Neutron Star Merger with Tabulated EOS and Spin

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Topics

Part 1: A recent merger simulation

- Gauge independent measures
- Structure of post-merger fluid flow
- Nature of hot spots
- Structure of merger remnant
- Matter ejection

Part 2: Influence of initial NS spin on

- Inspiral
- GW signal
- Matter ejection

Measuring Deformations

- Spatial gauge used in evolution bad for analysis of HMNS
- Define better coordinates
  - Consider the equatorial plane
  - Meaningful coordinate distances

$$g_{rr} = 1, \qquad g_{\phi\phi,\phi} = 0$$

  - Prevent spirals

$$\int_{-\pi}^{\pi} g_{r\phi} \, \mathrm{d}\phi = 0$$

  - Fix global rotation

$$\beta^{\phi} \to 0 \quad \text{for} \quad r \to \infty$$

  - Choice of origin: use π-symmetry axis

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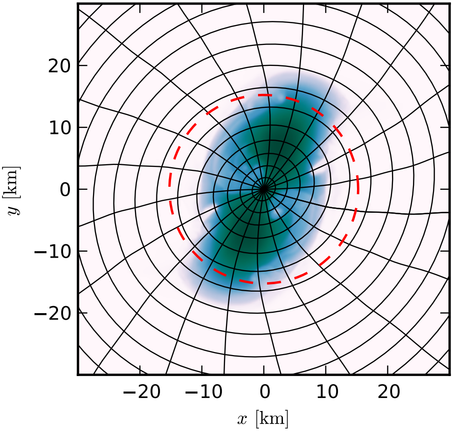

Measuring Compactness

Problem

- Want to quantify density profile and compactness
- Compactness should not be sensitive to low density parts
- Should not require symmetries or preferred coordinates

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Solution

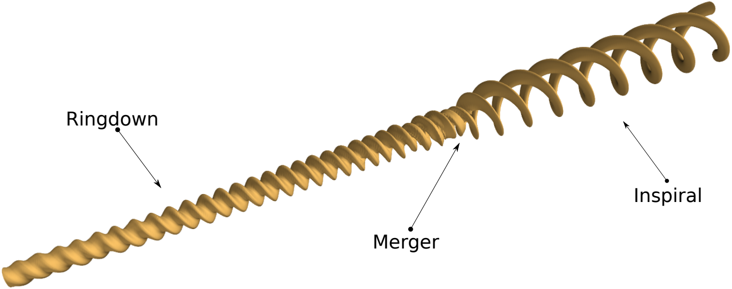
- Consider shells of constant (rest frame) mass density
- Each shell contains proper volume V and baryonic mass M_b
  $\Rightarrow$ Unambiguous baryonic mass versus proper volume relations
- Compute "volumetric" radius R_v of Euklidian sphere with same volume
- Define compactness $C = M_b/R_v$
- Define the "bulk" as shell with maximum compactness
  $\Rightarrow$ bulk mass, bulk volume, bulk entropy..

Initial data

- Irrotational, equal mass
- No magnetic field
- Zero temperature, β equilibrium
- EOS: G. Shen, Horowitz, Teige
- Baryonic mass $2 \times 1.513\ M_\odot$
- Bulk mass 98% total mass
- Grav. mass of single star $1.4\ M_\odot$
- Initial proper separation $57.6\ \mathrm{km} \Rightarrow$ 4 Orbits
- Maximum TOV baryonic mass $3.33\ M_\odot$
  $\Rightarrow$ Remnant is stable !
- Corner case, probably not realistic

Merger dynamics

Computed isodensity surfaces that contain $\frac{1}{4}$ of total mass.
Cut in $xy+t$:



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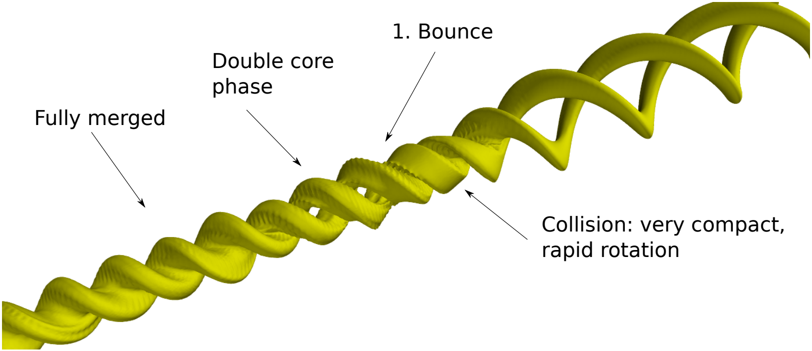

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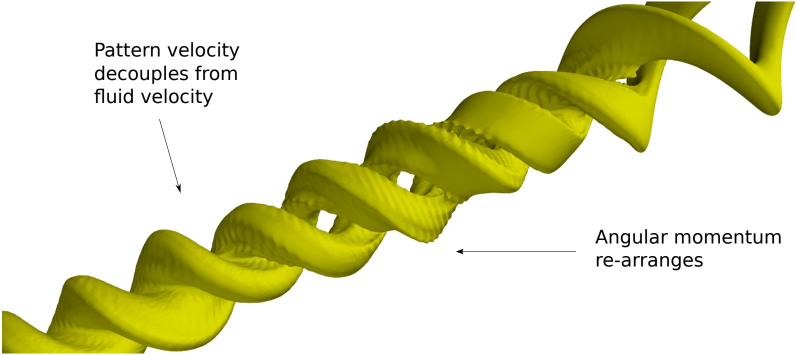
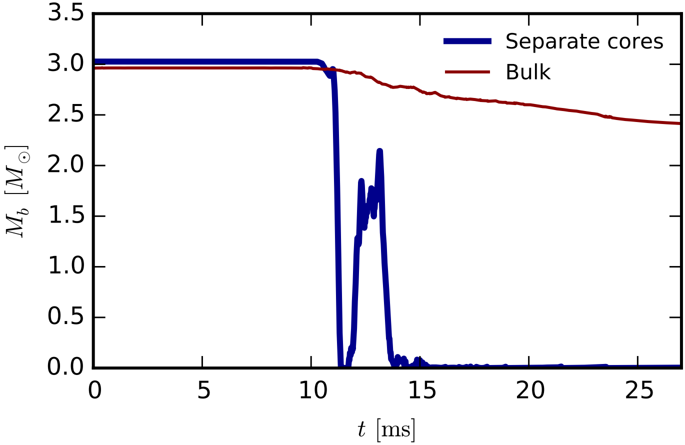
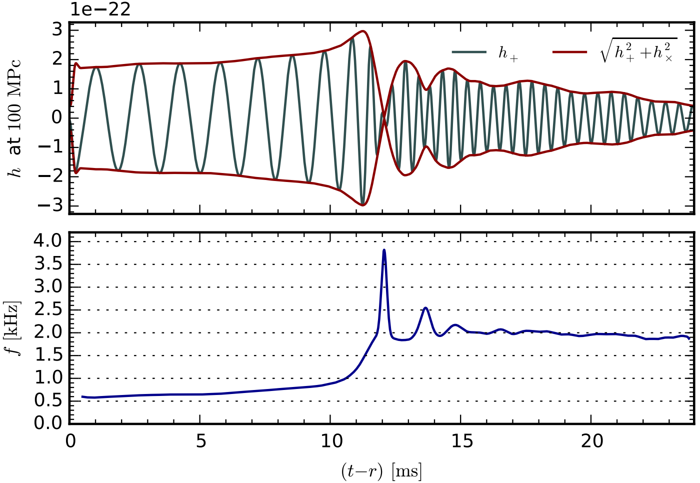


Merger dynamics

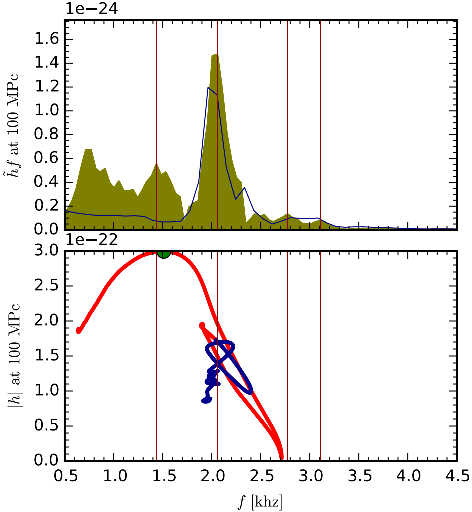
- Quantify mass in double core
- Total mass of matter with density $>$ central density



GW signal

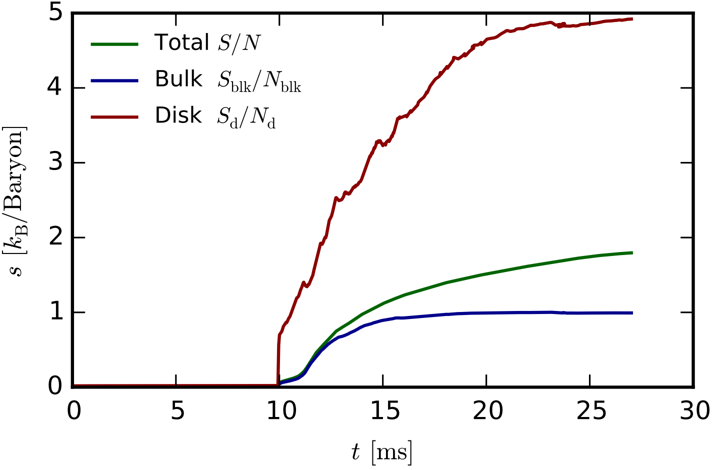

1e−22
3
2
1
0
−1
−2
−3
h at 100 MPc
h_+
$\sqrt{h_+^2 + h_\times^2}$
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
f [kHz]
0
5
10
15
20
$(t-r)$ [ms]

GW signal


1e−24
$\tilde{h}f$ at 100 MPc
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1e−22
$|h|$ at 100 MPc
0.0
0.5
1.0
1.5
2.0
2.5
3.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
f [khz]

Thermal evolution

- Bulk entropy produced at merger, then constant
- Matter outside bulk hotter, ongoing heating



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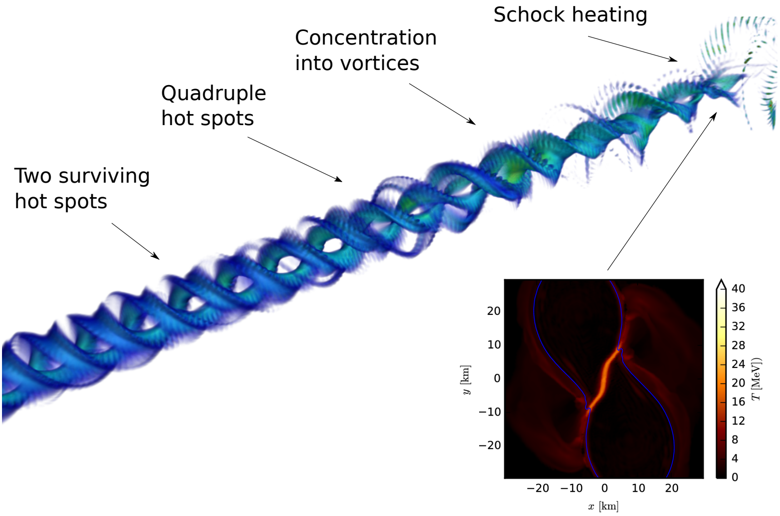
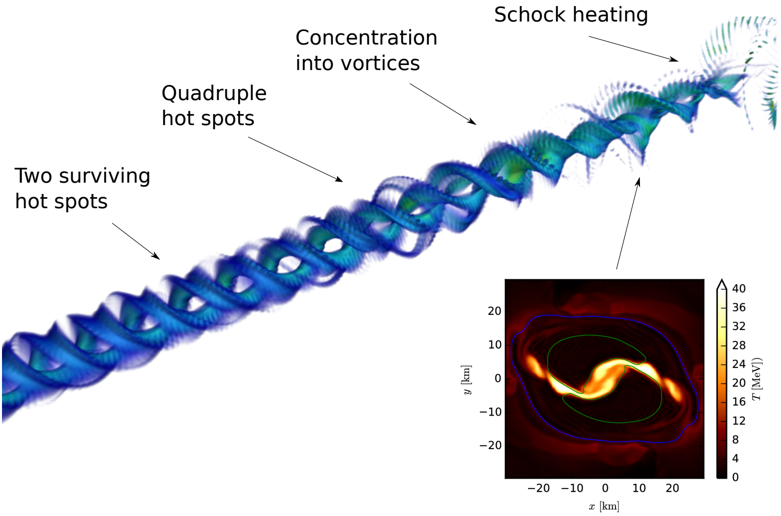


Thermal evolution



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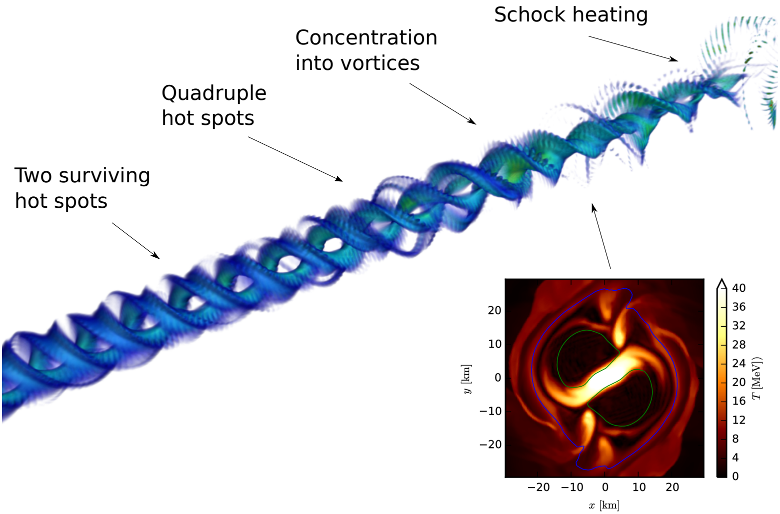

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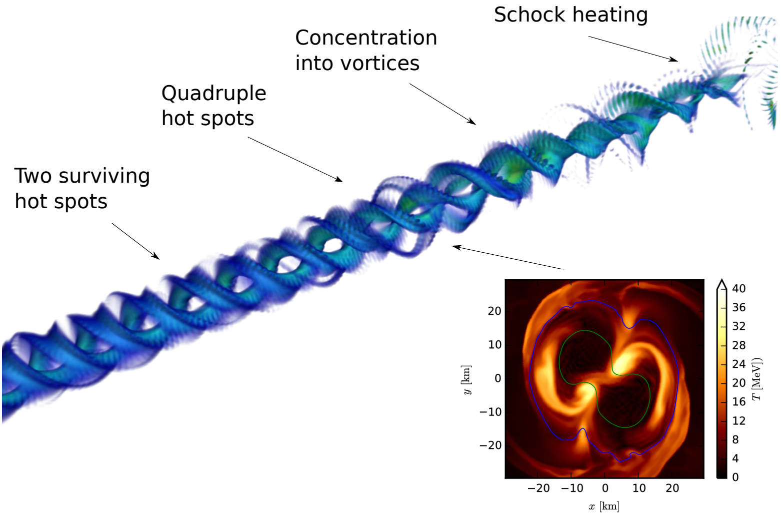

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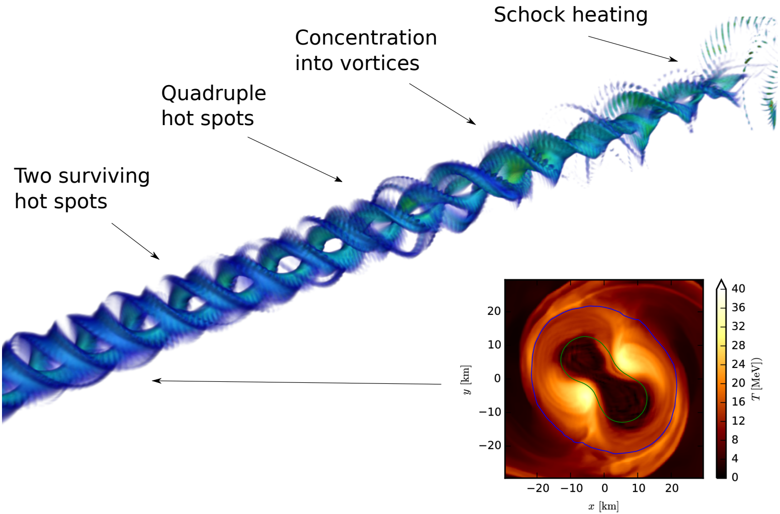
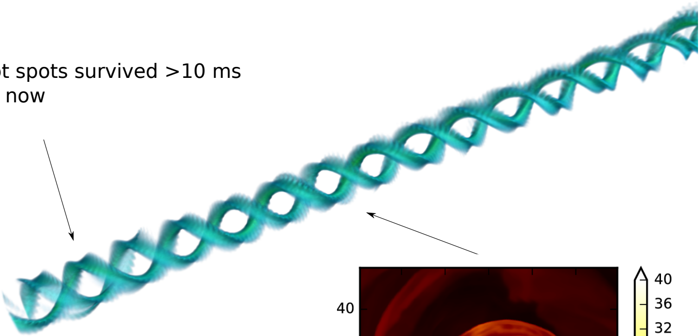
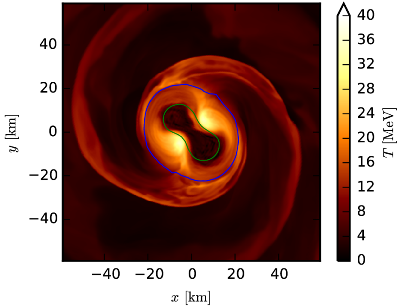


Thermal evolution

Hot spots survived >10 ms
by now





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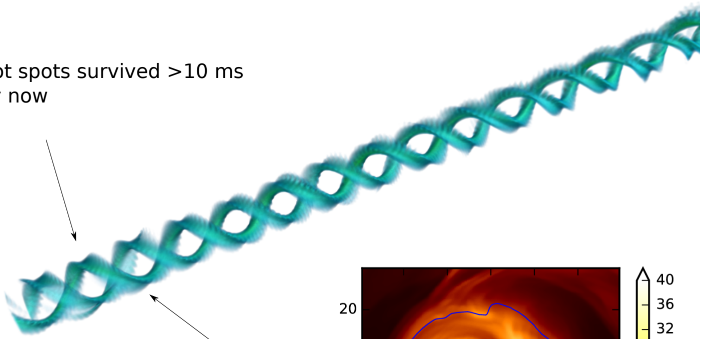

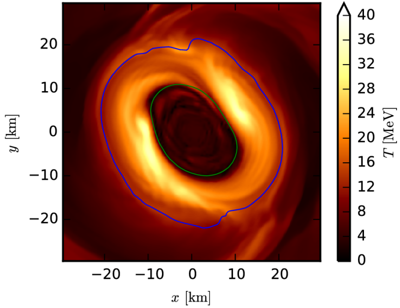

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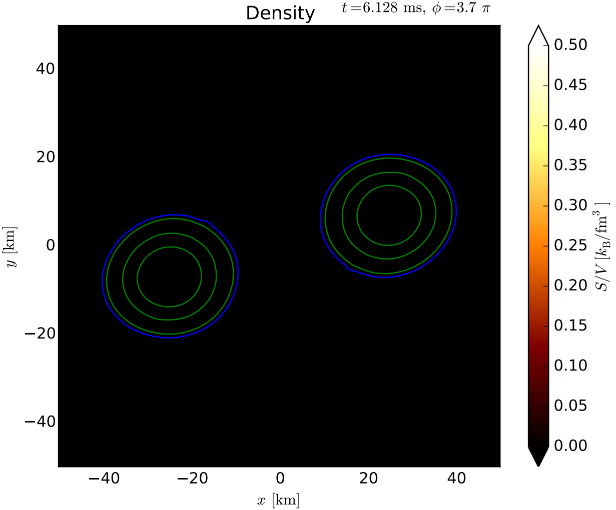

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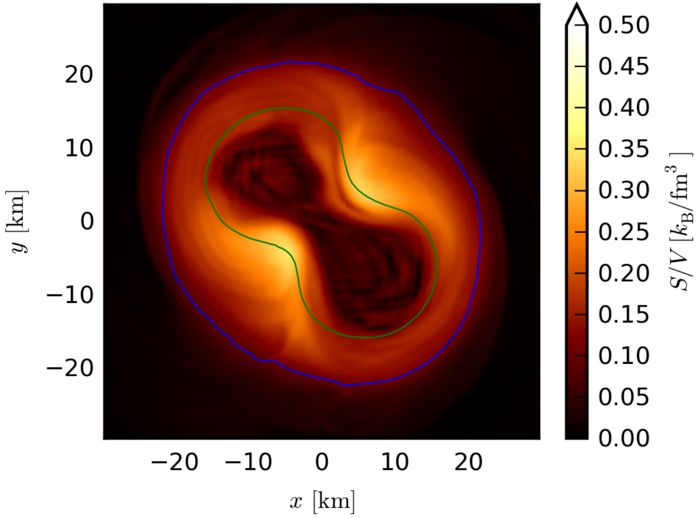

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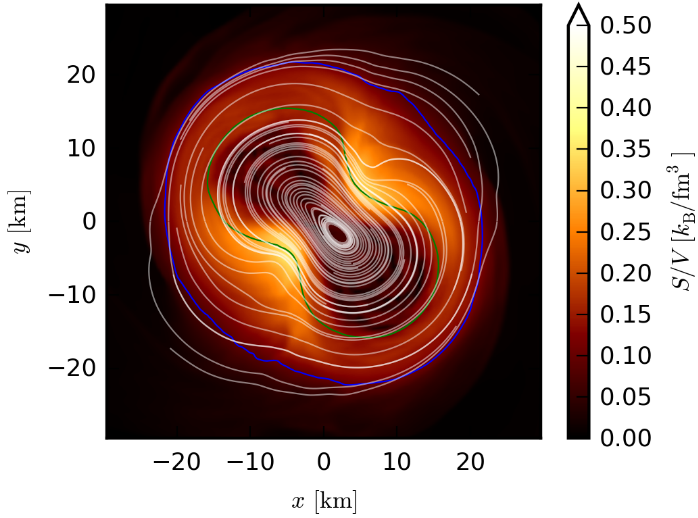
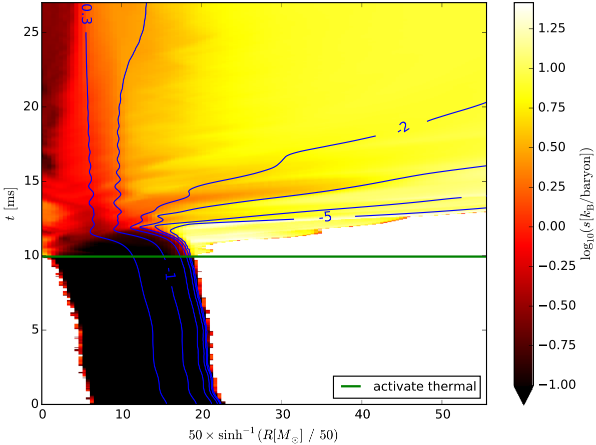


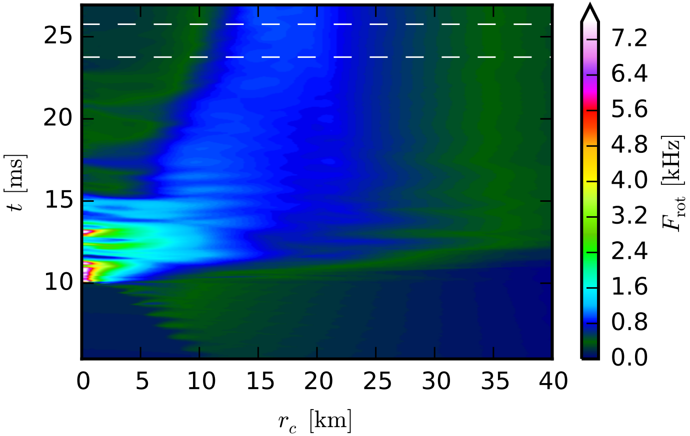
Thermal evolution

- Final state convectively stable
- Evolve adiabatically during inspiral



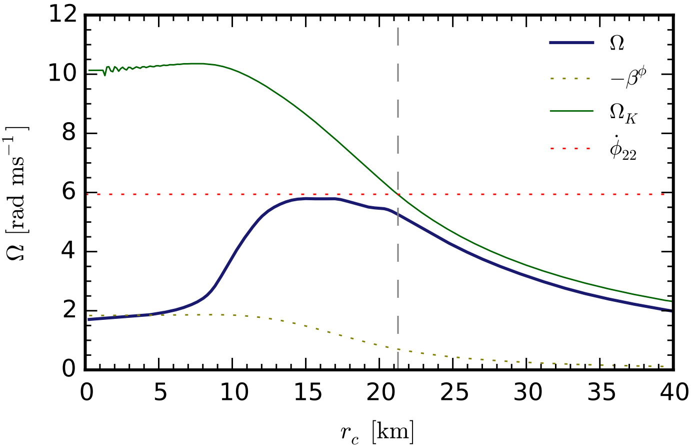
Rotation profile

- Violent rearrangement of rotation profile after merger



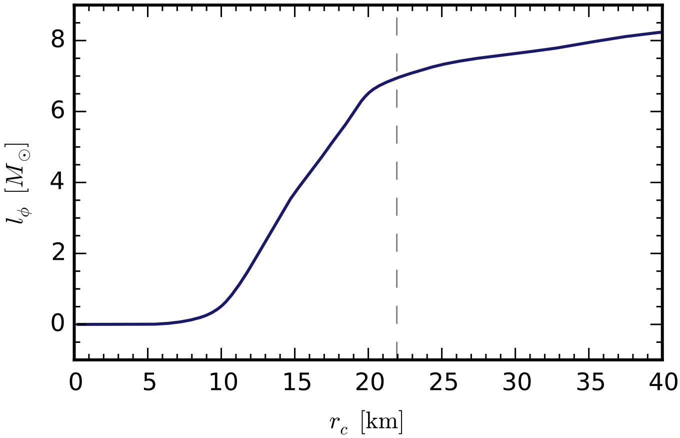
Rotation profile

- Remnant rotation profile has slowly rotating core
- Outer layers close to Kepler rate



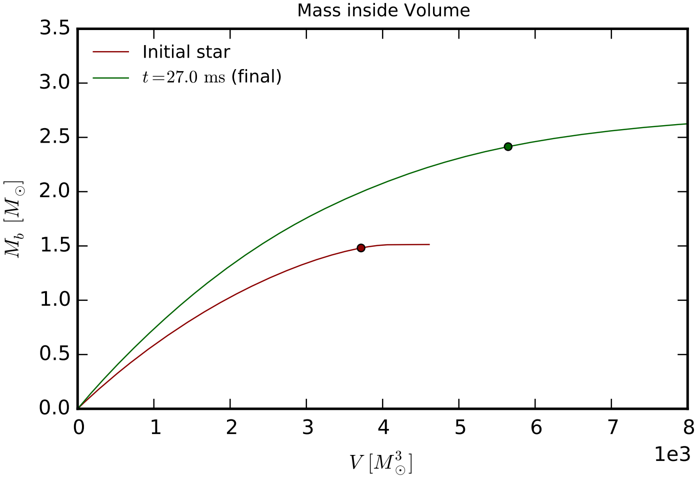
Rotation profile

- Final specific angular momentum profile stable
- Specific entropy profile adds even more stability



Remnant mass distribution

- Central region of remnant very similar to a TOV star



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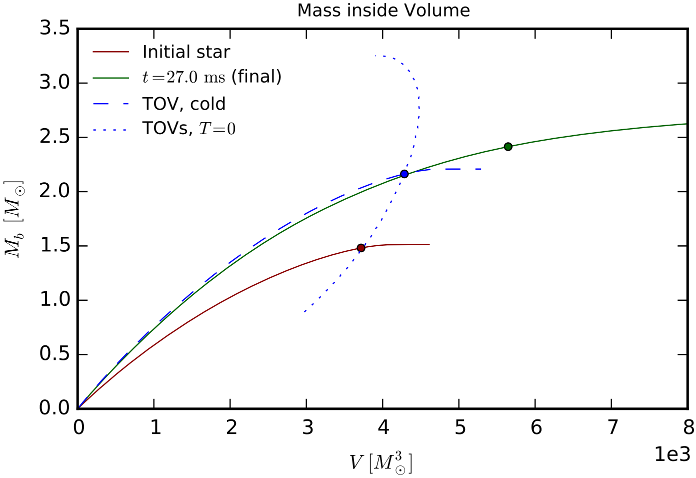

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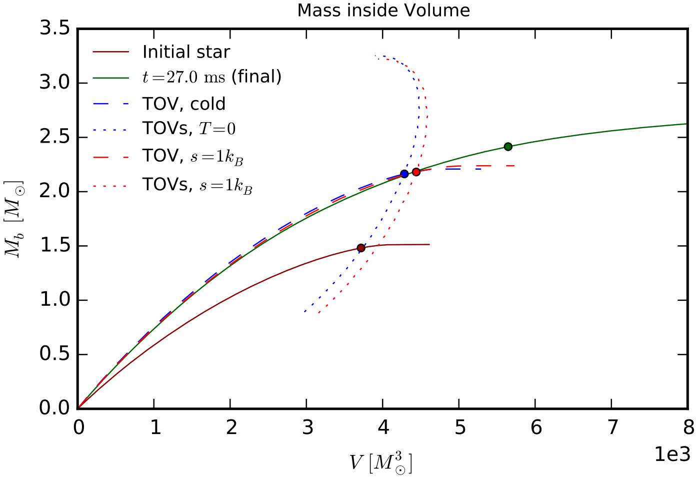
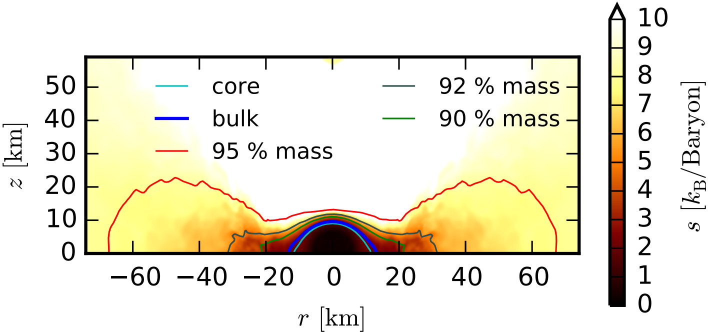


Remnant mass distribution

- Bulk baryonic mass 2.4 $M_\odot$
- TOV core equivalent mass 2.2 $M_\odot$
- Mass outside bulk (Envelope+Disk) 0.62 $M_\odot$
- Mass at $r > 20\ \mathrm{km}$ (Disk) 0.3 $M_\odot$



Measuring matter ejection

Previous estimate for unbound mass

- Assume stationary spacetime
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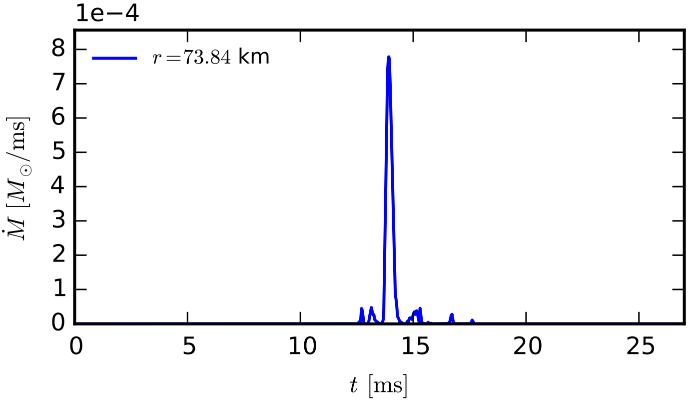
Solution

- Use flux of unbound baryonic mass through spherical shell
- Also compute flux of entropy, electron fraction

Matter Ejection

- One wave, launched at merger, escape velocity ≈ 0.17 *c*



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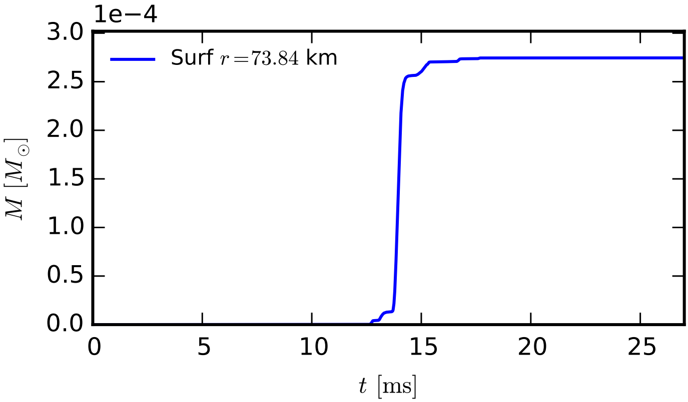
- One wave, launched at merger, escape velocity ≈ 0.17 *c*
- Relatively low amount of unbound matter



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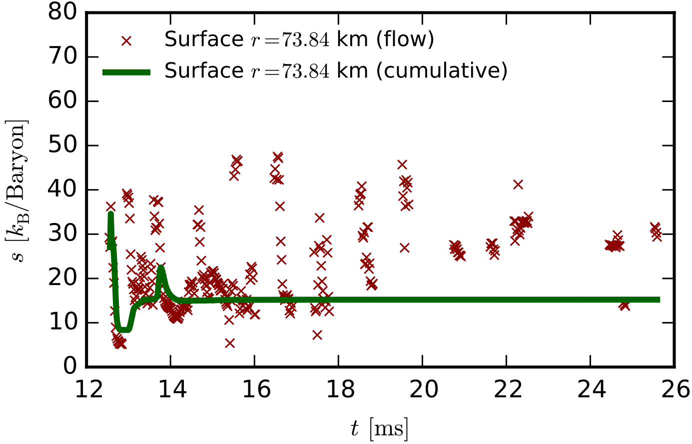

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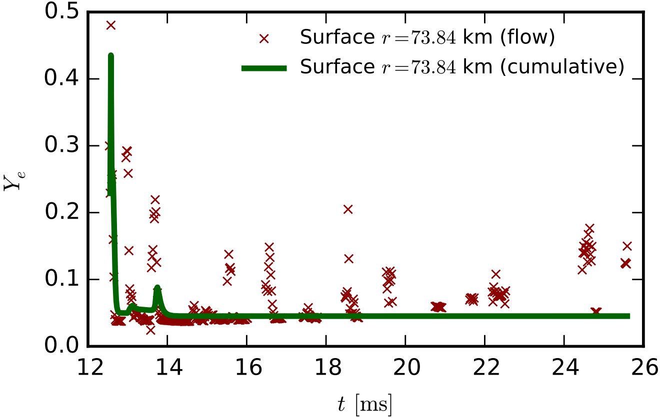
- Average specific entropy ≈ 15 $k_{\mathrm{B}}/\mathrm{Baryon}$
- Electron fraction (not accurate without neutrino radiation)



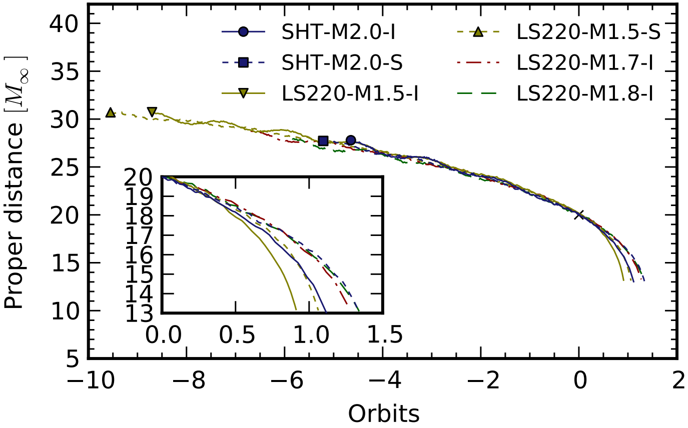
Spin – Initial data

Lattimer-Swesty ($K = 220\ \mathrm{MeV}$) EOS Equal mass, $M_\mathrm{B} = 3.12\ M_\odot = 1.10\ M_\mathrm{Kepler}$	
Irrotational	Aligned rotation $\Delta F_\mathrm{R} \approx 160\ \mathrm{Hz}$
G. Shen, Horowitz, Teige (NL3) EOS Equal mass, $M_\mathrm{B} = 4.01\ M_\odot = 1.01\ M_\mathrm{Kepler}$	
Irrotational	Aligned rotation $\Delta F_\mathrm{R} \approx 155\ \mathrm{Hz}$

W. Kastaun, F. Galeazzi, *Properties of hypermassive neutron stars formed in mergers of spinning binaries*, **Phys. Rev. D 91, 064027 (2015)**

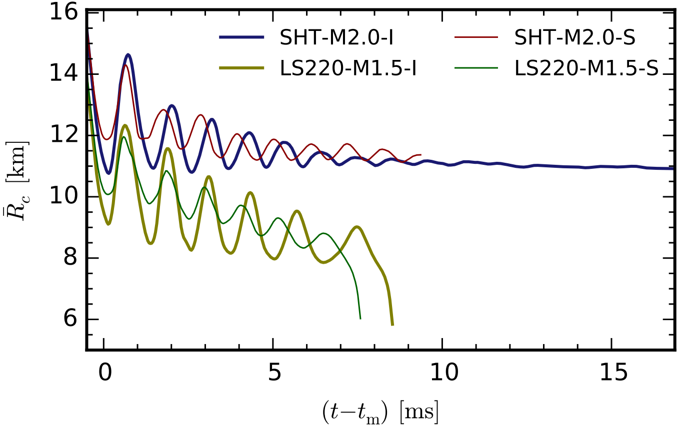
Spin – Inspiral

- Inspiral takes longer with spin
- Different impact trajectory



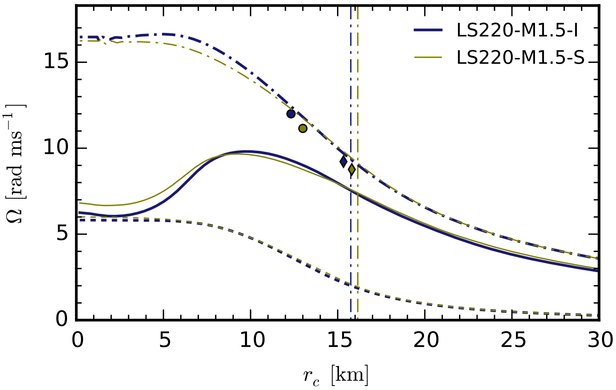
Spin – Radial Oscillations

- Strong quasi-radial oscilation
- Oscillation amplitude smaller for spinning NSs



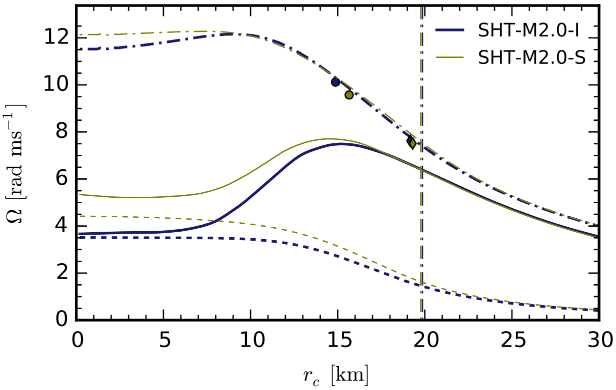
Spin – Rotation Profile

- Average rotation rate has central dip again



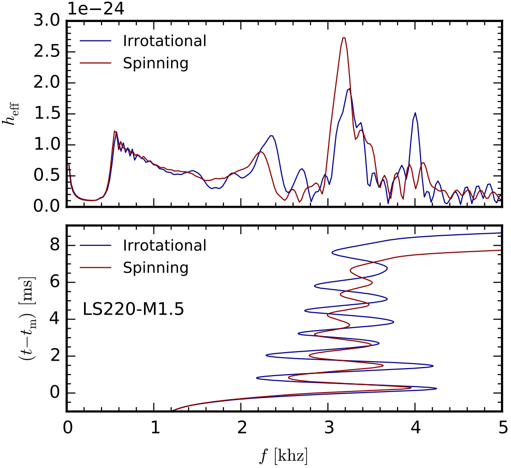
Spin – Rotation Profile

- Average rotation rate has central dip again
- Influence of initial spin varies



Spin – GW Spectrum

- No clear spin signature in post-merger spectra
- Better chances for inspiral+plunge



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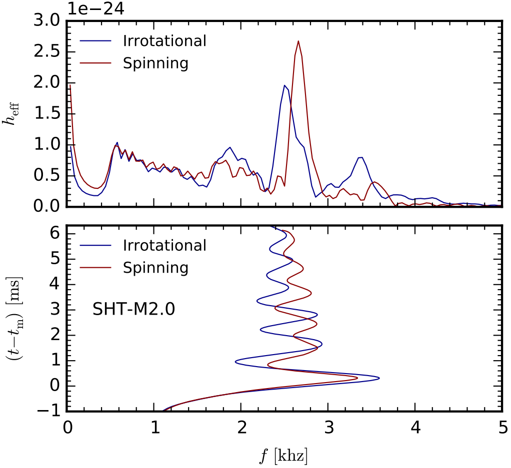
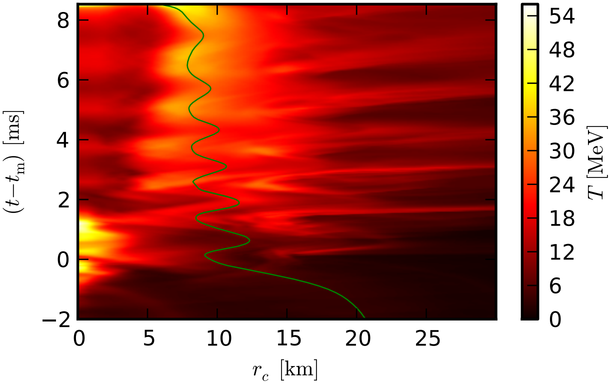


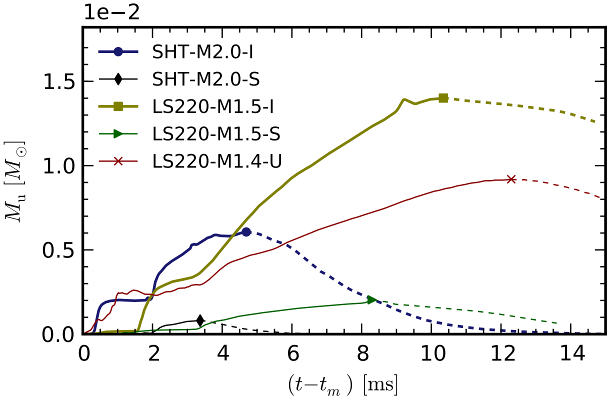
Spin – Matter ejection

- Matter ejected in spiral waves caused by $m = 2$ mode.
- Modulated by radial oscillation.



Spin – Matter ejection

- Matter ejected in spiral waves caused by $m = 2$ mode.
- Modulated by radial oscillation.
- Initial spin influences amount of ejected matter.



Summary

- Merger remnant cores rotate slowly
- Thermal effects unimportant for core profile
- Outer envelope supported mainly by centrifugal force
- New measure: Mass versus volume relation
- Observed dynamic hot spots,
  resilient to differential rotation
- Spin seems to influence matter ejection
- Weak and complicated influence on GW

Thanks!