The Core-collapse Supernova Mechanism

Christian Y. Cardall

Oak Ridge National Laboratory
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Terascale Supernova Initiative
http://www.phy.ornl.gov/tsi

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Christian Y. Cardall
Neutrinos: Data, Cosmos, and Plank Scale, 3-7 March 2003

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What are supernovae?

Survey of collapse simulations

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The name "supernova" dates from the 1930s.

- New stars or "novae" were well known.
- The debate about the nature of spiral nebulae led to the realization that there must be
  - "giant novae" (Lundmark 1920),
  - novae of "impossibly great absolute magnitudes" (Curtis 1921),
  - "exceptional novae" (Hubble 1929)
  - "Hauptnovae" (Baade 1929).

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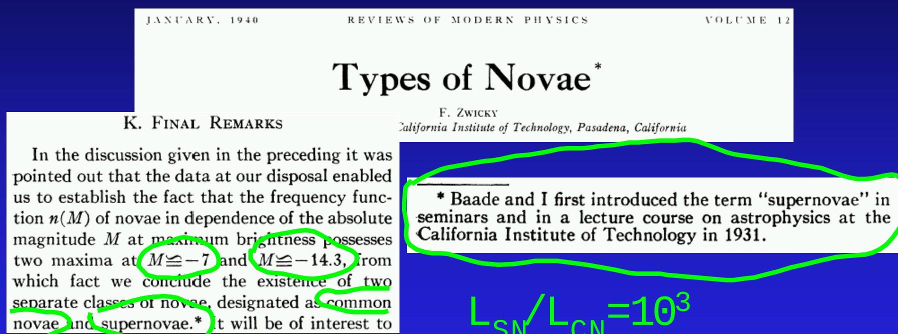
The name "supernova" dates from the 1930s.

The word "supernova" is claimed to have been used by Baade and Zwicky since 1931.



JANUARY, 1940 REVIEWS OF MODERN PHYSICS VOLUME 12

Types of Novae*

F. ZWICKY
California Institute of Technology, Pasadena, California

K. FINAL REMARKS

In the discussion given in the preceding it was pointed out that the data at our disposal enabled us to establish the fact that the frequency function $n(M)$ of novae in dependence of the absolute magnitude M at maximum brightness possesses two maxima at $M \cong -7$ and $M \cong -14.3$, from which fact we conclude the existence of two separate classes of novae, designated as common novae and supernovae.* It will be of interest to

* Baade and I first introduced the term "supernovae" in seminars and in a lecture course on astrophysics at the California Institute of Technology in 1931.

$L_{SN}/L_{CN}=10^3$

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Spectral classification of supernovae:

- Type I: Absence of H;
  - Type Ia: Strong Si feature;
  - Type Ib: Absent or weak Si features, strong He;
  - Type Ic: Absent or weak Si features, absent or weak He.
- Type II: Obvious H features;
  - Type IIL, IIP: Absorption features;
  - Type IIn: Absent or weak absorption features, prominent and narrow H emission.

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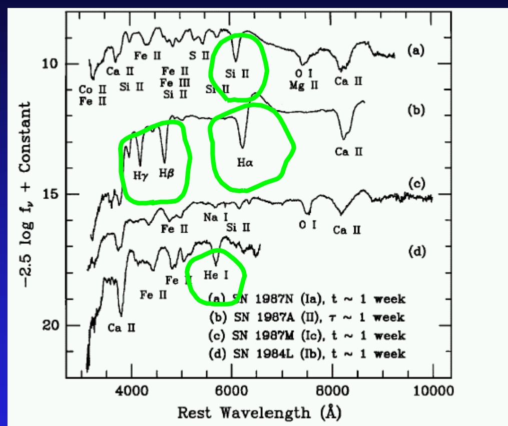
Spectral classification of supernovae:



Filippenko (1997)

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Light curve classification of supernovae:

- Type I: Linear decline in magnitude;
  - Type Ia: Luminosity/shape correlation allows use as a distance indicator.
- Type II: Wide variety;
  - Type IIL: Linear decline in magnitude;
  - Type IIP: Plateau before linear decline.

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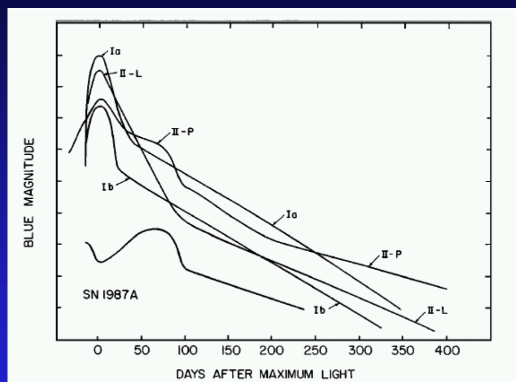
Light curve classification of supernovae:



Filippenko (1997)

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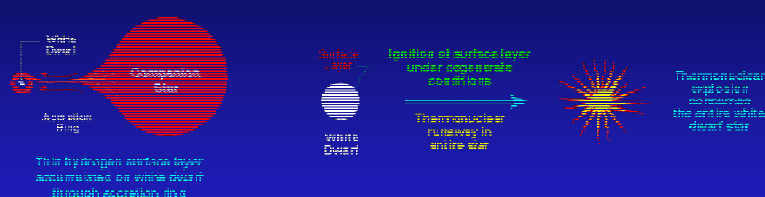
Physical classification of supernovae:

Thermonuclear runaway;

Type Ia, accretion onto a white dwarf.



(Images courtesy University of Tennesse Astronomy 162 Syllabus)

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Physical classification of supernovae:

Core collapse of a massive star;

- Type II, outer H layer remains at collapse;
- Type Ib, outer H layer stripped before collapse;
- Type Ic, outer H and He layers stripped before collapse.

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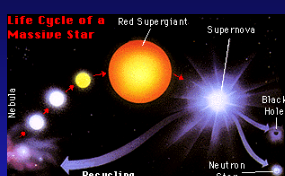
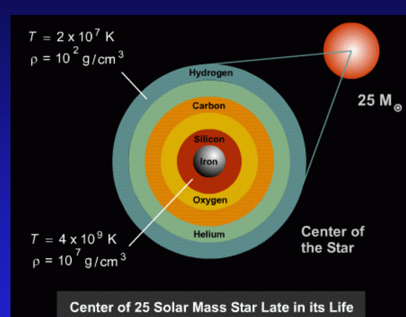
Physical classification of supernovae:

Core collapse of a massive star;





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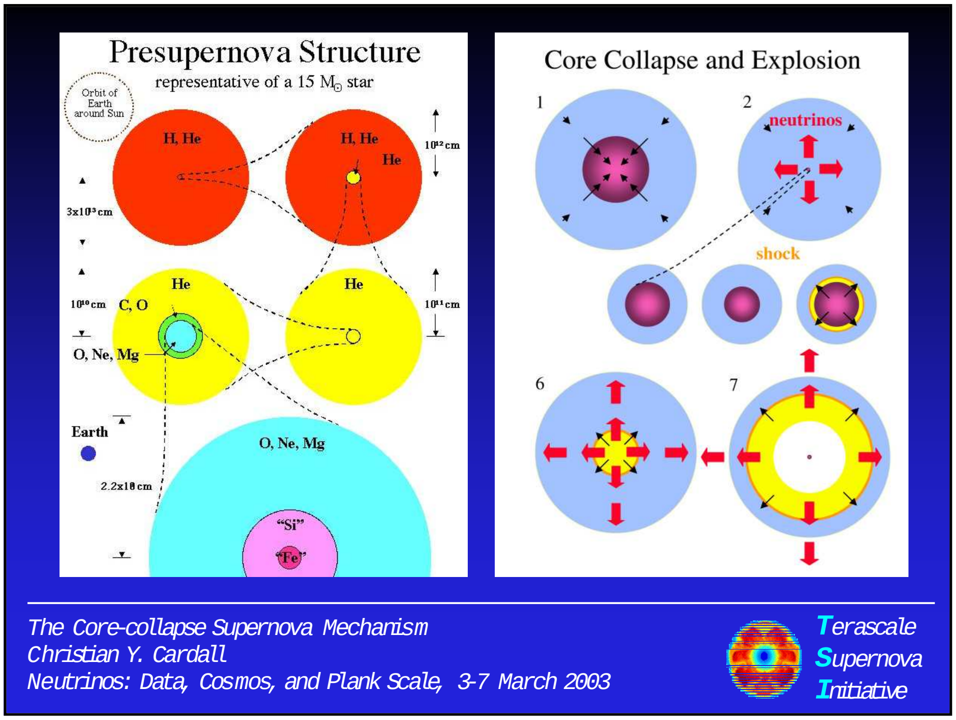
Presupernova Structure
representative of a 15 M$_\odot$ star
Orbit of Earth around Sun
H, He
H, He
He
10^{12} cm
3×10^{13} cm
He
He
10^{10} cm
C, O
10^{11} cm
O, Ne, Mg
Earth
O, Ne, Mg
2.2×10^{8} cm
"Si"
"Fe"
Core Collapse and Explosion
1
2
neutrinos
shock
6
7
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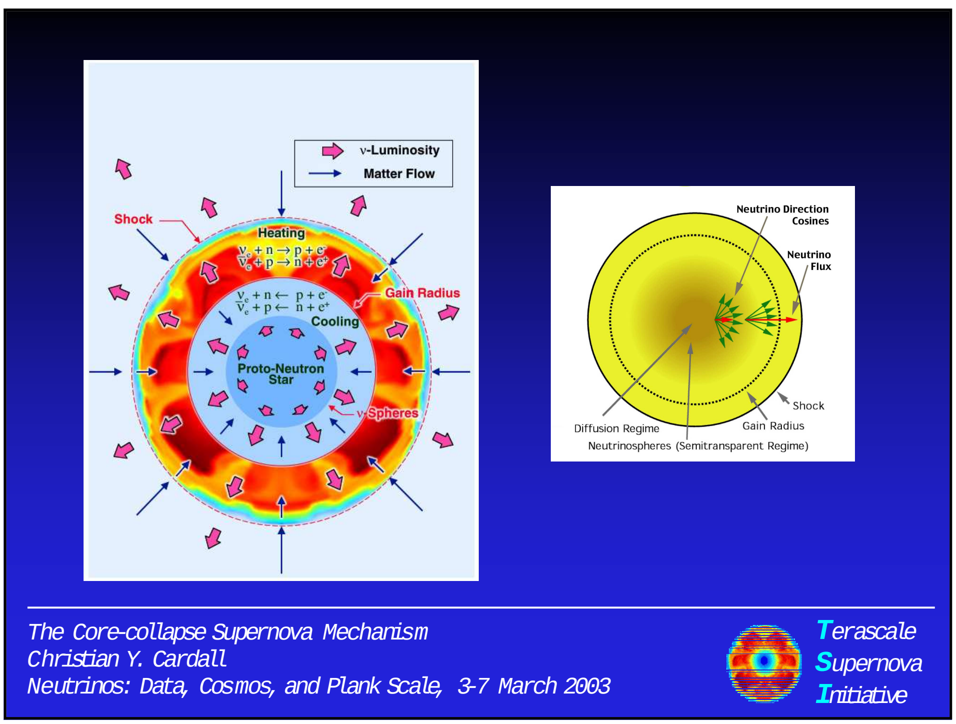
ν-Luminosity
Matter Flow
Shock
Heating
Gain Radius
Cooling
Proto-Neutron Star
ν-Spheres
Neutrino Direction Cosines
Neutrino Flux
Shock
Gain Radius
Diffusion Regime
Neutrinospheres (Semitransparent Regime)
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The observables to understand include

- Explosion;
- Neutrinos;
- Pulsar spins, kick velocities, and magnetic fields;
- Gravitational waves;
- Element *abundances;*
- Measurements across the EM spectrum,
  - IR, optical, UV, X-ray, gamma-ray;
    - images, light curves, spectra, polarimetry...

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Survey of collapse simulations

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Some key pieces of physics are

- Neutrino transport/interactions,
  - Spatial dimensionality;
  - Dependence on energy and angles;
  - Relativity;
  - Comprehensiveness of interactions;
- Hydrodynamics/gravitation,
  - Dimensionality;
  - Relativity;

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Some key pieces of physics are

- Equation of state/composition,
  - Dense matter treatments;
  - Number and evolution of nuclear species;
- Diagnostics,
  - Accounting of lepton number;
  - Accounting of total energy.

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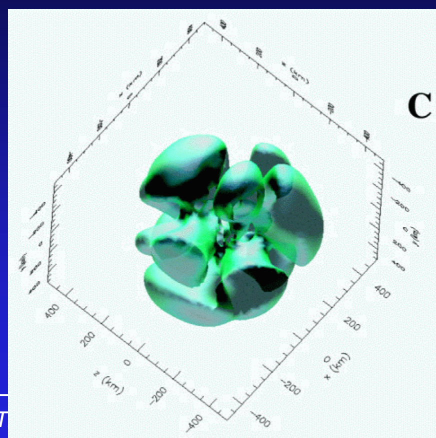
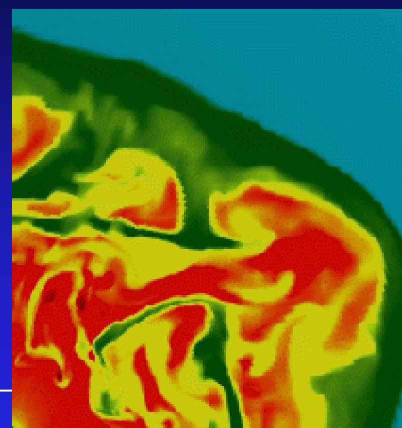
Simulations of collapse and explosion

Multiple spatial dimensions, simplified neutrino transport

Fryer & Warren (2002)



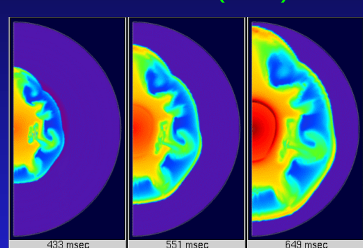
Burrows, Hayes, & Fryxell (1995)



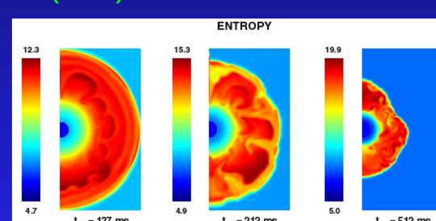
Simulations of collapse and explosion

Multiple spatial dimensions, simplified neutrino transport

Janka & Mueller (1996)

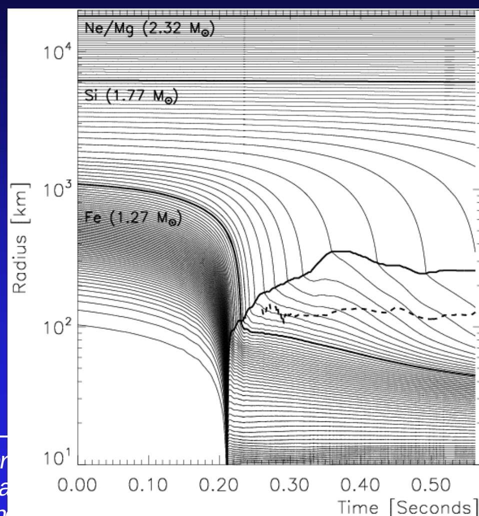


Mezzacappa, Calder, Bruenn, Blondin, Guidry, Strayer, & Umar (1998)



Simulations of collapse and explosion

Spherical symmetry, sophisticated neutrino transport



Rampp & Janka (2000)

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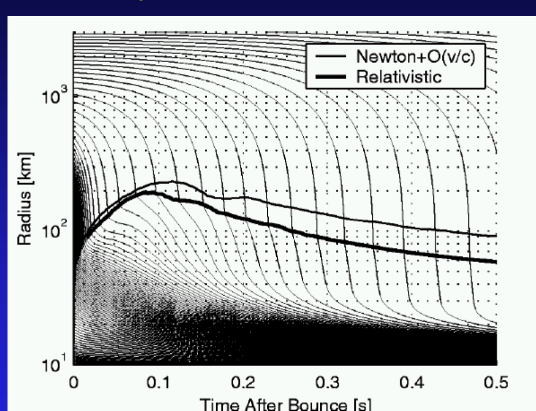
Simulations of collapse and explosion

Spherical symmetry, sophisticated neutrino transport



Liebendoerfer, Mezzacappa, Thielemann, Messer, Hix, & Bruenn (2001)

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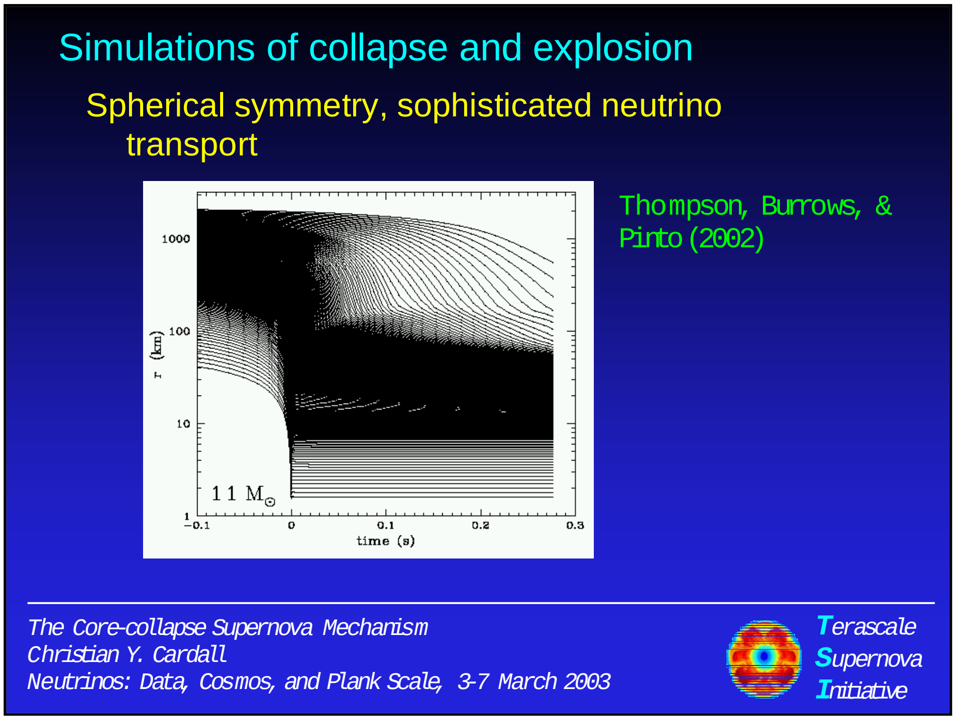
Simulations of collapse and explosion
Spherical symmetry, sophisticated neutrino transport
Thompson, Burrows, & Pinto (2002)
11 M⊙
r (km)
time (s)
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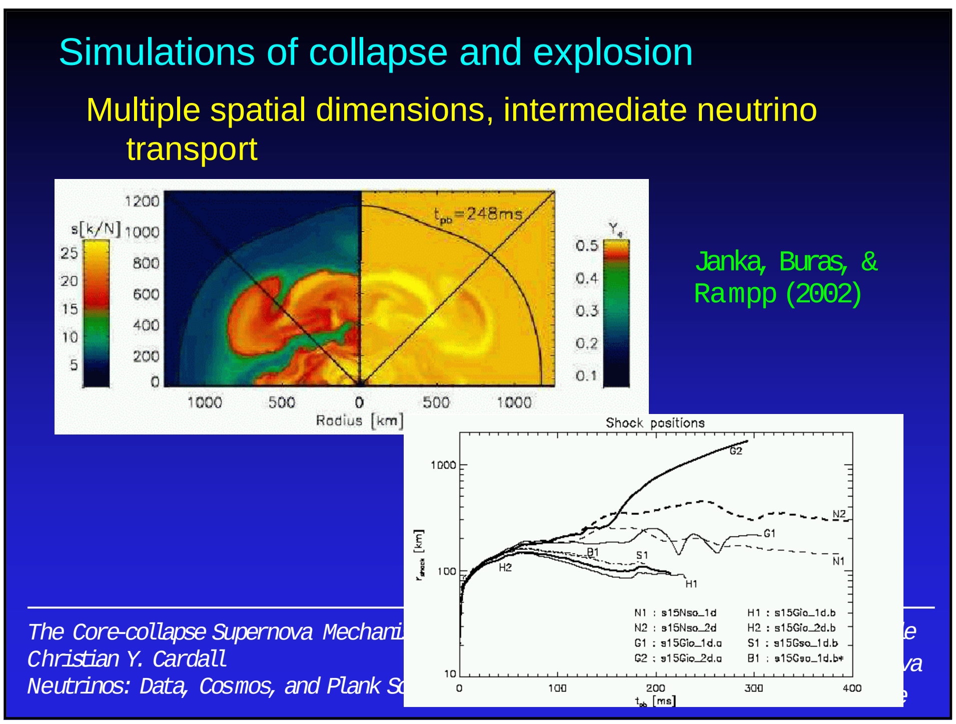
Simulations of collapse and explosion
Multiple spatial dimensions, intermediate neutrino transport
Janka, Buras, & Rampp (2002)
s[k/N]
t_{pb}=248ms
Y_e
Radius [km]
Shock positions
r_{shock} [km]
t_{pb} [ms]
N1 : s15Nso_1d
N2 : s15Nso_2d
G1 : s15Gio_1d.a
G2 : s15Gio_2d.a
H1 : s15Gio_1d.b
H2 : s15Gio_2d.b
S1 : s15Gso_1d.b
B1 : s15Gso_1d.b*
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A diverse and experienced investigator team...

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...with expertise in all necessary areas...

- Radiation transport,
- (Magneto-)hydrodynamics,
- Nuclear and weak interaction physics,
- Computer science,
  - Large sparse linear systems,
  - Data management and visualization;

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...and support from the U.S. Department of Energy:

- Funding through the DOE Office of Sciences' SciDAC program,
- Access to DOE's terascale machines (several 10^{12} bytes of memory and flops),
- Access to the expertise of teams specializing in
  - Advanced solvers,
  - Advanced computational meshes,
  - Performance on parallel architectures,
  - Data management and visualization,
  - Software interoperability and reusability.

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Mission- Explain supernova phenomena most closely associated with collapse:

- Successful launch of shock (explosion mechanism);
- Neutrino signatures;
- Pulsar spins, kick velocities, and magnetic fields;
- Gravitational waves;
- Heavy element (*r-process) abundances.*

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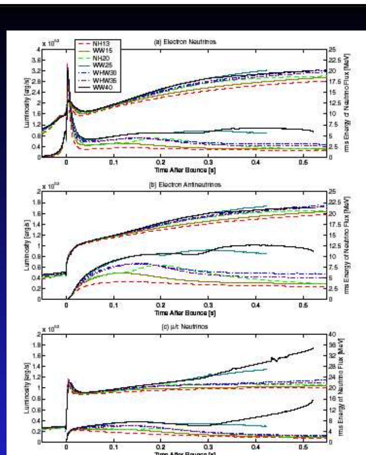
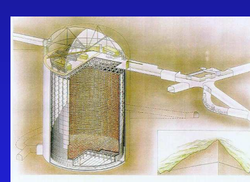
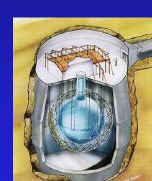


Neutrino Signature Collaborators:

- **Beacom (FNAL)**
- **Boyd (OSU, NSF)**
- **Bruenn (FAU)**
- **Heise (SNO)**
- **Vagins (Super-K)**





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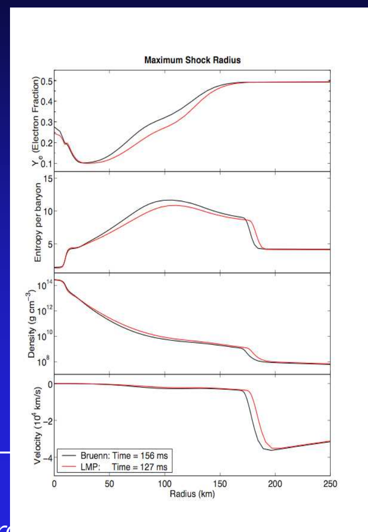
Improved electron capture rates

- Hybrid shell model/RPA, NSE distribution
- Maximum excursion of the shock:
  - 10 km further
  - 30 ms earlier



Hix, Messer, Mezzacappa et al. (2003)

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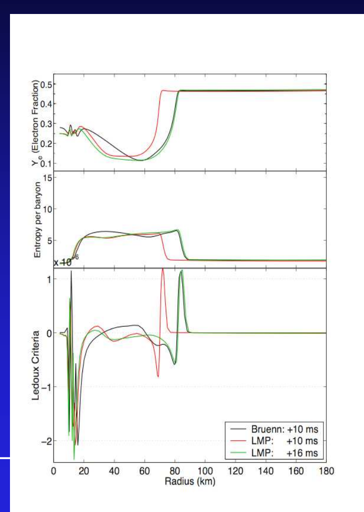
Improved electron capture rates

- Greater instability towards convection



Hix, Messer, Mezzacappa et al. (2003)

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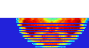
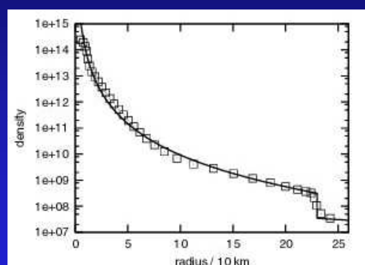


Initiative

Some recent pure hydro simulations...

A standing accretion shock, an analytic solution in spherical symmetry, is used as an initial condition.



Blondin, Mezzacappa, & DeMarino (2003)

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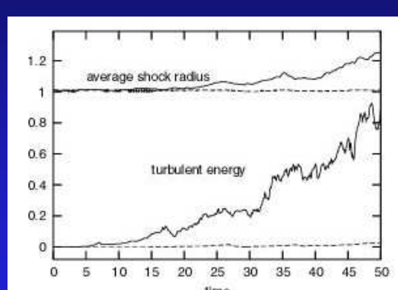
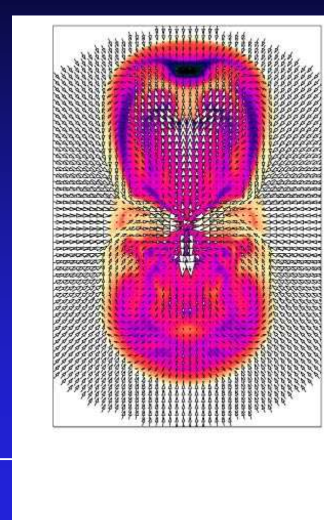
Some recent pure hydro simulations...

The standing accretion shock is unstable in 2D/3D to the point of explosion.





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Spatially multidimensional, energy- and angle-dependent neutrino transport

Conservative formulations of general relativistic kinetic theory

Cardall & Mezzacappa (2002)

$$p^{\hat\mu} \mathcal{L}^{\mu}{}_{\hat\mu} \frac{\partial f}{\partial x^{\mu}} - \Gamma^{\hat i}{}_{\hat\rho\hat\mu} p^{\hat\rho} p^{\hat\mu} \frac{\partial u^{\hat j}}{\partial p^{\hat i}} \frac{\partial f}{\partial u^{\hat j}} = C[f]$$

$$N^{\mu} = \int f\, p^{\mu}\, dP = \int f\, \mathcal{L}^{\mu}{}_{\hat\mu}\, p^{\hat\mu}\, dP$$

$$\frac{1}{\sqrt{-g}} \frac{\partial}{\partial x^{\mu}} \left(\sqrt{-g}\, N^{\mu} \right) = \int C[f]\, dP$$

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Spatially multidimensional, energy- and angle-dependent neutrino transport

Parallel transport solver

Cardall & Mezzacappa, in preparation

2D: solution vector of several 10^9 elements

3D: solution vector approaching 10^{12} elements

$$F[f] = 0$$

$$F = T + S + M + C$$

- $T : t$, backward differenced
- $S : \vec{x}$, nearest neighbor (linear)
- $M : \vec{p}$, nearest neighbor (linear)
- C : dense $\vec{p}$ coupling (nonlinear)

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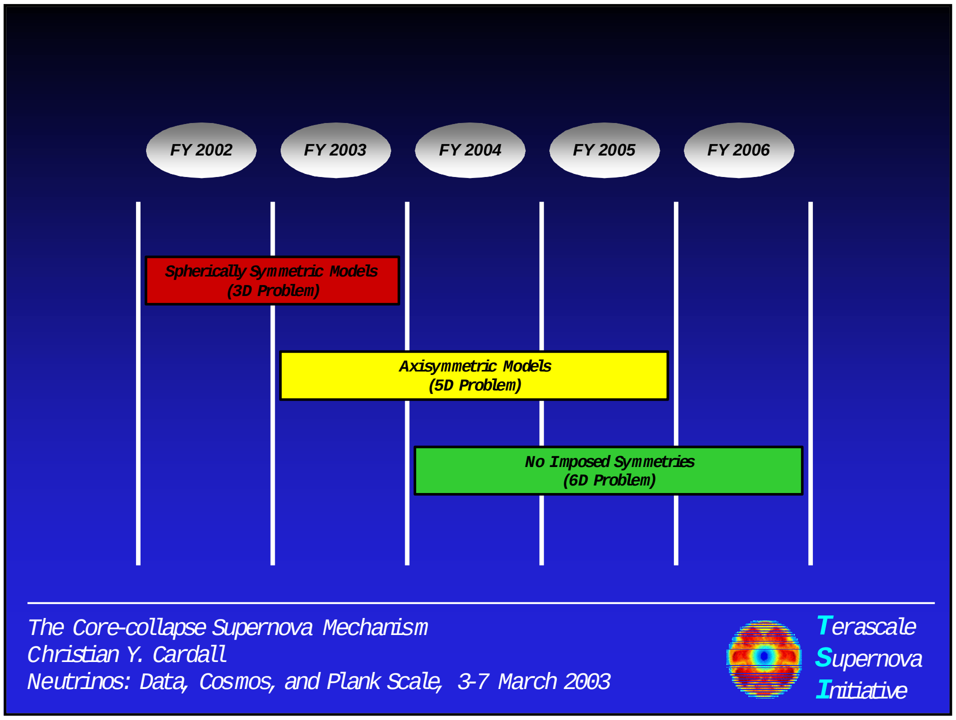
FY 2002
FY 2003
FY 2004
FY 2005
FY 2006
Spherically Symmetric Models
(3D Problem)
Axisymmetric Models
(5D Problem)
No Imposed Symmetries
(6D Problem)
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The New York Times
Editorial/Op-Ed
March 4, 2003
The Real Scientific Hero of 1953
By STEVEN STROGATZ
In 1953, Enrico Fermi and two of his colleagues at Los Alamos Scientific Laboratory, John Pasta and Stanislaw Ulam, invented the concept of a "computer experiment." Suddenly the computer became a telescope for the mind, a way of exploring inaccessible processes like the collision of black holes or the frenzied dance of subatomic particles – phenomena that are too large or too fast to be visualized by traditional experiments, and too complex to be handled by pencil-and-paper mathematics. The computer experiment offered a third way of doing science. Over the past 50 years, it has helped scientists to see the invisible and imagine the inconceivable.
But perhaps the most important lesson of Fermi's study is how feeble even the best minds are at grasping the dynamics of large, nonlinear systems. Faced with a thicket of interlocking feedback loops, where everything affects everything else, our familiar ways of thinking fall apart. To solve the most important problems of our time, we're going to have to change the way we do science.
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