Equation of State Dependence of Gravitational Waves from Core-Collapse Supernovae

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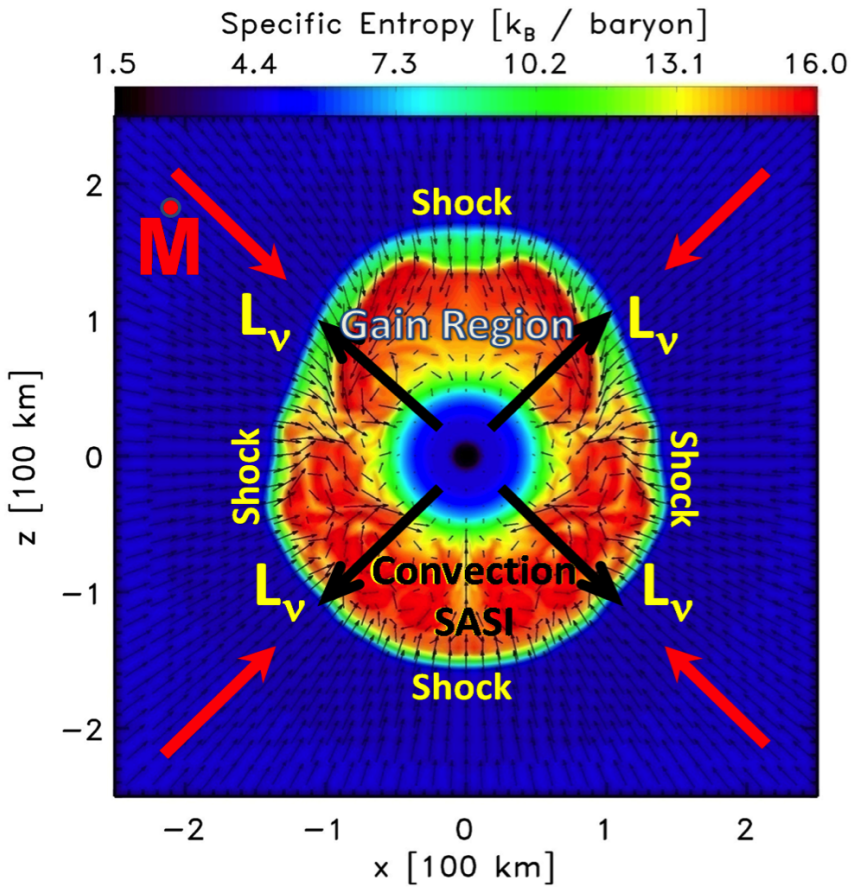
Rotating Core-Collapse

Core-Collapse Supernovae



(Ott 2009)

SN-GRB Association

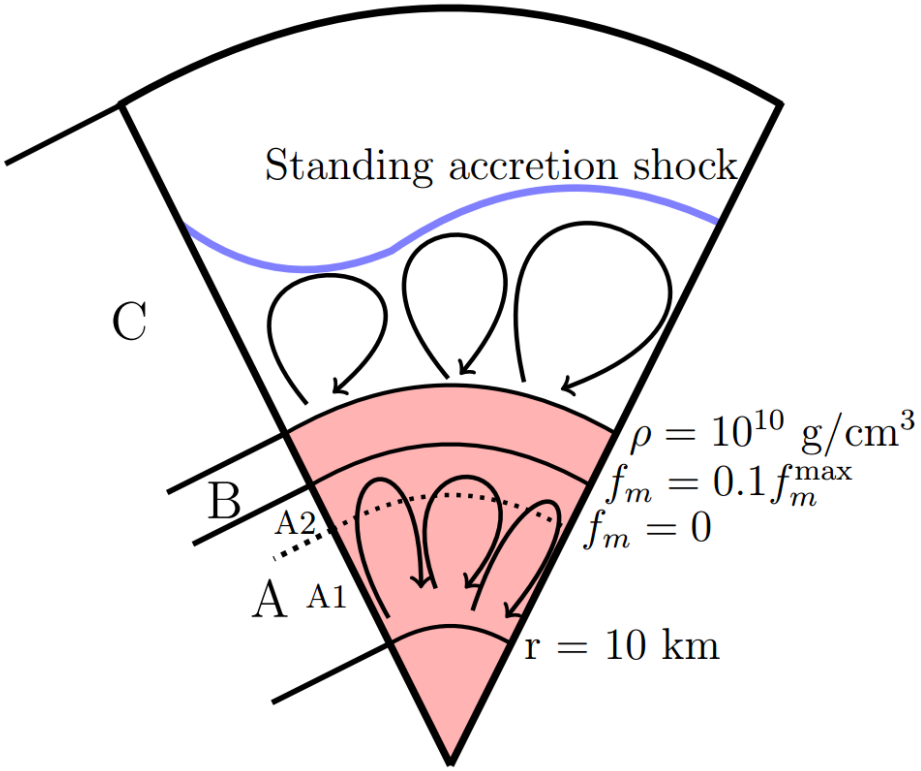
- Hypernovae
- Coincident GRB + SN Ic/bl
- Young star-forming regions

Interior rotation is still poorly understood.

Gravitational Waves from Core Collapse

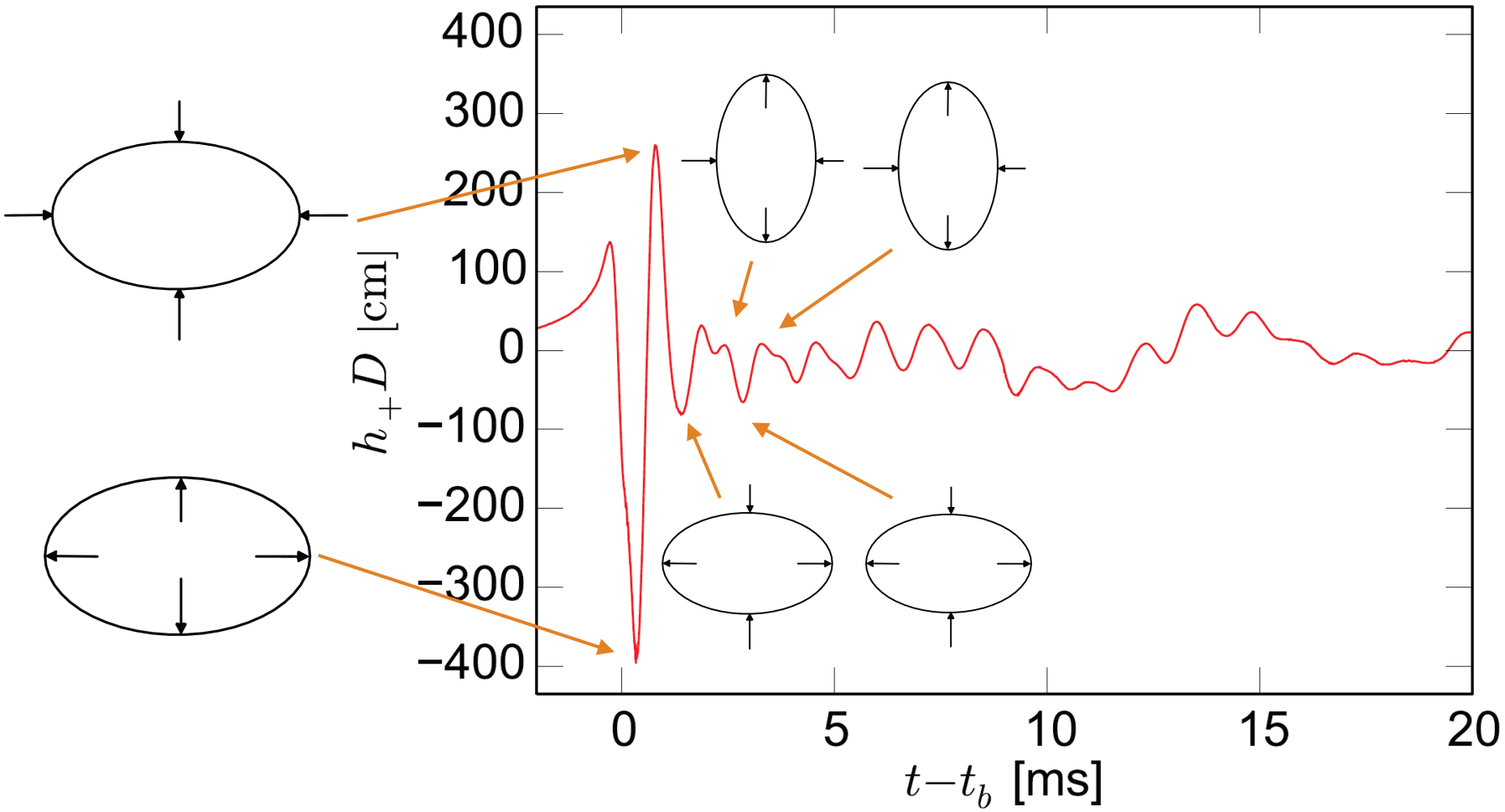
$$h \approx \frac{2G}{c^4 d}\ddot{I}$$ (Finn & Evans 1990)

- High-β dynamical instability
- Low-β secular instability
- Post-bounce convection / SASI
- r-mode instability
- Asymmetric energy distribution
- Rotating collapse and bounce
- ...

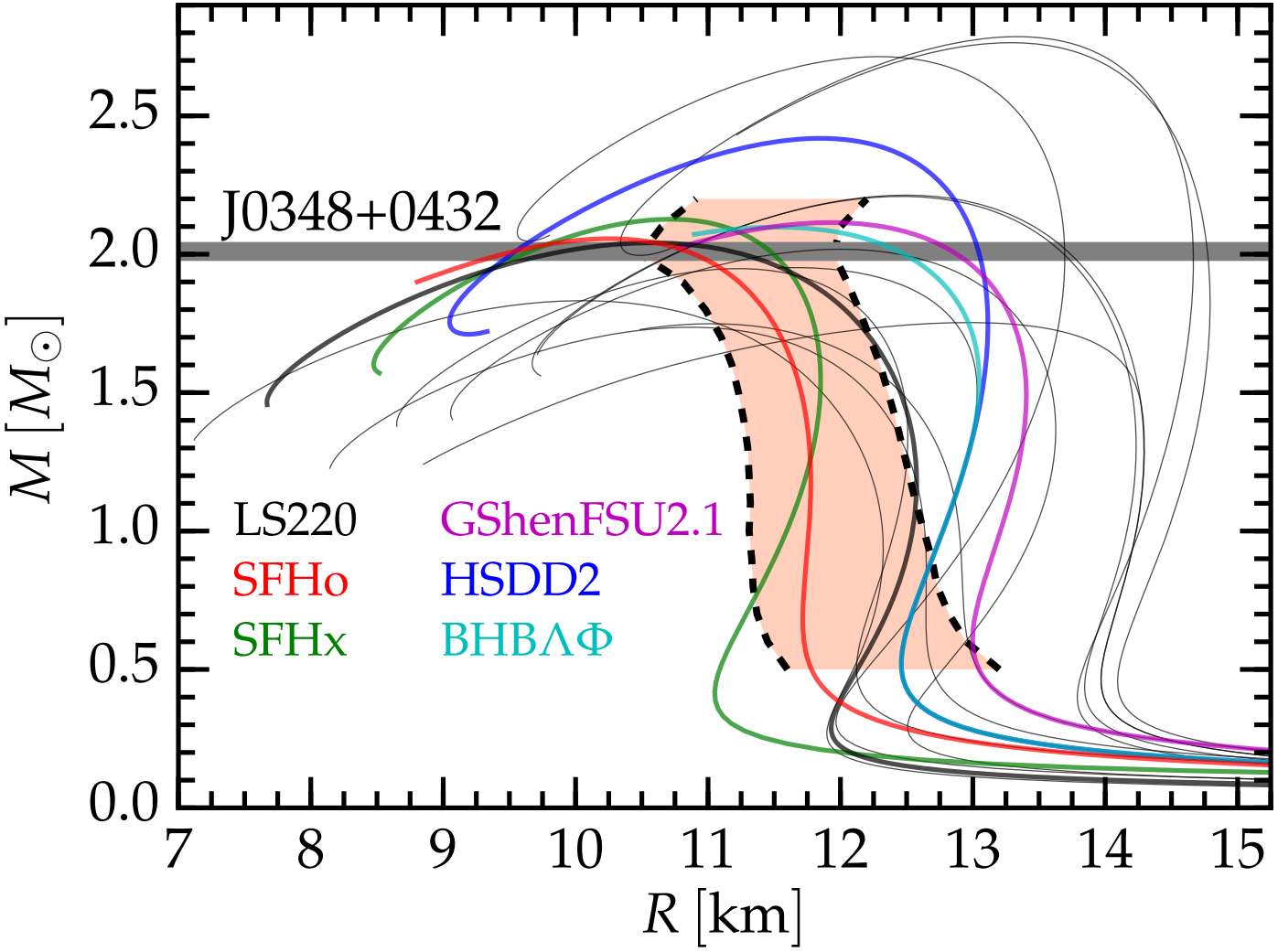


Andresen et al. 2016

Gravitational Waves from **Rapidly Rotating** Core Collapse



Many Available Equations of State



Parameter Study Methods

1824 Simulations

18 equations of state, 98 rotation profiles

2D Simulations (CoCoNuT)

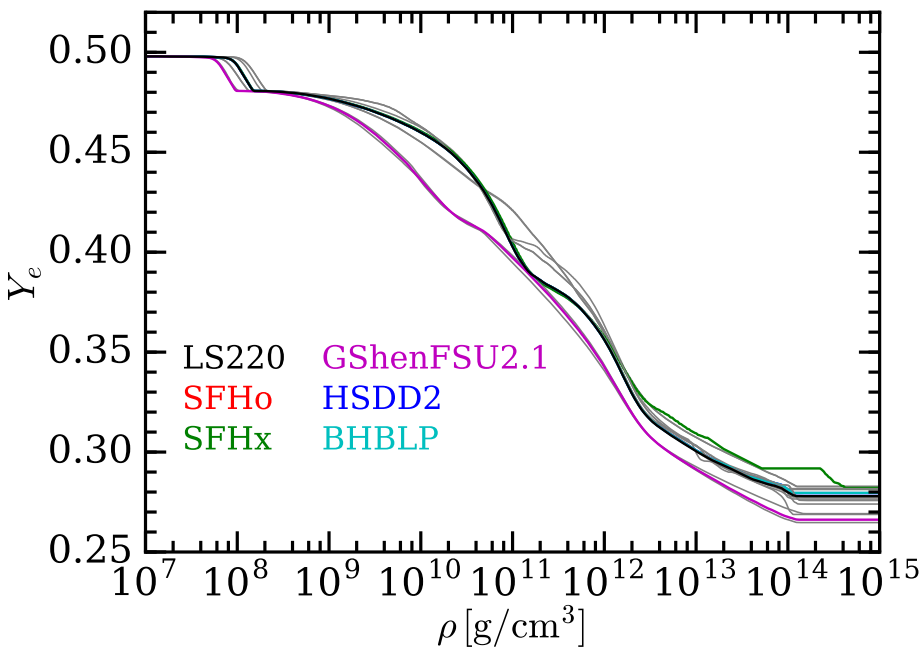
- Conformally flat GRHD
- Neutrino Leakage

  (Dimmelmeier+02,05)

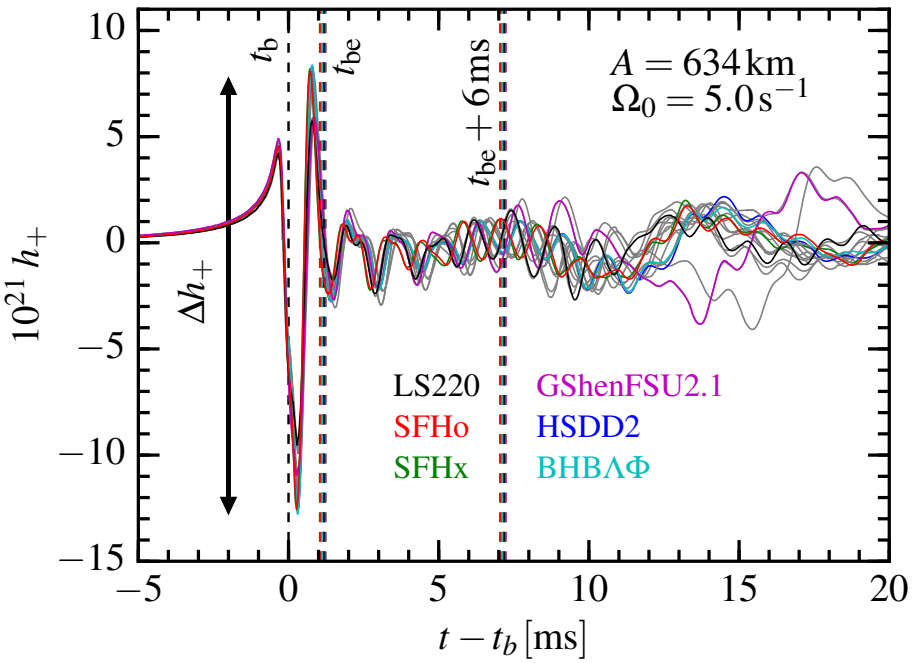
Deleptonization (GR1D)

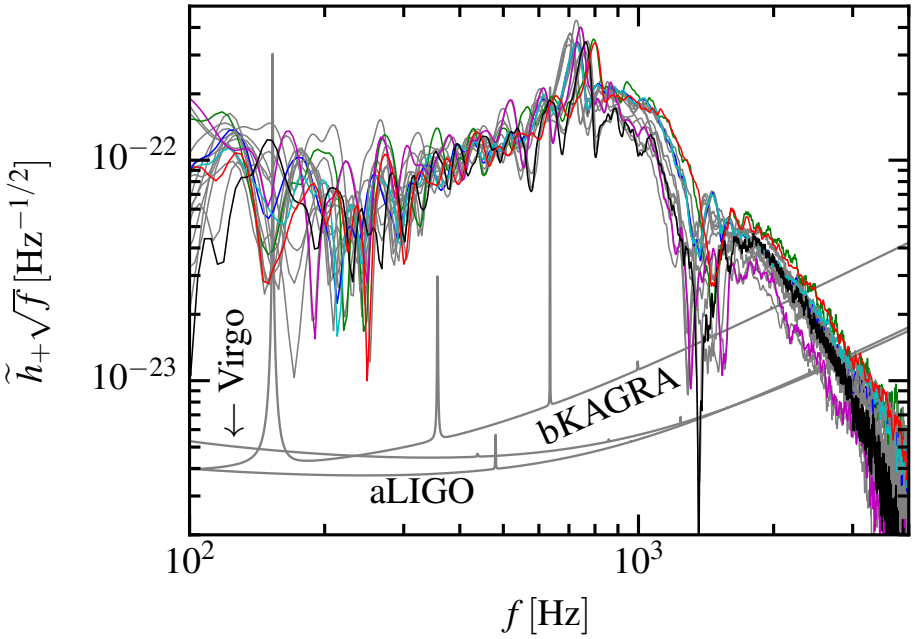
- Spherically symmetric GRHD
- M1 neutrino transport

  (O'Connor 2015)



GW Observables

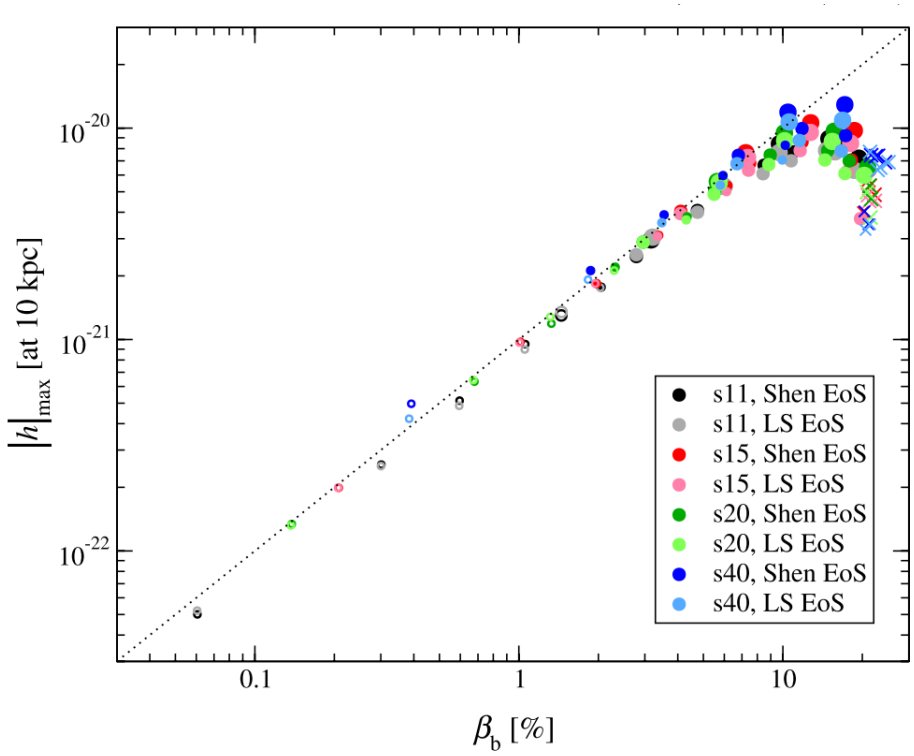


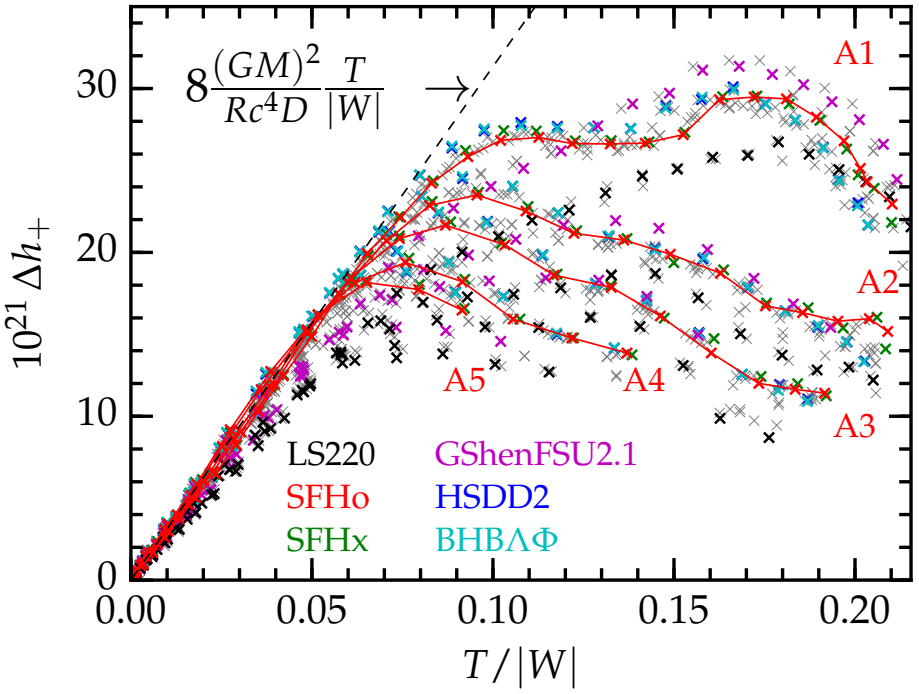


Bounce signal Δh_+ in time domain

Peak frequency f_{peak} in frequency domain.

Bounce Amplitude



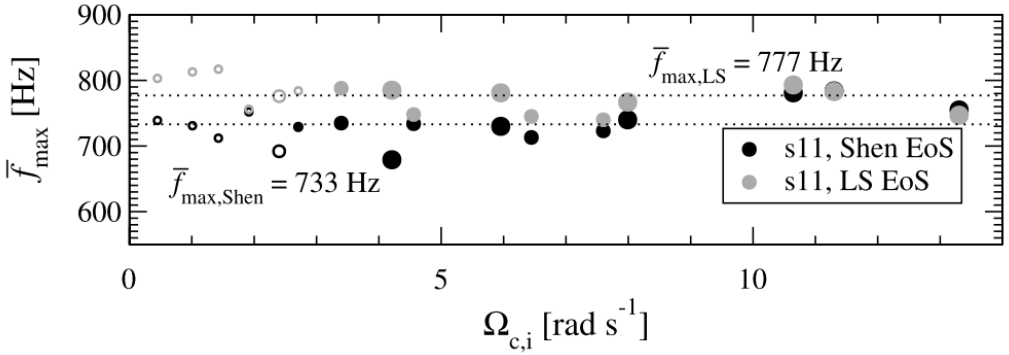


(Dimmelmeier et al. 2008)

EOS and rotation influence $M_{\mathrm{IC,b}}$.

Rotation increases deformation.

Peak Frequency

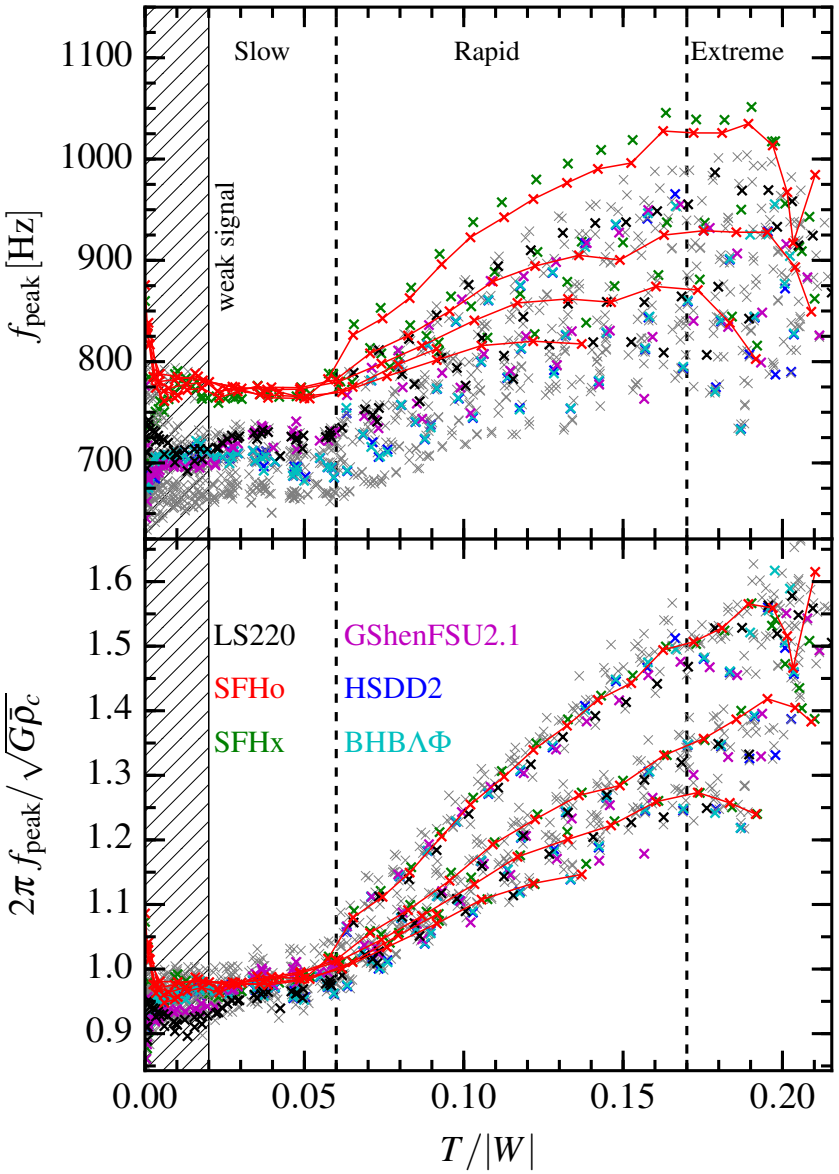


(Dimmelmeier+08)

150 Hz variation due to EOS

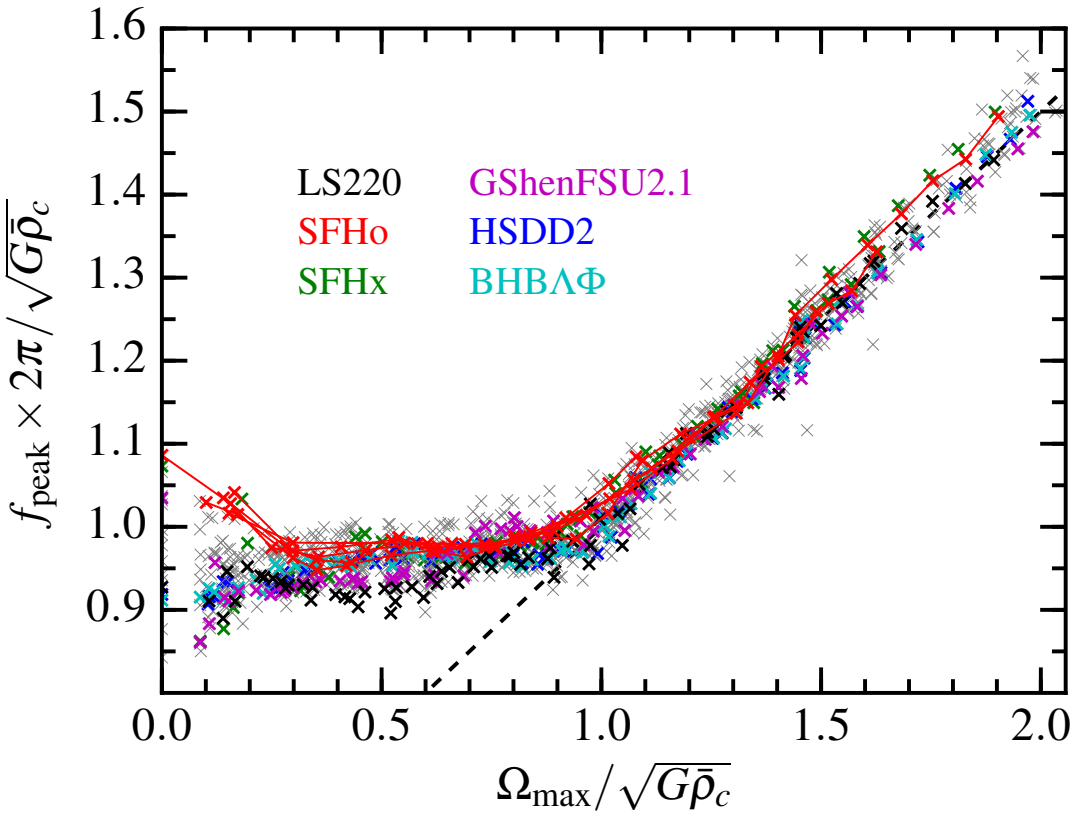
Explained by the **dynamical frequency**.

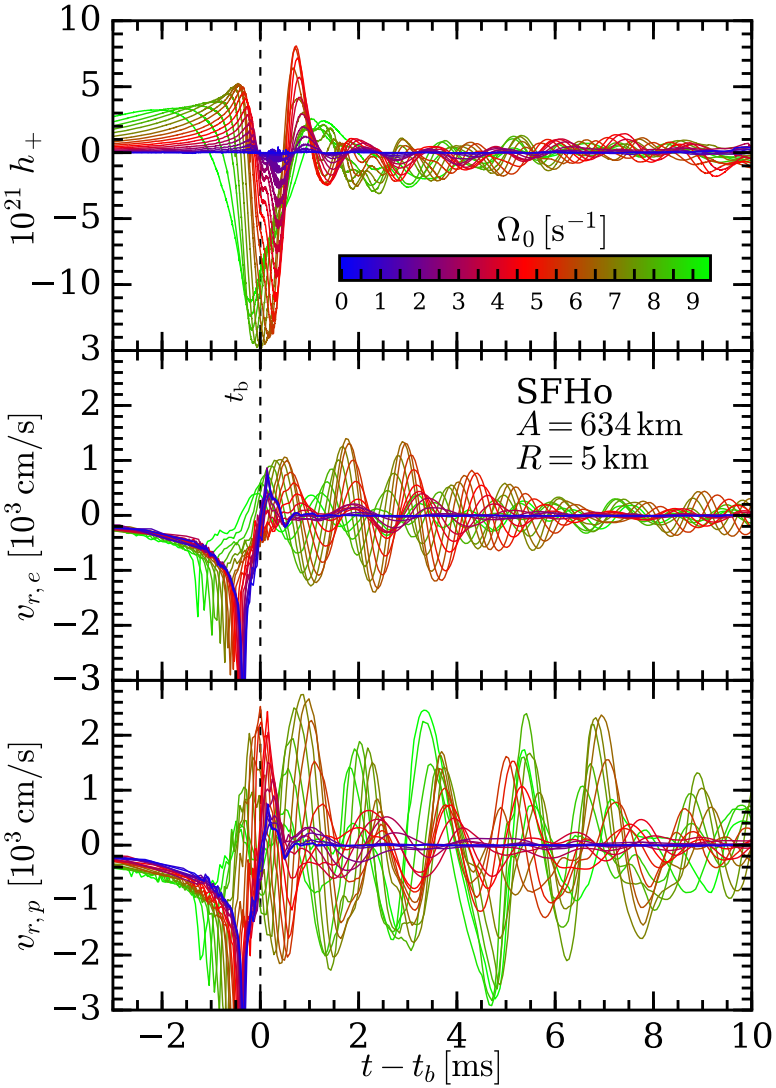
$$f_{\rm dyn} = 2\pi\sqrt{G\bar{\rho}_c}$$



Peak Frequency

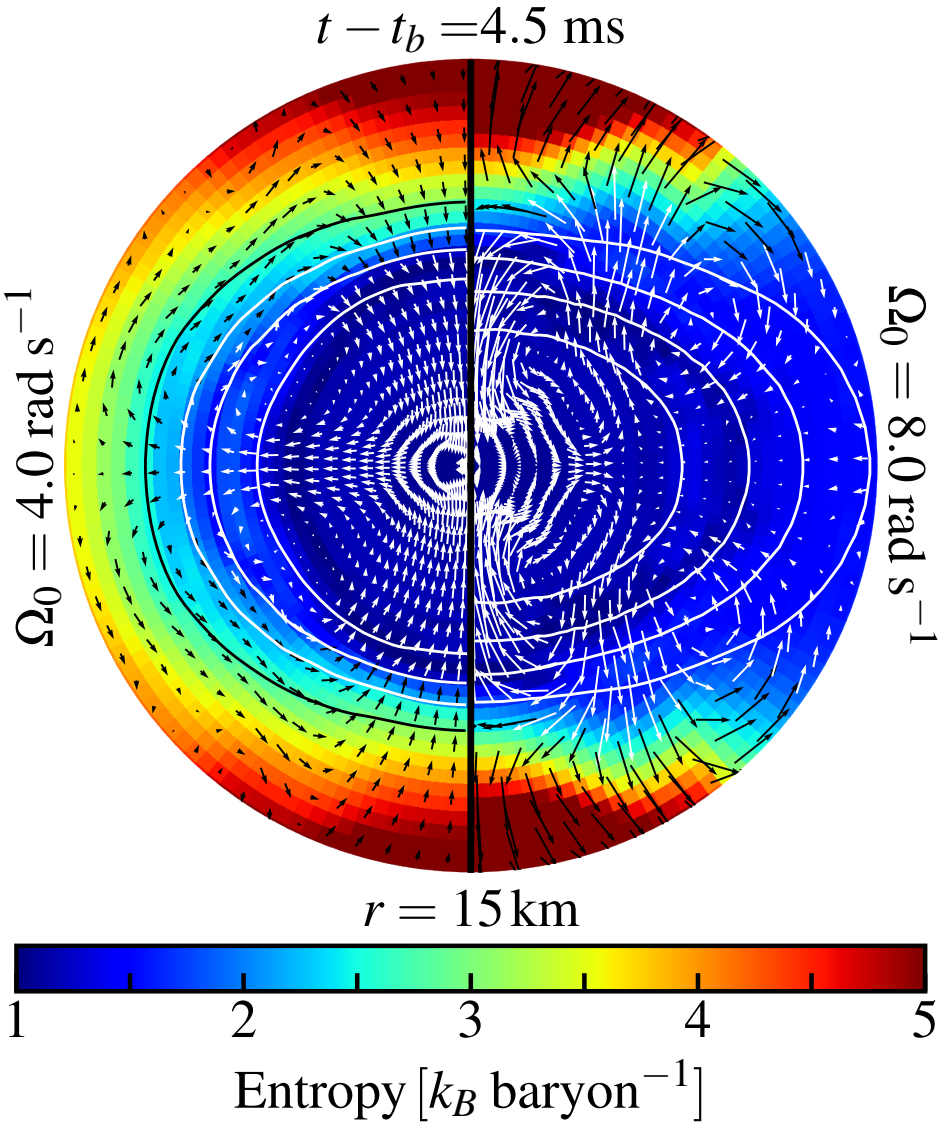
Now, let's measure rotation differently.





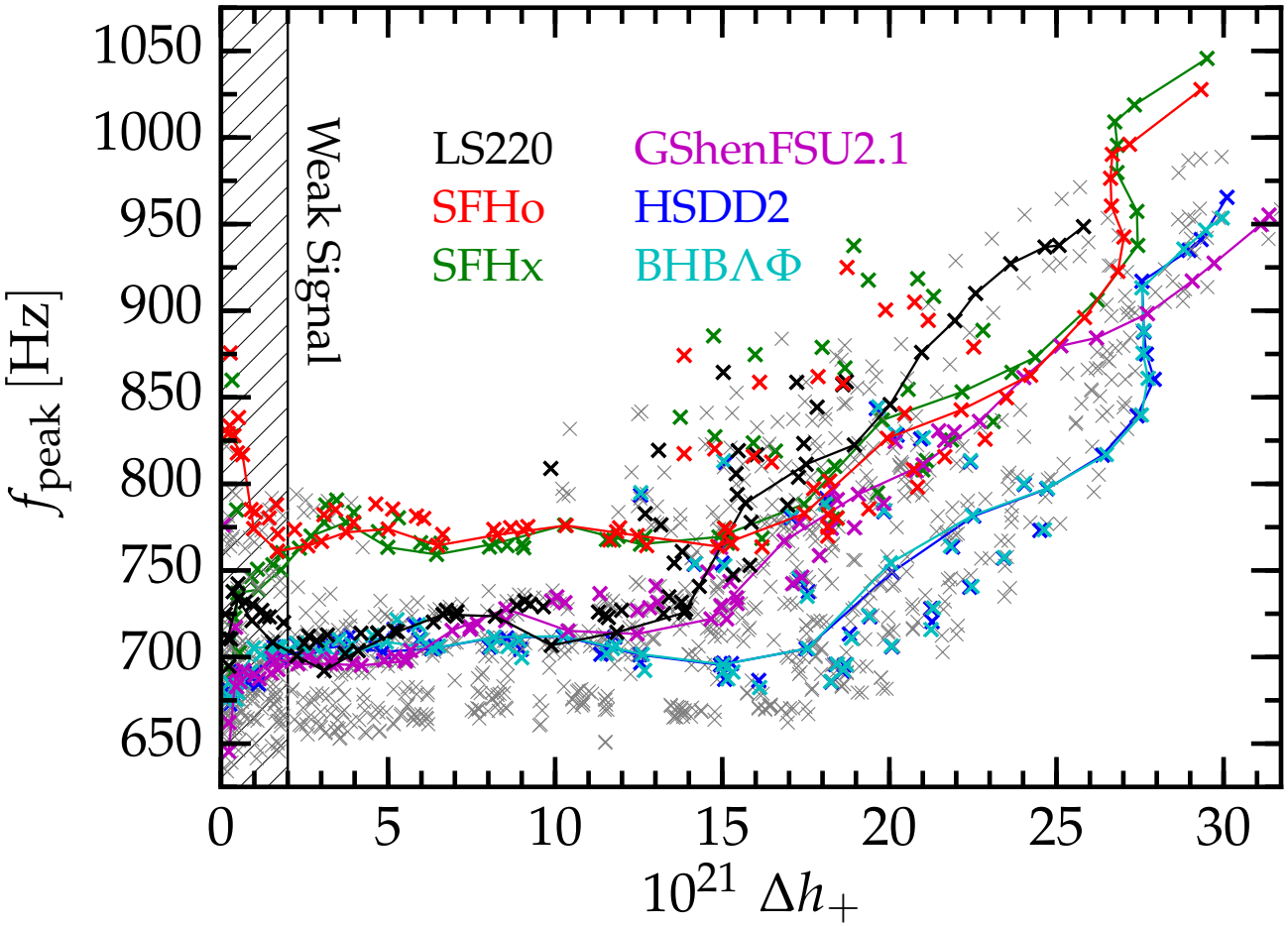
Inertial effects increase frequency and confine modes to poles.

Inertial Mode Character



High rotation rates suppress equatorial fluctuations.

Can We Constrain the EOS?



Probably not. Need detailed treatment of neutrino transport and **electron capture rates**.

Take Away

- A **universal relations** is obeyed by all EOS and rotation profiles.
- We **quantify uncertainties** in GW observables due to nuclear physics.
- GWs are sensitive to EOS properties at *both* **subnuclear** and **supernuclear** densities.
- Detailed **neutrino transport** and **electron capture rates** during collapse are required for reliable GW predictions.

arXiv:1701.02752

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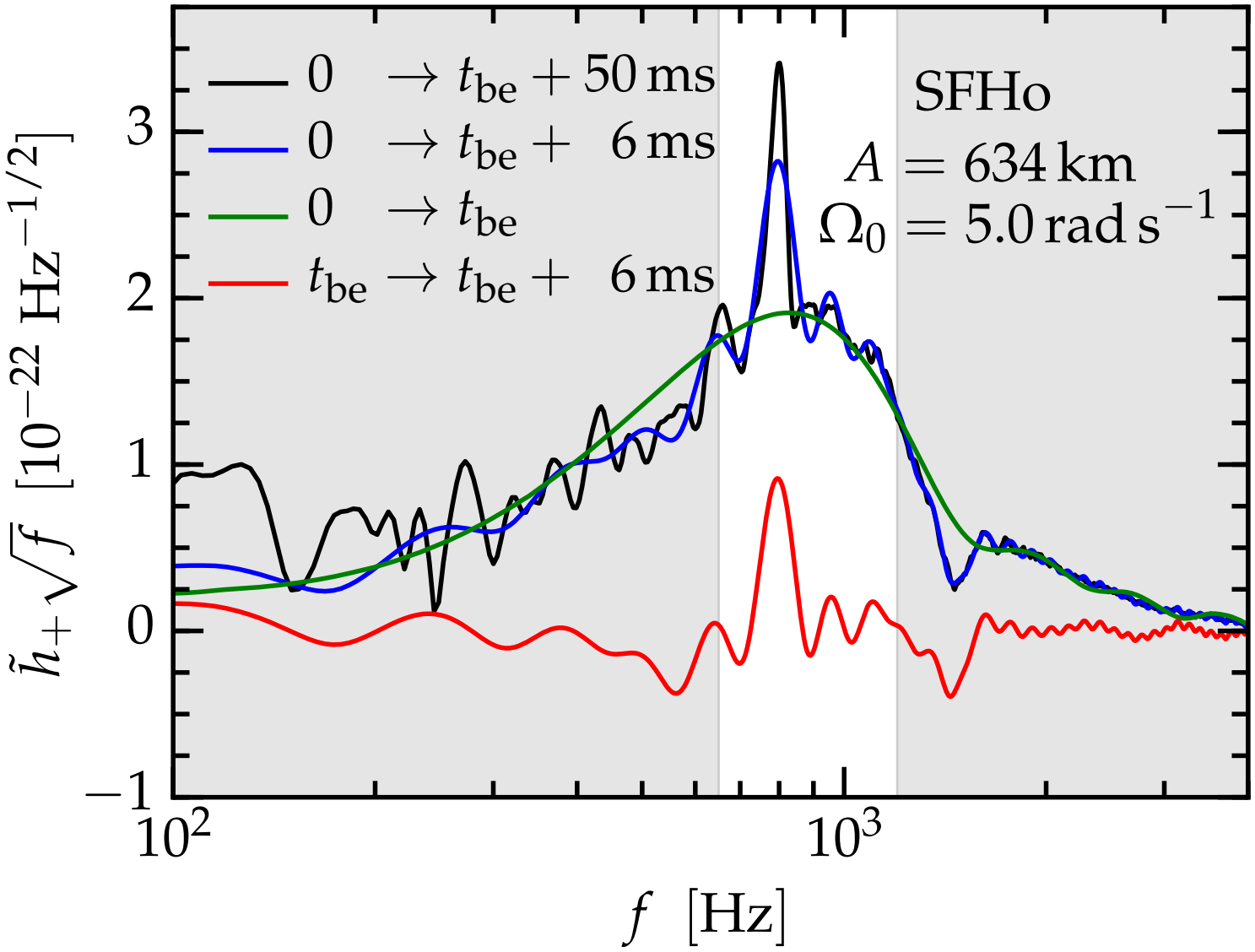
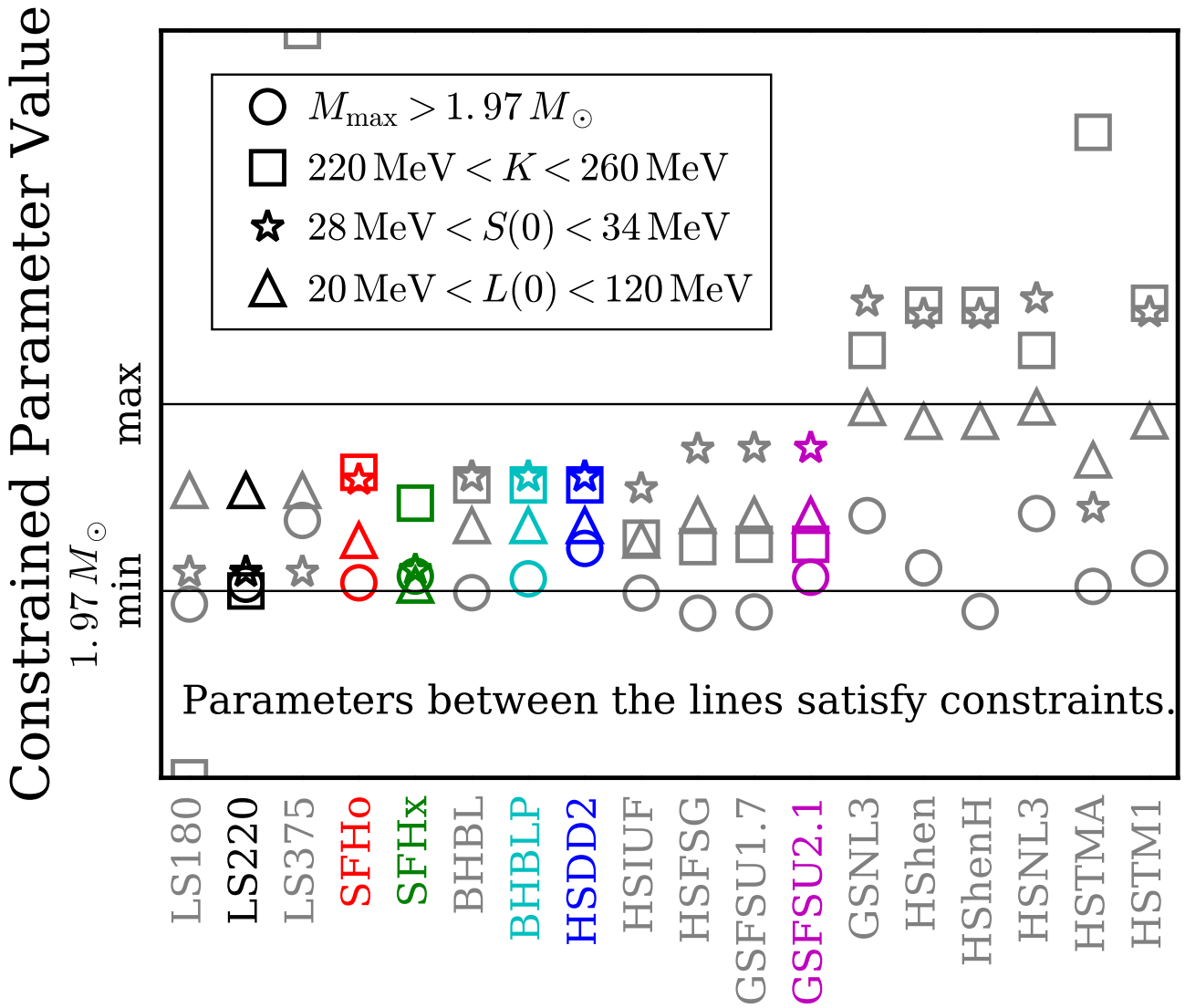
Fourier Analysis



18 Equations of State

$$E(x,\beta) = -E_0 + \frac{K}{18}x^2 + K'x^3 + ... + S_2(x)\beta^2 + S_4(x)\beta^4 + ...$$



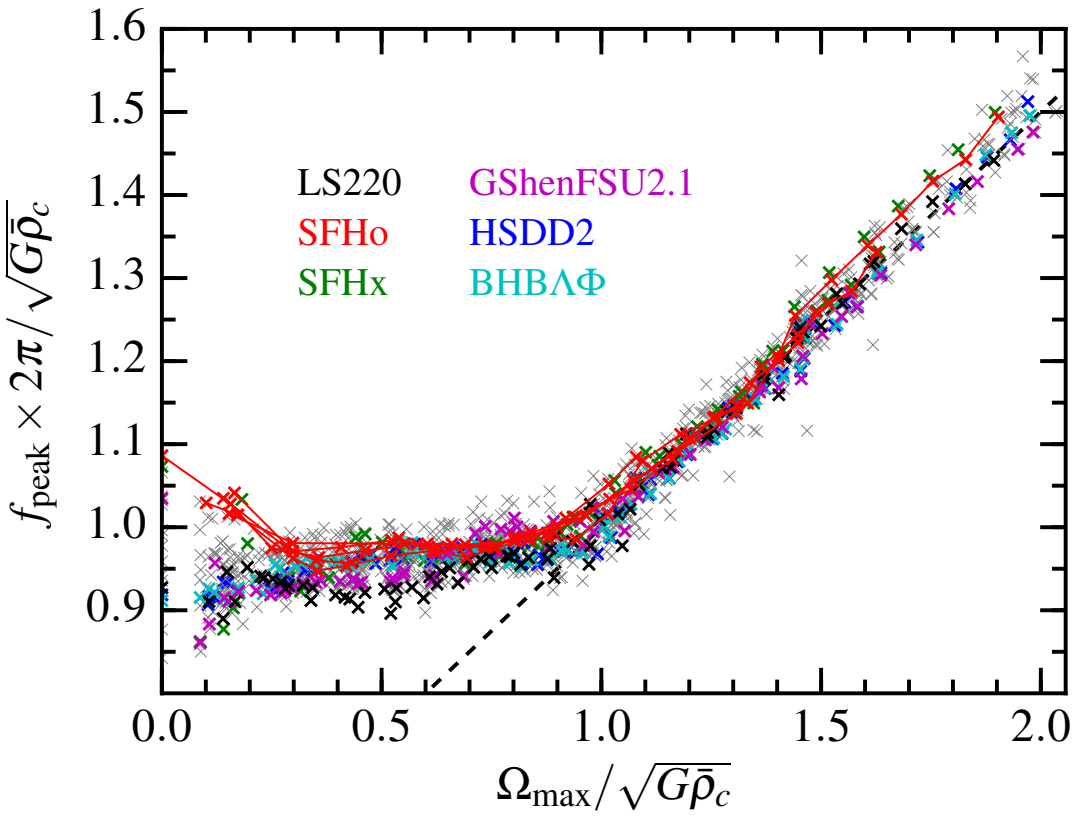
$$S_2(x) = J + \frac{L}{3}x + ...$$

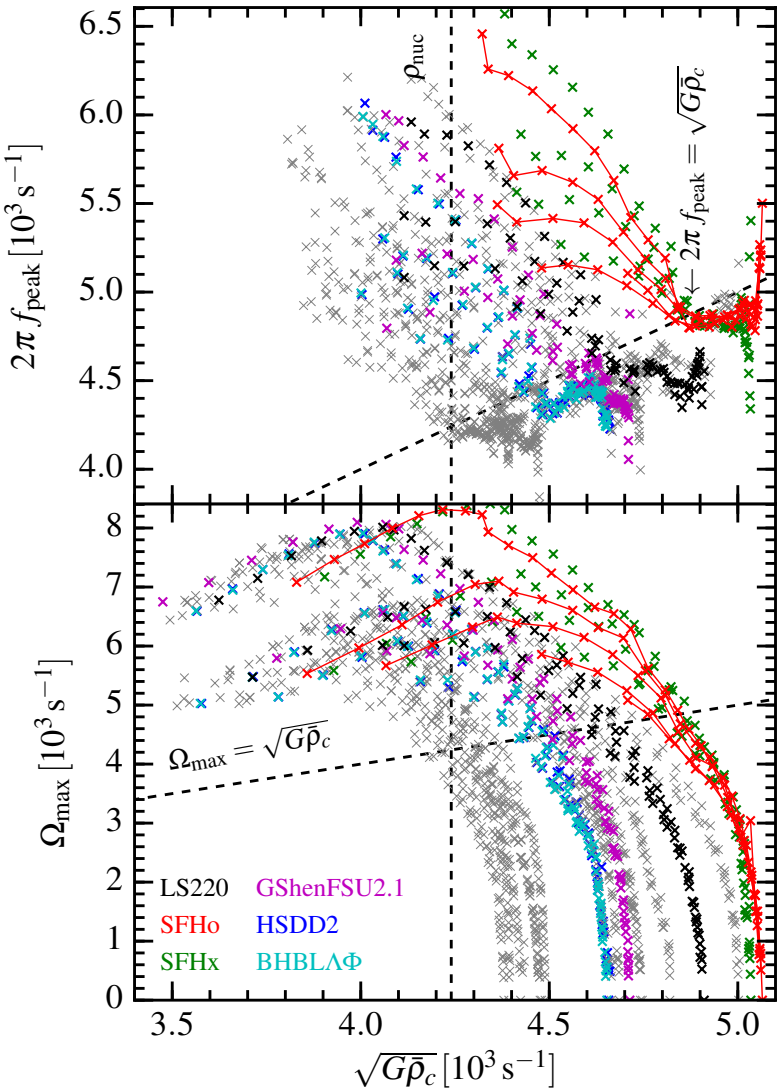
$$x = \frac{n - n_s}{n_s}$$

$$\beta = 2(0.5 - Y_e)$$

Peak Frequency

Now, let's measure rotation differently.





Inertial effects increase frequency and confine modes to poles.

Correlations

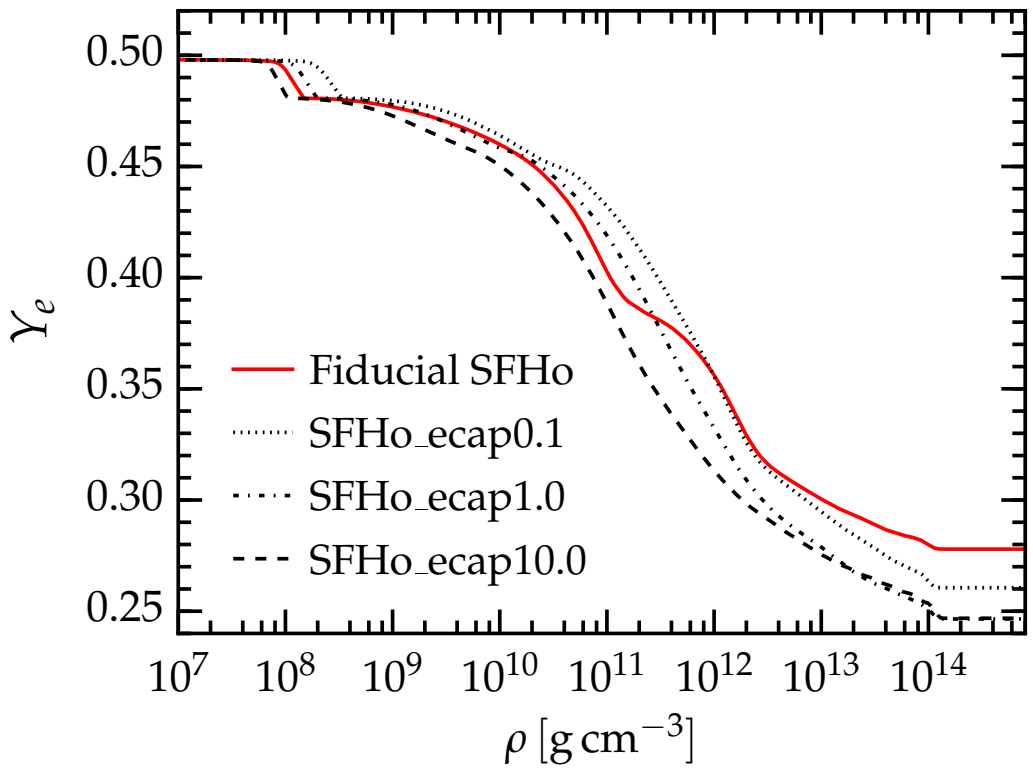
$$\mathcal{C}_{AB} = \frac{\sum\left(\frac{A-\bar{A}}{s_A}\right)\left(\frac{B-\bar{B}}{s_B}\right)}{N-1}$$

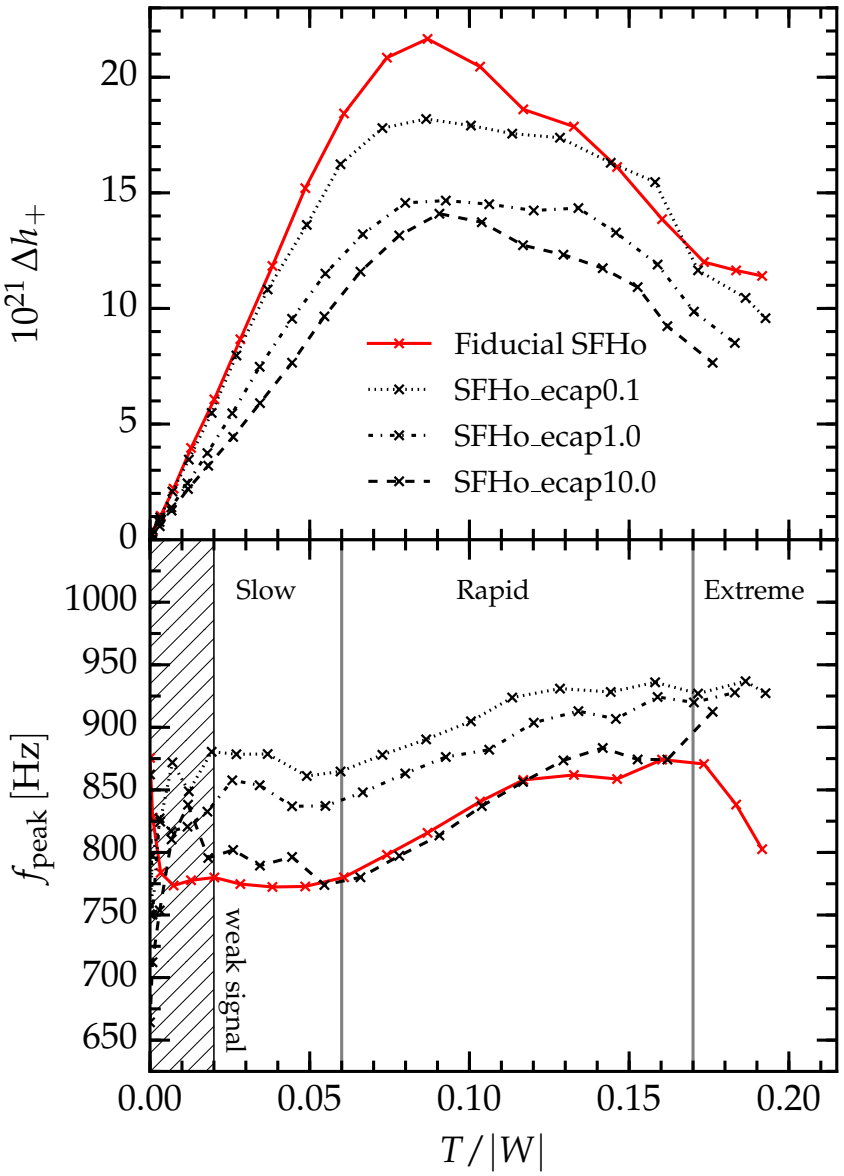
$\Omega_{\max} < \sqrt{G\bar{\rho}_c}$

	$M_{\mathrm{IC,b}}$	$j_{\mathrm{IC,b}}$	$T/\lvert W\rvert$	$\tilde{\Omega}_{\max}$	$\Omega_{\max}$	Δh_+	$\tilde{f}_{\mathrm{peak}}$	f_{peak}	Ω_0	A	$Y_{e,\mathrm{c,b}}$	L	J	K	$R_{1.4}$	$M_{\max}$
$M_{\mathrm{IC,b}}$		0.97	0.93	0.80	0.69	0.23	0.79	0.54	0.65	0.13	0.22	0.12	0.27	0.02	0.19	0.01
$j_{\mathrm{IC,b}}$	0.91		0.97	0.76	0.66	0.08	0.75	0.52	0.60	0.13	0.09	0.08	0.14	0.01	0.11	0.01
$T/\lvert W\rvert$	0.87	0.99		0.83	0.76	0.15	0.82	0.65	0.67	0.15	0.00	0.00	0.01	0.02	0.01	0.02
$\tilde{\Omega}_{\max}$	0.82	0.96	0.94		0.97	0.61	0.99	0.86	0.94	0.31	0.01	0.06	0.06	0.01	0.06	0.00
$\Omega_{\max}$	0.78	0.94	0.92	0.99		0.65	0.96	0.95	0.93	0.33	0.03	0.14	0.13	0.07	0.15	0.06
Δh_+	0.89	0.98	0.98	0.93	0.92		0.61	0.63	0.68	0.24	0.20	0.07	0.09	0.06	0.01	0.03
$\tilde{f}_{\mathrm{peak}}$	0.47	0.50	0.49	0.45	0.44	0.49		0.89	0.94	0.27	0.02	0.04	0.03	0.05	0.04	0.05
f_{peak}	0.17	0.01	0.05	0.04	0.12	0.04	0.46		0.86	0.27	0.09	0.32	0.31	0.09	0.34	0.05
Ω_0	0.75	0.88	0.86	0.95	0.94	0.85	0.39	0.02		0.36	0.04	0.04	0.02	0.02	0.03	0.01
A	0.09	0.12	0.12	0.06	0.06	0.13	0.10	0.03	0.11		0.12	0.02	0.03	0.03	0.01	0.02
$Y_{e,\mathrm{c,b}}$	0.35	0.05	0.01	0.00	0.01	0.08	0.09	0.18	0.01	0.00		0.16	0.38	0.01	0.07	0.25
L	0.13	0.04	0.00	0.00	0.07	0.02	0.08	0.66	0.01	0.00	0.19		0.77	0.43	0.88	0.36
J	0.34	0.07	0.01	0.00	0.07	0.02	0.06	0.65	0.00	0.01	0.35	0.76		0.22	0.81	0.25
K	0.08	0.01	0.01	0.00	0.04	0.01	0.10	0.39	0.00	0.00	0.01	0.42	0.21		0.58	0.51
$R_{1.4}$	0.23	0.05	0.01	0.00	0.09	0.01	0.06	0.78	0.00	0.00	0.04	0.88	0.80	0.57		0.50
$M_{\max}$	0.00	0.00	0.01	0.01	0.03	0.02	0.21	0.22	0.00	0.00	0.26	0.40	0.28	0.53	0.54	

$\Omega_{\max} \geq \sqrt{G\bar{\rho}_c}$

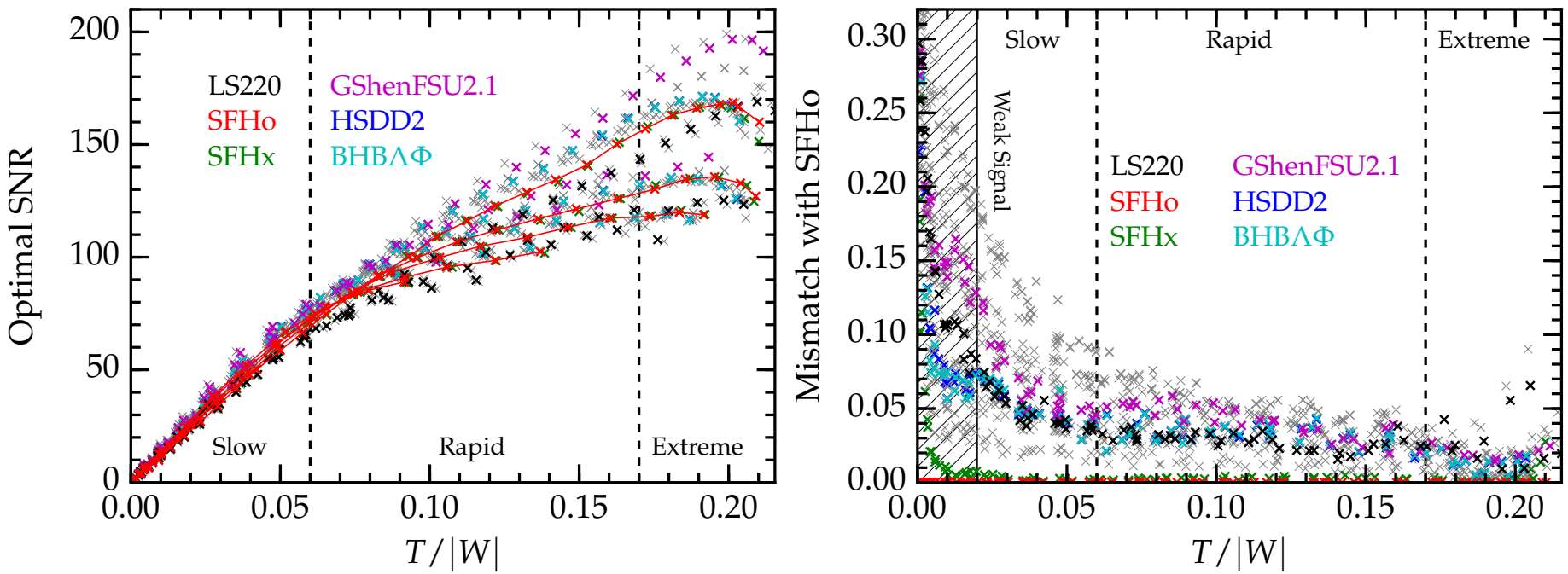
Can We Constrain the EOS?





The GW signal is sensitive to **systematic biases** in electron capture rates.

Can We Constrain the EOS?



High SNR at 10 kpc. Must be in the Milky Way or Magellanic Clouds.
Large mismatch between EOS due to pre- *and* post-collapse physics.

Looks great, right?