

MULTIMESSENGER ANALYSIS OF THE STANDING ACCRETION SHOCK INSTABILITY

Alphonse Moreau - Thierry Foglizzo

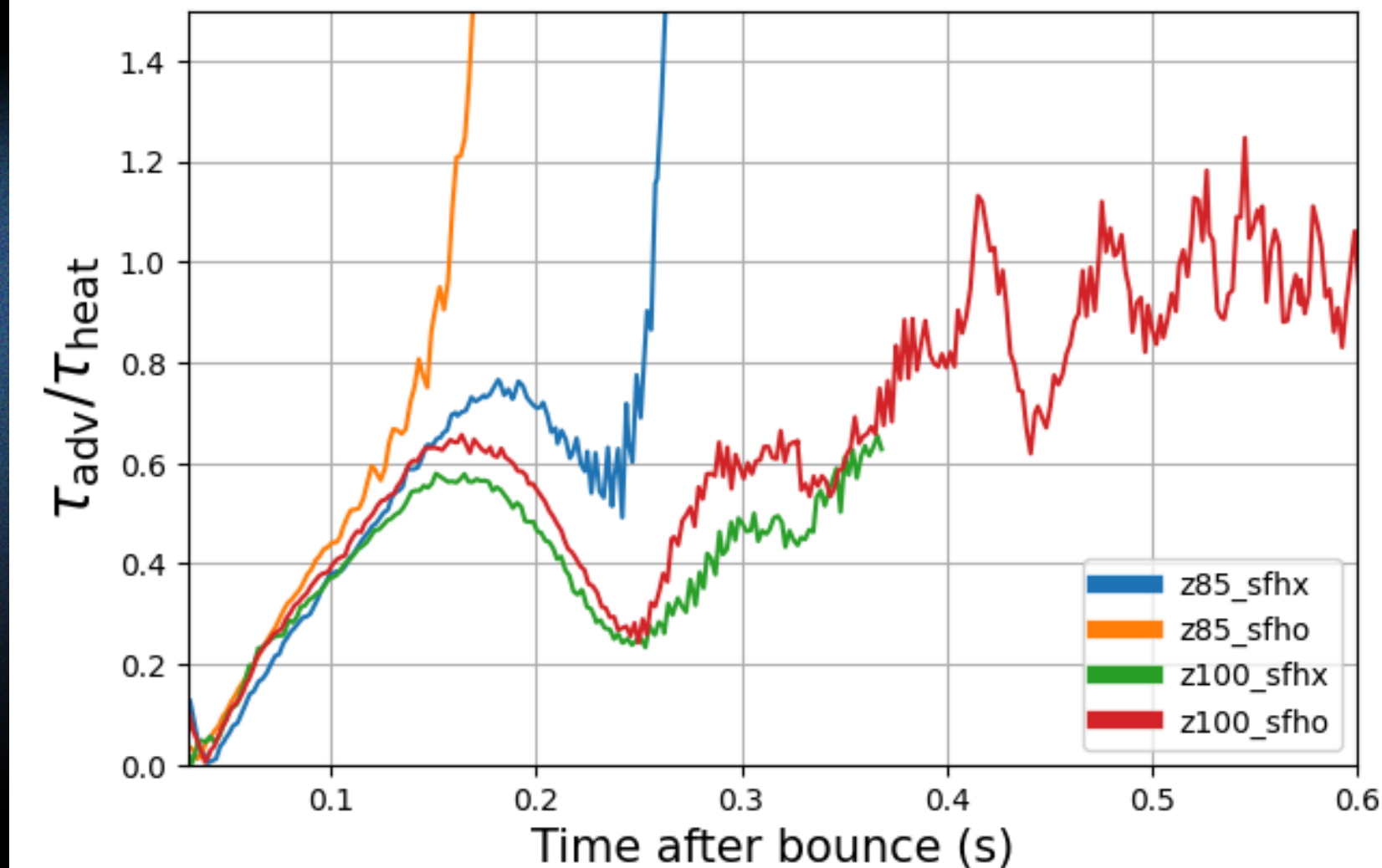
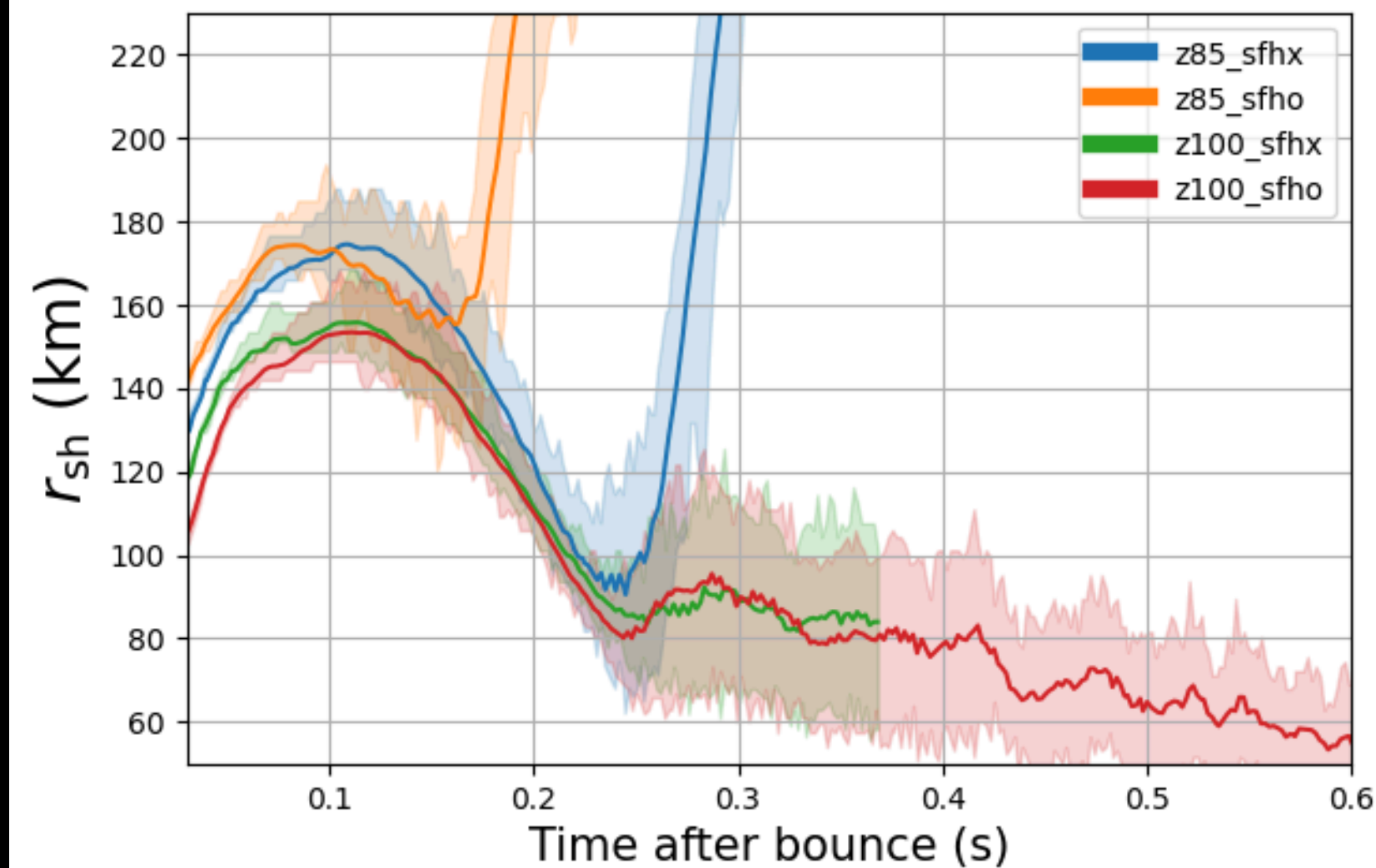
Eric Chassande-Mottin - Bernhard Müller - Jade Powell



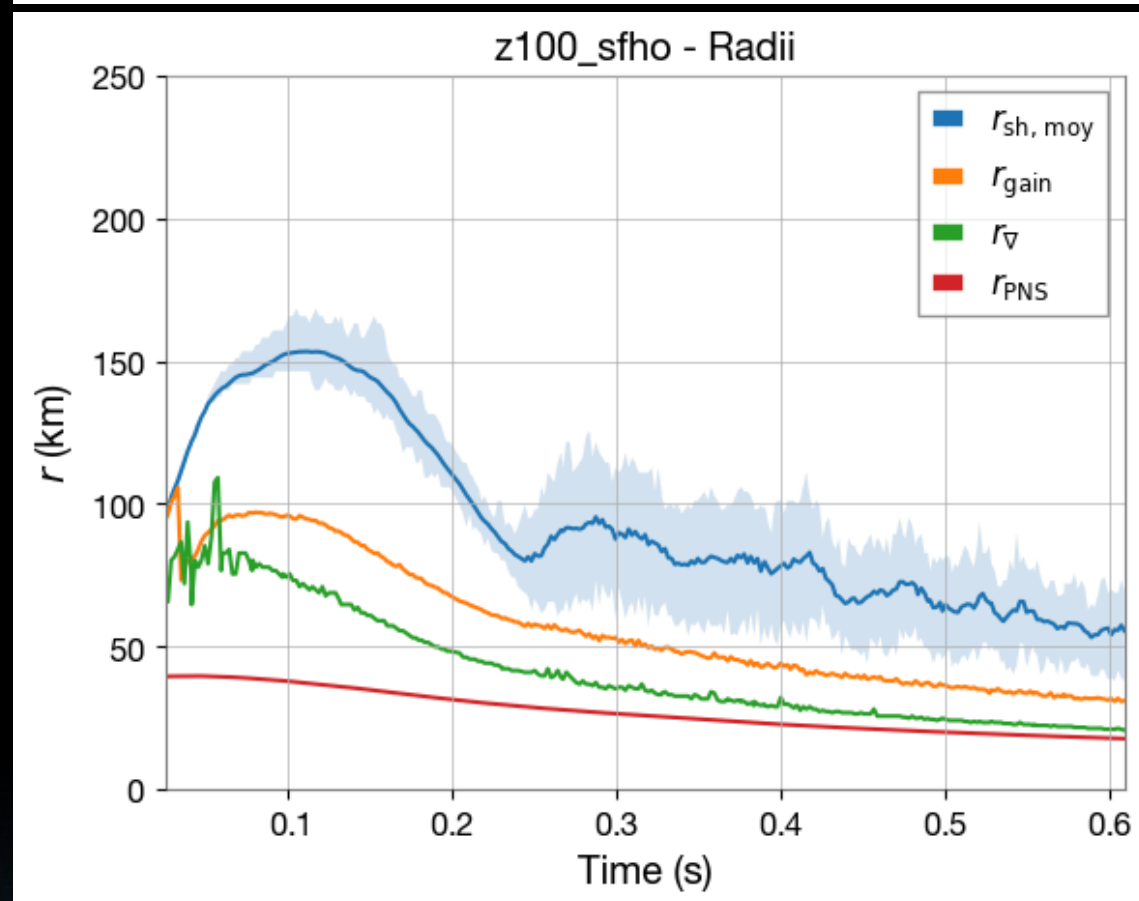
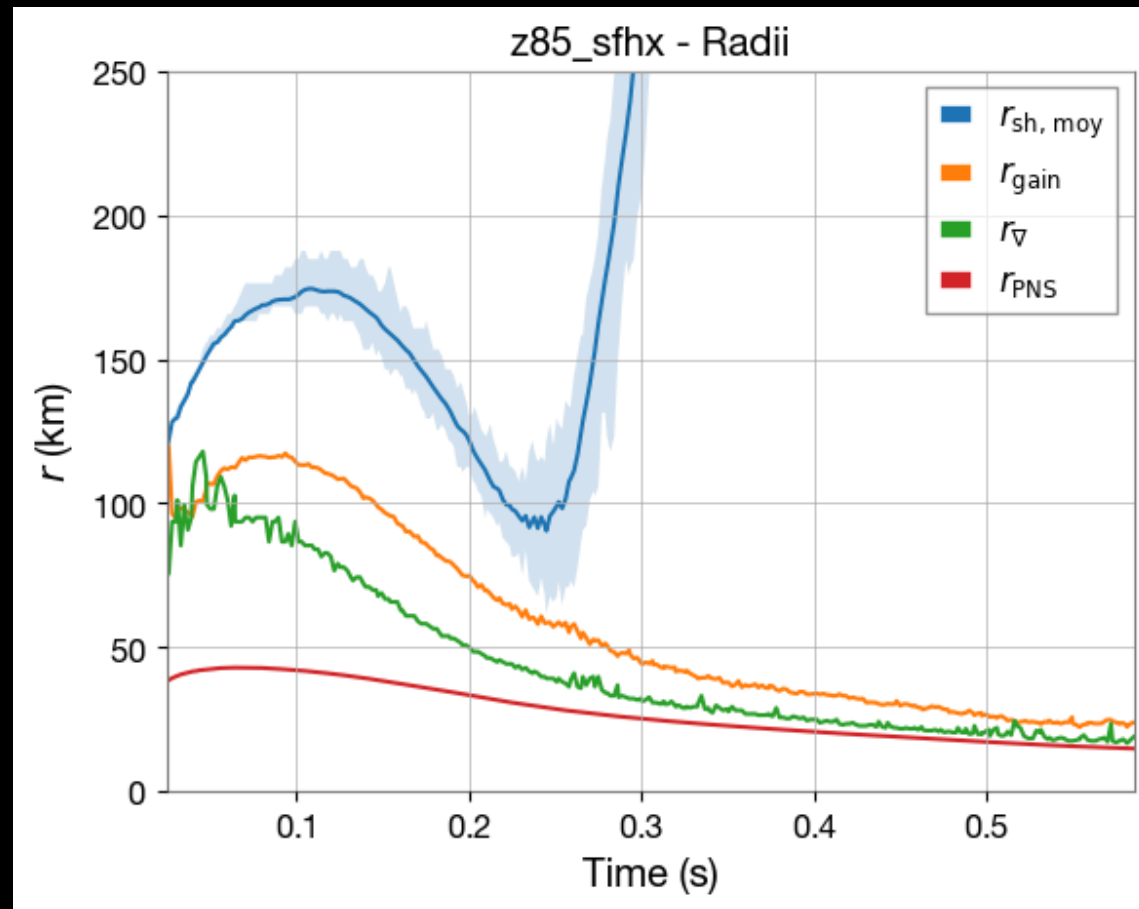
Numerical Simulations

- Powell & Müller 2021
- Pulsational pair instability SN = **Long lasting SASI**
- Neutrino hydrodynamics code COCONUT-FMT
- No rotation, no magnetic field

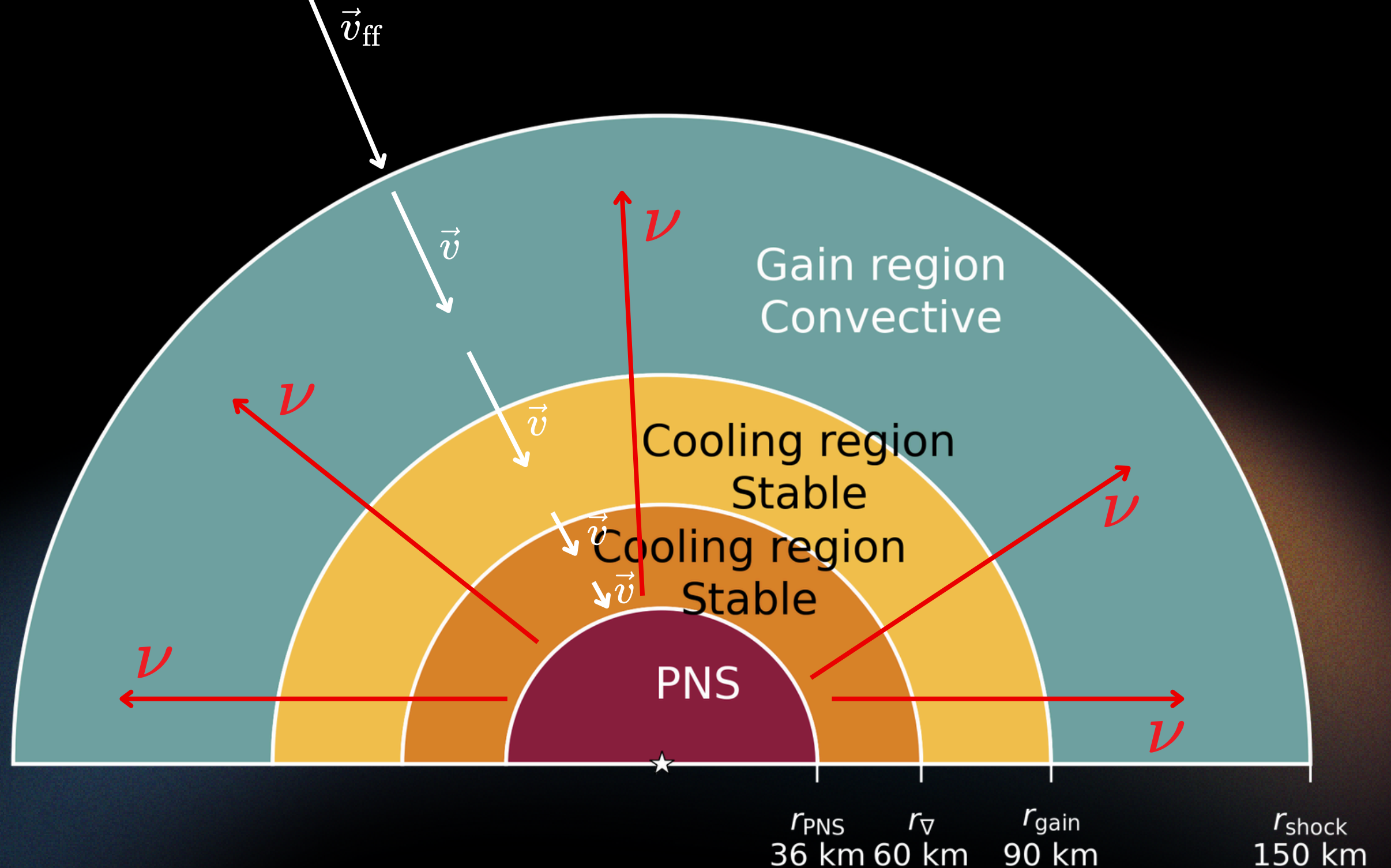
EOS/Progenitor	z85	z100
SFHx	Exploding	Non exploding
SFHo	Exploding	Non exploding



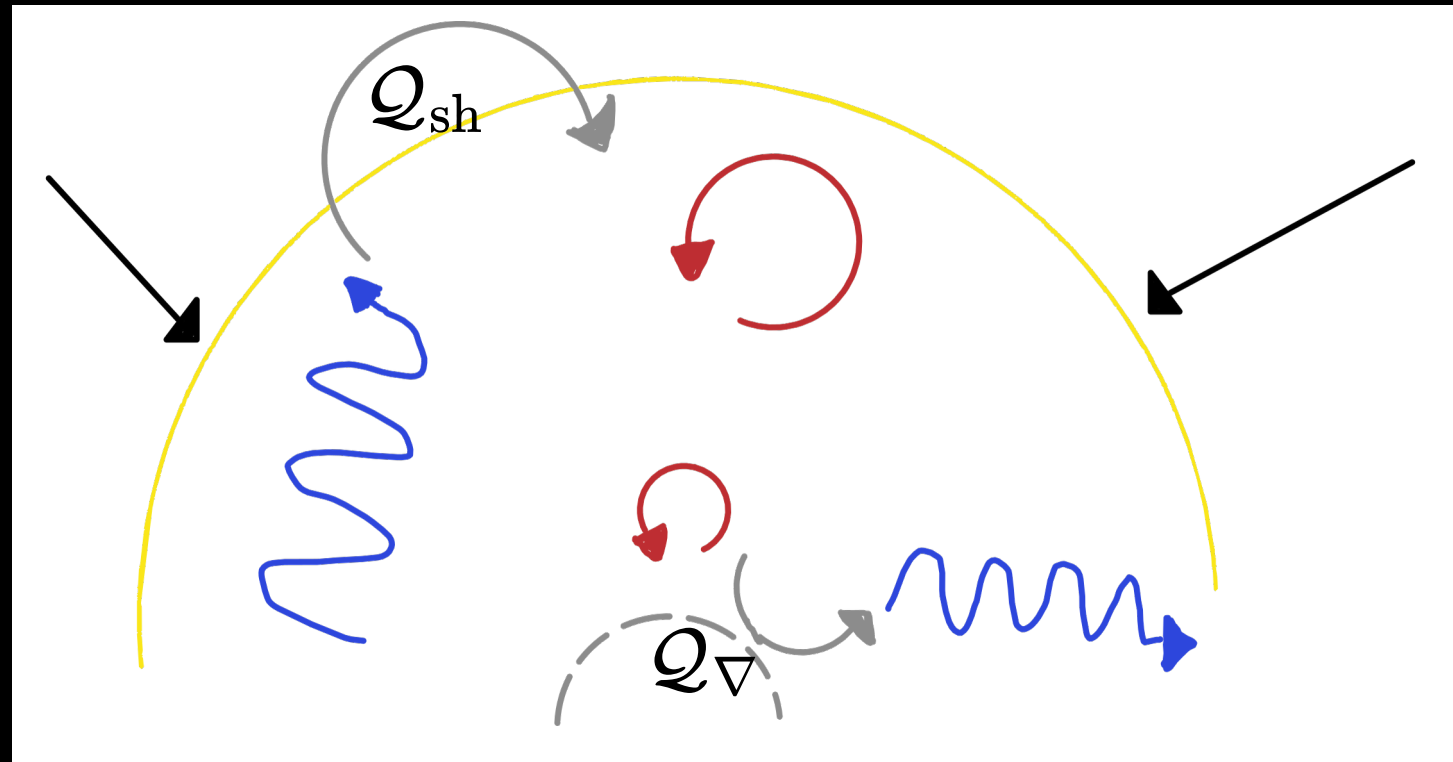
Recap about the post bounce structure



- Shock propagates, then quickly stalls at ~150 km
- r_{gain} : defines **heating and cooling region**
- r_{∇} : radius of **maximal deceleration**
- r_{PNS} ~30-50 km



Basics about Standing Accretion Shock Instability



**SASI impacts
neutrinos and GWs !**

Physical ingredients involved :
cooling, spherical geometry

- Instability at large angular scale (low ℓ)
- Advective-acoustic cycle under shock radius
- Low frequency : ~ 100 Hz
- Perturbative estimate of SASI frequency :

$$\omega^{\text{fit}}(\ell) \sim \frac{|v_{\text{sh}}|}{r_{\text{sh}}} F_{\ell} \left(\frac{r_{\text{sh}}}{r_{\nabla}} \right)$$

Foglizzo 2026

Missing ones : dissociation,
heating, non linearities, GR

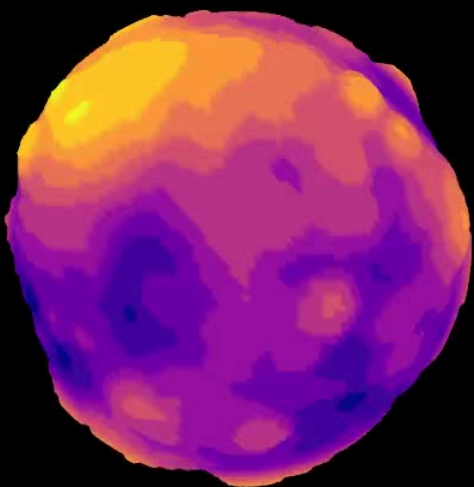
Goal of this work

- **Identify hydrodynamic instabilities in the numerical simulation**
- **Identify the key missing physical ingredients of SASI formulae from Foglizzo 2026**
- **Compare neutrino and GW signals : which mode drives them ?**
 - ↳ Frequencies
 - ↳ Time onset

Shock evolution : two hydrodynamic regimes

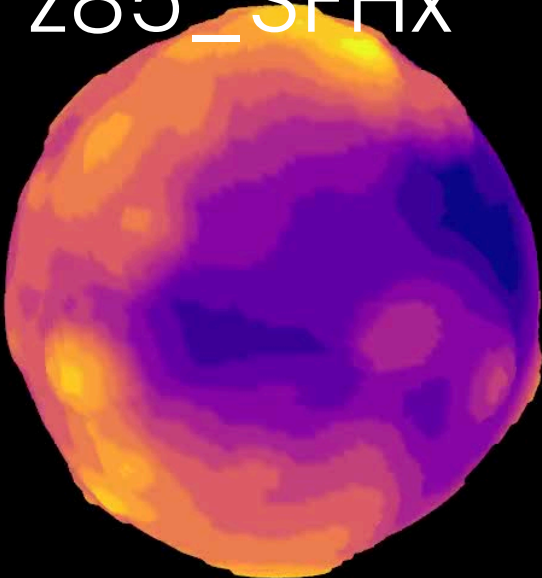
Angular scale of the most energetic transverse motions

z100_SFHo

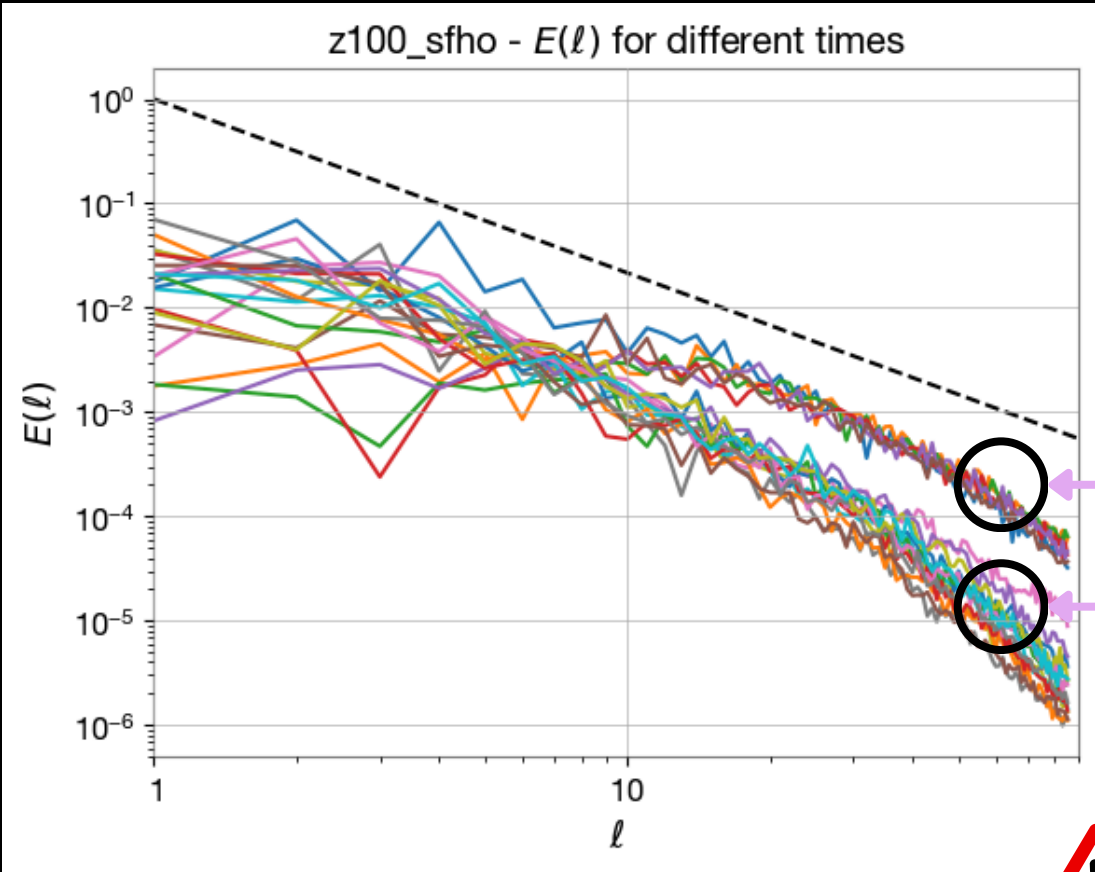


$t = 0.176$ s

z85_SFHX



$t = 0.171$ s

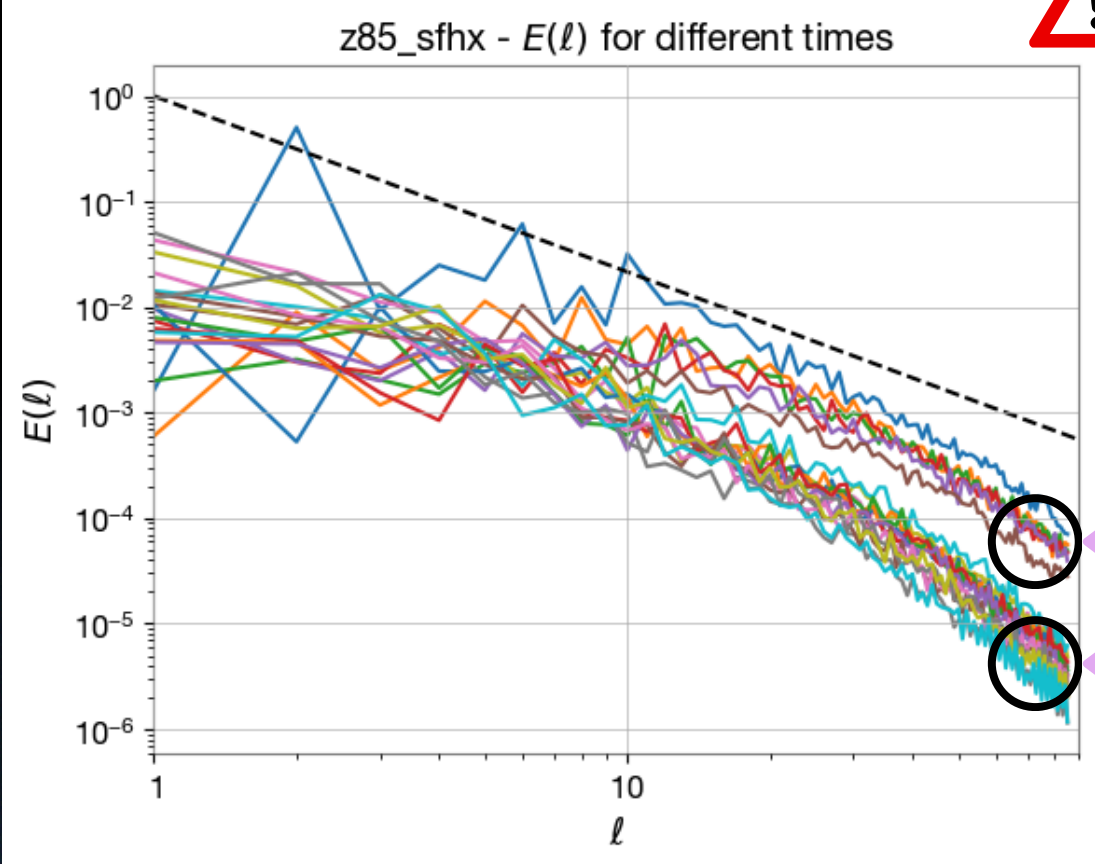


< 0.25 s

> 0.25 s

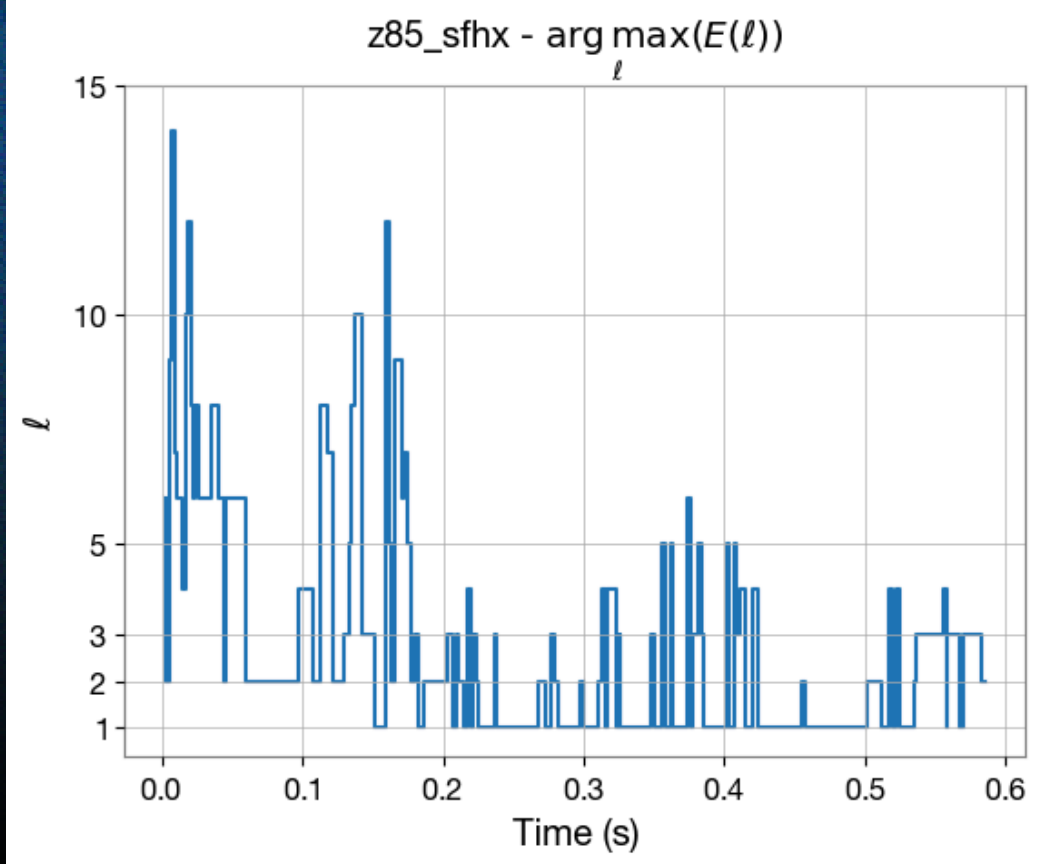
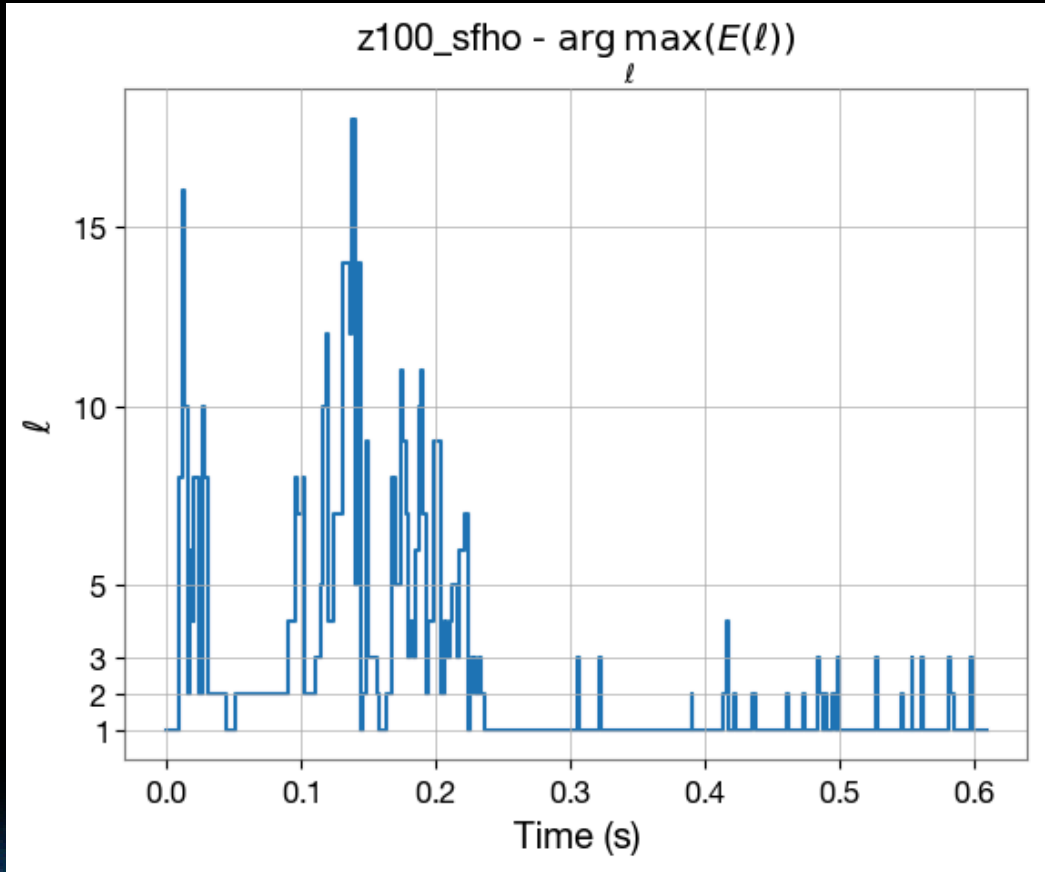


We reach limits of resolution



< 0.25 s

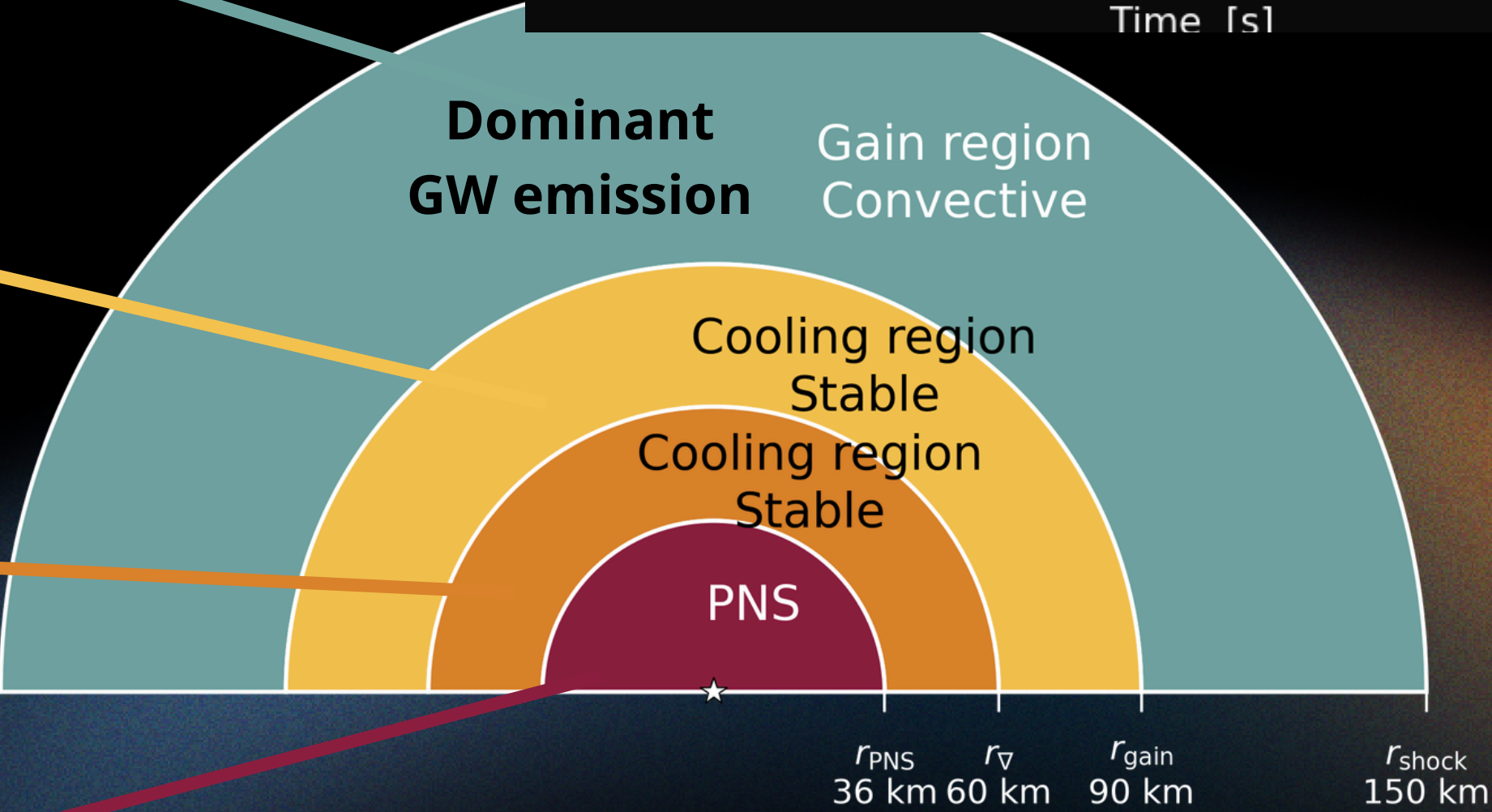
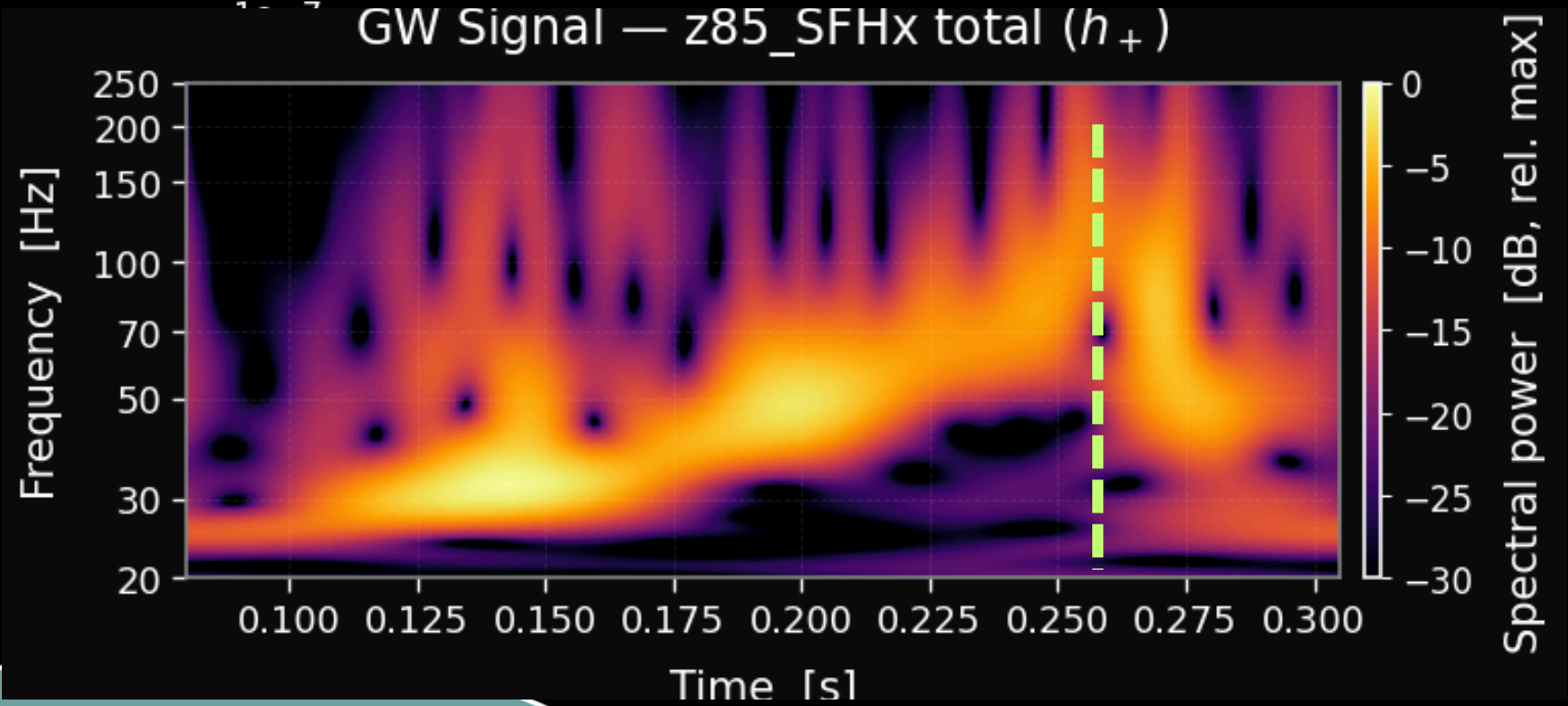
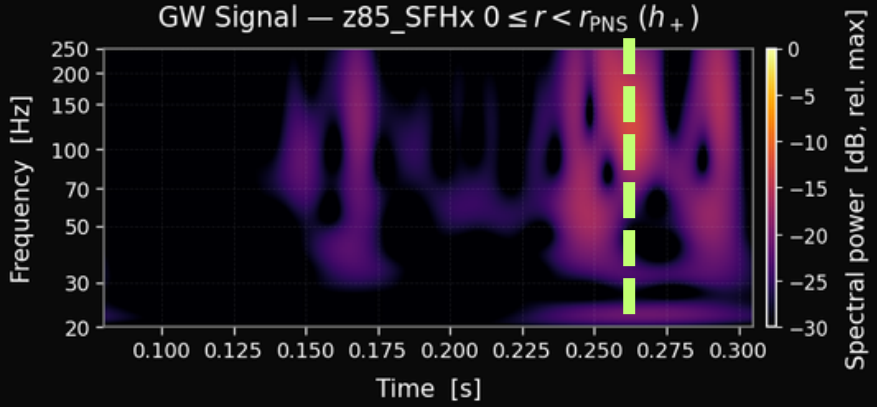
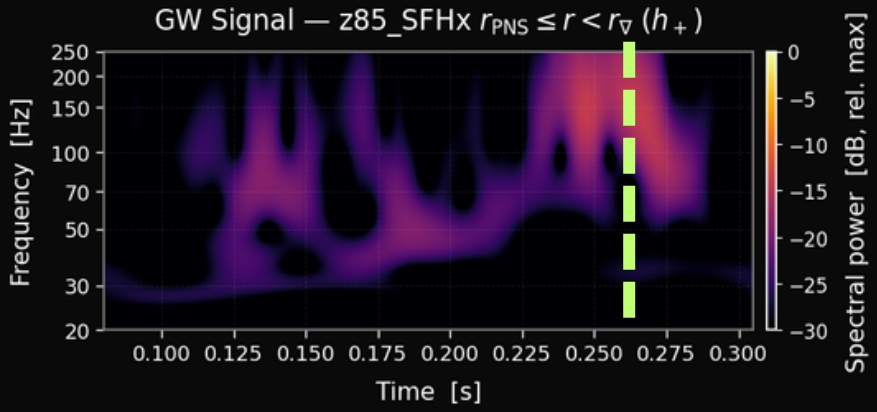
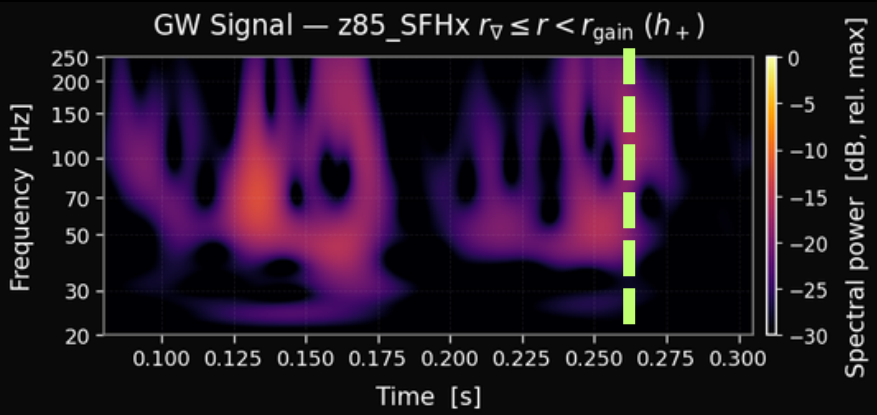
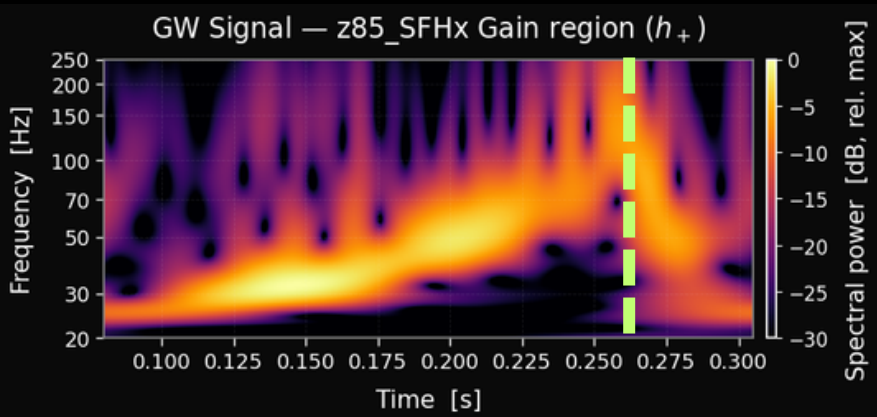
> 0.25 s



GW signal : spectrogram & radial location

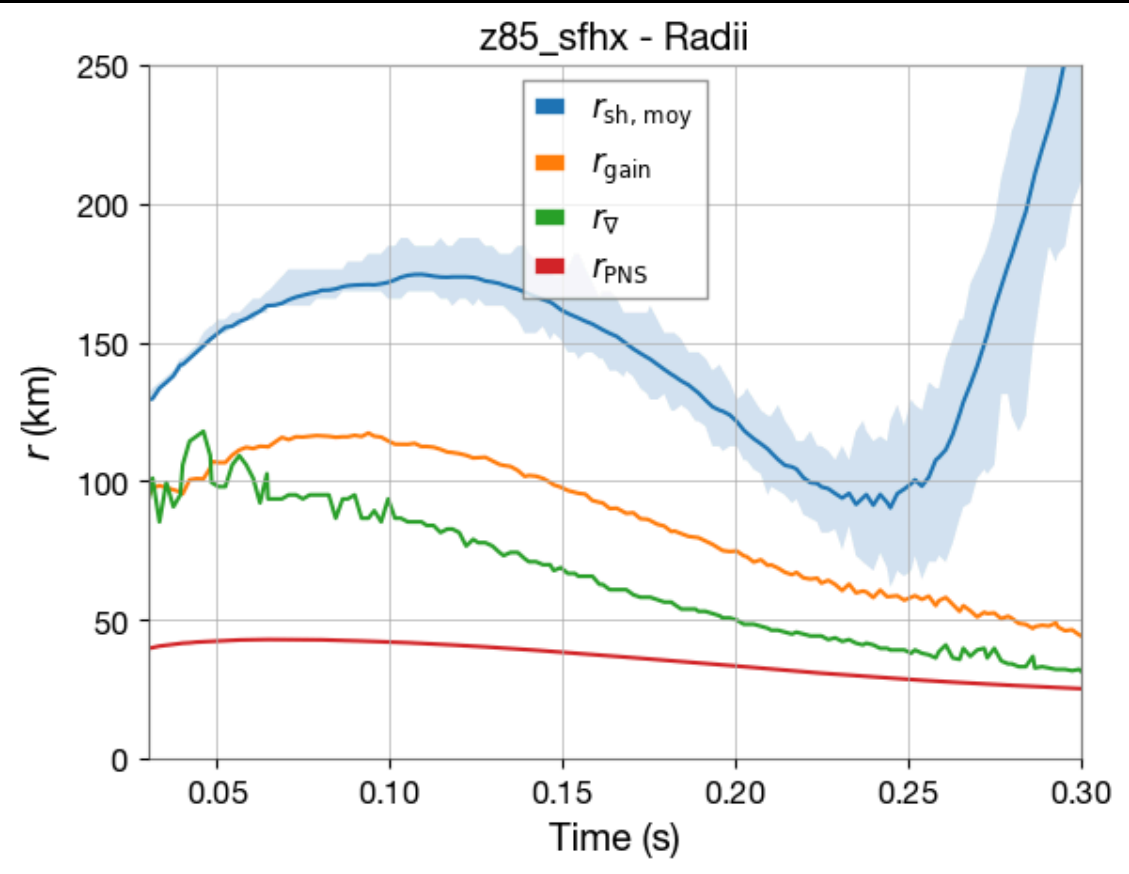
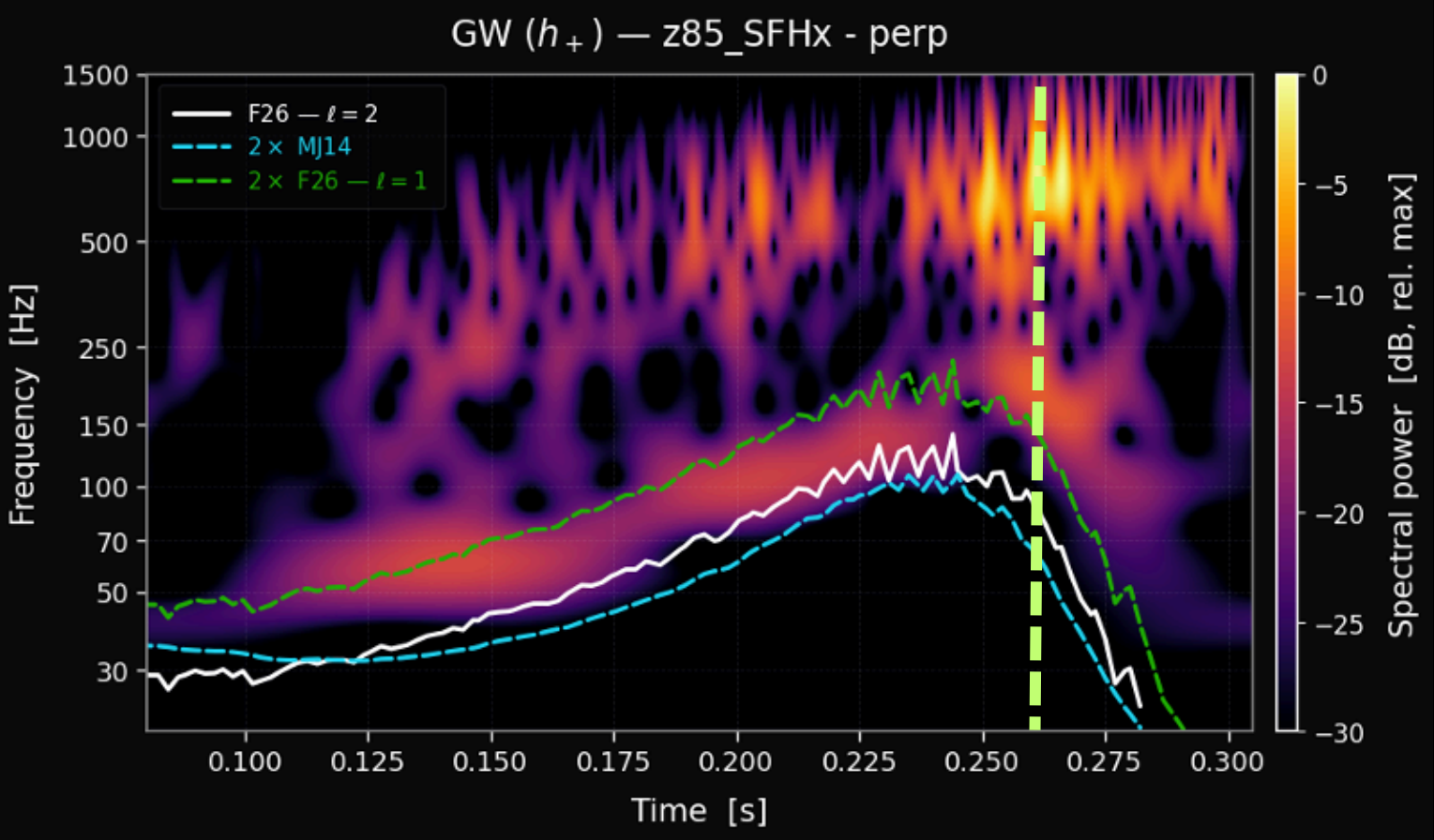
Quadrupolar motions = h_+ and h_x strain

$$\bar{h}_{ij}(t,r) = \frac{2G}{c^4 r} \ddot{I}_{ij}(t - r/c)$$

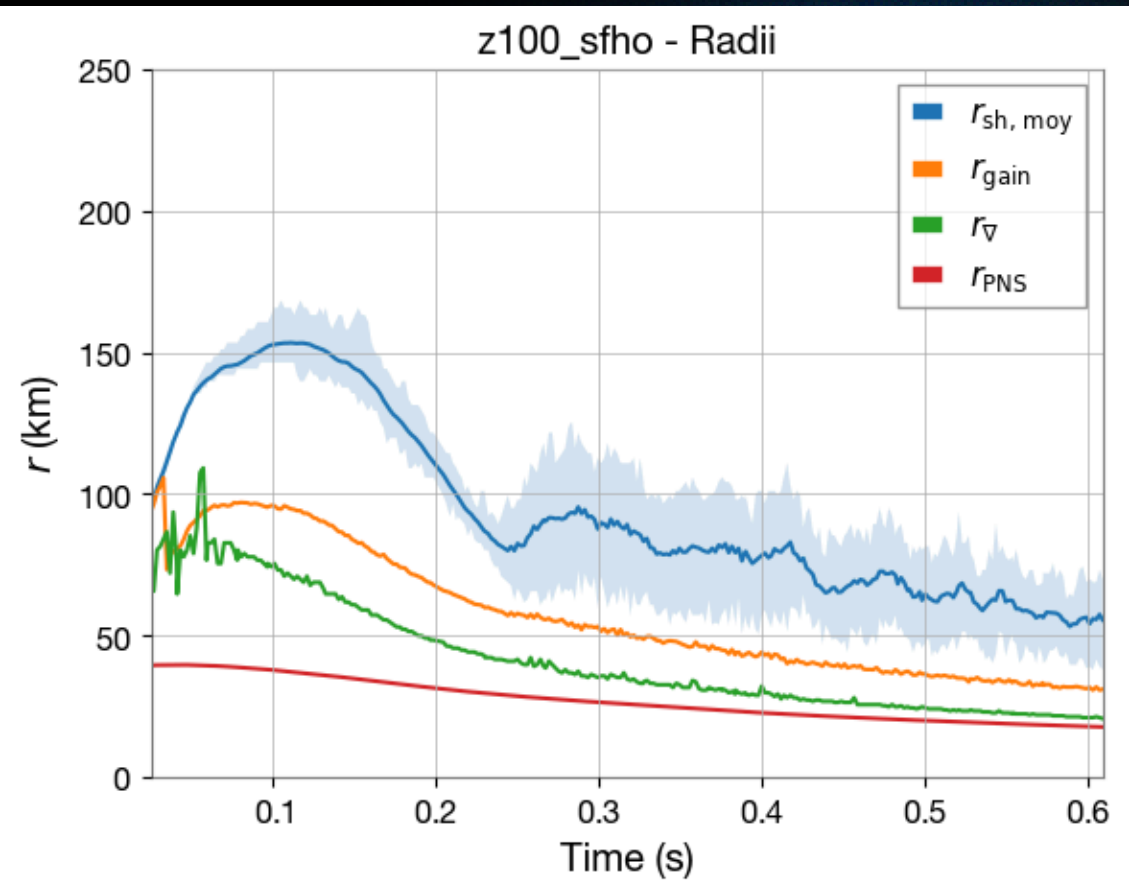
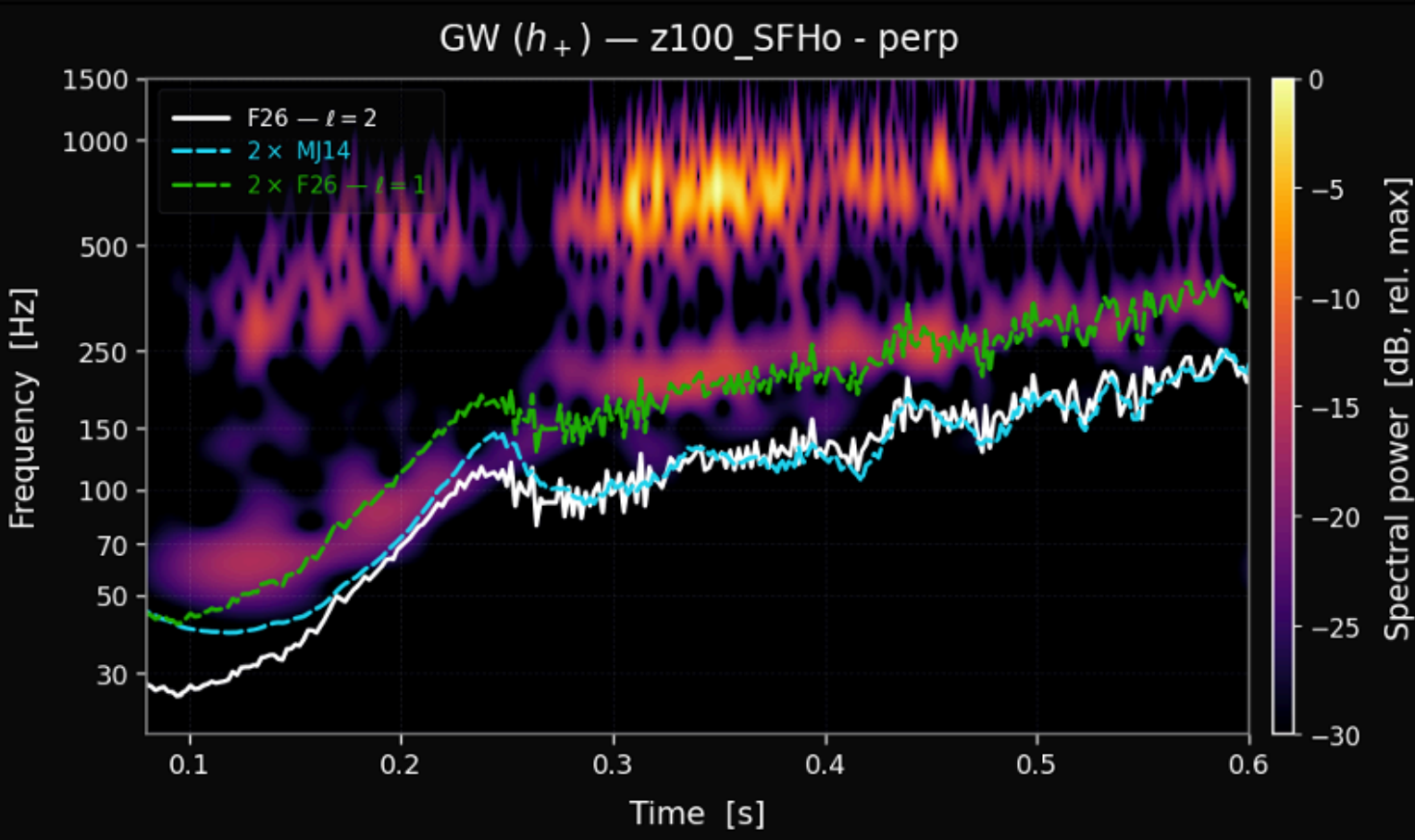


In agreement with the state of the art

GW signal : comparison with Foglizzo 2026 model



--- ${}^1f_{M14} \equiv \frac{52.6\text{Hz}}{\log(r_{sh}/r_{ns})} \left(\frac{100\text{km}}{r_{sh}} \right)^{\frac{3}{2}}$

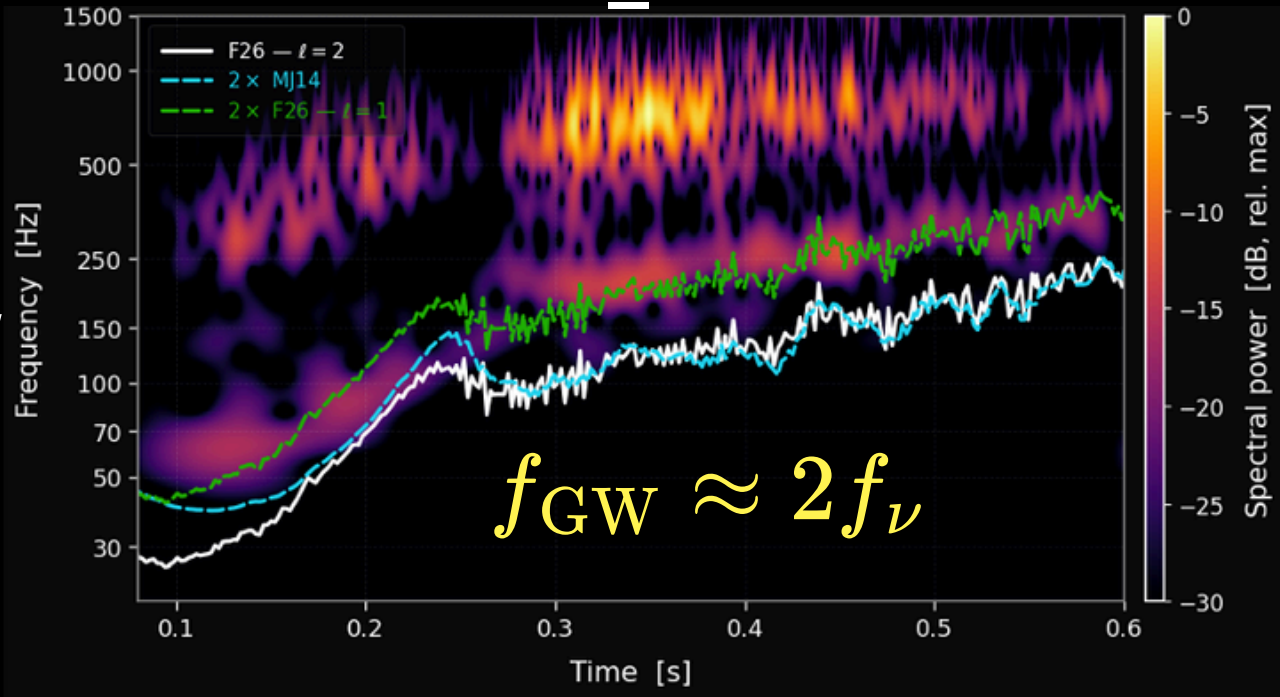


--- $\omega^{\text{fit}}(\ell) \sim \frac{|v_{sh}|}{r_{sh}} F_{\ell} \left(\frac{r_{sh}}{r_{\nabla}} \right)$

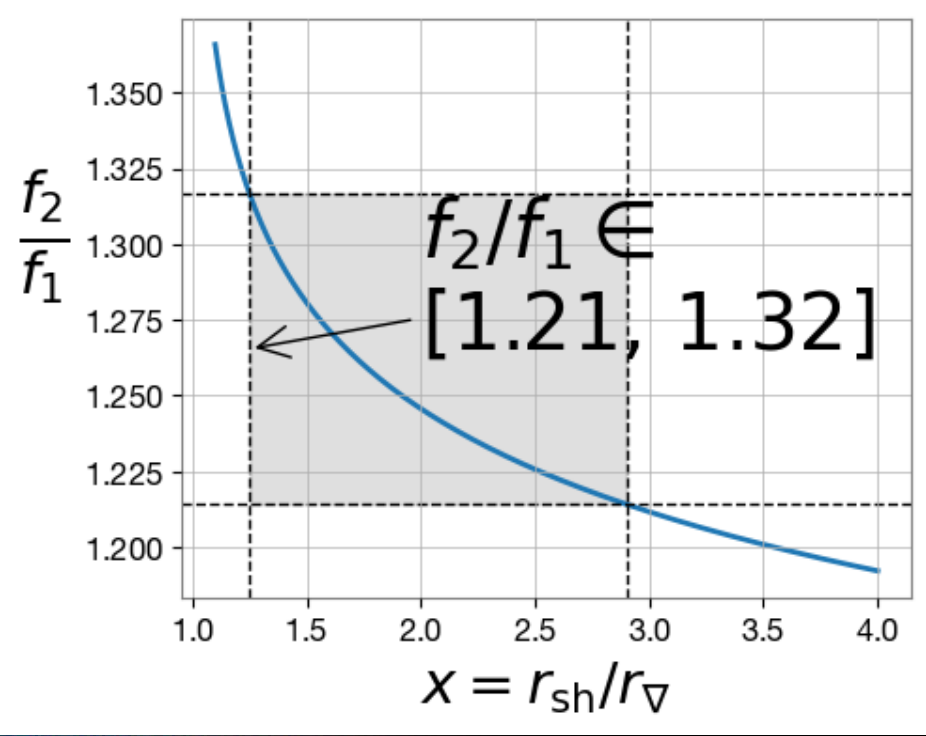
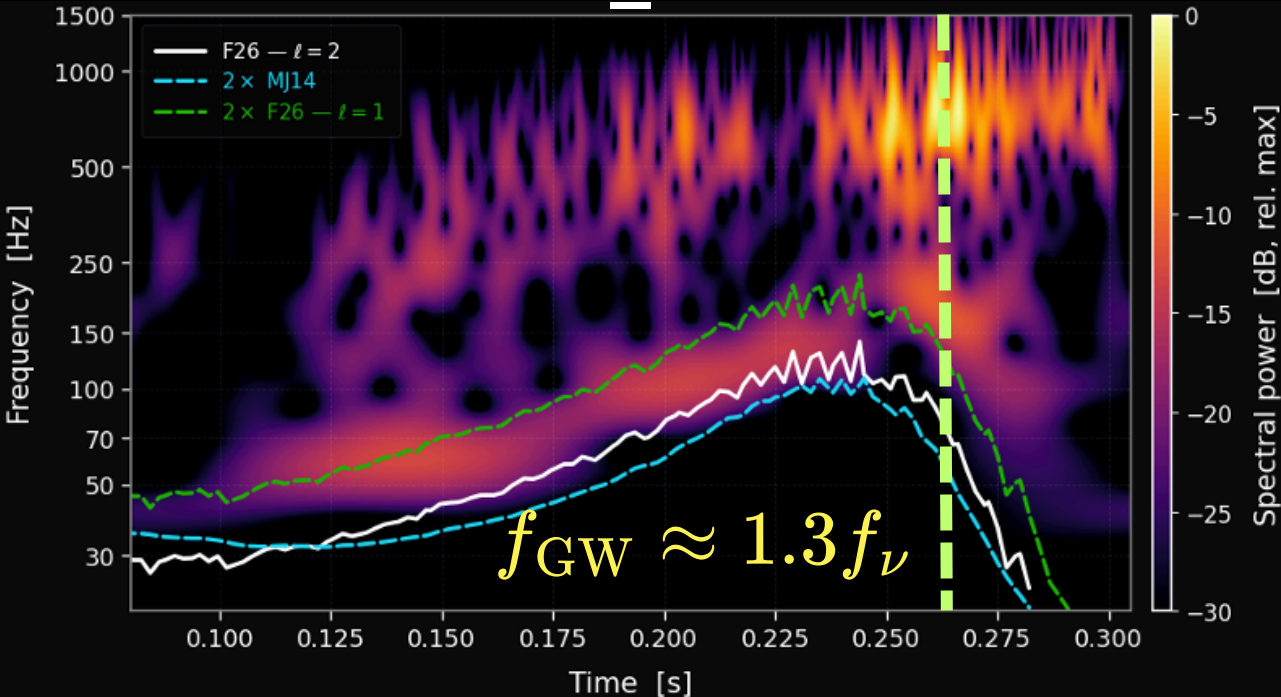
Neutrino vs GW : frequencies

$$\omega_{\ell}^{\text{fit}} \sim \frac{|v_{\text{sh}}|}{r_{\text{sh}}} F_{\ell} \left(\frac{r_{\text{sh}}}{r_{\nabla}} \right) \rightarrow \frac{F_2}{F_1} = 1.25(x - 1)^{-0.04} \text{ with } x = \frac{r_{\text{sh}}}{r_{\nabla}}$$

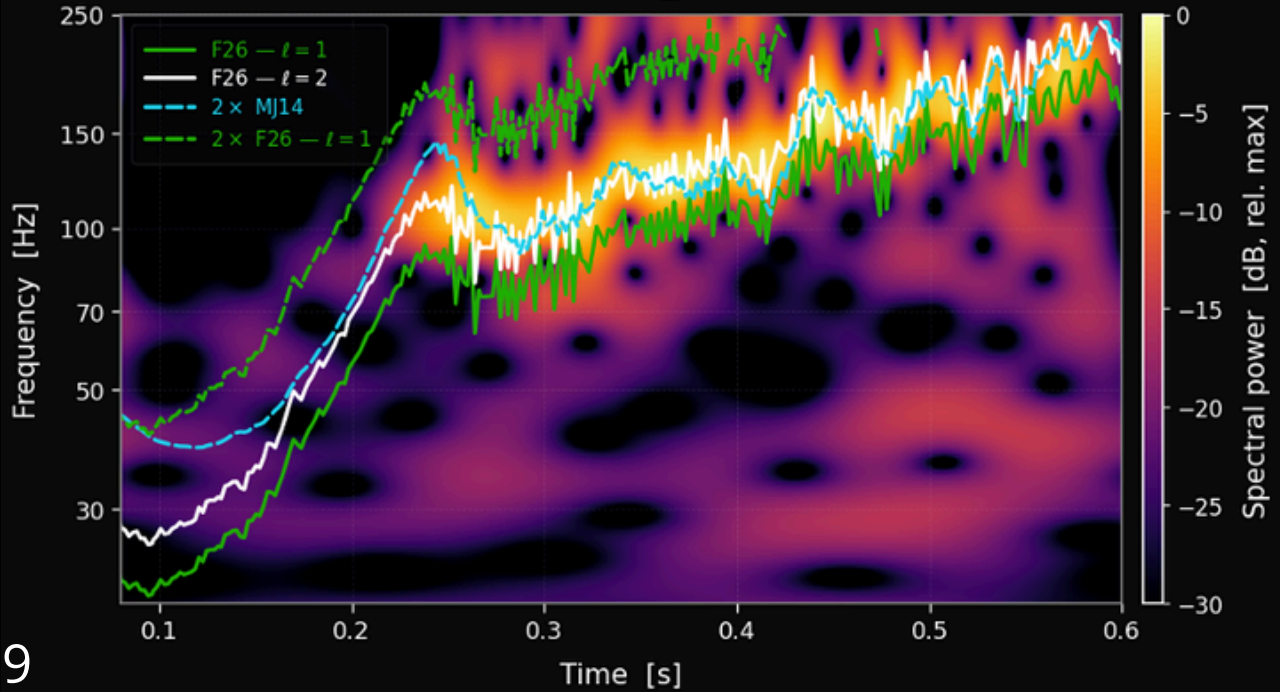
z100_SFHo



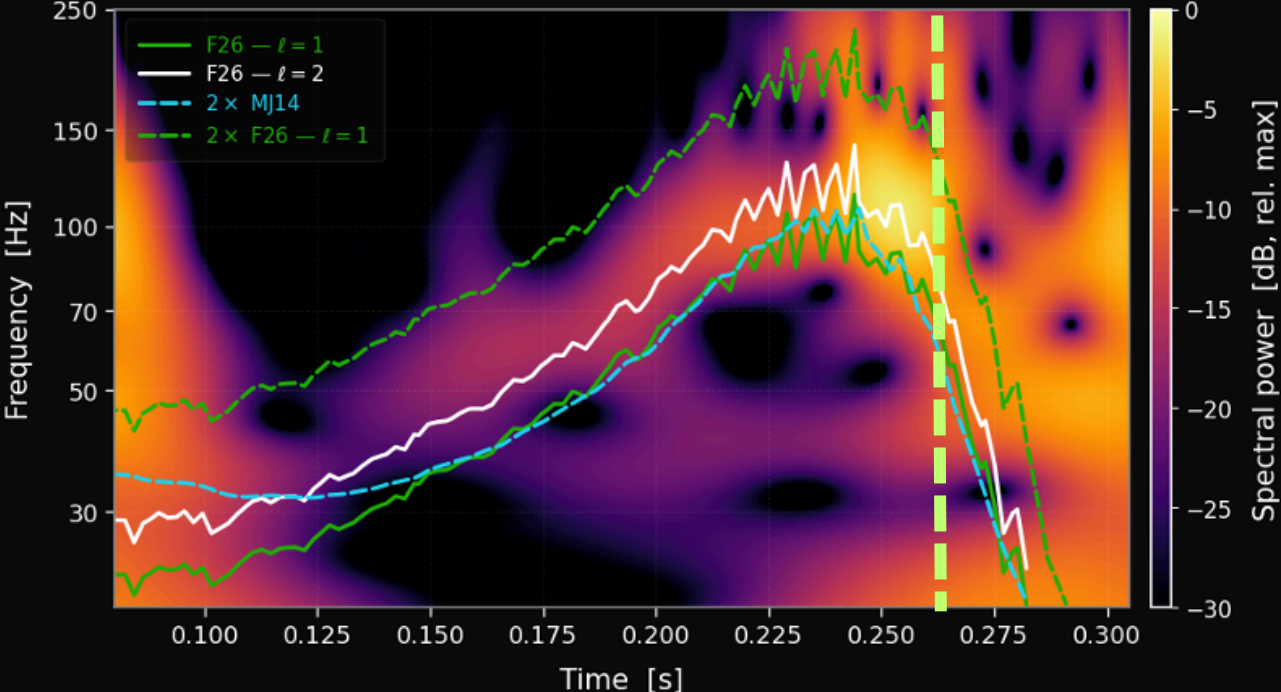
z85_SFHx



Neutrinos — z100_SFHo - para

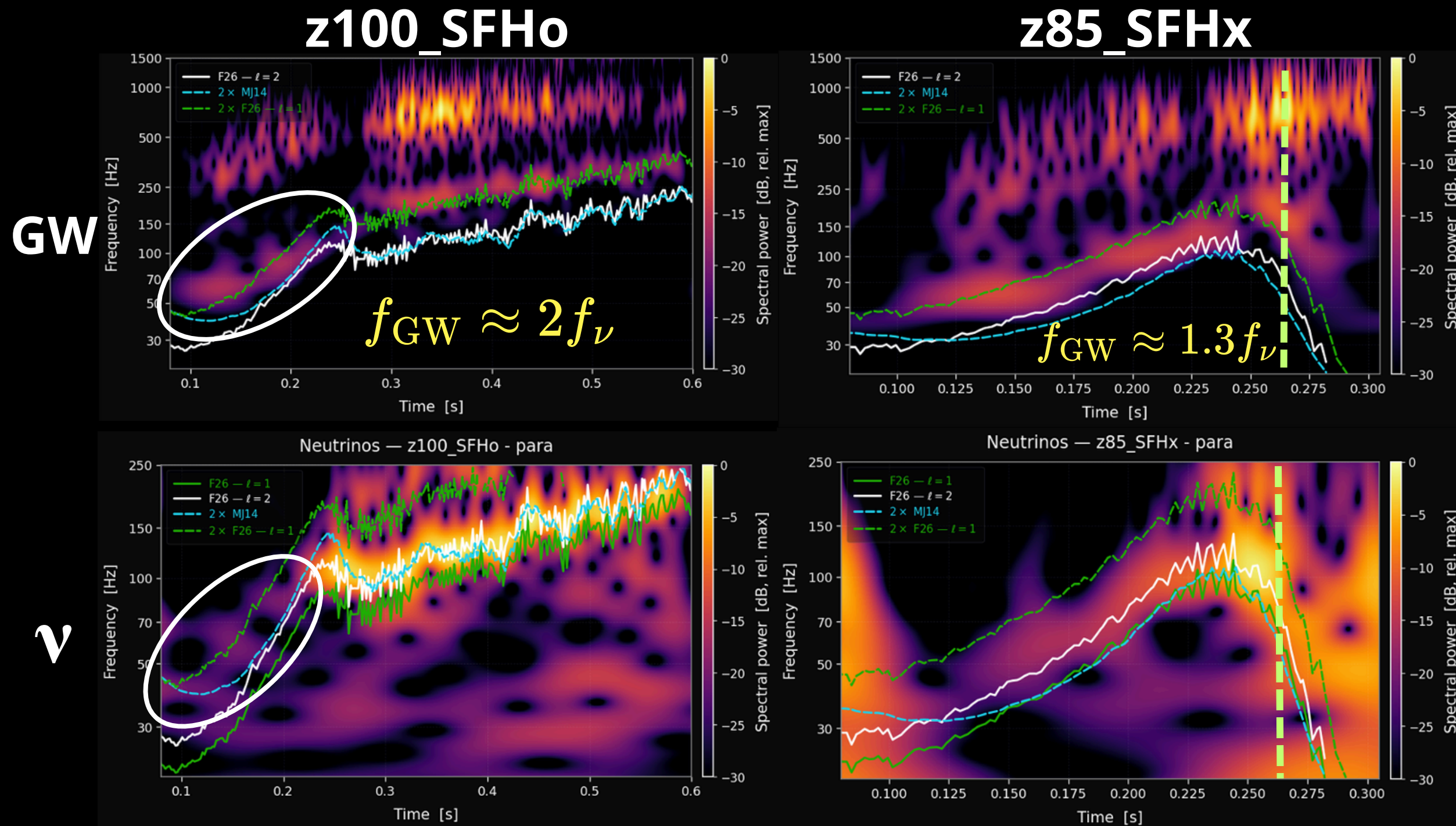


Neutrinos — z85_SFHx - para



- z100_SFHo GWs are consistent with nonlinear $\ell=1$ oscillations
- z85_SFHx GWs are consistent with $\ell=2$ oscillations

Neutrino vs GW : simultaneity

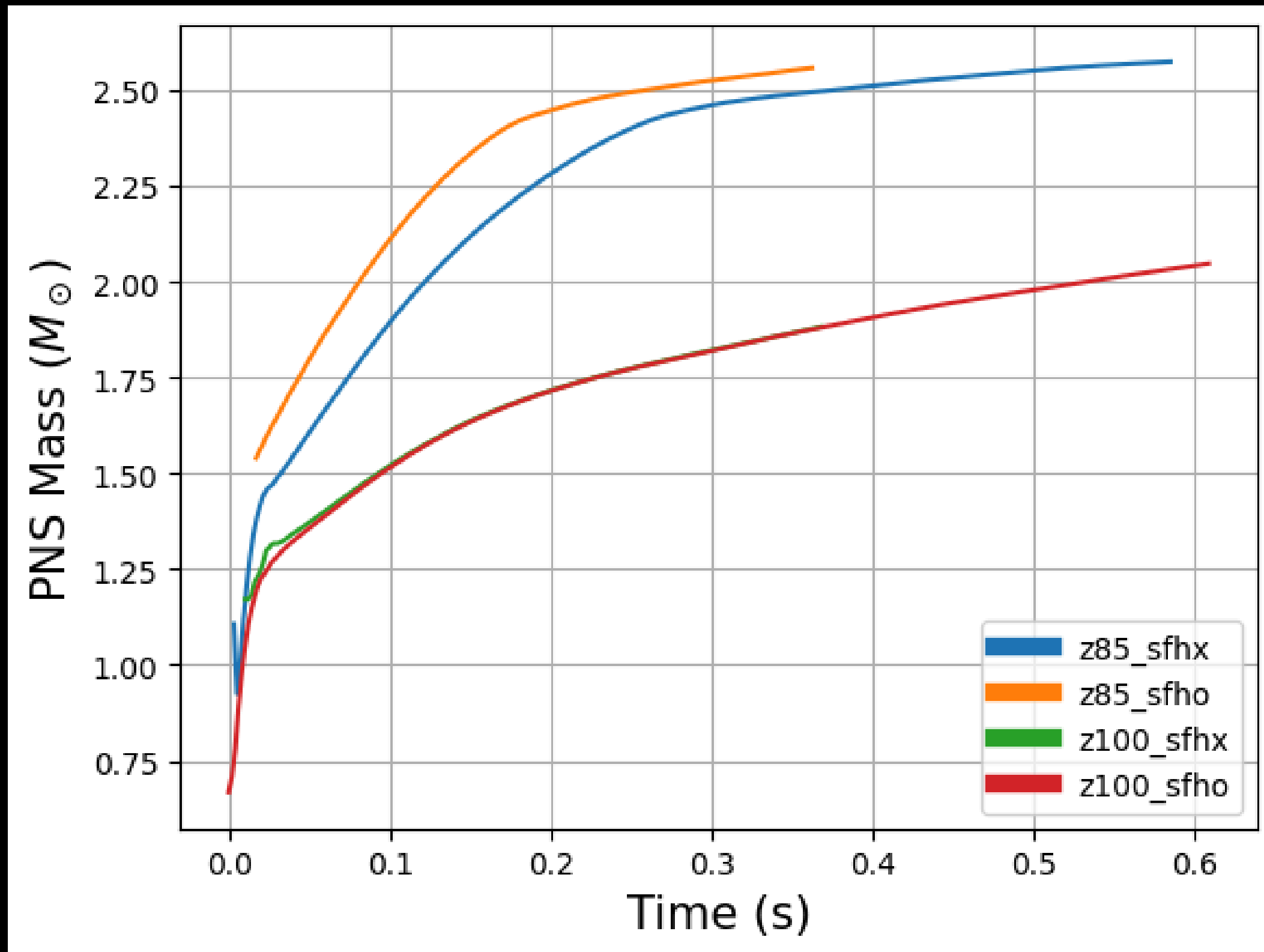


- **z100_SFHo : non simultaneity in ν and GWs for SASI !**
- **z85_SFHx : ν and GWs emits simultaneously**
- **Neutrinos are poorly sensitive to $\ell=2$ modes**

SASI motions can excite both $\ell=1$ and $\ell=2$ modes

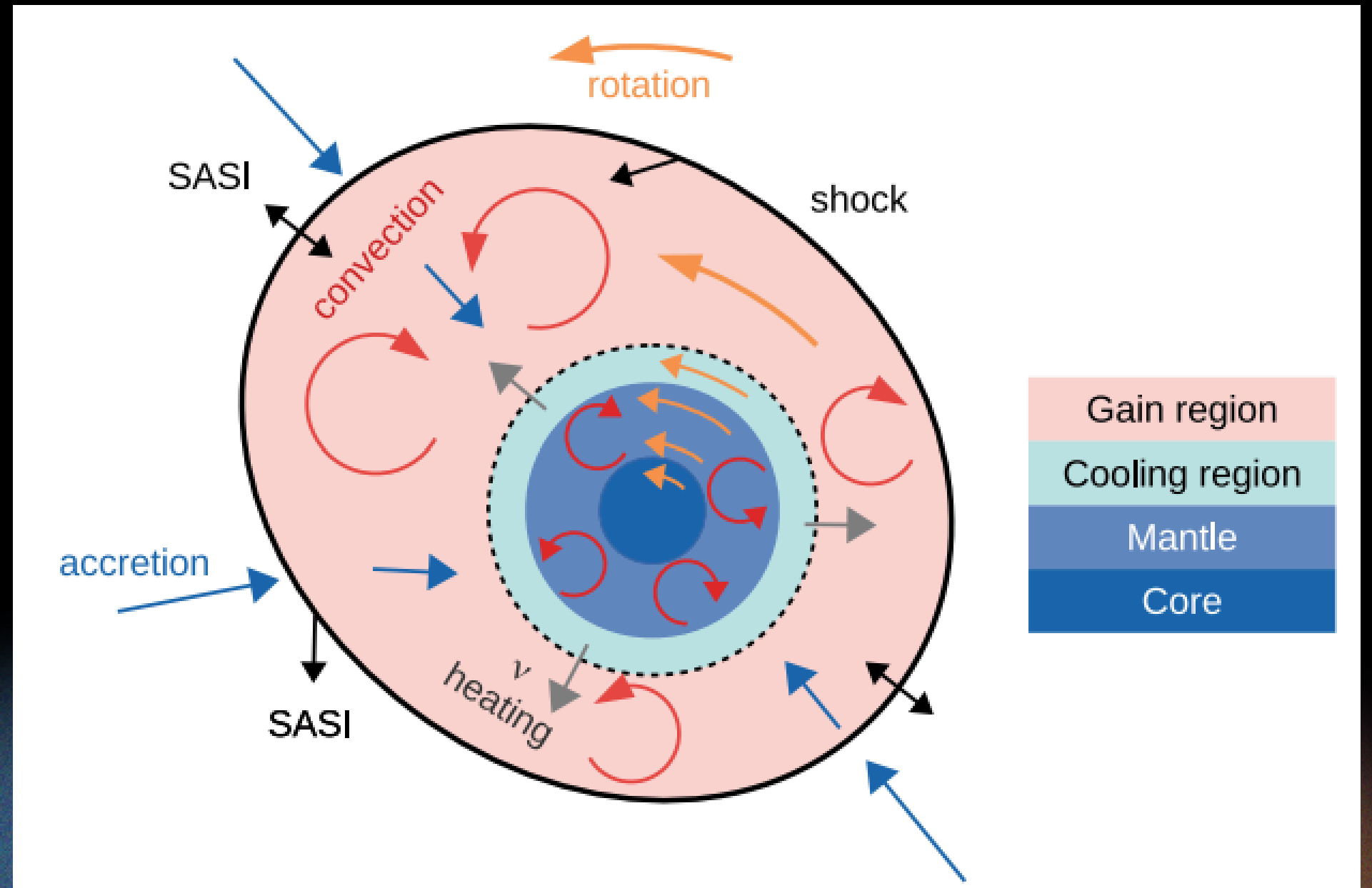
Open questions & Discussion

- Identification of two successive hydrodynamic regimes at different angular scales.
- SASI-related GWs can be produced by **both $\ell=2$ and $2\times\ell=1$** modes, depending on the progenitor.
- Comparing SASI signal to analytical formulae should help us understand **the impact of missing physical ingredients**.
- Conclusions of this work should be tested on other numerical simulations, **including rotation**.



Structure of the post-bounce phase : convective gain region

- Gain region : heated by neutrinos
- Negative entropy gradient : unstable to convection
- Small angular scale (high ℓ)
- Growth rate $\omega_{BV}^2 \propto \frac{dS}{dr}$



B. Müller, 2025