Unravelling the Explosion Mechanism of Massive Stars — Supernova Models Confronting Observations

Hans-Thomas Janka
Max Planck Institute for Astrophysics, Garching
SN-remnant Cassiopeia A

X-ray (CHANDRA, green-blue); optical (HST, yellow); IR (SST, red)
Outline

• Introduction: The neutrino-driven explosion mechanism

• Status of self-consistent models in two dimensions

• The question of dimensions: How does 3D differ from 2D?

• Observational consequences of neutrino-driven explosions
Stellar Core Collapse and Explosion
Stellar Collapse and Supernova Stages

Progenitor (~ 15 $M_\odot$) (Lifetime: 1 ~ 2 $\cdot 10^7$ y)

$\sim 10^{13}$ cm

Late Protoneutron Star
($R \sim 20$ km)

$10^6$ cm

~0.1–1 Sec.

~1 Sec.

Collapse of Core (~1.5 $M_\odot$)

30,000 – 60,000 km/s
($R \sim 10,000$ km)

 adapted from A. Burrows (1990)
Evolved massive star prior to its collapse:

Star develops onion-shell structure in sequence of nuclear burning stages over millions of years.
Evolved massive star prior to its collapse:

Star develops onion-shell structure in sequence of nuclear burning stages over millions of years.
Gravitational instability of the stellar core:

Stellar iron core begins collapse when it reaches a mass near the critical Chandrasekhar mass limit.

Collapse becomes dynamical because of electron captures and photo-disintegration of Fe-group nuclei.
Core bounce at nuclear density:

Inner core bounces when nuclear matter density is reached and incompressibility increases

Shock wave forms

Shock wave

Proto-neutron star
Shock stagnation:

Shock wave loses huge amounts of energy by photodisintegration of Fe-group nuclei.

Shock stagnates still inside Fe-core

Proto-neutron star

Accretion

Fe

n, p

Si
Shock “revival”:

Stalled shock wave must receive energy to start reexpansion against ram pressure of infalling stellar core.

Shock can receive fresh energy from neutrinos!

Shock wave

Proto-neutron star
Explosion:

Shock wave expands into outer stellar layers, heats and ejects them.

Creation of radioactive nickel in shock-heated Si-layer.
Nucleosynthesis during the explosion:

Shock-heated and neutrino-heated outflows are sites for element formation.

Shock wave

Neutrino-driven “wind”
Explosion Mechanism
by
Neutrino Heating
**Neutrinos & SN Explosion Mechanism**

**Paradigm:** Explosions by the neutrino-heating mechanism, supported by hydrodynamic instabilities in the postshock layer.

- **“Neutrino-heating mechanism”:** Neutrinos `revive' stalled shock by energy deposition (Colgate & White 1966, Wilson 1982, Bethe & Wilson 1985);
1D-2D Differences in Parametric Explosion Models

- Nordhaus et al. (ApJ 720 (2010) 694) and Murphy & Burrows (2008) performed 1D & 2D simulations with simple neutrino-heating and cooling terms (no neutrino transport but lightbulb) and found up to ~30% improvement in 2D for 15 $M_{\odot}$ progenitor star.

\[
\mathcal{H} = 1.544 \times 10^{20} \left( \frac{L_{\nu_e}}{10^{52} \text{ erg s}^{-1}} \right) \left( \frac{T_{\nu_e}}{4 \text{ MeV}} \right)^2 \\
\times \left( \frac{100 \text{ km}}{r} \right)^2 (Y_n + Y_p) e^{-\tau_{\nu_e}} \left[ \frac{\text{erg}}{\text{g s}} \right]
\]

\[
\mathcal{C} = 1.399 \times 10^{20} \left( \frac{T}{2 \text{ MeV}} \right)^6 (Y_n + Y_p) e^{-\tau_{\nu_e}} \left[ \frac{\text{erg}}{\text{g s}} \right]
\]
But: Is neutrino heating strong enough to initiate the explosion against the ram pressure of the collapsing stellar shells?

Most sophisticated, self-consistent numerical simulations of the explosion mechanism in 2D and 3D are necessary!
Predictions of Signals from SN Core

hydrodynamics of stellar plasma
(nuclear) EoS
neutrino physics
Relativistic gravity
progenitor conditions

SN explosion models

neutrinos
LC, spectra
nucleosynthesis
explosion asymmetries, pulsar kicks

gravitational waves
explosion energies, remnant masses
GR hydrodynamics (CoCoNuT)

CFC metric equations

\[
\frac{\partial\sqrt{\gamma}pW_{j}}{\partial t} + \frac{\partial\sqrt{-g}(pW^{2}v_{j}v^{i}_{i} + \delta_{j}^{i}P)}{\partial x^{i}} = \frac{1}{2}\sqrt{-g}T^{\mu\nu}\frac{\partial g_{\mu\nu}}{\partial x^{j}} + \left(\frac{\partial\sqrt{\gamma}S_{j}}{\partial t}\right)_{c},
\]

\[
\frac{\partial\sqrt{\gamma}r_{e}}{\partial t} + \frac{\partial\sqrt{-g}(r_{e}v_{i} + P_{i})}{\partial x^{i}} = \alpha\sqrt{-g}\left(T^{\mu\nu}\frac{\partial\ln\alpha}{\partial x^{\mu}} - T^{\mu\nu}T^{0}_{\mu\nu}\right) + \left(\frac{\partial\sqrt{\gamma}r_{e}}{\partial t}\right)_{c},
\]

\[
\frac{\partial\sqrt{\gamma}W_{Y_{e}}}{\partial t} + \frac{\partial\sqrt{-g}pW_{Y_{e}}v_{i}}{\partial x^{i}} = \left(\frac{\partial\sqrt{\gamma}r_{Y_{e}}}{\partial t}\right)_{c},
\]

\[
\frac{\partial\sqrt{\gamma}W_{X_{k}}}{\partial t} + \frac{\partial\sqrt{-g}pW_{X_{k}}v_{i}}{\partial x^{i}} = 0.
\]

\[
\Delta \Phi = -2\pi\phi^{5}\left(E + \frac{K_{ij}K^{ij}}{16\pi}\right),
\]

\[
\Delta(\alpha\Phi) = 2\pi\alpha\phi^{5}\left(E + 2S + \frac{7K_{ij}K^{ij}}{16\pi}\right),
\]

\[
\hat{\Delta} \beta^{i} = 16\pi\alpha\phi^{4}S^{i} + 2\phi^{10}K^{ij}\hat{\nabla}_{j}\left(\frac{\alpha}{\Phi^{6}}\right) - \frac{1}{3}\hat{\nabla}^{i}\hat{\nabla}_{j}\beta^{j},
\]

Neutrino transport (VERTEX)

\[
\frac{\partial W}{\partial t} + \frac{\partial}{\partial r}\left[\left(W_{r} - \beta_{r}v_{r}\right)\hat{H} + \left(W_{\phi} - \beta_{\phi}\right)\hat{H}\right] = -2\pi\phi^{5}\left(E + \frac{K_{ij}K^{ij}}{16\pi}\right),
\]

\[
\frac{\partial W}{\partial t} + \frac{\partial}{\partial r}\left[\left(W_{r} - \beta_{r}v_{r}\right)\hat{H} + \left(W_{\phi} - \beta_{\phi}\right)\hat{H}\right] = -2\pi\phi^{5}\left(E + \frac{K_{ij}K^{ij}}{16\pi}\right),
\]

General-Relativistic 2D Supernova Models of the Garching Group

# Neutrino Reactions in Supernovae

## Beta processes:
- \( e^- + p \rightleftharpoons n + \nu_e \)
- \( e^+ + n \rightleftharpoons p + \bar{\nu}_e \)
- \( e^- + A \rightleftharpoons \nu_e + A^* \)

## Neutrino scattering:
- \( \nu + n, p \rightleftharpoons \nu + n, p \)
- \( \nu + A \rightleftharpoons \nu + A \)
- \( \nu + e^\pm \rightleftharpoons \nu + e^\pm \)

## Thermal pair processes:
- \( N + N \rightleftharpoons N + N + \nu + \bar{\nu} \)
- \( e^+ + e^- \rightleftharpoons \nu + \bar{\nu} \)

## Neutrino-neutrino reactions:
- \( \nu_x + \nu_e, \bar{\nu}_e \rightleftharpoons \nu_x + \nu_e, \bar{\nu}_e \)
  \( (\nu_x = \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \text{or } \bar{\nu}_\tau) \)
- \( \nu_e + \bar{\nu}_e \rightleftharpoons \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau} \)
The Curse and Challenge of the Dimensions

Boltzmann equation determines neutrino distribution function in 6D phase space and time

\[ f(r, \theta, \phi, \Theta, \Phi, \epsilon, t) \]

Integration over 3D momentum space yields source terms for hydrodynamics

\[ Q(r, \theta, \phi, t), \dot{Y}_e(r, \theta, \phi, t) \]

Solution approach

- **3D hydro + 6D** direct discretization of Boltzmann Eq. (code development by Sumiyoshi & Yamada '12)
- **3D hydro + two-moment** closure of Boltzmann Eq. (next feasible step to full 3D; O. Just et al. 2013)
- **3D hydro + "ray-by-ray-plus"** variable Eddington factor method (method used at MPA/Garching)
- **2D hydro + "ray-by-ray-plus"** variable Eddington factor method (method used at MPA/Garching)

Required resources

- \( \geq 10–100 \) PFlops/s (sustained!)
- \( \geq 1–10 \) Pflops/s, TBytes
- \( \geq 0.1–1 \) PFlops/s, Tbytes
- \( \geq 0.1–1 \) Tflops/s, < 1 TByte
"Ray-by-Ray" Approximation for Neutrino Transport in 2D and 3D Geometry

Classic variable Eddington factor method (e.g. Mihalas & Mihalas 1984)

▷ use angular moments

\[ f(x, y, z, \theta, \phi, \epsilon, t) \leftrightarrow J, H, K, L(x, y, z, \epsilon, t) \]

to tame integro-differential character of Boltzmann equation (BE):

\[ \partial_t f + n \nabla_r f = \mathcal{F}(f, \int f \, d\theta d\phi) \]

≈ infinite system of moment equations (ME):

(0) \[ \partial_t J + \nabla \cdot H = \mathcal{F}^{(0)}(J, H) \]

(1) \[ \partial_t H + \nabla \cdot K = \mathcal{F}^{(1)}(J, H, K) \]

(2) \[ \partial_t K + \ldots \]

\ldots

≈ closure required: formal solution (efficient solution of Boltzmann equation if angular moments are known)

▷ variable Eddington factor:

\[ f_{\text{edd}}(x, y, z, \epsilon, t) = \frac{K}{J} \quad (0 \leq f_{\text{edd}} \leq 1) \]

▷ iteration of moment equations (0: energy), and (1: flux) with \( f_{\text{edd}} \)

▷ "exact" method
Structure of Jacobian

▷ Size of block-pentadiagonal matrix $\approx 60000^2$
  - $2 \times N_r \sim 1000$ rows of blocks
  - size of blocks: $(2 \ldots 4) \times N_\epsilon \sim 60$

Spherical symmetry of stellar gas:

▷ $f(x, y, z, \theta, \phi, \epsilon, t) \equiv f(r, \theta, \epsilon, t)$
  - $J \equiv J(r, \epsilon, t), H \equiv H(r, \epsilon, t)$

Moment equations

(0) $\partial_t J + \nabla \cdot H = \mathcal{F}^{(0)}(J, H)$

(1) $\partial_t H + \nabla \cdot (f_{edd} \cdot J) = \mathcal{F}^{(1)}(J, H)$

▷ System of moment equations is hyperbolic for “reasonable” $f_{edd}$
▷ Discretize MEs with implicit time differencing (e.g. backward Euler)
  - Newton-Raphson iteration, requires solution of linear system
"Ray-by-Ray" Approximation for Neutrino Transport in 2D and 3D Geometry

"Ray-by-ray-plus" approximation

▷ use spherical coordinates $(r, \vartheta, \varphi)$ in space
▷ solve $N_\vartheta \cdot N_\varphi$ independent "1D" transport problems of size $N_r \cdot N_\varepsilon$
▷ suggests efficient parallelization over $N_\vartheta, N_\varphi$ ("ray-by-ray")
▷ treat lateral coupling (e.g. $\partial_\vartheta H$, $\partial_\varphi H$) in operator-splitting step ("plus")
▷ lateral coupling (advection, radiation pressure) was found to be essential for physical consistency!
▷ advantage: 1D code already contains most of the algorithmic and numerical complexity (and expertise)

Parallelization strategy

▷ 1-to-1 mapping of rays to cores (resp. MPI-tasks or OpenMP threads)

≈ weak and strong scalability up to $N_\vartheta \cdot N_\varphi$ cores ($1^\circ$-resolution: $180 \cdot 360 = 64,800$ cores)
  + minor communication, nearly ideal scalability, simplicity of code
  - no strong scaling beyond $N_\vartheta \cdot N_\varphi$ cores, topology with multi-core nodes cannot be fully exploited, limited by memory per core resp. thread (BG/Q ?)
"Ray-by-Ray" Approximation for Neutrino Transport in 2D and 3D Geometry

Solve large number of spherical transport problems on radial “rays” associated with angular zones of polar coordinate grid

Suggests efficient parallelization over the “rays”
Axis-Free "Yin-Yang" Grid for 3D Simulations

(Wongwathanarat, Hammer, Müller, Astron. & Astrophysics 514, A48 (2010);
implemented in P-V by Tobias Melson, Diploma Thesis)
Explosion Mechanism: Most Sophisticated Current Models
Explosions of $M_{\text{star}} \sim 8-10 \, M_{\text{sun}}$ Stars
SN Progenitors: Core density profiles

~8–10 $M_{\text{sun}}$ (super-AGB) stars have ONeMg cores with a very steep density gradient at the surface

(====> rapidly decreasing mass accretion rate after core bounce)

>10 $M_{\text{sun}}$ stars have much higher densities outside of their Fe cores

(e.g. Heger et al., Limongi et al., Nomoto et al., Hirschi et al.)

(====> ram pressure of accreted mass decreases slowly after core bounce)

8.8 $M_{\text{sun}}$ progenitor model (Nomoto 1984):
2.2 $M_{\text{sun}}$ H+He, 1.38 $M_{\text{sun}}$ C+O, 1.28 $M_{\text{sun}}$ ONeMg
at the onset of core collapse

~30% of all SNe (Nomoto et al. 1981, 84, 87)

8.75 $M_{\text{sun}} < M_{\text{ZAMS}} < 9.25 M_{\text{sun}}$: < 20% of all SNe;
(Poelarends et al., A&A 2006), but mass range much larger at metallicities less than solar (Langer et al.)
SN Simulations: \( M_{\text{star}} \sim 8...10 \ M_{\odot} \)

"Electron-capture supernovae" or "ONeMg core supernovae"

- No prompt explosion!
- Mass ejection by “neutrino-driven wind” (like Mayle & Wilson 1988 and similar to AIC of WDs; see Woosley & Baron 1992, Fryer et al. 1999; Dessart et al. 2006)
- Explosion develops in similar way for soft nuclear EoS (i.e. compact PNS) and stiff EoS (less compact PNS)

Convection is not necessary for launching explosion but occurs in NS and in neutrino-heating layer.
2D SN Simulations: \( M_{\text{star}} \approx 8...10 \, M_{\text{sun}} \)
CRAB Nebula with pulsar, remnant of Supernova 1054

**Explosion properties:**

\[ E_{\text{exp}} \sim 10^{50} \text{ erg} = 0.1 \text{ bethe} \]
\[ M_{\text{Ni}} \sim 0.003 \text{ M}_{\odot} \]

Low explosion energy and ejecta composition (little Ni, C, O) of ONeMg core explosion are compatible with **CRAB (SN1054)**


Might also explain other low-luminosity supernovae (e.g. SN1997D, 2008S, 2008HA)
Explosions of Stars with $M_{\text{star}} > 10 M_{\text{sun}}$
Relativistic 2D CCSN Explosion Models


Basic confirmation of previous explosion models for 11.2 and 15 M\(_\text{Sun}\) stars by Marek & THJ (2009)
Violent, quasi-periodic, large-amplitude shock oscillations (by SASI) can lead to runaway and onset of explosion.

They also produce variations of neutrino emission and gravitational-wave signal.
**SASI: Standing Accretion Shock Instability**

Nonradial, oscillatory shock-deformation modes (mainly $l = 1, 2$) caused by an amplifying cycle of advective-acoustic perturbations.


\[ A \equiv r \text{div}(v_\theta e_\theta) \]

Fig. 1. Schematic view of the advective-acoustic cycle between the shock at $R_s$ (thick solid line) and the coupling radius, $R_c$ (thick dashed line), in the linear regime, shown for the case where the oscillation period of the shock ($\tau_{aac}$) equals the cycle duration, $\tau_{aac}$. Flow lines carrying vorticity perturbations downwards are drawn as solid lines, and the pressure feedback corresponds to dotted lines with arrows. In the gray shaded area around $R_c$ the flow is decelerated strongly.

\[ \tau_{aac} \equiv \int_{R_V}^{R_{sh}} \frac{dr}{|v|} + \int_{R_V}^{R_{sh}} \frac{dr}{c - |v|} \]

2D SN Explosion Models

- Basic confirmation of the neutrino-driven mechanism
- Confirmation of reduction of the critical neutrino luminosity for explosions in self-consistent 2D treatments compared to 1D

Explosions in 2D simulations were also obtained recently by Suwa et al. (2010, 2012), Takiwaki et al. (2013) and Bruenn et al. (ApJL, 2013).
BUT: There are important quantitative differences between all models.

Many numerical aspects, in particular also neutrino transport treatment, are different; code comparisons are needed!
2D explosions seem to be “marginal”, at least for some progenitor models and in some of the most sophisticated simulations.

Nature is three dimensional, but 2D models impose the constraint of axisymmetry (→ toroidal structures).

Turbulent cascade in 3D transports energy from large to small scales, which is opposite to 2D.

Does SASI also occur in 3D?

3D models are needed to confirm explosion mechanism suggested by 2D simulations!
2D vs. 3D Morphology

(Images from Markus Rampp, RZG)
Computing Requirements for 2D & 3D Supernova Modeling

Time-dependent simulations: \( t \sim 1 \text{ second}, \sim 10^6 \text{ time steps!} \)

CPU-time requirements for one model run:

- In 2D with 600 radial zones, 1 degree lateral resolution:
  \( \sim 3 \times 10^{18} \text{ Flops}, \text{ need } \sim 10^6 \text{ processor-core hours.} \)

- In 3D with 600 radial zones, 1.5 degrees angular resolution:
  \( \sim 3 \times 10^{20} \text{ Flops}, \text{ need } \sim 10^8 \text{ processor-core hours.} \)
3D Supernova Simulations

EU PRACE and GAUSS Centre grants of ~360 million core hours allow us to do the first 3D simulations on 16,000 cores.
Performance and Portability of our Supernova Code *Prometheus-Vertex*

- Code employs hybrid MPI/OpenMP programming model (collaborative development with Katharina Benkert, HLRS).
- Code has been ported to different computer platforms by Andreas Marek, High Level Application Support, Rechenzentrum Garching (RZG).
- Code shows excellent parallel efficiency, which will be fully exploited in 3D.
Performance and Portability of our Supernova Code *Prometheus-Vertex*

- Floating-point performance within roof-line model.
  - P-V achieves ~12% of peak performance for double precision calculations on 8-core node with two Intel Xeon E5540 “Nehalem” CPUs (2.53 GHz).
- Around 10% of peak performance obtained also on other platforms.
- Good performance for complex scientific application with non-trivial instruction mix.
- Further optimization by reducing number of memory references.

![Diagram showing performance and arithmetic intensity](image-url)
3D Core-Collapse Models

**27 M\(_{\odot}\) progenitor (WHW 2002)**

27 M\(_{\odot}\) SN model with neutrino transport develops **spiral SASI** as seen in idealized, adiabatic simulations by Blondin & Mezzacappa (Nature 2007)

3D Core-Collapse Models

27 \( M_{\text{Sun}} \) progenitor (WHW 2002): Spiral mode axis
3D Core-Collapse Models

27 Msun progenitor (WHW 2002)

F. Hanke et al., arXiv:1303.6269
"SWASI" Instability as an analogue of SASI in the supernova core
Foglizzo et al., PRL 108 (2012) 051103
3D Explosions?
Nordhaus et al. (ApJ 720 (2010) 694) performed 2D & 3D simulations with simple neutrino-heating and cooling terms (no neutrino transport but lightbulb) and found 15–25% improvement in 3D for 15 $M_{\odot}$ progenitor star.

\[
\mathcal{H} = 1.544 \times 10^{20} \left( \frac{L_{\nu_e}}{10^{52} \text{ erg s}^{-1}} \right) \left( \frac{T_{\nu_e}}{4 \text{ MeV}} \right)^2 \times \left( \frac{100 \text{ km}}{r} \right)^2 (Y_n + Y_p) e^{-\tau_{\nu_e}} \left[ \frac{\text{erg}}{\text{g s}} \right] \\
C = 1.399 \times 10^{20} \left( \frac{T}{2 \text{ MeV}} \right)^6 (Y_n + Y_p) e^{-\tau_{\nu_e}} \left[ \frac{\text{erg}}{\text{g s}} \right]
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\]

3D SNCC Models with Neutrino Transport

27 $M_{\text{Sun}}$ progenitor (WHW 2002)

Shock position (max., min., avg.)

Neutrino luminosities

Florian Hanke, PhD project
3D SNCC Models with Neutrino Transport

11.2 M$_{\text{Sun}}$ progenitor (WHW 2002)

Florian Hanke,
PhD project

Shock position (max., min., avg.)

Neutrino luminosities

Time scale ratio

Florian Hanke,
PhD project
3D SNCC Models with Neutrino Transport

20 M\(_{\text{Sun}}\) progenitor (WH 2007)

Shock position
(max., min., avg.)

Neutrino luminosities

Florian Hanke,
PhD project
2D models with relativistic effects (2D GR and approximate GR) yield explosions for “soft” EoSs, but explosion energy may tend to be low. Considerable quantitative differences compared to Bruenn et al. (ApJL 2013) demand detailed comparison.

3D modeling has only begun. No clear picture of 3D effects yet. But SASI can dominate (certain phases) also in 3D models!

3D models do not yet show explosions, but still need higher resolution for convergence.

Progenitors are 1D, but shell structure and initial progenitor-core asymmetries can affect onset of explosion (cf. Couch & Ott, arXiv:1309.2632)! How important is slow rotation for SASI growth?

Missing physics ??????
Numerical Convergence?

Figure 16. Turbulent energy spectra $E(l)$ as functions of the multipole order $l$ for different angular resolution. The spectra are based on a decomposition of the azimuthal velocity $v_\phi$ into spherical harmonics at radius $r = 150$ km and 400 ms post-bounce time for $15 M_\odot$ runs with an electron–neutrino luminosity of $L_{\nu_e} = 2.2 \times 10^{52}$ erg s$^{-1}$. Left: 2D models with different angular resolution (black, different thickness) and, for comparison, the 3D model with the highest employed angular resolution (gray). Right: 3D models with different angular resolution and, for comparison, the 2D model with the highest employed angular resolution (gray). The power-law dependence and direction of the energy and enstrophy cascades (see the text) are indicated by red lines and labels for 2D models in the left panel and 3D models in the right panel. The left vertical, dotted line roughly marks the energy-injection scale, and the right vertical, dotted line denotes the onset of dissipation at high $l$ for the best-displayed resolution.

Turbulent energy cascade in 2D from small to large scales, in 3D from large to small scales! =====> More than 2 degree resolution needed in 3D!
Some Observable Consequences of Neutrino-driven Explosions
Observational consequences and indirect evidence for neutrino heating and hydrodynamic instabilities at the onset of stellar explosions:

- Neutrino signals (characteristic modulations)

- Gravitational-wave signals

- Neutron star kicks
  (Scheck et al. 2004, 2006; Wongwathanat et al. 2010, 2012)

- Asymmetric mass ejection & large-scale radial mixing
  (Kifonidis et al. 2005, Hammer er al. 2010, Wongwathanat et al., in prep.)

- Progenitor – explosion – remnant connection
  (Ugliano et al. 2012)

- Lightcurve shape, spectral features (electromagnetic emission)

- Nucleosynthesis
  (e.g., Pruet et al. 2006, Wanajo et al. 2011, 2013)
Detecting Core-Collapse SN Signals

Superkamiokande

IceCube

VIRGO
3D Core-Collapse Models: Neutrino Signals

11.2, 20, 27 $M_{\odot}$ progenitors (WHW 2002)

SASI produces modulations of neutrino emission and gravitational-wave signal.

(Tamborra et al., PRL 111, 121104 (2013); arXiv:1307.7936)
3D Core-Collapse Models: Neutrino Signals

11.2, 20, 27 $M_{\odot}$ progenitors (WHW 2002)

SASI produces modulations of neutrino emission and gravitational-wave signal.

\[
 f_{\text{SASI}}^{-1} \sim \int_{R_{\text{NS}}}^{R_{\odot}} \frac{dr}{|v|} + \int_{R_{\text{NS}}}^{R_{\odot}} \frac{dr}{c_s - |v|}.
\]

(Tamborra et al., PRL 111, 121104 (2013); arXiv:1307.7936)