Gravitational Waves from the Collapse of Massive Stars

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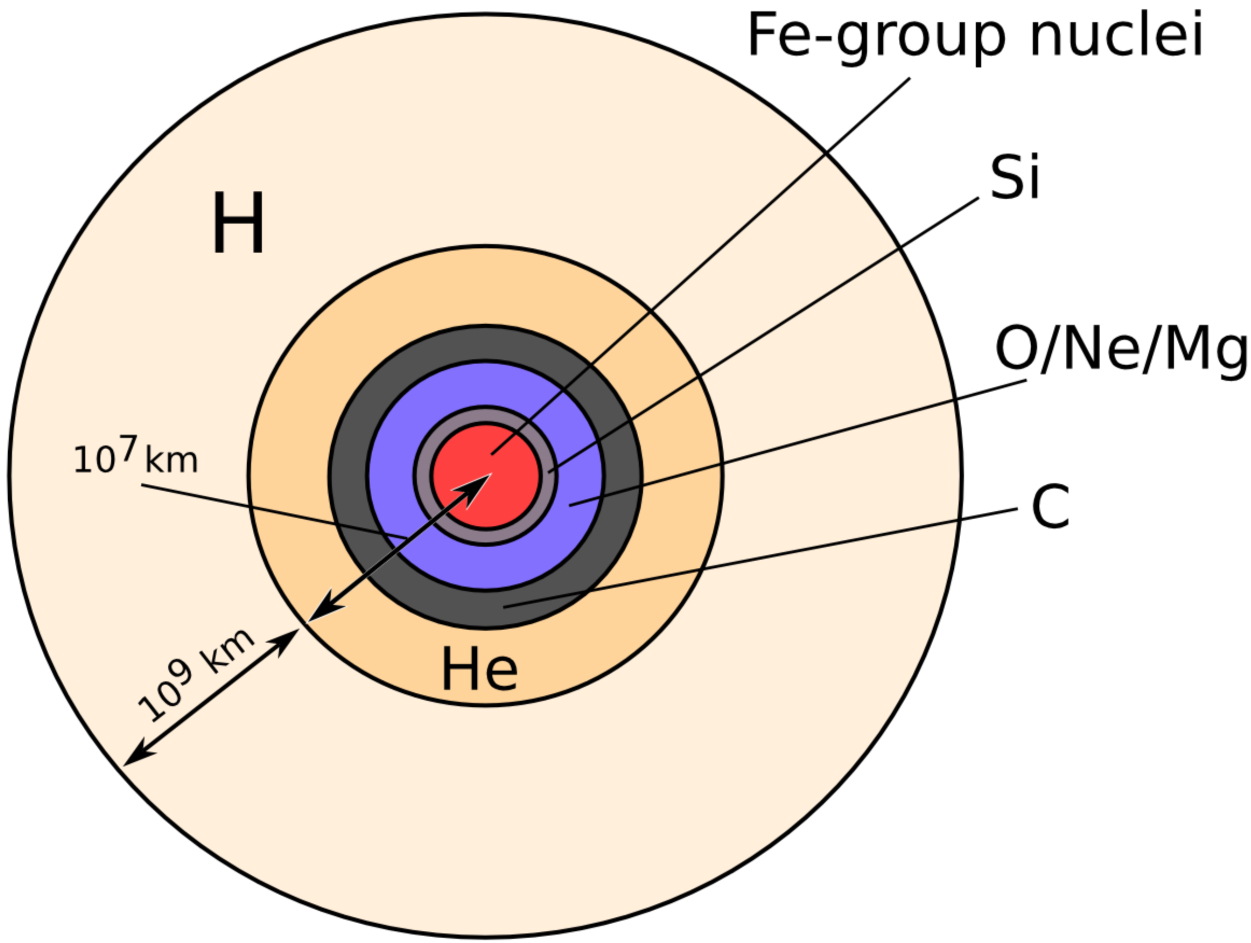
The Core Collapse Scenario



Evolved Massive Star

$M > 8\text{-}10\ M_{SUN}$

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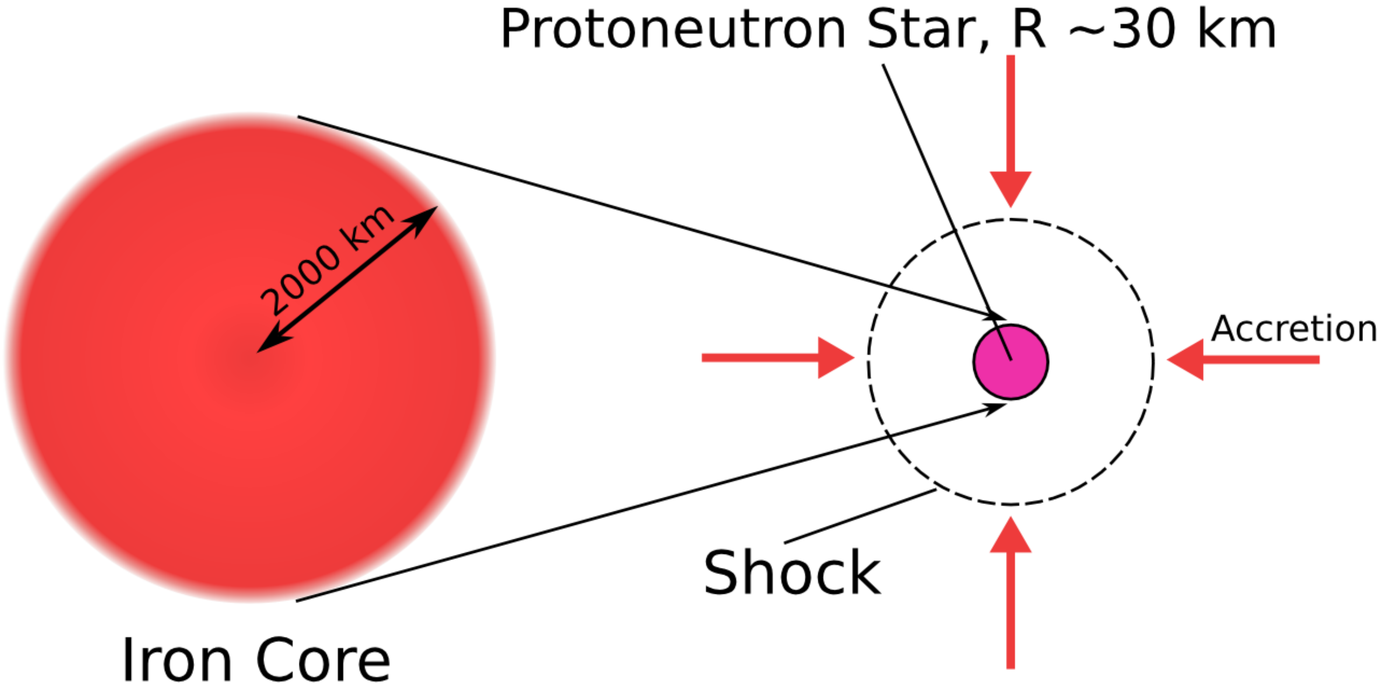
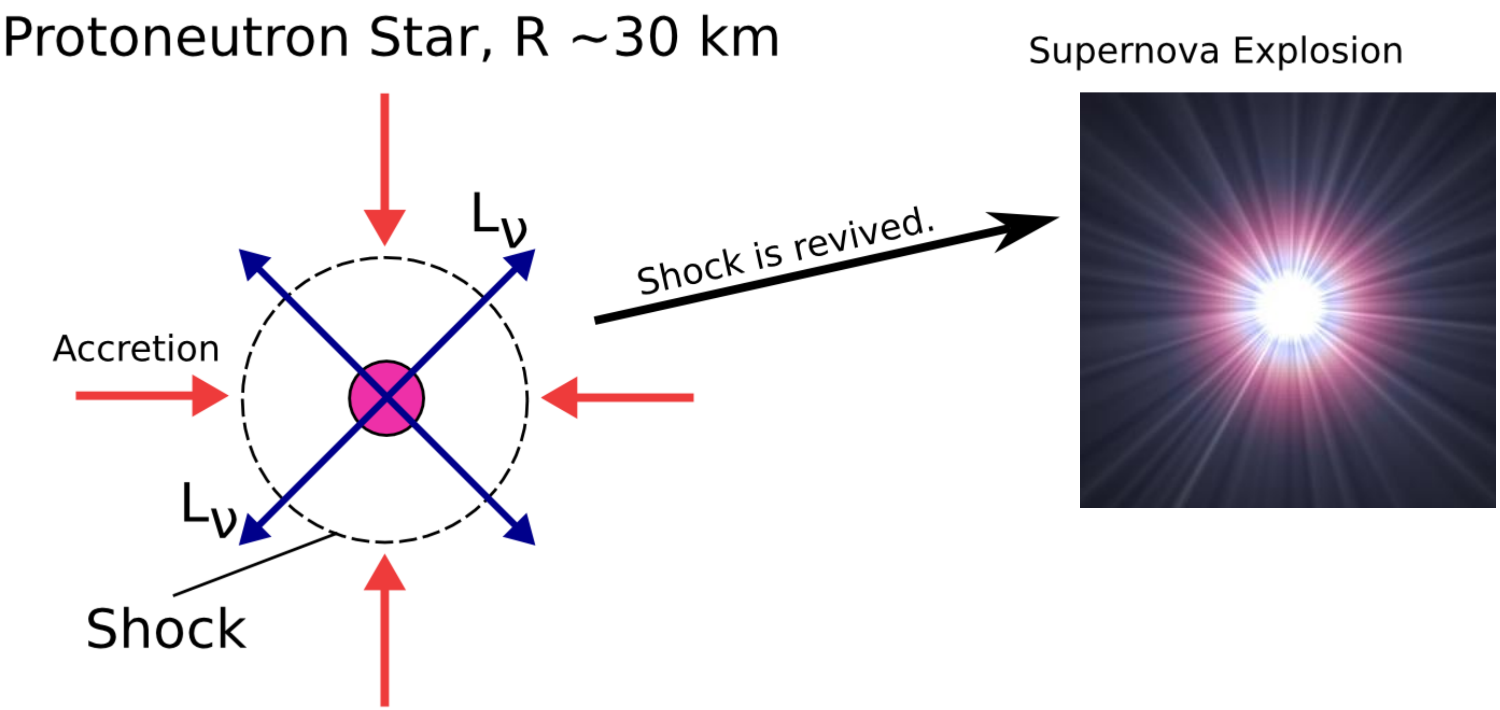


The Supernova Problem



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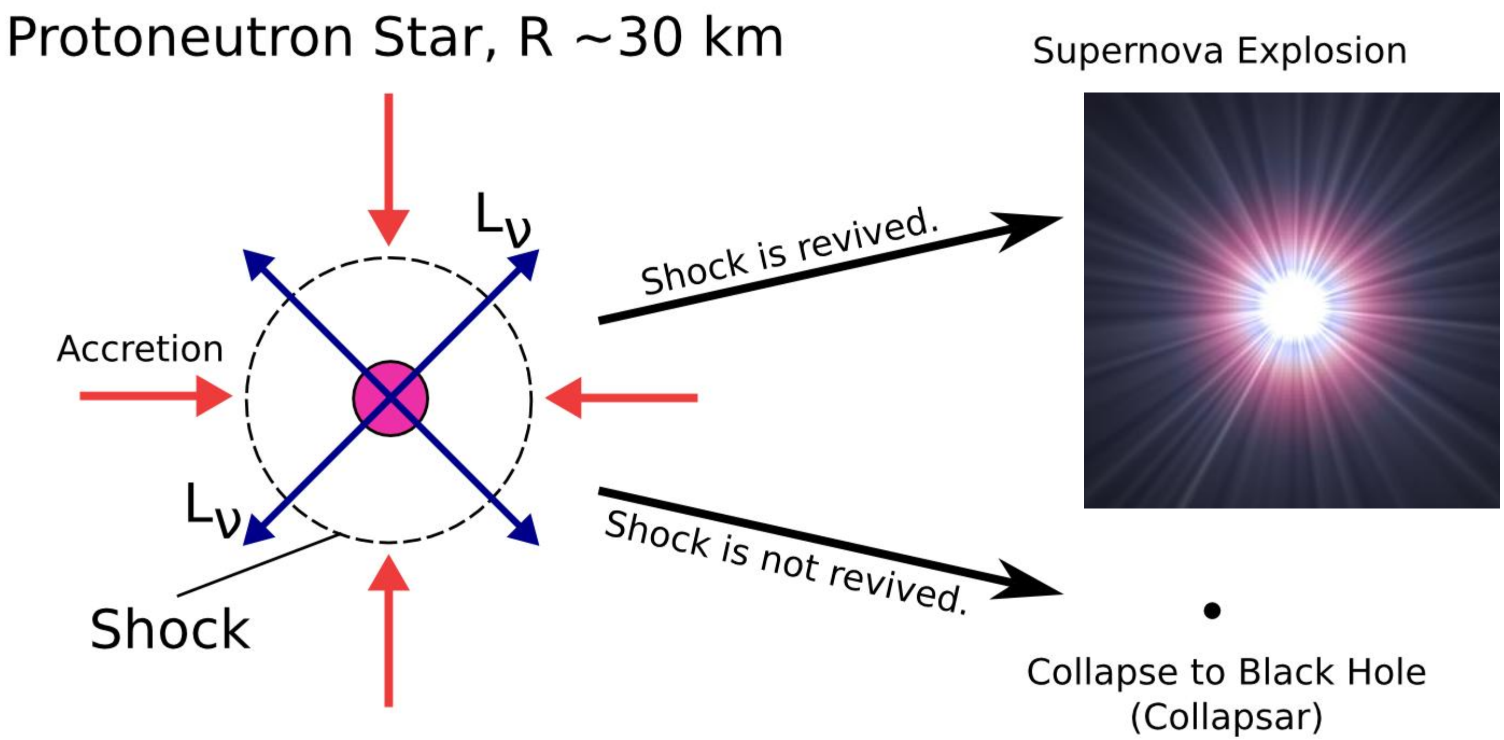
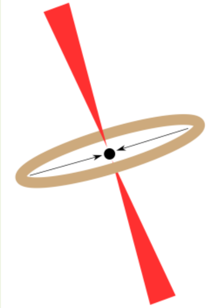
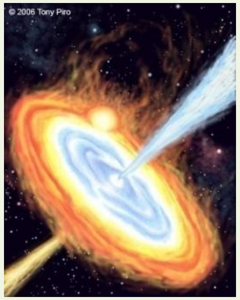


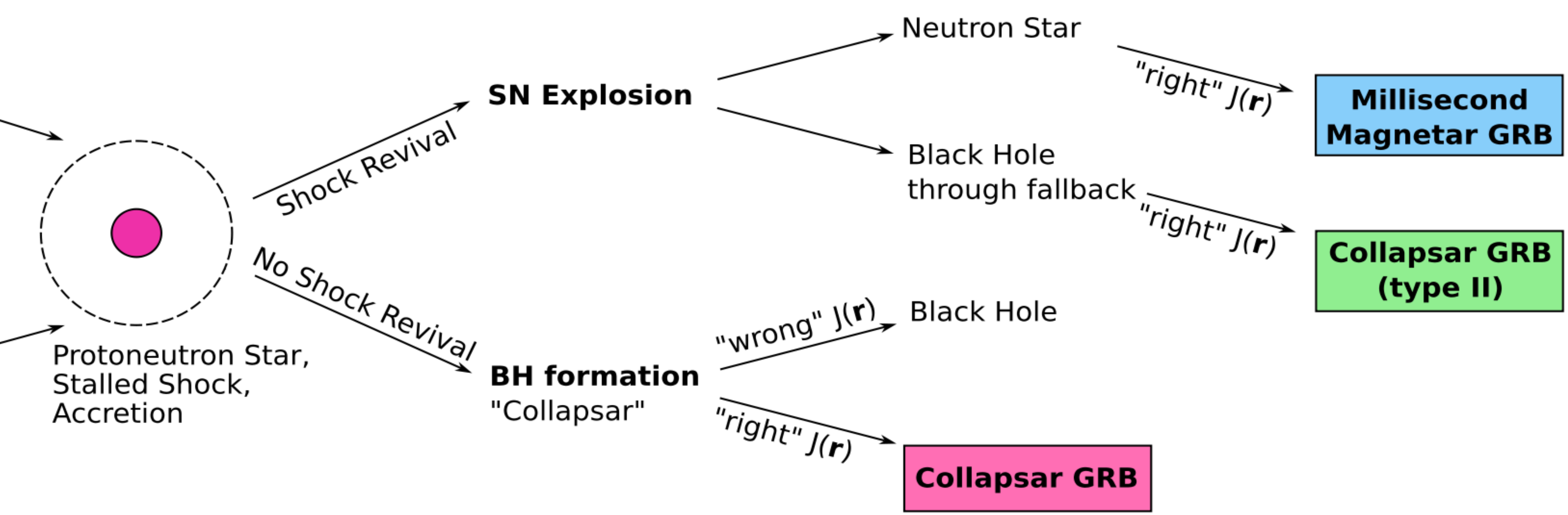
Needed: **Mechanism for Shock Revival** (The "Supernova Mechanism")



The CCSN – Long GRB Connection

[e.g., Heger et al. 2003, Woosley & Bloom 2006]





- Competing long GRB central engine scenarios:
  - (1) **Millisecond Magnetars** [e.g., Bucciantini, Thompson, Quataert, Metzger]
  - (2) **Collapsars: BH + accretion disk** [Woosley, MacFadyen and friends.]

Supernova Mechanisms

Neutrino Mechanism

[Nordhaus et al. ‘10, Marek&Janka’09]

Magnetorotational Mechanism

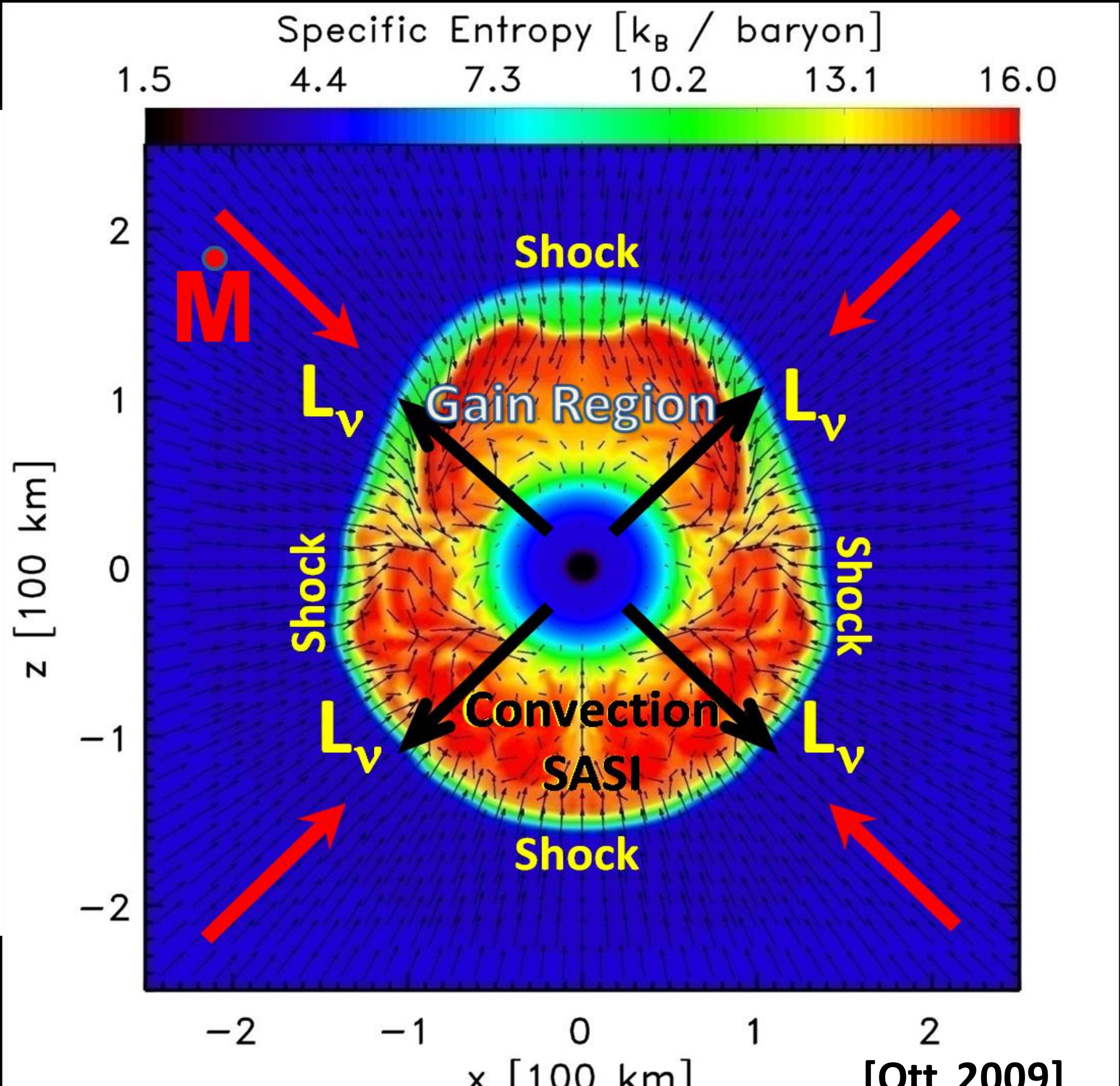
[Burrows et al. ’07]

Acoustic Mechanism

[Burrows et al. ’06,’07, Ott et al. ‘06, but: Weinberg & Quataert ‘08]

Phase-Transition-Induced Mechanism

[Fischer et al. ‘09]



[Ott 2009]

Supernova Mechanisms

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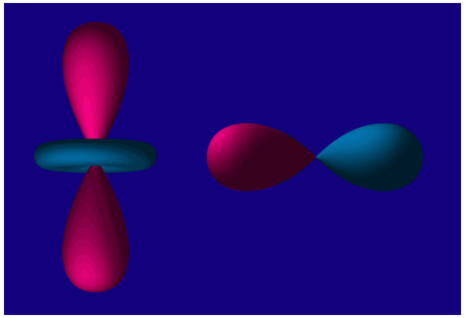
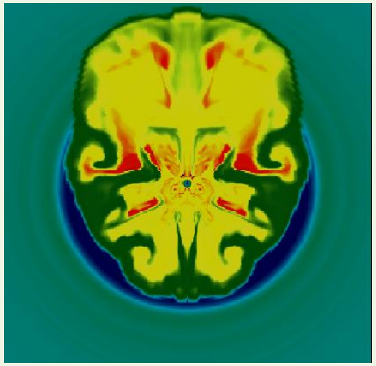
Require and Involve Multi-D dynamics -> Gravitational Waves

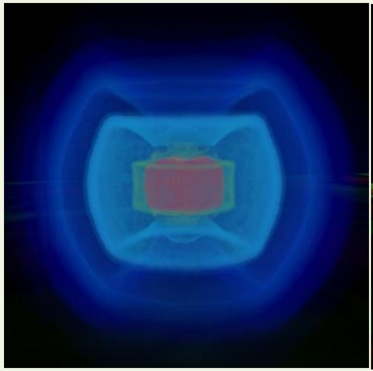


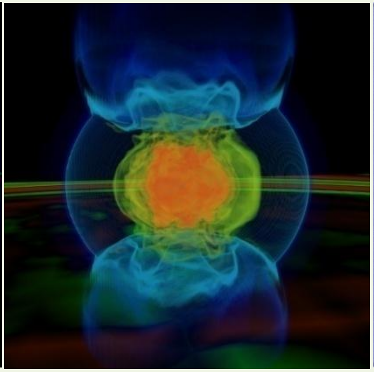
GW Emission Processes in Core-Collapse SNe

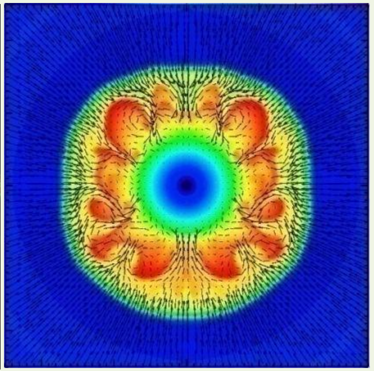
- Rotating core collapse and core bounce
- Dynamical 3D rotational instabilities
- Postbounce convection and SASI
- Protoneutron star pulsations
- BH formation
- Anisotropic neutrino emission
- Aspherical outflows
- Magnetic stresses

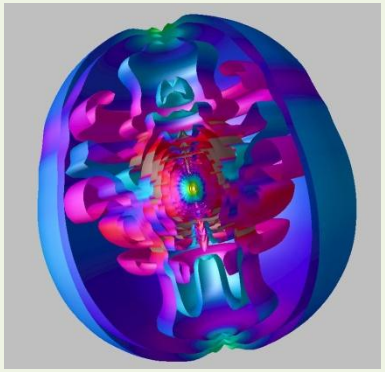
Reviews:
Fryer & New 2006
Kotake et al. 2006
Ott 2009

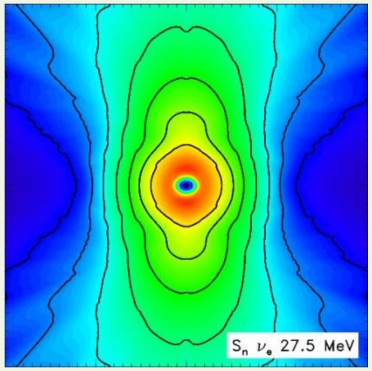












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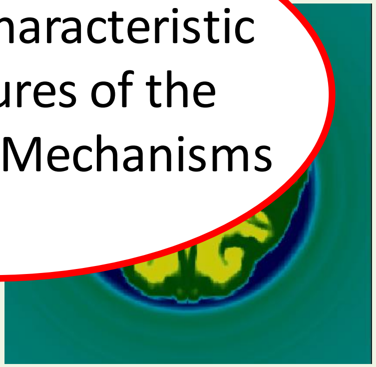
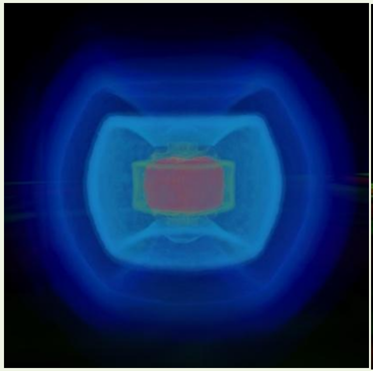
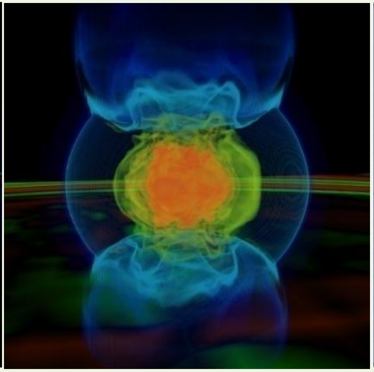
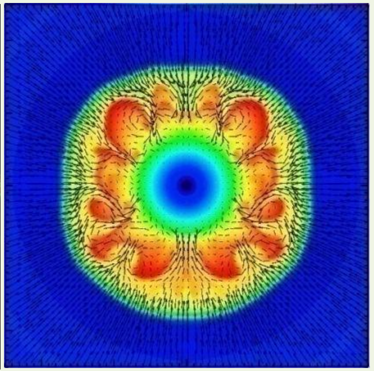
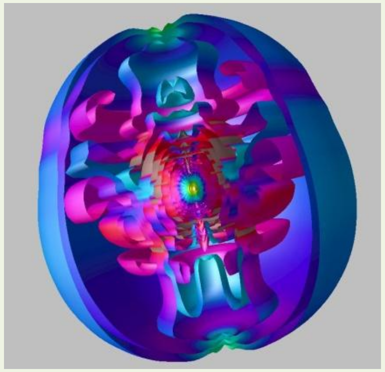
Determine characteristic GW signatures of the various CCSN Mechanisms

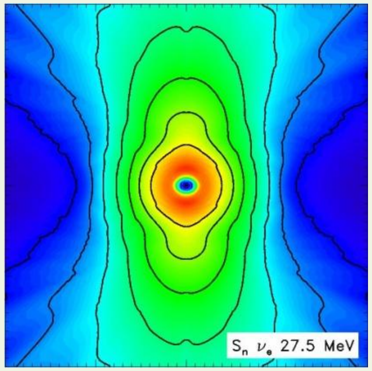












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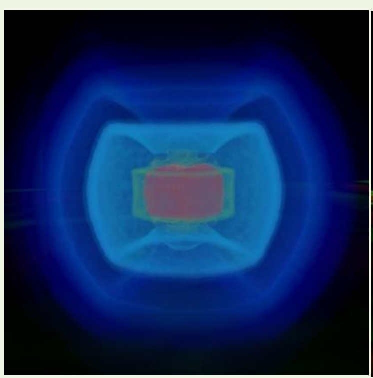
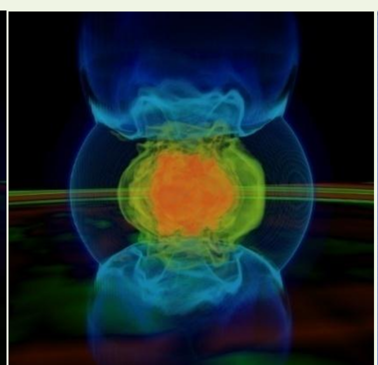
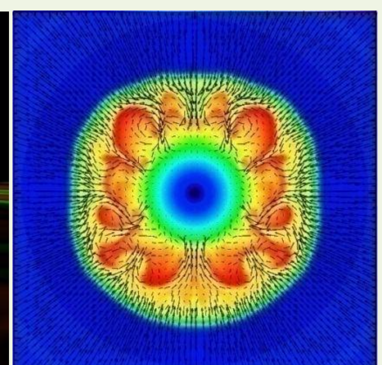
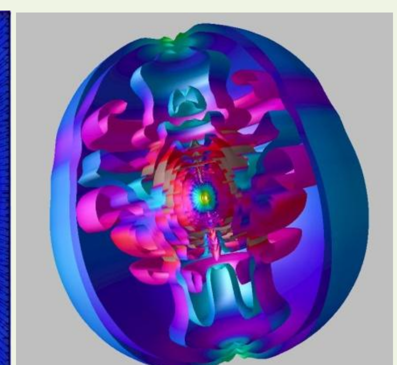
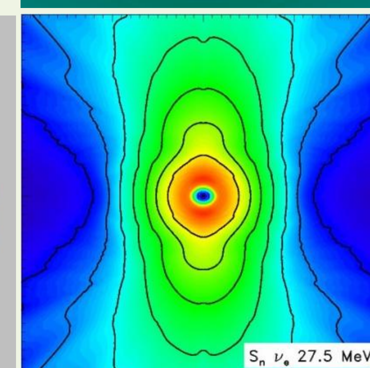




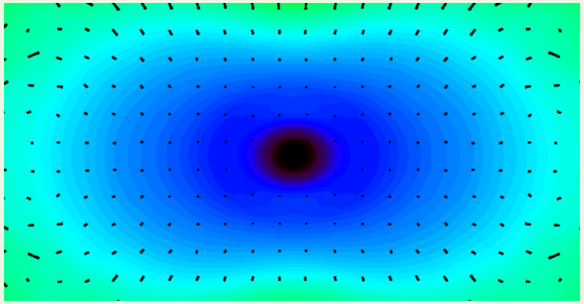




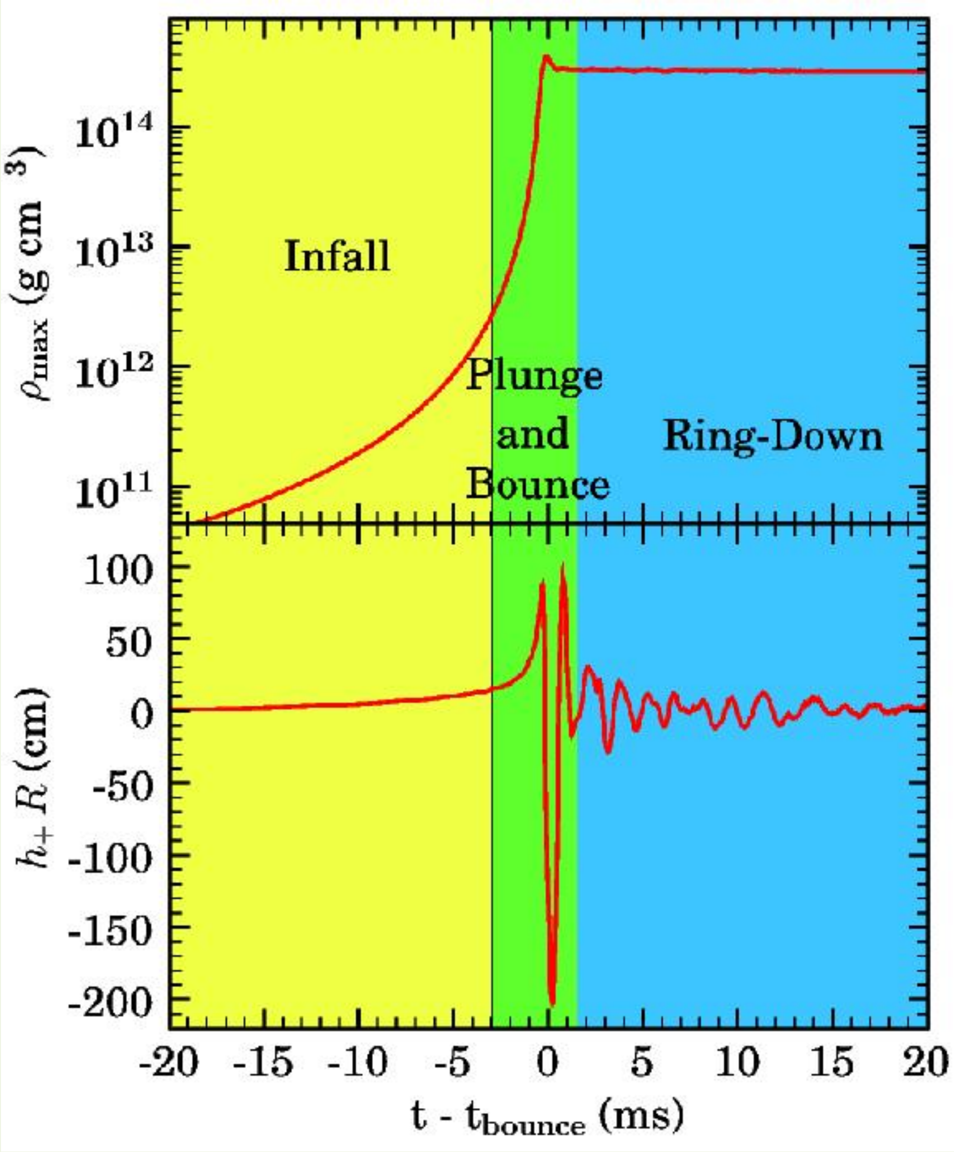


Rotating Core Collapse & Bounce

- Collapse: Angular momentum conservation leads to spin up & rotational deformation of inner core.

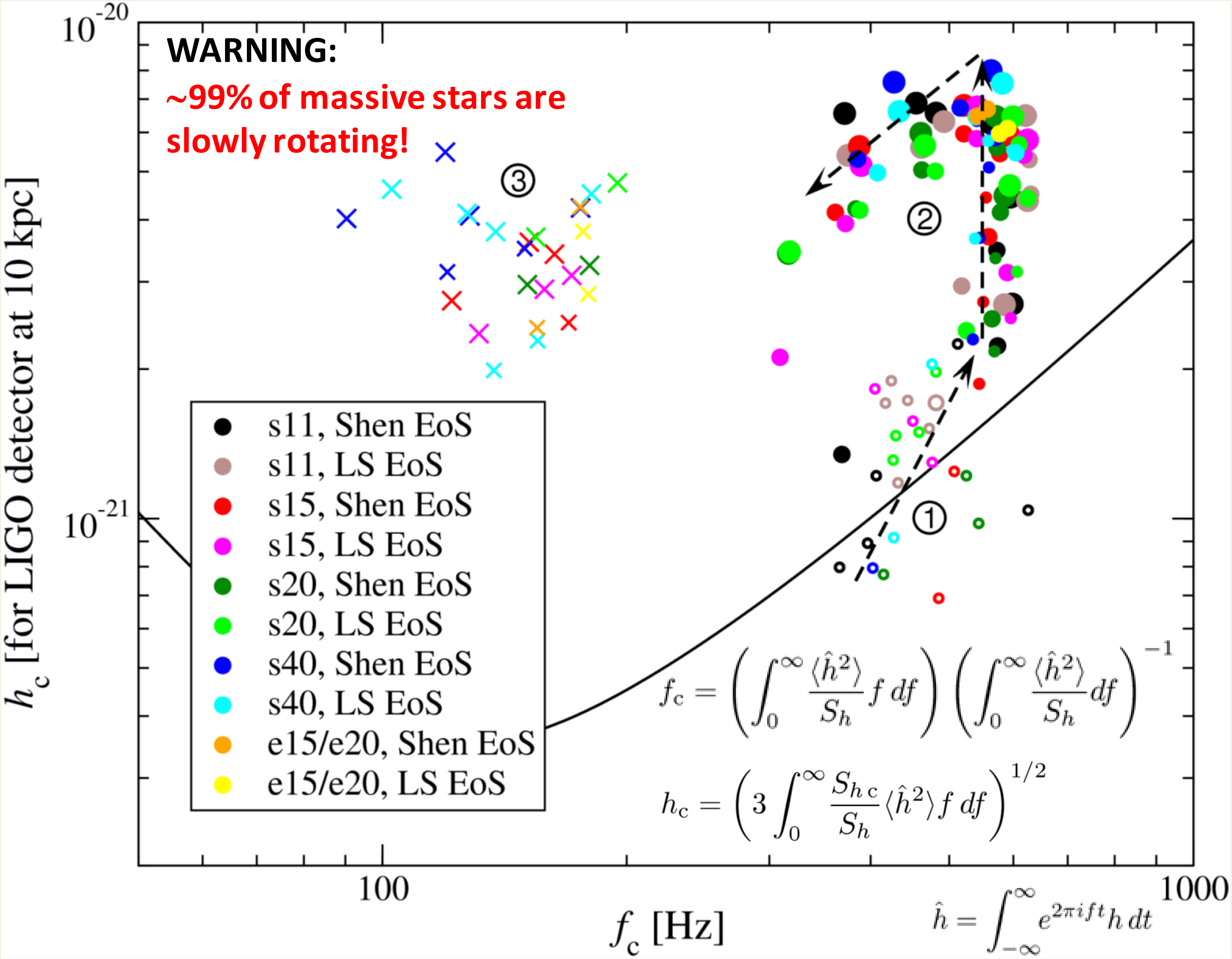


- At core bounce: Very large accelerations -> rapidly changing mass quadrupole moment.
- Most extensively studied GW emission in core collapse
- **Always axisymmetric: ONLY h_+**
- Simplest GW emission process: **Rotation** + **Gravity** + **Stiffening of EOS**.



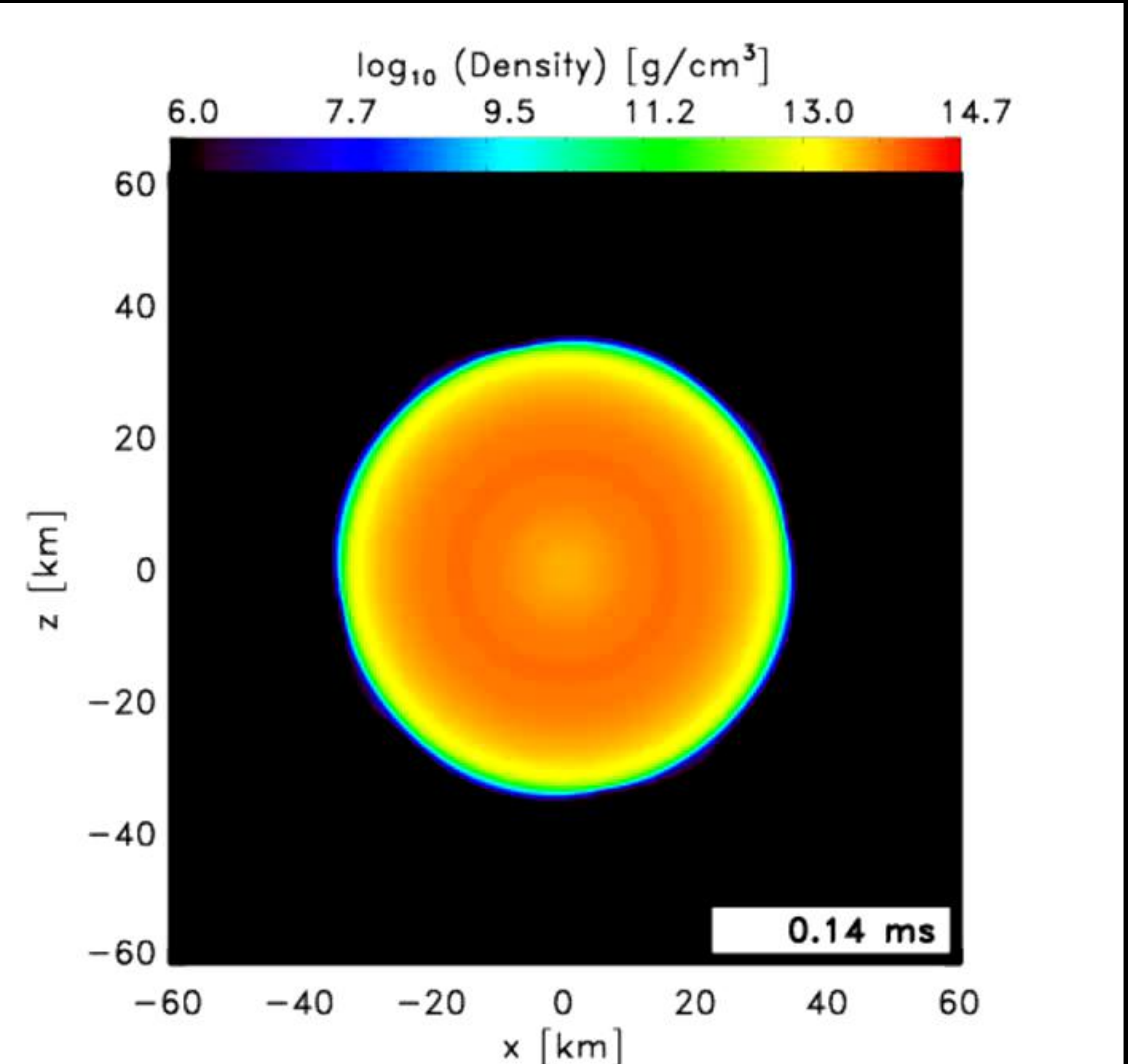
Extensive GR Model Set (2D)

[Dimmelmeier, Ott, Marek, and Janka 2008, Ott 2008, Dimmelmeier et al. 2007ab, Ott et al. 2007]



PNS Spin and Rotational Instabilities

[Dimmelmeier et al. 2008, Ott et al. 2007, Ott et al. 2006]

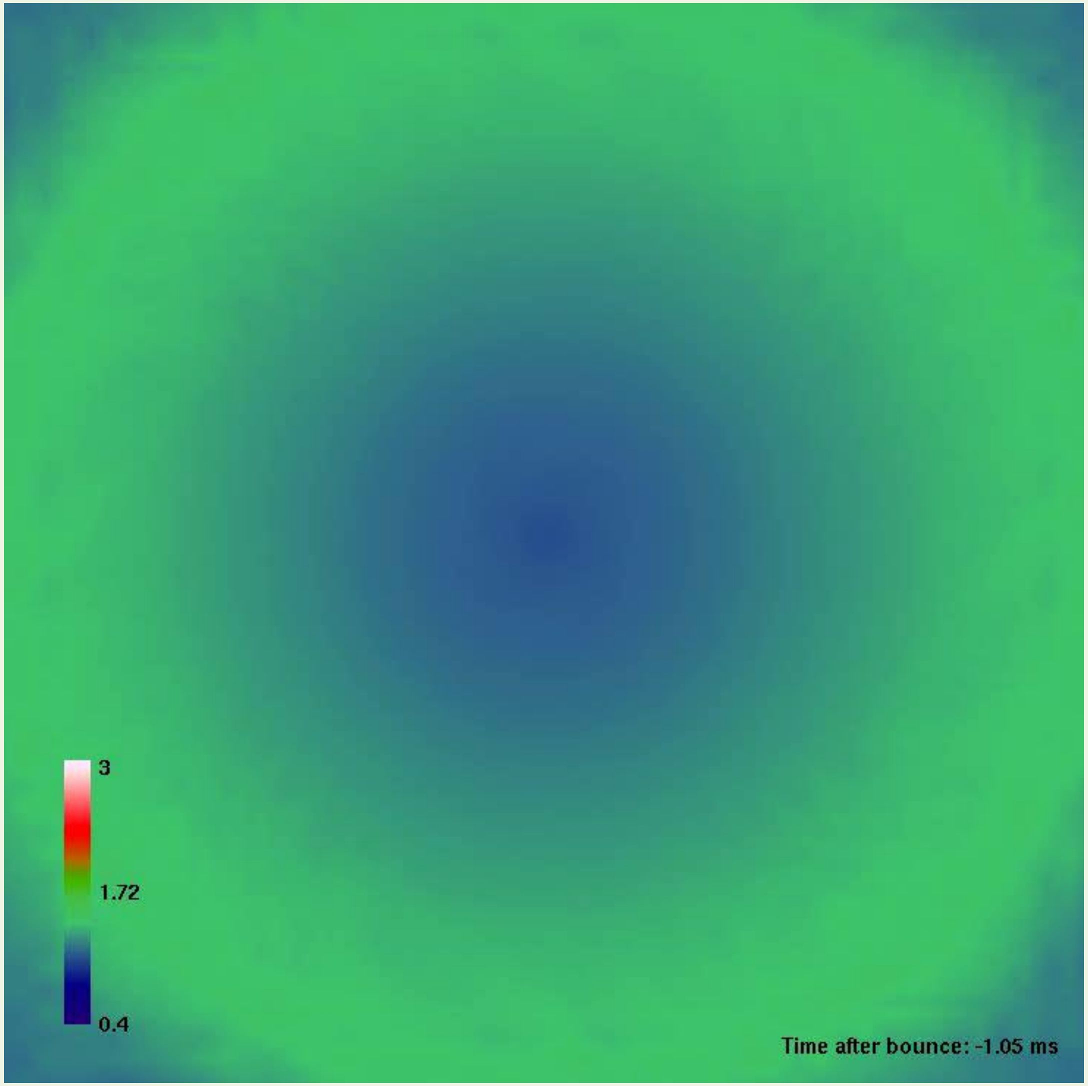


[Ott et al. 2009 in prep.]

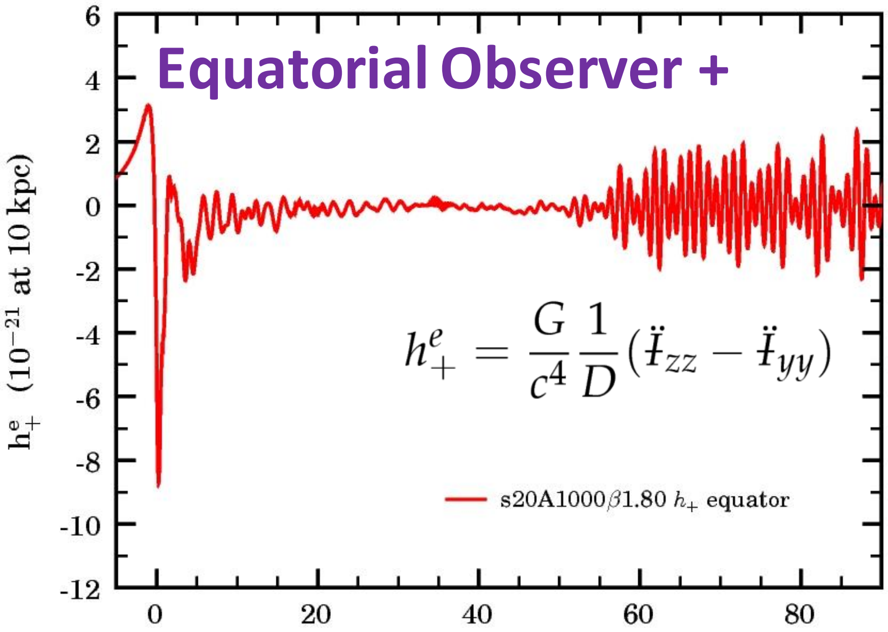
- **High T/|W| instabilities**. Azimuthal modes $\propto \exp(im\varphi)$. m=2 "bar-modes" $(T/|W|)_{dynamical} = 0.27$, $(T/|W|)_{secular} \approx 0.14$.
- Numbers hold roughly in GR and moderate differential rotation. [e.g., Baiotti et al. 2007]
- Caveat: Most (99%) PNS unlikely to spin sufficiently fast!

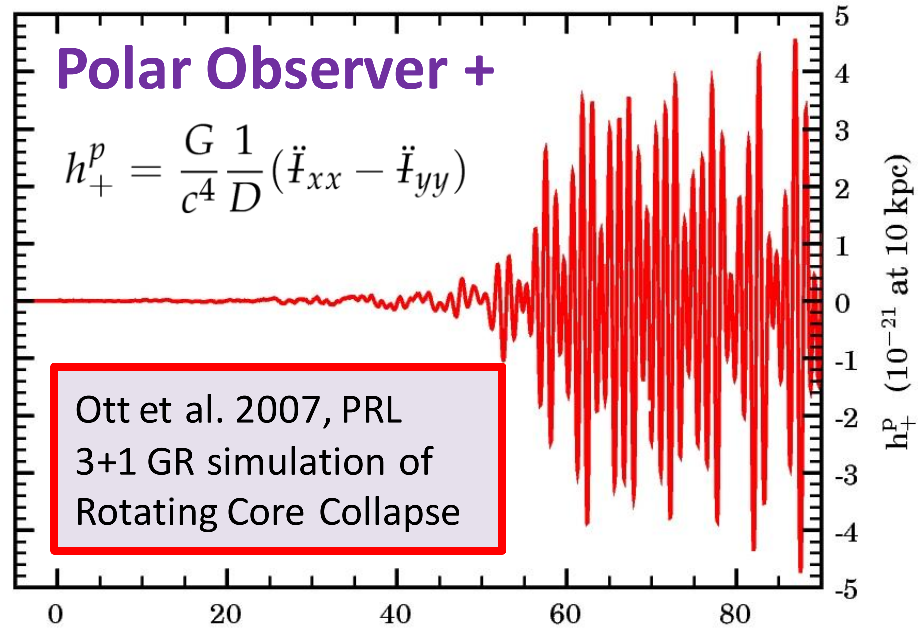
Rotational Instability at low T/|W|

- T/|W| at bounce: ~0.11. 3+1 GR collapse simulation.
- Dominant m=1 mode; m={2,3} modes mixed in (radial & temporal variation).
- Mechanism:
  Corotation instability
  Resonance of unstable mode with background fluid at corotation point(s).

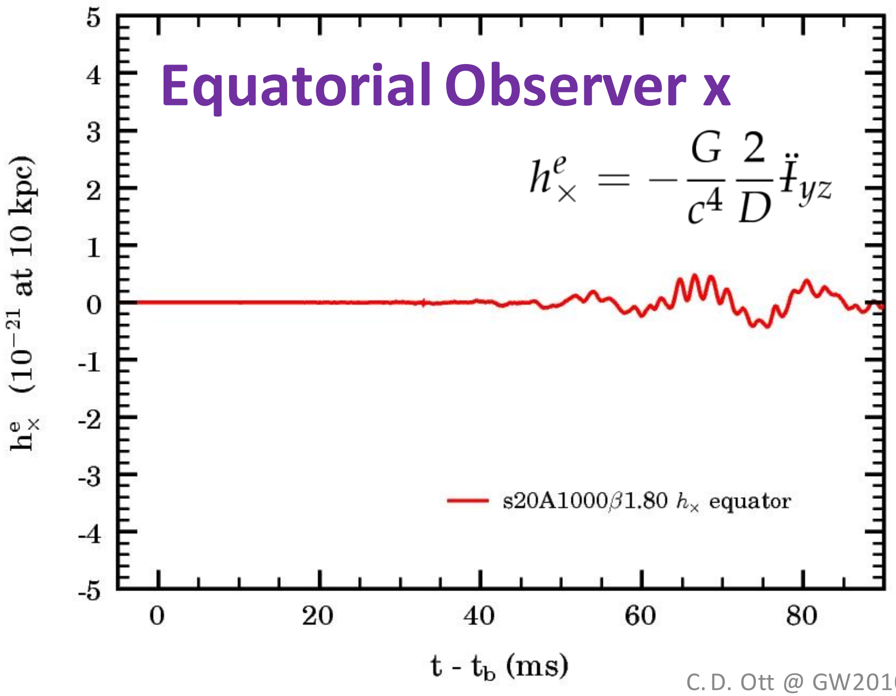


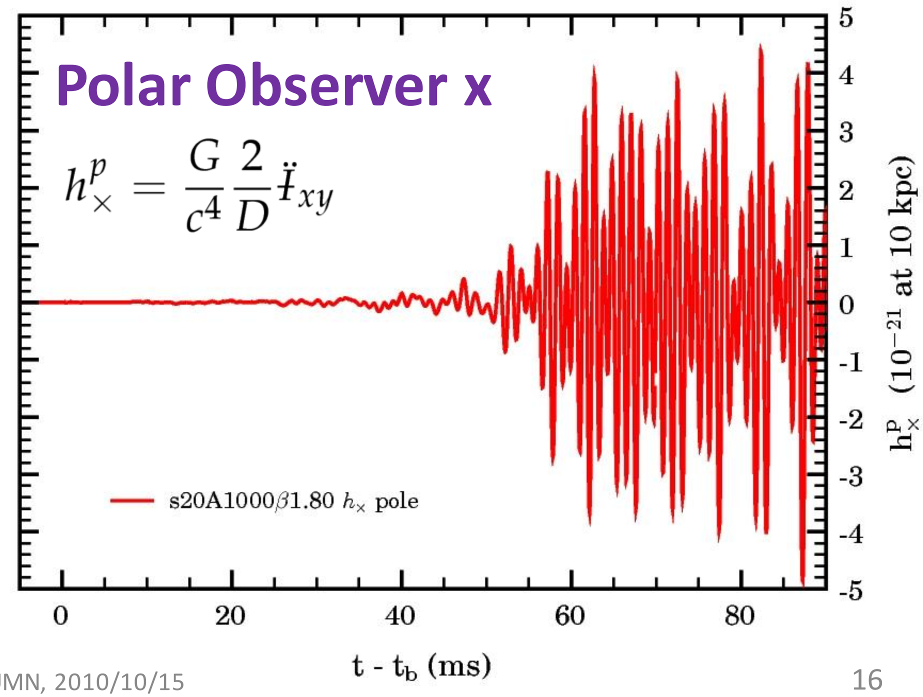
[Ott et al. 2007 PRL, 3+1 GR simulation]

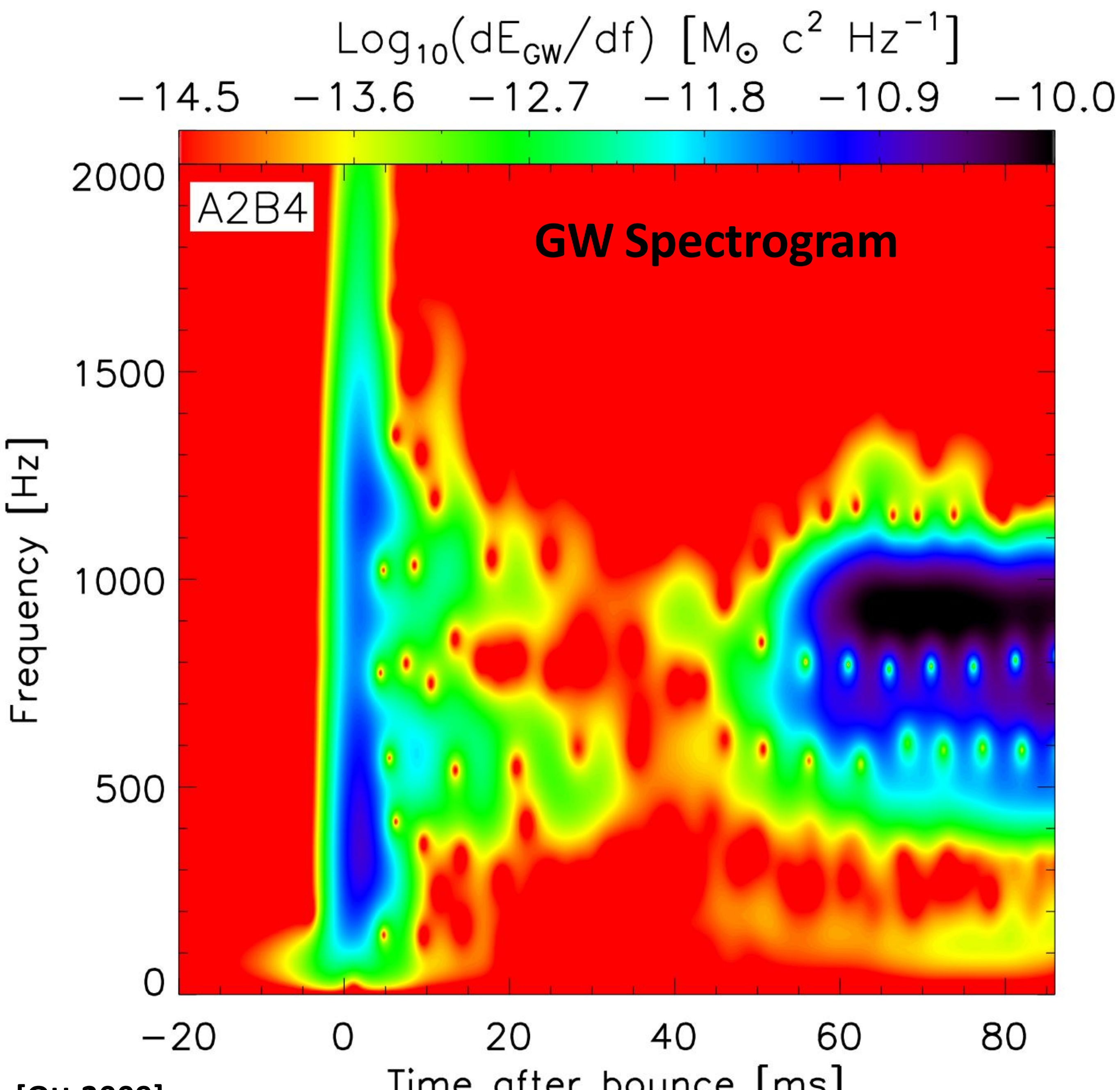




GW Emission, Model s20A2B4







Log10(dE_GW/df) [M⊙ c² Hz⁻¹]
−14.5 −13.6 −12.7 −11.8 −10.9 −10.0
A2B4
GW Spectrogram
Frequency [Hz]
2000
1500
1000
500
0
−20
0
20
40
60
80
Time after bounce [ms]

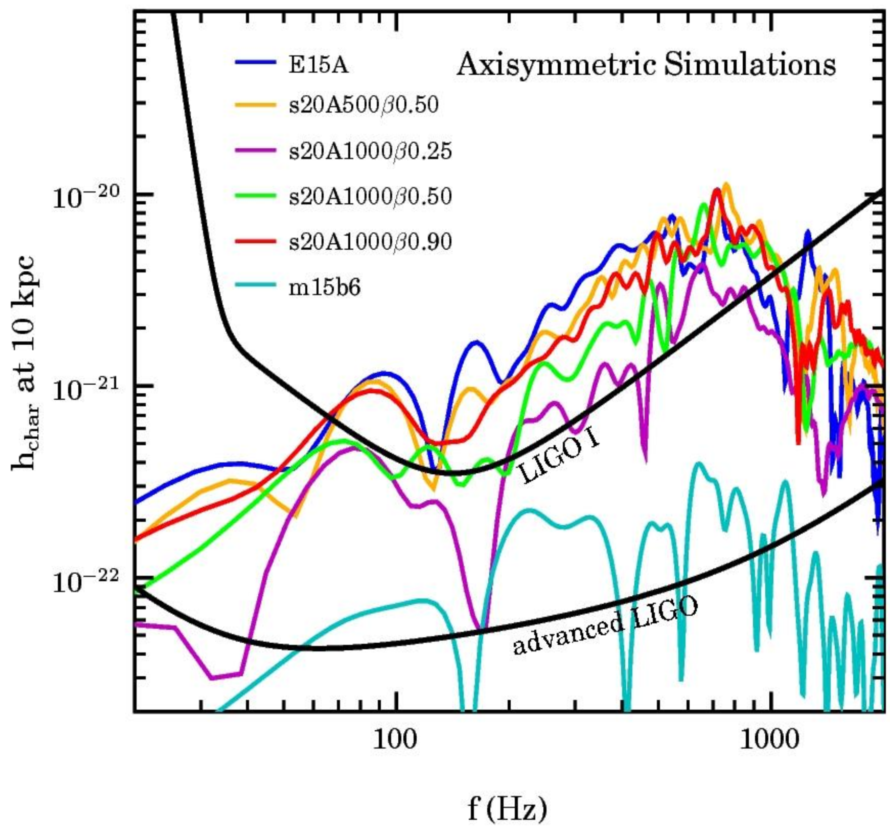
[Ott 2009]

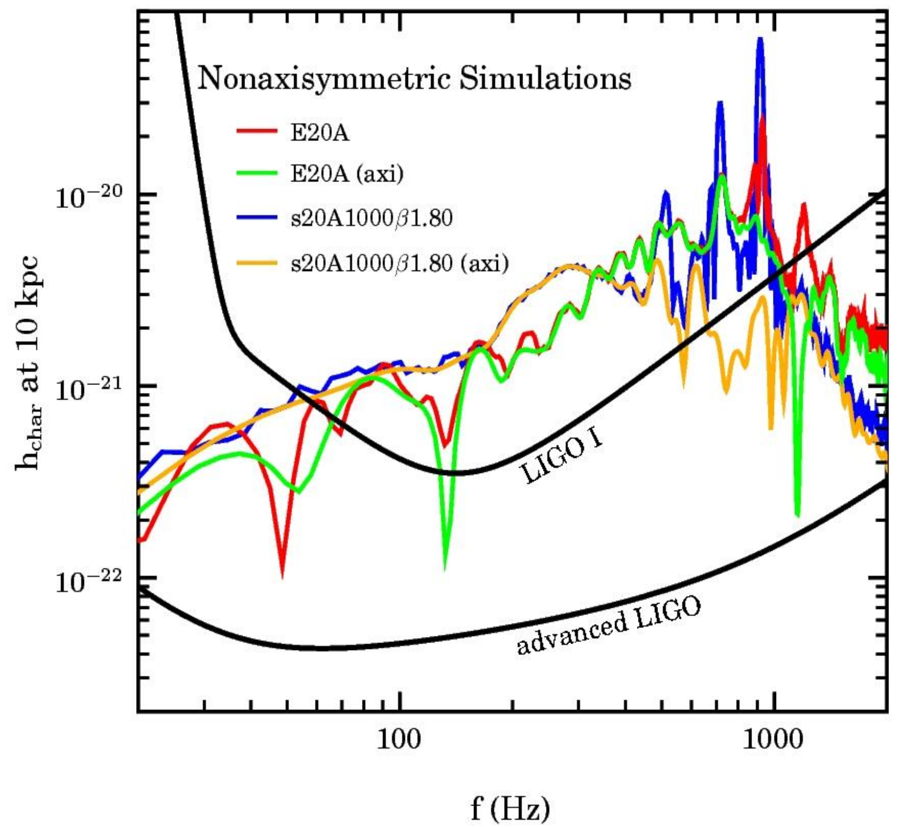
GW Emission vs. Detector Noise

$$h_{\rm char} = \sqrt{\frac{2}{\pi^2}\frac{1}{D^2}\frac{G}{c^3}\frac{dE_{\rm GW}}{df}}$$

$$S/N = \sqrt{\int_0^\infty d\ln f\ \frac{h_{\rm char}^2}{h_{\rm rms}^2}}$$

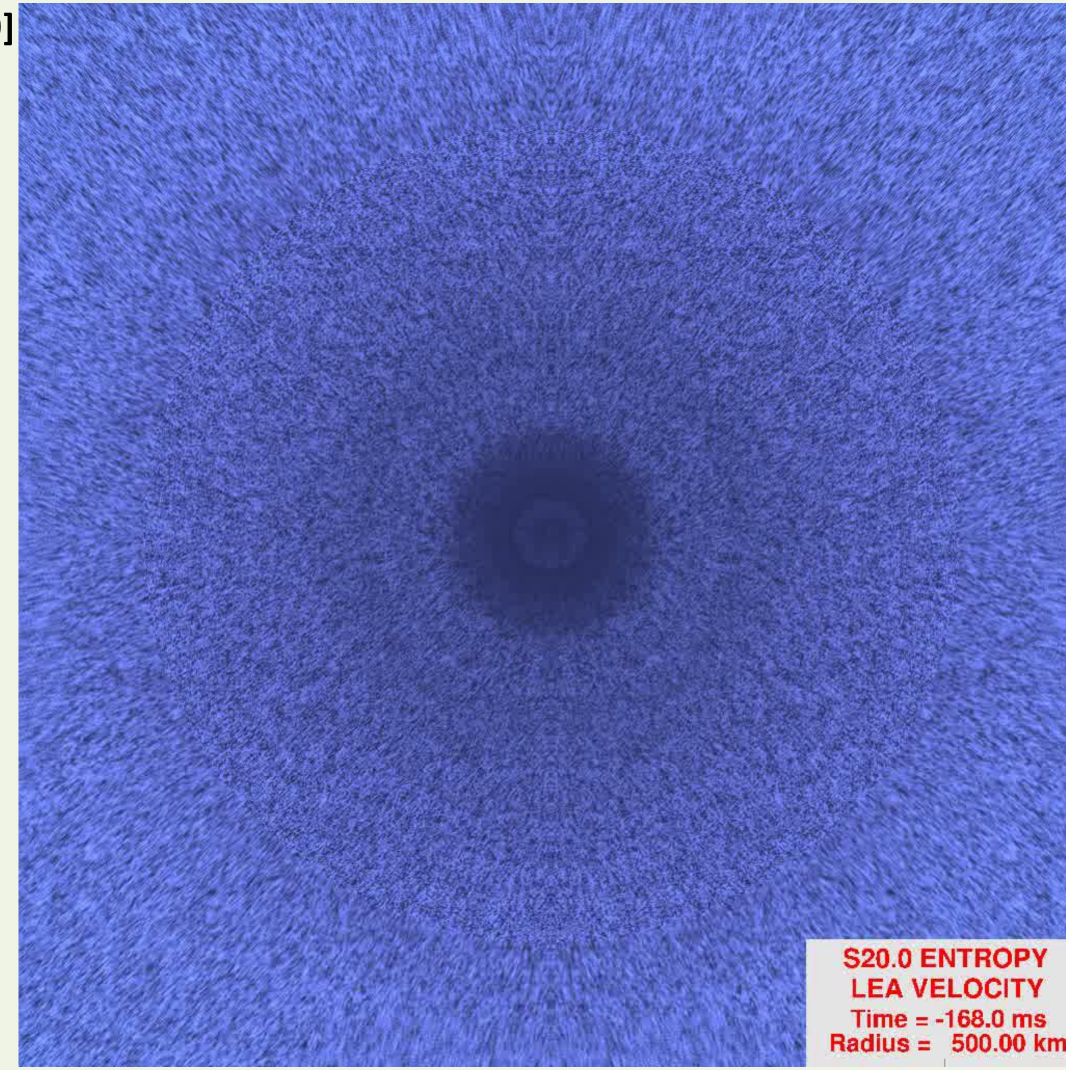
$$h_{\rm rms} = \sqrt{f S(f)}$$





GWs from Convection & the Standing Accretion Shock Instability

[Marek et al. '09, Murphy et al. '09, Yakunin et al. '10]

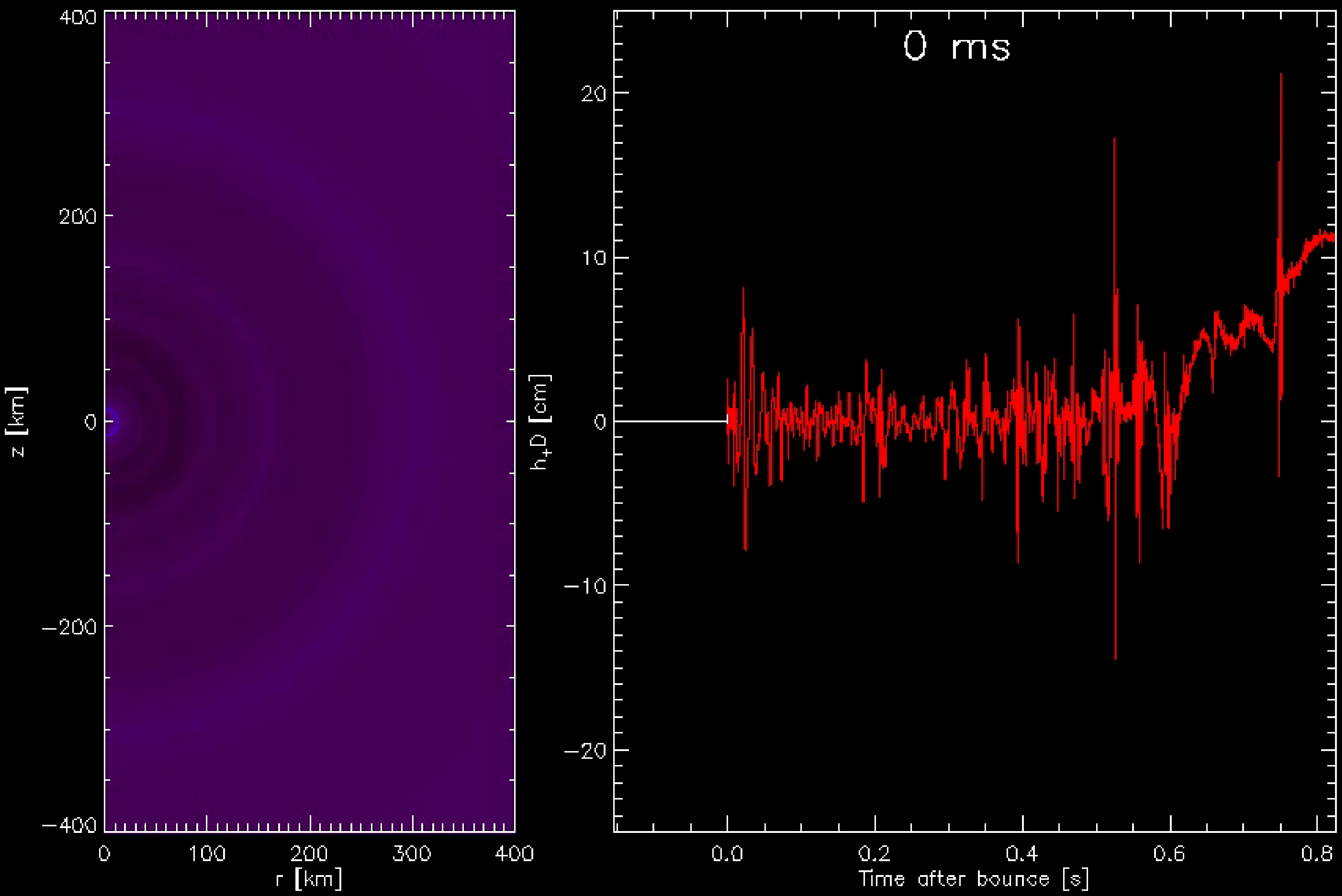


Dominant Multi-D Dynamics:

- Convection/Turbulence in the **protoneutron star** (PNS; $\tau > \sim 10$s)
- Convection/Turbulence in the **postshock region** ($\tau < 1$s)
- Standing accretion shock instability (**SASI**; $\tau < 1$s**)**

Expected GW Signal:

- Broadband
- Random polarization
- Low amplitude: $O(10^{-23} – 10^{-22})$ at 10 kpc

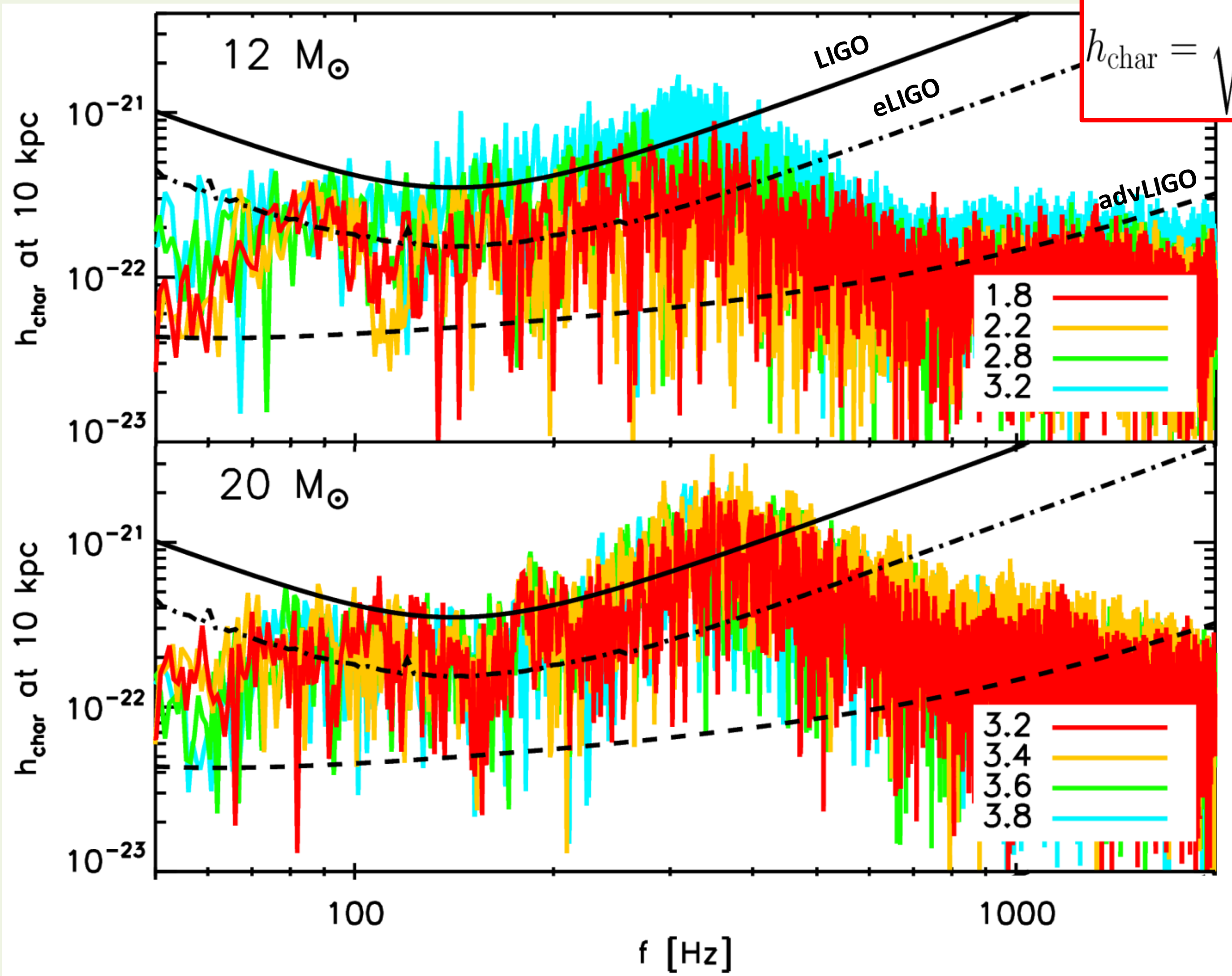


[Murphy, Ott and Burrows 2009]

Detectability; Dependence on Progenitor & ν-Luminosity

[Murphy, Ott & Burrows 2009]

$$h_{\rm char} = \sqrt{\frac{2}{\pi^2}\frac{1}{D^2}\frac{G}{c^3}\frac{dE_{\rm GW}}{df}}$$

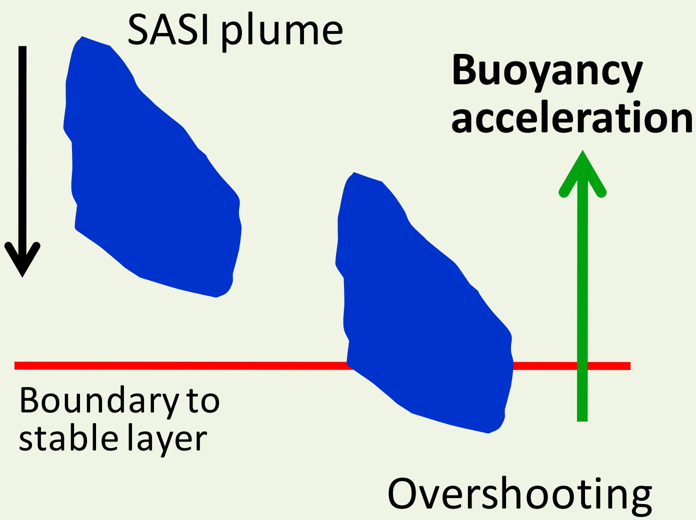


- **More massive progenitor** -> higher accretion rate **-> greater L_ν / heating required and longer time to explosion** -> **stronger GW emission**.

Understanding the Characteristic GW Frequencies

[Murphy, Ott & Burrows 2009]

- **Assumption**: Strongest GW emission comes from SASI a downflow plume that is decelerated at the PNS surface.
- Use convection theory to study behavior in linear limit.



Brunt-Väisälä:

$$N^2 = \left(\frac{GM_r}{r^3}\right)\left(\frac{1}{\Gamma_1}\frac{d\ln P}{d\ln r} - \frac{d\ln\rho}{d\ln r}\right)$$

$N^2 > 0$: stable, $N^2 < 0$: unstable

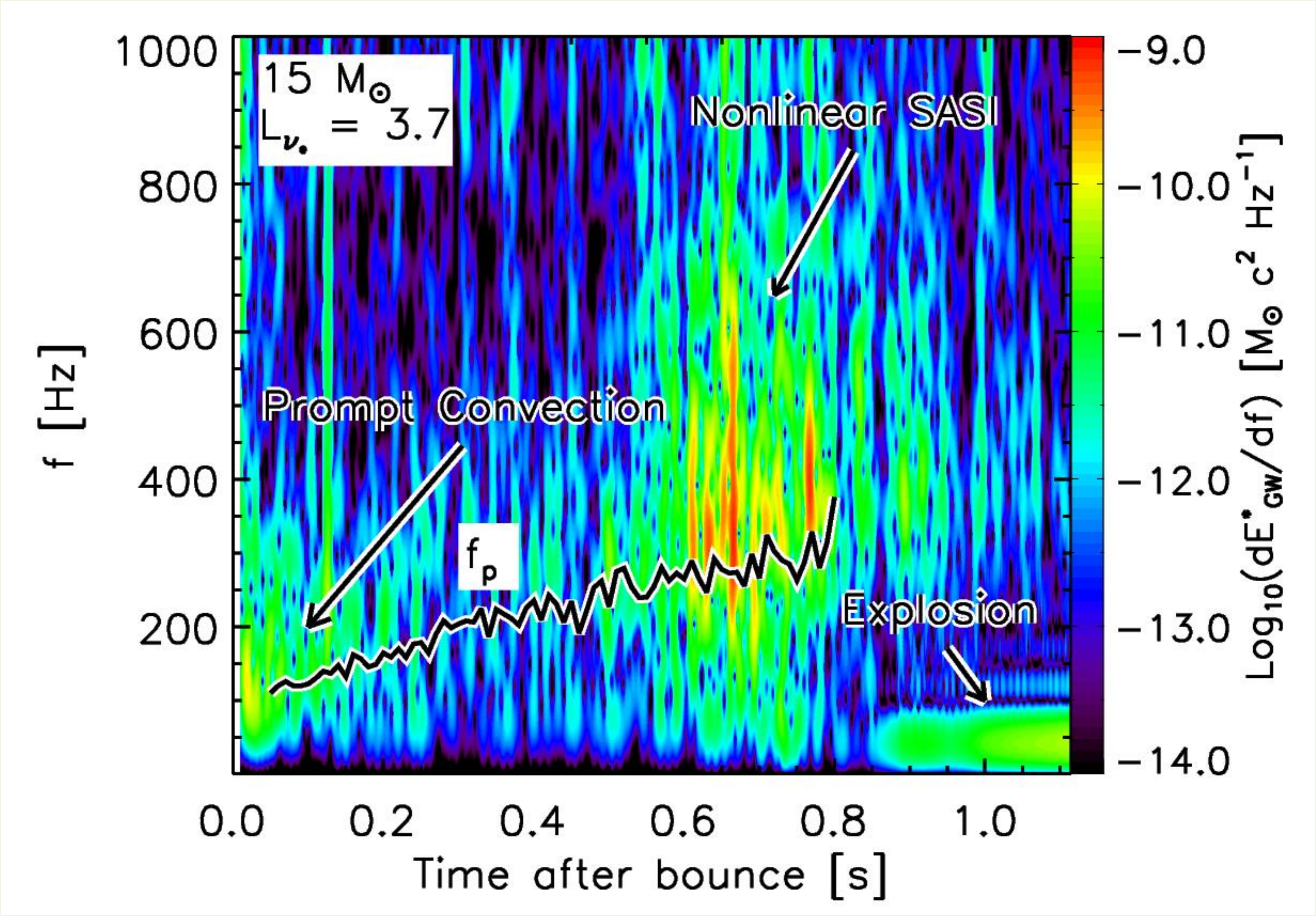
- Characteristic frequencies: Obtained through integration of buoyancy acceleration and analytic model for turning point:

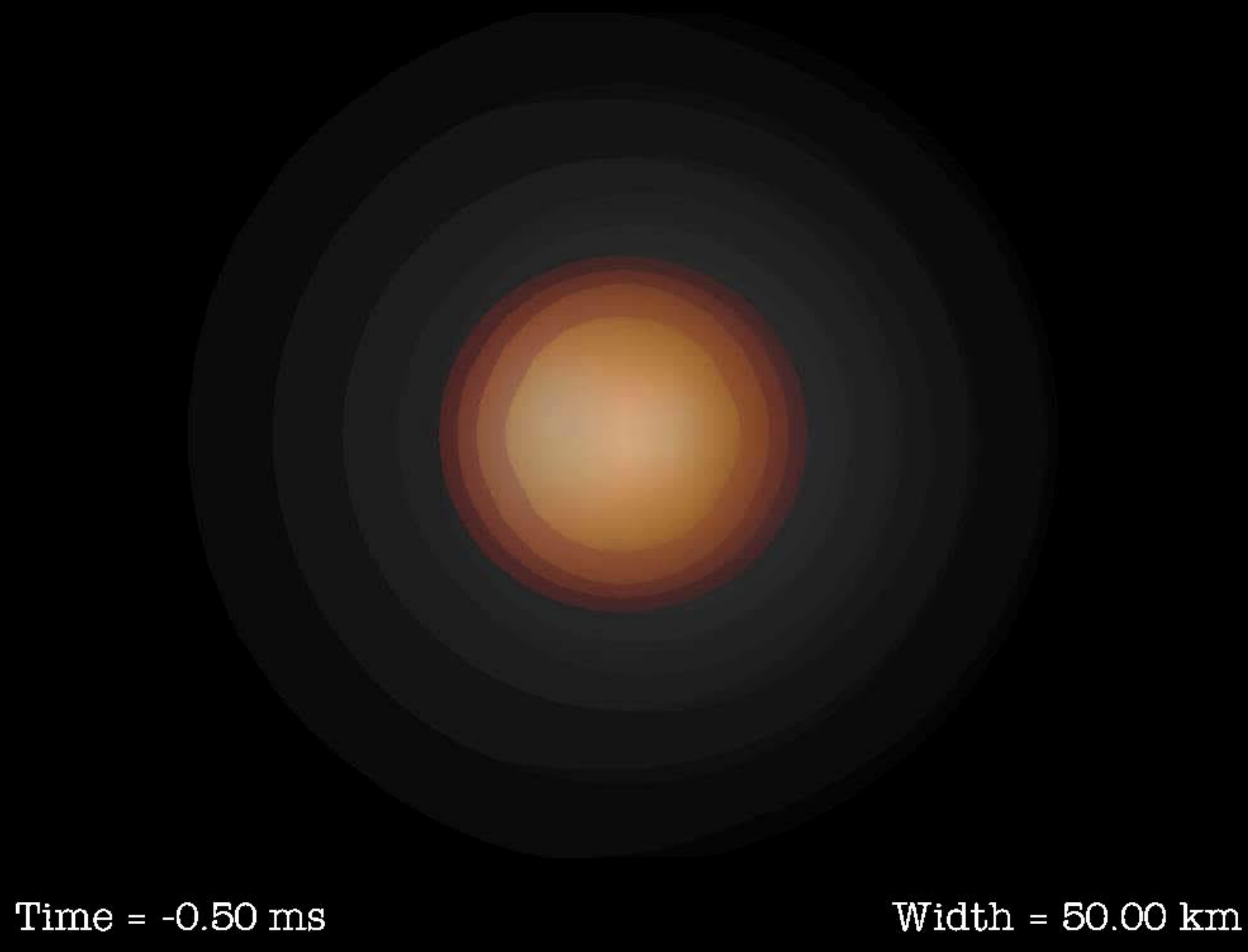
$$f_p = 1/(2\pi t_p)$$

$$f_p \sim \frac{N}{2\pi}$$

GW Time-Frequency Evolution

[Murphy, Ott & Burrows 2009]

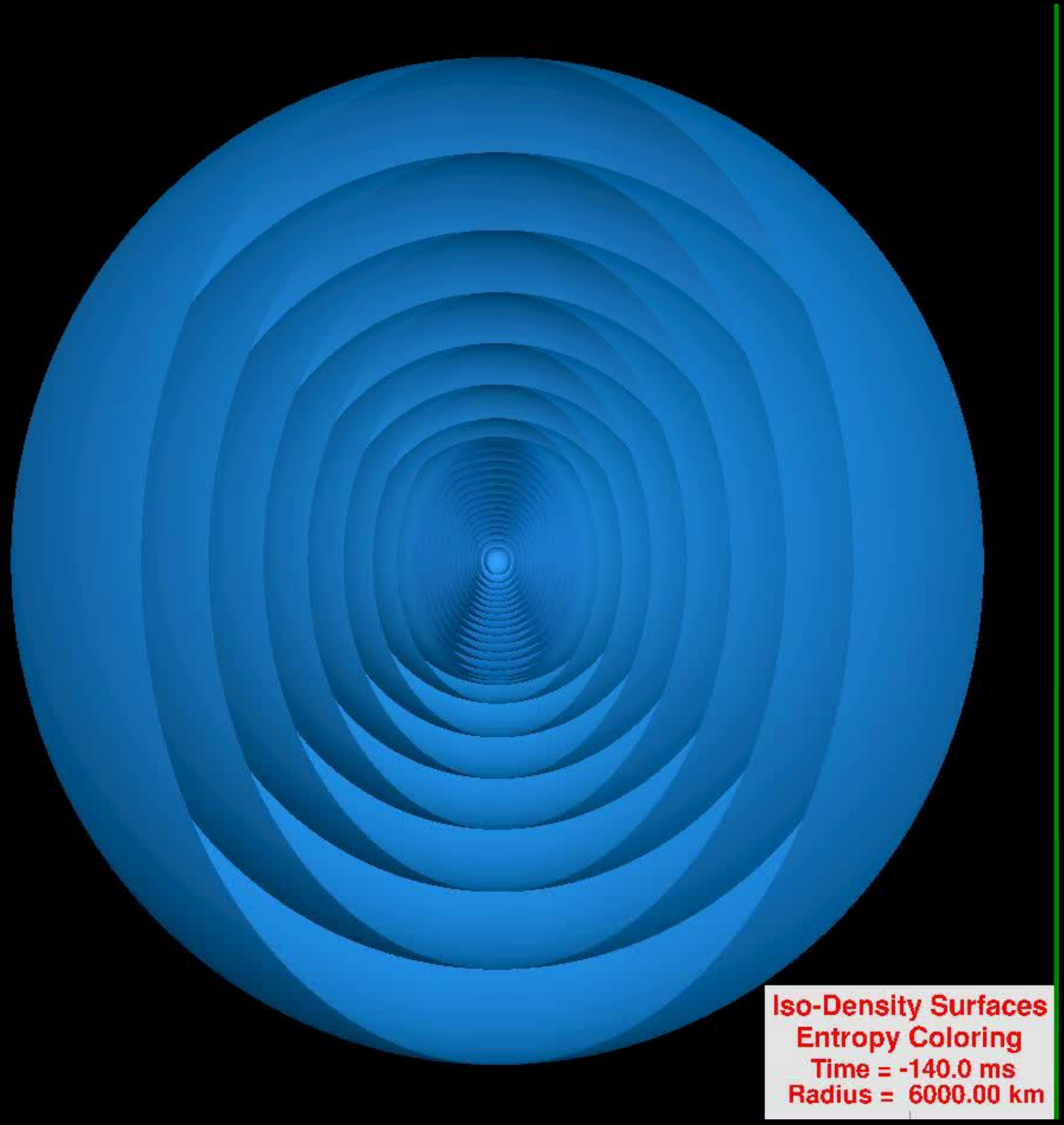




PNS core oscillations, “Acoustic Mechanism” -> Burrows et al. 2006, 2007; Ott et al. 2006
See also **Weinberg & Quataert 2008**.

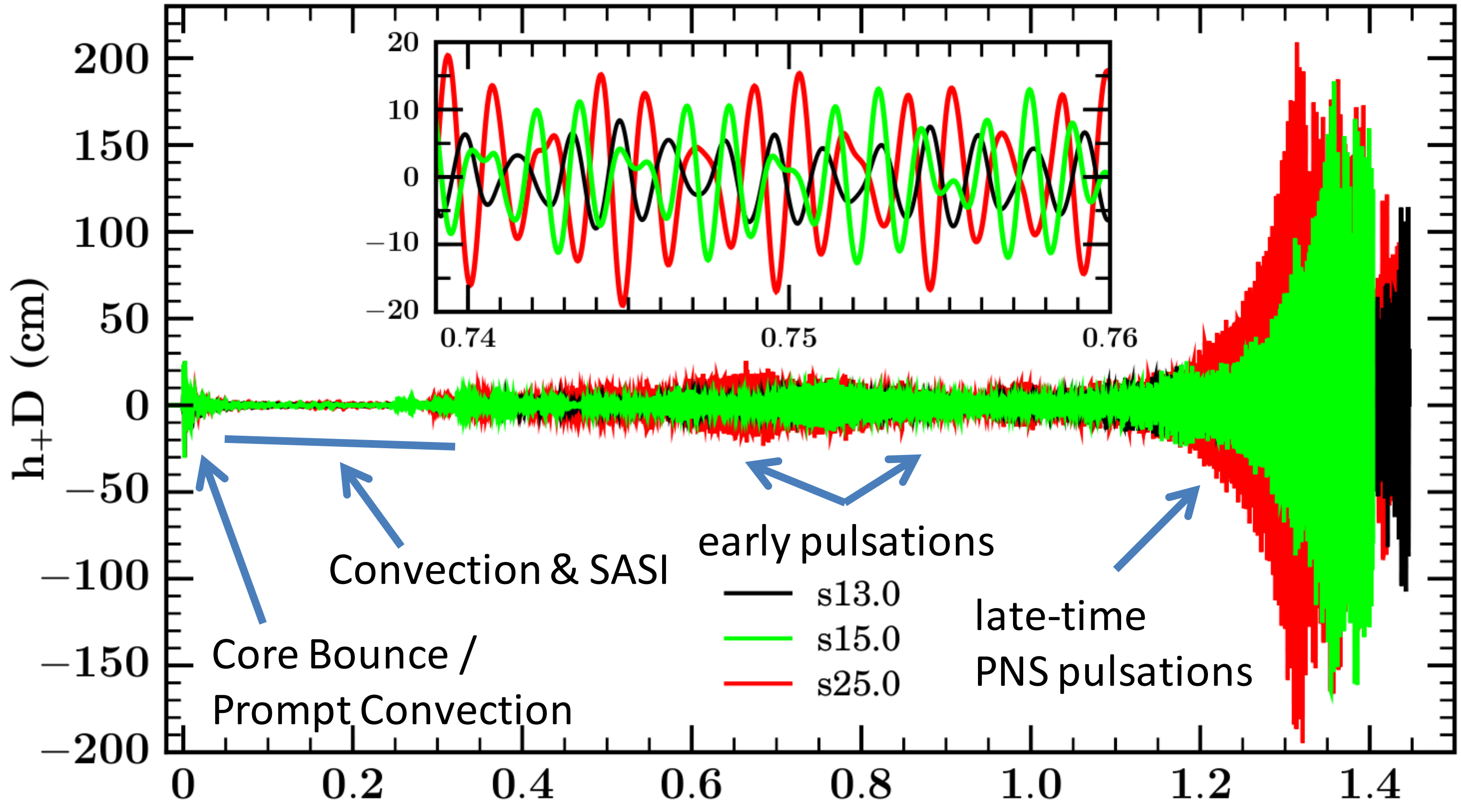
Acoustic Mechanism

[Burrows, Livne, Dessart, Ott, Murphy 2006, 2007b/c, Ott et al. 2006]



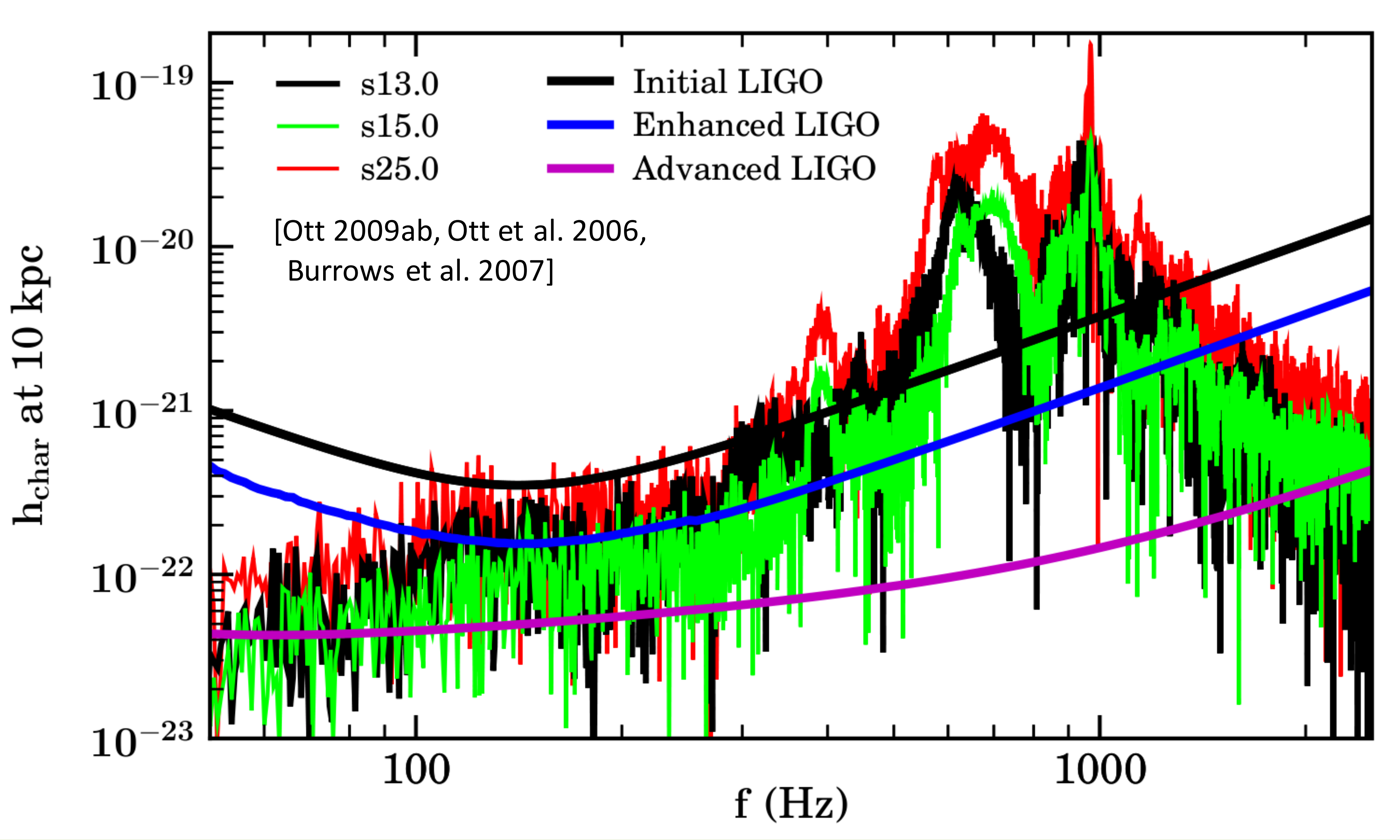
Seen by only one group!
So far unconfirmed.

GWs from PNS Core Pulsations in the Context of the Acoustic Mechanism



[Ott 2009ab, Ott et al. 2006]

GW Spectra and LIGO Sensitivity



- $E_{GW} \sim 10^{-8} - 10^{-6}\ M_{SUN}c^2$, one model $8 \times 10^{-5}\ M_{SUN}c^2$.
- Progenitor mass (= accretion rate) dependence.

Blowing up Massive Stars:
Core-Collapse SN Mechanisms

Neutrino Mechanism

Magnetorotational Mechanism

Acoustic Mechanism

Blowing up Massive Stars:
Core-Collapse SN Mechanisms

Dominant GW Emission Processes

Neutrino Mechanism → Convection and SASI.

Magnetorotational Mechanism

Acoustic Mechanism

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Dominant GW Emission Processes

Mechanism		Dominant GW Emission Processes
Neutrino Mechanism	→	Convection and SASI.
Magnetorotational Mechanism	→	Rotating core collapse & bounce, PNS rotational instabilities.
Acoustic Mechanism		

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Dominant GW Emission Processes

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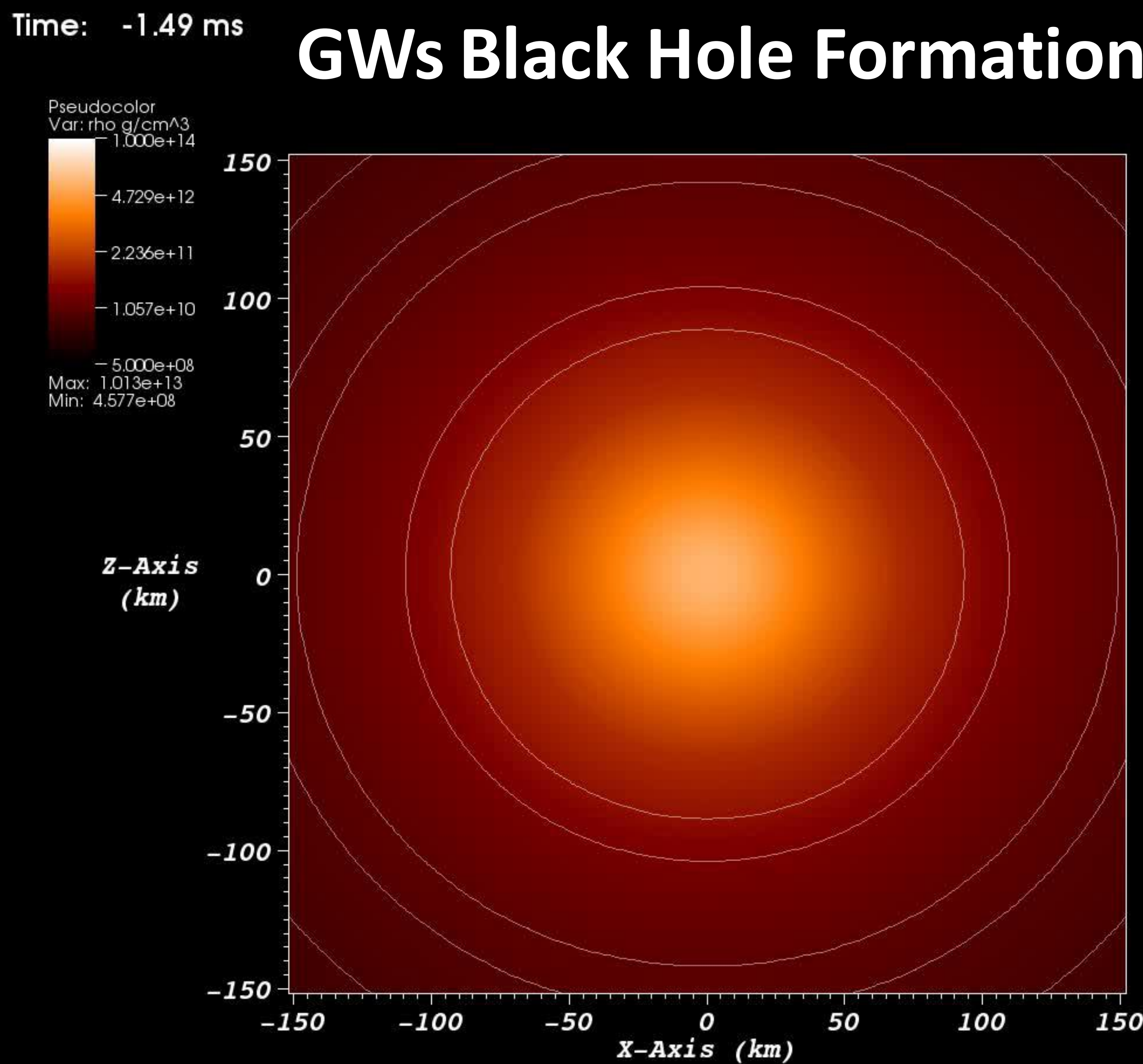
Magnetorotational Mechanism	→	Rotating core collapse & bounce, PNS rotational instabilities.
Acoustic Mechanism	→	PNS pulsations.

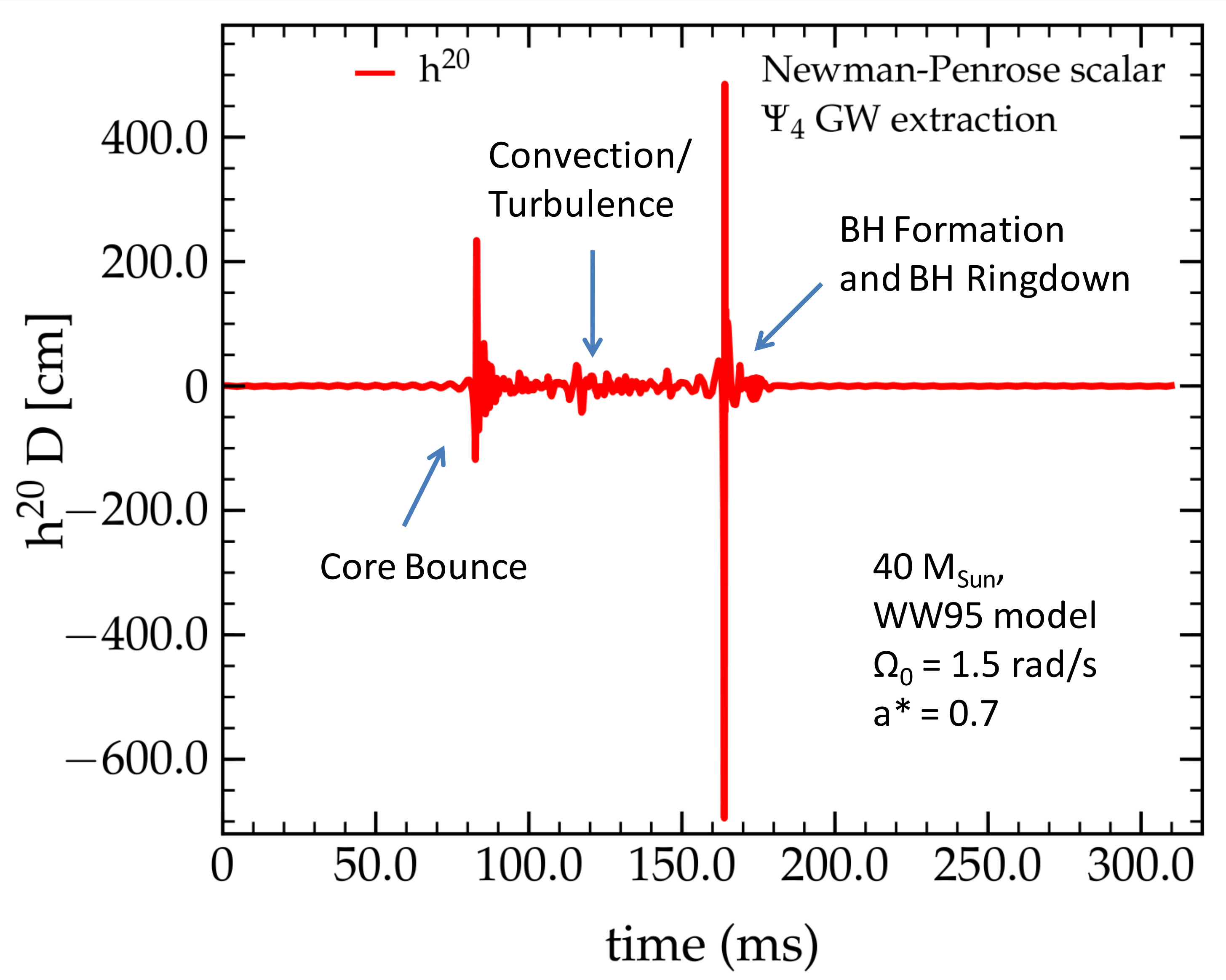
GWs Black Hole Formation



[3+1 GR simulation with the EinsteinToolkit; Ott et al. 2010 in prep.]

Gravitational Waves from BH Formation

[Ott et al. 2010 in prep.]



Summary and Remarks

- Multi-D core-collapse SN simulations are maturing -> 3 potential explosion mechanisms: **neutrino**, **MHD**, **acoustic**
- **The GW signatures of these three mechanisms are distinct, perhaps mutually exclusive**.
- **Galactic core-collapse SN would allow to constrain SN mechanism.**

- Problem: Galactic SN rate: 1 in ~40 years.
  Local group: 2 in ~40 years.

  -> Need to go out to 3-5 Mpc where rate jumps to 1 in ~2 years.

- **The Frontier:**
  - Full 3D radiation-(M)HD (GR) simulations -> *all groups moving towards this: LANL, Princeton, ORNL, Garching, Tokyo, Caltech*.
  - Connecting CCSN and long-GRB simulations.
  - Correct treatment of subscale effects: turbulence/magneto-turbulence.