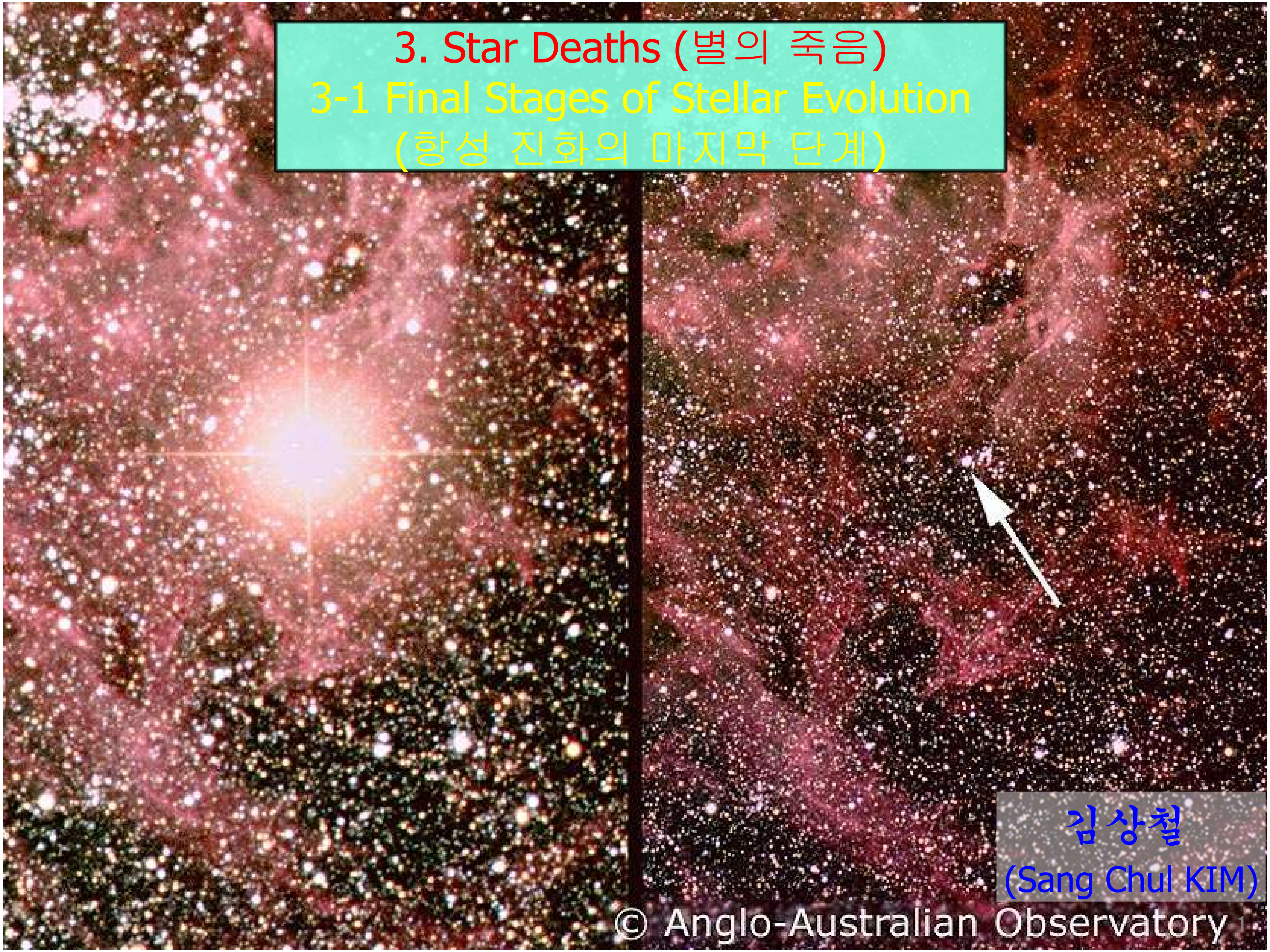
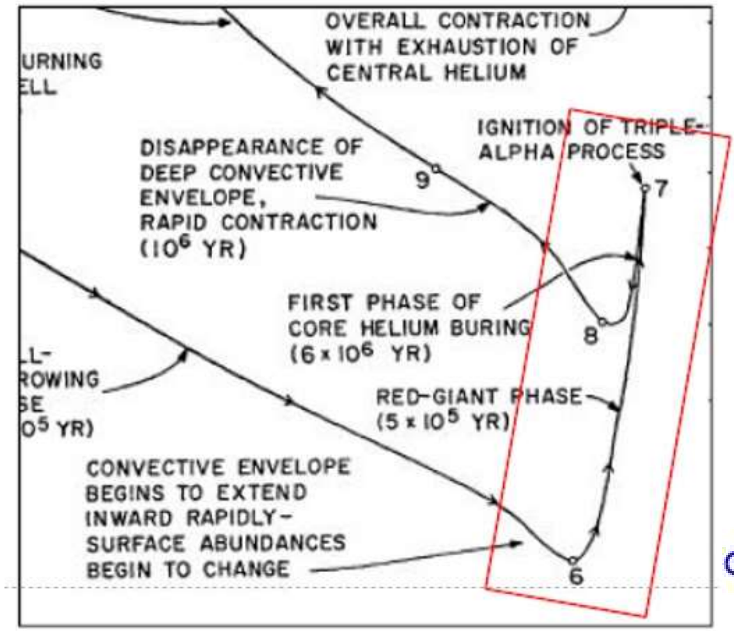
3. Star Deaths (별의 죽음)

3-1 Final Stages of Stellar Evolution
(항성 진화의 마지막 단계)



김상철
(Sang Chul KIM)

5 $M_\odot$ star evolution after ignition of the triple-α process



- At point 7 :
- $T_c = 1.3 \times 10^8$ K
- $\rho_c = 7700$ g/cm^3
- High central T and density → quantum-mechanical tunneling through the Coulomb barrier (acting between ${}^4_2$He nuclei) becomes effective → triple-α process begins

$$\epsilon_{3\alpha} \simeq \epsilon'_{0,3\alpha}\rho^2 Y^3 f_{3\alpha} T_8^{41.0}$$

(Strong T-dependence)

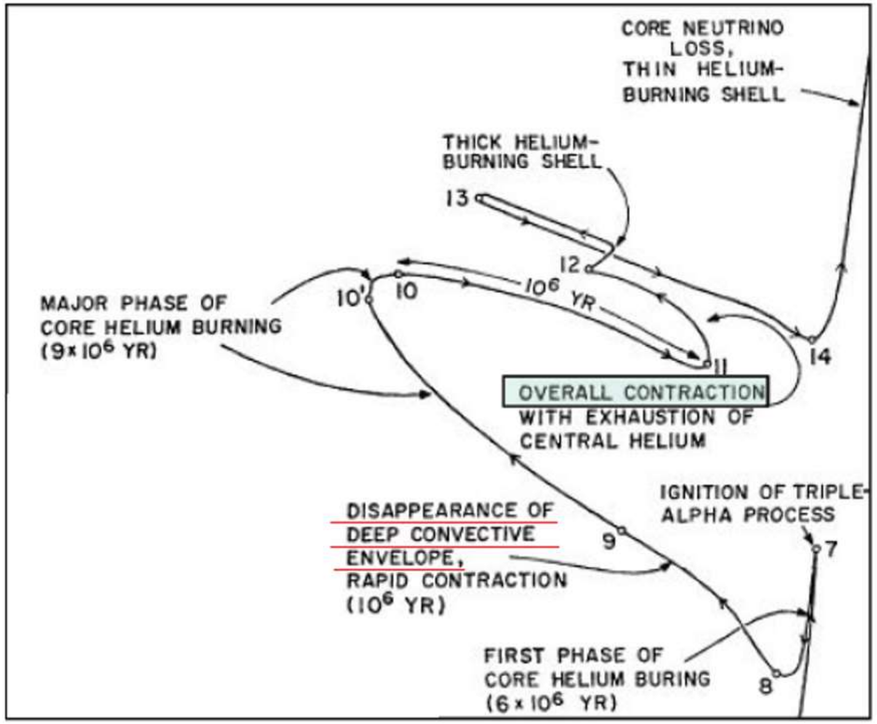
Contribution to Lum : Core – He-b (3α p) ∧ Shell – H-b

In the core,
new source of E → core expands and cools
→Shell E-output ↓
(7 → 8) →L ↓

- envelope contracts → T_{eff} ↑
- → H-b shell compresses
- → shell E-output ↑
- → Overall stellar E-output ↑ (8 → 10)

- Core He-b continues →

Horizontal Branch (HB) stage : core He-b



- At point 10'

: core mean-molecular weight increases enough

→ core contracts + envelope expands and **cools**

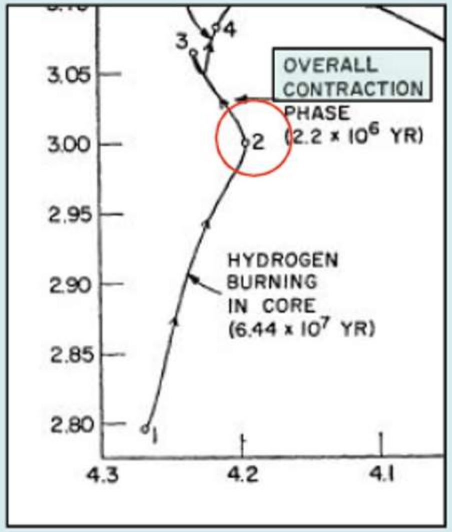
$R\uparrow$ **T**$\downarrow$

→ $L\downarrow$

- At point 11 : core He exhausted

  → entire star contracts

similar



End of MS phase

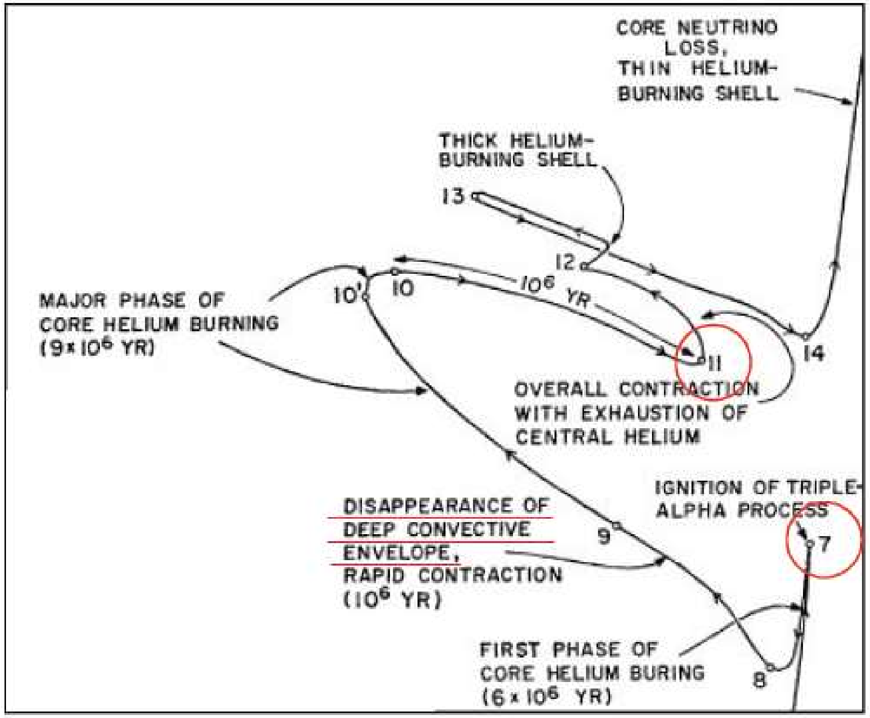
→ near depletion of H fuel in the core

→ $\boxed{\text{overall contraction}}$

$R\downarrow$ + **T**$\uparrow$ → $L\uparrow$

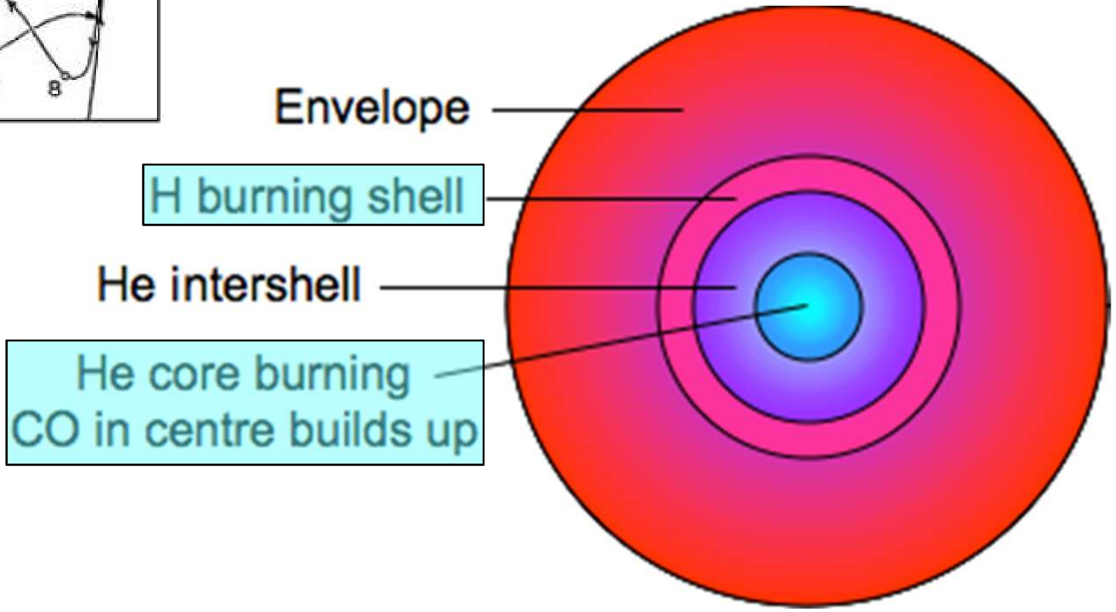
An Introduction to Modern Astrophysics (2nd edition), Bradley W. Carroll & Dale A. Ostlie (1996), p. 347, 499

Post-MS Stellar Evolution



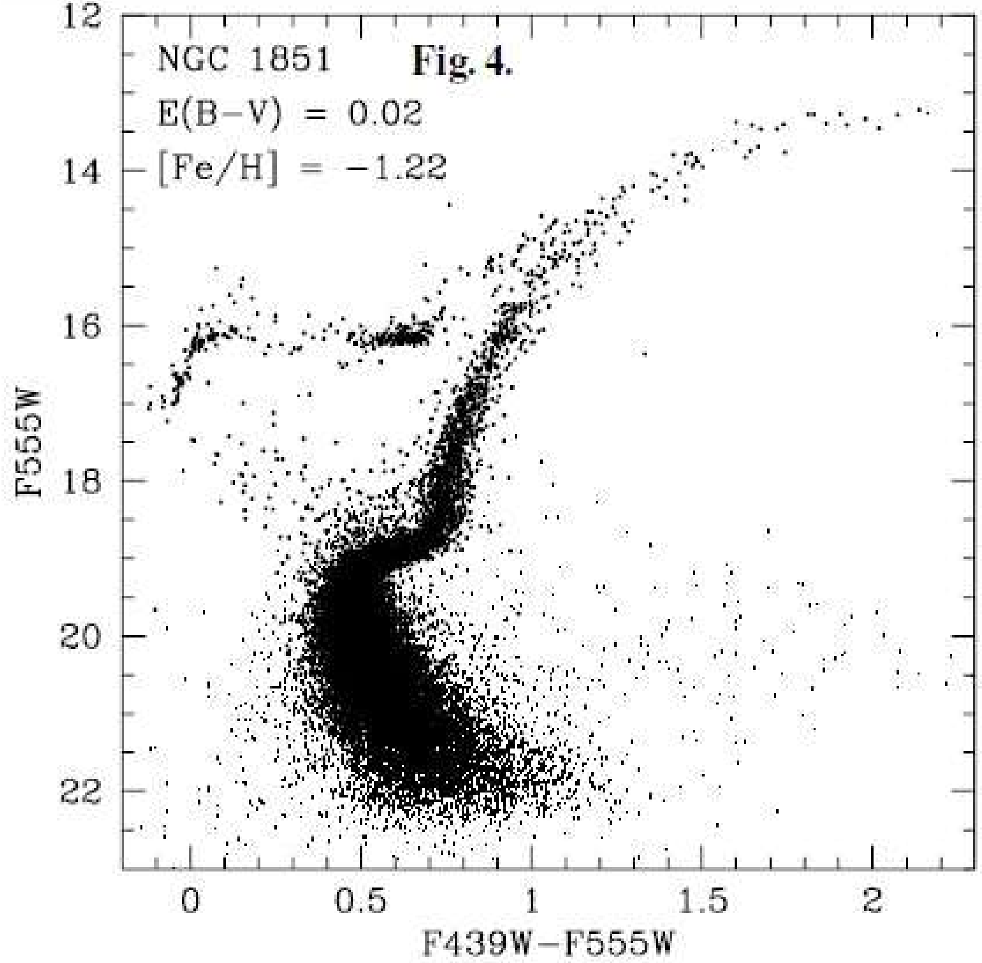
7-11 : generally horizontal evolution
"Horizontal branch (HB)"

He-b core + H-b shell

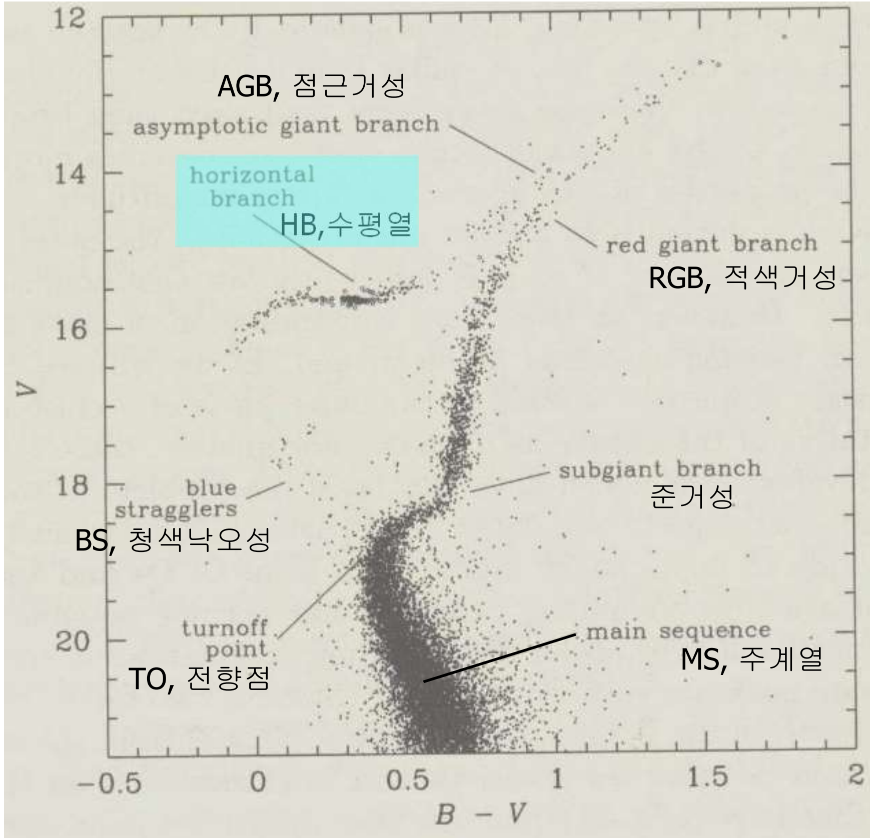


https://astronomy.swin.edu.au/cosmos/H/Horizontal+Branch+stars

Color-Magnitude Diagrams for globular clusters (GCs)



Piotto et al. (2002, A&A, 391, 945)



GC M3 (NGC 5272)
(variables=open circles)

Galactic Astronomy (J. Binney & M. Merrifield, 1998) p. 334

Pulsating Variable Stars

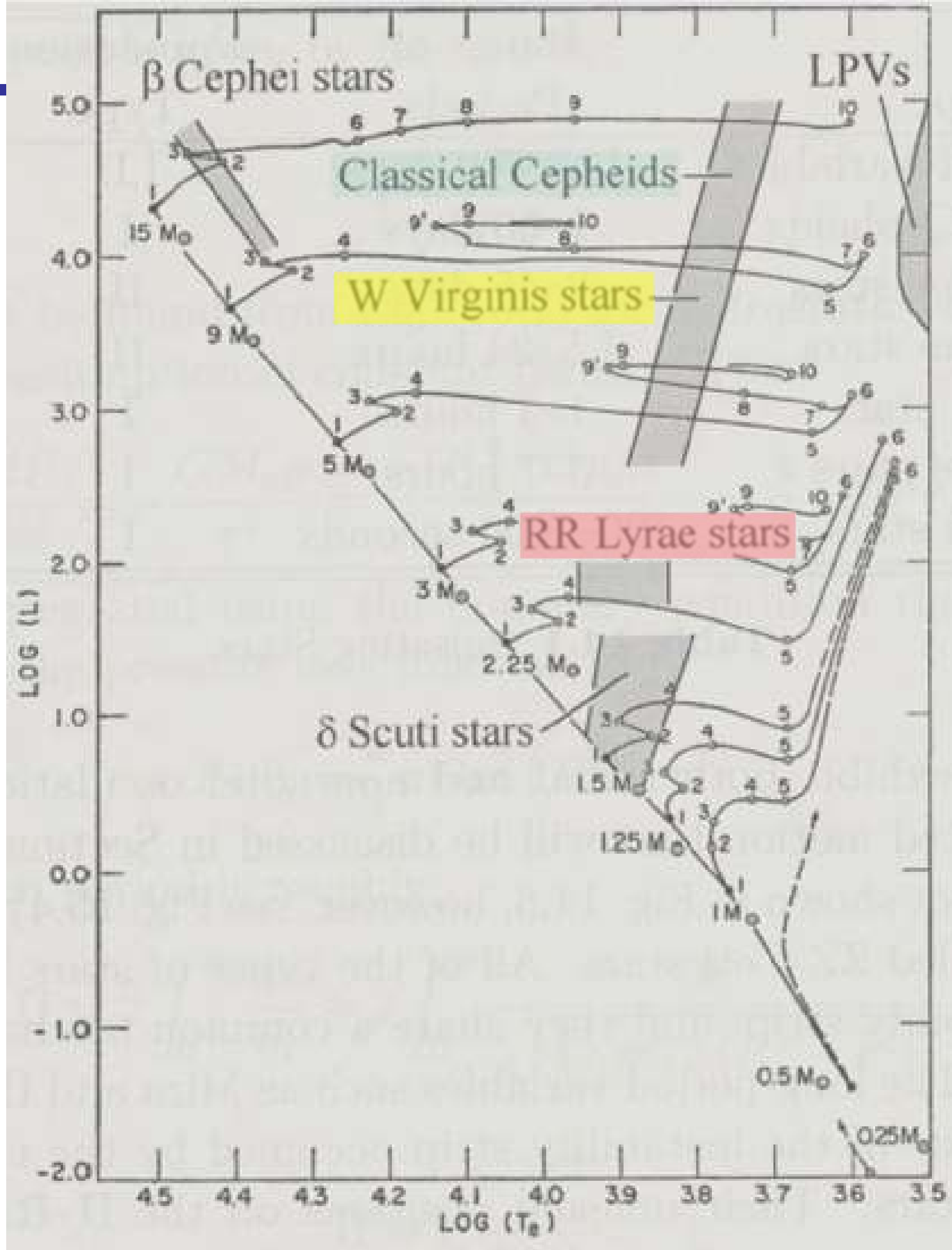
HB stars in the instability strip (IS) = RR Lyrae stars
→Instabilities in outer envelope
→Periodic pulsations
→Variations in L, T, R, surface radial vel.

Instability strip
: narrow (~600 – 1000K wide)

Stars evolve horizontally along the IS
→Enters : starts pulsating
→Leaves : cease pulsating

Type	Periods	Population	Comments
Classical Cepheids	1-50 days	I	Radial Pulsation
W Virginis stars (Pop II Cep)	2-45 days	II	Radial Pulsation
RR Lyrae stars	1.5 – 24 hours	II	Radial Pulsation

These stars are distance indicators !

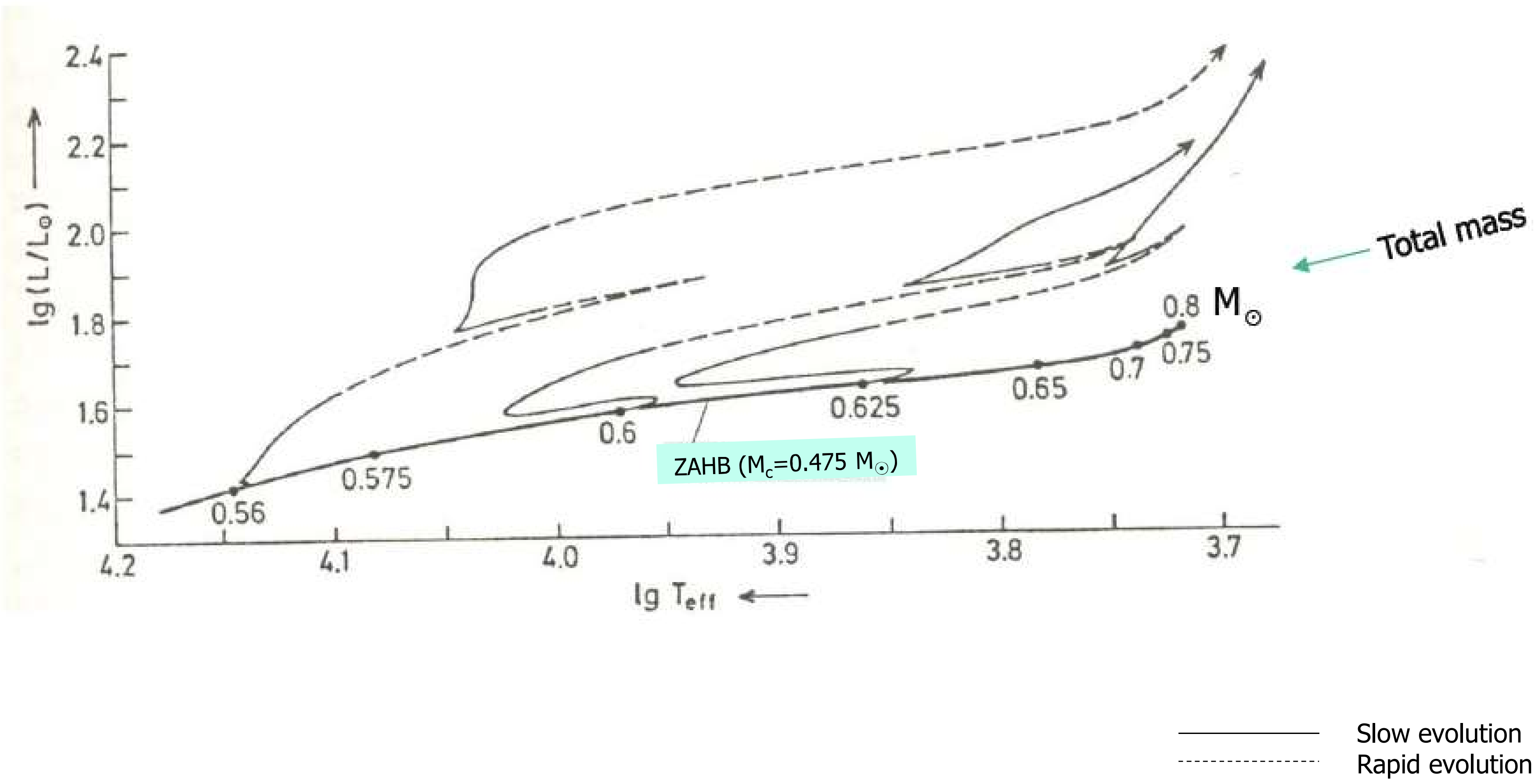


An Introduction to Modern Astrophysics (2nd edition), Bradley W. Carroll & Dale A. Ostlie (1996), p. 547

Post-HB Evolution – in HR diagram

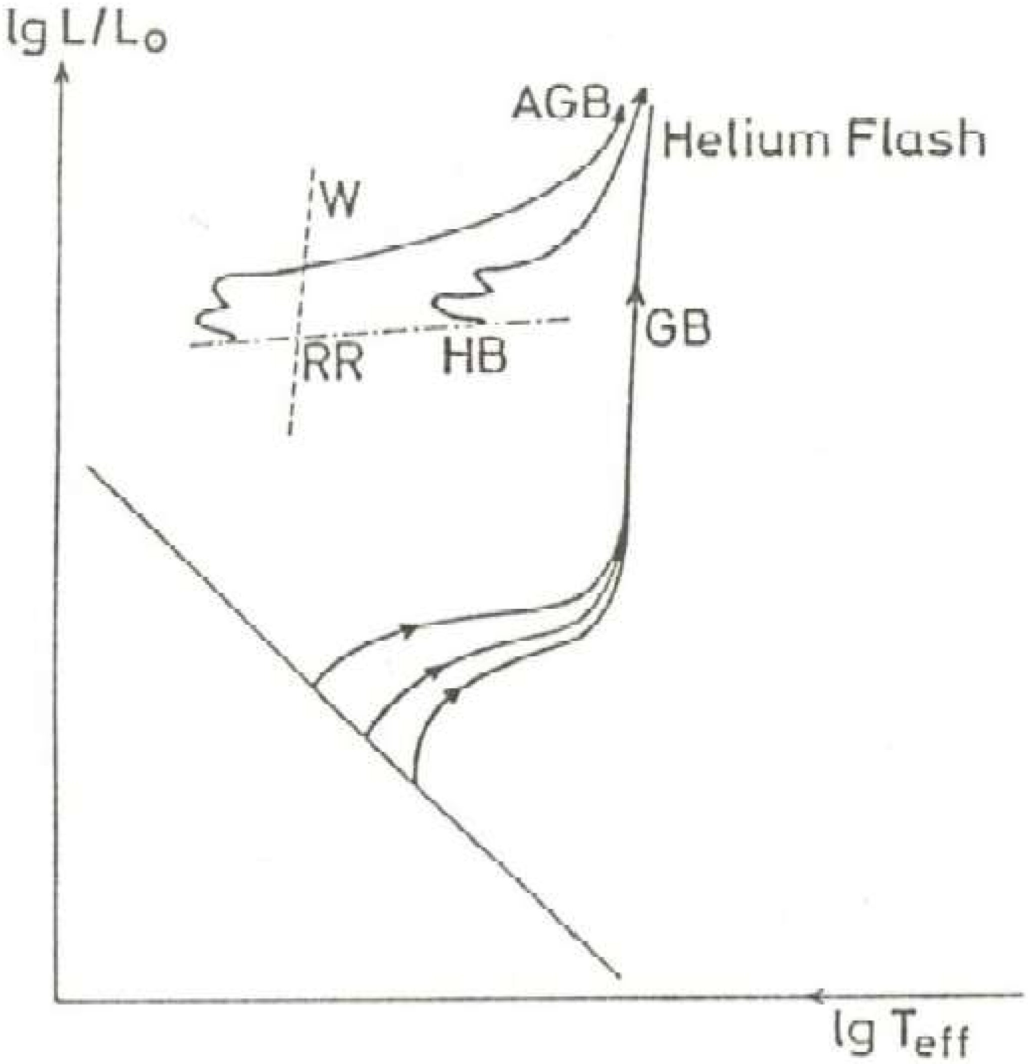
Zero-age HB (ZAHB) and evolution afterwards

For a He-core of $M_c = 0.475\ M_\odot$ and a H-rich envelope (X_H=0.699, X_{He}=0.3)



Stellar Structure and Evolution, R. Kippenhahn and A. Weigert (1990) p. 322 – Fig. 32.9

Post-HB Evolution – in HR diagram



- Evolution of low-mass stars, with three different masses

  (RR = RR Lyrae stars)

  (W = W Virginis stars)

Stellar Structure and Evolution, R. Kippenhahn and A. Weigert (1990) p. 323 – Fig. 32.10

RR Lyrae stars

- Periodic variable stars
- P = 1.5 to 24 h (~12 h), Peak M_V ~ 0-1 mag, spectra A2 to F6
- Current mass ~ 0.8 $M_\odot$ (original MS mass ~ 1 $M_\odot$), old, relatively metal-poor
- In GCs and in low-metallicity systems (population II) – But, some have high metallicity

$M_V(RR) = +0.71 \pm 0.12$ at $\langle[\mathrm{Fe/H}]\rangle = -1.61$ for the halo (162 stars)

$M_V(RR) = +0.79 \pm 0.30$ at $\langle[\mathrm{Fe/H}]\rangle = -0.76$ for the thick disk (51 stars)

Layden et al. (1996, AJ, 112, 2110)

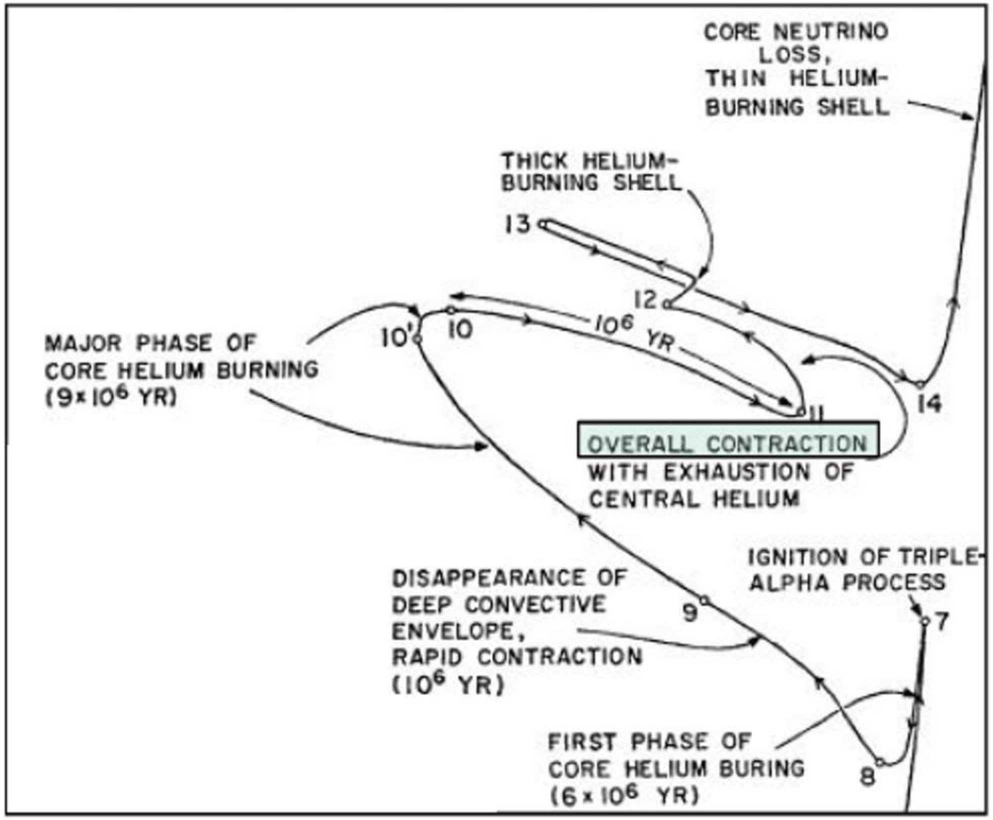
$$\langle M_V \rangle = (0.16 \pm 0.03)[\mathrm{Fe/H}] + 1.02 \pm 0.03 \quad (5.24)$$

$$\langle M_K \rangle = -(2.3 \pm 0.2)\log(P/1\,\mathrm{d}) - 0.88 \pm 0.06 \quad (5.25)$$

$$\langle M_K \rangle = -(2.0 \pm 0.3)\log(P/1\,\mathrm{d}) + (0.06 \pm 0.04)[\mathrm{Fe/H}] - 0.7 \pm 0.1 \quad (5.26)$$

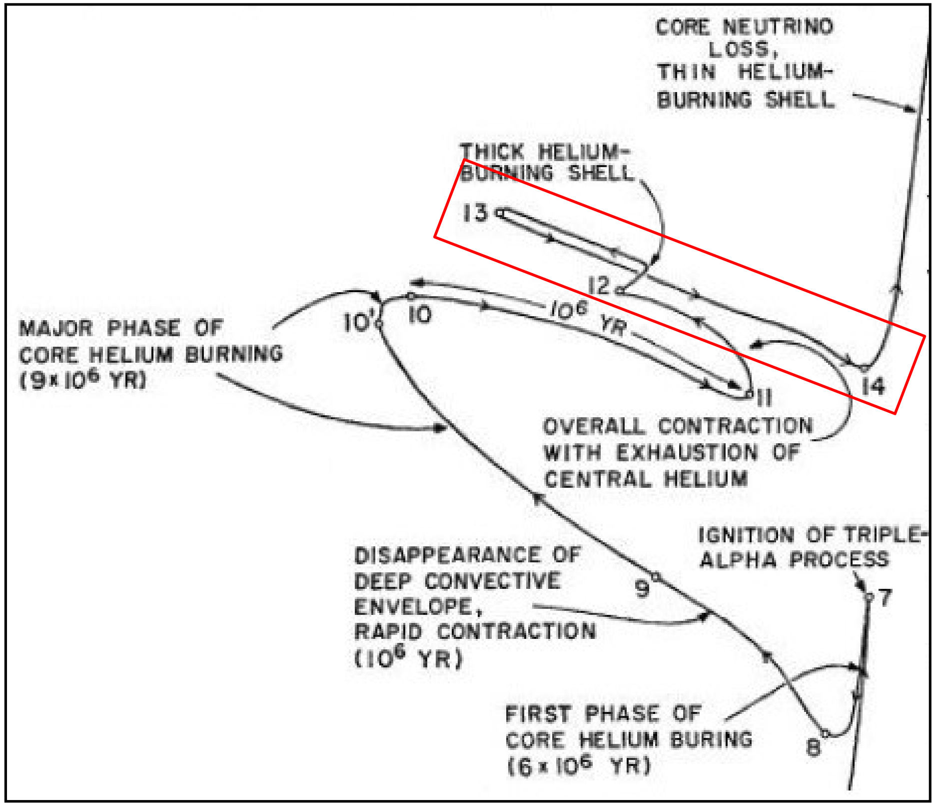
Galactic Astronomy (James Binney and Michael Merrifield, 1998) p. 296

Post-HB, early-AGB (E-AGB)



- At point 11 : core He exhausted
  → entire star contracts
  → core T ↑
- During 11 → 12
  : thick He-b shell develops

Early-AGB (E-AGB)



After point 12

- Core continues to contract,
  He-b shell narrows + produce more E
- Envelope expands + cools

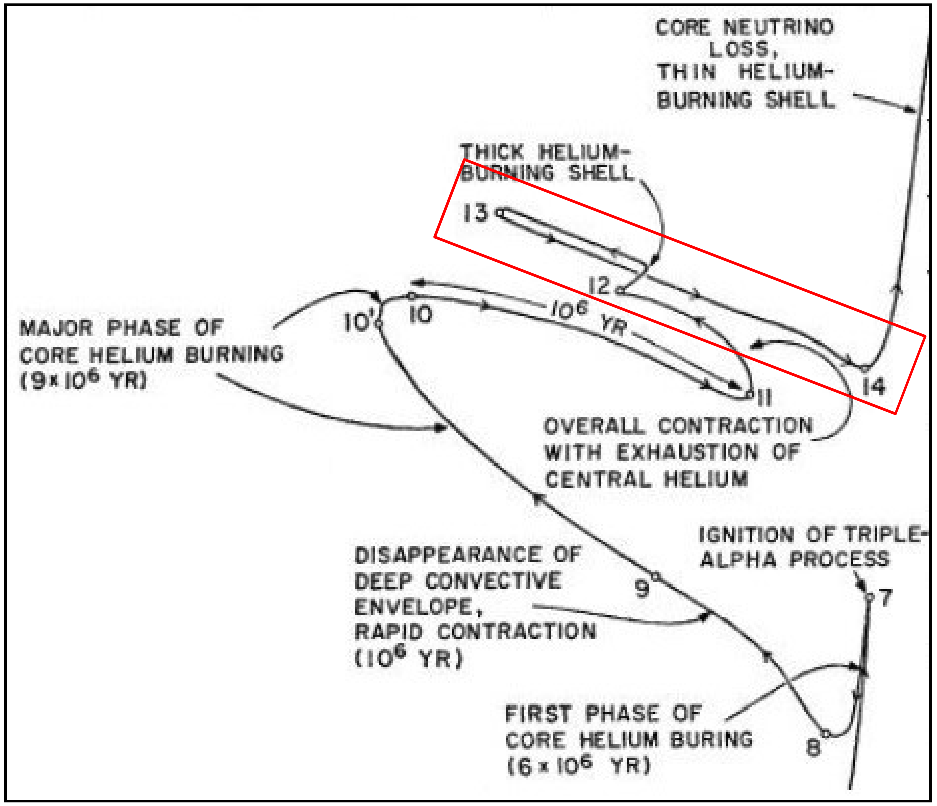
- T_{eff} ↓ → convective envelope deepens again (extending downward to the chemical discontinuity between the H-rich outer layers and the He-rich region above the He-b shell)

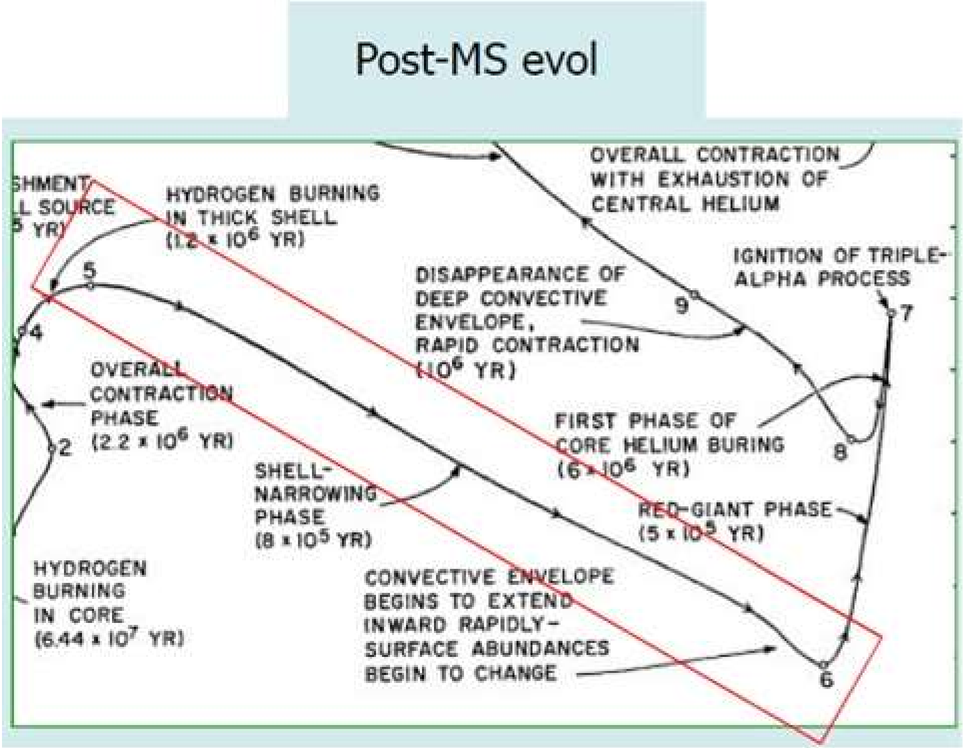
→ Mixing = **second dredge-up**

→ Increases He-, N-content of the envelope

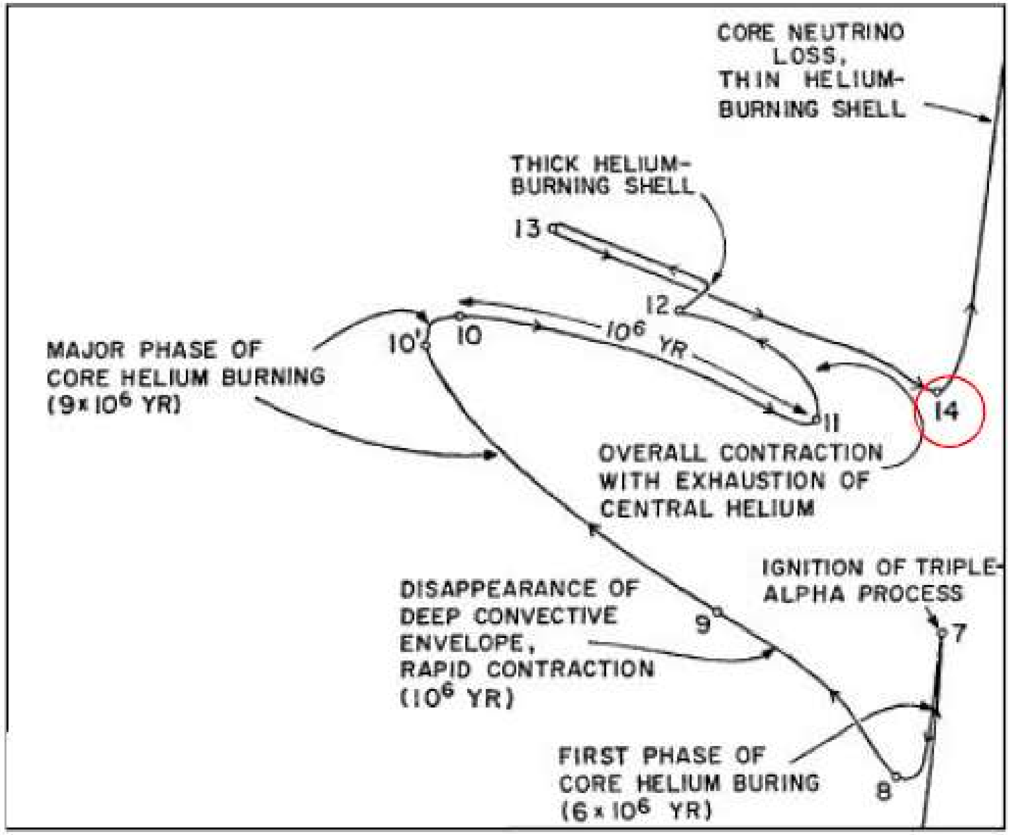
Early-AGB (E-AGB)

(13→14 →) similar to (5 → 6 →)





Early-AGB (E-AGB)



asymptotic giant branch (AGB)

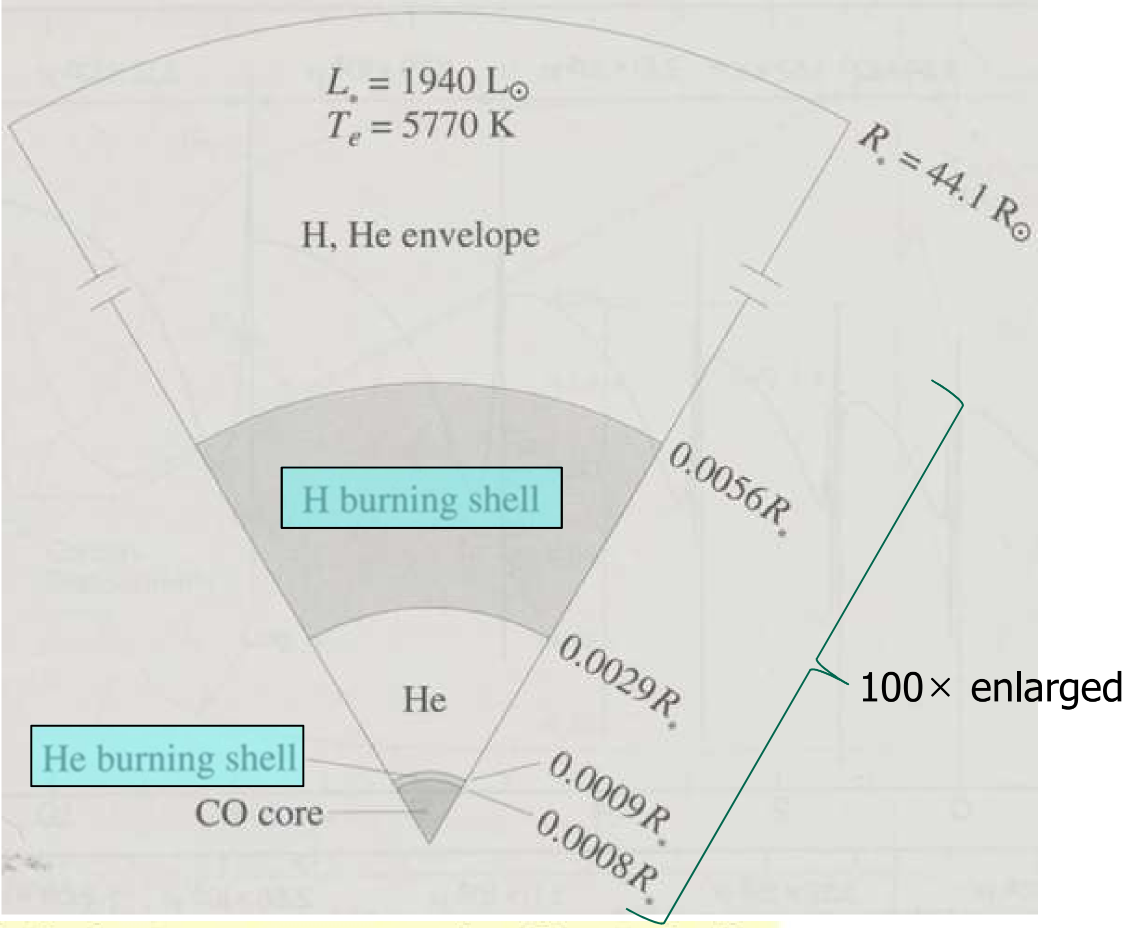
At near point 14 :

$T_c \sim 2\times10^8$ K, $\rho_c \sim 10^6$ g/cm^3

Interior structure at point 14 →

5 $M_\odot$ star - AGB (asymptotic giant branch)

Inert CO core +
Two shell sources
(not to scale)



Narrowing He-b shell : begins to turn-on and –off periodically

H-b shell dumps He onto the He-layer → the He-layer mass ↑, becomes slightly degenerate → as the He-shell T ↑ → He-shell flash occurs (~core He flash of low-mass stars, but much less energetic)

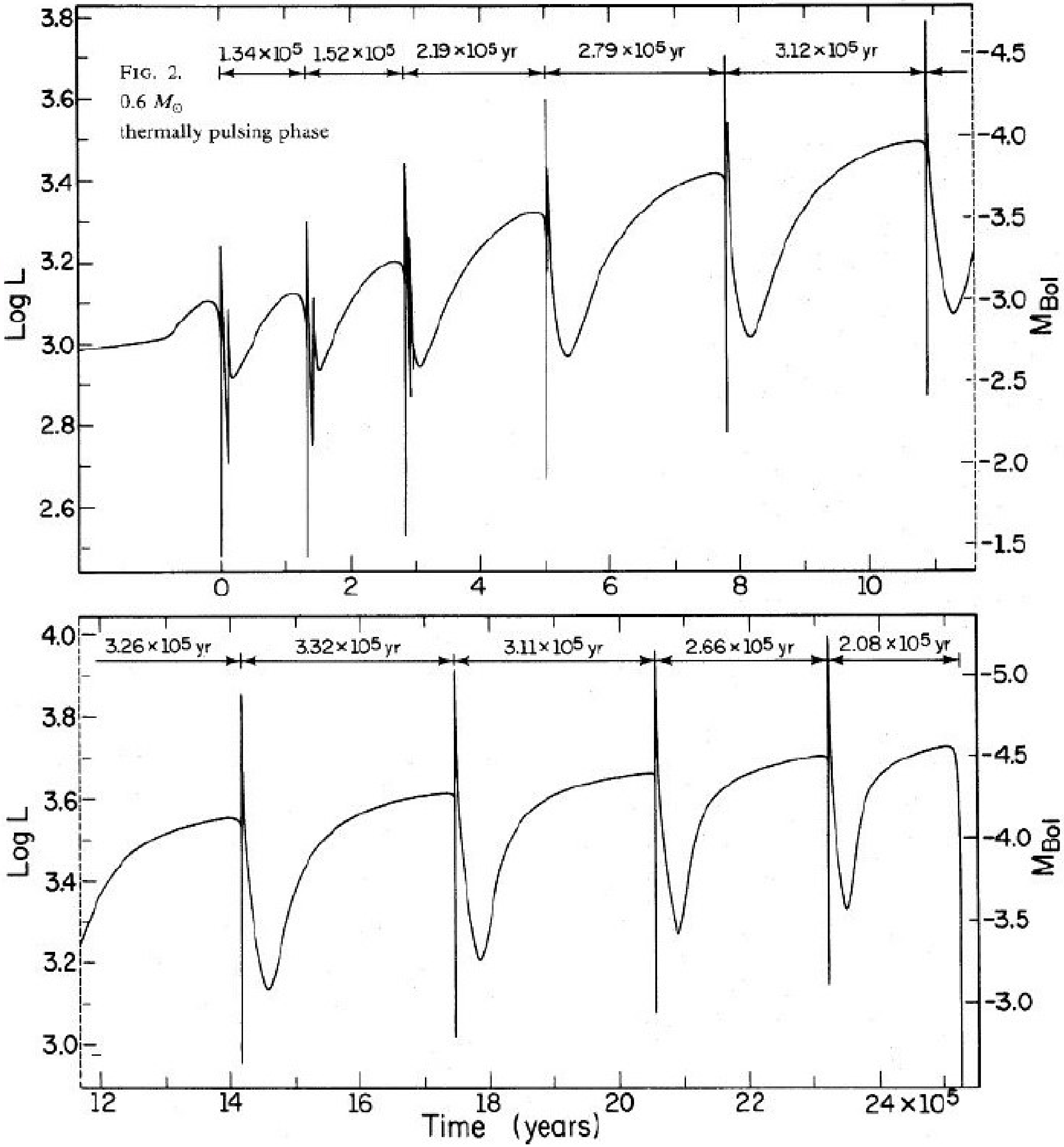
→ Drives H-b shell outward → cool, turn-off for a time

He-shell burning diminishes → contract, T↑ → H-shell burning recovers → repeats → **thermally pulsing AGB**

An Introduction to Modern Astrophysics (2nd edition), Bradley W. Carroll & Dale A. Ostlie (1996), p. 501

Thermally pulsing AGB (TPAGB)

- 0.6 $M_\odot$
- Pulse period = f(stellar mass) : from 10^3 years (~5 $M_\odot$) to 10^5 years (~0.6 $M_\odot$)
- Pulse amplitude grows w/successive event



Iben 1982 (ApJ, 260, 821 – Low mass AGB evolution. I.) – Fig. 2

AGB stars

- AGB stars – strong wind + rapid mass-loss $\dot{M} \sim 10^{-4} M_{\odot}\ yr^{-1}$

Cool (effective T ~3,000 K)

→ dust grains exist in the matter expelled

- O-rich environment → Silicate grains form
- C-rich environment → Graphite grains form

- Stellar initial masses evolving to AGB : $0.89 \le M/M_{\odot} \le 5.0$

(Vassiliadis & Wood 1993, ApJ, 413, 641 : Evolution of low- and intermediate-mass stars to the end of the AGB with mass loss)

- Evolution afterwards
  - depends on initial mass and mass-loss
  - massive stars – burnings up to form Fe → neutron stars (NSs), black holes (BHs)
  - low-mass stars – white dwarfs (WDs) + planetary nebulae (PNe)
  - dividing mass ~ $8\ M_{\odot}$

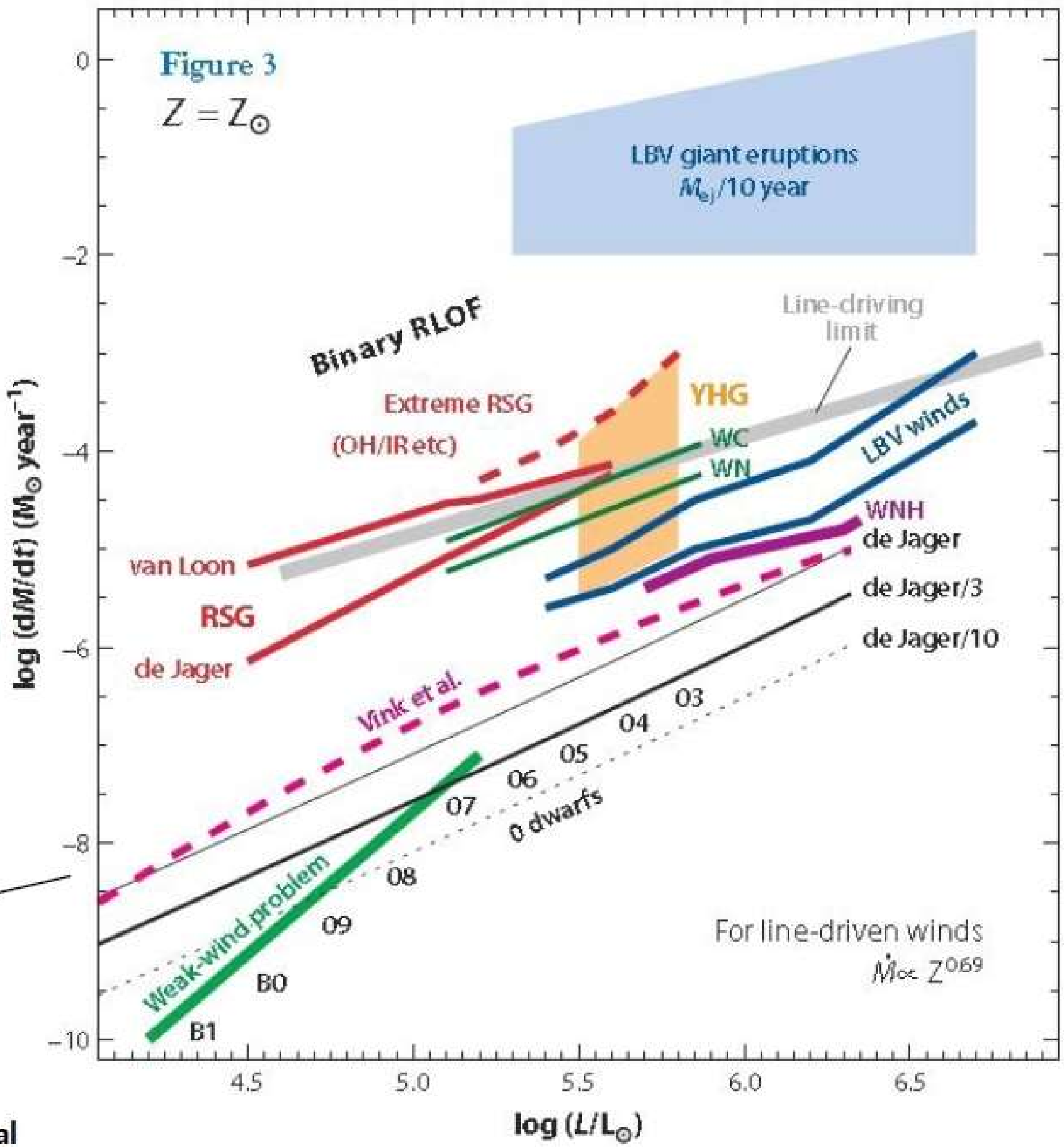
AGB – mass loss

- L ↑, R ↑ → Mass-loss rate ↑

Stellar mass ↓ → surface gravity ↓
→ surface material is less tightly bound

→mass-loss becomes progressively more important as AGB evolution continues

- At the end of the mass-loss phase
  → superwind ($\dot{M} \sim 10^{-4} M_{\odot}\ yr^{-1}$)



N. Smith 2014, ARA&A, 52, 487 (Mass Loss : Its Effect on the Evolution and Fate of High-Mass Stars)

- **RSG : van Loon+05 (A&A 438 273)**
- **RSG : de Jager+ 88 (A&AS 72 259)**
- **WNH : H-rich Wolf-Rayet stars**
- **O-type stars : Vink + 01 (A&A 531 A132)**
- **de Jager+88 (A&AS 72 259) = "standard" observational rates for O-type stars**
- **Weak-wind problem : lower mass-loss rates for late O-type and early B-type MS stars**

Thermonuclear Energy Generation Stages

Process	Fuel	Major products	Temperature (K)	Minimum mass ($M_\odot$)
H-burning	H	He	$1\text{-}3\times10^7$	0.1
He-burning	He	${}^{12}_{6}C$, ${}^{16}_{8}O$	2×10^8	1
C-burning	C	${}^{16}_{8}O$, ${}^{20}_{10}Ne$, ${}^{23}_{11}Na$, ${}^{23}_{12}Mg$, ${}^{24}_{23}Mg$	8×10^8	1.4
Ne-burning	Ne	${}^{16}_{8}O$, Mg	1.5×10^9	5
O-burning	O	${}^{24}_{12}Mg$, ${}^{27}_{13}Al$, ${}^{28}_{14}Si$, ${}^{31}_{15}P$, ${}^{32}_{16}S$	2×10^9	10
Si-burning	Mg to S	near Fe	3×10^9	20

- C-burning : near 6×10^8 K (Carroll & Ostlie, p. 348)
- Ne-burning : $1.2\text{-}1.9\times10^9$ K (El Eid+04 ApJ 611 452 – Evolution of massive stars up to the end of central Oxygen burning) (https://en.wikipedia.org/wiki/Neon-burning_process)
- O-burning : $1.5\text{-}2.6\times10^9$ K (El Eid+04 ApJ 611 452 – Evolution of massive stars up to the end of central Oxygen burning) (Carroll & Ostlie, p. 348)

Introductory Astronomy and Astrophysics (4th edition)
Michael Zeilik & Stephen A. Gregory (1998), p. 328

Thermonuclear Energy Generation Stages

Table 1 Evolution of a 15-solar-mass star.

Stage	Timescale	Fuel or product	Ash or product	Temperature (10^9 K)	Density (gm cm^{-3})	Luminosity (solar units)	Neutrino losses (solar units)
Hydrogen	11 Myr	H	He	0.035	5.8	28,000	1,800
Helium	2.0 Myr	He	C, O	0.18	1,390	44,000	1,900
Carbon	2000 yr	C	Ne, Mg	0.81	2.8×10^5	72,000	3.7×10^5
Neon	0.7 yr	Ne	O, Mg	1.6	1.2×10^7	75,000	1.4×10^8
Oxygen	2.6 yr	O, Mg	Si, S, Ar, Ca	1.9	8.8×10^6	75,000	9.1×10^8
Silicon	18 d	Si, S, Ar, Ca	Fe, Ni, Cr, Ti, ...	3.3	4.8×10^7	75,000	1.3×10^{11}
Iron core collapse*	$\sim$1 s	Fe, Ni, Cr, Ti, ...	Neutron star	>7.1	$>7.3 \times 10^9$	75,000	$>3.6 \times 10^{15}$

* The pre-supernova star is defined by the time at which the contraction speed anywhere in the iron core reaches 1,000 km s^{-1}.

Woosley & Janka 2005 Nature Physics, 1, 147

Stellar lifetimes

Table 1 Stellar lifetimes[a] for a selection of solar-metallicity ($Z = 0.014$) models (using models from Karakas 2014)

Mass/$M_\odot$	Main sequence	RGB	Core He burning	AGB	Total[b]
1.0	9685	2360	118.3	21.35	12,186
2.0	874.5	162.3	130.9	18.21	1185.9
5.0	80.03	3.053	23.07	1.997	108.15
8.0	29.12	0.484	6.475	0.435	36.519

[a]Lifetimes are in Myr (10^6 years)
[b]The total stellar lifetimes includes all nuclear burning phases but does not include the post-AGB or white dwarf cooling phases

A. I. Karakas 2017, Handbook of Supernovae, Volume 1, p. 461

Evolving up the AGB (asymptotic giant branch)

- Early-AGB (E-AGB) : He shell burning
  Radius increases (up to 1 AU ~215 $R_\odot$)

- Thermally pulsing AGB (TP-AGB) : when He shell runs out of fuel
  H shell burning
  When He builds up → He-shell ignites explosively (He-shell flash)

- He-b shell converts more and more of the He into C and then into O
  → CO core mass ↑/ core contracts slowly, ρ_c↑
  → electron degeneracy pressure begins to dominate

- Similar to the development of an electron-degenerate He-core
  in a low-mass star
  during its rise up the RGB

Massive ($M \geq 8\ M_\odot$) star evolution

- He-b shell → add ash to the CO core
- CO core continues to contract
- ${}^{12}_{6}C$-burning starts
- By-products : ${}^{16}_{8}O$, ${}^{20}_{10}Ne$, ${}^{23}_{11}Na$, ${}^{23}_{12}Mg$, ${}^{24}_{12}Mg$

- NeO core
- ${}^{16}_{8}O$-burning starts

→ Making ${}^{28}_{14}Si$-dominated (and ${}^{32}_{16}S$) core

At $T \sim 3 \times 10^9$ K → Si-burning starts

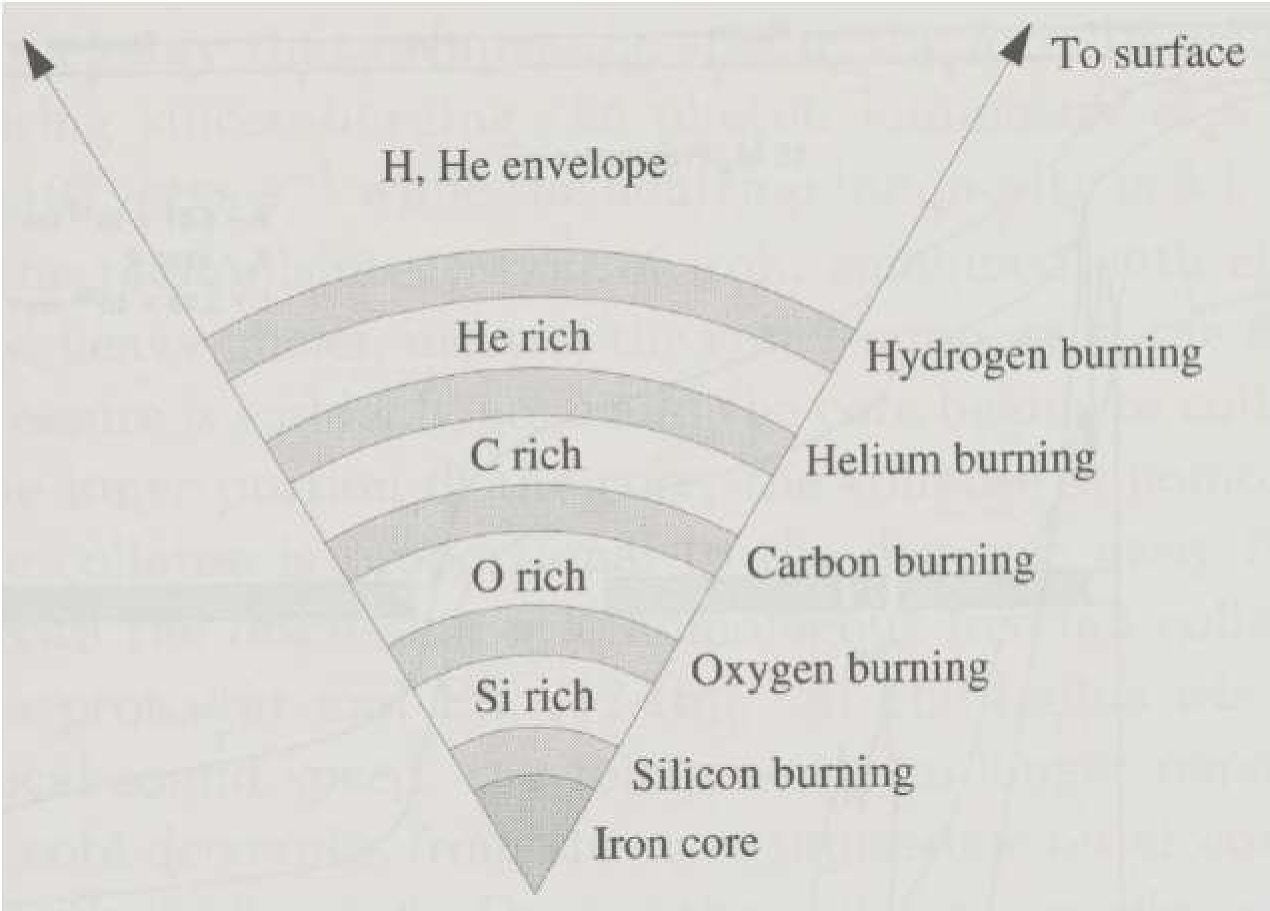
Making iron(${}^{56}_{26}Fe$)-peak elements, like ${}^{54}_{26}Fe$, ${}^{56}_{26}Fe$, ${}^{56}_{28}Fe$, and finally iron-core

$50 \leq A \leq 62$

(Atomic mass)

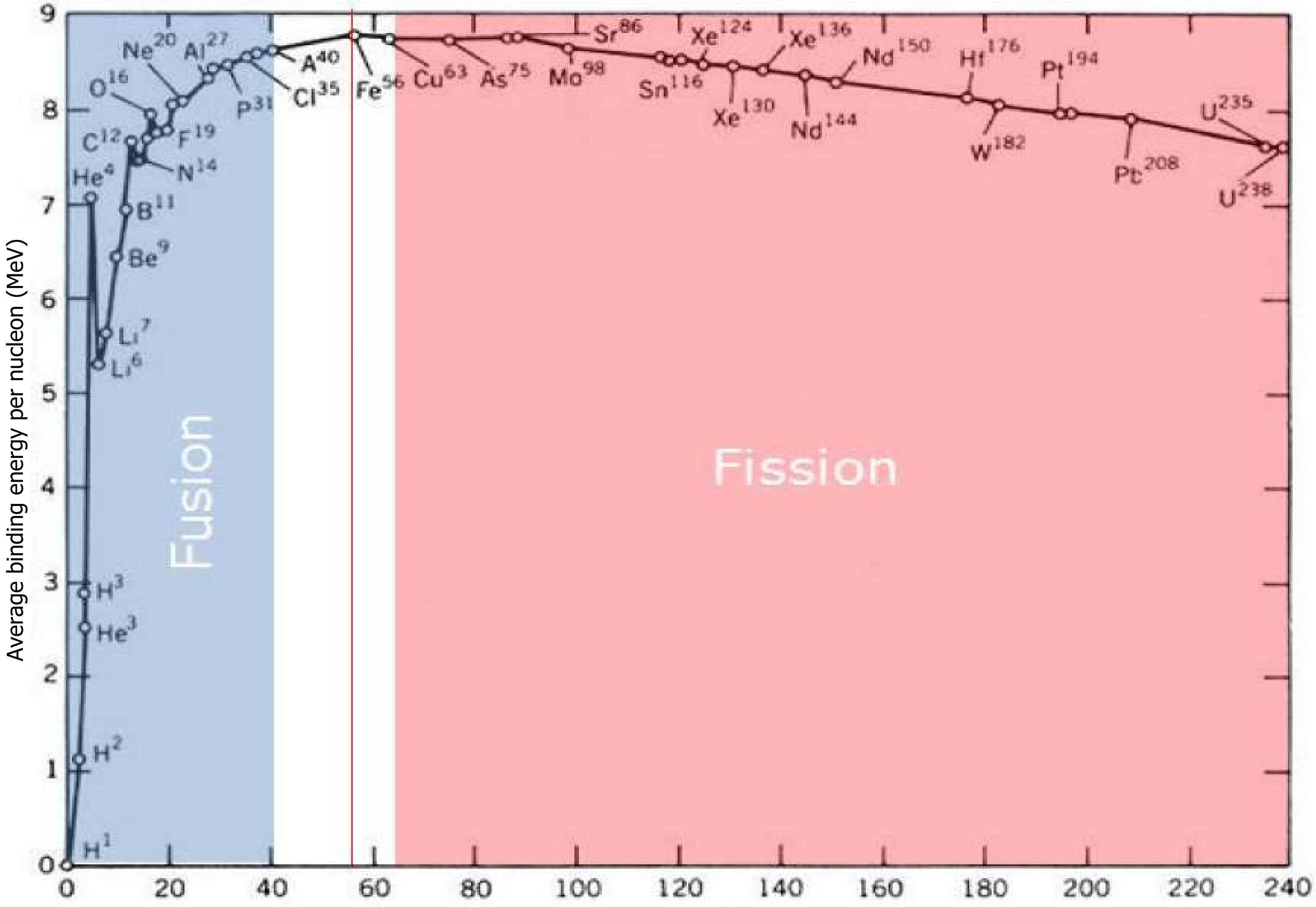
Massive ($M \geq 8\ M_\odot$) star evolution

Onion-like interior →
(not to scale)



An Introduction to Modern Astrophysics (2nd edition),
Bradley W. Carroll & Dale A. Ostlie (1996), p. 511

Binding energy per nuclear particle

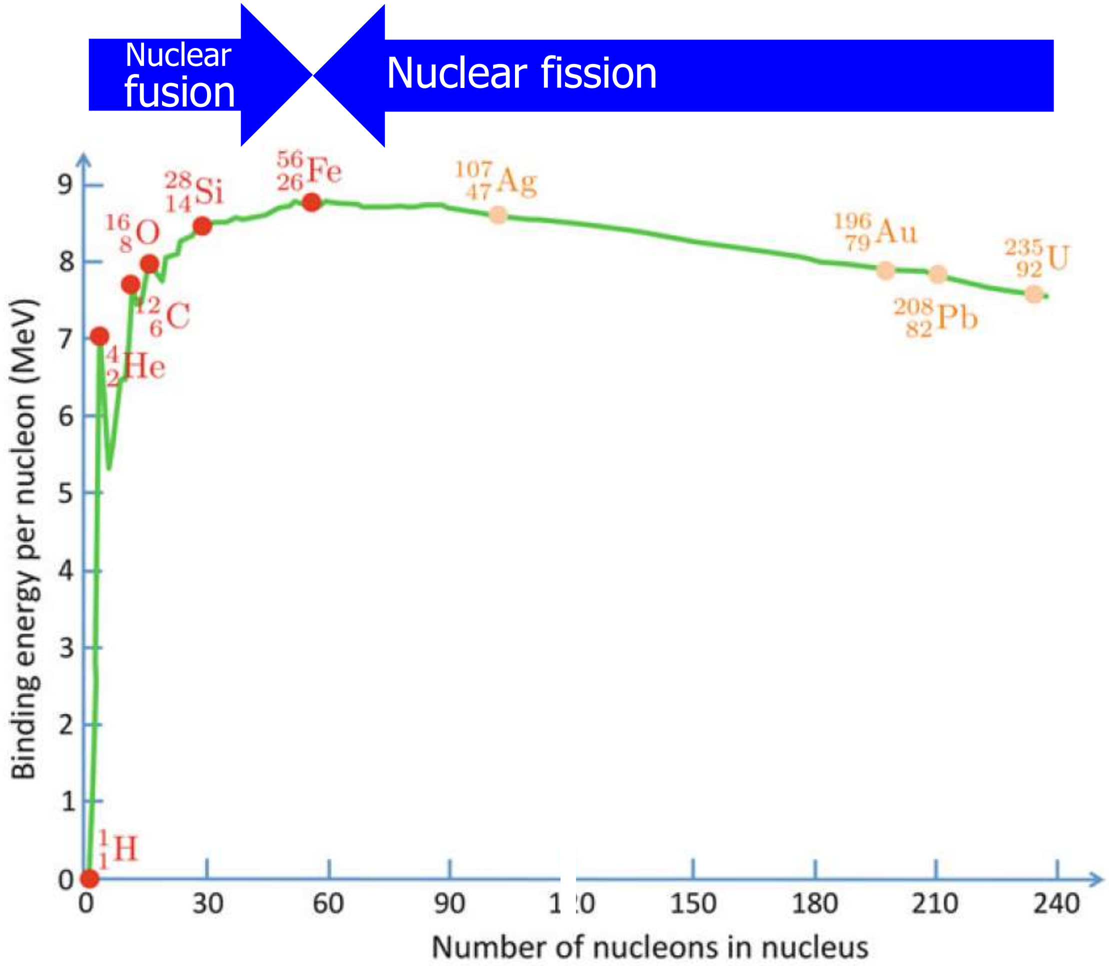


Number of nucleons in nucleus, *A* = Mass number

$^{56}_{26}Fe$: the most stable nuclei

http://www.earth-site.co.uk/Education/binding-energy/

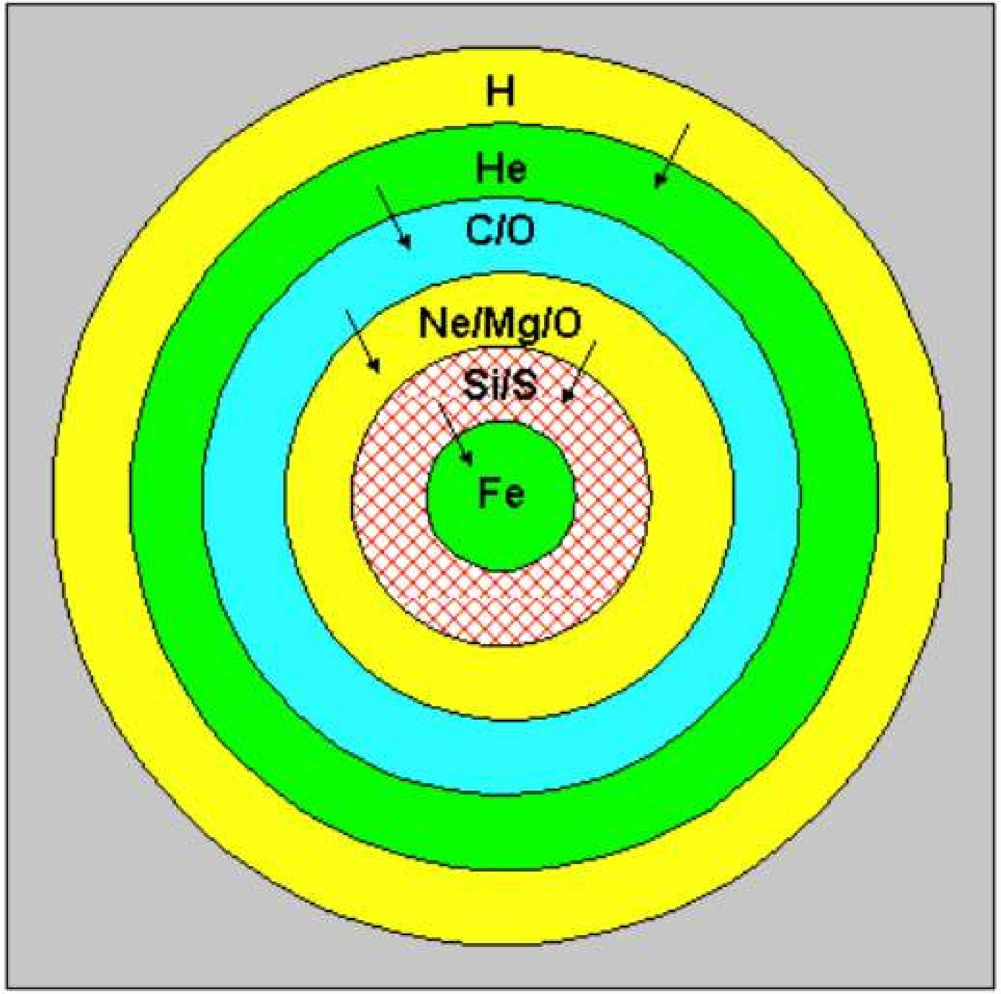
Binding energy per nucleon (E_b/A)



Fe : The largest binding energy
The most stable element
The final product of both nuclear fusion and nuclear fission

T. Foglizzo 2017, Handbook of Supernovae, Volume 2, p. 1053

End of Massive stars → Core-Collapse Supernovae (CCSNe)



https://www.astro.umd.edu/~richard/ASTR680/A680_SNR_2019_lec1.pdf

- Iron core collapse
  → shock wave propagates outward
  → outer layers (envelope) follows collapse
  → explosion!

- (expansion velocity ~a few 10^4 km/s)

- Final stage of the evolution of massive stars
  - Outer part → SN explosion → interstellar media
  - Inner part → neutron stars (pulsars) or black holes

Supernova SN 1987A (in Large Magellanic Cloud, LMC)

SN 1987A (II peculiar, LMC)

Tarantula Nebula

d~49.97 kpc (Pietrzynski+ 13 Nature 495 76)

1987 Feb 23.316 (UT)

B3 I (supergiant)

Peak : +2.9 mag

(B-V) = +0.085

T_{eff} = 16,000 K

$L \geq 10^5 L_\odot$

→ $M_{initial} \sim 20 M_\odot$ (N. Smith 2007 AJ 133 1034)

By David Malin
http://www.astronnewsroom.com/2012/02/25th-anniversary-of-sn1987a/

Yearly numbers of reported SN discoveries

Table 1 Yearly numbers of reported SN discoveries. Numbers in parentheses are that of confirmed and announced SNe on IAUCs/CBETs

Year	Discovery	1989	32	1998	163(162)	2007	607(572)
1981	11	1990	38	1999	206(201)	2008	520(261)
1982	27	1991	64	2000	185(184)	2009	475(390)
1983	28	1992	73	2001	307(305)	2010	586(337)
1984	22	1993	38	2002	338(334)	2011	902(298)
1985	21	1994	41	2003	426(335)	2012	1045(322)
1986	16	1995	58	2004	373(251)	2013	1457(228)
1987	20	1996	96	2005	377(367)	2014	1632(136)
1988	35	1997	163	2006	554(551)	2015	3412(61)

H. Yamaoka 2017, Handbook of Supernovae, Volume 1, p. 29

3. Star Deaths (별의 죽음)
3-2 Supernova Explosion (초신성 폭발)

https://www.supernovae.net/

Supernova (SN) types

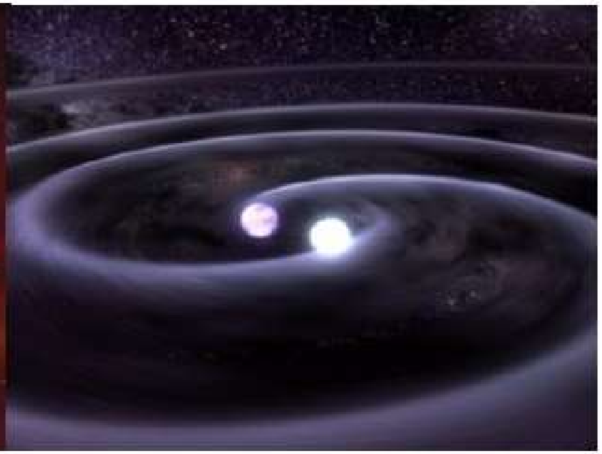
- Brightest objects in galaxies (M_V = -14 ~ -22)

- Typical types

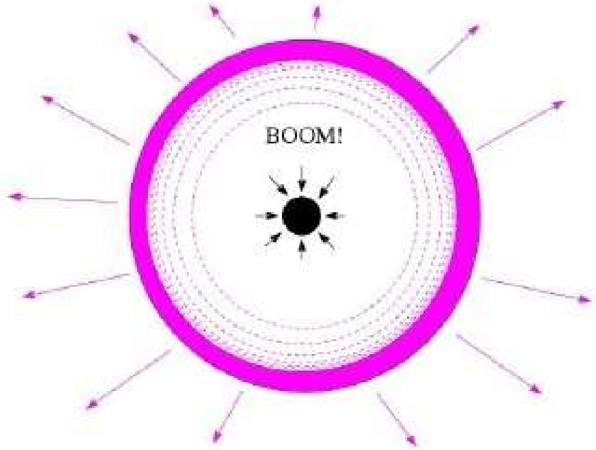
No H lines (pop II) → Type Ia Ib Ic

H lines (pop I) → Type II

WD + Giant/MS/He *
(Single Degenerate, SD)



WD + WD
(Double Degenerate, DD)



Core collapse

SNe Ia (thermonuclear stellar explosion)
(WD originated SNe)
백색왜성 기원 초신성

CC SNe

핵붕괴 초신성

http://dujs.dartmouth.edu/2008/05/type-ia-supernovae-properties-models-and-theories-of-their-progenitor-systems
http://wwwmpa.mpa-garching.mpg.de/mpa/research/current_research/hl2013-8/hl2013-8-en.html
http://spiff.rit.edu/richmond/sdss/sn_survey/sn_survey.html

Supernova (SN) types

- Brightest objects in galaxies (M_V = -14 ~ -22)

- Typical types

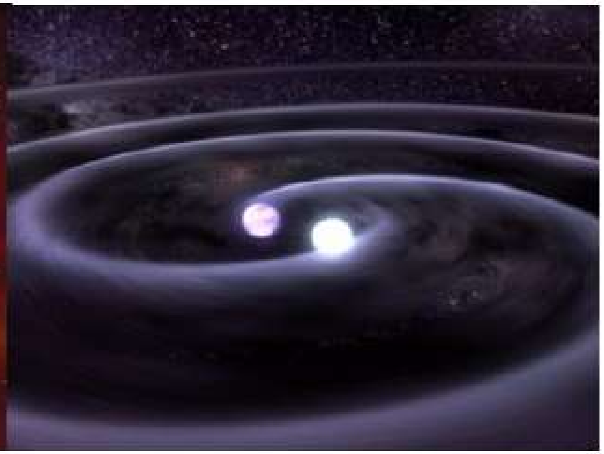
No H lines (pop II) → Type Ia

H lines (pop I) → Type II

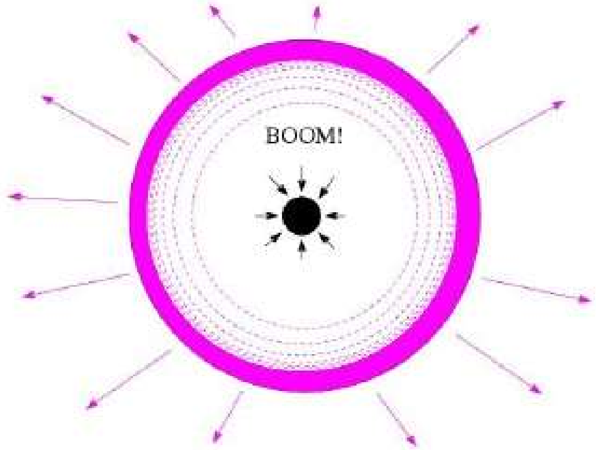
Ib

Ic

WD + Giant/MS/He *
(Single Degenerate, SD)



WD + WD
(Double Degenerate, DD)



Core collapse

SNe Ia (thermonuclear stellar explosion)
(WD originated SNe)
백색왜성 기원 초신성

CC SNe

핵붕괴 초신성

http://dujs.dartmouth.edu/2008/05/type-ia-supernovae-properties-models-and-theories-of-their-progenitor-systems
http://wwwmpa.mpa-garching.mpg.de/mpa/research/current_research/hl2013-8/hl2013-8-en.html
http://spiff.rit.edu/richmond/sdss/sn_survey/sn_survey.html

Supernovae taxonomy

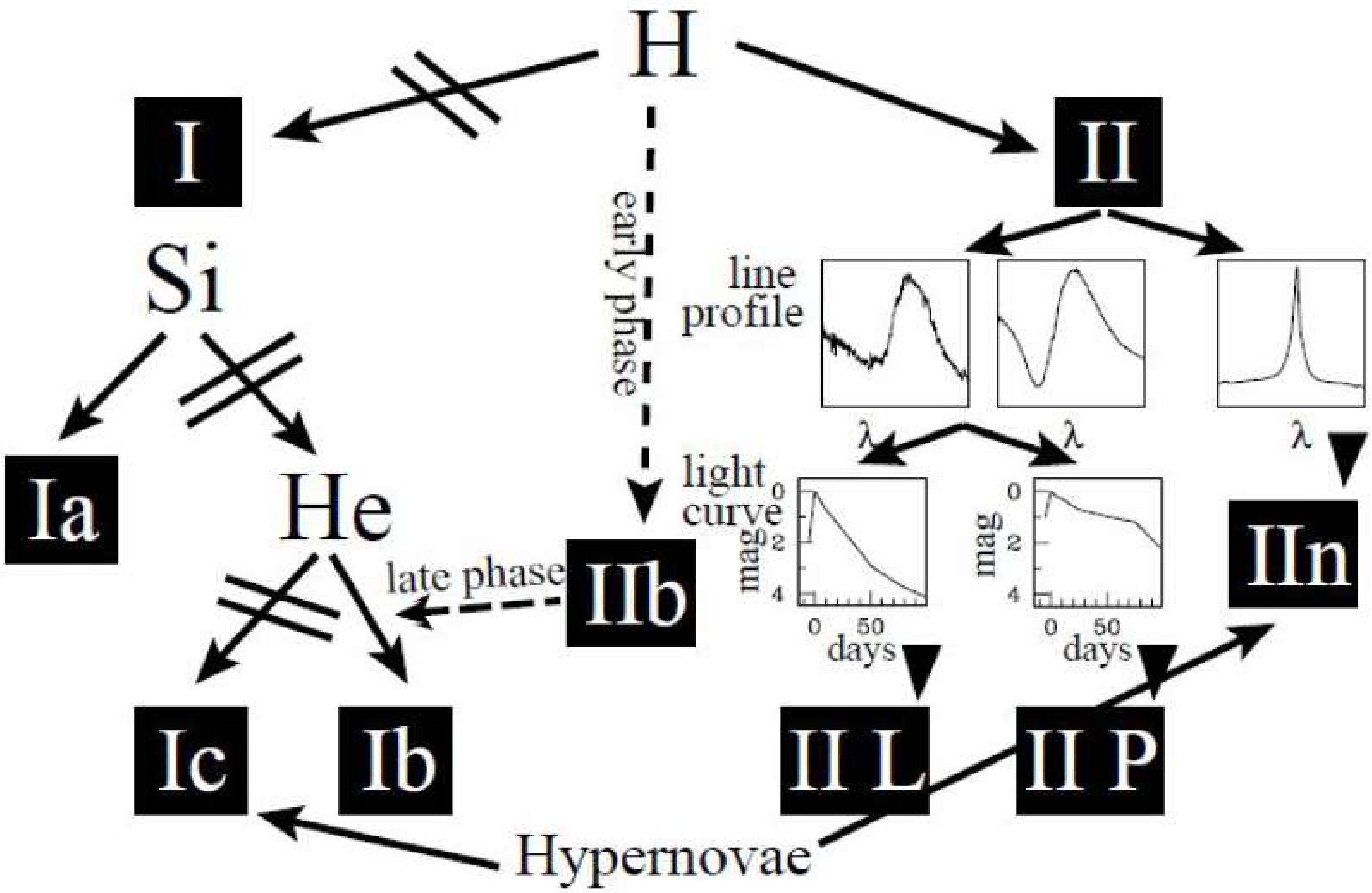
<table>
<tr><th>Type</th><th colspan="3">Sub-types</th></tr>
<tr><td rowspan="3">I
No H</td><td colspan="3">Ia
Si II (6150 Å) absorption near peak light</td></tr>
<tr><td rowspan="2">Ib/c
Weak/no Si absorption</td><td colspan="2">Ib
He I (5876 Å) emission</td></tr>
<tr><td colspan="2">Ic
Weak/no He</td></tr>
<tr><td rowspan="5">II
H</td><td rowspan="4">II-P/L/n</td><td rowspan="2">II-P/L
No narrow lines</td><td>II-P
Plateau in light curve(LC: mag vs time)</td></tr>
<tr><td>II-L
Linear decrease in LC</td></tr>
<tr><td rowspan="2">Some narrow lines</td><td>IIn : H lines</td></tr>
<tr><td>Ibn : He lines</td></tr>
<tr><td colspan="3">IIb : Spectrum changes to become like type Ib</td></tr>
</table>

Peculiar SNe

Ic-BL : sometimes associated with GRBs and/or hypernova (broad lines : $(2\text{-}3)\times 10^4$ km/s)
ultra-bright type II : $\sim 10^{51}$ erg radiation energy
.Ia : changing rapidly
Superluminous SNe, pair-instability SNe, Superluminous Ia
Subluminous SNe, Subluminous Ia
Super-Chandrasekhar Ia : mass > Chandrasekhar limit
Ia-IIn : CSM
Iax : Ia w/lower L, less E, less ejecta mass
Kilonova/macronova, SN imposters, magnetar

https://en.wikipedia.org/wiki/Supernova
http://astronomy.swin.edu.au/cosmos/S/Supernova+Classification

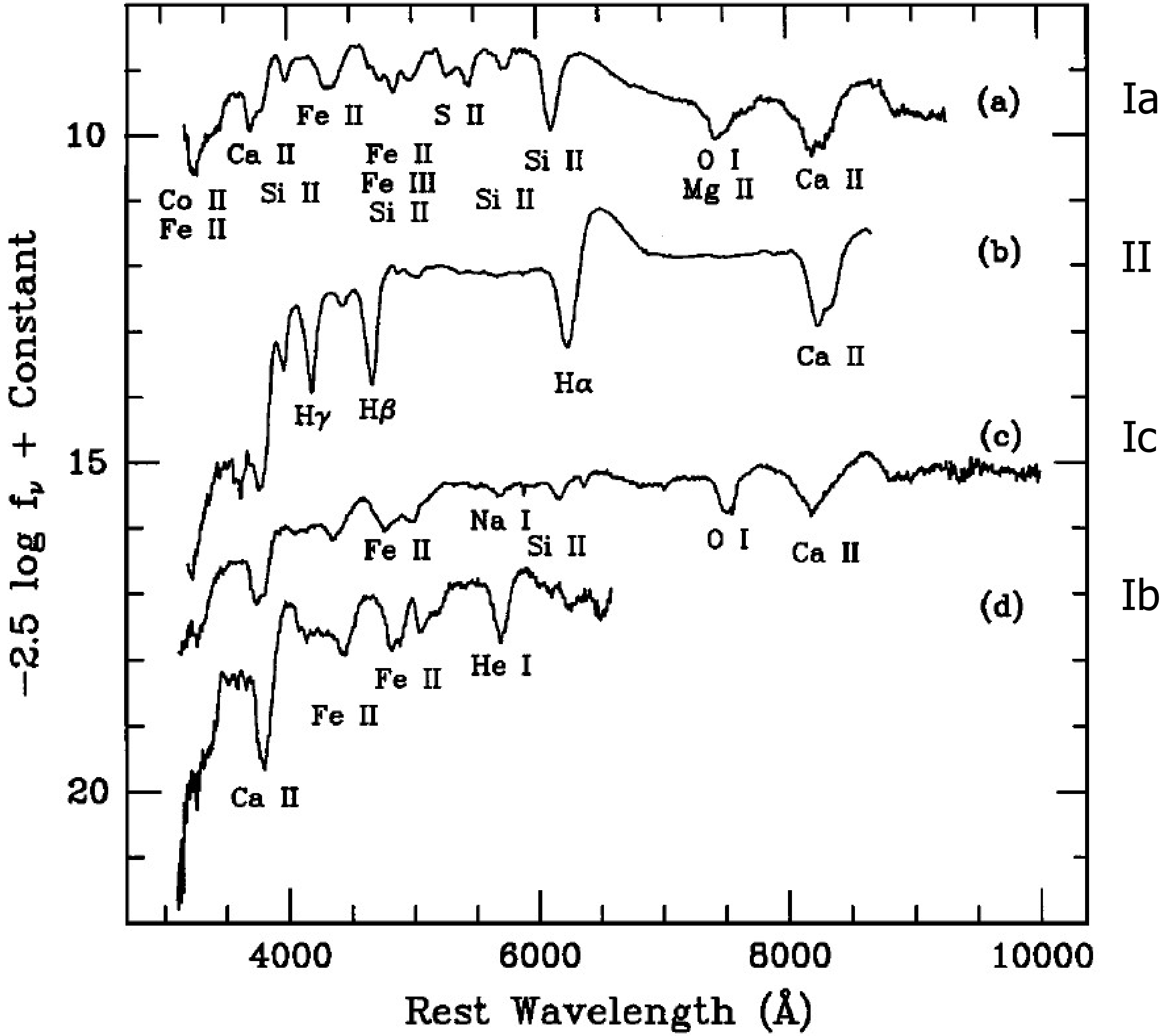
Supernova taxonomy



Cappellaro & Turatto (2000) Figure 2

https://arxiv.org/abs/astro-ph/0012455

Supernova taxonomy - spectra



Filippenko 1997 (ARA&A 35 309)

Supernova imposters

im·pos·tor, -post·er [impɑ́stər/-pɔ́s-] n.

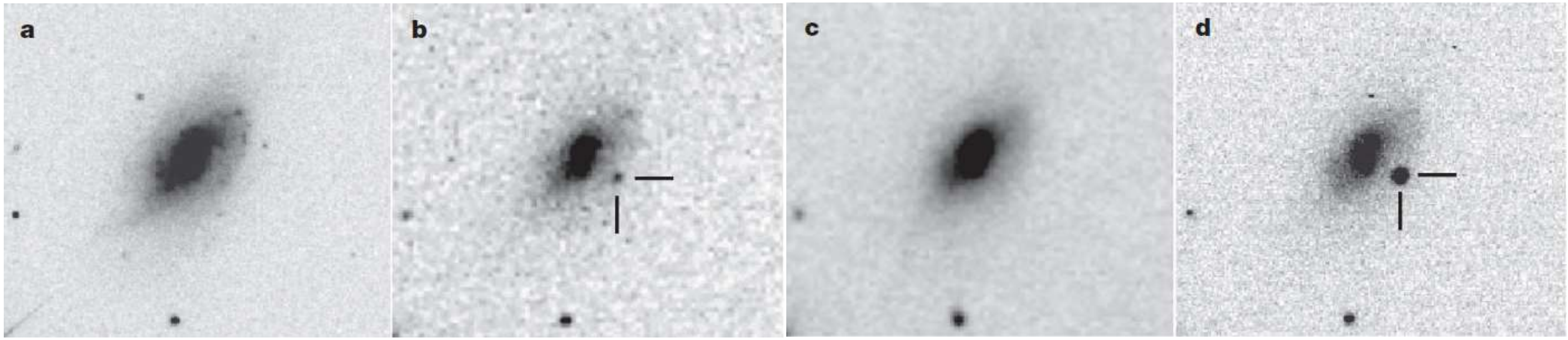
남의 이름을 사칭하는 자; 사기꾼, 협잡꾼.

impostor Cambridge Dictionary

a person who pretends to be someone else in order to deceive others:

- *He felt like an impostor among all those intelligent people, as if he had no right to be there.*

UGC 4904



2001 Dec 20, r'-band, Sloan Digital Sky Survey (SDSS)

2004 Oct 16, V=19.13±0.19 0.60-m f/5.7 reflector

2006 Sep 21

2006 Oct 29, R-band Asiago 1.82-m Telescope

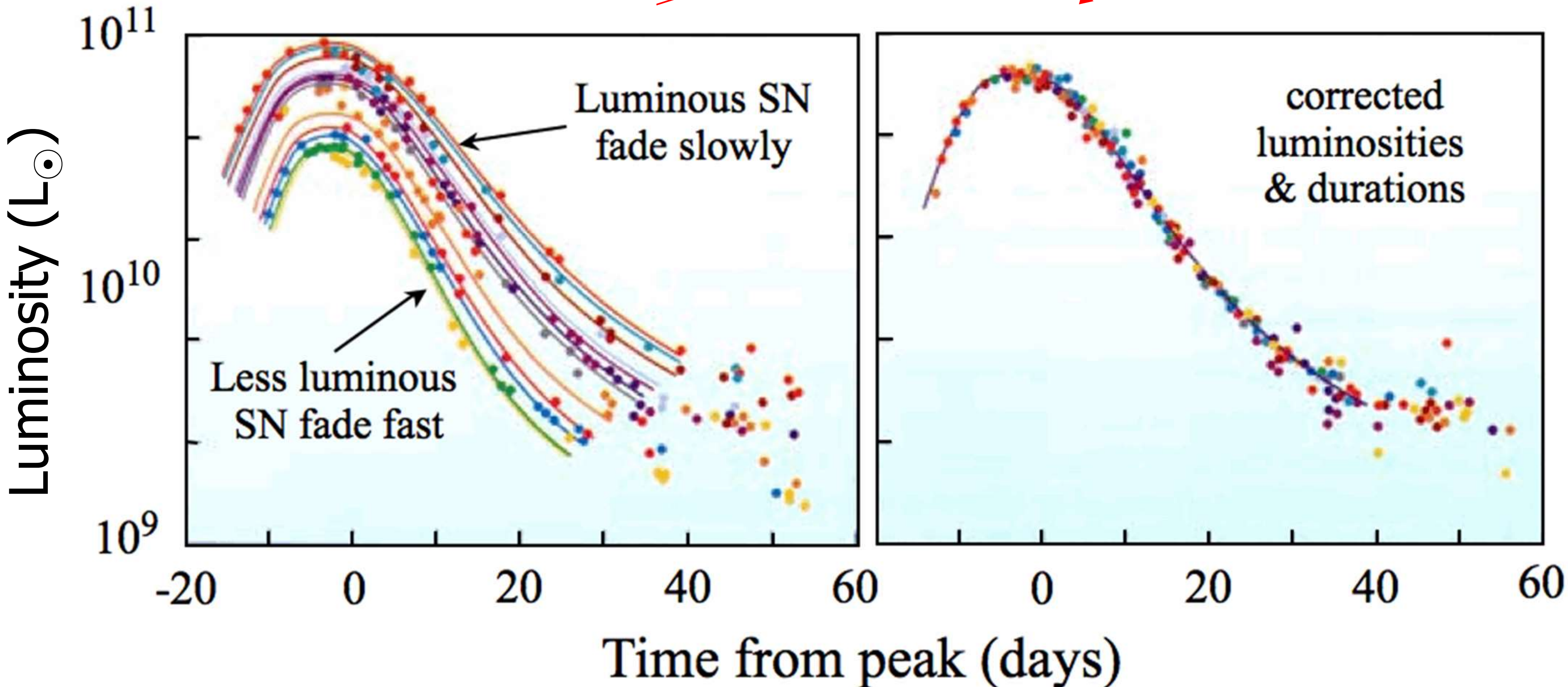
SN Imposter

SN, Peculiar Ib

Supernova(SN) Ia light curve (LC)

M_B

Correction (luminosity-decline rate relation)



LC width

https://johnlucey.webspace.durham.ac.uk/bridge/n2015m-bridge/

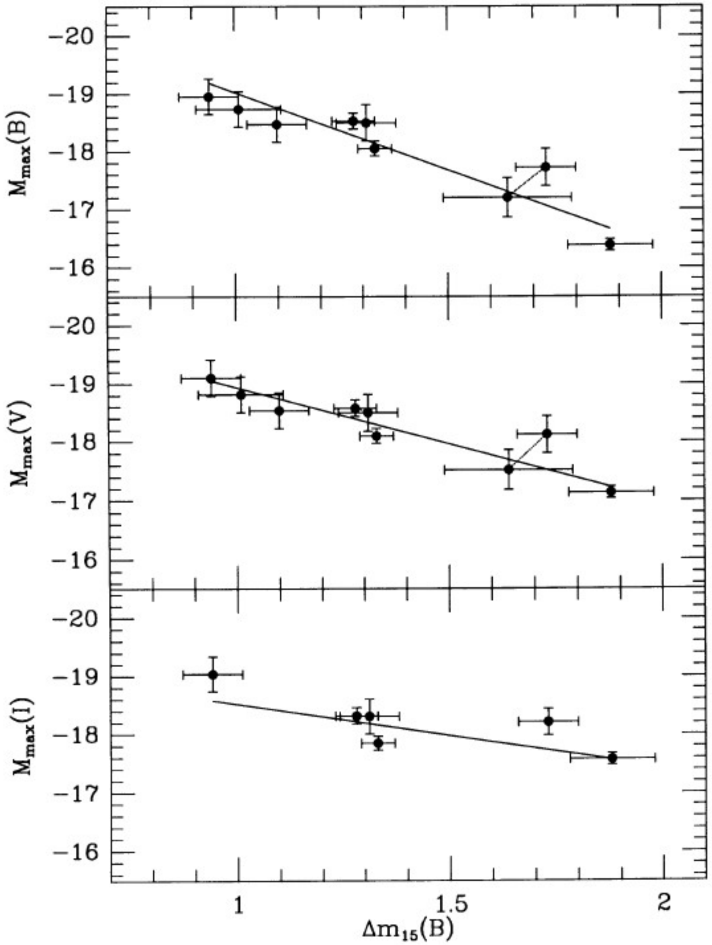
Supernova(SN) Ia light curve (LC)

Correction (luminosity-decline rate relation)

Philips 1993 ApJL 413, L105

M_B

Peak luminosity



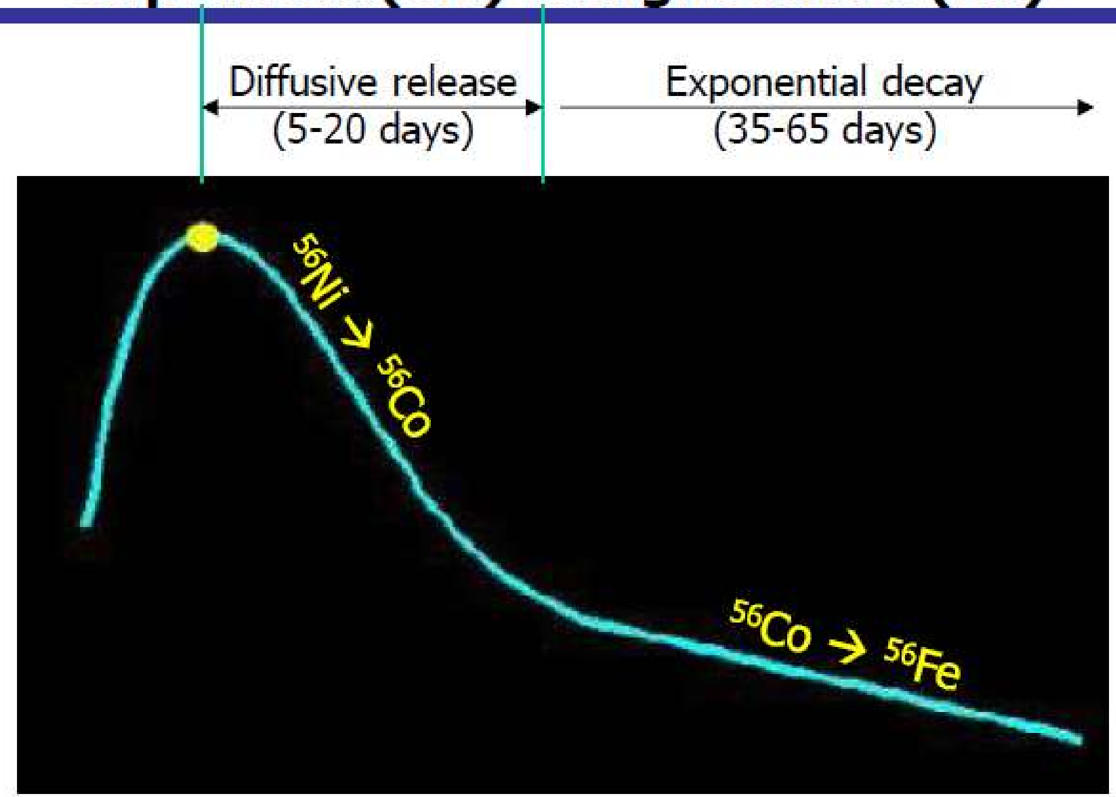
Decline rate

LC width

: Mag decrease from the peak mag for 15 days

FIG. 1.—Decline rate–peak luminosity relation for the nine best-observed SN Ia's. Absolute magnitudes in *B*, *V*, and *I* are plotted vs. $\Delta m_{15}(B)$, which measures the amount in magnitudes that the *B* light curve drops during the first 15 days following maximum.

Supernova(SN) Ia light curve (LC)



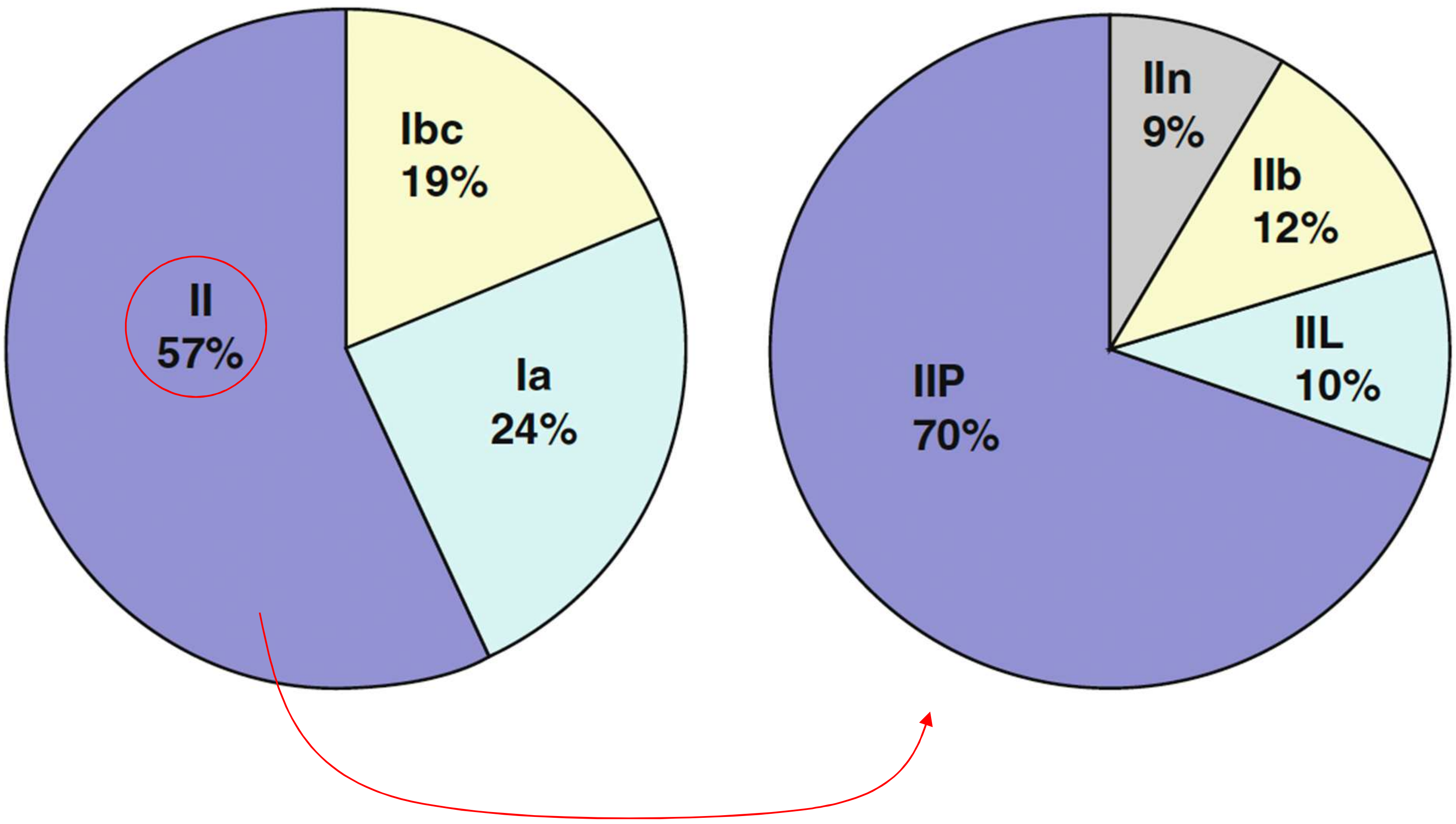
Radioactive decay of ^{56}Ni → ^{56}Co → ^{56}Fe
(Colgate & McKee 69 ApJ 157 623; Arnett 82 ApJ 253 785)

	half life
$^{56}_{28}\mathrm{Ni} \rightarrow {}^{56}_{27}\mathrm{Co} + e^+ + \nu_e + \gamma$	6.10 d, E=1.72 MeV
$^{56}_{27}\mathrm{Co} \rightarrow {}^{56}_{26}\mathrm{Fe} + e^+ + \nu_e + \gamma$	78.8 d, E=3.59 MeV

Piro & Nakar 2013, ApJ, 769, 67 (What can we learn from the rising LCs of radioactively powered SNe?)

SNe – number ratio

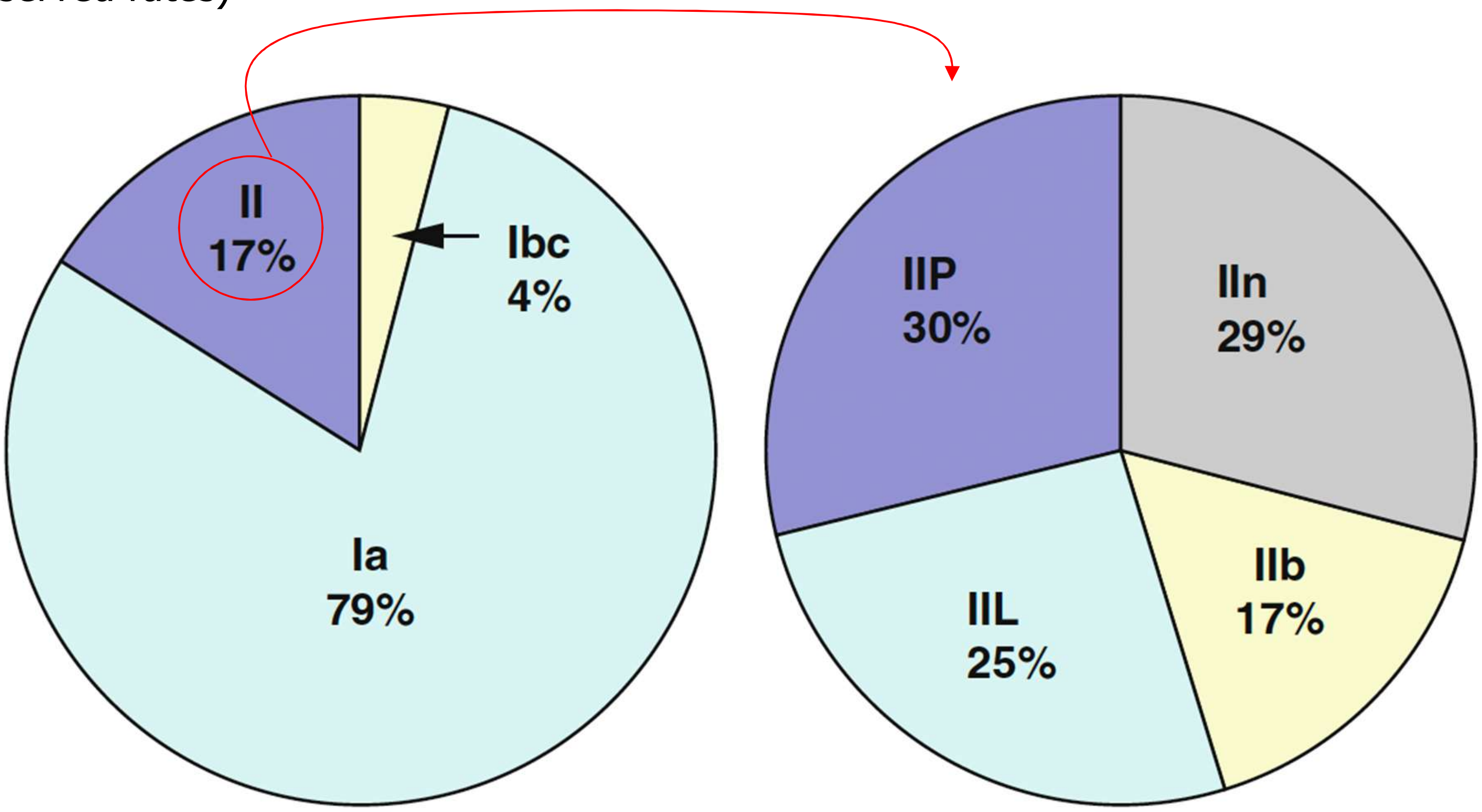
Volume-limited sample
(Intrinsic rates)



Li et al. 2011 (MN 412 1441)

SNe – number ratio

Magnitude-limited sample
(observed rates)

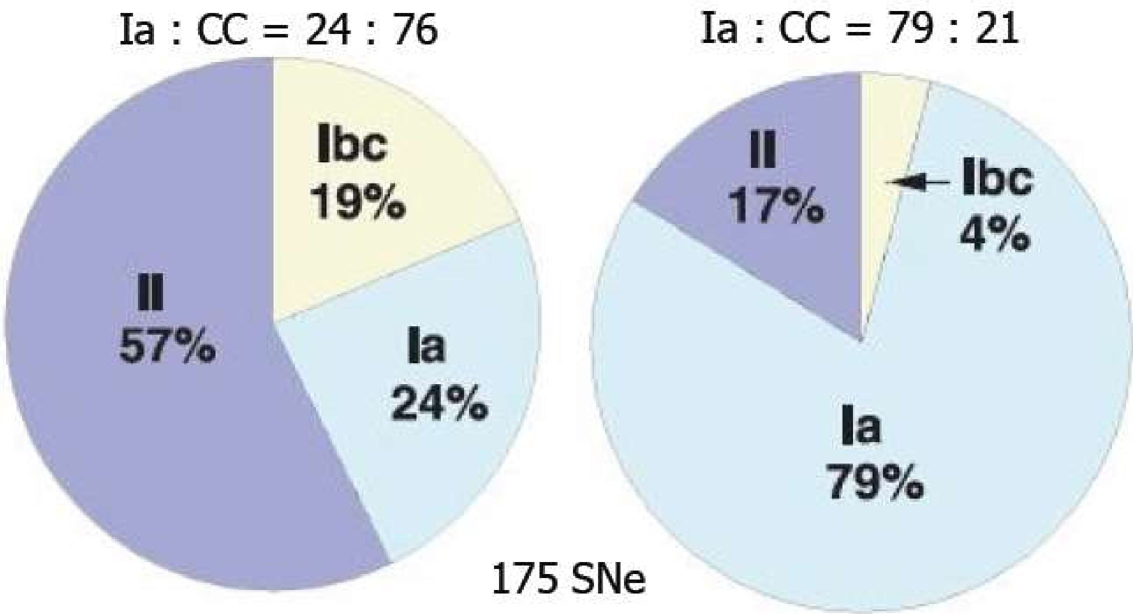


Li et al. 2011 (MN 412 1441)

SNe Ia – distance indicator

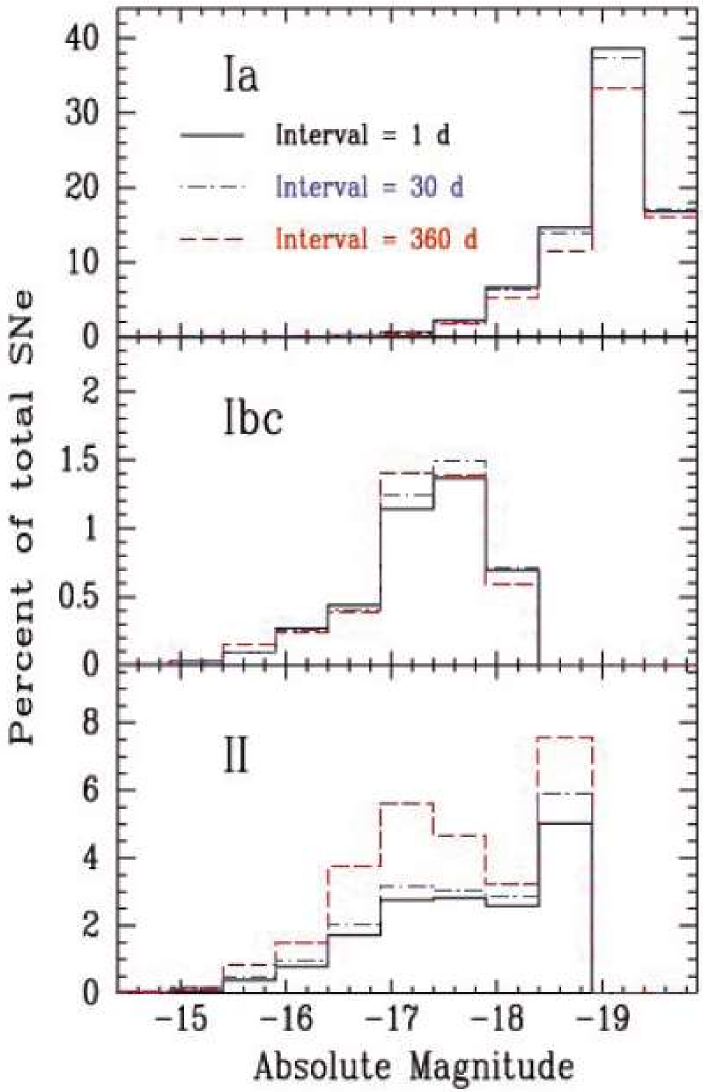
- SN Ia – maximum brightness (peak luminosity)
  $M_V \approx -19.30 \pm 0.03 + 5 \log (H_0 / 60)$
- Rising time ~ 20 days

Number ratio



Volume-limited sample
D ≤ 60 Mpc (CC SNe)
D ≤ 80 Mpc (SNe Ia)

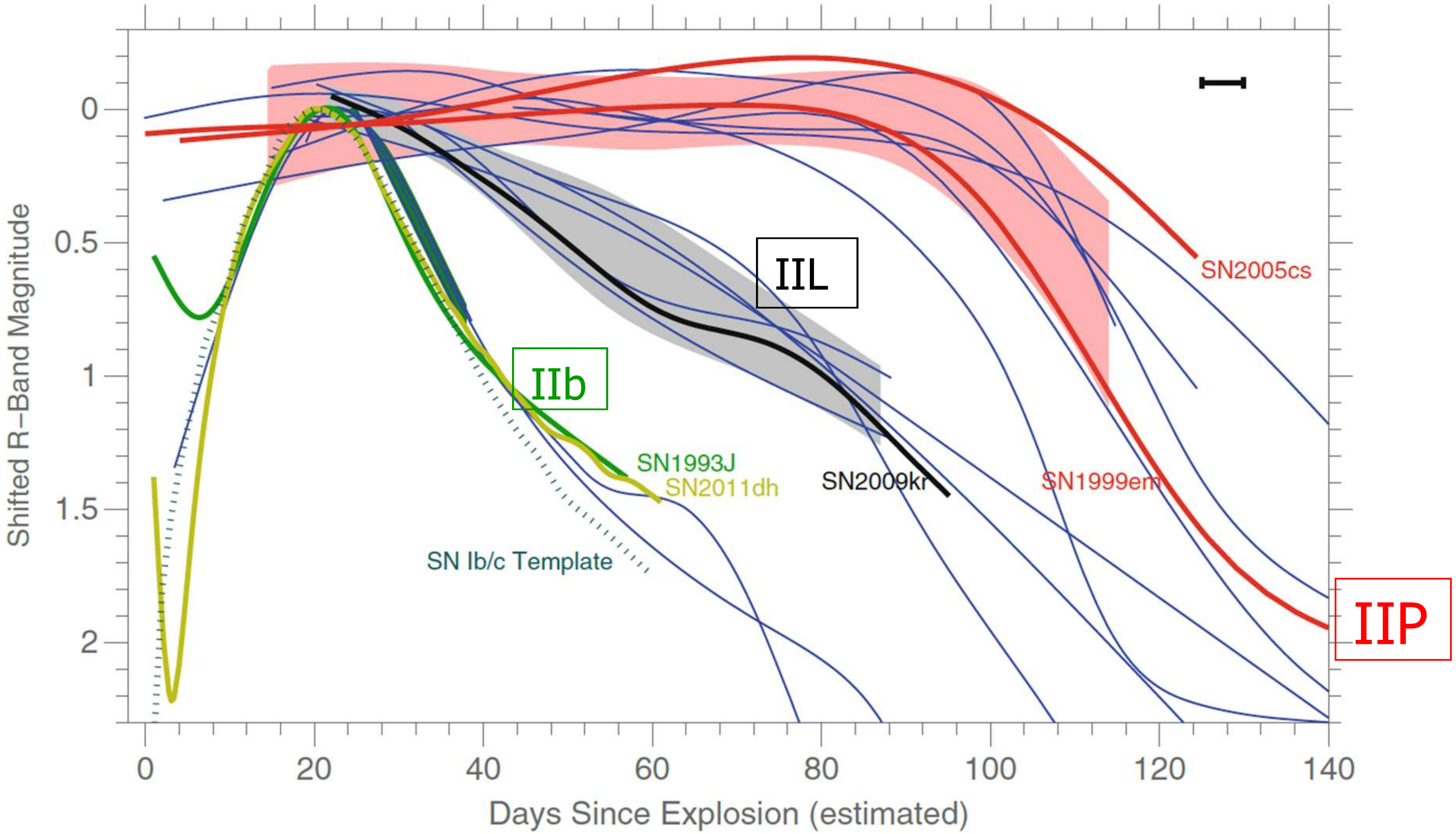
Ideal magnitude-limited sample



SN Ia : intrinsically brighter than CC SNe

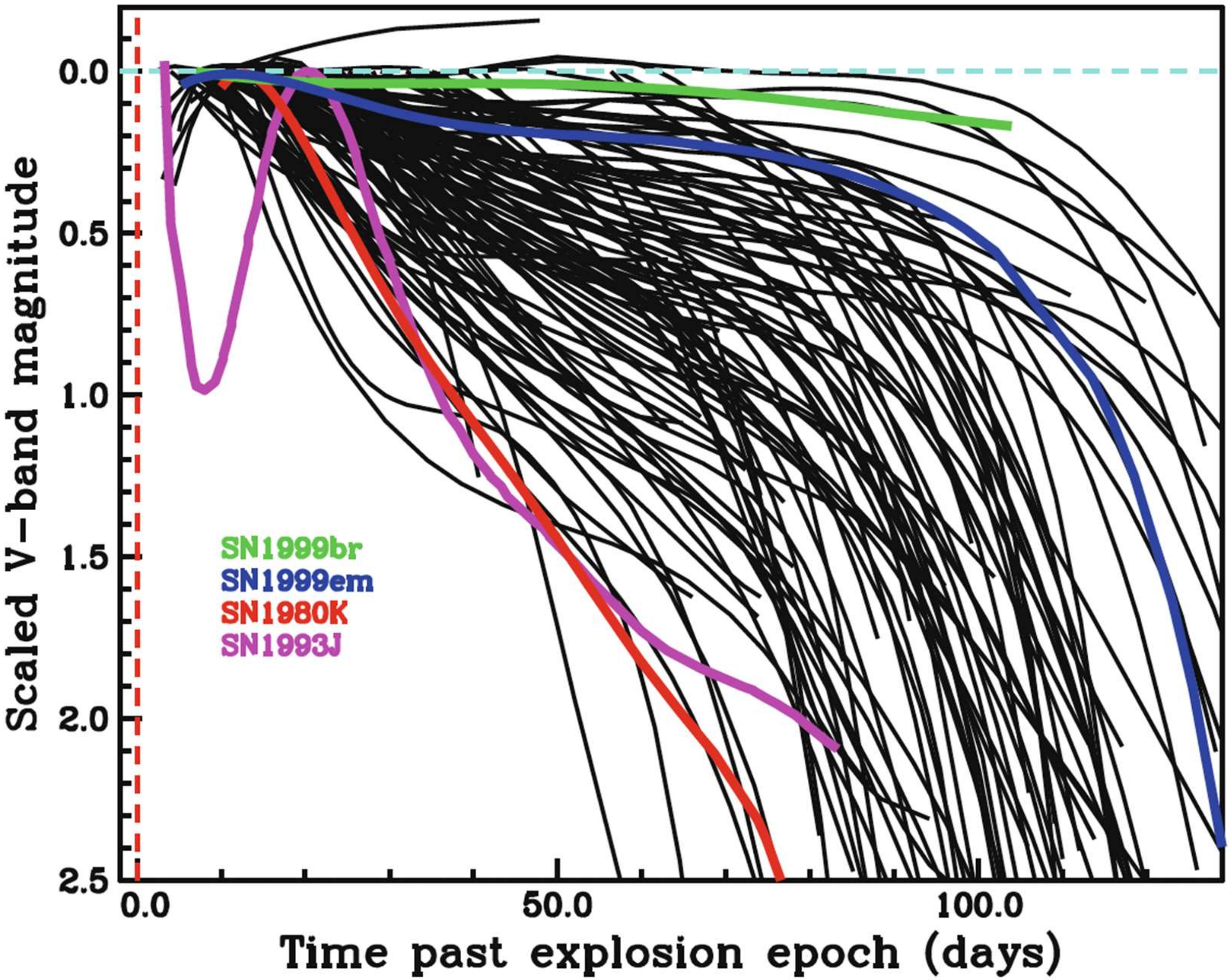
Li et al. 2011 (MN 412 1441)

Type II – Light Curves (LCs)



Arcavi+12 (ApJL 756 L30)
(see also Faran+14 MN 445 554)

Type II – Light Curves (LCs)



IIP

IIL

Continuity?

Anderson+14 (ApJ 786 67)
(see also Sanders+15 ApJ 799 208)

CC SNe vs. SNe Ia

- CC SNe : not in early-type galaxies, Spiral galaxies – spiral arms
- SN Ia : all types of galaxies (Spiral galaxies – no spatial preference)

- spiral arms = short-lived massive stars

→ CC SNe = massive stars

SN Ia = not that massive stars

- Total energy emitted in neutrinos 3×10^{53} erg
- Total kinetic energy $\sim 10^{51}$ erg = f.o.e. = foe

$\sim$1% of total kinetic energy comes in photons $\sim 10^{49}$ erg
(peak luminosity $\sim 10^{43}$ erg/s, $\sim 10^{9}\ L_{\odot}$, ~brightness of an entire galaxy)

CC SNe vs. SNe Ia

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~1% of total kinetic energy comes in photons ~10^{49} erg
(peak luminosity ~10^{43} erg/s, ~10^{9} $L_{\odot}$, ~brightness of an entire galaxy)

foe 미국식 [ˈfoʊ] 영국식

명사 an enemy

foe 미국식 [foʊ] 영국식 [fəʊ]

[명사] (구식 또는 격식) 적(敵)

https://endic.naver.com/

적² 敵

(원수) (the) enemy, (literary) **foe**

원수¹ 怨讐

(적)enemy, (literary) **foe**

3. Star Deaths (별의 죽음)
3-3 White Dwarfs, Neutron Stars, and Black Holes
(백색왜성, 중성자별, 검은구멍)

Helix Nebula in the Aquarius

https://www.dailymail.co.uk/sciencetech/article-3517714/The-dying-star-rewrite-know-stellar-evolution-White-dwarf-bizarre-atmosphere-oxygen.html

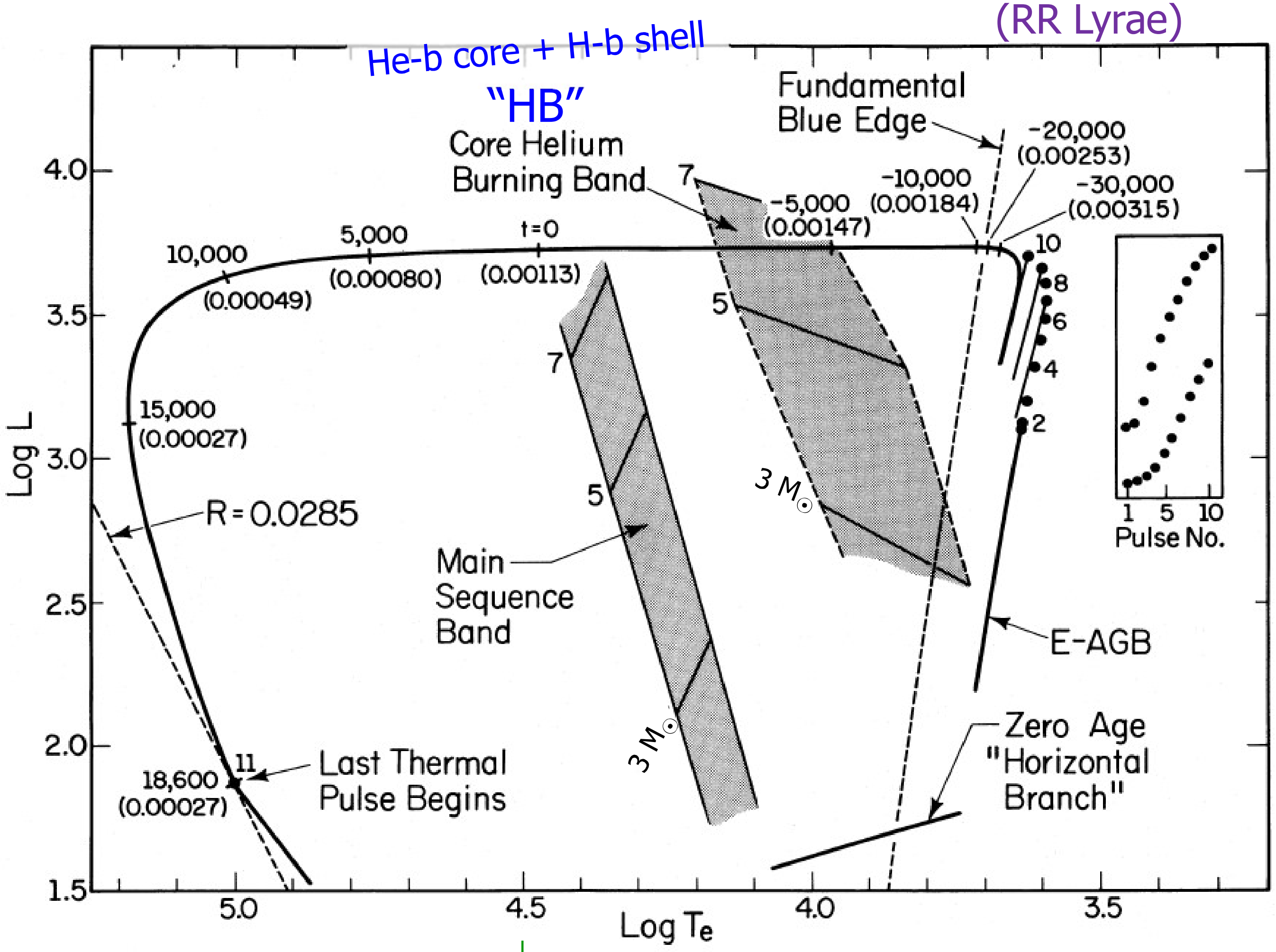
https://www.nasa.gov/audience/forstudents/5-8/features/nasa-knows/what-is-a-supernova.html

1. Planetary nebula evolution in the CMD

- M = 0.6 $M_\odot$
- CO-core
- Initial composition : X=0.749, Y=0.25, Z=0.001
- (amount of mass remaining in the H-rich envelope, $M_\odot$)
- After '11', loses last remnants of envelope

→ Becomes White Dwarf, R=0.0285 $R_\odot$ ~ 20,000 km

Instability strip (RR Lyrae)



11 He-shell flashes

30,000 K

An Introduction to Modern Astrophysics (2nd edition), Bradley W. Carroll & Dale A. Ostlie (1996), p. 509

WDs - general

RG

Extremely low-mass ($M_i \leq 0.2\ M_\odot$) → no He-b → He WD

$M_i \leq 8\ M_\odot$, $T_c < 10^9$ K, No C-burning → CO-core + PN

→ CO WD

$8 < M_i < 10.5\ M_\odot$ → C-b, but no Ne-b

→ ONeMg WD

No fusion reactions, supported by electron degenerate pressure

(Current) Mass : 0.55 – 0.6 $M_\odot$

- min mass ~ 0.4 $M_\odot$
- max mass for a non-rotating WD = Chandrasekhar mass ~1.4 $M_\odot$

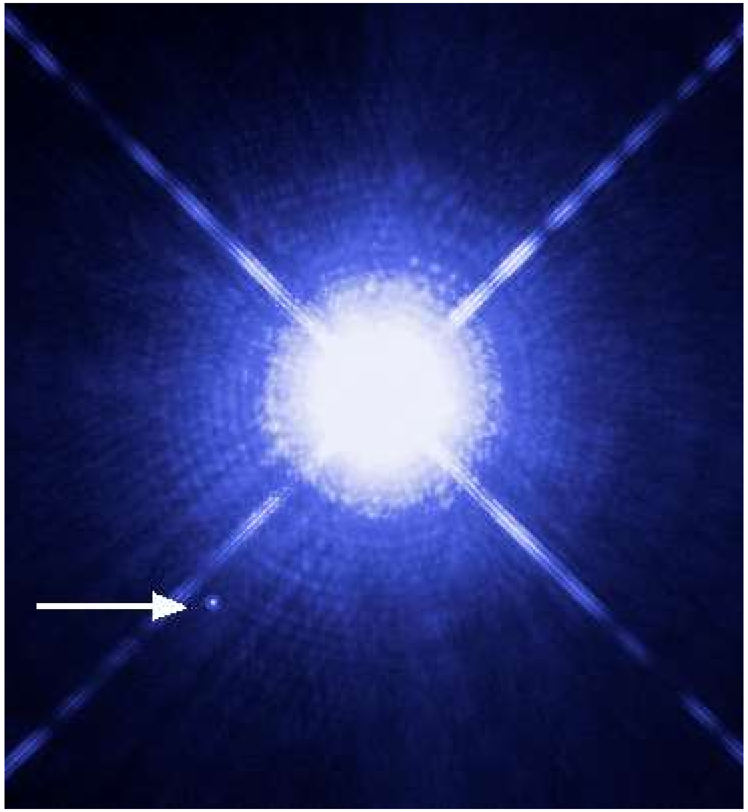
Typical density ~ 10^6 g/cm^3

Typical B ~ 10^6 Gauss (2×10^3 - 10^9 Gauss)

Binary – mass transfer from a companion → CO WD mass approaches the Chandrasekhar mass → C-detonation → SN Ia

Evolution : hot WD → E decreases, color reddens → black dwarf (timescale > 13.8 Gyr)

→ no black dwarf yet formed

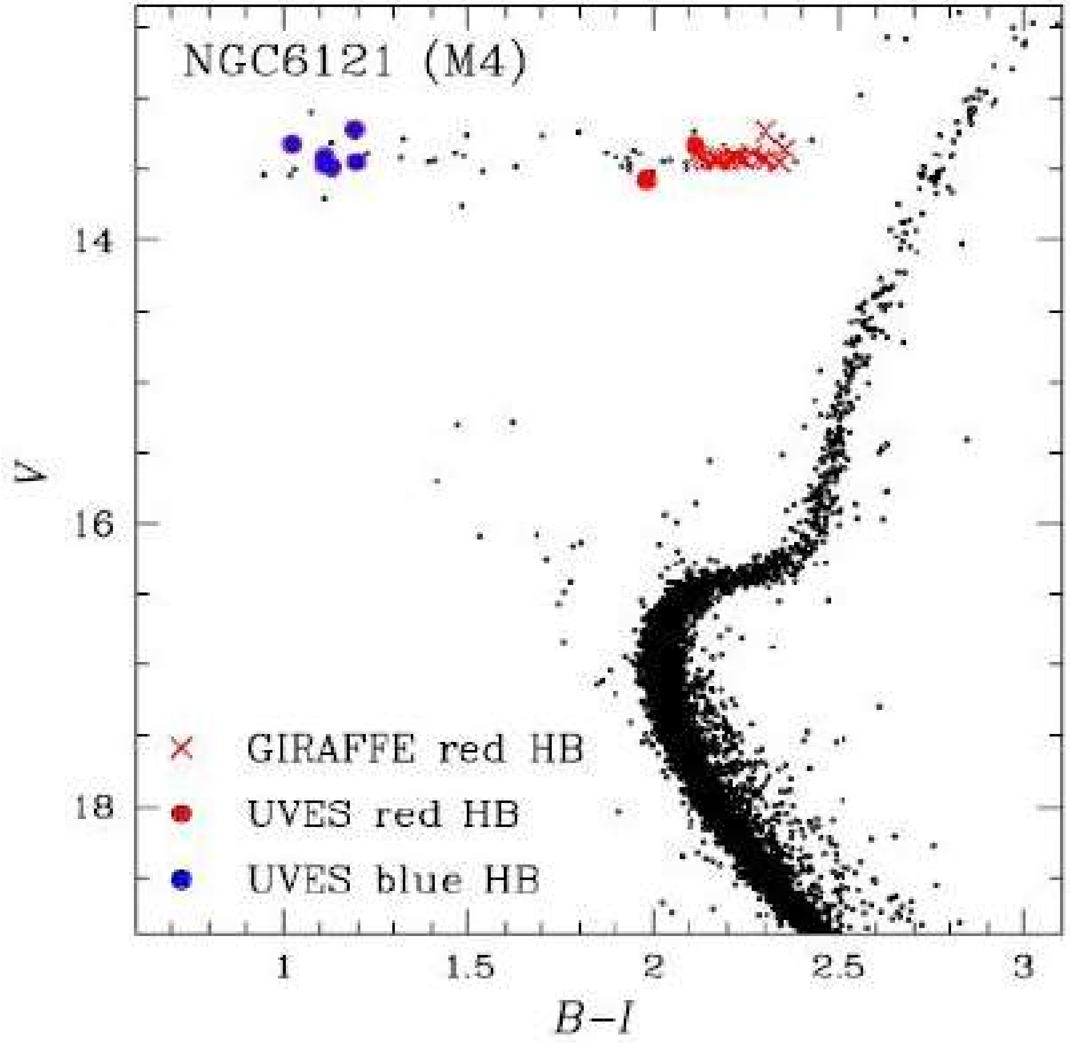


Sirius A, Sirius B (WD) - HST

https://en.wikipedia.org/wiki/White_dwarf

Galactic Astronomy (James Binney and Michael Merrifield, 1998) p. 267

WD – cooling sequence



Marino+11 (ApJ 730 L16 - Sodium-Oxygen Anticorrelation Among HB Stars in the GC M4)

VLT 8.2m

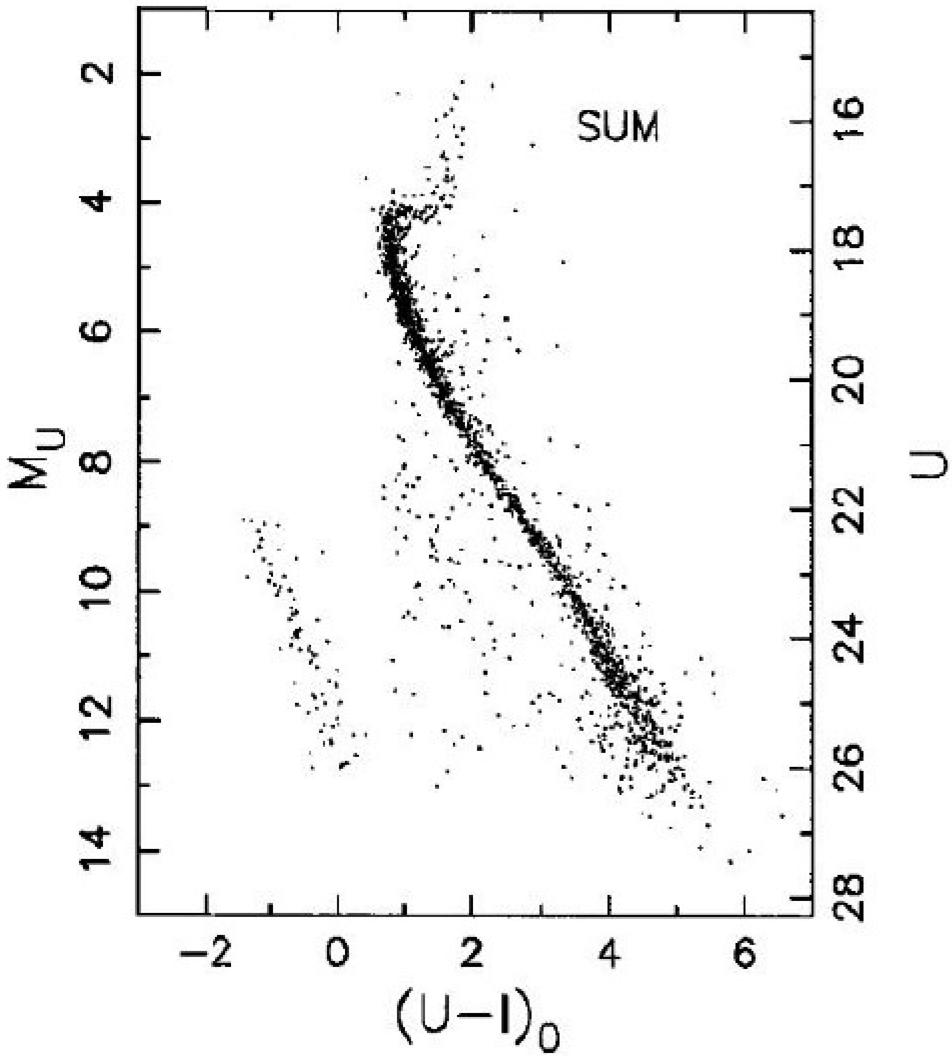
WD – cooling sequence

- WD cooling line of the GC M4
  : bluest stars
  : U = 22 – 26 mag

$$\boxed{L \propto T_{eff}^4}$$ or

$$M_{bol} = -10 \log T_{eff} + const.$$

- Constant radius line
- Roughly parallel to the MS
- Stretched not by mass, but by age
  (young → old)



U-(U-I) CMD of GC M4 (NGC 6121)
HST
Richer et al. 1995 (ApJ 451 L17 - HST Observations of WDs in the GC M4)

Galactic Astronomy (James Binney and Michael Merrifield, 1998) p. 281

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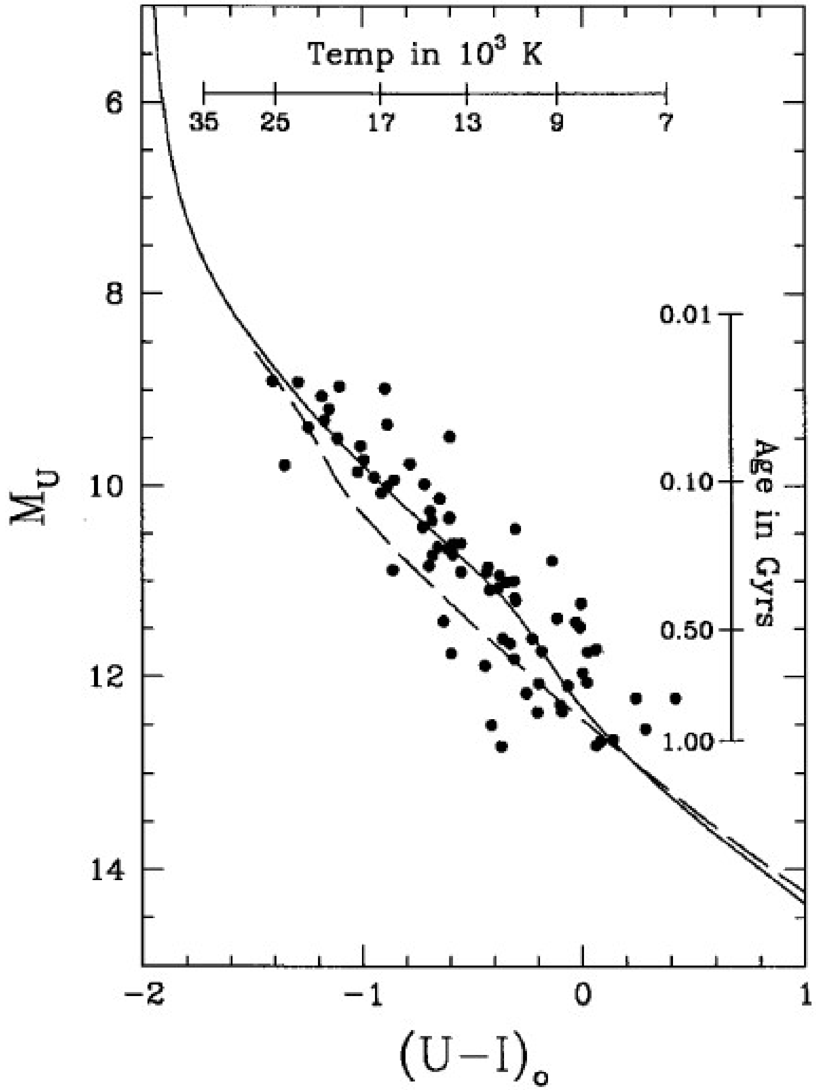

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Richer et al. 1995 (ApJ 451 L17 - HST Observations of WDs in the GC M4)

Galactic Astronomy (James Binney and Michael Merrifield, 1998) p. 281

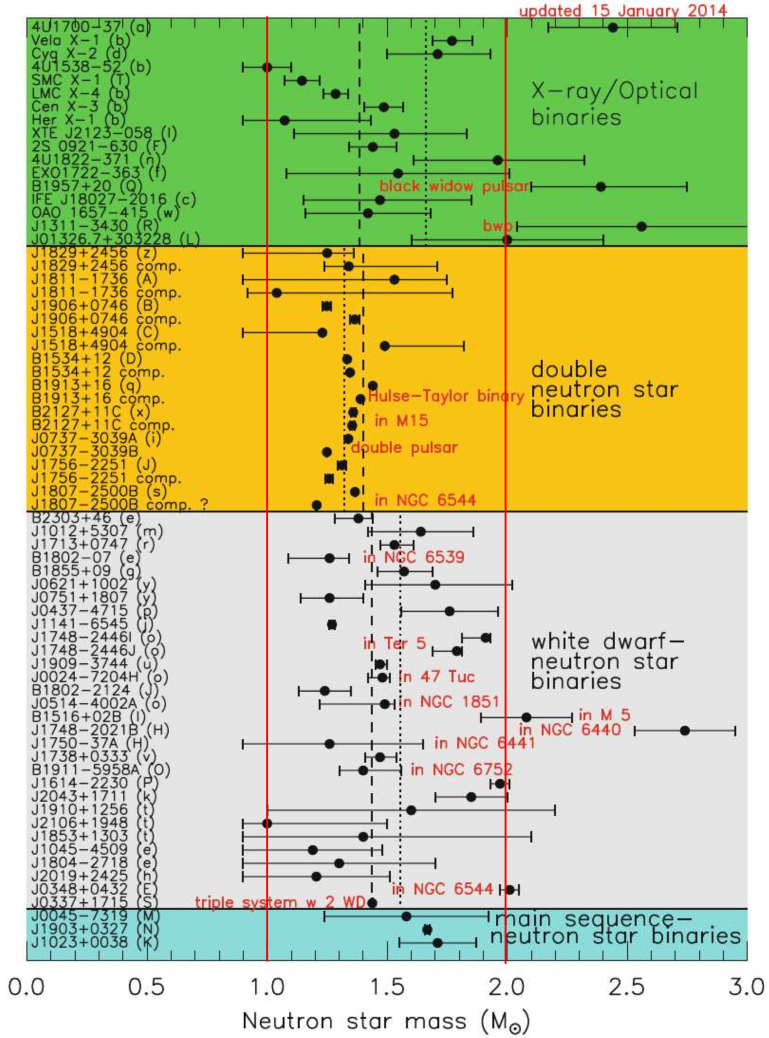
2. Neutron Stars (NSs, 중성자별)

- $M_i \geq 8\ M_\odot$
- $M_f > 1.4\ M_\odot$ → degenerate electron gas pressure cannot hold off gravity → matter is crushed to very high densities → inverse- β decay occurs :

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

(protons and electrons are squeezed into neutrons)

- Degenerate neutron gas → provides internal pressure
- Mass : 1.1 – 2 $M_\odot$ (upper limit ~ 3 $M_\odot$)



Horvath & Valentim 2017, Handbook of Supernovae, Volume 2, p. 1317

Typical mass ~ 1.4 $M_\odot$
Typical radius ~ 10 km
Typical density ~ 4 × 10^{14} g/cm³
(400,000 ton/mm³)
B ~ 10^{12} Gauss
Surface temp ~6 × 10^5 K

※ 1 Tesla = 10^4 Gauss
※ Sun : mean density ~ 1.408 g/cm³
$B_\odot$~1-2 Gauss
※ Earth : $B_\oplus$~0.1 Gauss
※ Magnetic Resonance Imager (MRI, 자기공명영상) :
B~10^5 $B_\oplus$ ~ 1 Tesla

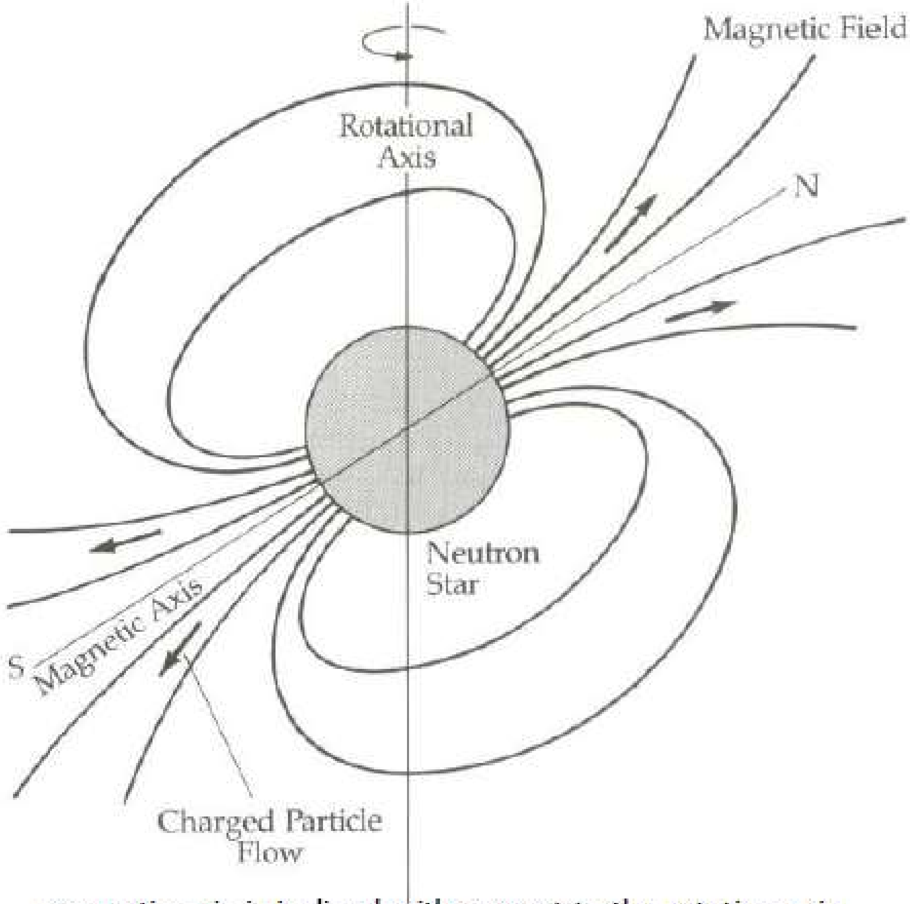
2-1. Pulsars (펄사)

- pulsating star = pulsar = rotating neutron stars
- 1967 discovered by Jocelyn Bell Burnell and Anthony Hewish (1974 Nobel prize)
  Radio pulses coming every 1.33730113s (at 81.5 MHz)+ 3 more objects
- Now, N~2300, P~1.6×10^{-3} to 4.0 s (average 0.65 s)

- Strong magnetic field
  → Synchrotron radiation along the magnetic dipolar axis

- Lighthouse model : transforms the rotational energy into electromagnetic energy → emits through the magnetic axes → pulse period = rotation period

- If the Sun becomes a NS → R = 7 km



magnetic axis is inclined with respect to the rotation axis

TABLE 17–1 Properties of Selected Pulsars

Name (PSR)	Period (s)	dP/dt (10^{-15} s/s)	DM(pc/cm^3)
1937 + 21	0.001557	1.07×10^{-4}	71.2
1855 + 09	0.005362	46421	13.3
0531 + 21 (Crab)	0.033326	421	56.8
0833 − 45 (Vela)	0.089234	124	69.1

Introductory Astronomy and Astrophysics (4th edition)
Michael Zeilik & Stephen A. Gregory (1998), p. 339

Introductory Astronomy and Astrophysics (4th edition)
Michael Zeilik & Stephen A. Gregory (1998), p. 341

2-1. Pulsars (펄사)

- Dispersion : a given pulse arrives at the Earth later as we look at lower frequencies
  - Due to a slowing down of the photon velocity by electrons in the line-of-sight (los)
  - Longer λ are slowed down more
  - Observations can tell us the mean electron density in the los
- If pulses of ν_1 and ν_2 $(\nu_1 > \nu_2)$ are emitted at time t_0 → they arrive at t_1 and t_2, respectively
- Then, $t_1 - t_0 = \dfrac{d}{v_1}$ and $t_2 - t_0 = \dfrac{d}{v_2}$
- We can measure $t_2 - t_1$ → equal to $\left(\dfrac{1}{v_2} - \dfrac{1}{v_1}\right)d$
- Velocities depend on the electron density → if we know the electron density, we can get the distance
- Dispersion Measure (DM) = integrated electron density : $\mathrm{DM} = \int_0^d n_e \, dl$

Introductory Astronomy and Astrophysics (4th edition)
Michael Zeilik & Stephen A. Gregory (1998), p. 340

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Introductory Astronomy and Astrophysics (4th edition)
Michael Zeilik & Stephen A. Gregory (1998), p. 339

2-1. Pulsars (펄사) - Discoverer

https://thewire.in/science/women-astrophysics-editors-stem

Jocelyn Bell Burnell (Source : YouTube)

Binary pulsars (쌍성 펄사)

- First binary pulsar, PSR B1913+16 : 1974 at Arecibo by Joseph H. Taylor, Jr. (조세프 테일러, b. 1941), Russell Hulse (러셀 헐스, b. 1950)
- "Hulse-Taylor binary pulsar"

- Einstein's theory of general relativity → two NSs would emit gravitational waves as they orbit a common center of mass
- Gravitational waves carry away orbital energy → cause the two stars get closer → orbital P ↓

The Nobel Prize in Physics 1993

Russell A. Hulse and Joseph H. Taylor Jr. "for the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation"

https://www.nobelprize.org/prizes/lists/all-nobel-prizes-in-physics/

https://en.wikipedia.org/wiki/Binary_pulsar

3. Black Holes (BHs, 검은구멍)

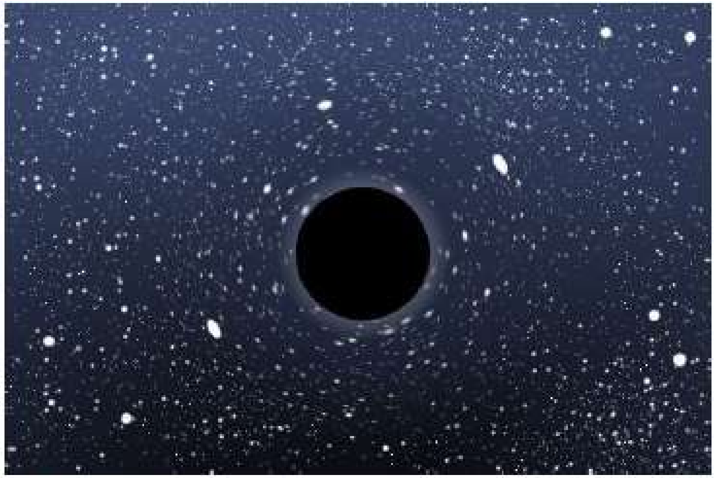
- A region of spacetime in which gravity is so strong that nothing (incl. light) can escape it
- Minimum mass ~ 3 $M_\odot$
- Theoretically zero volume and infinite density → "singularity" (breakdown of the laws of physics)
- An object with escape speed v_{esc} at the surface of the BH :

Total Energy = KE + PE = $\dfrac{mv_{esc}^2}{2} - \dfrac{GmM}{R} = 0$

- Assuming max escape velocity = c

$$\boxed{R = \frac{2GM}{c^2} = 3M \text{ km}}$$

Schwarzshild radius



black_hole_baird.jpg
http://sciencequestionswithsurprisinganswers.org/2013/06/18/can-you-go-fast-enough-to-get-enough-mass-to-become-a-black-hole/

- If the Sun becomes a BH → density ~10^{16} g/cm^3 (~nucleus of an atom)

- If an object cross the Schwarzshild radius, it crashes into a singularity (zero volume)

3. Black Holes (BHs, 검은구멍)

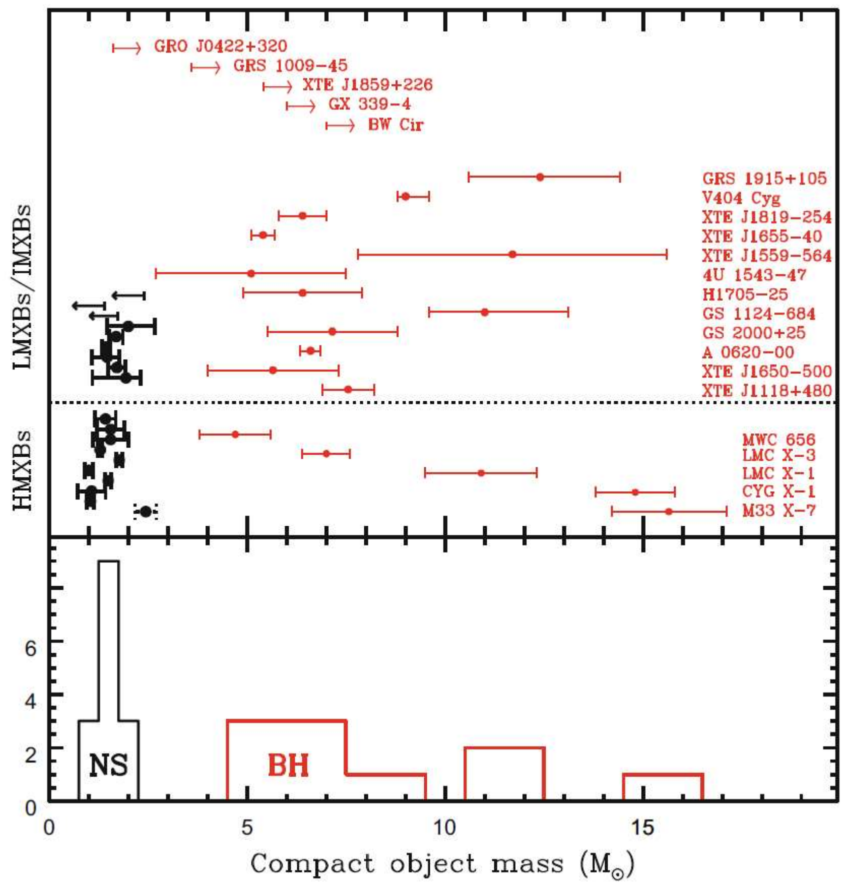


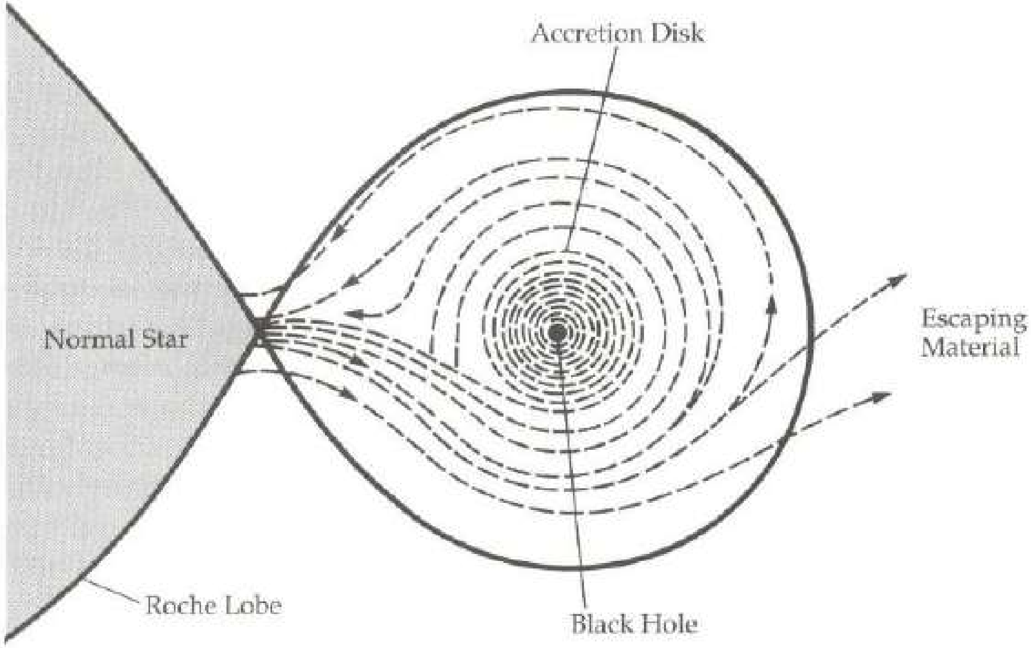
Fig. 2 *Top*: compact remnant masses measured in X-ray binaries. Neutron stars and black holes are indicated in *black* and *red colors*, respectively. 4U 1700-37 is plotted in *dotted-style line* because the nature of the compact star is uncertain. The *horizontal dotted line* divides LXMBs/IMXBs from HMXBs. *Bottom*: observed distribution of neutron stars and black hole masses

J. Casares et al. 2017, Handbook of Supernovae, Volume 2, p. 1499

3. Black Holes (BHs, 검은구멍)

- How to observe/find a BH?
- not for an isolated BH → but for a BH in a binary system (interactions with other material)
- matter falling toward a BH - gains kinetic energy → heats up, becomes ionized → emits electromagnetic radiation
- If T reaches a few $\times 10^6$ K → emits X-rays
- accreted material + initial angular momentum → form a disk around the BH : accretion disk (강착원반) = X-ray source

https://apod.nasa.gov/apod/ap080811.html



Introductory Astronomy and Astrophysics (4th edition)
Michael Zeilik & Stephen A. Gregory (1998), p. 348

- X-ray sources : good candidates for BHs