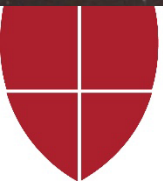


SOAR: Lives of Stars

Lives & Deaths of Large Stars

Aileen A. O'Donoghue
Henry Priest Professor of Physics



ST. LAWRENCE UNIVERSITY

The Lives of Stars

☆ Star Birth: 9/10/26

🌍 Nuclear Explosions Contained by Gravity

☆ Lives & Deaths of Small Stars: 9/17/26

🌍 Planetary Nebulae and White Dwarfs

☆ Deaths of Large Stars: 9/24/26

🌍 Supernovae, Neutron Stars and Black Holes

☆ Black Holes: 10/1/26

🌍 Spaghettification

Outline

☆ Review Small Star Deaths

- 🌍 Star life on the Main Sequence

- 🌍 Star Deaths

 - › Sol: Red Giant, Planetary Nebula, White Dwarf

☆ Evolution of Large Stars

- 🌍 Fusion Layers & Neutrinos

- 🌍 Type II Supernovae

 - › Neutron Stars & Pulsars

☆ Types of Supernovae

- 🌍 Origins of the Elements

☆ States of Matter

Outline

★ Review Small Star Deaths

- 🌍 Star life on the Main Sequence

- 🌍 Star Deaths

 - › Sol: Red Giant, Planetary Nebula, White Dwarf

★ Evolution of Large Stars

- 🌍 Fusion Layers & Neutrinos

- 🌍 Type II Supernovae

 - › Neutron Stars & Pulsars

★ Types of Supernovae

- 🌍 Origins of the Elements

★ States of Matter

Main Sequence Life

☆ Hydrostatic Equilibrium Fusing H to He

 Gravity pulling inward

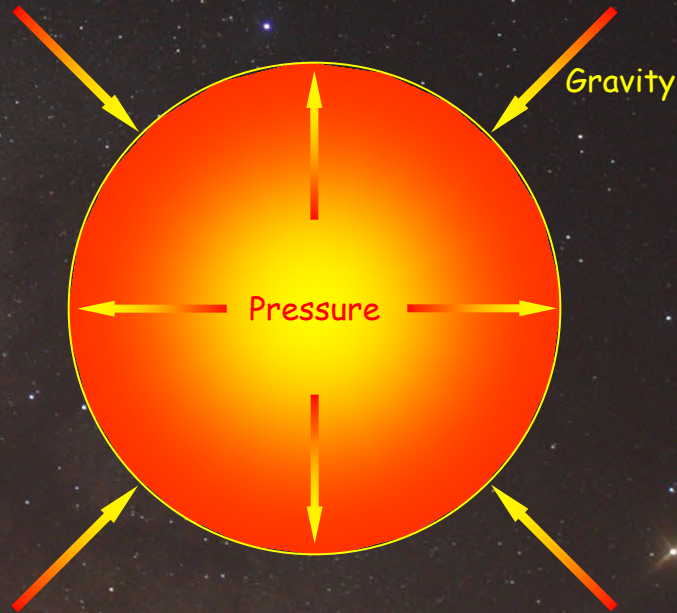
weight of upper layers tries to compress star

🌍 Pressure of heated gas pushing outward

» nuclear explosion tries to expand star

balance lost
when fuel runs out

Ultimately,
gravity will
win!



The Sun on the Main Sequence

A nuclear explosion
contained by gravity.



Sol turns 45 Aircraft Carrier masses of H
to pure energy each second ... every second!

Star Deaths

☆ Lifespan, death depend on star's mass

$$t_{\text{Main Sequence}} \approx 10^{10} \times M_{\text{solar masses}}^{-2.5} \text{ years}$$

☆ Small Stars ($0.1 M_{\text{Sol}} < M_{\text{star}} \leq 8M_{\text{Sol}}$)

🌍 Longish lives (10's of billions of years)

› No star smaller than $0.8 M_{\text{sol}}$ has lived out its life!

🌍 Planetary Nebula to White Dwarf

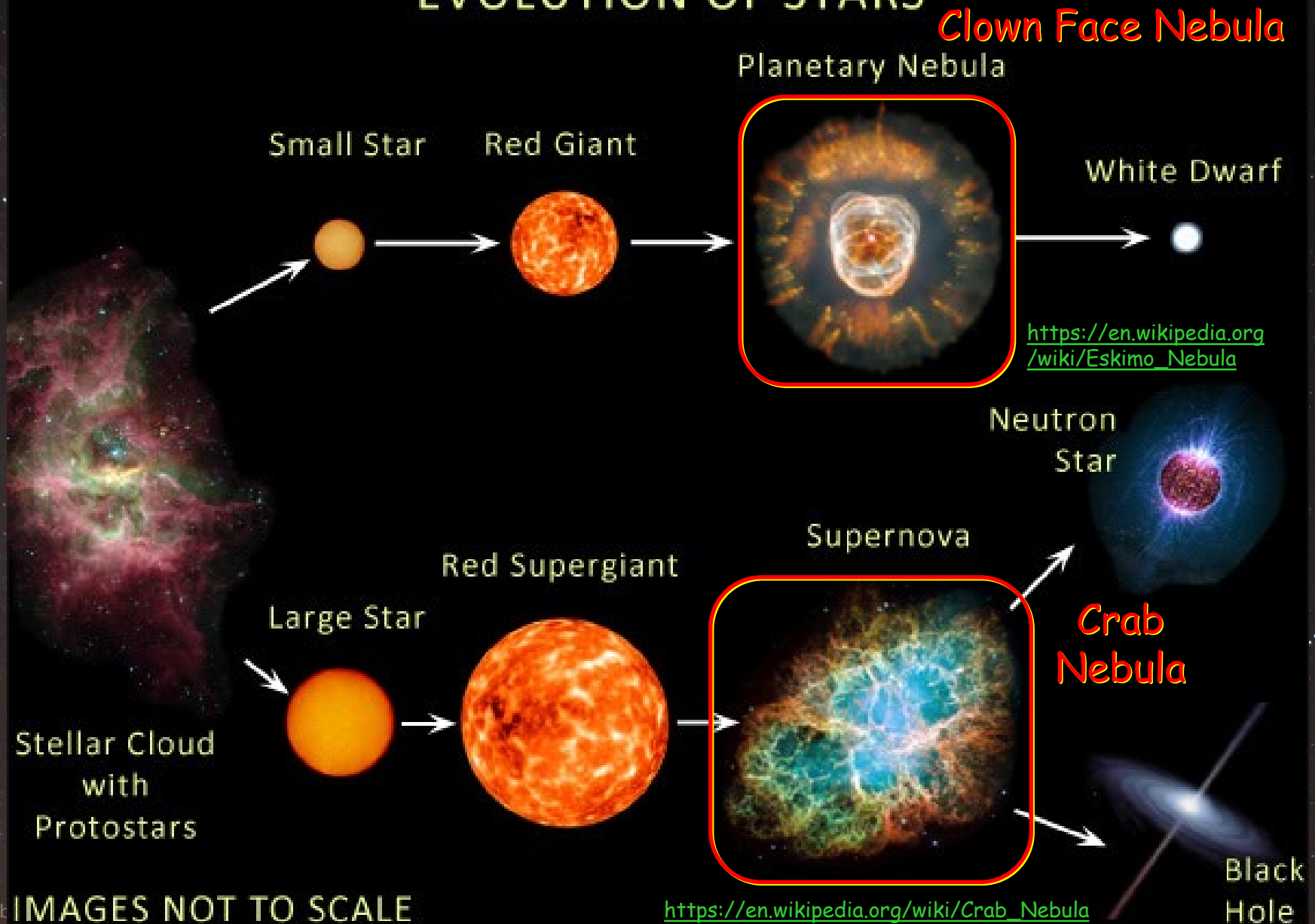
☆ Giant Stars ($M > 8M_{\text{Sol}}$, $M_{\text{max}} \approx 100 M_{\text{Sol}}$)

🌍 Lives can be very short (millions of years)

🌍 Supernova to Neutron Star or Black Hole

Star Death Depends on Mass

EVOLUTION OF STARS



Sol will Become a Red Giant ...

☆ Sol as red giant will engulf ♀ and ♀

The Sun as a main-sequence star
(diameter = 1.4×10^6 km $\approx \frac{1}{100}$ AU)

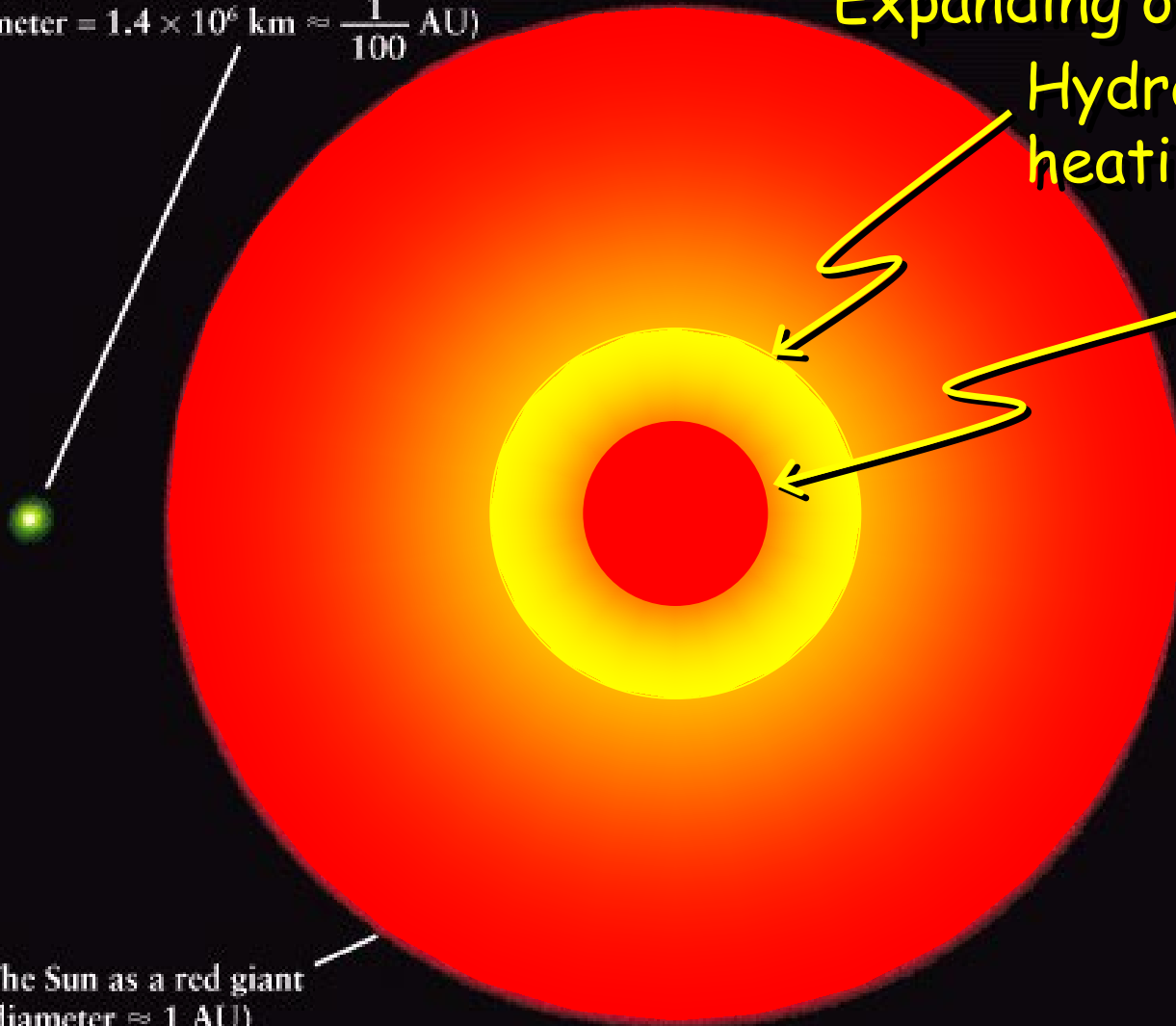
Expanding outer layers

Hydrogen fusing shell
heating outer layers

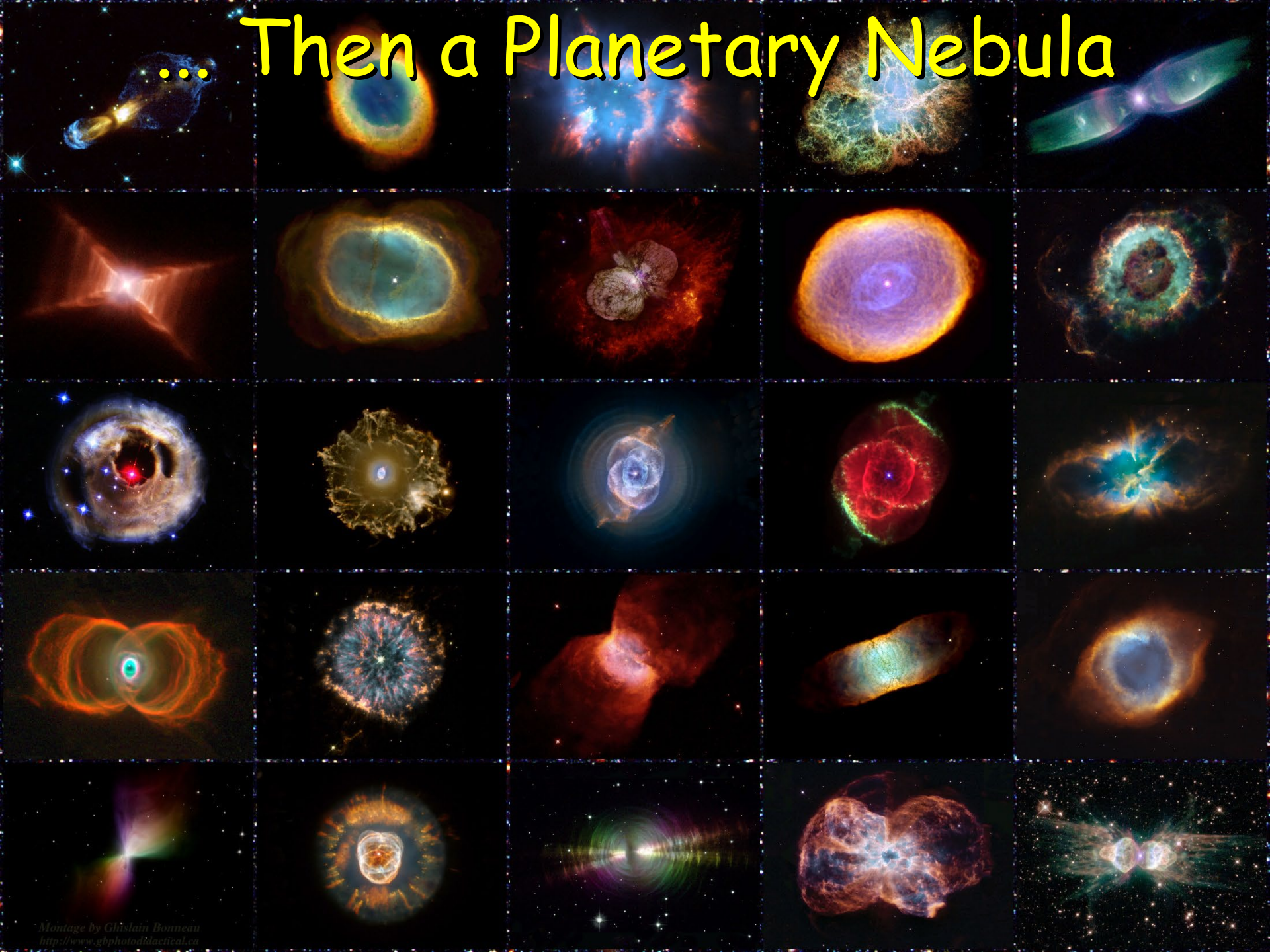
Shrinking He core
becoming
degenerate electron
gas

Sol may
engulf
Earth

The Sun as a red giant
(diameter ≈ 1 AU)

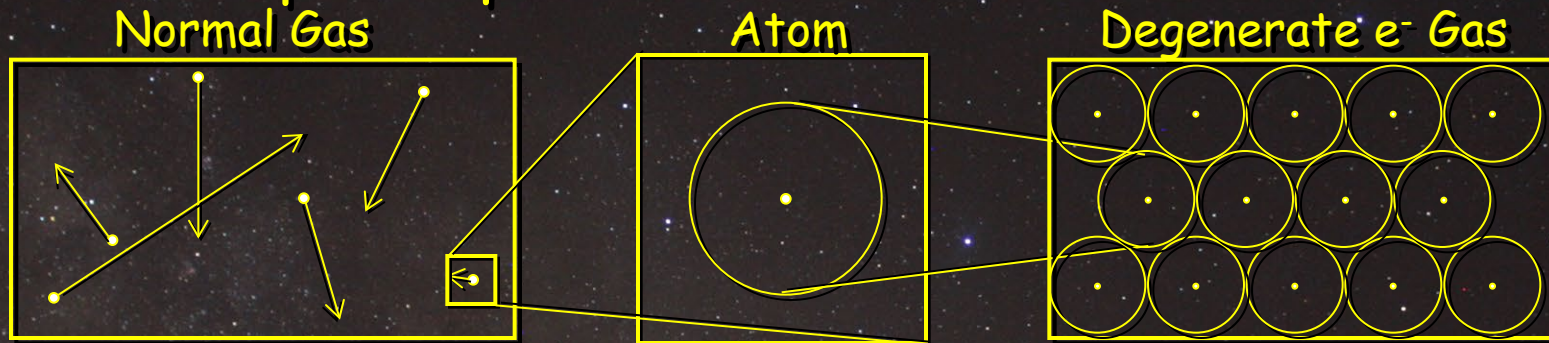


... Then a Planetary Nebula

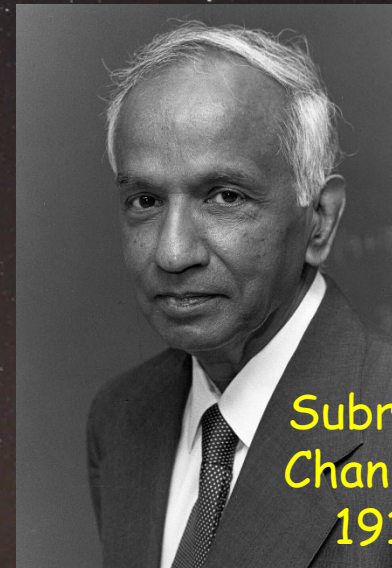


☆ Degenerate e^- gas

- 🌐 atoms packed as close as possible
 - » electron clouds packed together
 - » all space squeezed out from between atoms



- ② does not expand on heating
- ② maximum mass = $1.4 M_{\text{sol}}$
 - › Chandrasekhar Limit
 - › electron degeneracy can't hold itself up against gravity



Subrahmanyan Chandrasekhar 1910-1995

Outline

☆ Review Small Star Deaths

- 🌍 Star life on the Main Sequence

- 🌍 Star Deaths

 - » Sol: Red Giant, Planetary Nebula, White Dwarf

☆ Evolution of Large Stars

- 🌍 Fusion Layers & Neutrinos

- 🌍 Type II Supernovae

 - » Neutron Stars & Pulsars

☆ Types of Supernovae

- 🌍 Origins of the Elements

☆ States of Matter

Evolution of Massive Stars

- ☆ Hydrogen core used up quickly (10^7 yr!)
 - 🌍 Core contracts, heats, star expands
- ☆ Helium fusion begins easily,
 - 🌍 No Helium flash
 - 🌍 H fusion in shell surrounding He fusing core
- ☆ Helium core gets used up
 - 🌍 Core contracts, heats to fuse C easily (no C flash)
 - 🌍 He fusion in shell surrounding C fusing core
- ☆ Carbon fusion shrinks star!
 - 🌍 Energy lost by neutrinos ... heat pressure reduced
 - » Neutrinos only interact with atomic nuclei
 - » Neutrinos escape star quickly
 - ↯ Light takes a million years ... interacts with atoms

Neutrinos

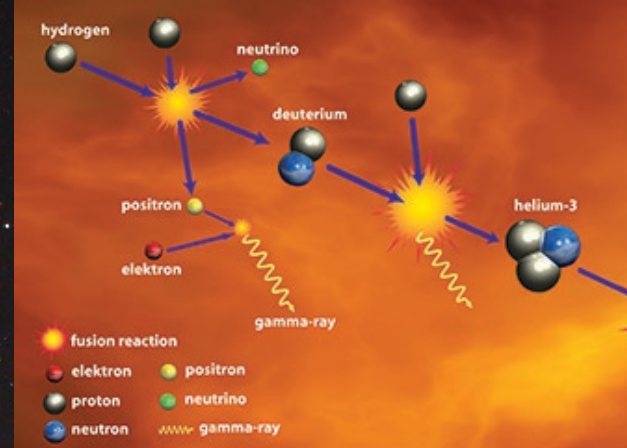
☆ Neutrinos

🌐 Produced in fusion reactions

🌐 Weakly interact with matter

› Pass through Sol, Earth, you constantly

› Hard to detect (only interact with nuclei)



<https://scienceinschool.org/wp-content/uploads/2014/11/issue19neutrinos.jpg>

☆ Predicted in 1930

🌐 Energy "missing" from nuclear reactions

› Pauli predicted particle

☆ Detected in 1956

🌐 Project Poltergeist

› Savannah River (nuclear)

Plant, S.C. provided neutrinos



Neutrinos

☆ Solar Neutrinos

① 2 Produced in each fusion

$$\frac{9 \times 10^{37} \text{ fusions}}{\text{second}} \Rightarrow \frac{18 \times 10^{37} \text{ neutrinos}}{\text{second}}$$

① Flux at Earth = 63 billion neutrinos/cm²!!

☆ Solar neutrino problem

① 1/3 of expected number detected in 1960s!

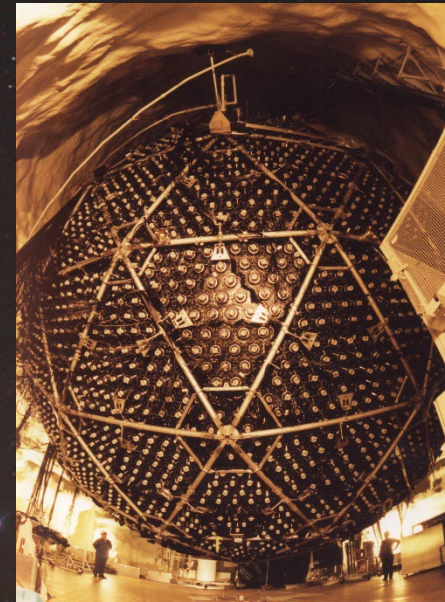
‣ Homestake Experiment, South Dakota

① Sudbury Neutrino Observatory

‣ neutrinos oscillate among 3 types

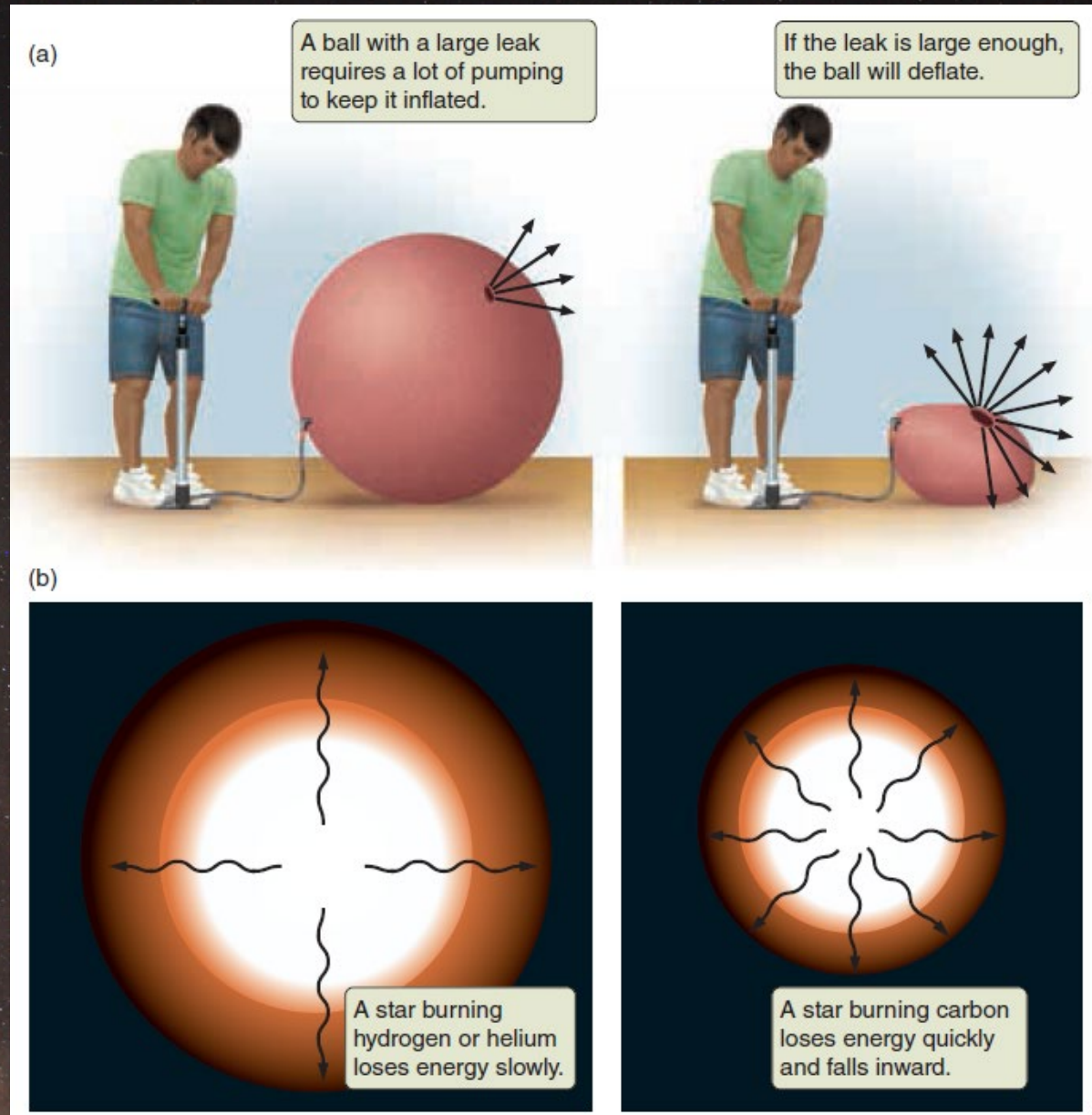
-- e^- , μ (mu) & τ (tau)

‣ SNO detected all three in 2002!



Carbon Fusion & Neutrinos

Star layers
being held up by
heat once
Carbon starts
fusing is like
pumping up a
leaky ball due to
production of
neutrinos!



Fusion Cores

☆ C fusion to N, Na, Mg

🌍 Shrinks star!

🌍 Energy escapes mostly in neutrinos

🌍 Star shrinks

🌍 Fusion increases (higher density!)

🌍 Luminosity is maintained

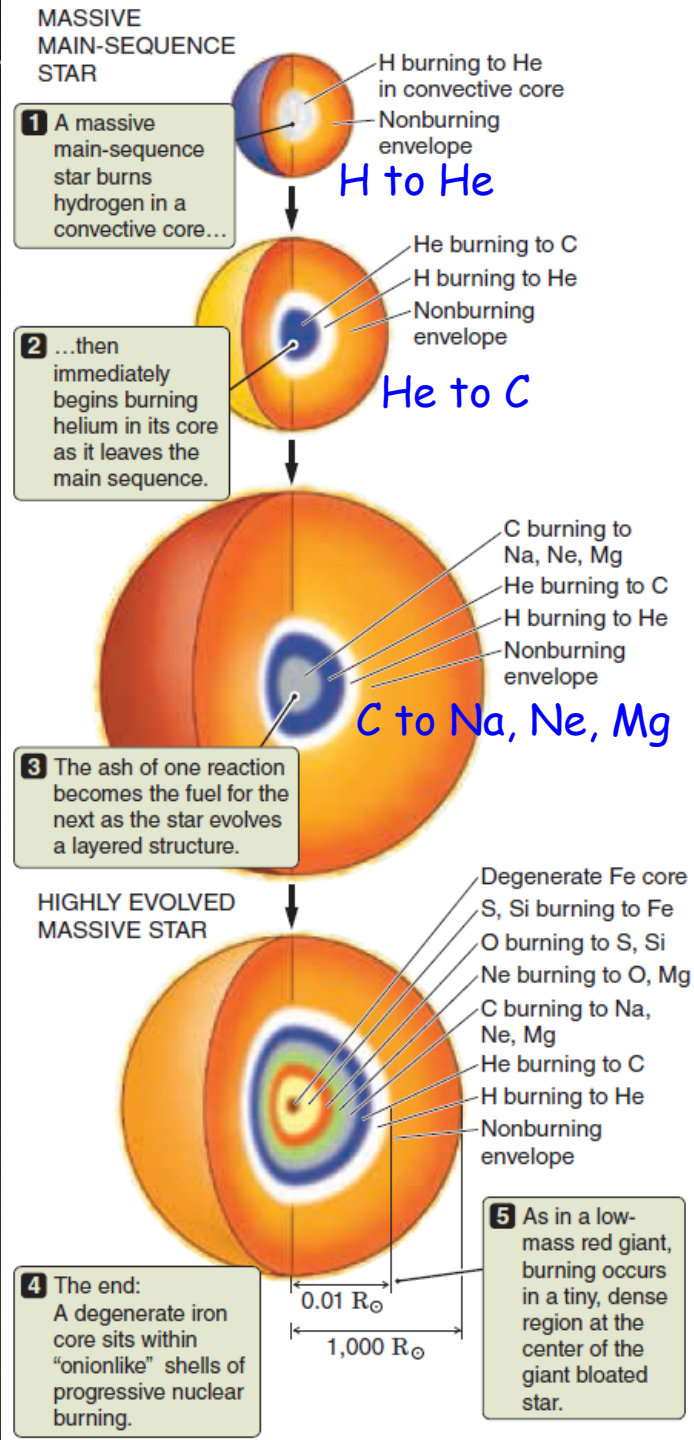
🌍 Supports star ~1000 years

☆ Ne fusion to O

☆ O fusion to S, Si

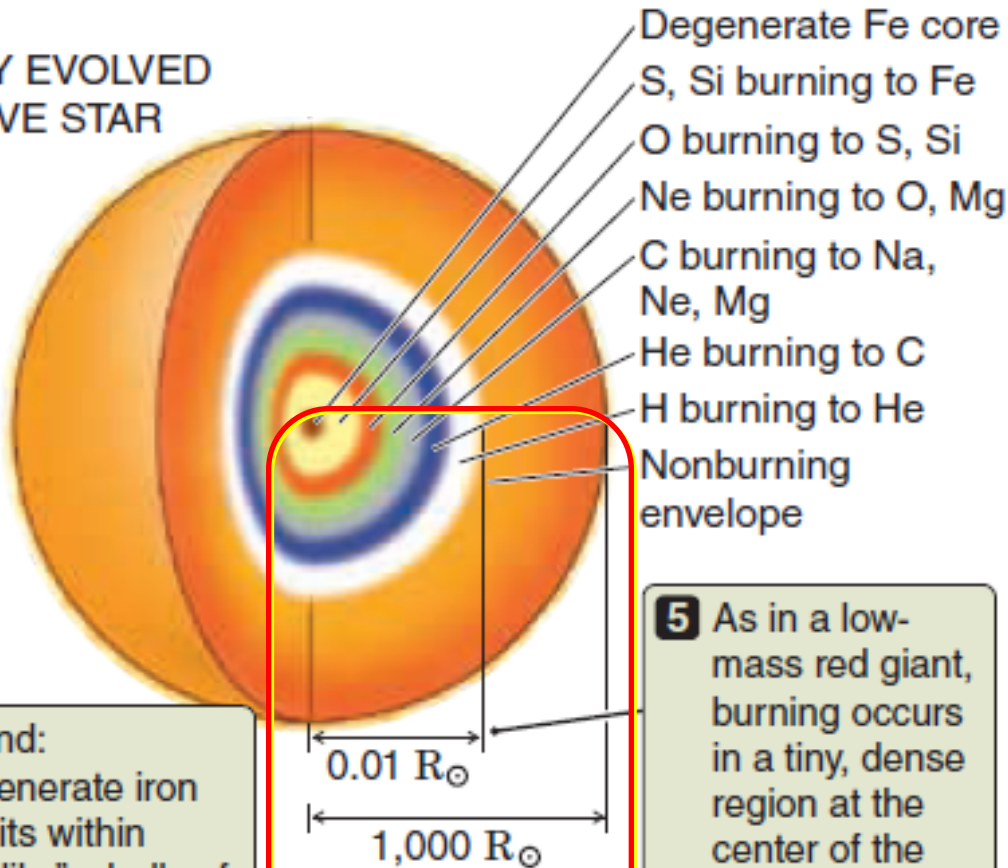
🌍 Supports star ~ 1 year

☆ Silicon fusion to iron



Fusion Cores

HIGHLY EVOLVED MASSIVE STAR



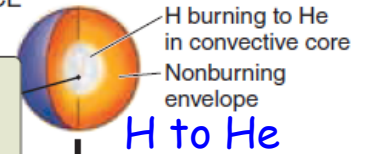
4 The end:
A degenerate iron core sits within "onionlike" shells of progressive nuclear burning.

5 As in a low-mass red giant, burning occurs in a tiny, dense region at the center of the giant bloated star.

Note Difference in scales!!

MASSIVE MAIN-SEQUENCE STAR

1 A massive main-sequence star burns hydrogen in a convective core...



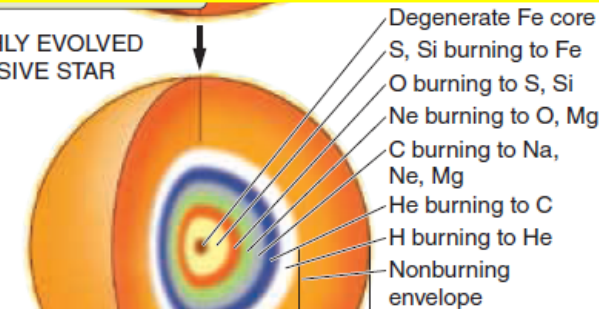
2 ...then immediately begins burning helium in its core as it leaves the main sequence.



3 The ash of one reaction becomes the fuel for the next as the star evolves a layered structure.



HIGHLY EVOLVED MASSIVE STAR

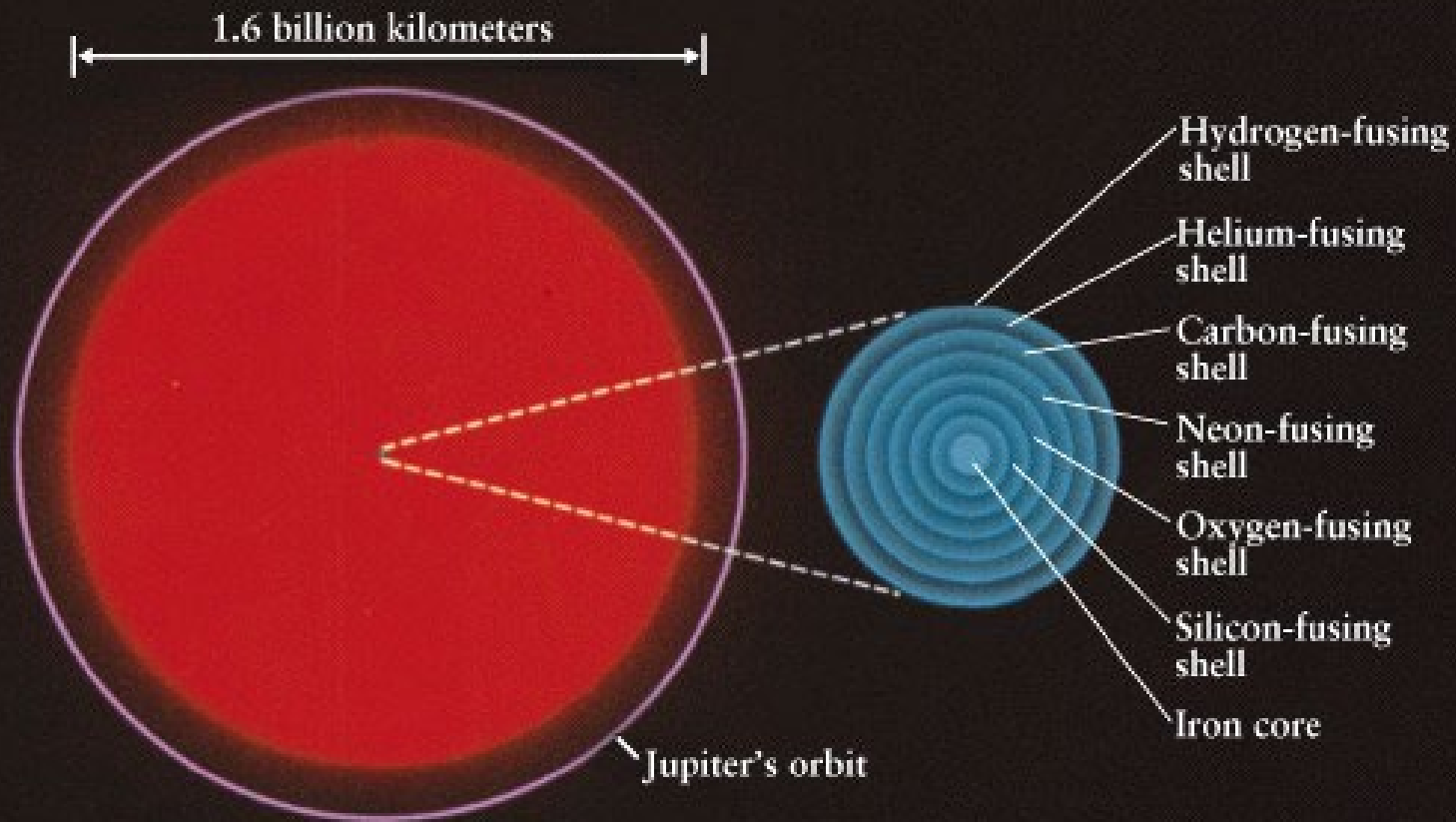


4 The end:
A degenerate iron core sits within "onionlike" shells of progressive nuclear burning.

5 As in a low-mass red giant, burning occurs in a tiny, dense region at the center of the giant bloated star.

Red Supergiants

☆ Formation of Iron Core is fatal ...



Betelgeuse, Antares ...

Outline

☆ Review Small Star Deaths

- 🌍 Star life on the Main Sequence

- 🌍 Star Deaths

 - › Sol: Red Giant, Planetary Nebula, White Dwarf

☆ Evolution of Large Stars

- 🌍 Fusion Layers & Neutrinos

- 🌍 Type II Supernovae

 - › Neutron Stars & Pulsars

☆ Types of Supernovae

- 🌍 Origins of the Elements

☆ States of Matter

Type II Supernovae

☆ Star is "onion" of fusion shells

☆ Iron core does not fuse

🌍 Iron fusion ABSORBS energy

» Iron most stable element

γ absorbs energy in fusion AND fission

🌍 Iron core builds to Chandrasekhar Limit ($1.4M_{\odot}$)

☆ Core implodes

☆ Star collapses in on itself

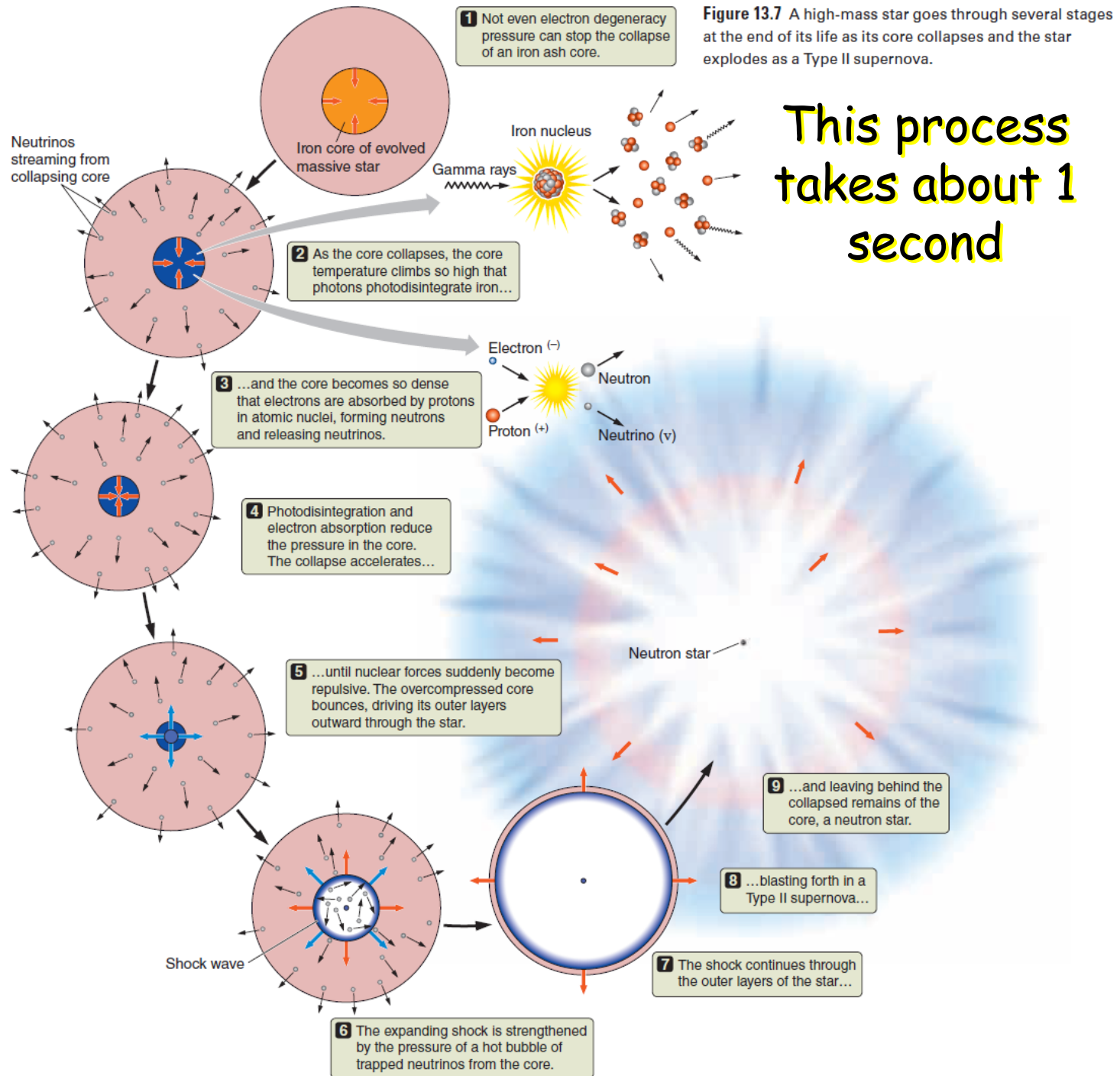
🌍 center gets very dense

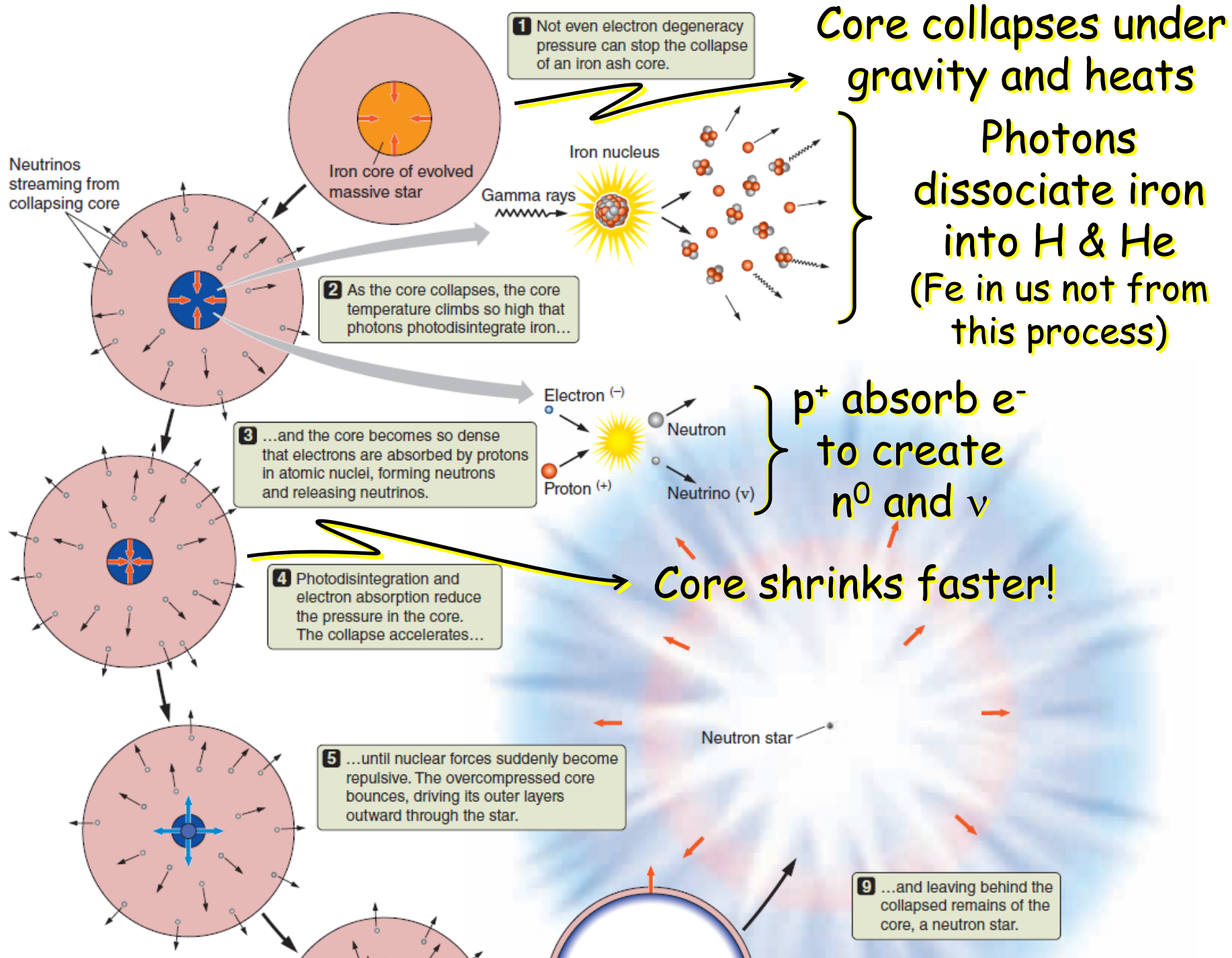
🌍 outer layers bounce off dense center

IVB	VB	VIB	VII	VIII	IX	X	XI	XII
22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn
40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd
72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg
104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn

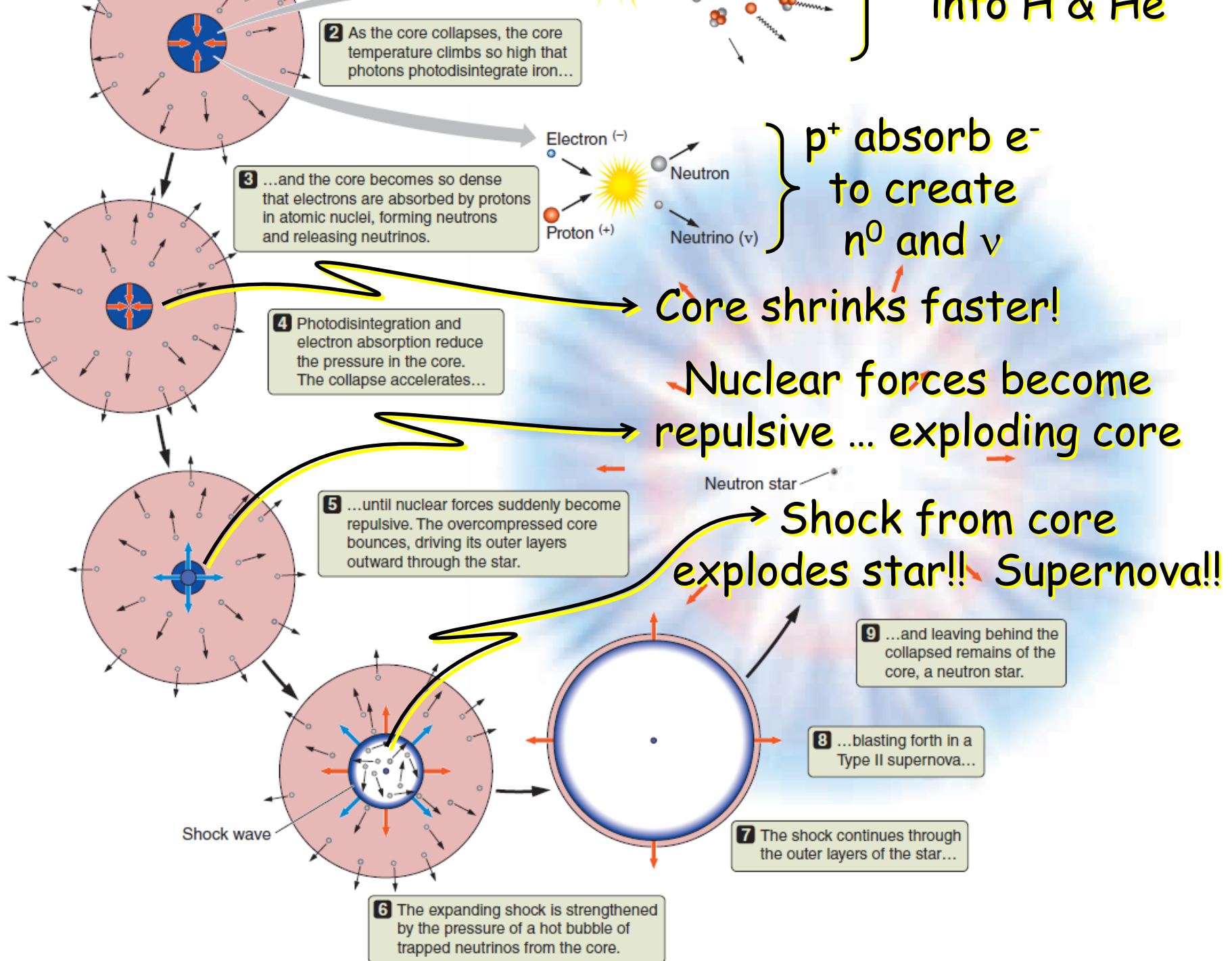
Iron - Fe
26 protons

Supernova

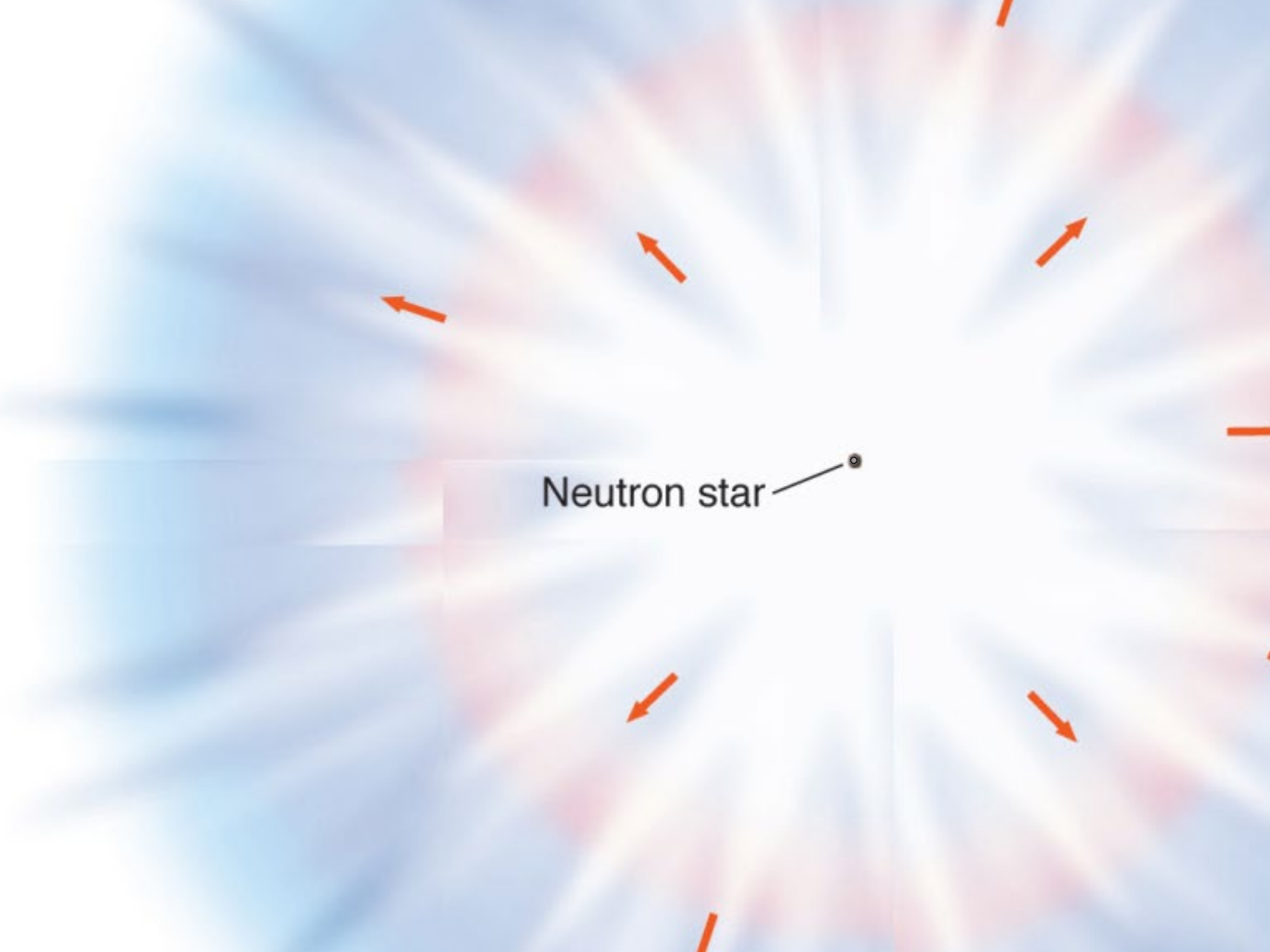




into H & He

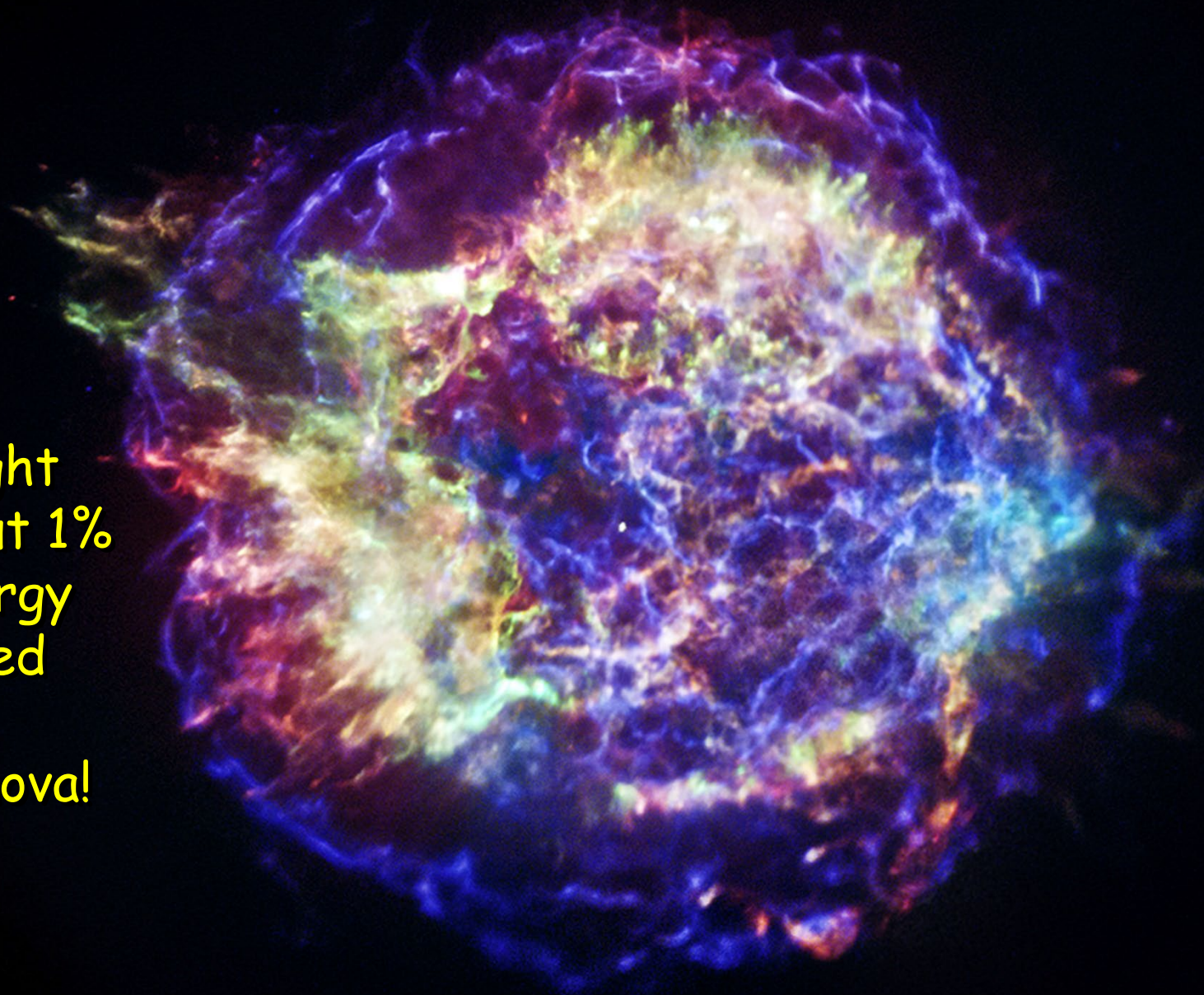


Neutron star

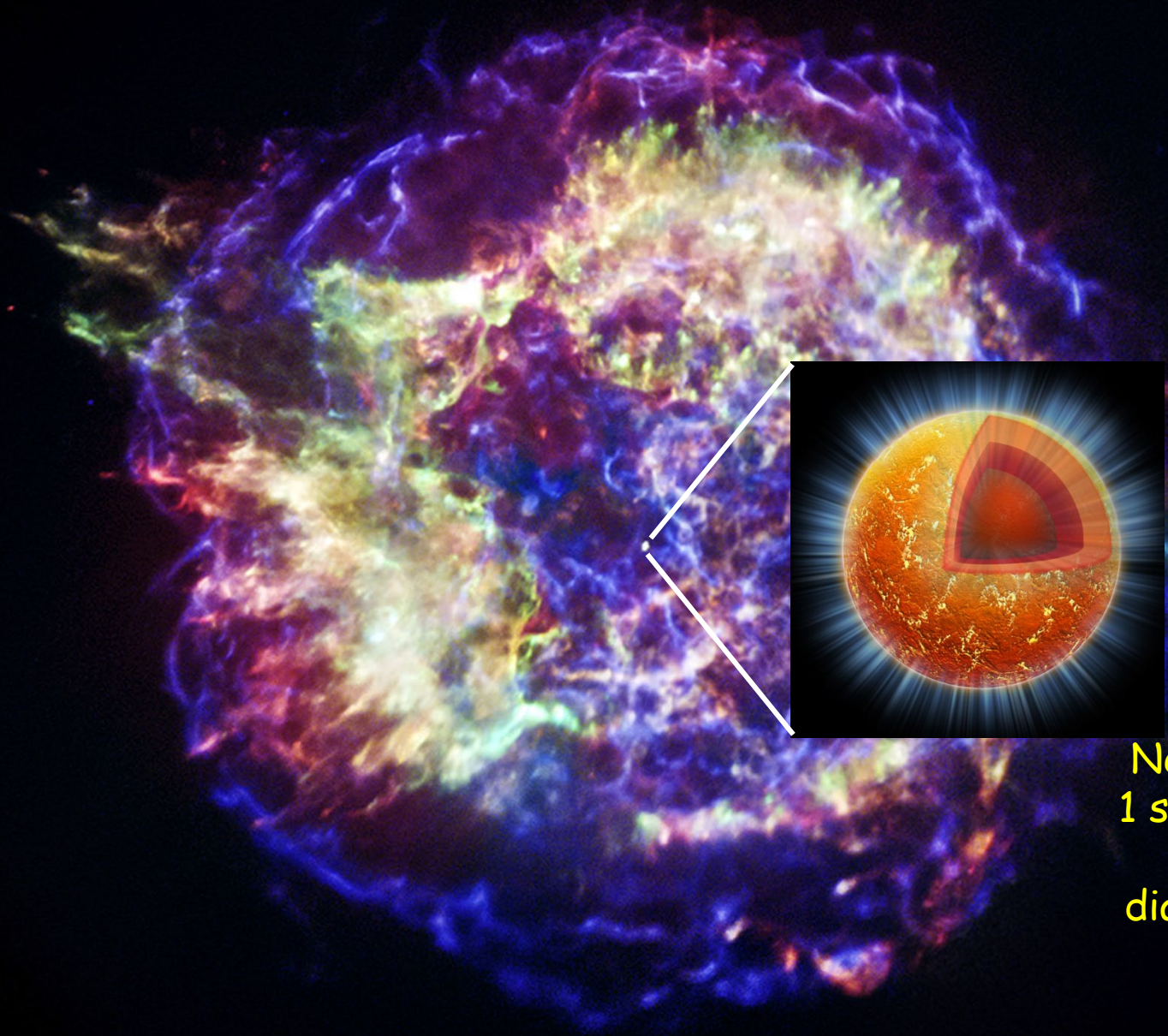


Cas A, Remnant of a Type II Supernova with a neutron star (~ 1660 s)

The light
is about 1%
of energy
released
by the
supernova!



Cas A, Remnant of a Type II Supernova with a neutron star (~1660)



Neutron star
1 solar mass in
a 10-mile
diameter ball.

Neutron Stars

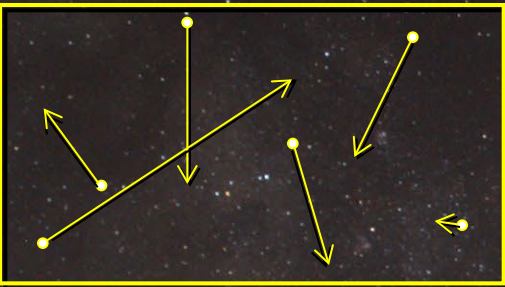
☆Dense

🌍 all **space squeezed out from within atoms**

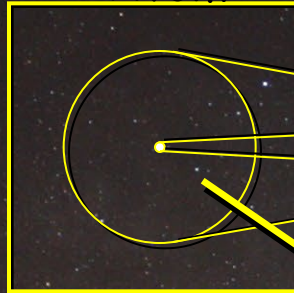
Enlarge H nucleus to size of a golf ball

The electron cloud is ~300 yards away

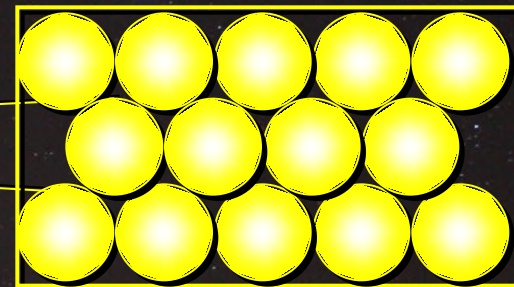
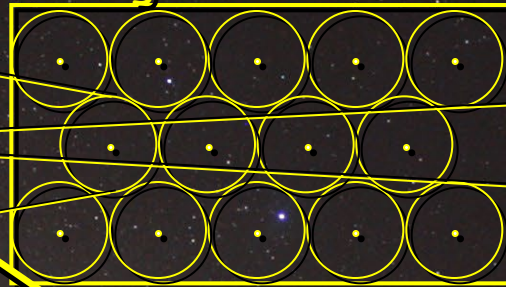
Normal Gas



Atom



Degenerate e⁻ Gas



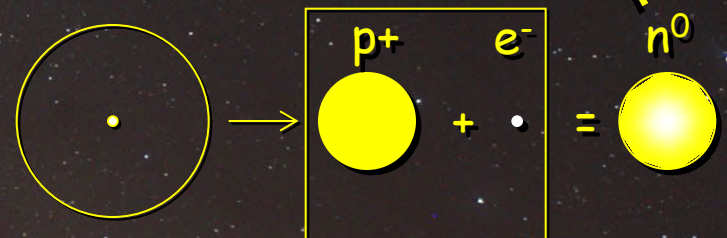
☆Rotate Very Quickly

🌍 spun up as core collapsed

☆Strong Magnetic Fields

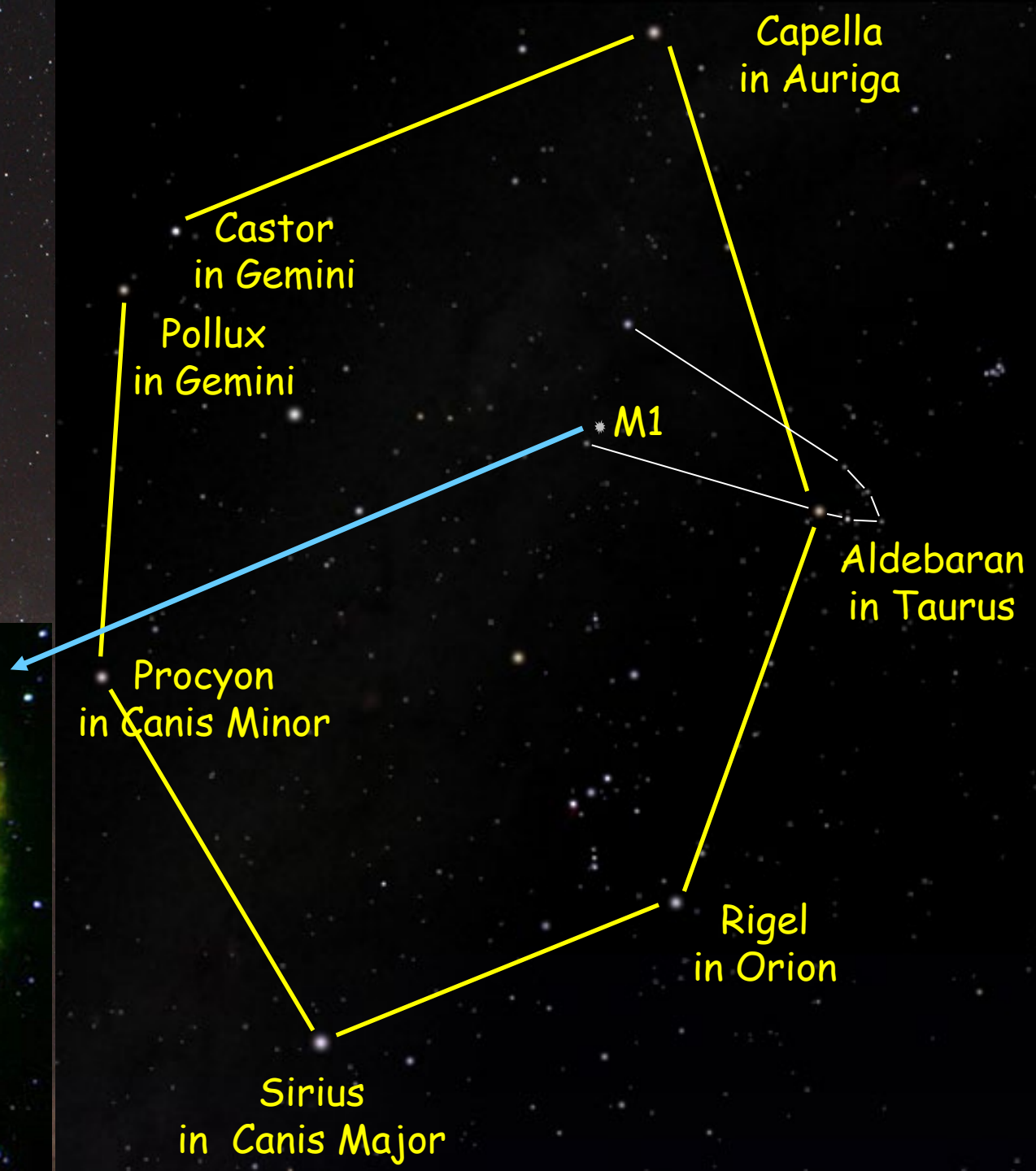
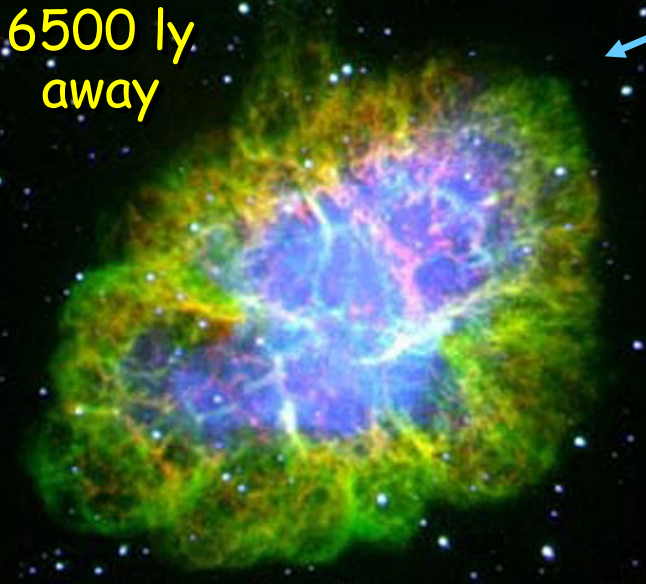
🌍 increased as core collapsed

🌍 Radiation strongly beamed along axis



Crab Nebula Supernova Observed in 1054 by Chinese & Anazazi

6500 ly
away



Capella
in Auriga

M1

Aldebaran
in Taurus

Rigel
in Orion

歷代名臣奏議卷之三百一

灾祥

宋仁宗至和二年侍御史趙抃上言曰臣伏見自去年五月已來妖
星遂見僅及周稔至今光耀未退此谷永所謂馳騁驟步芒炎長頸
所歷奸犯其為譎變甚可畏也又去冬連今春京東西路及陝右川
蜀諸郡旱暵不雨麥苗焦死民既艱食寇攘必興此京房所謂欲德
不用茲謂張厥災荒其為災沴復可懼也邇來岷峽山谷驚裂有聲
他郡數處地亦震動此伯陽所謂陽伏而不能出陰迫而不能升蓋
土失其性其為災異益可駭也夫變調陰陽者三公之職天戒若曰
陛下左右輔弼當得忠賢剛正之人為之乃可以召至和之氣消未
萌之眚不然何以妖星譎變也早暵炎沴也地震祥異也三者皆應
察明如是之著耶臣愚伏望陛下謹天之戒應天以實取天下公議
與天下瞻望之所謂賢人君子者陽之使居廟堂之上責以三公四
輔之事業要注而仰成之若然則陰陽以和災異以消朝廷清明美
狄畏服太平之風可翹足引領而待之也臣朝夕思慮載惟擇賢命
相繫國家休戚治亂之本伏願陛下慎重之然後發聖斷力行而不
疑則宗廟社稷之福天下生靈之幸

奏議卷之三百一

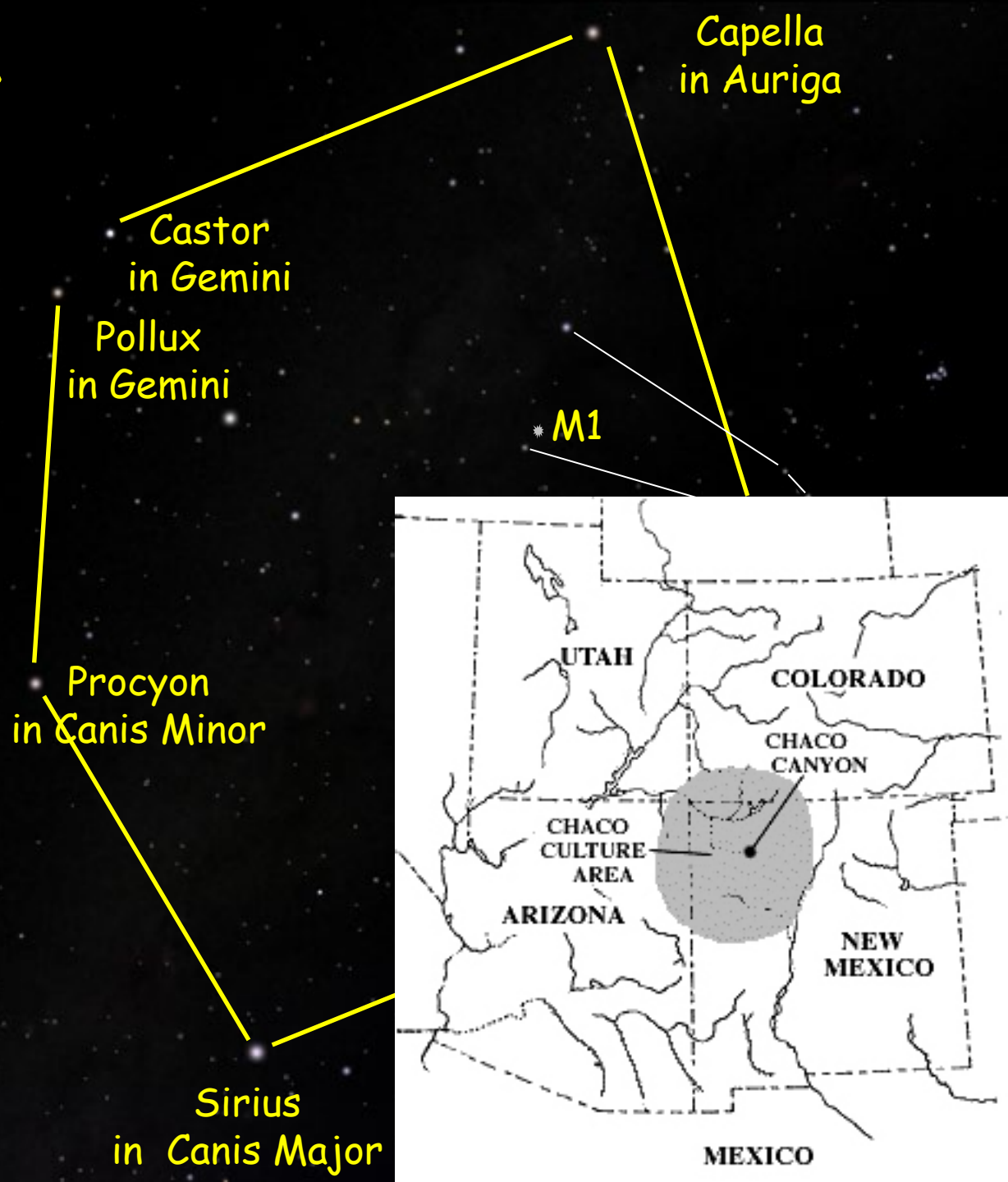
一

起居舍人知諫院范鎮上奏曰臣伏見去冬多南風今春多西北風
乍寒乍暑欲雨不雨又有黑氣蔽日此皆人事之所感動也黑氣陰
也小人也日陽也君象也黑氣蔽日者陰侵陽小人惑君也欲雨不
雨者政事不決也陳執中為相不病而家居者百日矣陛下以御史
之言決一婢死而欲退宰相為是即乞速退執中以解天意以御史
之言為非亦乞勅執中起視事無使天意久不決也寒暑者賞罰也
乍寒乍暑者不當賞而賞當罰而不罰也鄧保吉有過於法不當為



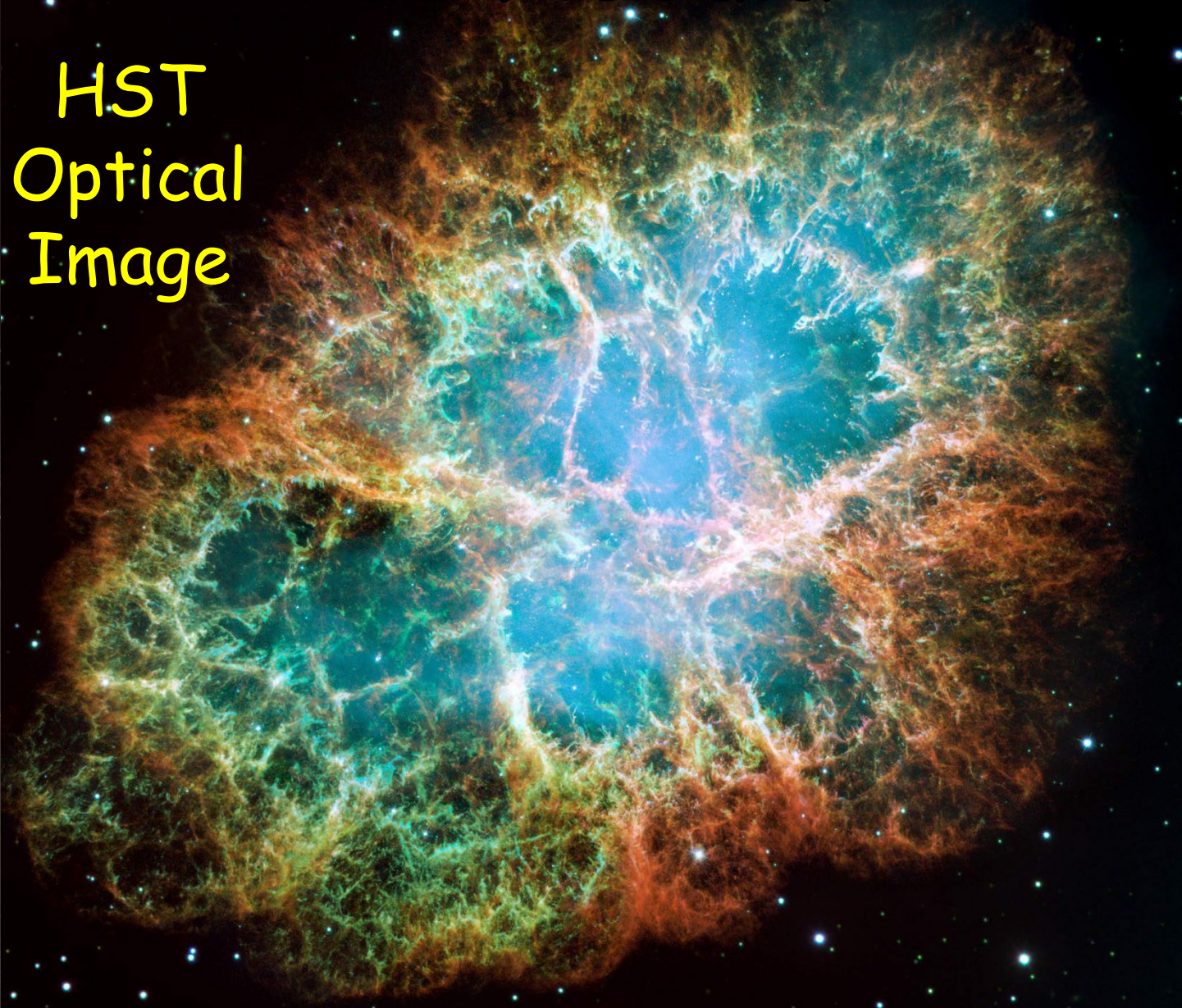
Crab Nebula

Observed 1054
by Chinese &
Anazazi in NM



Crab Nebula

HST
Optical
Image



Crab Nebula

Combined Optical, Infrared and X-ray Image



VLA Radio Image

A radio image of the Crab Nebula showing its complex, filamentary structure in shades of purple and magenta against a dark background.



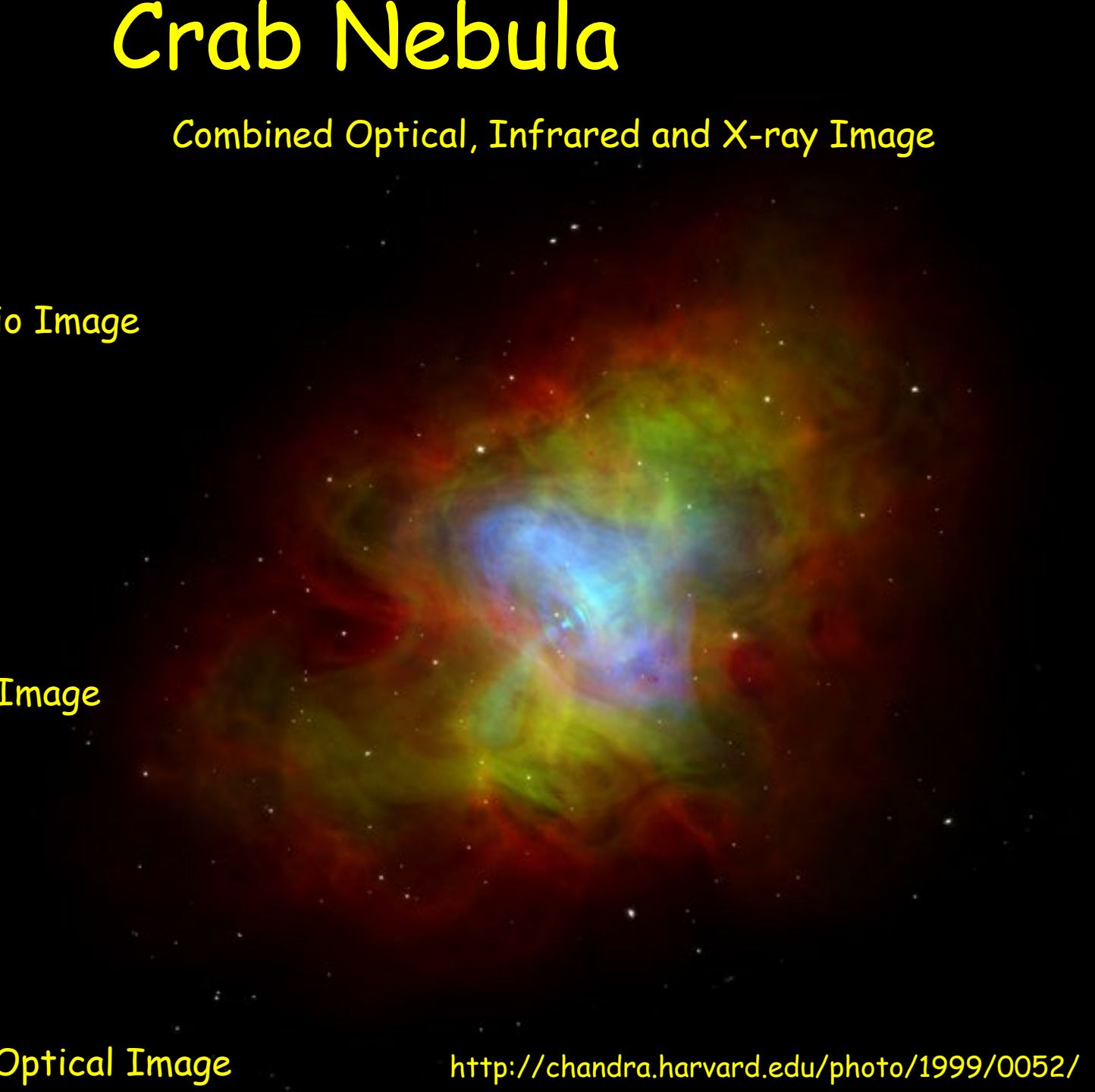
Keck IR Image

An infrared image of the Crab Nebula showing its structure in shades of red and orange, with bright, concentrated regions.



Palomar Optical Image

An optical image of the Crab Nebula showing its intricate filamentary structure in shades of green and blue, with a bright central region.



<http://chandra.harvard.edu/photo/1999/0052/>

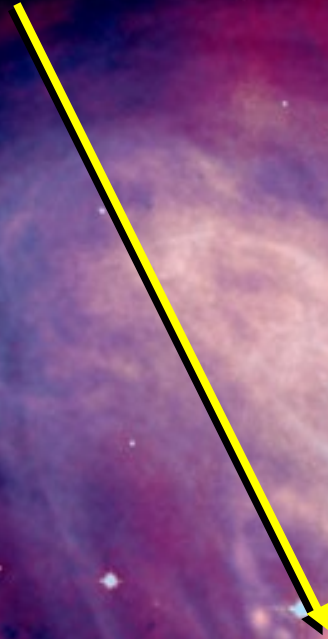
A large, detailed combined image of the Crab Nebula showing its complex structure in a wide range of colors, including red, orange, yellow, green, and blue, set against a black background with numerous stars.

Inner Crab

☆ Combined
HST optical
and Chandra
X-ray images.

☆ Pulsar
flashes 30
times per
second!

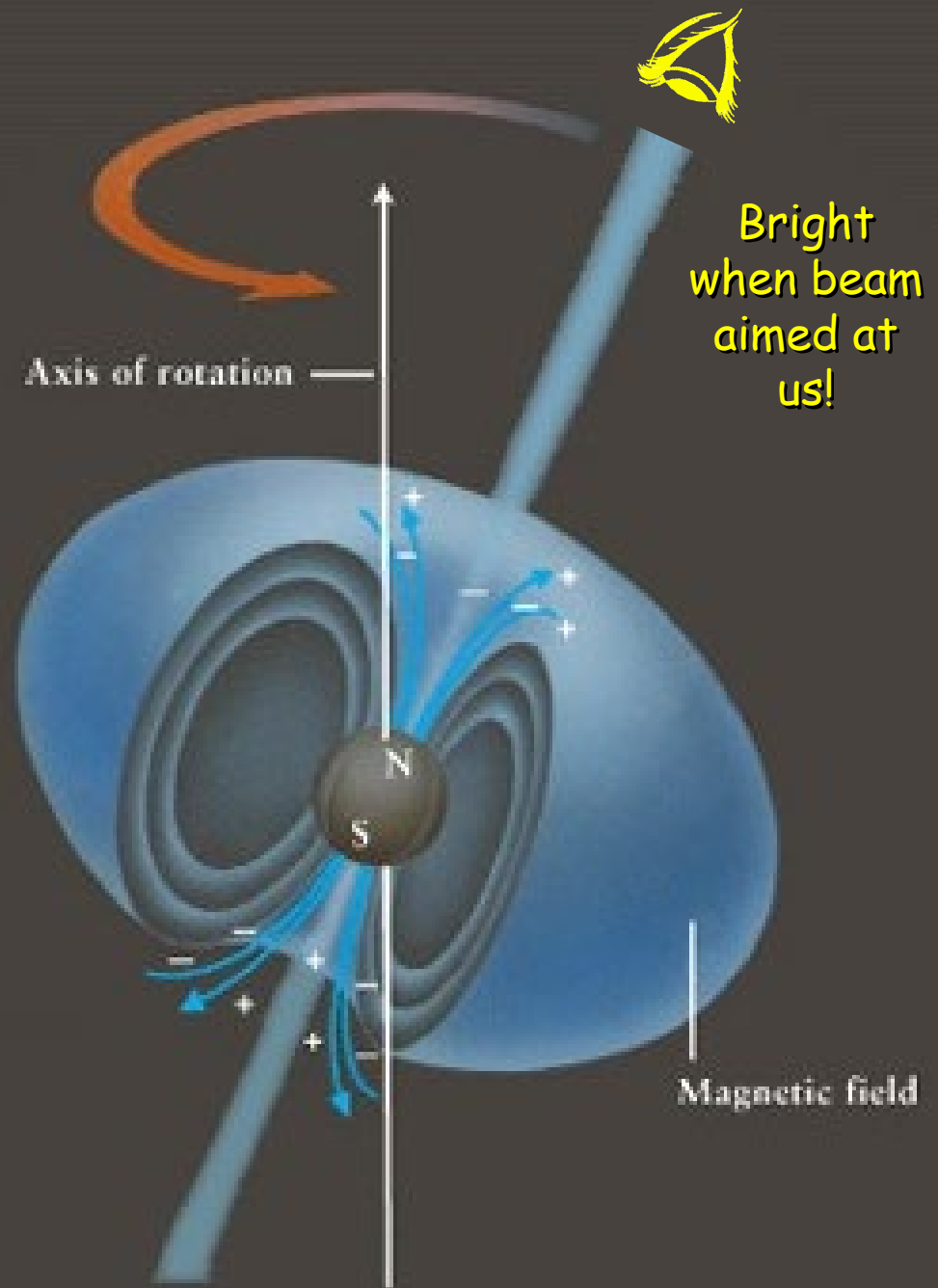
Pulsar ... a spinning neutron star!



Pulsars

☆ Rapidly Rotating Neutron Stars

- 🌐 Stars "spin-up" during collapse like spinning skaters
- 🌐 Emission "beamed" by magnetic fields
- 🌐 Bright when beam points at Earth



Crab Nebula in Motion

Chandra X-Ray Images

HST Optical Images



Pulsar rotating 30 times/second, driving emission from nebula.

Outline

☆ Review Small Star Deaths

- 🌍 Star life on the Main Sequence

- 🌍 Star Deaths

 - › Sol: Red Giant, Planetary Nebula, White Dwarf

☆ Evolution of Large Stars

- 🌍 Fusion Layers & Neutrinos

- 🌍 Type II Supernovae

 - › Neutron Stars & Pulsars

☆ Types of Supernovae

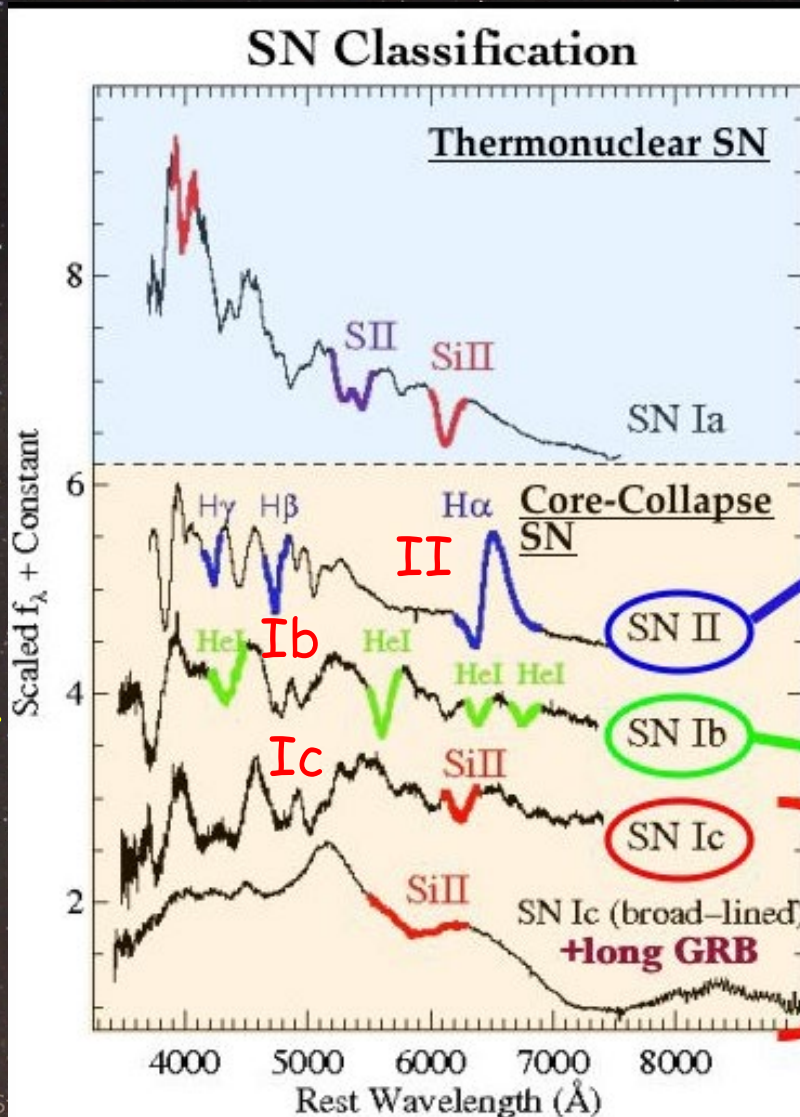
- 🌍 Origins of the Elements

☆ States of Matter

Types of Supernovae

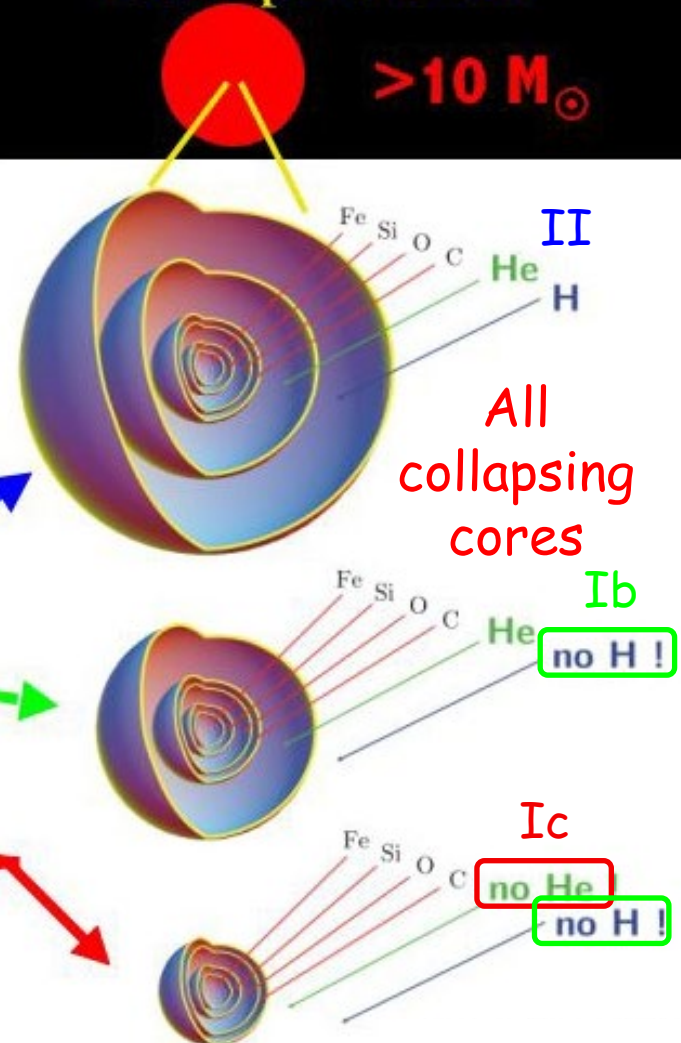
☆ Classified by their spectra

Core Collapse SNe



Pre-Explosion Star

$>10 M_{\odot}$



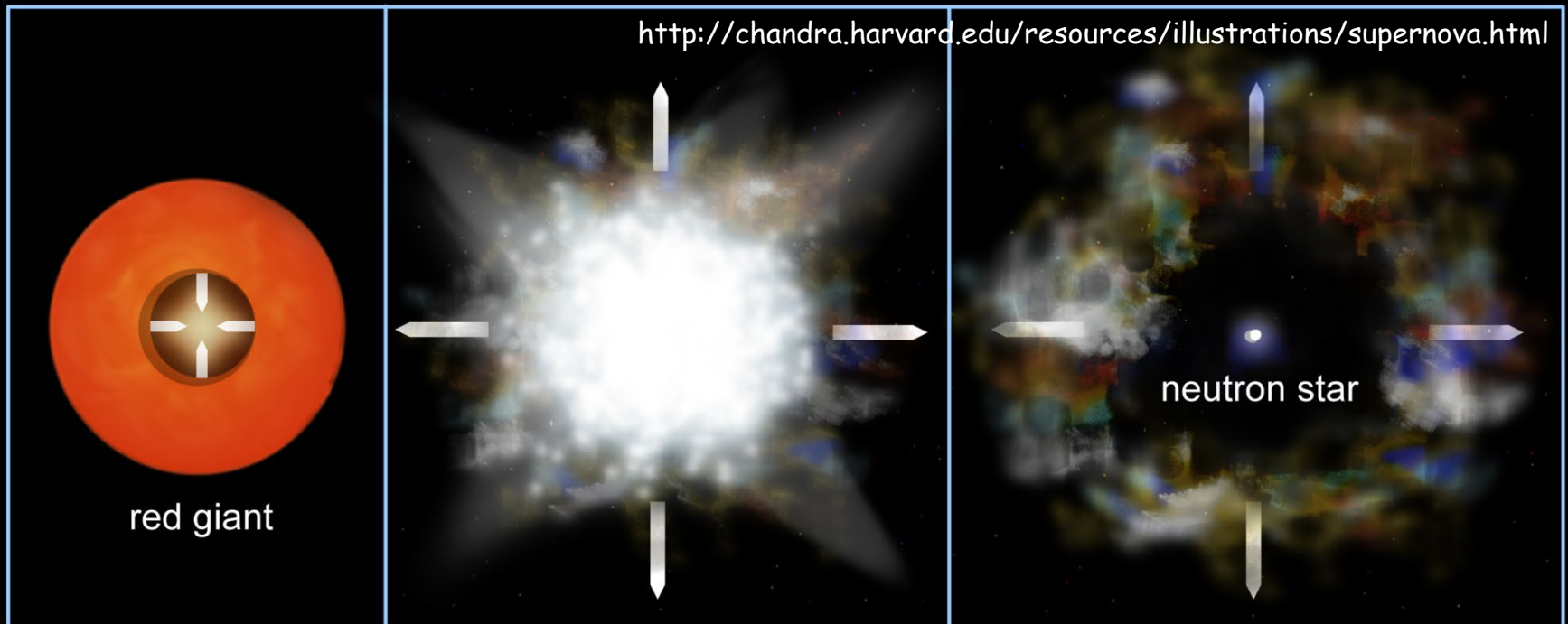
<http://cosmo.nyu.edu/~mmodjaz/research.html>

Supernovae

☆ Core Collapse SNe: Type II, Ib & Ic

🌐 Core left as neutron star, black hole or nothing

Birth of a Neutron Star and Supernova Remnant (not to scale)



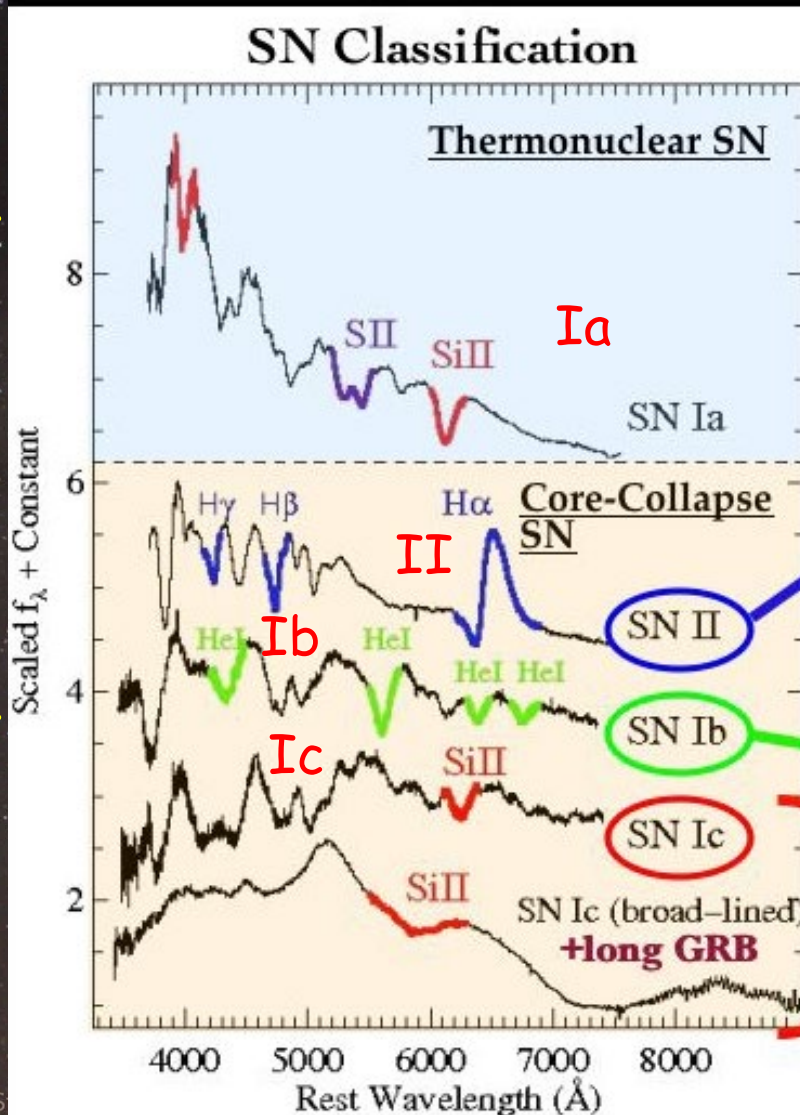
Core Implosion → Supernova Explosion → Supernova Remnant

Types of Supernovae

☆ Classified by their spectra

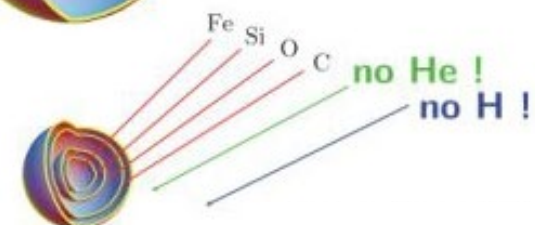
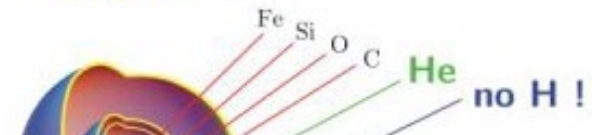
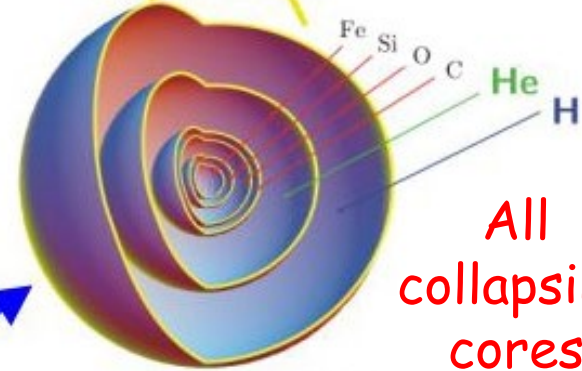
White Dwarf SNe

Core Collapse SNe



Pre-Explosion Star

$>10 M_{\odot}$



<http://cosmo.nyu.edu/~mmodjaz/research.html>

Supernovae

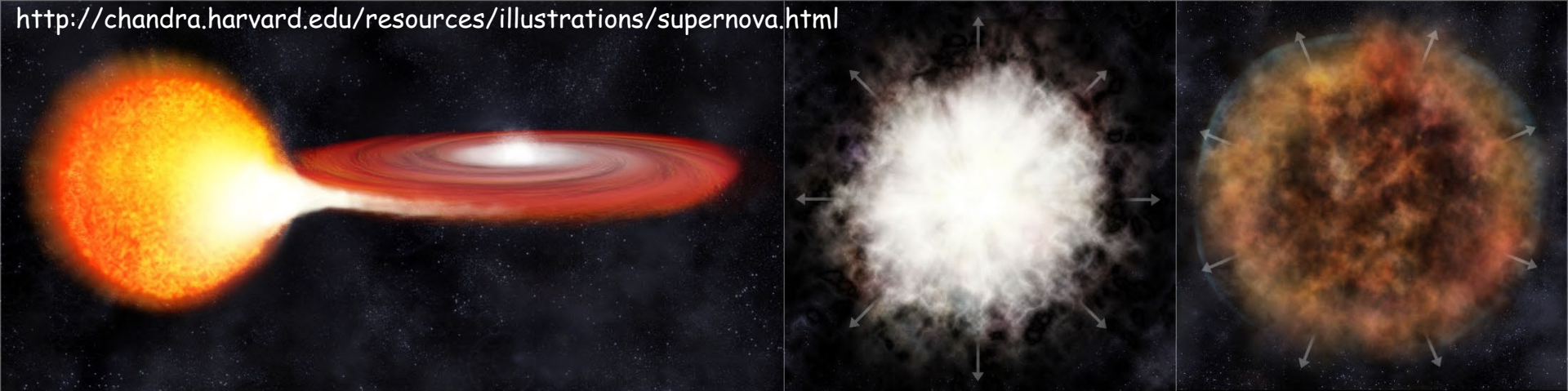
☆ White Dwarf SNe: Type Ia

- 🌍 Fusion starting in White Dwarf as it approaches $1.4 M_{\odot}$ (Chandrasekhar Limit)
- 🌍 Merger of two WDs
- 🌍 WD draws matter off companion
- 🌍 Most of Earth's Fe is from these!



TYPE IA (THERMONUCLEAR) SUPERNOVA

<http://chandra.harvard.edu/resources/illustrations/supernova.html>



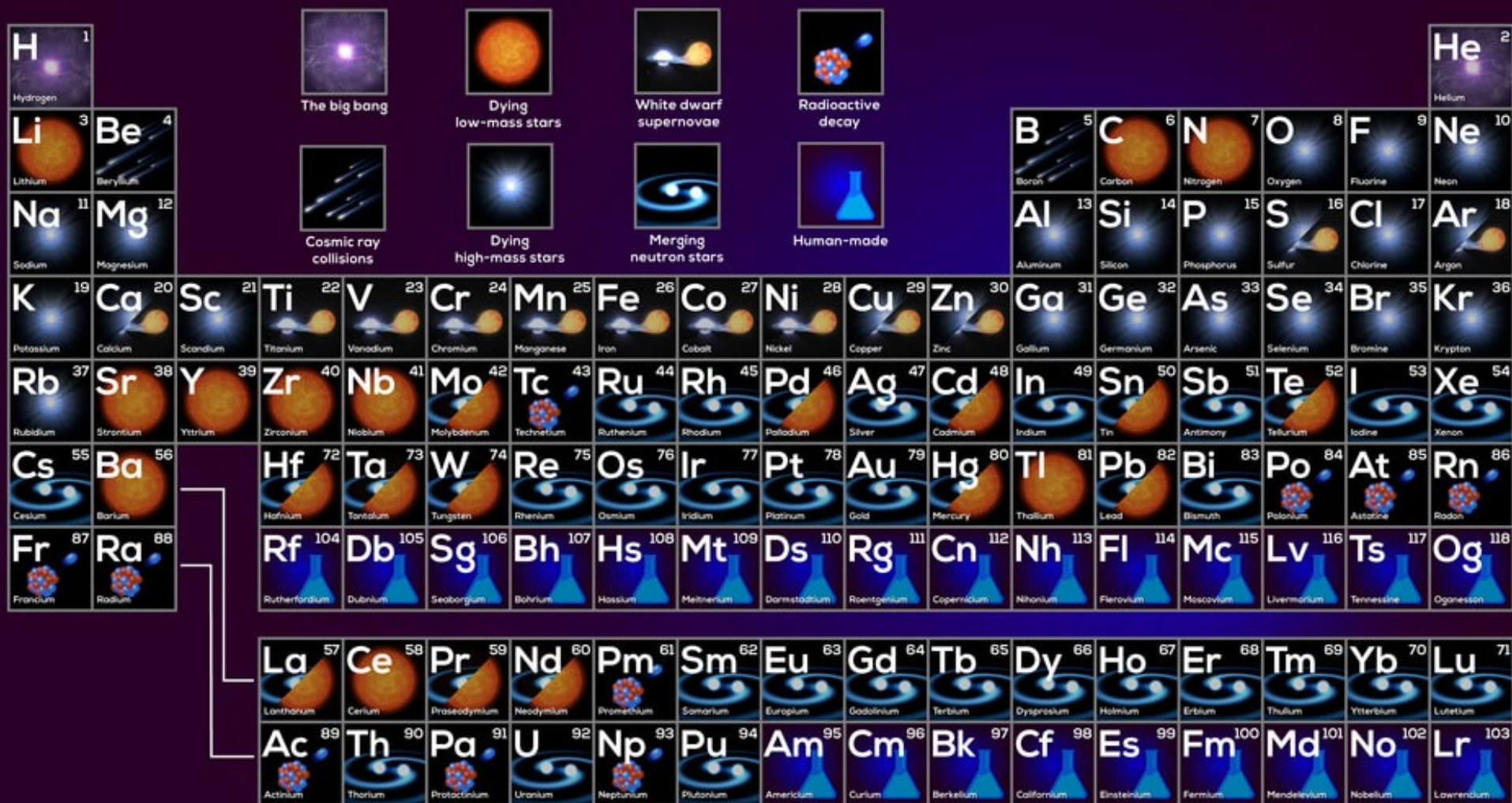
super-critical accretion onto a white dwarf star

thermonuclear supernova explosion

supernova remnant without a neutron star



ORIGINS OF THE ELEMENTS



This periodic table depicts the primary source on Earth for each element. In cases where two sources contribute fairly equally, both appear.

ORIGINS OF THE ELEMENTS



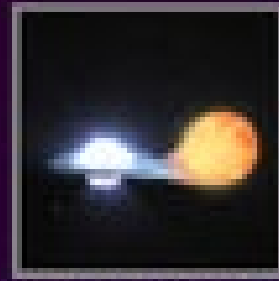
The big bang

Made from
energy!
 $E = mc^2$



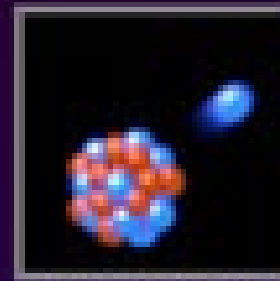
Dying
low-mass stars

Planetary
Nebulae



White dwarf
supernovae

Type Ia
Supernovae



Radioactive
decay

Arise from
other elements



Cosmic ray
collisions

CR from Sol
and SNe
explosions



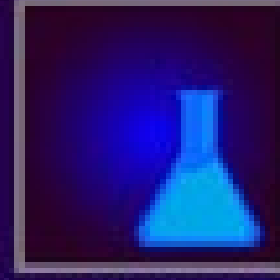
Dying
high-mass stars

Core Collapse
Supernovae



Merging
neutron stars

Neutron Stars
(not WDs!)

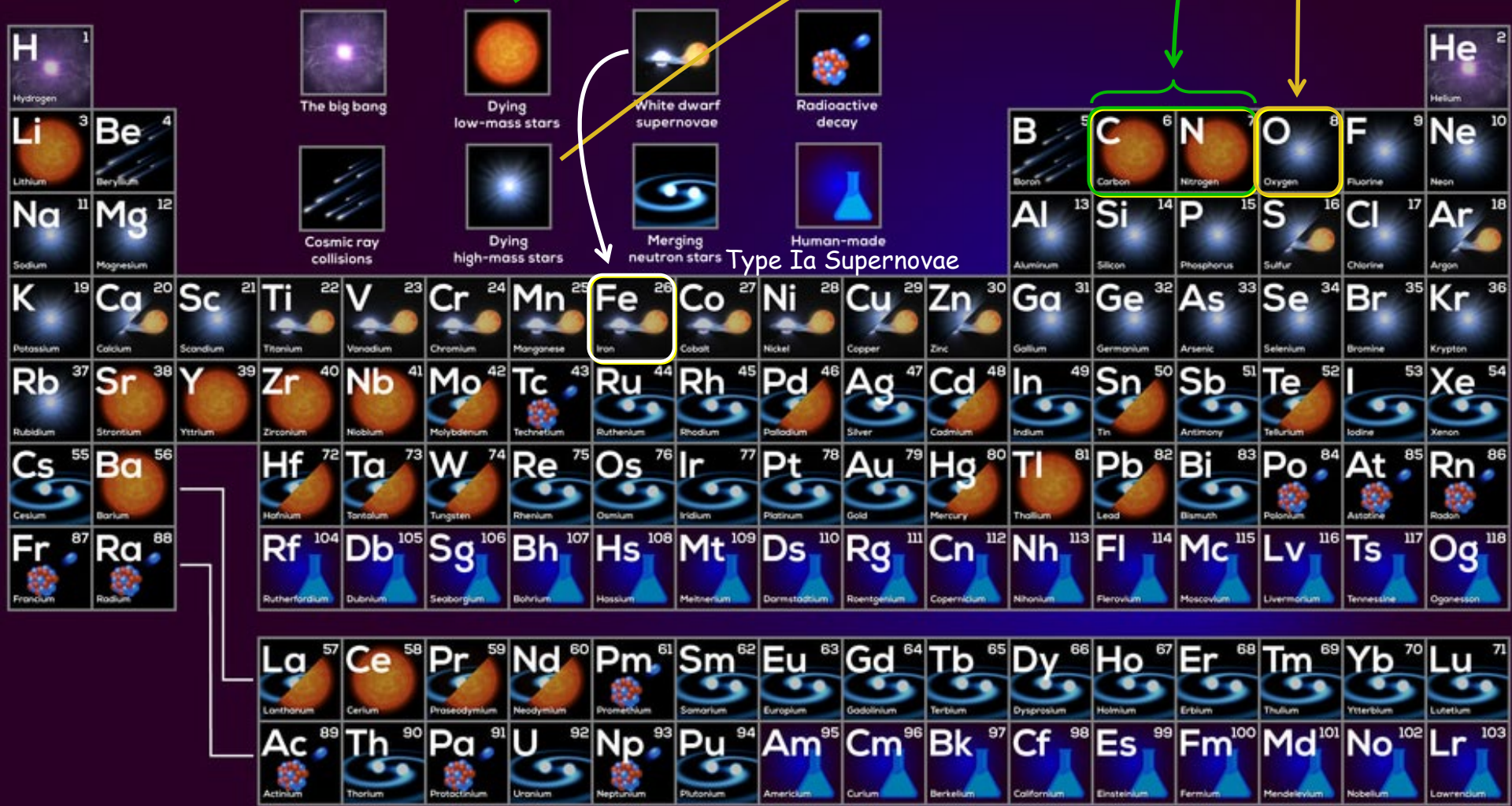


Human-made

Decay very
quickly ... not
found in nature



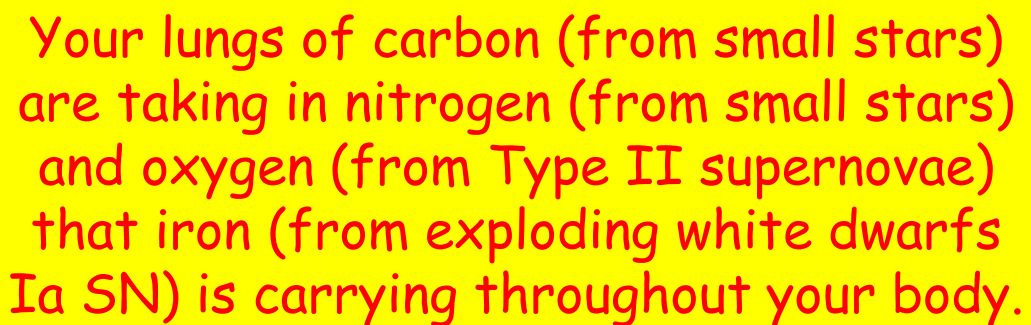
ORIGINS OF THE ELEMENTS



This periodic table depicts the primary source on Earth for each element. In cases where two sources contribute fairly equally, both appear.

Planetary Nebulae

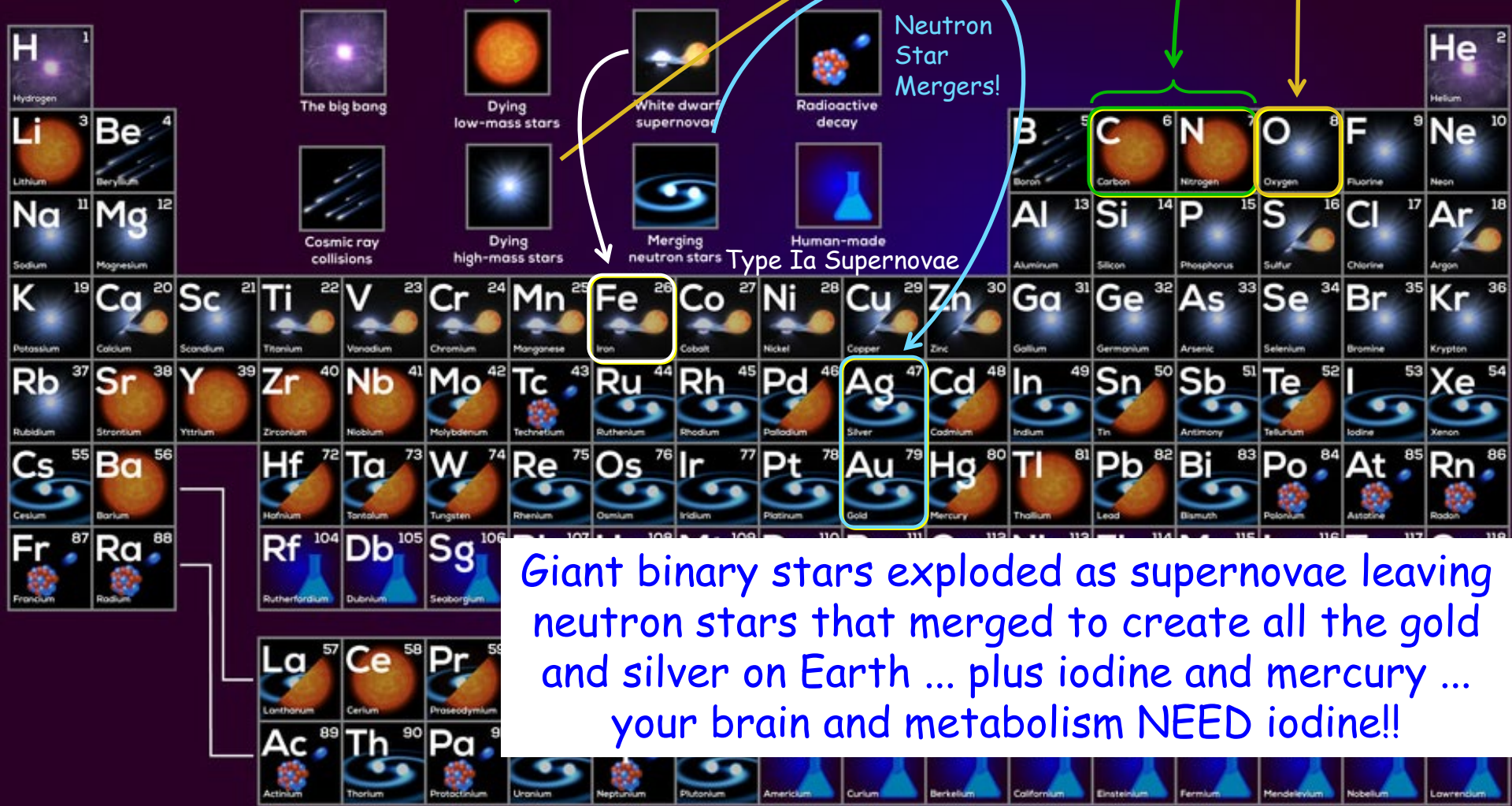
Core collapse SNe



This periodic table depicts the primary source on Earth for each element. In cases where two sources contribute fairly equally, both appear.



ORIGINS OF THE ELEMENTS



Giant binary stars exploded as supernovae leaving neutron stars that merged to create all the gold and silver on Earth ... plus iodine and mercury ... your brain and metabolism NEED iodine!!

This periodic table depicts the primary source on Earth for each element. In cases where two sources contribute fairly equally, both appear.

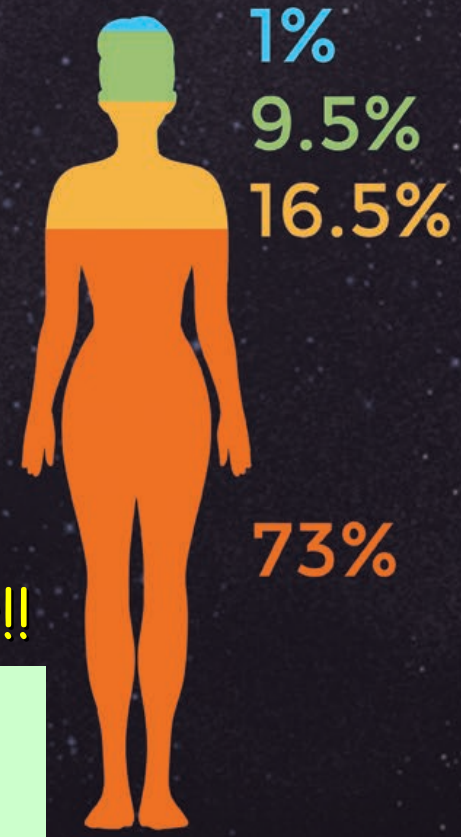
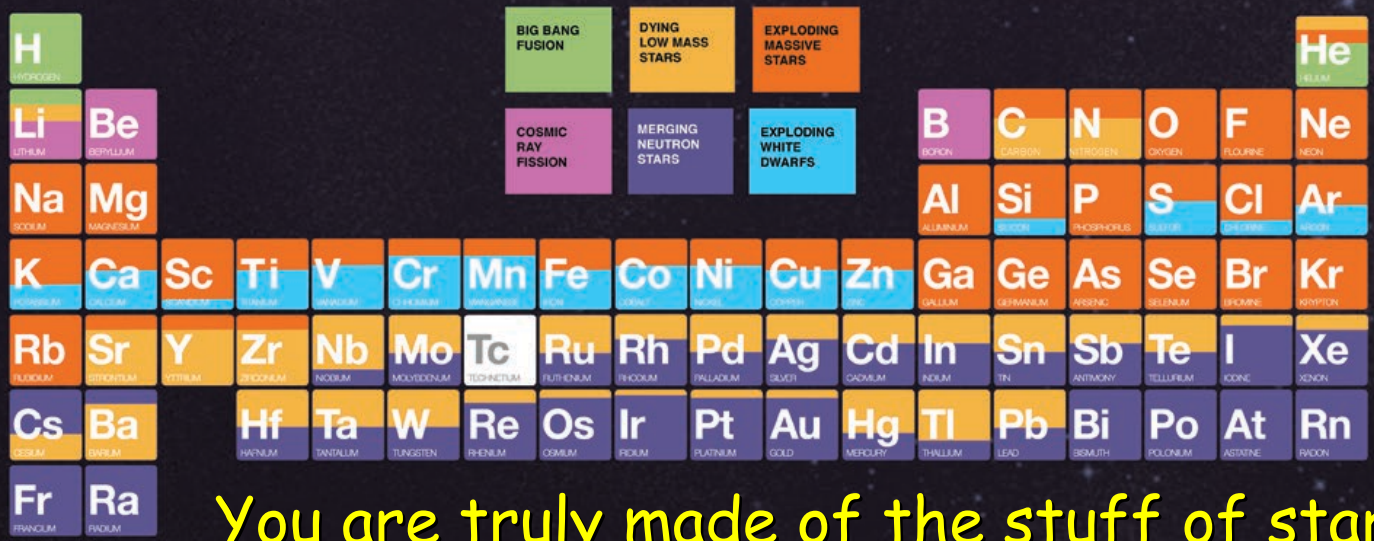


ORIGINS OF THE ELEMENTS

Planetary Nebulae

Core collapse SNe

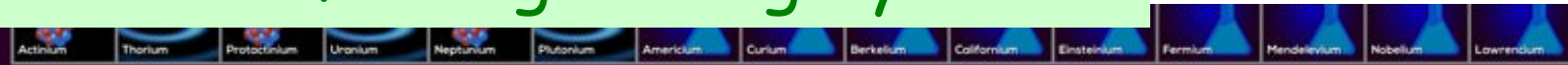
ORIGINS: SOLAR SYSTEM ELEMENTS



You are truly made of the stuff of stars!!

Breathe in ...
Breathe out ...
the universe is flowing through you ...

EED iodine!!



This periodic table depicts the primary source on Earth for each element. In cases where two sources contribute fairly equally, both appear.

Outline

☆ Review Small Star Deaths

- 🌍 Star life on the Main Sequence

- 🌍 Star Deaths

 - » Sol: Red Giant, Planetary Nebula, White Dwarf

☆ Evolution of Large Stars

- 🌍 Fusion Layers & Neutrinos

- 🌍 Type II Supernovae

 - » Neutron Stars & Pulsars

☆ Types of Supernovae

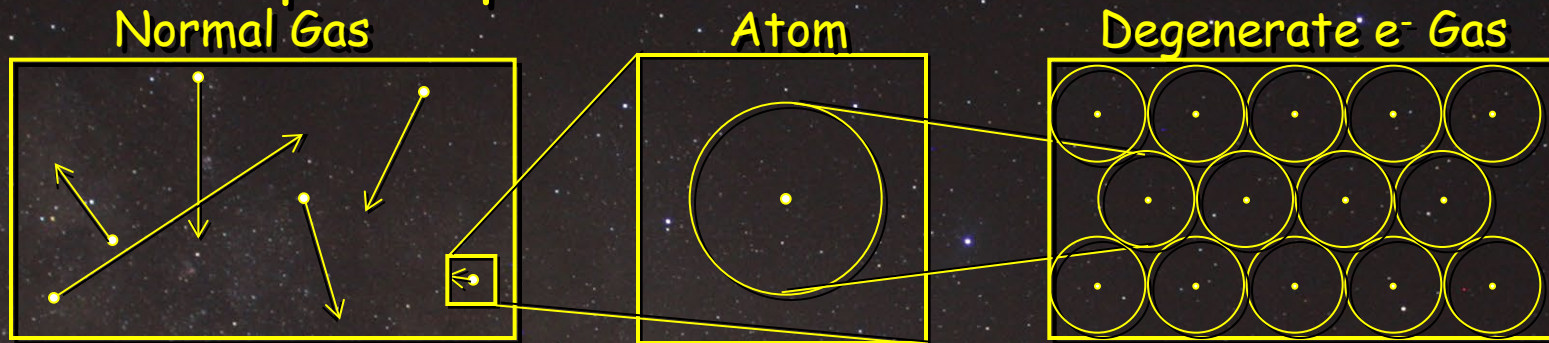
- 🌍 Origins of the Elements

☆ States of Matter

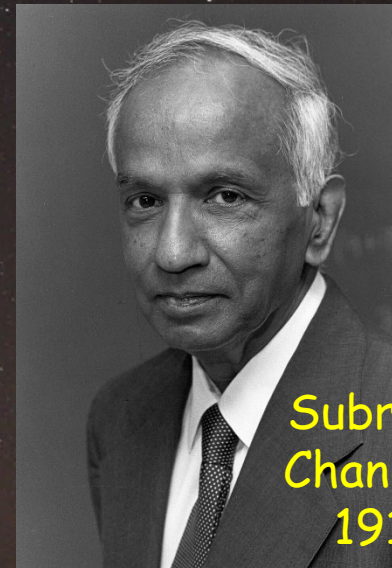
White Dwarf Stars

★ Degenerate e^- gas

- ☉ atoms packed as close as possible
 - › electron clouds packed together
 - › all space squeezed out from between atoms



- ☉ does not expand on heating
- ☉ maximum mass = $1.4 M_{\text{sol}}$
 - › Chandrasekhar Limit
 - › electron degeneracy can't hold itself up against gravity



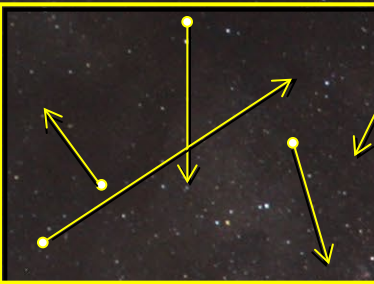
Subrahmanyan
Chandrasekhar
1910-1995

Neutron Stars

☆ All space squeezed out from within atoms

Enlarge

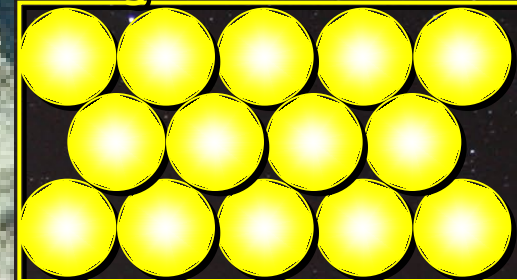
Normal Gas



Sol as a
neutron
star over
NYC

100 yards away

Degenerate n^0 Gas



☆ Rotate

🌍 spun

☆ Strong

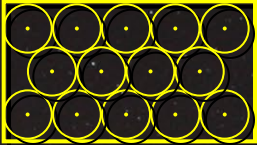
🌍 incre

🌍 Particles & radiation strongly beamed along axis

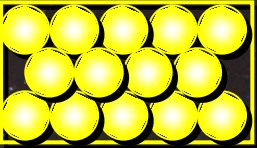
States of Matter

☆ Normal Gas  $R_{\text{Sol}} = 100R_{\text{Earth}}$

🌍 Lots of space between atoms

☆ Degenerate e^- gas  $R_{\text{Sol}} \approx R_{\text{Earth}}$

🌍 Space squeezed out from between atoms

☆ Degenerate n^0 gas  $R_{\text{Sol}} \approx 10 \text{ mi}$

🌍 Space squeezed out from within atoms

☆ Black Hole $R_{\text{Sol}} \approx 0$

🌍 Atoms squeezed out of space

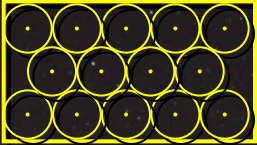
🌍 Quantum Foam

» spacetime & matterenergy recombined

States of Matter

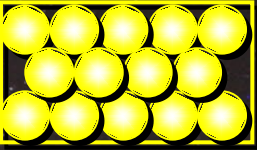
☆ Normal Gas  $R_{\text{Sol}} = 100R_{\text{Earth}}$

🌍 Lots of space between atoms

☆ Degenerate e^- gas 

$$\rho_{\text{WD}} = \frac{M_{\text{Sol}}}{V_{\text{Earth}}} = 1800 \frac{\text{kg}}{\text{cm}^3}$$

🌍 Space squeezed out from between atoms

☆ Degenerate n^0 gas 

$$\rho_{\text{NS}} = \frac{M_{\text{Sol}}}{V_{10\text{mi}}} = 100 \text{ billion } \frac{\text{kg}}{\text{cm}^3}$$

🌍 Space squeezed out from within atoms

☆ Black Hole $R_{\text{Sol}} \approx 0$

$$\rho_{\text{BH}} = \frac{M_{\text{Sol}}}{\text{zero}} \Rightarrow \infty \dots \text{OOPS!}$$

🌍 Atoms squeezed out of space

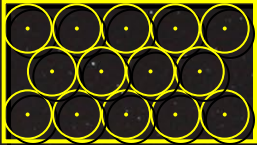
🌍 Quantum Foam

» spacetime & matterenergy recombined

States of Matter

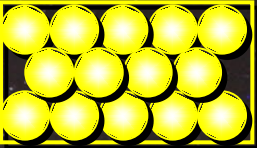
☆ Normal Gas  $R_{\text{Sol}} = 100R_{\text{Earth}}$

🌍 Lots of space between atoms

☆ Degenerate e^- gas 

$$\rho_{\text{WD}} = \frac{M_{\text{Sol}}}{V_{\text{Earth}}} = 1840 \frac{\text{kg}}{\text{cm}^3}$$

🌍 Space squeezed out from between atoms

☆ Degenerate n^0 gas 

$$\rho_{\text{NS}} = \frac{M_{\text{Sol}}}{V_{10\text{mi}}} = 100 \text{ billion } \frac{\text{kg}}{\text{cm}^3}$$

🌍 Space squeezed out from within atoms

☆ Black Hole $R_{\text{Sol}} \approx 0$

$$\rho_{\text{BH}} = \frac{M_{\text{Sol}}}{\text{zero}} \Rightarrow \infty \dots \text{OOPS!}$$

🌍 Atoms squeezed out of space

🌍 Quantum Foam

» spacetime & matterenergy recombined

Exploring the STARS!

THE ADVENTURE CONTINUES!