Low-Frequency Gravitational Waves from Core-Collapse Supernovae: Theory and Detection Prospects

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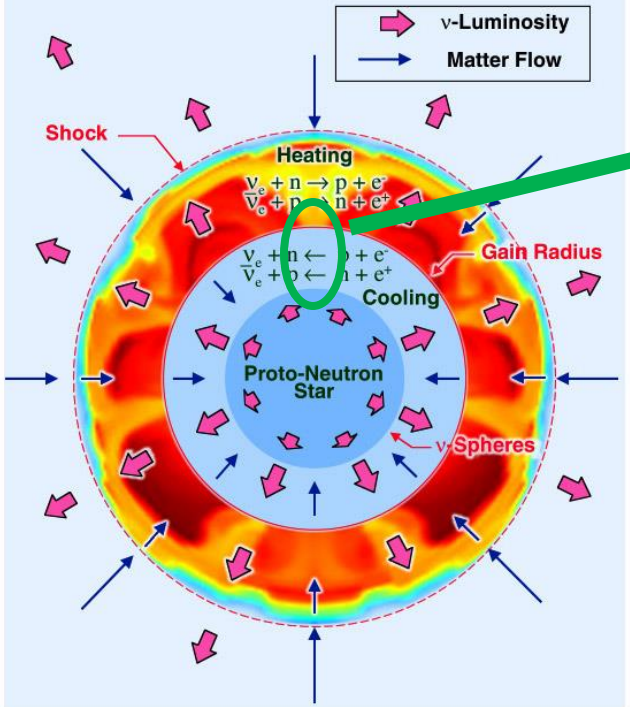
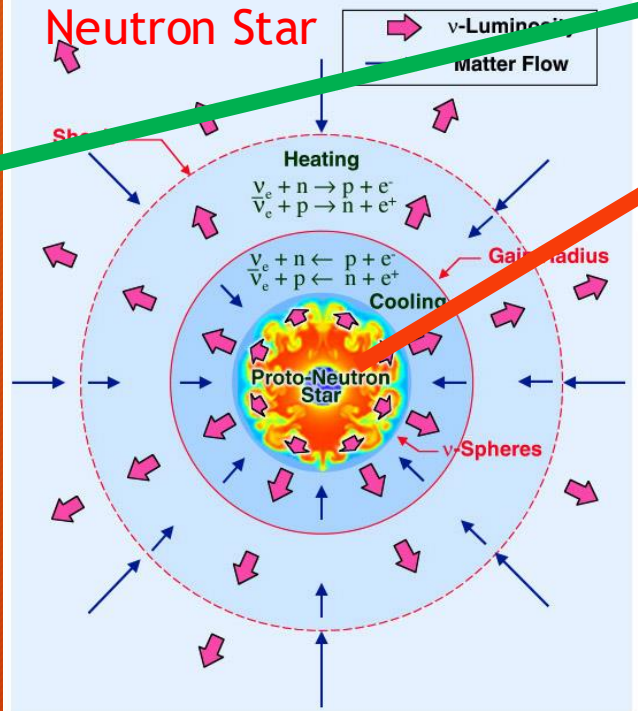
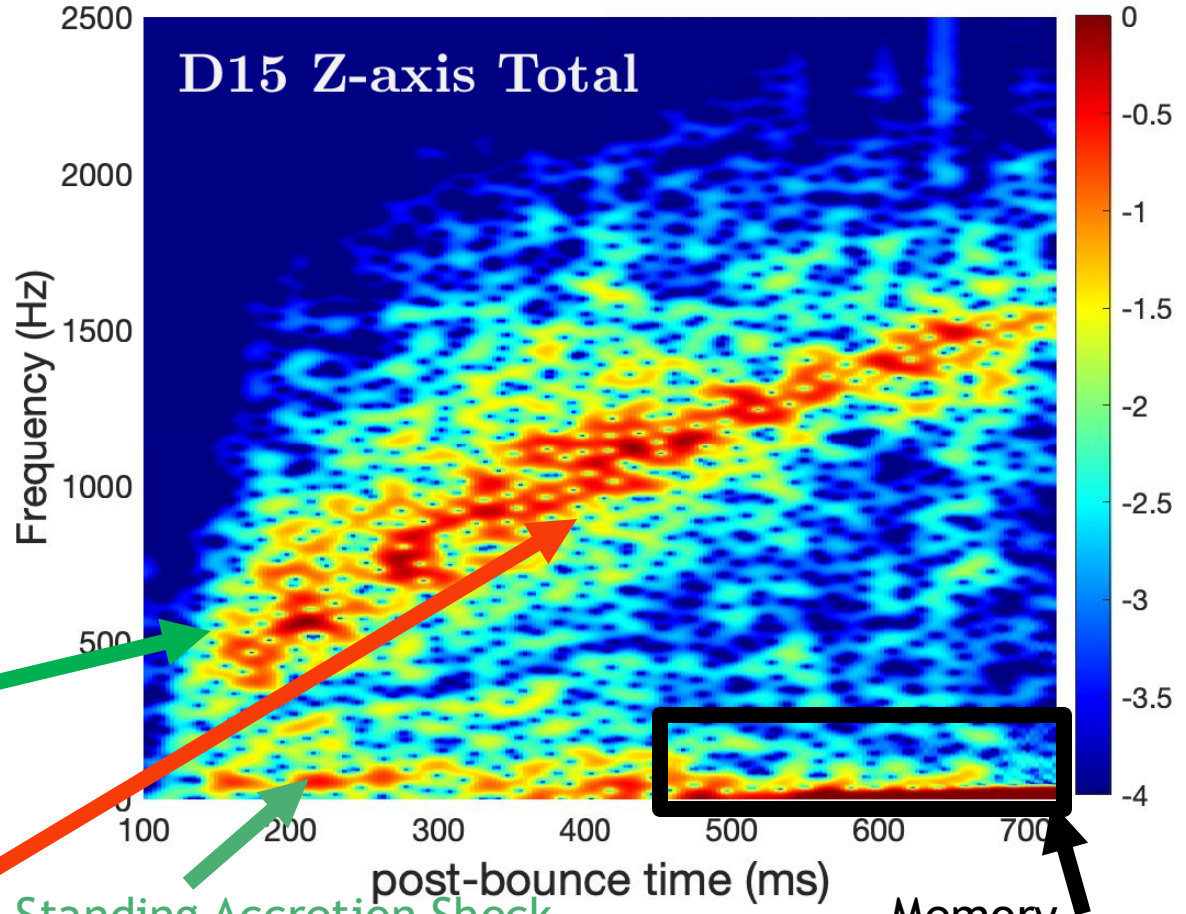
Neutrino Driven Convection

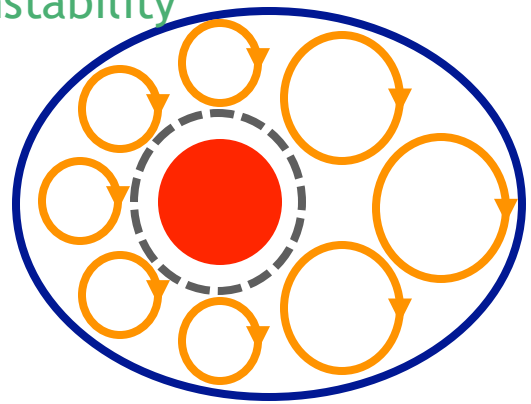


High Frequency Oscillations of the Proto-Neutron Star

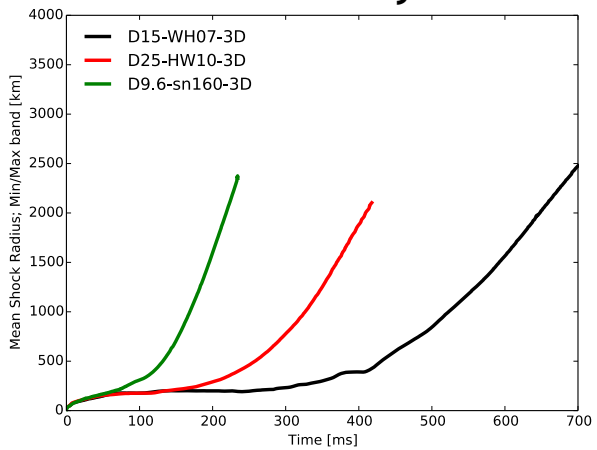




Standing Accretion Shock Instability

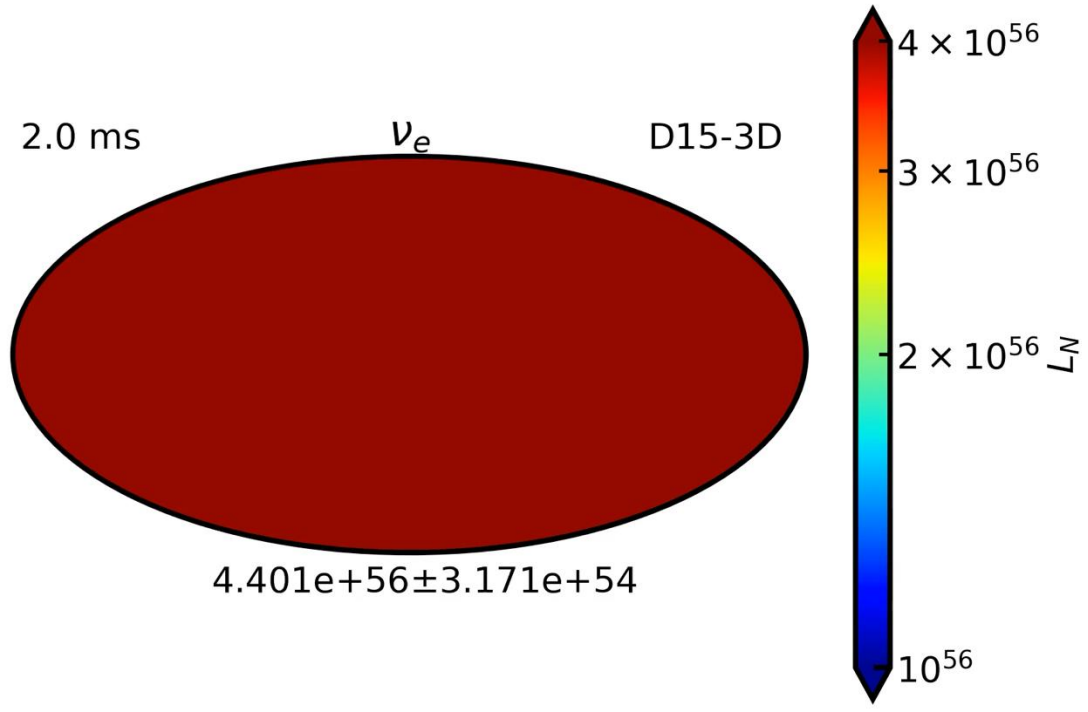


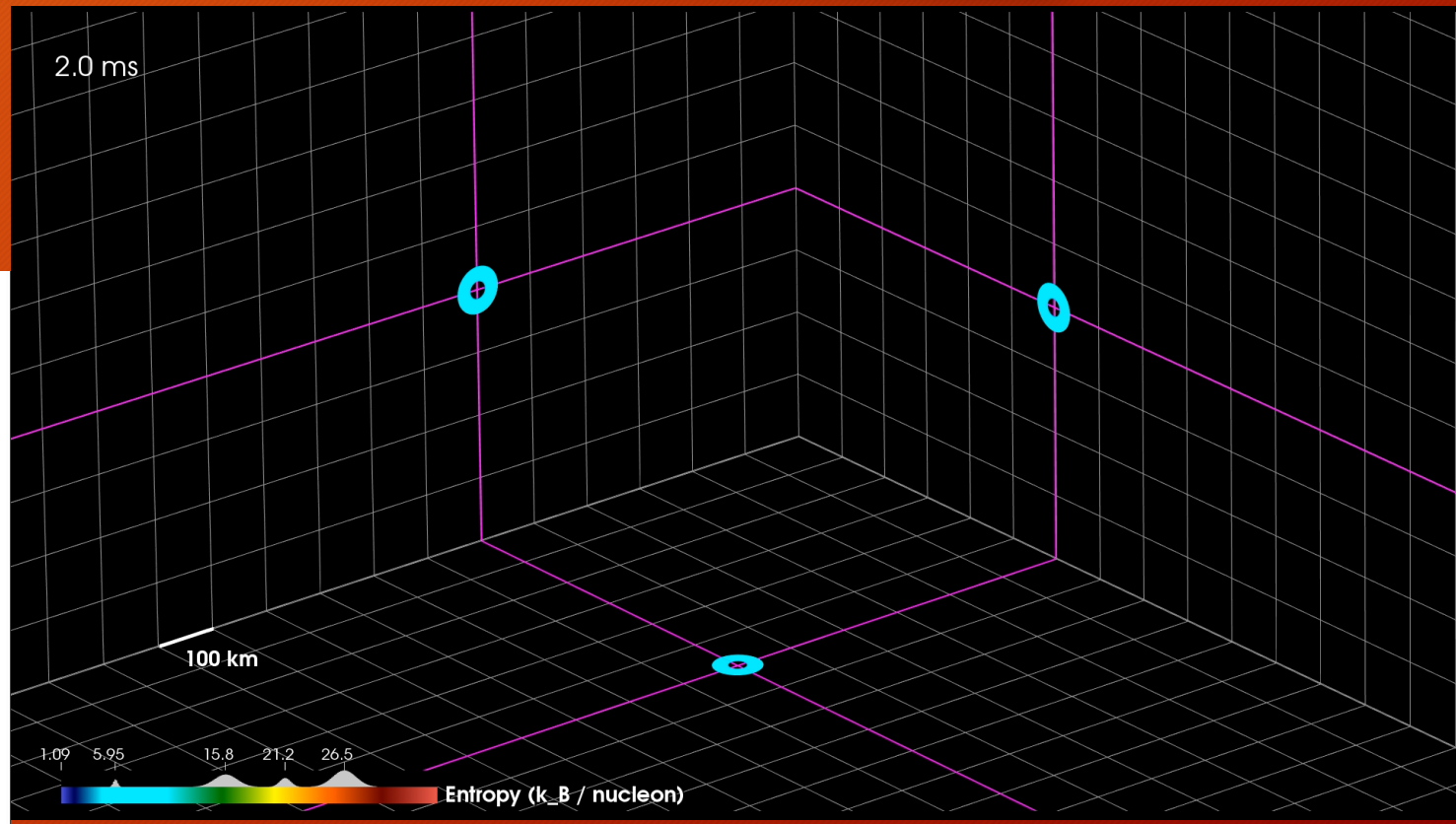
Memory



Sources of Low-Frequency GWs

- We look at GWs sourced from:
  - Large scale matter motions
  - Anisotropic neutrino emission

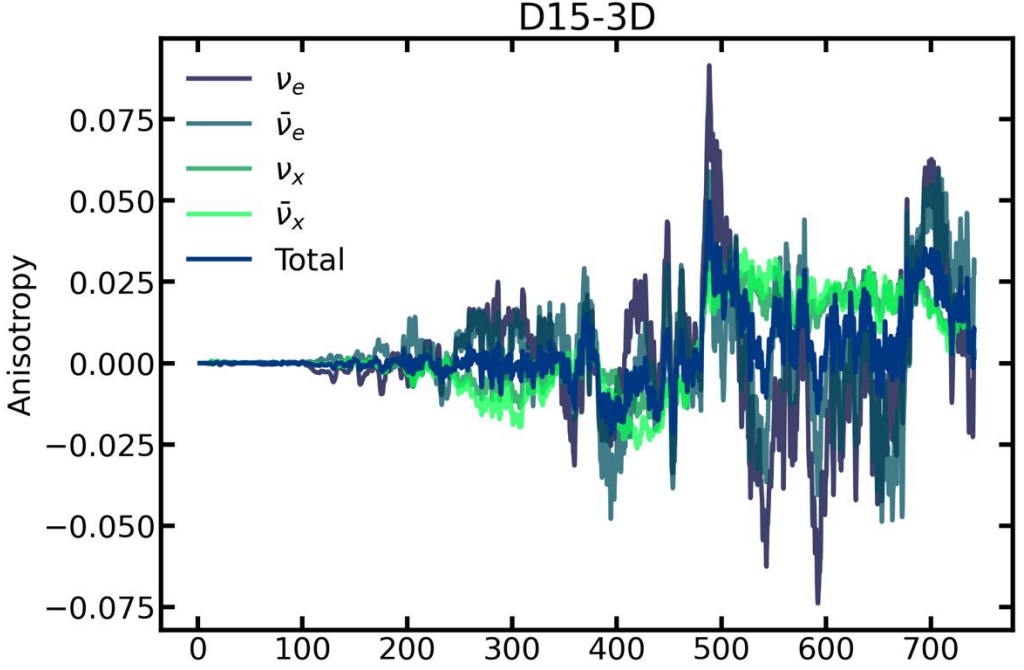


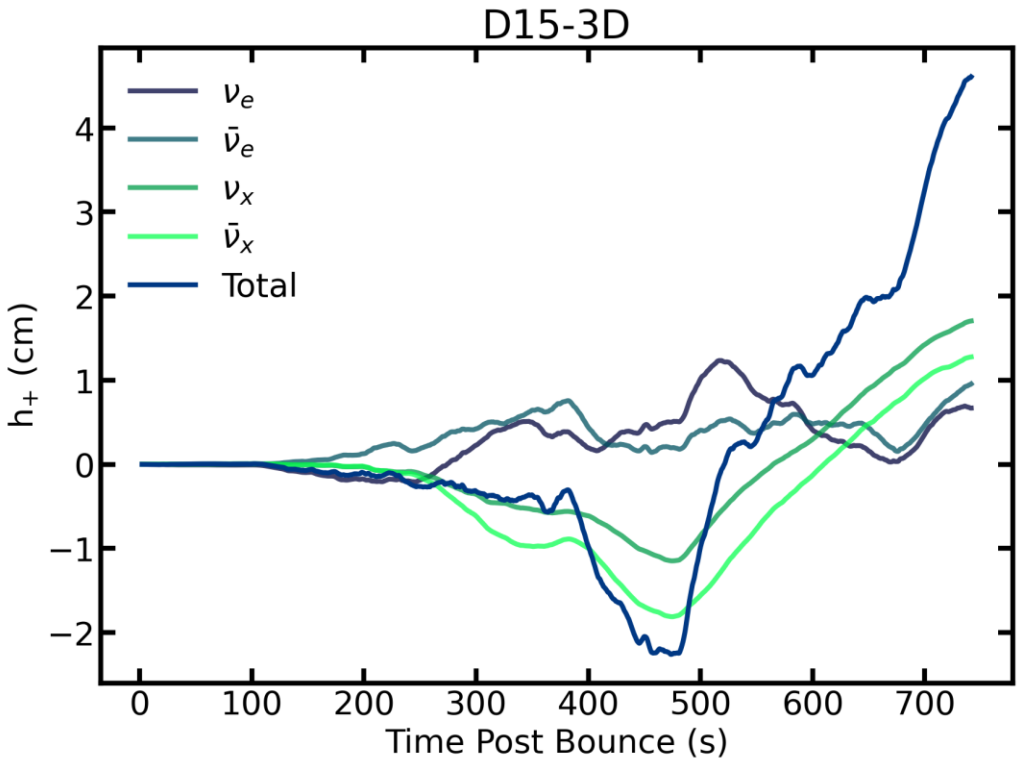


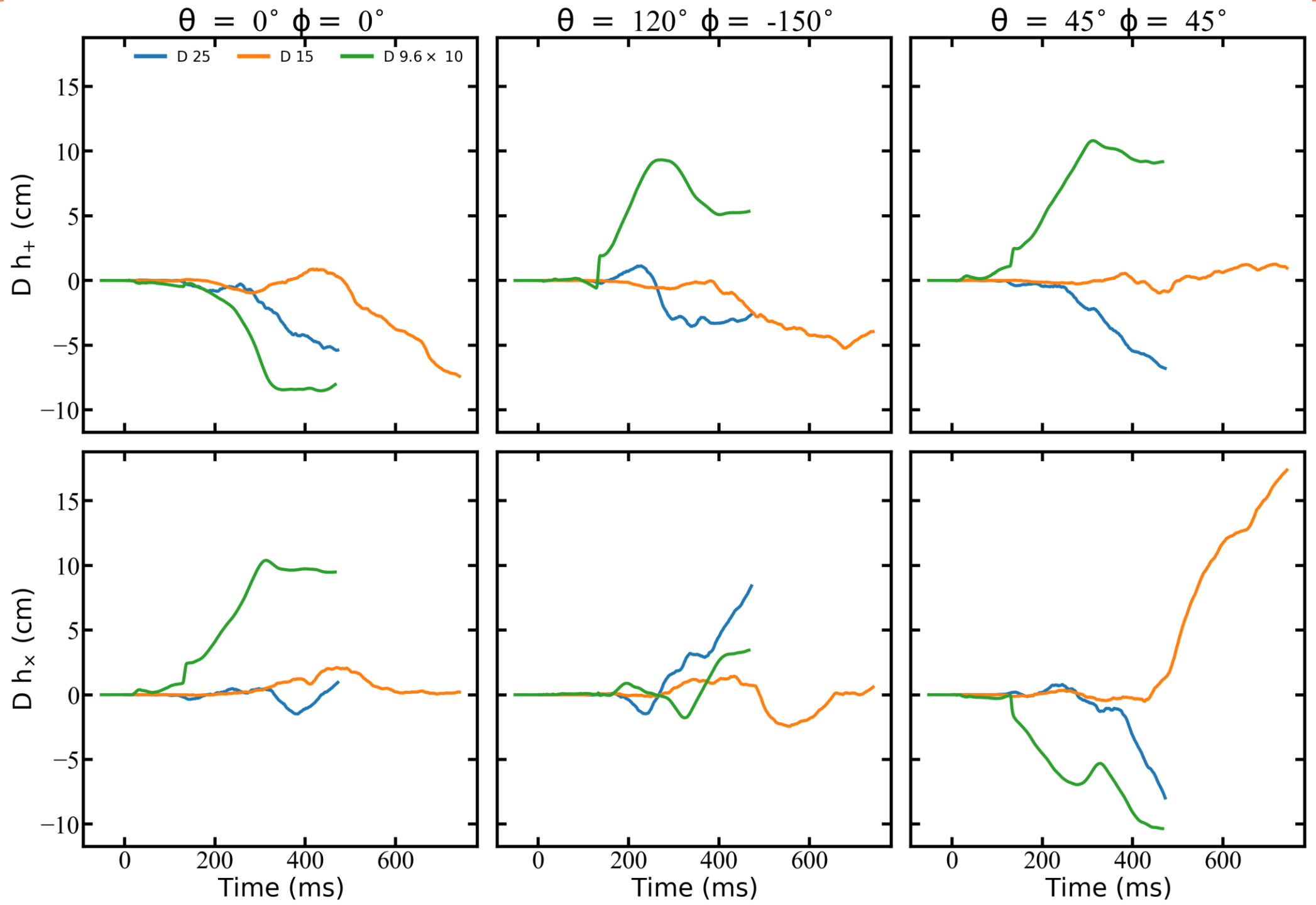
GWs from Neutrino Anisotropy

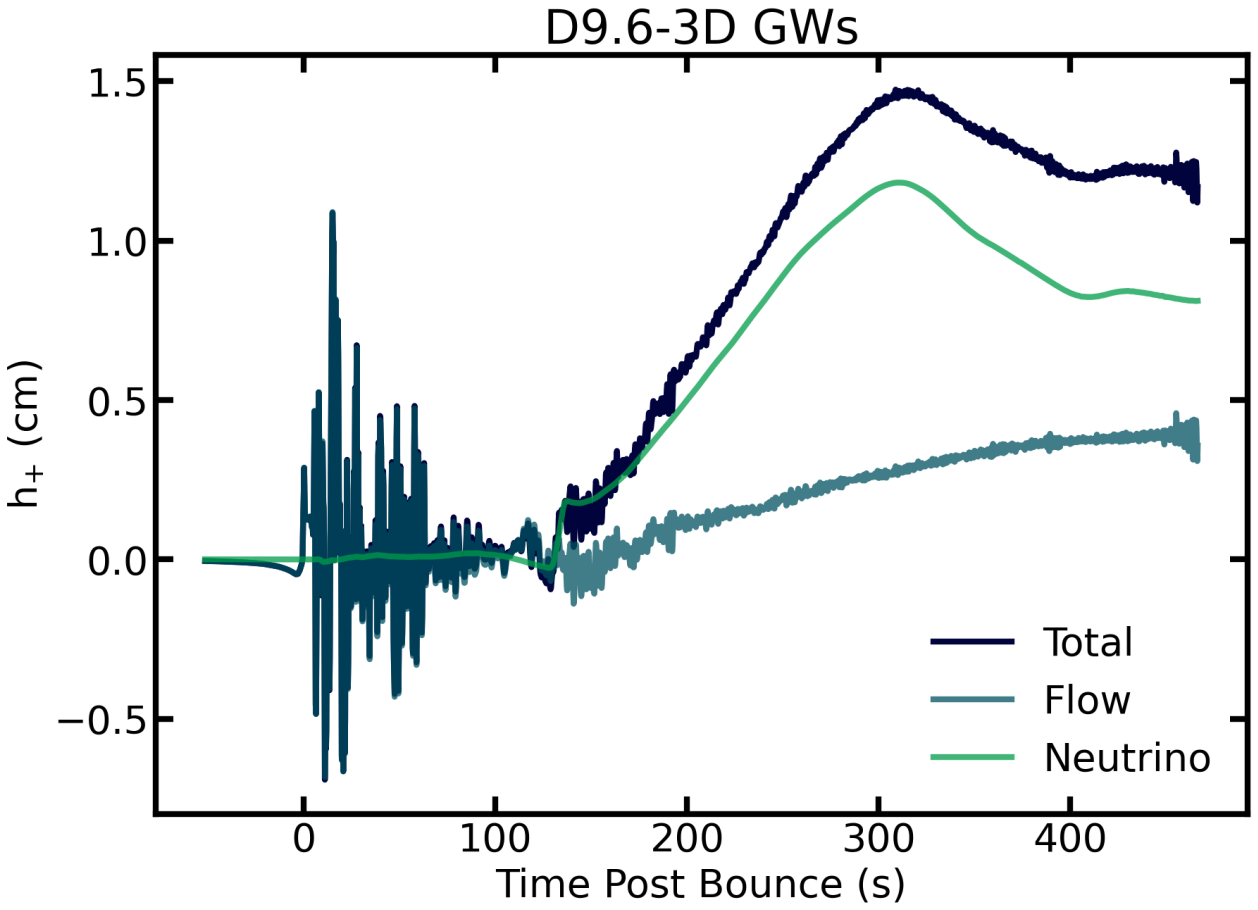
- We follow Epstein 1978, Mueller and Janka 1997, and Müller et al. 2012 and define the gravitational wave strain from the anisotropic neutrino emission in terms of an angular weight and the neutrino luminosity.

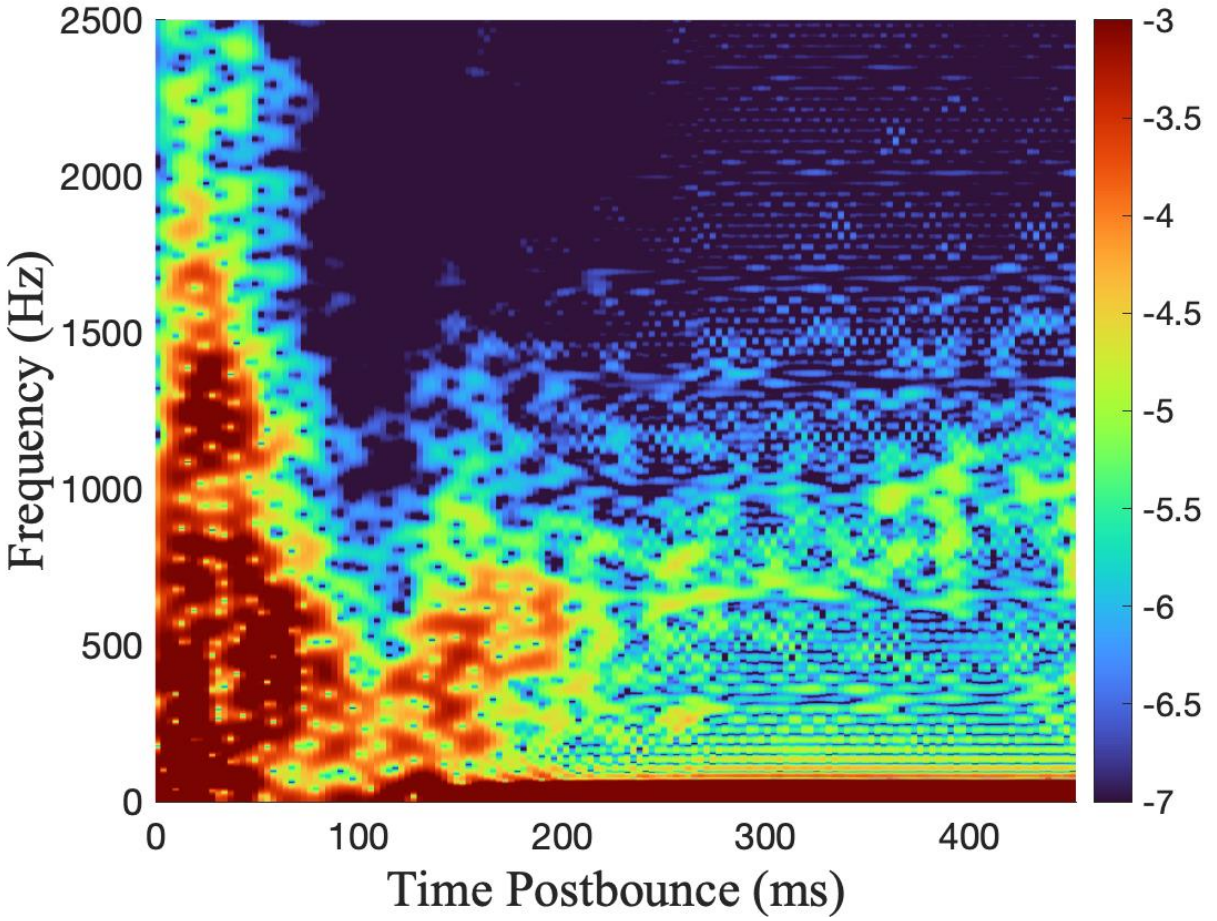
- $h_s^{\nu_i}(\mathrm{t},\alpha,\beta) = \frac{2}{r}\int_0^{t'}\int_{4\pi} dt' d\Omega' \, W_s(\alpha,\beta,\Omega')\frac{dL_E^{\nu_i}}{d\Omega'}(t',\Omega')$
- $h_s^{\nu_i}(\mathrm{t},\alpha,\beta) = \frac{2}{r}\int_0^{t'} dt' \alpha_s(t',\alpha,\beta) L_E^{\nu_i}(t')$
  - $\alpha_s(t,\alpha,\beta) = \frac{1}{L_E^{\nu_i}(t)}\int_{4\pi} d\Omega' \, W_s(\alpha,\beta,\Omega')\frac{dL_E^{\nu_i}}{d\Omega'}(t,\Omega')$

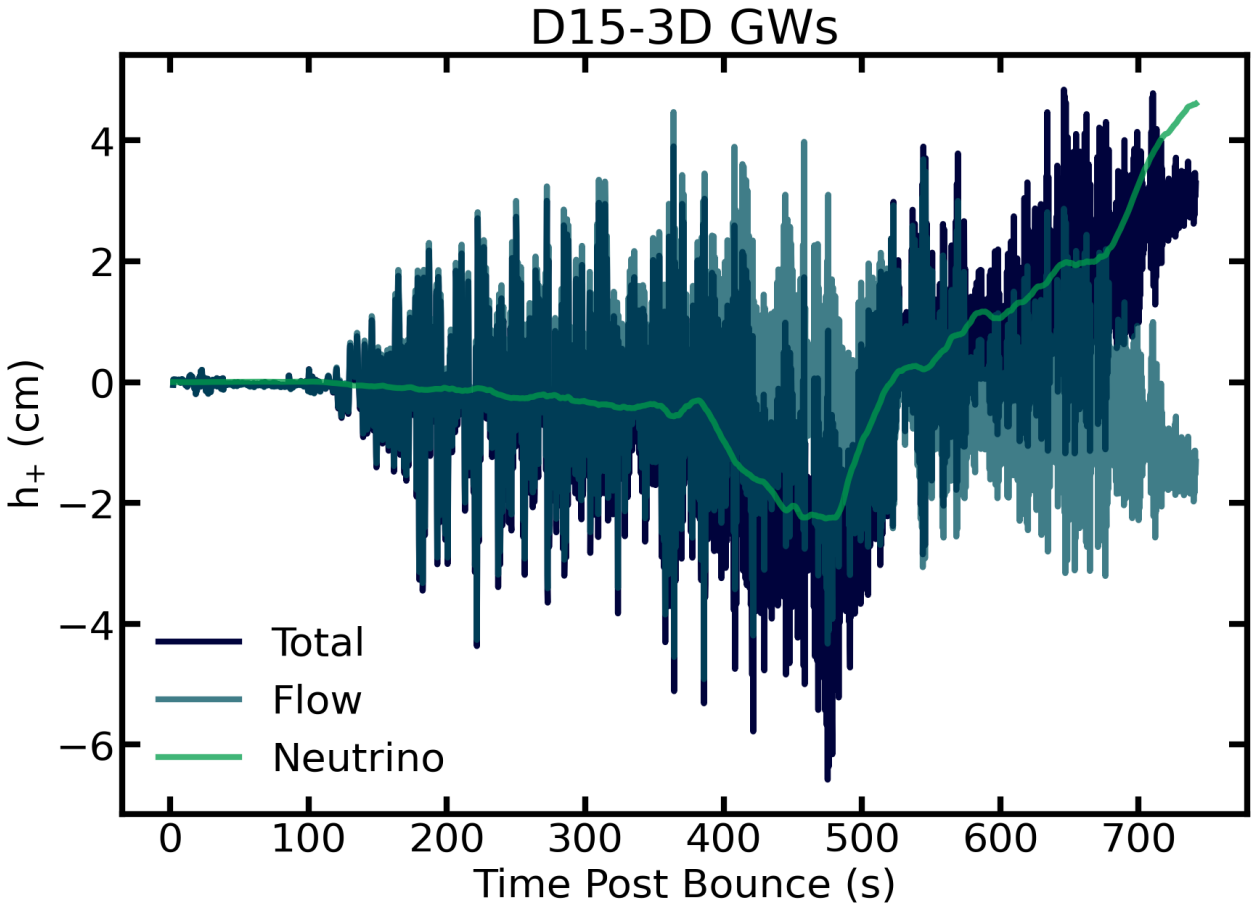


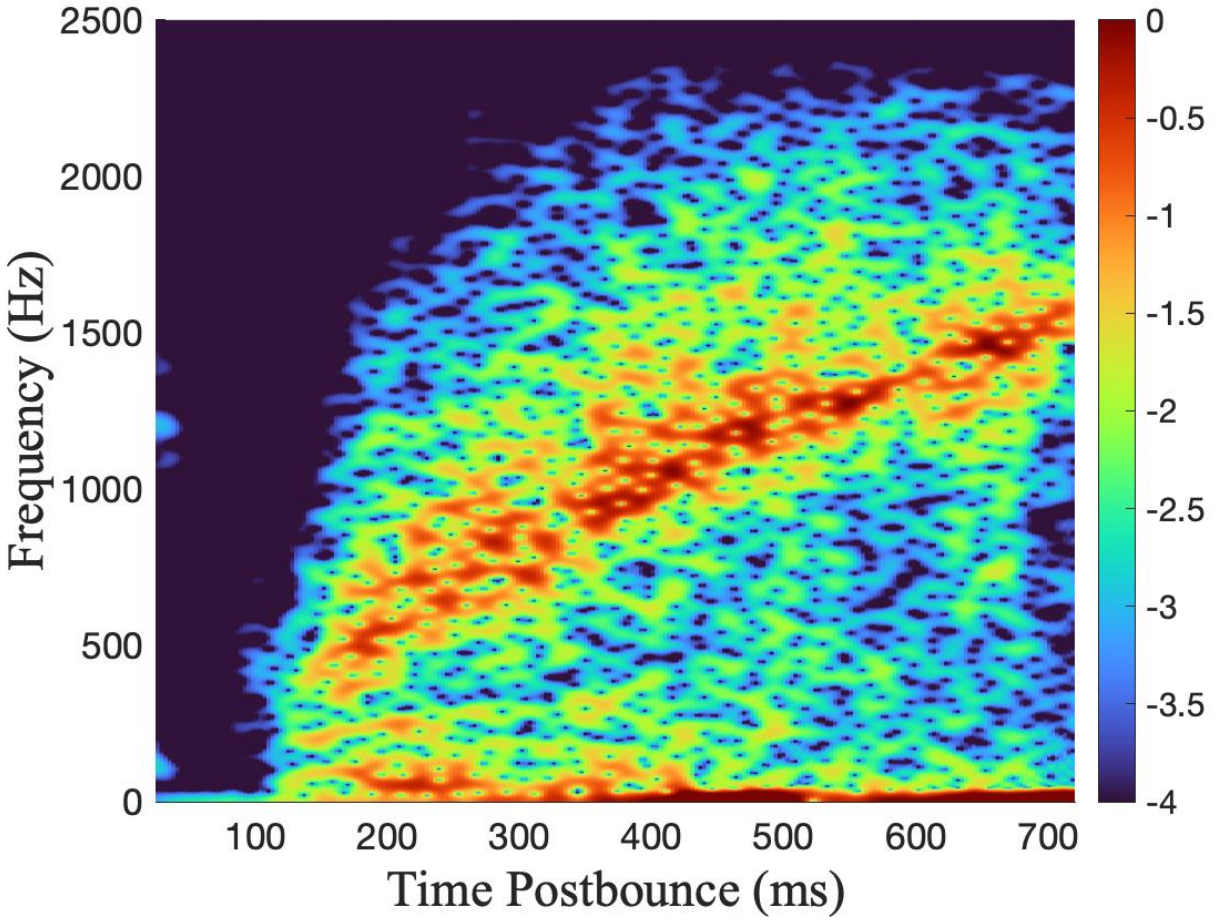


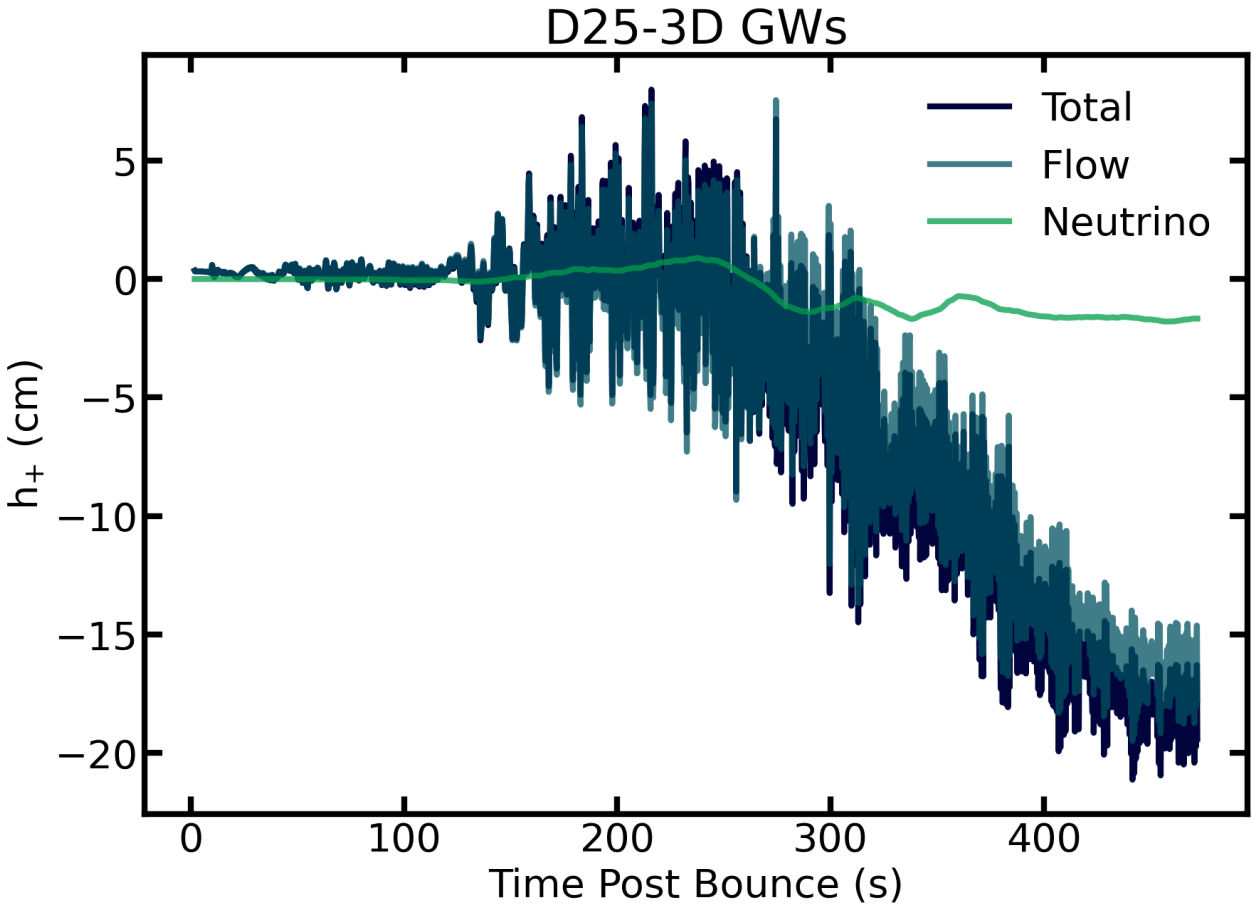

θ = 0° ϕ = 0°
θ = 120° ϕ = -150°
θ = 45° ϕ = 45°
D 25
D 15
D 9.6 × 10
D h+ (cm)
D h× (cm)
15
10
5
0
−5
−10
0
200
400
600
Time (ms)

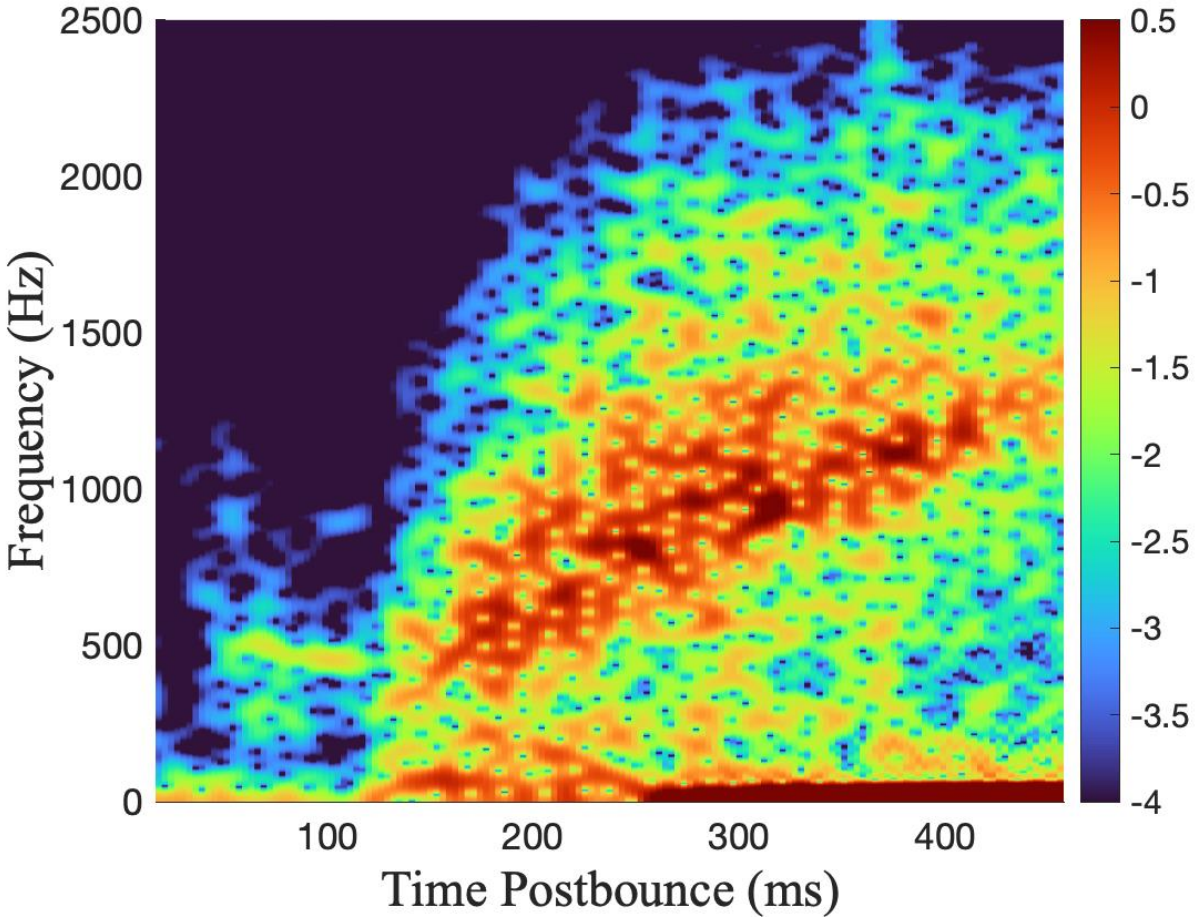

D9.6-3D GWs
1.5
1.0
0.5
0.0
−0.5
h_+ (cm)
0
100
200
300
400
Time Post Bounce (s)
Total
Flow
Neutrino


2500
2000
1500
1000
500
0
Frequency (Hz)
0
100
200
300
400
Time Postbounce (ms)
-3
-3.5
-4
-4.5
-5
-5.5
-6
-6.5
-7


D15-3D GWs
h_+ (cm)
4
2
0
−2
−4
−6
0
100
200
300
400
500
600
700
Time Post Bounce (s)
Total
Flow
Neutrino

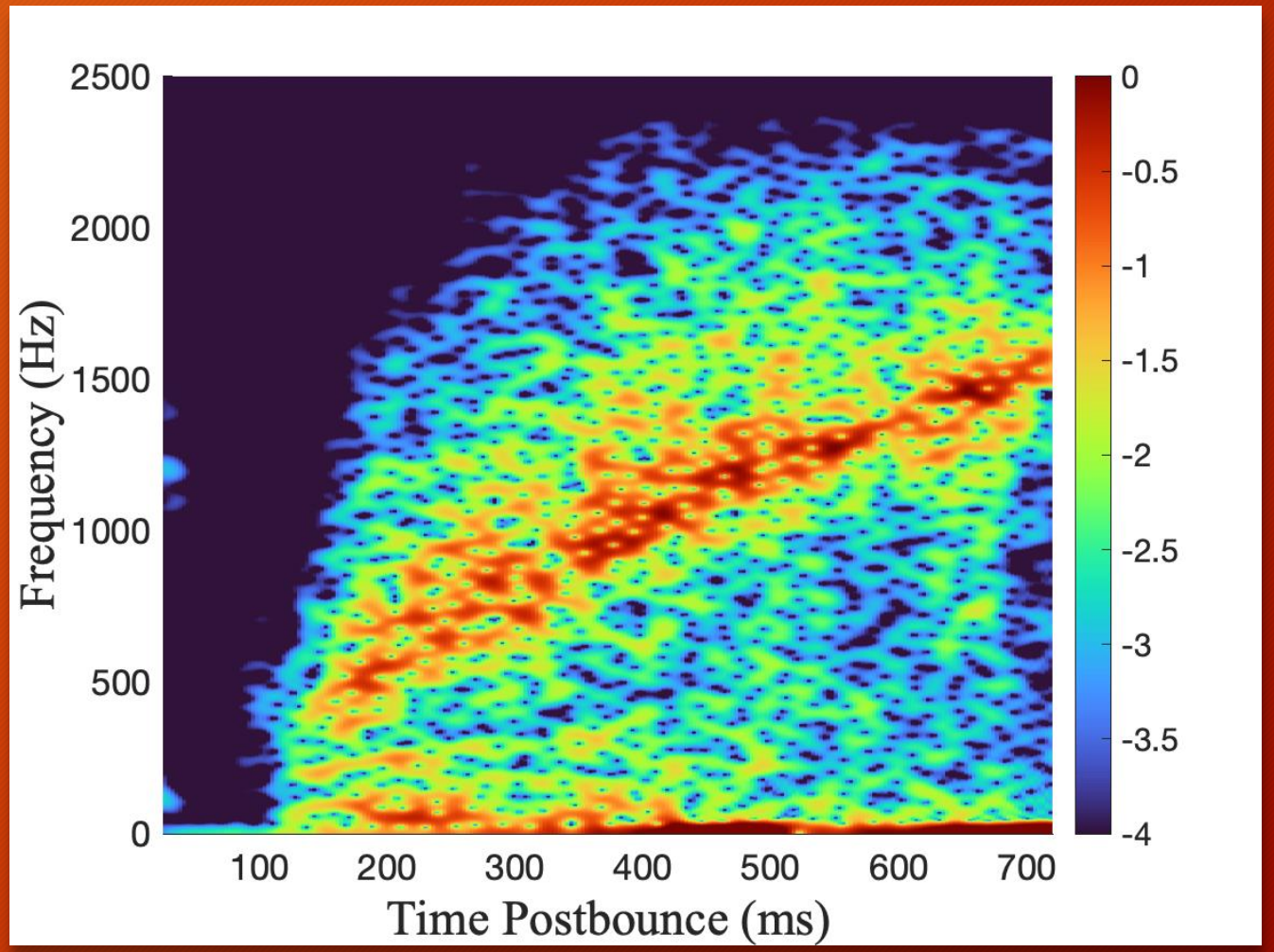

Frequency (Hz)
2500
2000
1500
1000
500
0
100
200
300
400
500
600
700
Time Postbounce (ms)
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4


D25-3D GWs
Total
Flow
Neutrino
5
0
−5
−10
−15
−20
h_+ (cm)
0
100
200
300
400
Time Post Bounce (s)


2500
2000
1500
1000
500
0
Frequency (Hz)
100
200
300
400
Time Postbounce (ms)
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4

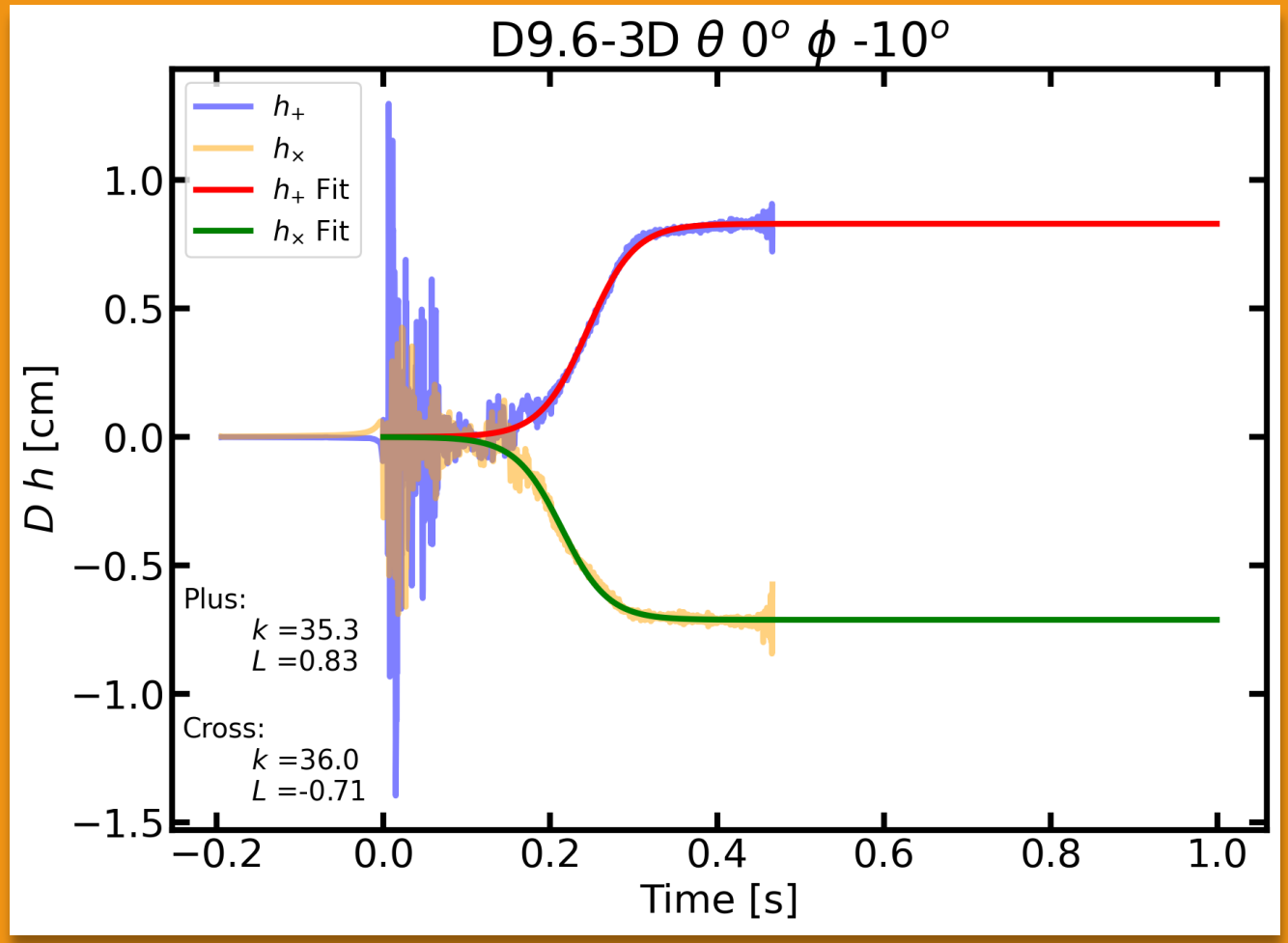
Matched Filtering

- A key point to note in the spectrograms is the evidence of the ramp-up to the memory at frequencies above zero, in this case somewhere between 30 and 50 Hz.
- From this we seek to investigate the memory utilizing matched filtering.



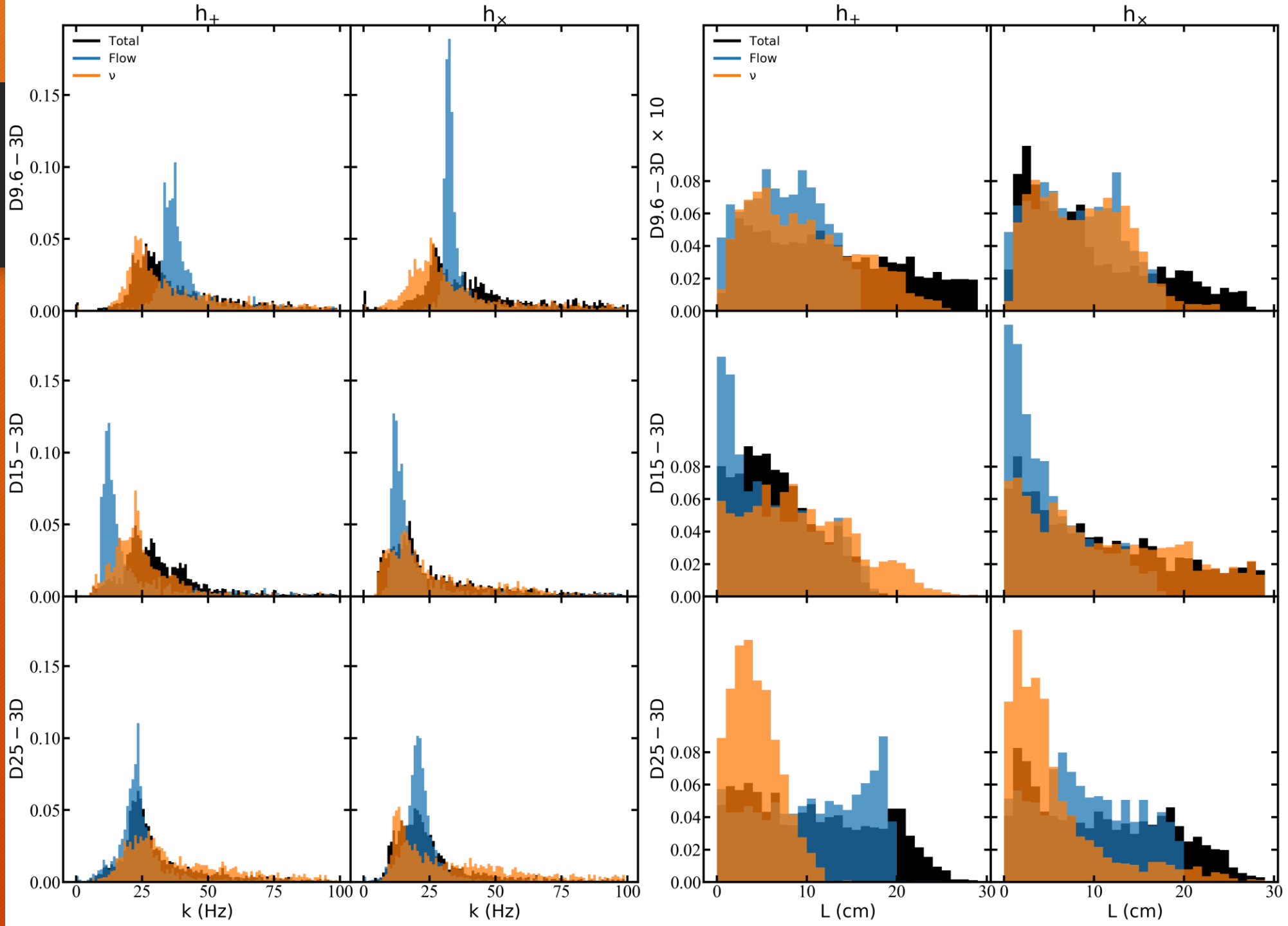
Template

- $f(t, k, L, t_0) = \frac{L}{1+e^{-k(t-t_0)}}$
  - L -> Amplitude of memory
  - k -> Ramp-up frequency to memory
  - t_0 -> Central time of ramp-up to memory.



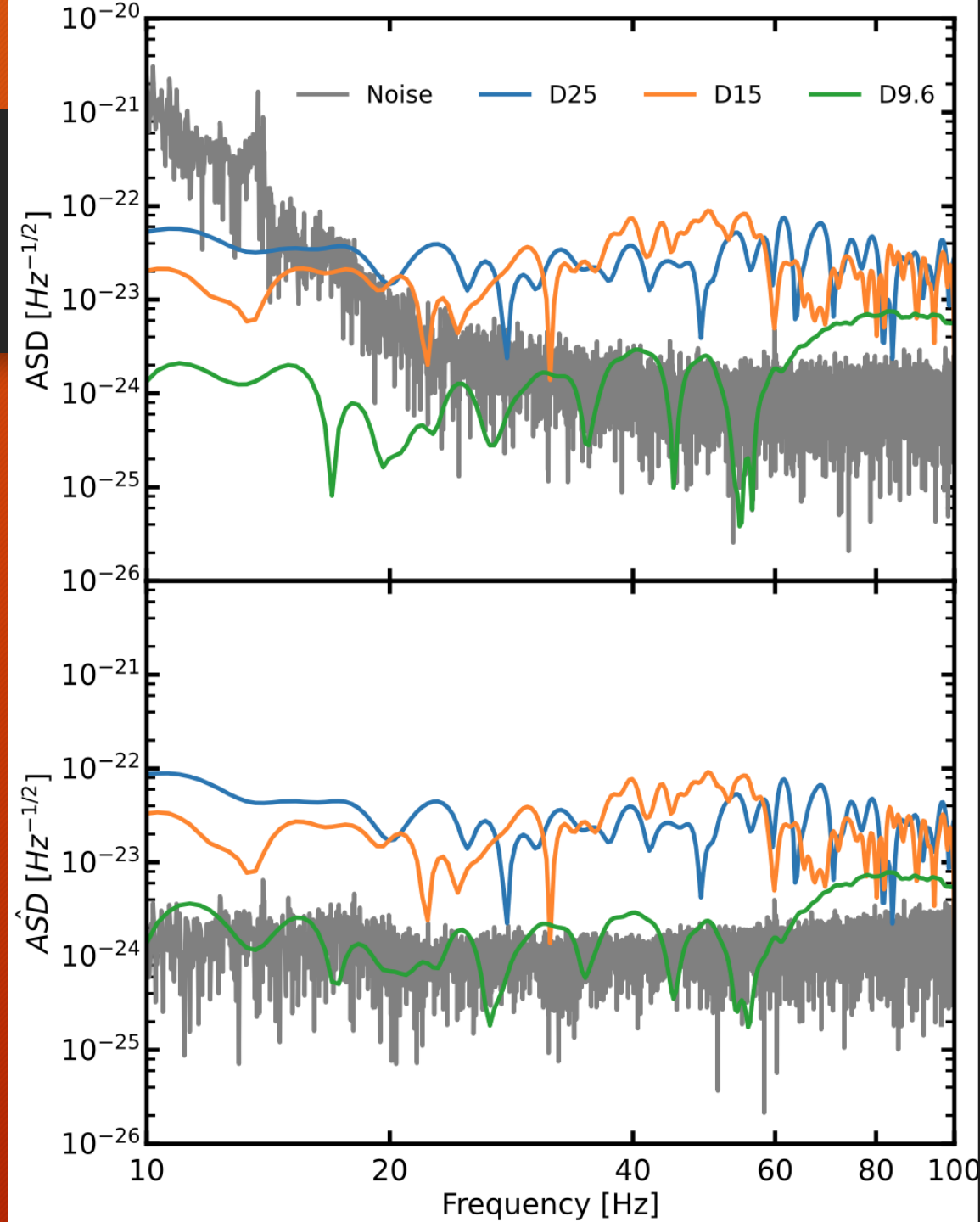
Template Statistics

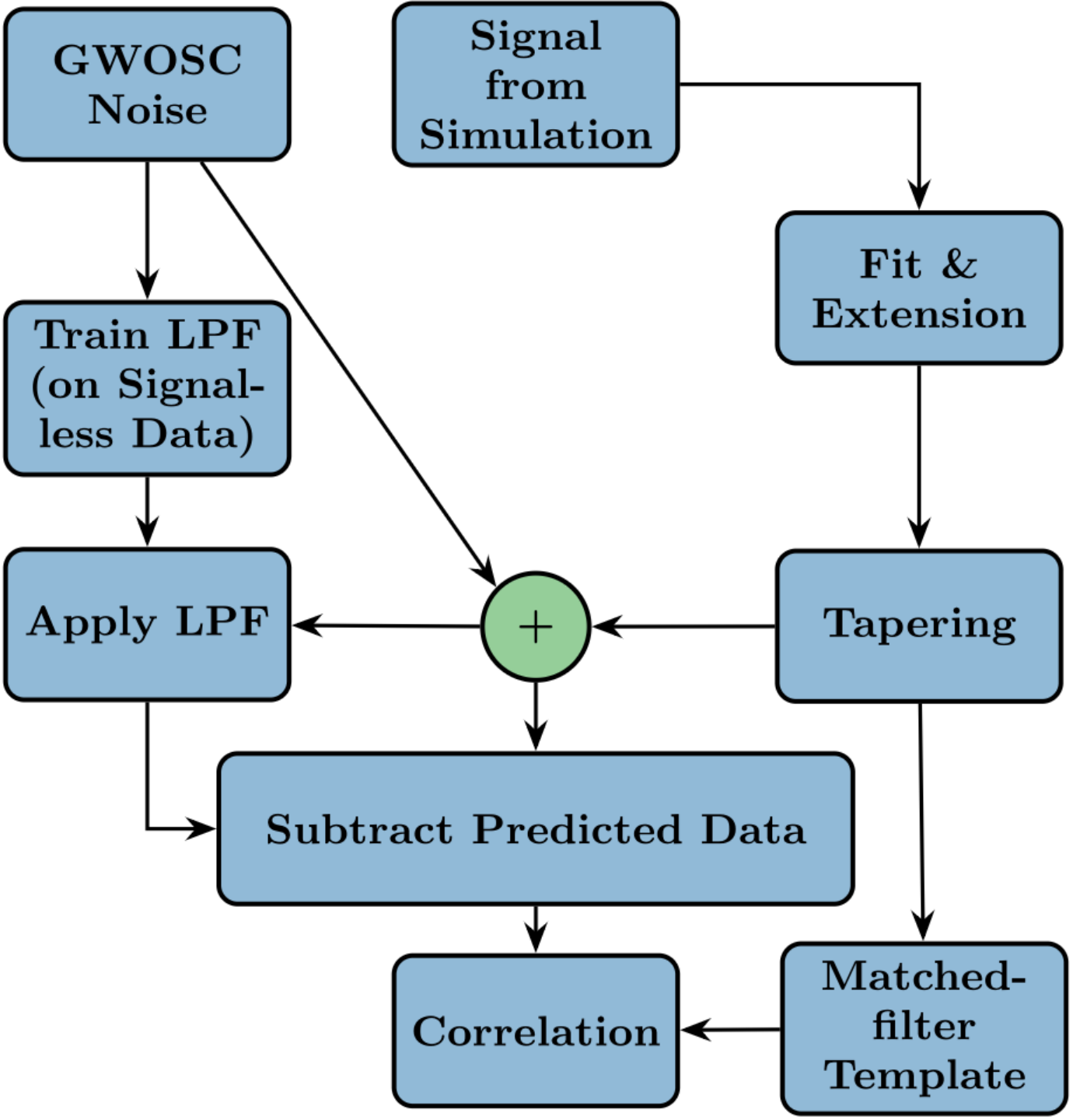
- We fit the template to signals from different observer orientations and the different sources.
- The ramp-up frequency of the total signal follows the distributions of the neutrino signal.
- There is no discernable relationship in the amplitude.

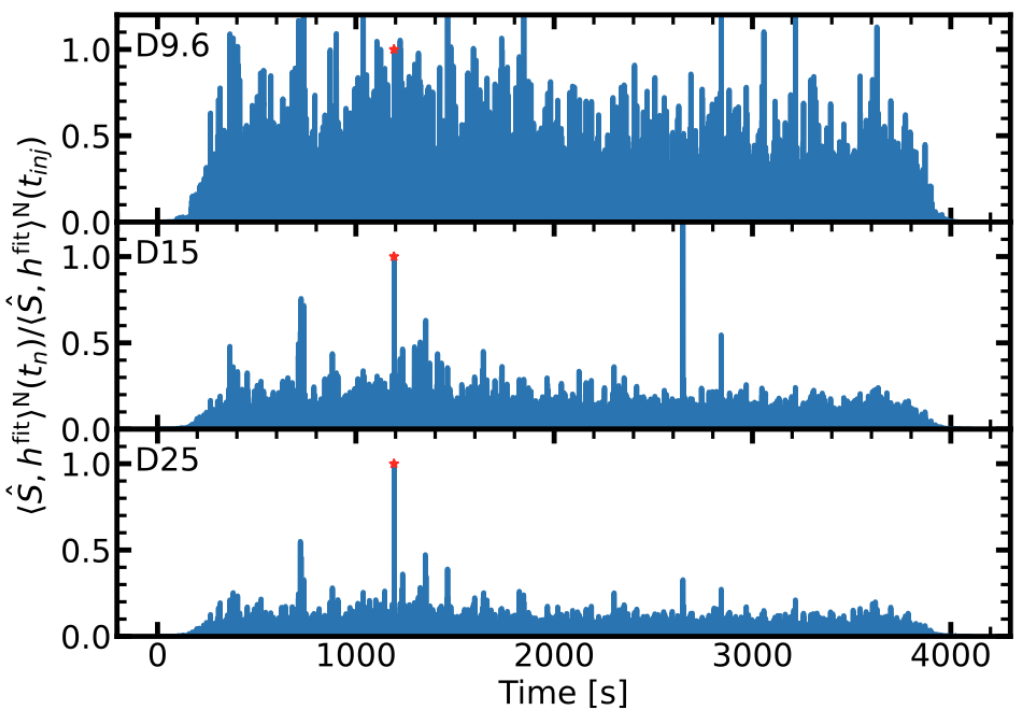


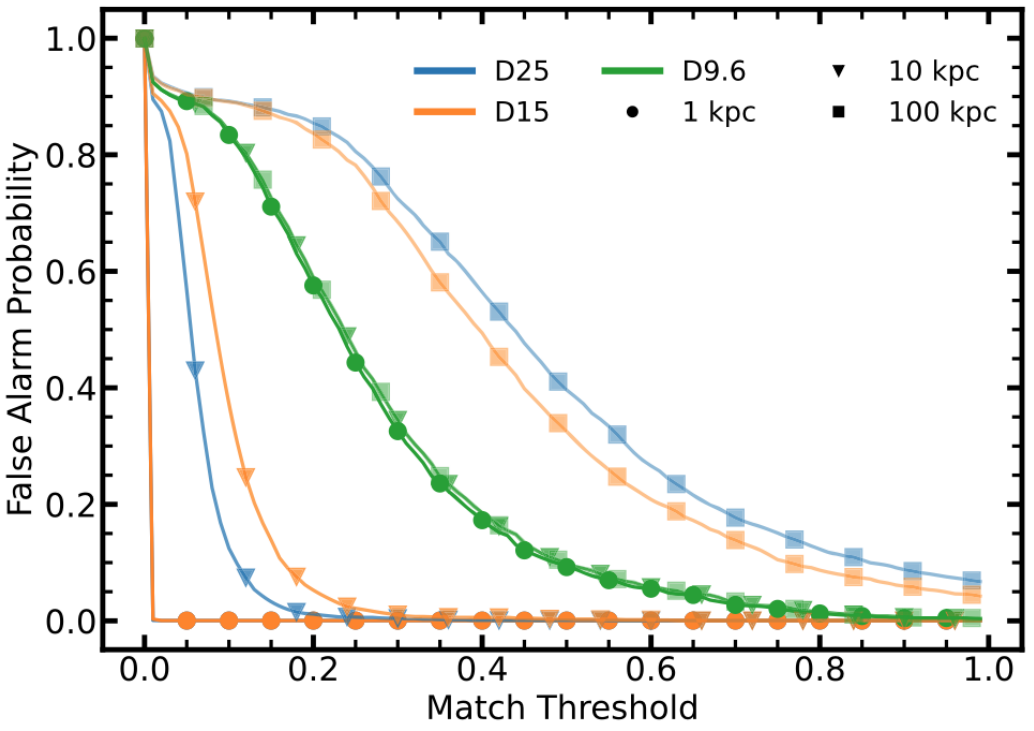
Linear Predictive Filter

- We train a Linear Predictor Filter on segments of GWOSC noise and then remove the predicted signal.
- Then we procced to the matcvhed filtering step.
- See Michele Zanolin's talk tomorrow for more information.




GWOSC Noise
Signal from Simulation
Fit & Extension
Train LPF (on Signal-less Data)
Apply LPF
+
Tapering
Subtract Predicted Data
Correlation
Matched-filter Template


D9.6
D15
D25
1.0
0.5
0.0
0
1000
2000
3000
4000
Time [s]
$\langle \hat{S}, h^{\rm fit} \rangle^{\rm N}(t_n)/\langle \hat{S}, h^{\rm fit} \rangle^{\rm N}(t_{inj})$


D25
D15
D9.6
1 kpc
10 kpc
100 kpc
False Alarm Probability
Match Threshold
0.0
0.2
0.4
0.6
0.8
1.0

Conclusions

- Low-frequency GWs are detectable in current interferometers utilizing linear predictive filtering and matched filtering.
- Studies involving the low-frequency of the GW signals need to include the contributions from the anisotropic emission of neutrinos.
- The Chimera group has a full data set of GWs sourced by both large-scale fluid motions and anisotropic neutrino emission for their latest 3D models, available at https://doi.ccs.ornl.gov/dataset/847fc720-6ff7-50eb-a747-12fbb23038db

References

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