“超新星爆発メカニズム”

- モデルの最近の進展 -

山田　章一

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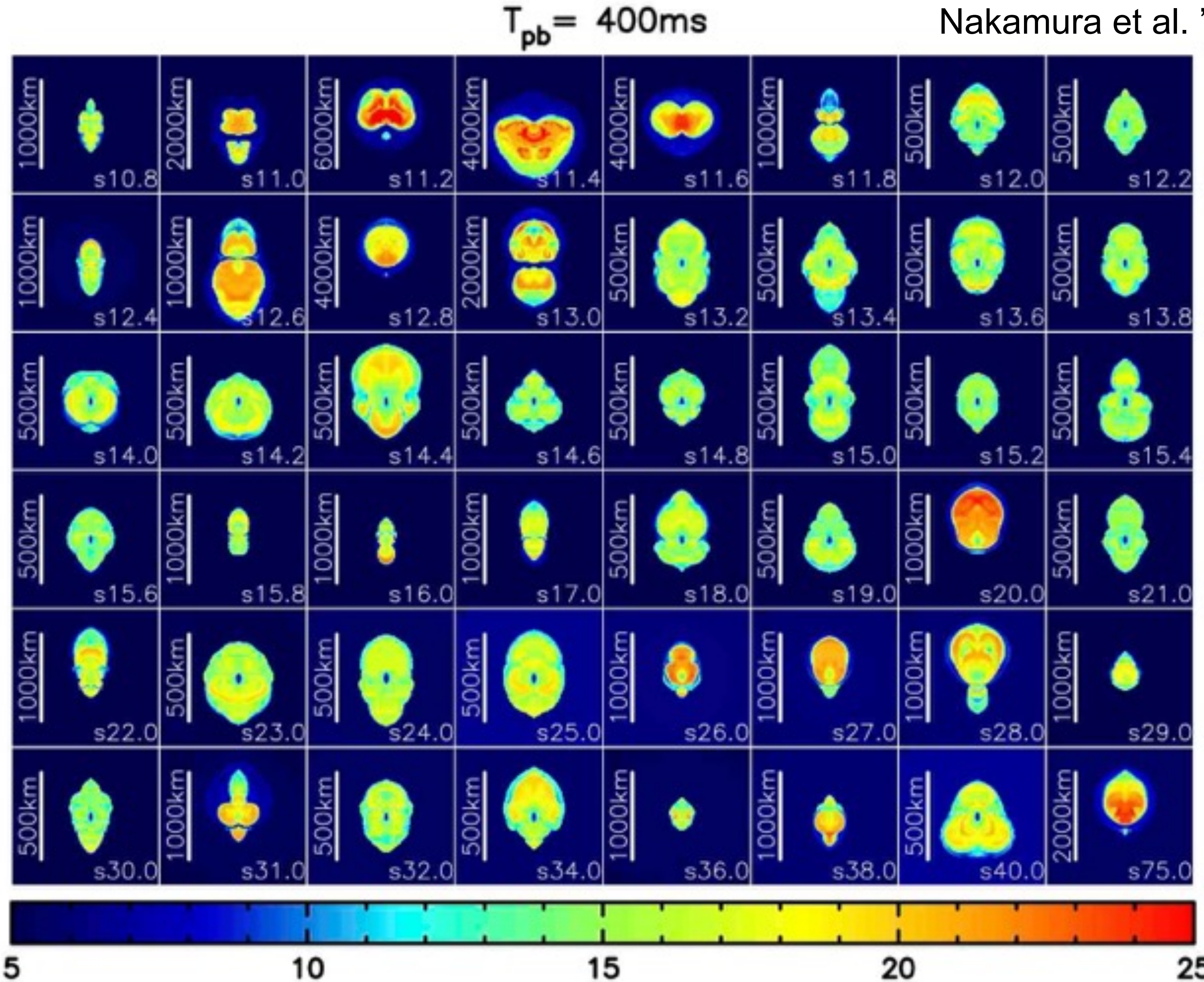
Nakamura et al. '15

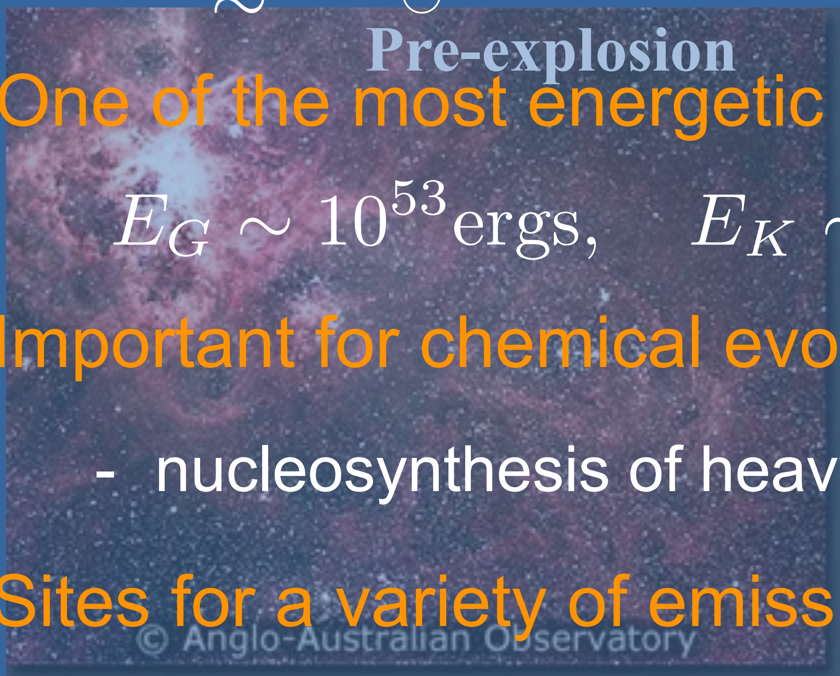


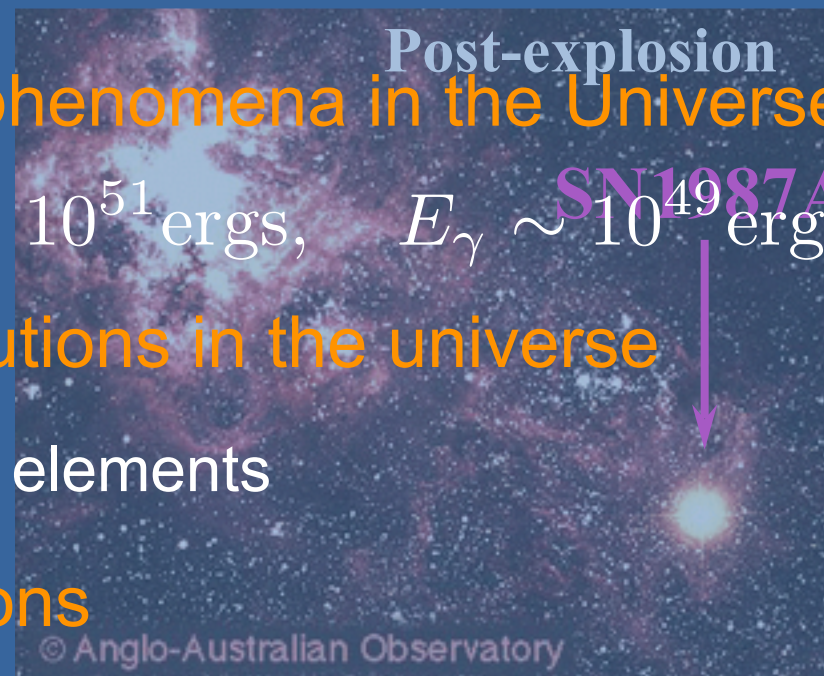
Introduction

Fundamentals of Core-Collapse Supernovae

- Triggered by the gravitational collapse of massive stars

$$M \gtrsim 8 M_\odot$$



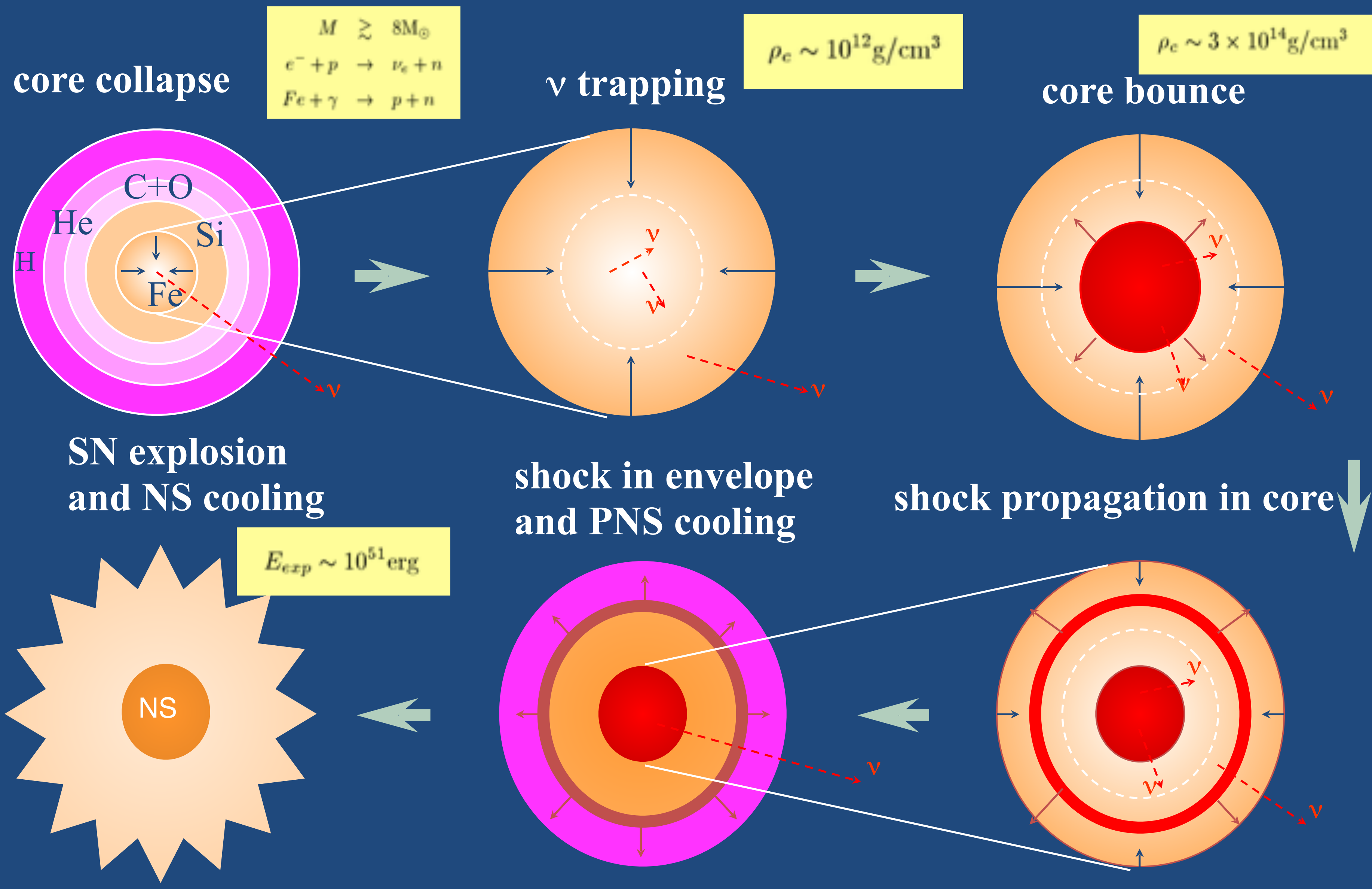


- One of the most energetic phenomena in the Universe

$$E_G \sim 10^{53} \text{ergs}, \quad E_K \sim 10^{51} \text{ergs}, \quad E_\gamma \sim 10^{49} \text{ergs}$$

- Important for chemical evolutions in the universe
  - nucleosynthesis of heavy elements
- Sites for a variety of emissions
  - neutrinos, gravitational waves, cosmic rays, UV, X-rays, gamma-rays in addition to optical photons

Scenario of Core-Collapse Supernovae



Some Scales of Relevance

✓ Length Scales

stellar radius: $10^{12} \sim 10^{14}\mathrm{cm}$

stellar core radius: $10^{8} \sim 10^{9}\mathrm{cm}$

neutron star radius: $\sim 10^{6}\mathrm{cm}$

ν mean free path: $\sim 10^{6}\mathrm{cm}\left(\frac{\varepsilon_\nu}{10\mathrm{MeV}}\right)^{-2}\left(\frac{\rho}{10^{12}\mathrm{g/cm^3}}\right)^{-1}$

- ✓ Neutrinos are effectively trapped in the core at $\rho \sim 10^{11}\mathrm{g/cm^3}$.
- ✓ β-equilibrium is established by weak interactions at $\rho \sim 10^{12}\mathrm{g/cm^3}$.

ν wave length: $\sim 20\mathrm{fm}\left(\frac{\varepsilon_\nu}{10\mathrm{MeV}}\right)^{-1}$

- ✓ Neutrinos are normally treated as classical particles except in considering neutrino oscillations.

nuclear radius: $\sim 5\mathrm{fm}\left(\frac{A}{56}\right)^{1/3}$

- ✓ Nuclei scatter neutrinos coherently if they are much smaller than the neutrino wave length.

Some Scales of Relevance

✓ Energy Scales

rest mass energy: $10^{54}\mathrm{erg}\left(\frac{M_{\mathrm{core}}}{\mathrm{M}_\odot}\right)$

gravitational energies:

pre-collapse core: $-10^{51}\mathrm{erg}\left(\frac{M_{\mathrm{core}}}{\mathrm{M}_\odot}\right)^2\left(\frac{R_{\mathrm{core}}}{10^8\mathrm{cm}}\right)^{-1}$

neutron star: $-10^{53}\mathrm{erg}\left(\frac{M_{\mathrm{core}}}{\mathrm{M}_\odot}\right)^2\left(\frac{R_{\mathrm{NS}}}{10^6\mathrm{cm}}\right)^{-1}$

shock wave energy at core bounce: $\sim$ several $\times\ 10^{51}\mathrm{erg}$

✓ The gravitational energy is mostly cancelled by the internal energy and the shock energy is a small residual.

✓ The internal energy is radiated as neutrinos later.

nuclear dissociation energy: $\sim 9\mathrm{MeV}$ per baryon $\sim 10^{51}\mathrm{erg}$ per $0.1\mathrm{M}_\odot$

✓ The shock energy is consumed mainly to dissociate nuclei.

✓ The shock is commonly stalled in the core.

Some Scales of Relevance

✓ Time Scales

life time of massive stars: $\lesssim 10^7 \mathrm{yrs}$

dynamical time scale: $\sim 10\mathrm{msec} \left(\frac{\rho}{10^{12}\mathrm{g/cm^3}} \right)^{-1/2}$

ν diffusion time: $\sim 100\mathrm{msec} \left(\frac{R_{\mathrm{core}}}{3 \times 10^6 \mathrm{cm}} \right)^2 \left(\frac{\varepsilon_\nu}{10\mathrm{MeV}} \right)^2 \left(\frac{\rho}{10^{14}\mathrm{g/cm^3}} \right)$

✓ The internal energy of proto neutron star is available for explosion only on this time scale, much longer than the dynamical time scale.

cooling time scale of proto neutron star:

$$\sim 10\mathrm{sec} \left(\frac{E_{\mathrm{PNS}}}{10^{53}\mathrm{erg}} \right) \left(\frac{L_\nu}{10^{52}\mathrm{erg/s}} \right)^{-1}$$

neutrino luminosities: $L_\nu \sim 2 \times 10^{52} \mathrm{erg/s} \left(\frac{R_{\mathrm{PNS}}}{10^6 \mathrm{cm}} \right)^2 \left(\frac{T_\nu}{4\mathrm{MeV}} \right)^4$

Challenges in Supernova Research

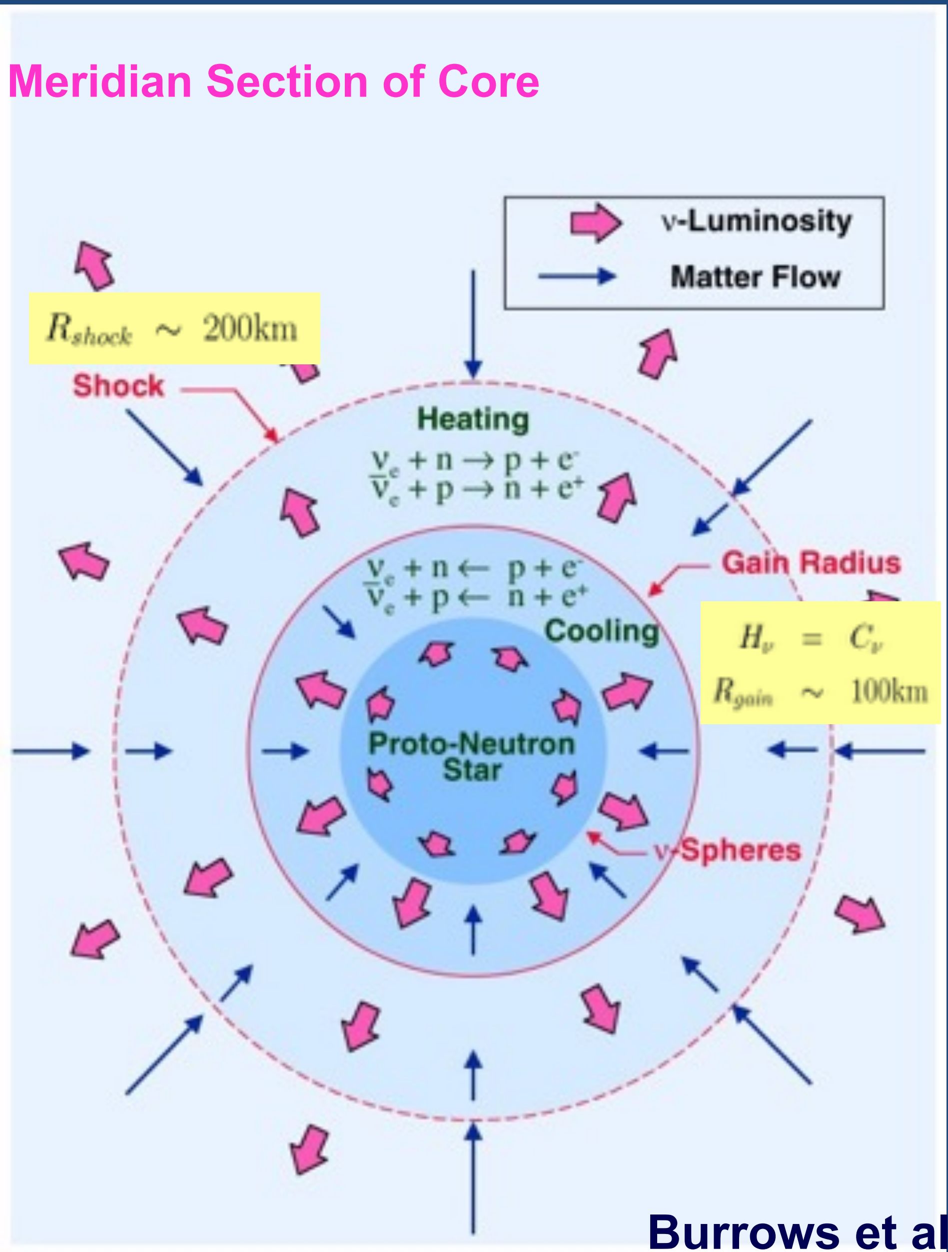
- ✓ The difficulty lies in transforming energies:

  gravitational energy → internal energy → kinetic energy

  gravitational energy → rotational energy → magnetic energy → kinetic energy

- ✓ At present, the neutrino-heating mechanism is supposed to be most promising.
  - Magnetorotational mechanism may be necessary to give hypernovae with explosion energies of ~10^{52}ergs.
  - Acoustic mechanism may work if nothing else succeeds in explosion.
- ✓ Multi-dimensional hydrodynamics is supposed to play a crucial role.
  - 3D dynamics, particularly instabilities such as ν-driven convections, standing accretion shock instability (SASI), magneto-rotational instability (MRI), etc.
  - Multi-dimensional ν transfer
  - rotation

Neutrino Heating Mechanism



Burrows et al.

- ✓ Most of the liberated gravitational energy is stored in the proto neutron star as internal energy, which can be tapped by neutrinos.

$$-E_G \sim E_{int} \sim 10^{53}\text{erg}$$

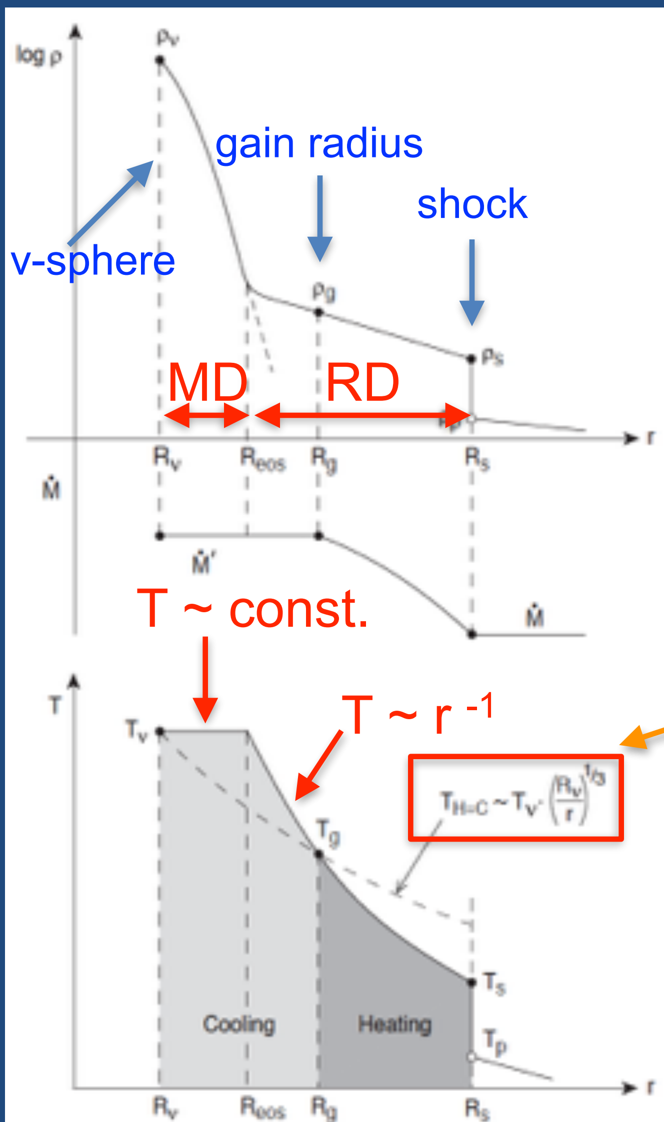
- ✓ The initial shock energy is not large enough to push through the outer core. The shock is stalled inside the core and becomes an standing accretion shock.

- ✓ Neutrinos cool matter near the proto neutron star and heat mattre near the shock. The gain radius divides the two regions.

- ✓ The spherically symmetric con-figuration is unstable and becomes non-spherical spontaneously.

Neutrino Heating Mechanism: why does it work?

Janka '01



✓ Neutrino Heating Rate

$$Q_\nu^+ \approx 160\mathrm{Mev/s}\frac{\rho}{m_a}\frac{L_{\nu_e,52}}{r_7^2\langle\mu_\nu\rangle}\left(\frac{T_{\nu_e}}{4\mathrm{MeV}}\right)^2$$

✓ Neutrino Cooling Rate

$$Q_\nu^- \approx 145\mathrm{Mev/s}\frac{\rho}{m_a}\left(\frac{T}{2\mathrm{MeV}}\right)^6$$

$$\Rightarrow \quad T_{H=C} \propto r^{-1/3}$$

✓ Heating balances cooling inside v-sphere.

✓ In matter-dominated region, *T* is nearly constant whereas *T* is proportional to 1/*r* in radiation dominated region.

✓ Gain radius occurs in RD regime as long as shock is located far enough.

Criterion for Successful Neutrino Heating

✓ For a given accretion rate, there is a critical neutrino luminosity, at which the stalled shock wave revives.

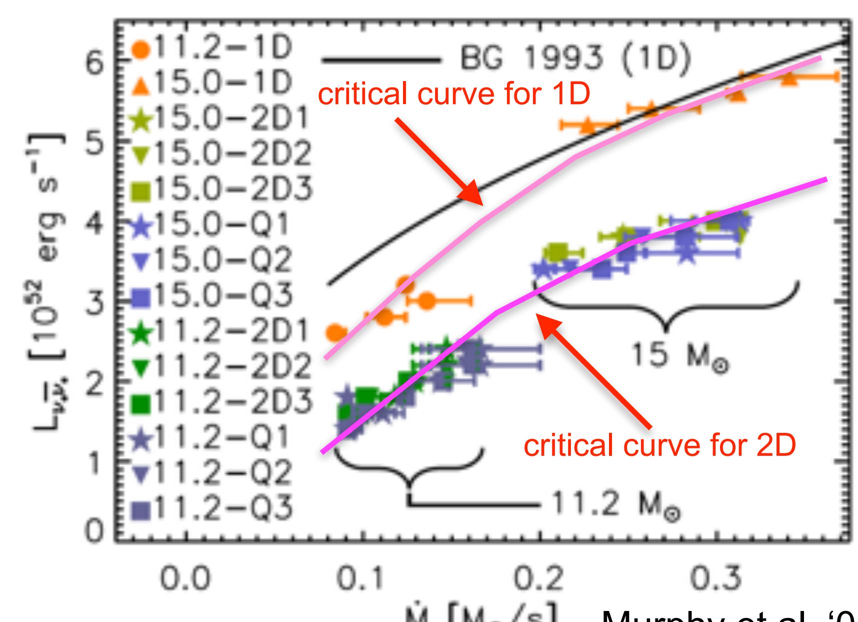
- There is a neutral radial mode at the critical luminosity.
- SASI sets in earlier than radial modes.

✓ The critical neutrino luminosity may be obtained from: $\tau_{adv} = \tau_q$

τ_{adv}: **advection time**

τ_q : **heating time**

✓ The critical luminosity is lower for 2D/3D than for 1D by enhanced ν-heating owing to efficient feeding of cold matter and longer dwell time in turbulence.



Murphy et al. '08

$$\tau_{\rm adv} = \int_{R_g}^{R_s} \frac{dr}{|v_r|} \propto R_S^{3/2} M_{\rm PNS}^{3/2}$$

$$\tau_{\rm q} = \frac{E_{\rm b}}{Q_\nu^+} \propto \frac{M_{\rm PNS} R_g}{L_\nu T_\nu^2}$$

$$R_g \propto R_\nu \propto \frac{L_\nu^{1/2}}{T_\nu^2} \qquad R_s \propto \frac{L_\nu^{4/3}}{\dot{M}^{2/3} M_{\rm PNS}^{1/3} T_\nu^{8/3}}$$

$$\tau_{\rm adv} = \tau_q \iff L_{\nu,c}(M) \propto \dot{M}^{2/5} M_{\rm PNS}^{4/5}$$

A Brief Review of the Research on CCSN Mechanism

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 modelling Colgate & White '66 Arnett '67		First 2D simulations LeBlanc & Wilson '70 Some early discussions on magneto-rotational scenario Bisnovatyi-Kogan et al. '76 Meier et al. '76
1975	Beginning of Modern Theory **Neutrino-trapping** Sato '75		

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	More precise treatment of neutrino transport Mezzacappa et al. ’93 Yamada et al. ‘97 Criterion for explosions via neutrino-heating mechanism Burrows & Goshy ’93	Beginning of modern multi-D Simulations Herant et al. ’94	Simulations of rapidly rotational collapse Moenchmeyer et al. ’91 Yamada & Sato ’94

Time Line	No Rotation or Slow Rotation: 1D	No Rotation or Slow Rotation: 2D/3D	Rapid Rotation and/or Magnetic Fields
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	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	Multi-D simulations with sophisticated neutrino transport **Neutrino-heating mechanism** Marek et al. '07 Bruenn et al. '06 Ott et al. '08 **Acoustic mechanism** Burrows et al. '07	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 3D magneto-rotational collapse Mikami et al. '08

Progenitor Mass	MPA	Oak Ridge	Arizona
$8.8M_{solar}$ ONeMg core (Nomoto '84)	○ **ν-heating without SASI** **t_{exp}~<100ms** **E_{exp}~10^{50}erg at t_{pb}~800ms**	—	—
$11M_{solar}$ (Woosley et al. '95)	—	○ **ν-heating with SASI + nucl. burning (※no explosion without nucl. burning)** **t_{exp}~100ms** **E_{exp}~10^{51}erg at t_{pb}~700ms**	○ **acoustic mechanism (※no explosion via neutrino heating)** **t_{exp}~500ms** **E_{exp} : unavailable but maybe small**
11.2 (Woosley et al. '02)	○ **ν-heating with SASI** **t_{exp}~100ms** **E_{exp}~10^{49}erg at t_{pb}~220ms**	—	○ **acoustic mechanism (※no explosion via neutrino heating)** **t_{exp}~1100ms** **E_{exp} : unavailable but maybe small**

Progenitor Mass	MPA	Oak Ridge	Arizona
$13M_{solar}$ (Woosley et al. '02)	—	—	○ **acoustic mechanism (※no explosion via neutrino heating)** **t_{exp}~1300ms** **E_{exp} : unavailable but maybe small**
$13M_{solar}$ (Nomoto et al. '88)	—	—	○ **acoustic mechanism (※no explosion via neutrino heating)** **t_{exp}~1100ms** **E_{exp} : unavailable but maybe small**
$15M_{solar}$ (Woosley et al. '02)	—	—	○ **acoustic mechanism (※no explosion via neutrino heating)** **t_{exp}~1100ms** **E_{exp} : unavailable but maybe small**

Progenitor Mass	MPA	Oak Ridge	Arizona
$15M_{solar}$ (Woosley et al. '95)	○ ν-heating with SASI t_{exp}~500ms E_{exp}~10^{49}erg at t_{pb}~700ms	○ ν-heating with SASI + nucl. burning (※no explosion without nucl. burning) t_{exp}~500ms E_{exp}~0.3×10^{51}erg at t_{pb}~700ms	—
$20M_{solar}$ (Woosley et al. '02)	× up to t_{pb}=250ms (※90deg. Wedge)	—	○ acoustic mechanism (※no explosion via neutrino heating) t_{exp}~1300ms E_{exp} : unavailable but maybe small
$25M_{solar}$ (Woosley et al. '02)	—	—	○ acoustic mechanism (※no explosion via neutrino heating)

- ✓ No model is studied by three groups.
- ✓ It is unclear why Arizona group does not observe neutrino heating mechanism for the models, for which another group does.
- ✓ The computations by MPA and Oak Ridge groups may be too short to see the acoustic revival.

✓ List of successful shock revival (from Kotake '12)

Progenitor	Group (Year)	Mechanism	Dim. (Hydro)	t_{exp} (ms)	E_{exp}(B) t_{pb} (ms)	ν transport (Dim, $\mathcal{O}(v/c)$)
8.8 $M_\odot$	MPA (2006,2011)	ν-driven	1D(2D) (PN)	$\sim$200	0.1 ($\sim$800)	Boltzmann 2, $\mathcal{O}(v/c)$
(NH88)	Princeton+ (2006)	ν-driven	2D (N)	$\lesssim$125	0.1 -	MGFLD 1, (N)
10 $M_\odot$ (WHW02)	Basel (2009)	ν+(QCD transition)	1D (GR)	255	0.44 (350)	Boltzmann 2, (GR)
11 $M_\odot$ (WW95)	Princeton+ (2006)	Acoustic	2D (N)	$\gtrsim$550	$\sim$0.1* (1000)	MGFLD 1, (N)
11.2 $M_\odot$	MPA (2006,2012)	ν-driven	2D (PN, *C-GR*)	$\sim$100 *$\sim$200*	$\sim$ 0.005, *0.025* $\sim$200, *900*	"RBR" Boltzmann, 2, $\mathcal{O}(v/c)$
(WHW02)	Princeton+ (2007)	Acoustic	2D (N)	$\gtrsim$1100	$\sim$0.1* (1000)	MGFLD 1, (N)
	Tokyo+ (2011)	ν-driven	3D (N)	$\sim$100	0.01 (300)	IDSA 1, (N)
12 $M_\odot$ (WHW02)	Oak Ridge+ (2009)	ν-driven	2D (PN)	$\sim$300	0.3 (1000)	"RBR" MGFLD 1, $\mathcal{O}(v/c)$
13 $M_\odot$ (WHW02)	Princeton+ (2007)	Acoustic	2D (N)	$\gtrsim$1100	$\sim$0.3* (1400)	MGFLD 1, (N)
(NH88)	Tokyo+ (2010)	ν-driven	2D (N)	$\sim$200	0.1 (500)	IDSA 1, (N)
15 $M_\odot$ (WW95)	MPA (2009,2012)	ν-driven	2D (PN, *C-GR*)	$\sim$600 *$\sim$400*	0.025, *0.125* ($\sim$700, *800*)	Boltzmann 2, $\mathcal{O}(v/c)$
(WHW02)	Princeton+ (2007)	Acoustic	2D (N)	-	- (-)	MGFLD 1, (N)
	OakRidge+ (2009)	ν-driven	2D (PN)	$\sim$300	$\sim$ 0.3 (600)	"RBR" MGFLD 1, $\mathcal{O}(v/c)$
20 $M_\odot$ (WHW02)	Princeton+ (2007)	Acoustic	2D (N)	$\gtrsim$1200	$\sim$0.7* (1400)	MGFLD 1, (N)
25 $M_\odot$ (WHW02)	Princeton+ (2007)	Acoustic	2D (N)	$\gtrsim$1200	- (-)	MGFLD 1, (N)
	Oak Ridge+ (2009)	ν-driven	2D (PN)	$\sim$300	$\sim$ 0.7 (1200)	"RBR" MGFLD 1, $\mathcal{O}(v/c)$

✓ MMCOCOS 2013

✓ More recently,

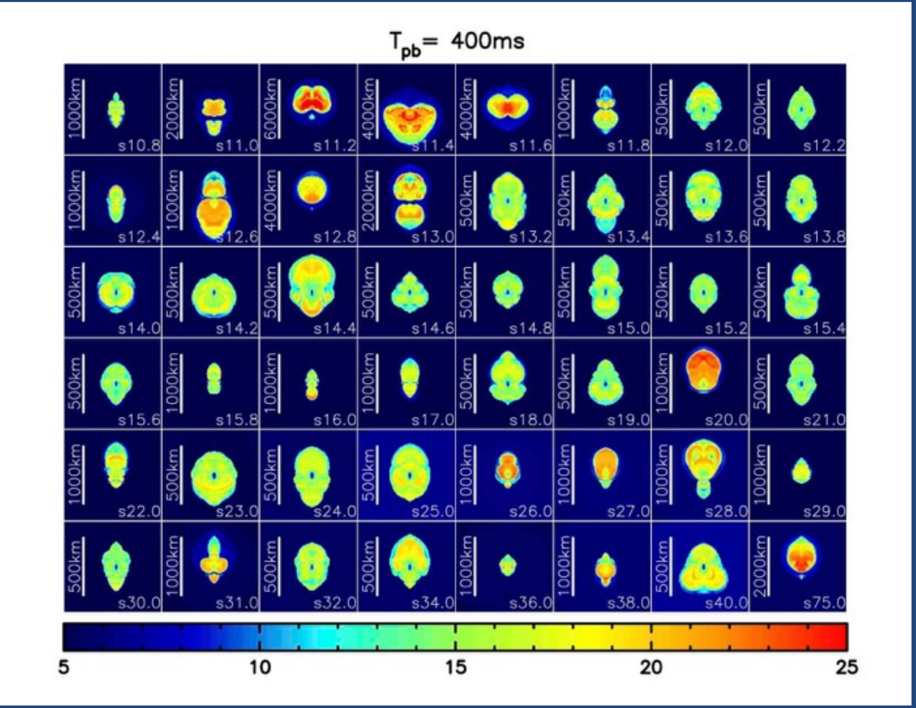
- MPA group added 2D GR simulations:
  - 8.1M_{solar} (Heger+12, Z=10^{-4}) ○
  - 9.6M_{solar} (Heger, Z=0) ○
  - 25M_{solar} (WHW02, Z_{solar}) ×
  - 27M_{solar} (WHW02, Z_{solar}) ○
- They also reported 3D simulations for
  - 11.2M_{solar}(WHW02)
    20M_{solar}(WH07)
    27M_{solar}(WHW02)

  which has not exploded so far.

Recent 2D Models

✓Nakamura et al. '14:

- more than 350 models in 2D
  - Solar-metallicity stars (s) : **101** models
    M_ZAMS = 10.8 - 40.0 + 75.0 Msun
  - UMP (Zsun/10^4) stars (u) : **247** models
    M_ZAMS = 11.0 - 60.0 + 75.0 Msun
  - Zero-metallicity stars (z) : **30** models
    M_ZAMS = 11.0 - 40.0 Msun



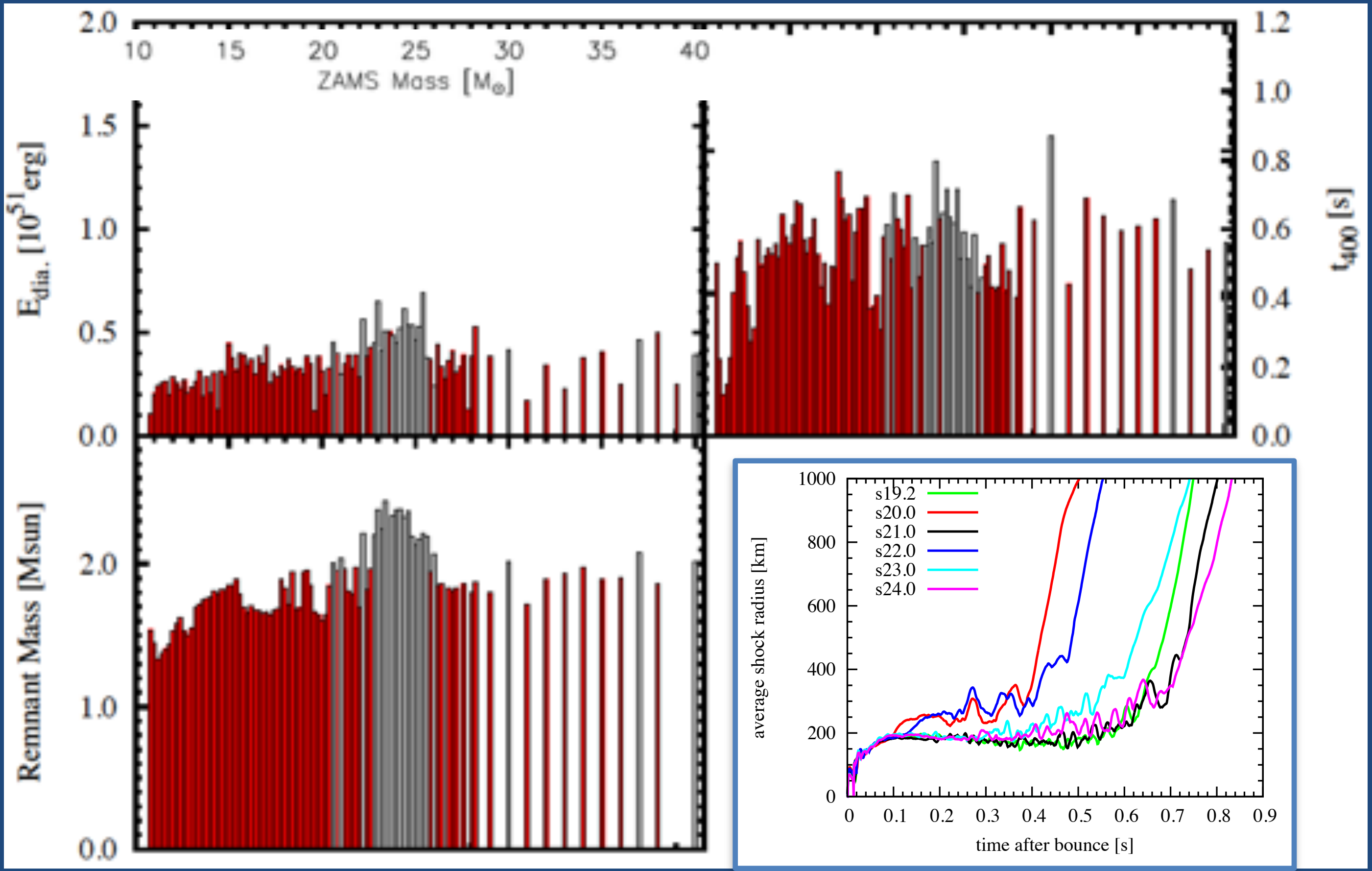
- investigate the systematics of shock revival by neutrino heating
  - shock revival obtains more often than not
  - importance of compactness
  - Horiuchi et al. '14 proposed a possible solution to the RSG problem and the SN rate problem.

Ab Initio 2D Simulations for Various Progenitors

✓ Shock radii are not monotonous with ZAMS.

✓ The compactness parameter again seems to be the best measure for the explosion properties.

✳ t_{400} is the time when the average shock radius reaches R = 400km.



✓ Beware: it is too early to judge the final outcomes.

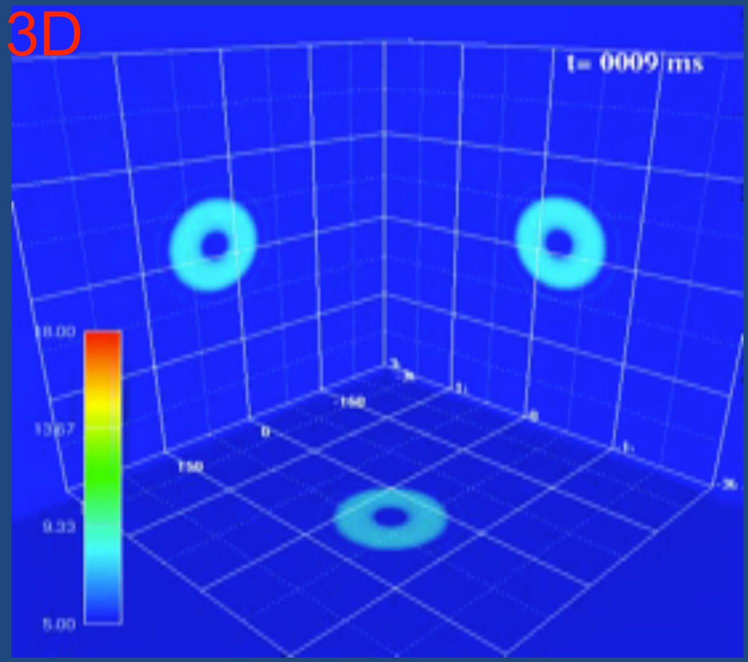
Longer simulations with an appropriate physics included are needed.

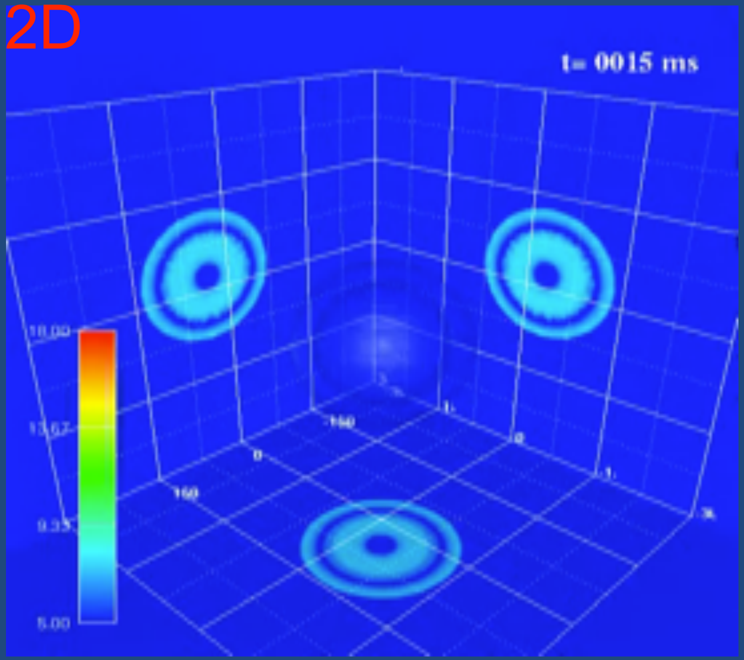
3D Models

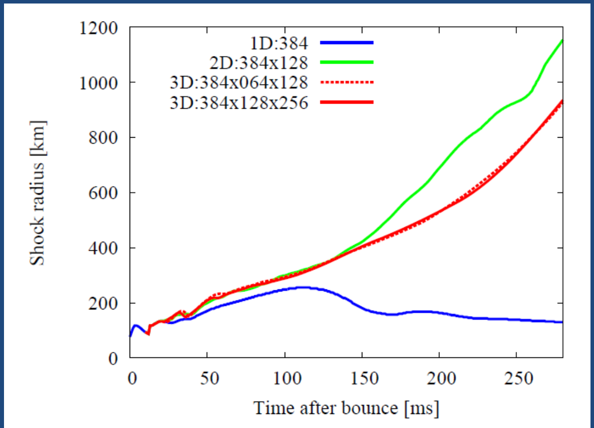
✓ Takiwaki, Kotake, Suwa '14:

- 11.2 M_{sun} progenitor (Woosley, Heger, Weaver, 2002)
- IDSA scheme, LS220 EOS

Next Talk !







✓ 2D is easier to explode.
- In 2D, coherent motions develop along "the axis".
- In 3D, kinetic energy "cascades" via turbulence into smaller scale.

✓ Systematic studies like those by Nakamura et al. in 2D are mandatory also in 3D!

What makes these differences after all?

- ✓ After many years of failed attempts to produce supernova explosions on computer, we now have a large number of models that lead to successful shock revival.
  - More than a hundred 2D models have been computed for a wide range of progenitor masses and metallicities, and shock revival has been observed more often than not.
  - There are some 3D models, e.g. $11.2M_{solar}$ model by Takiwaki et al. '13, which are reported to yield a successful shock revival.
- ✓ Ever increasing computer power as well as more elaborate numerical schemes for ν transfer are mainly responsible for the "differences".
  - In earlier simulations, computations were just too short and the choices of progenitor and/or EOS were also unlucky.
    - Ray-by-ray approximation, IDSA, FLD have made longer computations easier.
    - Lighter progenitors and/or softer EOS's are better for shock revival.
  - The importance of nuclear network calculations was disputed.
  - Although sophistications in the treatment of ν reactions and GR were often claimed to be important, it is unclear if they were the critical elements for the "differences".
    - e.g. non-isoenergetic scatterings on nucleons

Words of Caution

- ✓ The current situations remind me of those in the 1990's, when realistic 2D simulations had just begun and optimism prevailed in the society based on some results.
  - The early expectations fizzled as numerical methods were sophisticated.
- ✓ There are still some discrepancies between different groups, which may not be surprising, provided the different approximations to multi-dimensional ν transfer, treatments of various neutrino reactions and GR gravity.
  - For some progenitors, the success of ν-heating mechanism itself is challenged.
  - Even if different groups agree on the success of ν-heating mechanism, when and how shock revival occurs as well as the subsequent behavior of the revived shock wave are not agreed on.
  - It is also still inconclusive whether 3D is more advantageous for shock revival than 2D.
- ✓ All multi-dimensional simulations done so far employed approximations of various levels for neutrino transfer.
  - ray-by-ray, FLD, IDSA, leakage, light bulb
- ✓ Shock revival is a necessary but not a sufficient condition for successful SN explosions.
  - Observed explosion energy and nucleosynthetic yields should be reproduced.

When and How the Explosion Energy is Fixed?

- ✓ This is an important issue to to be settled now.
  - We have a large number of models to give shock revival.
  - The diagnostic explosion energy differs significantly from model to model at the end of simulations (t_{pb}~1sec).
  - Some of them appear promising. But are they really explode with appropriate energy and luminosity?

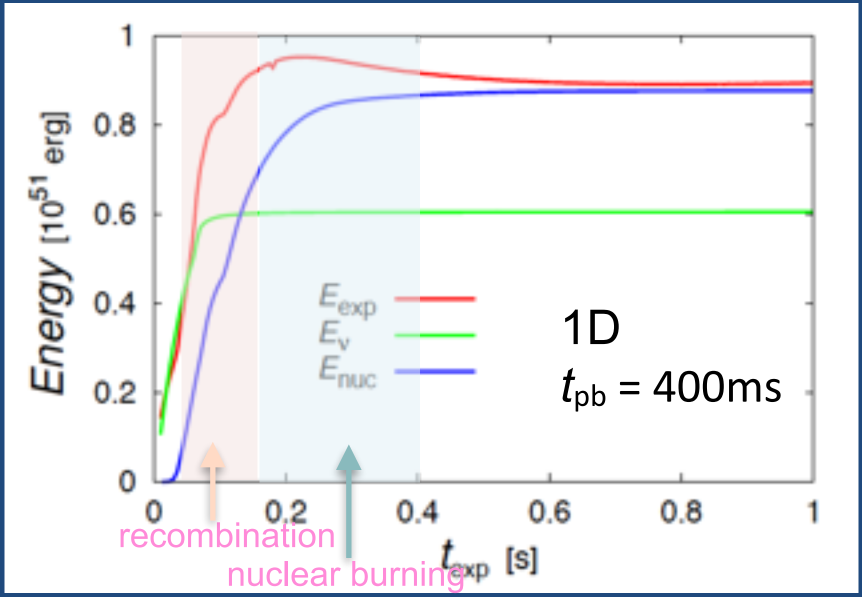
- ✓ Note that shock revival is a necessary condition for successful explosion but may not be a sufficient one indeed.
  - Numerical experiments demonstrated that it takes a few seconds until the explosion energy is fixed.
  - The mass of nickel to be ejected tends to be settled even later.
  - The explosion energy and nickel mass are functions of shock revival time and there appears to be a relatively narrow window that gives right values to them.

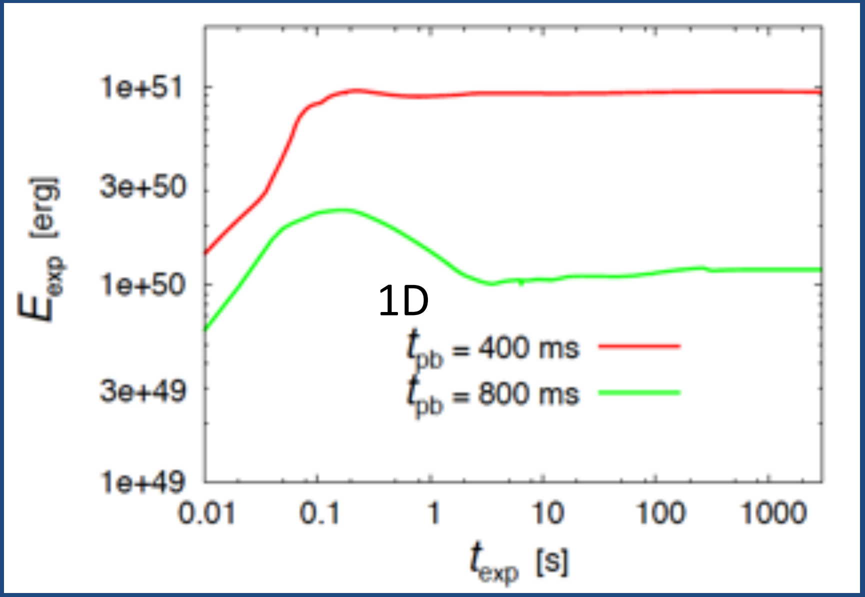
Shock revival may not be sufficient!

Yamamoto et al. ’12:

✓ Assuming that shock revival occurs somewhere on the critical line, they study the explosion energy & synthesized ^{56}Ni mass as a function of the shock revival time in 1D and 2D simulations.

— long-term simulations of post-shock-revival evolutions of ejecta
— nuclear reactions and their feedback to dynamics taken into account consistently with a non-NSE EOS.



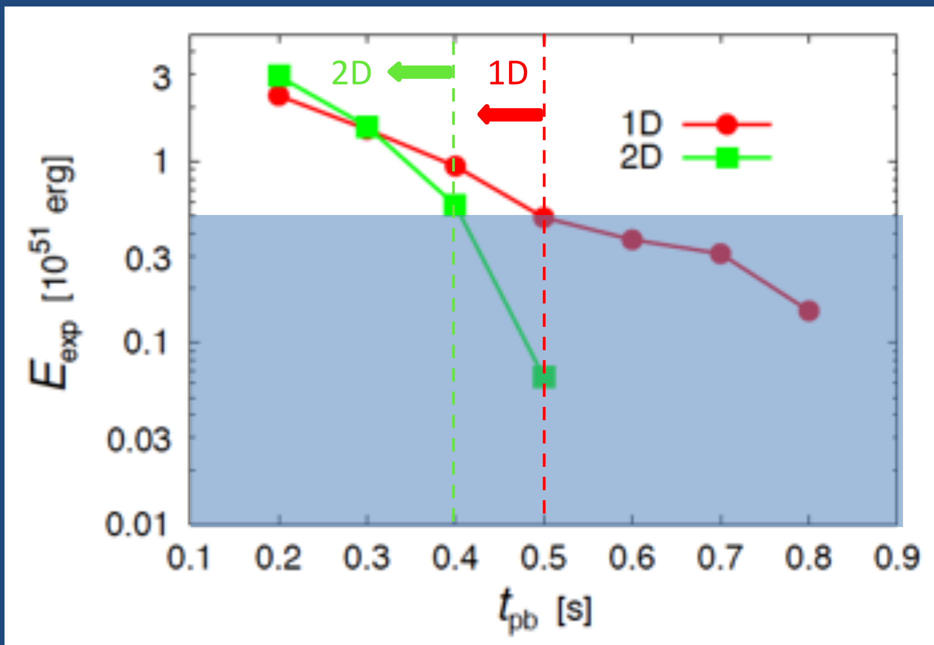


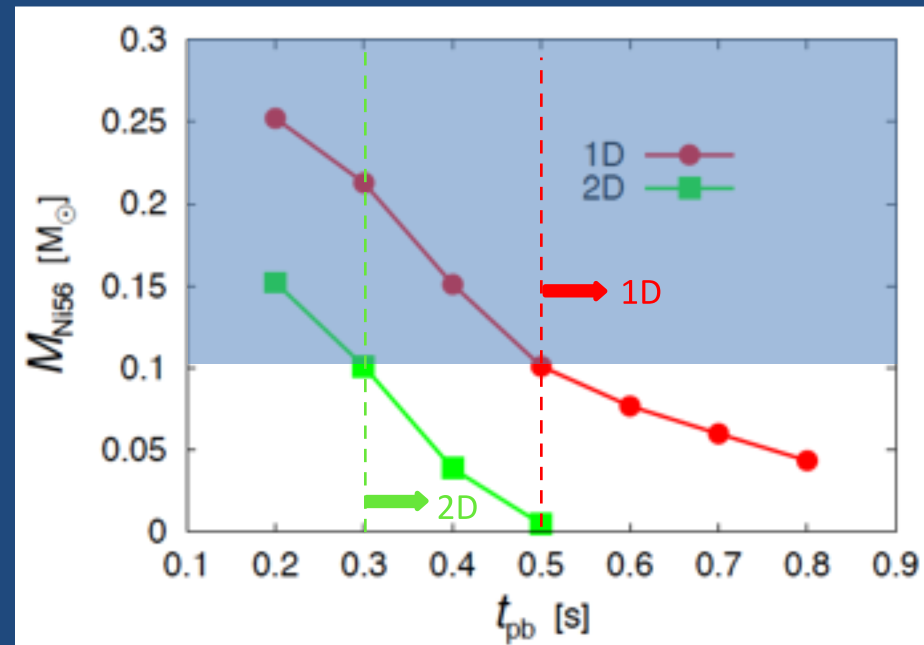
✓ It takes about 1 ~ 3 sec until the explosion energy is finally settled.

- The weaker the explosion is, the longer it takes.
- 2D is similar.

Shock revival may not be sufficient!

Yamamoto et al. '12:





✓ Appropriate explosion energy and ^{56}Ni mass are obtained for a rather narrow range of shock-revival time.

— 1D may be inappropriate also in this sense.

✓ The Inner boundary condition is a major source of uncertainty and fully self-consistent computations are definitely necessary and possible in 2D now.

Multi-Dimensional ν Transport

✓ Boltzmann equation: $$p^\mu \frac{\partial f(x,p)}{\partial x^\mu} + \frac{dp^i}{d\lambda}\frac{\partial f(x,p)}{\partial p^i} = \left(\frac{\delta f(x,p)}{\delta\lambda}\right)_c$$

✓ Self-consistency is a necessary condition but not a sufficient one.

- Multi-D ν transfer has been approximated one way or another so far.

✓ The effect of the approximation in ν transfer should be assessed by better treatments.

- lessons from 1D simulations: any approximation in ν transfer may have consequences.

✓ So far the best neutrino transfer code in multi-D is the 2D Boltzmann solver based on the S_N method by the Arizona-Princeton-Jerusalem collaboration: Ott et al. ’08, Brandt et al. ’11

- No v/c corrections
- no energy-redistribution by inelastic scatterings: Lentz et al. ’12

✓ Neglect of v/c corrections leads to a qualitatively wrong behavior of neutrino fluxes and, as a consequence, of lepton fractions.

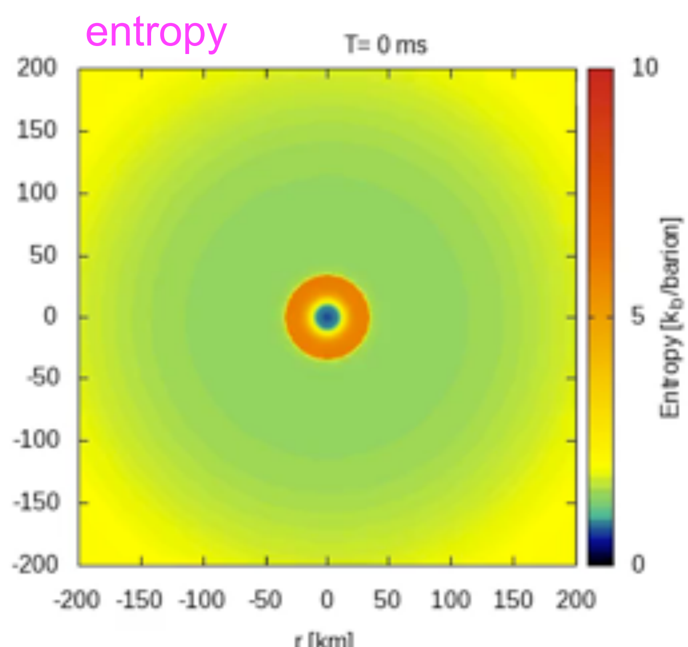
- In the Boltzmann transfer, neutrinos co-move with matter in the optically thick region as a result of v/c corrections.

Multi-Dimensional ν Transport with a Boltzmann Solver

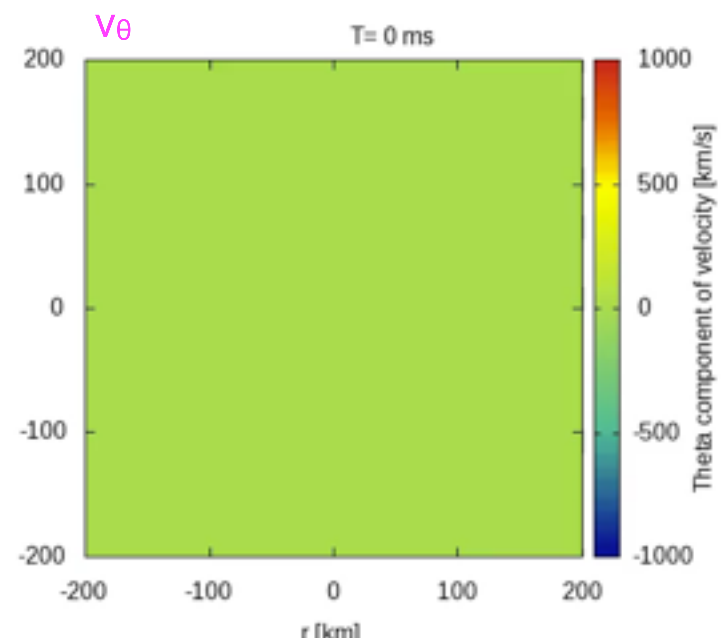
✓ Nagakura, Iwakami et al. '15 in preparation:

a multi-D Boltzmann solver in the mixed-frame formulation.

2D test run: post-bounce evolution of $15 M_\odot$



$N_r \times N_\theta \times N_{\epsilon_\nu} \times N_{\theta_\nu} \times N_{\phi_\nu} = 384 \times 64 \times 20 \times 6 \times 2$



We are going to run this and 11.2M_{solar} models on 京 supercomputer from this April with the resolution $N_r \times N_\theta \times N_\phi \times N_{\varepsilon_\nu} \times N_{\theta_\nu} \times N_{\phi_\nu} = 384 \times 128 \times 20 \times 10 \times 6$.

Stay Tuned!

Summary

- ✓ We are now in a new era, in which we have a lot of models that produce shock revival. 3D simulations will be the focus in the years to come. But other issues are no less important.
  - We are able to study systematics of shock revival.
  - We can afford long term simulations, which investigate the dynamics that follows shock revival.
  - Improvement in the treatment of neutrino transfer should be pursued further to validate the results obtained so far.
- ✓ Although the neutrino heating mechanism is currently the most promising, we had better not forget other possibilities.
  - High-energy (> ~10^{52}ergs) supernovae will not be produced by the neutrino heating mechanism.
  - Some of massive stars may be rapidly rotating.
  - New ideas are always welcome.
- ✓ Neutrino and GW carry valuable information on the physical processes going on deep inside massive stars, which could not be assessed otherwise.
  - ν and GW observations combined may give us the key quantities to approve or refute the neutrino heating mechanism.
  - EM observations are indispensable even in BH formations to provide much needed information on the structure of progenitors.