Modeling The Death of Massive Stars

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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]
Stellar Death & Supernova Explosions

- ~1 SN/s in the Universe
- ~1 SN/day discovered
- ~1 SN/50-100 yrs (?) in the Milky Way
- >1 SN/year within 10 Mpc

- ~20% thermonuclear SNe (Type Ia) -> exploding white dwarfs
- ~80% core-collapse SNe (CCSNe) -> exploding massive stars

- Class of energetic stripped-envelope explosions: Type Ic-bl ("broad lines")
- Some (>8) SNe Ic-bl associated with long gamma-ray bursts.
Core-Collapse Supernovae:

Explosions of Massive Stars $8M_\odot \lesssim M \lesssim 130M_\odot$

Supernova 1987A
Large Magellanic Cloud
Progenitor:
BSG Sanduleak -69° 220a, $\approx 18 M_\odot$
The Basic Theory of Core Collapse

\[ 8M_\odot \lesssim M \lesssim 130M_\odot \]

Fe-group nuclei

\[ \rho_c \approx 10^{10} \text{ g cm}^{-3} \]

\[ T_c \approx 0.5 \text{ MeV} \]

\[ Y_{e,c} \approx 0.43 \]

\[ M_{\text{Ch}} \approx 1.44 \left( \frac{Y_e}{0.5} \right)^2 \left[ 1 + \left( \frac{s_e}{\pi Y_e} \right)^2 \right] \]
Self-Similarity of Collapse

Homologously \( (v \propto r) \) collapsing \textbf{inner core}. Supersonically collapsing \textbf{outer core}.

Analytic similarity solutions:
- Goldreich & Weber 1980
- Yahil & Lattimer 1982
- Yahil 1983
Collapse and Bounce

Protoneutron Star, $R \sim 30$ km

Iron Core

Stiff Nuclear EOS: “Core Bounce”
Situation after Core Bounce
The Core-Collapse Supernova Problem

• The shock always stalls:
  Dissociation of Fe-group nuclei @ \( \sim 8.8 \) MeV/baryon (\( \sim 17 \) B/M\(_{\odot}\)).
  Neutrino losses initially @ >100 B/s (1 [B]ethe = 10\(^{51}\) ergs).

Hans Bethe
1906-2005

Animation
by Evan O’Connor
Caltech GR1D code
(open source!)
Postbounce Evolution

Protoneutron Star, $R \sim 30$ km

- Shock
- Accretion
- $L_\nu$

Shock is revived.

Supernova Explosion

Shock is not revived.

Collapse to Black Hole
Postbounce Evolution

What is the mechanism that revives the shock?

Topic of another talk!
Core-Collapse Supernova Energetics

• Collapse to a neutron star:
  \[ \sim 3 \times 10^{53} \text{ erg} = 300 \text{ [B]ethe} \]
  gravitational energy (\(\approx 0.15 \text{ M}_\odot c^2\)) released.
  Initially stored in protoneutron star.
  -> Any explosion mechanism must tap this reservoir.

• \[ \sim 10^{51} \text{ erg} = 1 \text{ B} \] kinetic and internal energy of the ejecta.
  (Extreme cases: \(10^8 \text{ B}; \) “hypernova”)

• 99% of the energy is radiated in neutrinos over tens of seconds in protoneutron star cooling.
  -> Strong evidence from SN 1987A neutrino observations.
Detailed Models: Ingredients

- Magneto-Hydrodynamics
  - Dynamics of the stellar fluid.

- General Relativity
  - Gravity

- Nuclear and Neutrino Physics
  - Nuclear EOS, nuclear reactions & ν interactions.

- Boltzmann Transport Theory
  - Neutrino transport.

Fully coupled!
Detailed Models: Ingredients

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

• Additional Complication: Core-Collapse Supernovae are 3D
  – Rotation, fluid instabilities (convection, turbulence, advective-acoustic, rotational), MHD, 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.
Next Step: Computation

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+ 07, Pejcha & Thompson ‘12

Cooling:

\[ Q_\nu^- \propto T^6 \]

Heating via charged-current absorption:

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

\[ Q_\nu^+ \propto \left( \frac{1}{F_\nu} \right) L_{\nu} r^{-2} \langle \epsilon_\nu^2 \rangle \]

Neutrino radiation field:

30 km  60 km  120 km  240 km

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1D Neutrino-Driven Explosions

Kitaura+ ‘06, Hüdepohl+ ’10, Fischer+ ’10, ‘12

Problem: 1D neutrino mechanism fails for more massive stars (which explode in nature).

Kitaura+ 2006

8.8 $M_{\text{SUN}}$

progenitor star

O-Ne-Mg core
Overview of Core-Collapse Supernova Models

1D -> 2D (axisymmetry)

- First simulations in 1990s:
  Herant+ ‘94, Burrows+ ’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.

Dessart+ ‘05

Proto-NS convection
Standing Accretion Shock Instability (SASI)

Blondin+’03
Foglizzo+’06
Scheck+ ’08
and many others

Movie by
Burrows,
Livne,
Dessart,
Ott, Murphy’06

S20.0 ENTROPY
LEA VELOCITY
Time = -168.0 ms
Radius = 500.00 km
Results of 2D Simulations

Recent 2D work: Buras+06, Ott+08, Marek+09, Murphy+08, Suwa+10, Müller+12abc, Bruenn+12

Net effect of 2D:
“Dwell time” in heating region increases.

-> 2D models explode more easily.

-> BUT explosions not robust:
  - marginal,
  - require fine-tuning,
  - not reproducible across codes.
What are we missing?

Dimensionality?
2D \rightarrow 3D

Physics?
Missing Physics: Neutrino Oscillations!?
Neutrino Oscillations
[Dasgupta, O’Connor, & Ott’12]

• Multiple kinds of oscillations:
  - **Vacuum oscillations**
  - Mikheyev–Smirnov–Wolfenstein (MSW) effect: $\nu - e^-$ scattering
  - **New**: Self-induced “collective” oscillations: $\nu - \nu$ scattering

  [Pantaleone ‘92, Hannestad/Raffelt et al. ‘06, Duan/Fuller et al. ‘06–’10, Dasgupta/Dighe ‘07–’11]

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

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Collective Oscillations

[Dasgupta, O’Connor, & Ott 2012]

- Example from Dasgupta, O’Connor & Ott ’12 – single-angle, multi-energy, effective 2-flavor approach: $\nu_e, \nu_x$
- First oscillation calculation tagging on to 2D radiation-hydro simulations. Work in 1D by Hamburg & Munich groups.

Spectral swaps!

Movie by Evan O’Connor
Impact of Collective Oscillations

[Dasgupta, O’Connor, & Ott ‘12]

• What is the effect on the CCSN mechanism?

Neutrino heating:

\[ Q_\nu^+ = \frac{X_n}{\lambda_0^a} \frac{L_{\nu e}}{4\pi r^2} \left\langle E_{\nu e}^2 \right\rangle \left\langle \frac{1}{F} \right\rangle + \frac{X_p}{\lambda_0^a} \frac{L_{\bar{\nu} e}}{4\pi r^2} \left\langle E_{\bar{\nu} e}^2 \right\rangle \left\langle \frac{1}{F} \right\rangle \]

Messer et al. ‘98
Janka ‘01

• Basic idea: swap of \( \nu_e/\nu_x \) and anti-\( \nu_e/\text{anti-}\nu_x \) spectra
- harder \( \nu_e/\text{anti-}\nu_e \) spectra -\>
increased heating.

• Key prerequisite:
Oscillations must occur below shock radius,

ideally below gain radius.
Impact of Collective Oscillations (2)

[Dasgupta, O’Connor, & Ott ‘12]

Radius [km]

s11.2WHW02
HShen EOS

North Pole
Average
South Pole

R$_g$
R$_{ve}$

75% of net heating

$0$ $0.05$ $0.1$ $0.15$ $0.2$ $0.25$ $0.3$ $0.35$ $0.4$

$t - t_{bounce}$ [s]
Impact of Collective Oscillations (3)

[Dasgupta, O’Connor, & Ott ’12]

Analytic & numerical oscillation calculations based on 2D radiation fields

See also:
Chakraborty et al. ’11ab
Suwa et al. ‘11
Pejcha et al. ’11

Radius [km]
Heating Enhancement?  
[Dasgupta, O’Connor, & Ott ‘12]

Progenitors:  
11.2 $M_{\text{Sun}}$  
15 $M_{\text{Sun}}$  
Woosley et al. ‘02

See also Suwa et al. ’11, Chakraborty et al. ‘11ab

optimistic guess by Suwa et al. (wrong!)  
results from actual calculations
Progenitors:
11.2 $M_{\text{Sun}}$
15 $M_{\text{Sun}}$
Woosley et al. ‘02

Conclusion:
Collective neutrino oscillations are **not dynamically relevant** for the core-collapse supernova mechanism

See also Suwa et al. ‘11, Chakraborty et al. ‘11ab
What are we missing?

Dimensionality?
2D -> 3D

Physics?
The Frontier: 3D Core-Collapse Supernovae

- 1D -> 2D: neutrino heating more efficient, some models explode.
- 2D -> 3D: (1) Character of turbulence changes; energy cascades to small scales (large scales in 2D).
  (2) Additional degree of freedom: nonaxisymmetric flow.

- Is the neutrino mechanism robust in 3D?

- Computational challenge:
  - Multi-scale: Resolve 10 m (turbulence) - 10000 km (outer core)
  - Multi-physics: GR, MHD, neutrinos, nuclear EOS, nuclear reactions
  - 3D estimates: Memory footprint: \(~10-100\) Terabytes
    Total # of floating point operations: \(~10^5\) Petaflops
  -> Approximations must be made!
3D Core-Collapse Supernova Simulations

• Some “early” work: Fryer & Warren ‘02, ‘04 (SPH)
• Lots of new work: Fernandez ’10, Nordhaus+11, Takiwaki+11, Burrows+12, Dolence+13 (Princeton), Hanke+12,13 (Garching), Kuroda+12 (Tokyo), Ott+13 (Caltech), Couch ‘13

• Approximations made:
  (1) **Gravity**: full GR (Ott+, Kuroda+) vs. 1D Newtonian.
  (2) **Neutrinos**: “light-bulb” (Princeton, Garching), “leakage” (Caltech), grey transport (Kuroda+), multi-group (Takiwaki+)
  (3) **Resolution**

• Some details of our work:
  • Open-source & based on Einstein Toolkit (einsteintoolkit.org)
  • **Full 3D GR** using BSSN system.
  • Neutrino leakage scheme, $\nu_e$, $\bar{\nu}_e$, $\nu_x$ with heating & deleptonization.
  • Multi-patch scheme with spherical outer, central Cartesian grid with AMR (Reisswig+13).
Results of 3D Simulations
(Warning: This is as of June 27, 2013 and is evolving quickly)

Does 3D help the explosion?

**Yes:**

Explosions start earlier in 3D

Nordhaus+10, Burrows+12, Dolence+13, Takiwaki+12
Results of 3D Simulations

(Warning: This is as of June 27, 2013 and is evolving quickly)

Does 3D help the explosion?

No:

Hanke+12,13 (Garching)
Couch 13 (Chicago)
3D simulations explode later than 2D ones.

Explanation(s)?

-> Hanke+12: Higher resolution makes it harder to explode in 3D.
Consequence of turbulent cascade? (answer not clear)
Results of 3D Simulations
(Warning: This is as of June 27, 2013 and is evolving quickly)

What does the SASI do in 3D?

• Absent / suppressed by convection or 3D effects?
  (Burrows+12, Murphy+12, Dolence+12)

• Present, but with different mode structure than in 2D, perhaps spiral mode?
  (Blondin&Mezzacappa 07, Iwakami+09, Fernandez 10, Hanke+13, Kuroda+13)

Motivation for Ott+ 13:

  2D simulation by B. Müller+12 of 27-M\textsubscript{Sun} progenitor star showing very strong SASI.

3D GR with neutrino leakage scheme

27-M$_{\text{Sun}}$ progenitor, shows strong SASI in 2D (Müller+12)

rendered by S. Drasco

Time since bounce: -6.18 ms

3D GR with neutrino leakage scheme

27-$M_{\text{Sun}}$ progenitor, shows strong SASI in 2D (Müller+12)

rendered by S. Drasco

-6.18 ms
**SASI in 3D?**

**Ott+13:**
- SASI present in 3D, but weaker than in 2D.
- 10 x smaller saturation amplitudes.
- Appears suppressed by convection in exploding models.

**BUT: Hanke+13:**
- Growth of spiral mode.
- ~3 x larger amplitudes than Ott+13.
- Comparable amplitudes to their 2D run (which disagrees with the B. Müller+12 simulation by the same group).

**Cause of the difference?**
- Resolution?
- Numerical scheme?
- Poor neutrino approx. in Ott+13?
- Magnitude of seed perturbations?
Summary of 3D Simulations

- Explosions developing with non-oscillatory, low-mode asymmetry and fine structure in shock front.

- Downside of current 3D models: Either underresolved or parameterized.

- Not yet clear if 3D key to robust neutrino-driven explosions. Increasing resolution in 3D appears to delay explosion (Hanke+’12).
Asymmetric explosions generic outcome in 3D (and even in 2D).

-> May explain pulsar kicks hydrodynamically. (Scheck+06, Nordhaus+10,12, Wongwathanarat+10,12)

But what about strong neutron star B-fields, extreme SNe and long GRBs?

-> possible key ingredient: rapid rotation
Rotating Core Collapse

see, e.g., Fryer & Heger ’02, Ott+ ’06, Thompson+ ’05, Burrows+ ’07, Cerda-Duran+ ’08, Ott+ ’08, Dessart+ ’08, ’12

- Core: x 1000 spin-up
- Differential rotation -> reservoir of free energy
Magnetorotational Explosions
e.g., Bisnovatyi-Kogan ‘70, Burrows+ ‘07, Dessart+ ’08, Takiwaki & Kotake ’11, Winteler+ ‘12

• **Rapid rotation:**
  \[ P_0 < 4-6 \text{ s} \rightarrow \text{millisecond PNS} \]
• PNS rotational energy:
  \[ \sim 10^5 \text{ erg} \]
• *Free energy of differential rotation.*
• Amplification of B fields up to equipartition: compression, winding, magnetorotational instability (MRI)
• **BUT:** MRI not resolved.
• Jet-driven outflows.
• Hypernova-scale explosion energies.
• Magnetar left behind.

VULCAN 2D R-MHD code, Livne+ ‘07, Burrows+ ‘07.
Probing the “Supernova Engine”
- Gravitational Waves
- Neutrinos
- EM waves (optical/UV/X/Gamma): secondary information, late-time probes of engine.

Red Supergiant Betelgeuse
D \sim 200 \text{ pc}

HST

Supernova “Central Engine”

800 million km

300 km
Neutrino Refresher

• **Emission**: Charged current & neutral current weak interactions.

\[ \nu_e, \nu_\mu, \nu_\tau \]

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

+ mixing

• **Detection**: (see Scholberg ‘12)

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

-> primary reaction in Water Cherenkov detectors Super-K & IceCube.

Other relevant interactions:

\[ \nu_x + e^- \rightarrow \nu_x + e^- \]

\[ \nu_e + (N, Z) \rightarrow (N - 1, Z + 1) + e^- \]

\[ \bar{\nu}_e + (N, Z) \rightarrow (N - 1, Z - 1) + e^+ \]

Water Cherenkov, liquid scintillator, liquid argon, lead detectors.

Most detectors will provide flux and spectral information.

Super-Kamiokande

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Core-Collapse Supernova Neutrinos

- Carry 99% of the energy: $\sim 300 \text{ B (3 x 10}^{53} \text{ erg)}$.
- Neutrinos and antineutrinos of ALL species:
  \[ \nu_e, \bar{\nu}_e \]
  
  \( ''\nu_\mu'' = ''\nu_x'' \)
  
  \[ = \{\nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau\} \]

- Emission at $\sim 1$-100 MeV:
  
  \[ e^- p \leftrightarrow \nu_e n \quad e^- e^+ \rightarrow \nu_i \bar{\nu}_i \]
  \[ e^+ n \leftrightarrow \bar{\nu}_e p \quad N N \rightarrow \nu_i \bar{\nu}_i \quad \gamma \rightarrow \nu_i \bar{\nu}_i \]

- 3 emission phases:
  1) neutronization burst
  2) accretion phase ($< 1$ s)
  3) cooling phase ($10+$ s)
Probing Stellar Structure with Pre-Explosion Neutrinos


• Neutrino signal in the pre-explosion phase is determined by (1) the accretion rate of the stellar envelope and (2) by the core temperature of the collapsing star.

Parameter encapsulating both (1) and (2):

\[ \xi_M = \left( \frac{M}{M_\odot} \right) \frac{R(M_{\text{bary}} = M) / 1000 \text{km}}{t = t_{\text{bounce}}} \]

“compactness parameter” measured at bounce. (O’Connor & Ott ‘11)
• Consider pre-explosion phase: clean, “collective oscillations” suppressed (?)  

\[ \xi_M = \frac{M / M_\odot}{R(\text{bary} = M) / 1000 \text{ km}} \bigg|_{t=t_{\text{bounce}}} \]
Probing Stellar Structure with Pre-Explosion Neutrinos


(SK: Super Kamiokande)

SK @ 10kpc
(no oscillations)

• Expected inverse beta decay events in Super-K using SNOwGLoBES (Scholberg ‘12).
  http://www.phy.duke.edu/~schol/snowglobes

\[ \xi_M = \frac{M/M_\odot}{R(M_{\text{bary}} = M)/1000 \text{km}} \bigg|_{t=t_{\text{bounce}}} \]
Progenitor Structure of SN 1987A

O’Connor & Ott ’13

Comparison with early phase of the observed SN 1987A neutrino signal.

-> Potential Conclusion: early explosion OR low-compactness progenitor core!

But: beware of small-number statistics!!

KII @ 51.4kpc
- 1987A

assumes
no oscillations

assumes $\nu_x \rightarrow \bar{\nu}_e$

and $\bar{\nu}_e \rightarrow \nu_x$

normal mass hierarchy
& large $\theta_{13}$

Cumulative $N_{IBD}$ hits

$t-t_{bounce}$ [ms]

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Gravitational Wave (GW) Refresher

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

  Quadrupole approximation

  \[
  h_{jk}^{TT}(t, \vec{x}) = \left[ \frac{2}{c^4} \frac{G}{|\vec{x}|} \, \ddot{\vec{x}}_j (t - \frac{|\vec{x}|}{c}) \right]^{TT} \frac{G}{c^4} \approx 10^{-49} \text{ s}^2 \text{ g}^{-1} \text{ cm}^{-1}
  \]

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

  -> must measure relative displacements of \(10^{-22}\)

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

  -> Advanced LIGO in 2015+, LIGO India (2020+), + international partners.

LIGO Livingston, Louisiana
The Advanced GW Detector Network: 2020+

Advanced LIGO
Hanford 2015+

Advanced LIGO
Livingston 2015+

Advanced Virgo 2015+

GEO 600 (operating)

LIGO India 2020+

KAGRA 2017+
Gravitational-Waves from Core-Collapse Supernovae

Recent reviews: Ott ‘09, Kotake ‘11, Fryer & New ‘11

Need:

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

accelerated aspherical (quadrupolar) mass-energy motions

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Candidate Emission Processes:

- Convection and SASI
- Rotating collapse & bounce
- Rotational 3D instabilities
- Black hole formation
- Pulsations of the protoneutron star
- Anisotropic neutrino emission
- Aspherical accelerated outflows
- Magnetic stresses
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GWs from Convection & SASI

Recent work: Kotake+ ‘09, ‘11, Murphy+’09, Yakunin+’10 E. Müller+’12, B.Müller+’13

• Prompt convection soon after bounce (Marek+ ‘09, Ott ‘09).
• Neutrino-driven convection & SASI (recent: Murphy+’09, Yakunin+10, Müller+12).
• Protoneutron star convection (e.g., Keil+ ’96, Müller+’04)

![Graph showing convection and SASI](image_url)

**Murphy+ ’09**, using simplified heating/cooling scheme.

Expect also: Correlations with neutrino signal. Lund+ ’10,’12, Marek+’09, Brandt+’11
Time-Frequency Analysis of GWs

Murphy, Ott, Burrows ’09, see also B. Müller+’13

Peak emission traces buoyancy frequency at proto-NS edge.

\[ f_p \sim \frac{\omega_{BV}}{2\pi} \]
New Results from General-Relativistic 3D Simulations


- Both polarizations: $h_+$ and $h_\times$.
- Prompt convection GWs: larger $|h|$ than 2D results of B. Müller+’13 -> sensitive to seed perturbations.
- Subsequent signal $\sim 1/5 \ |h| \ of \ 2D$ (3D: absence of large-scale SASI).

Figure 14. Left panel: Gravitational wave polarizations $h D$ and $h D$ (rescaled).
• Both polarizations: $h_+$ and $h_\times$.
• Prompt convection GWs: larger $|h|$ than 2D results of B. Müller+’13 -> sensitive to seed perturbations.
• Subsequent signal $\sim 1/5 \ |h| \ of \ 2D$ (3D: absence of large-scale SASI).
Ott+13
s27 simulation
rendered by S. Drasco
New Results from General-Relativistic 3D Simulations

\[ h_{\text{char}}(f) = \sqrt{\frac{2}{\pi^2}} \frac{G}{c^3} \frac{1}{D^2} \frac{dE_{\text{GW}}(f)}{df}, \]

\[ E_{\text{GW}} \gtrsim 4 \times 10^{-10} M_\odot c^2 \]
GWs from Rotating Collapse & Bounce

Recent work: Dimmelmeier+ ’08, Scheidegger+ ‘10, Ott+ ’12, Kuroda+ ‘13

Rapid rotation:
Oblate deformation of the inner core

• Most extensively studied
  GW emission in core collapse

• **Axisymmetric:** ONLY $h_+$

• Simplest GW emission process:
  **Rotation** + **Gravity** +
  **Stiffening of nuclear EOS.**

• Strong signals for rapid rotation
  (→ millisecond proto-NS).
GWs from Rotating Collapse & Bounce

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Correlated GW and Neutrino Signals: Rotation

Ott+‘12, PRD

-> Using simple neutrino “leakage” scheme.

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Correlated GW and Neutrino Signals: Rotation

Ott+‘12, PRD

-> Using simple neutrino "leakage" scheme <- results must be checked w/ transport.
What is going on?

Ott+ ‘12, PRD

\[ t - t_b = 0.25 \text{ ms} \]

s12WH07j4

\[ s \text{ [kB]} \]

\[ z \text{ [km]} \]

\[ x \text{ [km]} \]

\[ \Rightarrow \text{ prolate bounce of oblate core} \]

\[ \text{excites fundamental quadrupole oscillation mode.} \]
Movie by Steve Drasco (Grinnell/Caltech)
Can we observe this?

Ott+ ‘12, PRD

Gravitational Waves

\[ S(f) = \frac{1}{2\pi f} \left( \frac{P}{M} \right)^{3/2} \]

\[ h(f) = \frac{\sqrt{S(f)}}{\sqrt{f}} \]

\[ h_\text{char}(f) = \frac{1}{\sqrt{2\pi}} \left( \frac{f}{f_\text{char}} \right)^{-3/2} \]

\[ f_\text{char} = \frac{1}{2\pi M} \]

\[ E_{GW} \lesssim 10^{-8} M_\odot c^2 \]

Source at 10 kpc

-> Throughout Milky Way with aLIGO
Can we observe this? Neutrinos

Ott+ ‘12, PRD

\[ L_{\bar{\nu}_e} [B s^{-1}] \]

@1 kpc

\( t - t_{\text{bounce}} \text{ [ms]} \)

\~1 kpc with a megaton water-Cherenkov detector. IceCube limited by readout rate.
Summary

• Basics of core-collapse supernova theory on solid foundation; details to be worked out.

• Multi-D (3D?) neutrino mechanism best bet for blowing up ordinary massive stars. **Next:** Self-consistent 3D models.

• **The next galactic core-collapse supernova has already exploded.** (But its GWs/neutrinos/EM waves better not get here until 2015+ [-> advanced LIGO].)

• Gravitational waves and neutrinos probe the supernova engine and progenitor star properties.
Supplemental Slides
Perhaps: **Multi-D Stellar Evolution**

- All presently available presupernova stellar models are spherically symmetric with convection algorithms based on mixing-length theory.

- Late-stage oxygen burning very violent
  -> may lead to large-scale inhomogeneities in O/Si layer.

- Supernova evolution sensitive to local (and global) variations in the accretion rate
  -> potentially large effect, but presently ignored.

Arnett & Meakin 2011
Neutrino Signature of Convections/SASI

See: Ott+ ’08, Marek & Janka ‘09, Lund+ ’10, ‘12, Brandt +’11

- Neutrino signal can be used to probe supernova dynamics.
- Lund et al. ’10:
  IceCube can detect SASI for galactic event. Effect smaller in 3D simulations (Lund+12)
Gravitational Waves from BH Formation

Rotating Black Hole Formation

\[ E_{\text{GW}} \sim 10^{-7} M_\odot c^2 \]

Ott+ ’11, PRL
How Does the SASI work?

for details: see, e.g., Fernandez & Thompson ‘09ab, Foglizzo+ ‘06, ‘07, Scheck+ ‘08

Advective-acoustic cyle.

Fastest growing mode in linear analysis: $l = 1$

Non-linear saturation: sourcing of Kelvin-Helmholtz and Rayleigh-Taylor instability

SASI strongest if neutrino-driven convection absent, e.g., in idealized simulations w/o neutrino heating.
Interplay of SASI and v-driven Convection

for details: see, e.g., Fernandez & Thompson ‘09b, Foglizzo+ ‘06, ‘07, Scheck+ ‘08

• Turbulence may damp advective acoustic mode (Foglizzo+).
• Gain region: neutrino-driven convection – early growth may inhibit SASI.

\[
\chi \equiv \frac{\tau_{\text{adv}}}{\tau_{\text{buoy}}} \sim \frac{H\omega_{\text{buoy}}}{v}
\]

In CCSN context, neutrino-driven convection will have most unstable mode at l=5-8.

But: non-standard setting -> advection
Perturbations must grow to non-linear scale and become buoyant before advected out of unstable region.

\[
\chi \gtrsim 3
\]

required for small (< 1%) perturbation to grow before it is advected out.

Alternative: Larger perturbation!
Role of the Nuclear EOS and GR

Ott, O’Connor, & Dasgupta ’11, Marek et al. ‘09

\[ Q^+ \nu = \frac{X_n}{\lambda_0^a} \frac{L_{\nu e}}{4\pi r^2} \langle E_{\nu e}^2 \rangle \left\langle \frac{1}{F} \right\rangle + \frac{X_p}{\lambda_0^a} \frac{L_{\nu e}}{4\pi r^2} \langle E_{\nu e}^2 \rangle \left\langle \frac{1}{F} \right\rangle \]

• “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, \( K_0 = 180 \text{ MeV} \)

• Problem: Discovery of 2-M\( \odot \) neutron star (Demorest et al. ‘10)
  \textit{rules out many soft EOS}, including LS180.
Time: -1.49 ms
Nascent BH Spin and Mass Evolution

Ott+ 2011, PRL
Newtonian Radiation-MHD Simulations with VULCAN/2D

Magnetic field lines in Burrows, Dessart, Livne, Ott, Murphy ‘07.
Black Hole Formation:

- A protoneutron star always forms, but has a maximum mass! Exact value unknown, but $M_{\text{max}} > 2 M_{\odot}$ (J1614-2230, Demorest+’10)
- BH formation: (1) explosion fails, (2) fallback accretion [ (3) softening of nuclear equation of state ].
- What stars make black holes?
Strong equation of state dependence!

See also
Fischer+ '09, Sumiyoshi+ '08
How hard can it be to blow up a star?

Key parameter:

\[
\eta_\nu = \frac{Q_\nu^+}{L_{\nu_e} + L_{\bar{\nu}_e}} \quad \text{Heating Efficiency}
\]
How to Characterize Progenitor Stars

O’Connor & Ott 2011

Compactness Parameter

\[ \xi_M = \frac{M / M_\odot}{R(M_{\text{bary}} = M)/1000 \text{km}} \bigg|_{t=t_{\text{bounce}}} \]

here: use \( M = 2.5 M_\odot \) (typical mass scale for BH Formation)

Baseline set of simulations: no rotation, 4 equations of state, ~100 progenitor models.

-> compactness parameter + EOS completely control the dynamics.
What does it take to blow up a star?

O’Connor & Ott 2011

- Heating efficiency in multi-D simulations: 0.05 - 0.15
  [Marek & Janka ‘09, Ott et al. ’08]

![Diagram showing heating efficiency vs. compactness parameter](image)

Heating Efficiency

Explosion more difficult to achieve.
Mapping ZAMS Mass to Outcome

[O’Connor & Ott 2011]

What stars make black holes?

Large uncertainty at solar metallicity: **Physics of mass loss highly uncertain!**
Adding in Rotation: Testing Collapsar Progenitors

Dessart, O’Connor, Ott ’12, ApJ

Models of Woosley & Heger ‘06

Vast majority of long-GRB progenitors -> NS. BH-producing models have extreme spin -> magnetorotational explosion + NS?