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

Haakon Andresen

15.12.2016

MPA

Bernhard Müller, Ewald Müller and Thomas Janka arxiv:1607.05199

Quadrupole radiation

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

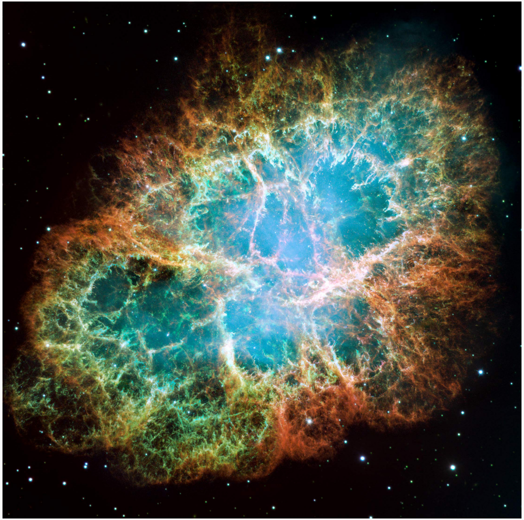
$$\boxed{\boldsymbol{h}^{TT}(\boldsymbol{X}, t) = \frac{1}{D} \left[A_+ \boldsymbol{e}_+ + A_\times \boldsymbol{e}_\times \right]}$$

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

Core collapse

- Massive stars (Ertl et al 2015)
- Shell burning
- Iron core collapse
- Repulsive nucleon interactions
- Core bounce

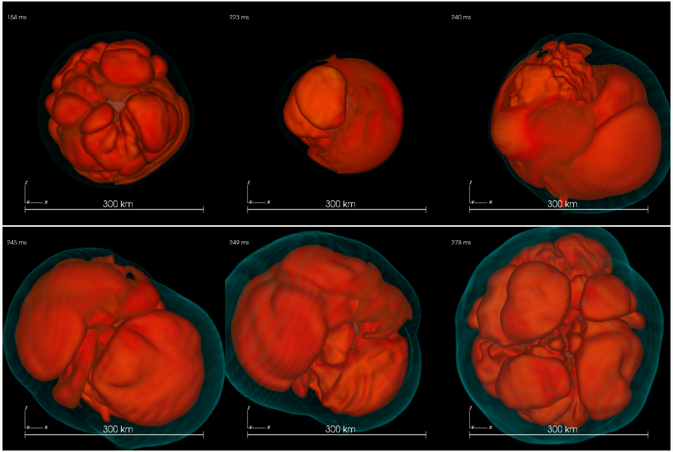
Image Credit: NASA, ESA, J. Hester



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

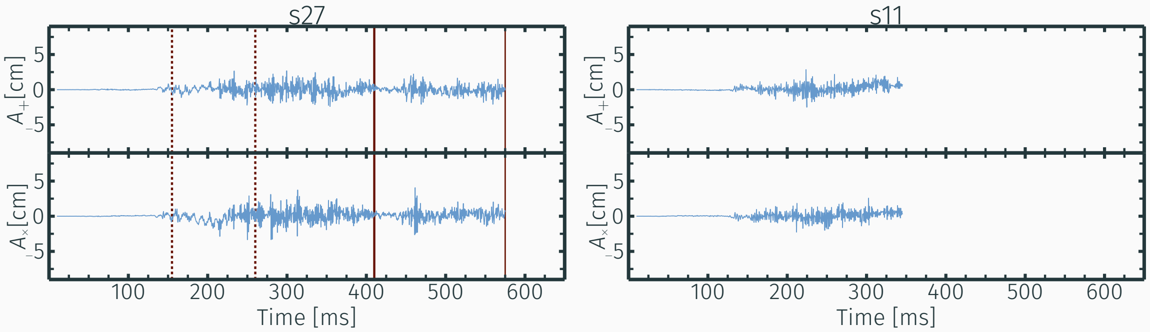
Progenitors:

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

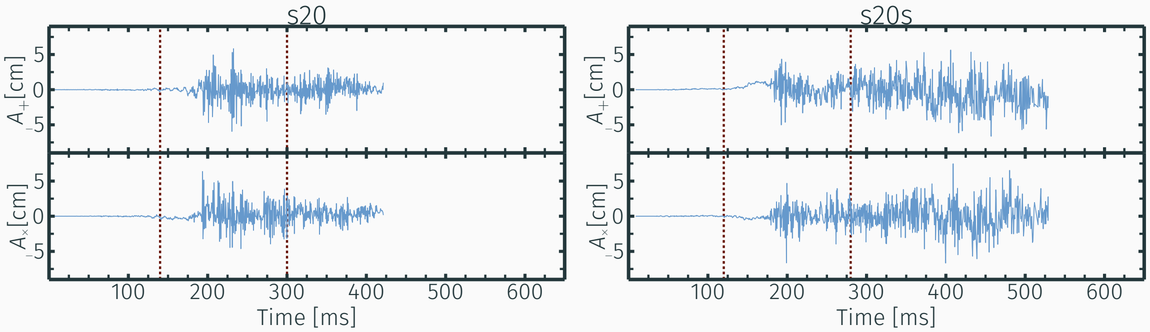
Numerical simulations

- 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

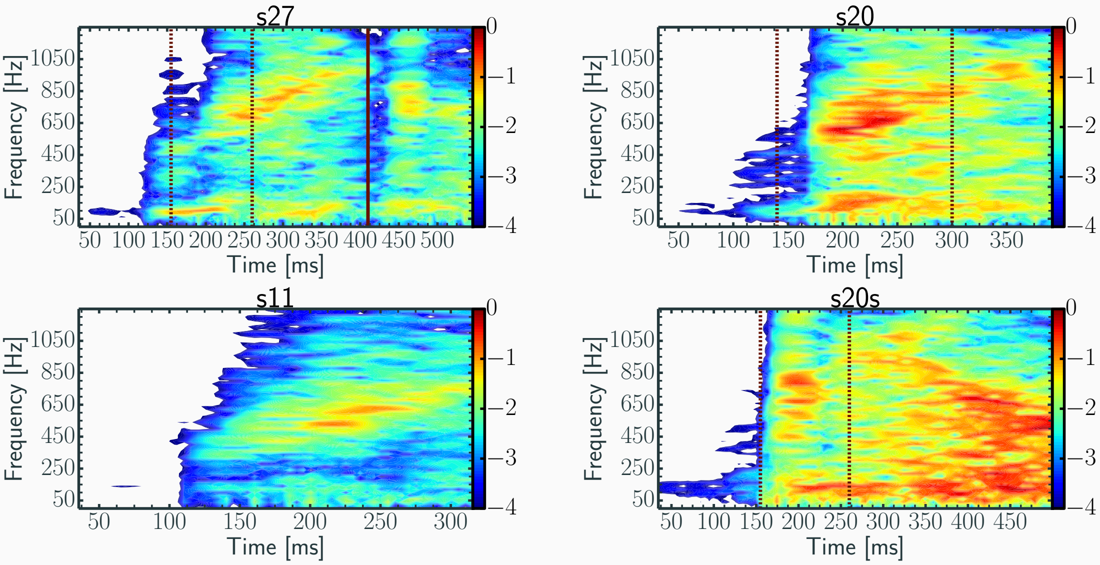
Waveforms



Waveforms

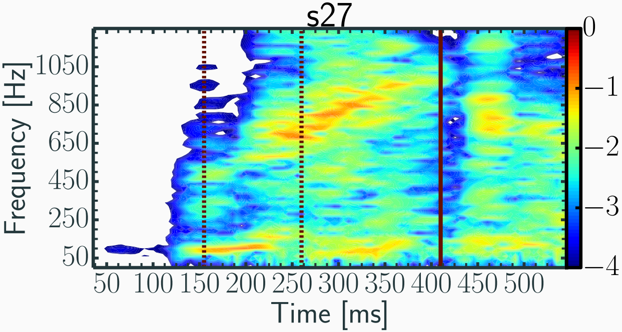


Spectrograms



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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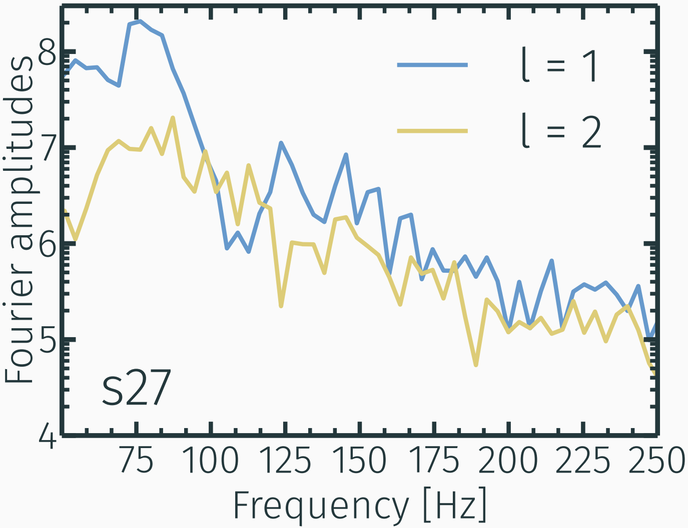
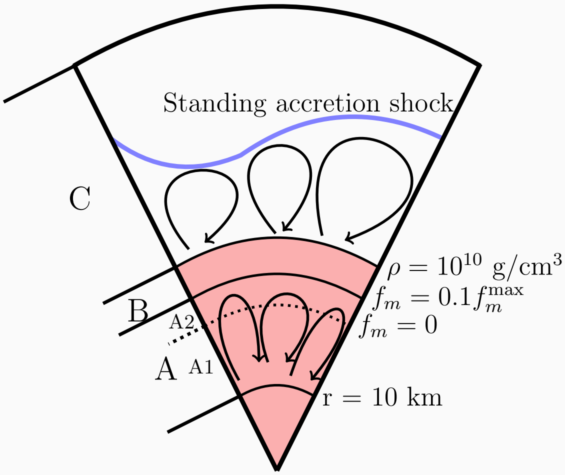


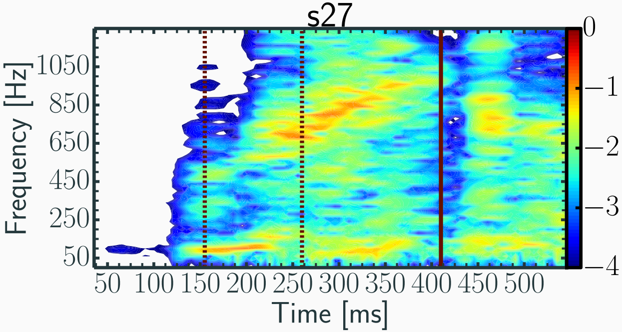
Low frequency signal

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



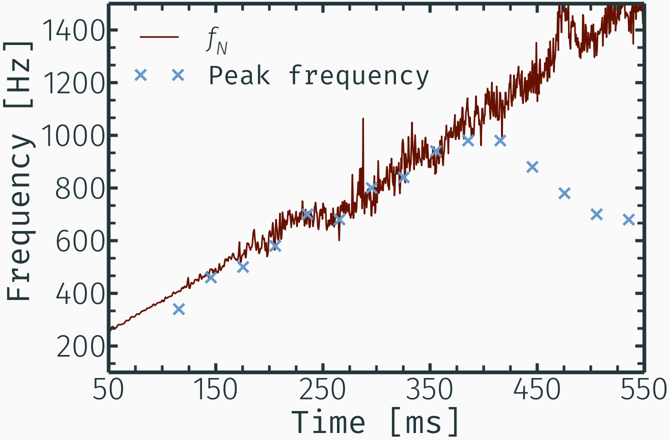
High frequency signal

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



High frequency signal

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



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

High frequency signal

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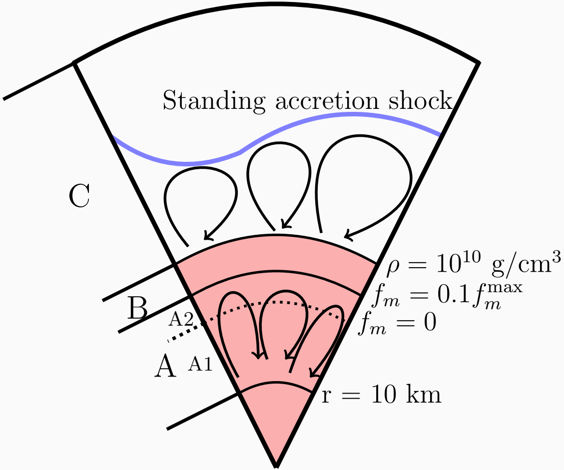
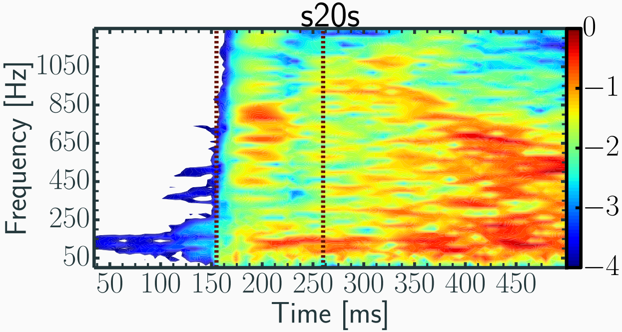
- Consistent with the theoretical frequency of buoyancy driven effects
- **Convection inside the proto-neutron star**



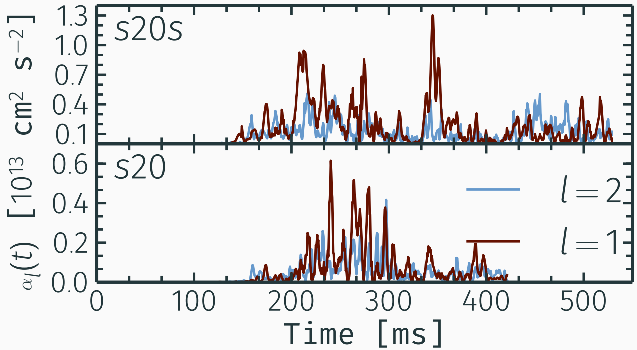
Exploding model

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



Exploding model

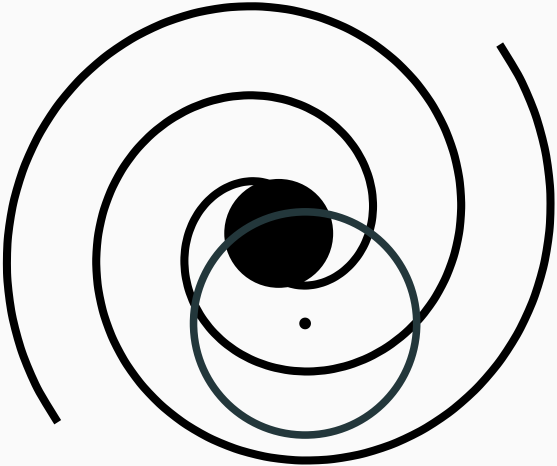
- Geometry of the convectively unstable region with in the PNS
- Shifts to a $l = 2$ dominated state



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

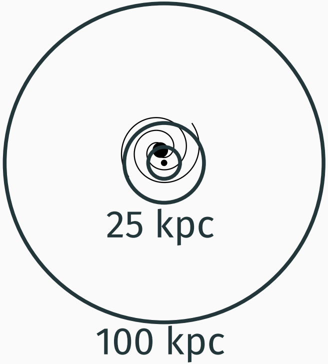
$$a_l^m(t_n) = \frac{(-1)^{|m|}}{\sqrt{4\pi(2l+1)}} \int v_r(\theta, \phi, t) Y_l^m \mathrm{d}\Omega. \tag{2}$$

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)

Detection prospects



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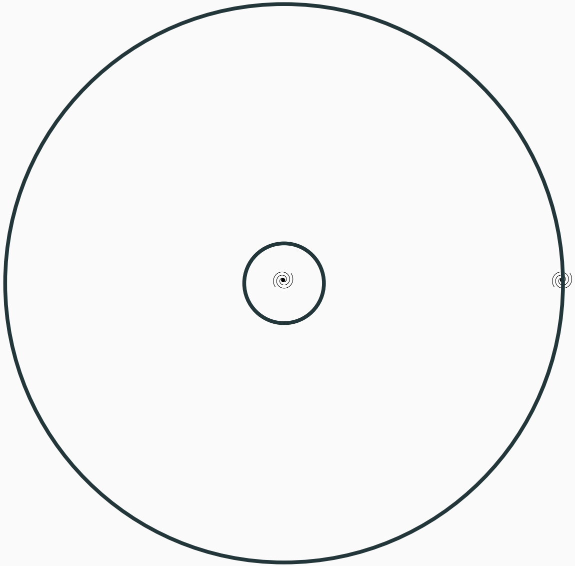

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  - Ratio of power in the low and high frequency band
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Conclusions

- Low frequency: SASI
- High frequency: PNS convection
- Good detection possibilities in future detectors

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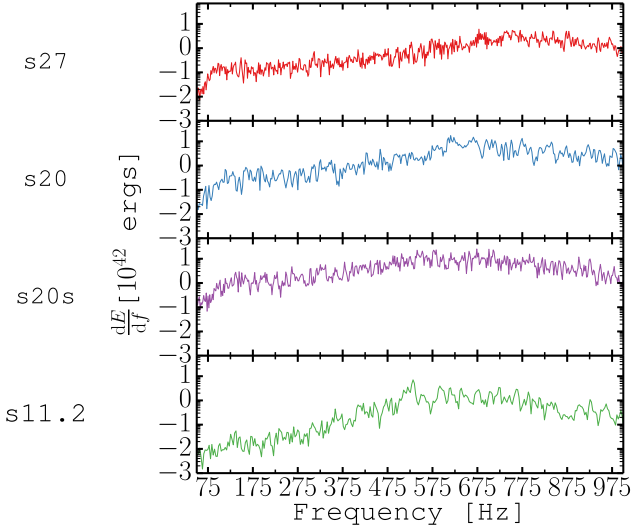
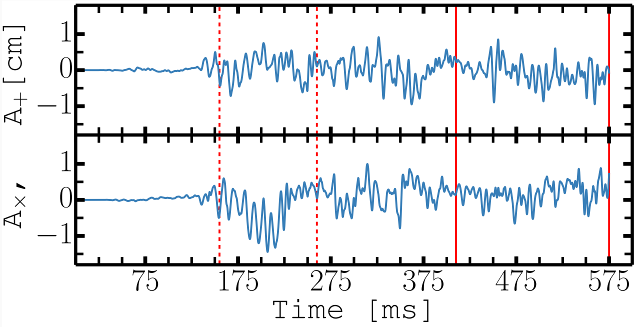
Energy

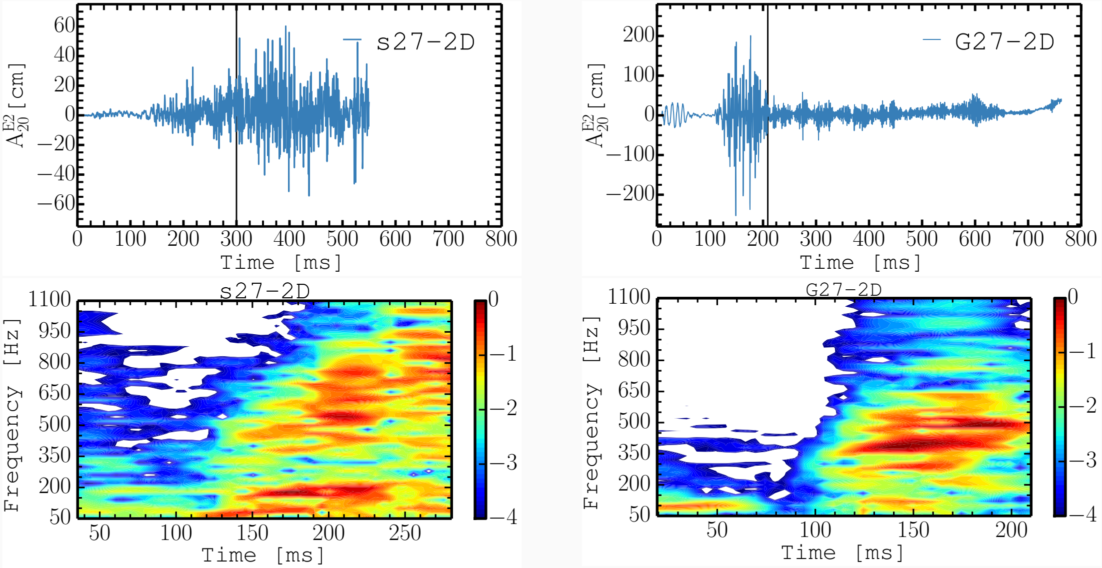


s27
s20
s20s
s11.2
$\frac{dE}{df}$ [10^{42} ergs]
1
0
−1
−2
−3
75 175 275 375 475 575 675 775 875 975
Frequency [Hz]

Low frequency amplitude

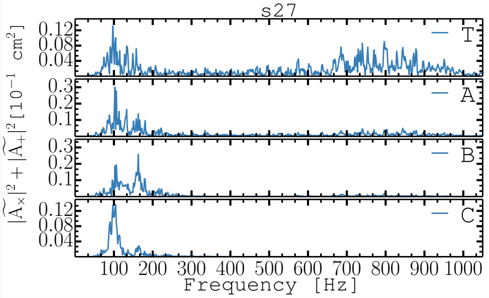


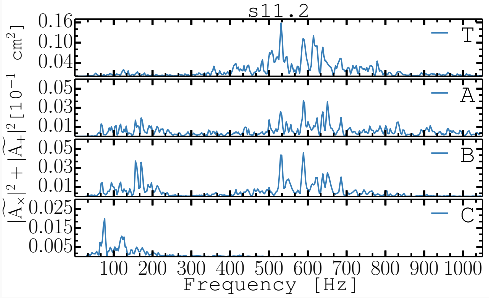
2D Models

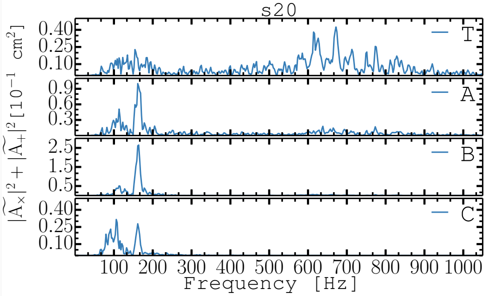


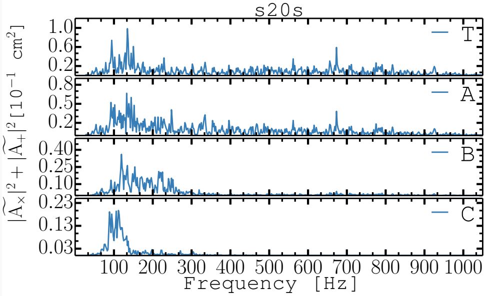
s27-2D
G27-2D
A_{20}^{E2} [cm]
Time [ms]
Frequency [Hz]
0
100
200
300
400
500
600
700
800
60
40
20
−20
−40
−60
−100
−200
1100
950
800
650
500
350
200
50
150
250
−1
−2
−3
−4

Cuts

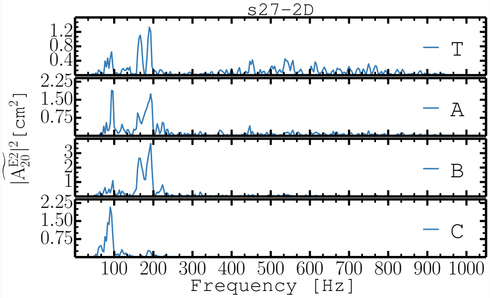

s27
$|\tilde{A}_\times|^2 + |\tilde{A}_+|^2\,[10^{-1}\ \mathrm{cm}^2]$
T
A
B
C
0.12 0.08 0.04
0.3 0.2 0.1
0.3 0.2 0.1
0.12 0.08 0.04
100 200 300 400 500 600 700 800 900 1000
Frequency [Hz]


s11.2
$|\tilde{A}_\times|^2 + |\tilde{A}_+|^2\,[10^{-1}\ \mathrm{cm}^2]$
T
A
B
C
0.16 0.10 0.04
0.05 0.03 0.01
0.05 0.03 0.01
0.025 0.015 0.005
100 200 300 400 500 600 700 800 900 1000
Frequency [Hz]

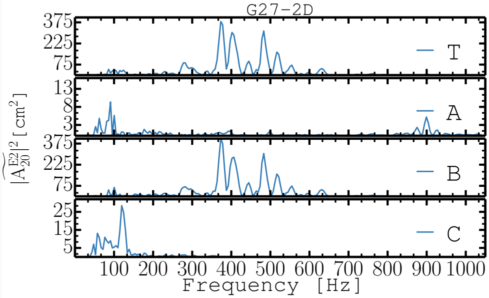

s20
$|\tilde{A}_\times|^2 + |\tilde{A}_+|^2\,[10^{-1}\ \mathrm{cm}^2]$
T
A
B
C
0.40 0.25 0.10
0.9 0.6 0.3
2.5 1.5 0.5
0.40 0.25 0.10
100 200 300 400 500 600 700 800 900 1000
Frequency [Hz]


s20s
$|\tilde{A}_\times|^2 + |\tilde{A}_+|^2\,[10^{-1}\ \mathrm{cm}^2]$
T
A
B
C
1.0 0.6 0.2
0.8 0.5 0.2
0.40 0.25 0.10
0.23 0.13 0.03
100 200 300 400 500 600 700 800 900 1000
Frequency [Hz]

Cuts



s27-2D
T
A
B
C
1.2
0.8
0.4
2.25
1.50
0.75
3
2
1
2.25
1.50
0.75
100 200 300 400 500 600 700 800 900 1000
Frequency [Hz]



G27-2D
T
A
B
C
375
225
75
13
8
3
375
225
75
25
15
5
100 200 300 400 500 600 700 800 900 1000
Frequency [Hz]

- Impact on the dynamics
  - Prompt convection
    - Dimmelmeier et al. 2008
    - Ott et al. 2012
  - Enhanced growth rate of the spiral SASI
    - Blondin & Mezzacappa 2007
    - Yamasaki & Foglizzo 2008
    - Iwakami et al. 2009
    - Kazeroni et al. 2016
    - Janka et al. 2016
- Rotation
  - Stellar evolution
    - Heger et al. 2005 (Magnetic fields)
    - Cantiello et al. 2014 (Winds, asteroseismology)
  - Pulsars
    - Popov & Turolla 2012
    - Noutsos et al. 2013

Name of Galaxy	Distance (kly)
Sagittarius Dwarf	78±7
Ursa Major II	100±156
Coma Berenices Dwarf	144±136
Large Magellanic Cloud	165±5
Small Magellanic Cloud	195±15
Boötes Dwarf	197±9
Ursa Minor Dwarf	215±104
Sculptor Dwarf	258±137
Draco Dwarf	267±204
Sextans Dwarf	280±130
Ursa Major I	325