# SN REGIONS CLASSIFICATION & OBSERVATIONS

## Reference from Murphy *et al.* (2025)

BRAJESH KUMAR PADHI (Intern)
Faculty of Physics, University of Warsaw
Date of completion of draft: 27/06/2025

# Classification Hypothesis

## 1 Objectives -

1. Understand properties of various SN regions.
2. Find a method to distinguish between various regions based on a single GW timeseries signal.

## 2 Foundational Theoretical Knowledge -

As discussed in Murphy *et al.* (2025), a simulated PNS structure can be spatially divided as layers akin to those of an onion. The center of the PNS consists of a spherically symmetric core with radius $\leq 8km$ which does not produce any GWs. For radii greater than that, the PNS structure is divided into 6 layers (0 to 5, with increasing radius) below the SN shockwave (although region 5 includes it) on the basis of their densities & dominant physical processes with the data having strain v/s post bounce time for all the regions and both the $h_+$ & $h_X$ polarizations. The Region 0 has negligible strain data & hence is neglected for this analysis. The various regions are described as follows -

1. Region 1 - Sustained Ledoux convection deep within the PNS, at densities above $10^{12} g/cm^3$.
2. Region 2 - Convective overshoot region.
3. Region 3 - Surface layer of the PNS, below a density of $10^{11} g/cm^3$, which we use to define the PNS surface .
4. Region 4 - Net neutrino cooling layer between the PNS surface and gain radius.
5. Region 5 - Above the gain radius till shockwave end.

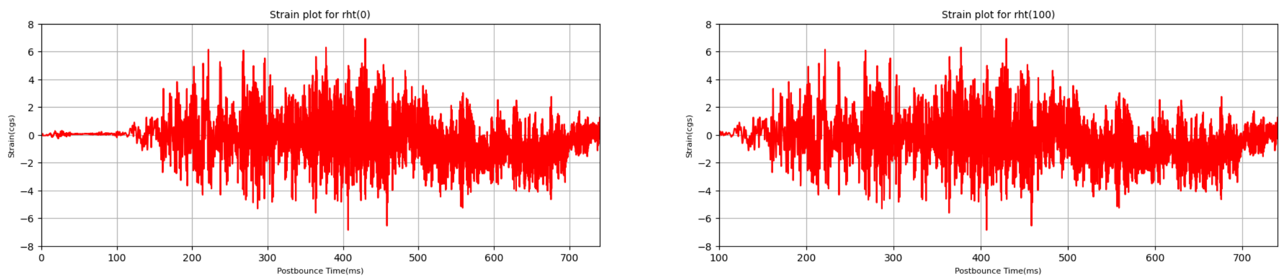
## 3 Time Evolution of Signals -

1. The strains start with small amplitudes in region 4 at $\approx$ 100 ms postbounce.
2. The strain amplitudes rise to similar levels in region 3 by $\approx$ 110 ms postbounce.
3. The strain amplitudes of region 2 become comparable to those of regions 3 and 4 by $\approx$ 160 ms postbounce.
4. Simultaneously, the strains in region 1 also increase but remain slightly below those of regions 2, 3, and 4.

5. The strains in regions 1 and 2 continue to grow while, starting at $\approx$ 440 ms postbounce for D15 and $\approx$ 300 ms postbounce for D25, the strains in regions 3 and 4 begin to decrease.
6. The strains in region 1 and 2 become approximately constant, on average, with the highest amplitude strains.

# 4 Observations & Inferences (D15) -

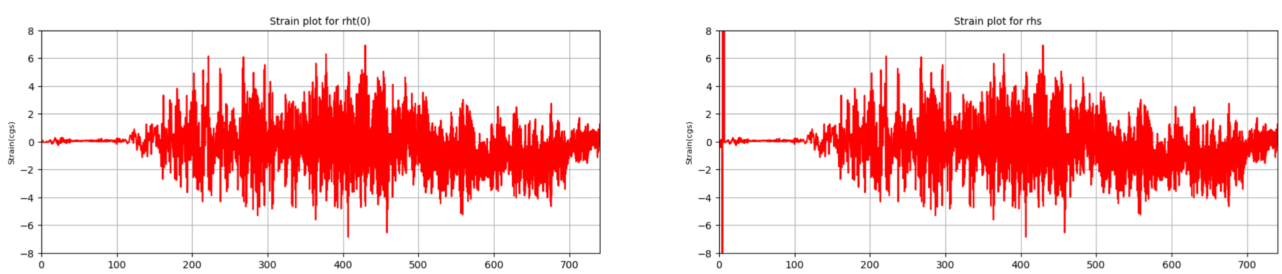
1. The signals of both the polarizations are combined since they have a similar trend. Also, in accordance to the reference, the usual range of data is taken after 100ms.




(a) rht(0ms) (b) rht(100ms)

Figure 1: Total signal for D15

2. The explicit addition of all signals is expected to be identical to individual addition of total strains for both polarizations. However, for a region between 0ms & 100ms, the former is observed to have a tremendously huge disturbance (both $+ve$ & $-ve$), which is absent in the latter; this requires more thought. However, apart from this anomaly, the signals superimpose perfectly as expected.

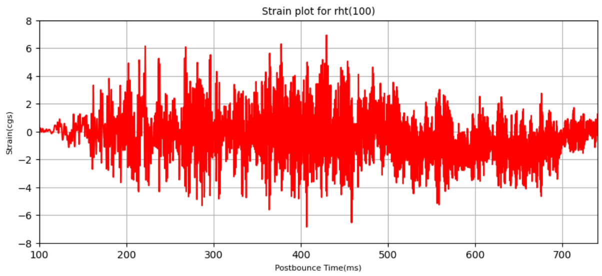



(a) rht (b) rhs

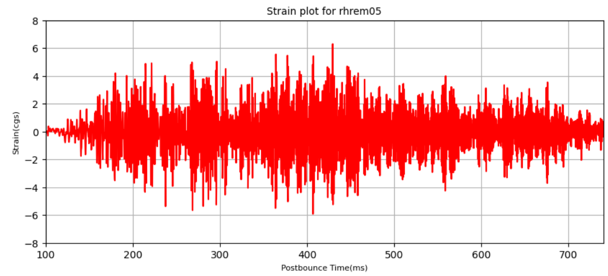
Figure 2: Initial peak in sum of signals for D15

3. The region 0 signals are neglected due to very low amplitude contributions. Its removal from total signal does not affect the plots much both qualitatively & quantitatively.

4. The region 5 can be easily distinguished due to presence of a positive or a negative memory/residual signal at the end of the timeseries. Its removal usually results in the mean signal to reach $\approx 0$ at the extreme later stages.



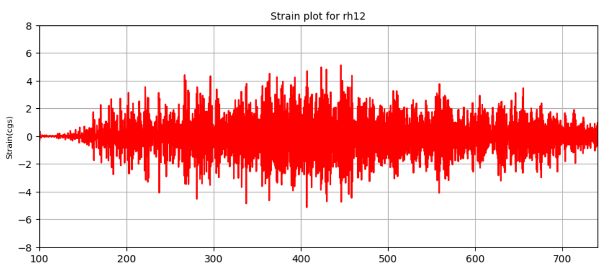

(a) rht



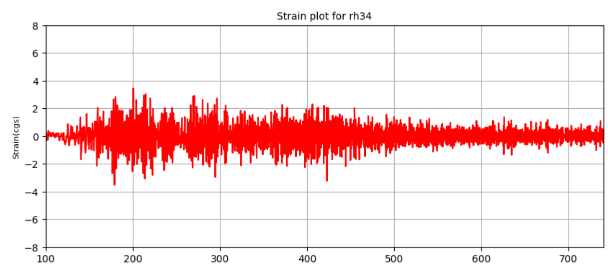

(b) rhrem05

Figure 3: Region 5 removal leads to removal of resdiual/memory signal in the end

5. There appears to be a combined correlation between regions 1 & 2 and regions 3 & 4, wherein both these combinations seem to have different trends with time evolution with their dominance in the signal at different times; R34 has an initial dominance which subsides gradually and R12 becomes dominant for most of the signal later.

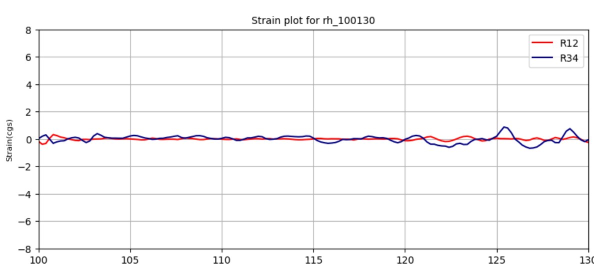



(a) rh12

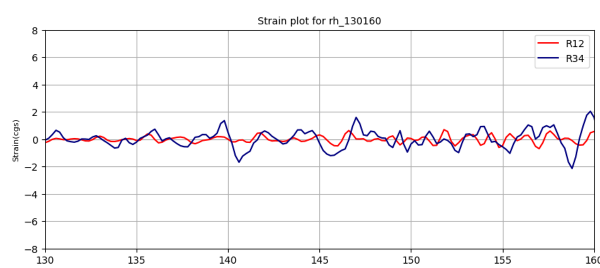



(b) rh34

Figure 4: Different amplitude trends for R12 & R34 with time evolution

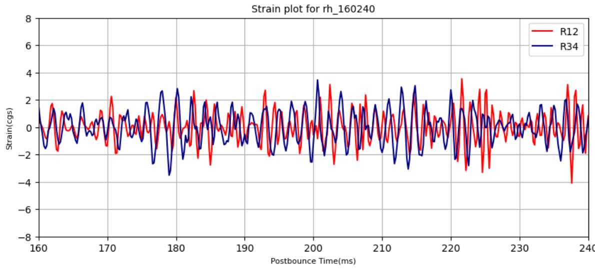



(a) 100-130

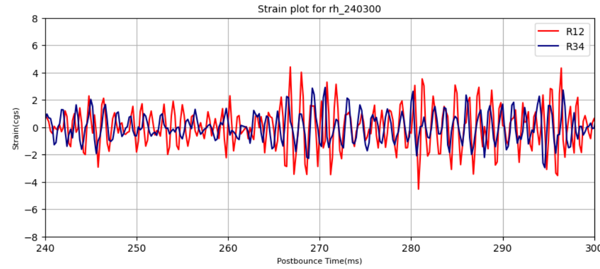



(b) 130-160

Figure 5: Higher signal for R34 due to net cooling and surface phenomena initially.
R12 contribute later due to Ledoux convection dominating




(a) 160-240




(b) 240-300

Figure 6: In the first range, R12 & R34 signals start matching in amplitudes while at a later range R12 starts dominating.

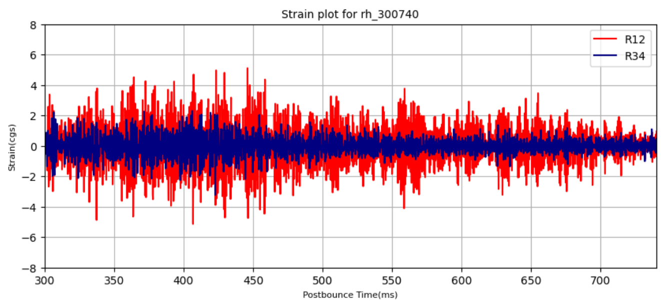
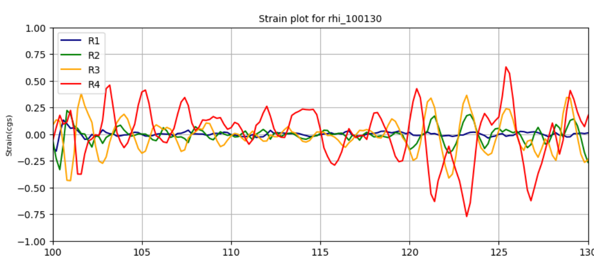
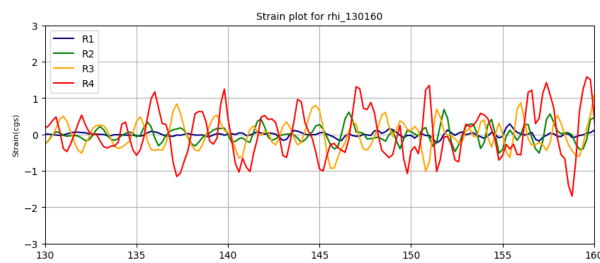



Figure 7: 300-740, R12 clearly dominates the signal

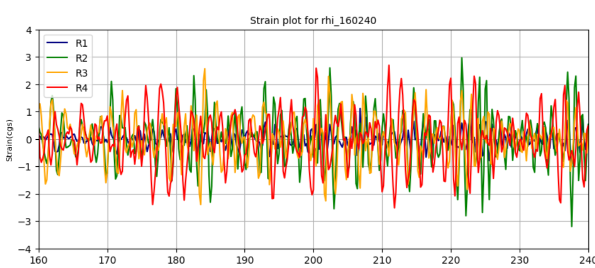
6. R1 & R2 behave in a similar nature while R3 & R4 behave in a similar nature throughout the signal.




(a) 100-130




(b) 130-160




(a) 160-240


(b) 240-300

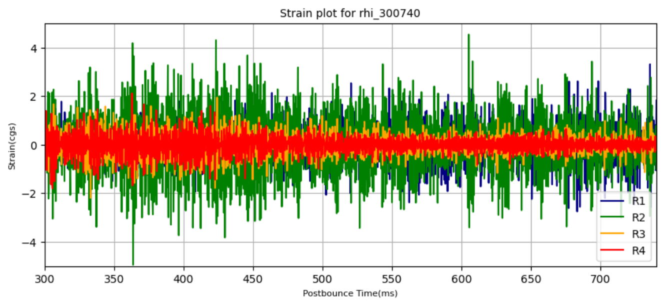
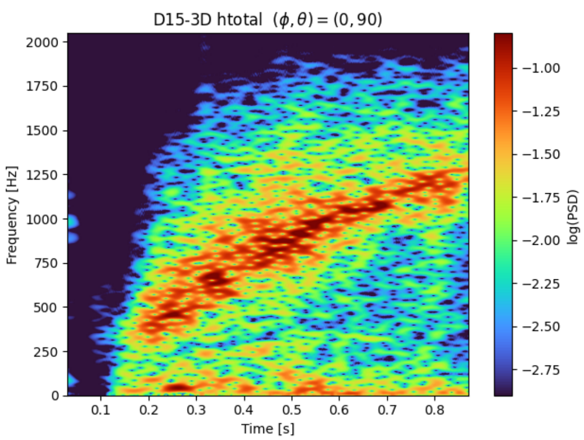
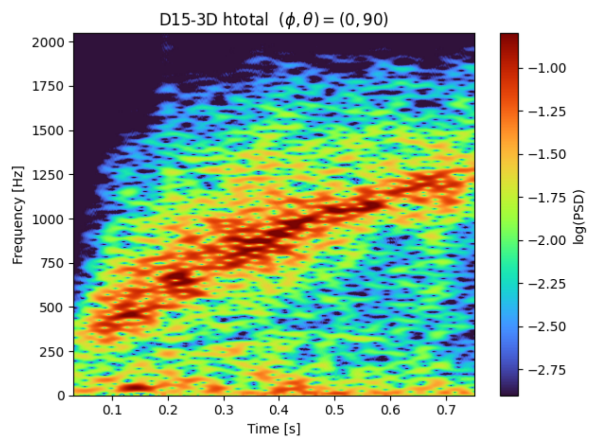



Figure 8: 300-740

7. Evidently, after time series analysis, spectrograms give a clearer picture. From 100ms post-bounce, an increasing frequency major region is observed.




(a) Total signal(0ms)(with R0 & R5)




(b) Total signal(100ms)(with R0 & R5)

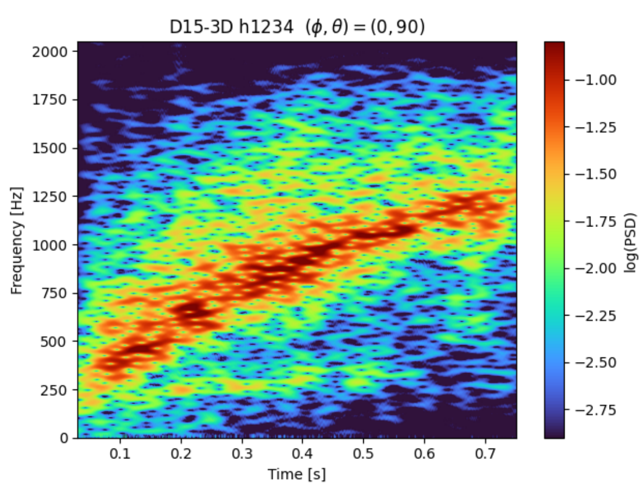
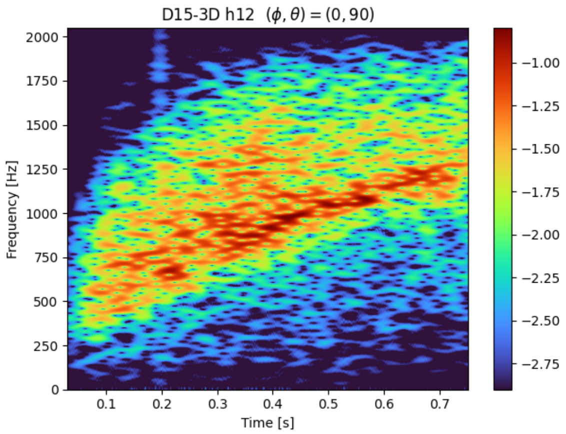
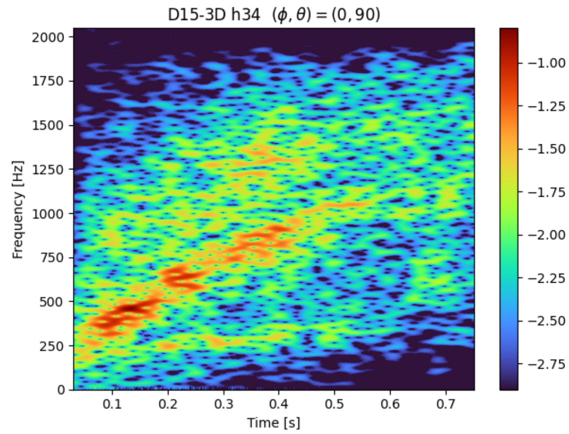



Figure 9: This is the signal from 100ms post bounce which is devoid of R0 & R5

8. Clearly from the spectrograms, R34 has a dominance at a lower frequency region with approximately all the PSD contributed by it. However, when this signal from R34 is removed, the overall signature leftover is entirely contributed by R12.




(a) Signal from R12

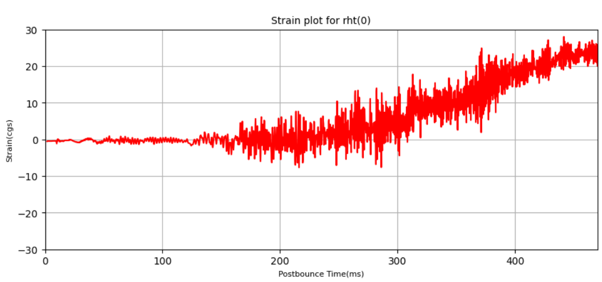



(b) Signal from R34

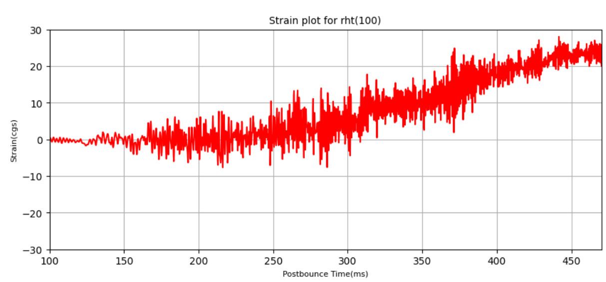
9. There is also an apparent phase shift of 180° in R3 & R4 signals upto ≈ 200ms, while for the same time interval, R2 & R3 seem to overally be in phase.

# 5 Observations & Inferences (D25) -

1. The signals of both the polarizations are combined since they have a similar trend. Also, in accordance to the reference, the usual range of data is taken after 100ms.



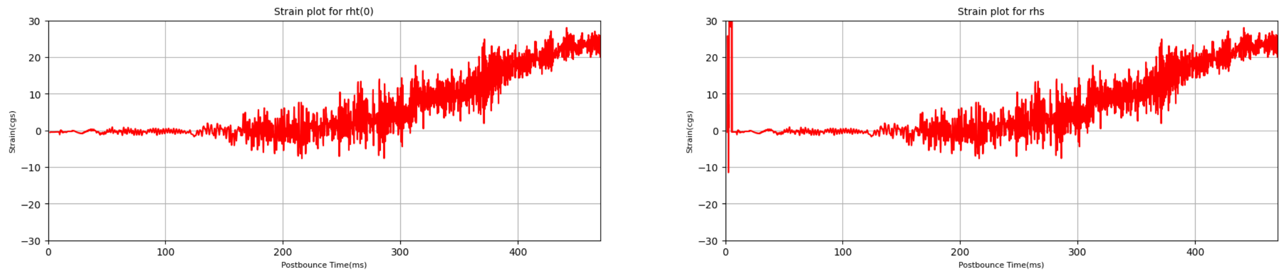

(a) rht(0ms)




(b) rht(100ms)

Figure 10: Total signal for D25

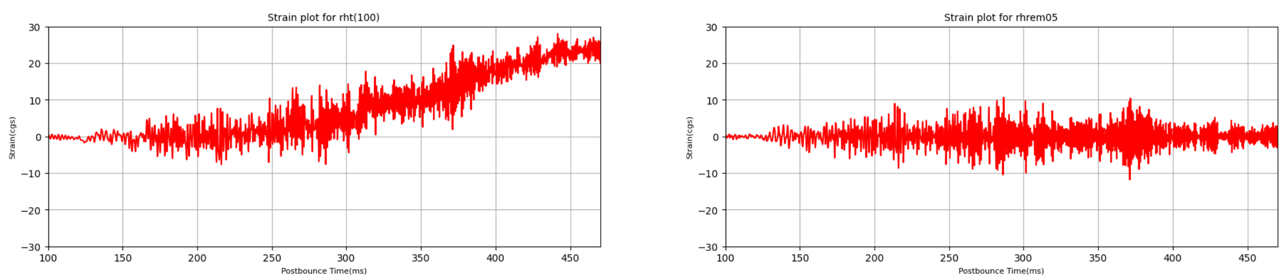
2. The explicit addition of all signals is expected to be identical to individual addition of total strains for both polarizations. However, for a region between 0ms & 100ms, the former is observed to have a tremendously huge disturbance (significantly $+ve$), which is absent in the latter; this requires more thought. However, apart from this anomaly, the signals superimpose perfectly as expected.




(a) rht (b) rhs

Figure 11: Initial peak in sum of signals for D25

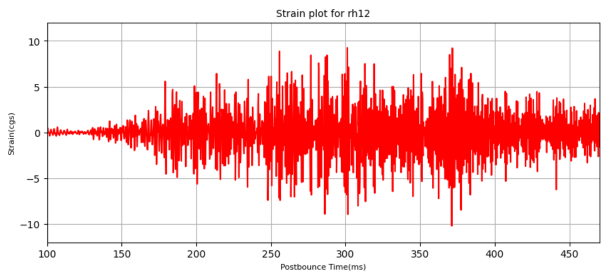
3. The region 0 signals are neglected due to very low amplitude contributions. Its removal from total signal does not affect the plots much both qualitatively & quantitatively.
4. The region 5 can be easily distinguished due to presence of a positive or a negative memory/residual signal at the end of the timeseries. Its removal usually results in the mean signal to reach $\approx 0$ at the extreme later stages.



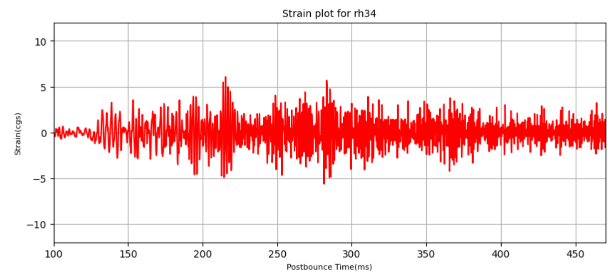

(a) rht (b) rhrem05

Figure 12: Region 5 removal leads to removal of resdiual/memory signal in the end

5. There appears to be a combined correlation between regions 1 & 2 and regions 3 & 4, wherein both these combinations seem to have different trends with time evolution with their dominance in the signal at different times; R34 has an initial dominance which subsides gradually and R12 becomes dominant for most of the signal later.
6. R1 & R2 behave in a similar nature while R3 & R4 behave in a similar nature throughout the signal.
7. Evidently, after time series analysis, spectrograms give a clearer picture. From 100ms post-bounce, an increasing frequency major region is observed.
8. Clearly from the spectrograms, R34 has a dominance at a lower frequency region with approximately all the PSD contributed by it. However, when this signal from R34 is removed, the overall signature leftover is entirely contributed by R12.

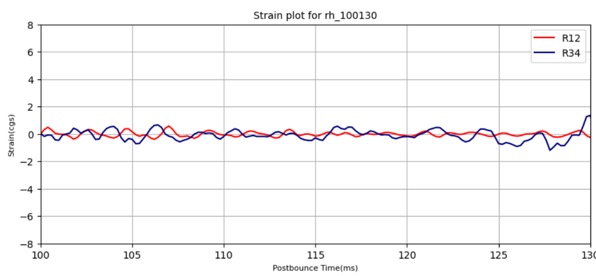



(a) rh12

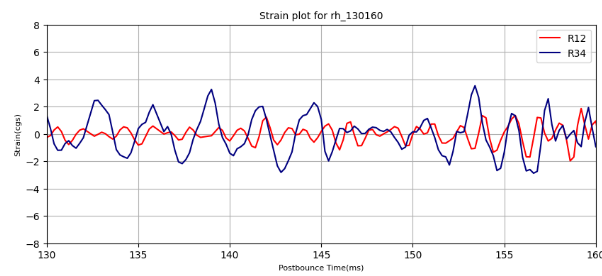



(b) rh34

Figure 13: Different amplitude trends for R12 & R34 with time evolution

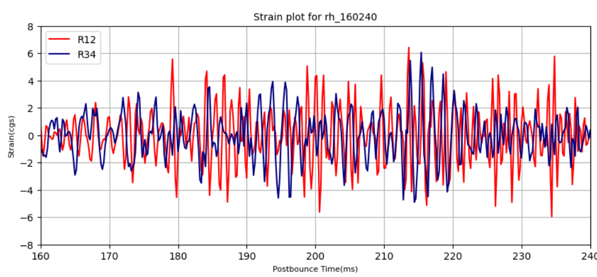



(a) 100-130

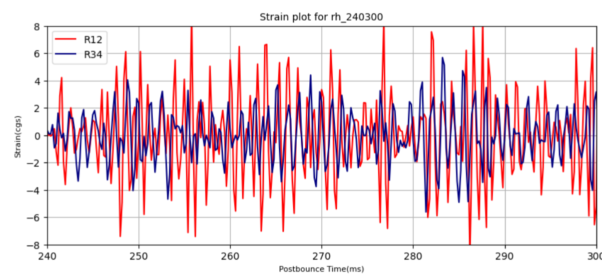



(b) 130-160

Figure 14: Higher signal for R34 due to net cooling and surface phenomena initially. R12 contribute later due to Ledoux convection dominating




(a) 160-240




(b) 240-300

Figure 15: In the first range, R12 & R34 signals start matching in amplitudes while at a later range R12 starts dominating.

9. There is also an apparent phase shift of 180° in R3 & R4 signals upto $\approx$ 200ms, while for the same time interval, R2 & R3 seem to overally be in phase.

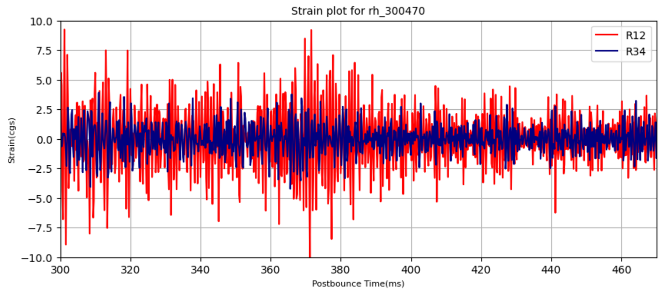
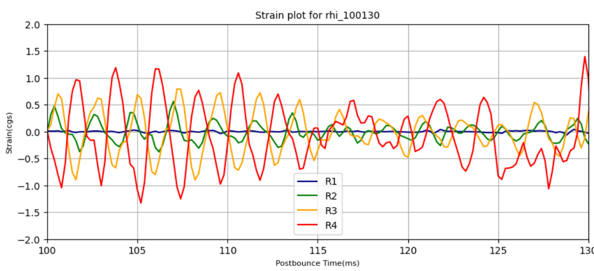
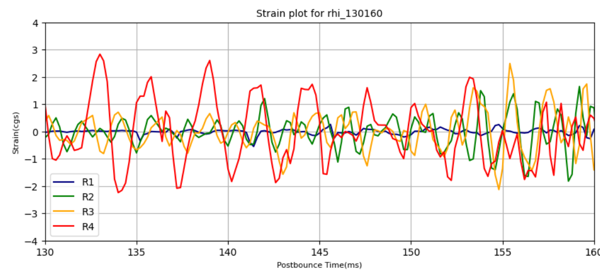


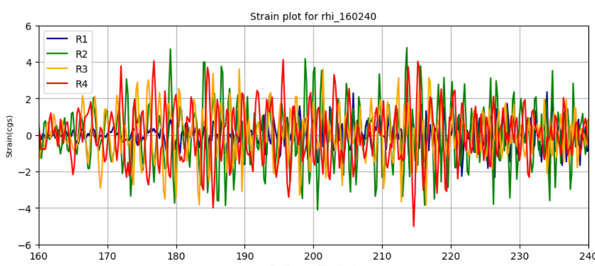

Figure 16: 300-470, R12 clearly dominates the signal



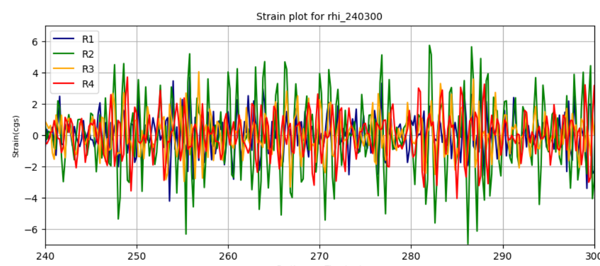

(a) 100-130




(b) 130-160




(a) 160-240




(b) 240-300

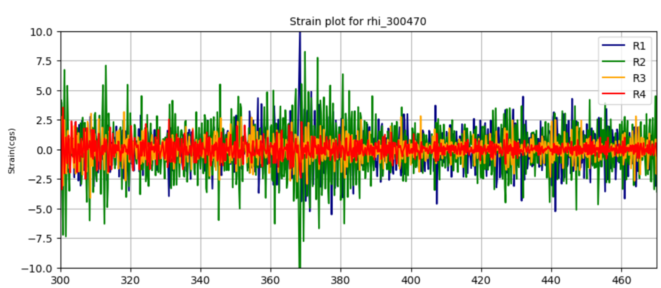
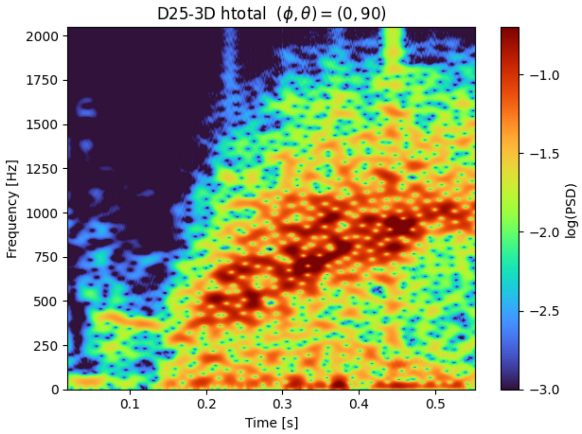
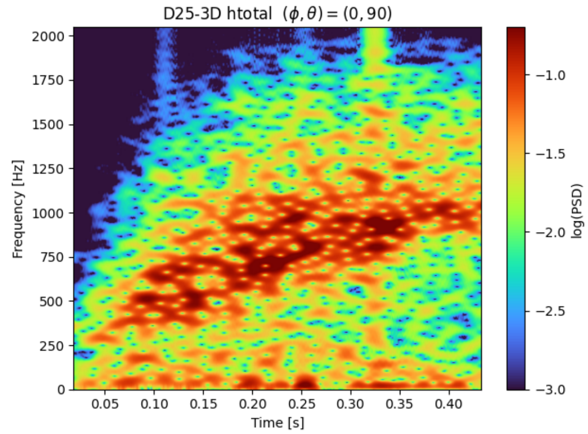



Figure 17: 300-470




(a) Total signal(0ms)(with R0 & R5)




(b) Total signal(100ms)(with R0 & R5)

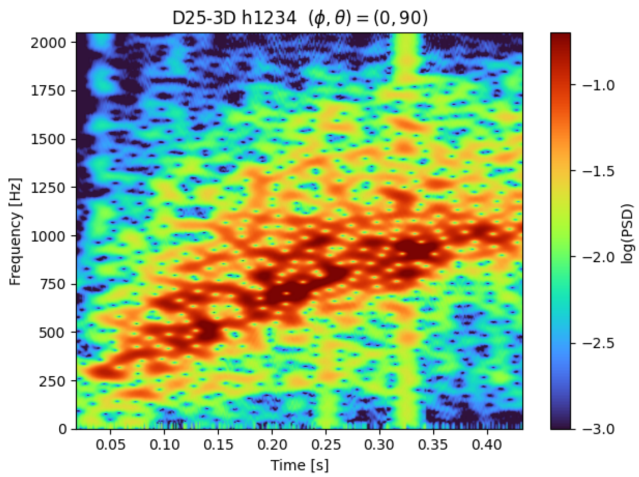
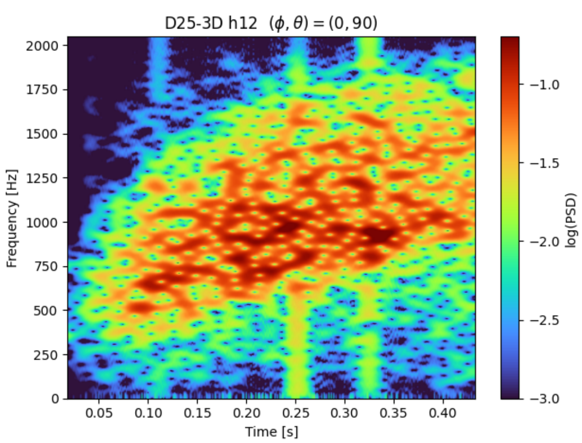
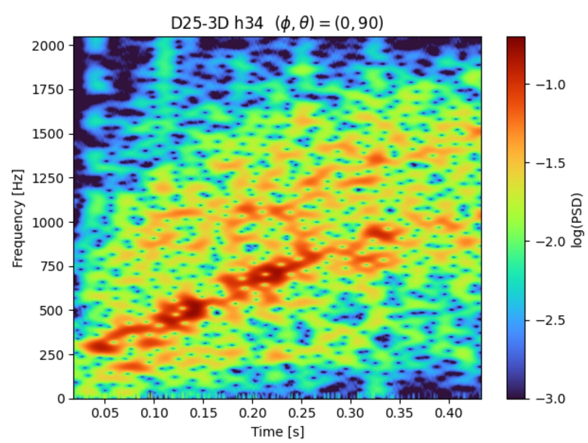



Figure 18: This is the signal from 100ms post bounce which is devoid of R0 & R5




(a) Signal from R12




(b) Signal from R34