The Theory of Three-Dimensional Core-Collapse Supernova Explosions

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Supported by:
DOE/SciDAC4
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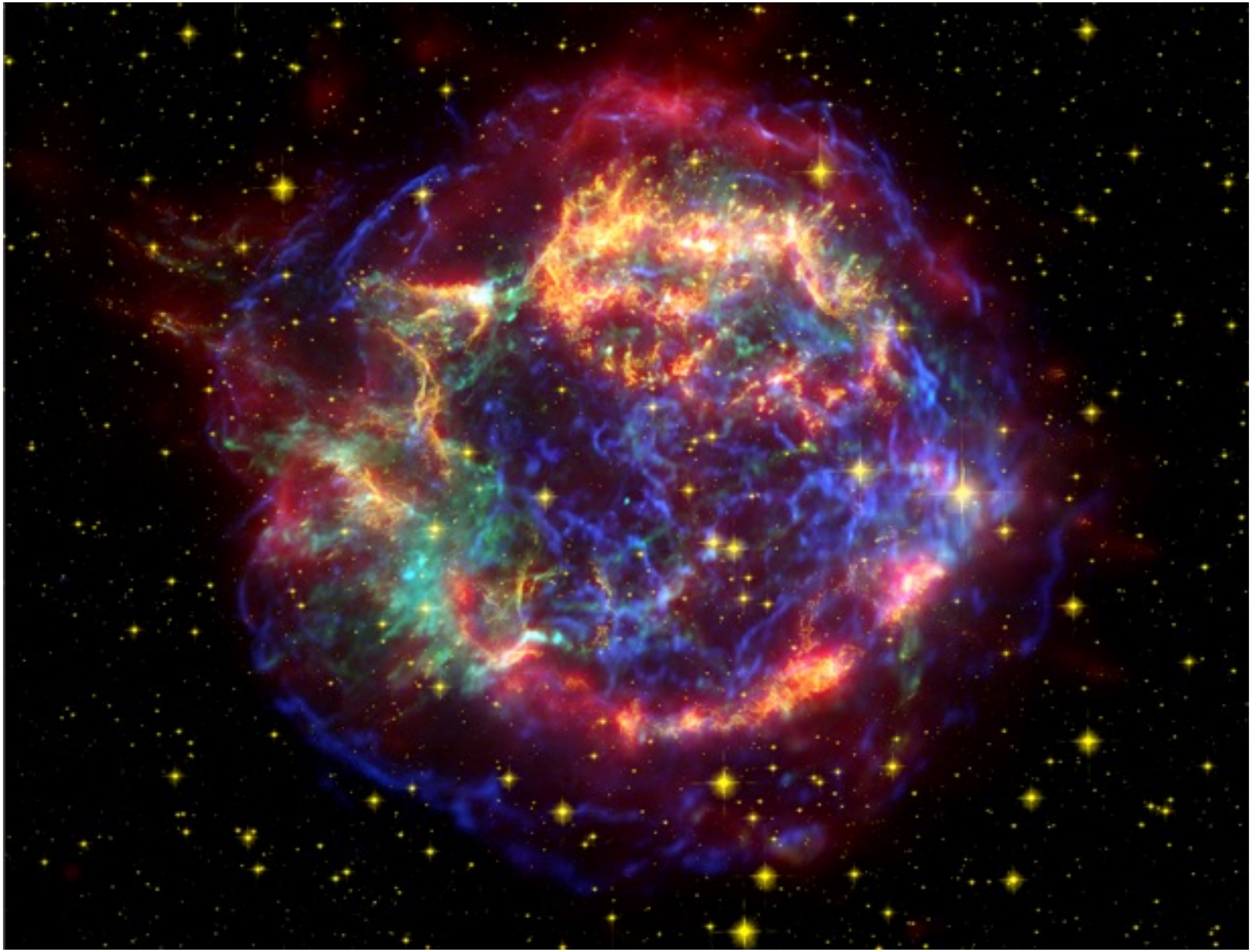
Supernova Remnant Cas A in X-rays



A Modern Generation of 3D Core-Collapse Supernova Simulations

Using Fornax, we have performed ~70 state-of-the-art 3D simulations – more than the rest of the world combined

Most models explode naturally

Lower-mass progenitors –> more "spherical" ejecta, lower NS masses, lower explosion energies, lower Ni-56 yields, [lower kick speeds (?), spins (?), B-fields (?)], all in a statistical sense

Higher-mass progenitors, the opposite, and take longer to "asymptote"

Observables and Systematics with Progenitor Structures/Mass

Explosion energy;
Pulsar/Neutron-star
Mass Distribution;
Nucleosynthesis and
3D distribution;
Blast Morphology;
Induced Spin;
Kick;
Birth B-fields and
Multipolarity;
Gravitational-Wave
and Neutrino
Signatures
Winds

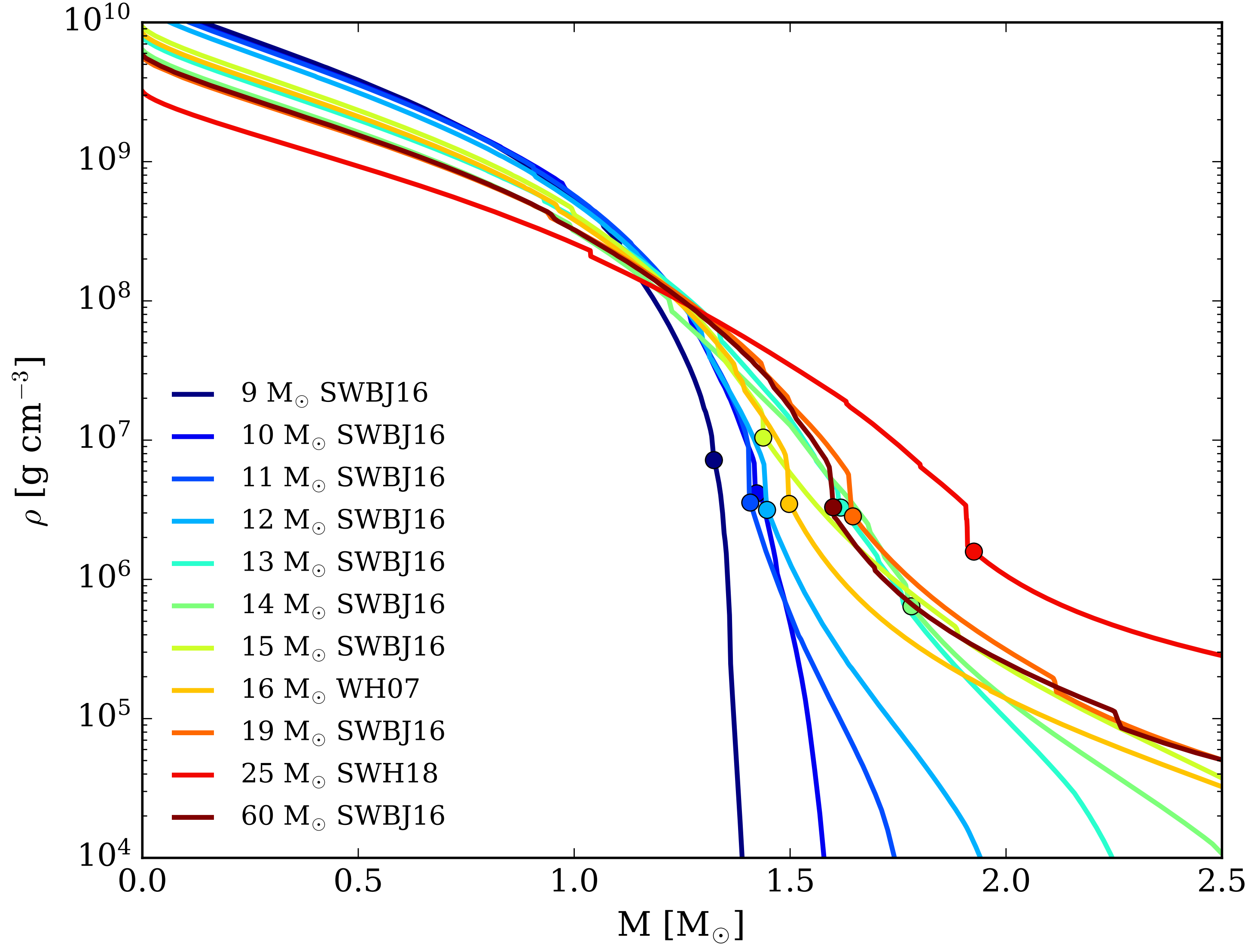
Core-Collapse Theory: What's New?

- Turbulence crucial to most explosions, necessitating multi-D treatment
- In 2015-2020, we could do multiple 2D simulations every year to explore parameters, understand systematics, and explore progenitor structure dependence.
- Techniques improved (Fornax) and computers sped up; resolution-dependence
- Now, we 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 – also, dynamo action?
- Incorporated inelastic neutrino-matter processes – extra neutrino heating
- Accretion of the Si/O interface; seed perturbations of progenitor (?)

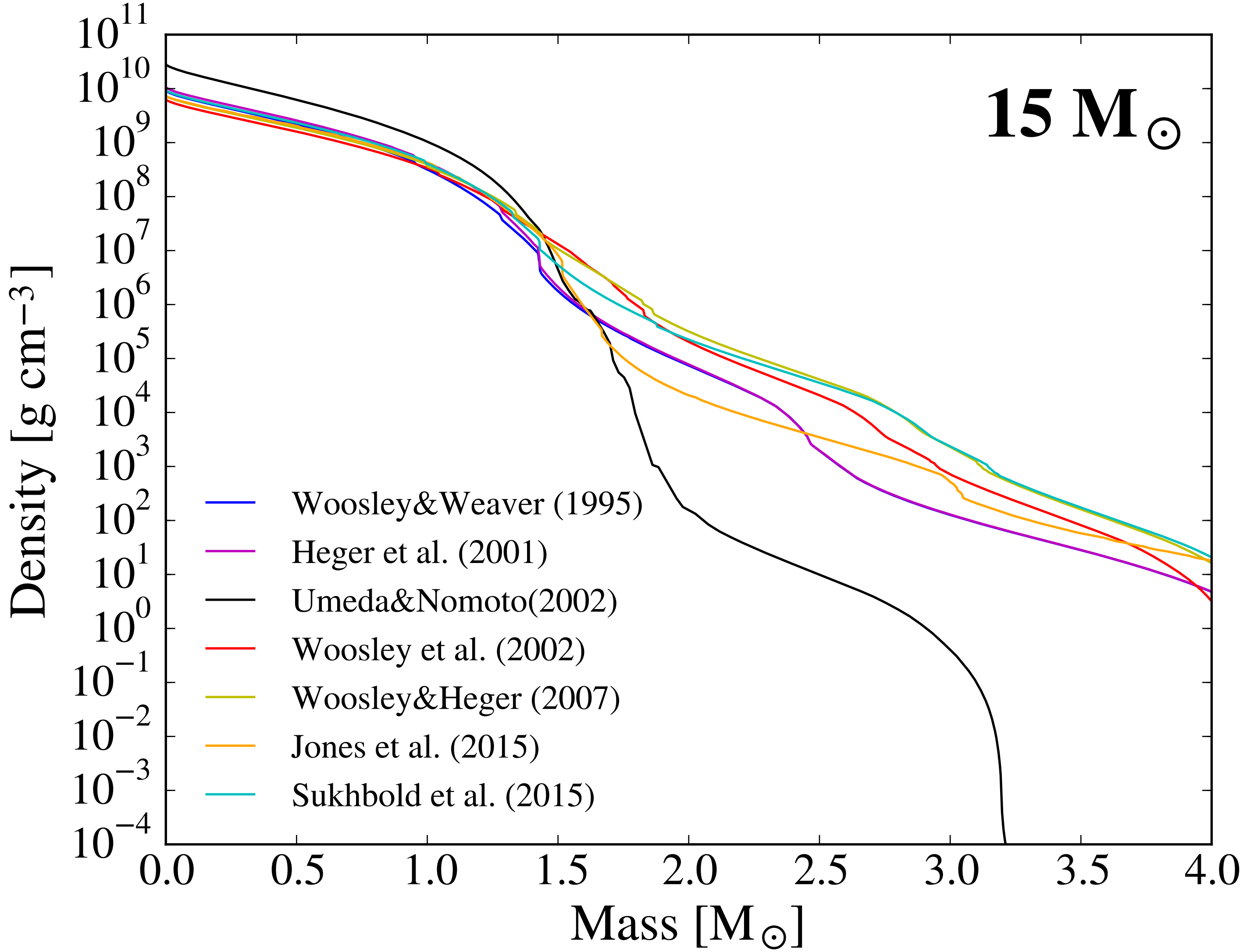
Important Roles of Progenitor Models:

Density Structures, Rotational Profiles, Seed Perturbations

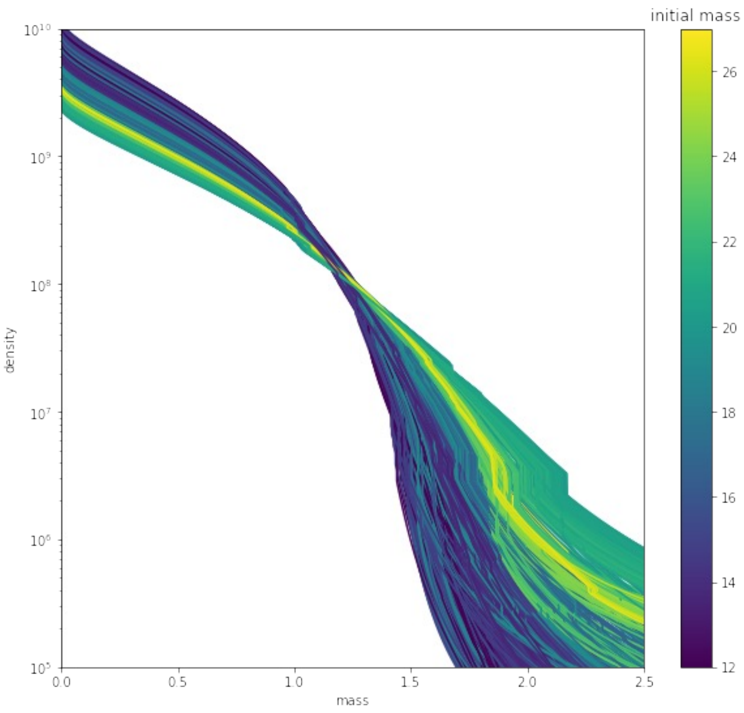
Progenitor Density Profiles



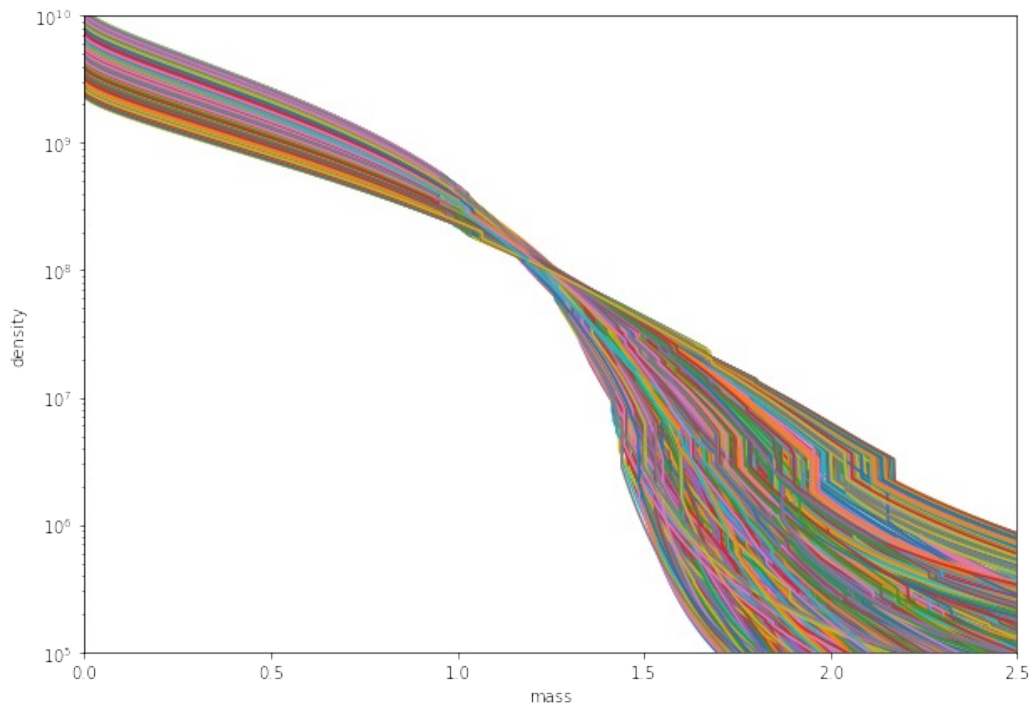
Different Groups, Same ZAMS Mass

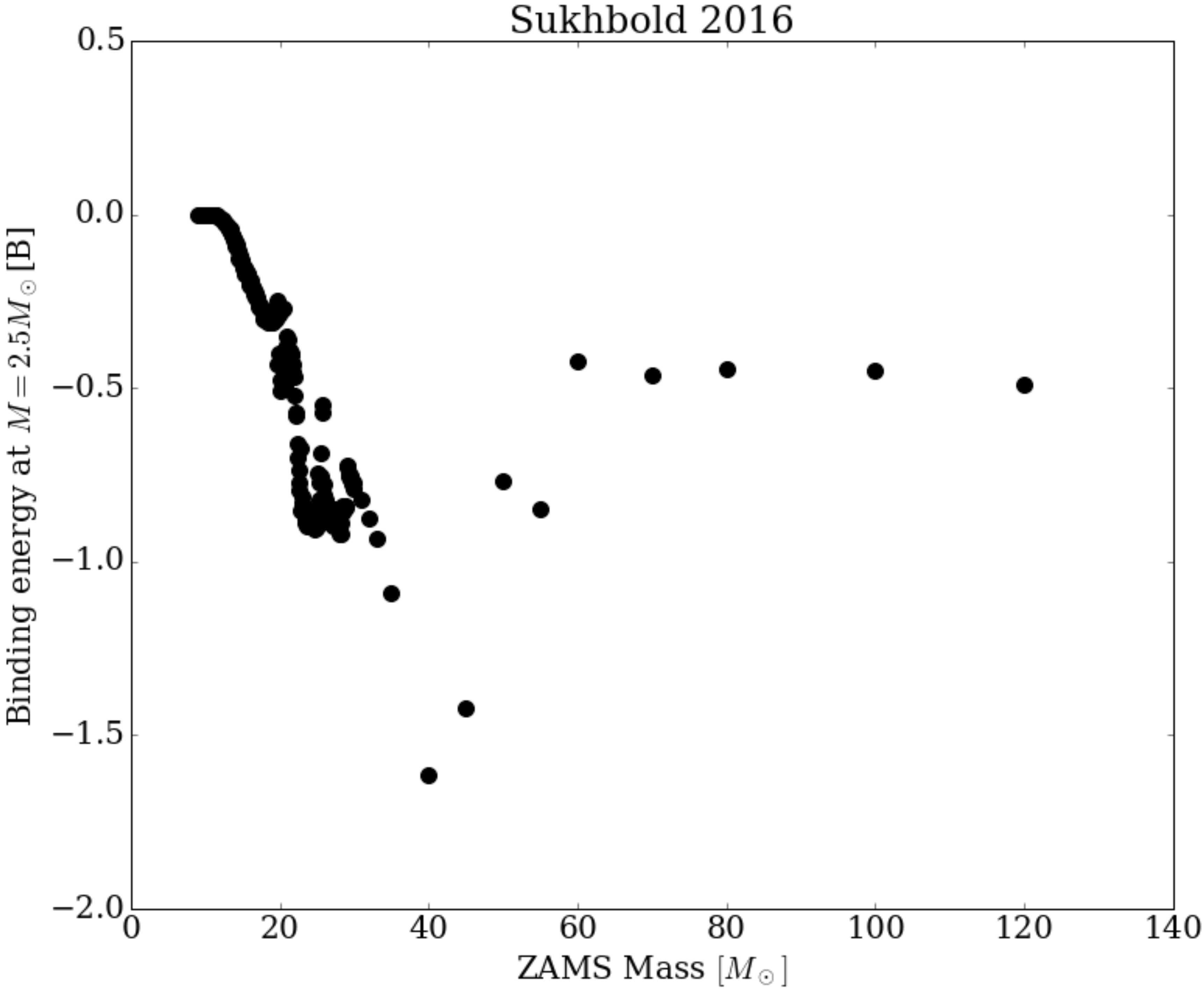


MESA Models



Sukhbold et al. Models




Sukhbold 2016
Binding energy at $M = 2.5 M_\odot$ [B]
ZAMS Mass $[M_\odot]$
0.5
0.0
−0.5
−1.0
−1.5
−2.0
0
20
40
60
80
100
120
140

Myths of Core-Collapse Supernova Theory

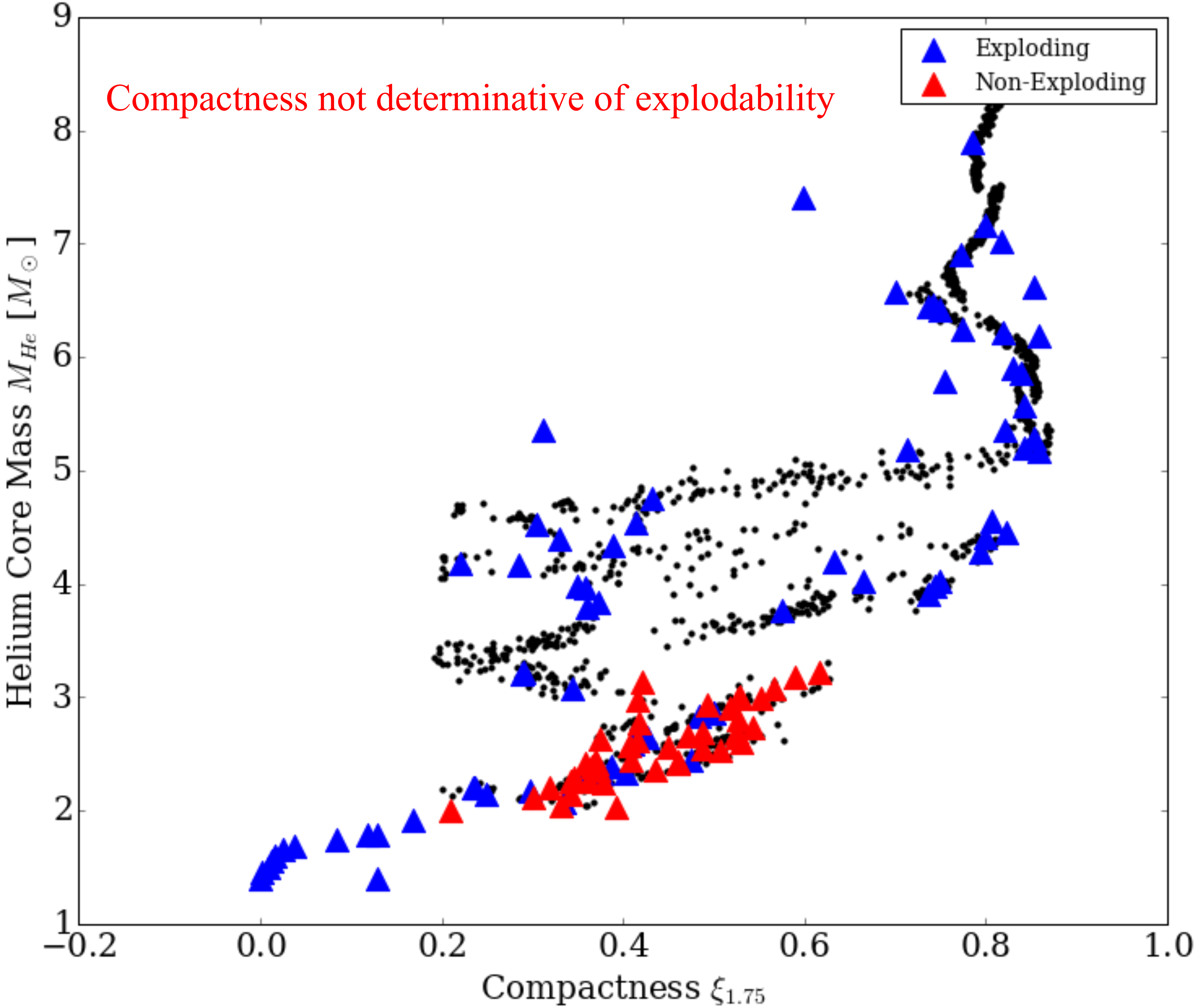
1) The “SASI” is next to irrelevant in CCSN Theory

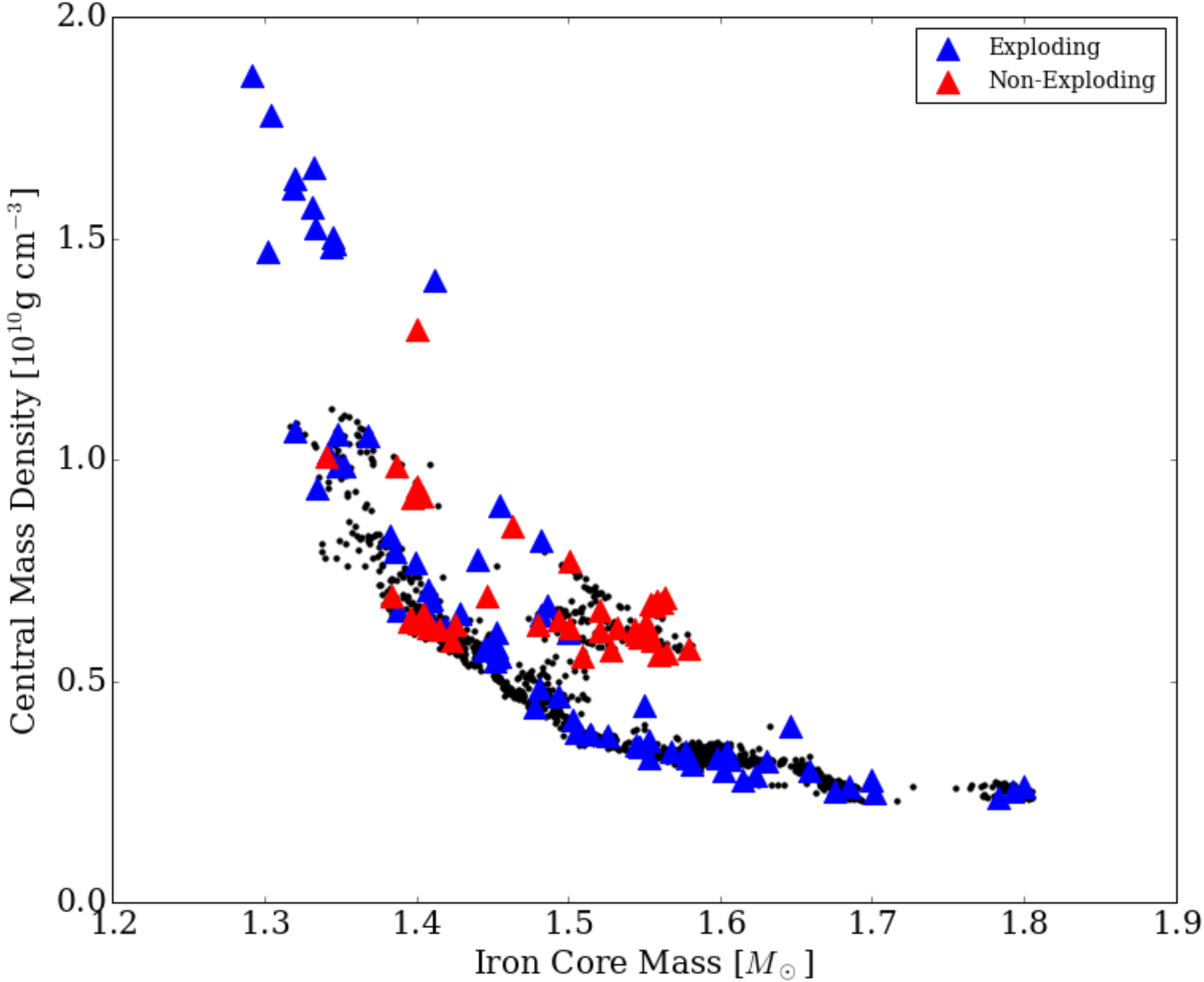
2) Low “compactness” is not a predictor of “explodability”

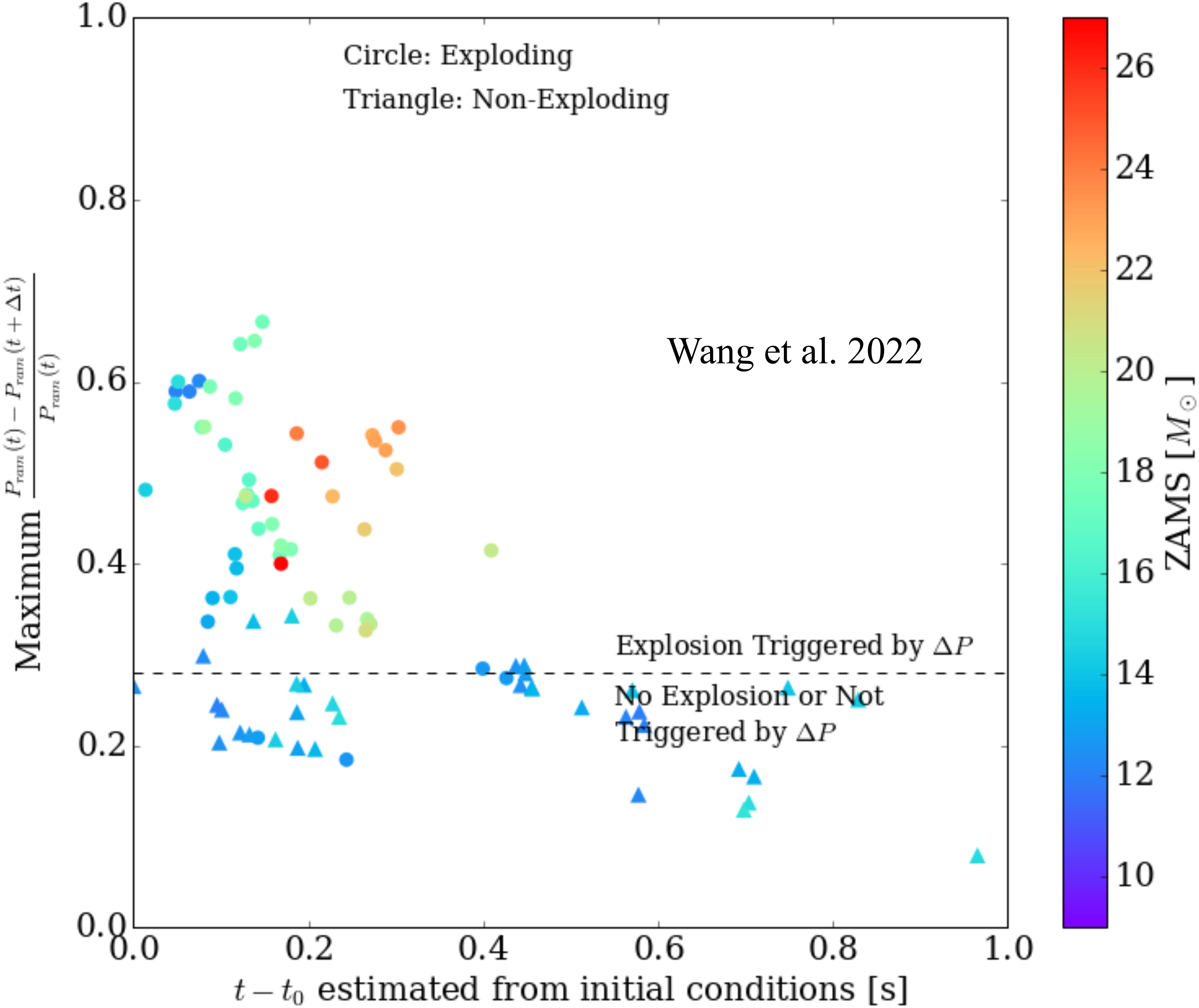
3) Exploding early does not lead to a more energetic explosion

4) The convective engine paradigm is a myth

5) There is no “rapid” and “delayed” distinction in the context of the neutrino mechanism of explosion


Compactness not determinative of explodability
Exploding
Non-Exploding
Helium Core Mass M_{He} [$M_\odot$]
Compactness $\xi_{1.75}$
9
8
7
6
5
4
3
2
1
−0.2
0.0
0.2
0.4
0.6
0.8
1.0


Exploding
Non-Exploding
Central Mass Density [10^{10}g cm^{-3}]
Iron Core Mass [$M_\odot$]
2.0
1.5
1.0
0.5
0.0
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9

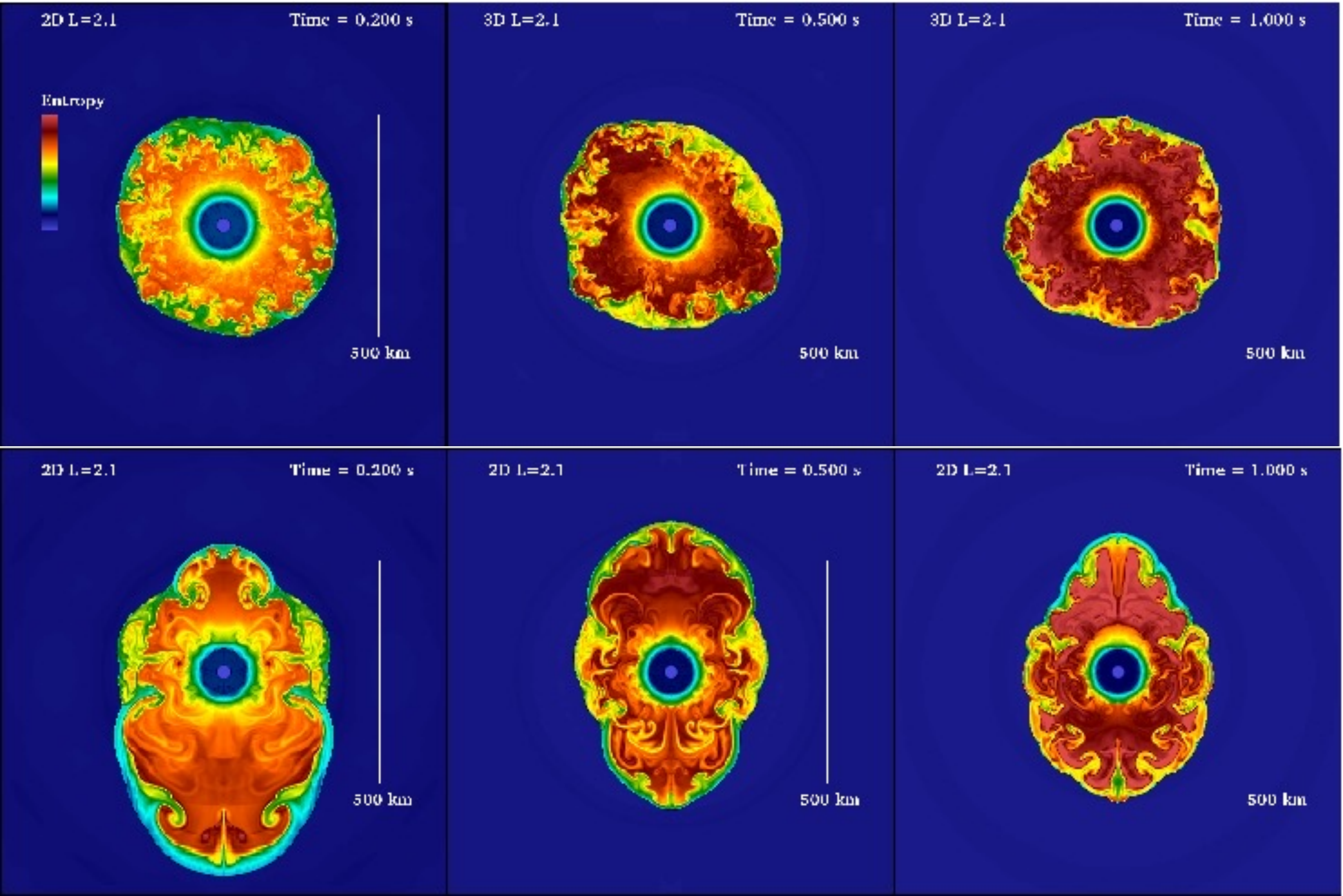


Circle: Exploding
Triangle: Non-Exploding
Wang et al. 2022
Explosion Triggered by ΔP
No Explosion or Not Triggered by ΔP
Maximum $\frac{P_{ram}(t) - P_{ram}(t+\Delta t)}{P_{ram}(t)}$
$t - t_0$ estimated from initial conditions [s]
ZAMS [$M_\odot$]
0.0
0.2
0.4
0.6
0.8
1.0
10
12
14
16
18
20
22
24
26

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

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

Comparison of 2D with 3D

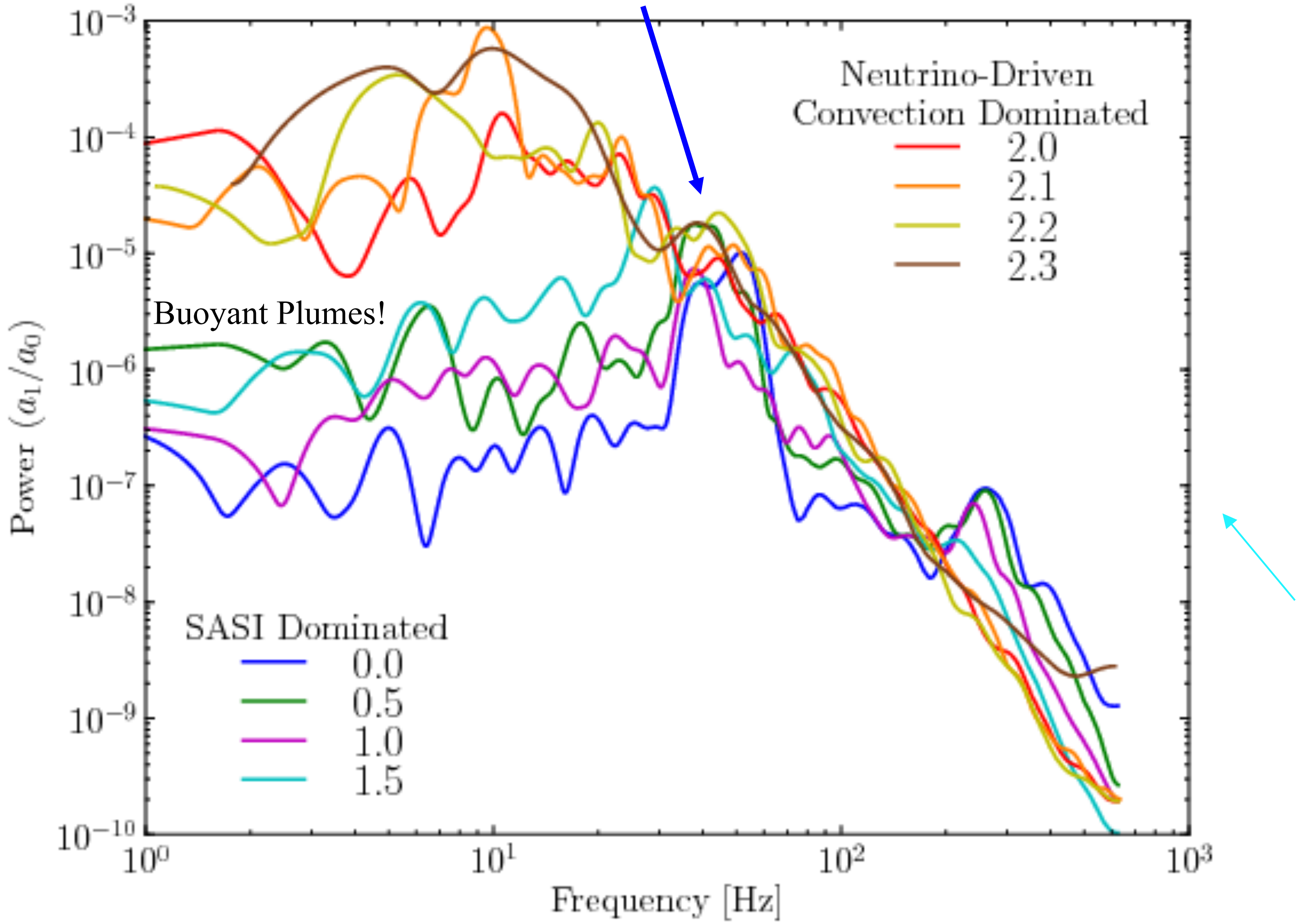


"SASI" (vortical-acoustic shock instability) not important in CCSNe –
Neutrino-driven convection dominates

Shock Surface Power Spectrum versus Driving Luminosity

SASI tone

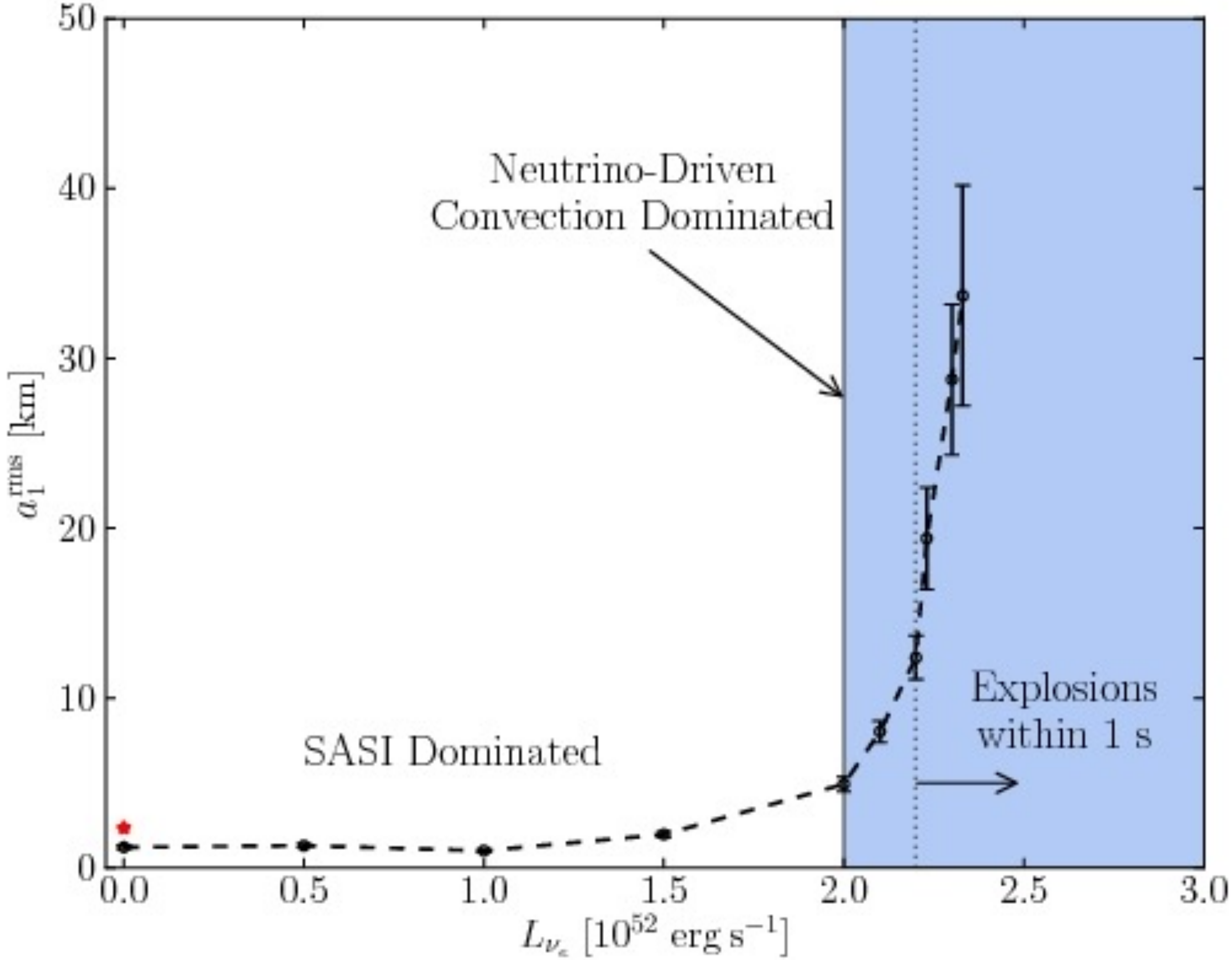
x100



Neutrino-driven Buoyancy, not SASI

Burrows et al. 2012; See also Fernandez et al. (2013) and Buellet et al. 2023)

Dipolar Amplitudes versus Driving Luminosity



Burrows, et al. 2012; See also Couch & O' Connor 2013, Murphy et al. 2013 SASI is subdominant for all neutrino-driven explosions

Buellet, Foglizzo, Guilet, and Abdikamalov 2023: arXiv:2301.01962; Caption to their Figure 2:

"Evolution of the modes as a function of χ parameter. Two instability domains can be identified: SASI (ωr ,0) for modest neutrino heating and the convective instability (ωr =0) for stronger heating."

"An Investigation into the Character of Pre-Explosion Core-Collapse Supernova Shock Motion," (Adam Burrows, Josh Dolence, & Jeremiah Murphy), 2012, Ap.J., 759, 5 (arXiv:1204.3088).

"The Dominance of Neutrino-Driven Convection in Core-Collapse Supernovae," (J.W. Murphy, J.C. Dolence, & A. Burrows), Ap.J., 771, 52, 2013 (arXiv:1205.3491).

See also Fernandez et al. (2013)

New Fornax 3D Simulations

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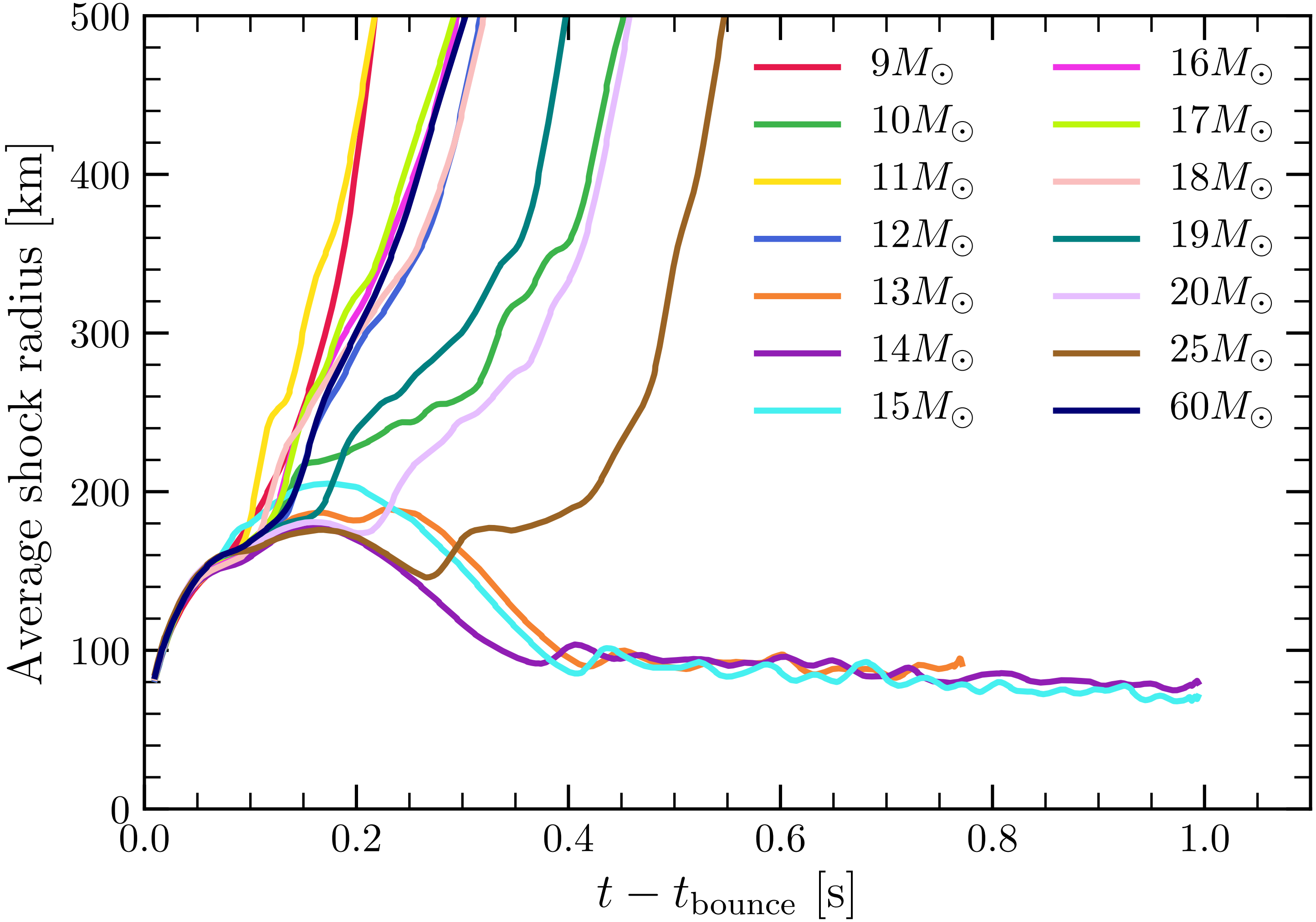
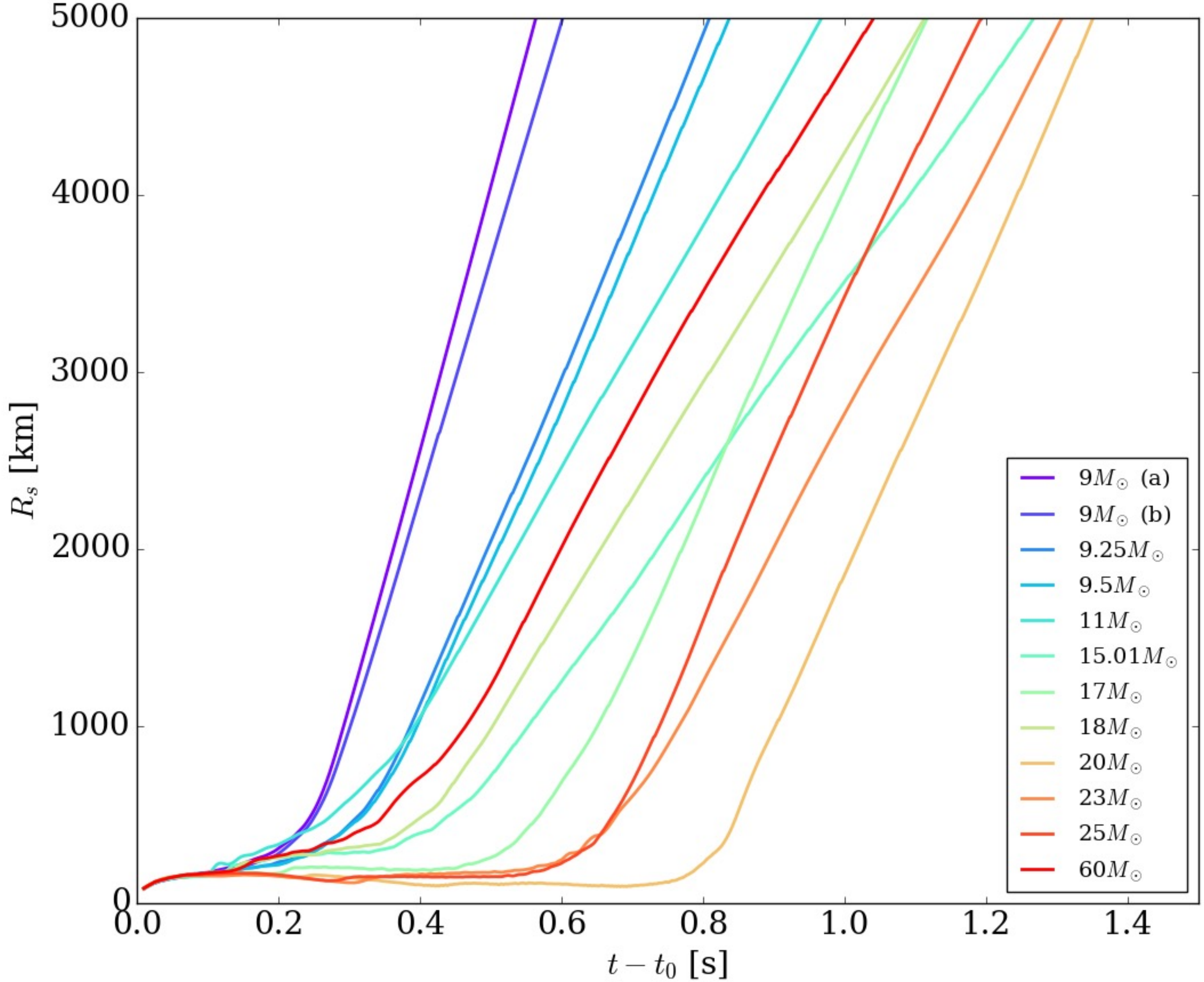
3D Models



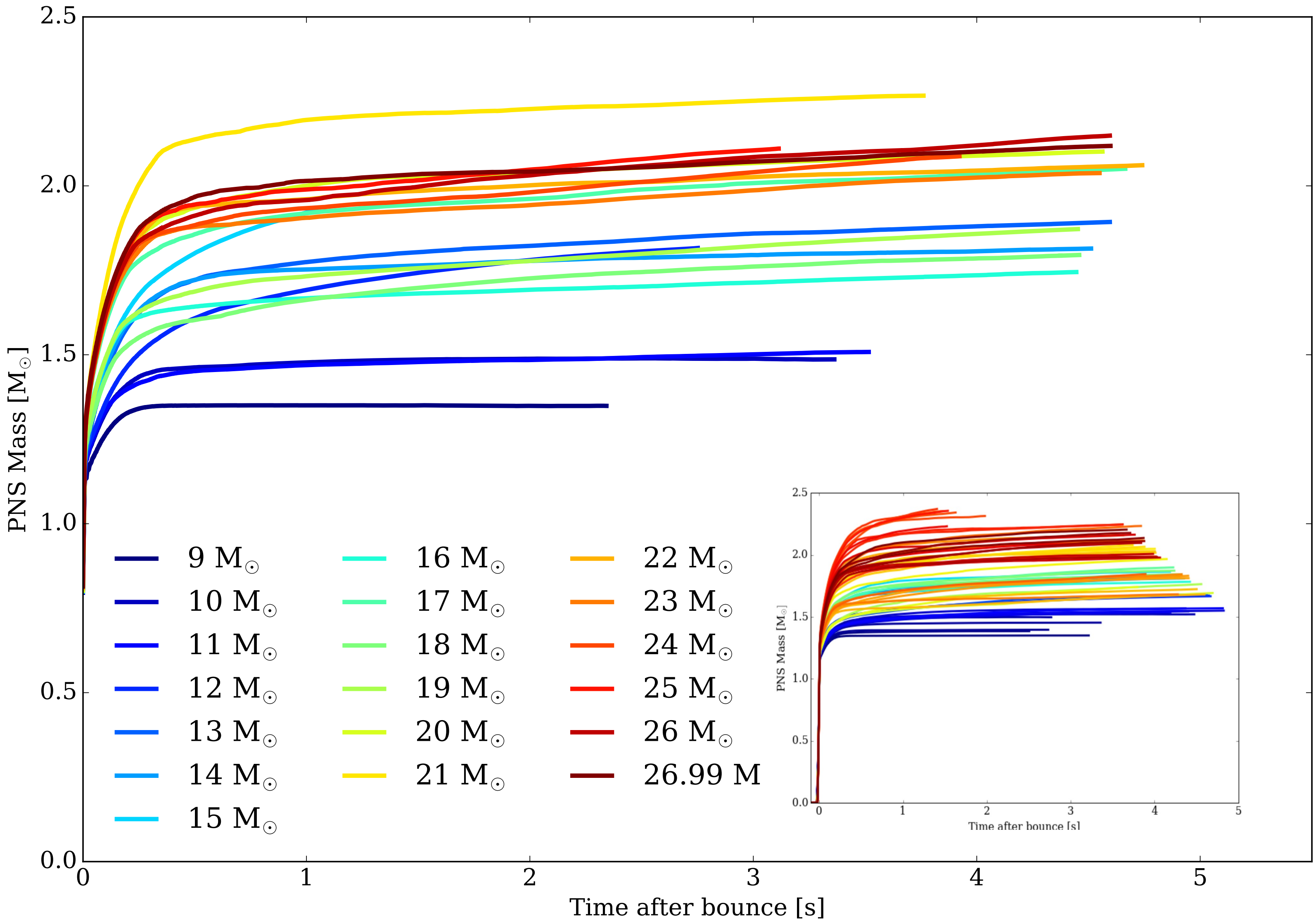
Burrows et al. 2019, 2020; Vartanyan et al. 2019ab; Radice et al. 2019

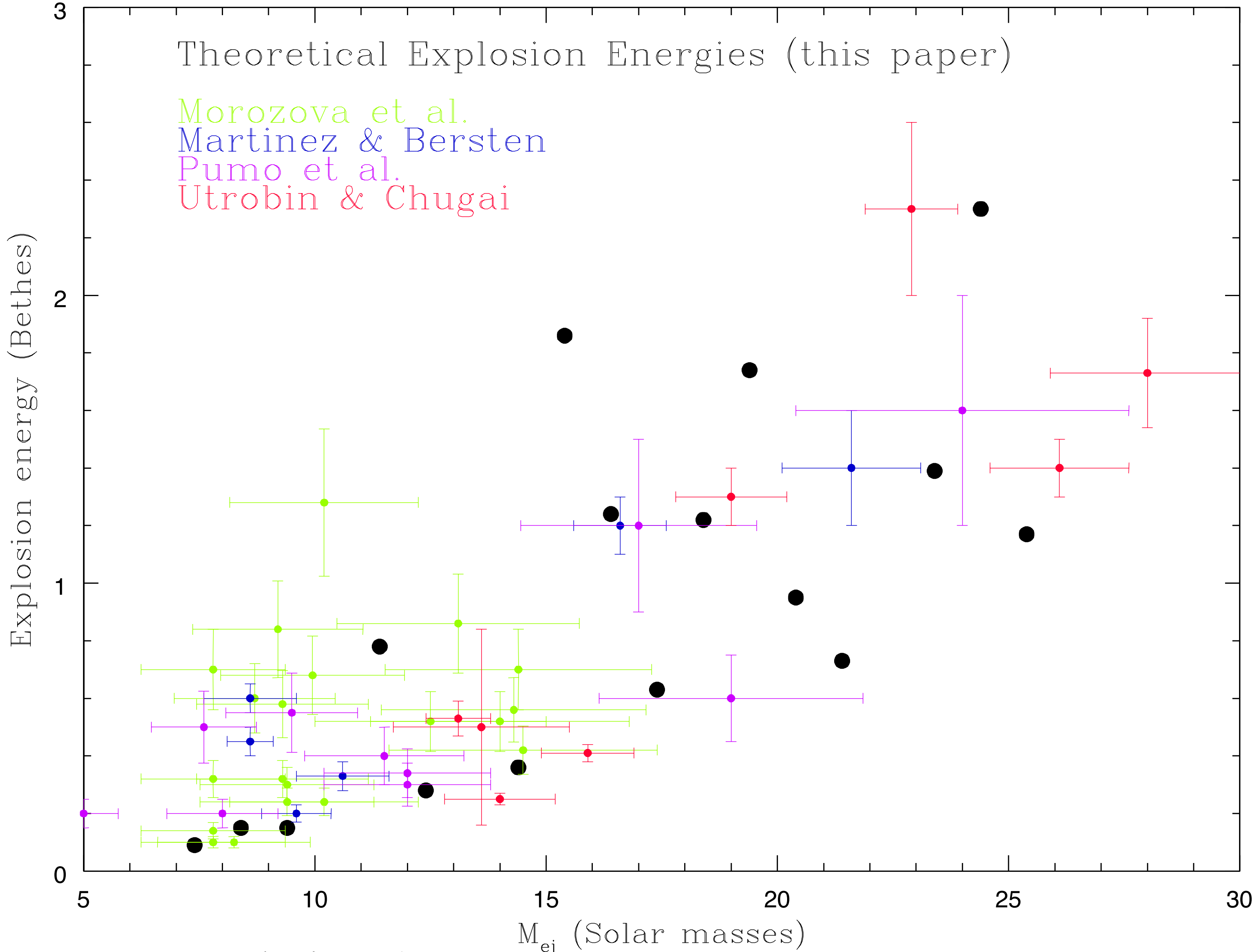
Mean Shock Radii (3D)



Long-Term 2D explosions (to 4.5 seconds)

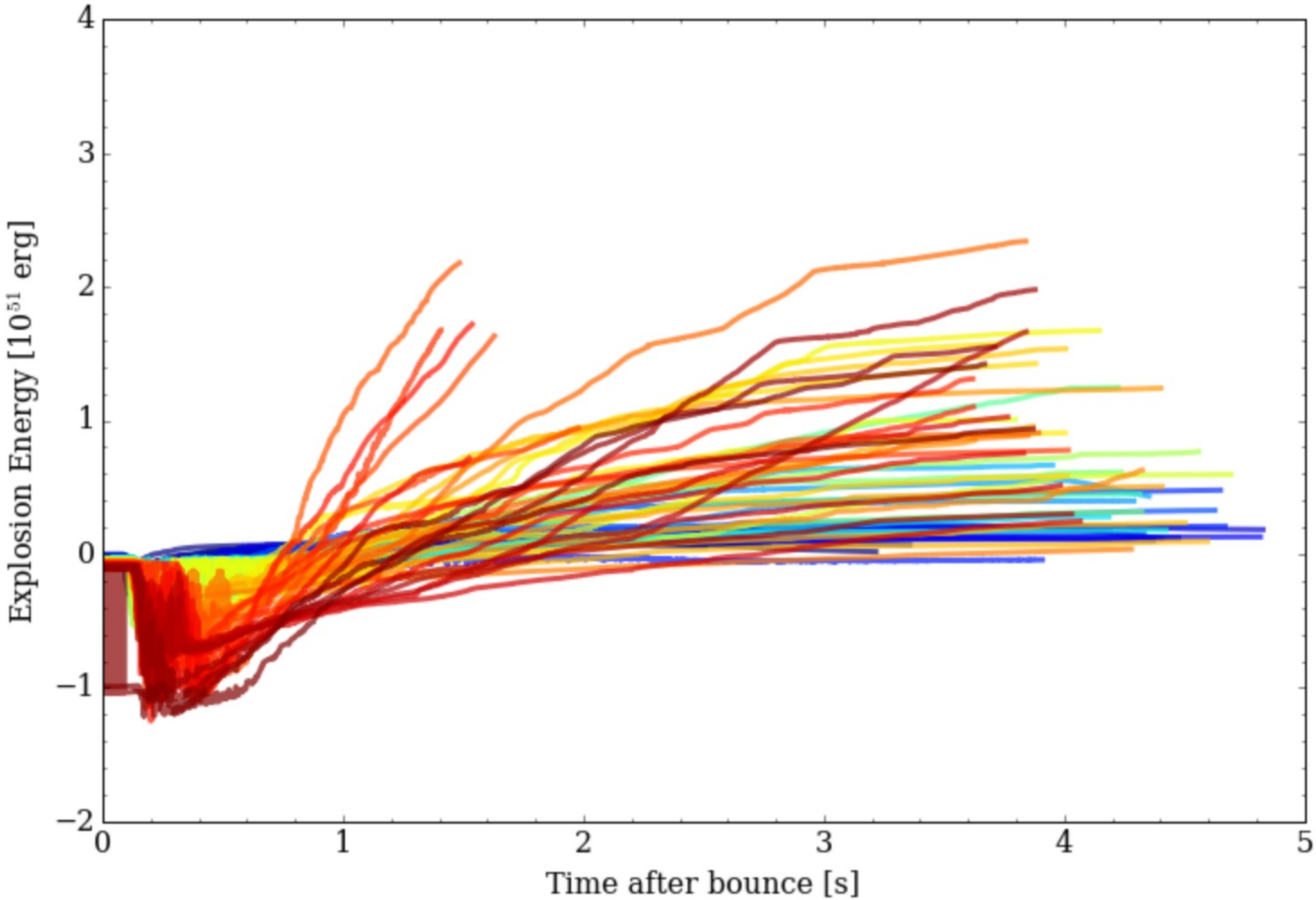
PNS Baryon Mass vs. Time: Grav. Mass = ~1.2 – 1.8 solar masses

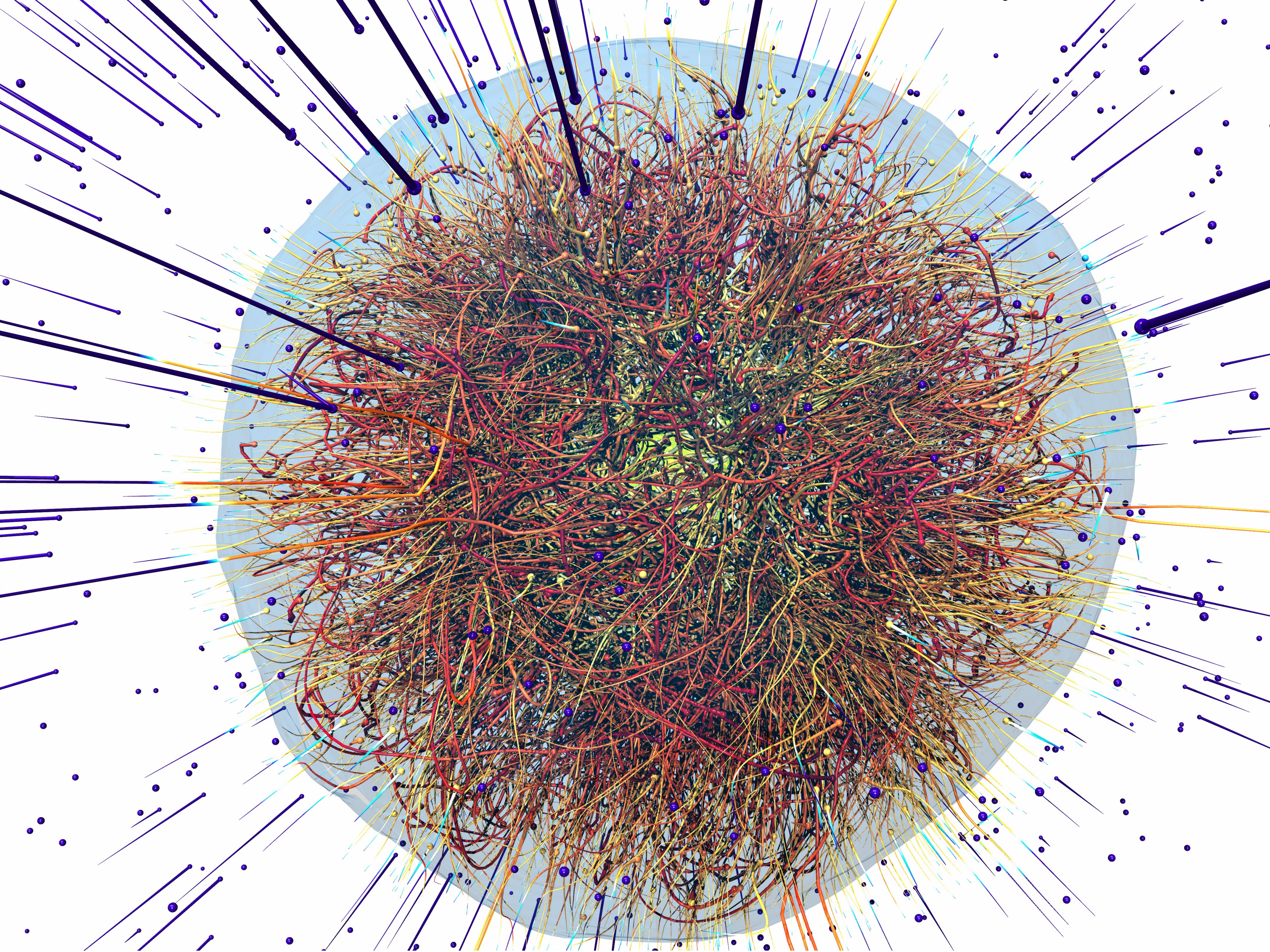




Long-Term 2D explosions (to 4.5 seconds)

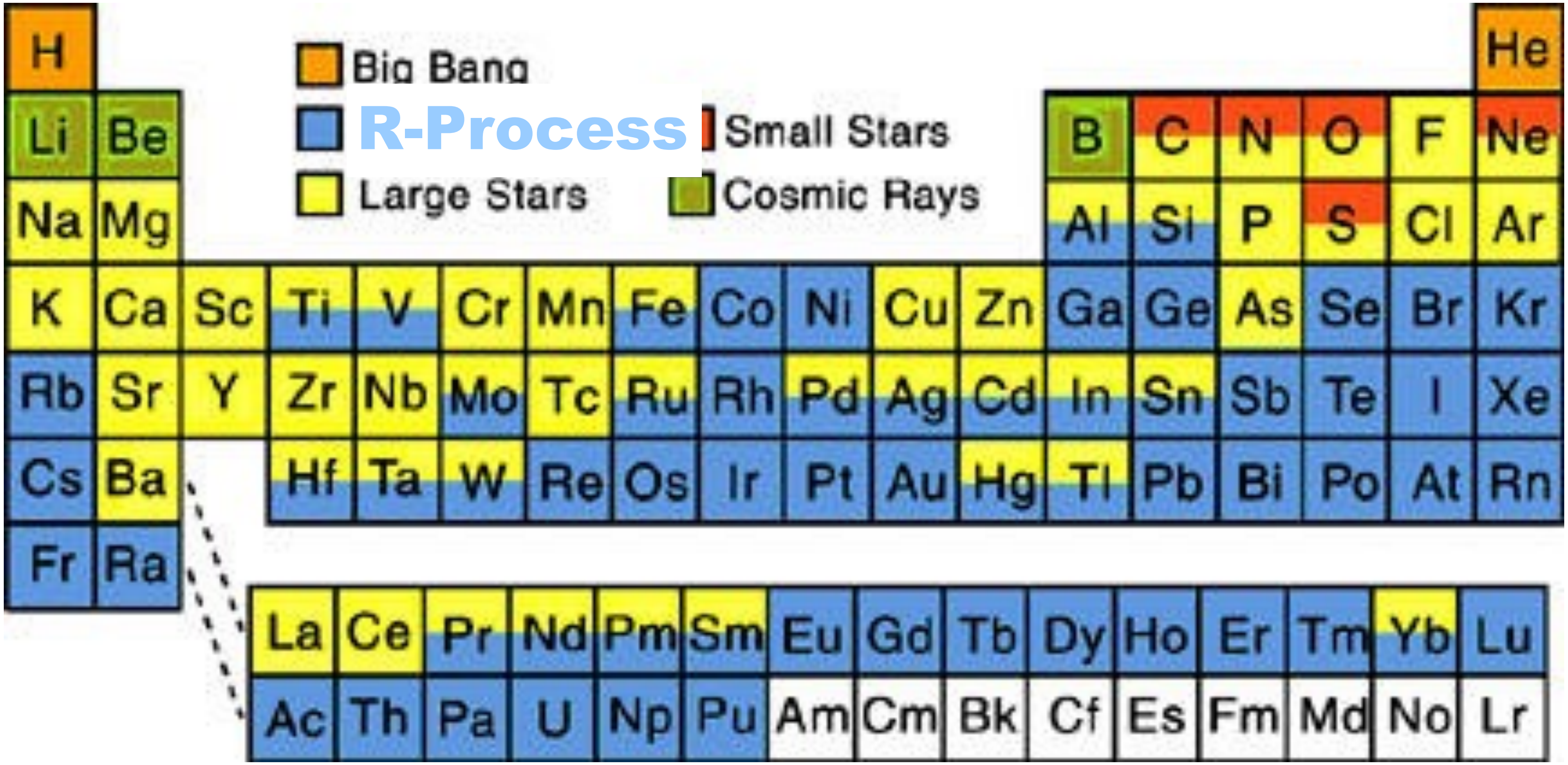
Explosion Energies (2D)





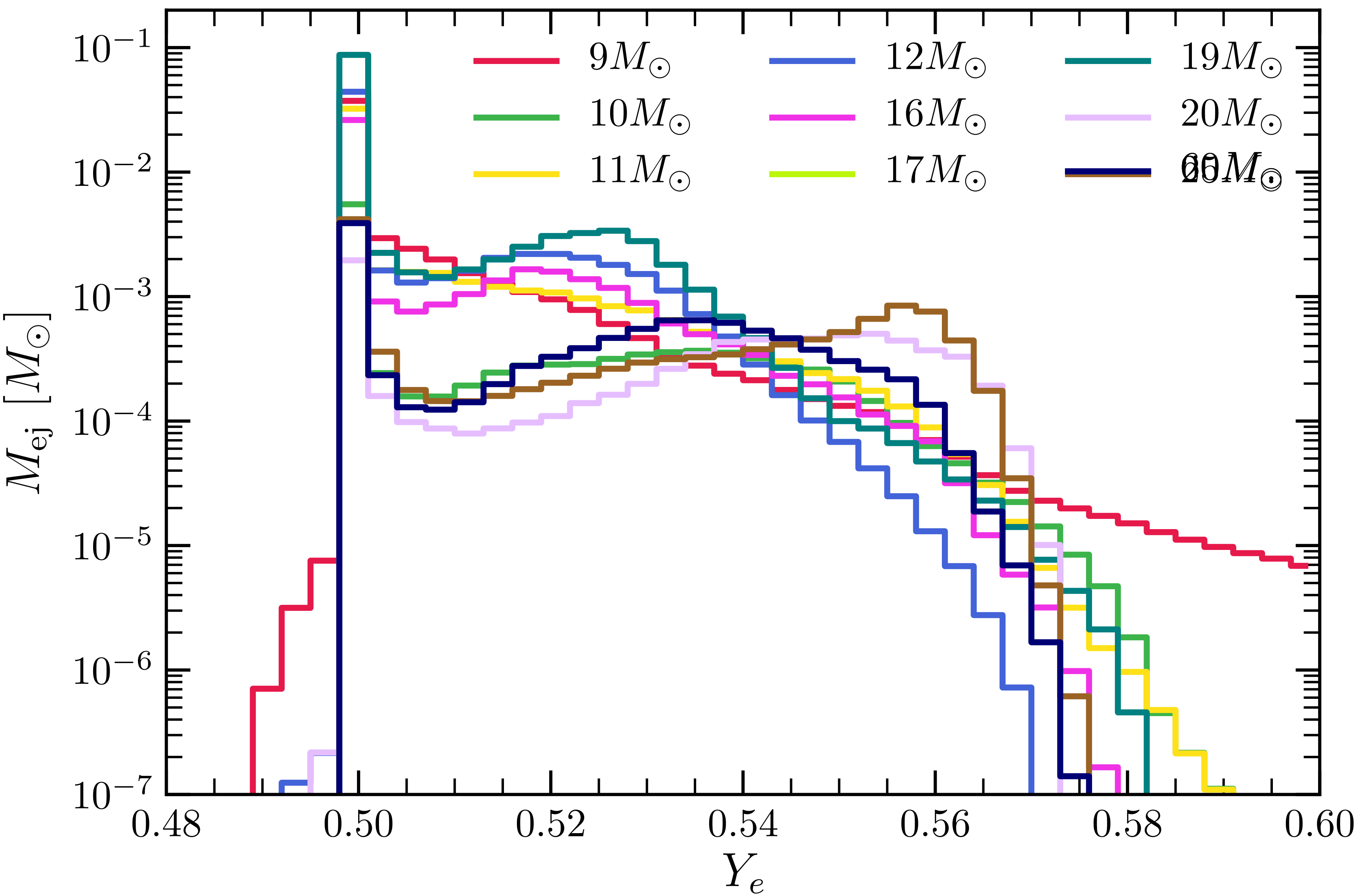
Ejecta Composition (Y_e) and Nucleosynthesis

The origin of the elements

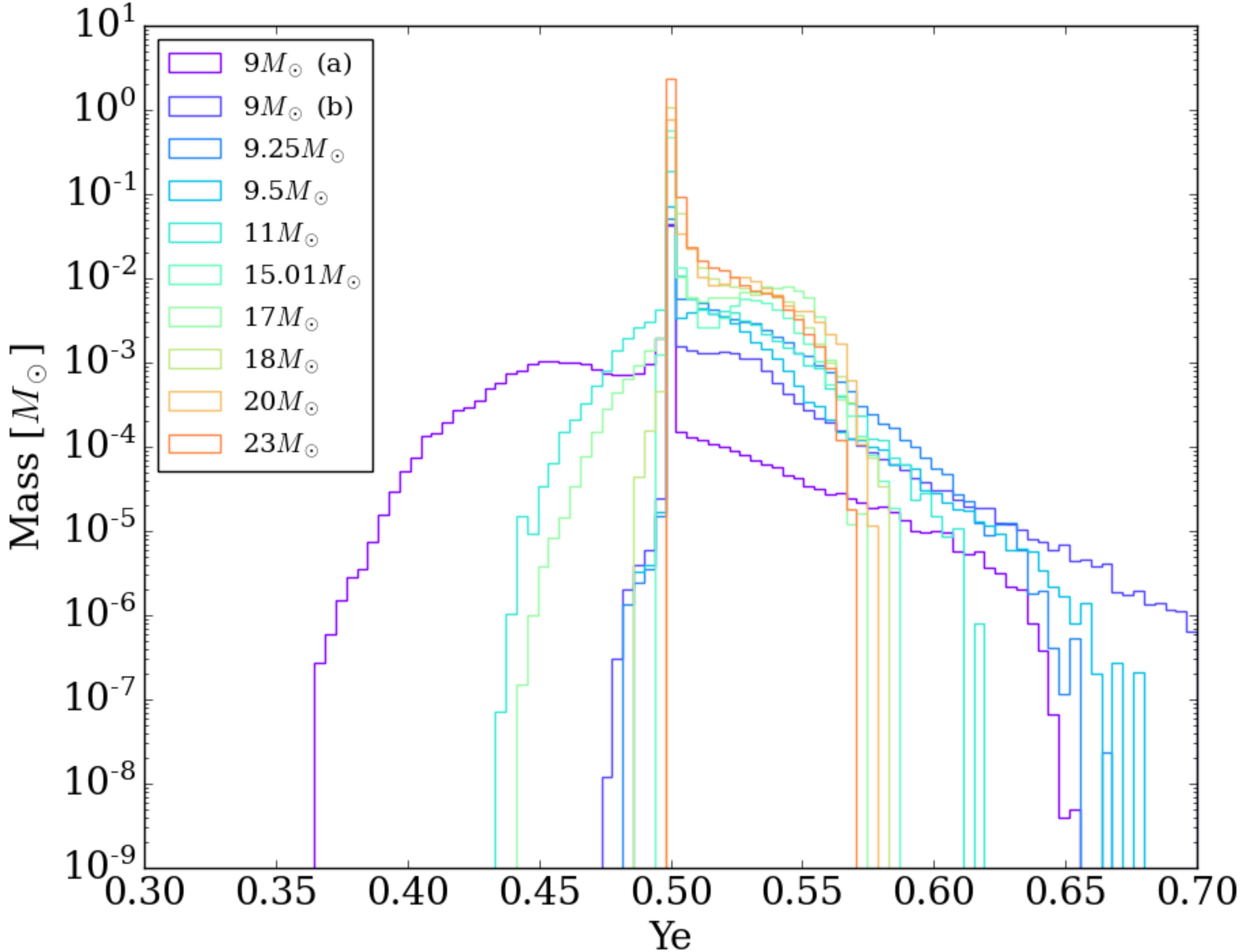


Are neutron star mergers the sites of the r-process?

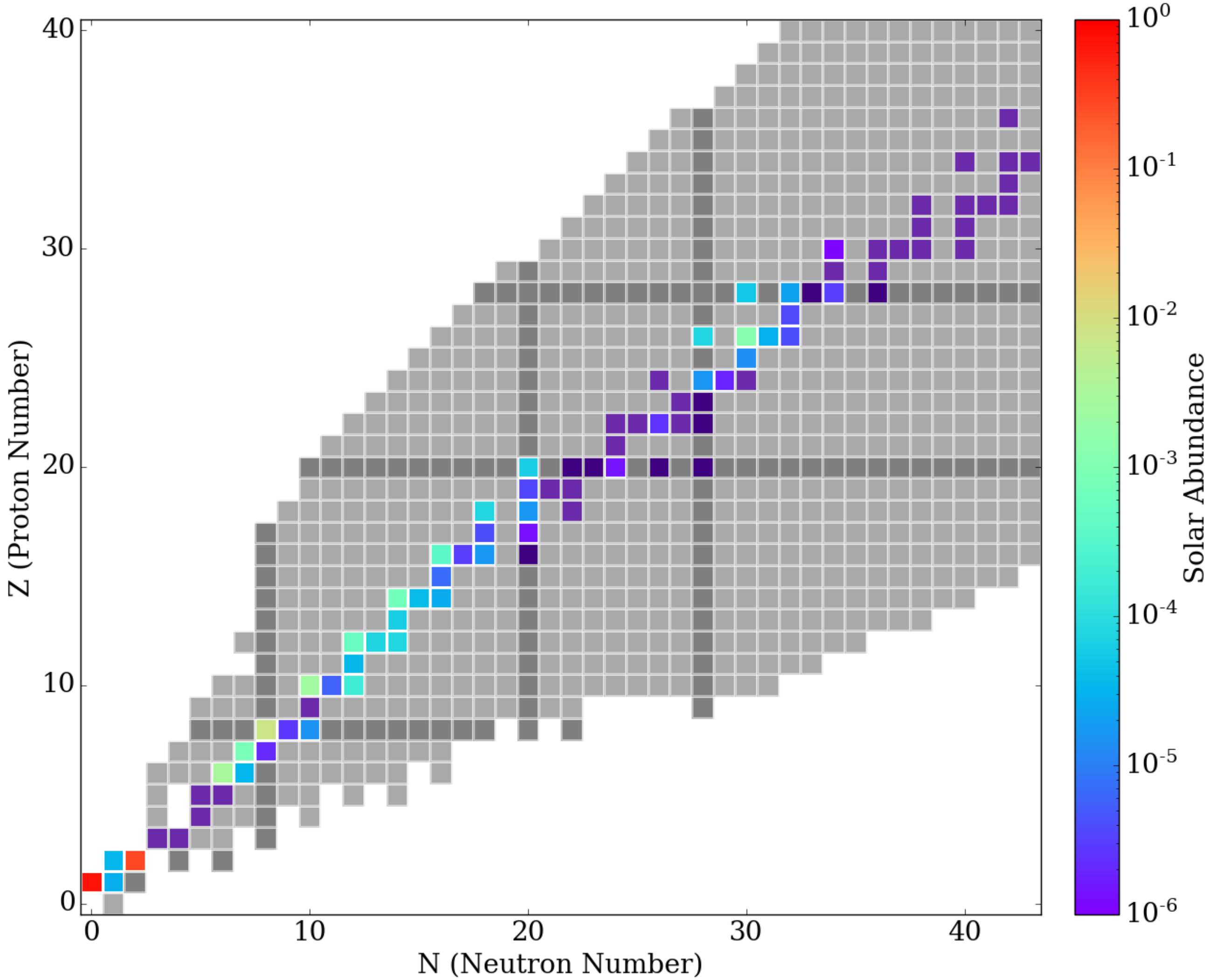
Y_e : 3D Explosion Models



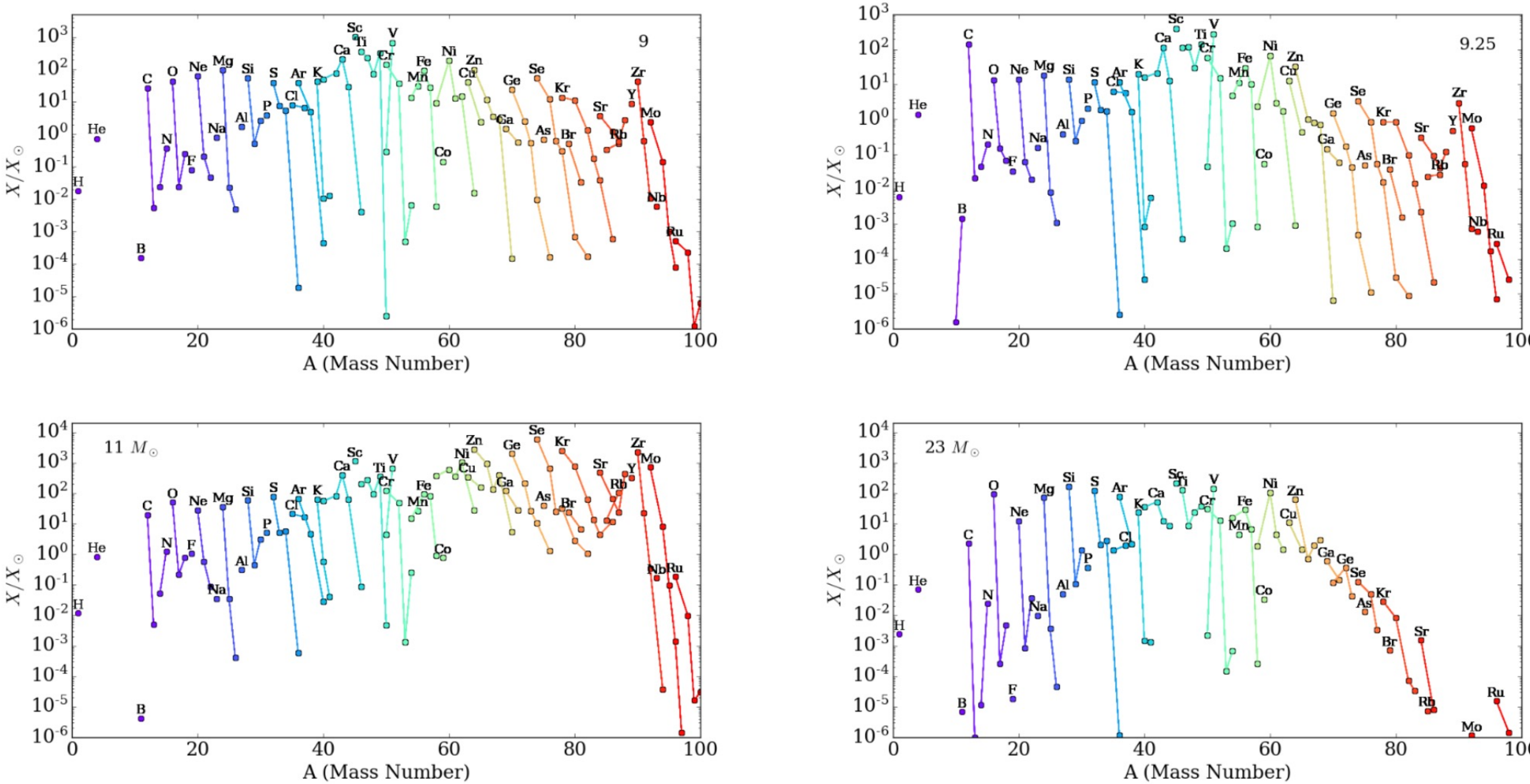
Y_e : 3D Explosion Models: New Vintage

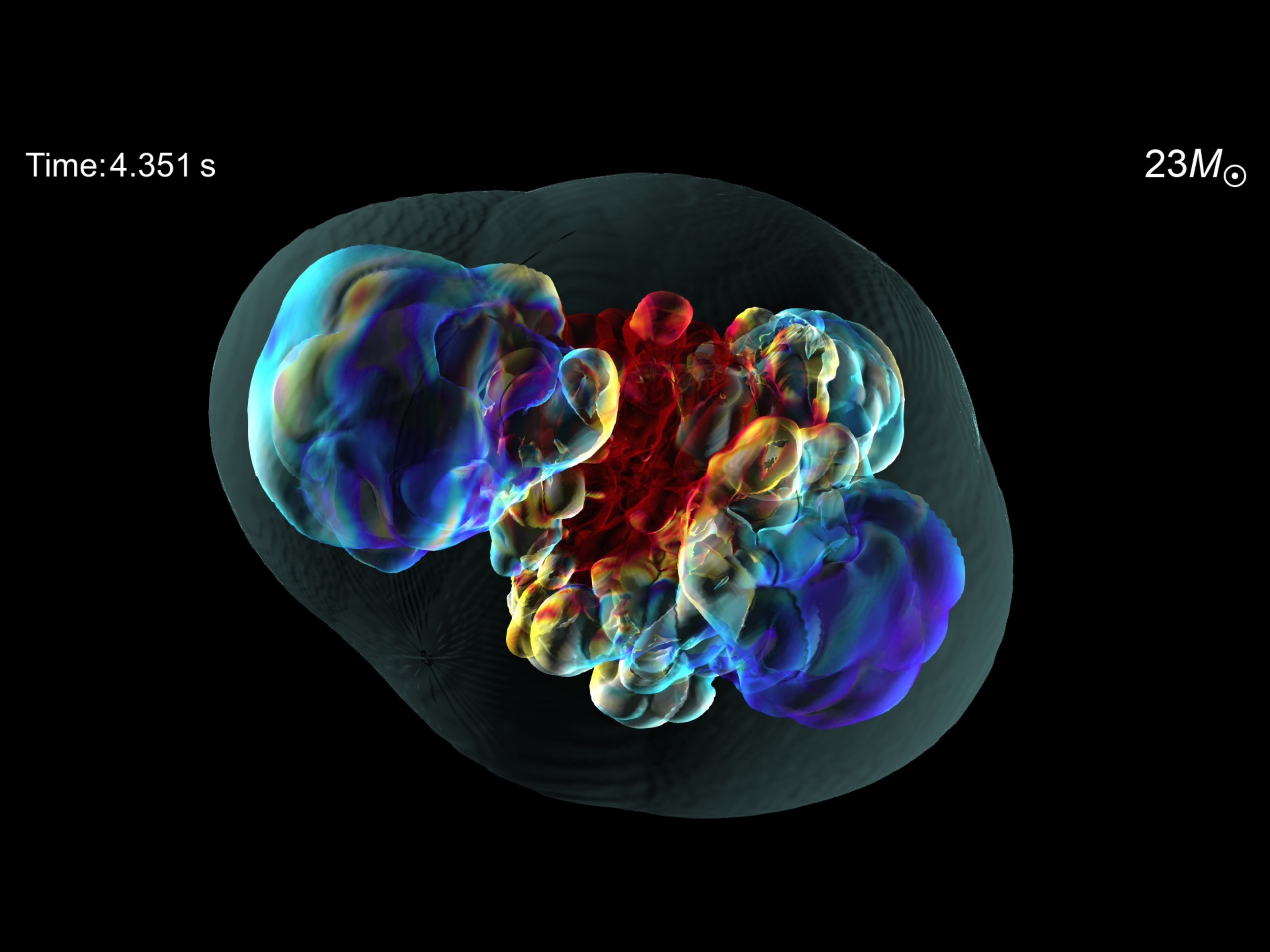


Network and Solar Abundances

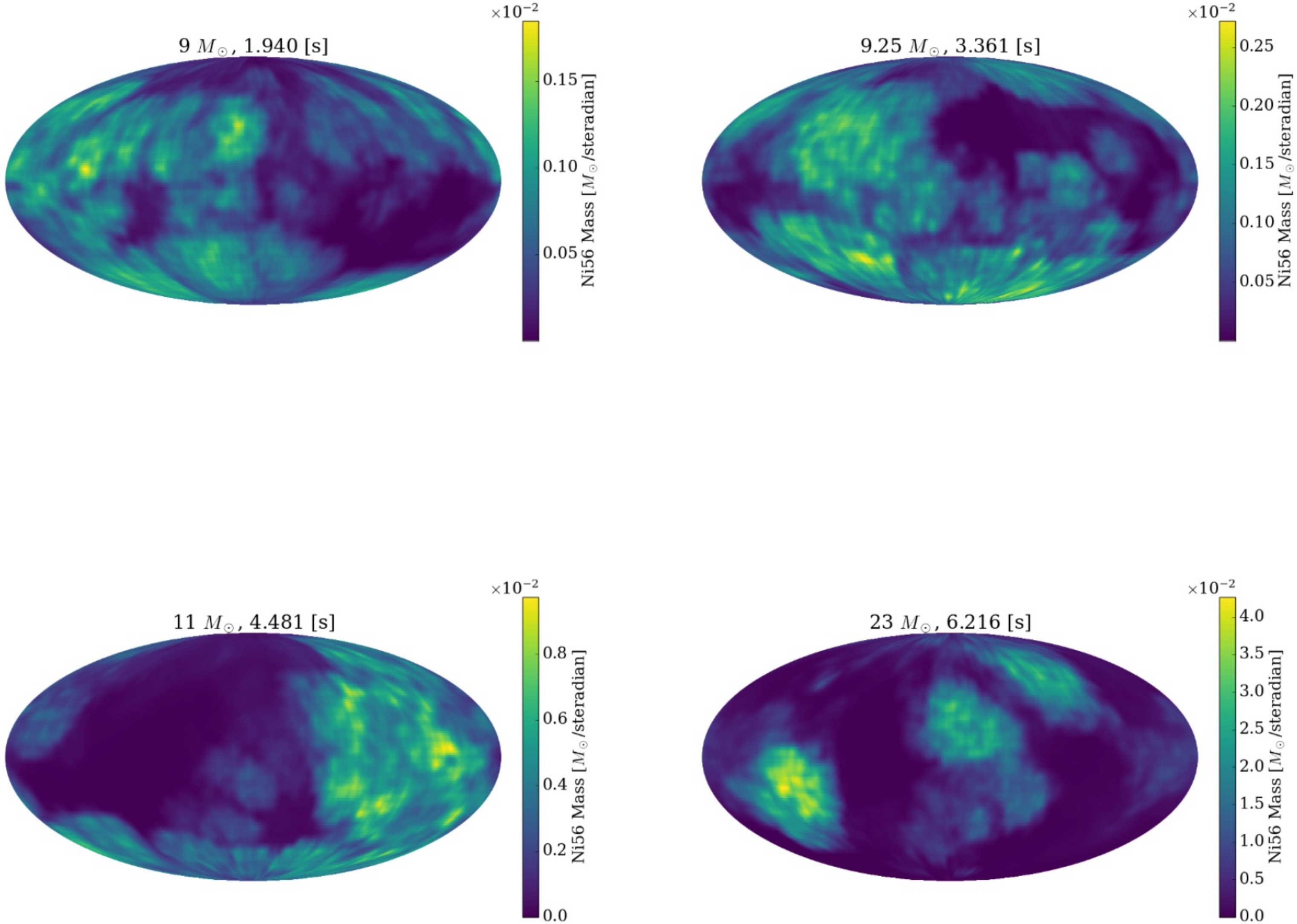


Element Production Factors



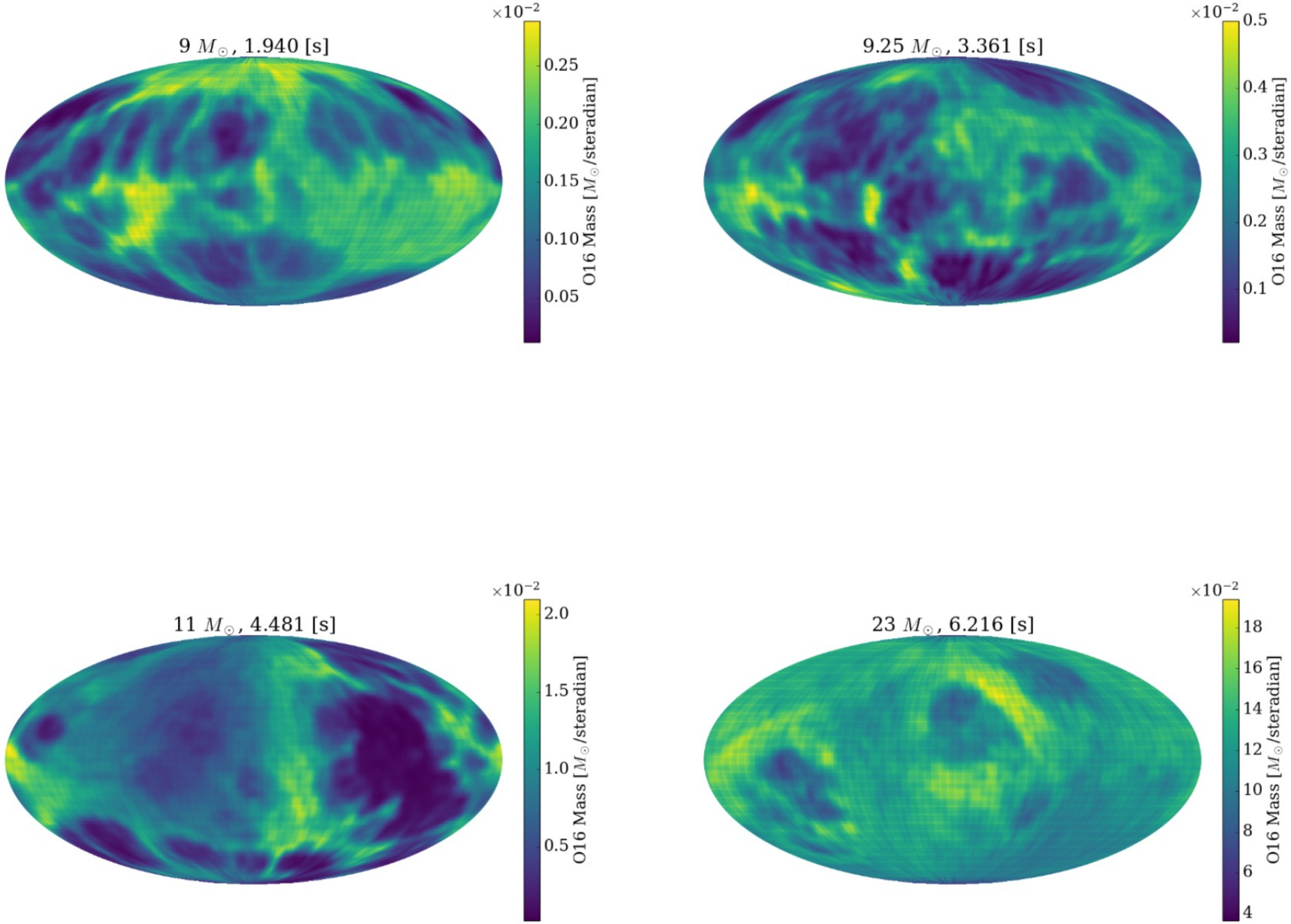

Time:4.351 s
$23M_{\odot}$

Nickel-56 Ejecta Areal distribution



Wang et al. 2023

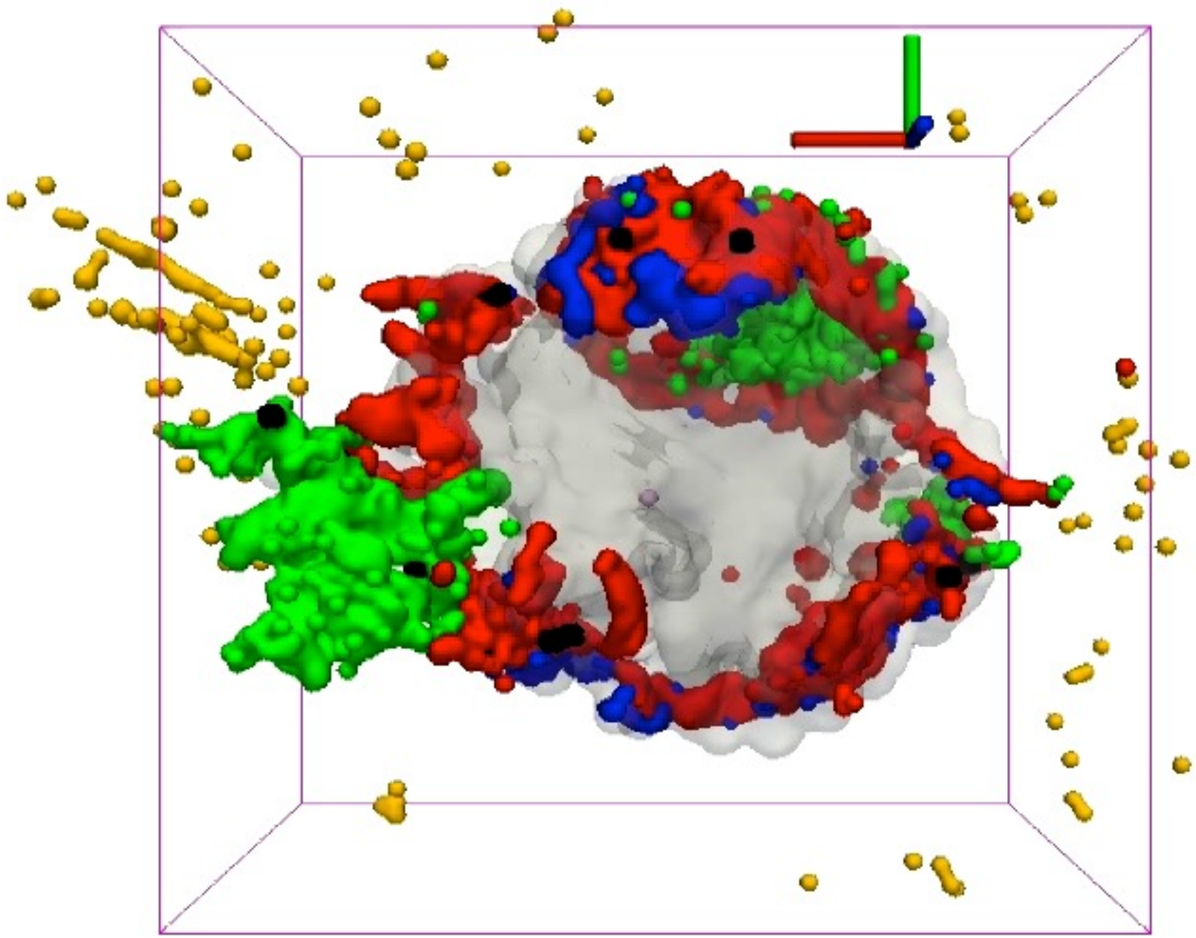
Oxygen-16 Ejecta Areal distribution



Cas A Remnant

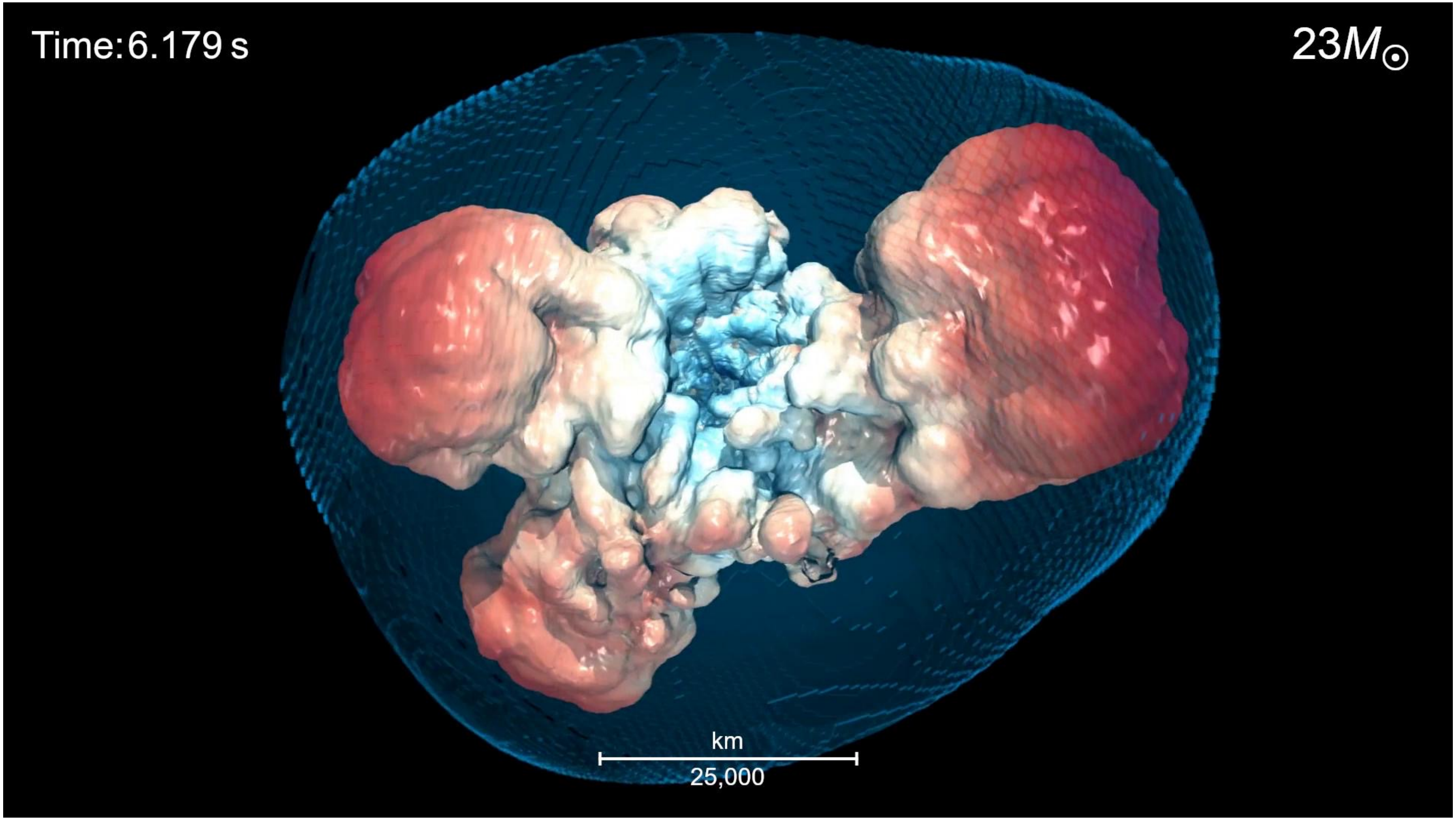
Fe

Si

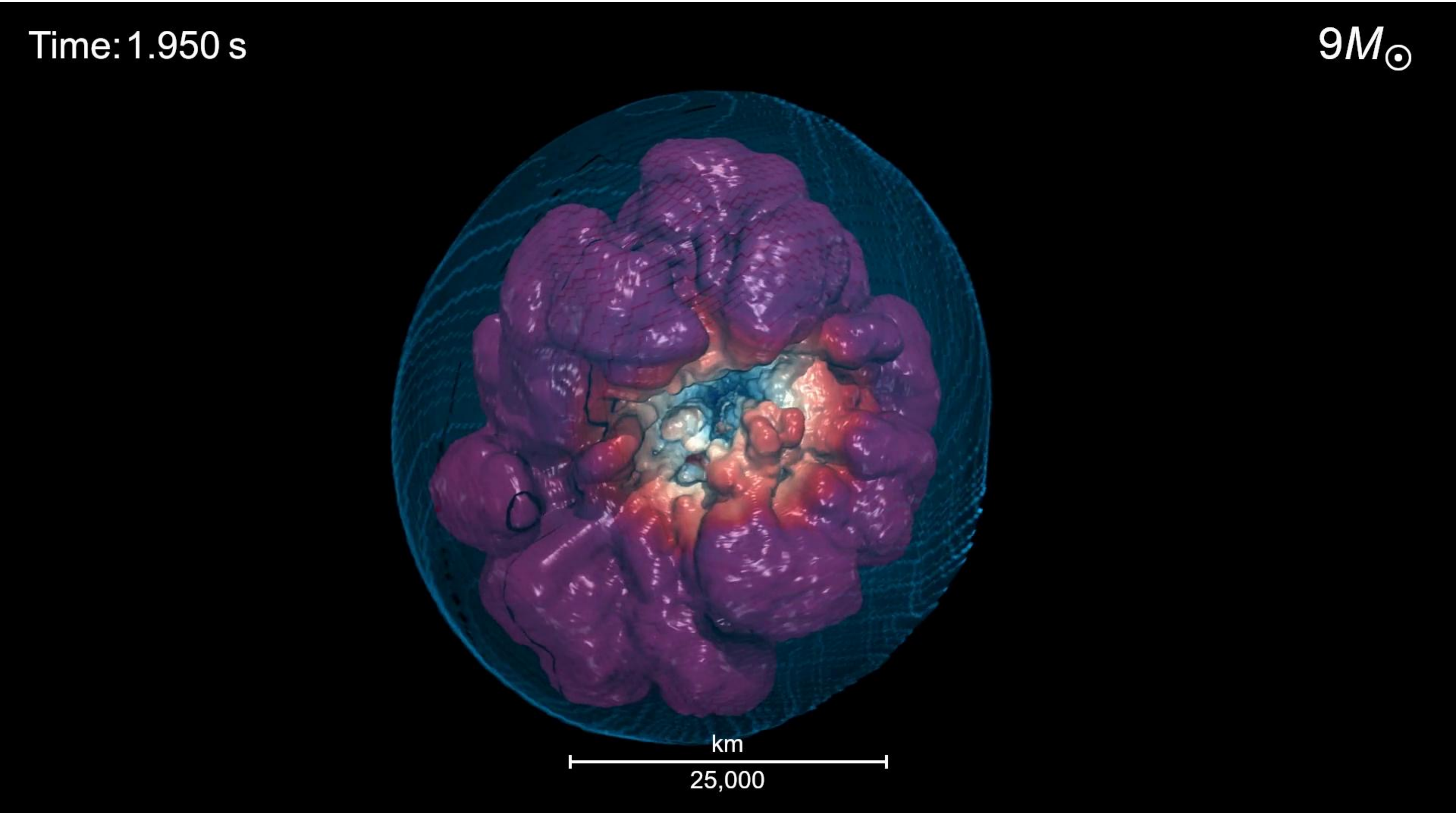


DeLaney et al. 2010

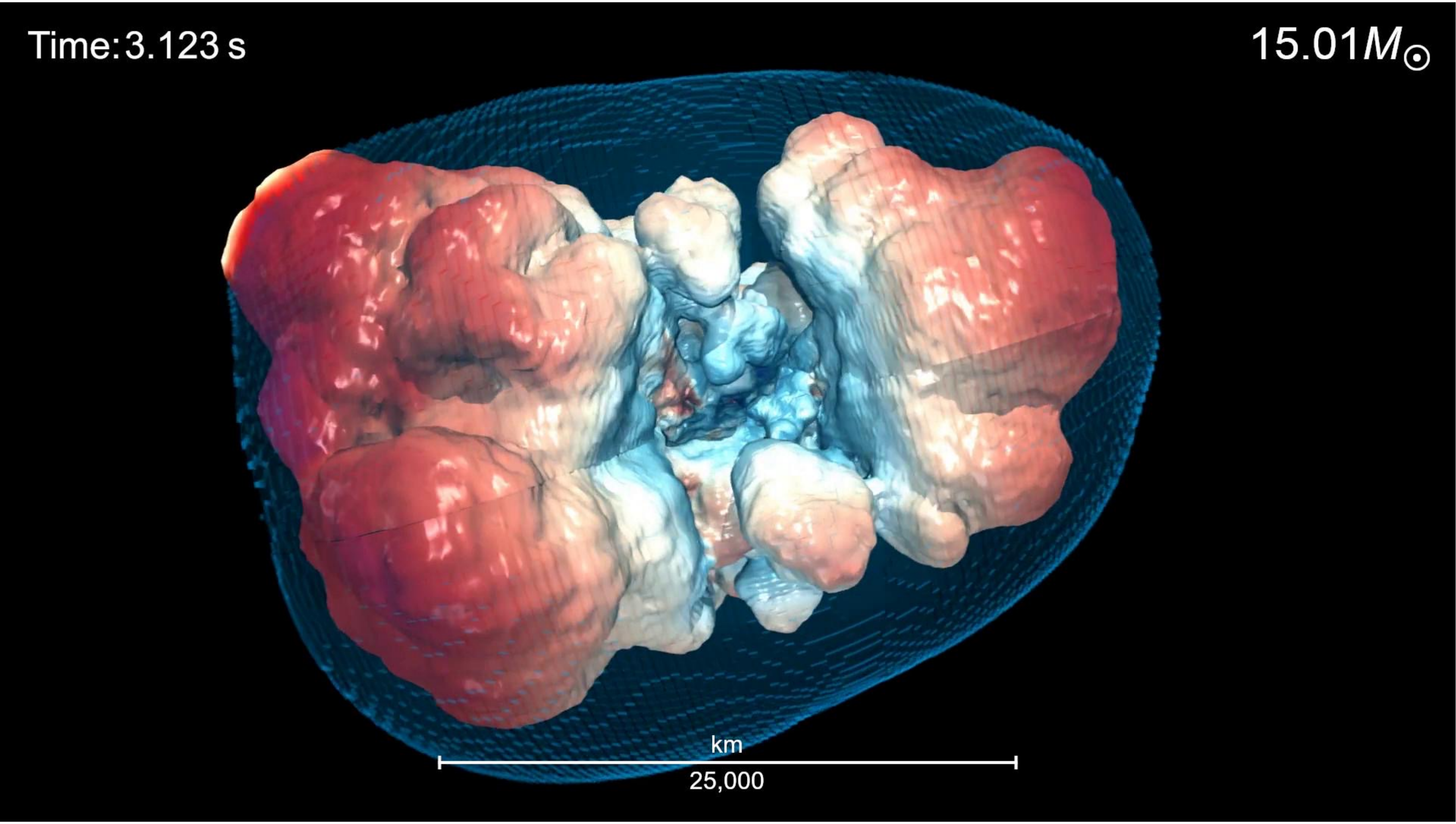
Nickel-56 Ejecta Spatial Distribution



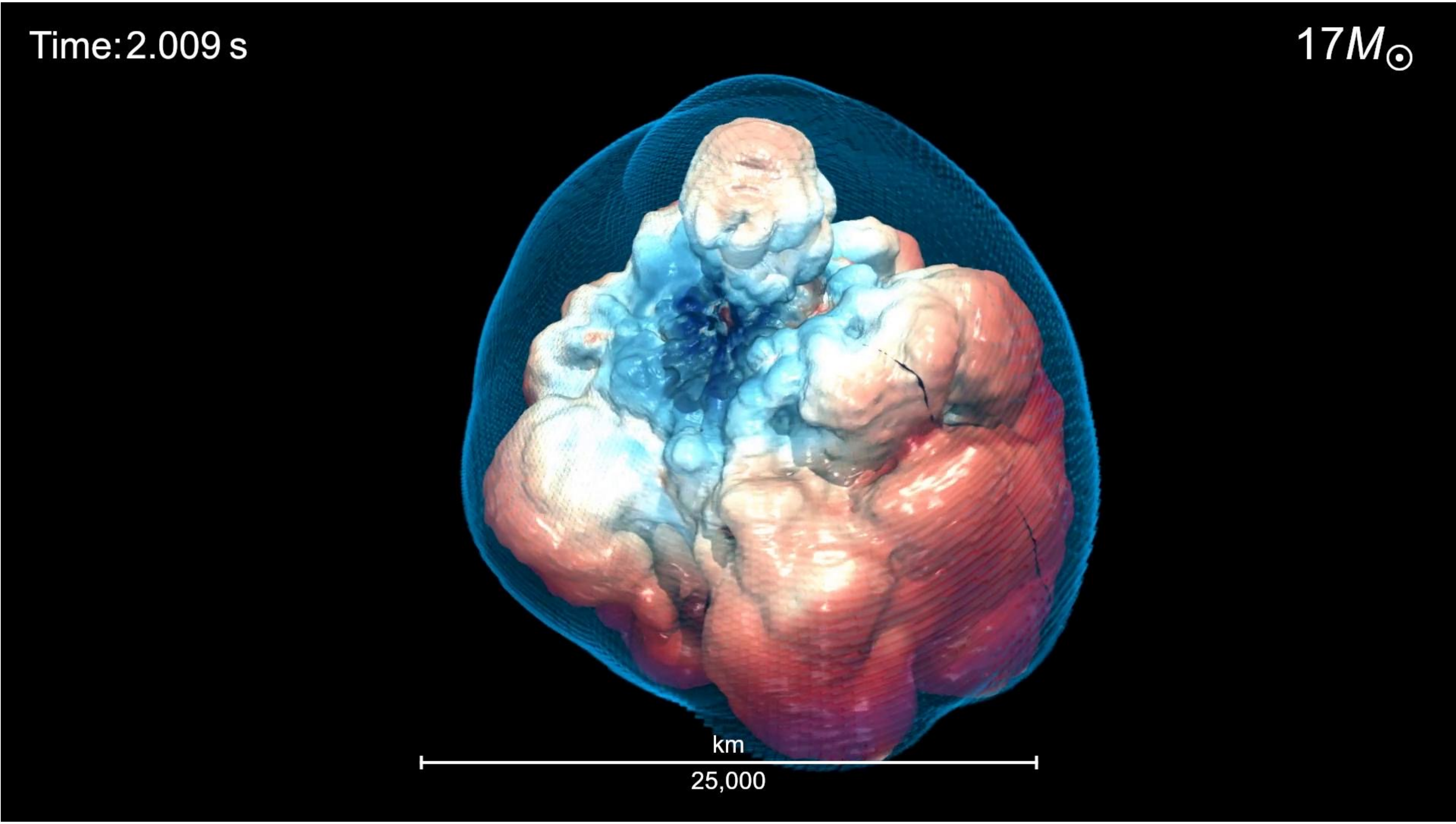
Nickel-56 Ejecta Spatial Distribution: 9 solar mass model



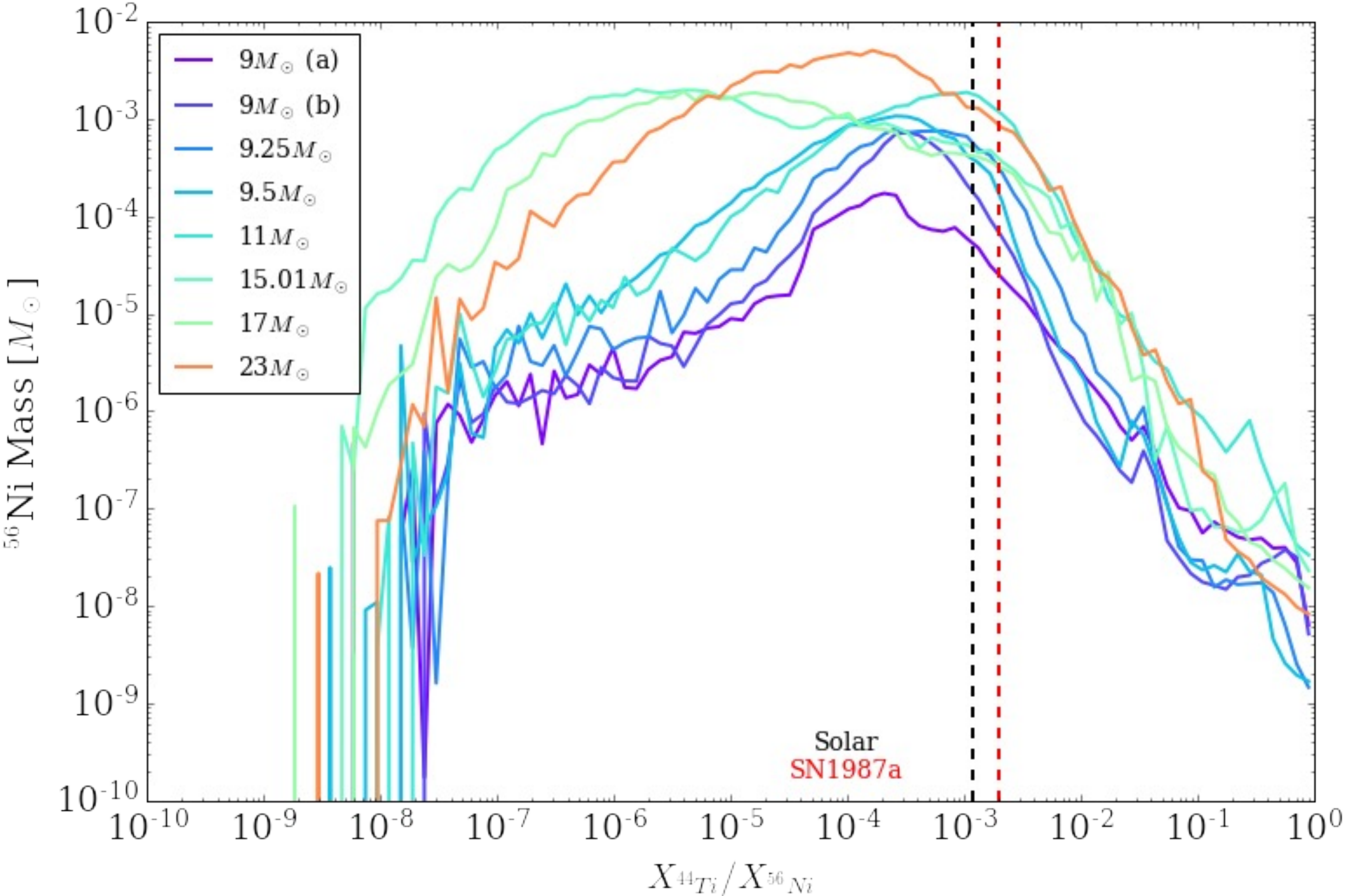
Nickel-56 Ejecta Spatial Distribution: 15.01 solar mass model



Nickel-56 Ejecta Spatial Distribution: 17 solar mass model



Ti-44/Ni-56 Ratio Distributions:
Cas A NuSTAR Data?

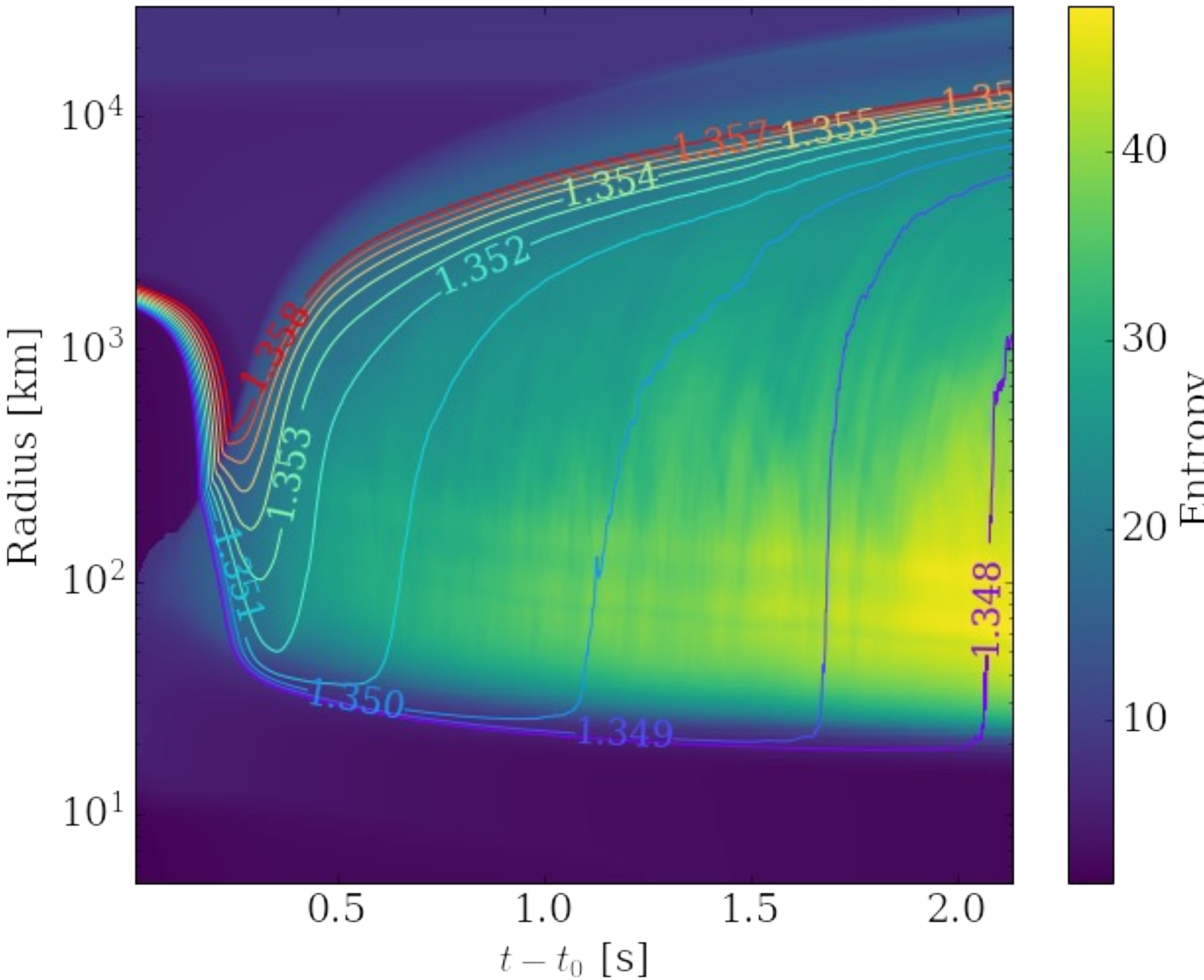


PNS Winds in the Context of 3D CCSN Explosions

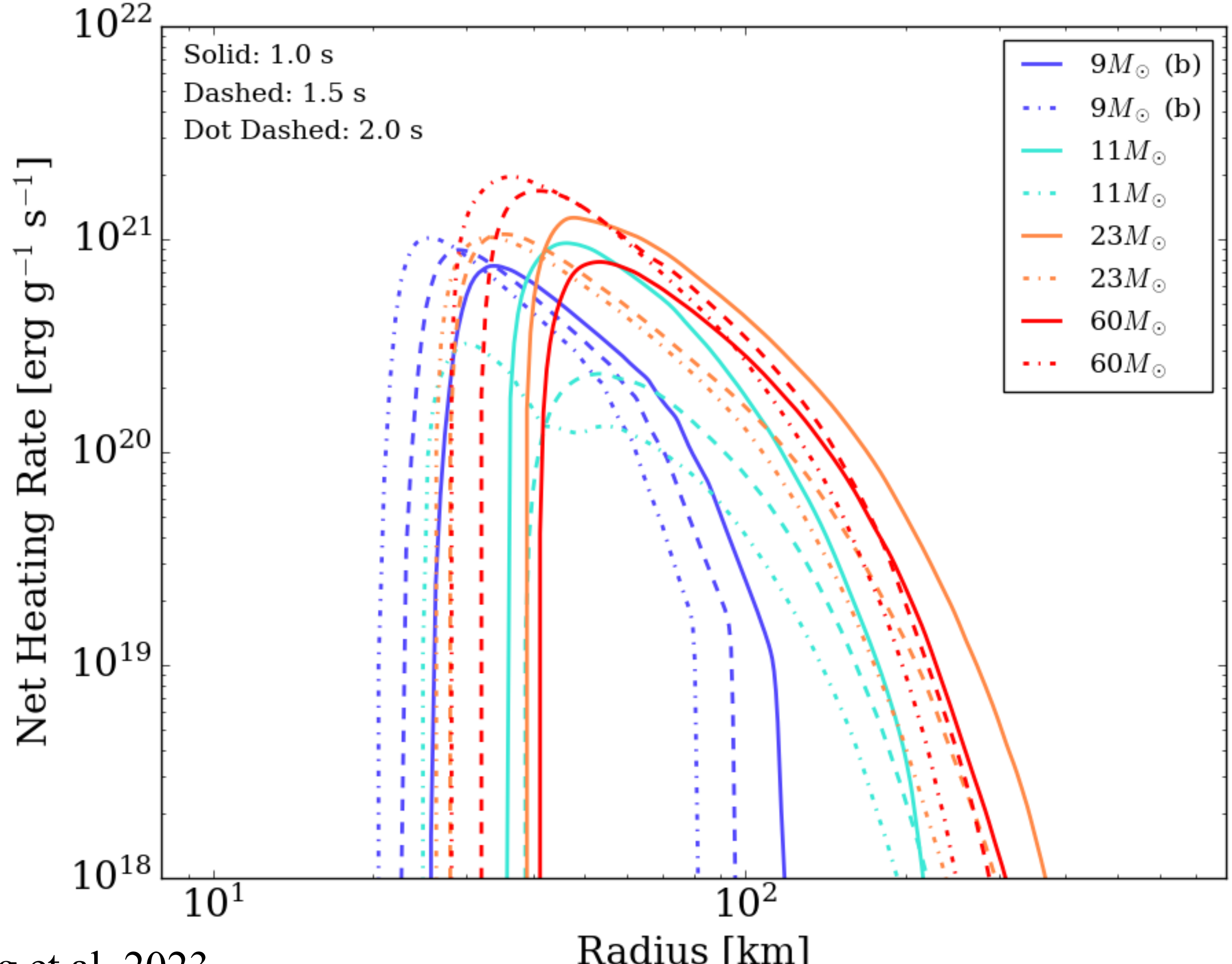
Complications: 1) Winds are not spherical; 2) the PNS atmosphere that launches them is turbulent; 3) The PNS atmosphere is rotating

Otherwise, α–rich freeze-out is clearly seen

The Emergence of Winds: 9 Solar Mass Model

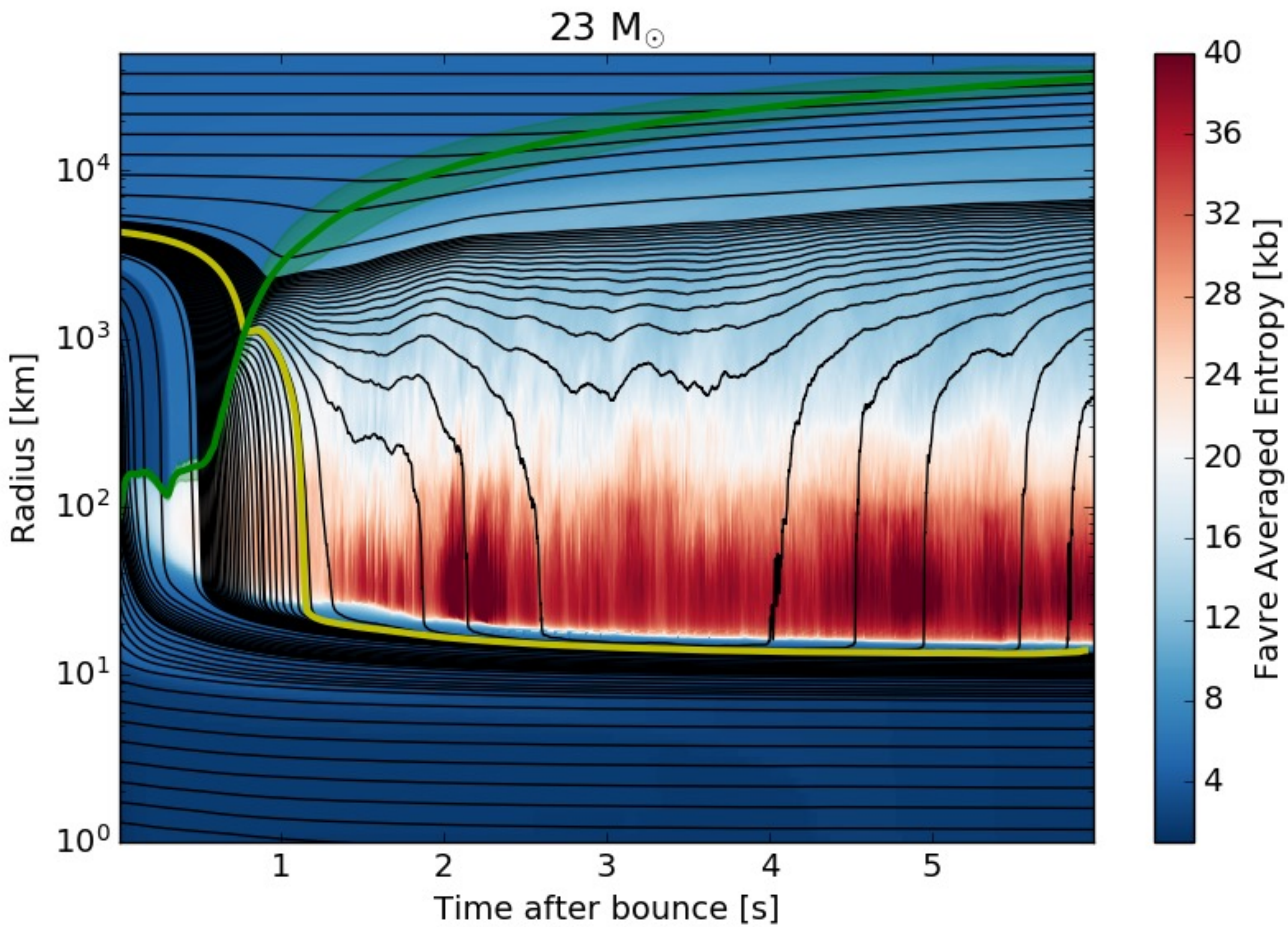


3D Average Wind Heating Profiles

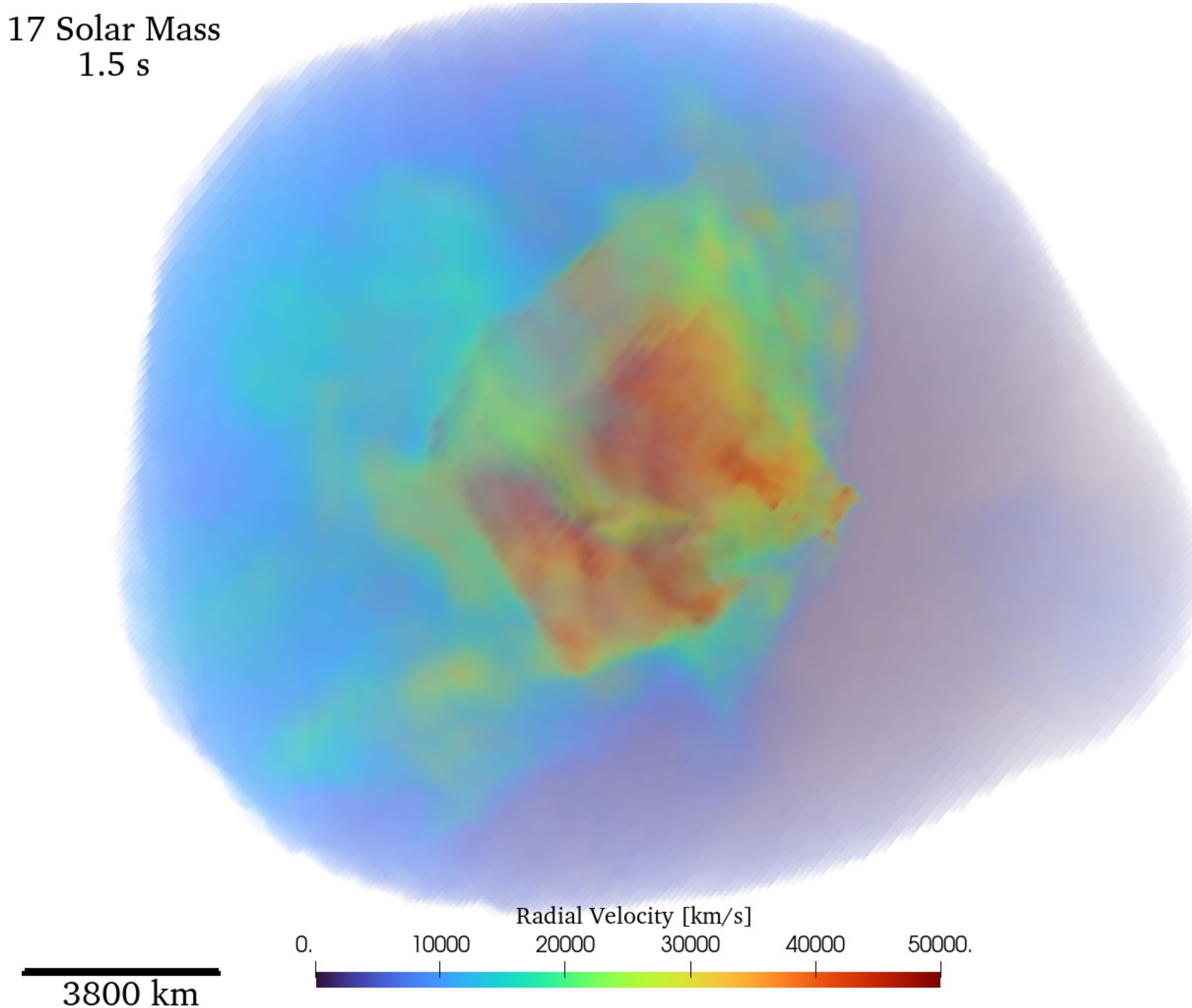


Wang et al. 2023

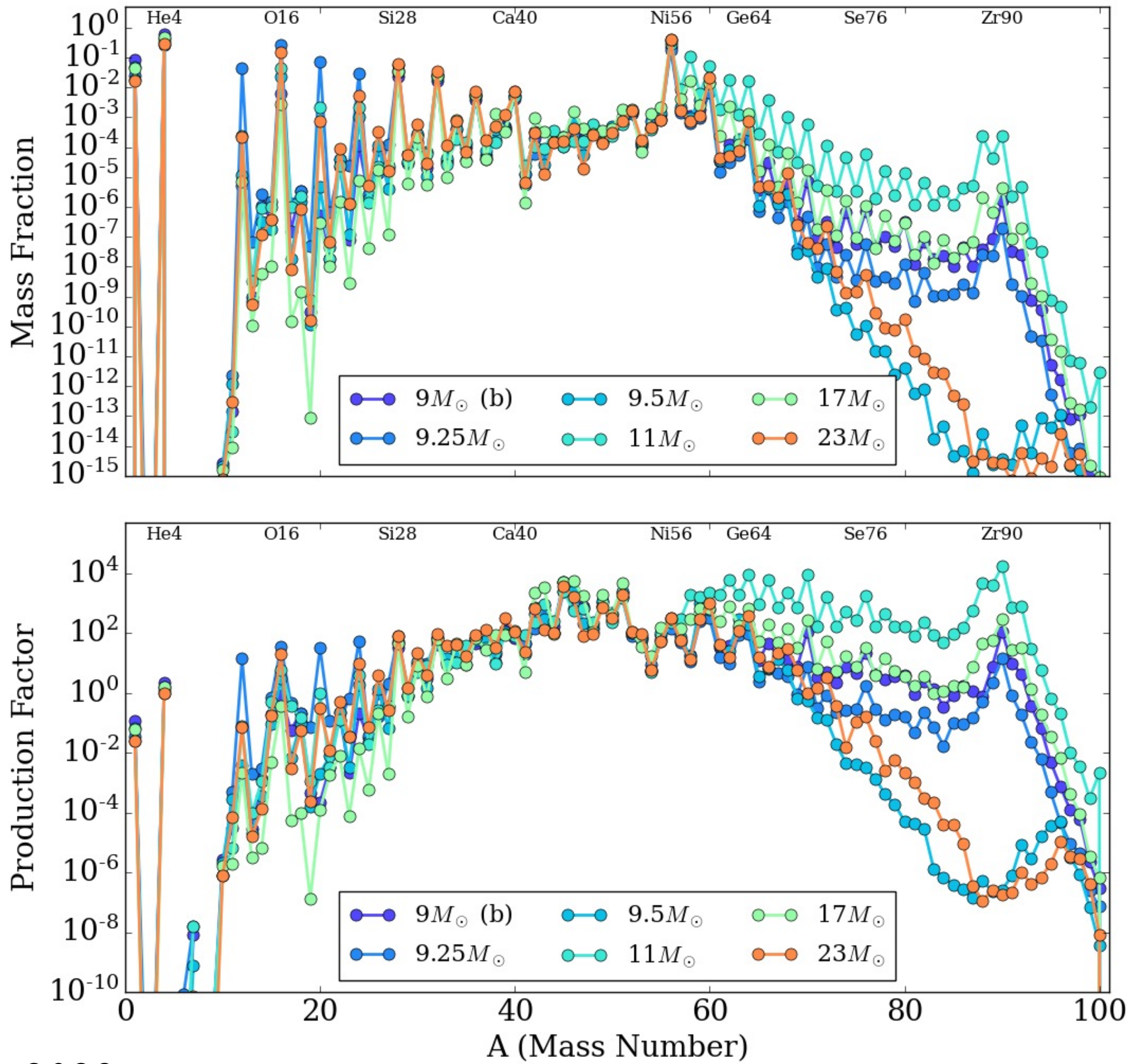
Fallback and the Emergence of Winds



Winds: 17 Solar Mass Model

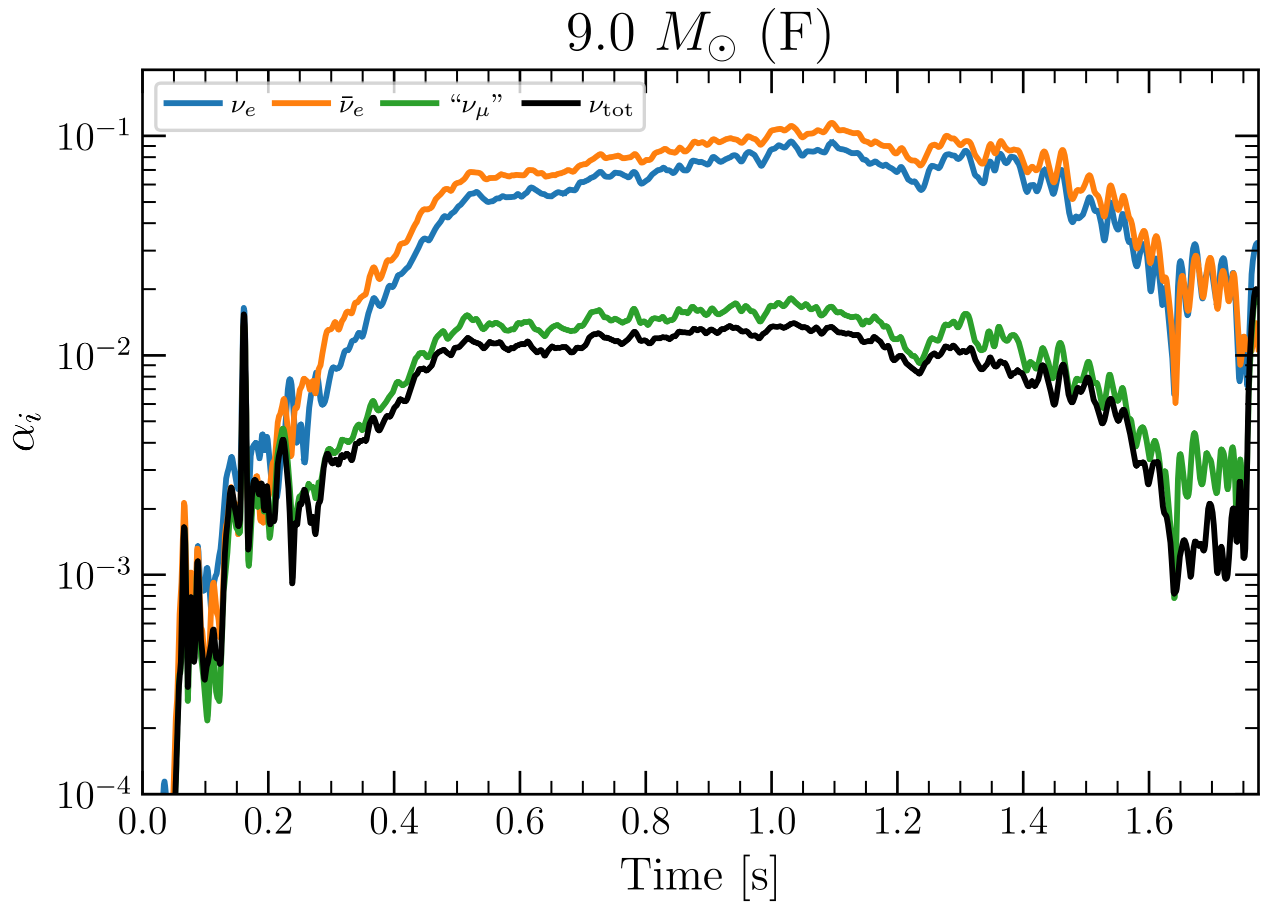


Production Factors for 3D CCSN Winds/explosions

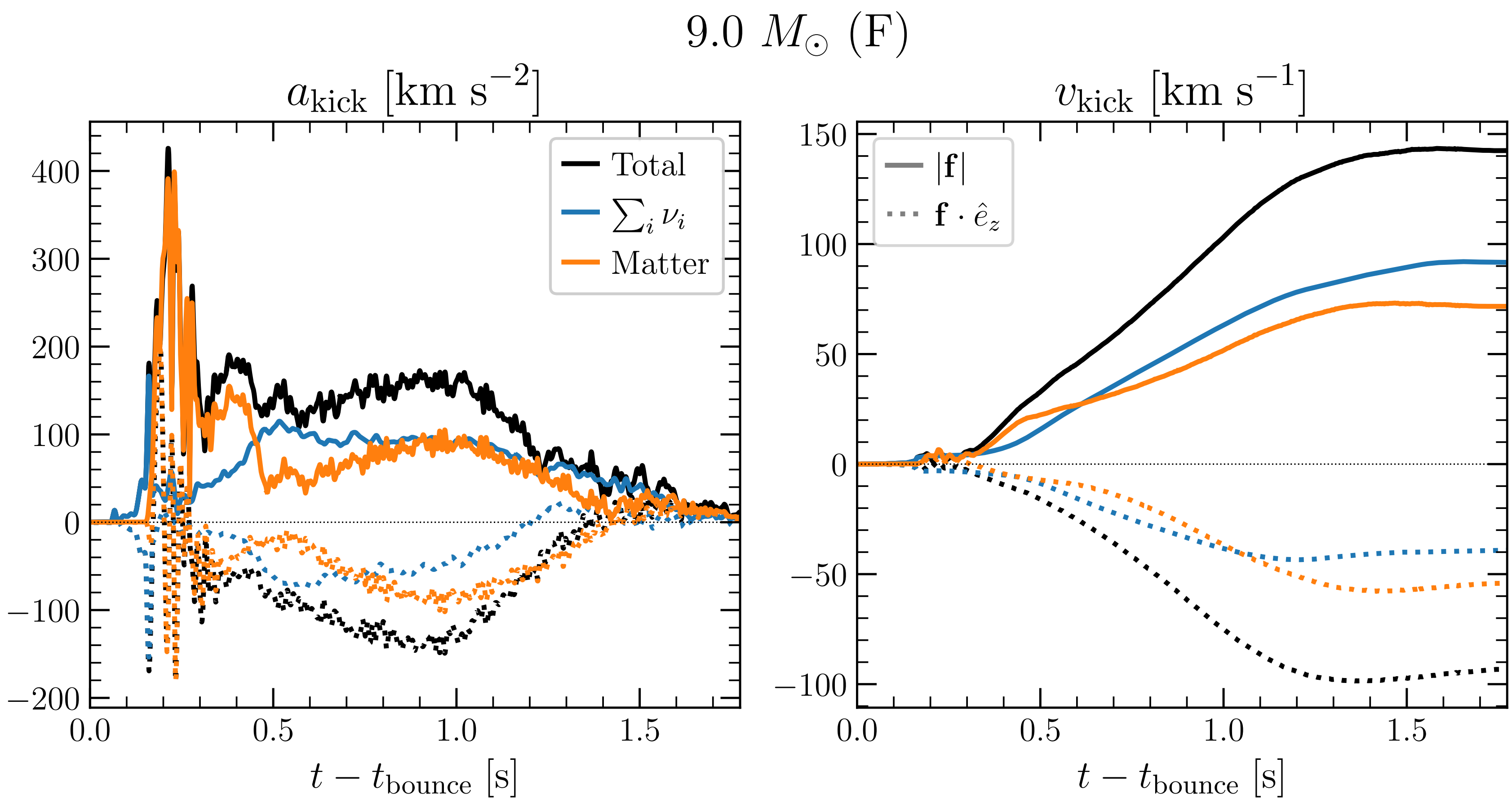


Wang et al. 2023

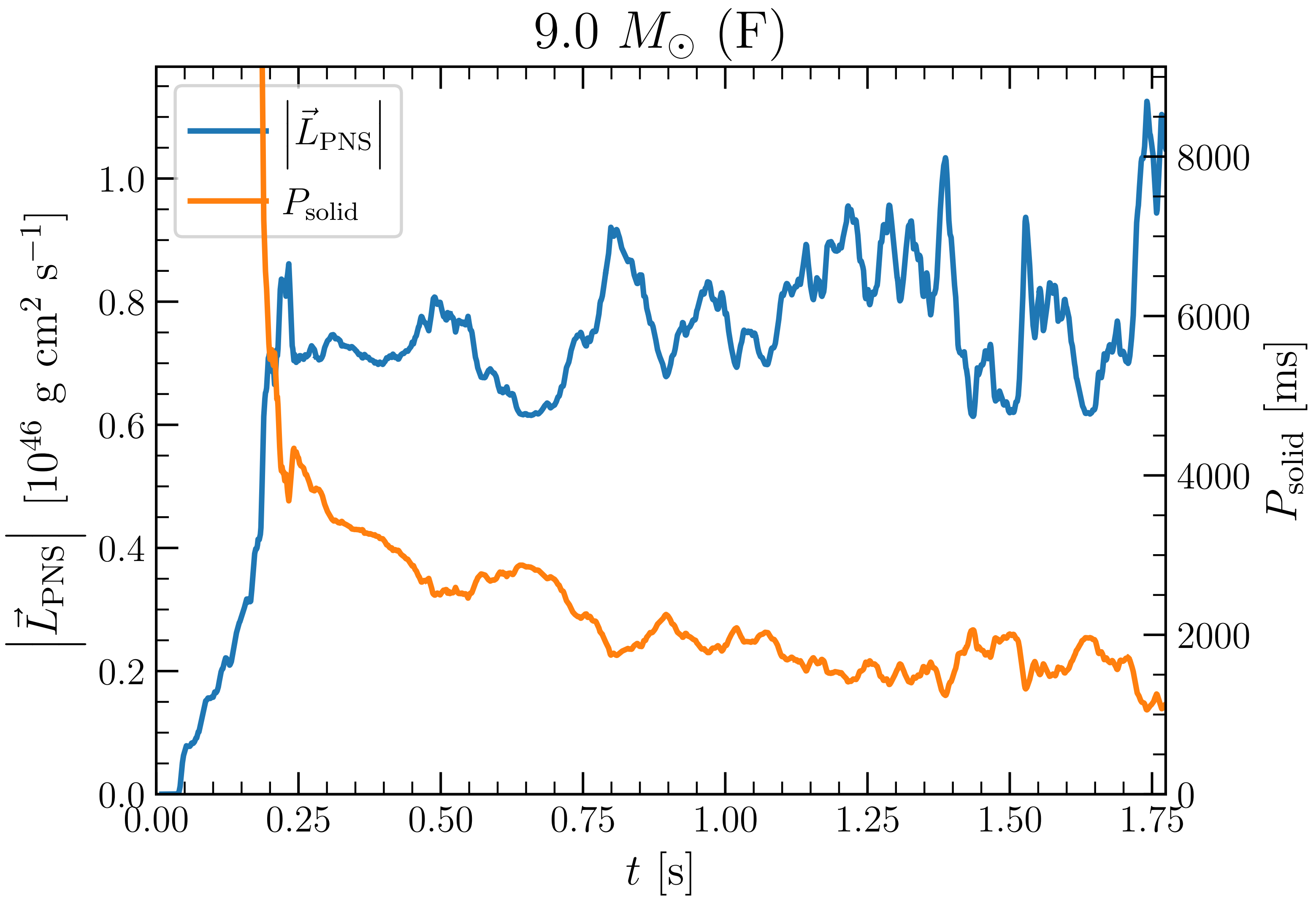
Induced Spins and Kicks at the Birth of Neutron Stars and Black holes



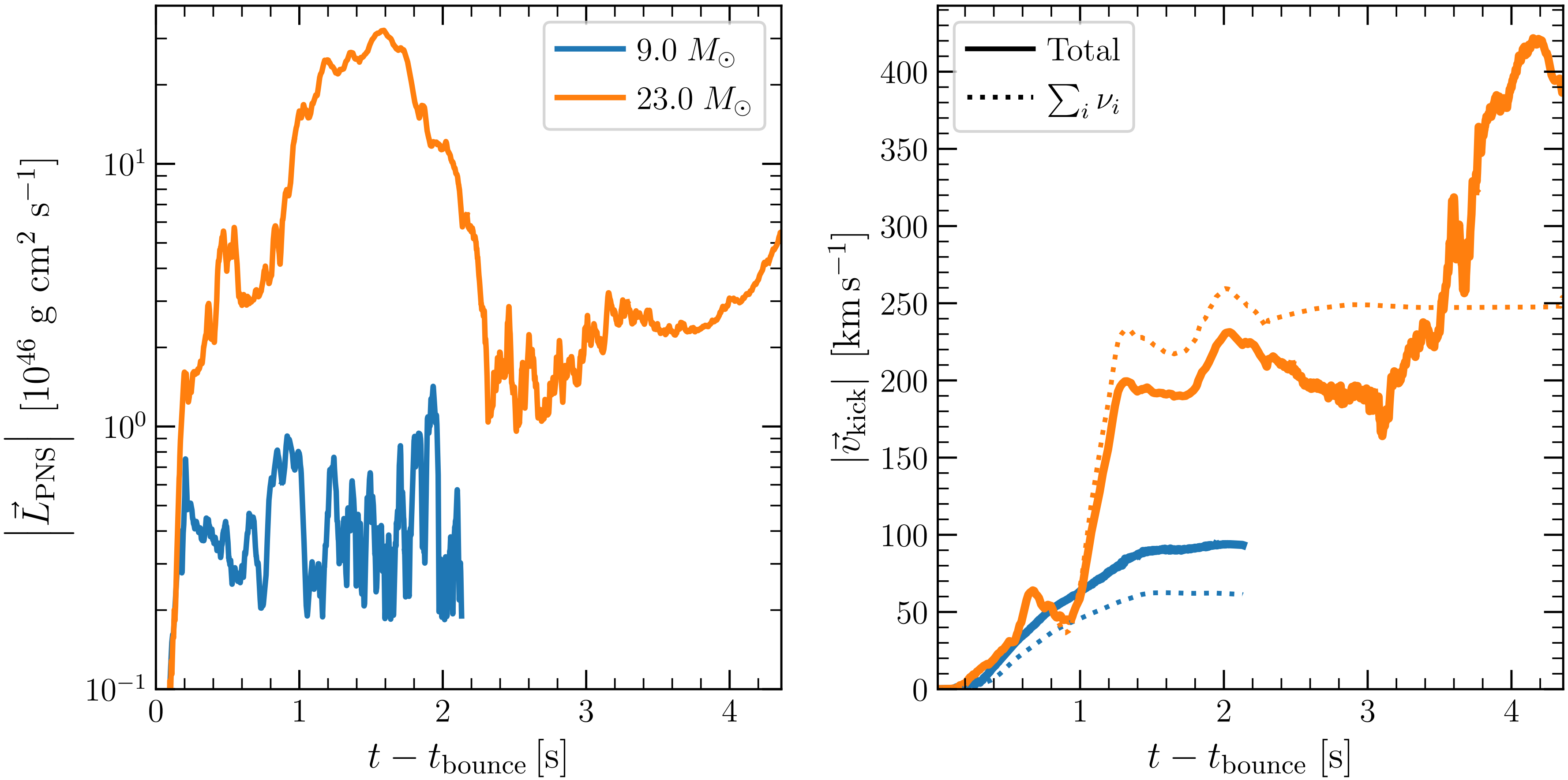
Kicks and Induced Spins to Neutron Stars (PNS) in the CCSN context



Kicks and Induced Spins to Neutron Stars (PNS) in the CCSN context



Kicks and Induced Spins to Neutron Stars (PNS) in the CCSN context



Kicks and Induced Spins to Neutron Stars (PNS) in the CCSN context – later times

Gravitational Radiation Signals from Core-Collapse Supernovae

D. Vartanyan, A. Burrows, T. Wang, D. Radice, V. Morozova, M. Coleman, C. White

2018-2023

CCSN Signal Features

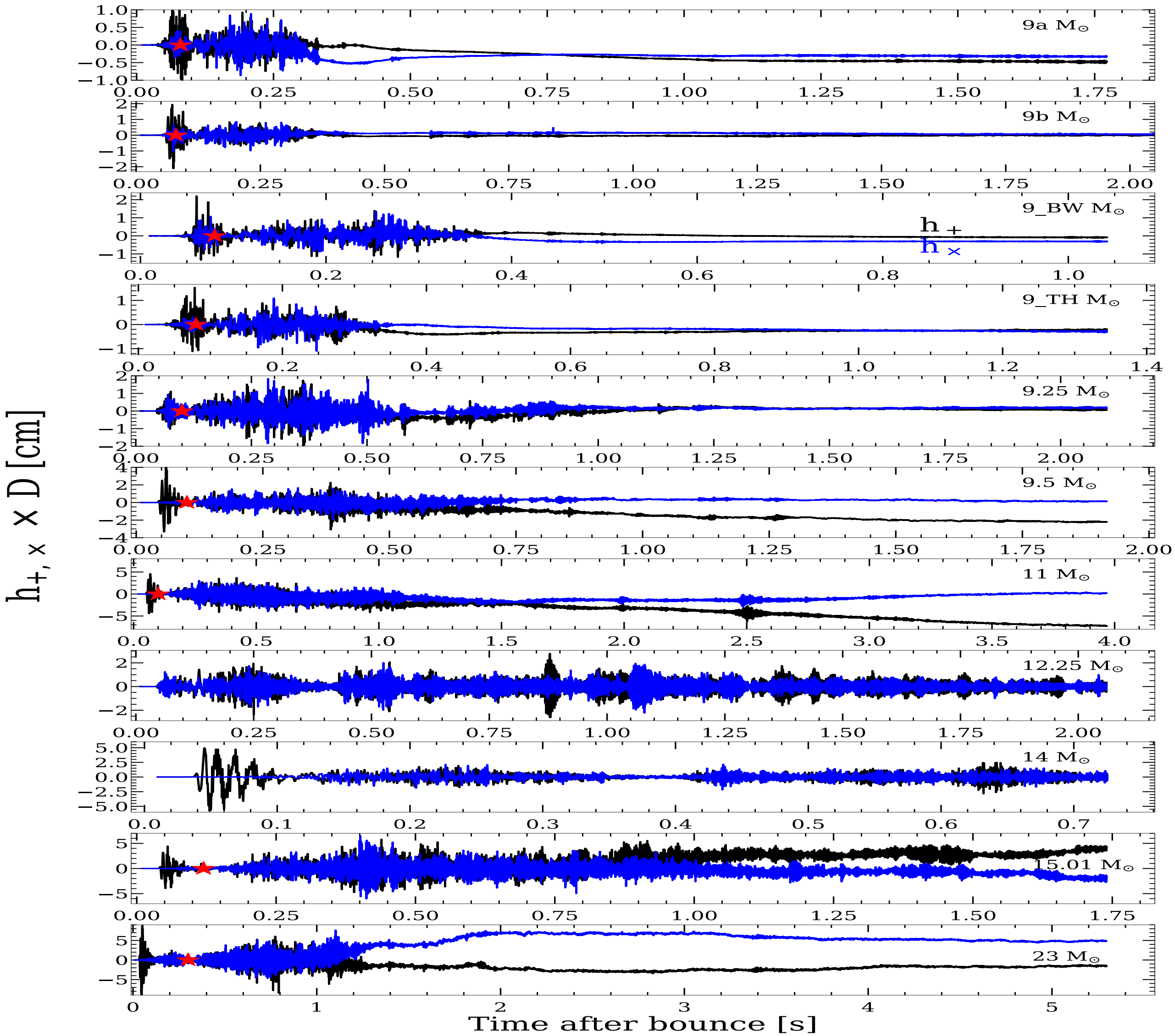
- Rotational bounce spike (rapid rotation?); differential rotation
- Initial Progenitor perturbation spike
- Outer Prompt convection (early, non-rotating)
- Quiescent phase (altered by progenitor perturbations?)
- Ramp up and saturation of turbulent convection and SASI
- Infall plume excitation of PNS 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!

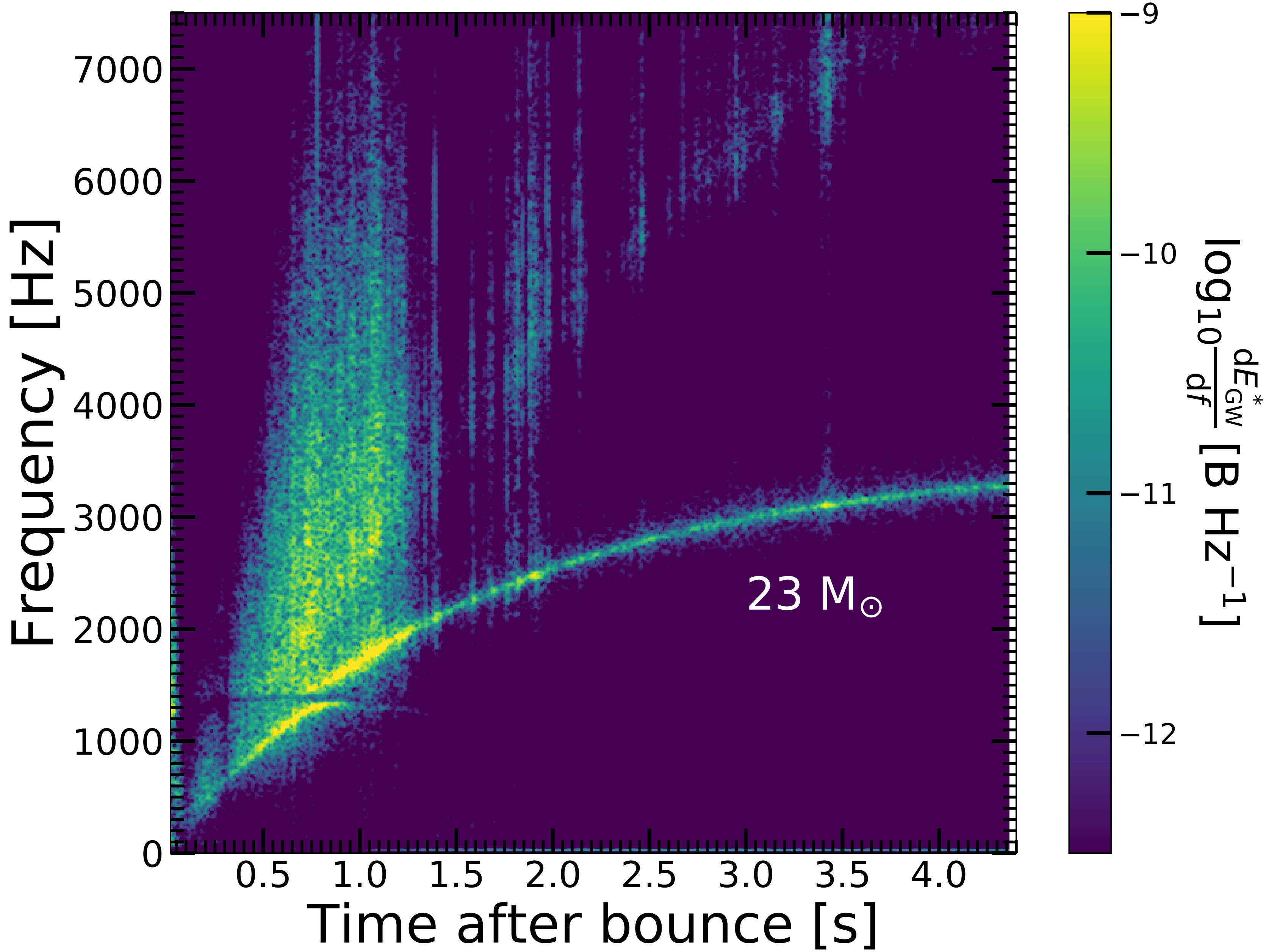
- Polarization (rotation and spiral SASI) – Enhance the effective SNR

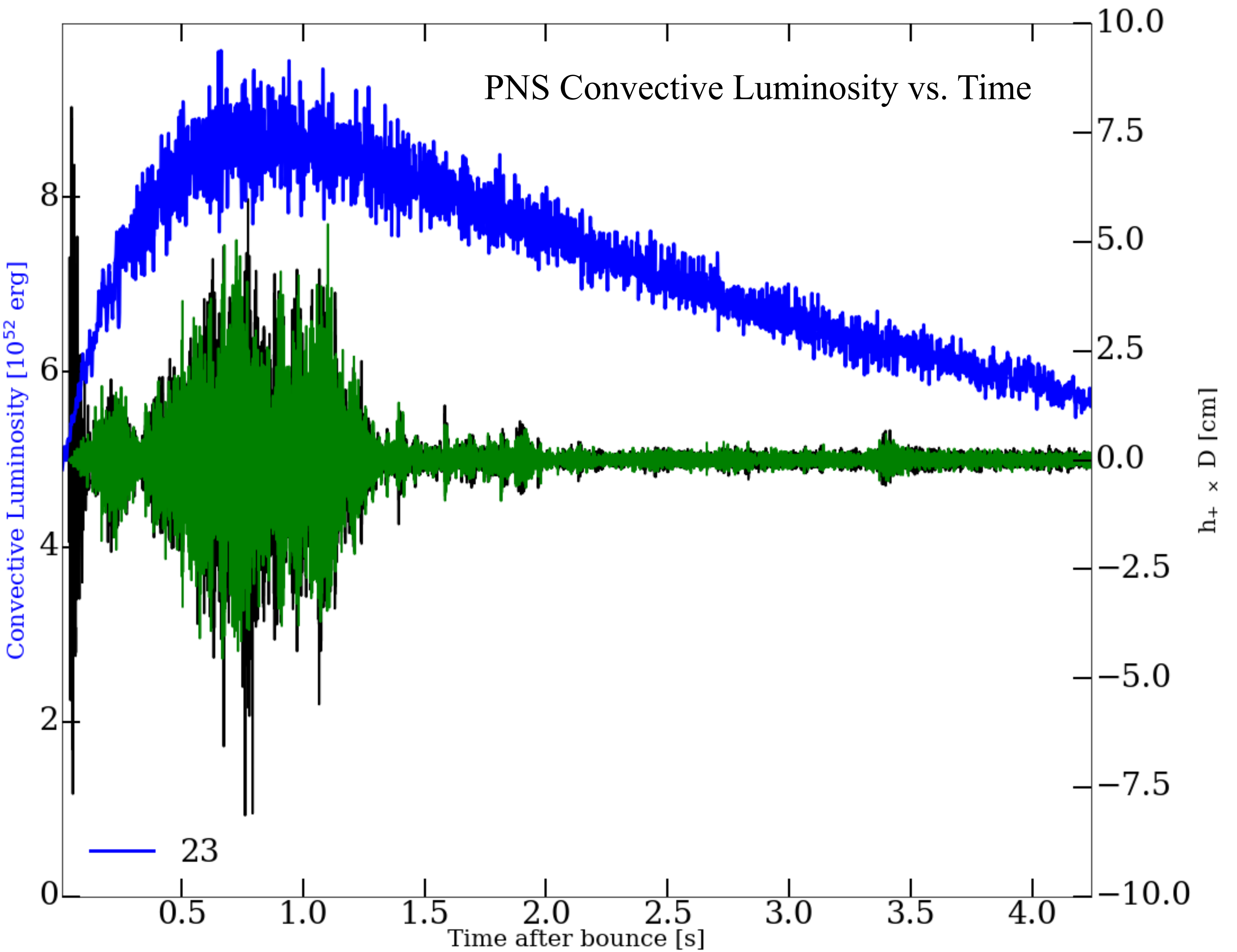
- Progenitor, rotation, orientation, explosion energy dependences?
- Duration of phases; frequency spectra; signal phase?

Vartanyan, Burrows, Wang, Coleman, and White 2023

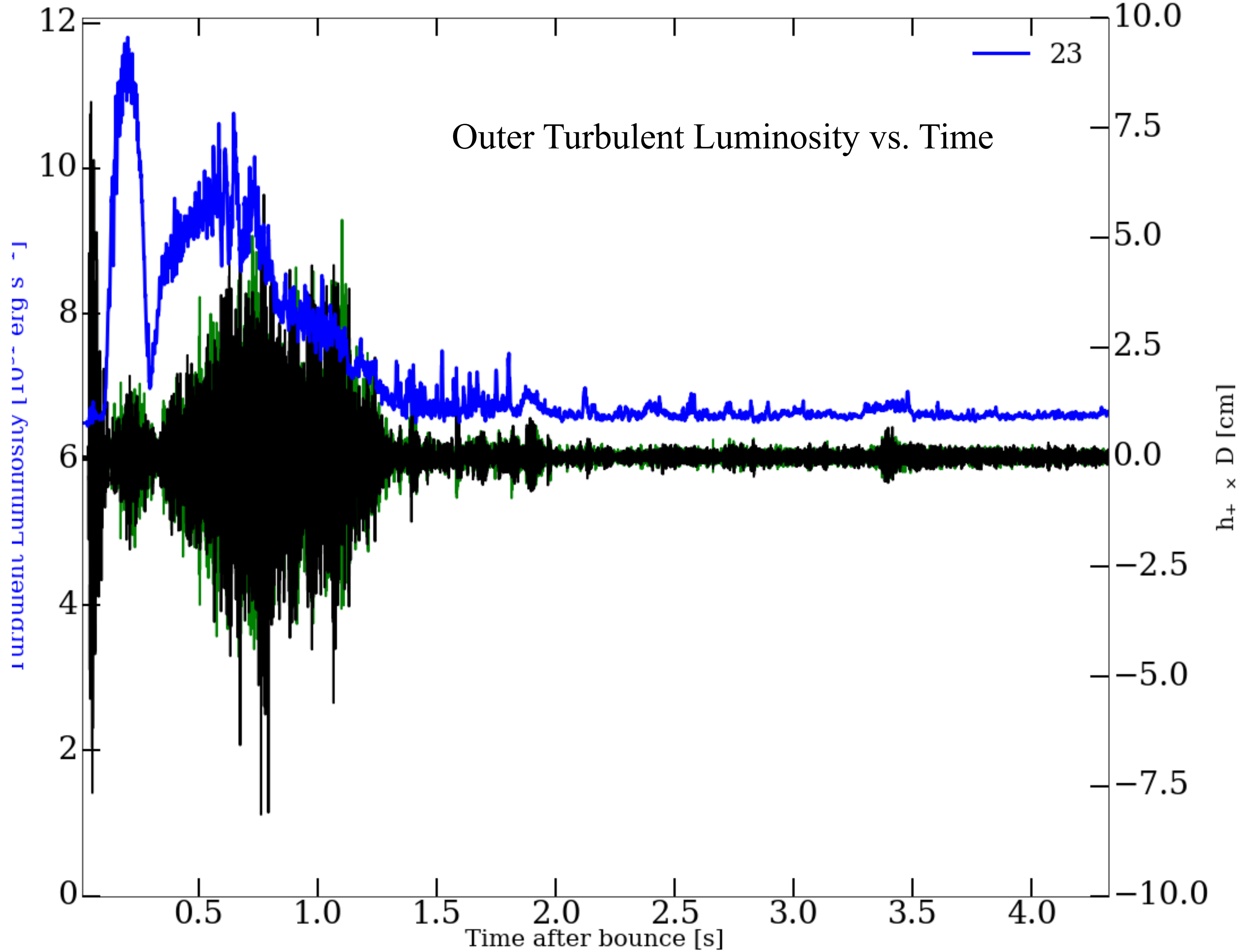


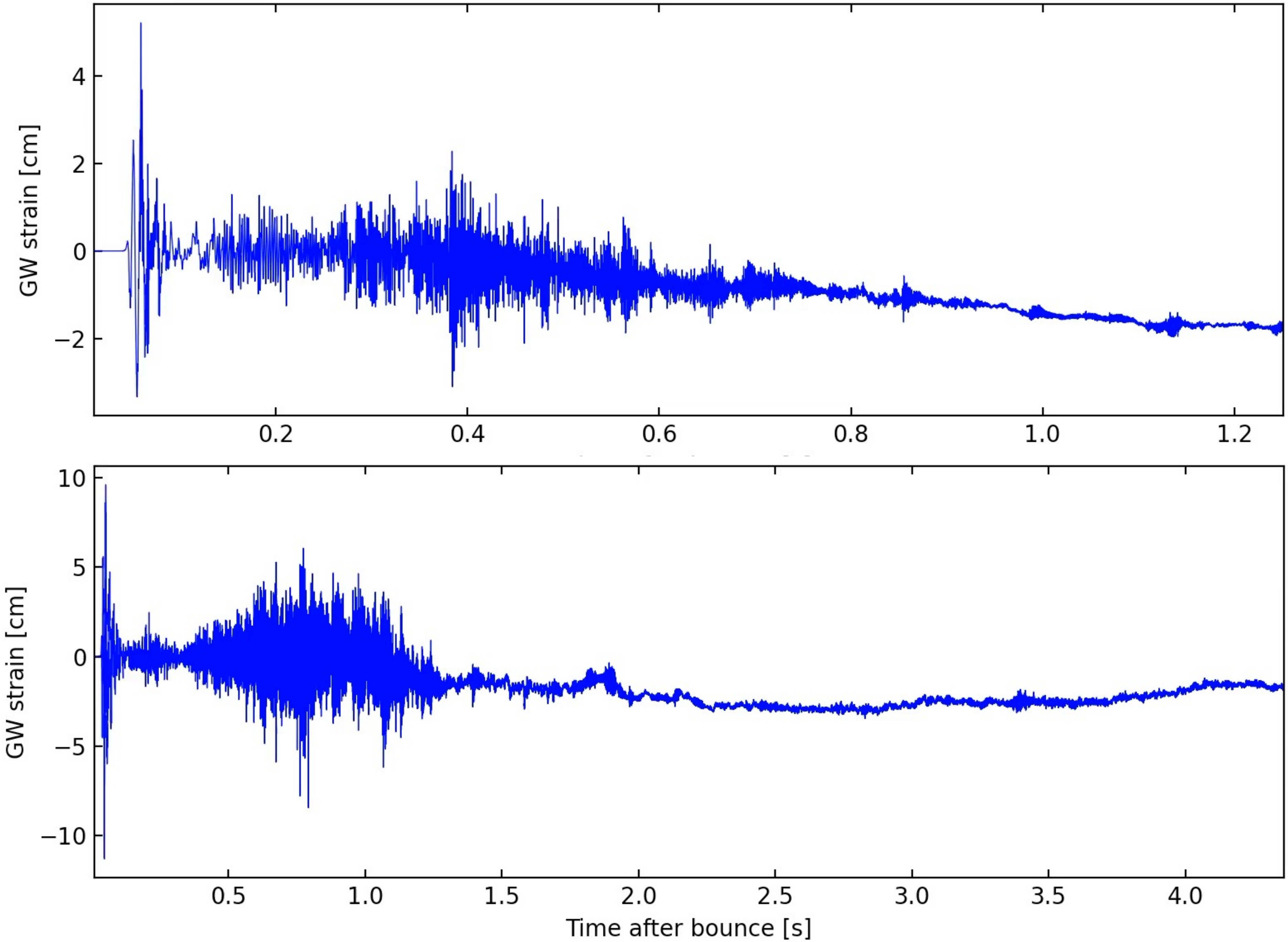
http://www.astro.princeton.edu/~burrows/gw.3d.new/

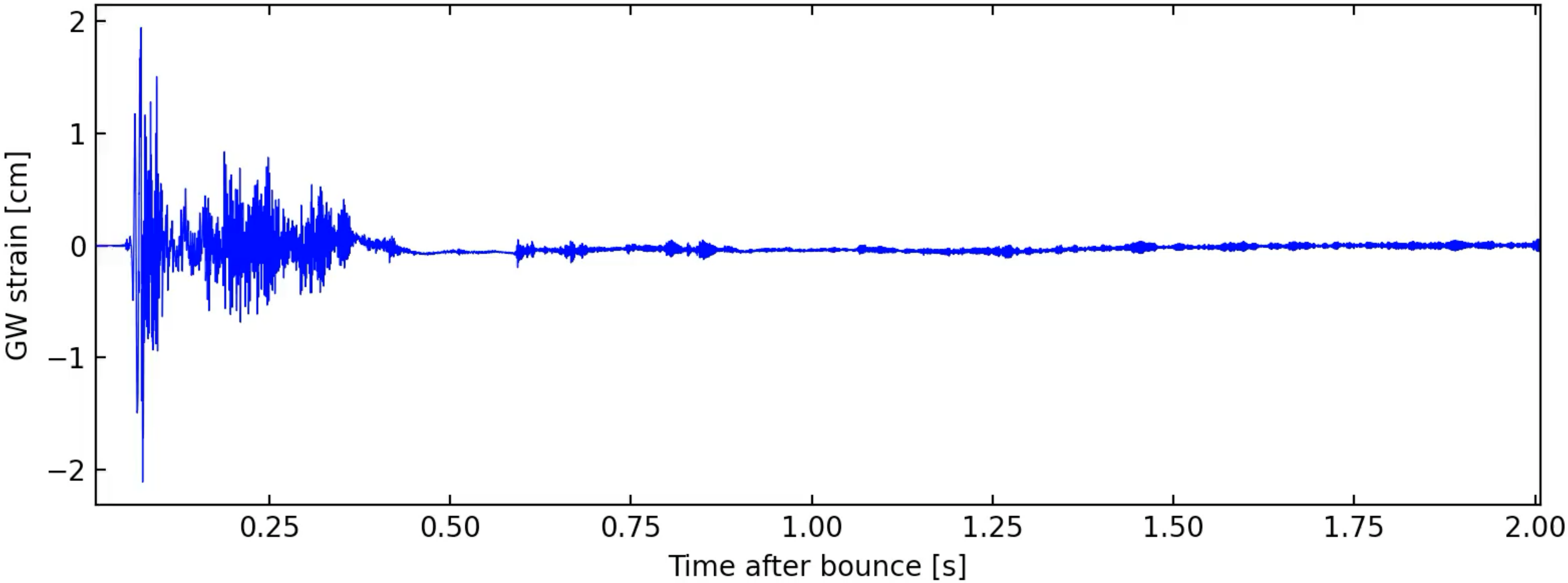
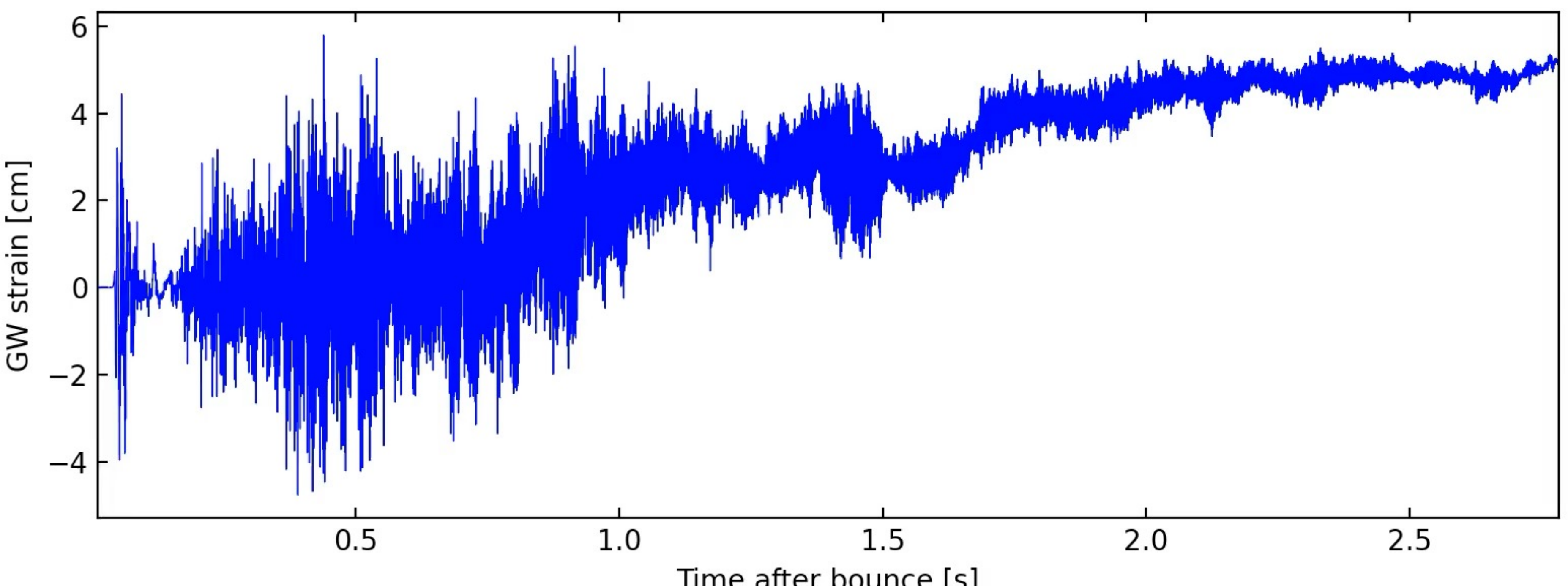

Frequency [Hz]
7000
6000
5000
4000
3000
2000
1000
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time after bounce [s]
23 $M_\odot$
−9
−10
−11
−12
$\log_{10}\frac{dE^*_{GW}}{df}$ [B Hz^{-1}]

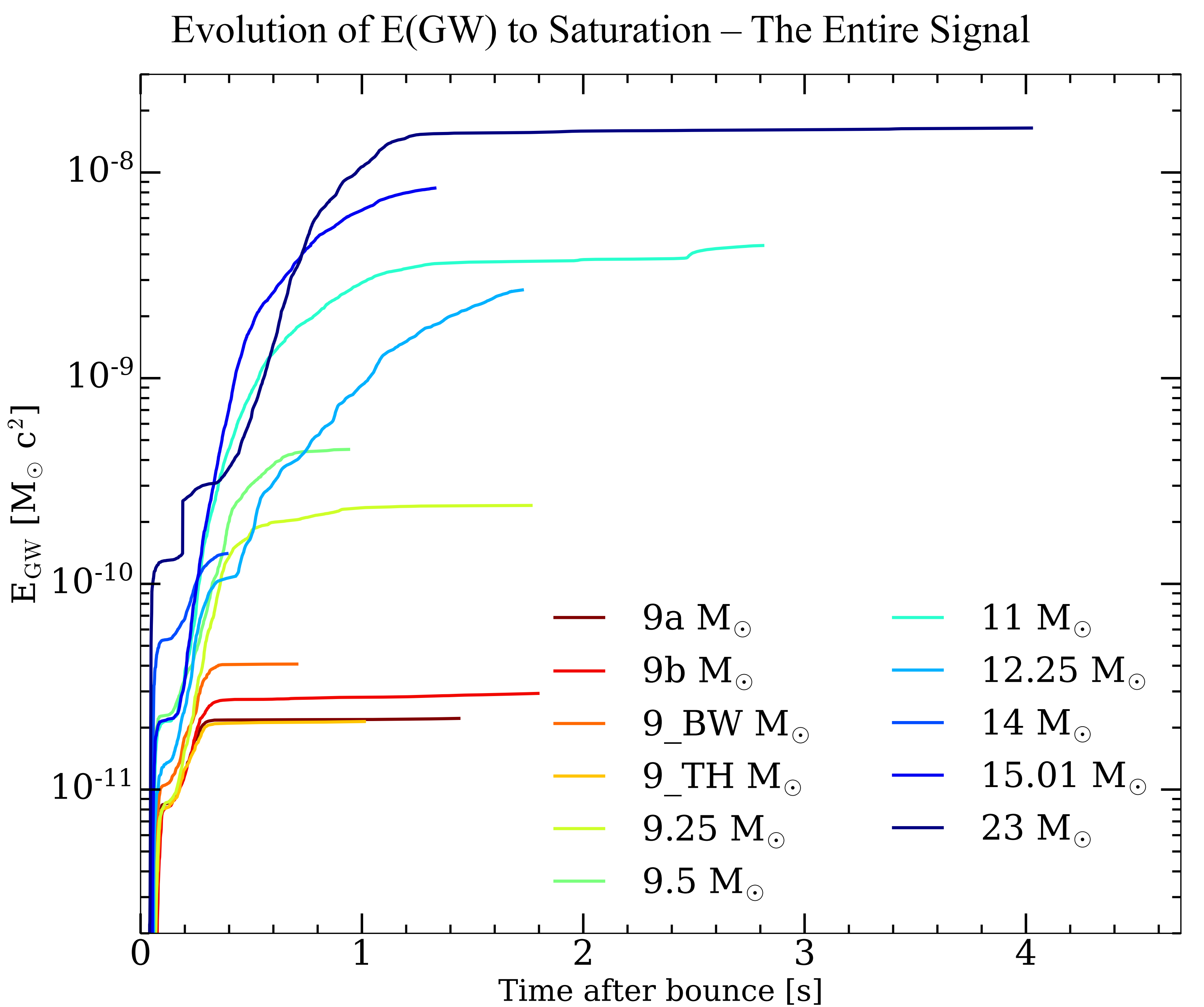


PNS Convective Luminosity vs. Time
Convective Luminosity [10^52 erg]
h+ × D [cm]
Time after bounce [s]
23
0
2
4
6
8
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
10.0
7.5
5.0
2.5
0.0
−2.5
−5.0
−7.5
−10.0


Outer Turbulent Luminosity vs. Time
23
Time after bounce [s]
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
0
2
4
6
8
10
12
10.0
7.5
5.0
2.5
0.0
−2.5
−5.0
−7.5
−10.0
$h_+ \times D$ [cm]

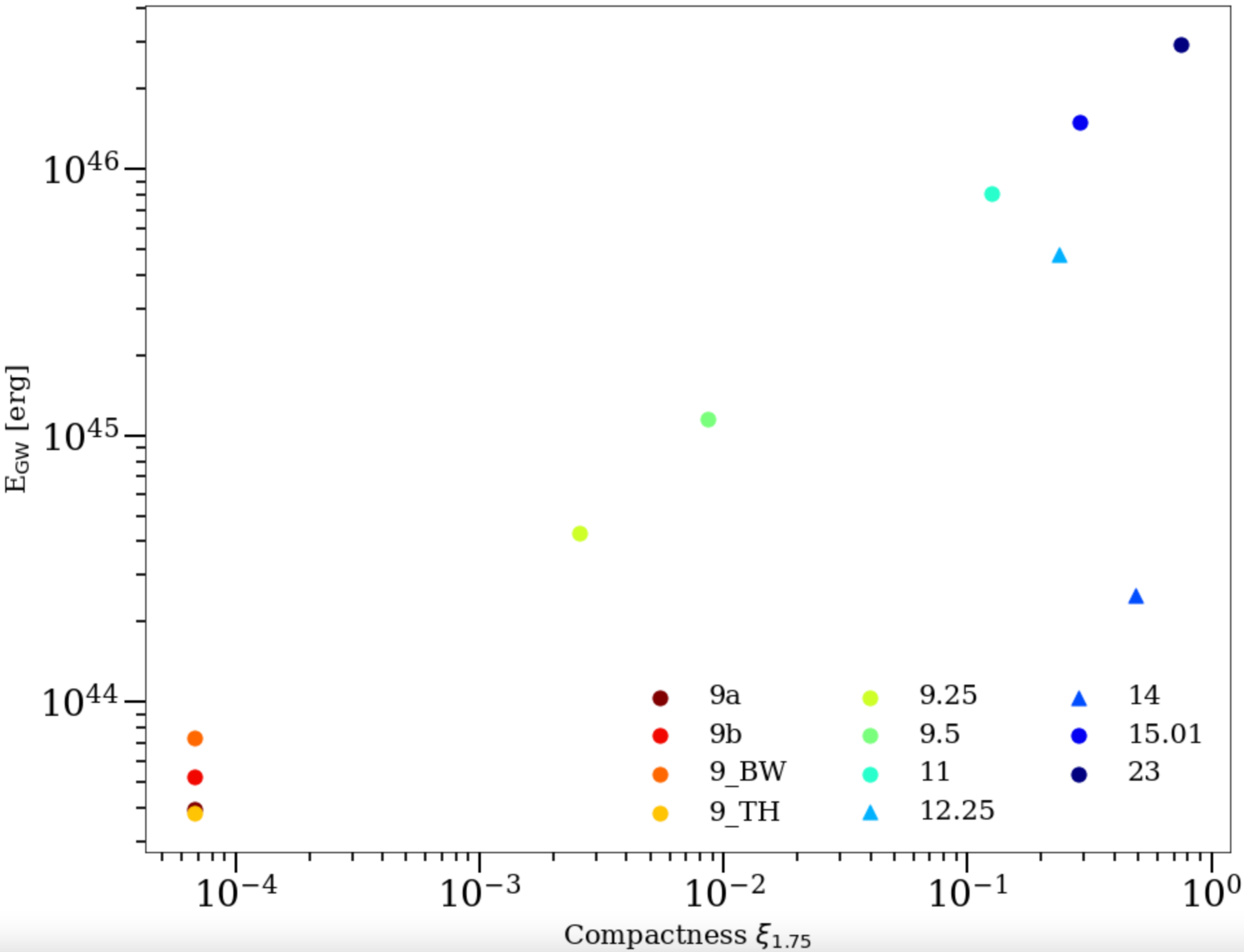

GW strain [cm]
4
2
0
−2
0.2
0.4
0.6
0.8
1.0
1.2
GW strain [cm]
10
5
0
−5
−10
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time after bounce [s]

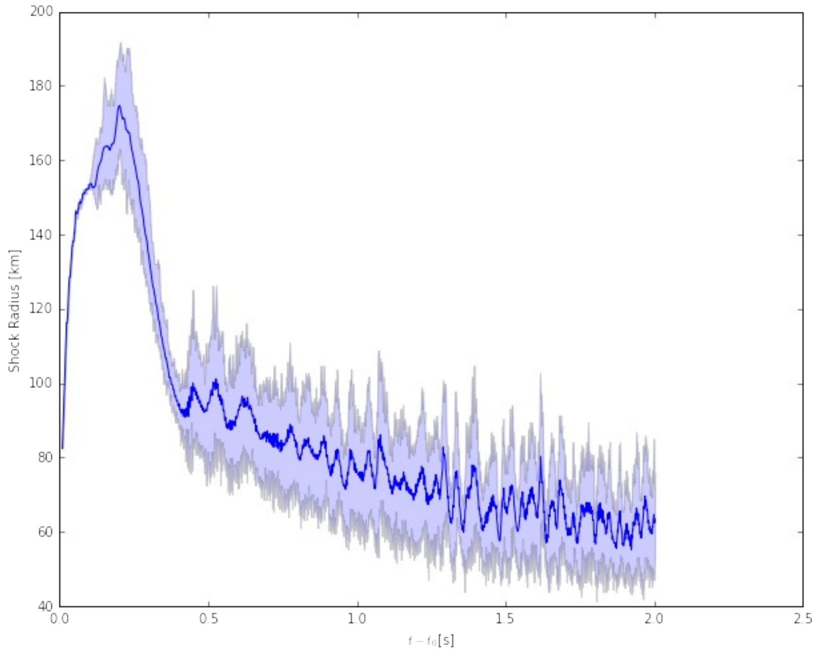

GW strain [cm]
Time after bounce [s]
2
1
0
−1
−2
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00

GW strain [cm]
Time after bounce [s]
6
4
2
0
−2
−4
0.5
1.0
1.5
2.0
2.5



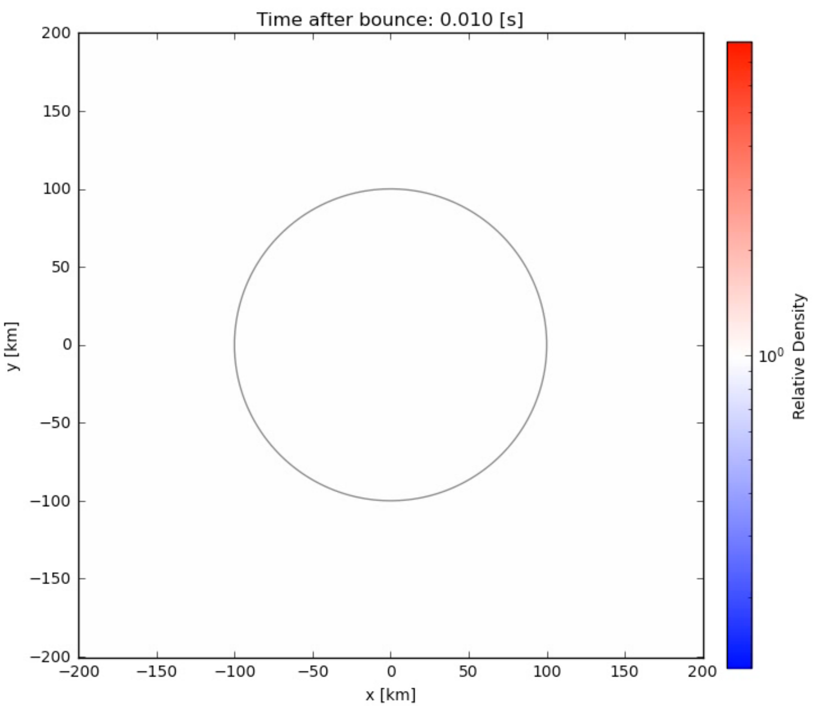
Evolution of E(GW) to Saturation – The Entire Signal
E_{GW} [$M_\odot$ c^2]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
0
1
2
3
4
Time after bounce [s]
9a $M_\odot$
9b $M_\odot$
9_BW $M_\odot$
9_TH $M_\odot$
9.25 $M_\odot$
9.5 $M_\odot$
11 $M_\odot$
12.25 $M_\odot$
14 $M_\odot$
15.01 $M_\odot$
23 $M_\odot$

Correlation of E(GW) and Compactness

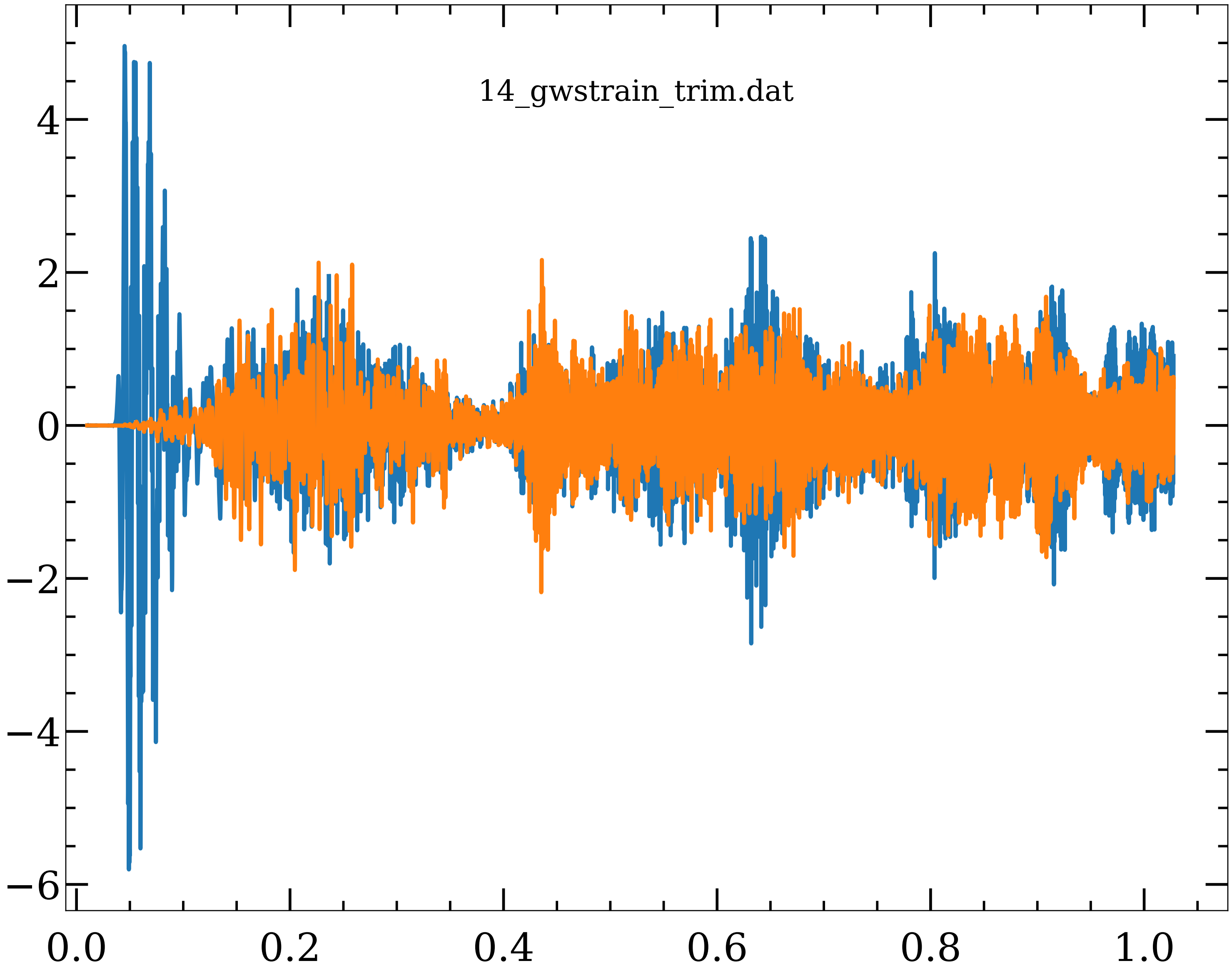




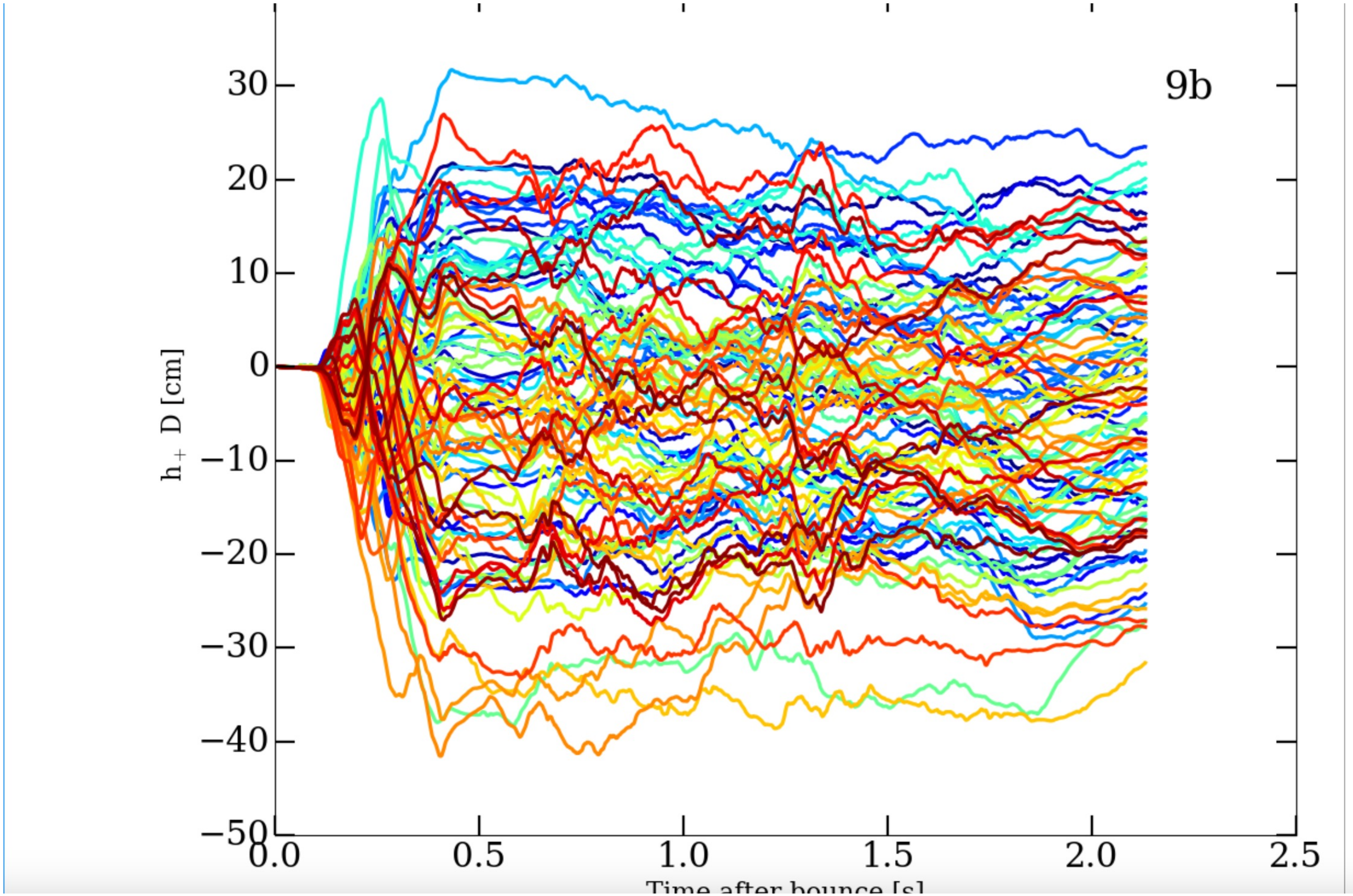
Shock Behavior: Black Hole forming 12.25 solar mass model



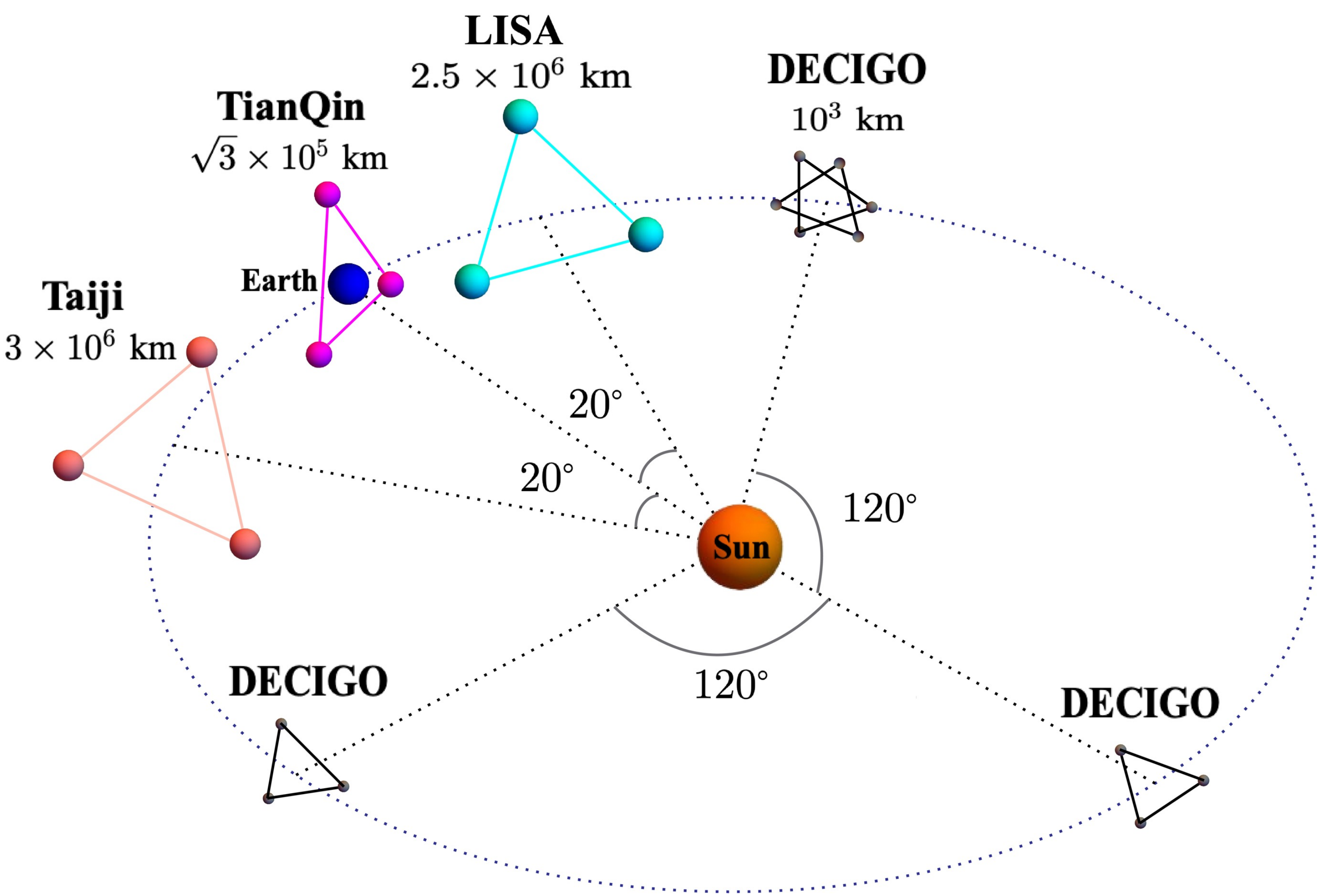
Spiral SASI Modulation when the Shock is Not Reignited



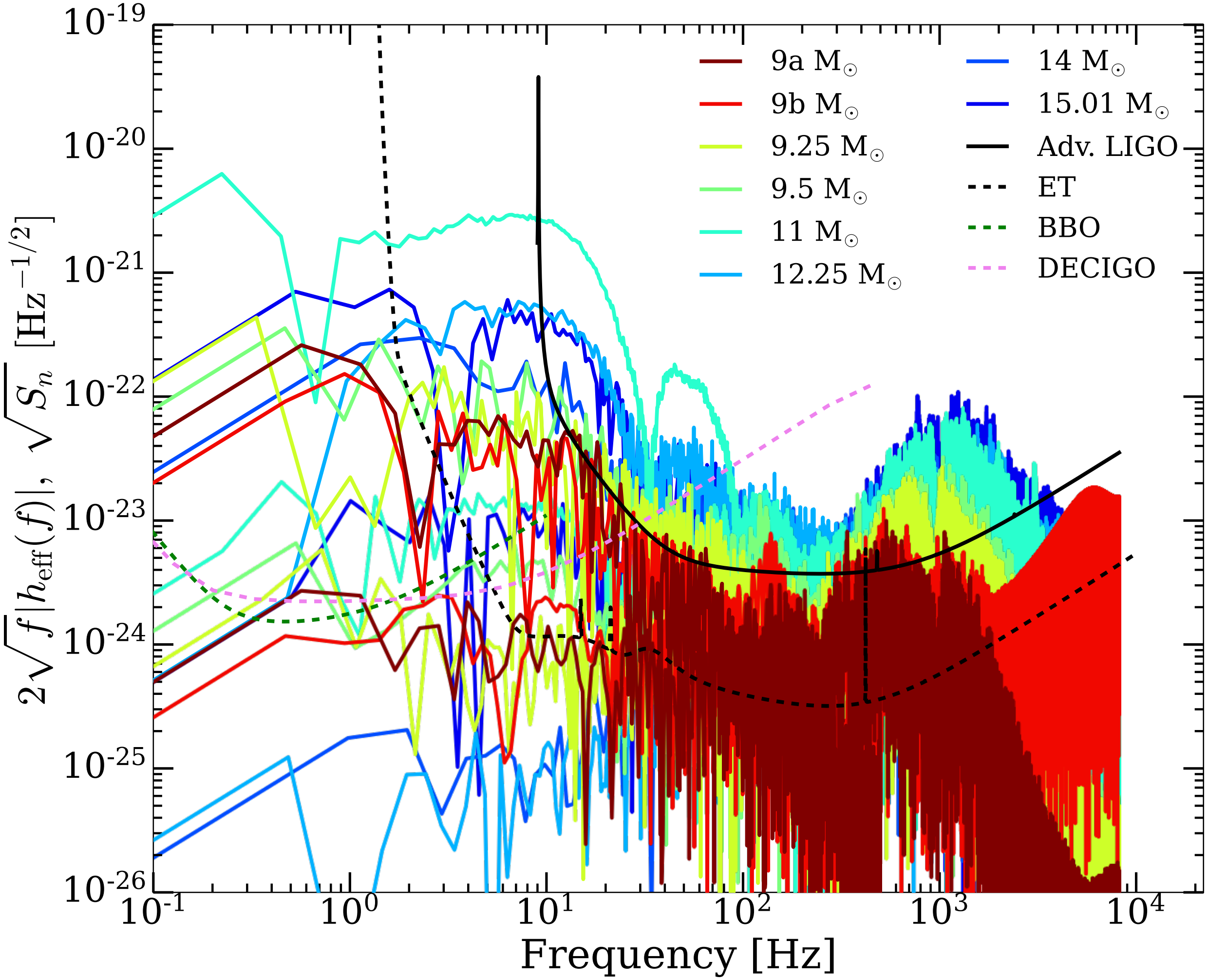
Low-Frequency (Memory) Gravitational Wave Anisotropy: Model 9b



Low-Frequency Gravitational Wave Observatories



CCSN/GW Spectra and Sensitivity Curves

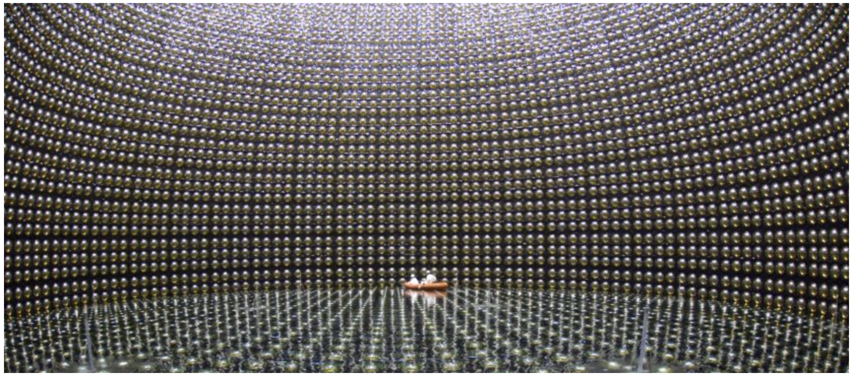


Supernova Neutrino Detection

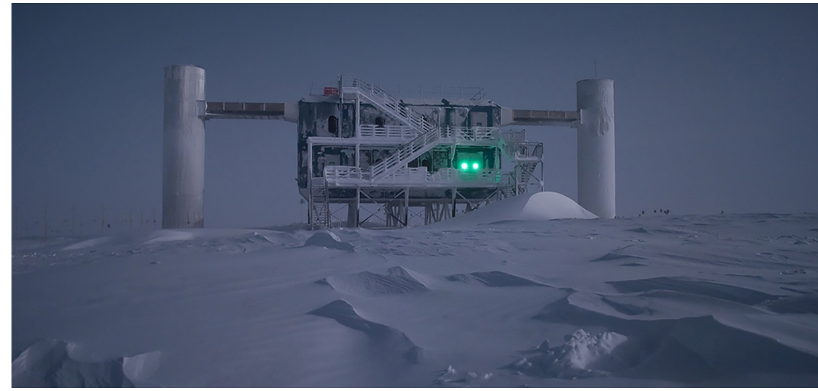
SUPERK, HYPERK, DUNE, JUNO, ICE CUBE, GranSasso

Retrieve 100 long-term neutrino signature models from:
http://www.astro.princeton.edu/~burrows/nu-emissions.2d.large

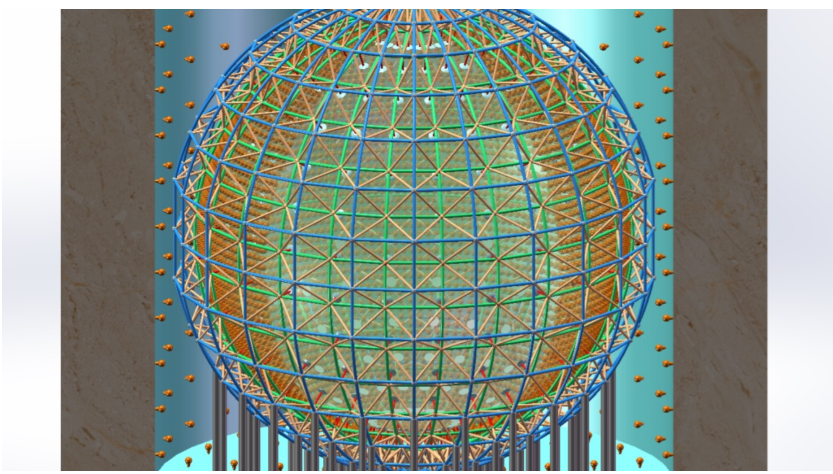
The Larger SN Neutrino Observatories



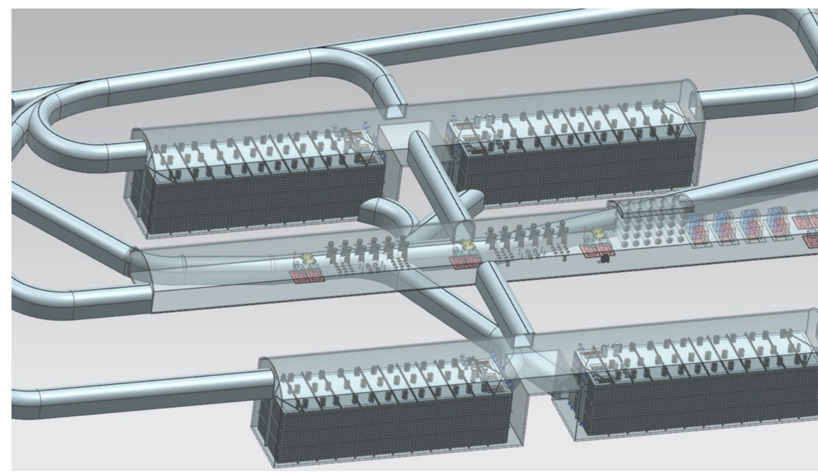
Super-Kamiokande
(Water Cherenkov)



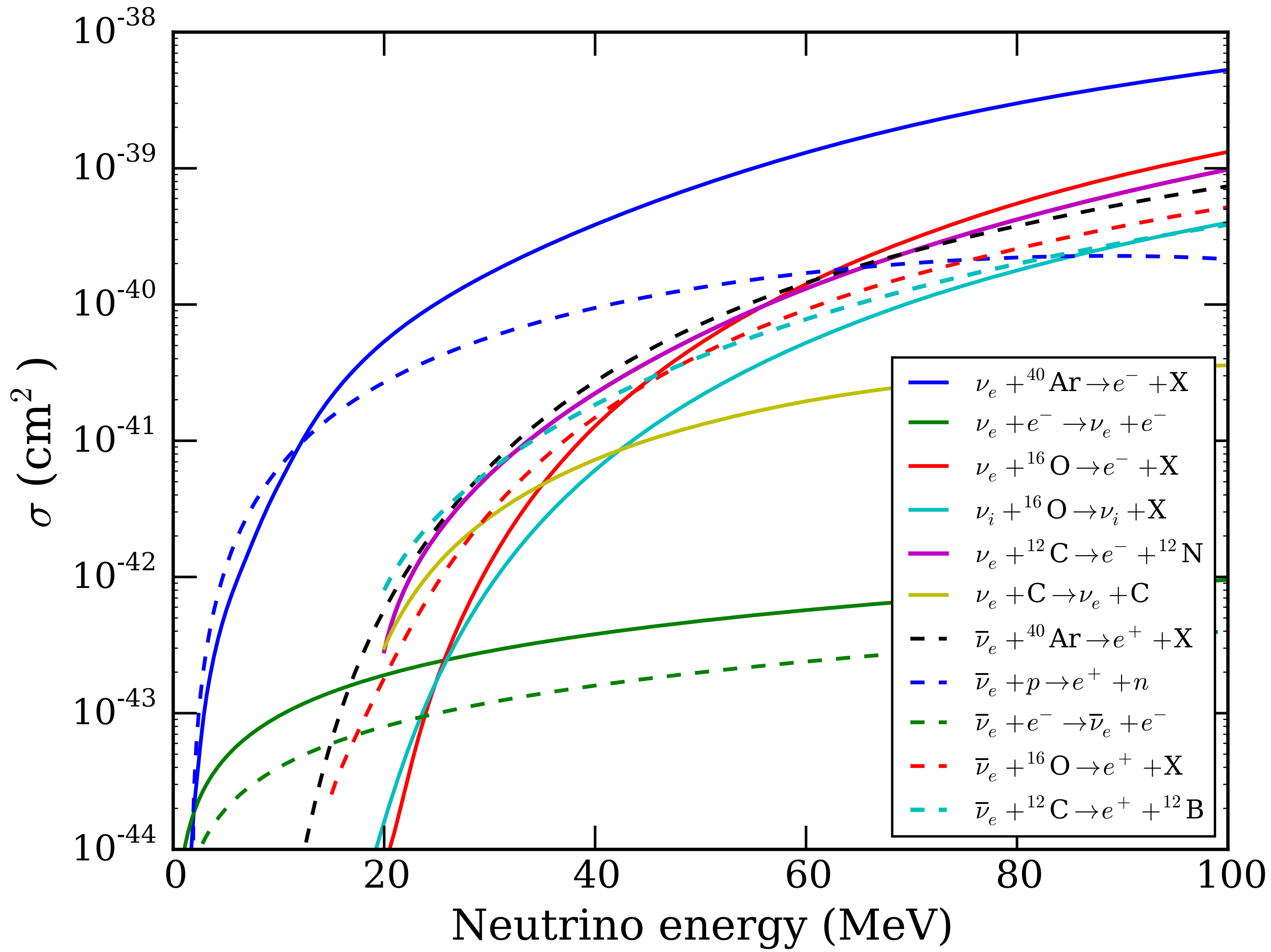
ICECUBE
(Longstring Ice)



JUNO
(Hydrocarbon Scintillator)

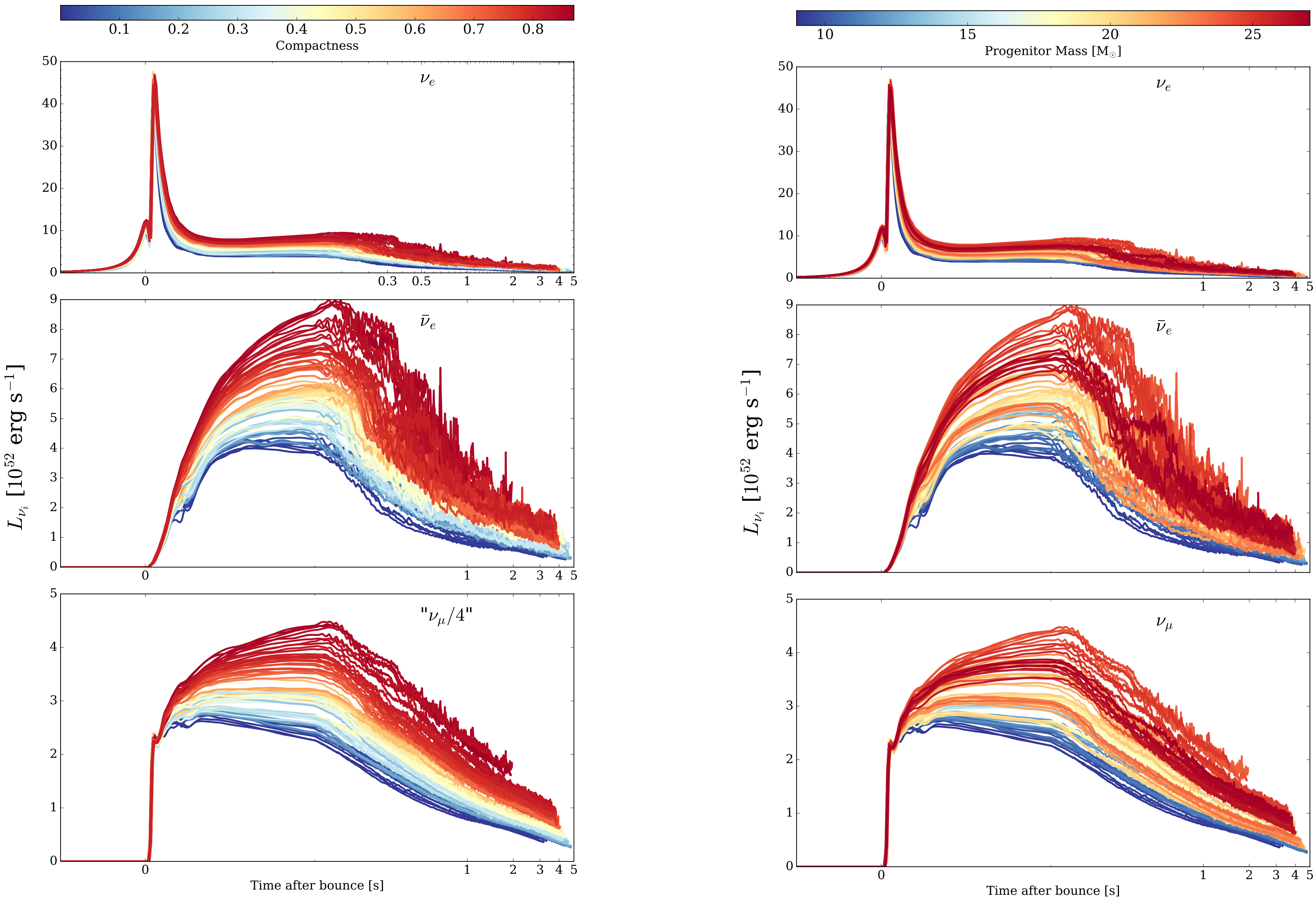


DUNE
(Liquid Argon TPC)



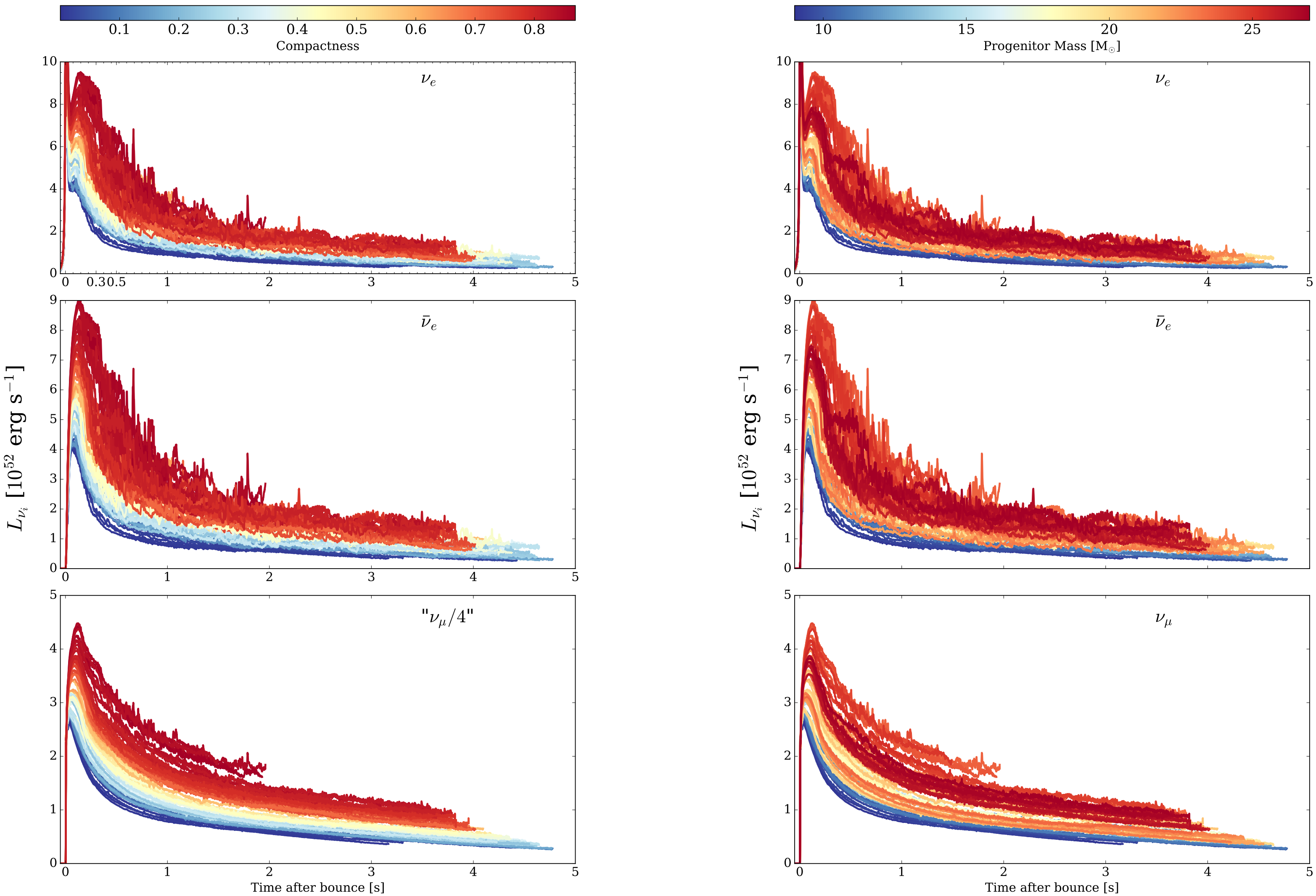
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
σ (cm^2)
0
20
40
60
80
100
Neutrino energy (MeV)
$\nu_e + ^{40}\mathrm{Ar} \to e^- + \mathrm{X}$
$\nu_e + e^- \to \nu_e + e^-$
$\nu_e + ^{16}\mathrm{O} \to e^- + \mathrm{X}$
$\nu_i + ^{16}\mathrm{O} \to \nu_i + \mathrm{X}$
$\nu_e + ^{12}\mathrm{C} \to e^- + ^{12}\mathrm{N}$
$\nu_e + \mathrm{C} \to \nu_e + \mathrm{C}$
$\overline{\nu}_e + ^{40}\mathrm{Ar} \to e^+ + \mathrm{X}$
$\overline{\nu}_e + p \to e^+ + n$
$\overline{\nu}_e + e^- \to \overline{\nu}_e + e^-$
$\overline{\nu}_e + ^{16}\mathrm{O} \to e^+ + \mathrm{X}$
$\overline{\nu}_e + ^{12}\mathrm{C} \to e^+ + ^{12}\mathrm{B}$

100 2D Neutrino Signal Models Simulated to Late Times



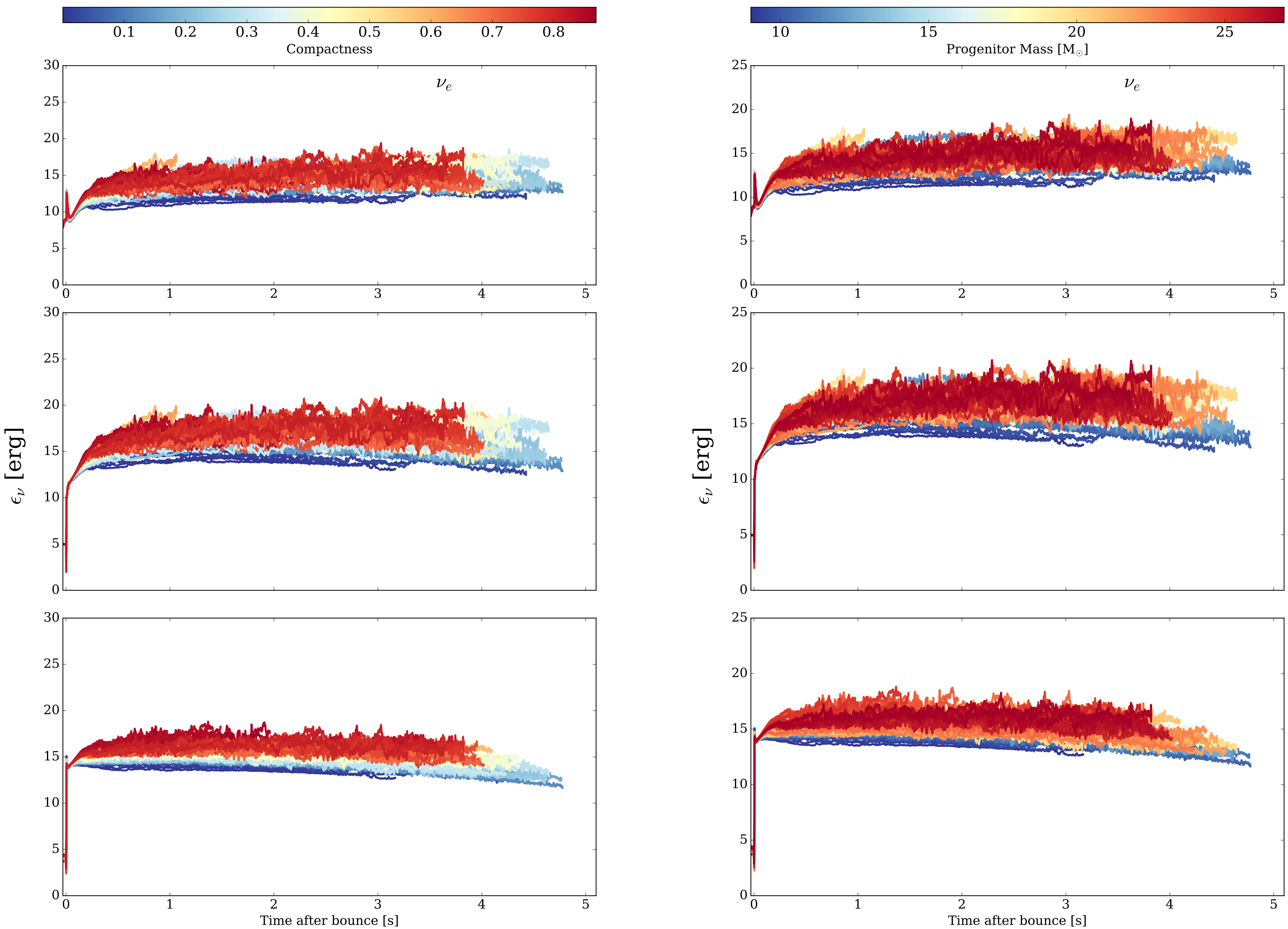
Retrieve 100 long-term neutrino signature models from:
http://www.astro.princeton.edu/~burrows/nu-emissions.2d.large

100 2D Neutrino Signal Models Simulated to Late Times

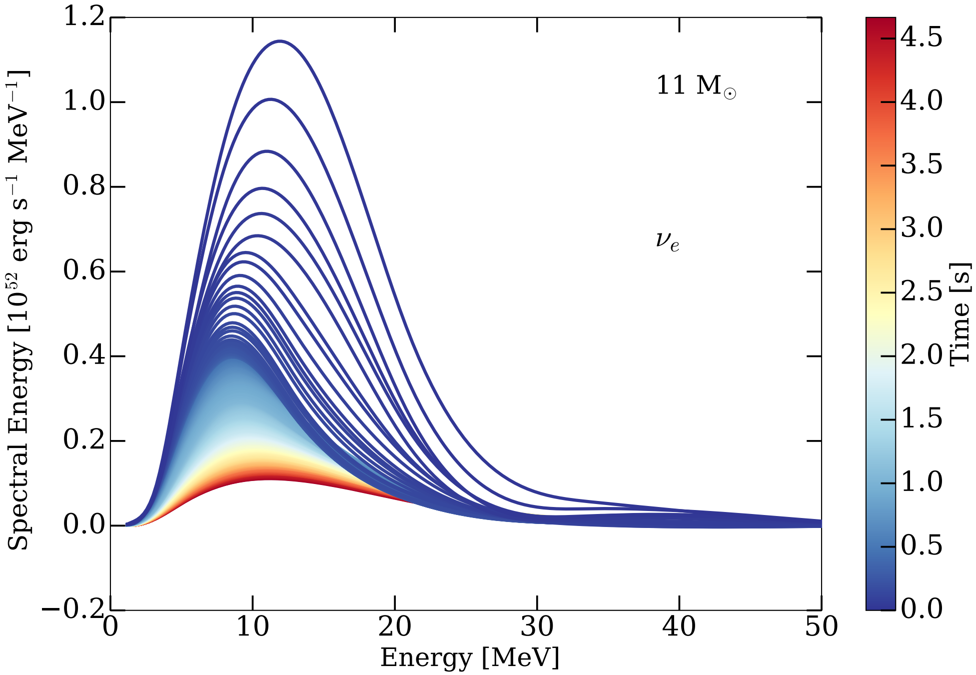


Retrieve 100 long-term neutrino signature models from:
http://www.astro.princeton.edu/~burrows/nu-emissions.2d.large

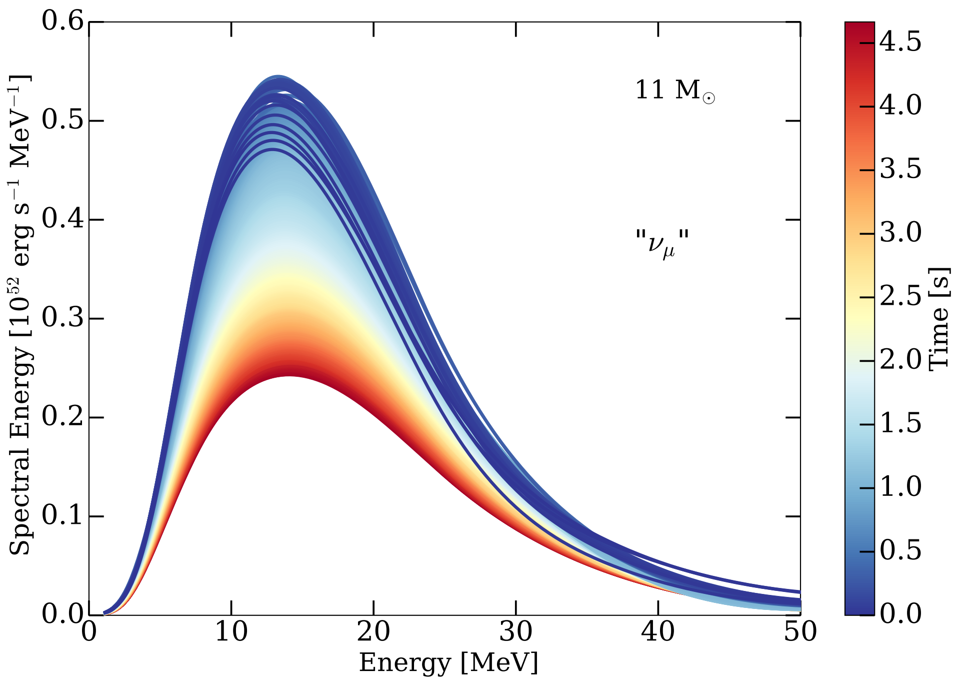
100 2D Neutrino Signal Models Simulated to Late Times



Retrieve 100 long-term neutrino signature models from:
http://www.astro.princeton.edu/~burrows/nu-emissions.2d.large

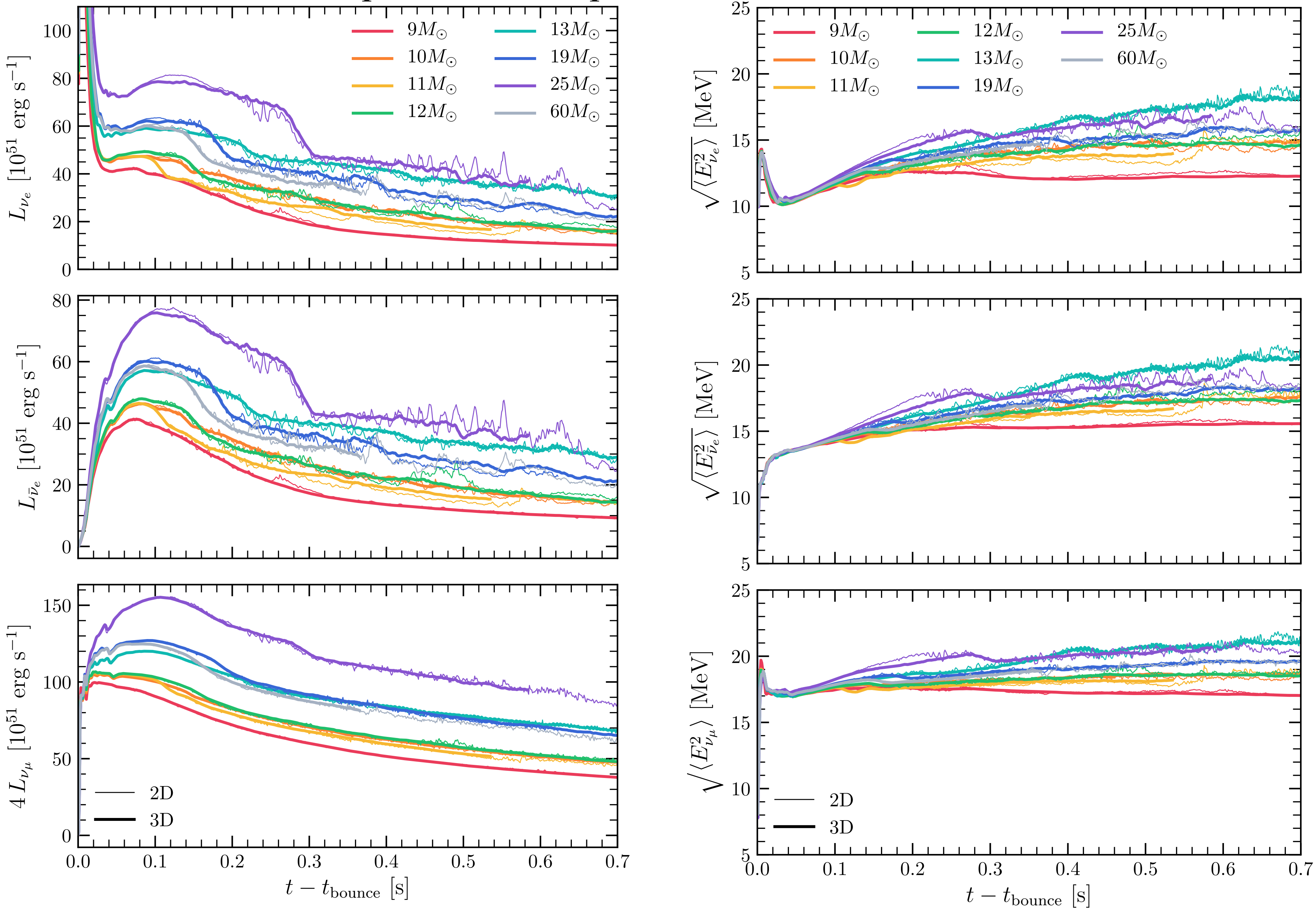


11 M$_\odot$
ν_e
Spectral Energy [10^{52} erg s^{-1} MeV^{-1}]
Energy [MeV]
Time [s]



11 M$_\odot$
"ν_μ"
Spectral Energy [10^{52} erg s^{-1} MeV^{-1}]
Energy [MeV]
Time [s]

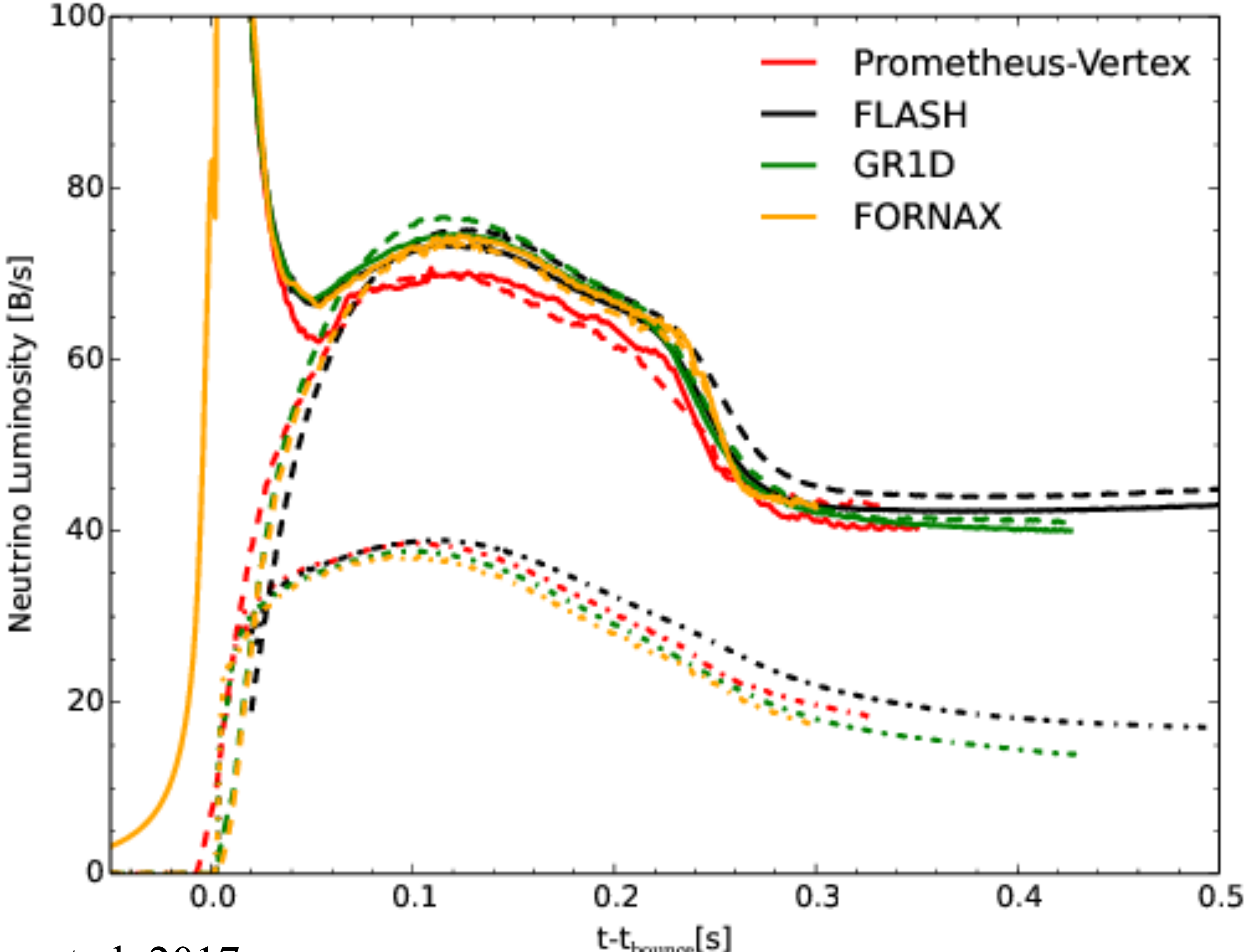
3D Models: http://www.astro.princeton.edu/~burrows/nu-emissions.3d/



Retrieve 100 long-term neutrino signature models

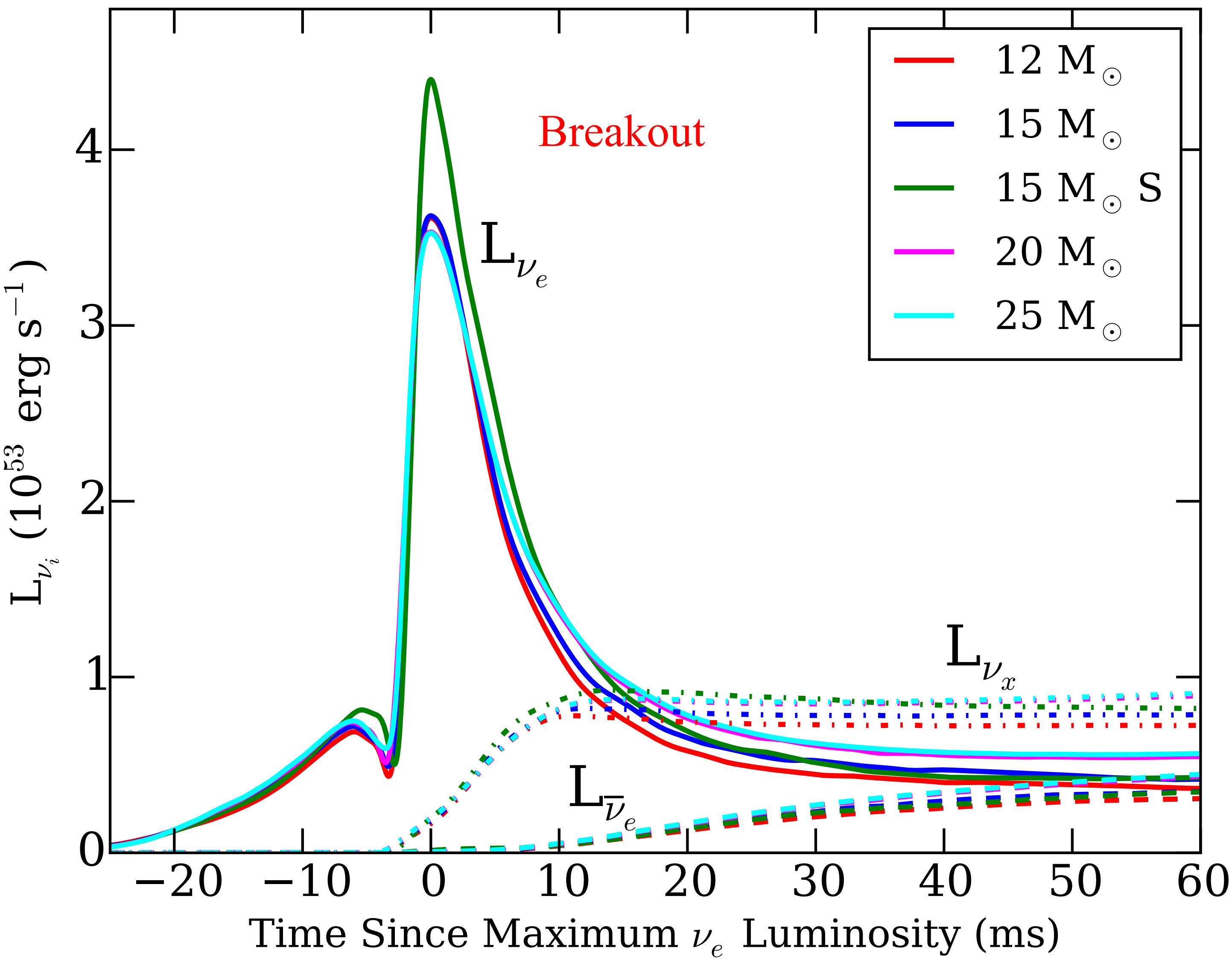
from: http://www.astro.princeton.edu/~burrows/nu-emissions.2d.large

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

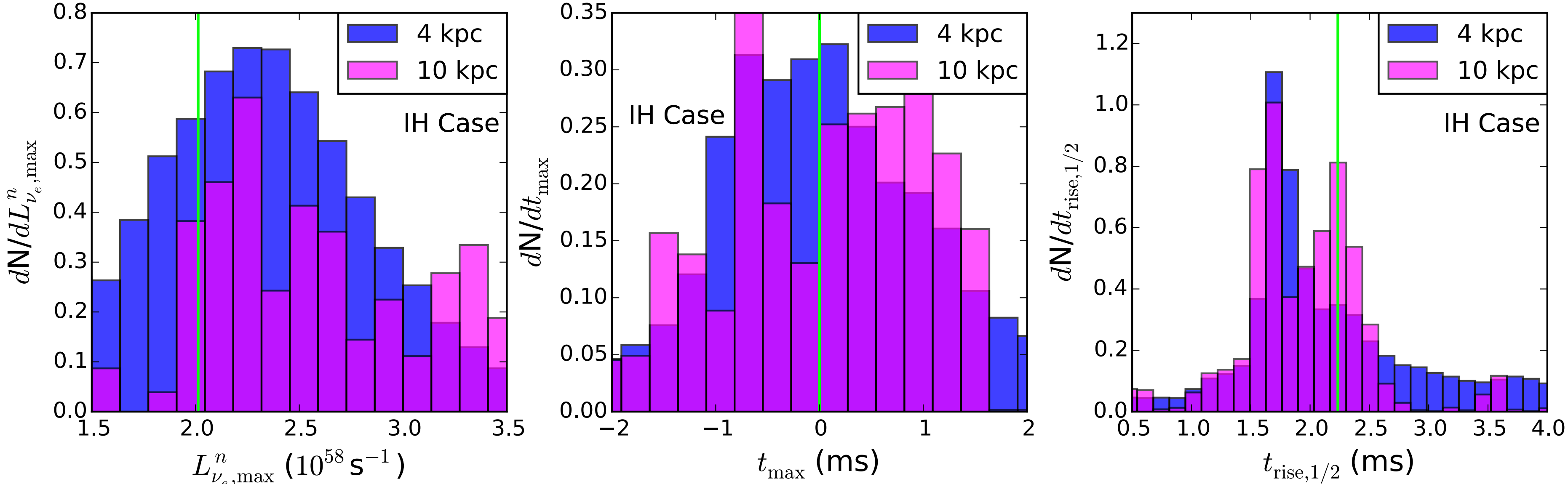


O'Connor et al. 2017

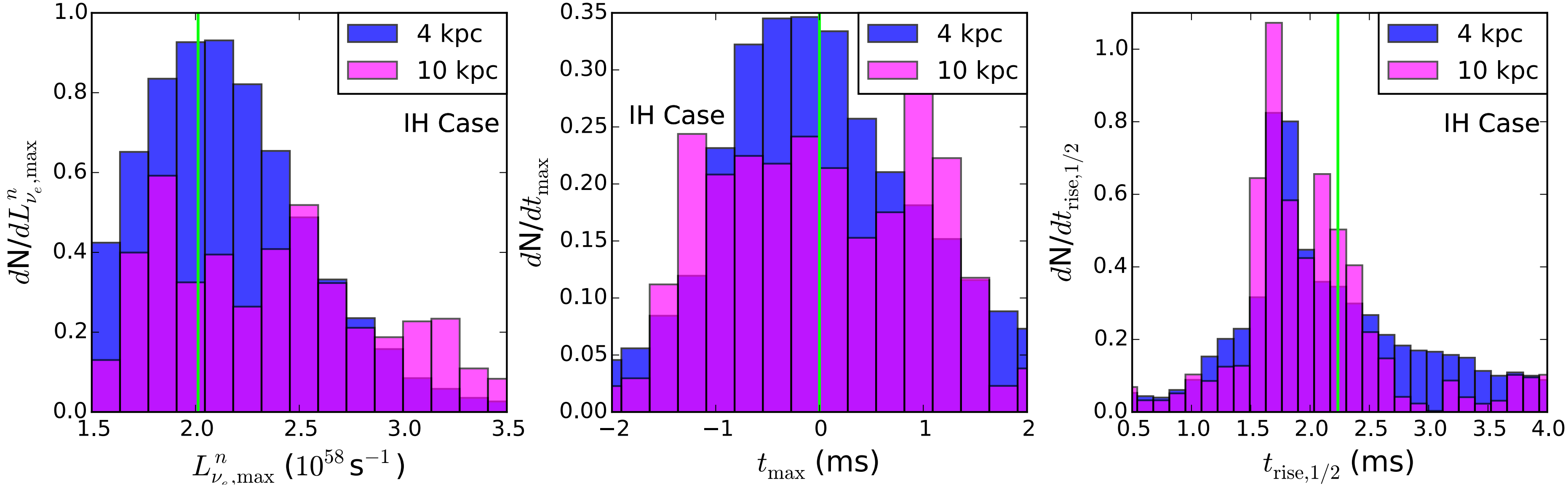
Wallace, Burrows, & Dolence 2016



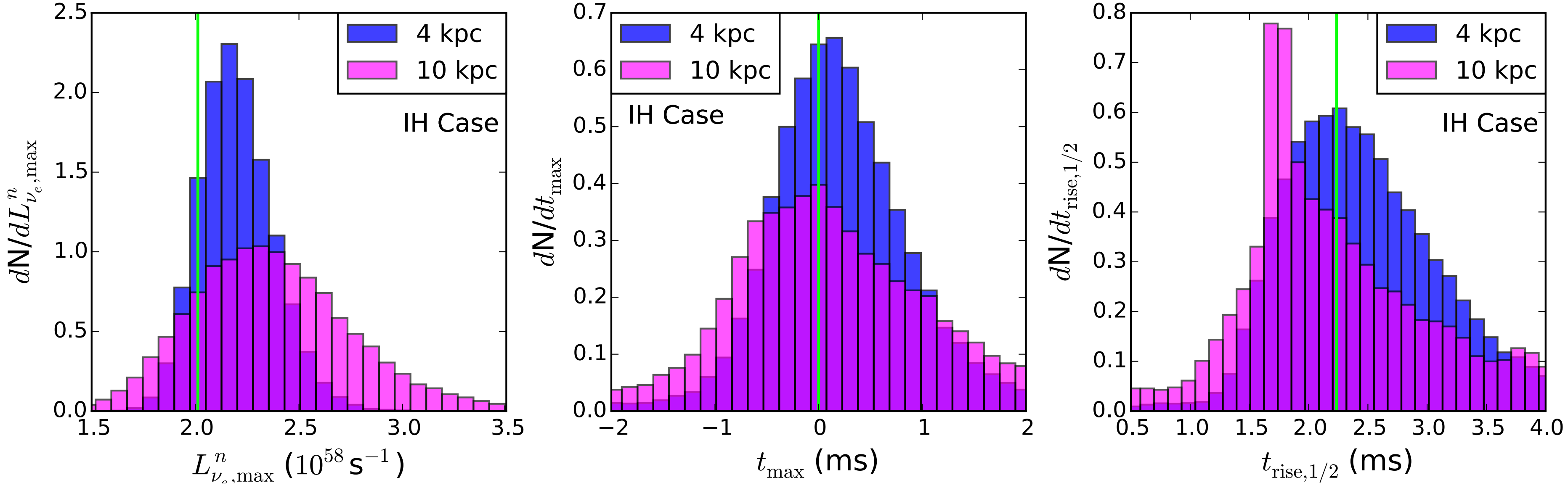
SUPERK


4 kpc
10 kpc
IH Case
$dN/dL^n_{\nu_e,\max}$
$L^n_{\nu_e,\max}$ (10^{58} s^{-1})
$dN/dt_{\max}$
$t_{\max}$ (ms)
$dN/dt_{\mathrm{rise},1/2}$
$t_{\mathrm{rise},1/2}$ (ms)

JUNO


4 kpc
10 kpc
IH Case
$dN/dL^n_{\nu_e,\max}$
$L^n_{\nu_e,\max}$ (10^{58} s^{-1})
$dN/dt_{\max}$
$t_{\max}$ (ms)
$dN/dt_{\mathrm{rise},1/2}$
$t_{\mathrm{rise},1/2}$ (ms)

DUNE



4 kpc
10 kpc
IH Case
$dN/dL^n_{\nu_e,\max}$
$L^n_{\nu_e,\max}$ (10^{58} s^{-1})
$dN/dt_{\max}$
$t_{\max}$ (ms)
$dN/dt_{\mathrm{rise},1/2}$
$t_{\mathrm{rise},1/2}$ (ms)

Core-Collapse Explosion Mechanism: 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.

- 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)!
- GR important?

- 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; Dynamo creation of magnetar and pulsar B-fields?

- Seed Perturbations
- But, Neutrino Oscillations!?
- 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