Core-Collapse Supernova Explosions and Their Gravitational Wave Signatures

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FORNAX: 1D,2D,3D, Multi-Group, Radiation/Hydrodynamics

FORNAX: 1D,2D,3D, Multi-Group, Explicit Radiation/Hydrodynamics

- Solves the Two-Moment Transport Equations, with 2nd and 3rd moment closures (not "ray-by-ray"); second-order accurate in space and time
- Explicit Riemann Godunov-like solution to the Transport operator
- Terms of O(v/c) included in transport
- Implicit solution to the local transport source terms
- Explicit hydro; full energy and momentum couplings – HLLC
- Conserves energy, momentum, and lepton number to machine precision
- Very good energy conservation with gravity included
- "6"– Dim. = 1(time) + 3(space) + 1(energy-group) + vector Flux
- Logically spherical coordinates – general metric/covariant formulation
- Multipole Gravity (can include GR-like modifications to the monopole)
- Multi-D calculated to the center - Core refinement ("dendritic grid") – improves timestepping by many factors (!); static mesh refinement
- For 2D, Axisymmetry – Rotation can be included (conserving angular momentum to machine precision)
- Good strong scaling in core count and scaling in energy group (linear)
- Result: Faster multi-D supernova code (by factor of ~5-10)

FORNAX (cont.)

- Includes: Inelastic scattering off electrons
- Inelastic scattering off nucleons
- Includes in-medium Many-body response corrections (Horowitz et al. 2017)
- General-relativistic monopole gravity correction and gravitational redshifts (can compare with Newtonian)
- Multi-D transport, with rbr+ option (for comparison)
- Weak magnetism and recoil corrections
- Multipole gravity (with monopole variant)

The Fornax Supernova Code

Dynamical Equations

$$\rho_{,t} + (\rho v^i)_{;i} = 0$$

$$(\rho v_j)_{,t} + (\rho v^i v_j + P\delta^i_j)_{;i} = -\rho\phi_{,j} + c^{-1}\sum_s \int_0^\infty (\kappa_{s\varepsilon} + \sigma^{\rm tr}_{s\varepsilon}) F_{s\varepsilon j} d\varepsilon$$

$$\left[\rho\left(e + \frac{1}{2}\|v\|^2\right)\right]_{,t} + \left[\rho v^i \left(e + \frac{1}{2}\|v\|^2 + \frac{P}{\rho}\right)\right]_{;i} = -\rho v^i \phi_{,i} - \sum_s \int_0^\infty \left(j_{s\varepsilon} - c\kappa_{s\varepsilon}E_{s\varepsilon} - \frac{v^i}{c}(\kappa_{s\varepsilon} + \sigma^{\rm tr}_{s\varepsilon})F_{s\varepsilon i}\right) d\varepsilon$$

$$(\rho Y_e)_{,t} + (\rho Y_e v^i)_{;i} = \sum_s \int_0^\infty \xi_{s\varepsilon}(j_{s\varepsilon} - c\kappa_{s\varepsilon}E_{s\varepsilon}) d\varepsilon$$

$$E_{s\varepsilon,t} + (\alpha F^i_{s\varepsilon} + \mathbf{v}^{\mathbf{i}}\mathbf{E}_{\mathbf{s}\varepsilon})_{;i} - \alpha \mathbf{v}^{\mathbf{i}}_{;\mathbf{j}} \frac{\partial}{\partial \ln \varepsilon}\mathbf{P}^{\mathbf{j}}_{\mathbf{s}\varepsilon\mathbf{i}} = \alpha(j_{s\varepsilon} - c\kappa_{s\varepsilon}E_{s\varepsilon}) + \alpha G^e$$

$$F_{s\varepsilon j,t} + (c^2\alpha P^i_{s\varepsilon j} + \mathbf{v}^{\mathbf{i}}\mathbf{F}_{\mathbf{s}\varepsilon\mathbf{j}})_{;i} + \alpha \mathbf{v}^{\mathbf{i}}_{;\mathbf{j}}\mathbf{F}_{\mathbf{s}\varepsilon\mathbf{i}} - \alpha \mathbf{v}^{\mathbf{i}}_{;\mathbf{k}} \frac{\partial}{\partial\varepsilon}(\varepsilon \mathbf{Q}^{\mathbf{k}}_{\mathbf{s}\varepsilon\mathbf{j}\mathbf{i}}) = -c\alpha(\kappa_{s\varepsilon} + \sigma^{\rm tr}_{s\varepsilon})F_{s\varepsilon j} + \alpha G^m_j$$

Approximate GR

$$\frac{d\phi_{\rm TOV}}{dr} = G\frac{m_{\rm TOV} + 4\pi r^3(P + P_\nu)/c^2}{r^2\Gamma^2}\left[\frac{\rho + E/c^2 + P/c^2}{\rho}\right]$$

$$\Gamma(r) = \sqrt{1 + v^2/c^2 - \frac{2Gm_{\rm TOV}(r)}{rc^2}}$$

$$\frac{dm_{\rm TOV}}{dr} = 4\pi r^2\left(\rho + E/c^2 + E_\nu/c^2 + \frac{\mathbf{v}\cdot\mathbf{F}_\nu/c^2}{\Gamma}\right)\Gamma$$

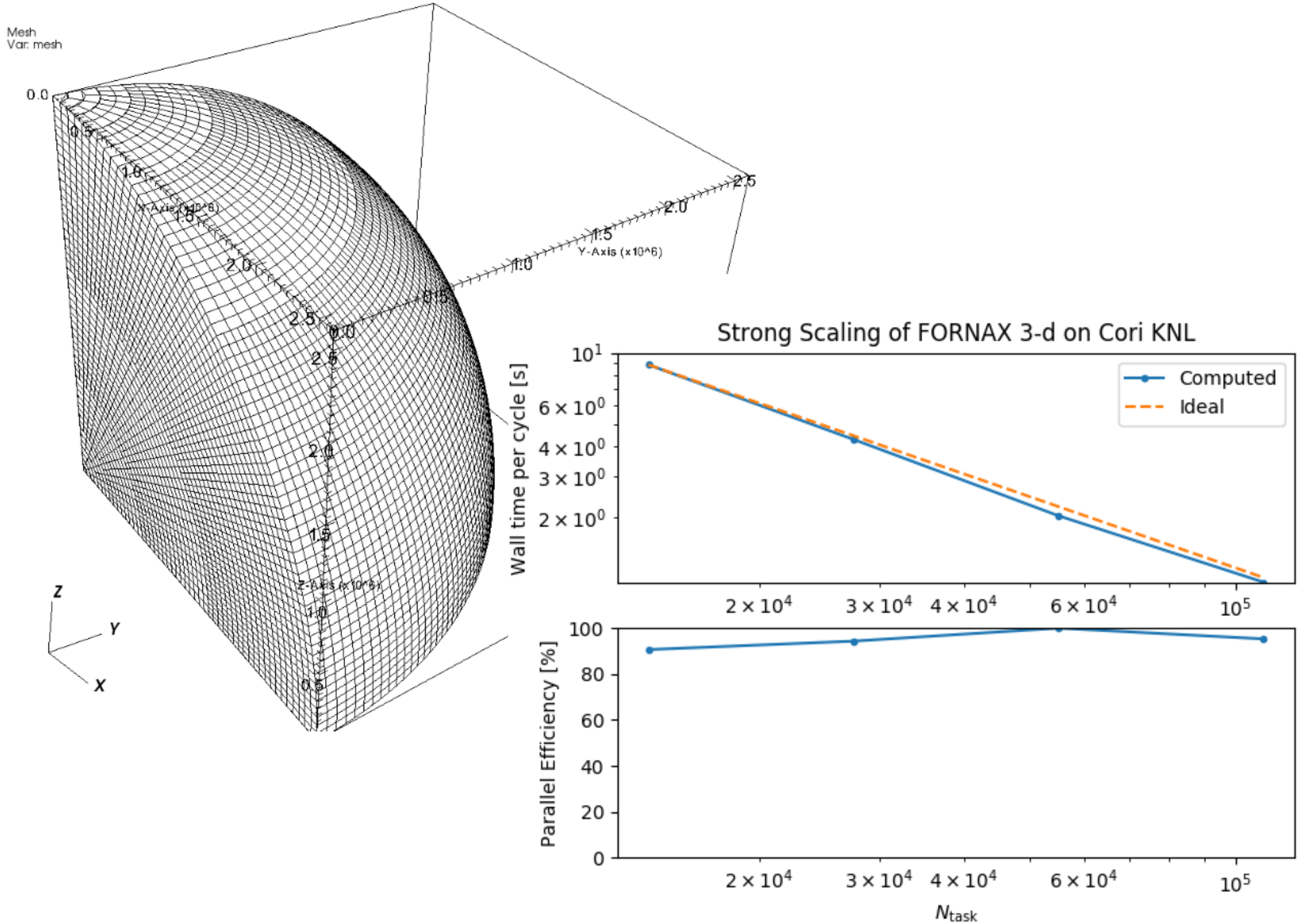
Auxiliary Definitions

$$\alpha = e^{\phi/c^2}$$

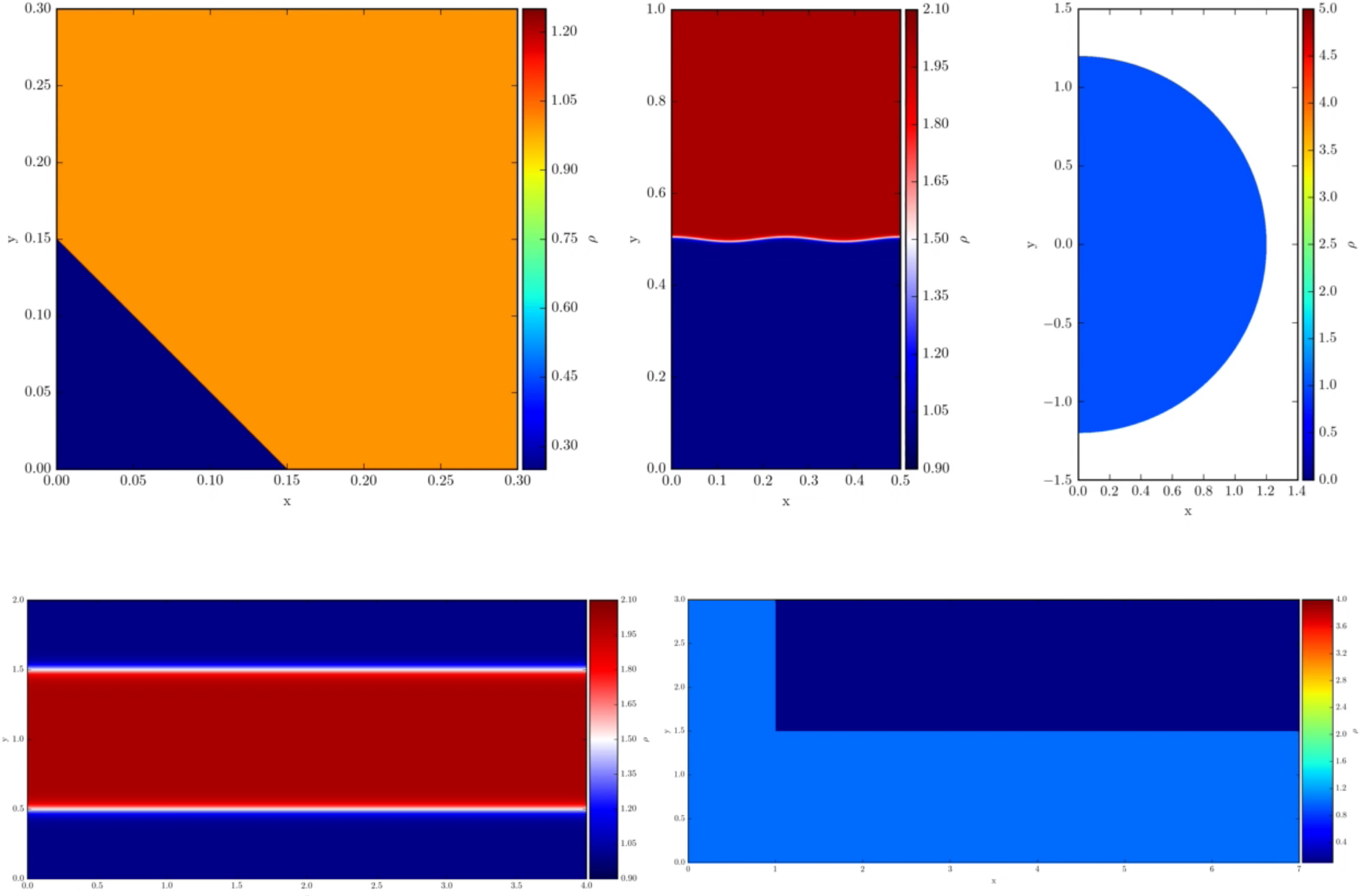
$$G^e = -\mathbf{F}_{\mathbf{s}\varepsilon}\cdot\nabla\phi/c^2 + \nabla\phi/c^2\cdot\partial(\varepsilon\mathbf{F}_{\mathbf{s}\varepsilon})/\partial\varepsilon$$

$$G^m_{\mathbf{j}} = -E_{s\varepsilon}\nabla_{\mathbf{j}}\phi/c^2 + \nabla_{\mathbf{i}}\phi/c^2\cdot\partial(\varepsilon\mathbf{P}^{\mathbf{i}}_{\mathbf{s}\varepsilon\mathbf{j}})/\partial\varepsilon$$

$$\xi_{s\varepsilon} = \begin{cases} -(N_A\varepsilon)^{-1} & s = \nu_e, \\ (N_A\varepsilon)^{-1} & s = \bar{\nu}_e, \\ 0 & s = \nu_x \end{cases}$$



Mesh
Var: mesh
X-Axis (x10^6)
Y-Axis (x10^6)
Z-Axis (x10^6)
Z
Y
X
Strong Scaling of FORNAX 3-d on Cori KNL
Wall time per cycle [s]
Computed
Ideal
Parallel Efficiency [%]
N_{task}



x
y
ρ

Different Groups get Different Explosion Times, Energies, Even Outcomes, etc.

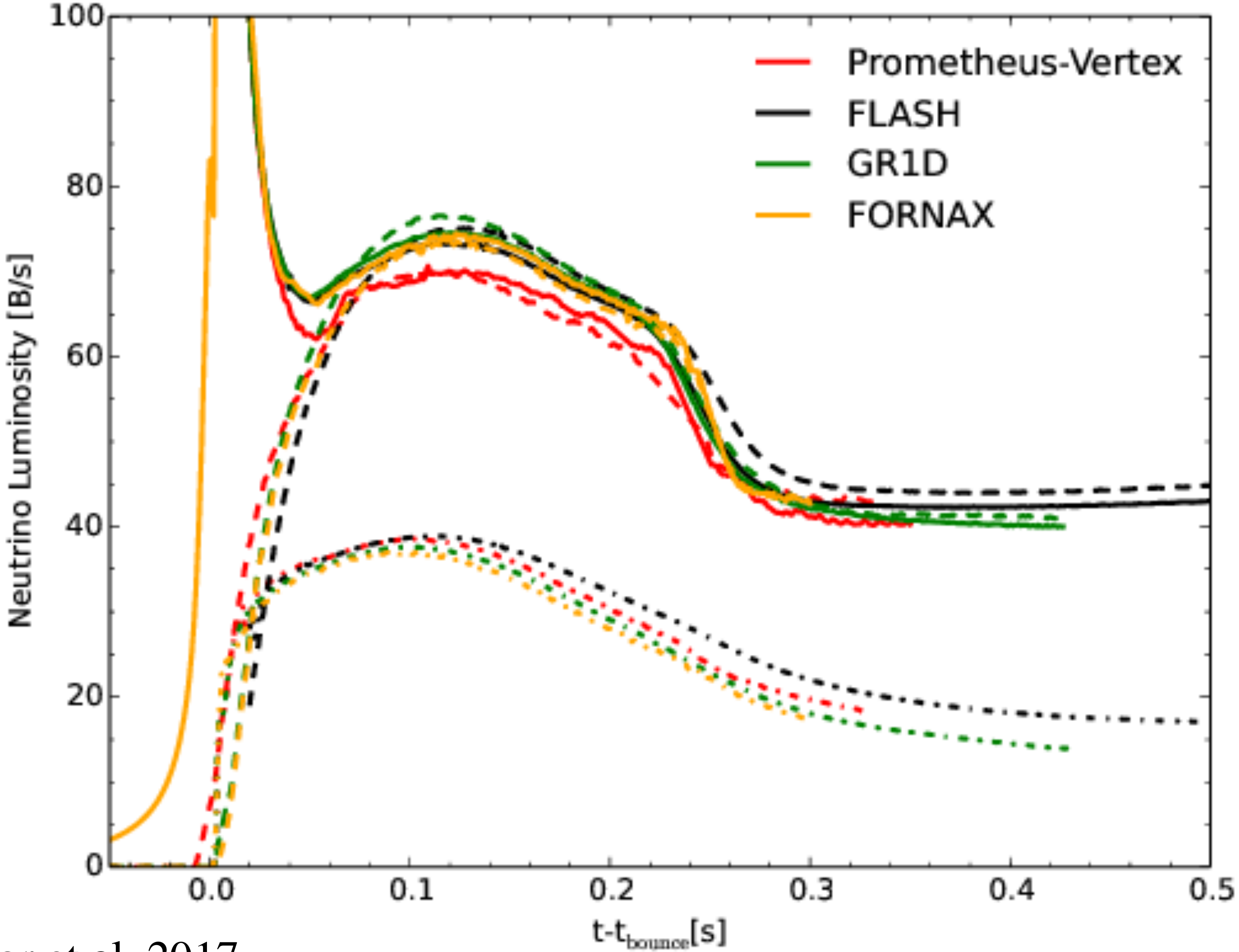
Why?

What are the Crucial Ingredients for a Robust Explosion?

Why are different groups witnessing different outcomes?

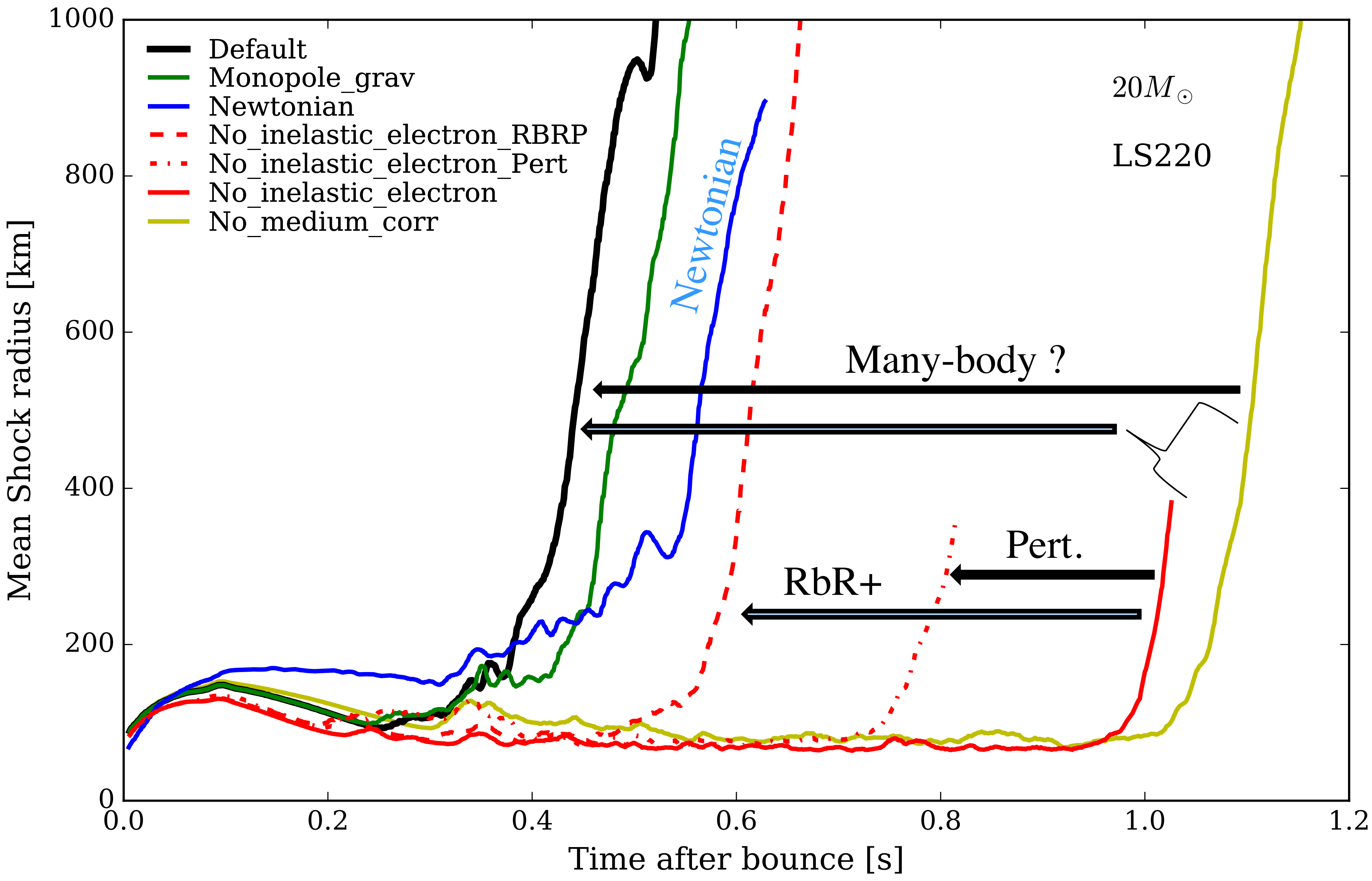
- Multi-D simulations are close to critical condition
- Flow is chaotic (positive Lyapunov exponents!)
- Whereas in 1D, there are severe feedbacks to changes in microphysics ("Mazurek's Law), in multi-D proximity to critical condition amplifies sensitivities to slight changes in interactions, methodology, resolution, etc.
- In-medium (many-body) structure factor/response corrections to neutrino-nucleon scattering (only 10's of %) – Burrows & Sawyer 1998; C. Horowitz/T. Fischer
- Spatial (!) and energy resolution
- Ray-by-ray+ ?
- Initial progenitor models
- "Seed" Perturbations
- Equation of state (EOS)
- GR/no-GR (strength of gravity -> core compression; redshifts)
- Weak magnetism and recoil corrections to interaction rates
- Inelastic scattering (neutrino-electron; neutrino-nucleon)
- Code/algorithm differences
- Optimization flags, machine compilers, machine precision

Luminosity Curve Comparisons (1D) – Different Groups; Sukhbold 2015/20 solar-mass; SFHo EOS, GR, IES



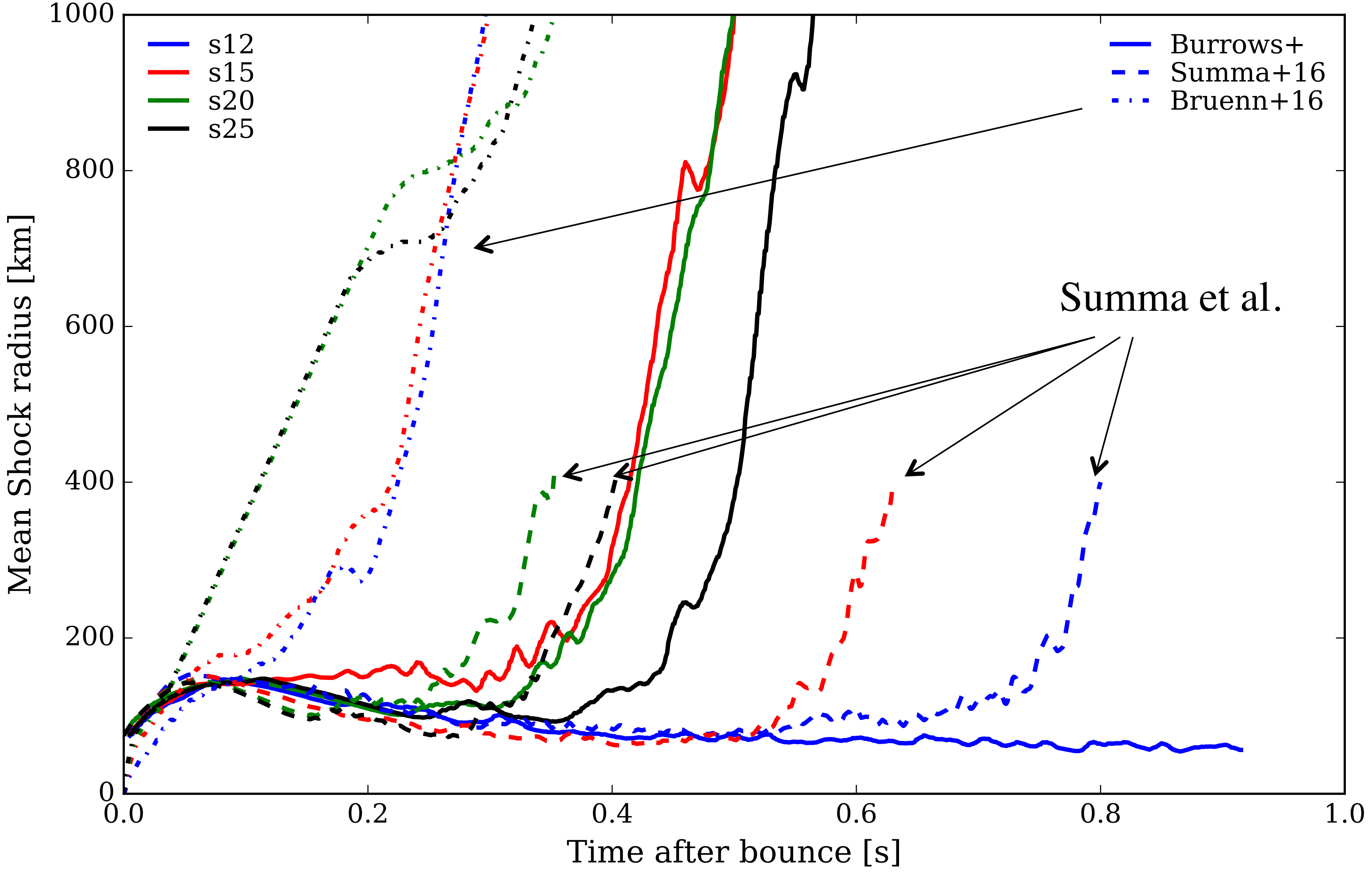
O'Connor et al. 2017

Small Changes and Differences Result in Significantly Different Outcomes



Fornax (GR) (20 solar mass): Burrows, Vartanyan et al. 2018

Different Groups Explode at Different Times

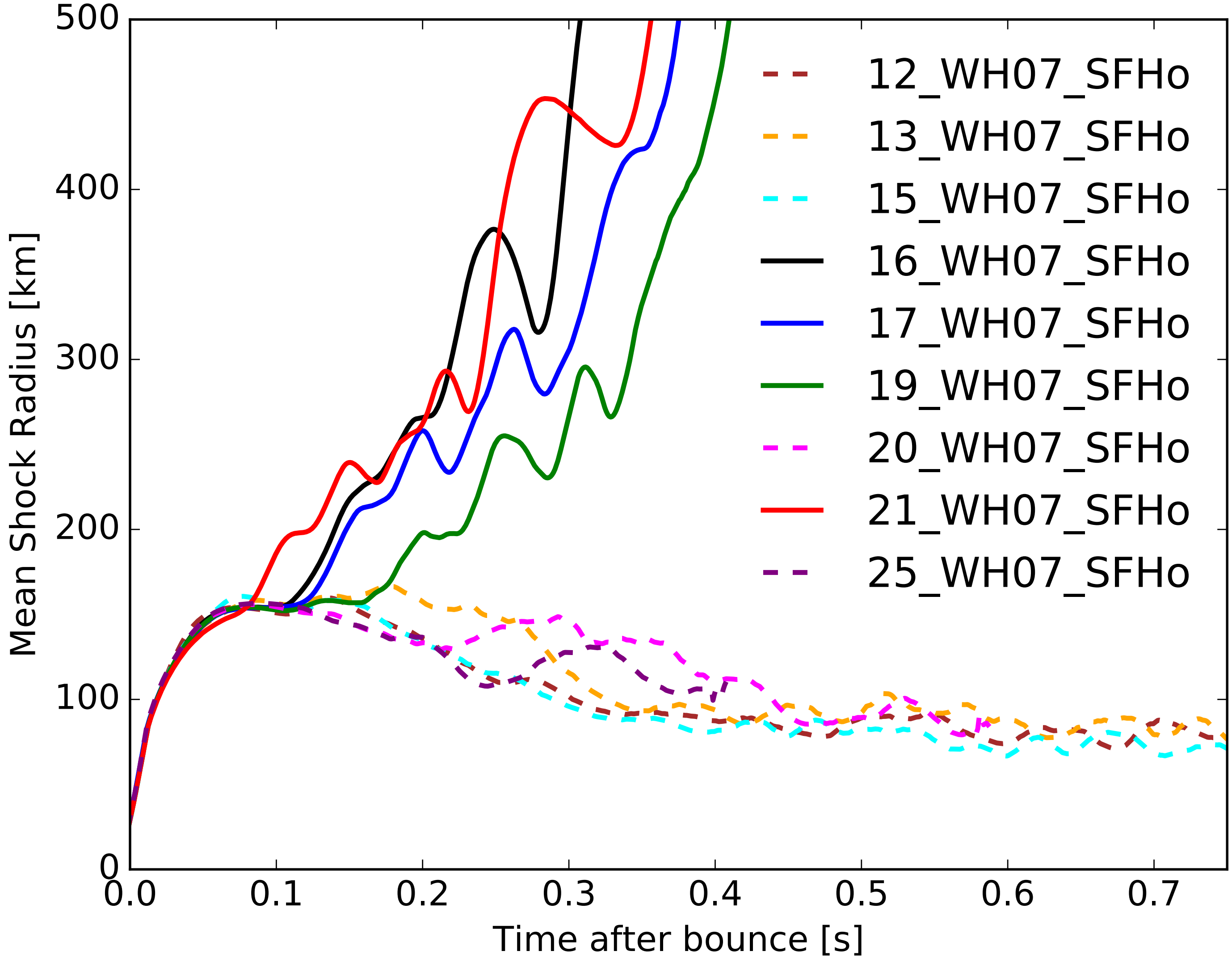


2D (Fornax): 9.0 solar-mass (Sukhbold et al.) model – Without and With Structure Factor/ Many-body Correction – Pressure/Acoustic Waves

Upshot(s):

- Explosions at significantly different post-bounce times (100s of ms!)
- Explosion versus no explosion
- Shock positions chaotic – fluctuate indeterminately
- All issues when inter-comparing in multi-D

Chaos in the turbulent context and proximity to criticality lead to a violation of “Mazurek’s Law”: Modest effects can make a difference in explosion time, and explodability



Vartanyan et al. 2017

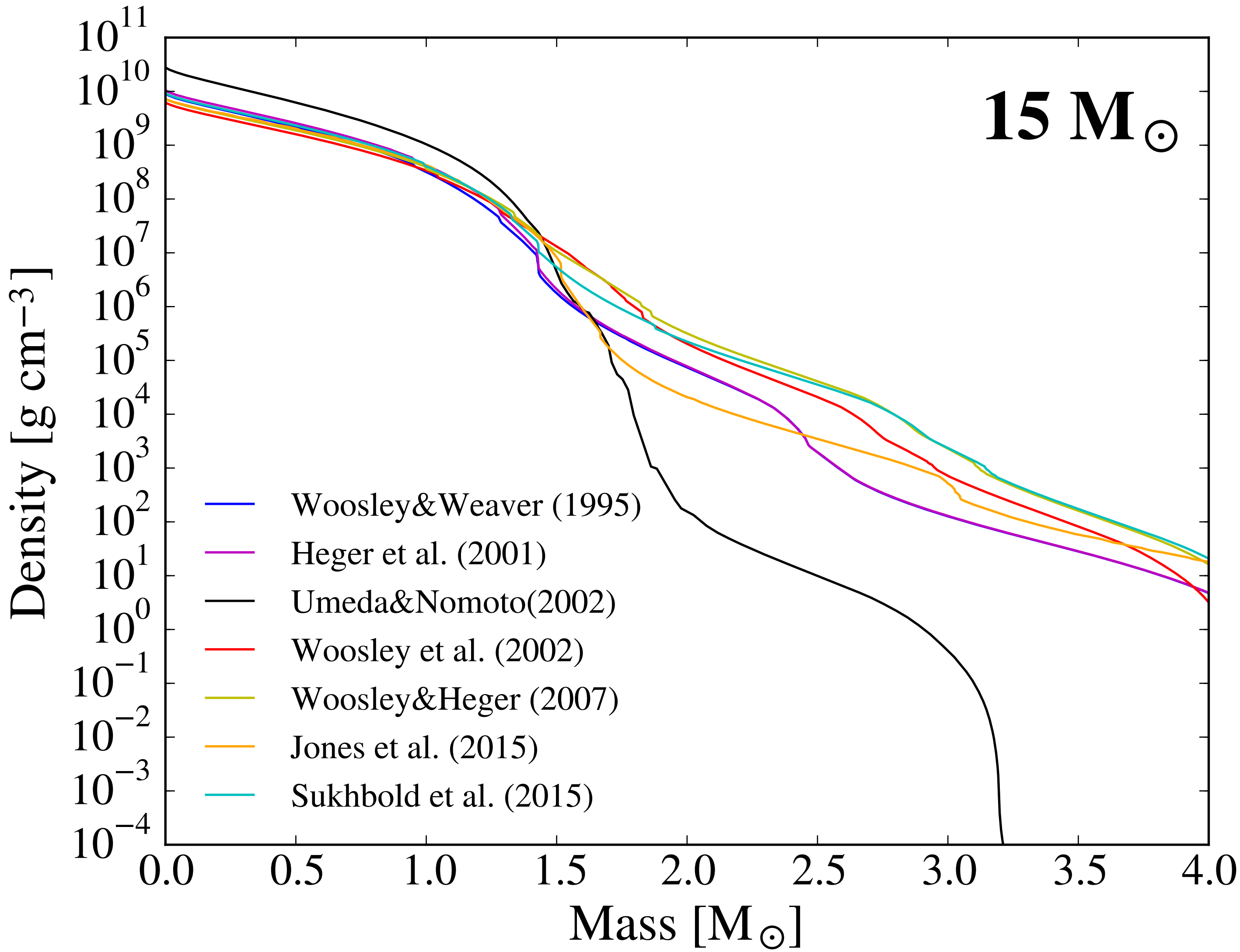
Vartanyan et al. 2017

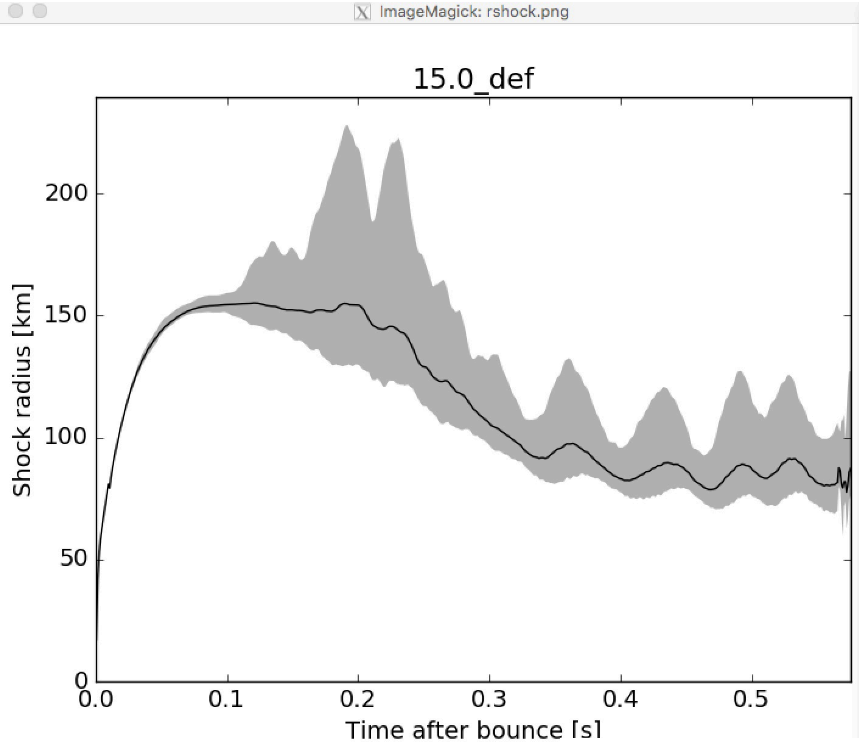
2D (Fornax): 16, 17, 19, 21 solar-mass (Woosley & Heger progenitors) - Baseline

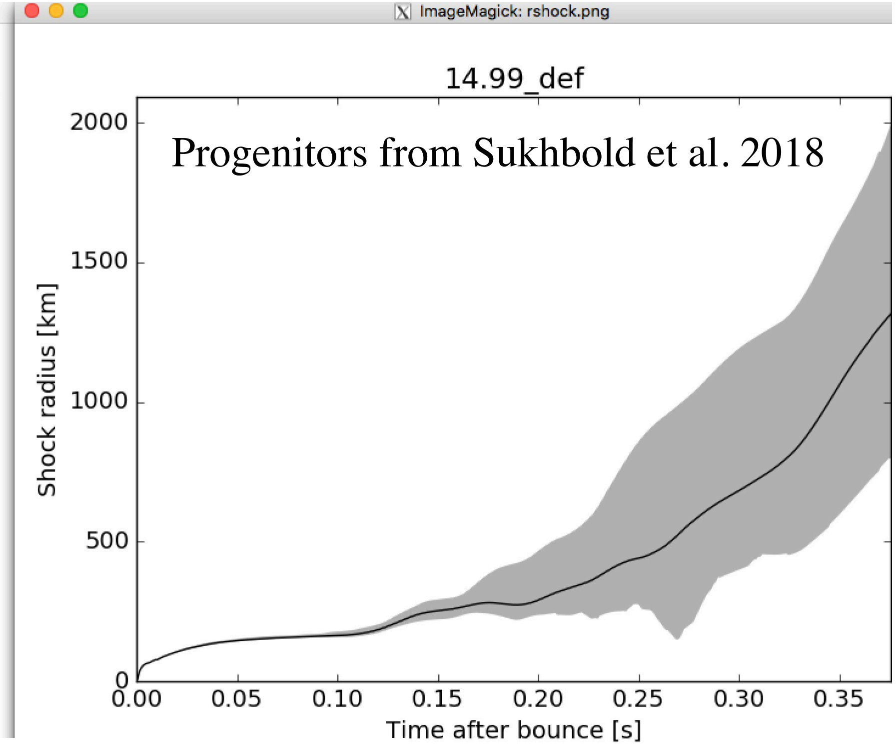
Important Roles of Progenitor Models:

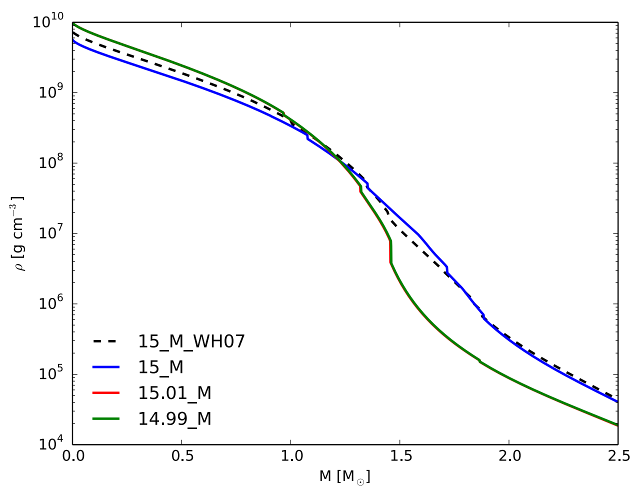
Density Structures, Rotational Profiles, Seed Perturbations

Different Groups, Same ZAMS Mass







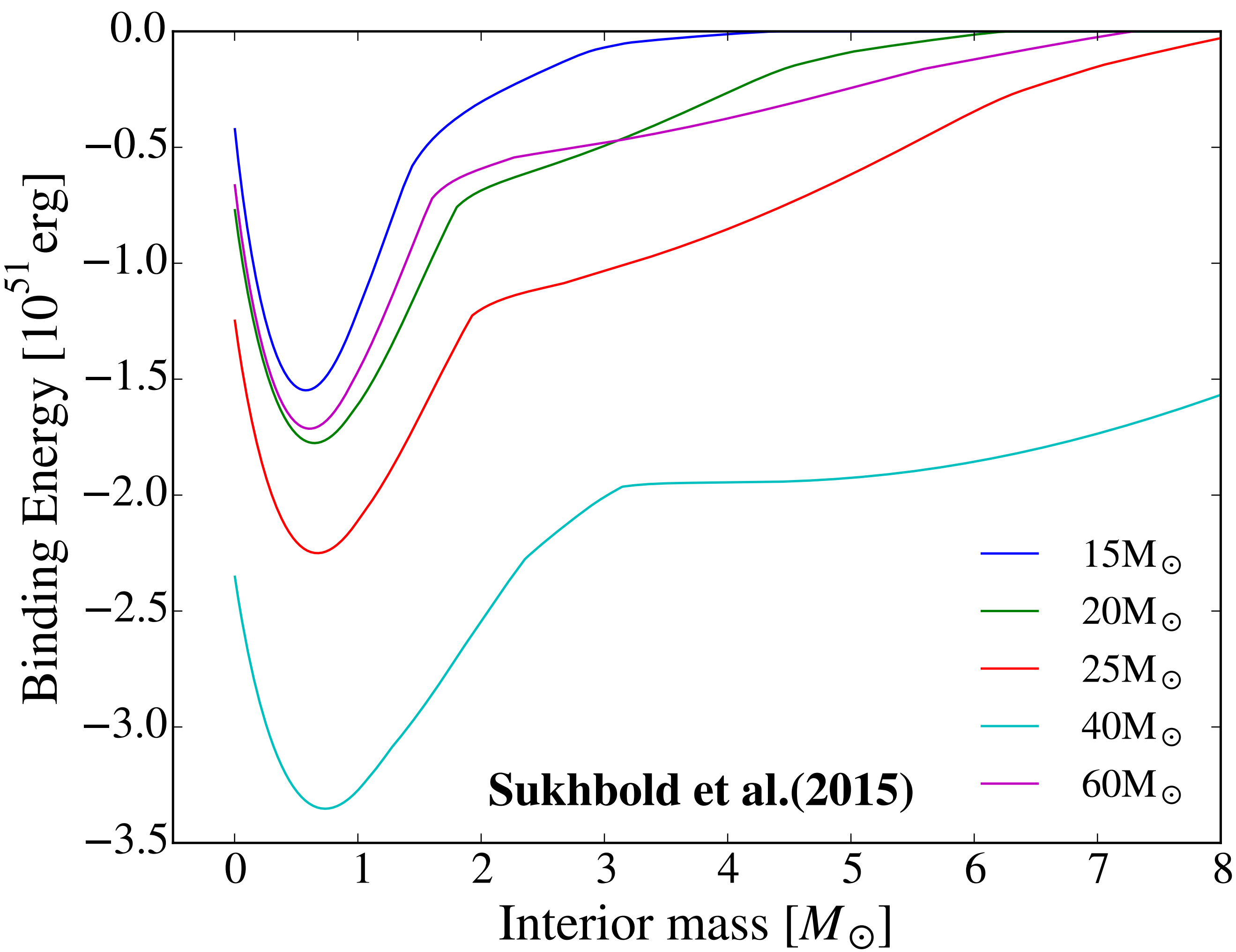


Vartanyan, Burrows, et al. 2018b

Are Progenitor Perturbations/Seeds crucial/ important?

2D (Fornax): Multi-D Transport – 20 solar-mass (WH07) model – With Structure Factor Correction, With and without Perturbations (without inelastic neutrino-electron scattering)

External Binding Energy More Important

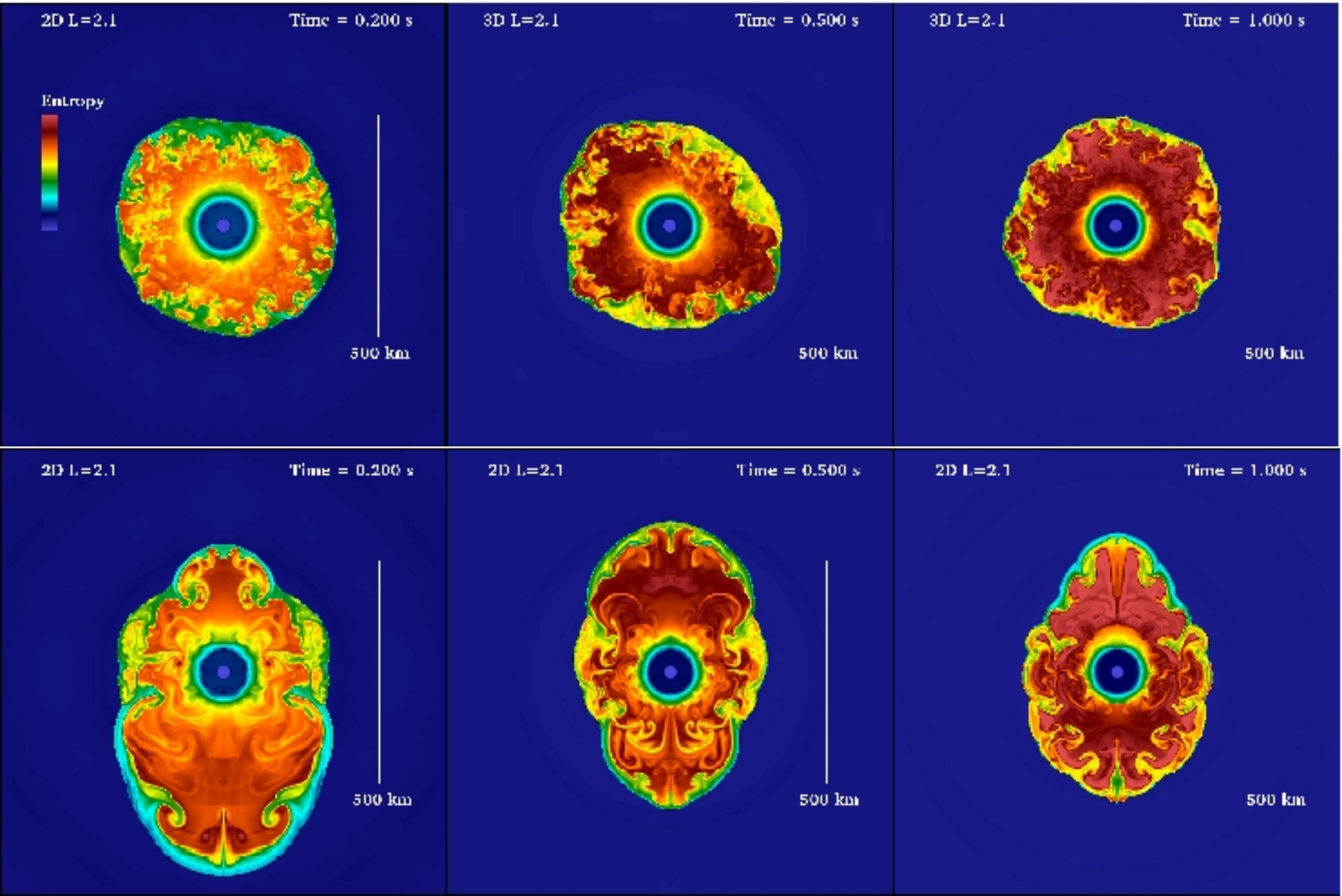


3D Simulations

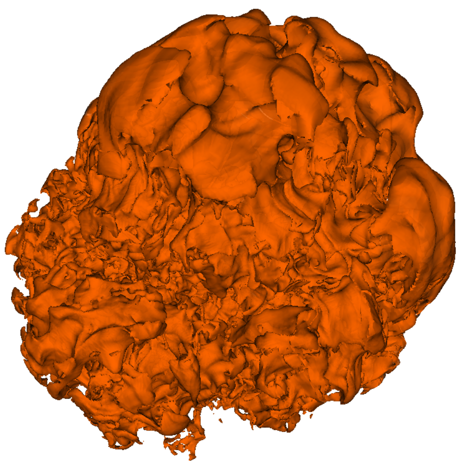
Character of 3D Turbulence Qualitatively Different than that in 2D

Amplitudes of Dipolar ("Sloshing") Modes much Smaller in 3D

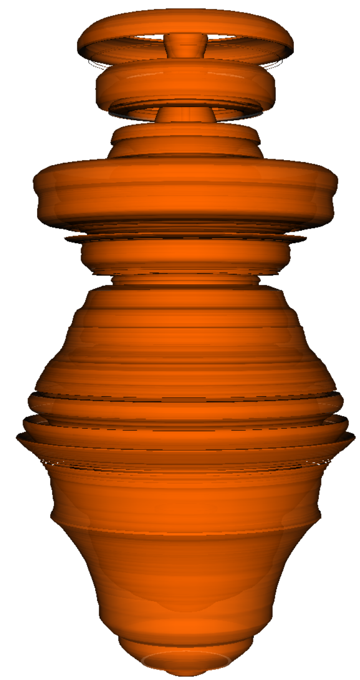
Comparison of 2D with 3D



3D

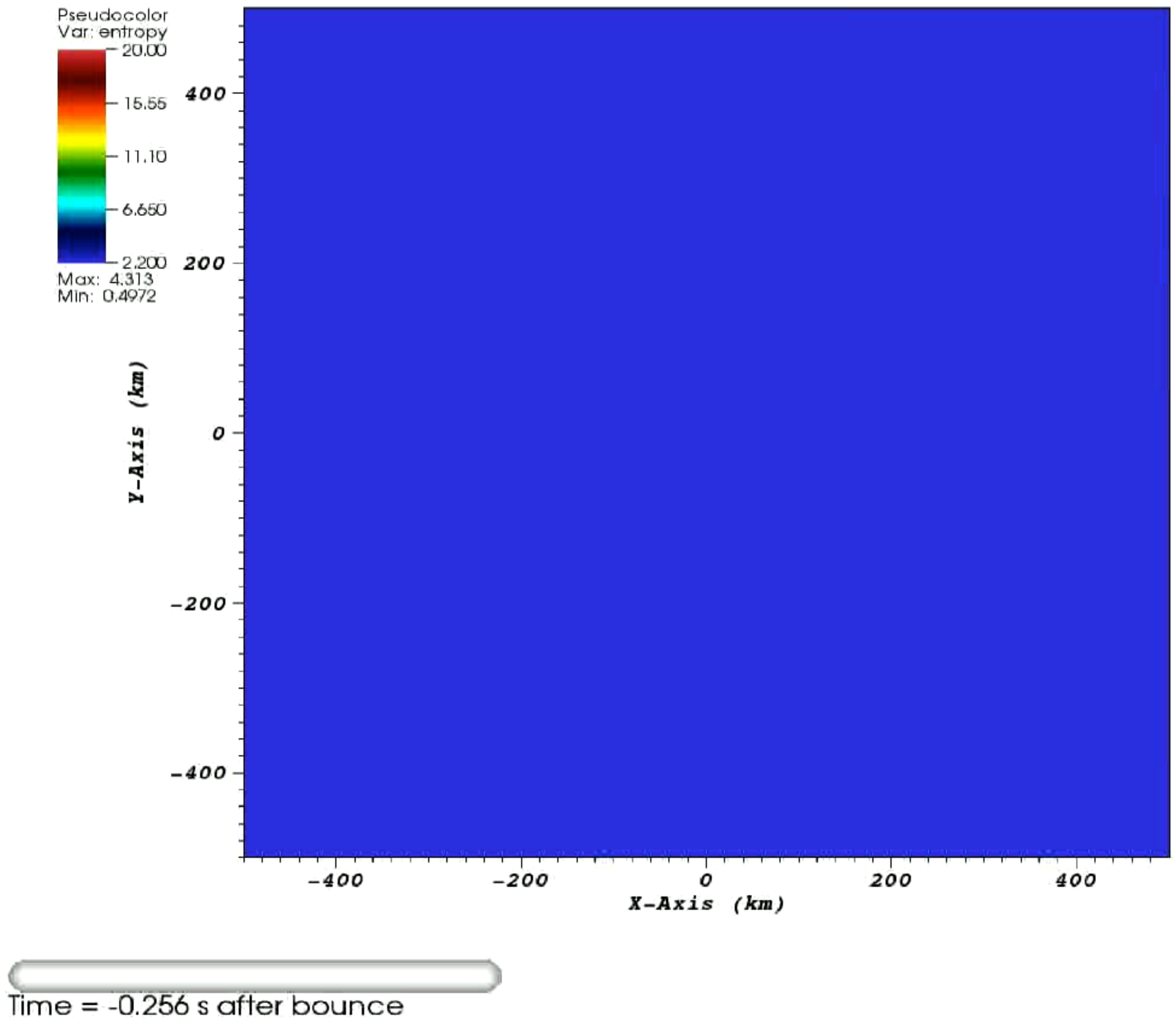


2D



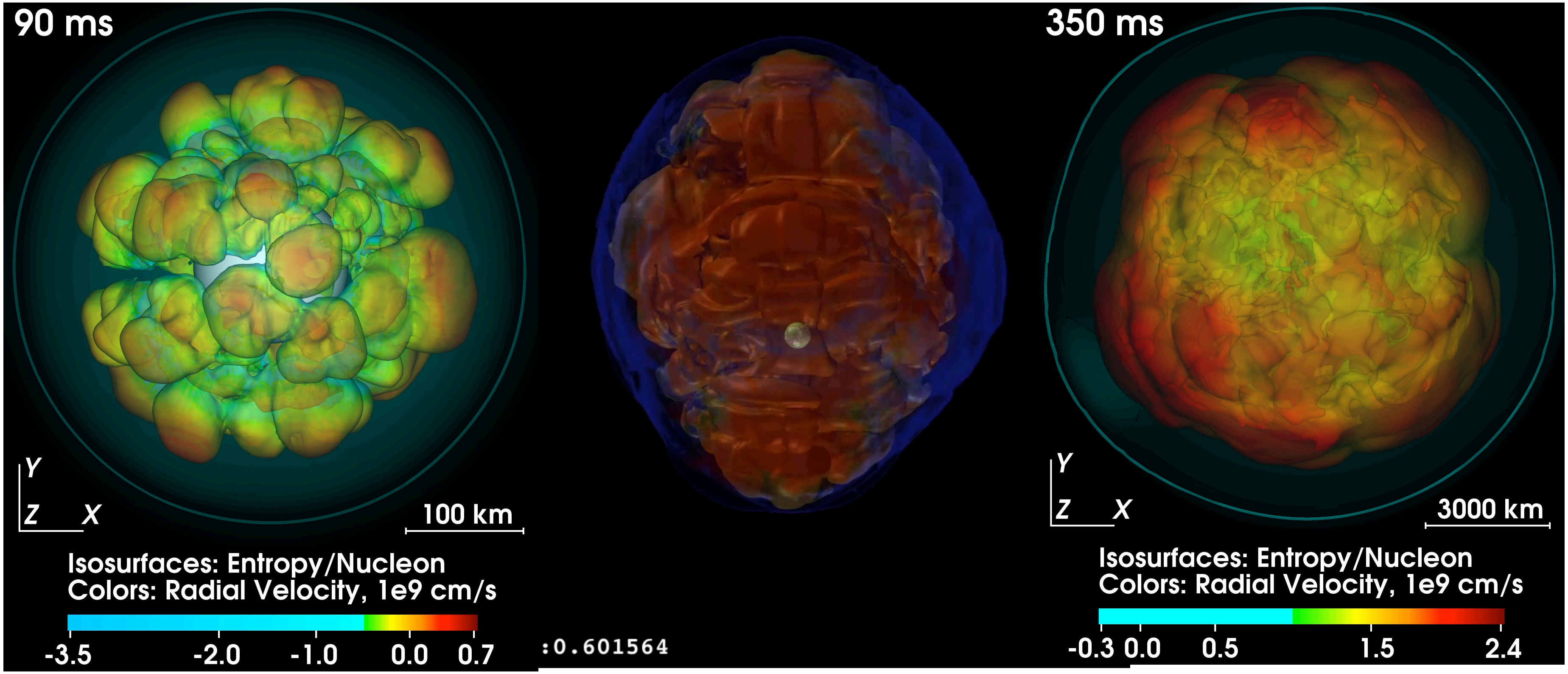
Couch 2012

Character of 3D turbulence and Explosion Very Different from those in 2D



Melson et al. (2015, MPA) – 3D (with strangeness correction - likely too large)

Lentz et al. (2015) - ORNL



Summa et al. 2017 (MPA) – rapidly rotating 3D models (but pulsar birth spins?)

New Fornax 3D Simulations

Adam Burrows, David Vartanyan, David Radice, Aaron Skinner, Viktoriya Morozova, Josh Dolence

Gravitational Radiation from Supernovae

Morozova, Radice, Burrows et al. 2018

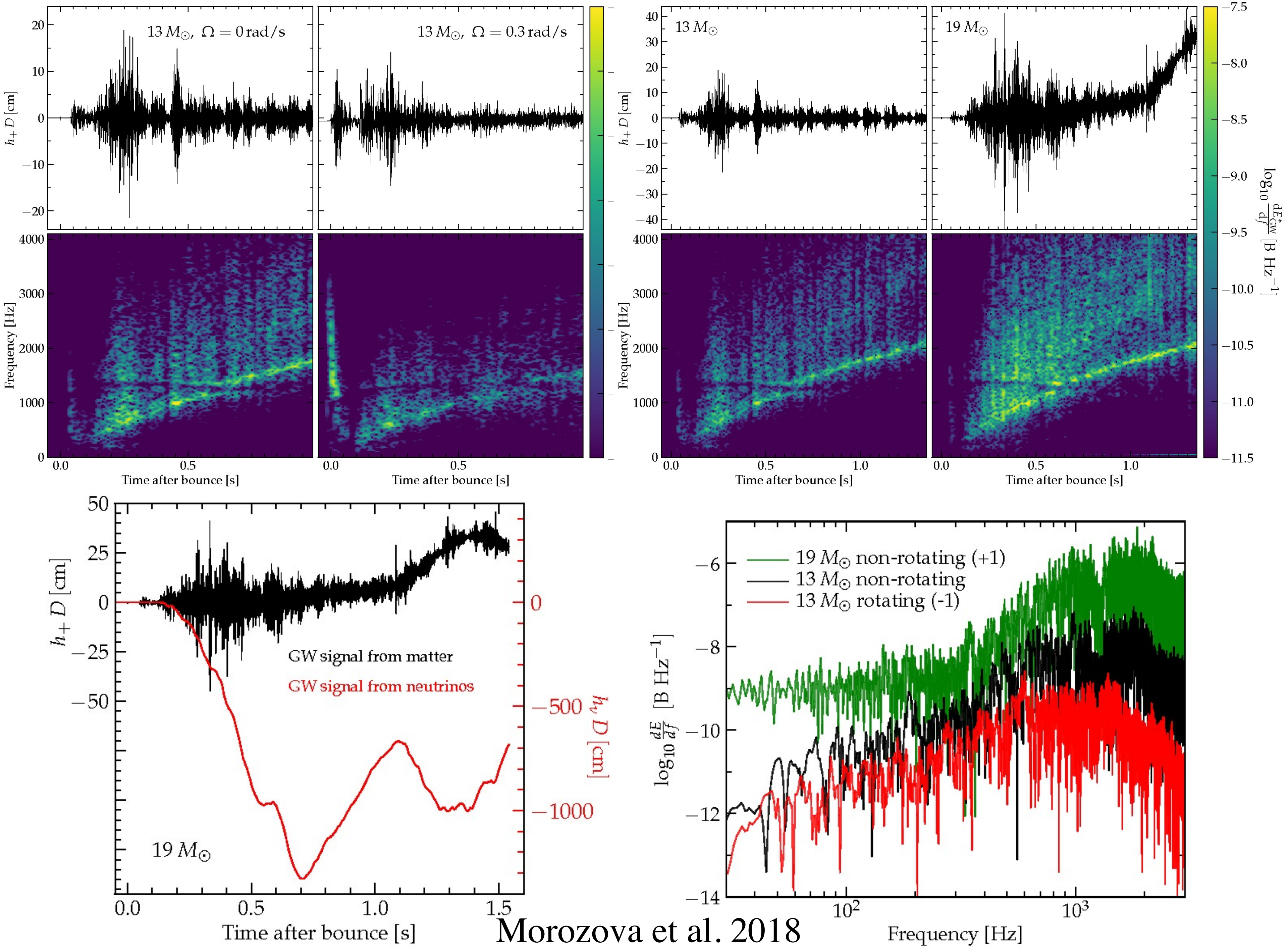
Identified/Discussed Signal Features

- Rotational bounce spike (rapid rotation?); differential rotation
- Initial Progenitor perturbation spike
- Outer PNS convection (early, non-rotating)
- Quiescent phase (altered by progenitor perturbations?)
- Ramp up and saturation of turbulent convection and SASI
- Infall plume excitation of PNS oscillations
- Inner PNS convection
- Transition to Explosion, leading to decreased accretion, occasioning signal turnover (near time of frequency peak?)
- Neutrino component
- Christodoulou Memory (low frequency): asymmetric explosion, neutrinos

- Progenitor, rotation, orientation, explosion energy dependences?
- Duration of phases; frequency spectra; signal phase?

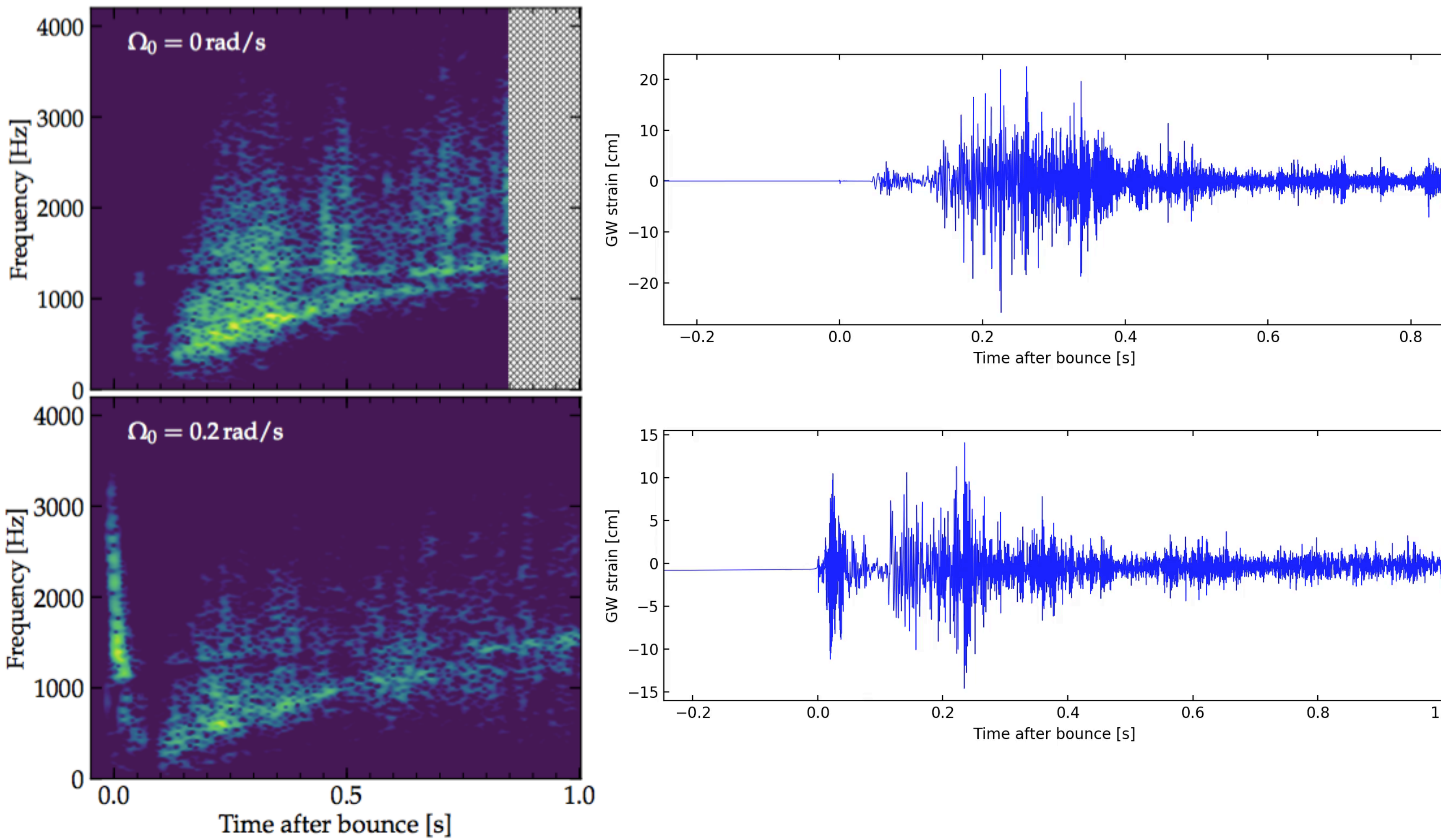
Sample References on the CCSN/GW Connection

- E. Muller 1982 (Rotation)
- Burrows & Hayes 1996 (Memory, neutrinos, progenitor asymmetry)
- Ott et al. 2004,2006 (Rotation); Dimmelmeier et al. 2008; Ott 2009; Logue et al. 2012; Ott et al. 2013 (3D, leakage)
- Summerscales et al. 2008 (Maximum entropy)
- Scheidegger et al. 2010; Basel
- Heng 2009; Rover et al. 2009
- Murphy et al. 2009 (PNS oscillations, signal sequence)
- Yakunin et al. 2010 (Newt.),2015 (2D),2017(3D); ORNL
- B. Muller et al. 2013 (2D); Andresen et al. 2016 (3D); Garching
- Kuroda et al. 2016 (3D, SASI); Fukuoka
- Gossan et al 2015; Powell et al. 2016 (Signal analysis); Caltech
- Richers et al. 2017 (EOS, rotation); Caltech
- Lynch et al. 2017 (oLIB, Bayes factor); MIT



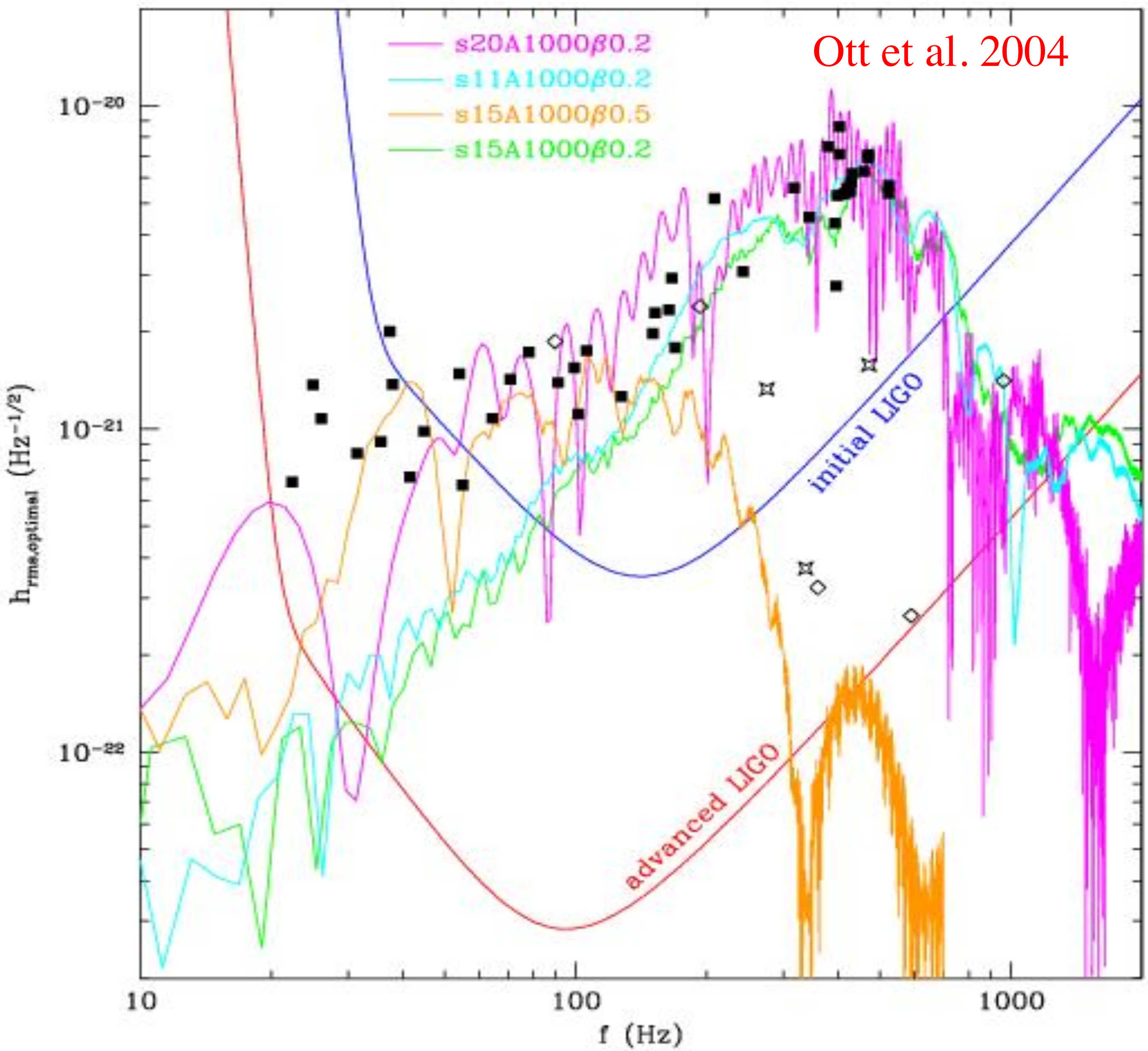
Morozova et al. 2018

Rotation



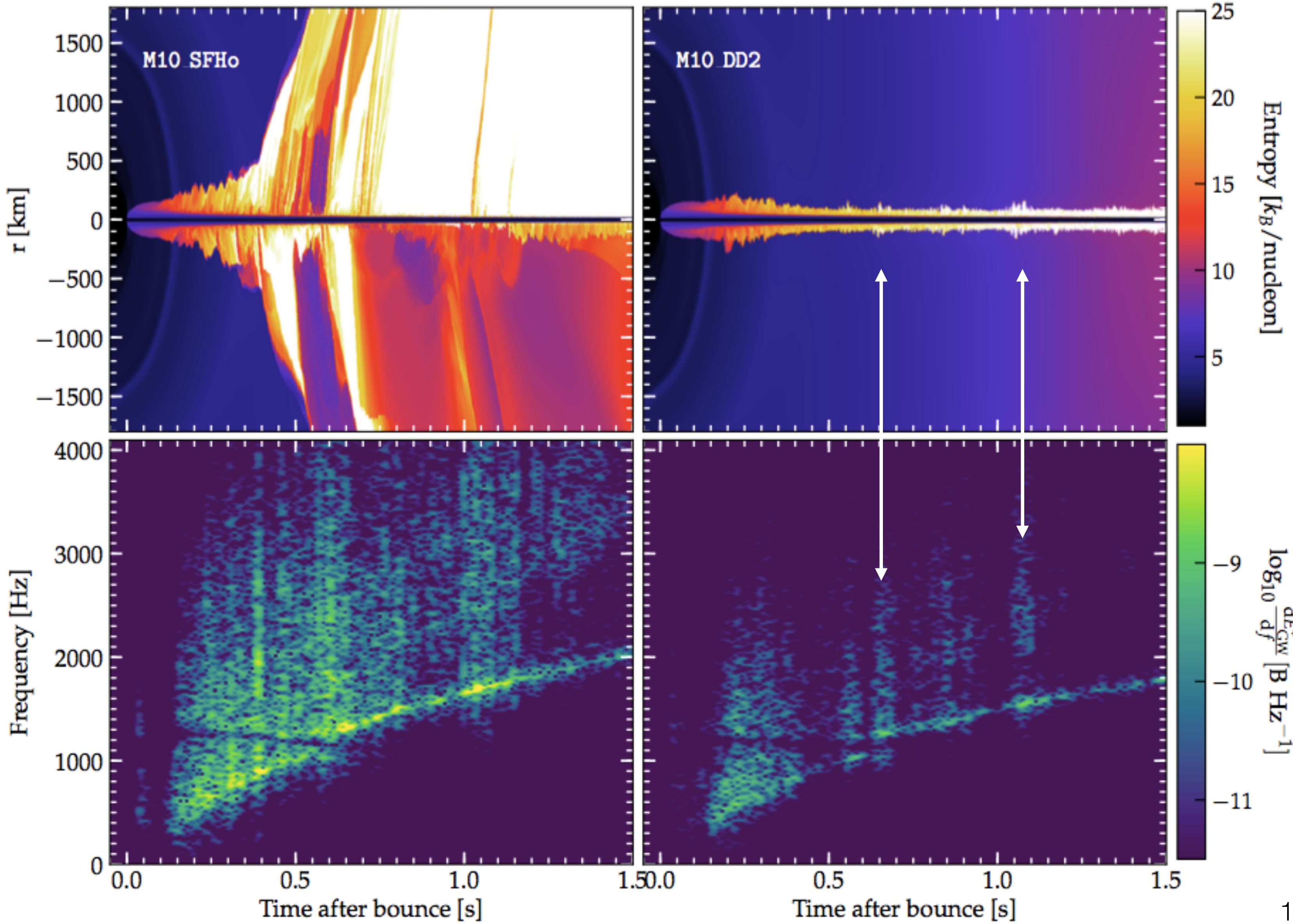
* The bounce signal is stronger, because the collapse is not symmetric
* The dominant frequency is nearly the same

Morozova et al. 2018



s20A1000β0.2
s11A1000β0.2
s15A1000β0.5
s15A1000β0.2
Ott et al. 2004
10^{-20}
10^{-21}
10^{-22}
$h_{rms,optimal}$ $(Hz^{-1/2})$
initial LIGO
advanced LIGO
10
100
1000
f (Hz)

Weaker convection leads to weaker signal



Morozova et al. 2018

Coupling between two oscillators leads to mode splitting

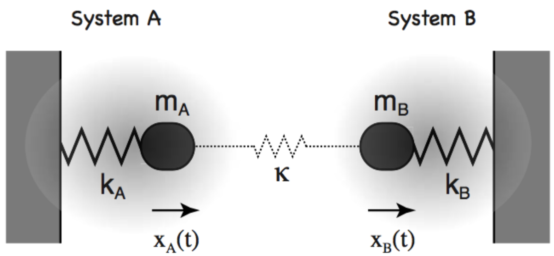


Fig. 1. Strong coupling regime illustrated by mechanical oscillators. The coupling κ of the two oscillators (mass m_i and spring constant k_i) leads to a shift of the eigenfrequencies and a characteristic frequency splitting.

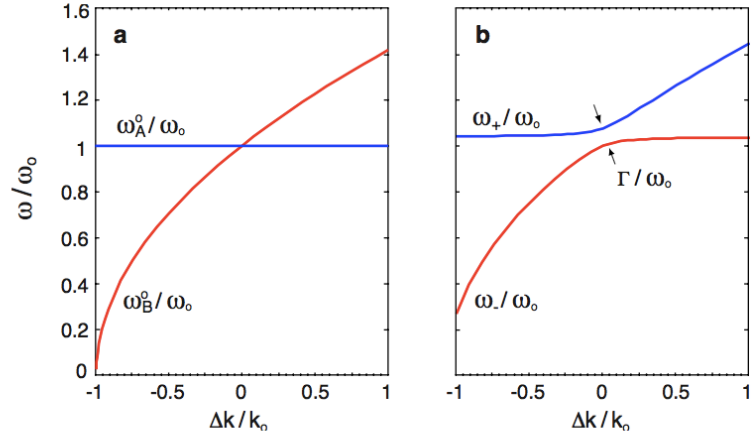
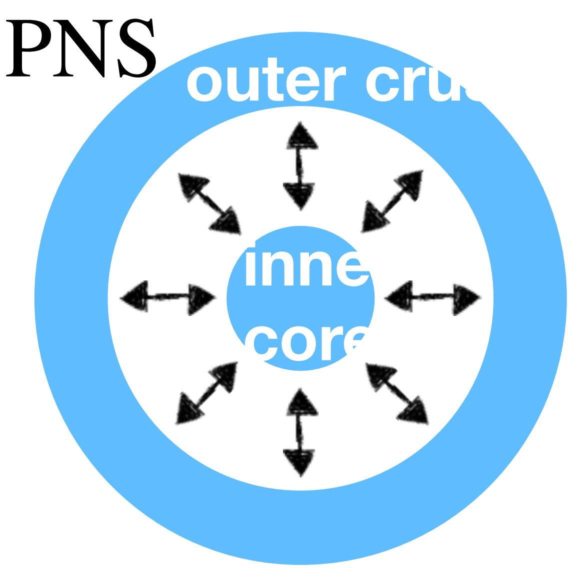


Fig. 2. (a) Eigenfrequencies of two uncoupled oscillators (κ=0) with equal mass and spring constants k_o and $k_o+\Delta k$. (b) Frequency anticrossing due to coupling of strength $\kappa=0.08k_o$. The frequency splitting $[\omega_+-\omega_-]$ scales linearly with the coupling strength κ.

Novotny (2010)



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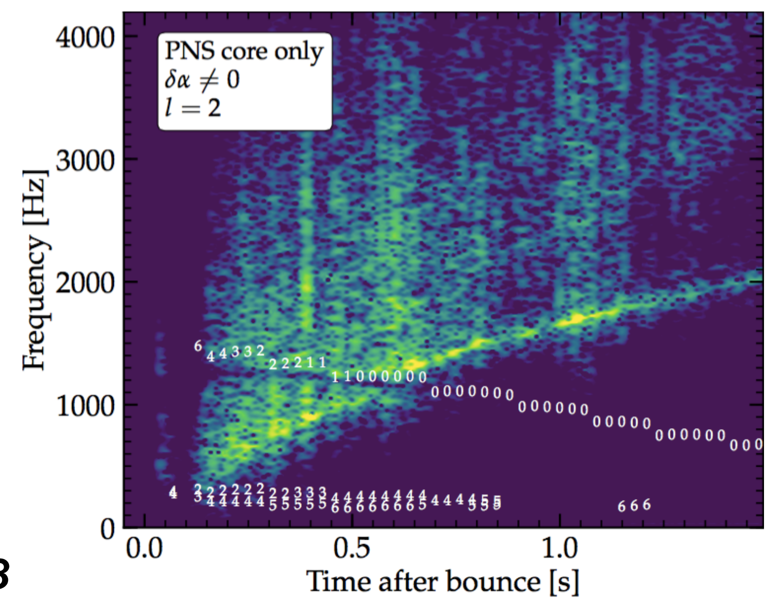
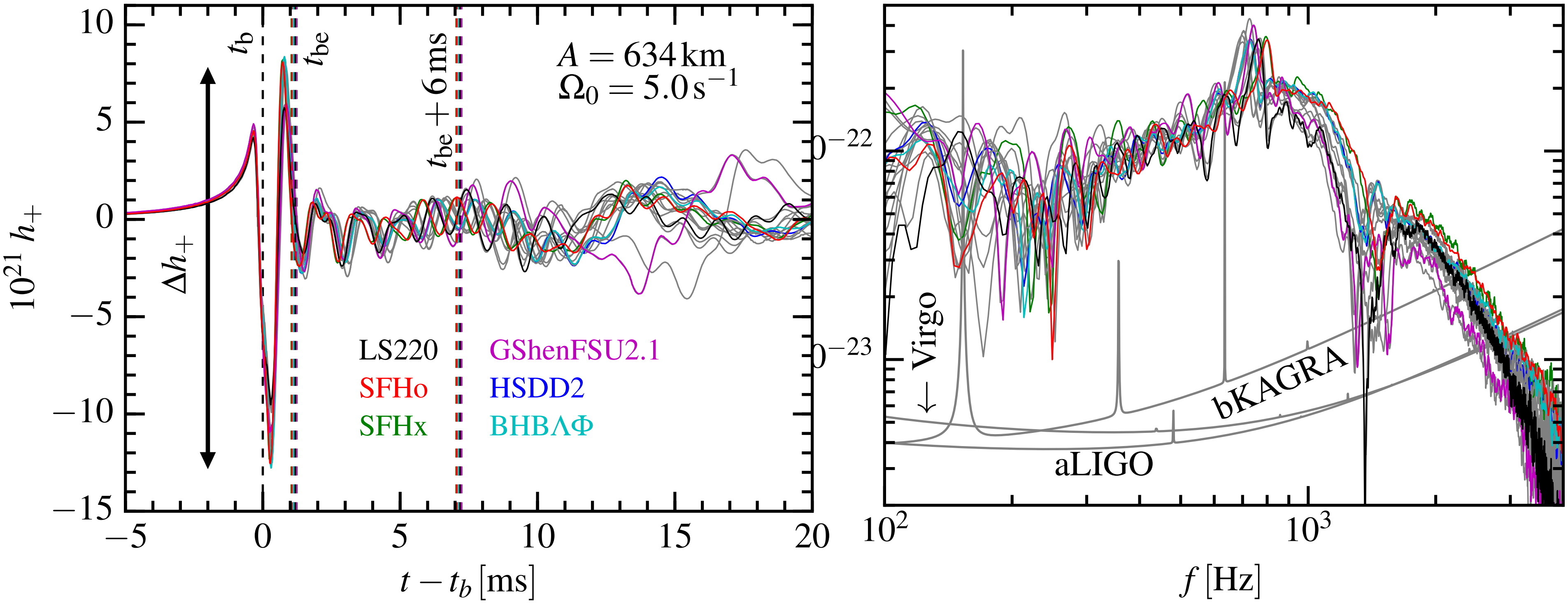


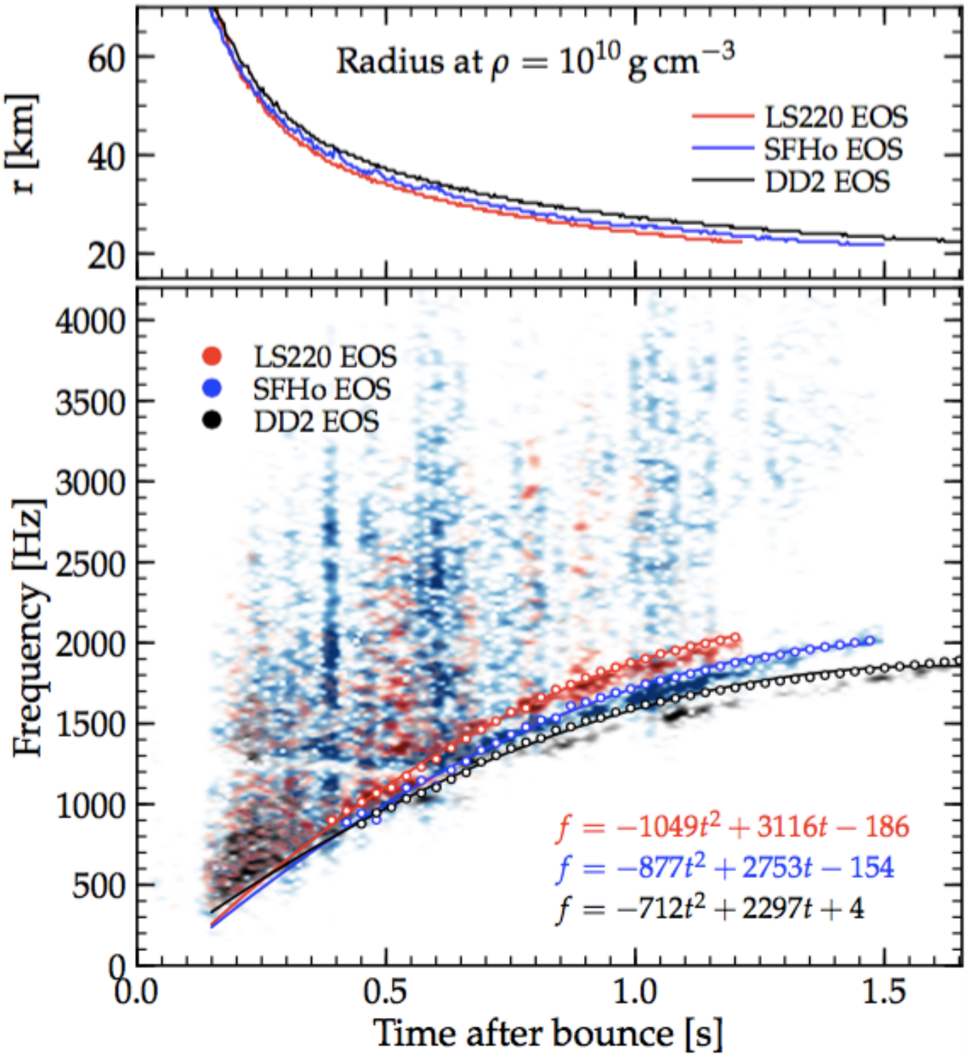
Morozova et al. 2018

EOS? Early Phase:



Richers et al. 2017

Dependence of the dominant GW frequency on the EOS

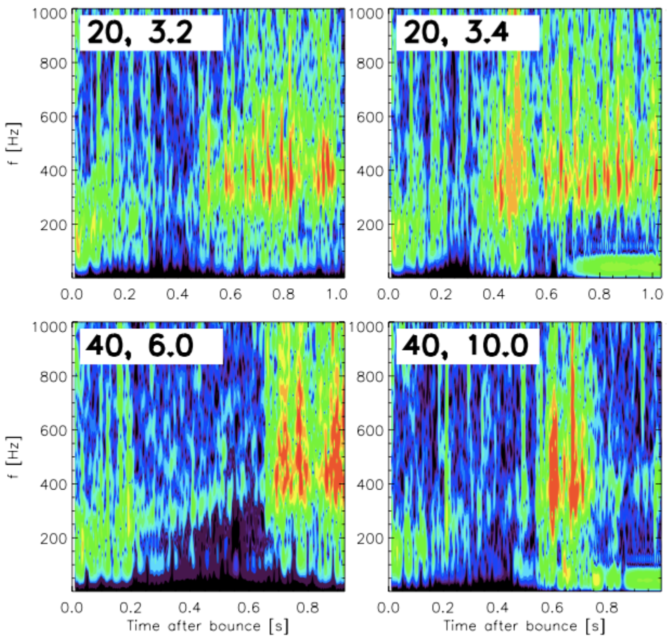


- Reflects the evolution of the PNS radius
- Captured reasonably well by the analysis
- Can be described by a quadratic function

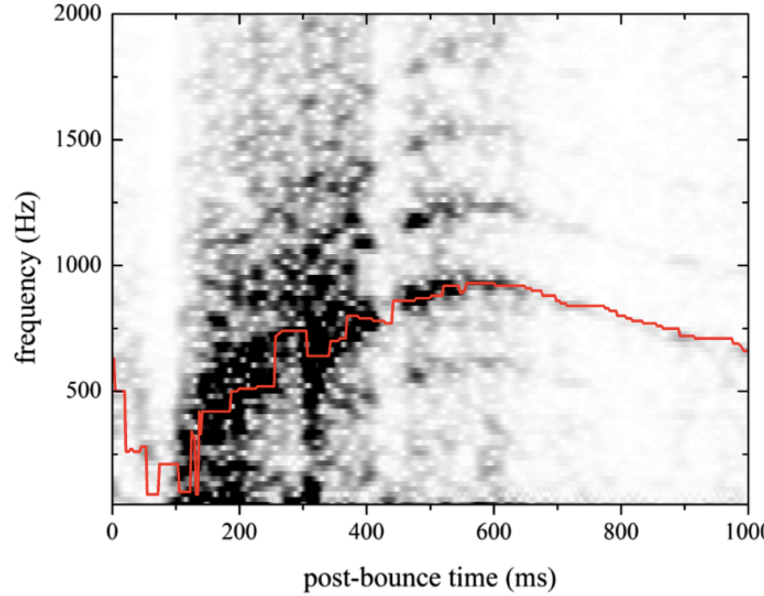
Morozova et al. 2018

Morozova et al. 2018

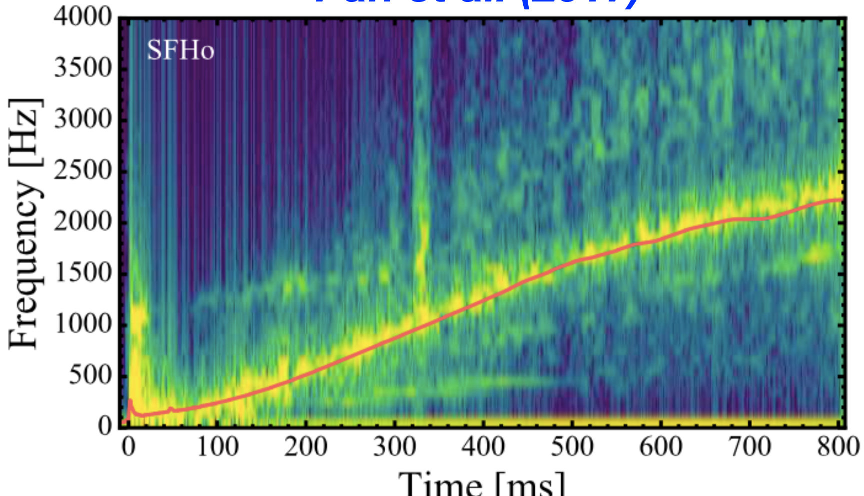
Murphy et al. (2009)



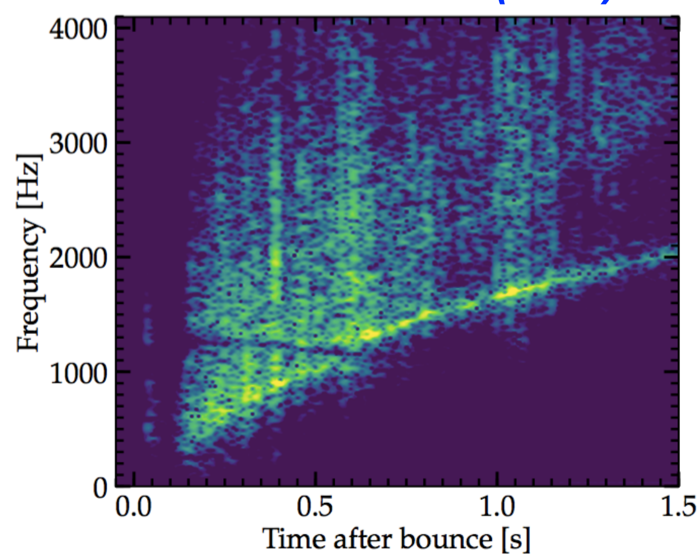
Yakunin et al. (2015)



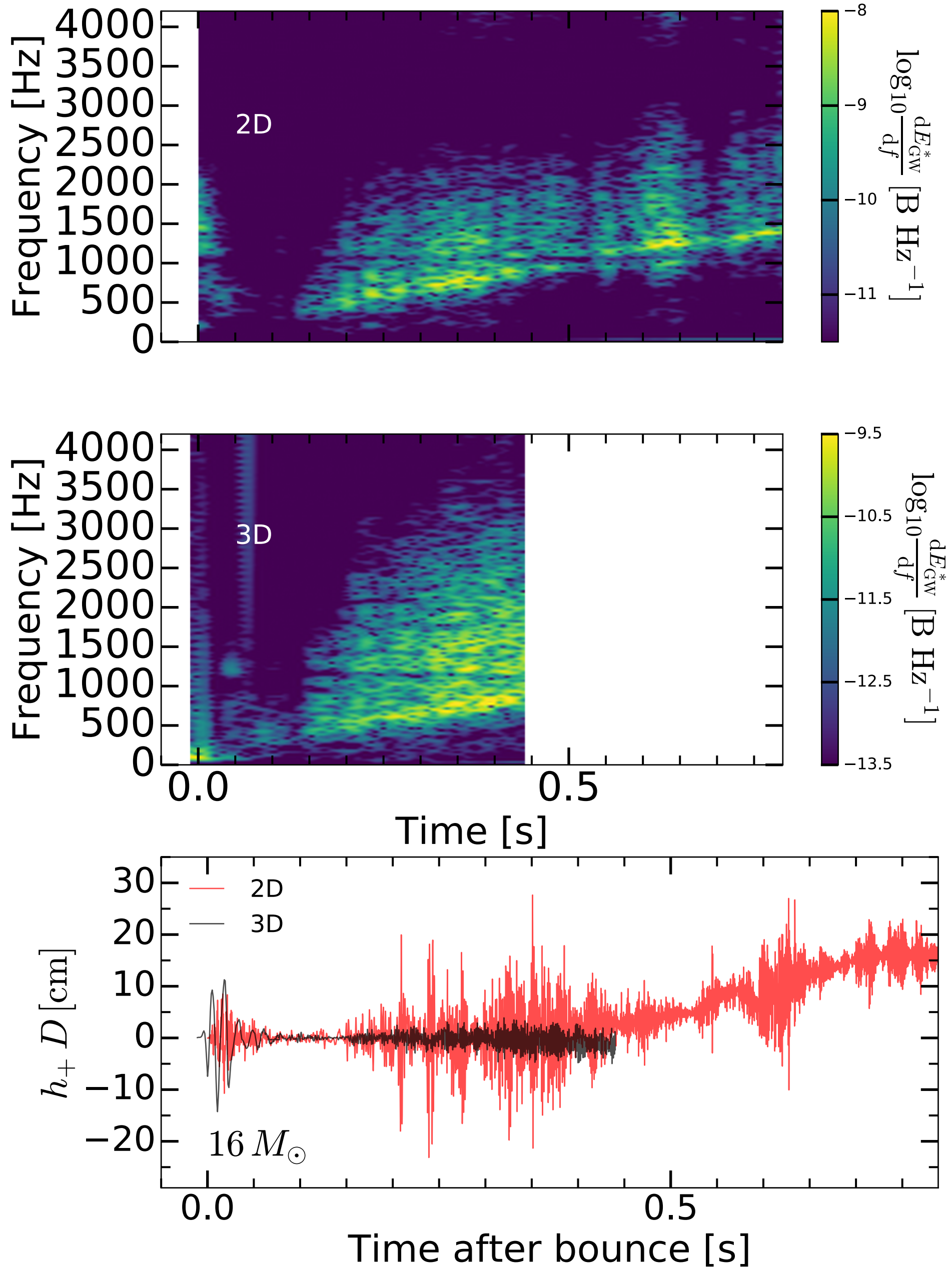
Pan et al. (2017)

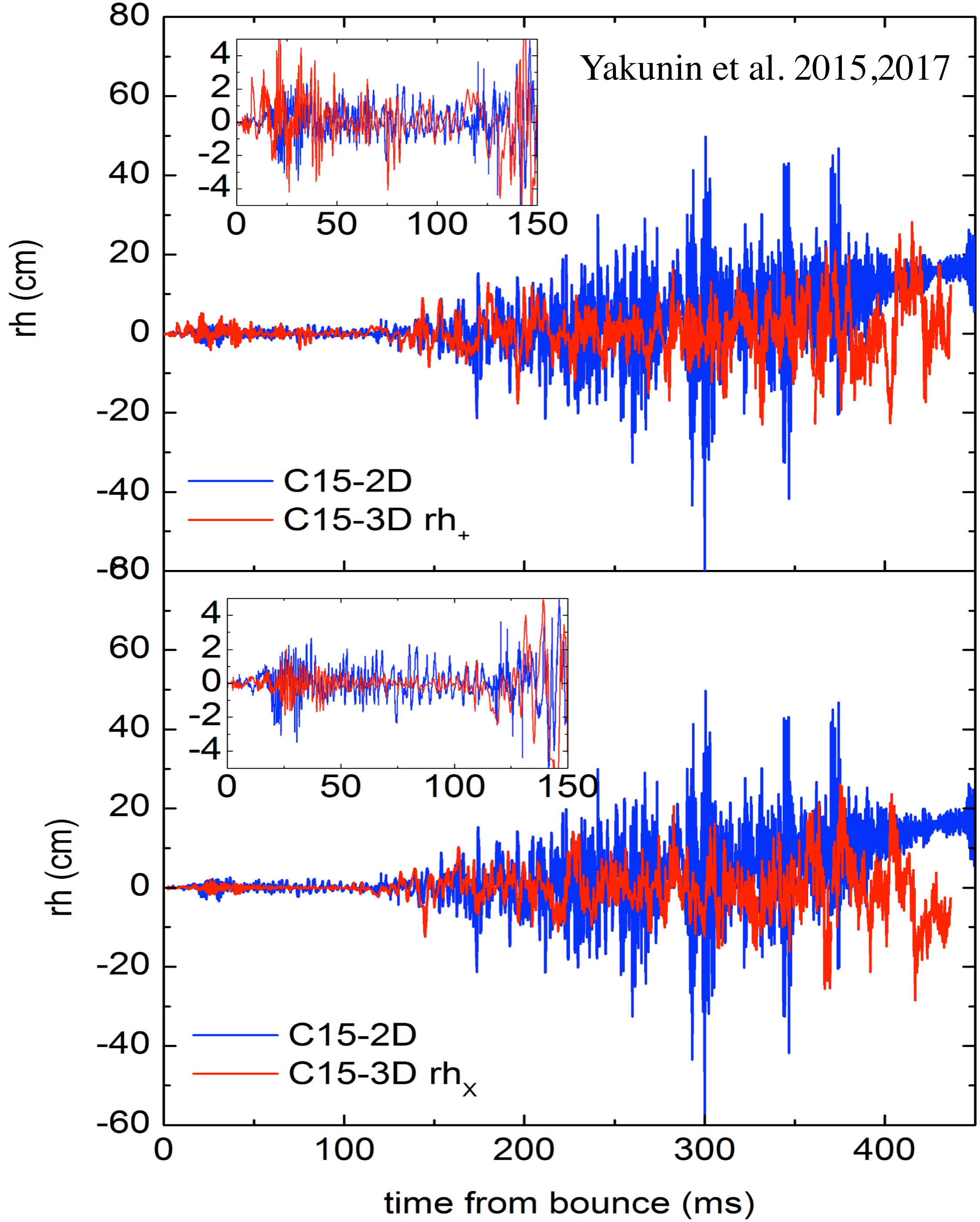


Morozova et al. (2018)



Vartanyan, Burrows, Radice et al. et al. 2018




Yakunin et al. 2015,2017
rh (cm)
C15-2D
C15-3D rh+
C15-2D
C15-3D rhx
time from bounce (ms)

Core-Collapse Theory: A Status Summary

- "Mazurek's Law" Violated in Multi-D near Criticality
- Feedbacks severe in 1D, but in 2D/3D there is a strong dependence on microphysics and computational details
- Proximity to critical explosion curve amplifies effects of sub-dominant processes, etc.
- Can explain current differences between groups (!?)

- Multi-D is Key Enabler of explosion for (almost) all viable mechanisms
- Neutrino-driven convection > SASI (when object explodes to yield SN)
- SASI is not a mechanism – can't generate much entropy
- "Ray-by-ray" is problematic in 2D
- 3D different from 2D (turbulent pressure, spectrum; scales)!
- GR important? Newtonian Models can explode

- Various heating processes (in-medium/many-body, inelastic on electrons, inelastic on nucleons) add "non-linearly"
- Structure factor/many-body corrections! Neutrino-matter interactions!

- Progenitor profiles/structure important! (e.g., Meakin & Arnett; Couch et al. 2015; B. Muller et al. 2016); Seed Perturbations, Density profiles, Si/O shelfs?
- Rotation!?
- Crucial role for microphysics – many-body/structure-factor corrections, inelastic scattering; when near critical curve, small effects are amplified – (partial) origin of differences between groups