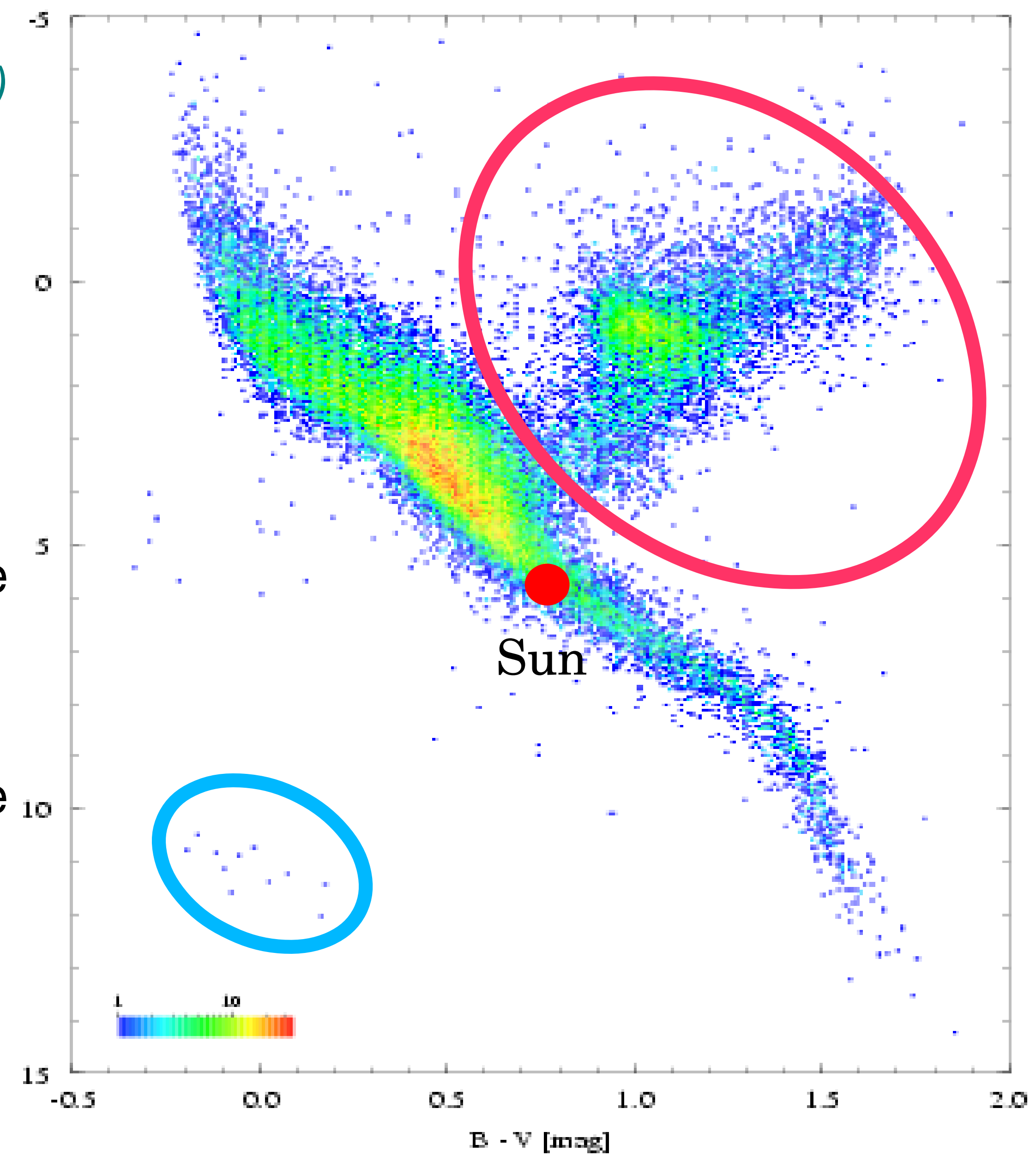
Stars: beyond the Main Sequence

Main-sequence
1) first and dominant stage in life,
2) H → He in the core *(subtle rise of L)*
3) >80% stars in MS

Low-mass stars
1) Ascend Giant Branch (H shell)
2) Red clump/Horizontal branch
   (He → C in core, H shell)
3) Asymptotic Giant (H, He shell)
4) Env. ejection → White Dwarf

Intermediate-mass stars
1) Expand at L~const, ignite He in core
2) Asymptotic Giant (H, He shell)
3) Env. ejection → White Dwarf

High-mass stars
1) Expand at L~const, ignite He in core
2) Fusion in stages, up to Si → Fe
3) Core collapse → Neutron star,
   Black hole



Hipparcos HRD

Understanding stellar structure & evolution (a success story of 20th century astrophysics)

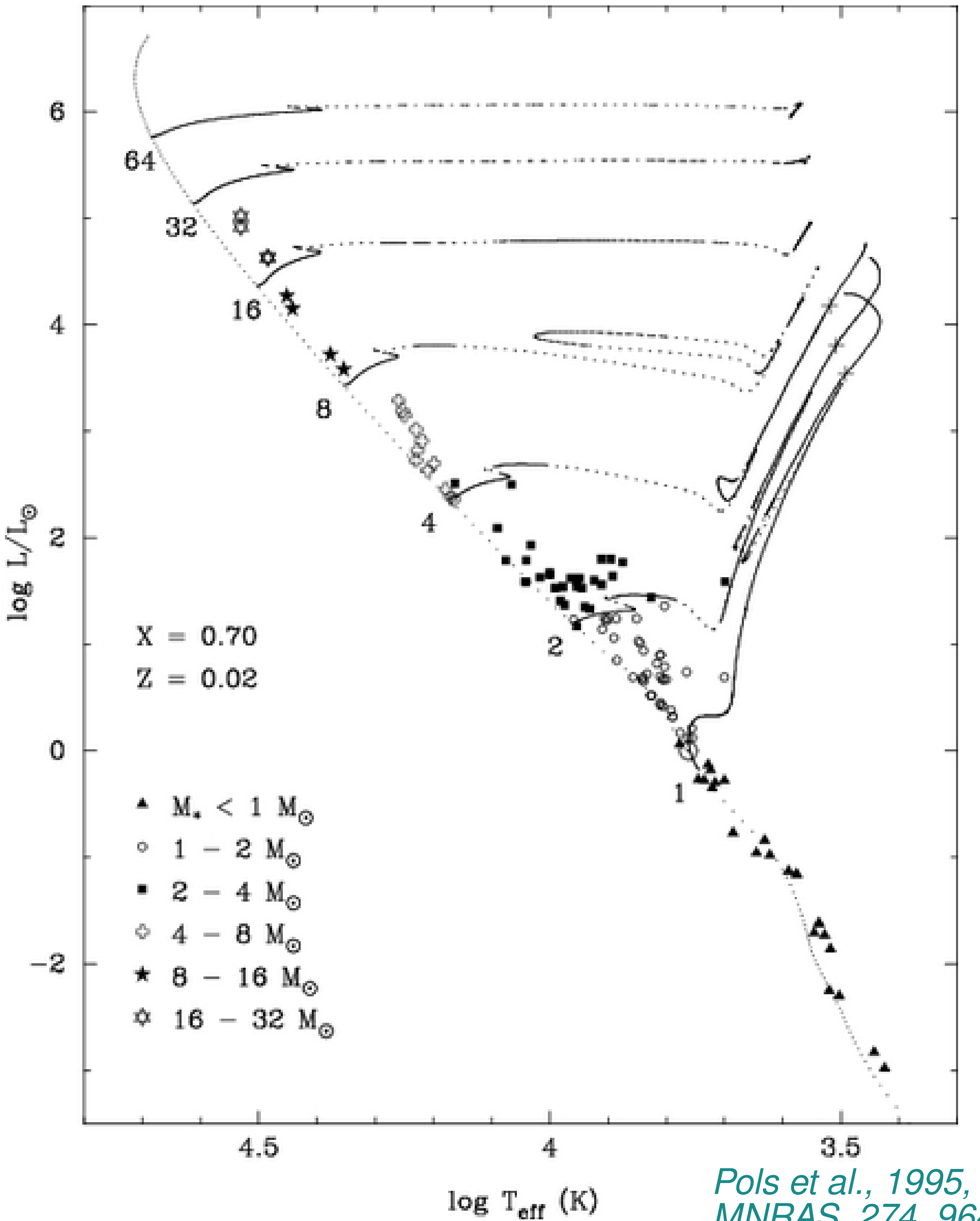
Founded on theory:

- hydrostatic equilibrium
- nucleosynthesis
- radiative transport (photon-matter interaction)
- equation of state (behaviour of matter)
- *classical physics + quantum mechanics*

Confirmed by observations:

- absorption spectra, spectral types
- color-magnitude diagram,
- stellar pulsation, binary stars, stellar clusters...

Evolutionary tracks:
what happens depends on mass



Pols et al., 1995, MNRAS, 274, 964

A star becomes a giant (much bigger & brighter) after the MS

1) Main-sequence: sun 70% H, 28% He to start with

   Core-hydrogen burning phase lasts ~ 80-90% of total life-time.
   More massive stars live shorter *(Sun ~ 10^{10} yrs)*
   Subtle rise in Luminosity as Helium fraction increases *(why?, μ -> HE!)*

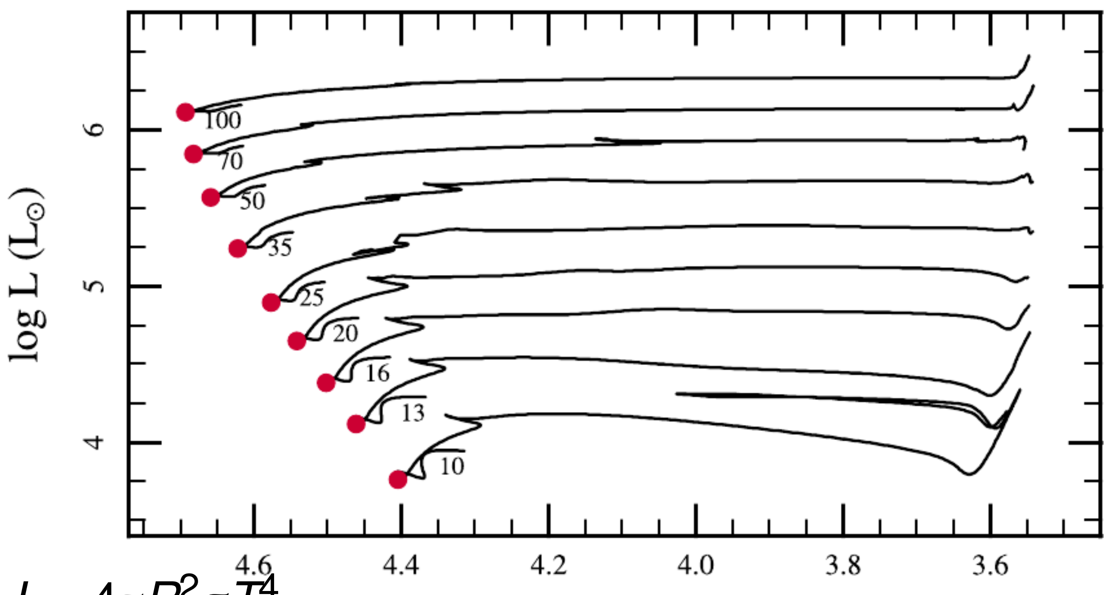
2) Core-hydrogen exhaustion: the end of the Main Sequence

   Helium burning requires higher temperature *(why?, ~10^8 K)*
   Core contracts in thermal timescale *(t_{KH} ~ E_{th}/L, why not t_{dyn}?)*
   For mass above ~2 $M_{\odot}$, heats up sufficiently to ignite He;
   Below, core becomes degenerate first (next lecture)

3) Shell (around core) heats up to 10^7 K

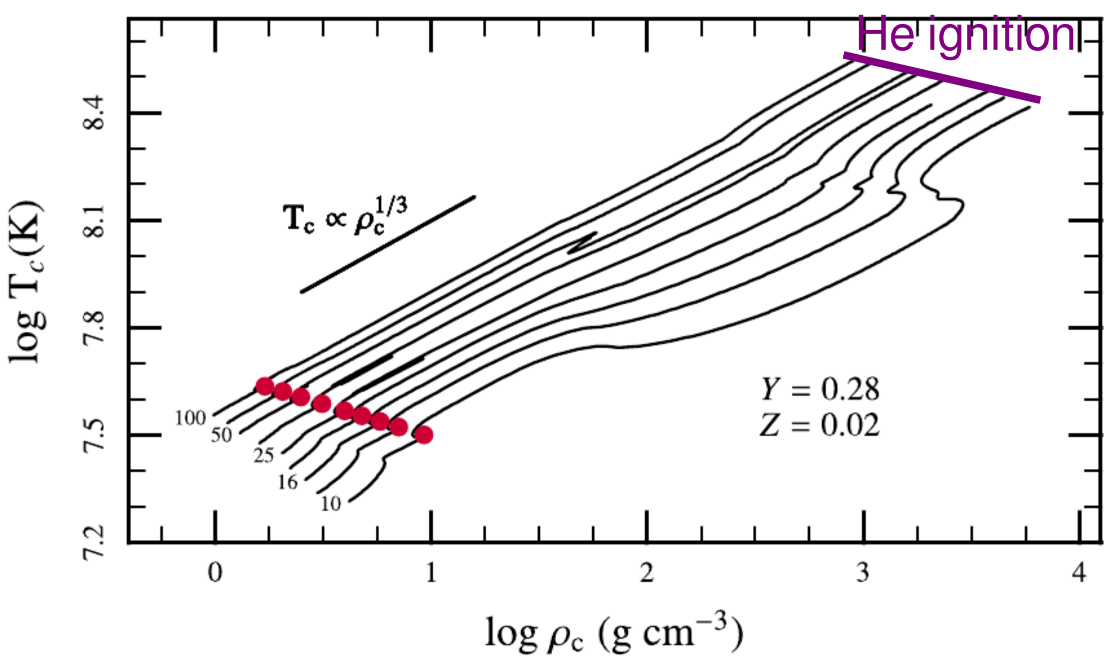
   Shell burning H $\rightarrow$ He

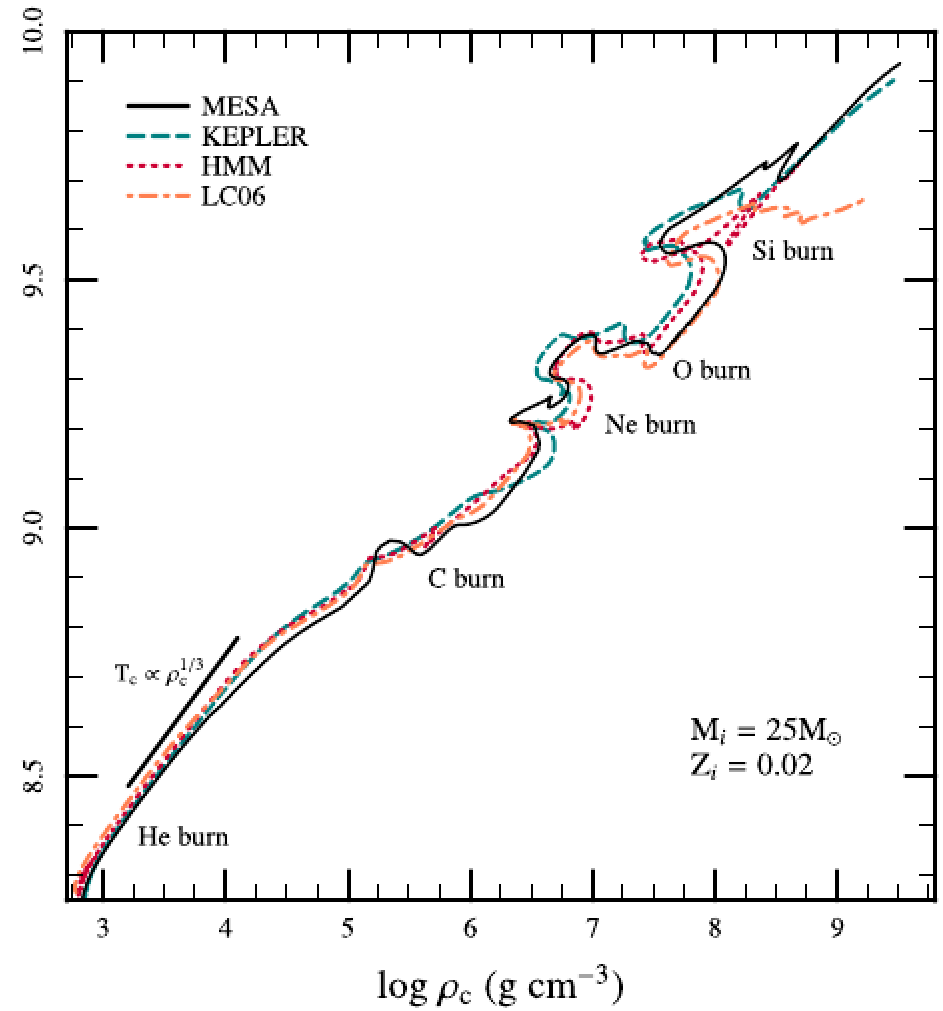
   For low-mass stars, rate >> main-sequence -> giant (next lecture)

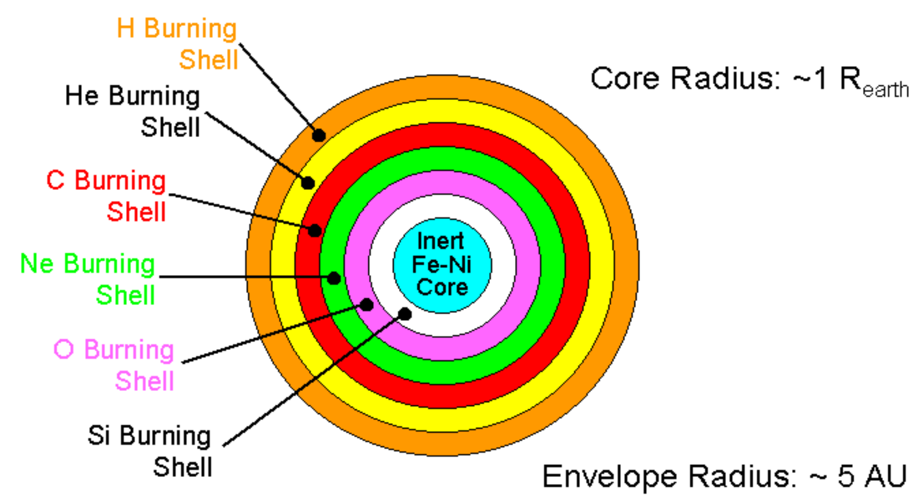


$L = 4\pi R^2 \sigma T^4$

$L \sim C \rightarrow$ turns change $T \rightarrow$ *expansion or contraction*







Paxton et al., 2011, ApJS 192:3

High-mass star (M > 8 $M_\odot$) fusion all the way from H $\rightarrow$ Fe

Fuel	T_c (K)	ρ_c (g/cm^3)	Time (yr)	$L_\nu/L_\odot$
H	4×10^7	5	7×10^6	small
He	2×10^8	700	5×10^5	small
C	6×10^8	2×10^5	600	8.3
Ne	1.2×10^9	4×10^6	1	6.5×10^3
O	1.5×10^9	1×10^7	0.5	1.9×10^4
Si	2.7×10^9	3×10^7	1 day	3.2×10^6

For 25 $M_\odot$ star:

~20 $R_\odot$, ~10^5 $L_\odot$, few 10^6 yr
(MS: as O&B spectral types)

giants: ~500 $R_\odot$, ~10^5 $L_\odot$
(core & shell burning,onion-shells, centre burned till Fe)

Supernova: $T_c >$ 5×10^9 K, nuclei photo-disintegrated
(undo all previous burning, neutrinos escape)

Neutron Stars (neutrons only ~ 1.4 $M_\odot$, ~ 10 km)
or Black Holes (space-time singularity, even photons cannot escape)

+ supernova remnant (~1-10 $M_\odot$, expansion @ ~10000 km/s, shines for ~ 10^4 yr)
net effect of a star's life:mass loss + SN -- metal enrichment of the interstellar medium

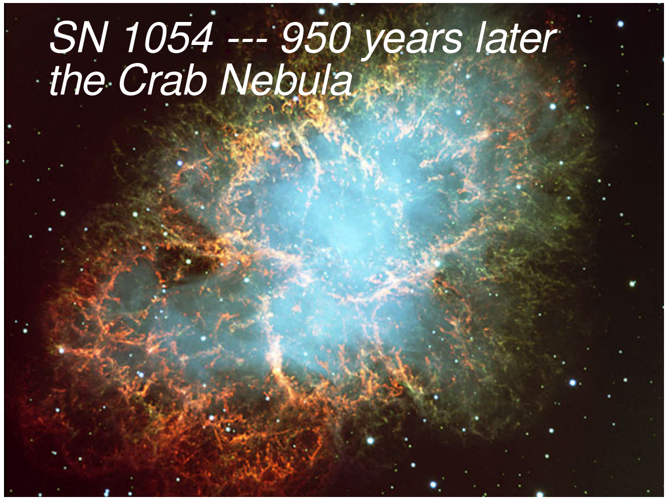
Supernova ---- irreversible violent collapse

1) Past Fe, nuclear burning endothermic,
   the very hot *(~5x10^9 K)* core *(~5000 km)* loses pressure support because:
   a) photo-disintegration of nuclei *undo previous nuclear fusion, $Fe + \gamma \rightarrow \alpha$'s + p^+ + n*
   b) electron capture into neutrons *e^- squeezed into p^+, loose e^- degen. P, produce ν*
   c) neutrino leakage out of the star $\sigma \sim 10^{-48}$ m^2, *reaction irreversible*
   core collapse proceeds in dynamical time-scale: $\tau_{dyn} \sim 1/(G\rho)^{1/2} \sim 10$ sec
   not thermal time-scale (like low-mass star cores)

2) Core collapse *(to ~ 10 km)* induces Supernova explosion
   total SN energy: release of grav. energy ~ 10^{46} J
   unbinding the envelope ~ 10^{44} J *(ejecta final kinetic energy ~10^{42} J)*
   photons: 10^{10} $L_\odot$ (~L_{galaxy}) for ~10 days ~10^{44} J
   SN 1054 (Crab Nebula, ~ 2kpc): ancient Chinese reports: seen during day time
   99% of the energy: neutrinos (ν) $L_\nu \sim 10^{19}$ $L_\odot$
   SN 1987A (Large Megellanic Cloud): 11 ν detected
   supernova remnant: SN ejecta hits interstellar gas

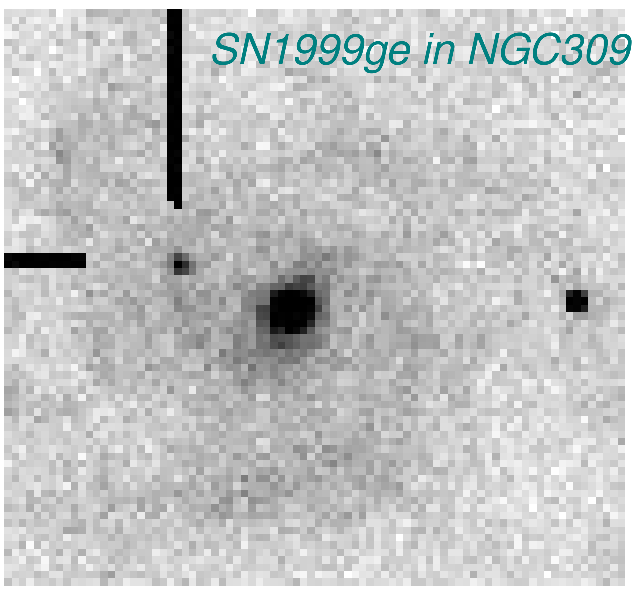
3) Neutron star supported by
   neutron degeneracy pressure plus strong force

4) Current investigations:
   Why do SN explode? Does it leave a NS or BH?
   NS are born with v ~ 300 km/s, what kicks it?
   Some NS with ultrastrong magnetic fields; why?



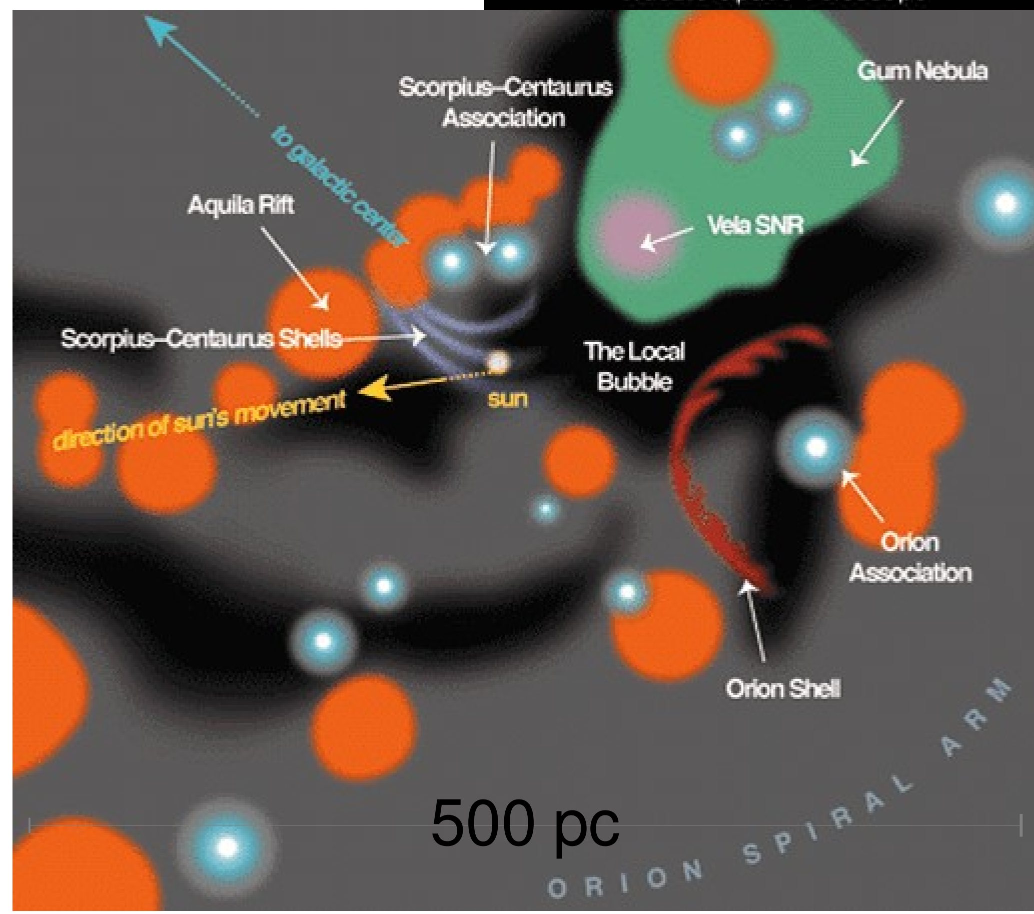
SN 1987A in
the Large Magellanic Cloud.....
.... and 4 years later

after before



SN1999ge in NGC309

SN rate: ~ 1/50yr/galaxy
last observed one in Milky Way: 1640 (Kepler)
(two further younger remnants known)



Local Bubble (Huff & Frisch)