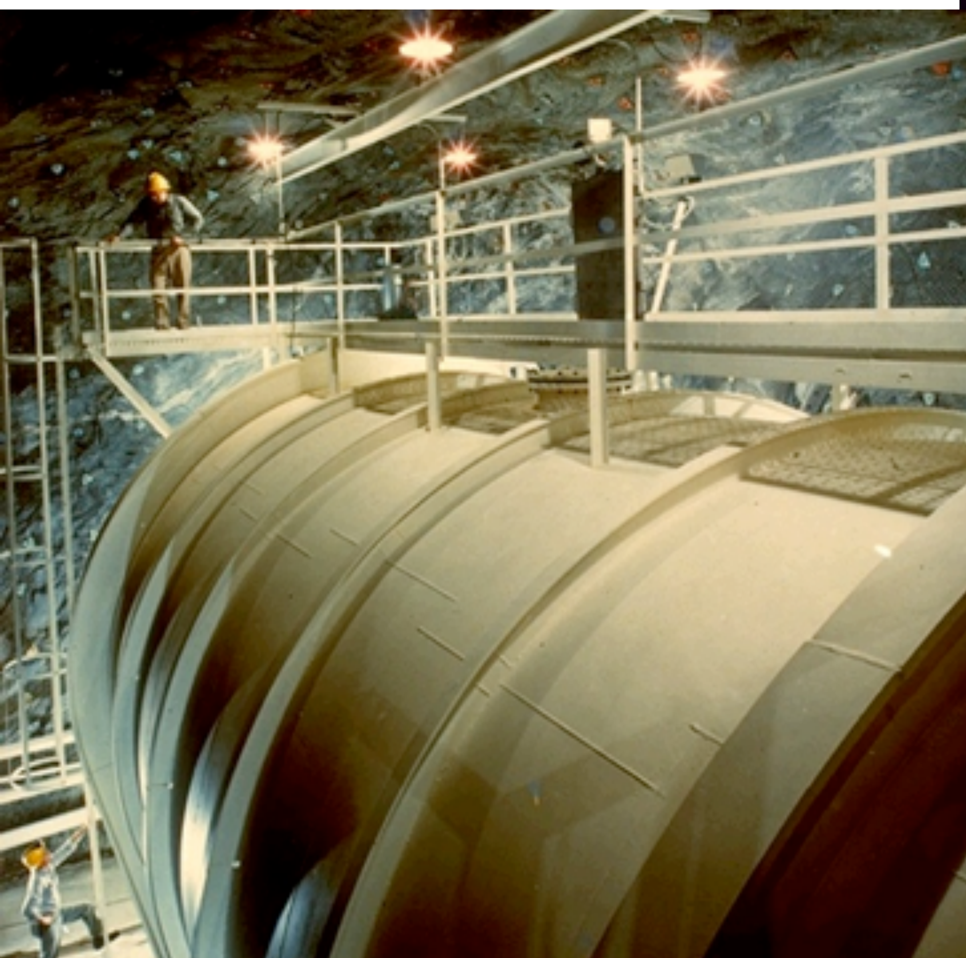
The Present and Future Sun
& the s-Process



Brian Fields

U. of Illinois

TALENT School, MSU, May 2014

The CNO Cycle

pre-existing C, N, O act as $4p \to {}^4$He *catalyst*

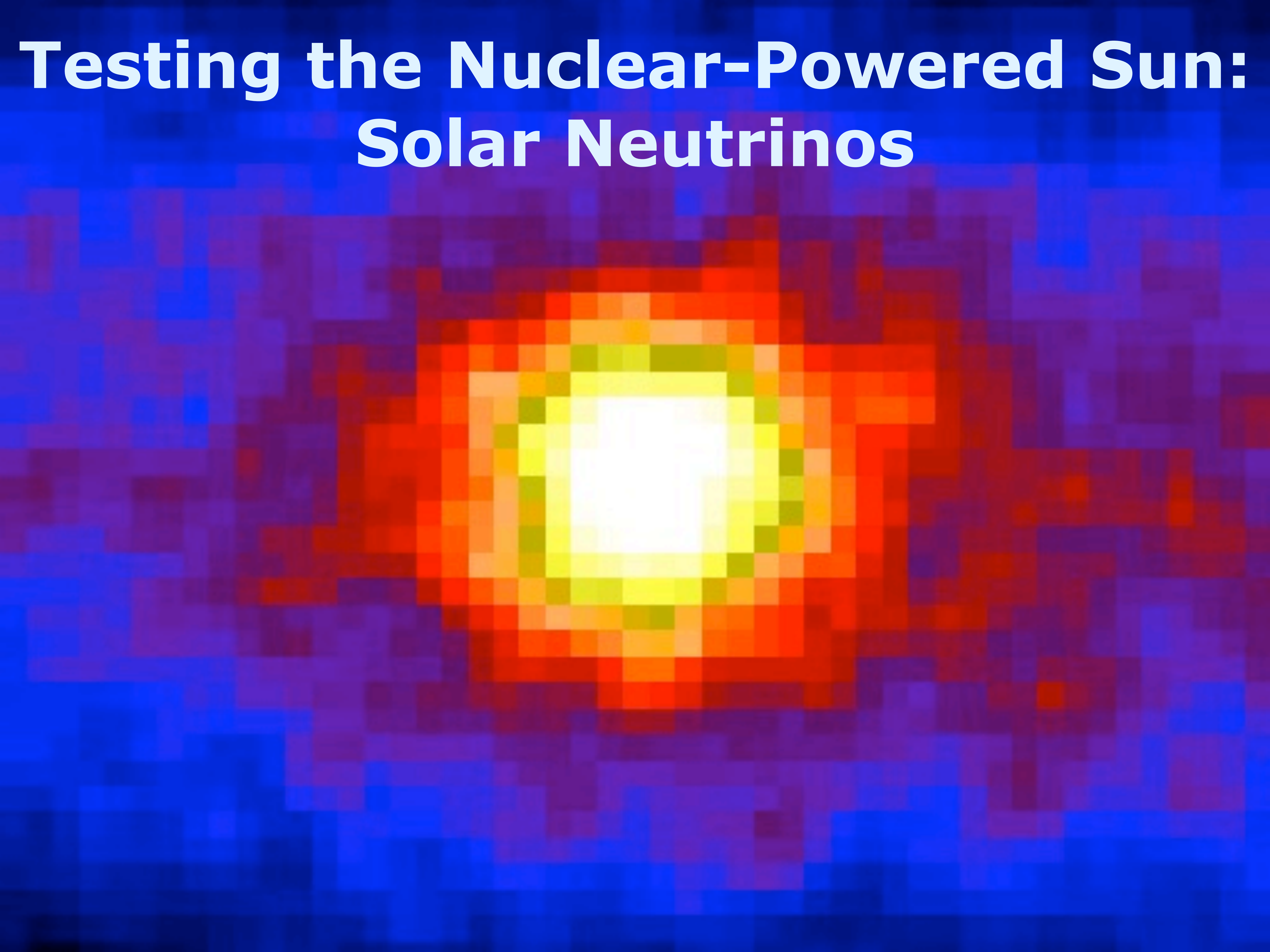
$$\begin{array}{ccccc} {}^{12}\mathrm{C} & \stackrel{(p,\gamma)}{\longrightarrow} & {}^{13}\mathrm{N} & \stackrel{e^+\nu_e}{\longrightarrow} & {}^{13}\mathrm{C} \\ (p,\alpha)\uparrow & & & & \downarrow(p,\gamma) \\ {}^{15}\mathrm{N} & \stackrel{e^+\nu_e}{\longleftarrow} & {}^{15}\mathrm{O} & \stackrel{(p,\gamma)}{\longleftarrow} & {}^{14}\mathrm{N} \end{array}$$

Coulomb barriers high ($Z = 6,7,8$): *need high T_c* to

$\Rightarrow$ CNO cycle minor in Sun (CNO $\to$1.6% $L_\odot$)

but main H-burner for $M \gtrsim 1.5 M_\odot$

Testing the Nuclear-Powered Sun: Solar Neutrinos



Solar Neutrino Production

Rxn	$E_{\nu,\mathrm{max}} = Q$	$\langle E_\nu \rangle$	Total SSM Flux Φ_ν (10^{10} ν cm^{-2} s^{-1})
$pp \rightarrow de\nu$	0.420 MeV	0.265 MeV	6.0
^{7}Be $e \rightarrow {}^{7}$Li ν	lines: ^{7}Li^{gs} = 0.861 MeV; ^{7}Li* = 0.383 MeV		0.47
^{8}B $\rightarrow {}^{8}$Be e ν	17.98 MeV	9.63 MeV	5.8×10^{-4}

Q: Why are the ^{7}Be *neutrinos monoenergetic?*

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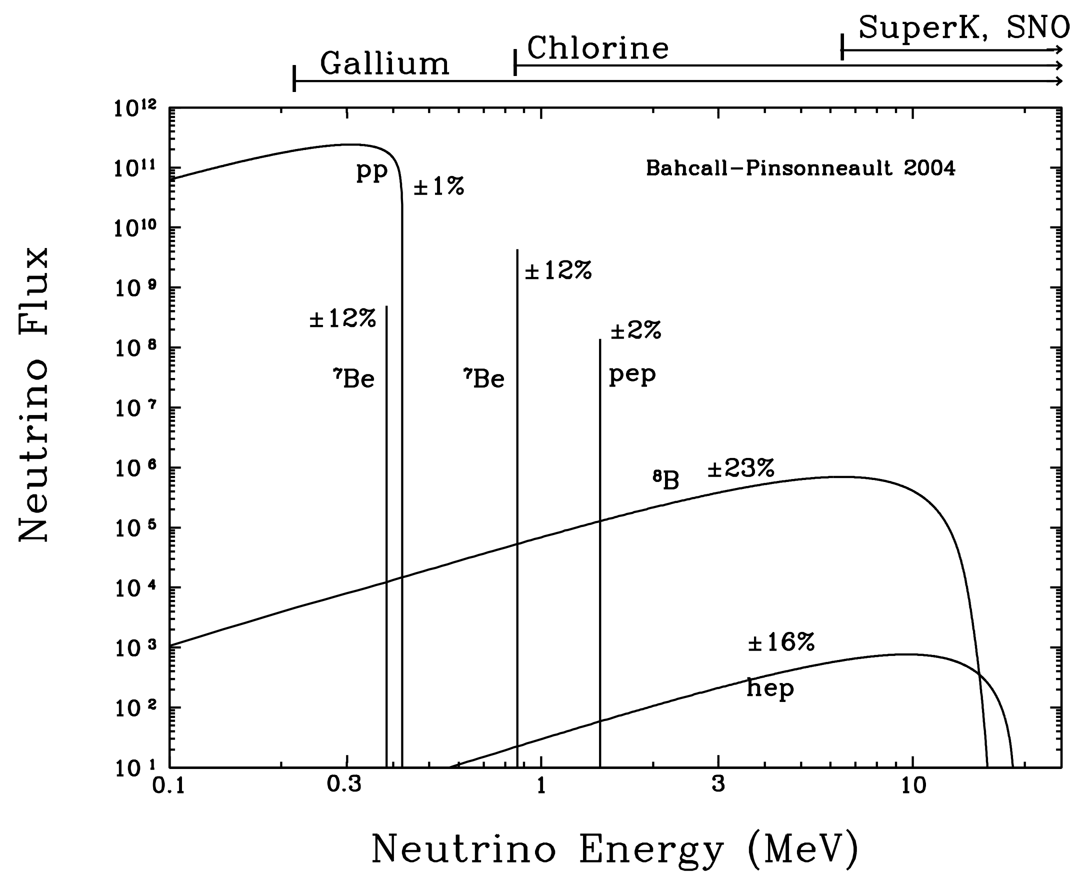

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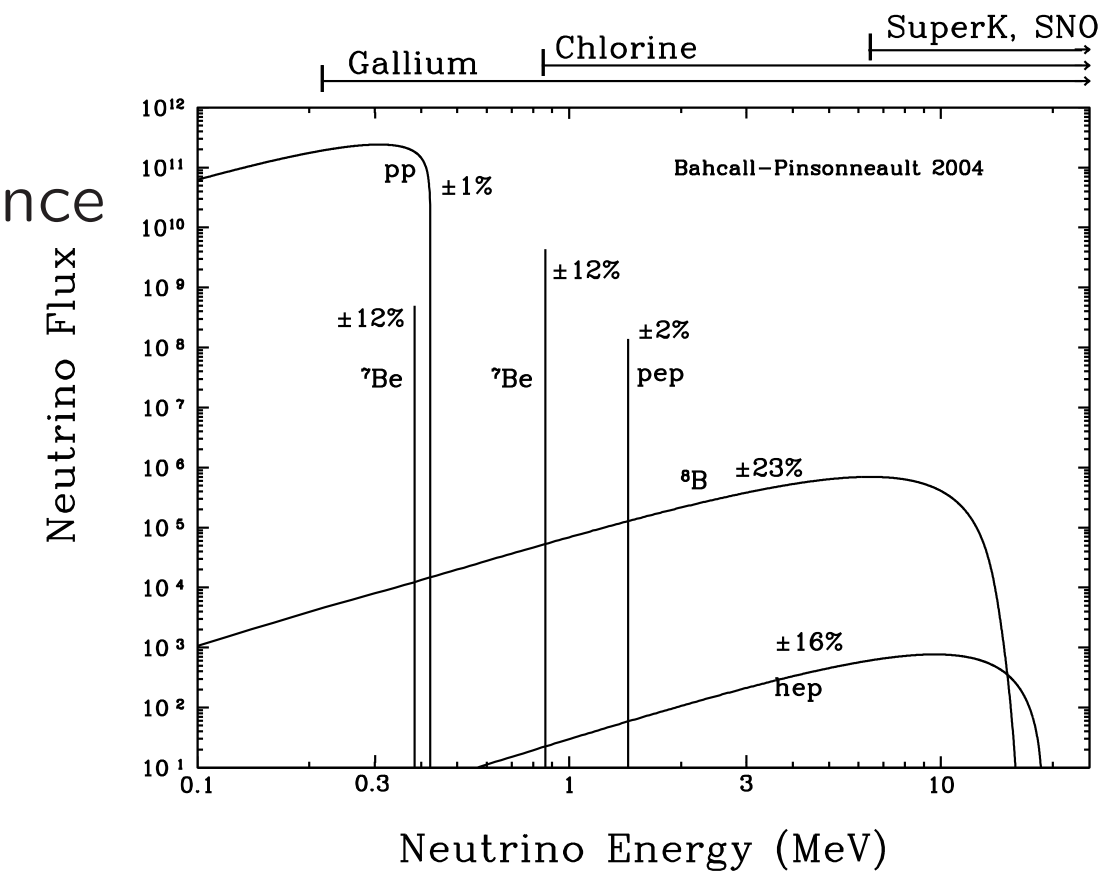
- **pp neutrinos** largest flux, but low energies
- **^{7}Be neutrinos** monoenergetic, strong $\sim T_c^8$ dependence
- **^{8}B neutrinos** continuum, ultrastrong $\sim T_c^{20}$ dep

What should this mean for production vs radius?



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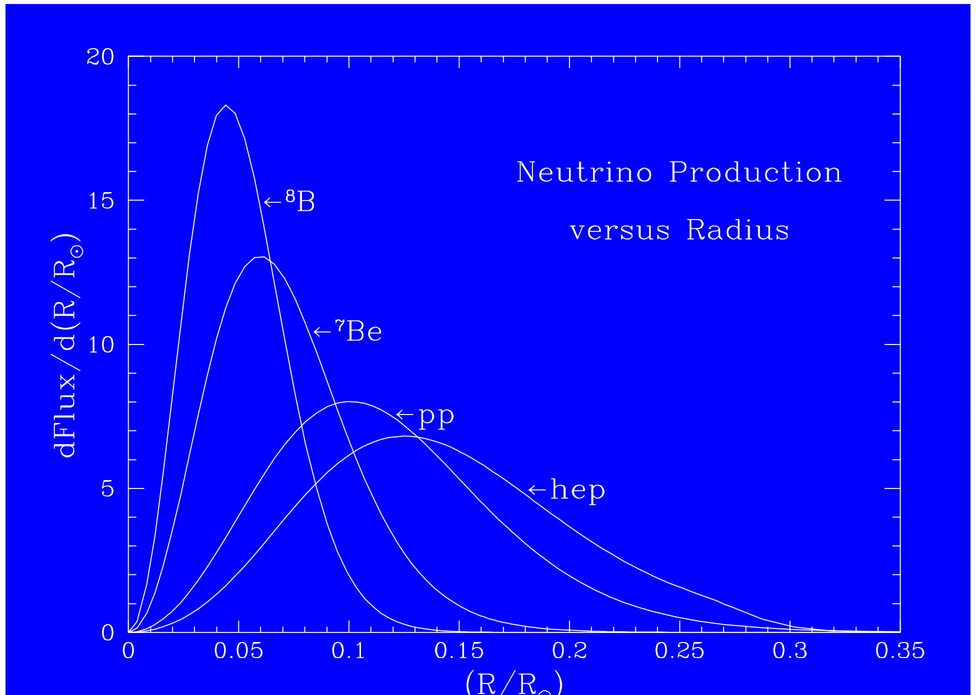


Standard Solar Model Predictions

What are key SSM ν ingredients, predictions?

- time variations: at source? in detectors?
- $L_\odot$ fixes what?
- what connection between $\Phi_\nu(^7\text{Be})$ and$\Phi_\nu(^8\text{B})$?
- ν spectra: determined by what?

Solar Neutrino Predictions

SSM Key Predictions:

- at source: steady ν_e flux from Sun
- elliptical Earth orbit $\rightarrow$ annual flux variation
  $\Delta\Phi_\nu/\Phi_\nu \simeq 2\delta r_\oplus/r_\oplus \sim 4e_\oplus \sim 7\%$
- pp flux $\sim$ fixed by $L_\odot$
- ^{7}Be, ^{8}B flux T-dep, but $\Phi_\nu(^7\text{Be}) > \Phi_\nu(^8\text{B})$
- neutrino spectra fixed by β decay
  indep of solar model (since $T_{c,\odot} \sim 1\text{keV} \ll \text{Q}_\text{nuke}$)

Solar Neutrino Experiments

Original motivation (Davis, Bahcall):

- confirm nuke energy generation
- measure $T_{\odot,c}$

Facts of life:

1. ν $\rightarrow$small σ
2. $E_\nu \lesssim few$ MeV $\rightarrow$ large natural background
   e.g., radioactivity, cosmic ray muons

Q: what is needed for neutrino observatory?

Neutrino Observatories: Design Requirements

1. **Large** detector.

ν-nucleus absorption $\sigma_{\nu A} \sim 10^{-44}$ cm^2

$\Rightarrow$ event rate per target $\Gamma_\nu(A) = \Phi_\nu \sigma_{\nu A} \sim 10^{-36}$ s^{-1}

Solar Neutrino Unit: 1 SNU $= 10^{-36}$ event s^{-1} target^{-1}

Want net rate $R = N_{\rm targ}\Gamma \gtrsim 1$ day^{-1} $\sim 10^{-5}$ s^{-1}

$\Rightarrow$ Need $N_{\rm targ} = R/\Gamma \sim 10^{31}$

$$M_{\rm targ} = A m_u N_{\rm targ} \sim 10^9 \left(\frac{A}{50}\right) \text{ g } \sim \left(\frac{A}{50}\right) \text{ kiloton}$$

big!

2. Go **underground**.

"Clean" lab, low-background material

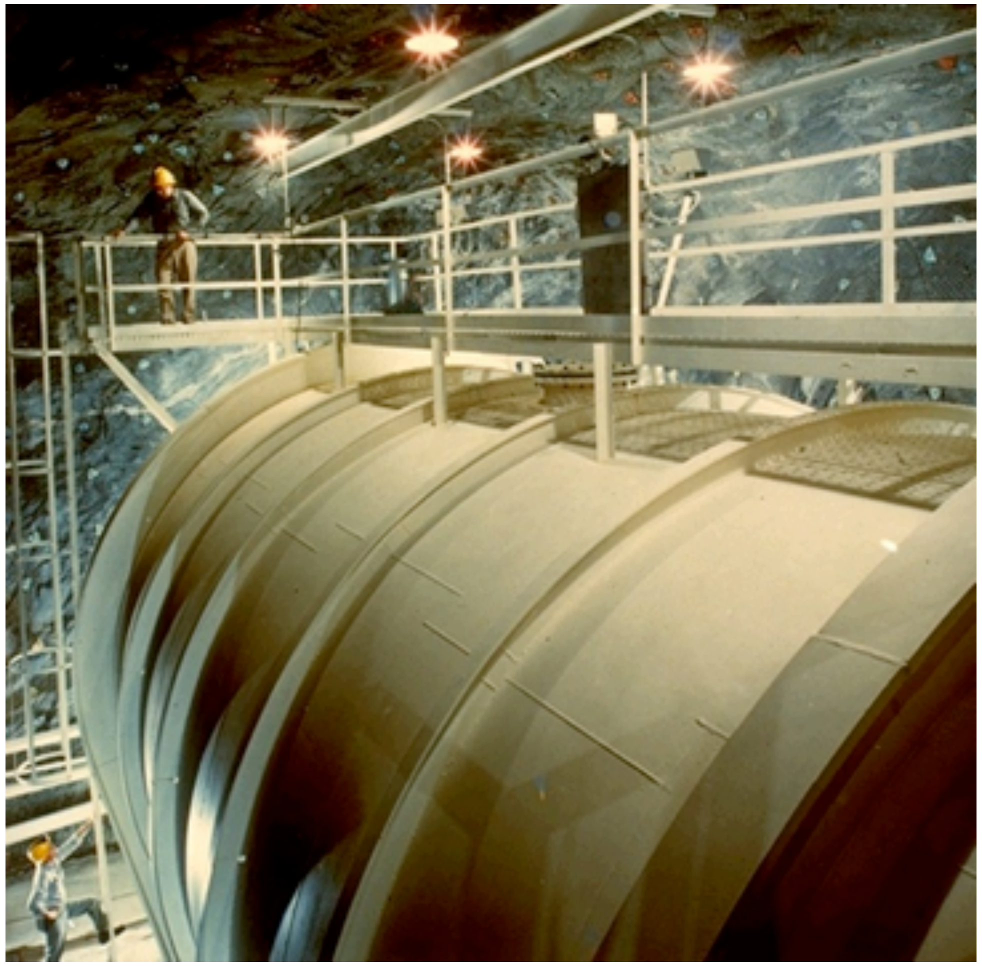
Radiochemical Experiments: Chlorine

Homestake Mine:

- Lead, SD 1967-1995

Ray Davis
& John Bahcall

target: chlorine (cleaning fluid!, 0.61 kton)
process: $^{37}\text{Cl} + \nu_e \rightarrow ^{37}\text{Ar} + e$ (endothermic)
threshold: ν must supply $|Q| = 0.814$ MeV
$\Rightarrow$ only measure ^{7}Be, ^{8}B νs
procedure: cycle fluid $\rightarrow$ filter, collect ^{37}Ar atoms: $\sim few$/week!



Measure:

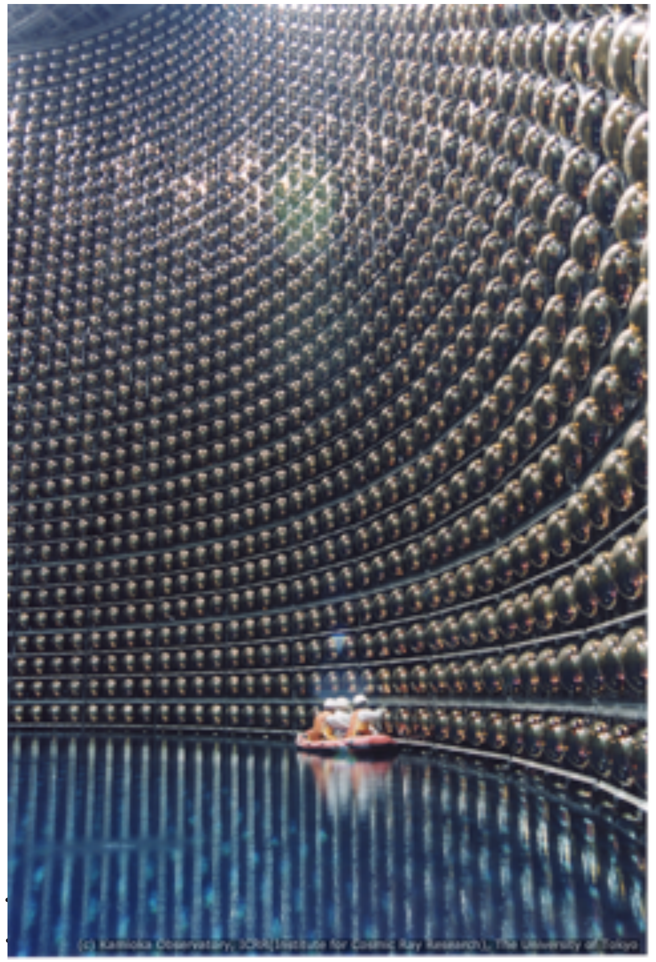
$$\Gamma_{\text{obs}} = 2.56 \pm 0.16 \pm 0.16 \text{ SNU}$$

Compare to SSM prediction:

$$\frac{\Gamma_{\text{obs}}}{\Gamma_{\text{SSM}}} = 0.33 \pm 0.03 \pm 0.05 \ll 1!$$

Only see $\sim 1/3$ of predicted flux!
$\Rightarrow$original *Solar ν problem*

Water Cerenkov Experiements



target: water

process: electron scattering $\nu e \rightarrow \nu e$

for $E_\nu \gtrsim 0.5$ MeV, recoil electron $v_e \sim c$

but in water, refactive index $n = 1.34 \Rightarrow v_e > c/n$

emit "sonic boom" photons: Čerenkov radiation

"optical shock wave," cone of light

cone opening angle depends on $v_e \rightarrow E_e$

Super-Kamiokande. Kamioka Mine, Japan:

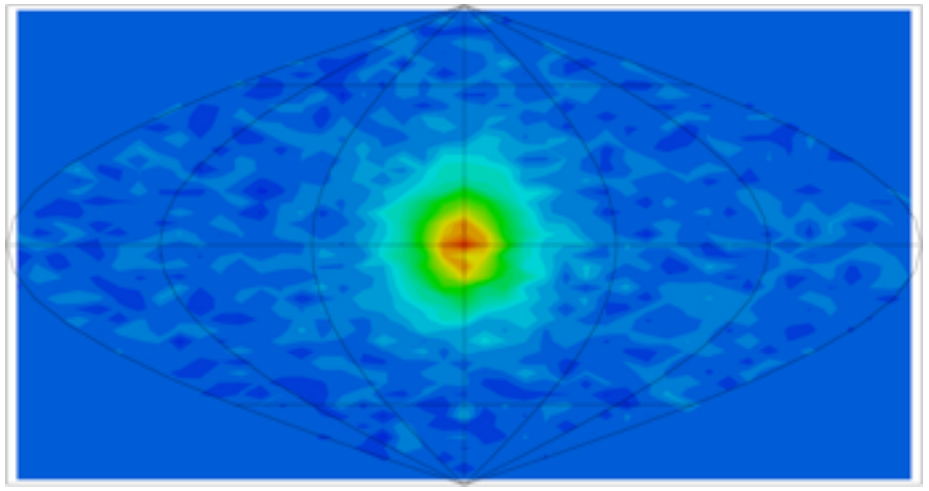
direction: νs point back to Sun (check)

$e\nu$ elastic scattering in pure water

Energy threshold: 5 MeV $\Rightarrow$ see only ^{8}B νs

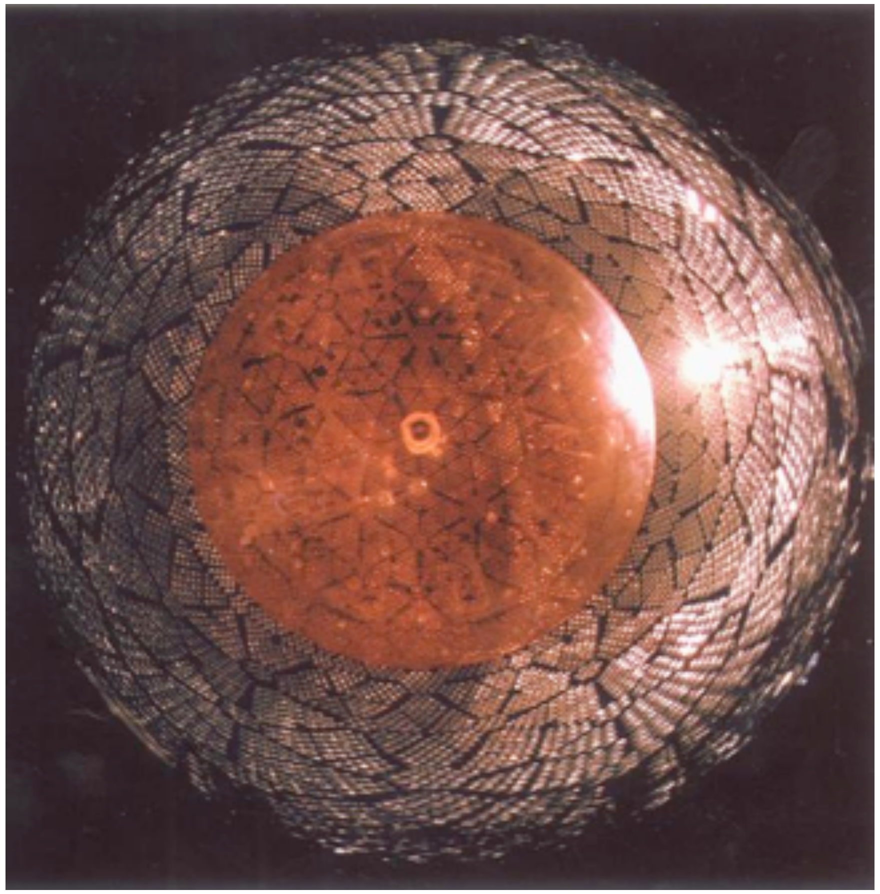
spectrum: shape matches SSM

...but $\Phi(^8\text{B})_{\text{SK}}/\Phi(^8\text{B})_{\text{SSM}} \sim 50\%$!



Sudbury Neutrino Observatory (SNO)

Sudbury, Ontario, Canada: 1999-
ultrapure heavy water: D_2O



Rxns:

$\nu_e + d \rightarrow e^- + p + p$ *Feynman diagram*

Charged current: ν_e *only*

Threshold: 1.4 MeV $\rightarrow$ ^{8}B only

$\nu_x + d \rightarrow \nu'_x + p + n$ *Feynman diagram*

ν' flavor = ν flavor

Neutral current: *all flavors*

Threshold: 2.2 MeV $\rightarrow$ ^{8}B only

also: Salt phase – dissolve NaCl in SNO tank
big σ for ^{35}Cl$(n,\gamma)^{36}$Cl $\rightarrow$ improved NC

SNO Results

Charged-current (ν_e flux):

$$\Phi_{\mathrm{CC}}^{\mathrm{SNO}} = \left[1.59^{+0.08}_{-0.07}(\mathrm{stat})^{+0.06}_{-0.08}(\mathrm{sys})\right] \times 10^6 \ \nu \ \mathrm{cm}^{-2} \ \mathrm{s}^{-1}$$

Neutral-current (all-ν flux):

$$\Phi_{\mathrm{NC}}^{\mathrm{SNO}} = [5.21 \pm 0.27(\mathrm{stat}) \pm 0.38(\mathrm{sys})] \times 10^6 \ \nu \ \mathrm{cm}^{-2} \ \mathrm{s}^{-1}$$

Thus we have

$$\frac{\Phi_{\mathrm{CC}}^{\mathrm{SNO}}}{\Phi_{\mathrm{NC}}^{\mathrm{SNO}}} = \frac{\nu_e \ \mathrm{flux}}{\mathrm{all} \ \nu \ \mathrm{flux}} = 0.306 \pm 0.026(\mathrm{stat}) \pm 0.024(\mathrm{sys})$$

Which means...

Implications: New Neutrino Physics

The Sun makes only ν_e

Q: why? e.g., why not ν_μ*?*

$\rightarrow$ if no new ν physics, only ν_e at Earth

$\rightarrow$ predict $\Phi_{\rm CC}(\nu_e) = \Phi_{\rm NC}(\nu_x)$

SNO measures $\Phi_{\rm CC}(\nu_e) > \Phi_{\rm NC}(\nu_x)$!

with *very* high confidence!

non-ν_e flux arriving in detector!

A big deal:

- demands new neutrino physics
- indep. of detailed solar model

Nobel Prize 2002

Ray Davis Jr.,
USA

Masatoshi Koshiba,
Japan

"for the detection of cosmic neutrinos"

The Future Sun

Beyond the Main Sequence

Main seqeunce: hydrogen burning

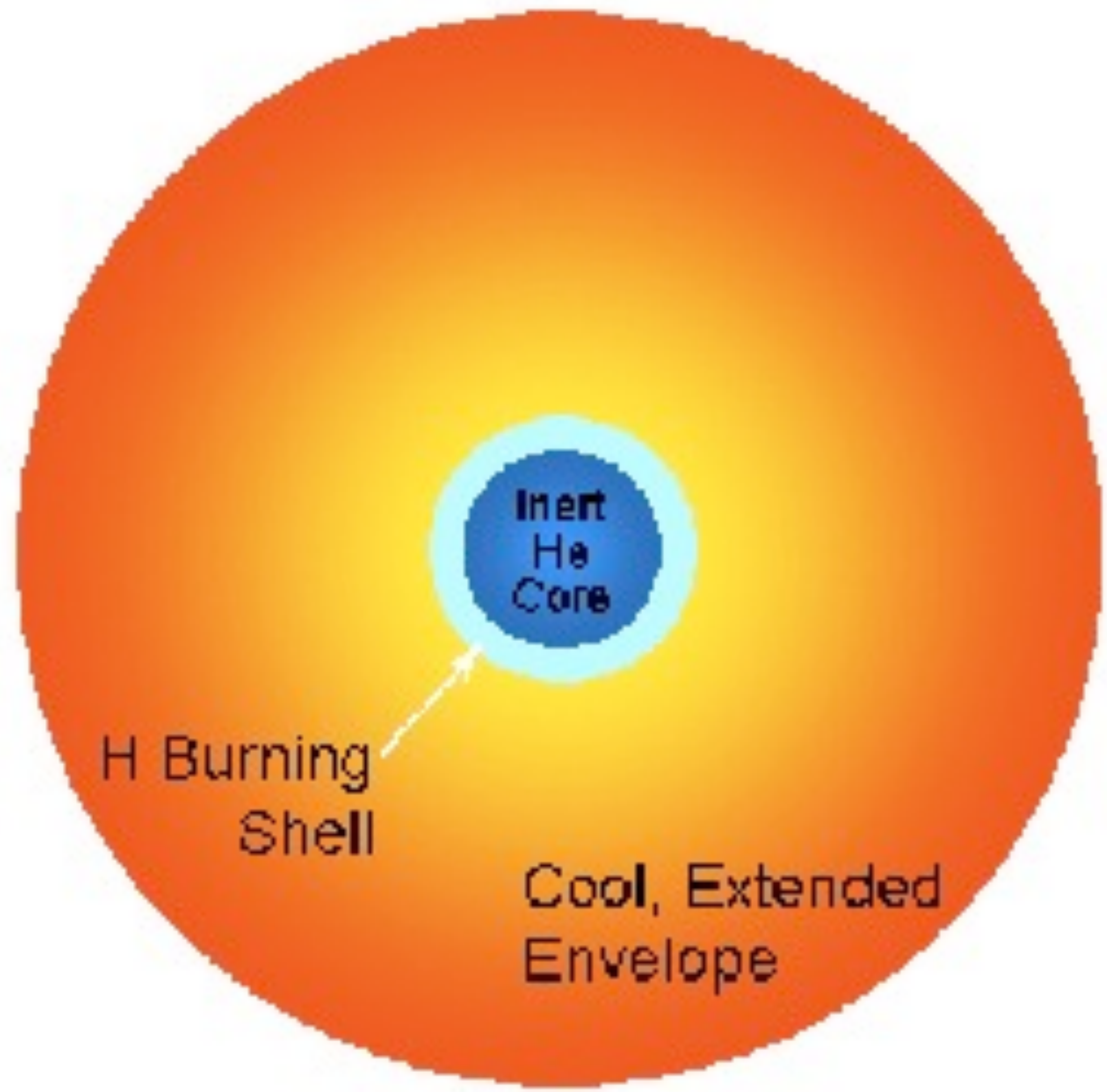
- M<1.1 Msun: pp chain
- M>1.1 Msun: CNO

Q: what happens when H exhausted in core?

when core is all He "ash":

- no source of thermonuclear energy = heat
- loss of pressure support
- core contracts
- compression heats core until burn He: $3\alpha \rightarrow {}^{12}C$

The Red Giant Phase: 6 Billion Years



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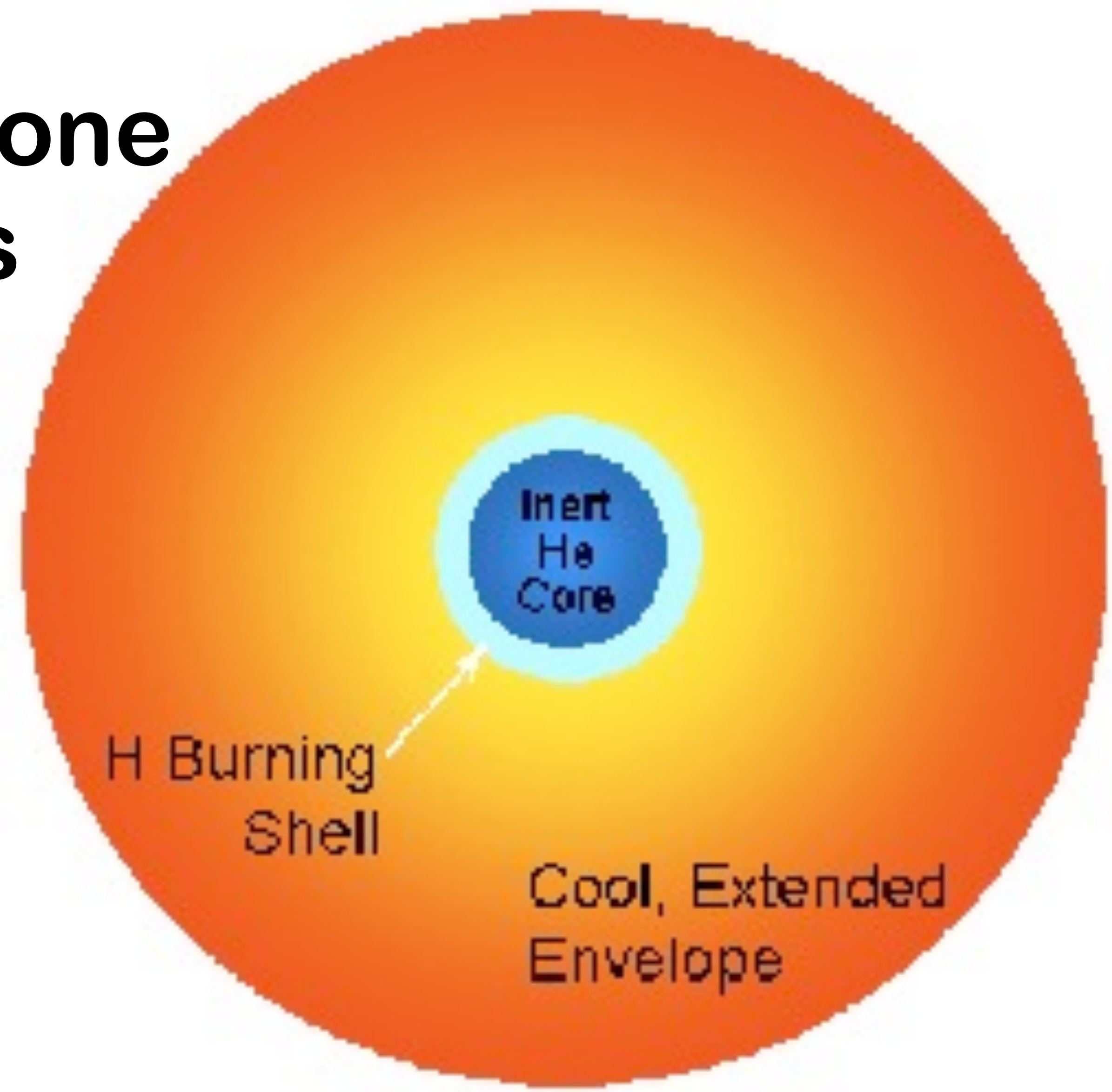
When the hydrogen is gone in the core, fusion stops



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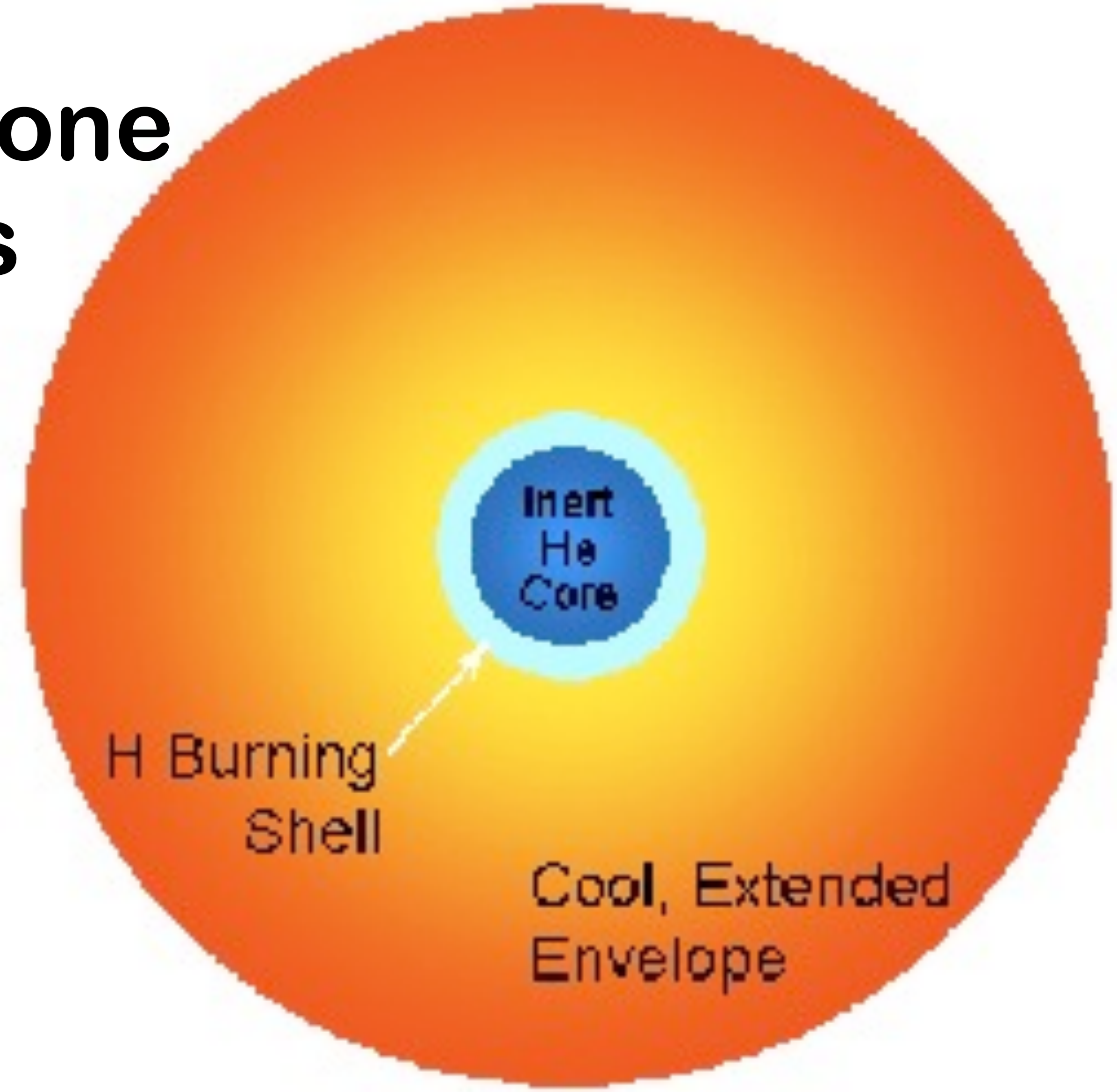
Equilibrium is shot.



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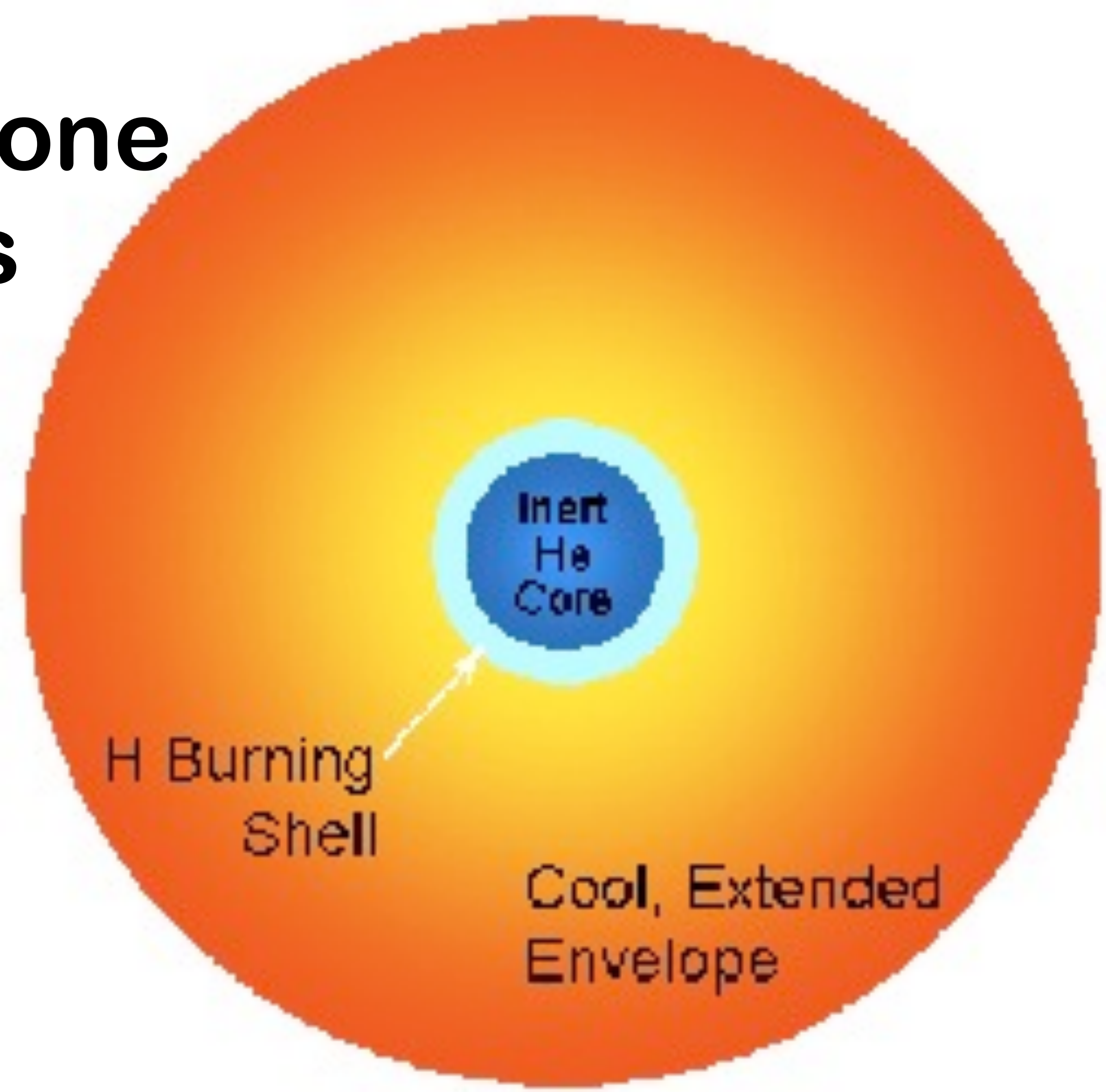
Core starts to contract under its own gravity



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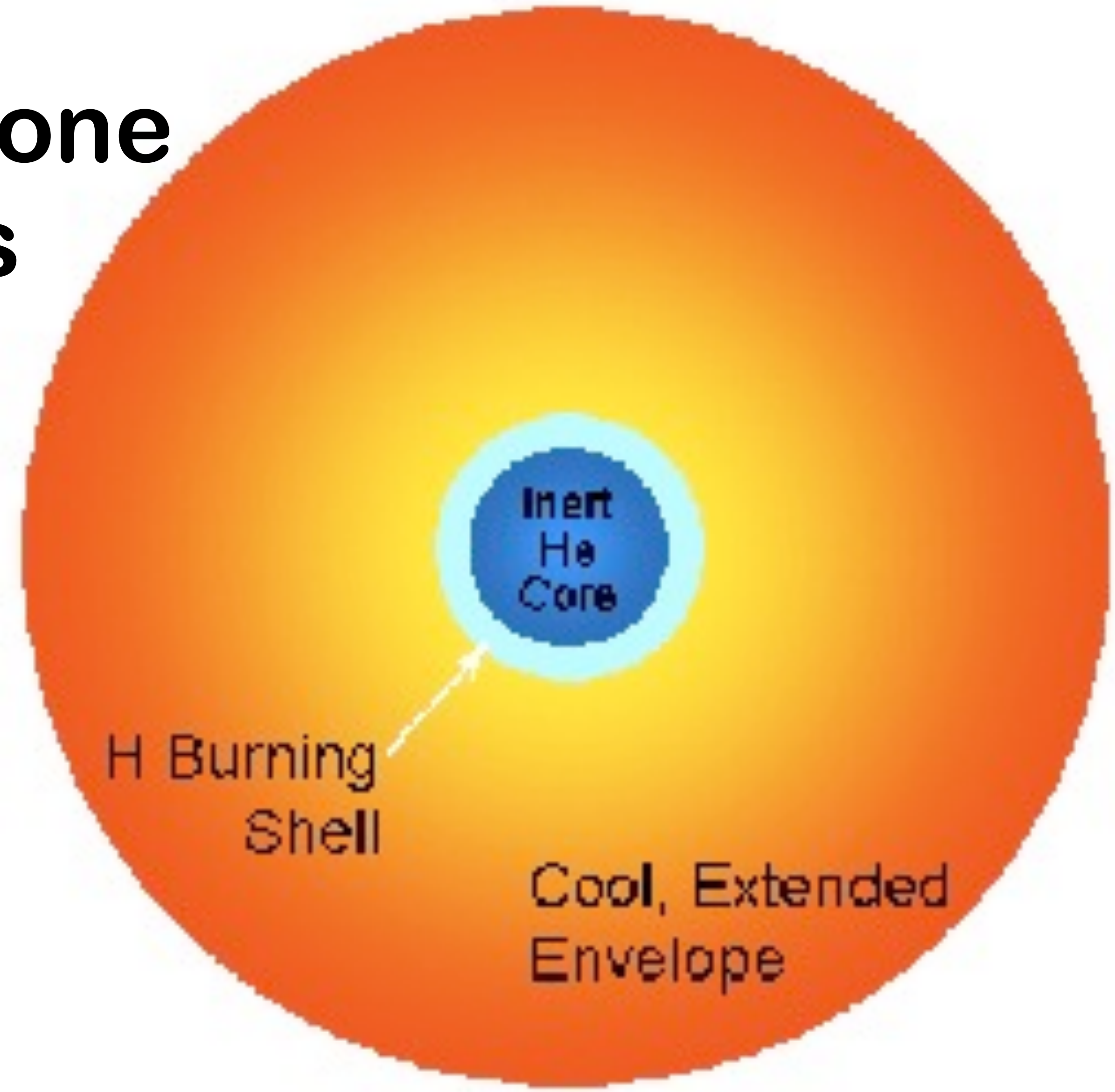
Core starts to contract under its own gravity

This contracting heats the core, and hydrogen fusion starts in a shell around the core



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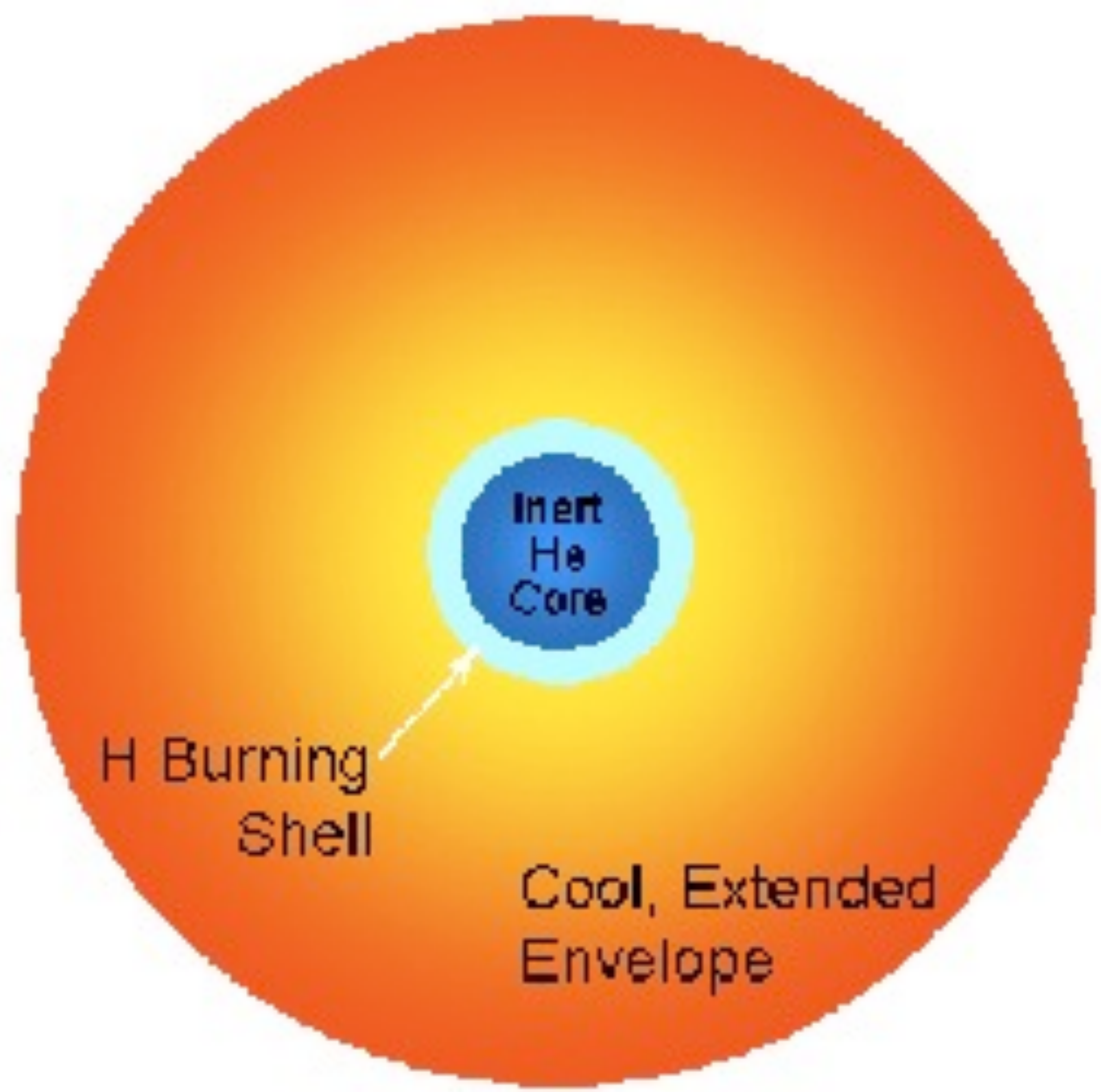
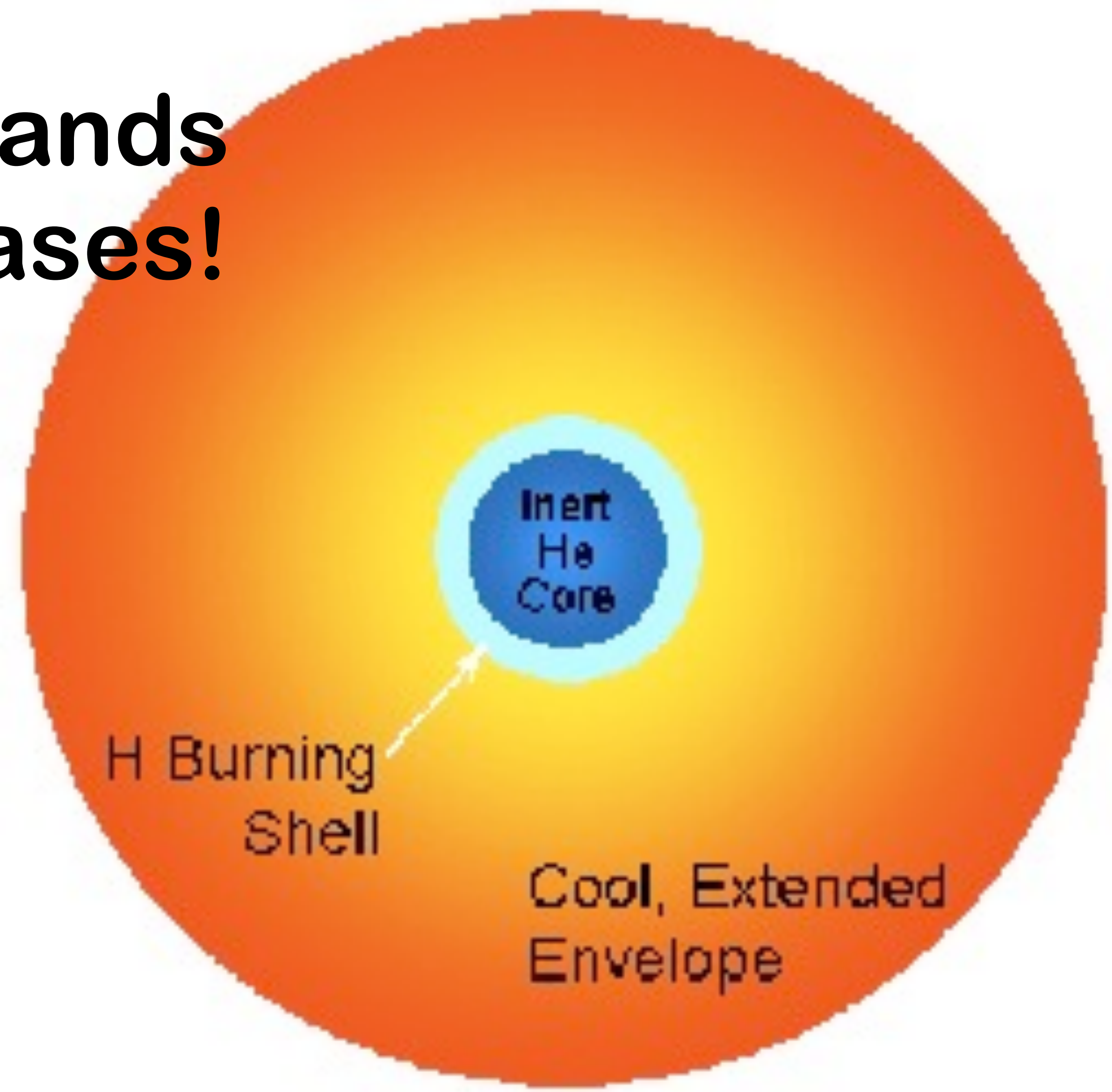


The Red Giant Phase: 6 Billion Years

Energy is released, expands envelope ⇒ Lum. increases!



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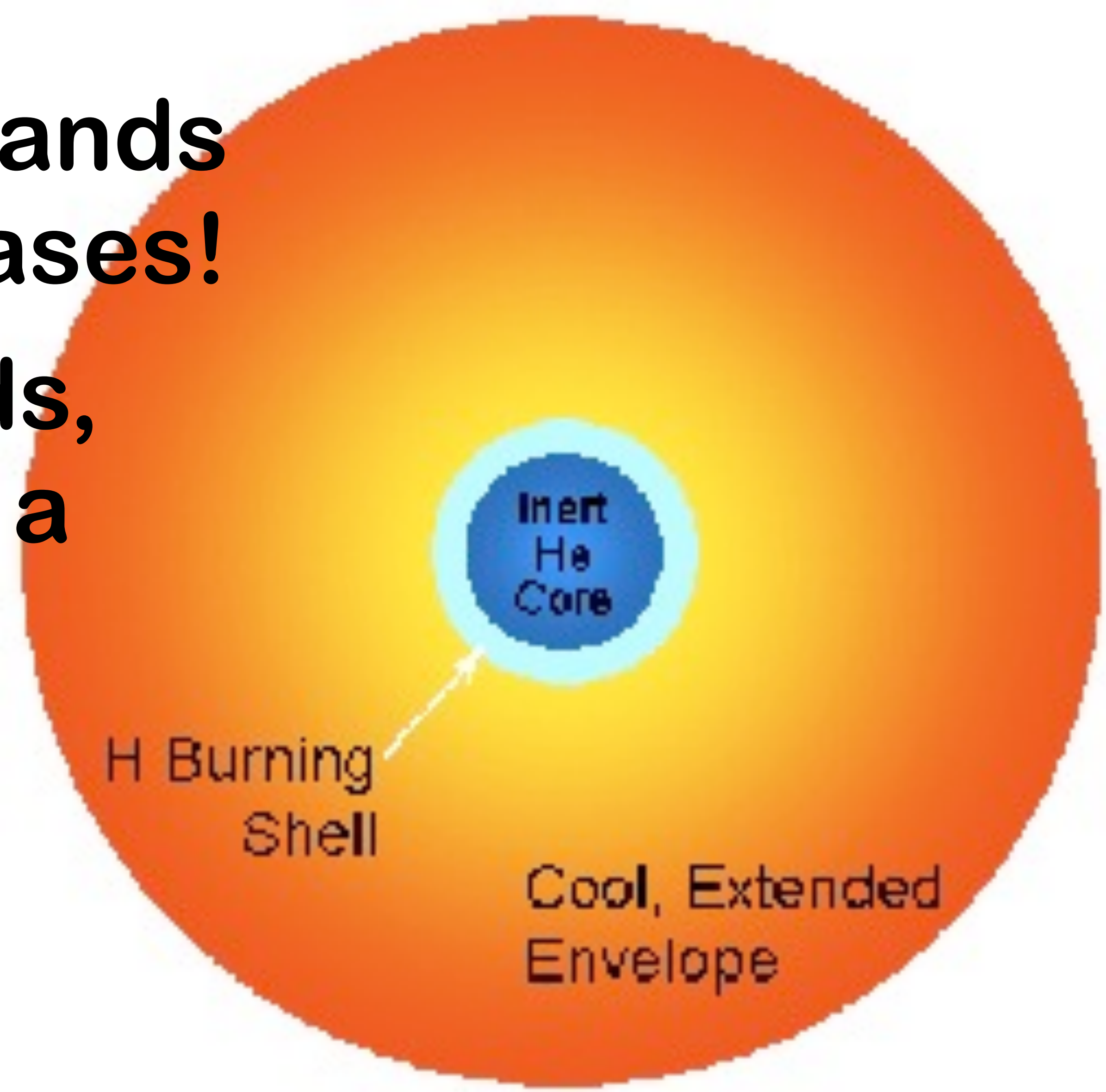
As the envelope expands, it cools – so it becomes a red giant.



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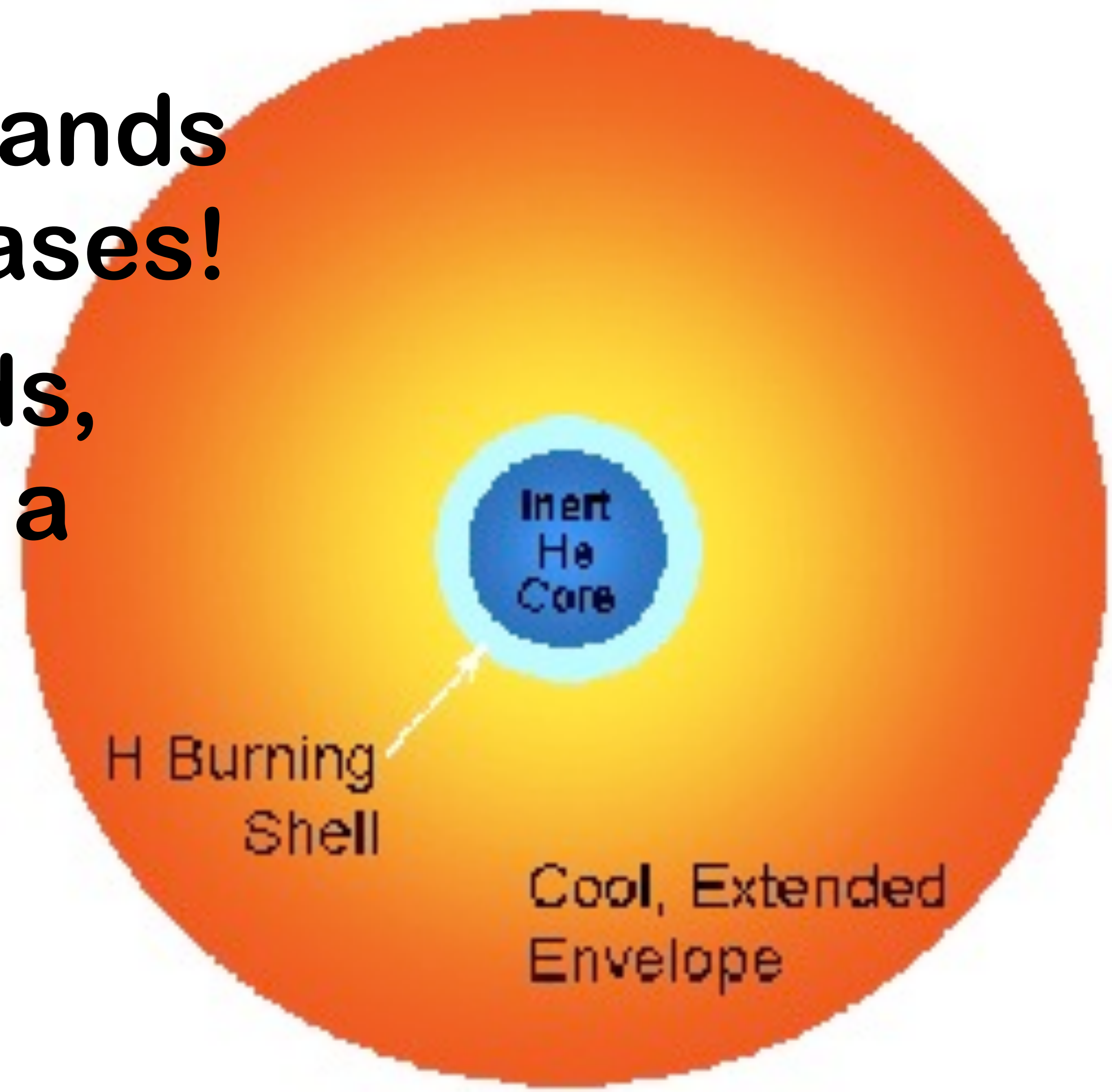


Energy is released, expands envelope ⇒ Lum. increases!

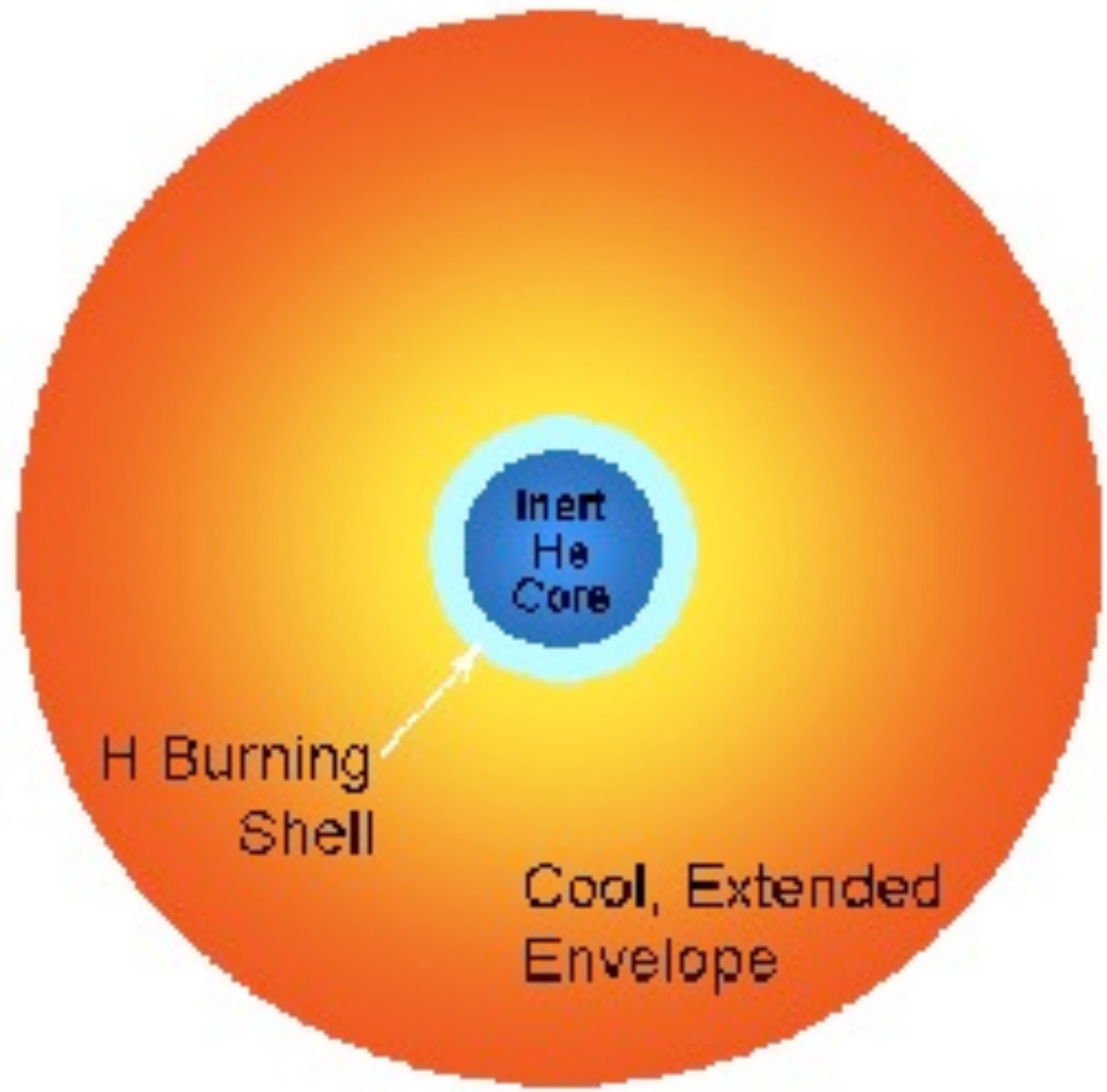
As the envelope expands, it cools – so it becomes a red giant.

This process takes 50-100 million years.

Cartoon version (way too fast)
http://www.youtube.com/watch?v=fOM7DMxOiAk&feature=related

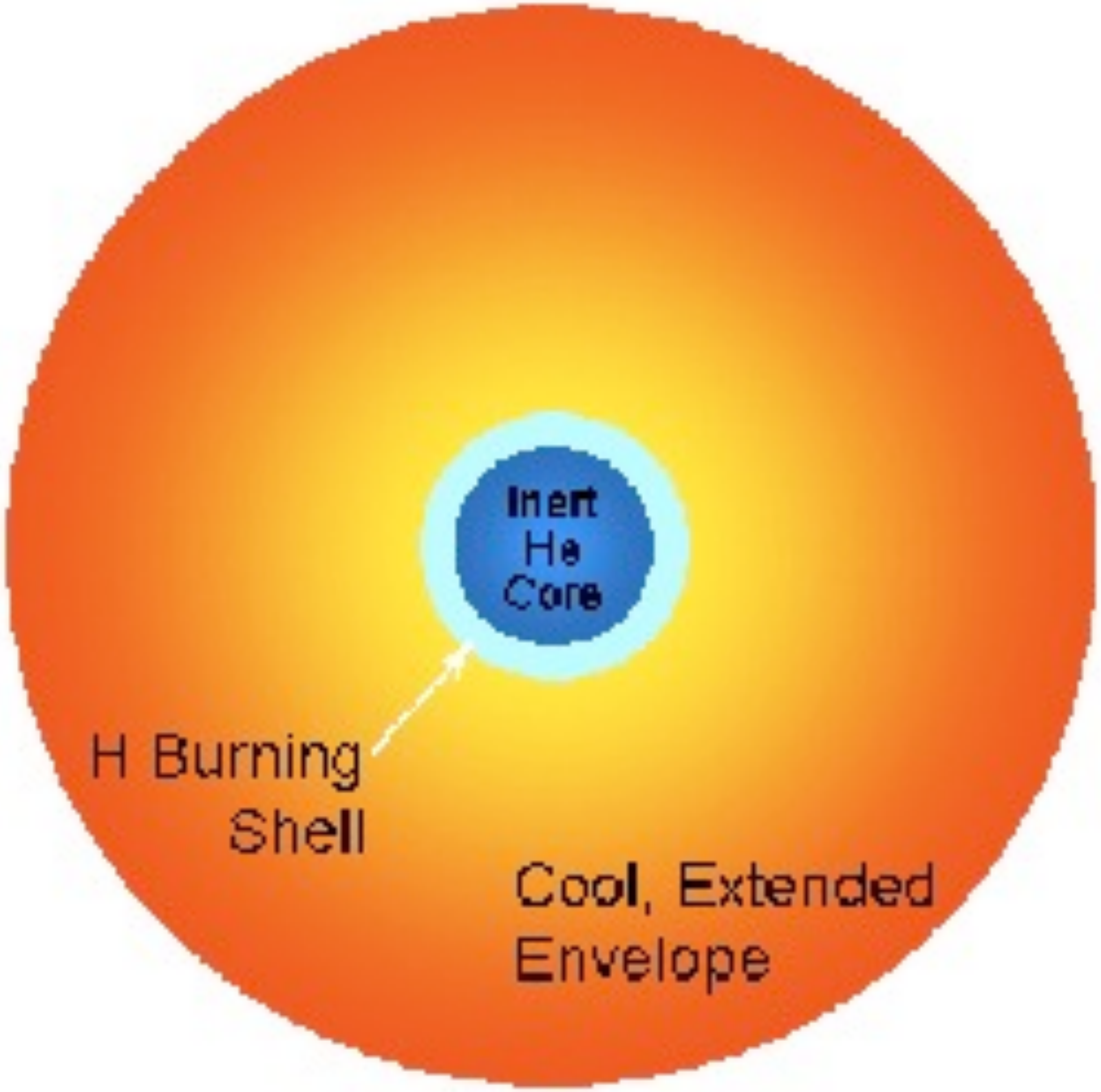
Contraction Junction

- In core, contraction increases density
- Hotter, and hotter, and hotter until…

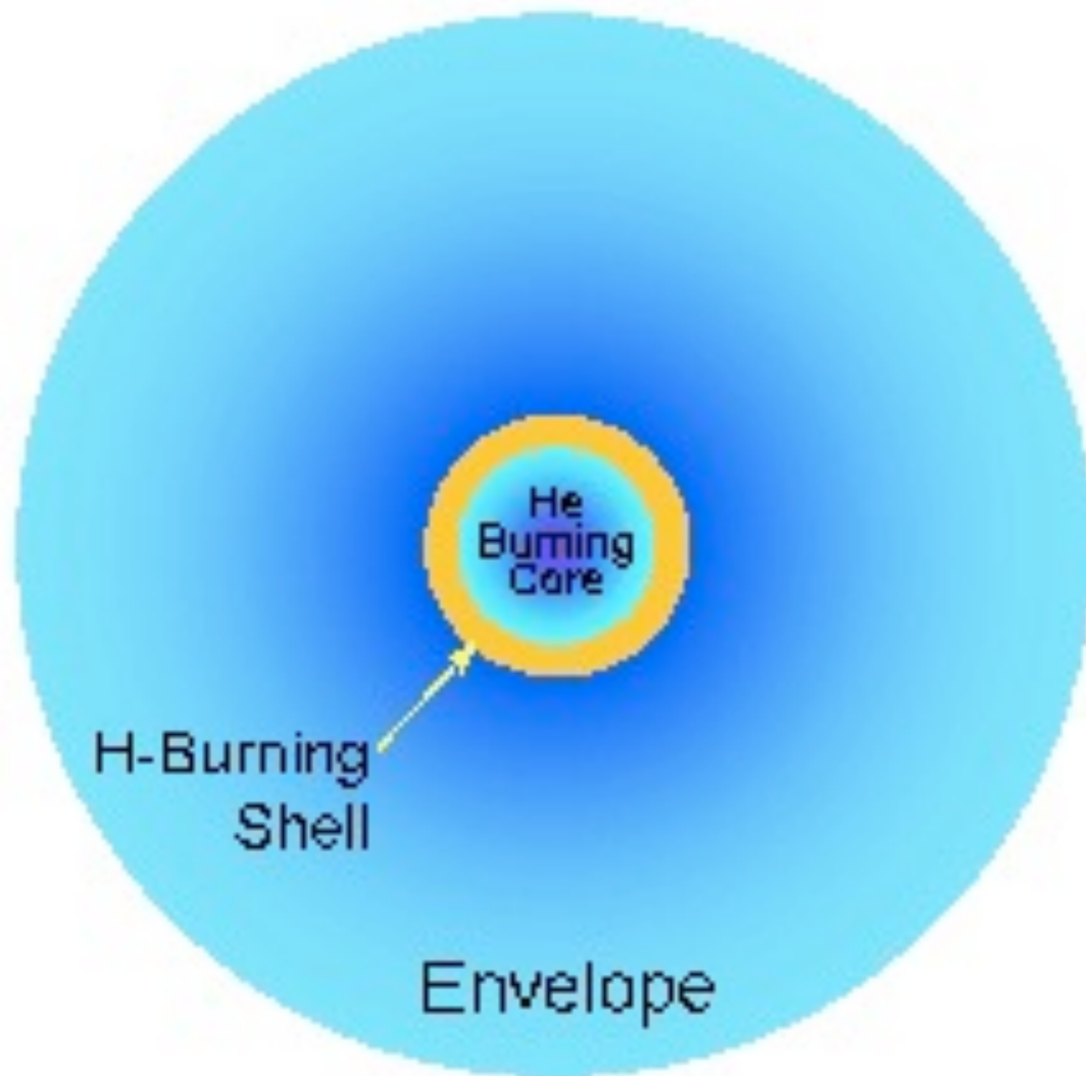


Contraction Junction

- 100 million degrees
- Core heats ⇒ He fusion ignite
- He ⇒ C & O

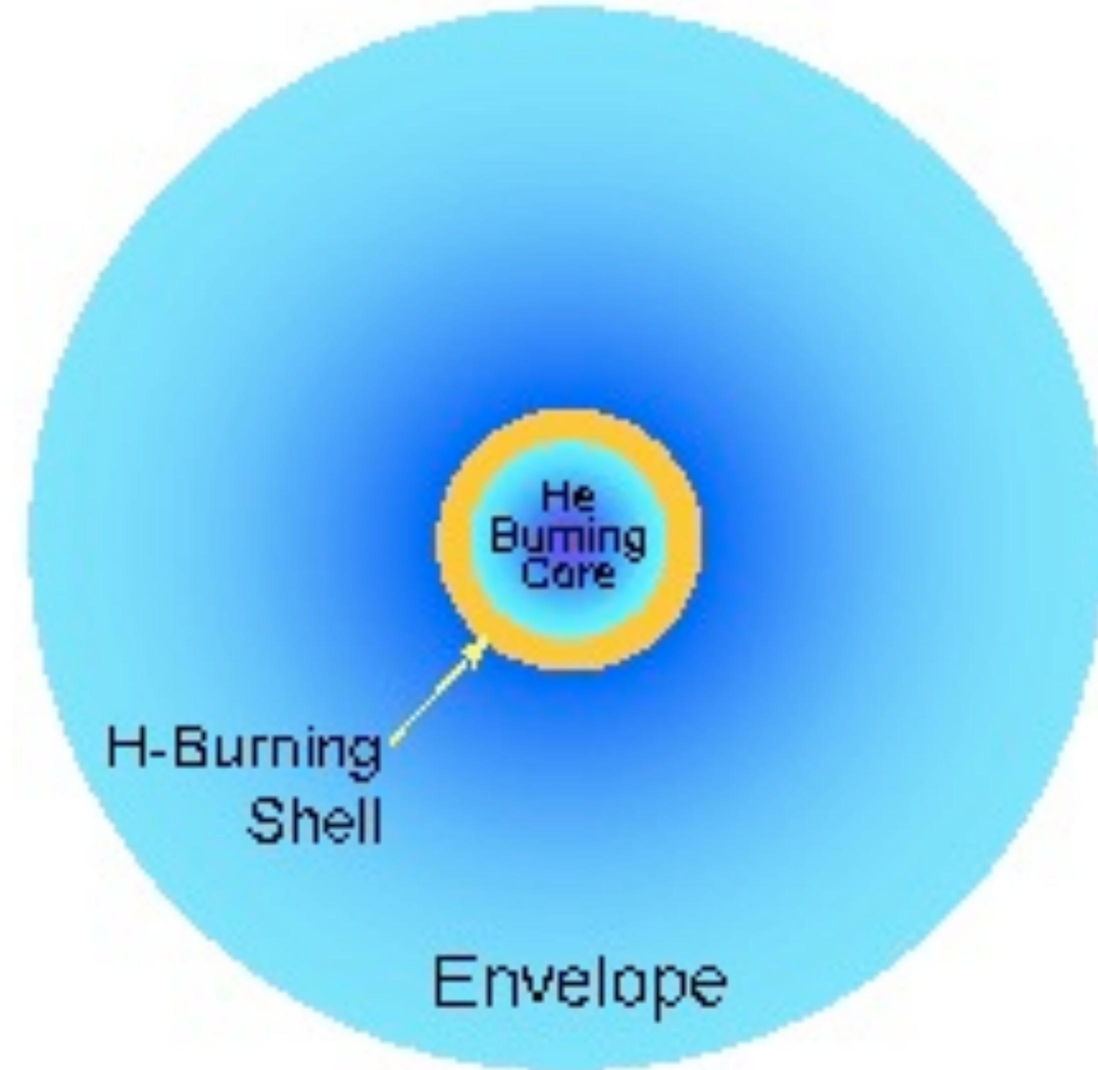


The Horizontal Branch



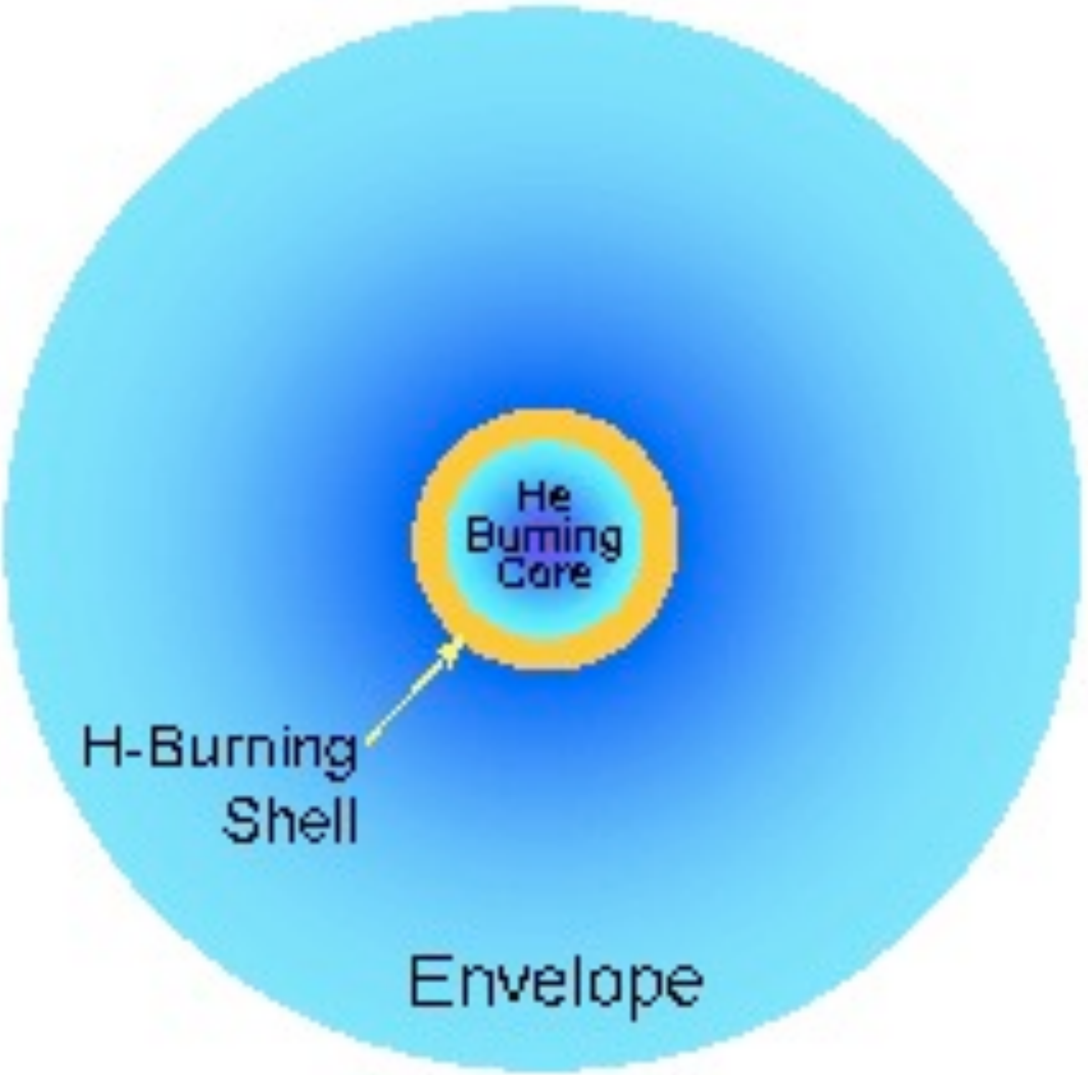
The Horizontal Branch

- Stars in helium burning phase:
  - "horizontal branch"



The Horizontal Branch

- Stars in helium burning phase:
  - "horizontal branch"
- Helium burning stabilizes the core
  - but destabilizes outer layers!



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- Stars in helium burning phase:
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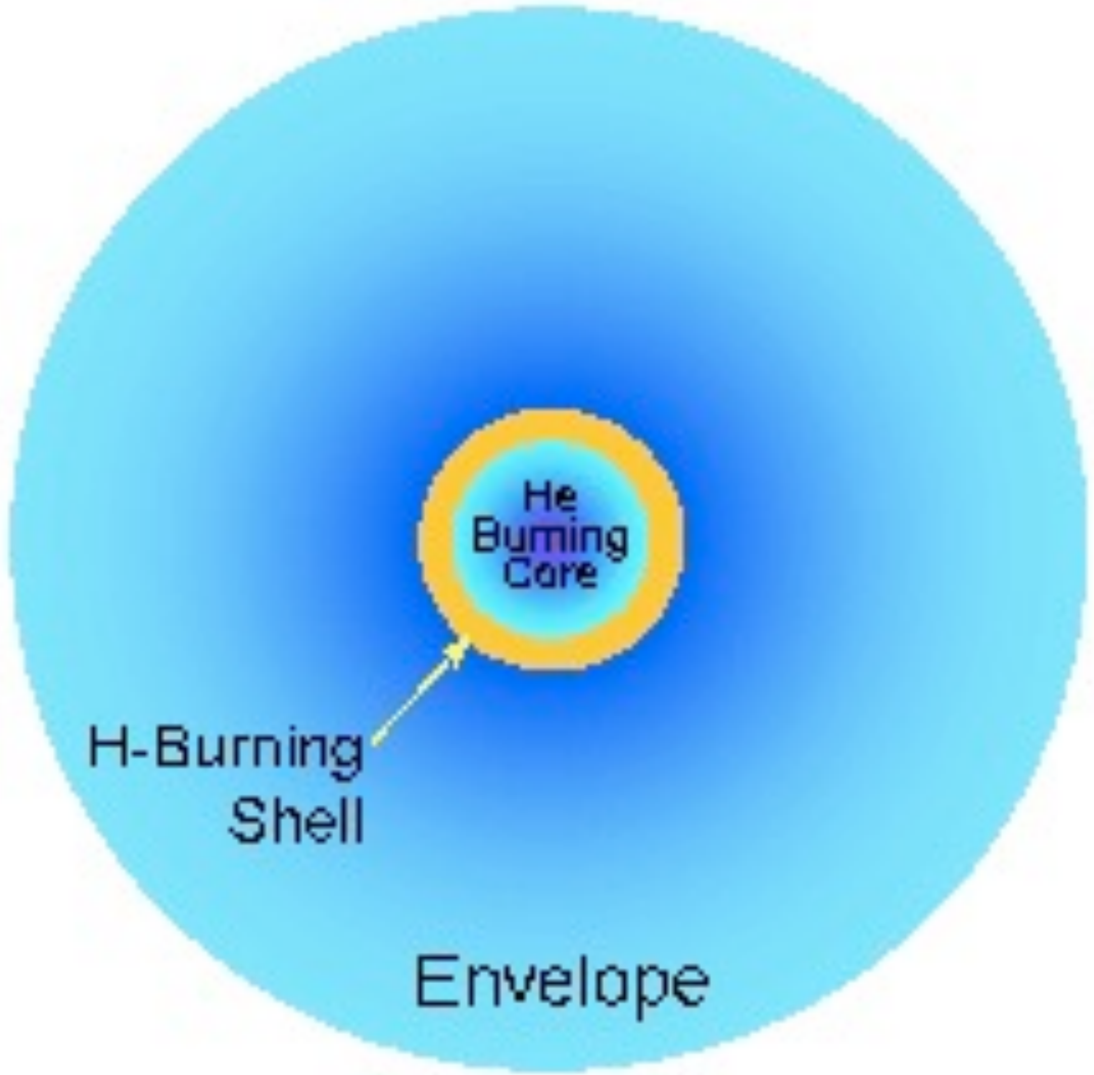
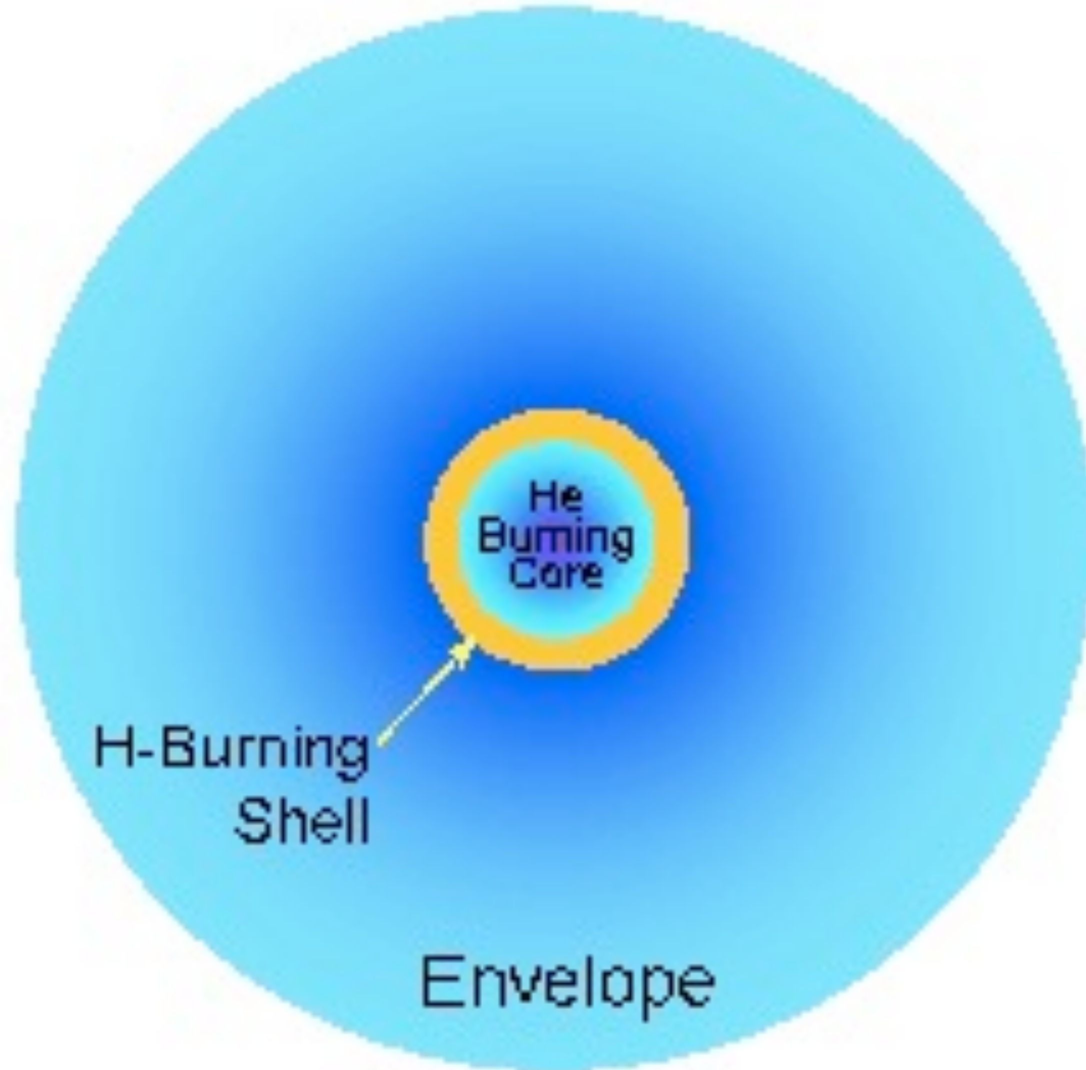
- The outer envelope shrinks, heats up, and dims slightly

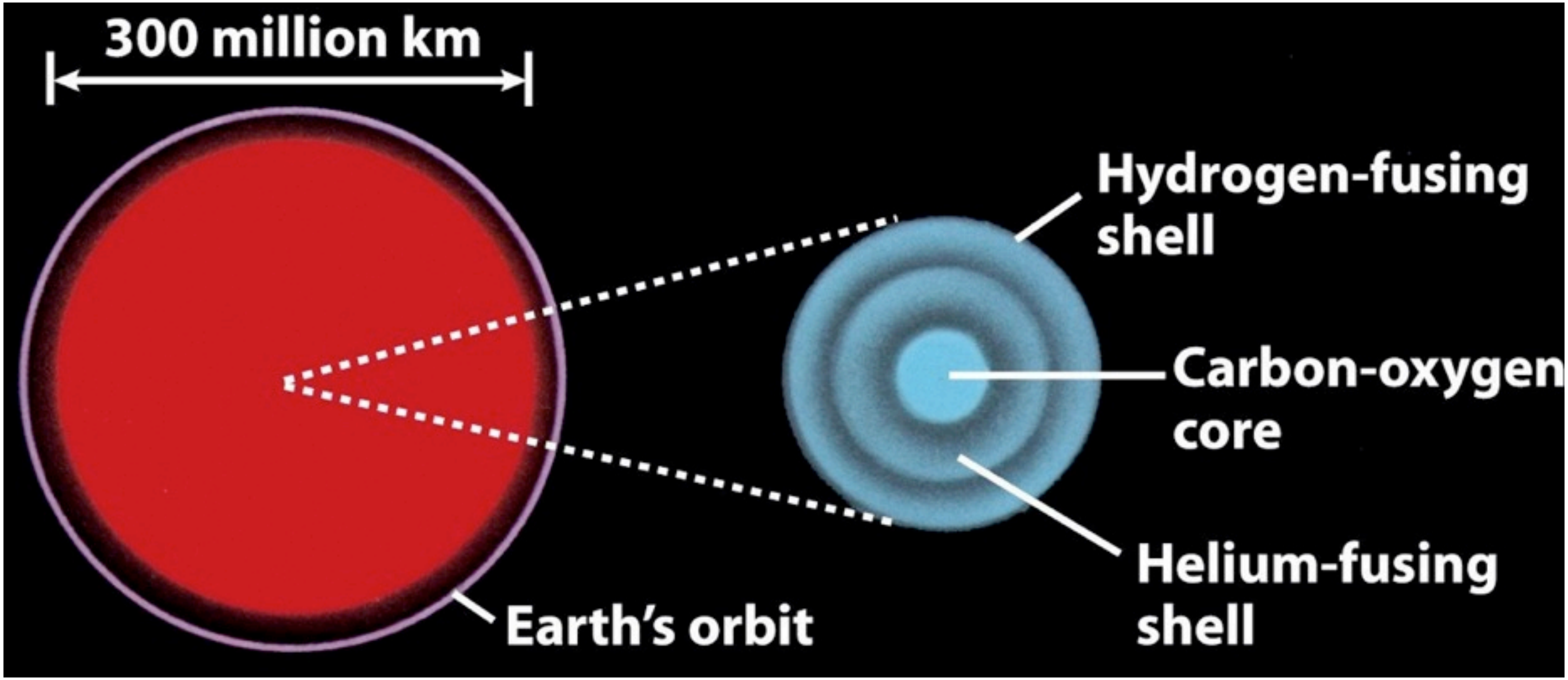


The Horizontal Branch

- Stars in helium burning phase:
  - "horizontal branch"
- Helium burning stabilizes the core
  - but destabilizes outer layers!
- The outer envelope shrinks, heats up, and dims slightly
- But helium doesn't last very long as a fuel
  - Horizontal branch lifetime is only about 10% that of a star's main sequence lifetime
  - Our Sun will burn helium for about a billion years

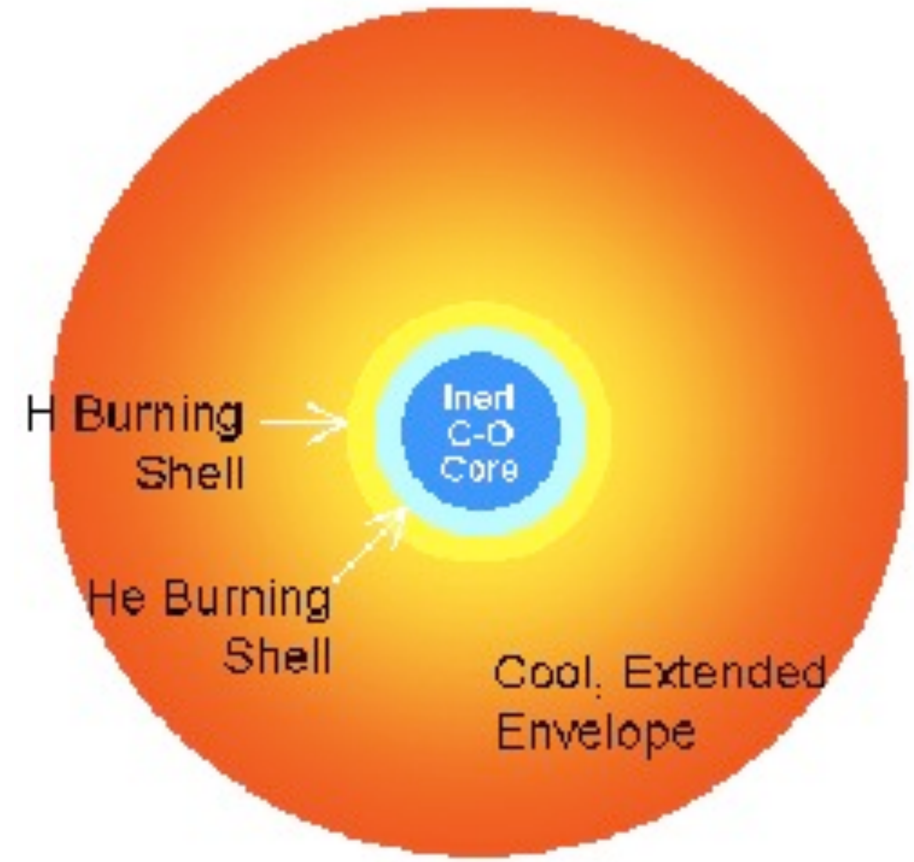


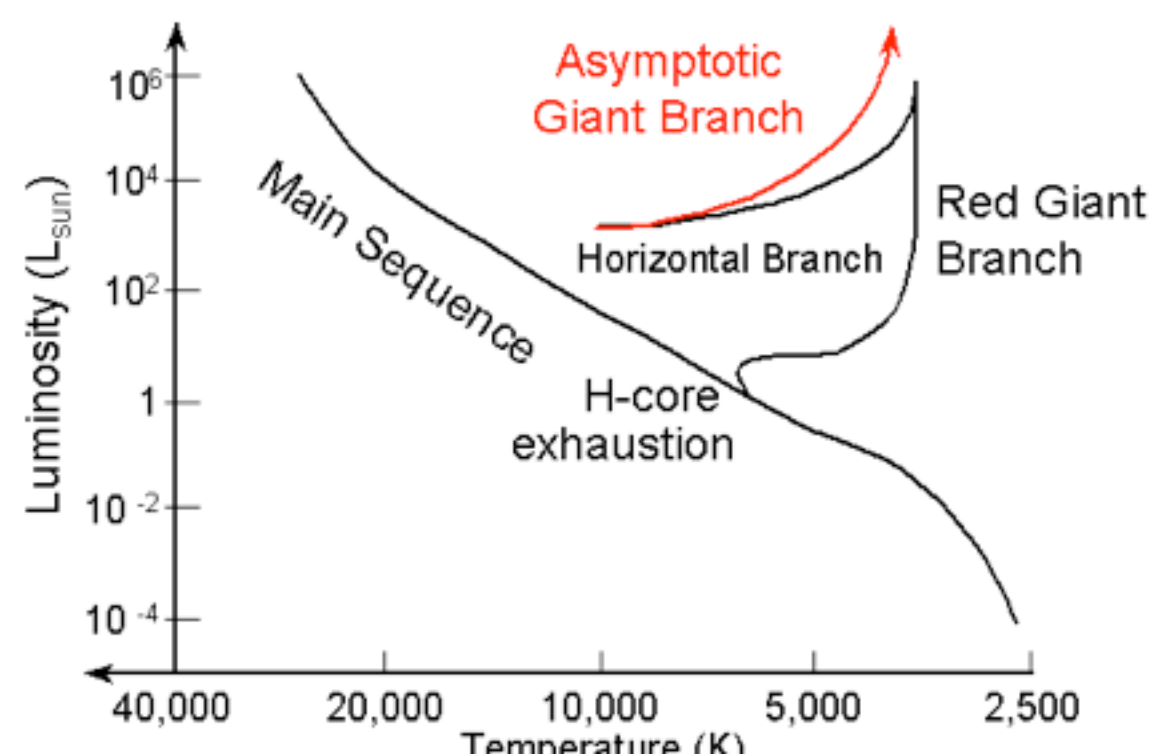
When helium runs out…



Star expands and cools again into a red giant, now with <u>two</u> fusion shells!

When Helium Runs Out…
7.8 Billion Years from Now





When Helium Runs Out…
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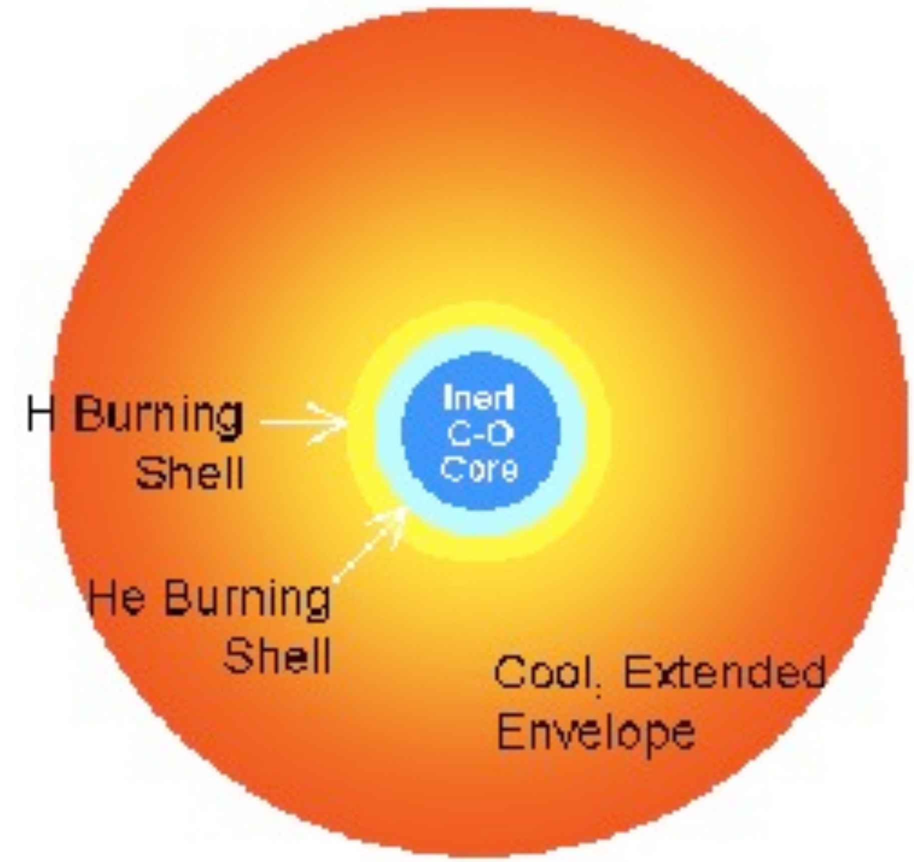
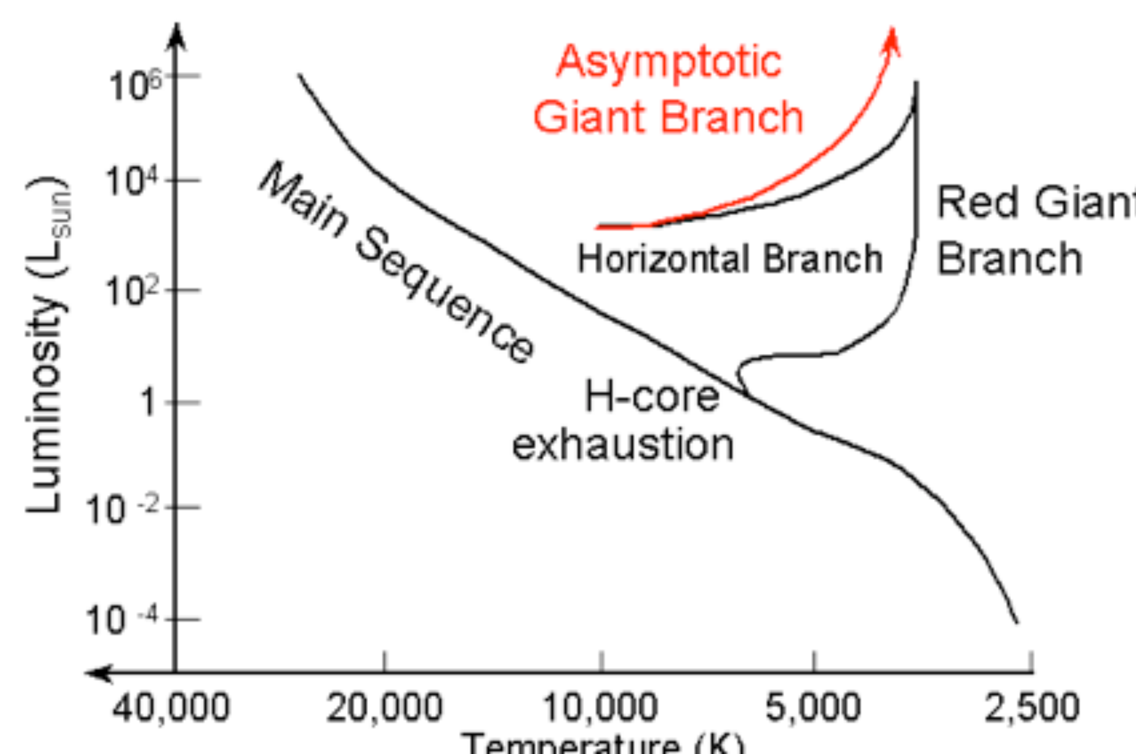
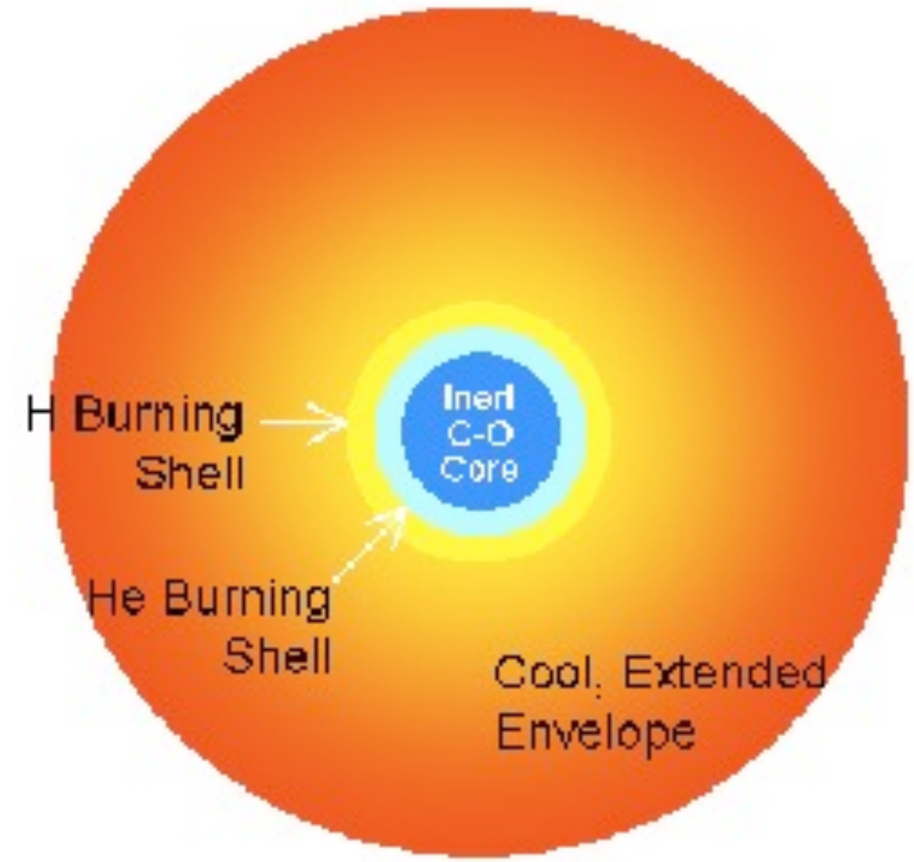
- Fusion in the core stops – the helium has been converted to carbon and oxygen

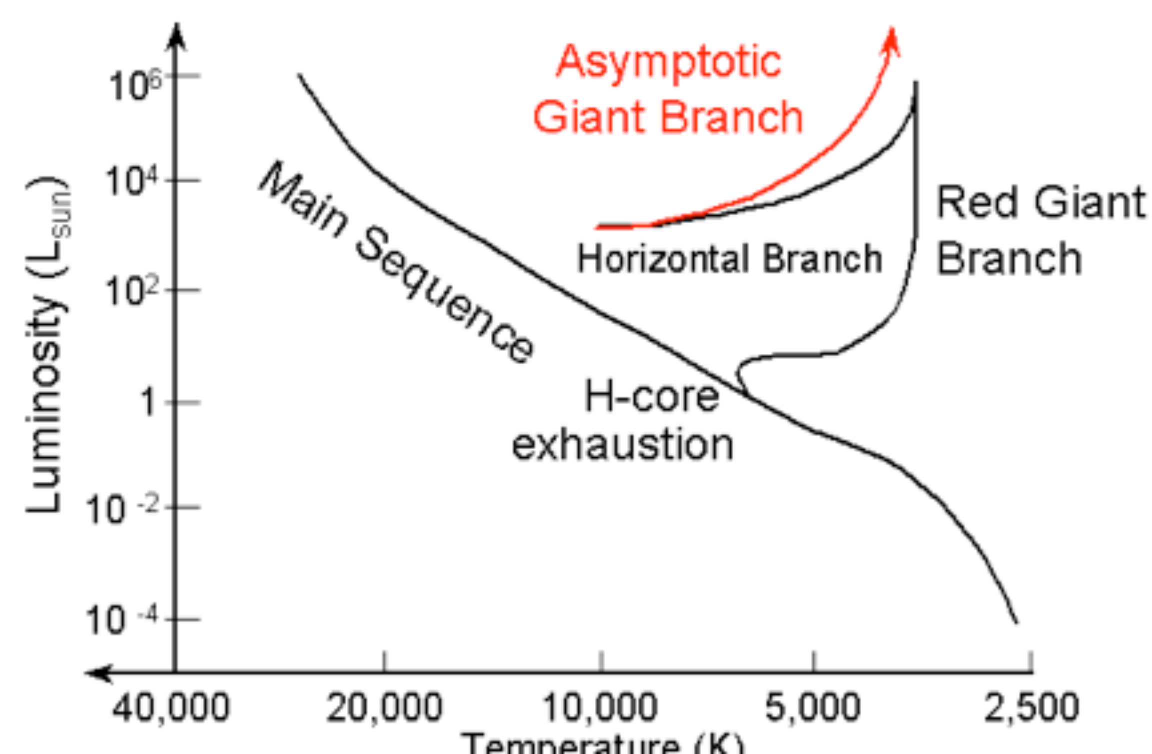




When Helium Runs Out…
7.8 Billion Years from Now

- Fusion in the core stops – the helium has been converted to carbon and oxygen
- Stellar core collapses under its own gravity again





When Helium Runs Out…
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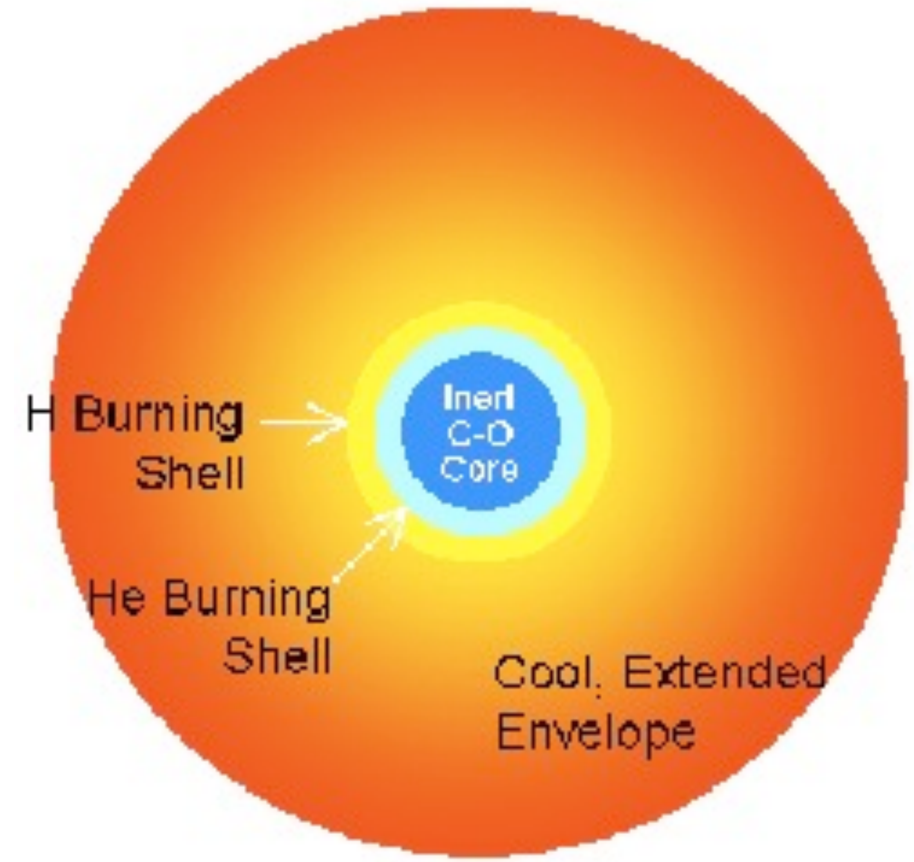
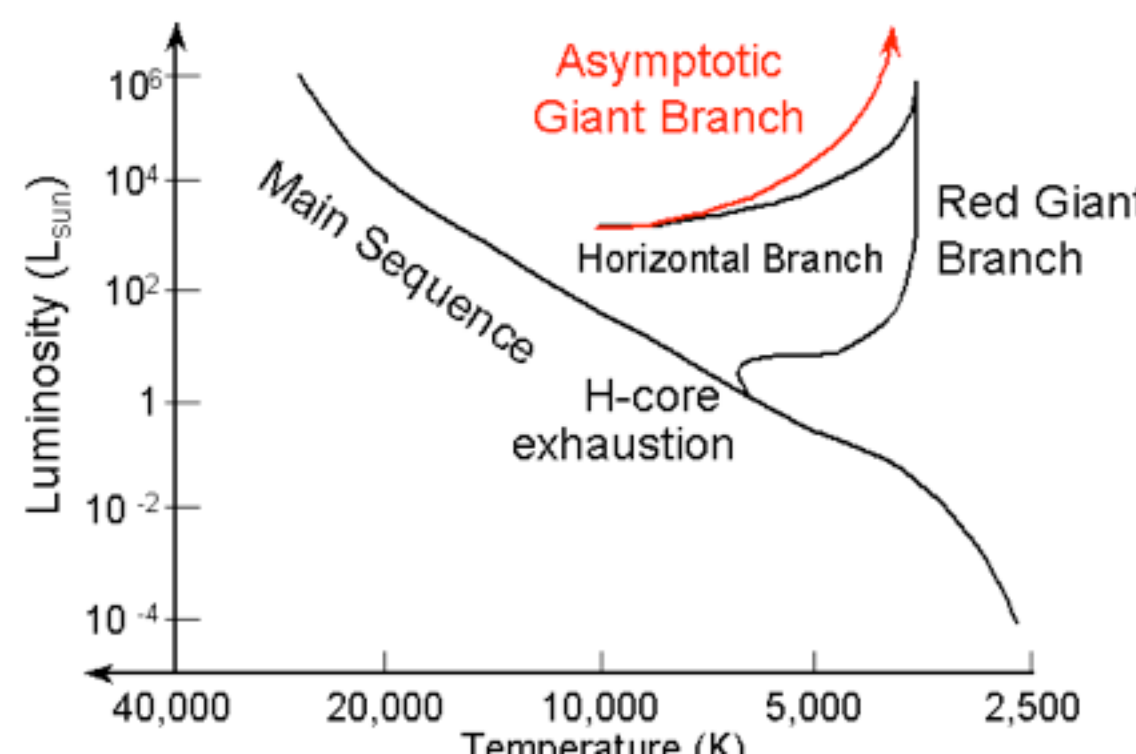
- Inner shell develops, starts fusing helium to carbon





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7.8 Billion Years from Now

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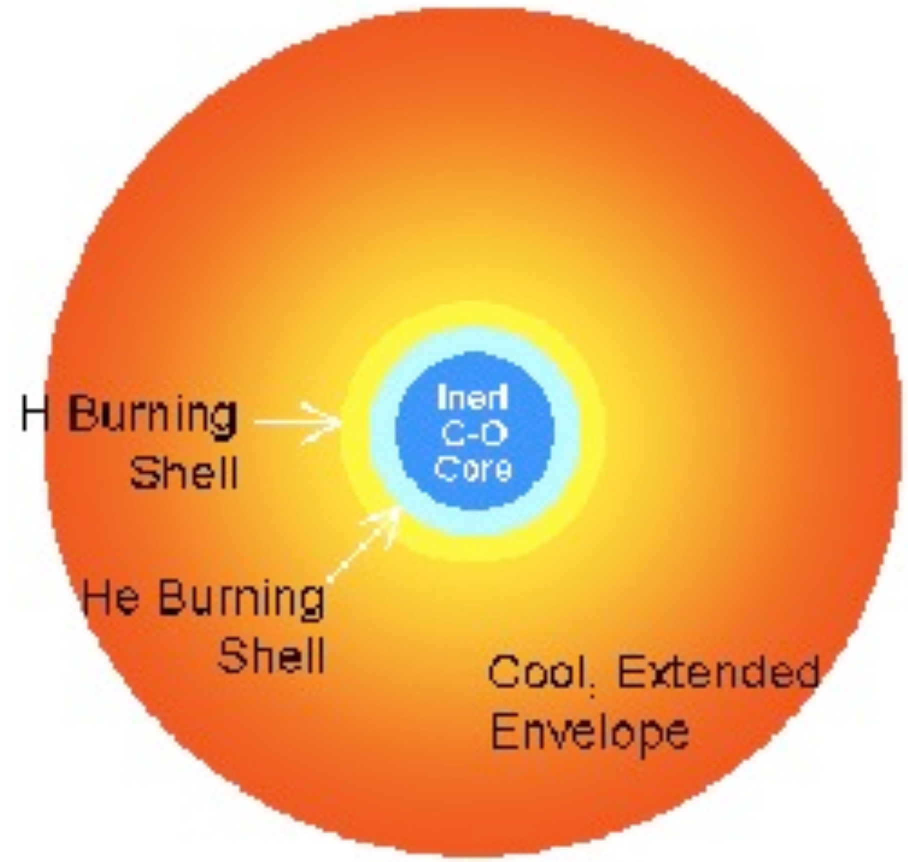
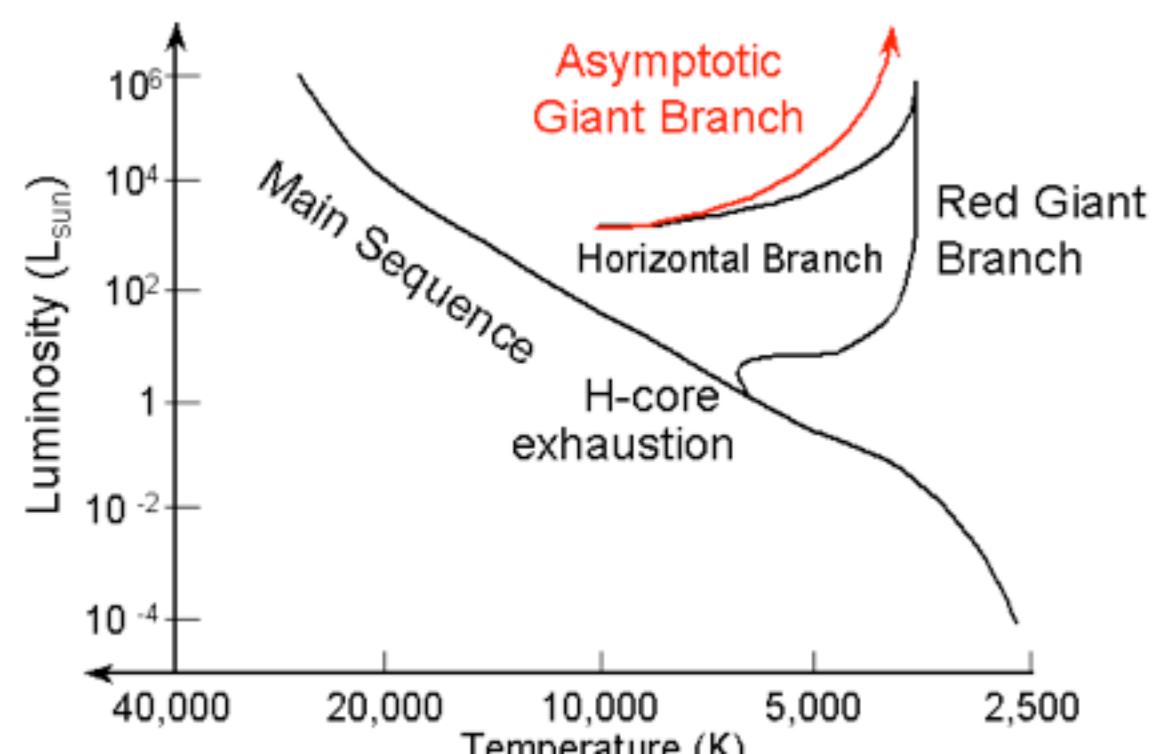
- Stellar core collapses under its own gravity again
- Inner shell develops, starts fusing helium to carbon
- outer hydrogen burning shell remains





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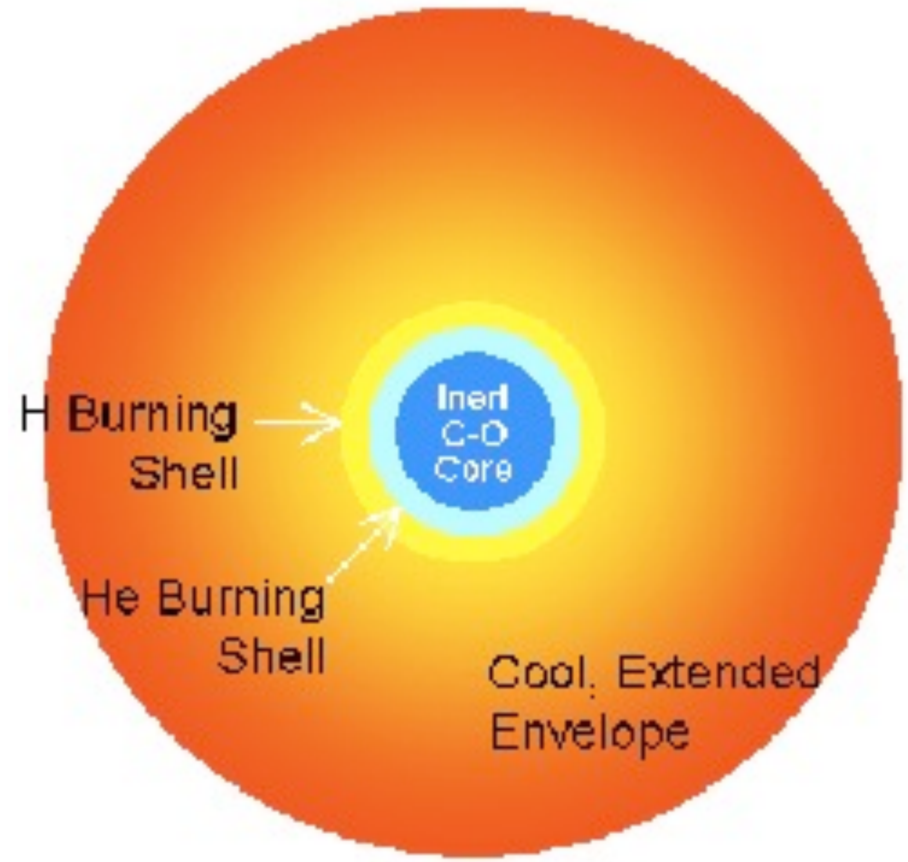
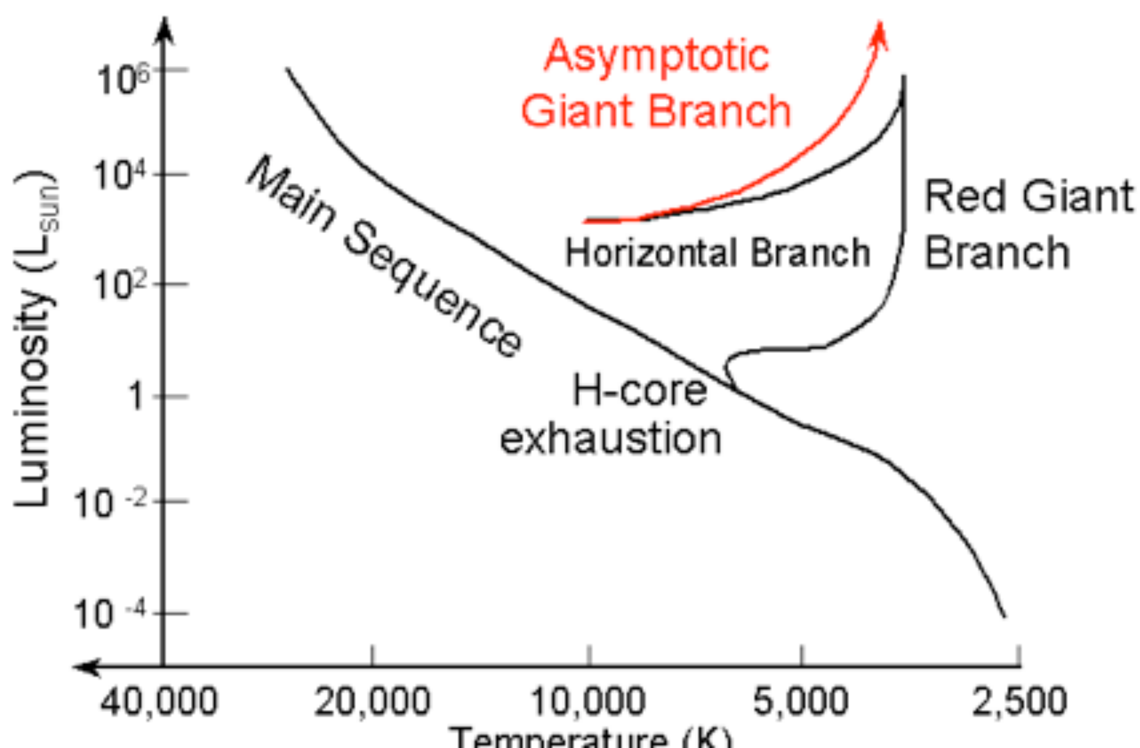
7.8 Billion Years from Now

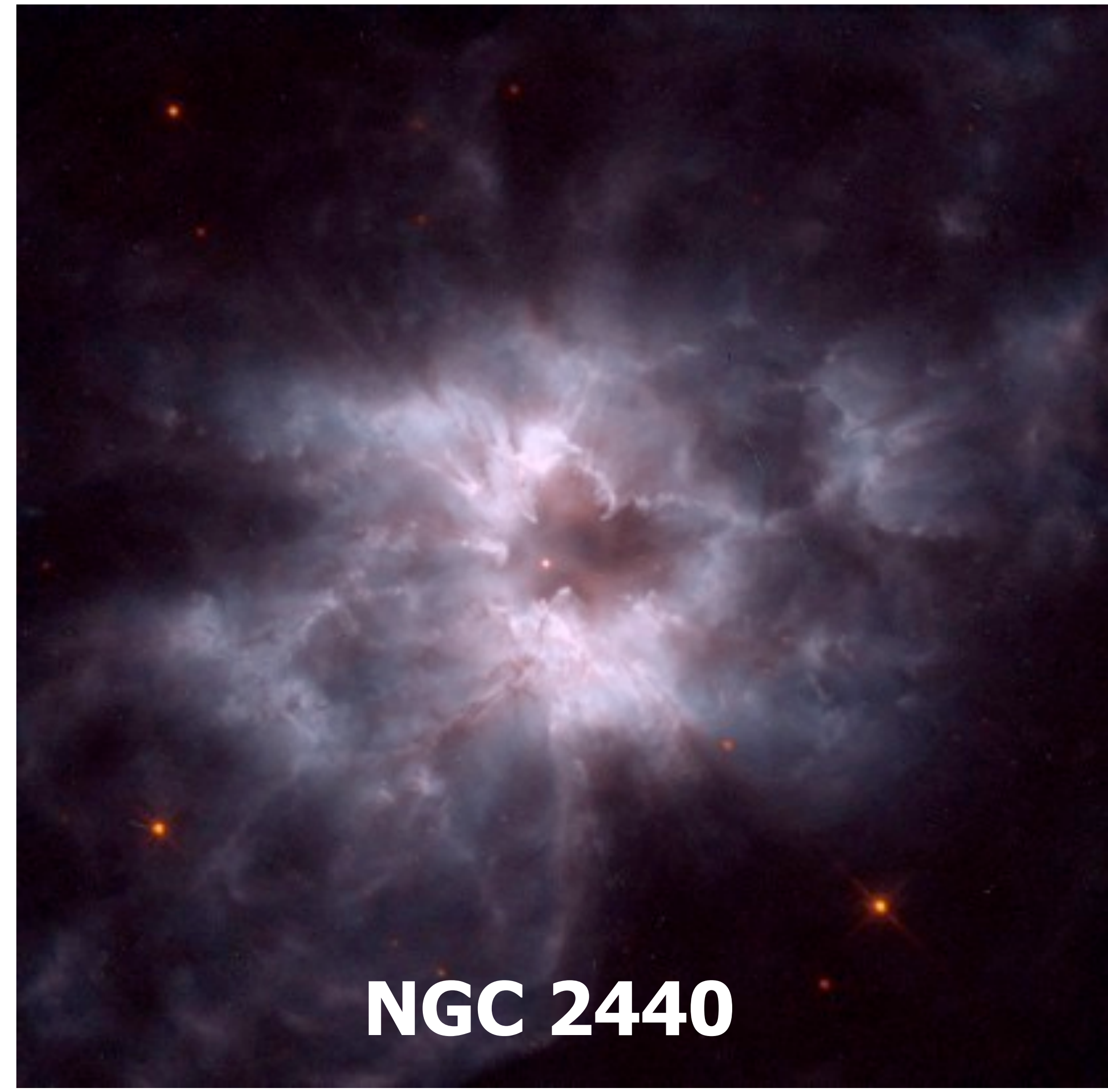
- Fusion in the core stops – the helium has been converted to carbon and oxygen
- Stellar core collapses under its own gravity again
- Inner shell develops, starts fusing helium to carbon
- outer hydrogen burning shell remains
- Star starts to grow and cool again: asymptotic giant branch





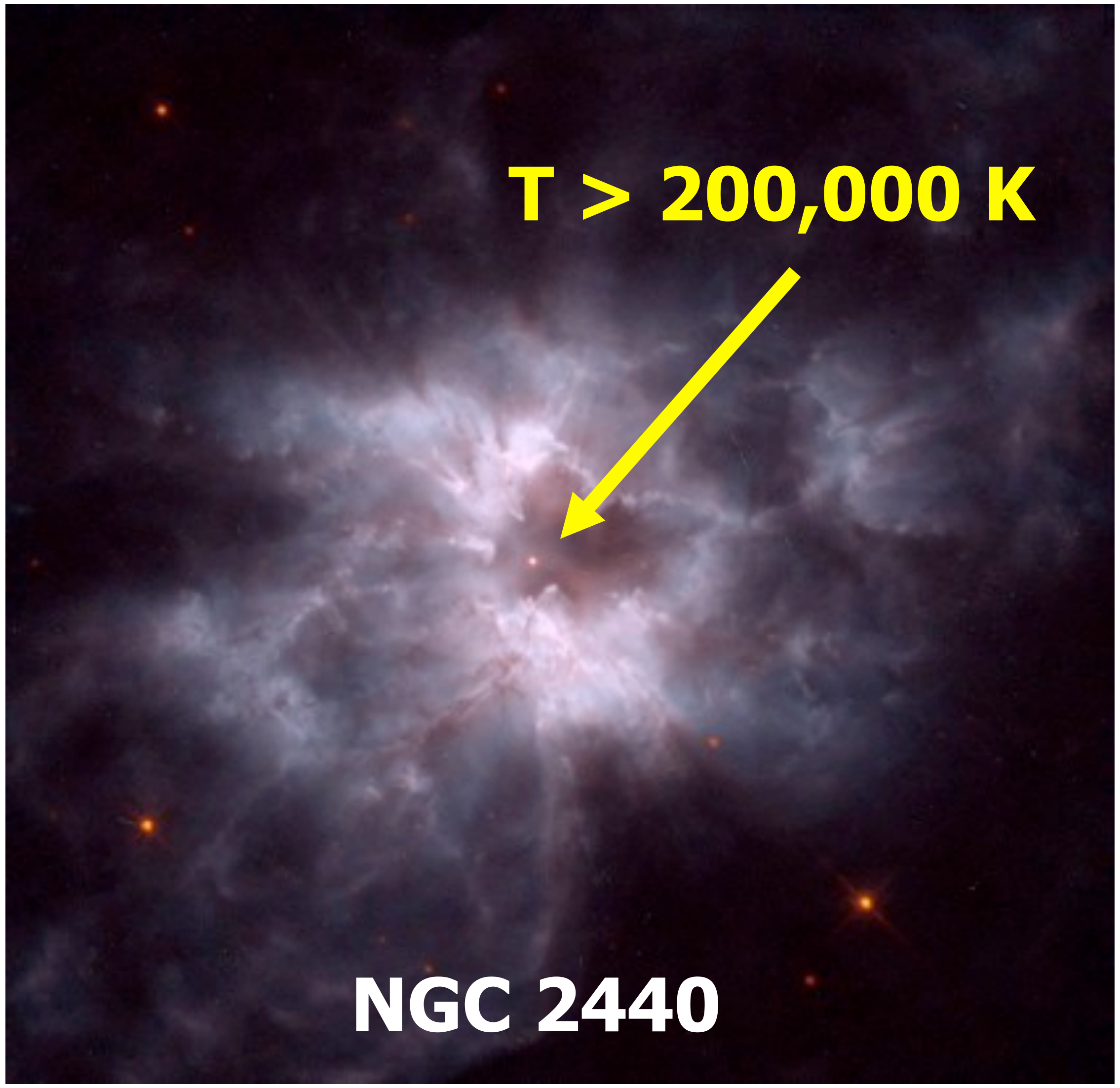
End Game

- At these last stages, the Sun will likely oscillate in size and temperature.
- The two burning shells are unstable and their oscillations lead to a “Superwind”
- Outer layers of the red giant star are cast off
  - Up to 80% (at least 50%) of the star’s original mass
  - carries away all but the innermost material of the star
  - including all of the new elements created there: helium, carbon

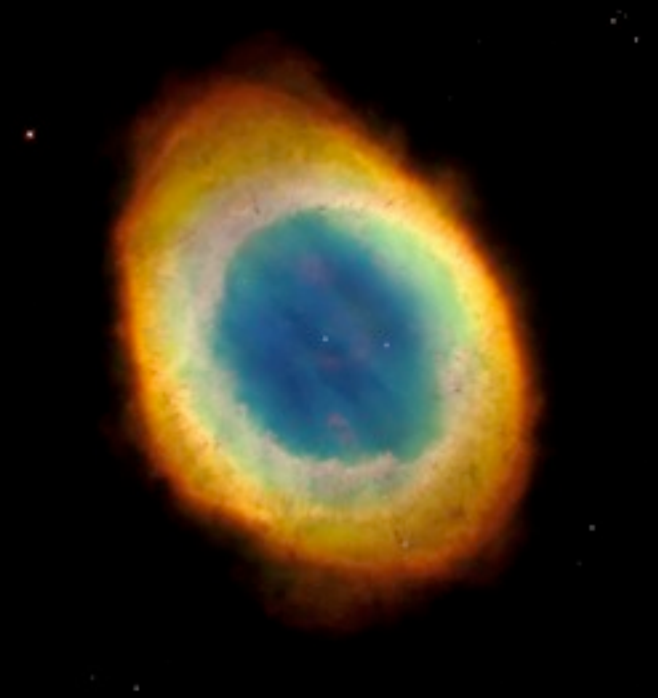


End Game

- The core remains, made of carbon/oxygen "ash" from helium fusion
  - The core is very hot, above 200,000 K
  - laid bare, and seen as "white hot"
- Ultraviolet radiation from the core ionizes the cast off outer layers
  - Becomes a *planetary nebula*
  - *Unfortunate name (nothing to do with planets), but some of the most beautiful objects in the sky.*

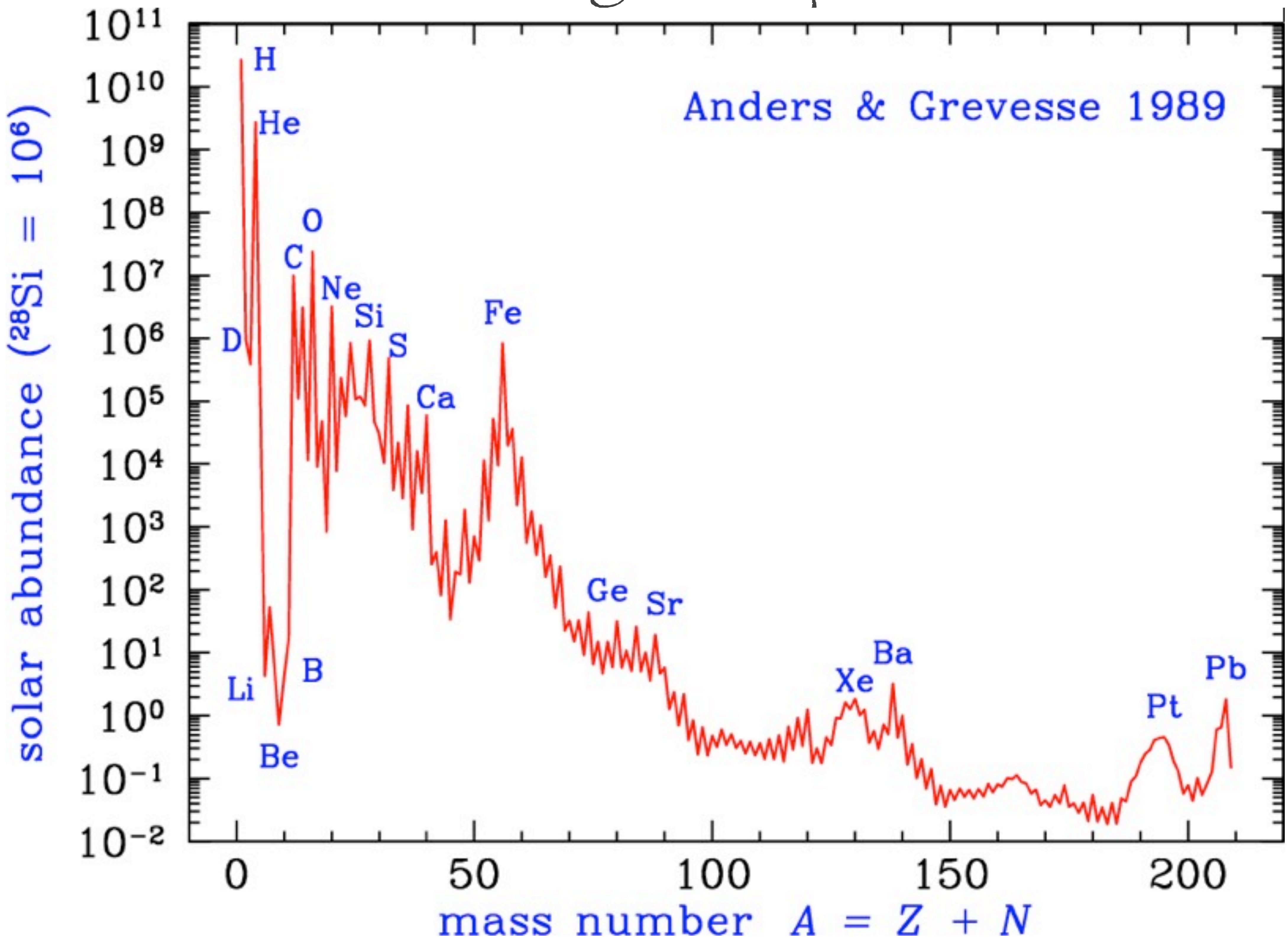


Planetary Nebulae



Solar System Abundances

Progress Report



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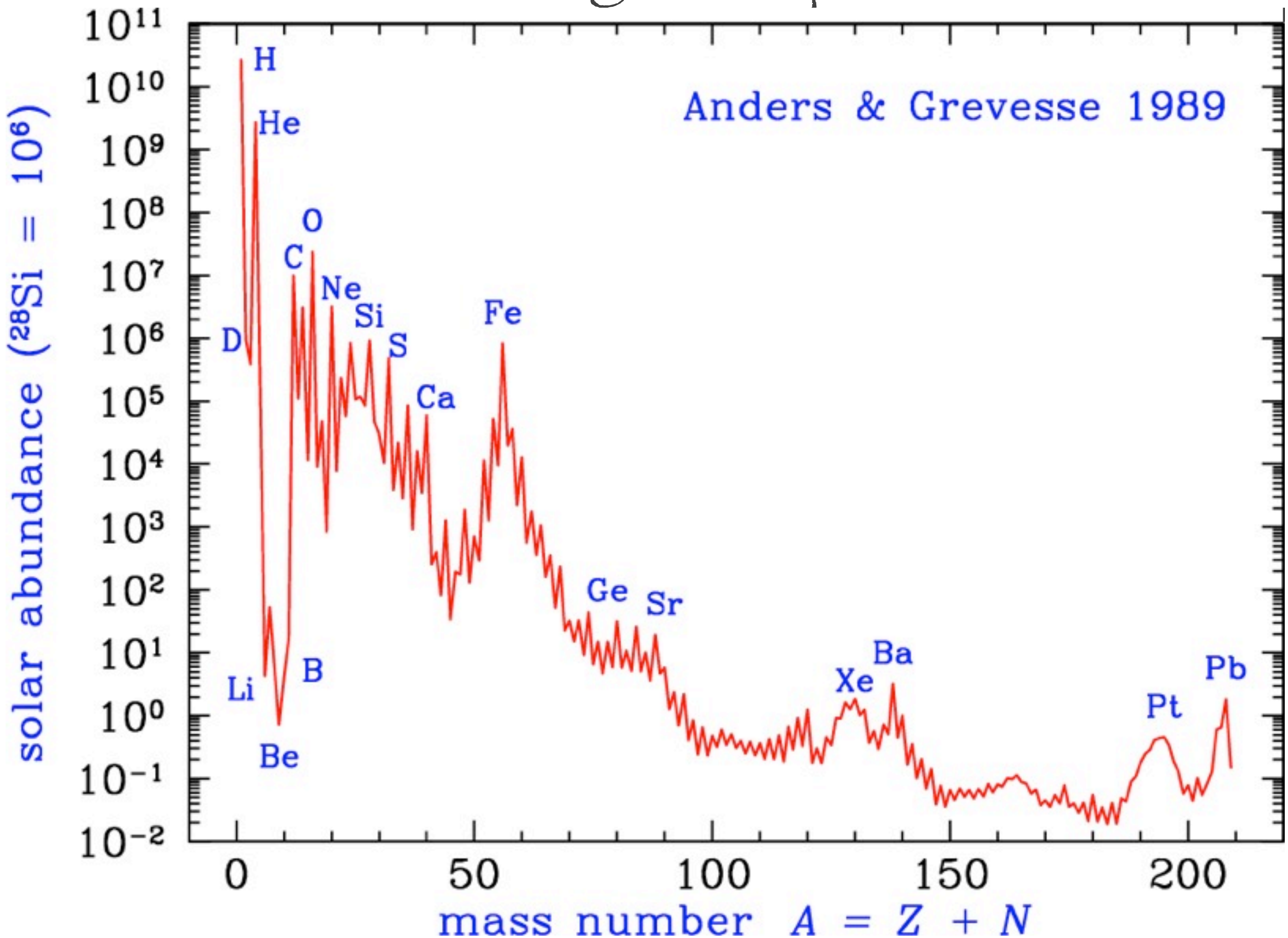


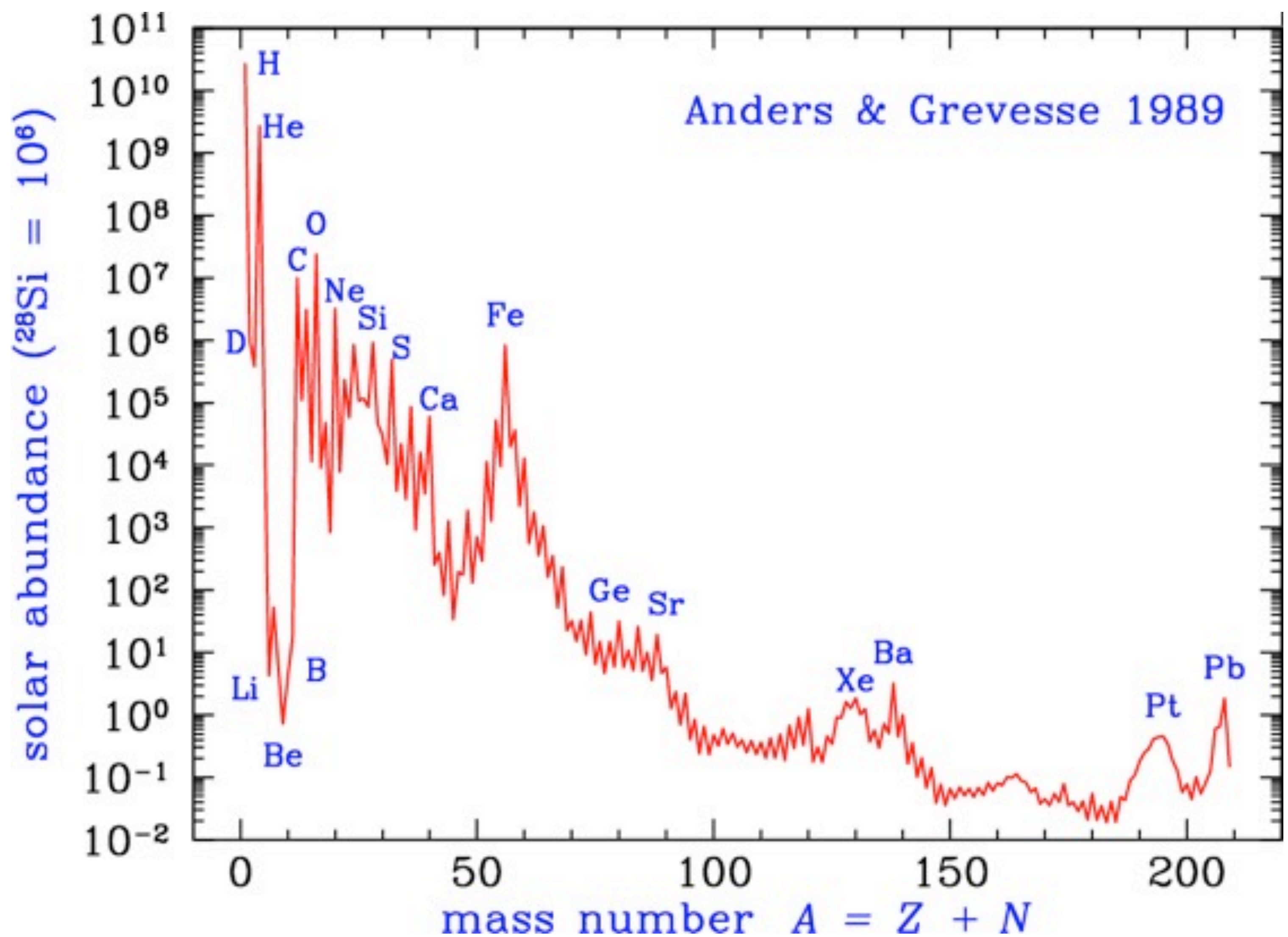
Q: what do we now understand

Solar System Abundances

Rosetta Stone of Nuclear Astrophysics

sums cumulative nucleosynthesis up to birth of solar system

progress so far:



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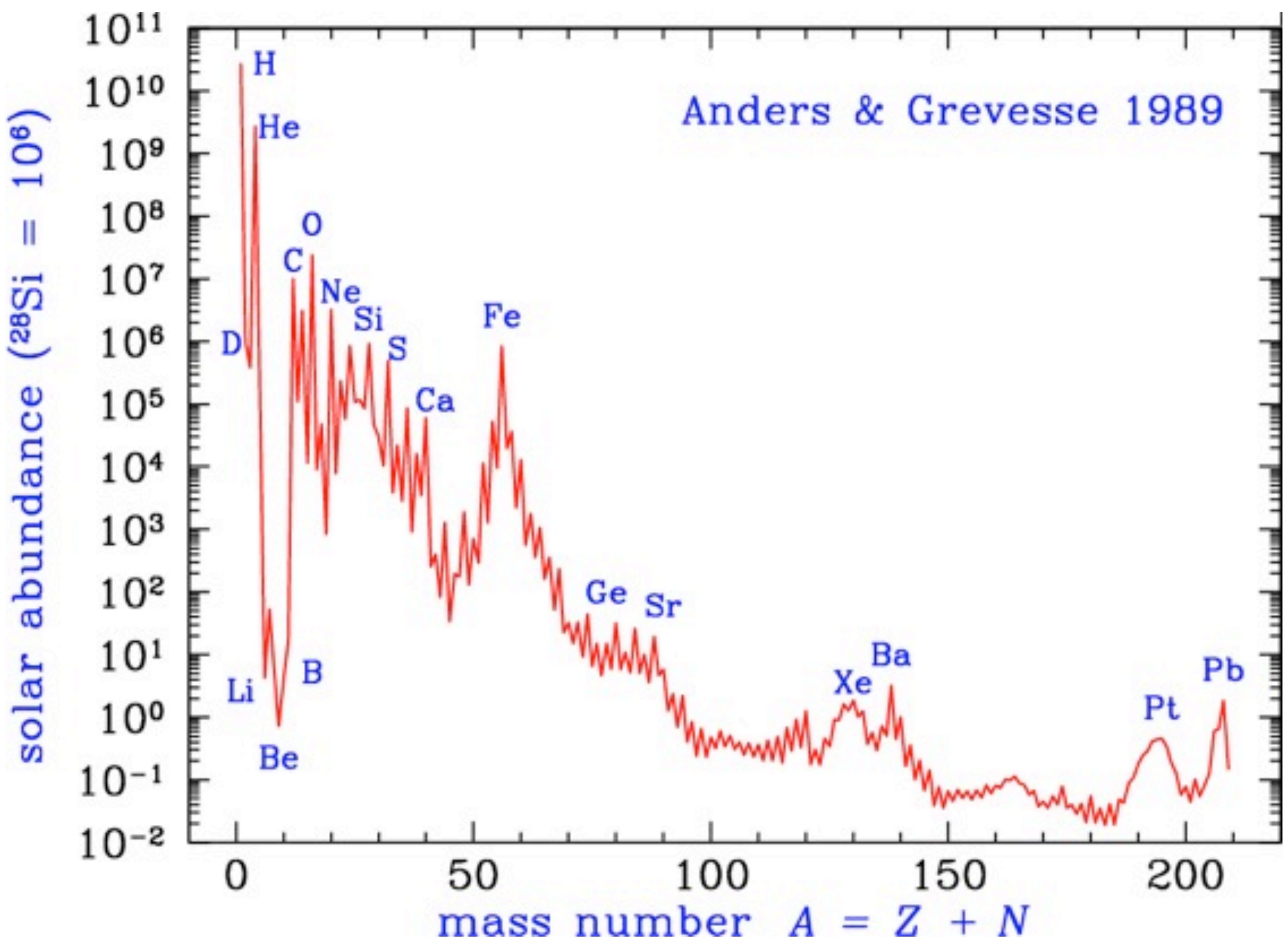

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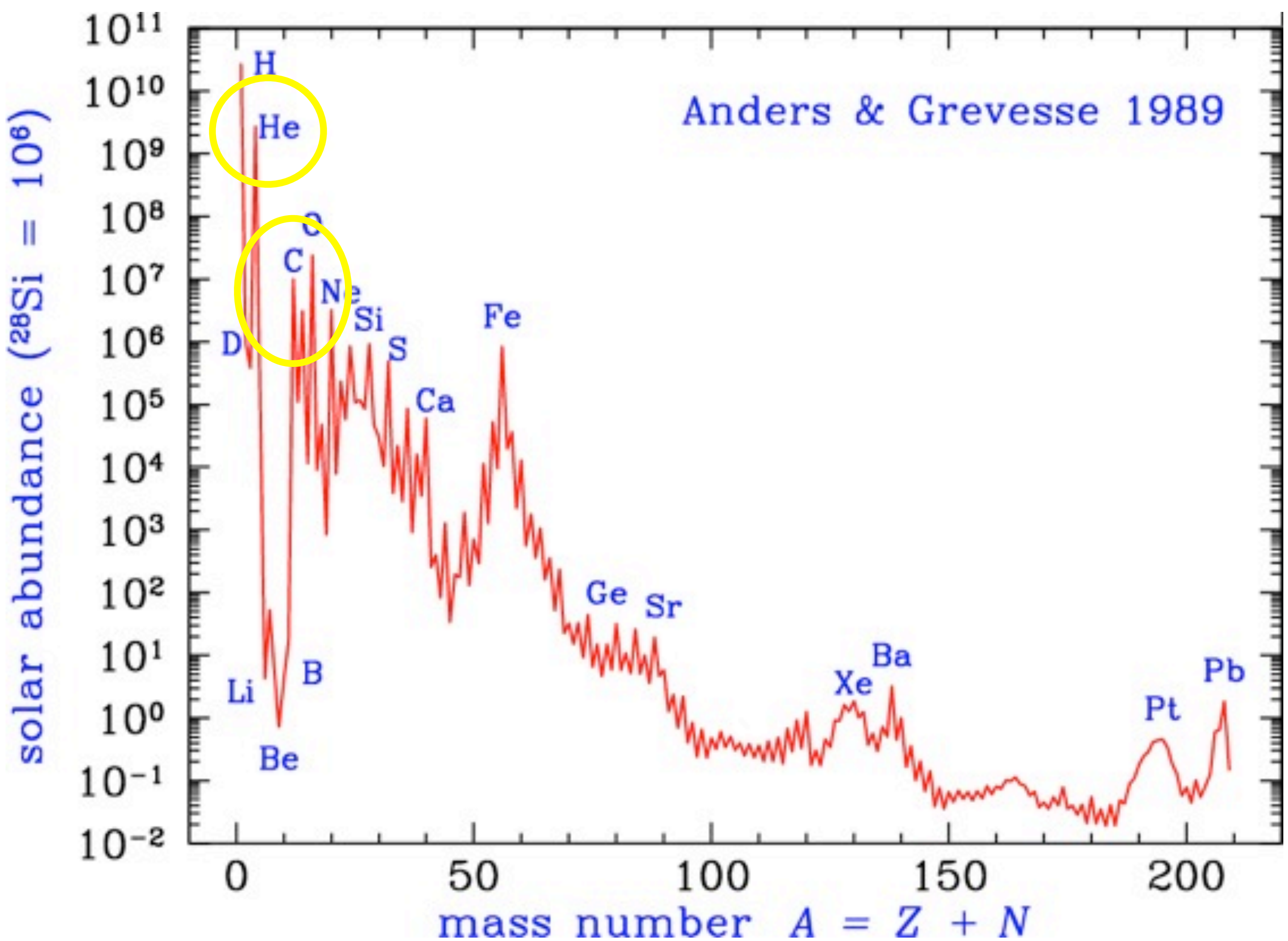

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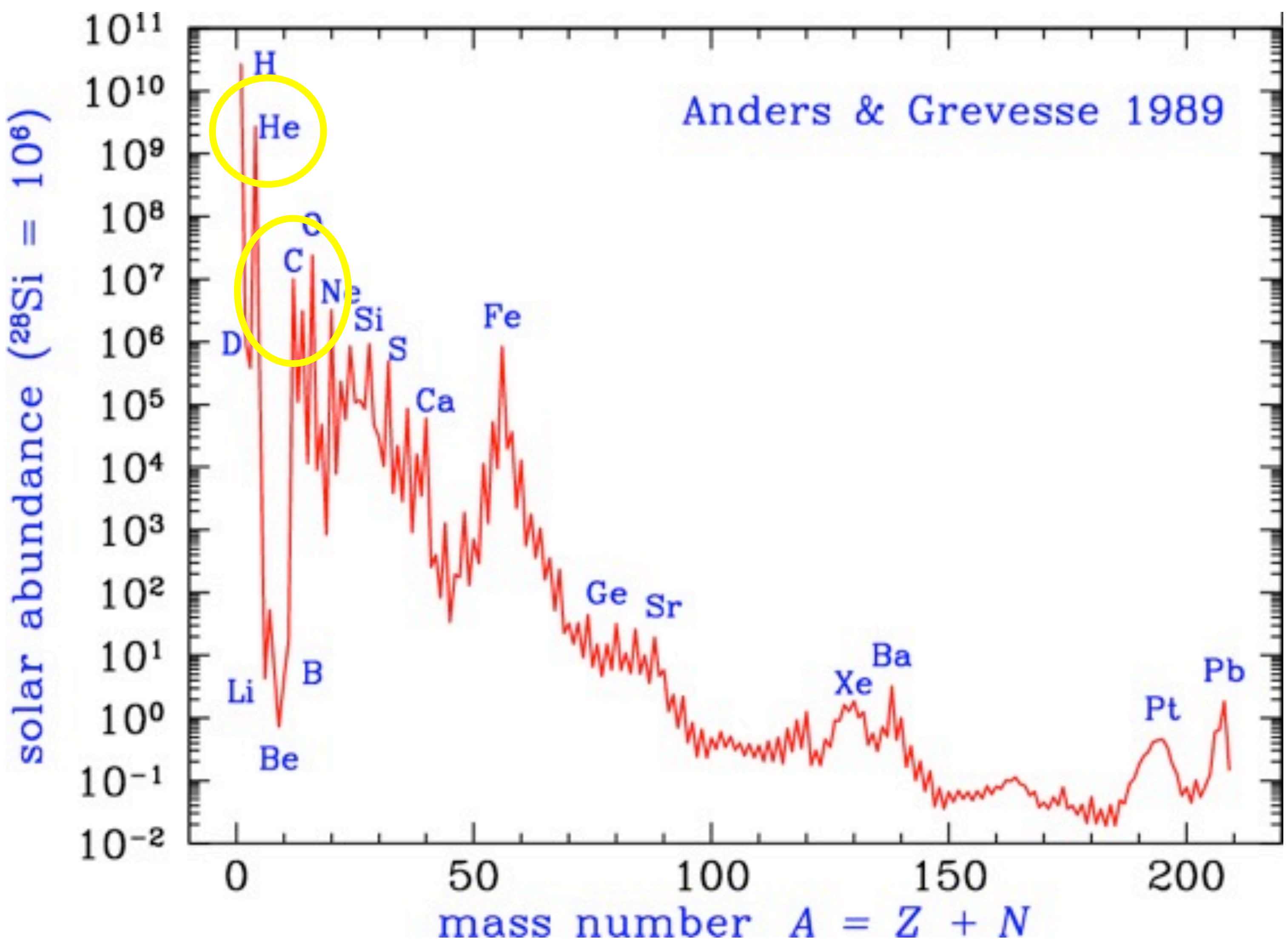
progress so far:

- **zig-zag: odd-even effect in nulcear binding**
- **^{4}He, ^{12}C, ^{14}N: contributions from H and He burning in low/ intermediate mass stars**

so far so good, but much more to understand!



Nucleosynthesis Beyond Iron: The s-Process

Margaret & Geoffrey Burbidge, Willy Fowler, Fred Hoyle

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Synthesis of the Elements in Stars*

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TABLE XII,1.

Elements	Mode of production	Total mass in galaxy ($M_\odot$ as unit)	Astrophysical origin	Total mass of all material ejected over lifetime of galaxy ($M_\odot$ as unit)	Required efficiency
He	H burning	8.1×10^9	Emission from red giants and supergiants	2×10^{10}	0.4
D	*x* process?	7.5×10^6?	Stellar atmospheres? Supernovae?	?	?
Li, Be, B	*x* process	8.5×10^2	Stellar atmospheres	?	?
C, O, Ne	He burning	4.3×10^8	Red giants and supergiants	2×10^{10}	2×10^{-2}
Silicon group	α process	4.0×10^7	Pre-Supernovae	2×10^8	0.2
Silicon group	*s* process	8.5×10^6	Red giants and supergiants	2×10^{10}	4×10^{-4}
Iron group	*e* process	2.4×10^7	Supernovae	2×10^8	0.1
$A>63$	*s* process	4.5×10^4	Red giants and supergiants	2×10^{10}	2×10^{-6}
$A<75$	*r* process	5×10^4	Supernovae Type II	1.7×10^8	3×10^{-4}
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Beyond the Iron Peak

if all heavy elements made only in burning to nuclear statistical equilibrium

- then should follow Fe peak, fall dramatically at high A
- would have much less of the very heavy elements

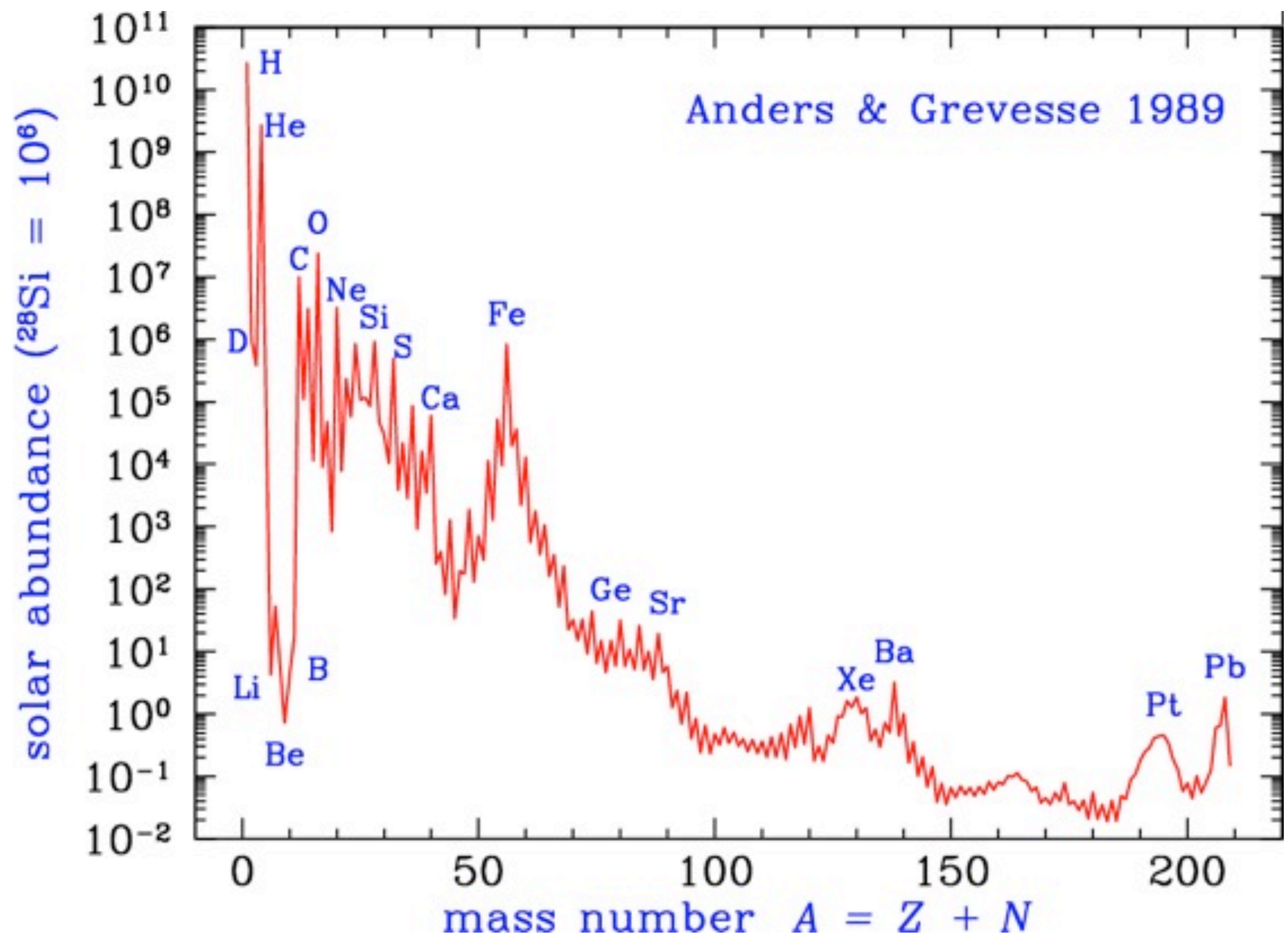
How to synthesize nuclei beyond iron peak?

- Coulomb barrier prohibitive
- fusion reaction not exothermic

Yet silver, gold, lead, uranium, ... all exist!

- nature has found a way

Q: Suggestions?



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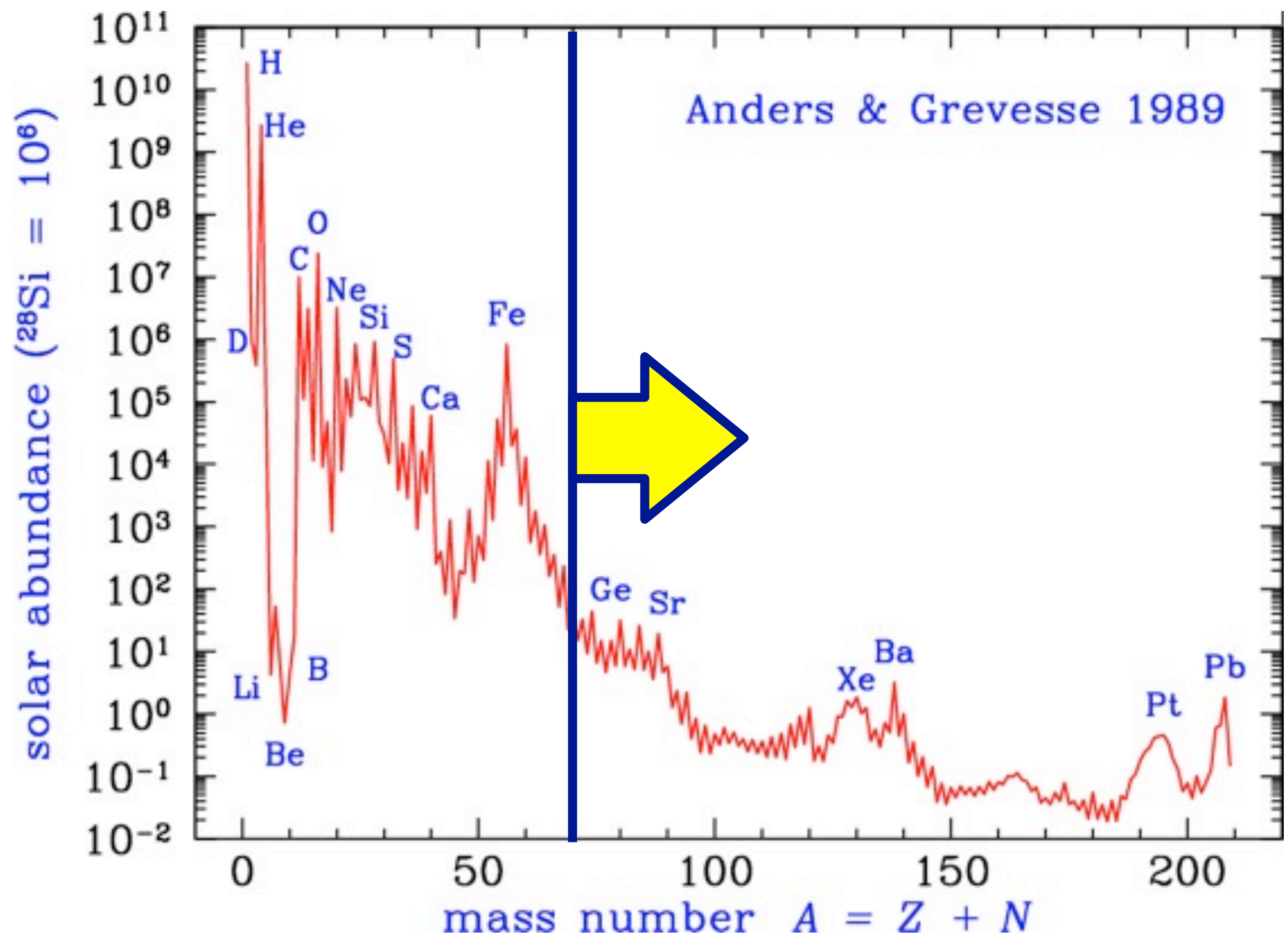

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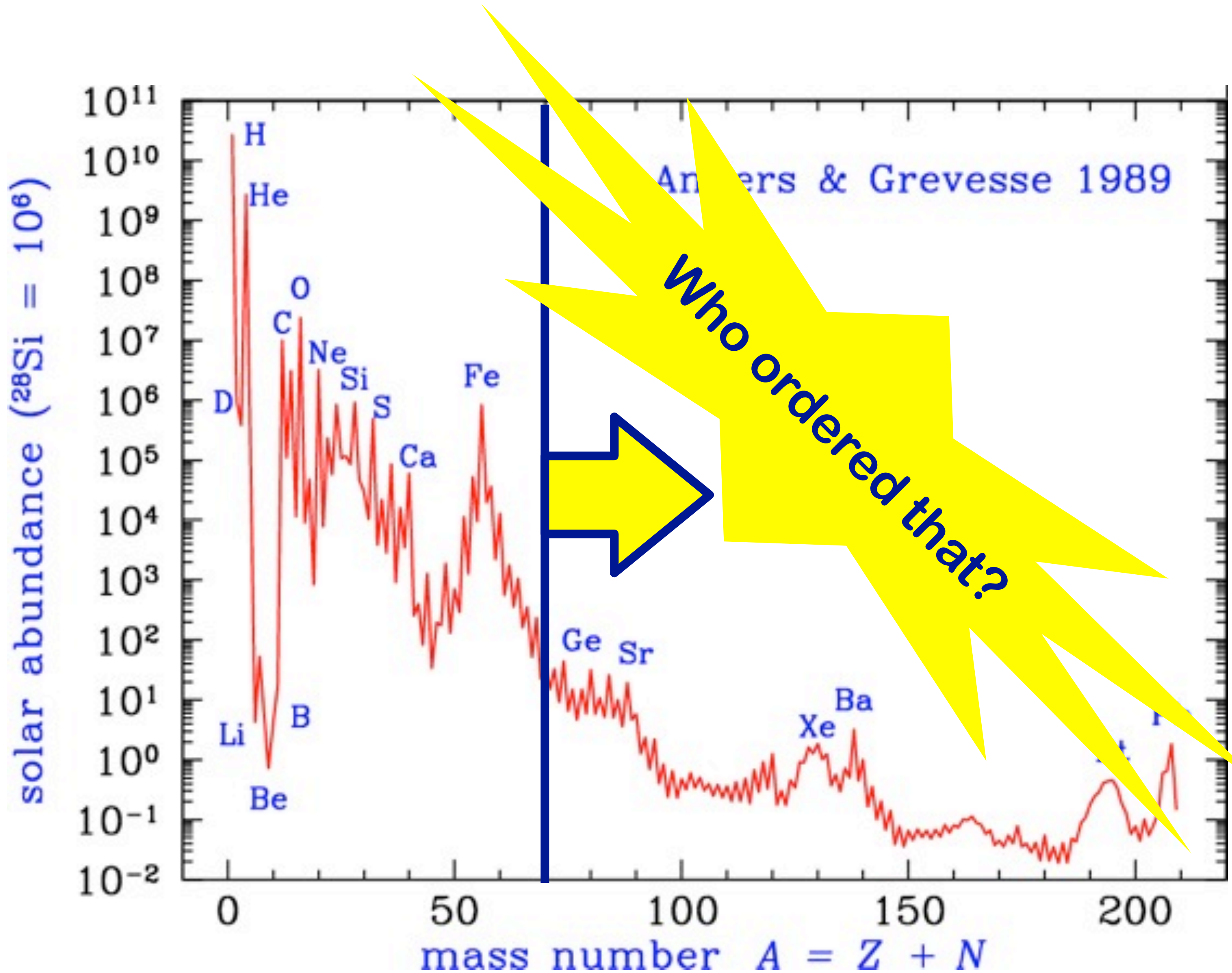

Neutron Capture Processes

Solution: neutrons

- no Coulomb barrier
- capture reactions occur even at small thermal speeds

Microscopic approach: identify the needed physics

(1) “let there be neutrons”

(2) assume a heavy “seed” nucleus (e.g., ^{56}Fe)

(3) ignore charged particle rxns (Coulomb suppressed)

Q: what can happen when adding n seeds?

A Tale of Two Limits

Neutron capture physics set by competition

- neutron capture $n + (A, Z) \rightarrow (A+1, Z) + \gamma$
- β decay $(A, Z) \rightarrow (A, Z+1) + e^- + \bar{\nu}_e$

Two regimes (BBFH 1957; Cameron 1957):

capture rate $\gg$ decay rate

$\Rightarrow$ rapid capture: *r*-process

decay rate $\gg$ capture rate

$\rightarrow$ slow capture: *s*-process

Detective story:

- do these limiting cases occur? (*Yes!*)
- what are astrophysical sites?

Neutron Capture Rates

n-capture cross sections:

typically, $\sigma \propto 1/v$

- enhanced at low energies!
- $\sigma v = \langle \sigma v \rangle = const$ → T-indep!
- fails for magic nuclei:

  tightly bound → small σ

Implications?

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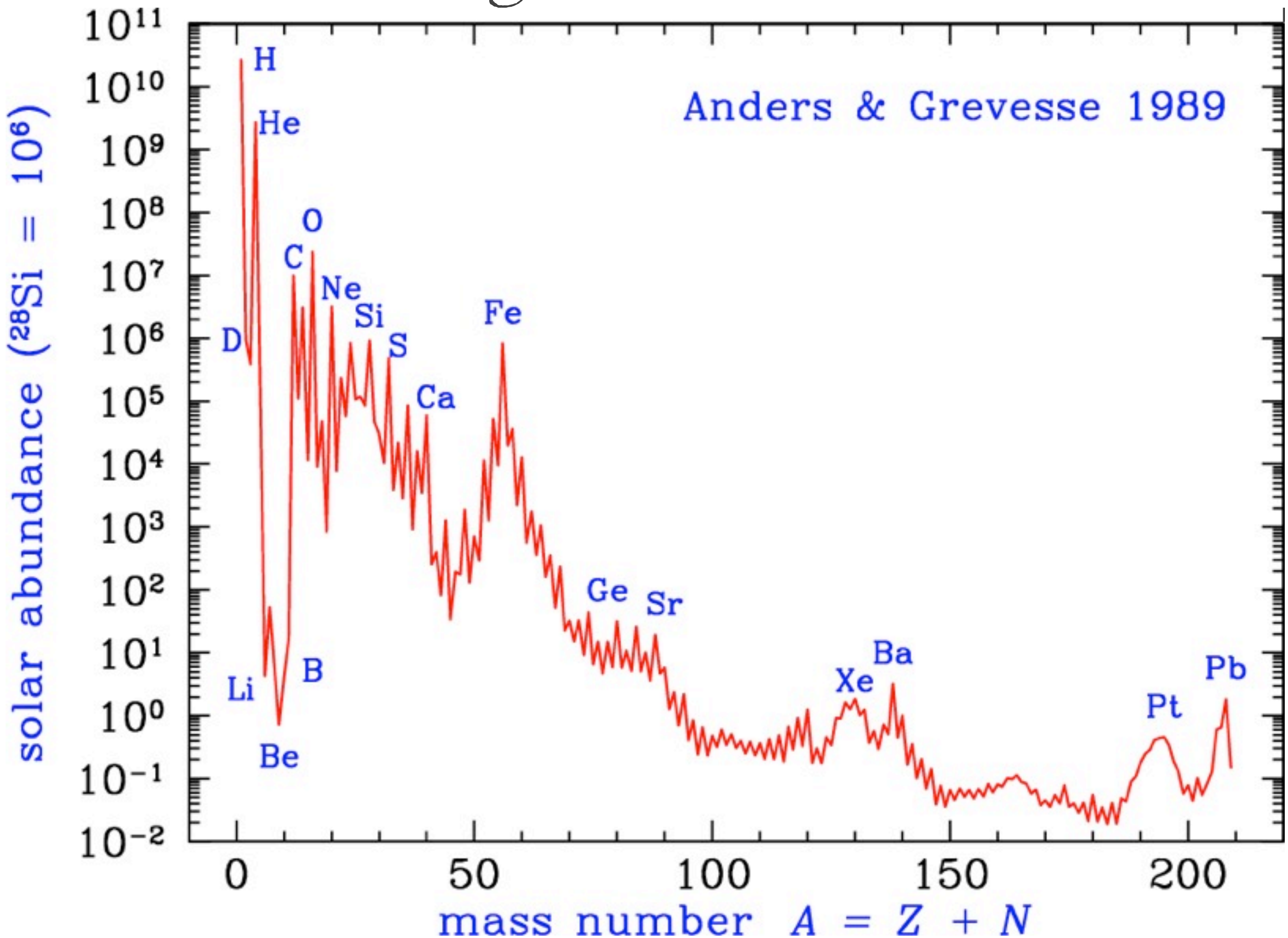
Implications?

Difficulty adding more neutrons to magic nuclei:

– **abundance pileup at magic N**

Solar System Abundances

Magic Neutron Numbers



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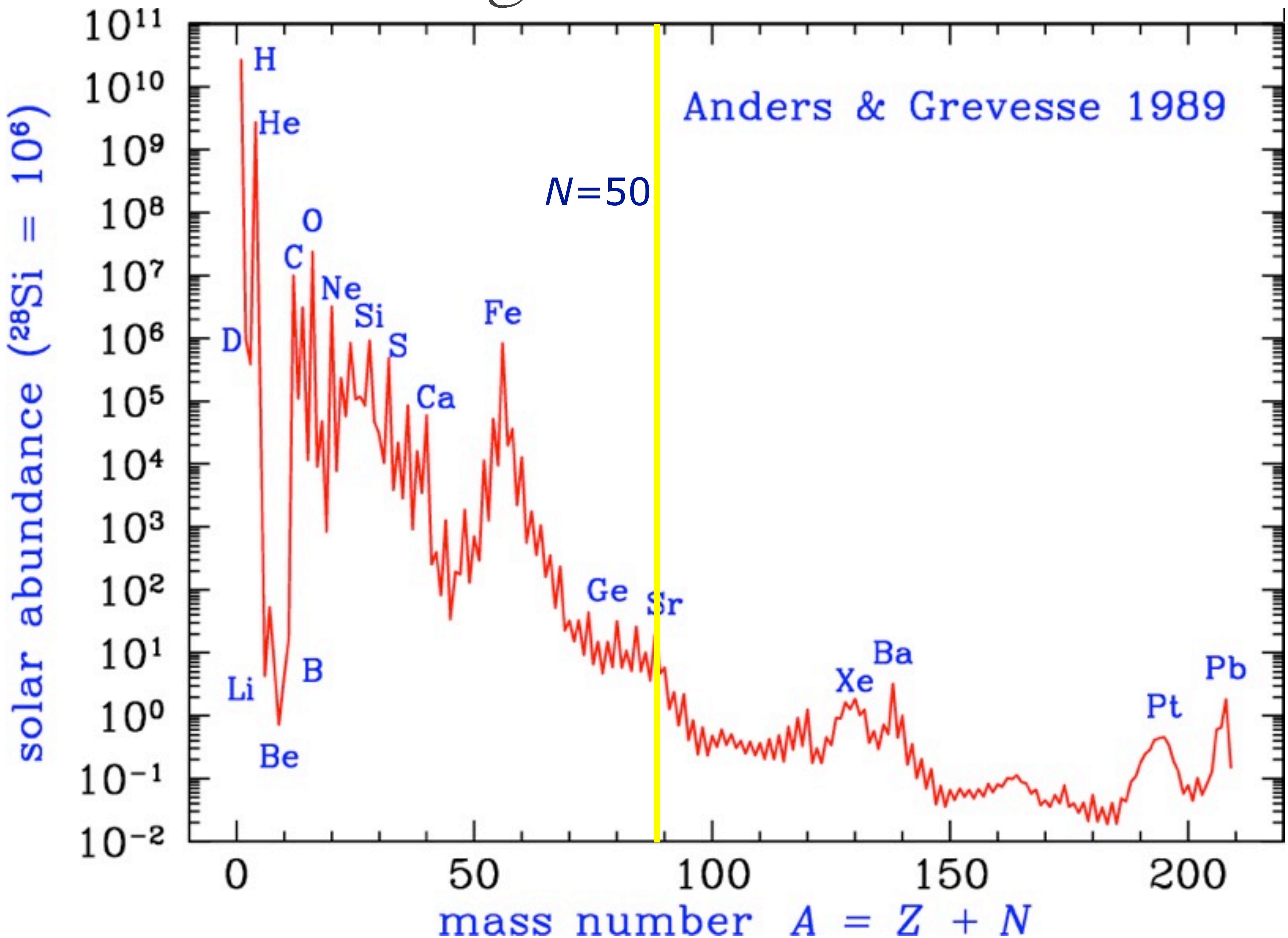

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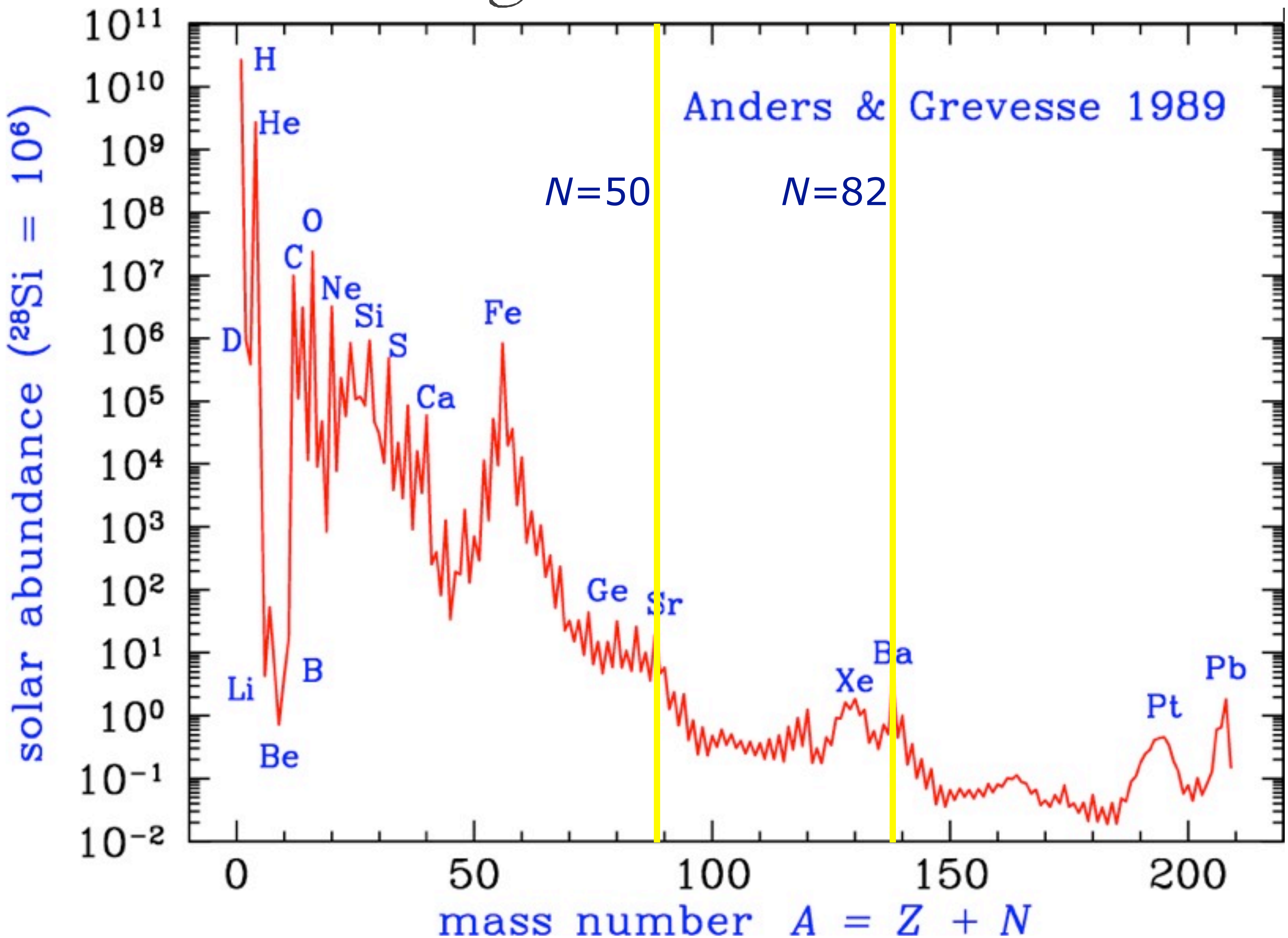

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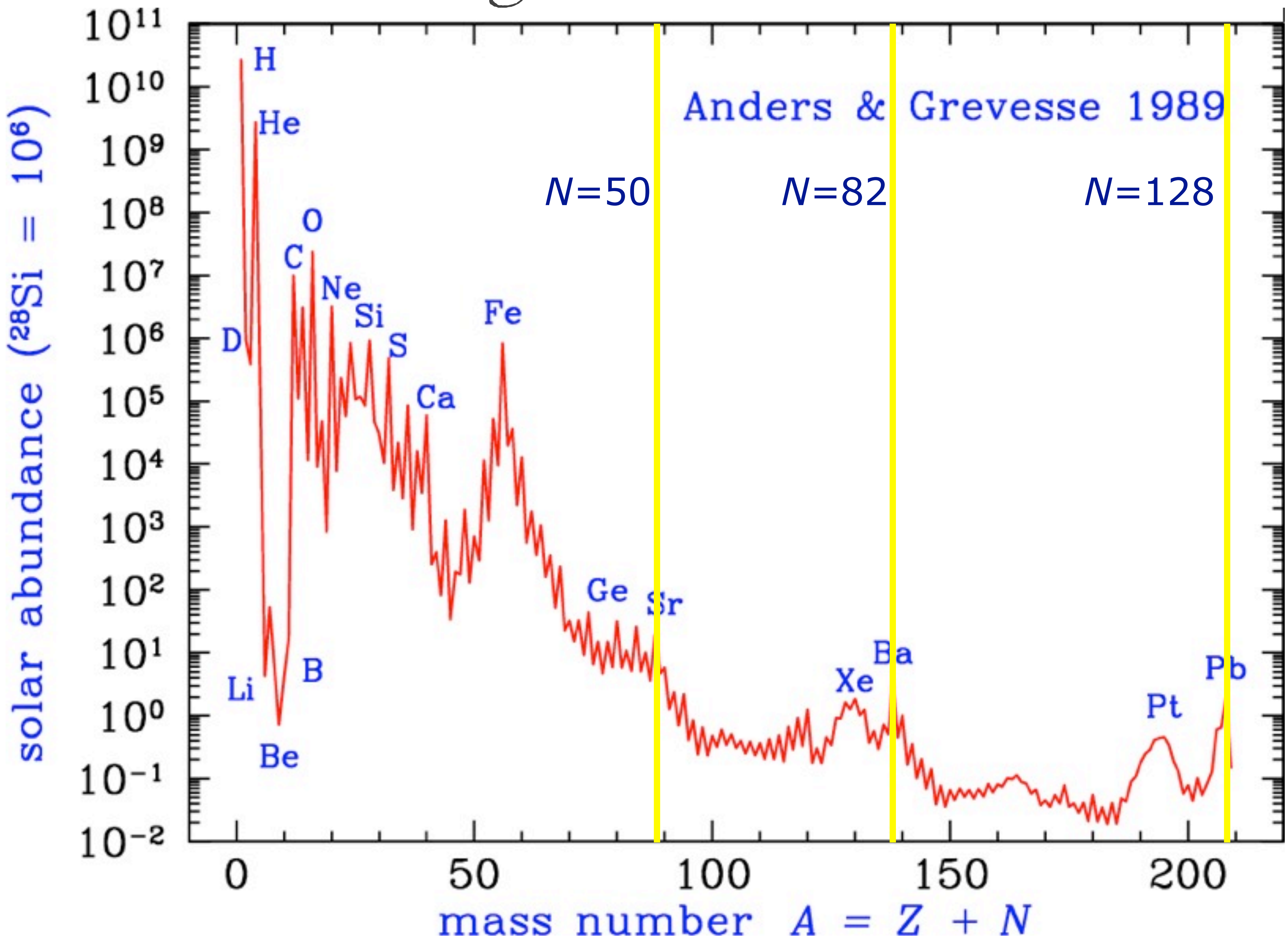


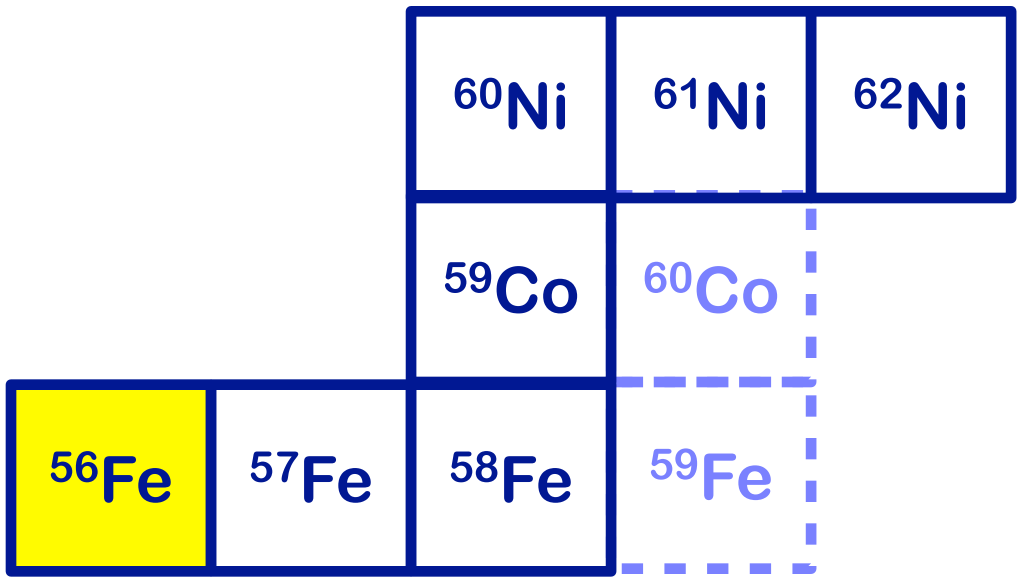
s-Process: Basic Physics

add neutrons to seeds slowly:

- capture time >> decay

Q: what happens?

Q: lessons?



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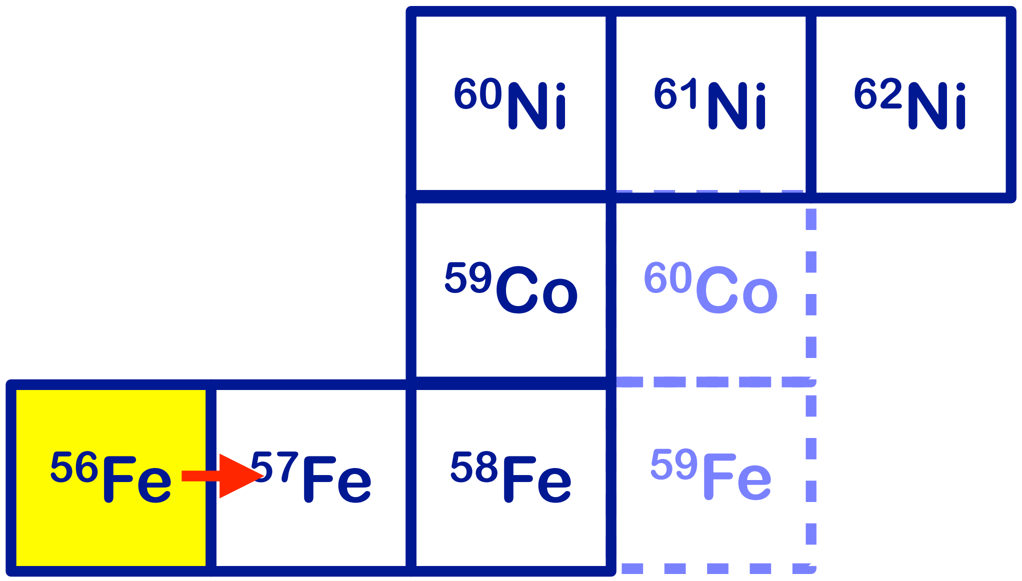

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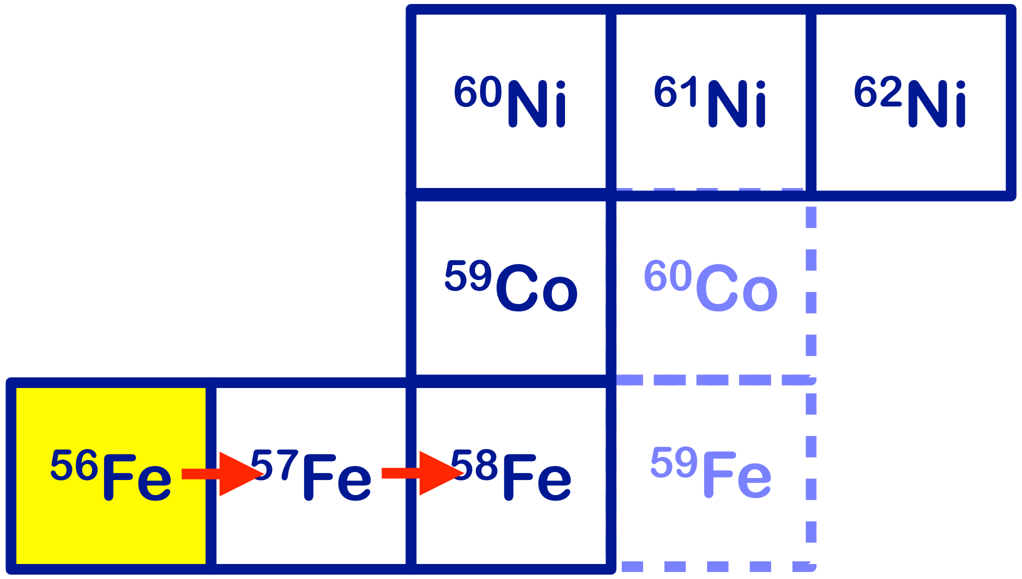

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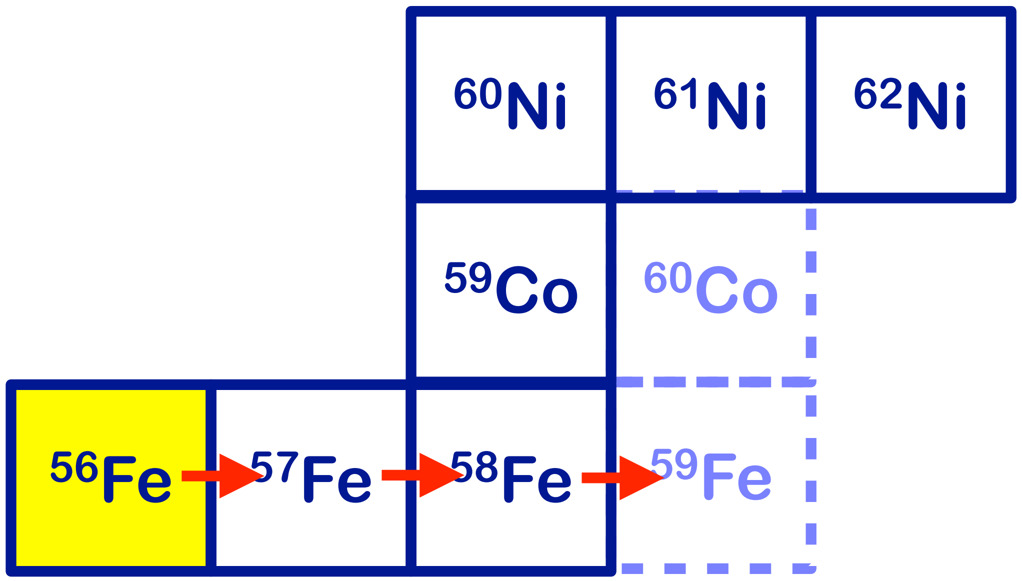

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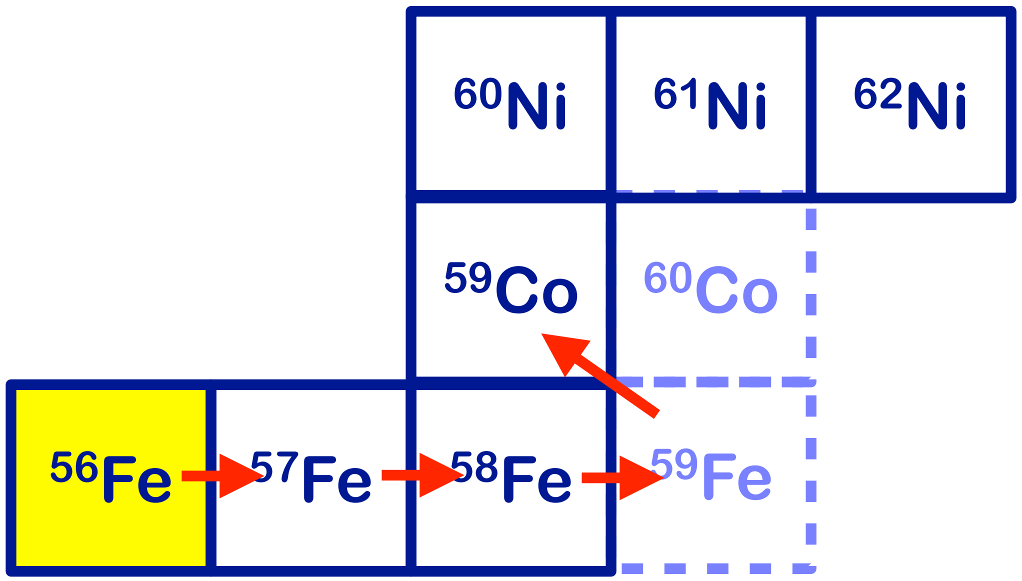

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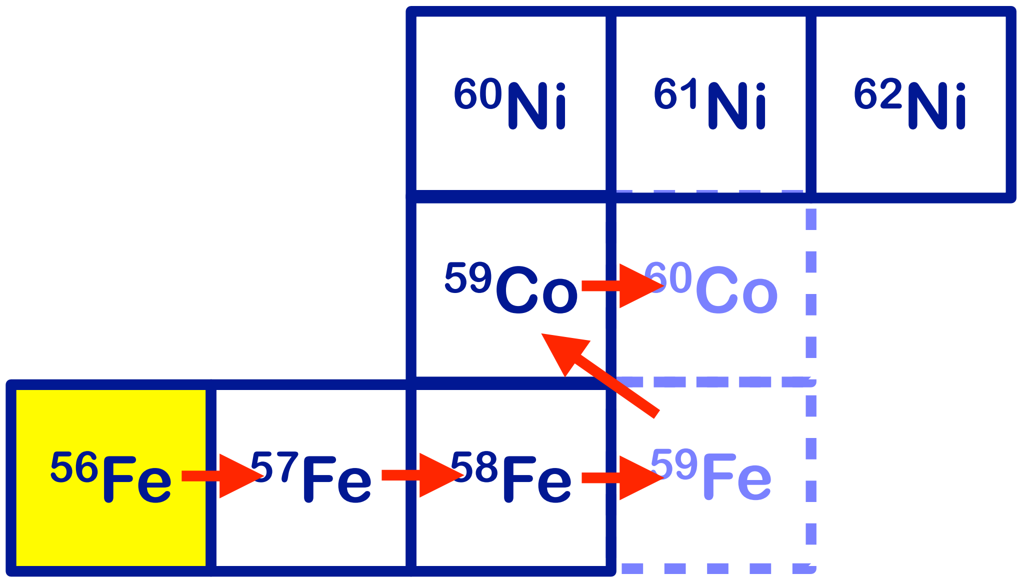

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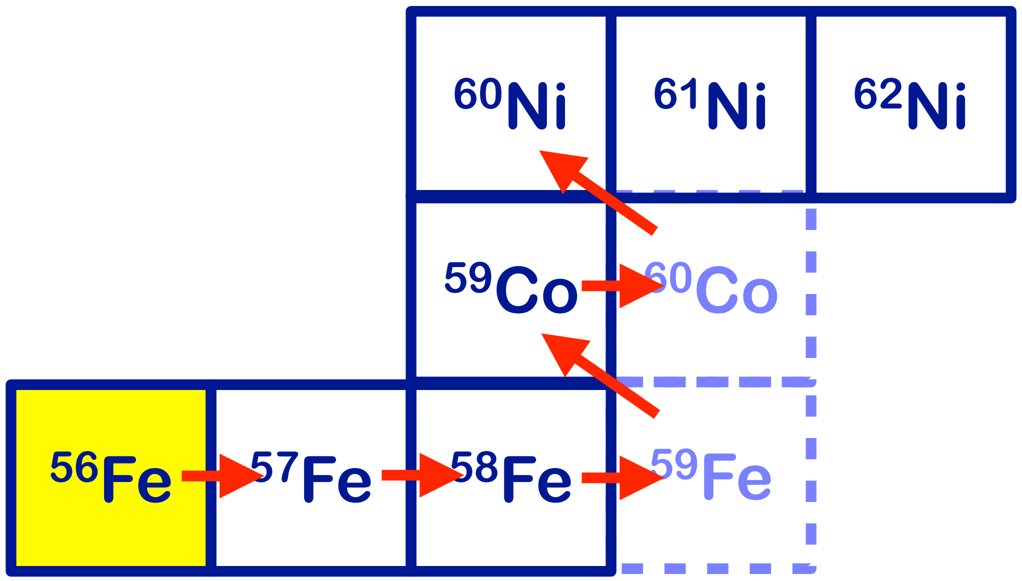

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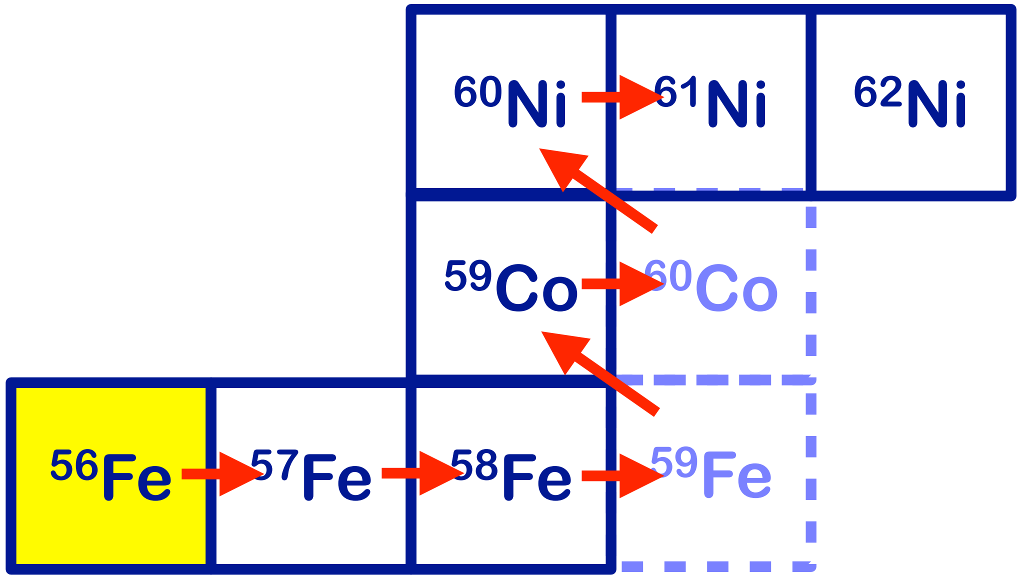

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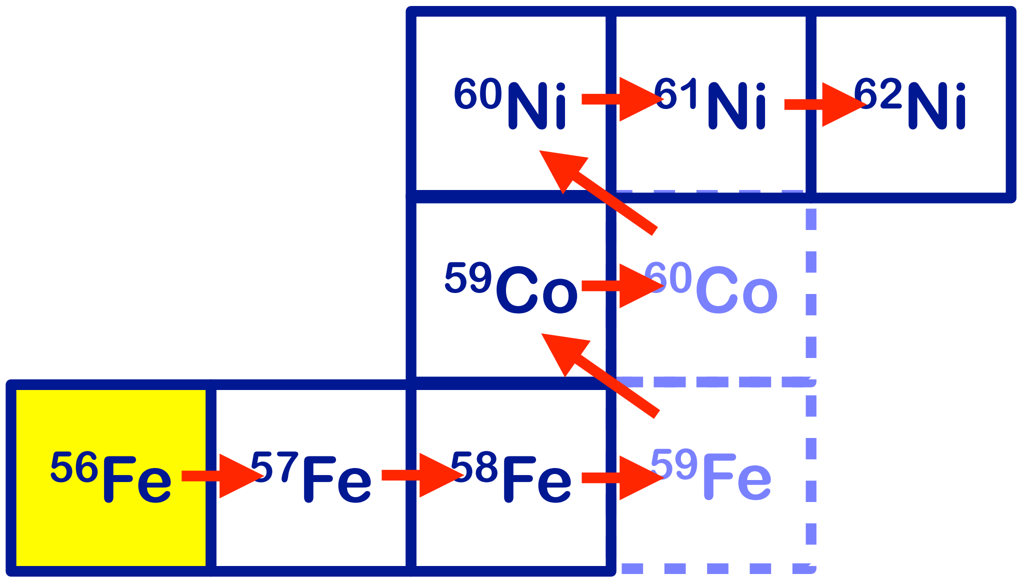

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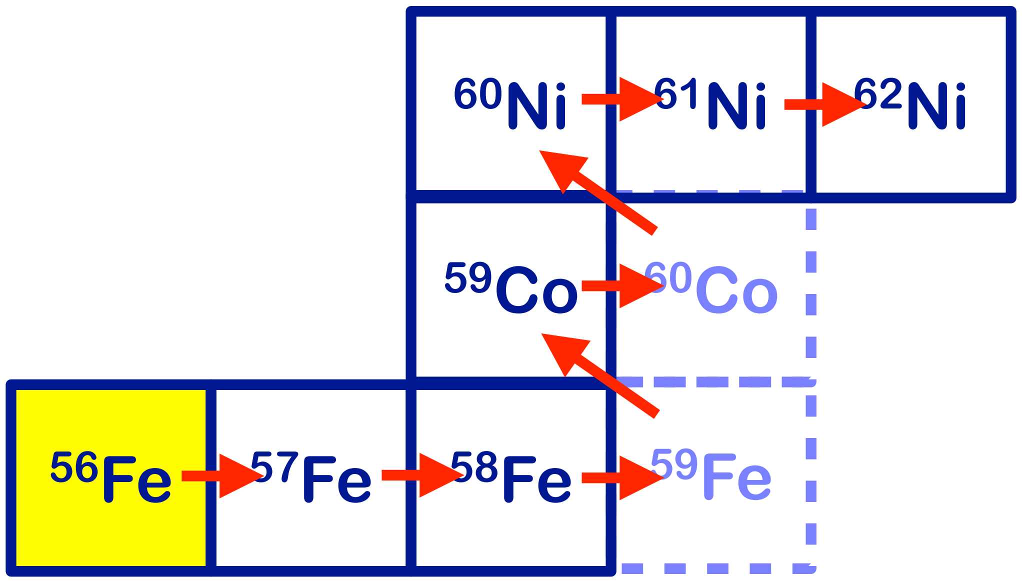

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slow n capture: $\Gamma_{n\gamma} \ll \Gamma_{\beta}$

$\Rightarrow$ path in chart of nuclides:

follow n-rich edge of β-stability

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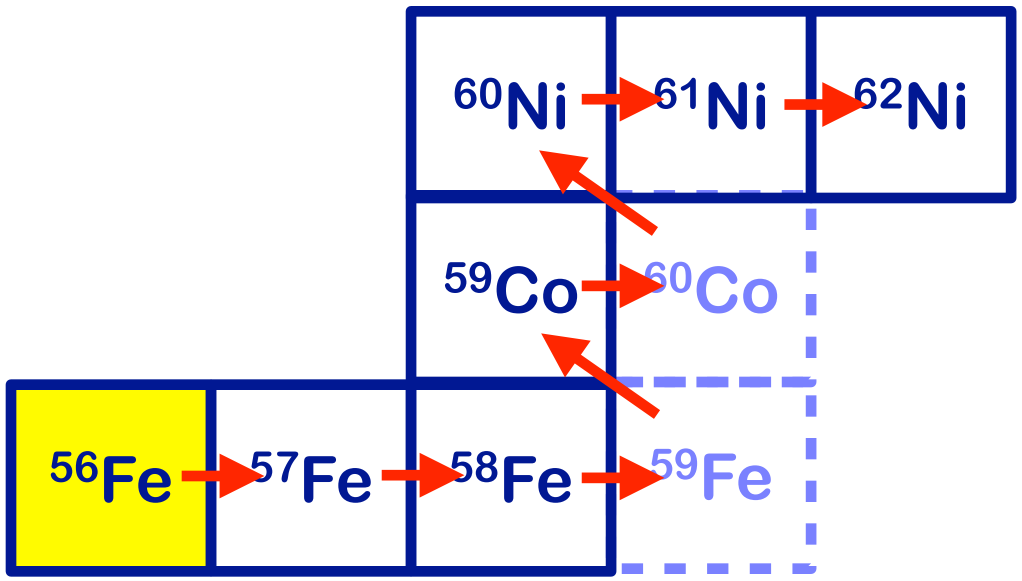

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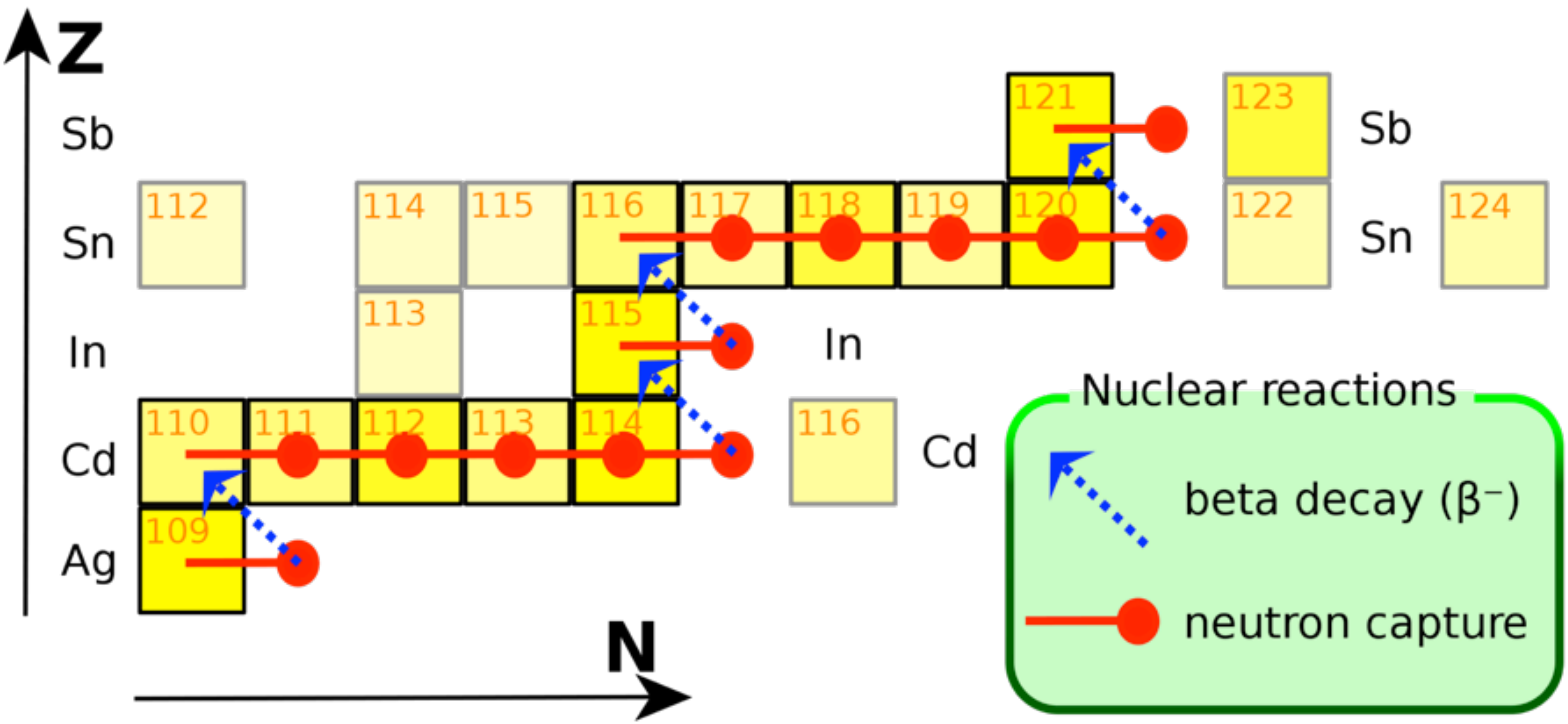
for isobar A

$$\frac{dn_A}{dt} = -\langle\sigma v\rangle_A n_n n_A + \langle\sigma v\rangle_{A-1} n_n n_{A-1}$$

except for seed (e.g., ^{56}Fe)

$$dn_{\text{seed}}/dt = -\langle\sigma v\rangle_A n_n n_{\text{seed}}$$

Q: what behavior expected for n_A?


Z
Sb
Sn
In
Cd
Ag
112
114
115
116
117
118
119
120
121
122
123
124
113
115
110
111
112
113
114
116
109
Sb
Sn
In
Cd
N
Nuclear reactions
beta decay (β⁻)
neutron capture

The Local Approximation

$$\begin{aligned}\frac{dn_A}{dt} &= -n_n v_T \left(\sigma_A n_A - \sigma_{A-1} n_{A-1}\right) \\ &= -n_n v_V \sigma_A \left(n_A - n_{\mathrm{eq}}\right)\end{aligned}$$

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Q: what if $n_A > n_{eq}$? $< n_{eq}$? lesson?

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evolution is another example of *self-regulating* equation

$\rightarrow$ expect abundance driven to equilibrium, $dn_A/dt = 0$

$\Rightarrow \sigma_A n_A = \sigma_{A-1} n_{A-1}$

$$\frac{n_A}{n_{A-1}} = \frac{\sigma_{A-1}}{\sigma_A}$$

$\Rightarrow$ the "local approximation"

only holds for non-magic nuclei

$\Rightarrow$ good between magic numbers

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Q: how to test this?

Solar Abundances and the s_process

For elements beyond Fe peak:

plot $N_A \sigma_A$ vs A

if *s*-process reaches equilibrium, predict flat curve

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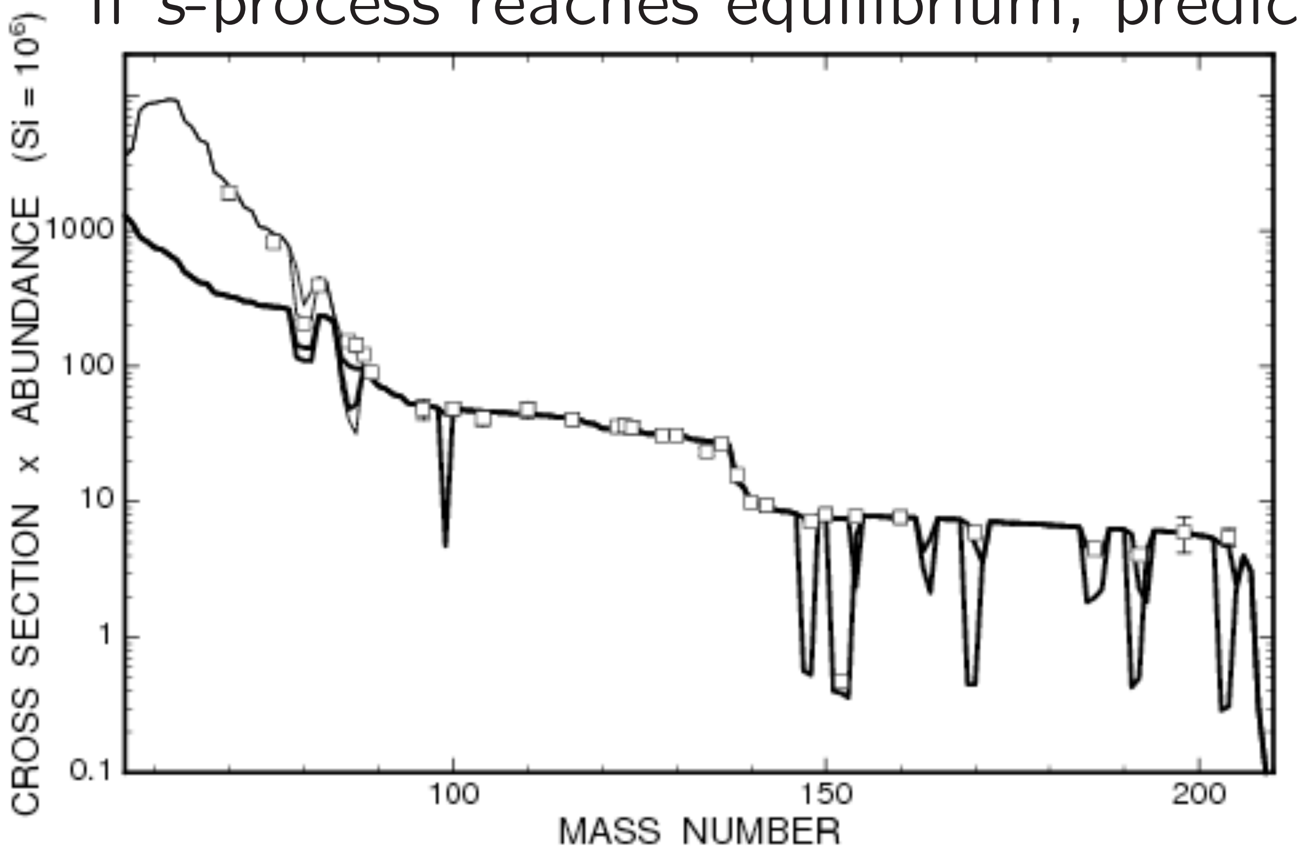

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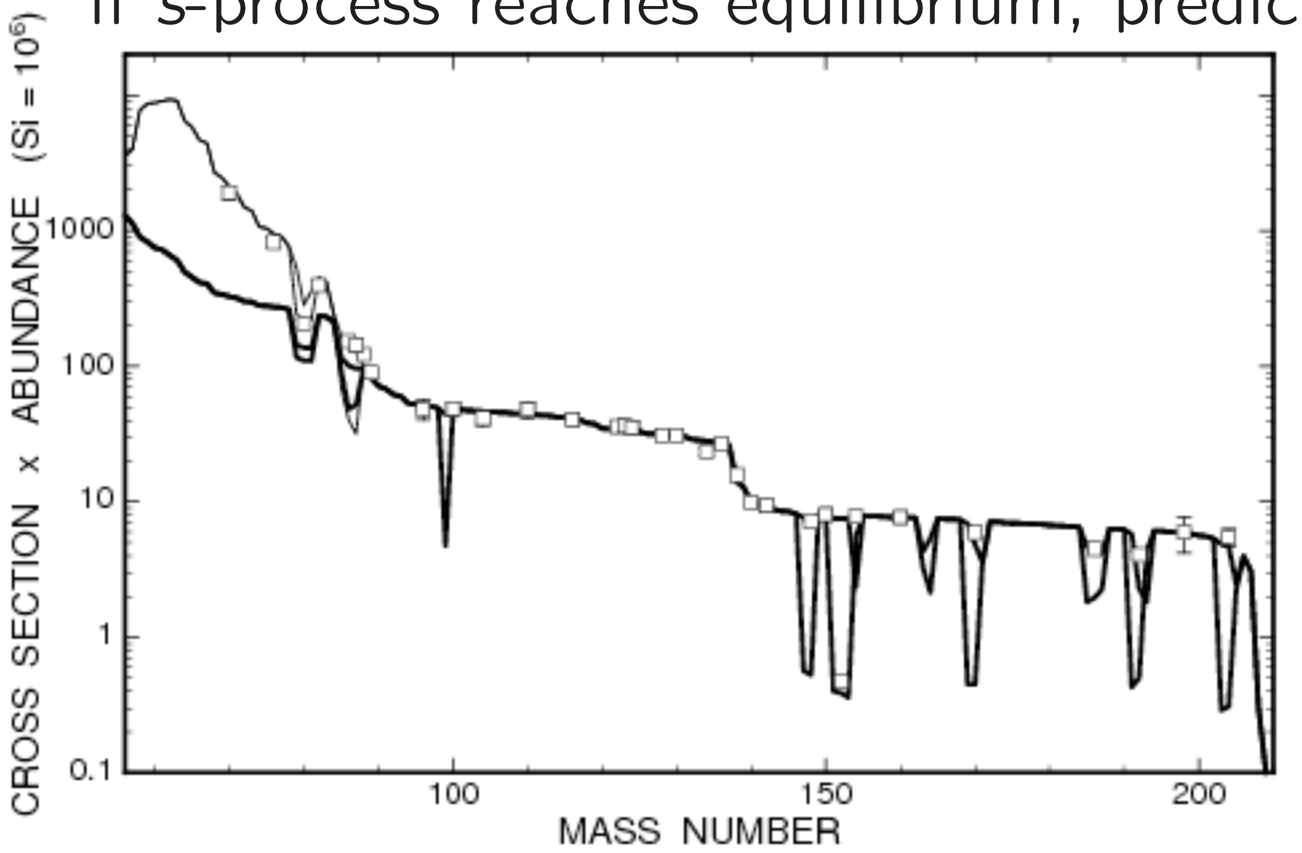

Lessons?

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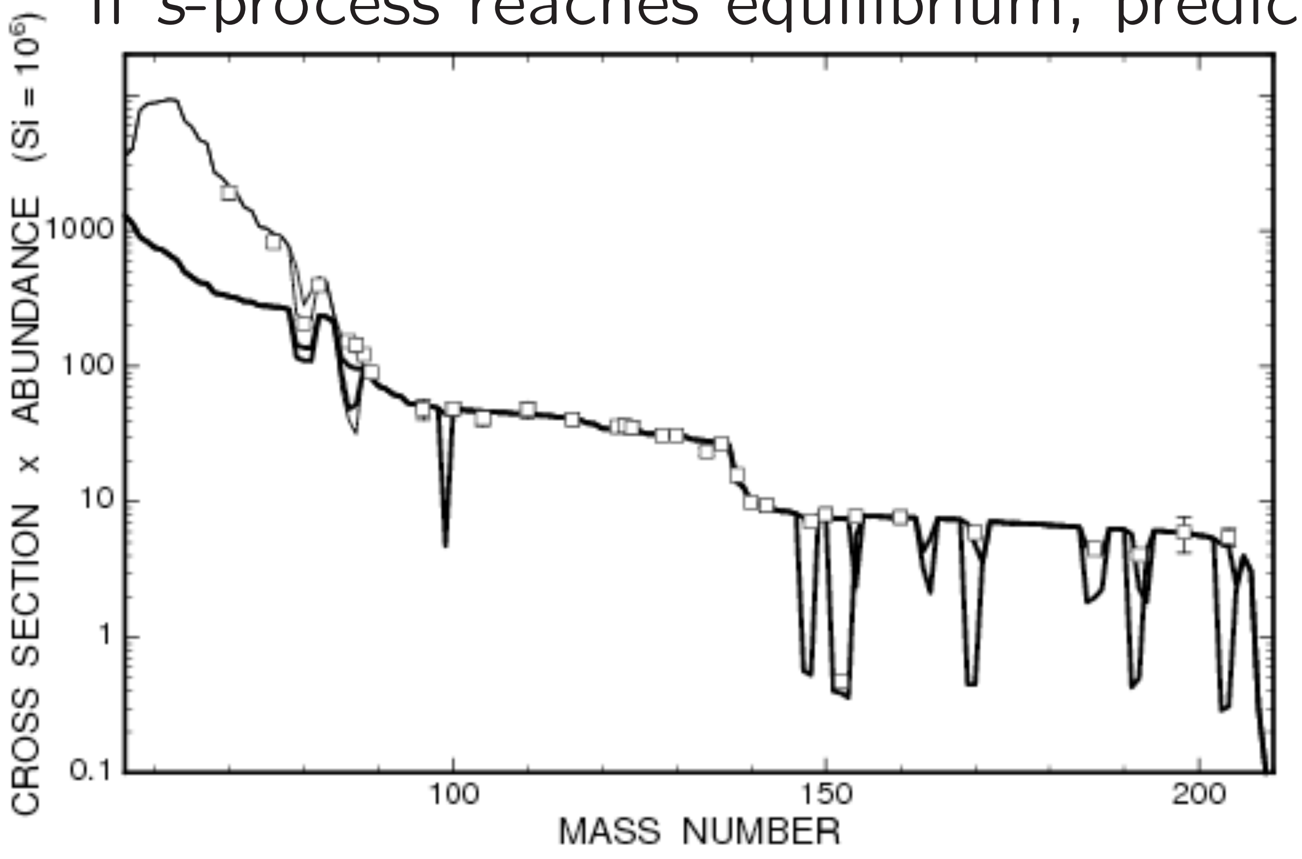


Lessons?

for adjacent nuclides, local approximation excellent

between magic N: good

but globally, fails

$\Rightarrow$ need distribution of τ

Roughly: exponential distribution of τ needed

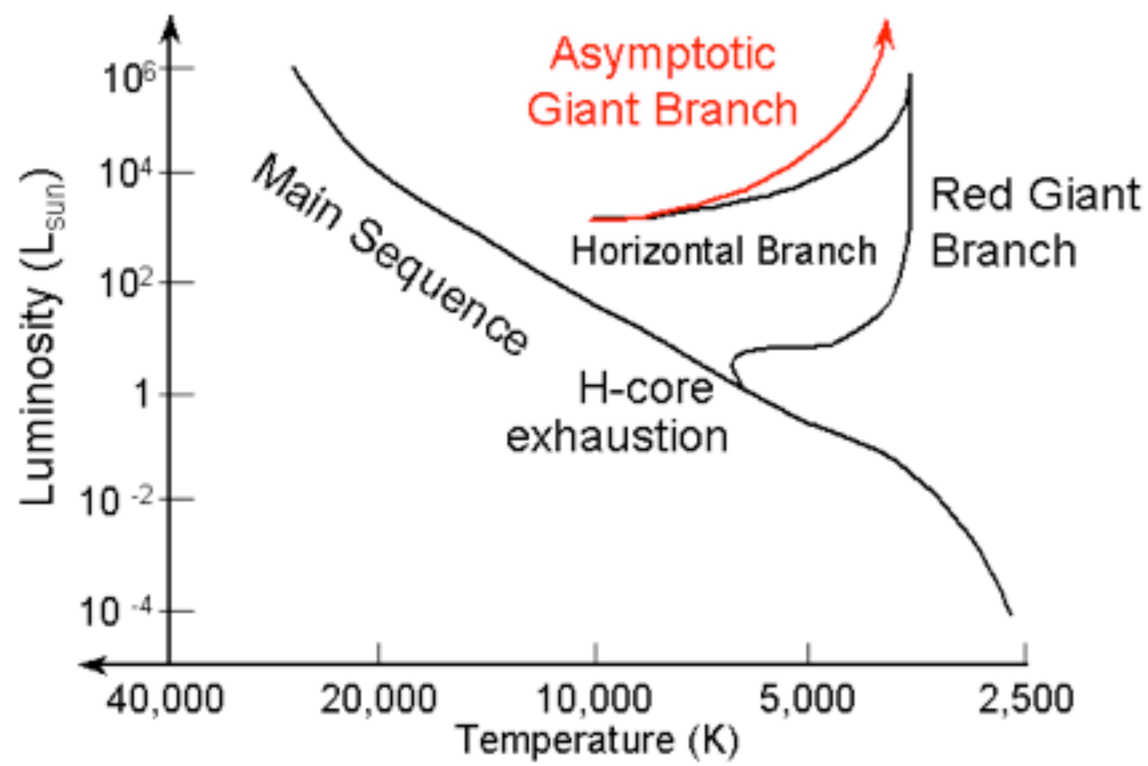
i.e., imagine series of n bursts of different intensities

Q: how does nature do this?

s-Process: Astrophysical Site

Intermediate mass stars: $\sim 3 - 8\ M_\odot$
recall–after main seq:
1. H shell burn $\rightarrow$ RGB
2. He ignition $\rightarrow$ core He burn

3 He shell burn $\rightarrow$ asymptotically approach RGB again
"asymptotic giant branch" $=$ AGB
HR diagram sketch



On AGB:
two burning shells: H, He
instability $\rightarrow$ thermal pulses (TP)

TP-AGB stars observed to have
- C/O > 1 – "carbon stars"
- high *s*-process! – "S-stars"

s-Process: Crown Jewel

technetium seen in AGB stars (Merrill 1952)

s-Process: Crown Jewel

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Q: why is this amazing?

s-Process: Crown Jewel

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Tc: no stable isotopes!

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Q: where did the stars get the neutrons? the seeds?

AGB neutron sources:

- ^{13}C from CNO cycle: $^{13}C(\alpha, n)^{16}O$
- ^{14}N from CNO cycle burnt to $^{14}N(\alpha, \gamma)^{18}F(\beta)^{18}O(\alpha, \gamma)^{22}Ne$ then $^{22}Ne(\alpha, n)^{25}Mg$

occurs in intershell region

n created during, between pulses

$\Rightarrow$ repeated n exposure of different intensities

$\Rightarrow$ can fit observed exposure distribution

...but now can make detailed, realistic models

in context of stellar evolution

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TABLE XII,1.

Elements	Mode of production	Total mass in galaxy ($M_\odot$ as unit)	Astrophysical origin	Total mass of all material ejected over lifetime of galaxy ($M_\odot$ as unit)	Required efficiency
He	H burning	8.1×10^9	Emission from red giants and supergiants	2×10^{10}	0.4
D	*x* process?	7.5×10^6?	Stellar atmospheres? Supernovae?	?	?
Li, Be, B	*x* process	8.5×10^2	Stellar atmospheres	?	?
C, O, Ne	He burning	4.3×10^8	Red giants and supergiants	2×10^{10}	2×10^{-2}
Silicon group	*α* process	4.0×10^7	Pre-Supernovae	2×10^8	0.2
Silicon group	*s* process	8.5×10^6	Red giants and supergiants	2×10^{10}	4×10^{-4}
Iron group	*e* process	2.4×10^7	Supernovae	2×10^8	0.1
$A>63$	*s* process	4.5×10^4	Red giants and supergiants	2×10^{10}	2×10^{-6}
$A<75$	*r* process	5×10^4	Supernovae Type II	1.7×10^8	3×10^{-4}
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