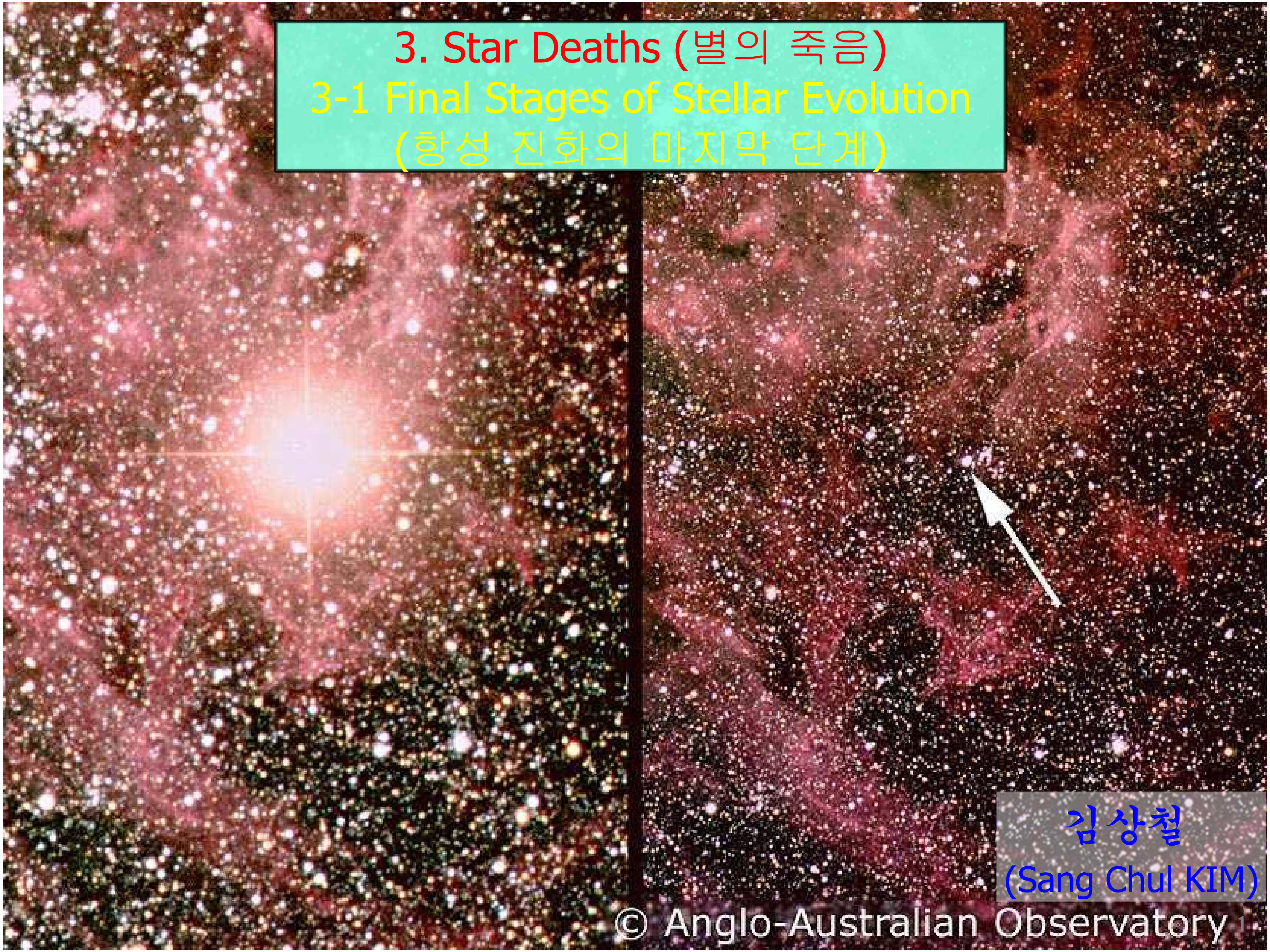
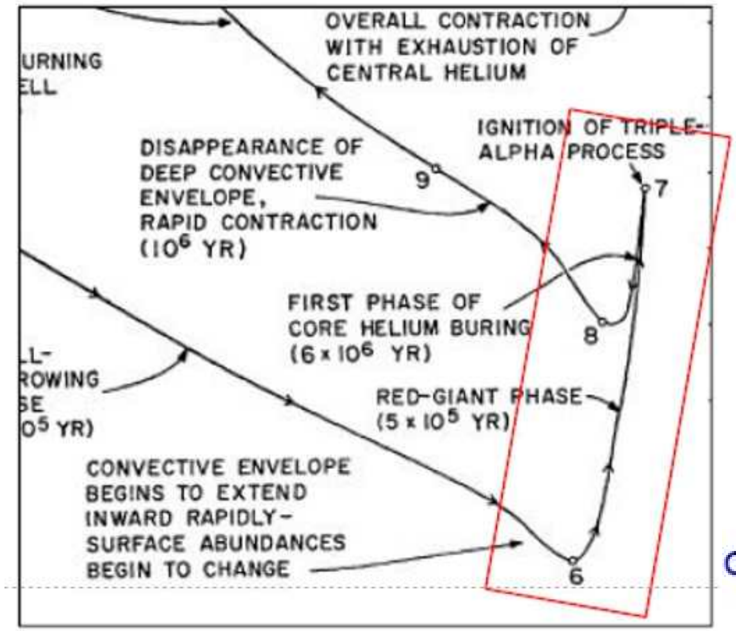
3. Star Deaths (별의 죽음)

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) $\wedge$ Shell – H-b

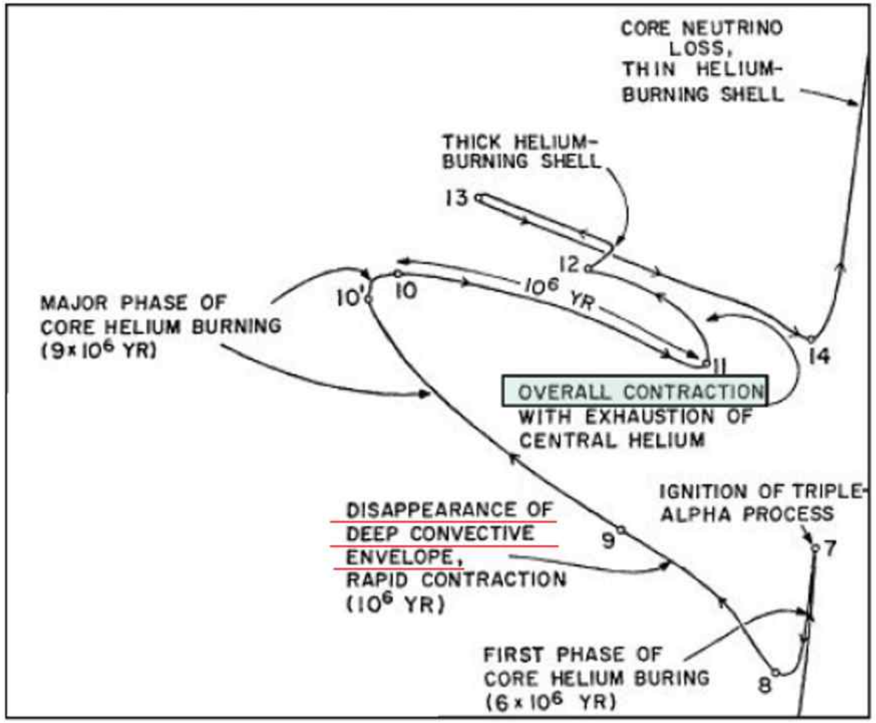
In the core,
new source of E → core expands and cools
→Shell E-output ↓
(7 → 8) →L ↓

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

- Core He-b continues →

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

Horizontal Branch (HB) stage : core He-b

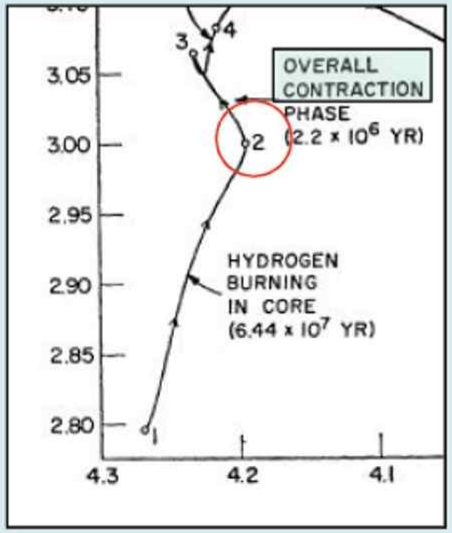


- At point 10'
: core mean-molecular weight increases enough
→ core contracts + envelope expands and **cools**
R↑ **T**↓

→ L ↓

- At point 11 : core He exhausted
  → entire star contracts

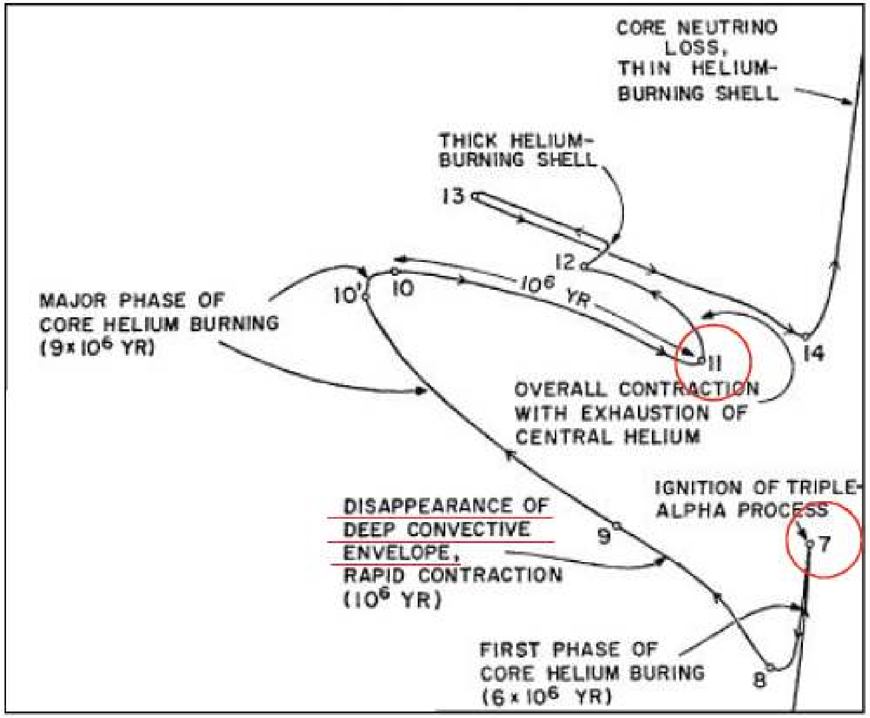
similar



End of MS phase
→ near depletion of H fuel in the core
→ overall contraction

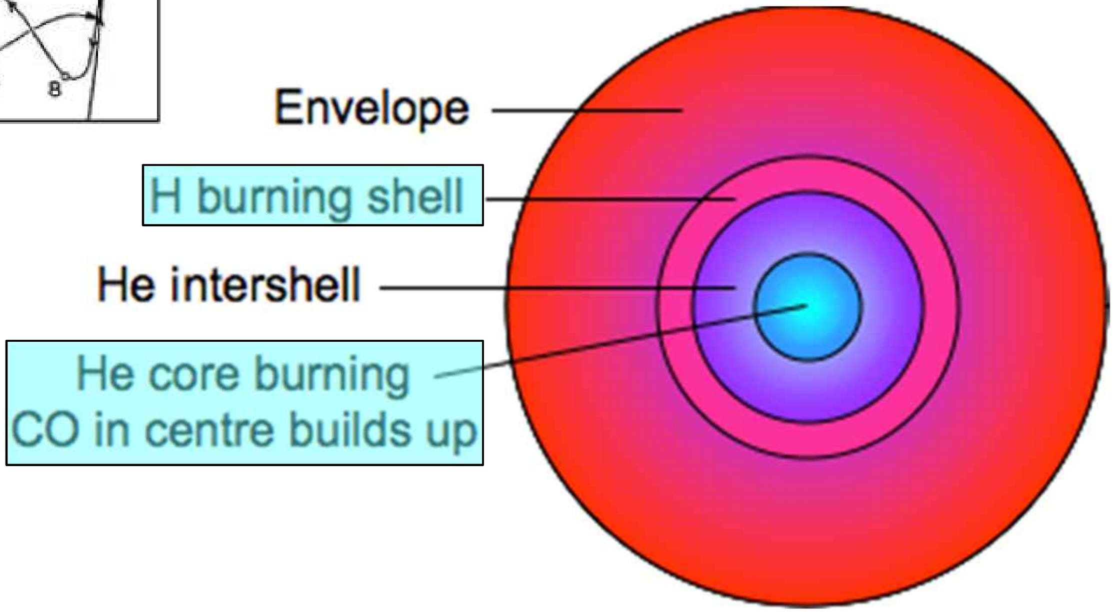
R↓ + **T**↑ → L↑

Post-MS Stellar Evolution



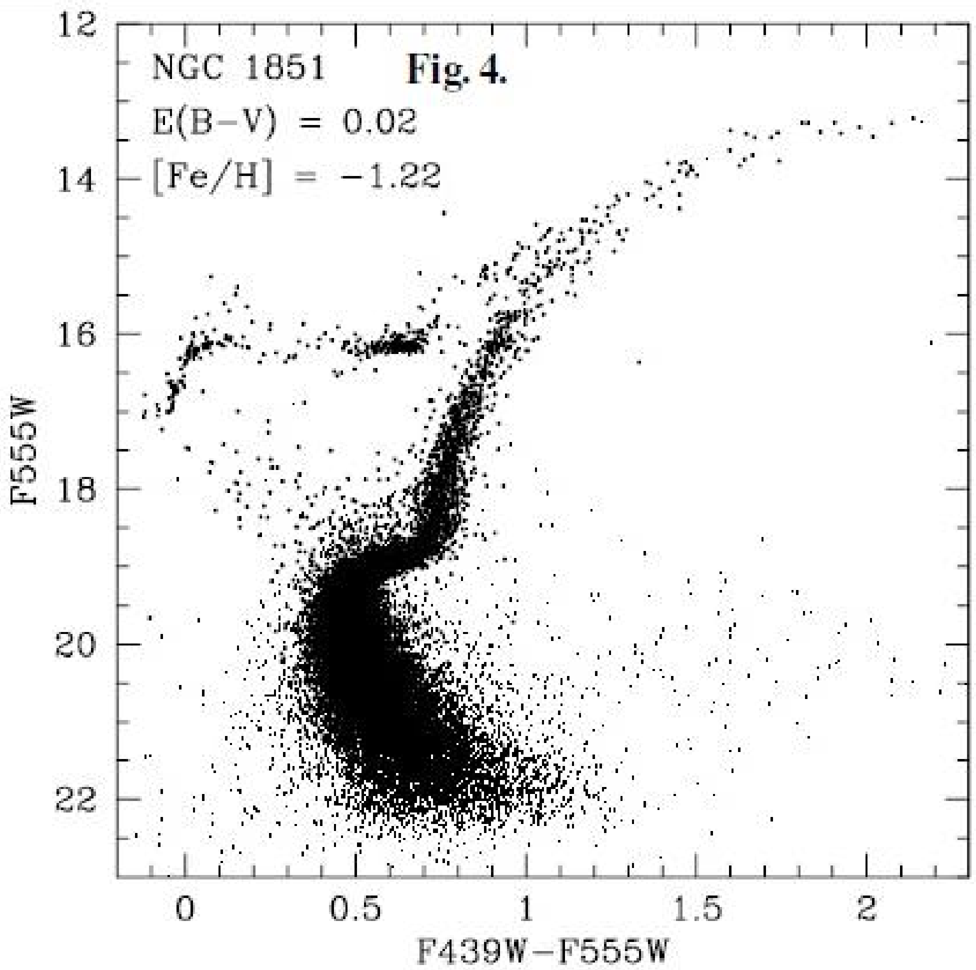
7-11 : generally horizontal evolution
"Horizontal branch (HB)"

He-b core + H-b shell

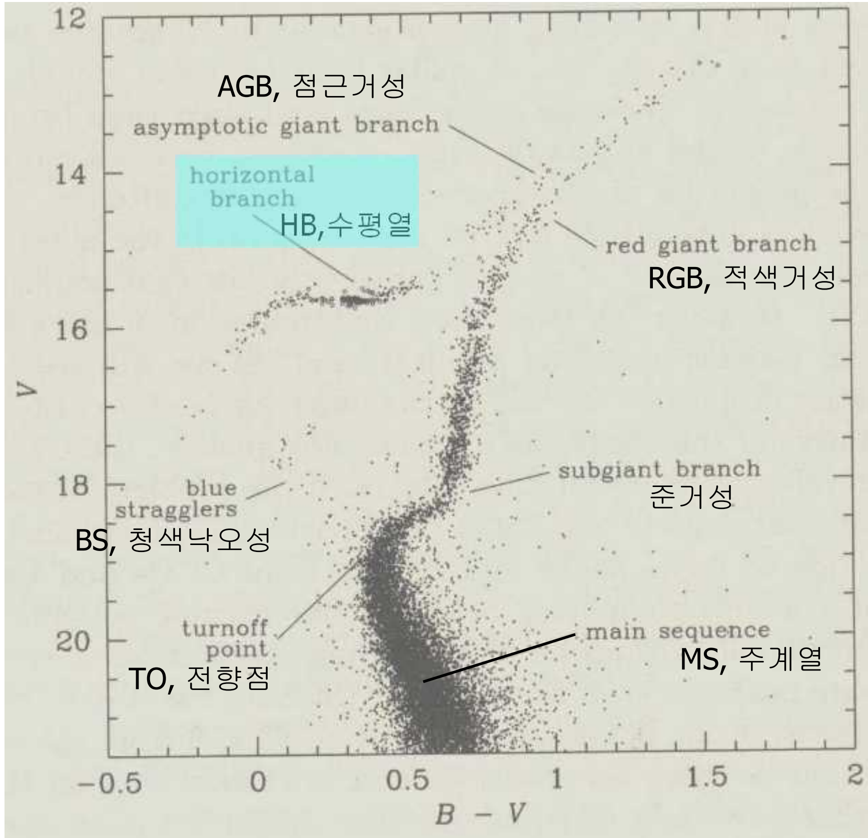


https://astronomy.swin.edu.au/cosmos/H/Horizontal+Branch+stars

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

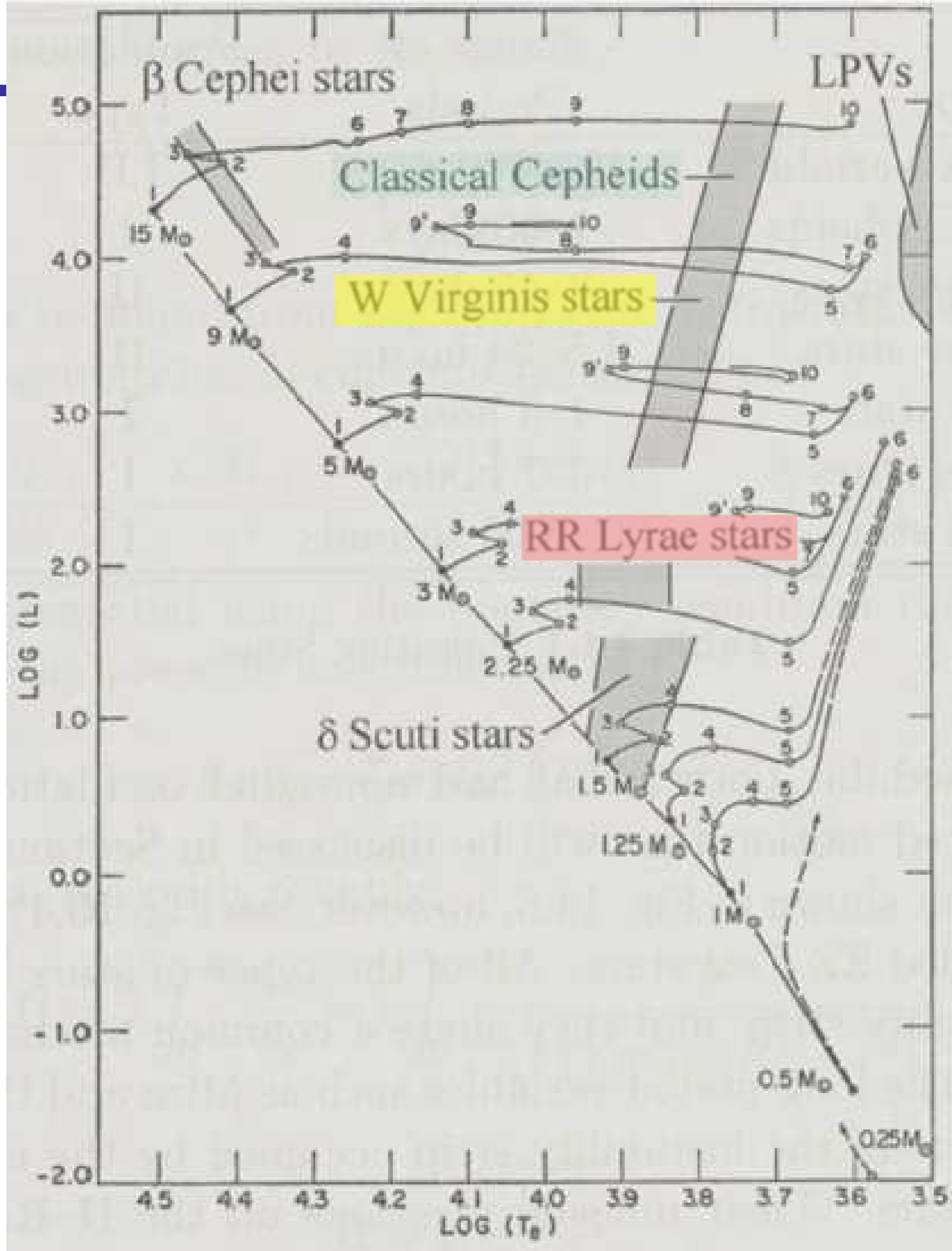
HB stars in the instability strip (IS) = RR Lyrae stars
→Instabilities in outer envelope
→Periodic pulsations
→Variations in L, T, R, surface radial vel.

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 !

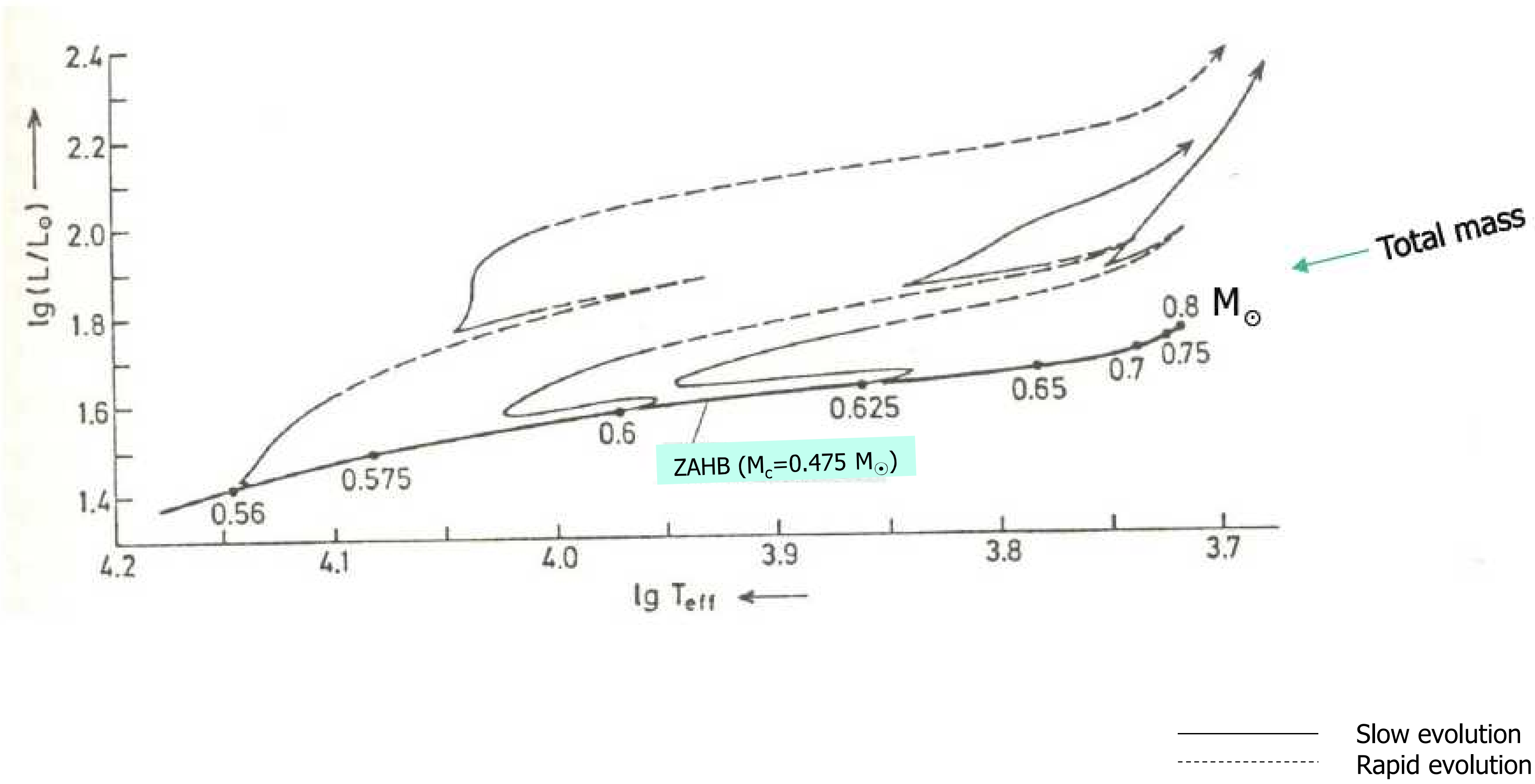


An Introduction to Modern Astrophysics (2nd edition),
Bradley W. Carroll & Dale A. Ostlie (1996), p. 547

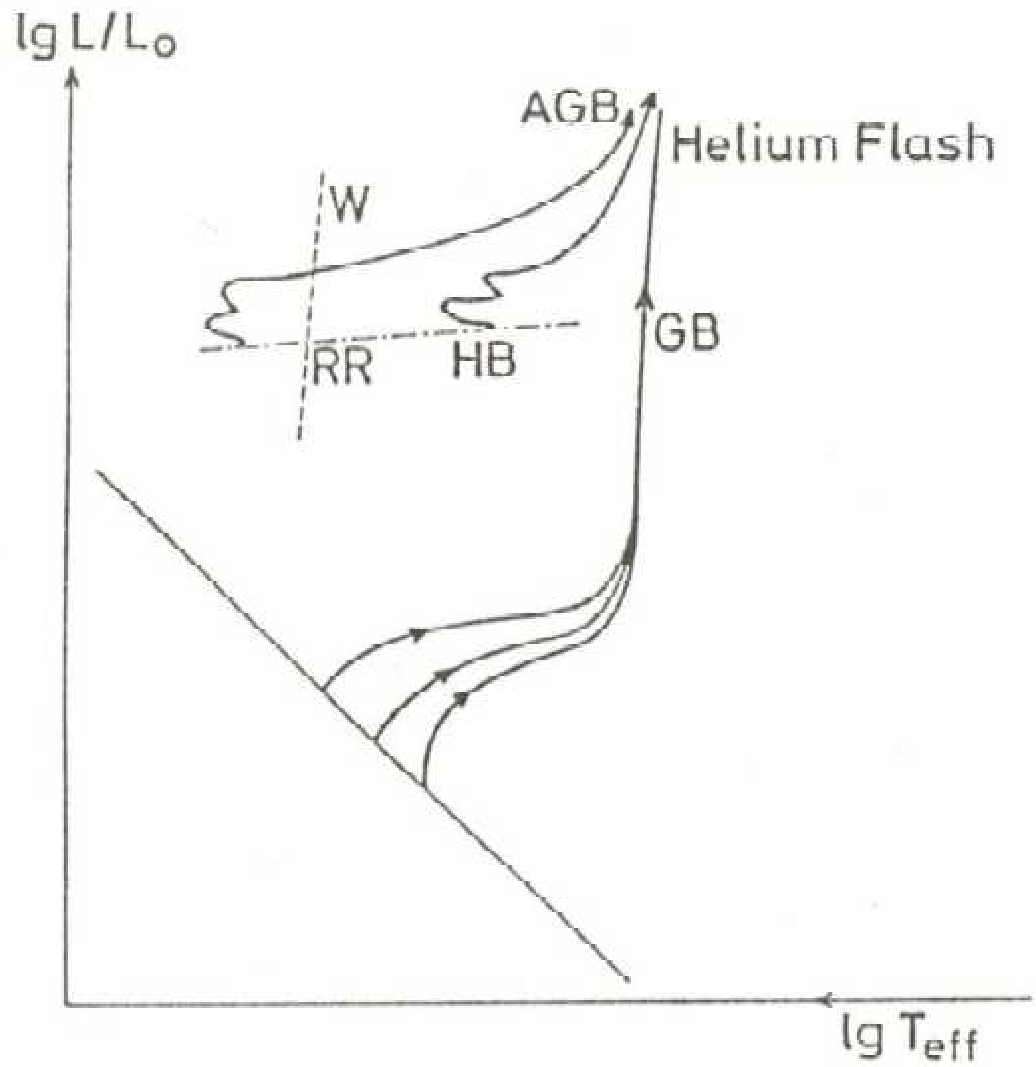
Post-HB Evolution – in HR diagram

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)



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)

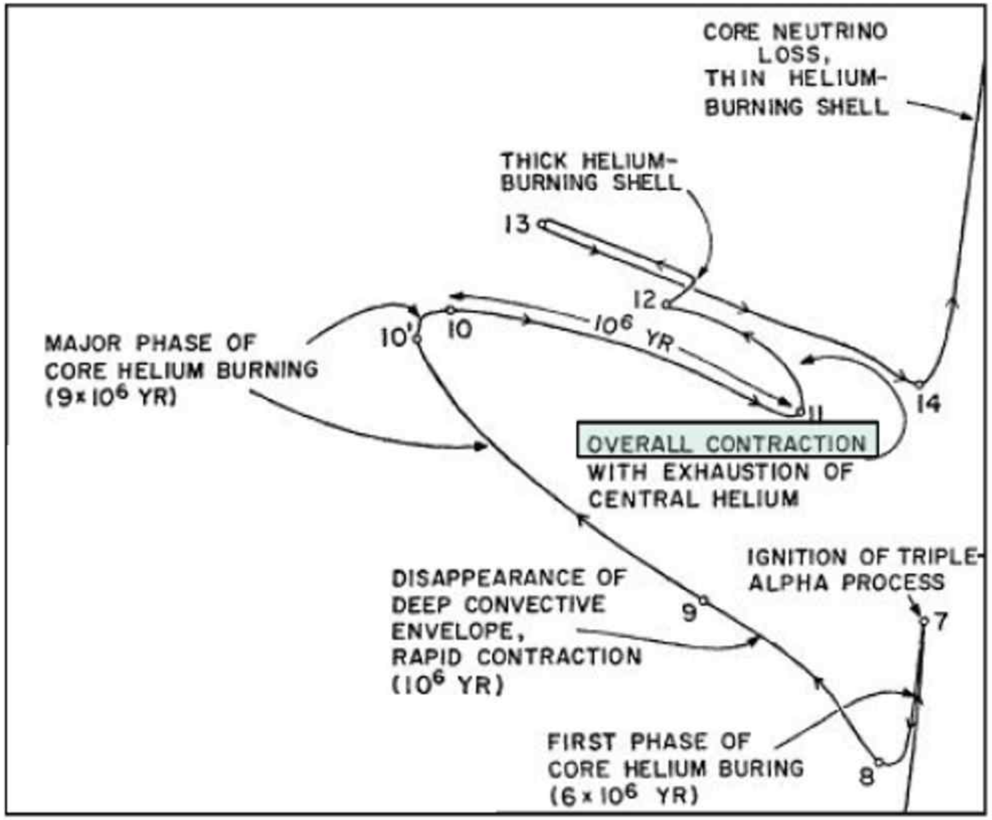
$$\langle M_V \rangle = (0.16 \pm 0.03)[\mathrm{Fe/H}] + 1.02 \pm 0.03 \qquad (5.24)$$

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

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

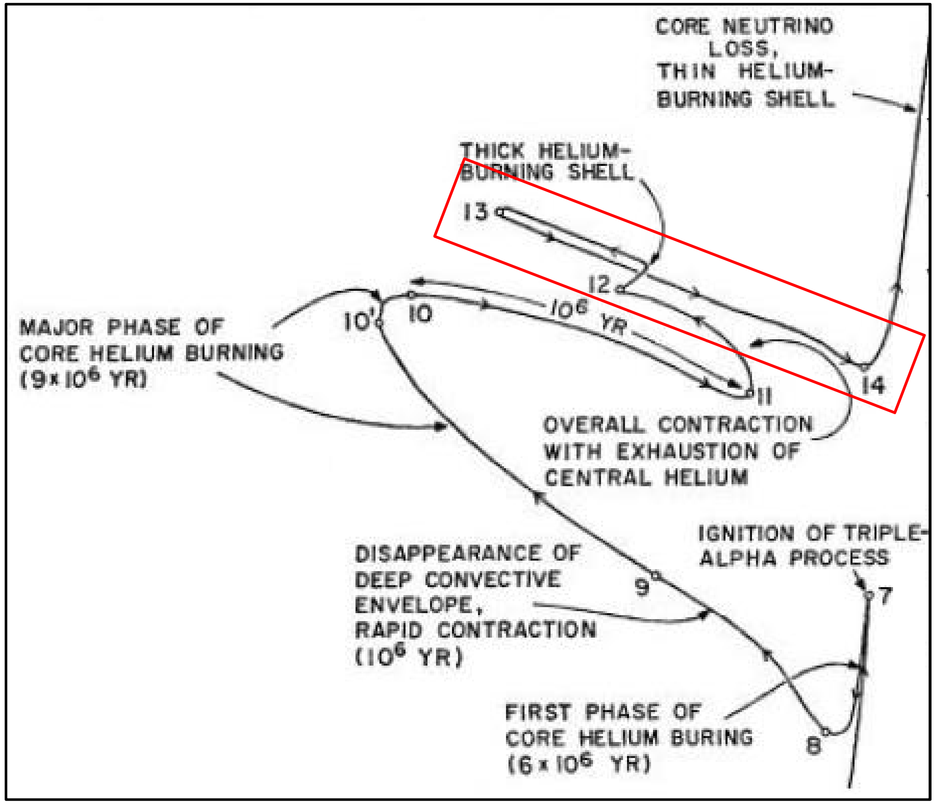
Galactic Astronomy (James Binney and Michael Merrifield, 1998) p. 296

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

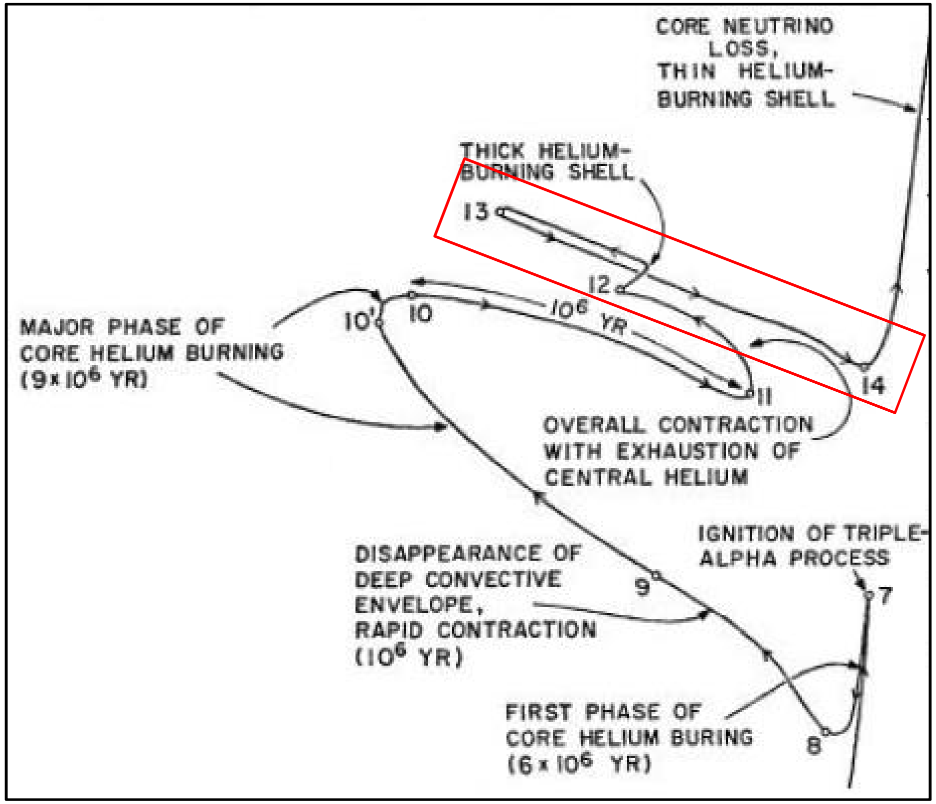
- T ↓ → convective envelope deepens again (extending downward to the chemical discontinuity between the H-rich outer layers and the He-rich region above He-b shell)

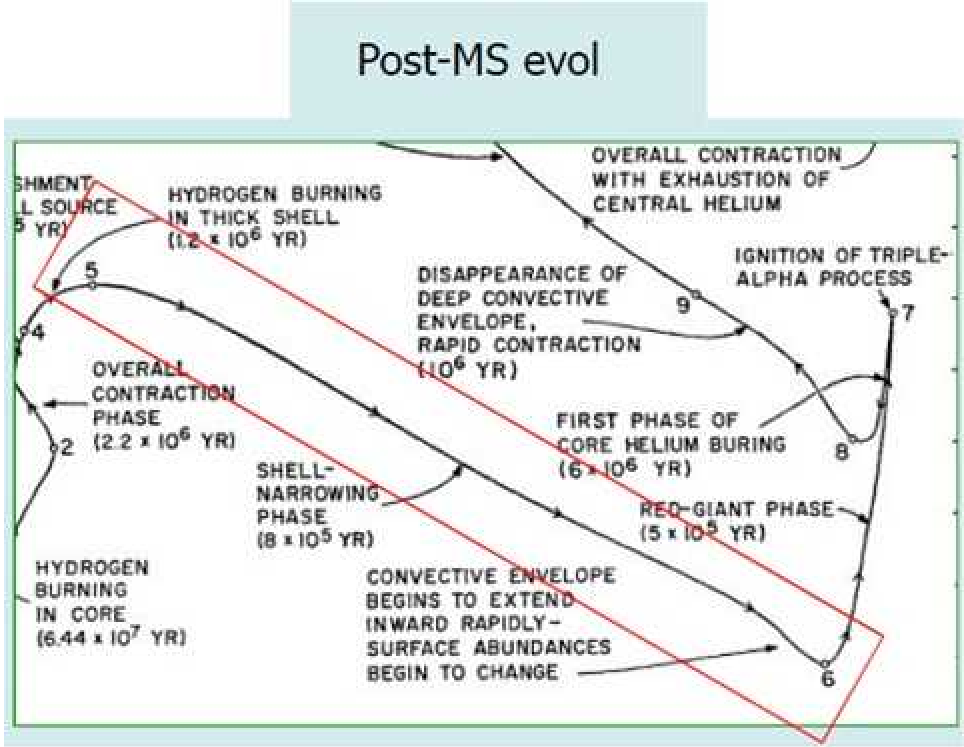
→ Mixing = **second dredge-up**

→ Increases He-, N-content of the envelope

Early-AGB (E-AGB)

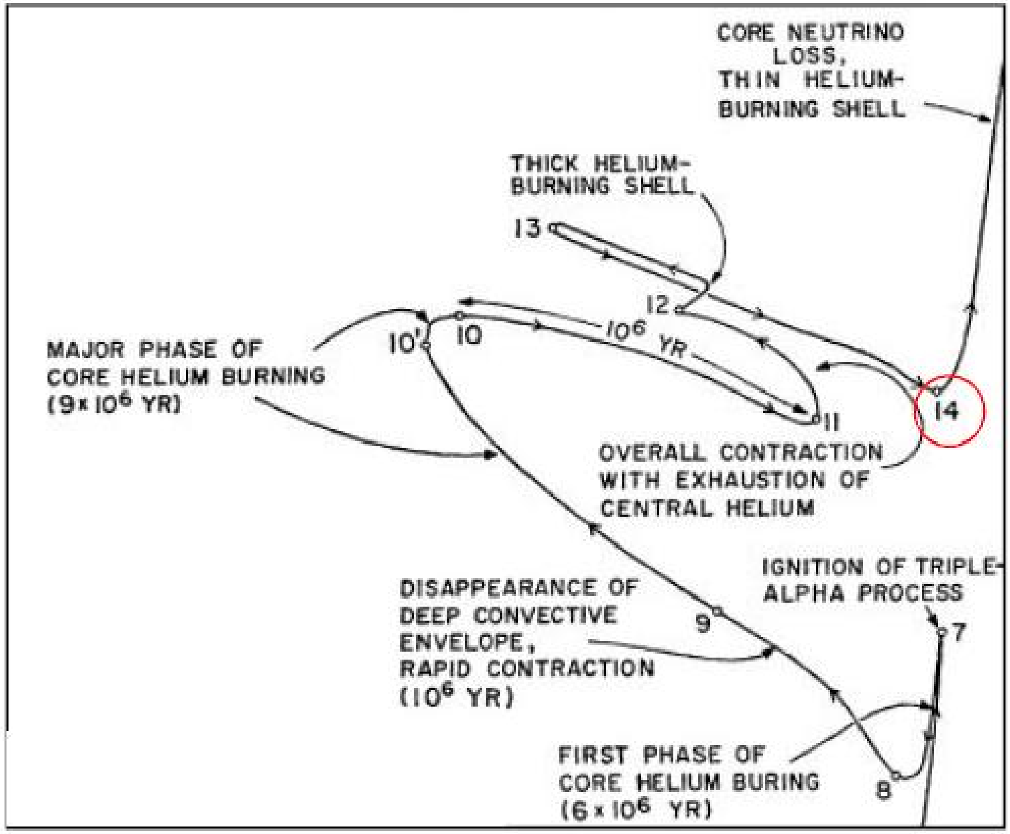
(13→14 →) similar to (5 → 6 →)





An Introduction to Modern Astrophysics (2nd edition), Bradley W. Carroll & Dale A. Ostlie (1996), p. 500

Early-AGB (E-AGB)



asymptotic giant branch (AGB)

At near point 14 :

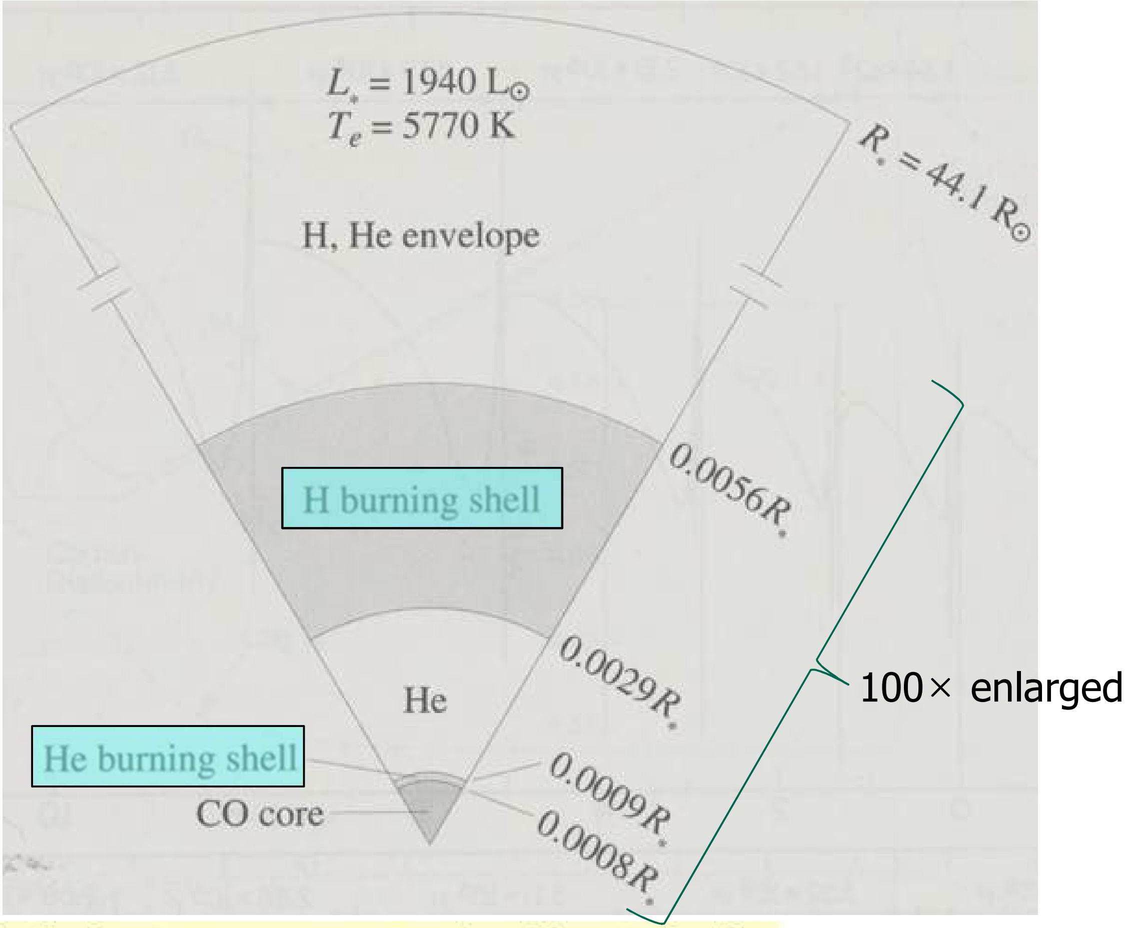
$T_c \sim 2 \times 10^8$ K, $\rho_c \sim 10^6$ g/cm^3

Interior structure at point 14 →

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

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)

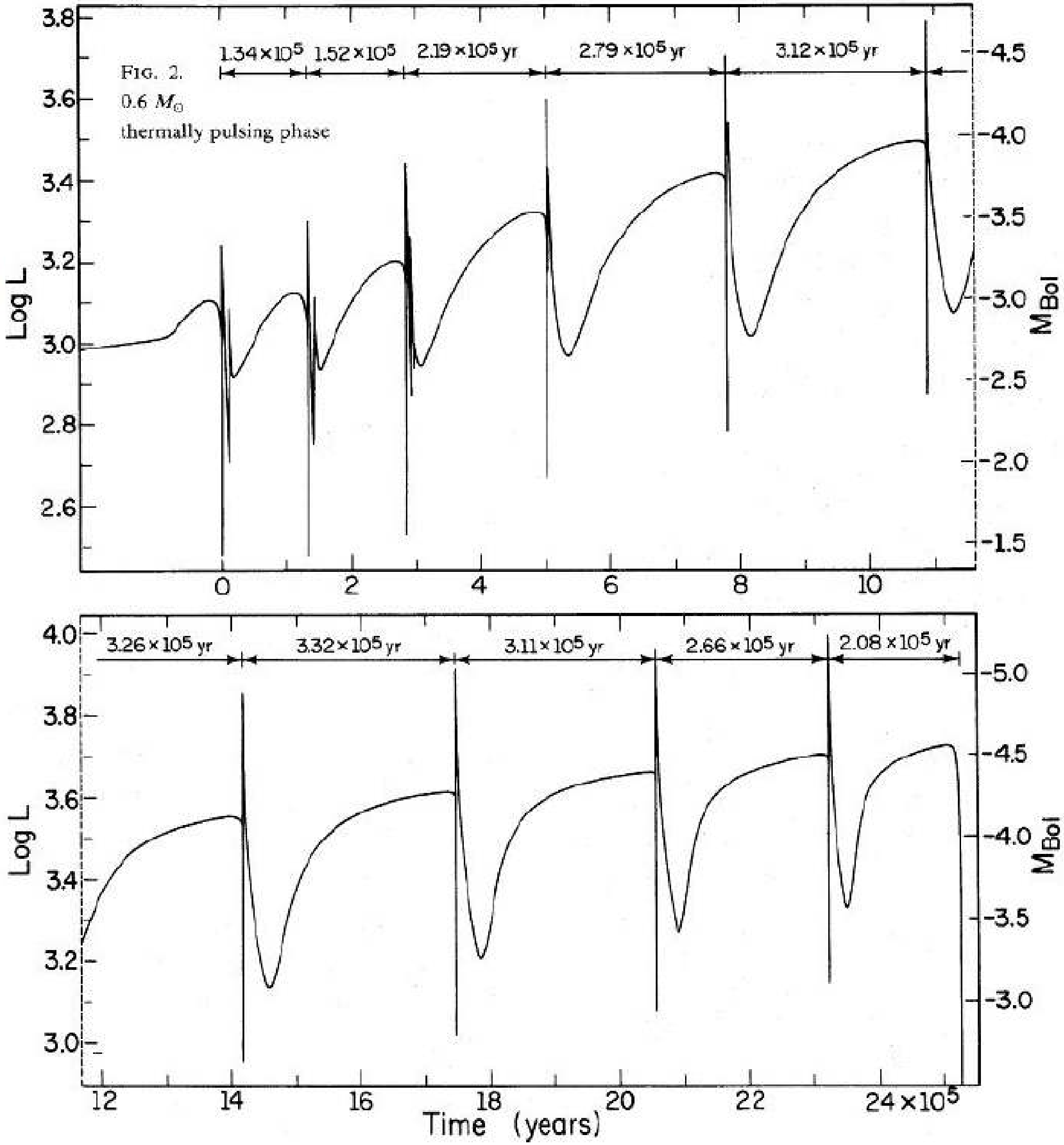
→ Drives H-b shell outward → cool, turn-off for a time

→ Convection between the two shells → H-shell T↑ and 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 ~ $8\ M_\odot$

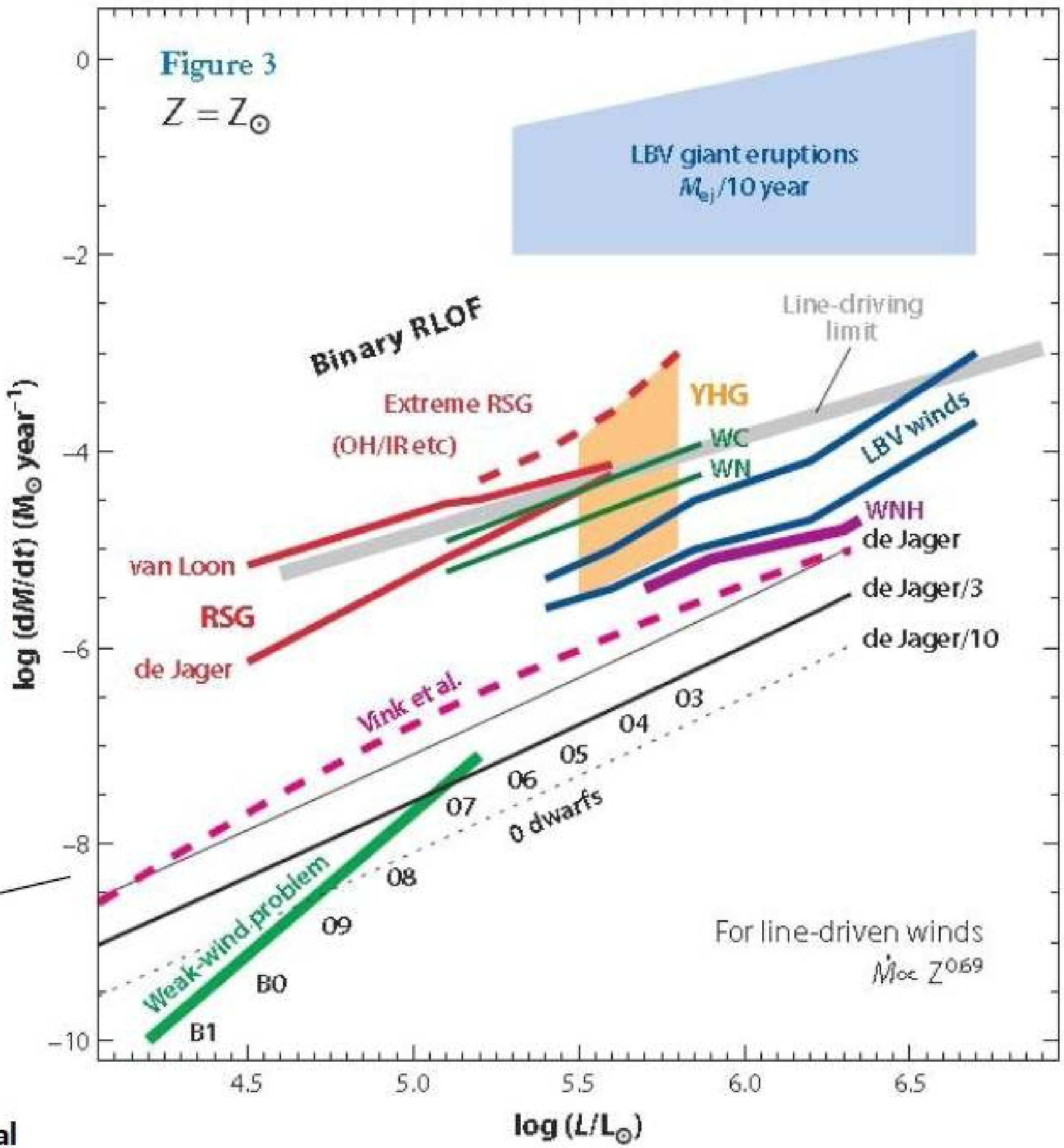
AGB – mass loss

- 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

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

$M_i < 4\ M_\odot$ → no CO-burning
$4 < M/M_\odot < 8$, if no mass-loss → CO-core mass increase → catastrophic core-collapse

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

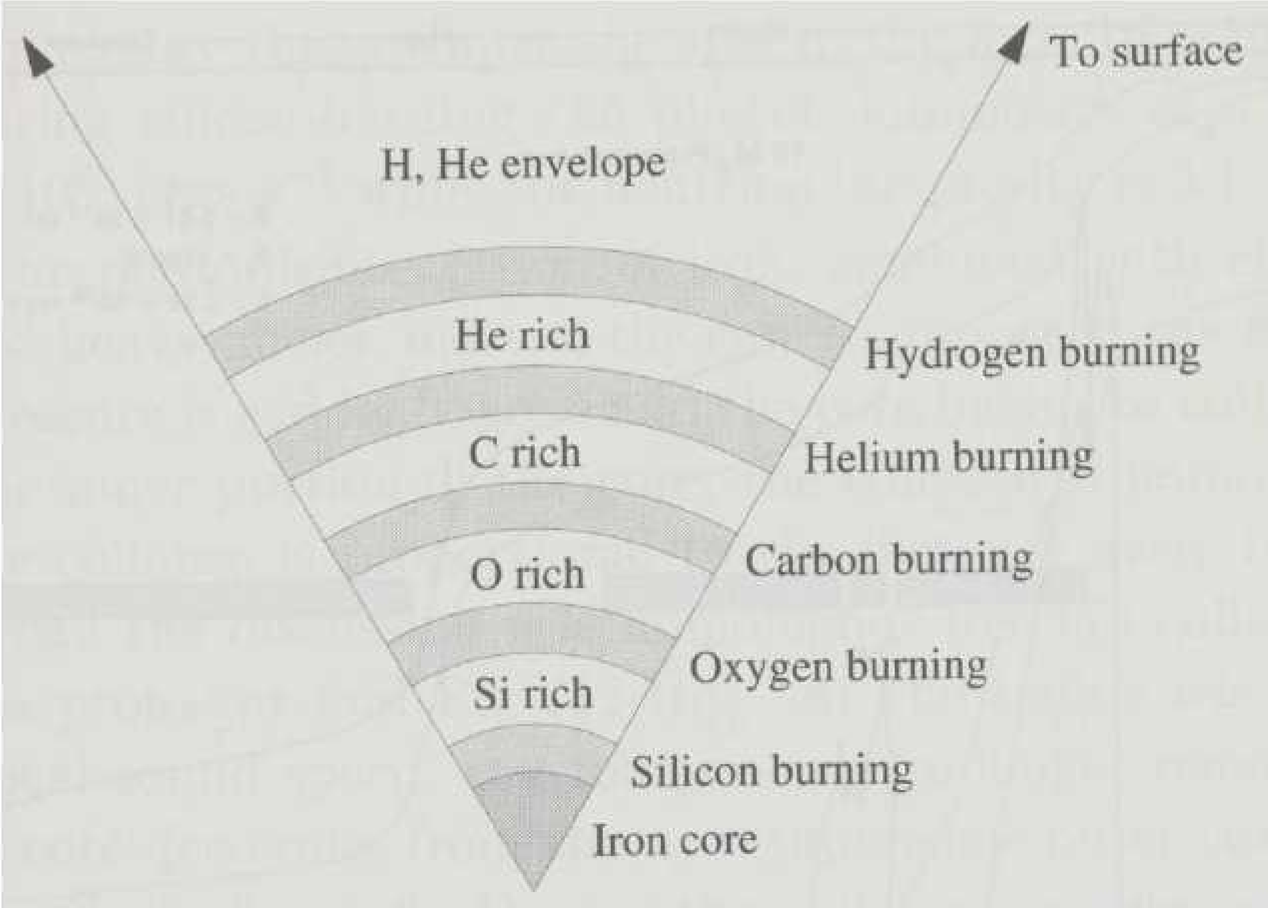
Making iron(${}^{56}_{26}Fe$)-peak elements, like ${}^{54}_{26}Fe$, ${}^{56}_{26}Fe$, ${}^{56}_{28}Fe$, and finally iron-core

$50 \leq A \leq 62$

(Atomic mass)

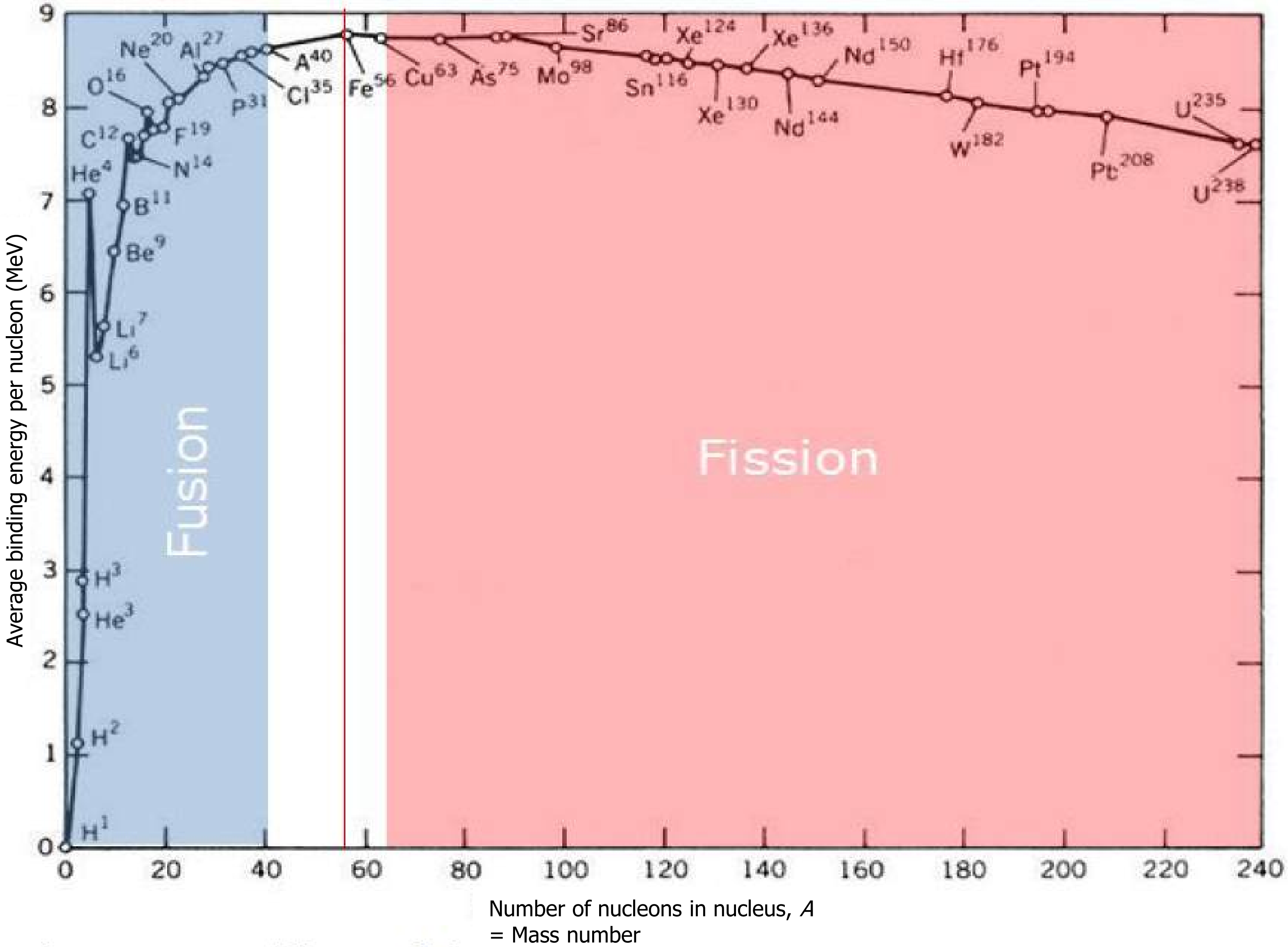
Massive (M ≥ 8 $M_\odot$) star evolution

Onion-like interior →
(not to scale)



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

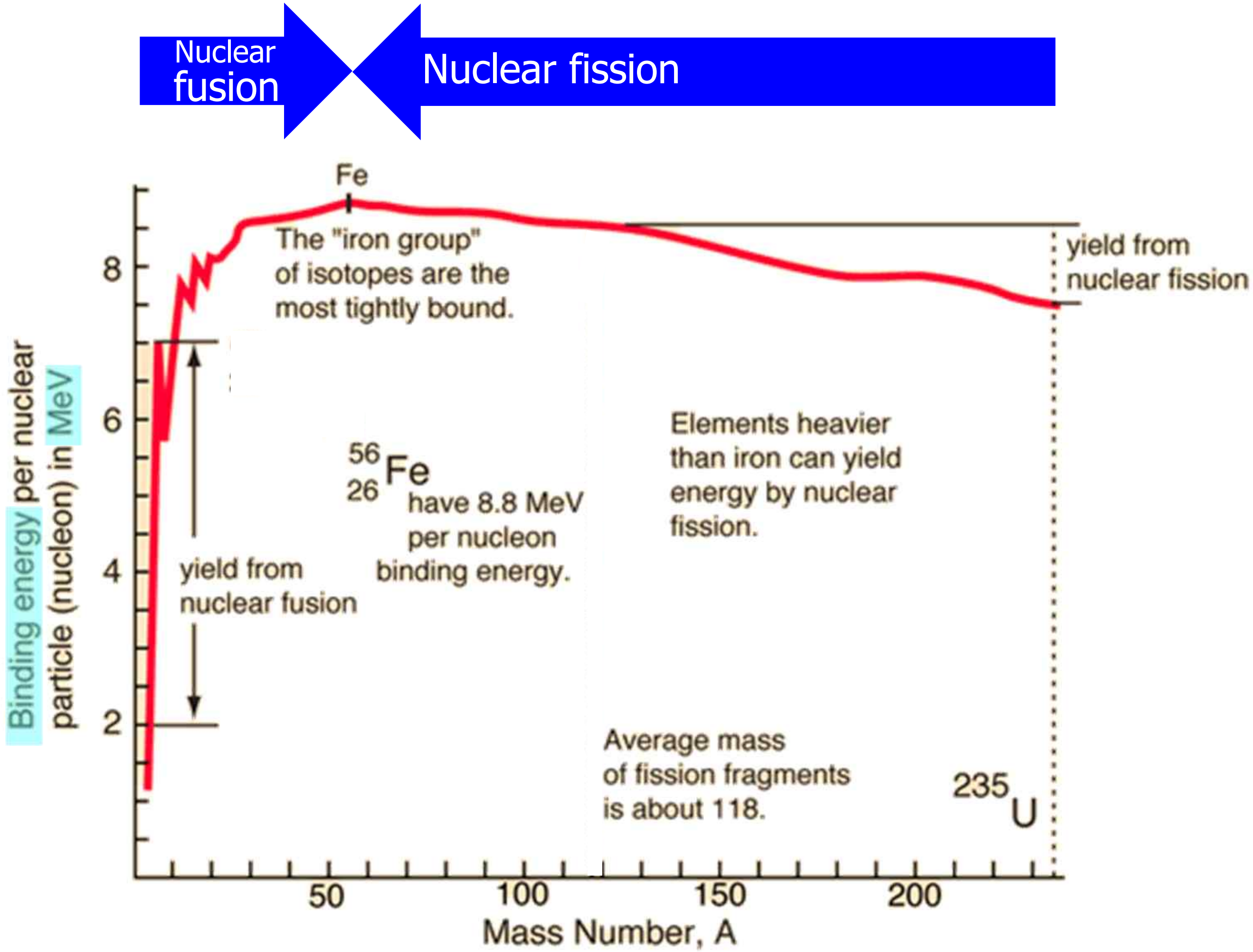
Binding energy per nuclear particle



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

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

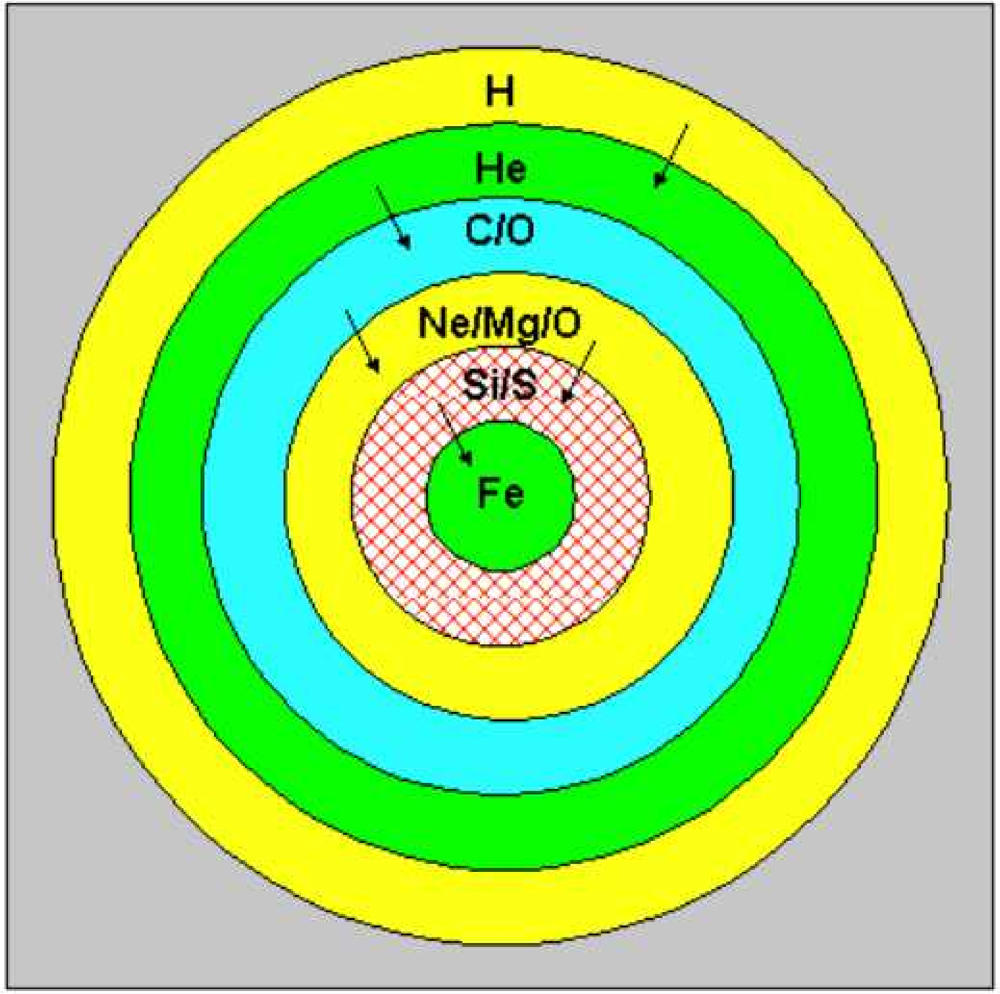
Binding energy per nucleon (E_b/A)



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

http://hyperphysics.phy-astr.gsu.edu/hbase/NucEne/nucbin.html

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

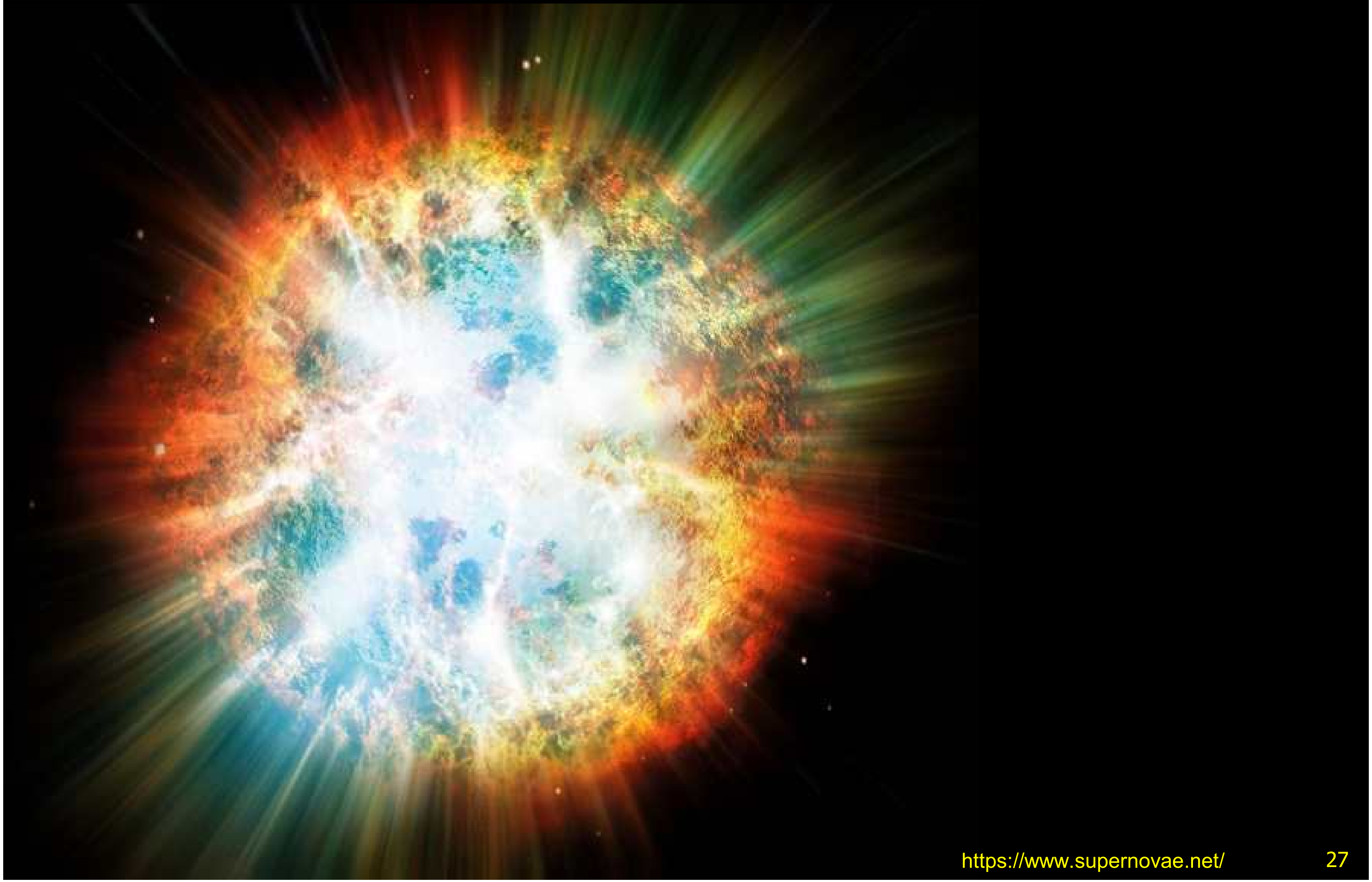
$L \geq 10^5 L_\odot$

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

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

3. Star Deaths (별의 죽음)

3-2 Supernova Explosion (초신성 폭발)



https://www.supernovae.net/

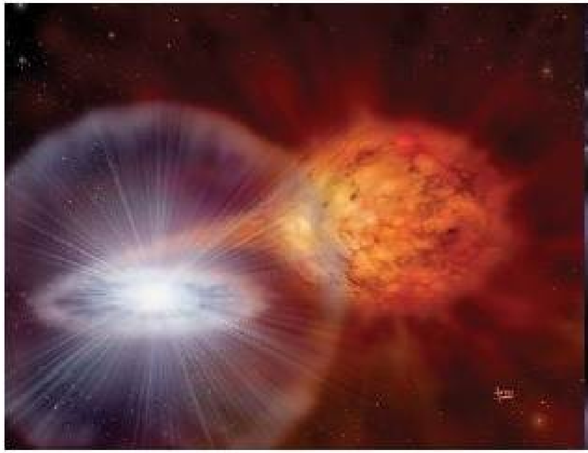
Supernova (SN) types

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

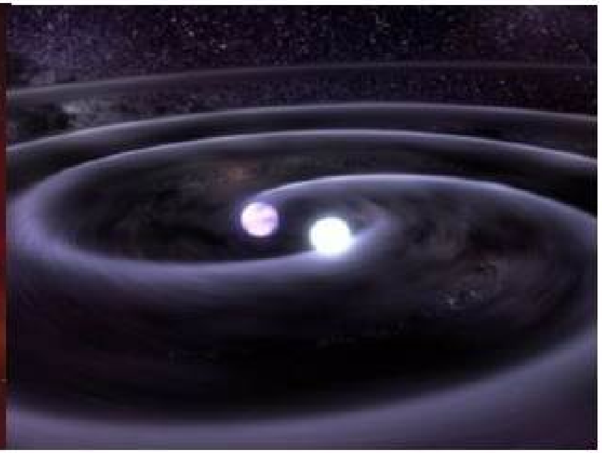
- **Typical types**

No H lines (pop II) → Type Ia Ib Ic

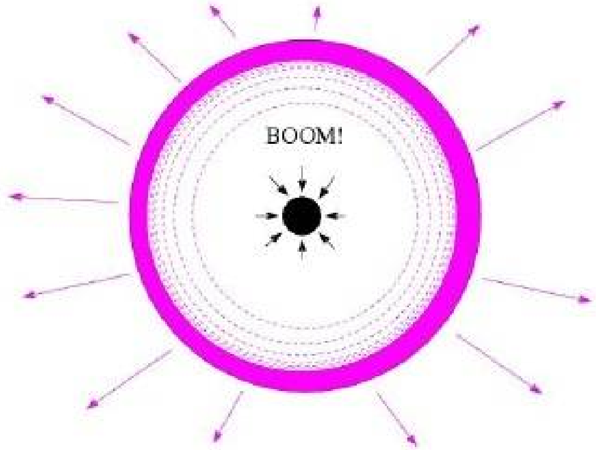
H lines (pop I) → Type II



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)

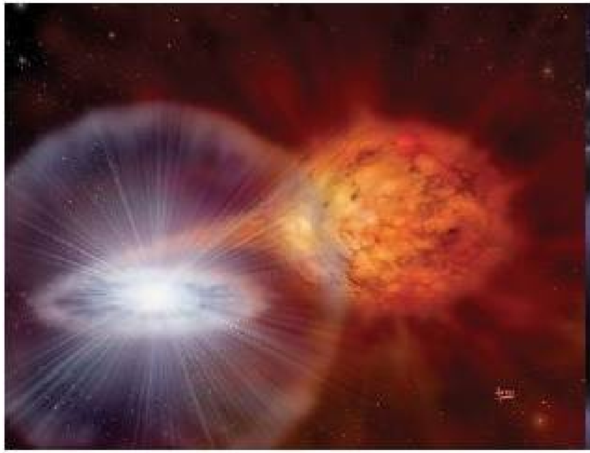
- Typical types

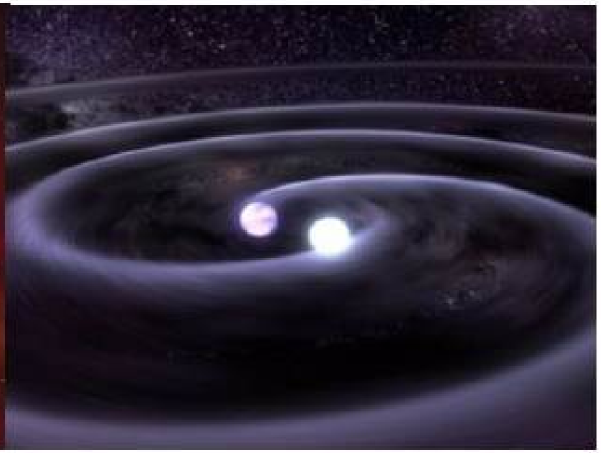
No H lines (pop II) → Type Ia

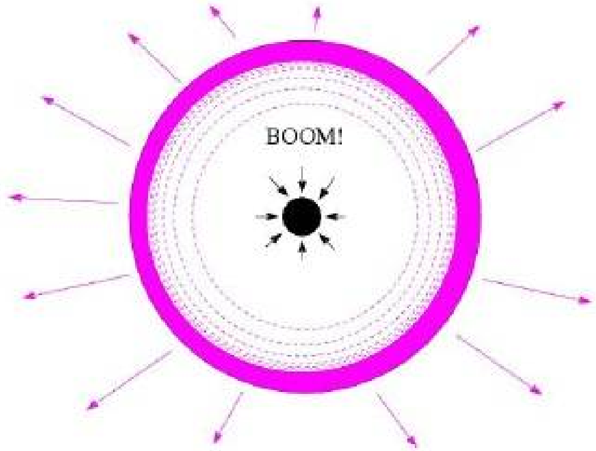
H lines (pop I) → Type II

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

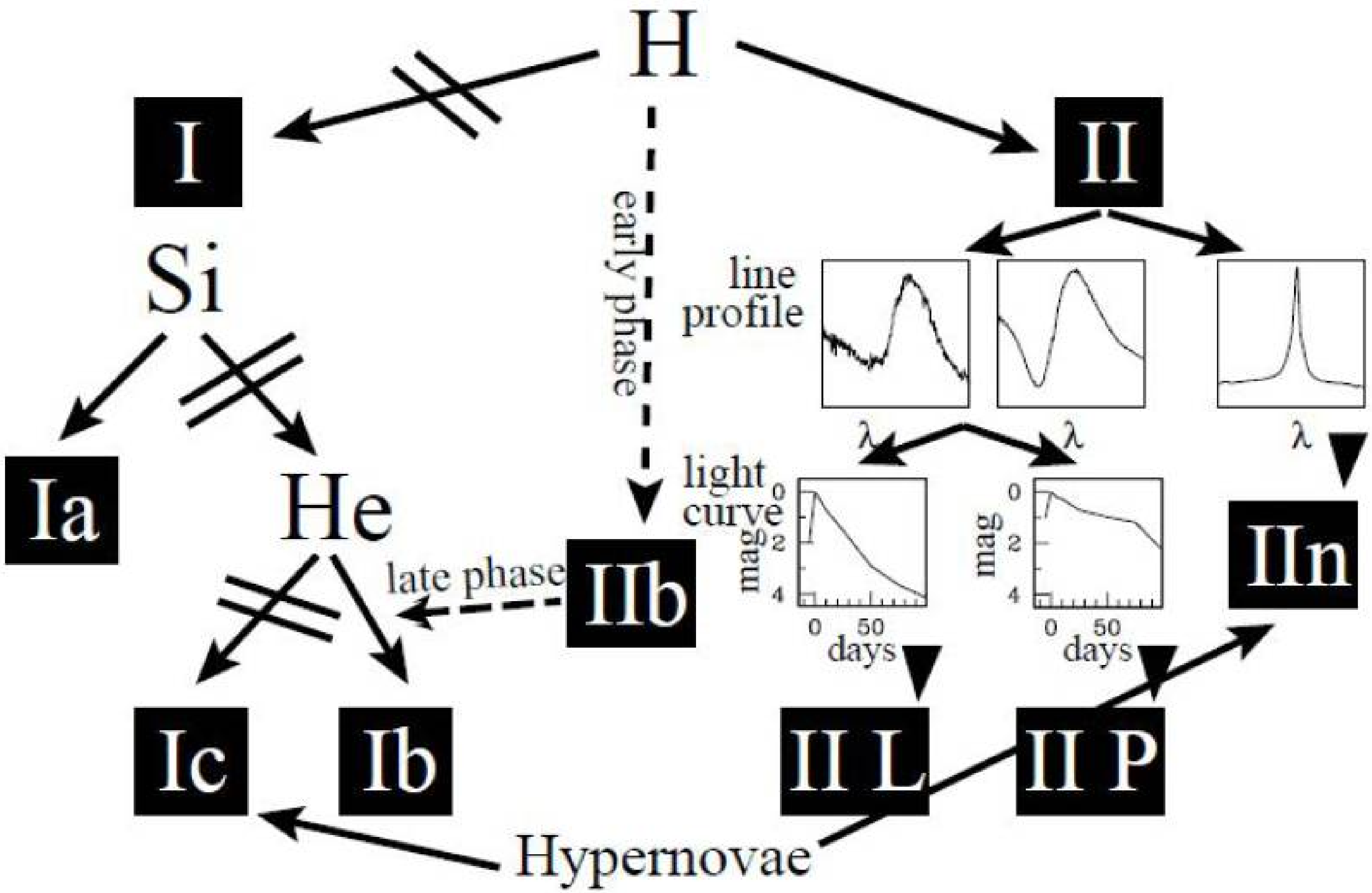
<table>
<tr><th>Type</th><th colspan="3">Sub-types</th></tr>
<tr><td rowspan="3">I
No H</td><td colspan="3">Ia
Si II (6150 Å) absorption near peak light</td></tr>
<tr><td rowspan="2">Ib/c
Weak/no Si absorption</td><td colspan="2">Ib
He I (5876 Å) emission</td></tr>
<tr><td colspan="2">Ic
Weak/no He</td></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 : (2-3)$\times 10^4$ km/s)
ultra-bright type II : ~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

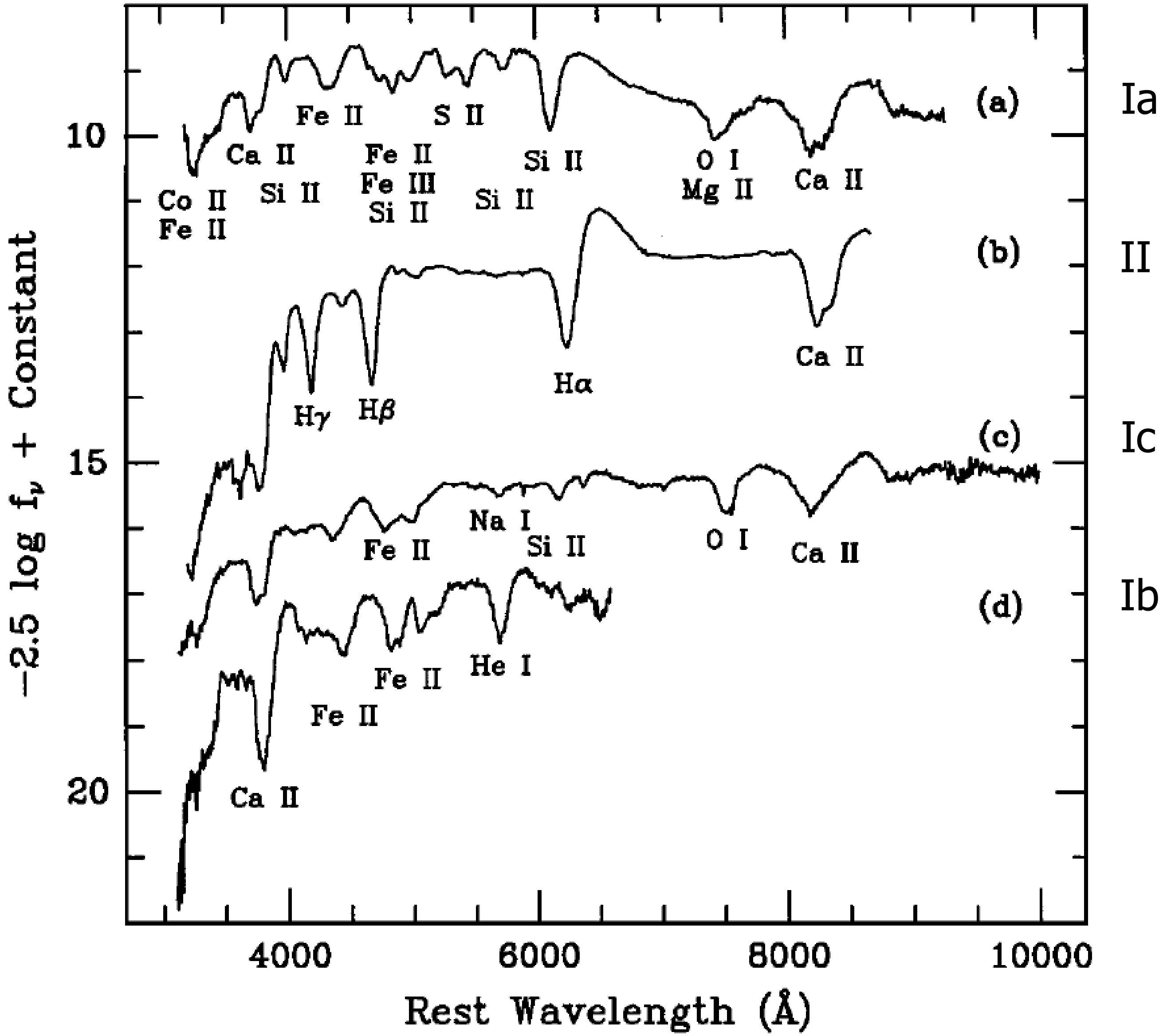
Supernova taxonomy



Cappellaro & Turatto (2000) Figure 2

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

Supernova taxonomy - spectra

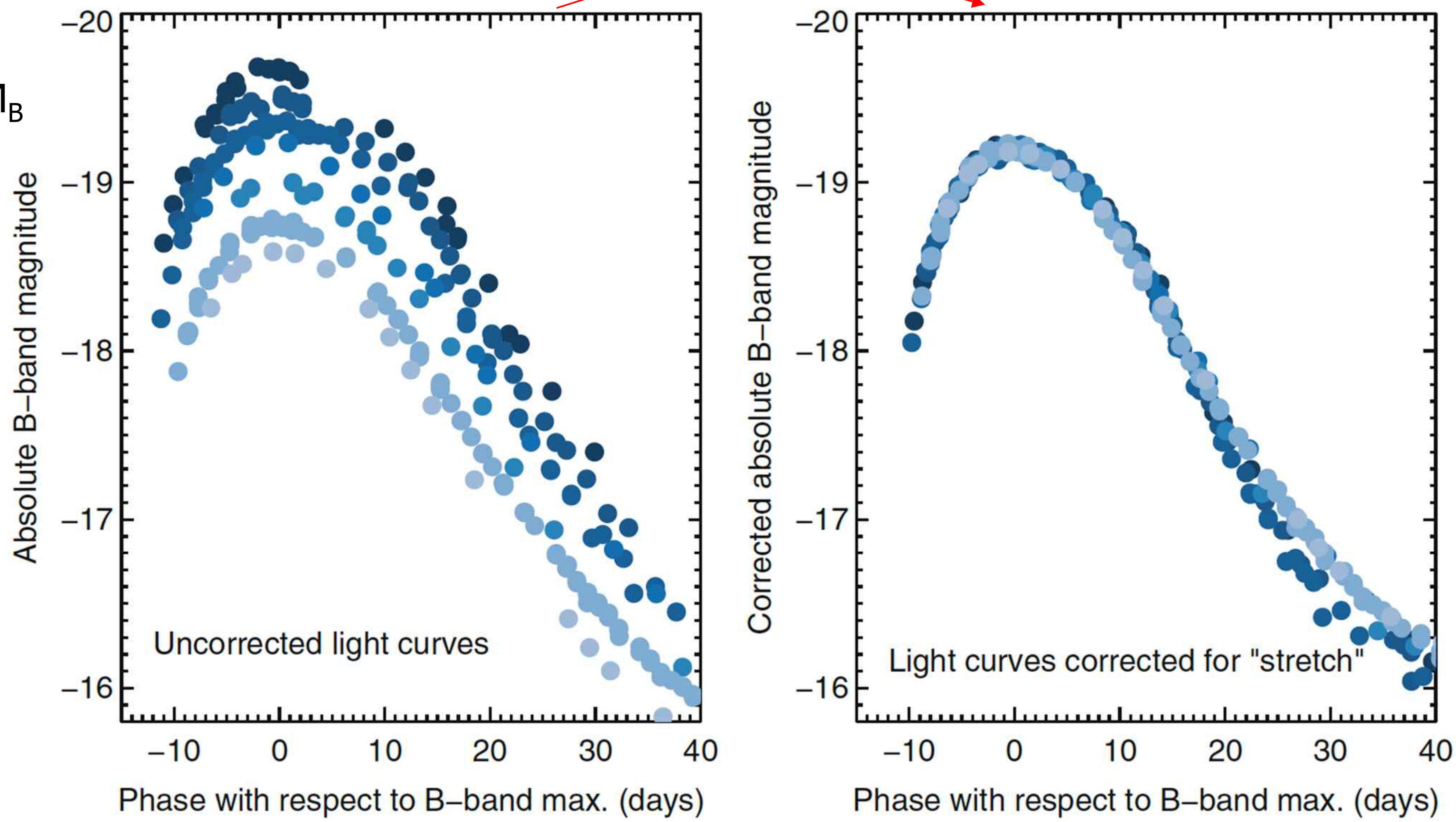


Filippenko 1997 (ARA&A 35 309)

Supernova(SN) Ia light curve (LC)

Correction (LC width-M_B relation)

M_B



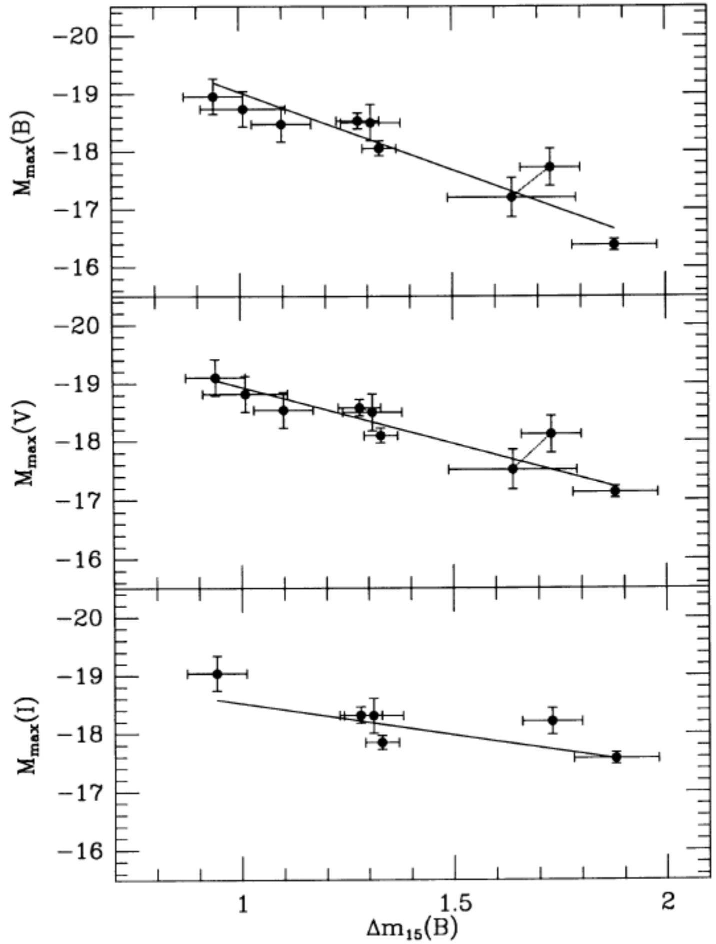
Hicken+ 09 (ApJ 700 331),
Stritzinger+11 (AJ 142 156)

Supernova(SN) Ia light curve (LC)

Correction (LC width-M_B relation)

Philips 1993 ApJL 413, L105

Peak luminosity

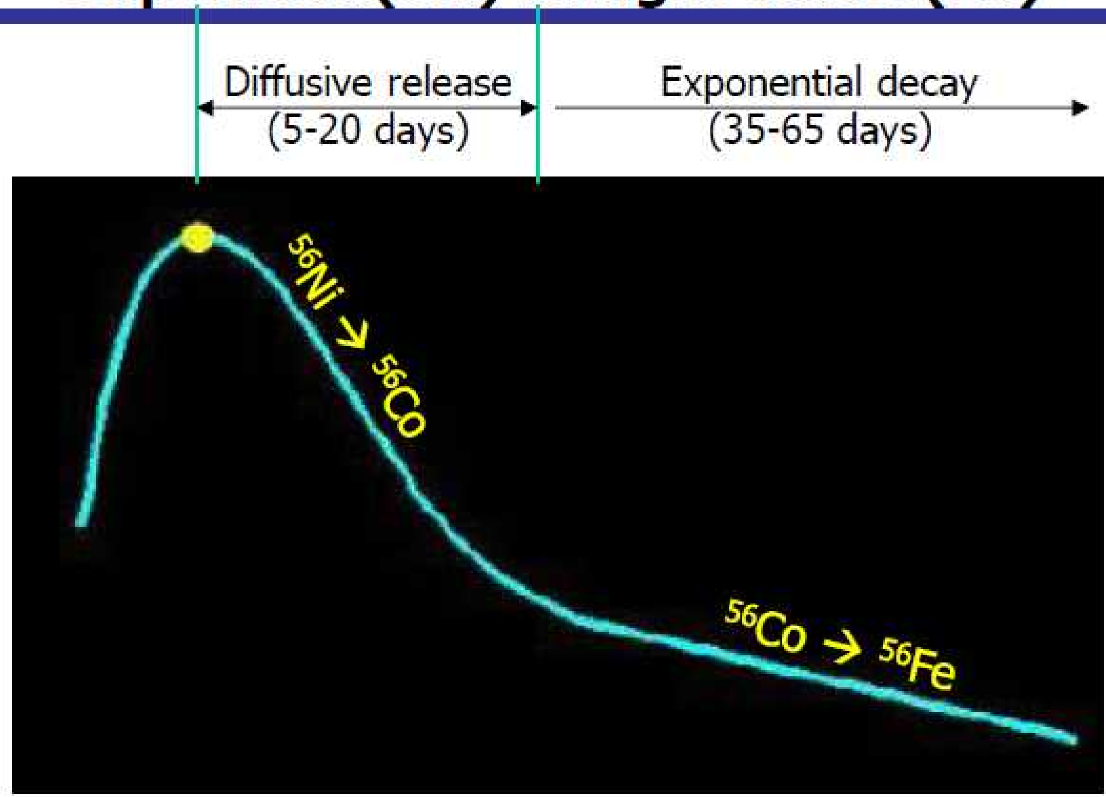


Decline rate

: 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)



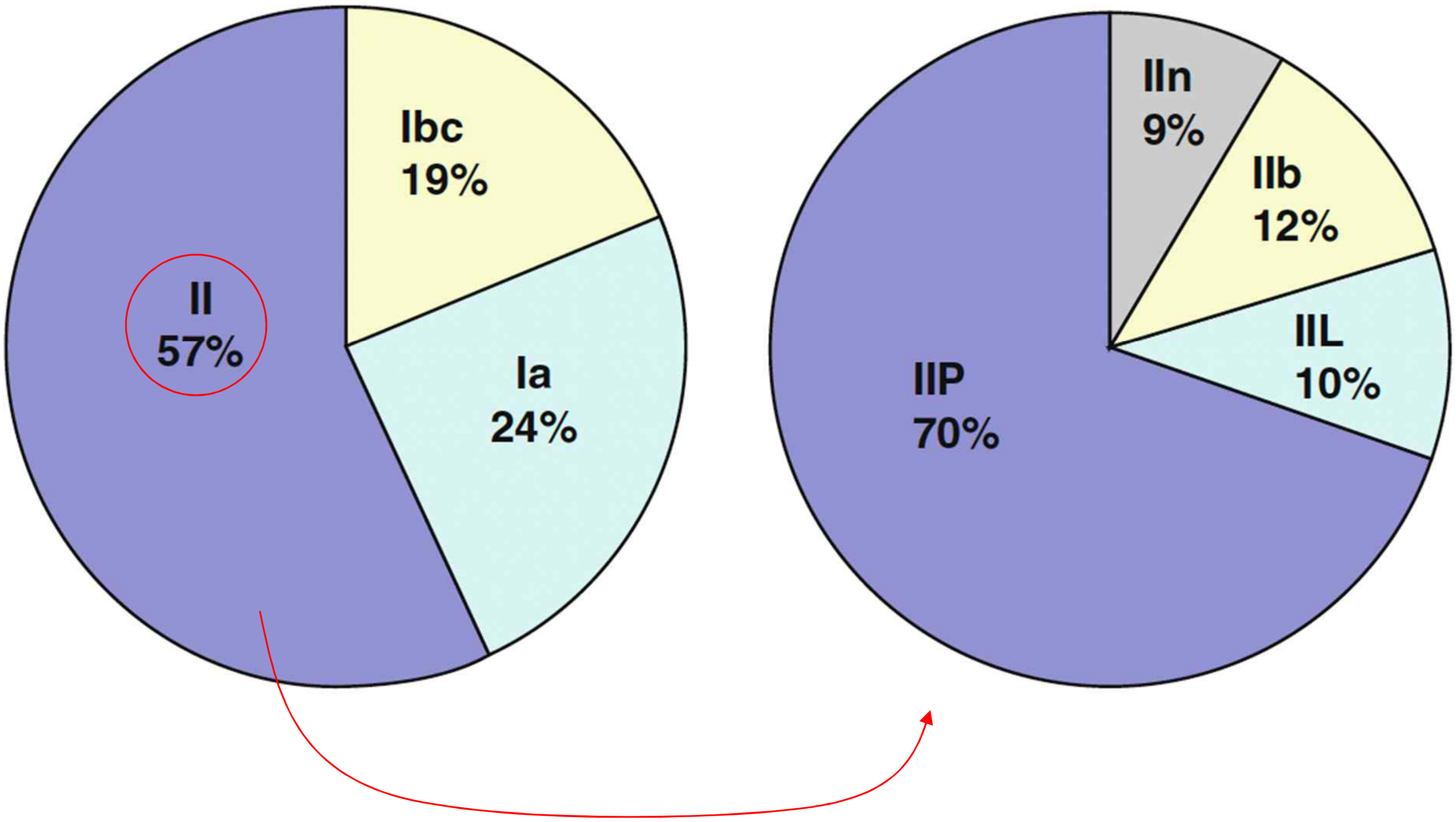
Radioactive decay of ^{56}Ni → ^{56}Co → ^{56}Fe
(Colgate & McKee 69 ApJ 157 623; Arnett 82 ApJ 253 785)

	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

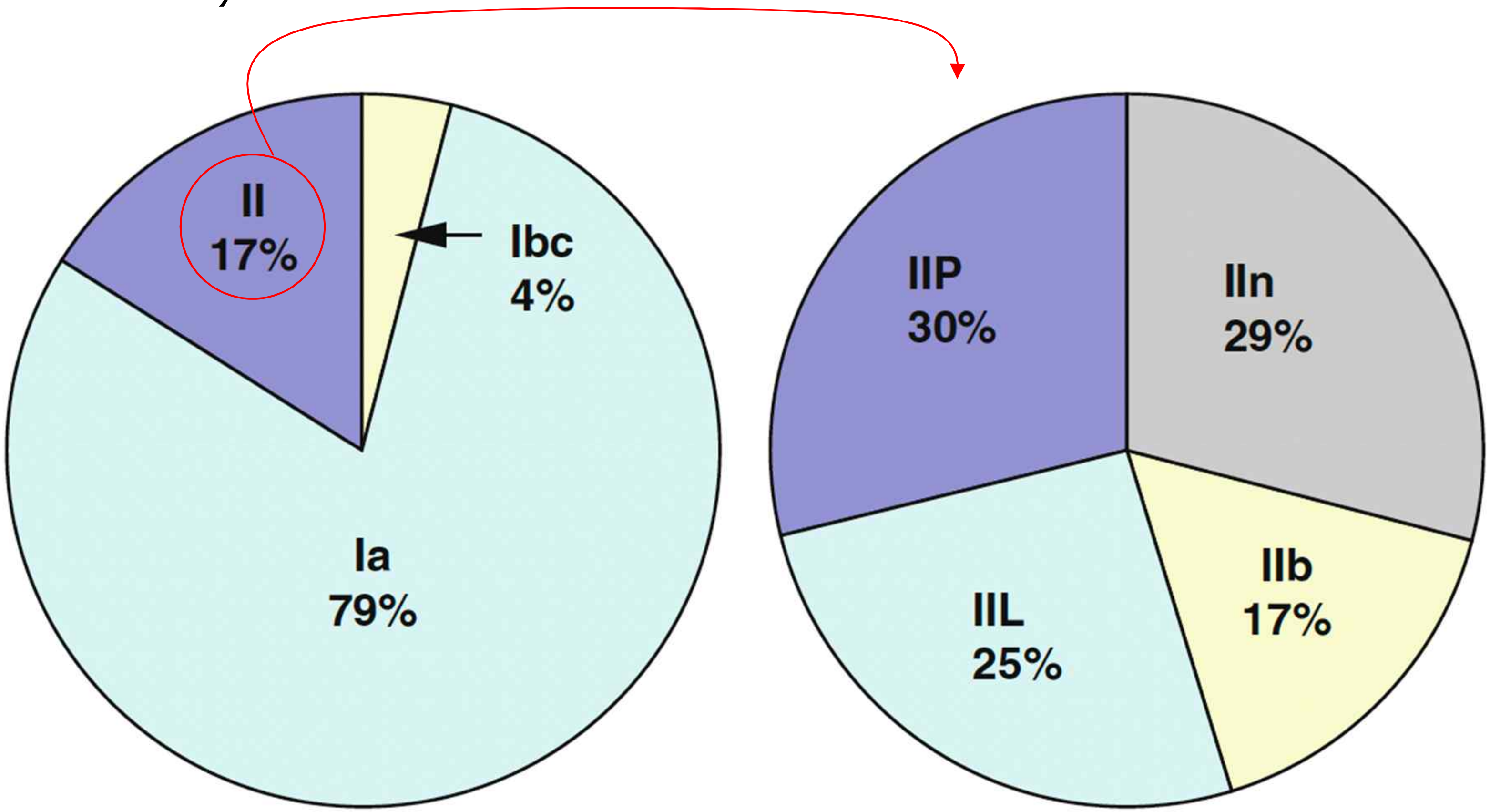
Volume-limited sample
(Intrinsic rates)



Li et al. 2011 (MN 412 1441)

SNe – number ratio

Magnitude-limited sample
(observed rates)

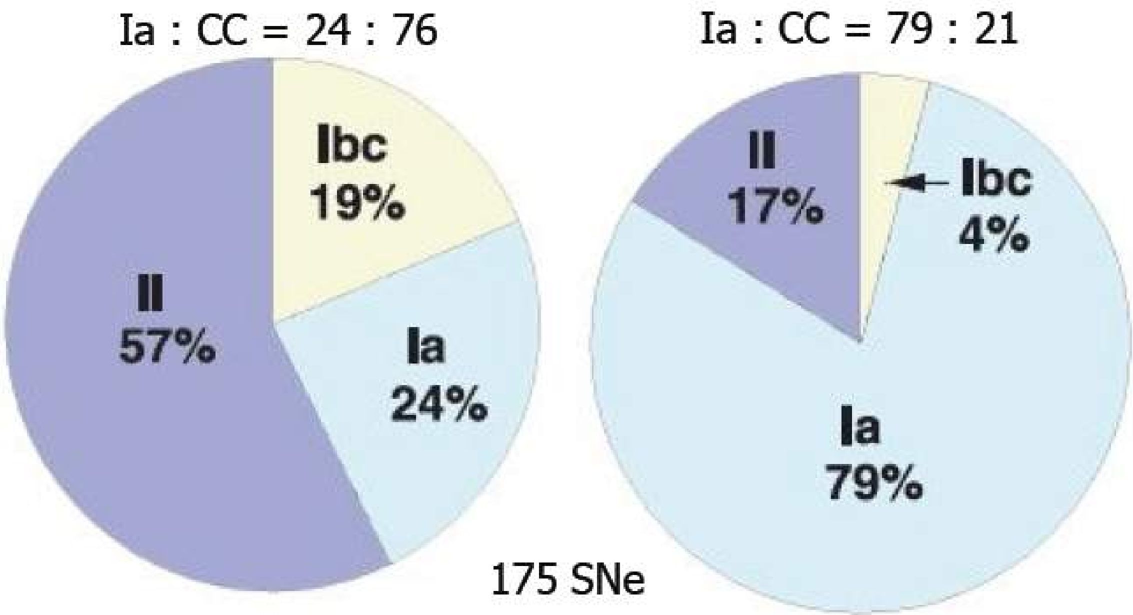


Li et al. 2011 (MN 412 1441)

SNe Ia – distance indicator

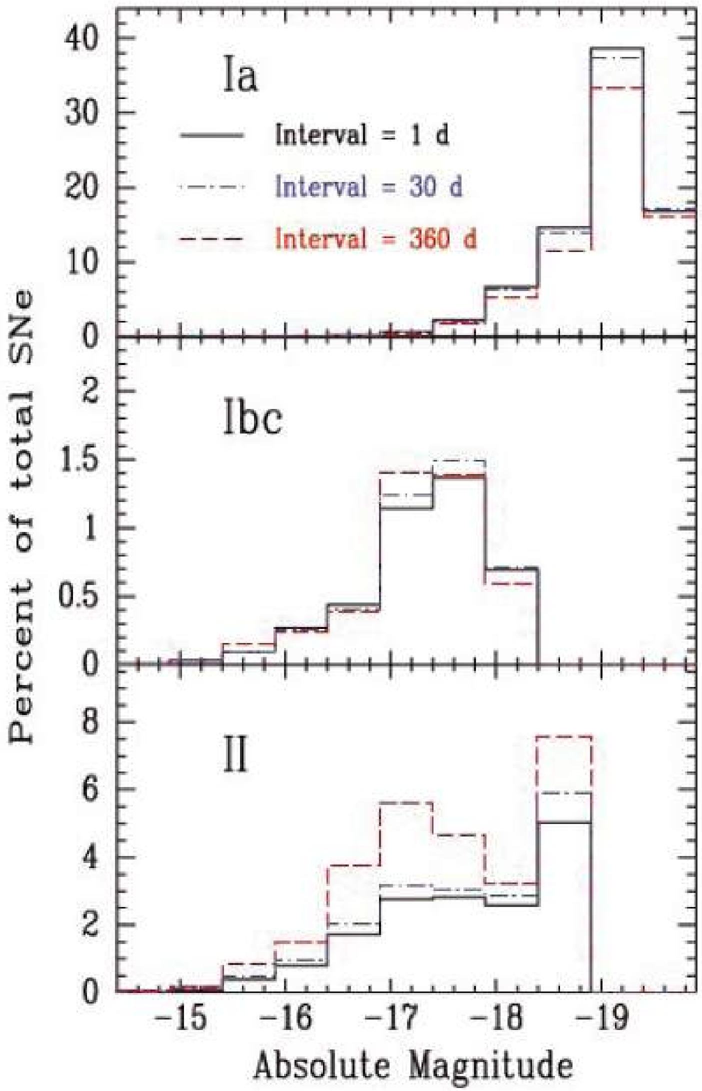
- SN Ia – maximum brightness (peak luminosity)
  $M_V \approx -19.30 \pm 0.03 + 5 \log (H_0 /60)$
- Rising time ~ 20 days

Number ratio



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

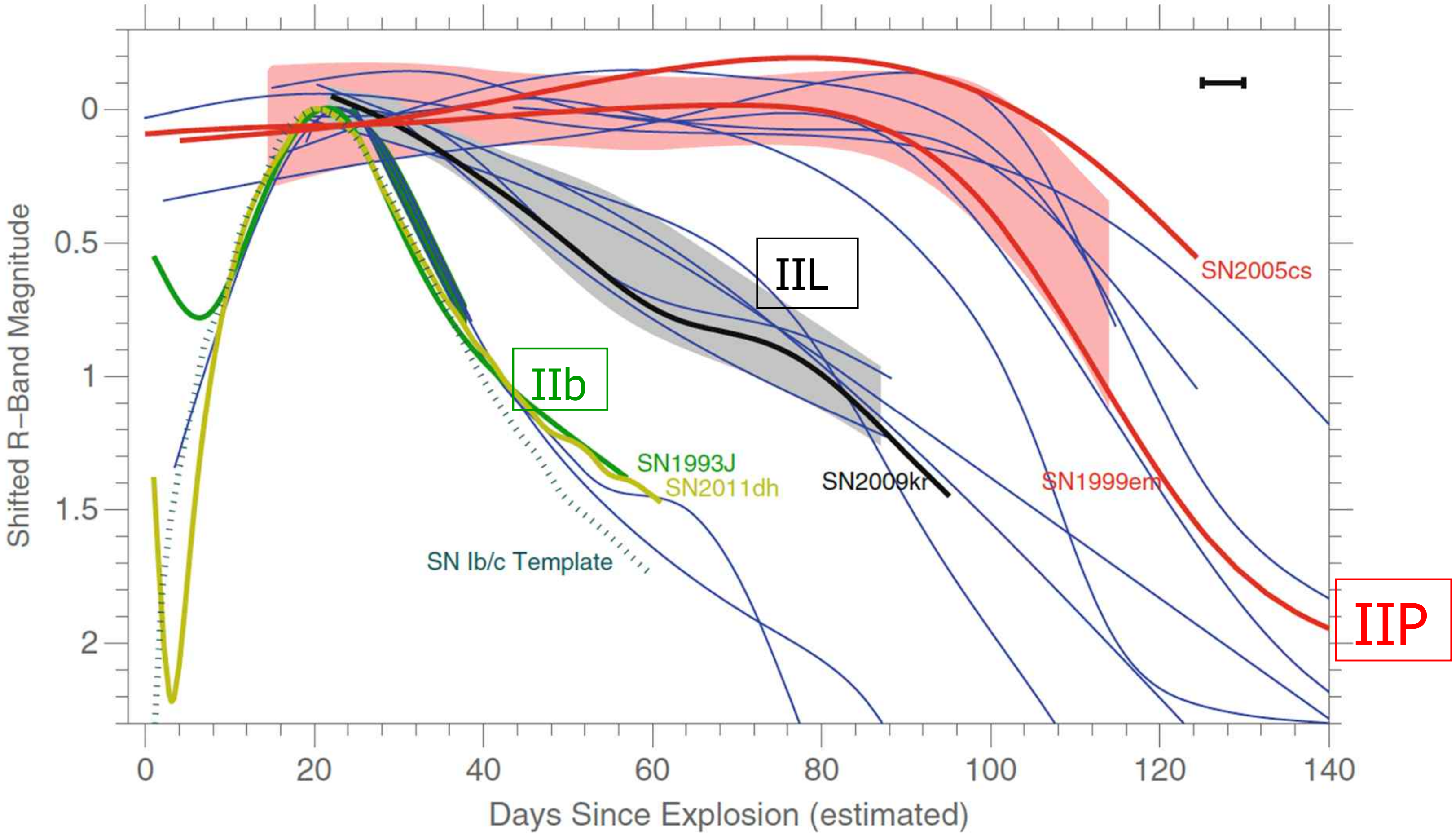
Ideal magnitude-limited sample



SN Ia : intrinsically brighter than CC SNe

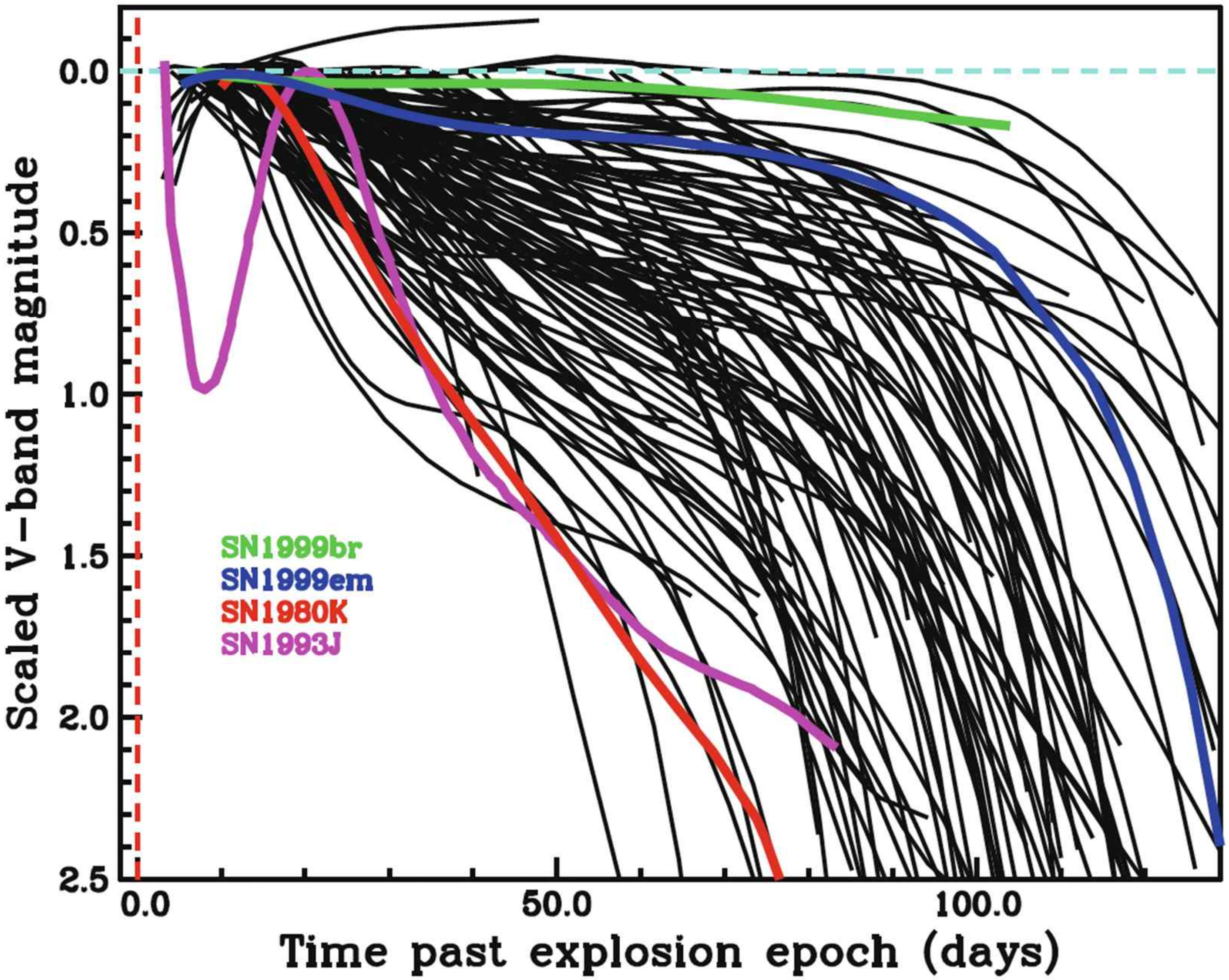
Li et al. 2011 (MN 412 1441)

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

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

~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]

https://endic.naver.com/

[명사] (구식 또는 격식) 적(敵)

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

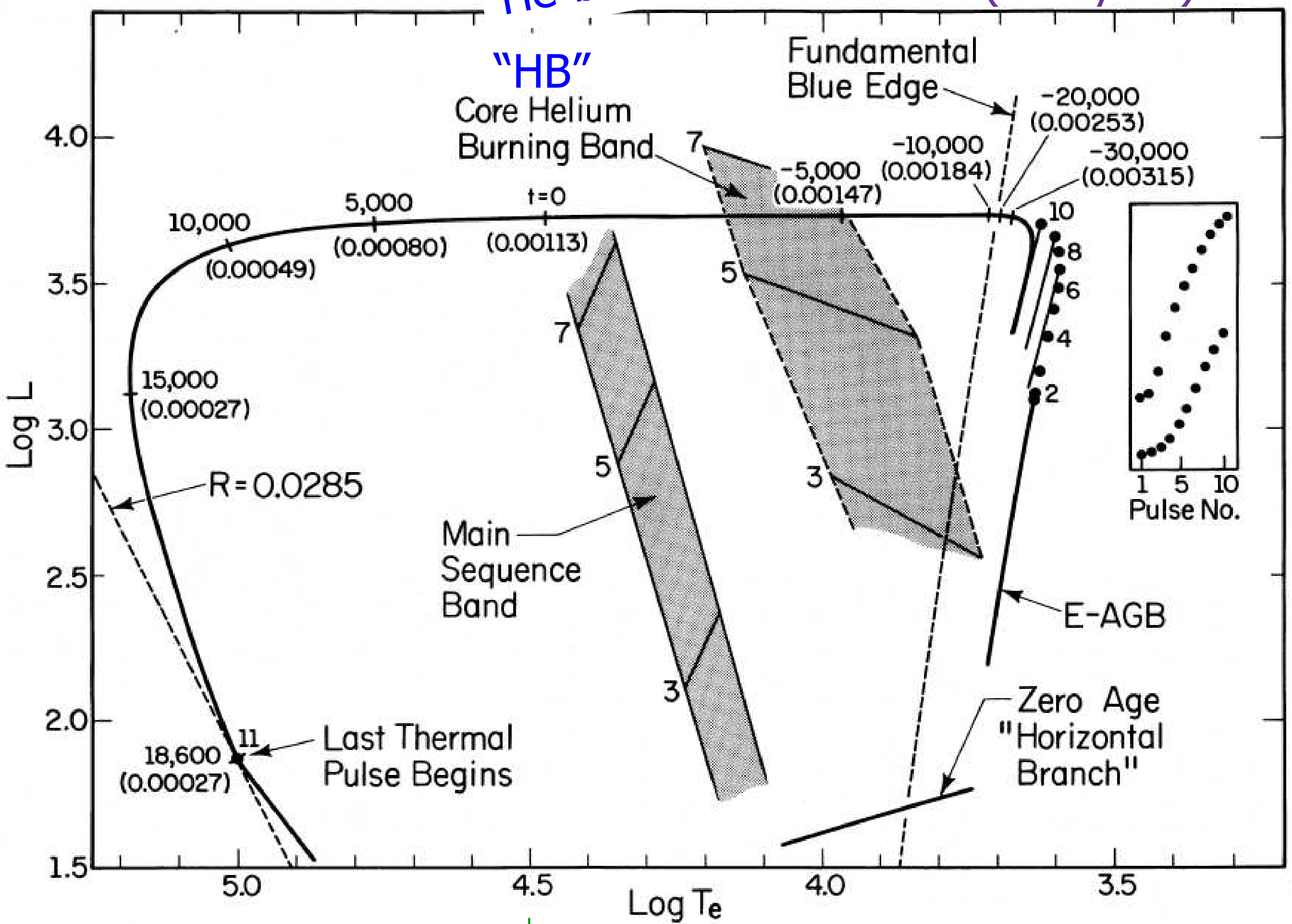
1. Planetary nebula evolution in the CMD

- 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



11 He-shell flashes

30,000 K

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 $M_\odot$

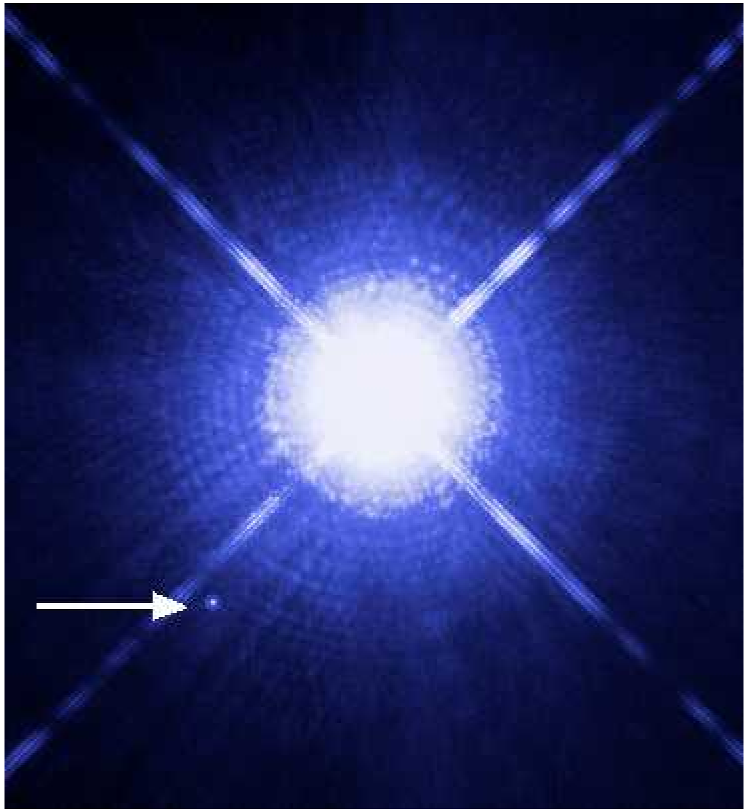
Typical density ~ 10^6 g/cm^3

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

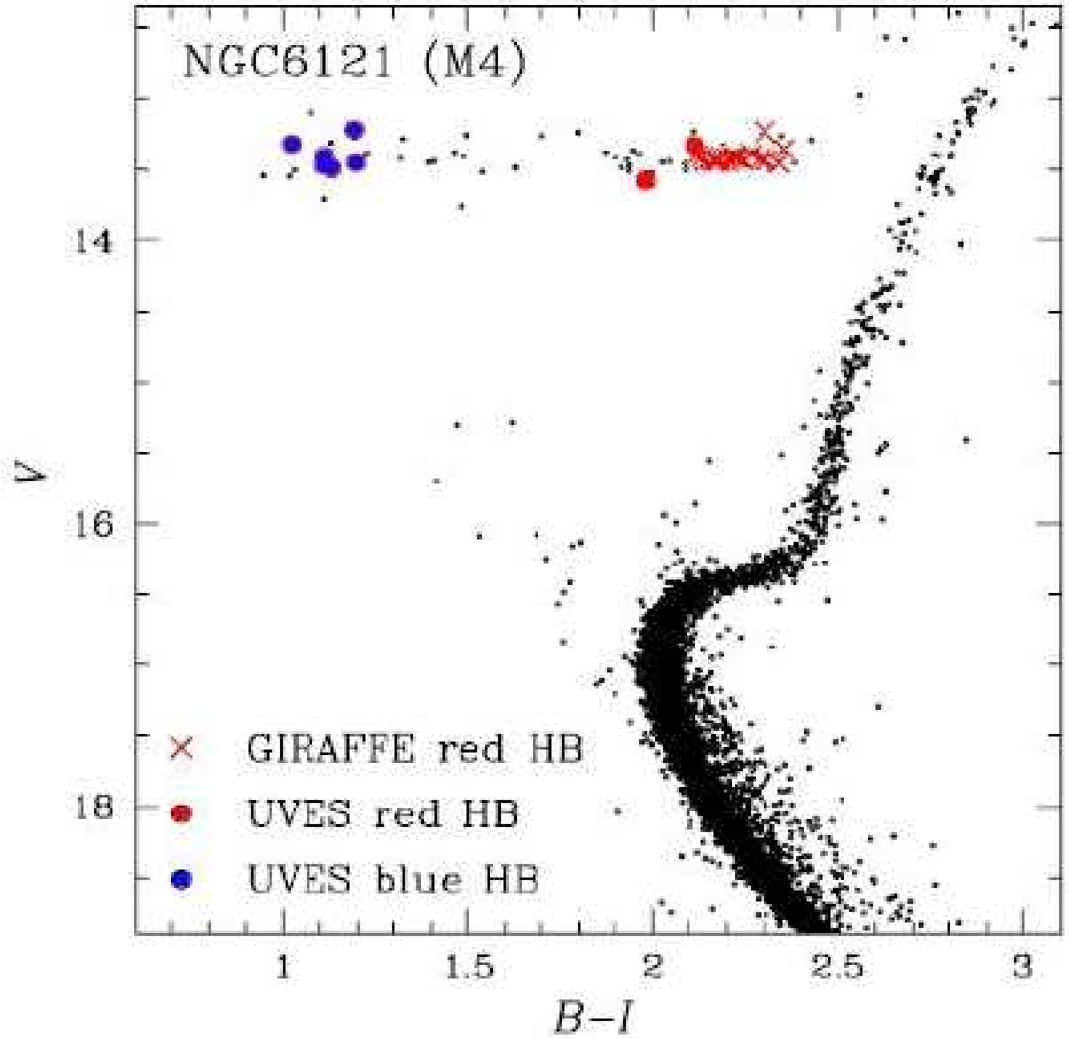


Sirius A, Sirius B (WD) - HST

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)

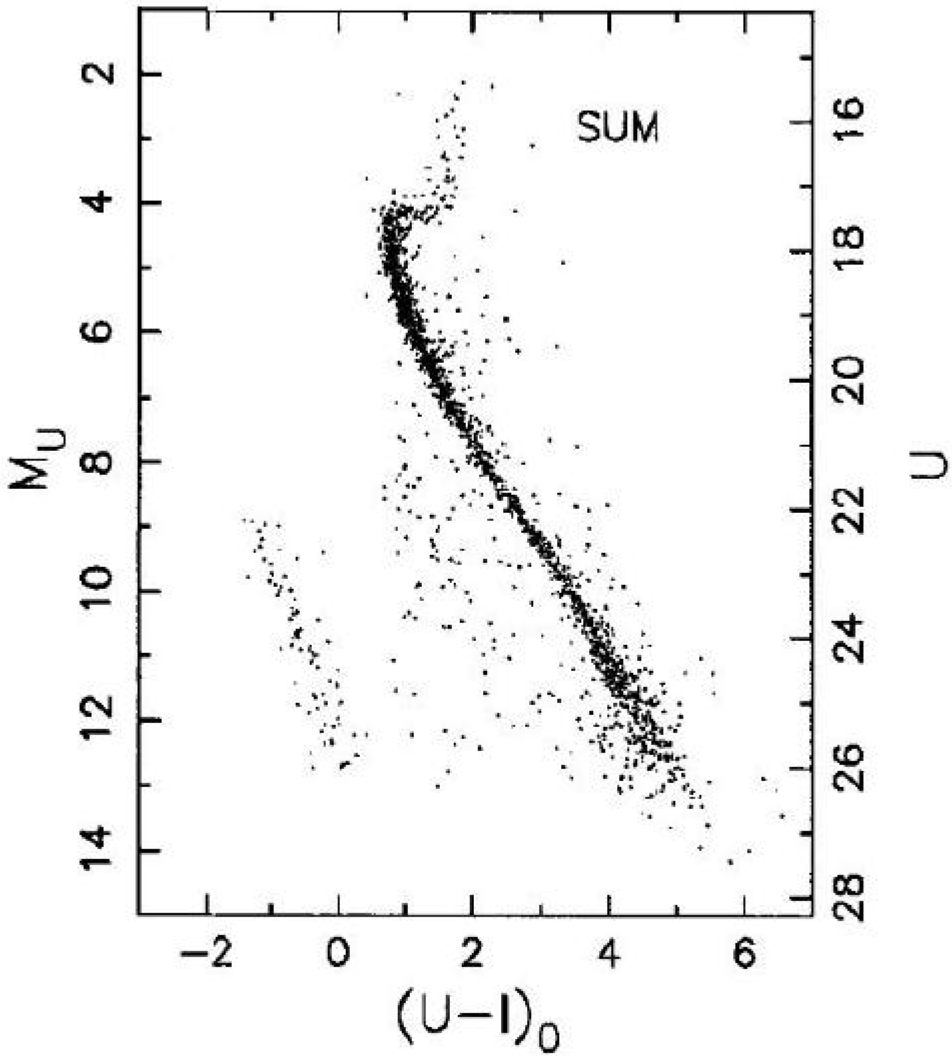
WD – cooling sequence

- 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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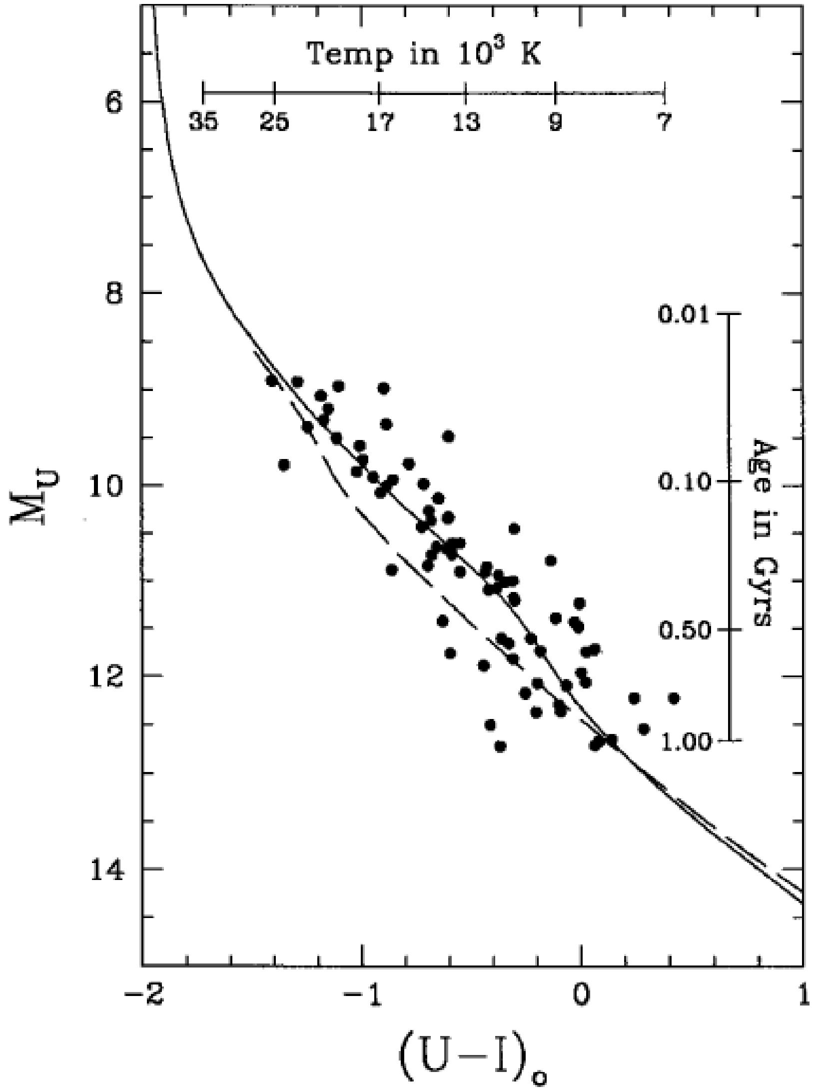


U-(U-I) CMD of GC M4 (NGC 6121)
HST
Richer et al. 1995 (ApJ 451 L17 - HST Observations of WDs in the GC M4)

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

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 :

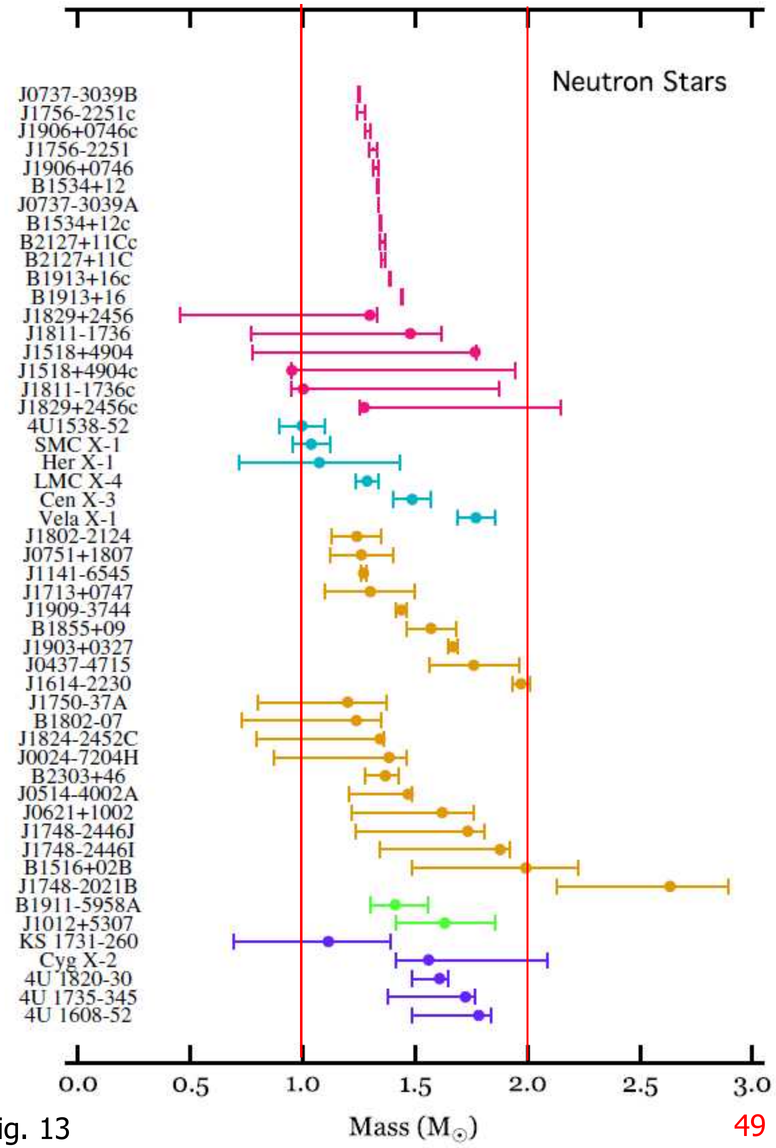
$$p^+ + e^- \rightarrow n + \nu$$

(protons and electrons are squeezed into neutrons)

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

Typical mass ~ 1.4 $M_\odot$
Typical radius ~ 10 km
Typical density ~ 4 × 10^{14} g/cm^3
(400,000 ton/mm^3)
B ~ 10^{12} Gauss
Surface temp ~6 × 10^5 K

※ 1 Tesla = 10^4 Gauss
※ Sun : mean density ~ 1.408 g/cm^3
$B_\odot$~1-2 Gauss
※ Earth : $B_\oplus$~0.1 Gauss
※ Magnetic Resonance Imager (MRI, 자기공명영상) :
B~10^5 $B_\oplus$ ~ 1 Tesla



Özel et al. (2012 ApJ 757 55 – On the mass distribution and birth masses of NSs) – Fig. 13

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

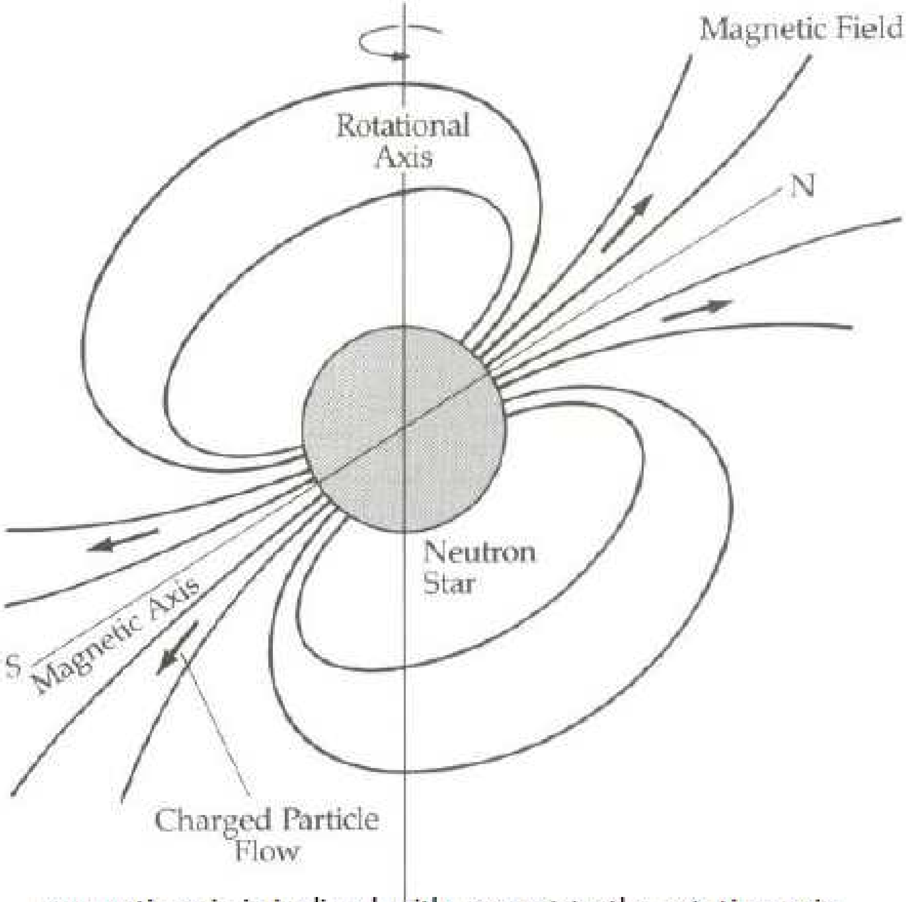
- Lighthouse model : transforms the rotational energy into electromagnetic energy → emits through the magnetic axes
  → pulse period = rotation period

- If the Sun becomes a NS → R = 7 km

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



magnetic axis is inclined with respect to the rotation axis

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 $(\dfrac{1}{v_2} - \dfrac{1}{v_1})d$
- 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

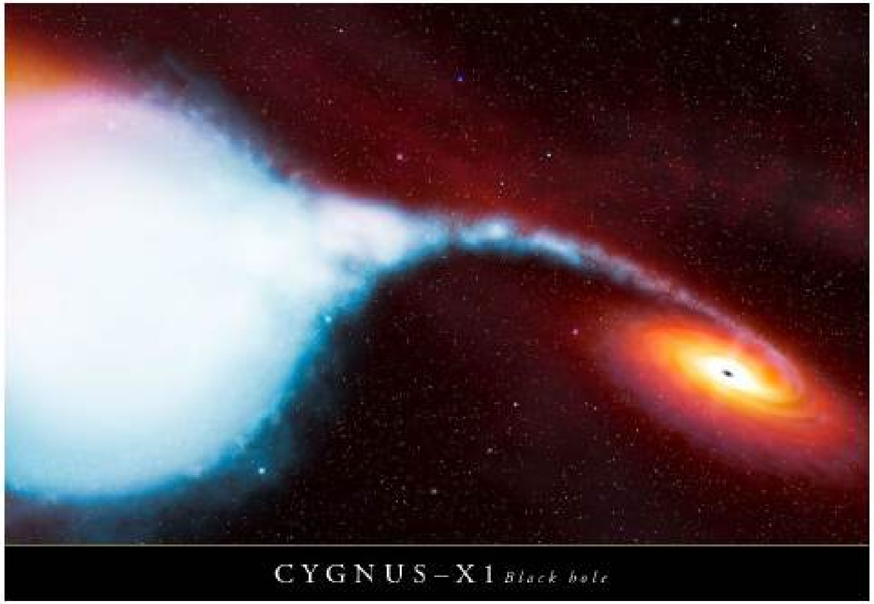
- If the Sun becomes a BH → density ~10^{16} g/cm^3 (~nucleus of an atom)

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

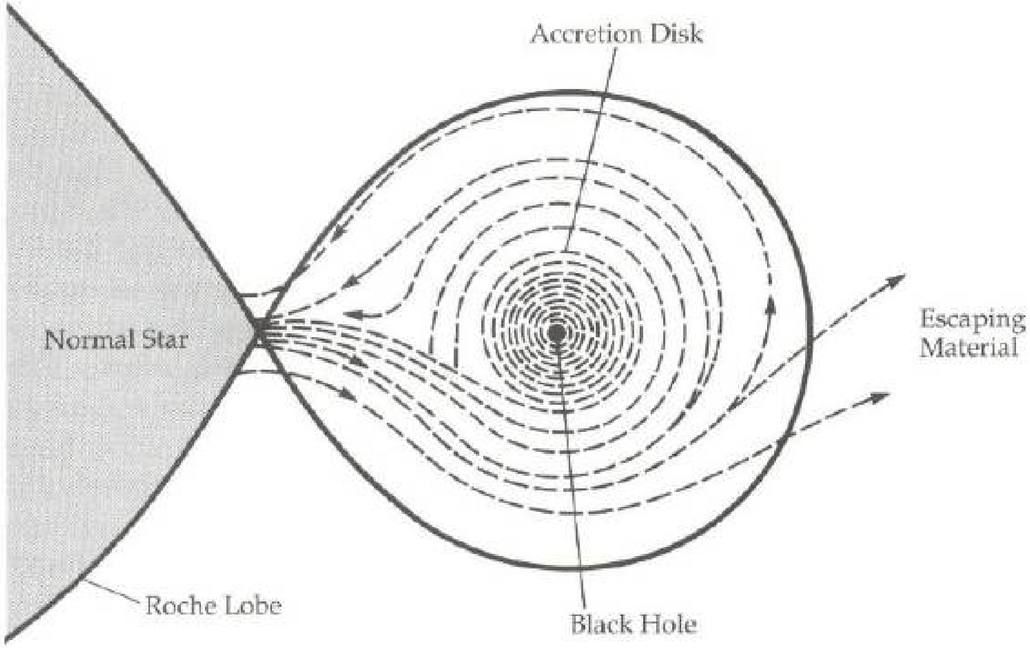
black_hole_baird.jpg
http://sciencequestionswithsurprisinganswers.org/2013/06/18/can-you-go-fast-enough-to-get-enough-mass-to-become-a-black-hole/

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