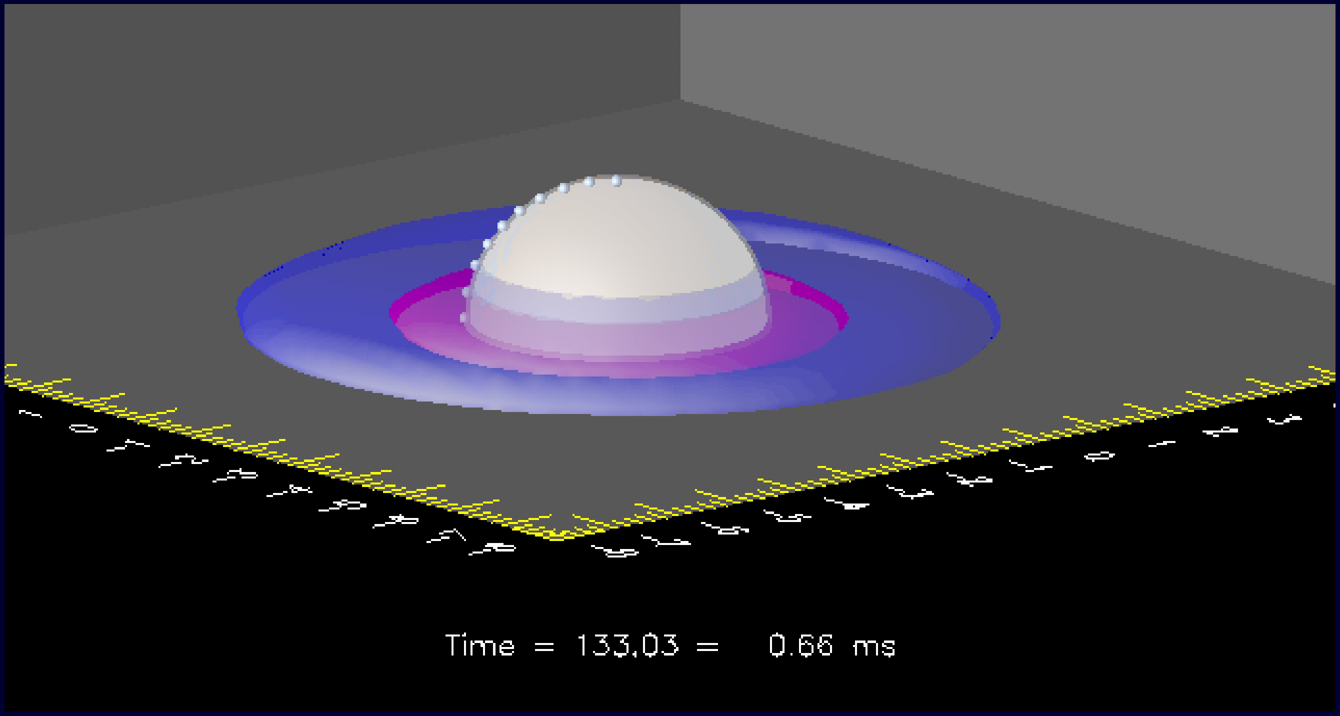
Dynamics in neutron star collapse to a black hole



This work is performed in collaboration with many inside the EU Network, particularly L. Baiotti, L. Rezzolla (SISSA), N. Stergioulas (AUTH), F. Löffler (AEI), A. Nerozzi (UP).

Neutron star collapse

- Neutron stars as the end state of astrophysical processes, e.g. core-collapse supernovae or binary star mergers.
- Instabilities can occur through e.g. accretion or some change in the pressure support through phase changes or cooling.
- The neutron star may then collapse to a black hole.
- We perform full 3D GR simulations of collapse using the EU Network hydro code. Particular attention is paid to the late stage of the collapse and the dynamics of the apparent and event horizons that form.

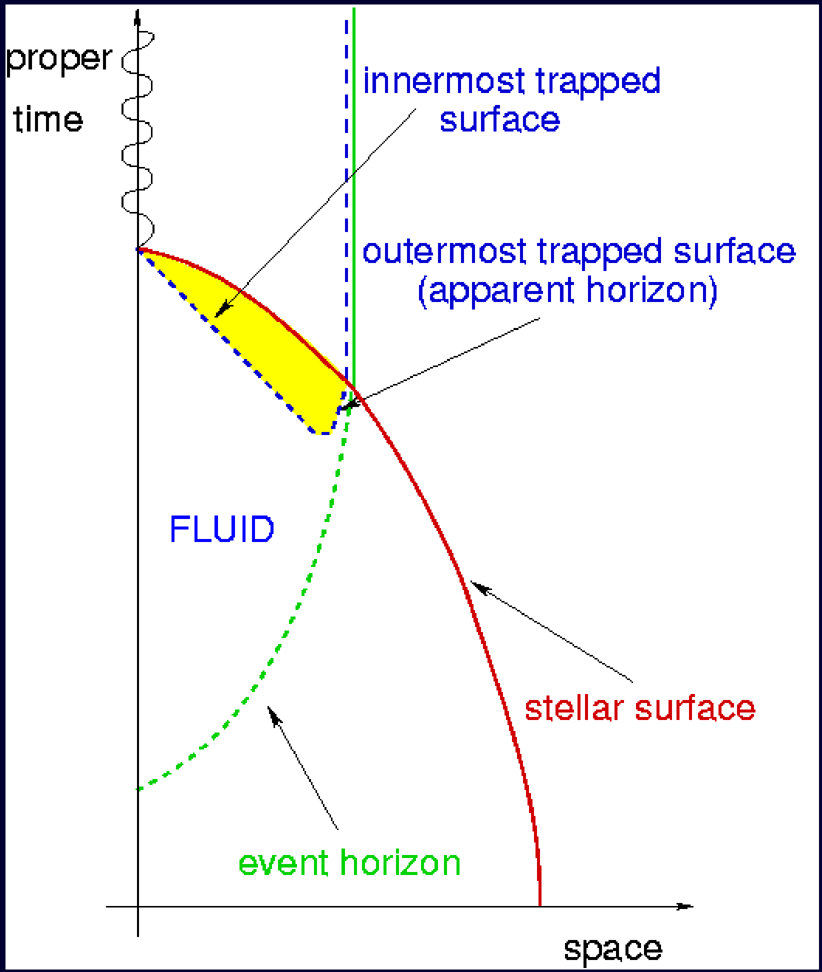
Previous work

- Nakamura (81, 83) checked that cosmic censorship would hold.
- Stark and Piran (85) showed
  - ⋆ Wave signal corresponds to QN mode of final black hole
  - ⋆ At most 0.1% of the energy emitted as gravitational waves
  - ⋆ Collapse "nearly spherical".
- Shibata (2000) used the "Cartoon" method - indications of disk formation for the ideal fluid case.
- Shibata and collaborators (2000) performed 3D simulations concentrating on the dynamics of the collapse, finding that polytropic models would collapse promptly to a BH.

Necessary tools

We use:

- The AEI BSSN code,
- The standard AEI gauge conditions ("1+log" and "Gamma driver")
- The EU Network hydro code (*Whisky*),
- J. Thornburg's fast apparent horizon finder (*AHFinderDirect*),
- P. Diener's event horizon finder,
- Other standard Cactus tools

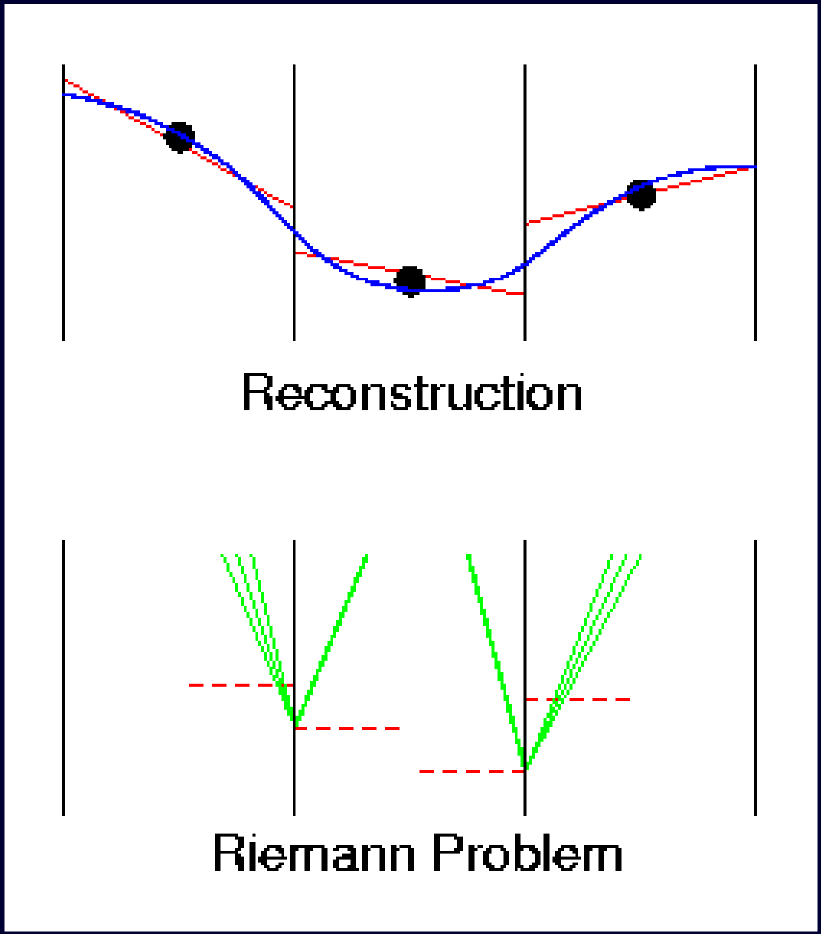


Hydrodynamics near singularities

To study late time behaviour or to extract wave signals at meaningful distances the simulation must continue long after the singularity has formed. To produce a stable evolution we must use excision.

The standard "lego" excision technique is applied to the spacetime.

Time derivative extrapolation is neither conservative nor TVD so will not work for hydrodynamics.

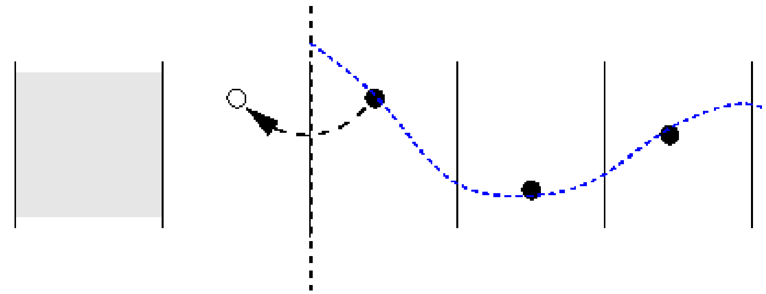


Excision and hydrodynamics

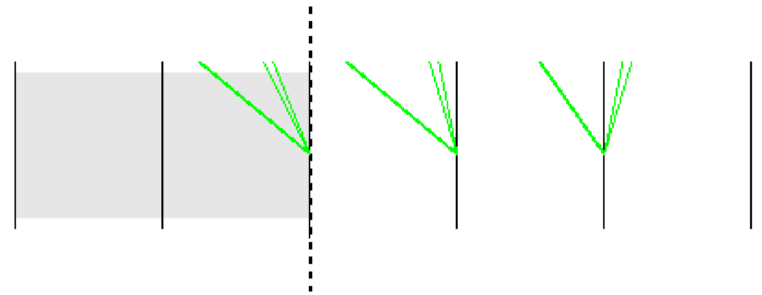
We take advantage of the adaptive stencil of the HRSC method.

- Copy the value across the excision boundary.
- Force the stencil to contain this cell but no others inside the horizon.
- Enforce a trivial Riemann problem at the excision boundary.

This is simple to implement for most HRSC methods.

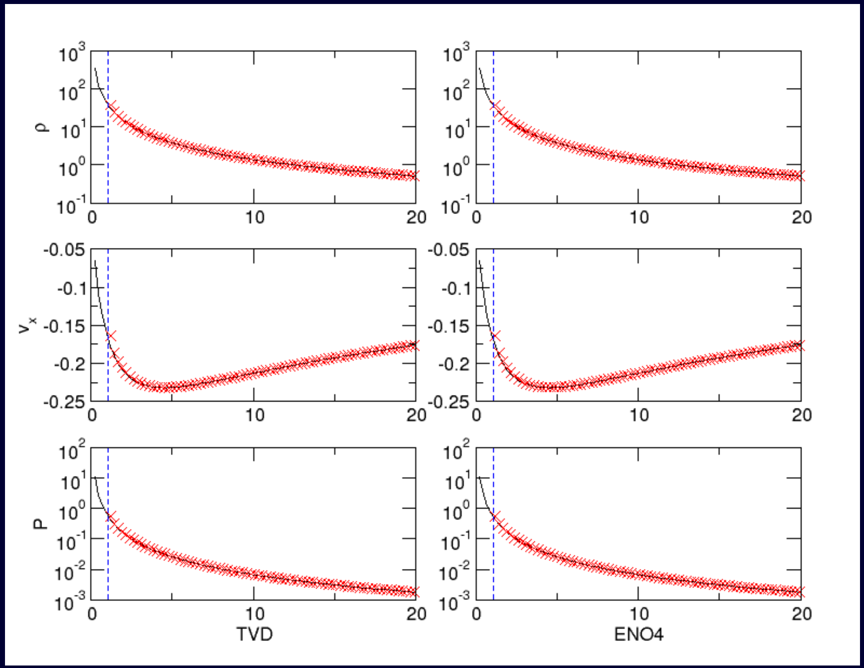


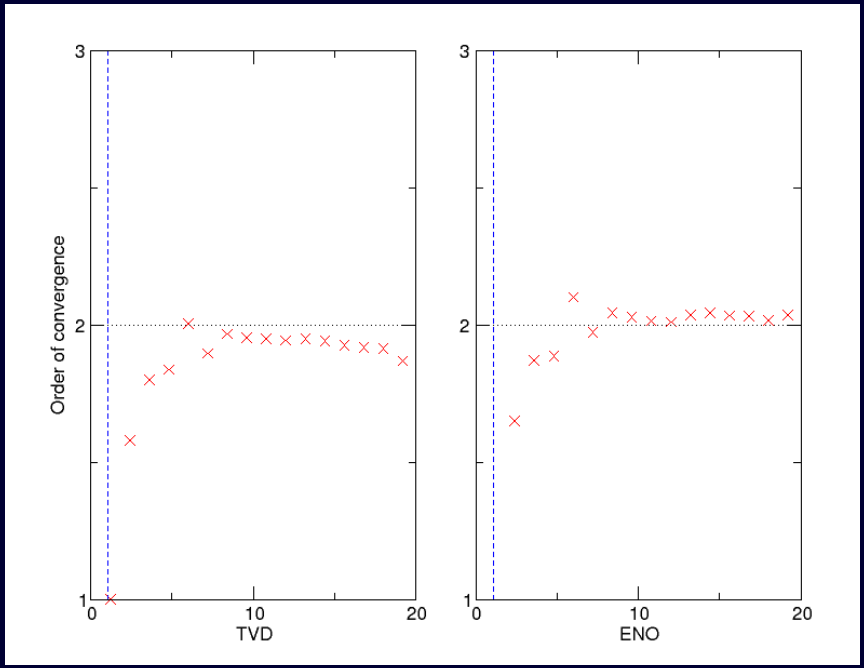
Copy to set up reconstruction. Force a trivial Riemann problem at the excision boundary.



Only fluxes for the boundaries of cells outside the excised region are required.

Excision and the Michel solution

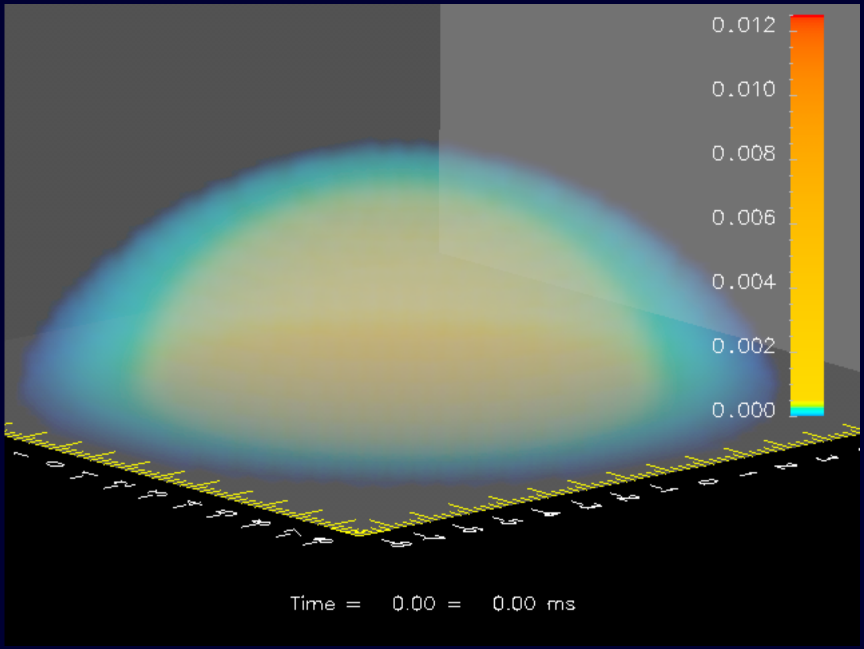




Rest mass density, a velocity component and the pressure are shown. The dashed blue line indicates the excision boundary. The excision method is stable, accurate and convergent, despite cubical excision.

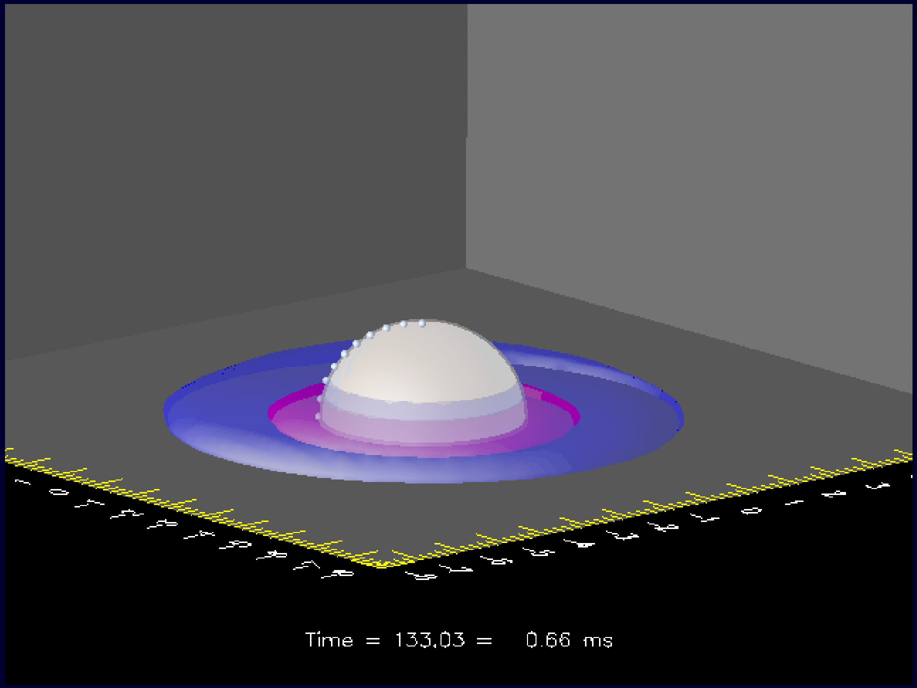
Work by IH, F. Löffler and A. Nerozzi.

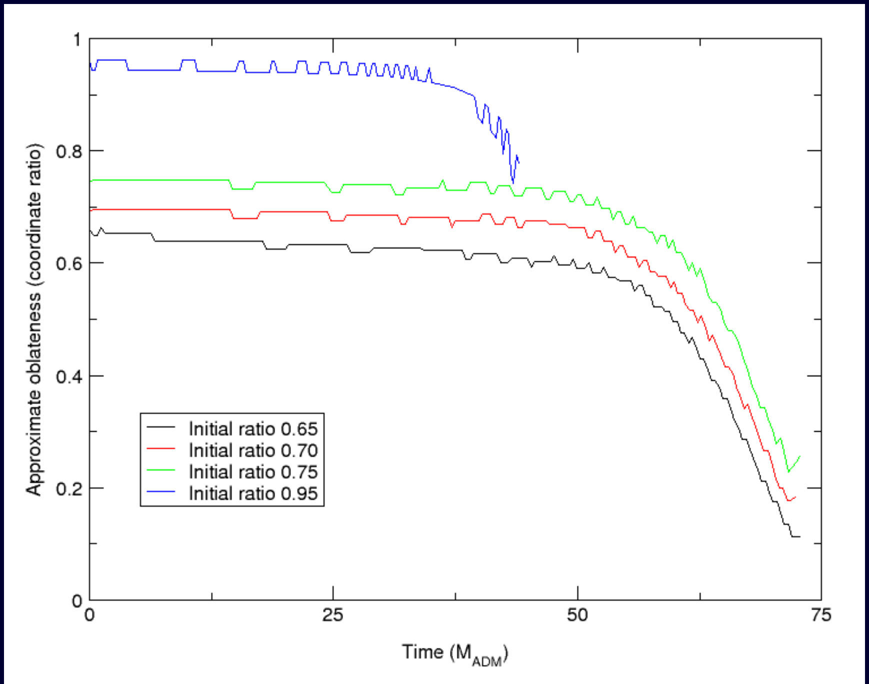
A collapse in progress



A rapidly rotating NS collapses to a black hole. The rest mass density is shown, along with the event horizon, some generators of the event horizon, and the apparent horizon, when these exist. Without excision the simulation fails almost immediately after horizon formation.

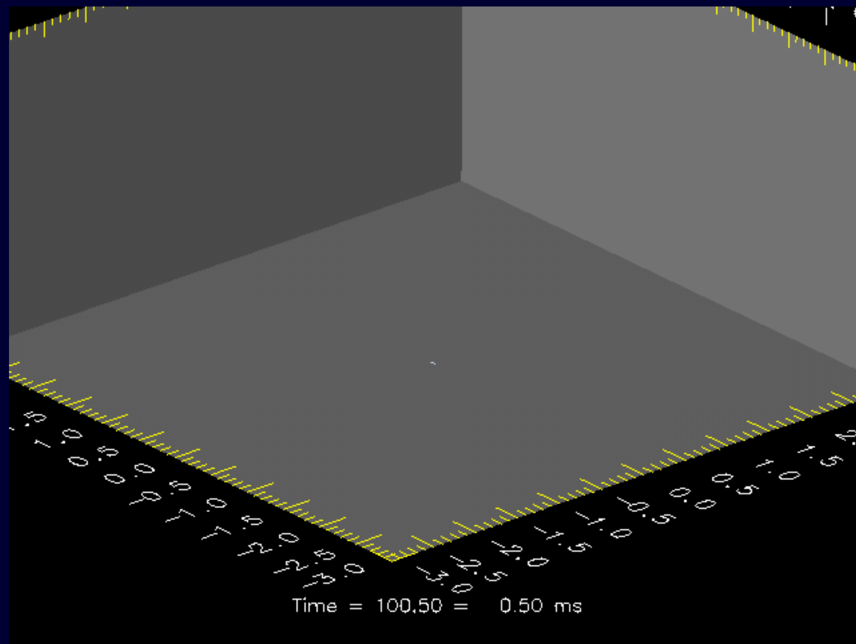
How oblate does the matter get?





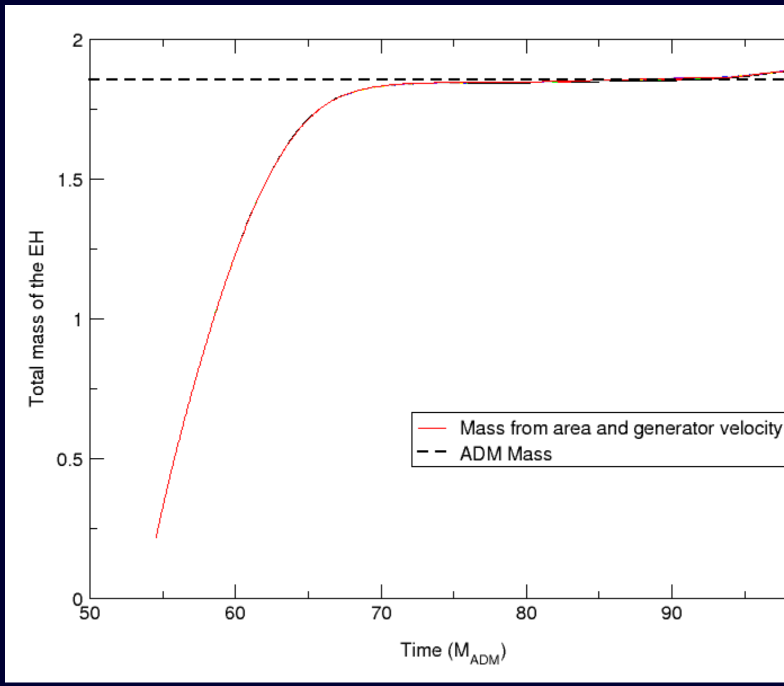
At high rotation rates the matter is sufficiently oblate (up to 10:1 ratio) for large amounts to remain outside the horizon. However, this is not stable, and the matter is accreted within at most $50M_{ADM}$ of the formation of the horizon.

The formation of the horizons



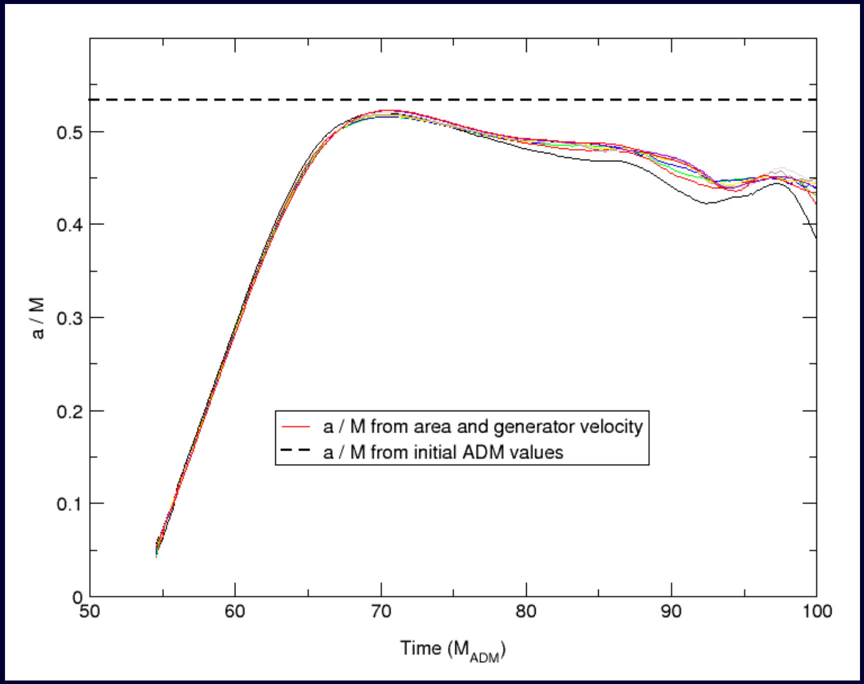
The event horizon forms at a point and rapidly grows. There is a gap (over $10M_{ADM}$) between the formation of the event and apparent horizons. The apparent horizon rapidly approaches the event horizon but is always contained within it.

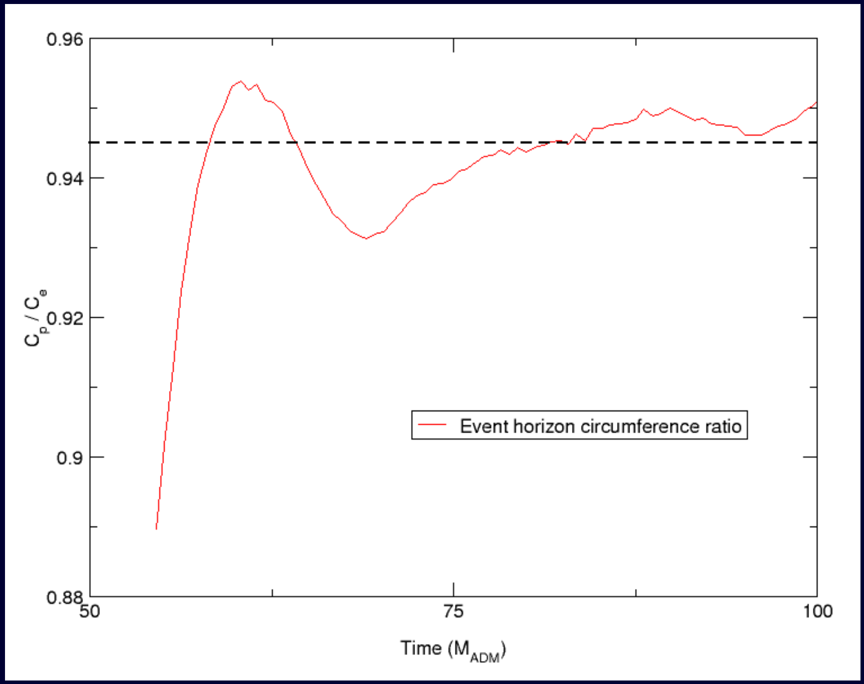
Physics from the horizons



We can bound the emitted energy by comparing the mass and angular momentum found from the event and apparent horizons with the total ADM mass and angular momentum of the initial data. Less than 1% of the mass is emitted.

The rotation rate of the horizon

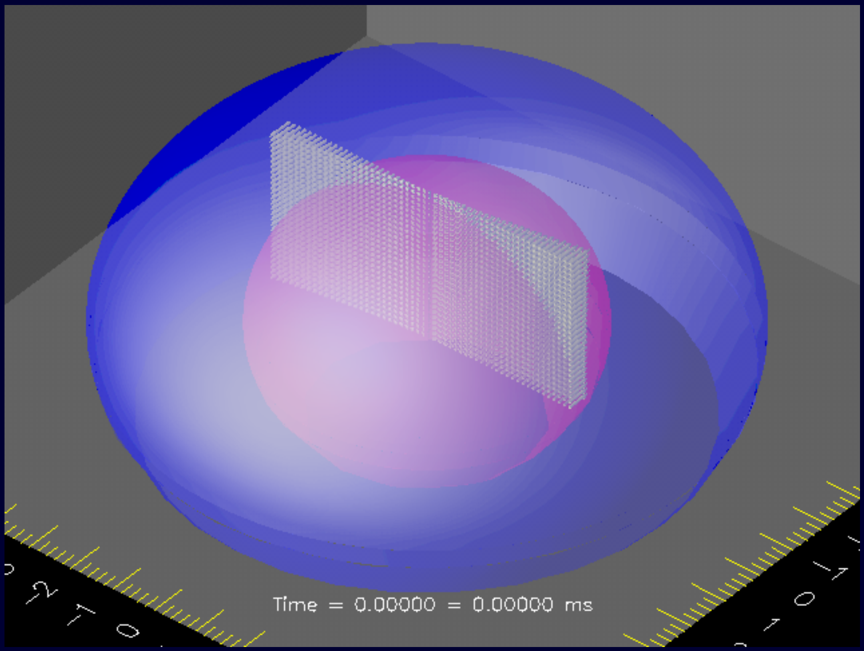




The rotation parameter a found from the generators and EH area give some indication of the angular momentum of the hole. Values from the distortion (from circumference ratios) of the EH and also the AH agree to within 10%.

Pushing the boundaries out

We can use mesh refinement to retain the resolution near the centre whilst pushing the boundaries out further.



Using *Carpet*, written by E. Schnetter, this simulation had the boundaries twice as far out using 10% of the resources.

Conclusions

- Using excision methods applied to the matter and spacetime fields, stable simulations of NS collapse can be performed sufficiently far past the formation of the BH to extract late time physics.

- It appears that stable disk structures are not formed when the initial data is a uniformly rotating polytrope. Even unstable structures require high rotation rates.

- Current simulations place an upper bound on the emitted energy of less than 1%.

- The use of mesh refinement allows us to compare the emitted energy calculated directly from wave extraction.