An extended equation of state for simulations of stellar collapse

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Microphysics input for core collapse simulations

What shall be simulated?

- Massive star at the end of its life whose iron core exceeds the Chandrasekar mass $\longrightarrow$ gravitational collapse (timescale $\sim$ 1s)
- Compact star formation:
  (depending on initial mass, metallicity, rotation, . . .)
  - neutron star (supernovae)
  - black hole (hypernovae, collapsar)
- Characteristic neutrino signal, gravitational waves, . . .

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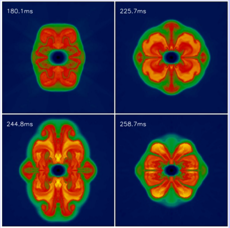
What do we need as input from microphysics?

- Neutrino-matter interactions
- Deleptonization rates



(Buras et al., MPA Garching, 2003)

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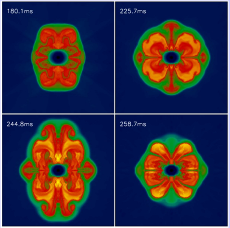


What do we need as input from microphysics?

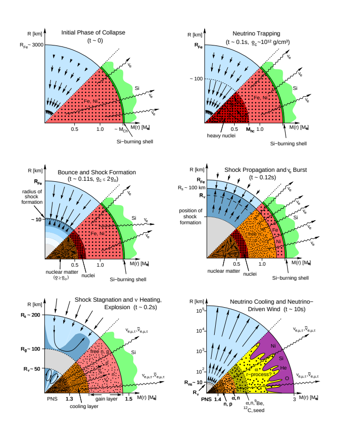
- Neutrino-matter interactions
- Deleptonization rates
- An equation of state

(Buras et al., MPA Garching, 2003)

Matter composition and the equation of state

Matter composition changes dramatically through the core collapse

- Starting point: onion like structure with iron/nickel core+ degenerate electrons
- Upon compression (+deleptonisation): heavier and more neutron rich nuclei
- For $\rho \gtrsim \rho_0/10$: nuclei disappear in favor of free nucleons
- Composition of matter above ρ_0 and at $T \gtrsim 10$ MeV relatively unknown



(Janka et al. '07)

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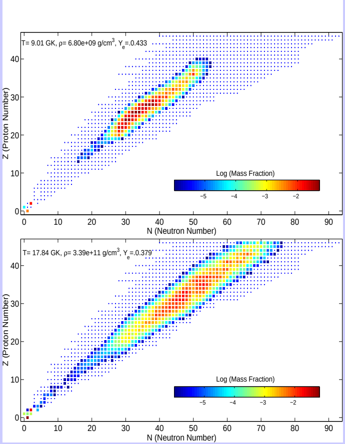

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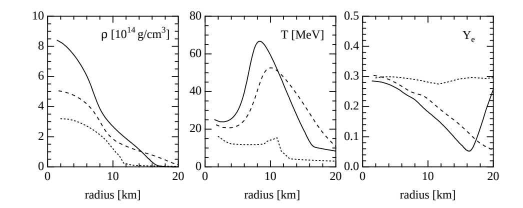
The two “standard” EOS

- Two EOS mainly used in simulations:
  - Lattimer-Swesty (1991):
    Non-relativistic nuclear liquid drop model including surface effects and Coulomb effects
    Thermodynamically consistent (minimisation of the free energy)
  - Shen et al. (1998):
    Relativistic mean field model with TM1 parameter set
    Finite size effects via Thommas-Fermi approximation
- Same limiting assumptions for particle content: free nucleons, α particles + one (average) heavy nucleus, electrons/positrons, photons
- Lattimer-Swesty and Shen et al. EOS publicly available in tabulated form

Is the classical picture adequate?

Example: profiles for the collapse of a $40 M_{sol}$ progenitor at $0, 500, 680$ ms after bounce (Sumiyoshi et al. ’09)



(Sumiyoshi et al. ’09)

Extreme conditions:

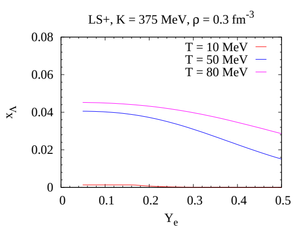
$$\rho = 10^6 \mathrm{g/cm}^3 \cdots 10^{15} \mathrm{g/cm}^3$$
$$T = 0.2 \mathrm{MeV} \cdots 150 \text{ MeV}$$
$$Y_e = 0.05 \cdots 0.5$$

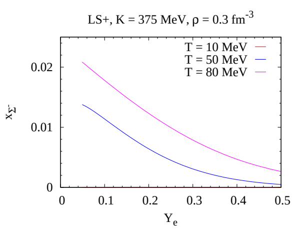
The temperatures and densities reached suggest that additional particles (hyperons, mesons, ...) should be added (as conjectured for neutron stars)!

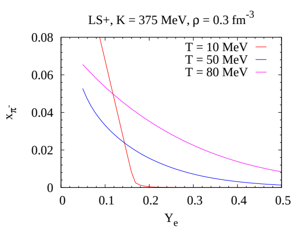
The extended equation of state

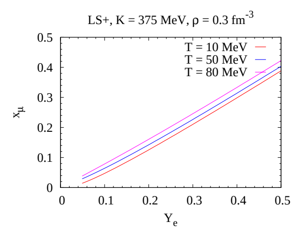
- Idea: add pions, muons and hyperons upon the Lattimer-Swesty (LS) EOS
- Advantages:
  - existing treatment of inhomogeneous matter can be used
  - matching of “new” and “old” EOS without non-physical “phase transition”
  - comparison with existing literature
- Construction conditions:
  - zero total charge, given baryon density (n_b), temperature (T) and electron fraction (Y_e)
  - Pions and muons added as free gas
  - Hyperons added too, but hyperon interaction badly known
    - Version 1: take the same type as nuclear interaction in LS with parameters adjusted to (not very well known) values extracted from hypernuclei data (Balberg & Gal ’97)
    - Version 2: interaction as derived from parametrization of G-Matrix calculations of cold hyperonic matter (Vidaña et al. ’10)

Particle fractions: temperature dependence



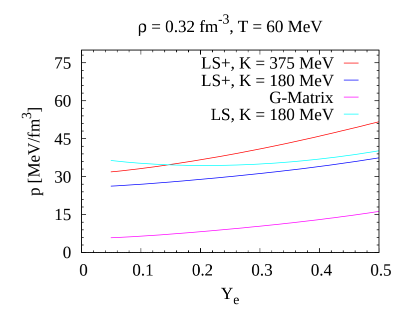


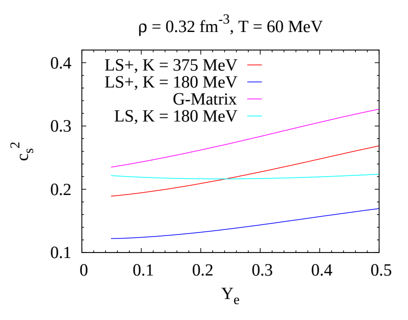




Some thermodynamics

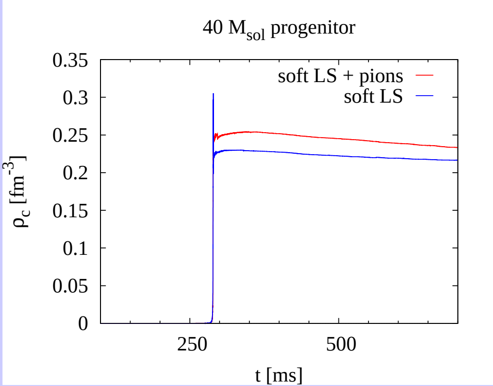
- Additional particles change considerably the thermodynamic properties of the EOS
- Example: pressure and sound speed (abundances of additional particles $\sim$ 5 %)





Effect of the improved EOS in simulations?

First preliminary result with LS + pions + muons (no hyperons) in 1D with CoCoNuT *http://www.mpa-garching.mpg.de/hydro/COCONUT/intro.php*



- Visible effect of pions: slightly larger central density at bounce
- No evolution after bounce because of missing neutrino treatment within the actual version of CoCoNuT

Summary and Outlook

Summary:

- Standard EOS (LS and Shen et al.) not adequate for collapse of massive ($\gtrsim 25 M_{sol}$) progenitors because of high temperatures and densities
- First results from LS + pions + hyperons + muons EOS
- Uncertainties mainly due to badly known hyperon interaction
- Softening of the EOS ($\rightarrow$ more energy availible for explosion?)

Outlook:

- Include improved EOS in simulations
- Determine corresponding electron capture and neutrino interaction rates for coherent neutrino treatment