ORNL Supernova Science Program Overview

Goals:

To ascertain the mechanism(s) of core collapse supernovae.

To predict supernova phenomenology.

Neutrino Signatures

Gravitational Wave Signatures

Neutron Star Kicks

Nucleosynthesis

People:

Staff

Mezzacappa

Postdocs

Cardall (DoE HENP PECASE)

Hix (NASA ATP)

Liebendoerfer (NSF Astronomical Sciences)

Messer (DoE HENP SciDAC "Seed" Funds)

Collaborators in Other Divisions

Azmy (CPED; Transport)

D'Azevedo (CSM Division; Applied Mathematics)

Dongarra (CSM Division, UTK; Applied Mathematics)

Romine (CSM Division; Applied Mathematics)

Toedte (CSM Division; Visualization)

Working to integrate our program with ORNL computational science program. Common needs (e.g., applied math, viz) among applications provides natural integration channel. We are also utilizing ORNL's computing/viz resources.

-We are now one of ORNL's showcase applications.

SciDAC Initiative [Terascale Supernova Initiative (TSI)]

ORNL Collaborations (Dean, Strayer)

University Collaborations (8 Universities)

ORNL Supernova Science Program Overview (Cont'd)

Select Projects:

1D Boltzmann Simulations (Newtonian and GR)
Neutrino Signature Predictions
Focus on Input Weak Interaction Physics
2D/3D Simulations with "Ray-by-Ray Transport"
2D/3D Boltzmann Transport
2D/3D GR Approximations
Neutrino Mass/Mixing Effects
Scalable Multi-D Neutrino Transport

Ties to Proposed DoE Facilities:

ORLaND

Neutrino-nucleus cross section measurements relevant to supernova dynamics and nucleosynthesis and neutrino oscillations in supernovae are among the motivating experiments.

RIA

Mass and lifetime measurements for nuclei along r-process path are among the motivating experiments. Core collapse supernovae are leading candidates for the r-process site.

Shedding New Light on Exploding Stars: Terascale Simulations of Neutrino-Driven Supernovae and Their Nucleosynthesis -Proposal Submitted to DoE HENP SciDAC Program

ORNL-Centered National Initiative Involving 8 Universities

University of Tennessee
State University of New York at Stony Brook
University of Illinois at Urbana-Champaign
University of California at San Diego
University of Washington
North Carolina State University
Clemson University
Florida Atlantic University

Investigator Team

Polly Baker (UIUC)
John Blondin (NC State)
Steve Bruenn (FAU)
David Dean (ORNL)
Jack Dongarra (UT)
George Fuller (UCSD)
Wick Haxton (UW)
John Hayes (UCSD)
Jim Lattimer (SUNYSB)
Brad Meyer (Clemson)
Tony Mezzacappa (ORNL)
Madappa Prakash (SUNYSB)
Faisal Saied (UIUC)
Paul Saylor (UIUC)
Mike Strayer (ORNL)
Doug Swesty (SUNYSB)
Ross Toedte (ORNL)

Shedding New Light on Exploding Stars: Terascale Simulations of Neutrino-Driven Supernovae and Their Nucleosynthesis

Community Advisory Panel (CAP)

Dave Arnett (University of Arizona)
Steve Koonin (Caltech; not yet confirmed)
Dimitri Mihalas (LANL)
Bob Rosner (PI, University of Chicago Flash Center)
Michael Wiescher (Notre Dame)
Jim Wilson (LLNL)
Stan Woosley (University of California at Santa Cruz; not yet confirmed)
CS Member(s) (to be determined)

Shedding New Light on Exploding Stars: Terascale Simulations of Neutrino-Driven Supernovae and Their Nucleosynthesis

Goals:
To ascertain the mechanism(s) of core collapse supernovae.
To predict supernova phenomenology.

- ***Neutrino Signatures***
- ***Gravitational Wave Signatures***
- ***Neutron Star Kicks***
- ***Nucleosynthesis***

Requires Multidimensional Simulations

- ***Multidimensional Hydrodynamics***
- ***Multidimensional Multifrequency Neutrino Transport***
- ✍ ***Multidimensional Radiation Hydrodynamics***
- ***Multdimensional Magneto-Radiation Hydrodynamics***
  (Magnetic Fields May Play a Role in the Explosion)

Must all be done scalably on parallel platforms.

- ✍ ***Scalable Large Sparse System Solution***
- ✍ ***Collaborative Visualization (Monitoring, Steering)***
  Challenge: Render very large data sets on the fly.

Enabling Technologies for DoE Strengths

- ***Climate***
- ***Combustion***
- ***Nuclear Medicine***

✍ ***White papers for these areas call for scalable radiation transport and radiation hydrodynamics in 3D, turbulent environments. Similar transport schemes used by neutron transport modelers for cancer treatments.***

Shedding New Light on Exploding Stars: Terascale Simulations of Neutrino-Driven Supernovae and Their Nucleosynthesis

Complementary Effort to University of Chicago ASCI Flash Center (Multidimensional Simulations of Reactive Flows; Radiation Transport Not Central, Type Ia Supernovae Not Radiatively Driven)

Combined initiatives would result in enabling technologies for many applications!

Multi-D hydrodynamics. (FLASH, TSI)
Multi-D radiation transport. (TSI)
Multi-D radiation hydrodynamics. (TSI)
Multi-D magnetohydrodynamics. (FLASH, TSI)
Multi-D magneto-radiation hydrodynamics. (TSI)

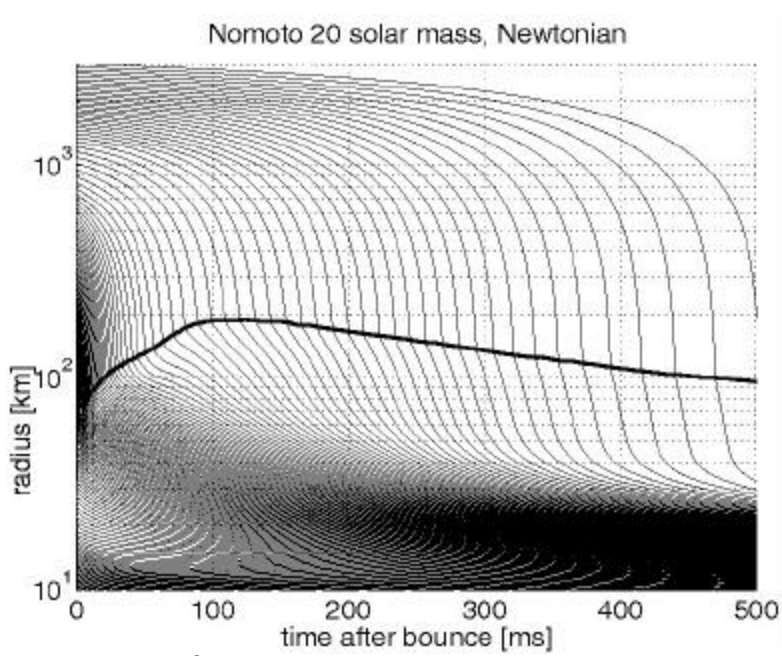
Newtonian Supernova Simulations with Boltzmann Neutrino Transport

The Science:

- *Core collapse supernovae are neutrino events, involving the release of more than 10^{53} erg of neutrino energy.*
- *The extreme sensitivity of the neutrino-driven explosion mechanism to neutrino radiation field quantities makes exact transport essential to determining it's viability.*

Our Work:

- *As part of a systematic attack, Newtonian gravity simulations of core collapse, rebound, and shock propagation in spherical symmetry have been performed for several progenitors using AGILE-BOLTZTRAN.*
- *Explosions are not seen in any of our simulations to date (Nomoto & Hashimoto 15 and 20 $M_\odot$ and Woosley & Weaver 15 $M_\odot$ progenitors).*



Mezzacappa, Liebendoerfer, Messer, Hix, Thielemann, Bruenn, Phys. Rev. Lett., accepted.
Mezzacappa & Messer, JCAM 109, 281 (1999)
Messer, PhD thesis, University of Tennessee (2000)

Effect of Improved Progenitor Physics on Core Collapse

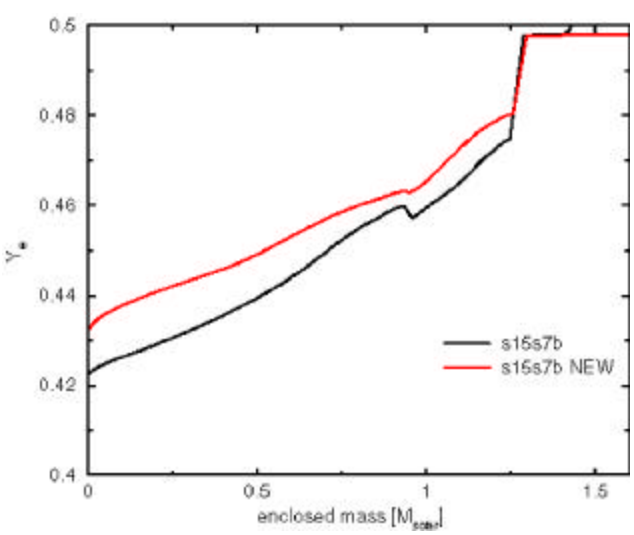
The Science:

- *Heger, et. al. (2000) have made available improved versions of the 15 and 25 $M_\odot$ models of Woosley & Weaver, incorporating shell model weak interaction rates, replacing the original FFN rates.*
- *Changing these rates lead to differences in the models' initial Y_e profiles of as much as 3%.*
- *The shock formation radius is proportional to Y_e^2, so a higher Y_e at bounce is beneficial to shock propagation..*

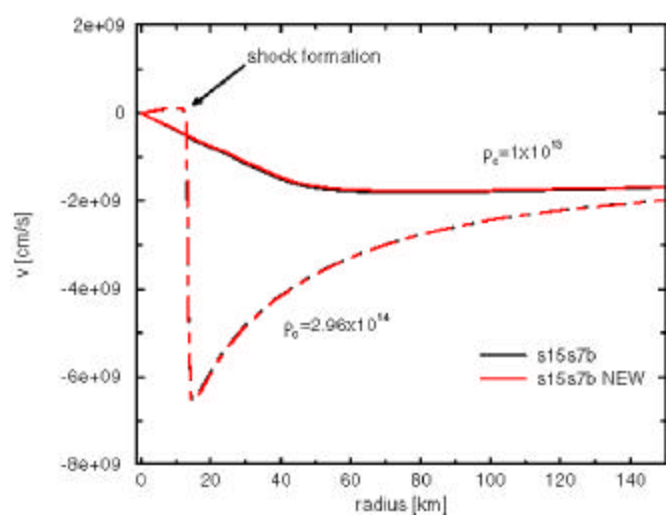
Our Work:

- *We investigated the dynamic effects of these initial differences by performing core collapse simulations with AGILE-BOLTZTRAN.*
- *Neutrino trapping and equilibration mean initial Y_e differences have no dynamic effect if no meaningful differences in initial temperature and density are present.*

Large initial Ye differences...



no dynamic effect



Messer, PhD thesis, University of Tennessee (2000)

High Density Neutrino Emissivities and Opacities

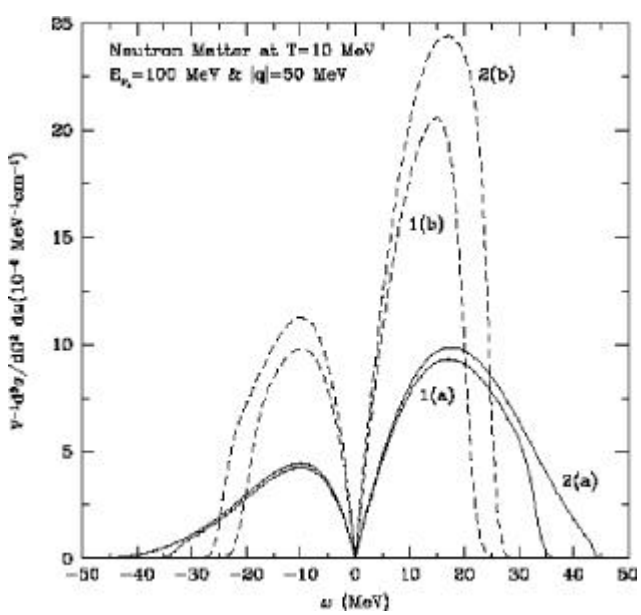
The Science:

- *Correlation effects, mediated by strong interactions in the PNS can increase neutrino mean free paths by a factor of 2-4 (Reddy, et. al., 1998).*
- *These modifications allow high energy neutrinos to escape from deep in the core. This hardens the neutrino spectra, increasing heating behind the shock.*

Our Plan:

- *We have initiated a collaboration with S. Reddy (INT, UW) to modify the opacities and emissivities in AGILE-BOLTZTRAN to include correlations.*
- *The formulation of Reddy, et. al. also allows the inclusion of nucleon-nucleon bremsstrahlung, which may be the primary production mechanism for ? and ? neutrinos.*

Total neutrino cross sections from Reddy, et. al. 1998
Results are shown for calculations with correlations [a] and without [b], and for densities of 0.32 fm^{-3} (1)and 0.64 fm^{-3} (2).



Parallel AGILE-BOLTZTRAN
Towards Scalable Algorithms for Radiation Transport

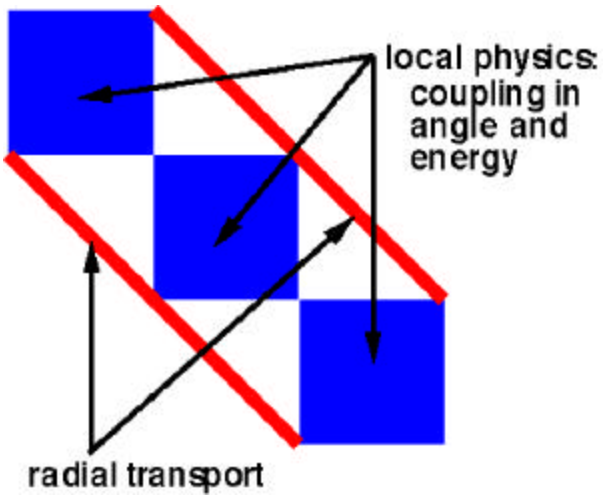
The Problem:

- *At the heart of AGILE-BOLTZTRAN is the solution of a large, sparse linear system.*
- *Increasing resolution and dimensionality of our simulations demands porting AGILE-BOLTZTRAN to parallel platforms .*

Our Plan:

- *We have started testing solvers and preconditioners from the ACTS toolkit (ScaLAPACK, PETSc, AZTEC).*
- *We have initiated a collaboration with C. Romine and E. D'Azevedo (ORNL CSM division) to investigate tailored preconditioners and solution methods.*

The matrix structure in AGILE-BOLTZTRAN.
The size of the dense, diagonal blocks scales
quadratically with number of energy groups and angle bins.



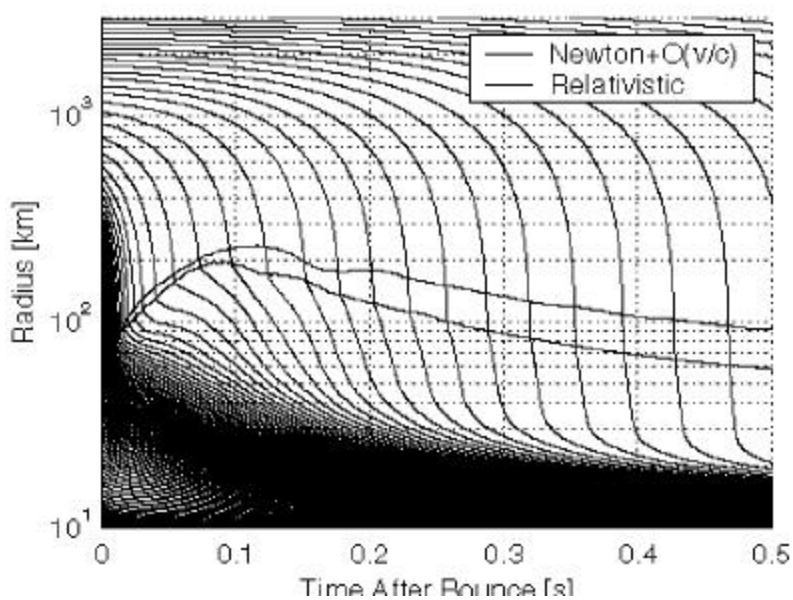
General Relativistic Boltzmann Neutrino Transport in Core-Collapse Supernovae

The Science:

- *Explosion energetics depend on the location of shock formation and the neutrino heating.*
- *The location of shock formation is set by general relativistic hydrodynamics and neutrino transport.*
- *The subtle balance between neutrino cooling and heating depends on the compactness of the enclosed proto-neutron star, general relativistic effects are significant.*

Our Work:

- *We provided the first general relativistic simulations of stellar core collapse and post bounce evolution with accurate Boltzmann neutrino transport and standard nuclear physics.*
- *Longstanding uncertainties in spherical supernova models have been resolved.*



Liebendörfer, Mezzacappa, Thielemann, Messer, Hix, and Bruenn, submitted to Phys. Rev. D, astro-ph/0006418

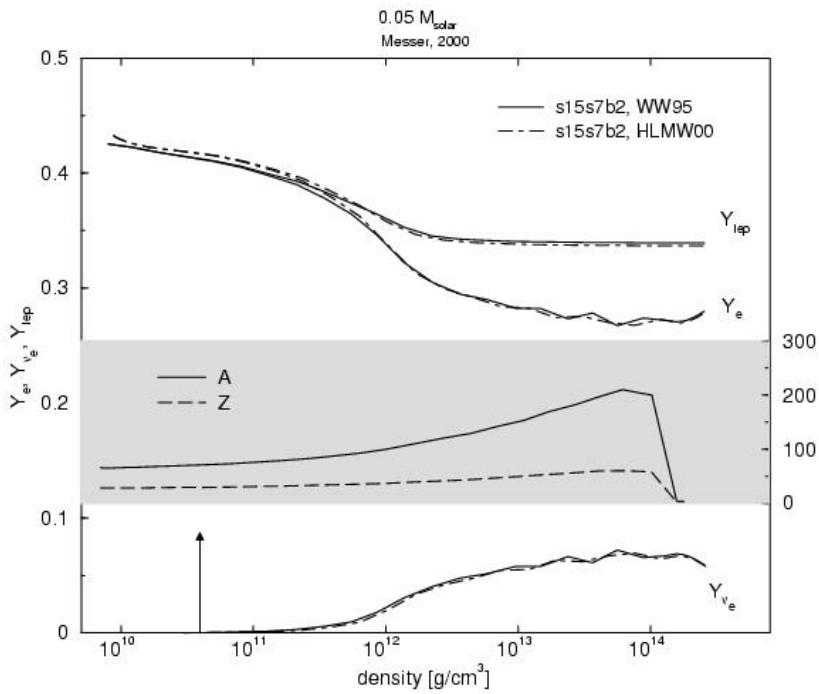
Core Collapse with Improved Electron Capture

The Science:

- *The shock energy depends on the location of shock formation because of the different dissociation losses in the outer core.*
- *The location of shock formation depends on the electron fraction, set by electron capture rates and neutrino transport during homologous collapse.*

Our Plan:

- *Using electron capture rates that surpass FFN and are applicable to heavier nuclei.*
- *Applying these rates to ensembles of nuclei in nuclear statistical equilibrium, instead of using representatives.*



Messer, Ph. D. thesis, (2000)

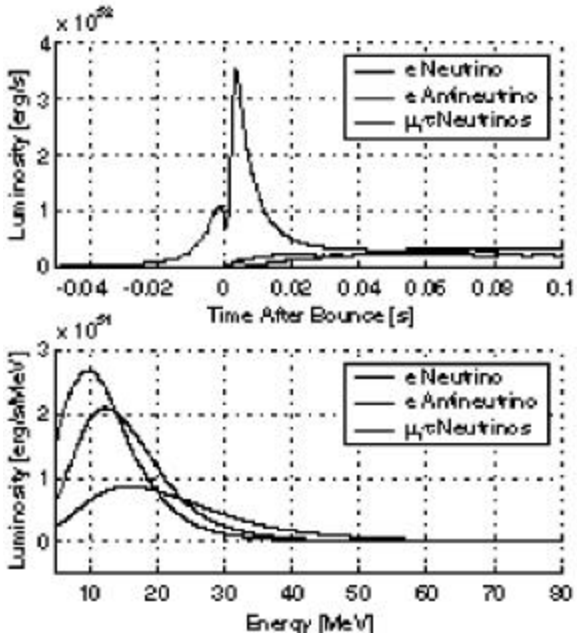
Supernova Neutrino Signatures

The Science:

- *Core collapse supernovae produce an energetic electron neutrino burst followed by declining luminosities in electron-, muon-, and tauon-flavors.*
- *This observable signal (SN1987A in Kamiokande, IMB) is related to the dynamics of the innermost core and provides a direct window to the controversial supernova mechansim.*

Our Ongoing Work:

- *First fully time-dependent calculation of the neutrino burst by solving the Boltzmann equation in general relativistic space-time.*
- *Carrying out neutrino signature predictions for different progenitors, post bounce evolutions, and detectors.*



Liebendörfer, Mezzacappa, Thielemann, Messer, Hix, and Bruenn, submitted to Phys. Rev. D, astro-ph/0006418

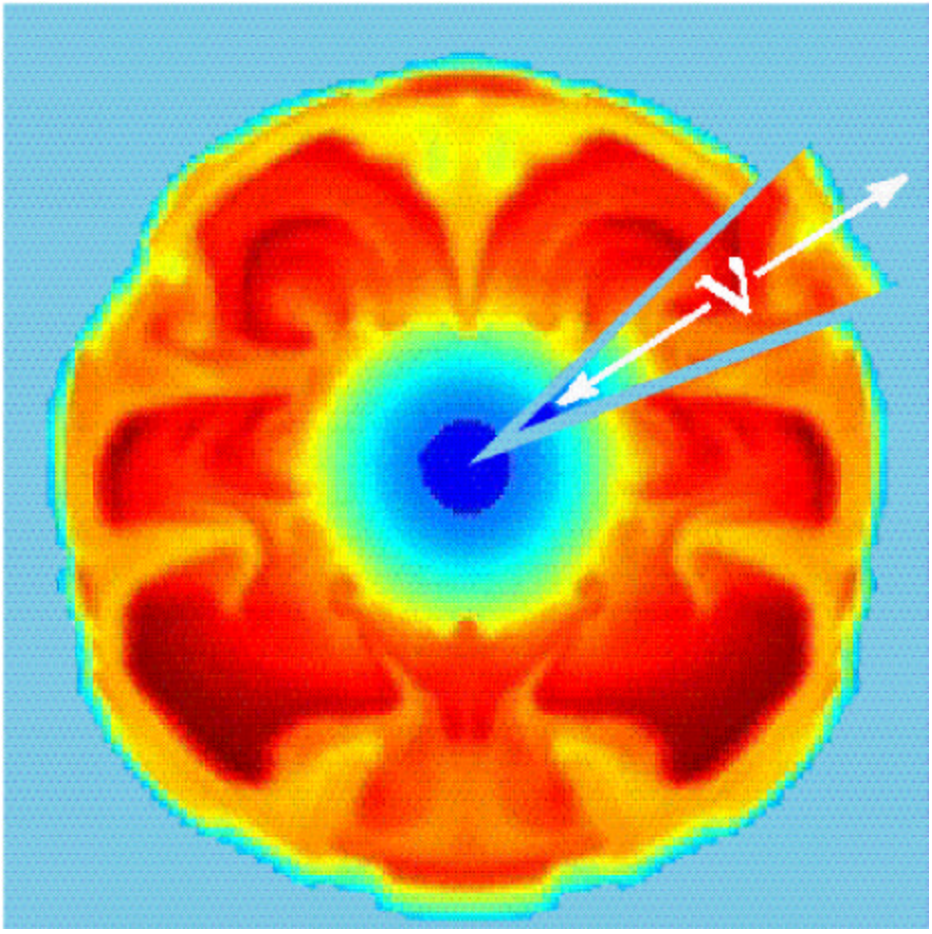
Towards Successful Supernova models: multi-dimensional hydrodynamics coupled to realistic transport

The science:

- *Successful supernova models have been produced by*
  1) using mixing length convection in a 1D simulation
  2) using approximate transport in a 2D hydro model
- *No simulations to date have employed multi-D hydrodynamics with realistic transport*

Our Plan:

- *Perform multi-dimensional simulations with an MPP capable code, adapted to use realistic EOS.*
- *Perform transport using BOLTZTRAN along 1D rays*
- *Eventually implement true Multi-dimensional transport*



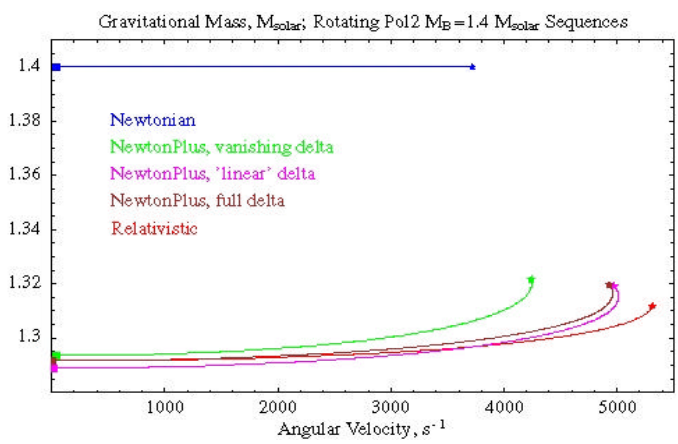
NewtonPlus: Approximate General Relativity for Multidimensional Supernova Simulations

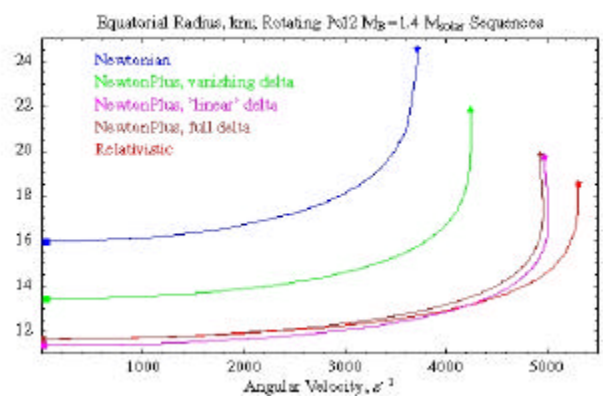
The Science:

- ***Supernova simulations in spherical symmetry show that there are important differences between Newtonian and relativistic treatments of gravity [1]***
- ***Multidimensional simulations will be necessary to include rotation and convection, which may play important roles***
- ***Attempted numerical treatments of three-dimensional relativity have led to inaccurate and unstable results [2]***

Our Work:

- ***We have developed a simplified treatment of relativity that captures the effects of dynamical importance in supernovae, and tested its validity in stationary, rapidly rotating stars [3]***





[1] S. Bruenn, K. R. De Nisco, and A. Mezzacappa, astro-ph/0101400 (2001)
[2] M. Alcubierre et al., Phys. Rev. D 62, 124011 (2000)
[3] C. Y. Cardall and A. Mezzacappa, in preparation (2001)

Development of Multidimensional Boltzmann Transport

The science:

- *Convection in the collapsed core may significantly boost neutrino luminosities, potentially leading to more vigorous supernova explosions [1]*
- *One-dimensional multi-group neutrino transport tends to smooth out this core convection [2]*
- *Multidimensional Boltzmann neutrino transport coupled with three-dimensional hydrodynamics is needed to fully assess the potential effects of core convection on neutrino luminosities*

Our Plan:

- *Building on previous work [3], we are deriving the equations for multidimensional relativistic Boltzmann transport*
- *We are exploring parallelizable strategies for solving these equations*

[1] J. R. Wilson and R. W. Mayle, Phys. Rep. 227, 97 (1993)

[2] A. Mezzacappa et al., Astrophys. J. 493, 848 (1998); 495, 911 (1998)

[3] R. W. Lindquist, Annals of. Physics 37, 487 (1966); A. Mezzacappa and R. A. Matzner, Astrophys. J. 343, 853 (1989)

Inclusion of Neutrino Mass and Flavor Mixing in Supernova Neutrino Transport

The science:

- *There is strong observational evidence that neutrinos have mass and undergo flavor mixing*
- *Neutrino mass and flavor mixing potentially affect the supernova explosion mechanism, nucleosynthesis, and observed signals in terrestrial detectors*
- *Existing formalisms can only treat flavor mixing--- a quantum mechanical phenomenon requiring coherence--- in stationary or homogeneous environments [1]*

Our Plan:

- *We are exploring approaches starting from nonequilbrium field theory [2] and Wigner functions [3] to generalize Boltzmann transport to be able to handle the flavor mixing in both time and space*

[1] G. Sigl and G. Raffelt, Nucl. Phys. B 406, 423 (1993)
[2] S. Yamada, Phys. Rev. D 62, 093026 (2000)
[3] M. Sirera and A. Perez, Phys. Rev. D 59, 125011 (1999)

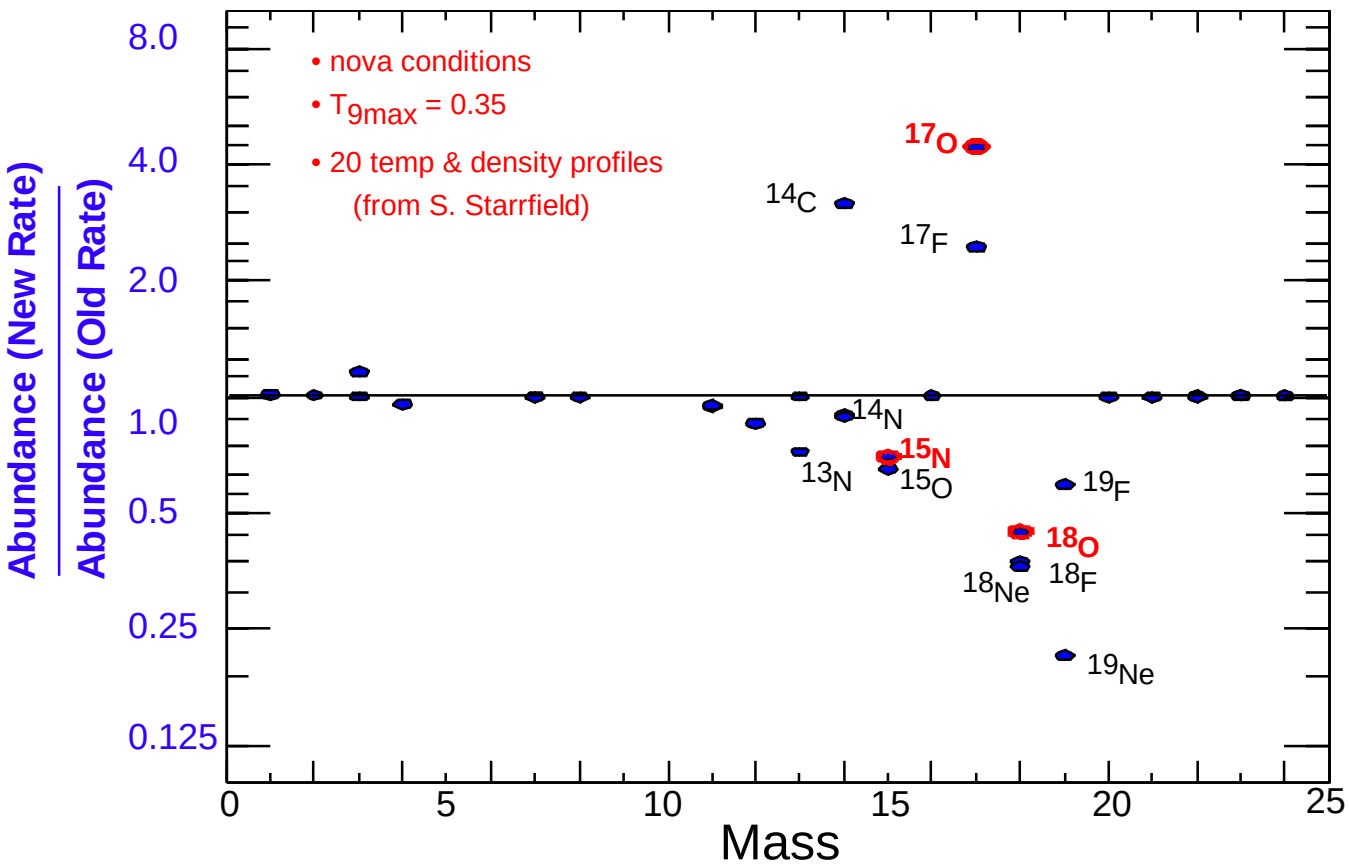
Impact of HRIBF $^{17}F(p,?)^{18}Ne$ rate measurement on Nova nucleosynthesis

The science:

- ***HRIBF measurement of new parameters for crucial ^{18}Ne resonance results in an improved rate for $^{17}F(p,?)^{18}Ne$***

Our Work:

- ***Examine how this new HRIBF rate might change nucleosynthesis***
  - ✍ ***In the hottest explosion zones, abundances for some isotopes differ by a factor of 1000***
  - ✍ ***Averaged over the entire explosion, abundances for some isotopes differ by up to a factor of 5.***



Parete-Koon, Hix, Smith, Starrfield, Bardayan & Guidry, in preparation

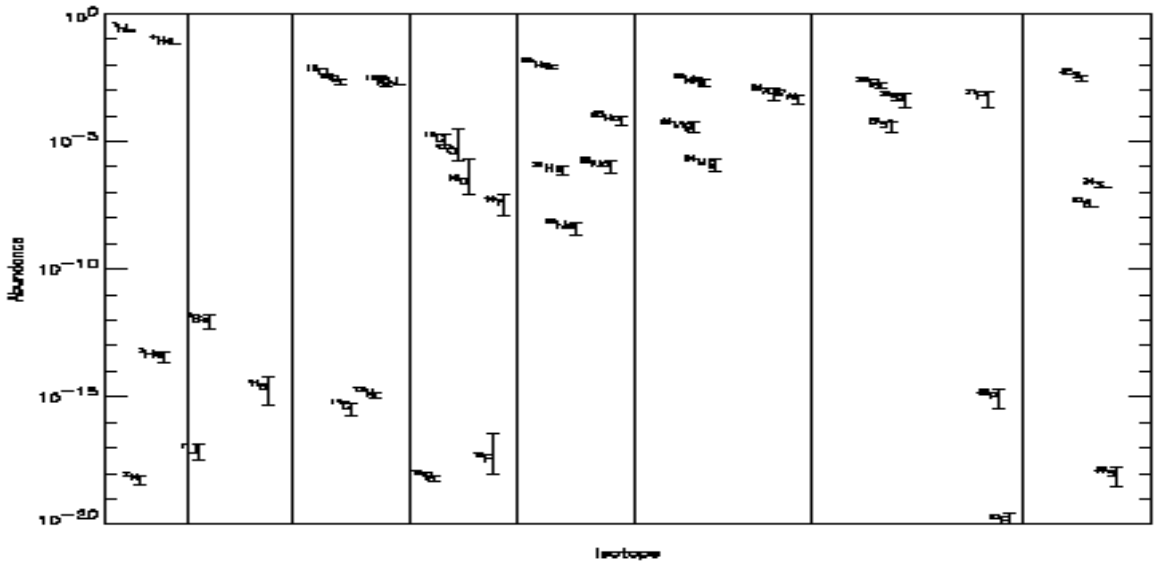
Nuclear Reaction Rate Uncertainties and their effects on Nova Nucleosynthesis Modeling

The science:

- ***Changes in the reaction rates used in a nova simulation can alter the production of individual isotopes (by an order of magnitude) and change global observables such as the peak luminosity and the amount of mass ejected by 10-30%[1].***

Our Work:

- ***First systematic analyses of the impact of reaction rate uncertainties on nova nucleosynthesis***
- ***Allows translation of reaction rate uncertainties into uncertainties in model nucleosynthesis [2] (see figure)***
- ***Demonstrated the usefulness of this technique in determining the relative importance to isotopic production due to changes in individual reaction rates[3].***



[1] *Starrfield, Truran, Wiescher & Sparks, MNRAS* ***296*** *502 (1998).*

[2] Hix, Smith, Mezzacappa & Starrfield, in Cosmic Explosions, ed. S.S. Holt, (Melville: AIP), 383 (2000).

[3] Hix, Smith, Mezzacappa, Starrfield & Smith, in Proceedings of the 2nd Chicago Conference on Astrophysical Explosions}, ed. Brown, Niemeyer, Rosner & Truran, in press.

Multi-dimensional simulations of nova outburst

The science:

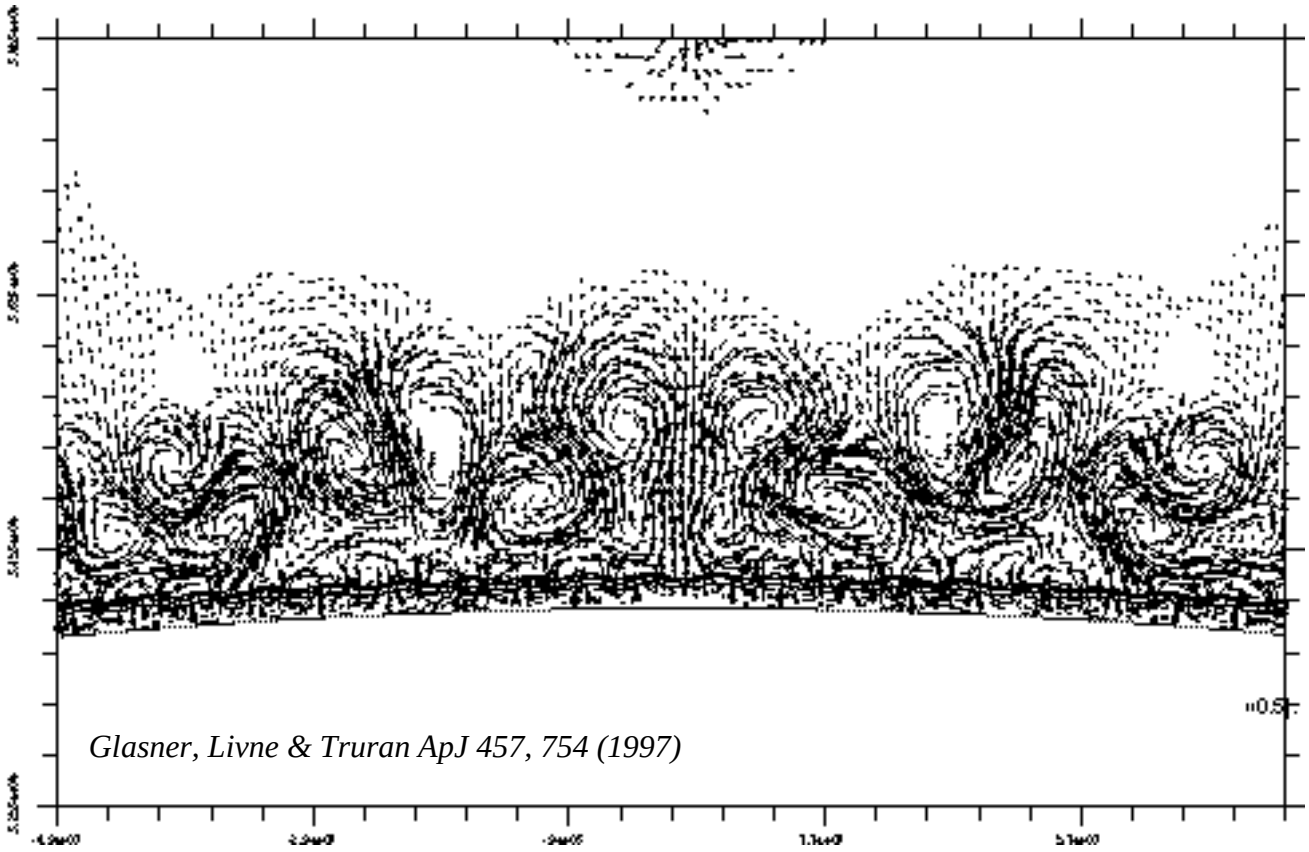
- ***Observations of nova ejecta show enhancement in CNO elements.***
- ***Energy release from solar composition is <1% that required to unbind the nova envelope.***

✍***mixing of white dwarf matter into the accreted envelope is necessary.***

- ***One promising mixing mechanism is convective overshooting early in the outburst.***

Our Work:

- ***Adapt VH1, a multi-dimensional ideal compressible PPM hydro code, for thermonuclear reactive flow.***
- ***Collaborate with S. Starrfield and H. Vanhala (ASU) to include nova relevant microphysics.***



Glasner, Livne & Truran ApJ 457, 754 (1997)