Discovery and Destabilization:

Experiments in Stellar Explosions at NERSC

F. Douglas Swesty & Eric S. Myra

DEPT. OF PHYSICS & ASTRONOMY

STATE UNIVERSITY OF NEW YORK AT STONY BROOK

SC06

11—17 November 2006

Tampa, FL

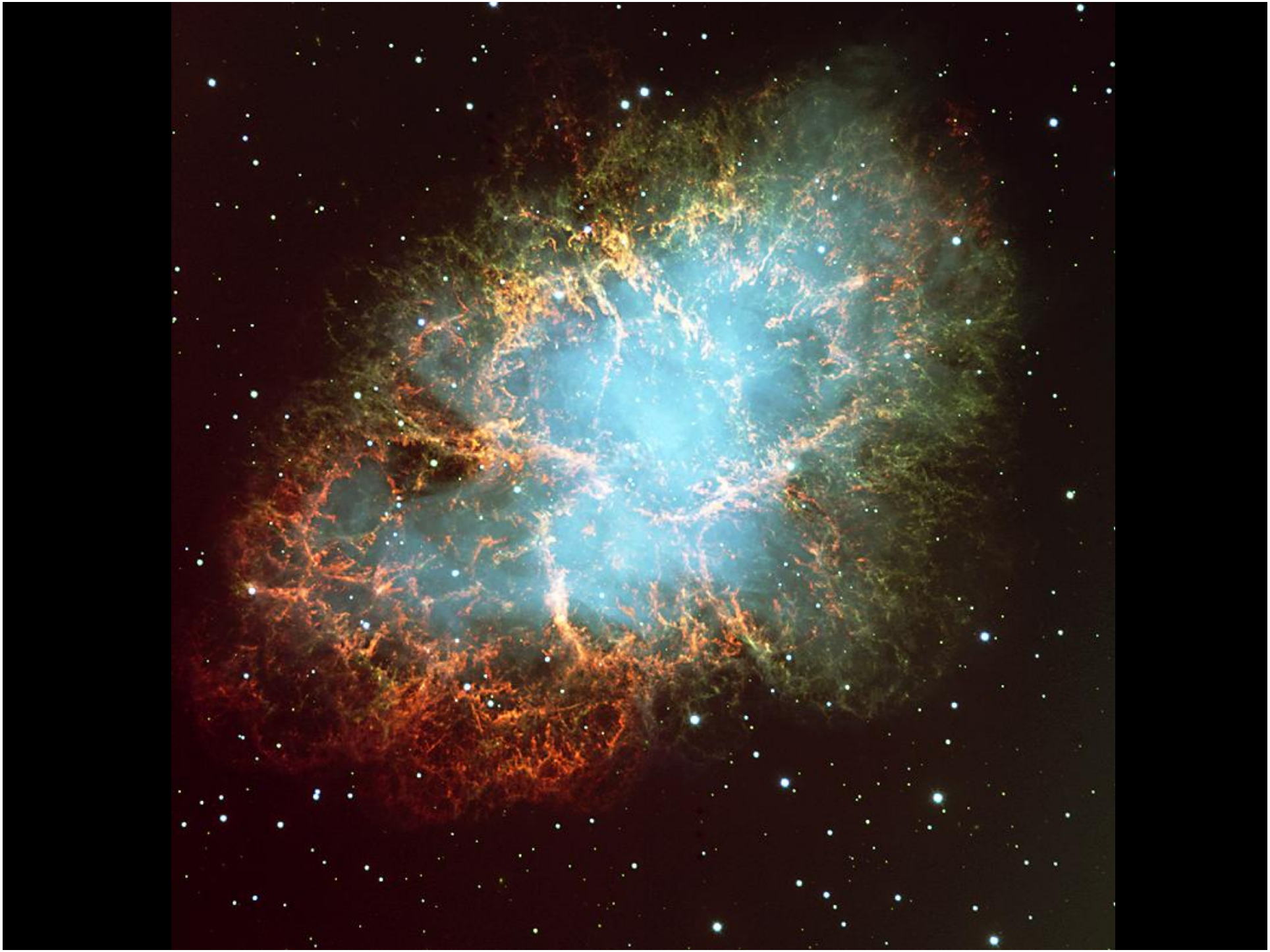
Collaborators for this work

- Jim Lattimer (SUNY at Stony Brook)
- Dennis Smolarski (Santa Clara University)
- Polly Baker (Indiana University)
- Ed Bachta (Indiana University)

- Ken DeNisco (SUNY at Stony Brook)
- Chris Tartamella (SUNY at Stony Brook)

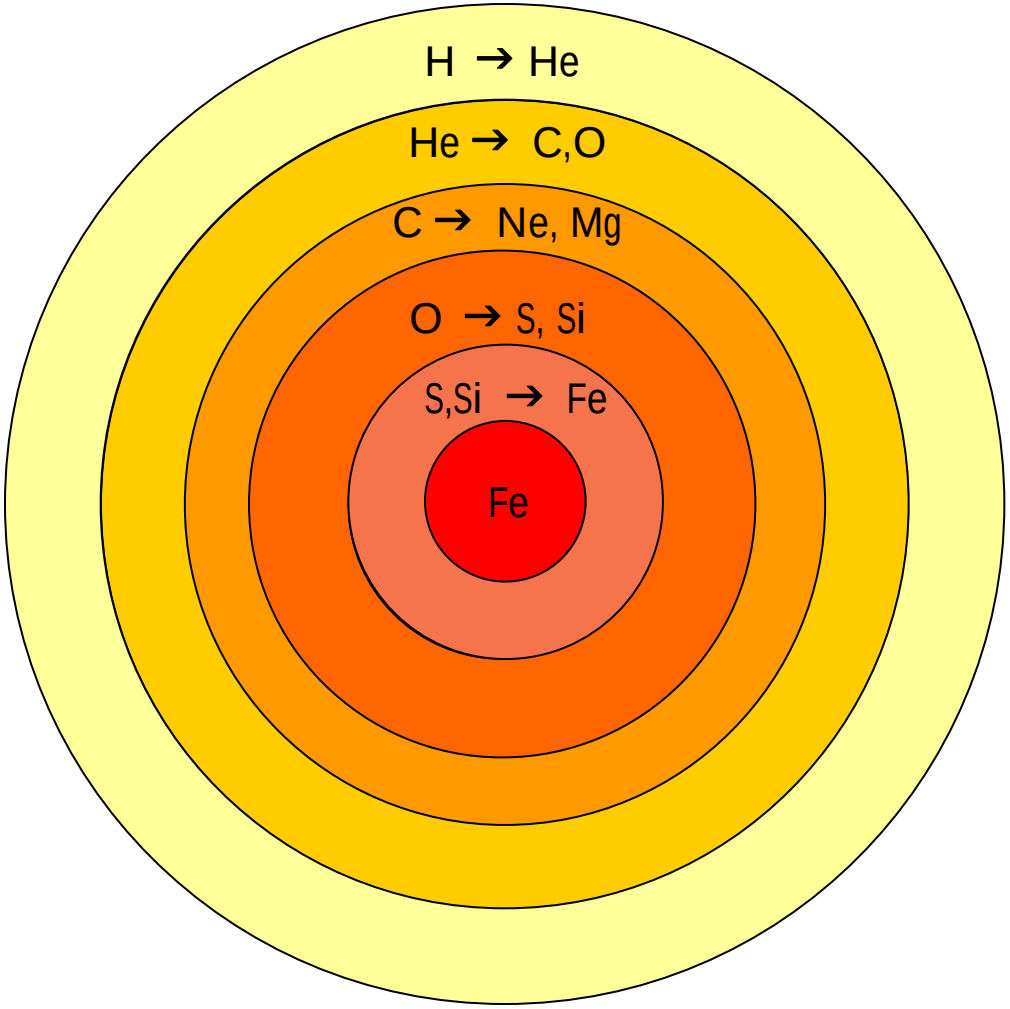
NERSC Staff (partial list!)

- Francesca Verdier, Wes Bethel,
- Richard Gerber, David Skinner,
- John Shalf, Eli Dart, Brent Draney



Initial Conditions: The pre-collapse of massive stars

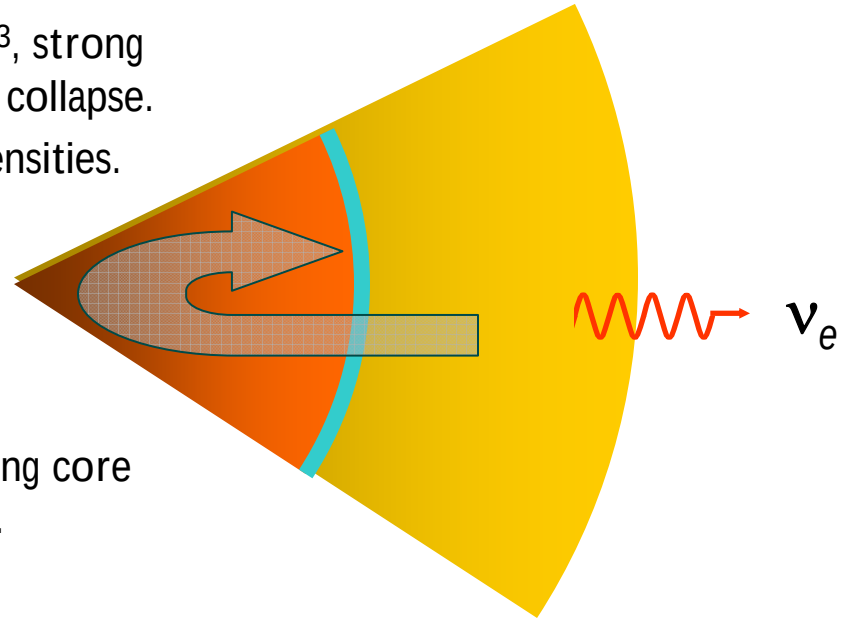
- Massive stars evolve by burning lighter elements (by thermonuclear fusion) into heavier elements.
- High mass stars produce elements up to iron.
- Star is like an onion, with layers of successively heavier elements.
- Each burning stage progresses more rapidly.
- When the iron core mass grows to about 1.2–1.4M_{sun} the core collapses under its own weight



The strong force causes the core to bounce

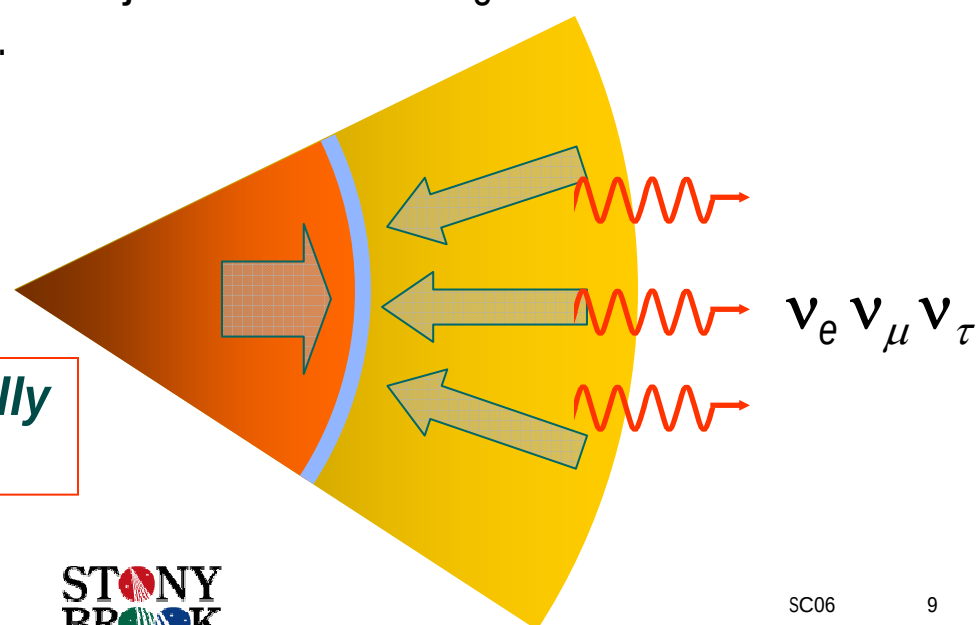
- Collapse is extremely violent
- During collapse, electrons combine with protons to form a neutron and an electron neutrino.

  $e- + p \rightarrow n + \nu_e$
- Above nuclear density, ~2.5 x 10^{14} g/cm^3, strong nuclear force is repulsive and arrests the collapse.
  - Neutrinos are "trapped" at these densities.
- Collapse stops at center.
  - Inner part of core rebounds.
- A shock wave forms where the rebounding core collides with infalling supersonic material.



The shock starts to advance…

- The force of the core bounce starts the shock advancing.
- Supersonic material in the outer core…
  - falls through the shock.
  - is dissociated (costing 8 MeV/baryon ~ 2 x 10^{51} erg/0.1M_{sun}).
- Dissociation and ν emission deplete the shock of energy.
- At densities well below nuclear density, ν's escape
- A successful explosion needs to inject about 10^{51} ergs of kinetic energy into the silicon layer.



"Prompt" shocks eventually stall!

Next-generation multi-dimensional models of the post-bounce epoch

Prior to a few years ago, state of the art was:

- 2-D models with parameterized neutrino spectra, approximate rates and opacities, and incomplete matter-radiation coupling.
  - Models produced explosions,…but for the correct reason?
- Uncoupled radial-ray multi-group (non-approximated spectrum) models, but with incomplete matter-radiation coupling and no allowance for lateral movement of neutrinos…
  - did not find explosions (in agreement with 1-D multi-group models)

Recent work by other groups: Partially coupled 2-D radiation-hydrodynamic models

- No explosions
- Very low spatial and energy resolution (and not highly scalable)
- Incomplete matter-radiation coupling

High resolution multi-group models described in this talk could not be done without unique resources at NERSC.

- Includes all radiation-hydrodynamic coupling terms
- Allows full 2-D movement of neutrinos
- No explosions…

Neutrino radiation-hydrodynamic model

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \qquad \frac{\partial (\rho Y_e)}{\partial t} + \nabla \cdot (\rho Y_e \mathbf{v}) = -m_b \sum_f \int d\epsilon \left(\frac{\mathcal{S}_\epsilon}{\epsilon} - \frac{\bar{\mathcal{S}}_\epsilon}{\epsilon} \right)$$

$$\frac{\partial E}{\partial t} + \nabla \cdot (E\mathbf{v}) + P \nabla \cdot \mathbf{v} = -\sum_f \int d\epsilon \left(\mathcal{S}_\epsilon + \bar{\mathcal{S}}_\epsilon \right)$$

$$E = f(T, \rho, Y_e)$$

$$P = g(T, \rho, Y_e)$$

$$\frac{\partial (\rho v_i)}{\partial t} + \nabla \cdot (\rho v_i \mathbf{v}) + (\nabla P)_i + \rho (\nabla \Phi)_i + \nabla \cdot \left\{ \sum_f \int d\epsilon \left(\chi_\epsilon E_\epsilon + \bar{\chi}_\epsilon \bar{E}_\epsilon \right) \right\} = 0$$

$$\nabla^2 \Phi = 4\pi \rho G_N$$

$$\frac{\partial E_\epsilon}{\partial t} + \nabla \cdot (E_\epsilon \mathbf{v}) - \nabla \cdot (D_\epsilon \nabla E_\epsilon) - \epsilon \frac{\partial}{\partial \epsilon} (\underline{\underline{\chi}}_\epsilon E_\epsilon) : \nabla \mathbf{v} = \mathcal{S}_\epsilon \qquad 0 \le E_\epsilon \le \frac{\epsilon^3}{\alpha}$$

$$\frac{\partial \bar{E}_\epsilon}{\partial t} + \nabla \cdot (E_\epsilon \mathbf{v}) - \nabla \cdot (\bar{D}_\epsilon \nabla \bar{E}_\epsilon) - \epsilon \frac{\partial}{\partial \epsilon} (\underline{\underline{\bar{\chi}}}_\epsilon \bar{E}_\epsilon) : \nabla \mathbf{v} = \bar{\mathcal{S}}_\epsilon \qquad 0 \le \bar{E}_\epsilon \le \frac{\epsilon^3}{\alpha}$$

$$\begin{aligned} \mathcal{S}_\epsilon = {} & S_\epsilon \left(1 - \frac{\alpha}{\epsilon^3} E_\epsilon \right) - c\kappa_\epsilon^a E_\epsilon + \left(1 - \frac{\alpha}{\epsilon^3} E_\epsilon \right) c \int d\epsilon' \kappa^s(\epsilon', \epsilon) E_{\epsilon'} \\ & - E_\epsilon c \int d\epsilon' \kappa^s(\epsilon, \epsilon') \left(1 - \frac{\alpha}{\epsilon'^3} E_{\epsilon'} \right) + \left(1 - \frac{\alpha}{\epsilon^3} E_\epsilon \right) \epsilon \int d\epsilon' G(\epsilon, \epsilon') \left(1 - \frac{\alpha}{\epsilon'^3} \bar{E}_{\epsilon'} \right) \end{aligned}$$

$$\begin{aligned} \bar{\mathcal{S}}_\epsilon = {} & \bar{S}_\epsilon \left(1 - \frac{\alpha}{\epsilon^3} \bar{E}_\epsilon \right) - c\kappa_\epsilon^a \bar{E}_\epsilon + \left(1 - \frac{\alpha}{\epsilon^3} \bar{E}_\epsilon \right) c \int d\epsilon' \bar{\kappa}^s(\epsilon', \epsilon) \bar{E}_{\epsilon'} \\ & - \bar{E}_\epsilon c \int d\epsilon' \bar{\kappa}^s(\epsilon, \epsilon') \left(1 - \frac{\alpha}{\epsilon'^3} \bar{E}_{\epsilon'} \right) + \left(1 - \frac{\alpha}{\epsilon^3} \bar{E}_\epsilon \right) \epsilon \int d\epsilon' G(\epsilon', \epsilon) \left(1 - \frac{\alpha}{\epsilon'^3} E_{\epsilon'} \right) \end{aligned}$$

Microphysics

T = temperature
r = mass density
Y_e = electron fraction
E_e = neutrino energy density

Equation of state is obtained from table via thermodynamically consistent interpolation scheme; also maintains continuity in derivatives of EOS w.r.t. *T* and ρ.

EOS uses bi-quintic Hermite interpolation in *T* and ρ; linear interpolation in Y_e

Neutrino microphysics coefficients from tri-linear interpolation scheme

Equation of State

$$E = E(T, \rho, Y_e)$$

$$P = P(T, \rho, Y_e)$$

Emissivity

$$S_\varepsilon = S_\varepsilon(T, \rho, Y_e)$$

Absorption Opacity

$$\kappa_\varepsilon^a = \kappa_\varepsilon^a(T, \rho, Y_e)$$

Diffusion Coefficient

$$D_\varepsilon = D_\varepsilon(T, \rho, Y_e)$$

Scattering Coefficients

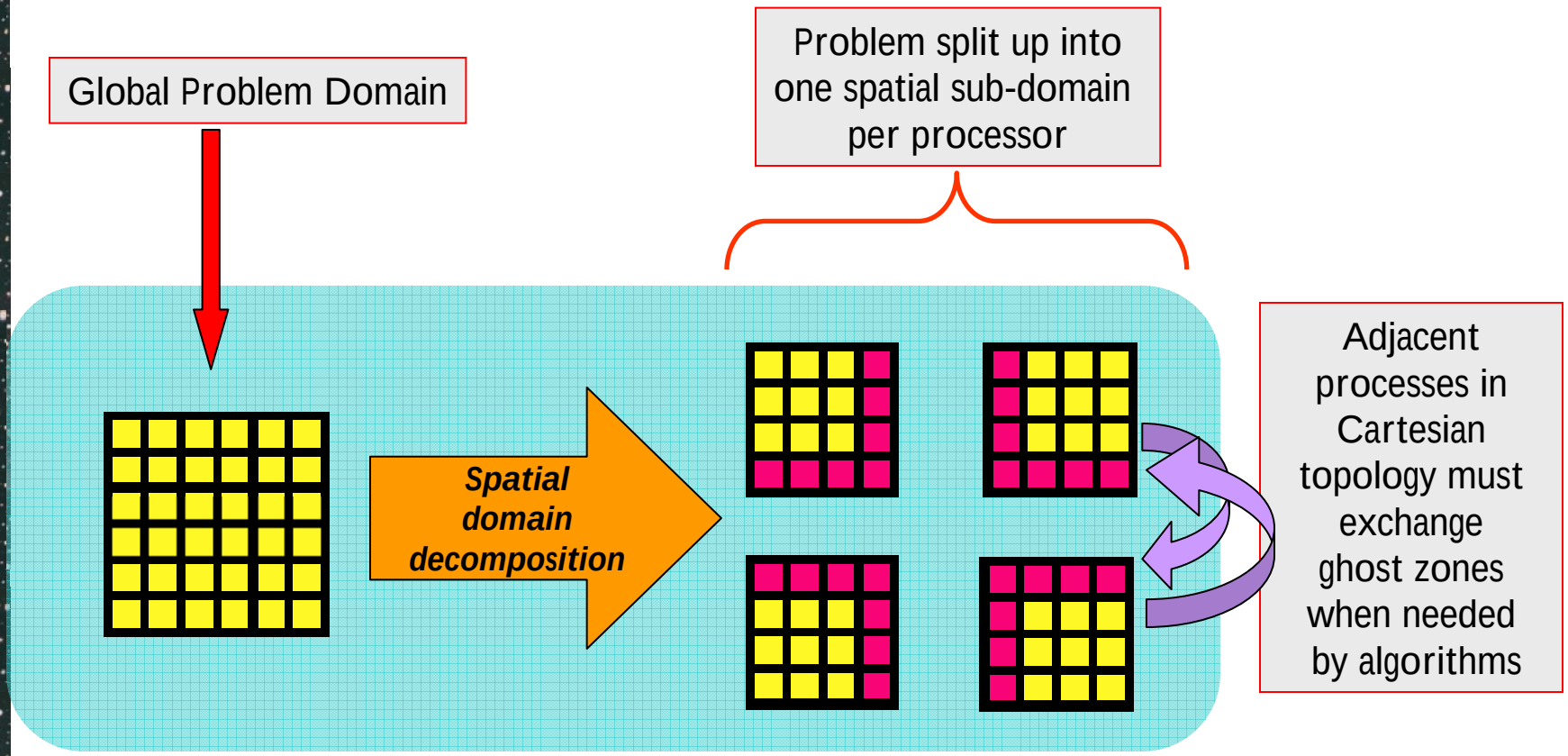
$$\kappa^{in}(\varepsilon, \varepsilon') = \kappa^{in}(\varepsilon, \varepsilon', T, \rho, Y_e)$$

$$\kappa^{out}(\varepsilon, \varepsilon') = \kappa^{out}(\varepsilon, \varepsilon', T, \rho, Y_e)$$

Pair Emissivity

$$G(\varepsilon, \varepsilon') = G(\varepsilon, \varepsilon', T, \rho, Y_e)$$

Parallel implementation



Code (V2D) written in F95
Continuous process of Verification & Validation
Componentized architecture
Message passing done in MPI
Parallel I/O done with parallel HDF5
Scalable to at least 1024-2048 processors for "medium sized" problems

Implicit neutrino transport with Newton-Krylov iteration

Newton-Krylov solution accomplished via Newton-BiCGSTAB

Using sparse parallel approximate inverse preconditioning (physics based) —highly parallel

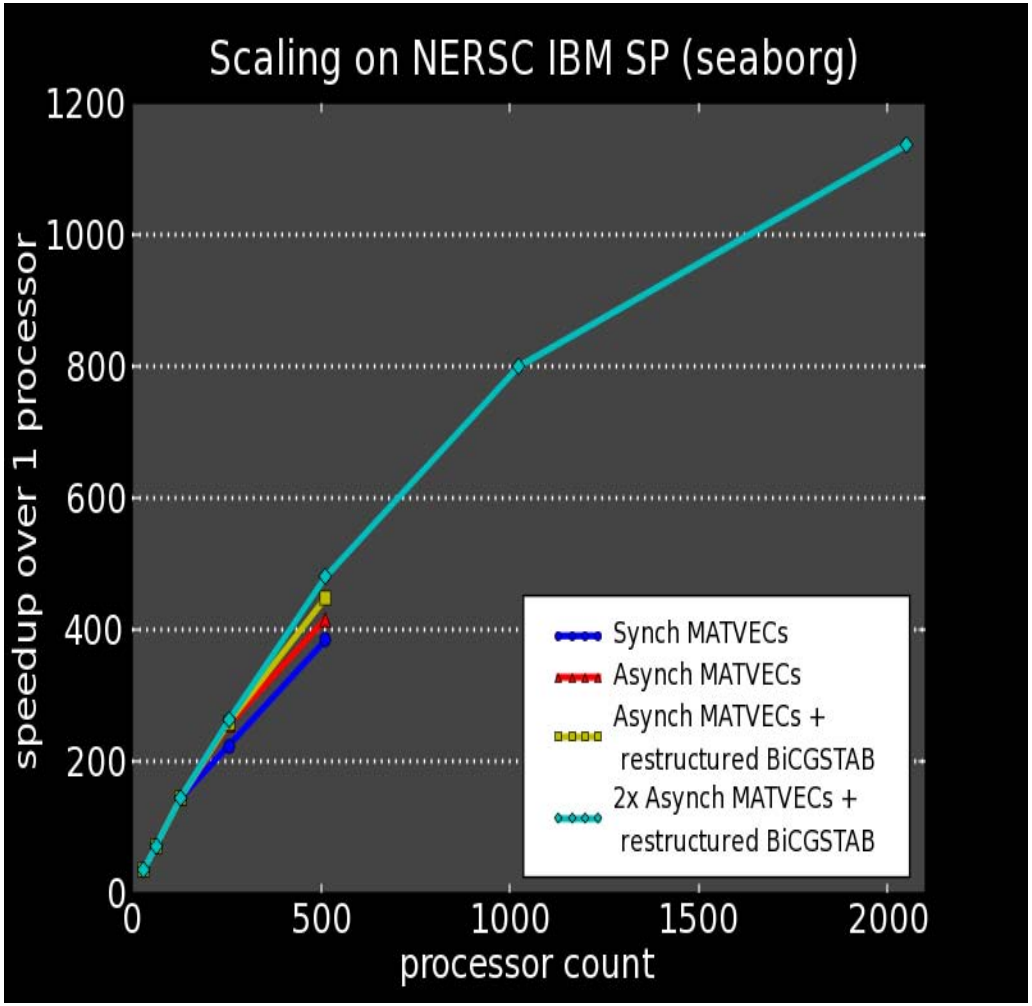
MATVECs can be carried out asynchronously to hide communication

BiCGSTAB can be restructured to reduce global reductions

Typically 10-20 BiCGSTAB iterations per Newton iteration; 2-3 Newton iterations

Implicit solvers have to be ultra-fast—few x 10^5 timesteps to complete simulation!

Incorporating new Newton-Krylov solvers into V2D for fully implicit radiation-hydro



Convective shock revitalization epoch

Supernova explosion

- Shock wave heats matter as it moves outward

- Hot (high entropy) matter starts rising upward (convection)

- Hot matter produces neutrino-antineutrino pairs of three types

$$e^+ + e^- \rightarrow \nu_x + \bar{\nu}_x$$

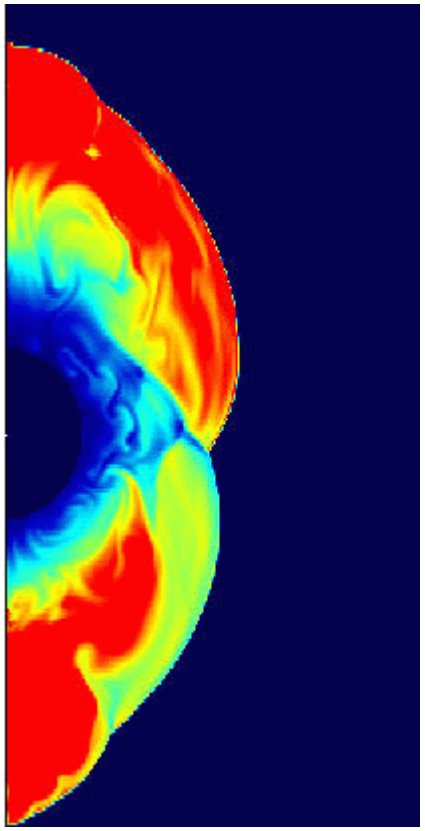
- A combination of convection and neutrino heating of the matter somehow revitalizes the stalled shock wave and causes the observed explosion

- Explosion leaves either a neutron star or a black hole behind

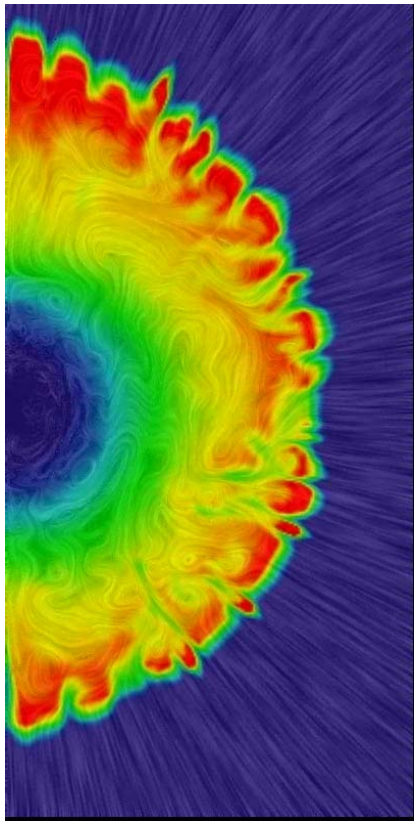
At 256x256 spatial resolution, we see much smaller convective flow features than other groups report.

Fully resolved? Probably not….

Large-scale simulations at NERSC have enabled discovery of local accretion-shock instabilities



Ideal gas hydro



Realistic equation of state with neutrino transport

Why do these shock fronts look so different?

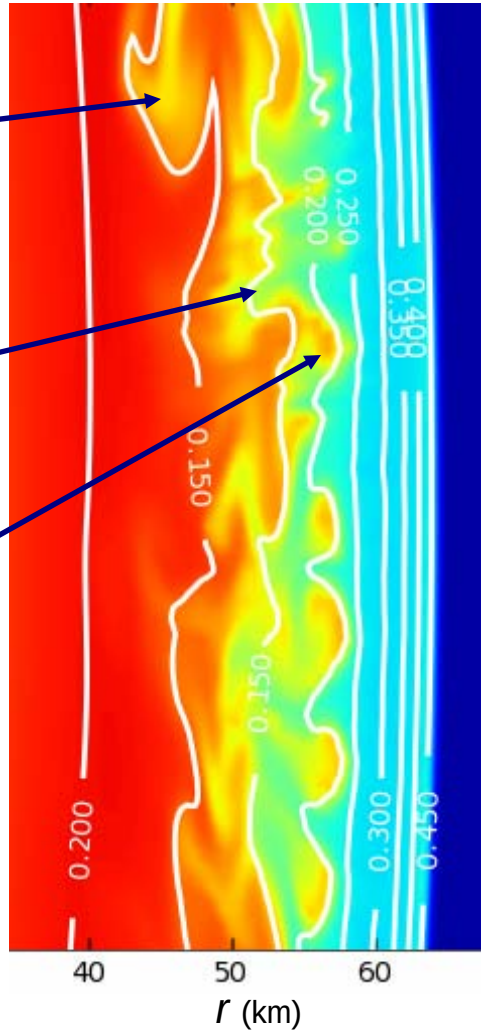
- Why causes the realistic shock to fragment?
- Why is the large-scale SASI-like mode more pronounced in the ideal-gas case?
- More realistic shocks have are radiative and have complex chemical reactions.
- Ideal-gas shocks are stable to local perturbations.
- Shocks with complex equations of state are not guaranteed to be stable (*Dyakov 1954*).
- Neutrino cooling of newly shocked material destabilizes the shock front by softening the equation of state?

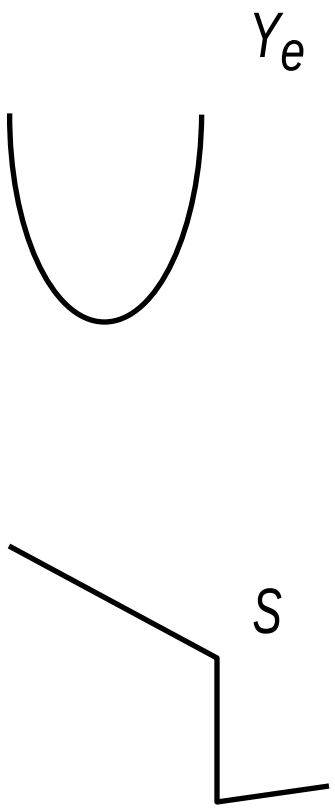
Electron capture deepens the pressure trough…

low S, low Y_e at trailing edge of Y_e trough

low S, high Y_e "fingers" descend into leading edge of Y_e trough

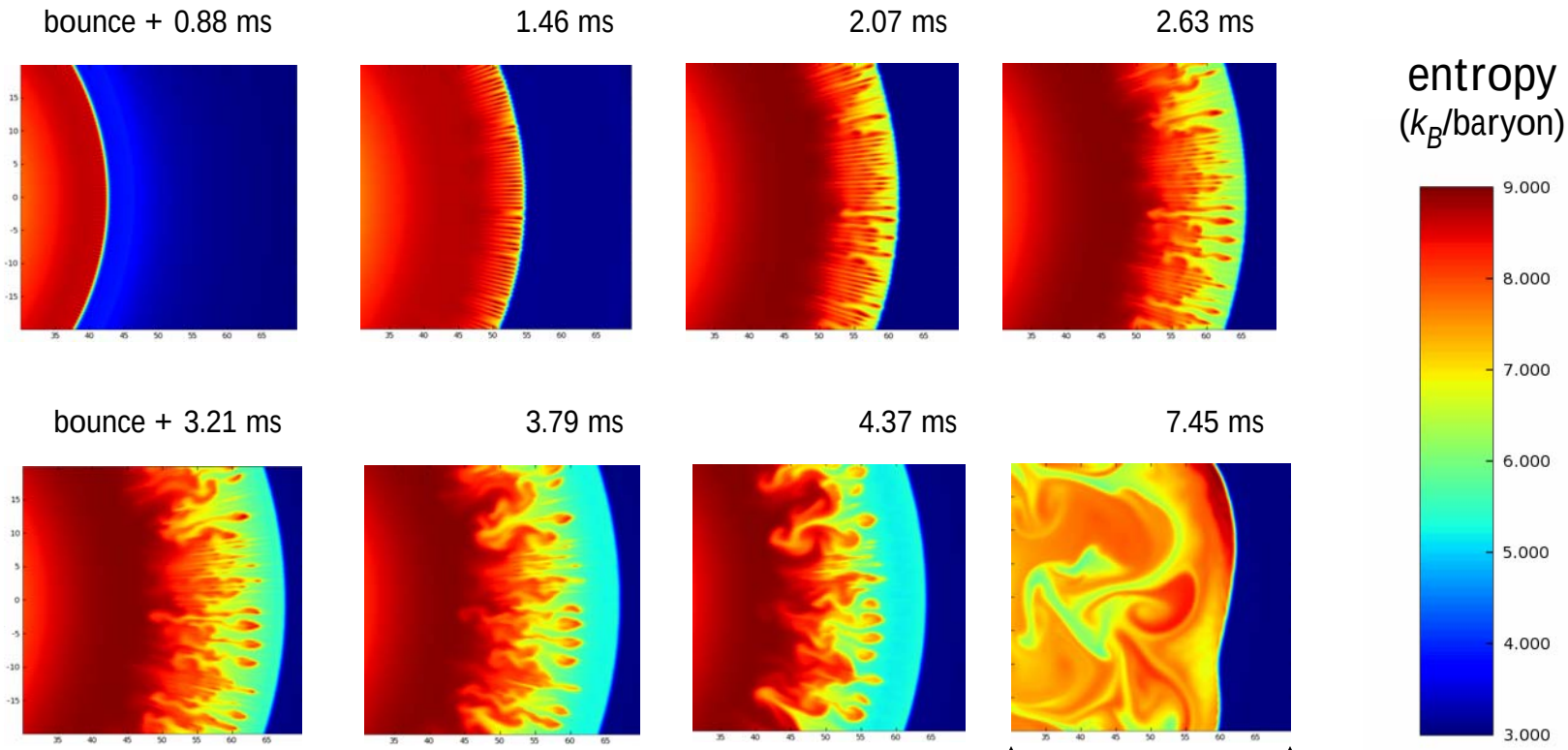
high S, low Y_e plumes extend leading edge of Y_e trough





This is a ν-translucent regime, so caution is warranted when applying simple analysis!

Higher-resolution studies



512 x 512 zones, 20 groups/flavor
At shock front, 1 zone ~ 0.3 km x 0.3 km

r = 30 km 70 km

Instabilities in the model are born as small scale perturbations of the shock front that quickly grow into larger-scale Raleigh-Taylor-like plumes

The future

- Higher-resolution studies of shock instability are needed ("shock in a box")
  - understand instability growth rate
  - what sets the length scale?
  - how do 3D models differ from 2D models?
  - how do local shock instabilities affect the cascade of length scales in the convective region below the shock?

- Working on an analytic theory to understand the origin of this instability, which was discovered numerically

- What is the structure of the radiating reactive flow in the shock?
  - how do unknown nuclear physics parameters in equation of state affect the dynamics of the instability

http://nuclear.astro.sunysb.edu

Evolution of entropy