超新星爆発理論

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Fundamentals of Core-Collapse Supernovae

- Gravitational collapses of massive stars ($\gtrsim 8M_\odot$)
- One of the most energetic phenomena in the Universe

  $E_\nu \sim 10^{53}$erg, $E_{kin} \sim 10^{51}$erg, $E_\gamma \sim 10^{49}$erg

- Productions of compact objects such as neutron stars and black holes
- Sites for productions of high energy particles and chemical evolutions of the universe

  — neutrinos, gravitational waves, cosmic rays,
  X-rays, gamma-rays

  — nucleosynthesis of heavy elements

Challenges in Supernova Research

The supernova theory must address the following issues :

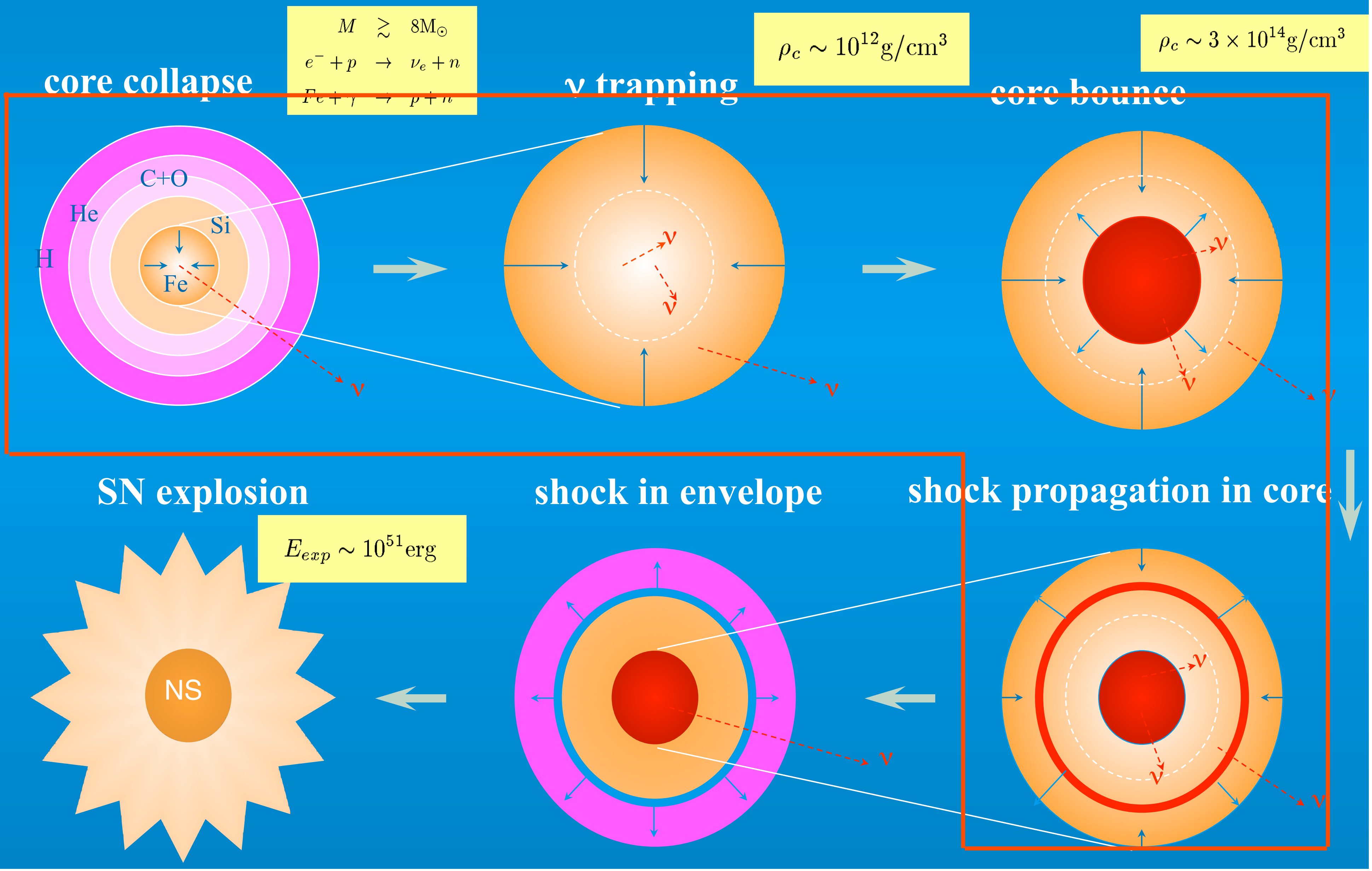
- ✓ **How does the explosion occur and determine the neutron star mass and explosion energy?**

- ✓ **How do syntheses of heavy elements proceed?**
  - **— explosive nucleosynthesis, r-process**

- ✓ **What is the origin of rotation, magnetic field, and proper motion of neutron stars?**

- ✓ **What is the relationship with other high energy objects such as GRBs**
  - **— mass threshold for NS/BH formations**
  - **— formations of hypernovae and magnetars**

Scenario of Core-collapse Supernovae



core collapse

$$\begin{aligned} M &\gtrsim 8\mathrm{M}_\odot \\ e^- + p &\rightarrow \nu_e + n \\ Fe + \gamma &\rightarrow p + n \end{aligned}$$

ν trapping

$$\rho_c \sim 10^{12}\mathrm{g/cm^3}$$

core bounce

$$\rho_c \sim 3 \times 10^{14}\mathrm{g/cm^3}$$

shock propagation in core

shock in envelope

SN explosion

$$E_{exp} \sim 10^{51}\mathrm{erg}$$

Challenges in Supernova Research

- ✓ **The difficulty lies in transforming the gravitational energy to the kinetic energy.**
- ✓ **The core-collapse supernova is a complex combination of microphysics and macrophysics.**

The interest of the supernova society is currently directed to 3-dimensional evolutions of post-bounce cores.

The currently viable mechanisms:

- ✓ SASI/convection-assisted ν-heating mechanism
  - standing accretion shock instability (SASI)+convection
- ✓ Acoustic mechanism
  - proto-neutron star (PNS) oscillations of g-mode nature
- ✓ Magneto-rotational mechanism
  - magneto-rotational instability (MRI)

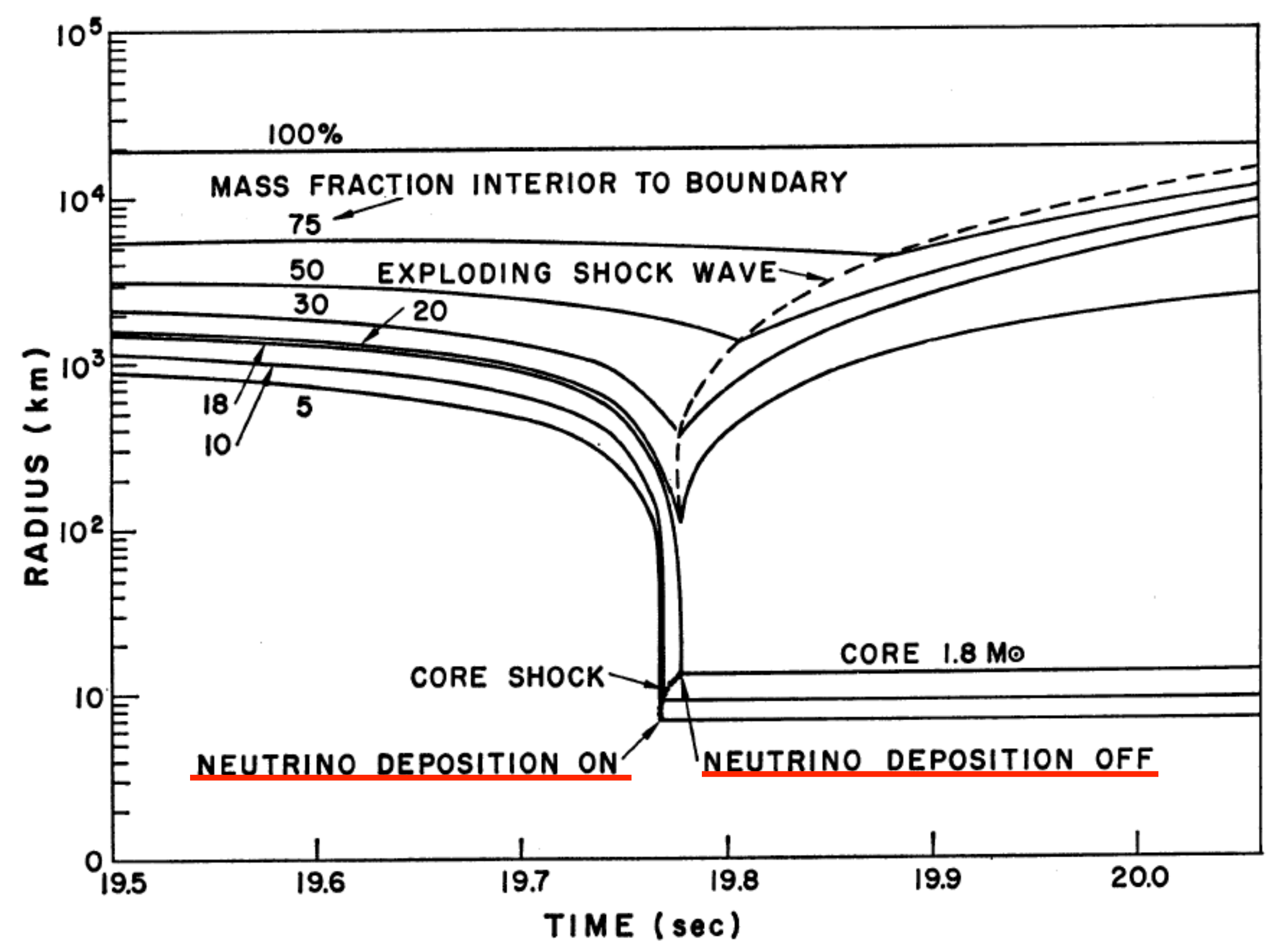
Brief History of Supernova Research

Time Line	No Rotation or Slow Rotation		Rapid Rotation and/or Magnetic Fields
	1D	2D/3D	
1934	Birth of SN theory Baade & Zwicky ’34		
1960s - early 1970s	Dawn of SN modeling Colgate & White ’66 Arnett ’67		First 2D simulations LeBlanc & Wilson ’70
1975	Beginning of Modern Theory Neutrino-trapping Sato ’75		Some early discussions on magneto-rotational scenario Bisnovatyi-Kogan et al. ’76 Meier et al. ’76

Time Line	No Rotation or Slow Rotation		Rapid Rotation and/or Magnetic Fields
	1D	2D/3D	
late 1970s – late 1980s	**Prompt Explosion** **vs** **Delayed Explosion** **Hillebrandt ’84** **Wilson ’82**	**Recognition of importance of non-sphericity** **Epstein ’78** **Early simulations of convection** **Livio et al. ’81** **Smarr et al. ’81**	**Rare 2D simulations** **Symbalisty ’84**
1987	SN1987A **Confirmation of Modern Theory**	**Discoveries of mixing in envelope and global non-sphericity**	
1990s	**Criterion for explosions via neutrino-heating mechanism** Burrows & Goshy ’93 **More precise treatment of neutrino transport** Mezzacappa et al. ’93 Yamada et al. ’97	**Beginning of modern multi-D Simulations** Herant et al. ’94 Burrrows et al. ‘95 Janka et al. ‘96	**Simulations of rapidly rotational collapse** Moenchmeyer et al. ’91 Yamada & Sato ’94

Time Line	No Rotation or Slow Rotation		Rapid Rotation and/or Magnetic Fields
	1D	2D/3D	
late 1990s - early 2000s	**State-of-the-art simulations** Liebendoerfer et al. ’01 Rampp et al. ’00 Thompson et al. ’03 Sumiyoshi et al. ’05	**Discovery of SASI** Blondin et al. ’03 Foglizzo et al. ’05 Ohnishi et al. ’06 Yamasaki et al. ‘07	**Introduction of MRI to SN theory** Akiyama & Wheeler ’03 **Simulations of magneto-rotational collapse** Yamada & Sawai ’04
latter half of 2000s up to present	**Black-hole-forming collapse** Sumiyoshi et al. ’06 Fischer et al. ‘09 O’Connor et al. ‘10	**2D simulations with sophisticated neutrino transport** **Neutrino-heating Mechanism** Kitaura et al. ‘07 Marek et al. ’07 Buras et al. ’08 Ott et al. ’08 **Acoustic mechanism** Burrows et al. ’07 **Criterion for neutrino Heating** Murphy et al. ‘09 Burrows et al. ‘10	**Rotational and magneto-rotational collapses with neutrino transport** Walder et al ’05 Burrows et al. ’07 **Magneto-rotational collapse in GR** Shibata et al. ’06 Kuroda et al. ‘10 **3D magneto-rotational collapse** Mikami et al. ’08

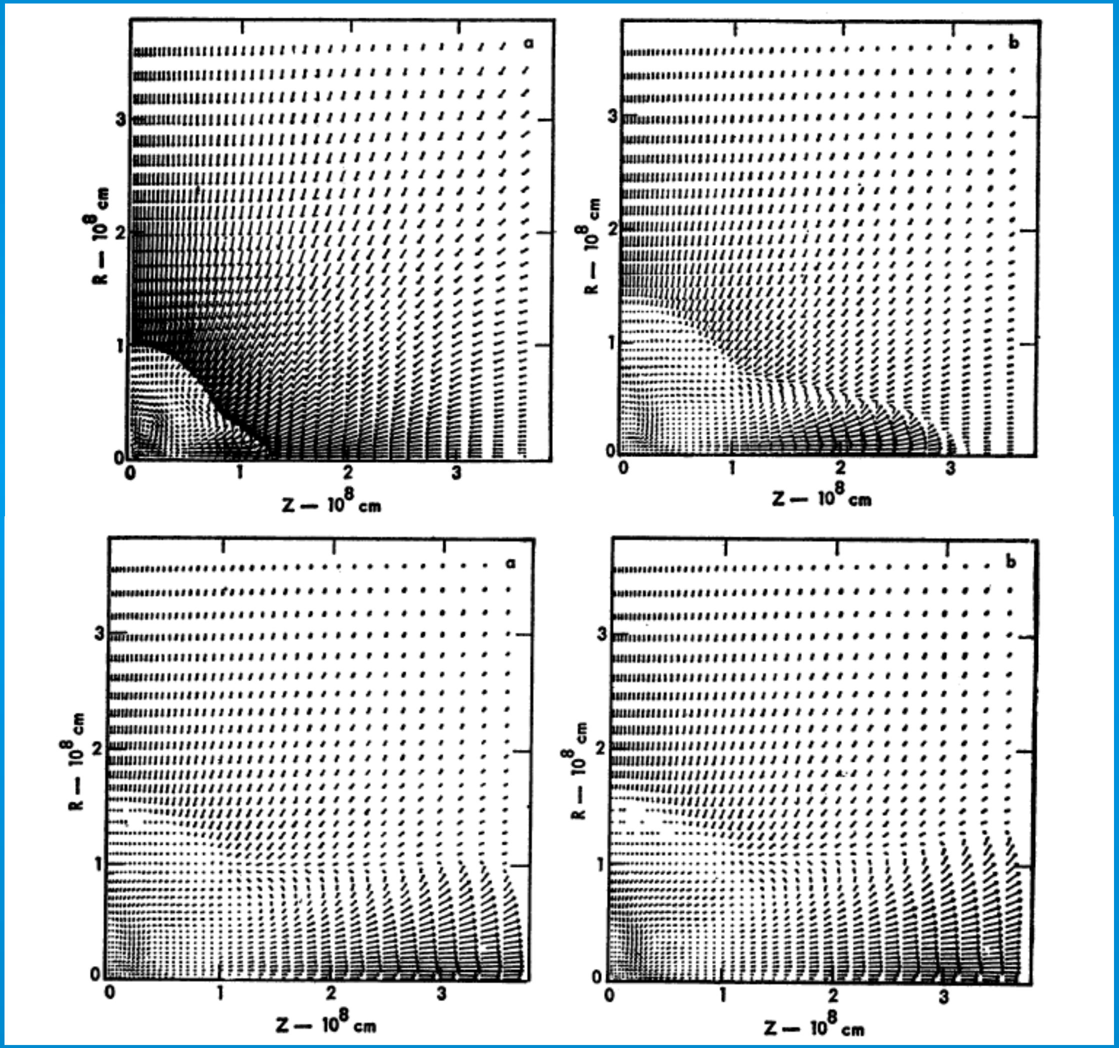
Dawn of Supernova Modeling



Colgate & White '66

- ν-heating mechanism
  - – energy deposited by hand
- criticized by Arnett
  - – neutrino transport should be taken into account properly
  - – no explosion found if this is accounted

First 2D Simulations



LeBlanc & Wilson ’70

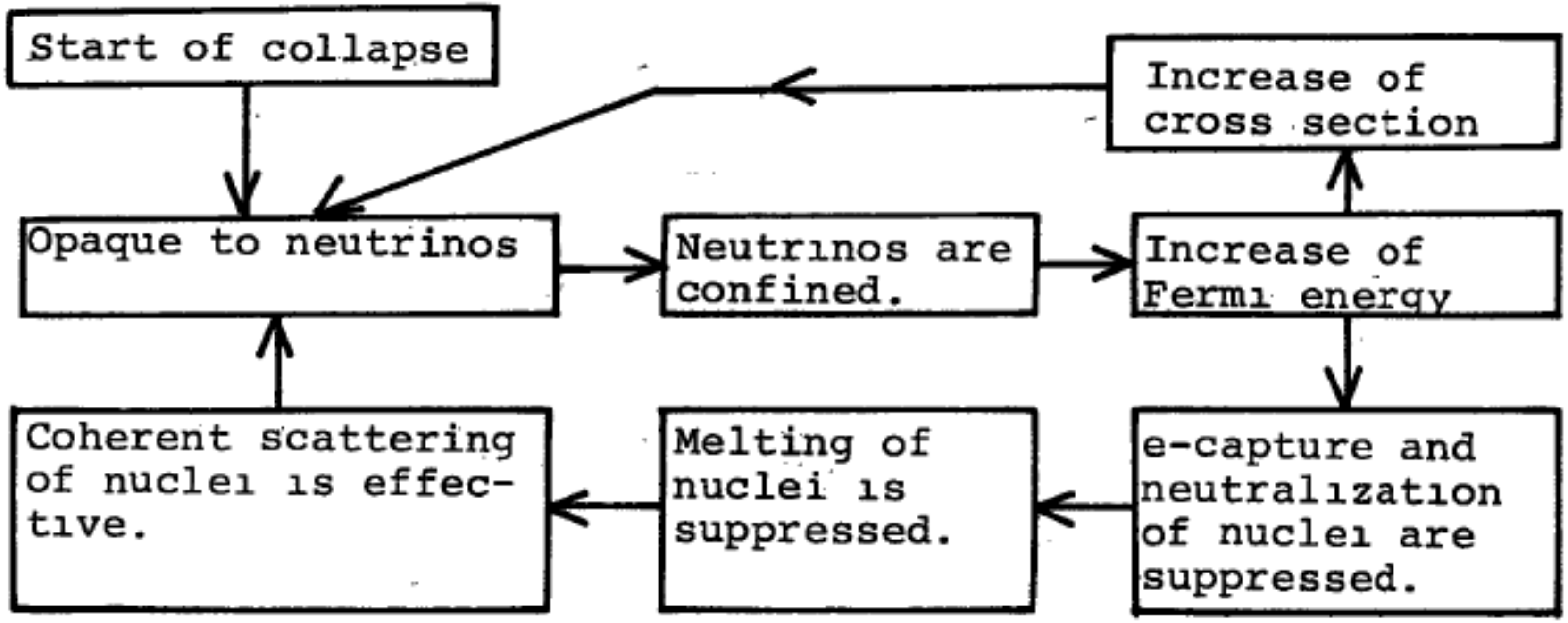
- rotational and magneto-rotational collapse of 7M$_{solar}$ star
  - $|T/W| = 0.25\%$
    $|M/W| = 0.025\%$

- a jet-like explosion found for magneto-rotational case
  - no explosion found for rotation alone

ν-trapping: The Herald of Modern Theory

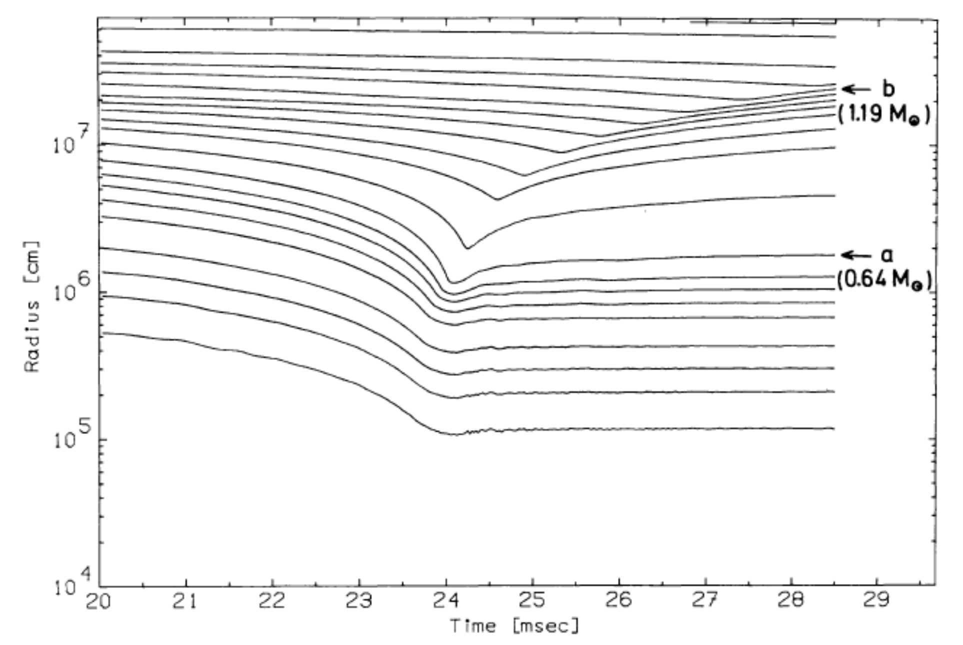
Sato '75

- ✓ Weak neutral currents predicted by W-S theory have profound implications for supernova theory
  - — Coherent scattering make a core opaque for neutrinos.
  - — Neutronization occurs much more slowly than previously thought.
  - — Neutrinos diffuse out of the core.

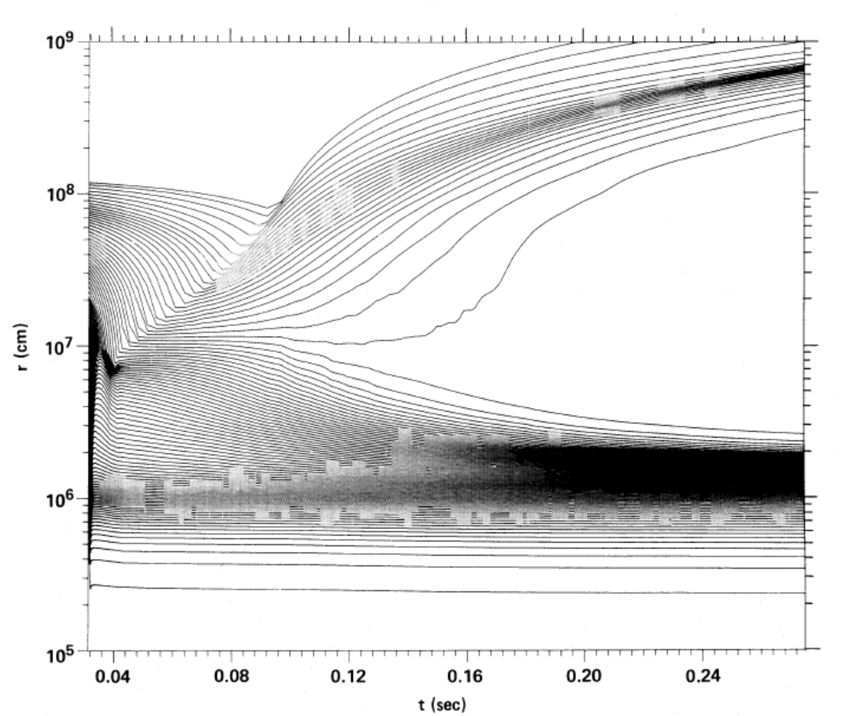


Prompt Explosion vs Delayed Explosion

Prompt Explosion Hillebrandt et al. ‘84



Delayed Explosion Mayle & Wilson ‘88



Two groups predicted different explosion modes for the same progenitor with an ONeMg core !

SN1987A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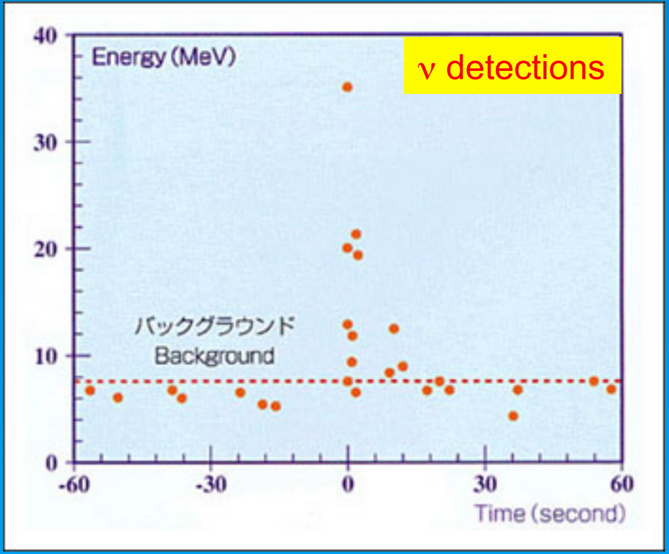
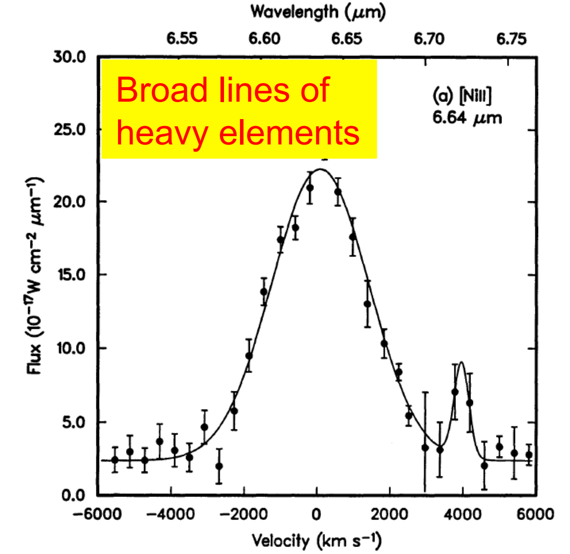
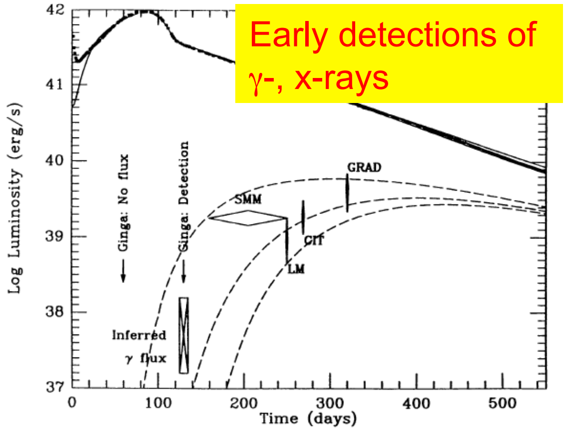
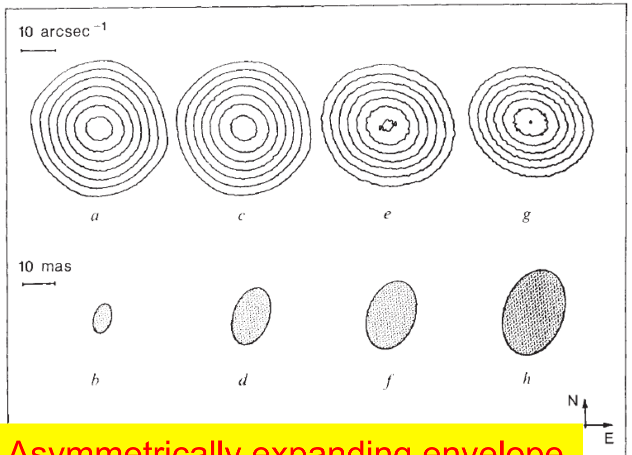

ν detections

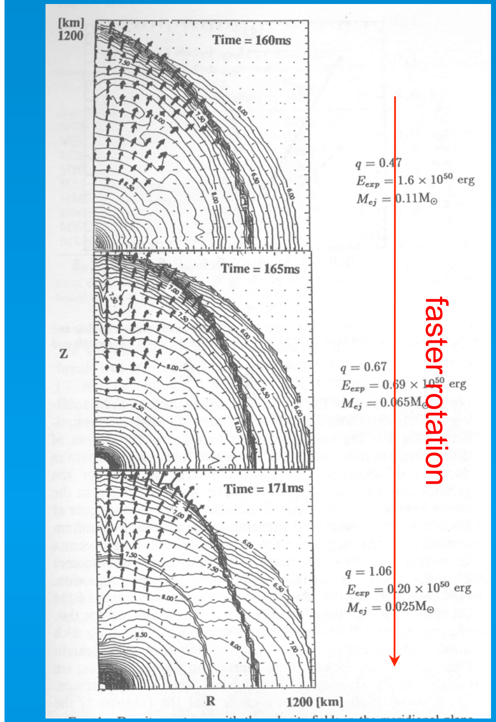

Broad lines of heavy elements

- ✓ Confirmed modern theory !
  - – NS is formed.
  - – Neutrinos are trapped and escape on a diffusion time scale.
- ✓ Revealed non-spherical aspects.
  - – Matter is not stratified in the envelope.
  - – The envelope is elongated.


Early detections of γ-, x-rays


Asymmetrically expanding envelope

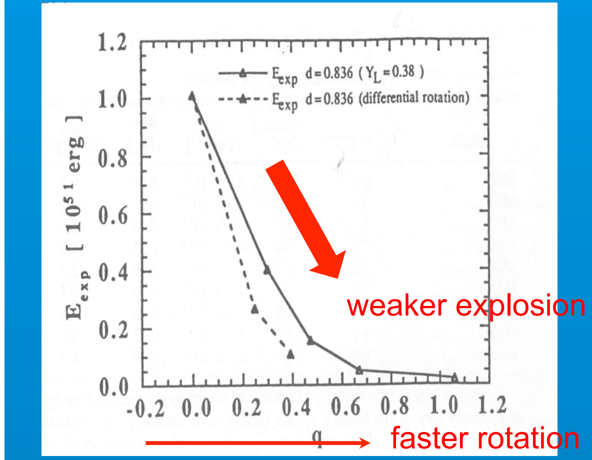
Effects of Rotation

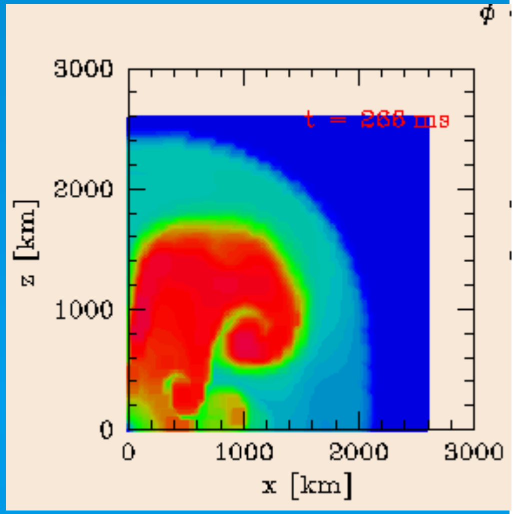


Yamada & Sato '95

Rotational effect on prompt explosion

- — jet-like explosion
- — core bounce at lower density
- — explosion weakened monotonically with angular momentum

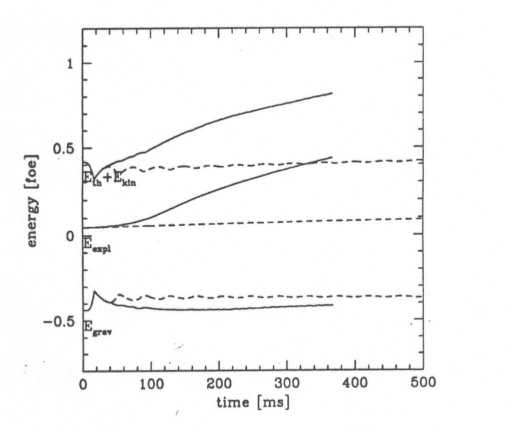




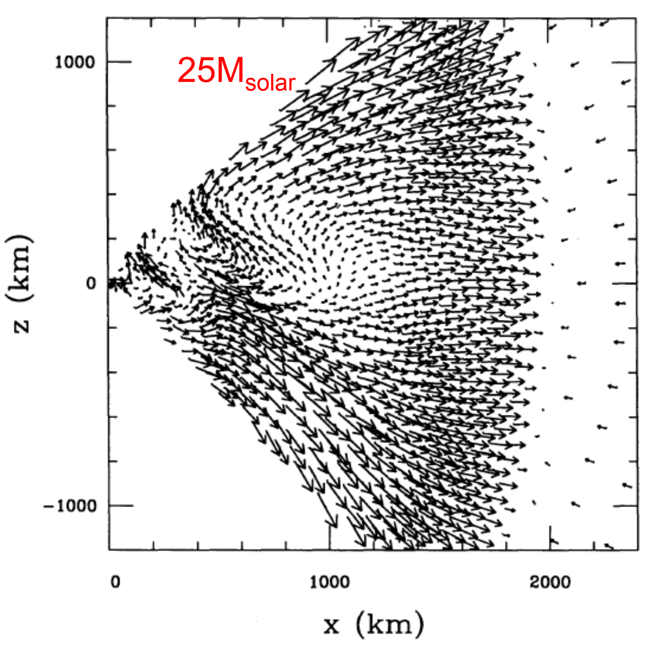
Shimizu et al. '01

Effect of anisotropic ν emissions on ν heating mechanism

- — ν-heating enhanced near a rotation axis
- — global convections induced in heating regions
  - — gravity waves
  - — proper motions of pulsars

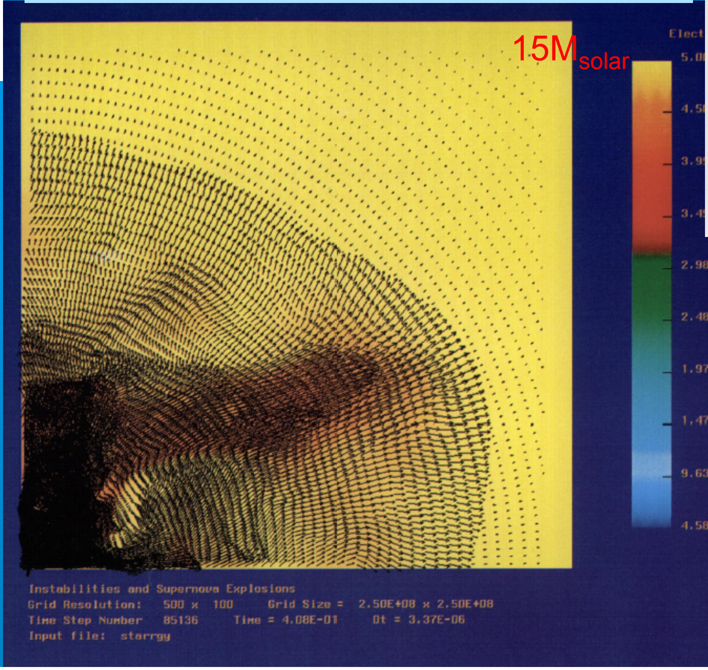


False Explosions in 90's



Herant et al. '94

- ✓ 2D axisymmetric simulations commonly obtained explosions via ν heating mechanism.
- ✓ Convection was supposed to be the key.
- ✓ Successful explosions were currently attributed to approximate ν transports and artificial inner boundaries put for numerical reasons.



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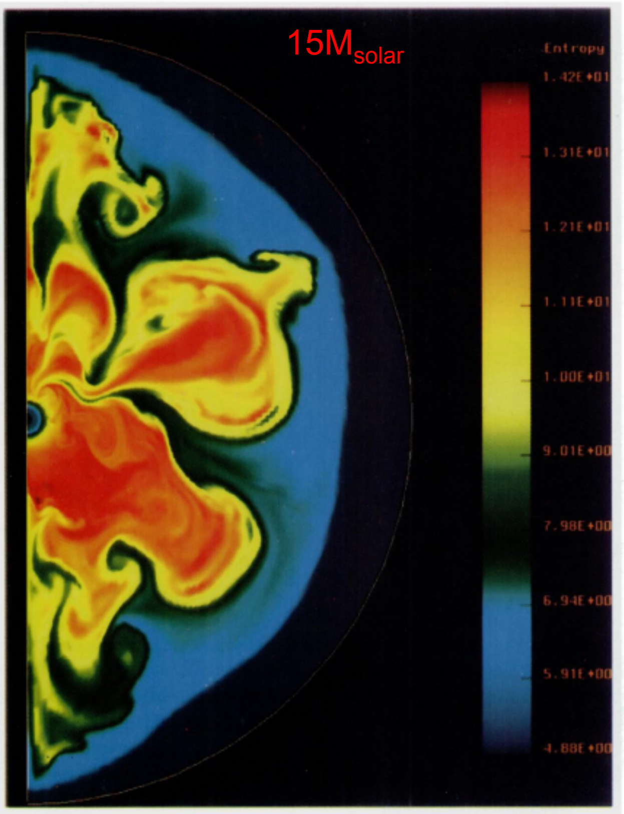
Instabilities and Supernova Explosions
Grid Resolution:   500 x  100     Grid Size =  2.50E+08 x 2.50E+08
Time Step Number   85136     Time = 4.08E-01     Dt = 3.37E-06
Input file:  starrgy
```

Burrows et al. '95



Janka et al. '96

Critical Neutrino Luminosity

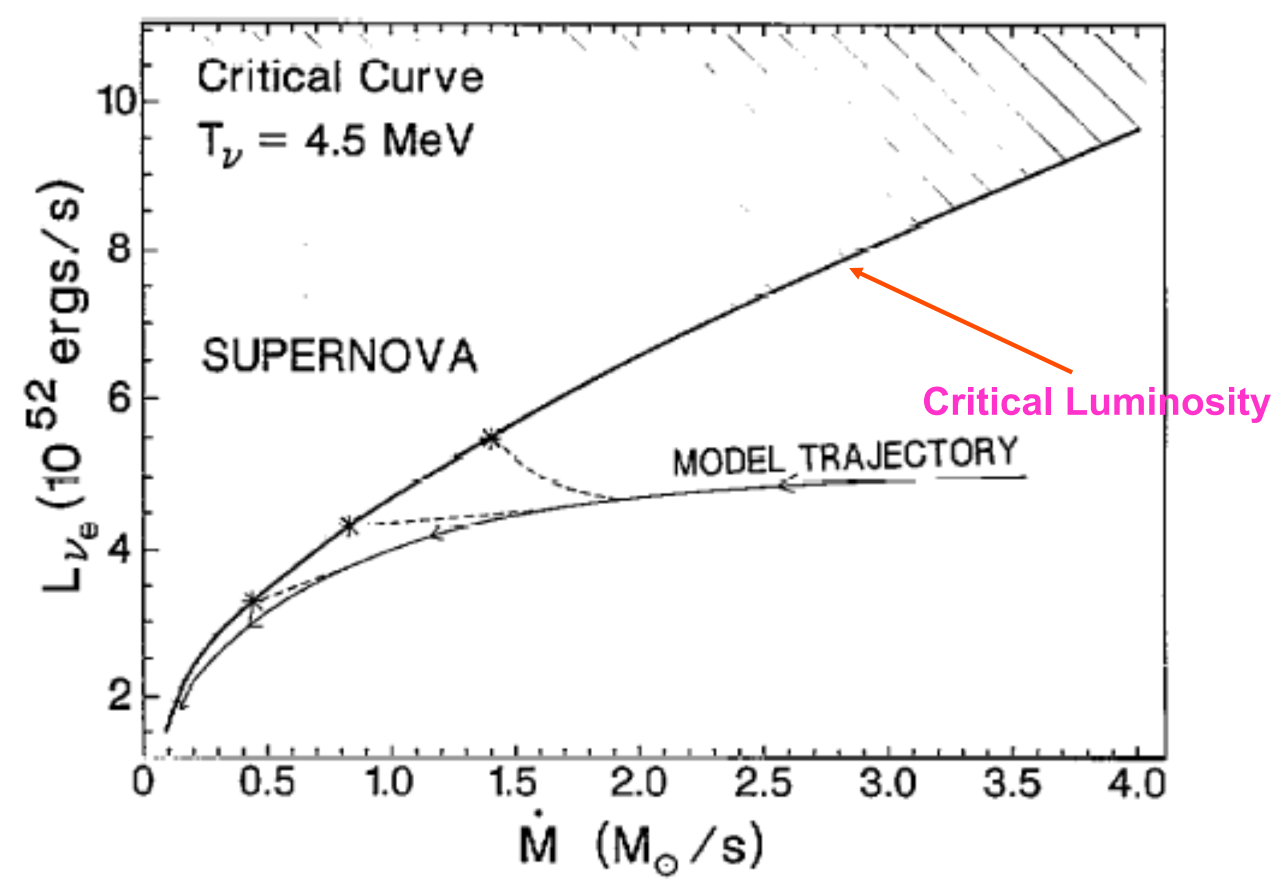
Burrows & Goshy ’93 :

— For a given mass accretion rate, there is a critical neutrino luminosity, above which no steady accretion flow exists.

— This may indicate the revival of shock wave.

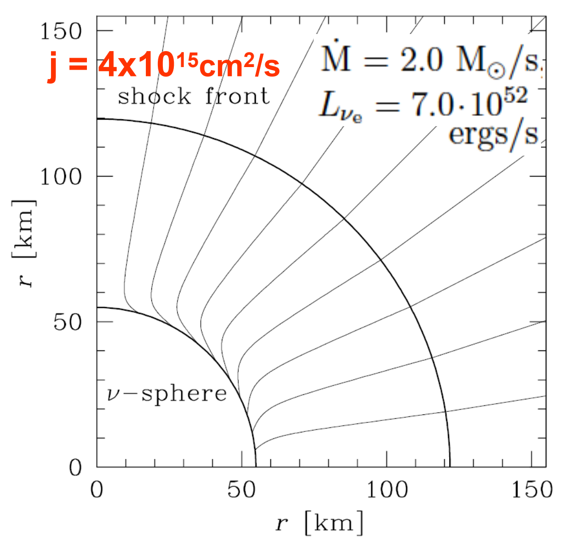
— Convection and rotation tend to lower the threshold.

Yamasaki & Yamada ’04, ’06a, ’06b

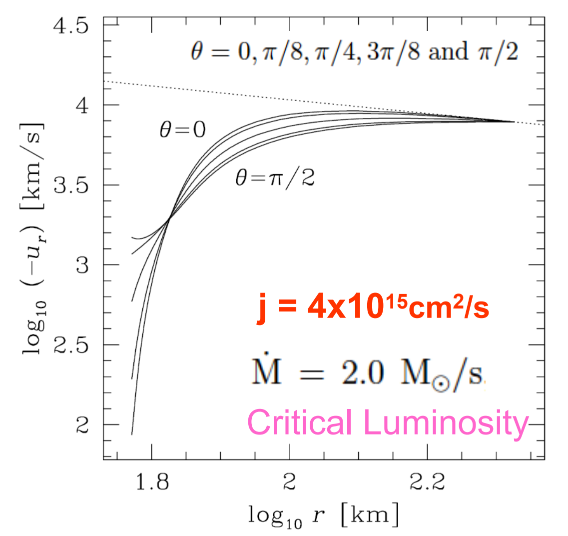


Effects of Rotation on Critical Luminosity

- Flow Pattern



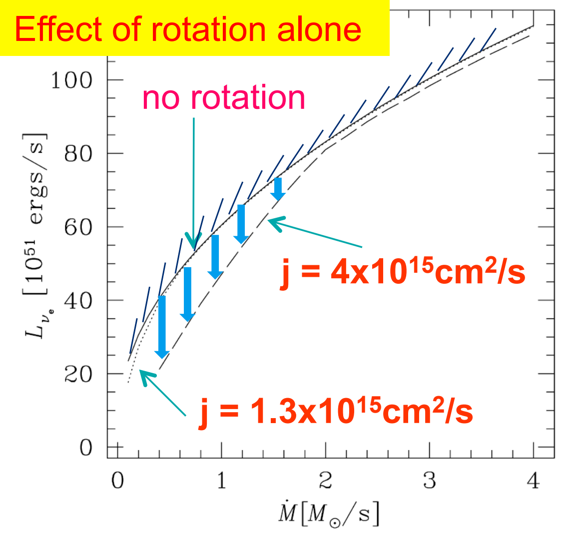
- Radial Velocities

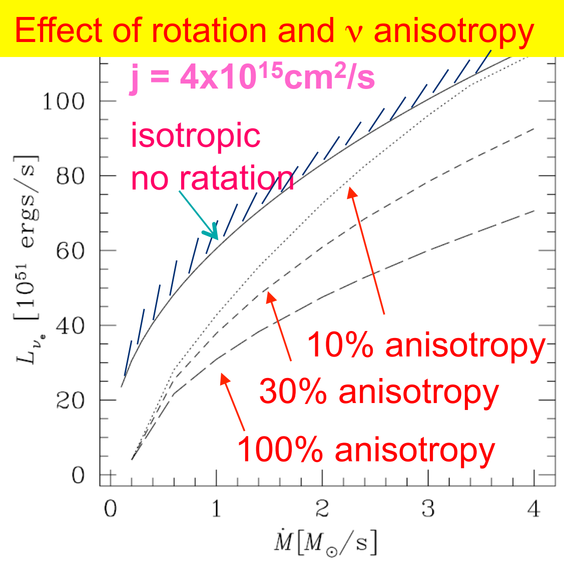


Yamasaki & Yamada '05, '06, '07

- ✓ The critical luminosity is reduced by rotation.
- ✓ It is further reduced by ν-anisotropy.
- ✓ The shock may be revived at the rotation axis.
  - — The critical point is reached in spherical symmetry when the radial acceleration satisfies a certain condition.
  - — In the rotational case, the condition is satisfied only on the rotation axis.
- ✓ Convection also reduces the critical luminosity.

- Critical Luminosities



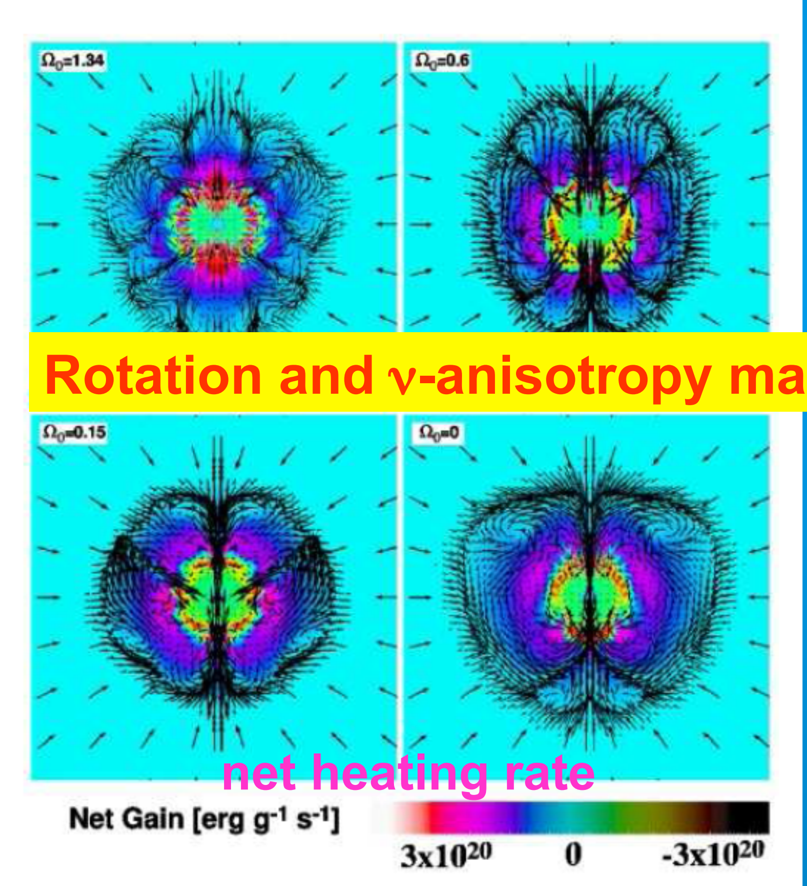


Asymmetric Neutrino Emission

Walder et al. ’05

Multi-D multi-group flux-limited diffusion
No electron scattering
Up to ~200ms seconds after bounce

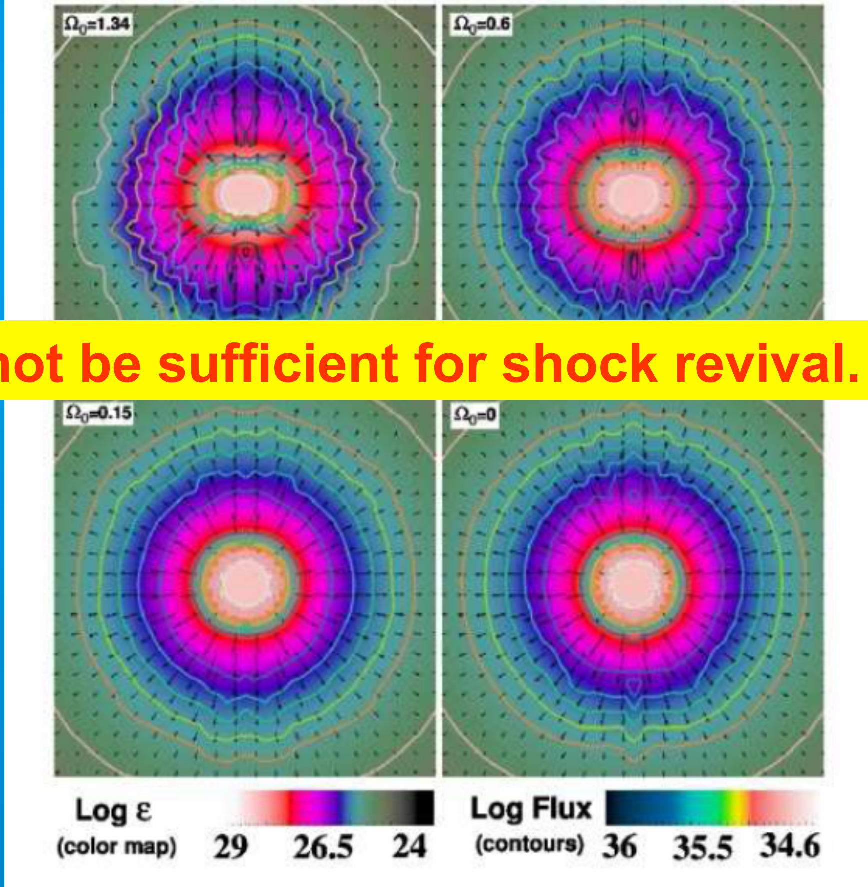
- ν-anisotropy of factor ~2 for most rapidly rotating models



net heating rate

ν-energy density & flux

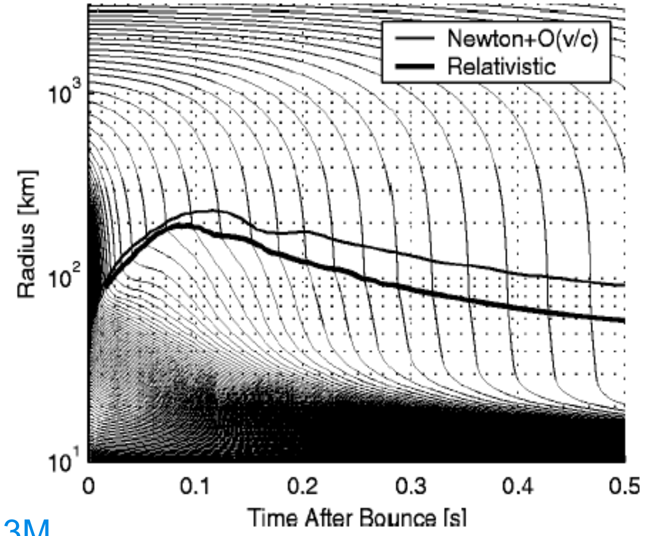
Walder ‘05



Rotation and ν-anisotropy may not be sufficient for shock revival.

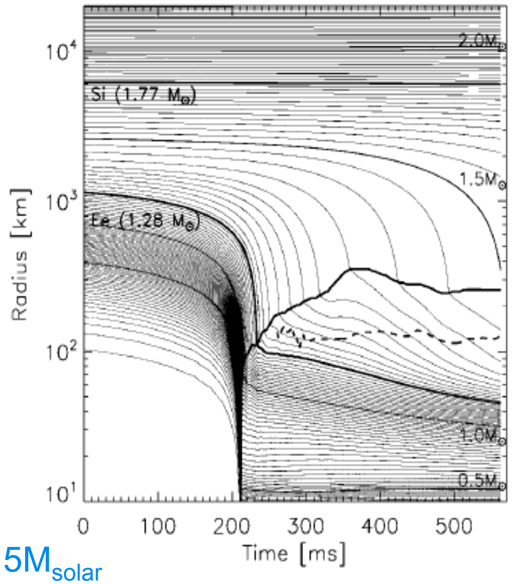
Unsuccessful 1D Simulations

- ✓ 1D spherically symmetric simulations with Boltzmann solvers commonly found no explosions via ν heating mechanism.
  - — tangent ray method and SN method
  - — Newtonian and GR
- ✓ Detailed comparisons were done for some models of different groups and reasonable agreement was found.



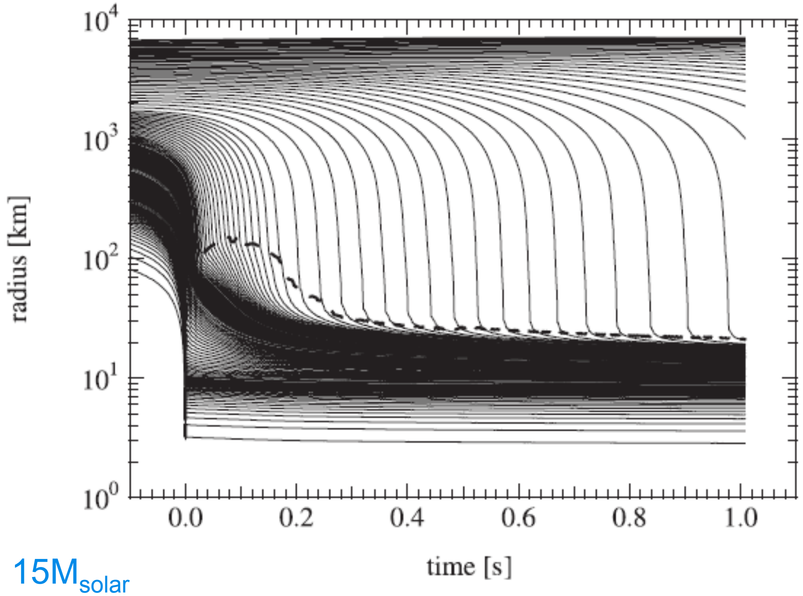
$13M_{solar}$

Liebendoerfer et al. 01



$15M_{solar}$

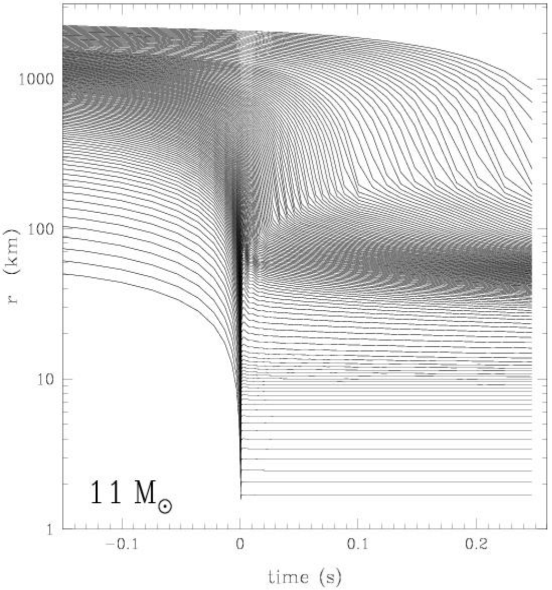
Rampp et al. 00



$15M_{solar}$

Sumiyoshi ‘05

Thompson et al. 03



SASI

Iwakami et al. '07

- ✓ spherically symmetric accretion flow
- ✓ non-axisymmetric perturbations
- ✓ realistic EOS & ν-heating rates

- spherical coordinates:300(r)x15(θ)x30(φ)
- computation domain

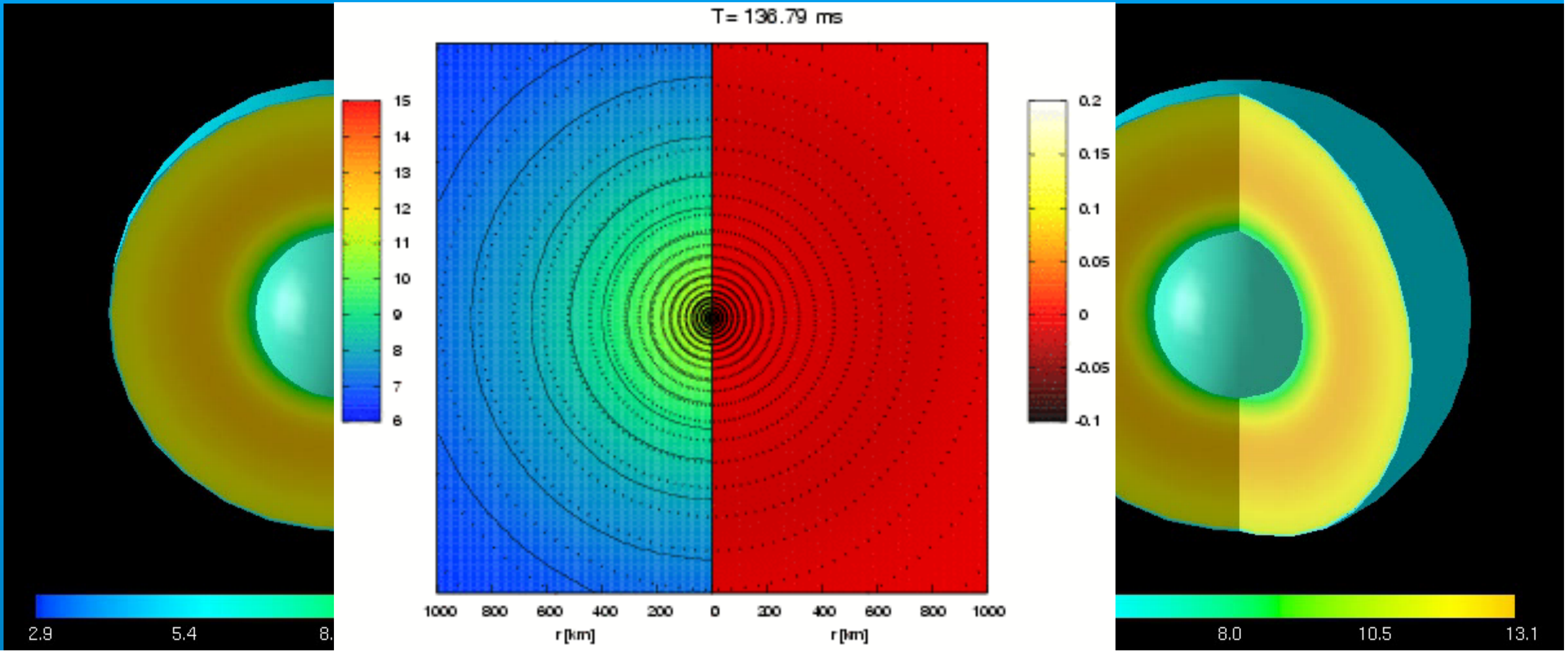
$$5.0\times10^{6} \leqq r \leqq 1.0\times10^{8},$$
$$0.0 \leqq \theta \leqq \pi,\ 0.0 \leqq \phi \leqq 2\pi$$

- model parameters

$$L_\nu = 6.0\times10^{52}\ [\mathrm{ergs/s}]$$
$$T_{\nu_e} = 4.5\,[\mathrm{MeV}]$$
$$dM/dt = 1.0M_\odot\ [s^{-1}]$$

Axisymmetric Case
l = 1, m = 0

Non-axisymmetric Case
initial = 1, m = ±1



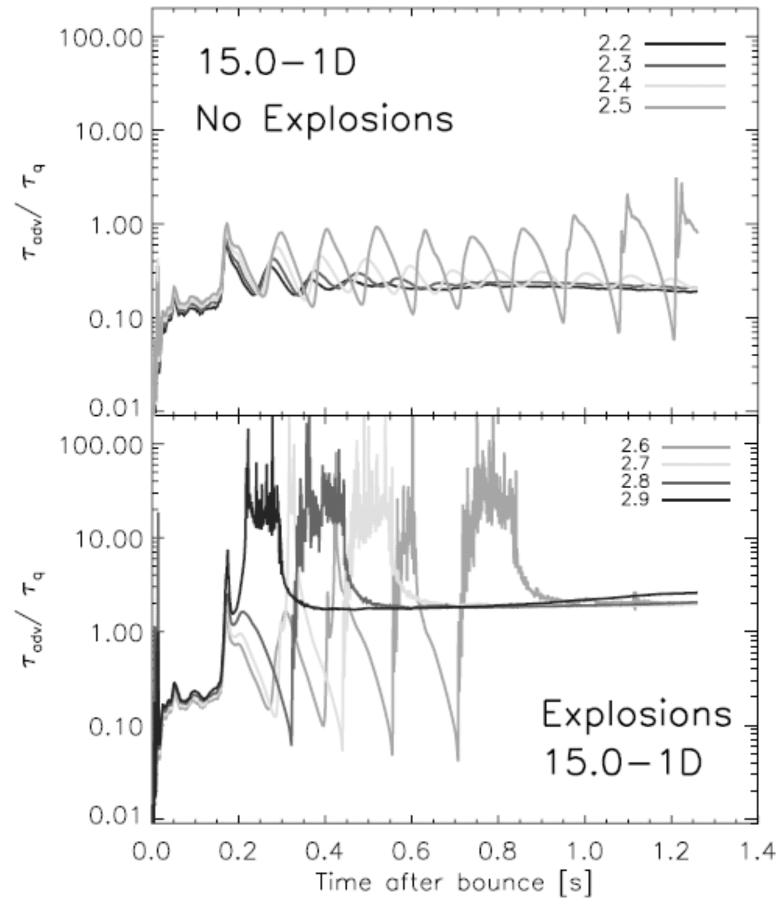
Criterion for Successful Neutrino Heating

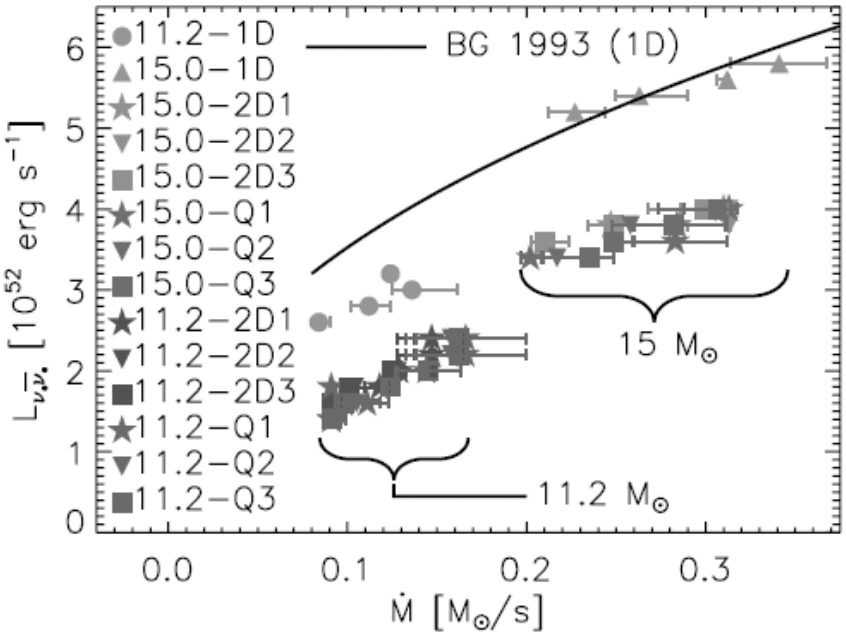
Murphy et al. '08

The critical neutrino luminosity is determined by the following relation:

$\tau_{adv} > \tau_q$

τ_{adv}: advection time
τ_q : heating time





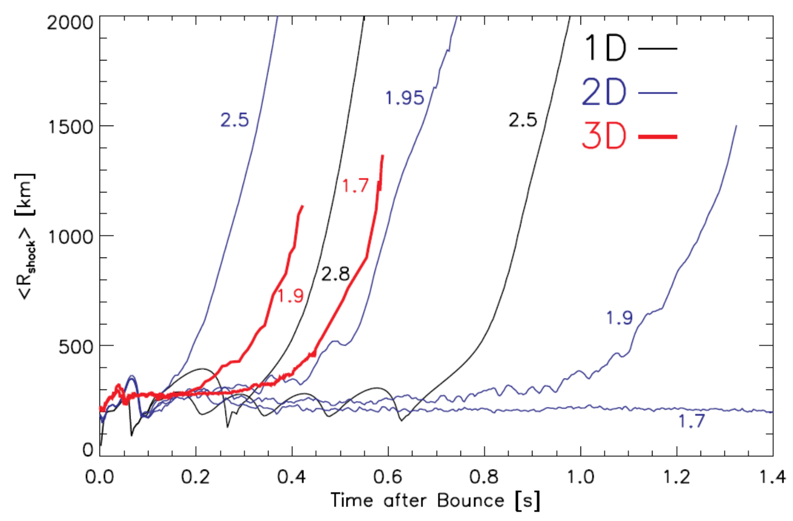
The critical luminosity is lower for 2D than for 1D, but is little affected by the l=1 SASI mode.

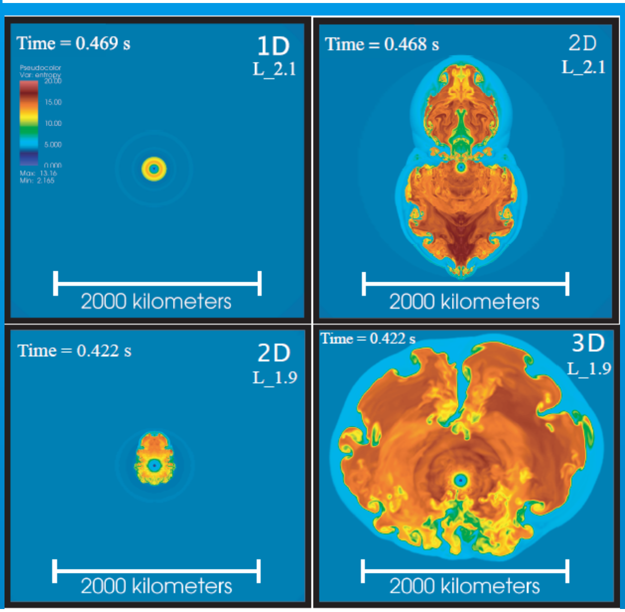
3D may be the key?

Nordhaus et al. ‘10

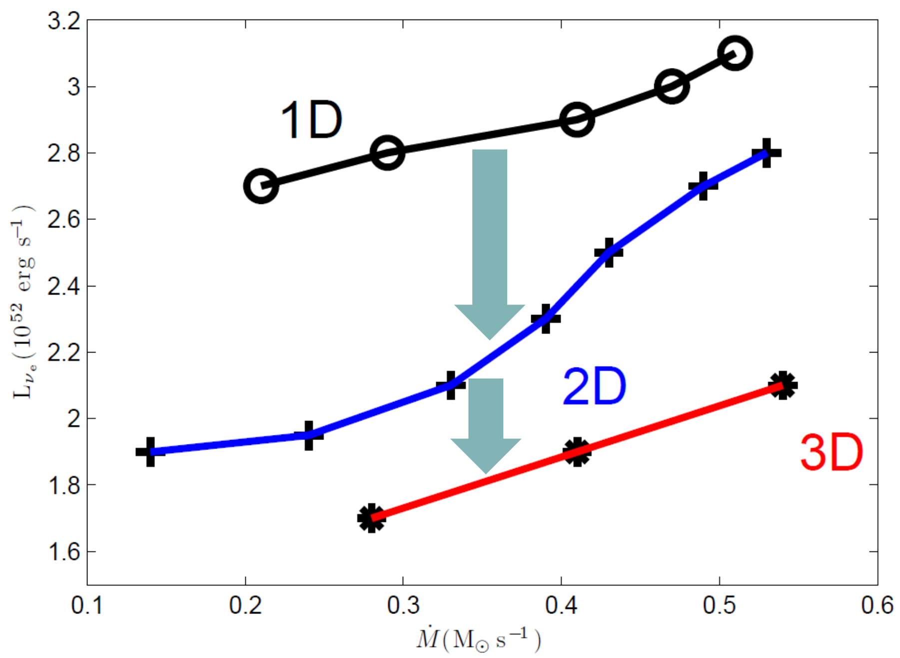
Direct extension of Murphy’s models to 3D

- ✓ The critical luminosity is a decreasing function of dimension. This may warrant a successful explosion for 3D models.
  - — Longer average dwell times lead to higher entropies.
- ✓ 3D models explode earlier than 1D and 2D models.
- ✓ Not only l=1, m=0 mode (sloshing mode) but l=1, m=+-1 modes are also excited to similar amplitudes.



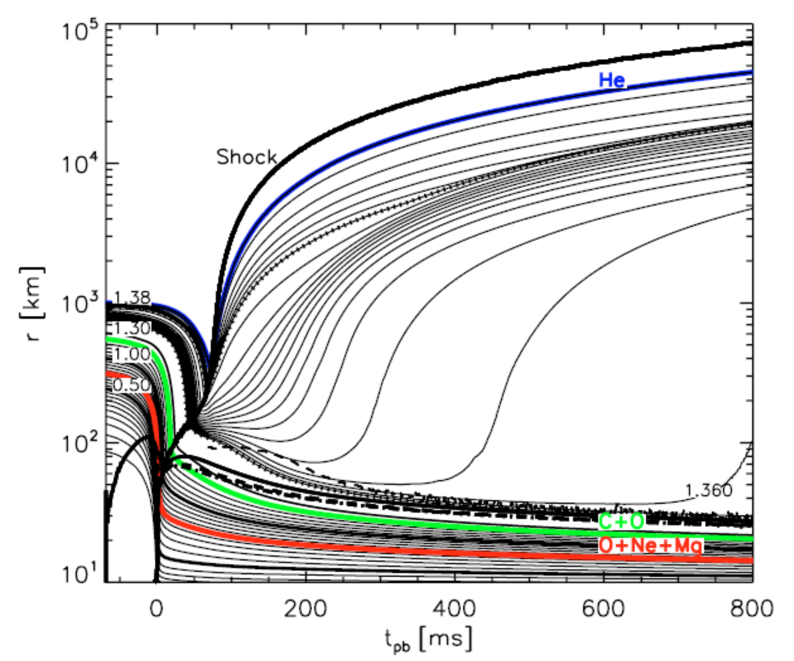


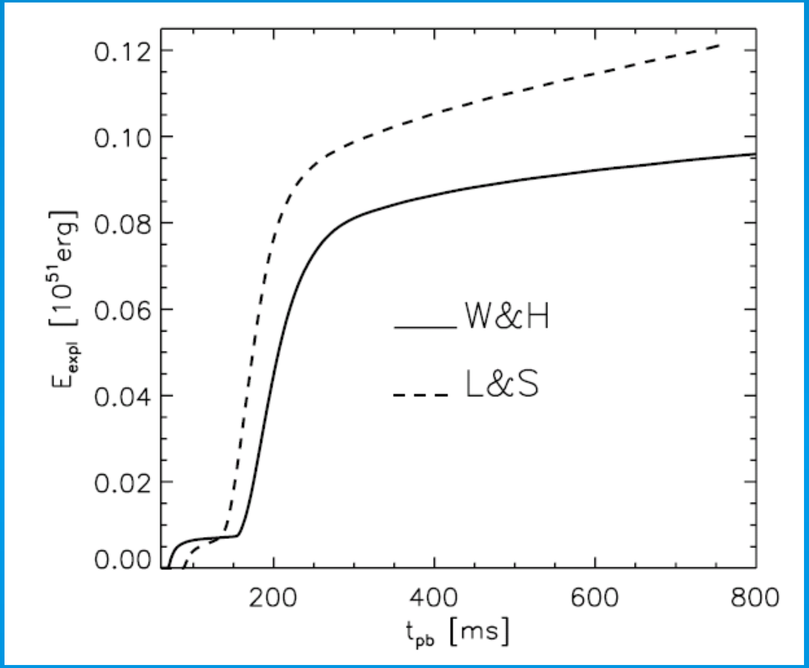
Critical Luminosity



Collapse of ONeMg Cores

Kitaura et al. ’06 : The same model as in Hillebrandt et al. ’84 and in Mayle & Wilson ’88.





✓ The latest simulation predicts that ONeMg core explodes via neutrino heating mechanism even in spherical symmetry.

— The explosion occurs rather quickly and there is no time for the instability to occur.

— This is the only model that explodes in spherical symmetry except for the accretion induced collapse.

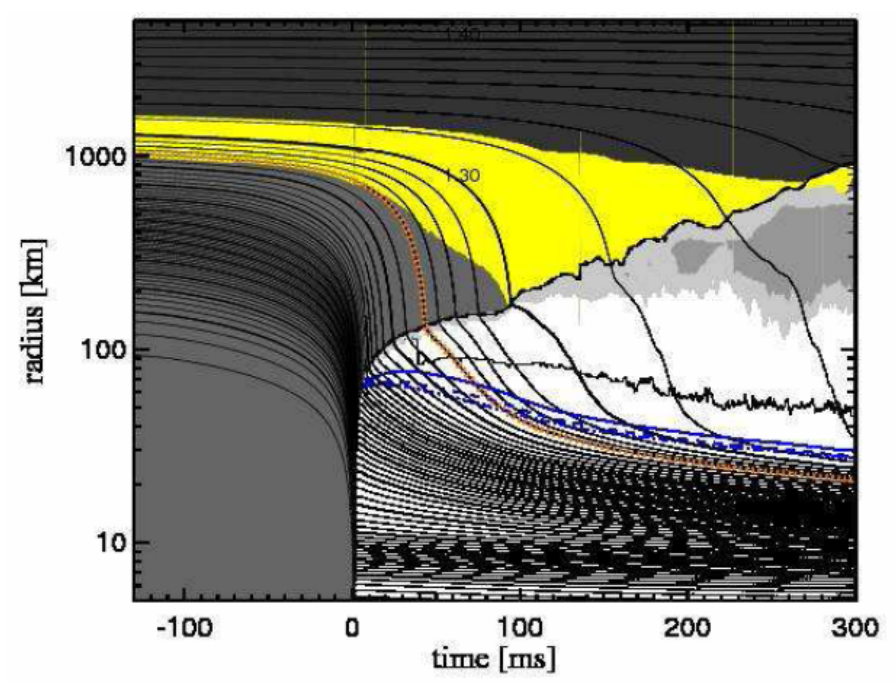
✓ The explosion is much weaker than was predicted previously in Mayle & Wilson ’88.

SASI-assisted Neutrino Heating Mechanism

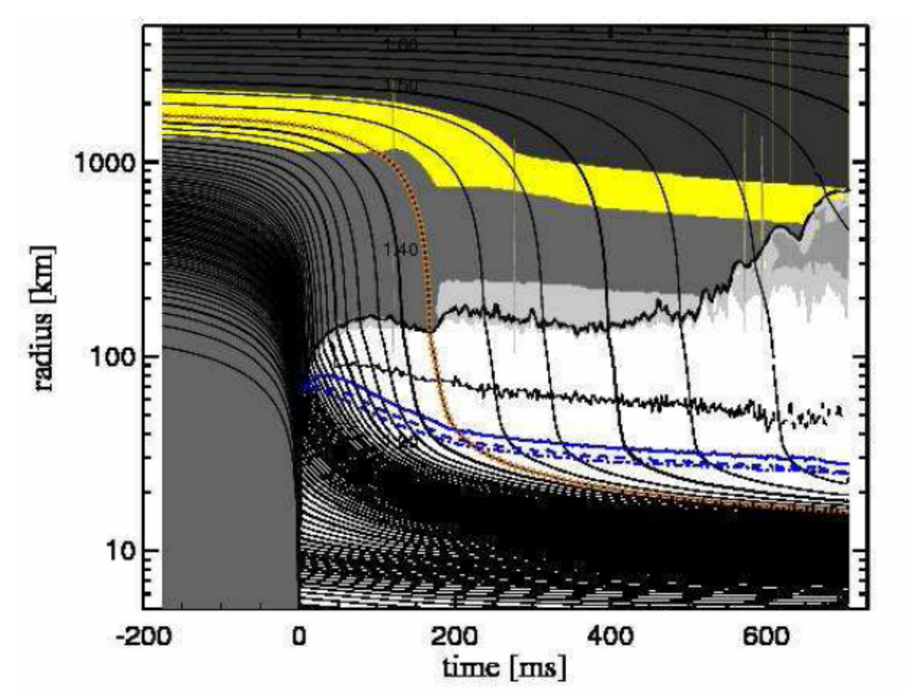
Marek and Janka '08

- ✓ 2D axisymmetric simulations
- ✓ ray-by-ray plus approximation
- ✓ Newtonian + phenomenological relativistic corrections
- ✓ Lattimer & Swesty EOS, Wolff EOS
- ✓ Flash approximation for nuclear reactions
- ✓ 11.2Msolar, 15Msolar Models

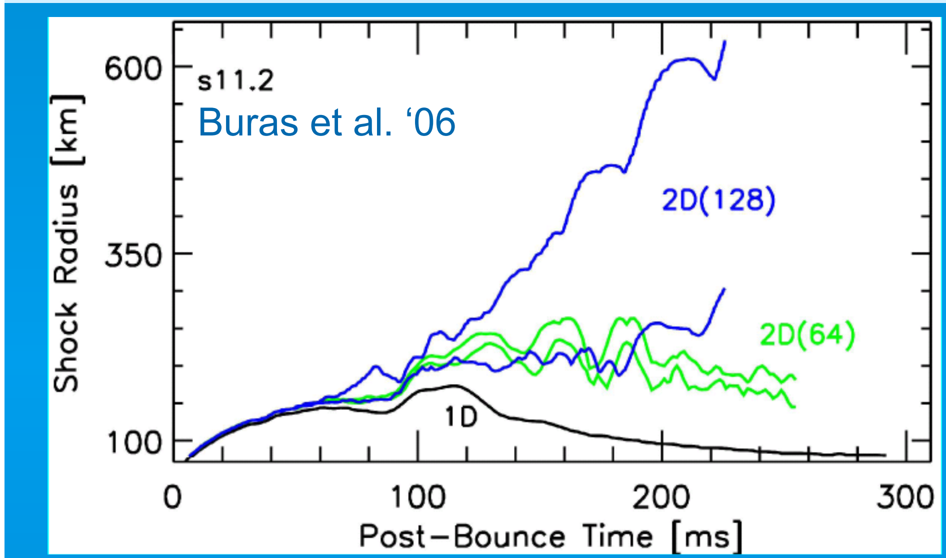
11.2Msolar Model

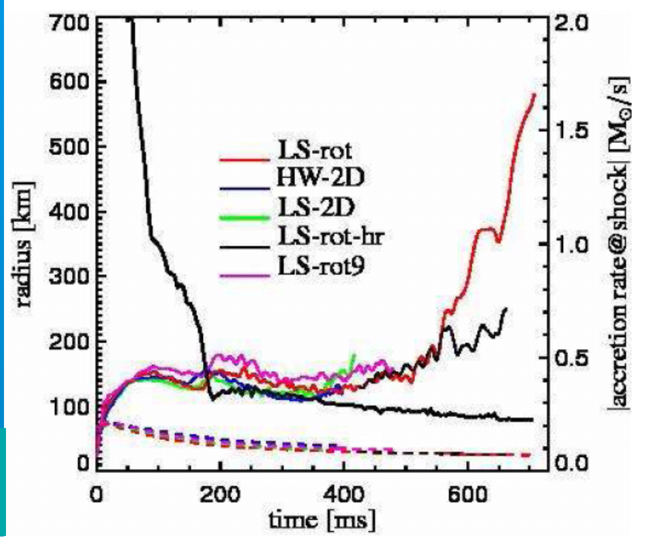


15Msolar Model

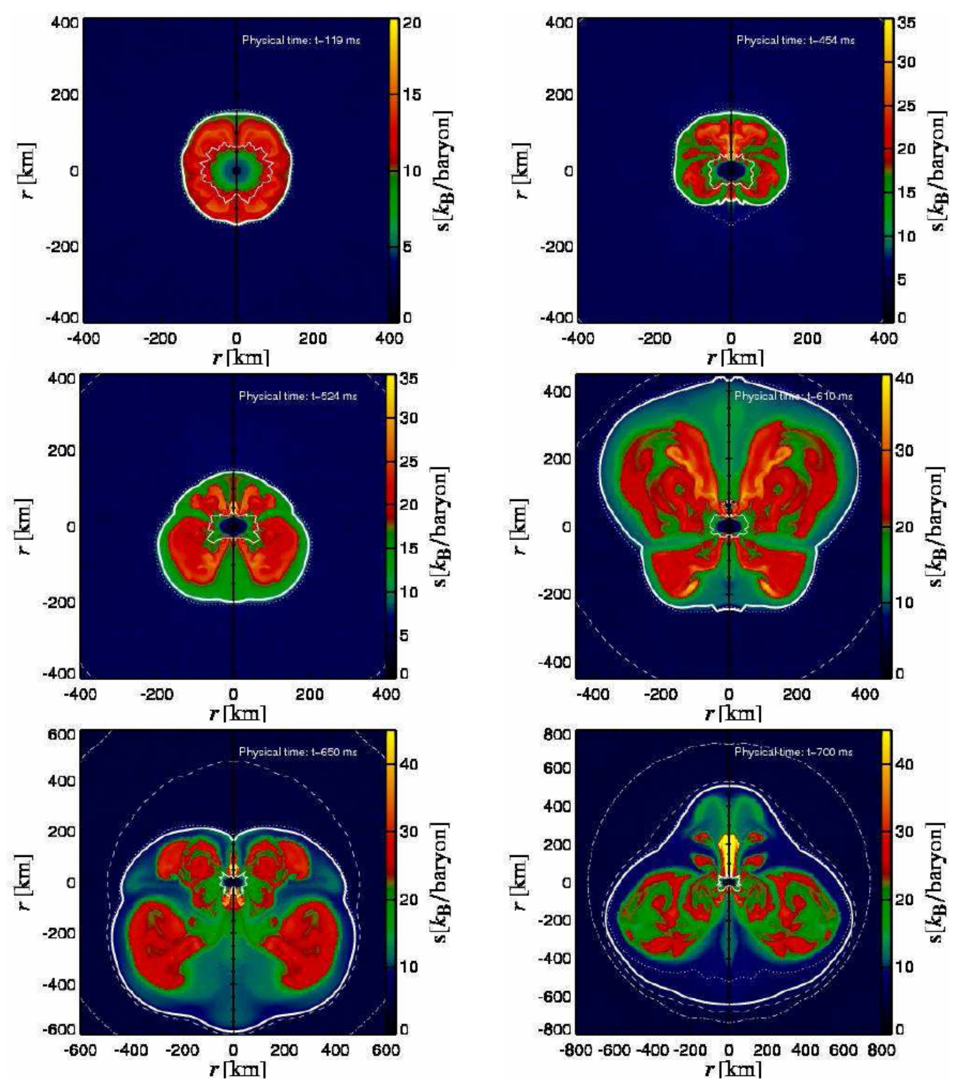


- ✓ **SASI is critically important and leads to a very asymmetric expansion.**
- ✓ **The explosion energy is very small (~10^{49}erg) at the end of computations but is increasing at a considerable rate.**
- ✓ **g-mode oscillations are not remarkable.**



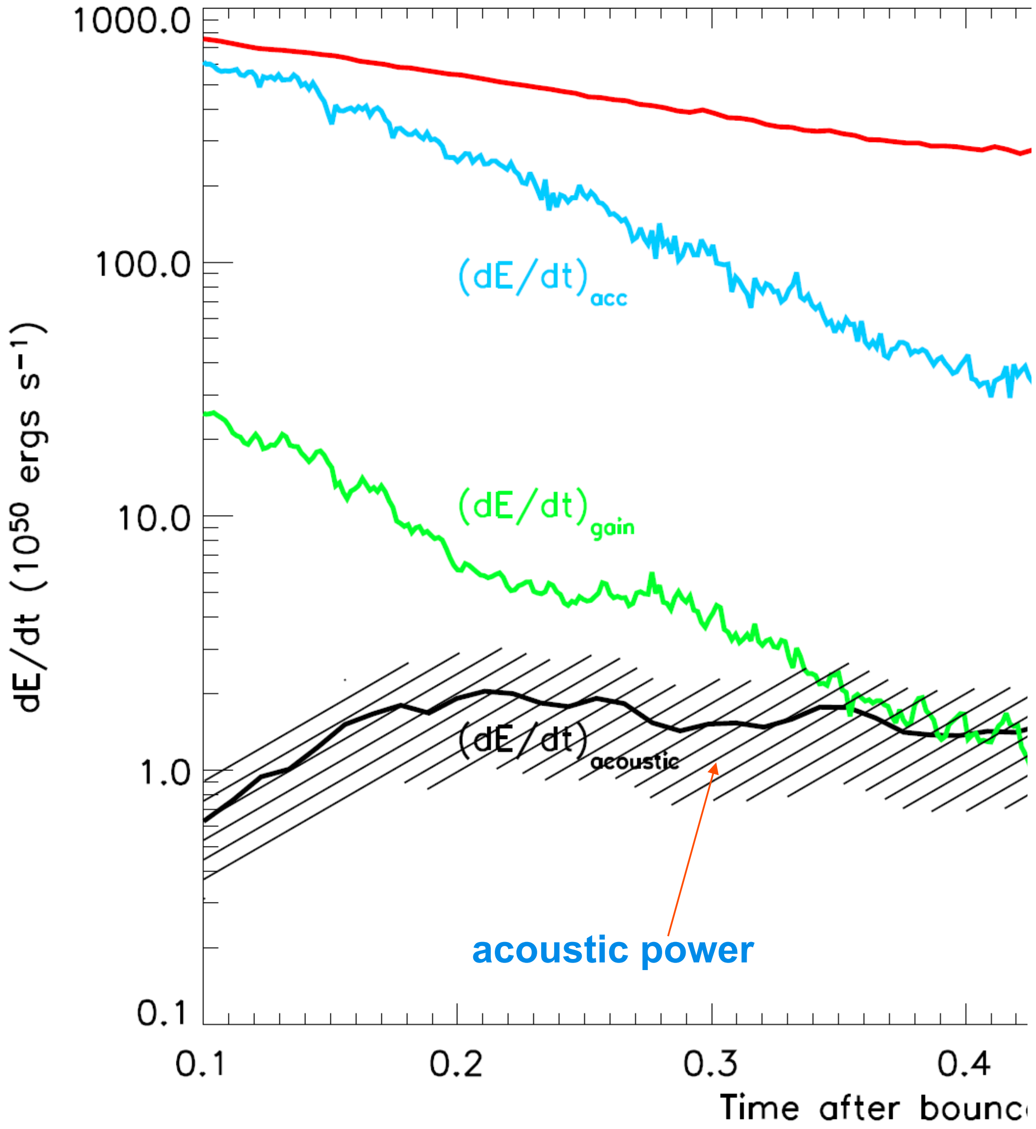


Marek et al. '08

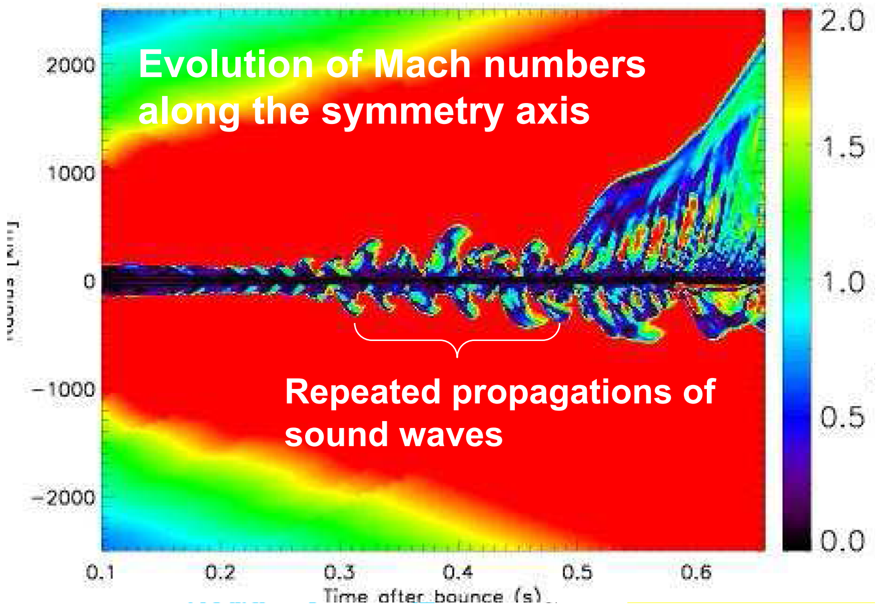


Acoustic Mechanism

Burrows et al. '06

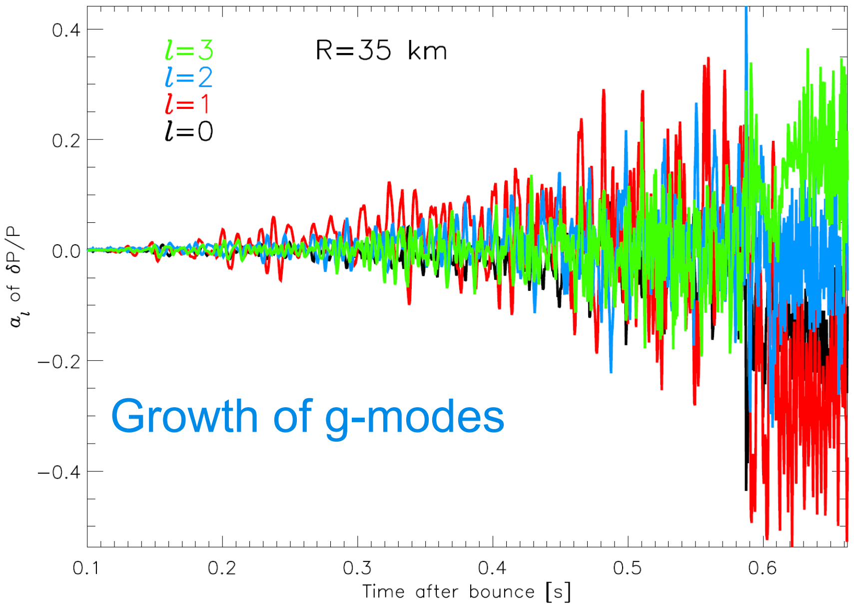


acoustic power



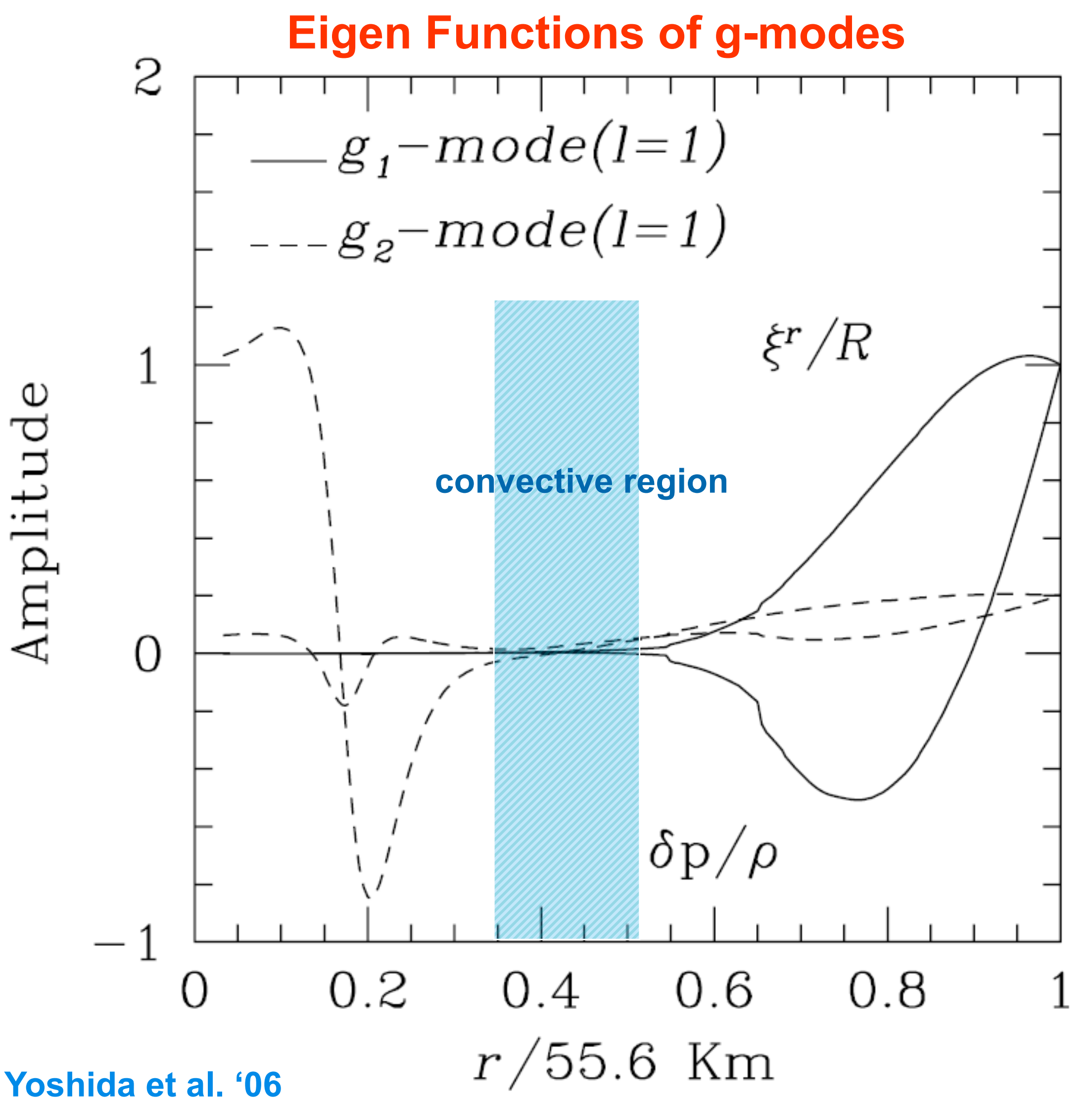
Evolution of Mach numbers along the symmetry axis

Repeated propagations of sound waves



Growth of g-modes

g-modes in a Proto Neutron Star



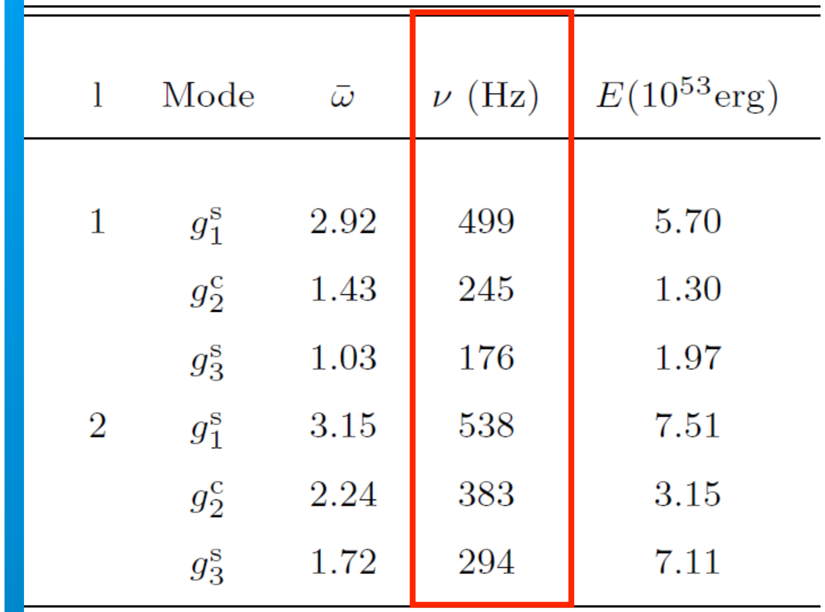
Yoshida et al. '06

— proto neutron star model

- spherically symmetric
- taken from the collapse-simulation of 15Msolar progenitor

- g-modes are divided into two classes:
  - core g-modes : g_n^c
  - surface g-modes : g_n

n:radial node number



l	Mode	$\bar{\omega}$	ν (Hz)	$E(10^{53}\text{erg})$
1	g_1^s	2.92	499	5.70
	g_2^c	1.43	245	1.30
	g_3^s	1.03	176	1.97
2	g_1^s	3.15	538	7.51
	g_2^c	2.24	383	3.15
	g_3^s	1.72	294	7.11

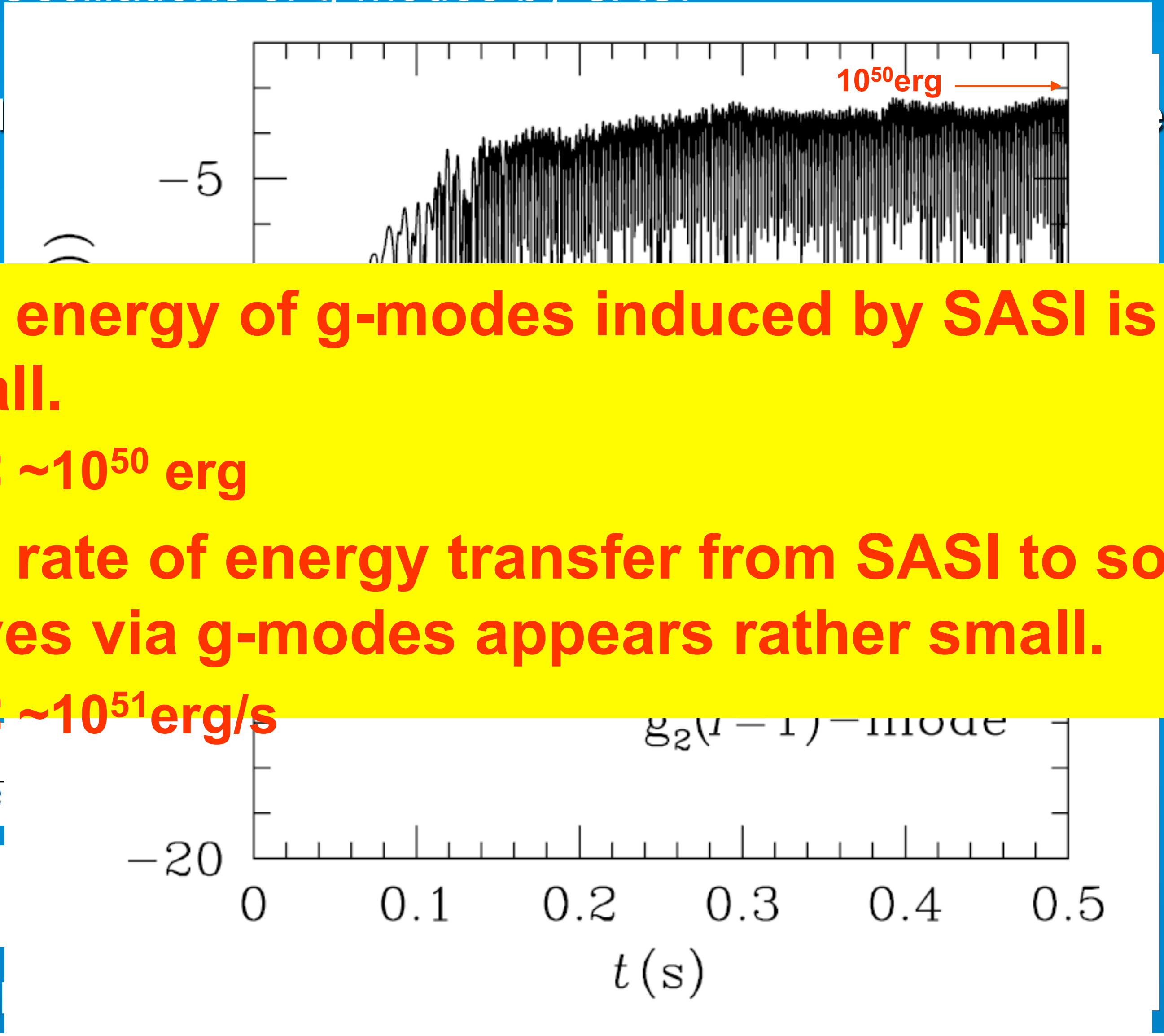
0 20 40 60

r(km)

g-mode Excitations by Nonlinear SASI

Yoshida et al. '07

- Forced Oscillations of g-modes by SASI
  - SASI … erturbation



l = 1
g_1-mode

- **The energy of g-modes induced by SASI is small.**
  - **< ~10^{50} erg**
- **The rate of energy transfer from SASI to sound waves via g-modes appears rather small.**
  - **< ~10^{51}erg/s**

$\frac{R}{GM^2}$

$B_\alpha(t)$

- Initial

g-mode Saturations via Mode-couplings

Weinberg & Quataert ‘08

- ✓ Equilibrium between a parent mode and two daughter modes (parametric resonance)

$$E_{1,\mathrm{eq}} = \frac{\gamma_2\gamma_3}{18\kappa^2\omega_2\omega_3}\left[1+\left(\frac{2\delta\omega}{\gamma_2+\gamma_3-\gamma_1}\right)^2\right]$$

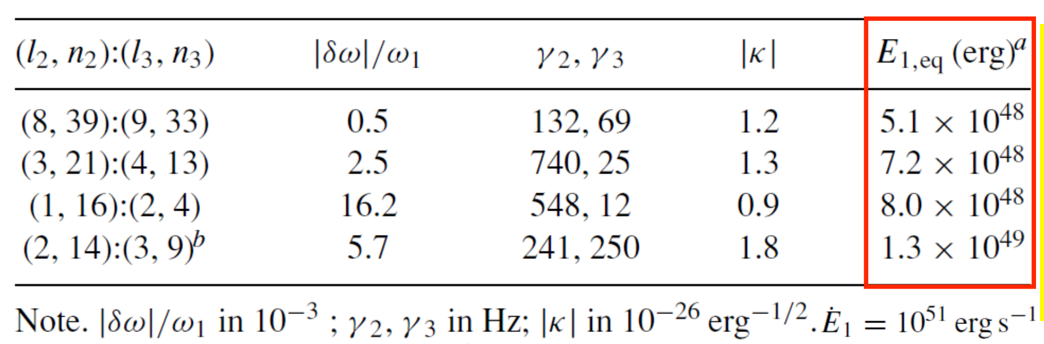
κ: coupling coefficient
ω: frequencies, γ: excitation or damping rates

— the parent mode : l=1, n=2 core g-mode
assumed to be excited at the rate of 10^{50}~10^{51} erg/s

— the daughter modes assumed to be damped by neutrino diffusions in the core

- ✓ Three mode couplings of the primary with all daughter modes with l=1~10, ω/ω_1=1/4~3/4 are taken into account.

— couplings between daughters with grand-daughters ignored



(l_2, n_2):(l_3, n_3)	$\lvert\delta\omega\rvert/\omega_1$	γ_2, γ_3	$\lvert\kappa\rvert$	$E_{1,\mathrm{eq}}$ (erg)[a]
(8, 39):(9, 33)	0.5	132, 69	1.2	5.1×10^{48}
(3, 21):(4, 13)	2.5	740, 25	1.3	7.2×10^{48}
(1, 16):(2, 4)	16.2	548, 12	0.9	8.0×10^{48}
(2, 14):(3, 9)[b]	5.7	241, 250	1.8	1.3×10^{49}

Note. $\lvert\delta\omega\rvert/\omega_1$ in 10^{-3} ; γ_2, γ_3 in Hz; $\lvert\kappa\rvert$ in 10^{-26} erg$^{-1/2}$. $\dot{E}_1 = 10^{51}$ erg s^{-1}

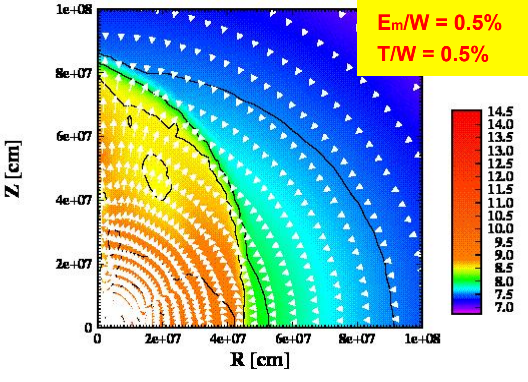
- ✓ The saturation levels are much smaller than found by Burrows et al.
- ✓ The daughter modes were not resolved by numerical simulati

Magneto-Rotational Mechanism

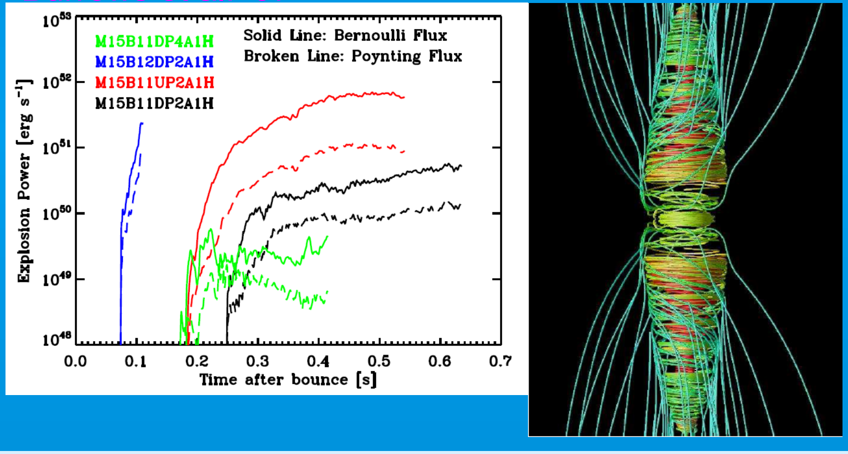
✓ Magnetic fields tap the free energy stored in differential rotations.

- gravitational energy → rotational energy → magnetic energy
- magnetic fields amplified by compression, wrapping and magneto-rotational instability (MRI)
- rapid rotation required: Ω_0 >~2s

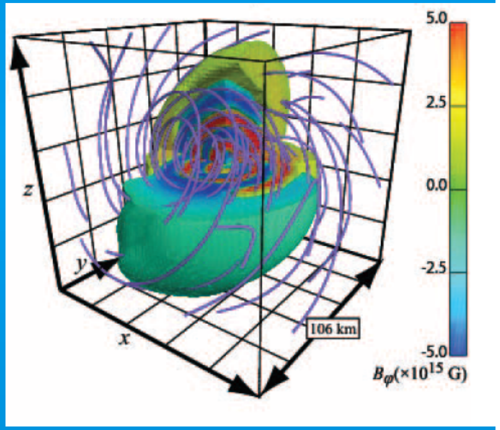
Yamada & Sawai '04



Burrows et al. '07



Mikami et al. '08



✓ Jets are commonly produced in the direction of the rotation axis either by the magneto-spring or magneto-centrifugal mechanism.

— Very strong initial field + rapid rotation induce explosions promptly.

— MRI will amplify magnetic fields exponentially if they are weak initially.

✓ Long term simulations suggest that the explosion may be "engine-driven".

✓ Toroidal fields change signs alternately for mis-aligned rotators in 3D.

Problems in Magneto-Rotational Mechanism

✓ MRI has not been fully resolved yet.

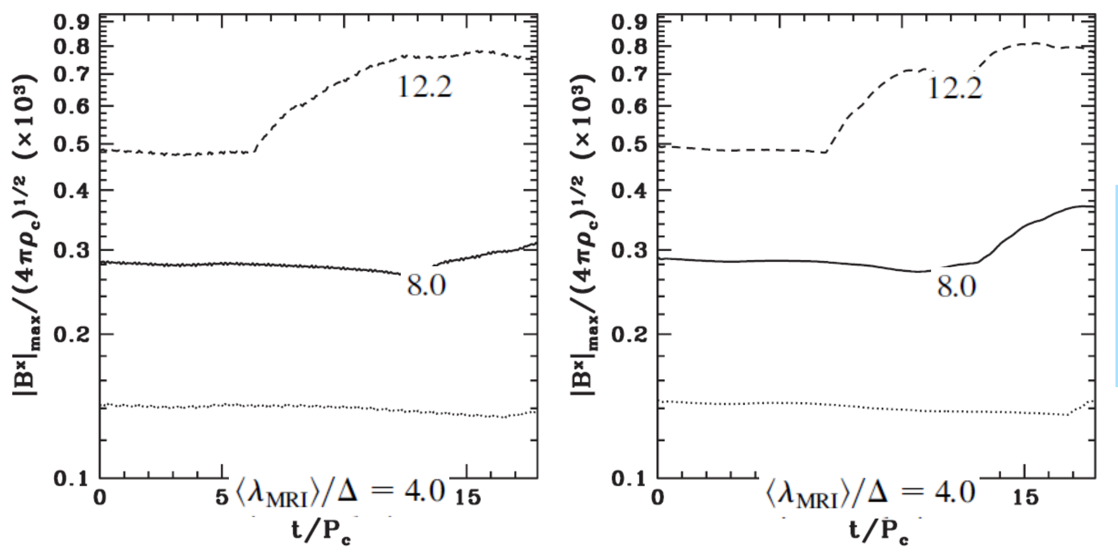
- MRI is supposed to be the most efficient agent to amplify magnetic fields.
- The wave length of the fastest growing mode of the magneto-rotational instability (MRI) is too small for realistic initial field strengths:

$$\lambda_{\mathrm{MRI}}^{\max} \approx \frac{2\pi v_A}{\Omega} \approx 10^4 \mathrm{cm}\, P_{10} \frac{B_{12}}{\rho_{11}^{1/2}}$$

- Relatively strong initial fields ($B_0 \gtrsim 10^{10}$ G) have been assumed so far.

✓ Rapid rotation ($\Omega_0 \gtrsim 2 \sec^{-1}$) is required.

✓ Initial field configurations are little known.

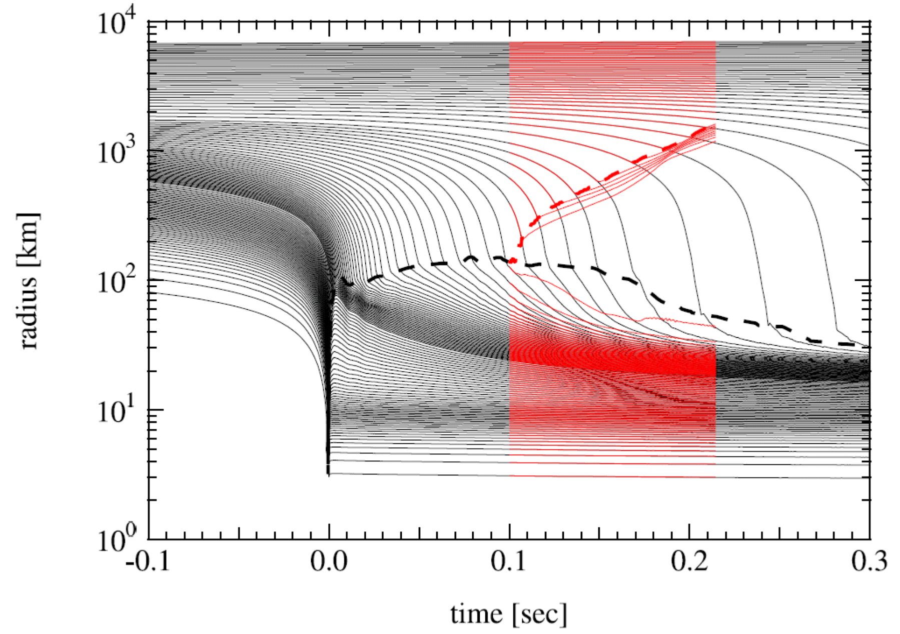


Etienne et al '06

✓ MRI could not be resolved unless the fastest growing mode wavelength is resolved by more than ~10 grid points.

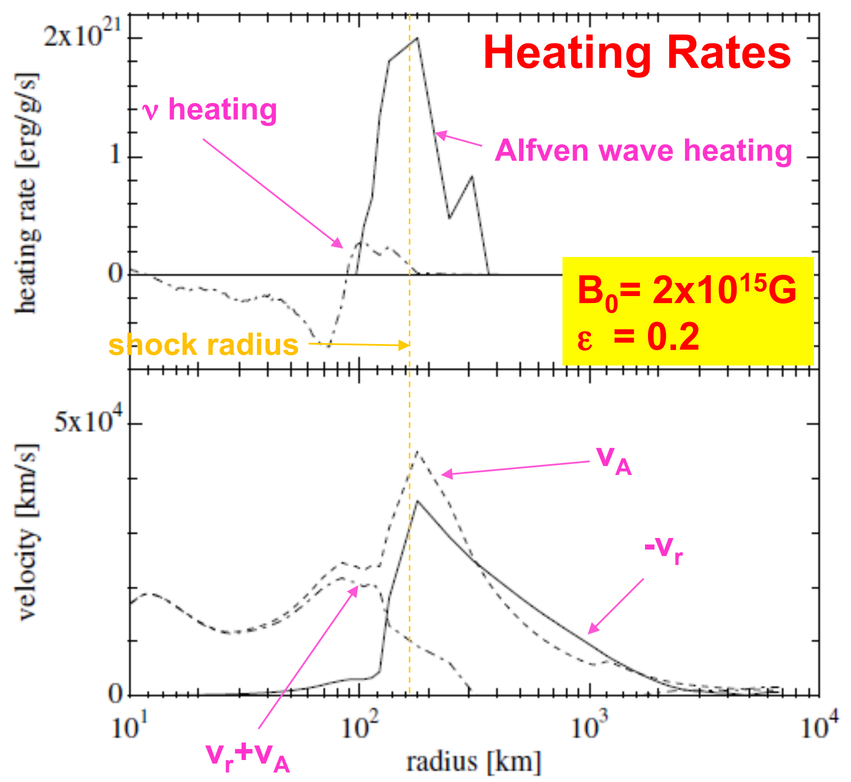
Alfven Wave Propagation and Dissipation

Suzuki et al. '07



The shock revives indeed!

※ Alfven wave heating added at 100ms after bounce



✓ Rotation is unnecessary if magnetic fields are strong enough.

✓ Alfven waves produced at the PNS surface propagate outward and are trapped near the shock. They dissipate by nonlinear wave couplings with other waves which then deposit energy to matter by shock heating.

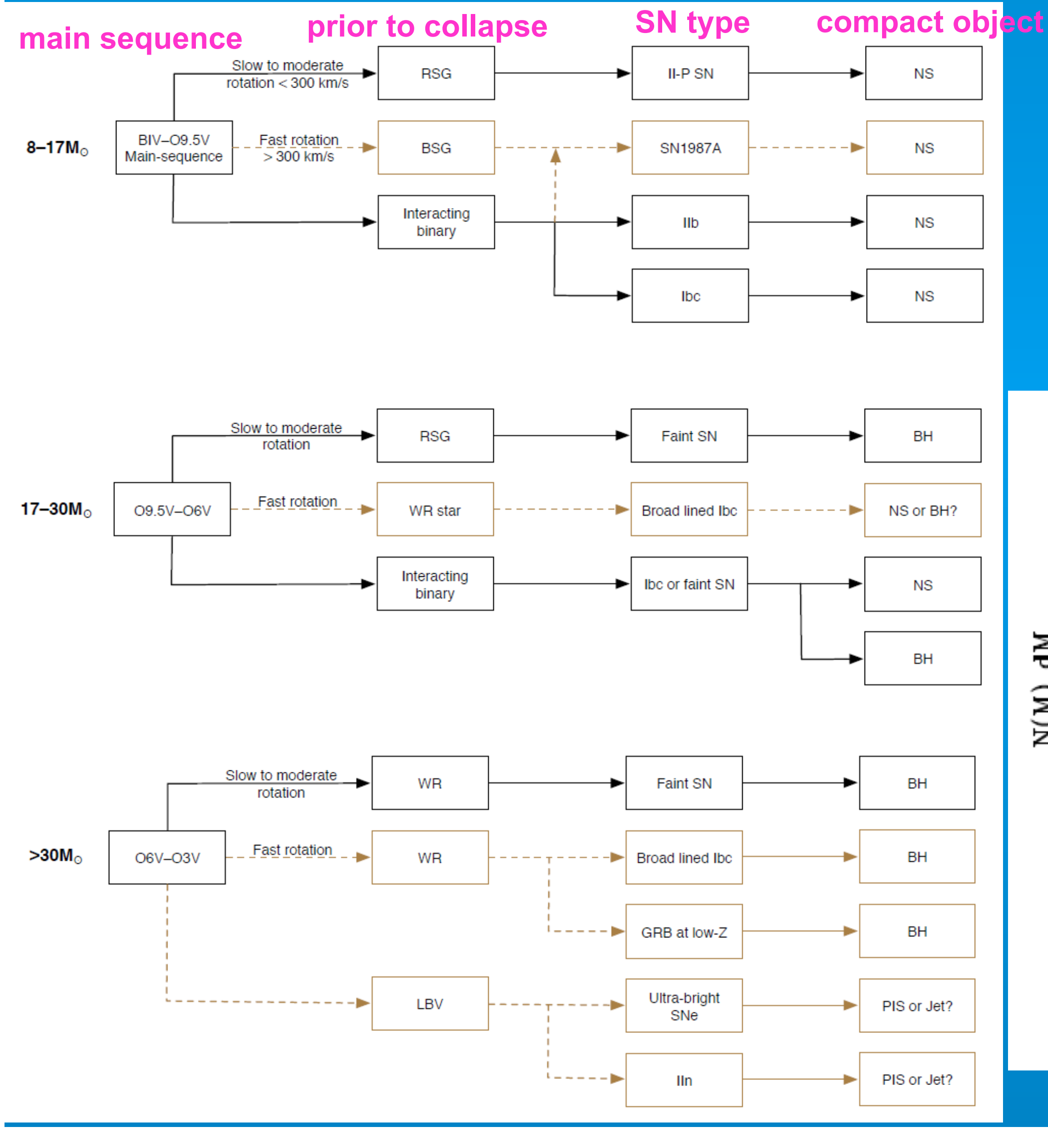
— dominant over ν heating if the surface magnetic field is of the magnetar scale and the velocity fluctuations are a few tens % of the sound velocity.

✓ Alfven wave heating occurs not only inside but also outside the stalled shock wave.

— preheating

Various Fates of Massive Stars

Smartt '09


main sequence
prior to collapse
SN type
compact object

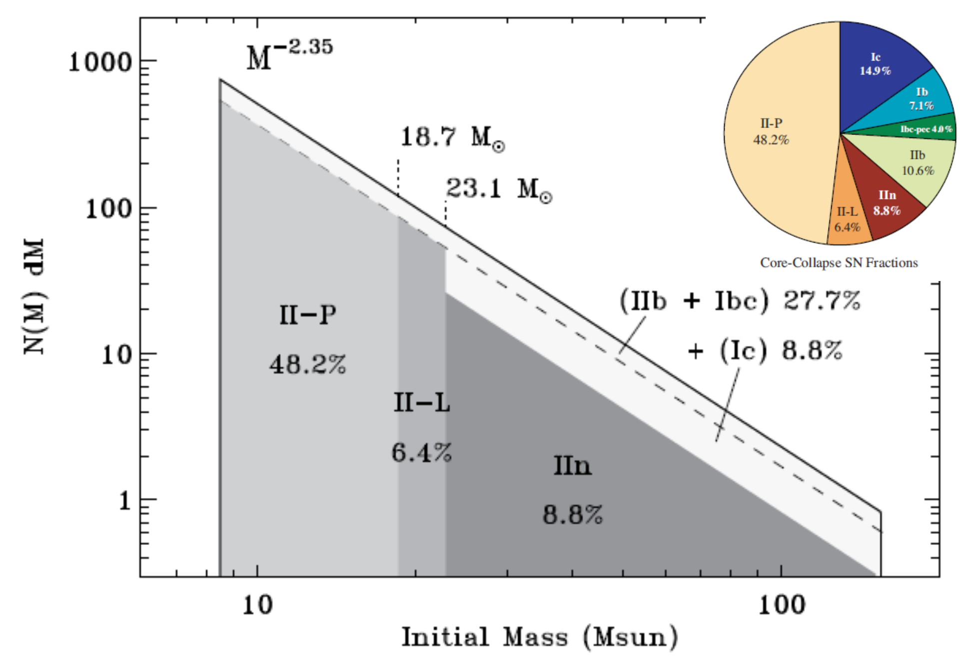
8–17M$_\odot$
BIV–O9.5V Main-sequence
Slow to moderate rotation < 300 km/s → RSG → II-P SN → NS
Fast rotation > 300 km/s → BSG → SN1987A → NS
Interacting binary → IIb → NS
Interacting binary → Ibc → NS

17–30M$_\odot$
O9.5V–O6V
Slow to moderate rotation → RSG → Faint SN → BH
Fast rotation → WR star → Broad lined Ibc → NS or BH?
Interacting binary → Ibc or faint SN → NS
Ibc or faint SN → BH

>30M$_\odot$
O6V–O3V
Slow to moderate rotation → WR → Faint SN → BH
Fast rotation → WR → Broad lined Ibc → BH
WR → GRB at low-Z → BH
LBV → Ultra-bright SNe → PIS or Jet?
LBV → IIn → PIS or Jet?

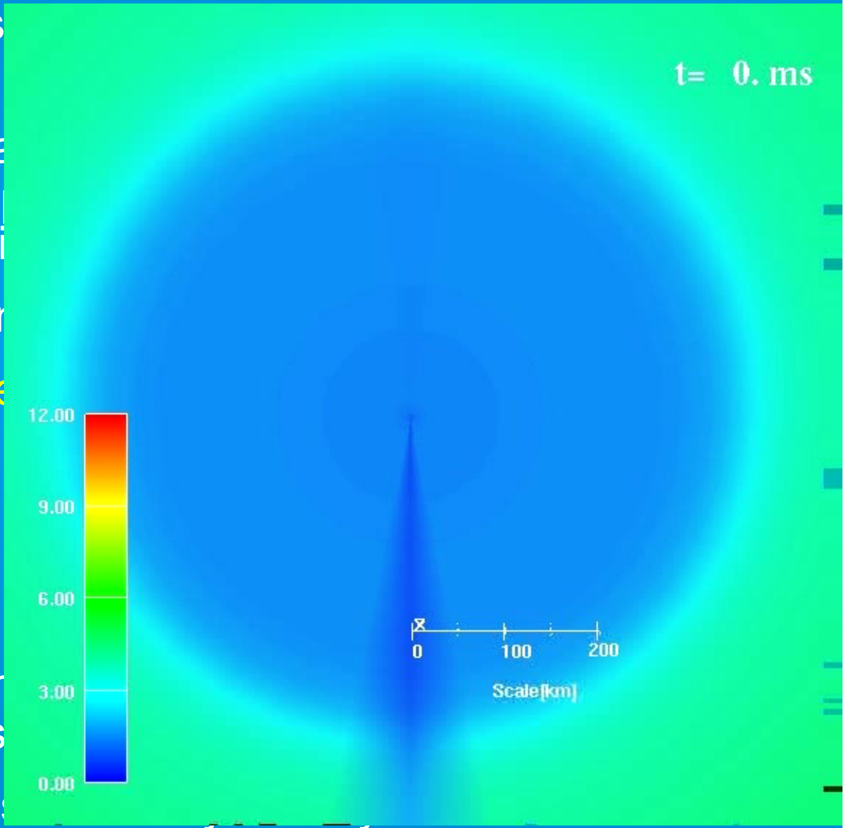
- ✓ Detections of some progenitors, more accurate estimates of SN rate and sophistication of stellar evolution theory give us better guess for the outcome of massive star collapses.

Smith '10



Summary

- The are currently three viable mechanisms: (1) neutrino heating, (2) acoustic, (3) magneto-rotational, but the first one is the most favorite in the supernova society. However,



  - — Neutrino heating seems to work only for less
    and to be under-energetic.
  - — The acoustic mechanism may work at very la
    fail and PNS oscillations are not severely su
    produce under-energetic explosions even if i
  - — The magneto-rotational mechanism works o
  - ※ Different mechanisms may operate for differe

- 3D may be the key ingredient.
  - — The critical luminosity may be smaller.
  - — 2D models are generically underenergetic a
    less massive stars at best. There are still dis
  - — SASI may be a natural explanation of the ob
    core-collapse supernova explosion.

- Further sophistications of the numerical treatment of neutrino transport, general relativity and magnetic field are needed.