

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

Presented by

Anthony Mezzacappa

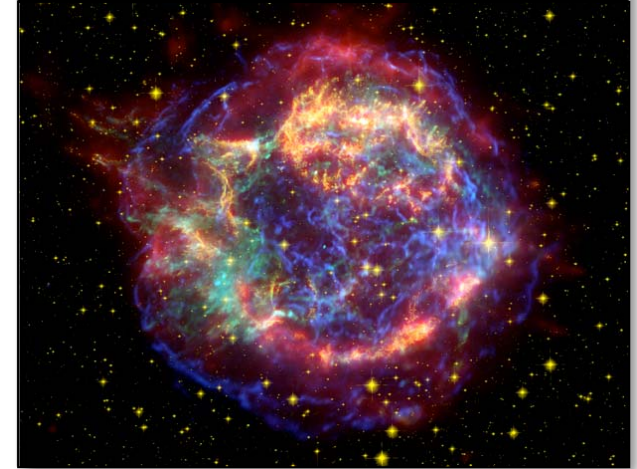
Physics Division
Theoretical Astrophysics



Core-collapse supernovas

- 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)



Periodic Table of the Elements

Alkali metals
Alkaline earth metals
Transition metals
Lanthanide series
Actinide series
Poor metals
Nonmetals
Noble gases
C Solid
 Br Liquid
 H Gas
 Tc Synthetic

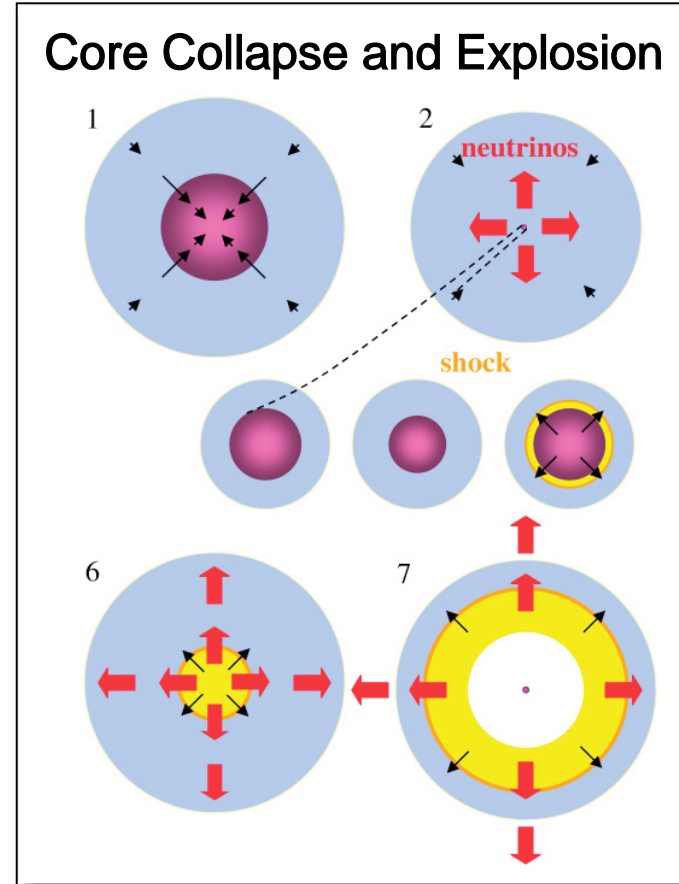
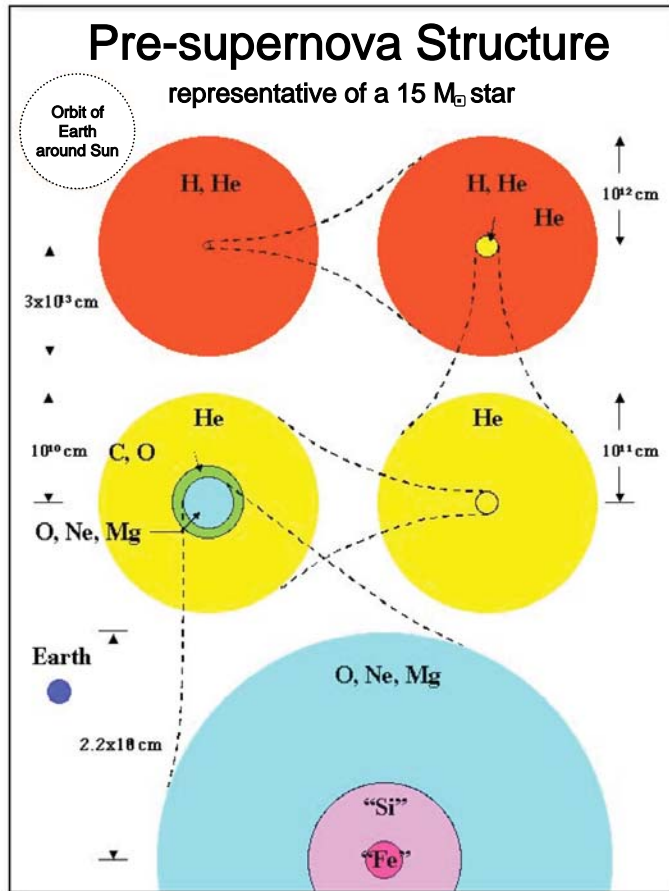
1 H Hydrogen 1.00794	2 He Helium 4.002602											3 B Boron 10.811	4 C Carbon 12.011	5 N Nitrogen 14.007	6 O Oxygen 15.999	7 F Fluorine 18.998	8 Ne Neon 20.1797	9 Na Sodium 22.989772	10 Mg Magnesium 24.305	11 Al Aluminum 26.9815385	12 Si Silicon 28.0855	13 P Phosphorus 30.973761508	14 S Sulfur 32.06	15 Cl Chlorine 35.453	16 Ar Argon 39.948	17 K Potassium 39.0983	18 Ca Calcium 40.078	19 Sc Scandium 44.955912	20 Ti Titanium 47.88	21 V Vanadium 50.9415	22 Cr Chromium 51.9961	23 Mn Manganese 54.938045	24 Fe Iron 55.845	25 Co Cobalt 58.933200	26 Ni Nickel 58.6934	27 Cu Copper 63.546	28 Zn Zinc 65.38	29 Ga Gallium 69.723	30 Ge Germanium 72.64	31 As Arsenic 74.9216	32 Se Selenium 78.96	33 Br Bromine 79.904	34 Kr Krypton 83.796	35 Rb Rubidium 85.4678	36 Sr Strontium 87.62	37 Y Yttrium 88.90585	38 Zr Zirconium 91.224	39 Nb Niobium 92.90638	40 Mo Molybdenum 95.94	41 Tc Technetium 98	42 Ru Ruthenium 101.07	43 Rh Rhodium 102.90550	44 Pd Palladium 106.42	45 Ag Silver 107.8682	46 Cd Cadmium 112.411	47 In Indium 114.818	48 Sn Tin 118.710	49 Sb Antimony 121.757	50 Te Tellurium 127.60	51 I Iodine 126.905	52 Xe Xenon 131.29	53 Cs Cesium 132.90545	54 Ba Barium 137.327	55 Fr Francium 223	56 Ra Radium 226	57 to 71 Lanthanide series	72 Hf Hafnium 178.49	73 Ta Tantalum 180.9479	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.222	78 Pt Platinum 195.078	79 Au Gold 196.966569	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.9804	84 Po Polonium 209	85 At Astatine 210	86 Rn Radon 222	87 to 103 Actinide series	104 Rf Rutherfordium 261	105 Db Dubnium 262	106 Sg Seaborgium 266	107 Bh Bohrium 264	108 Hs Hassium 265	109 Mt Meitnerium 268	110 Ds Darmstadtium 271	111 Rg Roentgenium 272	112 Uub Ununbium 285	113 Uut Ununtrium 284	114 Uuq Ununquadium 289	115 Uup Ununpentium 288	116 Uuh Ununhexium 289	117 Uuq Ununseptium 289	118 Uuo Ununoctium 289
-------------------------------	-------------------------------	--	--	--	--	--	--	--	--	--	--	---------------------------	----------------------------	------------------------------	----------------------------	------------------------------	----------------------------	--------------------------------	---------------------------------	------------------------------------	--------------------------------	---------------------------------------	----------------------------	--------------------------------	-----------------------------	---------------------------------	-------------------------------	-----------------------------------	-------------------------------	--------------------------------	---------------------------------	------------------------------------	----------------------------	---------------------------------	-------------------------------	------------------------------	---------------------------	-------------------------------	--------------------------------	--------------------------------	-------------------------------	-------------------------------	-------------------------------	---------------------------------	--------------------------------	--------------------------------	---------------------------------	---------------------------------	---------------------------------	------------------------------	---------------------------------	----------------------------------	---------------------------------	--------------------------------	--------------------------------	-------------------------------	----------------------------	---------------------------------	---------------------------------	------------------------------	-----------------------------	---------------------------------	-------------------------------	-----------------------------	---------------------------	-------------------------------	-------------------------------	----------------------------------	-------------------------------	--------------------------------	------------------------------	--------------------------------	---------------------------------	--------------------------------	-------------------------------	----------------------------------	---------------------------	---------------------------------	-----------------------------	-----------------------------	--------------------------	------------------------------	-----------------------------------	-----------------------------	--------------------------------	-----------------------------	-----------------------------	--------------------------------	----------------------------------	---------------------------------	-------------------------------	--------------------------------	----------------------------------	----------------------------------	---------------------------------	----------------------------------	---------------------------------

Atomic masses in parentheses are those of the most stable or common isotope.

Design Copyright © 1997 Michael Dayah (michael@dayah.com). <http://www.dayah.com/periodic/>

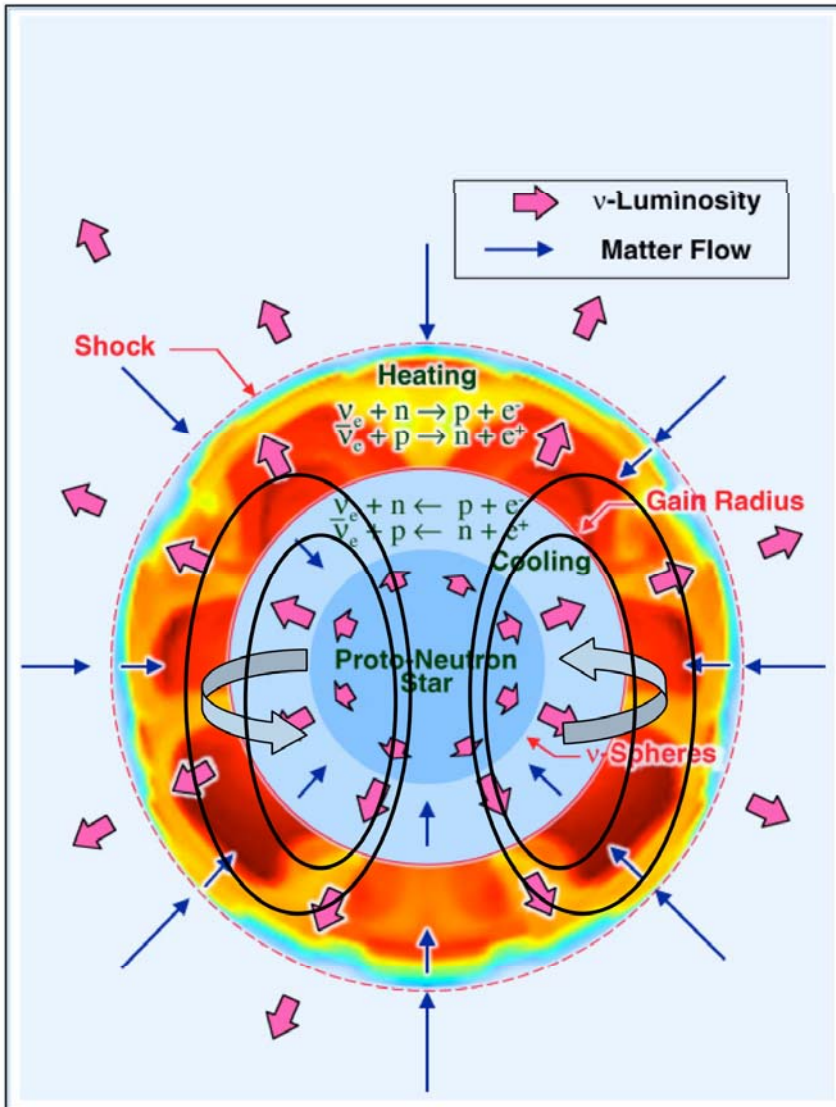
Note: The subgroup numbers 1-18 were adopted in 1984 by the International Union of Pure and Applied Chemistry. The names of elements 112-118 are the Latin equivalents of those numbers.

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
- Nuclear burning
- Rotation
- Magnetic fields

**New ingredient*

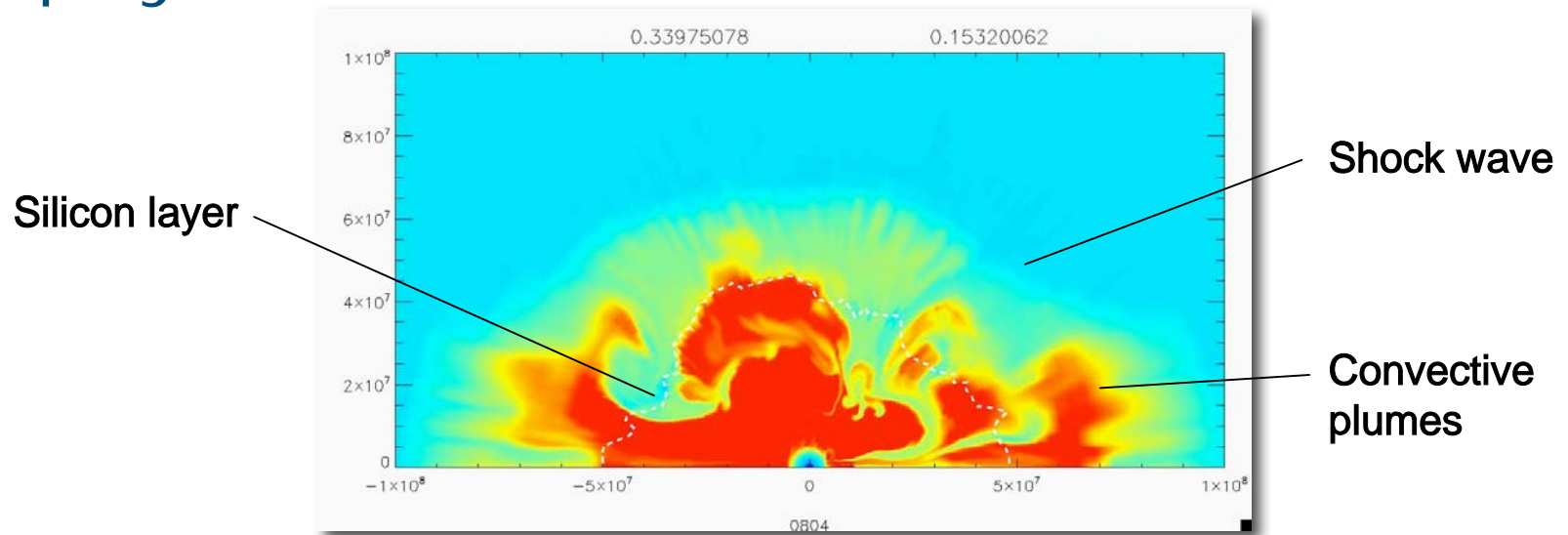
Conservative Hydrodynamics with Implicit Multi-Energy Radiation Algorithms

CHIMERA Code

- **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 2-D multiphysics models

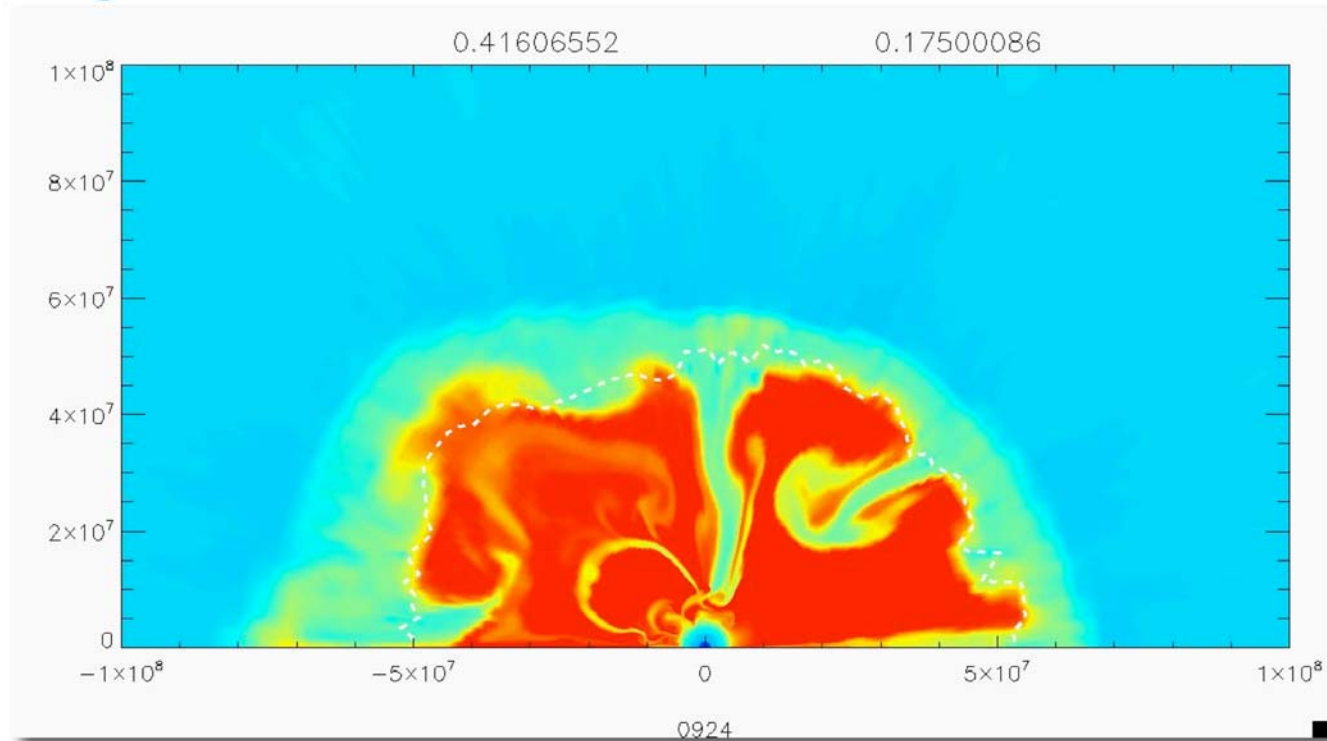


11-Solar-Mass Star

- Shock powered in part by neutrino (radiation) heating from below, aided by convection.
- Improved/additional neutrino interactions increase the neutrino heating.
- Shock distorted into cigar shape in part by the shock instability (SASI), which precipitates shock's arrival in silicon and oxygen layers (marked by white dashed line), where nuclear burning can occur behind the shock, further powering it.
- Density ahead of the shock decreases rapidly when it reaches the oxygen layer (less for the shock to plow through).

Confluence of neutrino heating with improved neutrino interactions, convection, the SASI, nuclear burning, and drop in density lead to an explosion.

An emerging picture for 2-D multiphysics models



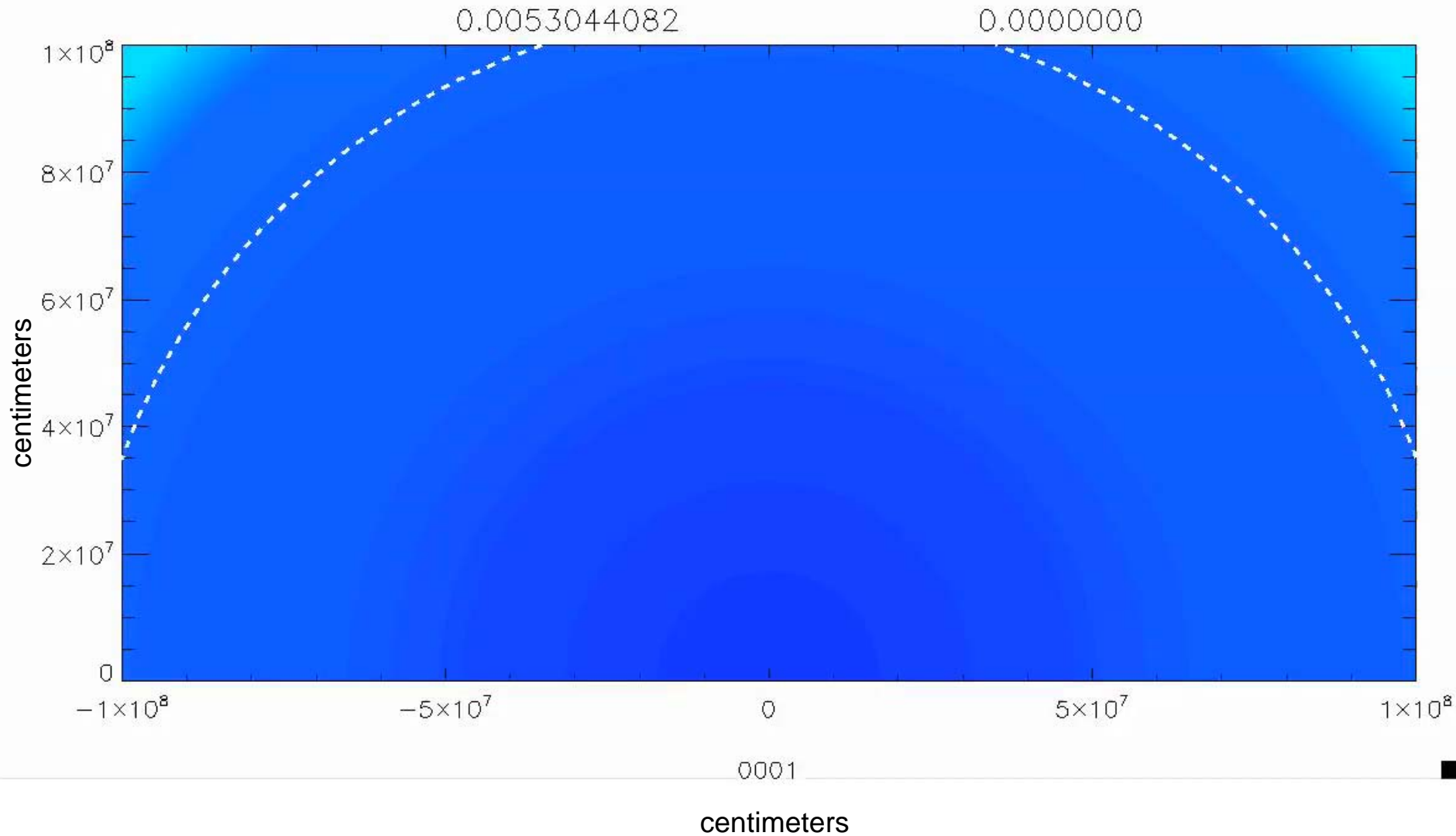
Bruenn et al., *J. Phys. Conf. Ser.*, **46**, 393 (2006)
Mezzacappa et al., *AIP Conf. Proc.*, **924**, 234 (2007)

20-Solar-Mass Star

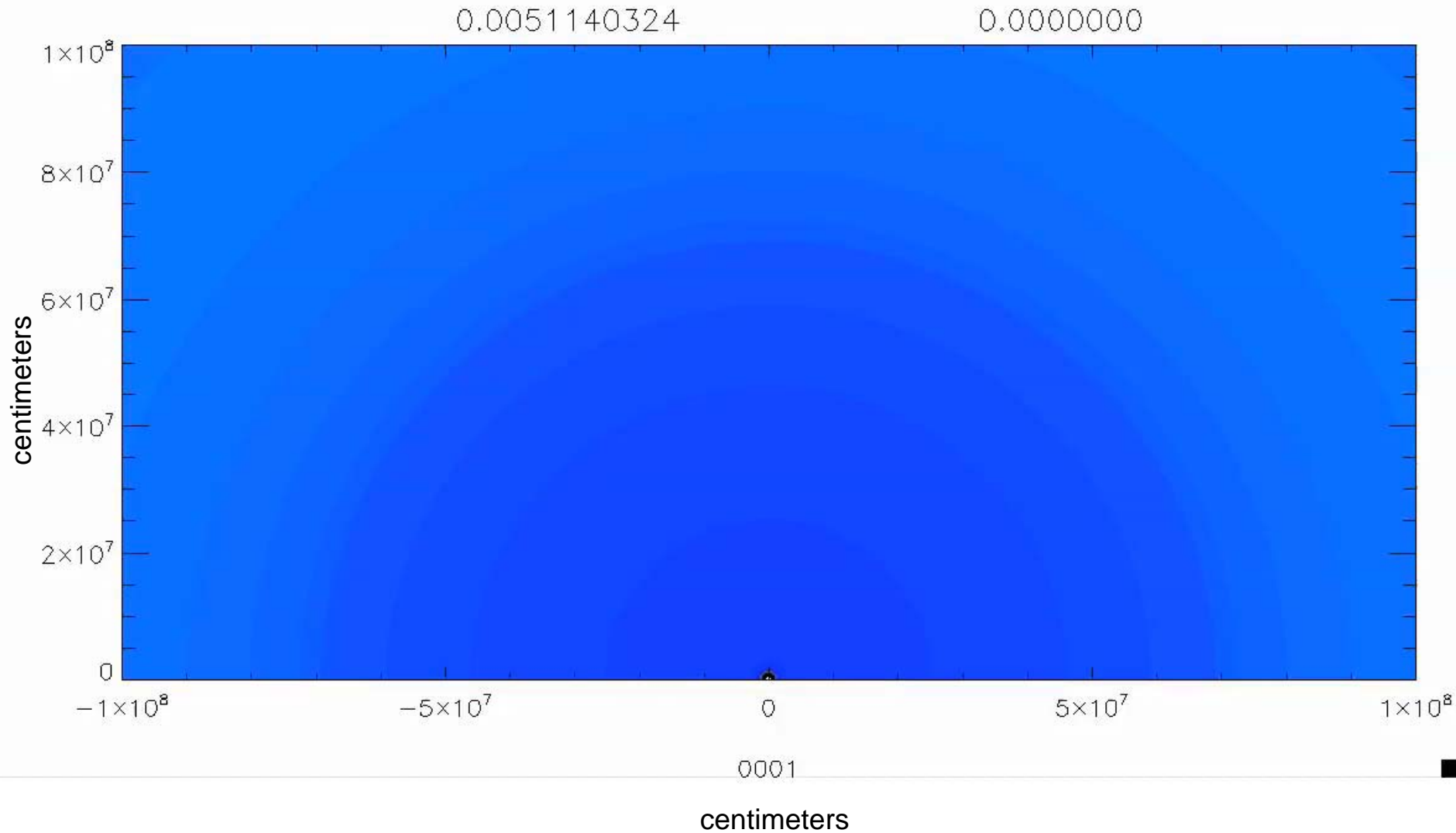
- Explosion occurs in this case as well.
- Two-dimensional results are very promising given they occur for a range of massive stars.

N.B. Progenitor for supernova SN1987A was a 20-Solar-mass star.

11-Solar-mass model



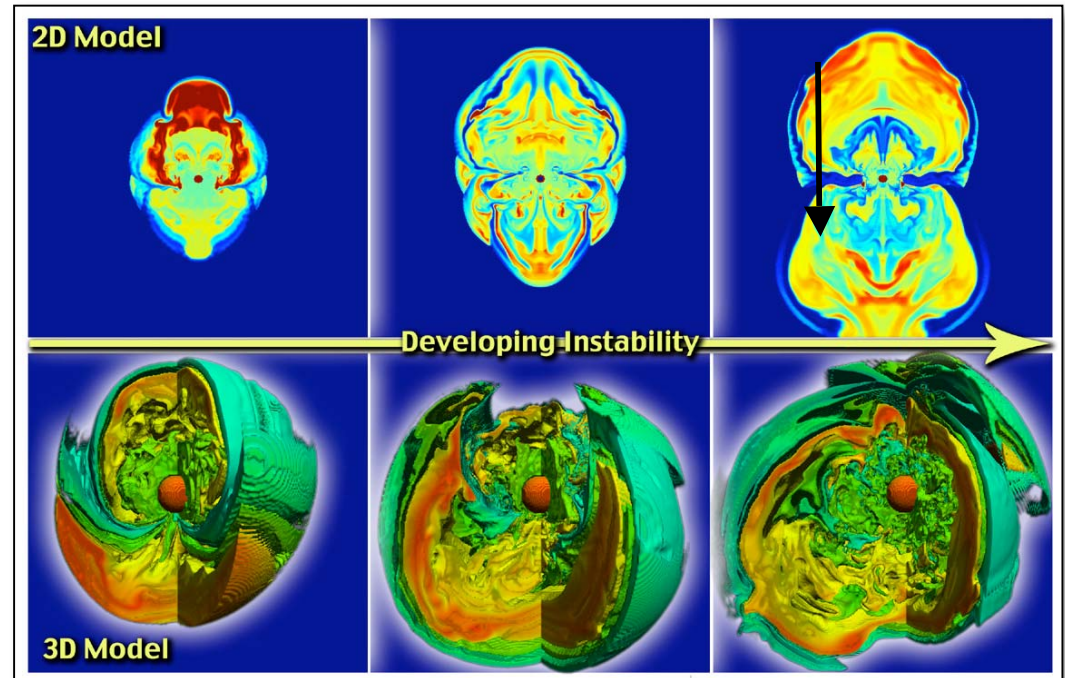
20-Solar-mass model



Need for 3-D

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

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



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

- SASI has axisymmetric and **nonaxisymmetric (3-D)** modes that are both linearly unstable!
 - Blondin and Mezzacappa, *Ap.J.* 642, 401 (2006)
 - Blondin and Shaw, *Ap.J.* 656, 366 (2007)

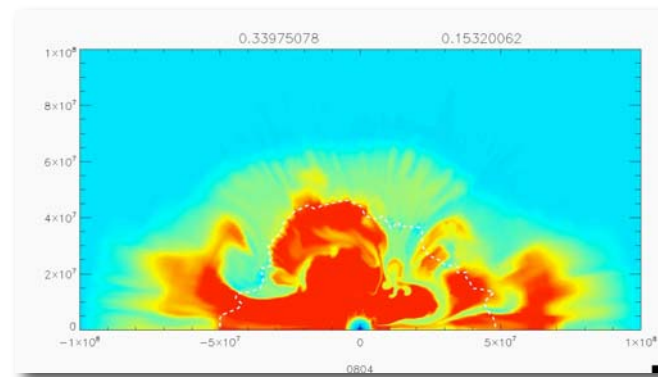
Summary and prospects

- 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 2-D and 3-D are.
- Two-dimensional multiphysics models reported here must be performed in 3-D.



- Ongoing and planned 3-D multiphysics simulations

- Preliminary low-resolution 3-D simulations ongoing at the Leadership Computing Facility (LCF).
- Higher-resolution models will require 32,768 cores and are planned for the 250 TF LCF platform.

- Longer term

- What role will magnetic fields play?

Collaboration



Cardall, Hix,
Messer,
Mezzacappa



Bruenn,
Marronetti

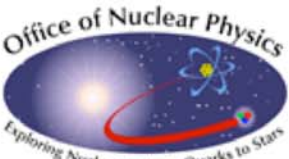


Blondin



Fuller

Funded by



Contact

Anthony Mezzacappa

Physics Division

Theoretical Astrophysics

(865) 574-6113

mezzacappaa@ornl.gov

