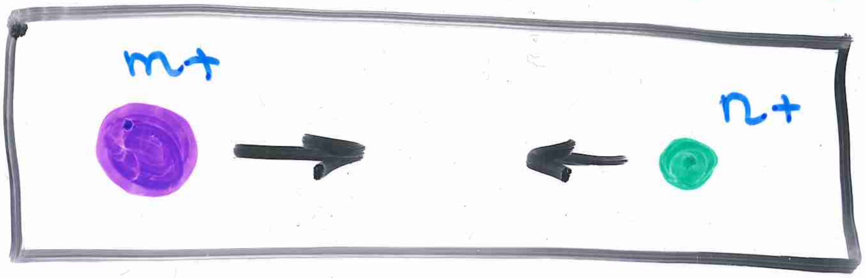
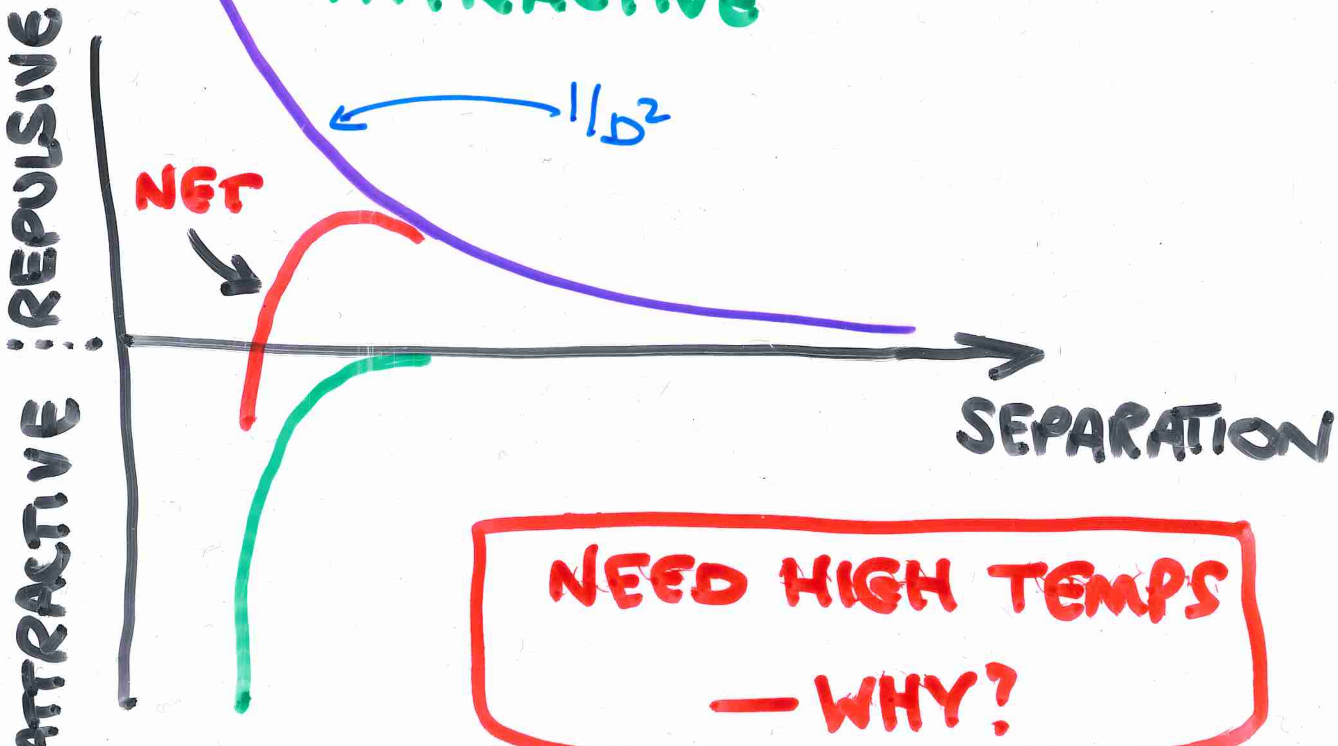
WHY HIGH TEMP. FOR NUCLEAR FUSION REACTIONS?



WHAT FORCES OPERATE?

- ELECTROSTATIC REPULSION
  - LONG RANGE ($/\text{DISTANCE}^2$)
  - $\propto m \times n$
- NUCLEAR ATTRACTIVE FORCE
  - VERY SHORT RANGE
  - ATTRACTIVE



NEED HIGH TEMPS — WHY?

STELLAR EVOLUTION

INITIAL MASS	REMNANT
LESS THAN 8 M_{SUN}	WHITE DWARF $m_{WD} \lesssim 1.4 M_{SUN}$ $\sim 0.6 M_{SUN}$ typically
GREATER THAN 8 M_{SUN}	NEUTRON STAR $m_{NS} \lesssim 3 M_{SUN}$ OR BLACK HOLE $m > m_{NS}, m_{WD}$ $\gtrsim 3 M_{SUN}$

WHAT'S THE NEXT STEP FOR He-RICH MAIN-SEQUENCE STARS?

- AS H SUPPLY IN CORE DECLINES, ENERGY SUPPLIED BY $4H \rightarrow He$ DECLINES TOO
- CORE MUST COLLAPSE: GRAVITY IN THE ASCENDANT TEMPORARILY: H CONTINUES TO BURN IN SHELL AROUND CORE
- COLLAPSE → HEATING (KELVIN - HELMHOLTZ "We told you") WITH TEMPERATURE RISING TO 200 MILLION KELVIN
- HOT CORE CAUSES OUTER LAYERS TO SWELL: STAR APPEARS AS RED GIANT / SUPERGIANT
- AT T ~ 200 MILLION K, HE BURNS: GRAVITY "FRUSTRATED" AGAIN.

He-BURNING

- $^4He + ^4He \rightarrow ^8Be + \gamma$

  BUT ^8Be FLYS APART INTO 2 ^4He IN 10^{-16} seconds

- $^4He + ^8Be \rightarrow ^{12}C + \gamma$

  ^{12}C IS STABLE

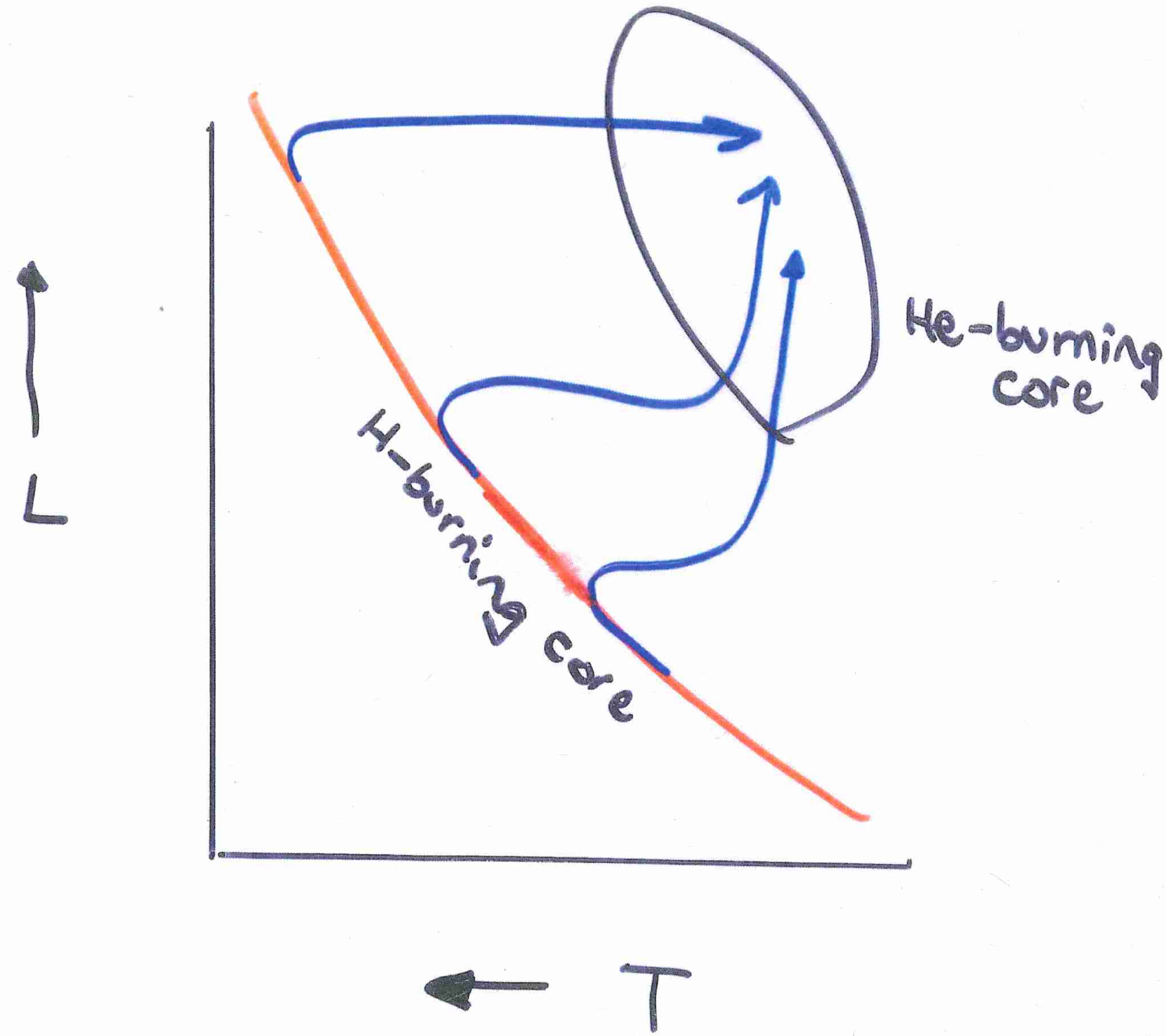
  ∴ THE PROCESS RUNS BY A TRIPLE COLLISION

$$\boxed{3\,^4He \rightarrow ^{12}C + \gamma}$$

"TRIPLE α PROCESS"

- AT HIGH TEMPERATURES, ALSO

$$\boxed{^{12}C + ^4He \rightarrow ^{16}O + \gamma}$$


He-burning core
H-burning core
L
T

- HE-BURNING OCCURS AT HIGHER TEMPERATURES & HIGHER DENSITIES THAN H-BURNING

- HE-BURNING IS LESS EFFICIENT (10 TIMES) THAN H-BURNING

SUN: $\begin{cases} 10^{10} \text{ years for H-burning} \\ 200 \times 10^{6} \text{ years for He-burning} \end{cases}$

- ALL STARS EXPERIENCE HE-BURNING

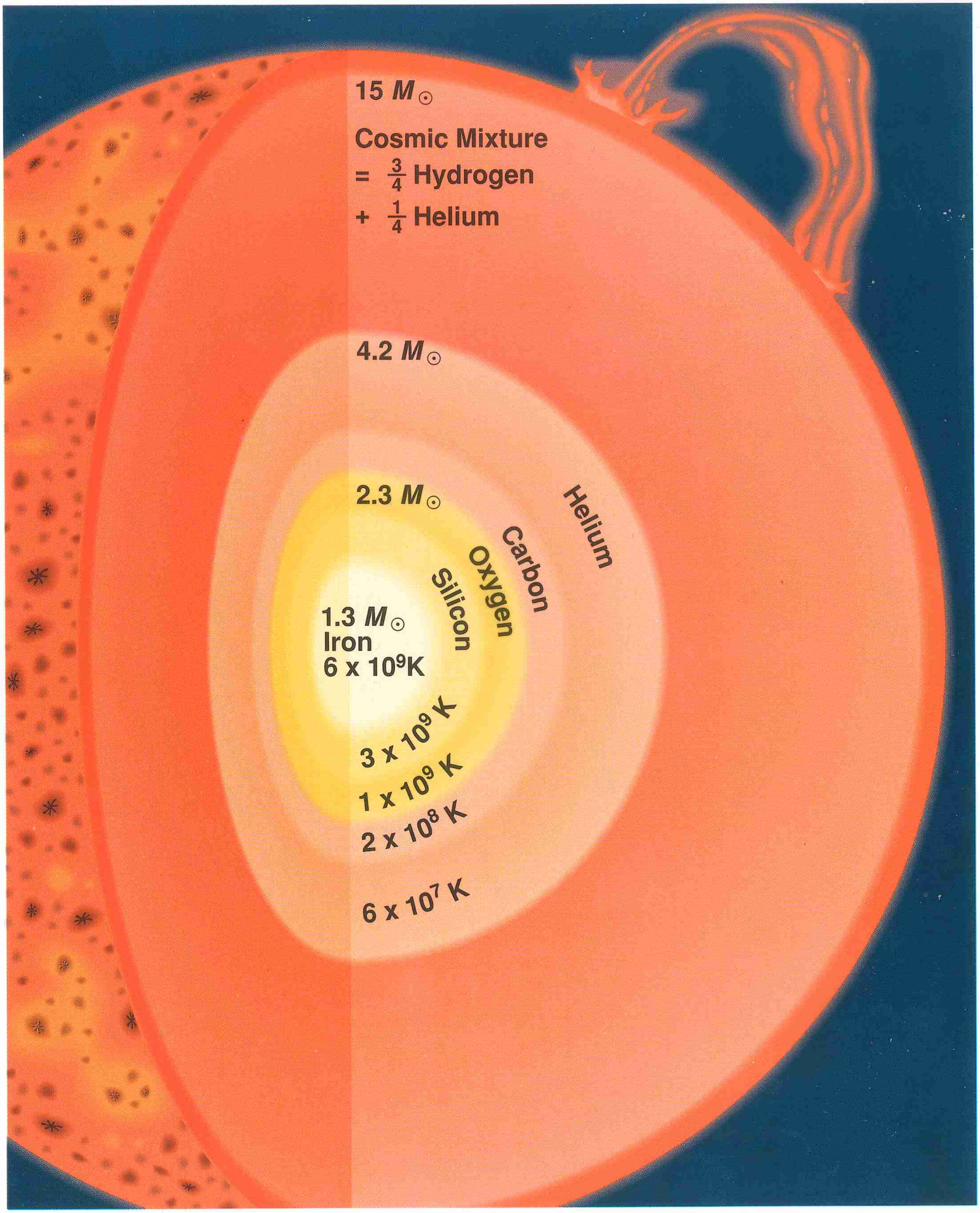
- $\begin{cases} \text{HIGH MASS STARS BURN C AND O} \\ \text{LOW MASS STARS DO NOT} \end{cases}$

MASSIVE STARS - after He-burning

- CYCLE continues:
  - BURN FUEL (H, He, ...) TO OPPOSE COLLAPSE
  - ON FUEL EXHAUSTION, GRAVITY COLLAPSES CORE, RAISES TEMPERATURE
  - ASH IGNITED TO SERVE AS NEW FUEL
    ONLY CENTRAL REGIONS BURNT
- CYCLE ends with IRON core following

  H, He, C, Ne, O, AND Si BURNING

- FUSION OF IRON CONSUMES ENERGY



Onion-skin layering of elements in 15-$M_\odot$ star

Hartmann/Impey: The Cosmic Journey, 5th ed., Fig. 19-4; Hartmann: The Cosmic Voyage, 1992 ed., Fig. 19-7

Nuclear Fuels used by Massive ($M > 8M_{\odot}$) Stars

Process	Temp (K)	Time*
H Burning $4H \rightarrow He$ via CNO cycles	40 million	70 million yrs
He Burning $He \rightarrow {}^{12}C, {}^{16}O$ via 3 α-Process	200 million	500,000 yrs
C Burning $2\,{}^{12}C \rightarrow {}^{4}He, {}^{20}Ne, {}^{24}Mg, {}^{16}O, \ldots$	600 million	600 yrs
Ne Burning ${}^{20}Ne \rightarrow {}^{16}O, {}^{24}Mg, {}^{28}Si$	1200 million	1 yr
O Burning $2\,{}^{16}O \rightarrow {}^{4}He, {}^{28}Si, {}^{32}S, \ldots$	1500 million	1/2 yr
Si Burning $2\,{}^{28}Si \rightarrow {}^{56}Ni \rightarrow {}^{56}Co \rightarrow {}^{56}Fe$	4000 million	1 day

Table is for a 20 M_{sun} star.

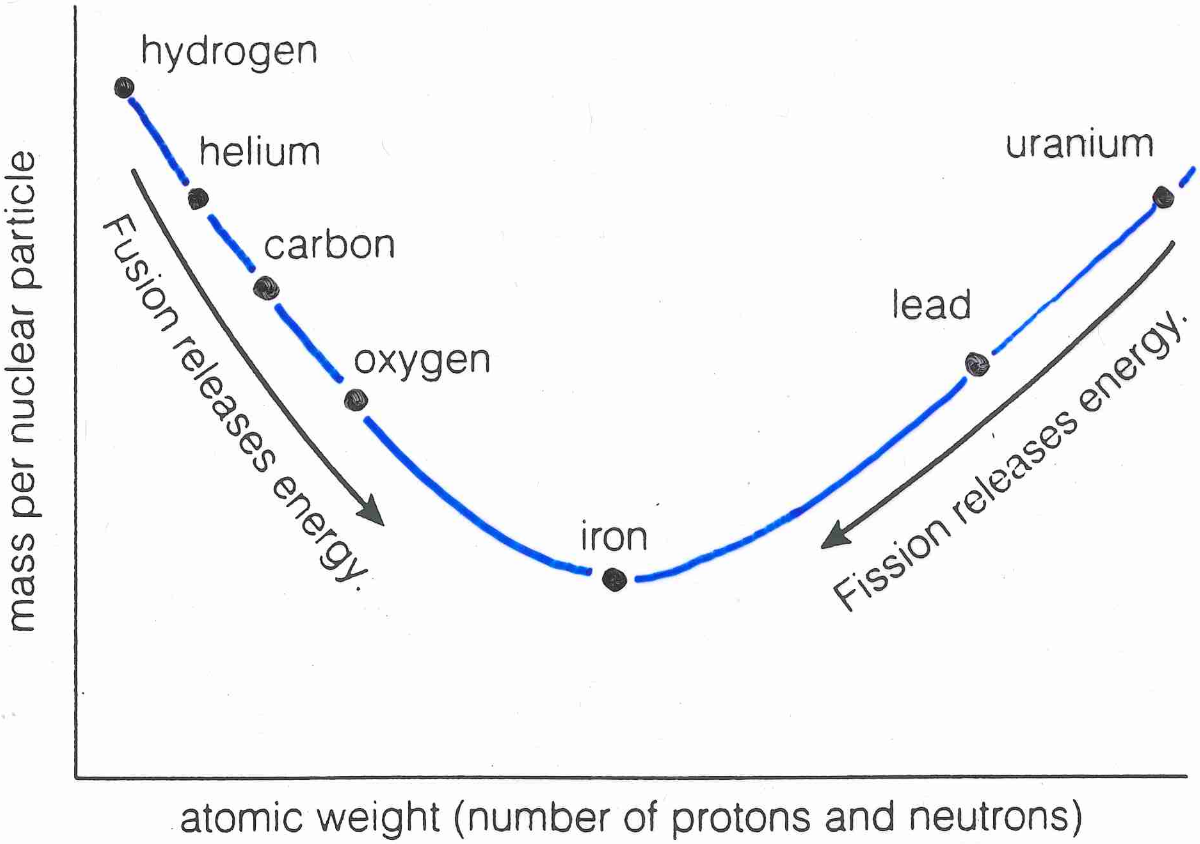


FIGURE 14.16 Overall, the average mass per nuclear particle declines from hydrogen to iron and then increases. Selected nuclei are labeled to provide reference points. (This graph shows the most general trends only; a more detailed graph would show numerous up-and-down bumps superimposed on the general trend.)

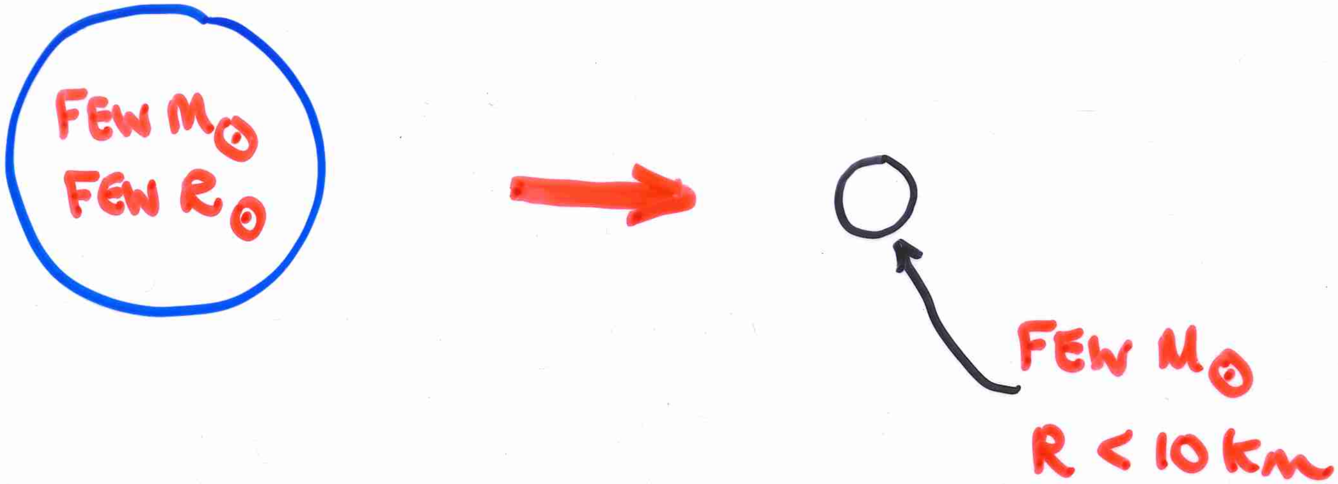
- IRON CORE MUST COLLAPSE TO DENSITY OF ATOMIC NUCLEUS (NUCLEI IN CONTACT)

- IRON NUCLEI BROKEN UP BY RADIATION

$$\gamma + Fe \rightarrow 14\,{}^4He$$
$${}^4He + \gamma \rightarrow 2p + 2n$$
$$p + e \rightarrow n + \nu_e$$

} CONSUMES ENERGY, ACCELERATES COLLAPSE

- ENERGY NEEDED TO CONVERT Fe CORE TO $n + \nu_e$ MAINLY FROM GRAV. COLLAPSE (KELVIN-HELMHOLTZ AGAIN!)



ALL IN A FRACTION OF A SECOND!

- CORE ENDS AS A
  - NEUTRON STAR (STABLE)

  OR A
  - BLACK HOLE (CONTINUES TO COLLAPSE)

- CORE COLLAPSE TRIGGERS AN EXPLOSION AND EJECTION OF OUTER LAYERS
  - OUTER LAYERS COLLAPSE WITH CORE, ARE HEATED, BURN
  - EJECTION DRIVEN BY
    - ENERGY RELEASED BY BURNING?
    - NEUTRINO TRAPPING AROUND CORE?
- SUPERNOVA RESULTS (TYPE II SN)

TYPES OF SUPERNOVAE

SN II : HYDROGEN IN SPECTRUM

EXPLOSION OF MASSIVE ($>8 M_\odot$) STAR

SN Ia : NO HYDROGEN IN SPECTRUM

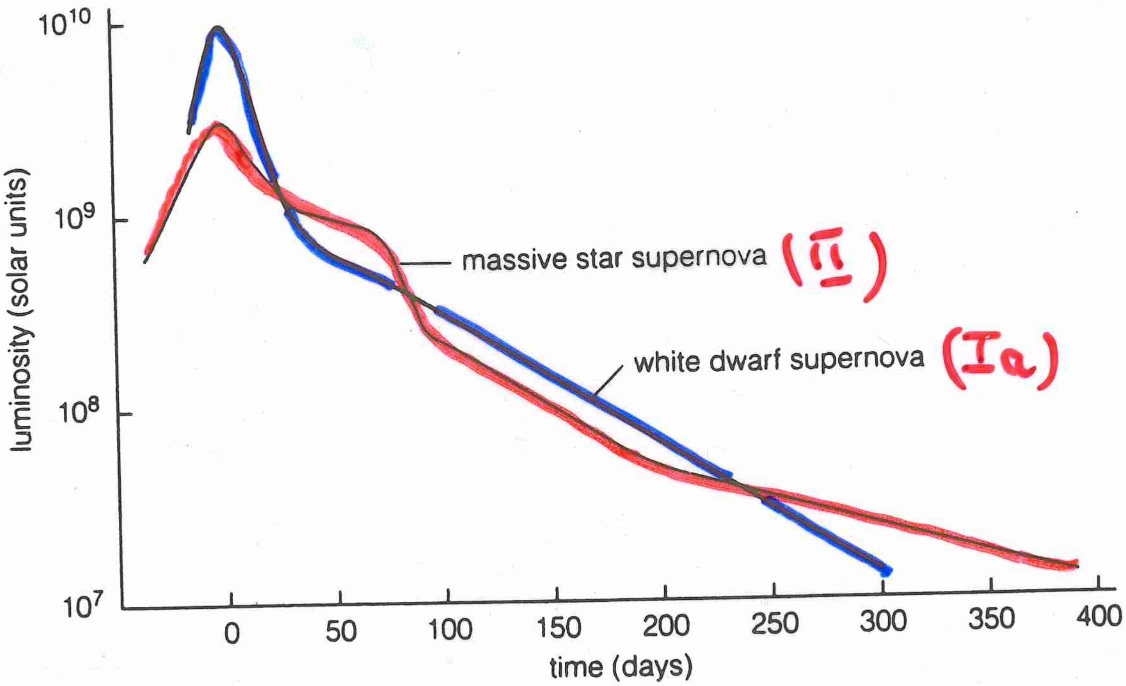
EXPLOSION OF WHITE DWARF THAT EXCEEDS CHANDRASEKHAR LIMIT

SN Ib : NO HYDROGEN IN SPECTRUM

EXPLOSION OF MASSIVE STAR THAT LOST ITS H-RICH ENVELOPE PRIOR TO EXPLOSION (WIND? BINARY?)

TYPICAL GALAXY

MOST MASSIVE MAIN SEQ. *

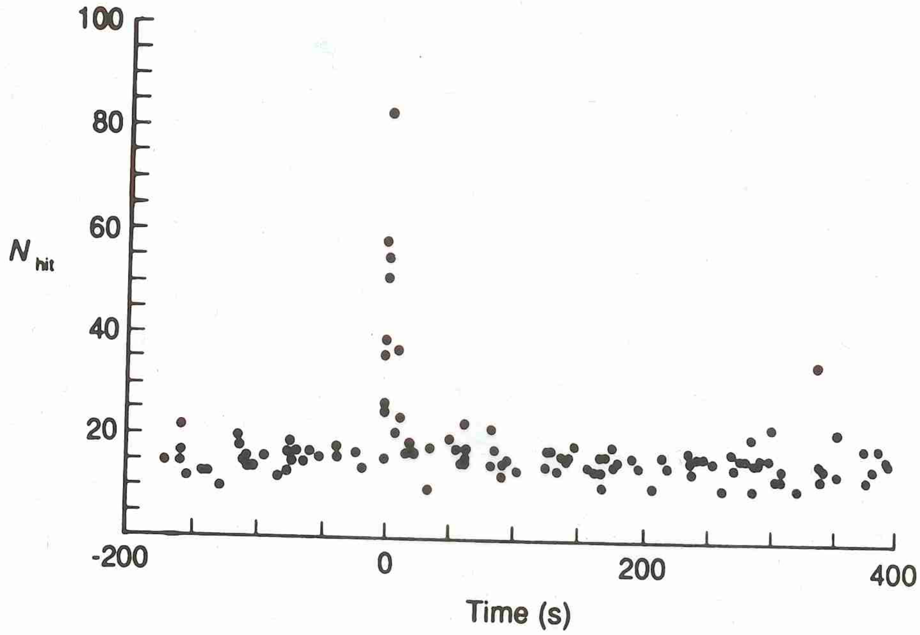


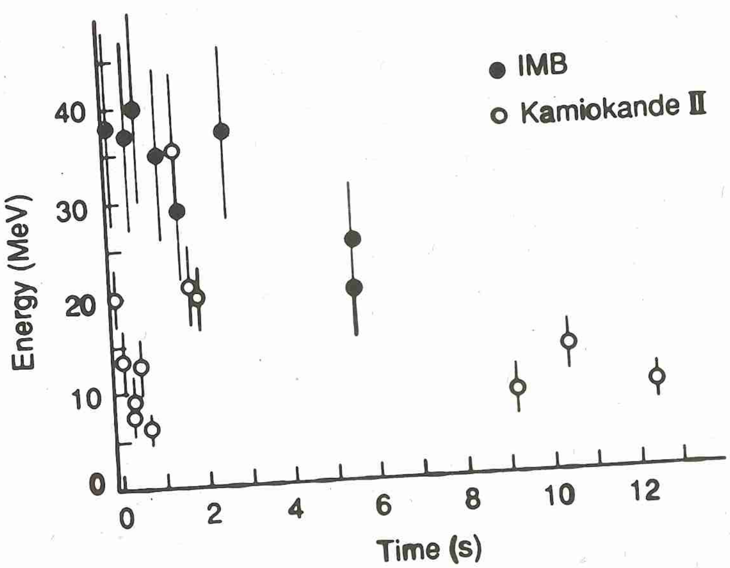
- Ia LIGHT CURVES – very similar one SN to another

- II LIGHT CURVES – variety

- SN Ia more luminous than SN II
- SN Ia's are STANDARD CANDLES

→ VERY USEFUL FOR MEASURING DISTANCES TO GALAXIES (if/when they show a SN Ia)





SPREAD OVER SEVERAL SECONDS (AS EXPECTED)

PORTRAIT OF A TYPE II SUPERNOVA

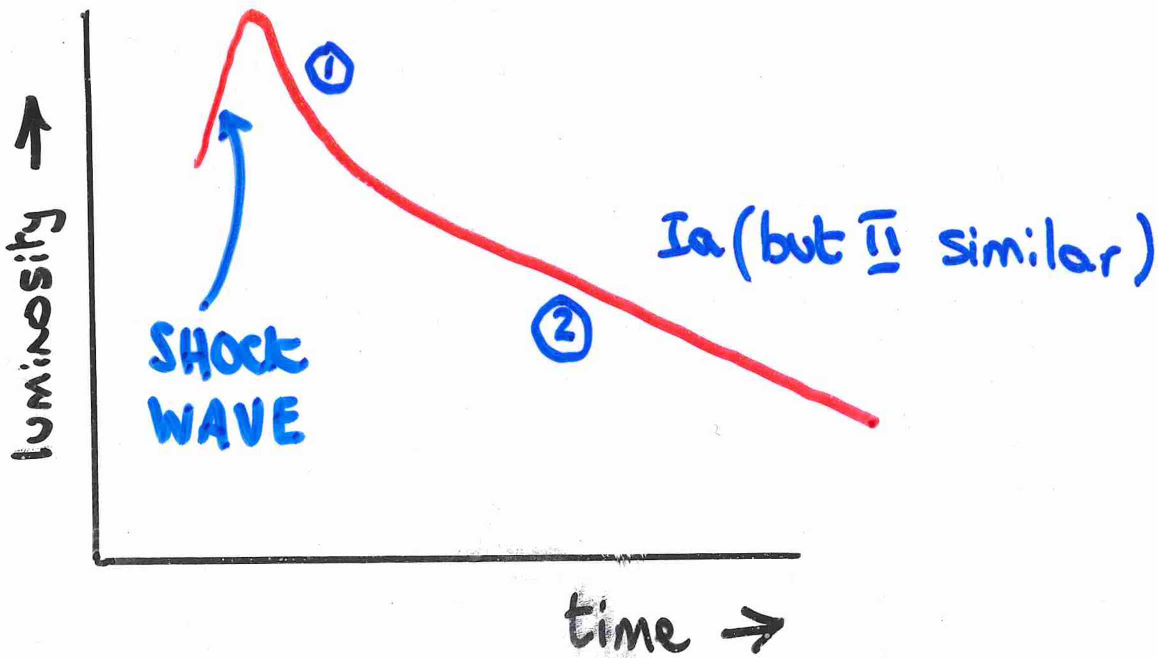
SN 1987A IN LMC : FEB 24 1987
CLOSE, BRIGHT, V. WELL STUDIED

- SANDULEAK −69° 202 EXPLODED
  BLUE SUPERGIANT ($\sim 20 M_{SUN}$)

- NEUTRINOS DETECTED BY KAMIOKANDE, IMB
  - 18 HOURS BEFORE VISIBLE BRIGHTENING
  - TOTAL ENERGY = PREDICTED FROM COLLAPSE OF CORE → NEUTRON STAR BIRTH

- STEADY DECLINE IN BRIGHTNESS AFTER FEB 1987
  RADIOACTIVE DECAY POWERS DECLINE

SN POWER SOURCE



① DECAY OF RADIOACTIVE ^{56}Ni { PRODUCED DEEP IN SN

$$^{56}Ni \rightarrow {}^{56}Co + \gamma$$

$t_{1/2} = 5.5$ DAYS

{ $0.2 M_\odot$ OF ^{56}Ni

② DECAY OF RADIOACTIVE ^{56}Co

$$^{56}Co \rightarrow {}^{56}Fe + \gamma$$

$t_{1/2} = 78$ DAYS

γ-RAYS TRAPPED → HEATING → VISIBLE PHOTONS

- GAMMA RAYS DETECTED FROM SN1987A
  THROUGH HOLES IN EJECTA

- IRON TO COBALT CONVERSION SEEN IN
  EJECTA

MASSIVE STARS AS MANUFACTURERS & DISTRIBUTORS OF 'CHEMICALS'

- HYDROGEN → HELIUM, C, N, O, ... Fe ....