The Theory of Core-Collapse Supernovae: Where we are and where we are heading.

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Outline of this Talk

1. Overview and state of core-collapse supernova modeling.

2. New aspects & boundary conditions of core-collapse supernova theory.

3. Core-collapse supernova astrophysics with neutrinos (and gravitational waves).
In addition, the new problem of developing a more detailed picture of the happenings in a super-nova now confronts us. With all reserve we advance the view that a super-nova represents the transition of an ordinary star into a neutron star, consisting mainly of neutrons. Such a star may possess a very small radius and an extremely high density. As neutrons can be packed much more closely than ordinary nuclei and electrons, the “gravitational packing” energy in a cold neutron star may become very large, and, under certain circumstances, may far exceed the ordinary nuclear packing fractions. A neutron star would therefore represent the most stable configuration of matter as such. The consequences of this hypothesis will be developed in another place. [PNAS, 20:259, 1934, APS 12/33]
Core-Collapse Supernovae: Explosions of Massive Stars, $M > 8-10 \, M_{\odot}$

Supernova 1987A
Large Magellanic Cloud
Progenitor:
BSG Sanduleak -69° 220a, $\approx 18 \, M_{\odot}$
Neutrinos from SN 1987A
Confirmation of the Basic Model

- Collapse to neutron star: ~300 [B]ethe (3 x 10^{53} erg).
- ~99% emitted in neutrinos over 10s of seconds.
- Typical SN “explosion energy” ~1 B (10^{51} erg), extreme cases: ~10 B (“hypernova”).
- Key question: What mechanism mediates the explosion?
The Baseline Core Collapse Model

Nuclear equation of state (EOS) stiffens at nuclear density.

Inner core (~0.5 $M_{\text{Sun}}$) -> protoneutron star core. Shock wave formed.

Outer core accretes onto shock & protoneutron star. Shock dissociates Fe-group nuclei (at 8.8 MeV/baryon) + neutrino burst.

-> Shock stalls at ~100 km, must be “revived” to drive explosion.

Reviews:
Bethe ‘90
Kotake et al. ‘06
Janka et al. ‘07
Neutrino Burst

• Neutrinos and Anti-neutrinos of ALL species:

\[ \nu_e, \bar{\nu}_e \]

"\( \nu_\mu \)" = "\( \nu_x \)"

\[ \{ \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau \} \]

• Emission:

\[ e^- p \leftrightarrow \nu_e n \]

\[ e^+ n \leftrightarrow \bar{\nu}_e p \]

\[ e^- e^+ \leftrightarrow \nu_i \bar{\nu}_i \]

\[ N N \leftrightarrow \nu_i \bar{\nu}_i \]

\[ \tilde{\gamma} \leftrightarrow \nu_i \bar{\nu}_i \]
Detailed Models: Ingredients

- Magneto-Hydrodynamics
  - Dynamics of the stellar fluid.
- General Relativity
  - Gravity
- Nuclear and Neutrino Physics
  - Nuclear EOS, nuclear reactions & \( \nu \) interactions.
- Boltzmann Transport Theory
  - Neutrino transport.

Fully coupled!
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- Additional Complication: **Core-Collapse Supernovae are 3D**
  - Rotation, **fluid instabilities** (convection, turbulence, advective-acoustic, rotational), **MHD dynamos**, multi-D structure from convective burning.
  - Need multi-D (ideally 3D) treatment.

- Route of Attack: **Computational Modeling**
  - Complexity dominated by neutrino transport:
    - Full problem is 3 (space) + 3 (momentum space) + 1 (time) dimensional
  - Approach: employ reduced dimensionality in space and momentum space.
Overview of Core-Collapse Supernova Models (I)

1D (spherical symmetry)

- First simulations: 1960-70 by Colgate & White, Wilson, Arnett
- Bethe & Wilson ‘85: “Neutrino Mechanism”
Neutrino Mechanism
Bethe & Wilson ’85; also: Janka ‘01, Janka et al. 07, Pejcha & Thompson ‘12

Cooling:
\[ Q_v^- \propto T^6 \]

Heating:
\[ Q_v^+ \propto L_v r^{-2} \langle \epsilon_v^2 \rangle \]

Charged-current absorption:
\[ \nu_e + n \rightarrow p + e^- \]
\[ \bar{\nu}_e + p \rightarrow n + e^+ \]

Ott et al. ’08
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1D Neutrino-Driven Explosions

Kitaura et al. ‘06, Hüdepohl et al. ’10, Fischer et al. ’10, ‘12

Problem:
1D neutrino mechanism fails for more massive stars (that are observed to explode in nature).

Kitaura et al. 2006
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– **Problem:**
  Explosions found only for lowest-mass massive stars \((M \lesssim 9 \, M_\text{Sun})\).

– **Detailed long-term cooling simulations now available.**
Detailed Long-Term Proto-NS Cooling Calculations

Hüdephol et al. ’10, PRL 104, 251101
Fischer et al. ‘10, A&A 517, A80, and ‘12, PRD 85, 083003
Overview of Core-Collapse Supernova Models (II)

1D -> 2D (axisymmetry)

- First simulations in 1990s:
  Herant et al. ‘94, Burrows et al. ’95, Janka & Müller ’96

- Multi-D dynamics:
  - Convection in proto-NS and in the heating region.
  - Instability of the stalled shock ("SASI").
  - Rotation & magnetic fields
    -> “magnetorotational” explosions.

Dessart et al. ‘05
Multi-D Neutrino Mechanism

Specific Entropy \([ k_B / \text{baryon} ]\)

\[
\begin{array}{cccccc}
 1.5 & 4.4 & 7.3 & 10.2 & 13.1 & 16.0 \\
\end{array}
\]

- Shock
- Gain Region
- Convection SASI
- Shock

\(L_\nu\)

Axisymmetry (2D)

[Ott 2009]
Standing Accretion Shock Instability (SASI)

Blondin et al., Foglizzo et al.

Movie by Burrows, Livne, Dessart, Ott, Murphy’06
Neutrino Signature of the SASI

Lund et al. ‘10, PRD 82, 063007 and Marek et al. ’09, A&A 496, 475

- Neutrino signal can be used to probe supernova dynamics.
- **Lund et al. ‘10**: IceCube can detect SASI for galactic event.
Magnetorotational Explosions
[e.g., Burrows, Dessart, Livne, Ott, Murphy ’07, Takiwaki & Kotake ‘11]

Burrows, Dessart, Livne, Ott, Murphy et al. ‘07
• Fluxes highest along rotation axis.

• Softer spectrum in equatorial regions; harder spectrum along rotation axis.
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    -> “magnetorotational” explosions.

- Consequence of 2 dimensions:
  “Dwell time” of matter in heating region increased -> more efficient heating. Conditions more favorable for explosion.

- Successful neutrino-driven explosions for stars from 11 to 27 M_{Sun}.
  Buras et al. ‘06, Marek&Janka’09, Sawai ’10, Yakunin et al. ‘10, Müller et al. ‘11, ’12
  (all using energy-dependent neutrino transport, approx-GR or GR gravity).

- Possibly magnetorotational explosions to power hypernovae.
Overview of Core-Collapse Supernova Models (III)

1D -> 2D -> 3D (no symmetries)

– First 3D simulations: Fryer & Warren ‘02, ‘04

– 3D vs. 2D:
  – Additional degree of freedom.
  – Physical cascade of turbulent power (to small scales).

Ott et al. ‘12 (in prep.)
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– Nordhaus et al.’ 10, approx. & parameterized models:
  3D most favorable for explosion.

– Hanke et al.’ 11 (same physics):
  no improvement 2D->3D.

– Simulations with improved physics pioneered by Tokyo group: Takiwaki et al. ‘12,
  Kuroda et al. ‘12

Nordhaus et al. ‘10
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As of June 2012:

No fully self-consistent long-term 3D simulations with energy-dependent neutrino transport & GR gravity yet.

-> expect such simulations in 2013/14.
New Aspects and Boundary Conditions:

Nuclear equation of state (EOS) constraints

Collective neutrino oscillations
Constraints on the Nuclear Equation of State

Figure by Evan O’Connor, Ott et al., arXiv:1111.6282

1.97 $M_\odot$
Demorest et al. (2010)

Gravitational Mass [$M_\odot$]

Hebeler, K. et al. (theory) (2010)

Steiner, A. et al. (observations) (2010)

Özel et al. (2010)

(observations)

(observations)
Collective Neutrino Oscillations
For more details see B. Balantekin’s talk!

• Multiple kinds of oscillations:
  Vacuum, MSW, collective (non-linear, $\nu$-$\nu$ scattering)

Pantaleone ’92, Hannestad/Raffelt et al. ‘06, Duan/Fuller et al. ‘06–’10, Fogli et al. ’08, Chakraborti et al. ’11ab, Dasgupta/Dighe ‘07–’11, Balantekin, + many others

• Collective oscillations need high neutrino density
  -> near the core of a core-collapse supernova.

• Consequence:
  in inverted hierarchy spectral swap of $\nu_e$ and $\nu_\mu/\nu_\tau$ & antis

• Potential impact:
  Increased neutrino heating = easier to explode?

For more details see B. Balantekin’s talk!

courtesy of Huaiyu Duan
Impact of Collective Oscillations

High matter density suppresses collective oscillations during the pre-explosion evolution.

-> no impact on explosion mechanism.

Dasgupta, O’Connor, Ott ‘12, PRD 85, 065008

See also:

Chakraborty et al. ’11ab
Suwa et al. ‘11
Pejcha et al. ‘11

Chakraborty et al. ’11, PRL
Astrophysics with Supernova Neutrinos

Probing the “Supernova Engine”
- Neutrinos
- Gravitational Waves

**EM waves (optical/UV/X/Gamma):** secondary information, late-time probes of engine.

Red Supergiant Betelgeuse
D ~200 pc

Supernova “Central Engine”

- HST
- 800 million km
- 300 km
Black Hole Forming Collapse

Massive stars in the nearby universe will **not directly collapse to a black hole**

> **There will always be a proto-NS phase with \( \nu \) emission.**

(see O’Connor & Ott ’11, Sumiyoshi et al. ’06,’07,’08, Fischer et al. ’09, Nakazato et al. ‘08, ‘10, ‘12)

- If explosion fails, black hole is ultimate outcome.
- Duration of neutrino emission determined by **progenitor star structure** (accretion rate) and **nuclear equation of state** (max. proto-NS mass)
Correlated **Neutrino** and **Gravitational Wave Signals**

Ott et al. ‘12, arXiv:1204.512

- If star is spinning rapidly -> quadrupole deformation
- Fundamental quadrupole oscillations excited at core bounce.
Correlated Neutrino and Gravitational Wave Signals

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Can we observe this?
[Ott et al. ‘12, arXiv:1204.0512]

- GWs: Throughout Milky Way with advanced detectors: KAGRA (Japan), LIGO (US & India), GEO (Germany), Virgo (Italy)
- Neutrinos: ~1 kpc with a megaton water-Cherenkov detector. IceCube limited by readout rate.
Summary

• 78 years after Baade & Zwicky 1934, 25 years after SN 1987A: 
  Core-collapse supernova basics confirmed, 
  important details unclear.

• “Neutrino mechanism” most likely the driver 
  behind most core-collapse supernovae.
  – Detailed neutrino predictions from 1D models.
  – Multi-D simulations add exciting new variations 
    on baseline neutrino signature.
  – Next step: self-consistent 3D simulations.

• Great prospects for astrophysics with neutrinos & 
  gravitational waves from the next nearby core 
  collapse event.
  -> now is the time to think about joint analyses 
     of v/GW data with KAGRA, aLIGO, LIGO-India, 
Supplemental Slides
Why not use the mass of the progenitor star as a parameter?

> stellar mass is a very poor parameter:
Supernovae and their Rates

- \(~20\%\) thermonuclear SNe (Type Ia)
- \(~80\%\) core-collapse SNe (CCSNe) (Type II, Ib/c & subtypes)
- \(~1\) SN/s in the Universe
- \(~1\) SN/day discovered
- \(~1\) SN/50-100 yrs (?) in the Milky Way
- >1 CCSN/year within 10 Mpc; 2011dh (M51, \(~7\) Mpc) 2011ja (NGC 4945, \(~3.5\) Mpc) 2012A (NGC 3239, \(~8\) Mpc) 2012aw (M 95, \(~10\) Mpc)
Gravitational Wave (GW) Refresher

- **Emission**: Accelerated quadrupole bulk mass-energy motion.

Quadrupole approximation

\[
h_{jk}^{TT}(t, \vec{x}) = \left[ \frac{2}{c^4} \frac{G}{|\vec{x}|} \dddot{I}_{jk}(t - \frac{|\vec{x}|}{c}) \right]^{TT}
\]

\[
\frac{G}{c^4} \approx 10^{-49} \text{ s}^2 \text{ g}^{-1} \text{ cm}^{-1}
\]

10 kpc \( \approx 3 \times 10^{22} \text{ cm} \)

- **Detection**: Measure changes in separations of test masses with laser interferometry. 

*LIGO, Virgo, GEO, KAGRA.* 

Advanced LIGO in 2015+, LIGO India (2020+)
GW & Neutrino Signal Correlations: SASI

s15WH07
HShen EOS

$\nu_e$, North Pole
$\nu_x$, South Pole

Luminosity [$10^{52}$ erg s$^{-1}$]

$\nu_e$, Equator

$[\text{Ott+ '12 in prep.}]$
The Neutrino Radiation Field

Ott et al. ’08
Brandt, Burrows,
Livne, Ott ‘11

$S_{16} \nu_e 12.6$ MeV, equator, $\vartheta = \pi/2$
Maximum NS Mass: Constraints on the EOS

• Most solid if inclination constrained by Shapiro delay.

• J1903+0327 -> 1.671 +/- 0.008 M_{Sun}

• New: J1614-2230
  Demorest et al. 2010: 1.97 +/- 0.04 M_{Sun}
“Soft” EOS
- compact protoneutron star, $\nu$ decouple at smaller radius,
- harder neutrino spectrum.
- increased neutrino heating.

“Stiff” EOS
- more extended protoneutron star, $\nu$ decouple at larger radius,
- softer neutrino spectrum,
- increased neutrino heating.

General relativity: Effective softening -> harder $\nu$ spectrum.

“Favorite EOS”: Lattimer & Swesty ‘91, $K_0 = 180$ MeV

Problem: Discovery of 2-M$\odot$ neutron star (Demorest et al. ‘10) rules out many soft EOS, including LS180.
Detailed Models of Core-Collapse Supernovae

short overview: in Ott+ ‘11 (arXiv:1111.6282); reviews: Janka et al. ‘07, Kotake et al. ‘12

(Incomplete) List of key questions to be answered:

- Explosion mechanism
- Neutrino signature
- Gravitational wave signature
- Optical/UV/X-ray signature, explosion morphology
- Nucleosynthetic yields
- Neutron star vs. black hole
- Connection to gamma-ray bursts
- Pulsar spin & B-field
- Pulsar “birth kicks”

C. D. Ott @ Neutrino 2012, 2012/06/09