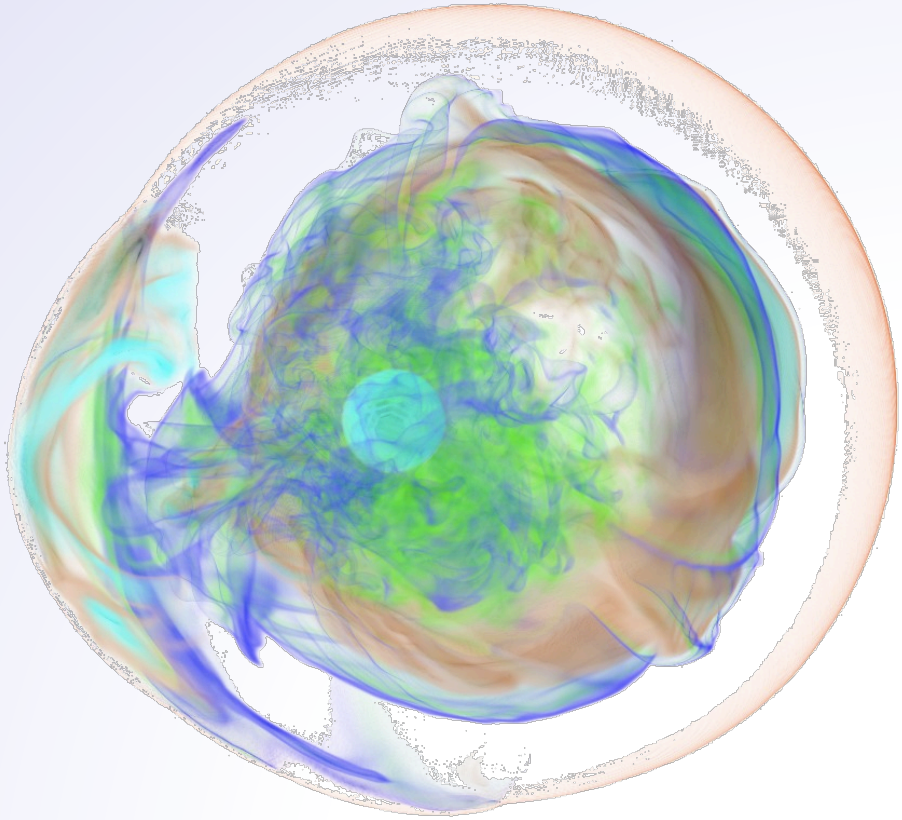
# The Hydrodynamic Behavior of Supernovae Explosions*



John M. Blondin
NC State University

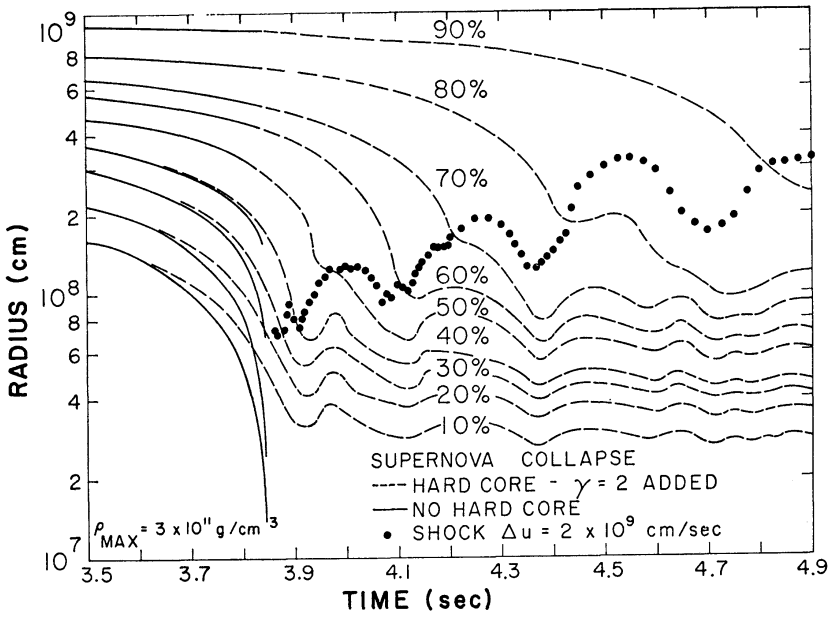
NC STATE ASTROPHYSICS

# THE HYDRODYNAMIC BEHAVIOR OF SUPERNOVAE EXPLOSIONS*

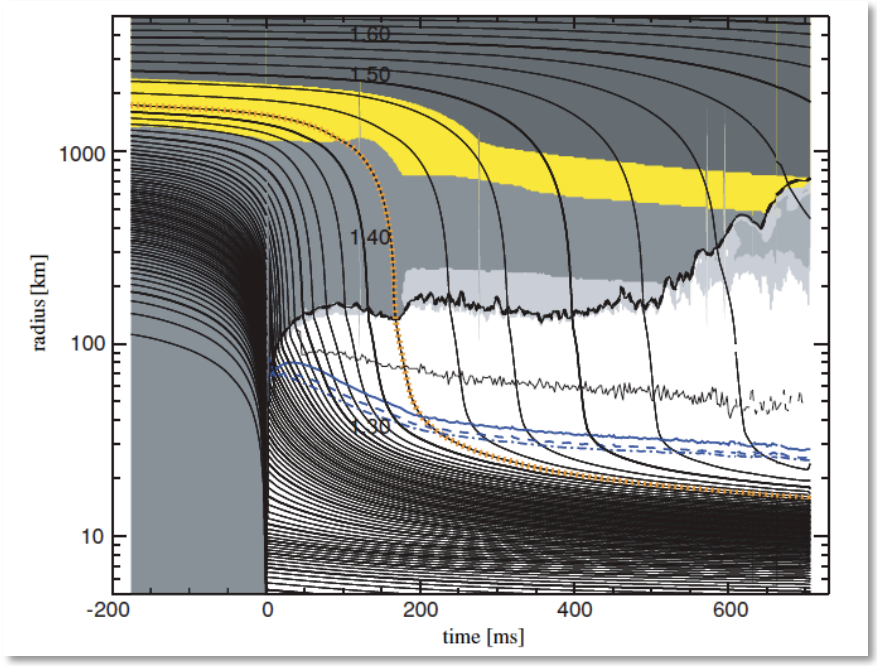
STIRLING A. COLGATE AND RICHARD H. WHITE
Lawrence Radiation Laboratory, University of California, Livermore, California
*Received June 29, 1965*

## ABSTRACT

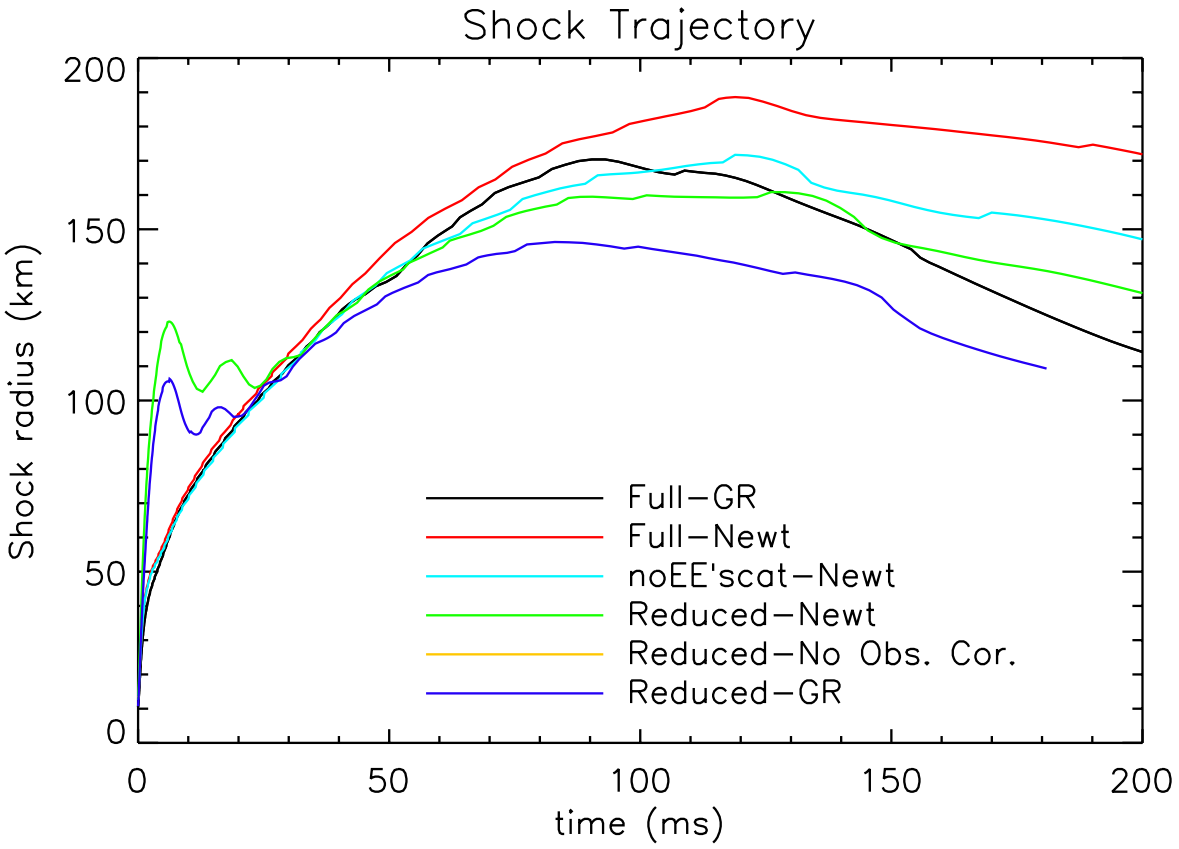
We regard the release of gravitational energy attending a dynamic change in configuration to be the primary energy source in supernovae explosions. Although we were initially inspired by and agree in detail with the mechanism for initiating gravitational instability proposed by Burbidge, Burbidge, Fowler, 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.



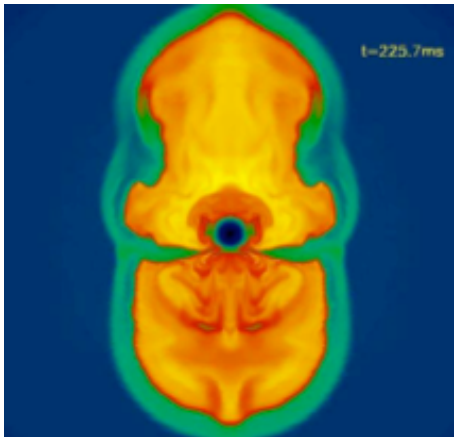
# 45 years later…

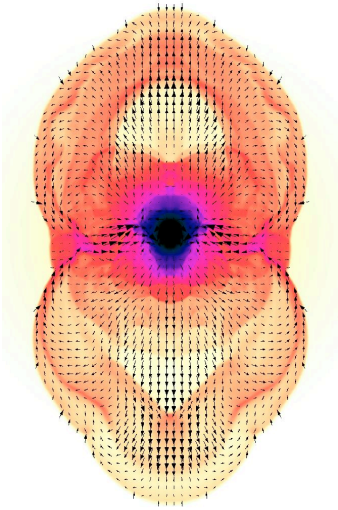


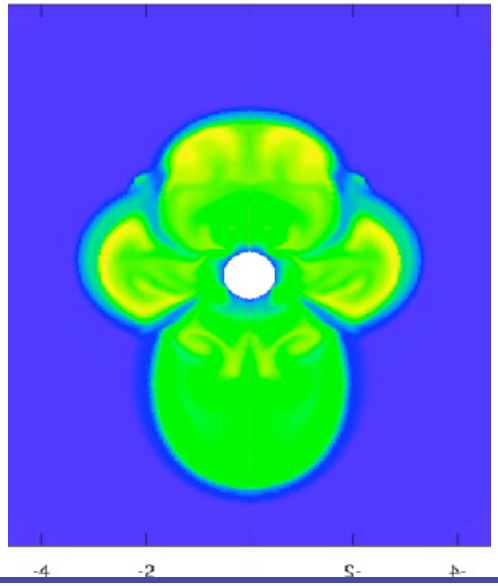

Marek & Janka 2009

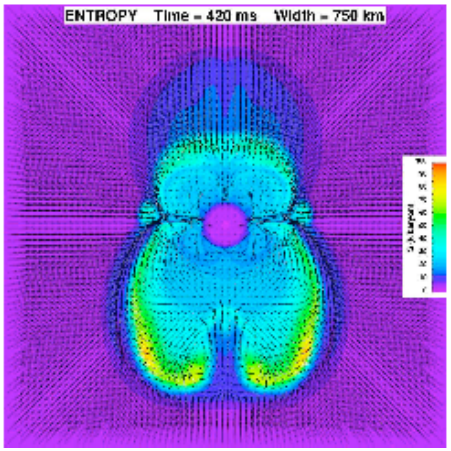

Shock Trajectory
Shock radius (km)
time (ms)
0
50
100
150
200
Full−GR
Full−Newt
noEE'scat−Newt
Reduced−Newt
Reduced−No Obs. Cor.
Reduced−GR

I. Physics Matters
II. Physics Doesn't Matter

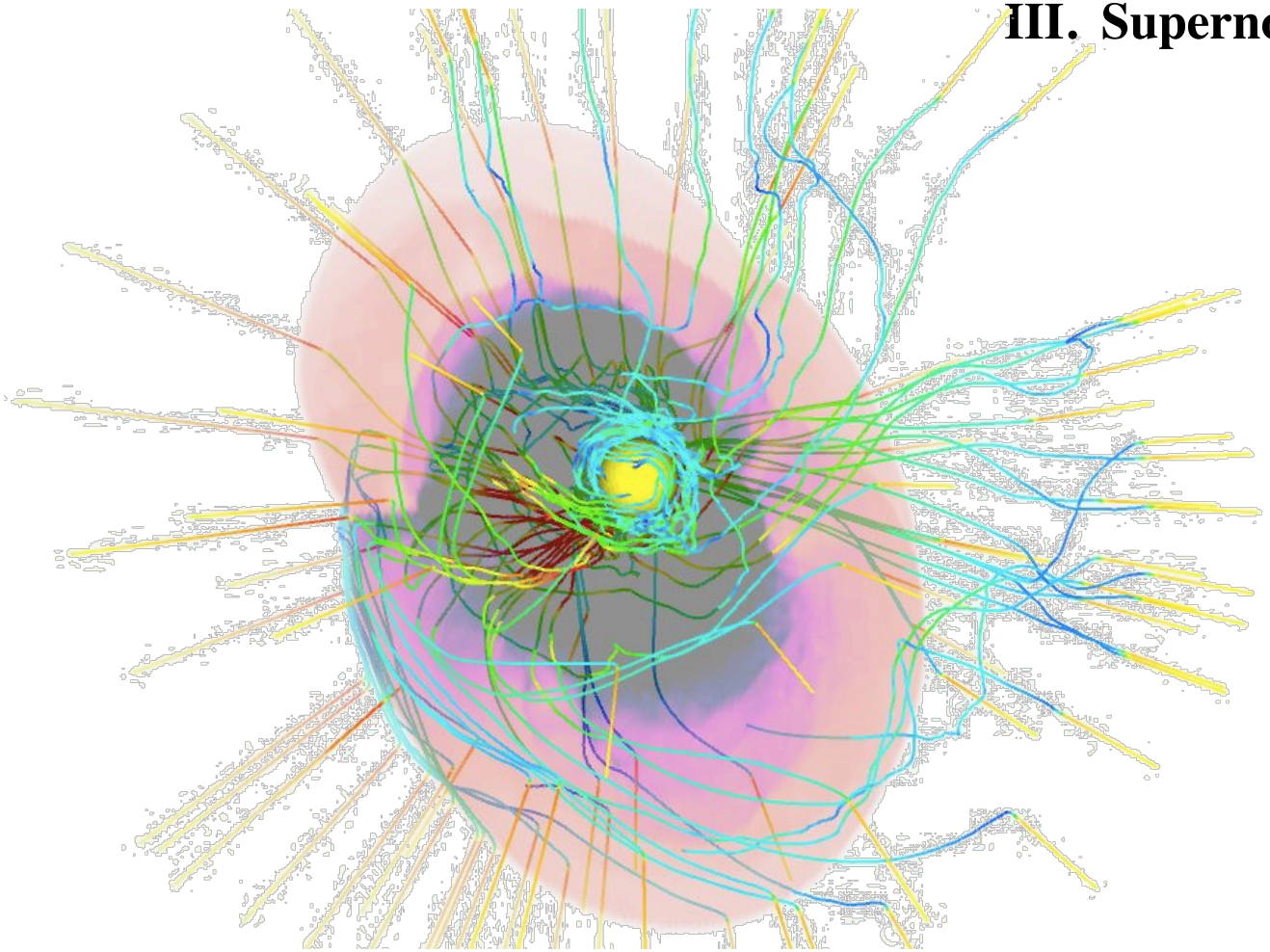


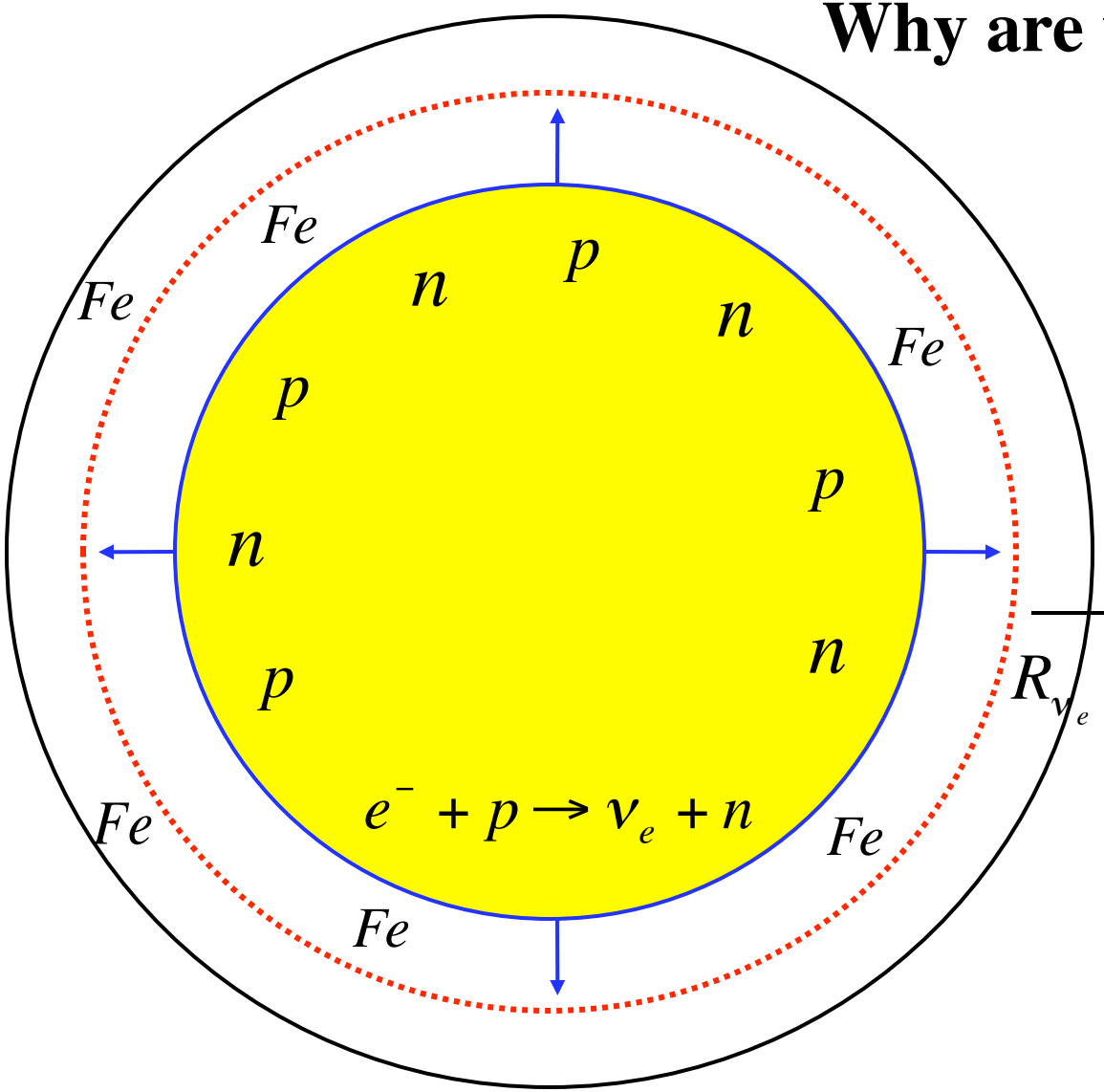




I. Physics Matters
II. Physics Doesn't Matter
III. Supernovae are 3D



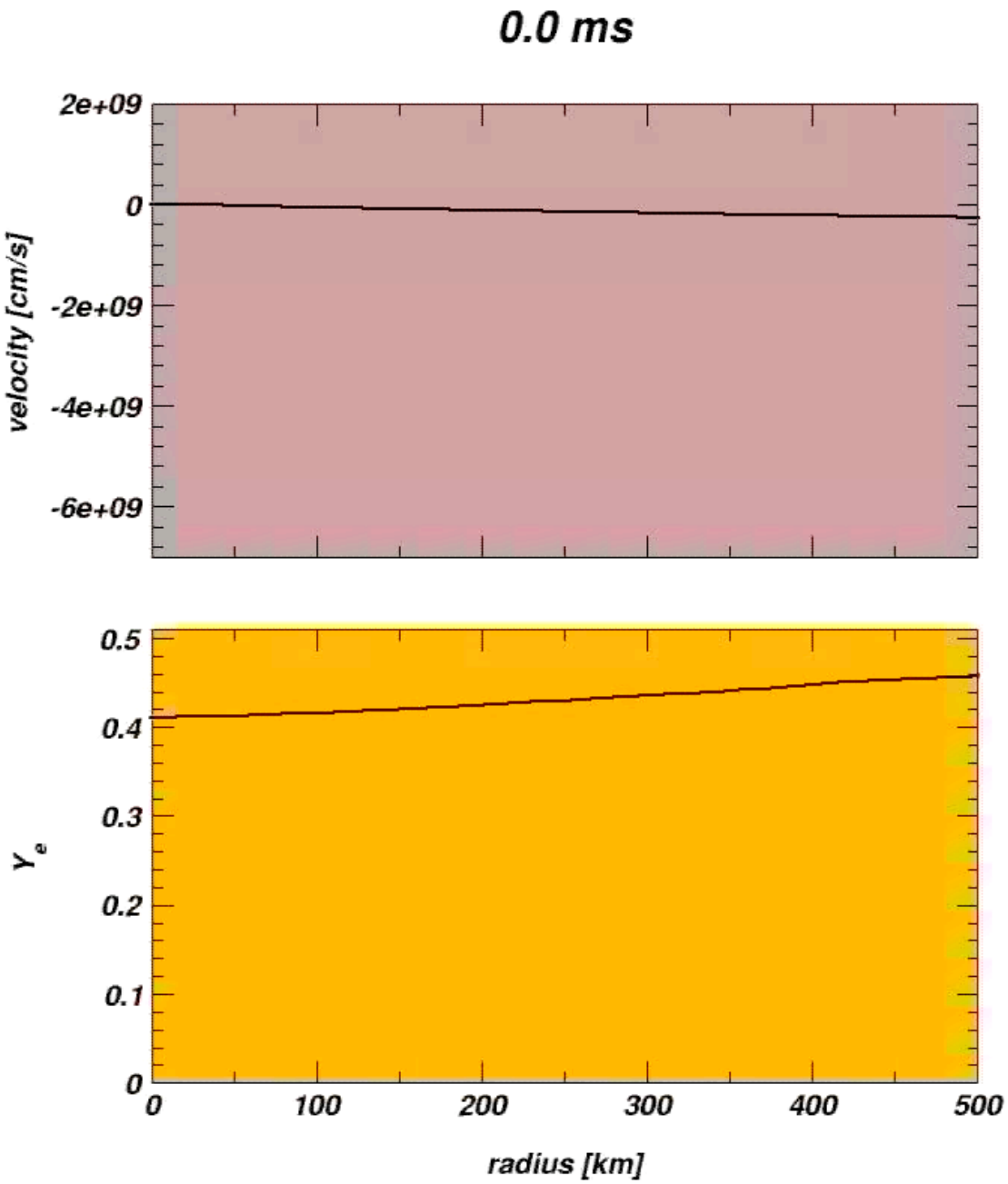
# Why are we still struggling after 45 years?



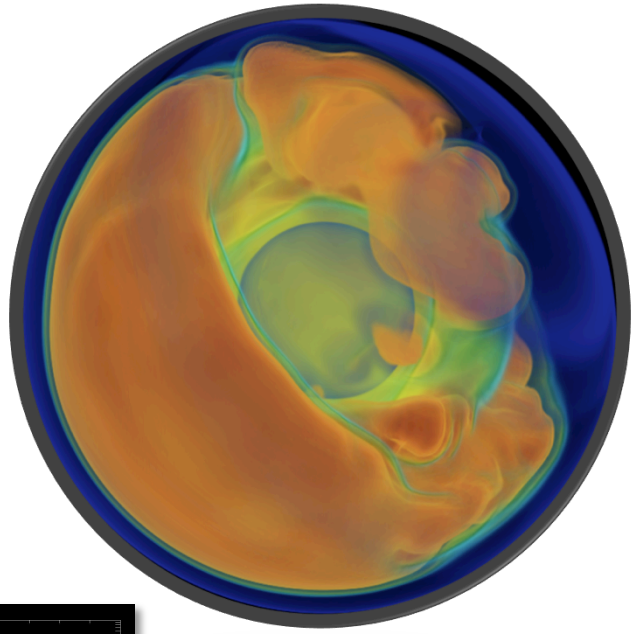

"Neutrinosphere"

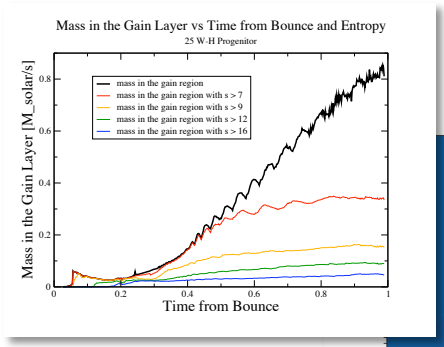
$$\tau_{\nu_e} \sim \frac{2}{3}$$

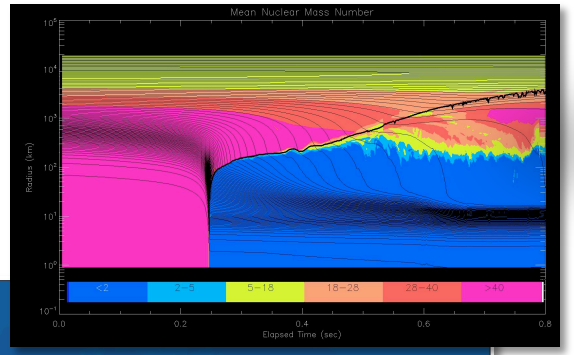
When shock passes electron neutrinosphere, they escape in a burst. Energy loss contributes to stalled shock.

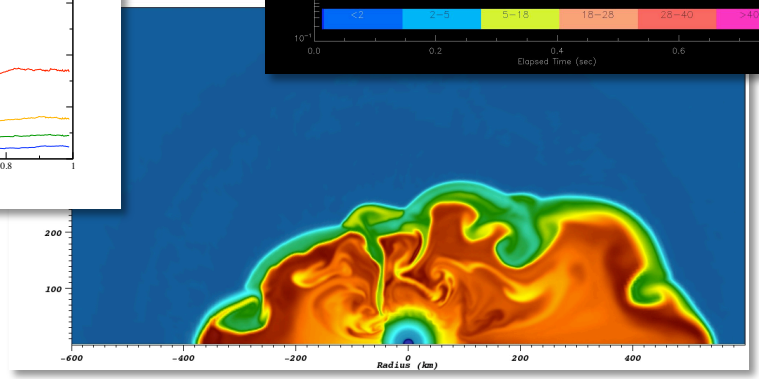

0.0 ms
2e+09
0
-2e+09
-4e+09
-6e+09
velocity [cm/s]
0.5
0.4
0.3
0.2
0.1
0
$Y_e$
0
100
200
300
400
500
radius [km]

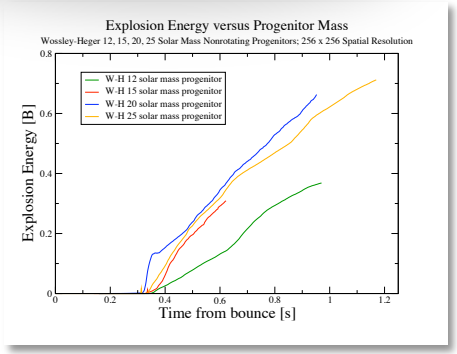
# A variety of approaches in 1, 2, & 3D will be needed to *understand* supernovae.





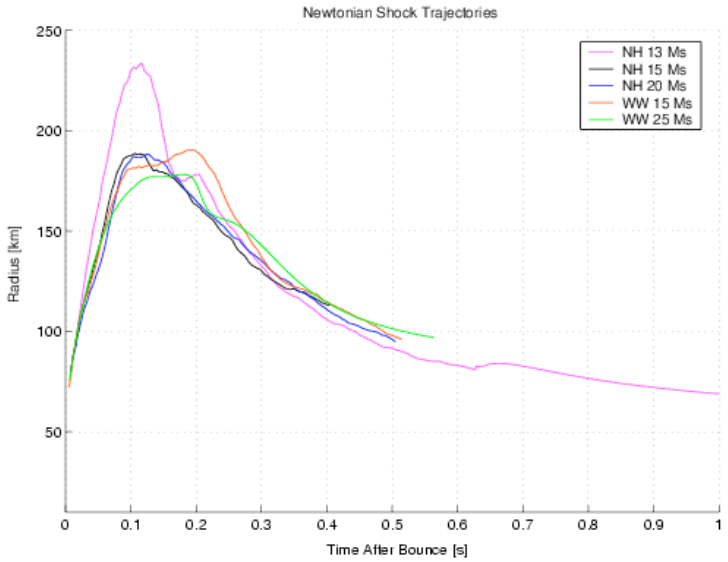



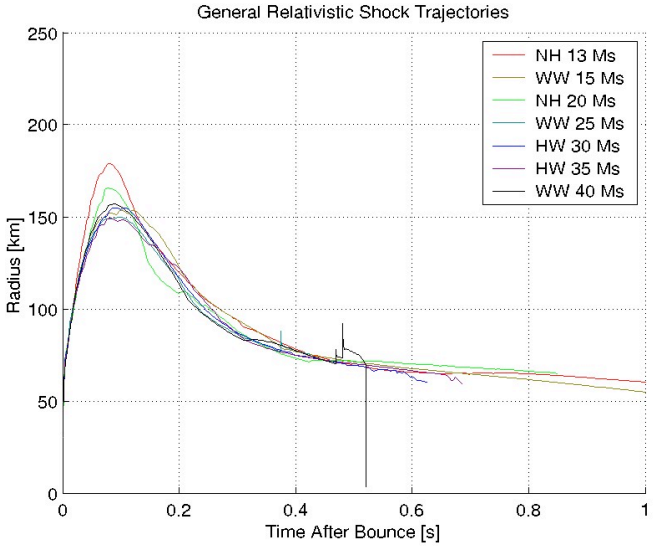
# 1D can be done very carefully, but no explosions…

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.***

# Important Neutrino Emissivities/Opacities

## "Standard" Emissivities/Opacities

Bruenn, *Ap.J. Suppl.* (1985)
- Nucleons in nucleus independent.
- No energy exchange in nucleonic scattering.

★ $e^{-(+)} + p(n), A \leftrightarrow \nu_e(\bar{\nu}_e) + n(p), A'$

Langanke et al. PRL, 90, 241102 (2003)
- Include correlations between nucleons in nuclei.

$e^+ + e^- \leftrightarrow \nu_{e,\mu,\tau} + \bar{\nu}_{e,\mu,\tau}$

★ $\nu + n,p,A \rightarrow \nu + n,p,A$

$\nu + e^-,e^+ \rightarrow \nu + e^-,e^+$

Reddy, Prakash, and Lattimer, PRD, 58, 013009 (1998)
Burrows and Sawyer, PRC, 59, 510 (1999)
- (Small) Energy is exchanged due to nucleon reco
- Many such scatterings.

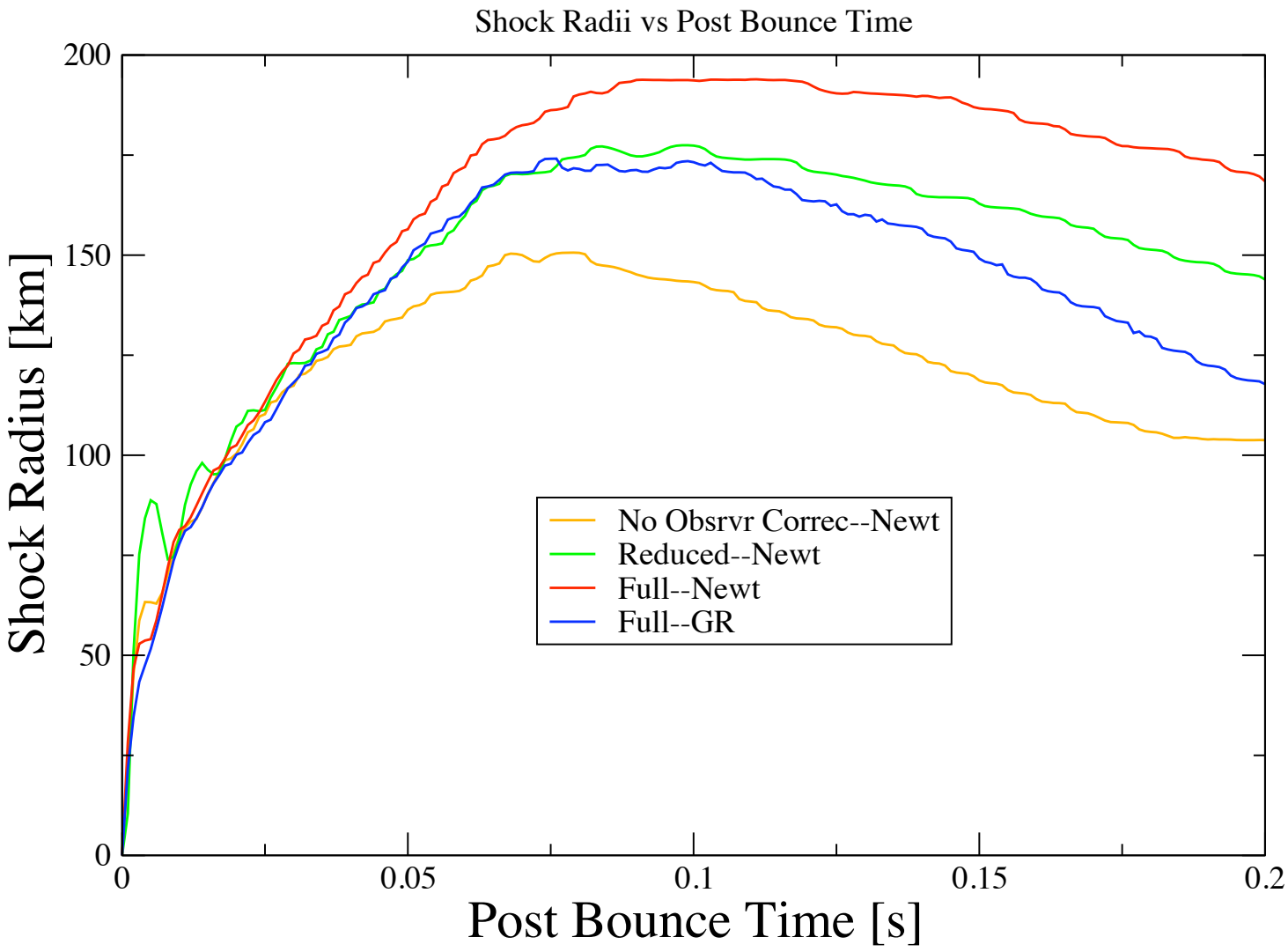
★ $N + N \leftrightarrow N + N + \nu_{e,\mu,\tau} + \bar{\nu}_{e,\mu,\tau}$

$\nu_e + \bar{\nu}_e \leftrightarrow \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau}$

Hannestadt and Raffelt, *Ap.J.* 507, 339 (1998)
Hanhart, Phillips, and Reddy, *Phys. Lett. B*, 499, 9 (2001
- New source of neutrino-antineutrino pairs.

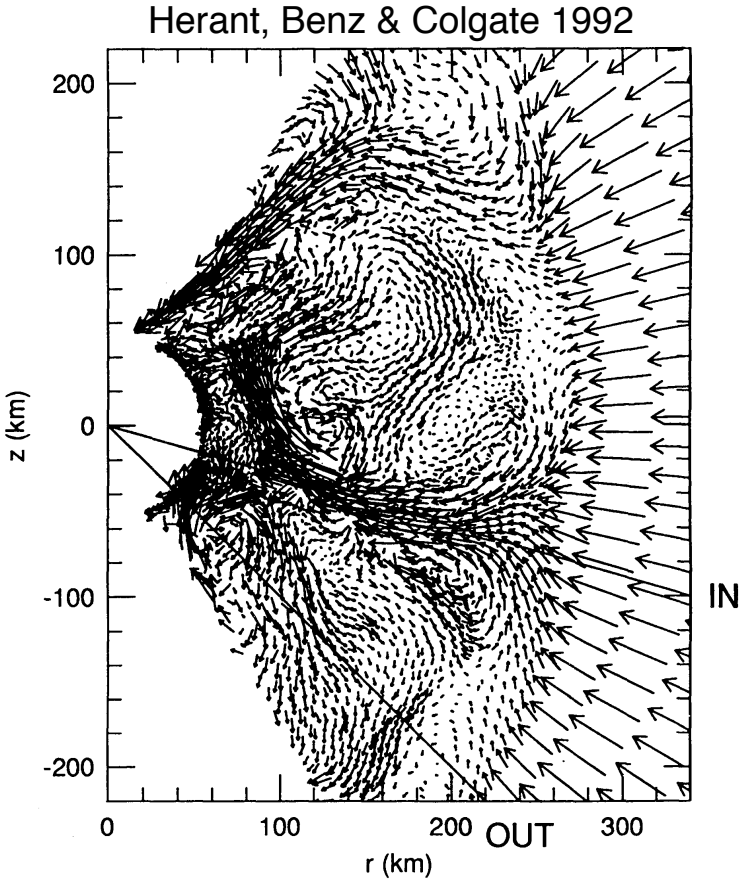
Janka et al. PRL, 76, 2621 (1996)
Buras et al. *Ap.J.*, 587, 320 (2003)

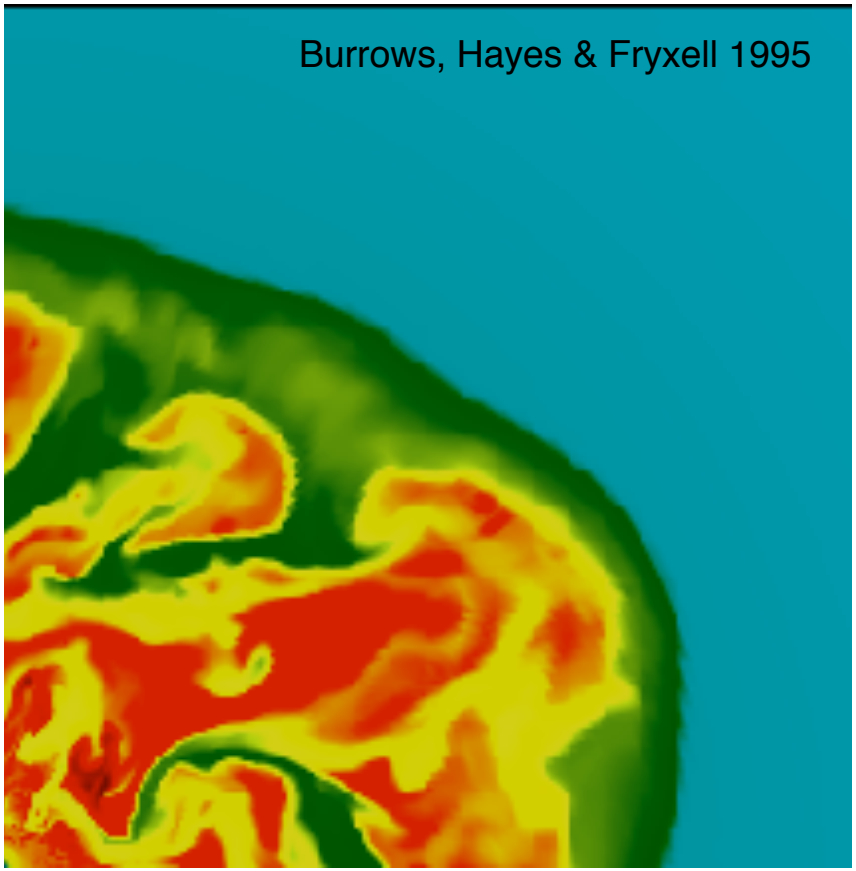
# Comparison of 1D Simulations; 15 W-H Progenitor



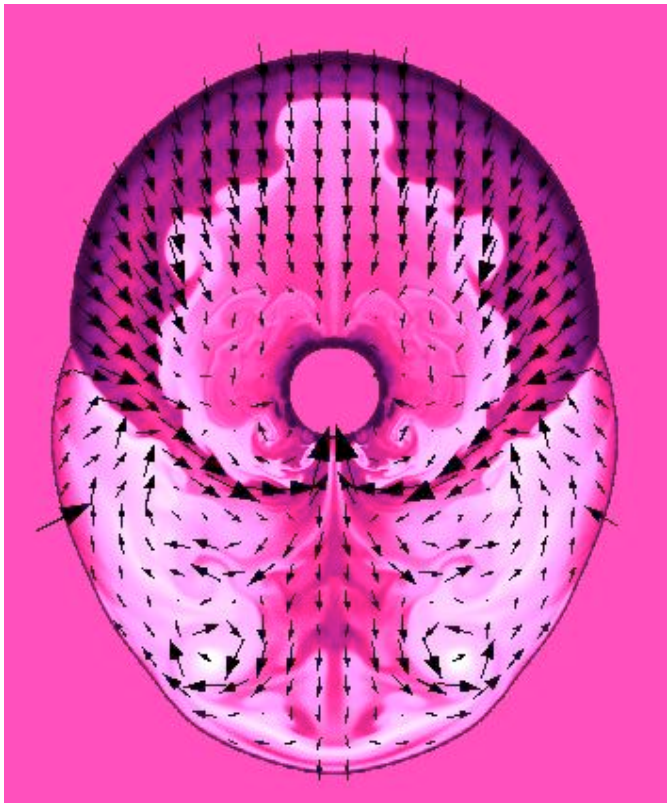
# Breaking spherical symmetry was a breakthrough!

First generation of 2D SN models showed low-order asymmetry in the accretion shock.

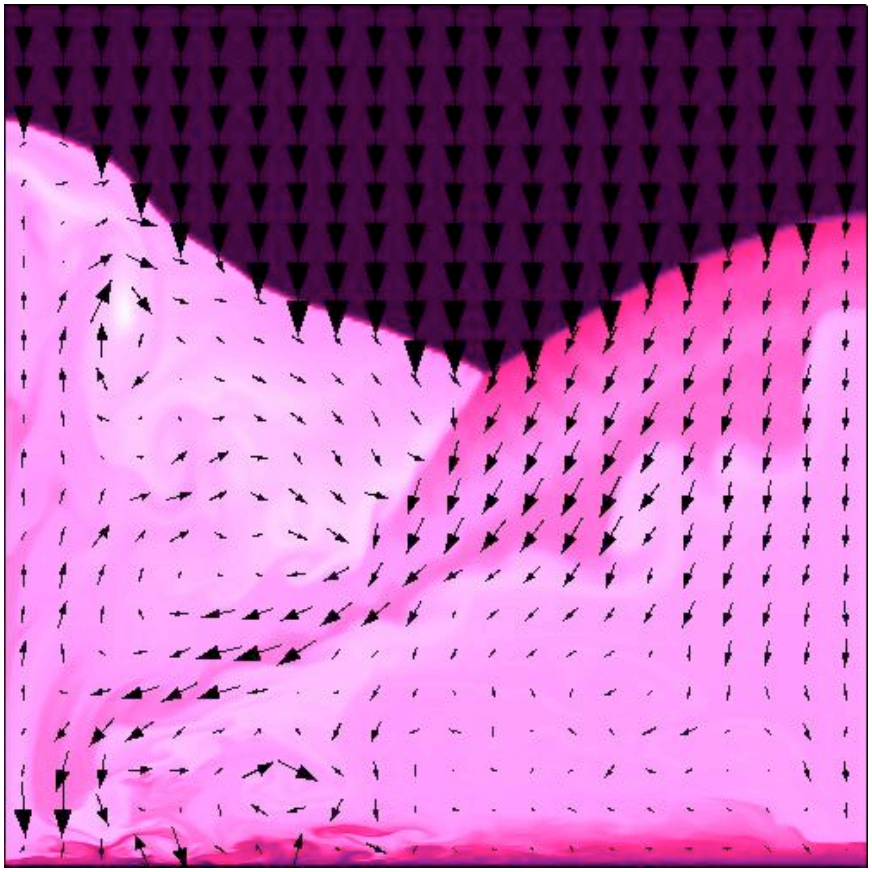


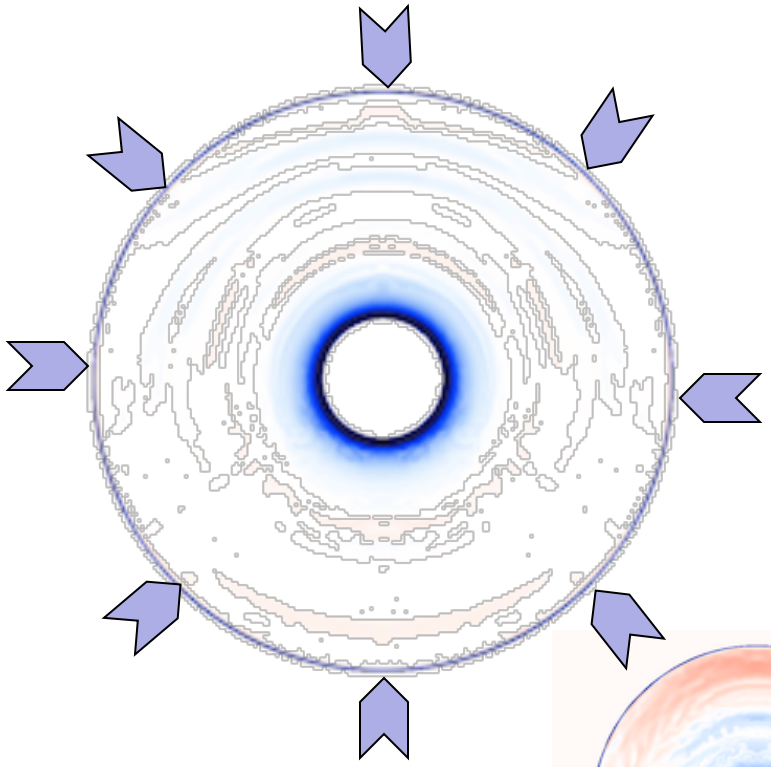
# Does large-scale flow driven by convection distort the spherical shock?



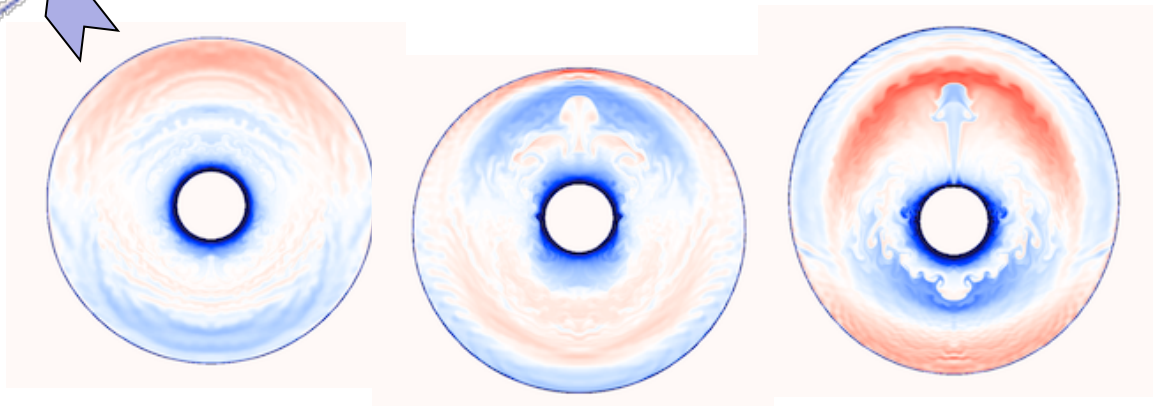
# Or are bulk flows and entropy variations **created** by the oblique shock?



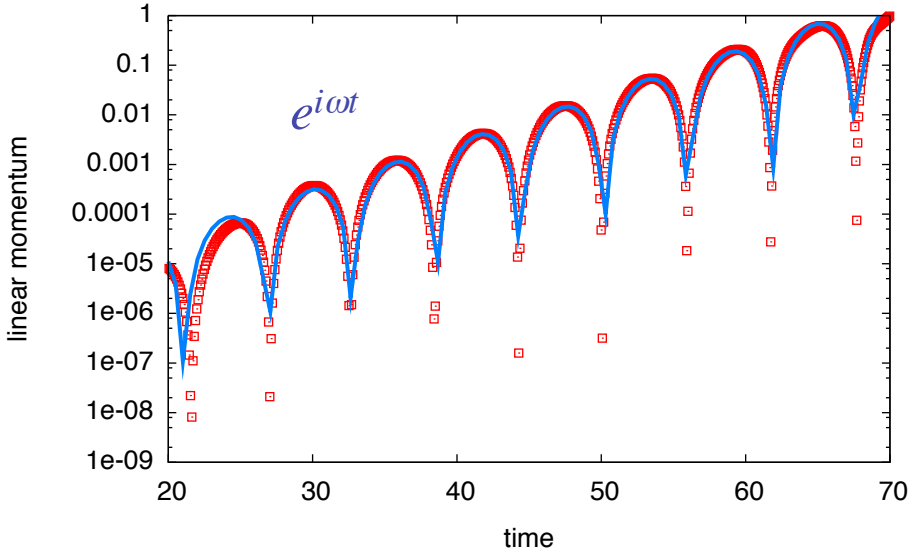
# Standing Accretion Shock Instability

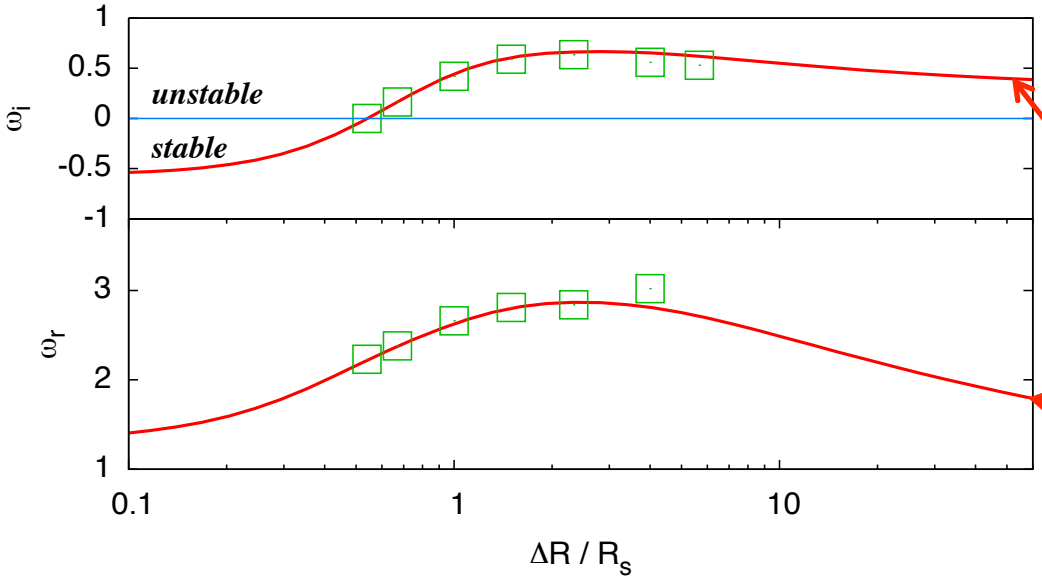


Even in the absence of convection, spherical symmetry is broken by the SASI.



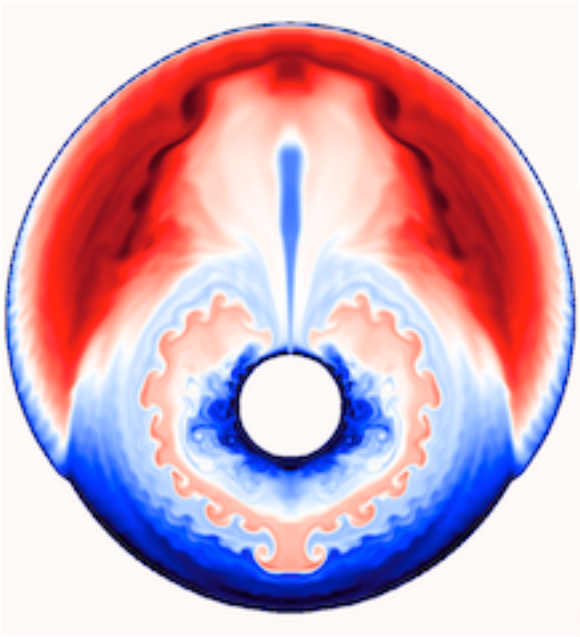
Good agreement between analytic and numerical methods for linear growth of the SASI.

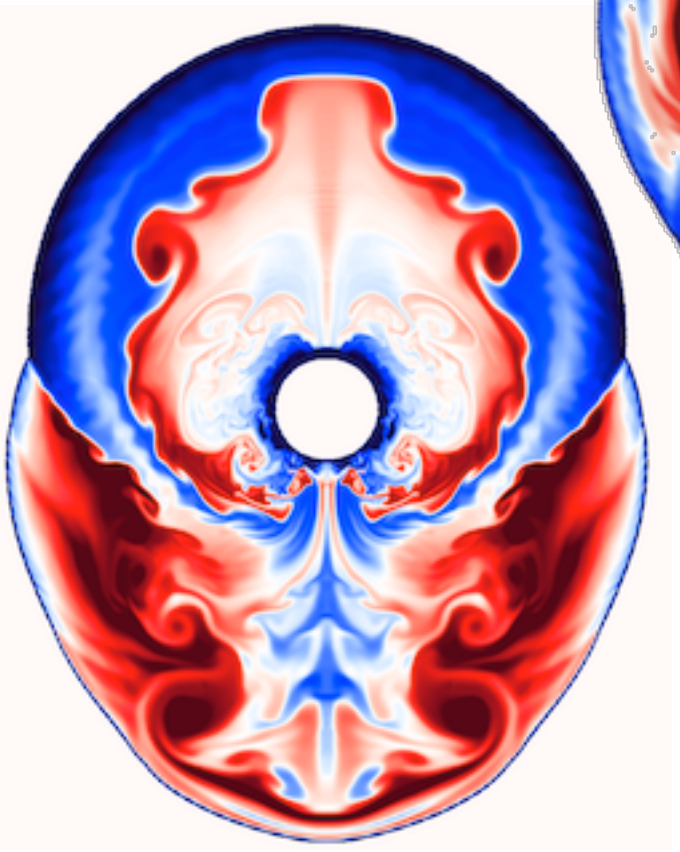


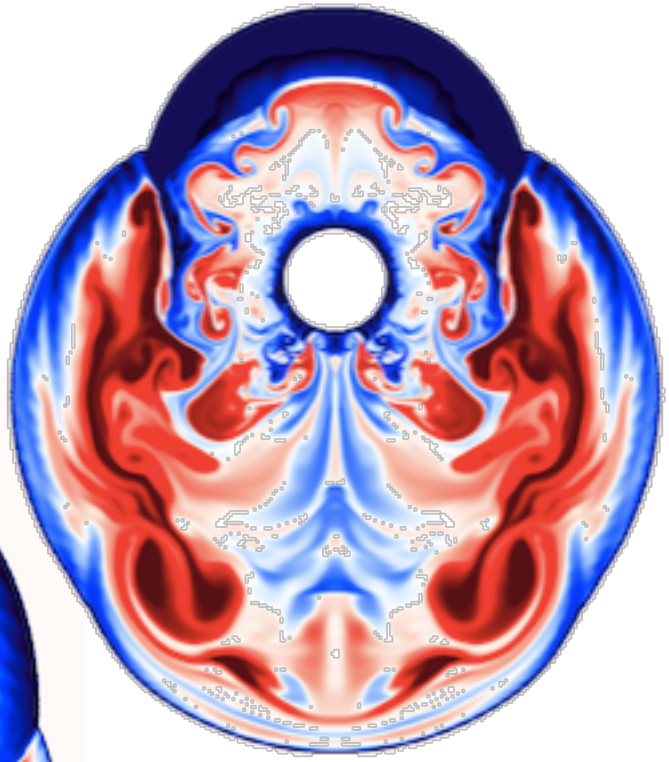




Foglizzo, Galletti, Sheck & Janka 2007

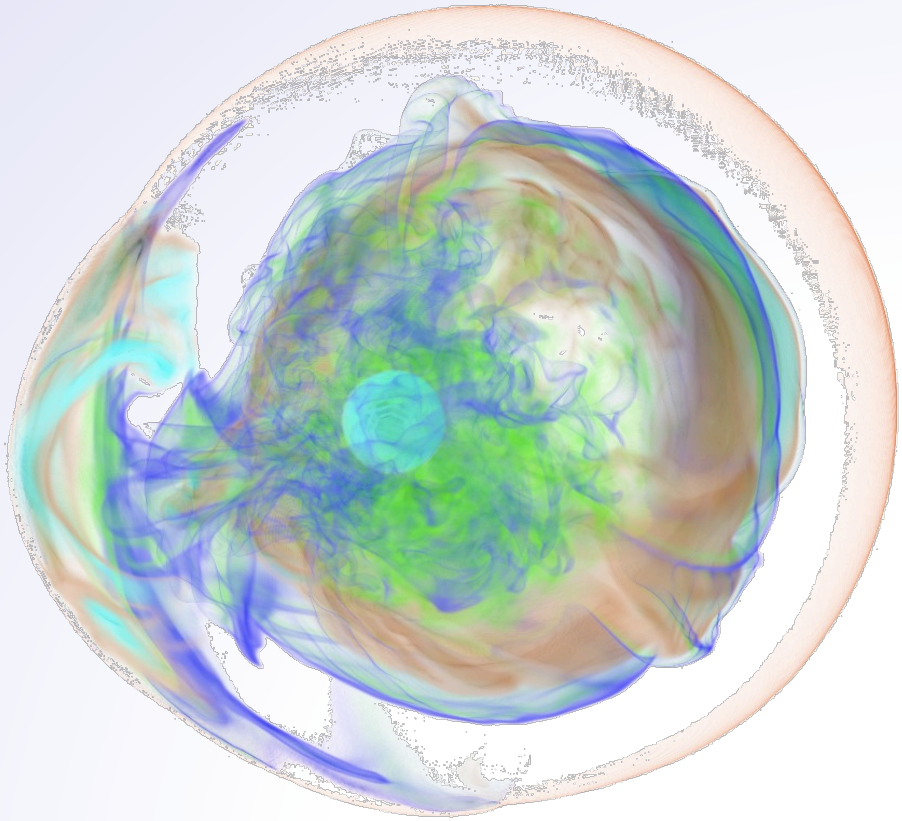
Nonlinear evolution of the SASI.





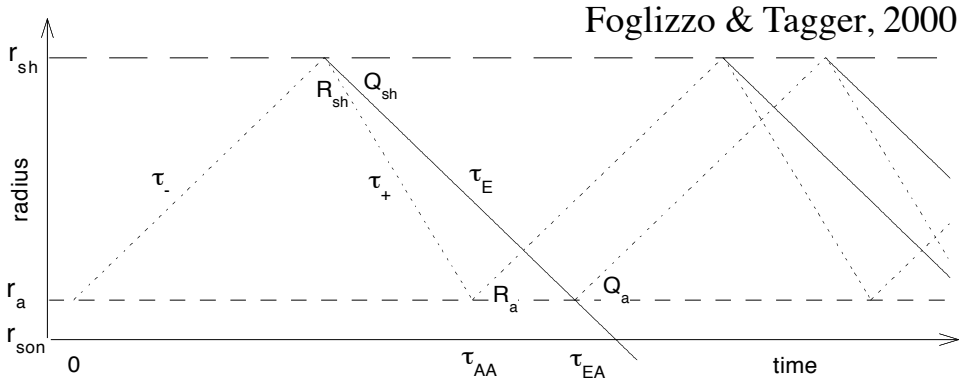


# But what IS the SASI?

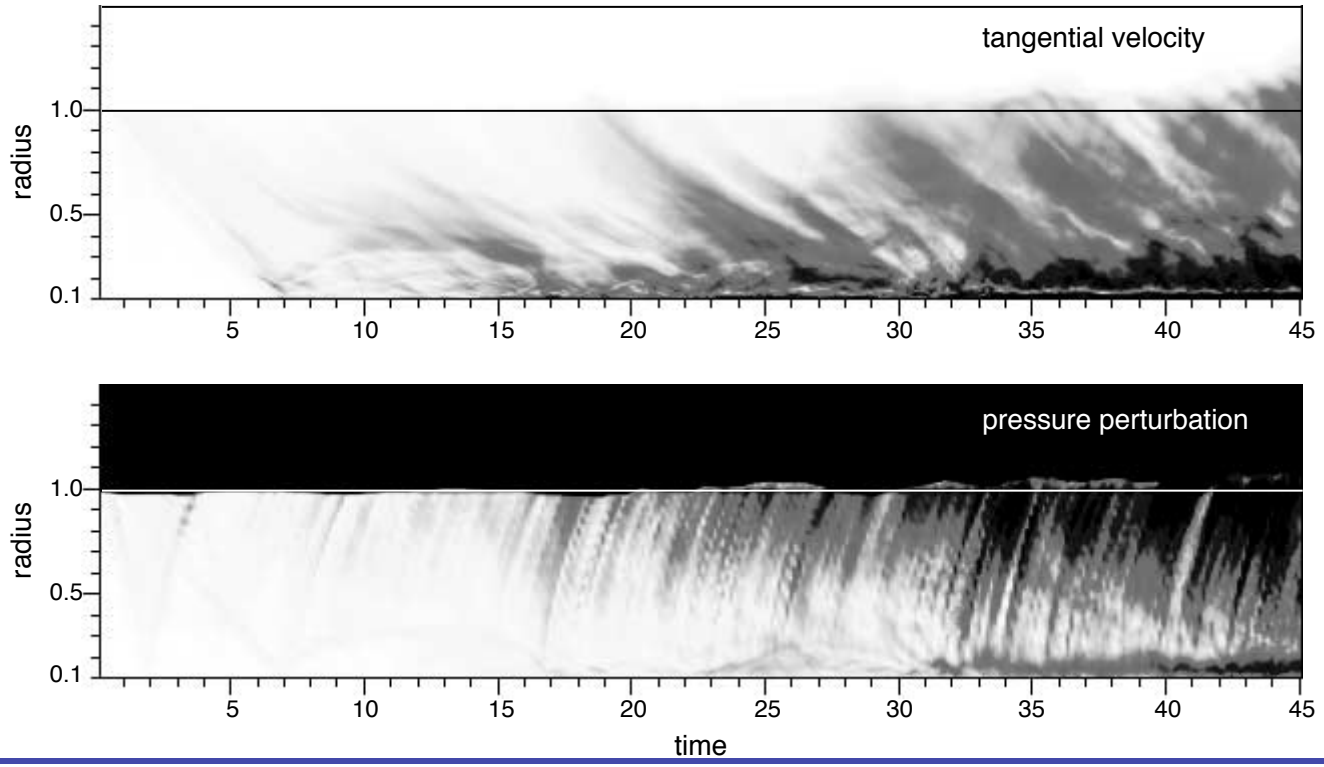


**Is this another example of the advective-acoustic instability?**

Foglizzo & Tagger, 2000

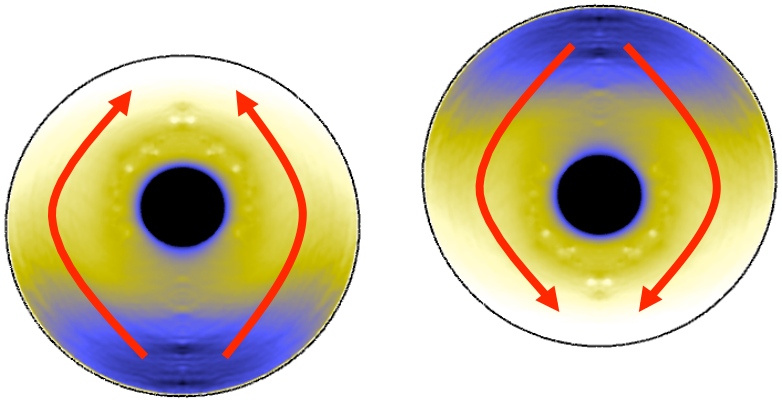



Blondin, Mezzacappa, DeMarino, 2003



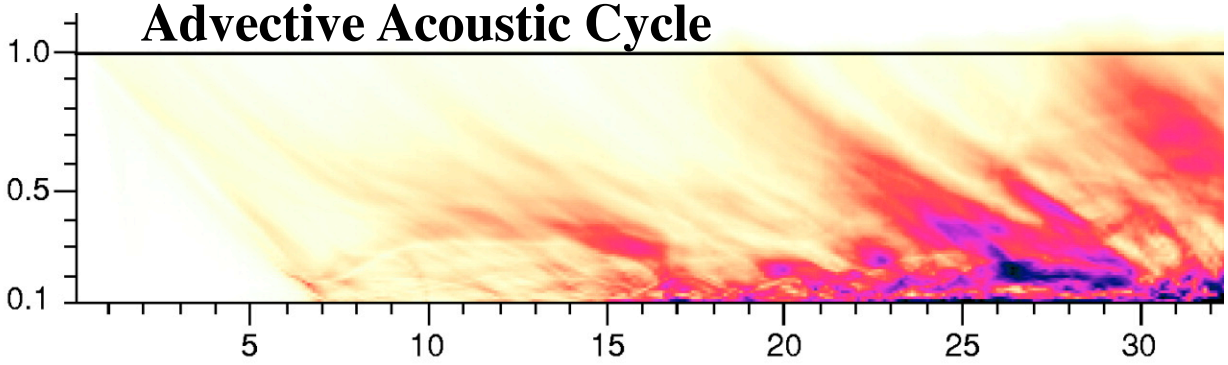
# Which Acoustic Mechanism?

## Trapped Global Pressure Waves



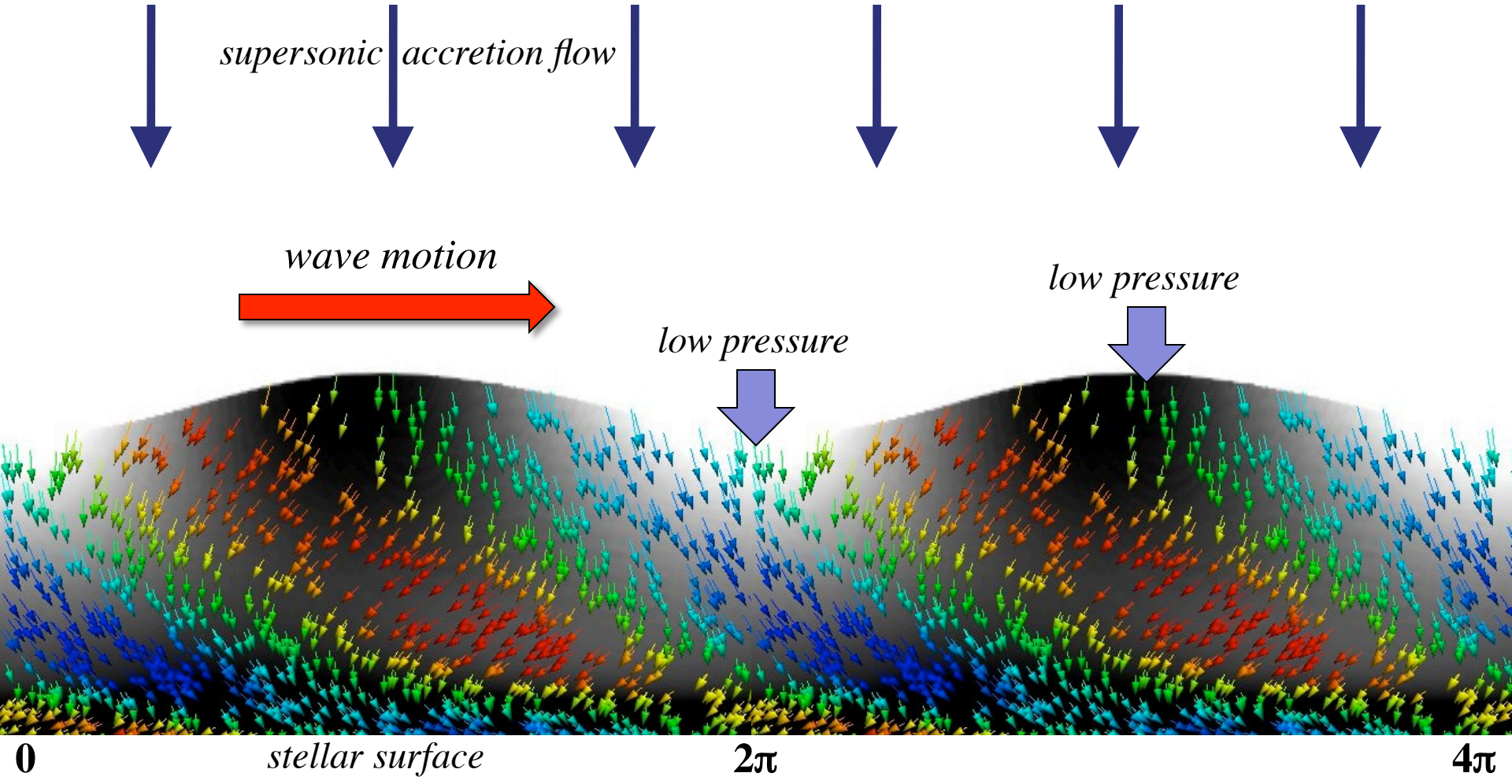
The spherical accretion shock acts as an acoustic cavity, with a trapped standing wave growing exponentially with time.

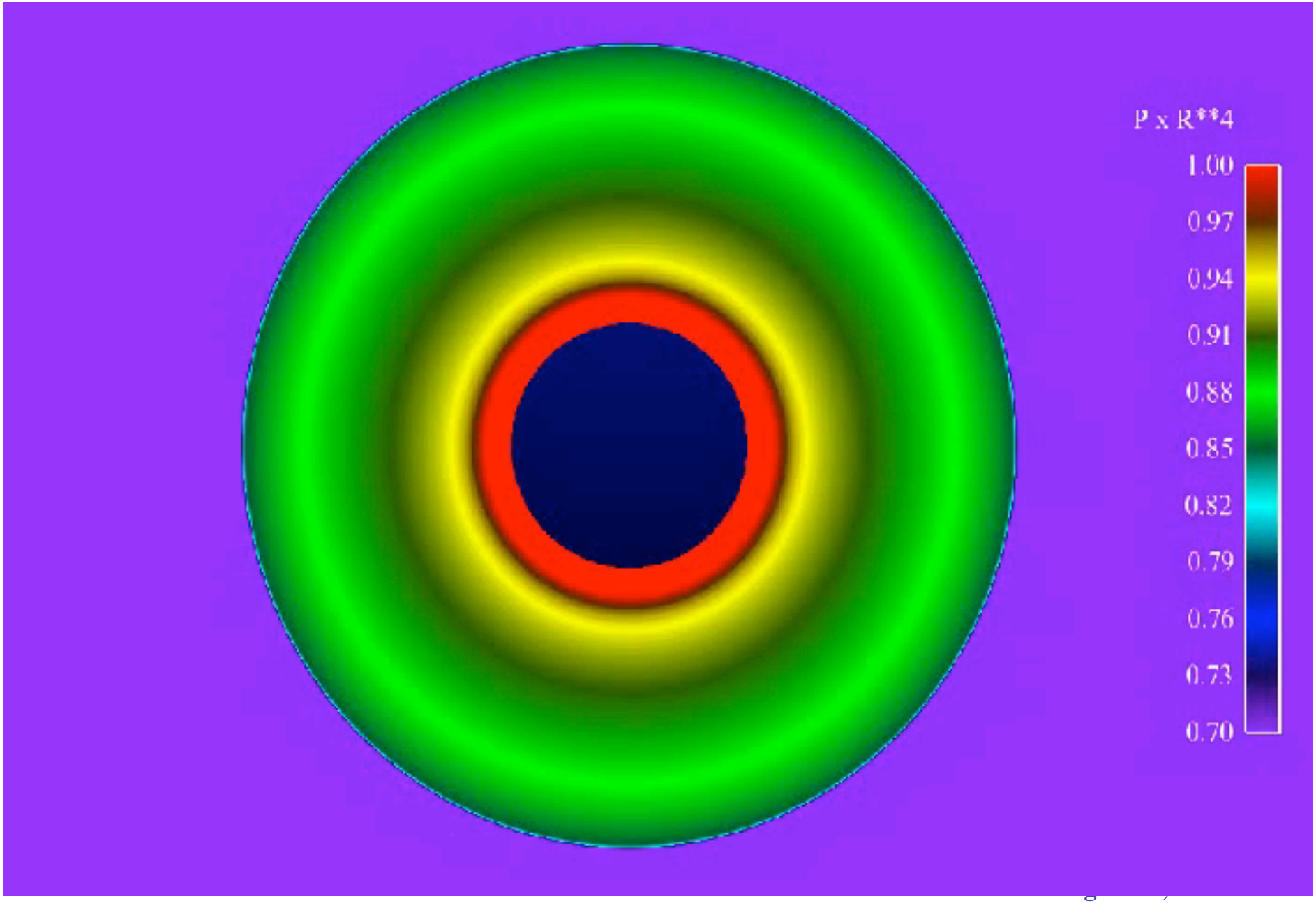
## Advective Acoustic Cycle




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

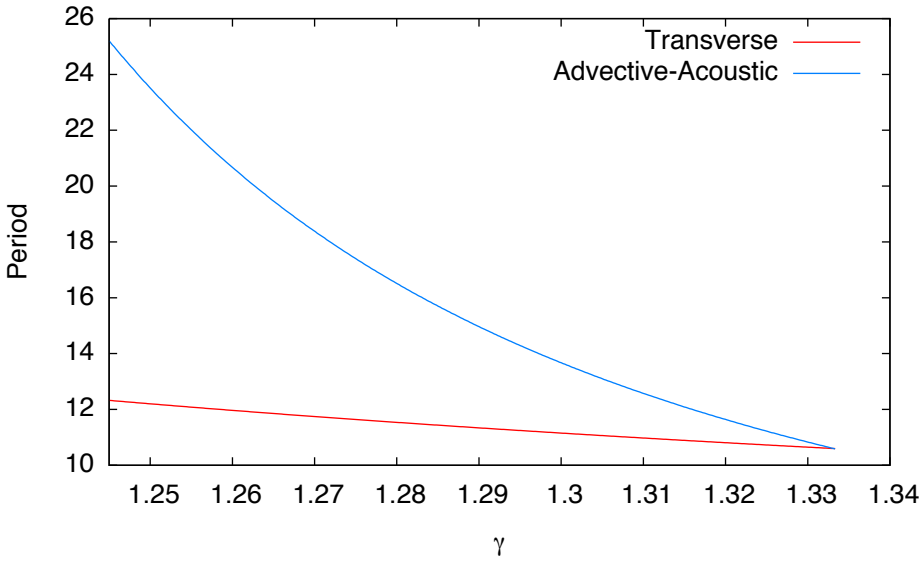
# Anatomy of a SASI wave

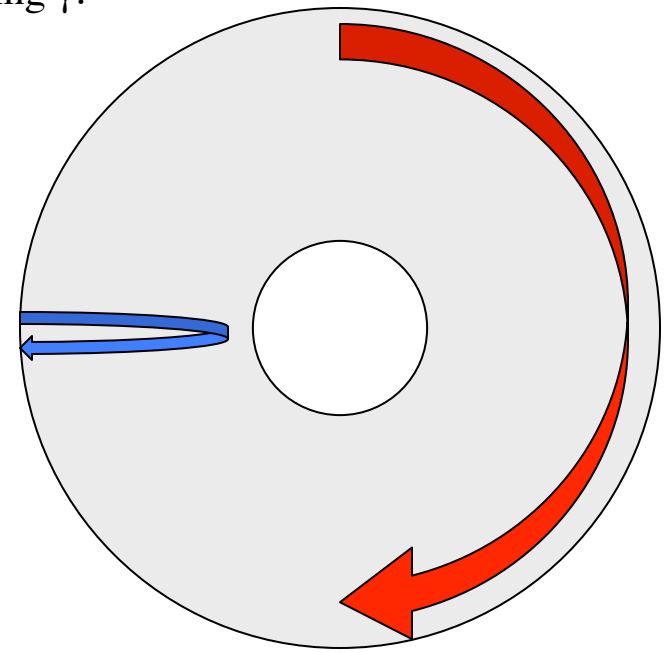



P x R**4
1.00
0.97
0.94
0.91
0.88
0.85
0.82
0.79
0.76
0.73
0.70

# Can we separate these two waves?

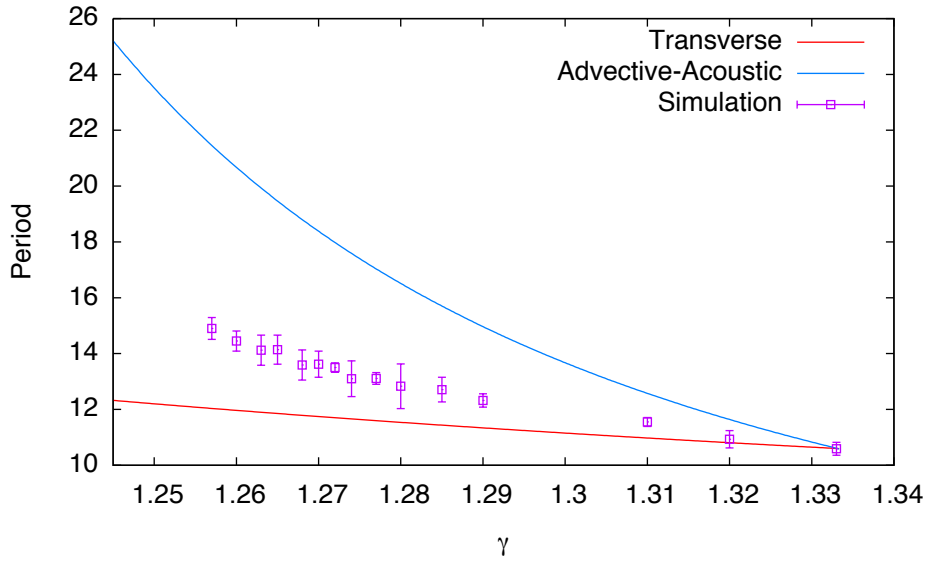
Post-shock sound speed is relatively independent of γ.
Advection time increases dramatically with decreasing γ.



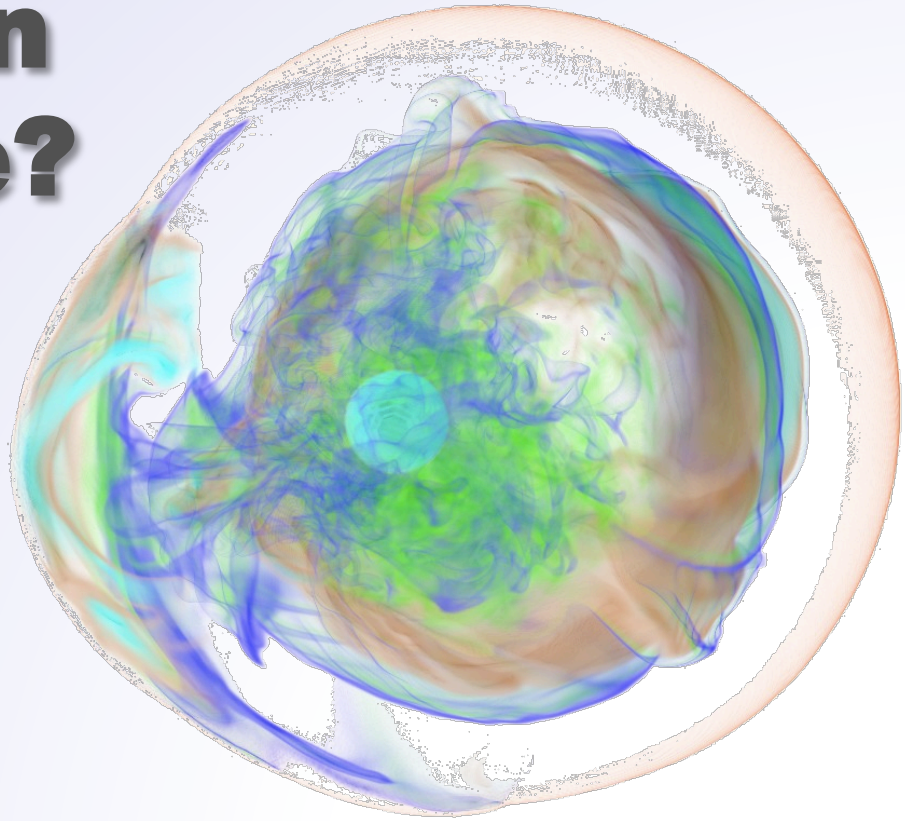



For small values of γ the radial advective-acoustic period will differ from the period for a sound wave to travel the circumference of the shock cavity.

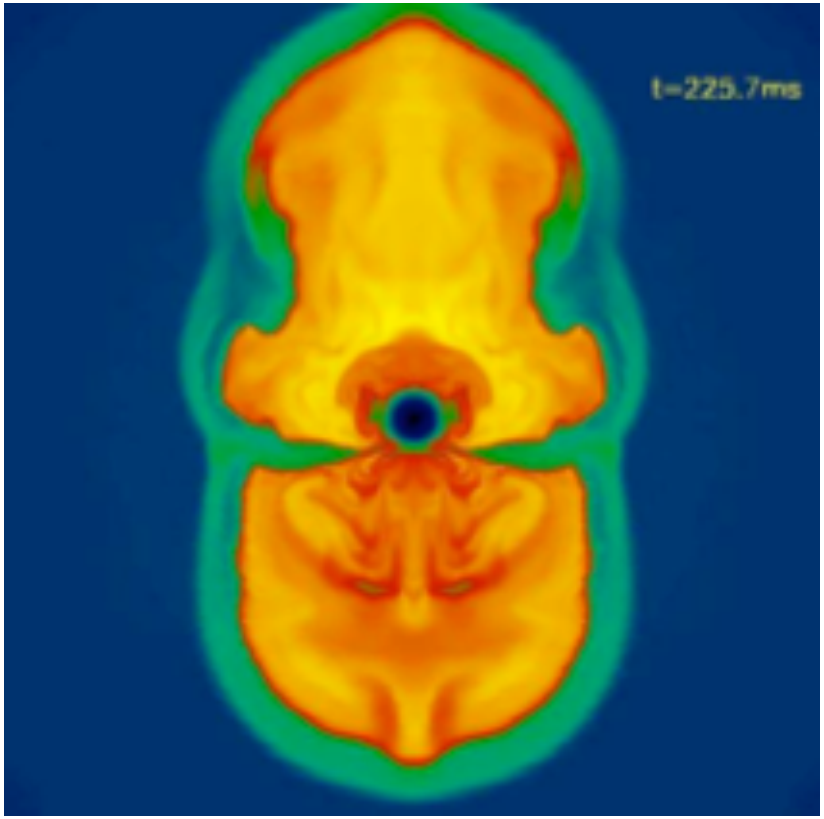
# What have we learned?



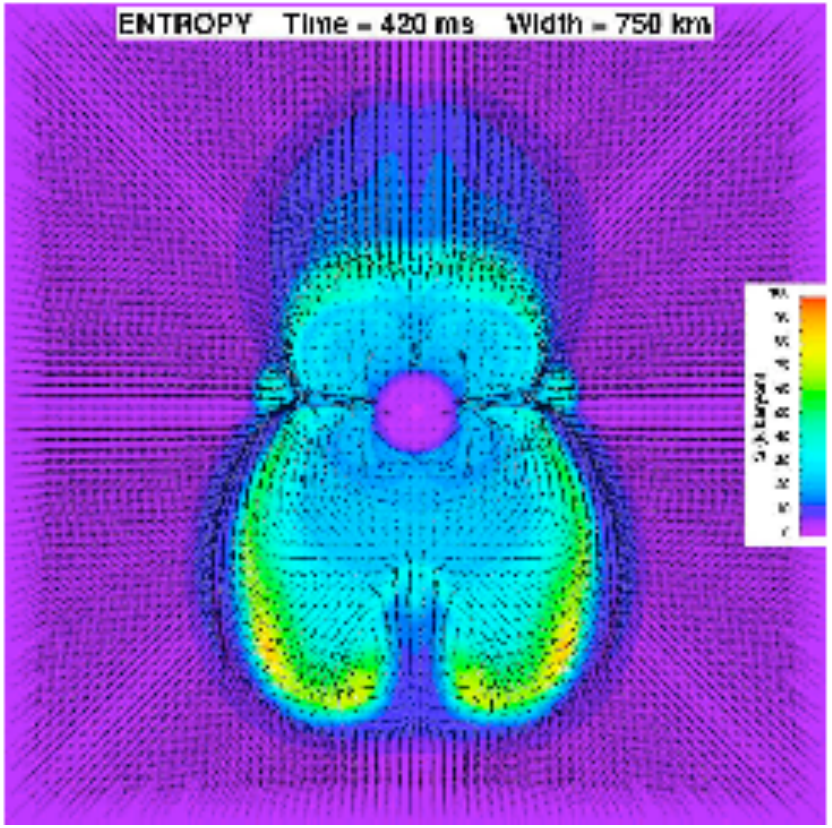
# Why is the SASI important in supernovae?



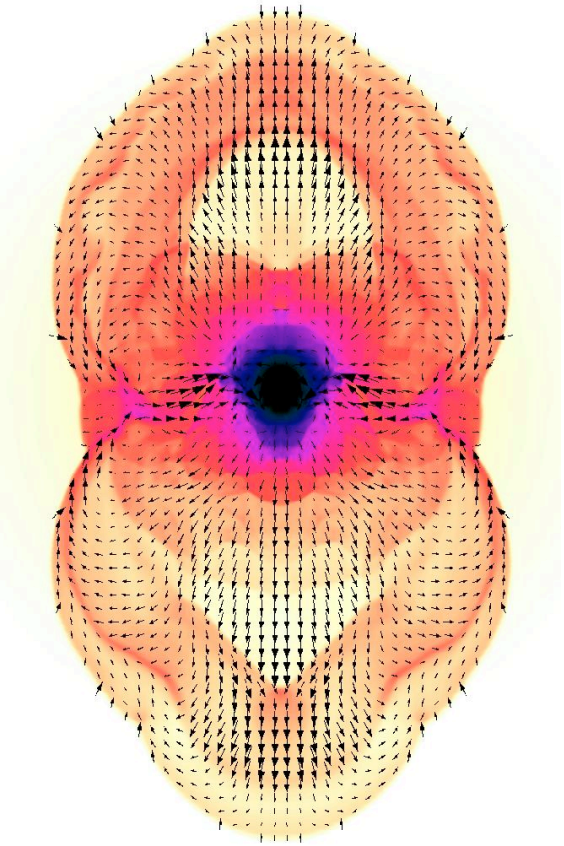
# SASI sets the structure of the shock…



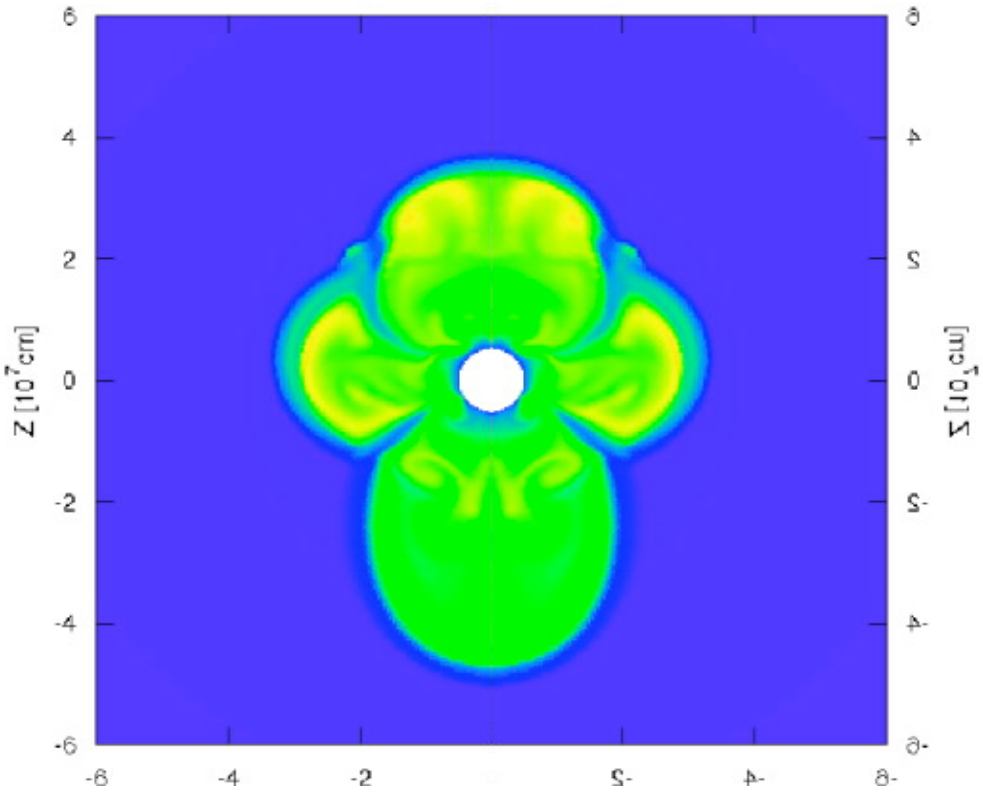

Janka et al.




Burrows et al.

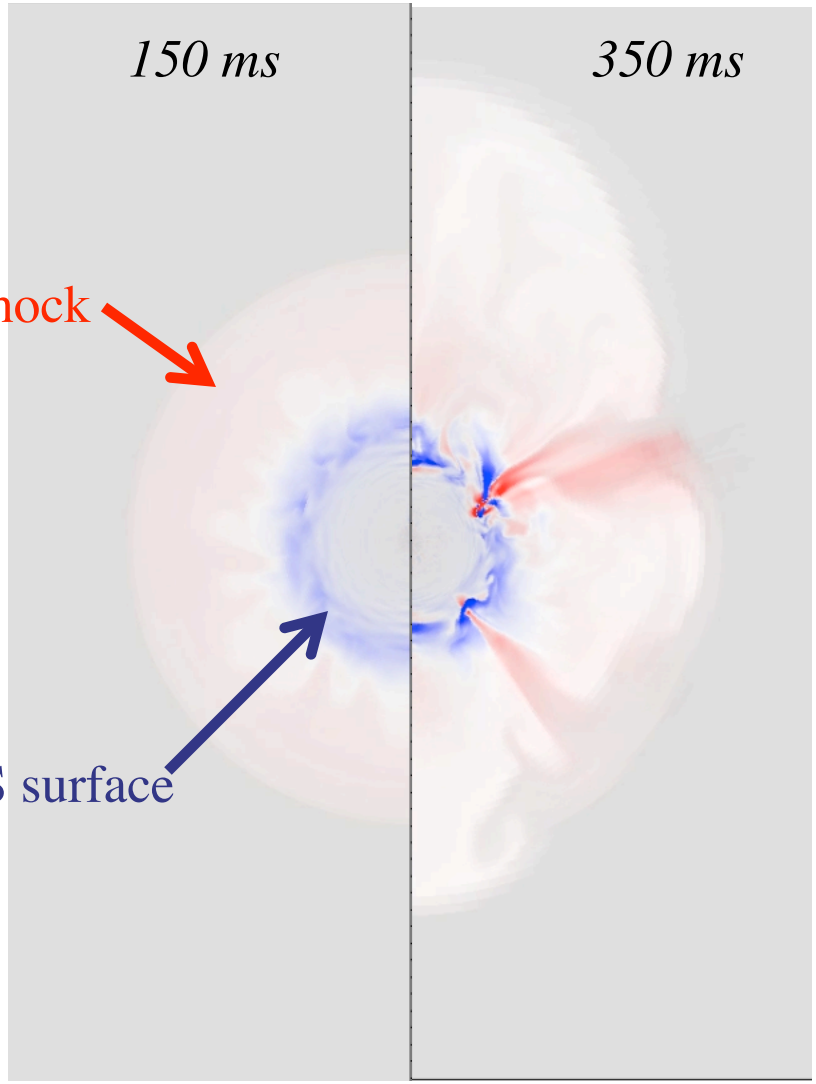


Blondin et al.




Kotake, Ohnishi & Yamada, 2007

# SASI helps drive explosion…




Kinks in accretion shock feed downflows of low-entropy gas that are rapidly heated as they approach the PNS surface.

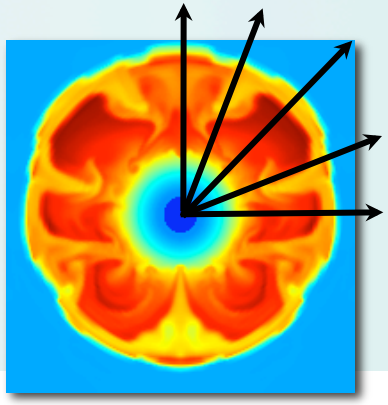
# Ongoing 2D, 3D Multi-Physics Supernova Models

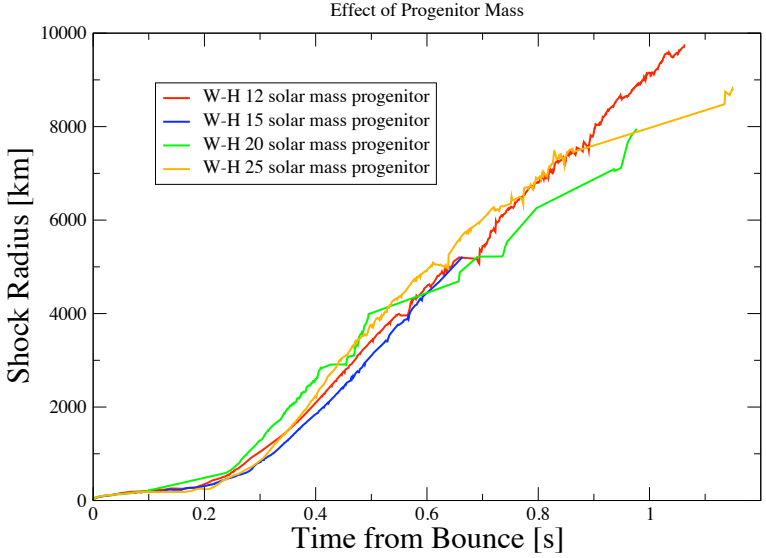
**Simulation Building Blocks**

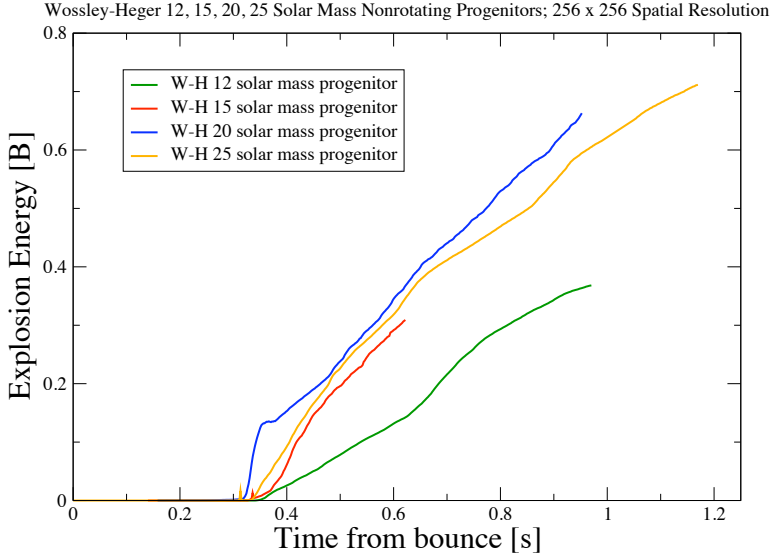
CHIMERA

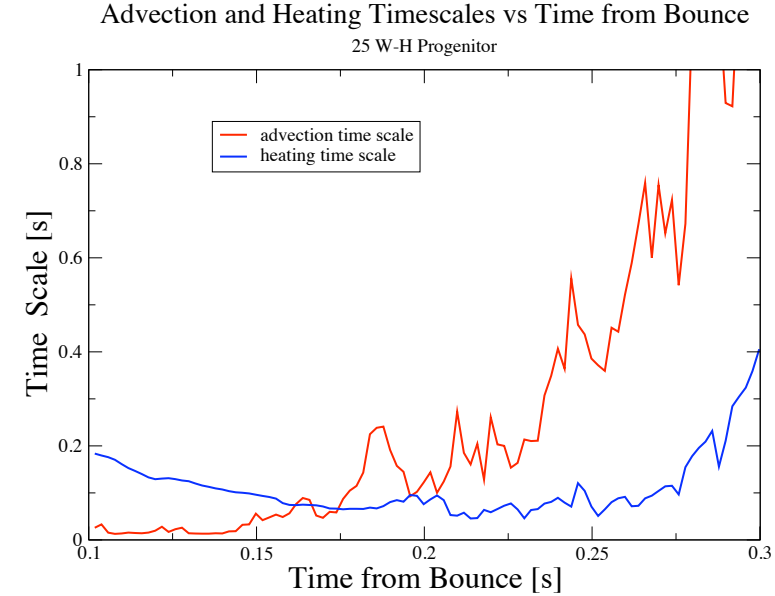
- *"RbR-Plus" MGFLD Neutrino Transport*
  - *O(v/c), GR time dilation and redshift, GR aberration (in flux limiter)*
- *PPMLR Hydrodynamics*
  - *GR time dilation, effective gravitational potential, adaptive radial grid*
- *Lattimer-Swesty EOS*
  - *180 MeV (nuclear compressibility), 29.3 MeV (symmetry energy)*
- *Nuclear (Alpha) Network*
  - *14 alpha nuclei between helium and zinc*
- *Effective Gravitational Potential*
  - **Marek et al. *A&A*, 445, 273 (2006)**
- *Neutrino Emissivities/Opacities*
  - *"Standard" + Elastic Scattering on Nucleons + Nucleon–Nucleon Bremsstrahlung*

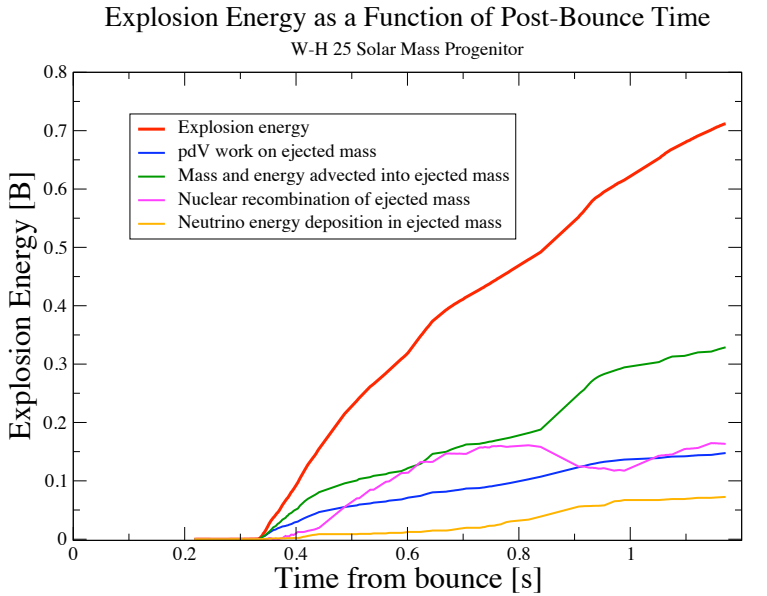
**"Ray-by-Ray-Plus" Approximation**
- **Solve set of 1D problems.**
- **Ignore differences in lateral fluxes.**
  - **Buras et al. *A&A*, 447, 1049 (2003)**





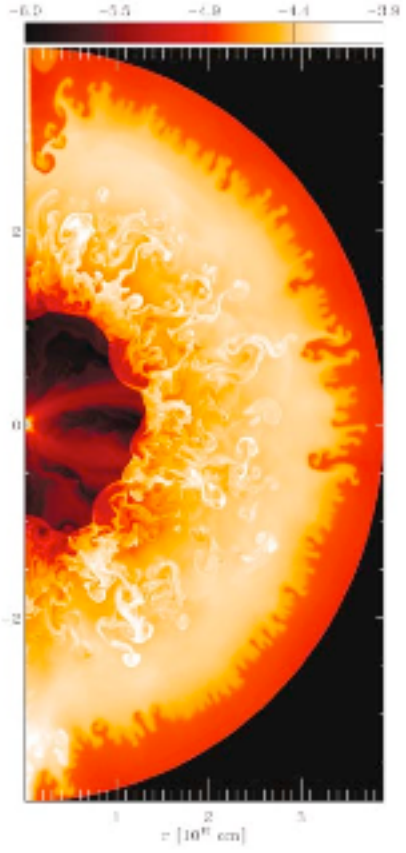




August 11, 2011

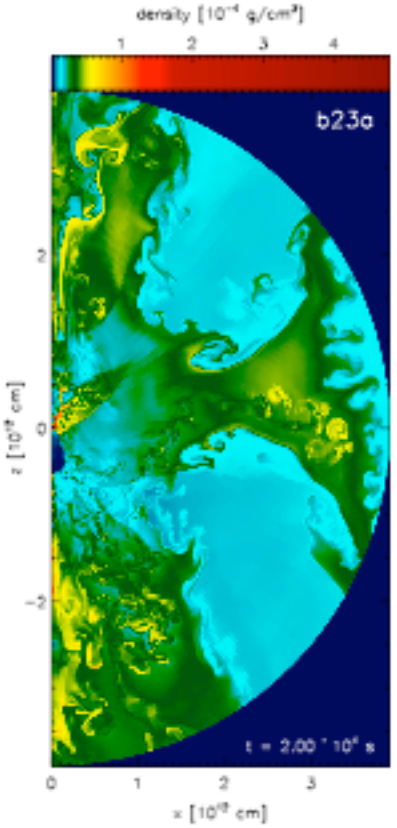
**Bruenn et al., *Journ. Phys. Conf. Ser.* 180, 012018 (2009)**

# SASI leaves imprint on ejecta



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

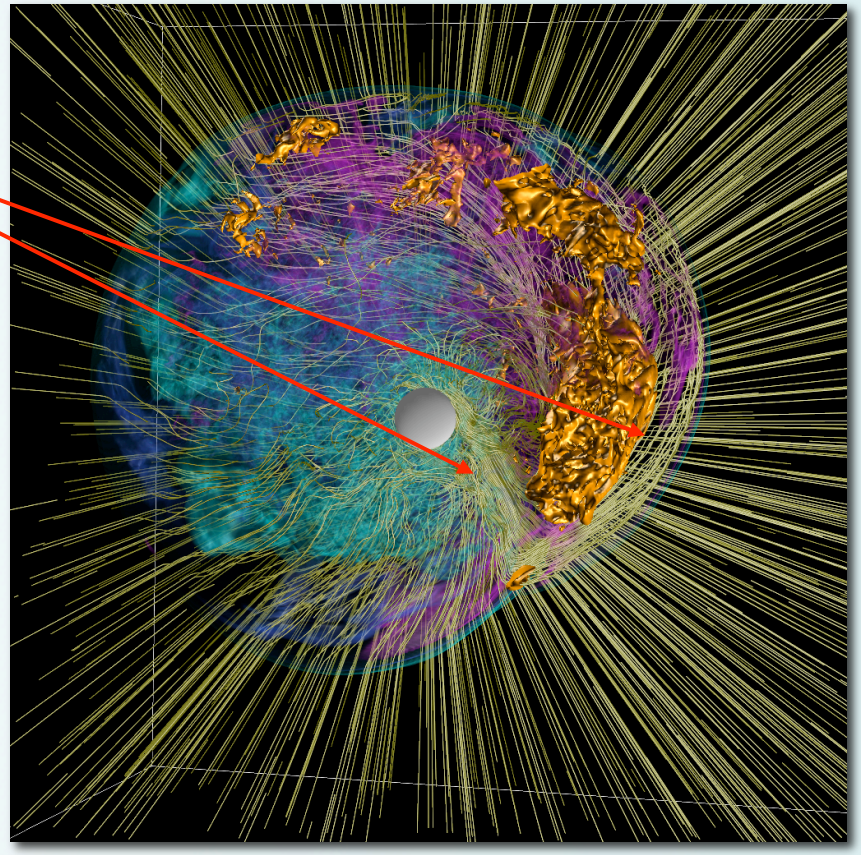
# SASI generates rotation

**SASI-induced counter rotating flows.**

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

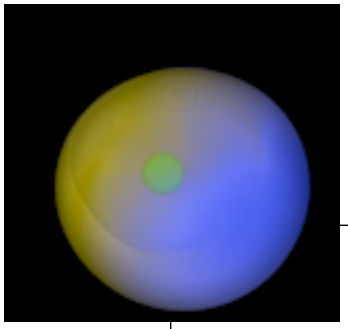
**Implications for**

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



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

# Evolution of SASI in 3D





**linear**

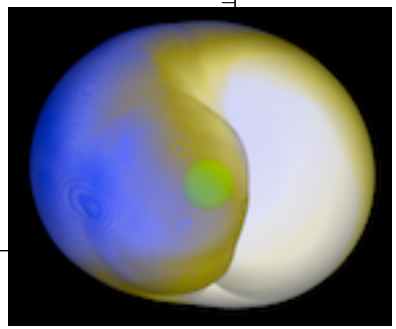
radial flow;
exponential
growth of *l=1*

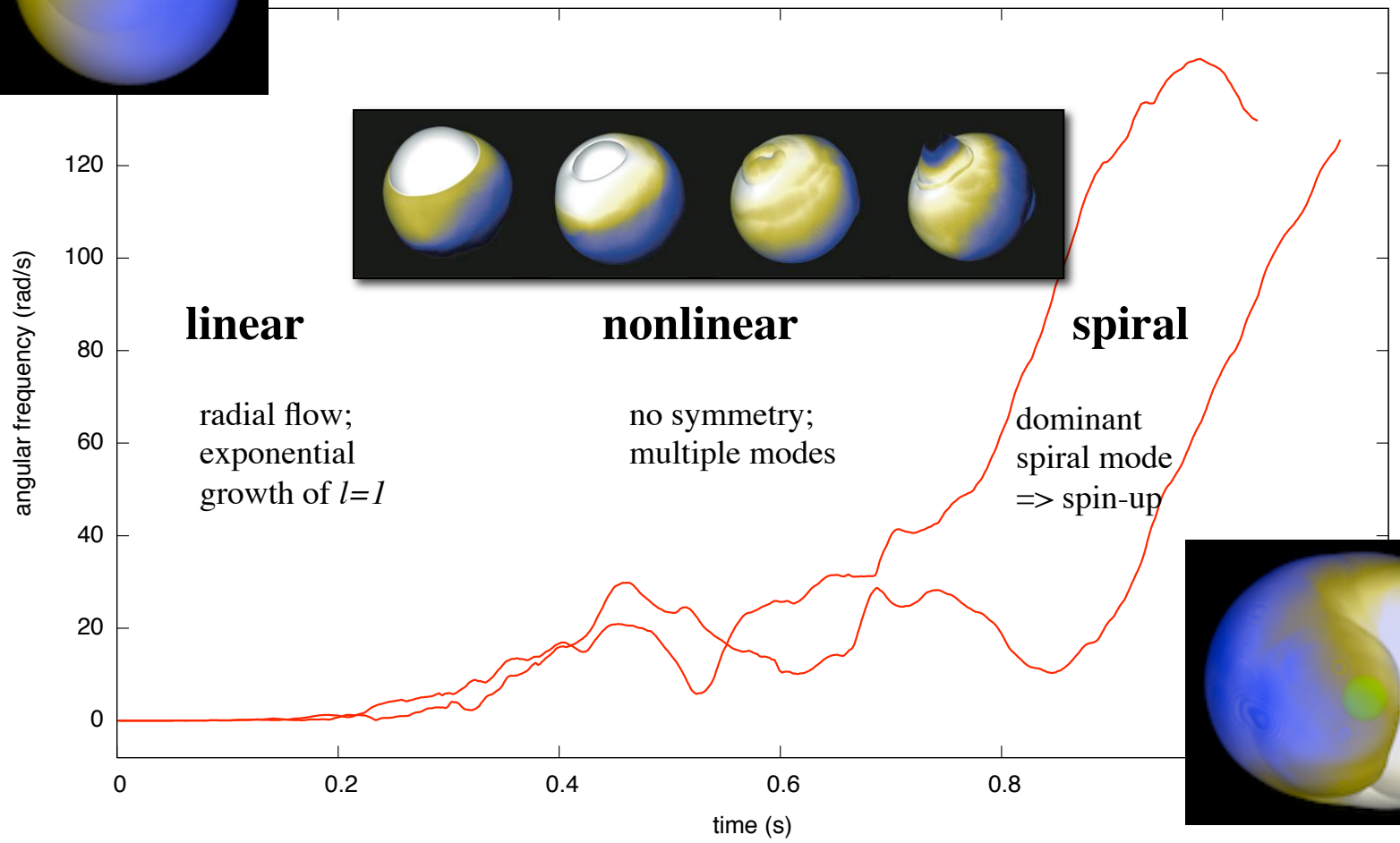
**nonlinear**

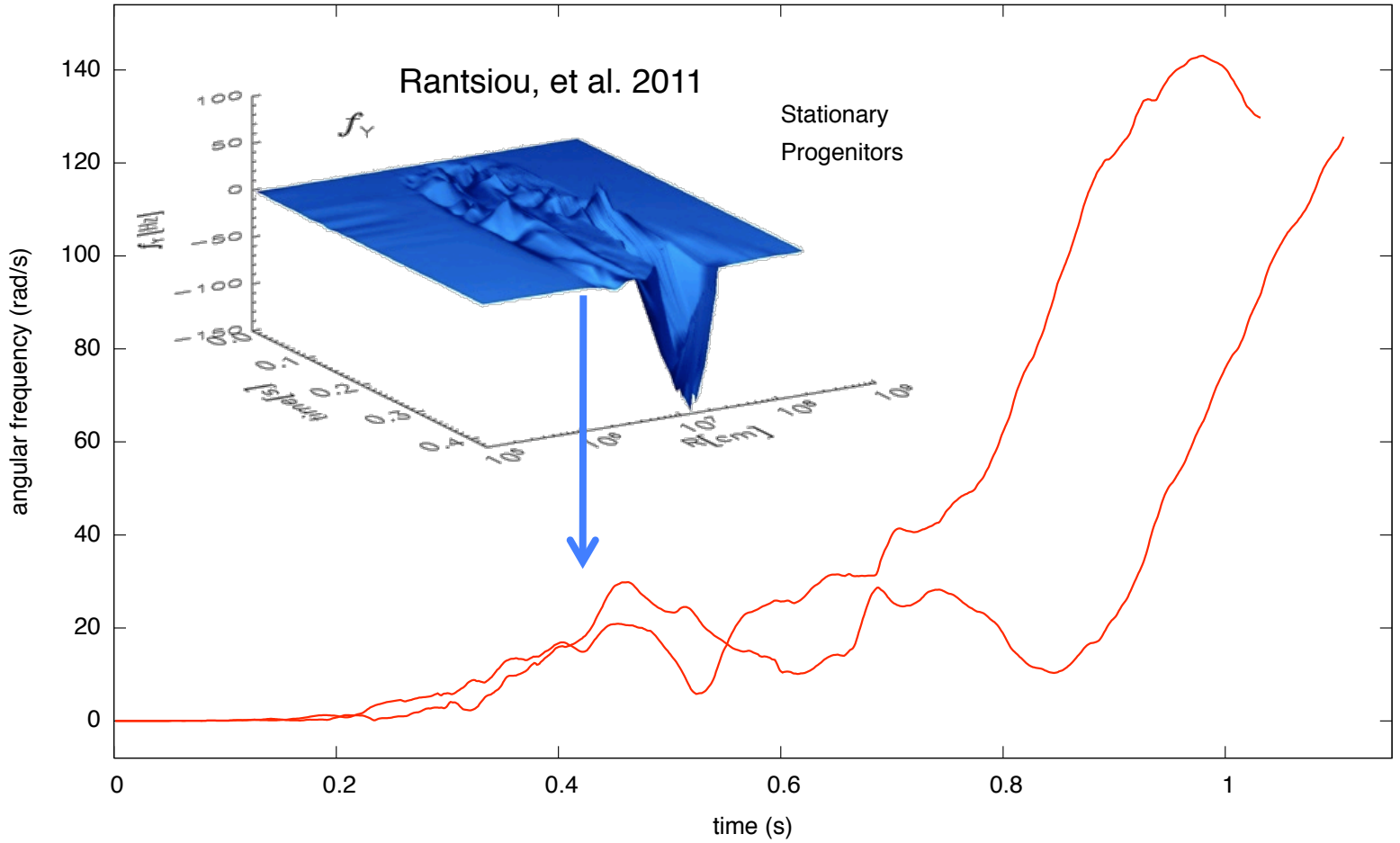
no symmetry;
multiple modes

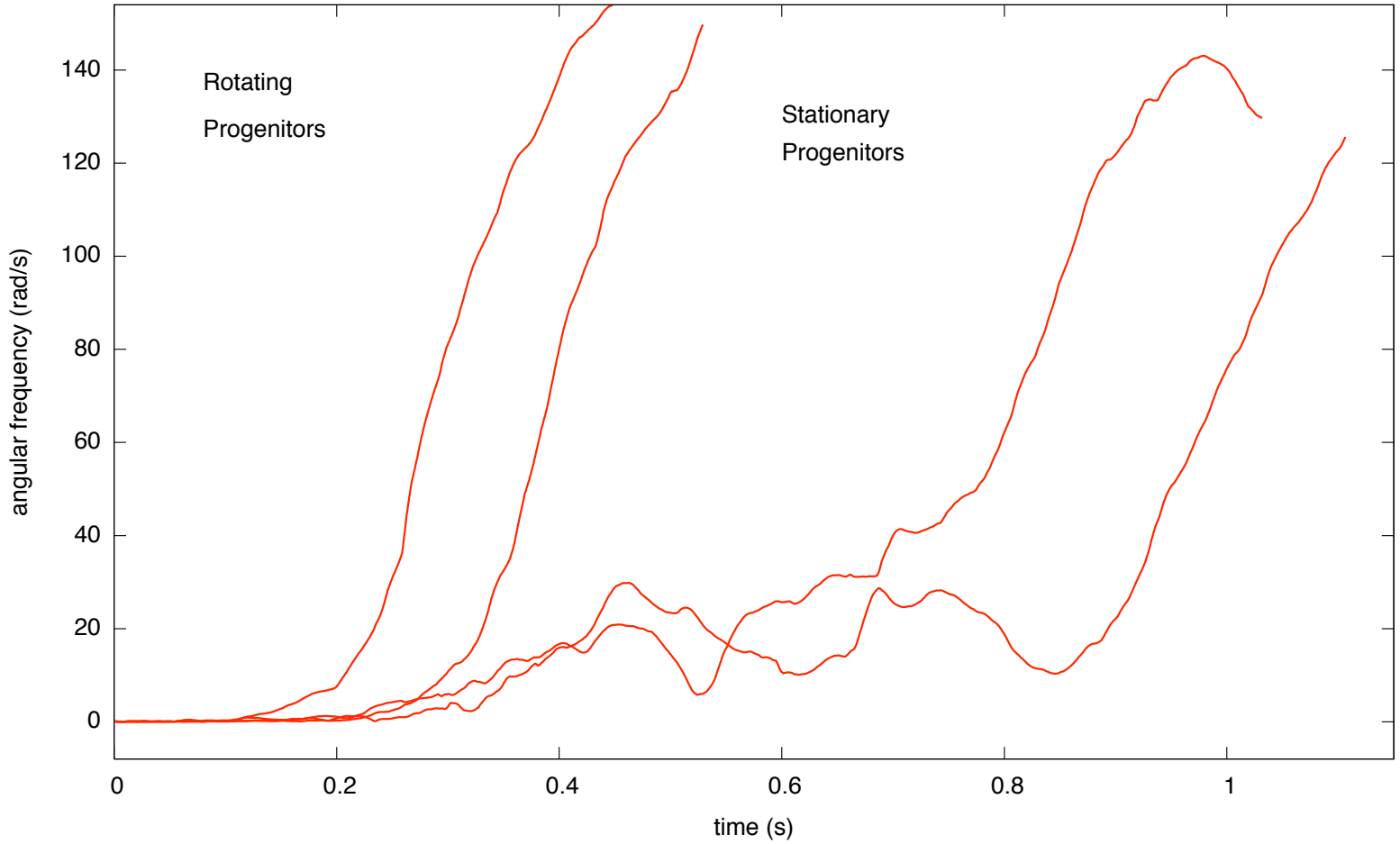
**spiral**

dominant
spiral mode
=> spin-up

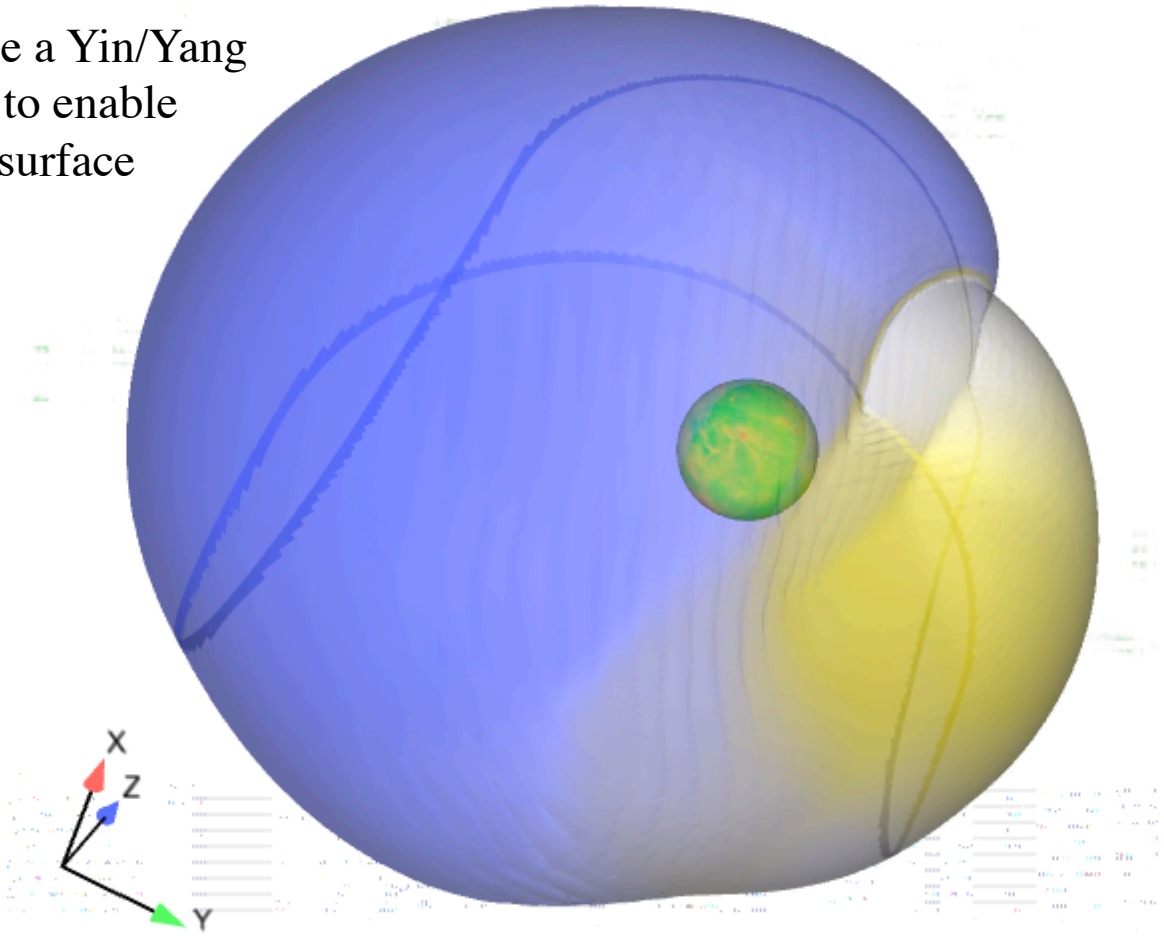




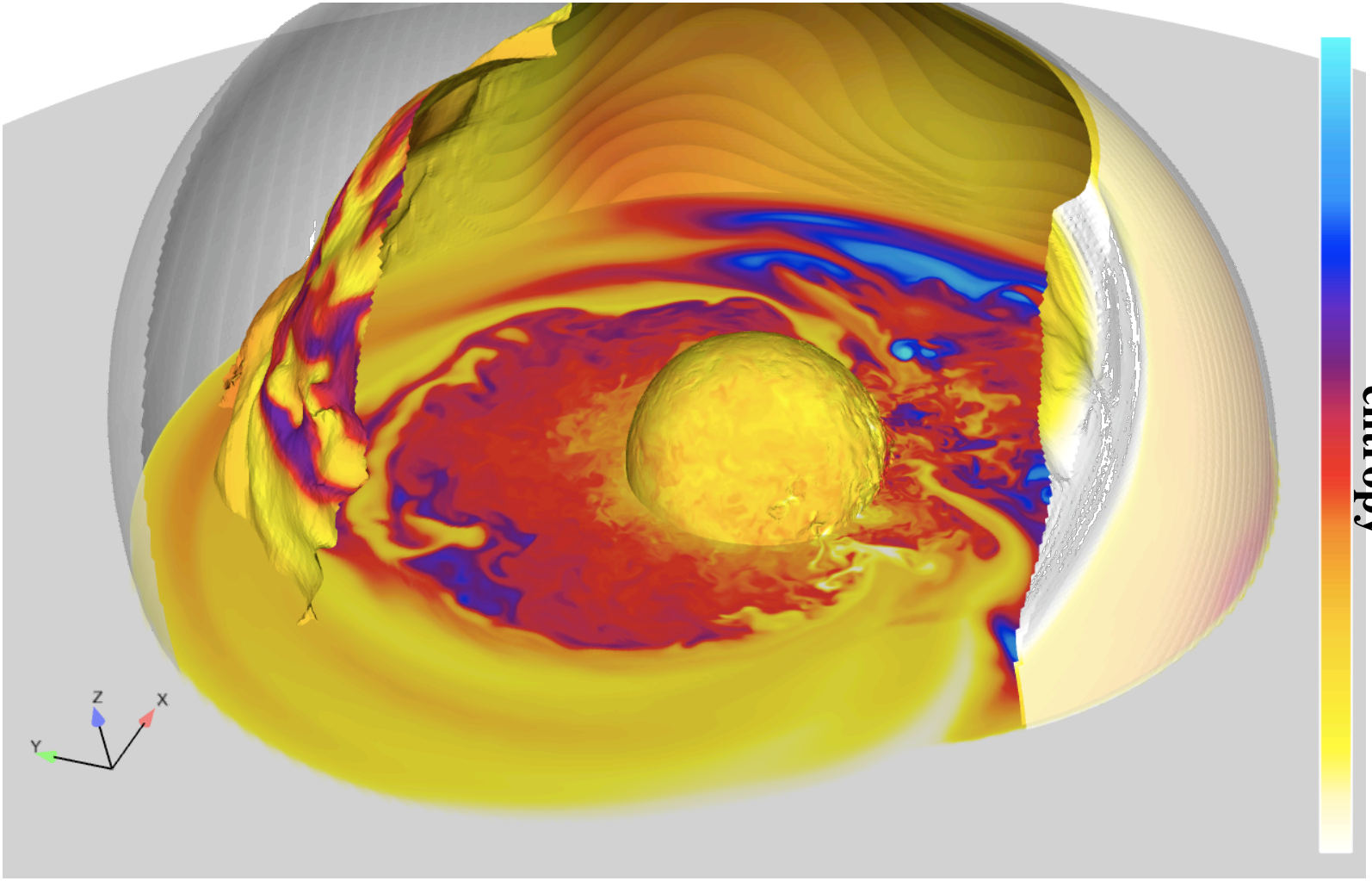

Rantsiou, et al. 2011
Stationary
Progenitors
angular frequency (rad/s)
time (s)
0
20
40
60
80
100
120
140
0
0.2
0.4
0.6
0.8
1


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

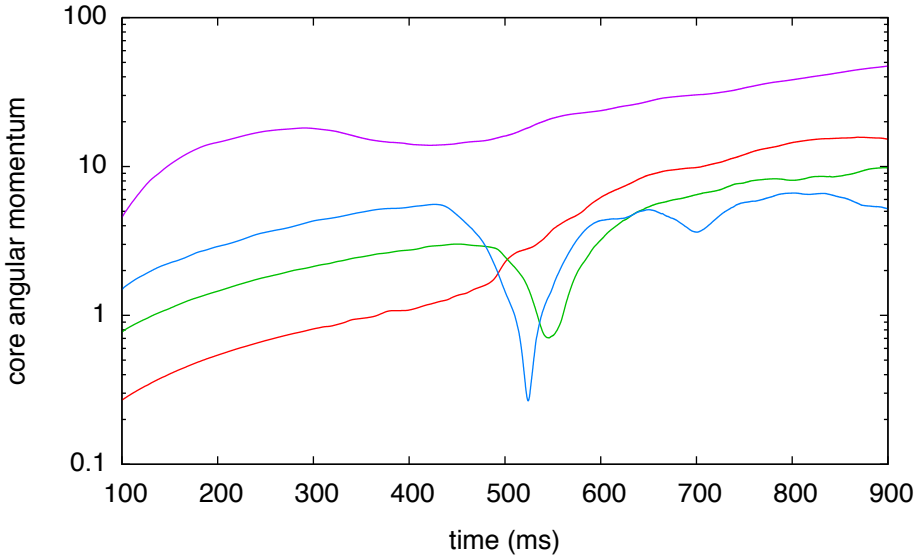
Current 3D models use a Yin/Yang overset spherical grid to enable high resolution at the surface of the accreting core.



# Rotating Progenitor: SASI starts in spiral mode



# Rotating Progenitor: spiral SASI kicks in immediately



# It Takes a Village

Bruenn
Marronetti
Yakunin

Blondin
Mauney
Melton

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***