The simulation of core-collapse supernovae

Christian Y. Cardall

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Physics Division

Uni...

Te...

What are supernovae?

Survey of collapse simulations

The Terascale Supernova Initiative

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What are supernovae?

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).

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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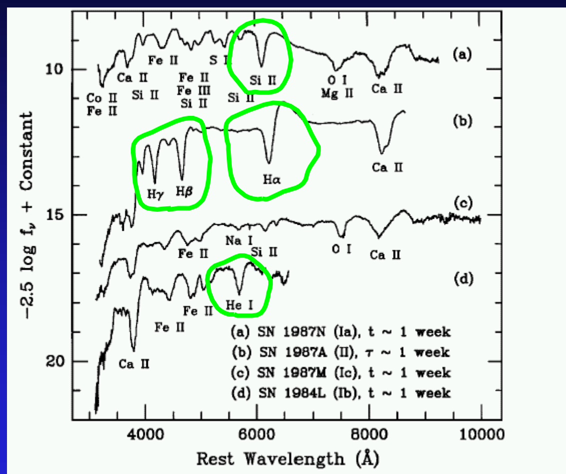
Spectral classification of supernovae:



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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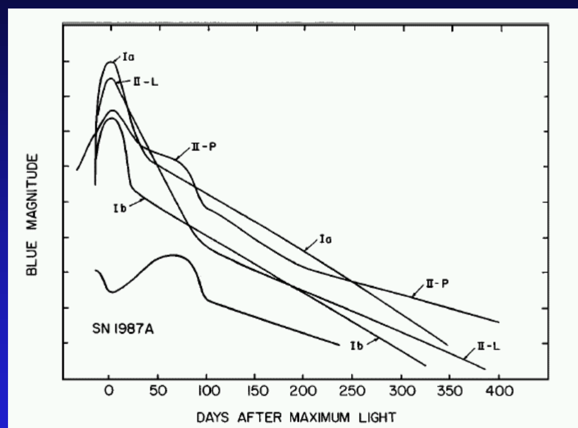
Light curve classification of supernovae:



Filippenko (1997)

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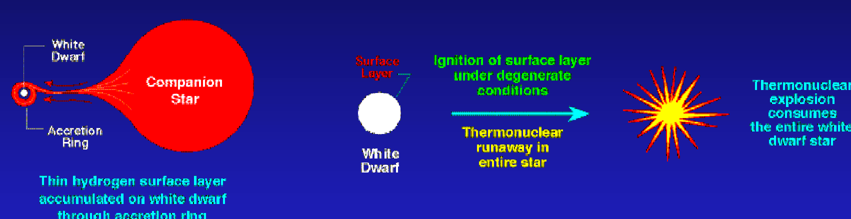
Physical classification of supernovae:

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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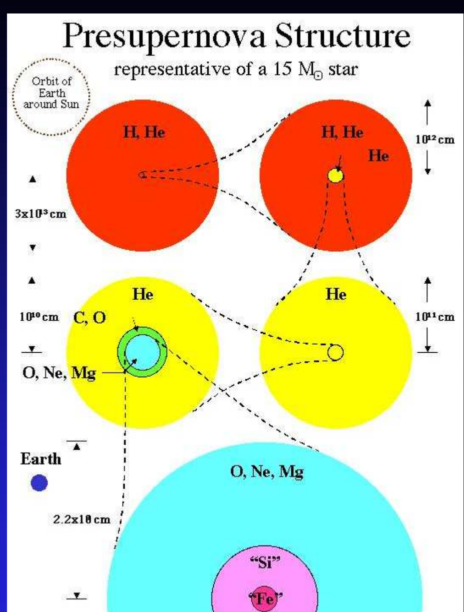

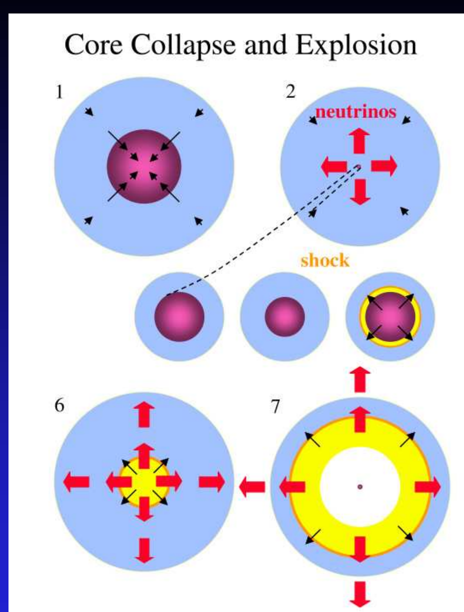

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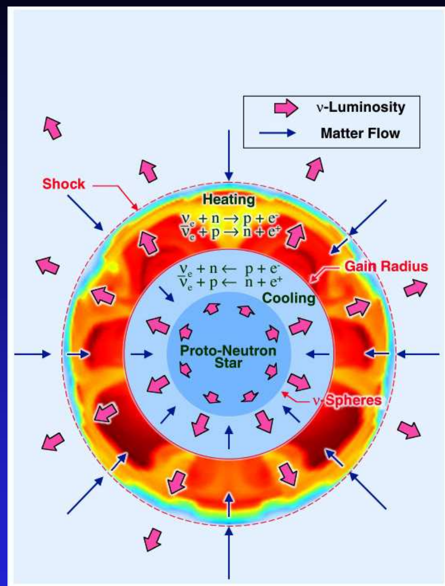

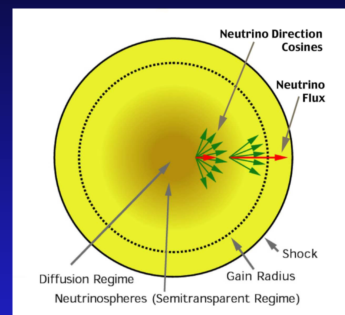

The observables to understand include

- 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;
- (Magneto)Hydrodynamics/gravitation,
  - Dimensionality;
  - Relativity;
- 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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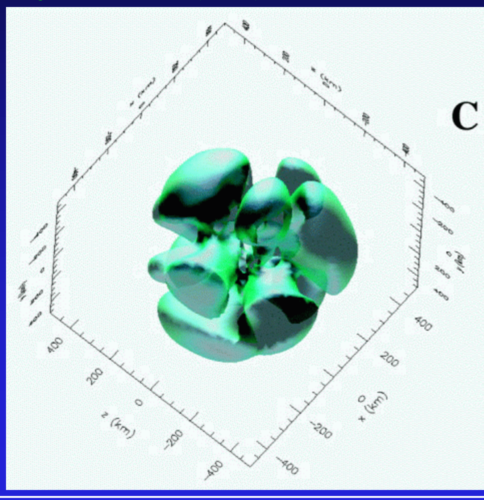
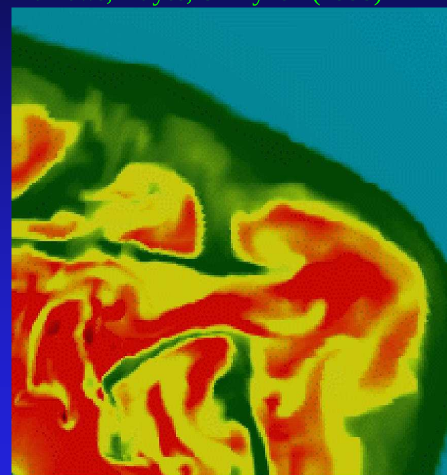
Simulations of collapse and explosion

Multiple spatial dimensions, simplified neutrino transport

Fryer & Warren (2002)



Burrows, Hayes, & Fryxell (1995)



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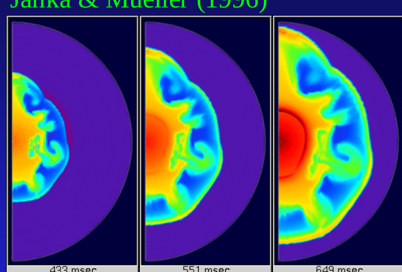
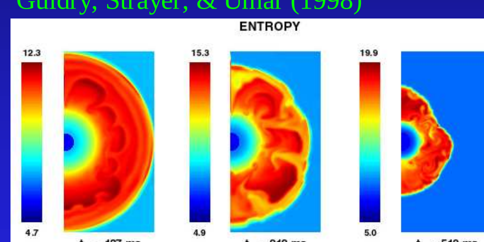
Simulations of collapse and explosion

Multiple spatial dimensions, simplified neutrino transport

Janka & Mueller (1996)



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



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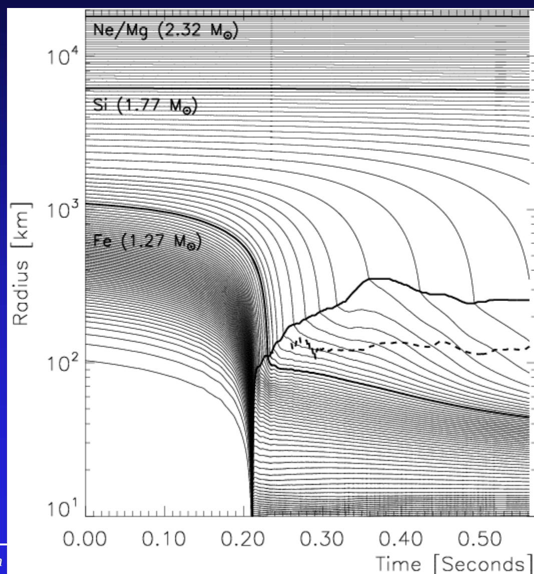
Simulations of collapse and explosion

Spherical symmetry, sophisticated neutrino transport



Rampp & Janka (2000)

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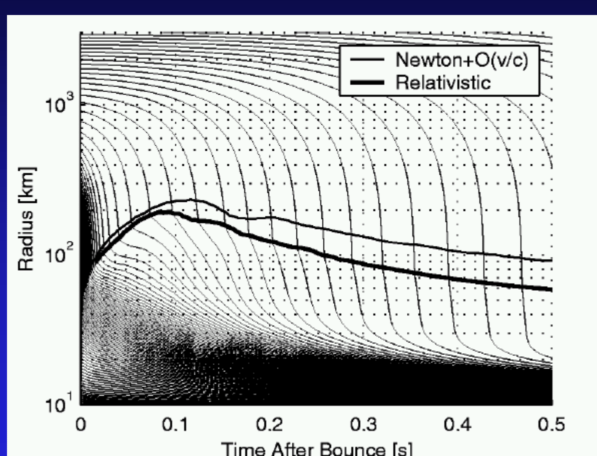
Simulations of collapse and explosion

Spherical symmetry, sophisticated neutrino transport



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

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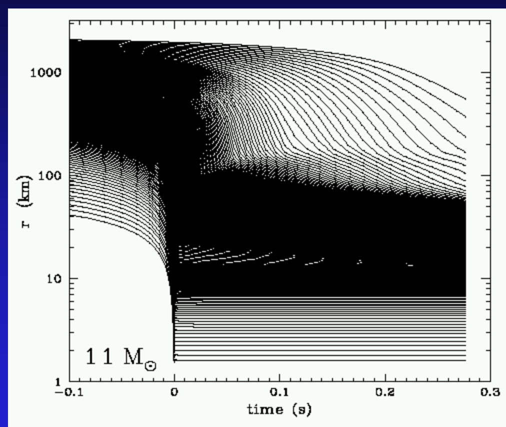
Simulations of collapse and explosion

Spherical symmetry, sophisticated neutrino transport



Thompson, Burrows, & Pinto (2002)

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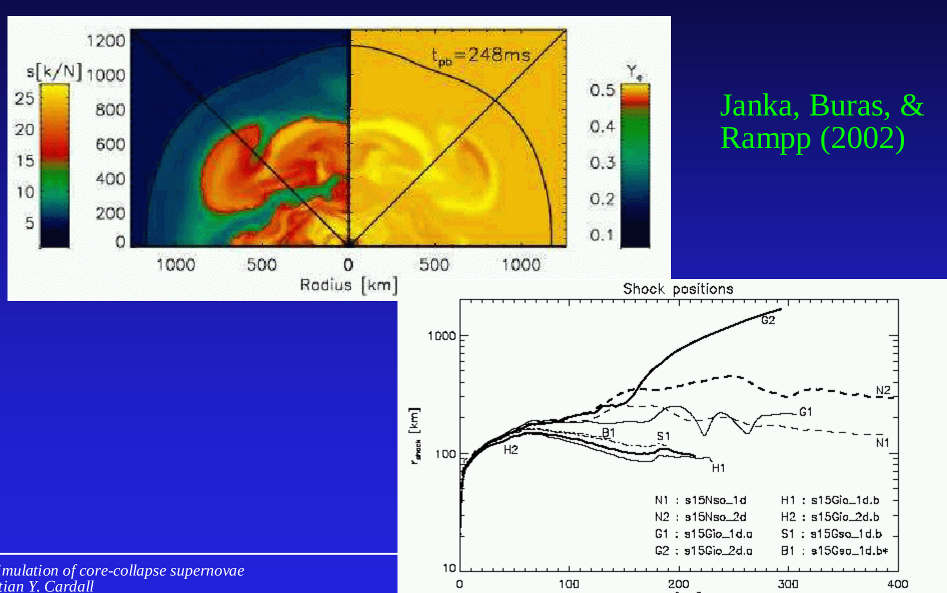
Simulations of collapse and explosion

Multiple spatial dimensions, intermediate neutrino transport



Janka, Buras, & Rampp (2002)

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The Terascale Supernova Initiative

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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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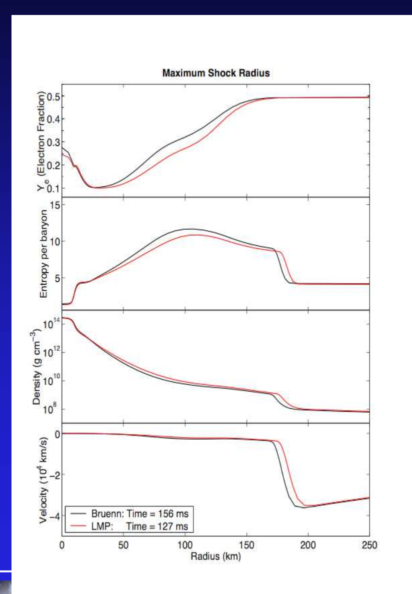
Improved electron capture rates

- 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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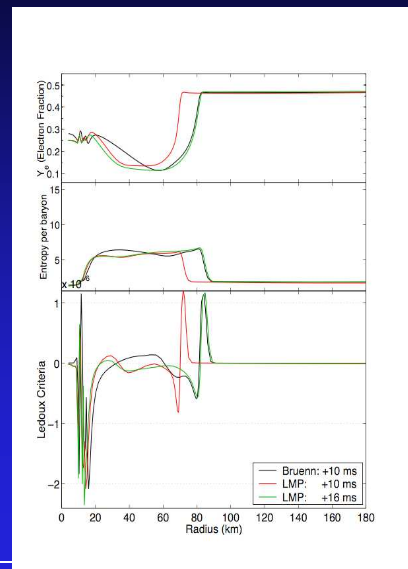
Improved electron capture rates

Greater instability towards convection



Hix, Messer, Mezzacappa et al. (2003)

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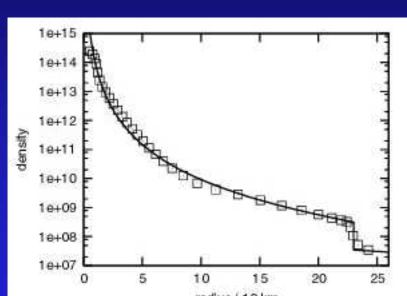
Some recent pure hydro simulations...

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



Blondin, Mezzacappa, & DeMarino (2003)

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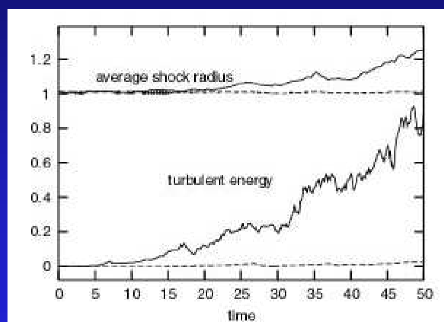
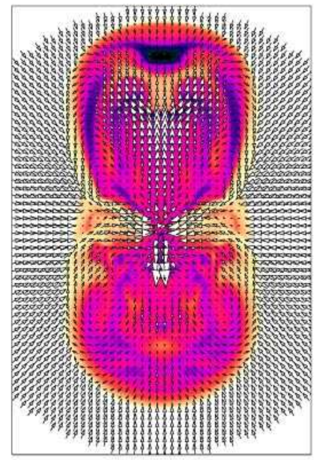
Some recent pure hydro simulations...

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





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QuickTime™ and a Compact Video decompressor are needed to see this picture.

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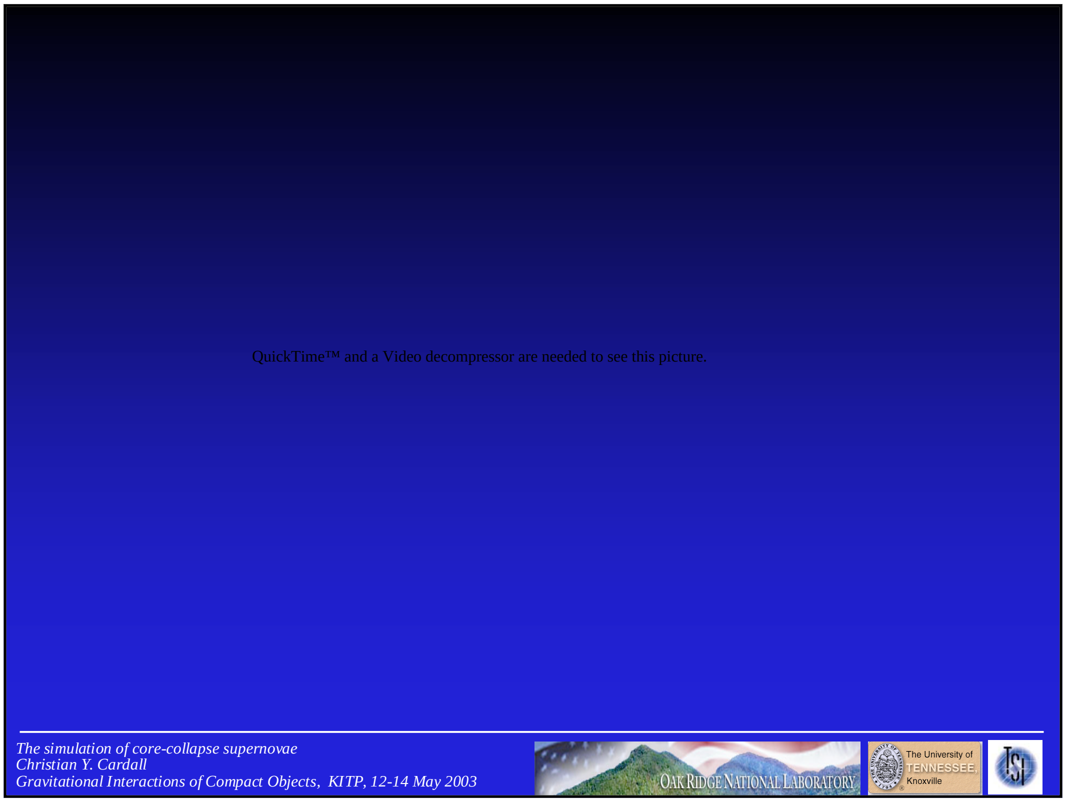
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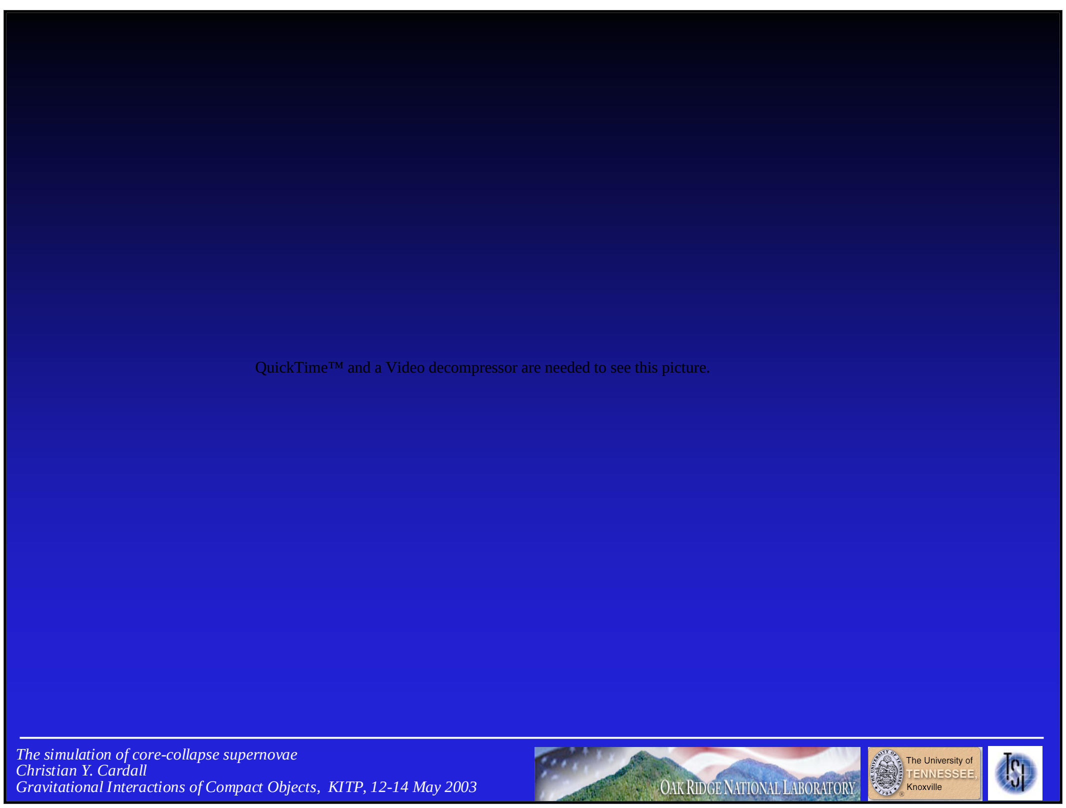
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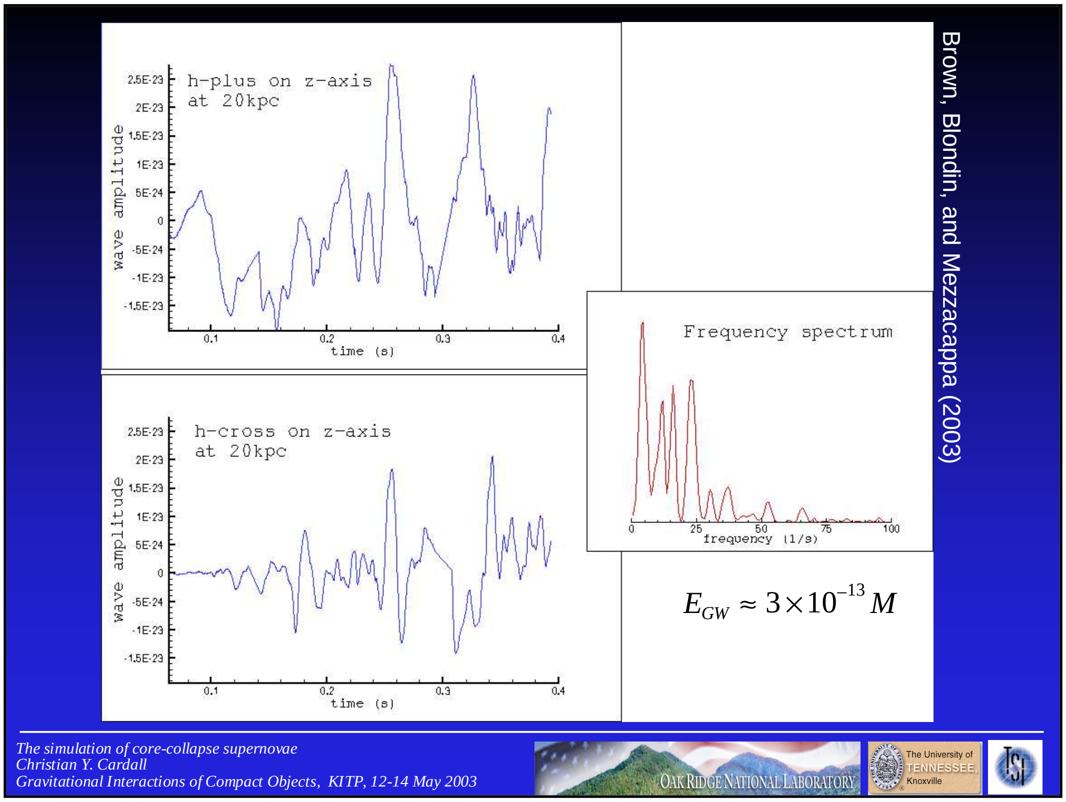
h-plus on z-axis
at 20kpc
wave amplitude
time (s)
h-cross on z-axis
at 20kpc
Frequency spectrum
frequency (1/s)
$E_{GW} \approx 3\times10^{-13} M$
Brown, Blondin, and Mezzacappa (2003)
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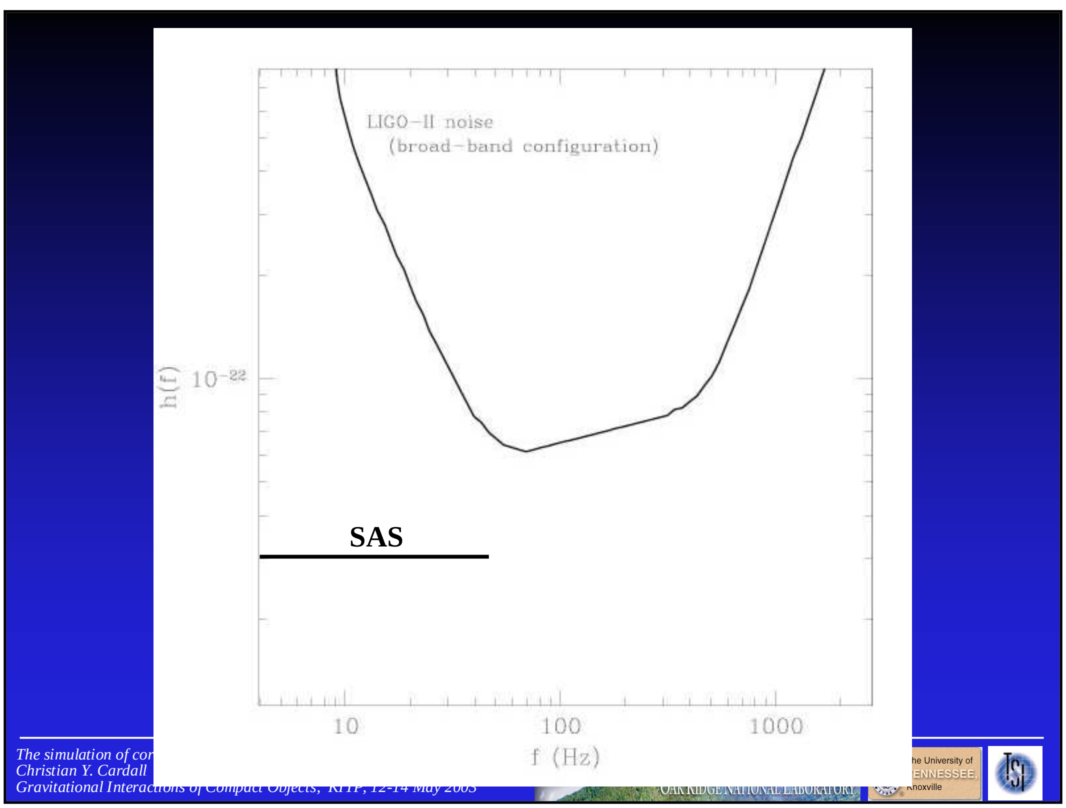
LIGO-II noise
(broad-band configuration)
h(f)
10^{-22}
SAS
10
100
1000
f (Hz)
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Spatially multidimensional, energy- and angle-dependent neutrino transport

Conservative formulations of general relativistic kinetic theory

Cardall & Mezzacappa (2003)

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

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

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

Spatially multidimensional, energy- and angle-dependent neutrino transport

Massively parallel neutrino transport solver

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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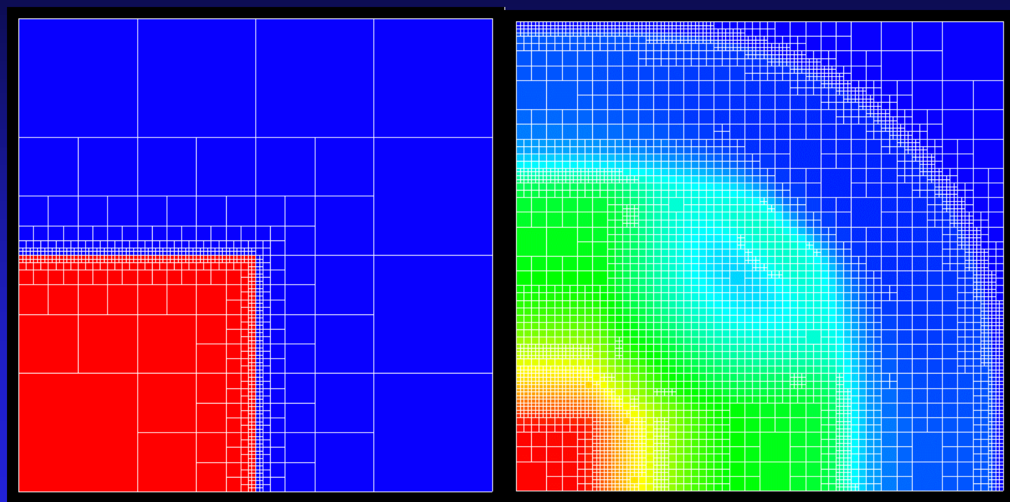
Towards three spatial dimensions…

Zone-by-zone adaptive mesh refinement: GenASiS

(*Gen*eral *A*strophysical *Si*mulation *S*ystem)



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Towards three spatial dimensions…

- Pure hydrodynamics:
  - Block structured approach
  - Explicit time evolution of individual blocks
  - Simple serial solver used repeatedly
- Radiation hydrodynamics
  - Implicit time evolution of the entire mesh structure
  - An integrated solver needed
  - Zone-by-zone refinement more natural

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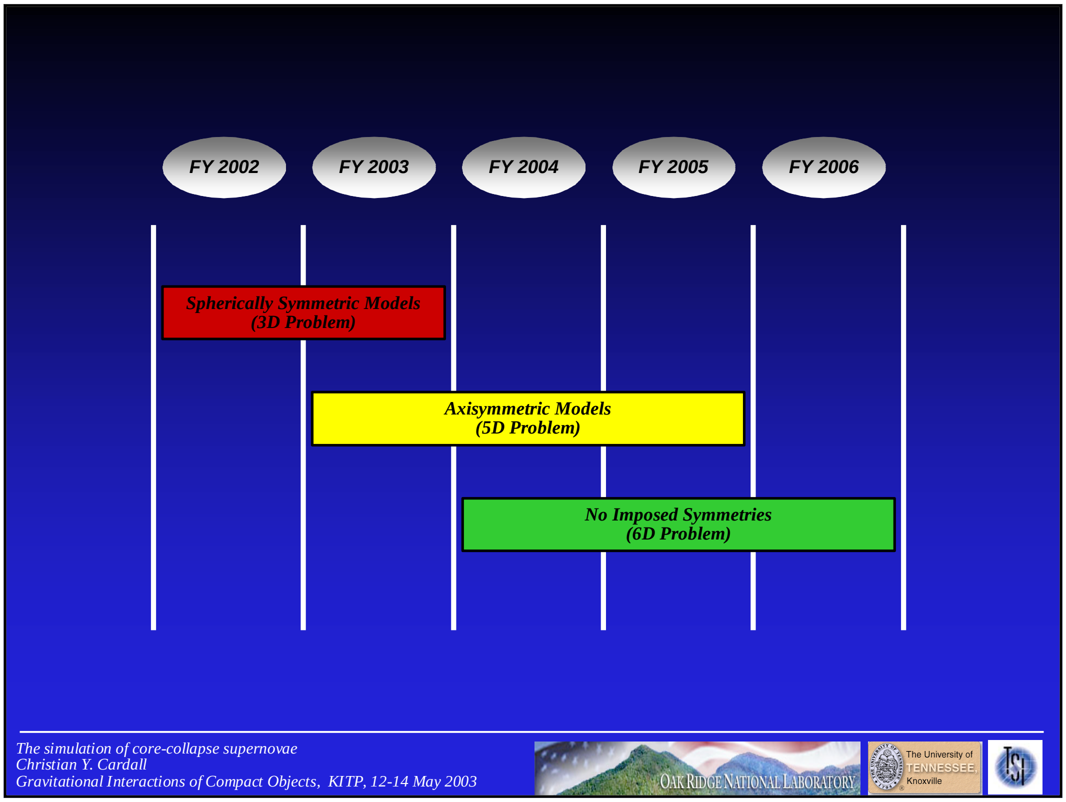

Gravity summary

Our supernova simulations will be Newtonian for the next few years.

Collapse has been done in spherical symmetry.

Post-bounce evolution gives signals that probably are too weak for LIGO.

We have developed and are working with conservative formulations of relativistic radiative transfer.

We are developing GenASiS, an AMR code with radiation transport; make progress on the “dirty astrophysics” of NS-NS mergers.

We want to incorporate full relativity in GenASiS.

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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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