Modelling stellar collapse : a challenge that pushes us to the limit of human knowledge about dense and hot matter

Rencontre des Jeunes Physicien·ne·s

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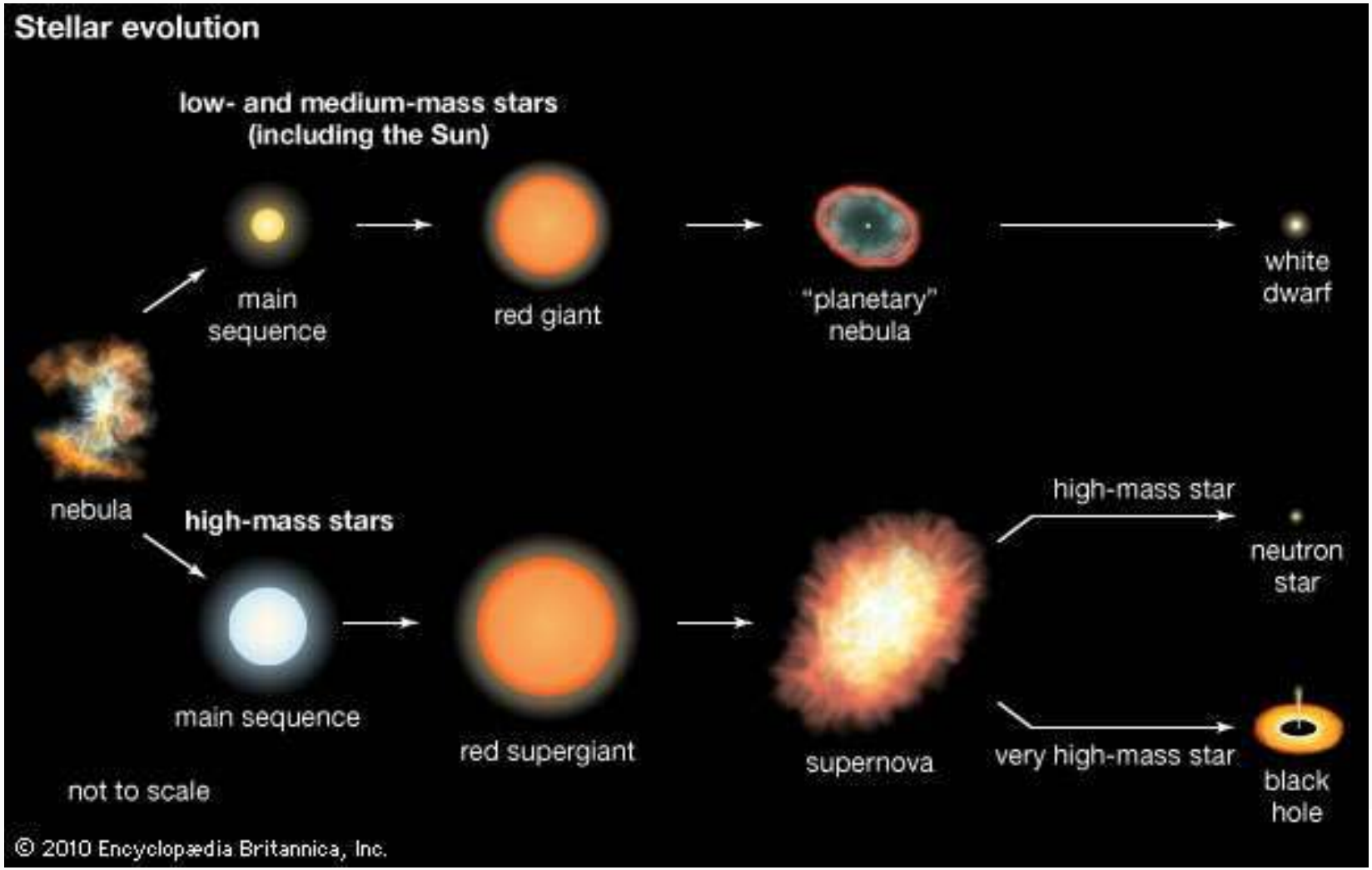
Stellar Evolution



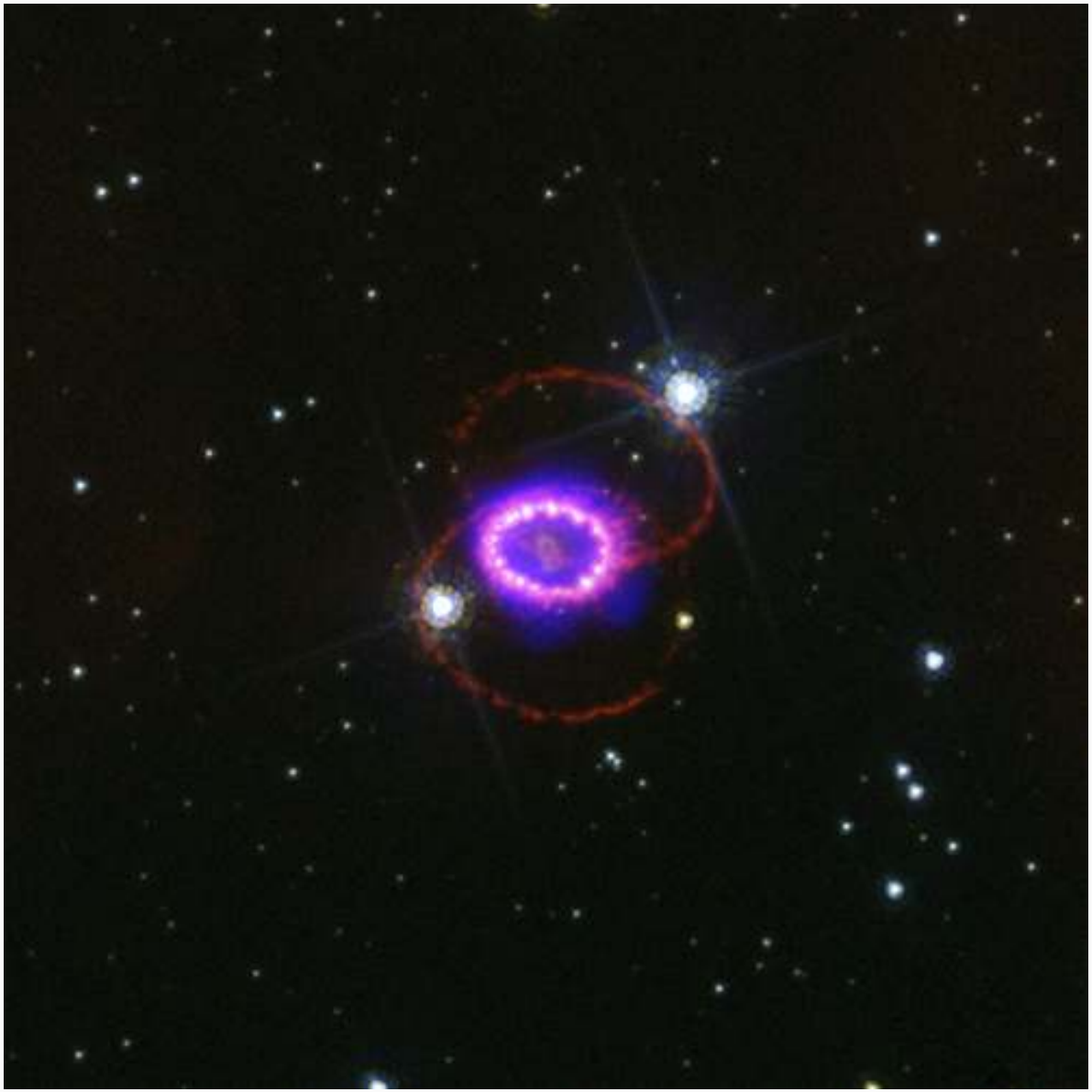
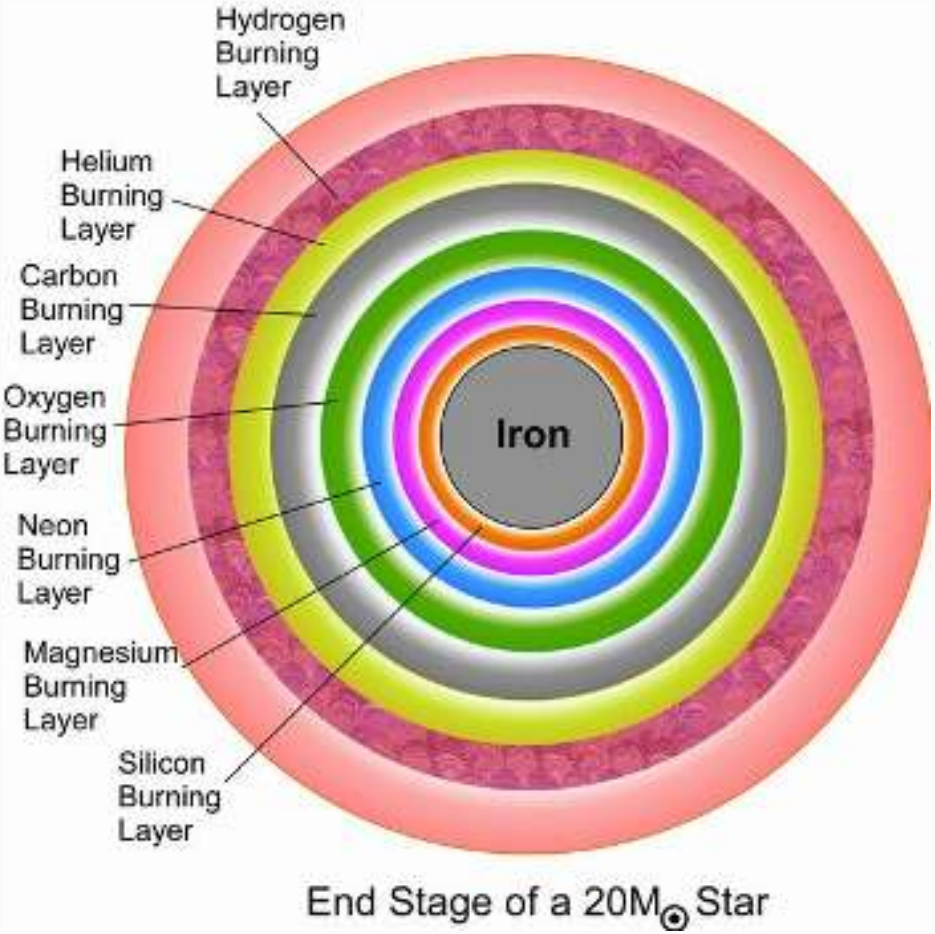


Figure 1: SN1987A remnant, in the large magellanic cloud (51.5 kpc).

Core-collapse supernovae

Stellar Iron core and onion like structure



$R_{\text{iron core}} \sim R_{\text{earth}}$

$R_{\text{star}} \sim 5\,\text{au}$

$T_{\text{iron core}} \sim 0.1\,\text{MeV} \sim 10^9\,\text{K}$

Onset of the collapse

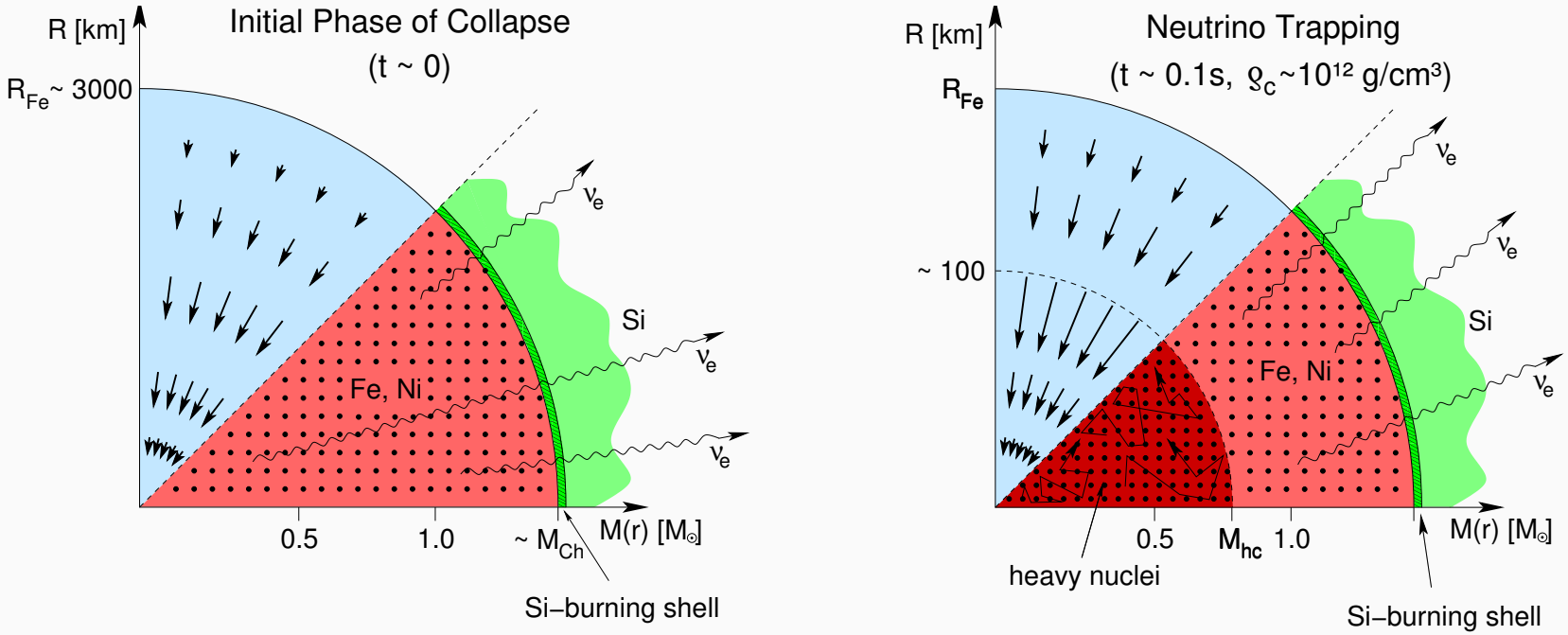


Figure 2: Core-collapse mechanism, figure extracted from Janka et al. (2007)

Inverse beta reactions : $e^- + p \rightarrow n + \nu_e$

$\Rightarrow$ the core deleptonize

Bounce and shock

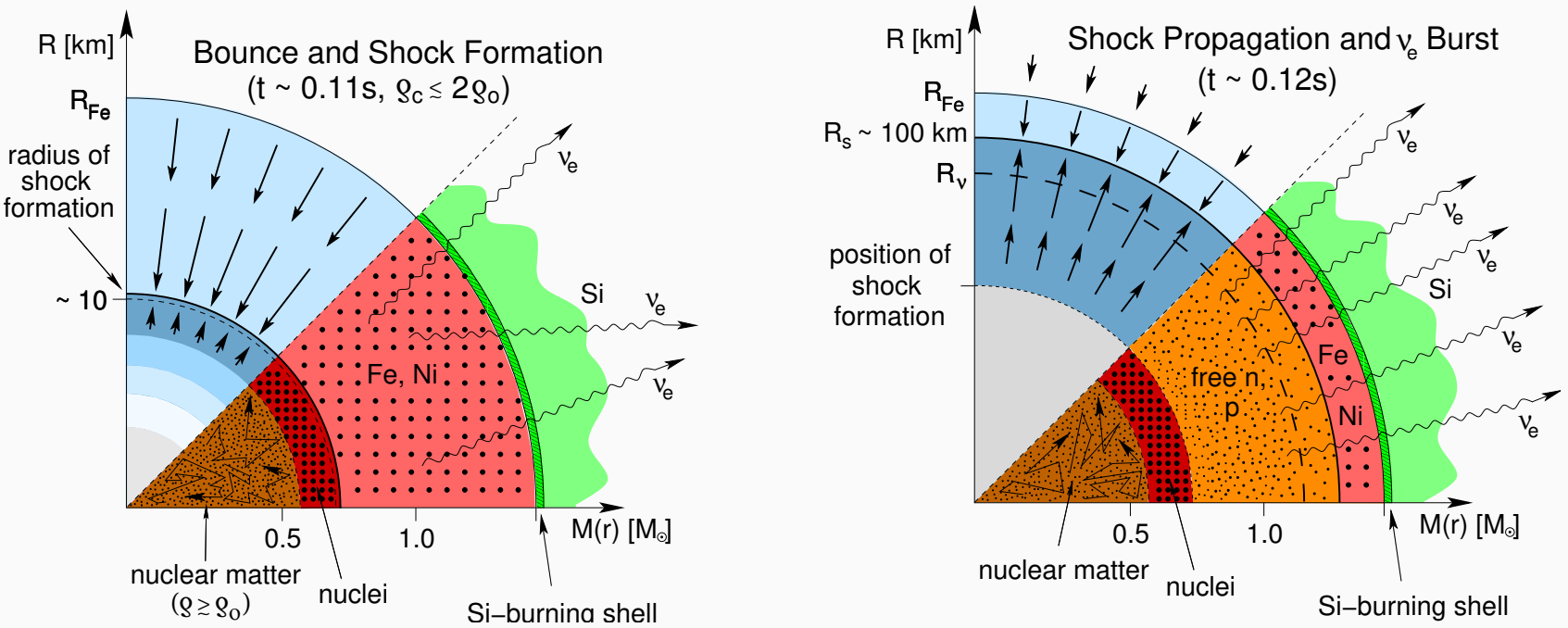


Figure 3: Core-collapse mechanism, figure extracted from Janka et al. (2007)

Nuclear density threshold $n_0 = 0.16\,\text{Baryon}\,\text{fm}^{-3}$
(i.e. $\rho_0 = 2.6 \times 10^{17}\,\text{kg}\,\text{m}^{-3}$)
$\Rightarrow$ core bounce and shock formation

Stagnation and... explosion ?

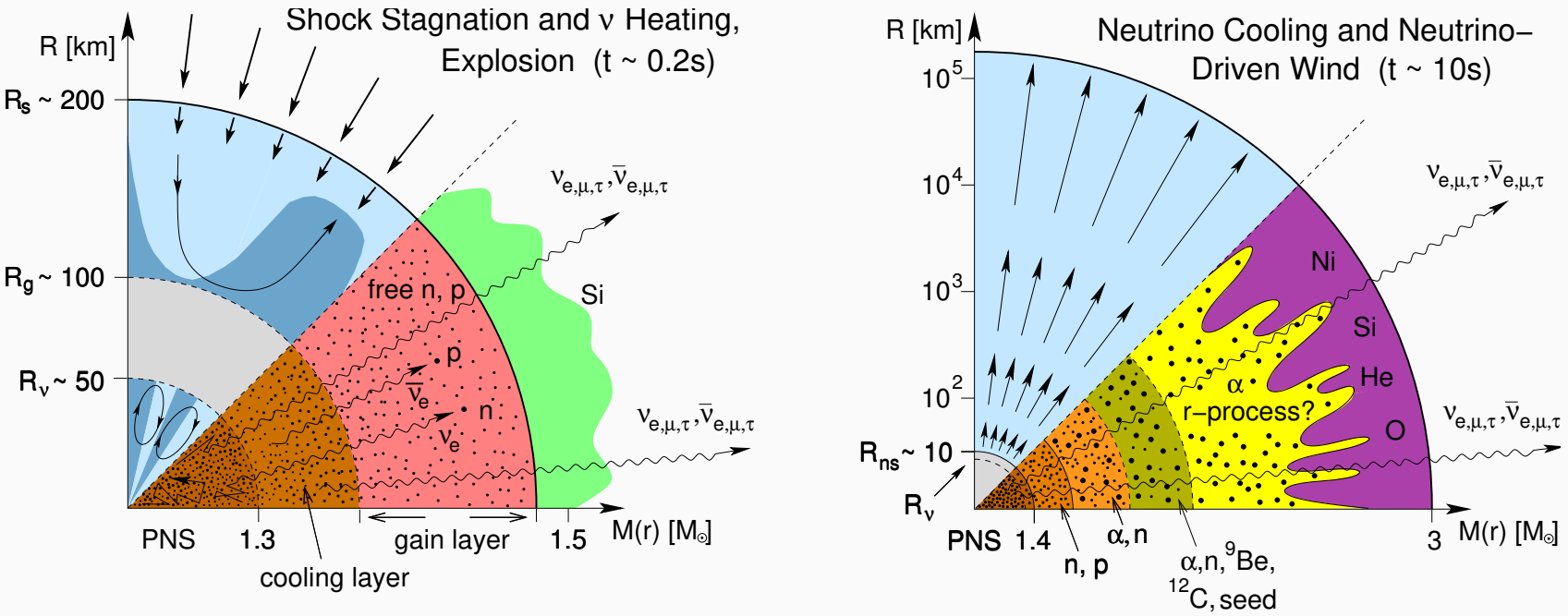


Figure 4: Core-collapse mechanism, figure extracted from Janka et al. (2007)

Shock not enough ! $\Rightarrow$ stagnation

until shock revival by ν-heating ? or re-collapse ?

A problem with many difficulties

Densities : $10^7\,\mathrm{kg\,m^{-3}} \leq \rho \leq 10^{15}\,\mathrm{kg\,m^{-3}}$

Temperatures : $10^9\,\mathrm{K} \leq T \leq 10^{12}\,\mathrm{K}$

- modelling nuclear interaction between many baryons is an extremely tough problem
- matter is extremely neutron rich $\Rightarrow$ we are far from the laboratory conditions (far from the valley of stability)
- neutrino behaviour (cross sections, flavor oscillations...) is not well understood

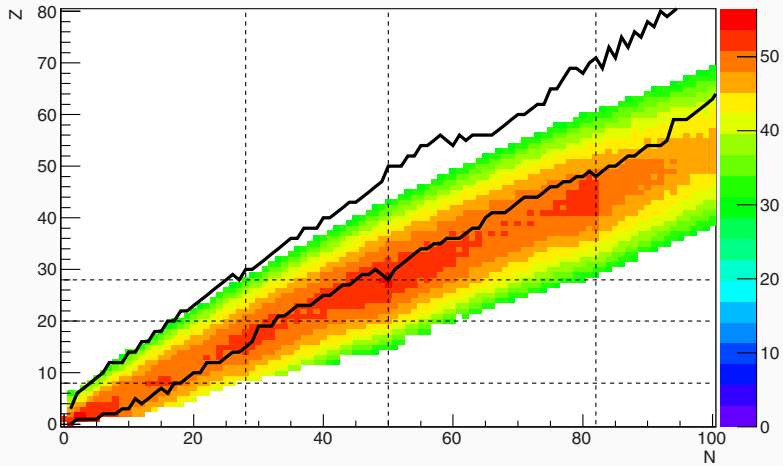


Figure 5: Typical nuclear abundance near the end of the collapse Raduta et al. (2016) (arbitrary unit), solid lines mark boundaries of experimental mass measurements, dashed lines mark magic numbers

Numerical models

What you need :

- a solver for the gravitational field (general relativity)
- a solver for general relativistic hydrodynamics
- an equation of state for matter in extreme temperature and densities
- a radiation transfert algorithm to handle neutrinos (they are out of equilibrium $\Rightarrow$ they cannot be embbed in an EoS)

An exemple of result : sensitivity to e^--capture cross sections

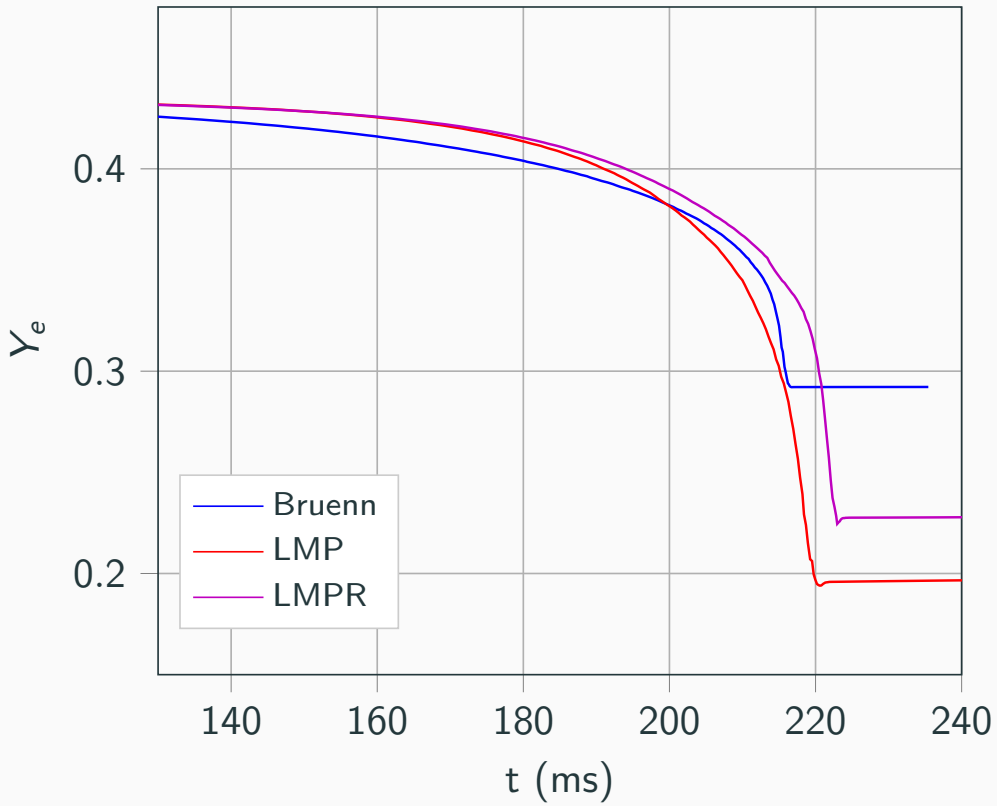


Figure 6: Evolution of the electron fraction at the center during a collapse for different cross section models

Inverse beta reactions : $e^- + p \rightarrow n + \nu_e$

Conclusion

- supernova core-collapse simulations are difficult because a lot of physics is needed and because we do not fully undertand the behaviour of matter in those conditions
- but this is precisely what makes them invaluable natural laboratories to get informations on conditions impossible to reproduce in experiments


A&A

Why does the fate of the star depends on its mass ?

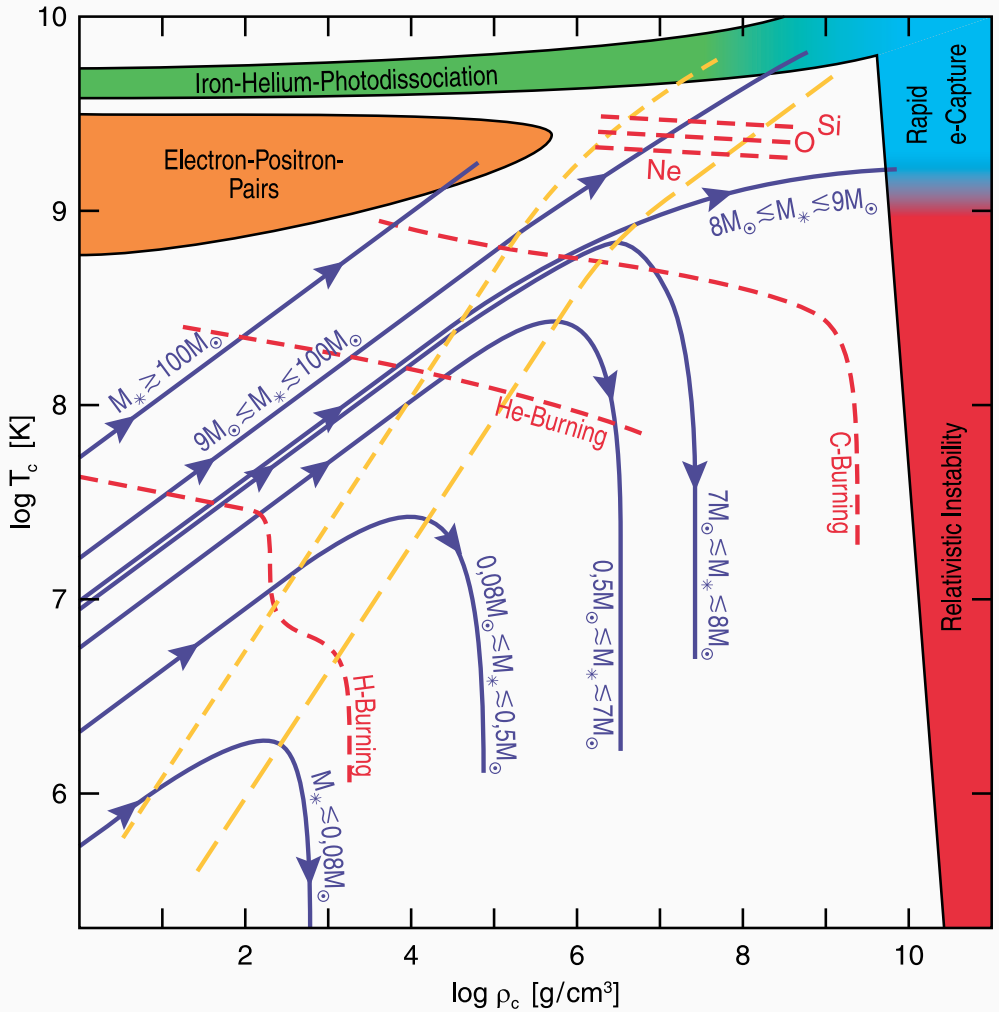


Figure 7: Stellar evolution T versus rho diagram. Blue tracks represents stellar trajectories, red dashed lines are fusion threshold, yellow dashed lines are electron degeneracy threshold and coloured region are death zones. Figure extracted from Janka (2012)