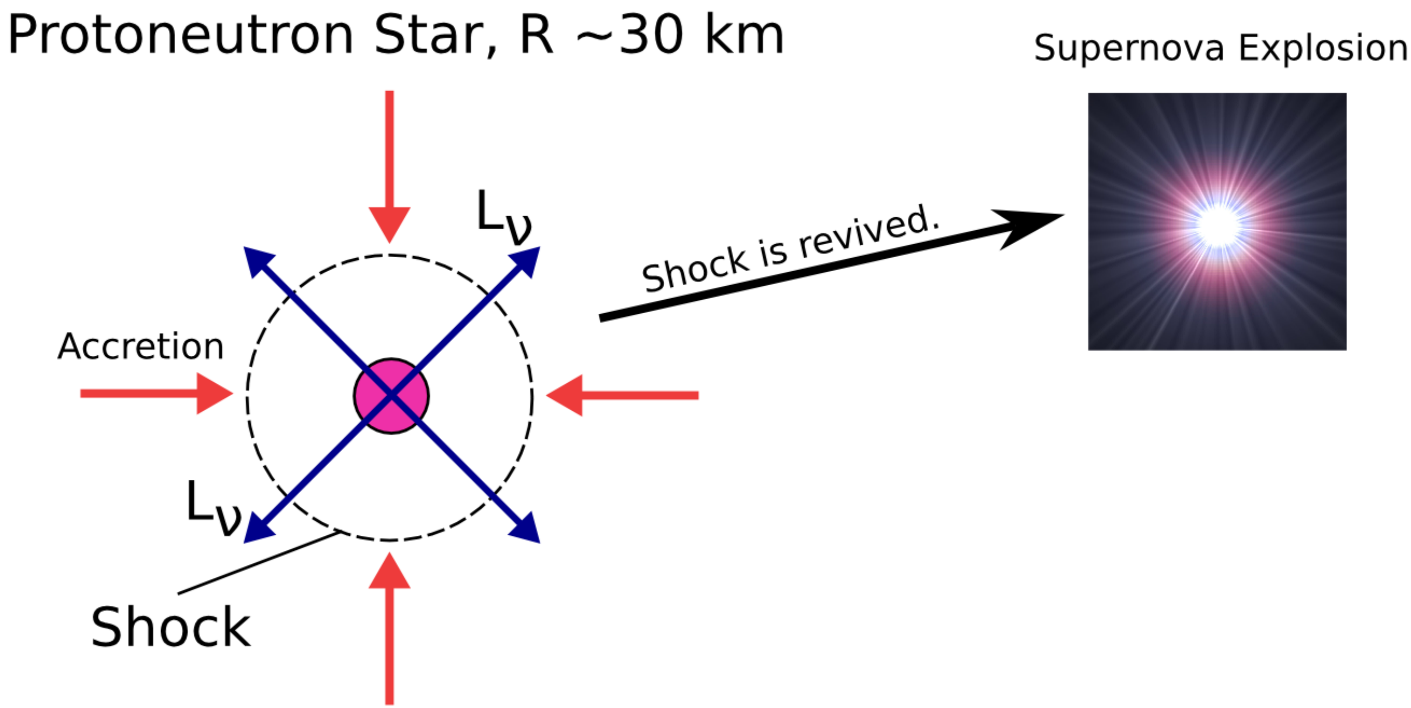
Shock loses energy by dissociating nuclei of infalling outer material into free protons and neutrons!

Problem: Shock always stalls!

Scenarios

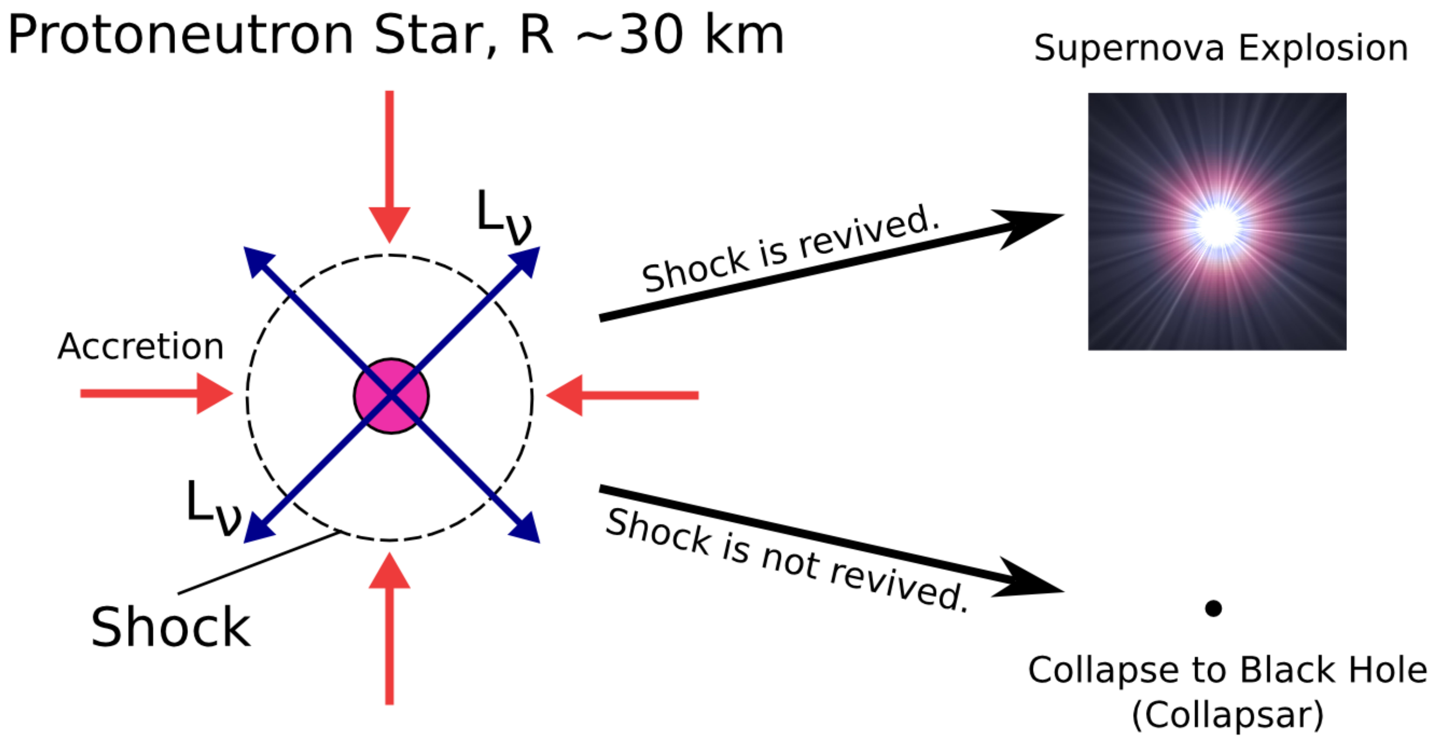


Scenarios



Possible mechanism: Neutrino heating

Scenarios

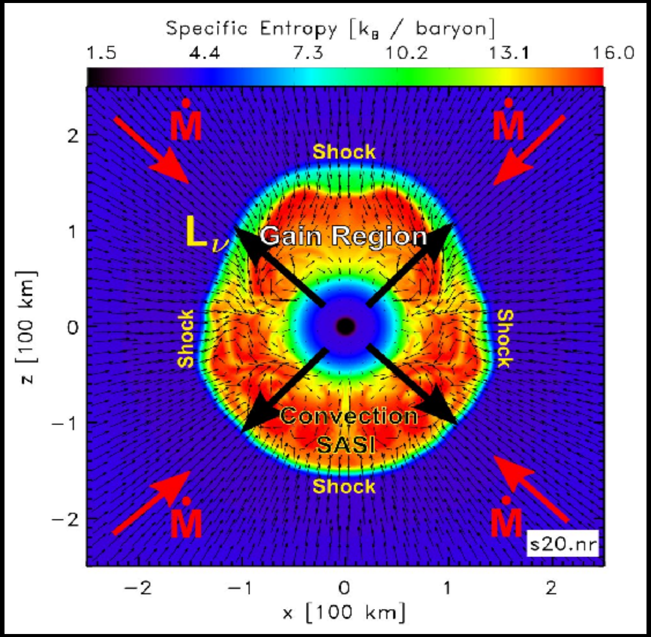


If: Sufficient mass,right angular momentum
(Then): Long gamma-ray burst

Source of GWs

- Without rotation:

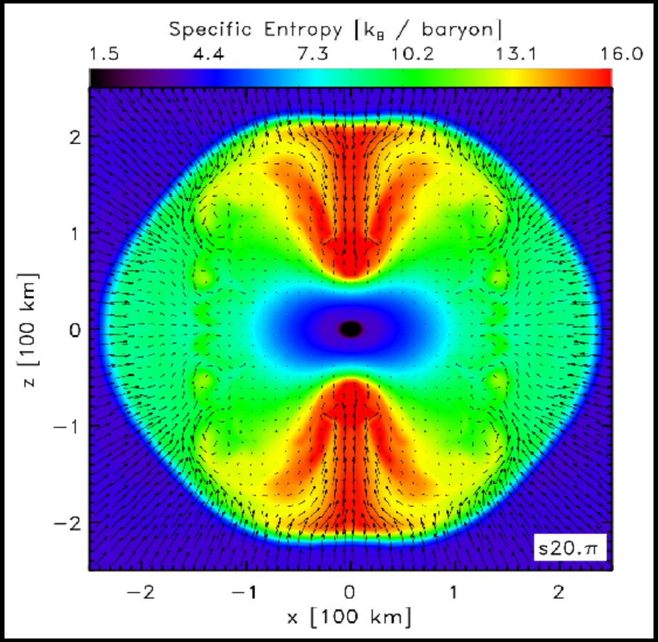
  Prompt convection, protoneutron star pulsation, SASI after core bounce



Figures: Ott '09

- With rotation:

  Rotational flattening of inner core leads to quadrupole moment during collapse and bounce

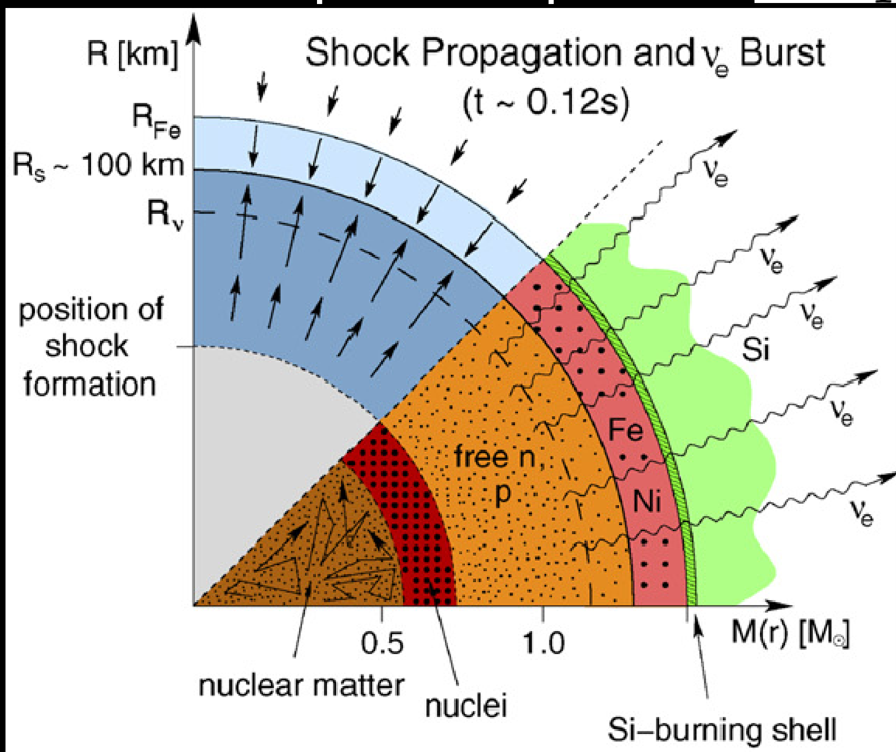


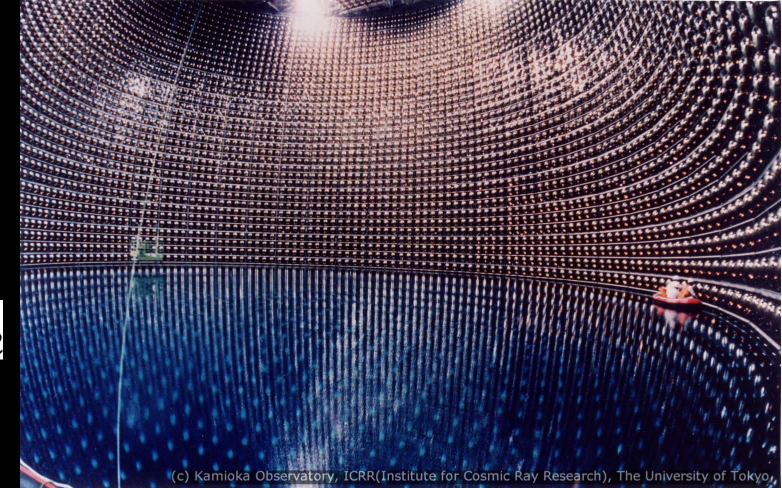
For alternative sources, see Ott '09

Source of Neutrinos

- Electron neutrinos:

  Electron capture on protons $e + p \rightarrow n + \nu_e$

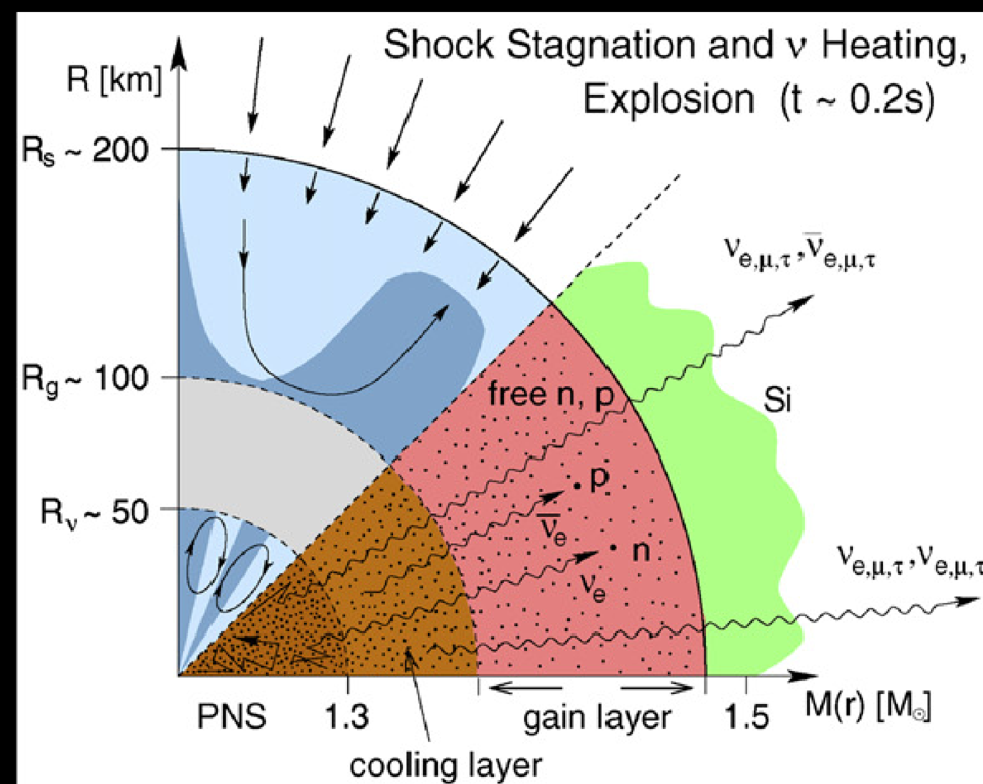




Figures: Janka '07

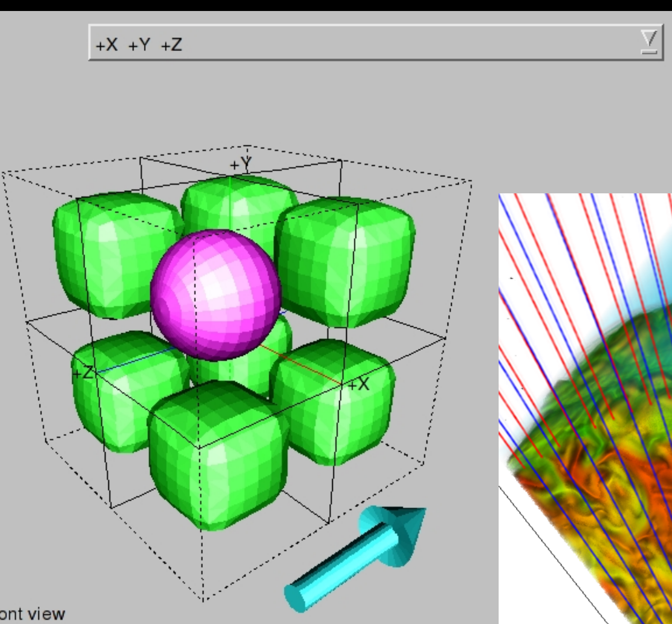
- Other neutrino flavors:

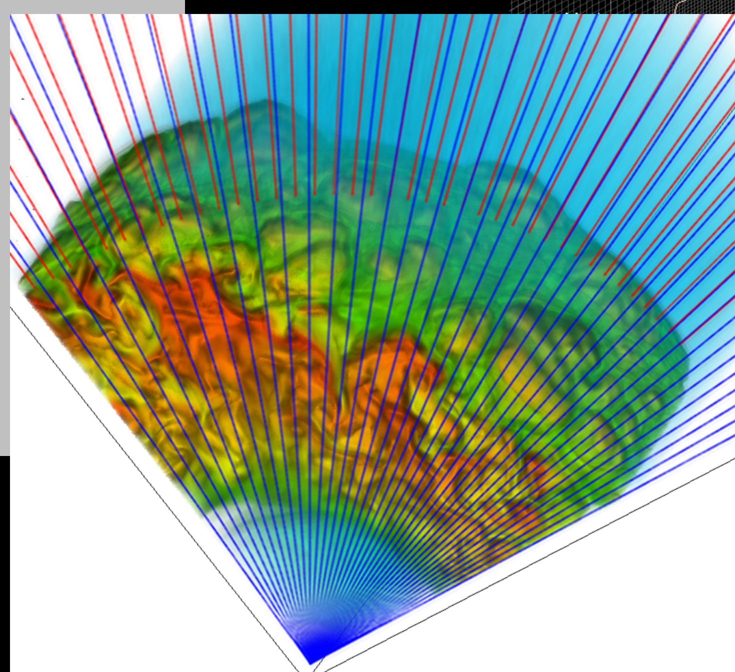
  pair production, nucleon-nucleon Bremsstrahlung, electron neutrino – electron anti neutrino annihilation

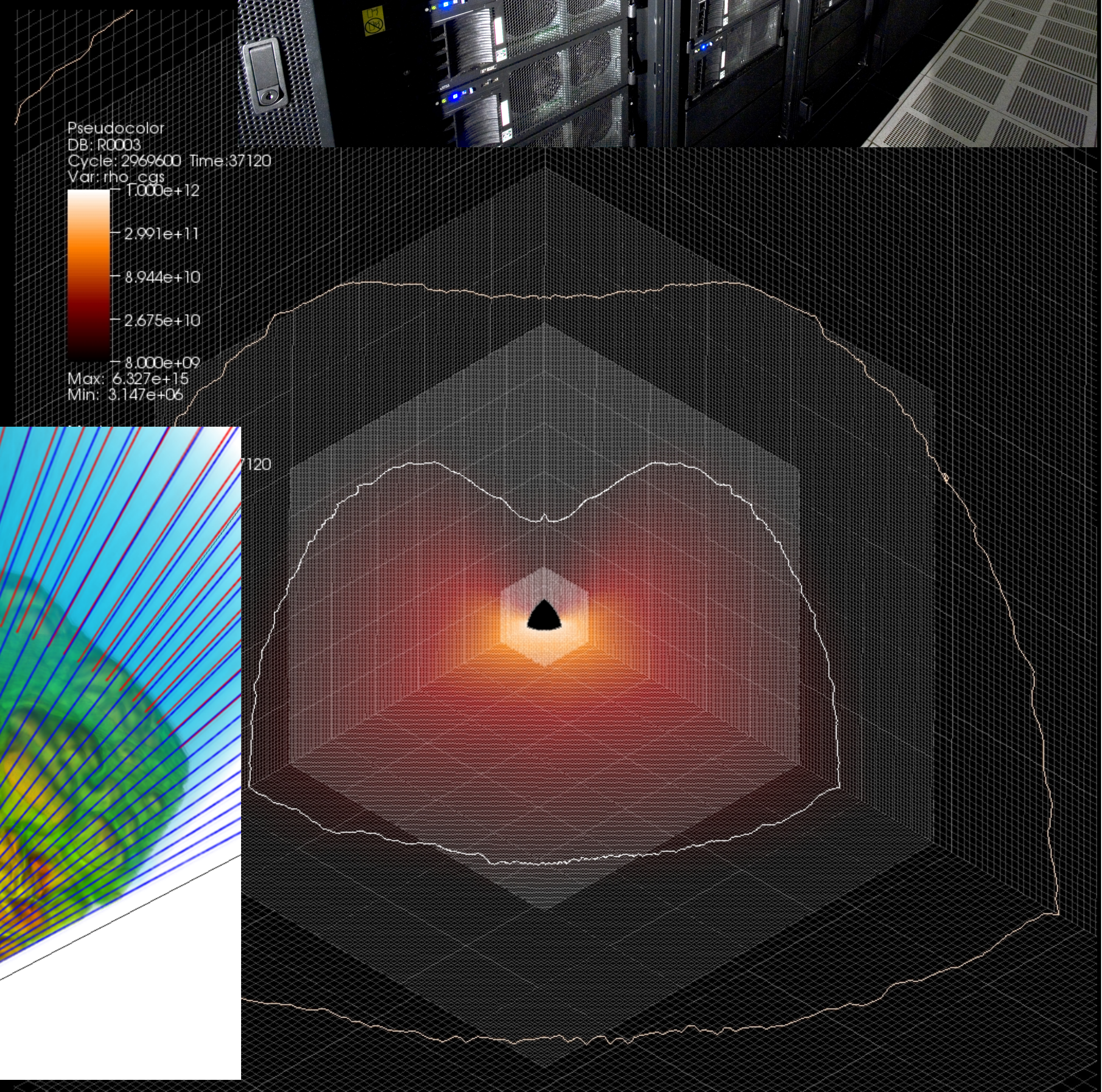


Computational Modeling

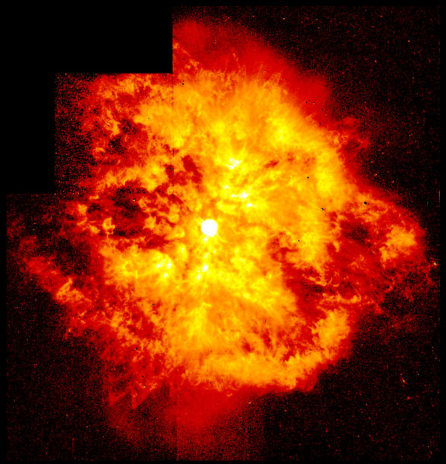
- General Relativistic Hydrodynamics
- Finite Volume Scheme with adaptive mesh refinement
- Realistic equation of state
- Neutrino Transport (leakage scheme)
- 3D (octant symmetry)







Initial stellar models

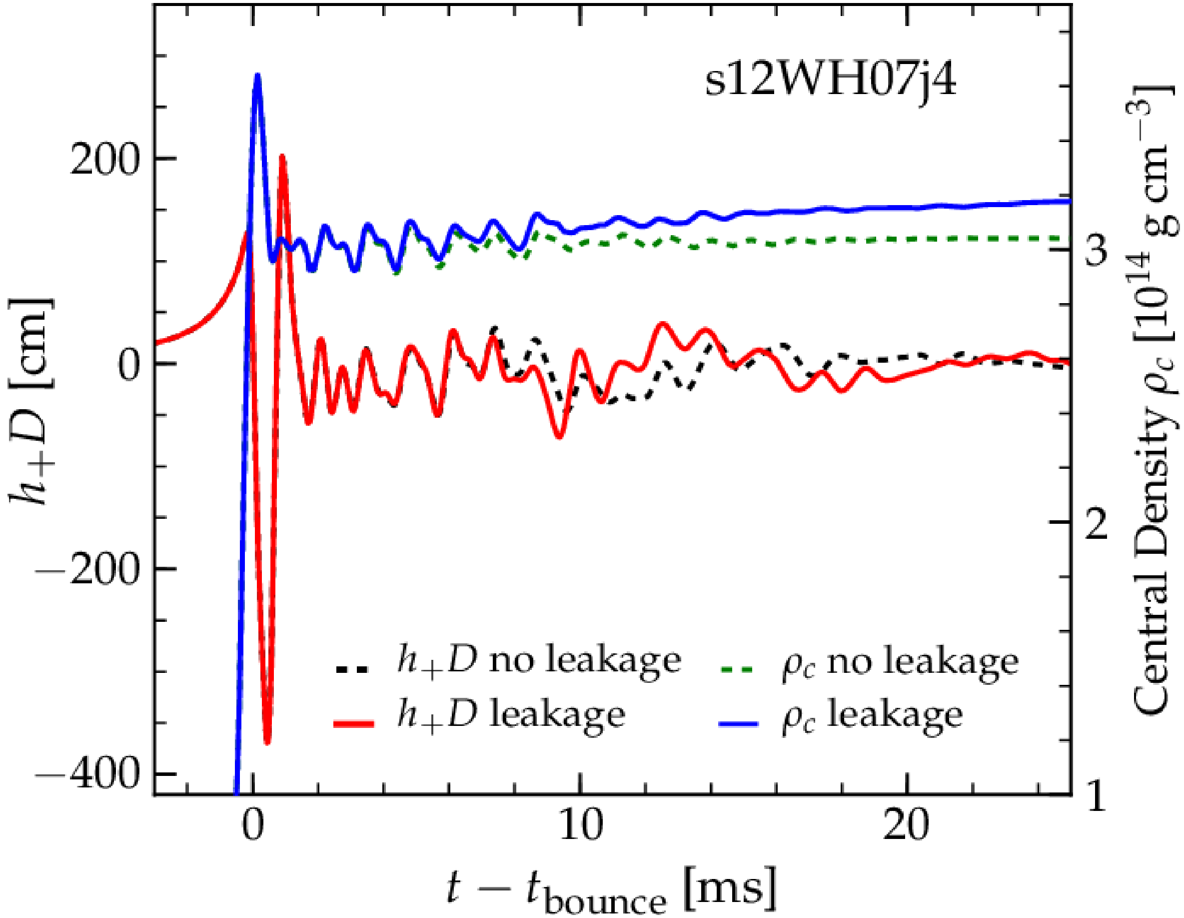


From Woosley & Heger (2007): 12 Msol, solar-metalicity star (red supergiant)
40 Msol, solar-metalicity star (Wolf-Rayet)

6 rotational setups: no rotation – moderate rotation – rapid rotation

GWs from collapse, bounce, and ring down: leakage vs. non-leakage

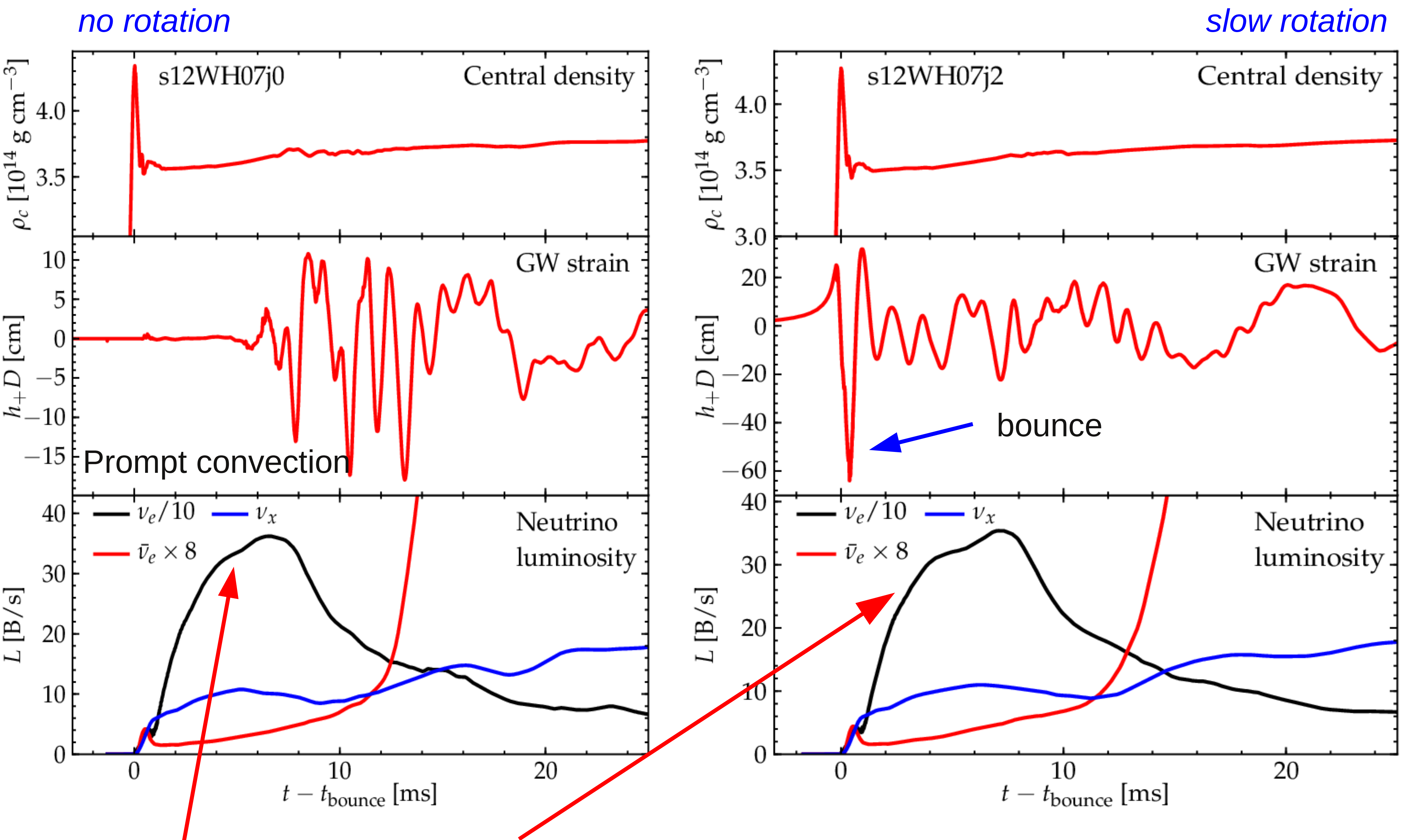
Ott, Abdikamalov, O'Connor, Reisswig, et al. '12



Conclusion: postbounce neutrino leakage has little effect on the ring-down oscillations of protoneutron star.

Correlated GW and neutrino signals

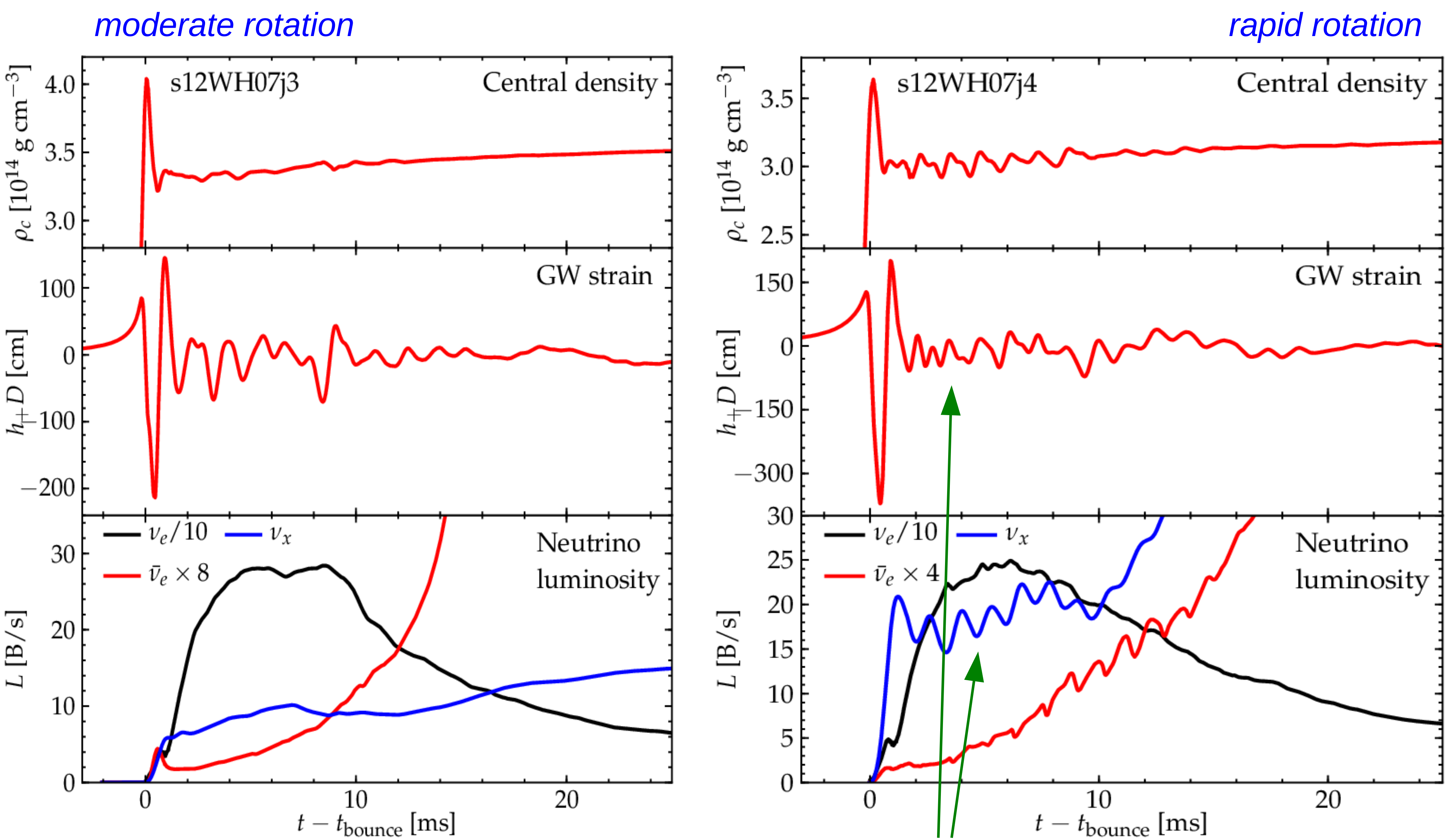
Ott, Abdikamalov, O'Connor, Reisswig, et al. '12



electron-neutrino burst at shock break out

Correlated GW and neutrino signals

Ott, Abdikamalov, O'Connor, Reisswig, et al. '12



GWs and neutrino signal exhibit correlated oscillations in *rapidly rotating collapse*!

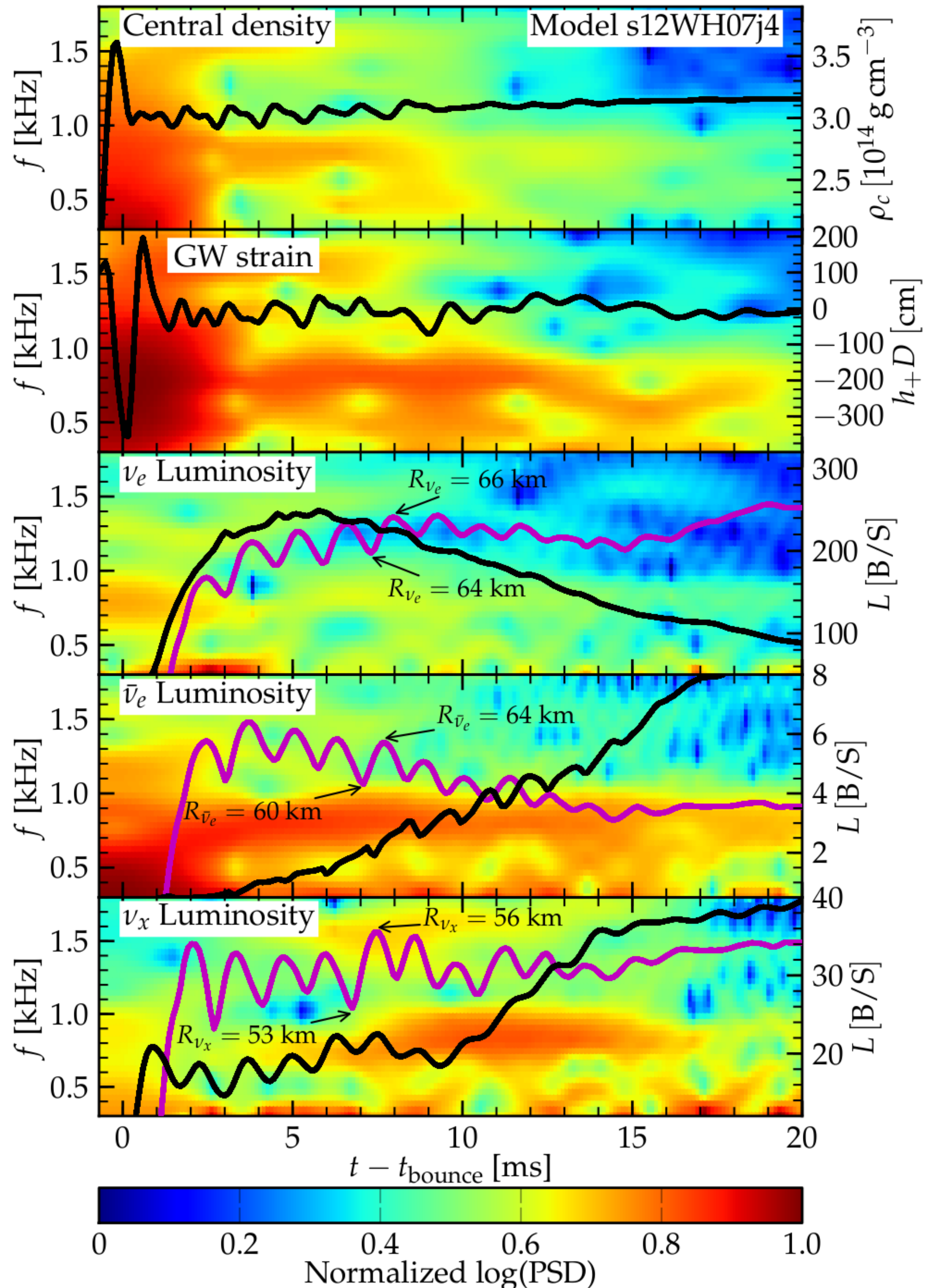
Correlated GW and neutrino signals

Ott, Abdikamalov, O'Connor, Reisswig, et al. '12

rapid rotation

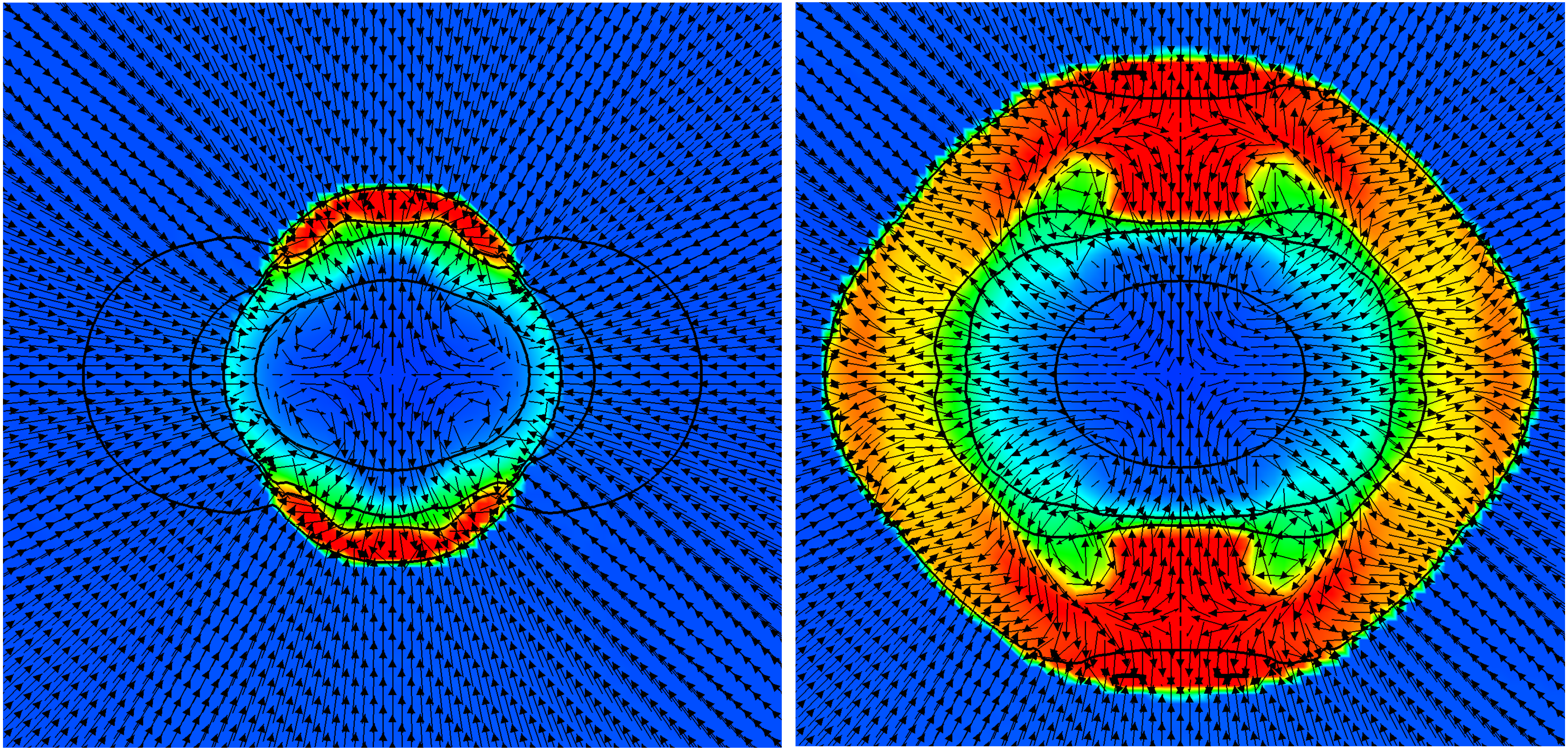
GWs and neutrino signal exhibit correlated oscillations in *rapidly rotating collapse*!

Significant correlated excess power around 700-800Hz!



What is producing these oscillations?

Ott, Abdikamalov, O'Connor, Reisswig, et al. '12



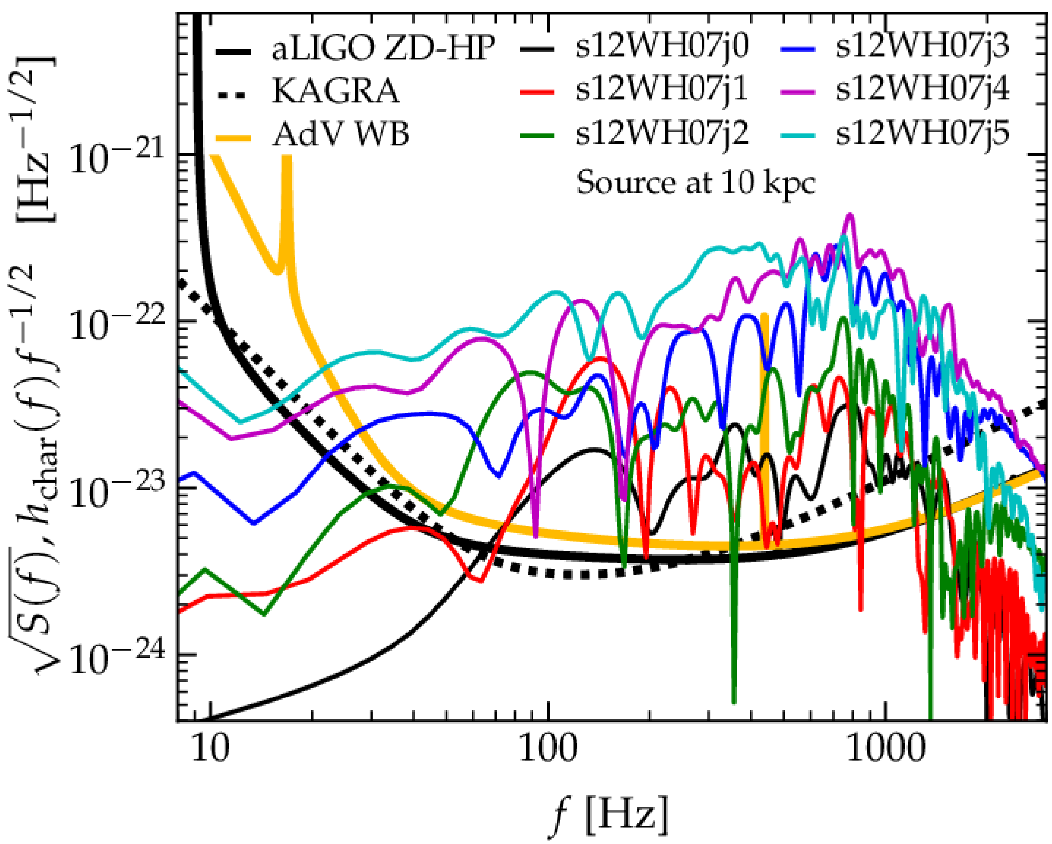
$t - t_{\mathrm{bounce}} = 0.25\mathrm{ms}$ $t - t_{\mathrm{bounce}} = 0.64\mathrm{ms}$

Rotationally flattened bounce excites fundamental quadrupole mode of nascent protoneutron star.

Detectability

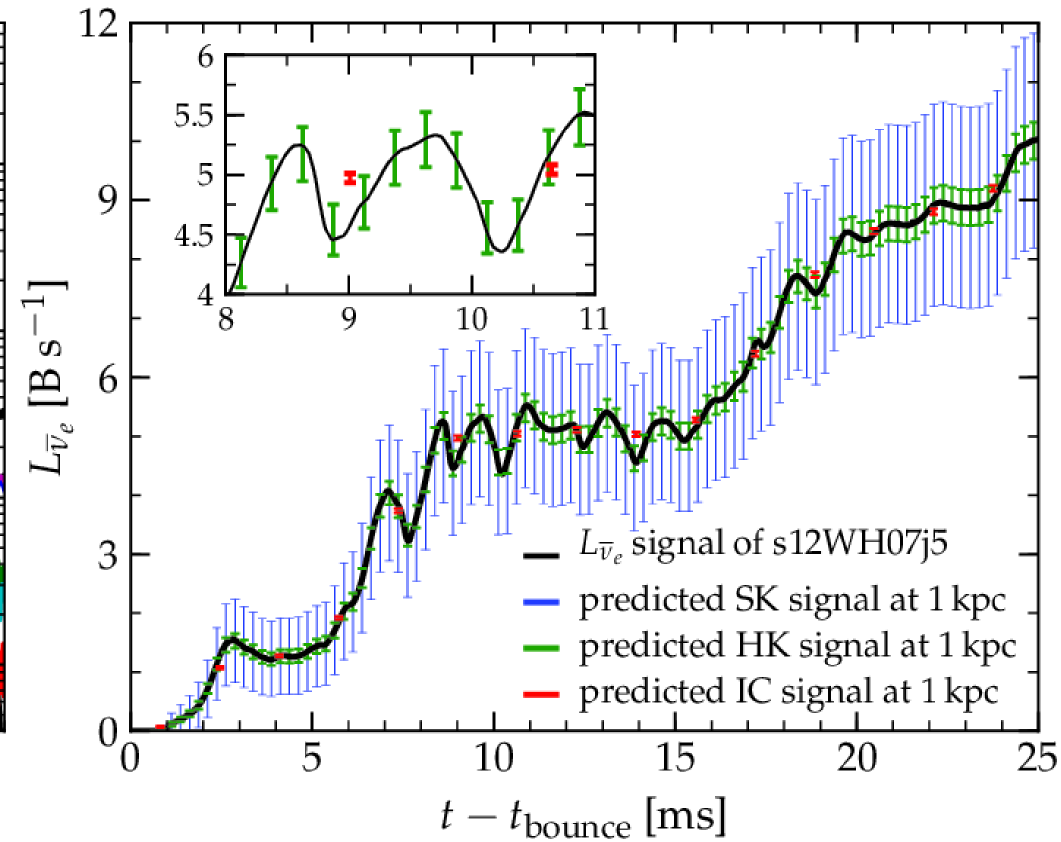
Ott, Abdikamalov, O'Connor, Reisswig, et al. '12

Gravitational waves



aLIGO SNR at 10 kpc: ~6 (model j0)
~73 (model j4)

Neutrinos

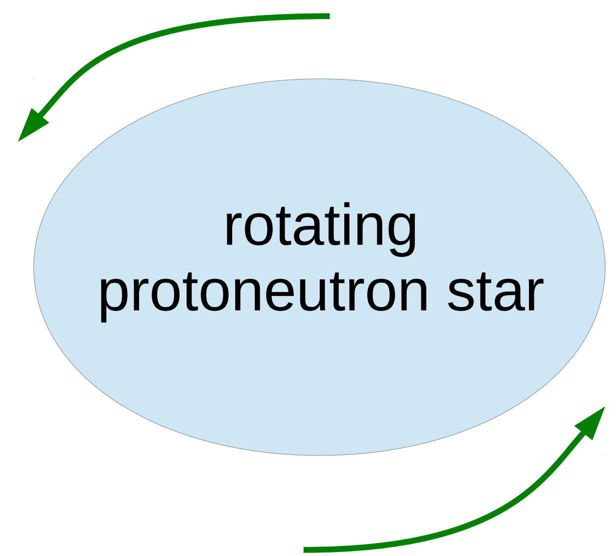


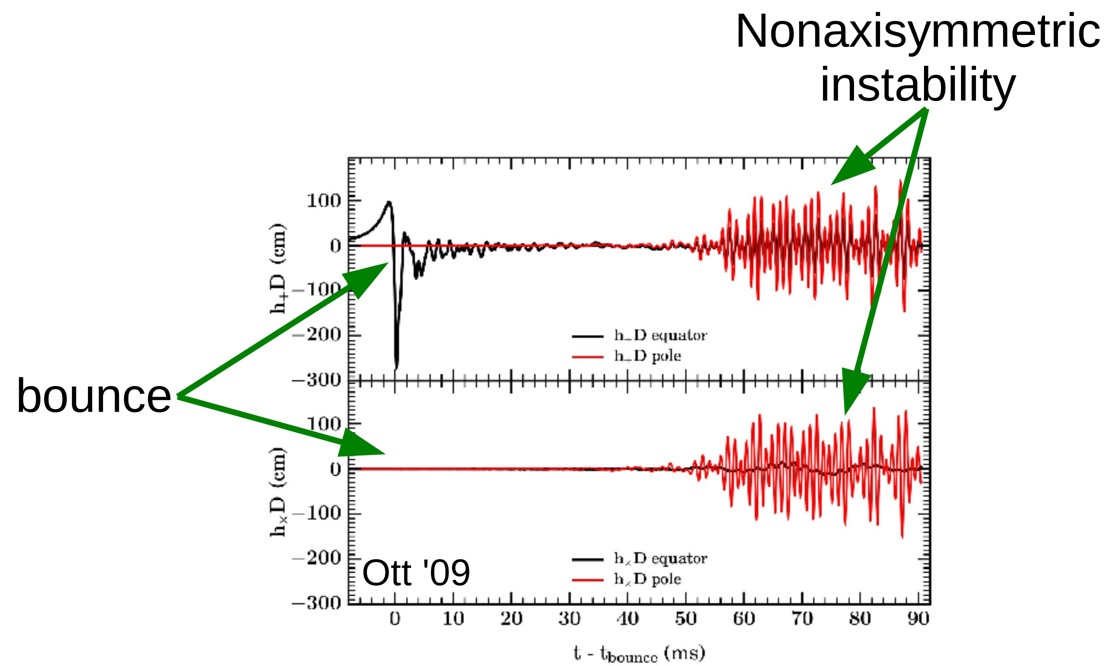
IceCube's timing resolution too low
Super-Kamiokande's error bar too large

Hyper-Kamiokande would see oscillations at 1kpc

Postbounce rotational instabilities

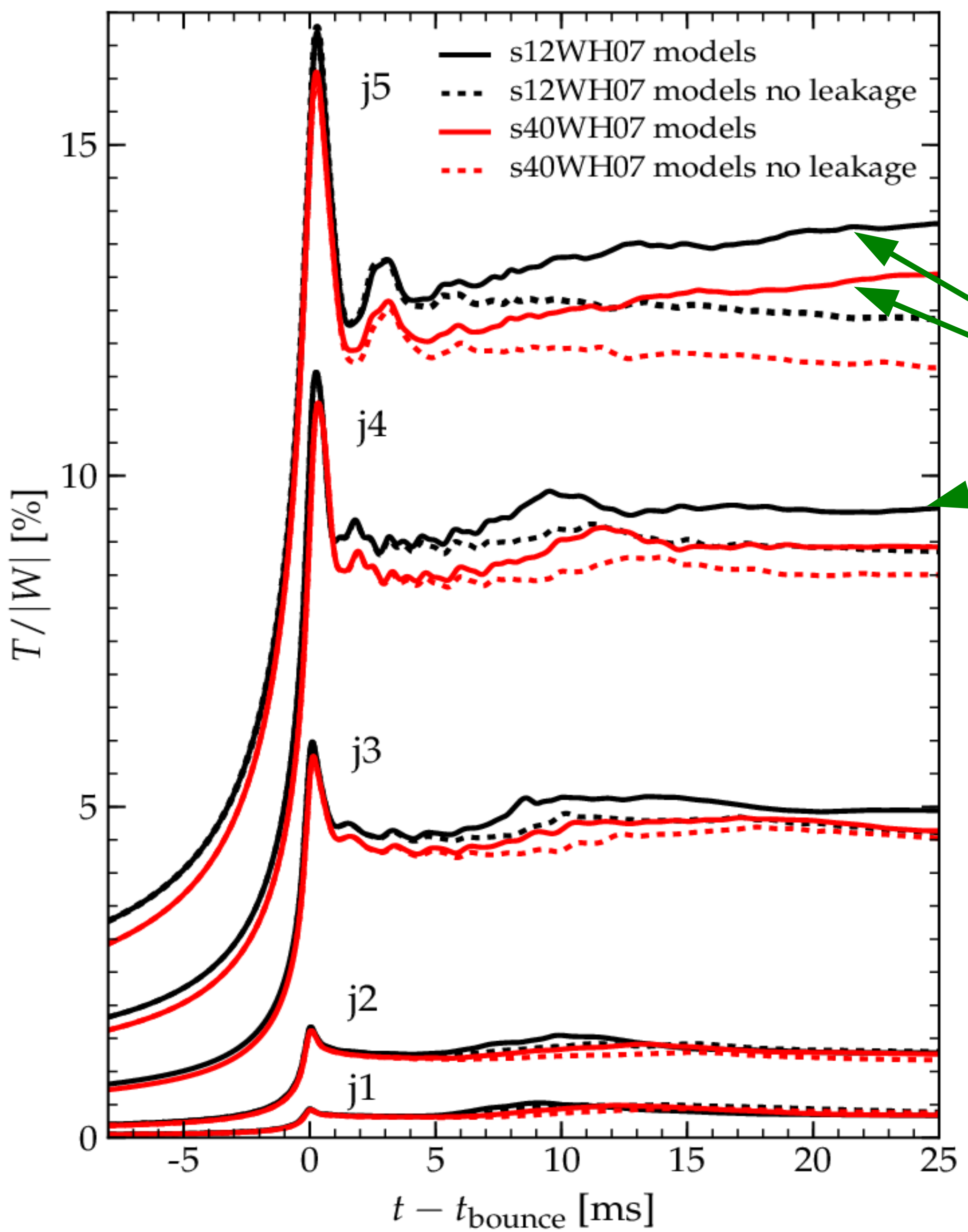
- High-T/|W| dynamical
  - Occurs at T/|W|≥0.26.
- Low-T/|W| dynamical
  - Occurs at lower T/|W| but requires differential rotation.
- Secular





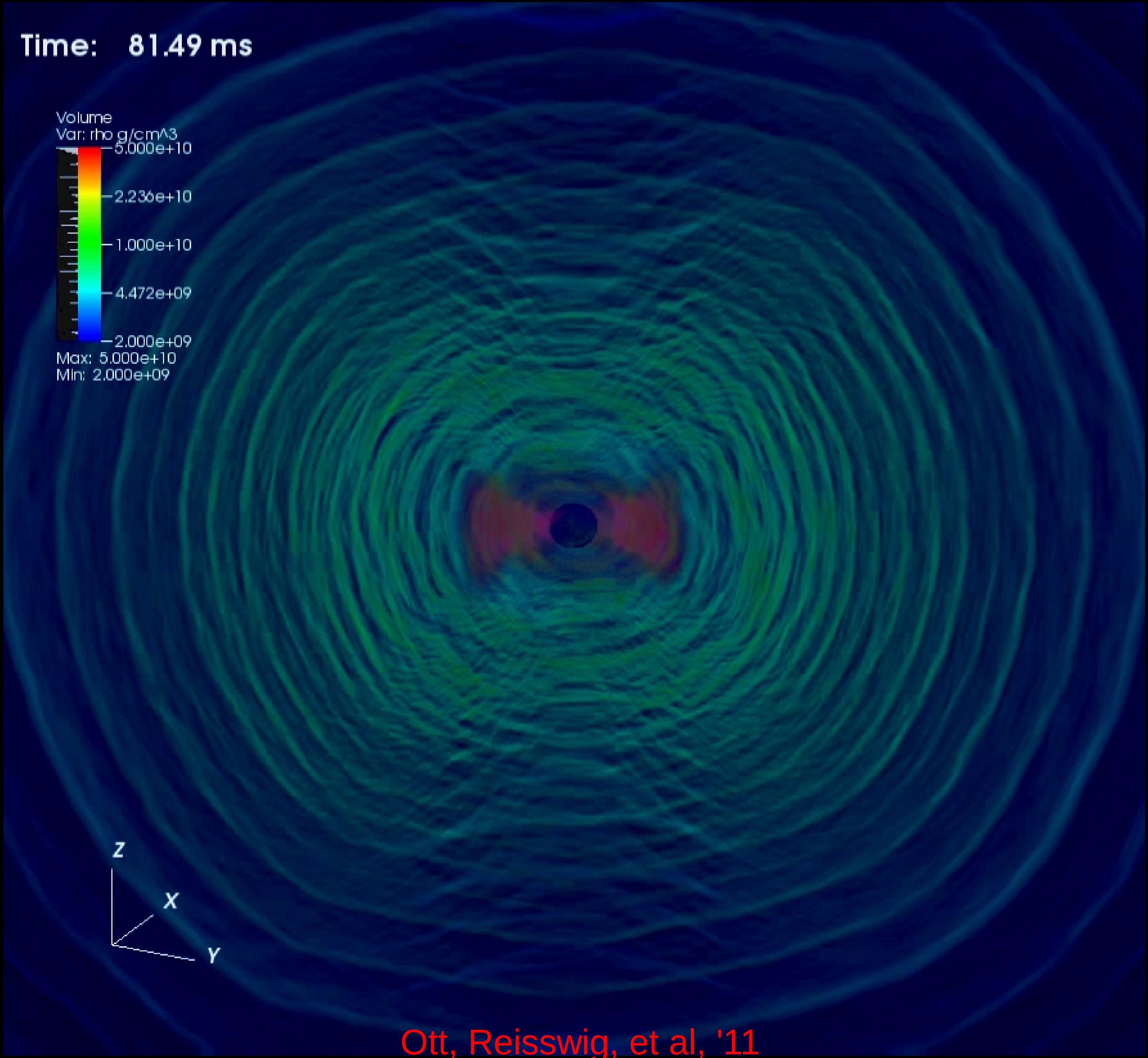
Postbounce rotational instabilities

Ott, Abdikamalov, O'Connor, Reisswig et al. '12



Increase of T/|W| due to neutrino cooling.

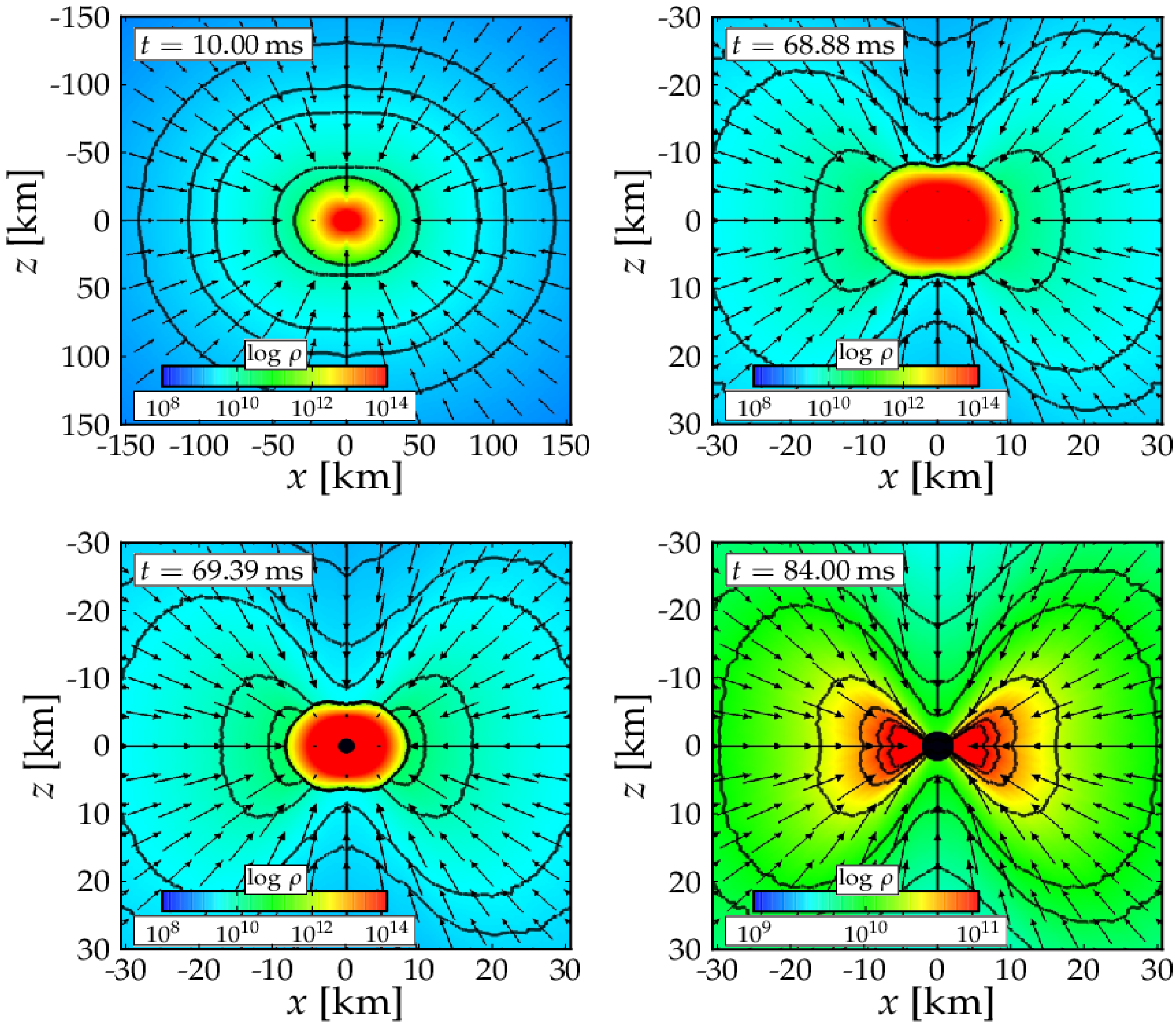
Black hole formation



Ott, Reisswig, et al, '11

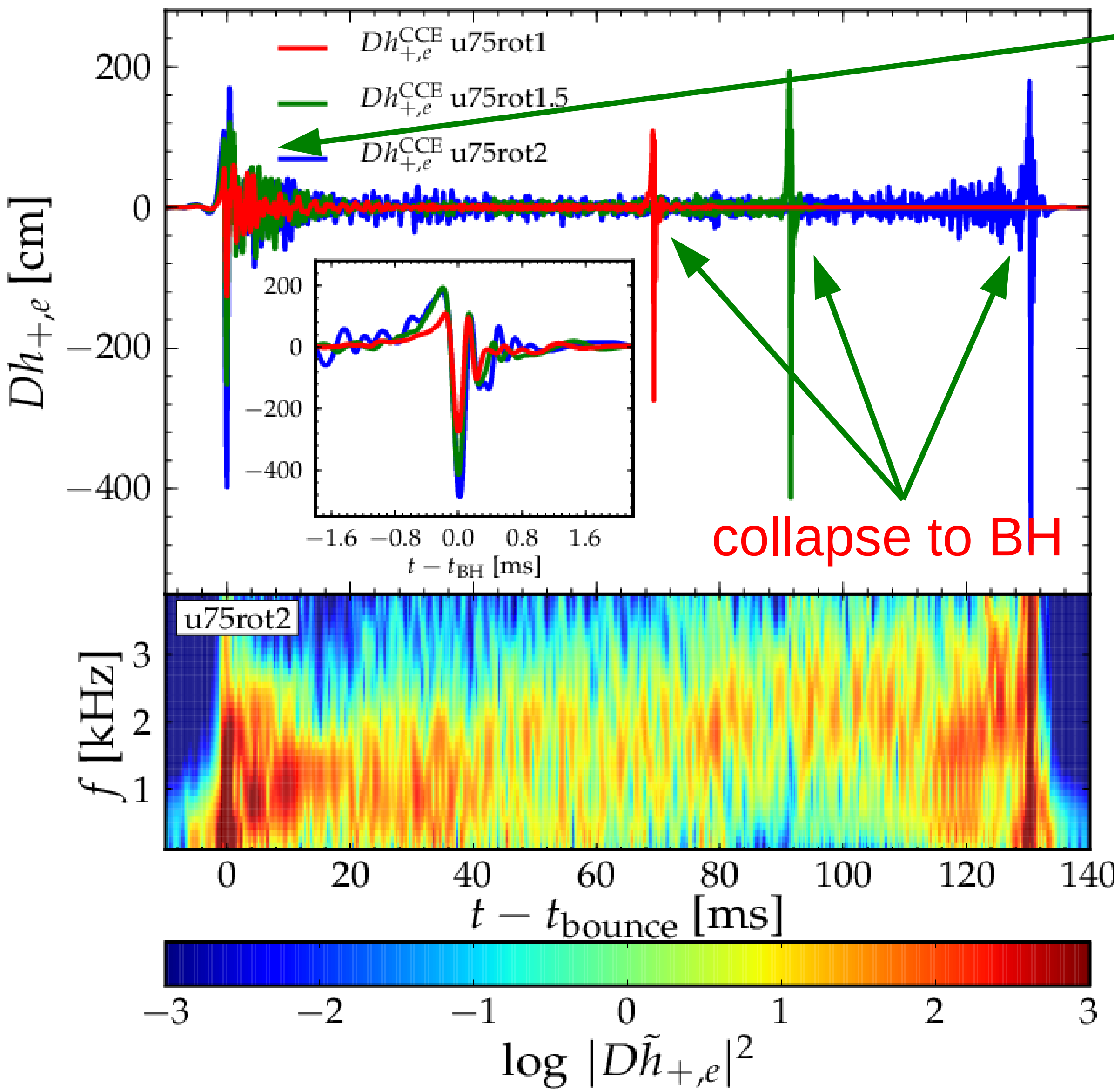
Black hole formation

Ott, Reisswig, et al. '11



GW signal of black hole formation

Ott, Reisswig et al. '11



Wave extraction using full curvature-based techniques at future null infinity!

Cauchy-characteristic Extraction

Reisswig, Ott, et al '11

Summary

- Postbounce neutrino leakage has little effect on the ring-down oscillations...
- ...but can be important at later times (nonaxisymmetric instabilities).
- Correlation between GWs and neutrino signal in rapidly rotating core collapse due to fundamental mode excitation in nascent protoneutron star...
- ...if we observe oscillations in neutrino luminosity and variations in GW signal, we have rapid rotation!
- GW emission from collapse to BH leads to unique signal.