How does moderate progenitor rotation affect the gravitational wave signal from core-collapse supernovae?

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MPA

Gravitational waves

- Solution of the Einstein equations

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = \frac{8\pi G}{c^4}T_{\mu\nu}$$

R : Ricci scalar

$R_{\mu\nu}$: Ricci tensor

$g_{\mu\nu}$: Metric tensor

$T_{\mu\nu}$: Energy-momentum tensor

$$\boxed{g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}}$$

- Quadrupole radiation

$$Q^{ij} = \int \mathrm{d}^3x\rho(x^i x^j - \frac{1}{3}r^2\delta^{ij})$$

$$\boxed{\boldsymbol{h}^{TT}(\boldsymbol{X}, t) = \frac{1}{D}\left[A_+\boldsymbol{e}_+ + A_\times\boldsymbol{e}_\times\right]}$$

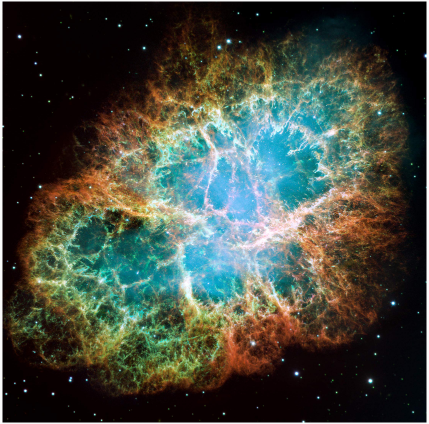
$$A_{\times/+} = f(\ddot{Q}^{ij})$$

- First direct detection by LIGO (Fall 2015)
- Two merging black holes (∼36 and 29 solar masses)

Why are gravitational waves from core-collapse supernovae interesting?

- Optical observations can not directly probe the central core
  - Photons from the core are absorbed by the stellar envelope
- Gravitational waves
  - Sensitive to the dynamics of the core
  - Propagates unhindered through the star
- Neutrinos

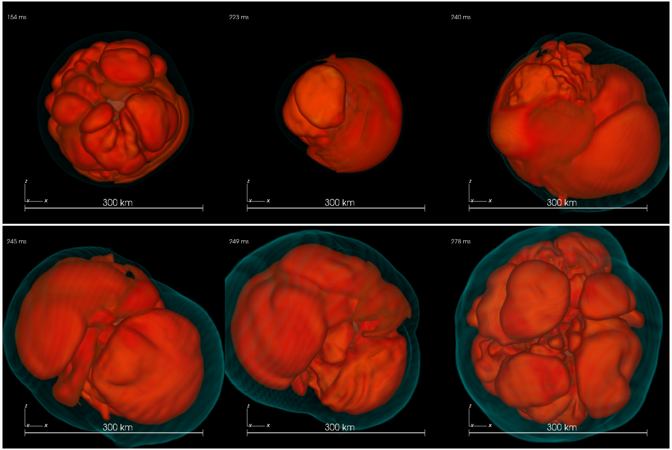
Image Credit: NASA, ESA, J. Hester



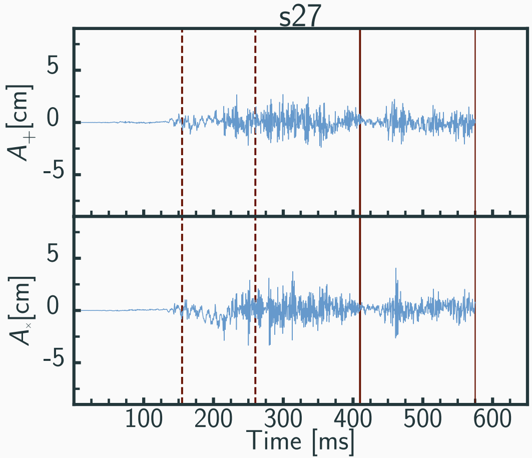
Why are gravitational waves from core-collapse supernovae interesting?

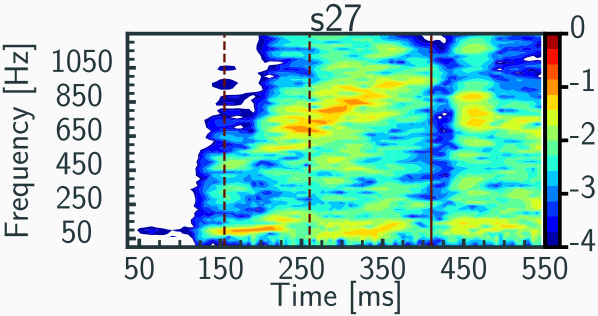
- Stalled accretion shock
  - Hot bubble convection
  - Large scale shock deformation (SASI)
- Shock revival
  - Neutrino heating
  - Supported by SASI activity

Image credit:
F.Hanke et al 2013



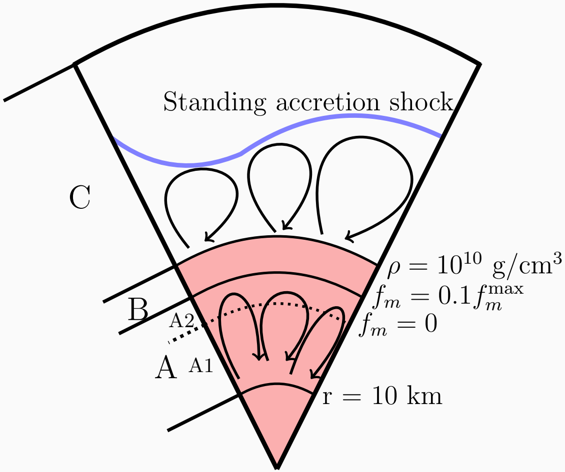
Non-rotating models





Non-rotating models

- Low frequency emission (Kuroda 16, Andresen 17)
  - Standing accretion shock instability
  - Post-shock volume mass distribution
  - Interaction with proto-neutron star
- High frequency emission (Marek 09, Murphy 09, Müller 13)
  - Proto-neutron star convection
  - Hot bubble convection



The effects of rotation

Rapid rotation:

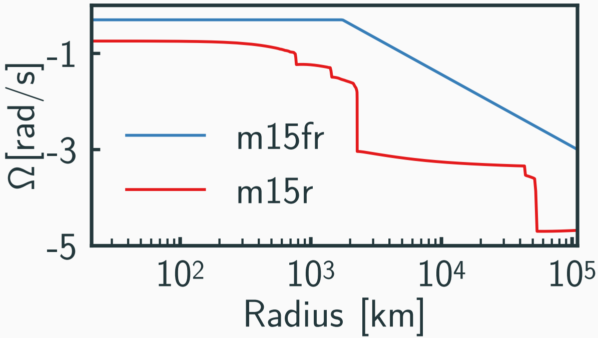
- Low T/W instability
- Bar-like deformation of the inner core
- Bounce signal

- The influence of moderate rotation
- Progenitor: $15M_{\odot}$ (Woosley et al 2005)

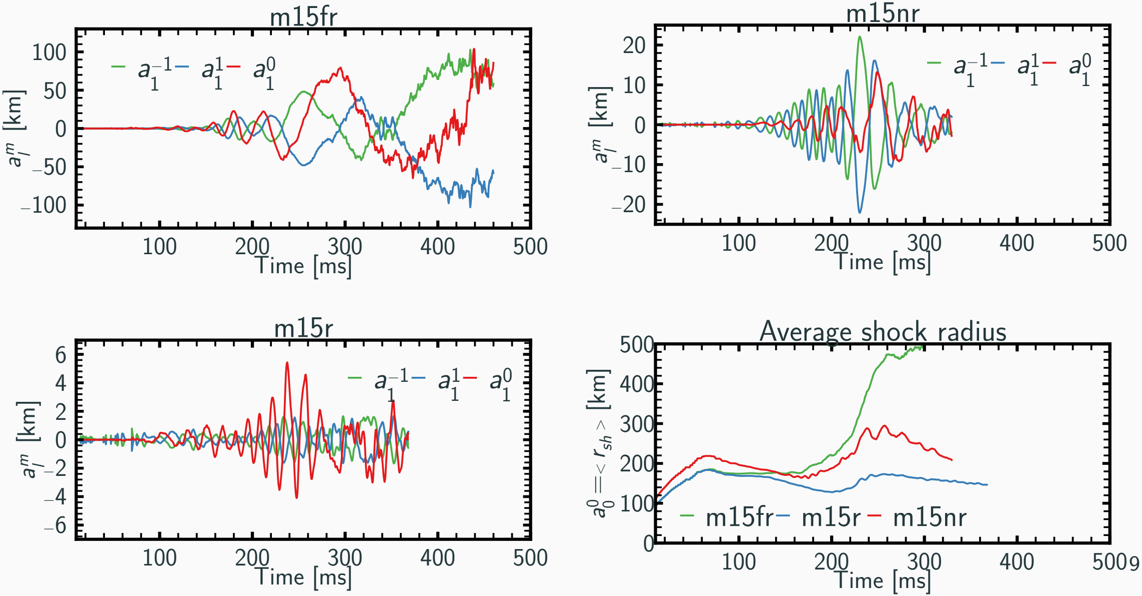
The rotating models

Numerical simulations:

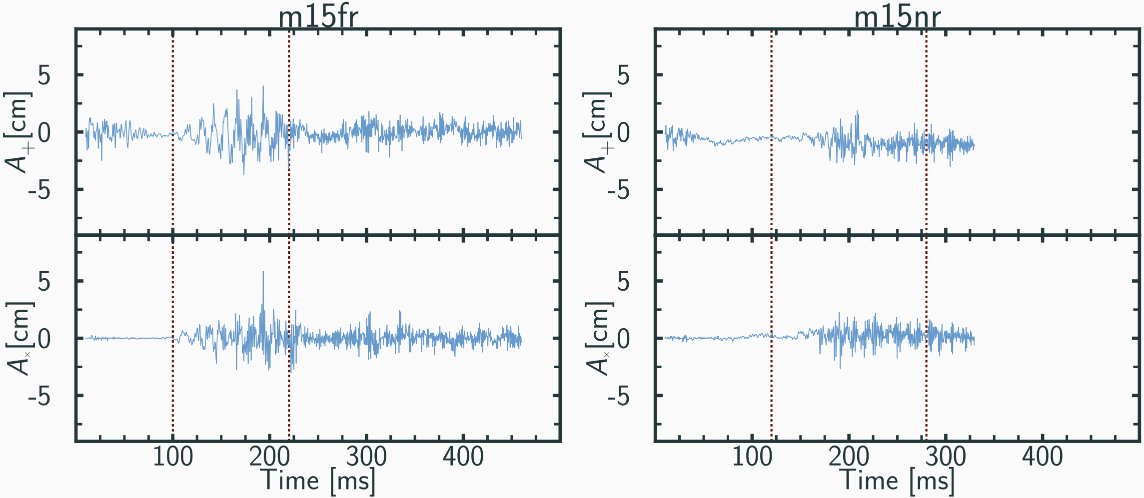
- Two rotating models: m15r and m15fr
  - One successful explosion: m15fr
- One non-rotating model: m15nr



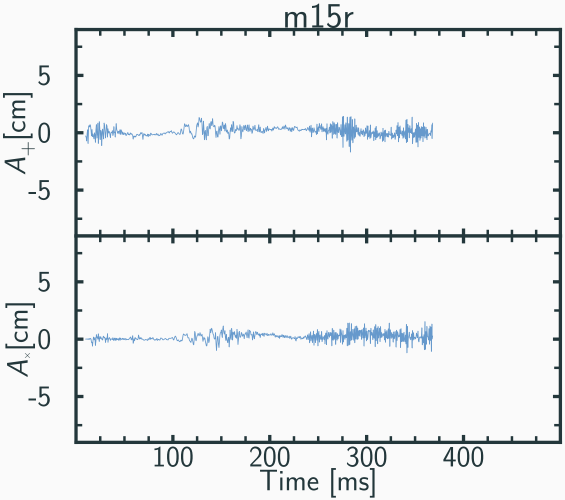
Model dynamics



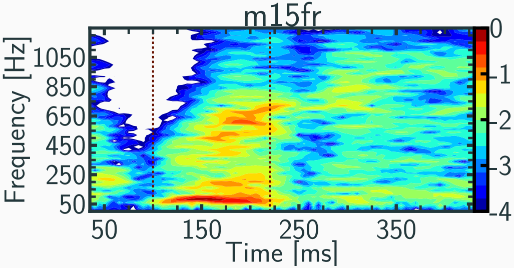
Waveforms

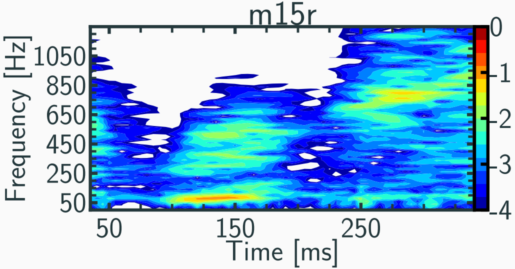


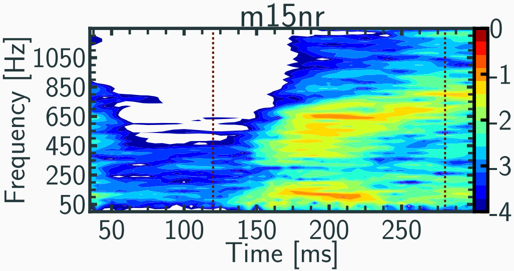
Waveforms



Spectrograms

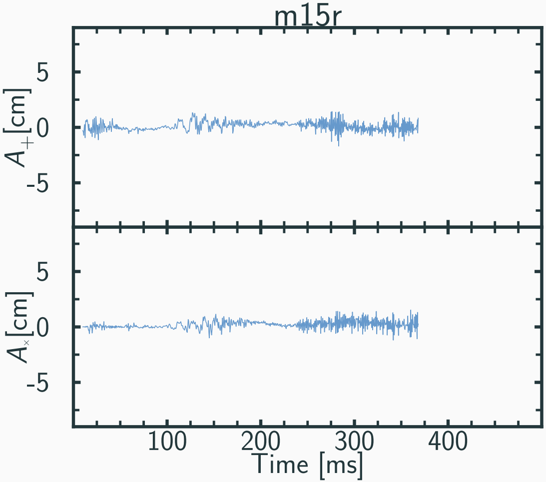






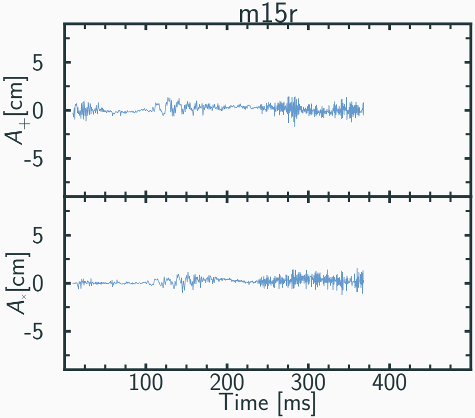
- Similar to the non-rotating models
- The signal is weakest in model m15r
- No strong SASI activity in model m15r

The influence of rotation



- Growth of the SASI
- PNS convection

Proto-neutron star convection



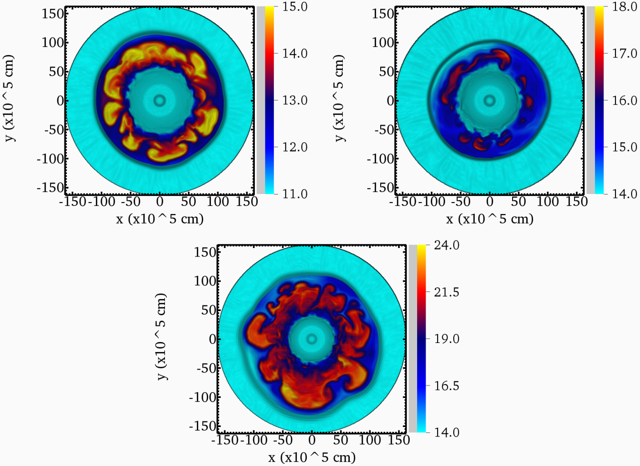
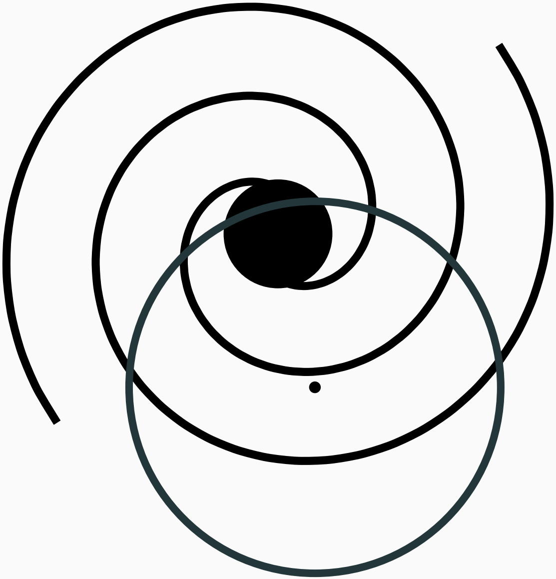


Figure 1: The entropy per baryon in the xy-plane of the Yin-grid for model m15r. Shown at at 167, 210, and 343 ms post bounce.

Growth of the SASI

- Linear growth (Blondin 17, Yamasaki & Foglizzo 08)
- Non-linear regime (Kazeroni 17)
- Resolution (Hanke 12, Abdikamalov 15)

Detection prospects



- Advance LIGO (D $\sim$ 1 kpc)
- Einstein Telescope (D $\sim$ 10 kpc)

Conclusions

- Low-frequency: SASI
- High-frequency: PNS convection
- Rotation reduces the signal from PNS convection
- Interplay between the SASI and rotation is not fully understood, but important for the strength of the low-frequency signal
- A Galactic event would be detectable

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