Role of Dense Matter in Supernova

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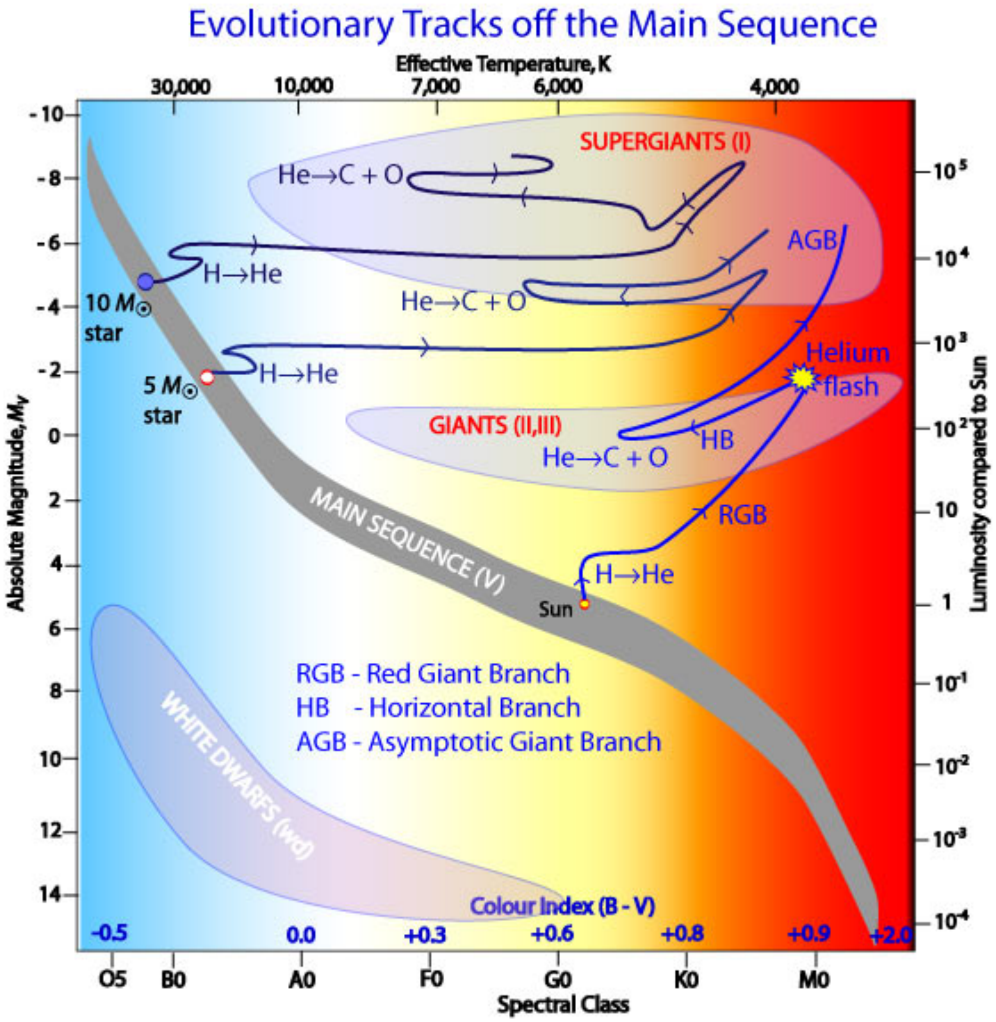
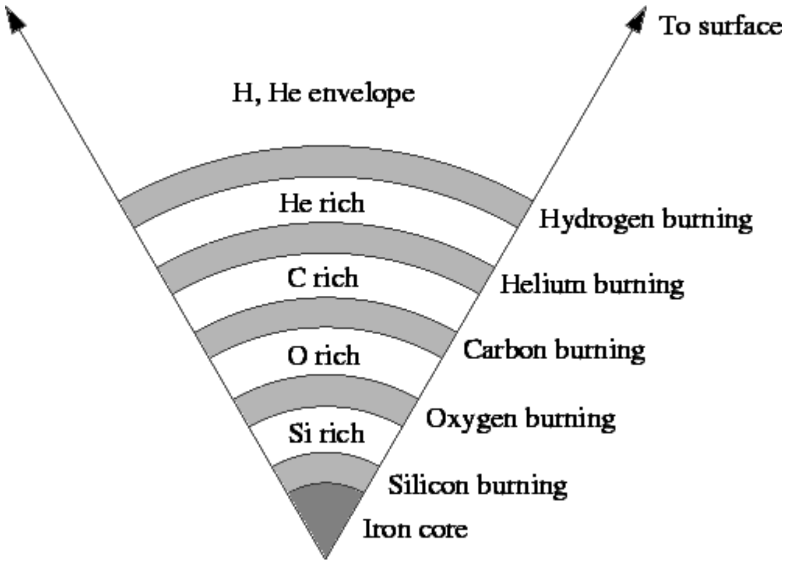
Stellar Evolution



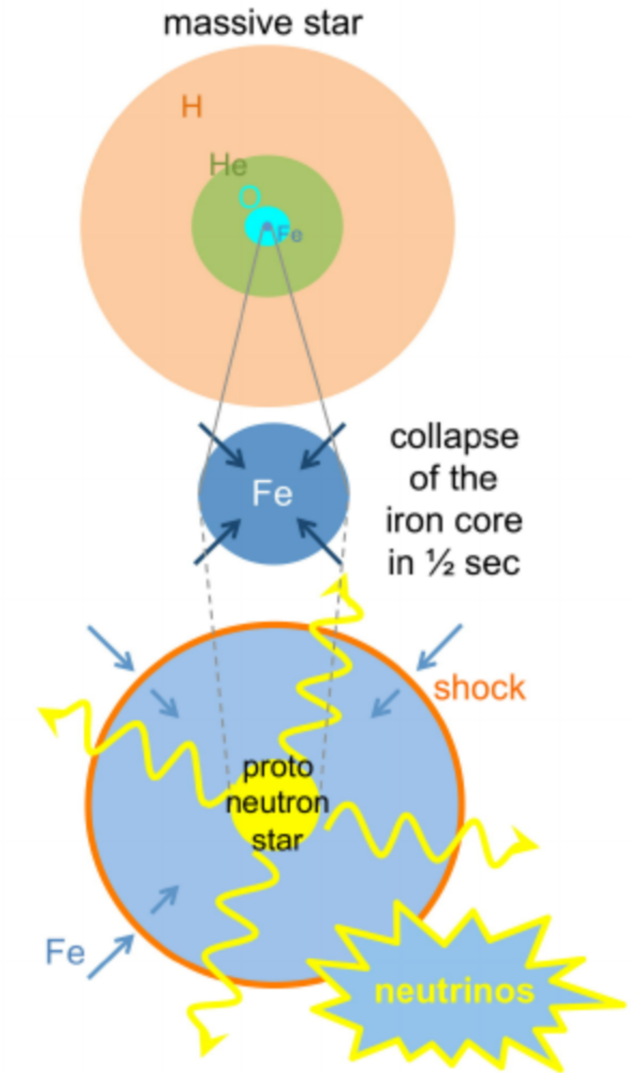
www.atnf.csiro.au



Pre-supernova at the end of the massive star evolution

http://burro.astr.cwru.edu

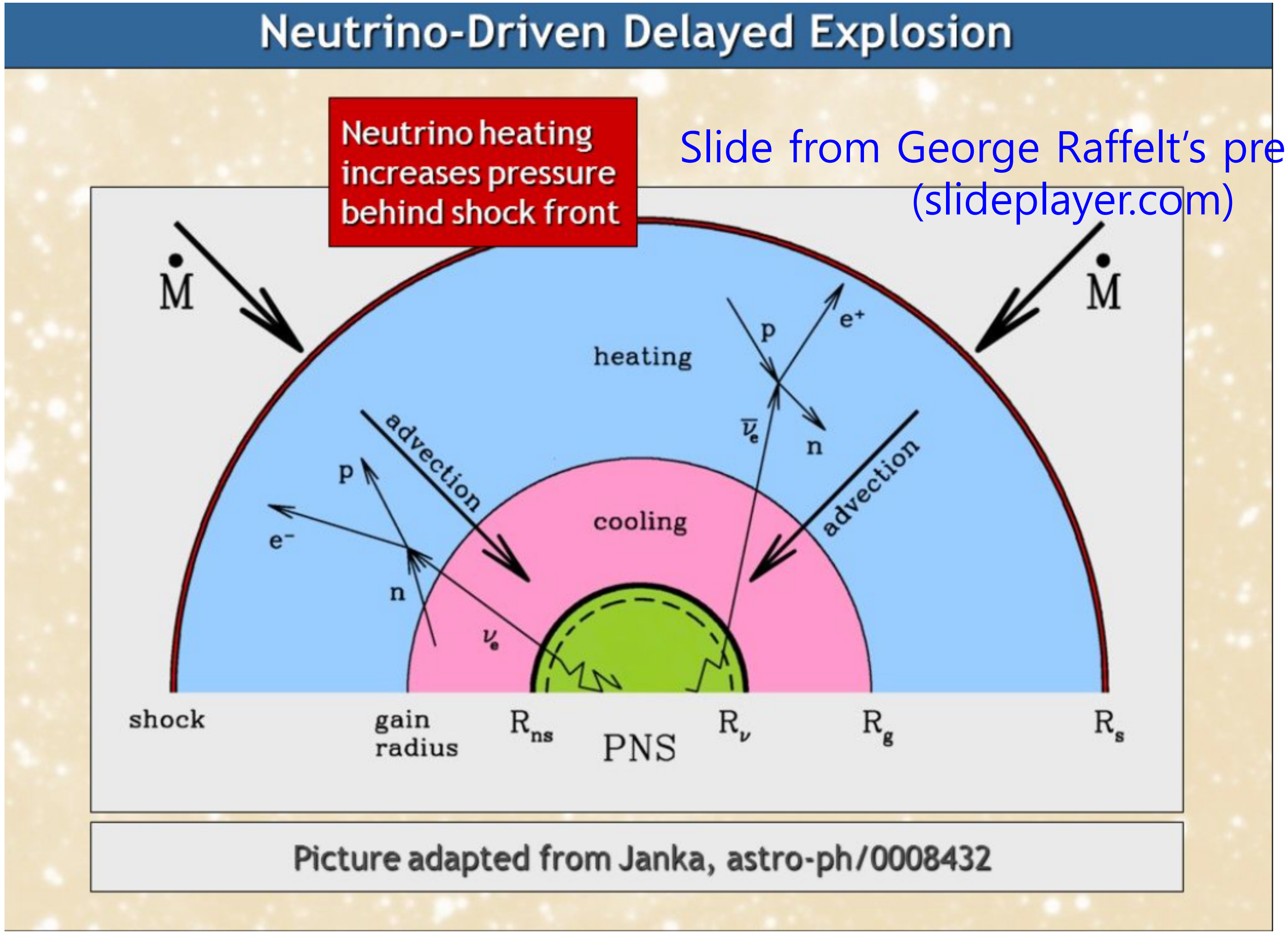
On the Way to Supernova Explosion



- ✓ Inner core (about 0.5 $M_\odot$) contracts homologously.
- ✓ Size of inner core weakly depends on the pre-SN structure.
- ✓ Outer core falls supersonically.
- ✓ Central region exceeds nuclear saturation density, which leads to bounce depending of equation of state. Alternatively, it collapses into a black hole.
- ✓ Bouncing results in shock wave that forms near the edge of inner core.

(From Introduction of Pejcha & Thomson 2015. See the references therein.)

Figure from www.researchgate.net.



Neutrino-Driven Delayed Explosion

Neutrino heating increases pressure behind shock front

Picture adapted from Janka, astro-ph/0008432

Slide from George Raffelt's presentation
(slideplayer.com)

- ✓ Shock wave is stalled by losing energy to dissociate iron.
- ✓ Standing accretion shock forms through the balance between neutrino emission from proto-neutron star (PNS) and infalling matter from outer core. (From Introduction of Pejcha & Thomson 2015. See the references therein.)

Uncertainties in Supernova Simulations

- Uncertain physics
  - Neutrino self-interactions including oscillation at high luminosity
  - Equation of state for dense (nuclear/quark) matter that affects the emissivity and opacity of neutrino transport
  - Other mechanisms (e.g., rotational energy)
- Technical (numerical) challenges
  - Proper implementation of general relativity
  - 3D simulations with neutrino radiative transfer
  - Other effects (e.g., inclusion of magnetic field)

EoS for SN Simulations

- EoS for (cold) neutron star
    - At beta equilibrium and $T \approx 0$
- A wider range (general purpose EoS)
    - $0 \le T \le 100$ MeV
    - 10^4 g/cm^3 $\le \rho \le 10^{15}$ g/cm^3
    - $0 \le Ye \le 0.6$
- Needs to cover gaseous nuclei to uniform nuclear matter
- Mixture of nuclei and nucleon
    - Phase transition

Handling the Mixture

- Thomas–Fermi approximation
  - Nucleus at the center (body-centered cubic) to minimize the Coulomb lattice energy
  - Wigner–Seitz cell: approximation with sphere

$$n_i\left(r\right)=\begin{cases}\left(n_i^{\mathrm{in}}-n_i^{\mathrm{out}}\right)\left[1-\left(\frac{r}{R_i}\right)^{t_i}\right]^3+n_i^{\mathrm{out}}, & 0\le r\le R_i,\\ n_i^{\mathrm{out}}, & R_i\le r\le R_{\mathrm{cell}},\end{cases}$$

$$n_\alpha\left(r\right)=\begin{cases}-n_\alpha^{\mathrm{out}}\left[1-\left(\frac{r}{R_p}\right)^{t_p}\right]^3+n_\alpha^{\mathrm{out}}, & 0\le r\le R_p,\\ n_\alpha^{\mathrm{out}}, & R_p\le r\le R_{\mathrm{cell}},\end{cases}$$