# Can Gravitational Waves provide insights about the Core-Collapse Supernova mechanism?

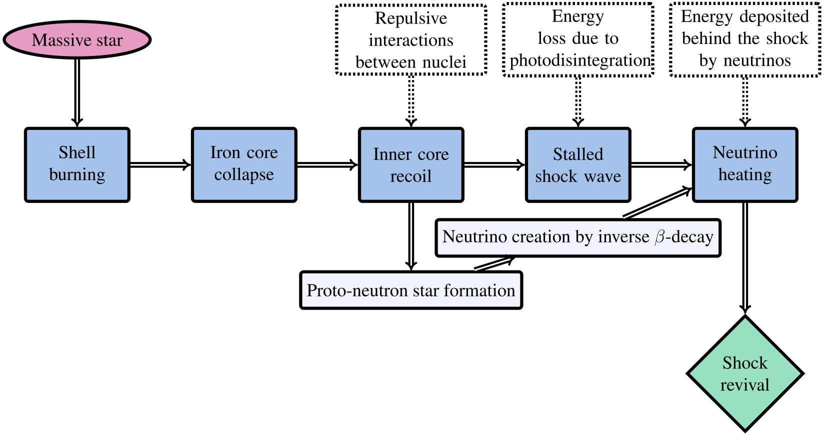
Haakon Andresen

MPA

02.09.2016

Ewald Müller, Thomas Janka and Bernhard Müller (arXiv:1607.05199)

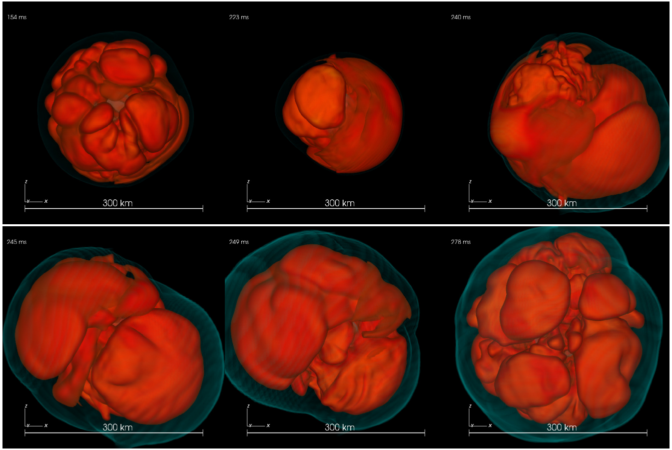
# Explosion mechanism



# Post bounce

- 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



# Numerical models

Progenitors:
$11.2M_\odot$, $20M_\odot$ and $27M_\odot$
(Woosley et al 2002 & 2007)

Numerical simulations

- Three non-exploding models: s11.2, s20, s27 (Hanke et al 2013)
- One successful explosion: s20s (Melson et al 2015)
  - Strange quark contributions to the nucleon spin

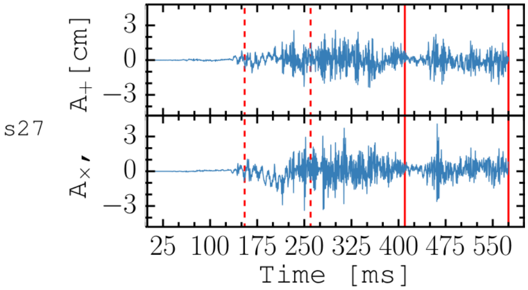
# Quadrupole radiation

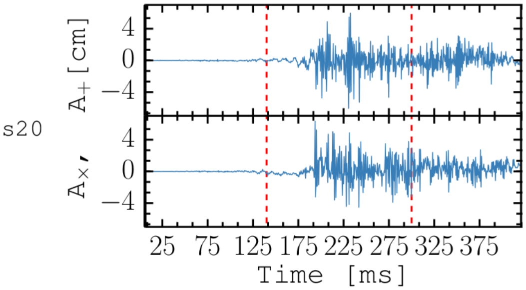
$$Q^{ij} = \int \mathrm{d}^3 x \rho (x^i x^j - \frac{1}{3} r^2 \delta^{ij})$$

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

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

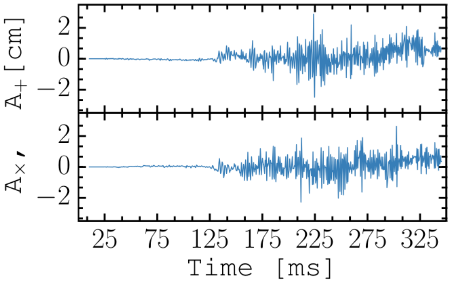
# Wave forms


s27
$A_+$ [cm]
$A_\times$
3
0
−3
3
0
−3
25 100 175 250 325 400 475 550
Time [ms]

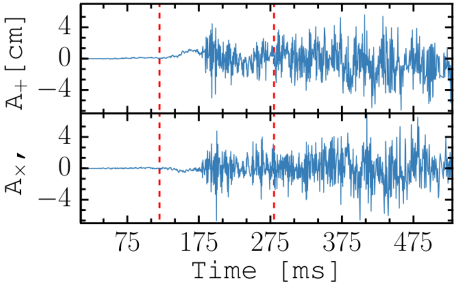

s20
$A_+$ [cm]
$A_\times$
4
0
−4
4
0
−4
25 75 125 175 225 275 325 375
Time [ms]

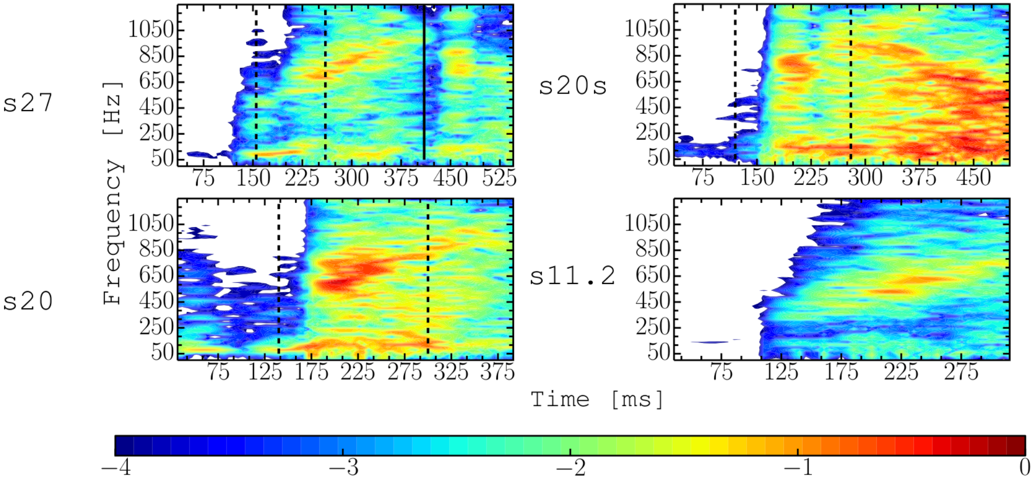
## Wave forms

s11.2




s20s

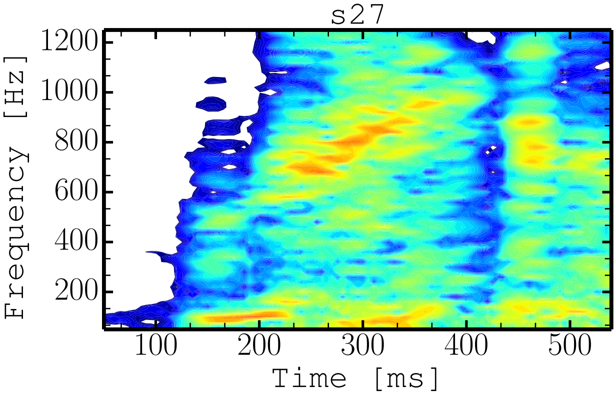




s27
s20s
s20
s11.2
Frequency [Hz]
Time [ms]
1050
850
650
450
250
50
75
150
225
300
375
450
525
125
175
275
325
−4
−3
−2
−1
0

# Low frequency signal

- Large scale shock deformation (SASI)
  - Only seen in models with strong SASI activity
  - Frequency overlap with the SASI



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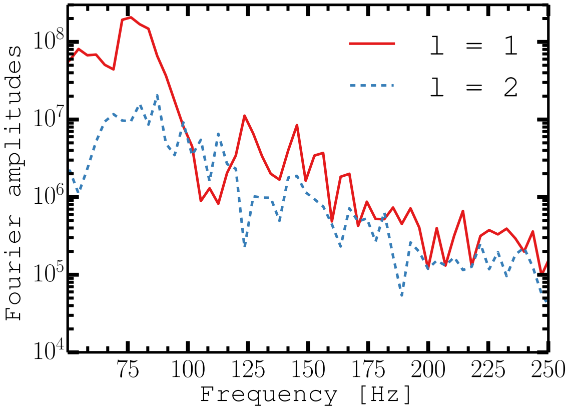
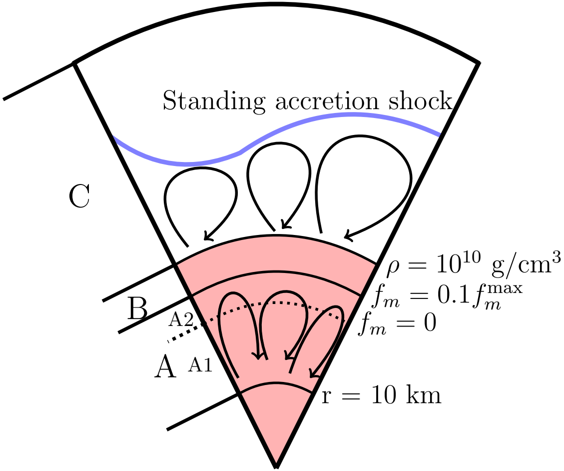


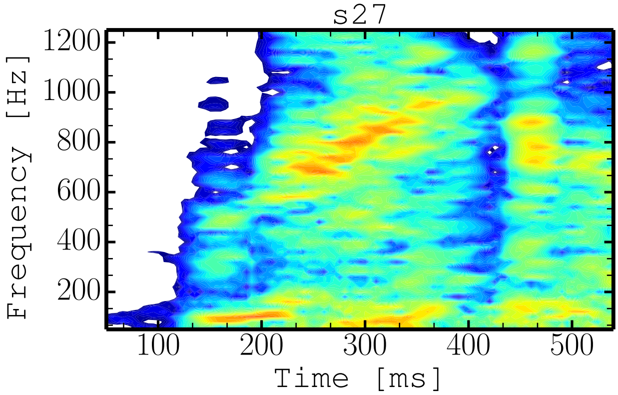
## Low frequency signal

- Large scale shock deformation
  - Post-shock volume mass distribution
  - Interaction with proto-neutron star



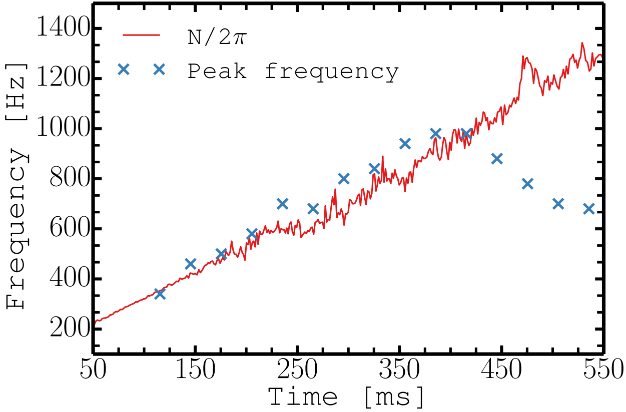
# High frequency signal

- Present in all models
- Consistent with the theoretical frequency of buoyancy driven effects



# High frequency signal

- Present in all models
- Consistent with the theoretical frequency of buoyancy driven effects
- Convection inside the proto-neutron star




$$f_N = N/2\pi = \frac{1}{2\pi}\sqrt{\frac{1}{\rho}\frac{\partial\Phi}{\partial r}\left[\frac{1}{c_s^2}\frac{\partial P}{\partial r} - \frac{\partial\rho}{\partial r}\right]}$$

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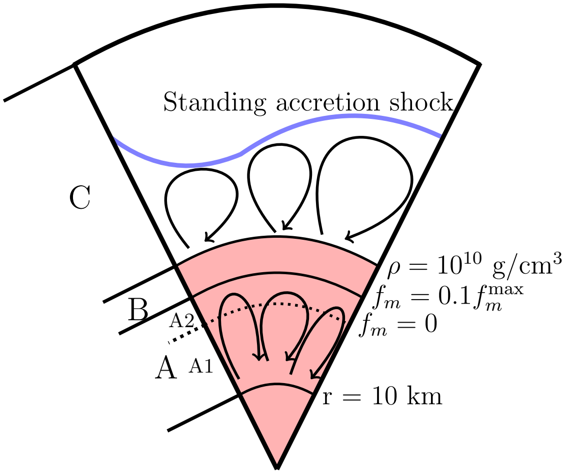
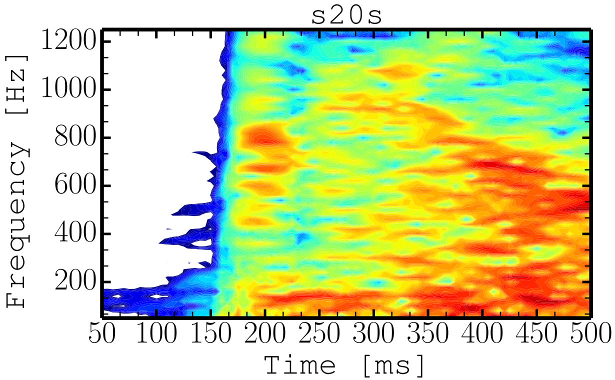


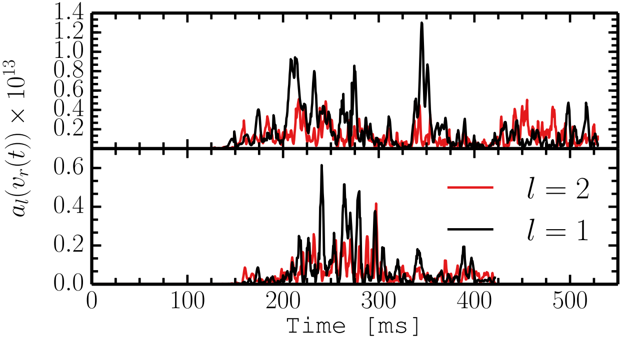
## Exploding model

- Similar to non-exploding models before onset of shock expansion
- Increased gravitational wave emission



# Exploding model

- Geometry of the convectively unstable region with in the PNS
- Shifts to a $l = 2$ dominated state




$$\sum_{m=-l,l} |a_l^m(t)|^2 \quad (l = 1, 2), \tag{1}$$

$$a_l^m(t_n) = \frac{(-1)^{|m|}}{\sqrt{4\pi(2l+1)}} \int v_r(\theta, \phi, t) Y_l^m \mathrm{d}\Omega. \tag{2}$$

## Detection prospects

- Optimal orientate detector signal-to-noise ratio
  - Ratio of power in the low and high frequency band
- Advance LIGO (D $\sim$ 1 kpc)
- Einstein Telescope (D $\sim$ 10 kpc)

# Conclusions

- Core collapse supernovae are a promising source for gravitational waves and more importantly gravitational waves can provide insight into the collapse scenario
- Good detection possibilities in future detectors

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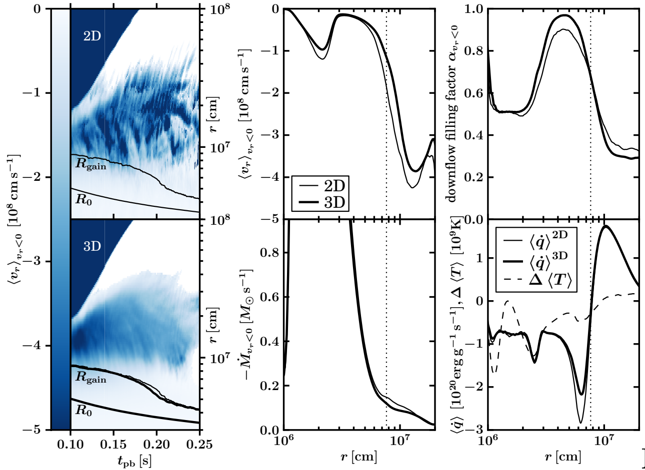


Melson et al 2015

| | s27 | | | | s20 | | | | s11.2 | | | | s20s | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Low | High | Total | Low/High | Low | High | Total | Low/High | Low | High | Total | Low/High | Low | High | Total |
| AdvLIGO | 3.7 | 4.5 | 8.8 | 0.82 | 5.3 | 7.7 | 9.4 | 0.82 | 1.3 | 4.1 | 4.3 | 0.32 | 10.2 | – | – |
| ET-C | 50.0 | 64.0 | 81.3 | 0.78 | 73.9 | 109.3 | 131.9 | 0.83 | 18.1 | 50.9 | 53.9 | 0.36 | 139.7 | – | – |
| ET-B | 78.5 | 73.7 | 107.7 | 1.07 | 113.9 | 127.0 | 170.6 | 0.74 | 28.0 | 67.3 | 72.8 | 0.42 | 217.3 | – | – |

50 million core hours
1/2 year
SuperMUC (LRZ Garching) and MareNostrum (Barcelona)