Criteria for Core-collapse Supernova Explosions by the Neutrino Mechanism

by

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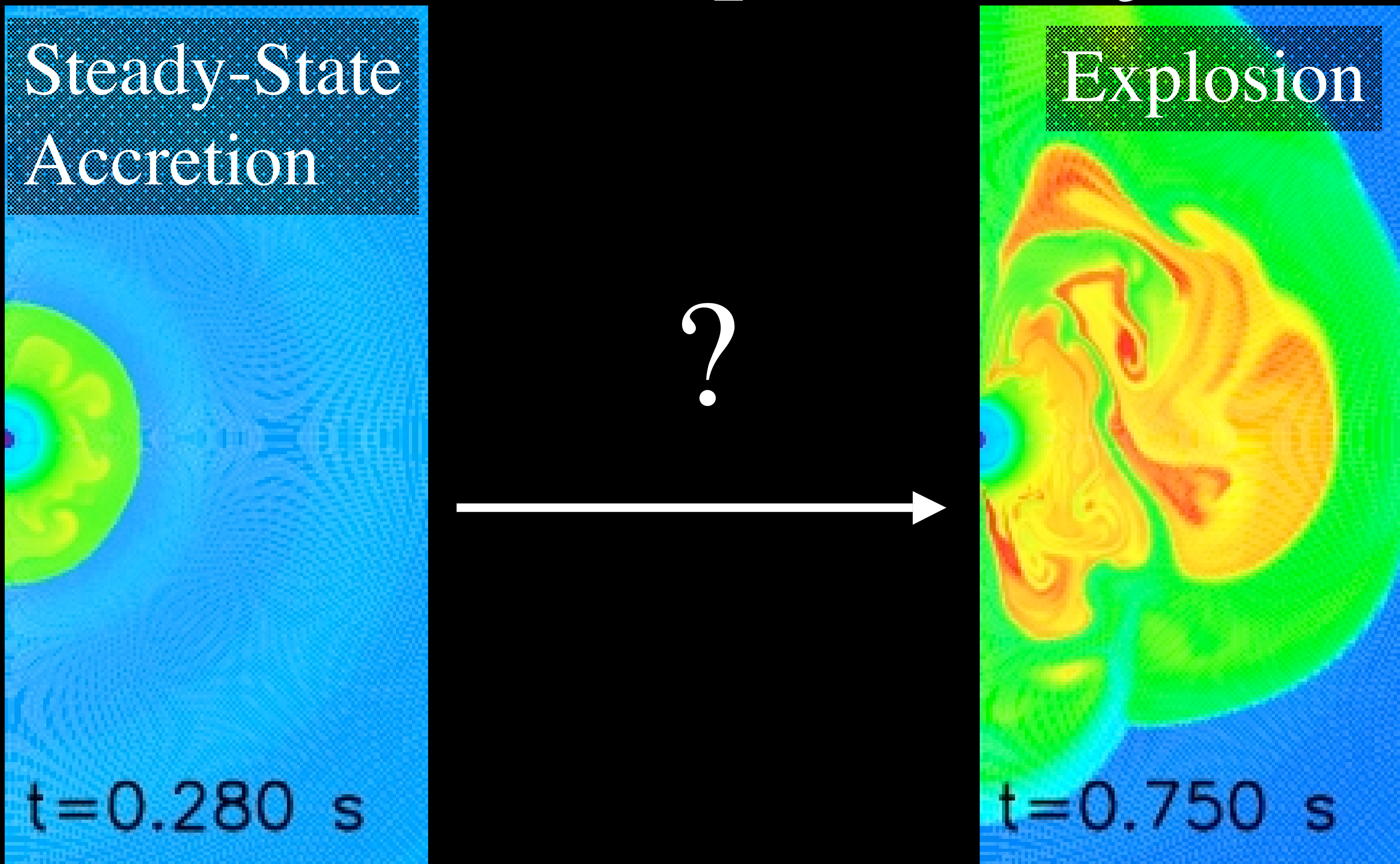
- Prompt Mechanism (~‘80s)
- Delayed neutrino-mechanism (Bethe & Wilson ‘85)
- 1D detailed radiation-hydrodynamics (80’s, 90’s, &Today)
    - No explosions
- 2D hydro & various approx. of transport (90’s & Today)
    - Convection
    - SASI (Advective-Acoustic Mechanism?)
- Only least massive of massive stars explode
- Nature suggests many more
- What is missing?
    - Rotation, MHD?
    - Acoustic-powered Mechanism?
      (SASI + core oscillations)
    - 3D?

Fundamental Question of Core-Collapse Theory



And why is it easier to explode in 2D compared to 1D?

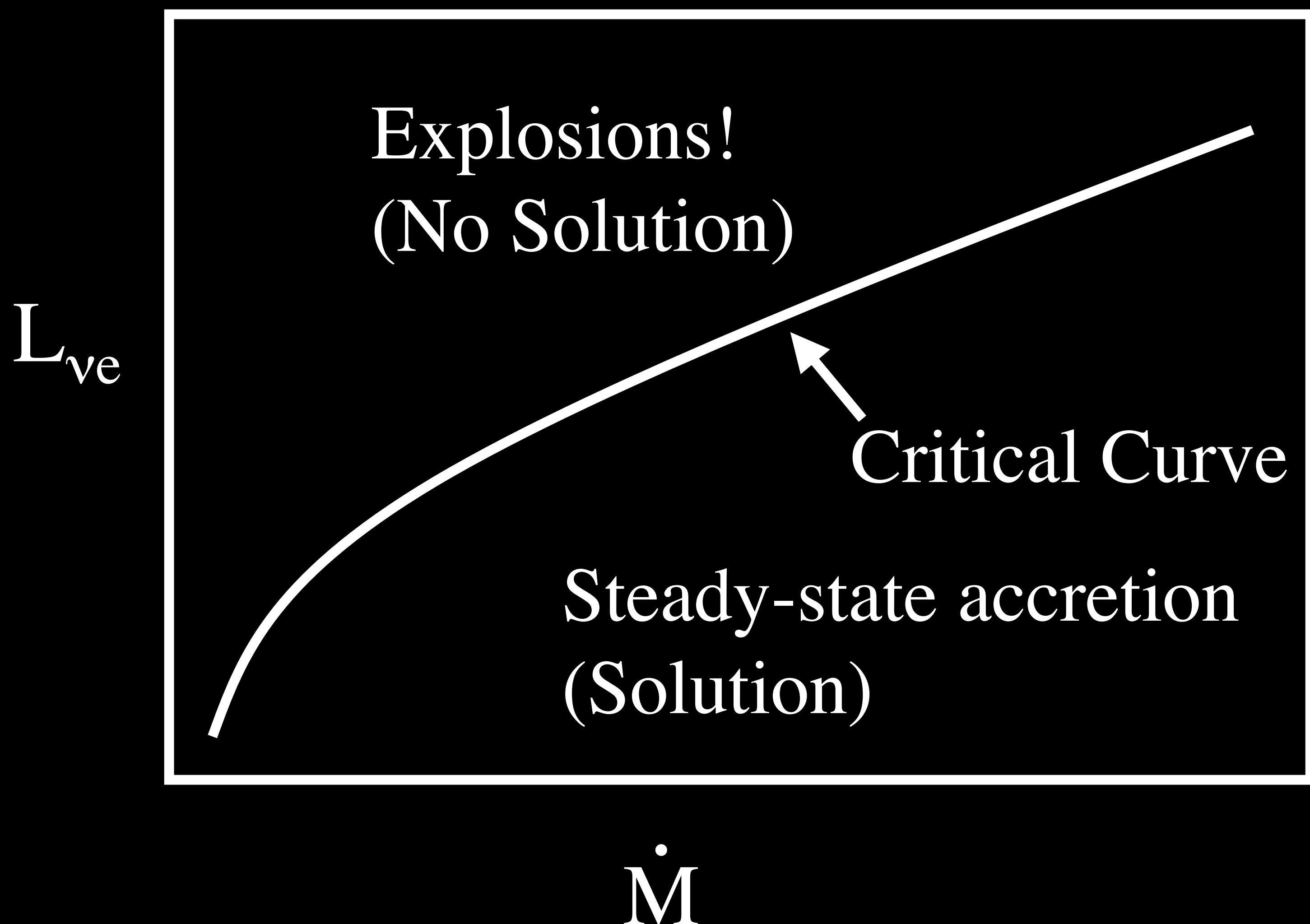
Two Paths to the Solution

- Detailed 3D radiation-hydrodynamic simulations
  ("Accurate" energies, NS masses, nucleo., etc.)

- Parameterizations that capture essential physics
  (Tease out fundamental mechanisms)

Burrows & Goshy ‘93

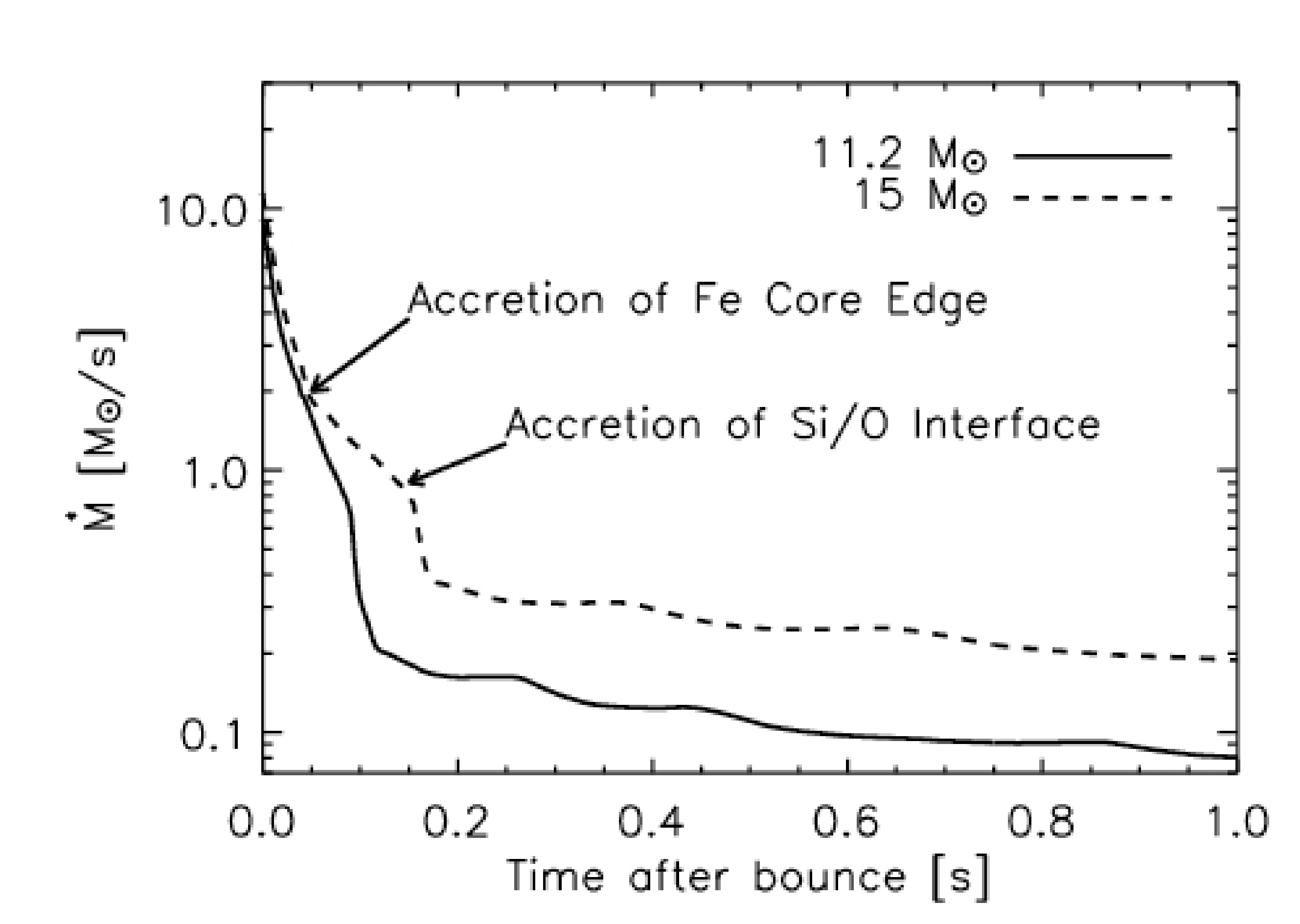
Steady-state solution (ODE)



Conditions for Explosions by the Neutrino Mechanism

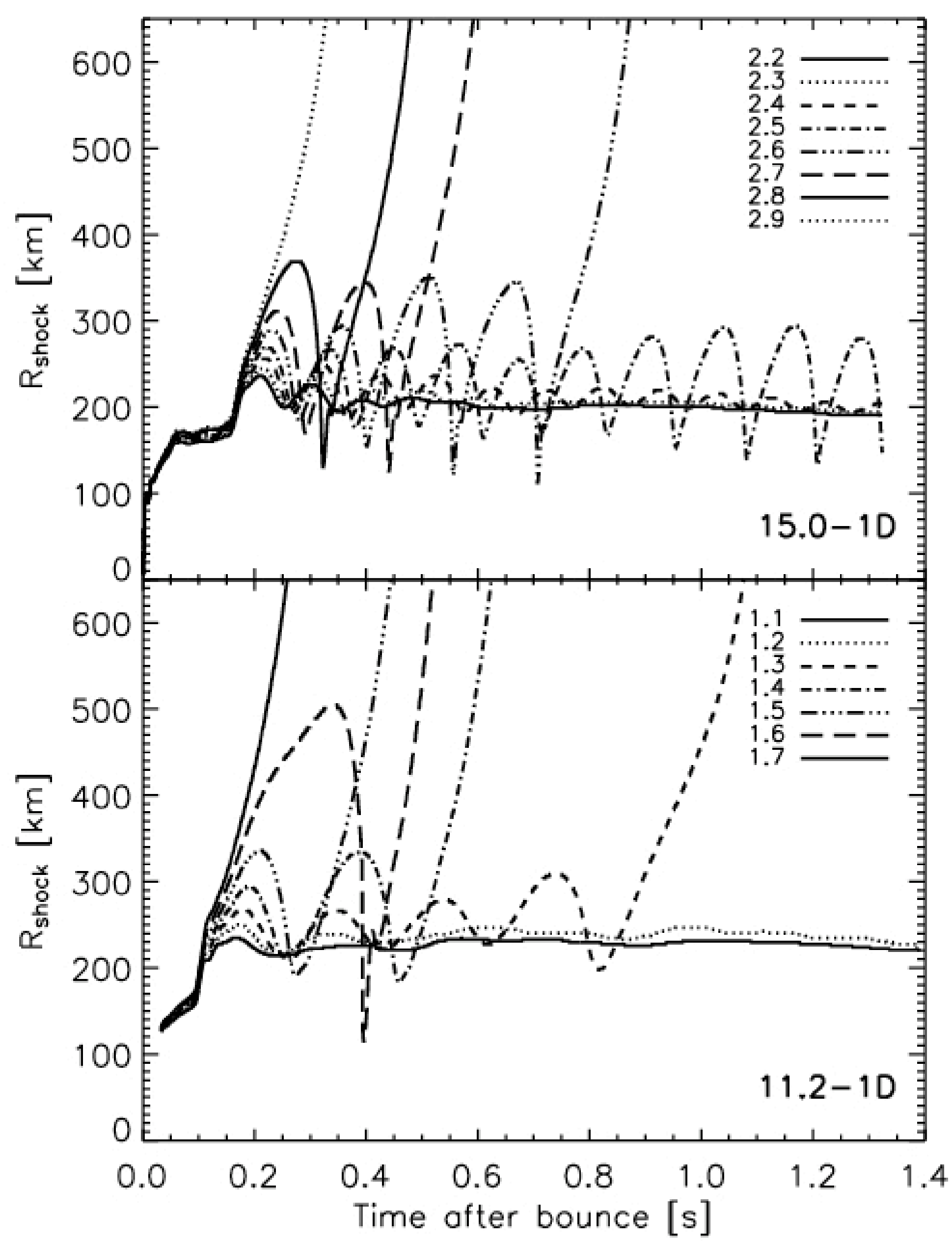
Parameter Study

- Neutrino Luminosity (Local heating and cooling)
- 1D, 2D (90^{o} and 180^{o})
- 11.2 and 15 $M_{\odot}$ (range of accretion rates)
- Resolution
- ~100 simulations

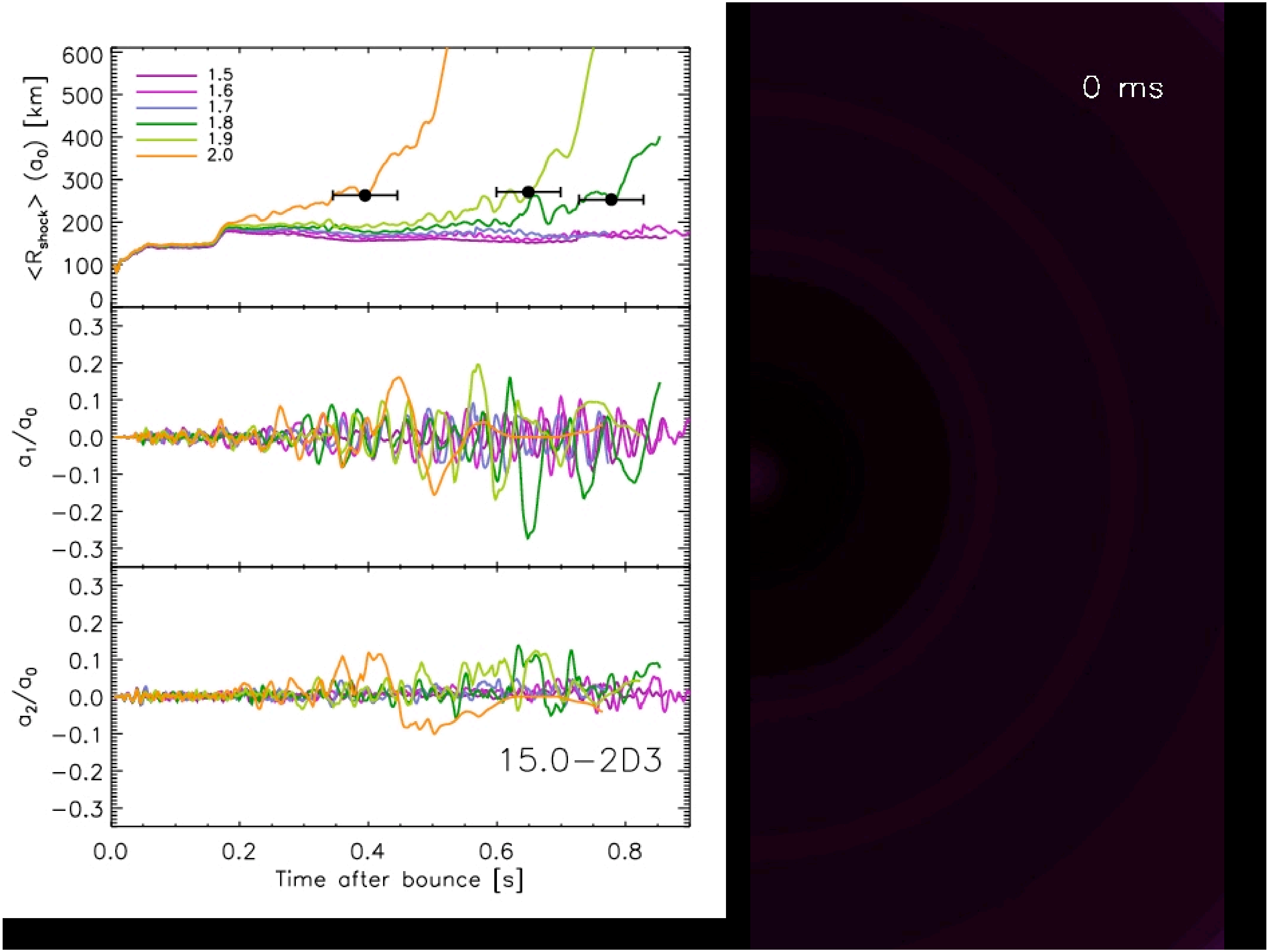

11.2 M⊙
15 M⊙
Accretion of Fe Core Edge
Accretion of Si/O Interface
10.0
1.0
0.1
Ṁ [M⊙/s]
0.0
0.2
0.4
0.6
0.8
1.0
Time after bounce [s]

Is a critical luminosity relevant in hydrodynamic simulations?

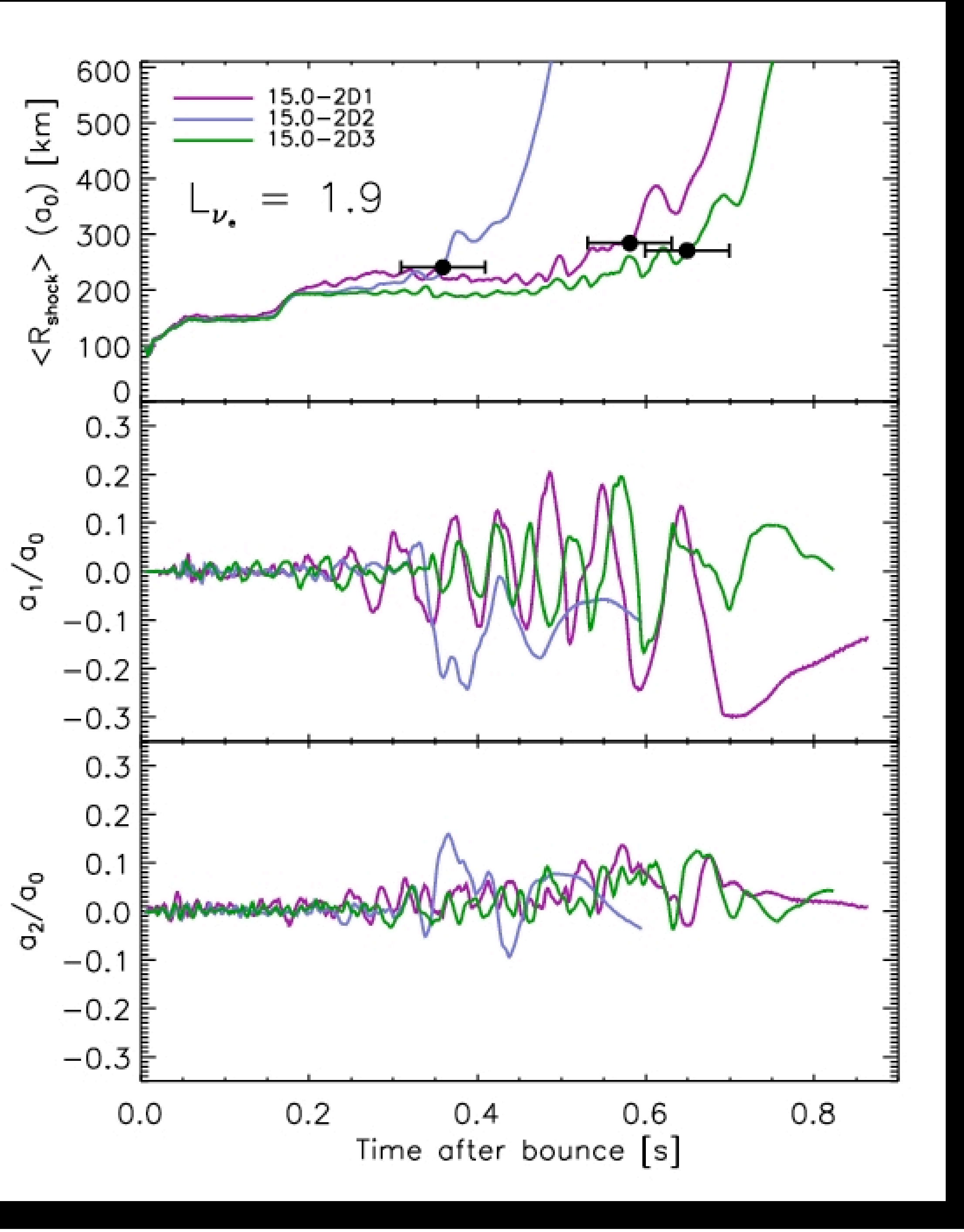
- 1D
- 2D Convection and SASI?



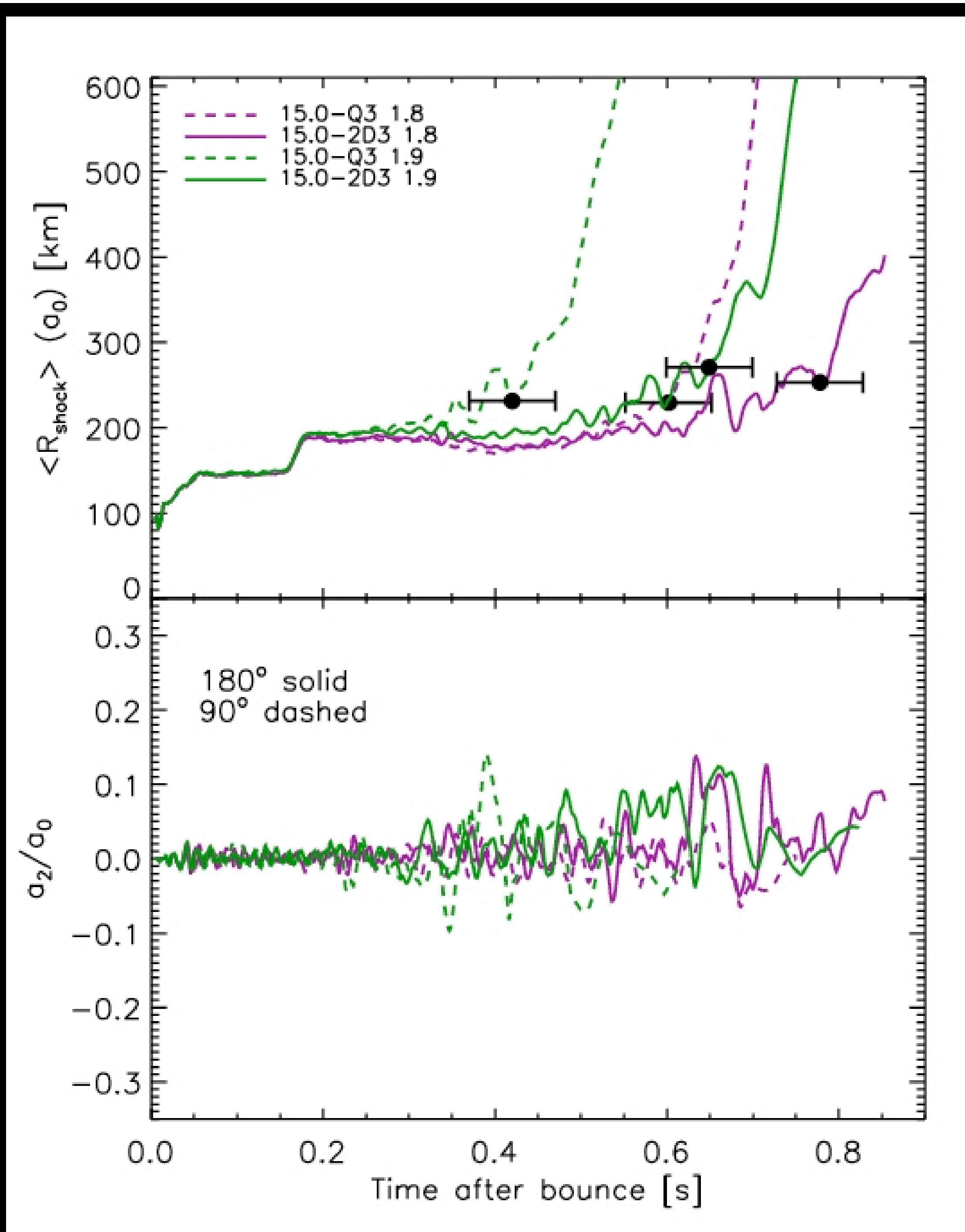
600
500
400
300
200
100
0
R_{shock} [km]
2.2
2.3
2.4
2.5
2.6
2.7
2.8
2.9
15.0−1D
1.1
1.2
1.3
1.4
1.5
1.6
1.7
11.2−1D
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Time after bounce [s]



1.5
1.6
1.7
1.8
1.9
2.0
$\langle R_{shock} \rangle$ (a_0) [km]
a_1/a_0
a_2/a_0
15.0−2D3
Time after bounce [s]
0 ms

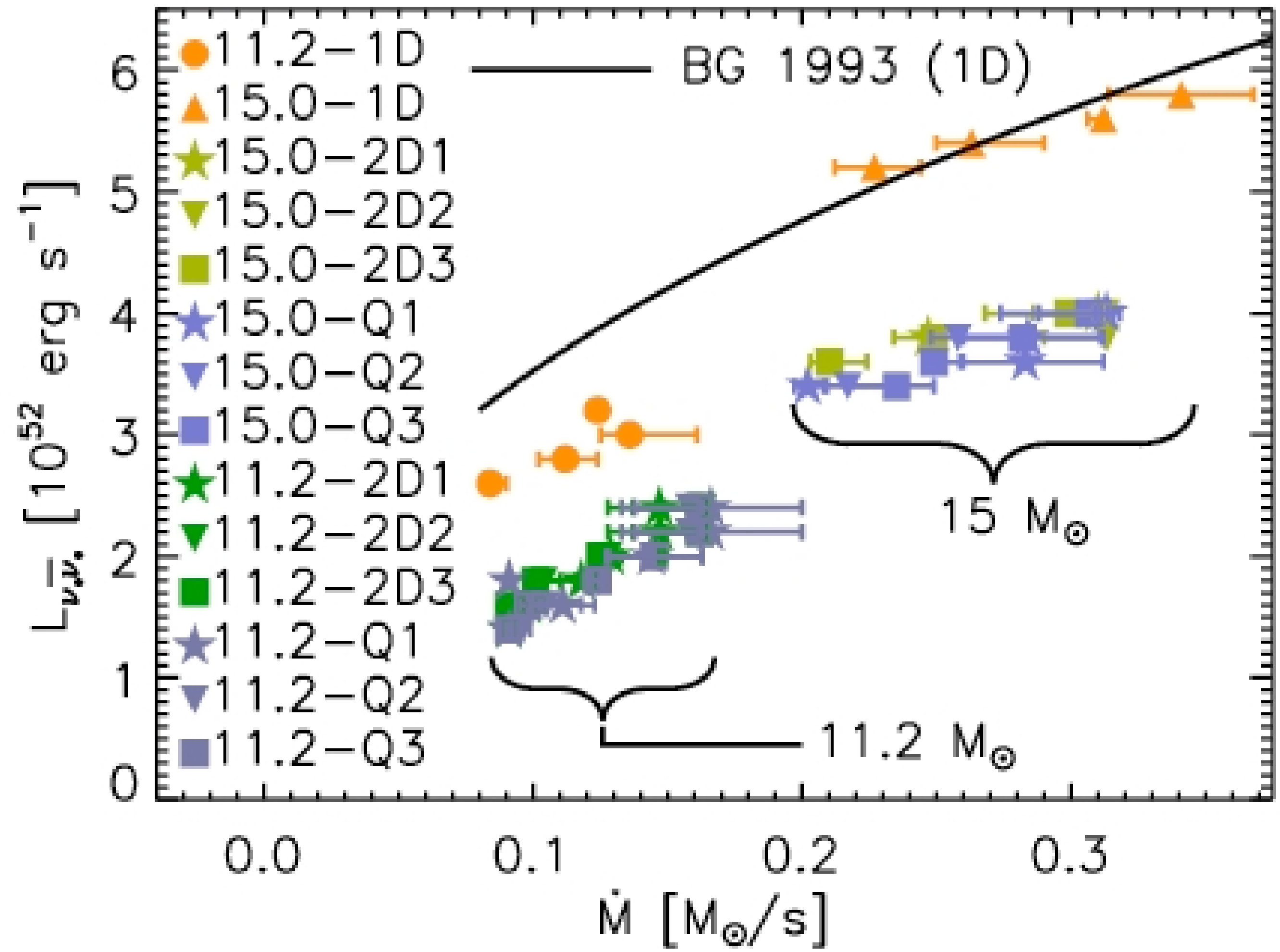


15.0−2D1
15.0−2D2
15.0−2D3
L_{ν_e} = 1.9
$\langle R_{shock} \rangle$ (a_0) [km]
a_1/a_0
a_2/a_0
Time after bounce [s]



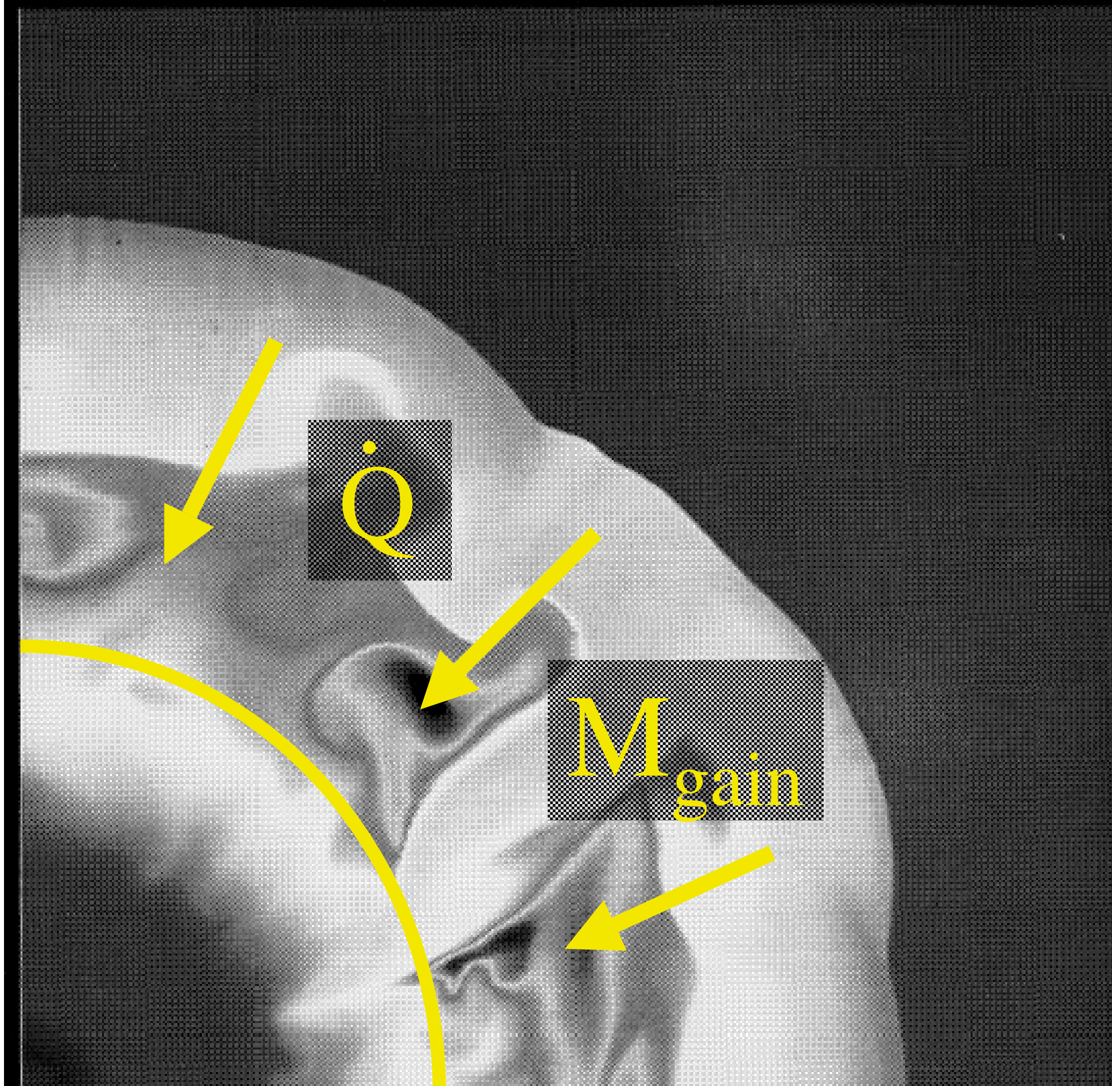
15.0−Q3 1.8
15.0−2D3 1.8
15.0−Q3 1.9
15.0−2D3 1.9
<R_shock> (a_0) [km]
600
500
400
300
200
100
0
180° solid
90° dashed
a_2/a_0
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
0.0
0.2
0.4
0.6
0.8
Time after bounce [s]

How do the critical luminosities differ between 1D and 2D?


11.2−1D
15.0−1D
15.0−2D1
15.0−2D2
15.0−2D3
15.0−Q1
15.0−Q2
15.0−Q3
11.2−2D1
11.2−2D2
11.2−2D3
11.2−Q1
11.2−Q2
11.2−Q3
BG 1993 (1D)
15 $M_\odot$
11.2 $M_\odot$
$L_{\nu_e\bar{\nu}_e}$ [10^{52} erg s^{-1}]
$\dot{M}$ [$M_\odot$/s]
0
1
2
3
4
5
6
0.0
0.1
0.2
0.3

Why is critical luminosity of 2D simulations ~70% of 1D?

Conditions during Explosion

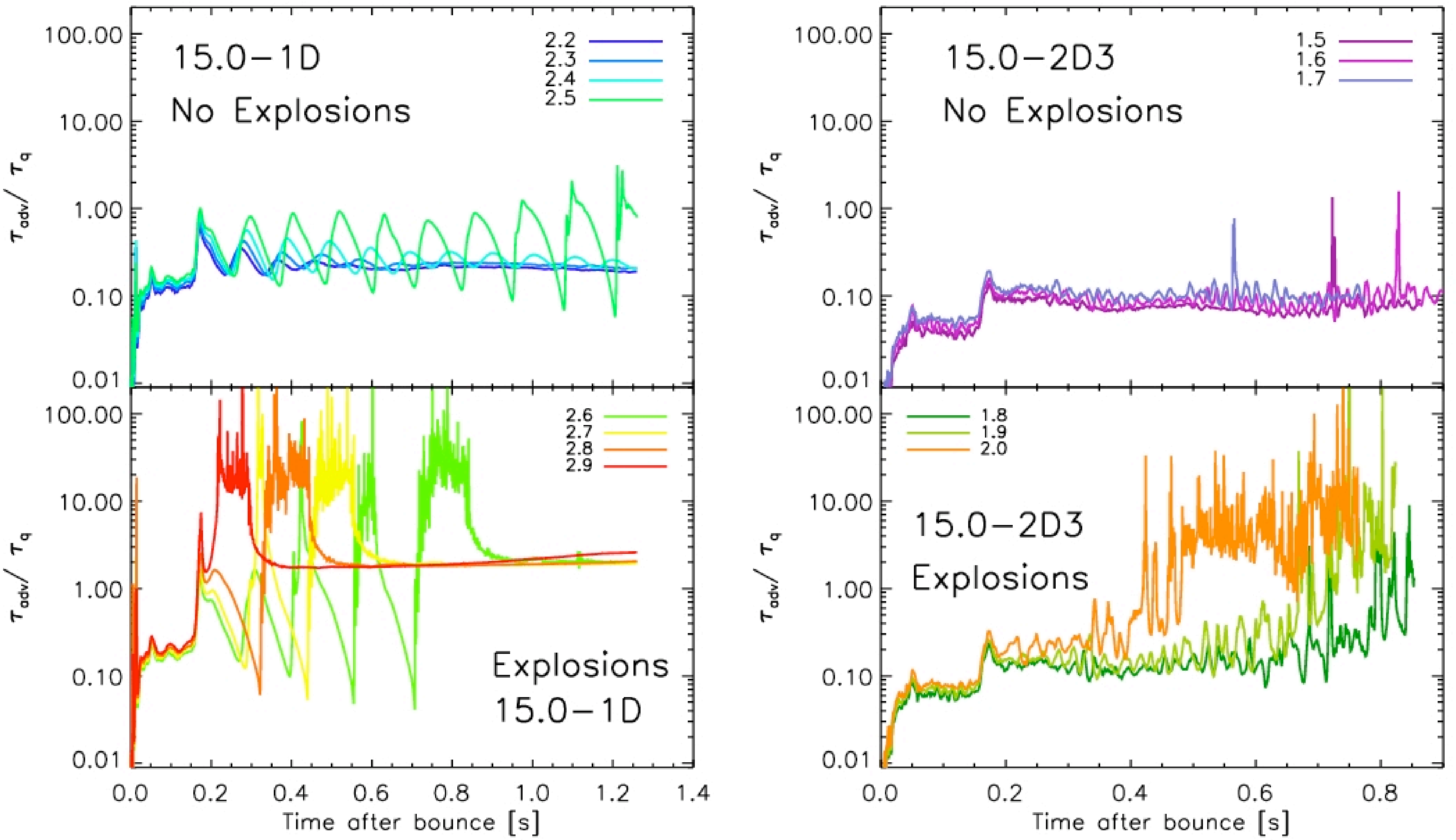


$$\tau_{adv} = \frac{\Delta r_{gain}}{v_r}$$

$$\tau_q = \frac{E}{\dot{Q}}$$

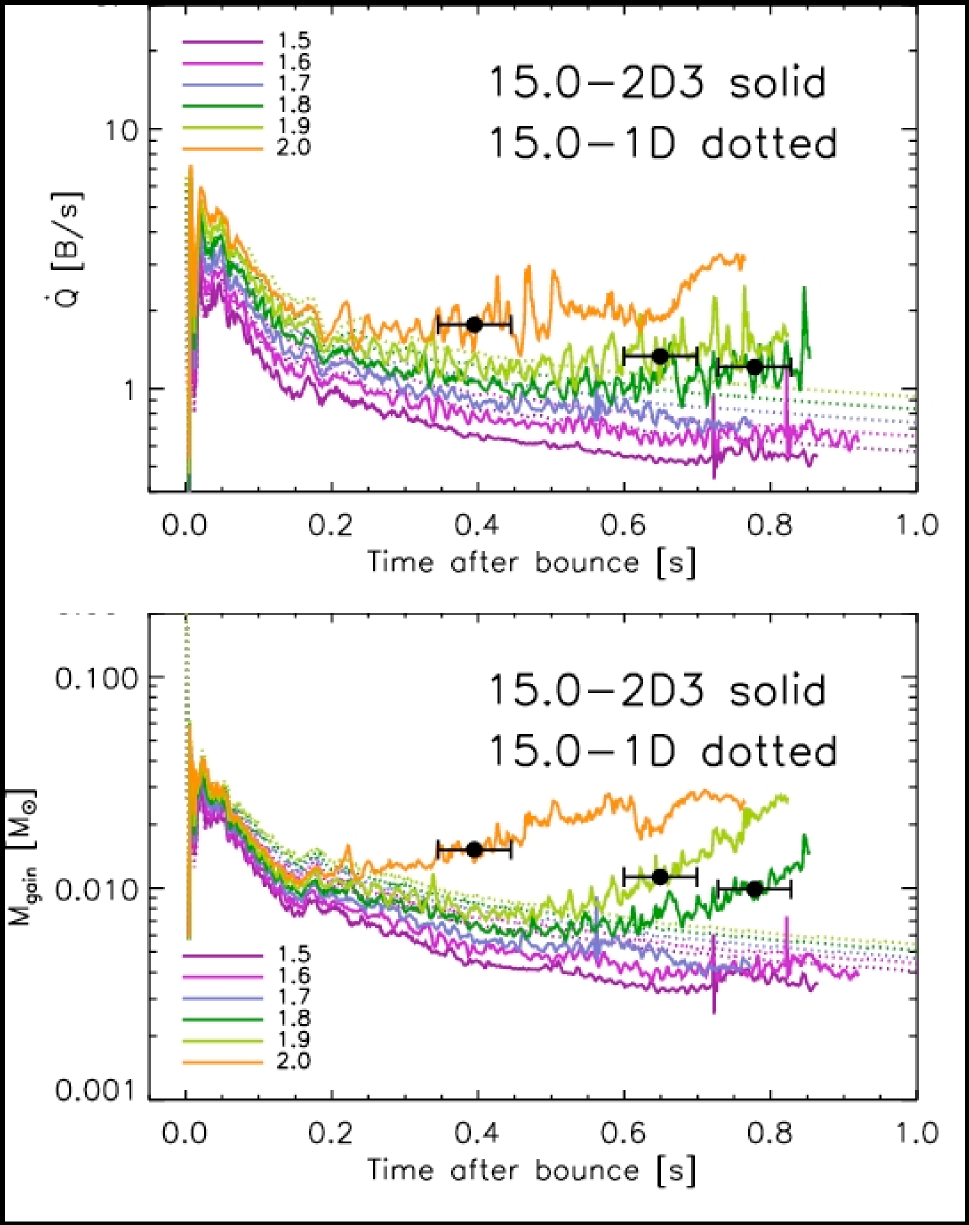
$$\frac{\tau_{adv}}{\tau_q} \gtrsim 1$$

[redacted]

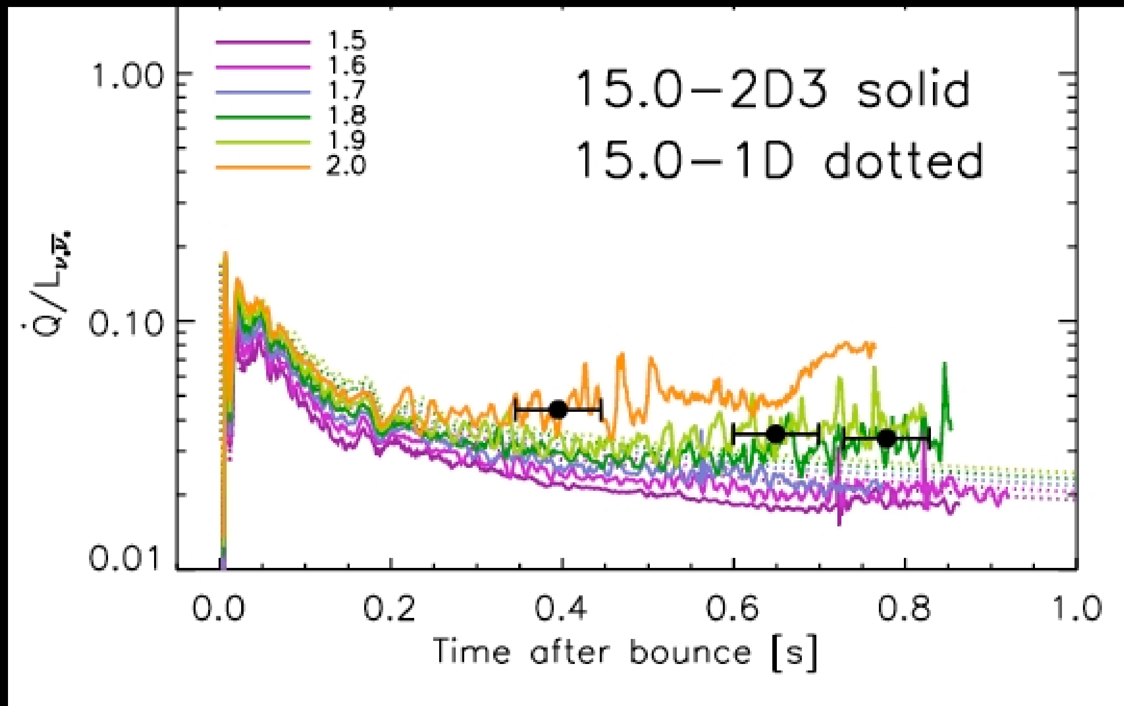


[redacted]

1D vs. 2D

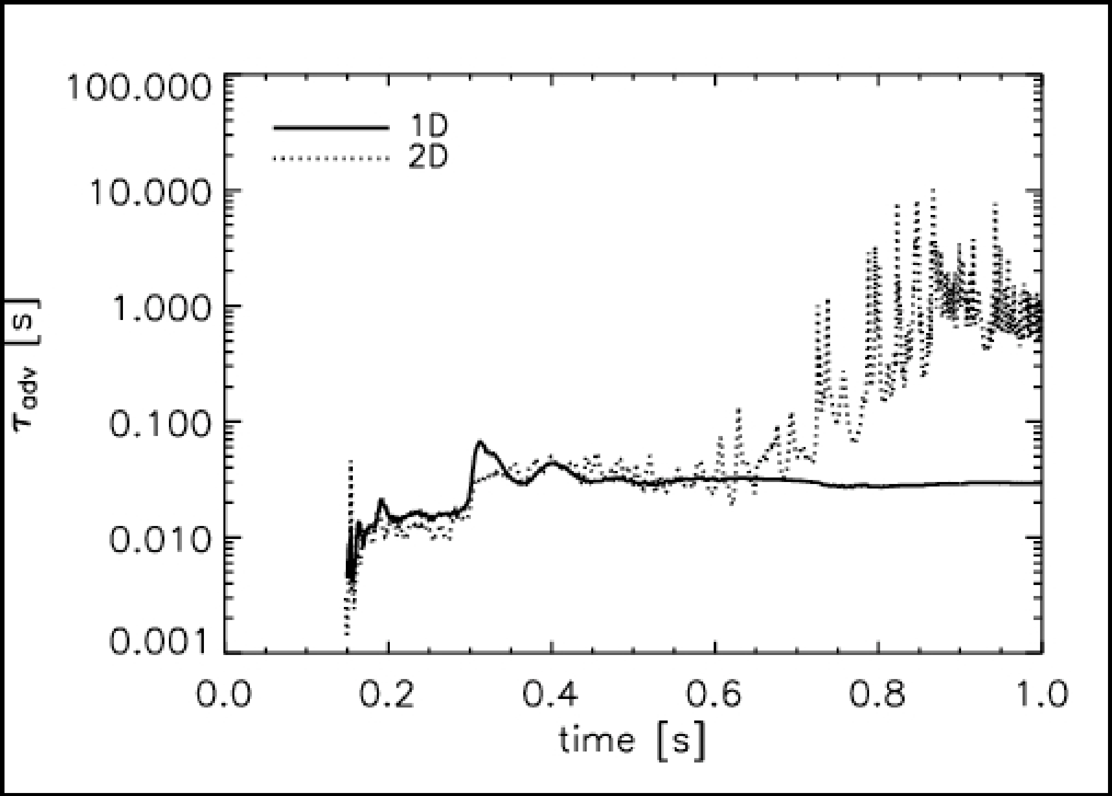


1.5
1.6
1.7
1.8
1.9
2.0
15.0−2D3 solid
15.0−1D dotted
$\dot{Q}$ [B/s]
10
1
0.0
0.2
0.4
0.6
0.8
1.0
Time after bounce [s]
15.0−2D3 solid
15.0−1D dotted
M_{gain} [$M_\odot$]
0.100
0.010
0.001
1.5
1.6
1.7
1.8
1.9
2.0
0.0
0.2
0.4
0.6
0.8
1.0
Time after bounce [s]


1.5
1.6
1.7
1.8
1.9
2.0
15.0−2D3 solid
15.0−1D dotted
1.00
0.10
0.01
$\dot{Q}/L_{\nu_e\bar{\nu}_e}$
0.0
0.2
0.4
0.6
0.8
1.0
Time after bounce [s]

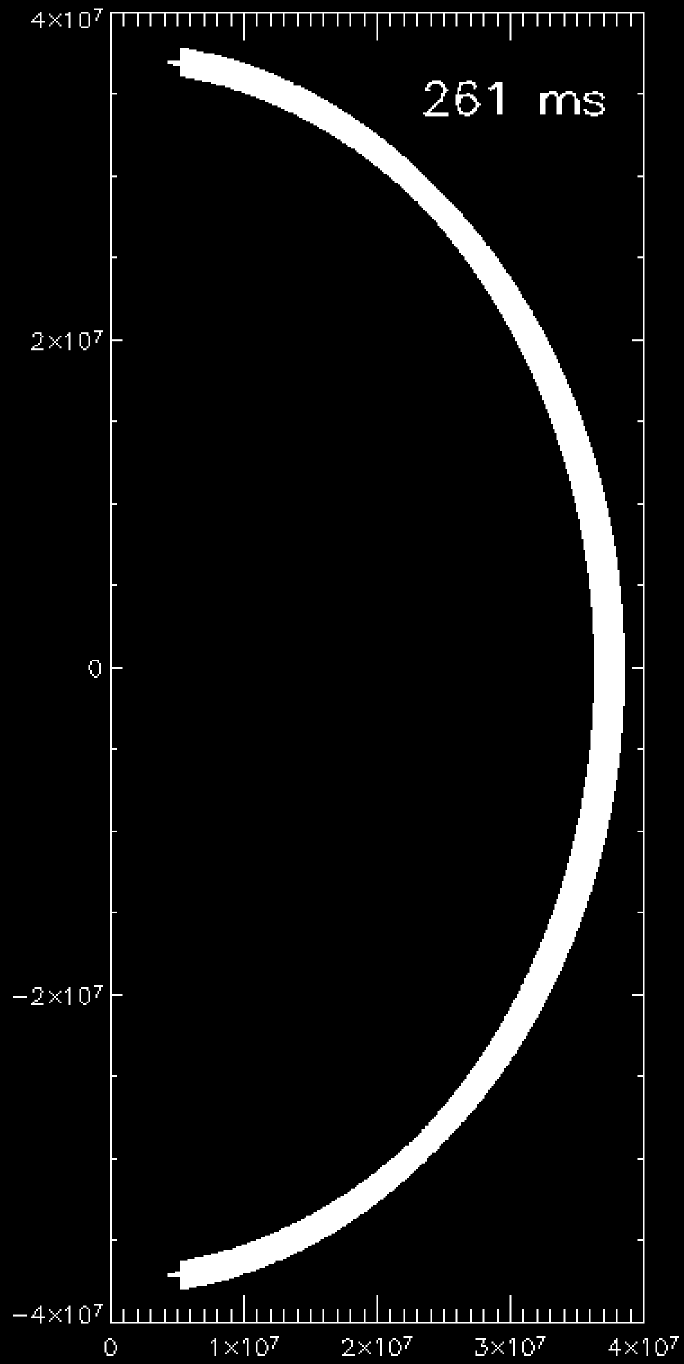
Why?

Average Advection Timescale



$$\langle v_r \rangle = \frac{\dot{M}}{4\pi r^2 \rho}$$

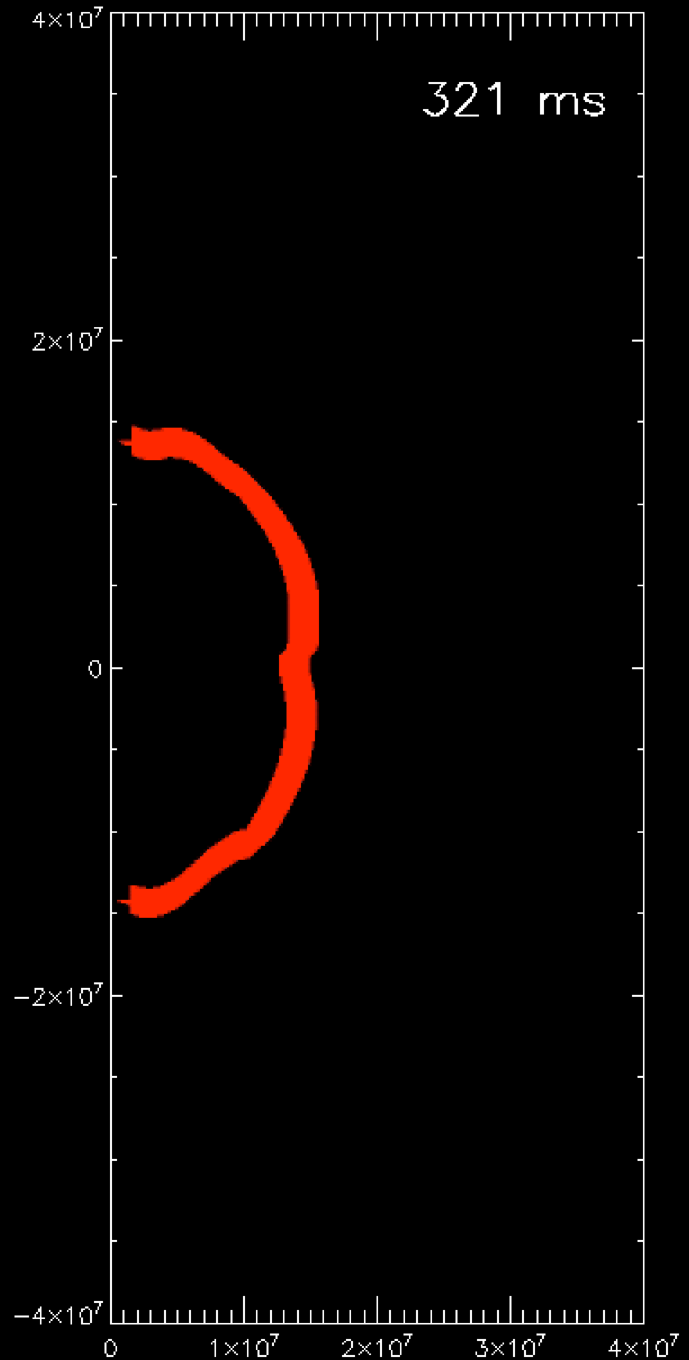
$$\tau_{adv} = \frac{\Delta r_{gain}}{v_r}$$



Distribution of Residence Times

- 50,000 tracer particles at 400 km (outside of shock)
- Follow trajectories for 150 ms
- White = exterior to shock
- Red = net heating
- Blue = net cooling
- Distribution of τ_r

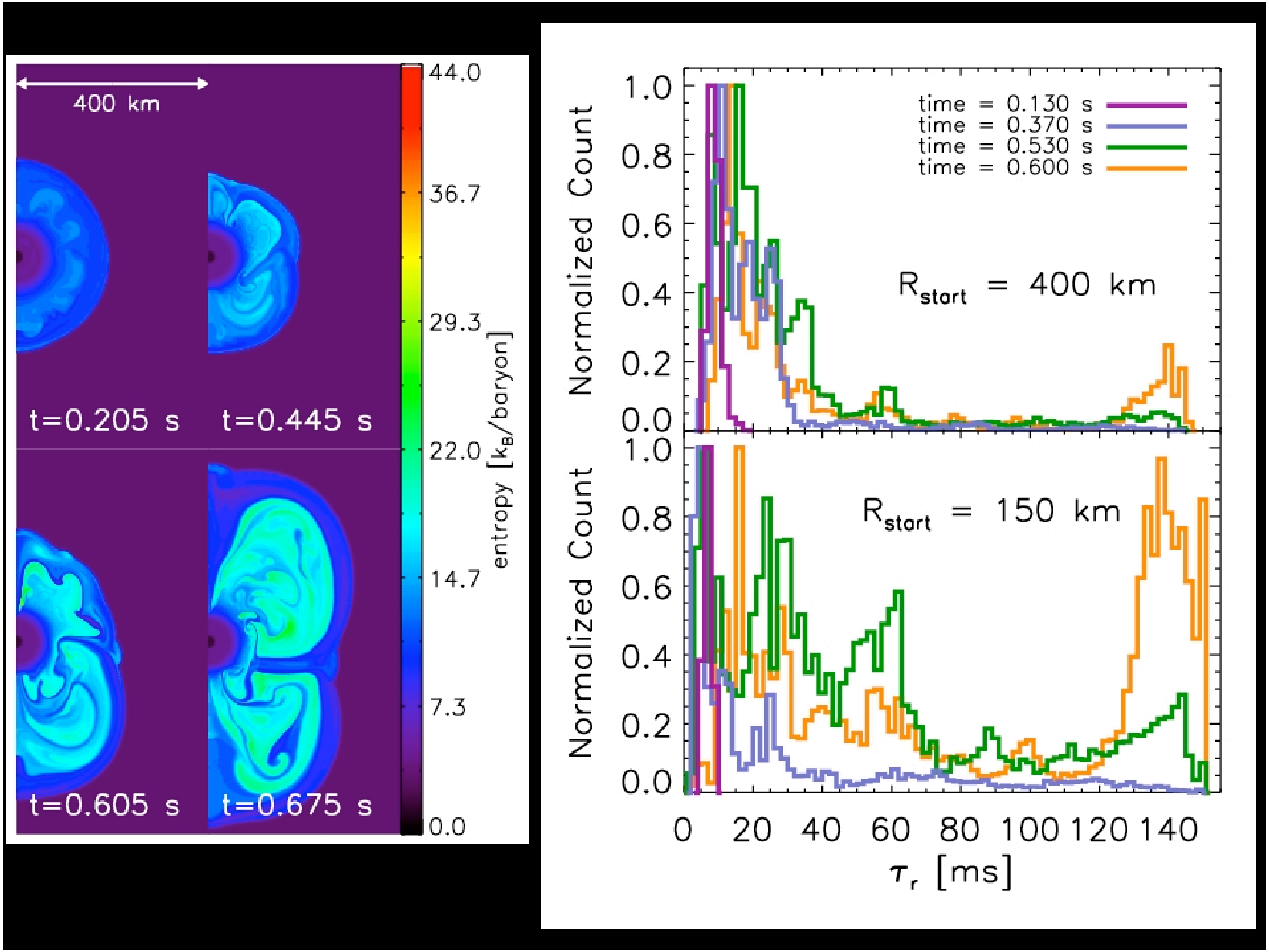
- Most accrete through gain region quickly



Distribution of Residence Times

- 50,000 tracer particles at 150 km (inside gain region)
- Follow trajectories for 150 ms
- White = exterior to shock
- Red = net heating
- Blue = net cooling
- Distribution of τ_r

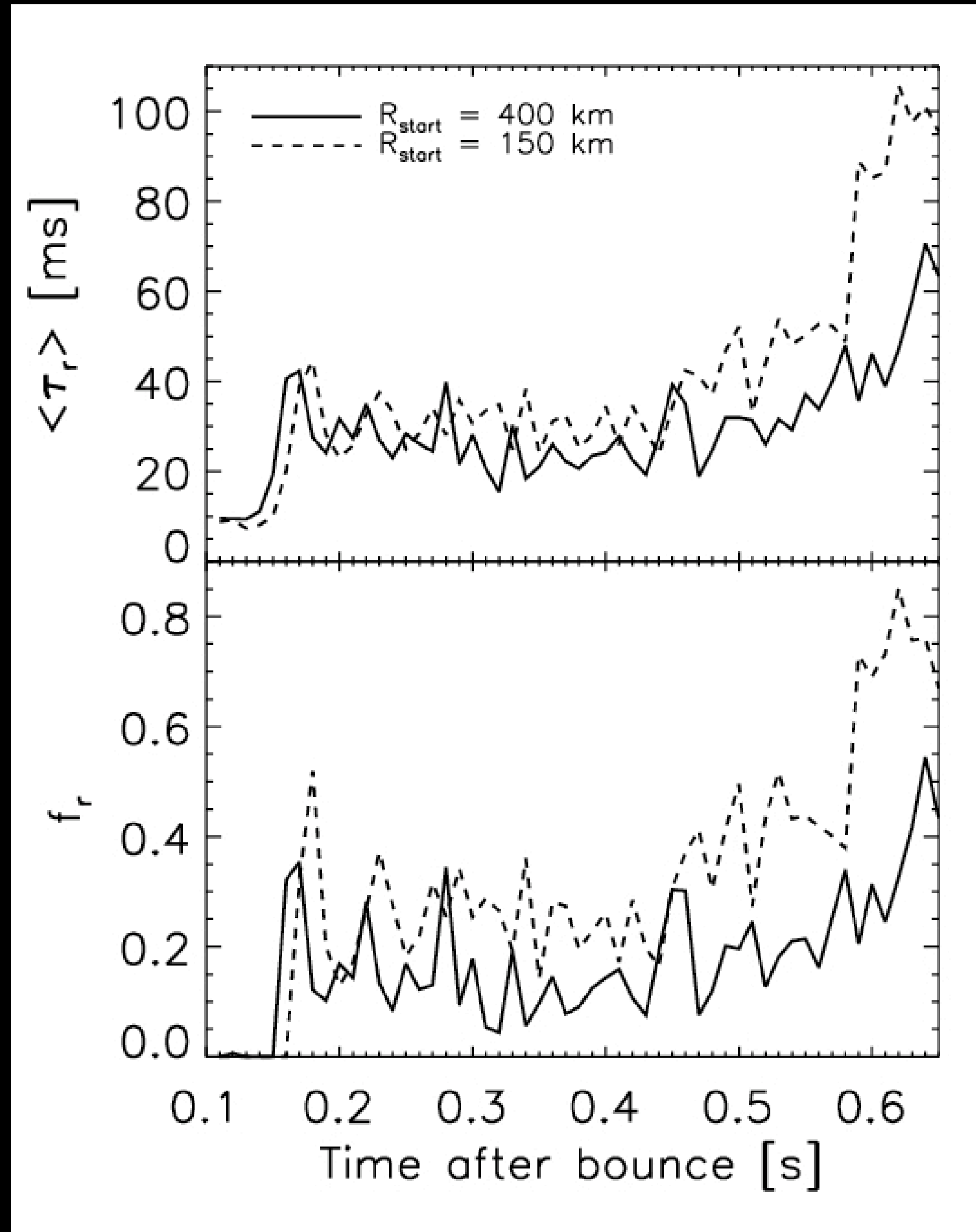
- A larger fraction have longer dwell times



400 km
t=0.205 s
t=0.445 s
t=0.605 s
t=0.675 s
44.0
36.7
29.3
22.0
14.7
7.3
0.0
entropy [kB/baryon]
time = 0.130 s
time = 0.370 s
time = 0.530 s
time = 0.600 s
Rstart = 400 km
Rstart = 150 km
Normalized Count
Normalized Count
τr [ms]

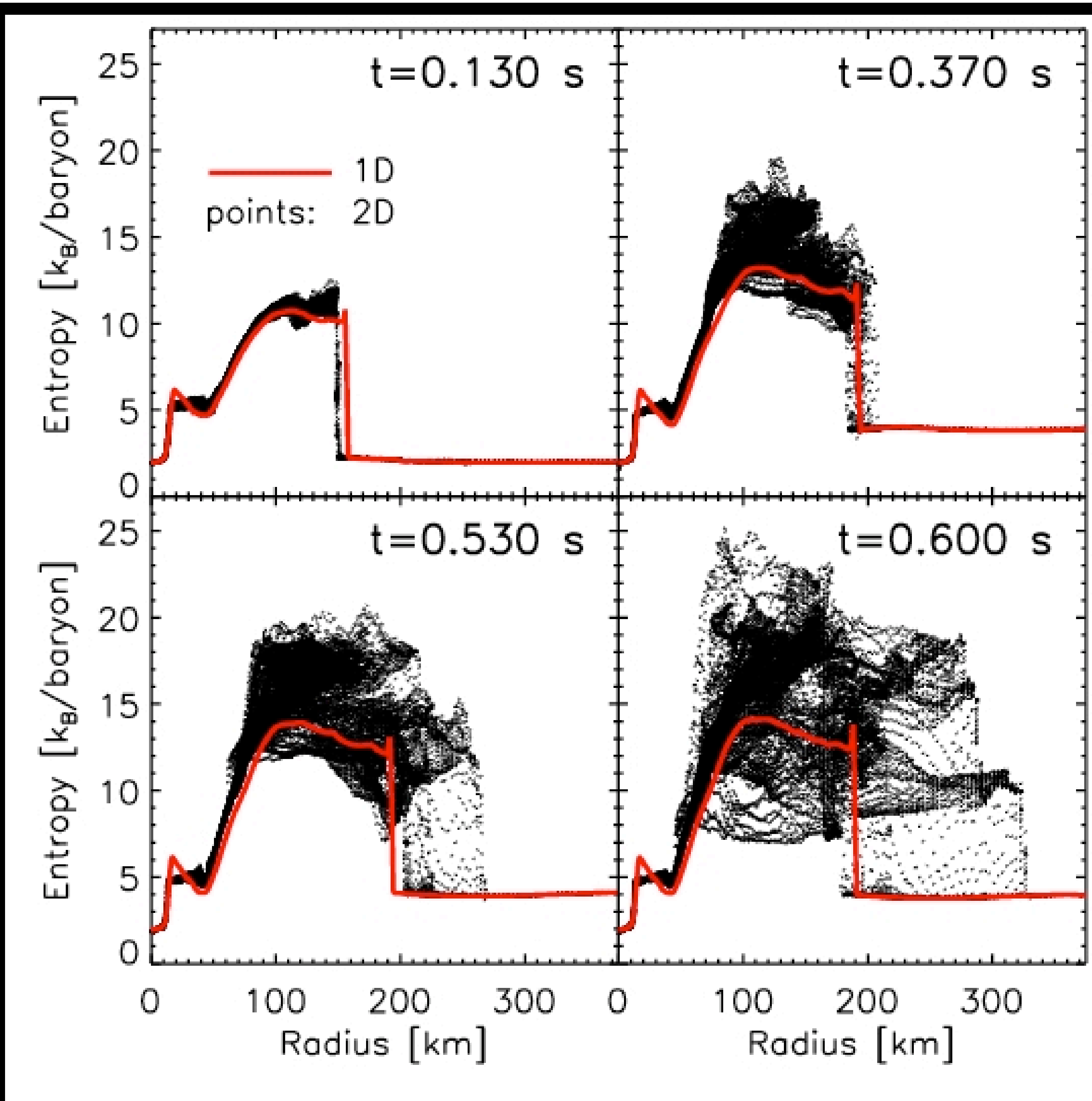
Average Residence Time

Fraction of particles
With $\tau_r > 40$ ms



Do large τ_r translate to extra heating?

$$\Delta S = \frac{Q}{T}$$



t=0.130 s
t=0.370 s
t=0.530 s
t=0.600 s
1D
points: 2D
Entropy [k_B/baryon]
Radius [km]

Conclusions

- Critical luminosity in hydrodynamic simulations (1D & 2D)
- Radial oscillations vs. SASI
- 2D ~70% of 1D
- Insensitive to resolution or angular domain
- Residence time in multi-D simulations
- Long τ_r explains reduction in critical luminosity