Towards a Standard Model of Core Collapse Supernovae

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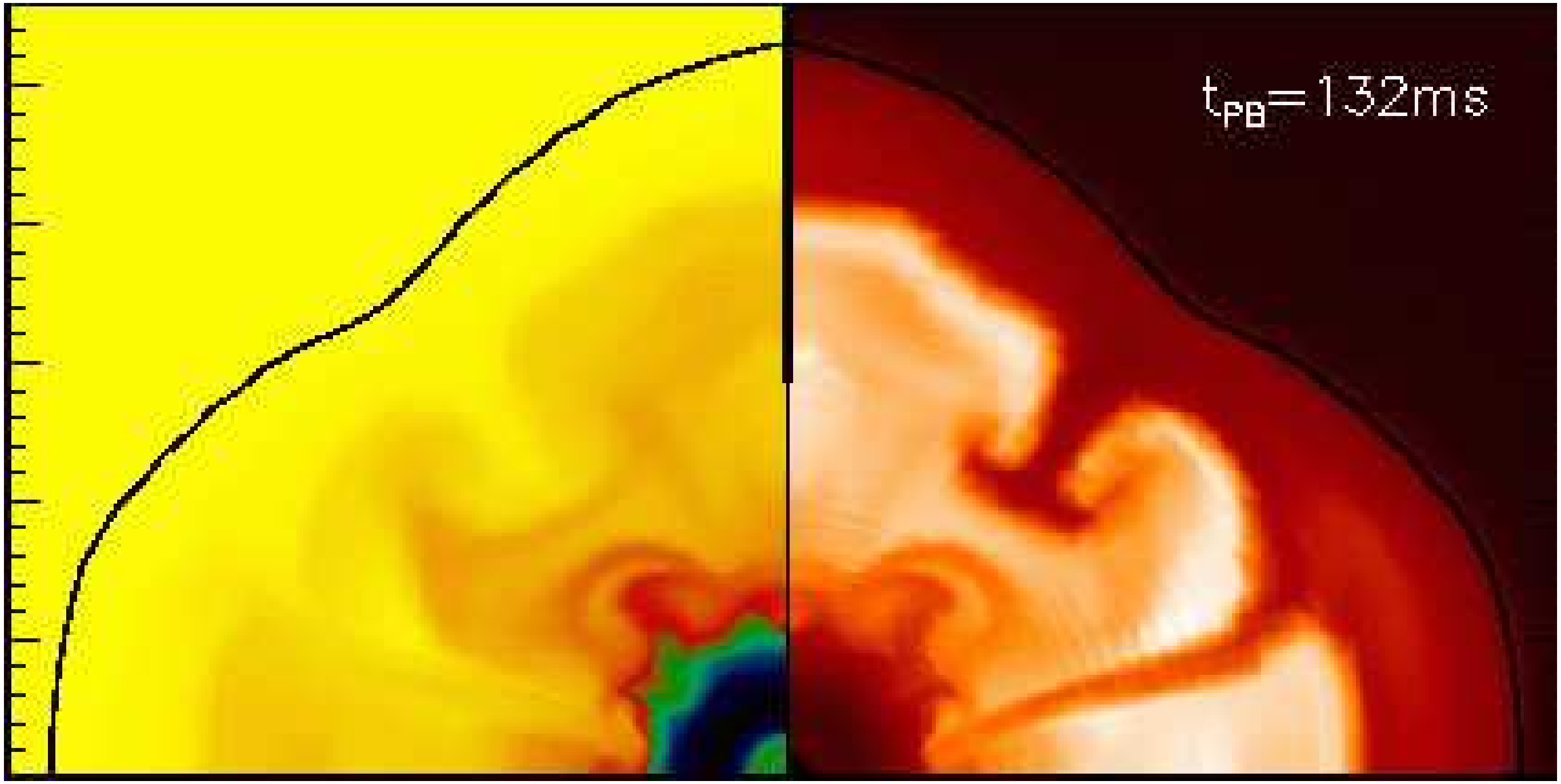
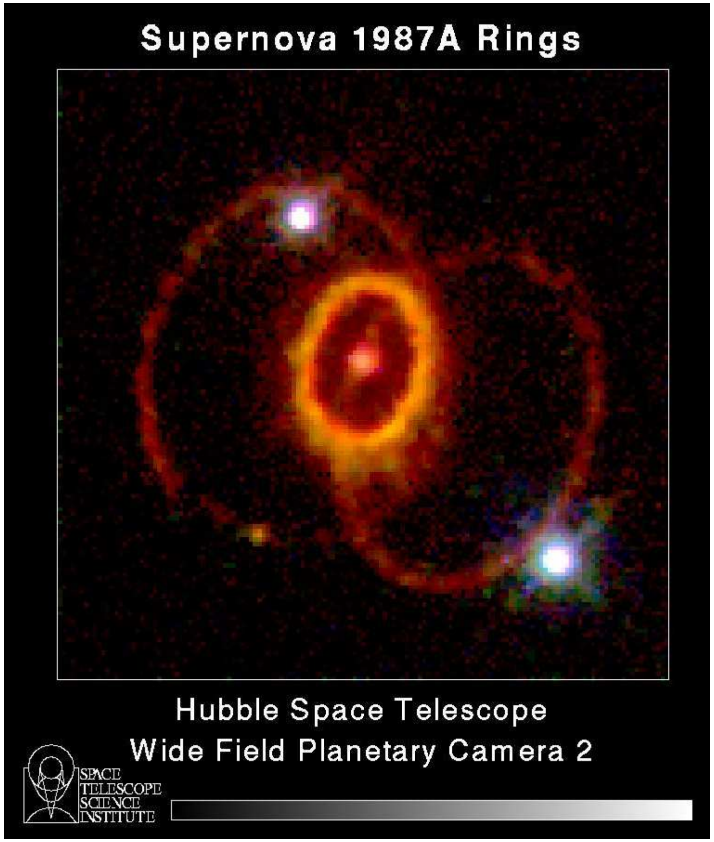


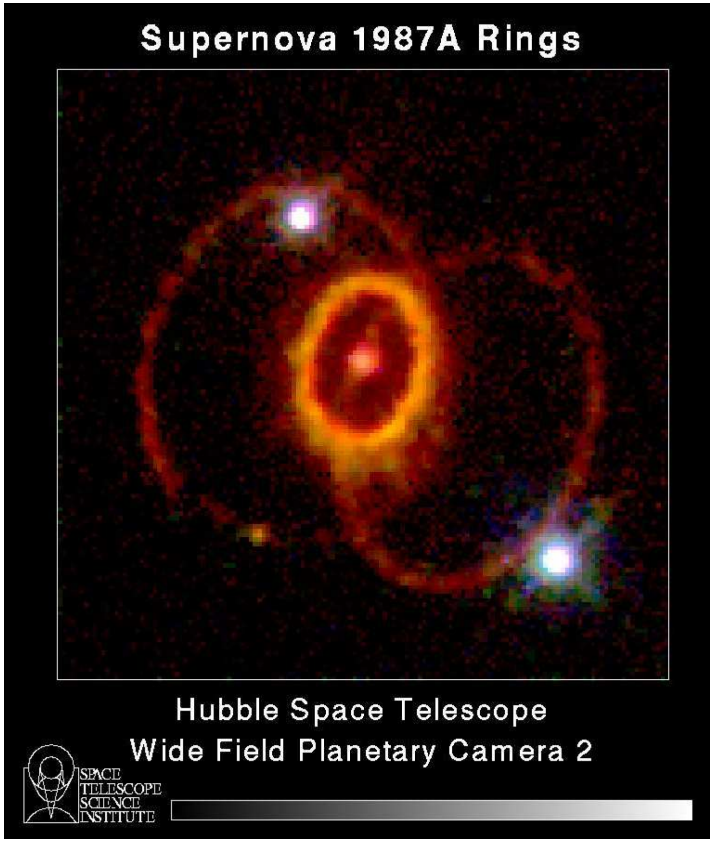
Core Collapse Supernovae

- Supernovae (SN) are VERY powerful explosions
- A lot of progress in understanding SN throughout last four decades
- But: The explosion mechanism is not yet understood!
- Important link between evolution of stars, nucleosynthesis and observation via light and neutrinos



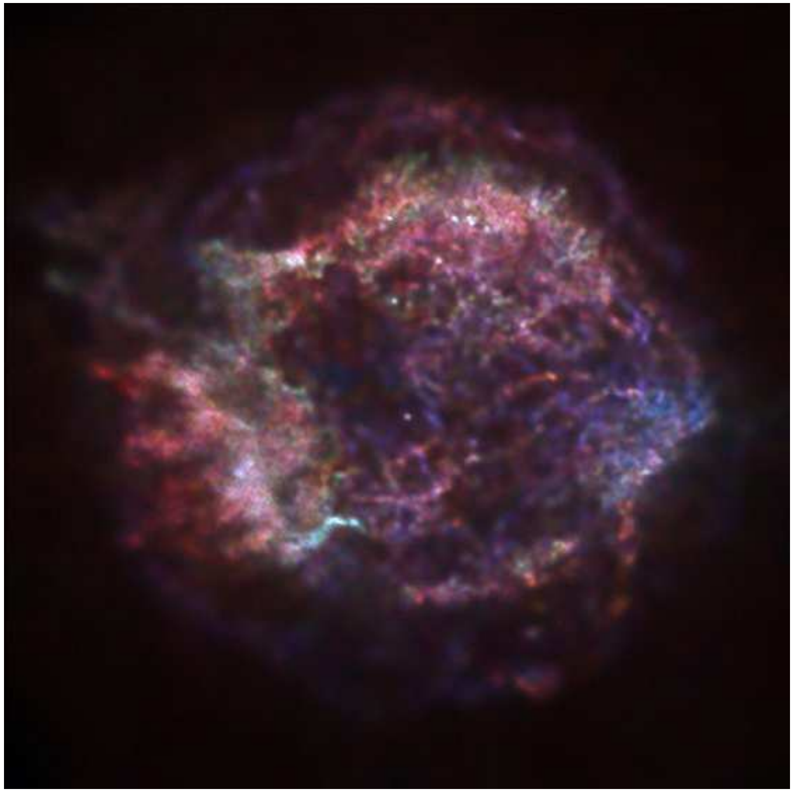
Core Collapse Supernovae

- Introduction
- The struggle with the mechanism
- Latest Results



What is a Core Collapse Supernova?

A Core Collapse Supernova (CCSN) occurs when the core of a massive star at the end of its life collapses to a neutron star (NS)/black hole (BH), creating a shock wave which drives off the stellar mantle.



Chandra X-ray picture of Cassiopeia A

Some facts

Masses and Radii: $M_{\text{prog}} > 8M_\odot,\ r_{\text{prog}} \simeq 10^8\text{km}$

$M_{\text{NS}} \simeq 1.4M_\odot,\ R_{\text{NS}} \simeq 20\text{km},$

$R_{\text{init,NS}} \simeq 10^3\text{km}$

Released gravitational binding energy of NS:

$$E \approx \frac{GM_{\text{NS}}}{R_{\text{NS}}} \approx 3 \cdot 10^{53}\text{erg} = 3 \cdot 10^{46}\text{J} \approx 0.1M_\odot$$

Kinetic explosion energy: $E_{\text{kin}} \approx 10^{51}\text{erg}$

Emitted photon energy: $E_{\text{lum}} \approx 10^{49}\text{erg}$

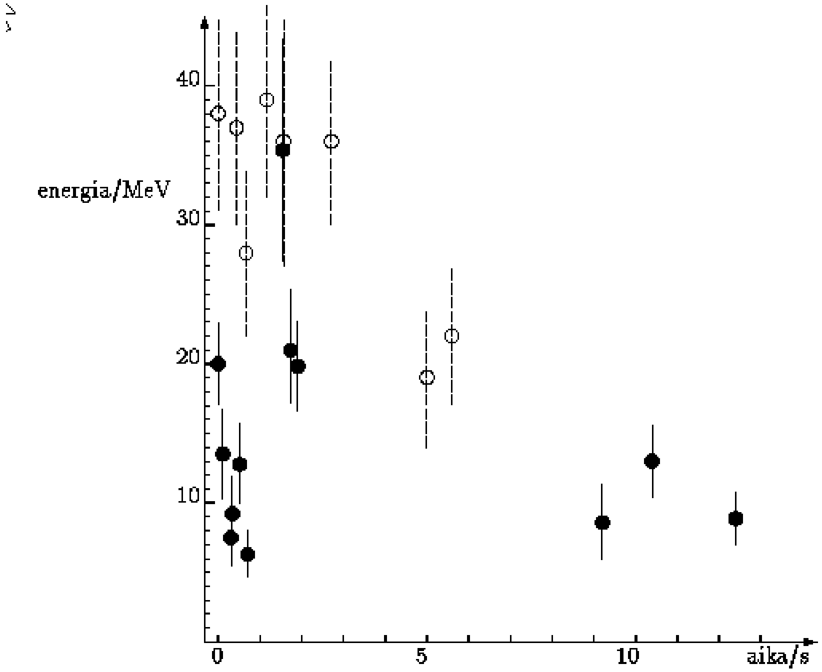
The rest is neutrinos! Neutrinos transport the energy away from the Neutron Star most efficiently.

The beach

The beach

Measuring neutrinos

- The burst of supernova neutrinos can be detected!
- SN1987A in Large Magellanic Cloud (10^5 Lyr): 19 neutrinos in IMB, Baksan, Kamiokande II
Conclusion: Idea of core collapse SN confirmed



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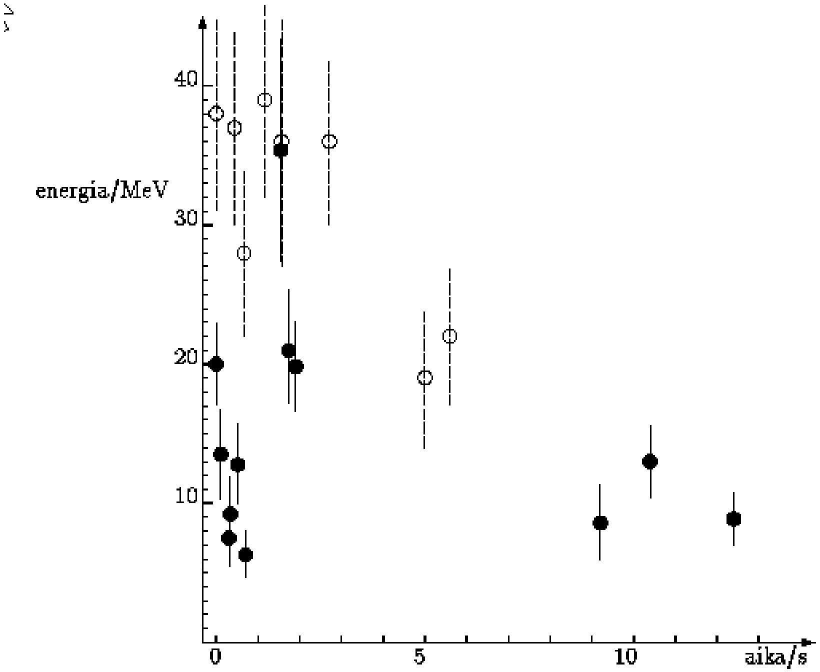

- With neutrinos, we obtain information of the processes happening close to the proto-neutron star.
- With Superkamiokande and SNO, thousands of neutrinos would be detected from a galactic SN.
- But we can only expect few galactic SN per century! So . . .

Old-fashioned observations

- Only 10% of the galactic SN visible in light
- Extra-galactic SN are bright enough to be seen! They overshine their host galaxies

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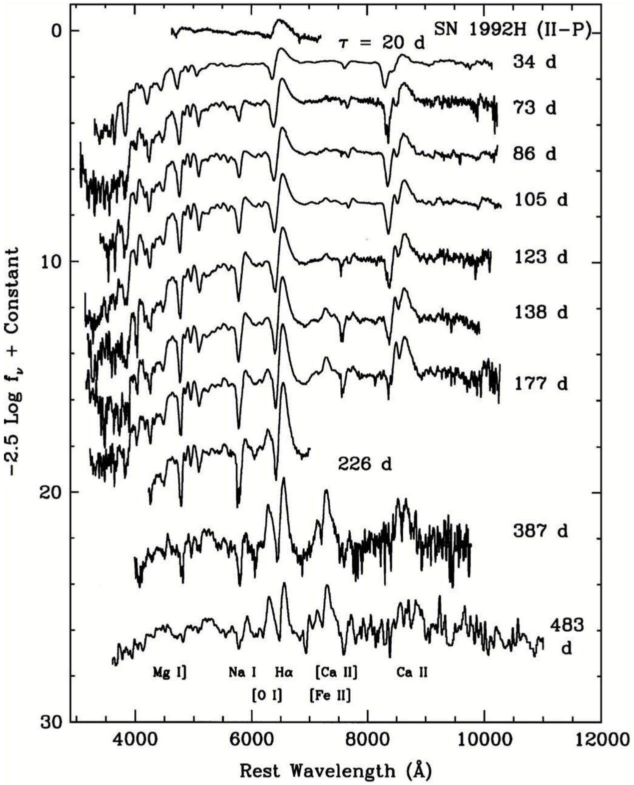
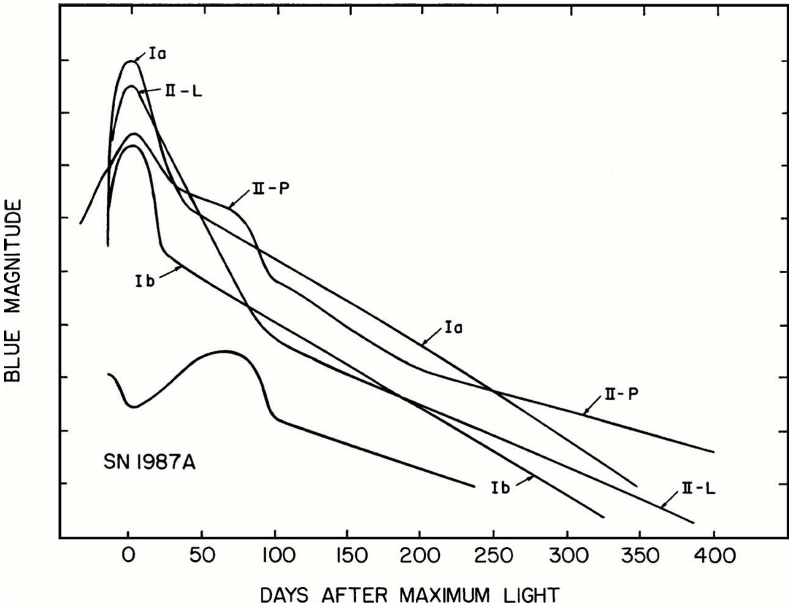




Old-fashioned observations

- Only 10% of the galactic SN visible in light
- Extra-galactic SN are bright enough to be seen! They overshine their host galaxies
- Some conclusions:
    - CCSN create elements (up to Fe, r-process?)
    - The 10^8 galactic SN have created a large fraction of the element abundances
    - The shock waves create seeds for star formation in the interstellar matter
    - Some remnants have been found: pulsars ($=$ NS)

Evolution of massive stars

- The evolution is governed by hydrostatic equilibrium; the virial theorem tells us that

$$E_{\mathrm{int}} = E_{\mathrm{rad}} = -\frac{1}{2}E_{\mathrm{grav}}$$

so that radiation leads to contraction.

- When T_{core} reaches critical value, hydrogen burning starts.

$$4\mathrm{H} \rightarrow {}^{4}\mathrm{He} + 2\mathrm{e}^{+} + 2\nu_{\mathrm{e}}$$

- The burnt helium core contracts further until:

$$3\,{}^{4}\mathrm{He} \rightarrow {}^{12}\mathrm{C}$$

- If star mass is large enough, the temperatures in the core get high enough to subsequently burn the fusion products until ${}^{56}\mathrm{Fe}$, the most stable element. Farther out in the star, fusion of lighter elements proceeds.

Evolution of the Collapse

Collapse sets in when degenerate electron pressure cannot hold gravitational pull.

$$P_{\mathrm{EoS}} \sim a\left(Y_{\mathrm{e}}\rho\right)^{\Gamma} + bT\rho;\ \Gamma = 4/3 \qquad P_{\mathrm{grav}} \sim c\rho^{4/3}$$

When iron core reaches $M_{\mathrm{chandrasekhar}} \sim 1.4 M_{\odot}$, we have $T_{\mathrm{c}} \sim 0.7\mathrm{MeV}$, $\rho_{\mathrm{c}} \sim 4 \cdot 10^{9}\mathrm{g/ccm}$. Thus, we have energetic photons dissociating Fe to α and n.

$$\mathrm{Fe} + \gamma \leftrightarrow 13\alpha + 4\mathrm{n}$$

Internal energy loss leads to contraction, increase of temperature and thus further dissociation.
$\Rightarrow$ Core becomes unstable.

Evolution of the Collapse

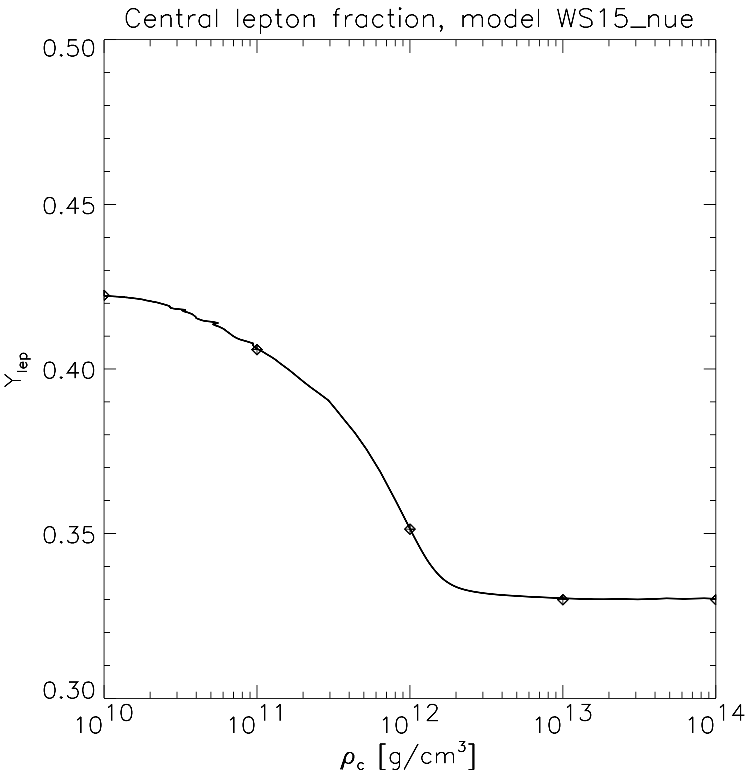
Electron capture on bound protons reduce electron pressure

$$e^- + (p) \rightarrow (n) + \nu_e$$

When neutrino trapping sets in at $\rho \sim 3 \cdot 10^{11} \mathrm{g/ccm}$ due to coherent scattering and neutrino-electron scattering, pressure reduction ends.

$$\nu_e + A \rightarrow \nu_e + A$$

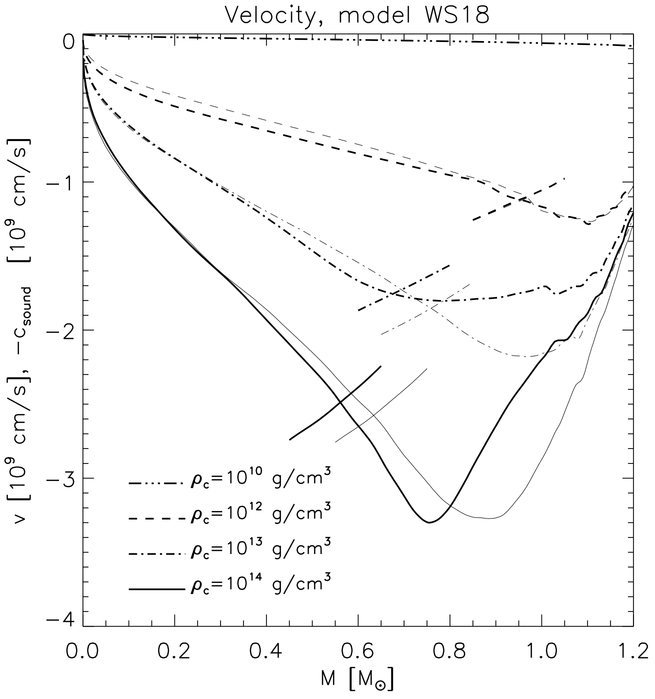
$$\nu_e + e^- \rightarrow \nu_e + e^-$$

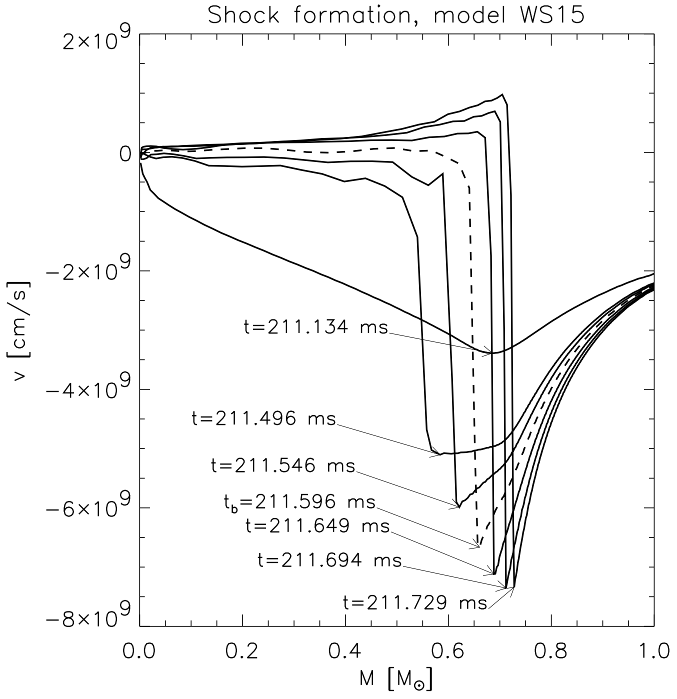


Source: Rampp

Bounce and Prompt Shock

- At nuclear densities ($\rho \simeq 3 \cdot 10^{14}\mathrm{g/ccm}$) the pressure increases drastically due to the degeneracy of the nucleons.
- The inner $0.6 M_{\odot}$ bounce homologously, a shock forms outside this region with $E \sim \mathrm{few} \cdot 10^{51}\mathrm{erg}$.





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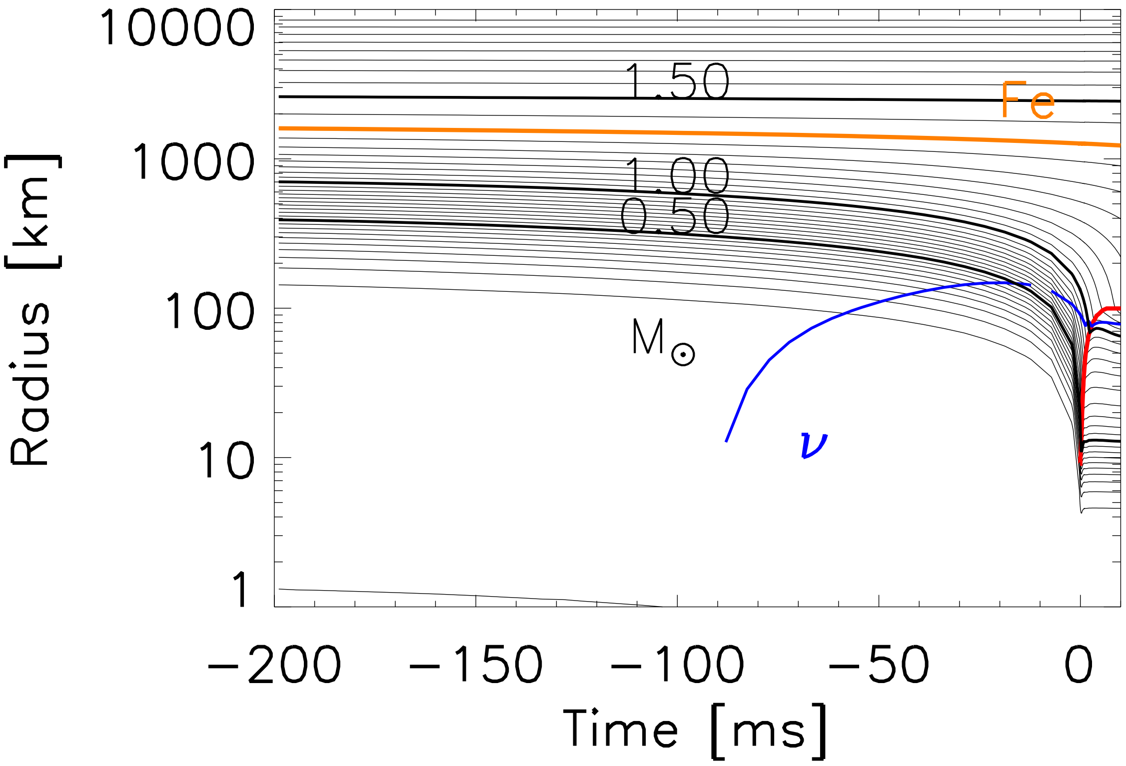
- The inner $0.6 M_\odot$ bounce homologously, a shock forms outside this region with $E \sim \mathrm{few} \cdot 10^{51} \mathrm{erg}$.
- This energy is lost due to dissociation of the infalling shocked material and strong neutrino emission when the shock leaves the ν-opaque region.

The stalled shock



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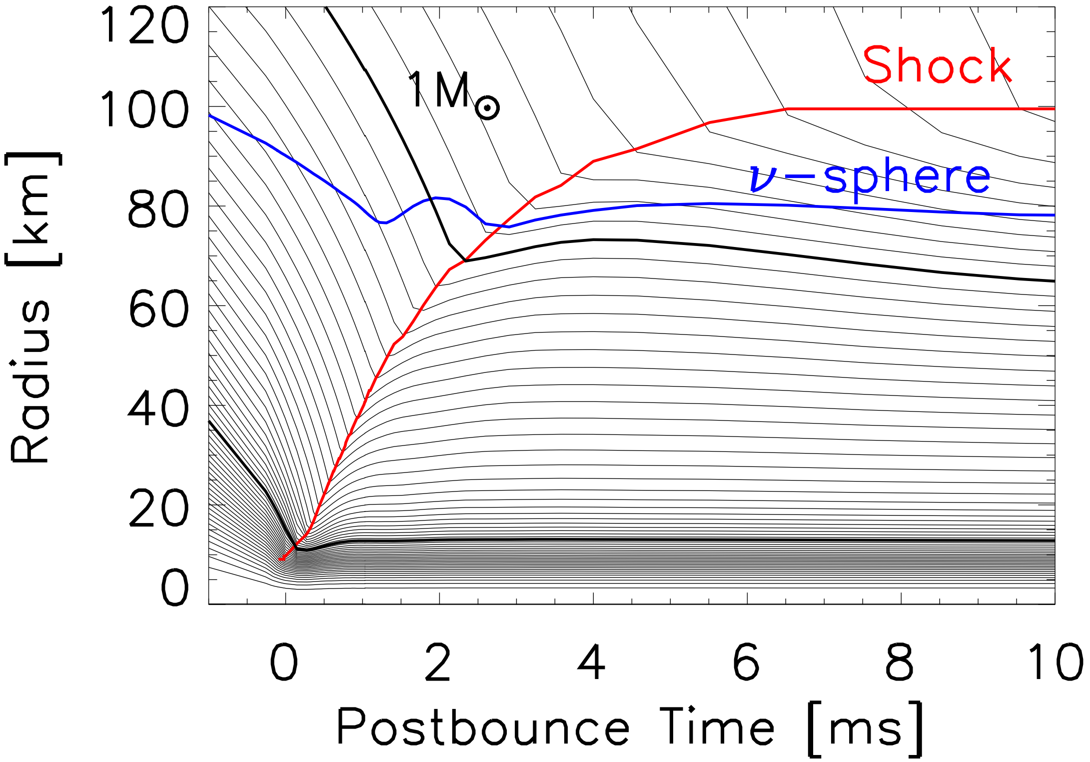


What now?

• What do we want?	Explosion!
• What is missing?	Energy behind the shock.
• Where do we get the energy from?	Proto-neutron Star. $\mu_{\mathrm{e}} \sim 150\mathrm{MeV},\ T \sim 20\mathrm{MeV}$
• How do we make use of this energy?	$\ldots$

Requirements

Neutrino Transport (Colgate & White 1966)		
Convection (Epstein 1979)		
Equation of State (e.g. Wilson)		
General Relativity		
Magnetohydrodynamics		
Rotation		

Requirements

	Input Physics	Computational Needs
Neutrino Transport (Colgate & White 1966)	Weak interaction rates	Boltzmann equations
Convection (Epstein 1979)		2D 3D
Equation of State (e.g. Wilson)	EoS at nuclear densities?	
General Relativity	+	(+)
Magnetohydrodynamics	+	3D
Rotation	Initial angular momentum	2D 3D

The Neutrino driven Mechanism

Basically, ν_e and $\bar{\nu}_\mathrm{e}$ emitted from the neutrinosphere heat up the cooler matter below the shock via absorption.

$$\mathrm{p} + \mathrm{e}^- \leftrightarrow \mathrm{n} + \nu_\mathrm{e}$$

$$\mathrm{n} + \mathrm{e}^+ \leftrightarrow \mathrm{p} + \bar{\nu}_\mathrm{e}$$

It can be shown analytically that there always exists a heating region!

$$Q_- \propto T^6 \propto r^{-6} \qquad Q_+ \propto \frac{L_\nu \left\langle \varepsilon_\nu^2 \right\rangle}{r^2}$$

First success by accident (Wilson 1982)

⇒ Timescale of neutrino heating much longer than of prompt shock

Computational Difficulties

1D-Boltzmann equations (BE) are coupled integro-differential equations, very time consuming!

$$D_t I(t,r,\varepsilon,\theta) = f_{\mathrm{B}}(I(t,r,\varepsilon',\theta'))$$

Simplifications:

- Flux-limited diffusion (FLD): $\vec{F}_\nu \propto \Lambda \cdot \vec{\nabla} E_\nu$
  FLD can be energy-dependent or "grey"
- Moment equations (ME):
  $D_t(E_\nu) = \ldots,\ D_t(F_\nu) = \ldots,\ P_\nu = f_{\mathrm{ed}} \cdot E_\nu$

Drawbacks:

- $\sigma \propto \varepsilon^2 \ \Rightarrow$ radius of ν-sphere is energy-dependent
  $\Rightarrow$ no black-body distribution
- Λ, f_{ed} are difficult to determine $\Rightarrow$ often set by hand!

$\Rightarrow$ Errors around 20% in the heating region not unusual!

Physical input

- Neutral current interactions have a strong impact on opacity and energy redistribution.

  Neutrino scattering with electrons,nucleons and nuclei (coherent)

- Also, ν_μ, ν_τ and their anti-particles are created in pair-process, this increases the cooling of the NS, but hardly increases the heating below the shock.

  e^+-e^- Pair annihilation, Bremsstrahlung, Neutrino-neutrino interactions

- Last but not least, an accurate treatment of the processes is necessary.

  Nucleon recoil, effective mass reduction of nucleon mass due to nucleon-nucleon interactions, blocking effects of all particles involved, weak magnetism, many-body effects, . . .

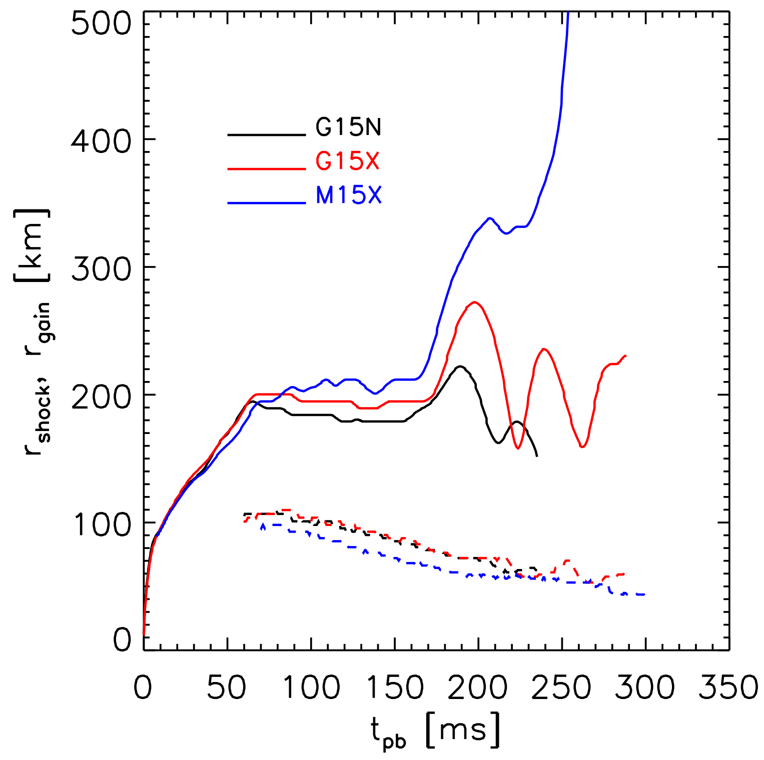
Any of these points affects the evolution of the Supernova significantly!

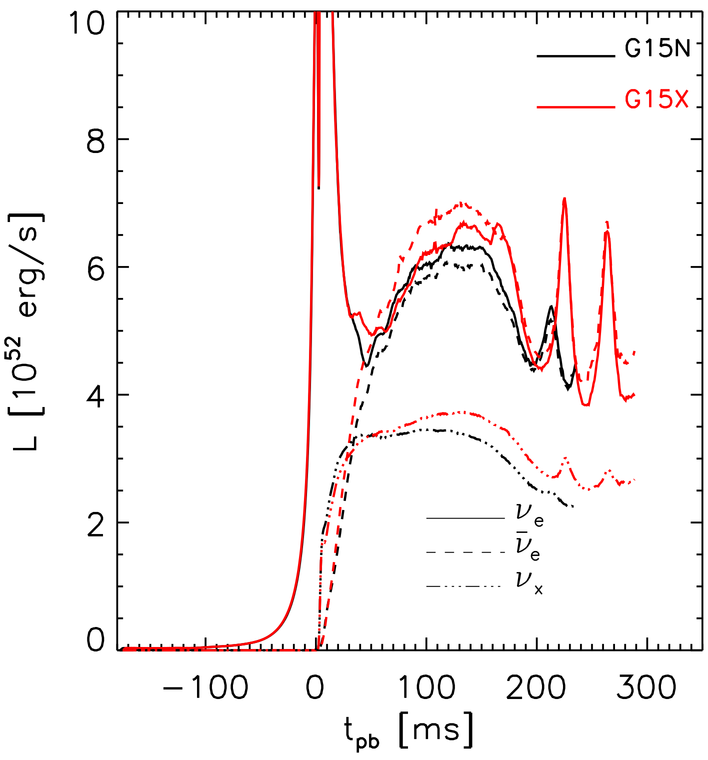
The transport mechanism: Results

The conclusion of state-of-the-art neutrino transport is:

(Mezzacappa et al. 2001, [Rampp et al. 2002])

It's close, but it's not enough!



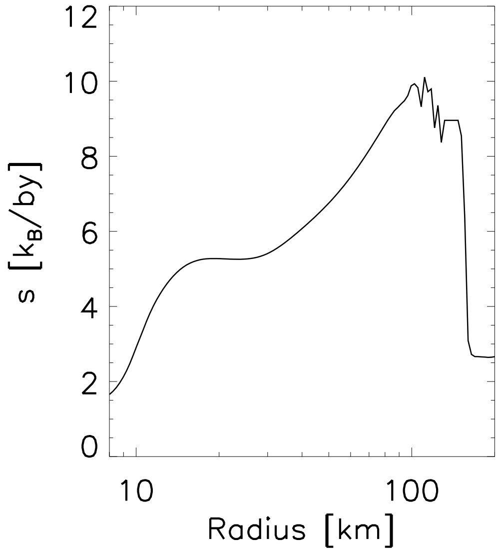


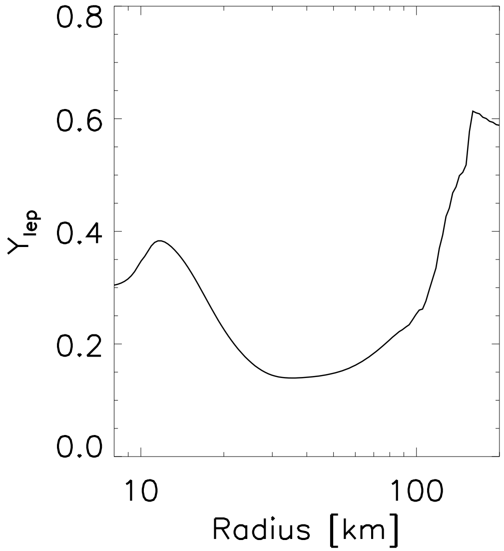
Convection

Mechanism:
A perturbed fluid element moves up or down due to its' changed density. Depending on the stellar structure and the equation of state the density discrepancy either decreases (⟶ stable system) or increases (⟶ convection).

E.g. the criterium for Ledoux-convection is:

$$\mathcal{C}_L \equiv \left(\frac{\partial \rho}{\partial S}\right)_{Y_{\mathrm{lep}},P} \frac{dS}{dr} + \left(\frac{\partial \rho}{\partial Y_{\mathrm{lep}}}\right)_{S,P} \frac{dY_{\mathrm{lep}}}{dr} > 0$$





Neutron Star Convection

Its' existence and character is controversial; the appearance strongly depends on the Equation of State in the core.
Examples:

- Wilson (86): Neutron finger convection just below neutrinosphere, not generally accepted.
- Keil et al. (96): Ledoux-convection deep in the NS, significantly increases the neutrino luminosities on a timescale of several 100ms.

Hot bubble convection

- The instability below the shock is seen in all existing simulations!
- Origin: The negative entropy gradient appears when the prompt shock looses energy, driving the entropy of the shocked material to lower and lower values.
  Later, the stronger neutrino heating close to the NS maintains the negative gradient.
- Effect of convection: Strongly heated material close to neutrinosphere rises, cools ("hot bubbles") $\longrightarrow$ less energy loss via cooling, energy is transported to shock.
  Cool material drops <u>simultaneously</u> to heating region ("downflow") $\longrightarrow$ efficient heating, material to support hot bubbles from below.
- Effective timescale relatively short, $t \sim 50ms$.

Hot bubble convection

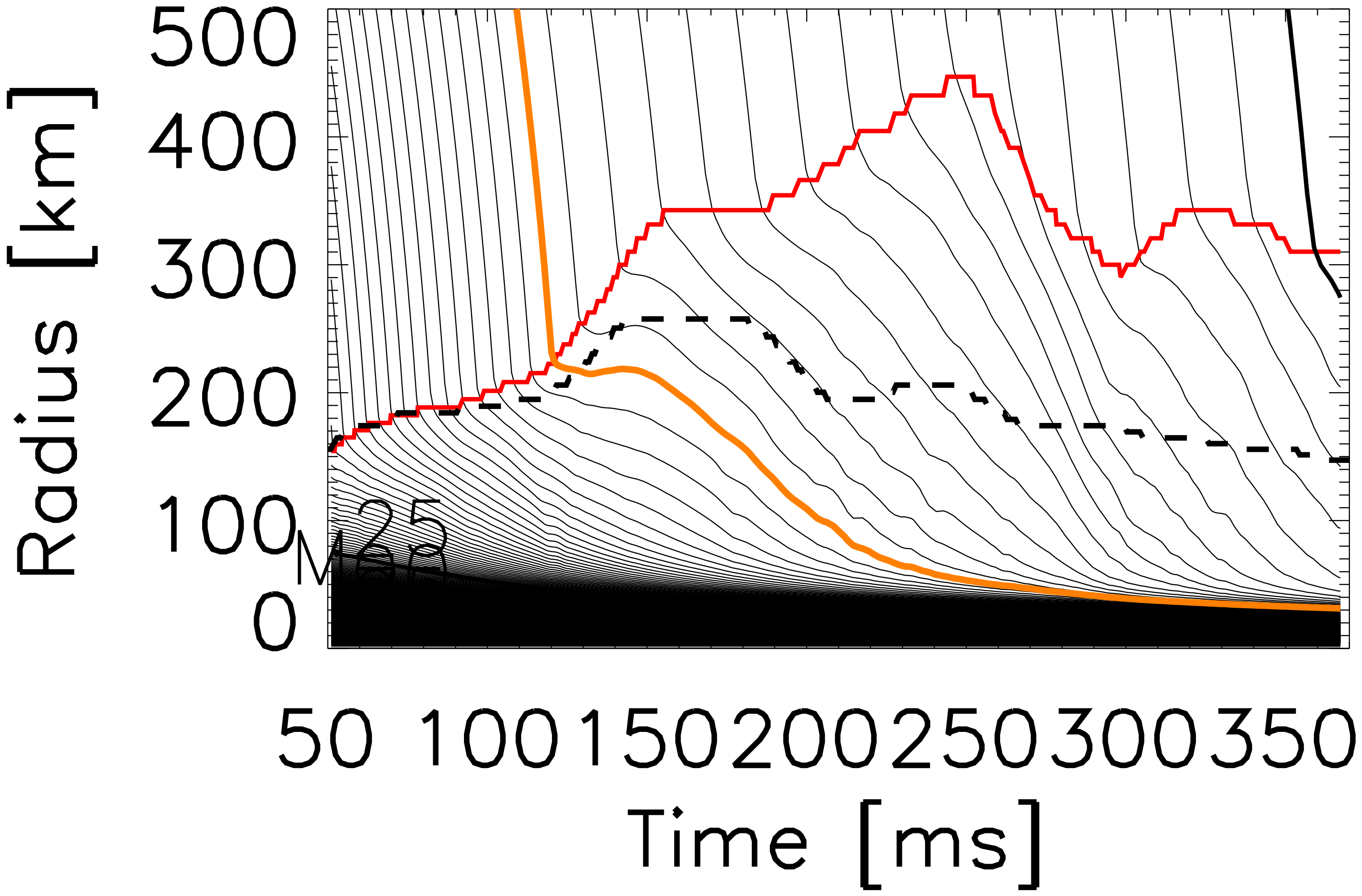
- Parameter studies, simulations and analytic discussions show that hot bubble convection can drive the explosion under certain conditions. (e.g. Janka et al. (96))
- The observations (e.g. SN1987A) suggest convection in the crucial part of the explosion :
  - Smooth light curve → Mixing of H, He deep into interior
  - Ni clumps with high velocity must stem from interior!
  - Early X-ray detection → metallic nuclei in H mantle
  - Early γ-ray detection → radioactive nuclei in H mantle

Convective results (incomplete)

- Wilson (86): 1D, exotic EoS (pion condensate), simulated "neutron finger convection" with mixing length algorithm
  $\Rightarrow$ Successful, but input physics is highly questionnable.
- Herant (94), Burrows (95), Fryer (99,02): 2D and 3D, grey flux-limited diffusion
  $\Rightarrow$ Successful, but very simple neutrino transport
- Swesty (98): 2D, grey fld
  $\Rightarrow$ success varies dramatically on decoupling point
- Mezzacappa (98): 2D multi-energy flux-limited diffusion, not self-consistent $\Rightarrow$ Fizzles!
- RB, Janka, Kifonidis, Rampp (prel.): 2D (transport 1.5D Boltzmann), no GR, "standard" opacities $\Rightarrow$ Fizzles!
- BJKR (prel.): 2D (transport 1.5D Boltzmann), "GR", "SOTA" opacities
  $\Rightarrow$ . . .

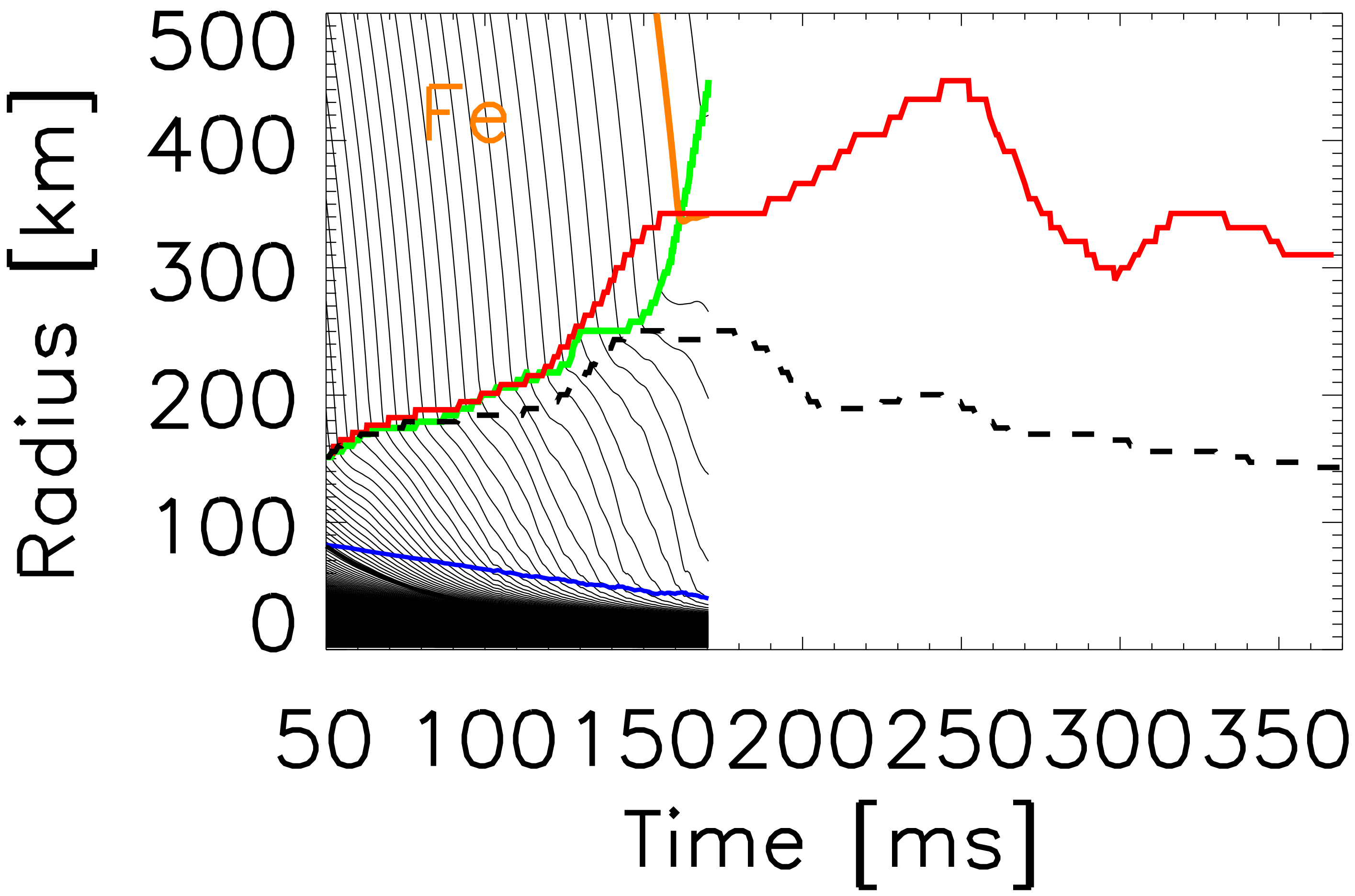
Our first 2D calculation

Newtonian, “standard” opacities



Our results from yesterday

General relativity, “state-of-the-art” opacities



Conclusions

- There exists (?) a successful simulation with correct physical input and without computational bugs (?)
- The mechanism is (almost) understood!
  It does NOT work with neutrino mechanism only
  It does NOT work with Convection only
  It DOES work with the combination of both (+GR)
- Next step: build a Virtual Supernova factory to
  - test consistency with observations (nucleosynthesis, convection)
  - test different progenitor/EoS models
  - find answers to still unresolved questions (pulsar kicks, GRB)
  - find out if some CCSN underlie a totally different explosion mechanism