State-of-the-art 3D Supernova Explosion Simulations

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Supported by:
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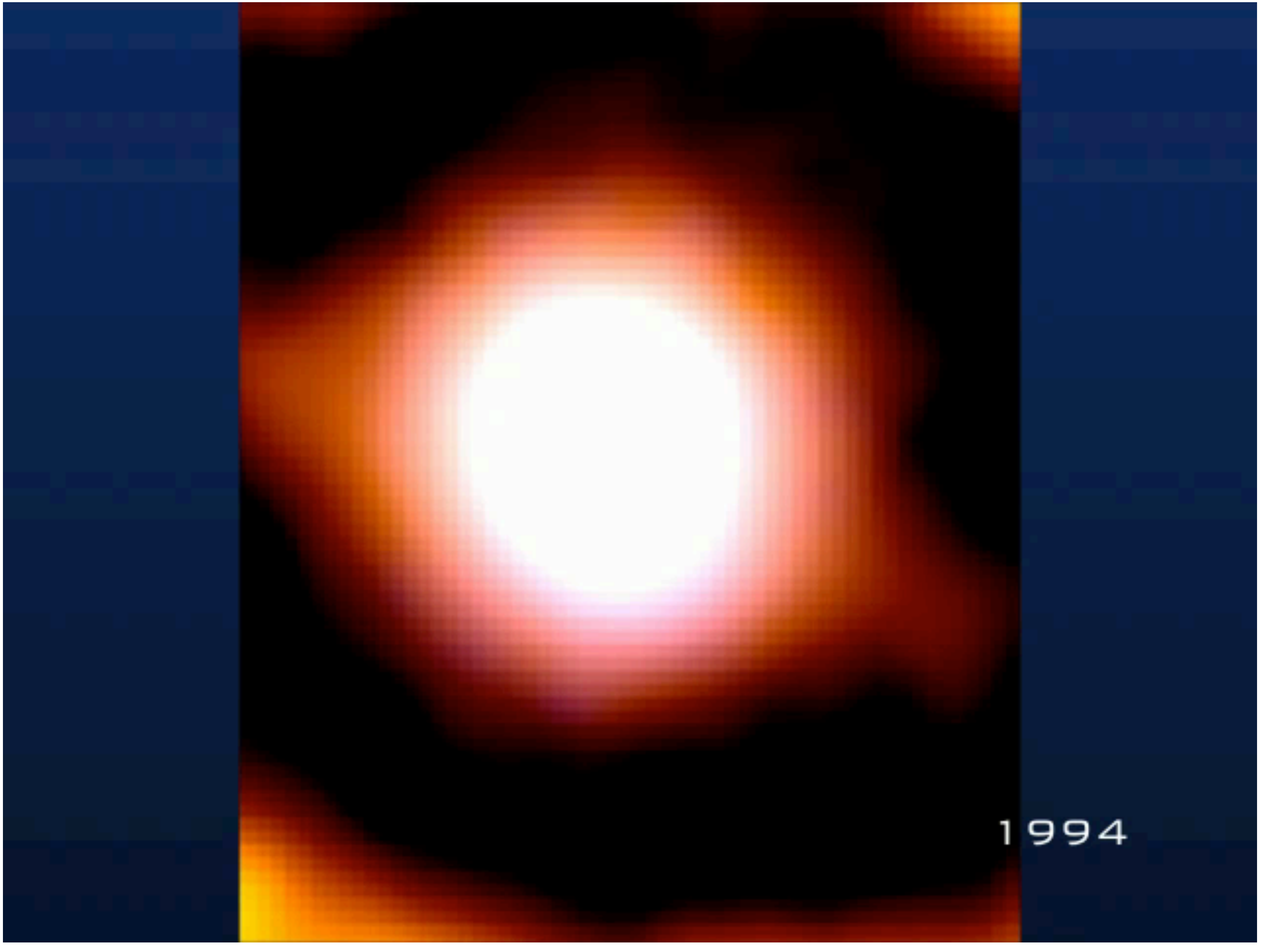
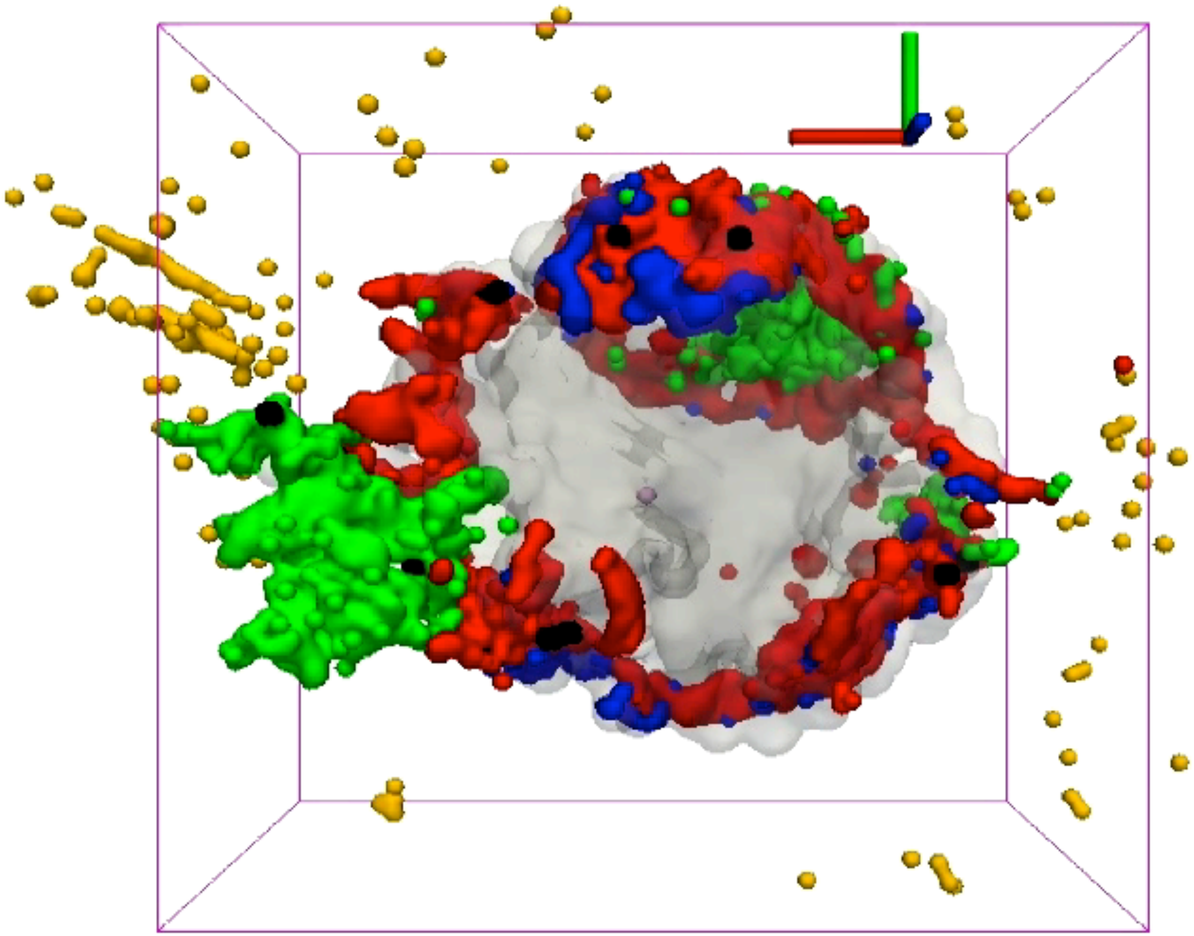
SN1987a (Pete Challis)



Cas A Remnant

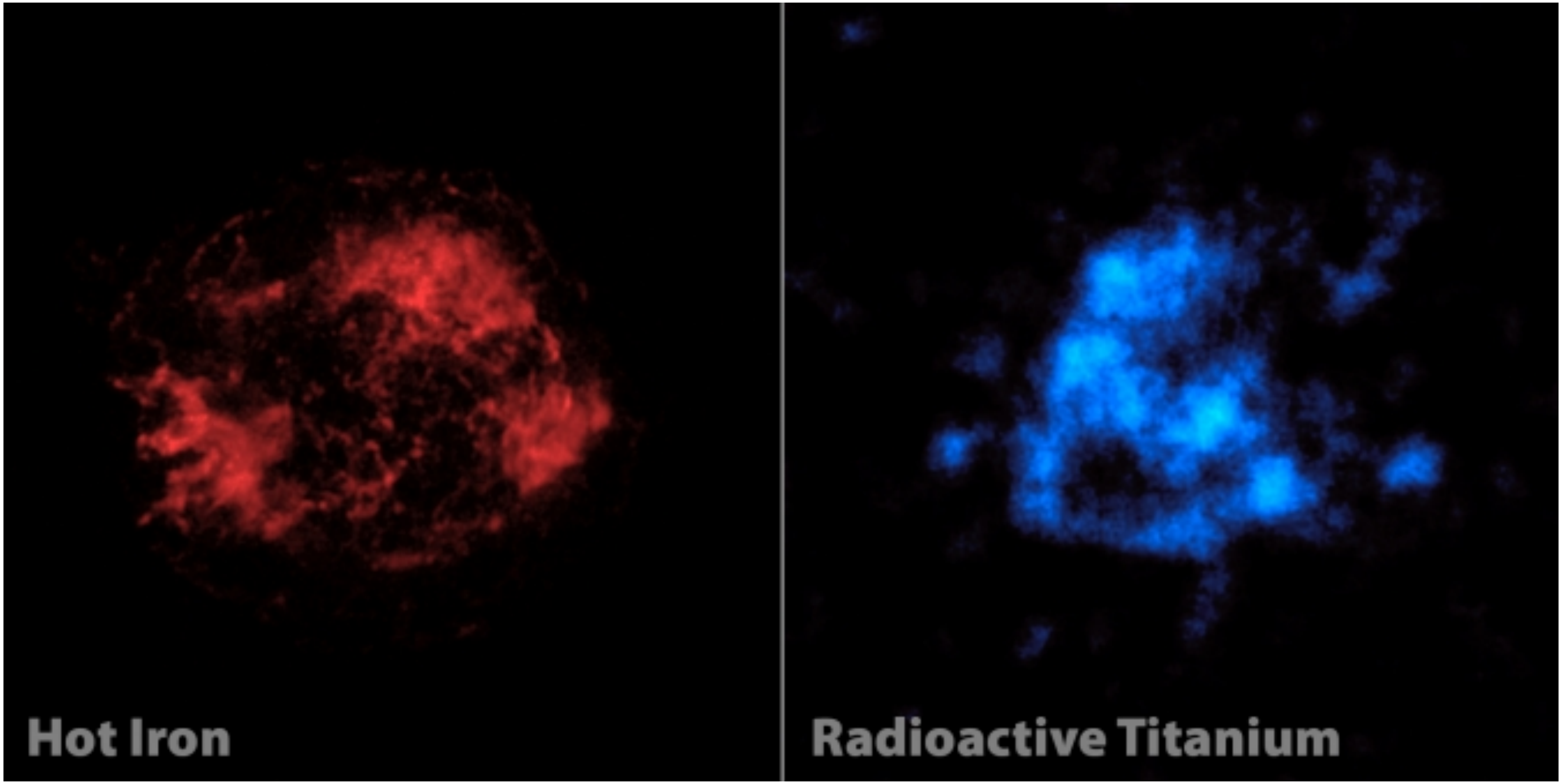
Fe

Si



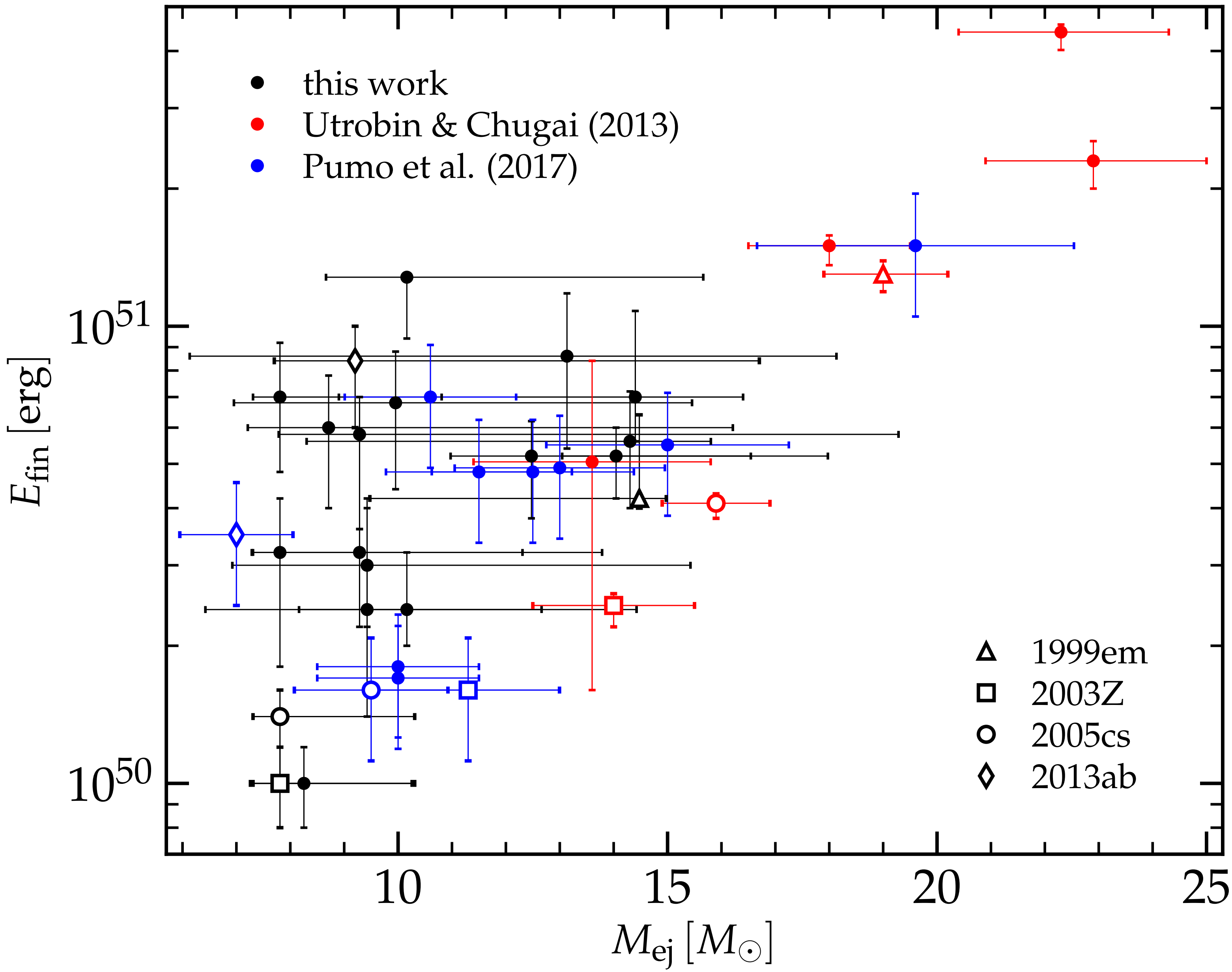
DeLaney et al. 2010

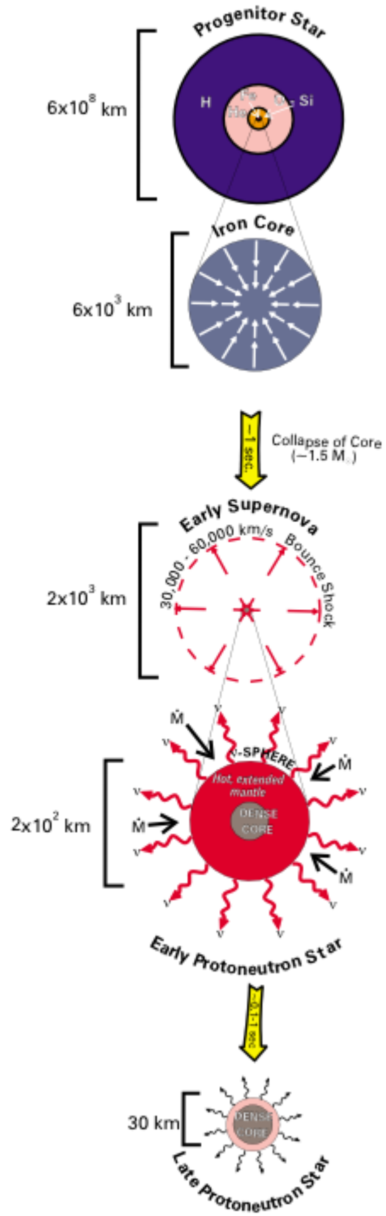
Cas A Remnant in ^{44}Ti



NuSTAR: Grefenstette et al. 2014

Morozova et al. 2018





Progenitor Star
$6x10^8$ km
H
He
Si
Iron Core
$6x10^3$ km
~1 sec.
Collapse of Core
(~1.5 $M_\odot$)
Early Supernova
30,000 - 60,000 km/s
Bounce Shock
$2x10^3$ km
ν-SPHERE
Hot, extended mantle
DENSE CORE
$2x10^2$ km
Ṁ
ν
Early Protoneutron Star
~0.1-1 sec
30 km
DENSE CORE
Late Protoneutron Star

Essential Elements of Neutrino Mechanism

- Pseudo-Chandrasekhar core collapses for hundreds of seconds
- Bounces at nuclear densities and launches a shock wave
- Shock wave stalls due to breakout neutrino losses and photodissociation of accreta within 10's of milliseconds at ~100-150 km into an accretion shock

- Neutrino emission from the inner core (PNS) heats the "gain region" behind the shock, and drives turbulent convection
- Neutrino energy deposition behind the shock and turbulent pressure together eventually overcome the ram pressure of the continuing accretion to launch a supernova
- Delayed Explosion

- Core-collapse supernova explosion is a critical phenomenon/ bifurcation between steady solutions and exploding solutions
- Multi-D (expensive) necessary because most models don't explode (aren't reenergized) in 1D (spherical), but require the extra turbulent pressure/stress of neutrino-driven convection (and other effects)

Core-Collapse Theory: What's New?

- Turbulence crucial to most explosions, necessitating multi-D treatment
- In the last ten years, we could do multiple 2D simulations every year to explore parameters, understand systematics, and explore progenitor structure dependence.
- Techniques improved and computers sped up; resolution-dependence
- Can now do multiple 3D simulations per year (and afford to make a few mistakes!)
- GR, Many-body neutrino-matter corrections (more to do), and PNS convection lead to enhanced ν_μ losses, faster contraction, hence hotter ν_e and anti-ν_e neutrinospheres
- Incorporated inelastic neutrino-matter processes – extra neutrino heating
- Accretion of the Si/O interface; seed perturbations of progenitor (?)

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

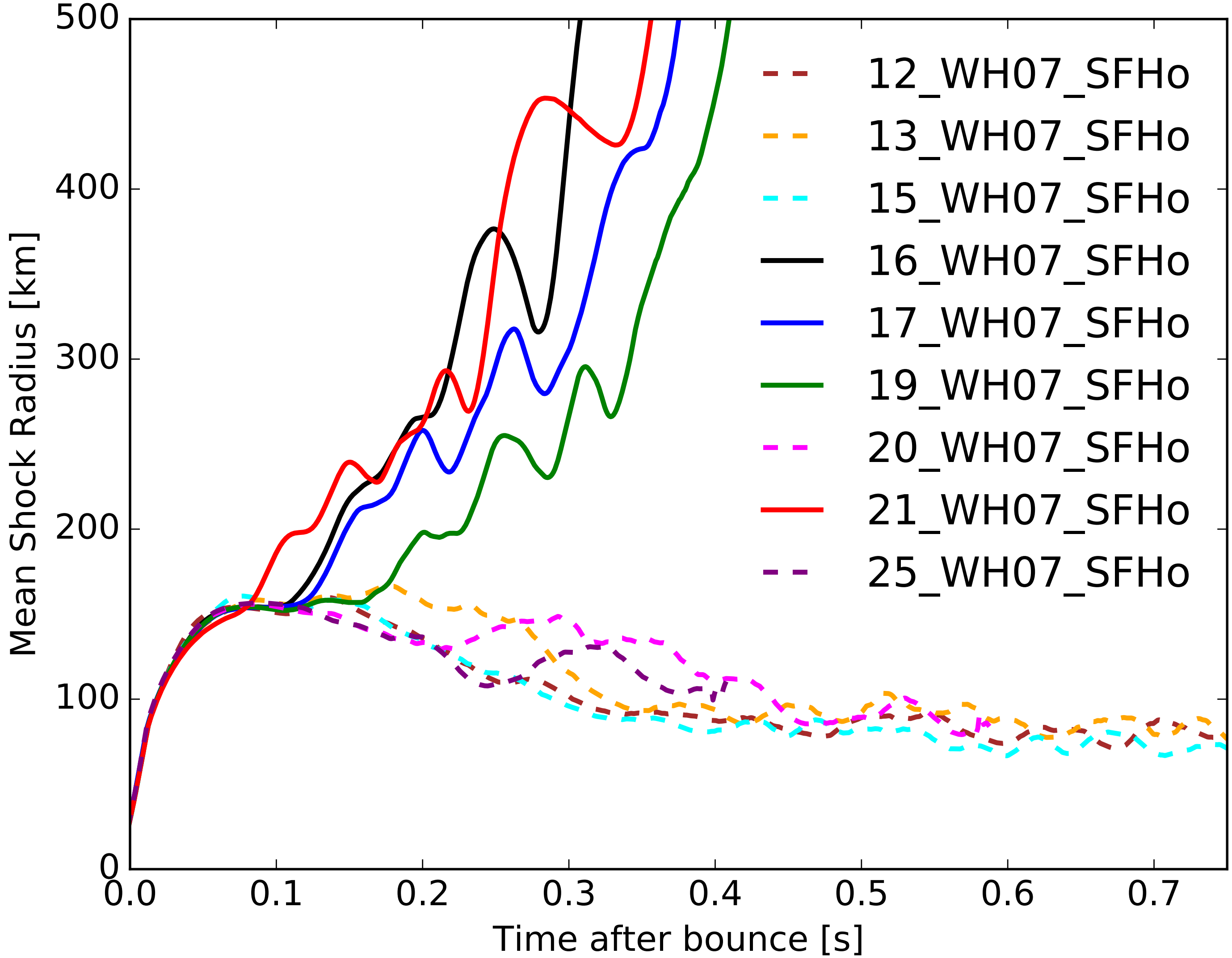
FORNAX: 1D,2D,3D, Multi-Group, Explicit Radiation/Hydrodynamics

- 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; inelastic/redistribution scattering
- Implicit solution to the local transport source terms
- Explicit hydro; full energy and momentum couplings – HLLC
- Conserves energy and momentum 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
- Good strong scaling in core count and scaling in energy group
- Result: Fast multi-D supernova code (by factor of ~5-10 x many other codes)
- Skinner et al. 2016 ; Radice et al. 2017; Burrows et al. 2018; Skinner et al. 2019; Burrows et al. 2019; Vartanyan et al. 2018,2019

FORNAX (cont.)

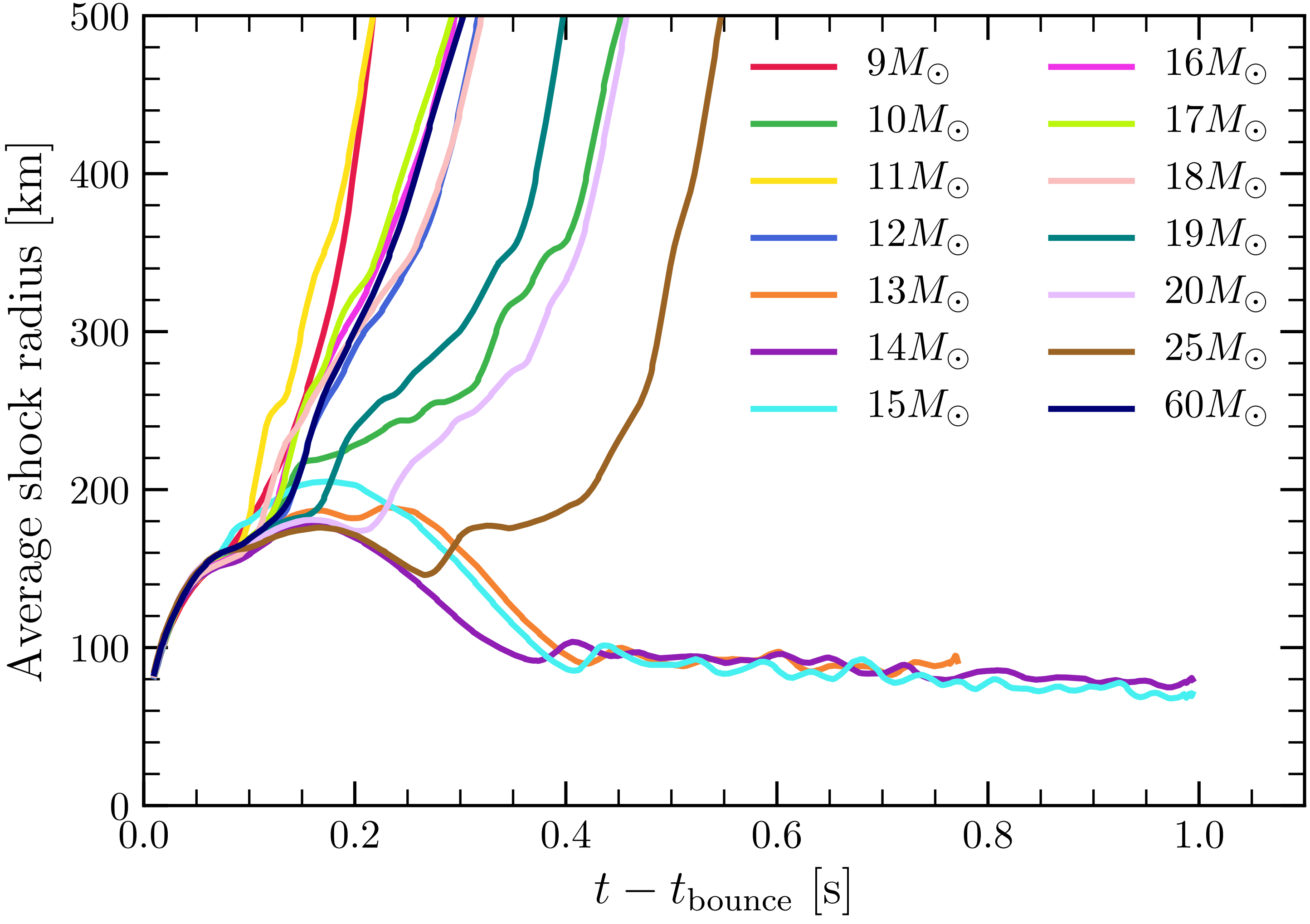
- Includes: Inelastic scattering off electrons
- Inelastic scattering off nucleons
- Includes in-medium Many-body response corrections (Horowitz et al. 2017)
- General-relativistic monopole gravity correction and gravitational redshifts (can compare with Newtonian)
- Multi-D transport, with rbr+ option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

2D Models



Vartanyan et al. 2017

3D Models

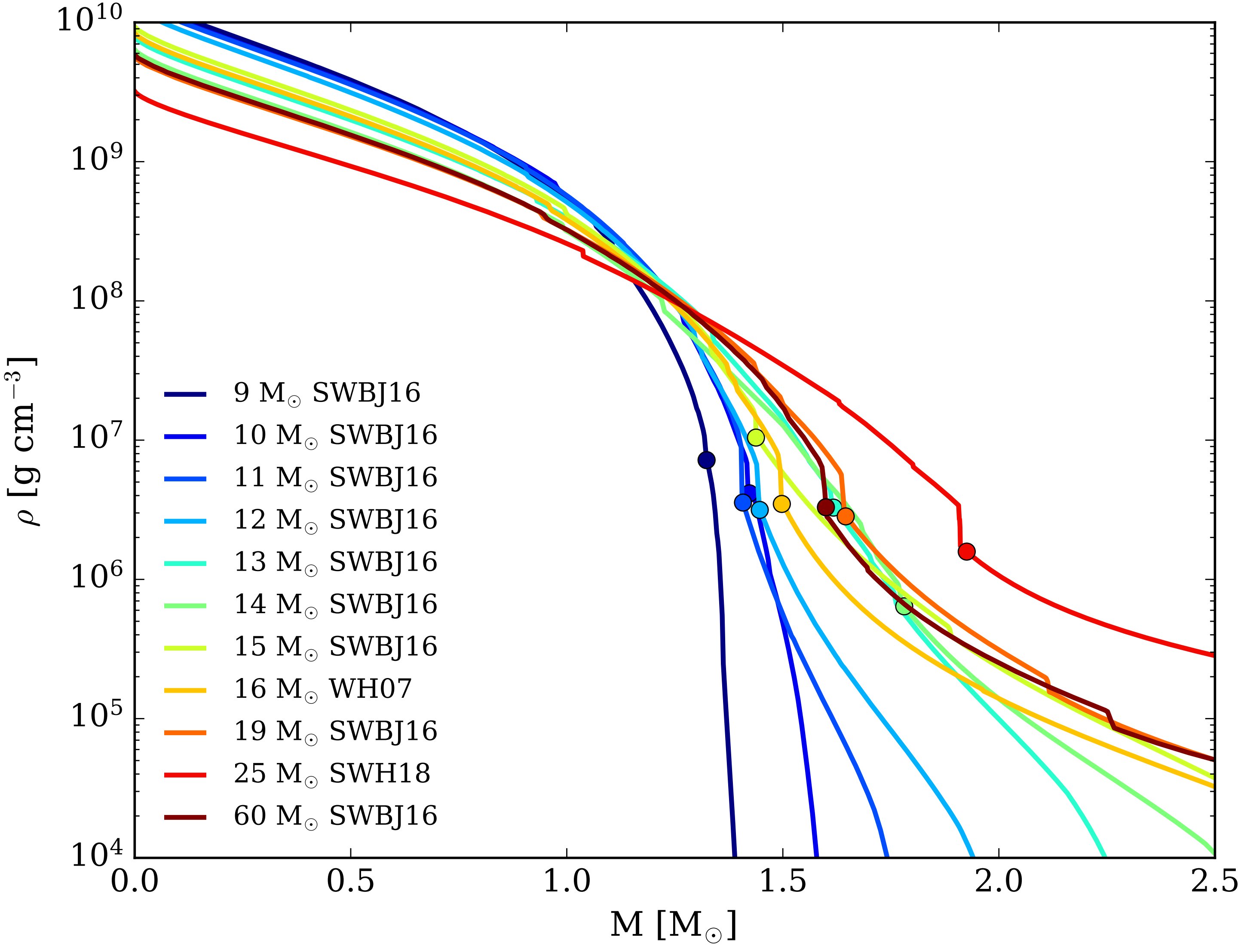


Burrows et al. 2019; Vartanyan et al. 2019ab; Radice et al. 2019

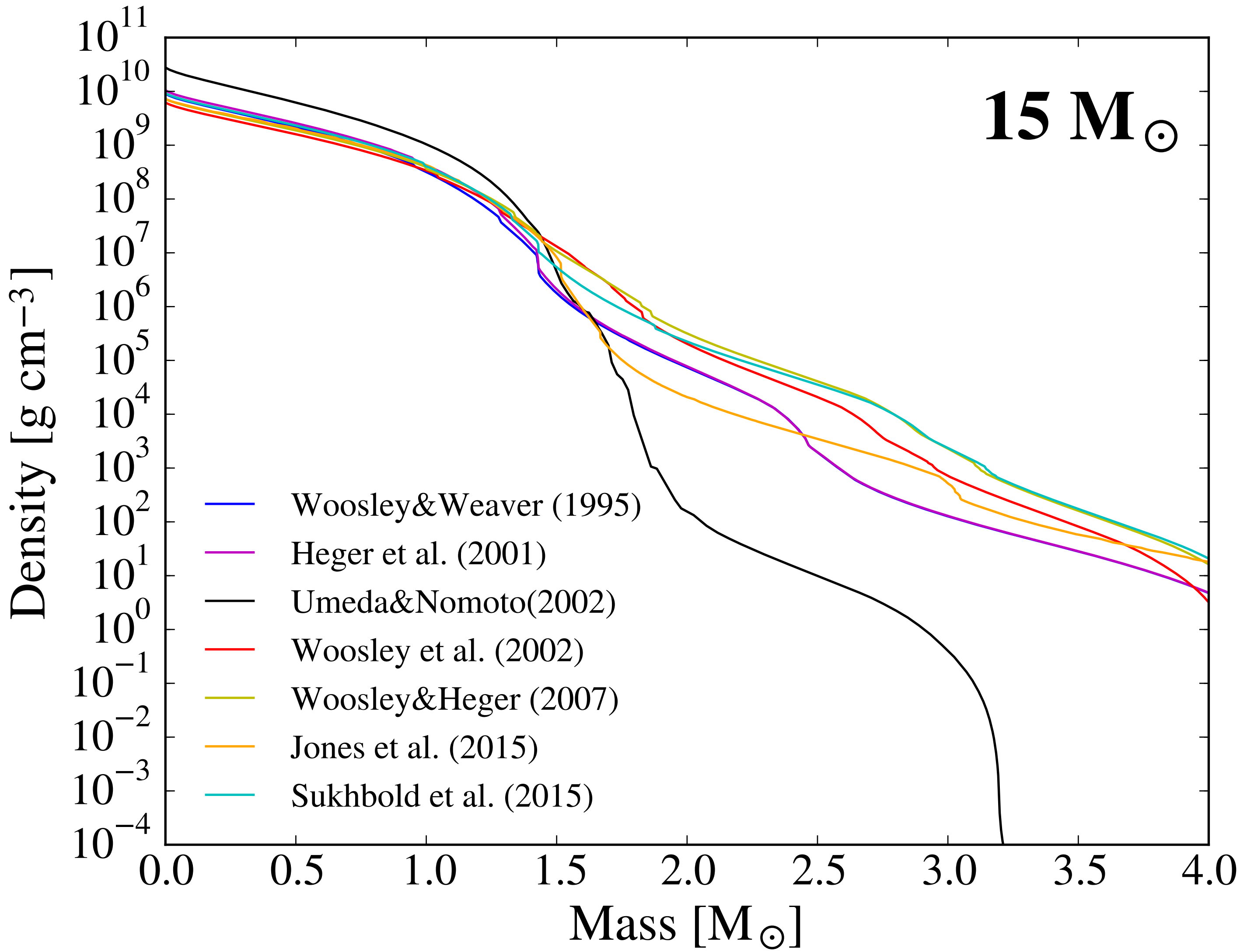
Important Roles of Progenitor Models:

Density Structures, Rotational Profiles, Seed Perturbations

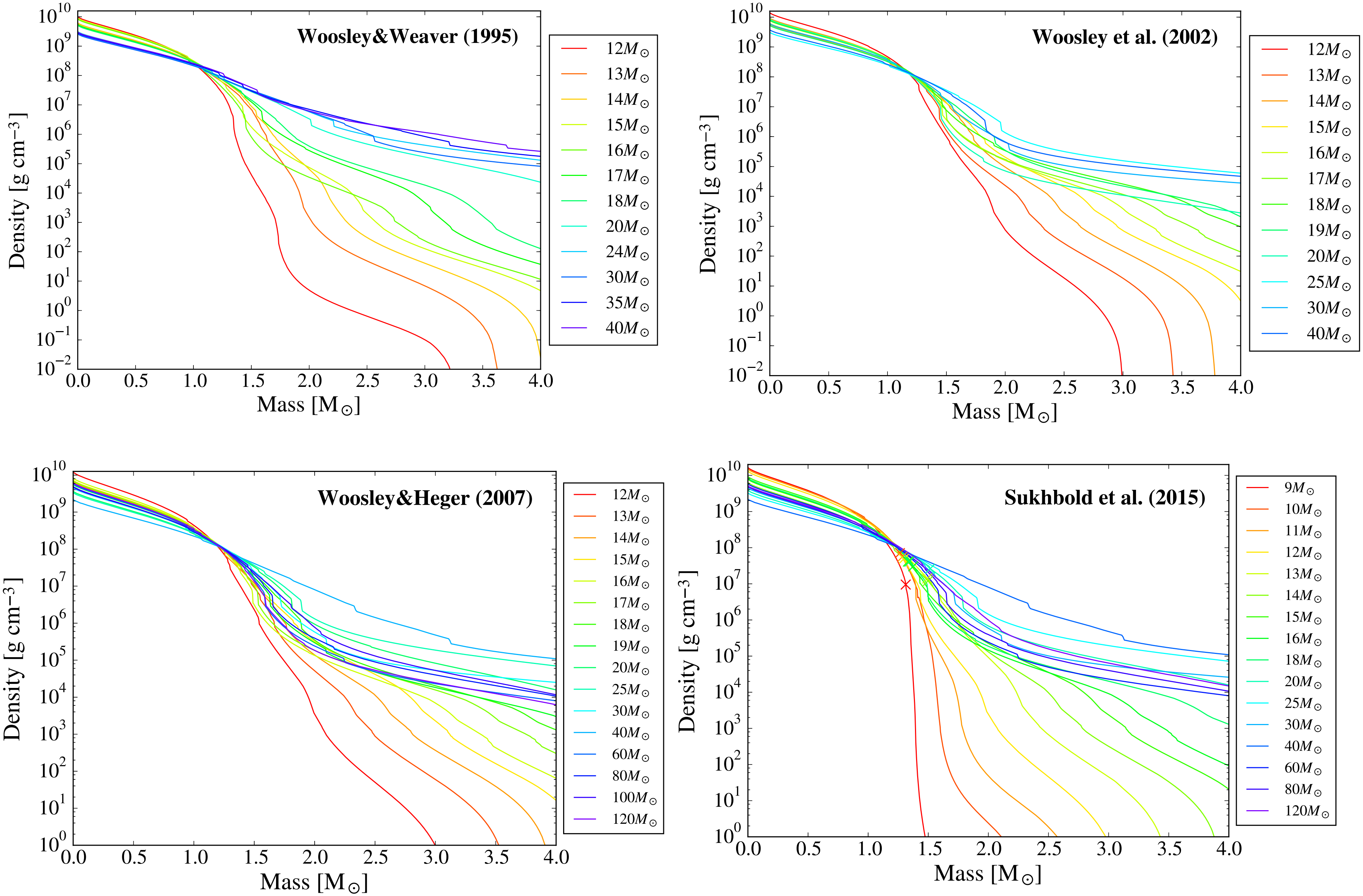
Progenitor Density Profiles



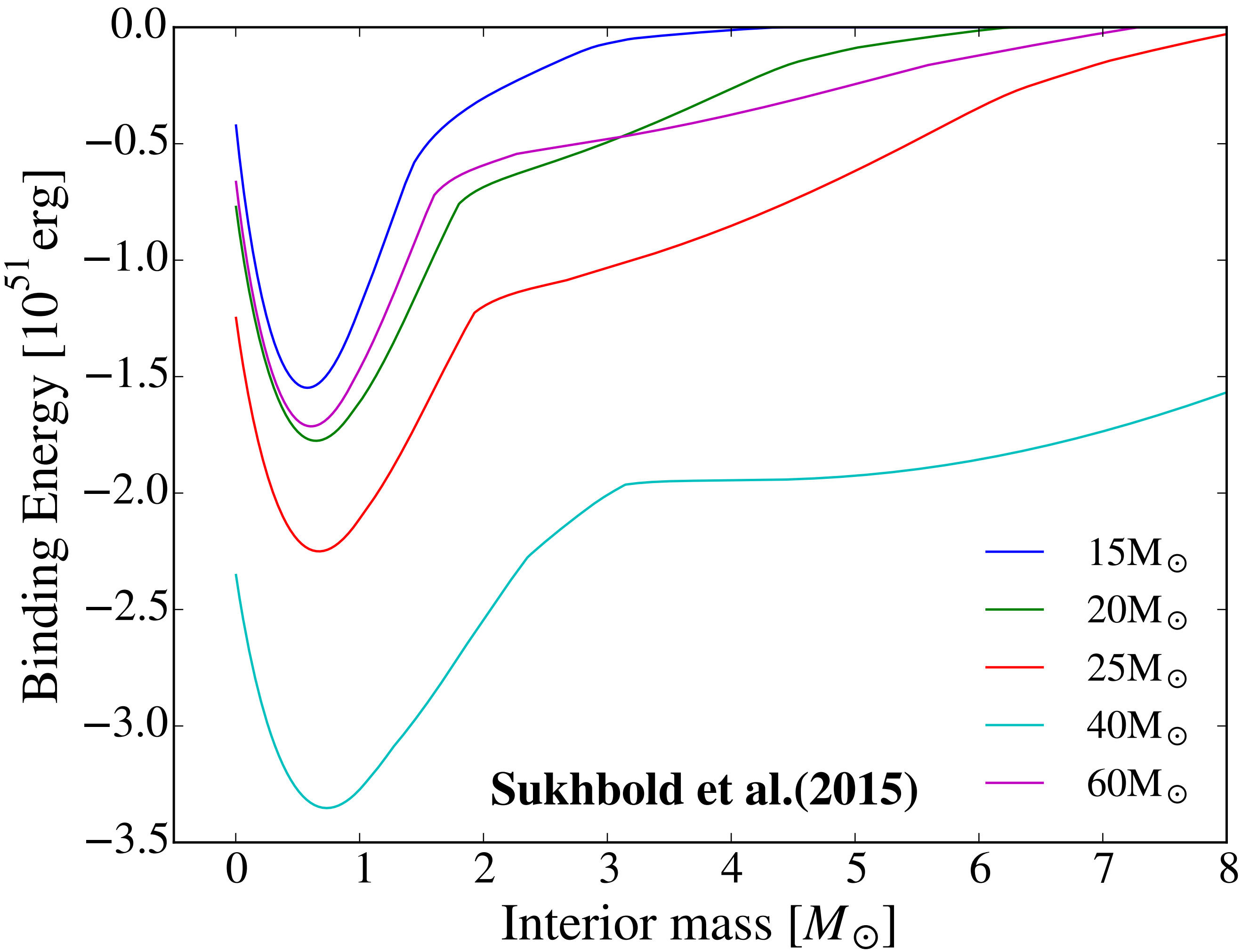
Different Groups, Same ZAMS Mass

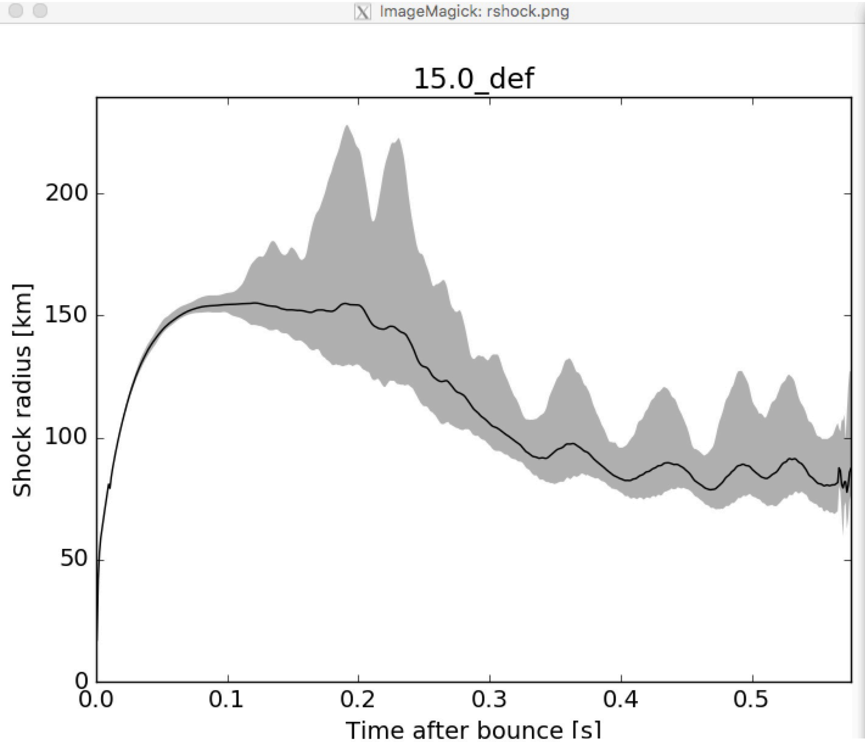


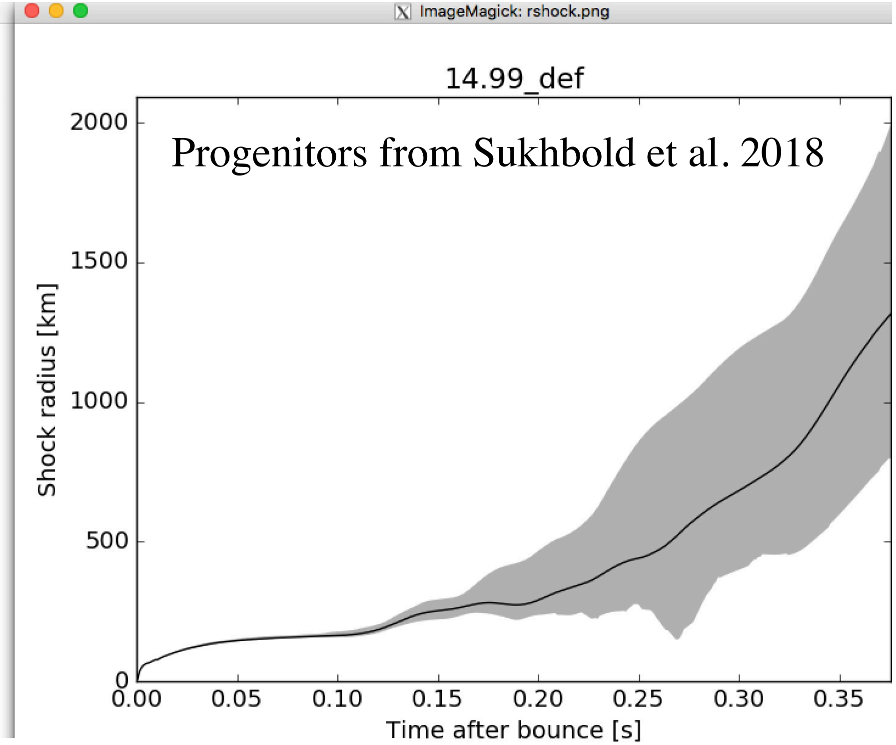
Density Profiles of Supernova Progenitor Cores: "Same" Group, Different Models

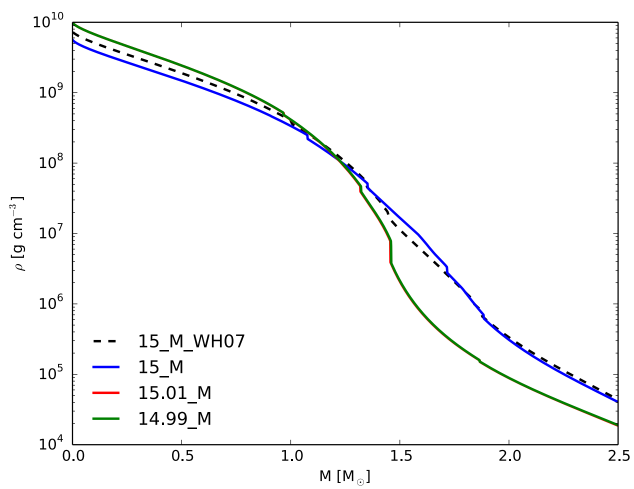


External Binding Energy More Important









Vartanyan, Burrows, et al. 2018b

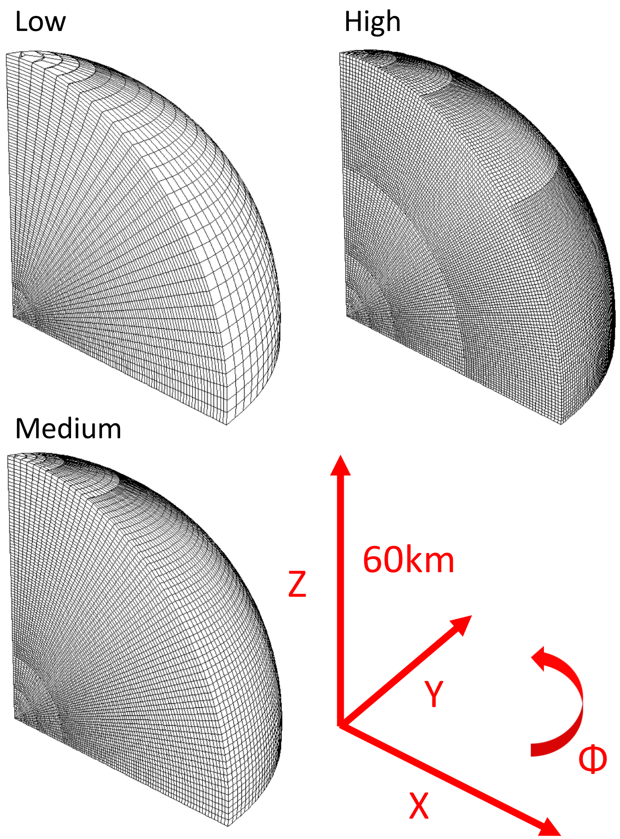
New Fornax 3D Simulations

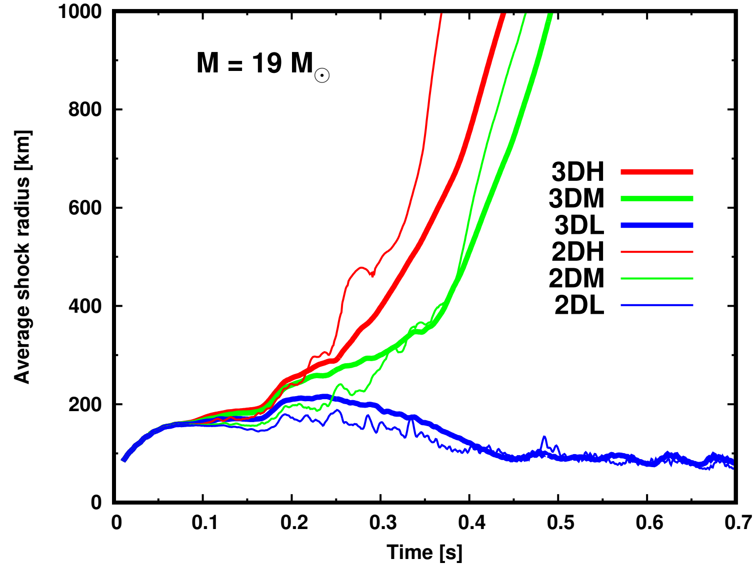
Adam Burrows, David Vartanyan, David Radice, Aaron Skinner, Viktoriya Morozova, Josh Dolence

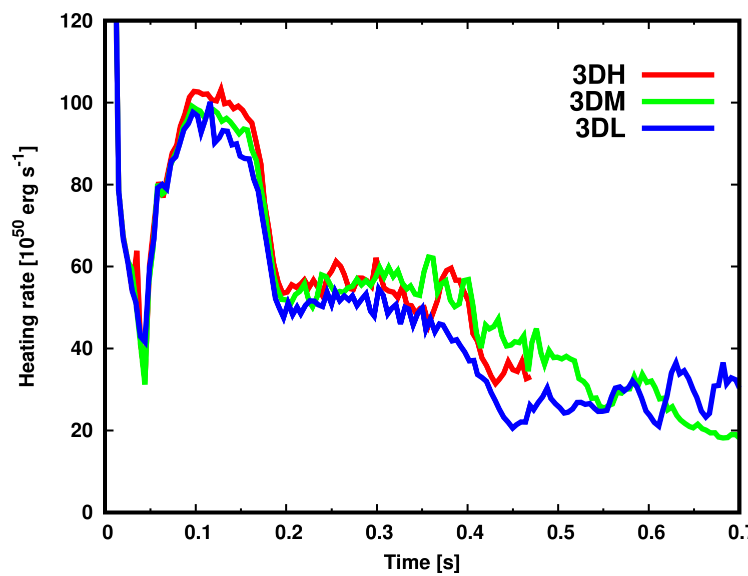
2D versus 3D

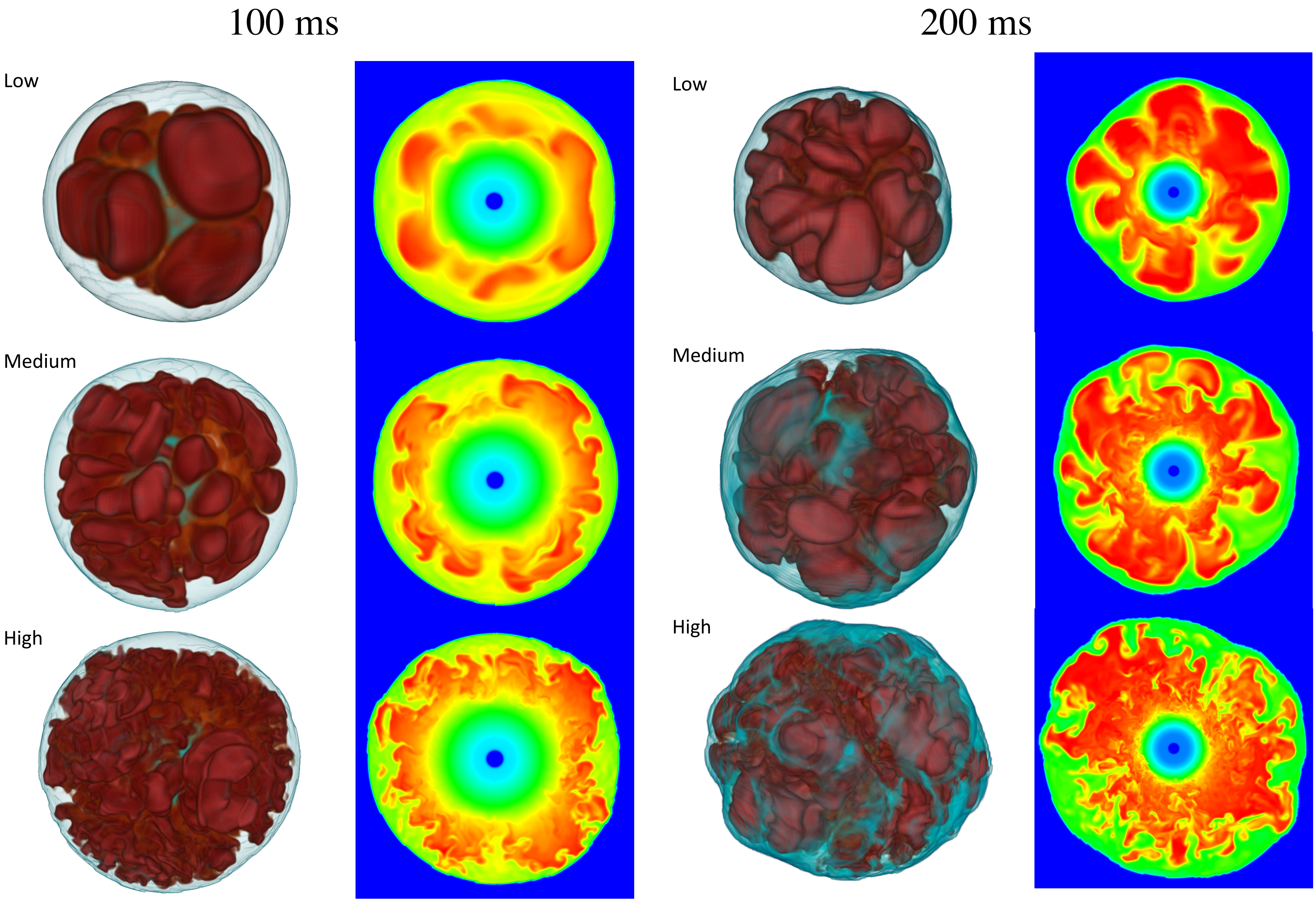
Spatial Resolution Dependence

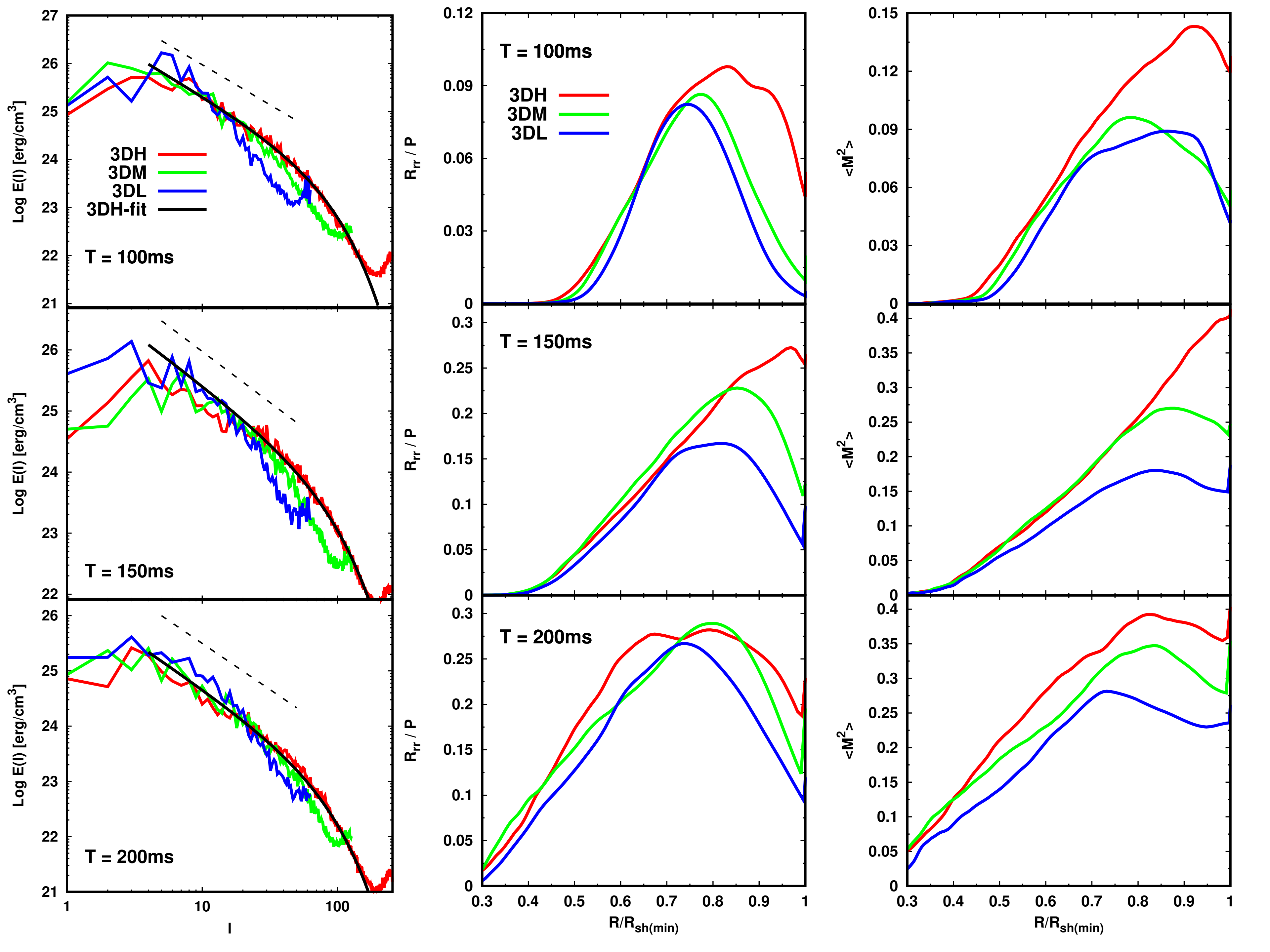
Nagakura et al. 2019


Low
High
Medium
60km
Z
Y
X
Φ


M = 19 M☉
Average shock radius [km]
Time [s]
3DH
3DM
3DL
2DH
2DM
2DL
0
200
400
600
800
1000
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7


Heating rate [10^50 erg s^-1]
Time [s]
3DH
3DM
3DL
0
20
40
60
80
100
120
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7


100 ms
200 ms
Low
Medium
High
Low
Medium
High

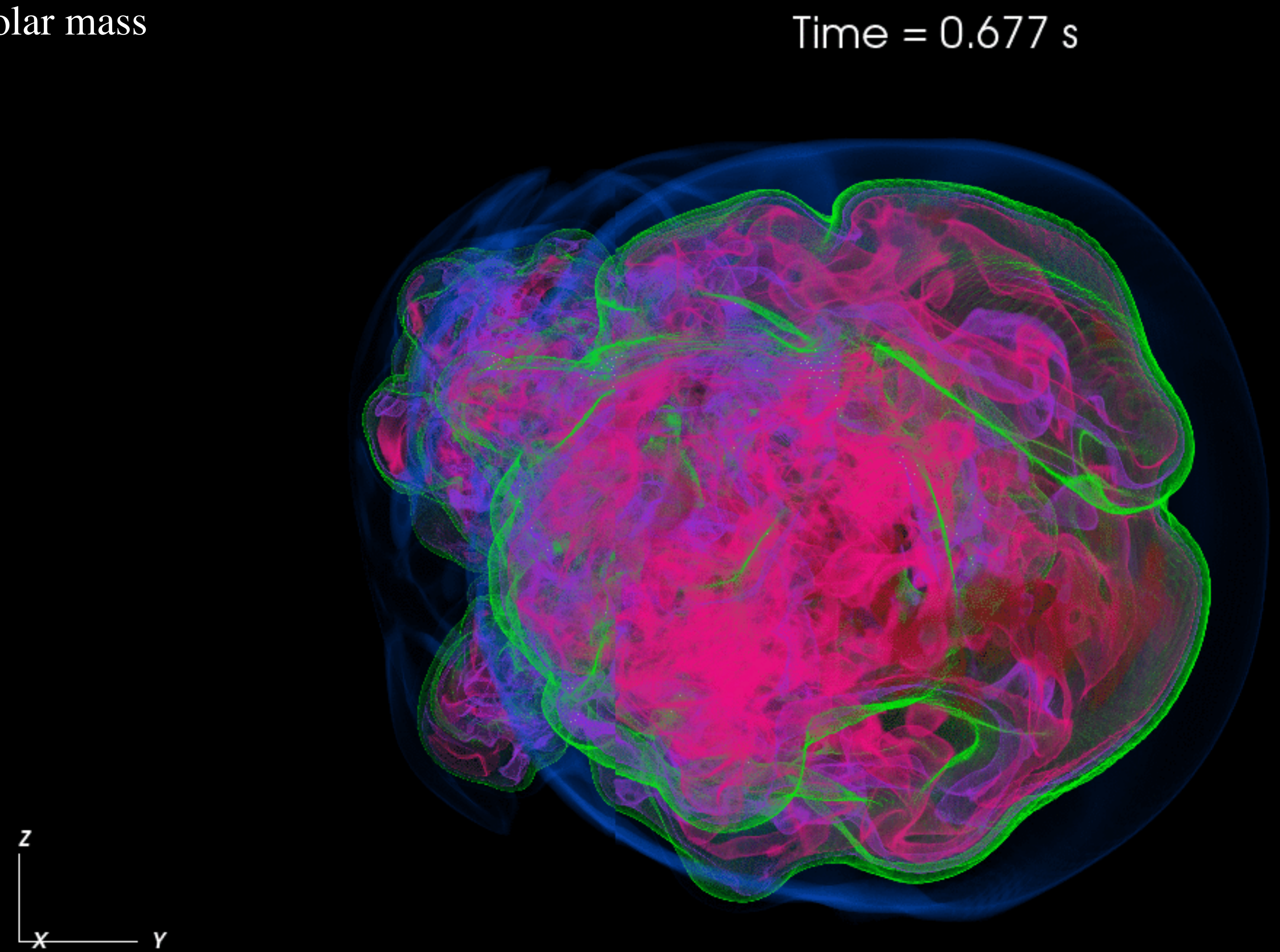


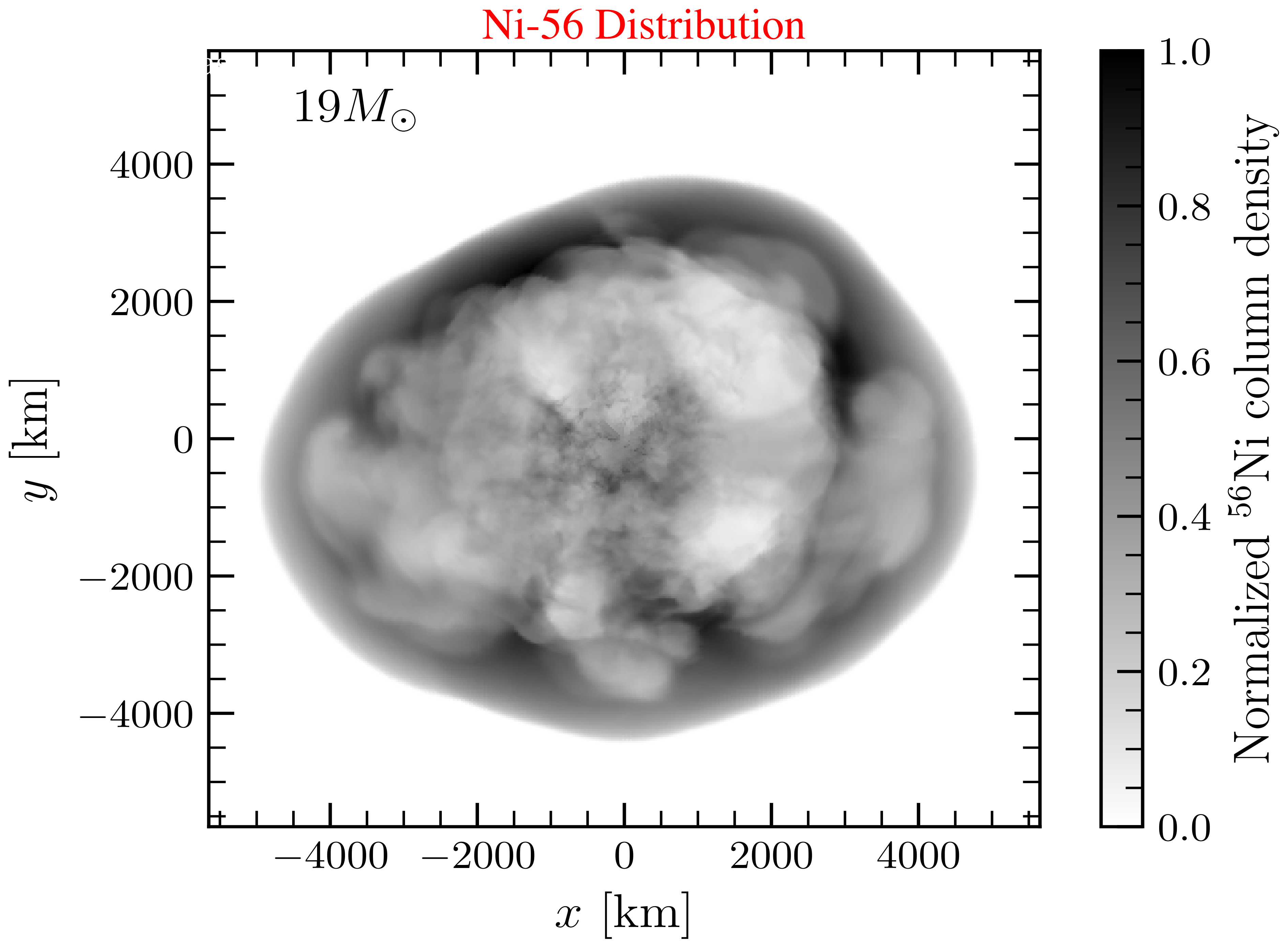
Log E(l) [erg/cm^3]
l
3DH
3DM
3DL
3DH-fit
T = 100ms
T = 150ms
T = 200ms
R_{rr} / P
$\langle M^2 \rangle$
R/$R_{sh(min)}$

Nagakura et al. (2019) –

19 solar masses resolution study

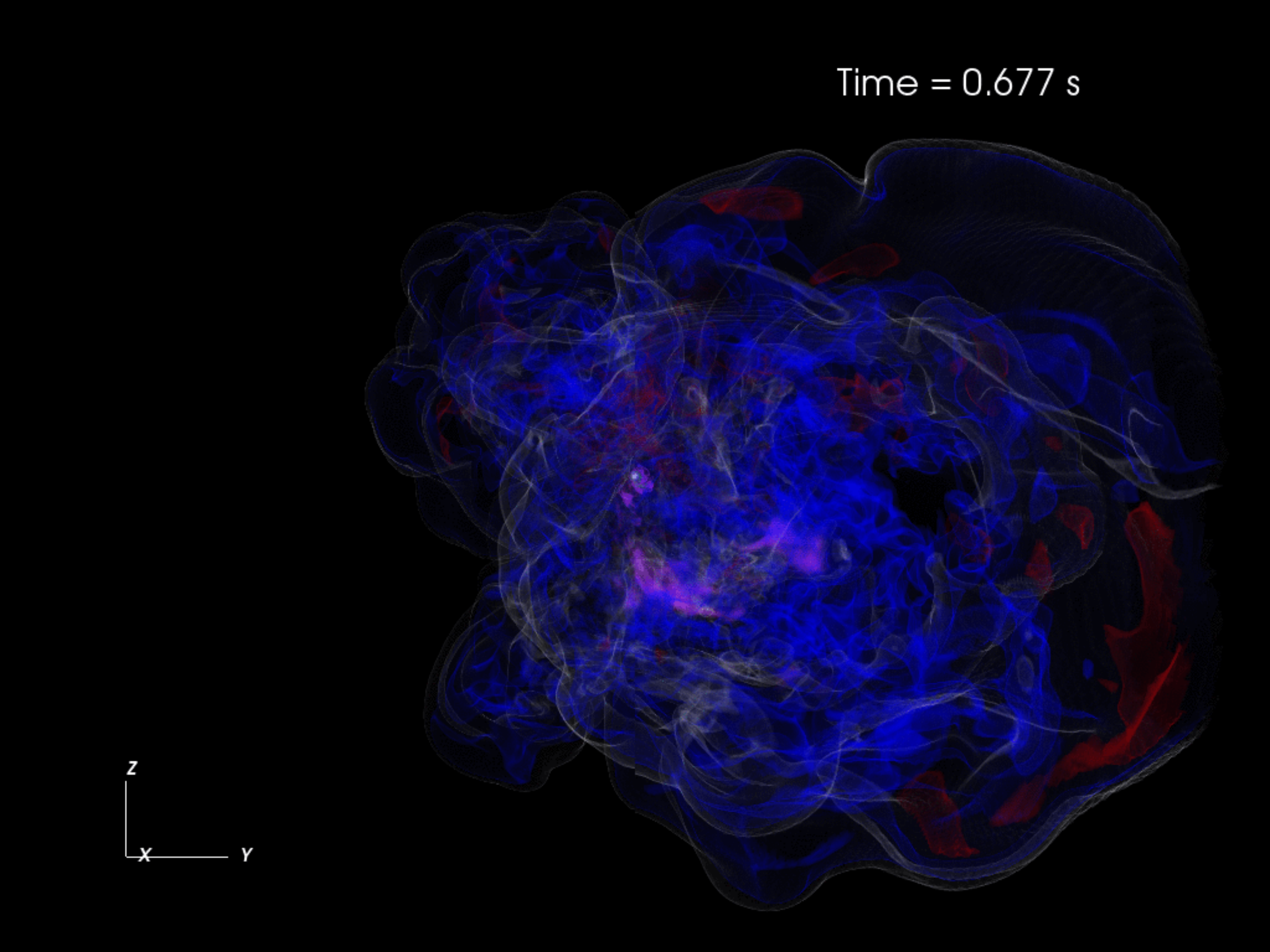
16 solar mass





Ni-56 Distribution
$19M_\odot$
4000
2000
0
−2000
−4000
y [km]
−4000
−2000
0
2000
4000
x [km]
1.0
0.8
0.6
0.4
0.2
0.0
Normalized ^{56}Ni column density

Burrows et al. (2019) – 13
solar mass (horo)

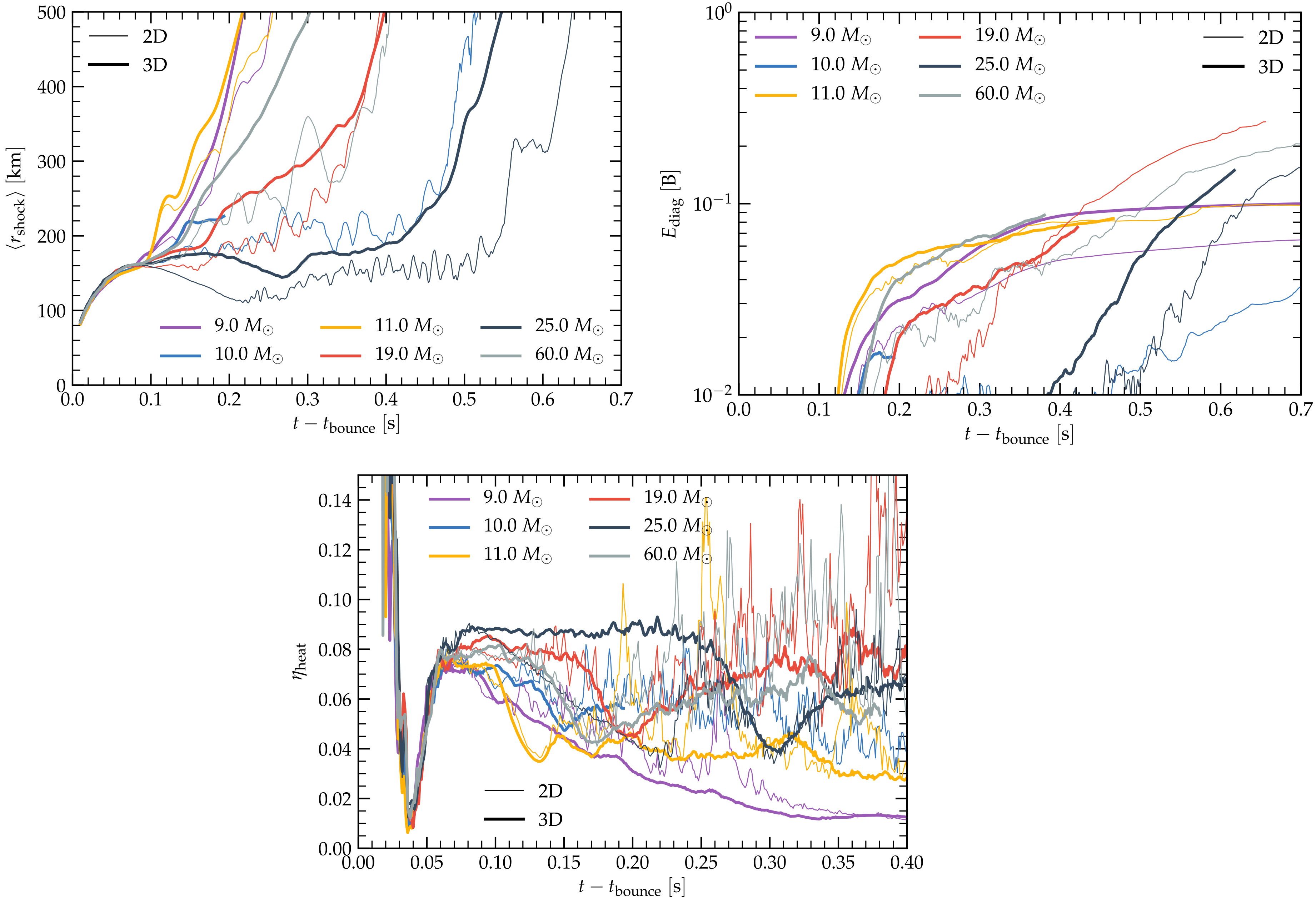

Time = 0.677 s
Z
X
Y

Radice, Burrows et al.
(2019)– 25 solar mass

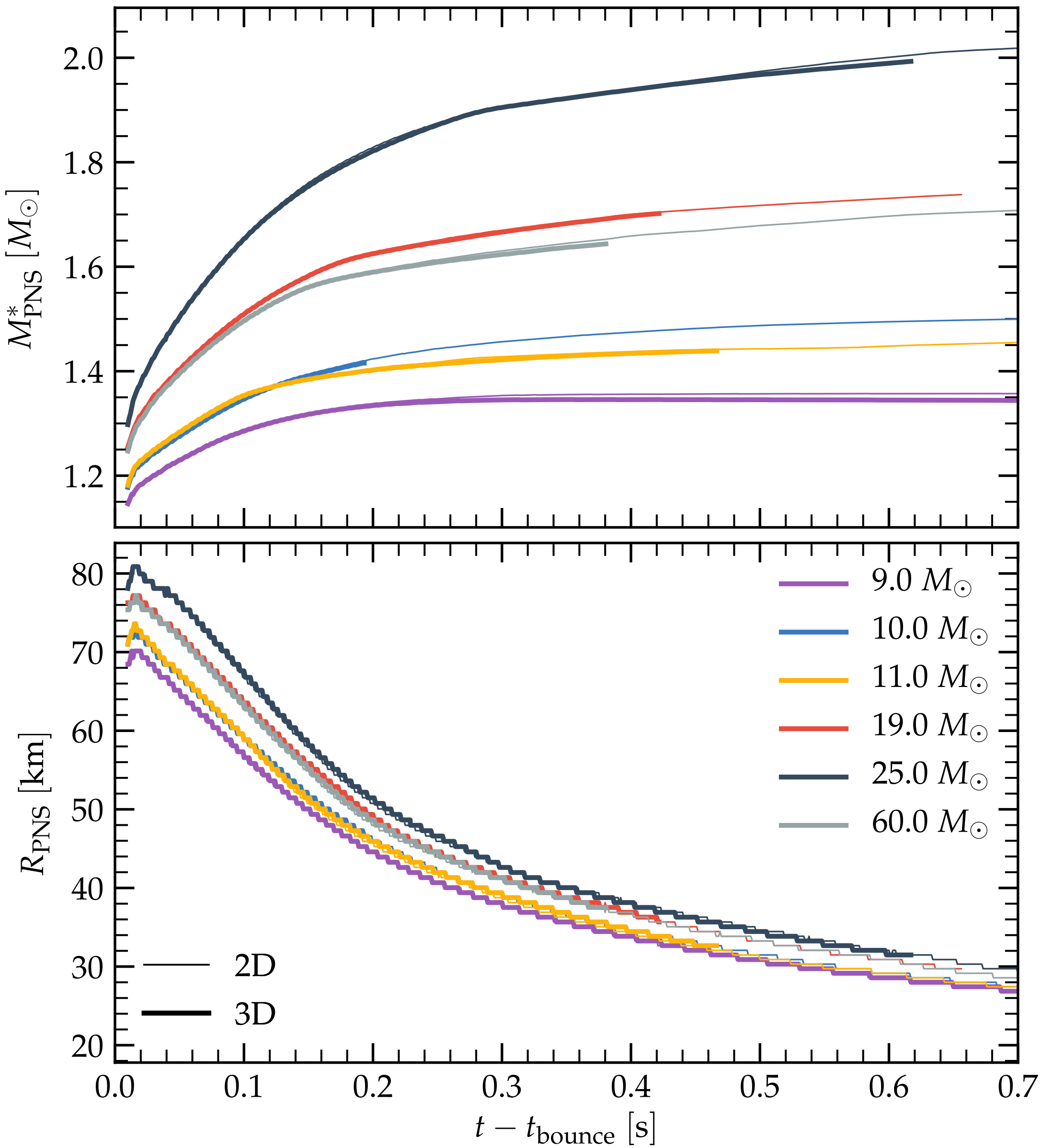
Time: 0.100 s

Radice, Burrows et al. (2019)– 25 solar mass

16 solar mass



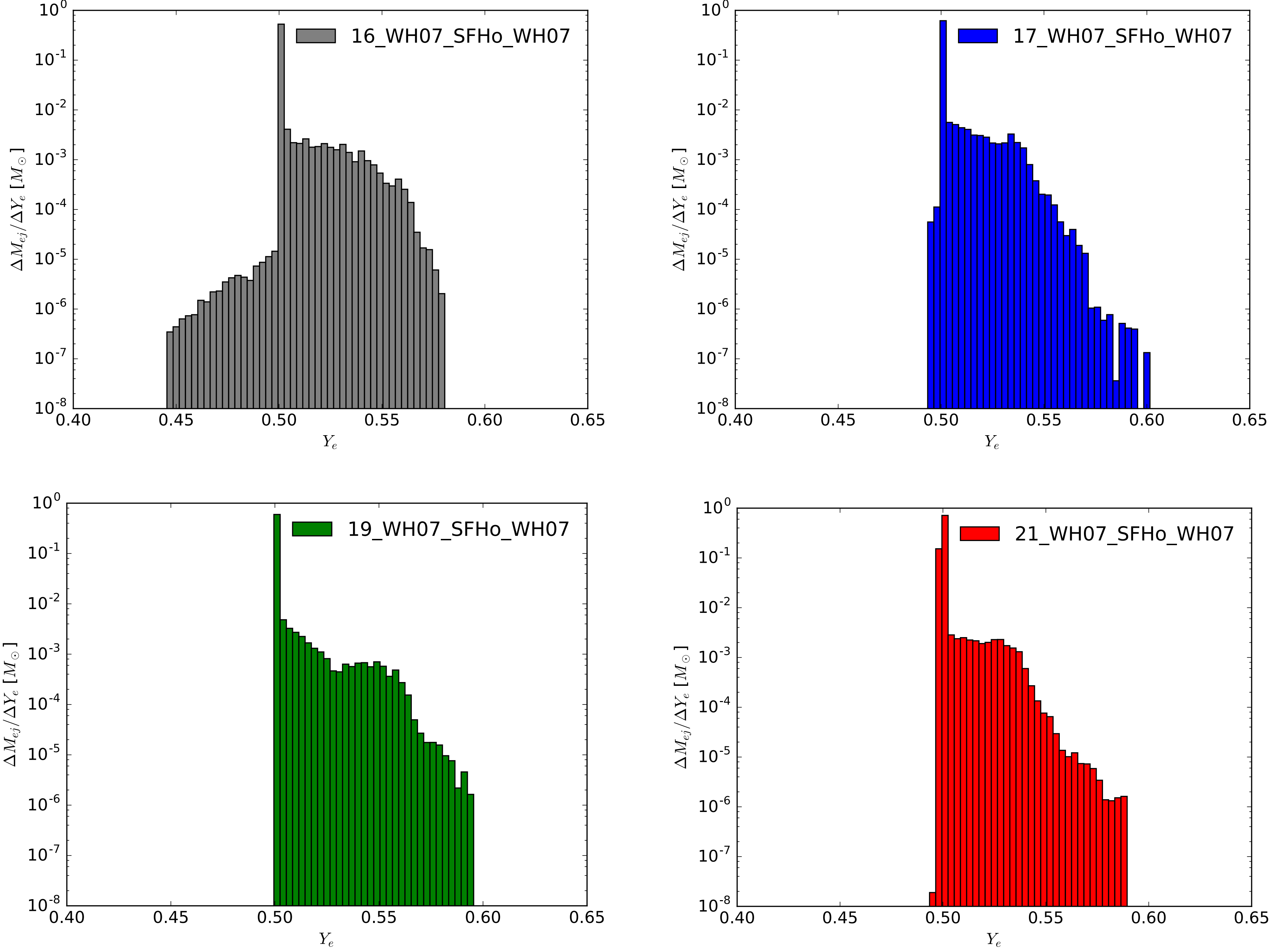
2D
3D
9.0 $M_\odot$
10.0 $M_\odot$
11.0 $M_\odot$
19.0 $M_\odot$
25.0 $M_\odot$
60.0 $M_\odot$
$\langle r_{\rm shock} \rangle$ [km]
$E_{\rm diag}$ [B]
$\eta_{\rm heat}$
$t - t_{\rm bounce}$ [s]

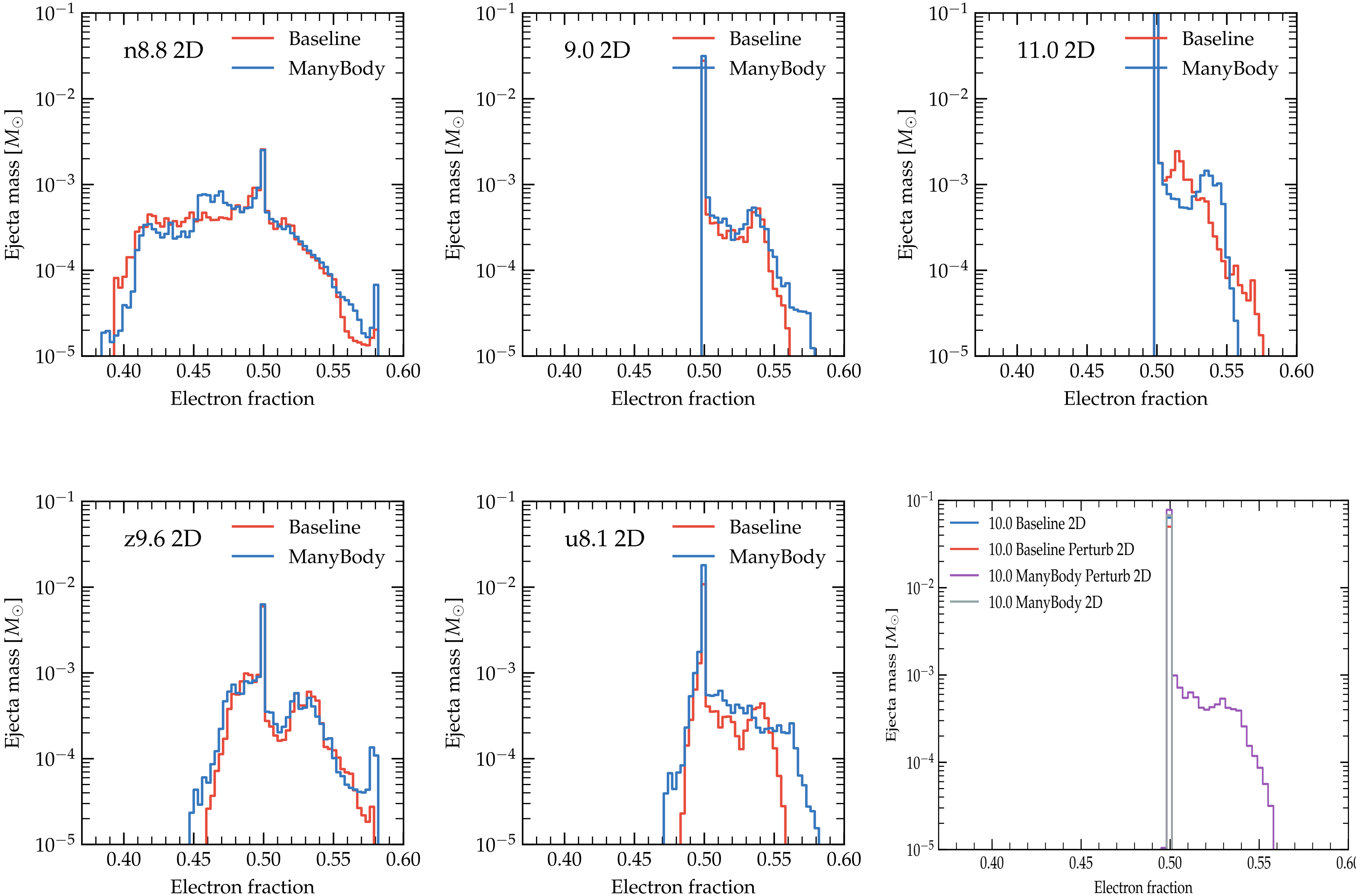


$M^*_{\rm PNS}\ [M_\odot]$
$R_{\rm PNS}$ [km]
$t - t_{\rm bounce}$ [s]
9.0 $M_\odot$
10.0 $M_\odot$
11.0 $M_\odot$
19.0 $M_\odot$
25.0 $M_\odot$
60.0 $M_\odot$
2D
3D

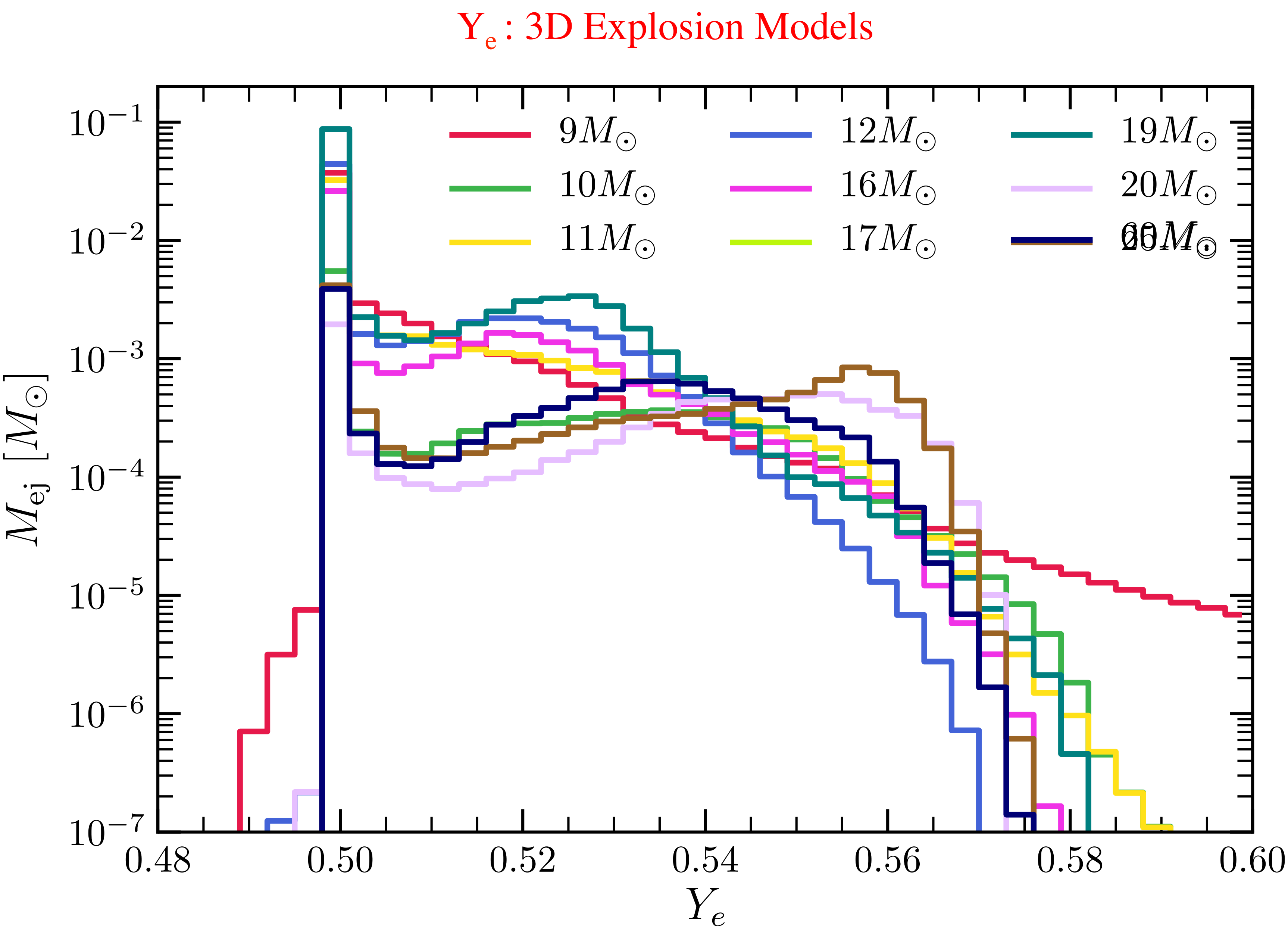
Ejecta Composition (Y_e)

Y_e : 2D Explosion Models





n8.8 2D
9.0 2D
11.0 2D
z9.6 2D
u8.1 2D
Baseline
ManyBody
10.0 Baseline 2D
10.0 Baseline Perturb 2D
10.0 ManyBody Perturb 2D
10.0 ManyBody 2D
Ejecta mass [$M_\odot$]
Electron fraction
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0.40
0.45
0.50
0.55
0.60



Y$_e$: 3D Explosion Models
$9M_\odot$
$12M_\odot$
$19M_\odot$
$10M_\odot$
$16M_\odot$
$20M_\odot$
$11M_\odot$
$17M_\odot$
$25M_\odot$
$60M_\odot$
$M_{\rm ej}\ [M_\odot]$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0.48
0.50
0.52
0.54
0.56
0.58
0.60
Y_e

Y_e Histograms: 16-solar-mass model

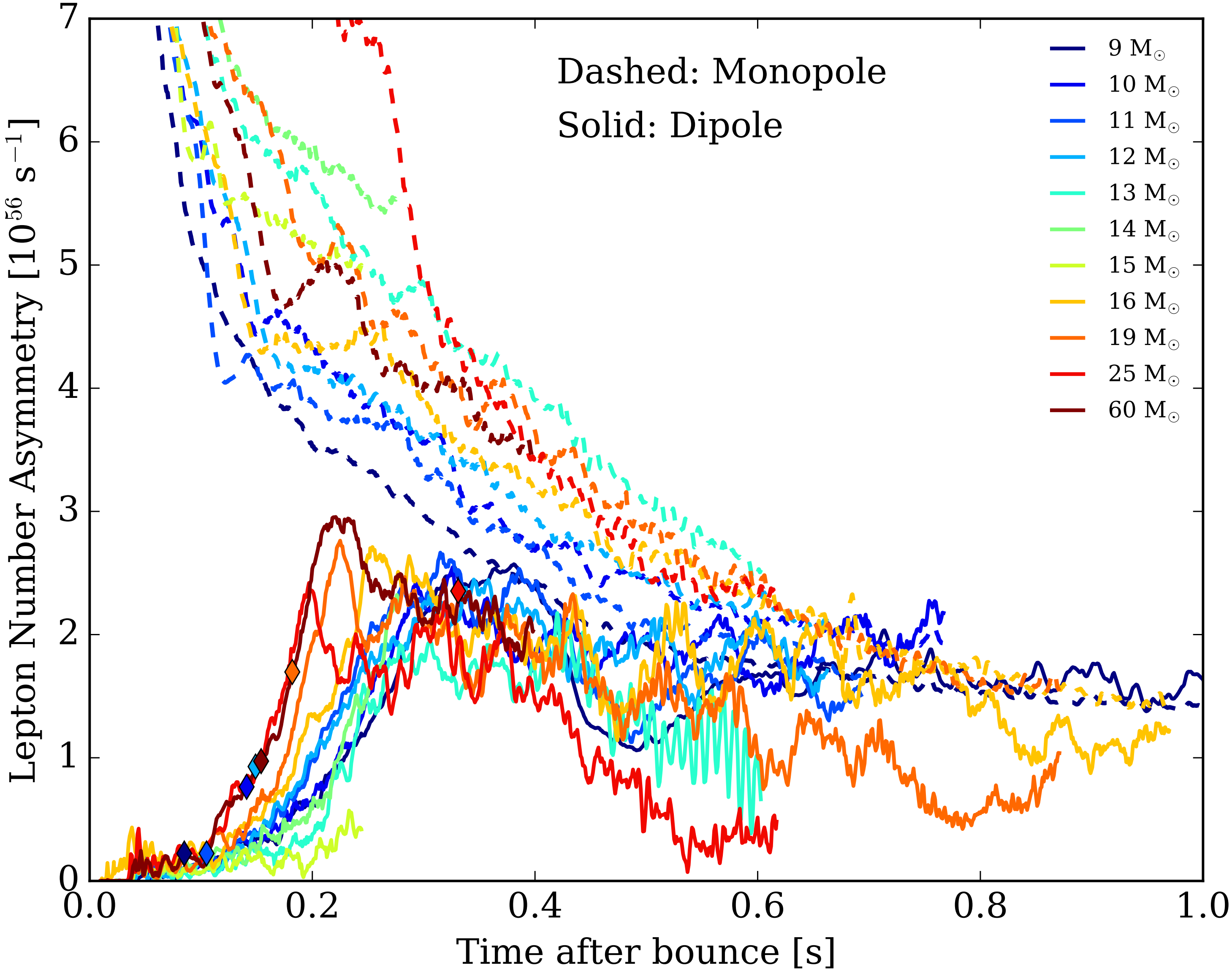
3D

2D

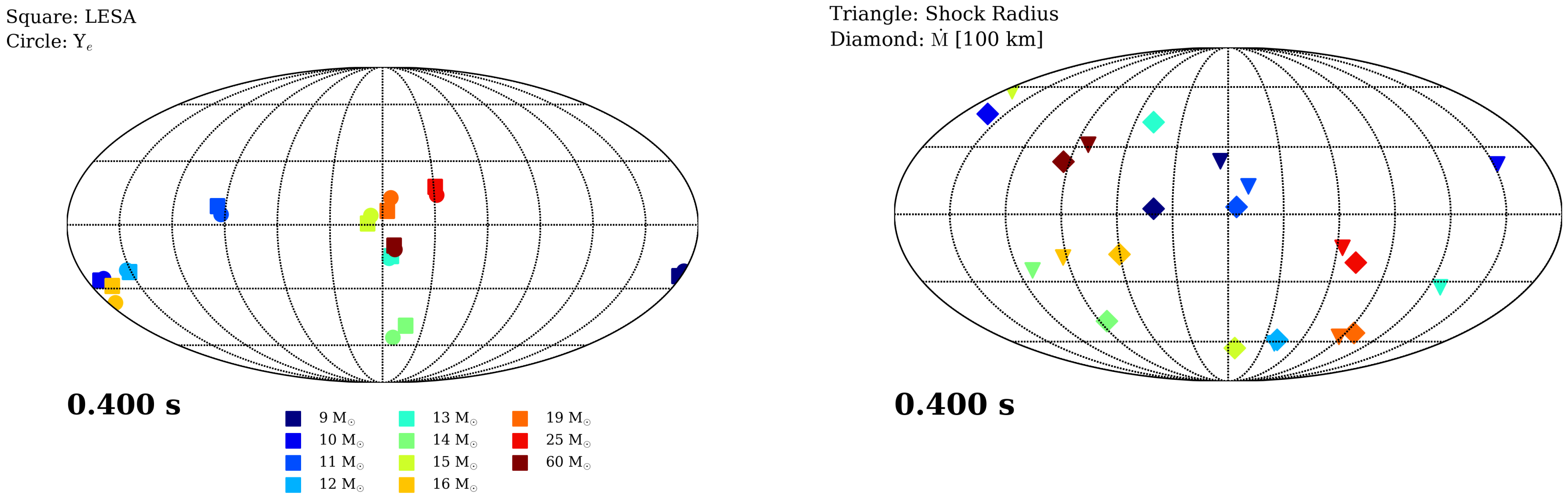
Vartanyan et al. 2018

LESA in 3D

LESA in 3D: Monopole and Dipole



Correlations in 3D

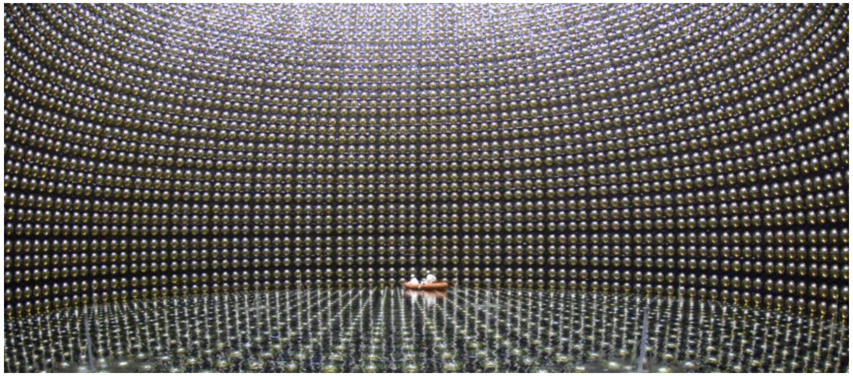


Vartanyan, Burrows, & Radice 2019b

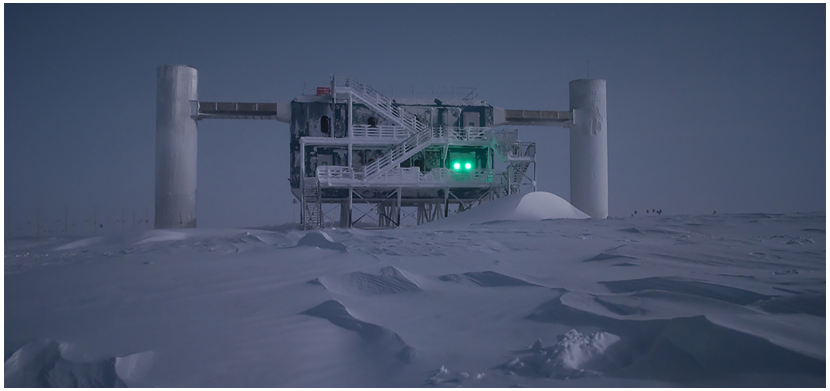
Supernova Neutrino Detection

SUPERK, HYPERK, DUNE, JUNO, ICE CUBE

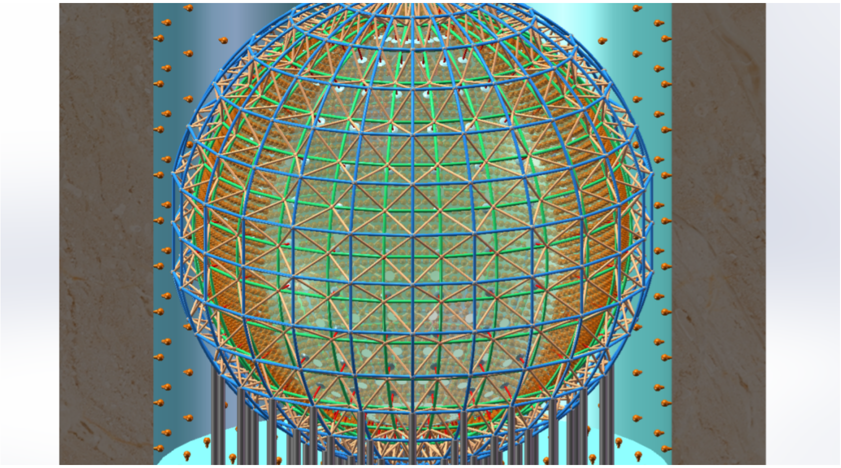
SN Neutrino Observatories



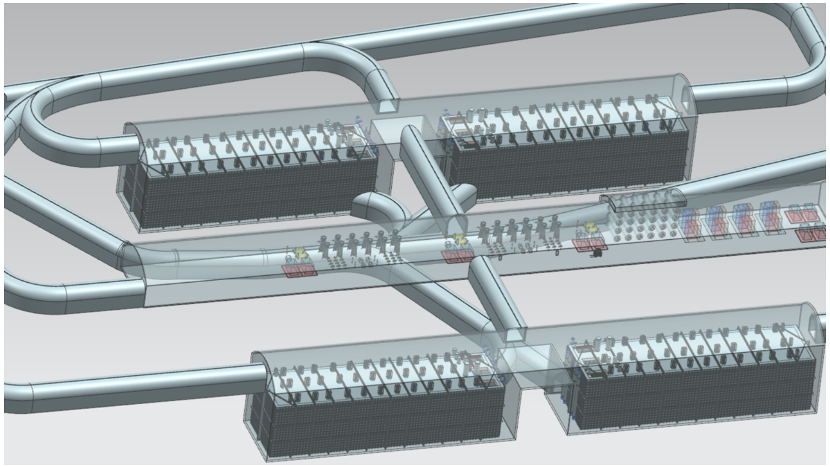
Super-Kamiokande
(Water Cherenkov)



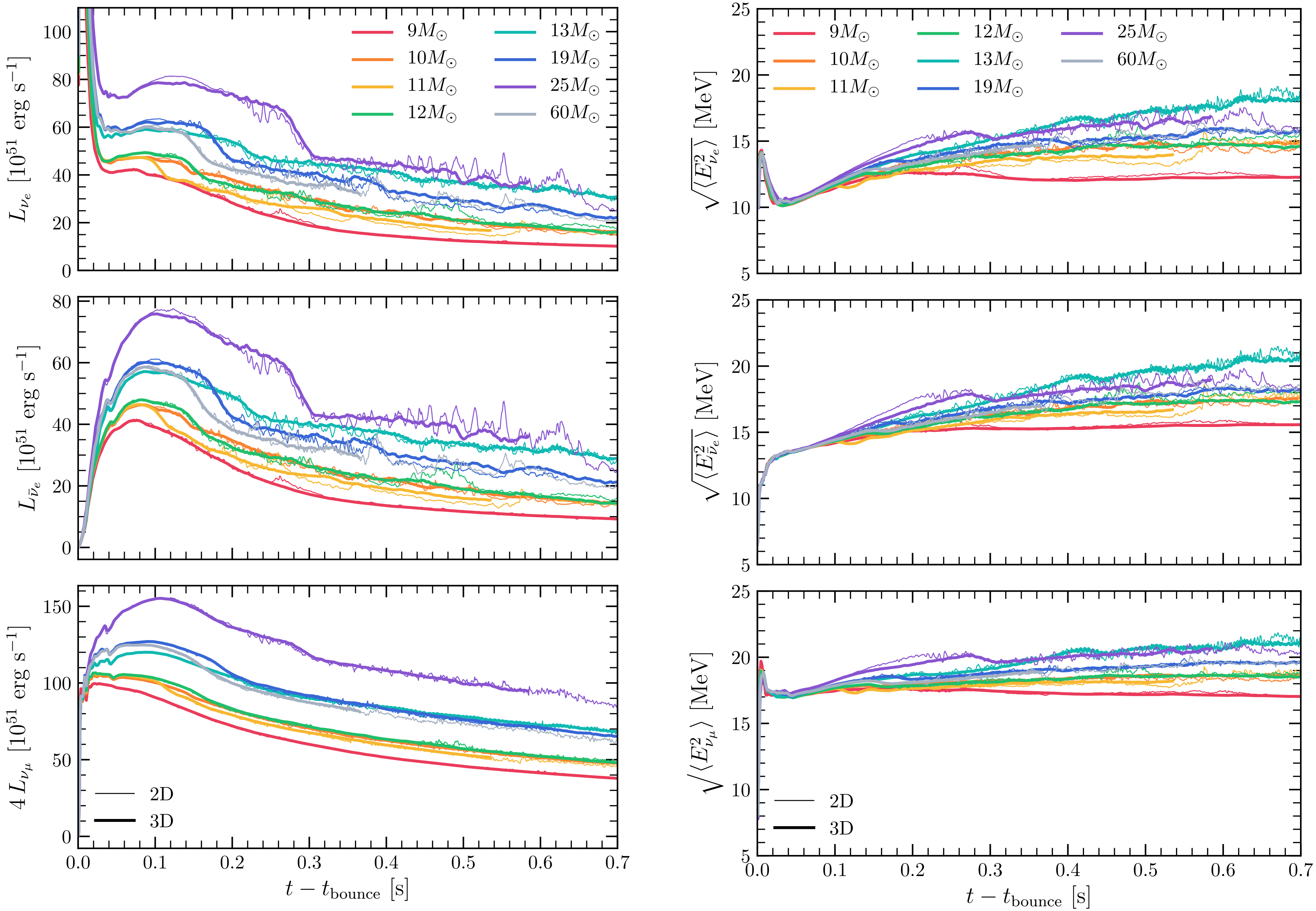
ICECUBE
(Longstring Ice)



JUNO
(Hydrocarbon Scintillator)



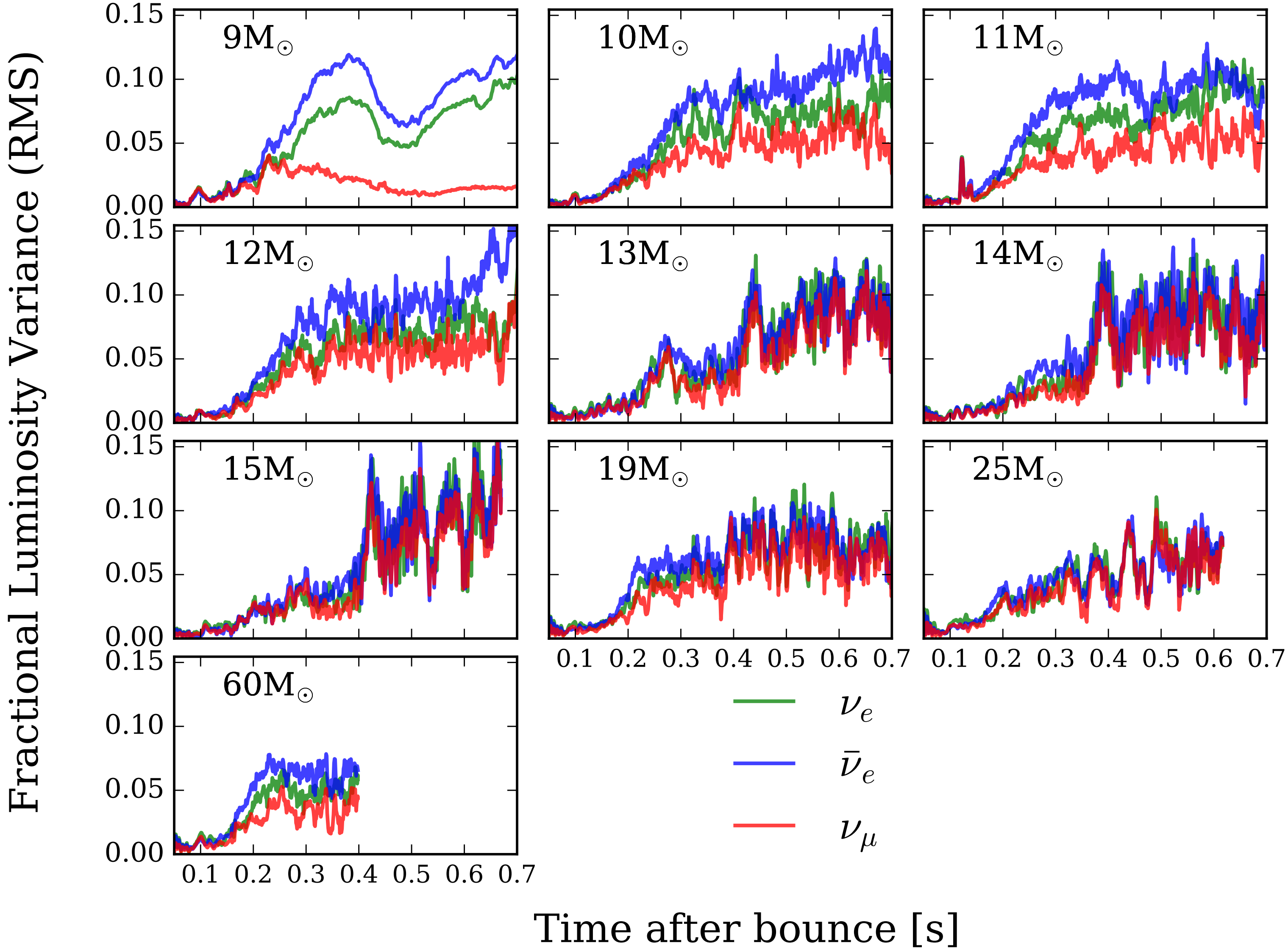
DUNE
(Liquid Argon TPC)



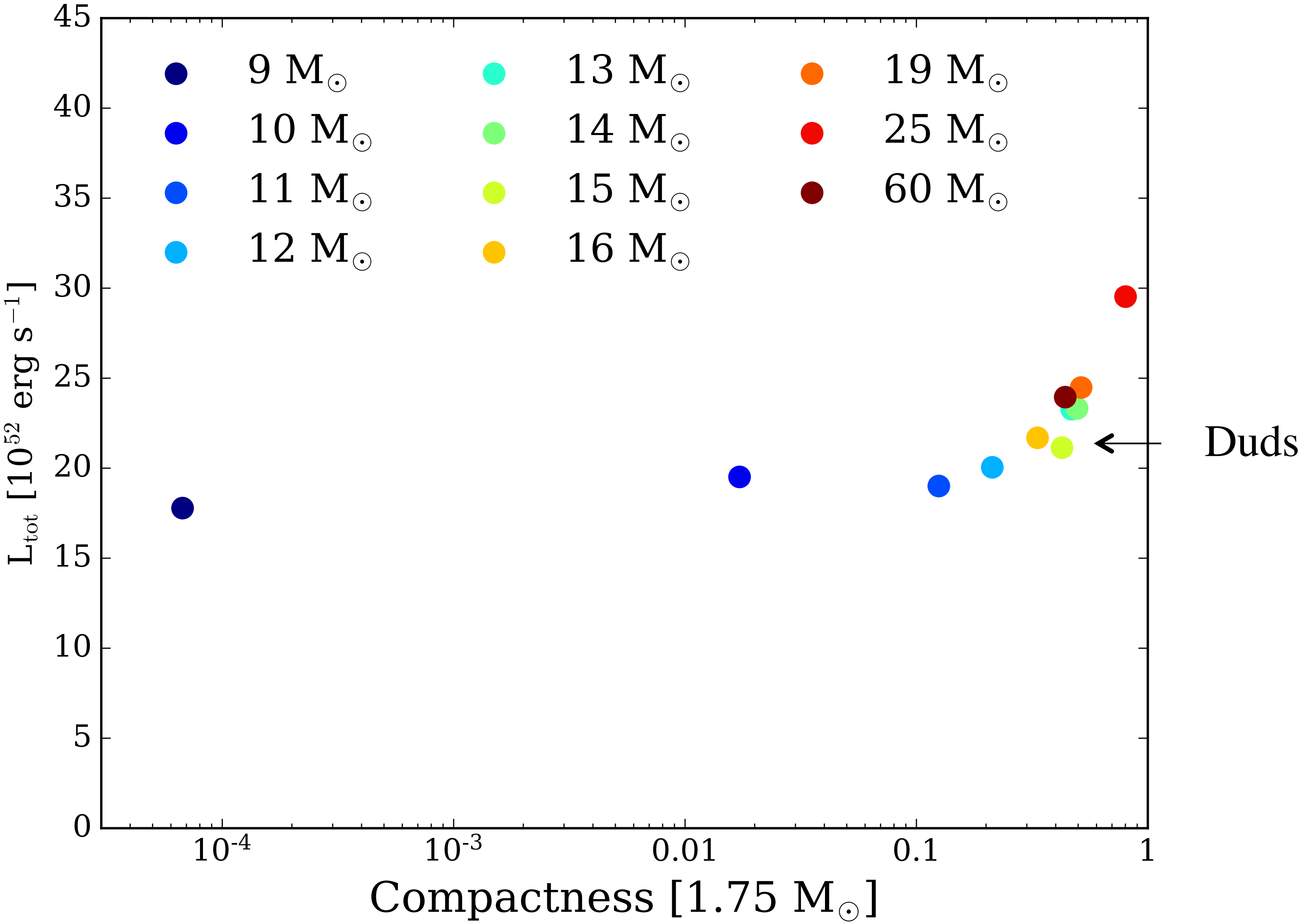
L_{ν_e} [10^{51} erg s^{-1}]
$L_{\bar{\nu}_e}$ [10^{51} erg s^{-1}]
$4\,L_{\nu_\mu}$ [10^{51} erg s^{-1}]
$\sqrt{\langle E^2_{\nu_e}\rangle}$ [MeV]
$\sqrt{\langle E^2_{\bar{\nu}_e}\rangle}$ [MeV]
$\sqrt{\langle E^2_{\nu_\mu}\rangle}$ [MeV]
$t - t_{\rm bounce}$ [s]
$9M_\odot$
$10M_\odot$
$11M_\odot$
$12M_\odot$
$13M_\odot$
$19M_\odot$
$25M_\odot$
$60M_\odot$
2D
3D

Vartanyan et al. : 3D
25 solar mass model

Neutrino Emissions as a Function of Solid Angle: Variance vs. Time



Peak Accretion Luminosity vs. Compactness: Compactness is not monotonic with explodability



Vartanyan et al. : 3D
25 solar mass model

Gravitational Radiation Signals from Core-Collapse Supernovae

Radice, Morozova, Burrows, Vartanyan et al.
2018-2019

CCSN Signal Features

- Rotational bounce spike (rapid rotation?); differential rotation
- Initial Progenitor perturbation spike
- Outer Prompt 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
- Spiral SASI
- Transition to Explosion, leading to decreased accretion, occasioning signal turnover (near time of frequency peak?)
- Neutrino component
- Christodoulou Memory (low frequency): asymmetric explosion, neutrinos

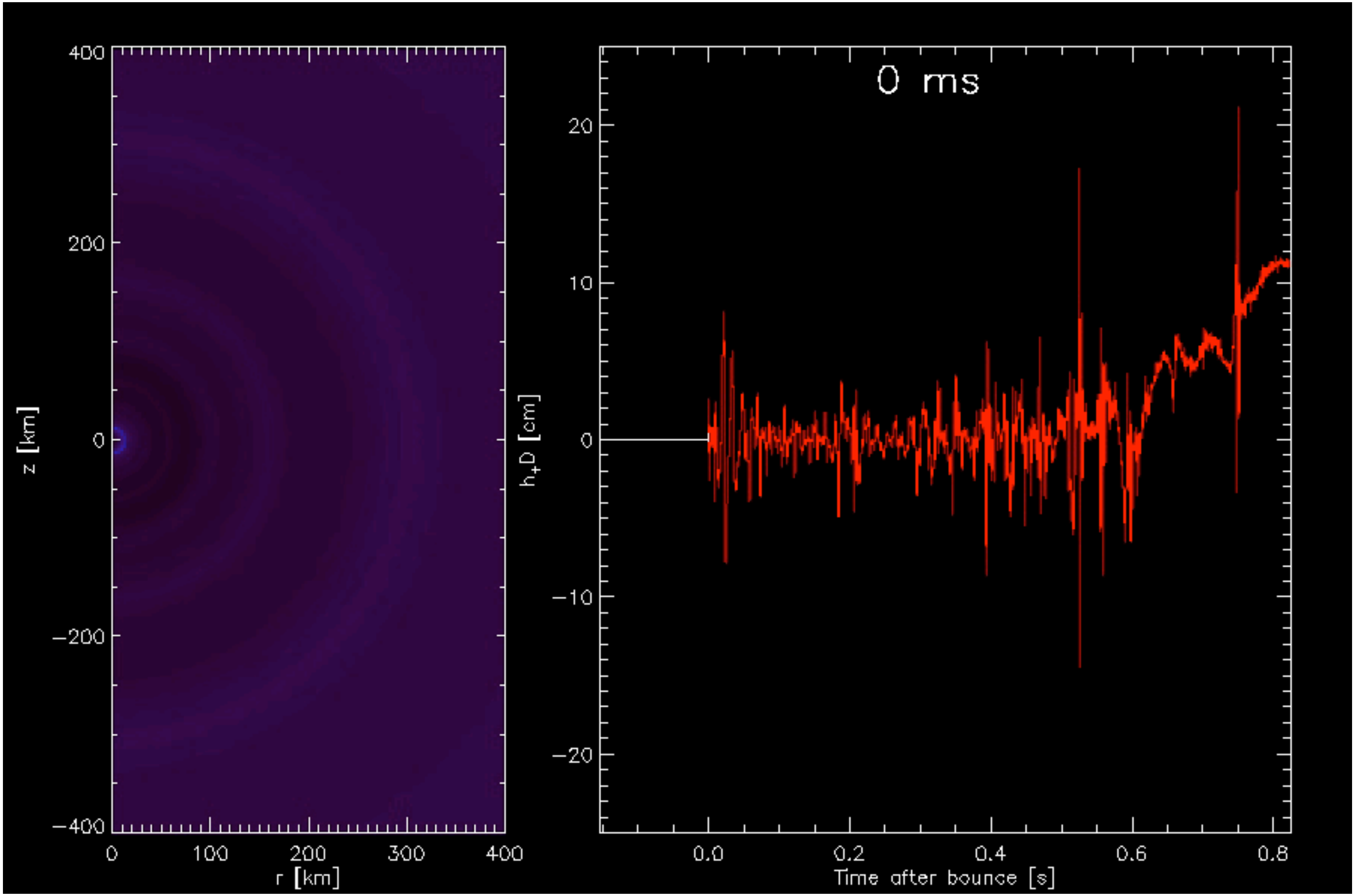
- PNS F/g-mode excitation: Asteroseismology!

- Polarization (rotation and spiral SASI) – Enhance the effective SNR

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

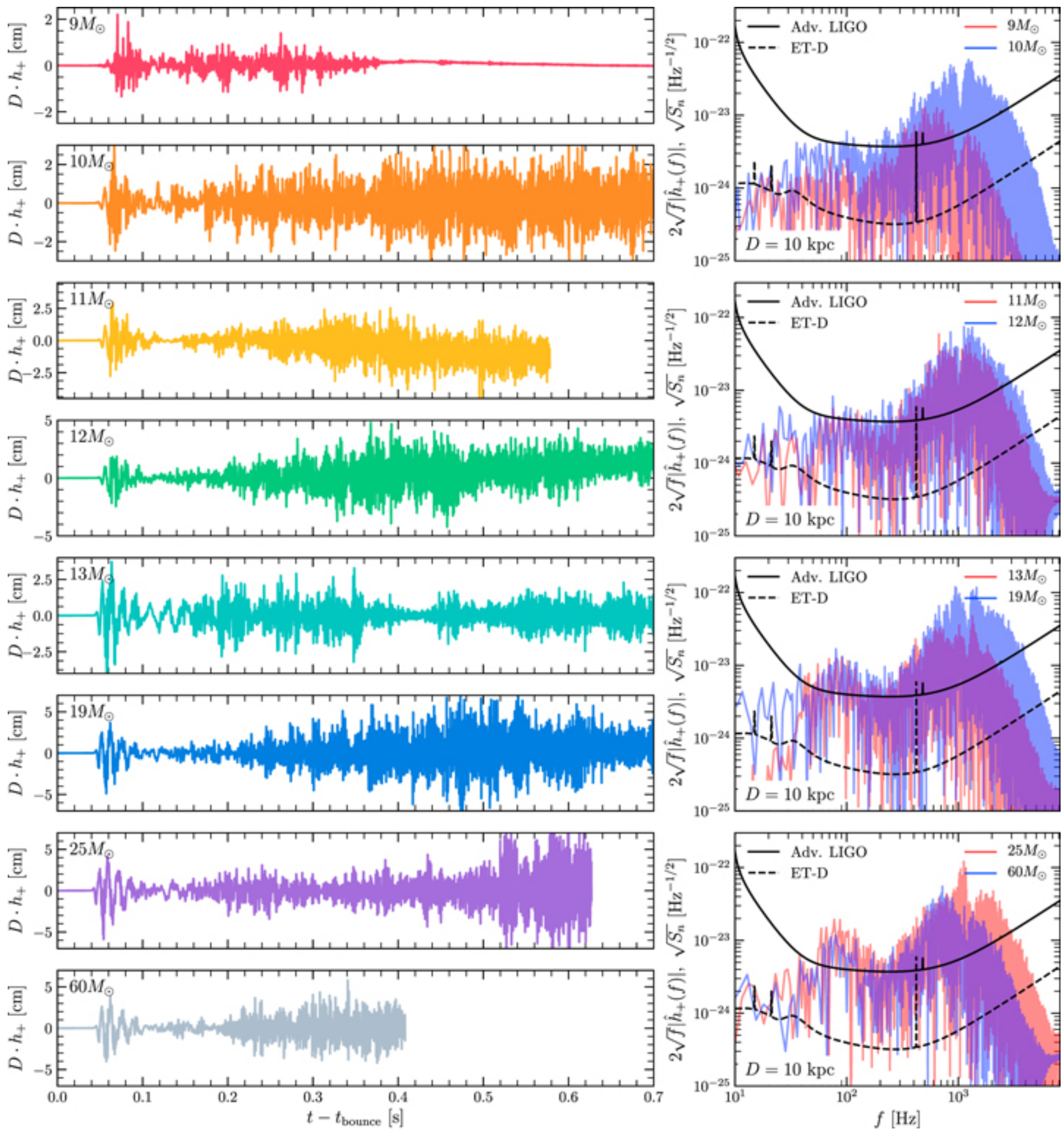
Sample References on the CCSN/GW Connection

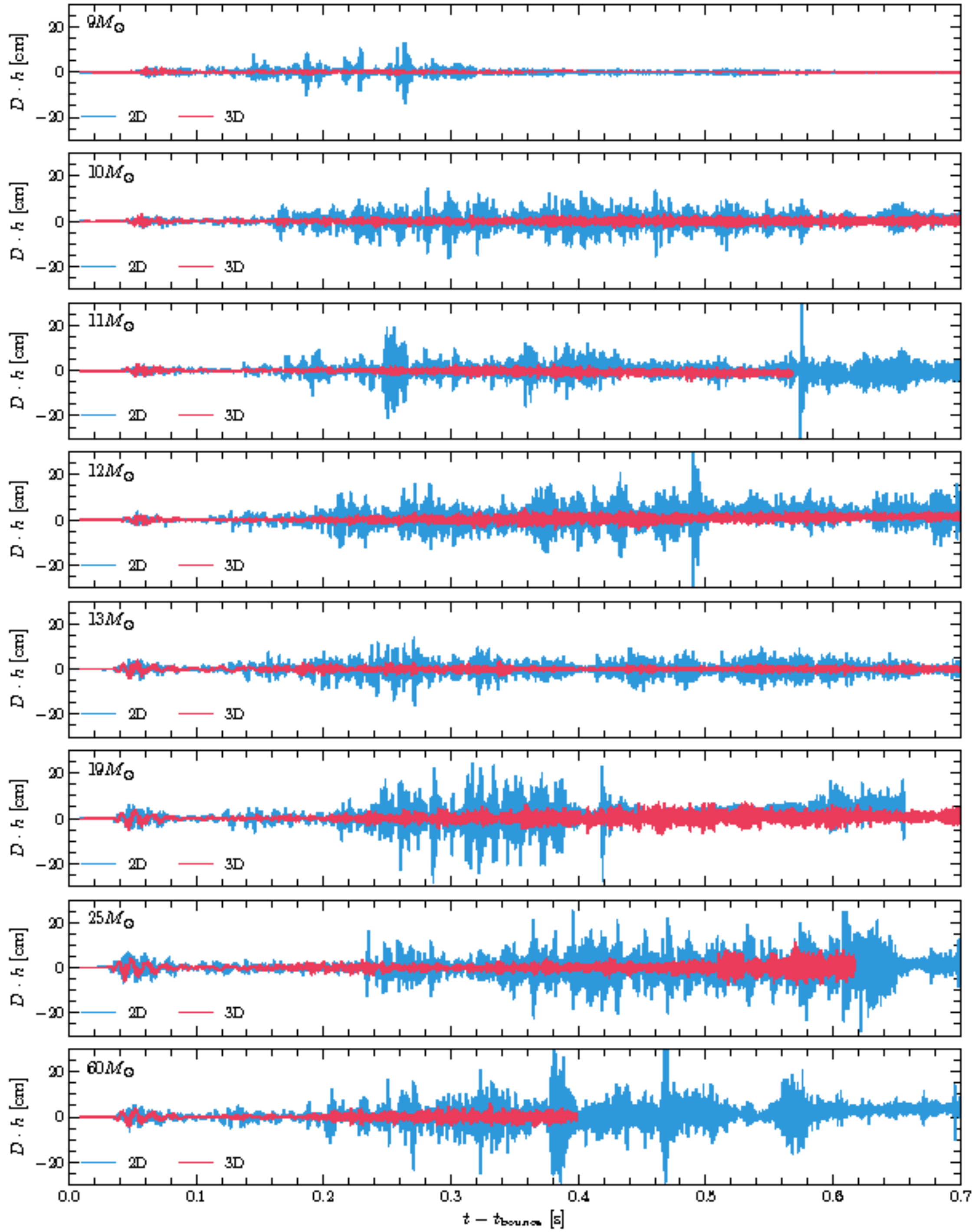
- E. Muller 1982 (Rotation)
- Burrows & Hayes 1996 (Memory, neutrinos, progenitor asymmetry)
- Ott et al. 2004,2006 (Rotation); Dimmelmeier et al. 2008; Ott 2009; Logue et al. 2012; Ott et al. 2013 (3D, leakage)
- Summerscales et al. 2008 (Maximum entropy)
- Scheidegger et al. 2010; Basel
- Heng 2009; 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 (g/f-modes, spectrogram); Radice et al. 2019



Murphy et al. 2009

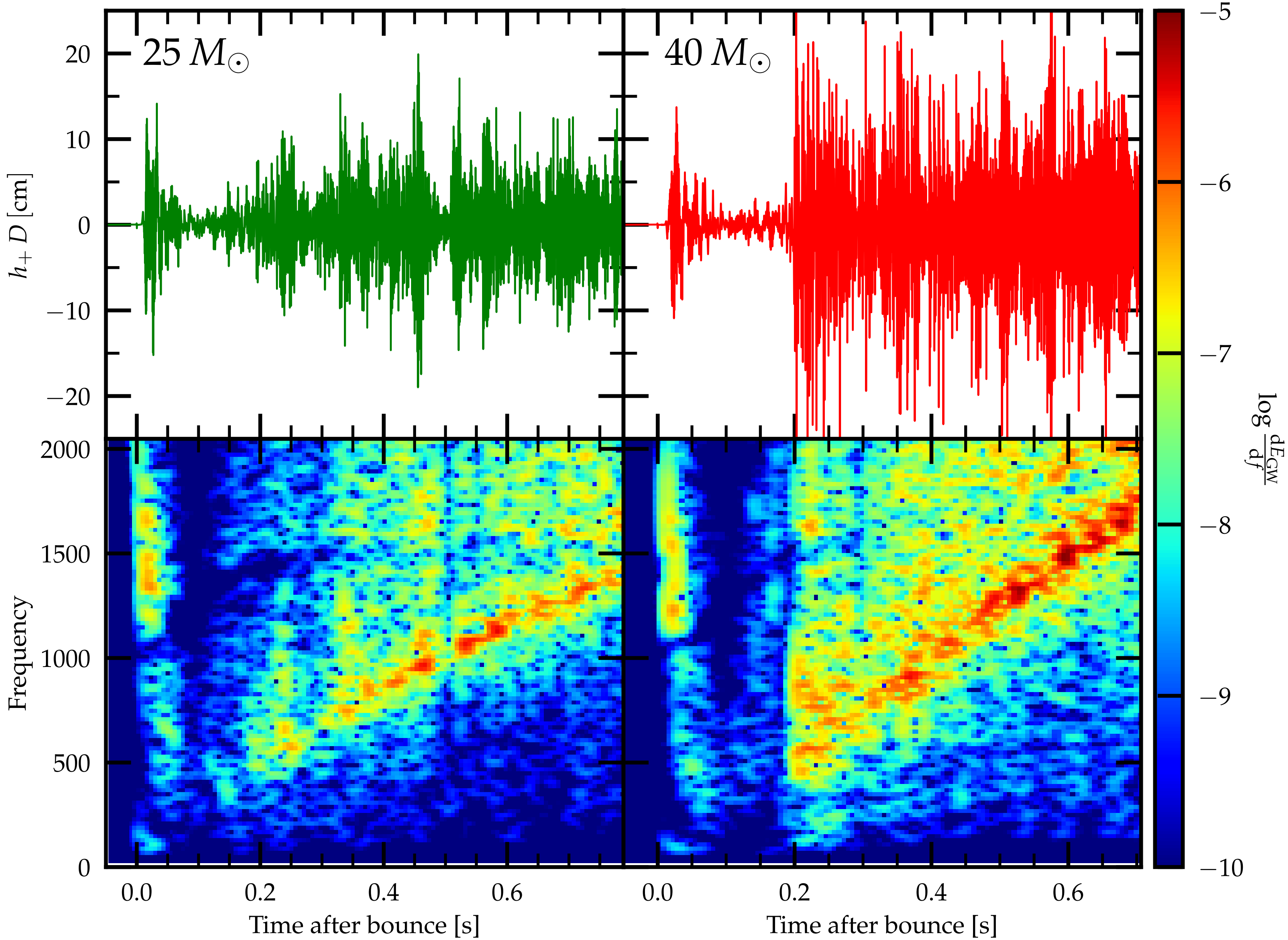
Radice et al. 2019



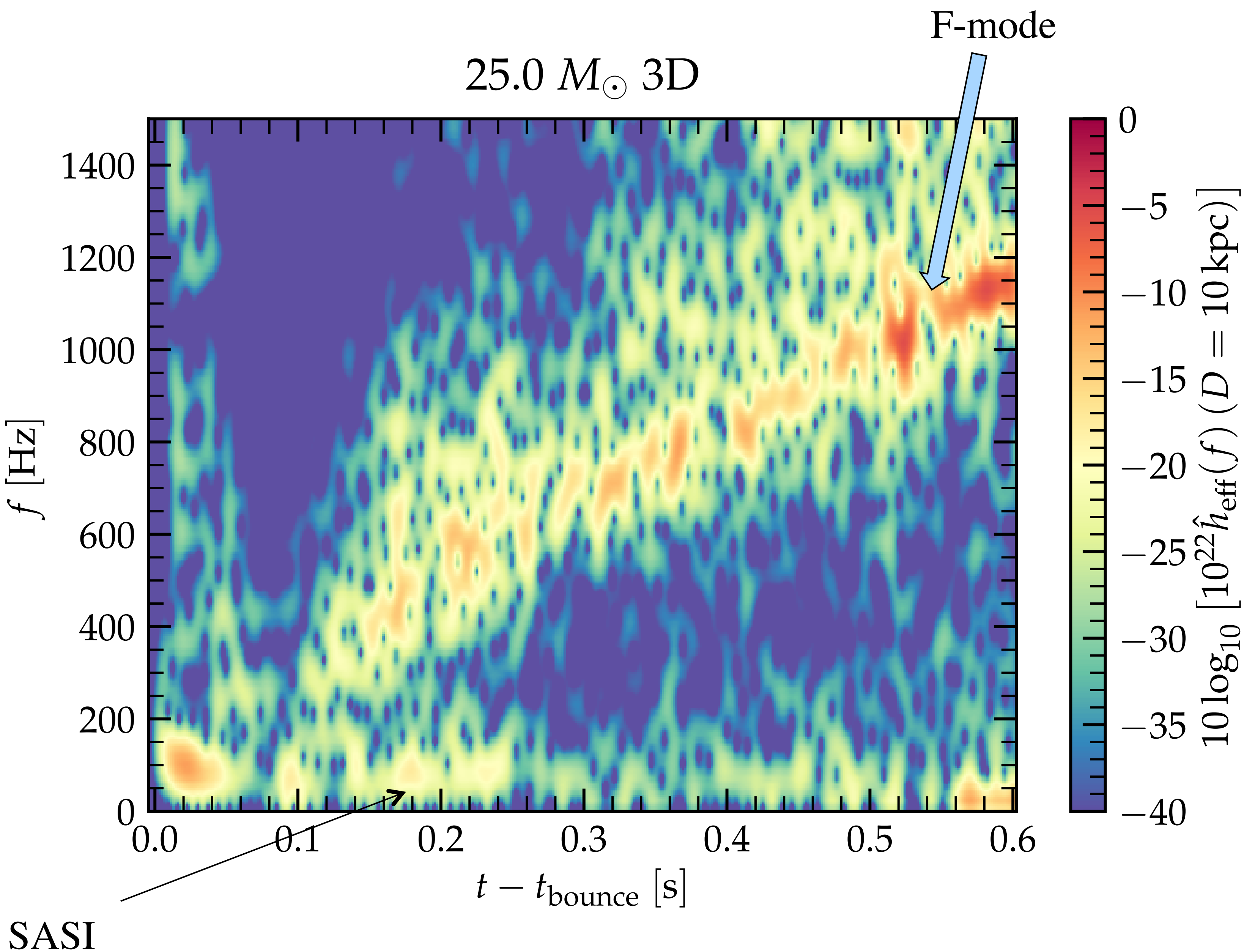


9$M_\odot$
10$M_\odot$
11$M_\odot$
12$M_\odot$
13$M_\odot$
19$M_\odot$
25$M_\odot$
60$M_\odot$
2D
3D
$D \cdot h$ [cm]
20
0
−20
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
$t - t_{\rm bounce}$ [s]

2D vs. 3D

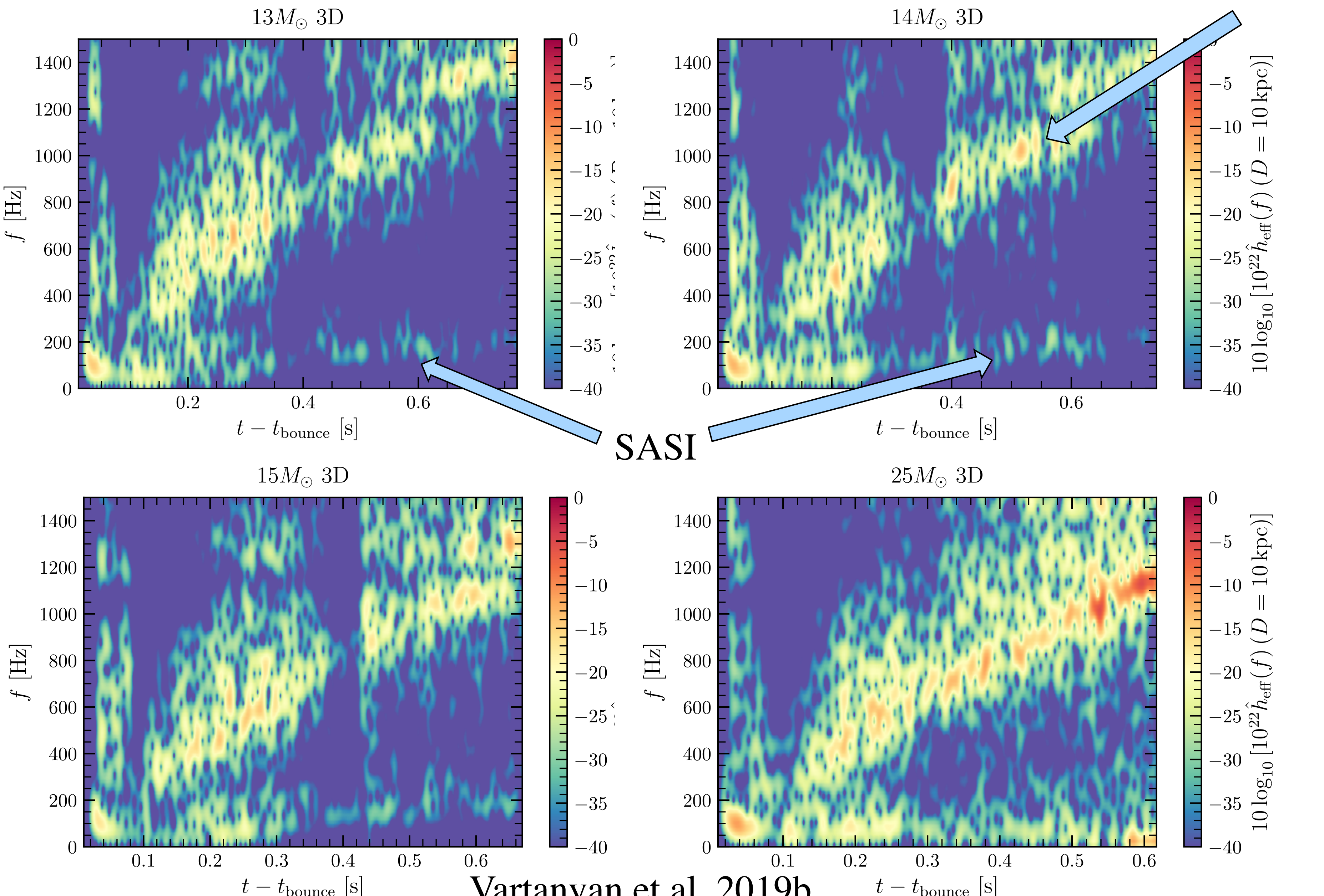


25 $M_\odot$
40 $M_\odot$
$h_+ D$ [cm]
Frequency
Time after bounce [s]
Time after bounce [s]
$\log \frac{dE_{GW}}{df}$

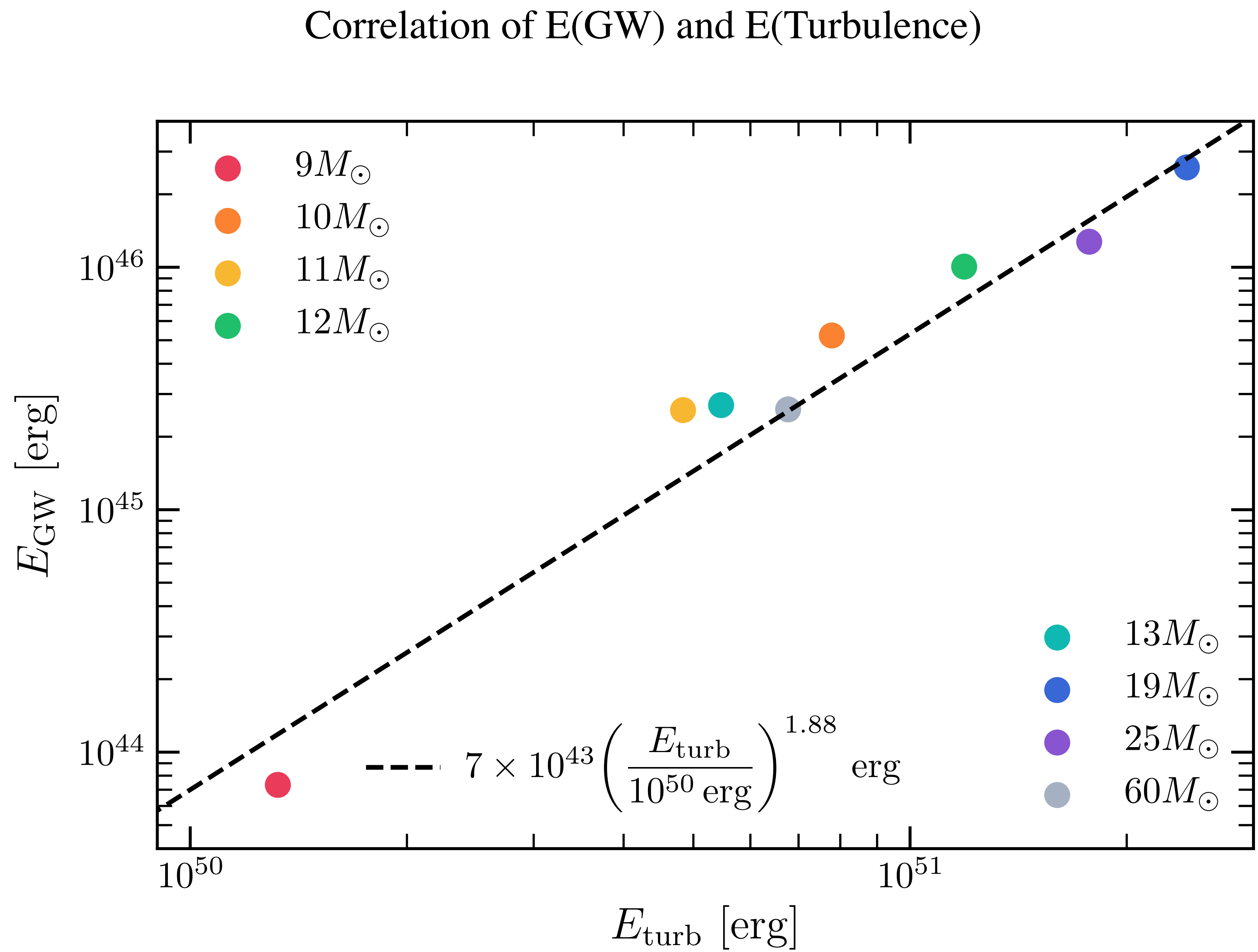


Radice et al. 2019

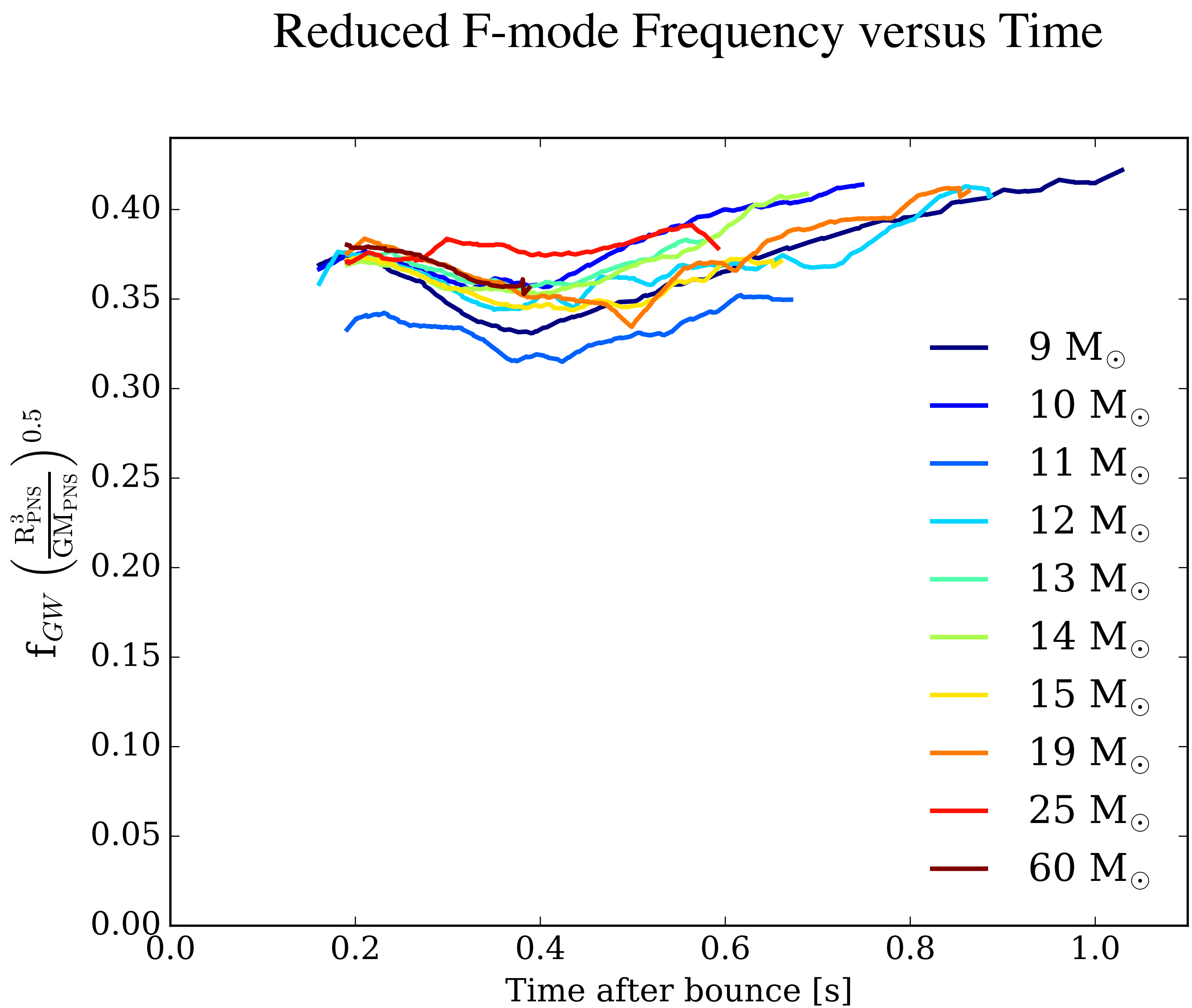
SASI (spiral): Emerges mostly when shock is compact and explosion has failed



Vartanyan et al. 2019b

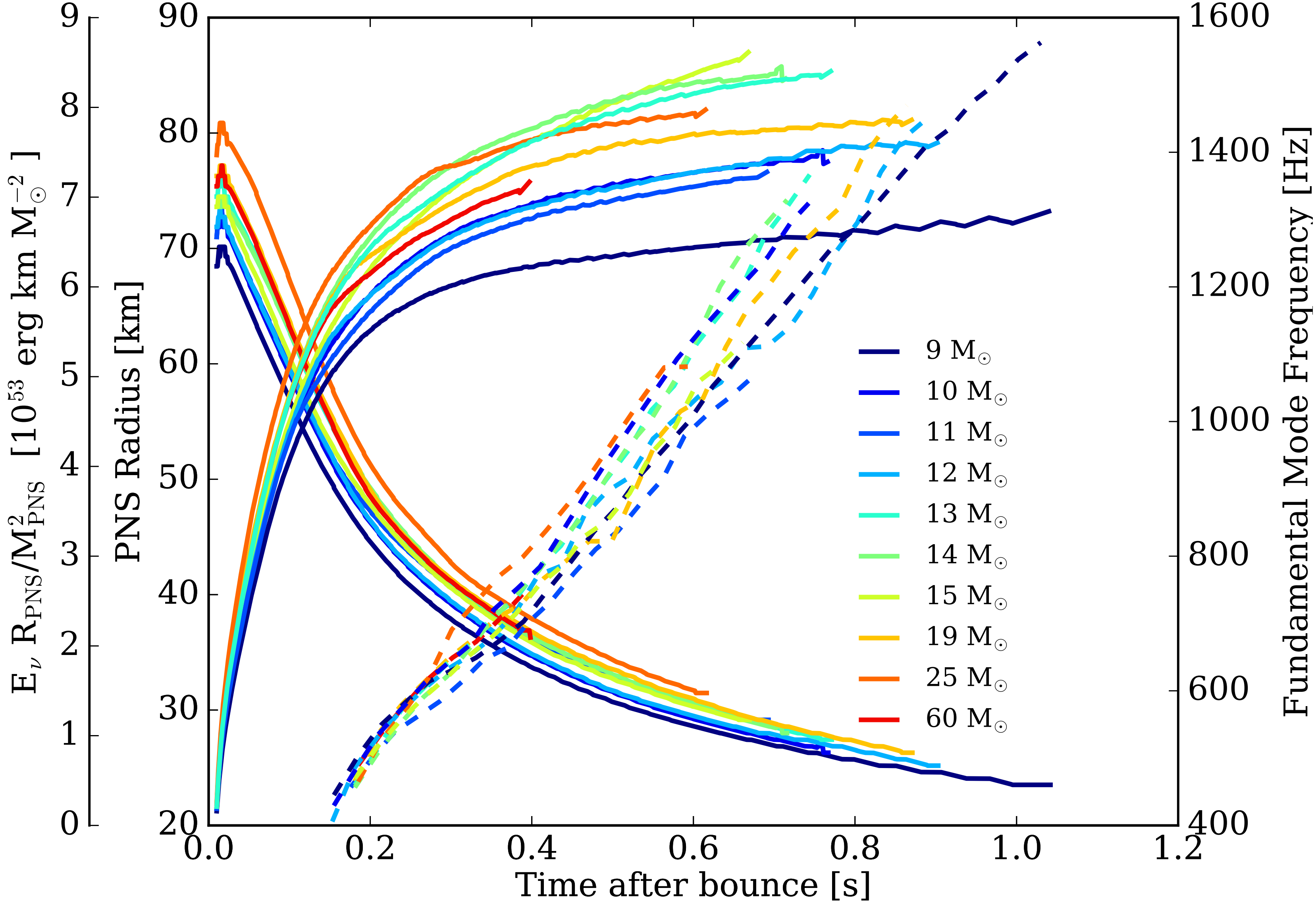


Correlation of E(GW) and E(Turbulence)
$9M_\odot$
$10M_\odot$
$11M_\odot$
$12M_\odot$
$13M_\odot$
$19M_\odot$
$25M_\odot$
$60M_\odot$
$7 \times 10^{43} \left(\frac{E_{\rm turb}}{10^{50}\,{\rm erg}} \right)^{1.88}$ erg
10^{44}
10^{45}
10^{46}
10^{50}
10^{51}
$E_{\rm GW}$ [erg]
$E_{\rm turb}$ [erg]

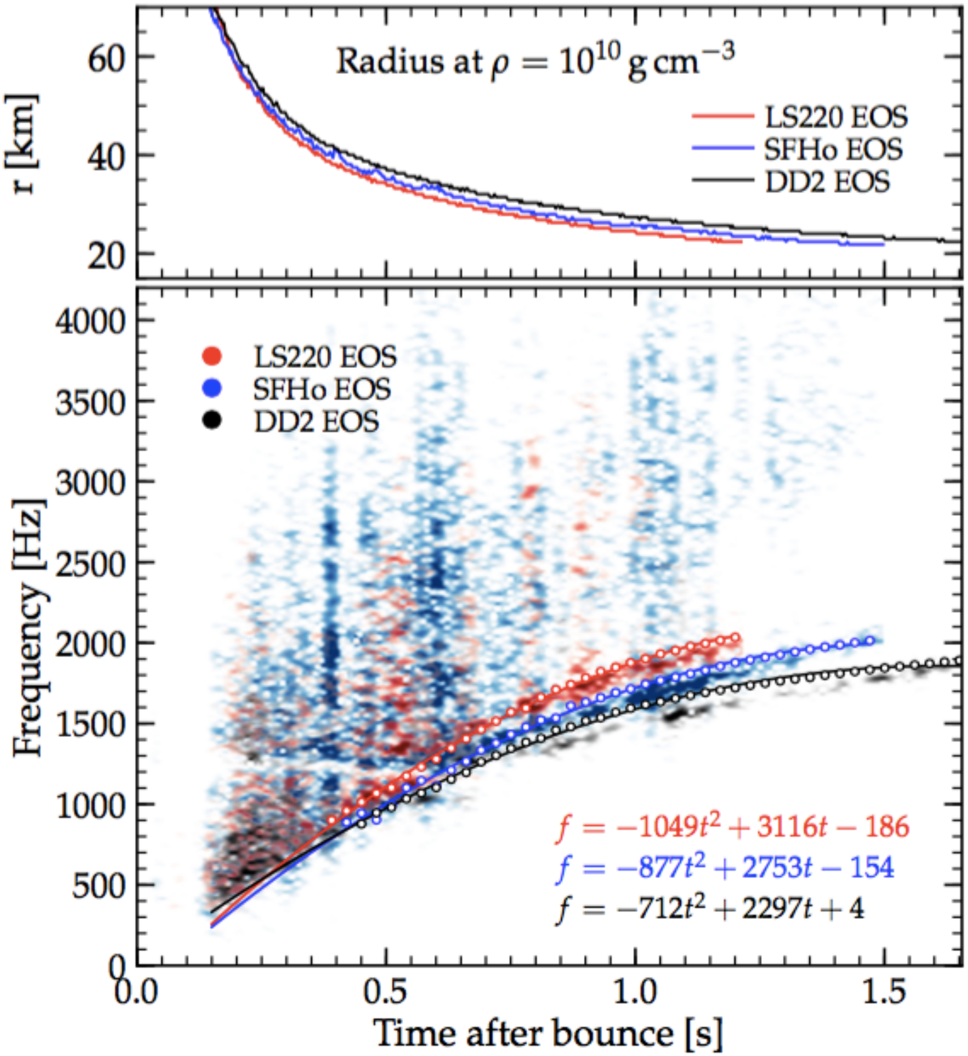


Reduced F-mode Frequency versus Time
$f_{GW} \left(\frac{R_{PNS}^3}{GM_{PNS}}\right)^{0.5}$
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.0
0.2
0.4
0.6
0.8
1.0
Time after bounce [s]
9 $M_\odot$
10 $M_\odot$
11 $M_\odot$
12 $M_\odot$
13 $M_\odot$
14 $M_\odot$
15 $M_\odot$
19 $M_\odot$
25 $M_\odot$
60 $M_\odot$

Correlation of R_{pns} , f-mode Frequency, and Total Neutrino Losses



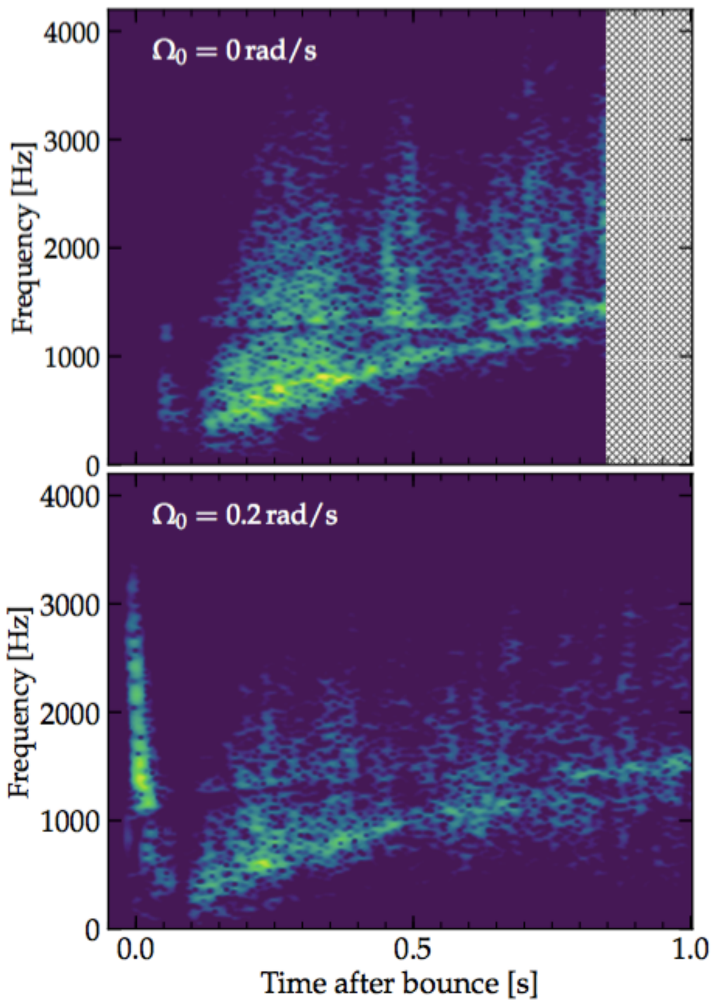
Dependence of the dominant GW frequency on the EOS

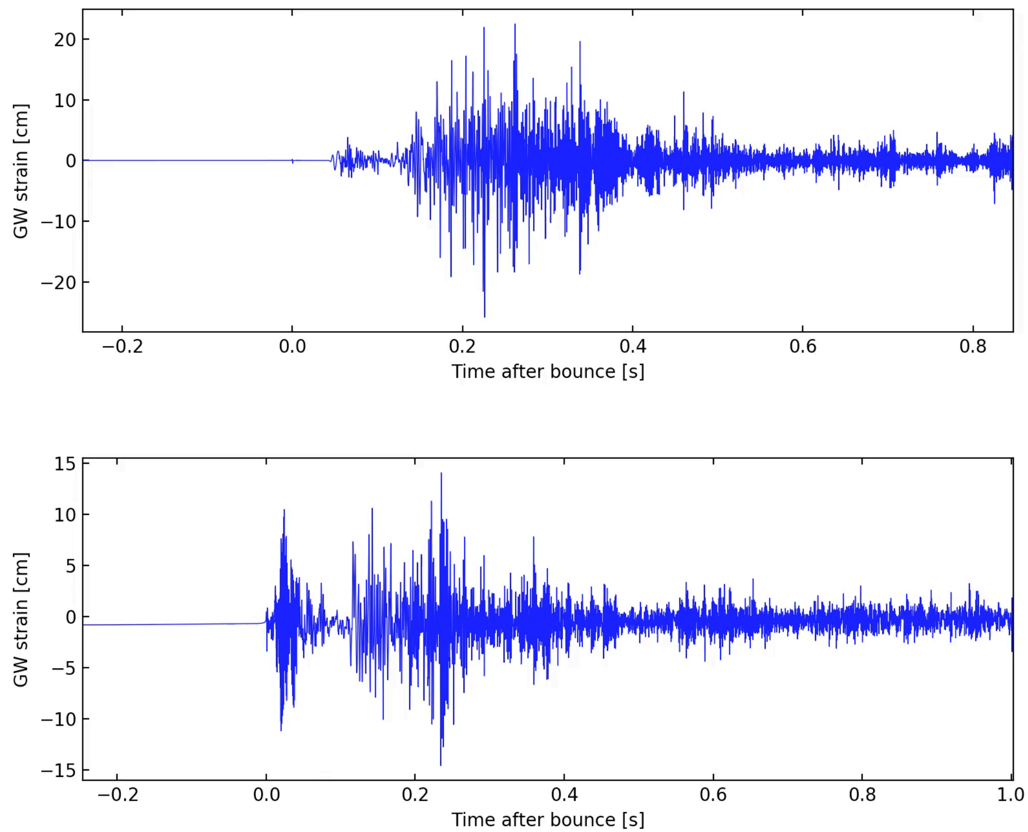


- Reflects the evolution of the PNS radius
- Captured reasonably well by the analysis
- Can be described by a quadratic function

Morozova et al. 2018

Rotation



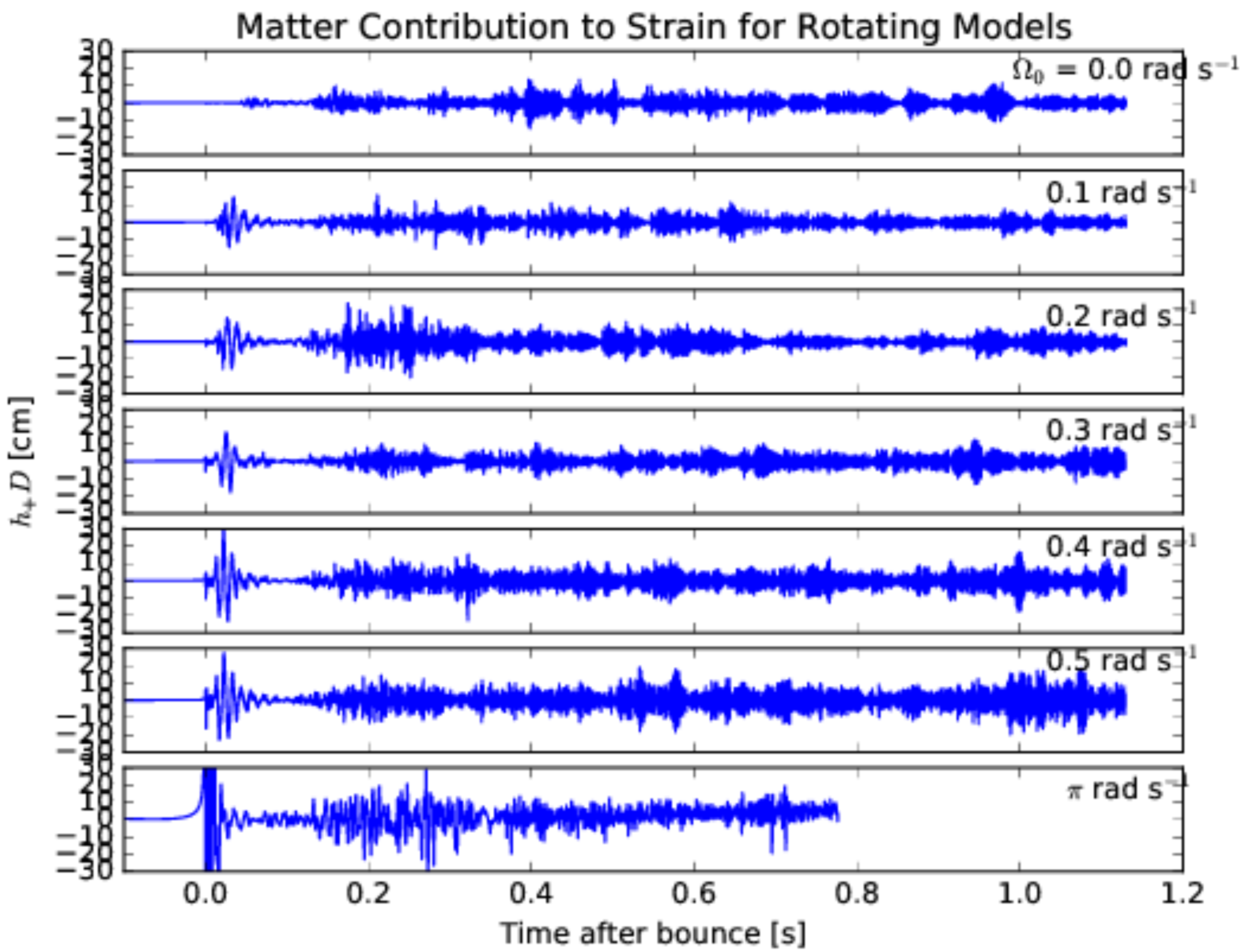


* The bounce signal is stronger, because the collapse is not symmetric

* The dominant frequency is nearly the same

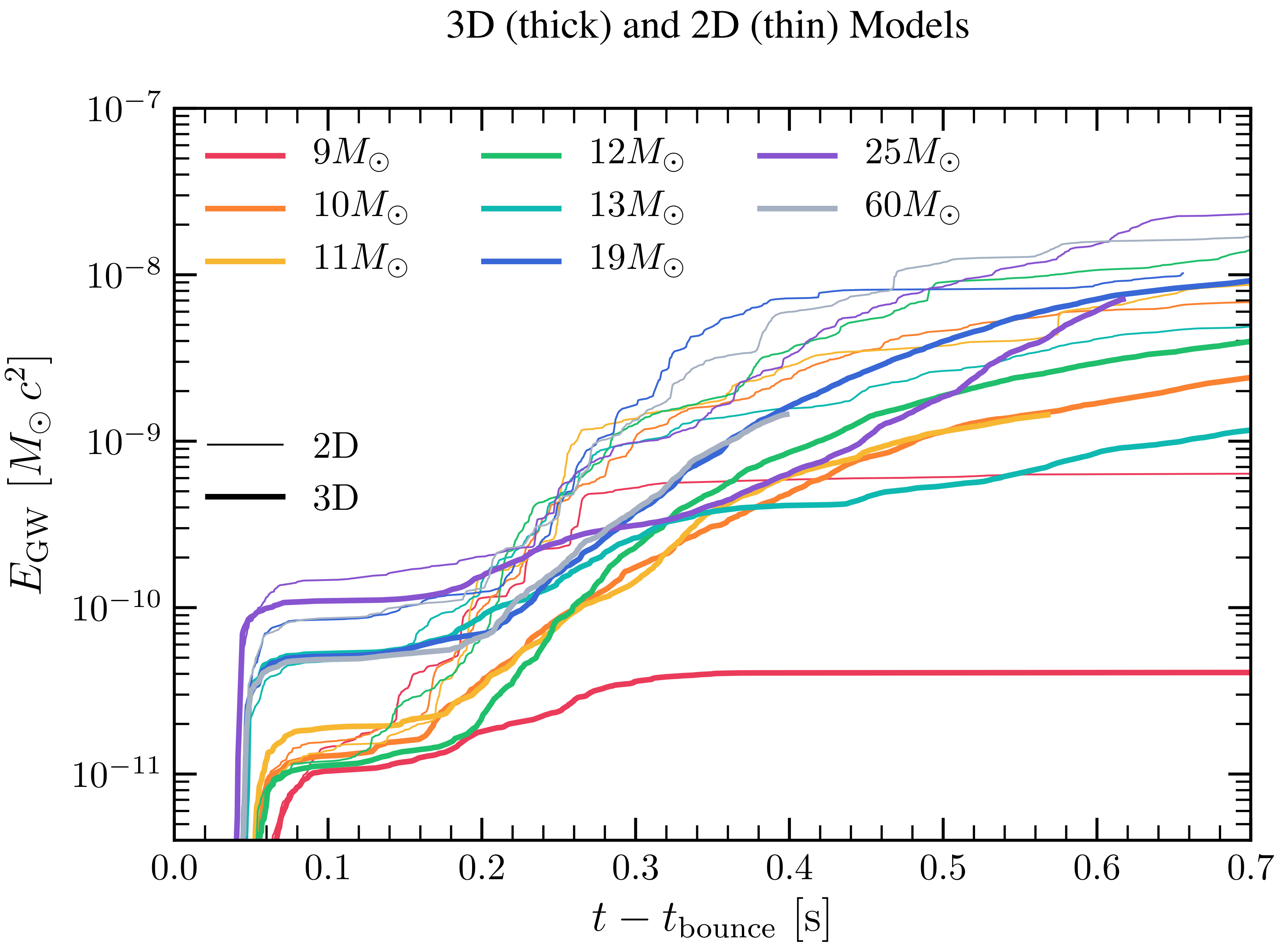
Morozova et al. 2018

Vartanyan et al.

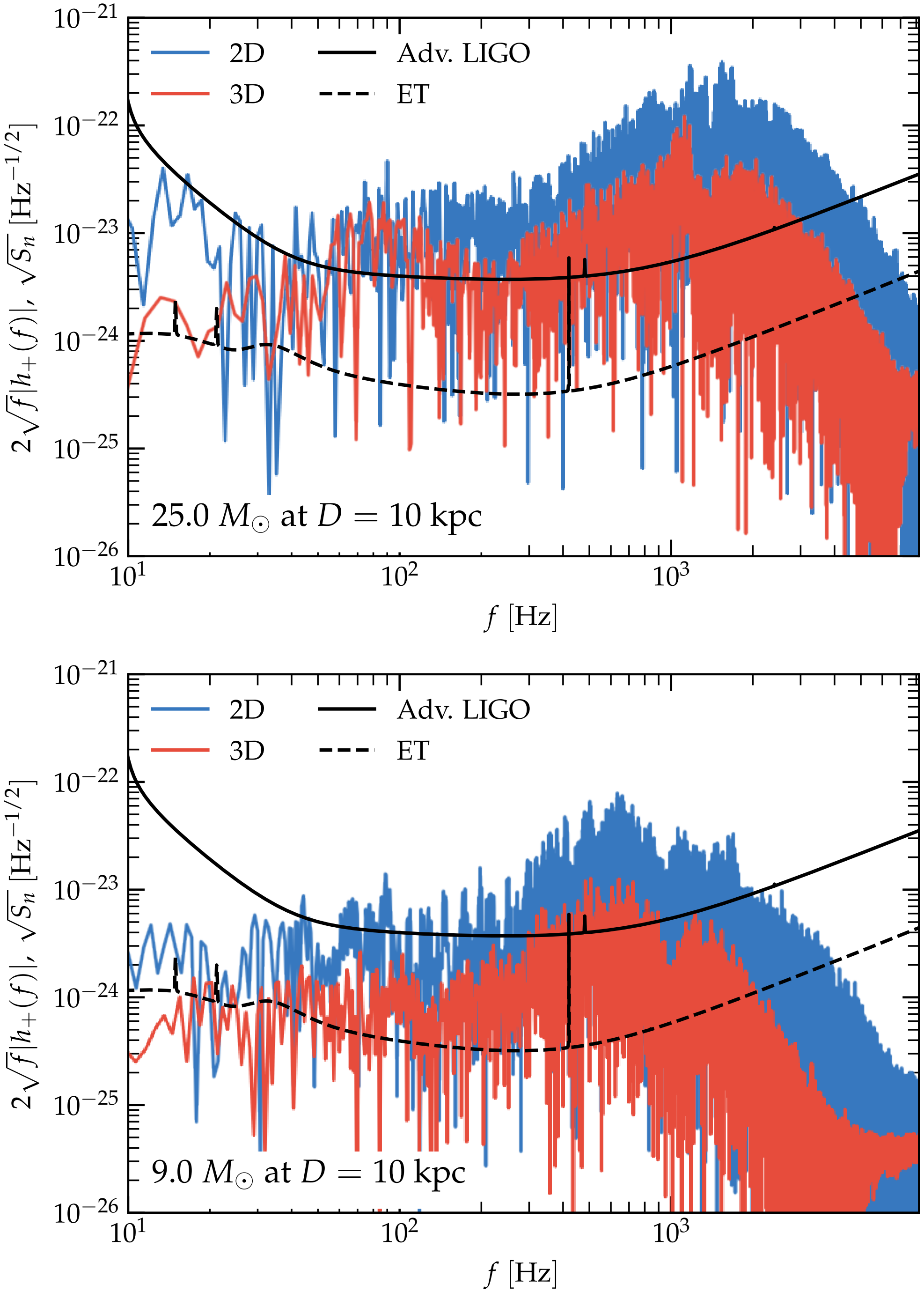






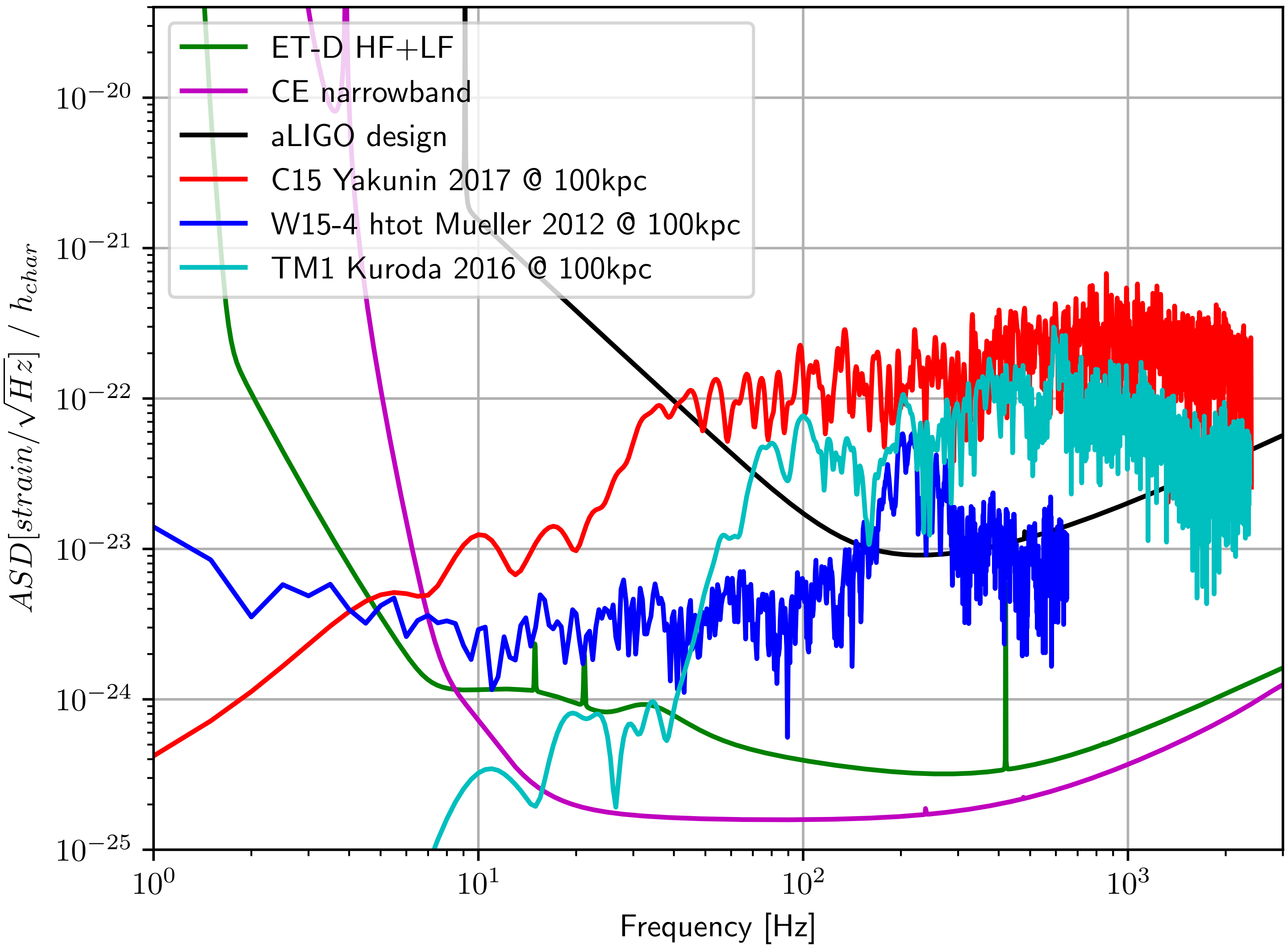


3D (thick) and 2D (thin) Models
$9M_\odot$
$10M_\odot$
$11M_\odot$
$12M_\odot$
$13M_\odot$
$19M_\odot$
$25M_\odot$
$60M_\odot$
2D
3D
$E_{\rm GW}$ $[M_\odot\, c^2]$
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
$t - t_{\rm bounce}$ [s]



2D
3D
Adv. LIGO
ET
25.0 $M_\odot$ at $D = 10$ kpc
9.0 $M_\odot$ at $D = 10$ kpc
$2\sqrt{f}|h_+(f)|$, $\sqrt{S_n}$ [Hz$^{-1/2}$]
f [Hz]

Bizouard et al. 2018



Core-Collapse Theory: A Status Summary

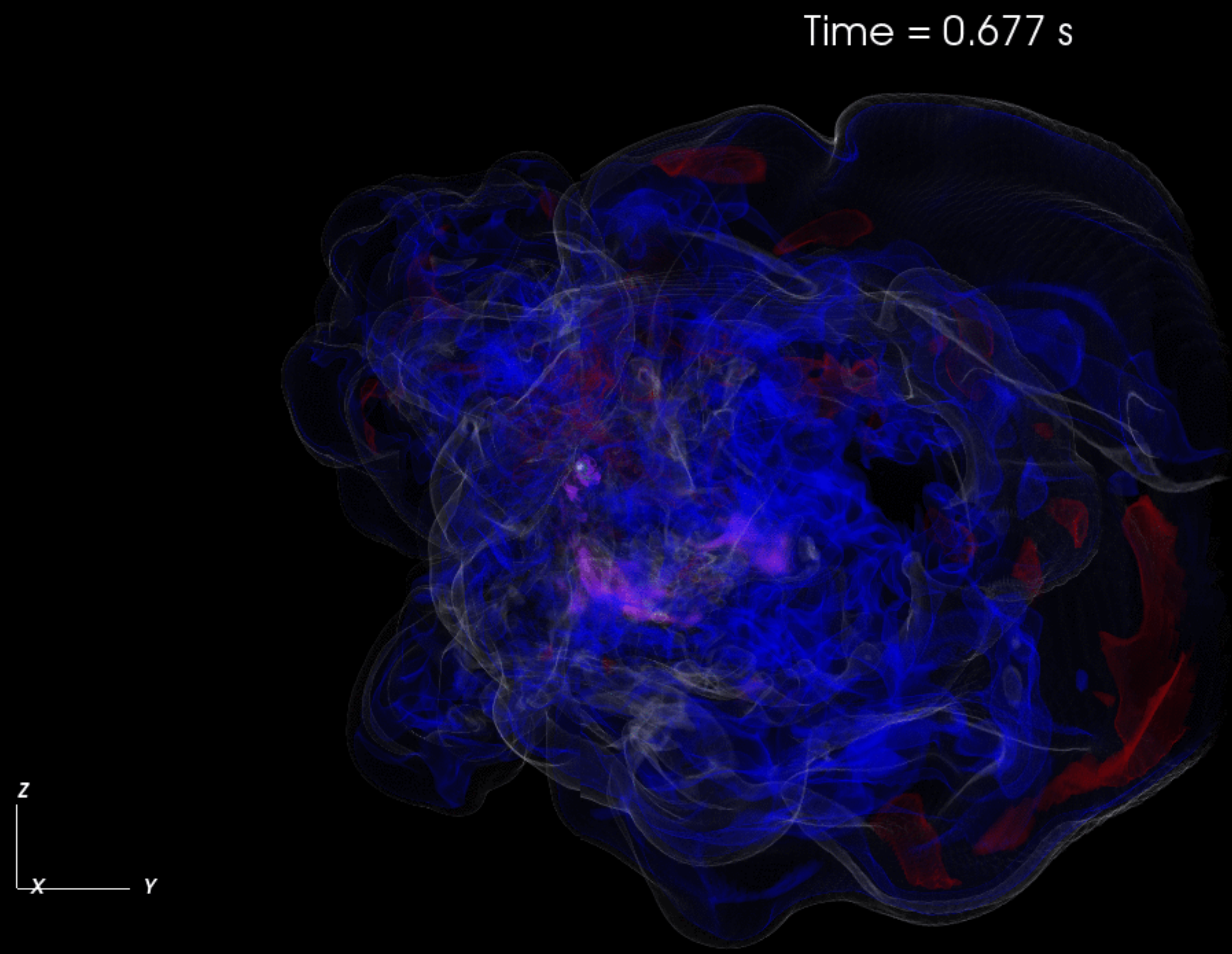
- Feedbacks severe in 1D, but in 2D/3D there is a strong dependence on microphysics and computational details (algorithm, resolution, etc.)
- Proximity to critical explosion curve amplifies effects of sub-dominant processes, etc.
- Can explain current differences between groups?

- Turbulent convection is Key Enabler of explosion for (almost) all viable mechanisms; turbulent stress, simultaneous accretion and explosion
- Neutrino-driven convection > SASI (when object explodes to yield SN)
- SASI is not a mechanism – can't generate much entropy
- Accretion of the Si/O interface
- 3D different from 2D (turbulent pressure, spectrum; scales)! 3D more explosive than 2D
- 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!

- Proto-neutron Star (PNS) Convection - boosts ν_μ neutrino luminosity
- Seed Perturbations

- 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


Time = 0.677 s
Z
X
Y