Understanding Core-Collapse Supernovae with the Help of Gravitational Waves

[Ott, arxiv:0809.0695, CQG topical review]

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The Core-Collapse SN Scenario

- $M_{ZAMS} \geq 8 - 10 \, M_{\odot}$
- Nuclear fusion up to iron-group nuclei.
- Iron core: electron degenerate, Chandrasekhar-mass object; EOS: $P \approx K \rho^{4/3} + P_{\text{thermal}}$
- Effective Chandrasekhar mass: $M_{\text{Ch}} \approx 5.38 \, Y_e^2 \left[ 1 + \frac{s_e^2}{\pi k_B Y_e} \right] \, M_{\odot}$, 1.4 – 2 $M_{\odot}$.
- Onset of gravitational collapse when pushed over effective $M_{\text{Ch}}$: Photodissociation of nuclei and electron capture.
Collapse, Bounce & Explosion

- Collapse separates iron core into homologously ($v \propto r$) collapsing inner core and supersonically collapsing outer core.
- EOS stiffens at $\rho_{\text{nuc}}$: Inner core bounce, hydrodynamic bounce shock.
- Shock loses kinetic energy to dissociation + neutrino losses: -> Shock stalls.
- Shock revival and SN explosion or collapse to BH (collapsar/GRB?).
- What is the mechanism of shock revival?
The Essence of Core-Collapse Supernova Explosion Mechanisms

• Collapse to neutron star:
  \[ \sim 3 \times 10^{53} \text{ erg} = 300 \text{ Bethe [B] gravitational energy.} \]

• \[ \sim 10^{51} \text{ erg} = 1 \text{ B kinetic and internal energy of the ejecta.} \]
  (Extreme cases: \( 10^{52} \text{ erg}; \) “hypernova”)

• 99% of the energy is radiated as neutrinos over hundreds of seconds as the protoneutron star (PNS) cools.

Explosion mechanism must tap the gravitational energy reservoir and convert the necessary fraction into energy of the explosion.
45+ Years of Theory & Modeling

- **Bounce shock always stalls.** Direct hydrodynamic “prompt” mechanism fails.

- **Neutrino-driven mechanism:** Based on subtle imbalance between neutrino heating and cooling in postshock region.

Problem: Fails to explode garden-variety massive stars in spherical symmetry.

[Wilson 1985; Bethe & Wilson 1985]


Breaking of spherical symmetry is the key ingredient of the SN mechanism!
Standing Accretion Shock Instability

[e.g., Blondin et al. 2003, 2006; Foglizzo et al. 2006, Scheck et al. 2006, 2007, Burrows et al. 2006, 2007]

Advective-acoustic cycle drives shock instability.

Seen in simulations by all groups!
Rapid Rotation and Nonaxisymmetric Dynamics

3D GR simulation Ott 2006, rendition by R. Kähler, Zuse Institute, Berlin
Time = -0.50 ms  
Width = 50.00 km

PNS core oscillations, Burrows et al. 2006, 2007; Ott et al. 2006
Core-Collapse Supernova Timeline

- Energy reservoir: few \( \times 10^{53} \) erg (100 B)
- Explosion energy: \( \sim 1 \) B
- Time frame for explosion: \( \sim 0.3 \) – 1.5 s after bounce.
- BH formation at baryonic PNS mass \( \geq 1.8 \) – 2.5 \( M_{\text{SUN}} \).
- Aside: No direct BH formation in pop I/II stars!
Blowing up Massive Stars: Core-Collapse SN Mechanisms

Introduced by:

- **Neutrino Mechanism**

- **MHD-Jet Mechanism**

- **Acoustic Mechanism**
  - [proposed by Burrows et al. 2006, 2007; not (yet?) confirmed by other groups/codes]
MHD-driven Explosions


- **Rapid rotation**: $P_0 < 4$-$6$ s
  -> millisecond PNS
- PNS rotational energy: $\sim 10$ B
- Amplification of B fields up to equipartition:
  - compression
  - dynamos
  - magneto-rotational instability (MRI)
- Jet-driven outflows.
- MHD-driven explosion may be GRB precursor.
Acoustic Mechanism

[Burrows et al. 2006, 2007b/c]

- SASI-modulated supersonic accretion streams and SASI generated turbulence excite lowest-order (l=1) g-mode in the PNS. f \approx 300 \text{ Hz}.

- g-modes reach large amplitudes \sim 500 \text{ ms} \sim 1 \text{ s} after bounce.

- Damping by strong sound waves that steepen into shocks; deposit energy in the stalled shock.

- \sim 1 \text{ B} explosions at late times.

- (1) hard to simulate; unconfirmed,
  (2) possible parametric instability, limiting mode amplitudes.


Iso-Density Surfaces
Entropy Coloring
Time = -140.0 \text{ ms}
Radius = 6000.00 \text{ km}
Observing the Explosion Mechanism

Classical Observational Astronomy:
- Explosion morphology, lightcurve, energy, chemical composition.
- Progenitor type / mass.
- Pulsar kicks.
- Neutron star mass.

Secondary Observables
**Observing the Explosion Mechanism**

**Neutrino and Gravitational Wave Astronomy**

- Direct “live” information from the supernova engine.
- **GWs**: Directly linked to the ubiquitous multi-D dynamics in the postshock region and in the PNS.

**Primary Observables**
GW Emission Processes in Core-Collapse SNe

- Rotating core collapse and core bounce
- Dynamical rotational 3D instabilities
- Postbounce convection and SASI
- PNS core pulsations
- BH formation
- Anisotropic neutrino emission
- Aspherical outflows
- Magnetic stresses

Newtonian Quadrupole Formula:

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

Bursts with “Memory”
GW Emission Processes in Core-Collapse SNe

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[see Ott 2008 for a review]

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Bursts with “Memory”
Rotating Core Collapse and Bounce

- Collapse: Angular momentum conservation leads to spin up & rotational deformation of inner core.

- At core bounce: Very large accelerations -> rapidly changing mass quadrupole moment.

- Most extensively studied GW emission in core collapse:
  - Ruffini & Wheeler 1971
  - Thuan & Ostriker 1974
  - Saenz & Shapiro 1978-1981
  - Moncrief 1979
  - Mueller 1981
  - Detweiler & Lindblom 1981
  - Turner & Wagoner 1979
  - Seidel et al. late 1980s
  - Finn & Evans 1990
  - Moenchmeyer et al. 1991
  - Bonazzola & Marck 1993
  - Yamada & Sato 1995
  - Zwerger & Mueller 1997
  - Dimmelmeier et al. 2002
  - Ott et al. 2004
  - Shibata & Sekiguchi 2004
New Extended 2D GR Model Set

• >140 2D GR models with $Y_e(\rho)$. 6 pre-SN models.
• Slow to rapid rotation.
• Solid-body to moderately differential rotation.
• Shen and LS-EOS.

• GW signature of rotating collapse multi-degenerate.
• Key parameters:
  - Precollapse central $\Omega$.
  - Iron-core mass/entropy.

But note: ~99% of massive stars are slowly rotating!
PNS Spin and Rotational Instabilities

[Dimmelmeier et al. 2008, Ott et al. 2007, Ott et al. 2006]

- Classical picture: **High T/|W| instabilities.**
  
  Azimuthal modes $\propto \exp(\text{i}m\varphi)$. $m=2$ “bar-modes”
  
  $(T/|W|)_{\text{dynamical}} = 0.27$, $(T/|W|)_{\text{secular}} \approx 0.14$. [e.g., Chandrasekhar 1969]
  
  Numbers hold roughly in GR and moderate differential rotation. [e.g., Baiotti et al. 2007]
  
  ![Graphs showing the evolution of PNS spin and rotational instabilities over time](image)

[Shibata et al. 2000, 3+1 GR simulations]
PNS Spin and Rotational Instabilities

[Dimmelmeier, Ott et al. 2008 in preparation, Ott et al. 2007, Ott et al. 2006]

• Classical picture: **High \( T/|W| \) instabilities.**
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  Numbers hold roughly in GR and moderate differential rotation.
  [e.g., Baiotti et al. 2007]

• **Can a realistic PNSs reach such high \( T/|W| \)?**

  • Direct numerical simulation: No – Collapsing cores hit rotational barrier.

  • Critical \( T/|W| \) (secular/dynamical) attainable during PNS cooling.

  • Don’t forget MHD!
A Low-$T/|W|$ Rotational Instability

- Dynamical rotational instability at low $T/|W|$. 
- Dominant $m=1$ mode; $m=\{2,3\}$ modes mixed in (radial & temporal variation).
- Mechanism: 
  Corotation instability (?) 
  Resonance of unstable mode with background fluid at corotation point(s).
- Spiral density waves – relationship to accretion and galactic disks? SASI? 
  \(\rightarrow\) angular momentum transport.
- Note: PNS embedded in SN core and continuously accreting angular momentum. Cannot be described by an equilibrium NS model!
Equatorial Observer +

\[ h^e_+ = \frac{G}{c^4 \frac{D}{2}} (\tilde{\varepsilon}_{zz} - \tilde{\varepsilon}_{yy}) \]

Polar Observer +

\[ h^p_+ = \frac{G}{c^4 \frac{D}{2}} (\tilde{\varepsilon}_{xx} - \tilde{\varepsilon}_{yy}) \]

Equatorial Observer ×

\[ h^e_\times = -\frac{G}{c^4 \frac{D}{2}} \tilde{\varepsilon}_{yz} \]

Polar Observer ×

\[ h^p_\times = \frac{G}{c^4 \frac{D}{2}} \tilde{\varepsilon}_{xy} \]
• 3D component: lower in amplitude than core-bounce GW spike, but greater in energy! Emission in narrow frequency band around 900—930 Hz (~2 x pattern speed of the unstable mode!) models.
Switching Gears:

GWs emitted by Convection, SASI

(Most) Calculations performed with the axisymmetric Newtonian VULCAN/2D radiation-(magneto)hydrodynamics code.

[Livne et al. ‘93, ‘04, ‘07, Burrow et al. ‘06, ‘07abc, Dessart et al. ‘06,ab ’07, Ott et al. ‘06ab, ‘08]
• **Prompt postbounce convection.**
  - Sensitive to perturbations in precollapse core.

• **Neutrino-driven convection & SASI in postshock region.**
  - Sensitive to neutrino luminosity/spectrum, nuclear EOS, gravity, accretion rate, dimensionality (2D/3D).

• **Lepton-gradient driven convection inside the PNS.**

• SASI modifies/distorts convection, leads to enhanced accretion.

• **Turbulence/convection/SASI are “stochastic” sources of GWs; impossible to template.**

• **Positive specific angular momentum gradient damps convection.**
### Convection & SASI (cont’d)

![Graph showing gravitational wave amplitude](image)

**Limiting Factors or Processes**
- Seed perturbations, entropy/lepton gradient, rotation
- BH formation, strong PNS g-modes
- Rotation, explosion, BH formation

| Process     | Typical $|h|$ (at 10 kpc) | Typical $f$ (Hz) | Duration $\Delta t$ (ms) | $E_{GW}$ $(10^{-10} M_\odot c^2)$ | Limiting Factors or Processes |
|-------------|------------------------|------------------|--------------------------|----------------------------------|-------------------------------|
| Prompt      | $10^{-23} - 10^{-21}$  | 50 - 1000        | 0 - $\sim 30$           | $\lesssim 0.01 - 10$            | Seed perturbations, entropy/lepton gradient, rotation |
| Convection  | (Emission characteristics depend on seed perturbations.) |                  |                          |                                  |                               |
| PNS         | $2 - 5 \times 10^{-23}$ | 300 - 1500       | 500 - several 1000      | $\lesssim 1.3 \left( \frac{\Delta t}{1s} \right)$ | BH formation, strong PNS g-modes |
| Convection  |                       |                  |                          | $\gtrsim 0.01 \left( \frac{\Delta t}{100 ms} \right)$ |                               |
| Neutrino-driven | $10^{-23} - 10^{-22}$ (peaks up to $10^{-21}$) | 100 - 800        | 100 - $\gtrsim 1000$    | $\lesssim 15 \left( \frac{\Delta t}{100 ms} \right)$ | Rotation, explosion, BH formation |
| Convection and SASI |                        |                  |                          |                                  |                               |
Switching Gears again:

GWs emitted by Protoneutron Star g-Mode Pulsations

Calculations performed with the axisymmetric Newtonian VULCAN/2D radiation-(magneto)hydrodynamics code.

[Livne et al. ‘93, ‘04, ‘07, Burrow et al. ‘06, ‘07abc, Dessart et al. ‘06,ab ‘07, Ott et al. ‘06ab, ‘08]
GWs from PNS core g-modes:
The GW Signature of the Acoustic Mechanism

- Core bounce: prompt convection.
- Convection: PNS and v-driven.
- SASI
- g-modes: \( l=2 \) components emit GWs.
- But: g-modes may saturate at low level.

\[ \text{[Weinberg & Quatert 2008]} \]

\[ \text{[Ott 2008, Ott et al. 2006]} \]
GW Spectra and LIGO Sensitivity

- $E_{GW} \sim 10^{-8} - 10^{-6} \, M_{\text{SUN}} c^2$, one model $8 \times 10^{-5} \, M_{\text{SUN}} c^2$.
- Progenitor mass (= accretion rate) dependence.
Putting Things Together:

GWs as Indicators for the Core-Collapse Supernova Explosion Mechanism

Mechanism → GW Emission Process → Characteristic GW Signature
Blowing up Massive Stars: Core-Collapse SN Mechanisms

- Neutrino Mechanism
- MHD-Jet Mechanism
- Acoustic Mechanism
Blowing up Massive Stars: Core-Collapse SN Mechanisms

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Dominant GW Emission Processes

- Convection and SASI.
- Rotating core collapse & bounce, PNS rotational instabilities.
- PNS pulsations.
### GWs as Indicators for the SN Mechanism

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- Galactic SN necessary with LIGO I, Advanced LIGO: Local Group
- Caution: Explosion mechanisms may “mix”!
Switching Gears:

Observational Aspects
Core-Collapse Supernova Rates

- Local group of galaxies: $V \sim 30 \text{ Mpc}^3$
  - Milky Way, Andromeda (M31), Triangulum (M33) + $\sim 30$ small galaxies/satellite galaxies (incl. SMC & LMC).

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>Distance (kpc)</th>
<th>Core-Collapse SN Rate (100 yr)$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Milky Way</td>
<td>0–$\sim 15$</td>
<td>0.50–2.50</td>
</tr>
<tr>
<td>LMC</td>
<td>$\sim 50$</td>
<td>0.10 – 0.50</td>
</tr>
<tr>
<td>SMC</td>
<td>$\sim 60$</td>
<td>0.06 – 0.12</td>
</tr>
<tr>
<td>M31</td>
<td>$\sim 770$</td>
<td>0.20 – 1.20</td>
</tr>
<tr>
<td>M33</td>
<td>$\sim 840$</td>
<td>0.16 – 0.68</td>
</tr>
<tr>
<td>IC 10</td>
<td>$\sim 750$</td>
<td>0.05 – 0.11</td>
</tr>
<tr>
<td>IC 1613</td>
<td>$\sim 770$</td>
<td>$\sim 0.04$</td>
</tr>
<tr>
<td>NGC 6822</td>
<td>$\sim 520$</td>
<td>$\sim 0.04$</td>
</tr>
</tbody>
</table>

Compiled from long list of references, e.g. Cappellaro et al., den Bergh & Tammann.

- Local group: worst case 1 SN in 90 years, best case 1 SN in 20 years.
- Most local group events with $\sim 100$ kpc from Earth.
Nearby Core-Collapse Supernovae

Core-collapse SNe within 5 Mpc since the beginning of LIGO operations:

<table>
<thead>
<tr>
<th>SN</th>
<th>Host Galaxy</th>
<th>Date</th>
<th>Type</th>
<th>Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008bk</td>
<td>NGC 7793</td>
<td>20080325</td>
<td>II-P</td>
<td>$\sim 3.9$</td>
</tr>
<tr>
<td>2005af</td>
<td>NGC 4945</td>
<td>20050208</td>
<td>II-P</td>
<td>$\sim 3.6$</td>
</tr>
<tr>
<td>2004dj</td>
<td>NGC 2403</td>
<td>20040731</td>
<td>II-P</td>
<td>$\sim 3.3$</td>
</tr>
<tr>
<td>2004am</td>
<td>M 82</td>
<td>20040305</td>
<td>II-P</td>
<td>$\sim 3.5$</td>
</tr>
<tr>
<td>2002kg</td>
<td>NGC 2403</td>
<td>20021026</td>
<td>IIn</td>
<td>$\sim 3.3$</td>
</tr>
</tbody>
</table>

C. D. Ott @ CaJAGWR Nov 2008
SN 2008bk

- SN 2008bk (type IIp) discovered on 03/25/08. Core collapse between 02/15 and 03/05.
- LIGO L1 & H1 and VIRGO down for upgrades. LIGO H2 and GEO600 in Astrowatch mode.

<table>
<thead>
<tr>
<th>Process</th>
<th>Model</th>
<th>LIGO2 4 km</th>
<th>LIGO L1/H1</th>
<th>LIGO H2</th>
<th>GEO600</th>
<th>VIRGO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotating Collapse &amp; Bounce</td>
<td>s11A2O13 [20]</td>
<td>0.124</td>
<td>0.008</td>
<td>0.005</td>
<td>0.001</td>
<td>0.009</td>
</tr>
<tr>
<td></td>
<td>s20A2O09 [20]</td>
<td>0.130</td>
<td>0.008</td>
<td>0.006</td>
<td>&lt; 0.001</td>
<td>0.010</td>
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<tr>
<td></td>
<td>s40A3O12 [20]</td>
<td>0.214</td>
<td>0.024</td>
<td>0.013</td>
<td>&lt; 0.001</td>
<td>0.018</td>
</tr>
<tr>
<td>Rotational Instability</td>
<td>s20A2B4 [44, 52]</td>
<td>0.319</td>
<td>0.021</td>
<td>0.014</td>
<td>0.003</td>
<td>0.022</td>
</tr>
<tr>
<td></td>
<td>s20A2B4 (×5) [44, 52]</td>
<td>0.713</td>
<td>0.047</td>
<td>0.031</td>
<td>0.007</td>
<td>0.049</td>
</tr>
<tr>
<td>PNS g-modes</td>
<td>s11.2 [21]</td>
<td>0.147</td>
<td>0.006</td>
<td>0.005</td>
<td>0.002</td>
<td>0.009</td>
</tr>
<tr>
<td></td>
<td>s15.0 [21]</td>
<td>0.454</td>
<td>0.021</td>
<td>0.015</td>
<td>0.006</td>
<td>0.027</td>
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<tr>
<td></td>
<td>s25.0 [21]</td>
<td>0.612</td>
<td>0.029</td>
<td>0.020</td>
<td>0.007</td>
<td>0.037</td>
</tr>
<tr>
<td></td>
<td>s25.0 (×2) [21]</td>
<td>0.866</td>
<td>0.041</td>
<td>0.029</td>
<td>0.009</td>
<td>0.052</td>
</tr>
<tr>
<td></td>
<td>s25WW [22]</td>
<td>5.331</td>
<td>0.217</td>
<td>0.151</td>
<td>0.057</td>
<td>0.328</td>
</tr>
</tbody>
</table>

\[ S/N = \sqrt{\int_0^\infty d\ln f \frac{h_{\text{char}}^2}{h_{\text{rms}}^2}} \]

- Even LIGO 2 would have had trouble seeing a core-collapse SN at \( \sim 4 \) Mpc.

Thanks: Erik Katsavounidis & Michael Landry

[Ott 2008]
SNR Scaling: Rotating Collapse & Bounce

Rotating Core Collapse and Bounce

Optimal single-detector SNR vs Distance

- Advanced LIGO burst
- Initial LIGO L1/H1
- Initial LIGO H2, S5
- GEO 600

Distance units: kpc, Mpc

C. D. Ott @ CaJAGWR Nov 2008
SNR Scaling: PNS 3D Rotational Instabilities

Optimal single-detector SNR

Distance

Model s20A2B4
Ott et al. 2007, upper bound scaled by \( \sqrt{5} \) to account for longer durations.

- Adv. LIGO burst
- LIGO L1/H1
- LIGO H2, S5
- GEO 600

Protoneutron Star Rotational Instability

SN 2008bk
SN 1987A
SNR Scaling: Convection & SASI

Convection + SASI
Models of Ott 2008,
upper bound scaled by $\sqrt{5}$
to account for longer durations /
greater emission strengths
seen in Marek et al. 2008.
SNR Scaling: PNS Pulsations


Distance

Optimal single-detector SNR

- Adv. LIGO burst
- LIGO L1/H1
- LIGO H2, S5
- GEO 600
Summary and Remarks

• Multi-D core-collapse SN simulations are maturing -> 3 potential explosion mechanisms: ν, MHD, acoustic

• The GW signature of the 3 considered mechanisms is likely to be mutually exclusive.

• **Galactic core-collapse SN would allow to constrain SN mechanism.**

• Problem: Galactic SN rate: 1 in ~40 years.
  Local group: 2 in ~40 years.

  -> Need to go out to 3-5 Mpc where rate jumps to 1 in ~2 years.

  *Further problem: adv. LIGO not sufficiently sensitive:*

• **Need more adv. LIGO sensitivity between 500 and 1000 Hz.**

• Status of the modeling of GW emission processes:
  • Rotating collapse & bounce: getting robust
  • Convection, SASI: need detailed 3D models.
  • All other mechanisms: need more simulations to understand systematics and emission characteristics.
Supplemental Slides
Neutrino Mechanism


- Deposition of energy by neutrinos in gain region.
- Works in 1D for lowest-mass massive stars (ONeMg; \( \sim 8 \, M_{\text{SUN}} \)) [Kitaura et al. 2006, Burrows 1987, Burrows 2007c]
- Requires multi-D processes to work for more massive stars:
  - convection
  - standing accretion shock instability (SASI)
- May work best in nonrotating or slowly rotating stars.
  (\(<\) rapid rotation damps convection & modifies SASI)

[Model run with VULCAN/2D, MGFLD and angle-dependent neutrino transport! Ott et al. 2008]
Rotating Collapse and Bounce


- First 2D/3D GR simulations with hot microphysical EOS & deleptonization during collapse.
- GW signature determined by inner core mass, inner core angular momentum, and (to some extent) nuclear EOS.
- GW signal of generic shape; no “multiple centrifugal bounce”.
- GWs from “quickly” spinning cores (precollapse $P_0 < \sim 8$ s) “detectable” throughout the Milky Way.
- Important finding: Cores stay axisymmetric through bounce and early postbounce phase.
GWs from Anisotropic Neutrino Emission


- Any accelerated mass-energy quadrupole will emit GWs. Anisotropic neutrino radiation:

\[ h^{TT}_{+e}(t) = \frac{2G}{c^4D} \int_{-\infty}^{t-D/c} \alpha(t')L_{\nu}(t') dt' \]

\[ \alpha(t) = \frac{1}{L_{\nu}(t)} \int_{4\pi} \psi(\vartheta', \varphi') \frac{dL_{\nu}(\vec{\Omega}', t)}{d\Omega'} d\Omega' \]

- GW “Memory”

- Anisotropic neutrino emission in core-collapse SNe:
  - Convective overturn: small-scale variations.
  - Rapid rotation: large-scale anisotropy.
  - Large-scale asymmetries: large-scale anisotropy.
• Neutrino component dominates in amplitude, but not in energy.
• Rotation yields largest possible anisotropy!
GWs from Aspherical Outflows


• Precollapse inhomogeneities in nuclear silicon/oxygen burning may be large, leading to density perturbations O(10%). [Bazan & Arnett ’97, Meakin et al. ’06].

• May result in asymmetric explosions (→ pulsar recoils) and emission of GW burst (with memory!) from mass motions and neutrinos.

• Somewhat unexplored: Only 2 studies; most stellar evolution is done in 1D. Would need large parameter study.

• Aspherical outflows also in jet-driven explosions: See Kei Kotake’s talk!
Remarks on the Mechanisms

- **Neutrino Mechanism:**
  - Needs convection & SASI, so far shown to work only with (too) soft EOS.
  - May not work with: rapid rotation, stiffer EOS.

- **MHD Mechanism:**
  - Requires very rapid rotation \( P_0 < \sim 4 \text{ s} \), but most iron cores may be rotating with \( P_0 > 30 \text{ s} \).
  - Precollapse magnetization probably very weak. -> Mechanism depends on efficiency of dynamical magneto-rotational instabilities / dynamos.

- **Acoustic Mechanism:**
  - Proposed by Burrows et al.
    Independent confirmation difficult: Requires singularity-free numerical grid.
  - Explosions occur late \( t > 1 \text{ s} \) and are often under-energetic.
  - May not work with rapid rotation.
  - Arguments for mode saturation at low powers [Weinberg & Quatert 2008].
Newtonion & simple GR models


• 2 general type of dynamics, waveform morphology
• Type I: Pressure-dominated bounce.
• Type II: Rotation dominated, centrifugal bounce.
Core-Collapse Supernova Simulations with the VULCAN/2D Code


• 2.5D (axisymmetric) Newtonian (magneto-)hydrodynamics.
• Unsplit arbitrary Eulerian/Lagrangian scheme.
• Newtonian Self gravity.
• Neutrino Radiation Transport:
  – 2 versions: Flux-limited diffusion & Boltzmann transport.
  – Multiple energy groups, $\nu_e$, $\bar{\nu}_e$, “$\nu_\mu$” species.
Testing the Acoustic Mechanism

- So far no independent confirmation of the acoustic mechanism.
- However: unstable physical g-modes PNS shown to exist.
- Key questions:
  - Do g-mode reach amplitudes as high as seen in our calculations?
  - Can the neutrino mechanism be made to work generically?
  - Effects of GR and 3D?
- Fundamental prerequisite for non-linear numerical tests of g-mode excitation: Grid must be singularity free & allow change of the inner core’s geometric center.

[Ferrari et al. 2003, 2007; Yoshida et al. 2007]
[e.g., Ferrari et al. 2007; Burrows et al. in preparation]
11 solar-mass model, Burrows et al. 2006. Acoustic Mechanism works, but takes a long time!
MHD jet/explosion launched when $P_{\text{mag}} / P_{\text{gas}} \sim 1$
• Dominant $m=1$ mode; $m=\{2,3\}$ mixed in.
• GW emission from quadrupole components. “bar-like” emission.
• Growth time $8—10\ \tau_{\text{dyn}}$. 
Corotation?
PNS Rotational Configuration

[Ott et al. 2006b, Ott 2006 PhD Thesis]
Iron Core – PNS Spin Mapping

- Fastest young pulsar: $P \sim 16$ ms [Marschall et al. 1998].
- Most pre-collapse iron cores probably have $P > \sim 30$ s.