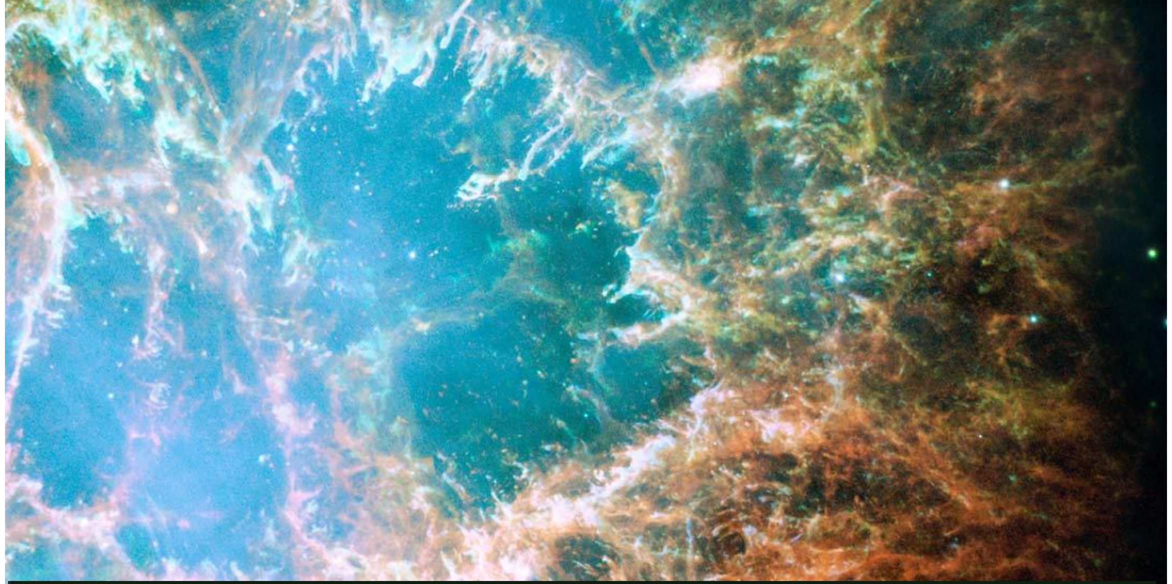
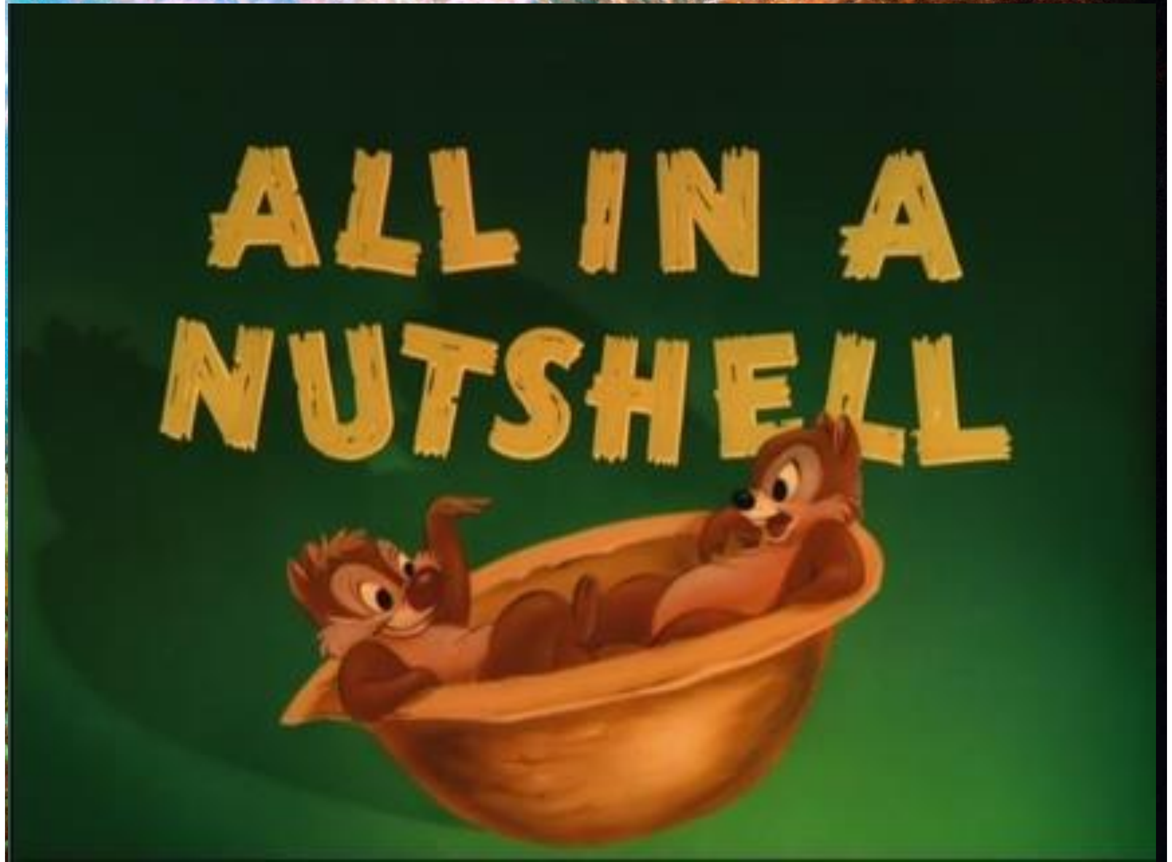
TRIUMF

Nuclear Astrophysics in a Nutshell





How stars produce heavy elements

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Adjunct Professor (University of Victoria)

Discovery, accelerated

TRIUMF is located at the South Campus of the University of British Columbia in Vancouver

Discovery, accelerated

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You can sign up to (some) TRIUMF mailing list via

http://lists.triumf.ca/mailman/listinfo

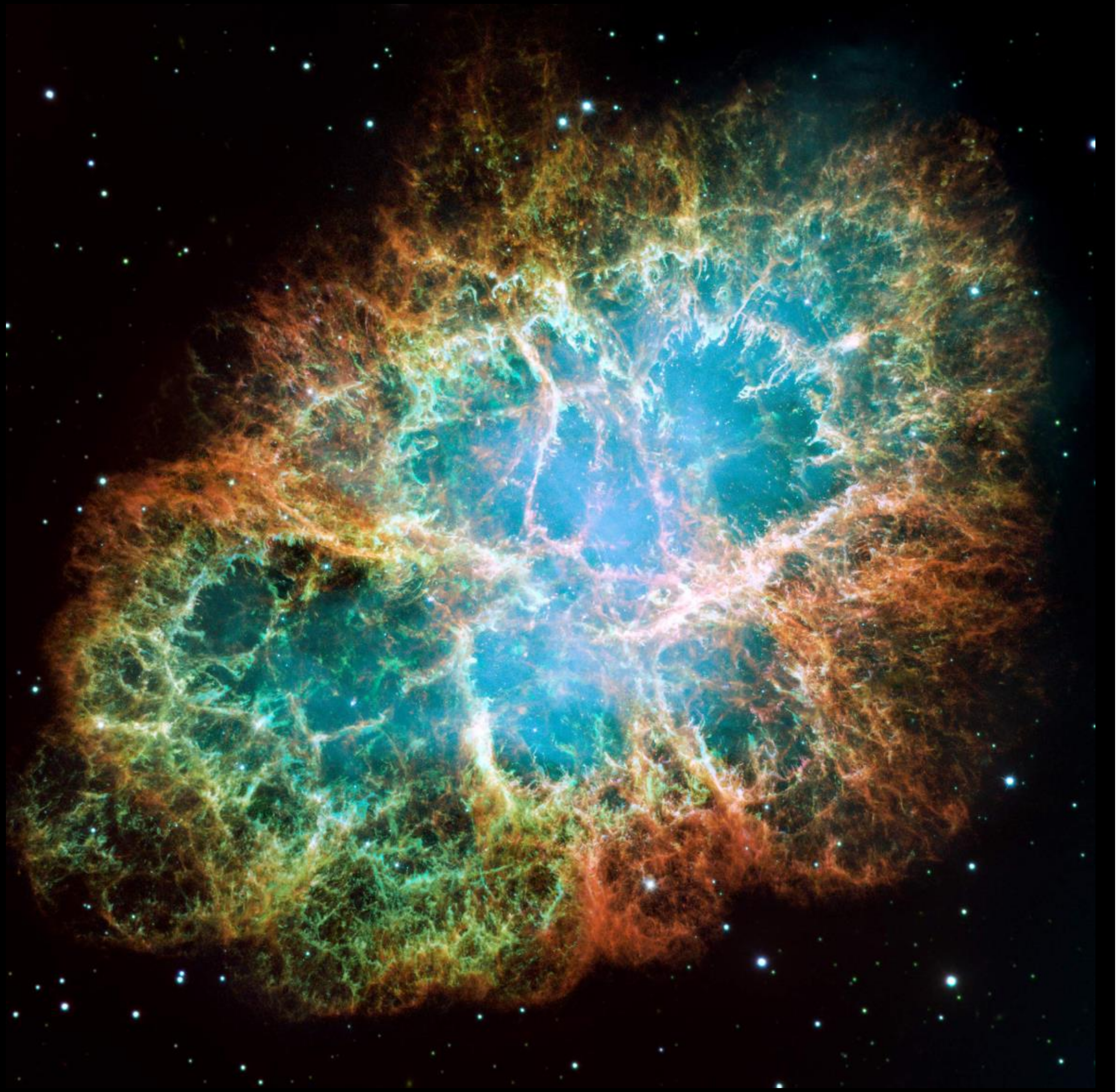
e.g.

- “Triumf-User”: TRIUMF User Group
- “Employment-opportunities”
- “Triumf-seminars”: Colloquia and seminars

“The nitrogen in our DNA,
the calcium in our teeth,
the iron in our blood,
the carbon in our apple pies
were made in the interiors of
collapsing stars.

We are made of star stuff.”

Carl Sagan
(1934-1996)



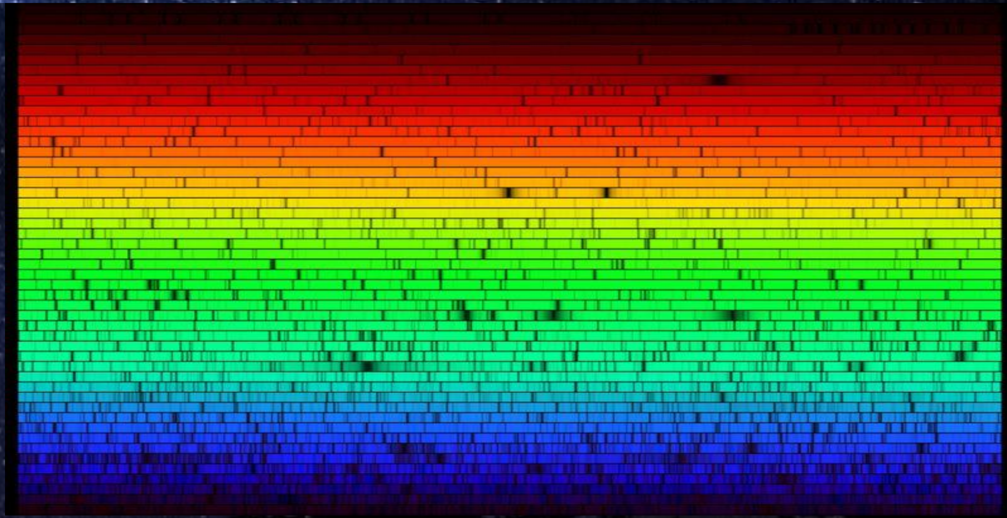
Discovery, accelerated

Each atom in our body was built and processed through **~100-1000 star generations** since the initial Big Bang event!

How do we investigate the star stuff we are made of?

- Multi-messenger Astronomy
- 3D Astrophysical Computer Simulations
- Laboratory Nuclear Astrophysics

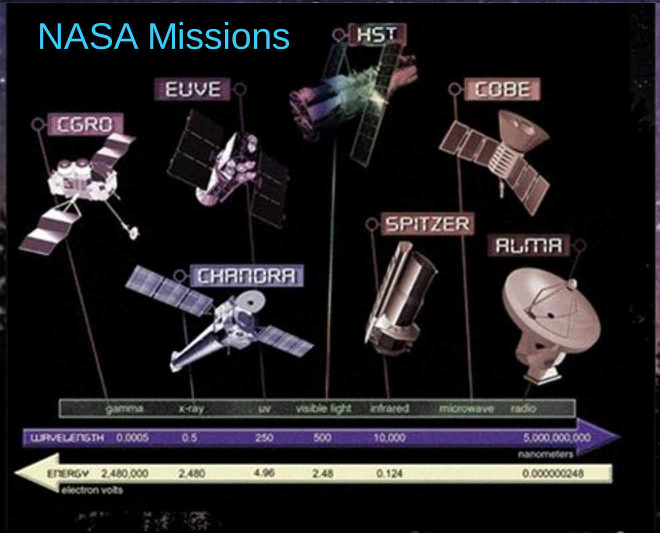
(aka. "Multi-messenger Nuclear Physics")



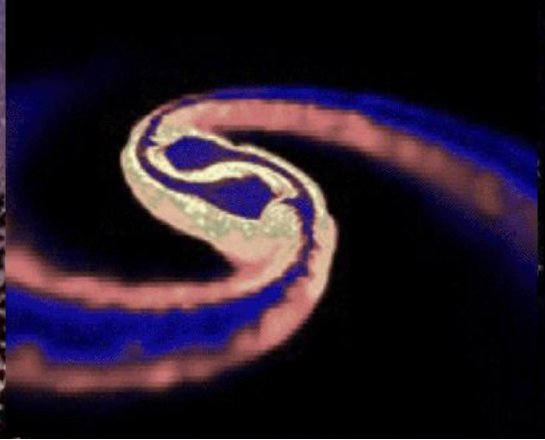
Fraunhofer absorption lines of the Sun

LIGO Livingston

NASA Missions

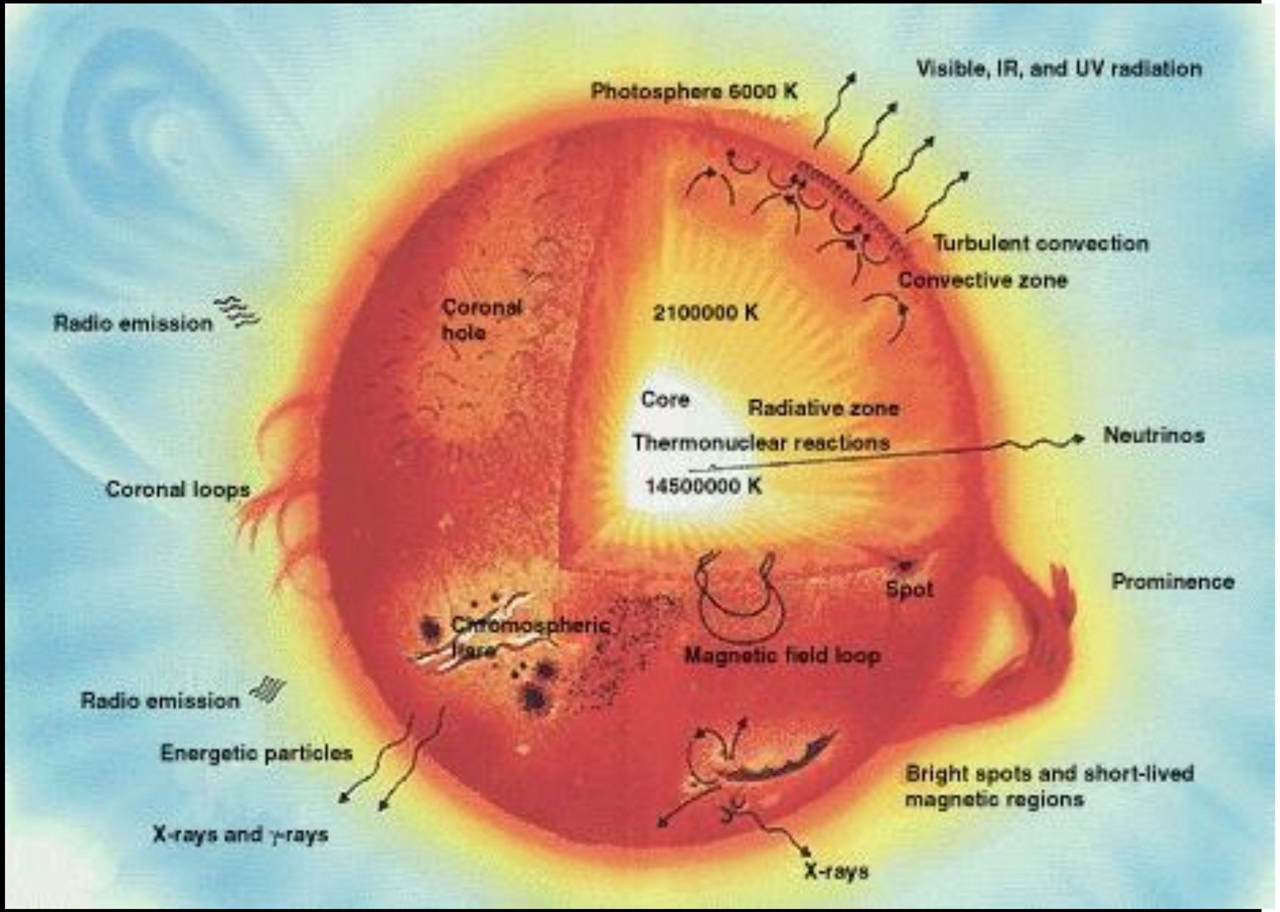


Neutron star merger simulation (Stefan Rosswog, U Stockholm)



Advanced Radioactive IsotopE Laboratory (ARIEL) at TRIUMF

The Sun- A star

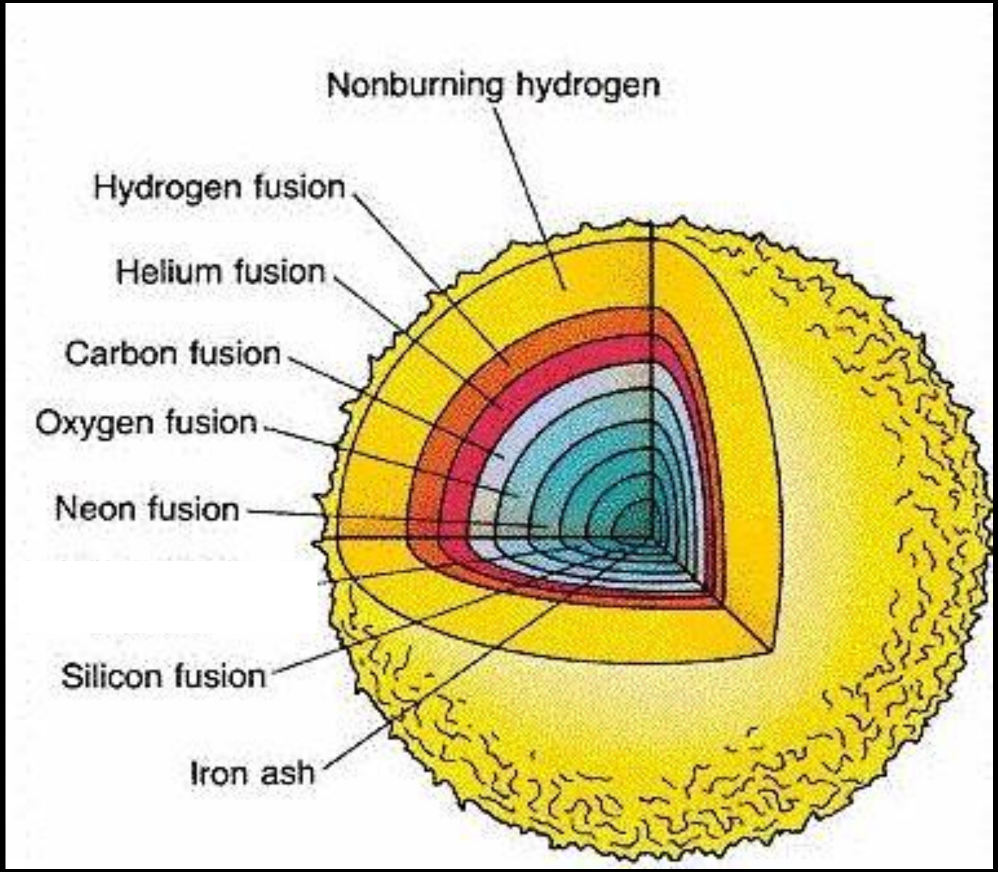


$T_{surface}$= 6000 K: *Atomic absorption lines*

T_{core}~ 15 million K: *Nuclear fusion*

Discovery, accelerated

Stellar "burning" = Nuclear reactions, fusion into heavier isotopes



Hydrostatic burning ⟷ Explosive burning

Steady burning over long timescales

During Supernova explosions, for ≈10s
Only in shells

Core burning ⟷ Shell burning

Definition of mass ranges

Solar masses

< 0.01 $M_\odot$: ***Giant Planet*** (M<13 M_{Jup})

0.01-0.08 $M_\odot$: ***Brown Dwarf*** (M=13-75 M_{Jup})

not stars

0.08 – 0.4 $M_\odot$: ***Red Dwarf*** (only core H burning)

0.4 – 1.5 $M_\odot$: ***Low mass star*** (H burning; T>100 MK: He burn.)

1.5 – 8 $M_\odot$: ***Intermediate mass star*** (H burning; T>100 MK: He burn.)

"stars"

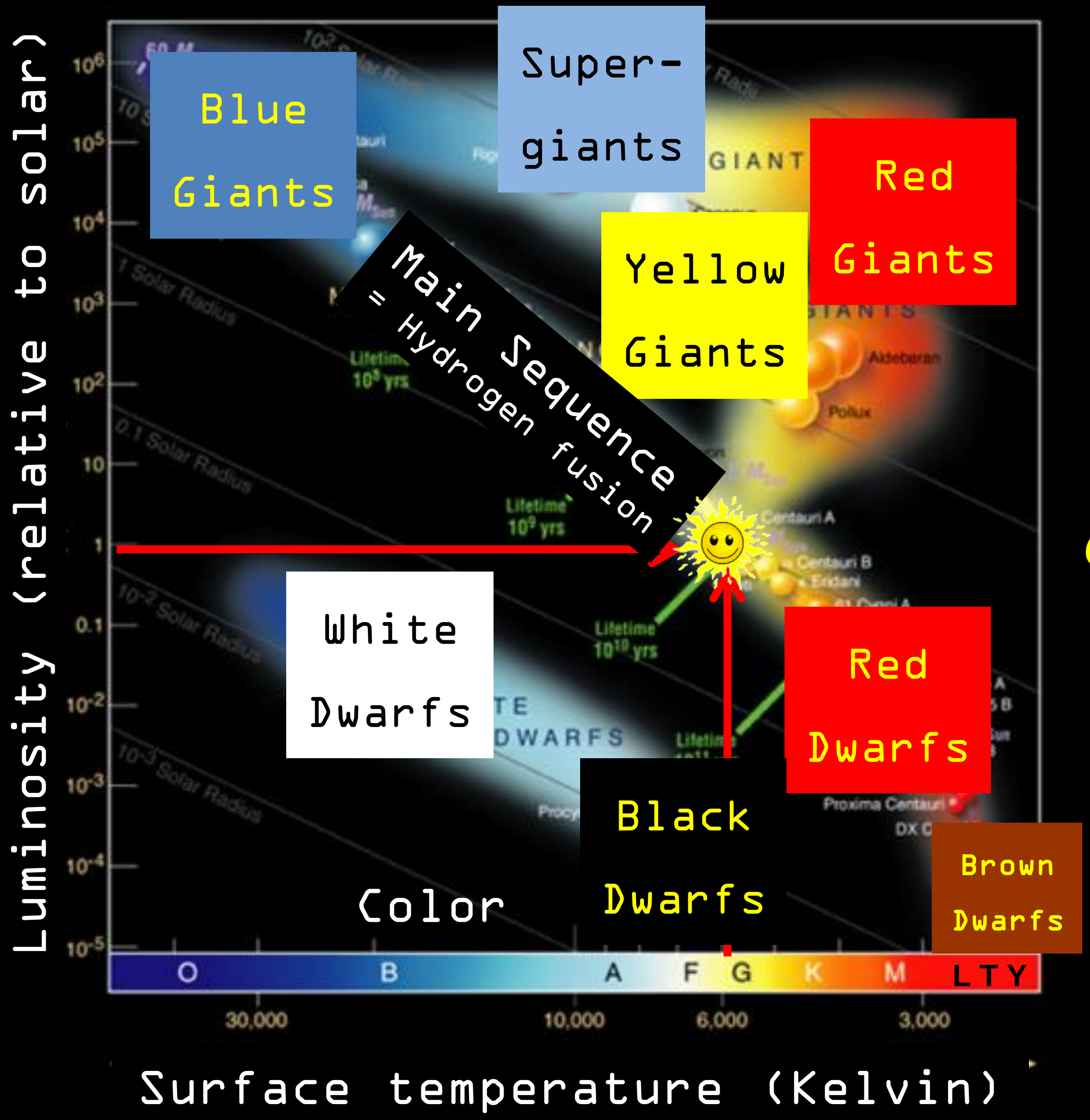
>8 $M_\odot$: ***Massive star*** (all burning phases, **Core Collapse Supernovae**)

M(sun)	M < 0.08	M > 0.08	M > 0.4 - 8	M > 8
H burning		x	x	x
He burning			x	x
C burning				x
Ne burning				x
O burning				x
Si burning				x

Advanced burning phases

“Hertzsprung-Russell diagram” (1910)

HR-diagram is a snapshot of today’s stars



Giants

and
Dwarfs

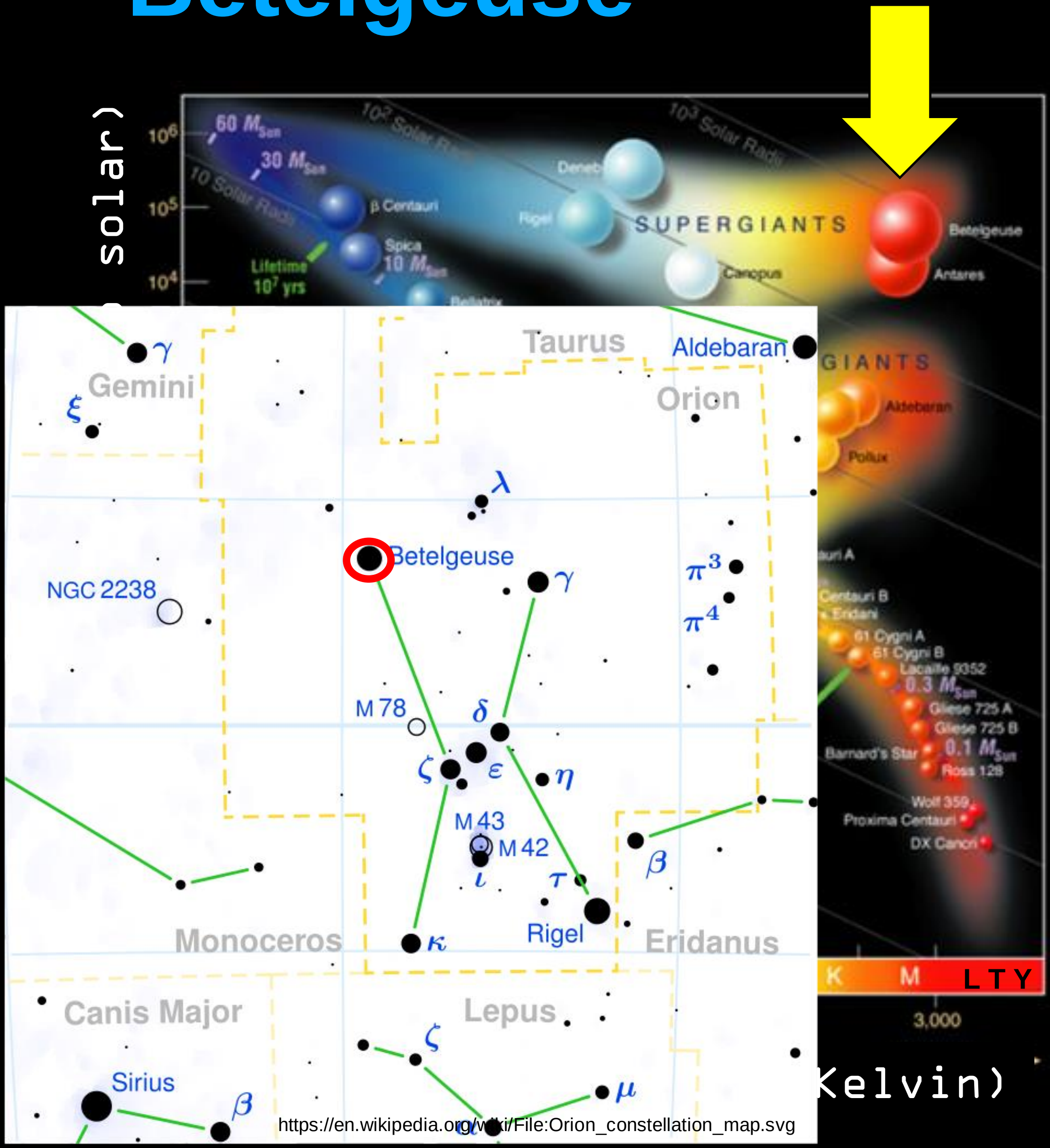
Harvard Spectral Classification:
***O**h **B**e **A** **F**ine **G**irl/**G**uy **K**iss **M**y **L**ips **T**onight (**Y**eah!)*

Brown Dwarfs

***O**range **B**usinessman, **A**wful **F**or **G**overnment. **K**eeps **M**aking **L**aughable **T**weets, **Y**es?*

Discovery, accelerated

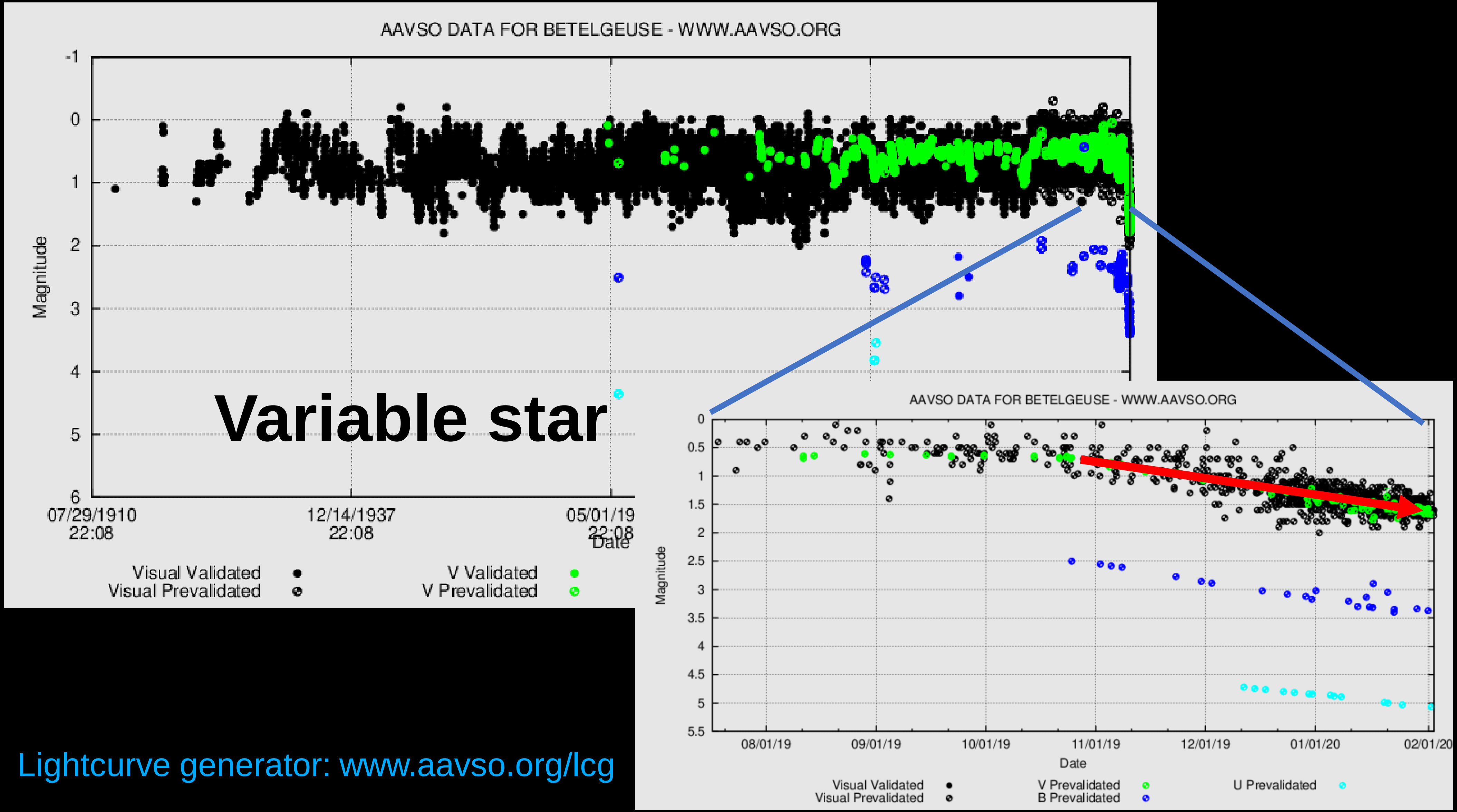
Betelgeuse



https://en.wikipedia.org/wiki/File:Orion_constellation_map.svg

- **Red Supergiant (>10 $M_\odot$)**
- Will end as **supernova** within next ~100000 years
- Age ~10 million years
- Distance **~700 light years**
- Constellation: Orion
- **Size ~3 astronomical units (AU)**
- (Was) 11th brightest star in the night sky
- Semi-regular **variable star** (varying apparent brightness)
- **Dimming observed by factor 2.5 since October 2019**

Lightcurve of Betelgeuse (since 1910)



Variable star

Lightcurve generator: www.aavso.org/lcg

Discovery, accelerated

Will Betelgeuse go supernova soon?

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SPACE

One of the brightest stars in the sky is dimming. Could it be on the verge of a supernova?

Betelgeuse has created a sense of suspense in the astronomy world, which is hoping to someday observe a nearby supernova in real time.

SPACE.com

News Tech Spaceflight

TRENDING Best Telescopes Spac

Space is supported by its audience. When you pu

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Will Bright Star Betelgeuse Finally Explode? A Look at the Dimming Red Giant in Orion's Shoulder

By Chelsea Gohd 2020-01-03T12:23:17Z

It can't hurt to look up at the night sky just in case.

The New York Times

Waiting for Betelgeuse to Explode

By Jonathan Corum Jan. 9, 2020

cnet

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Massive star Betelgeuse continues to act weird on an unprecedented scale

Just a few months ago it was 2.5 times brighter, which means it could be thrashing around preparing to explode.

Eric Mack February 3, 2020 10:13 AM PST

LISTEN - 01:34

Betelgeuse is a gigantic red supergiant star that was the 10th brightest star in the sky as recently

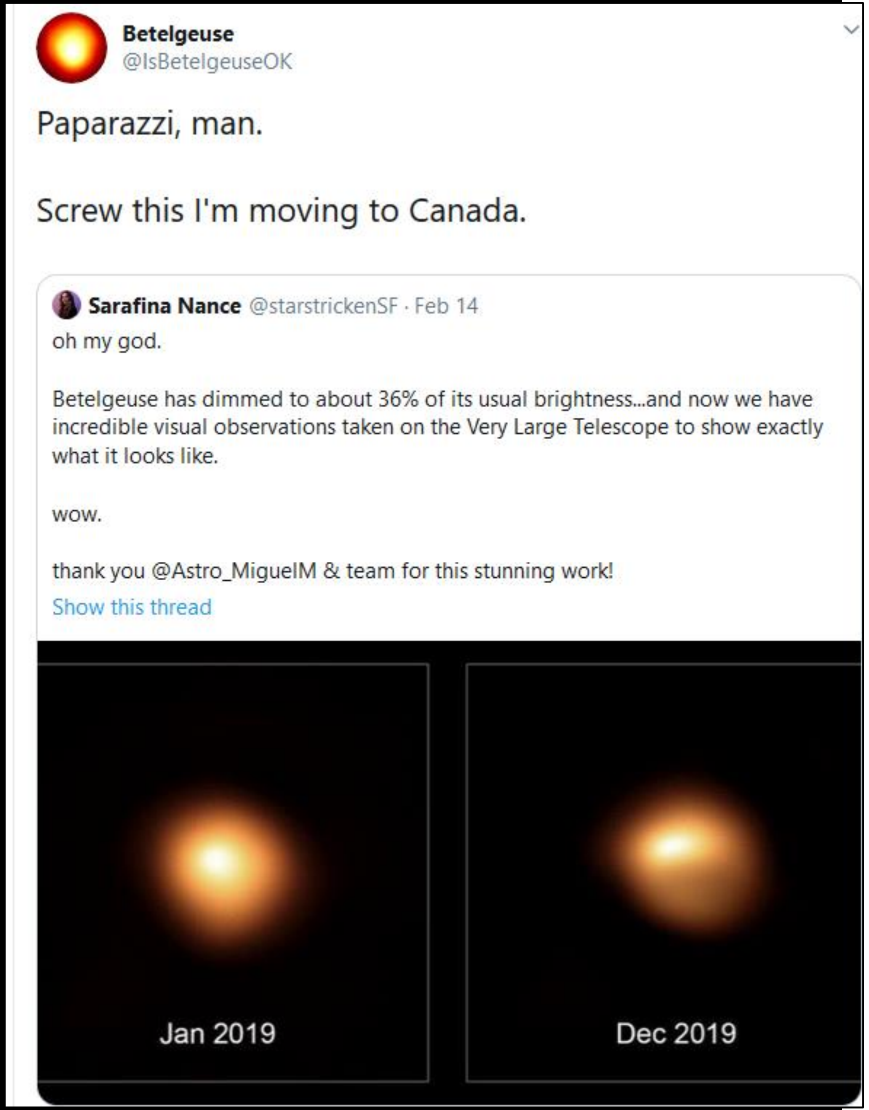
Betelgeuse supernova: Star reaches its dimmest point yet as it could EXPLODE

BETELGEUSE continues to dim in the night's sky as experts warn it could be set to supernova.

By SEAN MARTIN

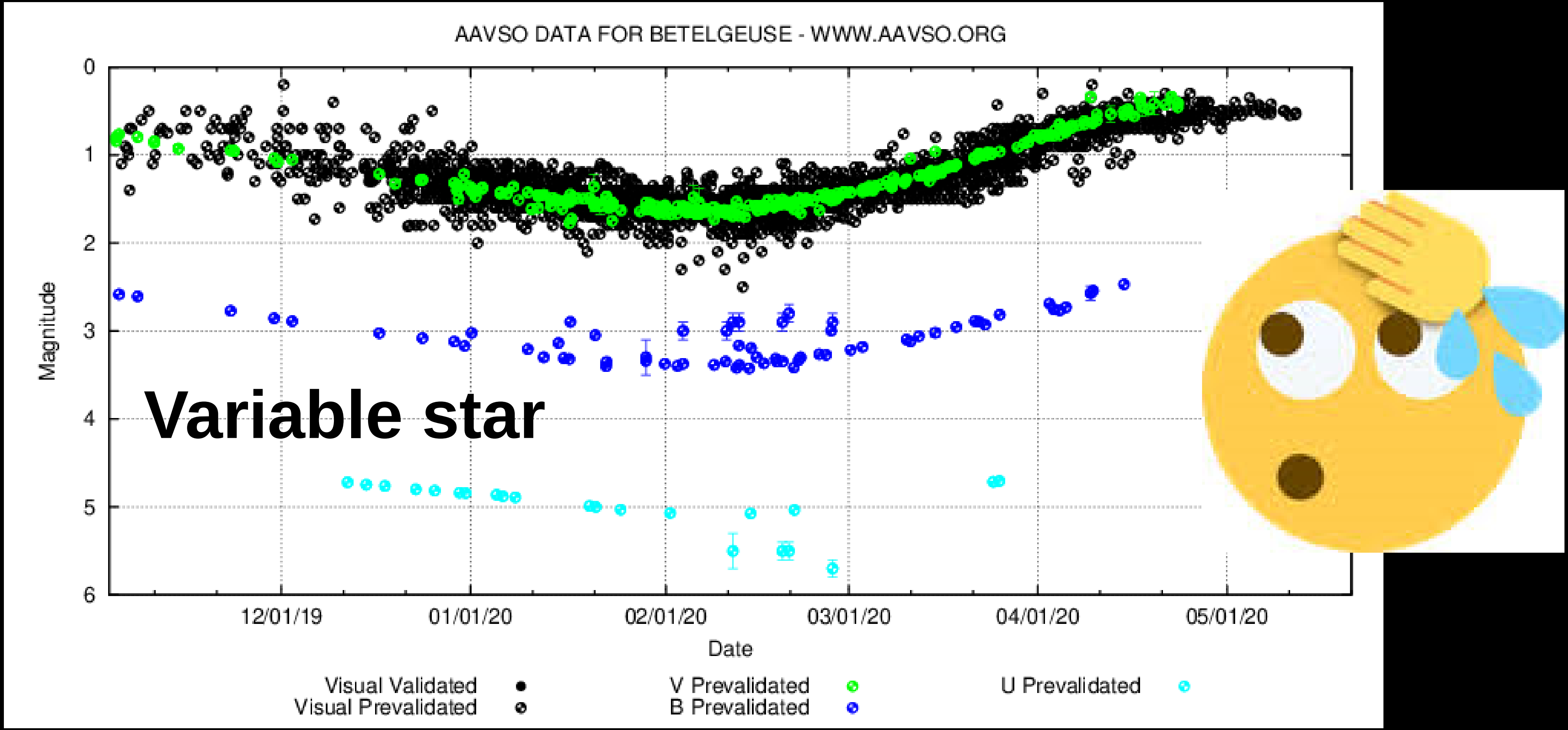
PUBLISHED: 07:49, Tue, Feb 4, 2020 | UPDATED: 07:59, Tue, Feb 4, 2020

@IsBetelgeuseOK on Twitter



Discovery, accelerated

Lightcurve of Betelgeuse (last 6 months)



Lightcurve generator: www.aavso.org/lcg

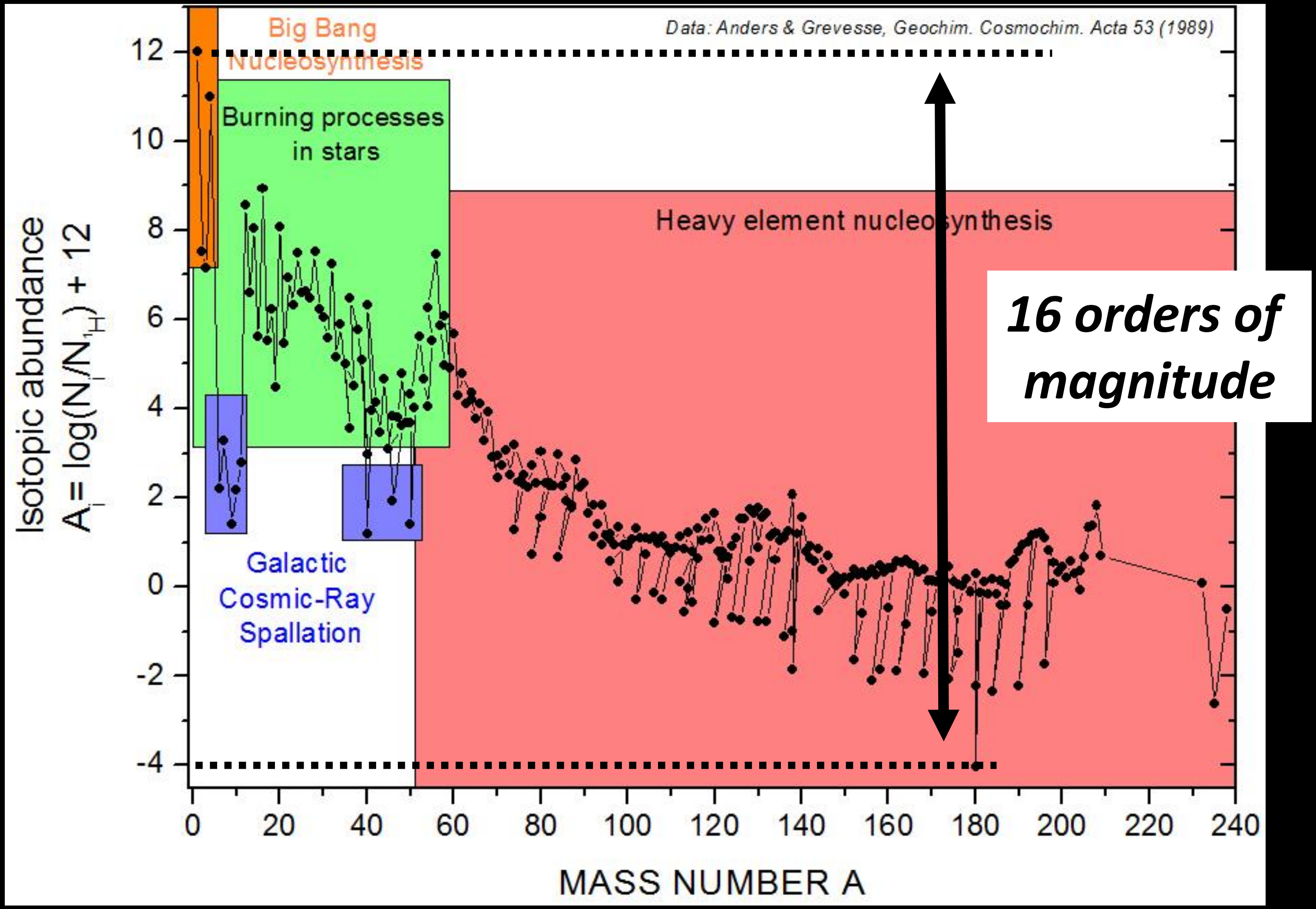
How are the heavy elements created?
“Nucleosynthesis”

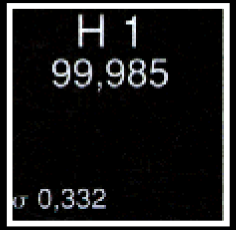
Can we say when
Betelgeuse will explode?

"Solar isotopic abundances"

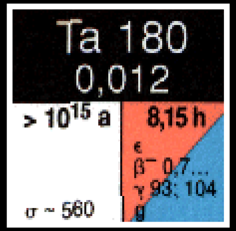
Characteristic isotopic abundances for materials within the solar system

⇨ also valid outside solar system? („Galactic" abundances?)





How are the isotopes produced?



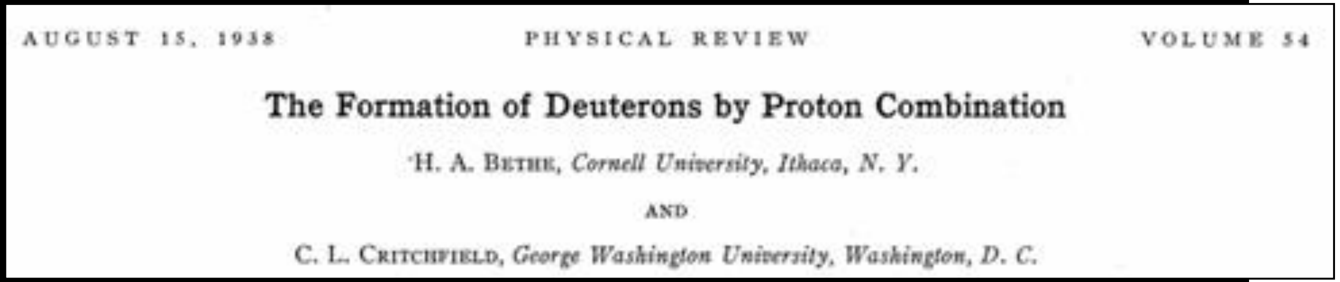
Hydrogen burning

Hans Bethe
(1906-2005)

Carl Friedrich von Weizsäcker
(1912-2007)


ATOMIC SYNTHESIS AND STELLAR ENERGY. III

R. D'E. ATKINSON

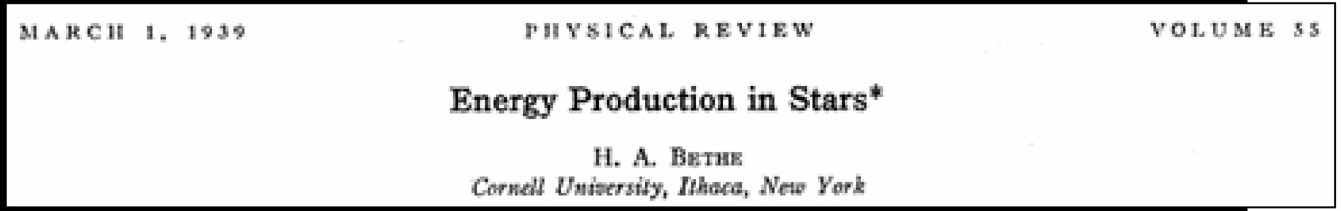

AUGUST 15, 1938 PHYSICAL REVIEW VOLUME 54

The Formation of Deuterons by Proton Combination

H. A. BETHE, *Cornell University, Ithaca, N. Y.*

AND

C. L. CRITCHFIELD, *George Washington University, Washington, D. C.*


MARCH 1, 1939 PHYSICAL REVIEW VOLUME 55

Energy Production in Stars*

H. A. BETHE
Cornell University, Ithaca, New York

$4\,p \rightarrow {}^4He$

- $p + p \rightarrow \cancel{[^2He]}$, $[^2He] + p \rightarrow \cancel{[^3Li]}$; …
- Probability for fusion of 4 protons at the same time: very low
- Solution for reaction mechanisms: **"pp chain"** and **"CNO cycle"**

R. D' F. Atkinson, Astrophys. J. 84, 73 (1936)
C.F. von Weizsäcker, Physikalische Zeitschrift 39, 633 (1938)

Discovery, accelerated

Start of pp chain

$$p + p \rightarrow D + e^{+} + \nu$$

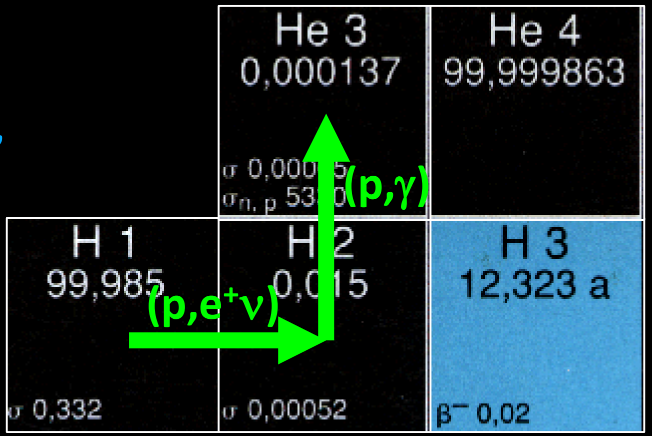
H.A. Bethe, C.L. Critchfield, Phys. Rev. 54, 248–254 (1938)

can escape,
E(aver.)$_\nu$~265 keV

*The average proton in the core of the Sun waits **9 billion years** before it successfully reacts with another proton!*

- Weak interaction: slow reaction rate ⇨ long lifetime of stars
- Reaction rate: not yet measured!
- (Theoretical) experiment: I= 1 A (=6.241*10^{18} p/s), E_p=1 MeV,

N_{target}=10^{20} p/cm^2 ⇨ 1 reaction in 6 years

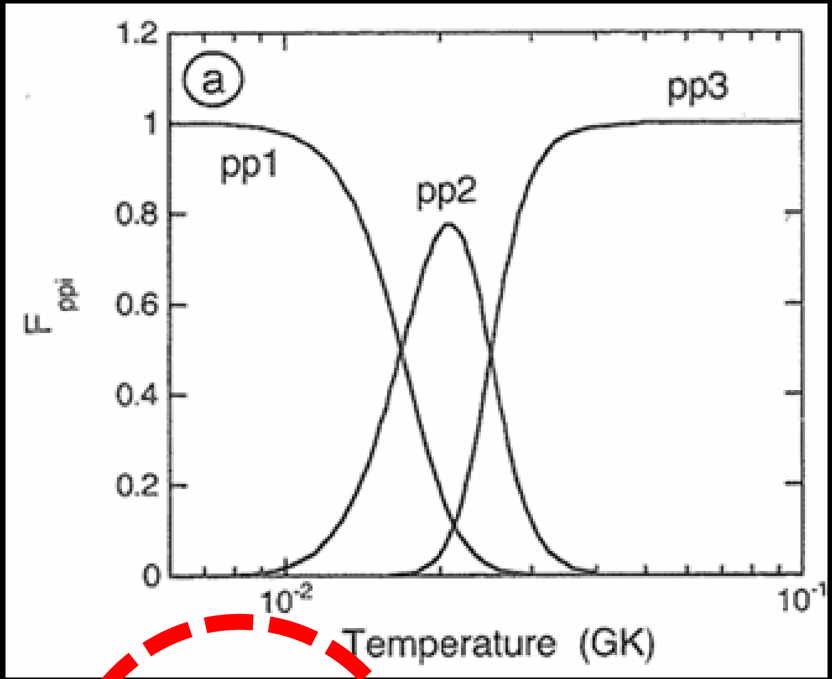


$$D(p,\gamma)^{3}He$$

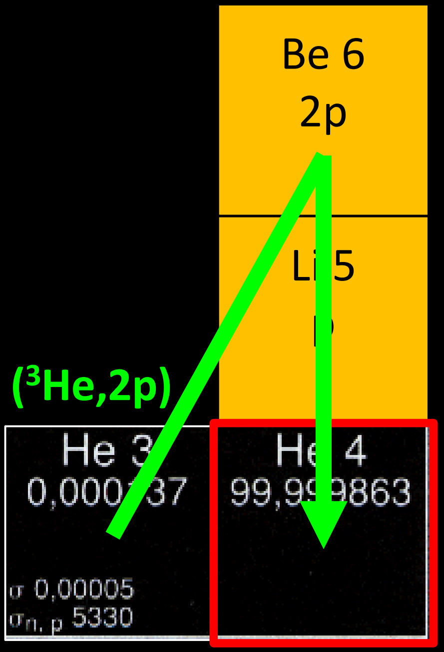
if T_{core}>0.4 MK
(distinguishes Brown Dwarfs from Giant Planets)

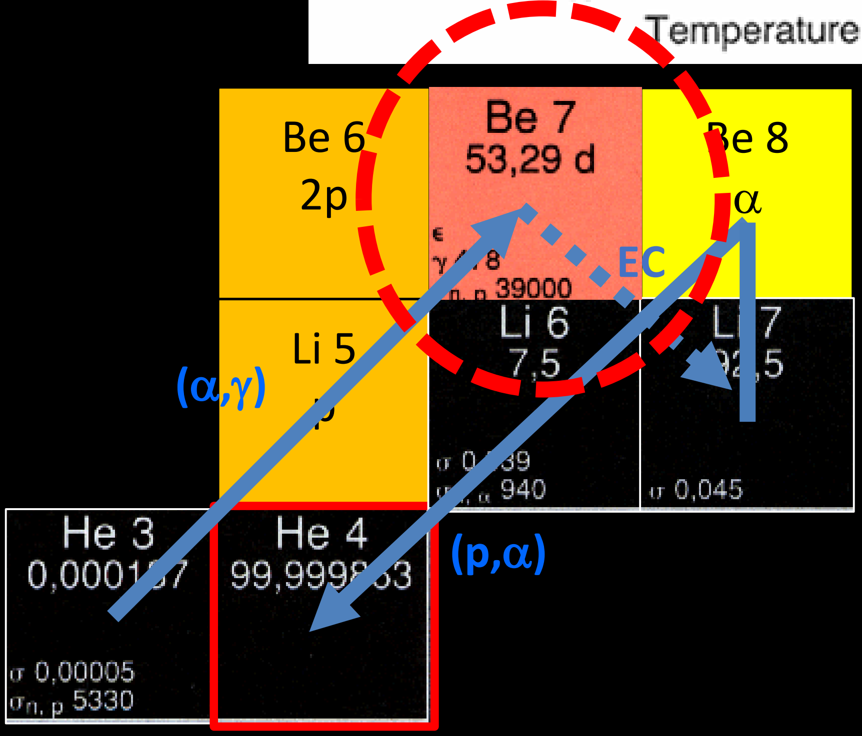
pp-I/ II/ III chain

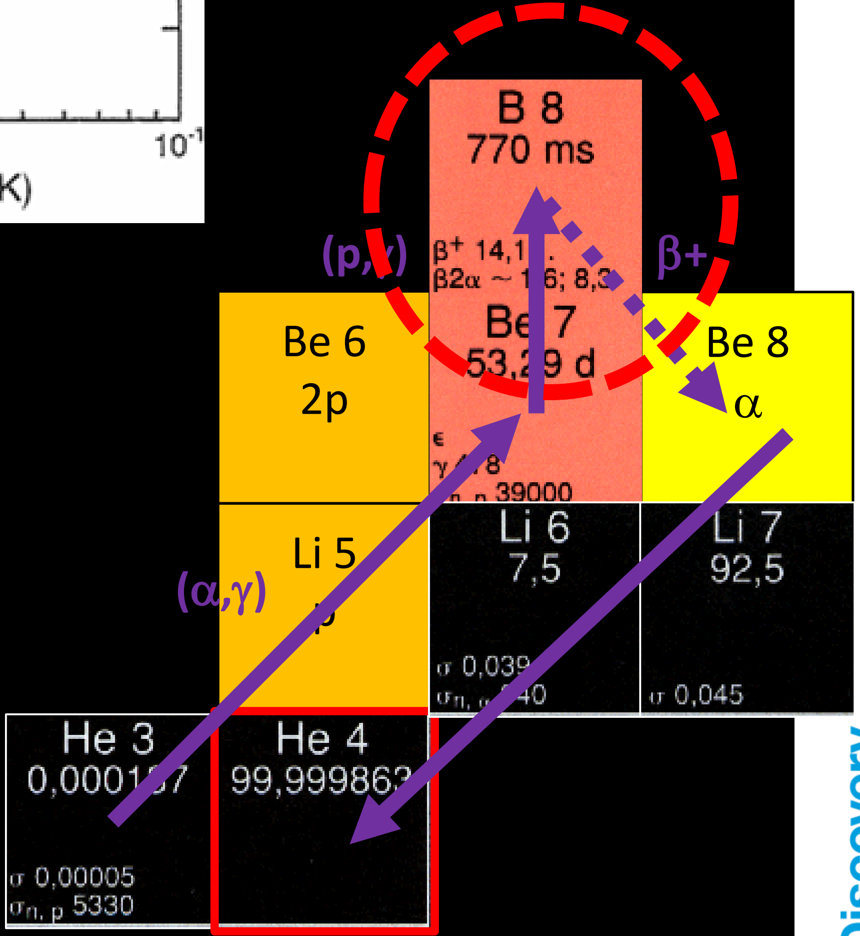
$^3He \rightarrow {}^4He$



C. Iliadis, Nuclear Physics of Stars



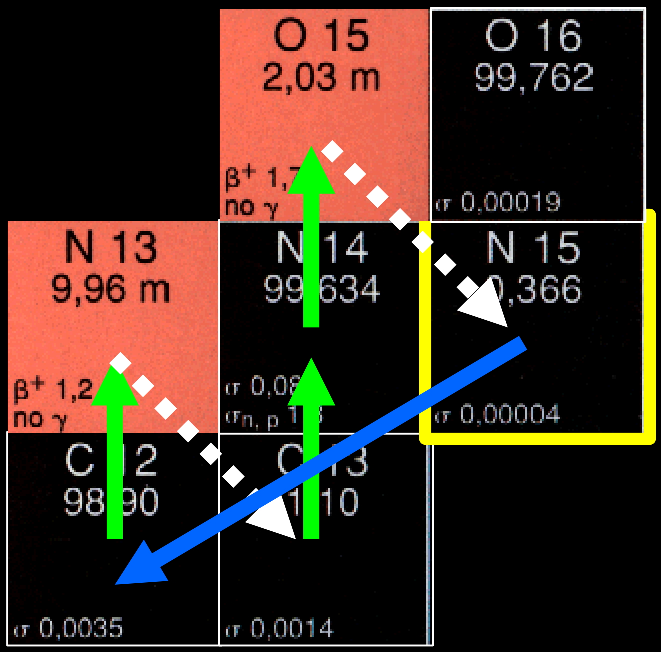




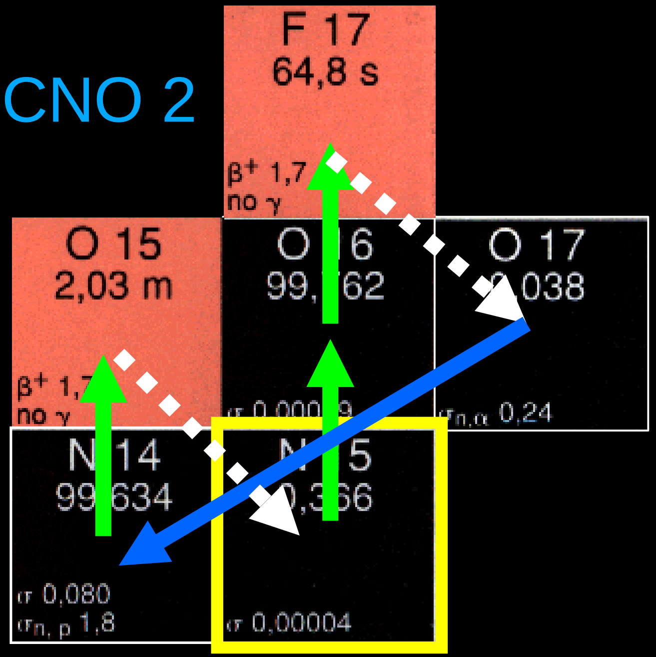
Alternative ^{4}He production: "CNO cycles"

C+N from previous star generations

CNO 1



CNO 2

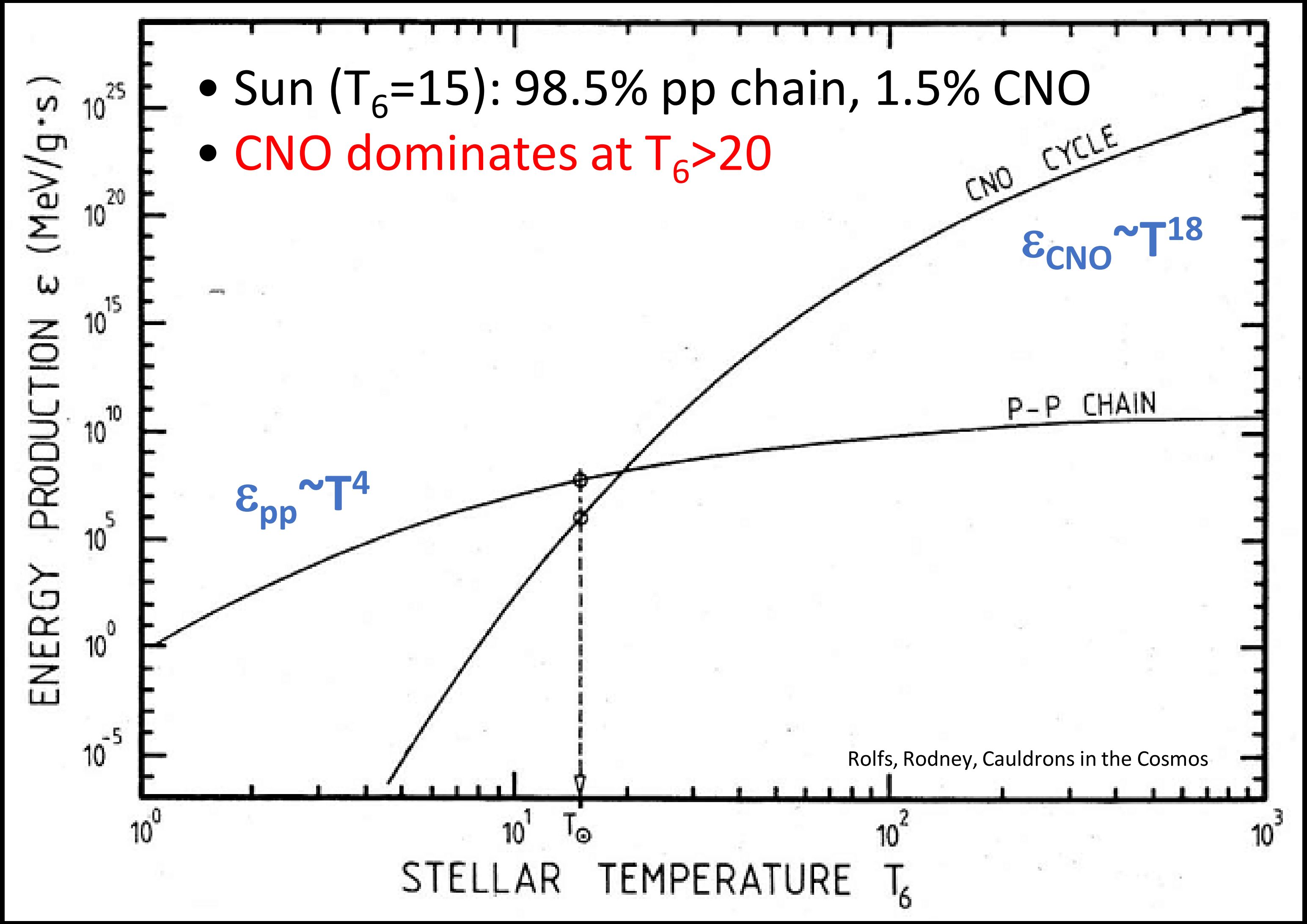


- Ratio CNO 1 vs. CNO 2 : ratio of ^{15}N(p,α)^{12}C vs. ^{15}N(p,γ)^{16}O ≈ **1000:1**
- Important for production of ^{16}O and ^{17}O

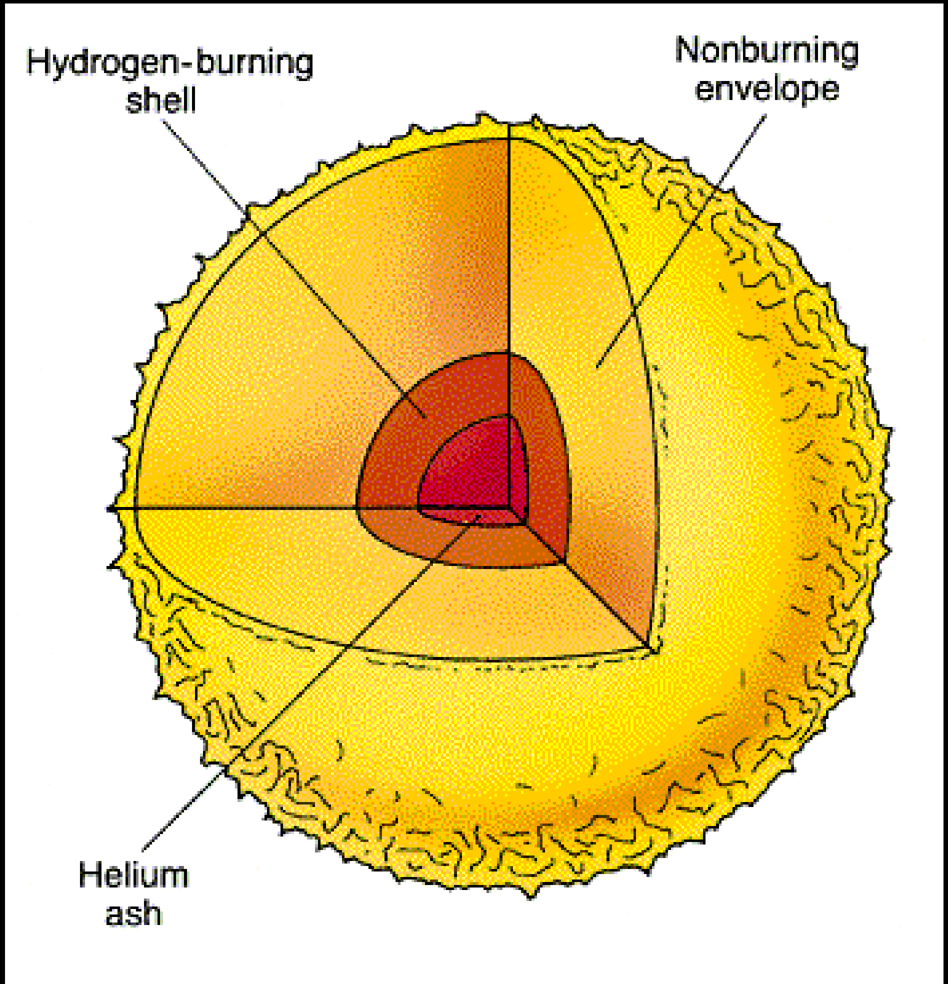
Σ: 4p → ^{4}He + 2e^{+} + 2ν + 26.73 MeV

C.F. von Weizsäcker, Physikalische Zeitschrift 39, 633 (1938)
H.A. Bethe, Physical Review 55 (5), 434 (1939)

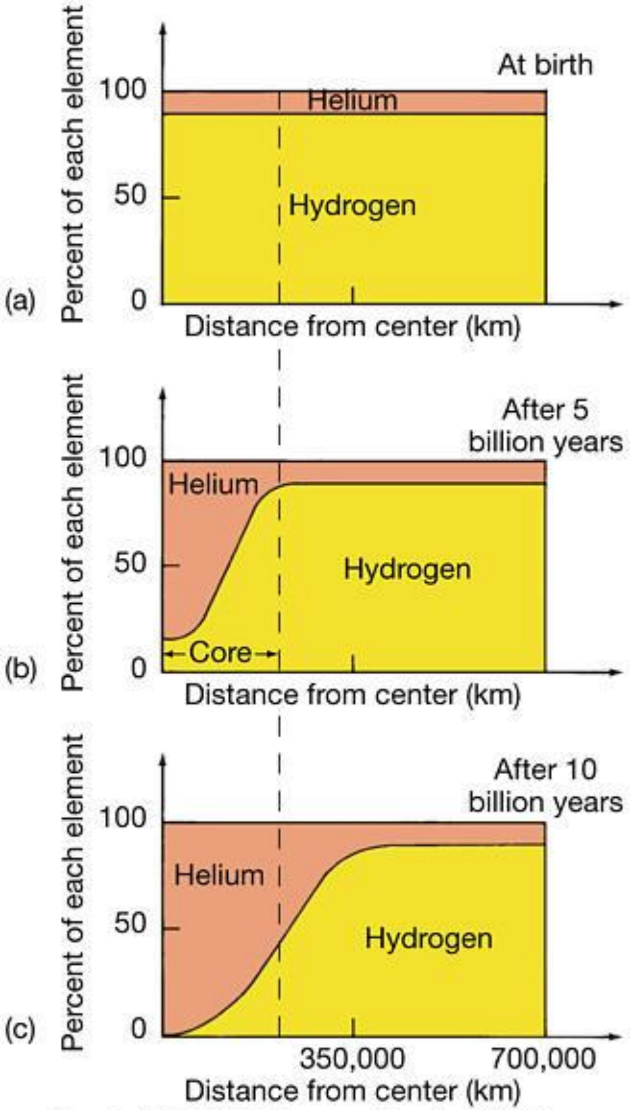
Energy generation: pp chain vs. CNO cycle



A star at the end of hydrogen burning

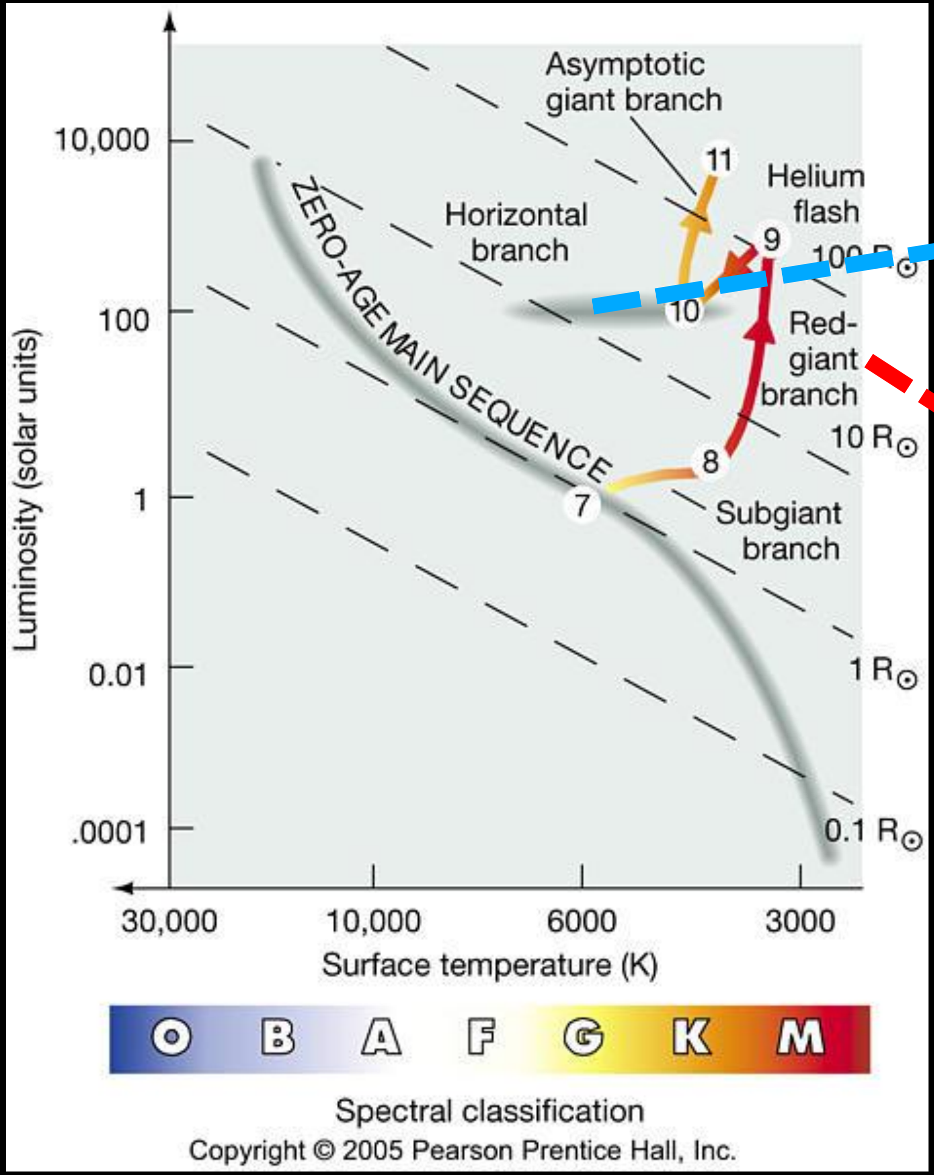


http://www.pas.rochester.edu/~afrank/A105/LectureX/LectureX.html



Discovery, accelerated

Hydrogen → Helium burning



Horizontal Branch:

He core burning ignited if
T>100 MK (M>0.5M☉)

H shell burning (CNO cycle) continues

Star leaves Main Sequence and becomes ***Red Giant***

H shell burning (CNO cycle) continues

Discovery, accelerated

He burning: “Triple-α process”

Simultaneous reaction of 3 α particles energetically possible, but low probability

- Salpeter (1952): 2-step process:

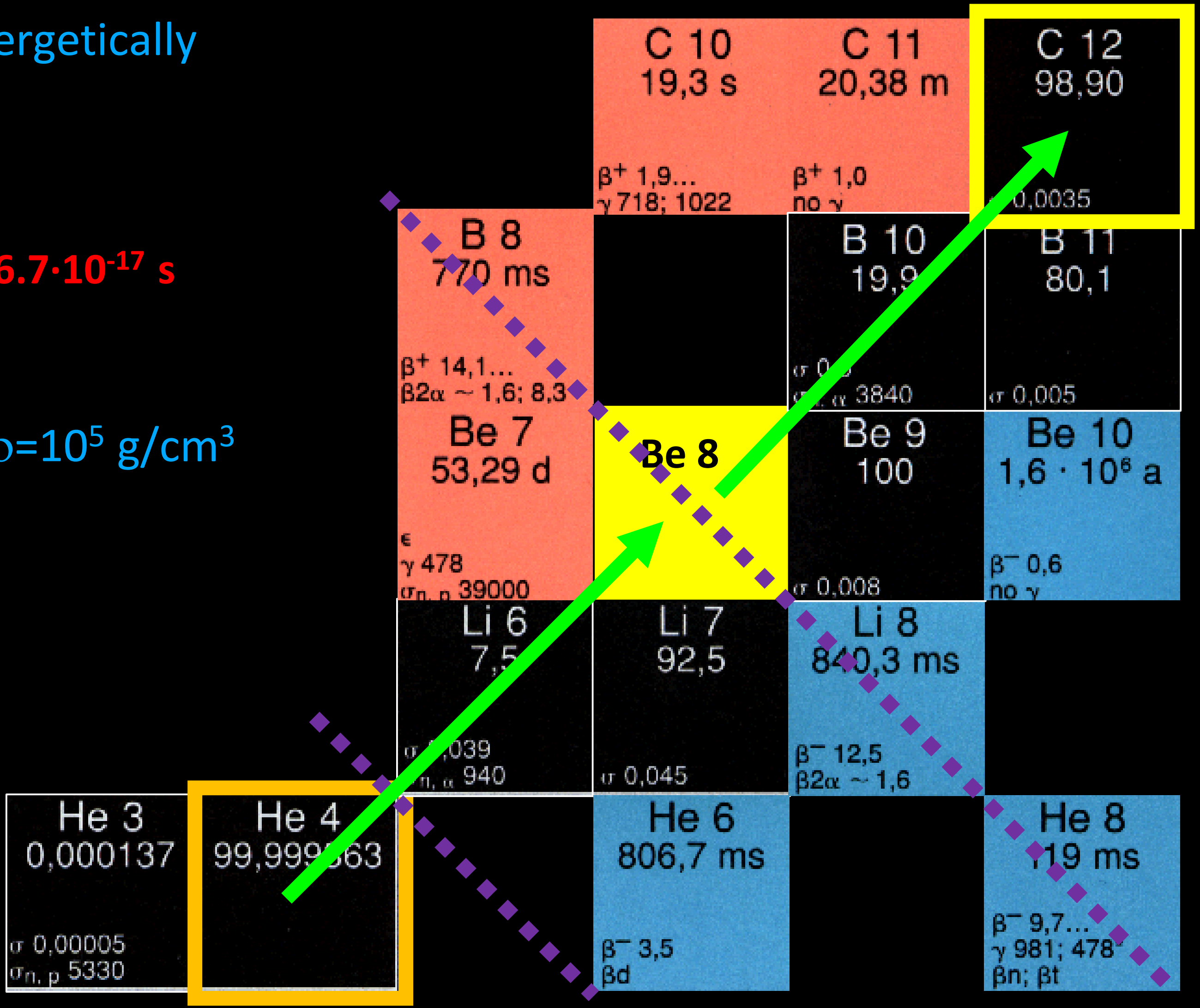
$$ {}^{4}He + {}^{4}He \Leftrightarrow \left[{}^{8}Be\right] $$

$t_{1/2}({}^{8}Be)=6.7\cdot10^{-17}$ s

- Equilibrium concentration at T= 100 MK, $\rho=10^{5}$ g/cm^{3}

$$ \frac{N\left({}^{8}Be\right)}{N\left({}^{4}He\right)} = 5.2\cdot10^{-10} $$

$$ \left[{}^{8}Be\right] + {}^{4}He \rightarrow {}^{12}C $$



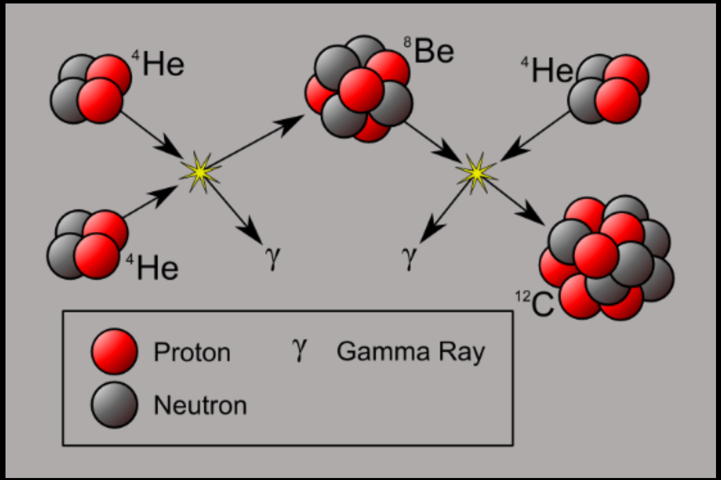
E.E. Salpeter, Astrophys. J. 115, 326 (1952)

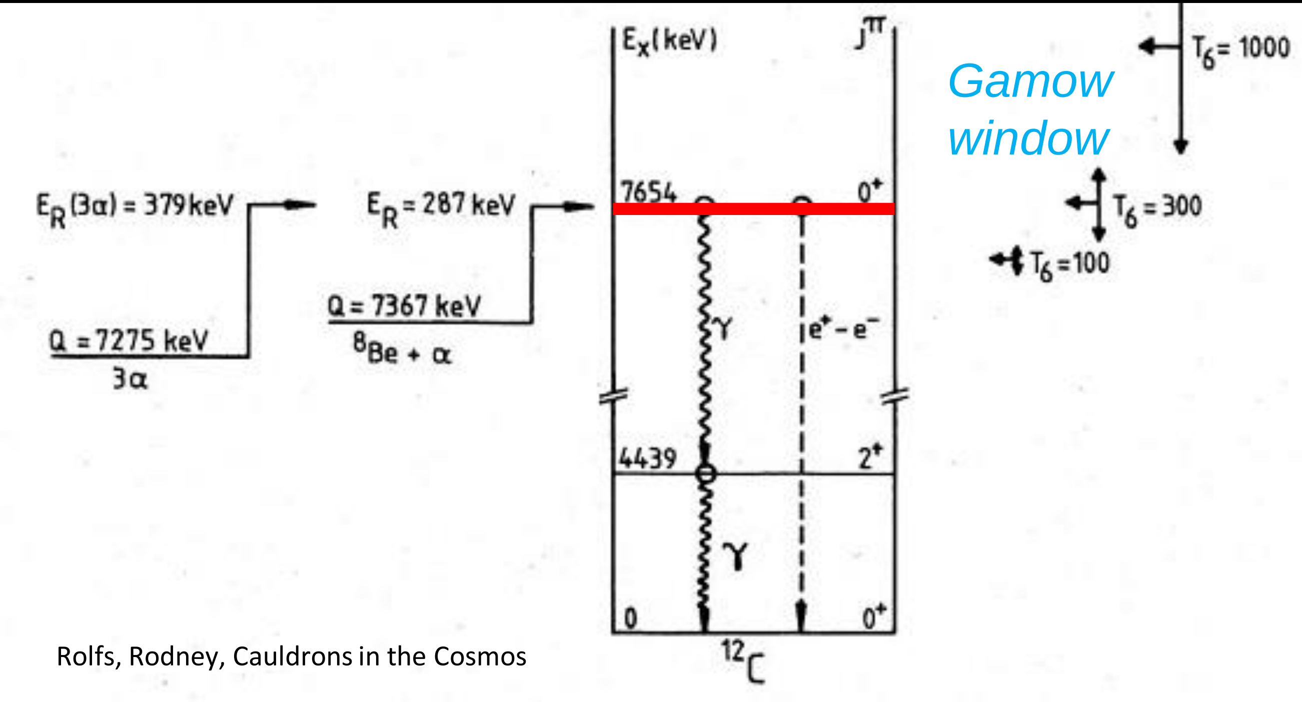
The "Hoyle state"

Are we just lucky or did someone plan/ create this state?

- Conversion into ^{12}C is slow unless enhanced rate via resonance near threshold
- High solar C abundance → Postulation of a $J^{\pi}=0^{+}$ state at $E_x \approx 7.6$ MeV **(„Hoyle state")**
- Experimentally confirmed in 1950's

Fred Hoyle (1915-2001)



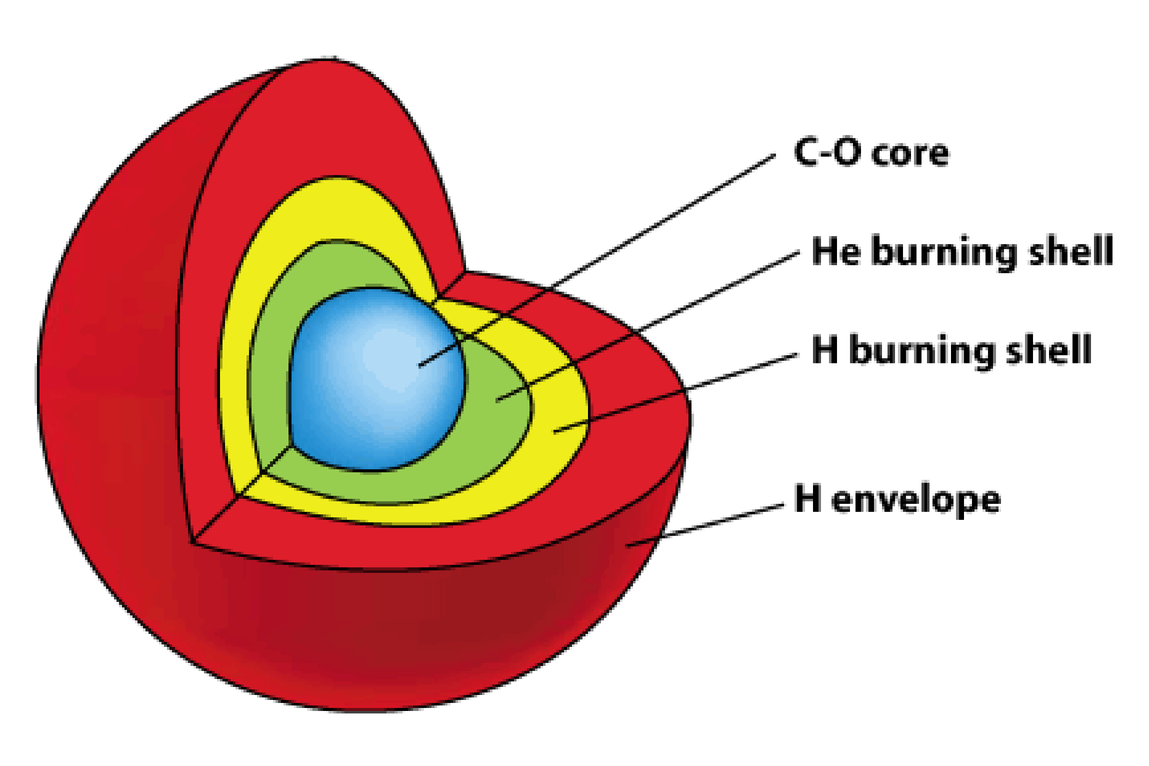


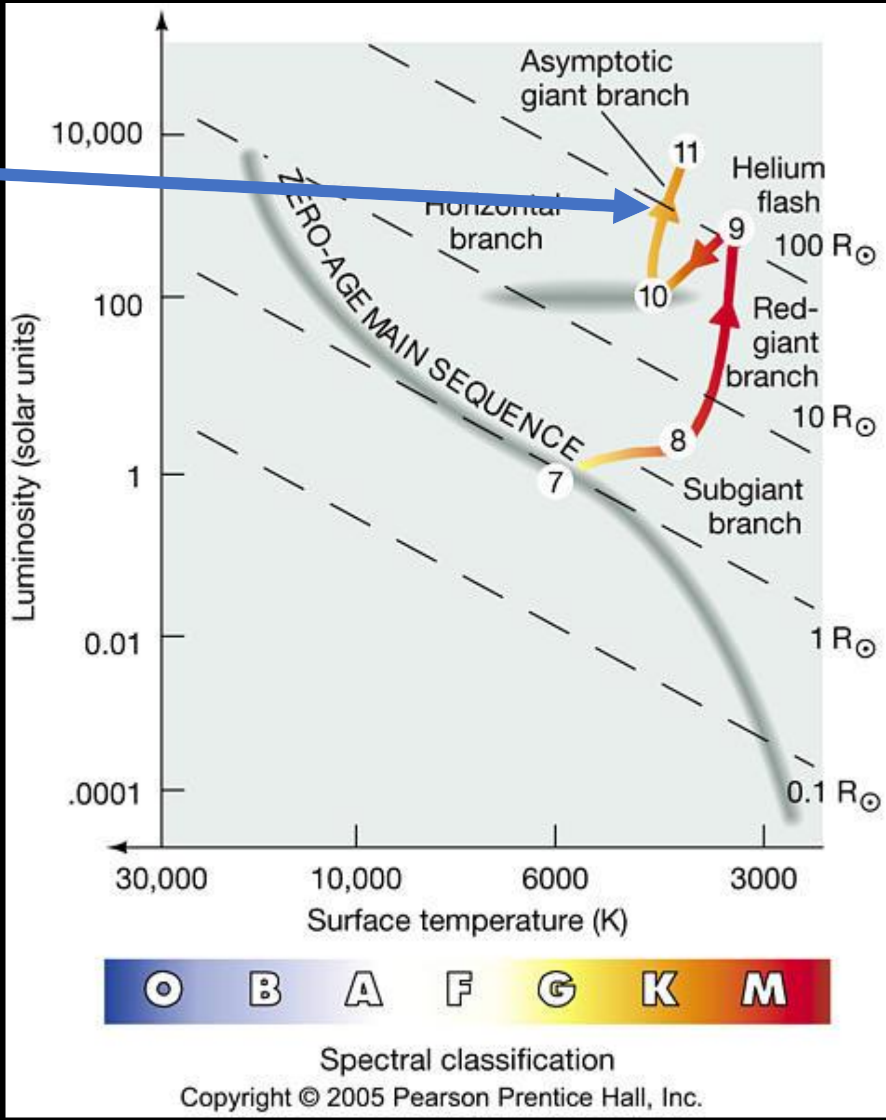
Rolfs, Rodney, Cauldrons in the Cosmos

Discovery, accelerated

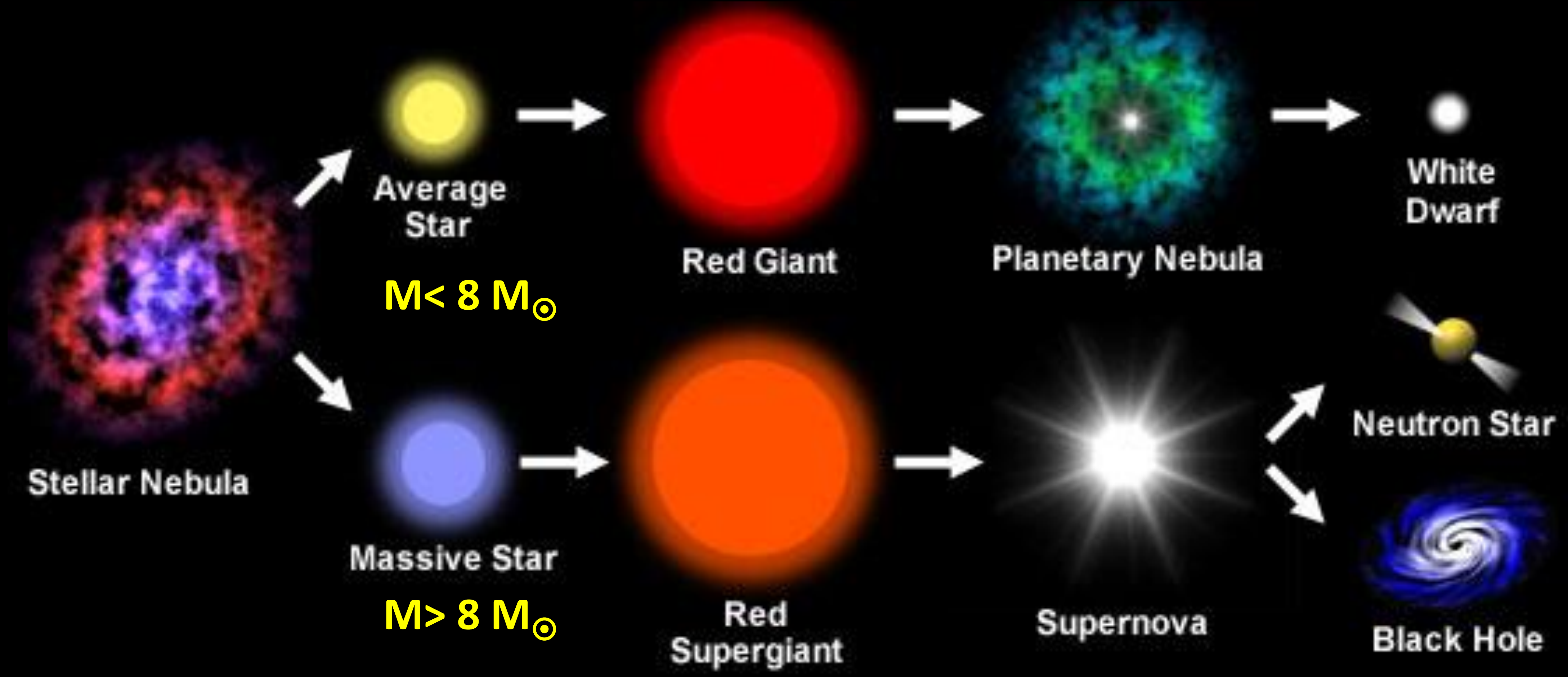
Structure of a star after He burning

Asymptotic Giant Branch (AGB):
similar to Horizontal Branch:
He shell burning continues around a C-O core
Expansion of outer shells (increased luminosity)





Fate of stars

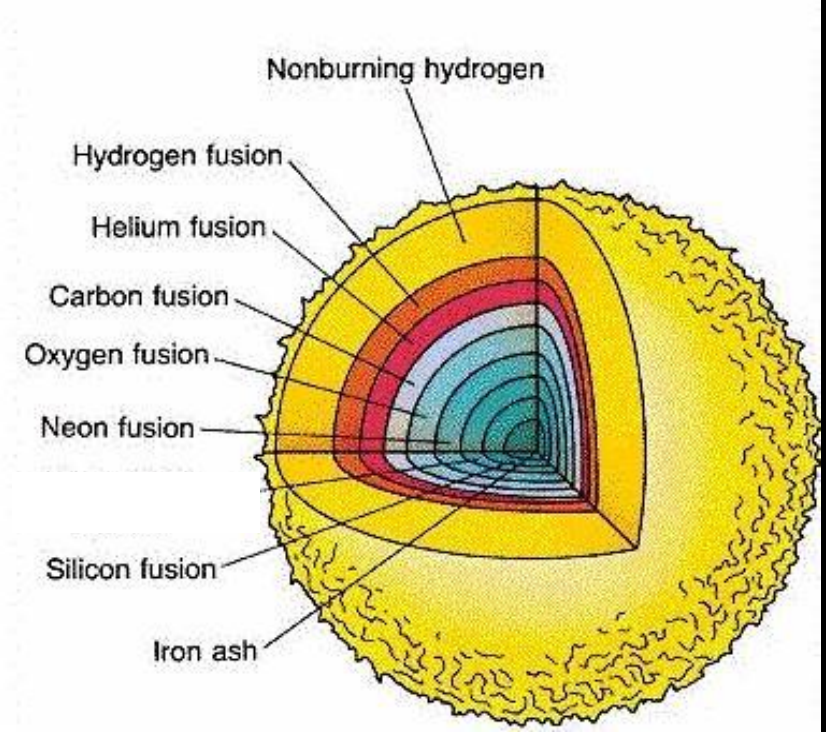


$M < 8\,M_{\odot}$

$M > 8\,M_{\odot}$

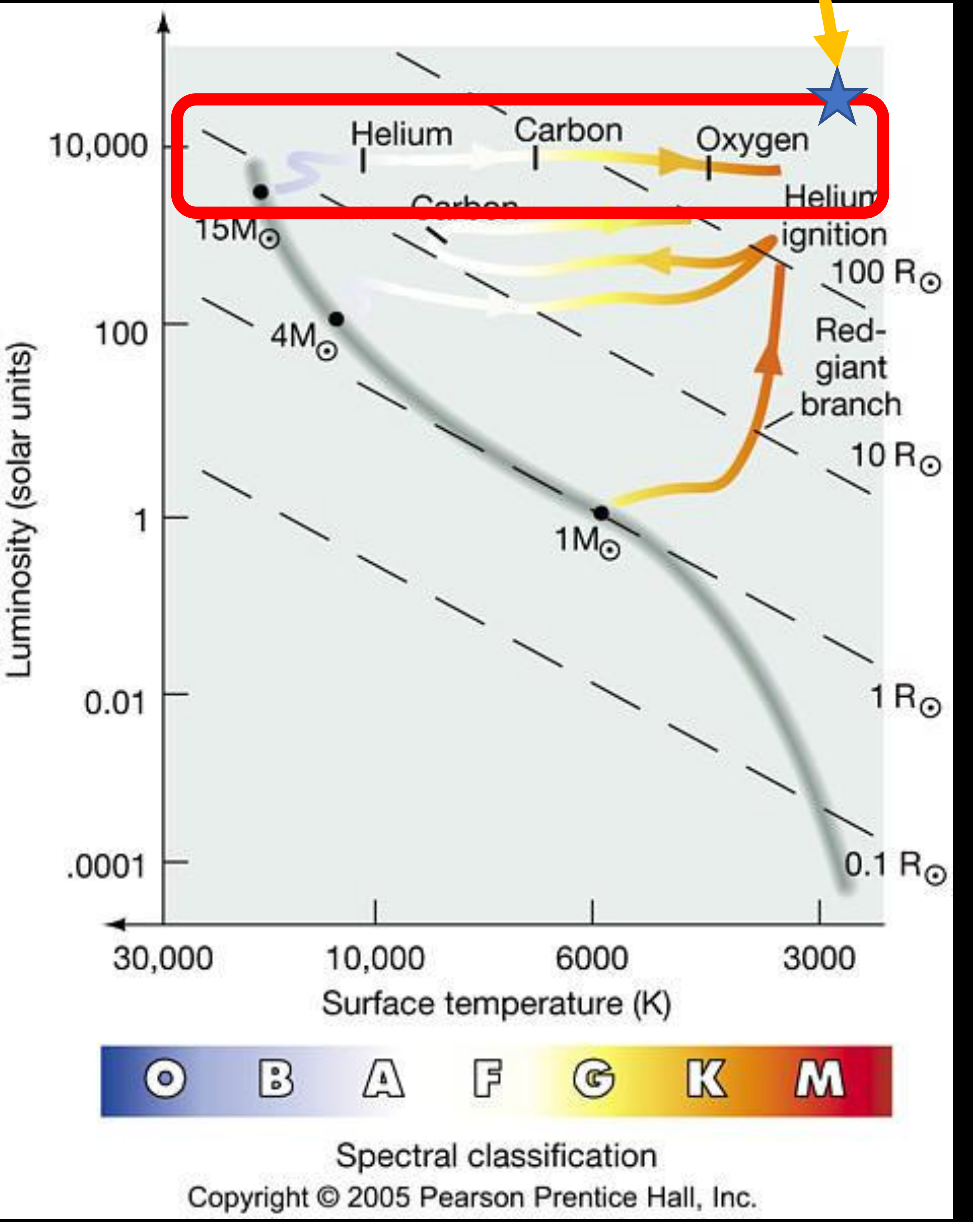
What is happening with Betelgeuse?

- Red Supergiant (>10 $M_\odot$) = massive star
- Advanced burning phases: C burning, Ne burning, O burning, Si burning

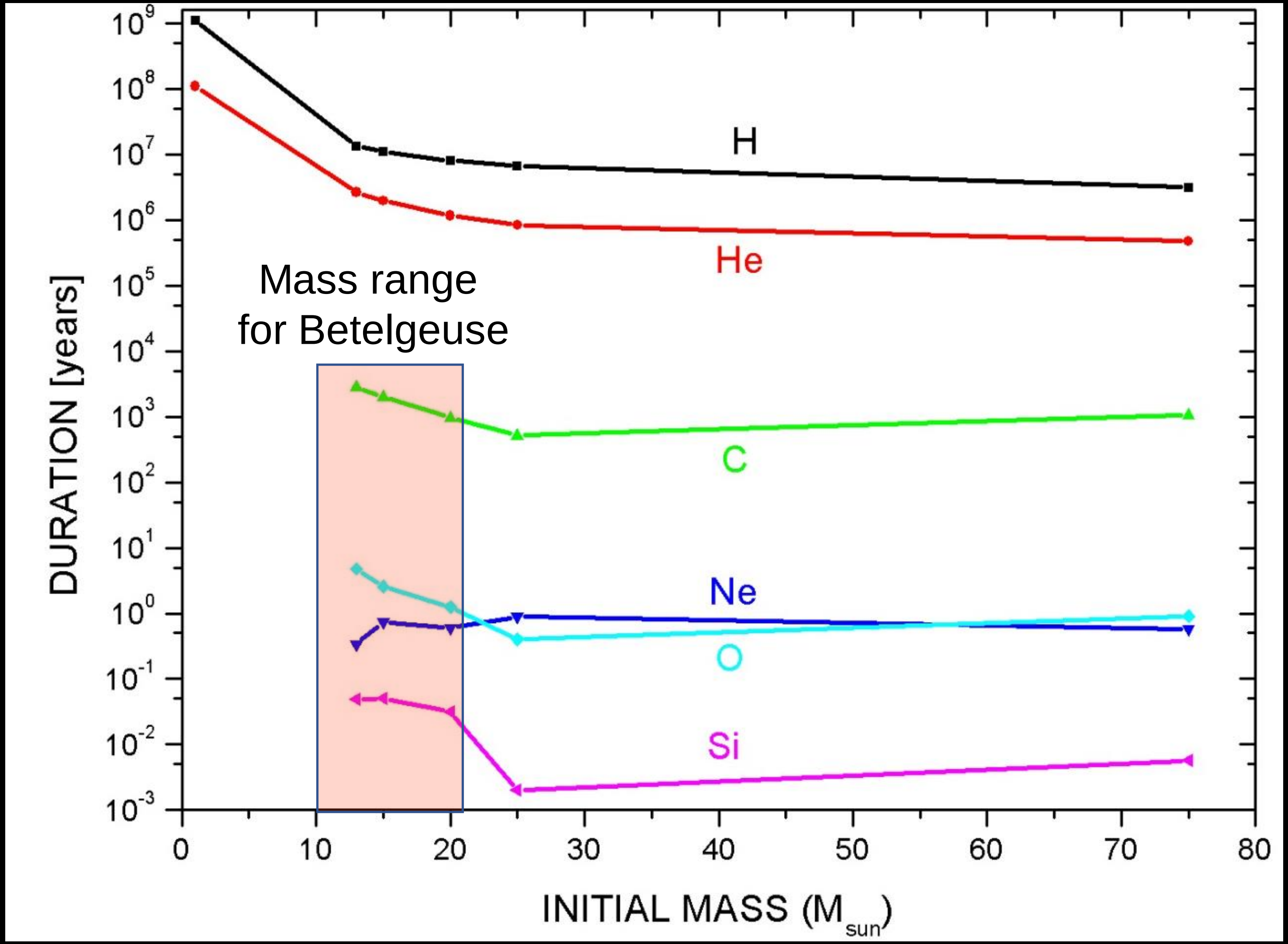


www.noao.edu

Betelgeuse



Duration of burning phases

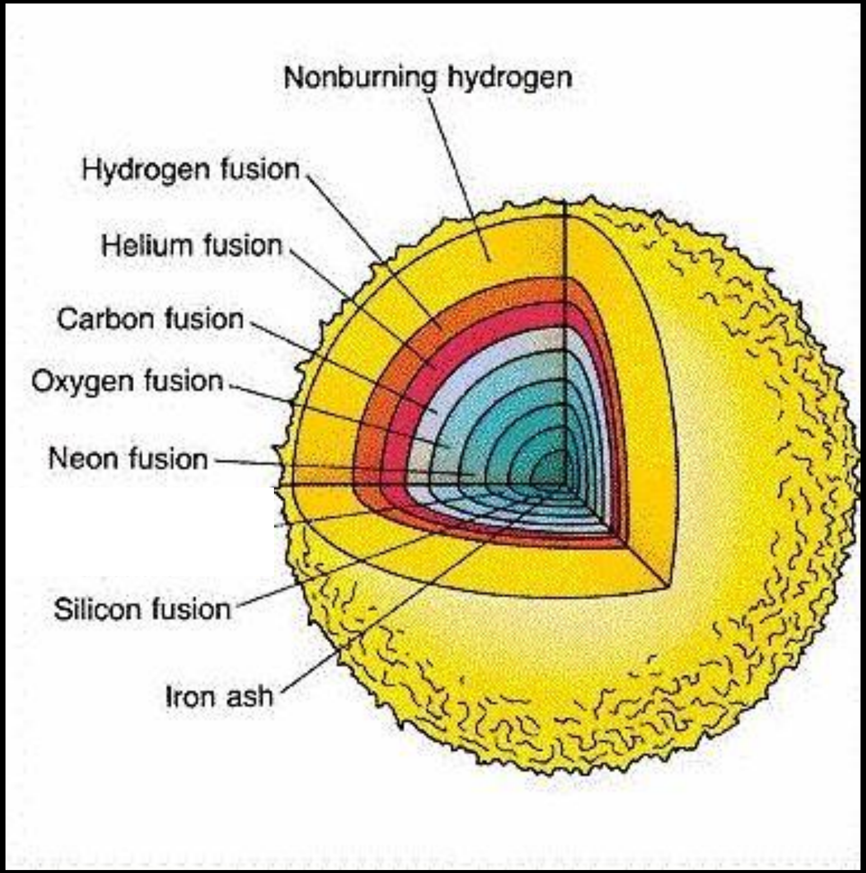


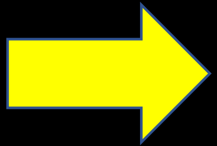
We don’t know in which advanced burning phase Betelgeuse is!

We don’t know when exactly Betelgeuse will explode!

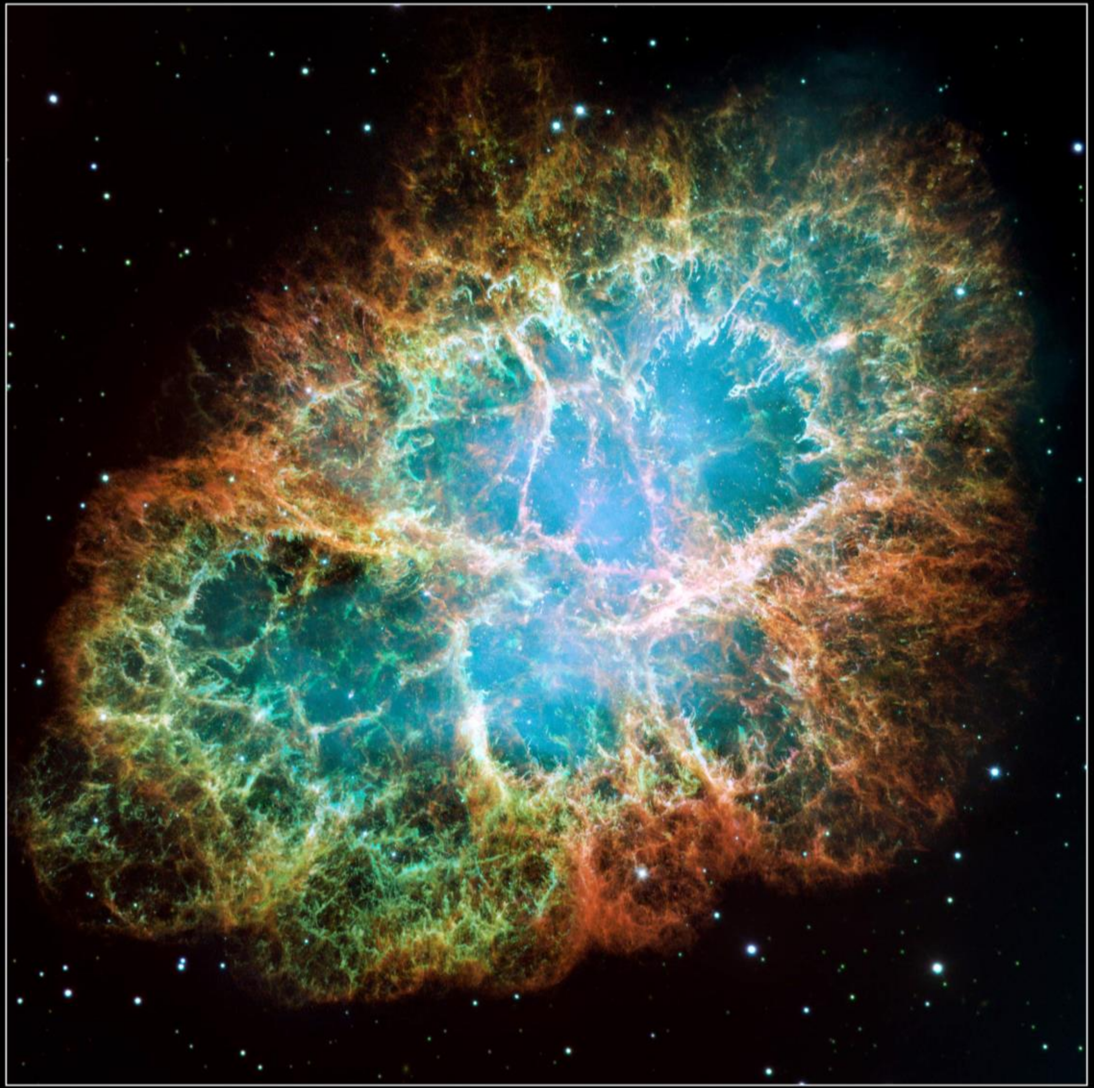
Woosley, Heger, Weaver, Revs. Mod. Phys. 74 (2002) 1016

Supernova





Core Collapse Supernova (CCSN)



Crab Nebula • M1
Hubble Space Telescope • WFPC2

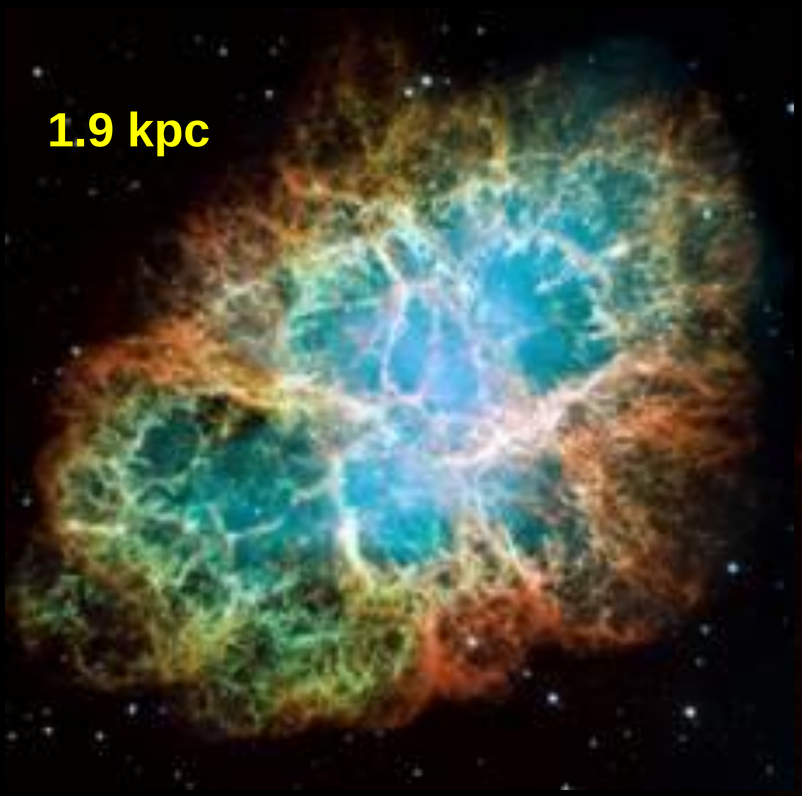
NASA, ESA, and J. Hester (Arizona State University) STScI-PRC05-37

Discovery, accelerated

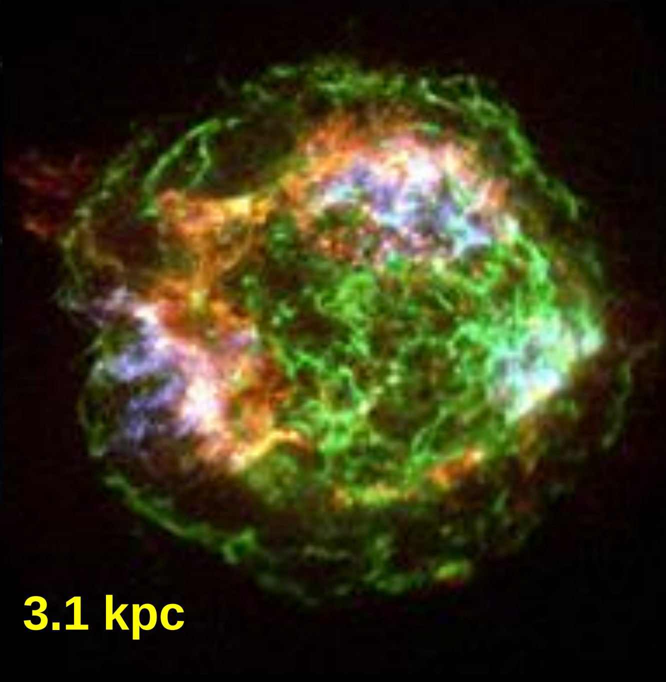
Historical Core Collapse SN

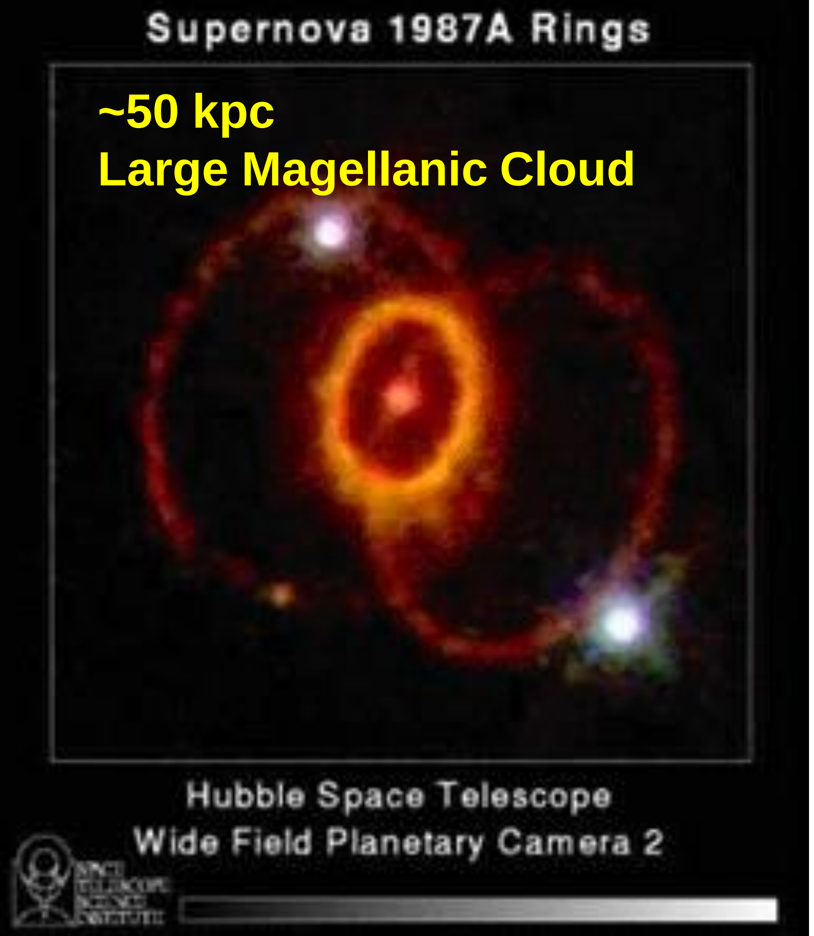
1 kiloparsec (kpc)
= 3260 light years

Crab Nebula (SN 1054)



Cassiopeia A (SN 1667)





Feb. 23, 1987
(Hubble launched in 1990)

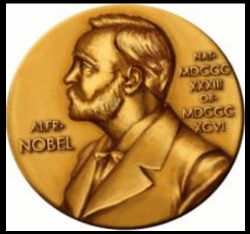
2-3h before visible observation: detection of neutrino burst at 07:35 UT (13 s):

- Kamiokande II (Japan): 12 ν's
- IMB (USA): 8 ν's
- Baksan (SSSR): 5 ν's

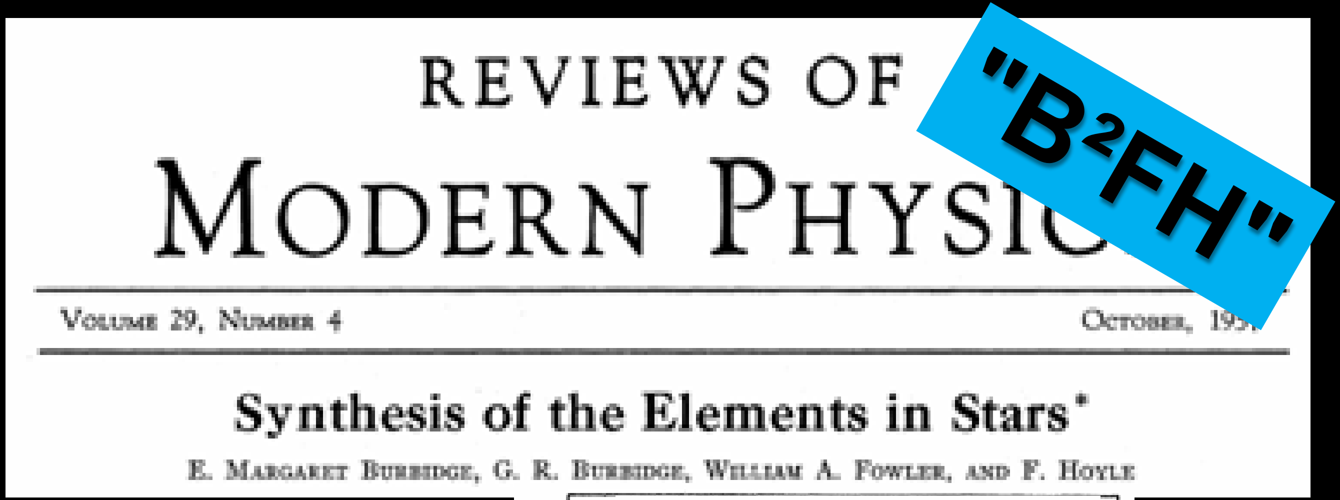
How are the elements heavier than iron produced?

1956/57: The birth of modern astrophysics

William A. Fowler



1983 (Physics):
„For his theoretical and experimental studies of the nuclear reactions of importance in the formation of the chemical elements in the universe"


REVIEWS OF MODERN PHYSIC[S]

"B²FH"

VOLUME 29, NUMBER 4 OCTOBER, 195[7]

Synthesis of the Elements in Stars*

E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE

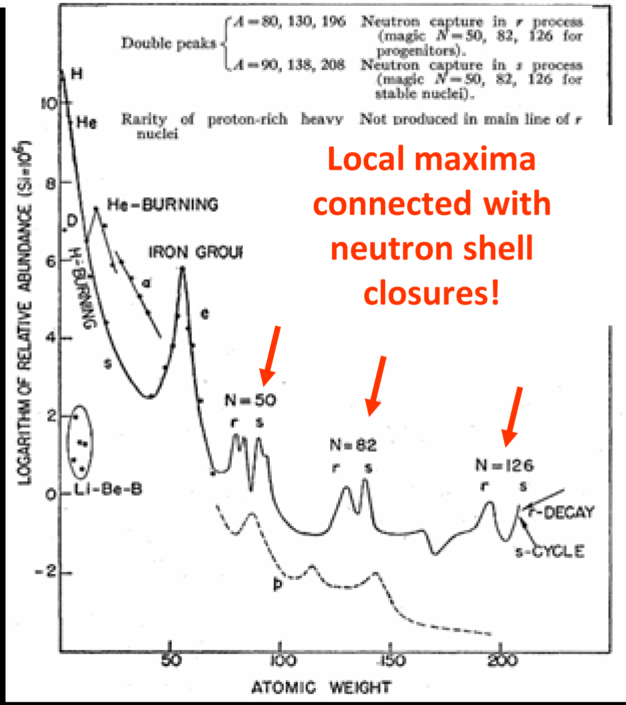
Nuclei heavier than iron are produced by <u>3 different processes</u> in <u>different astrophysical scenarios</u>:

s process *(slow neutron capture)*

r process *(rapid neutron capture)*

"p process" *(proton-rich isotopes)*

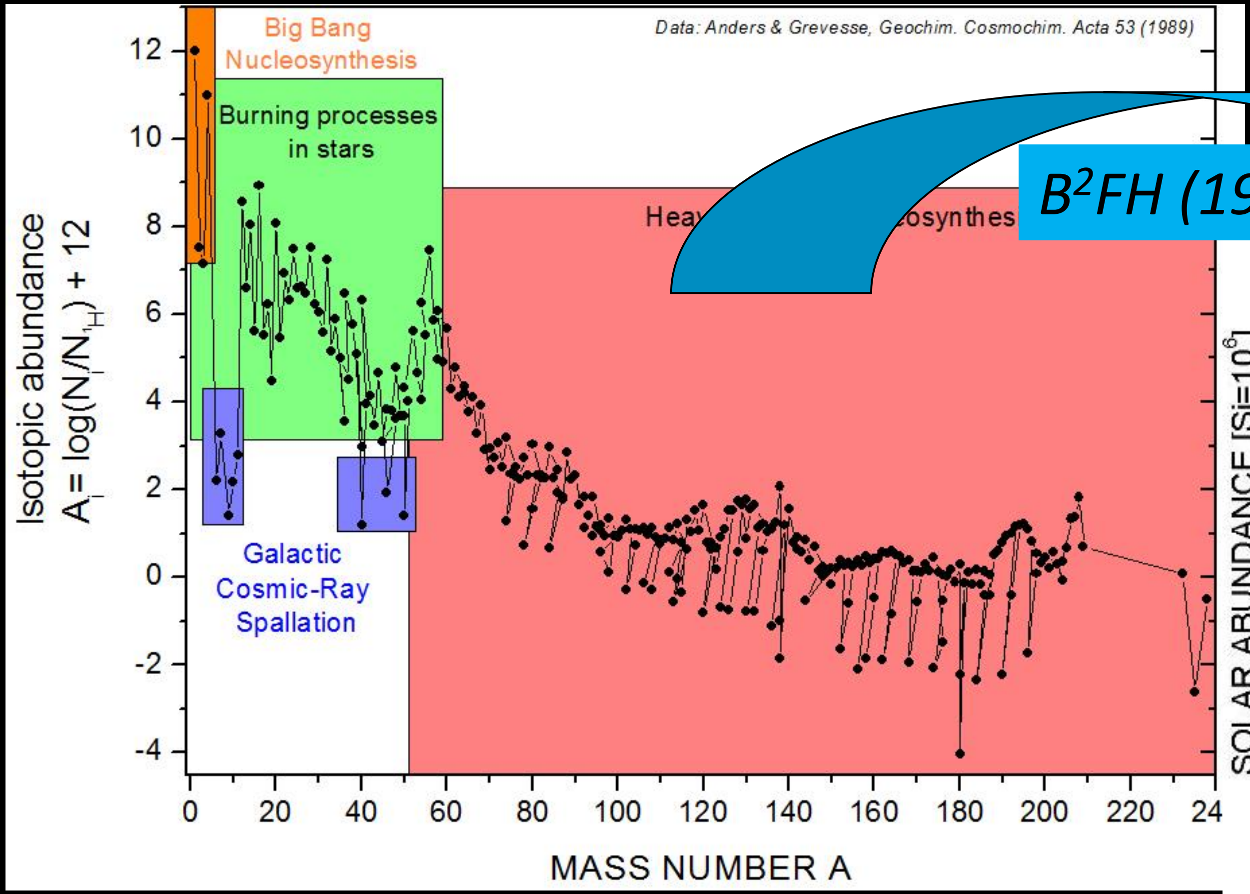
$$N_\odot = N_s + N_r + N_p$$



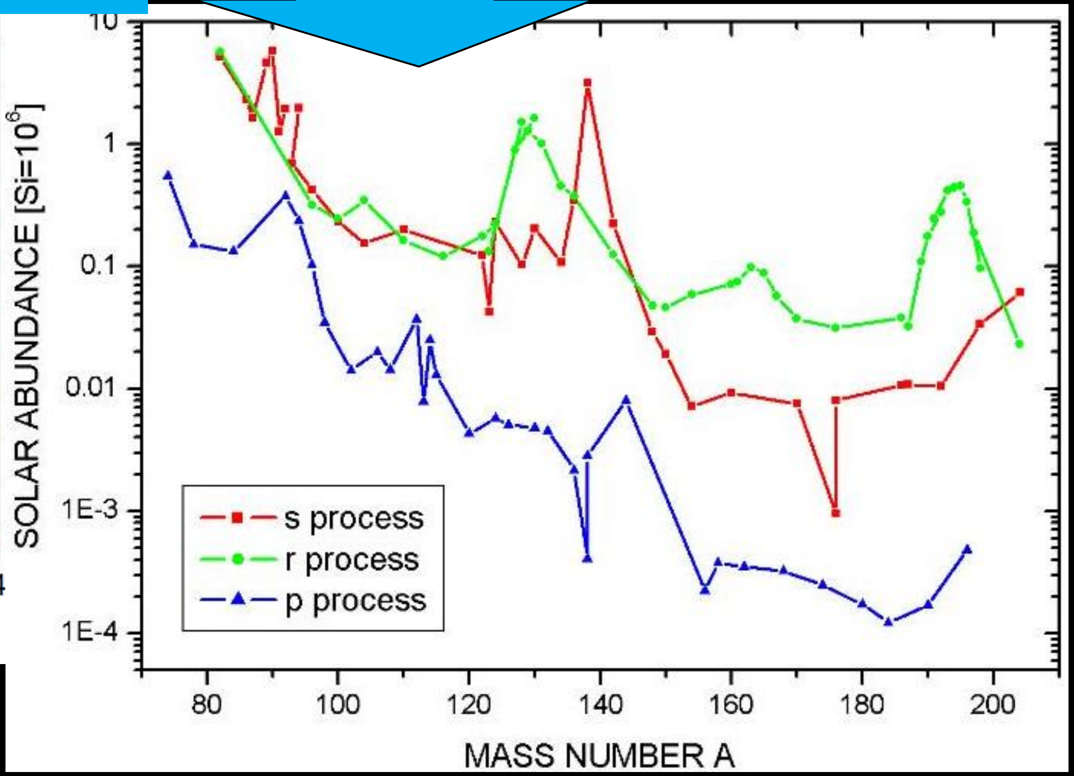
Discovery, accelerated

Solar abundances: Synthesis beyond iron

$$N_{\odot} = N_s + N_r + N_p$$



B²FH (1957)

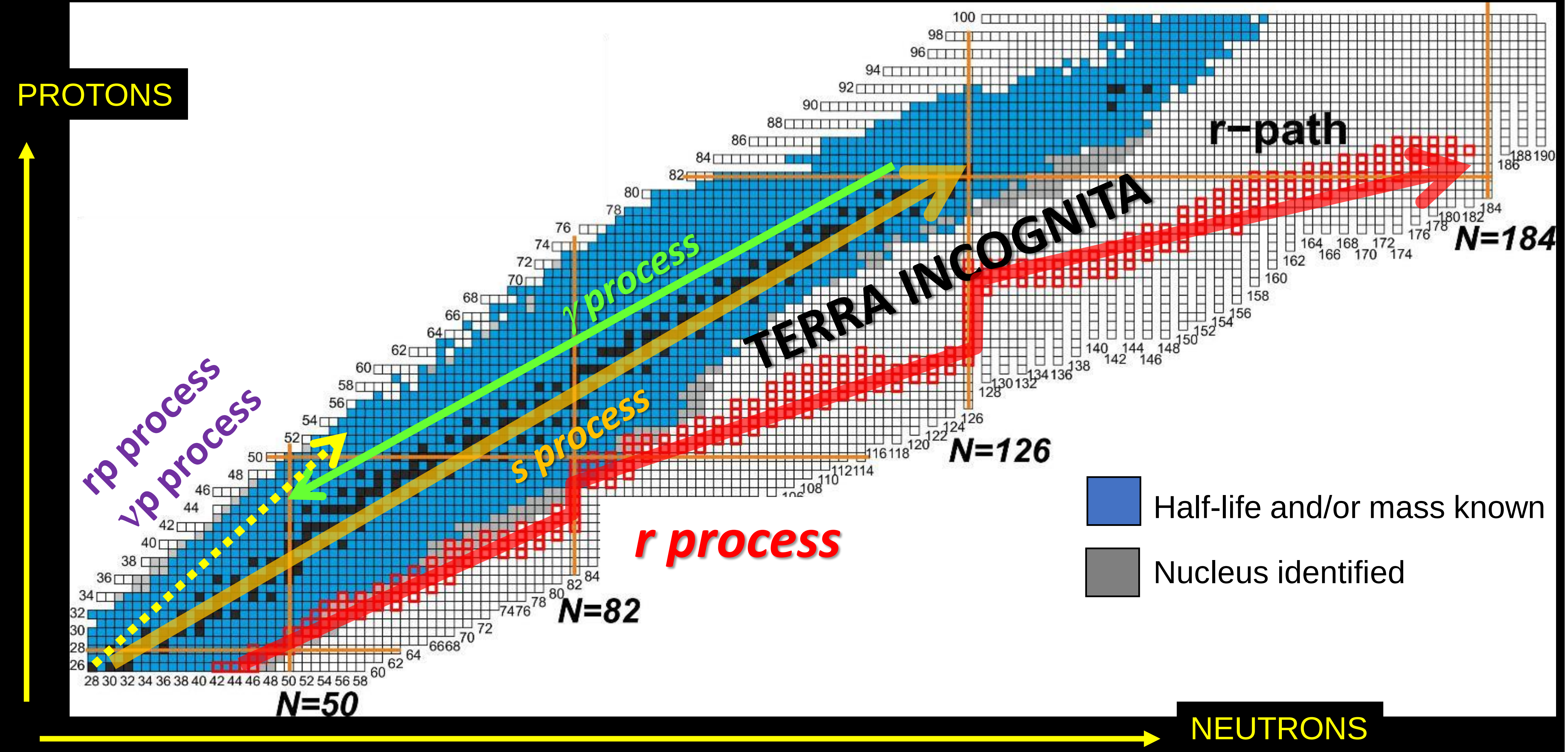


"slow neutron capture process"

"rapid neutron capture process"

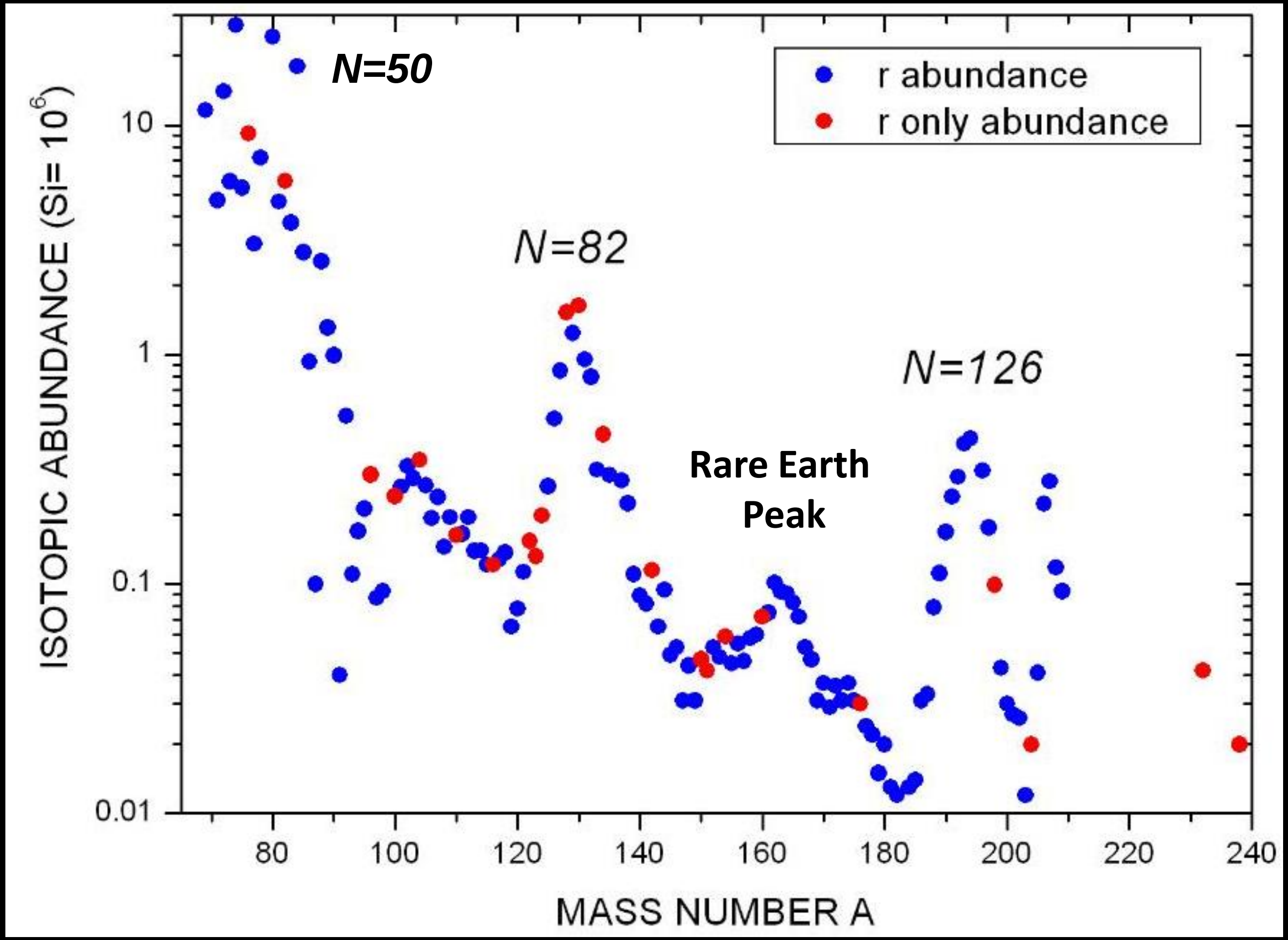
Production of p-rich isotopes

Reaction pathways



"Rapid neutron capture process"

$$N_r = \underbrace{N_\odot}_{\text{measured}} - \underbrace{N_s}_{\text{well-known}} - \underbrace{N_p}_{\text{negligible}}$$



Mirror of nuclear structure far off stability

- *neutron shell closures*
- *deformed regions (mid-shell nuclei)*

How are these nuclei created in stars?

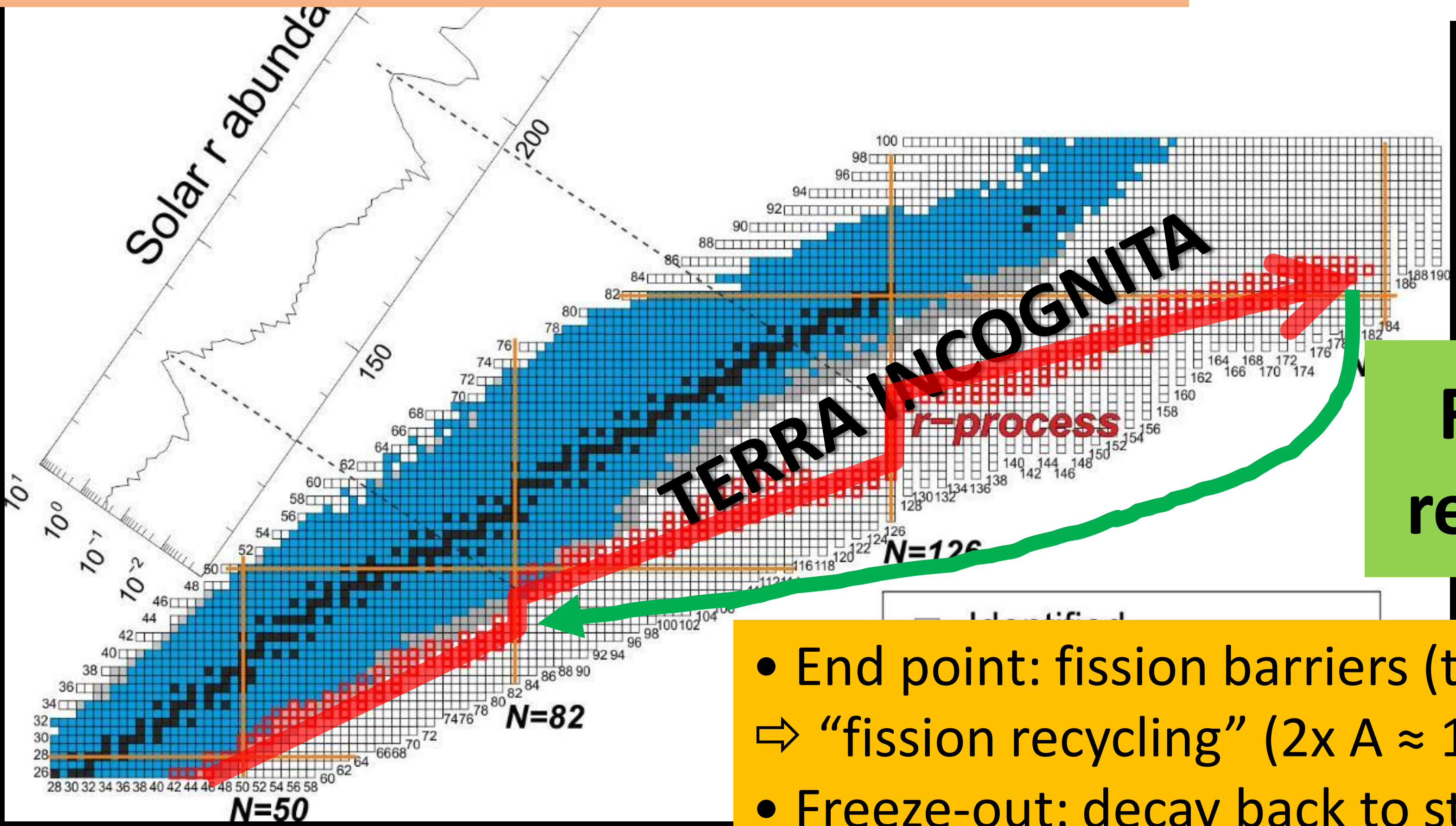
Discovery, accelerated

Conditions and reaction path

1980's: "Canonical" r-process
Site-free, mathematical approach

- High neutron densities (n_n>> 10^{20} cm^{-3}) ⇨ ≈1 ms per capture
- "Moderate" temperatures (T=1-2 GK)
  ⇨ ^{56}Fe to ≈ Pu (Z=94, A ≈ 260) in few seconds

Explosive astrophysical scenario



Fission recycling

- End point: fission barriers (theory!)
⇨ "fission recycling" (2x A ≈ 130)
- Freeze-out: decay back to stability

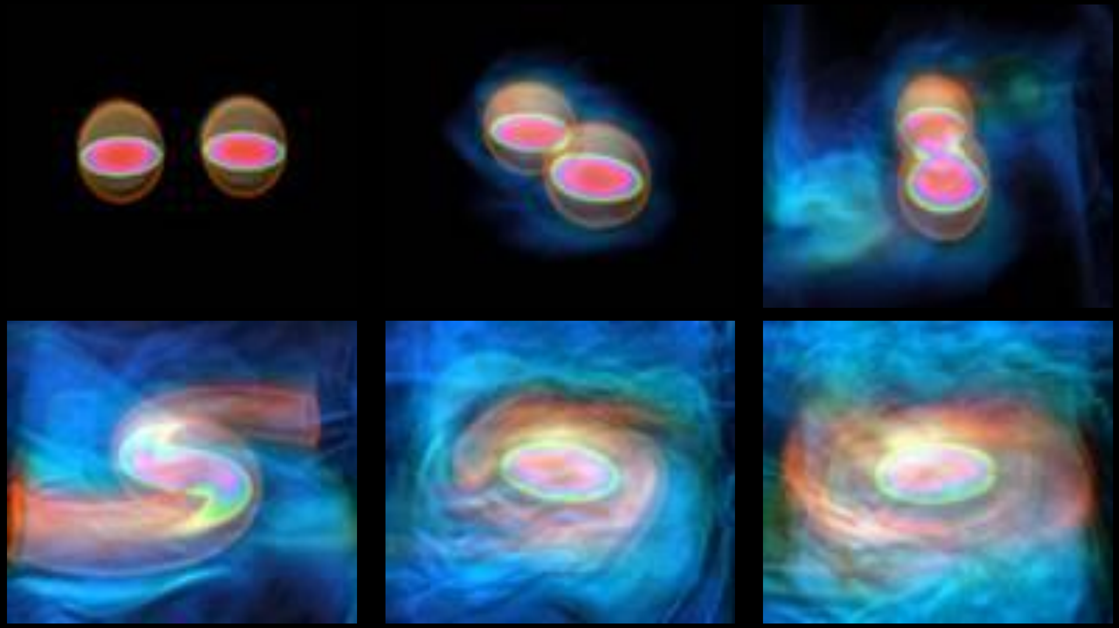
Discovery, accelerated

Astrophysical scenarios of the r-process

Core collapse supernova

Layers close to
forming neutron star

Neutron star mergers

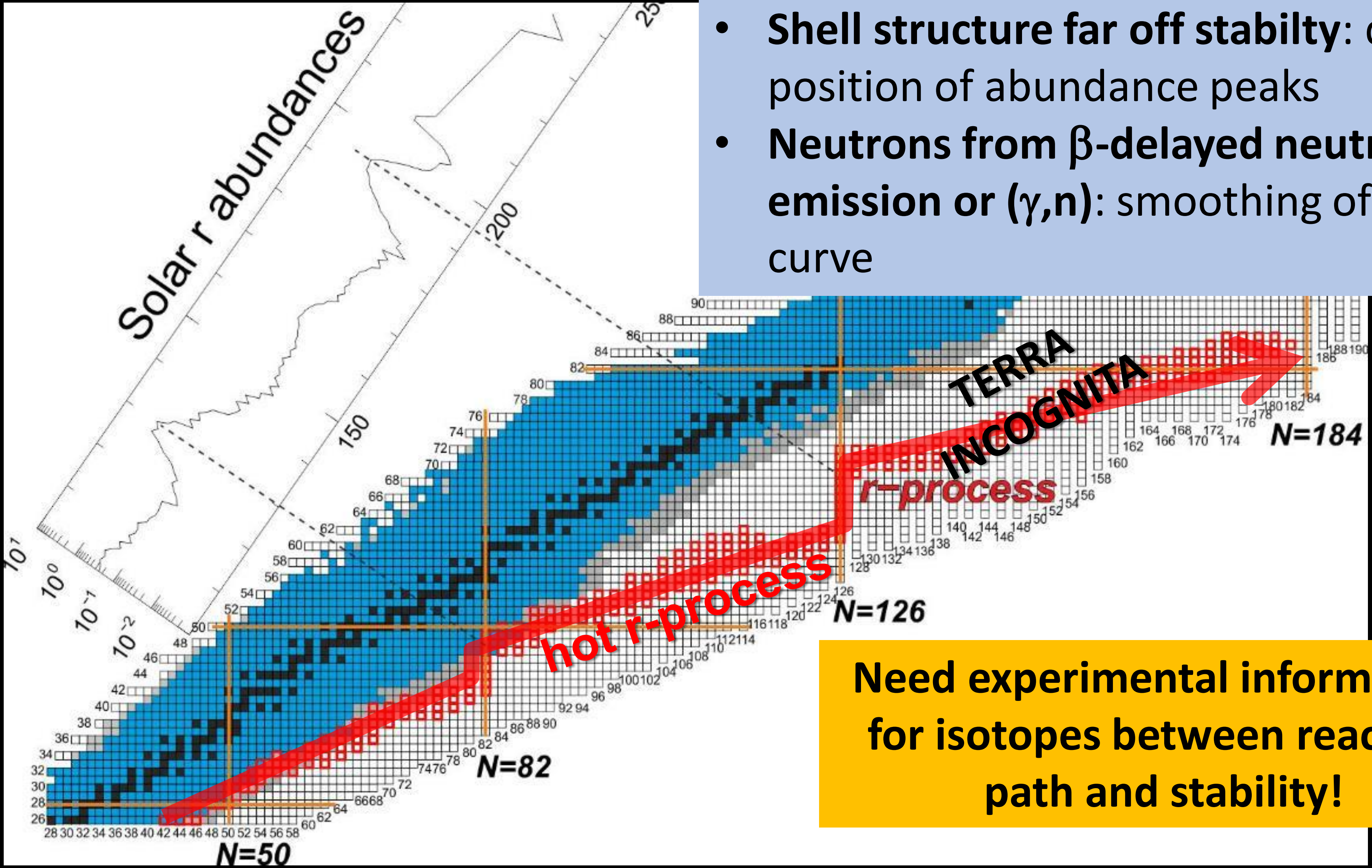


Time-delay: Neutron stars must form first,
then meet...later phases of evolution

Open question: How much does each scenario contribute to the solar abundances?

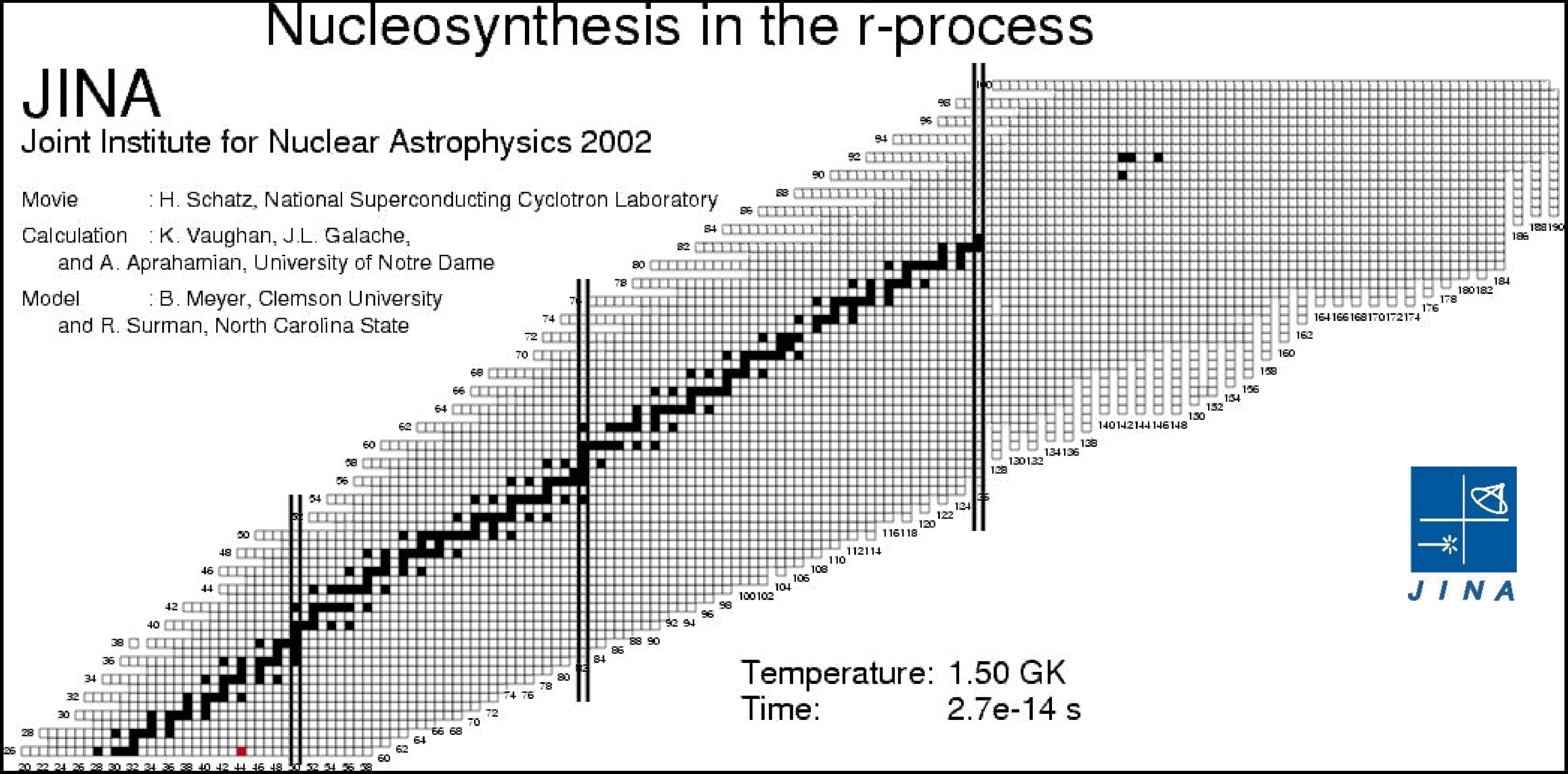
r-process

- **Masses**: define reaction path
- **Half-lives**: define shape
- **Shell structure far off stabilty**: defines position of abundance peaks
- **Neutrons from β-delayed neutron emission or (γ,n)**: smoothing of abundance curve



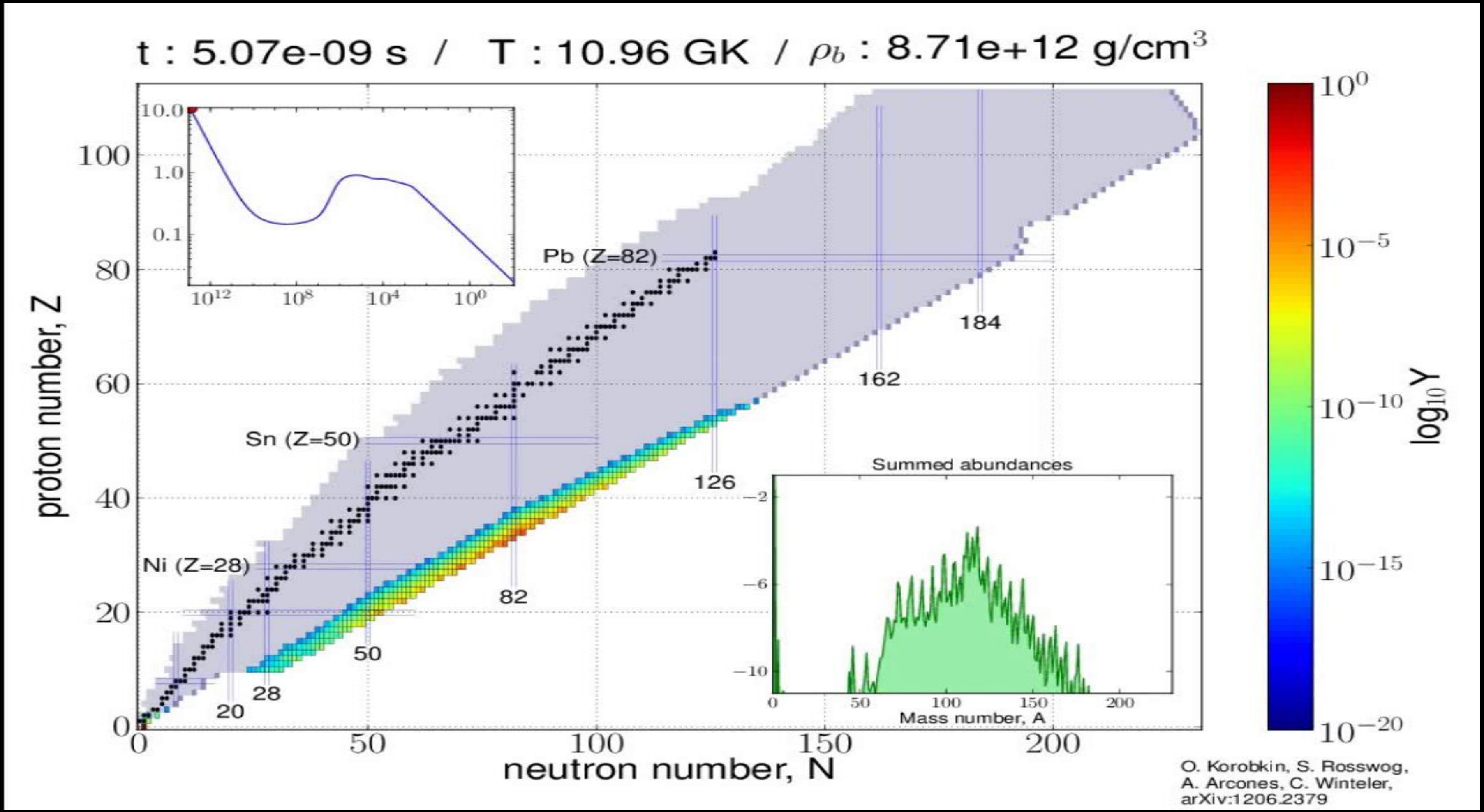
Need experimental information for isotopes between reaction path and stability!

r-process in Core Collapse Supernovae



http://www.jinaweb.org/html/movies.html

r-process in Binary Neutron Star Mergers



O. Korobkin, S. Rosswog, A. Arcones and C. Winteler, MNRAS 426, 1940 (2012)

S. Rosswog
http://compact-merger.astro.su.se/movies.html#nsbh

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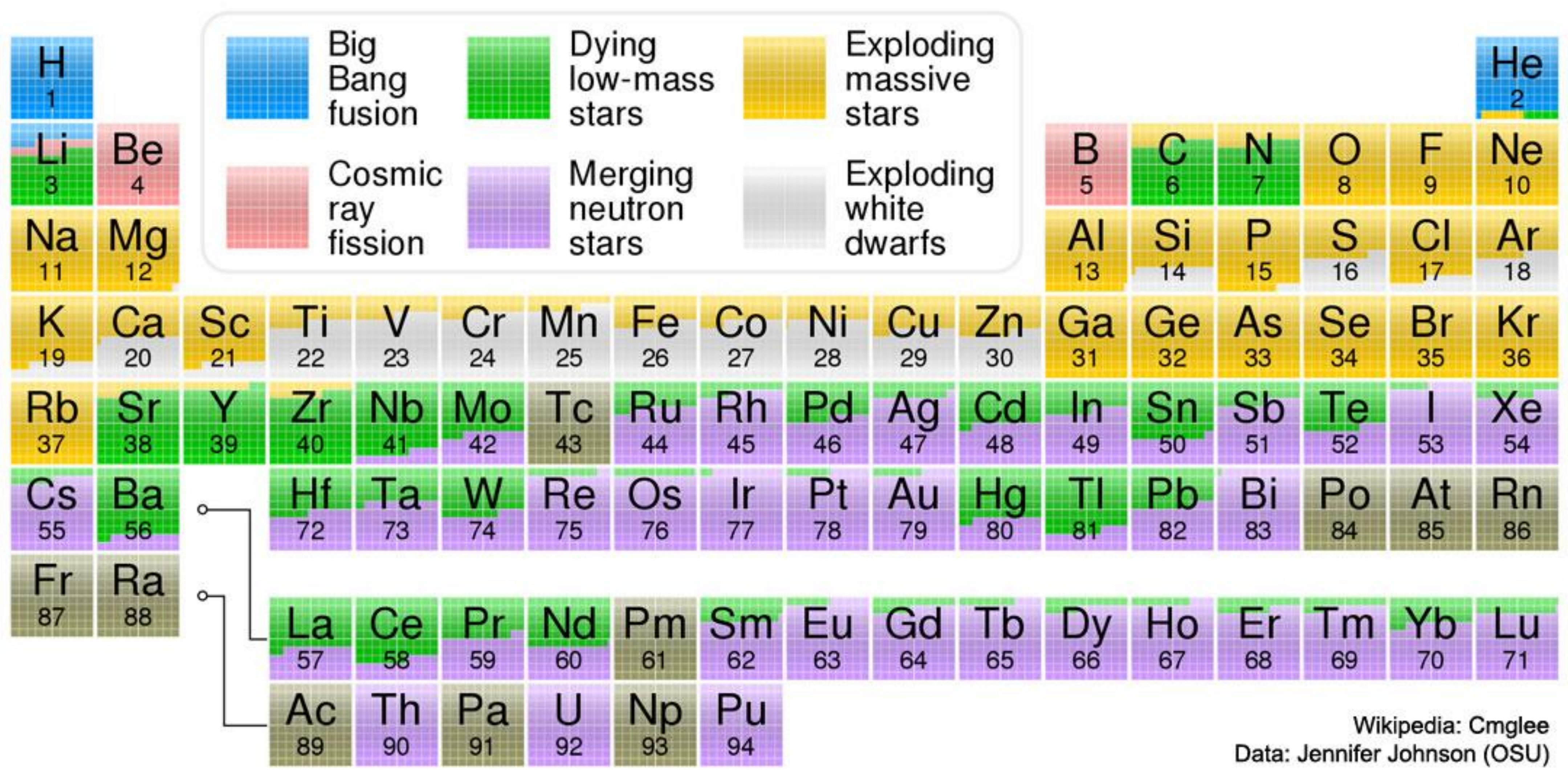
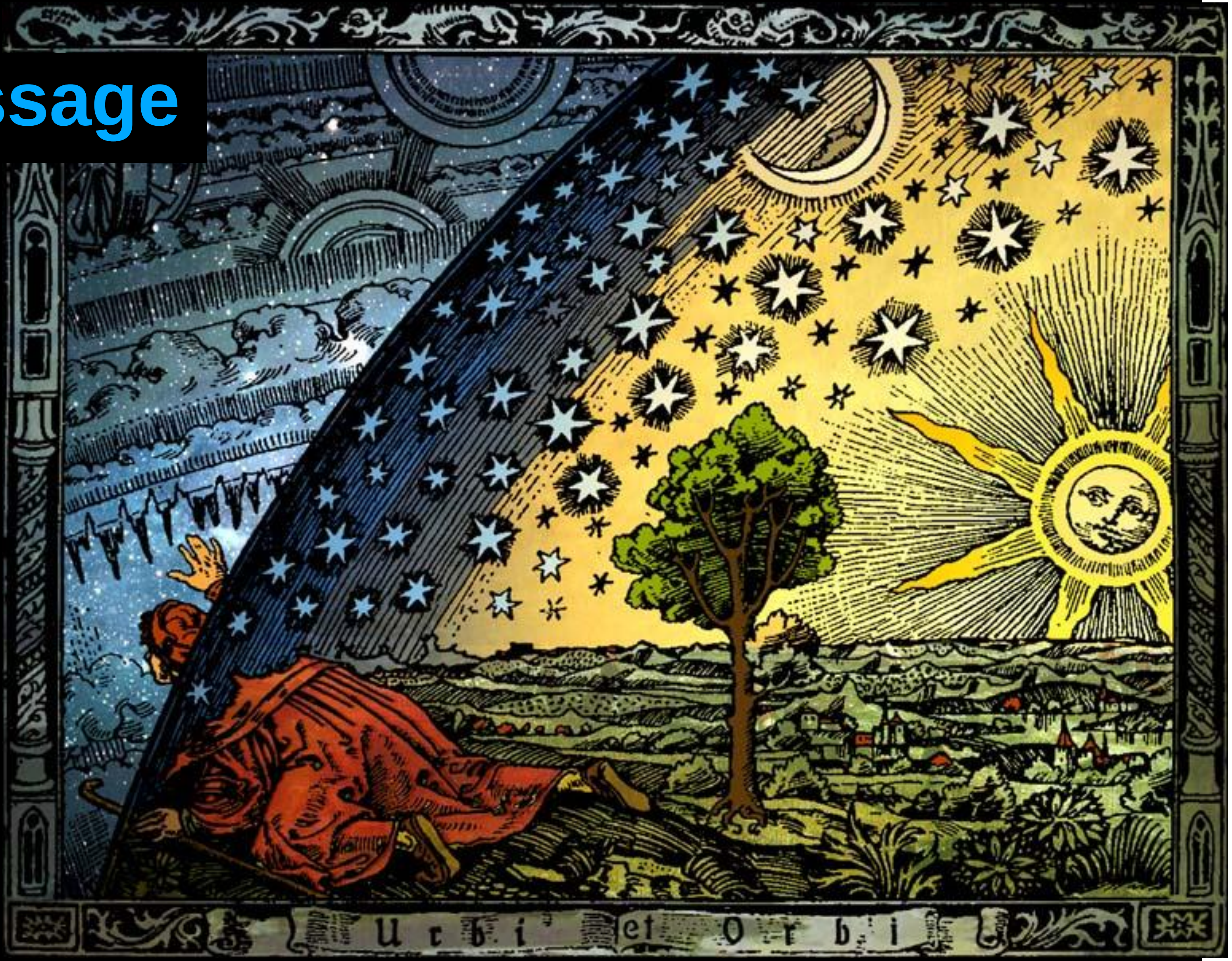
Summary



Discovery, accelerated

Take Home Message

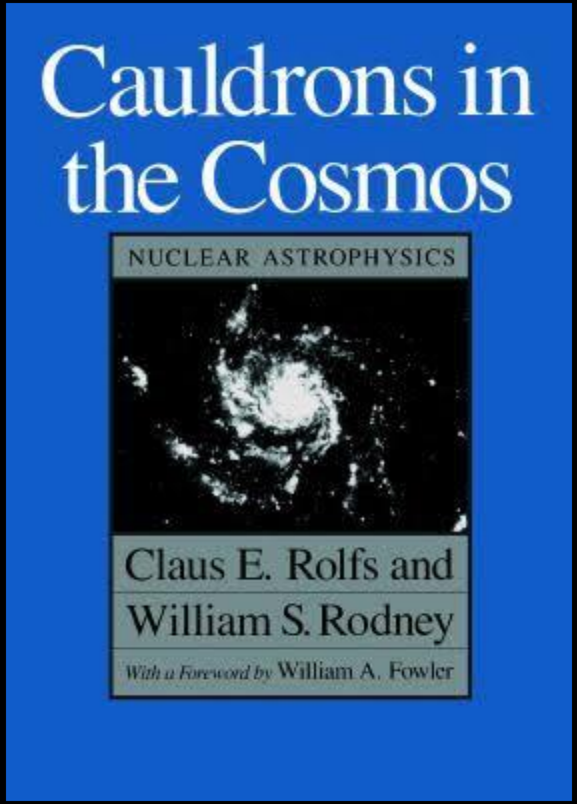
- We create and investigate isotopes that are produced in stars
- New radioactive beam facilities are under construction and will allow better access to these short-lived isotopes
- This is needed for a better understanding of where the star stuff we are made of comes from



Engraving from Camille Flammarion: L'Atmosphere - Météorologie Populaire. Paris 1888.
Color: Heikenwaelder Hugo, Wien 1998.

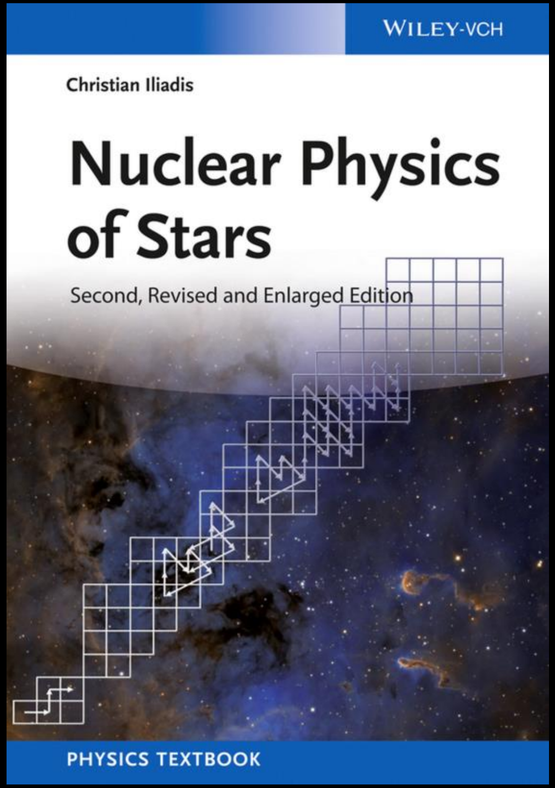
Reading Suggestions

Claus E. Rolfs and
William S. Rodney:
“Cauldrons in the Cosmos”



University of Chicago Press, 1988

Christian Iliadis:
“Nuclear Physics of Stars”



Wiley-VCH, 2008

Discovery, accelerated

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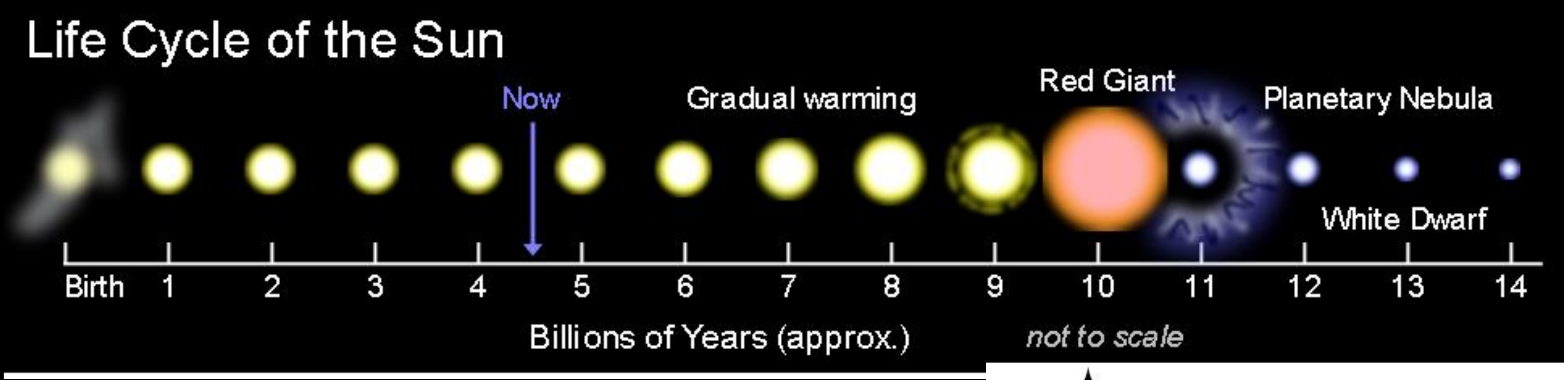
Thank you
Merci

www.triumf.ca

Follow us **@TRIUMFLab**

Discovery, accelerated

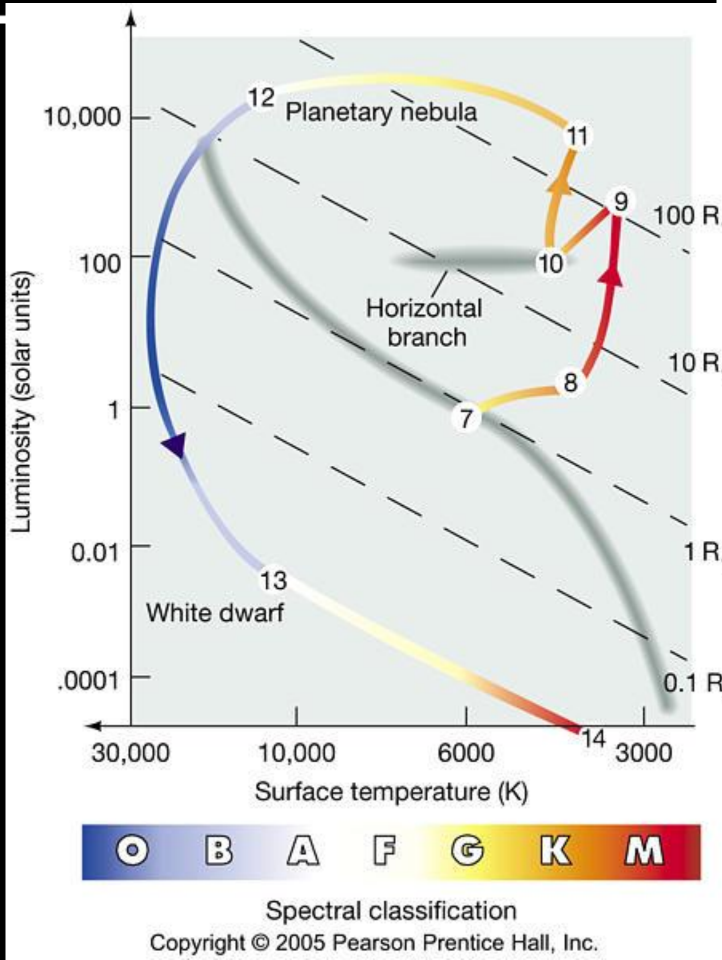
$M<8M_\odot$



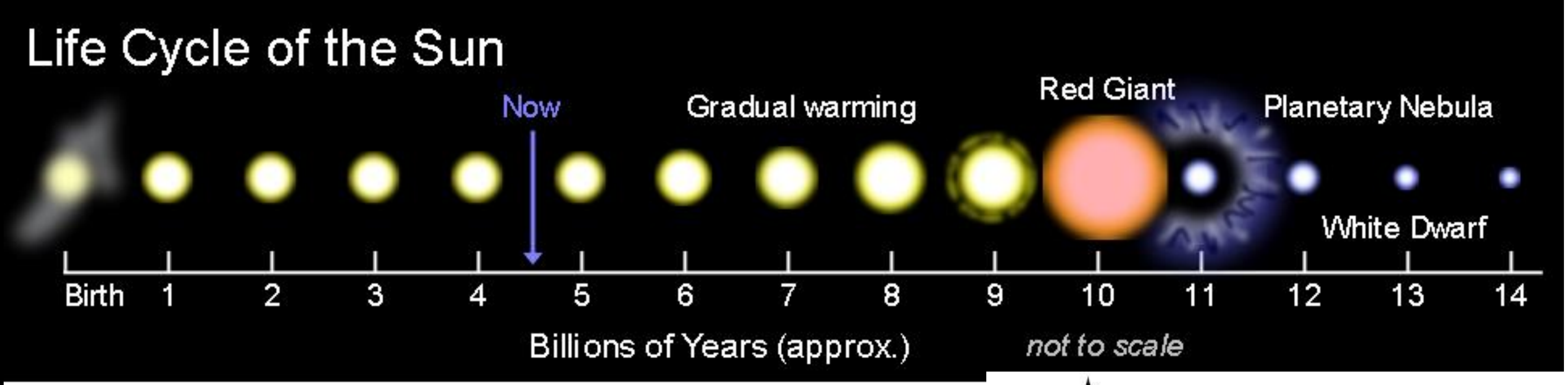
(7) 10 billion y: End of Main Sequence **(H shell burning)**

(8) $R \approx 2.5R_\odot$, $T_{surf} \approx 4500K$: Gravitational contract of core

(9) $R \approx 200R_\odot$, $T_{core} \approx 200$ MK, $T_{surf} \approx 3500$ K (**Red Giant stage):** 3α process ignited



$M<8M_\odot$

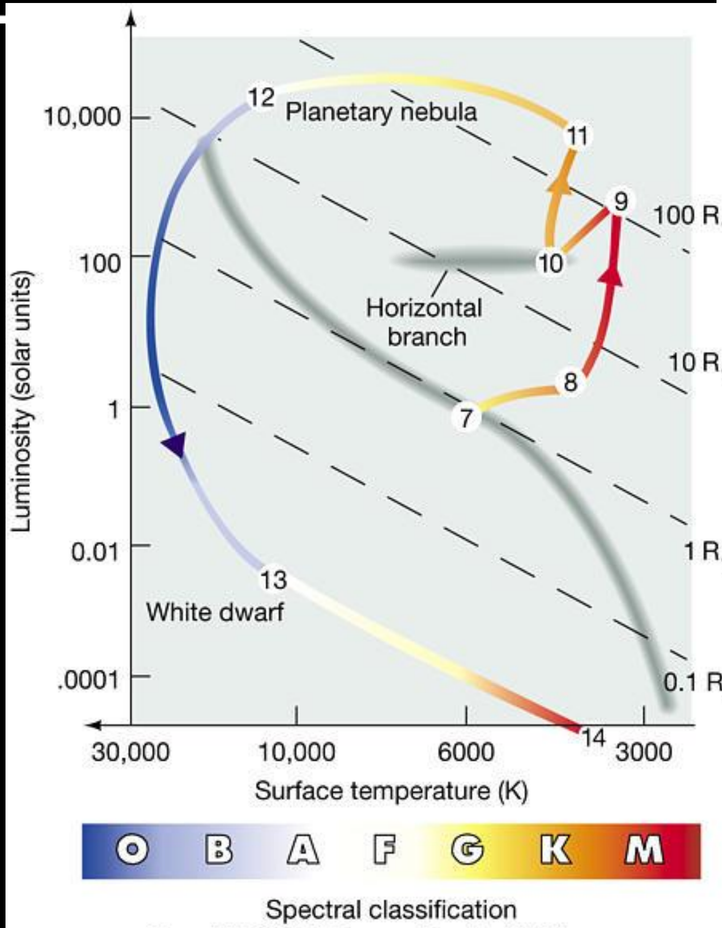


(10) Core He burning (T_{core} ≈ 200 MK, T_{surf} ≈ 9000 K) and **shell H burning (Horizontal branch)**

(11) He in core is exhausted, CO core contracts (H and He shell burning continues); **He shell burning**: thermal pulse ejects up 10% of mass

(12) 11 billion y: **Planetary nebula**

(13) White Dwarf/ (14) Black Dwarf: R ≈ R_{earth}, T_{surf} ≈ 30000-5000K



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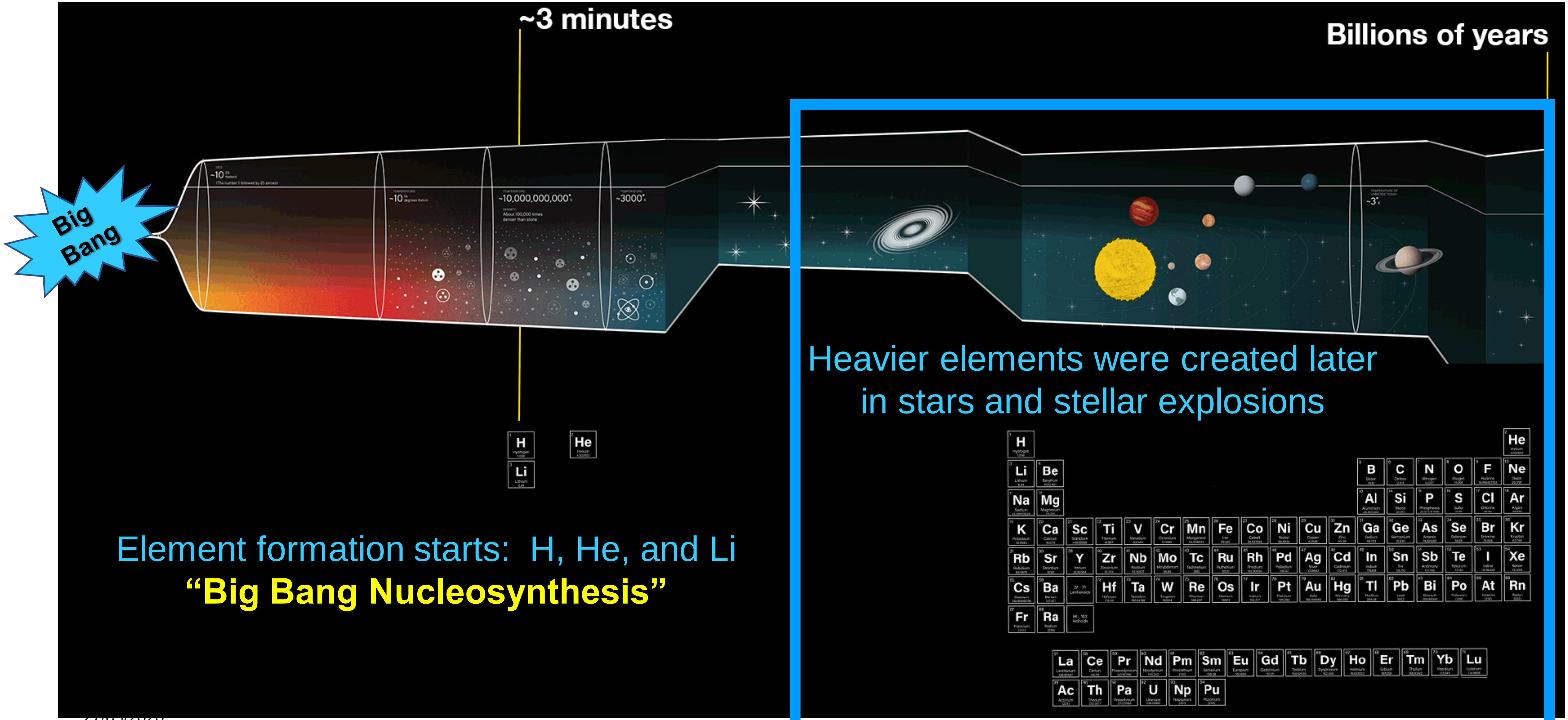
When were the elements created?



Heavier elements were created later in stars and stellar explosions

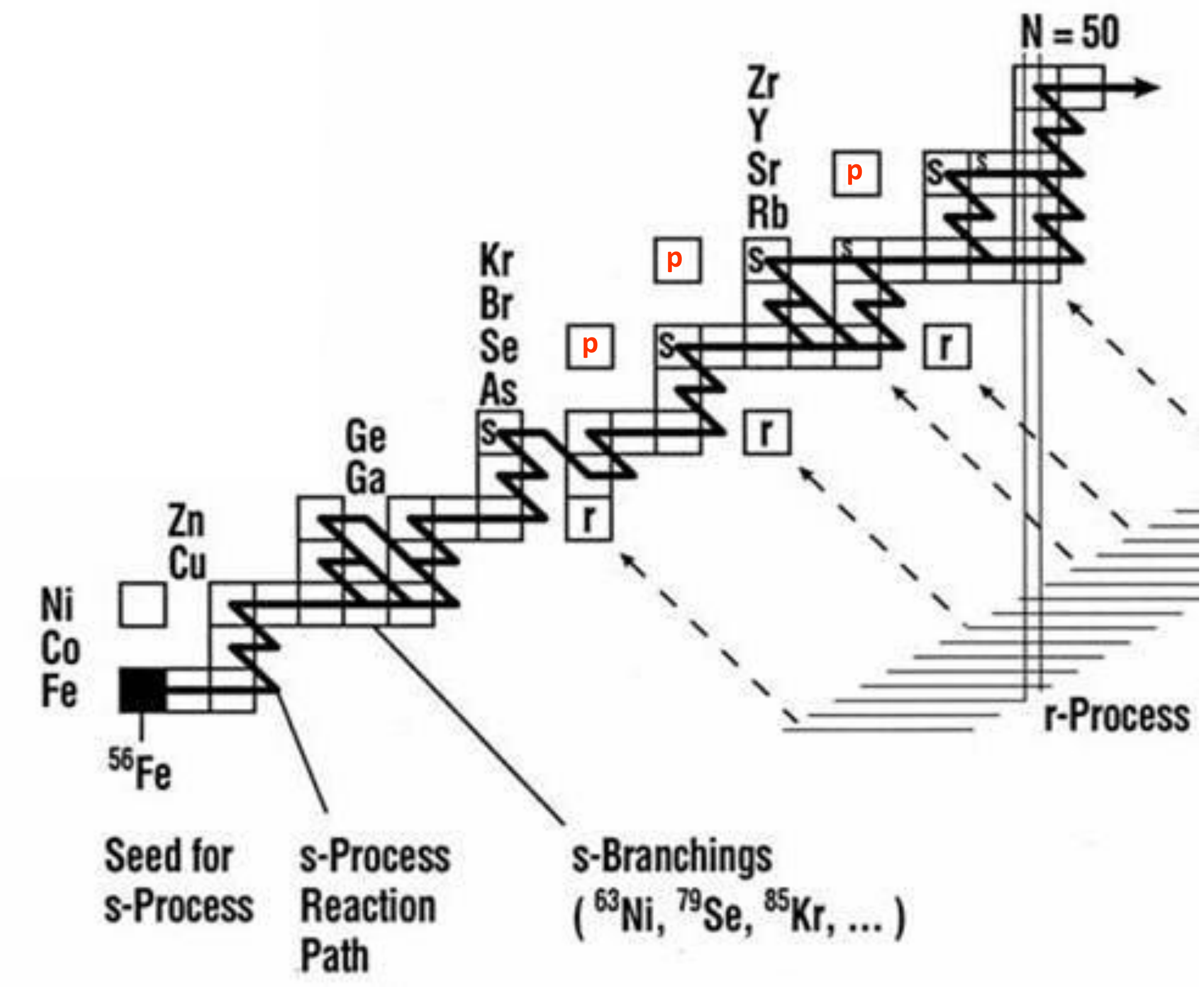
Element formation starts: H, He, and Li

“Big Bang Nucleosynthesis”

Slow neutron capture process

≈50% of abundances >Fe

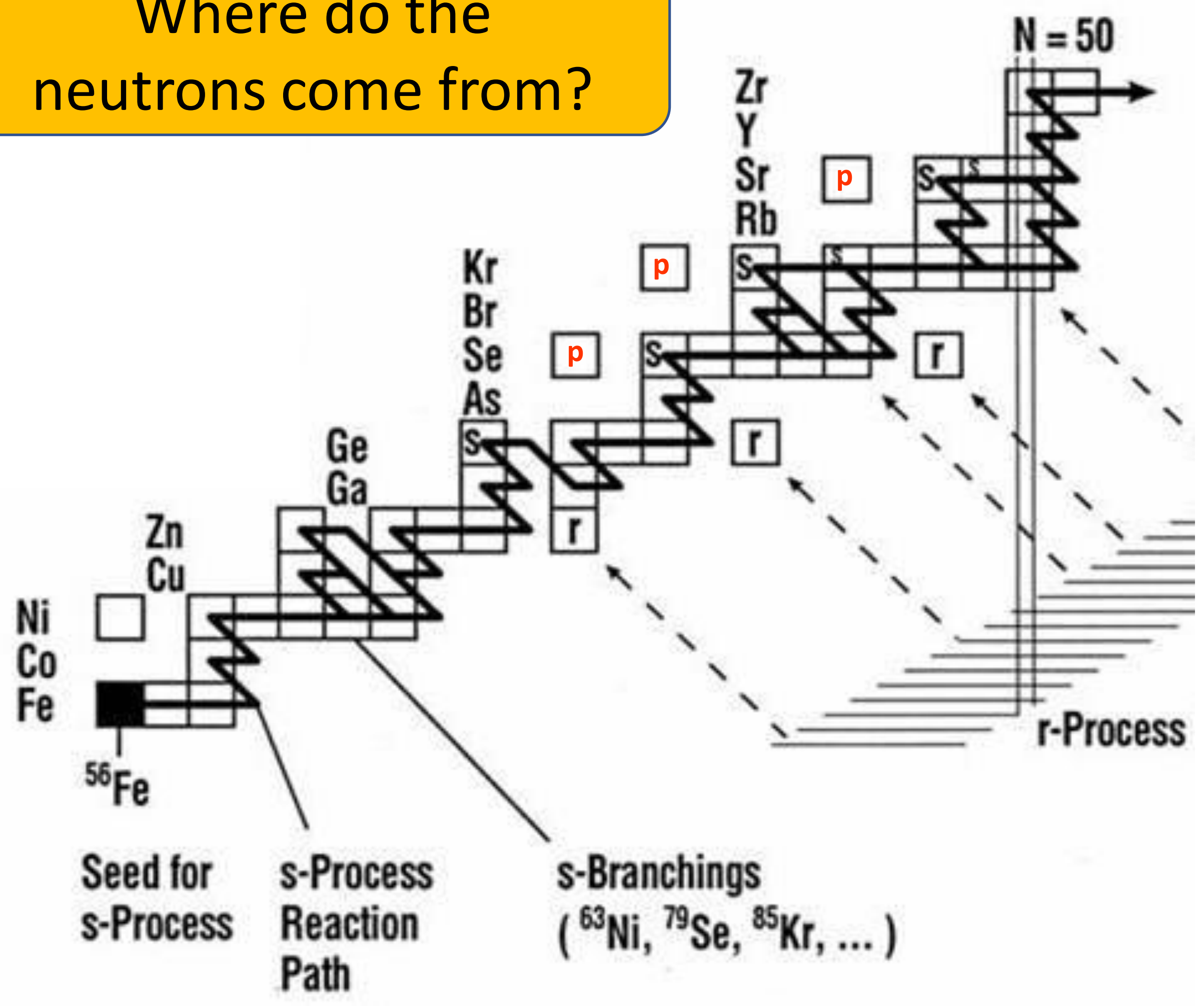
- **Neutron capture slowly** compared to β-decay (1 capture per ≈1000 y)
- Well defined **path along line of stability** ⇨ **Well understood from astrophysical and nuclear physics side**
- End point: $\mathbf{^{209}Bi}$

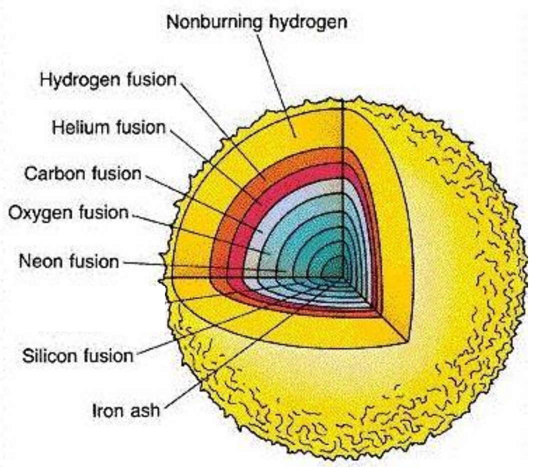


Slow neutron capture process

≈50% of abundances >Fe

Where do the neutrons come from?



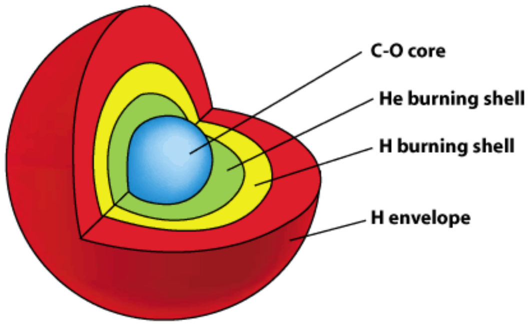


Massive star

Core He burning
Shell C burning

TP-AGB star

(thermally pulsing asymptotic giant branch)



Shell H burning
Shell He burning flashes

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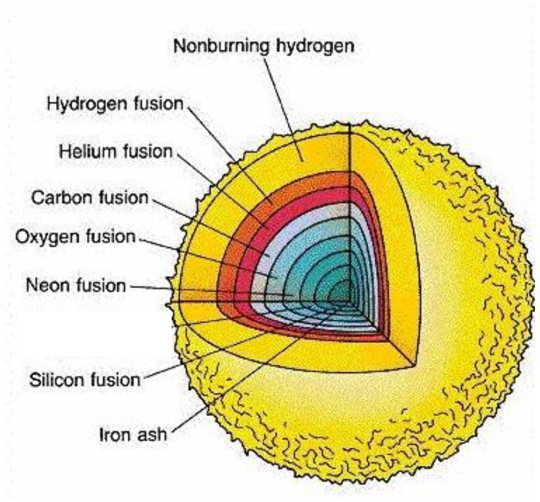
s-process in a nutshell

	Weak component		Main component	
Mass region	A<90 (Fe - Zr)		A>(56) 90 (Zr - Bi)	
Stellar site	Massive stars (>8 M_{sun})		TP AGB stars (1-3 M_{sun})	
Stellar burning phase	core He	shell C	Shell H burning	He shell flashes
Temperature [MK]	300 (kT= 26 keV)	1000 (kT= 90 keV)	90 (kT= 8 keV)	250 (kT= 23 keV)
Neutron source	**Ne-22(α,n)Mg-25**	**Ne-22(α,n)Mg-25**	**C-13(α,n)O-16**	**Ne-22(α,n)Mg-25**
Av. neutron density [cm^{-3}]	10^6	10^{11}	10^7	10^{11}
Duration [y]	10^6	1-20	10^4	10

Massive star



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TP-AGB star

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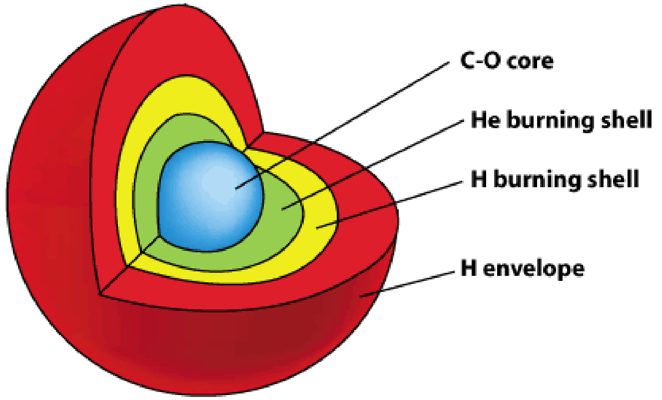

Important nuclear physics input for the s process

1) Neutron capture cross sections (on stable and long-lived radioactive nuclei ($t_{1/2}$>50 y); Neutron energy: E_n= eV…500 keV (kT=5-100 keV)
2) Decay half-lives close to stability
3) Low-lying isomeric states