Max Planck Institute for Gravitational
Physics
(Albert Einstein Institute)

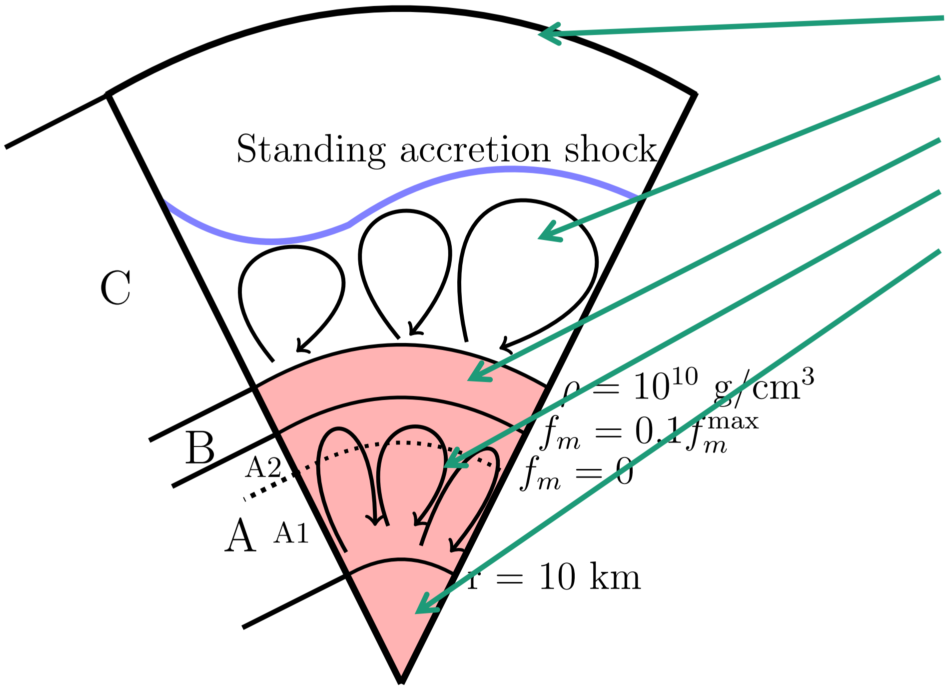
Vniversitat de València

CoCoNut Meeting 2018
CEA (Saclay, France), November 14-16, 2018

Towards core-collapse parameter estimation with gravitational-waves

Alejandro Torres-Forné

Introduction – GW emission



Shock

Hot bubble →convection/SASI

PNS surface (stable) → g-modes

PNS interior →convection

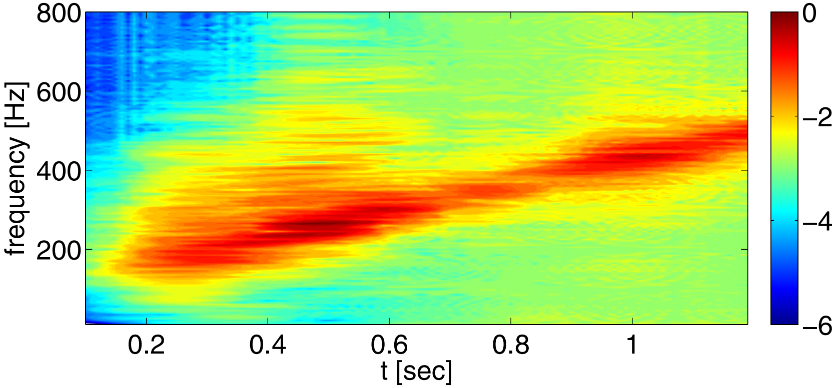
Inner core (stable)→g-modes

Andresen et al 2016

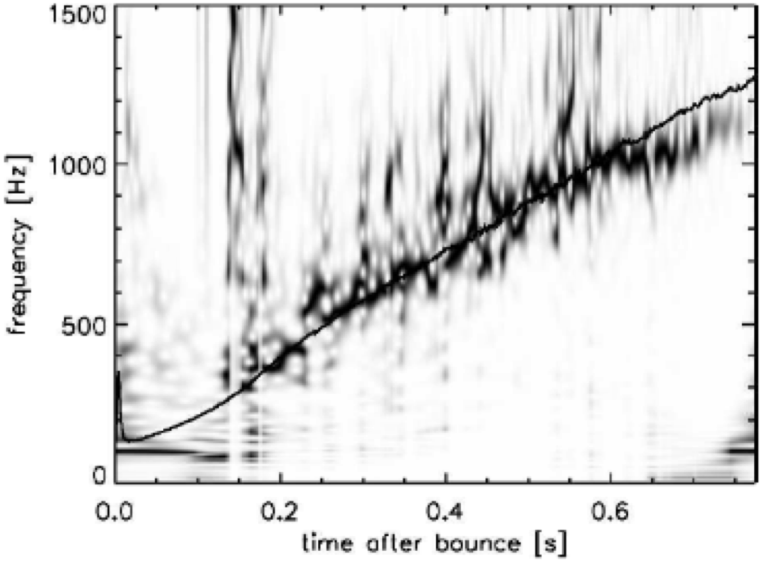
The most likely nearby CC event is from a non-rotating progenitor (neutrino-driven)

The proto-neutron star (PNS) is the source of most of the GW emission

Gravitational wave signal (Supernovae)

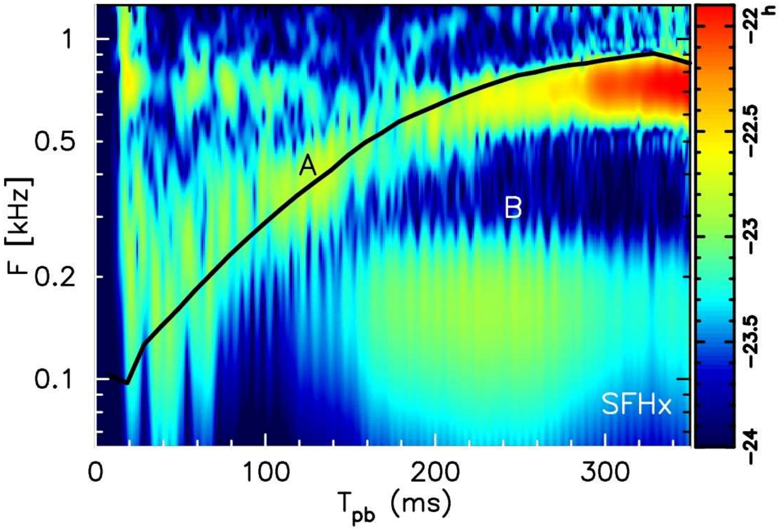


Müller et al 2012



Müller et al 2013

- Arches with raising frequency associated with g-modes of the PNS
- Observed systematically in all simulations (2D and 3D)
- If SASI is present, additional SASI modes.

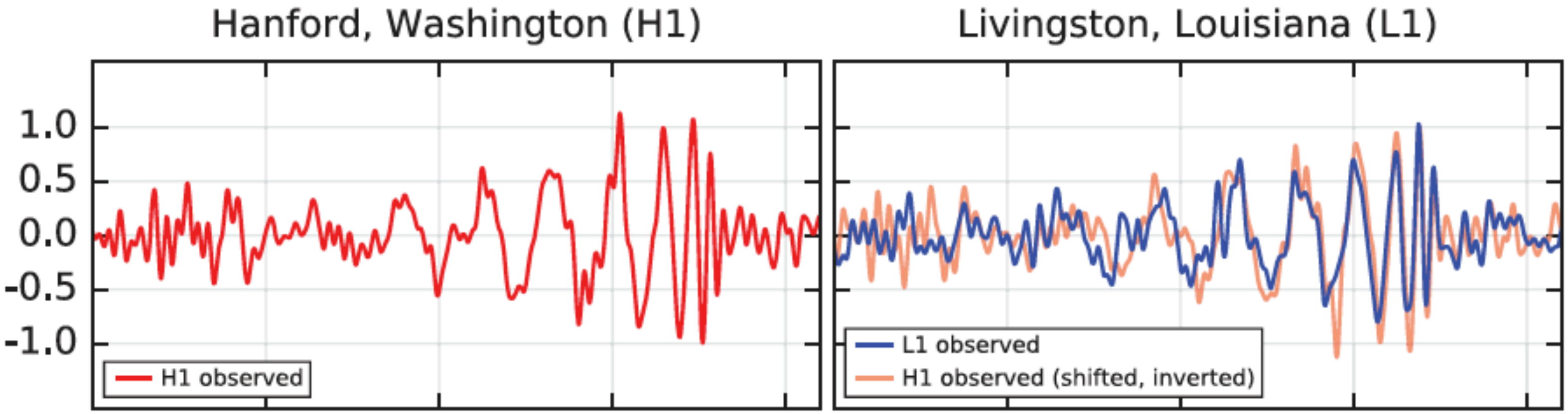


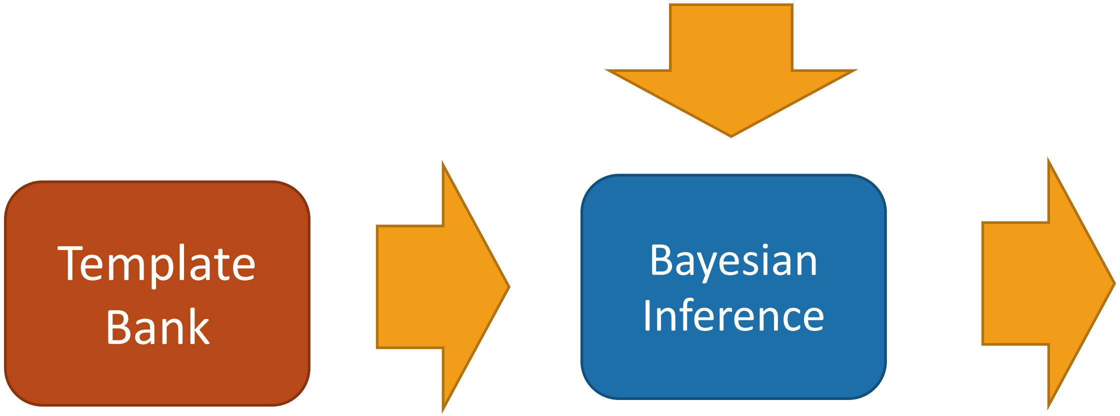
Kuroda et al 2016

Motivation

Parameter estimation for binary black hole mergers.

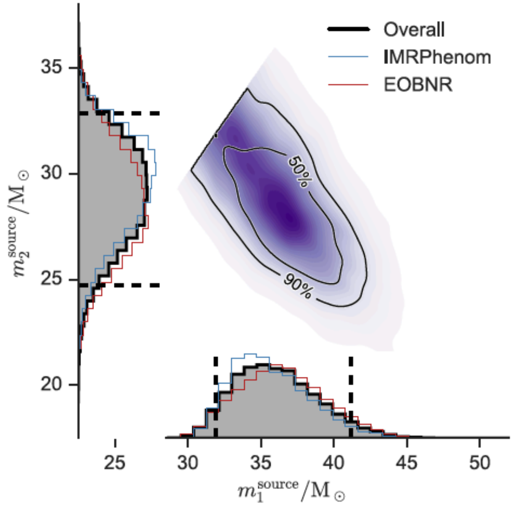
B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration) Phys. Rev. Lett. 116, 061102





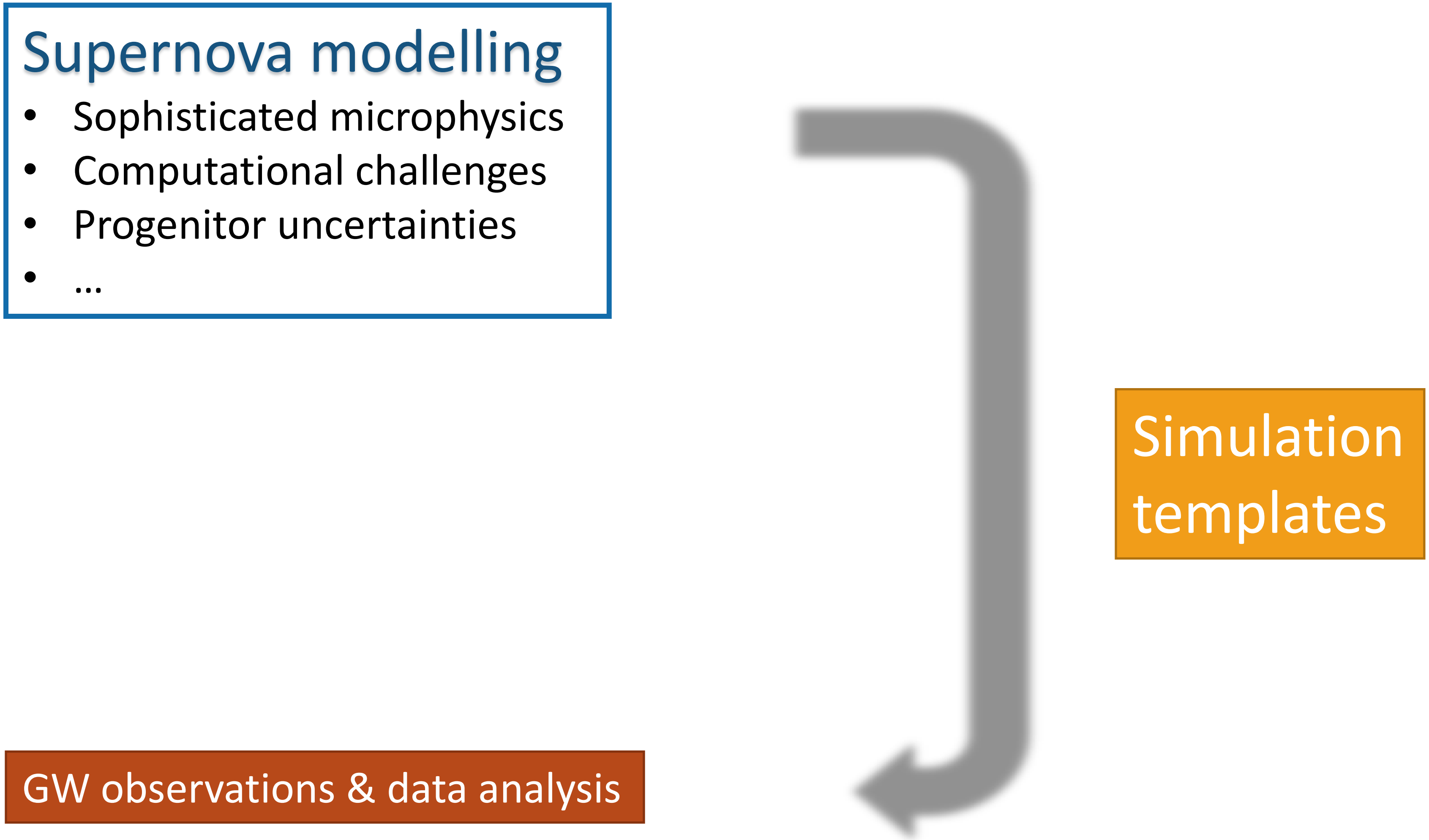
Template Bank

Bayesian Inference



250,000 templates!

Motivation



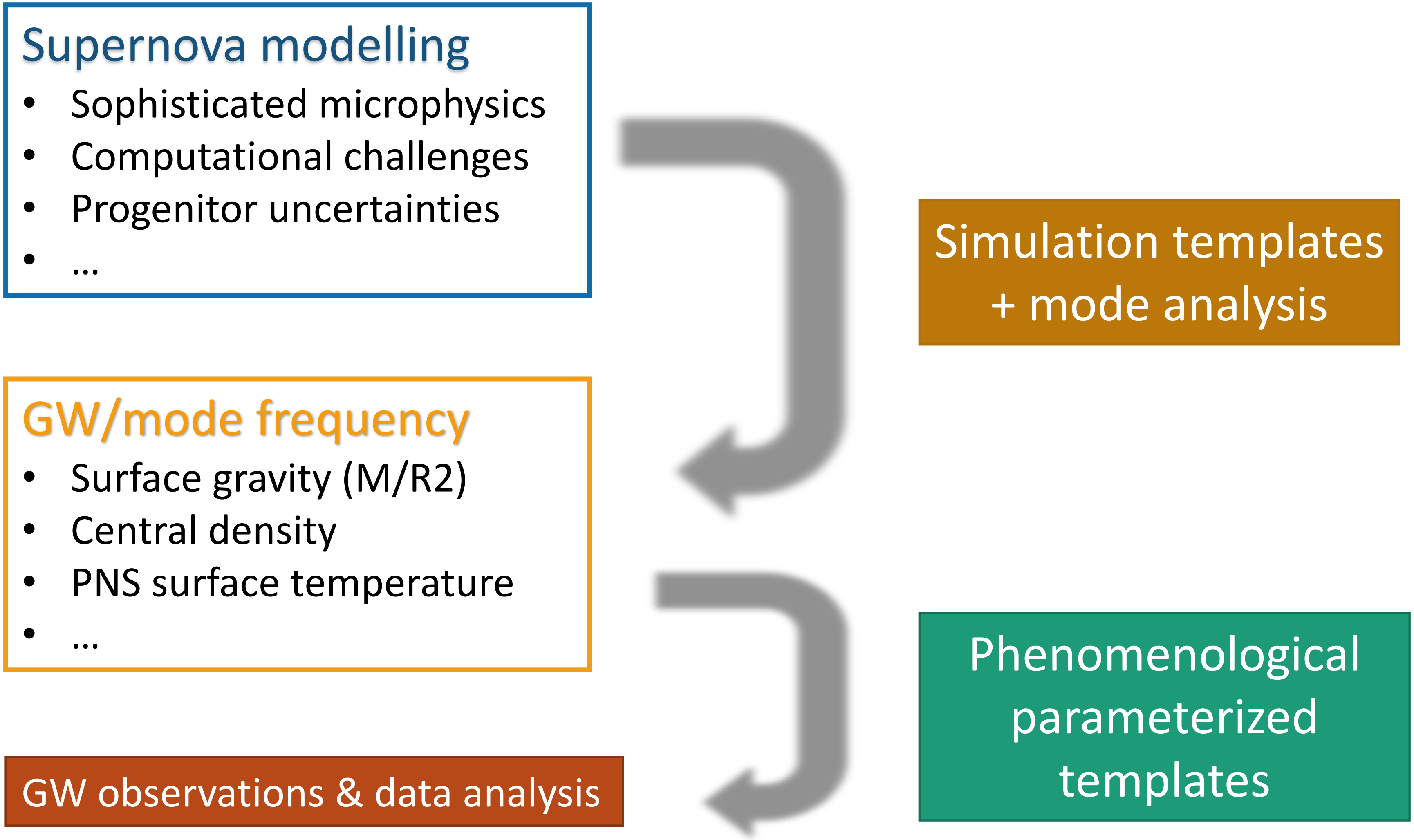
Supernova modelling

- Sophisticated microphysics
- Computational challenges
- Progenitor uncertainties
- …

Simulation templates

GW observations & data analysis

Motivation



Supernova modelling

- Sophisticated microphysics
- Computational challenges
- Progenitor uncertainties
- …

Simulation templates
+ mode analysis

GW/mode frequency

- Surface gravity (M/R2)
- Central density
- PNS surface temperature
- …

Phenomenological
parameterized
templates

GW observations & data analysis

Proto-neutron star oscillations

Linear perturbations of a spherical background

- Simplified background: Reisenegger & Goldreich 1992, Ferrari et al 2003, 2004, Passamonti et al 2005, Krüger et al 2015, Camelio et al 2017
- Background based on simulations (f, p and w modes): Sotani et al 2017
- Background from simulations + Cowling approximation (g,f,p-modes): Torres-Forné et al 2018a
- Background from simulations + lapse perturbations: Morozova et al 2018
- Torres-Forné et al 2018b (arXiv:1806.11366)
    - Space-time perturbations (lapse and conformal factor)
    - Quadrupolar modes (l=2)
    - Quasi-radial (l=0) oscillations of deformed stars
    - Boundary conditions at the shock location

GREAT = General Relativistic Eigenmode Analysis Tool

https://www.uv.es/cerdupa/codes/GREAT/

Linear perturbation analysis – Spacetime perturbations

$$\partial_r \eta_r + \left[\frac{2}{r} + \frac{1}{\Gamma_1}\frac{\partial_r P}{P} + 6\frac{\partial_r \psi}{\psi}\right]\eta_r + \frac{\psi^4}{\alpha^2 c_s^2}\left(\sigma^2 - \mathcal{L}^2\right)\eta_\perp = \frac{1}{c_s^2}\frac{\delta\hat{Q}}{Q} - \left(6 + \frac{1}{c_s^2}\right)\frac{\delta\hat{\psi}}{\psi}, \tag{33}$$

$$\partial_r \eta_\perp - \left(1 - \frac{N^2}{\sigma^2}\right)\eta_r + \left[\partial_r \ln q - \mathcal{G}\left(1 + \frac{1}{c_s^2}\right)\right]\eta_\perp = \frac{\alpha^2}{\psi^4\sigma^2}\left[\partial_r(\ln \rho h) - \left(1 + \frac{1}{c_s^2}\right)\mathcal{G}\right]\left(\frac{\delta\hat{Q}}{Q} - \frac{\delta\hat{\psi}}{\psi}\right), \tag{34}$$

$$\hat{\nabla}^2 \delta\hat{\psi} = -2\pi\psi^5\left[\left(5e + \frac{\rho h}{c_s^2}\right)\frac{\delta\hat{\psi}}{\psi} - \frac{\rho h}{c_s^2}\frac{\delta\hat{Q}}{Q}\right] - 2\pi\rho h\psi^5\left(\frac{\psi^4\sigma^2}{\alpha^2 c_s^2}\eta_\perp - \mathcal{B}\eta_r\right), \tag{37}$$

$$\hat{\nabla}^2 \delta\hat{Q} = 2\pi(\rho h + 5P)\alpha\psi^5\left(\frac{\delta\hat{Q}}{Q} + 4\frac{\delta\hat{\psi}}{\psi}\right) + 2\pi\rho h\alpha\psi^5\left[\left(6 + \frac{1}{c_s^2}\right)\left(\frac{\psi^4\sigma^2}{\alpha^2}\eta_\perp - \frac{\delta\hat{Q}}{Q} + \frac{\delta\hat{\psi}}{\psi}\right) - \eta_r\mathcal{B}\right], \tag{38}$$

where

$$\hat{\nabla}^2 \equiv \partial_{rr} + \frac{2}{r}\partial_r - \frac{l(l+1)}{r^2}. \tag{39}$$

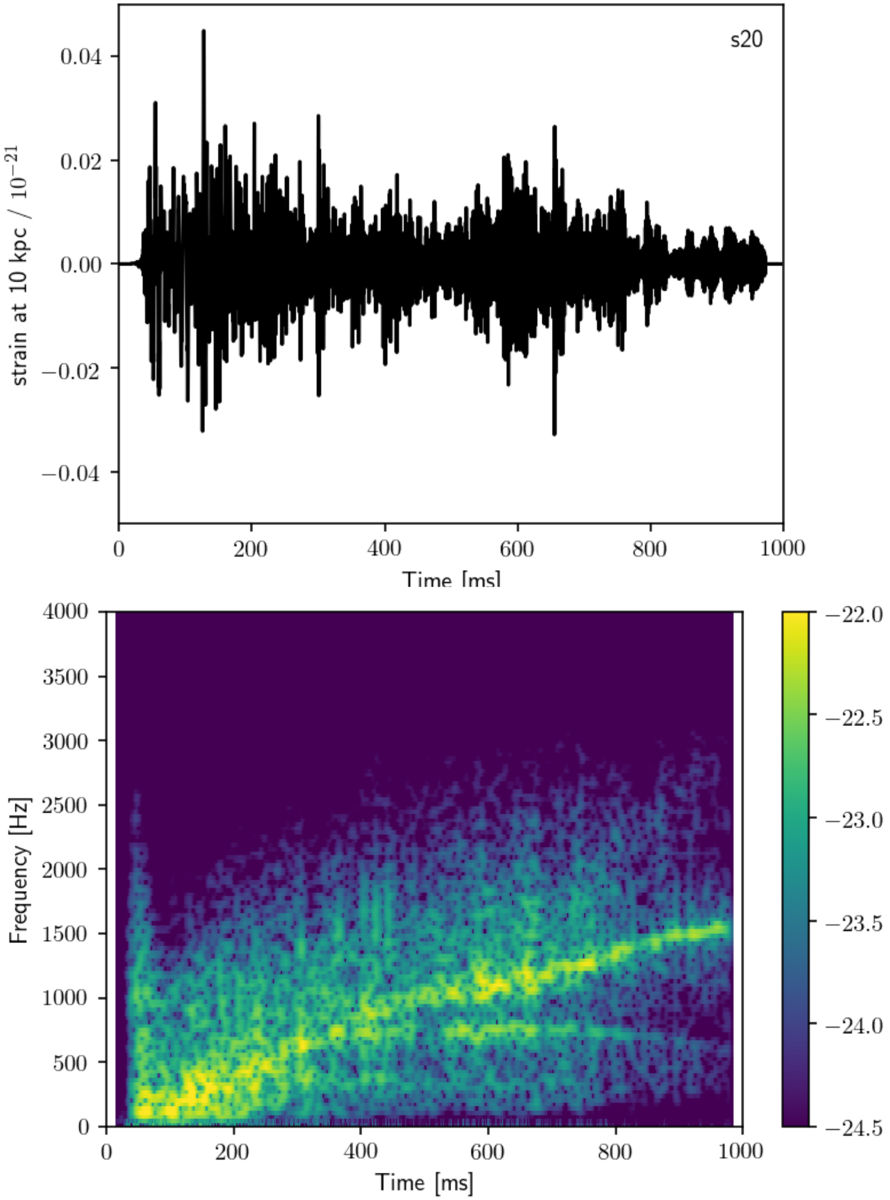
Linear perturbations of a spherical background

Procedure:

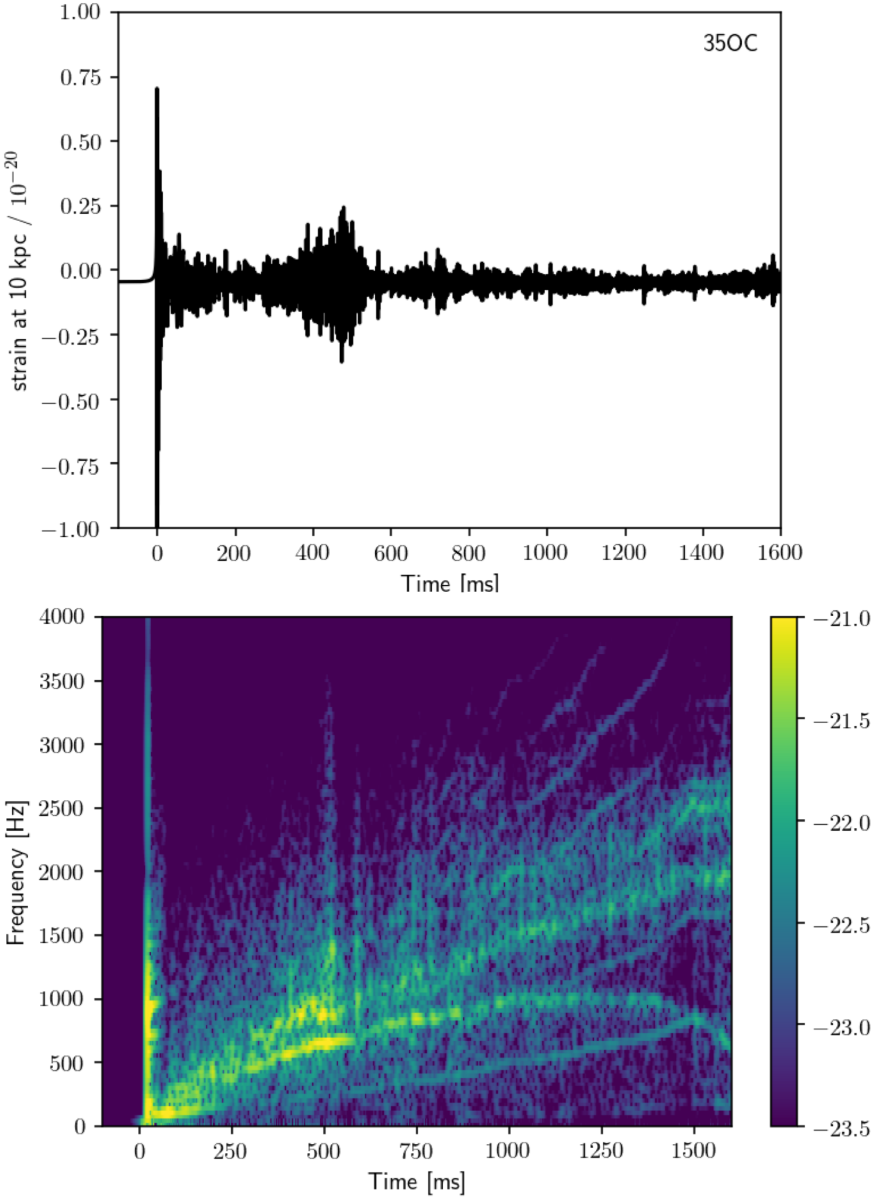
- 2D simulation with GW emission
- Angular averages to generate 1D profiles
- Linear perturbation analysis → Calculation of eigenfrequencies and eigenfunctions
- Classification of eigenmodes: p/f/g-modes
- Comparison with GW from simulation

Numerical simulations

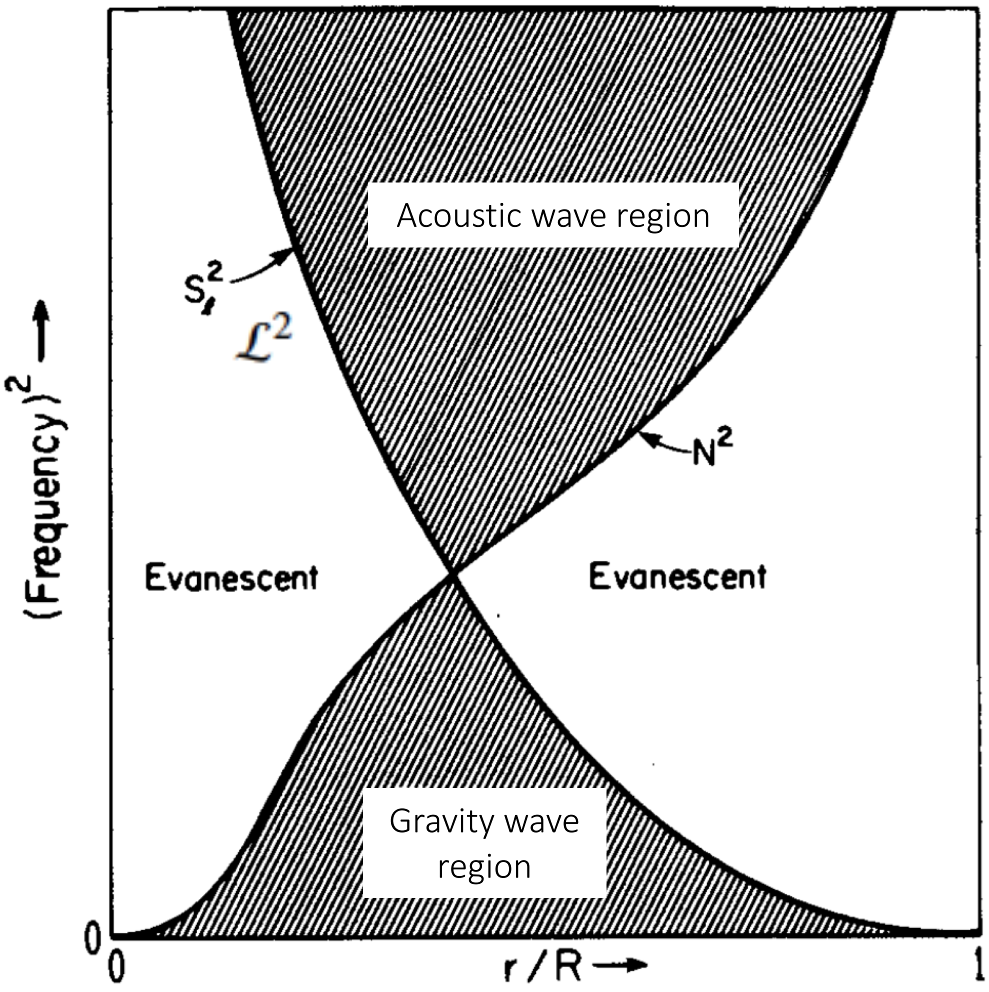
Obergaulinger M., Just O., Aloy M. Á., 2018, J. Phys.G. in press,



Cerdá-Durán P., DeBrye N., Aloy M. A., Font J. A., Obergaulinger M., 2013, ApJ, 779, L18



What are p/g/f-modes?



Cox 1980

$\mathcal{N}^2$: Brunt-Väisälä frequency

$\mathcal{L}^2$: Lamb frequency

Acoustic wave region:

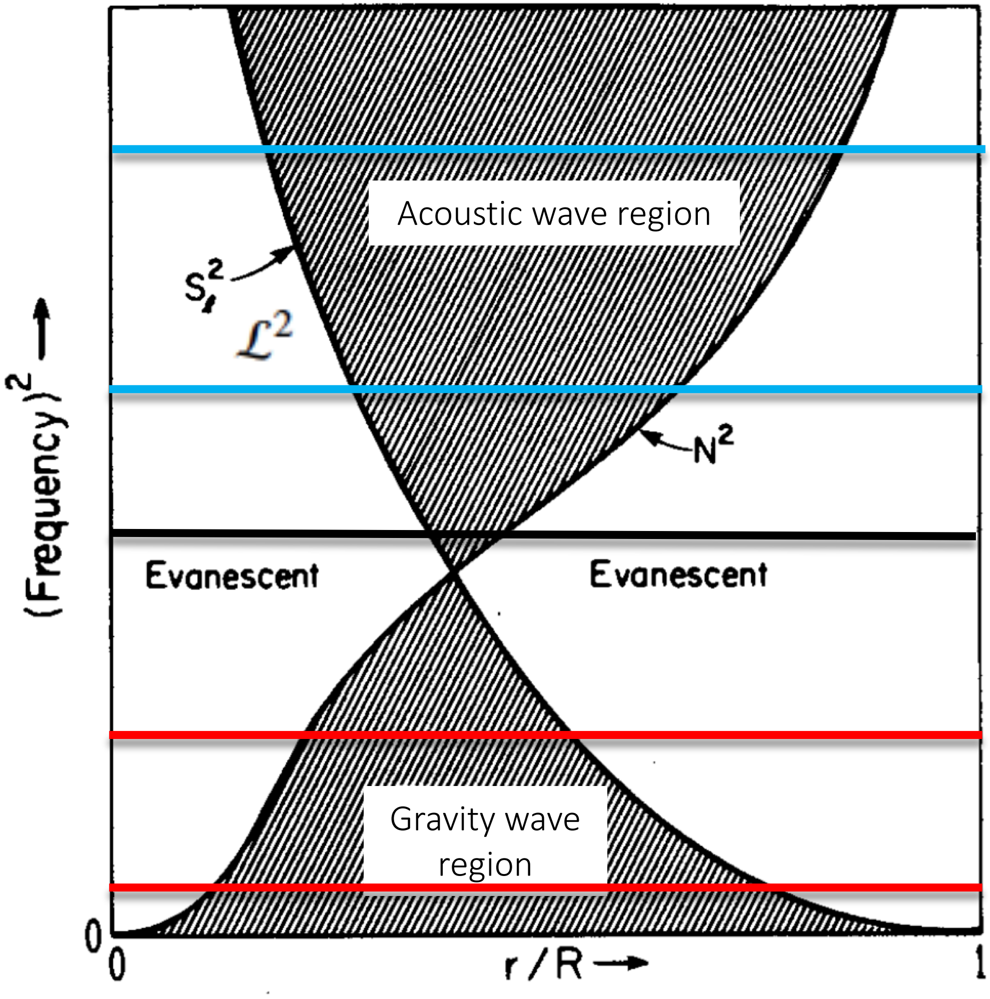
$$\sigma^2 > \mathcal{N}^2, \mathcal{L}^2$$

Gravity wave region:

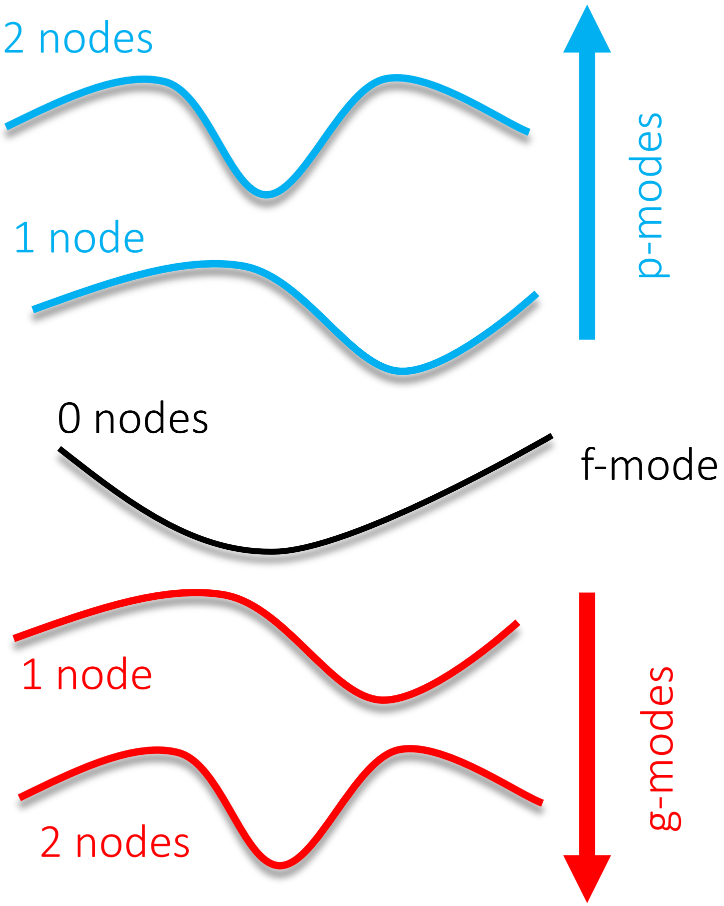
$$\sigma^2 < \mathcal{N}^2, \mathcal{L}^2$$

Propagation diagram

What are p/g/f-modes?

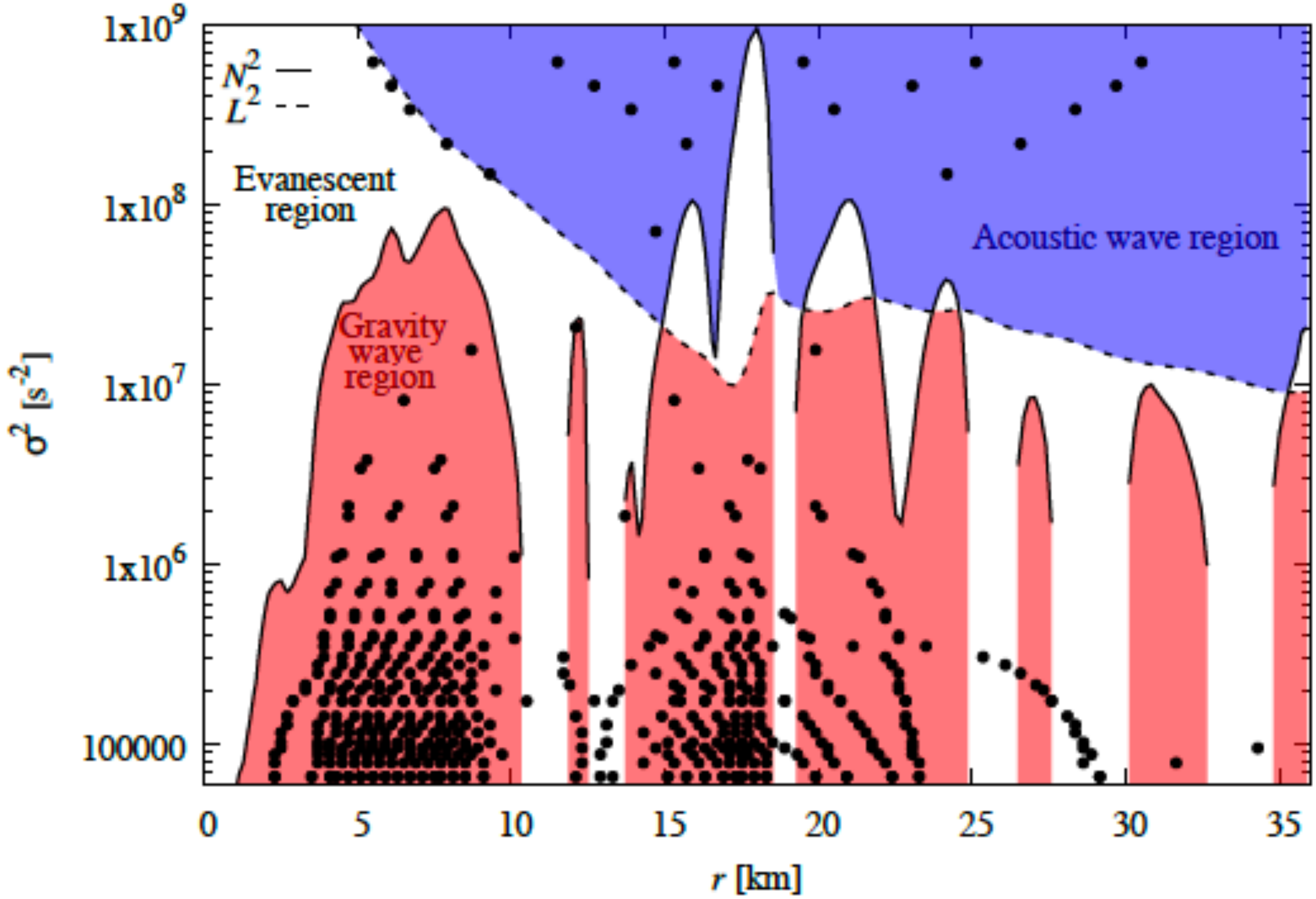


Cox 1980



Cowling 1941 classification

p/g/f-modes in real life

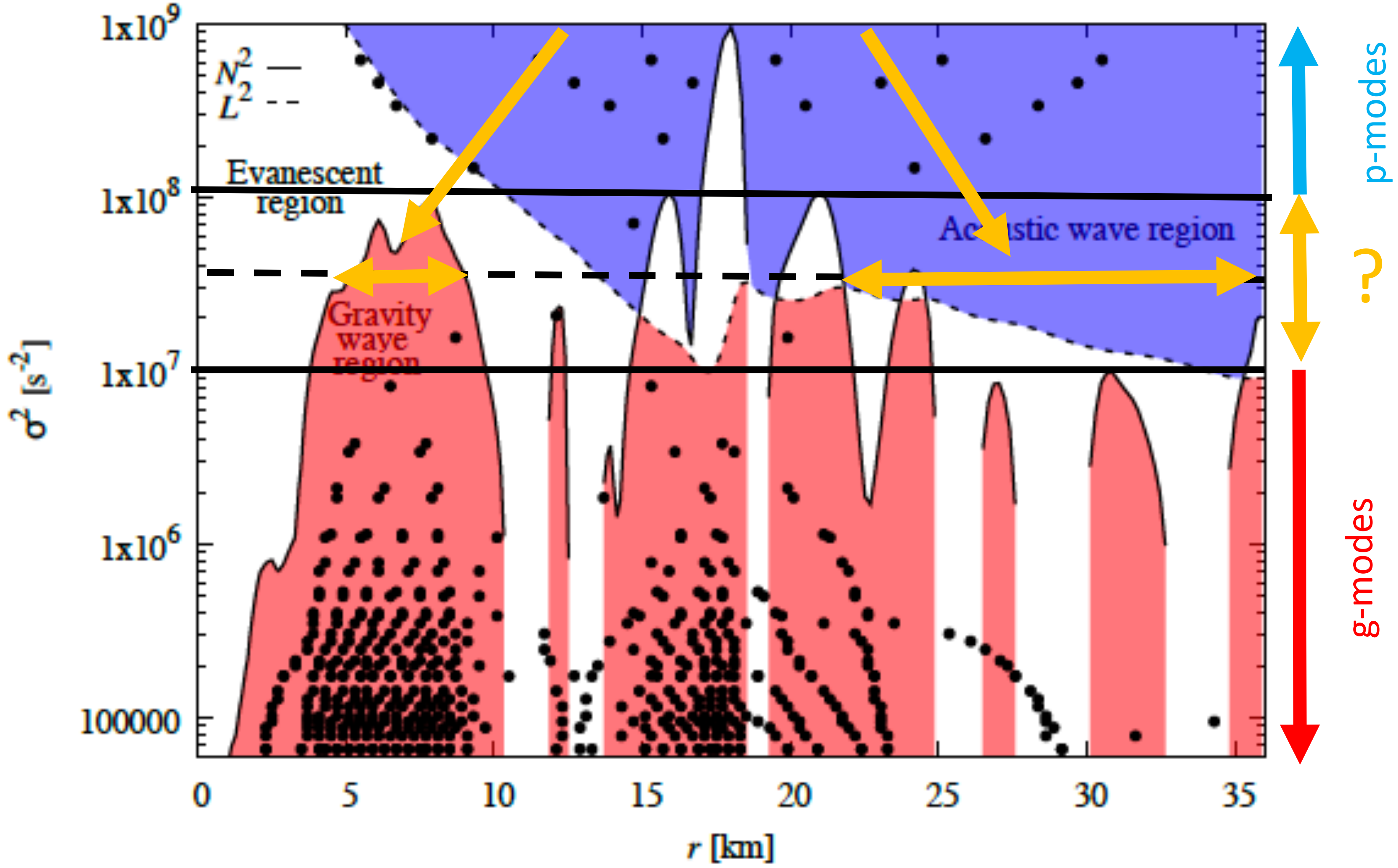


TF et al 2018b

35OC, 1.3 s post-bounce

p/g/f-modes in real life

Trapped-interacting modes

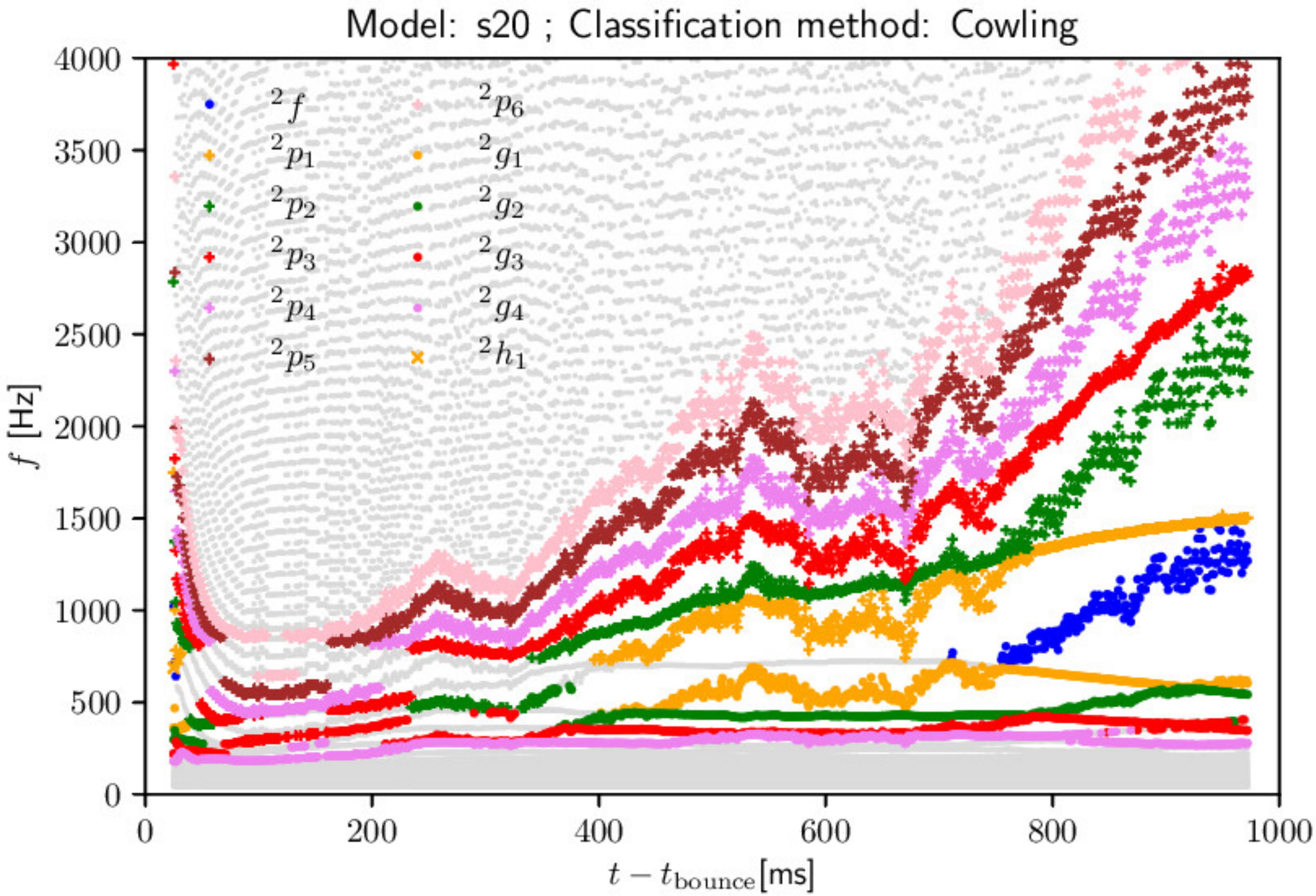


TF et al 2018b

35OC, 1.3 s post-bounce

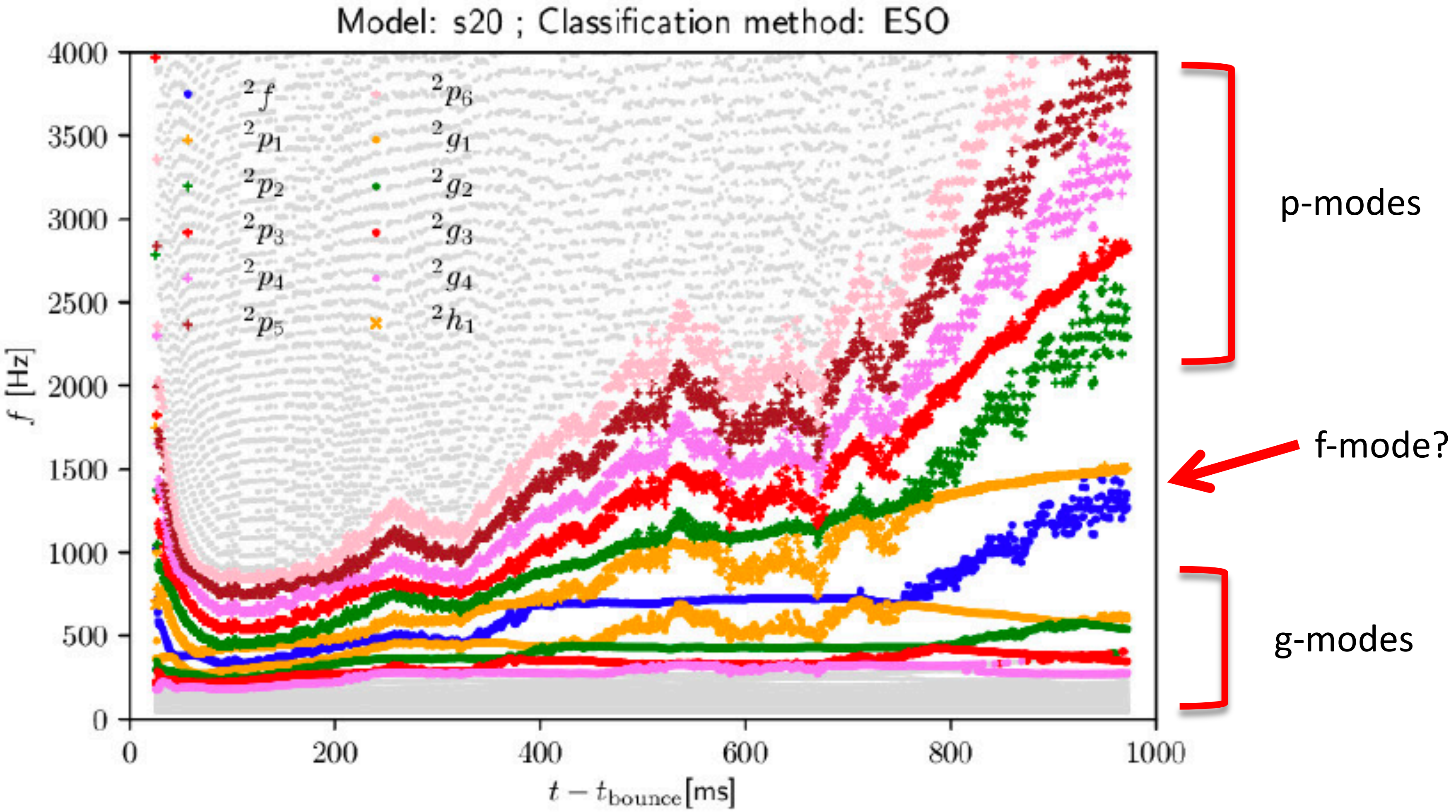
Mode classification - Cowling

In TF 2018a, we perform a **automatic classification** based on the **number of nodes (n)** and on their **origin**, namely gravity modes (g-modes) and acoustic modes (p-modes).



Mode classification - ESO

ESO classification scheme (Eckart 1960, Sculflaire 1974, Osaki 1975) improves Cowling classification scheme



p-modes

f-mode?

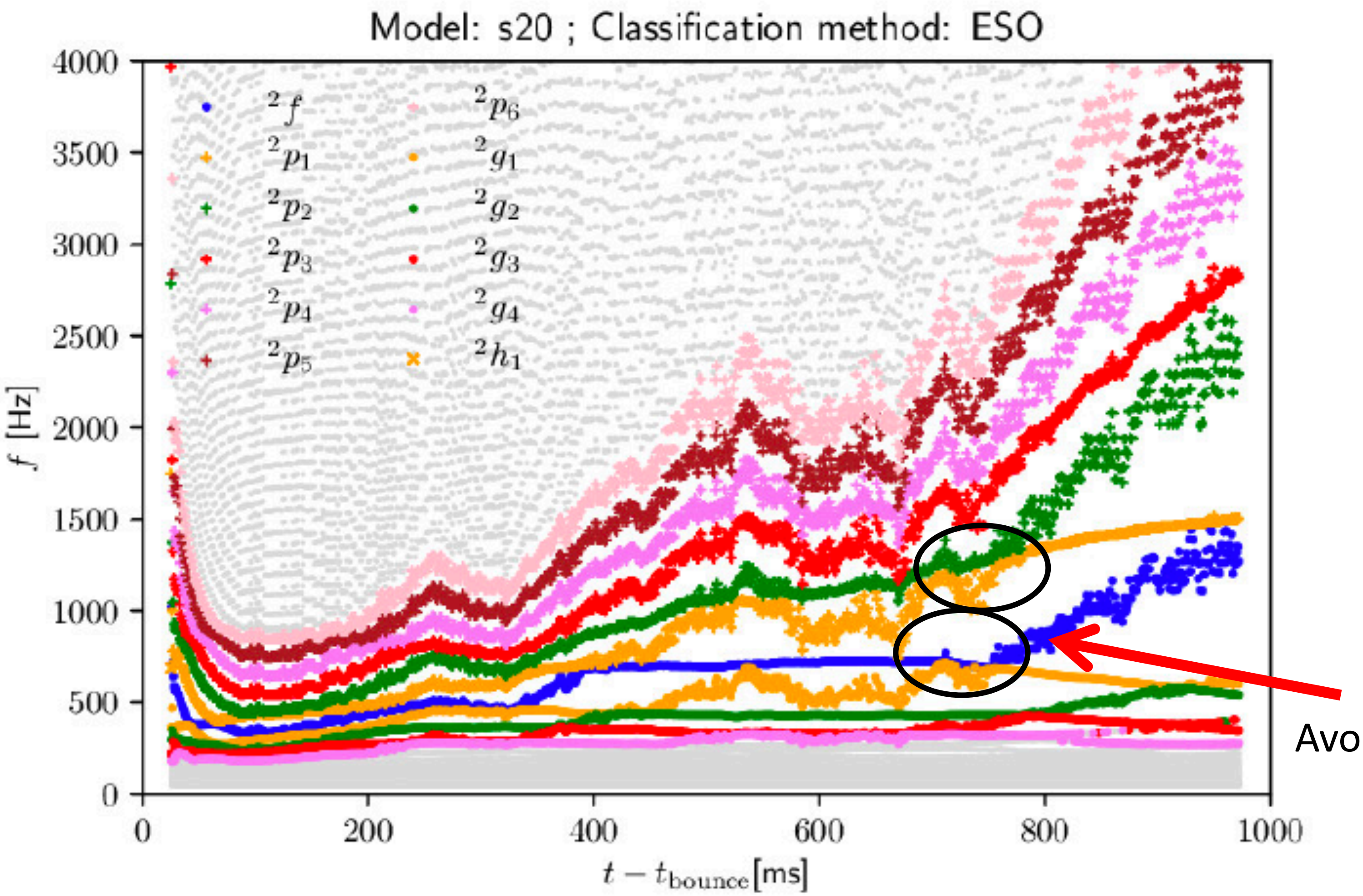
g-modes

TF et a 2018b

s20, SFHo EOS

Mode classification – ESO

Avoided crossings correspond to trapped modes interacting with each other.
ESO scheme misclassifies modes across these crossings.



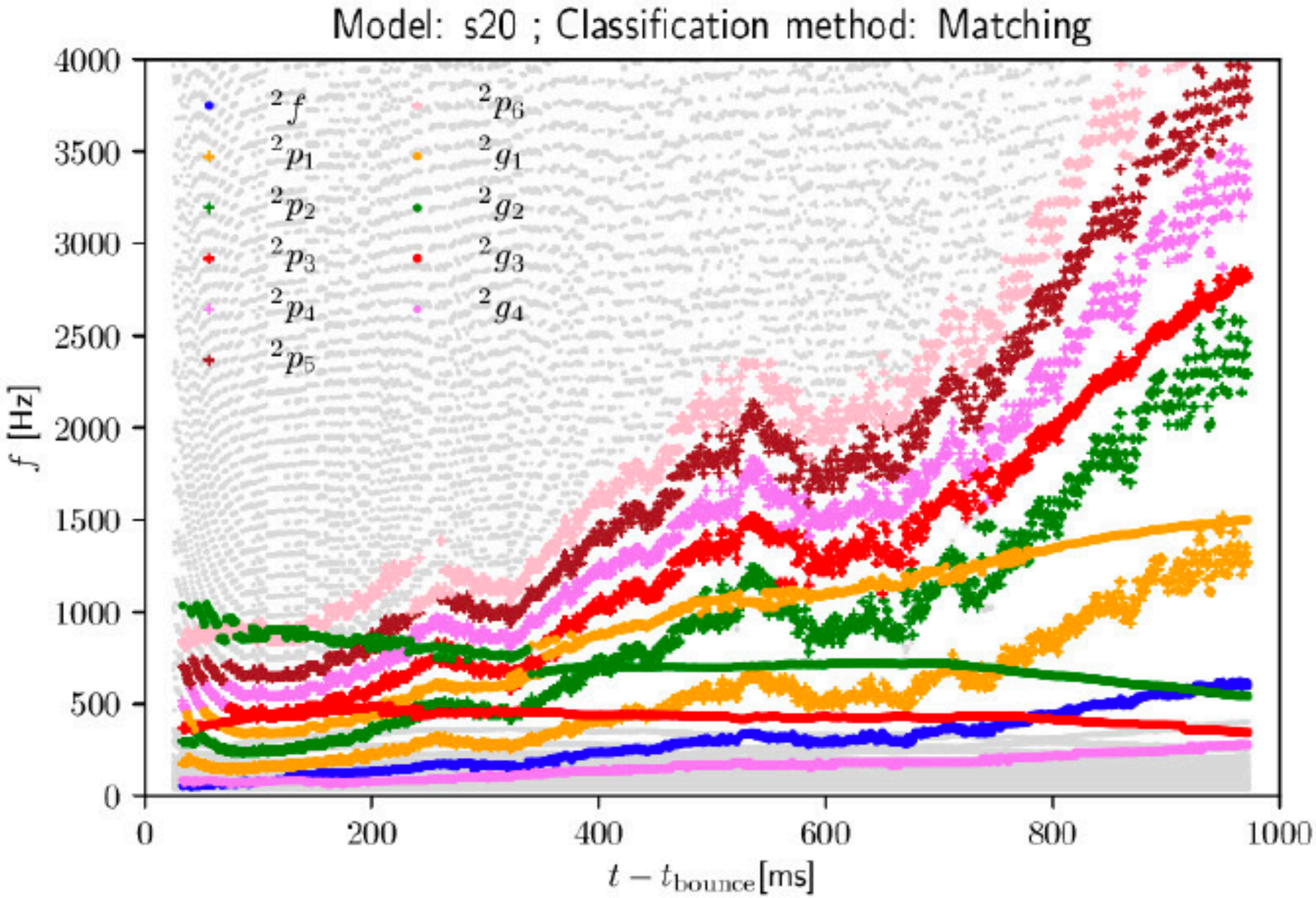
Avoided crossings

TF et a 2018b

s20, SFHo EOS

Mode classification – Matching

- Based on similarity of eigenfunctions (see Torres-Forné et al 2018b for details)
- Partially supervised (semi-automatic):



- Reproduce features of decoupled g/p modes
- Recovers ESO classes for high/low frequencies
- p-modes are integer multiples of the f-mode

Torres-Forné et a 2018b

s20, SFHo EOS

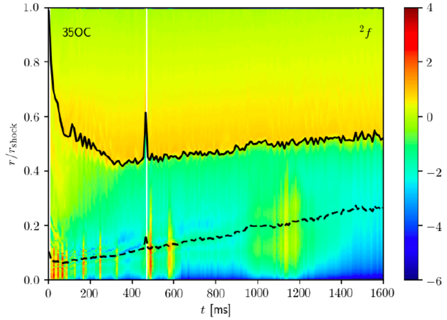
Asteroseismology of core-collapse supernovae

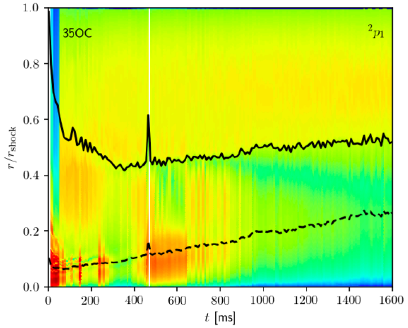
Eigen-mode morphology

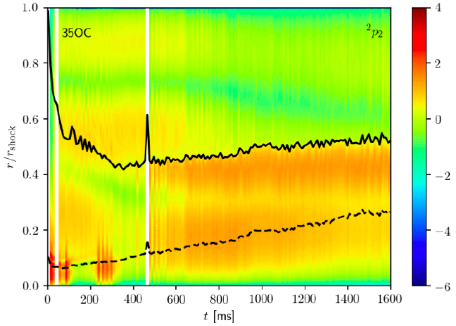
f-mode

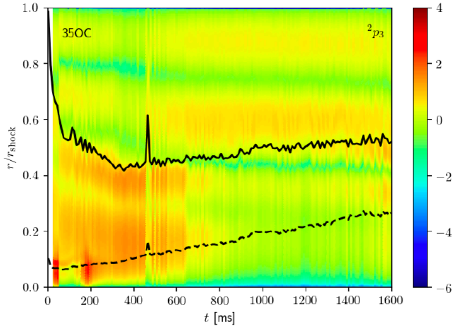
Torres-Forné et a 2018b (35OC model)

p-modes

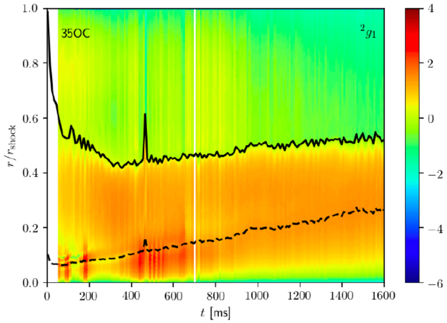


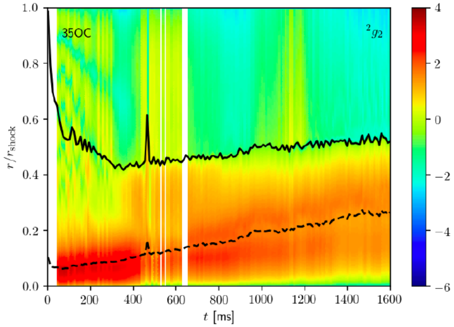


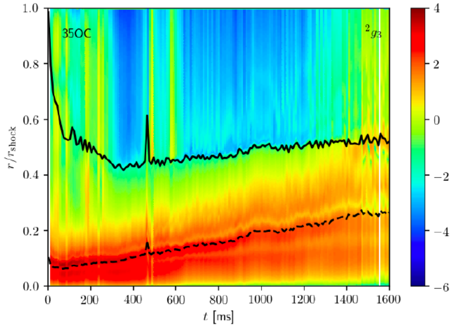


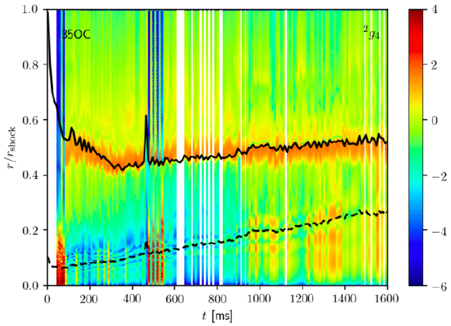


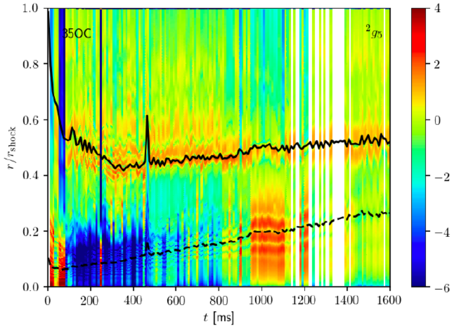
core g-modes



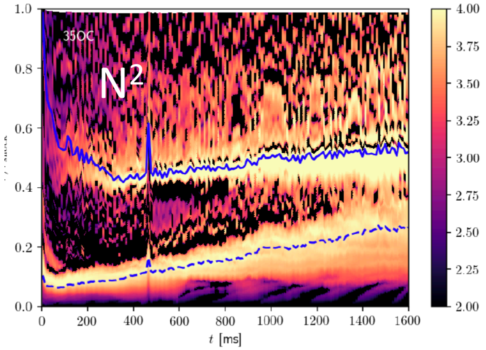






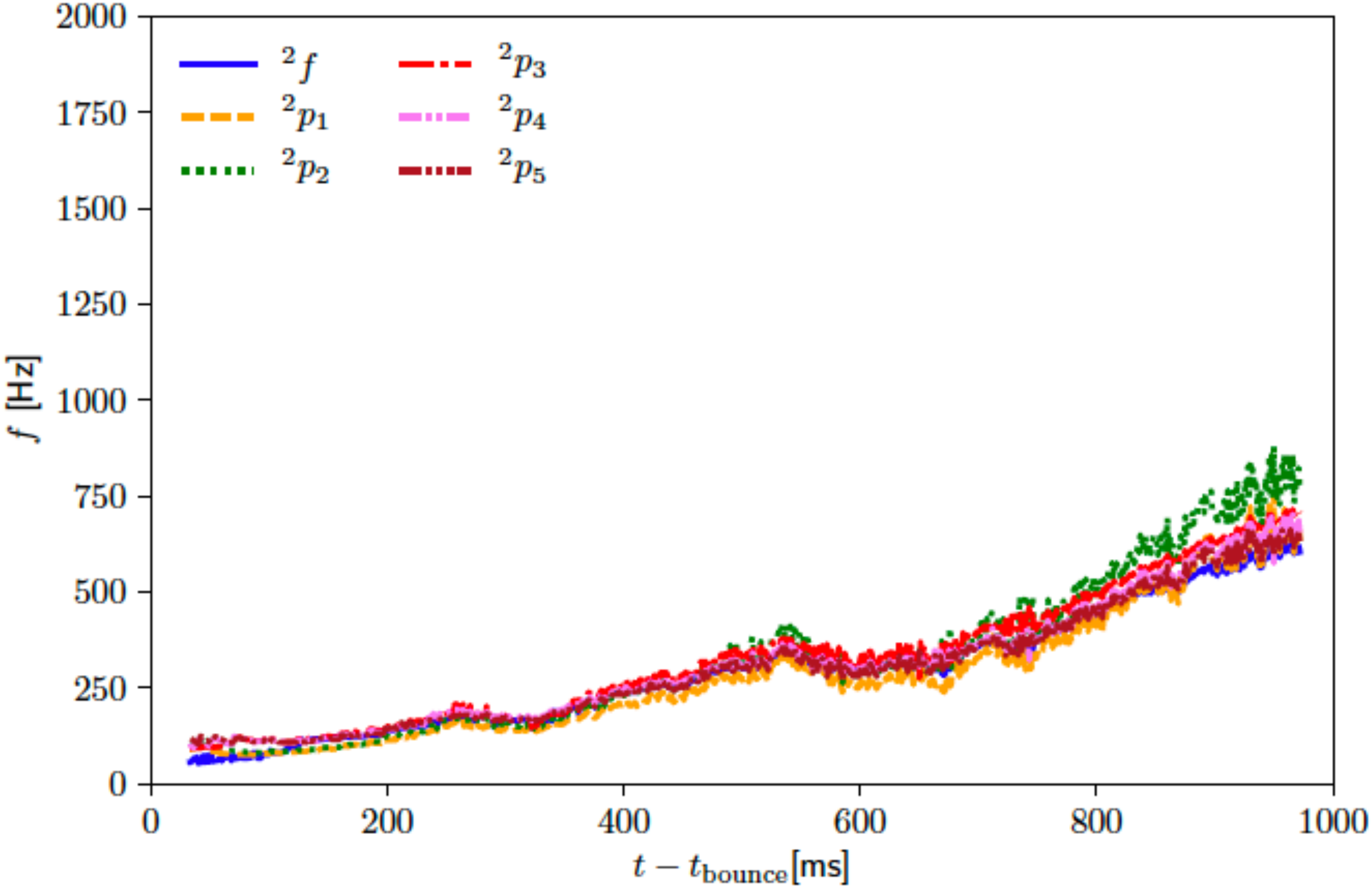


surface g-modes

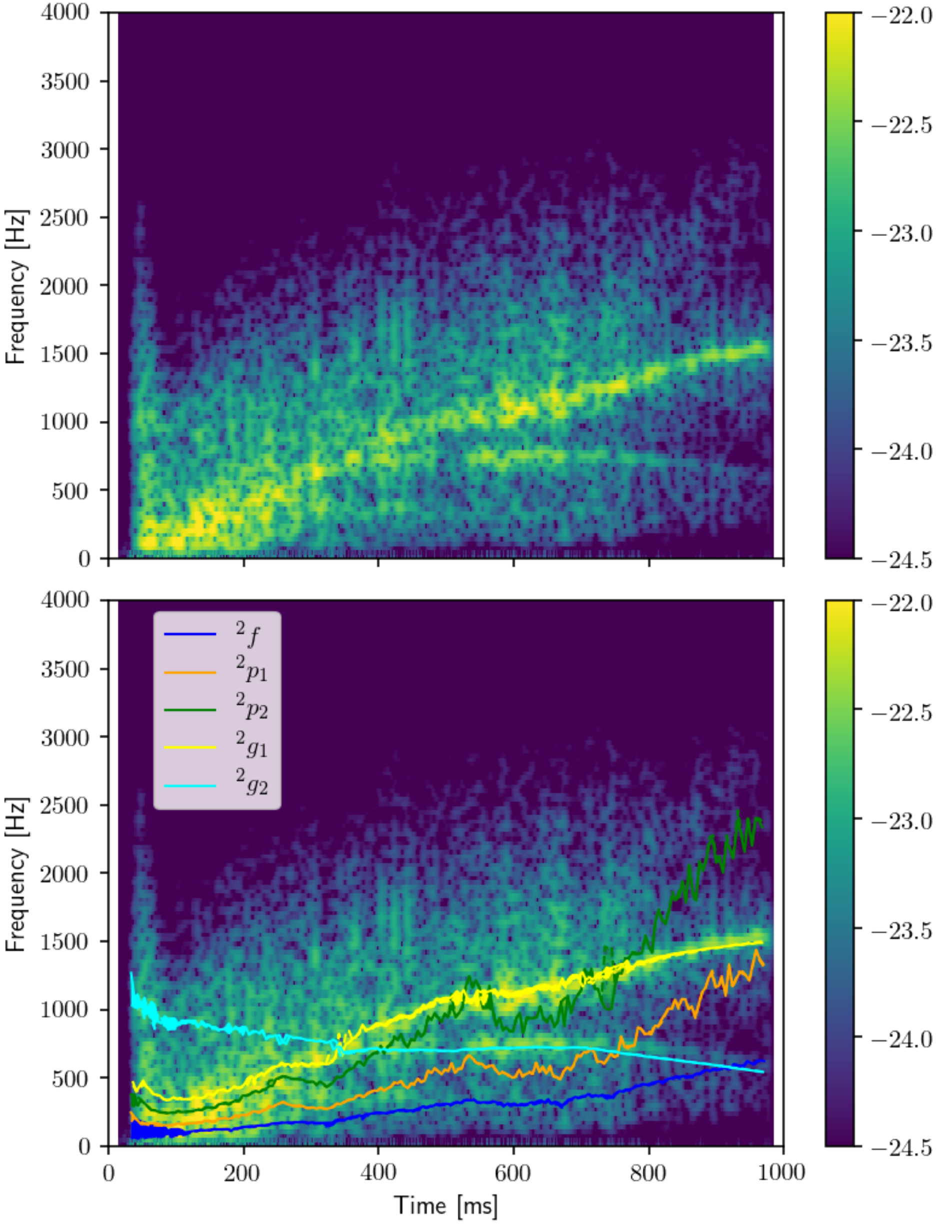


P –modes vs f-mode

Frequency / n+1



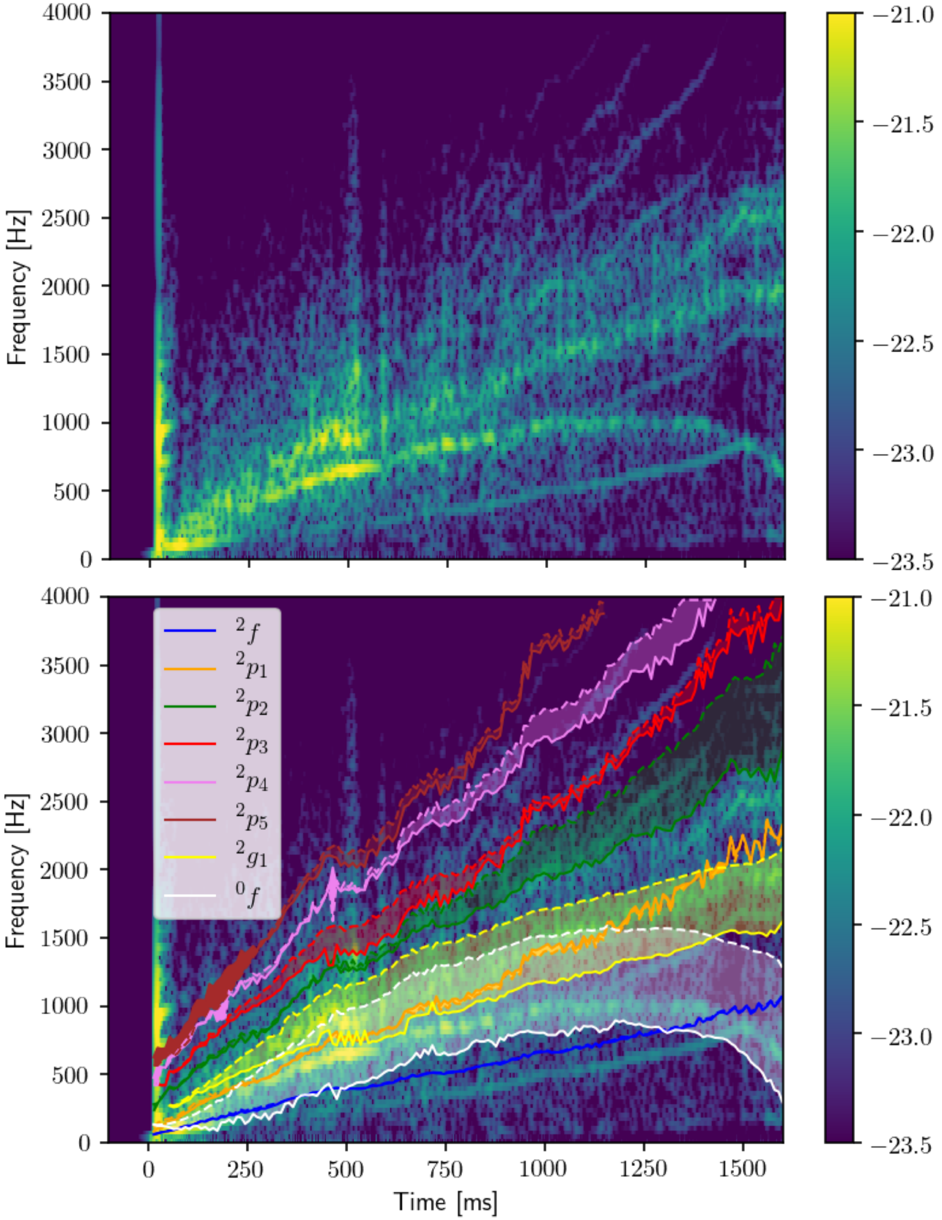
Comparison with the simulation



- Lowest-order core g-mode ($^2g_1$) is the dominant mode
- $^2g_2$ also visible
- Hints of the f-mode

Lowest order modes are dominant

Comparison with the simulation - Rotation



35OC is fast rotating (strong deformations)
SASI develops during simulation

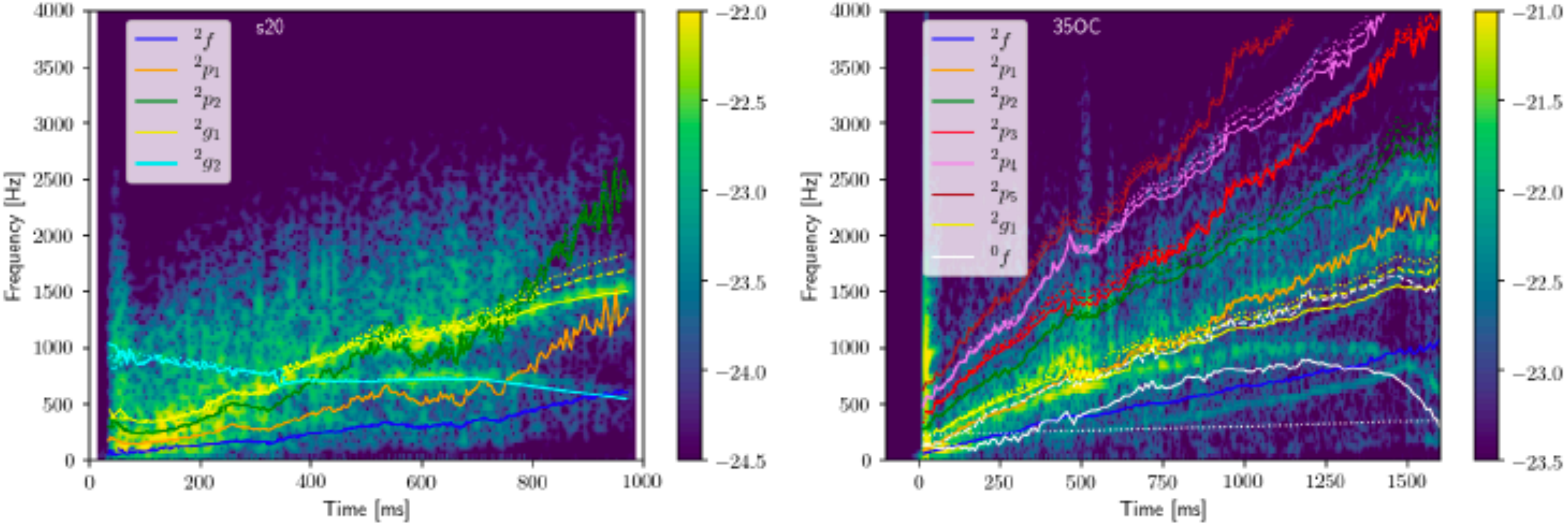
- Lowest-order core g-mode ($^2g_1$) is the dominant mode
- f and p-modes visible
- Fundamental l=0 mode visible
- Uncertainties due to rotation

Lowest order modes are dominant

f/p modes excited (due to SASI?)

Is the SASI mode the f-mode?

Effect of space – time perturbations



Space-time perturbations (lapse and conformal factor) are needed to:

- Match GW behaviour at late times (higher compactness)
- Get the correct behaviour of the fundamental quasi-radial (l=0) mode at BH formation
- Shift perturbation not needed for the non-rotating case but may be important in the case of rotation.

Parameter estimation

- Which information can we extract from the measurement of the frequency evolution?

- Are there Universal relations between PNS parameters and the mode frequencies?

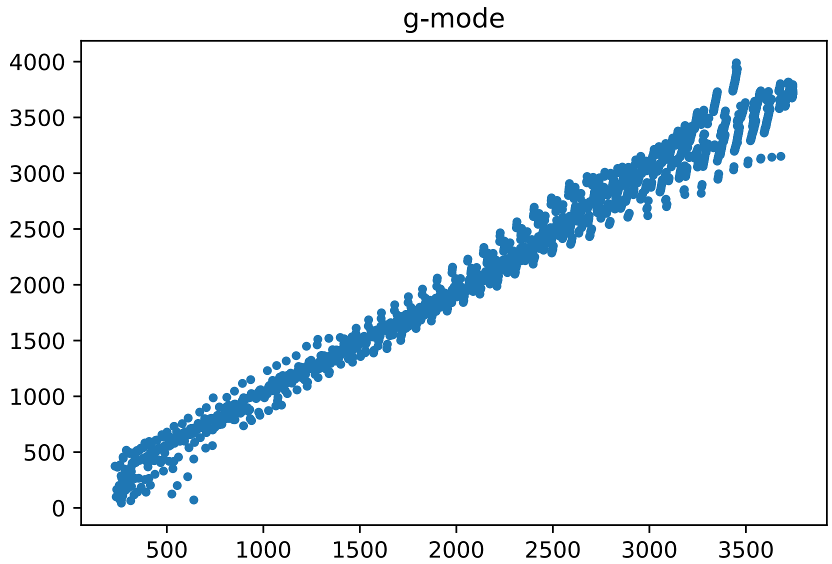
Parameter estimation

- Set of 1D simulations (18)
  - 6 different EOS
  - 2 different gravity treatment
  - Progenitor masses from 11.2 to 75 M_{sun}
  - Solar metallicity + u20
- AENUS code
- No GW emission (1D)
- Computation and classification of eigenmodes
- TF et al (2018) in preparation

Fundamental relations?

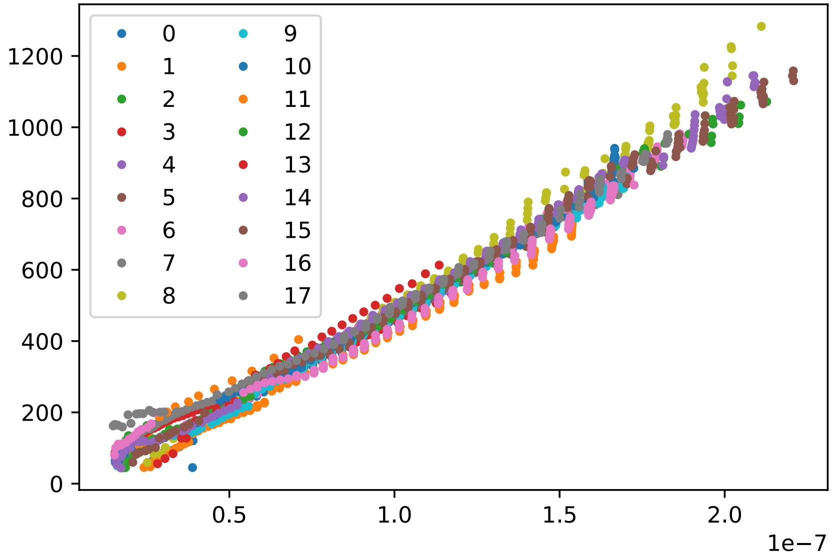
Preliminary

- g-modes scale with surface gravity
- f-mode scale with sqrt of mean density



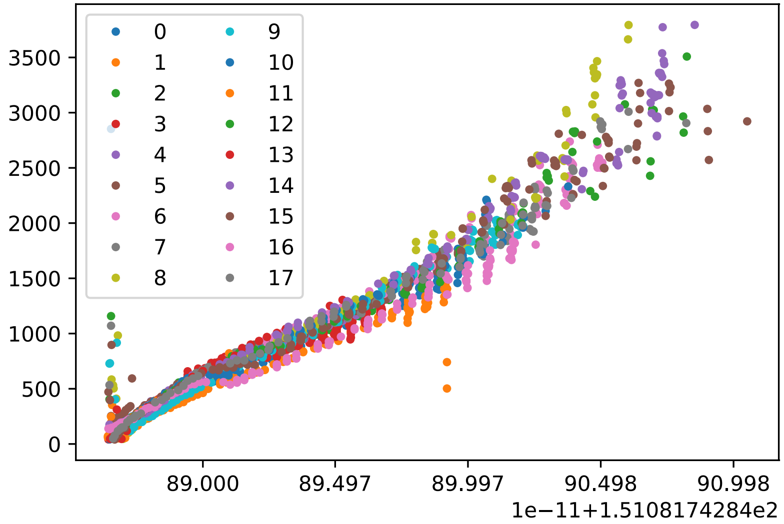
$A+B\ M_{PNS}/R_{PNS}^2 + C\ (M_{PNS}/R_{PNS}^2)^2$

- These relations can be used for the inversion problem
- Can we measure M and R independently (with detector noise)?



$A+B\ \mathrm{sqrt}(M_{PNS}/R_{PNS}^3)$

Fundamental relations?



$A+B\, M_{PNS}/R_{PNS}^2 + C\, (M_{PNS}/R_{PNS}^2)^2$

Preliminary

- g-modes scale with surface gravity
- f-mode scale with sqrt of mean density
- p-mode scale with surface gravity but require a second order fit to reduce dispersion

- These relations can be used for the inversion problem
- Can we measure M and R independently (with detector noise)?

Conclusions – Open questions

- Is it always a mode ($^2g_1$) the dominant mode in the GW emission? (3D?)
- Are there sources of confusion? (e.g. convection)
- Are the SASI-mode and the f-mode the same?
- Is the f-mode always excited by SASI?
- Do universal relations hold for 2D/3D simulations?
- What are the typical mode energies in simulations (2D/3D)?

Thanks for your attention!

Upcoming GR22/Amaldi13 conference in Valencia

www.gr22amaldi13.com

We hope to see you all in Valencia in July 2019 !