Criteria for Core-Collapse Supernova Explosions by the Neutrino Mechanism

Jeremiah W. Murphy[1,2] & Adam Burrows[3]

[1]NSF Astronomy and Astrophysics Postdoctoral Fellow, [2]Astronomy Department, University of Washington,
[3]Department of Astrophysical Sciences, Princeton University

Summary

We investigate the criteria for successful core-collapse supernova explosions by the neutrino mechanism. We find that a critical-luminosity/mass-accretion-rate condition distinguishes non-exploding from exploding models in hydrodynamic one-dimensional (1D) and two-dimensional (2D) simulations. We present 95 such simulations that parametrically explore the dependence on neutrino luminosity, mass accretion rate, resolution, and dimensionality. While radial oscillations mediate the transition between 1D accretion (non-exploding) and exploding simulations, the non-radial standing accretion shock instability characterizes 2D simulations. We find that it is useful to compare the average dwell time of matter in the gain region with the corresponding heating timescale, but that tracking the residence time distribution function of tracer particles better describes the complex flows in multi-dimensional simulations. Integral quantities such as the net heating rate, heating efficiency, and mass in the gain region decrease with time in non-exploding models, but for 2D exploding models, increase before, during, and after explosion. At the onset of explosion in 2D, the heating efficiency is ~2\% to ~5\% and the mass in the gain region is ~0.005 $M_\odot$ to ~0.01 $M_\odot$. Importantly, we find that the critical luminosity for explosions in 2D is ~70% of the critical luminosity required in 1D. This result is not sensitive to resolution or whether the 2D computational domain is a quadrant or the full 180°. We suggest that the relaxation of the explosion condition in going from 1D to 2D (and to, perhaps, 3D) is of a general character and is not limited by the parametric nature of this study.
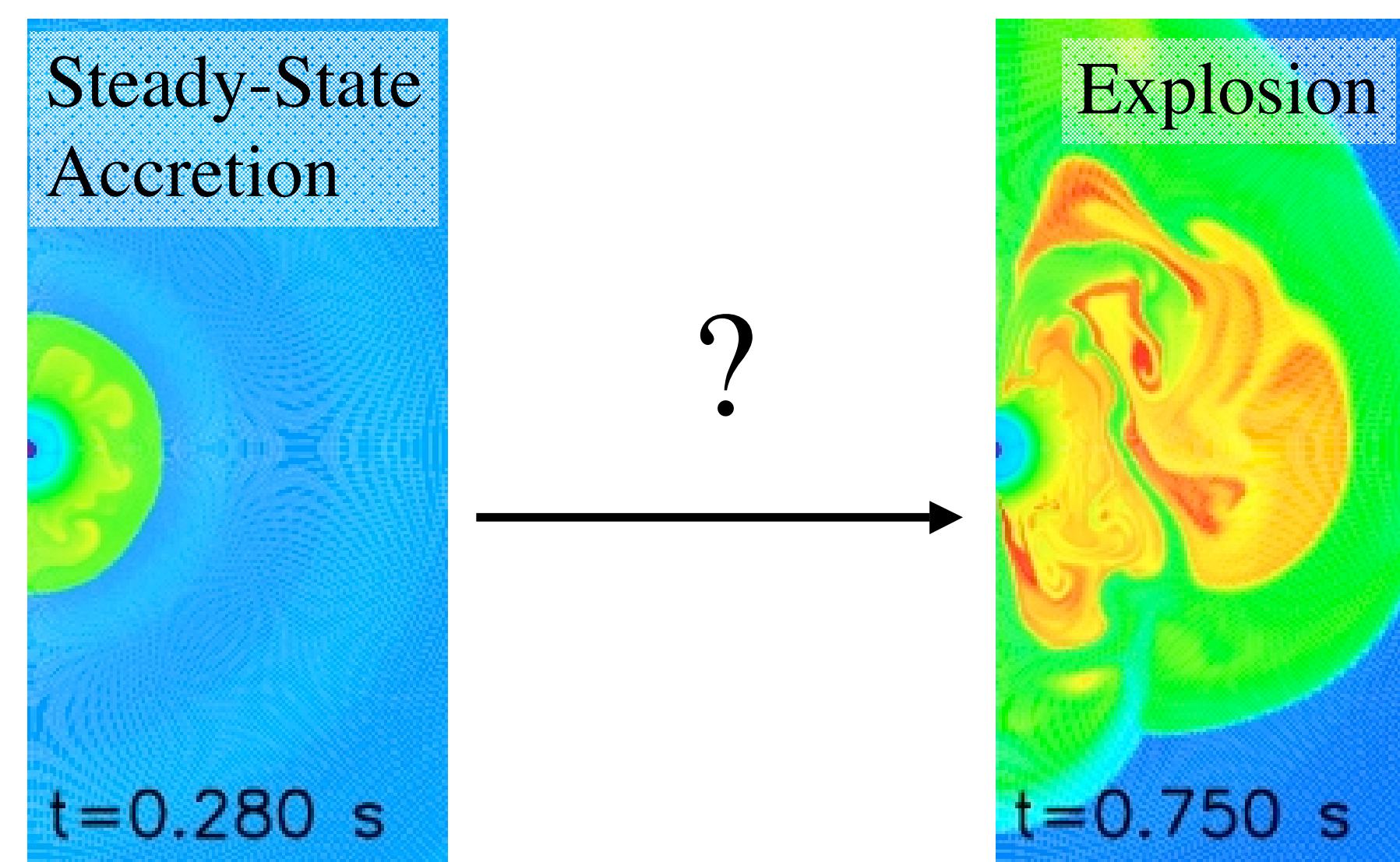
Fundamental Questions of Core-Collapse Theory

Core-collapse supernovae (CCSNe) are among the most energetic events in the Universe; they herald the birth of neutron stars and black holes, are a major site for nucleosynthesis, influence galactic dynamics, trigger further star formation, and are prodigious emitters of neutrinos and gravitational waves. Hence, it is important to understand the mechanism of explosion, yet the details have remained elusive for many decades.

For more than two decades, it has been recognized that the bounce shock quickly stalls due to nuclear dissociation, electron capture, and neutrino losses (Mazurek et al., 1982). Since then the fundamental question of core-collapse theory has been, how does the steady-state stalled accretion shock evolve into an explosion?

Bethe & Wilson 1985 and suggested that a fraction of the neutrinos being emitted from depth (< 100 km) would be recaptured in the gain region (> 100 km), reviving the stalled shock into explosion. However, detailed one-dimensional (1D) simulations have shown that this mechanism, the neutrino mechanism, fails in 1D. Since the mid 90s, 2D simulations that are subject to aspherical instabilities, specifically postshock convection, which is driven by neutrino heating in the gain region and the SASI, suggest that the neutrino mechanism may yet succeed, though it fails in 1D. Why is it easier to explode by the neutrino mechanism in 2D simulations compared to 1D simulations?

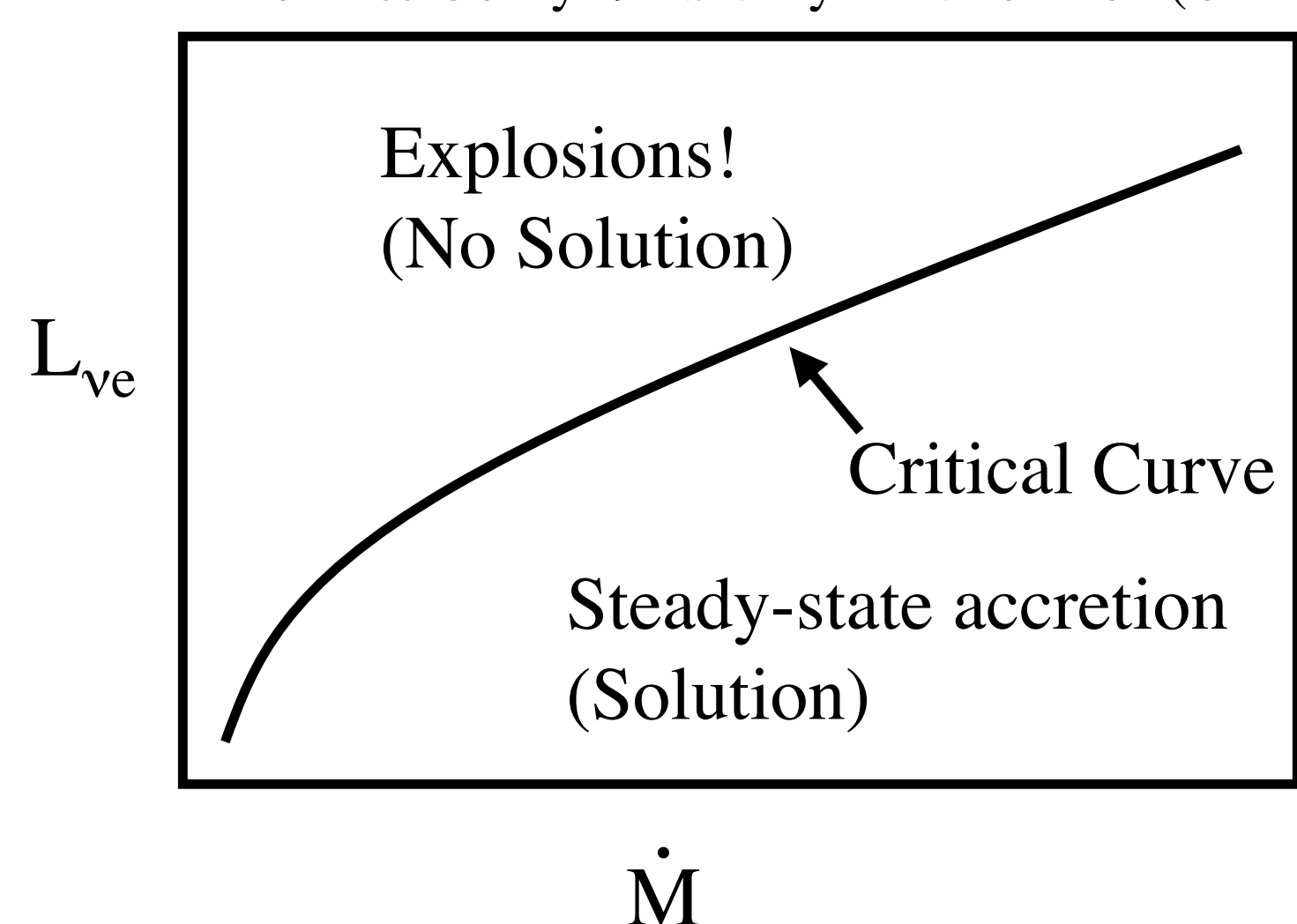### How does the steady-state stalled accretion shock evolve into an explosion?

Steady-State Accretion — t=0.280 s

Explosion — t=0.750 s

Why is it easier to explode by the neutrino mechanism in 2D simulations compared to 1D simulations?

Conditions for Successful Explosions: A Simple Framework

Generically, there are two paths to the solution of the core-collapse mechanism problem. To produce quantifiable theories that can be compared to observations (i.e. explosion energies, neutron star masses, nucleosynthesis, etc.), the community must perform 3D radiation-hydrodynamic simulations. However, these simulations are time consuming and it is difficult to disentangle and understand the various physical processes. To help tease out the important mechanisms we employ parameterizations that capture the essential physics and enable a timely study of the neutrino mechanism.

Burrows & Goshy 1993 suggested a simple framework for determining the conditions for successful explosions by the neutrino mechanism. They approximated the stalled shock and accretion phase as a steady-state problem, transforming the governing partial differential equations into ordinary differential equations. By parameterizing the electron-neutrino luminosity, $L_{\nu e}$, and the mass accretion rate, dM/dt, they identified a critical $L_{\nu e}$-dM/dt curve that distinguishes steady state accretion solutions (lower luminosities) from explosions (high luminosities). This implied that global conditions, not local conditions, mediate the transition from accretion to explosion, which in turn suggests that core-collapse explosion is a global instability. Is this critical luminosity condition relevant in dynamic simulations? If so, how does the critical luminosity of 2D simulations, which exhibit convection and the SASI, compare to 1D simulations?

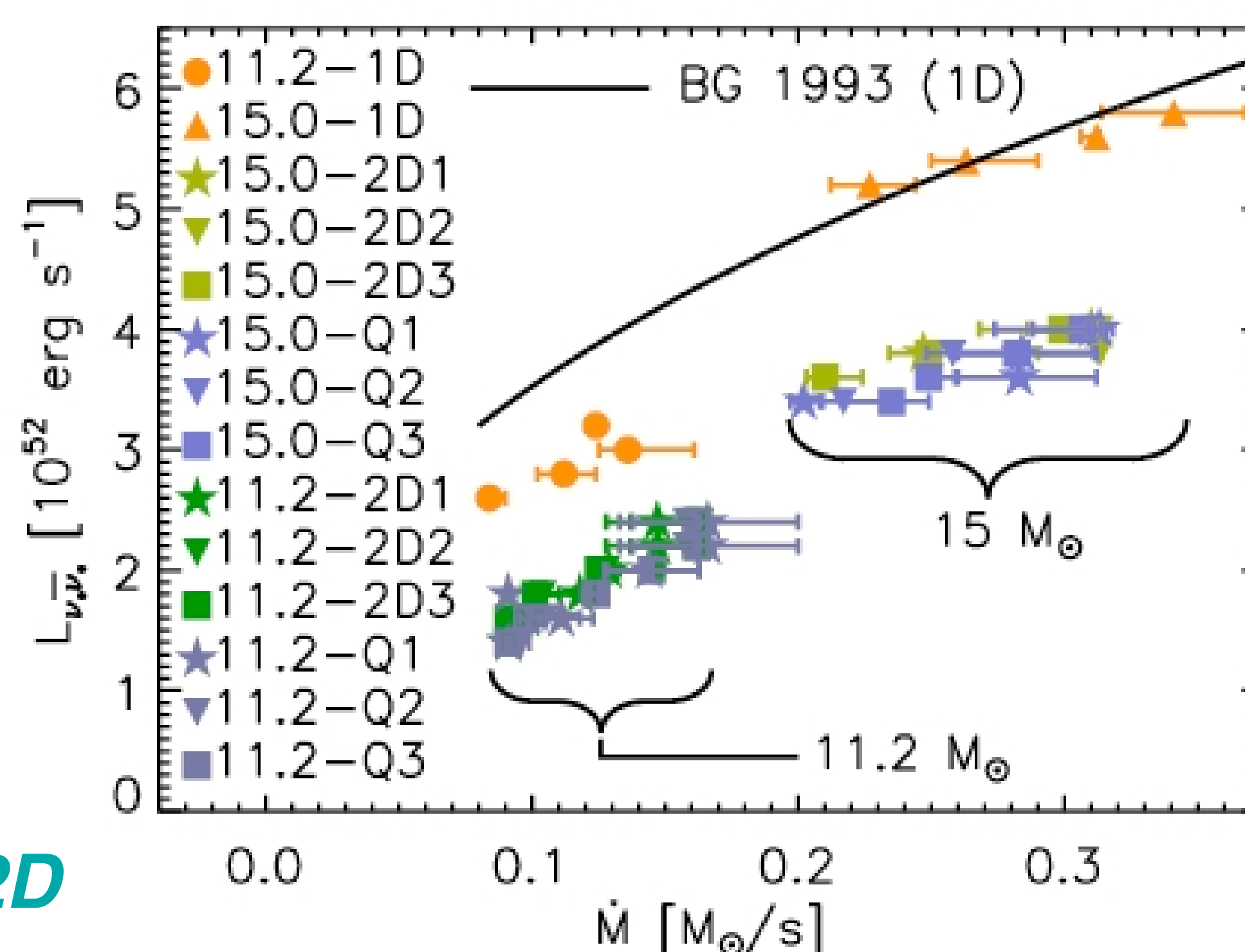### A Simple Framework: Critical Luminosity Curve for Explosion

Burrows & Goshy '93 Steady-state solution (ODE)

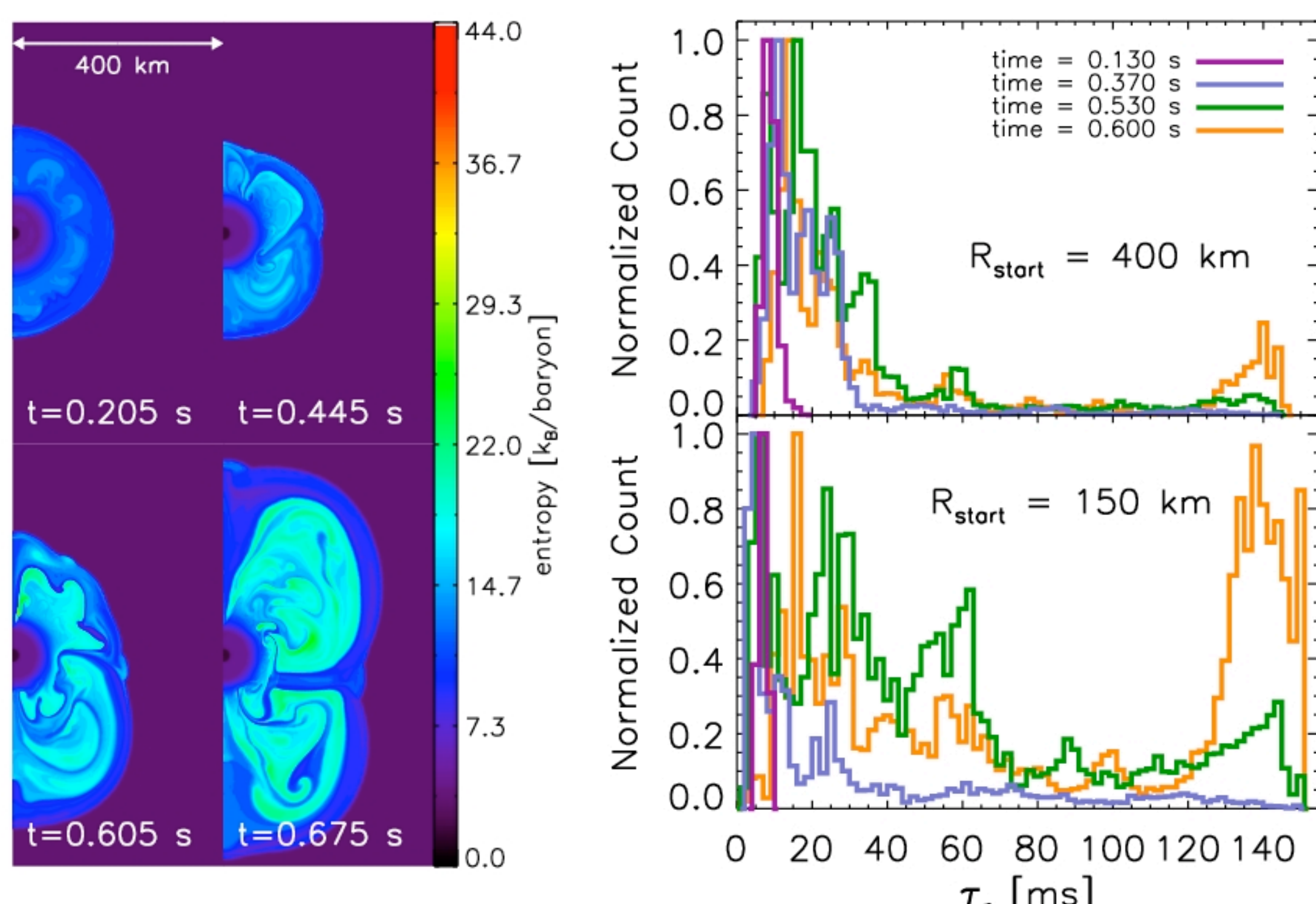
Explosions! (No Solution)

Critical Curve

Steady-state accretion (Solution)

L_{ve} vs $\dot{M}$

Critical Luminosity for 2D is ~70% of 1D

A Parameter study

To address these questions, we conduct 1D and 2D simulations for various values of L_{ve}. In addition to L_{ve} and dM/dt, we compare simulations with different spatial resolutions. Using the code, BETHE-hydro (Murphy & Burrows, 2008a), we simulate the core-collapse, bounce, and post-bounce phases in time-dependent 1D and 2D simulations. These simulations have no inner boundary and include the PNS core. A finite-temperature EOS that accounts for nucleons, nuclei, photons, electrons, positrons, and all the appropriate phase transitions is used (Shen et al. 1998). Employing 11.2- and 15-$M_\odot$ progenitors as initial conditions, a wide range of dM/dt is sampled (from ~0.08 $M_\odot$/s to ~0.3 $M_\odot$/s). Finally, we use standard approximations for neutrino heating and cooling that enable a straightforward parameterization of L_{ve} (Bethe & Wilson 1985).

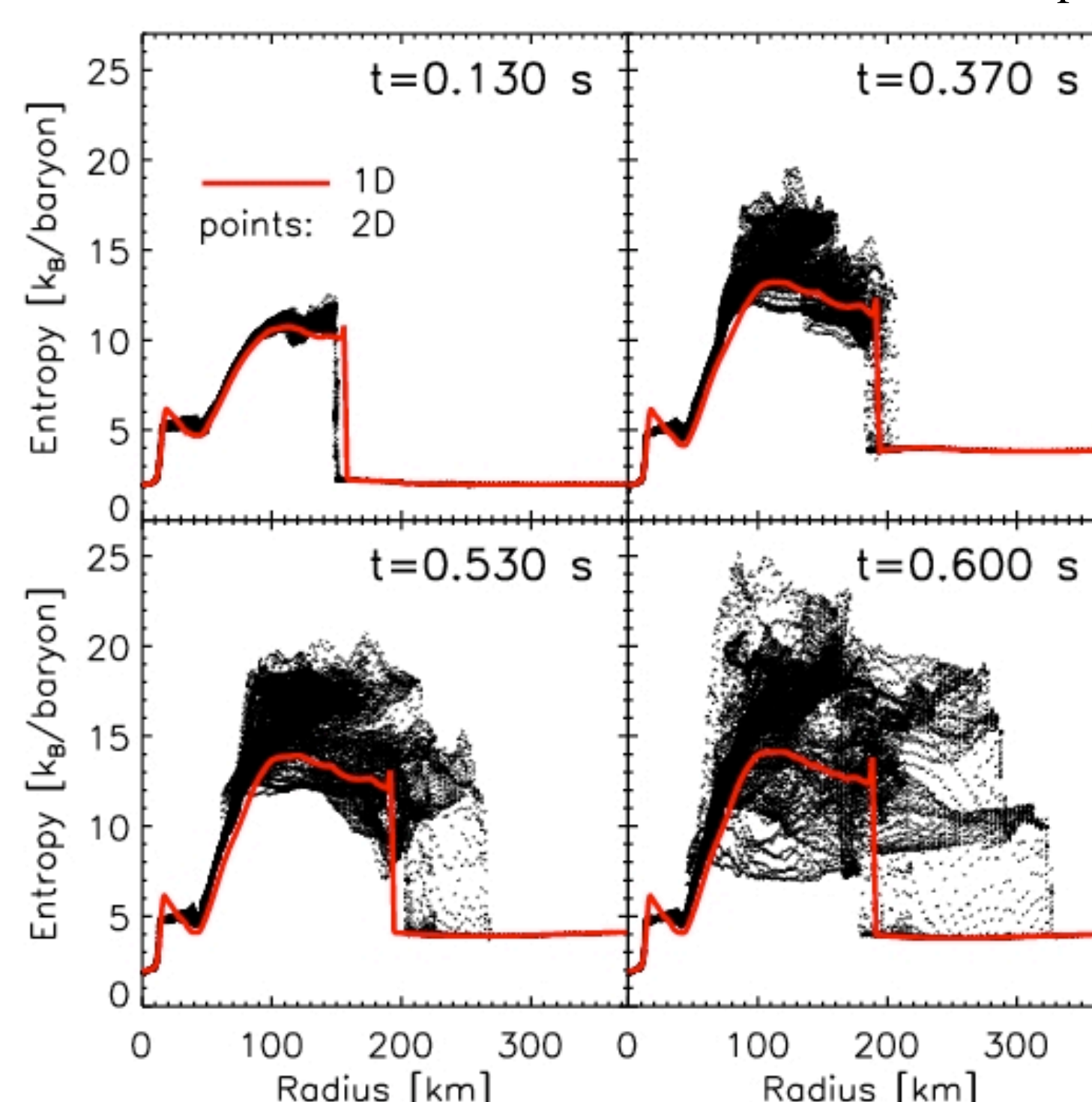### Why is Critical Luminosity of 2D simulations ~70% of 1D?

Breaking of spherical symmetry leads to longer dwell times in the gain region. For comparison, 1D dwell times are ~20-30 ms.

Longer dwell times lead to more heating (higher entropy)

Results

Indeed, the critical luminosity vs. accretion rate condition for successful explosions is relevant for time-dependent simulations, and the critical luminosity of 2D simulations is ~70% of the critical luminosity for 1D simulations. Why is the critical luminosity of 2D simulations ~70% of 1D?

Our analysis shows that as matter advects through the gain region (where the heating and cooling by neutrinos results in net energy deposition), the breaking of spherical symmetry in 2D simulations leads to longer residence times for some of the accreting matter. The matter with longer dwell times leads to more heating for a given neutrino luminosity. In effect, the convective and SASI motions in the postshock region leads to more efficient heating, hence the critical luminosity for successful explosions is lower in 2D simulations compared to 1D simulations. All else being equal, some matter advecting through the gain region experiences more heating (higher entropy) in 2D than in 1D simulations.

References:
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Bethe & Wilson, 1985, ApJ, 295, 14
Burrows & Goshy, 1993, ApJ, 416, L75
Murphy & Burrows, 2008a, ApJS, 179, 209
Shen, Oyamatsu, & Sumiyoshi, 1998, Nucl. Phys. A, 637, 435