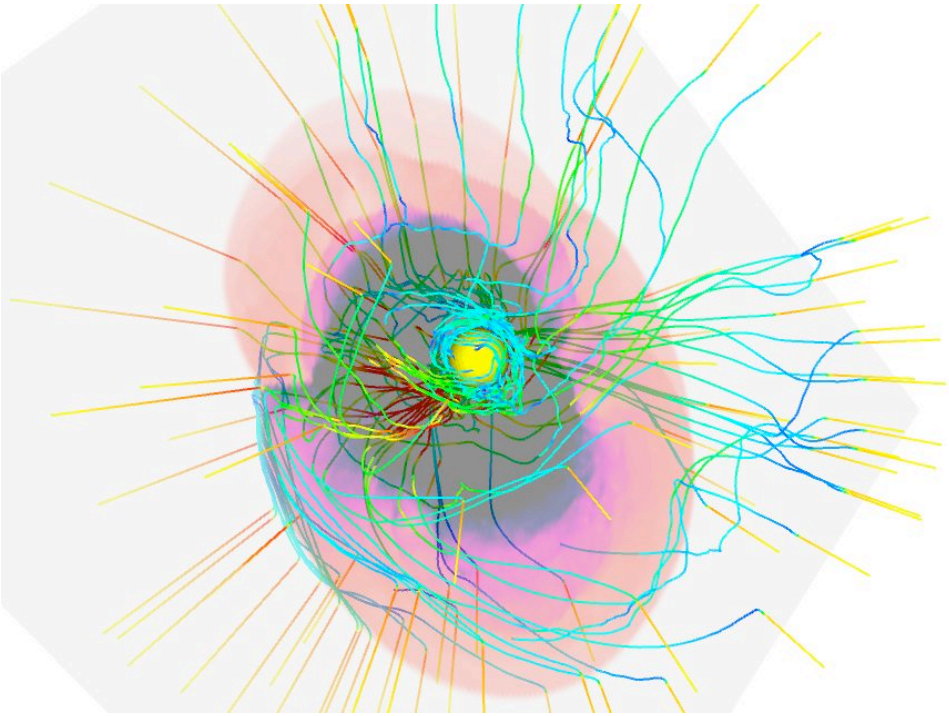
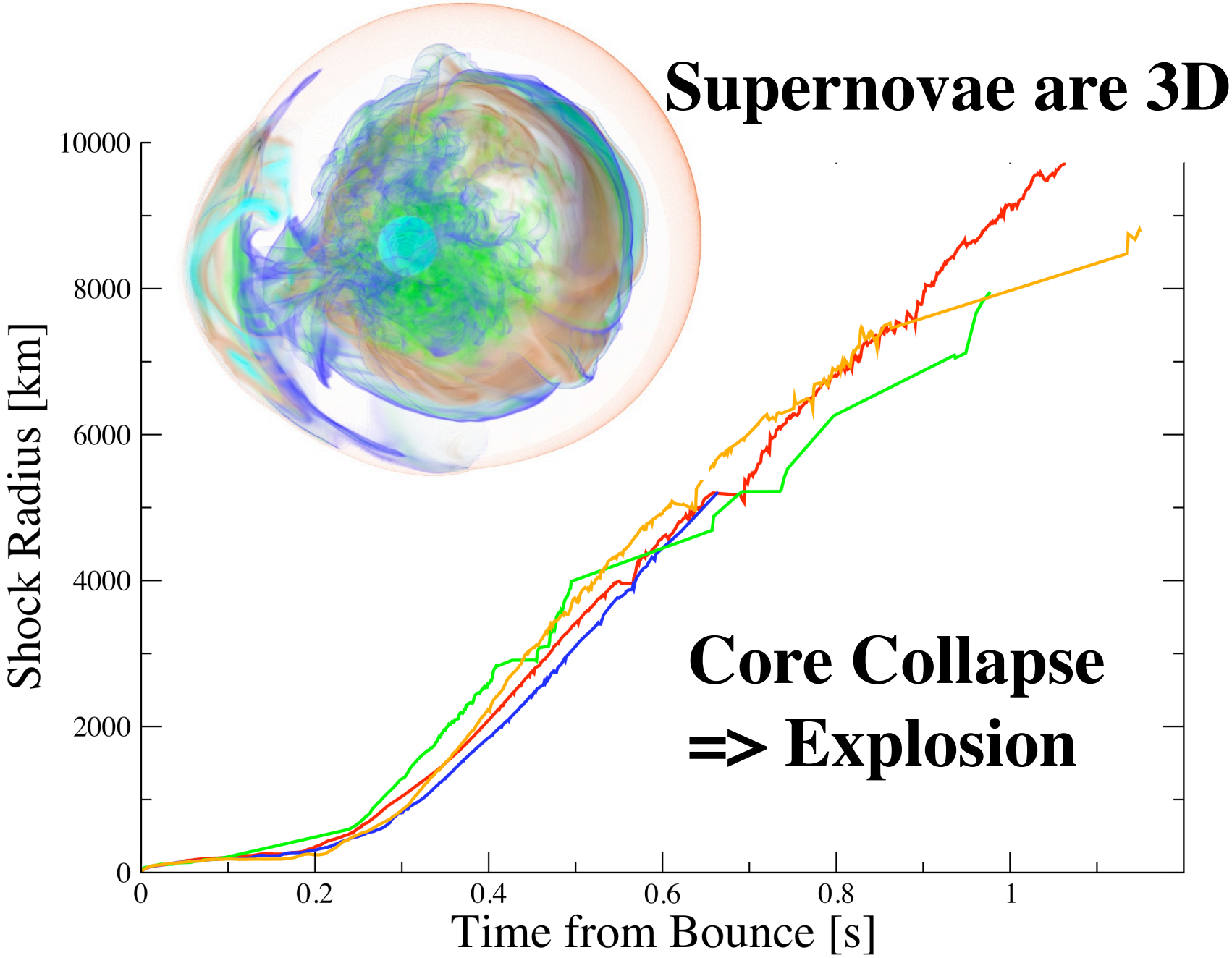
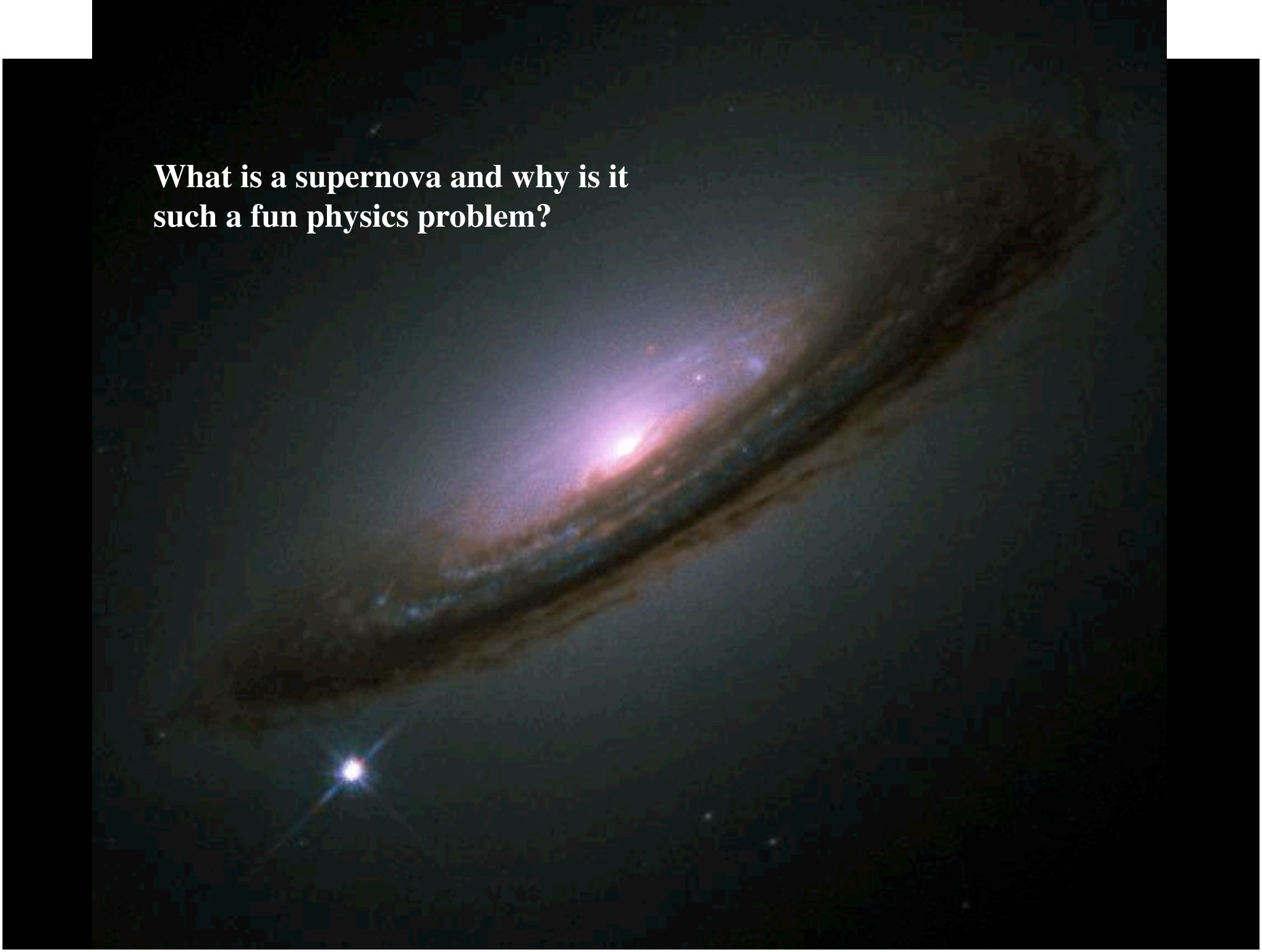
Breakthrough Science at the Petascale: Core Collapse Supernovae

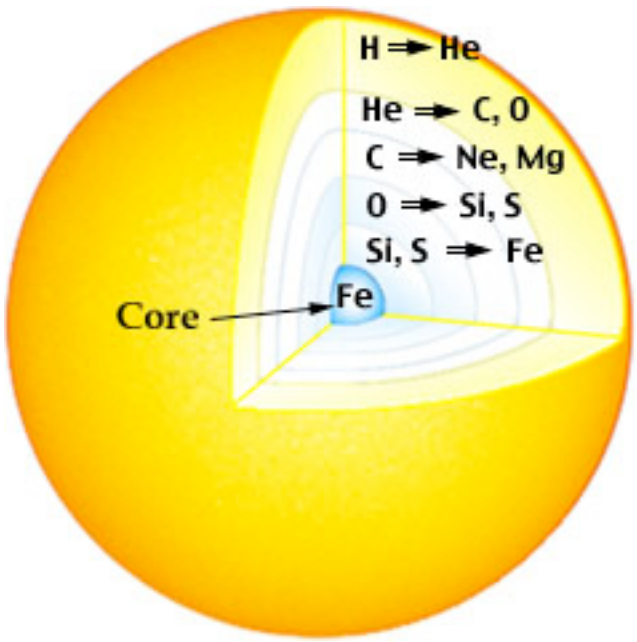


John M. Blondin
NC State University

NC STATE ASTROPHYSICS


Supernovae are 3D
Core Collapse
=> Explosion
Shock Radius [km]
Time from Bounce [s]
10000
8000
6000
4000
2000
0
0
0.2
0.4
0.6
0.8
1


What is a supernova and why is it
such a fun physics problem?



Gravity

Electromagnetic

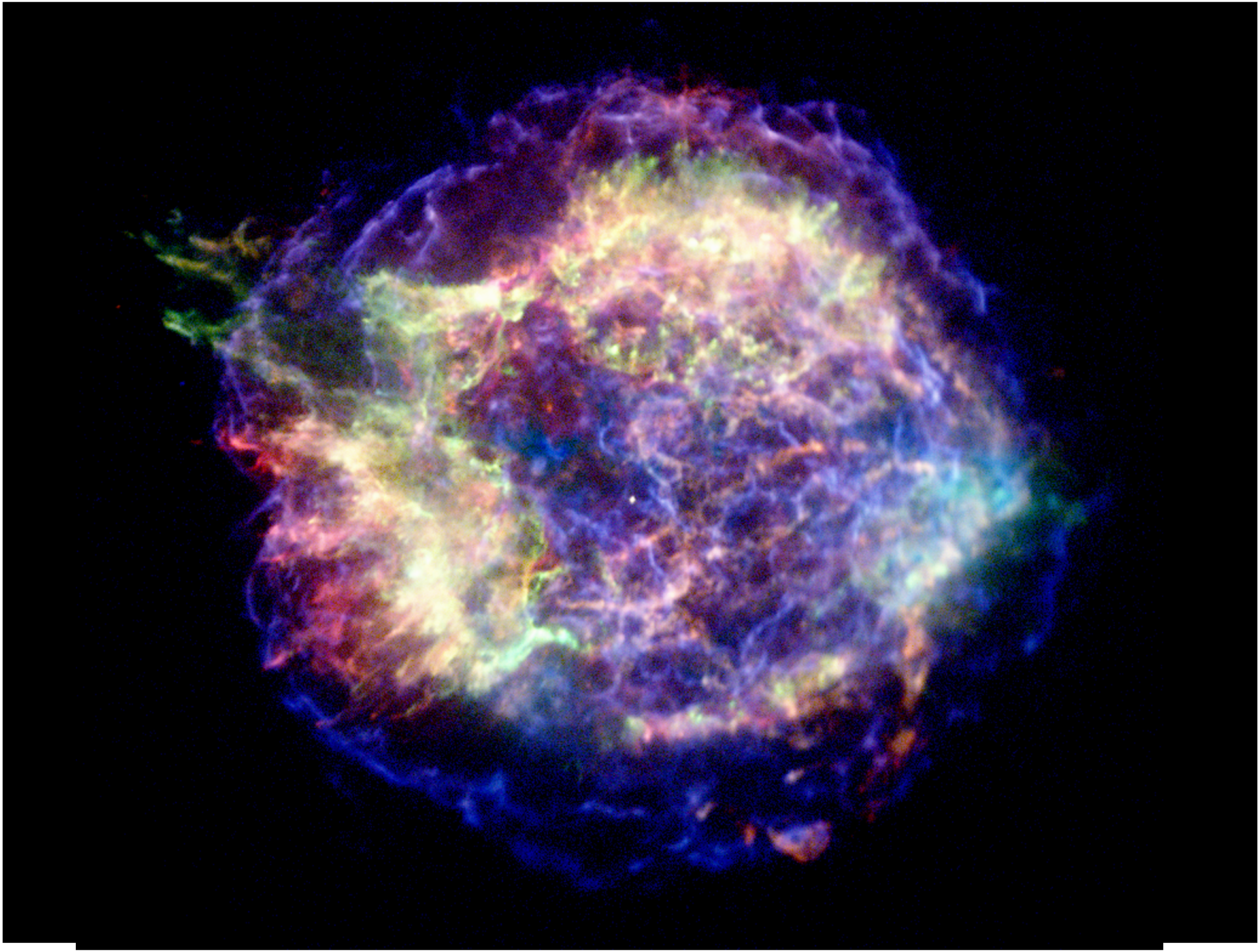
Strong Nuclear

Weak Nuclear

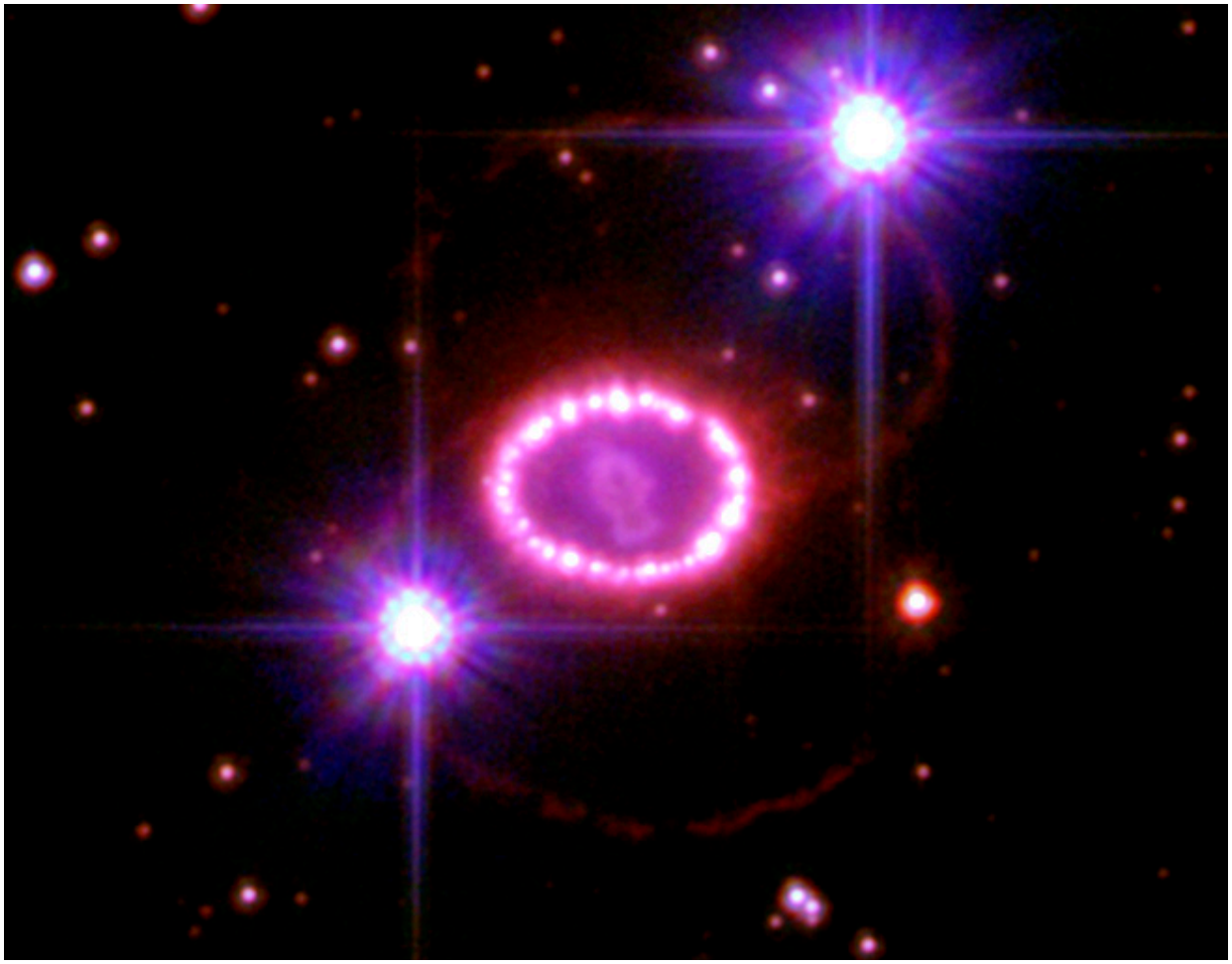
The iron core contains about 3 times the mass of our Sun, but it is roughly the size of our Earth.

This iron core collapses under its own weight until it is small enough to fit inside Puget Sound.

At this point the core is as dense as the nucleus of an atom and it cannot compress any further. The rest of the star 'bounces' off this hard core and explodes off into space???



SN 1987A: Supernovae are Asymmetric

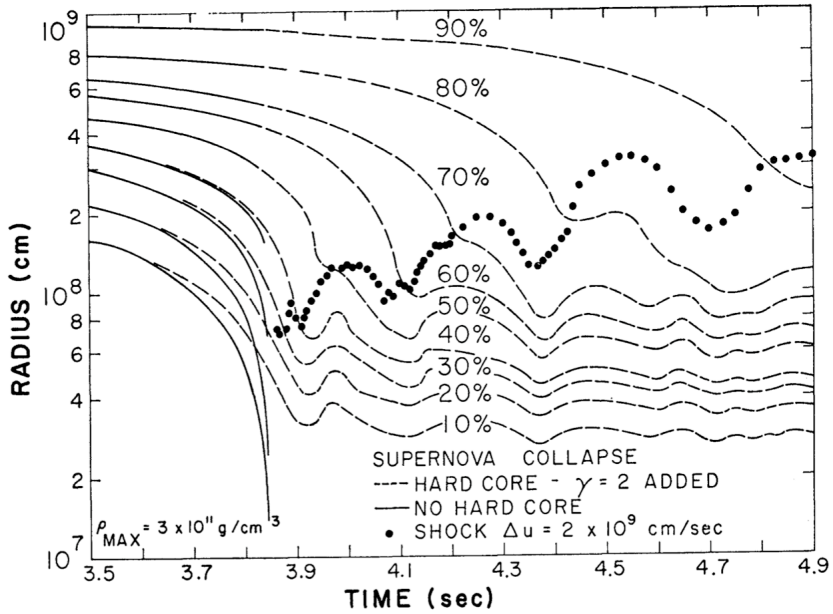


THE HYDRODYNAMIC BEHAVIOR OF SUPERNOVAE EXPLOSIONS*

STIRLING A. COLGATE AND RICHARD H. WHITE
Lawrence Radiation Laboratory, University of California, Livermore, California
Received June 29, 1965

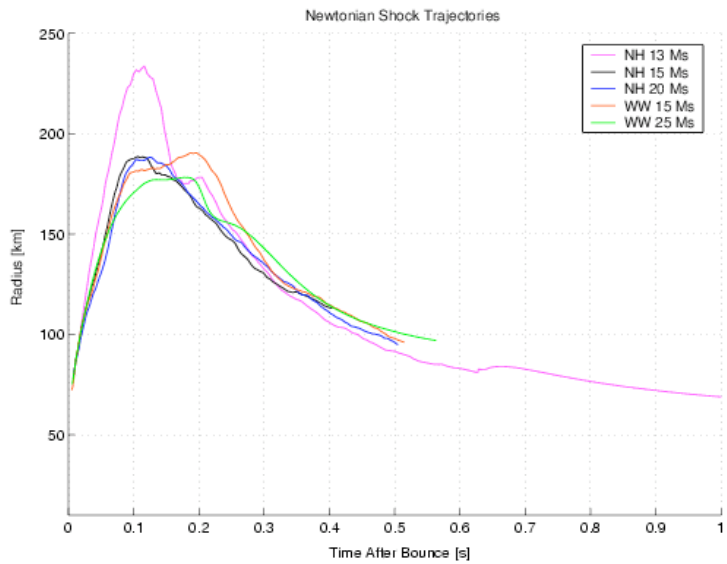
ABSTRACT

We regard the release of gravitational energy attending a dynamic change in configuration to be the primary energy source in supernovae explosions. Although we were initially inspired by and agree in detail with the mechanism for initiating gravitational instability proposed by Burbidge, Burbidge, Fowler, and Hoyle, we find that the dynamical implosion is so violent that an energy many times greater than the available thermonuclear energy is released from the star's core and transferred to the star's mantle in a supernova explosion. 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.



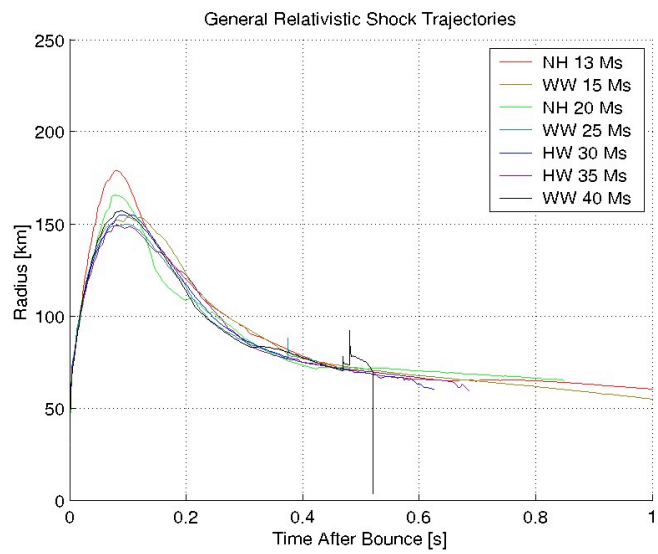
Completed: Spherical Models with Boltzmann Transport

Newtonian



Mezzacappa et al., PRL, 86, 1935 (2001)

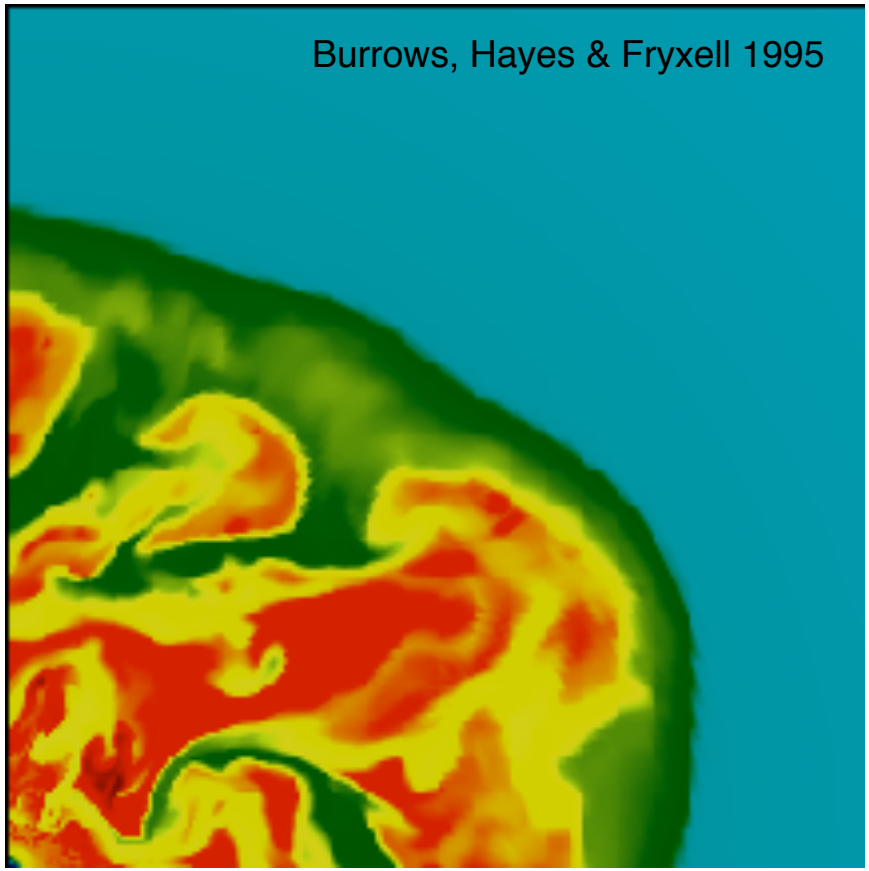
General Relativistic



Liebendoerfer et al., PRD, 63, 103004 (2001)

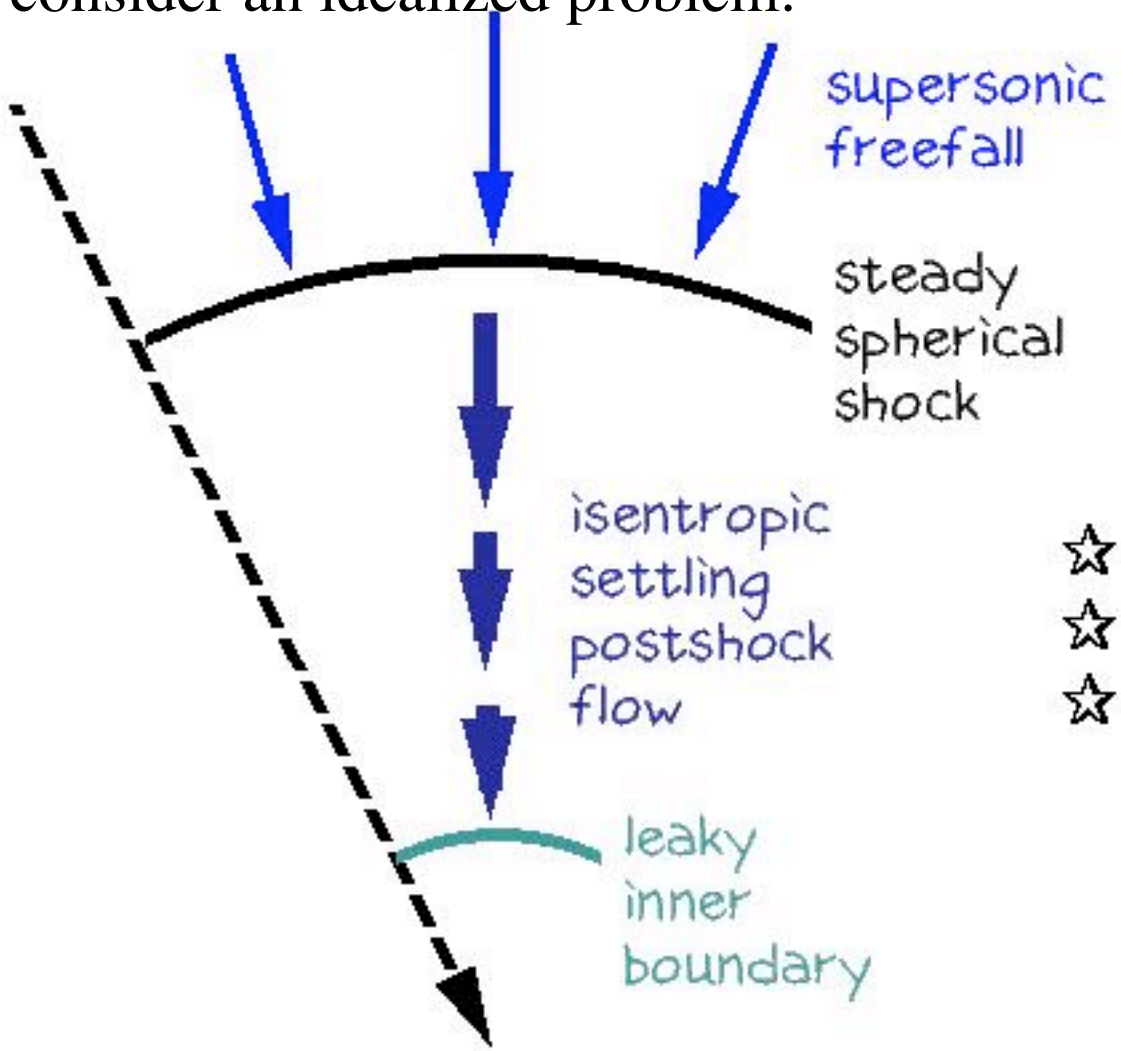
The simulation of core collapse supernovae with fully general relativistic, multi-angle, multi-frequency, Boltzmann neutrino transport has been achieved for spherically symmetric cases.

Go back to the first generation of 2D SN models which showed low-order asymmetry in the accretion shock.



Neutrino-driven convection breaks the initial spherical symmetry, but is not consistent with the low-order asymmetry seen at late times (100's of msec after bounce).

To investigate the dynamics of the stalled supernova shock, we consider an idealized problem:



- ☆ **Steady State**
- ☆ **Spherical**
- ☆ **Ideal Gas**

We focus on the hydrodynamics of the SN shock.

Euler equations for an ideal gas

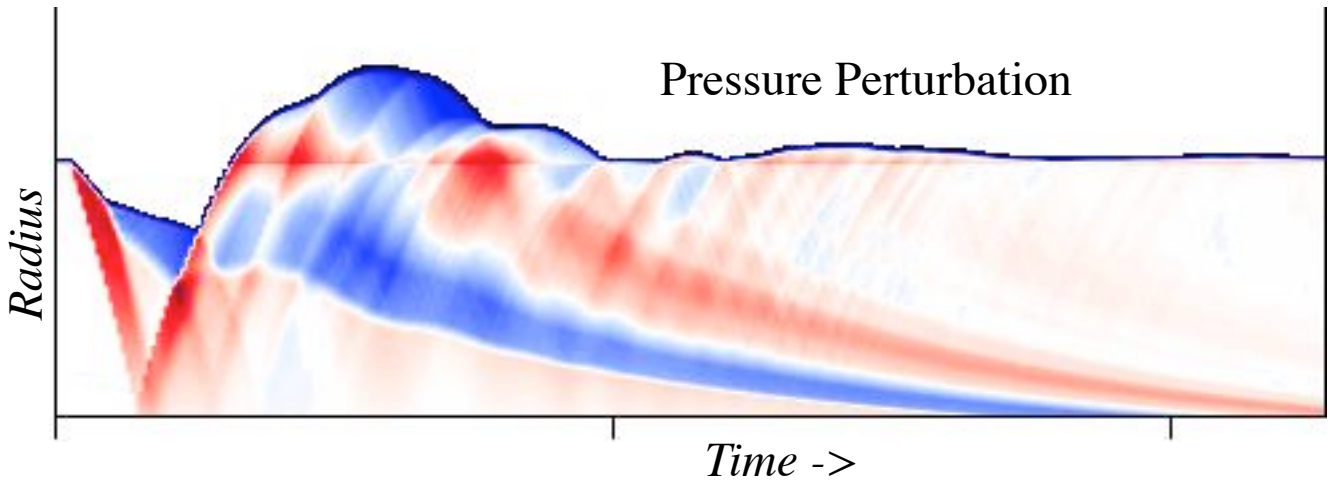
$$\partial_t \rho + \nabla \cdot (\rho \mathbf{u}) = 0,$$
$$\partial_t (\rho \mathbf{u}) + \nabla \cdot (\rho \mathbf{u}\mathbf{u}) + \nabla p = \mathbf{F},$$
$$\partial_t (\rho \mathcal{E}) + \nabla \cdot (\rho \mathcal{E} \mathbf{u}) + \nabla (p \mathbf{u}) = G + \rho \mathbf{u} \cdot \mathbf{F},$$

Equations are evolved using VH-1,
based on the piecewise parabolic method.

In One Dimension:

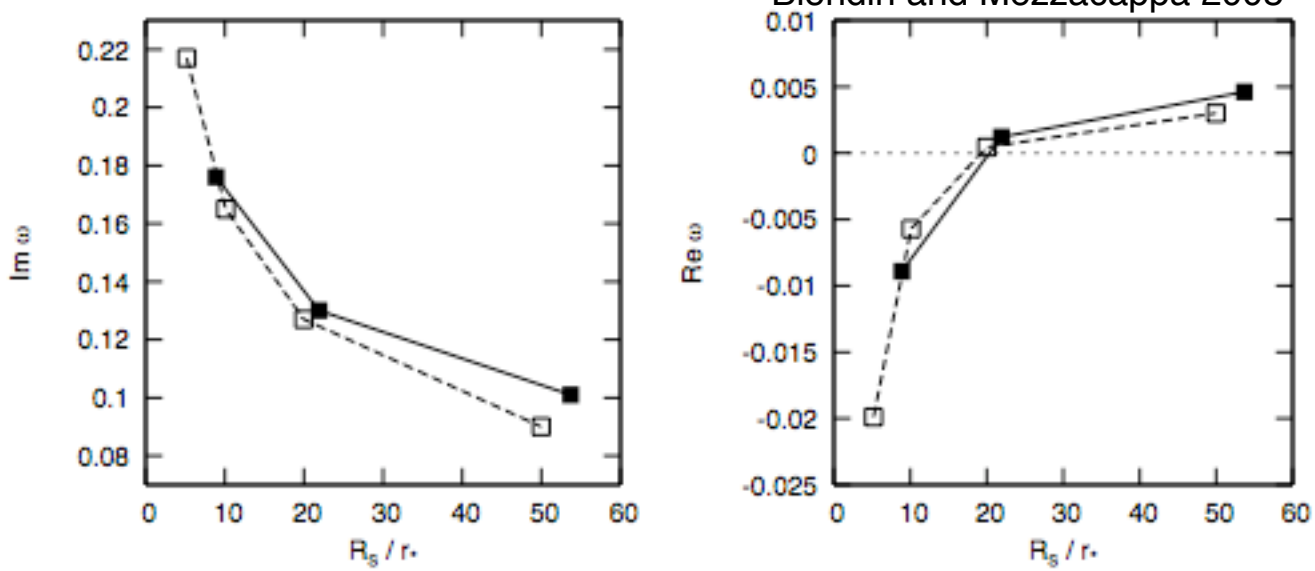
Analytical: Houck & Chevalier (1992) presented a linear stability analysis.

Numerical: Blondin et al. (2003) perturb SAS and watch the evolution.



SN Code Verification

Houck and Chevalier 1992
Blondin and Mezzacappa 2005

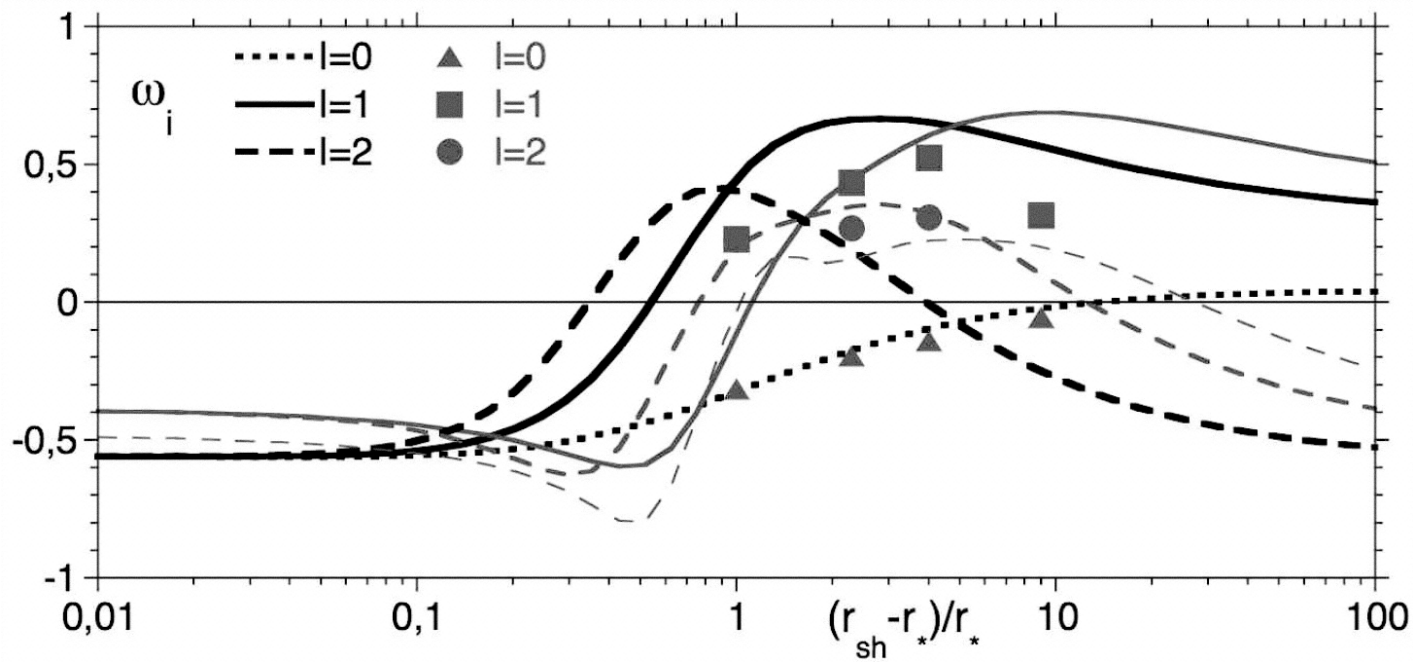


This post-bounce model provides an opportunity to verify supernova codes against the results of a linear perturbation analysis.

analytic

numerical

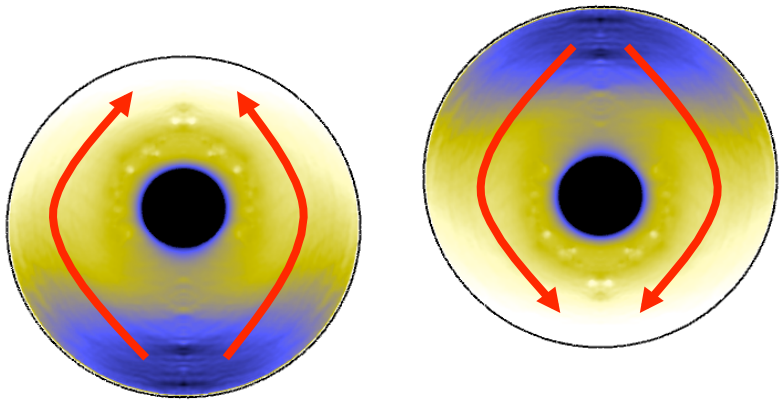
Foglizzo, Galletti, Sheck & Janka 2007



Agreement between analytic and numerical methods for linear growth of the SASI is OK – or not?

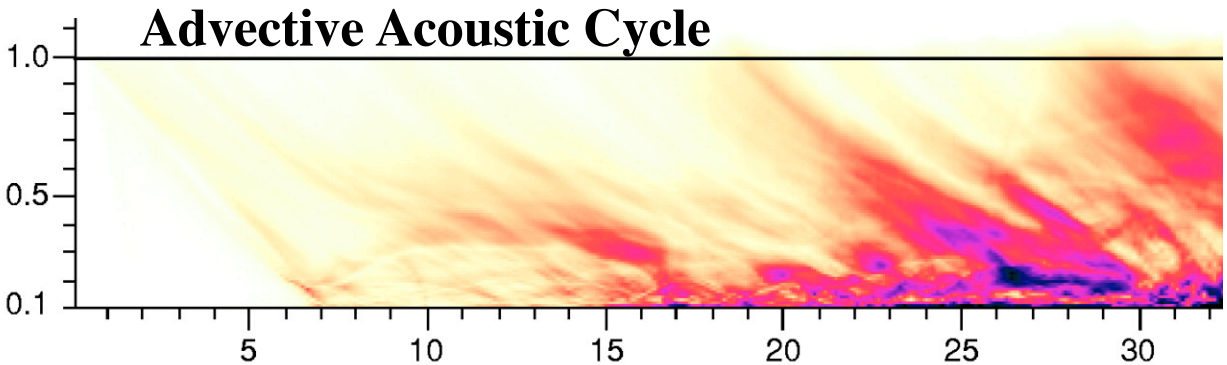
Which Acoustic Mechanism?

Trapped Global Pressure Waves



The spherical accretion shock acts as an acoustic cavity, with a trapped standing wave growing exponentially with time.

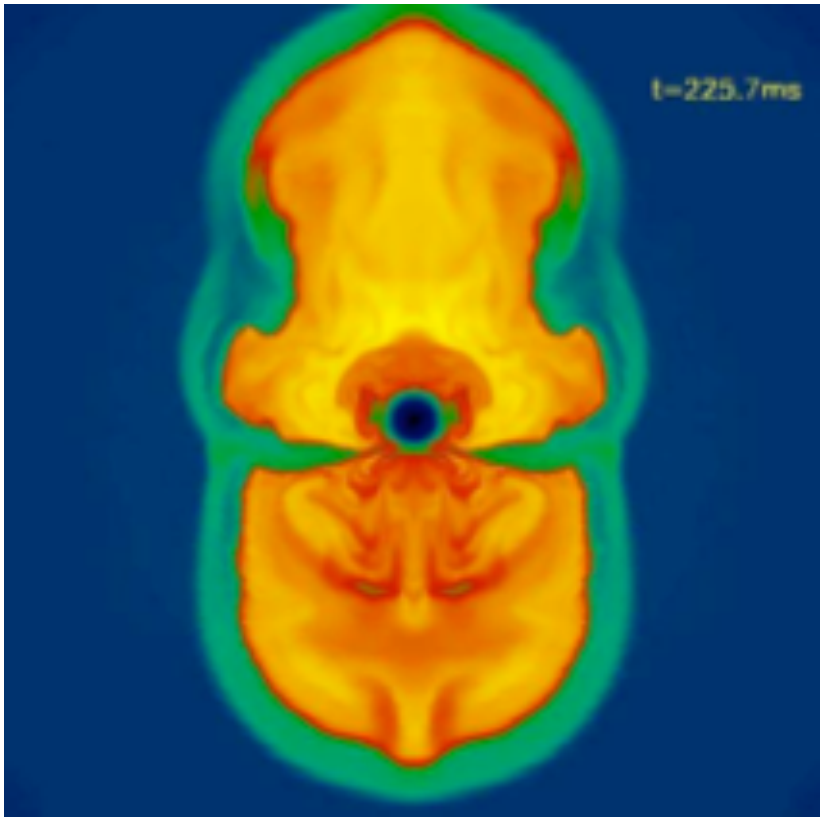
Advective Acoustic Cycle



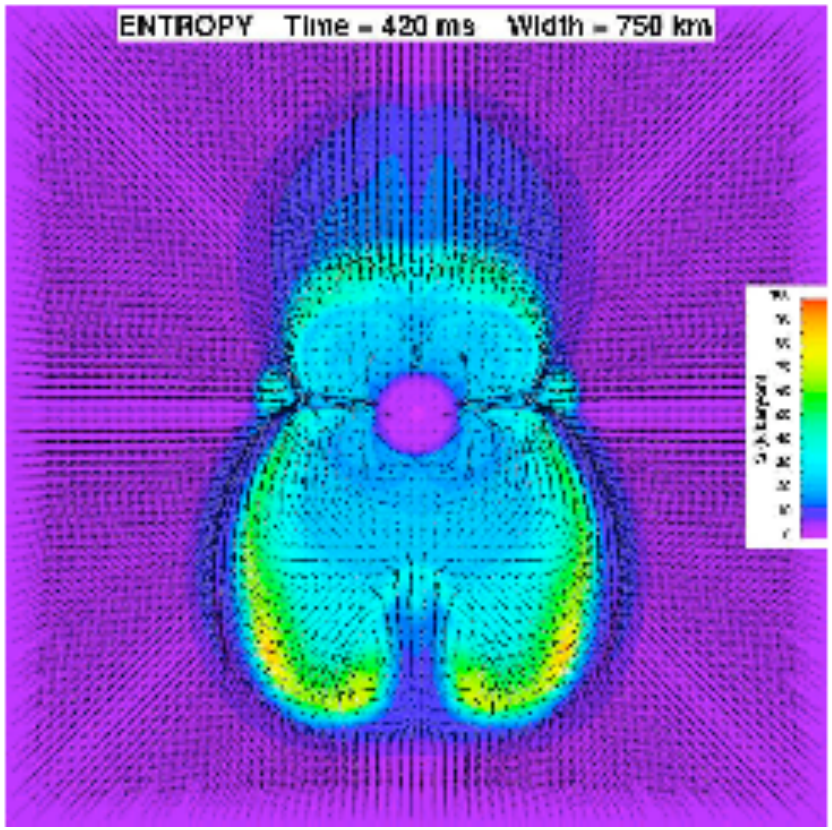
Advected vorticity couples to pressure perturbations at some small radius, which propagate radially outward and perturb the shock.

(NOT 'The Acoustic Mechanism' of Burrows et al.!)

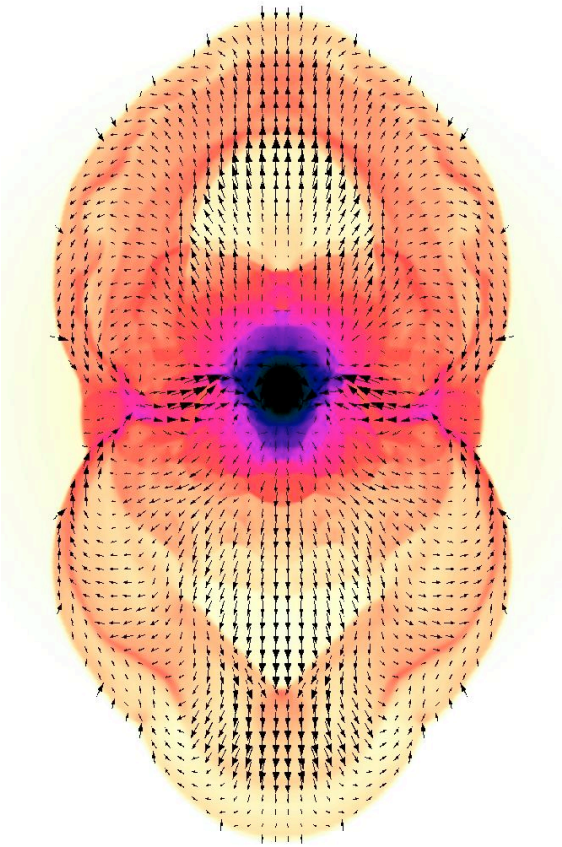
The SASI is a common feature of 2D SN simulations…

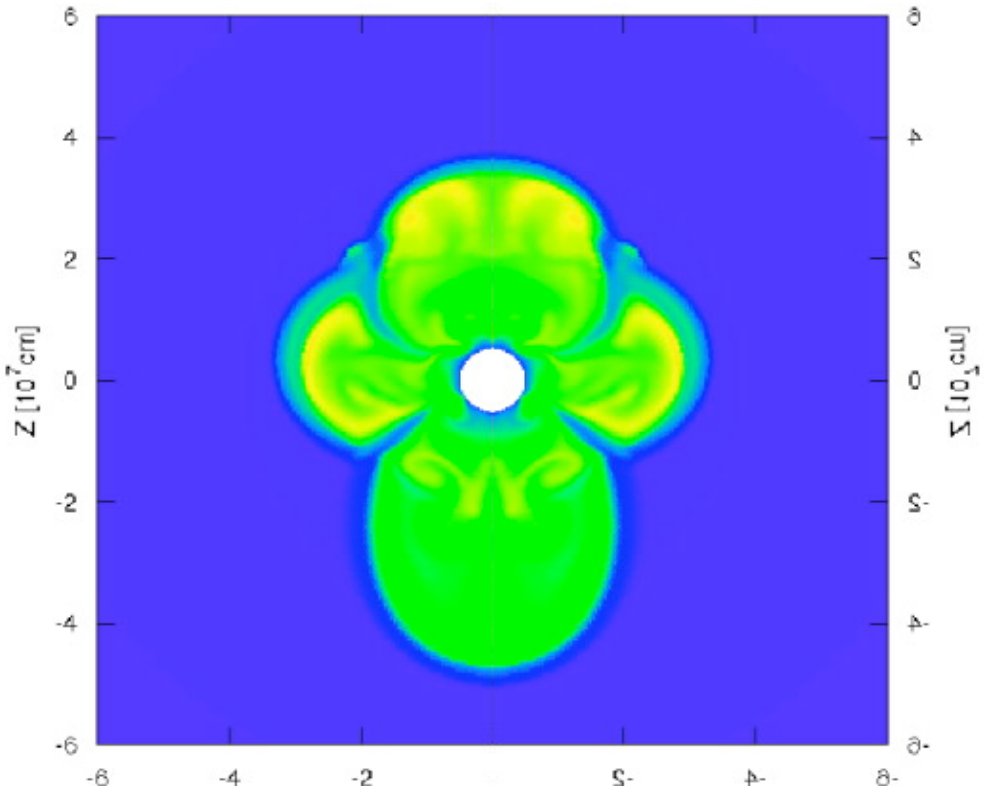


Janka et al.



Burrows et al.

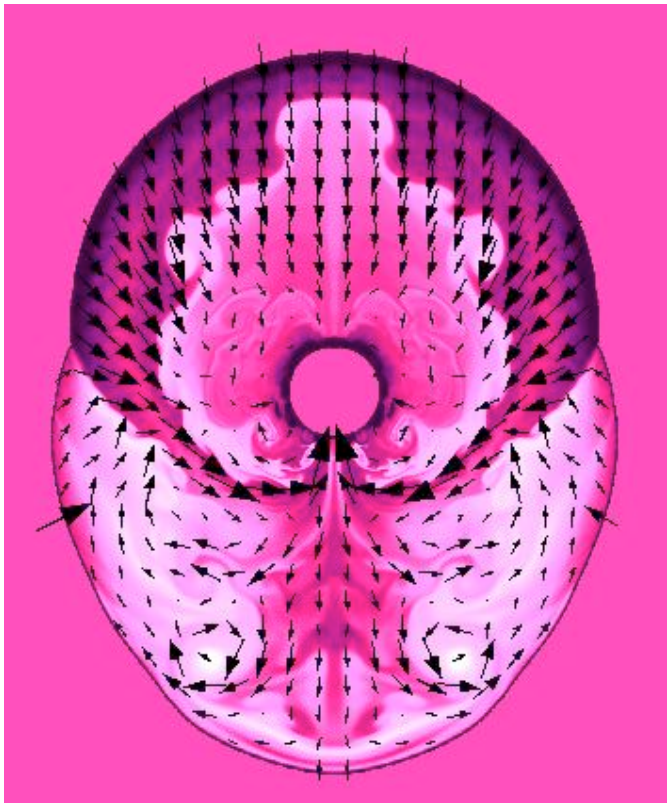




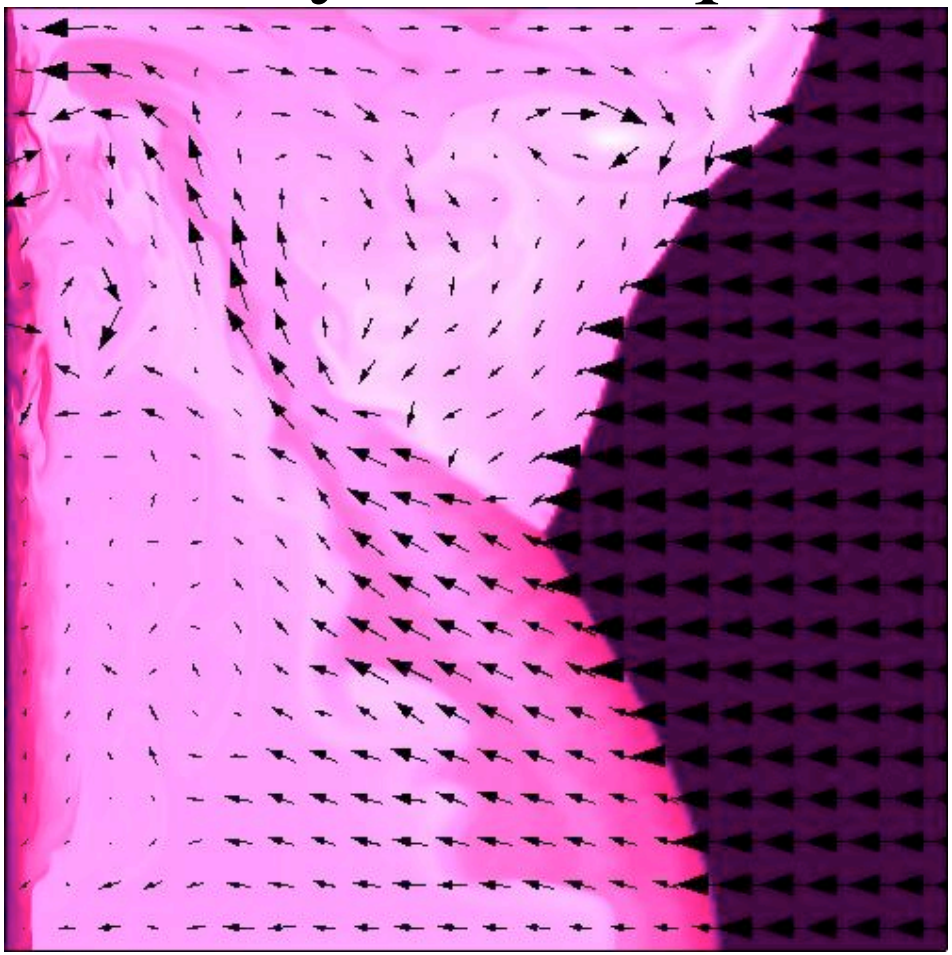
Blondin et al.

Kotake, Ohnishi & Yamada, 2007

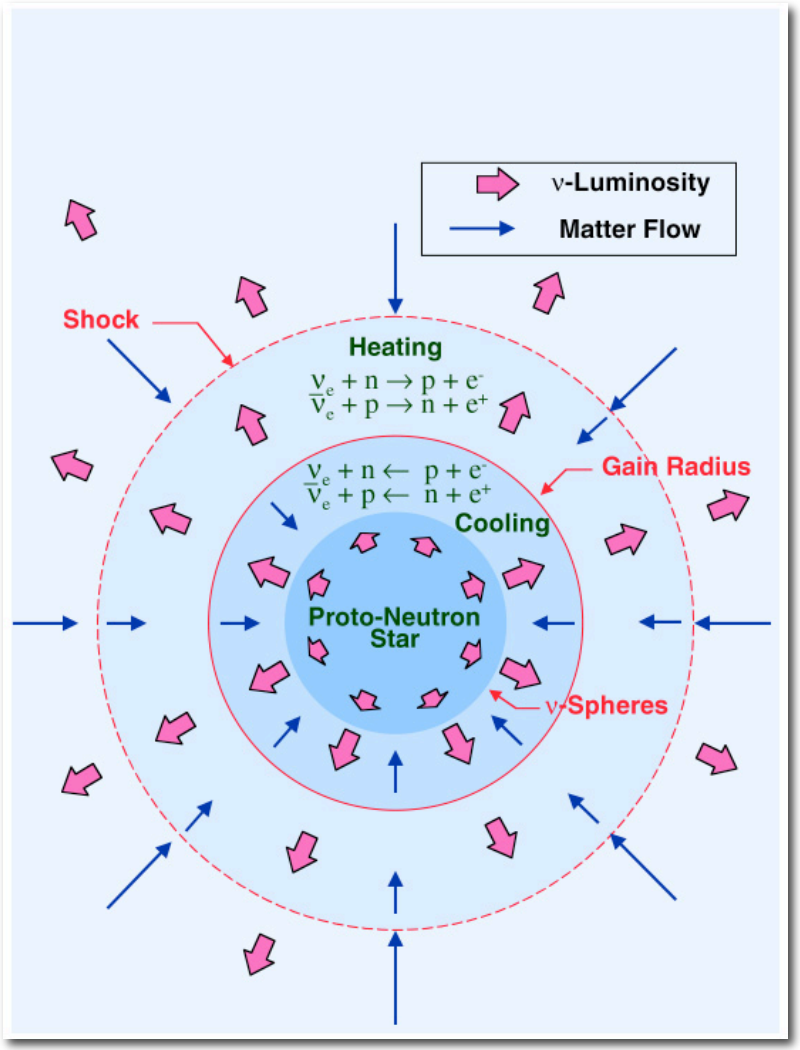
Does large-scale flow driven by convection distort the spherical shock?



Are bulk flows and entropy variations **created** by the oblique shock?



The Heart of the Matter



Neutrino heating depends on neutrino luminosities, spectra, and angular distributions.

$$\dot{\epsilon} = \frac{X_n}{\lambda_0^a}\frac{L_{\nu_e}}{4\pi r^2}\langle E_{\nu_e}^2\rangle\langle\frac{1}{\mathcal{F}}\rangle + \frac{X_p}{\bar{\lambda}_0^a}\frac{L_{\bar{\nu}_e}}{4\pi r^2}\langle E_{\bar{\nu}_e}^2\rangle\langle\frac{1}{\bar{\mathcal{F}}}\rangle$$

Neutrino heating is sensitive to all three (most sensitive to neutrino spectra).

⇨ ***Must compute neutrino distributions.***

$$f(t,r,\theta,\phi,E,\theta_p,\phi_p)$$

Multifrequency Multiangle

$$E_R(t,r,\theta,\phi,E) = \int d\theta_p\, d\phi_p\, f$$

Multifrequency (*Parameterize Isotropy*)

$$E_R(t,r,\theta,\phi) = \int dE\, d\theta_p\, d\phi_p\, f$$

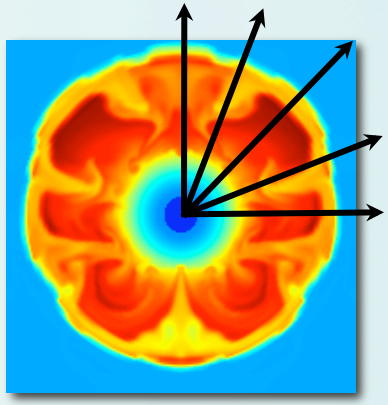
Gray (*Parameterize Isotropy and Spectra*)

Ongoing 2D,3D Multi-Physics Supernova Models

Simulation Building Blocks

- ➲ *"RbR-Plus" MGFLD Neutrino Transport*
- ➲ *2D PPM Hydrodynamics*
- ➲ *Lattimer-Swesty EOS*
- ➲ *Nuclear (Alpha) Network*
- ➲ *2D Newtonian Gravity with GR Corrections*
- ➲ *Neutrino Emissivities/Opacities*
  - *"Standard" + Elastic Scattering on Nucleons + Nucleon–Nucleon Bremsstrahlung*

CHIMERA



"Ray-by-Ray" Approximation

Size:

- 150,000 lines of executable code.

Language:

- Fortran 90

Parallel Programming Model

- MPI (some OpenMP)

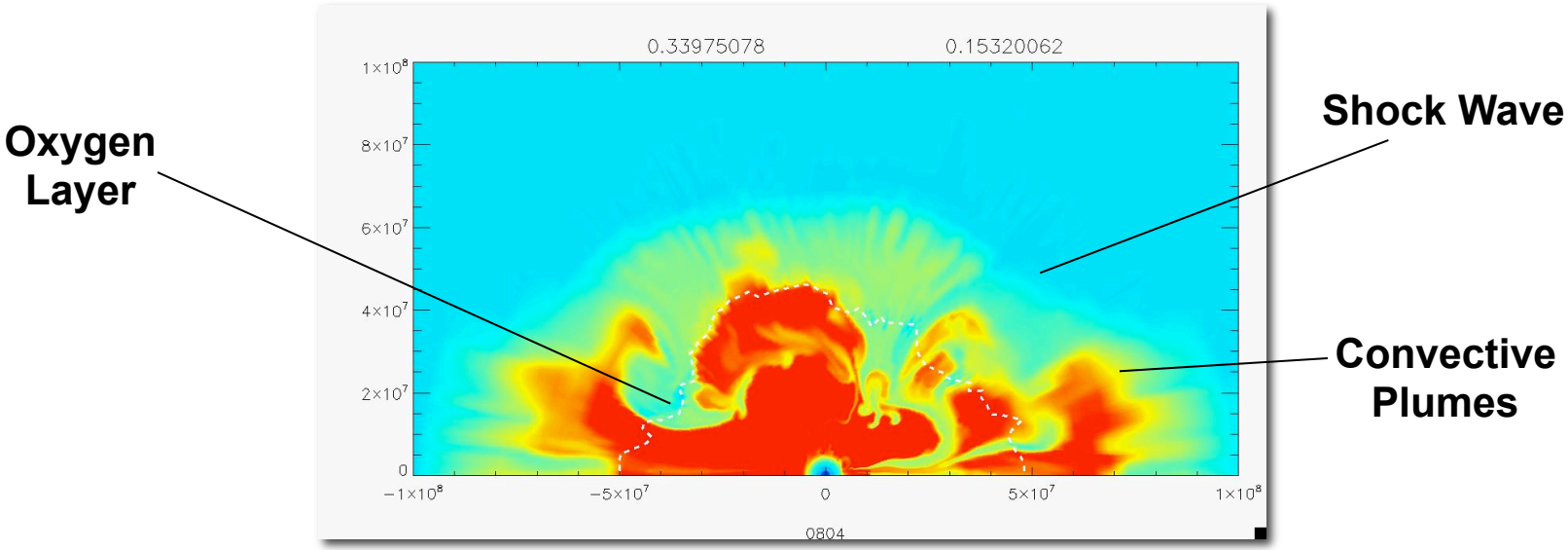
Major Components:

- Hydrodynamics: MVH3 (latest version of VH-1)
- Neutrino Transport: MGFLD_TRAN
- Nuclear Network: XNET

Libraries:

- LAPACK
- HDF5, pNETCDF

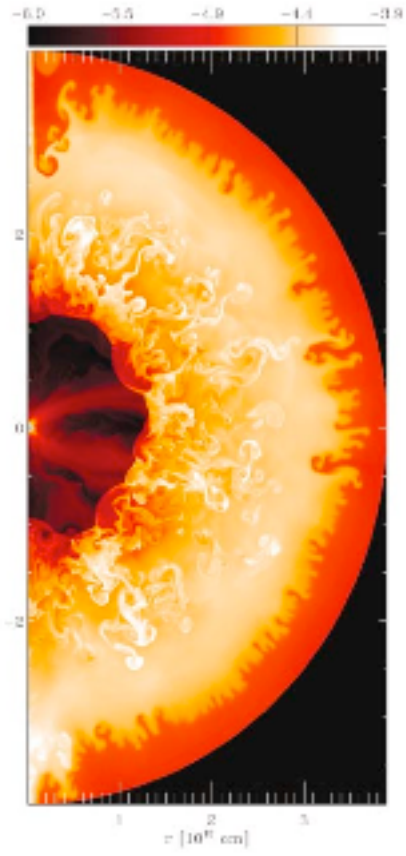
An Emerging Picture from 2D Multi-Physics Models



- ➲ Shock powered in part by neutrino heating from below, aided by convection.
- ➲ Shock distorted into cigar shape by the shock instability (SASI), which precipitates arrival in oxygen layer.
- ➲ Explosion occurs when shock reaches oxygen layer (marked in white).
  - ⇨ Density ahead of shock decreases rapidly there (less for shock to plow through).
  - ⇨ Nuclear burning (of oxygen) begins, depositing additional energy.

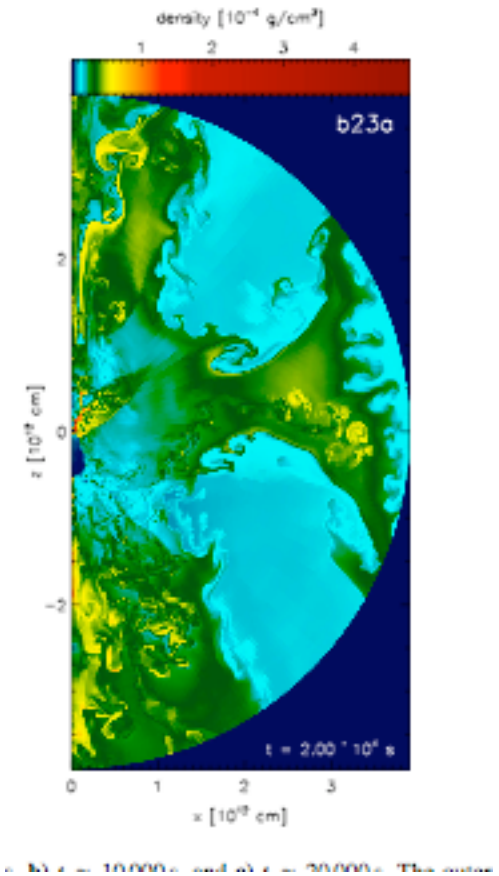
⇨ ***Confluence of neutrino heating, convection, the SASI, nuclear burning, and drop in density lead to an explosion at late times.***

SASI leaves imprint on supernova after breakout.



Originally used high neutrino luminosity to drive explosion; only small-scale anisotropy.

Later, used self-consistent model with delayed explosion and SASI. Large-scale anisotropy explains many features of SN 1987A.

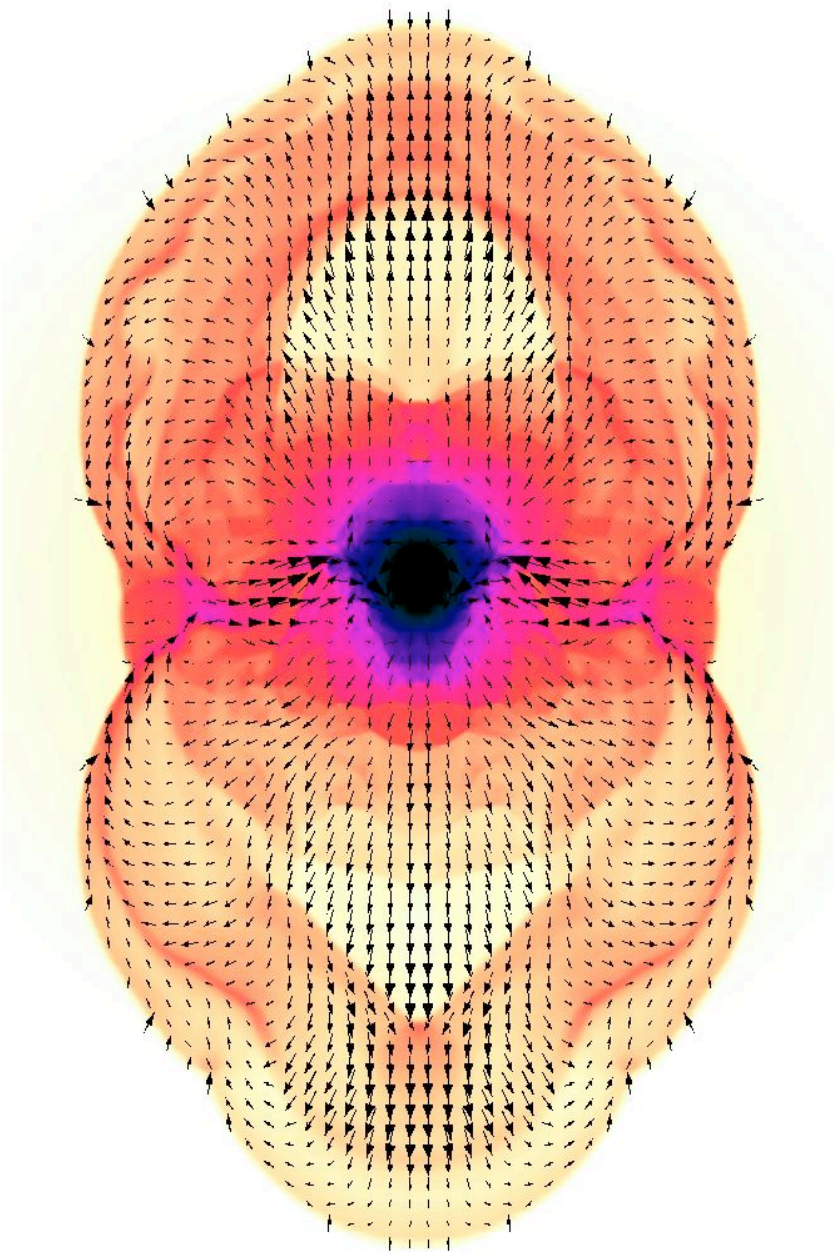


Kifonidis et al. 2003

Kifonidis et al. 2006

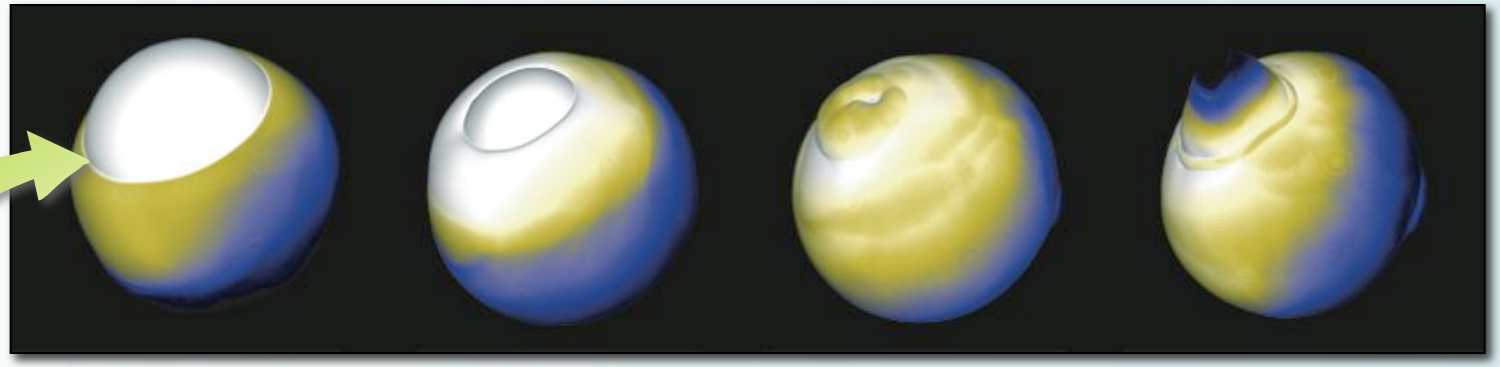
Must move to 3D!

The initial SASI discovery with axisymmetric 2D simulations pointed to the obvious need for models in full 3D.

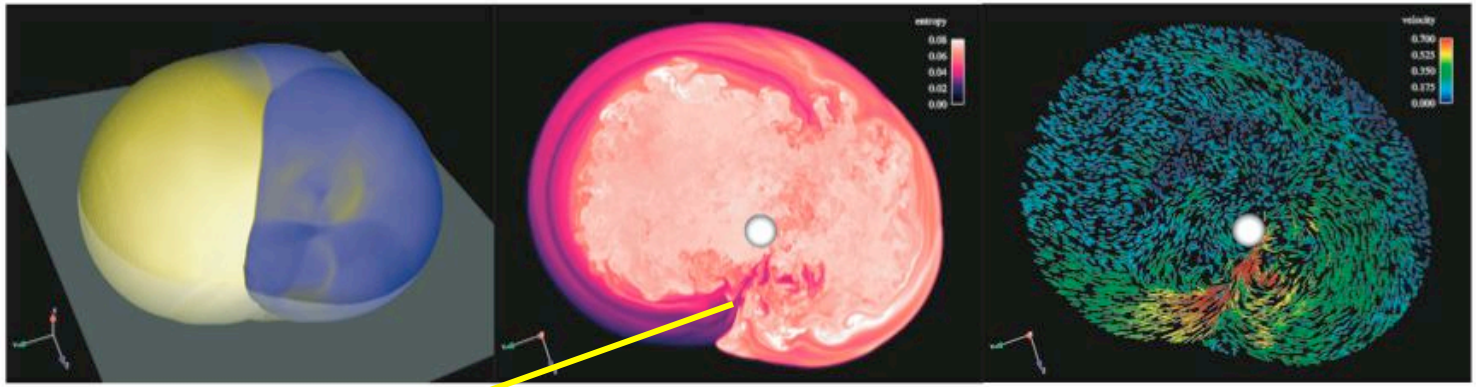


Evolution of the Mach Reflection

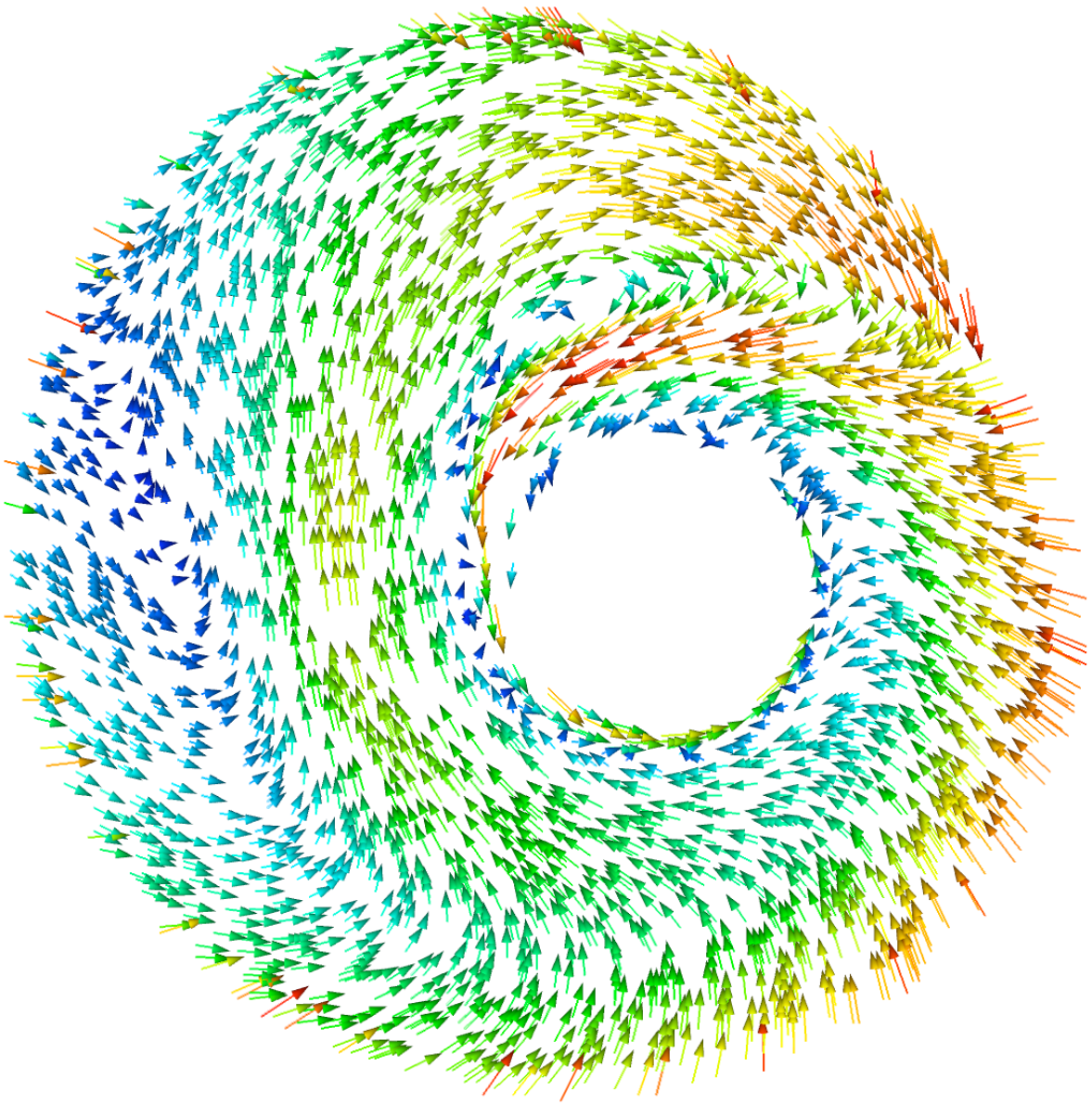
- Symmetry of Mach reflection broken in three dimensions.



Mach Reflection



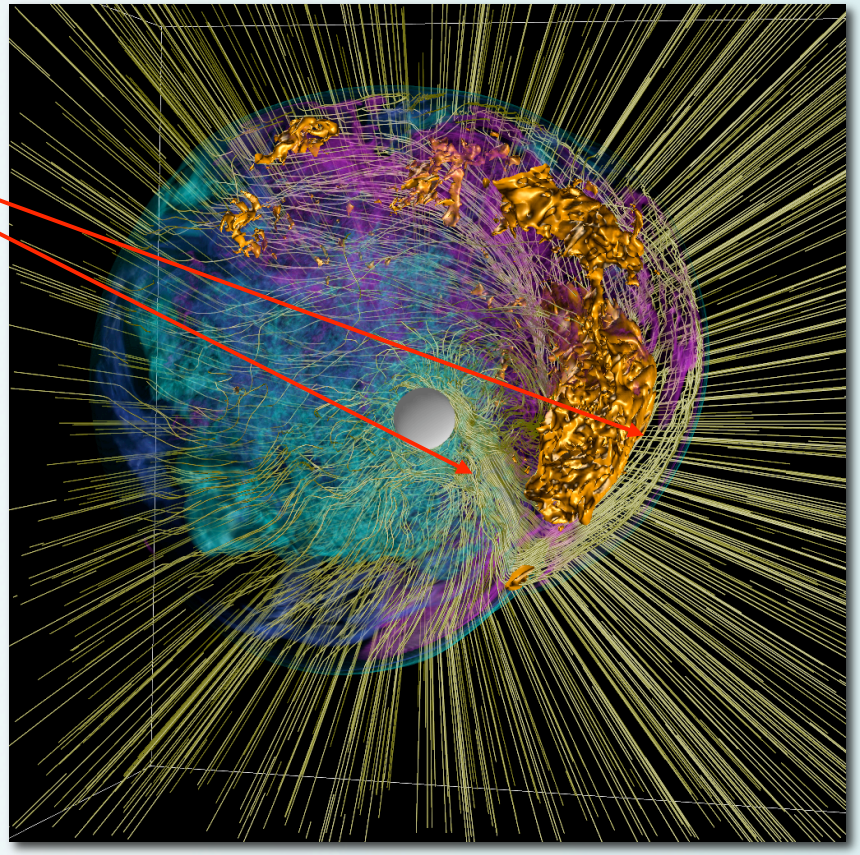
- Internal shock (orthogonal to supernova shock) leads to two counter rotating flows.



Ramifications...

SASI-induced counter rotating flows.

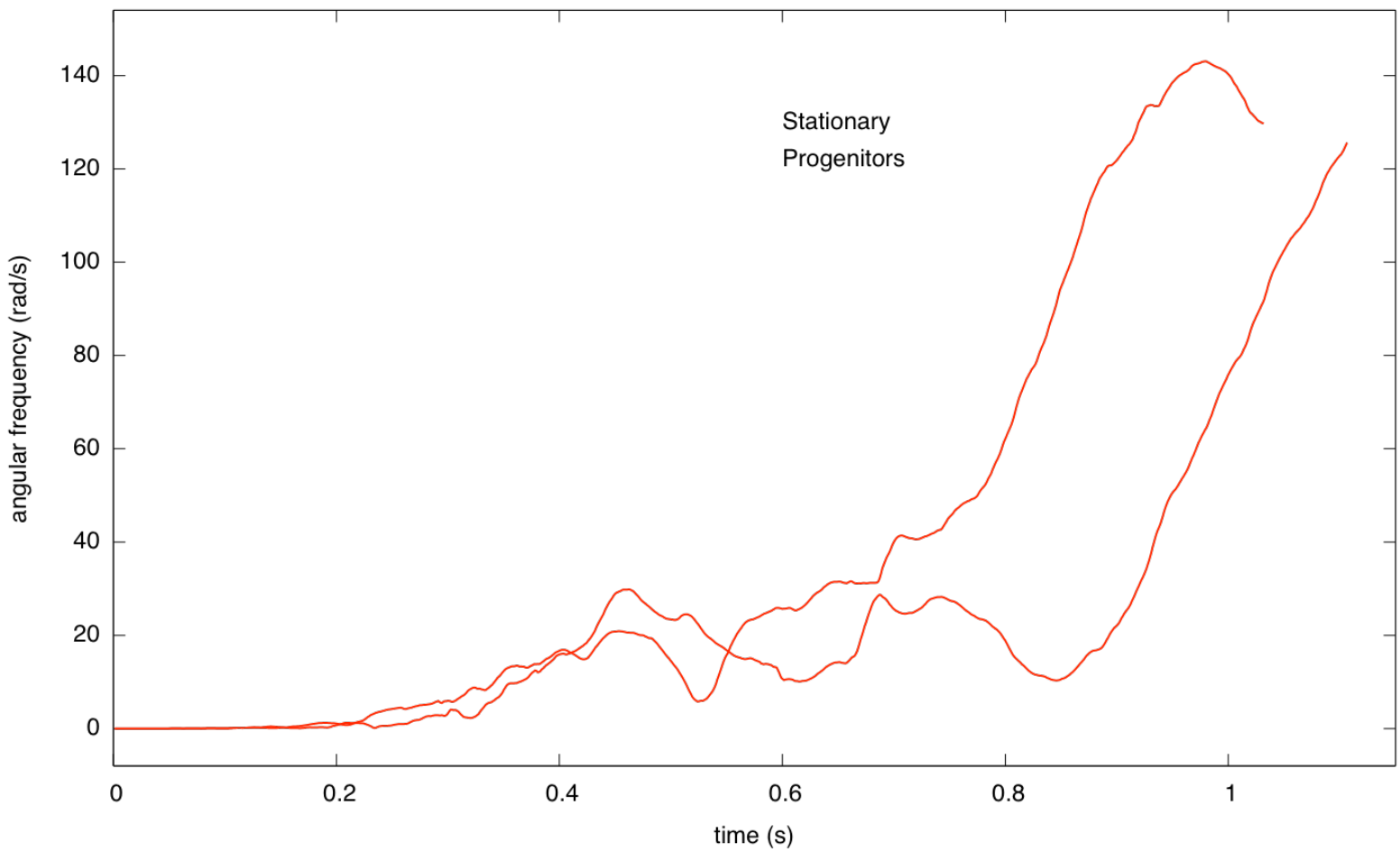
Inner flow capable of spinning up remnant NS to 50 ms periods, even beginning with spherically symmetric initial conditions.

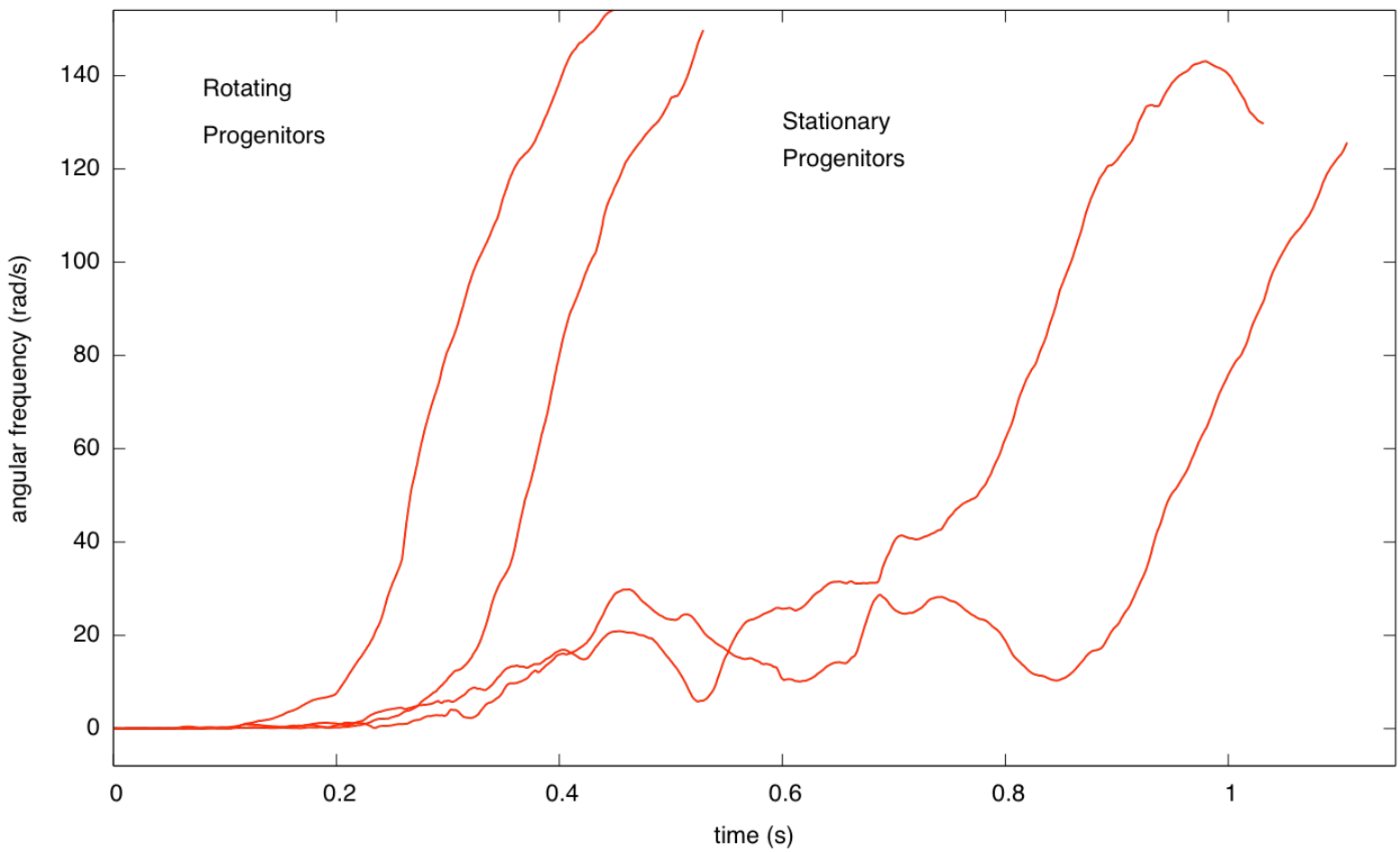


Blondin and Mezzacappa, *Nature*, 445, 58 (2007)

Implications for

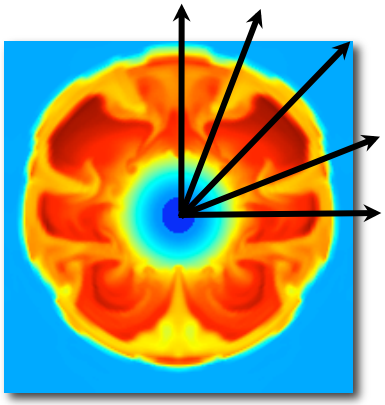
- ⇨ the growth of B fields?
- ⇨ the supernova mechanism?
- ⇨ supernova observables?


Stationary
Progenitors
angular frequency (rad/s)
time (s)
0
20
40
60
80
100
120
140
0
0.2
0.4
0.6
0.8
1


Rotating
Progenitors
Stationary
Progenitors
angular frequency (rad/s)
140
120
100
80
60
40
20
0
0
0.2
0.4
0.6
0.8
1
time (s)

3D Multi-Physics: A Quantum Leap in Difficulty

Ray-by-Ray Approximation

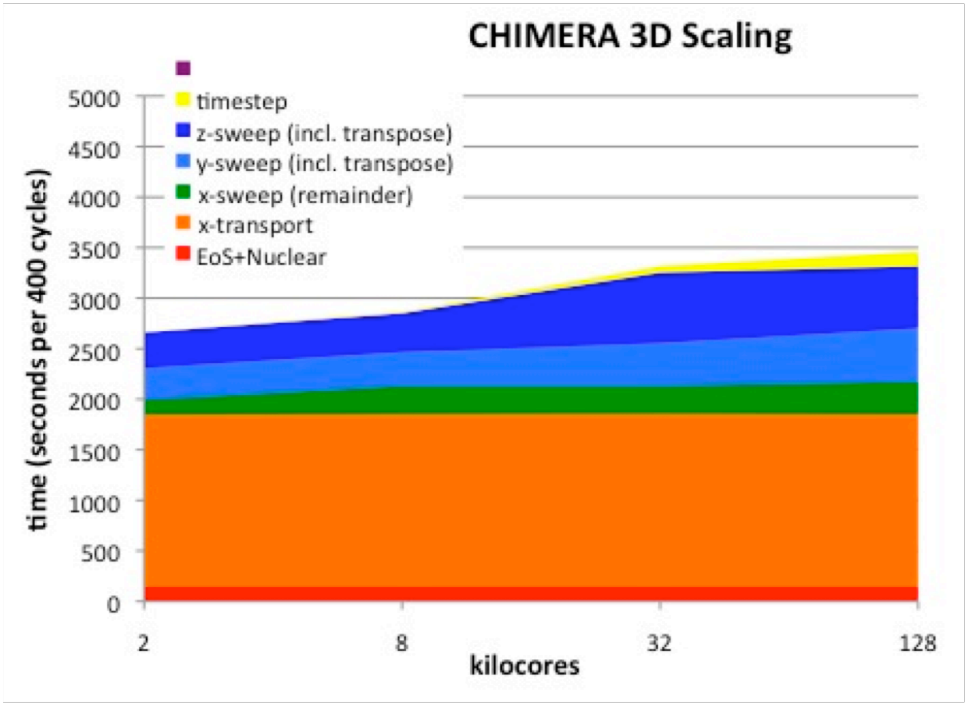


$$N_{\text{cores}} = N_{\text{rays}} = N_{\theta} \times N_{\phi}$$

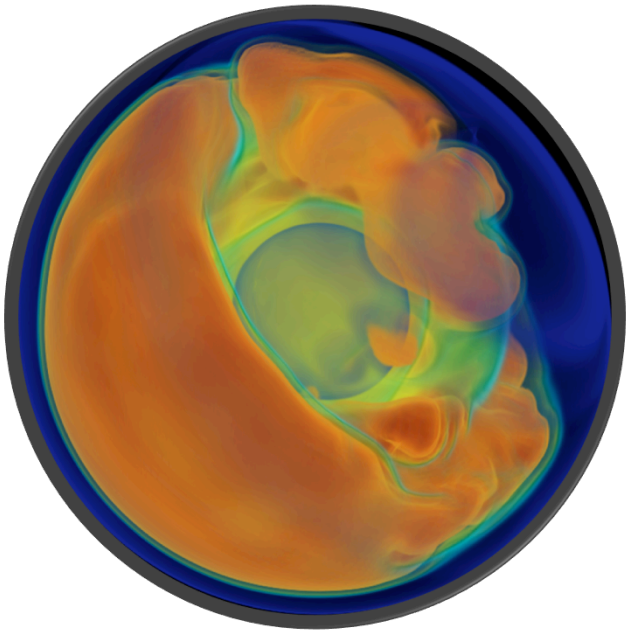
	Number of Cores	Latitudinal Zones	Longitudinal Zones
CY08	12,168 (250 TF)	78 (2-3 Degree Resolution)	156 (2-3 Degree Resolution)
CY09	73,728 (1 PF)	192 (1 Degree Resolution)	384 (1 Degree Resolution)

Runtime: ~1 month per run at 1 ray per core.

- ⇨ ***CY08: ~10 M processor-hours/run.***
- ⇨ ***CY09: ~50 M processor-hours/run.***

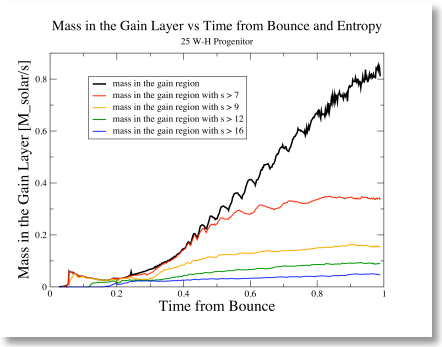

CHIMERA 3D Scaling
timestep
z-sweep (incl. transpose)
y-sweep (incl. transpose)
x-sweep (remainder)
x-transport
EoS+Nuclear
time (seconds per 400 cycles)
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
2
8
32
128
kilocores

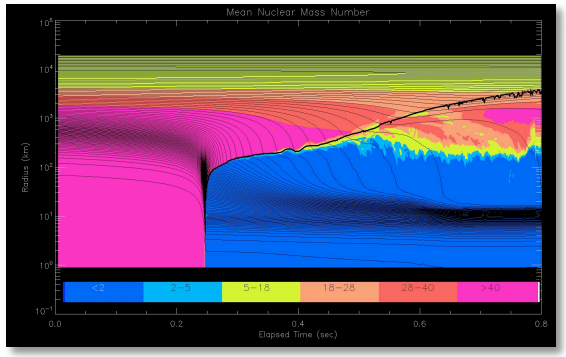
CHIMERA

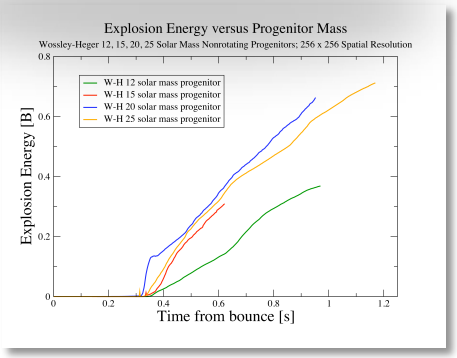


3D simulations are running

Ongoing 1D & 2D to *understand* results







Ultimately need to move beyond radial transport…

Size:

- 40,000 lines of executable code *and climbing*.

Language:

- Fortran 90/95

Parallel Programming Model

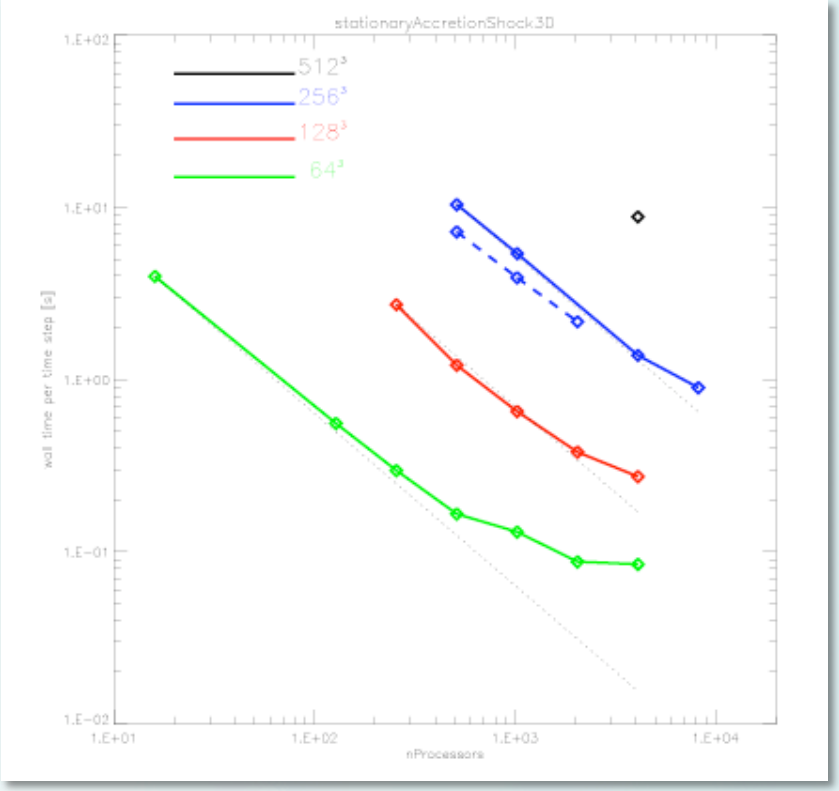
- MPI

Major Components:

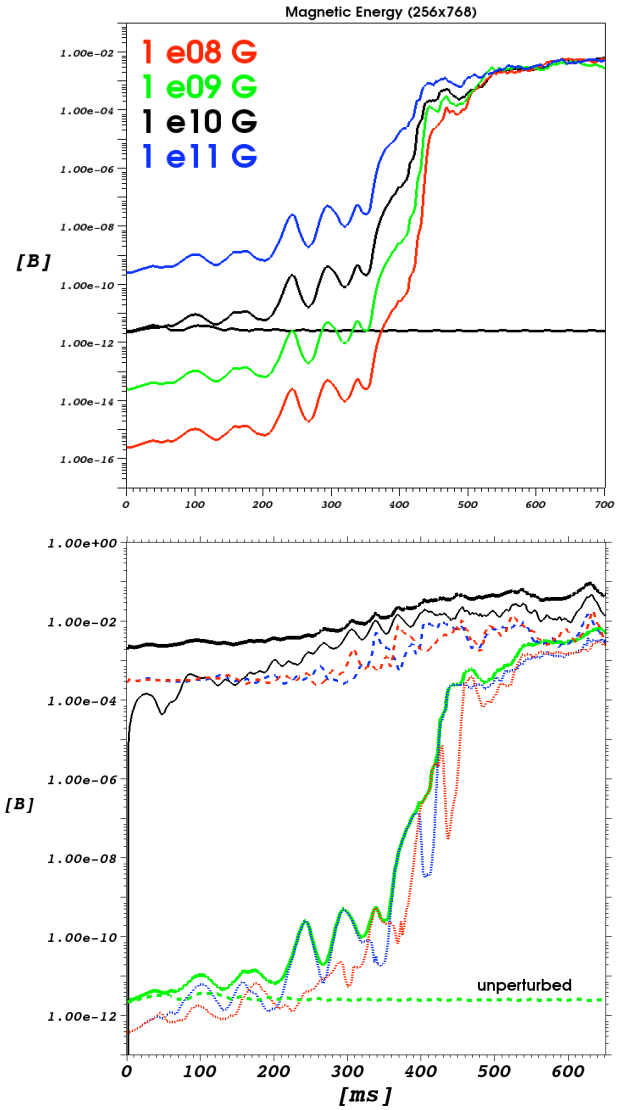
- Cell-by-cell AMR
- Magnetohydrodynamics
- (3D) Self-gravity
- Neutrino Transport (future)
- Nuclear Network (future)

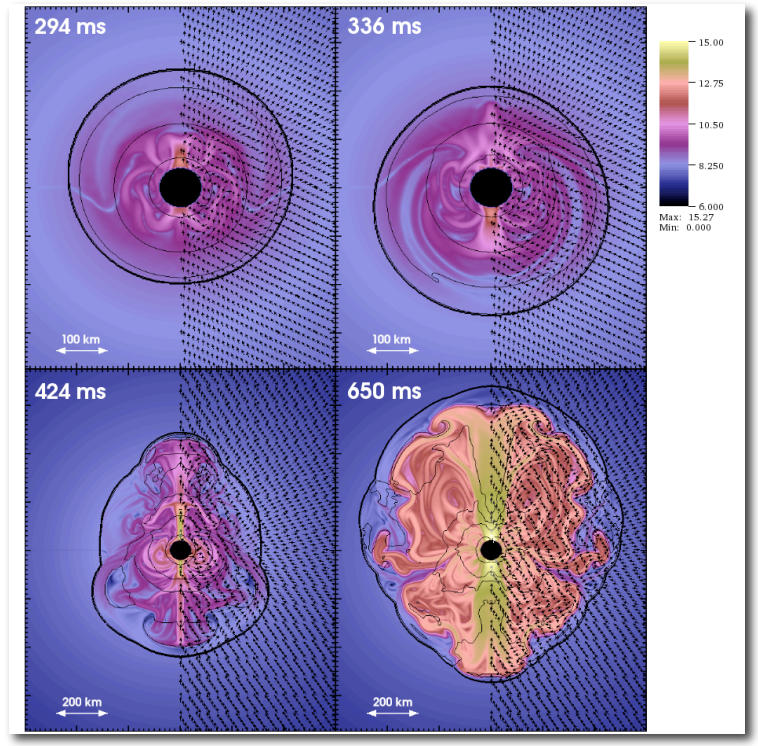
Libraries:

- LAPACK (future)
- FFTW
- Silo/HDF5



GenASiS: First Science Results





Conclusion: There can be significant amplification of the stellar core magnetic fields due to the SASI.

- ***Fields amplified to 10^{15} Gauss!***
- **Fields become dynamically significant.**

Endeve, Cardall, and Mezzacappa (2008), in preparation

The Need for Exascale Resources

Dominated by preconditioning of dense blocks.

$$\text{FLOPS} \sim N_t N_s N_i f N_m^{\,2} \sim 8 \times 10^{22} f$$

N_t = number of time steps $\sim 1 \times 10^6$

N_s = number of spatial zones $\sim 512 \times 512 \times 512$

N_i = number of outer iterations per time step ~ 10

N_m = number of neutrino momentum zones

$f \in [1, N_m] = [1, 7680]$

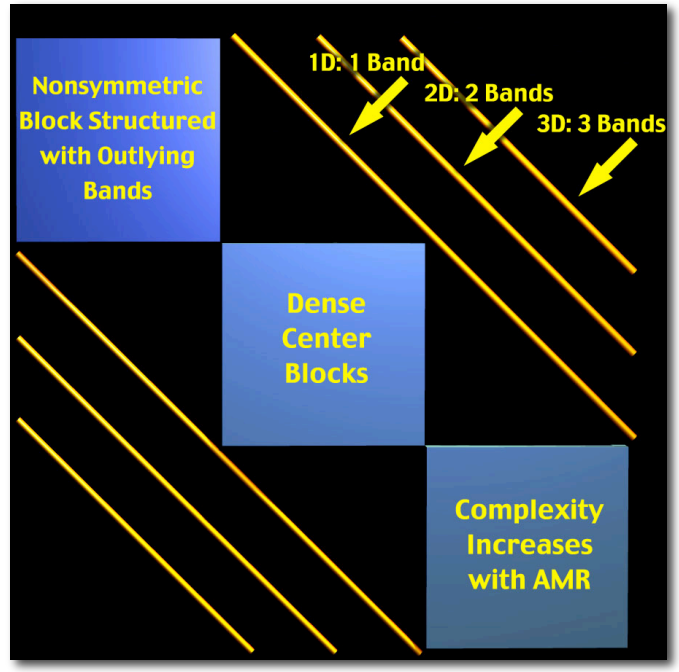
$$N_m = N_\nu \times N_E \times N_p \times N_a$$

$N_\nu = 6$

N_E = number of neutrino energy groups ~ 20

N_p = number of neutrino polar direction angles ~ 8

N_a = number of neutrino azimuthal direction angles ~ 8

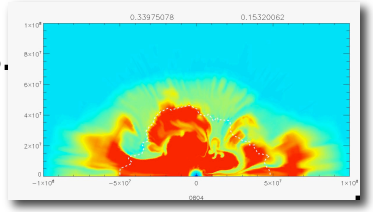


Algorithms critical!

Runtime: ~ 5*f* days per run on a 1 EF machine (at 20% of peak).

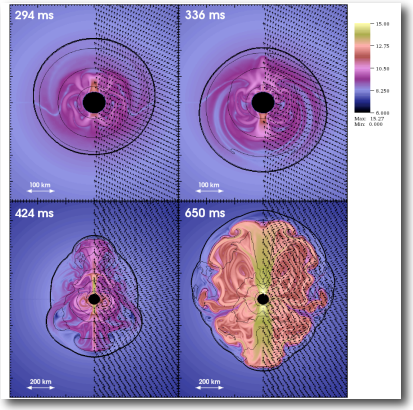
Summary and Outlook

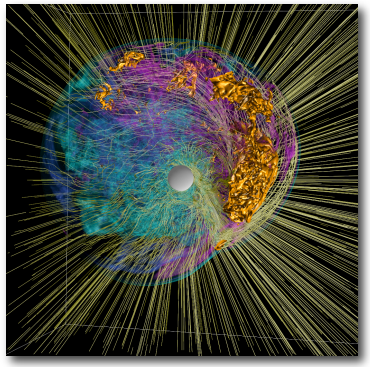
- What has changed?
  - New weak interaction physics.
  - SASI.
  - Longer simulation times.



- What's next?
  - 3D.
    - ⇨ 3D SASI studies demonstrate need for 3D.
    - ⇨ First 3D multi-physics simulation w/ multi-frequency transport running on the ORNL LCF.

- Longer Term
  - Magnetic fields.
  - Neutrino mixing.
  - GenASiS.





- Challenges that lie ahead:
  - Scaling.
  - Fault tolerance.
  - 3D stellar evolution.

- The need for exascale computing.
  - No progress by waiting.
  - Discovery at the terascale has changed supernova theory.

- What role, large-scale, high-performance computing?
  - Tightly coupled, nonlinear, multi-physics problem.
  - Discovery through computing.

It Takes a Village

Bruenn
Marronetti
Yakunin

Blondin
Warren

Fuller

Budiardja
Cardall
Endeve
Hix
Lee
Lentz
Messer
Mezzacappa

Funded by

Collaborators
Data Management: Barreto, Canon, Klasky, Meredith, Podhorszki
Networking: Beck, Moore, Rao; Solvers: D'Azevedo
Visualization: Ahern, Ma, Toedte