Toward the Explosion Mechanism for Core-Collapse Supernovae: An Emerging Picture

Presented by

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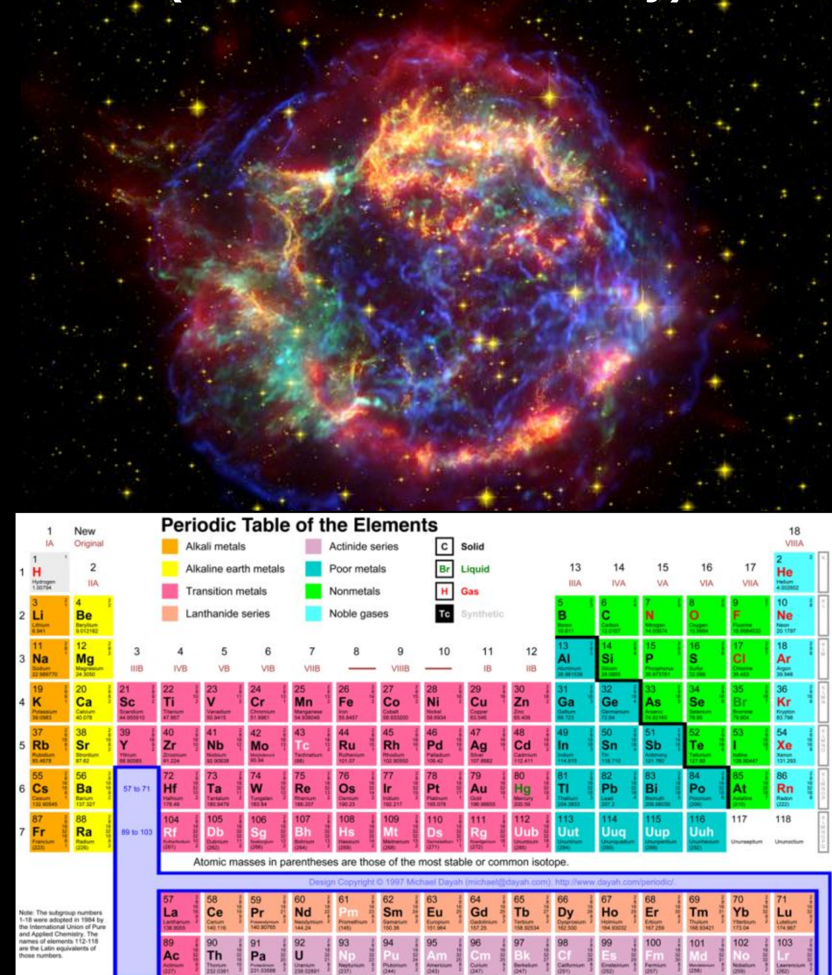
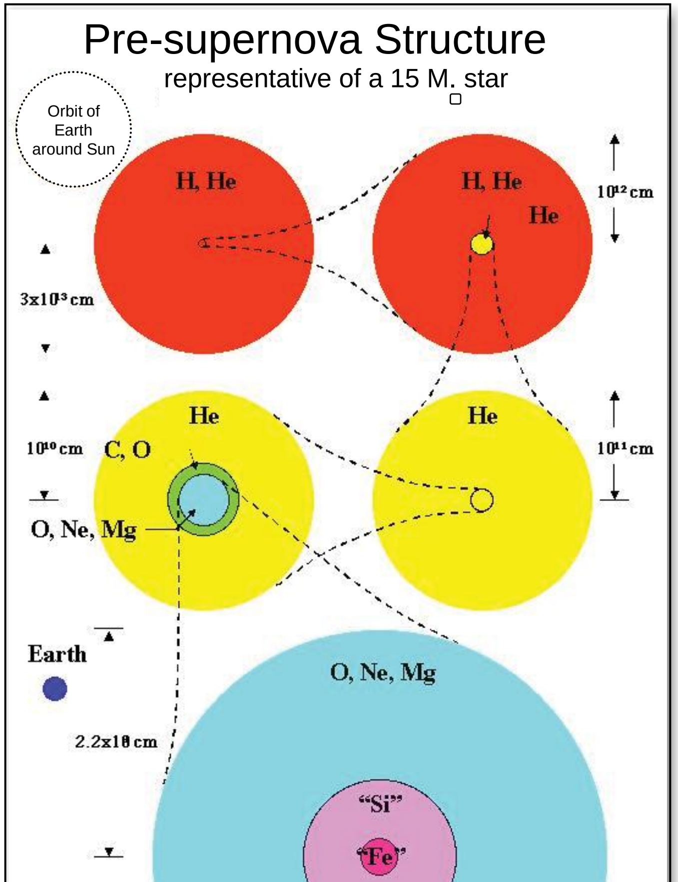
Core-collapse supernovae

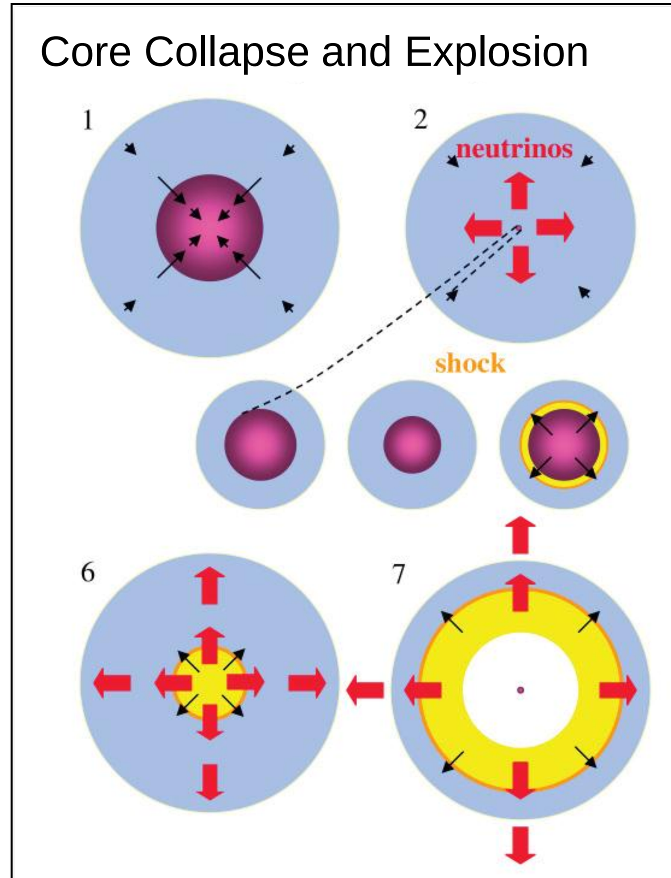
- What are they?
  - Explosions of massive stars
- How often do they occur?
  - About twice per century in our galaxy
- Why are they important?
  - Dominant source of elements in the universe

Cas A Supernova Remnant
(Chandra Observatory)



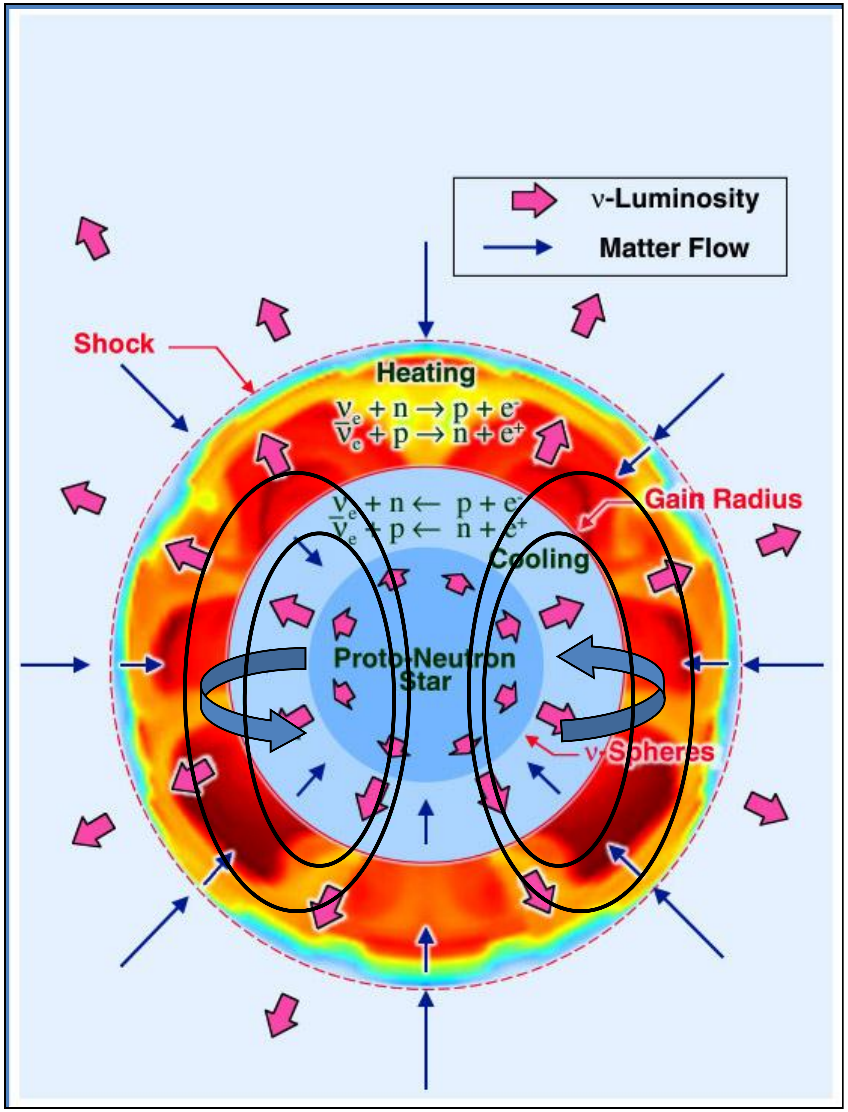
Core-collapse supernova paradigm





The star's iron core becomes unstable, collapses, rebounds, and launches a shock wave into the star, which stalls

How is the supernova shock wave revived?

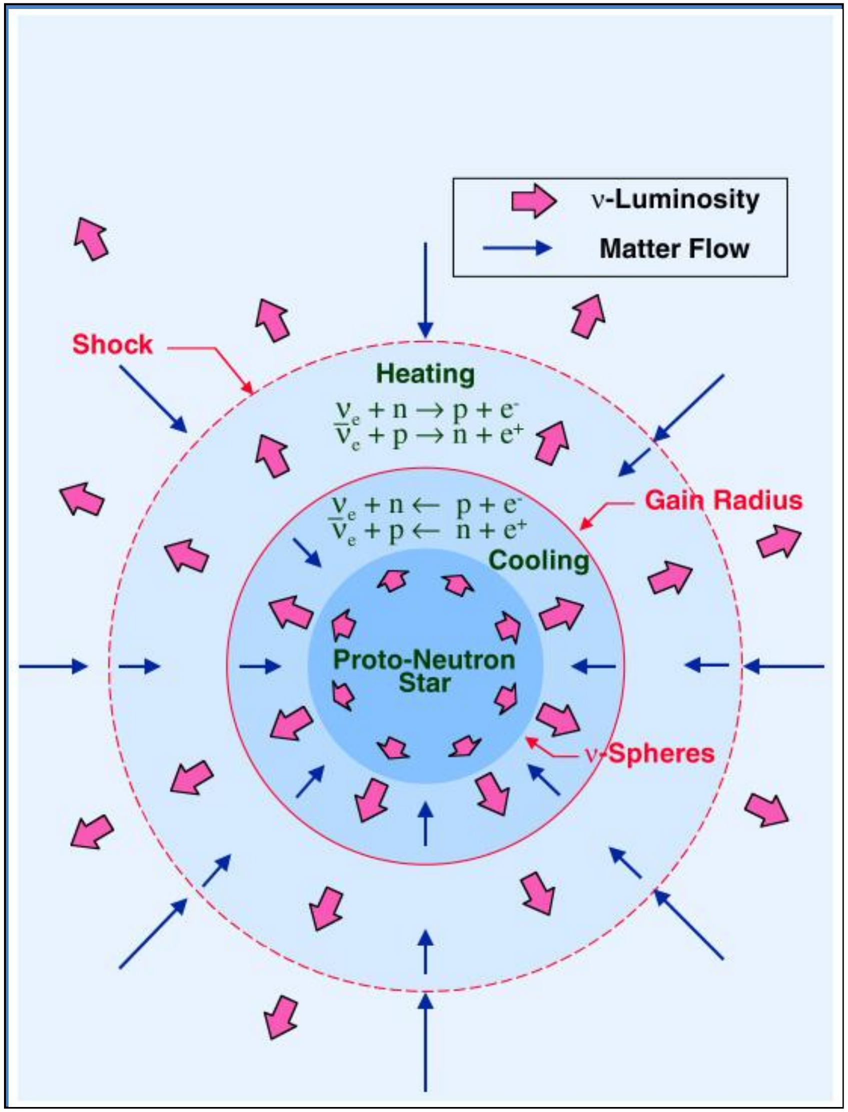


The most fundamental question in supernova theory

- Neutrino (radiation) heating
- Convection
- Shock instability (SASI)
- Nuclear burning
- Rotation
- Magnetic fields

**New ingredient*

How is the supernova shock wave revived?



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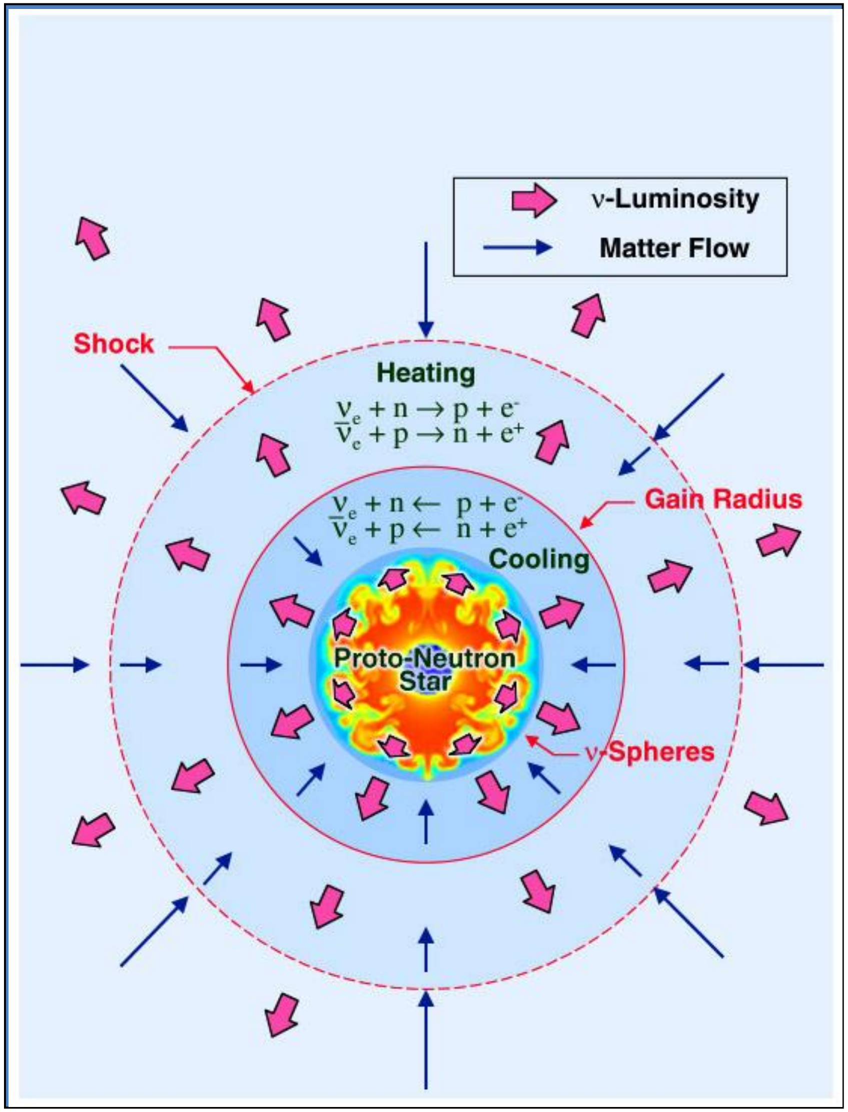

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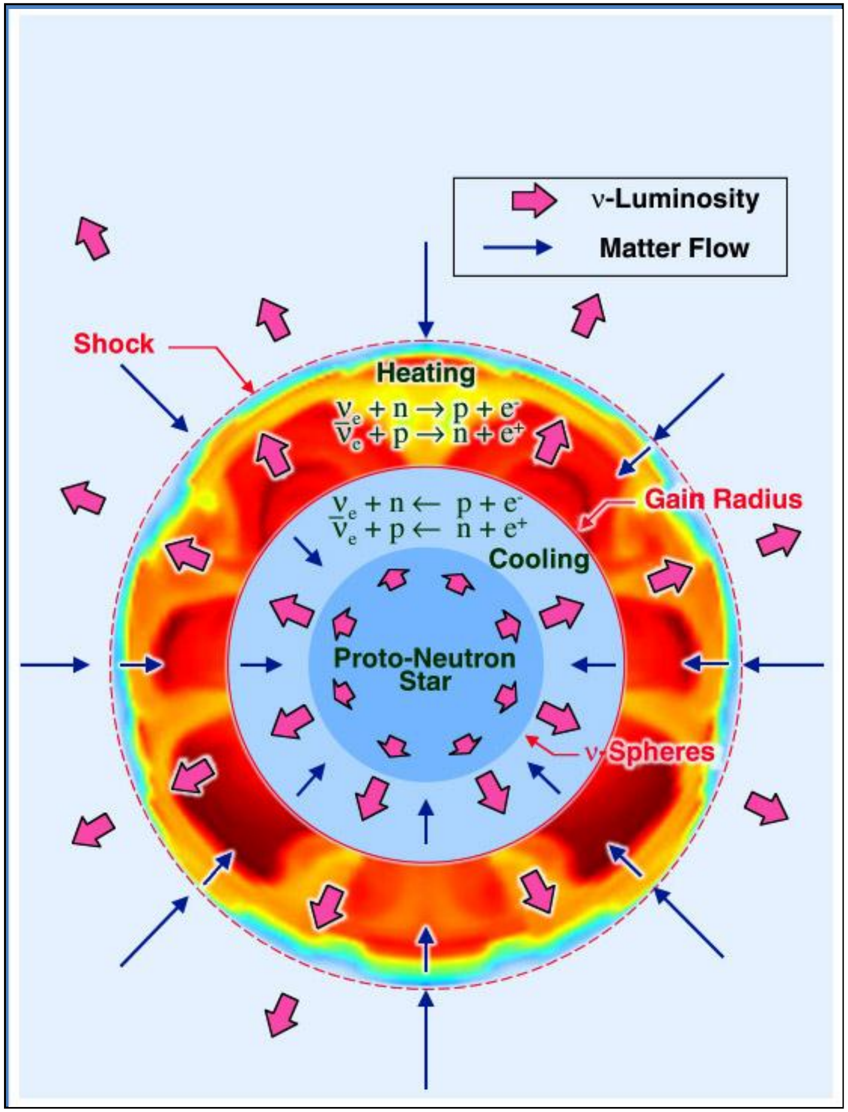

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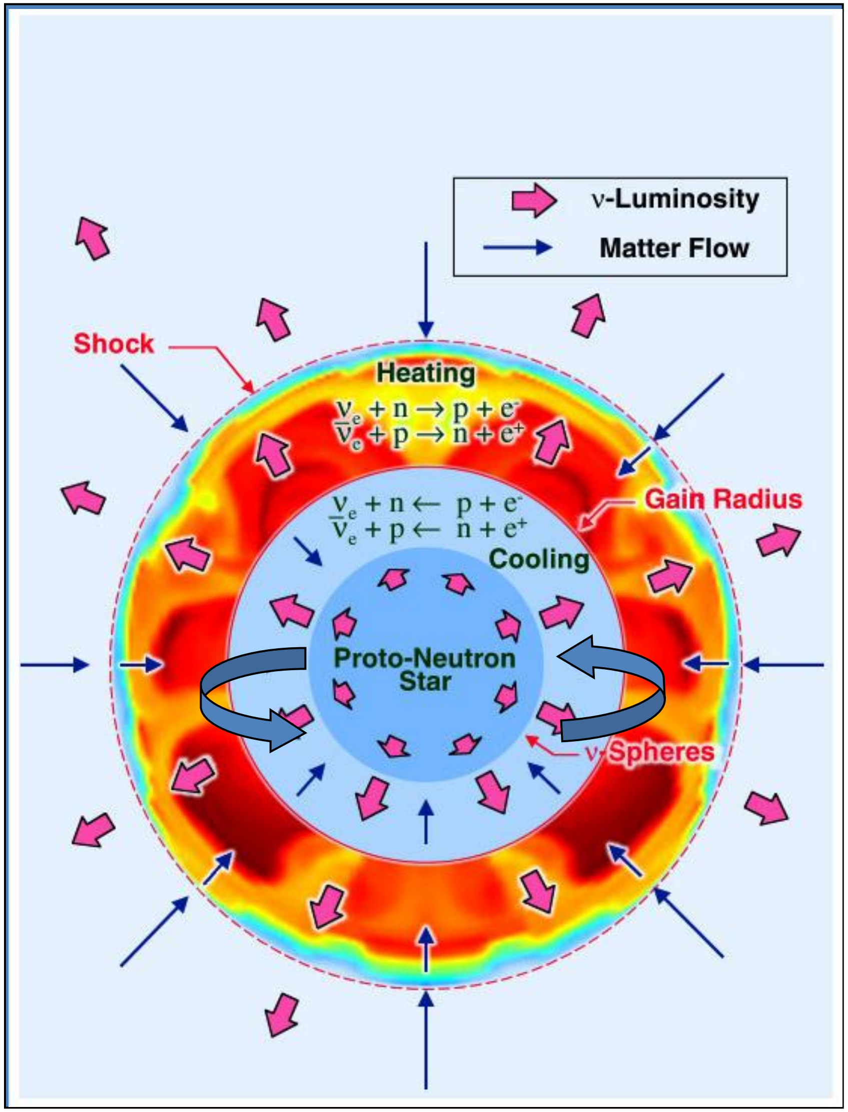

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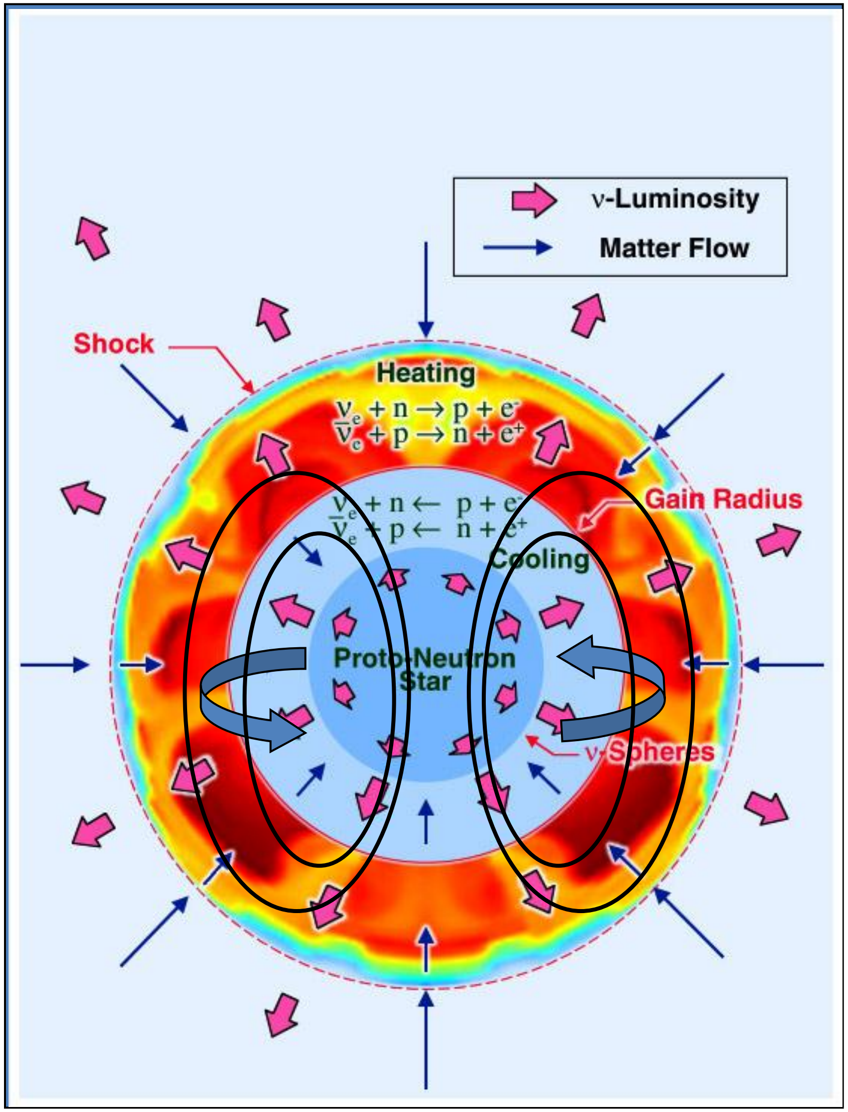

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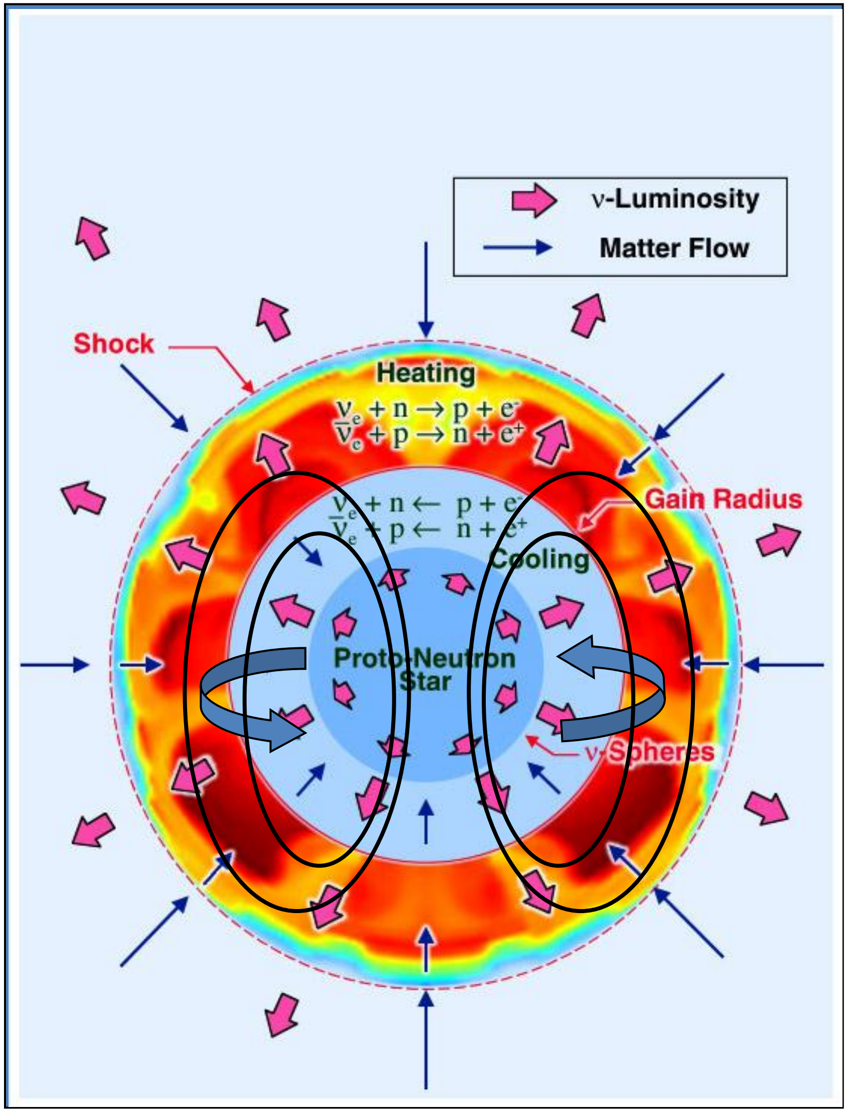

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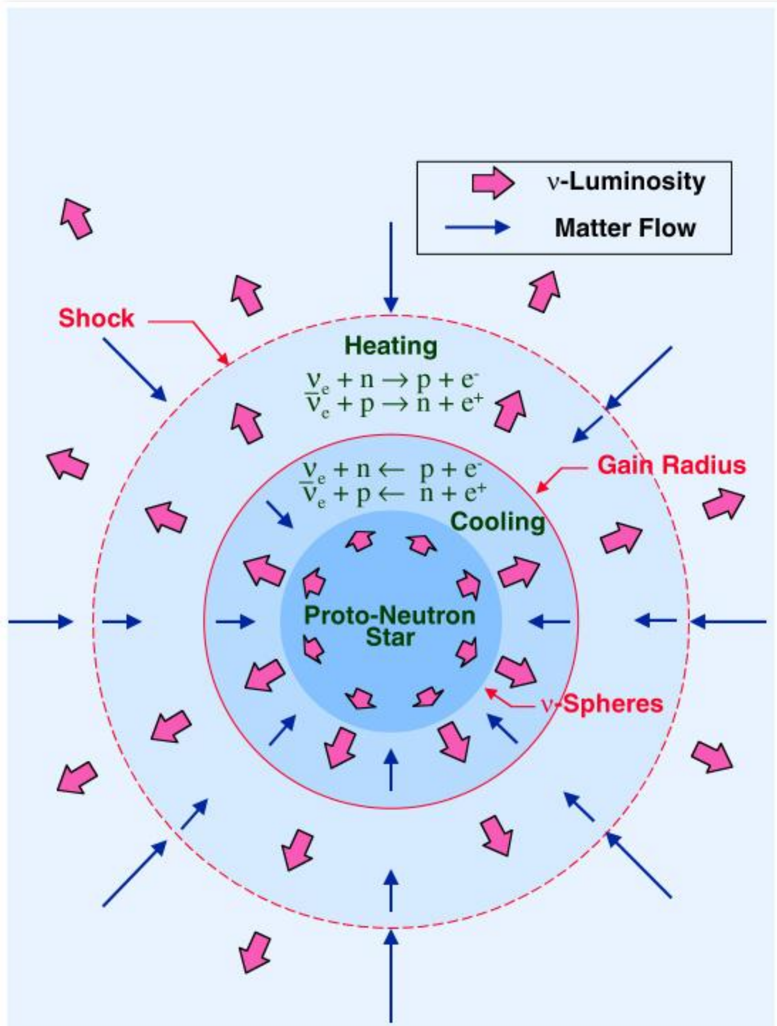
**New ingredient*

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*)

GenASiS

Exascale

Multifrequency and Multiangle Neutrino Transport

Petascale

Multifrequency Neutrino Transport

Terascale

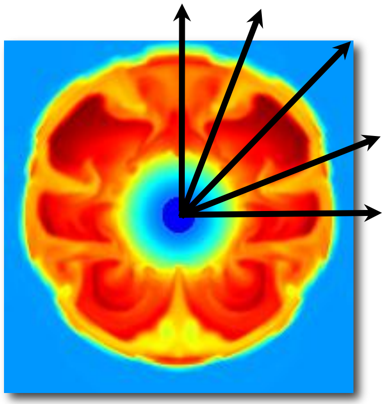
Gray Neutrino Transport

CHIMERA

Axisymmetric multiphysics supernova models

Simulation Building Blocks

- "RbR-Plus" MGFLD Neutrino Transport
  - O(v/c), GR time dilation and redshift, GR aberration (in flux limiter)
- 2D PPM 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
- 2D Effective Gravitational Potential
  - Marek et al., A&A 445, 273 (2006)
- Neutrino Emissivities/Opacities
  - "Standard" + Elastic Scattering on Nucleons + Nucleon–Nucleon Bremsstrahlung



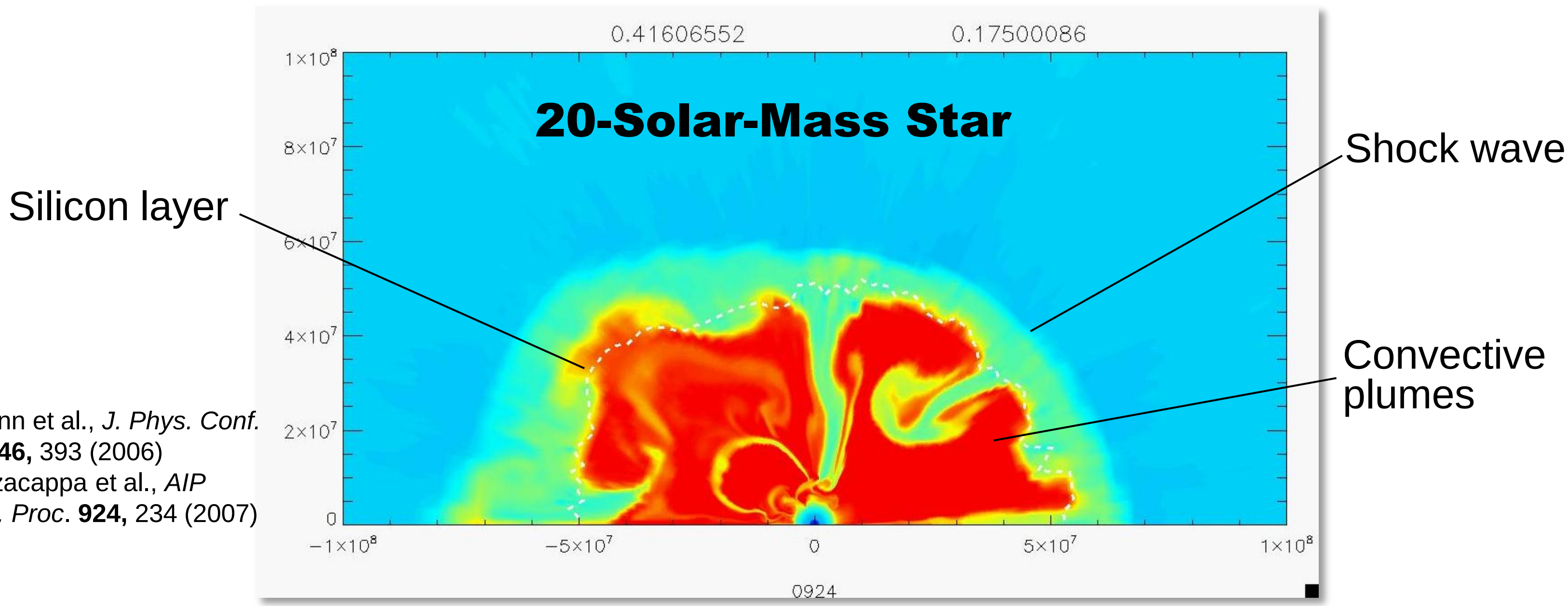
"Ray-by-Ray-Plus" Approximation

- Radial transport allowed
- Lateral transport suppressed

  - Buras et al., *A&A* **447,** 1049 (2003)

CHIMERA

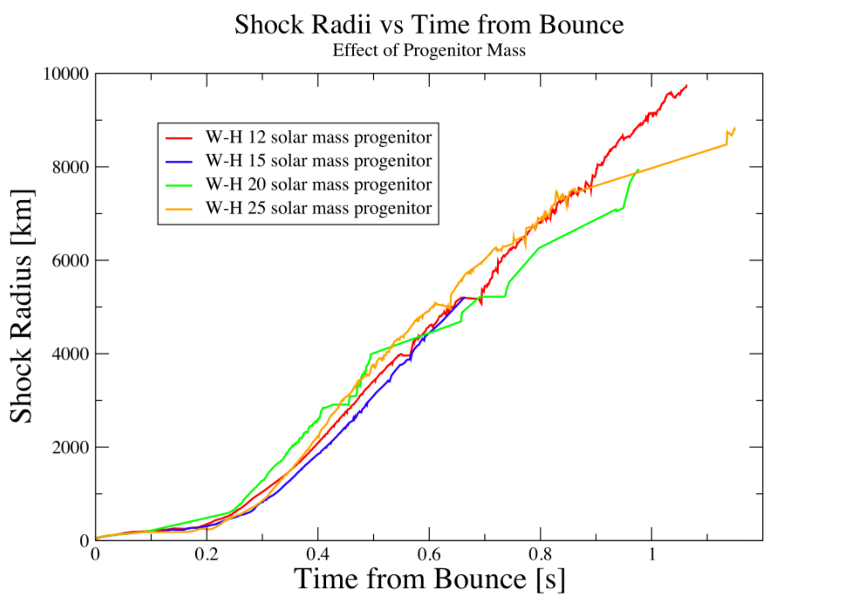
An emerging picture from 2D multiphysics models

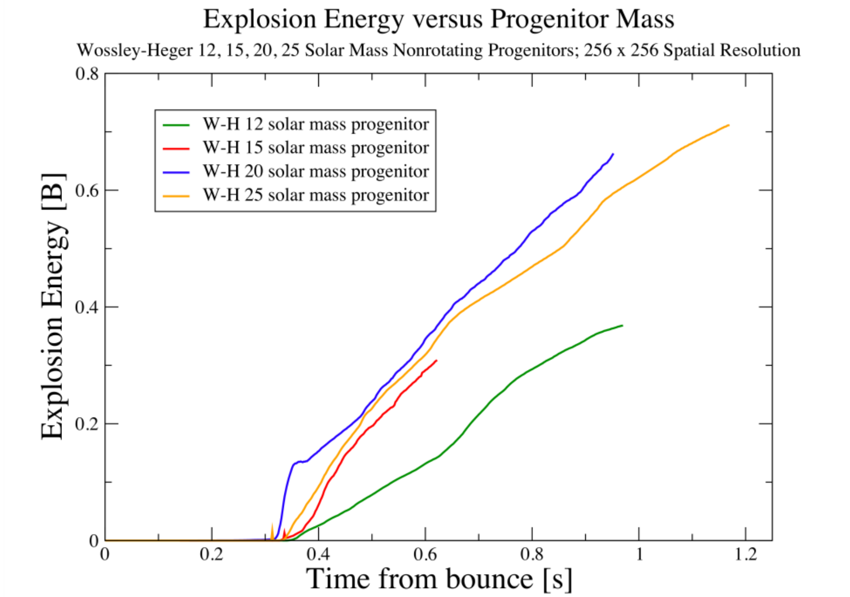


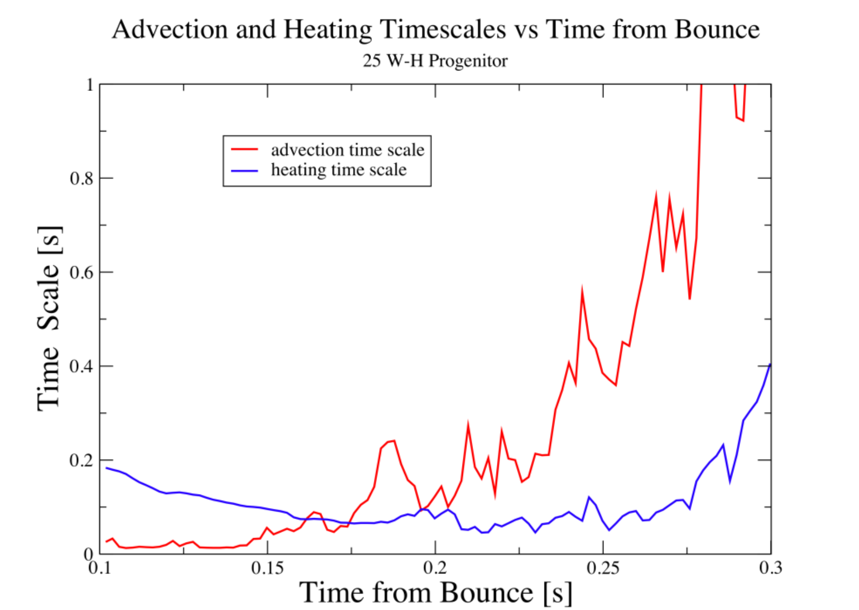
Bruenn et al., *J. Phys. Conf. Ser.* **46,** 393 (2006)
Mezzacappa et al., *AIP Conf. Proc*. **924,** 234 (2007)

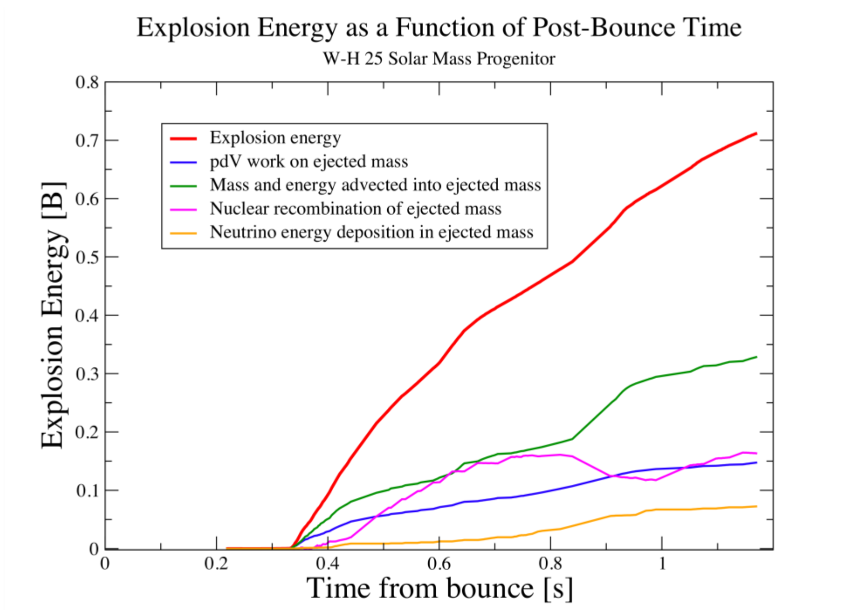
Confluence of neutrino heating with improved neutrino interactions, convection, the stationary accretion shock instability (SASI), nuclear burning, and drop in density leads to an explosion.

Two-dimensional results are very promising; successful explosions are achieved across a range of initial stellar masses.

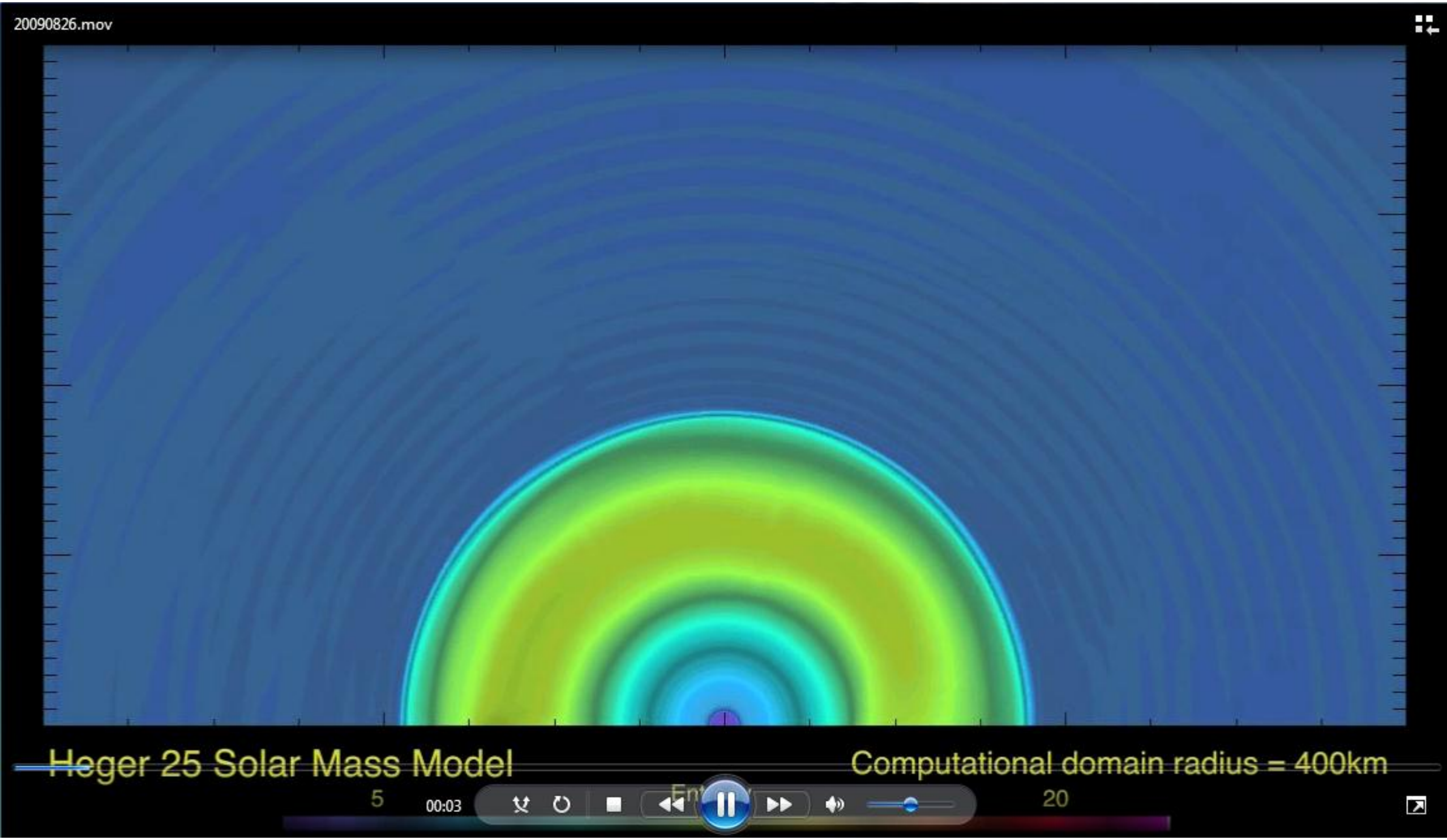








Bruenn et al., *J. Phys. Conf. Ser.* **180,** 012018 (2009)
Messer et al., *Proceedings of Nuclei in the Cosmos XI,* 027 (2010)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Heger 25 Solar Mass Model
Computational domain radius = 400km
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00:03
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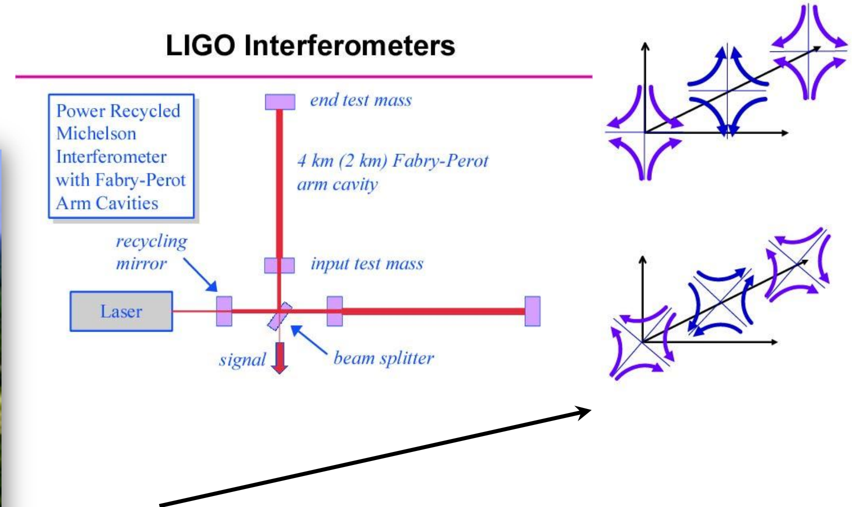
The advent of gravitational wave astronomy

Laser Interferometric Gravitational Wave Observatory

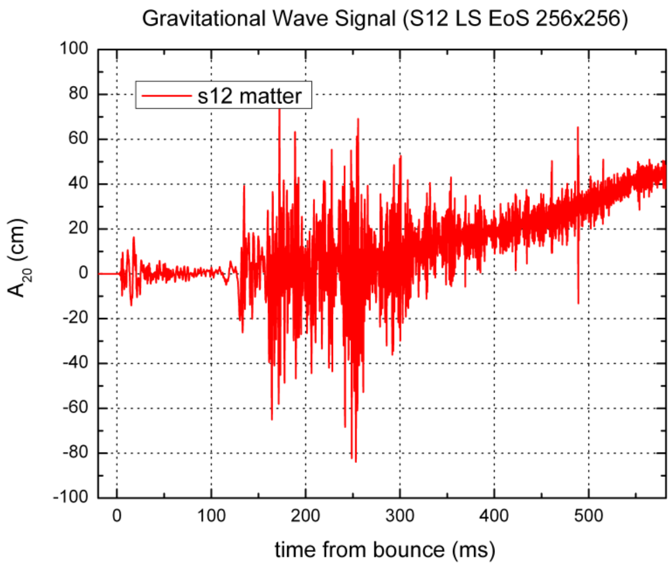


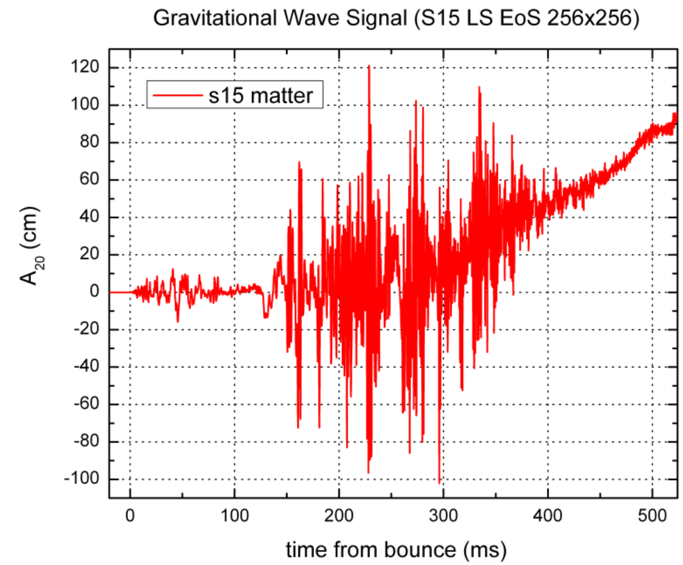
Gravitational waves are quadrupolar

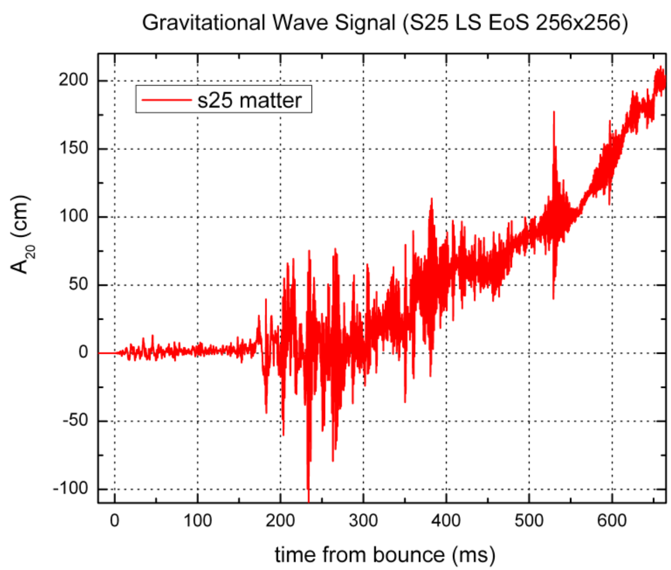
Test masses will move 1 trillionth the width of a human hair

Other Observatories: TAMA, VIRGO, GEO, LISA, …

Sources: Core Collapse Supernovae, Neutron-Star Mergers, Black Hole Mergers







$$h_+ D = \frac{1}{8}\sqrt{\frac{15}{\pi}}(\sin^2\theta)A_{20}$$

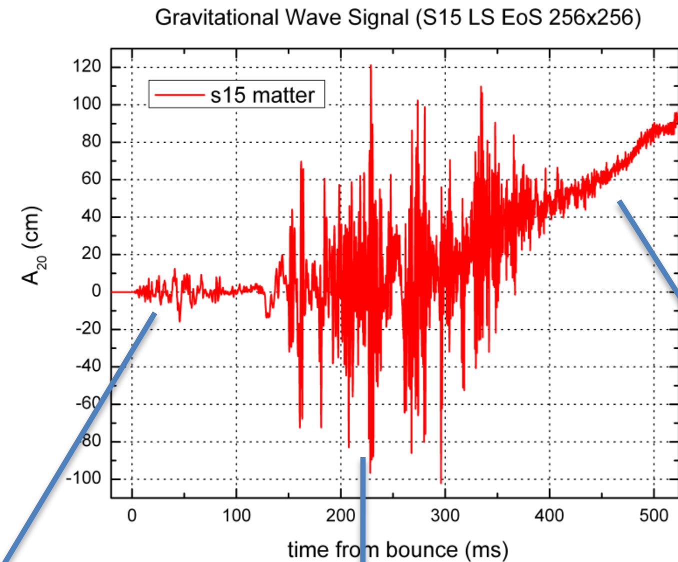
First complete gravitational waveforms based on 2D self-consistent explosion models

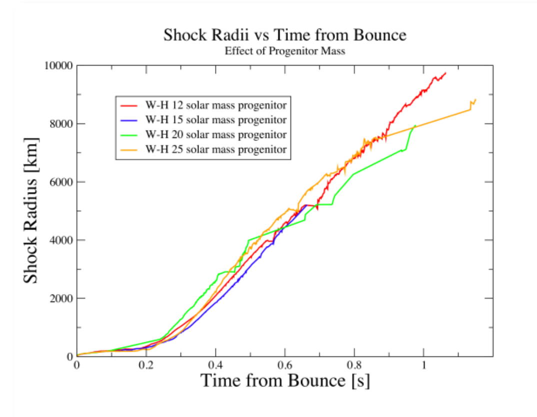
All phases included core bounce, early postbounce phase, neutrino-driven convection and SASI phase, and explosion phase

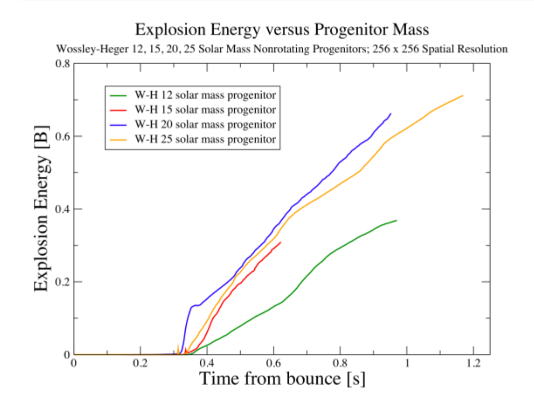
Computed using data from 2D CHIMERA simulations reported here

Yakunin et al., *Class. Quant. Grav*., **27,** 194005 (2010)

Anatomy of a gravitational wave signal



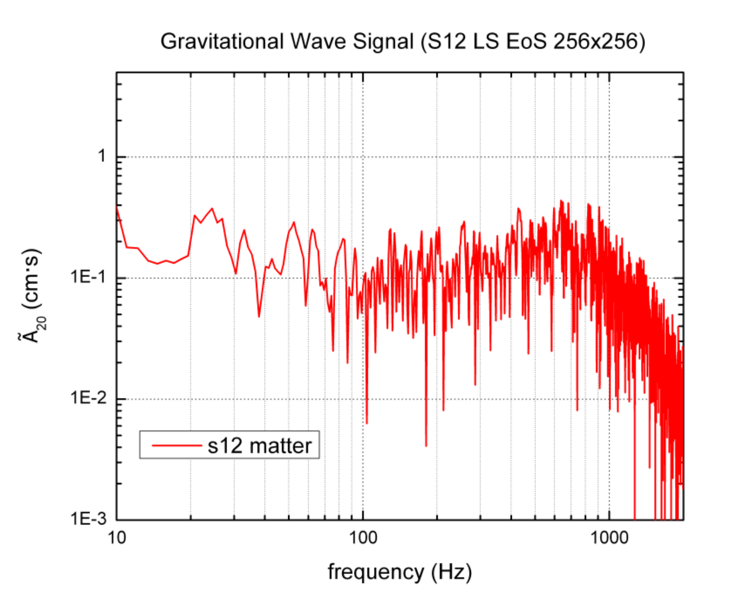


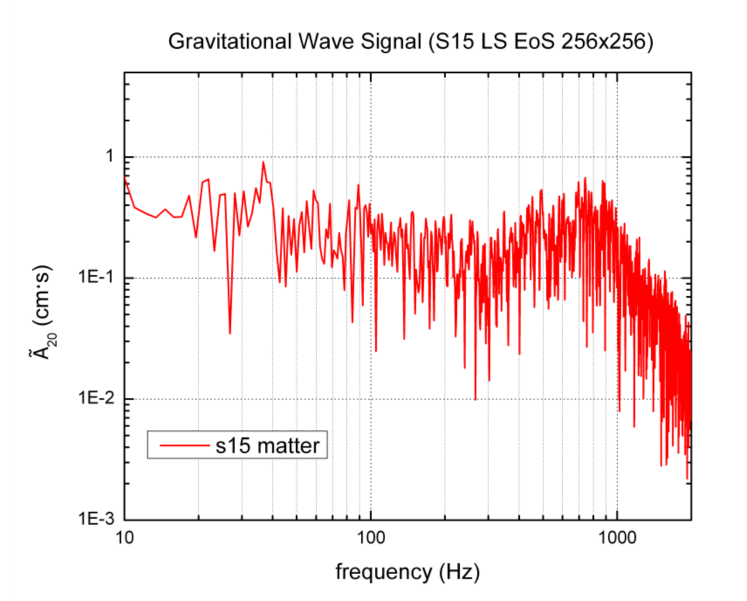


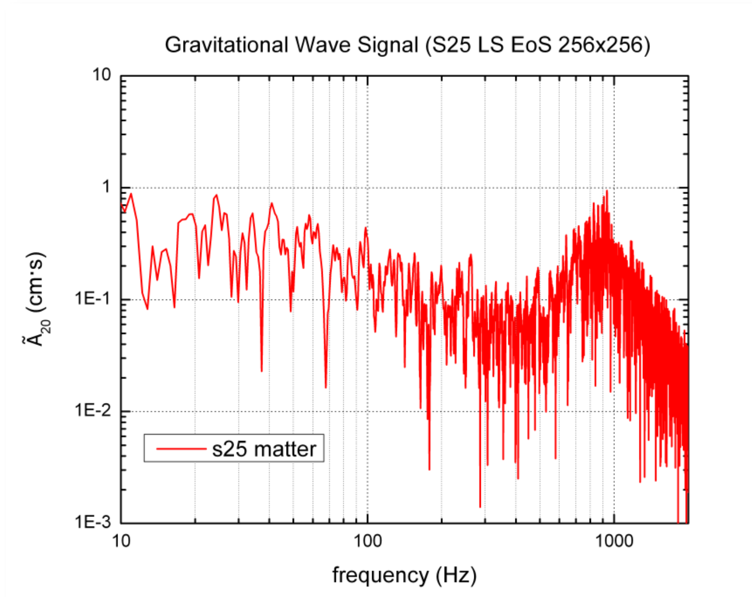
- Prompt Convection
- Early Shock Deceleration

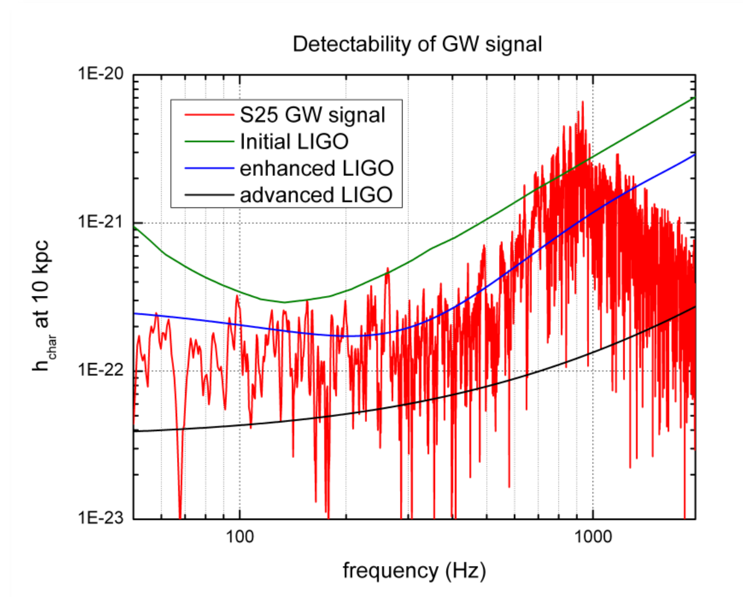
- Lower-Frequency Envelope: SASI-Induced Shock Excursions
- Higher-Frequency Variations: Impingement of Downflows on PNS from Neutrino-Driven Convection and SASI

- Later Rise: Prolate Explosion/Deceleration at Shock





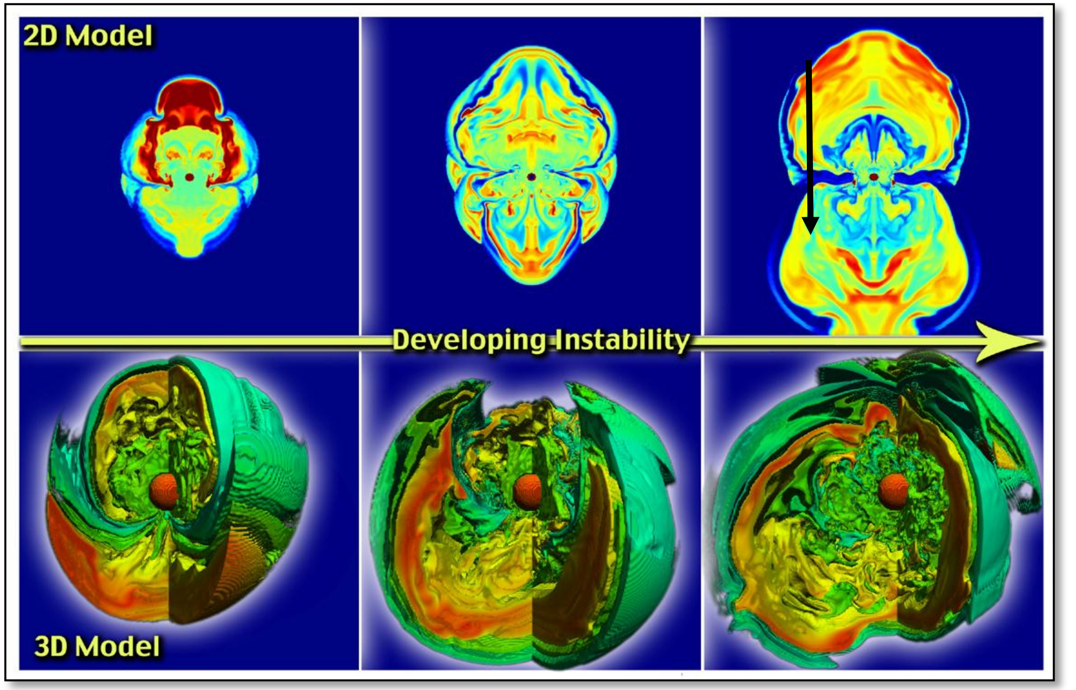




Yakunin et al., *Class. Quant. Grav.*, **27**, 194005 (2010)

Need for 3D

Simulations of the SASI in 2D and 3D reveal new modes/dynamics in 3D that qualitatively alter simulation outcomes



Blondin, Mezzacappa, and DeMarino, *Ap. J.* **584,** 971 (2003)

Promising 2D simulations reported here must be performed in 3D

SASI has axisymmetric and nonaxisymmetric (3D) modes that are both linearly unstable!

- Blondin and Mezzacappa, *Ap. J.* **642**, 401 (2006)
- Blondin and Shaw, *Ap. J.* **656**, 366 (2007)

3D multiphysics simulations

Simulation Building Blocks

- RbR-Plus" MGFLD Neutrino Transport
  - O(v/c), GR time dilation and redshift, GR aberration (in flux limiter)
- 3D PPM Hydrodynamics
  - GR time dilation, effective gravitational potential, adaptive radial grid
- Lattimer-Swesty EOS
  - 180 MeV (nuclear compressibility), 29.3 MeV (symmetry energy)
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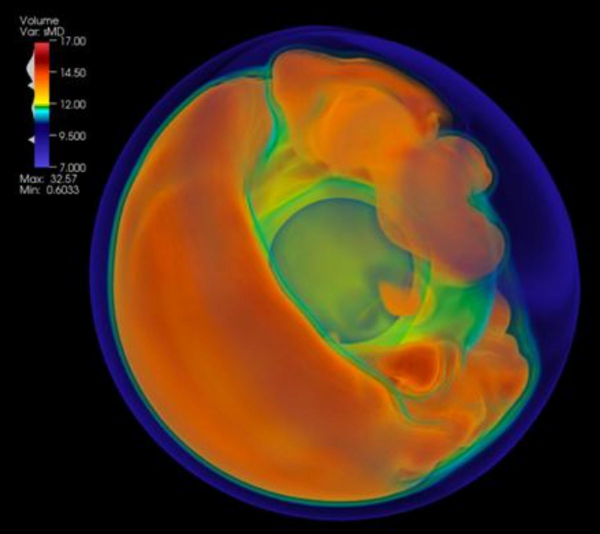
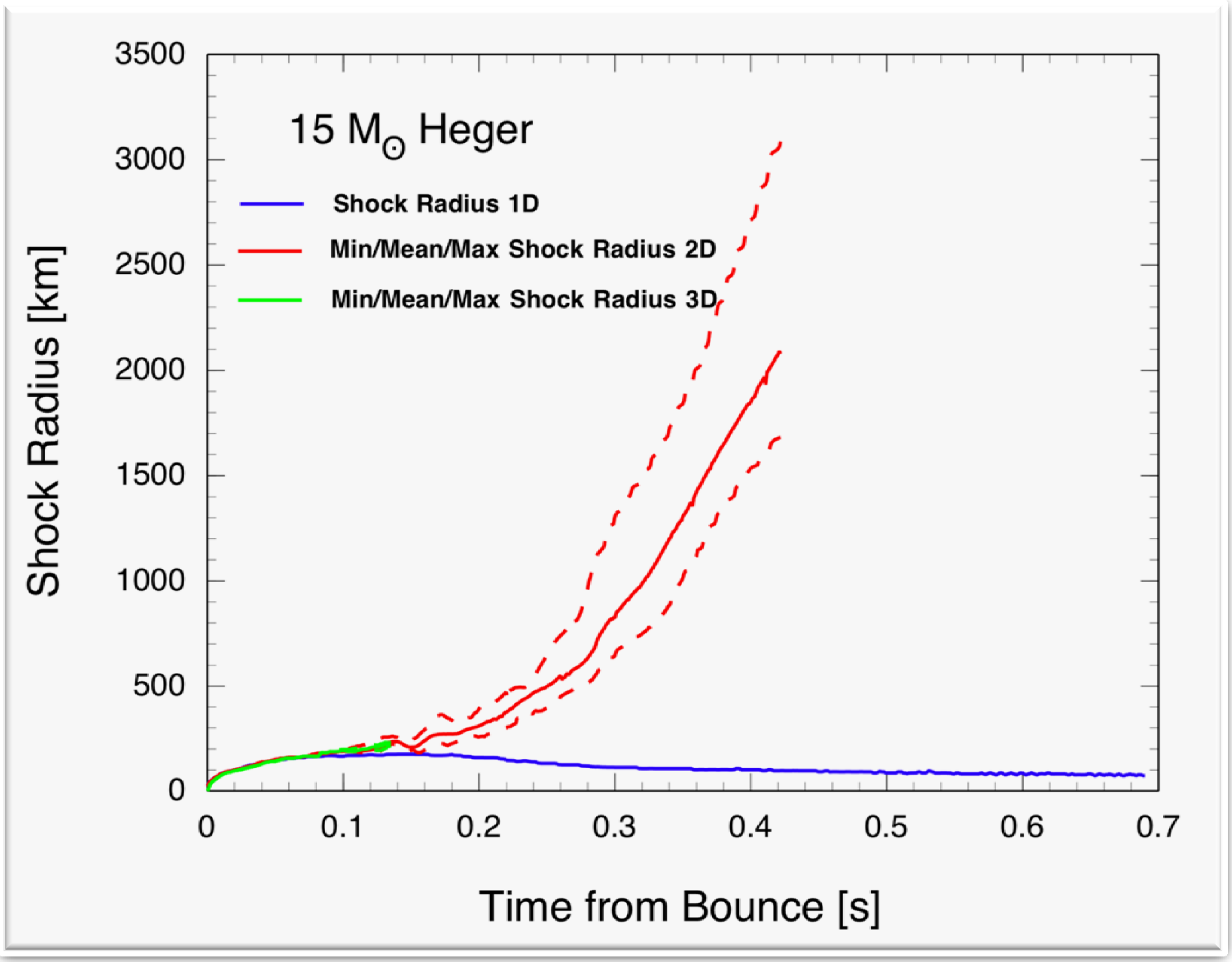


Bruenn et al., *J. Phys. Conf. Ser.* **180,** 012018 (2009)

<u>Resolution</u>

Initial Model: 304 X 76 X 152
⇒ 11,552 processors

Matching the 2D models requires: 512 X 256 X 512
⇒ 131,072 processors



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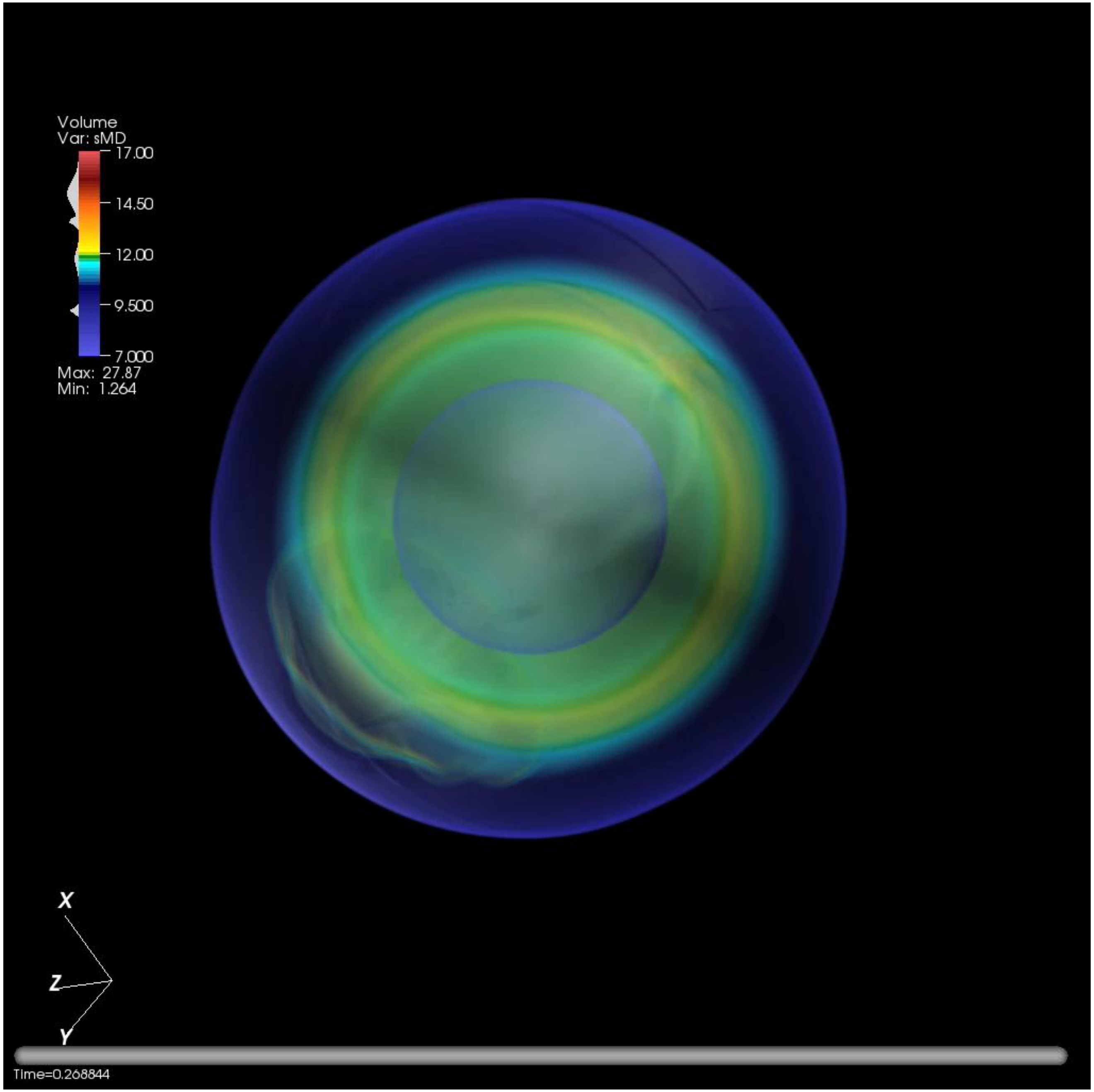
Messer et al., *Proceedings of Nuclei in the Cosmos XI,* 027 (2010)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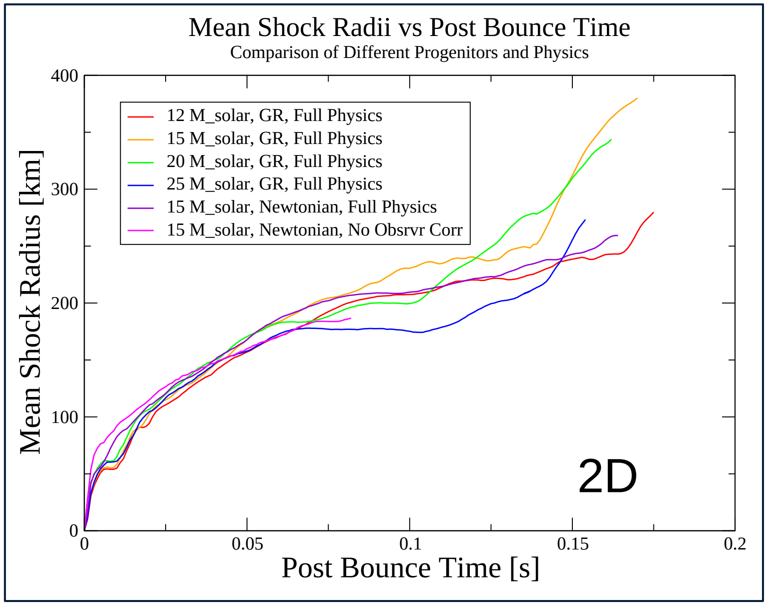
Ongoing Efforts

Recent improvements in CHIMERA has prompted a fresh look at the 2D models.

- *Improved handling of Courant limitation near r =0.*
- *Better prevention of odd-even decoupling in grid-aligned shocks.*
- *Replacement of EoS composition at low density with NSE and use of Lattimer-Swesty EOS with 220 MeV nuclear compressibility.*
- *Additional neutrino opacities.*

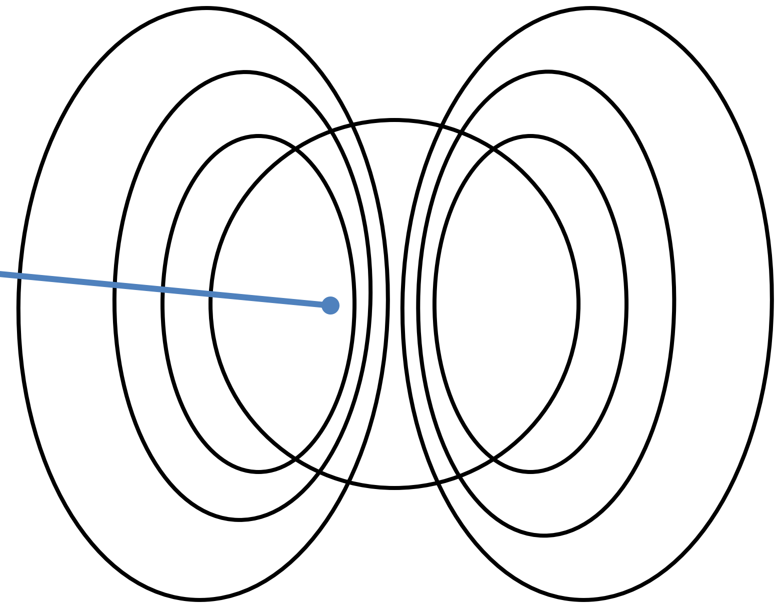


Additional improvements are underway, targeting 3D.

- *New model (512 X 64 X 128) launched with same improvements as 2D.*
- *Development of overset (Yin-Yang) grid will allow Courant limit in 3D to grow as large as in 2D, accelerating solution by allowing much larger time steps to be taken.*
- *Implementation of OpenMP will enable strong scaling, permitting >100,000 cores to be tasked. This will allow the desired 24,576 ray, 65 million CPU-hour model to complete in weeks instead of months.*

The role of magnetic fields

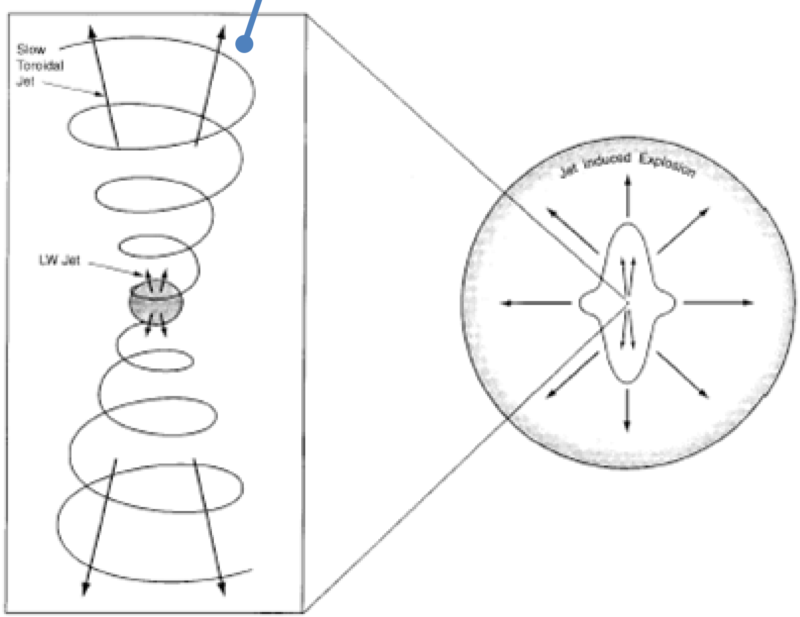
Leblanc and Wilson, *Ap. J.* **161,** 541 (1970)
Symbalisty, *Ap. J.* **285,** 729 (1984)



Stellar Core Magnetic Field Amplification

Wheeler, Meier, and Wilson, *Ap. J.* **568,** 807 (2002)
Akiyama et al. *Ap. J.* **584,** 954 (2003)

- ⇨ Compression
- ⇨ Wrapping
- ⇨ Shear (MRI)



Key Questions:

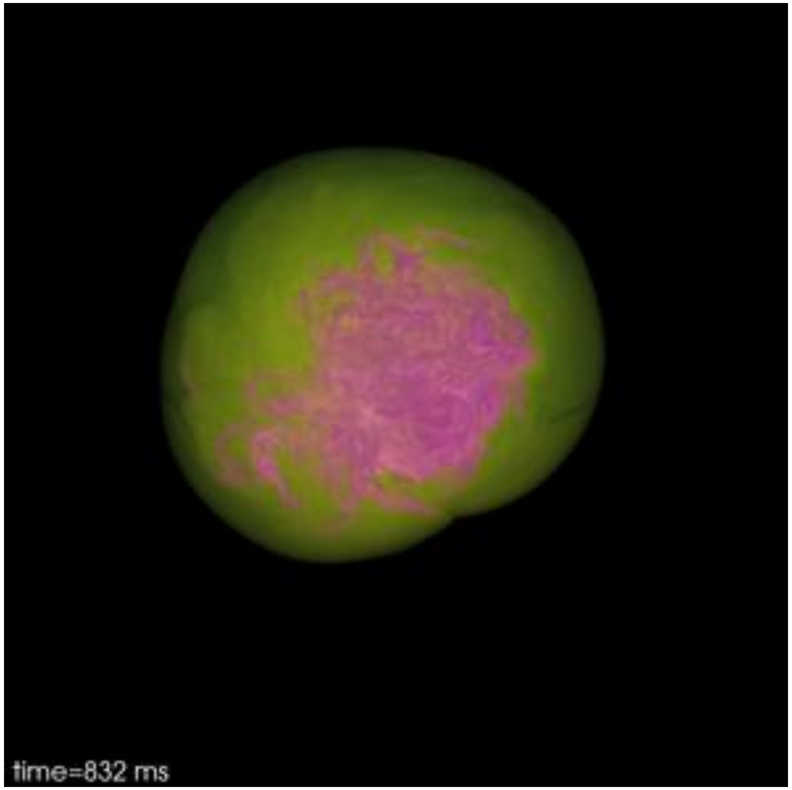
- ***Are the core magnetic fields significantly amplified?***
- ***Will they collimate and drive outflows?***

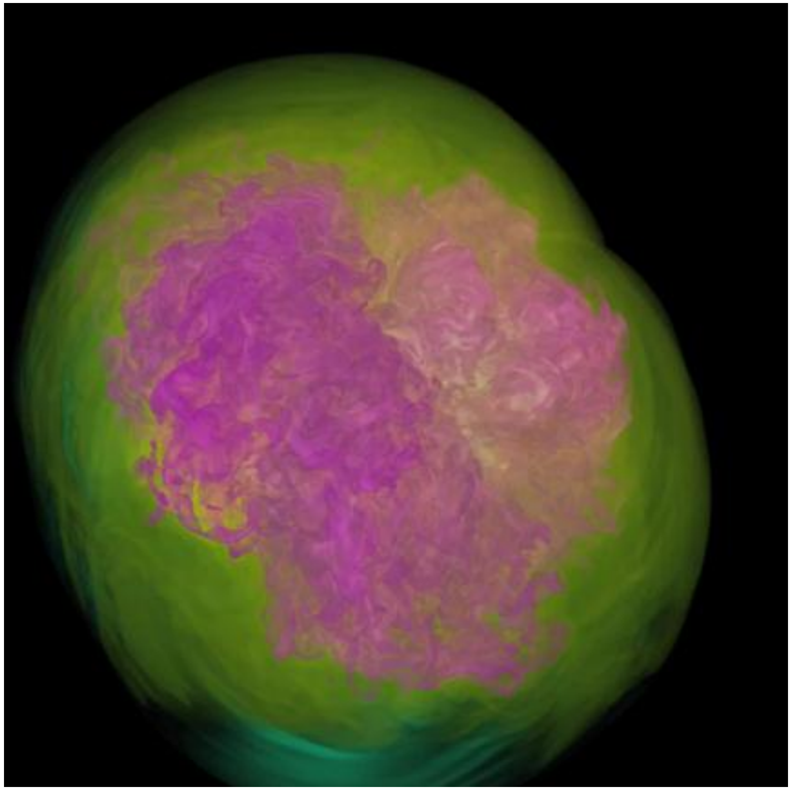
The role of the SASI (no initial rotation)

Turbulence introduced by SASI-induced shear flow amplifies magnetic field strength

- **Field topology is complex, consisting of numerous intertwined tubules**
- **Size of the tubules and field strength is limited by numerical resolution**
- **Field strength is not amplified to dynamically significant levels**
- **Field strength is amplified to levels observed in neutron stars**

GenASiS





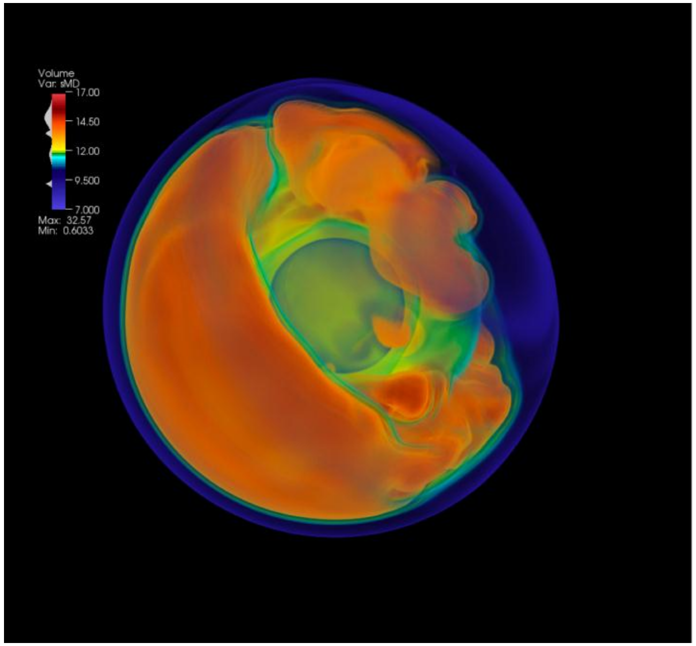
Endeve et al., *Ap. J.* **713,** 1219 (2010)

Summary and prospects

- Two-dimensional models

  Confluence of neutrino heating with improved neutrino interactions, convection, the SASI, nuclear burning, and sufficient simulation time for shock to reach silicon/oxygen layers leads to explosions over a range of supernova progenitors

- Three-dimensional (SASI, hydrodynamics-only) models
  - Demonstrate how different 2D and 3D are
  - Two-dimensional multiphysics models reported here must be performed in 3D



- Ongoing and planned 3D multiphysics simulations
  - Preliminary 3D simulations ongoing at the Leadership Computing Facility (LCF)
  - Higher-resolution models will require >100,000 cores and are planned for the 2-20 PF LCF platform
- Longer term
  - What role will magnetic fields play in the explosion mechanism?
  - MHD SASI simulations performed with GenASiS suggest the SASI can produce the magnetization observed in neutron stars

OAK RIDGE National Laboratory

Collaboration

Oak Ridge National Laboratory: Budiardja, Cardall, Endeve, Hix, Lentz, Lingerfelt, Messer, Mezzacappa, Parete-Koon

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NC State University: Blondin

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Office of Nuclear Physics

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