Core-collapse supernova simulations

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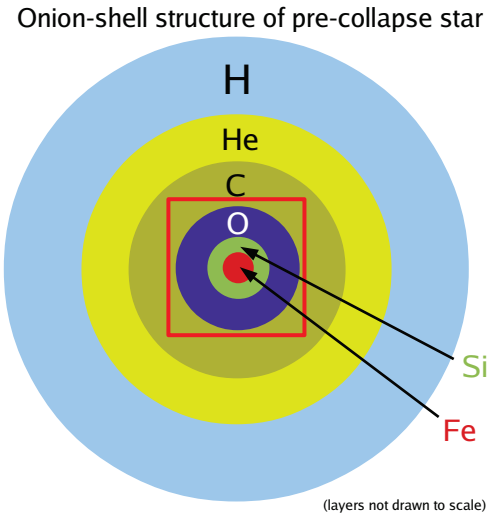
Core-collapse supernova

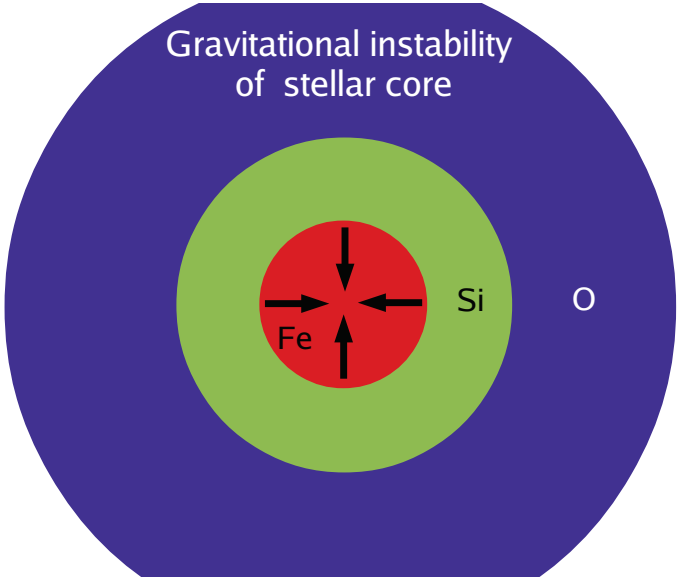
Collapse. . . bounce. . .

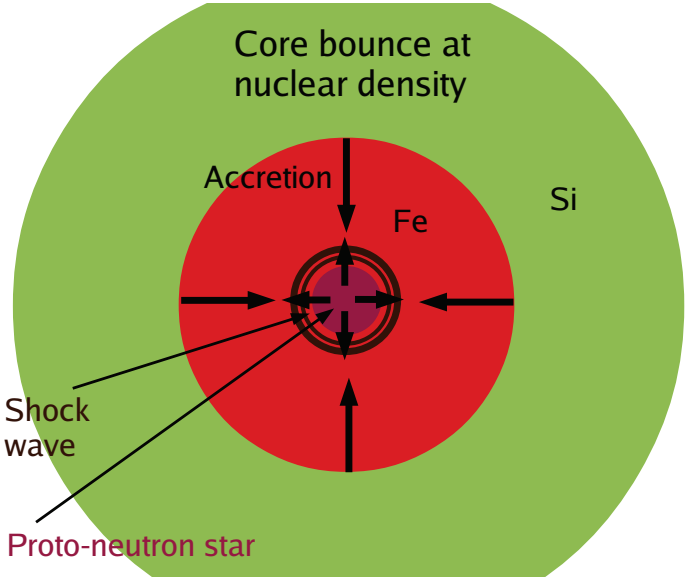
- End of main-sequence life for massive stars ($\gtrsim 8M_\odot$).
- Heavier elements with higher temperatures and densities:
  $\Rightarrow$up to iron, most stable nucleus

Electron capture on nuclei:

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

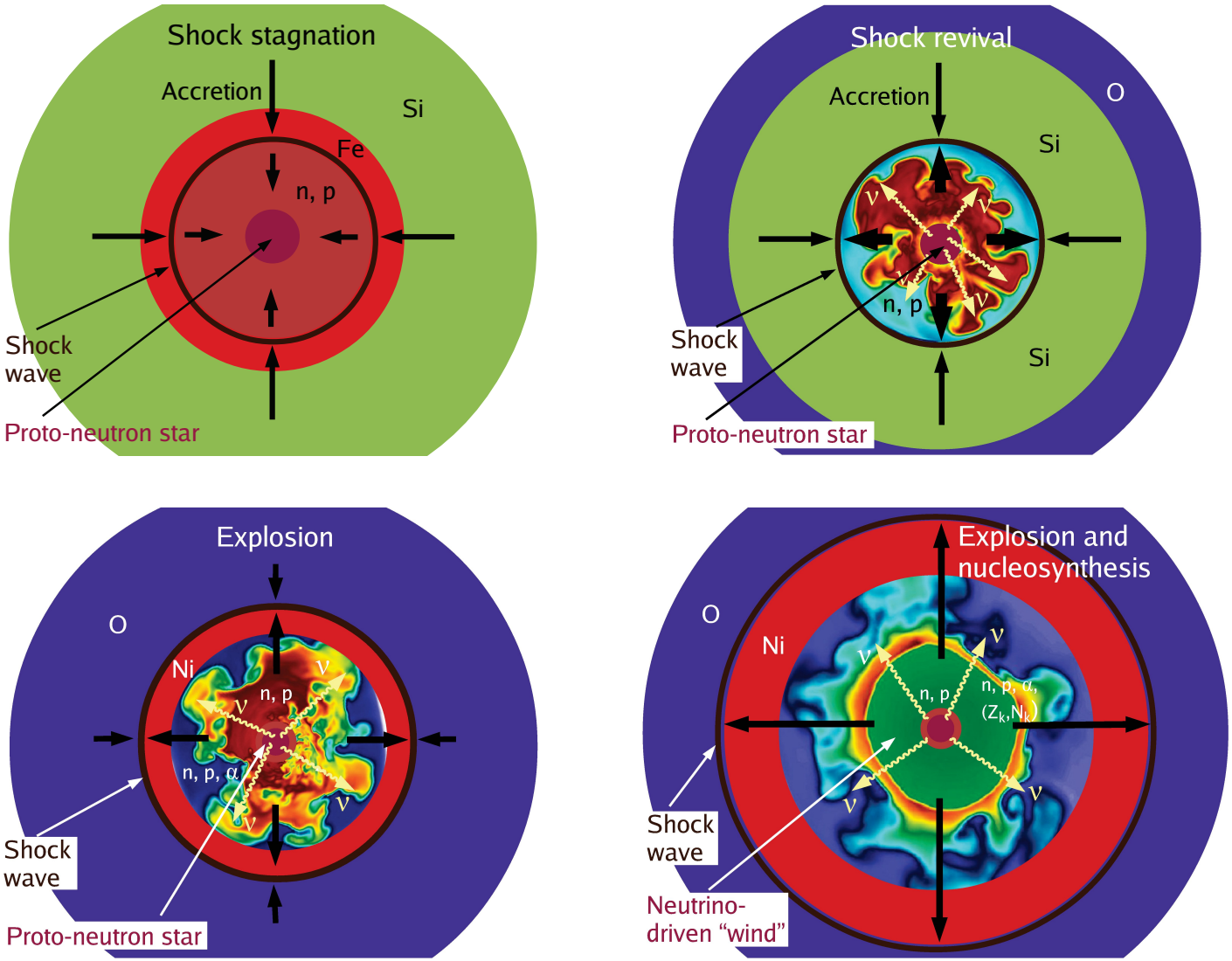






Core-collapse supernova

explosion ?



Janka et al. (2012)

Many physics

- Gravitation: General Relativity $\frac{2GM}{Rc^2} \sim 0.1$
- Hydrodynamics: relativistic $\frac{v}{c} \sim 0.3$; importance of convection and other instabilities (SASI).
- Equation of state (EoS): hot matter up to nuclear densities ; plasma, nuclei, nucleons and other particles (hyperons, ...). $T \sim 50$ MeV ; $\rho_c \sim 2 - 3 \times 10^{14}$ g.cm^{-3}.
- neutrino transport in nuclear matter : all ranges of optical depths from opaque to transparent regimes...
- Rotation and magnetic fields poorly known for progenitor stars.
- ...?

$\Rightarrow$Need a lot of computer power (exaflop?).
Effect of dimensionality (convection / turbulence).

Numerical simulations

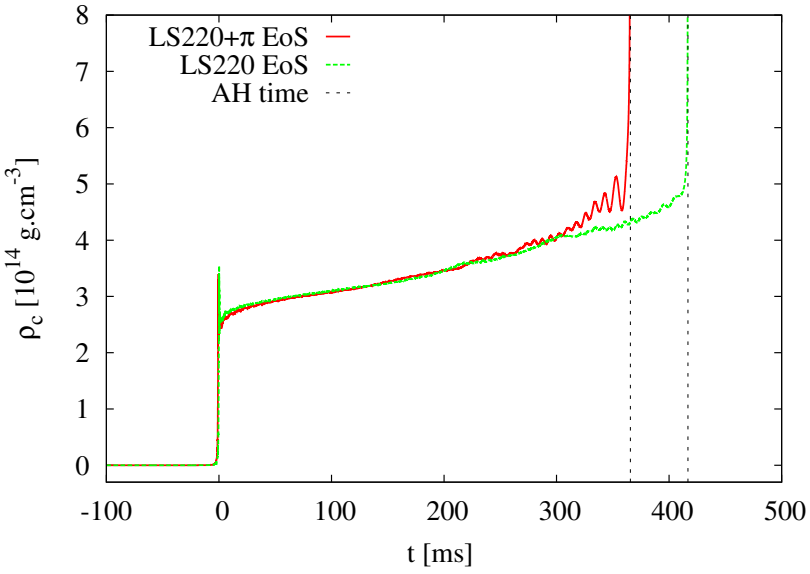
Development of CoCoNuT code, in collaboration with MPA (Garching) and DAA (Valencia) [*Dimmelmeier et al. (2005)*]

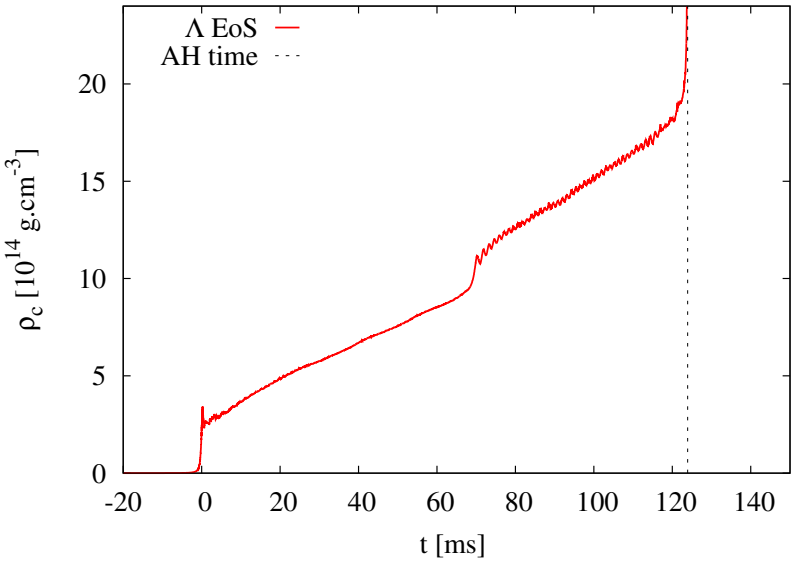
- First, aimed at determination of gravitational waves from core-collapse.
- Relativistic hydrodynamics, with Godunov (finite-volume shock-capturing) methods.
- Einstein equations in conformal flatness condition (CFC), with spectral methods.
- More development to include realistic EoS, deleptonization and neutrinos. Leakage scheme for the moment $\Rightarrow$full transport? [*Peres et al. (2014)*]
- Simulation of black hole formation (failed supernova), with excision (talk by I. Cordero-Carrion).

Models at LUTH

Black hole formation

Black holes from failed supernovas may reprensent $\sim 23 - 90\%$ of compact remnants.
Composition of matter at very high densities poorly known: influence of additional particles: pions, hyperons ?





$\Rightarrow$phase transition induces oscillations of the proto-neutron star before its collapse to a black hole [*Peres et al. (2013)*].

Conclusions - Perspectives

- Simulation of core-collapse for (failed) supernovas is an ongoing effort in LUTh (not yet at best international level).
- Very complex problem requiring expertise in astro, hydro, GR, nuclear and particle physics (+ numerics!).
- First 1D-studies on black hole formation and influence of additional particles.

More to come:

- Extension to 2D-studies of hyperon influence $\Rightarrow$observable through gravitational waves (Virgo)?
- Parallelization of the code $\Rightarrow$2D and 3D runs, with enhanced neutrino treatment, to get their signal.
- Determination of observable signals: radioactive ejecta, neutrinos and gravitational waves $\Rightarrow$constraints on the nuclear/neutrino reactions...