Endpoints of stellar evolution

The end of stellar evolution is an inert core of spent fuel that cannot maintain gas pressure to balance gravity

Such a core can be balanced against gravitational collapse by electron degeneracy pressure IF the total mass is less than the Chandrasekhar mass limit:

Chandrasekhar Mass:

Only if the mass of a inert core is less than Chandrasekhar Mass M_{ch}

$$M_{Ch} \approx 5.85\, Y_e^2 M_\Theta$$

Electron degeneracy pressure can prevent gravitational collapse

In more massive cores electrons become relativistic and gravitational collapse occurs (then $p \sim n^{4/3}$ instead of $p \sim n^{5/3}$).

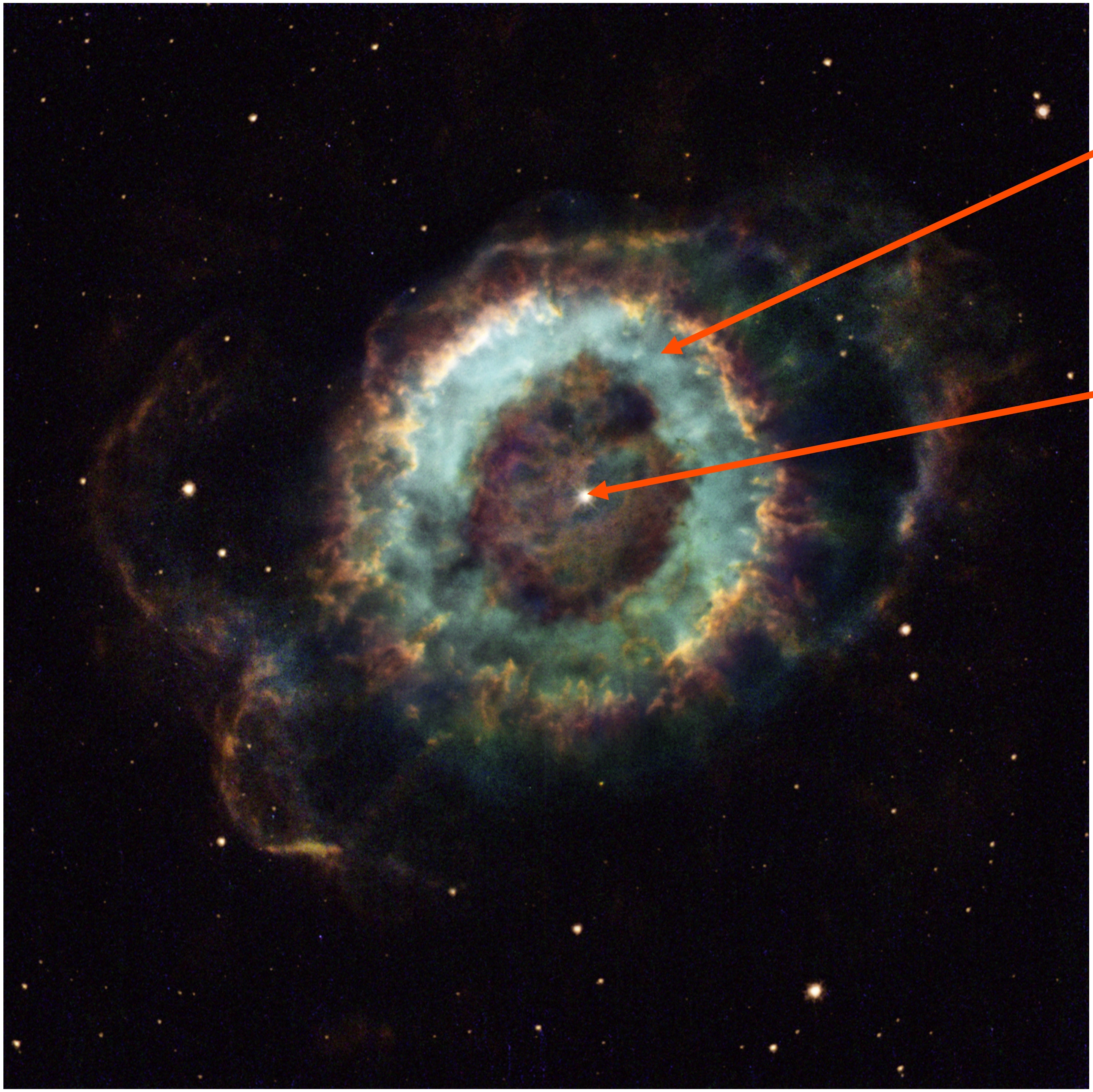
For N=Z M_{Ch}=1.46 M_0

Mass and composition of the core depends on the ZAMS mass and the previous burning stages:

M_{ZAMS}	Last stage	Core	Mass	Result
$< 0.3\ M_0$	H burning	He	$M<M_{Ch}$	**core survives**
0.3- $8\ M_0$	He burning	C,O		
8-$12\ M_0$	C burning	O,Ne,Mg		
> 8-$12\ M_0$	Si burning	Fe	$M>M_{Ch}$	**collapse**

How can 8-$12M_0$ mass star get below Chandrasekhar limit ?

Death of a low mass star: a “Planetary Nebula”



Envelope of star blown into space

And here’s the core !
a “white dwarf”

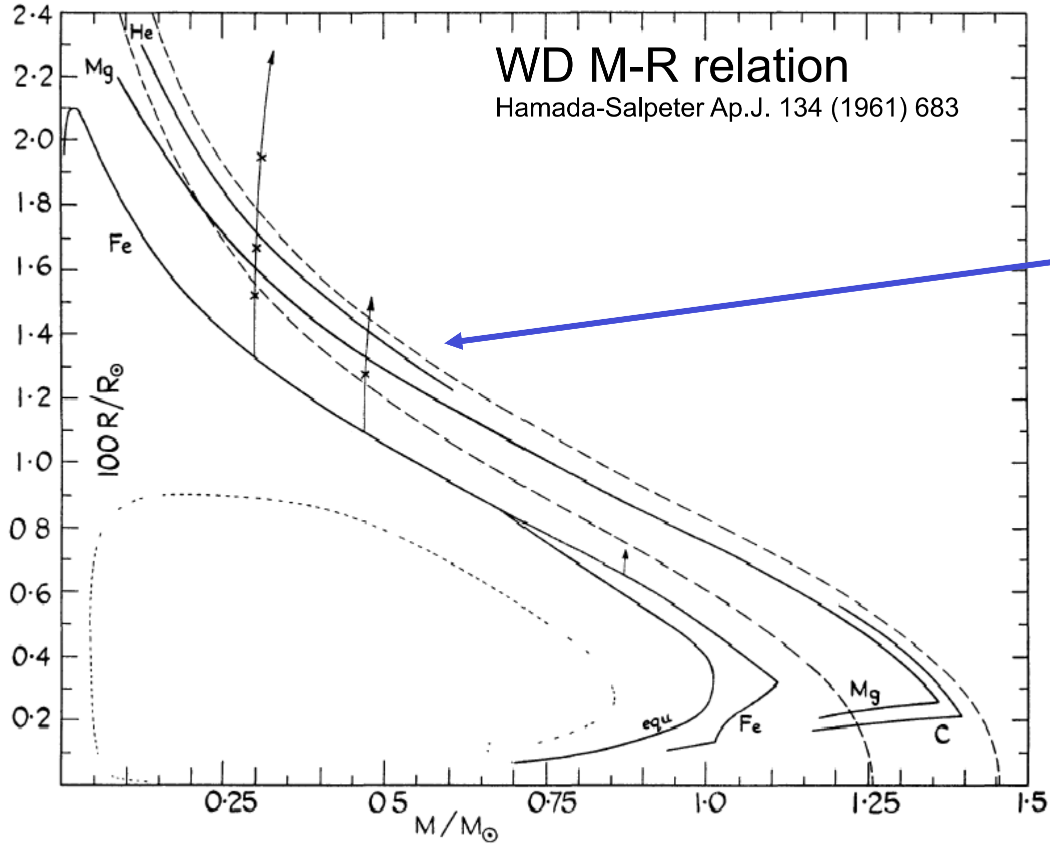
image: HST
Little Ghost Nebula
distance 2-5 kLy
blue: OIII
green: HII
red: NII

Why “white dwarf” ?

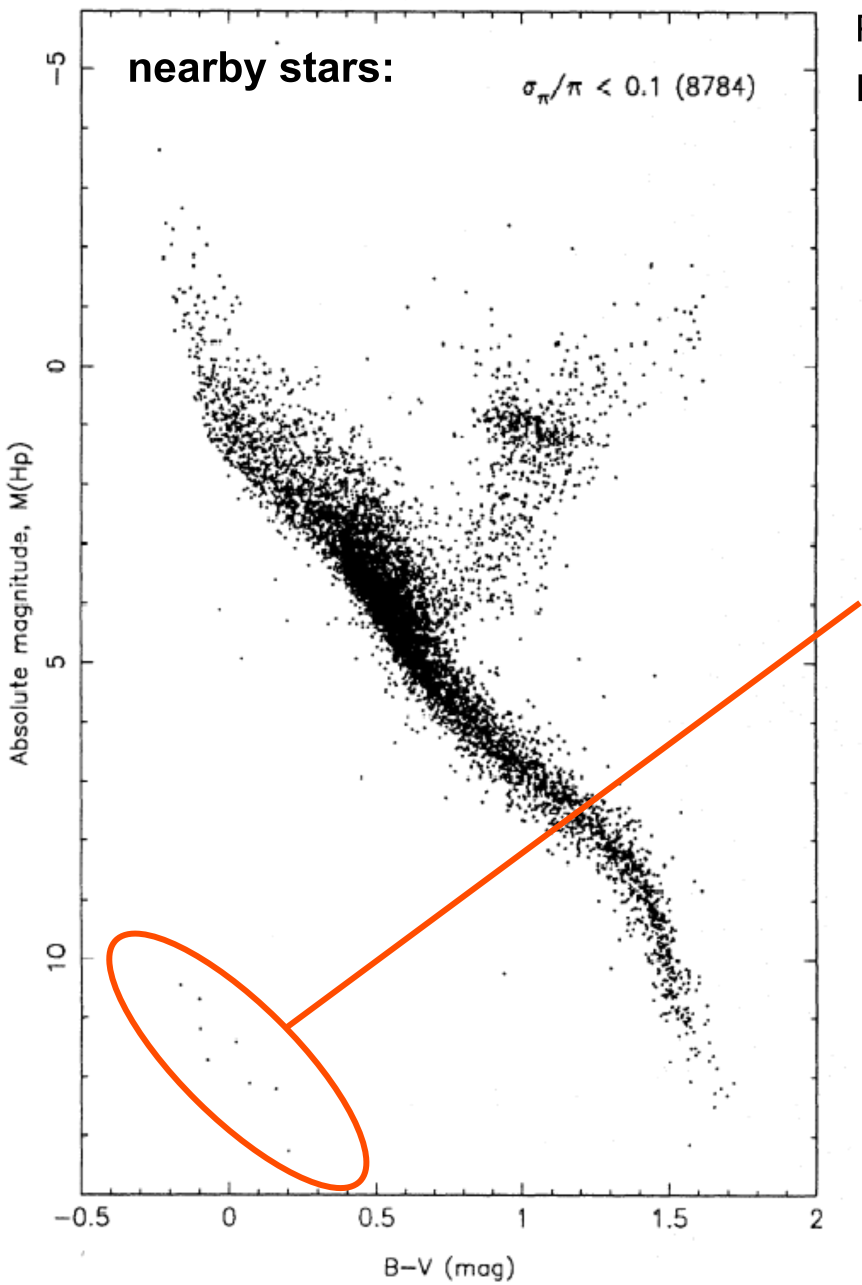
• core shrinks until degeneracy pressure sets in and halts collapse

→ star is HOT (gravitational energy !)

→ star is small



$$R \sim M^{-1/3}$$

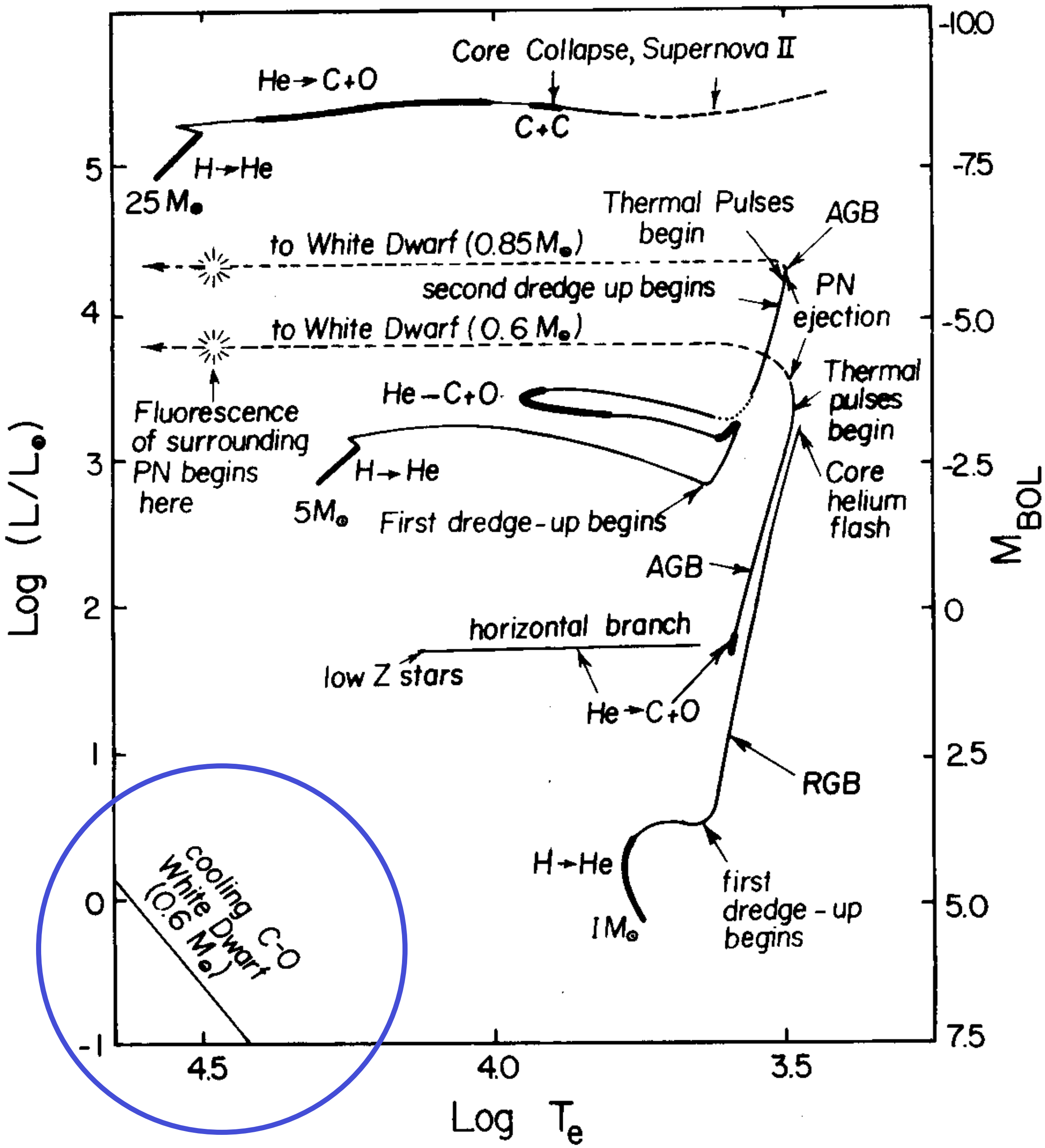


Perryman et al. A&A 304 (1995) 69

HIPPARCOS distance measurements

Where are the white dwarfs ?

there (small but hot white (B~V))



Pagel, Fig. 5.14

Supernovae

If a stellar core grows beyond its Chandrasekhar mass limit, it will collapse.

Typically this will result in a **Supernova explosion**
→ at least the outer part of a star is blown off into space

But why would a collapsing core explode ?

a) CO or ONeMg cores that accrete matter from a companion star can get beyond the Chandrasekhar limit:

Further collapse heats star and CO or ONeMg burning ignites explosively

⟶ **Whole star explodes – no remnant**

b) collapsing Fe core in massive star (but not too massive) → neutron star

Fe cannot ignite, but collapse halted once densities of ~2x nuclear density are reached (repulsive nuclear force)

Some facts about Supernovae:

1. Luminosity:

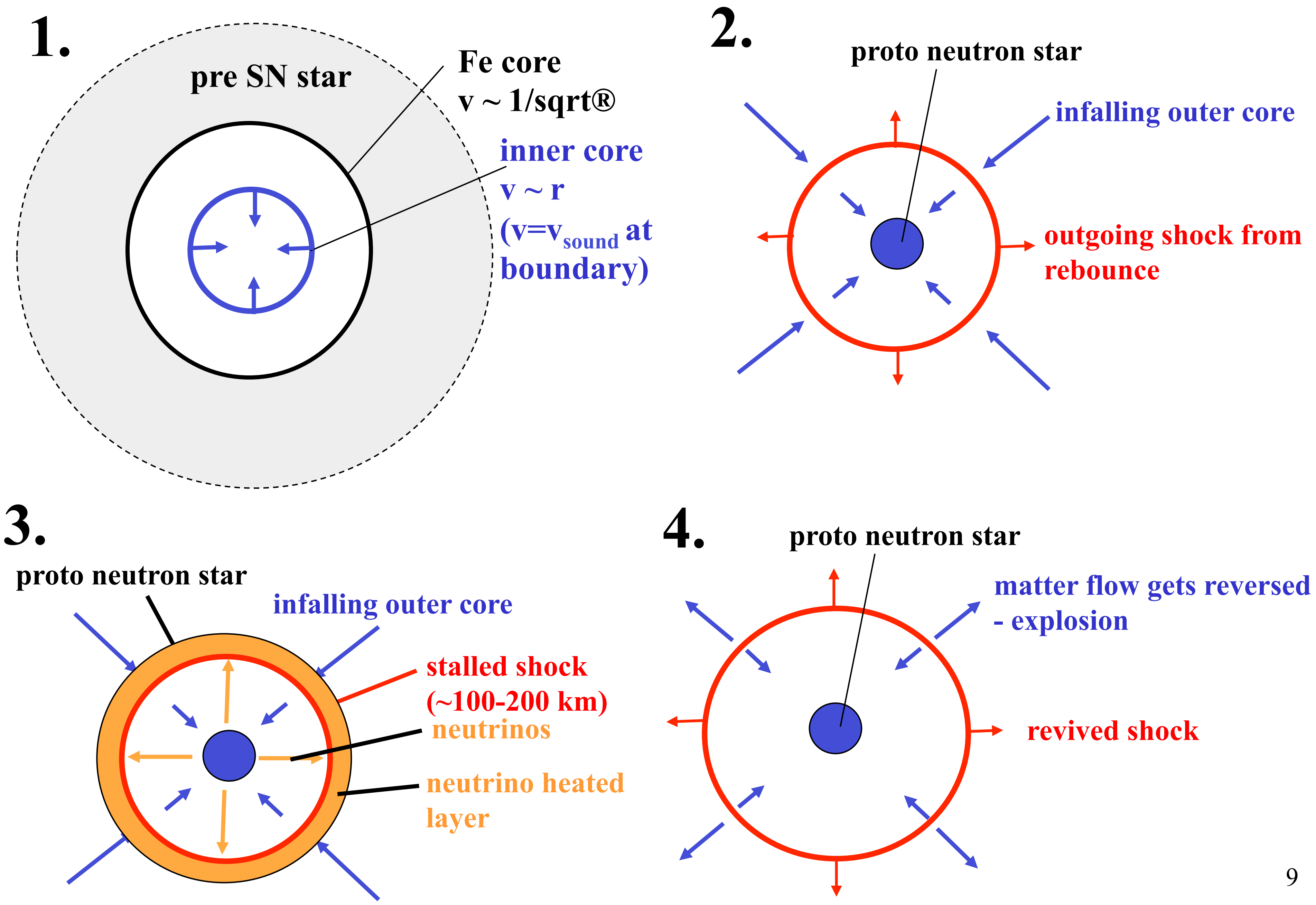
Supernovae might be the brightest objects in the universe, and can outshine a whole galaxy (for a few weeks)

Energy of the visible explosion: ~10^{51} ergs (= 1 foe = 1 Bethe)
Total energy : ~10^{53} ergs (most in neutrinos)
Luminosity : ~10^{9-10} L_0

2. Frequency:

~ 1-10 per century and galaxy

core collapse supernova mechanism



A star ready to die

Neutron
star forms
(size ~ 10 km radius)

Matter evaporated off the hot neutron star

r-process site ?

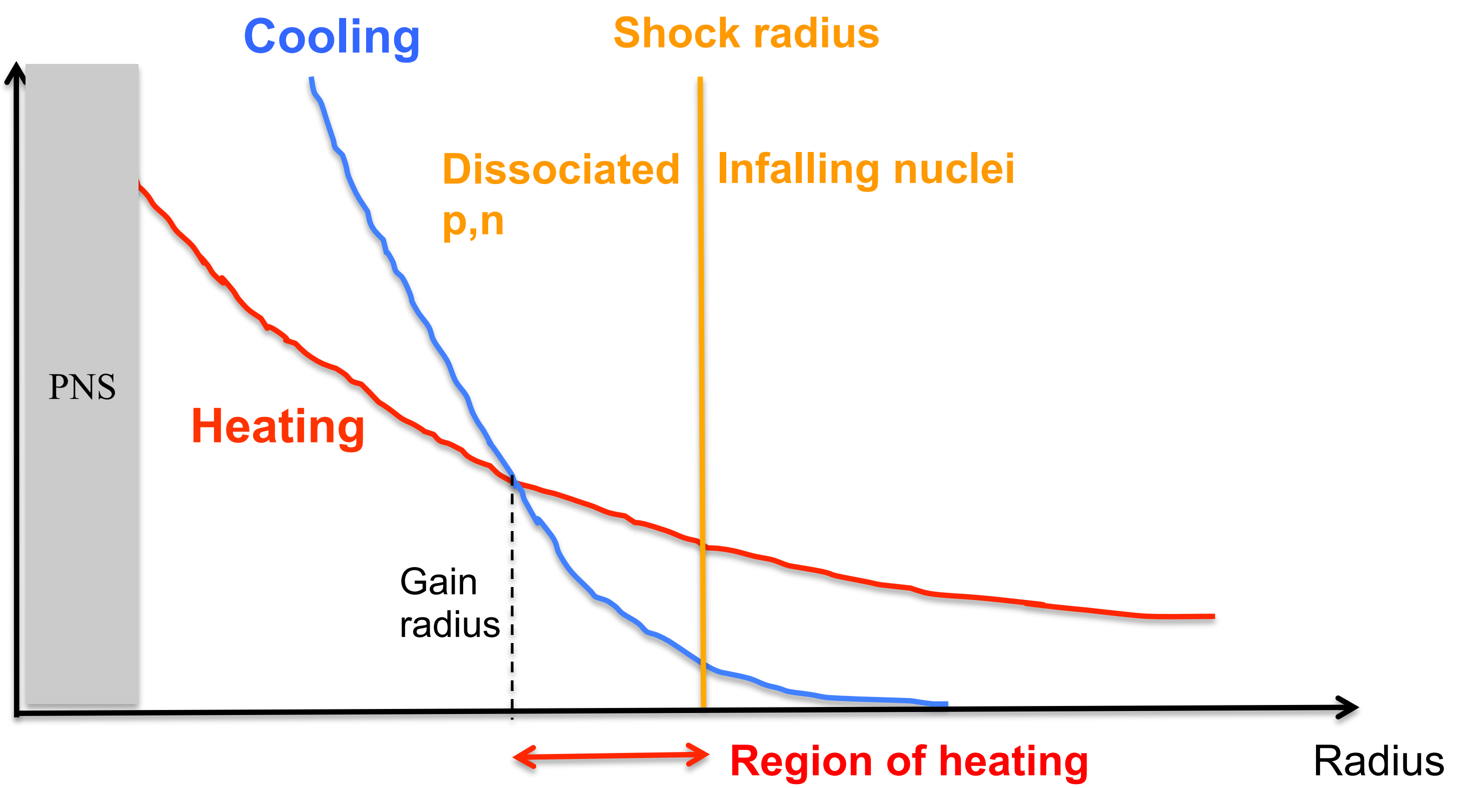
Gain layer explained

Neutrino absorption and emission via

$$\nu_e + n \longleftrightarrow p + e^-$$
$$\bar{\nu}_e + p \longleftrightarrow n + e^+$$

→ Cooling rate ~T^6 As T~1/r cooling decreases with radius as ~$1/r^6$

→ Heating ~$1/r^2$ Requires free protons and neutrons



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General Relativistic Collapse of Rotating Stellar Cores in Axisymmetry

Harald Dimmelmeier
José A. Font
Ewald Müller

References:

- Dimmelmeier, H., Font, J. A., and Müller, E., *Astron. Astrophys.*, 388, 917–935 (2002), astro-ph/0204288.
- Dimmelmeier, H., Font, J. A., and Müller, E., *Astron. Astrophys.*, submitted (2002), astro-ph/0220489.

Status of delayed detonation mechanism

- Its considered the most promising avenue by all groups

- **1D Models:**
  - Reasonable microphysics (neutrino transport) possible
  - Most 1D models do not explode (except very low mass end)
- **2D Models:**
  - Reasonable microphysics now possible (cutting edge)
  - Latest 2D models show some explosions but often too low in energy
    - Garching group gets now explosions for (8.1, 8.8, 9.6, 11.2, 15, and 27 $M_\odot$)
- **3D Models:**
  - Only exploratory studies with simplified microphysics
  - Key results:
    - significant qualitative differences from 2D to 3D – nature of turbulence, SASI very strong in 2D, not at all in 3D → 2D might be misleading
    - Tendency of easier explosions from 1D → 2D → 3D (though debate)

Prospects

- Generally delayed explosion mechanism suspected to solve the problem eventually
- Probably need full 3D to solve the problem

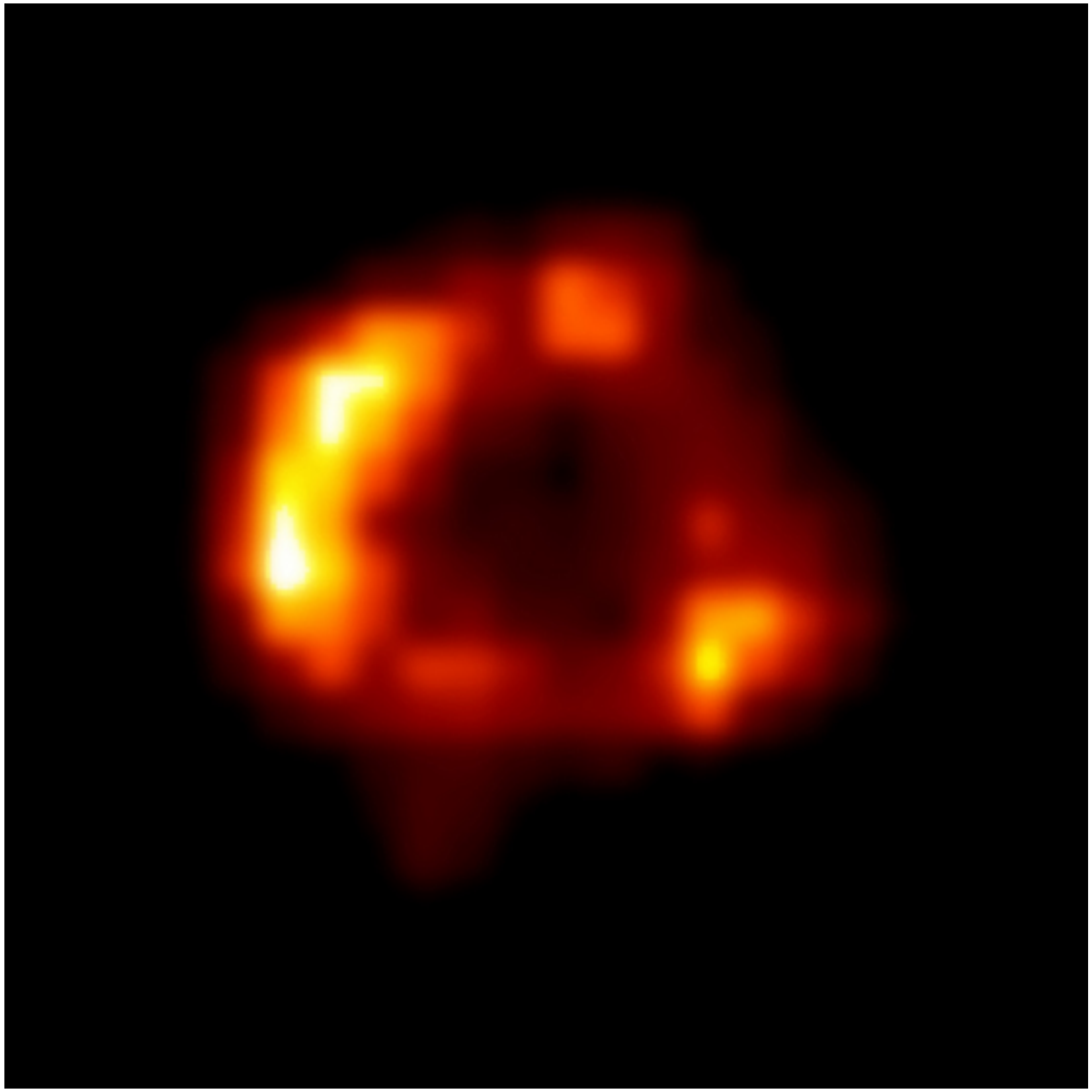
Key effects of multi-D vs 1D:

- Neutrino heating induced convection
  - Pushes shock out and increases gain region
  - Dredges material down into gain region
- SASI (Standing Accretion Shock Instability) would help
  - Possibly not important in 3D?
- Magnetic fields, rotation → might add energy
- Acoustic vibrations?

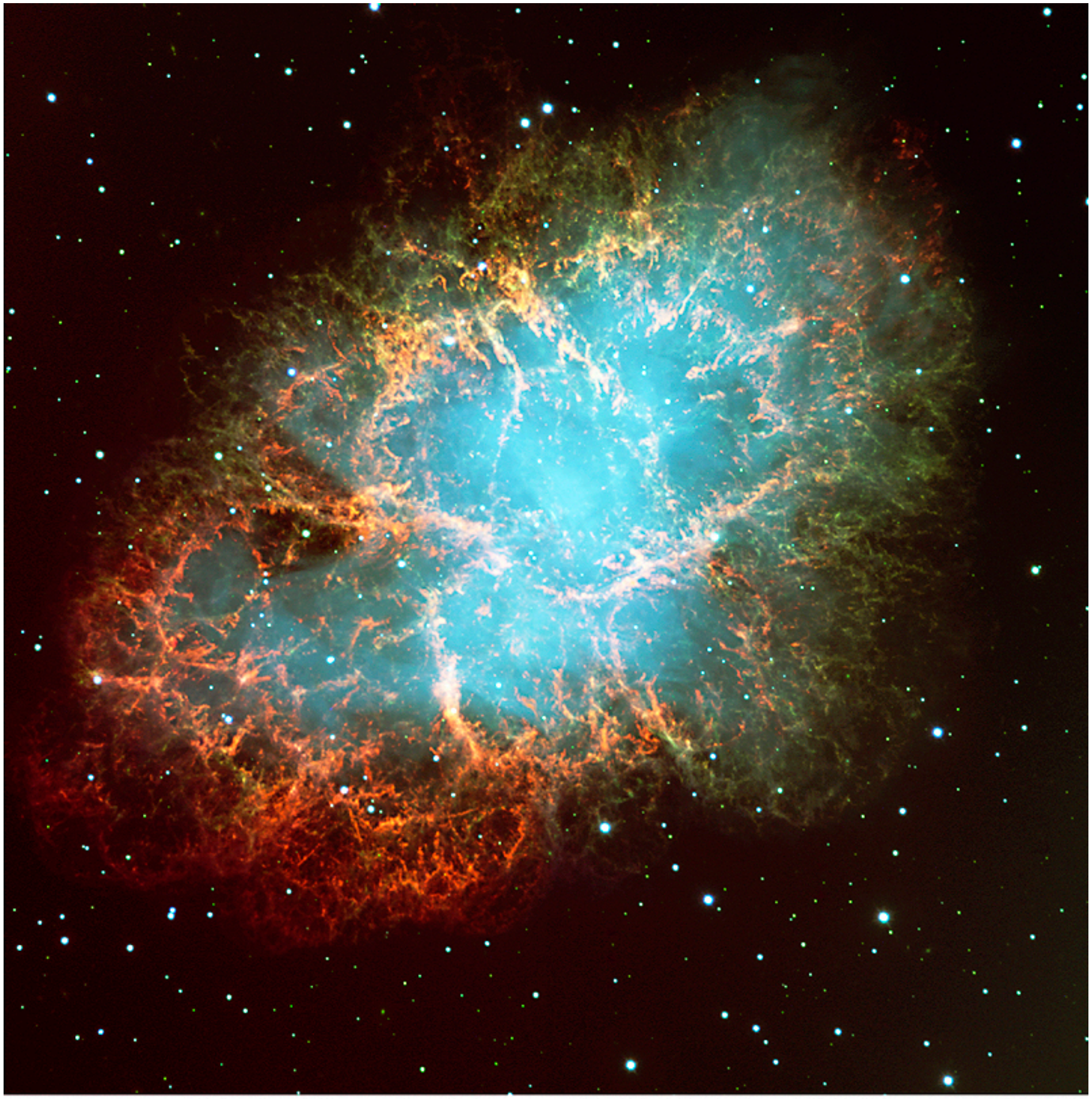
Tarantula Nebula in LMC (constellation Dorado, southern hemisphere)
size: ~2000ly (1ly ~ 6 trillion miles), disctance: ~170000 ly

Tarantula Nebula in LMC (constellation Dorado, southern hemisphere)
size: ~2000ly (1ly ~ 6 trillion miles), disctance: ~180000 ly

Supernova 1987A seen by Chandra X-ray observatory, 2000

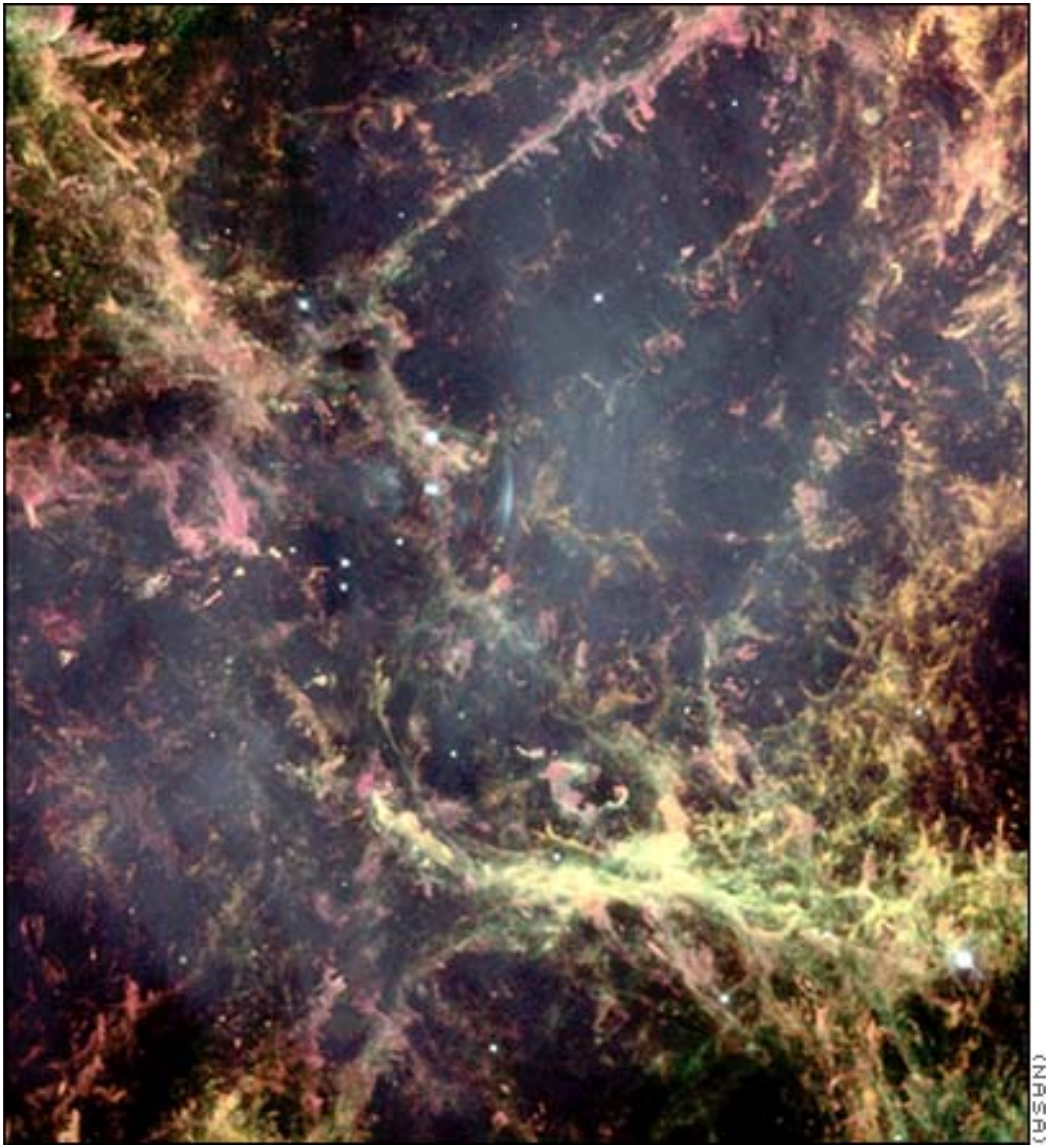


Shock wave hits inner ring of material and creates intense X-ray radiation



The Crab Nebula in Taurus (VLT KUEYEN + FORS2)

ESO PR Photo 40f/99 (17 November 1999)

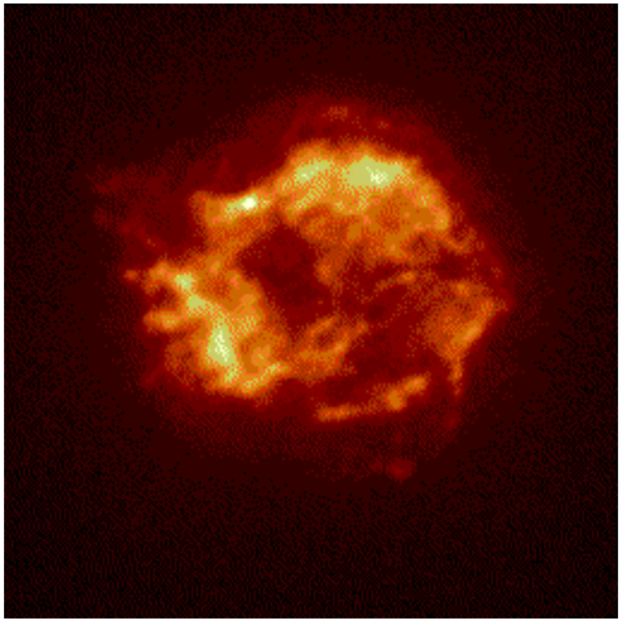


HST picture

Crab nebula
SN July 1054 AD
Dist: 6500 ly
Diam: 10 ly,
pic size: 3 ly
Expansion: 3 mill. Mph
(1700 km/s)
Optical wavelengths
Orange: H
Red : N
Pink : S
Green : O

Pulsar: 30 pulses/s

Cas A supernova remnant



… seen over 17 years

youngest supernova in our galaxy – possible explosion 1680
(new star found in Flamsteeds catalogue)

3. Observational classes (types):

Type I no hydrogen lines

depending on other spectral features there are sub types Ia, Ib, Ic, ...

Type II hydrogen lines

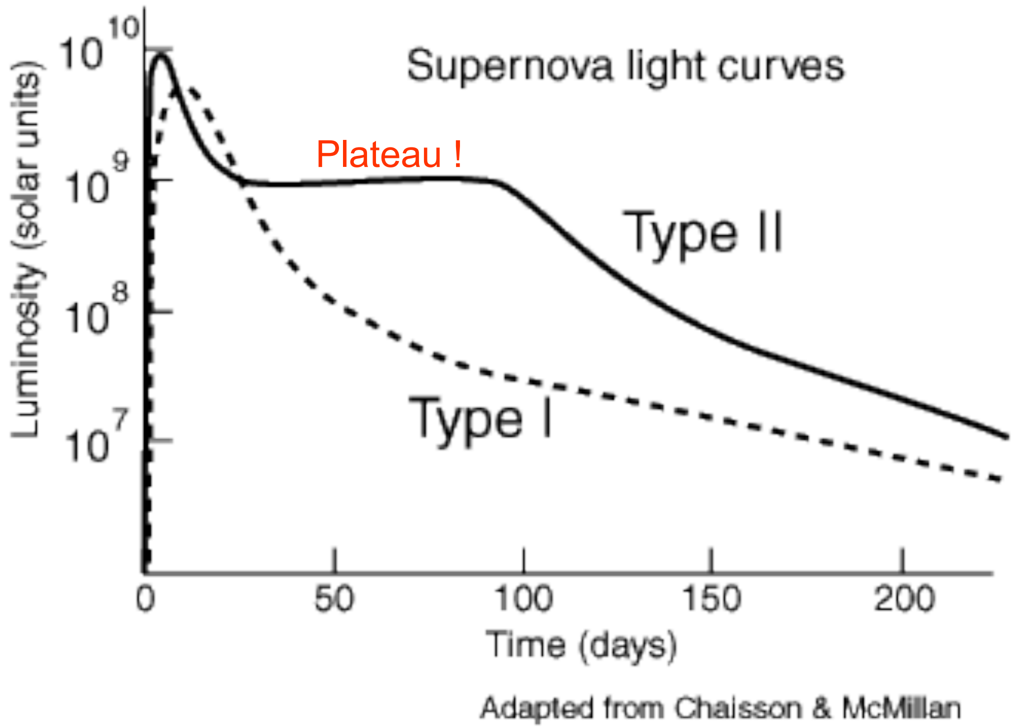
<u>Why are there different types ?</u> **Answer: progenitor stars are different**

Type II: **collapse of Fe core** in a normal massive star (H envelope)

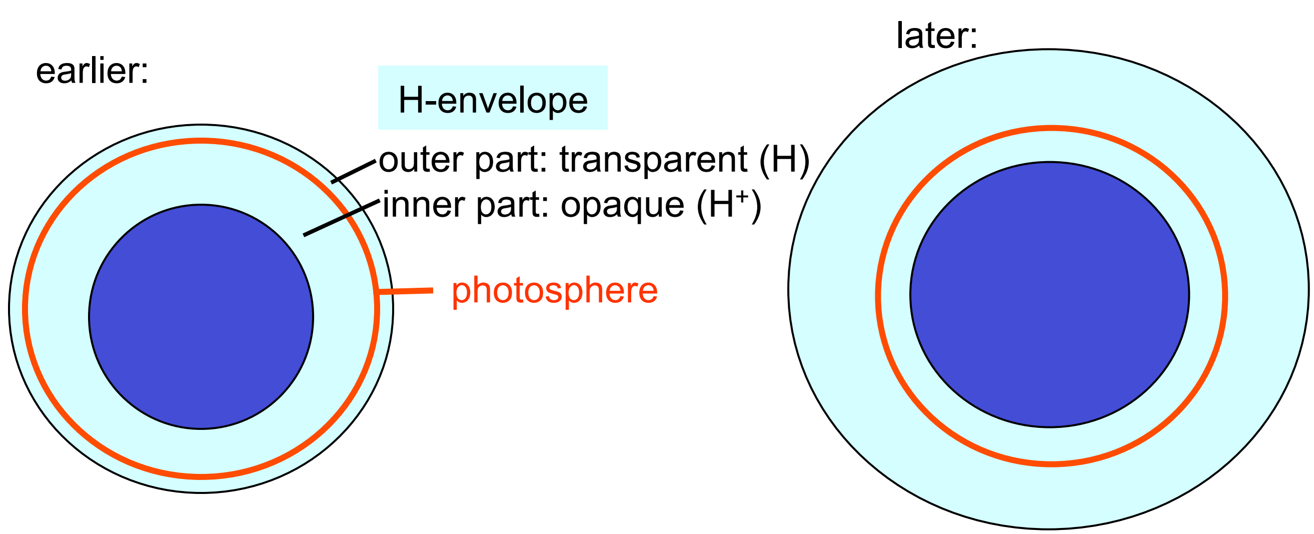
Type I: 2 possibilities:

Ia: **white dwarf accreted** matter from companion

Ib,c **collapse of Fe core** in star that blew its H (or He) envelope into space prior to the explosion



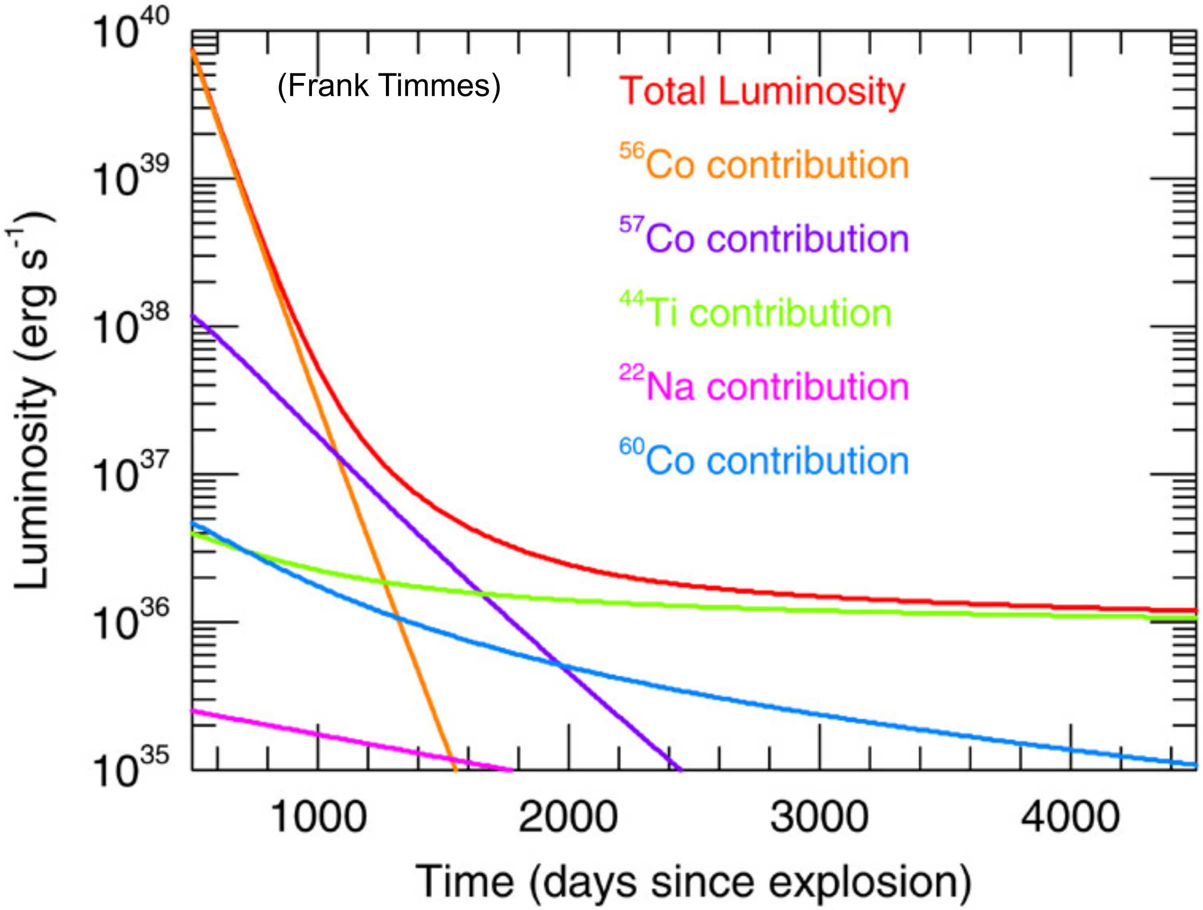
Origin of plateau:



As star expands, photosphere moves inward along the T=5000K contour (H-recombination)

T,R stay therefore roughly fixed = Luminosity constant (as long as photosphere wanders through H-envelope)

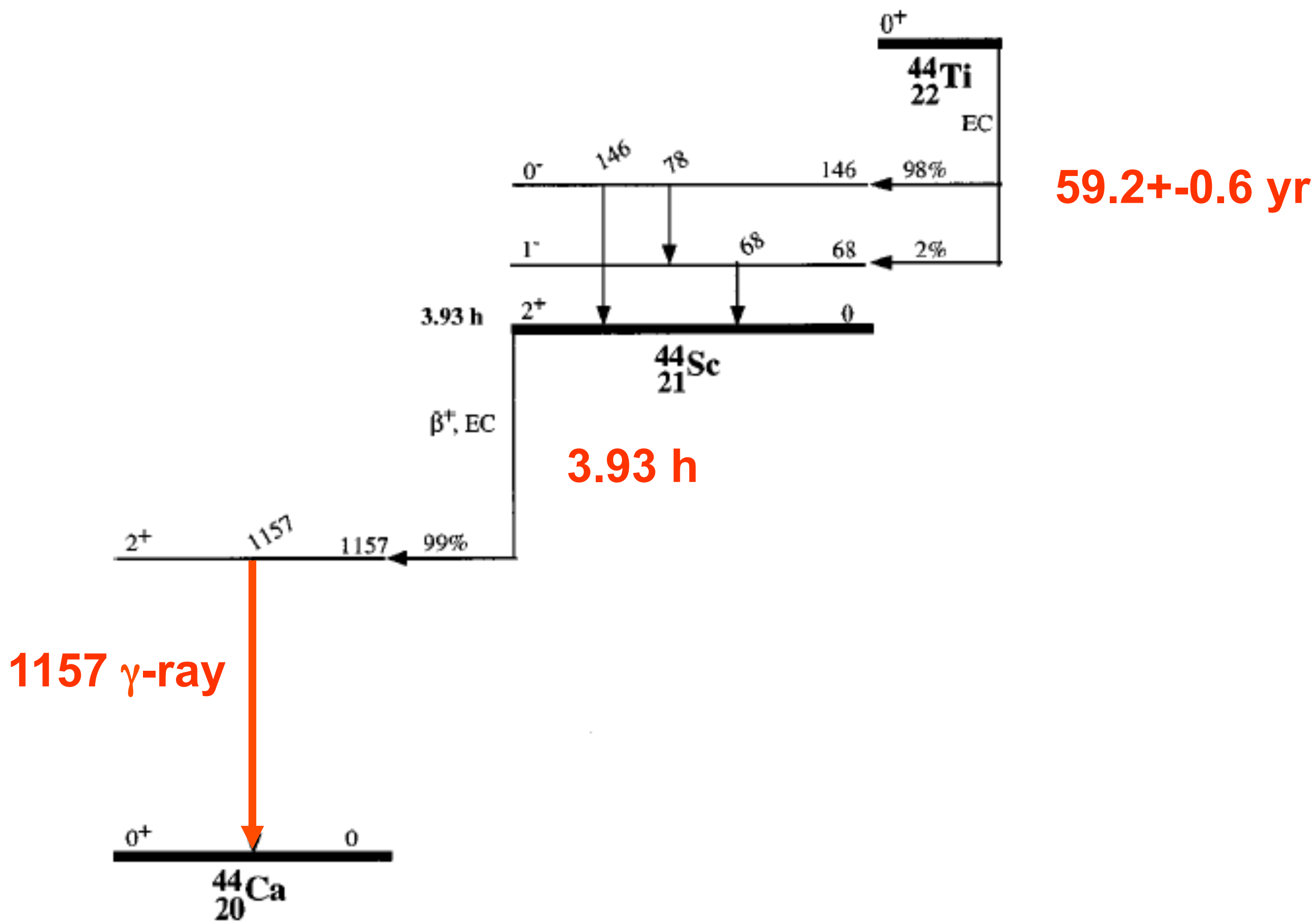
There is another effect that extends SN light curves: Radioactive decay !

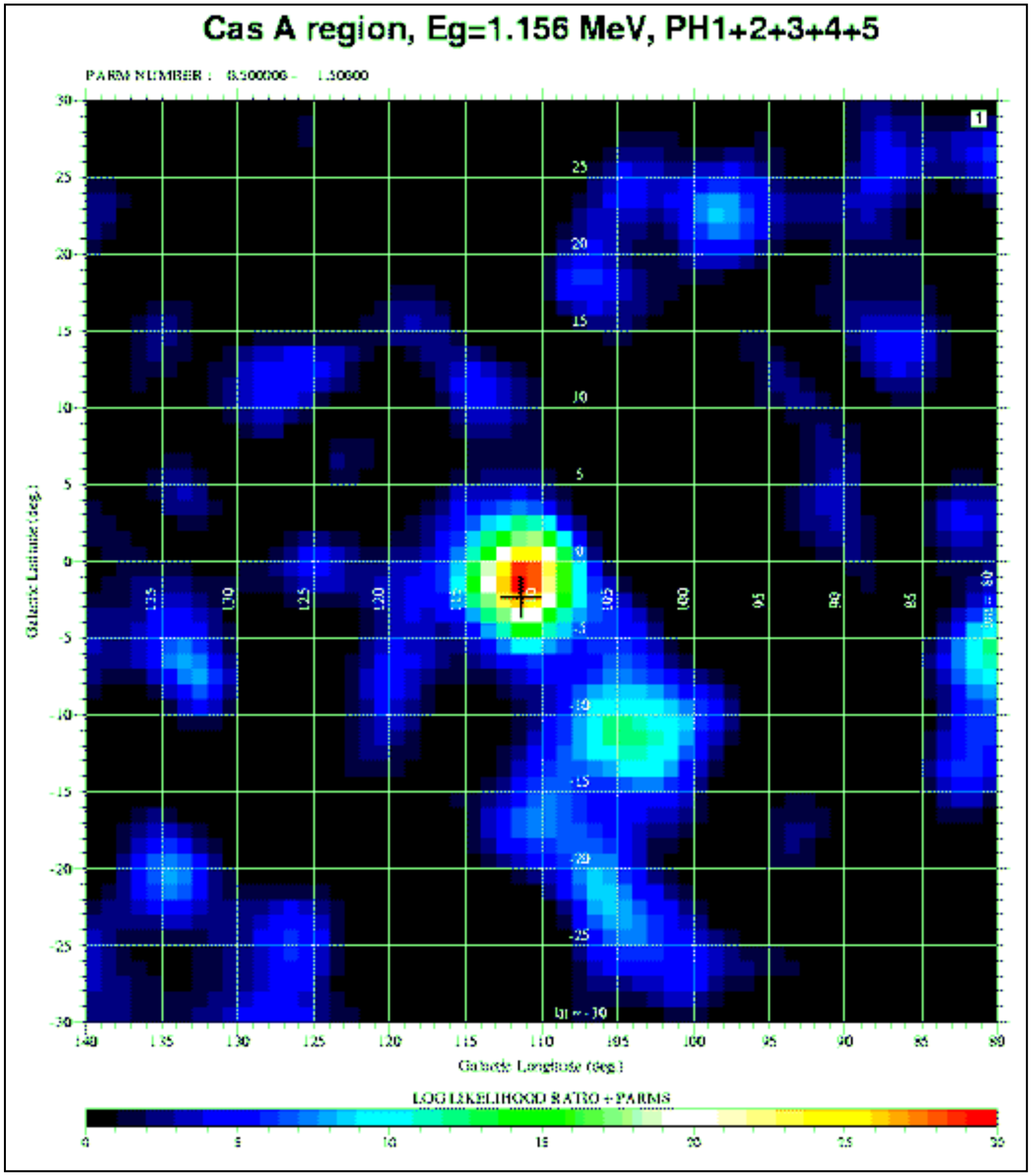


→ Radioactive isotopes are produced during the explosion

→ there is explosive nucleosynthesis !

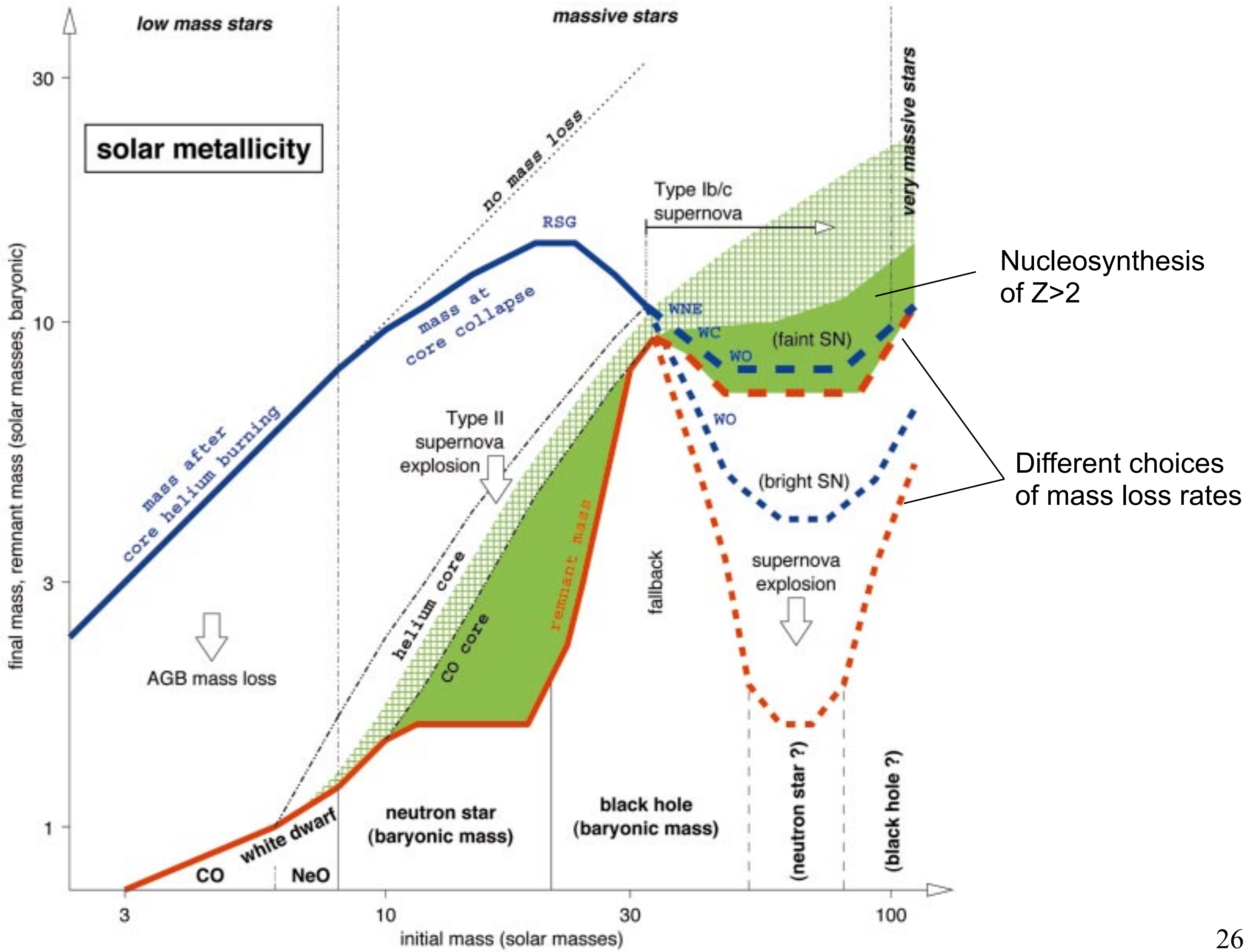
44Ti


0+
44 22 Ti
EC
59.2+-0.6 yr
0-
146
78
146
98%
1-
68
68
2%
3.93 h
2+
0
44 21 Sc
β+, EC
3.93 h
2+
1157
1157
99%
1157 γ-ray
0+
0
44 20 Ca

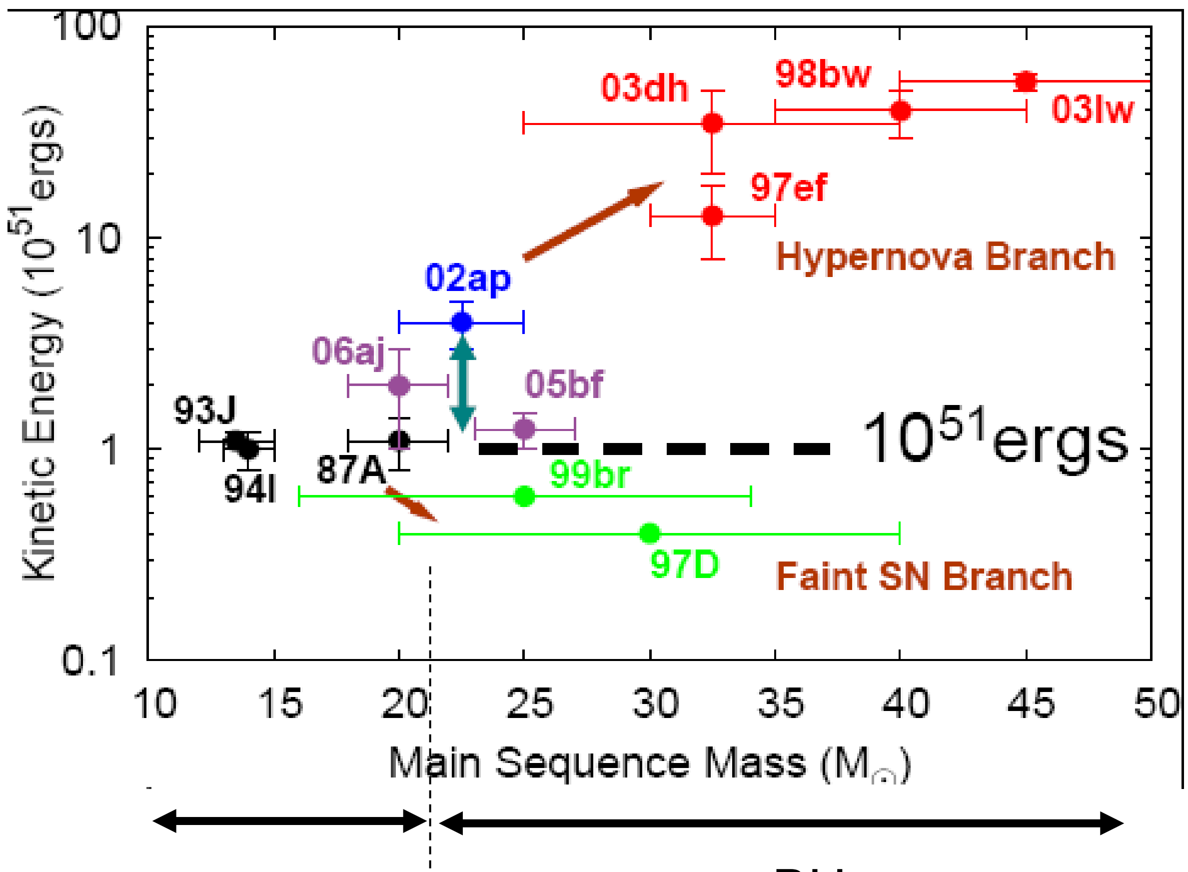


Distance 10,000 ly

Mass loss and remnants



Hypernovae and faint SN



GRBs?

NS
(bounce driven SN)

BH
(L (jet) driven SN)