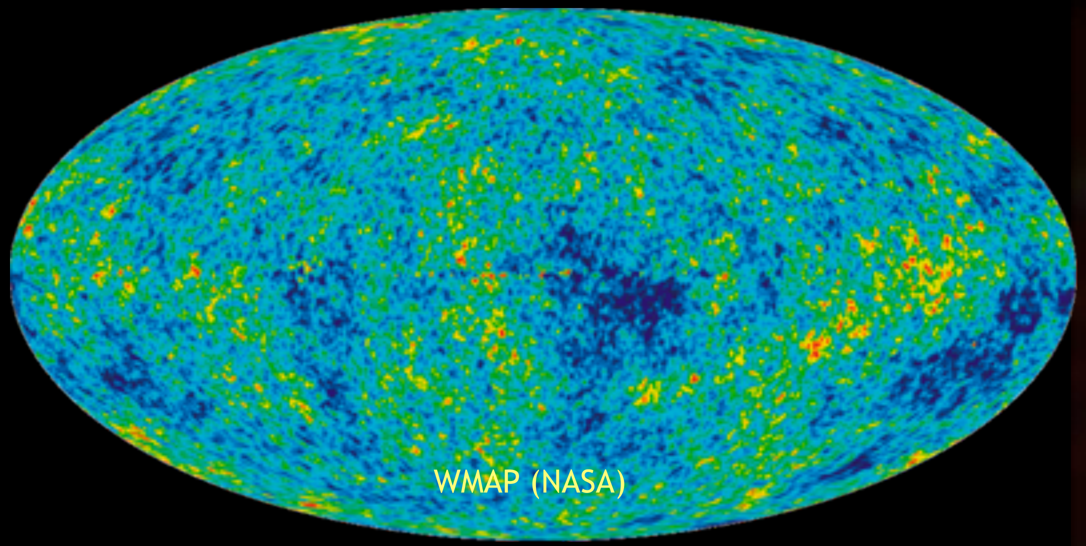
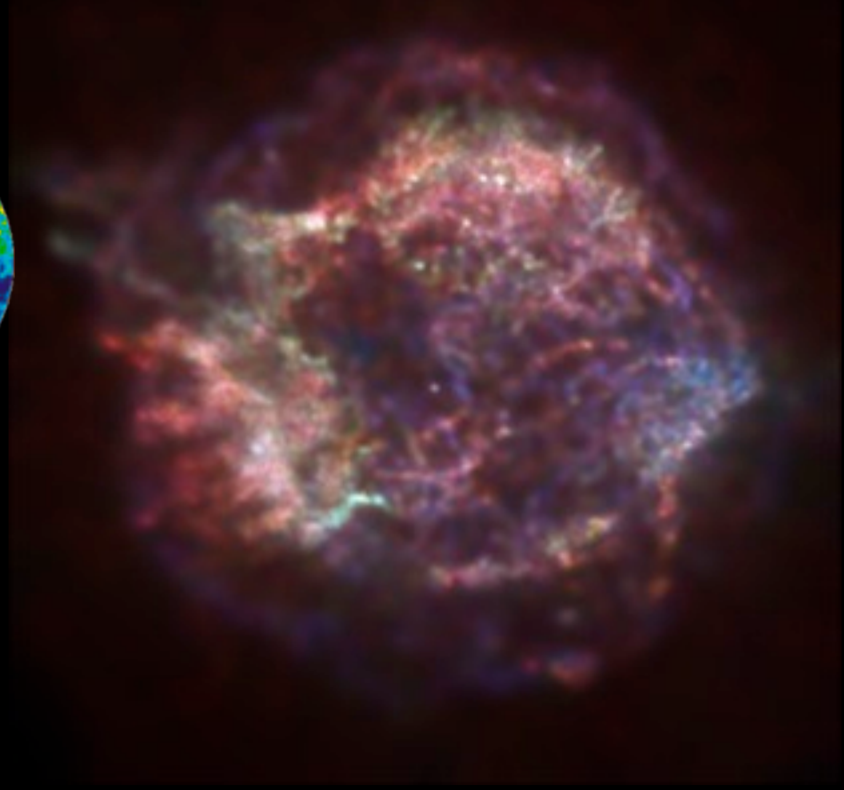
NGC6543 (Harrington & Borkowski /NASA)



WMAP (NASA)

SNR Cassiopeia A (Hughes et al/Chandra/NASA)



Nuclear Astrophysics

Stardust (JPL-Caltech/NASA)

SNO (NSERC)

W. Raphael Hix

ORNL Physics Division and
UTK Department of Physics
& Astronomy

Integral (ESA)

VLT (ESO)

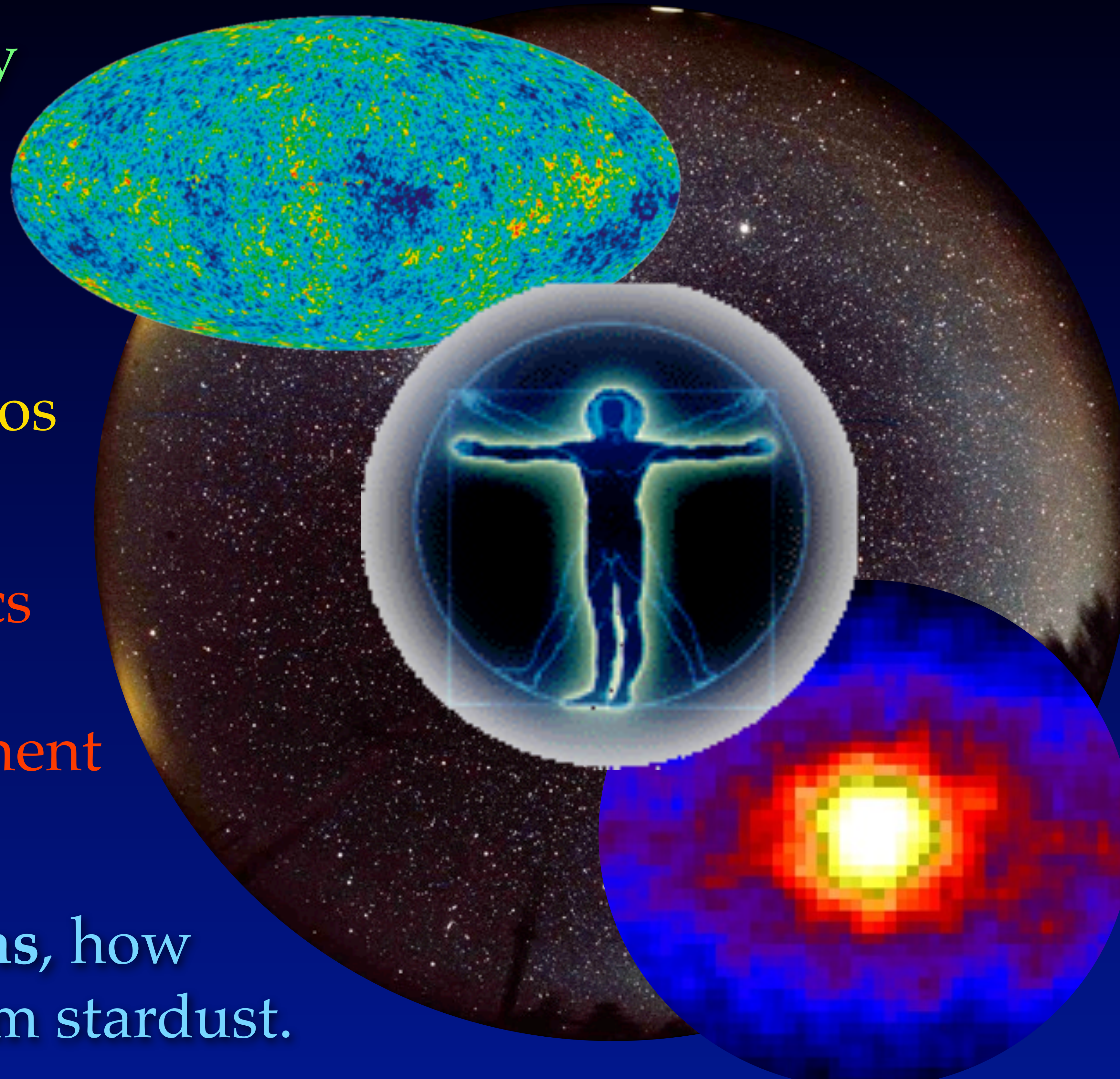
Why Study Astrophysics?

Explore the beauty of the night sky

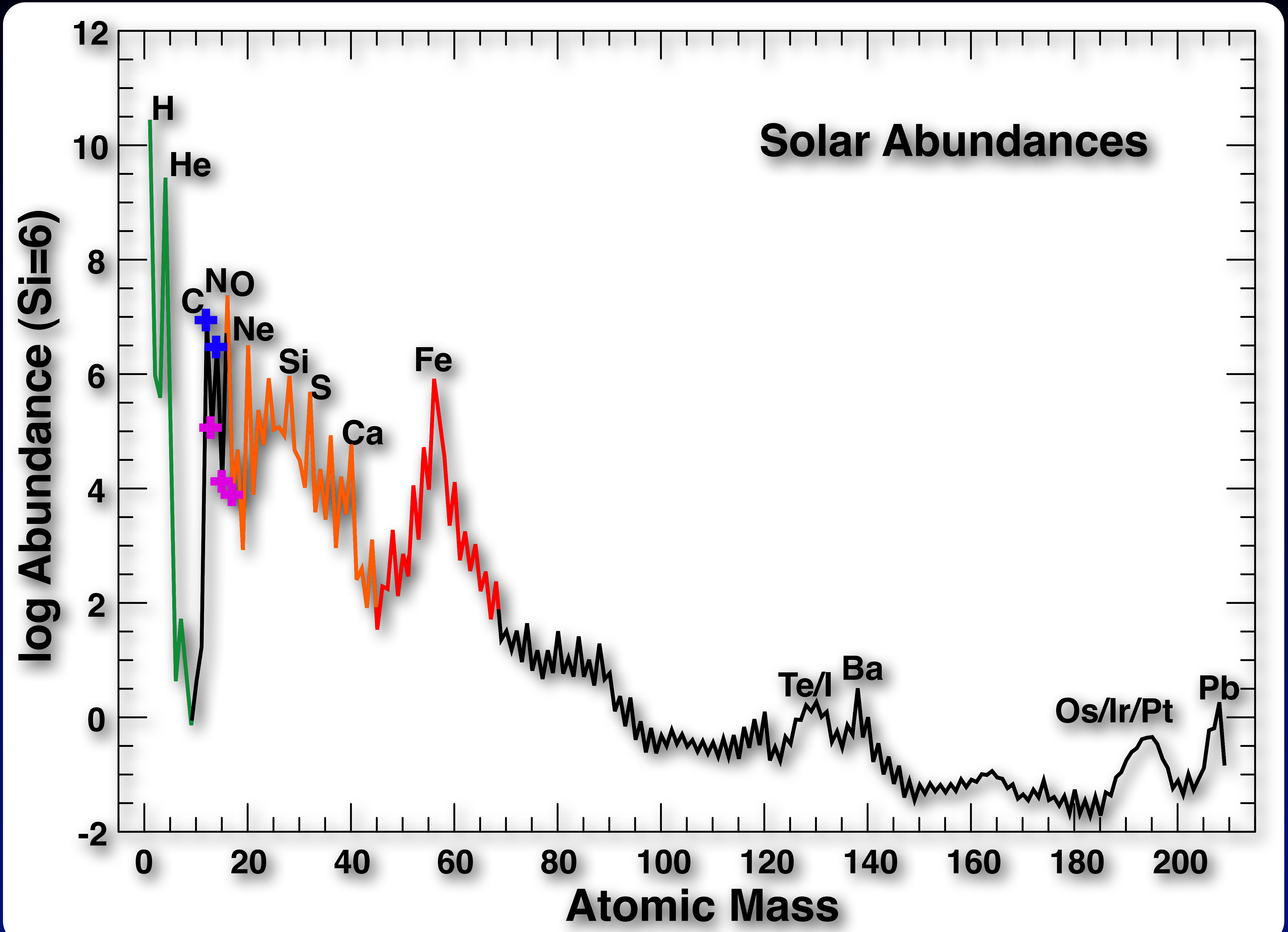
Understand our place in the Cosmos

Investigate physics inaccessible to terrestrial experiment

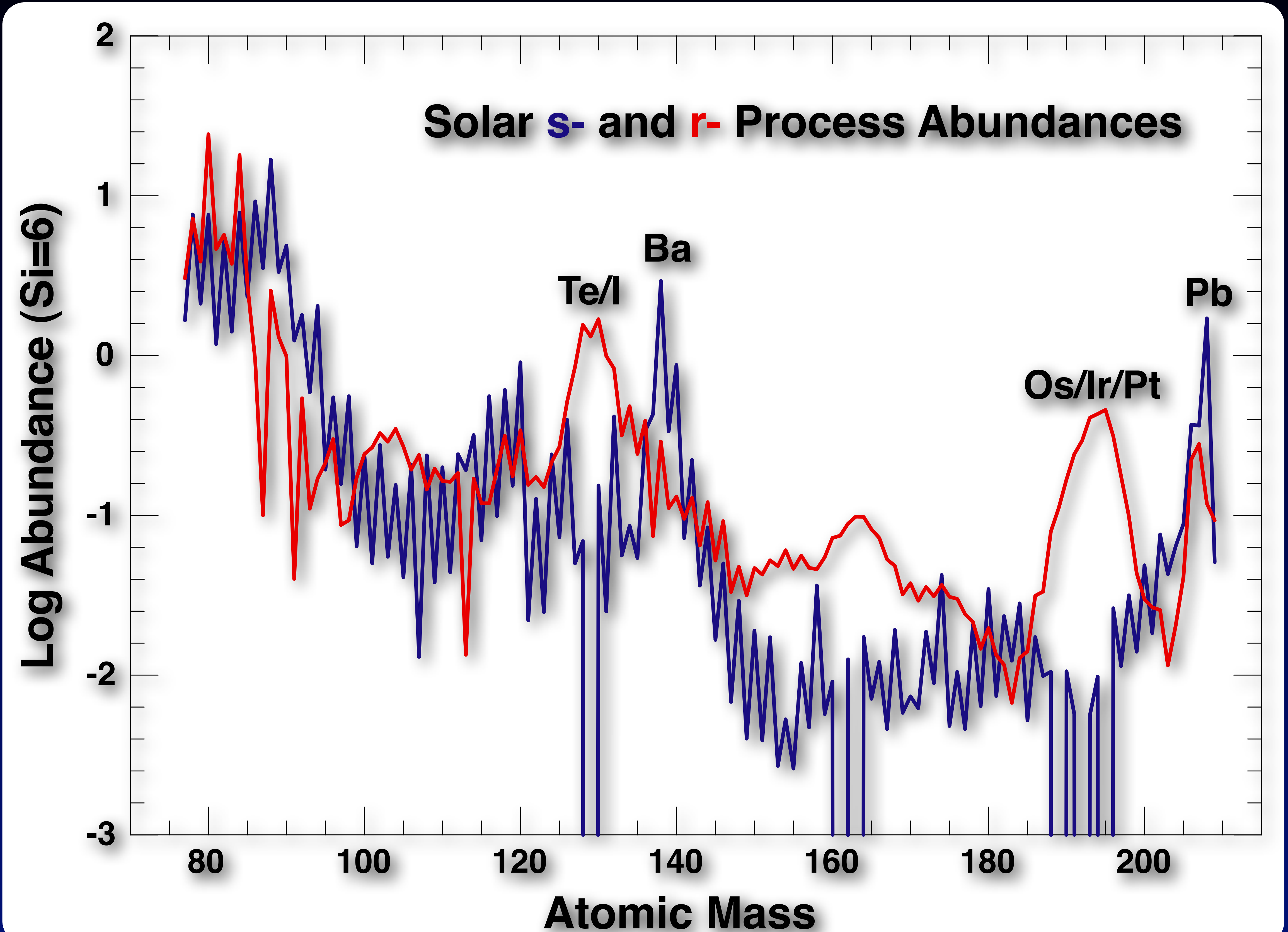
Explain our **origins**, how we came to be from stardust.



Of what are we made?

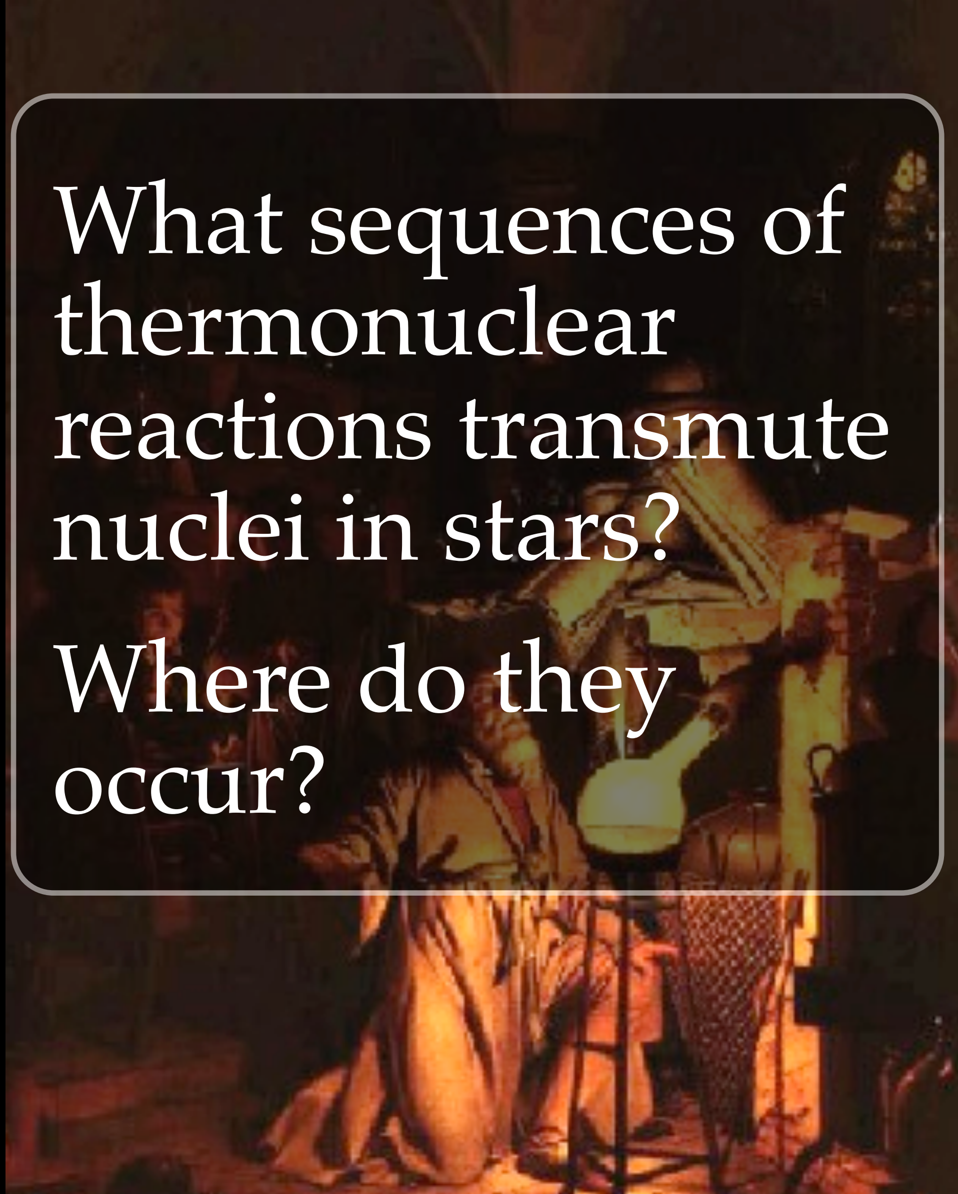


Of what are we made?



Alchemy

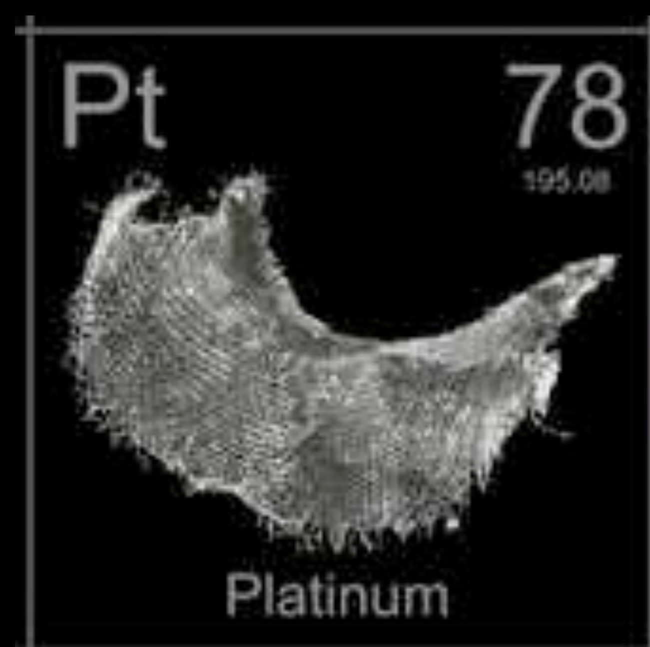
M. Smith



What sequences of thermonuclear reactions transmute nuclei in stars?

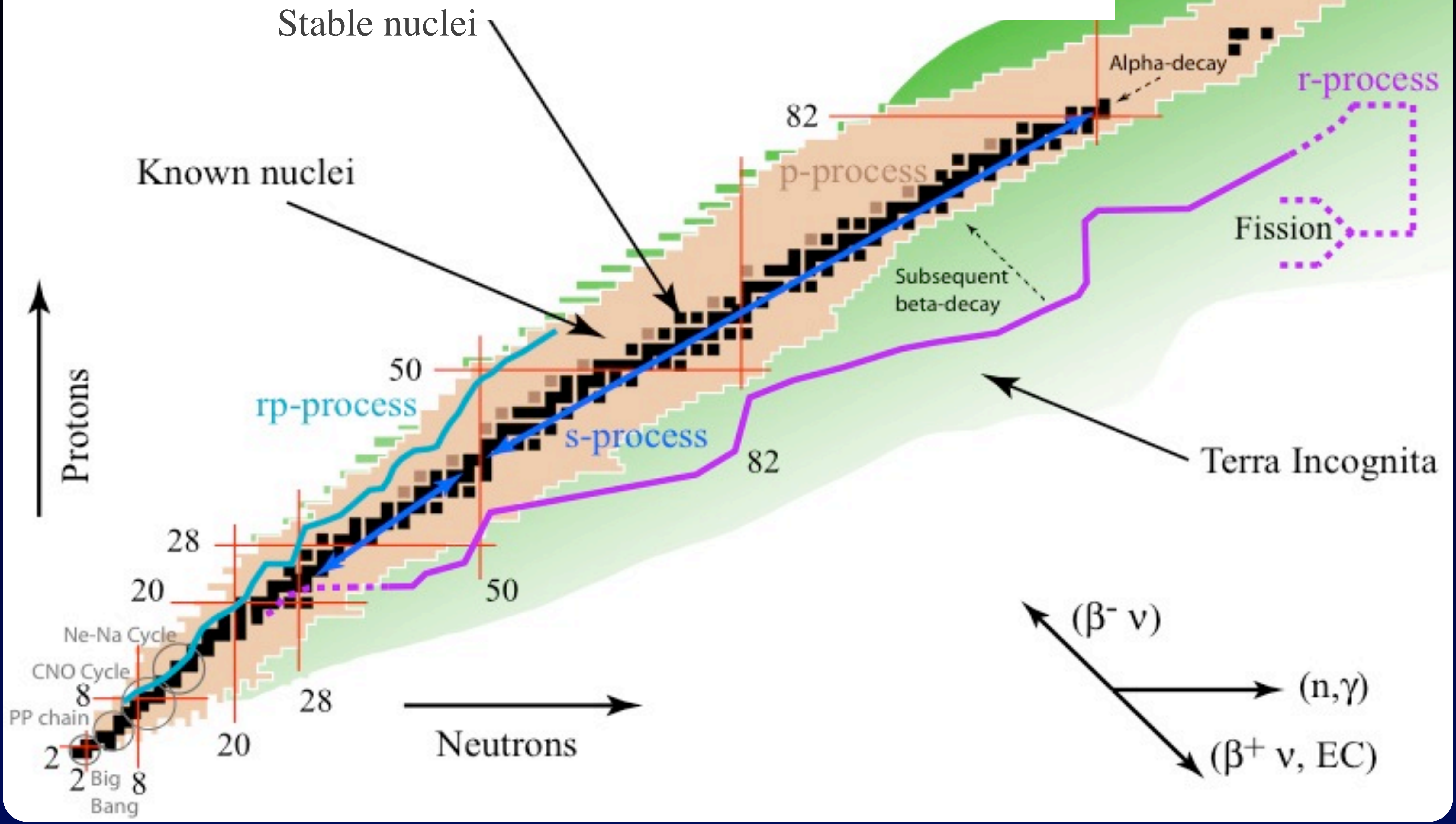
Where do they occur?

Stellar Alchemy



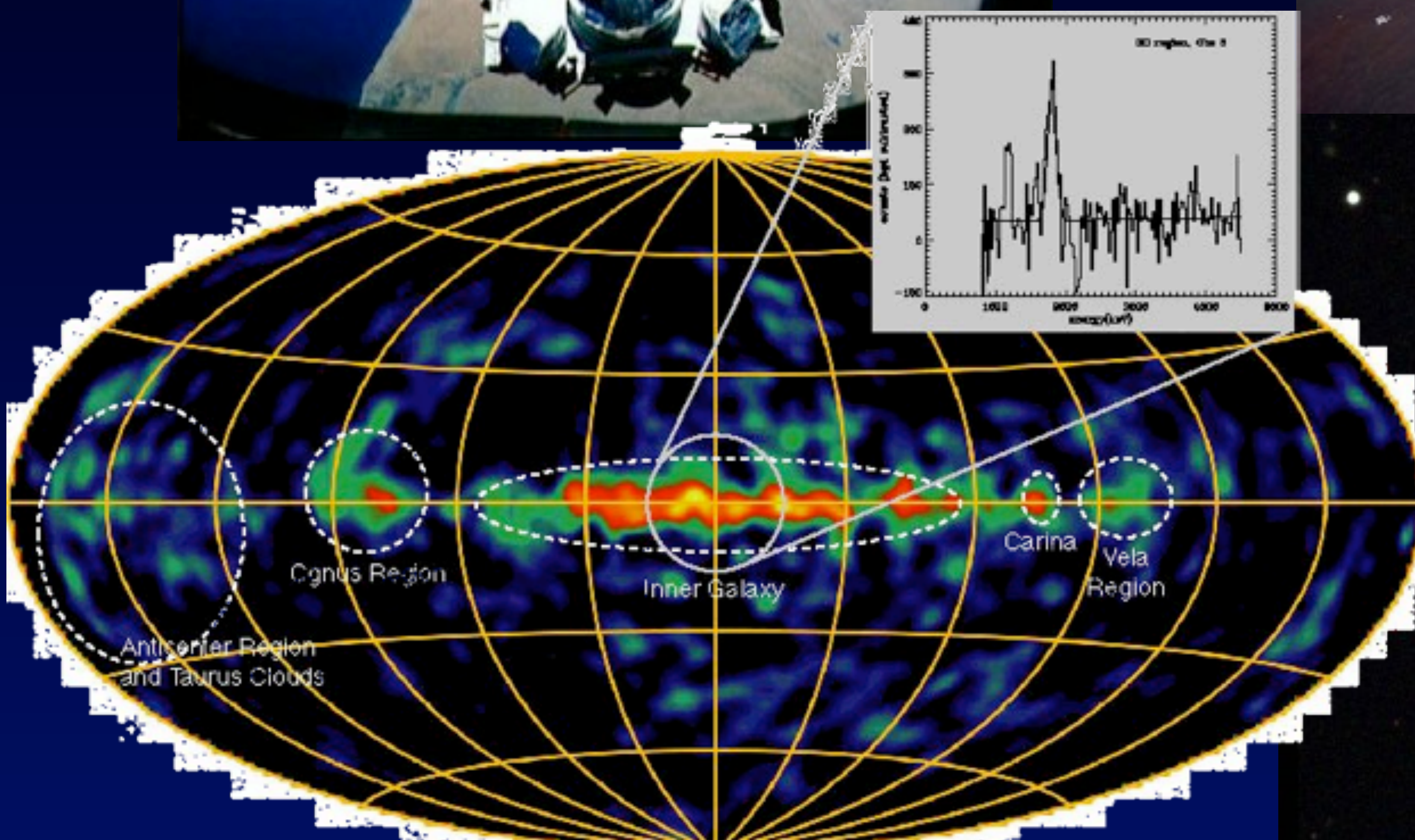
M. Smith

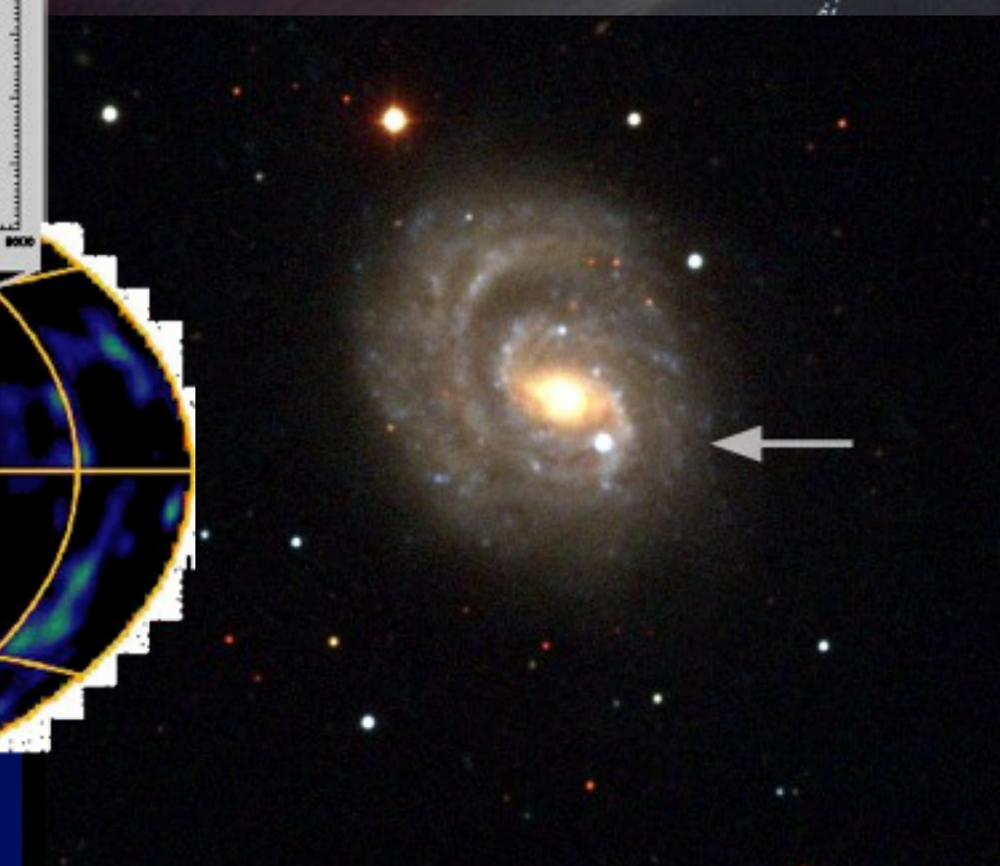
Processes and Sites



Understanding Origins means understanding processes that transmute nuclei and the sites where these processes occur.

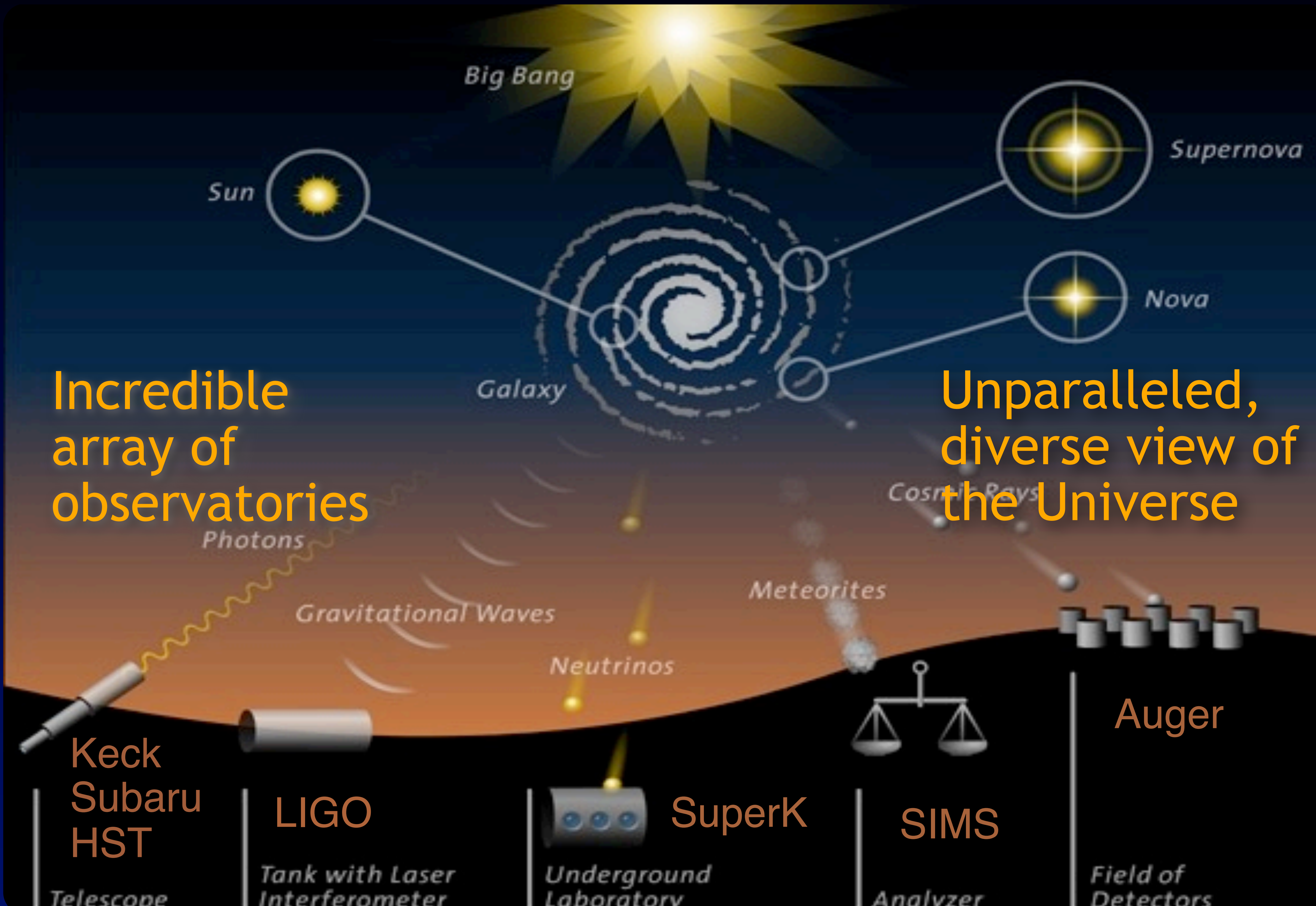
Astrophysical Observations...





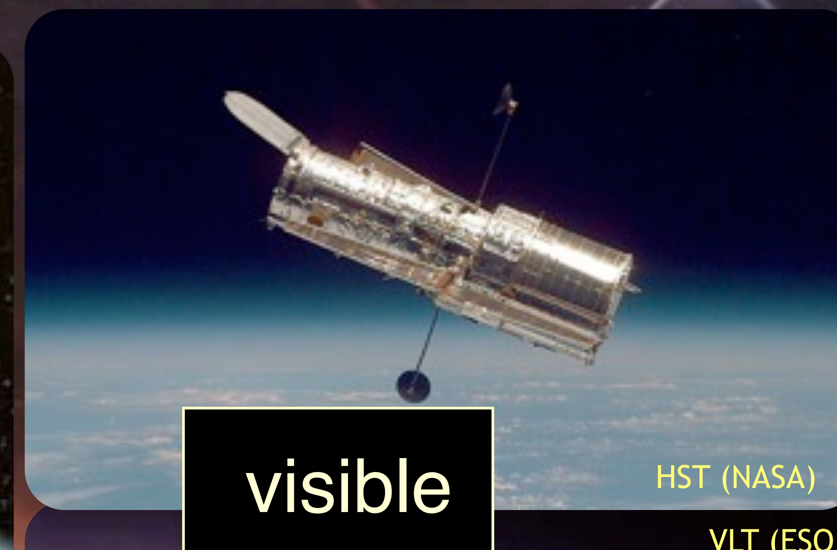
... of Nuclear Evolution

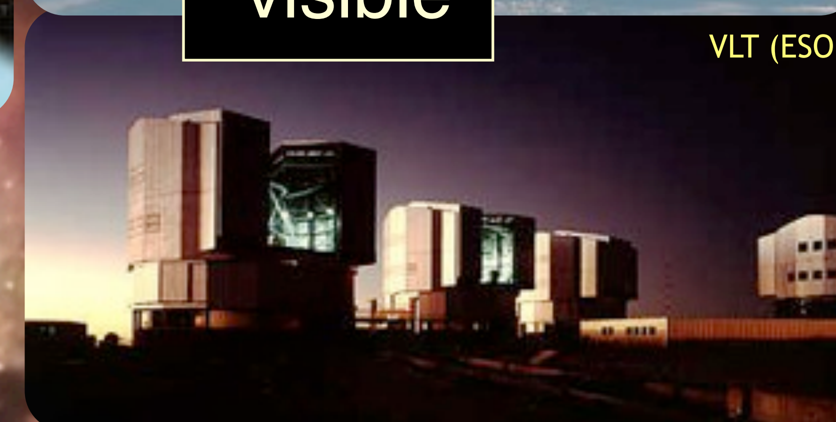
Golden Age of Observation



M. Smith

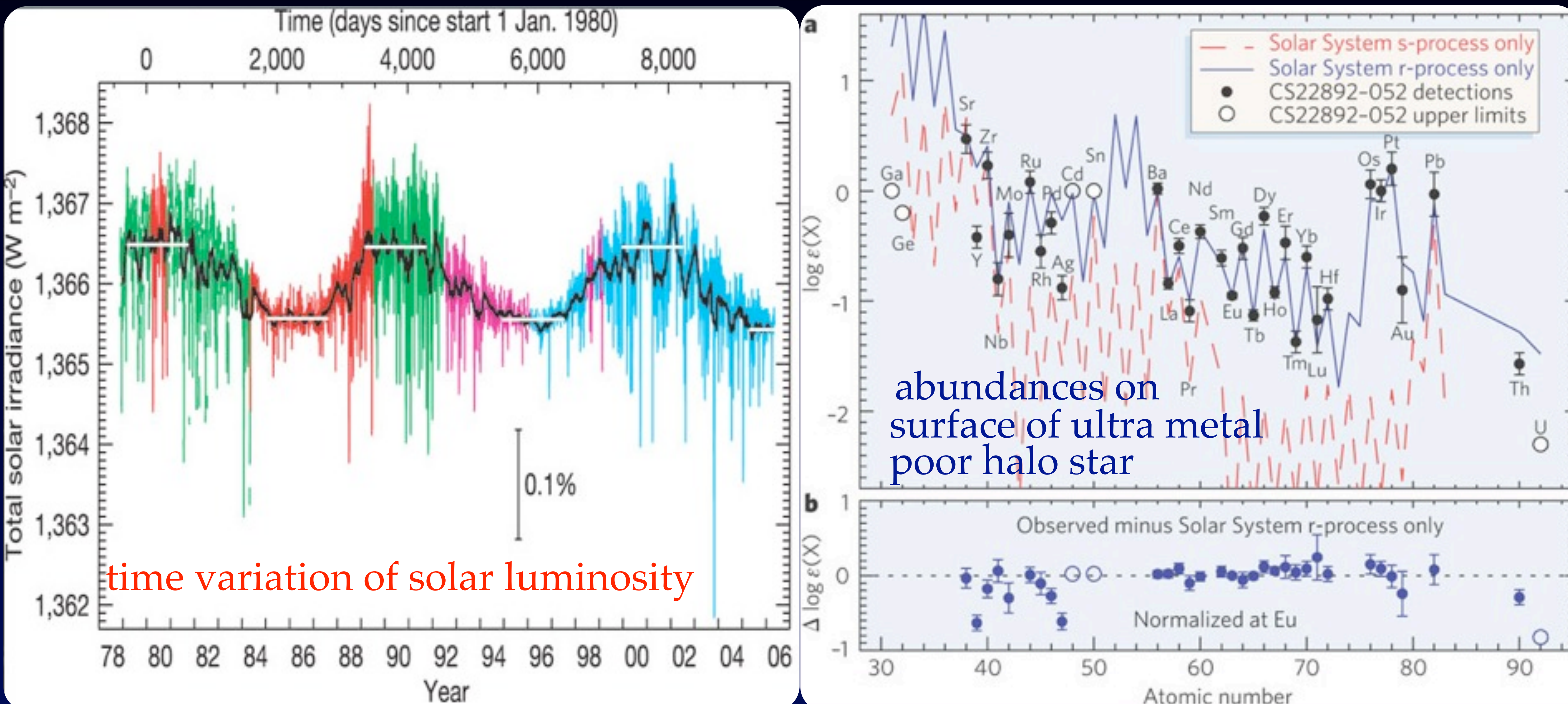
Photons of all sorts!





What do observations tell us?

1) Surface properties of stars

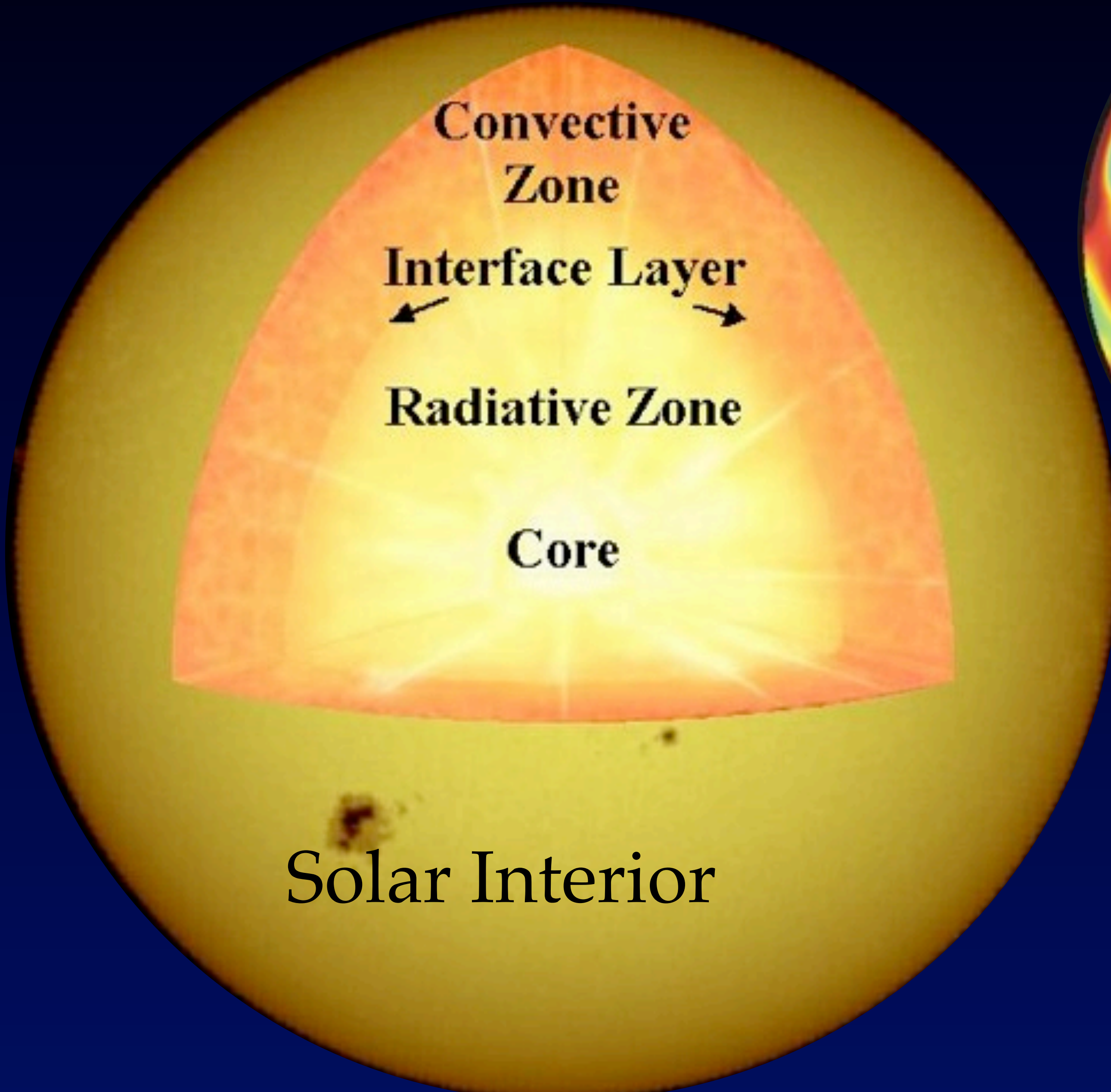


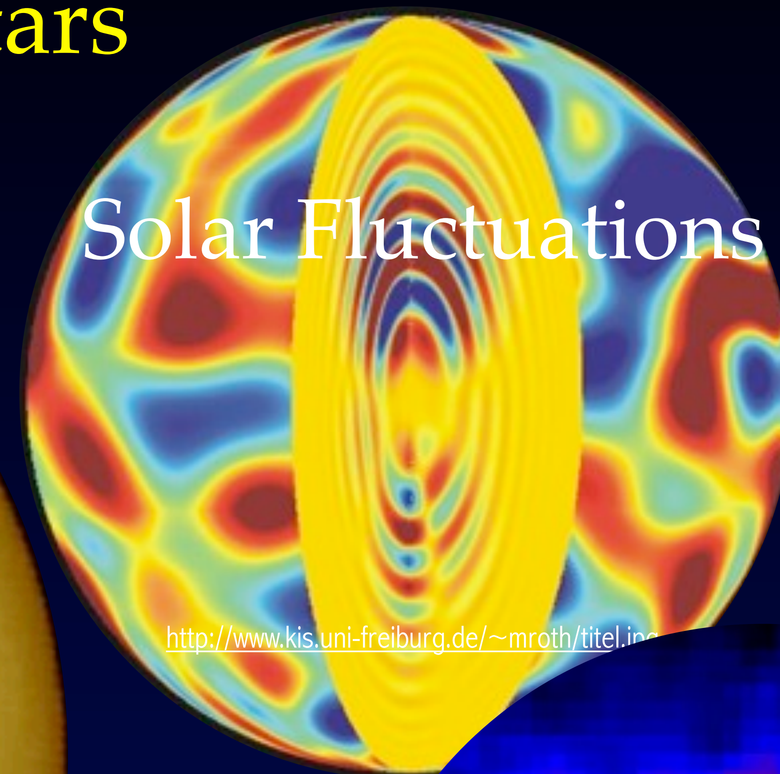
Directly, we measure luminosity and spectra.

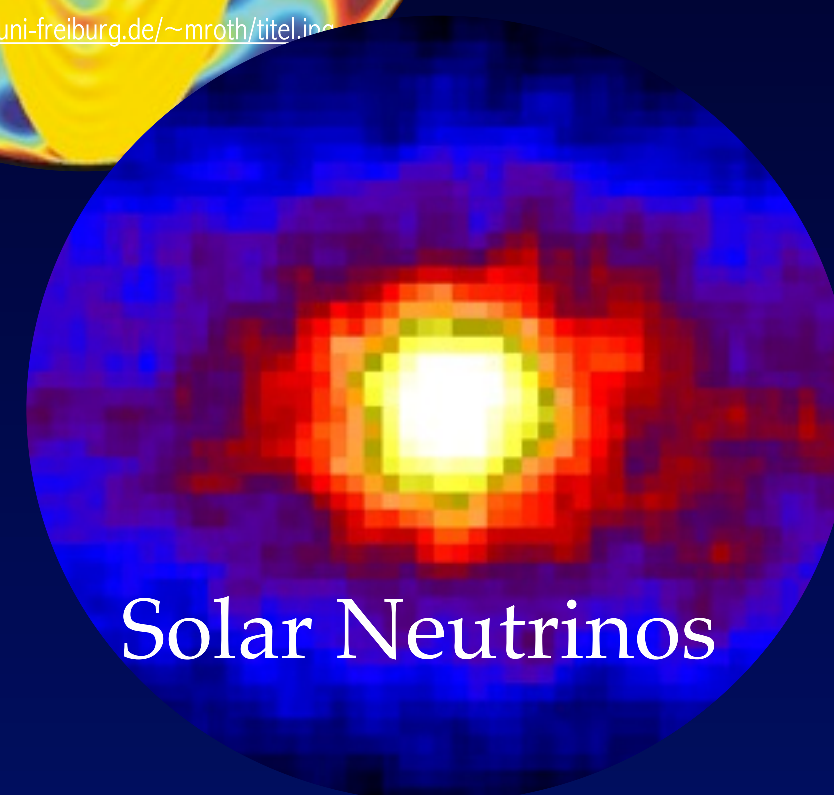
Indirectly, we measure temperature, radius, elemental composition, and their variations.

What do observations tell us?

2) Clues to the interiors of stars





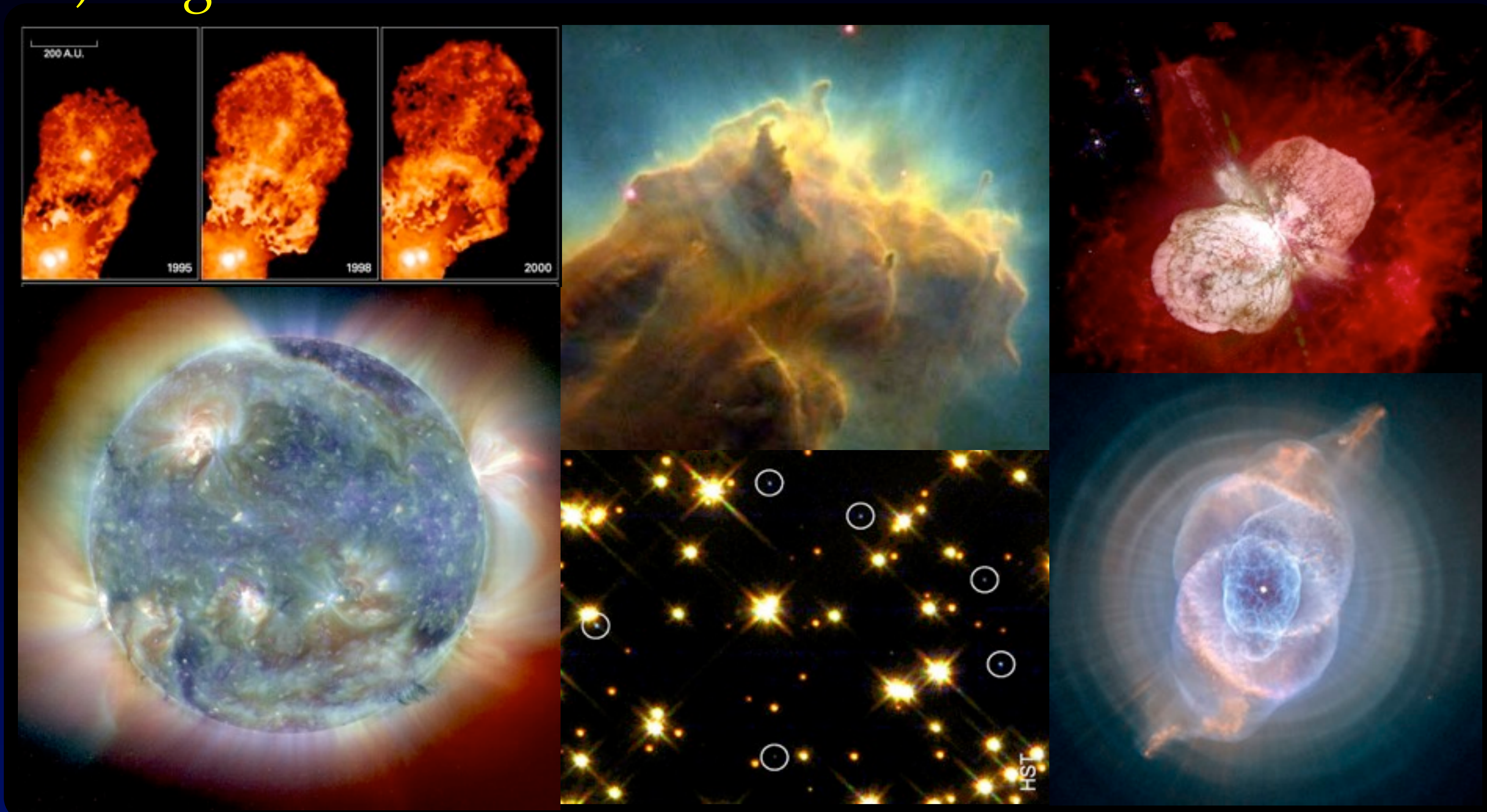


helioseismology - vibrations of solar surface probe interior

neutrinos - emitted in the core & (almost) free stream out

What do observations tell us?

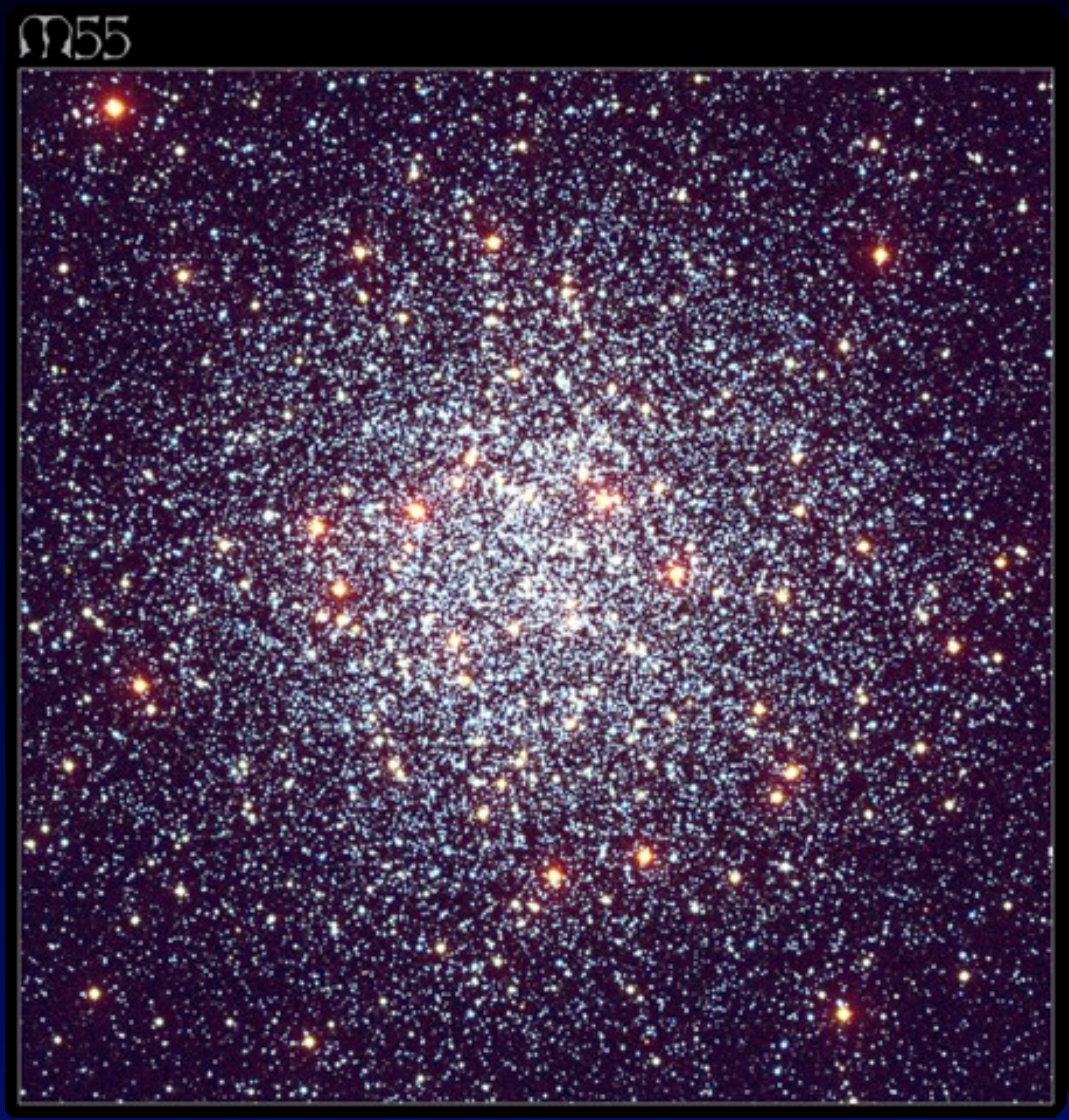
3) Stages of stars lives

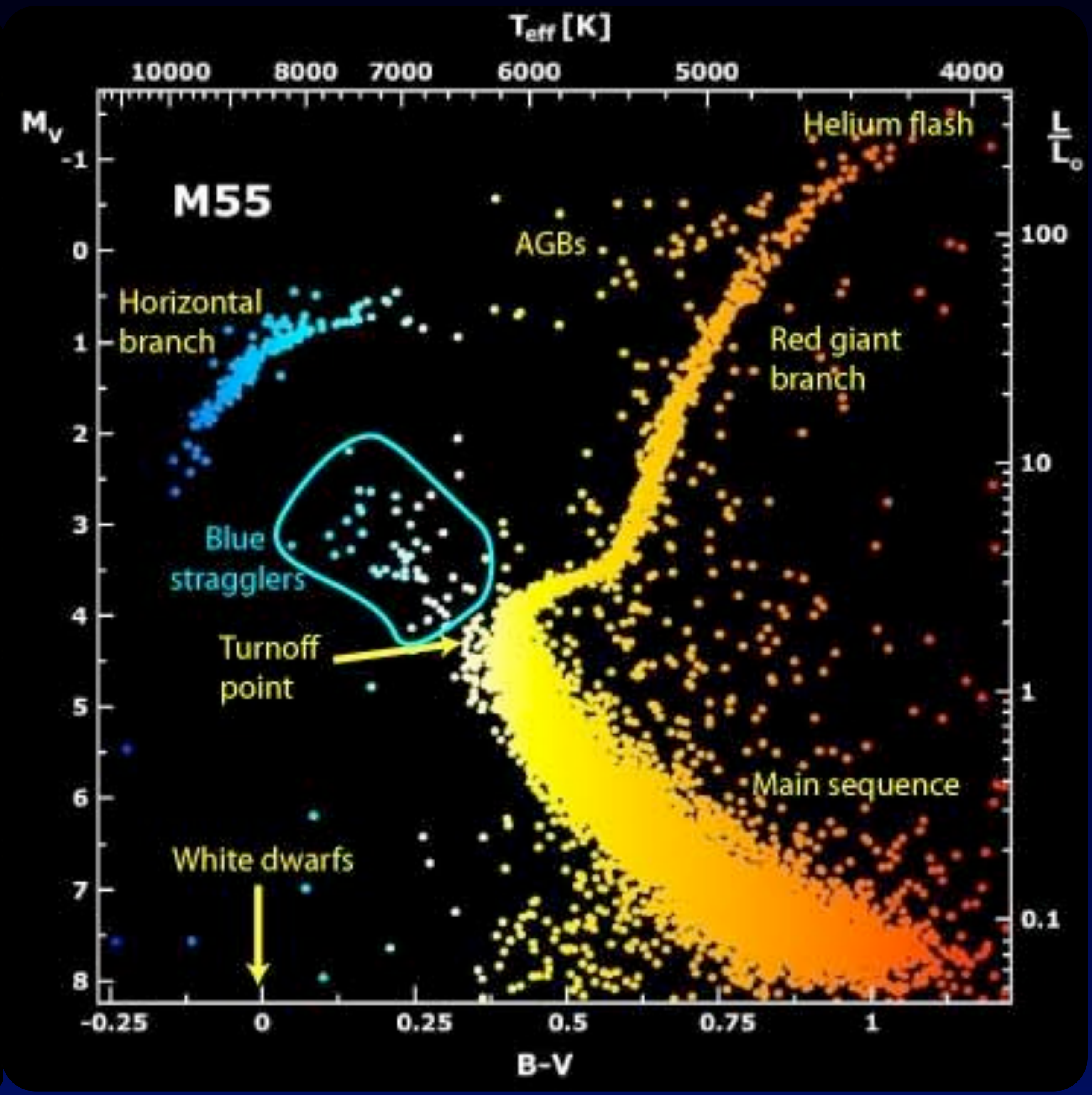


Birth from clouds of gas and dust, normal burning, death in explosions or by fading out…

What do observations tell us?

4) Lifecycle of stars

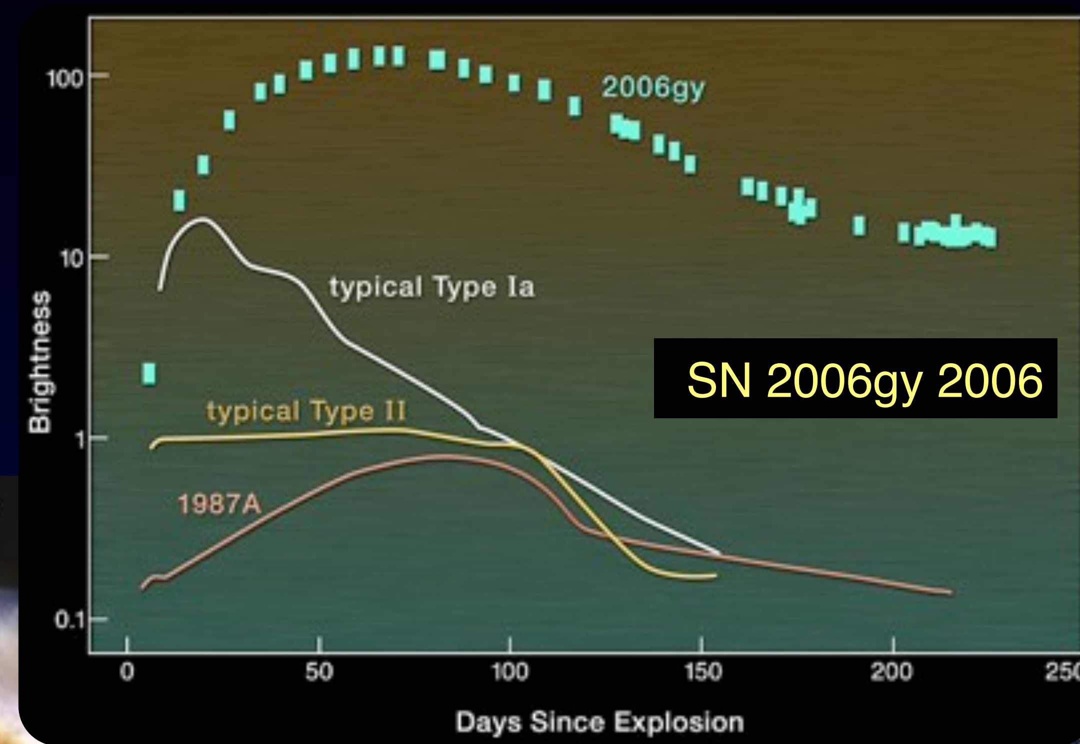


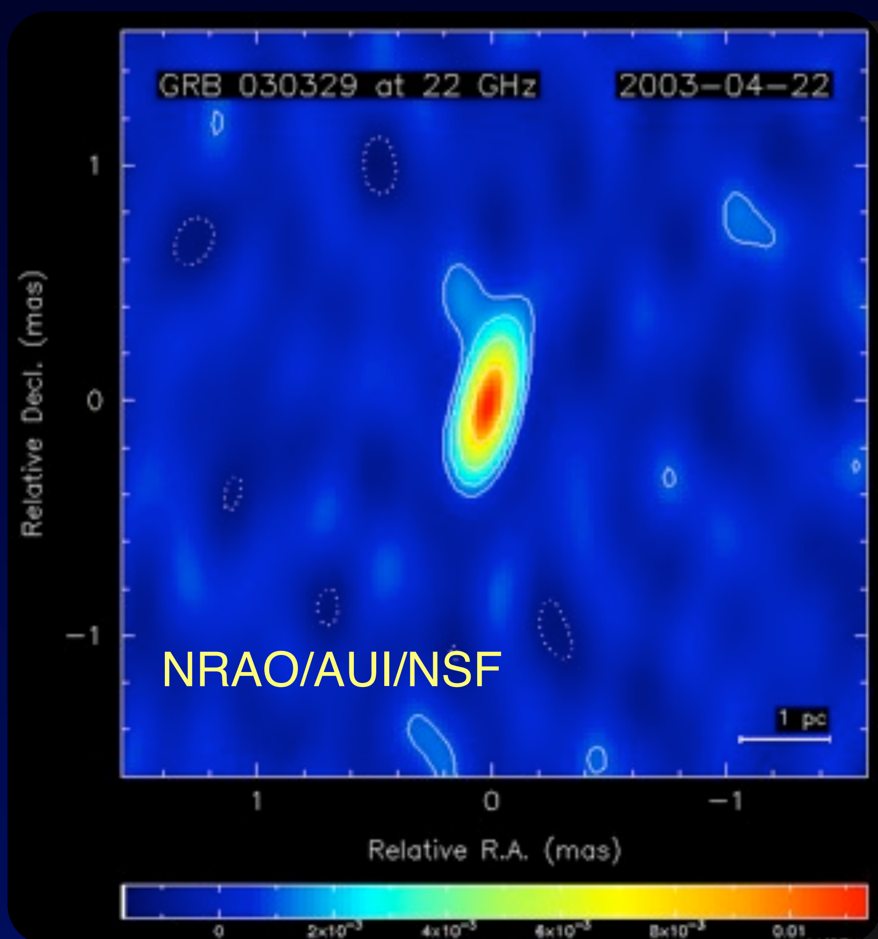


The census of these many stages reveals the stellar lifecycle.

What do observations tell us?

5) New surprises and unexpected connections





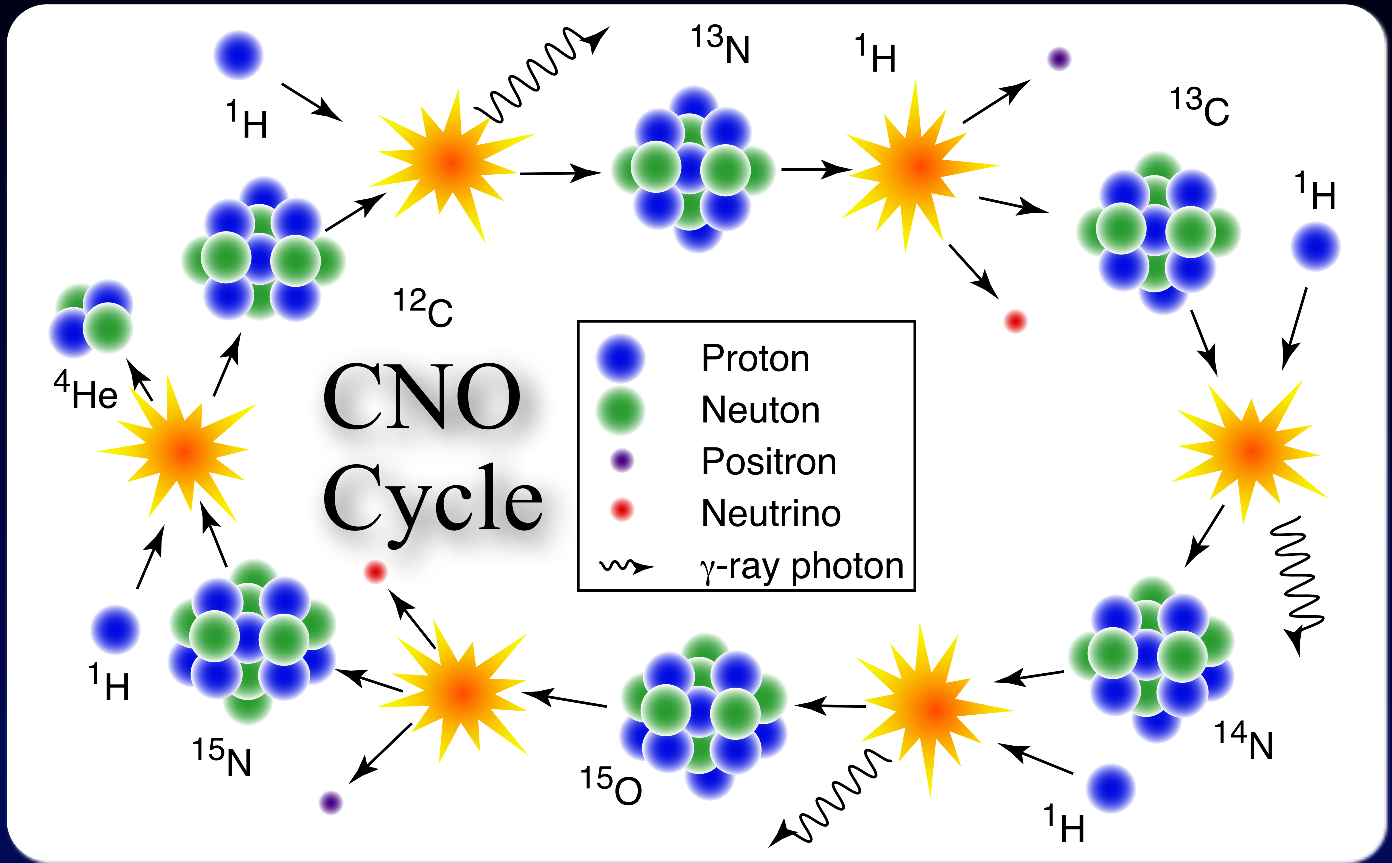
Hypernovae, GRB - supernova - collapsar connection, dwarf-classical nova connection

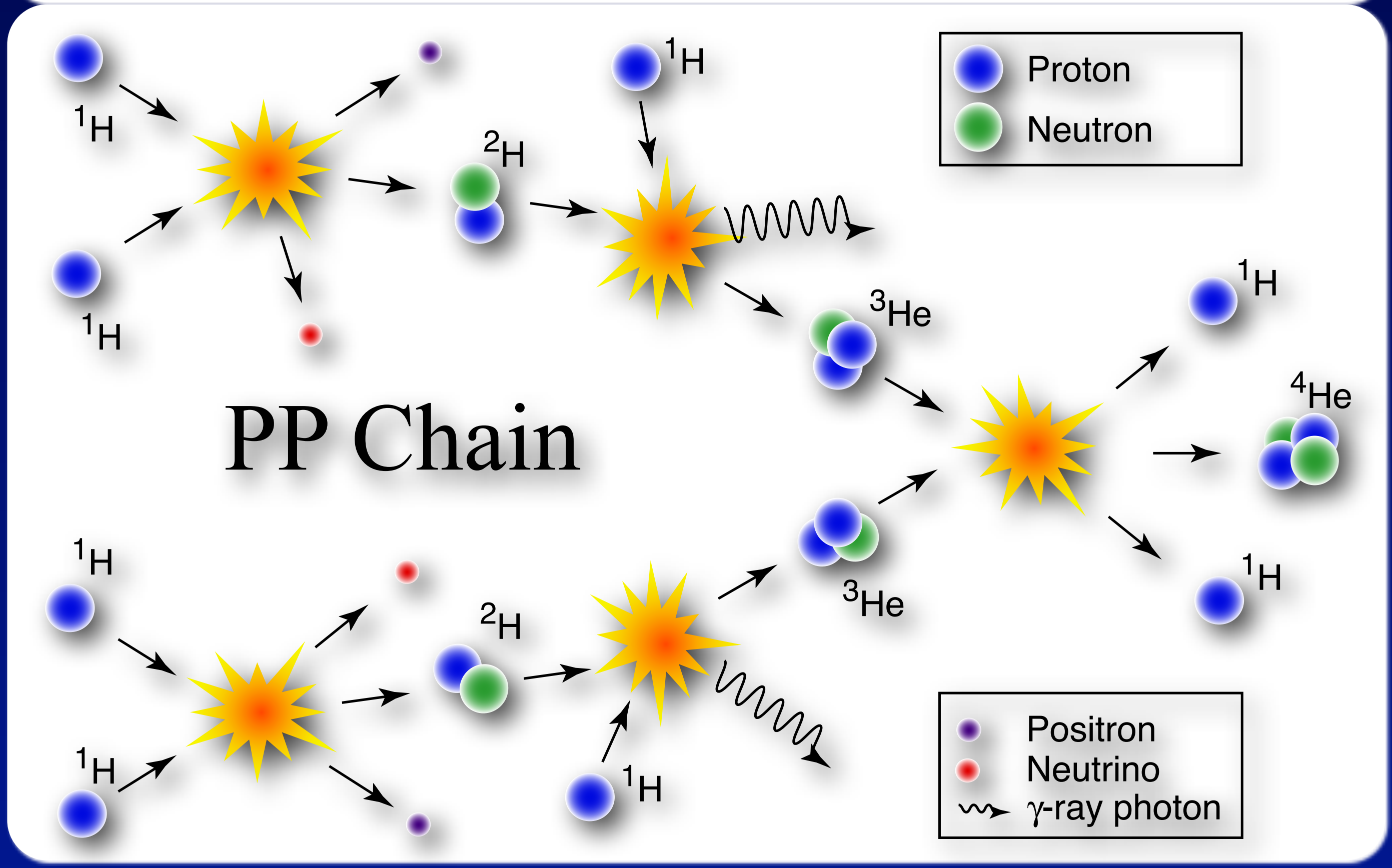
Conversion of H to He

Two sequences of nuclear reactions were proposed for stellar energy generation.

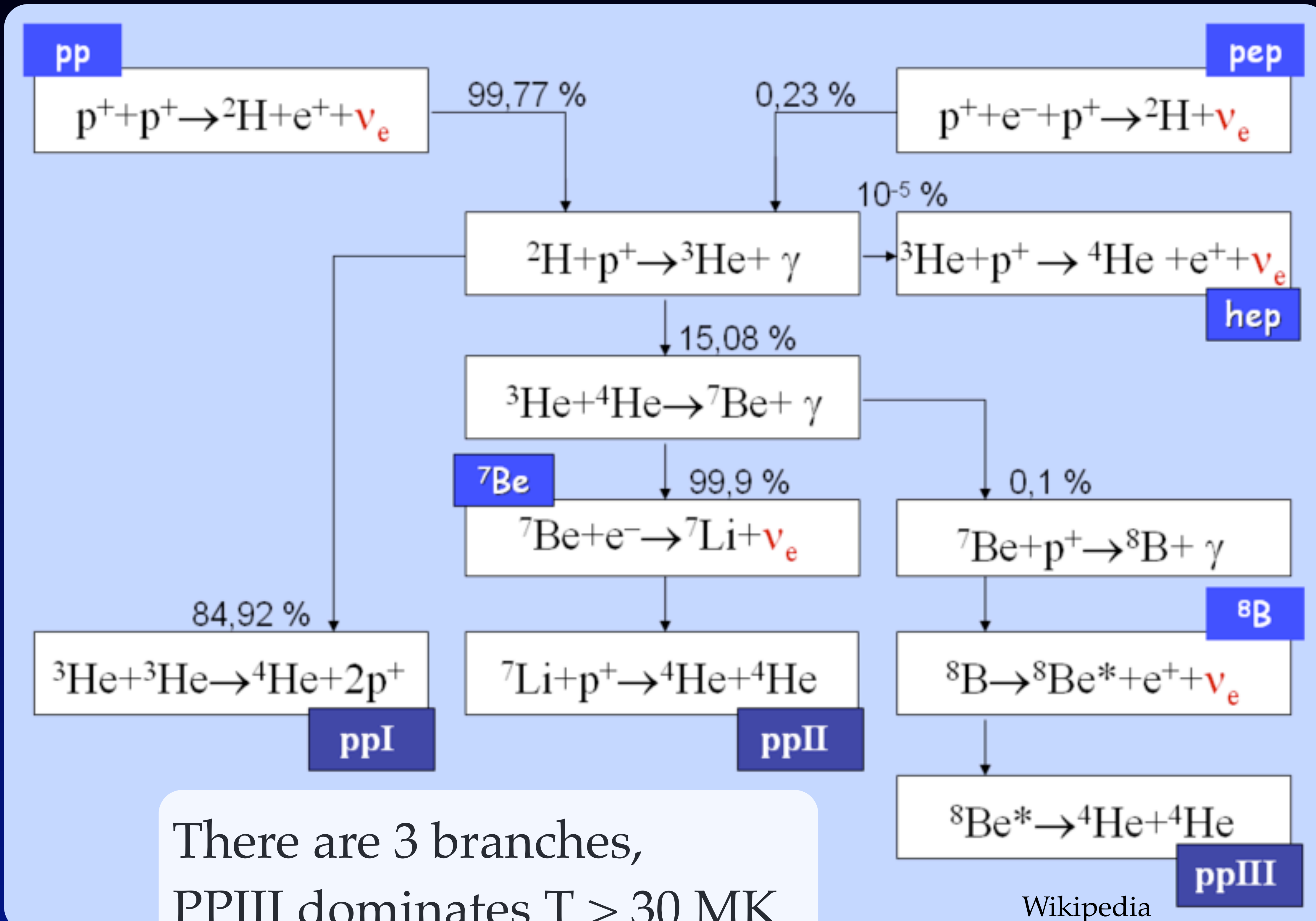
The CNO cycle, proposed by Weizacker (1938) and Bethe (1939), involves catalytic reactions on pre-existing C, N and O atoms.

The PP Chain, proposed by Bethe (1939), involves direct reactions, starting with $^{1}H + ^{1}H \rightarrow ^{2}H$.





PP CHAINS



Wikipedia

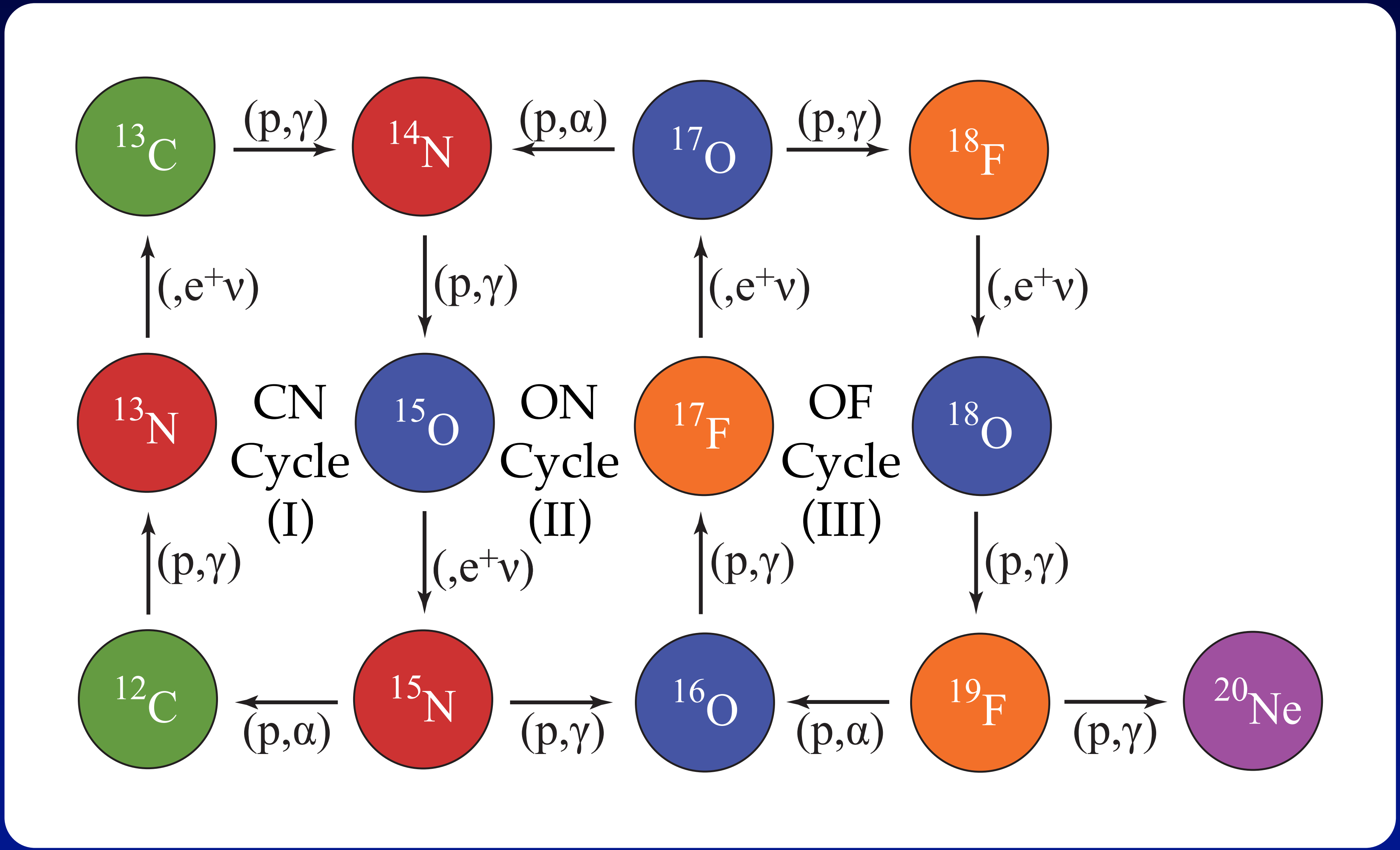
There are 3 branches,
PPIII dominates T > 30 MK
PPI for T < 15 MK.

CNO Cycles

CNO cycle burning occurs through multiple interconnected cycles. All are catalytic cycles: reaction sequence starts from a pre-existing "seed" nucleus, consumes 4 protons ("fuel"), creates helium ("ash") & regenerates seed.

As temperatures increase, additional reaction cycles can contribute.

For temperatures found in stellar cores, proton capture reaction timescales are much longer than β^+ decays.



CNO or PP?

Both the CNO cycle and the PP chain are operative in the Sun, so how do we know the PP chain dominates?

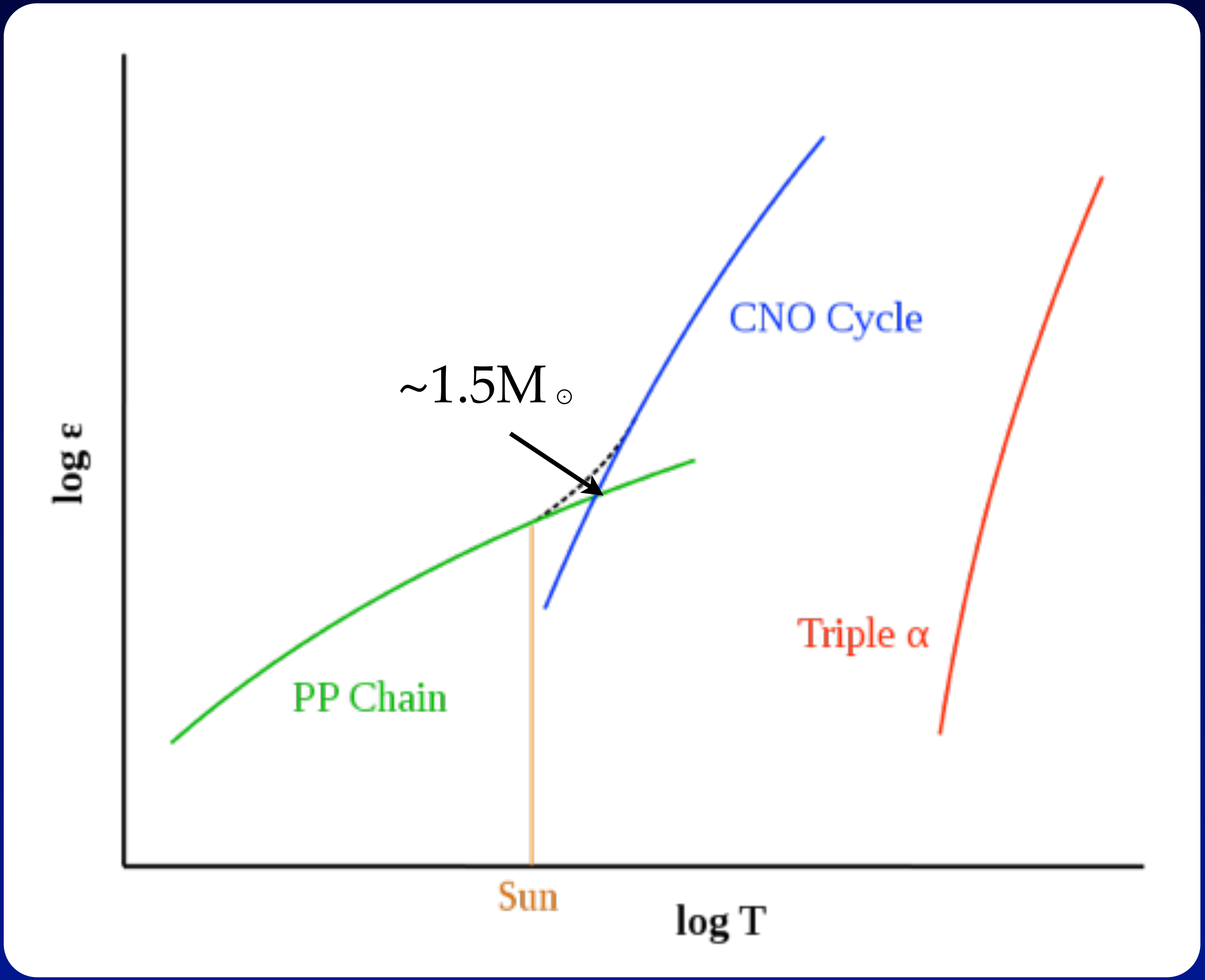
Each reaction sequence has a different sensitivity to temperature and density, thus their energy production, ε, also varies.

$$\varepsilon(\rho, T)_{\mathrm{PP}} \propto \rho T^4$$

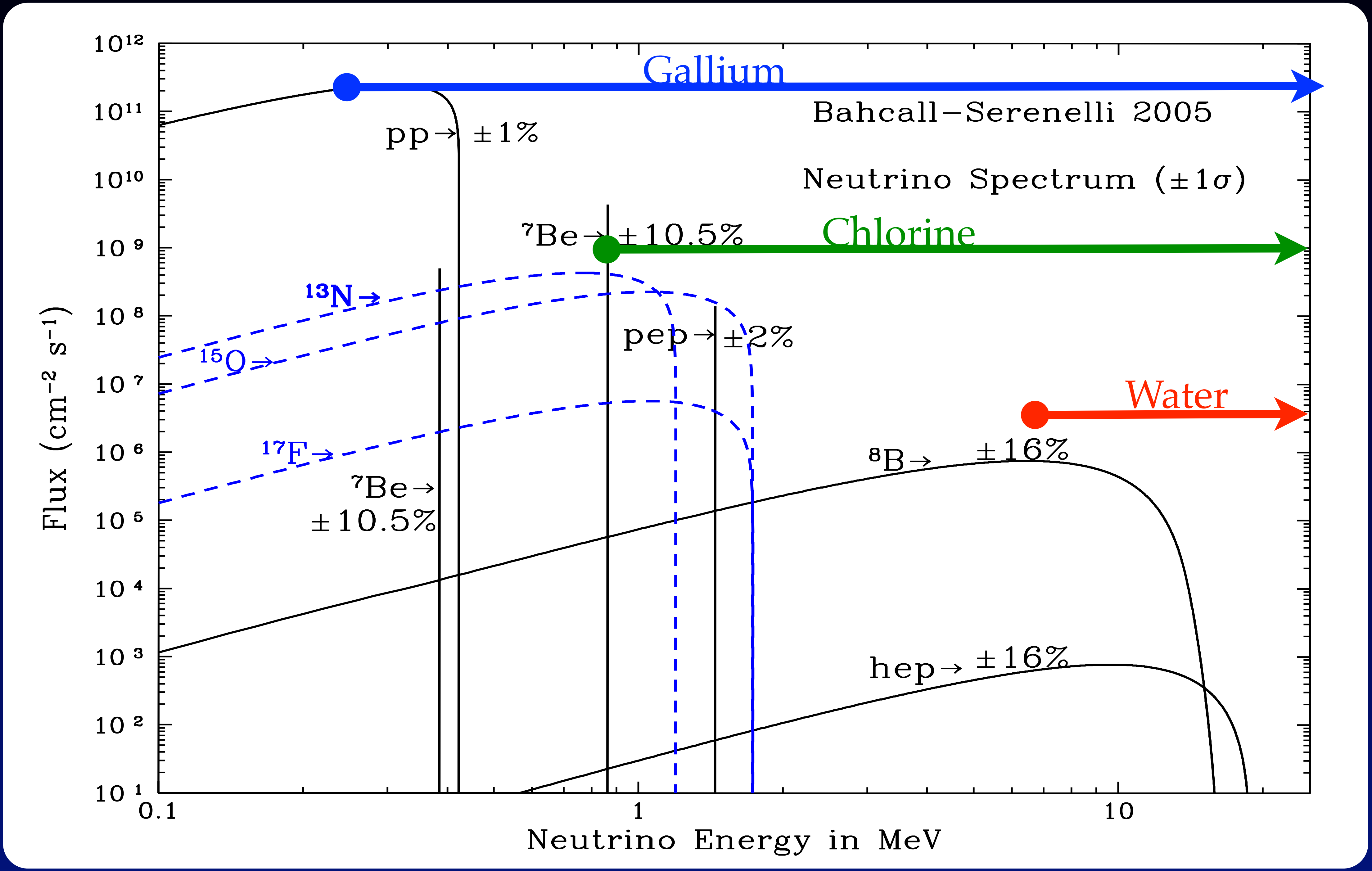
$$\varepsilon(\rho, T)_{\mathrm{CNO}} \propto \rho T^{20}$$

$$\varepsilon(\rho, T)_{3\alpha} \propto \rho^2 T^{30}$$

For the Sun, PP chain dominates but for more massive stars, with higher T_c, CNO dominates.



Solar Neutrinos



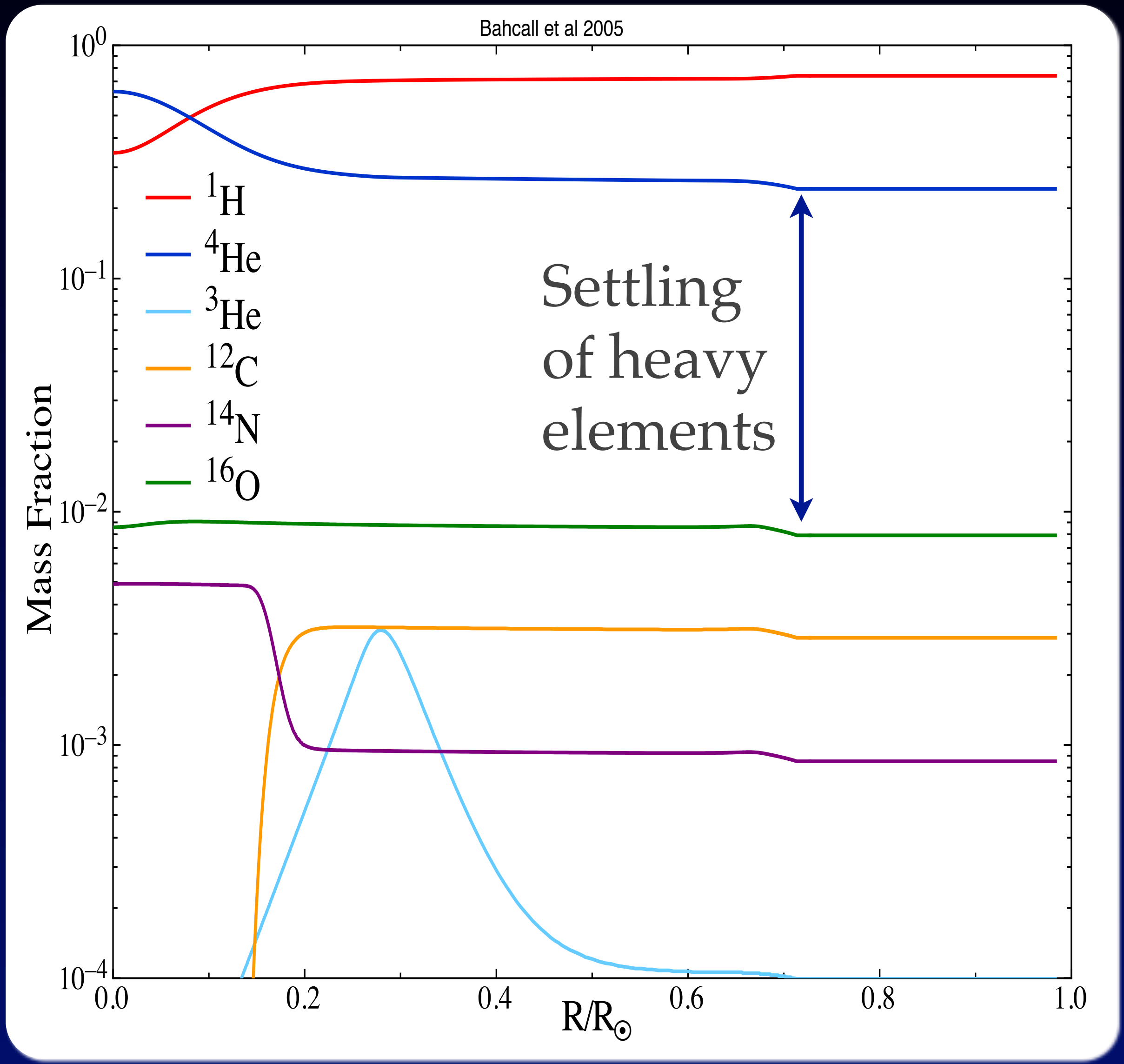
Both PP and CNO neutrinos contribute to Solar Neutrino Flux.

Stellar Nuclear Physics

Nuclear Reactions

generate energy

change number density of nuclear species in the star



Rate of energy generation and compositional change depends on

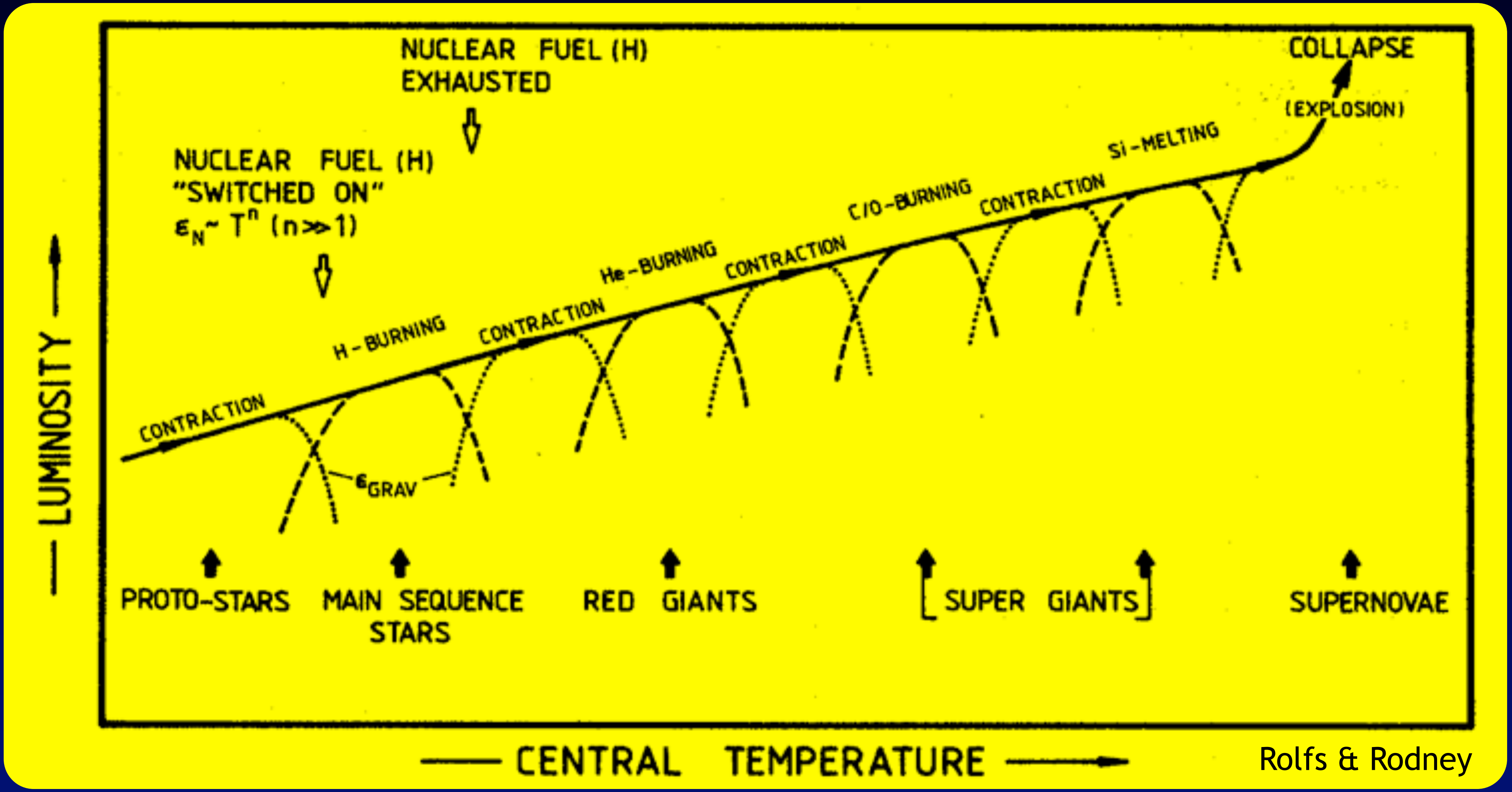
rate of their interactions

number density of nuclear species

Determination of reaction rates absolutely necessary to understand how nuclear physics influences energy generation & element production in stars.

Stellar Stages & Nuclear fuel

Eventually the sun will exhaust it's H fuel (leaving He).

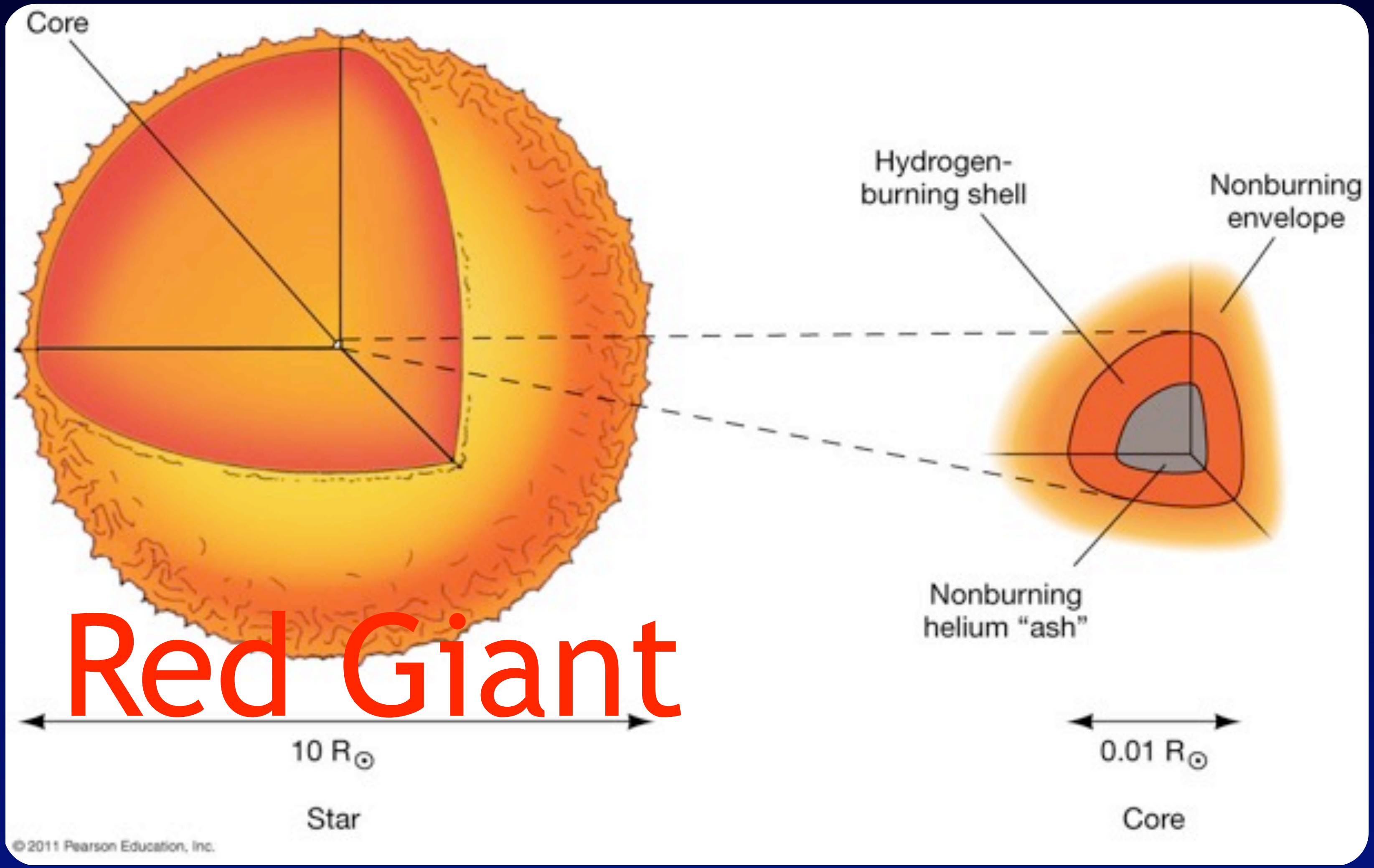


Without nuclear energy to balance, gravitational contraction resumes.

Core temperature rises as it contracts until He becomes a "fuel" for new thermonuclear burning.

Edge Effects

Contraction of the core raises the temperature and density of the H-rich matters lying above it, leading to the ignition of a H burning "Shell" around the core.



Rate of burning in the shell is governed by the gravitational gradient of the core, not the shell's own hydrostatic evolution, resulting in a tremendous increase in luminosity.

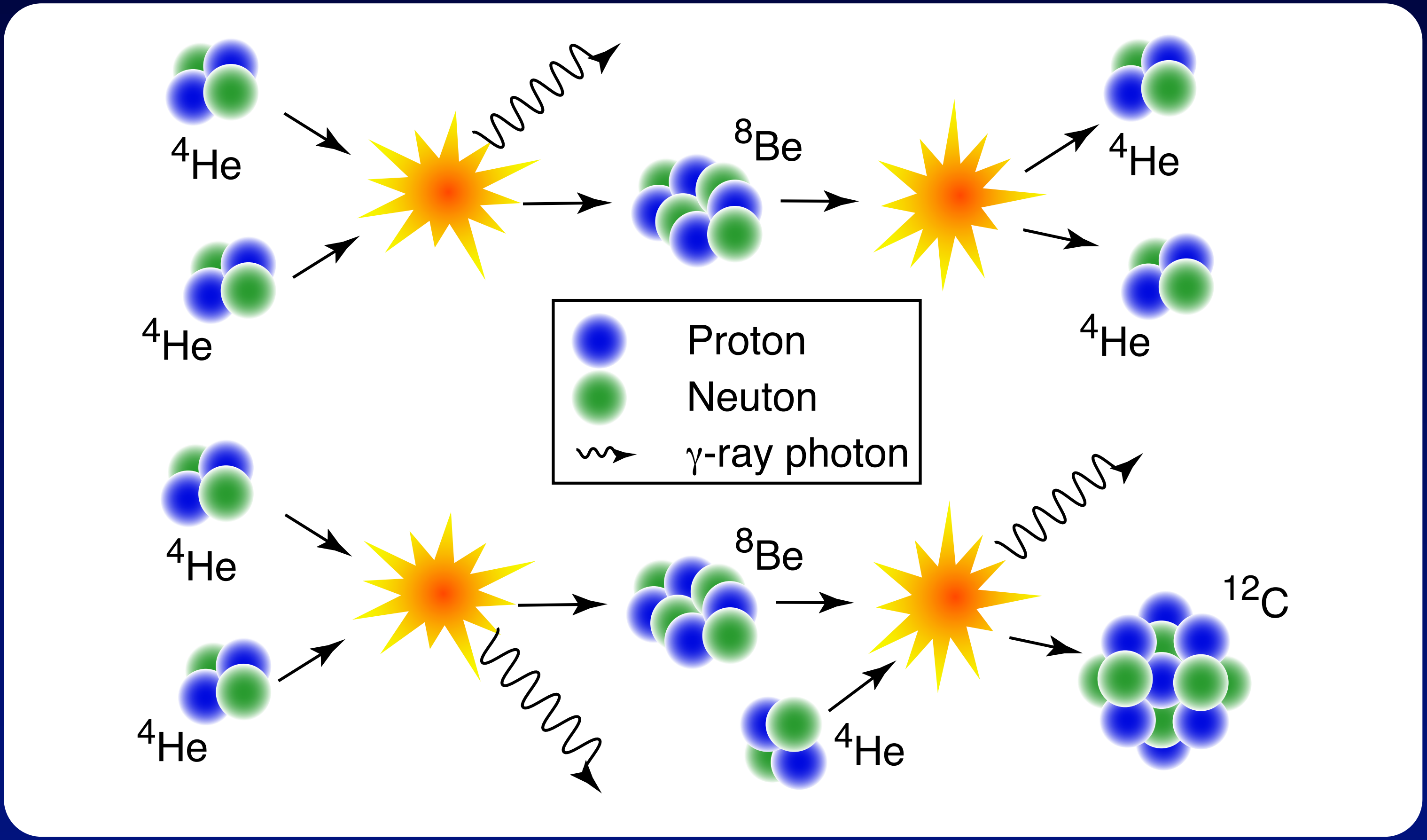
This causes the envelope to expand. The expanded envelope grows cooler, turning the star red.

Triple Alpha

Once the hydrogen is exhausted in the heart of a star, the next central burning stage is helium burning via the triple alpha reaction.

Overcoming the larger Coulomb potential requires much higher temperatures.

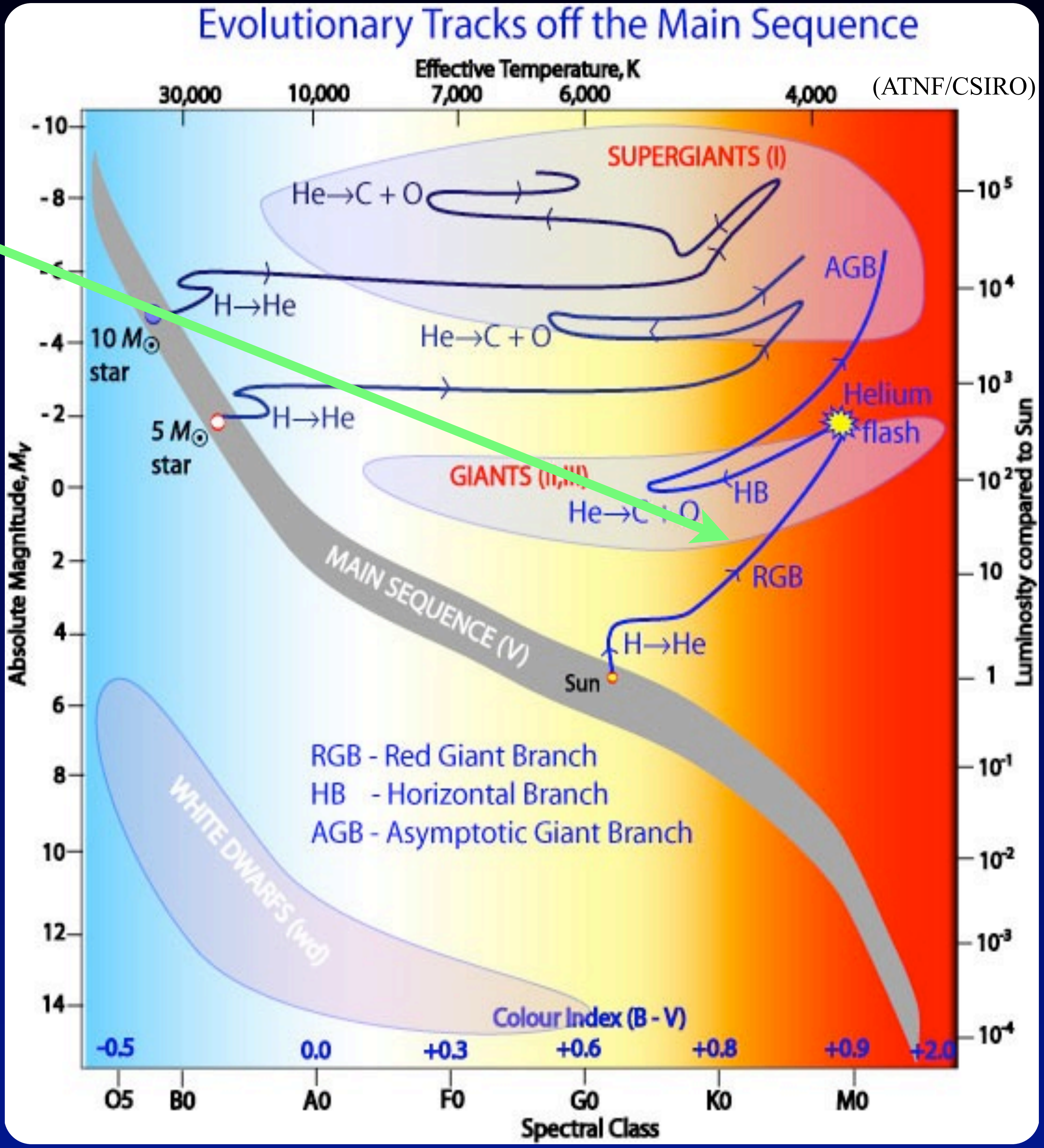
Furthermore, ^{8}Be is unstable, with a lifetime of 2.6×10^{-16} seconds, so only rarely does a third ^{4}He nucleus collide with the ^{8}Be to form ^{12}C before the ^{8}Be nucleus decays back to 2 ^{4}He.



As a result the rate of $3\alpha \propto \rho^2 T^{30}$.

Stellar Stages

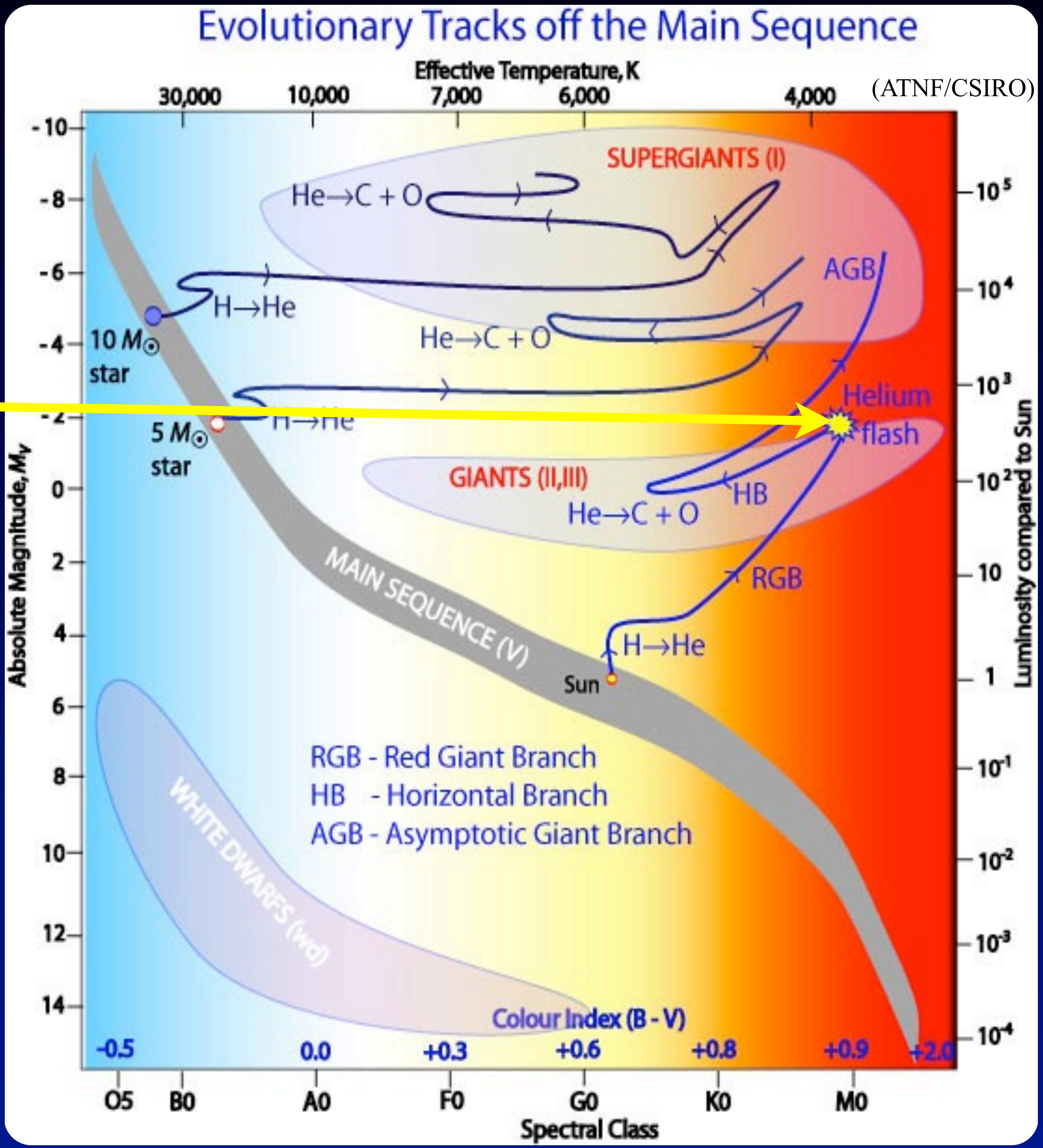
When H is exhausted in core, hydrogen burning ignites in shell around the core.



Stellar Stages

When H is exhausted in core, hydrogen burning ignites in shell around the core.

Once hot enough, He burning begins in the core, until He is exhausted.

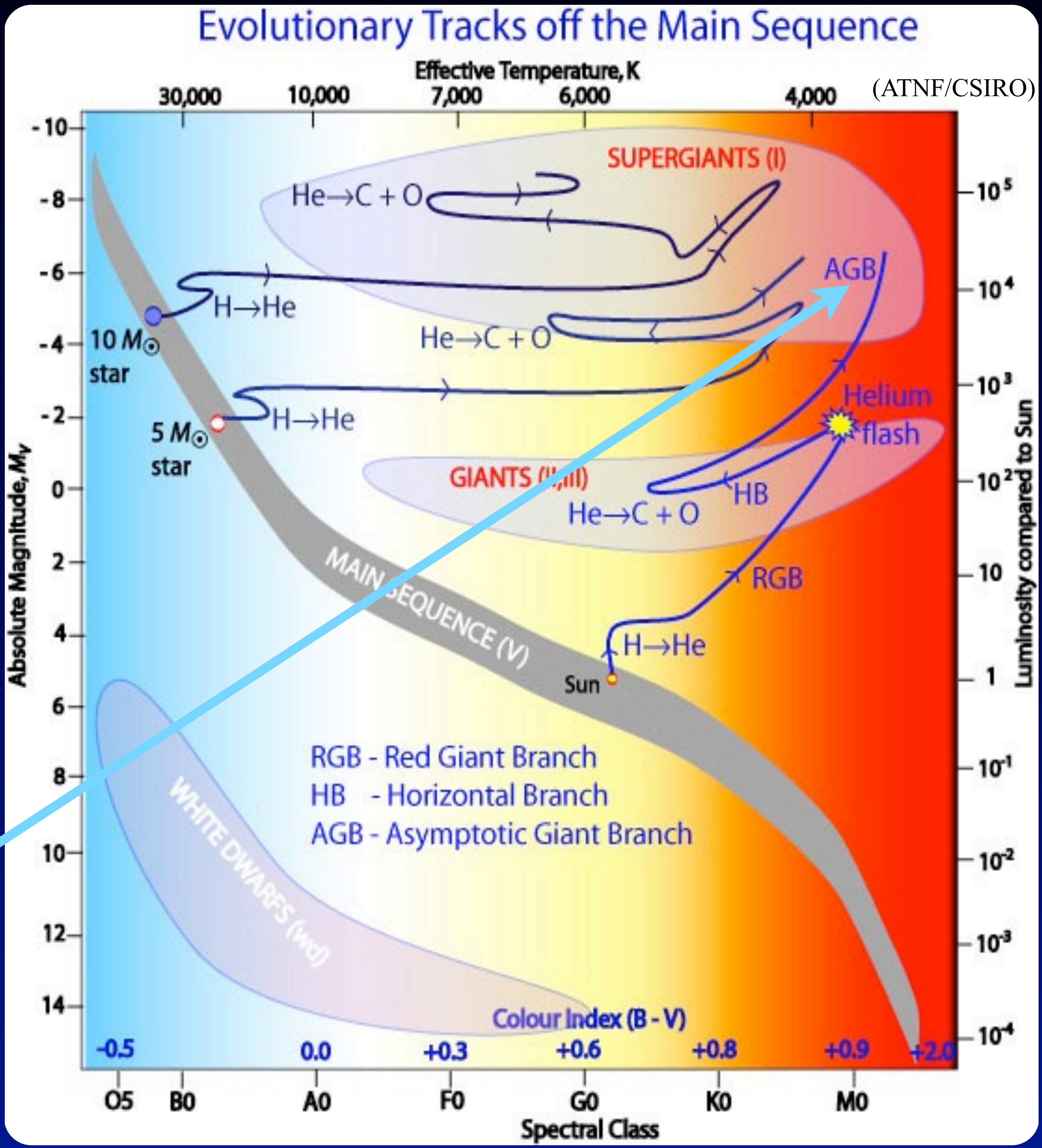


Stellar Stages

When H is exhausted in core, hydrogen burning ignites in shell around the core.

Once hot enough, He burning begins in the core, until He is exhausted.

Another round of contraction leads to H and He burning shells around a C+O core producing a Asymotic Giant Branch (AGB) Star for solar-like stars or a Supergiant for massive stars.

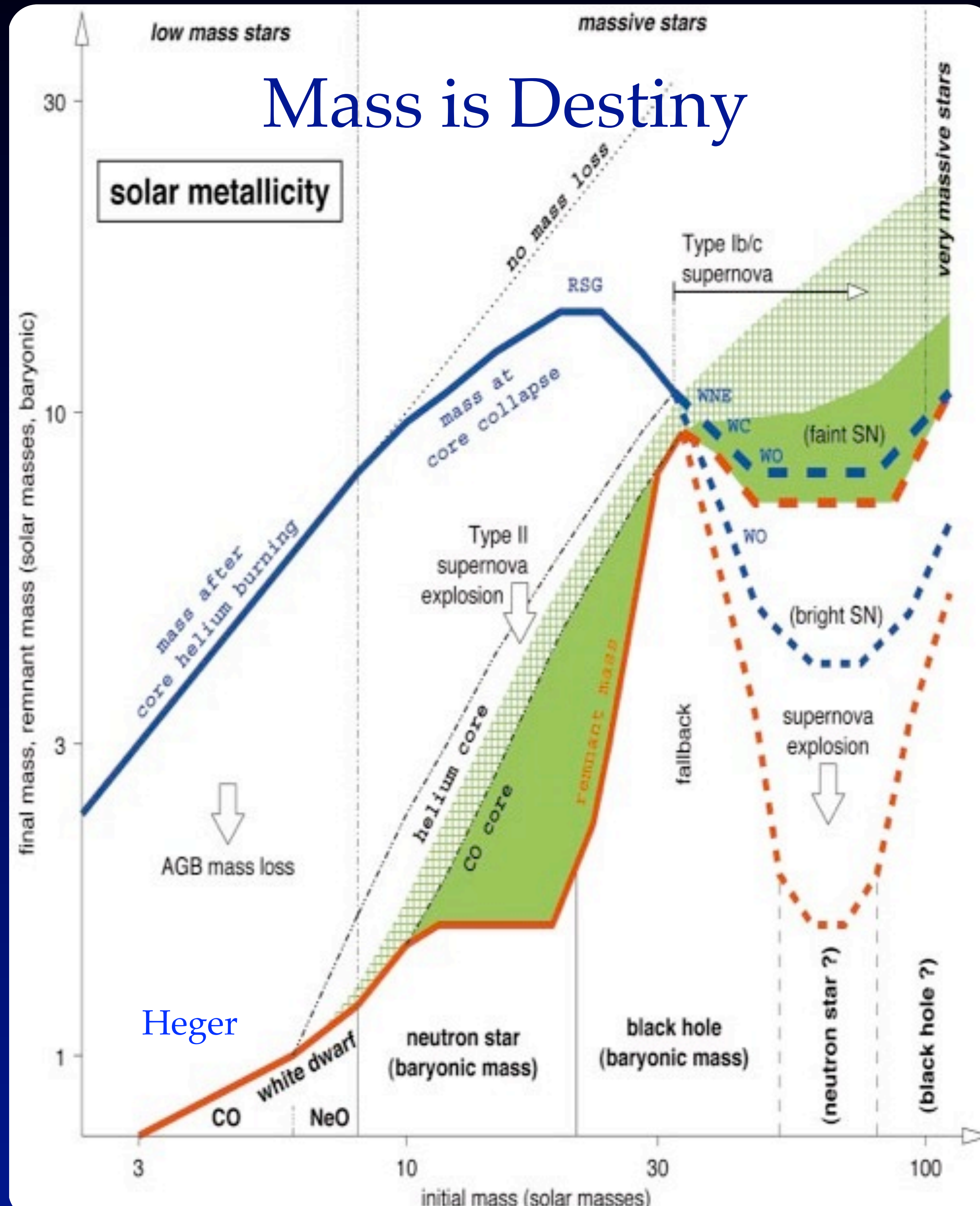


RUSSELL-VOGT THEOREM

The final fate of a single star depends on many facets, the most important is its mass at birth.

Mass loss is also important. Very Massive stars can lose much of their envelope, leaving the He or C/O core visible.

Metallicity, the abundance of non-H and He is also important.

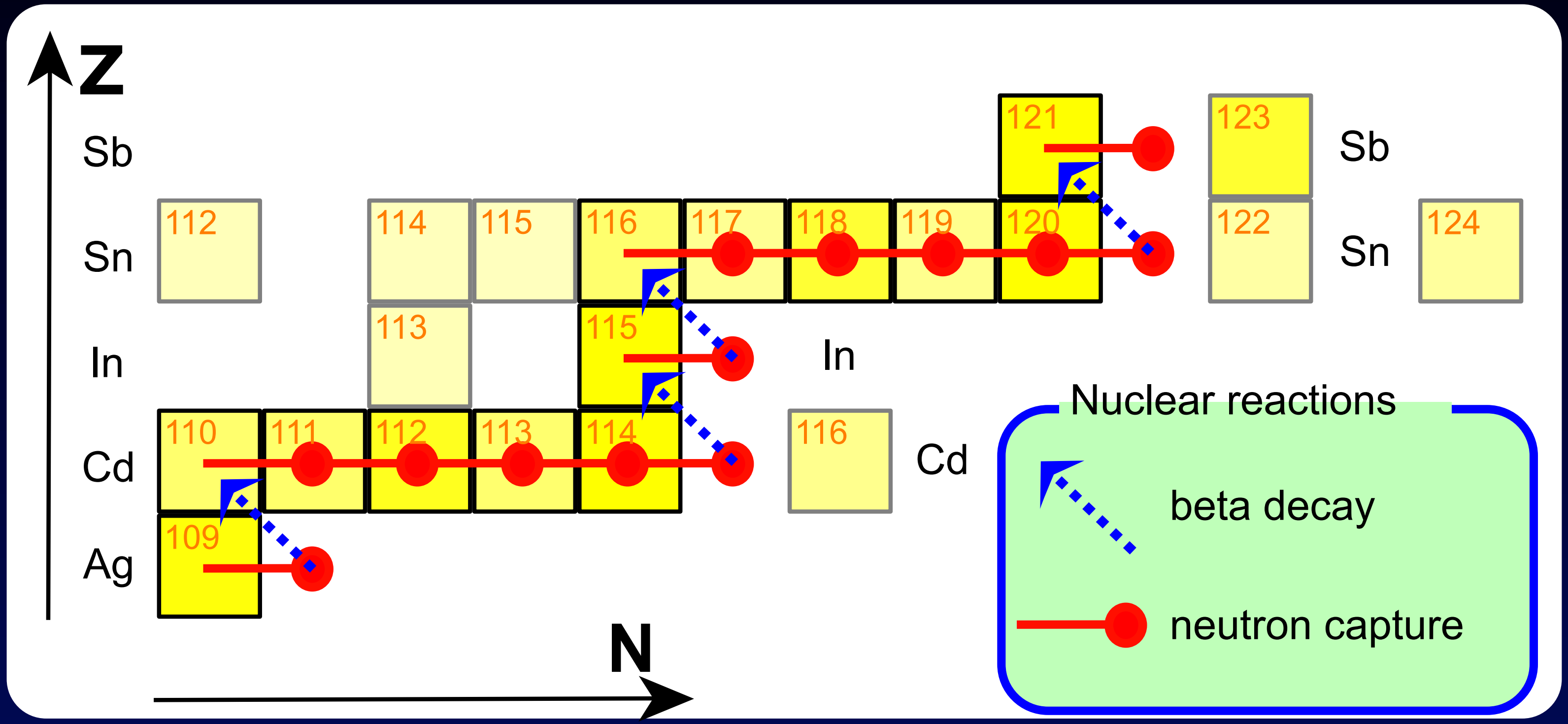


s-Process

The slow neutron capture (s-) process creates ~ half of all nuclei more massive than Fe.

Occurs during pulsations in red giant stars via chains of (n,γ) reactions linked by β decays.

Neutrons are produced by $^{13}C(\alpha,n)^{16}O$ and $^{22}Ne(\alpha,n)^{25}Mg$. Production of ^{13}C requires ^{1}H to be mixed into C-rich region.



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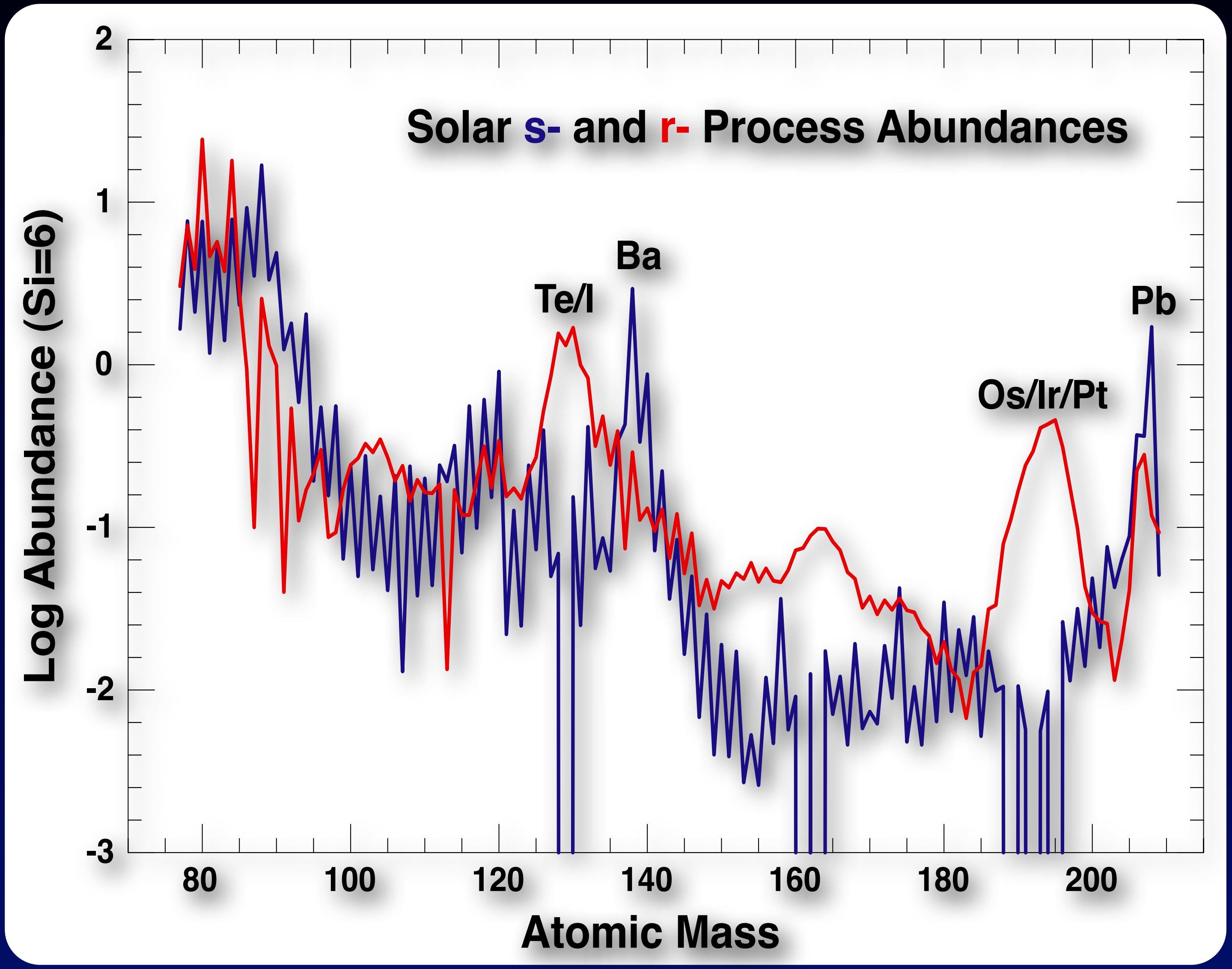
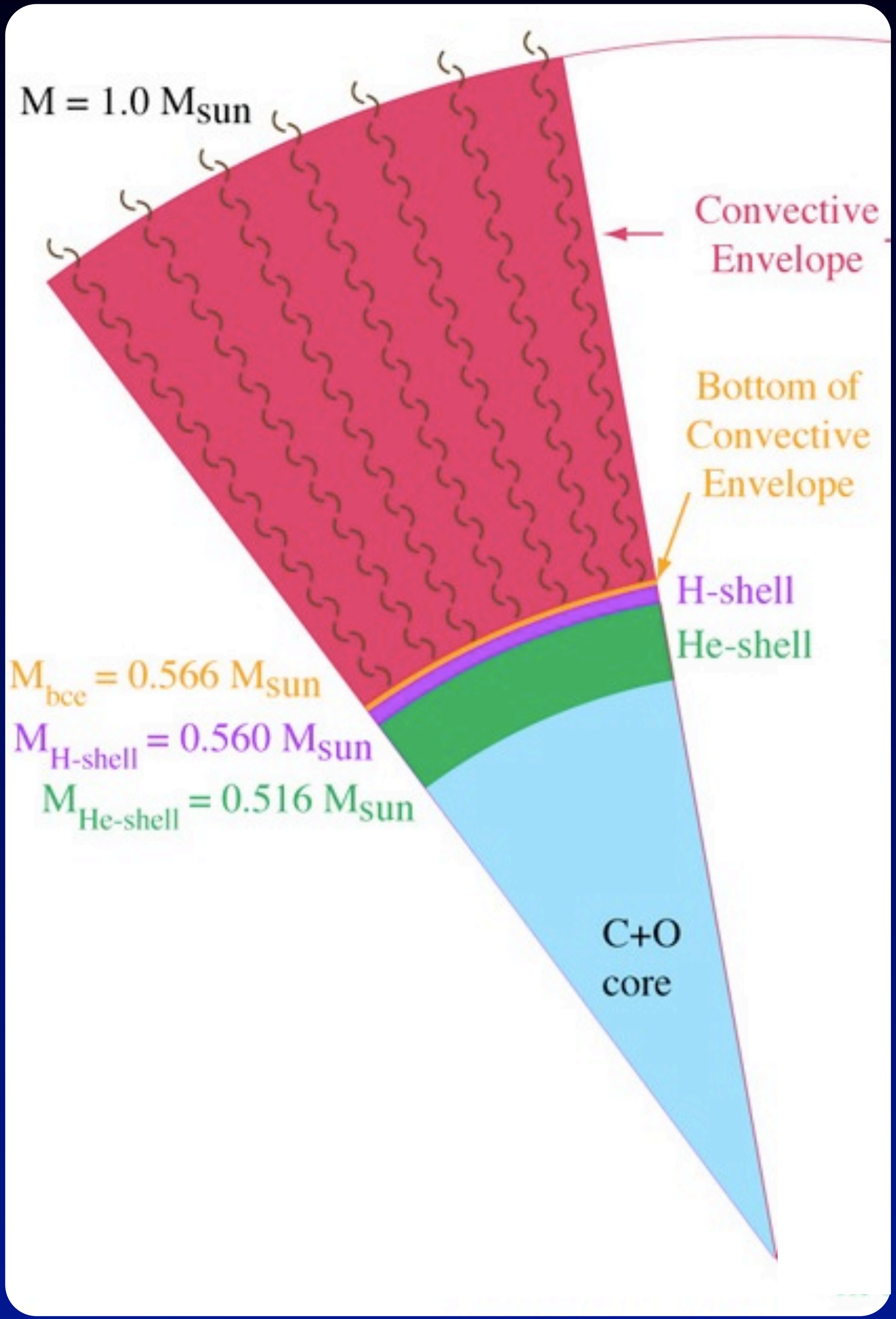
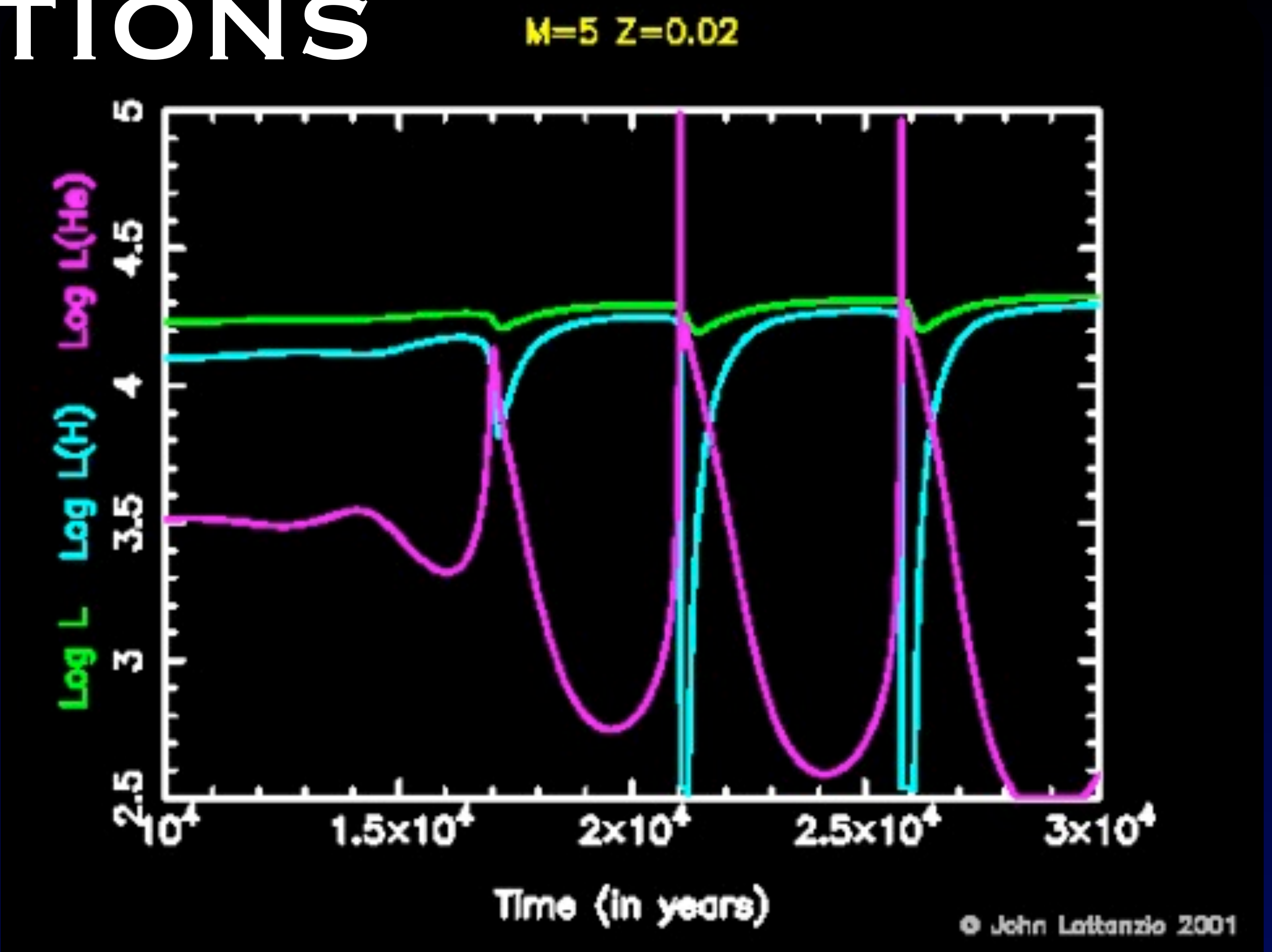
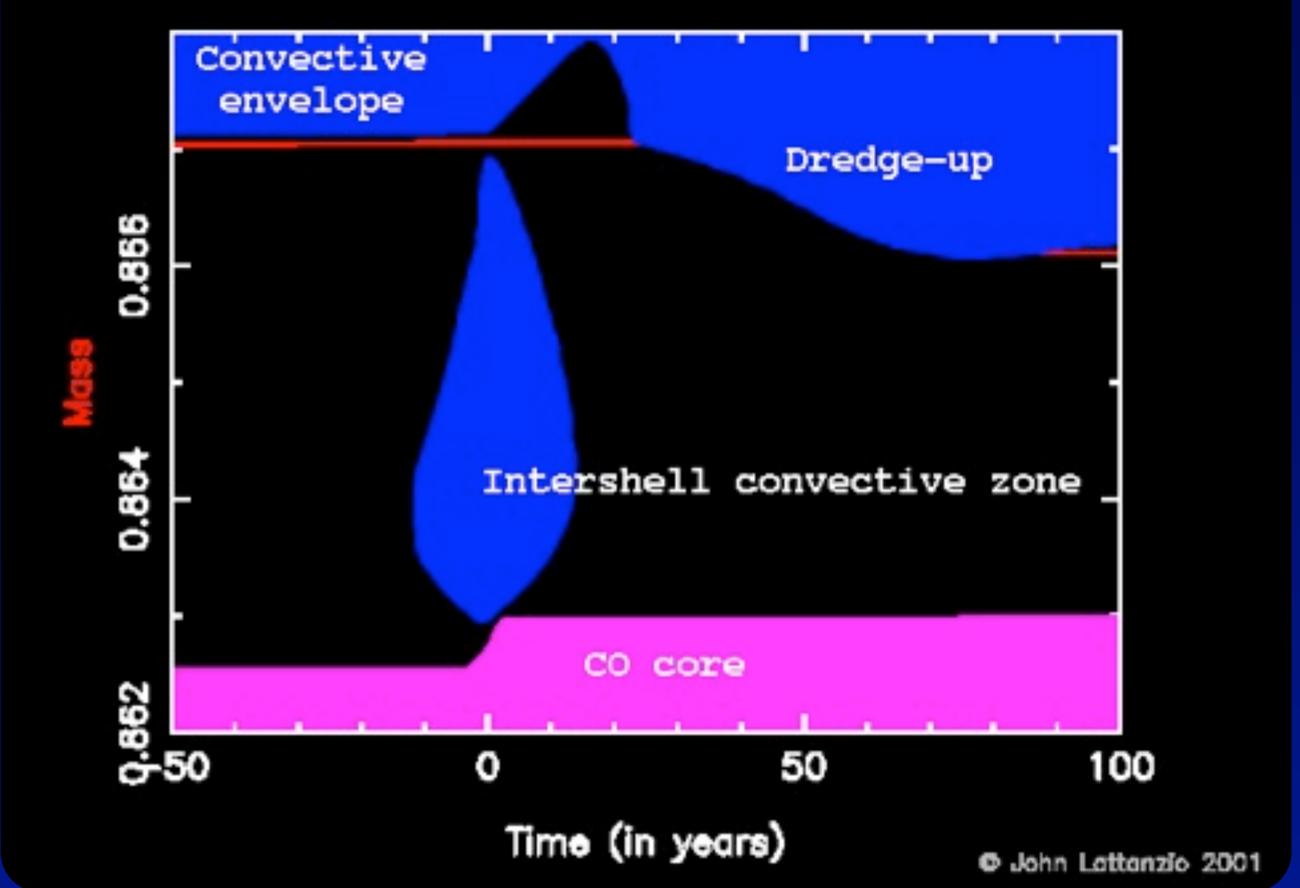


Neutron capture rate is slower than beta decays, so s-process path follows the value of stability. Slowest rates at closed shells accumulate flow, producing s-process peaks.

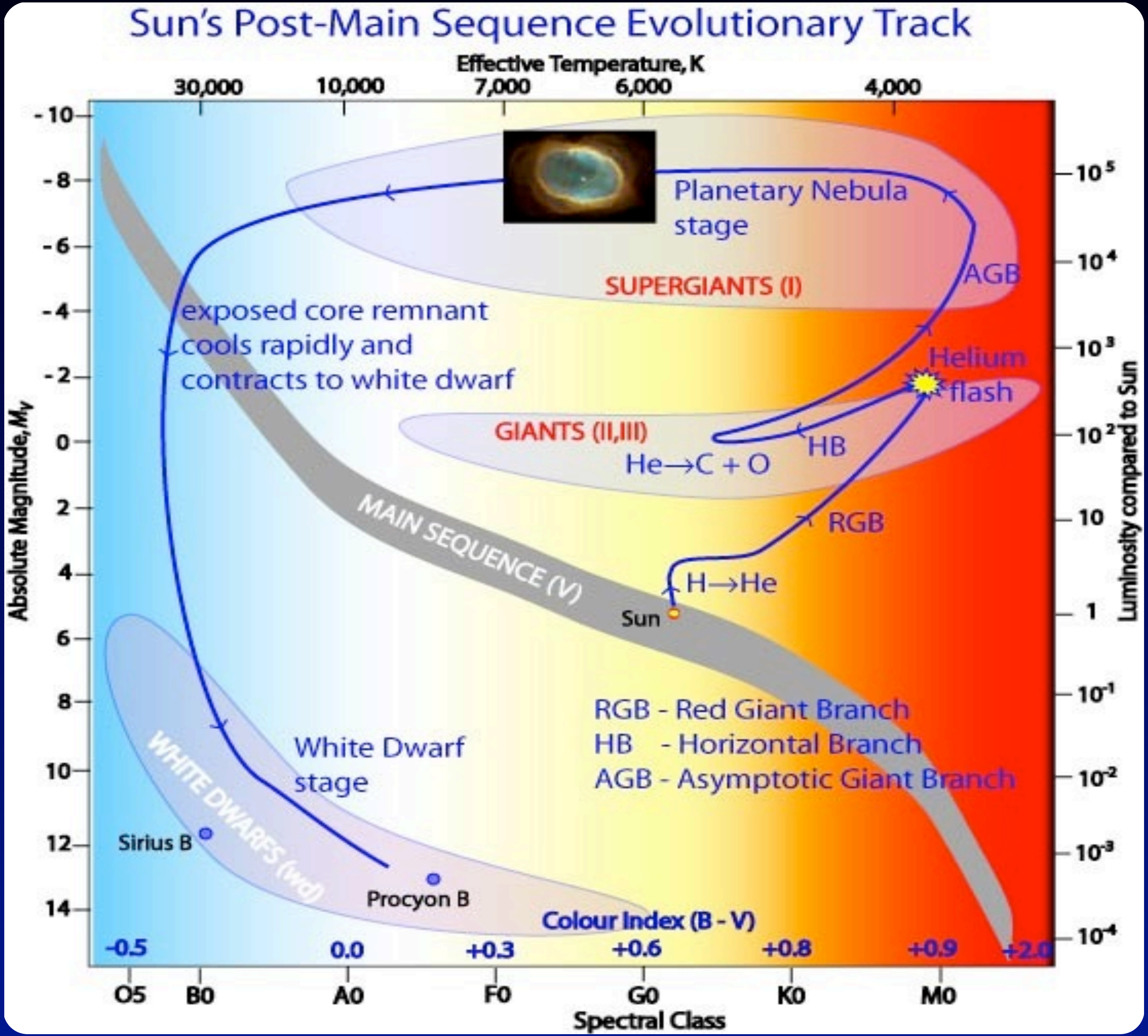
Thermal Pulsations in AGB





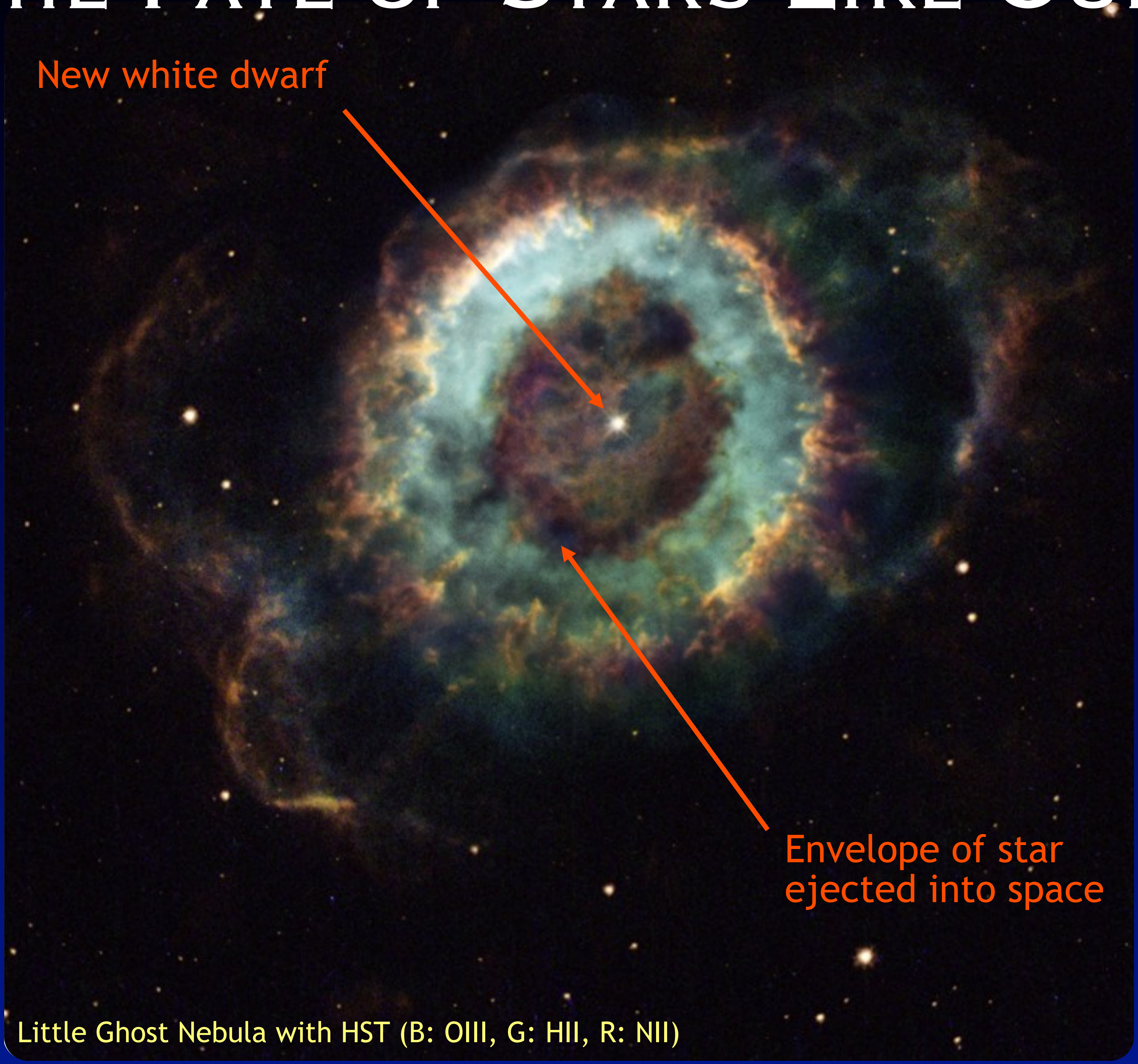


The Fate of Stars Like Ours



W. R. Hix, Exotic Beam Summer School, Oak Ridge July 2014

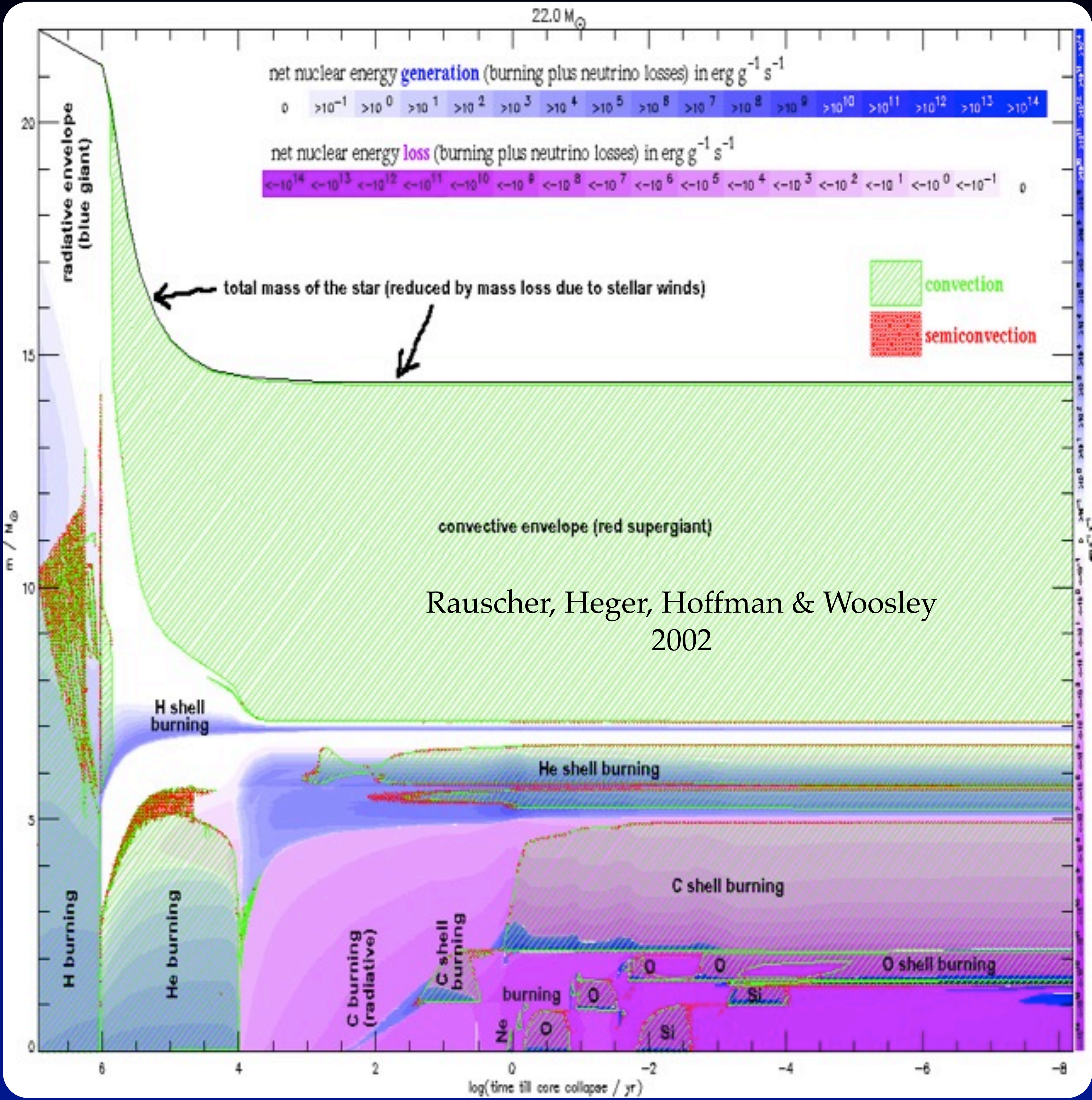
The Fate of Stars Like Ours



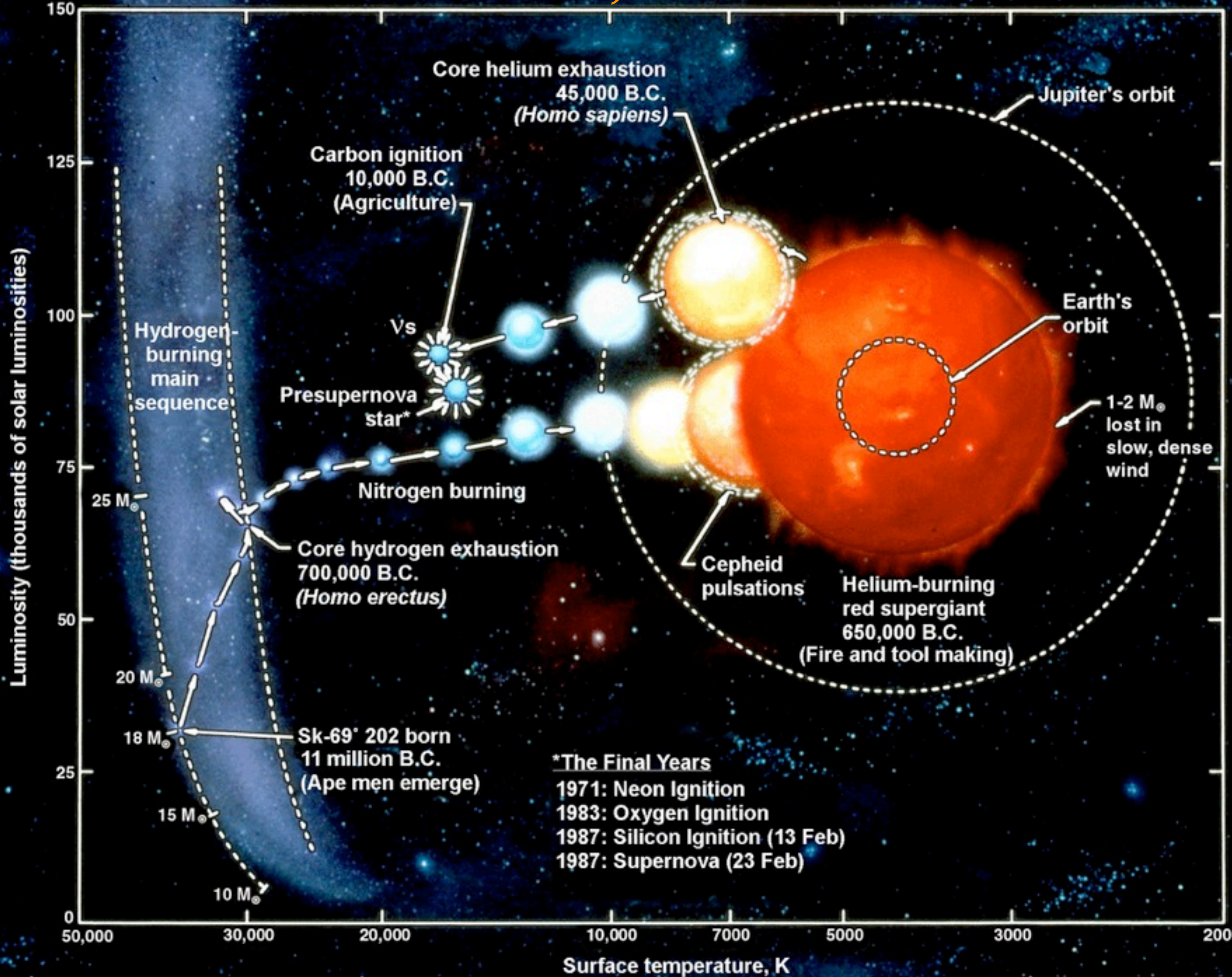
Inside a Massive Star

Stars that ignite Carbon burning meet a very different fate.

They progress through Carbon, Neon, Oxygen and Silicon burning, leaving a core of Iron surrounded by concentric layers of lighter elements.

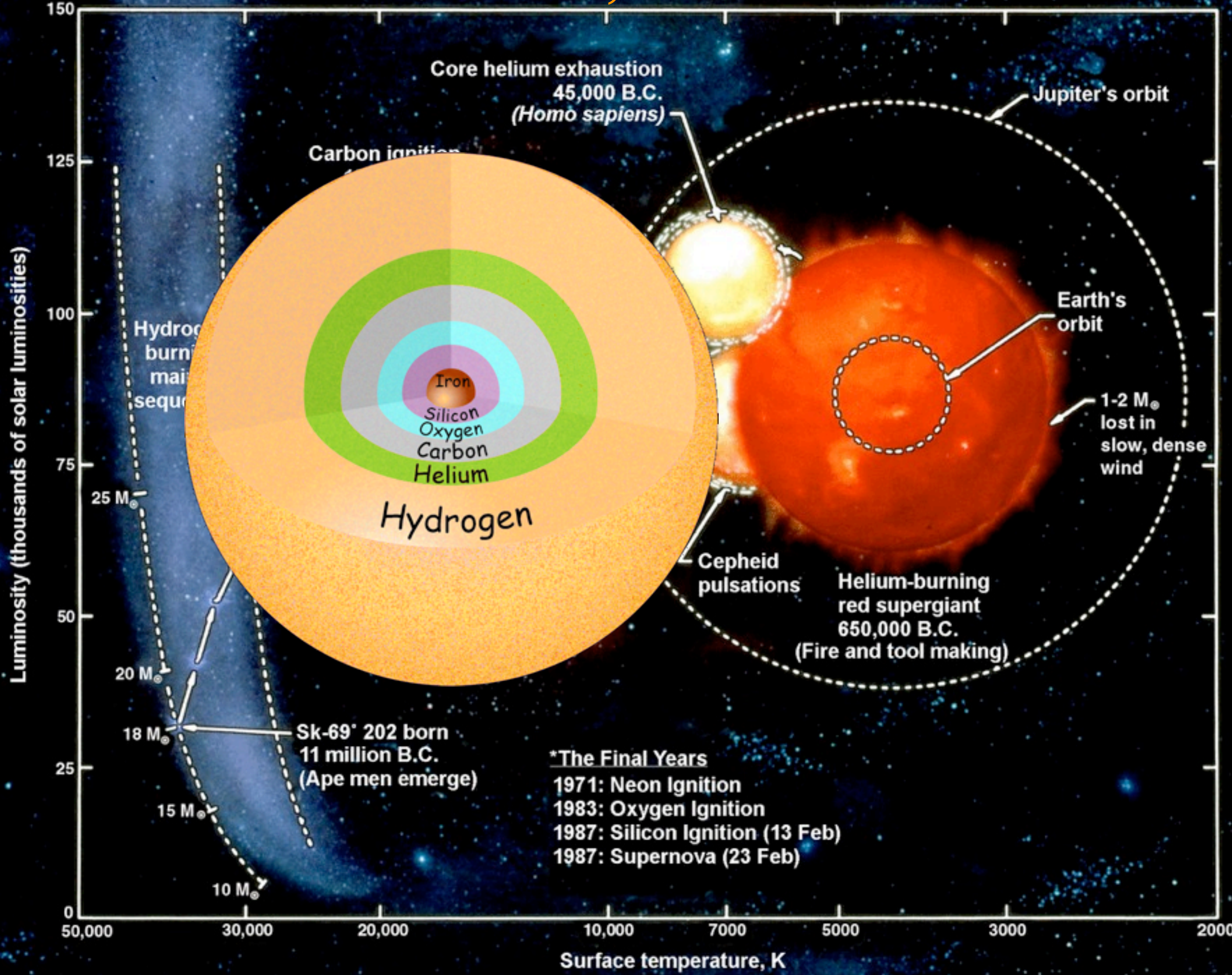


Live Fast, Die Young!



Scientific American

Live Fast, Die Young!



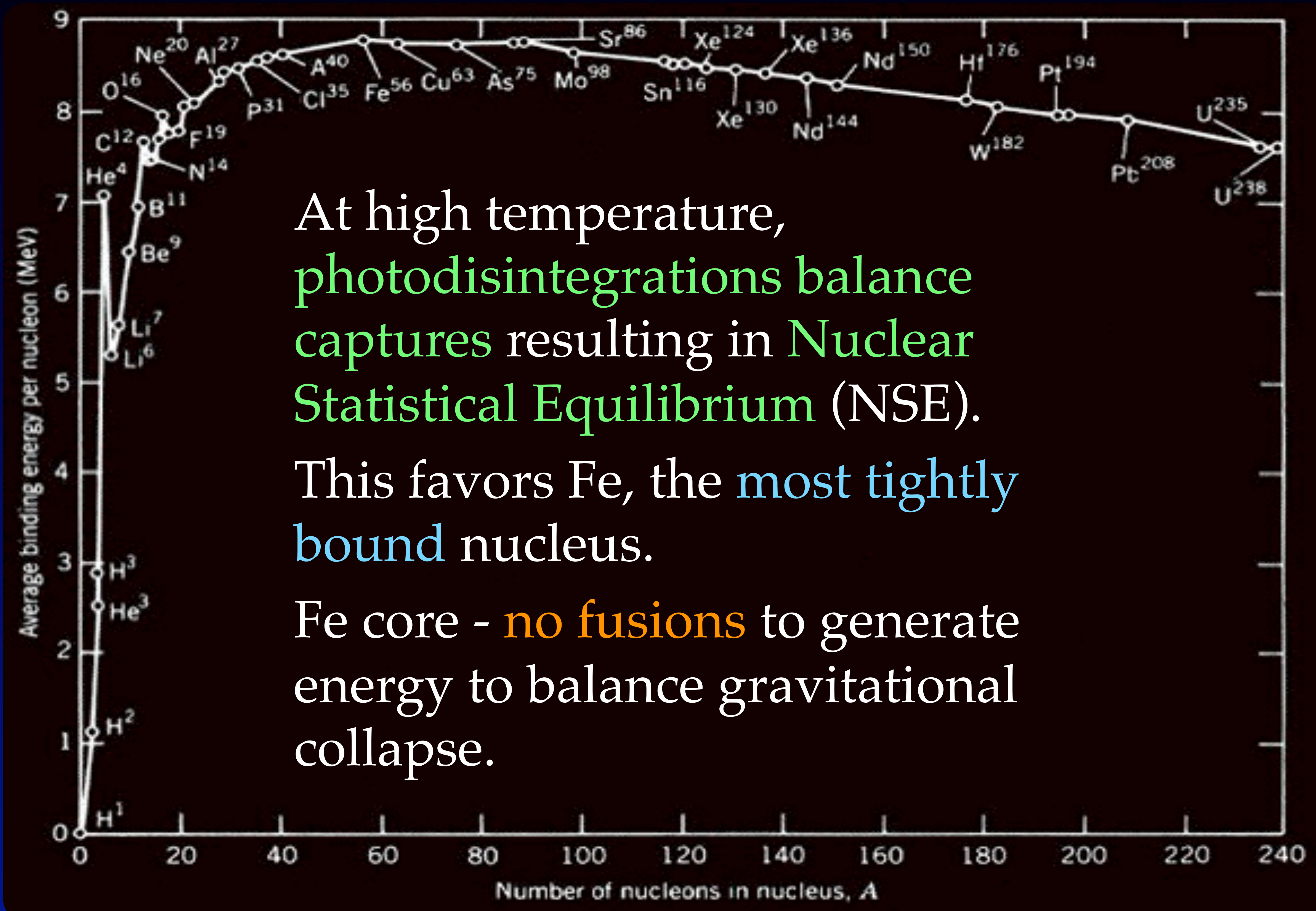
Scientific American

Massive stellar burning stages

Process	Fuel	Ash	Temperature	Duration
H Burning	H	He	30 MK	10^{14} s
He Burning	He	C	200 MK	10^{13} s
C Burning	C	O, Ne, Mg	800 MK	10^{9} s
Ne Burning	Ne	O, Mg	1.5 GK	10^{7} s
O Burning	O	Mg-Si-S	2 GK	10^{7} s
Si Burning	Si	Fe-Co-Ni	3 GK	10^{5} s
Collapse		up to Th	$>$ 3 GK	0.3 s

Nuclear reactions drive the evolution of stars with the ash of each stage forming the fuel for the next stage.

Why Stop at Iron?

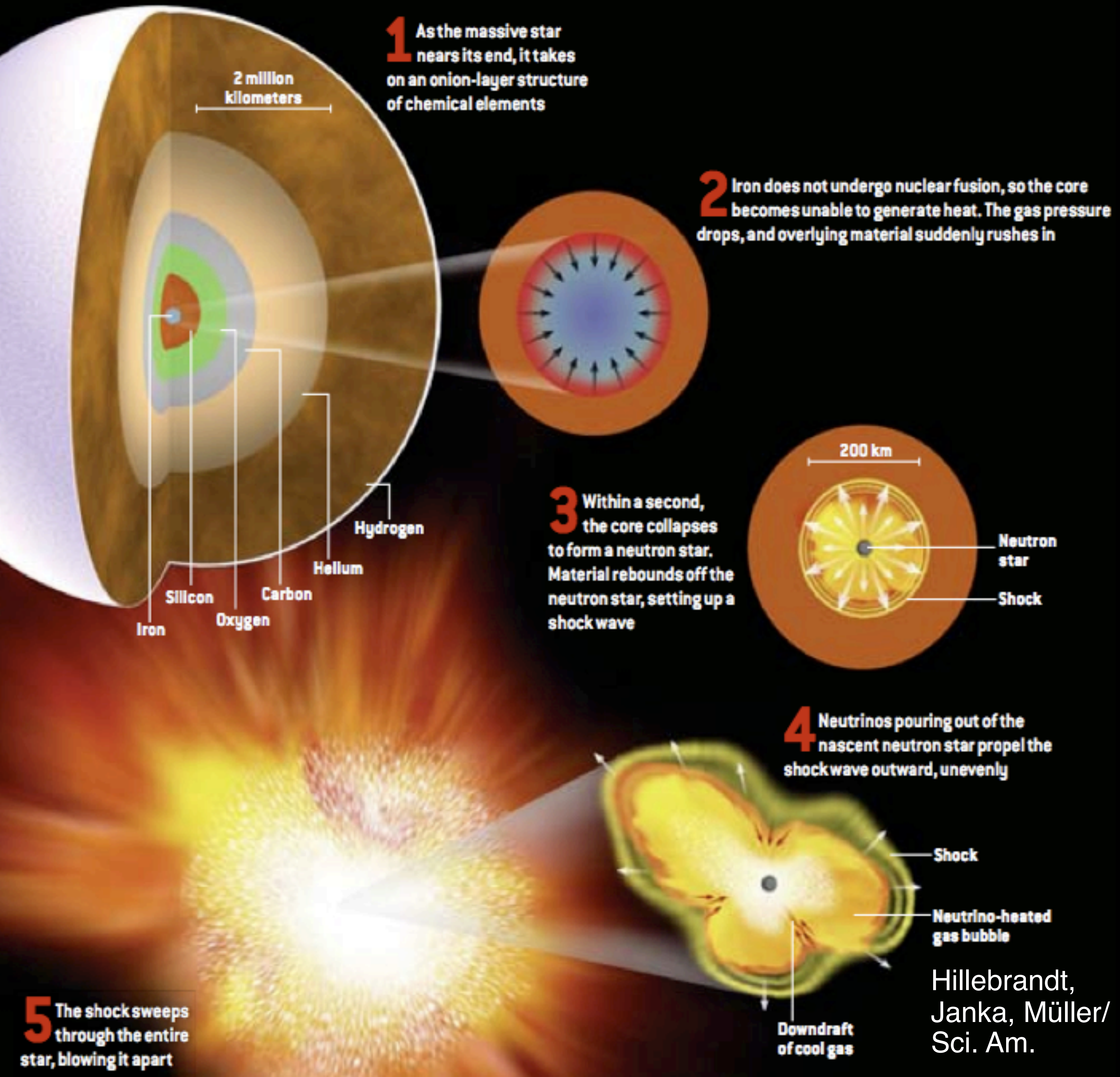


At high temperature, photodisintegrations balance captures resulting in Nuclear Statistical Equilibrium (NSE).

This favors Fe, the most tightly bound nucleus.

Fe core - no fusions to generate energy to balance gravitational collapse.

Core-Collapse Supernova

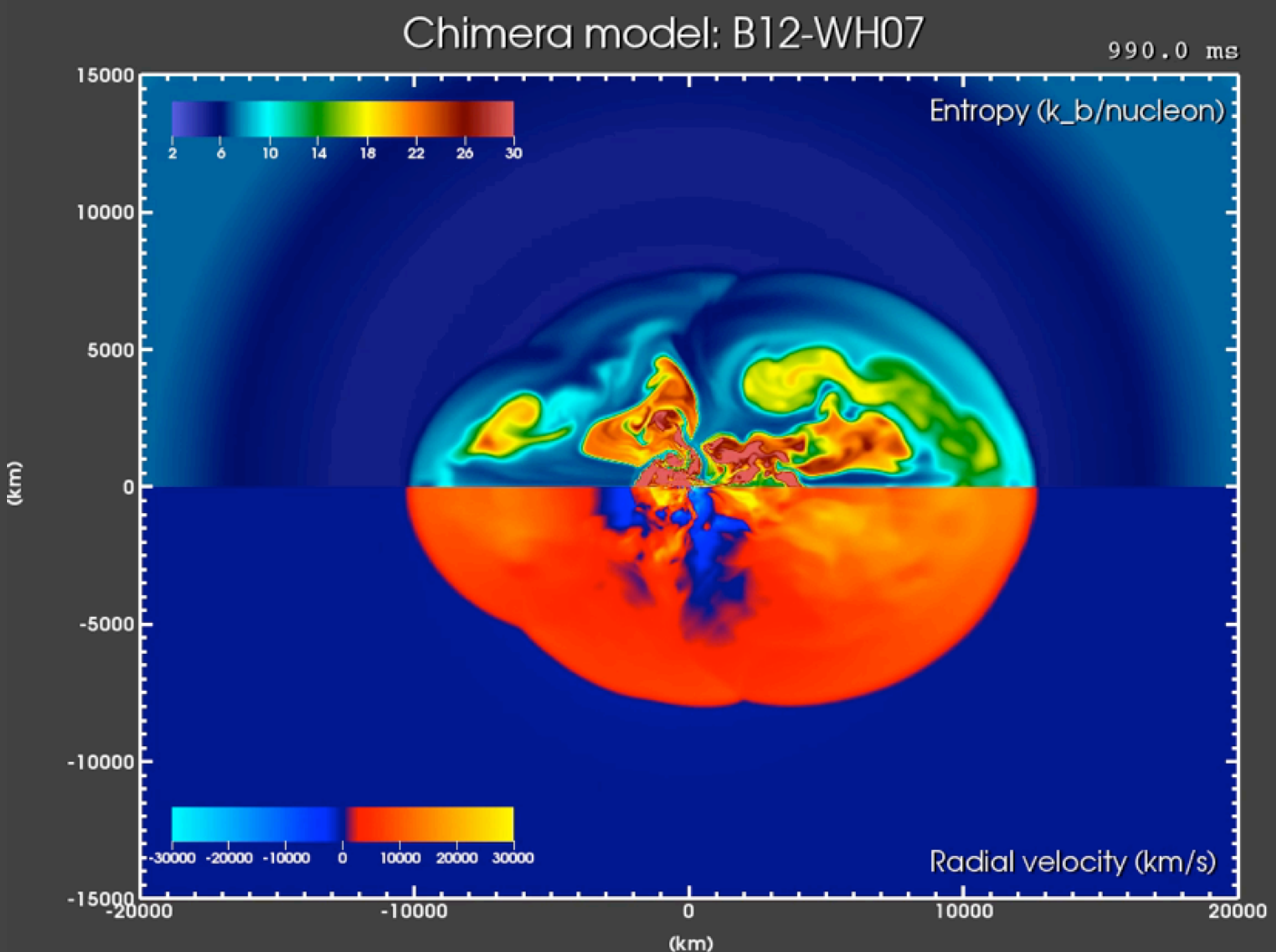


Hillebrandt, Janka, Müller/ Sci. Am.

A Core-Collapse Supernova is the inevitable death knell of a massive star (~10+ $M_\odot$).

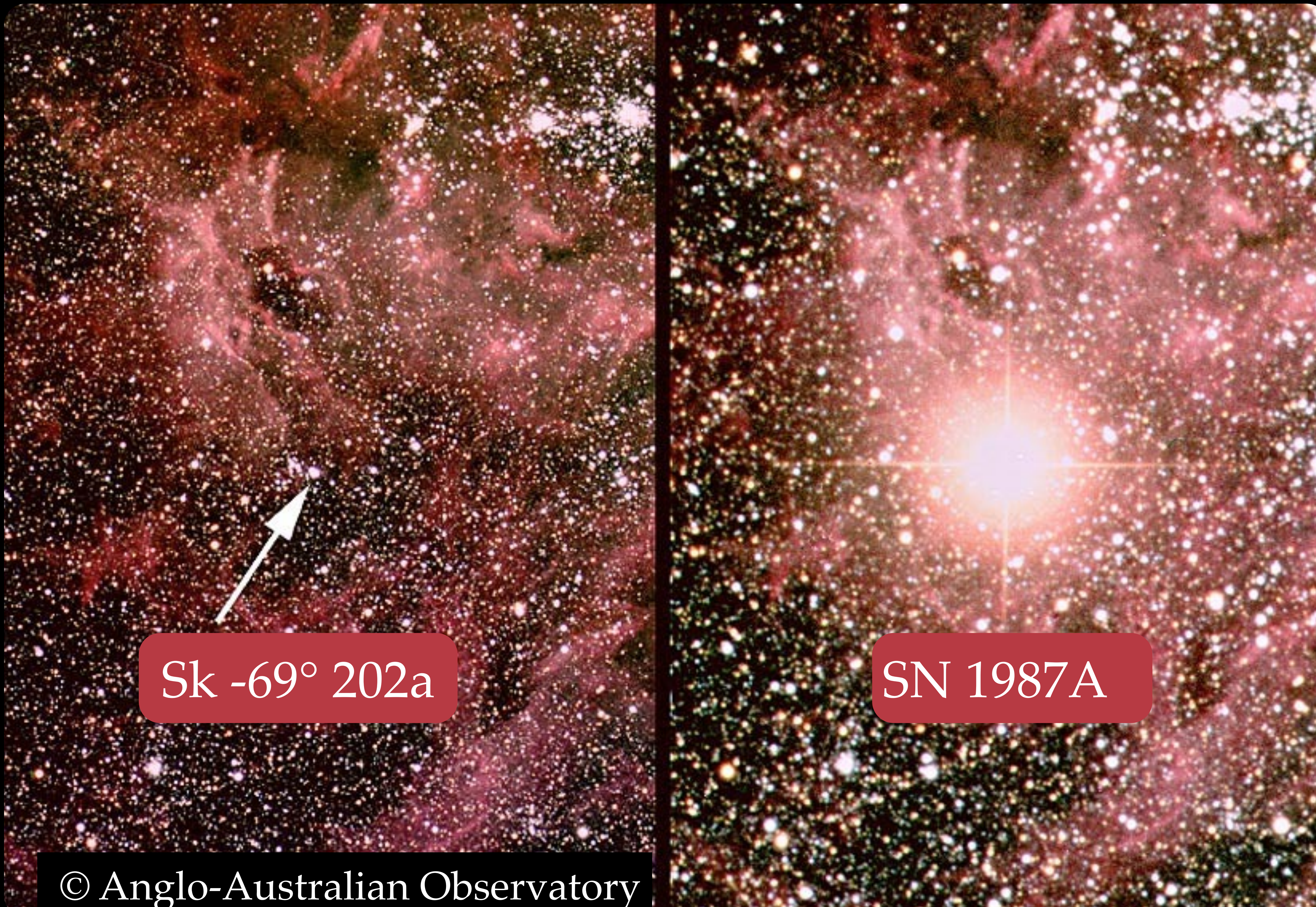
Once central iron core grows too massive to be supported by electron degeneracy pressure, collapse ensues, accelerated by electron capture.

Supernova Simulation

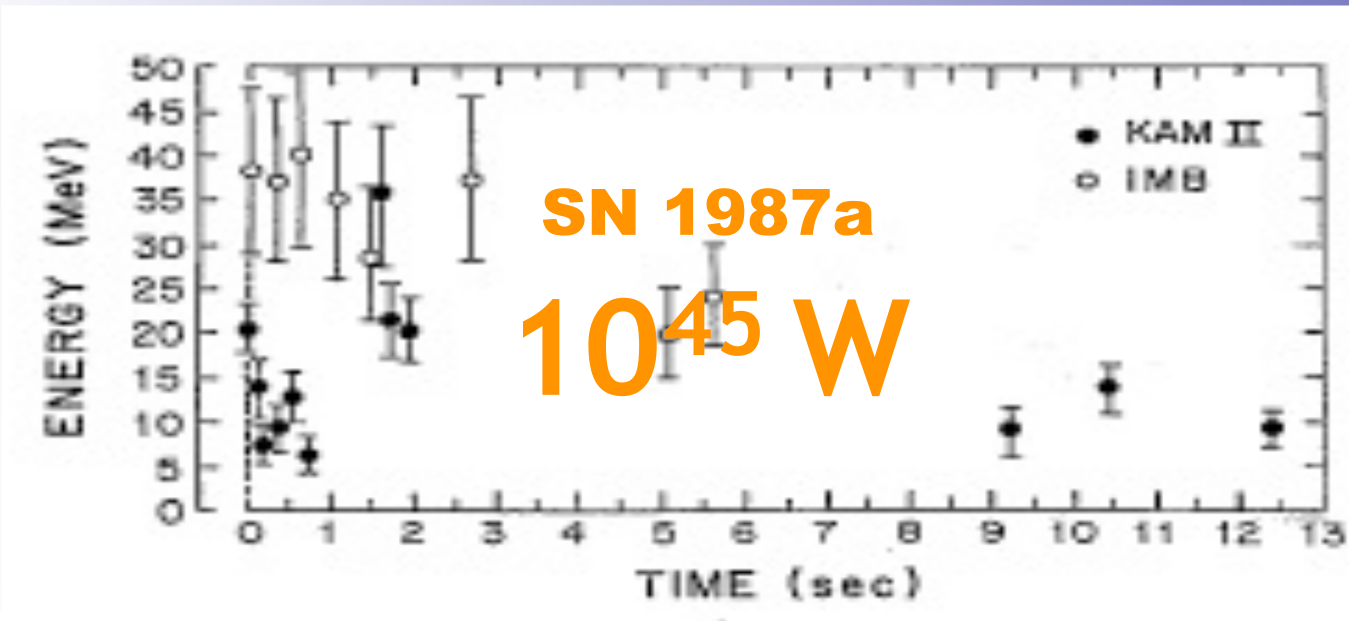


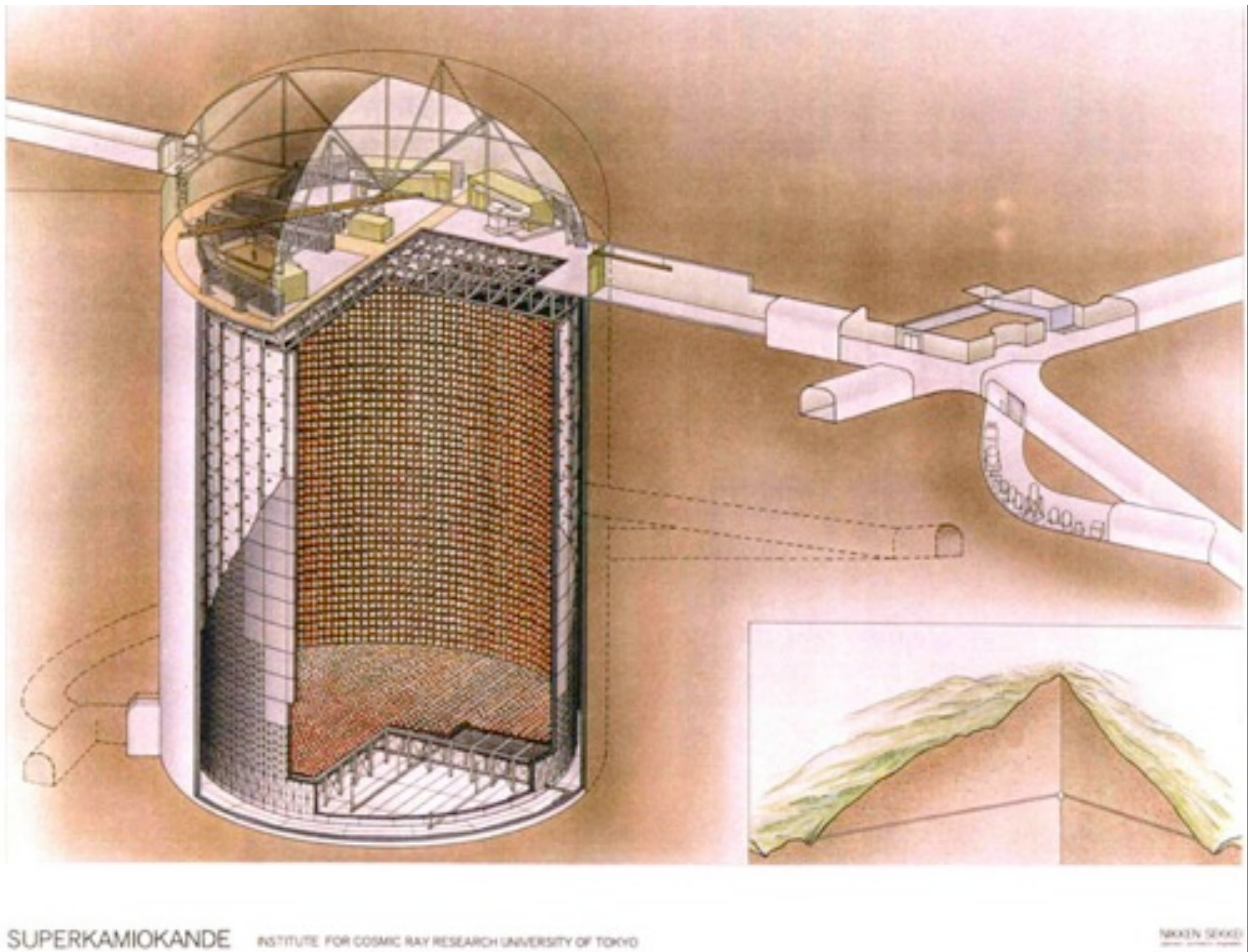
Bruenn, Mezzacappa, Hix, … (2013)

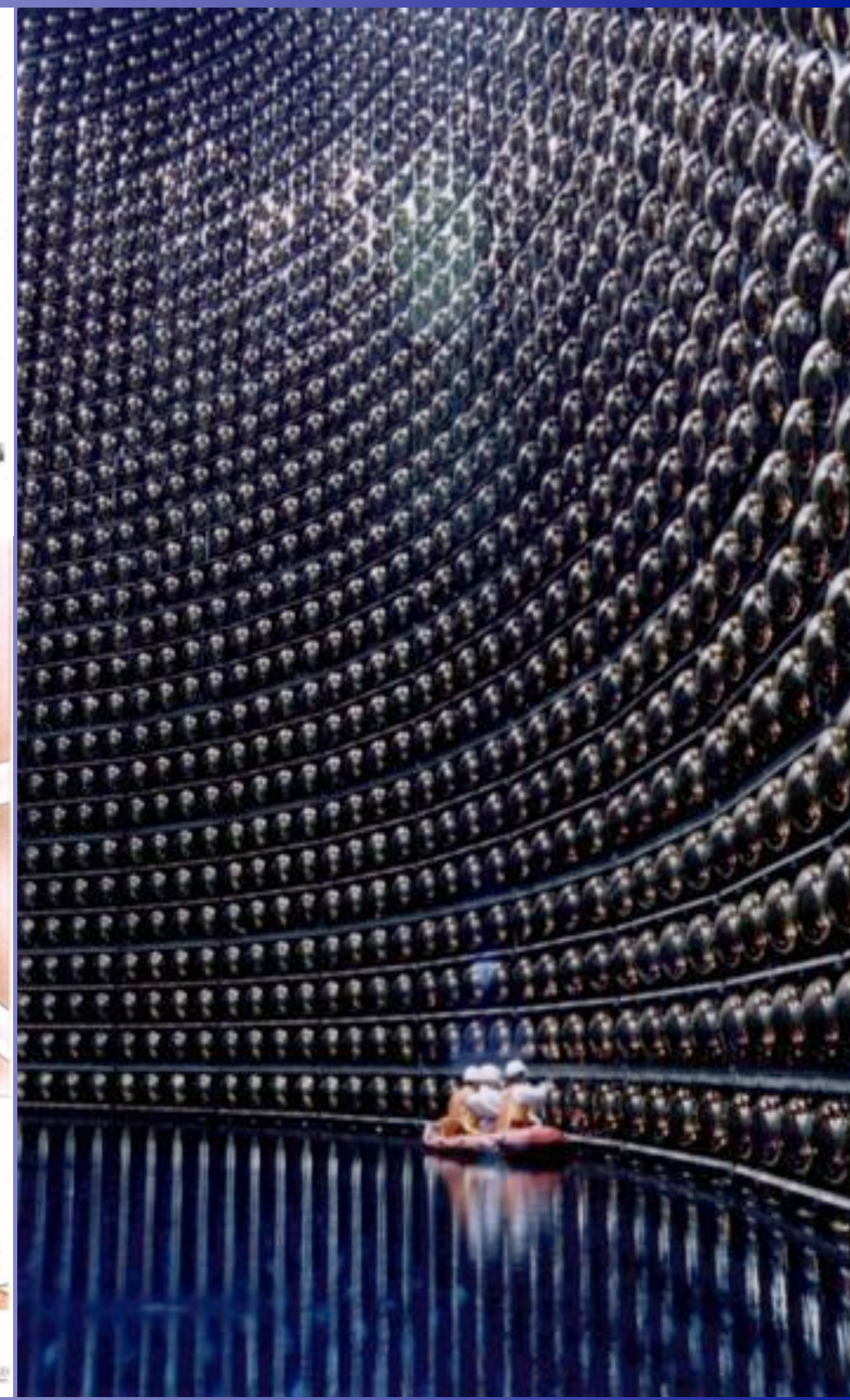
Supernova!



Observing Supernova Neutrinos







Supernova Taxonomy

Observationally, there are 2 types (7 subtypes) based on their spectra and light curves.

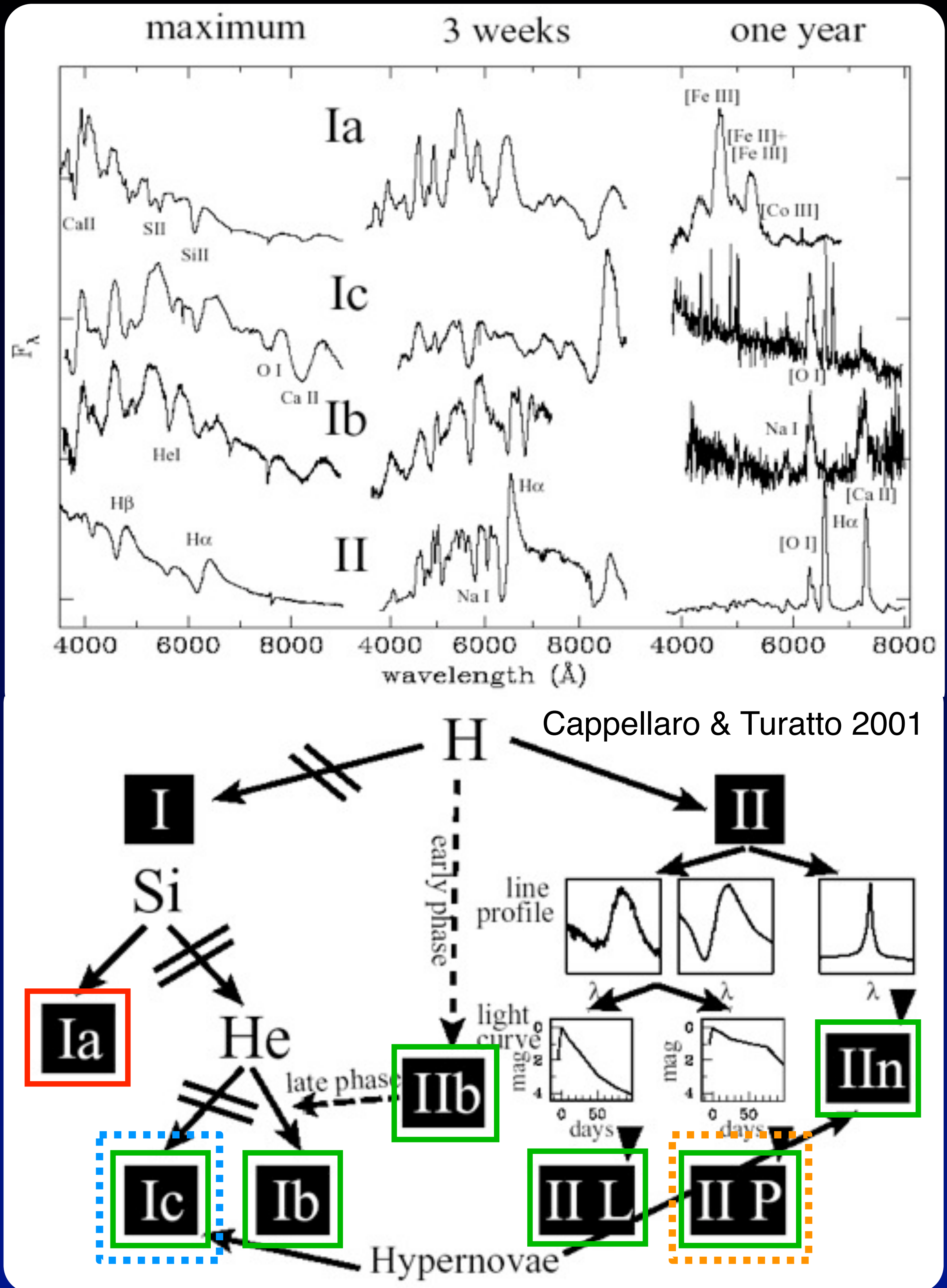
Physically, there are ~~2~~ ~~3~~ 4 mechanisms,

thermonuclear (white dwarf),

core collapse (massive star),

collapsar or magnetar (very massive star),

pair instability (very, very massive star)



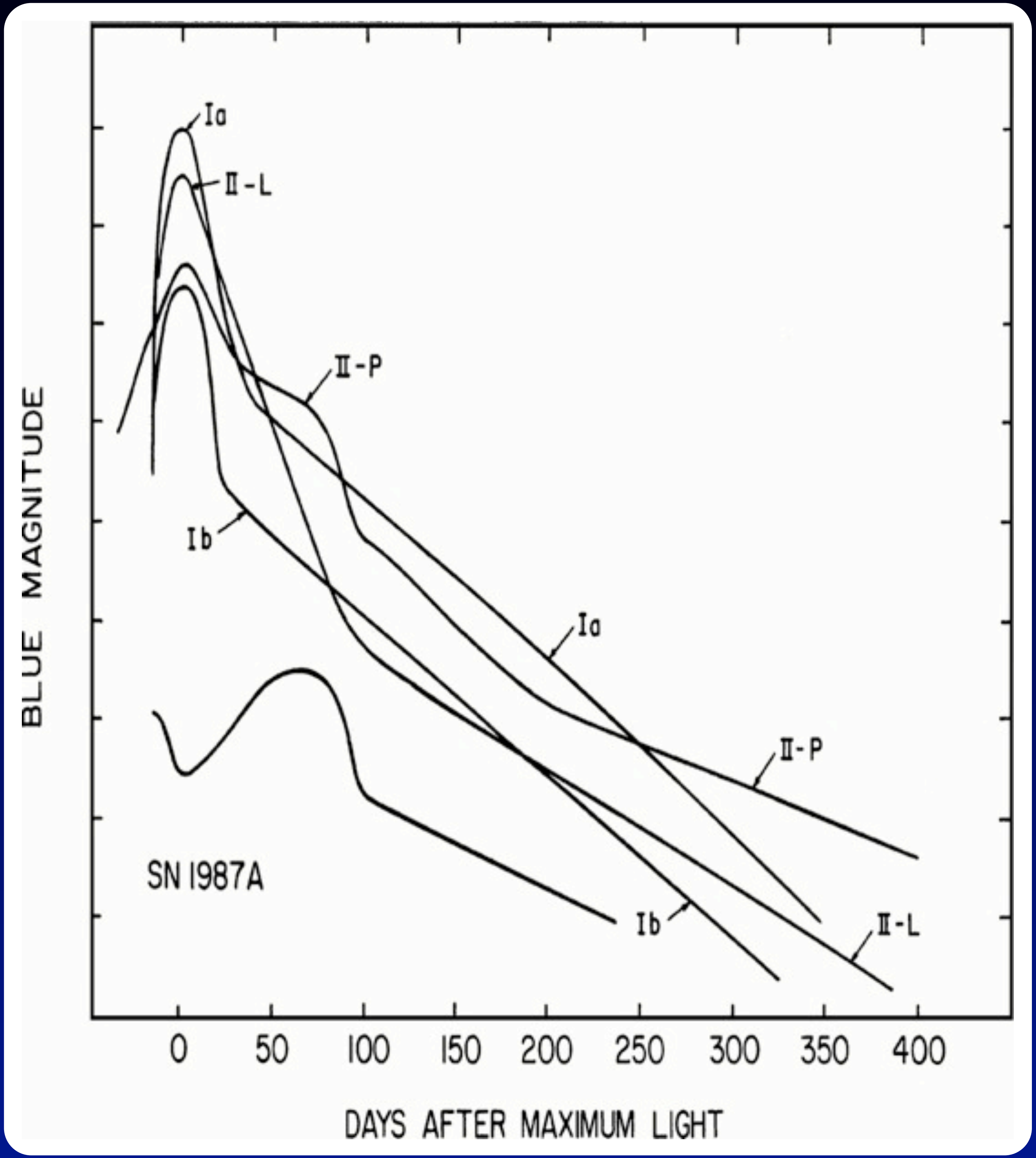
Cappellaro & Turatto 2001

6 FROM 1, 1 FROM ANOTHER

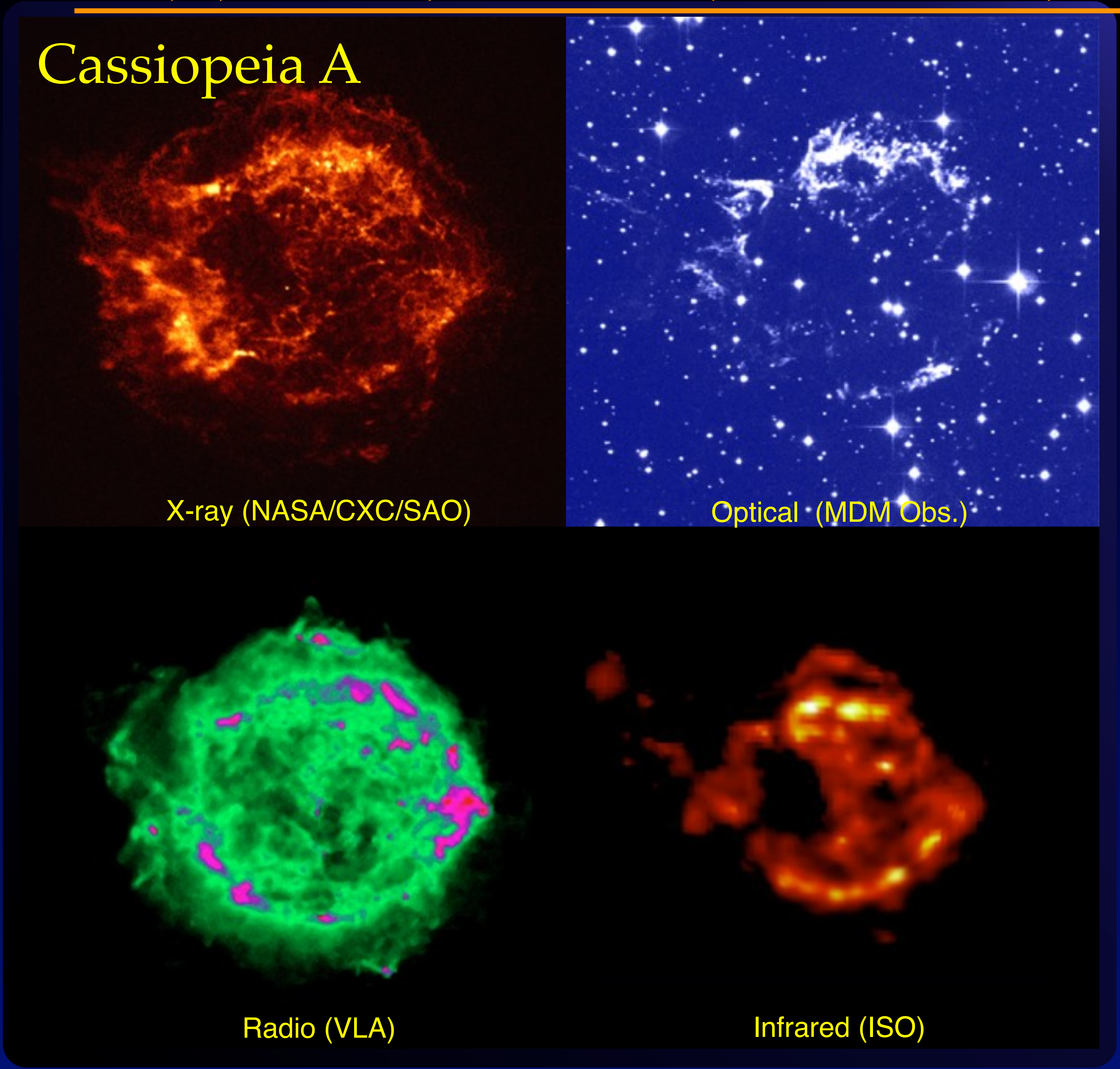
The core collapse mechanism results in supernovae with quite varied spectra and light curves.

Differences due to variations in the stellar envelope which surrounds the central engine.

In contrast, the Type Ia SN are remarkable similar, suggesting a mechanism with little variation.

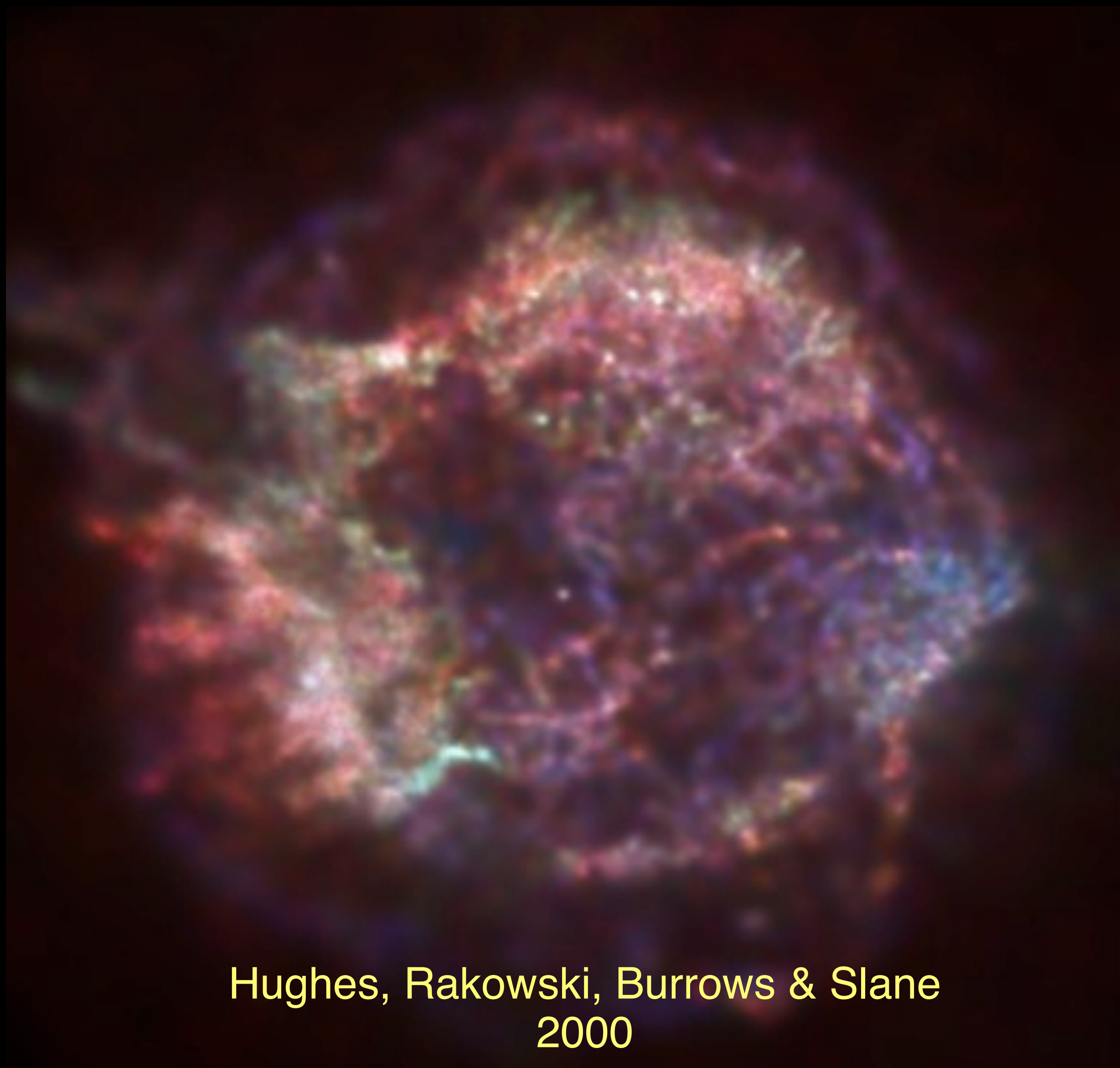


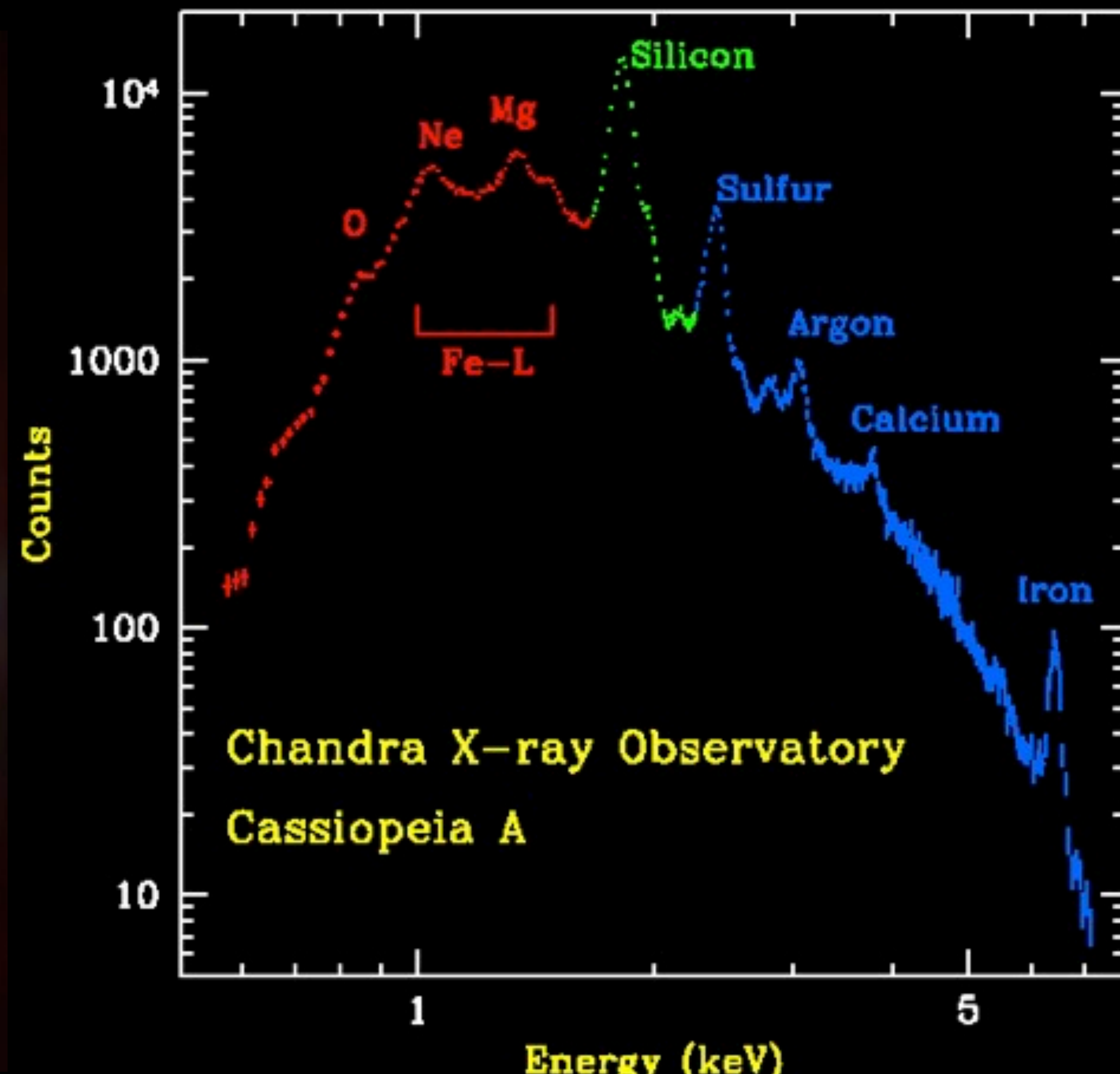
320 Year Old Supernova



Supernova deposits 10^{44} J (10^{28} Mega-Tons of TNT) of Kinetic Energy into the ISM, providing a major source of heat to interstellar gas.

Ejecta Rich in Heavy Elements

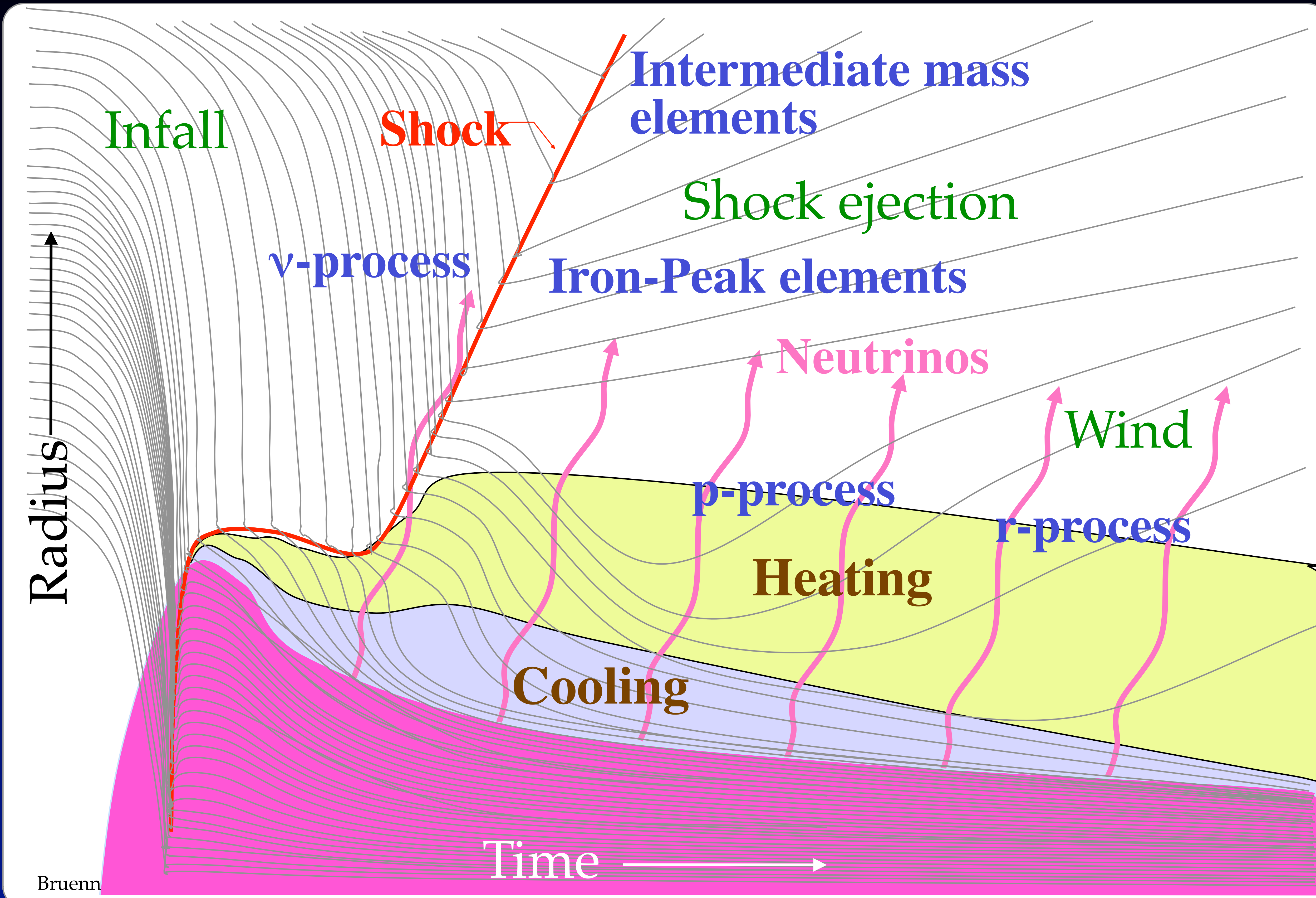




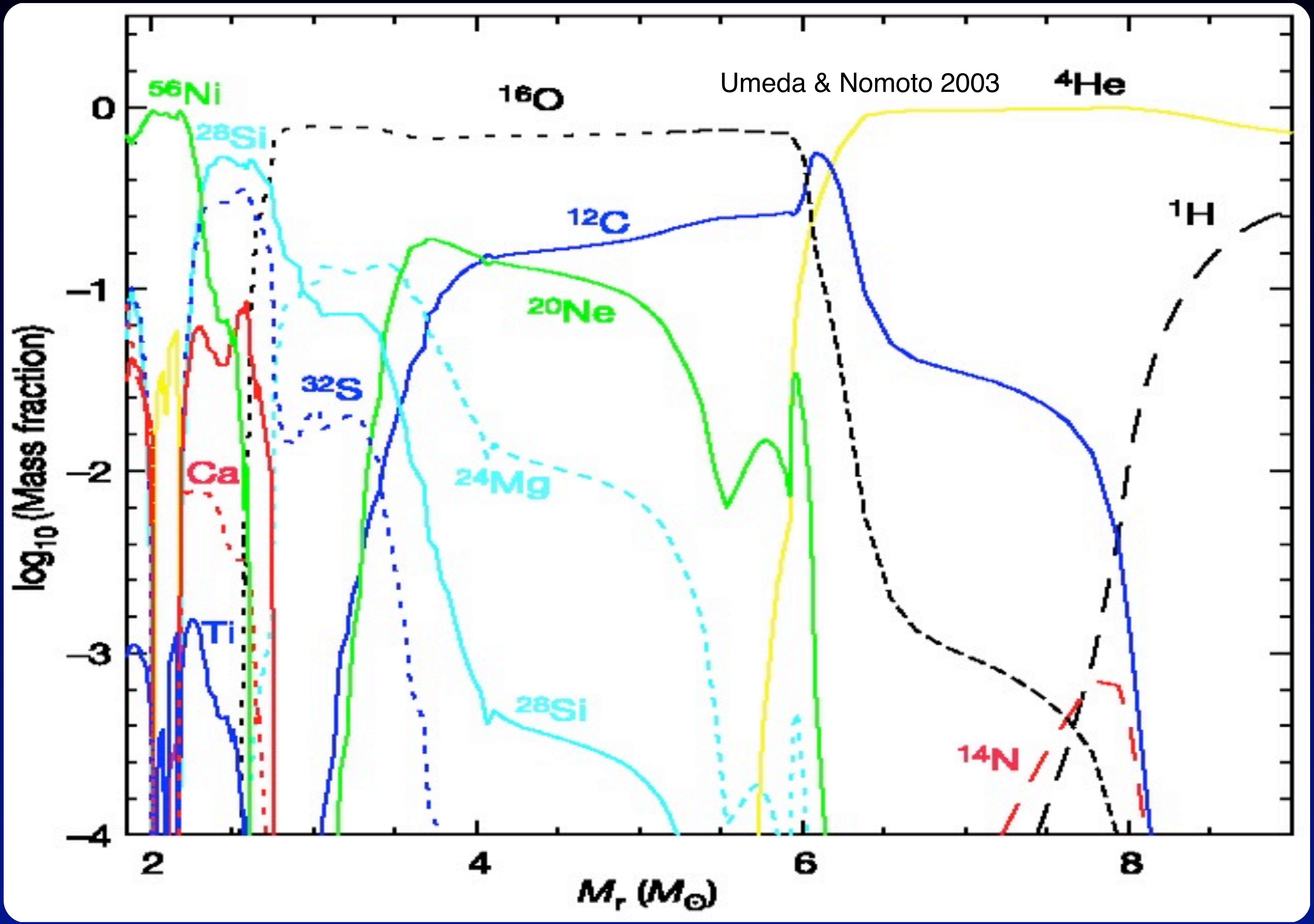
Supernovae from Massive Stars produce most of the elements from Oxygen through Silicon and Calcium and half of the Iron/Cobalt/Nickel.

They may also be responsible for the r-process.

Supernovae Nucleosynthesis



Models rich in heavy elements



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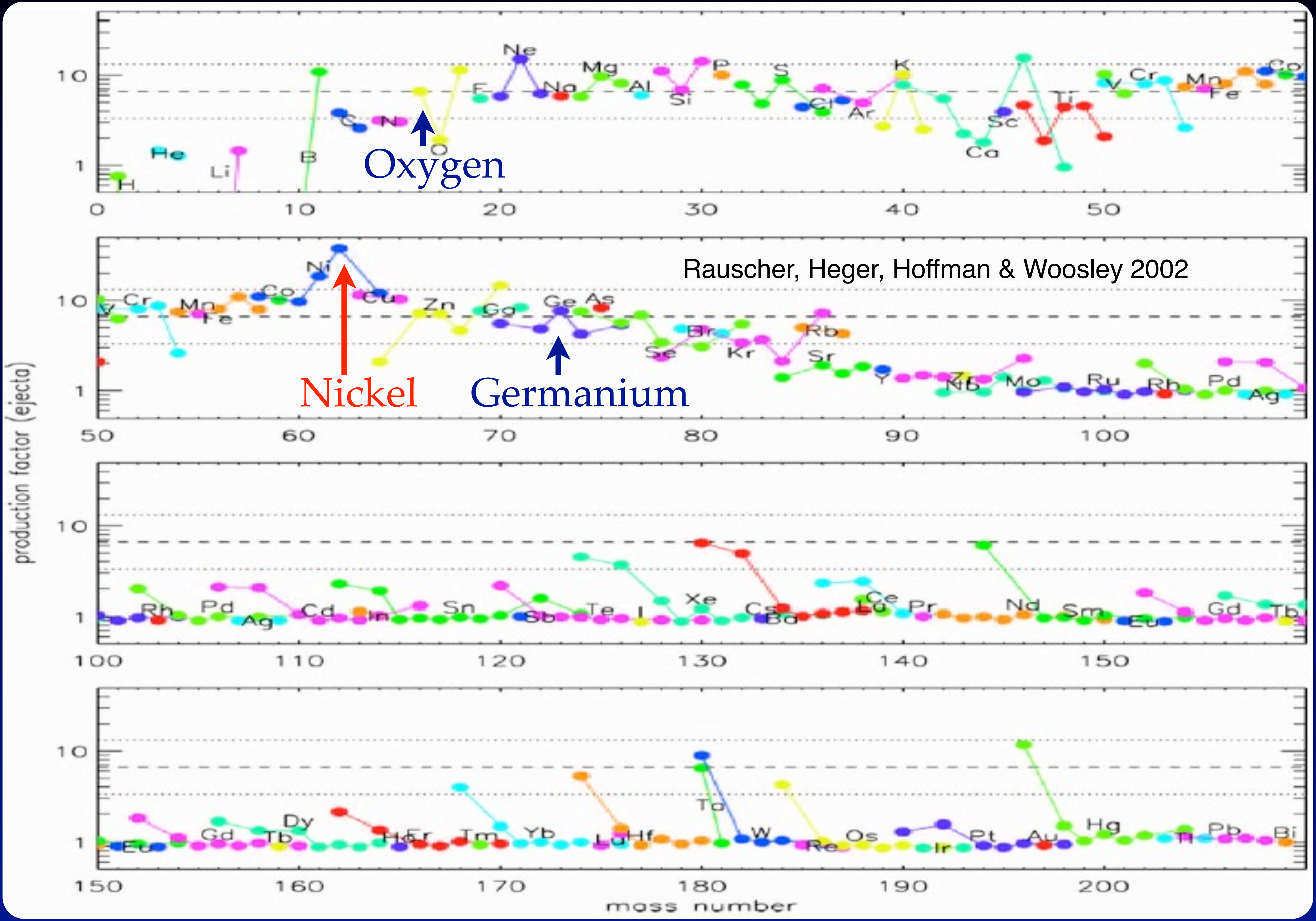
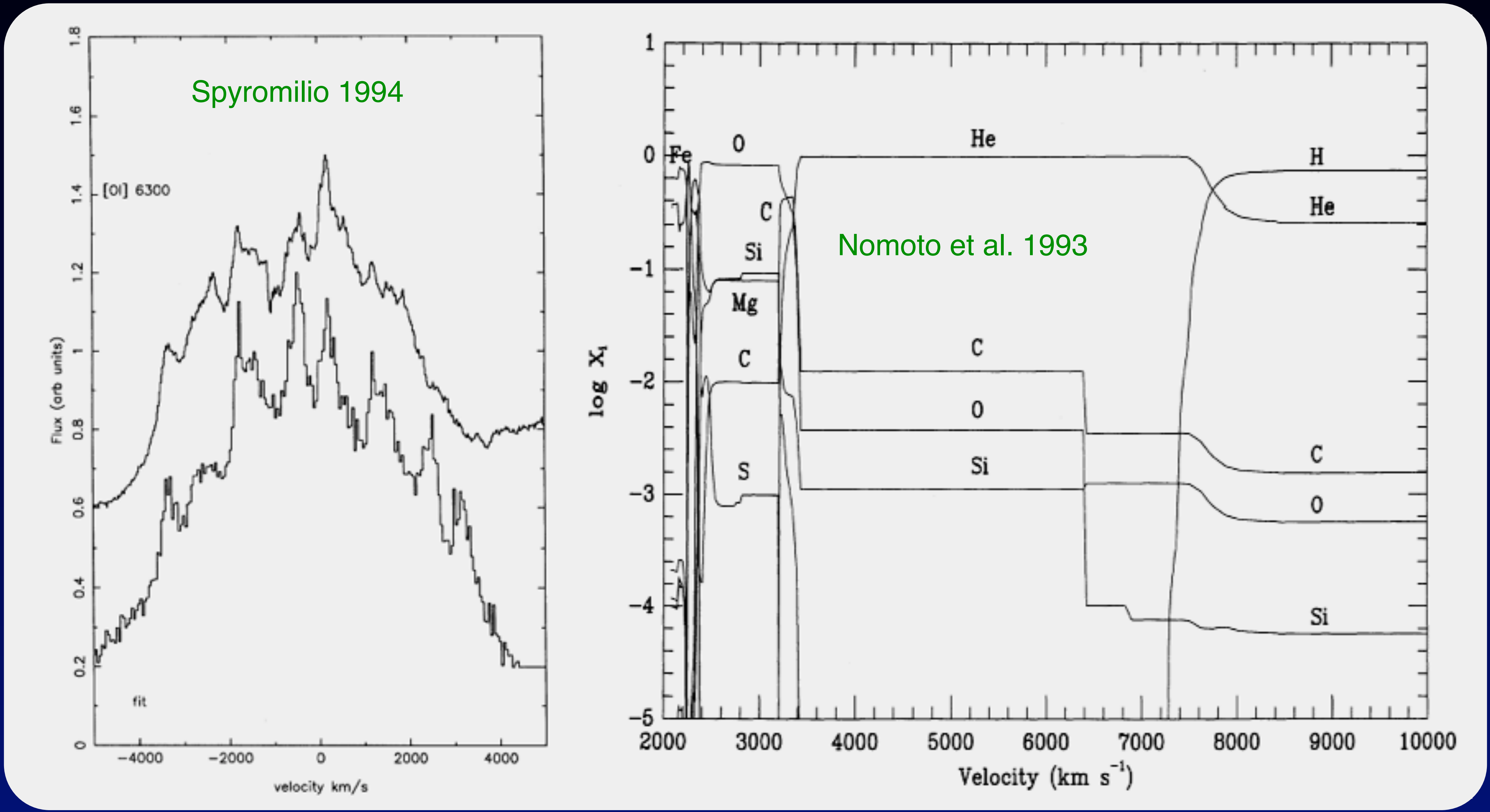


Tuning the Explosion



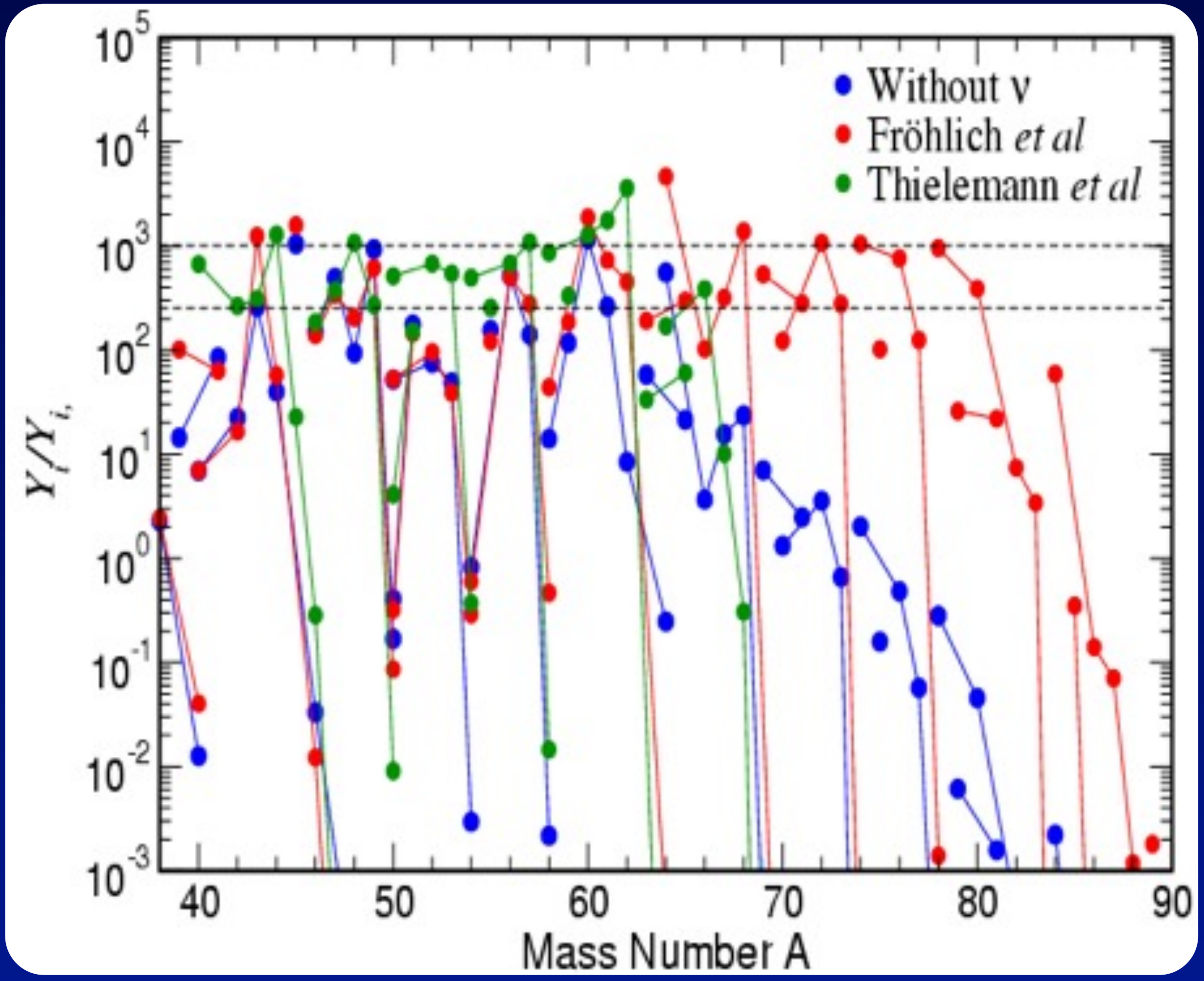
In current nucleosynthesis models, 2 parameters, the Bomb/Piston energy and the mass cut, are constrained by observations of explosion energy and mass of ^{56}Ni ejected.

Neutrinos & Nucleosynthesis

Despite the perceived importance of neutrinos to the core collapse mechanism, models of the nucleosynthesis have largely ignored this important effect.

Nucleosynthesis from neutrino-powered supernova models shows several notable improvements.

1. Over production of neutron-rich iron and nickel reduced.



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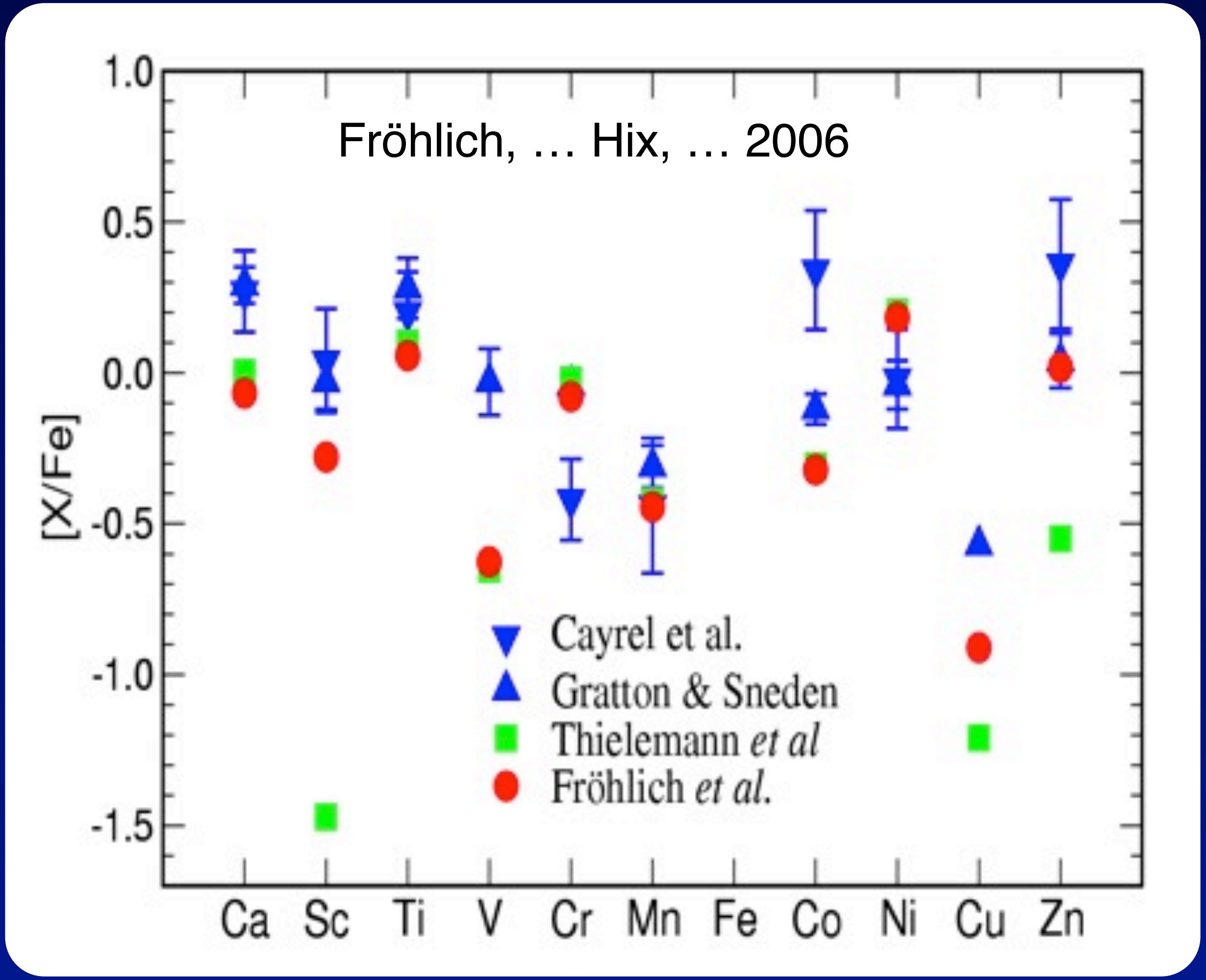

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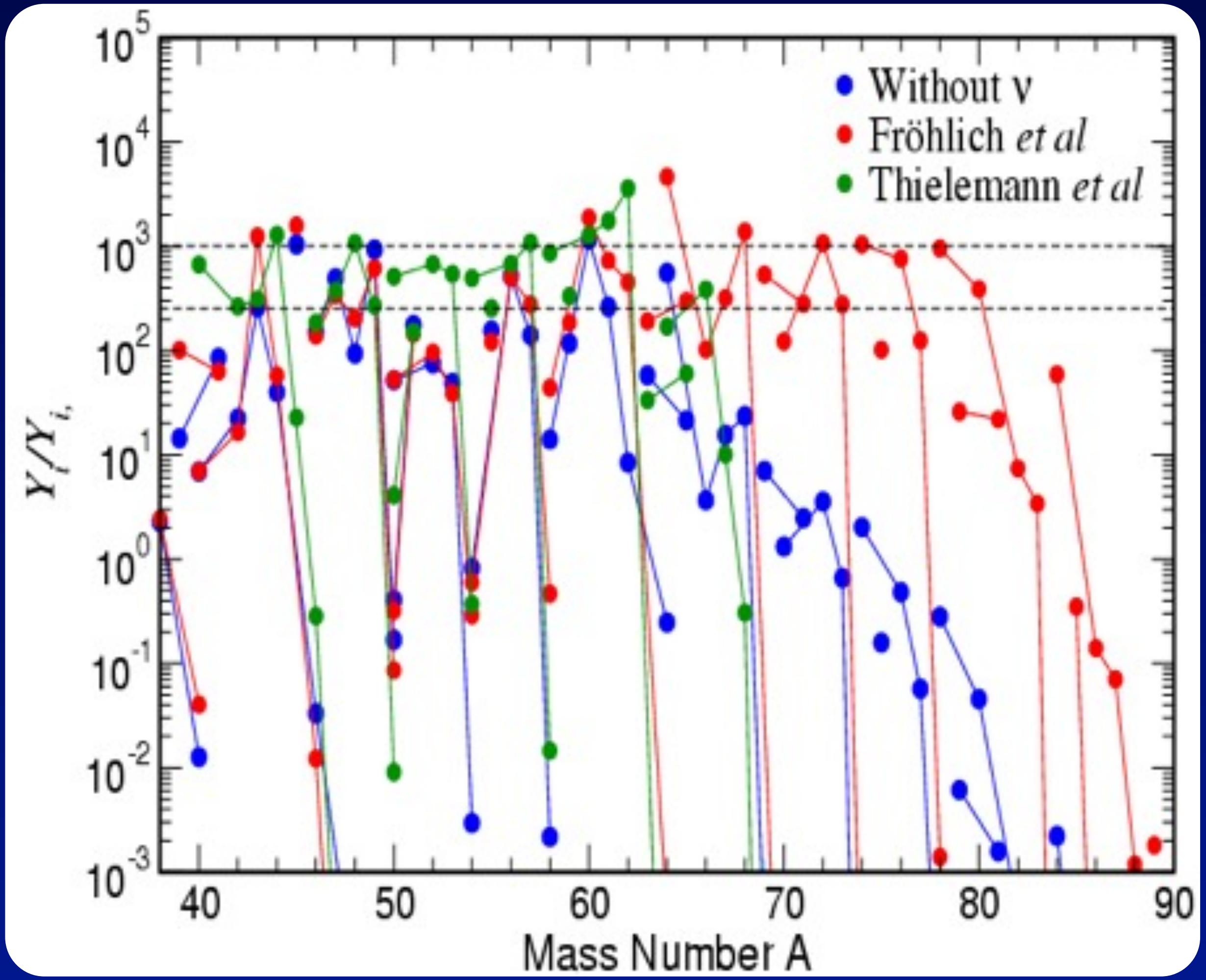
Nucleosynthesis from neutrino-powered supernova models shows several notable improvements.

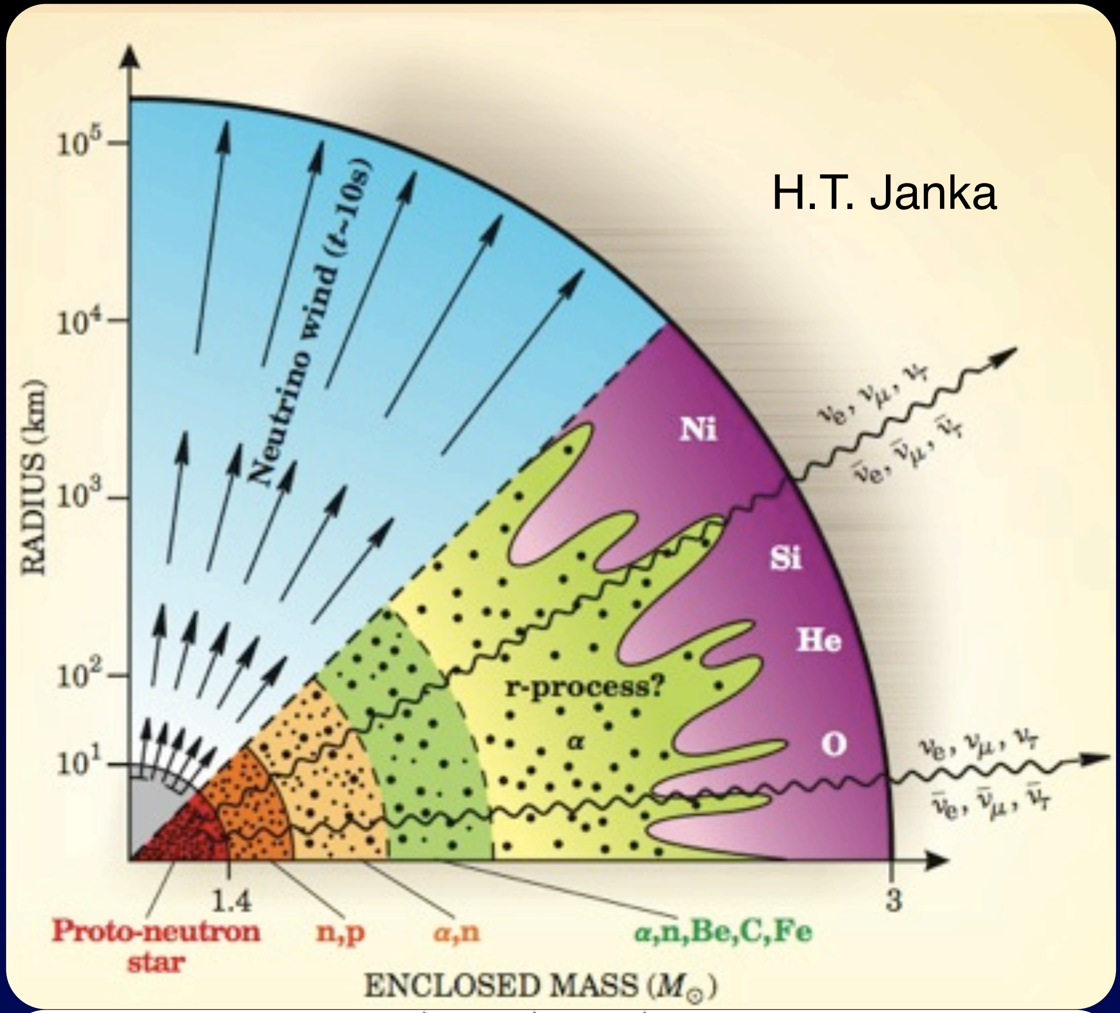
1. Over production of neutron-rich iron and nickel reduced.
2. Elemental abundances of Sc, Cu & Zn closer to those observed in metal-poor stars.
3. Potential source of light p-process nuclei (^{76}Se, ^{80}Kr, ^{84}Sr, ^{92,94}Mo, ^{96,98}Ru).

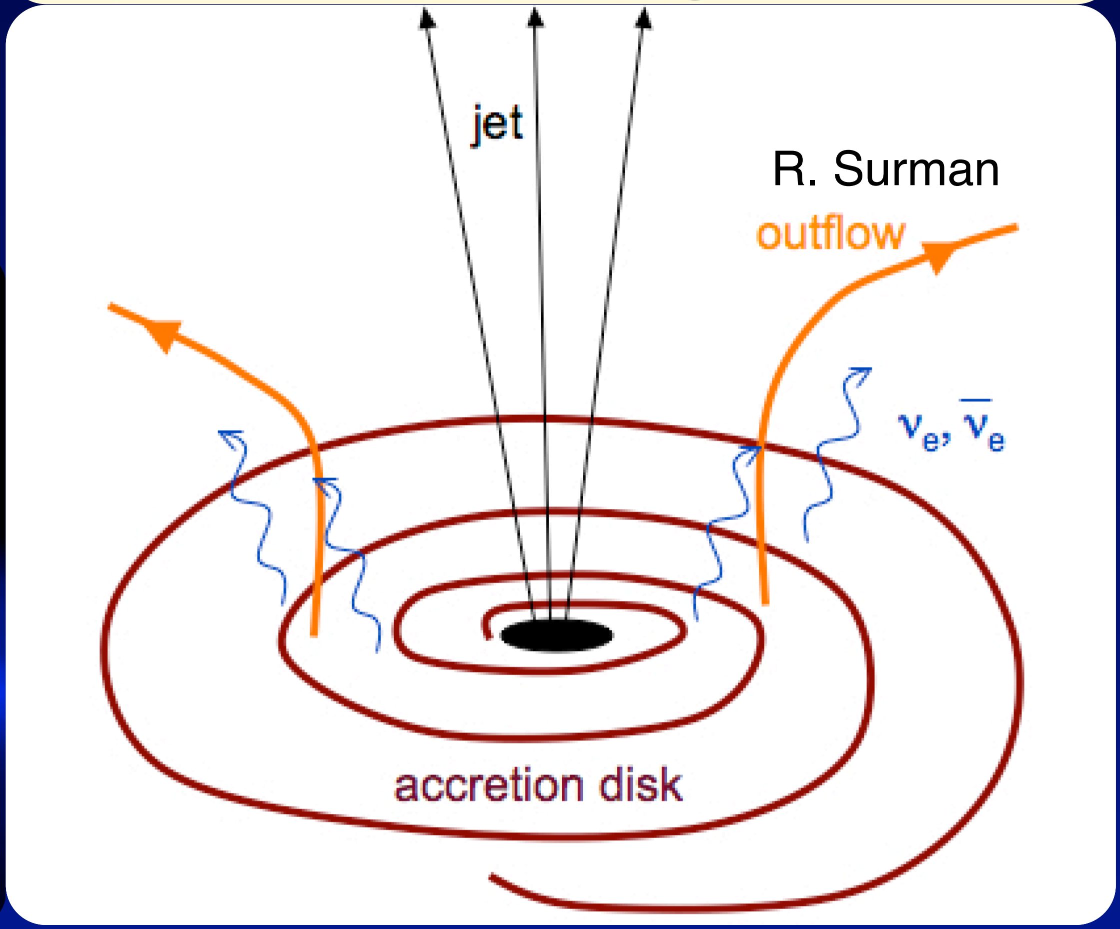


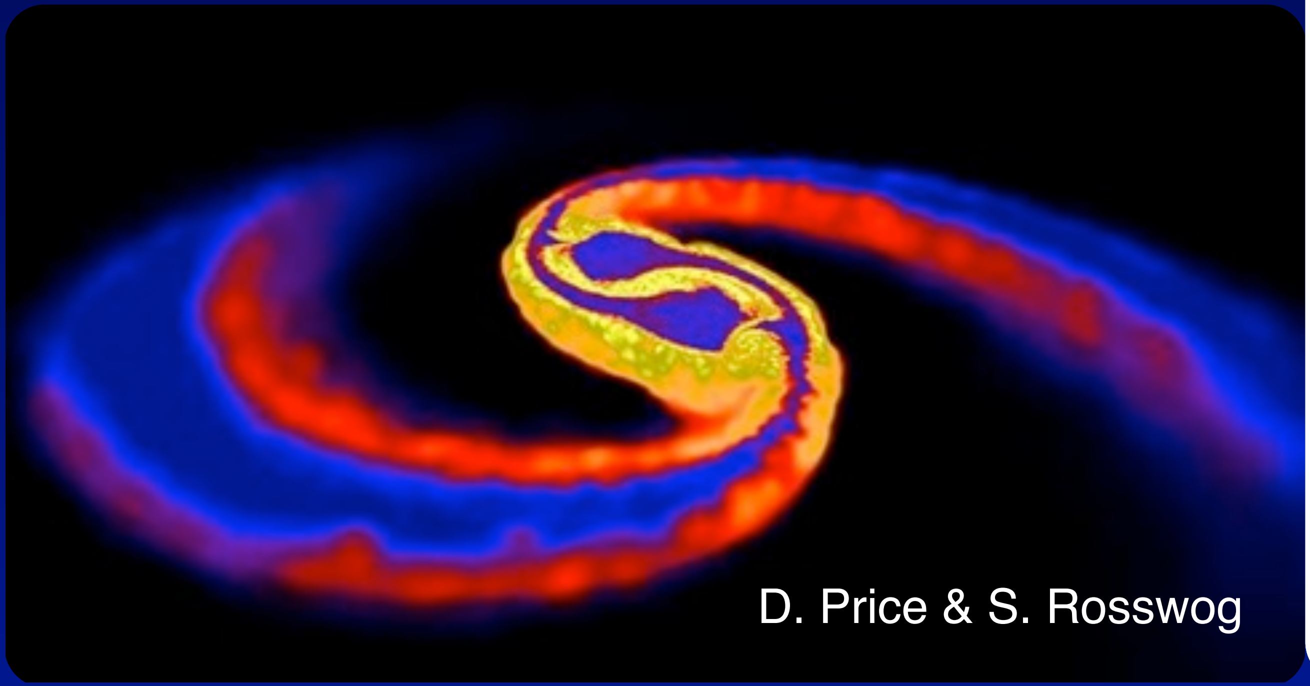
Site of the r-process

Formation of r-process requires neutron-rich, high entropy matter. May occur in

1) PNS wind in an SN,
2) in a wind from a collapsar disk, or
3) in a neutron star merger.

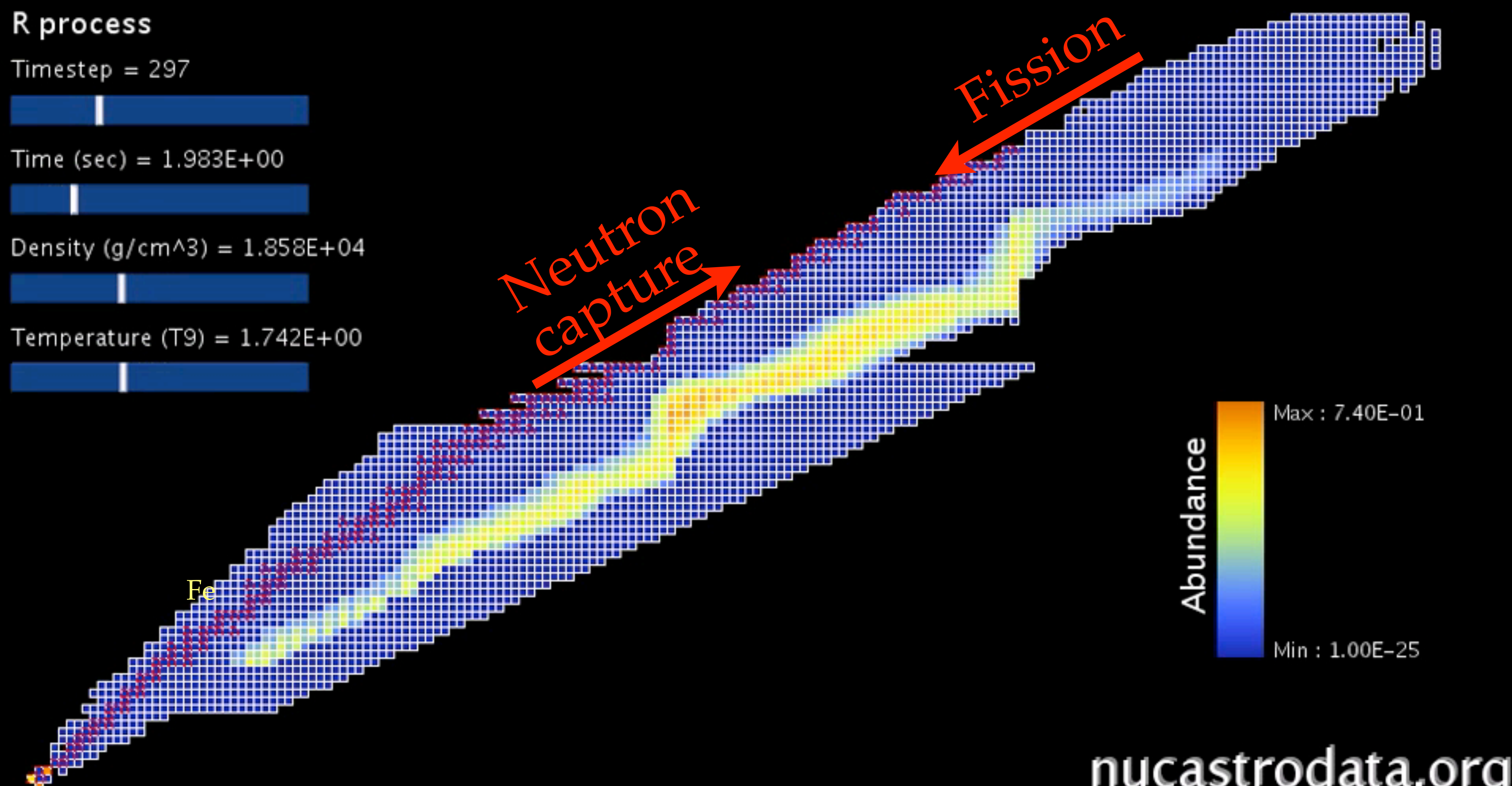






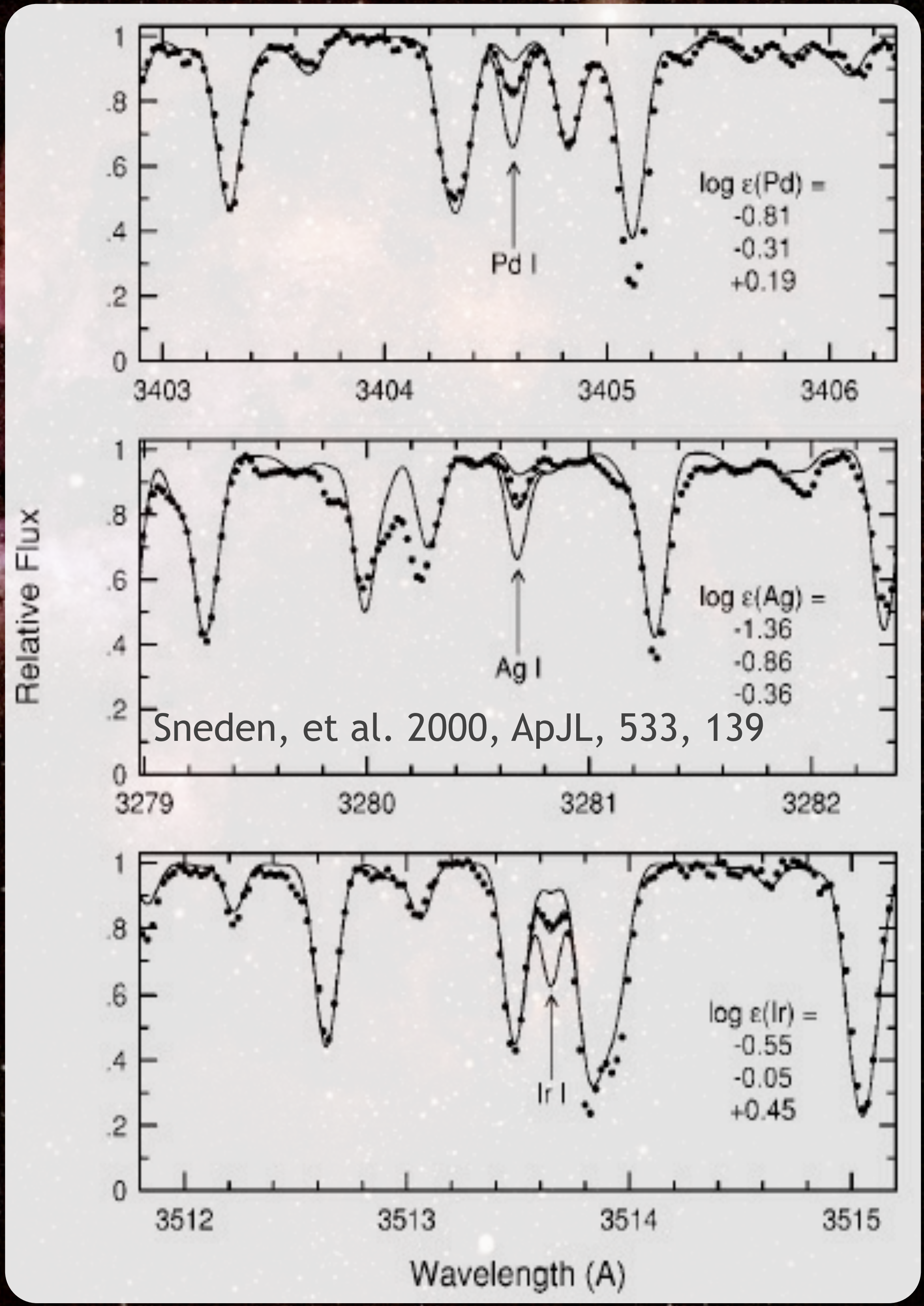
Simulating the r-process

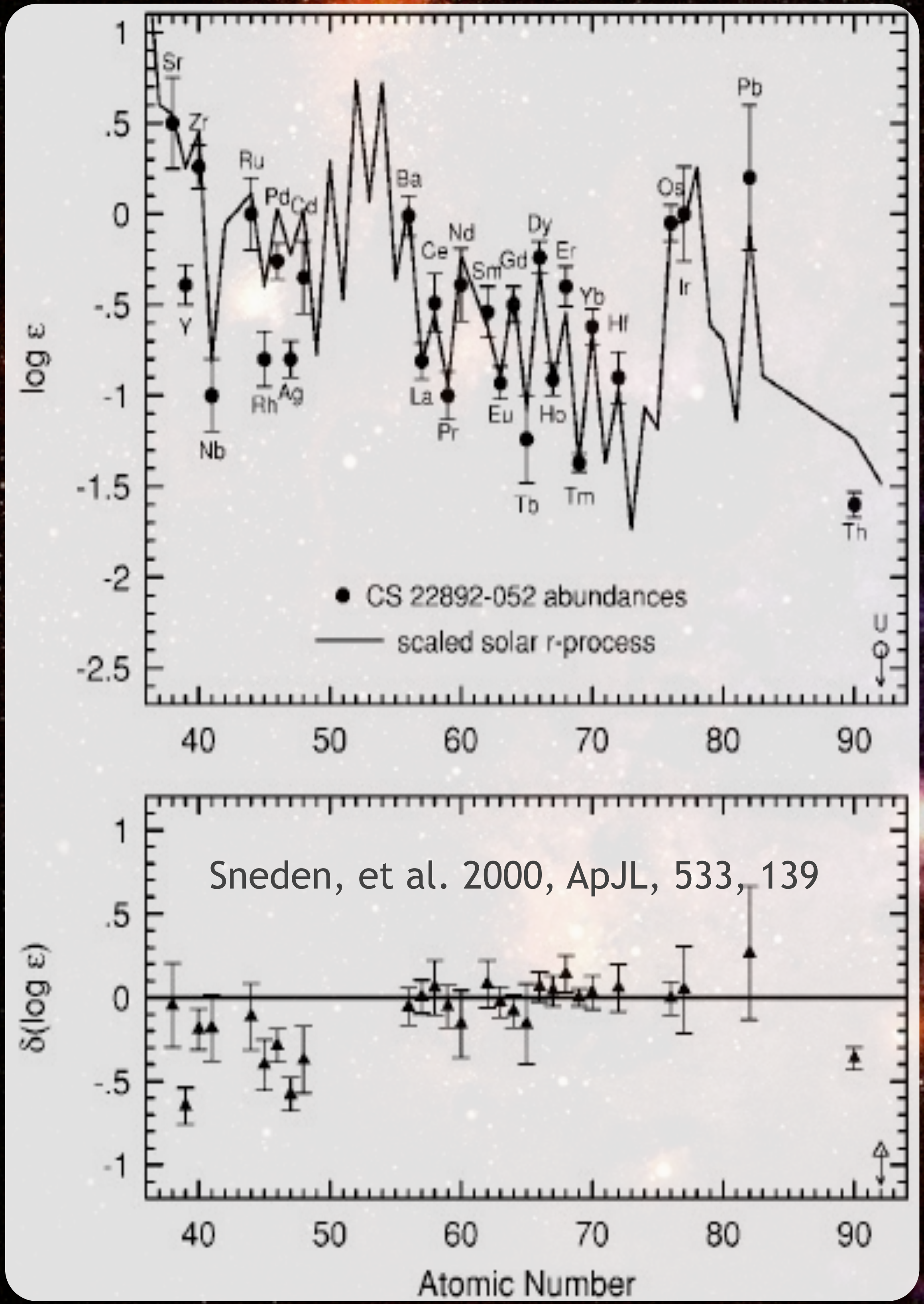
Uncertainties about the site of the r-process provide considerable latitude for modeling.



Beun, McLaughlin, Surman & Hix 2006

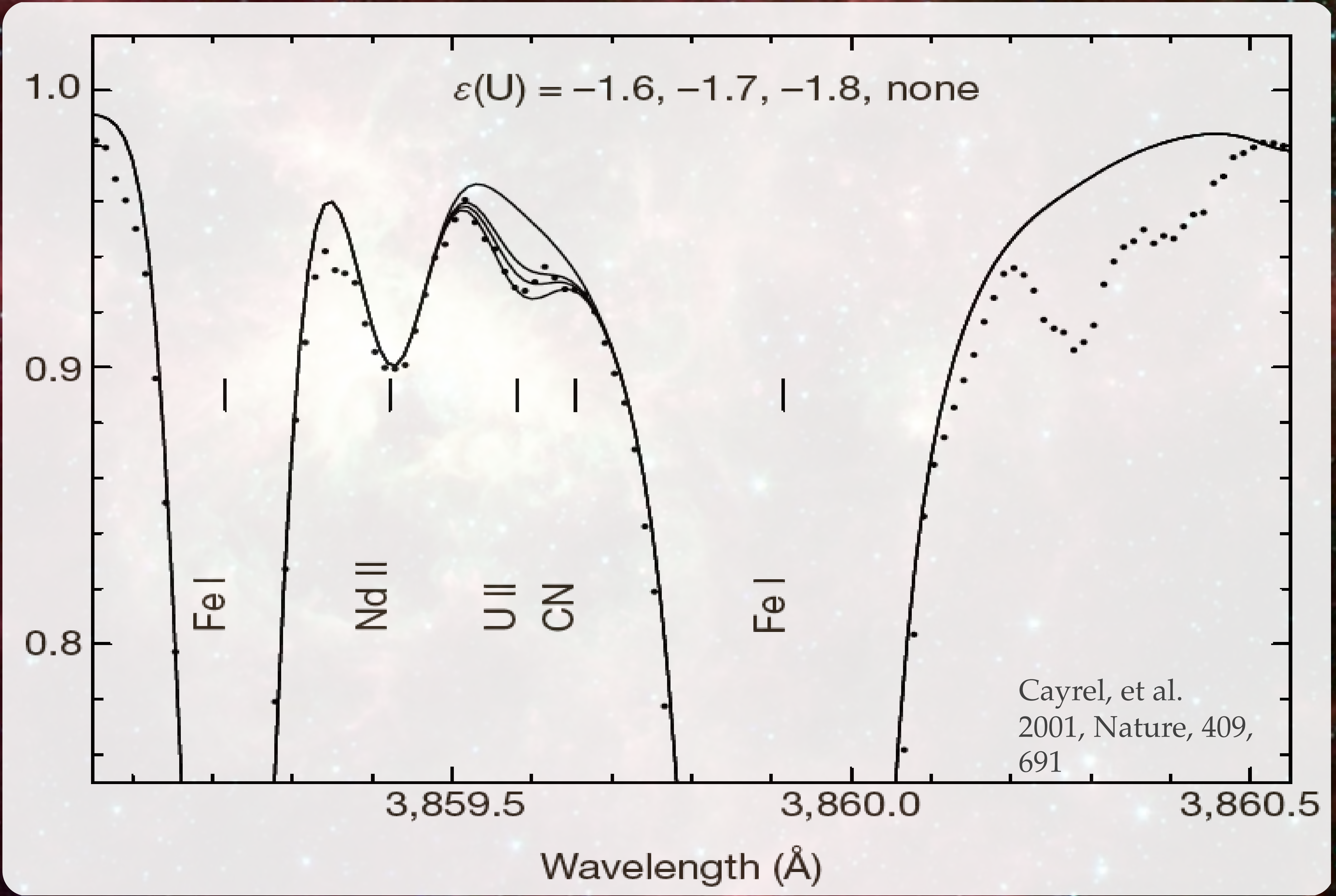
r-process Elements in old stars





Uranium?

CS31082-001 has 1/800 Solar Fe but 1/9 Solar Os/Ir

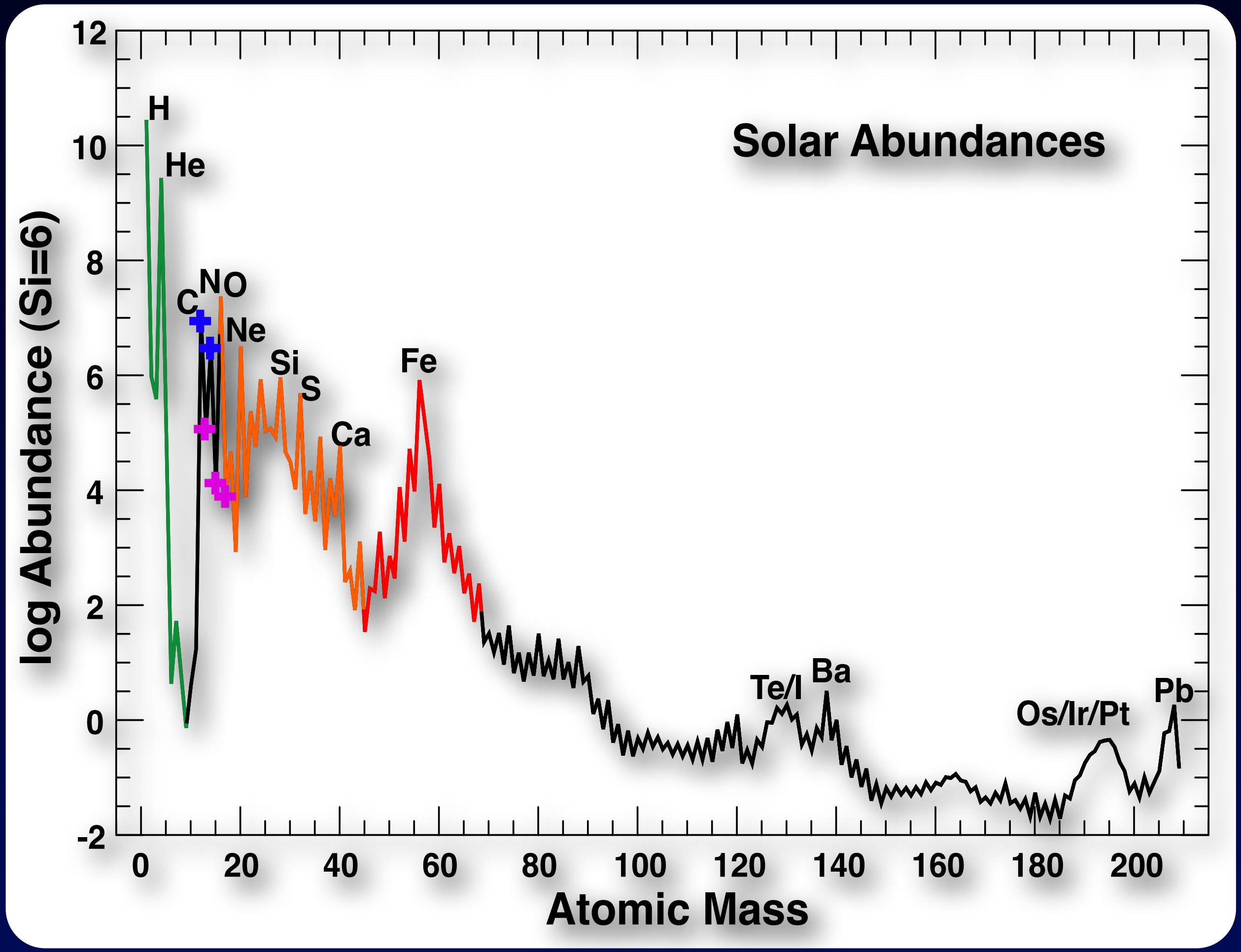


Decay of ^{238}U ($\tau_{1/2} = 4.5$ Gyr) implies 12.5±3 Gyr

Summary

What role do star, supernovae, novae & X-ray bursts play in cosmic nuclear evolution?

- Core Collapse Supernovae produce the intermediate mass elements, O - Si- Ca, and ~½ of Iron Peak species.
- Thermonuclear supernovae produce ~½ of the Iron peak isotopes.
- Stars produce C, N & s-process.



- Novae are likely responsible for odd mass isotopes of light elements like C, N, O.

Nuclear physics drives all of these events and their resulting nucleosynthesis.