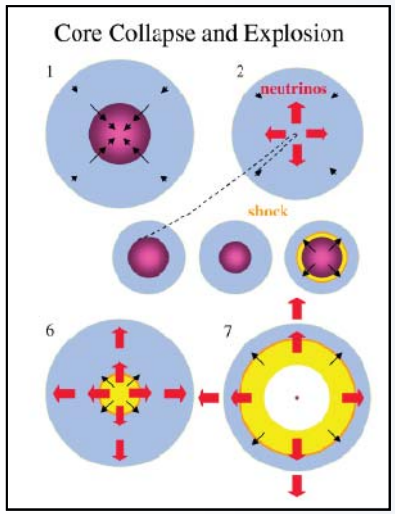
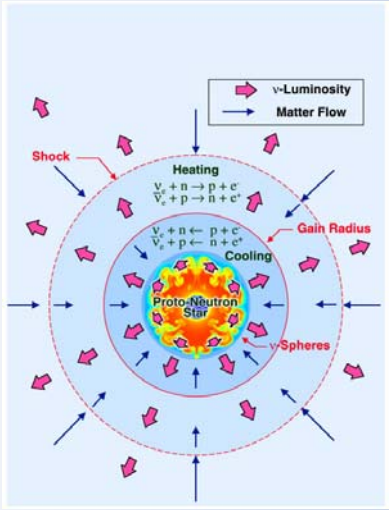
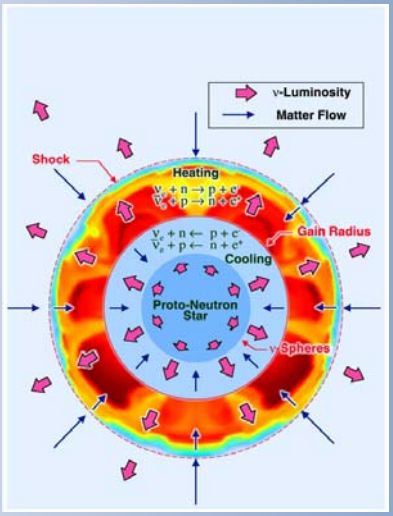
Neutrino-Driven CCSNe: Sources of Gravitational Waves



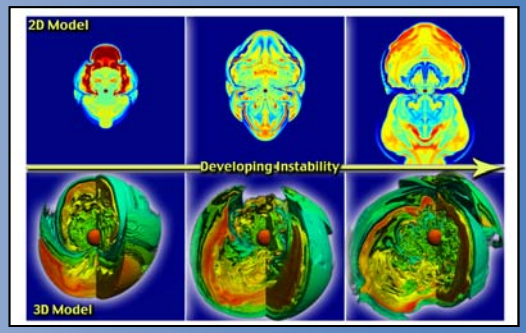
Stellar Core Bounce



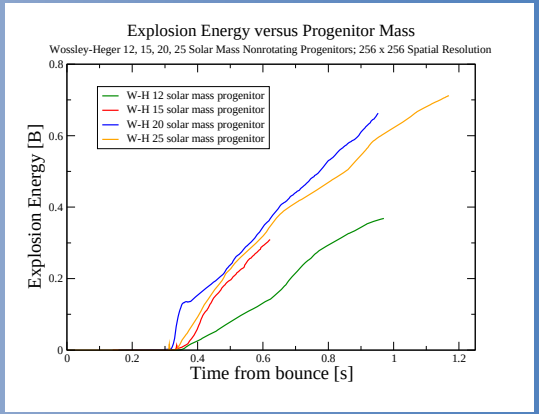
Proto-Neutron Star (PNS) Instabilities



Post-Shock Region Neutrino-Driven Convection Induced



Standing Accretion Shock Instability (SASI) Induced

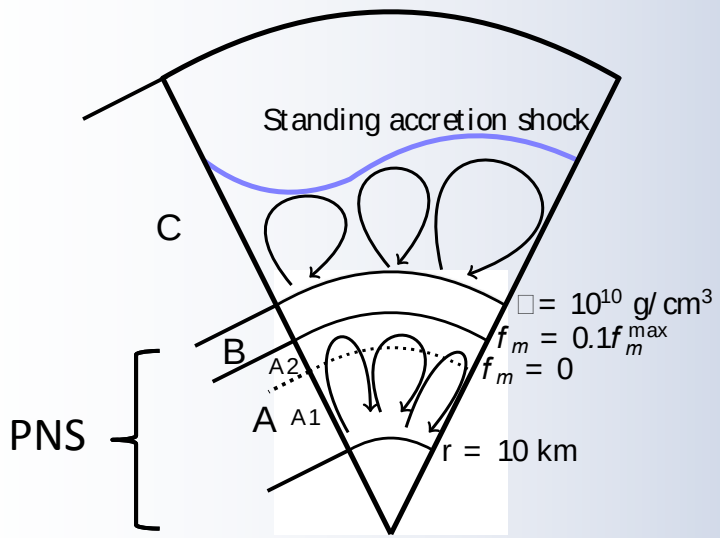


Explosion

Kei Kotake will give an extensive overview as part of the Status of Core Collapse Supernova Modeling Panel.

Gravitational Wave Signal Source Analysis

(5) SASI-Induced Modulation (Low Frequency)



- Andresen et al. 2017 arXiv:1607.05199

Sources of Gravitational Radiation

(1) PNS convection in region A.

(2) Acoustic waves in the PNS initiated by PNS convection.

(3) Deceleration of infalling convective plumes.

(4) Excitation of PNS g-modes by these down flows (2D) or by PNS convection (3D).

- Marek, Janka, and Mueller, *A&A* **496**, 475 (2009)
- Murphy, Ott, and Burrows *Ap.J.* **707** 1173 (2009)
- Mueller, Janka, and Marek *Ap.J.* **766**, 43 (2013)

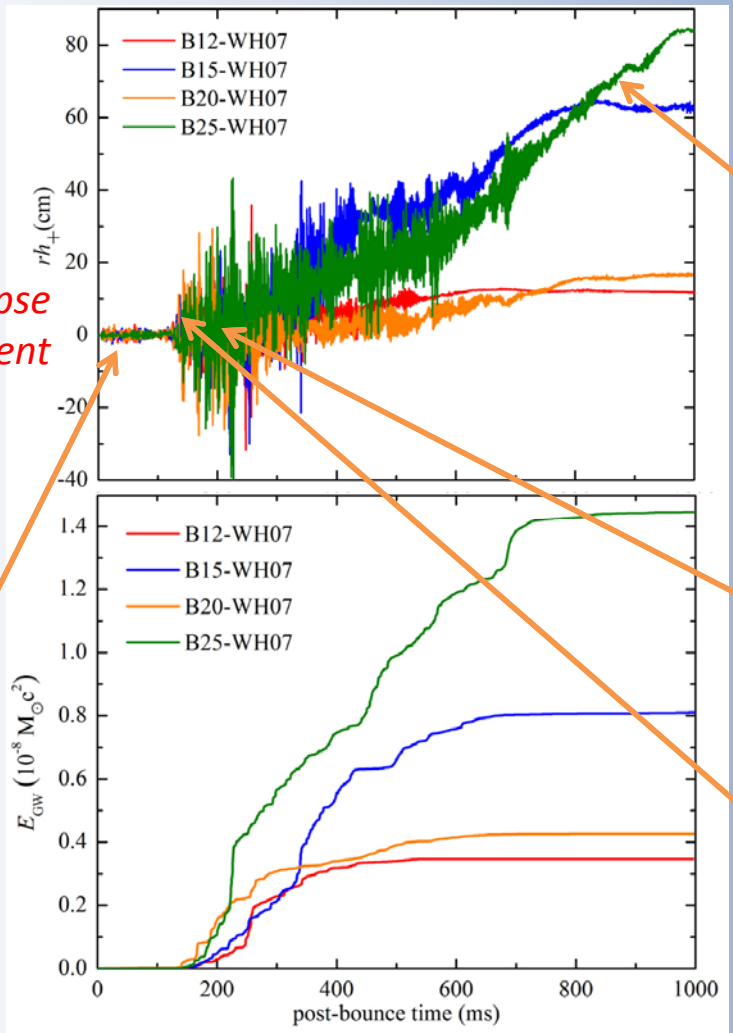
g-Mode Frequency (Brunt-Vaisala Frequency)

$$f_p = \frac{N}{2\pi} = \frac{1}{2\pi}\frac{GM}{R^2}\sqrt{\frac{(\Gamma-1)m_n}{\Gamma k_b T}}\left(1-\frac{GM}{Rc^2}\right)^{3/2}$$

The late-time, high-frequency GW is given by the g-mode frequency in B (A2) for the 2D (3D) case.

Gravitational Wave Signals: 2D (Amplitudes)

Quasi-Spherical Collapse
=> Bounce Signal Absent



PNS Instabilities Induced GW

Source: PNS

Explosion Induced GW

Source: Ejected Matter

Neutrino-Driven Convection and SASI Induced GW

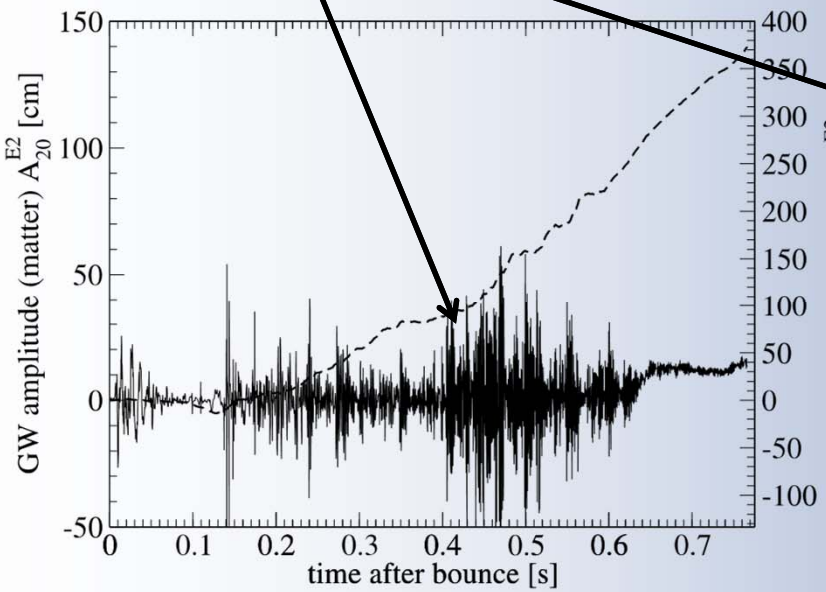
Source: PNS

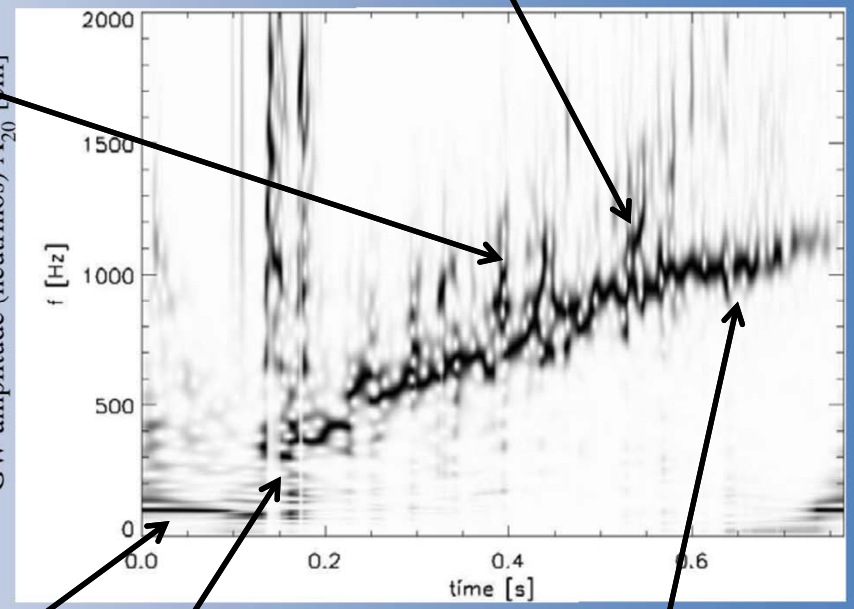
Modulated by SASI

N.B. Low-Frequency Envelope

Yakunin et al. 2015 PRD **92** 084040

Signal Breakdown





Correlated

Deceleration of Convective Plumes (Stochastic)

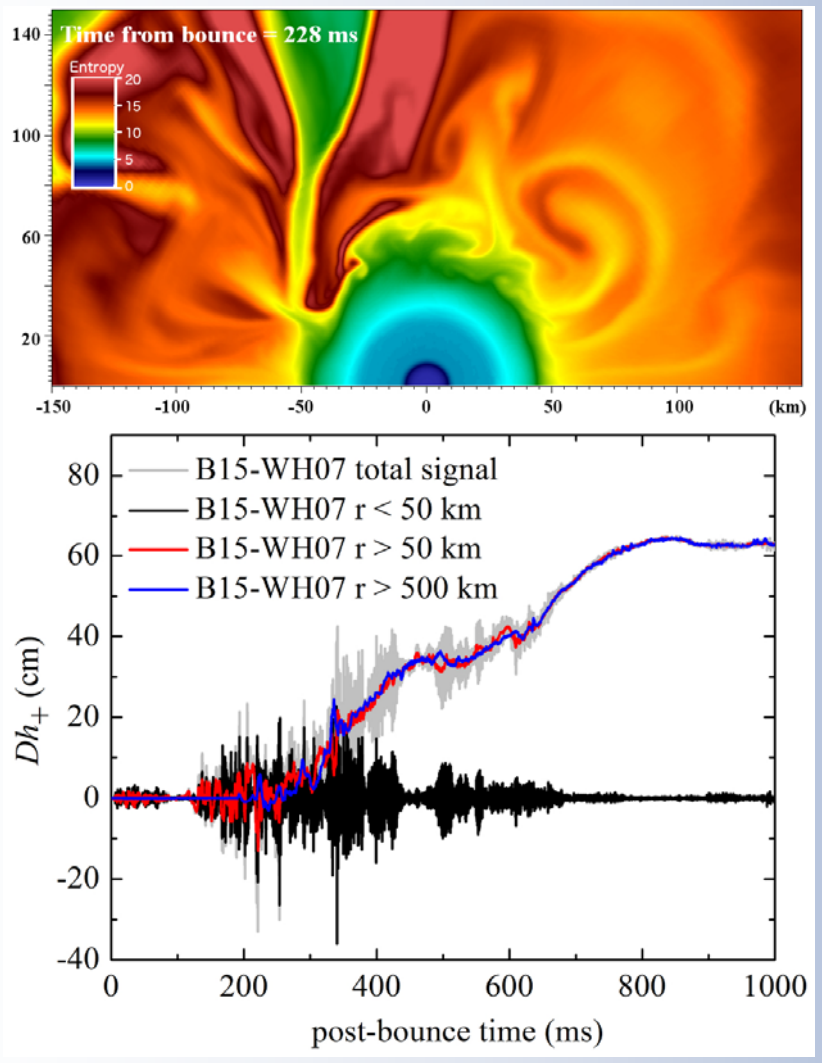
Prompt Convection Acoustic Waves

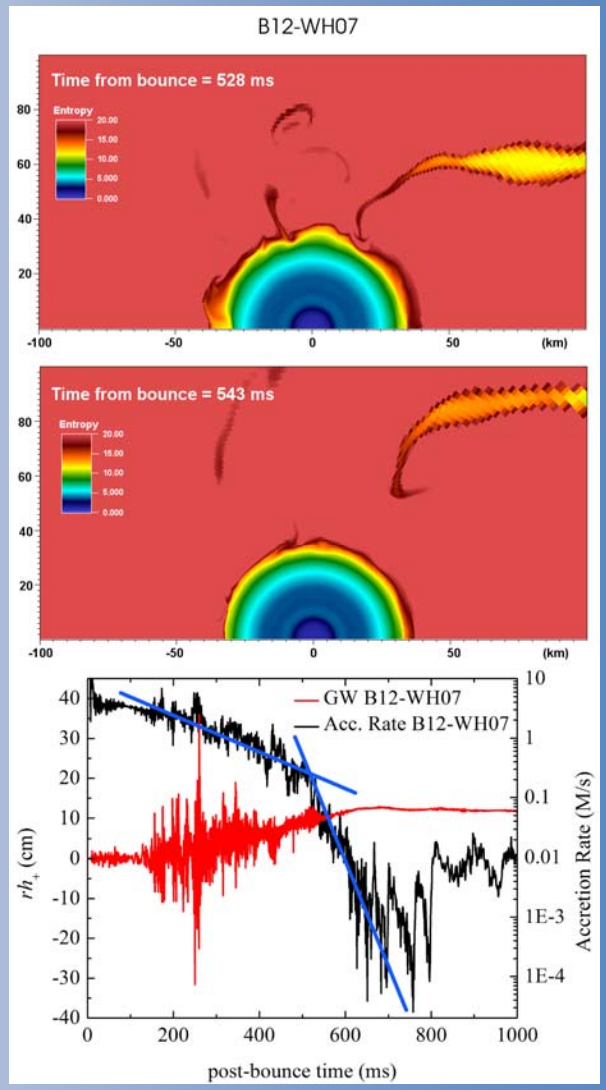
Quiescent Phase

Neutrino-Driven Convection/ SASI Induced g-Modes

Mueller, Janka, and Marek *Ap.J.* **766**, 43 (2013)

GW Amplitude: Correlation with Accretion





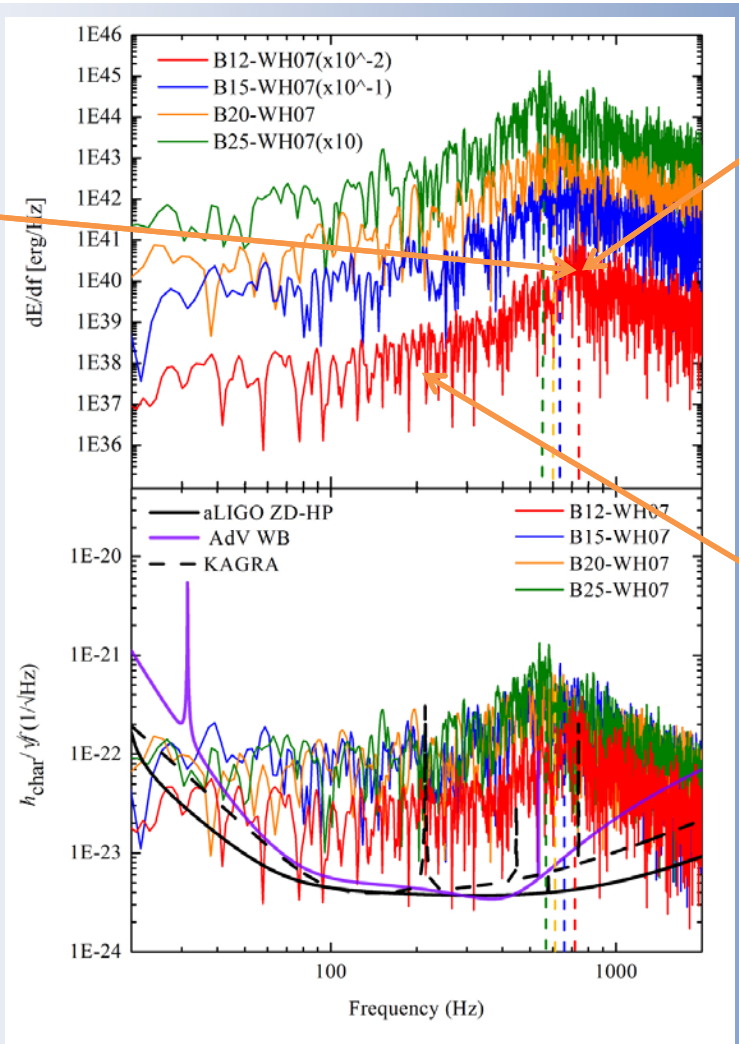
Cessation of accretion corresponds to cessation of high-frequency component of GW amplitude.

Yakunin et al. 2015 PRD **92** 084040

Gravitational Wave Signals: 2D (Frequency)

PNS Instabilities
Induced GW Signal

Source: PNS



Neutrino-Driven Convection
and
SASI
Induced GW Signal

Source: PNS

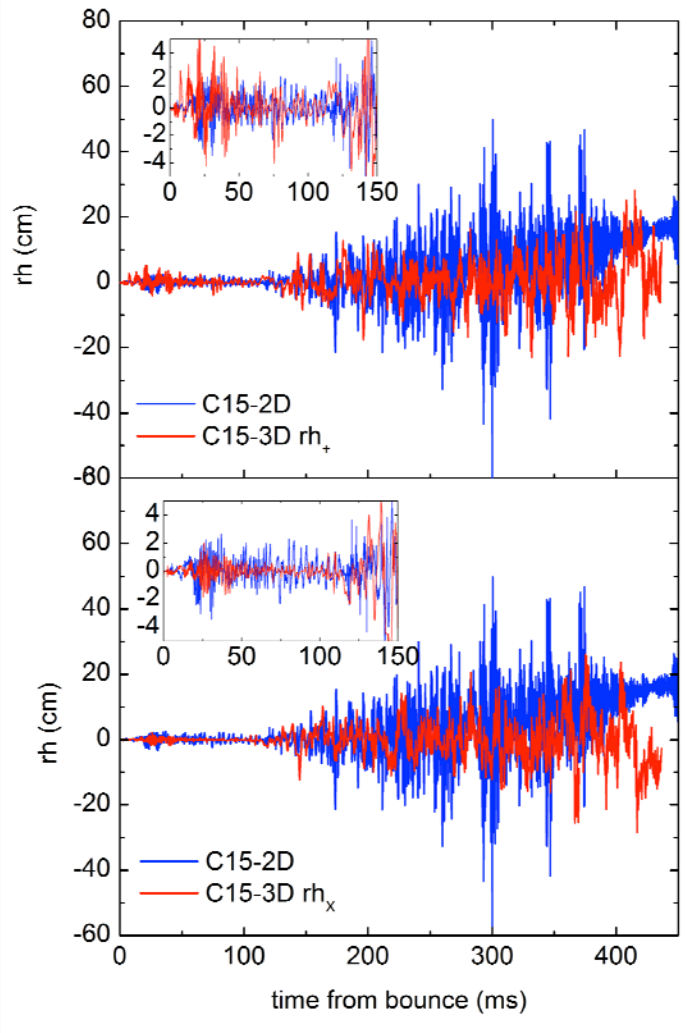
SASI
Induced Modulation
of PNS GW Signal

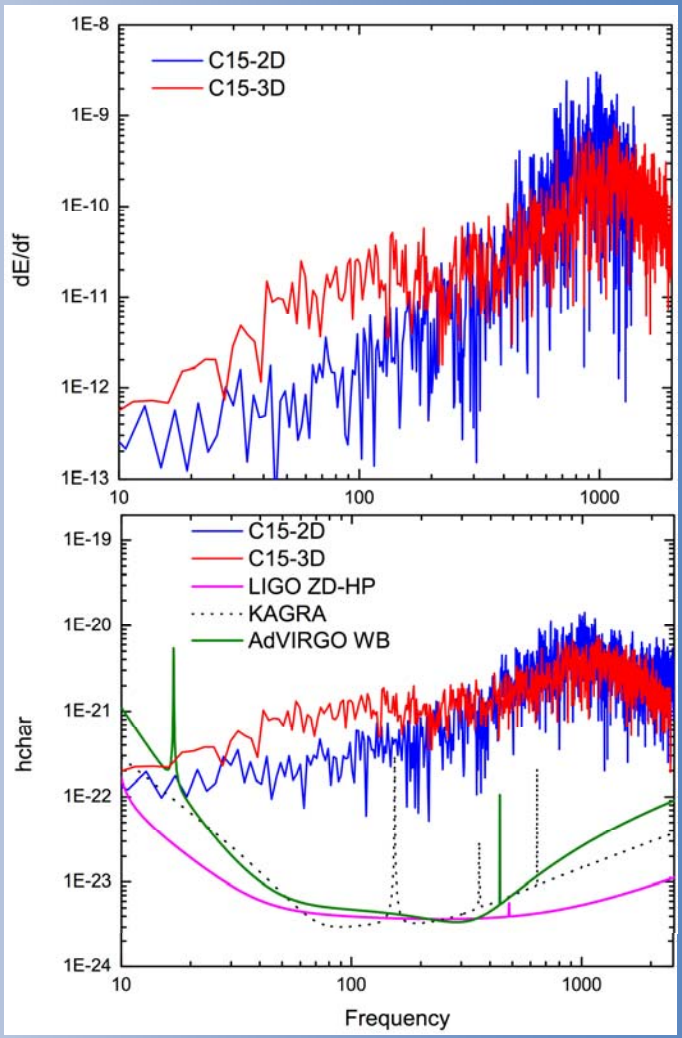
Yakunin et al. 2015 PRD **92** 084040

Distinguish convection- and SASI-dominated models by ratio of high- to low-frequency power?

- *Andresen et al. 2017 arXiv:1607.05199*

Gravitational Wave Signals: 2D vs. 3D



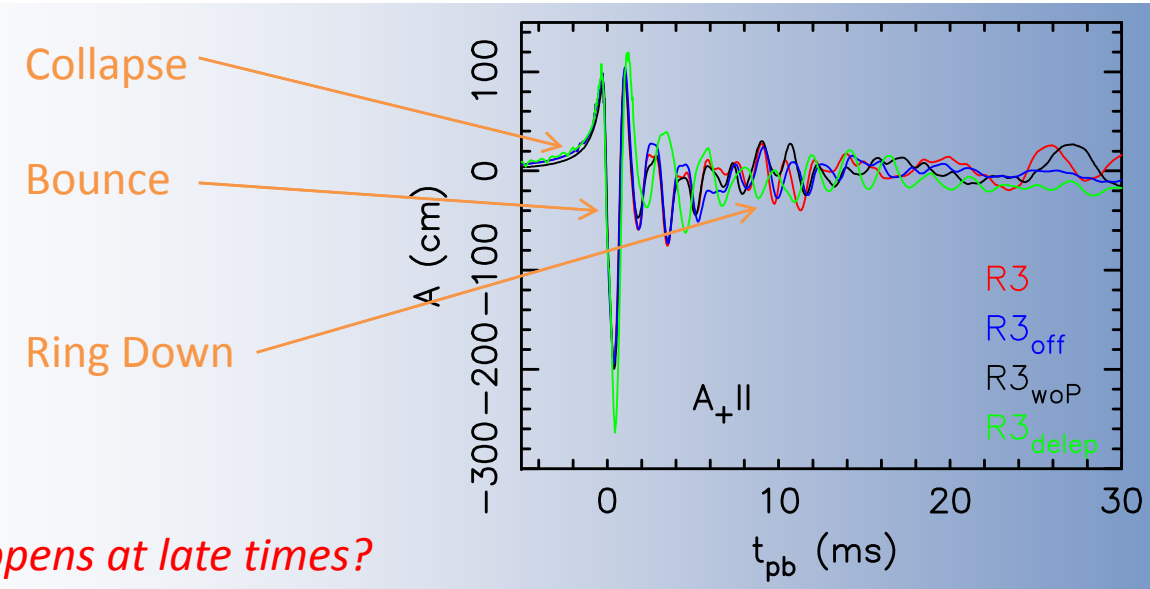


Yakunin et al. 2017, arXiv:1701.07325v1

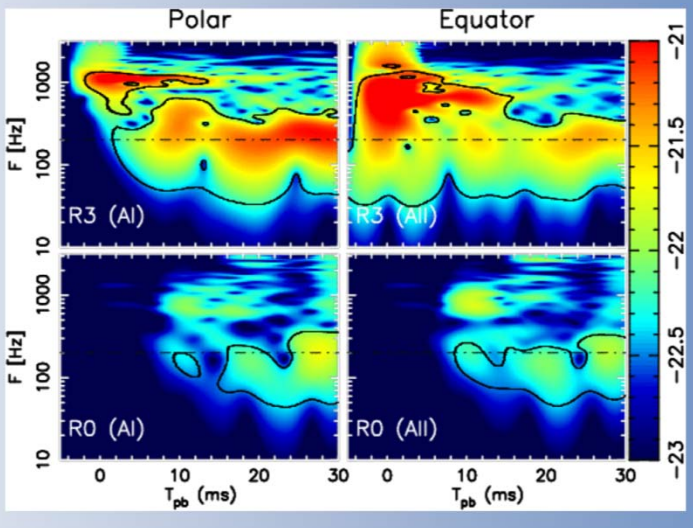
Comparisons use same time window (from 3D) and temporal resolution (from 2D).

See also Andresen et al. 2017 arXiv:1607.05199.

Signals from Magnetorotationally-Driven CCSNe



What happens at late times?



Kuroda, Takiwaki, and Kotake PRD 89 044011 (2014)