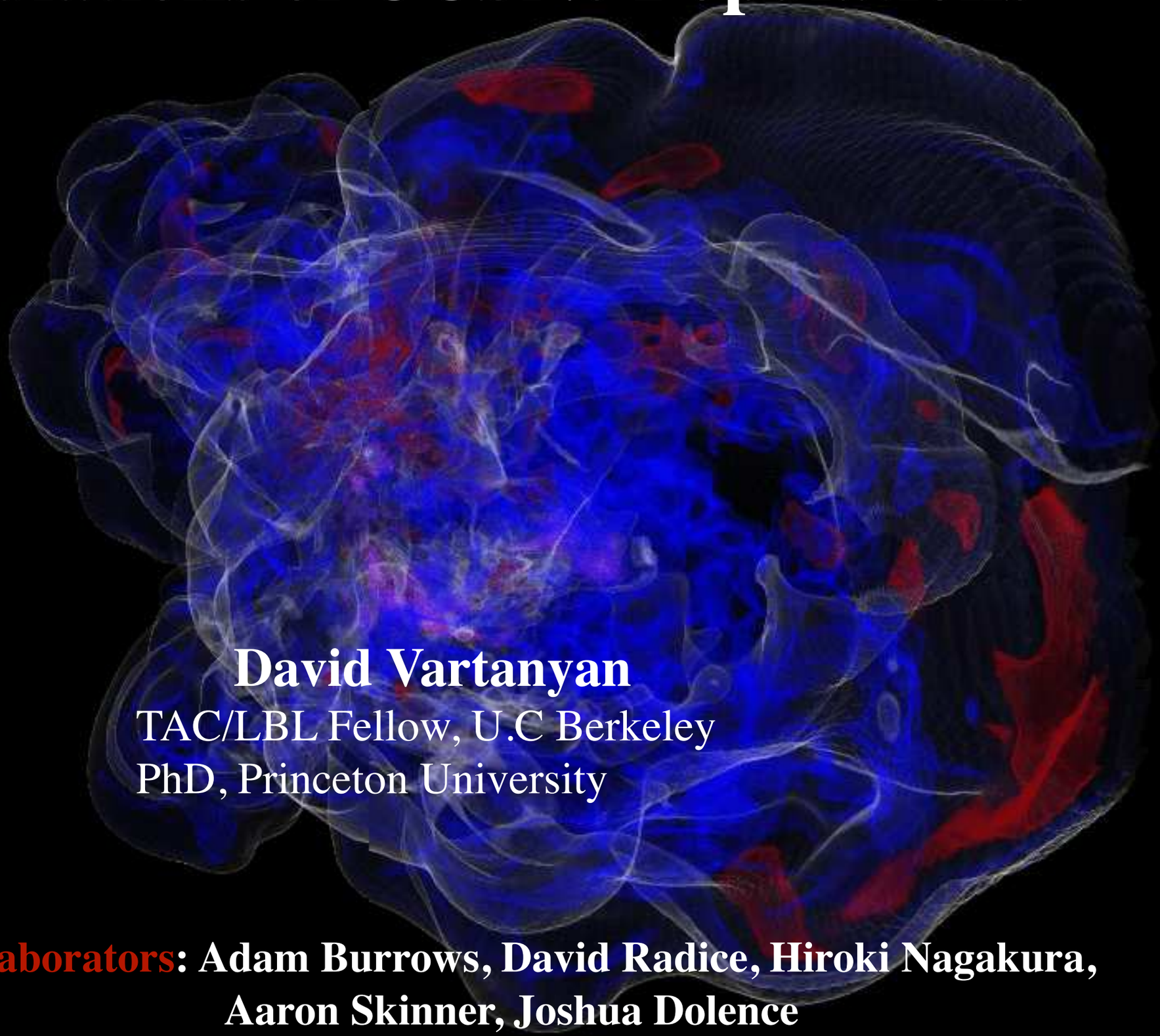
3D Simulations of CCSNe Populations

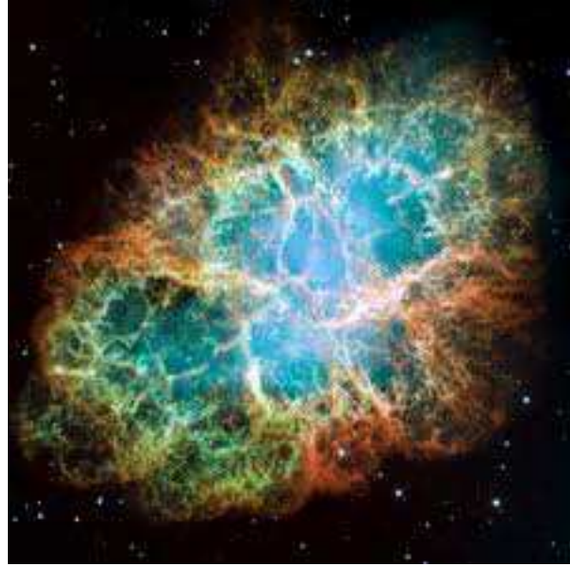


David Vartanyan
TAC/LBL Fellow, U.C Berkeley
PhD, Princeton University



Collaborators: Adam Burrows, David Radice, Hiroki Nagakura, Aaron Skinner, Joshua Dolence

Core-Collapse Supernovae



Progenitors: Massive stars **8 - 60** $M_\odot$

Evolution: Iron core unstable

Collapse, bounce, and explode over ~1 second

Hydrodynamically-driven shock stalls

Require **neutrino heating** to revive stalled shock

Explosion: Ejecta Kinetic Energy$\sim 10^{51}$ ergs

Theory and observed light curves, photospheric velocities of Type II SNe (e.g, Kasen, Woosley 2009)



Remnant: Neutron Stars,
Black Holes?

Prehistoric Astronomy

Burzahom, India 3000 BC? SN HB9





Crab Nebula SN1054



SN 1987a

A History

1934: Baade & Zwicky:
Coined "**super-novae**": produce neutron stars, source cosmic rays

1935: Chandrasekar :
Iron core heavier than 1.4 $M_\odot$ **gravitationally unstable**

1940: Gamow & Schoenberg
"the emission of a large number of neutrinos… stellar collapses of this kind are responsible for the phenomena of novae and supernovae"

1957: BBFH:
Supernovae synthesize and disseminate heavy elements; mechanism of core instability

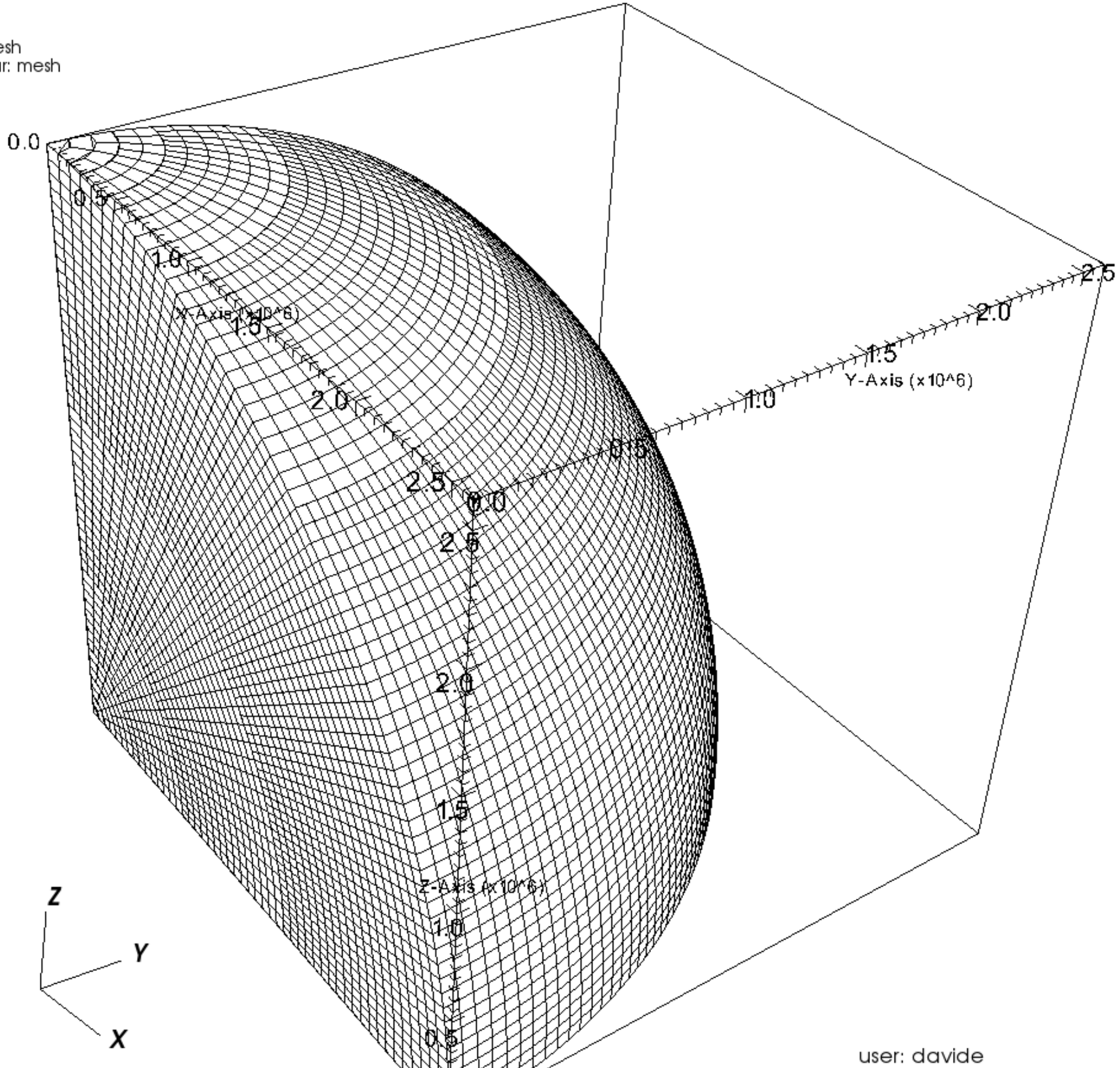
1966: Colgate & White
"The energy released corresponds to the change in gravitational potential of the unstable imploding core; the transfer of energy takes place by the emission and deposition of neutrinos"

1985: Bethe & Wilson
"Revival of a stalled supernova shock by neutrino heating": only about 0.1% of [the neutrino] energy is absorbed

1987: SN detection of neutrinos & radioactive decay

Unsolved problem for over 50 years

DB: grid.vtk


Mesh
Var: mesh
0.0
0.5
1.0
1.5
2.0
2.5
Y-Axis (x10^6)
0.0
0.5
1.0
1.5
2.0
2.5
X-Axis (x10^6)
0.0
0.5
1.0
1.5
2.0
2.5
Z-Axis (x10^6)
Z
Y
X
user: davide

Numerical Methods

1. Conservation Equations

mass

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

momentum

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

energy

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

lepton number

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

2. Radiative Transfer: M1 Closure

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

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

3. Detailed Balance

Process
β processes
$\nu_e + n \rightleftharpoons e^- + p$
$\bar{\nu}_e + p \rightleftharpoons e^+ + n$
$\nu_e + (A, Z) \rightleftharpoons e^- + (A, Z+1)$
Scattering reactions
$\nu + (A, Z) \rightleftharpoons \nu' + (A, Z)$
$\nu + N \rightleftharpoons \nu' + N$
$\nu + e^\pm \rightleftharpoons \nu' + e^\pm$
("Thermal") pair production
$\nu + \bar{\nu} \rightleftharpoons e^- + e^+$
Nucleon-nucleon bremsstrahlung
$\nu + \bar{\nu} + N + N \rightleftharpoons N + N$
Reactions between neutrinos
$\nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau} \rightleftharpoons \nu_e + \bar{\nu}_e$
$\nu_x + \{\nu_e, \bar{\nu}_e\} \rightleftharpoons \nu'_x + \{\nu'_e, \bar{\nu}'_e\}$

OUTLINE

I. Exploding Stars:

a. Progenitors

b. Input Physics

II. Exploding Stars Robustly

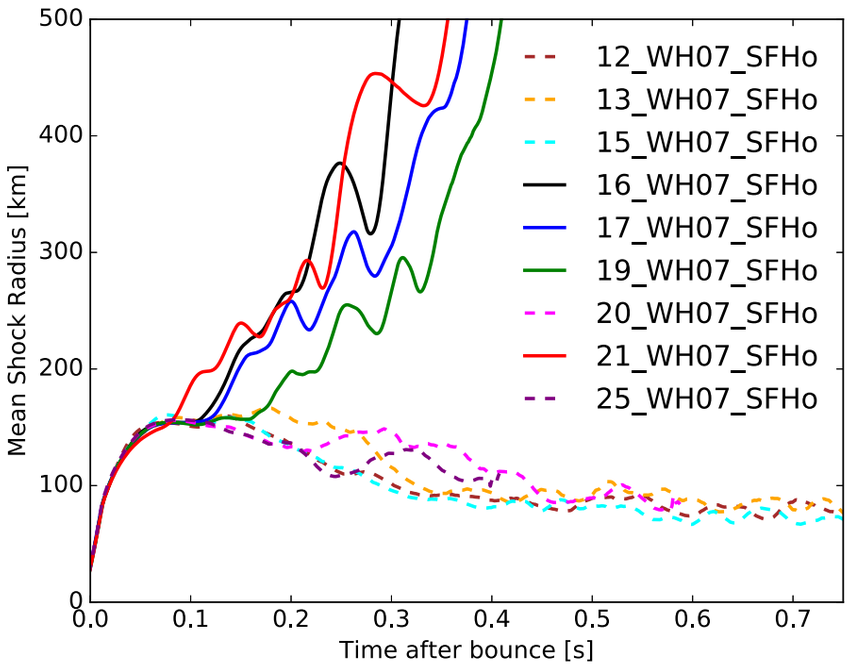
The Journey to 1 Bethe

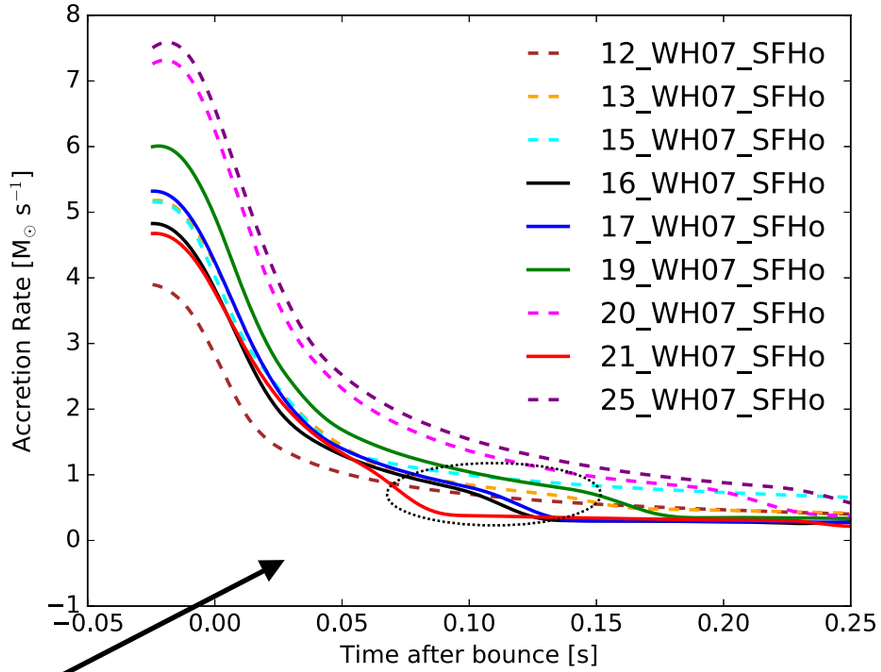
III. Exploding Stars Verifiably

GW & Neutrino Signatures

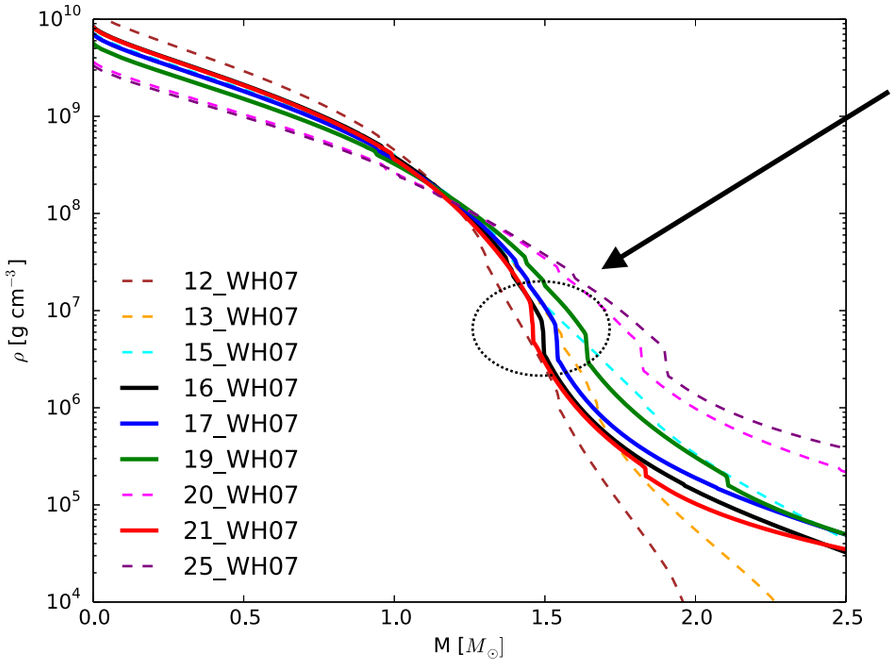
I. Exploding Stars: Progenitor

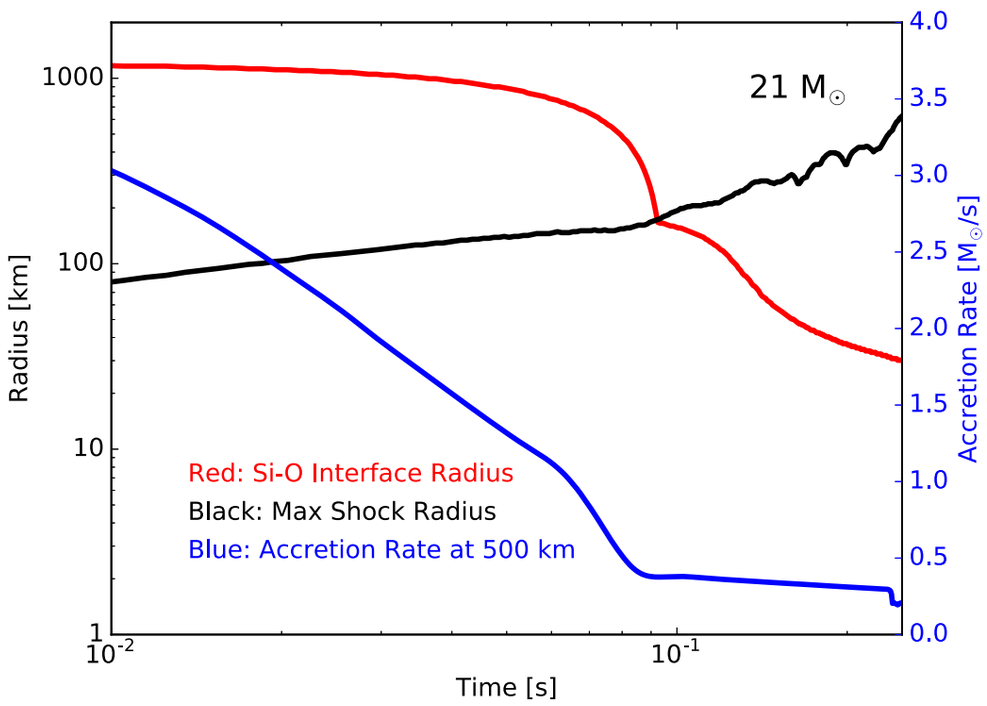
Vartanyan+ 2018a



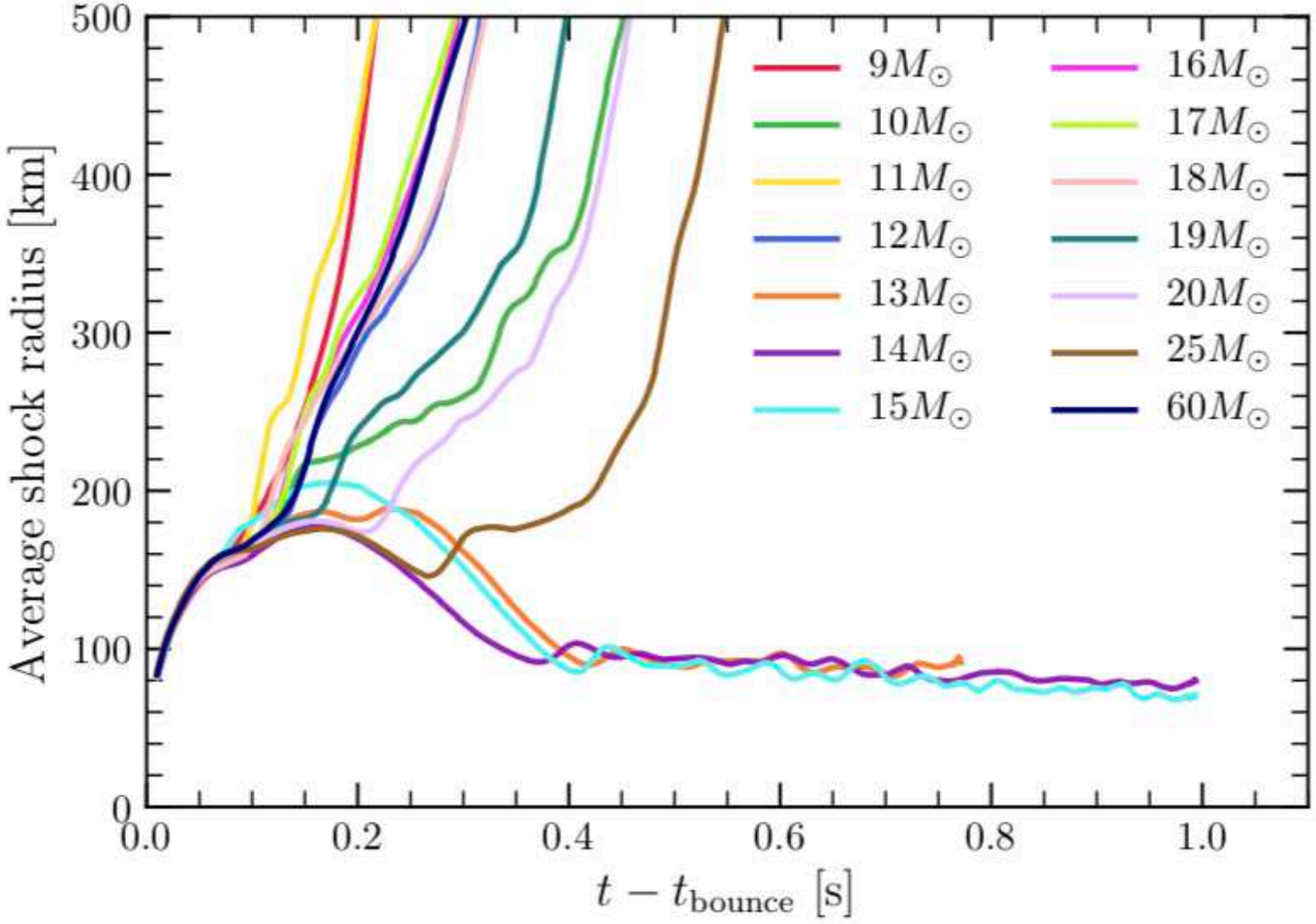


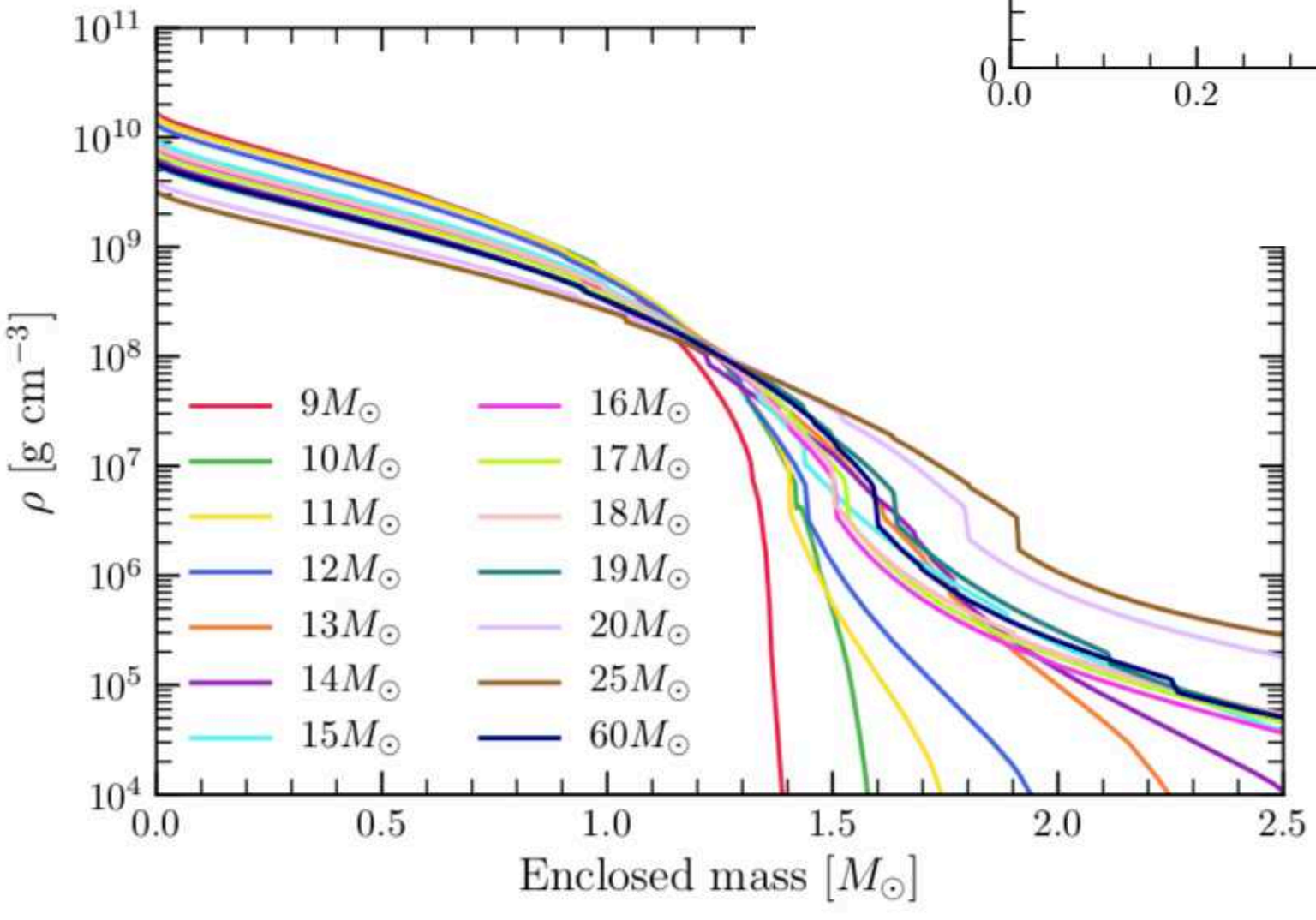
2 classes of models:
explosion determined by
Si-O interface accretion

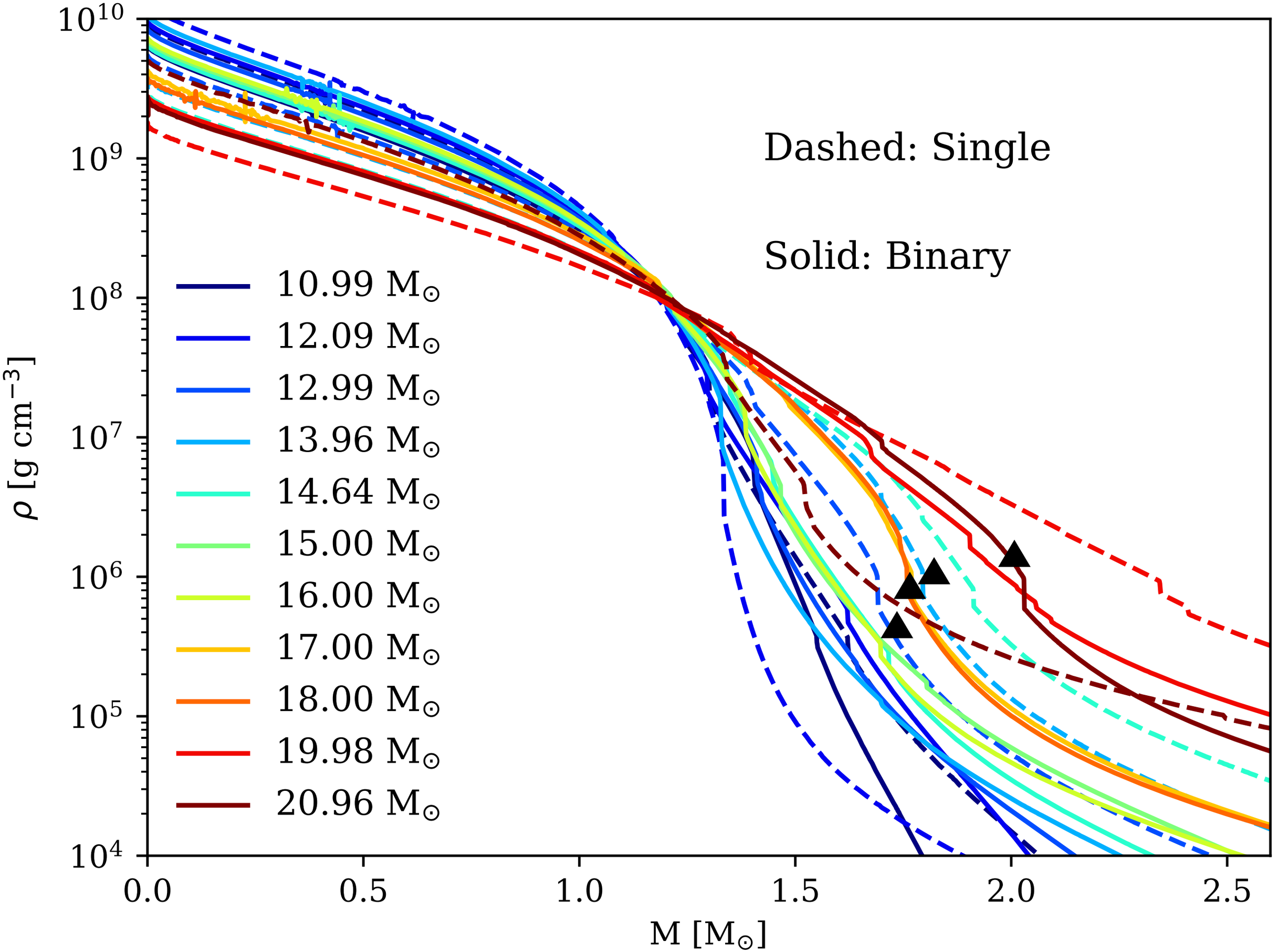




…and in 3D

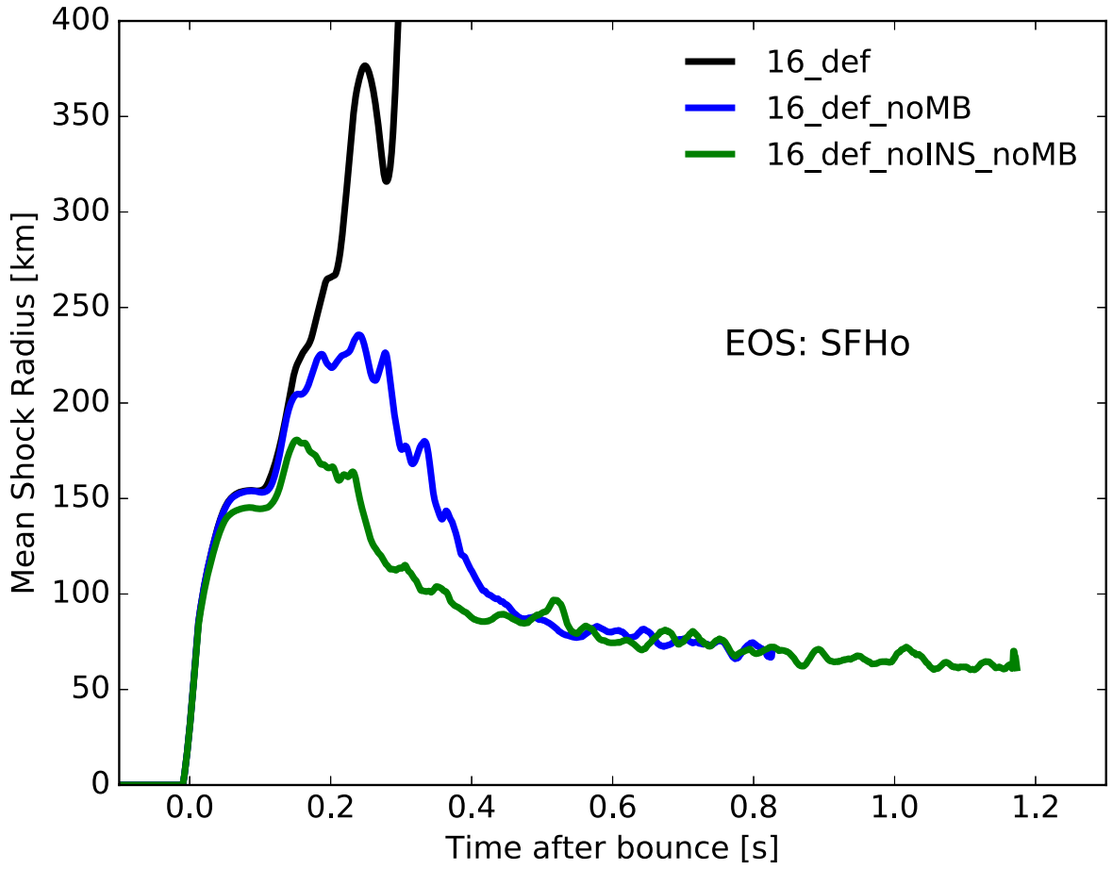

Average shock radius [km]
500
400
300
200
100
0
0.0
0.2
0.4
0.6
0.8
1.0
$t - t_{\rm bounce}$ [s]
$9M_\odot$
$10M_\odot$
$11M_\odot$
$12M_\odot$
$13M_\odot$
$14M_\odot$
$15M_\odot$
$16M_\odot$
$17M_\odot$
$18M_\odot$
$19M_\odot$
$20M_\odot$
$25M_\odot$
$60M_\odot$


ρ [g cm^{-3}]
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
0.0
0.5
1.0
1.5
2.0
2.5
Enclosed mass [$M_\odot$]
$9M_\odot$
$10M_\odot$
$11M_\odot$
$12M_\odot$
$13M_\odot$
$14M_\odot$
$15M_\odot$
$16M_\odot$
$17M_\odot$
$18M_\odot$
$19M_\odot$
$20M_\odot$
$25M_\odot$
$60M_\odot$

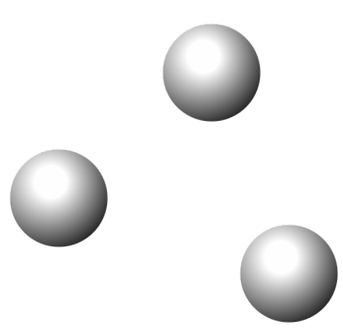

Dashed: Single
Solid: Binary
10.99 M⊙
12.09 M⊙
12.99 M⊙
13.96 M⊙
14.64 M⊙
15.00 M⊙
16.00 M⊙
17.00 M⊙
18.00 M⊙
19.98 M⊙
20.96 M⊙
ρ [g cm⁻³]
M [M⊙]
10^10
10^9
10^8
10^7
10^6
10^5
10^4
0.0
0.5
1.0
1.5
2.0
2.5

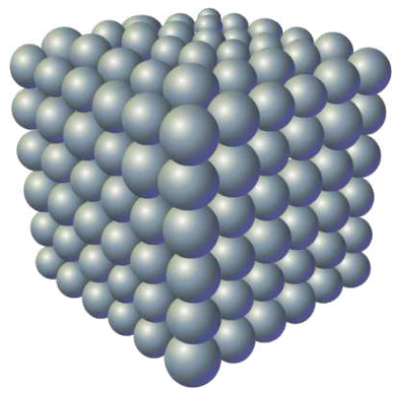
I. Exploding Stars: Input Physics

Microphysics: Medium Correction to Neutrino-Nucleon Scattering



$$\frac{d\sigma_0}{d\Omega} = \frac{G_F^2 \epsilon^2}{4\pi^2}\left[c_v^2(1+\cos\theta) + c_a^2(3-\cos\theta)\right],$$





1. $\sigma \downarrow$, $L_{\nu,\mu} \uparrow$
2. core shrinks, heats
3. $\epsilon_{\nu,e} \uparrow$

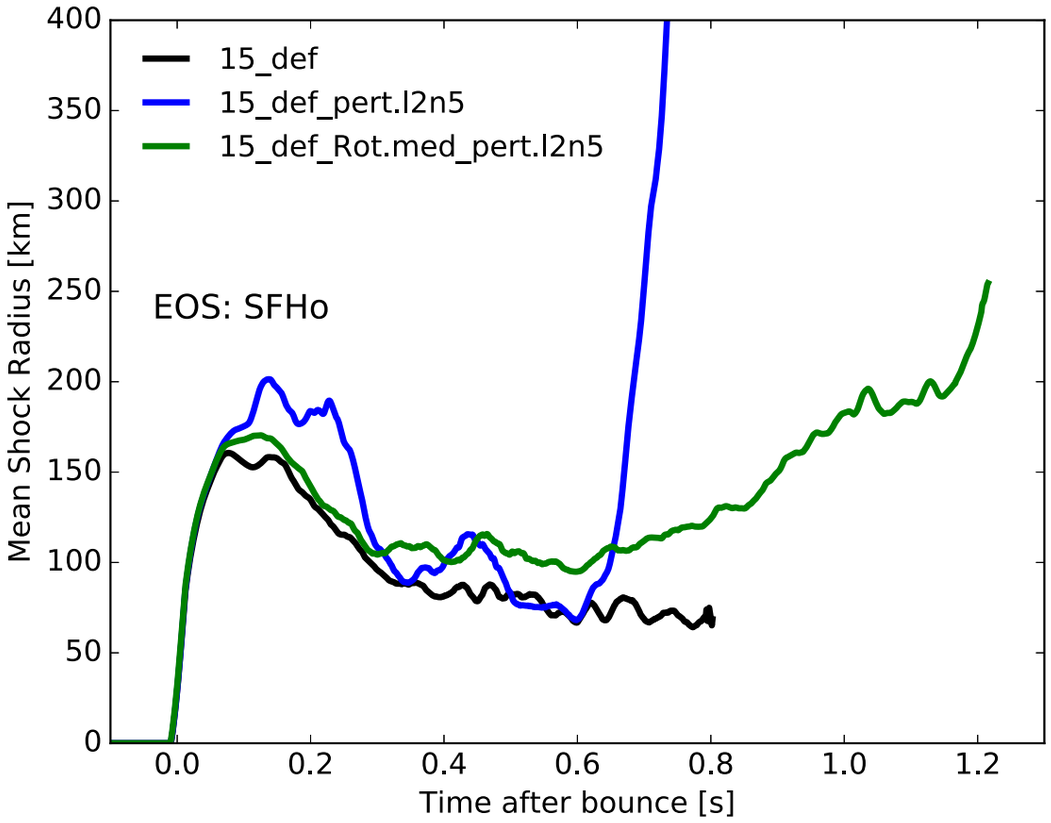
MB effect (Horowitz+ 2017) and **inelastic scattering** of neutrinos off electrons + nucleons **promote explosion**

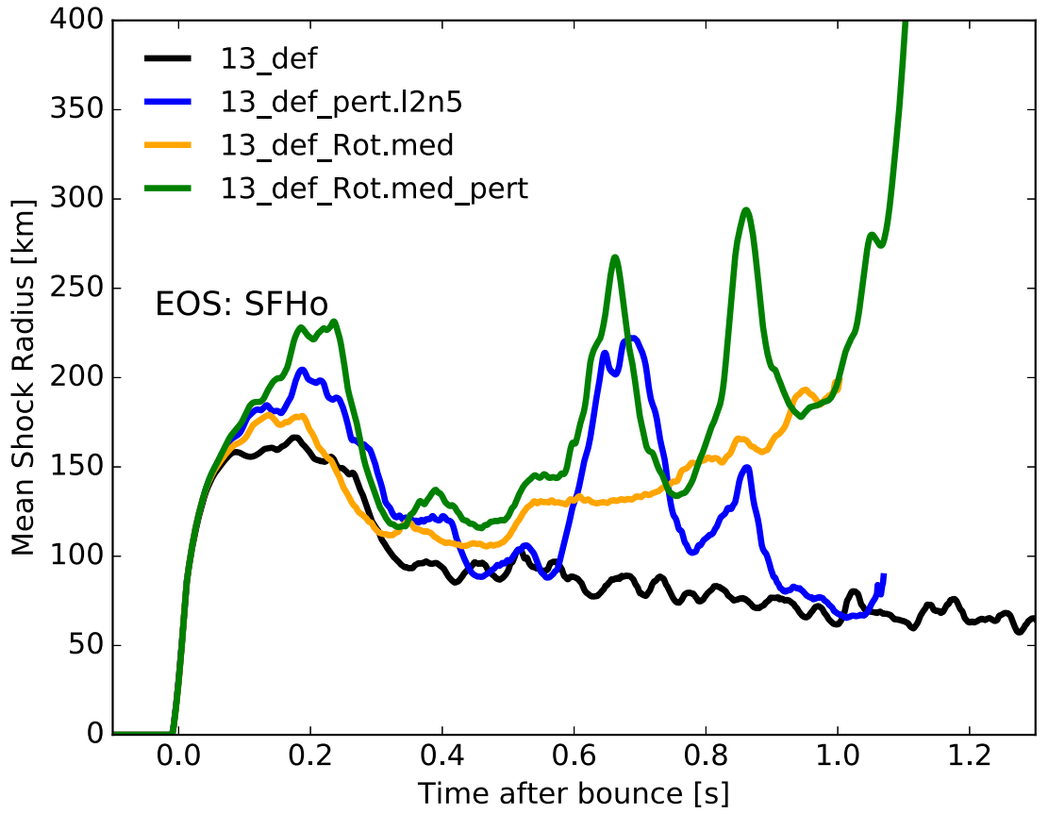
Burrows, **Vartanyan**+ 2018

Exploding Stars: Input Physics

Can we explode the duds?

Macrophysics: Velocity Perturbations & Rotation

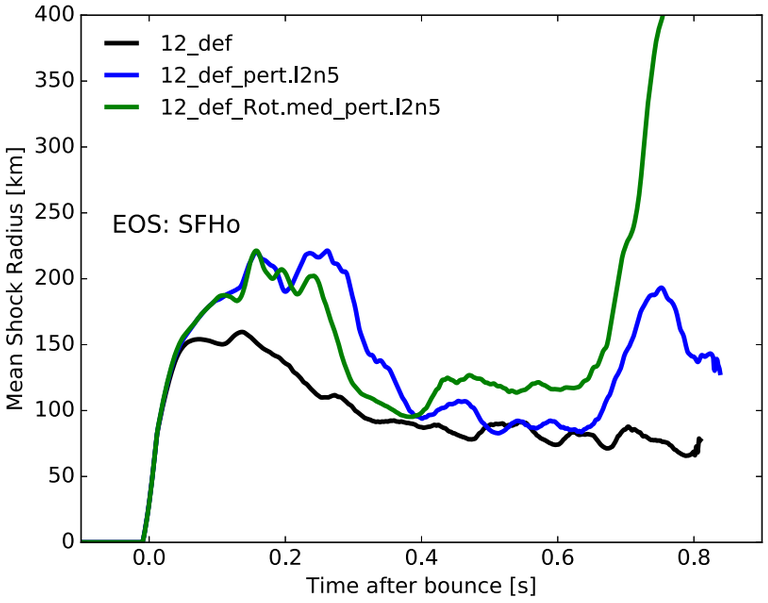


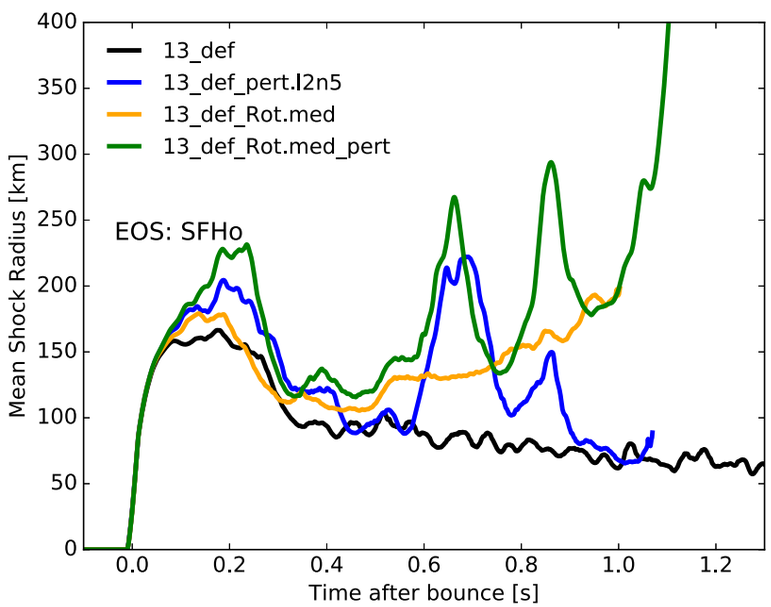


- moderate rotation → non-monotonic results
- perturbation to infall velocities important

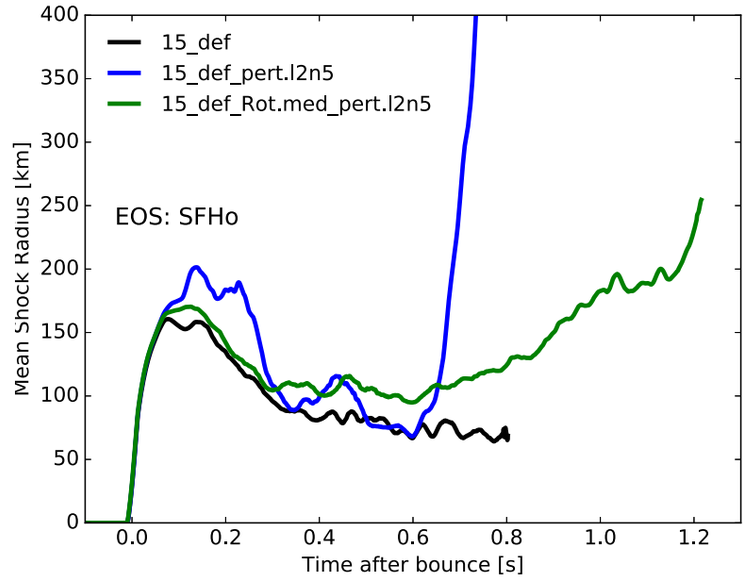
models are close to the critical condition for explosion

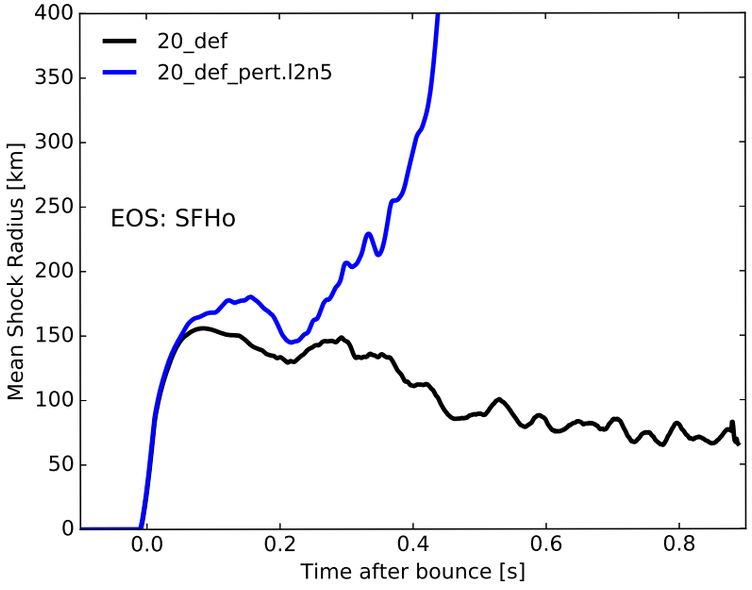
Vartanyan+ 2018a

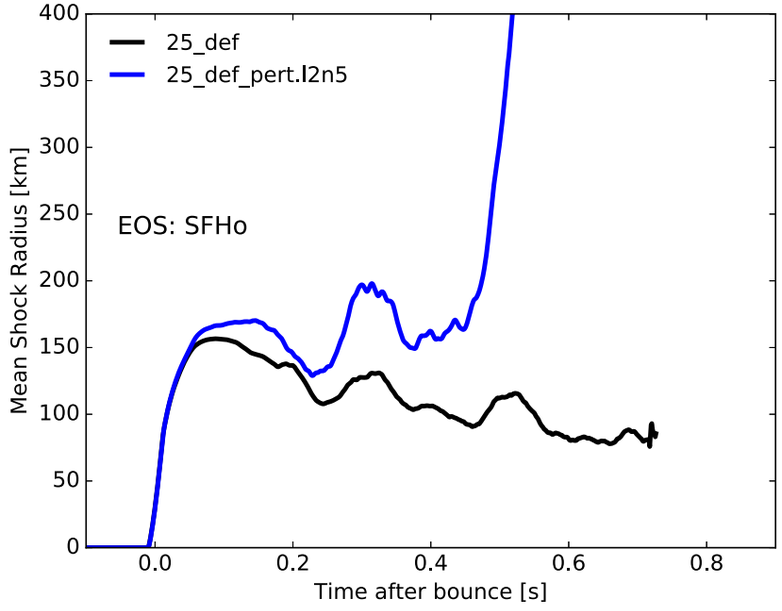




All models explode





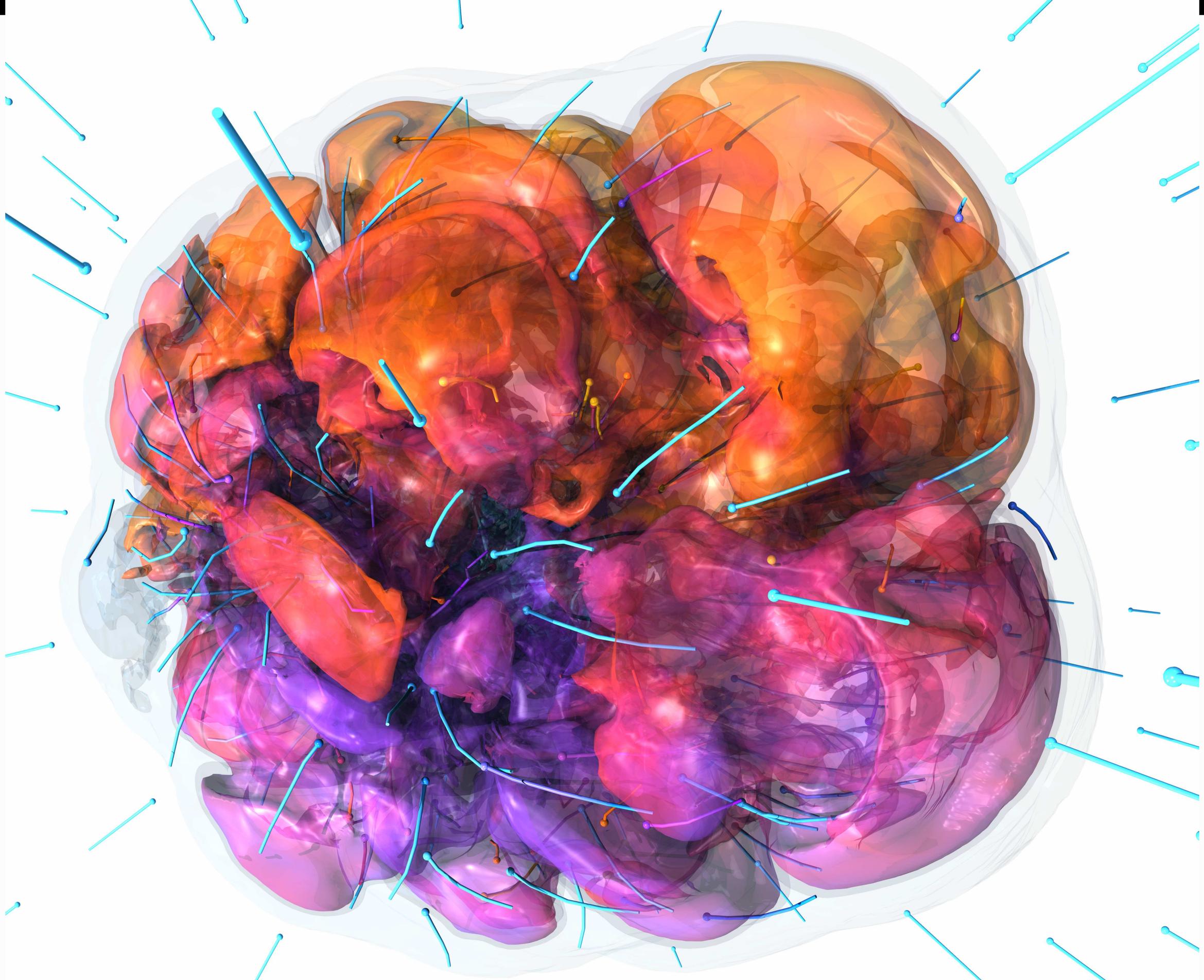


Vartanyan+ 2018a

How Do Stars Explode?



Vartanyan+ 2018b



Induced Rotation & Low-Y_e Tail



Time = 0.010 s

t = 0.010 s

9-$M_\odot$

t = 0.010 s

10-$M_\odot$

t = 0.010 s

11-$M_\odot$

t = 0.010 s

12-$M_\odot$

Time = 0.000 s

16-$M_\odot$

t = 0.010 s

13-$M_\odot$

t = 0.010 s

19-$M_\odot$

t = 0.010 s

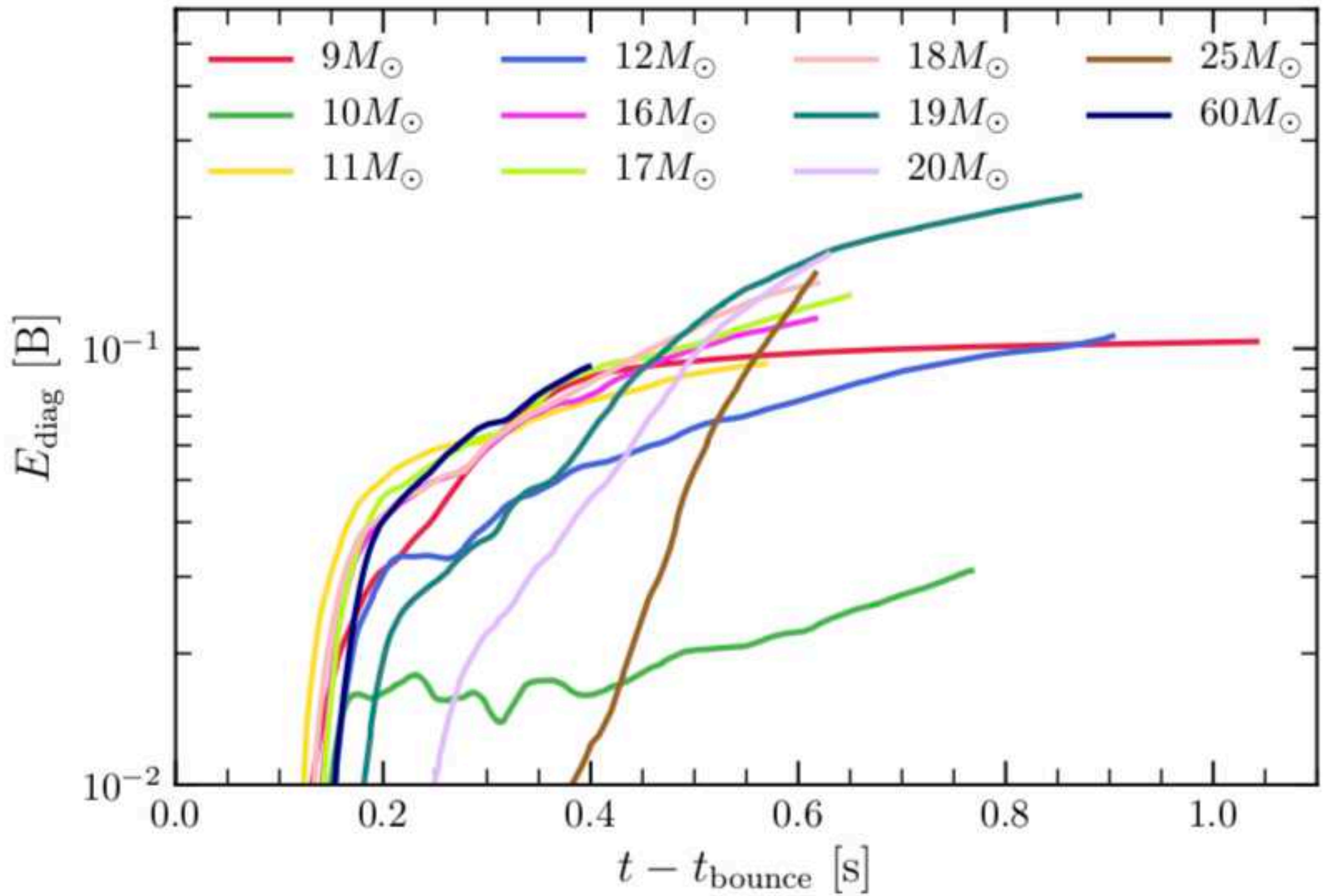
25-$M_\odot$

t = 0.010 s

60-$M_\odot$

Vartanyan et. al 2019a,b; Burrows et. al 2019 a,b; Radice et. al 2019

II. Exploding Stars Robustly

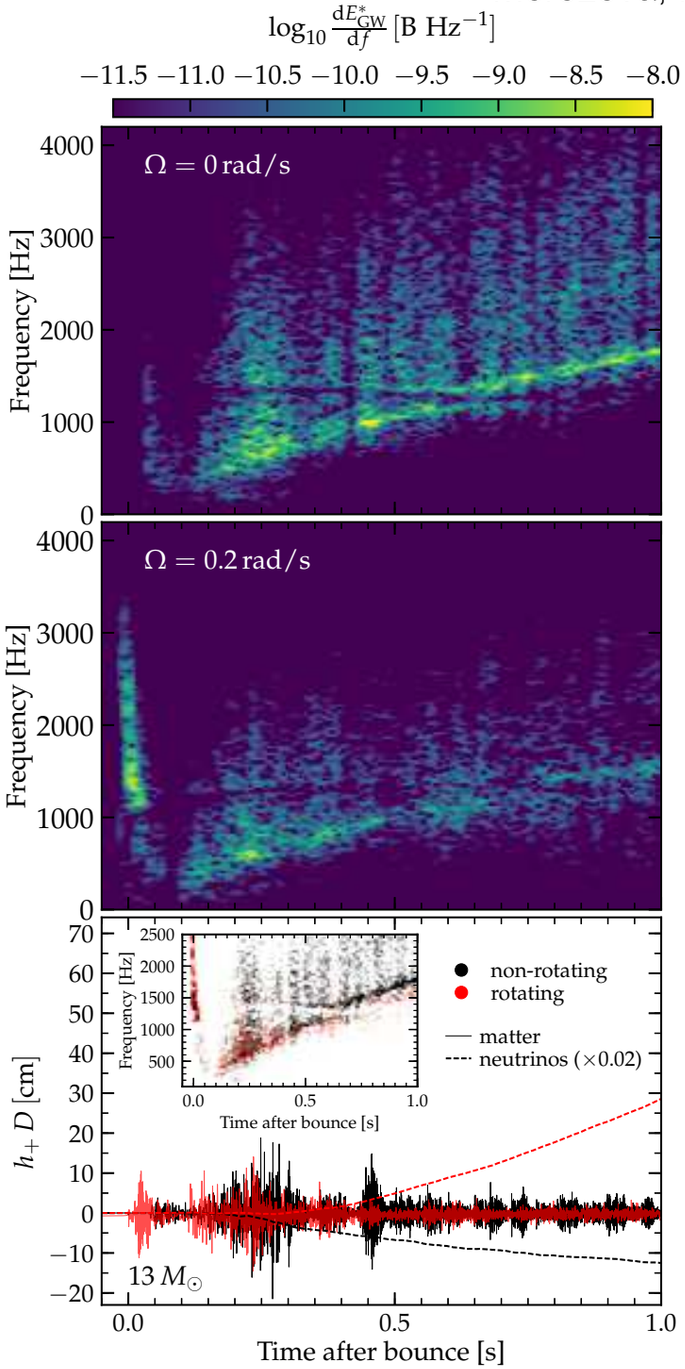


Energy growth rates from 0.25 to 1 Bethe per second

III. Exploding Stars Verifiably: Observational Signatures

GW

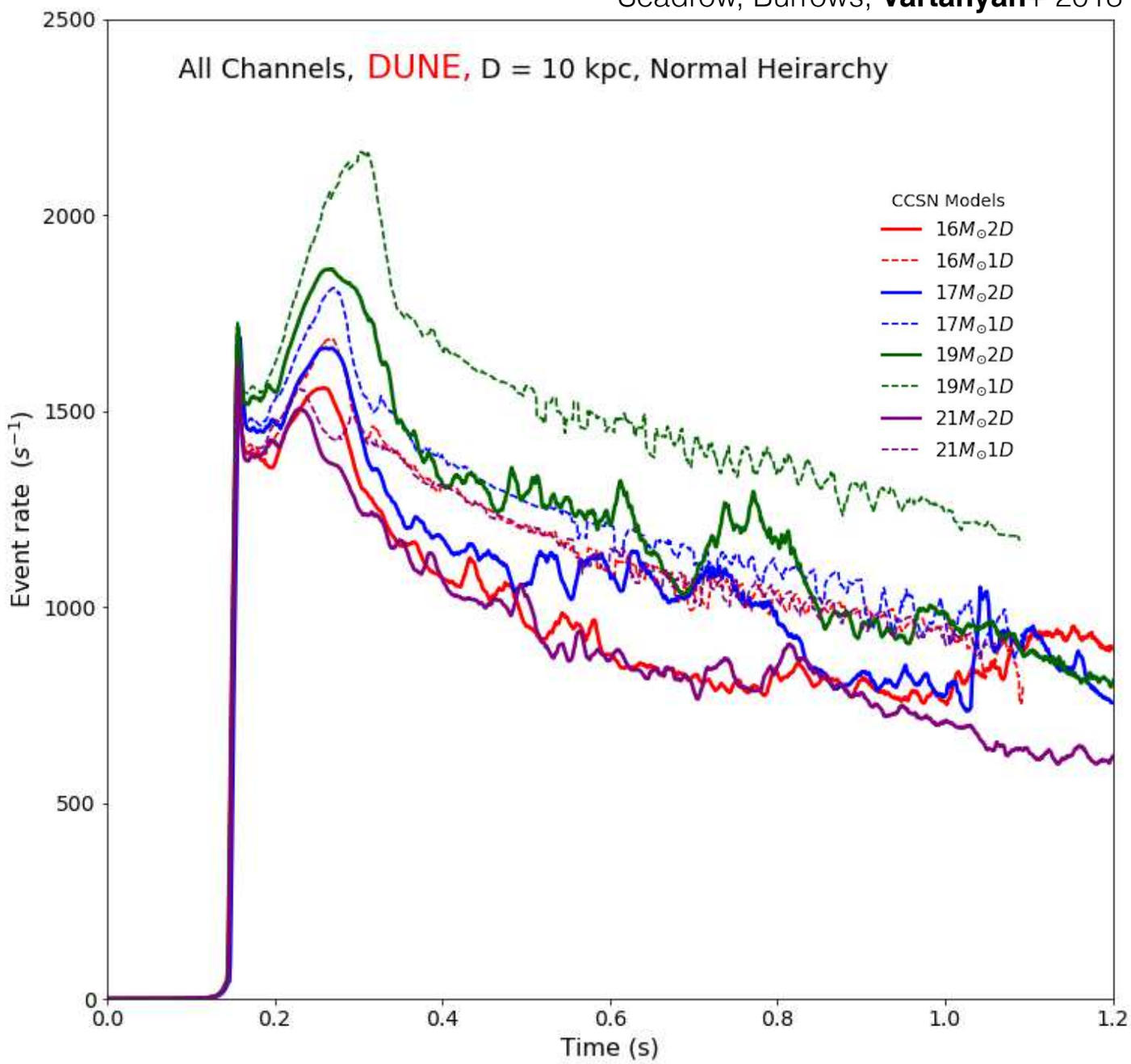
Morozova, Radice, Burrows, **Vartanyan+** 2018



GW within aLIGO's bandpass & threshold

Neutrinos

Seadrow, Burrows, **Vartanyan**+ 2018

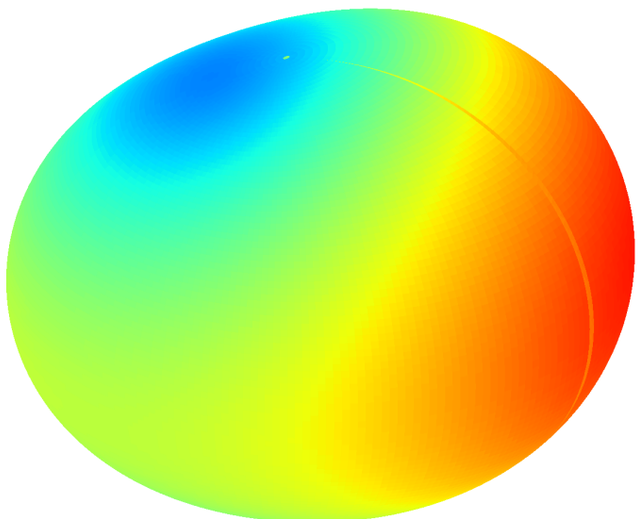


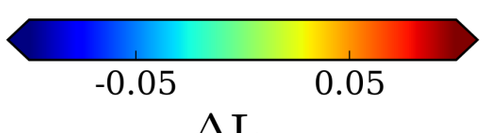
explosions have distinct **GW** & **neutrino** signals

L_{ν_e}-Viewing Angle Variation

Time = 0.21 s

25 $M_\odot$

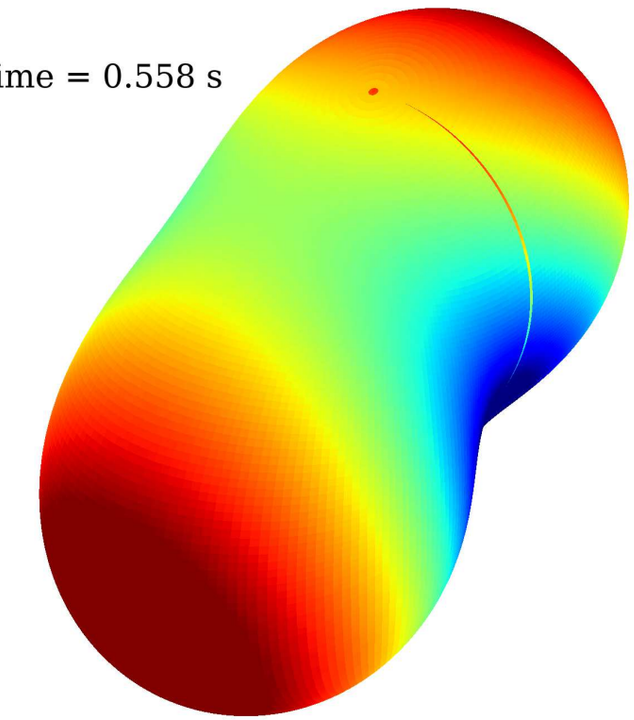




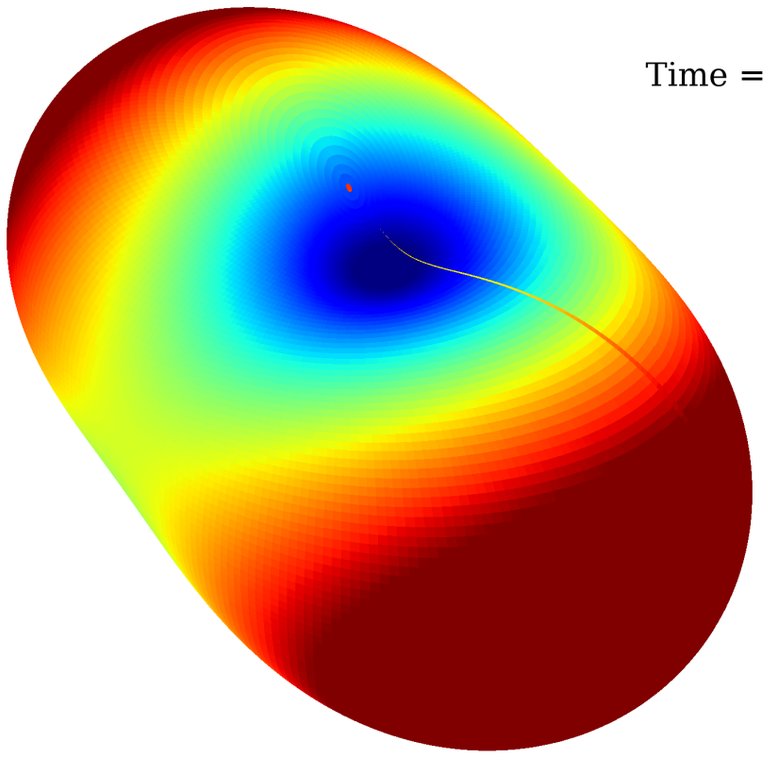
$\overline{\langle L_{\nu_e} \rangle}$

25-$M_\odot$

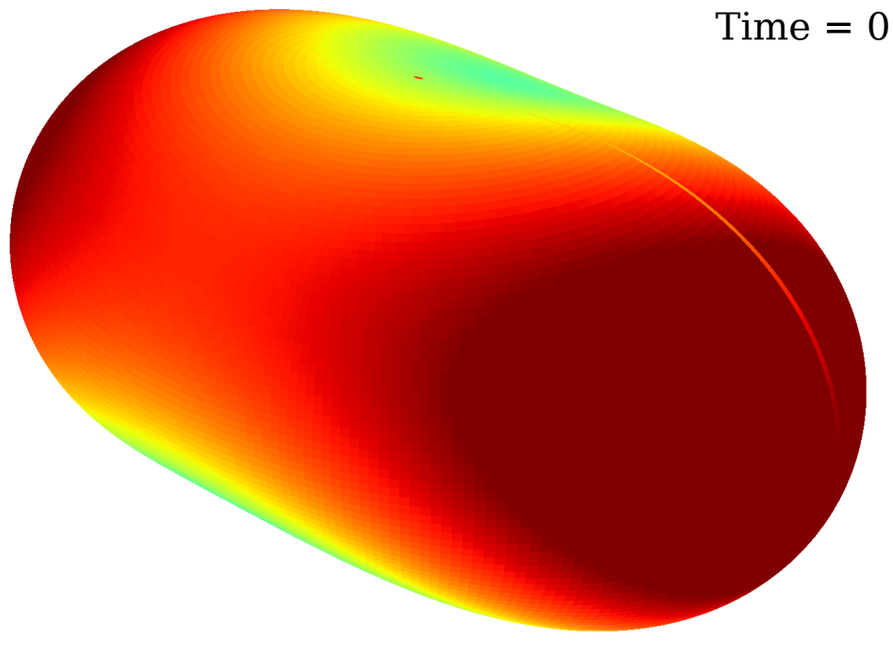
Time = 0.558 s



Time = 0.446 s

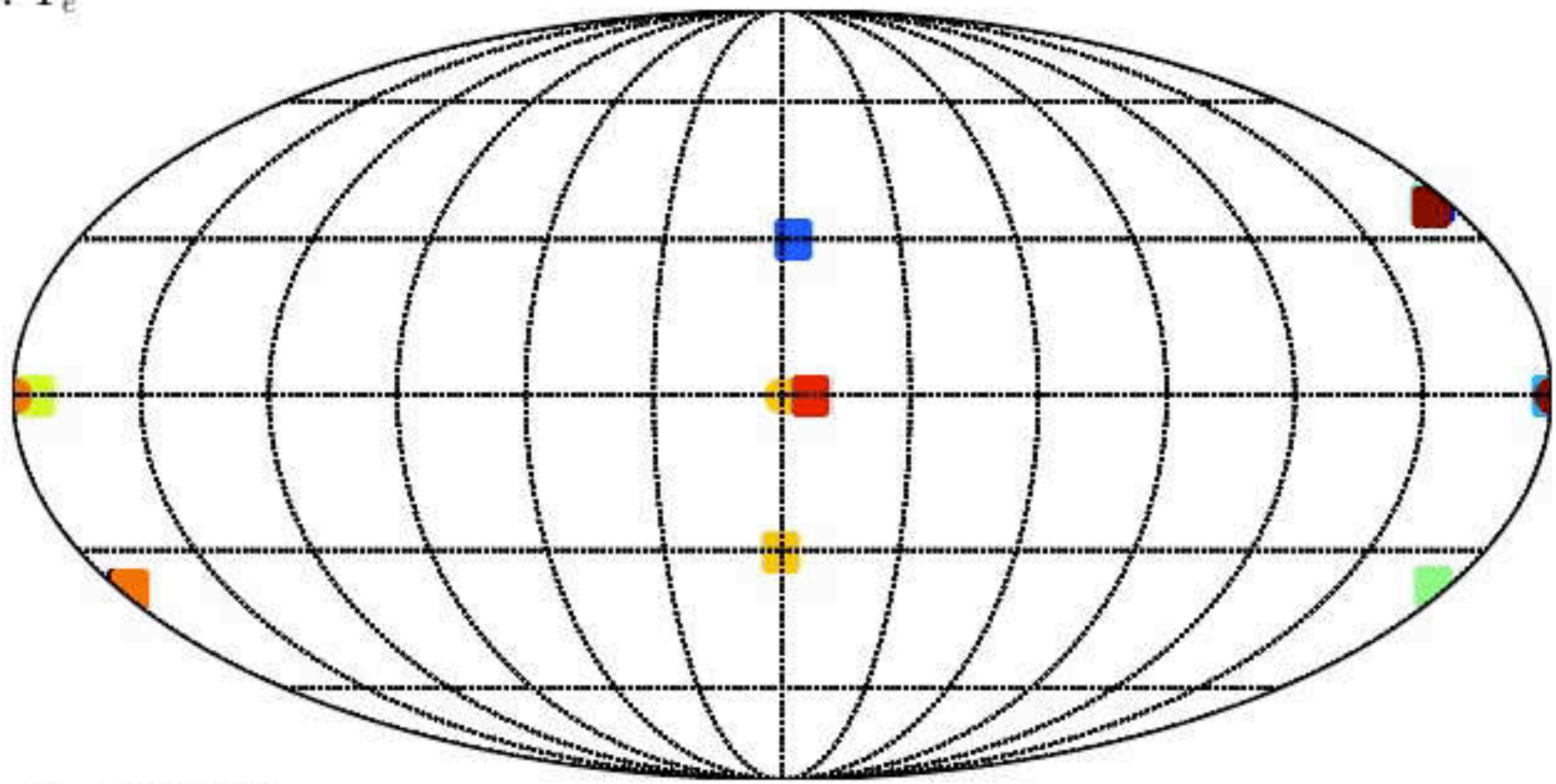


Time = 0.616 s



Vartanyan et. al 2019b

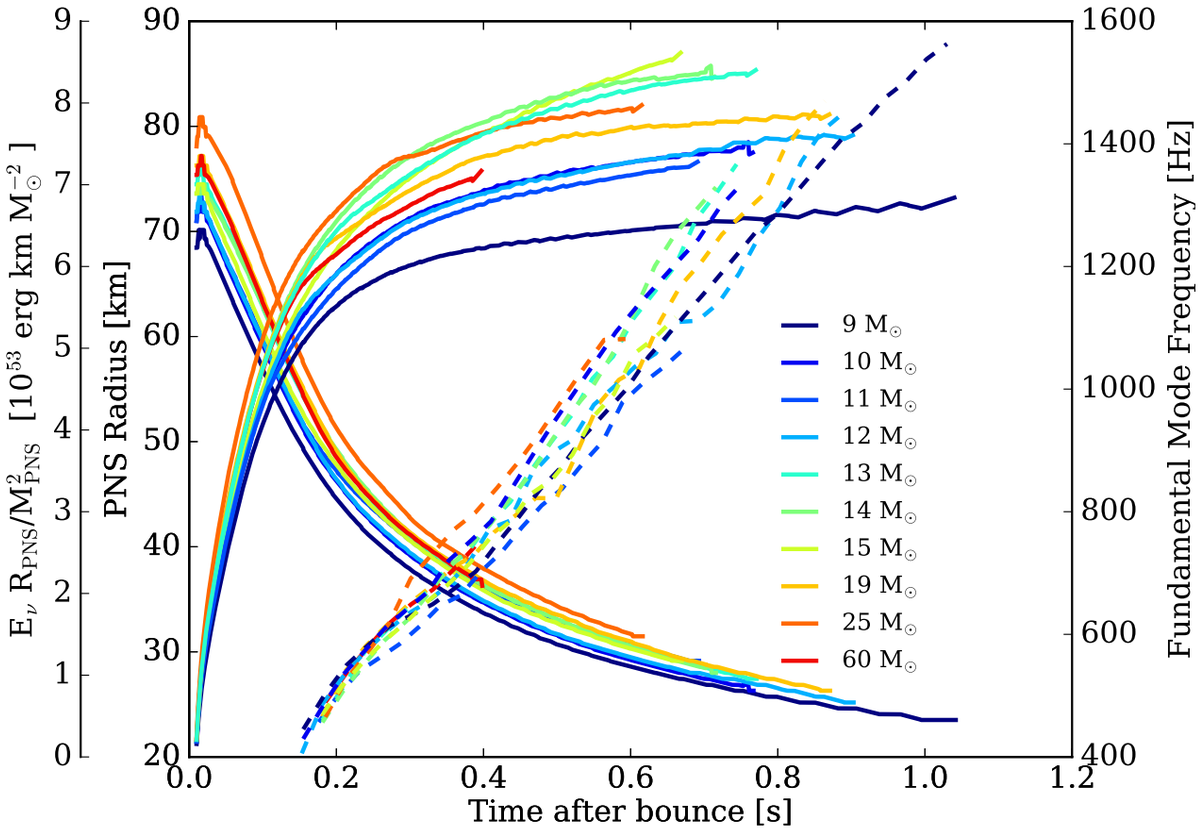
Square: LESA
Circle: Y_e



0.010 s

9 $M_\odot$
10 $M_\odot$
11 $M_\odot$
12 $M_\odot$
13 $M_\odot$
14 $M_\odot$
15 $M_\odot$
16 $M_\odot$
19 $M_\odot$
25 $M_\odot$
60 $M_\odot$

Gravitational Waves & Core Dynamics

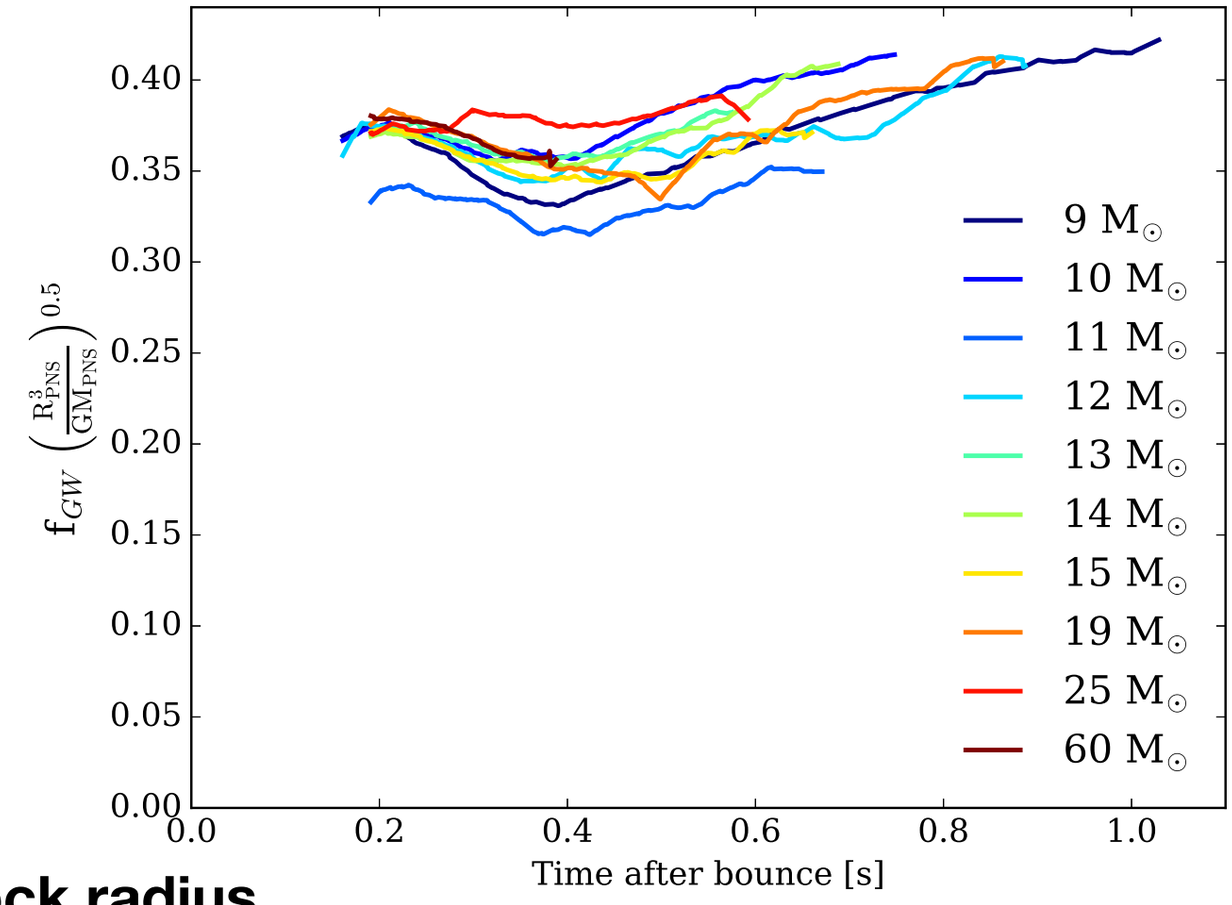


Fundamental Mode probes core density

Gravitational Waves

↓

PNS Radius



GW & Luminosity probe accretion rate;
Luminosity evolution also correlates with shock radius

Vartanyan et. al 2019b

Conclusions

Massive stars explode

More uncertainty in stellar evolution than in CCSNe

Conclusions, cont.

1) **Explosion != Progenitor Mass or Compactness**

2) **Sharp Si/O interface: More Explodable**

3) **Microphysics Matter**

4) **Explosions are Robust: Energy Growth rates up to 1 Bethe/s**

5) **Higher Resolution: More Explodable**

Neutrino and GW signatures constrain core properties and explosion dynamics

Future Work

- Pre-CCSNe:

  binary progenitors + progenitor physics

- Simulation physics

  axial-vector & vector Many-body

  corrections (charged & neutral current) with

  self-consistent EoS + opacities,

  B fields + rotation

- Post-CCSNe:

  Pulsar kicks, Black Hole Formation,

  Nucleosynthesis

- Multi-second simulation with

  3D progenitor code result comparison

  with multi-messenger astrophysics

