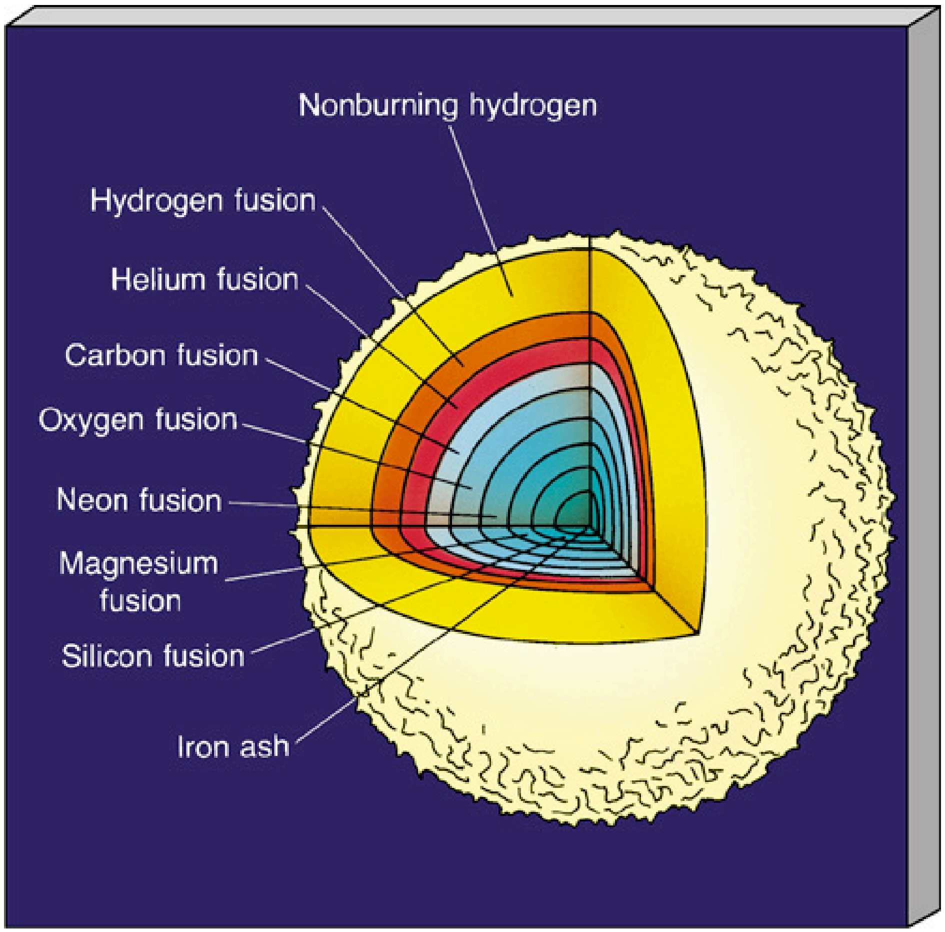
The Evolution of High-mass Stars

- For stars with initial main-sequence mass greater than around $6M_o$ the evolution is much faster and fundamentally different.

$1M_o$	10×10^9 years
$3M_o$	500×10^6 years
$15M_o$	15×10^6 years
$25M_o$	3×10^6 years

Massive Star Evolution



- The critical difference between low and high-mass star evolution is the core temperature.
- In stars with $M>6M_o$ the central temperature is high enough to fuse elements all the way to Iron (Fe)

Nucleosynthesis in Massive Stars

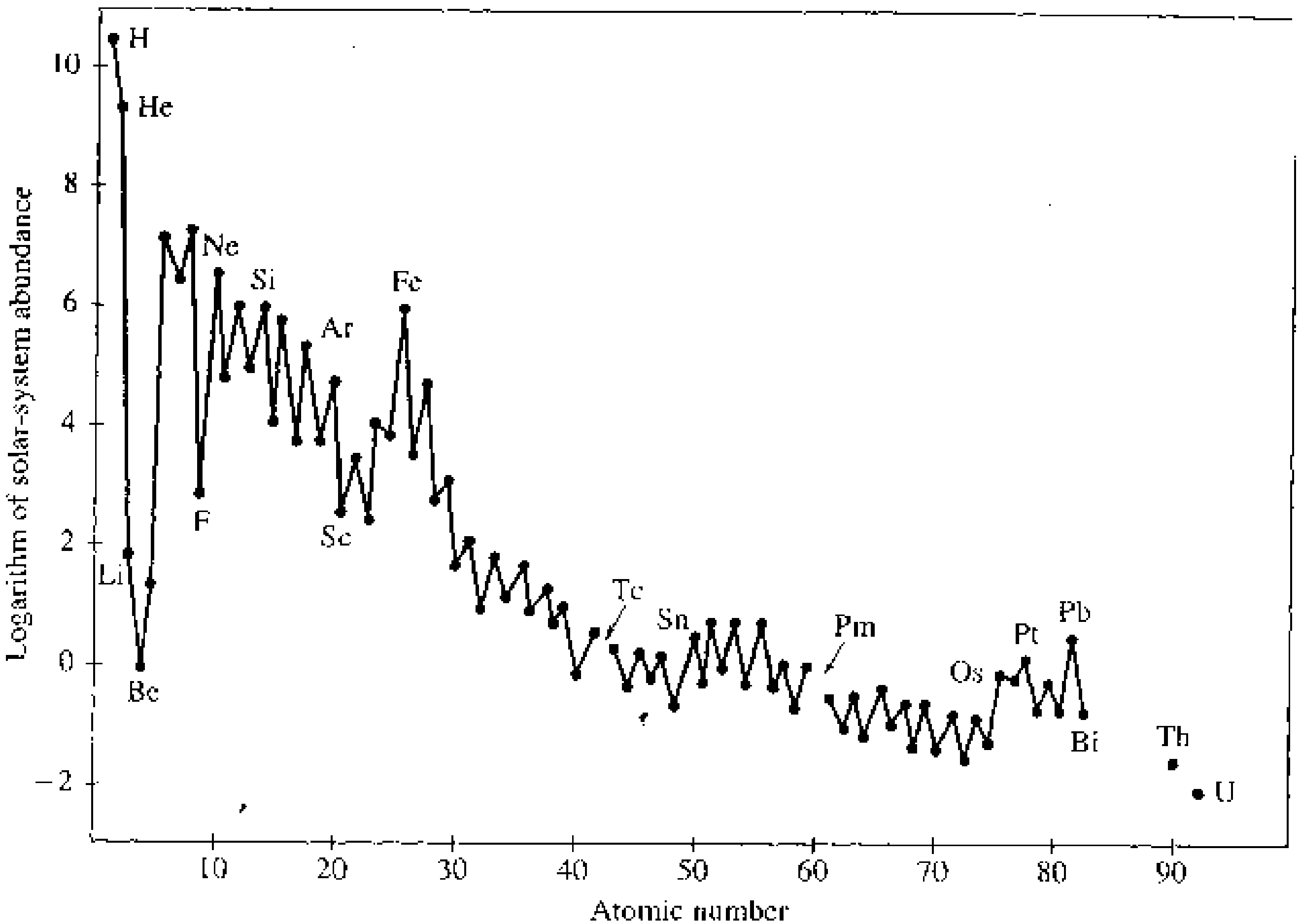
- Fusing nuclei to make new elements is called nucleosynthesis.

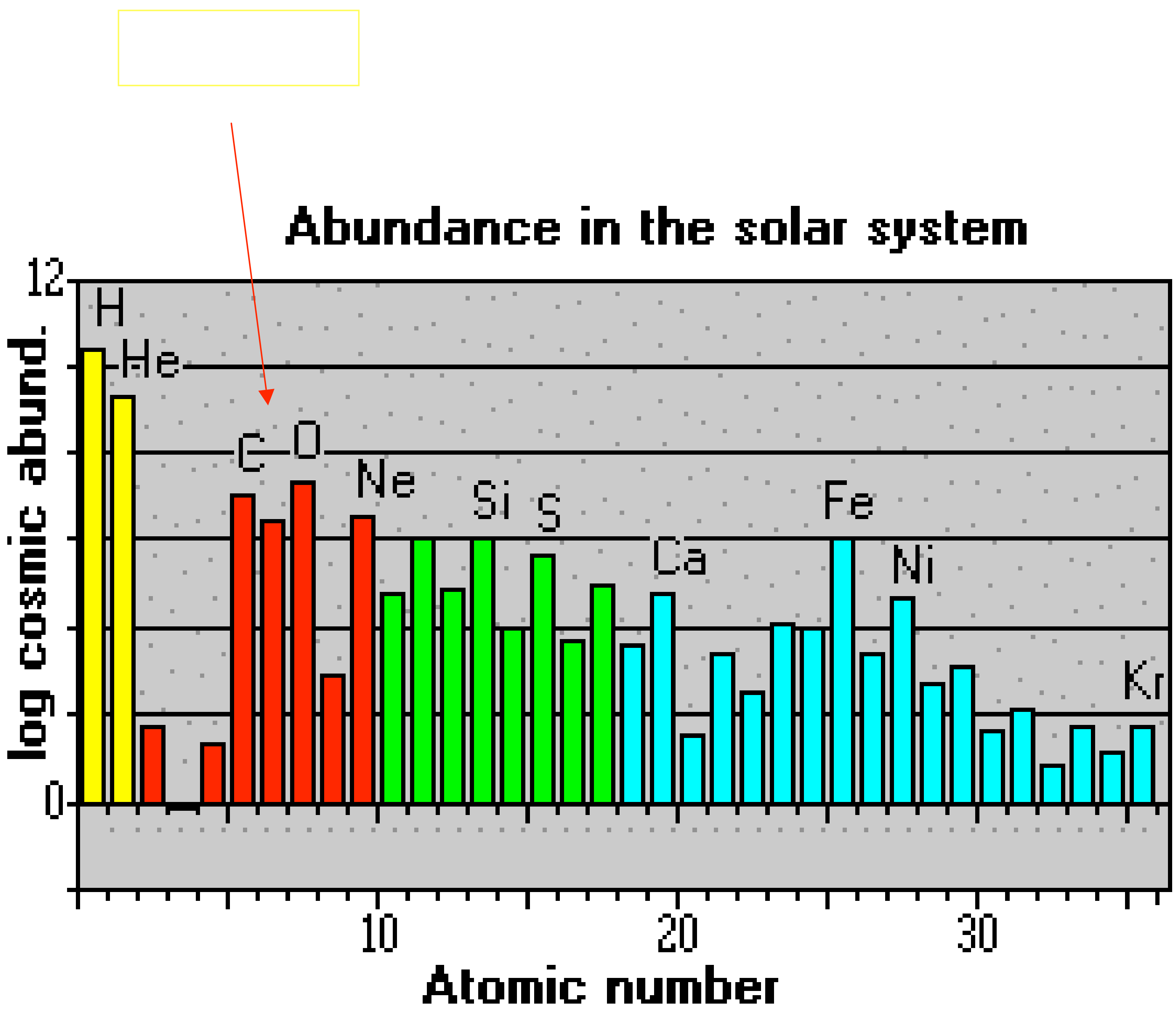
Temperature	Fusion reaction
15 million K	H -> He^{4}
100 million K	He^{4}-> C^{12}
600 million K	C^{12}-> O^{16} (Mg^{24})
15000 million K	O^{16}-> Ne^{20} (S^{32})
etc	etc

Massive Star Nucleosynthesis

- In a $25M_o$ star nucleosynthesis proceeds quickly to Fe (why it stops there we will get to in a minute).
- The most common reaction is called the \`alpha process' and it is fusing He^4 to existing nuclei. This process is reflected in to abundance of various elements in the Universe today.

Nucleosynthesis in Massive Stars

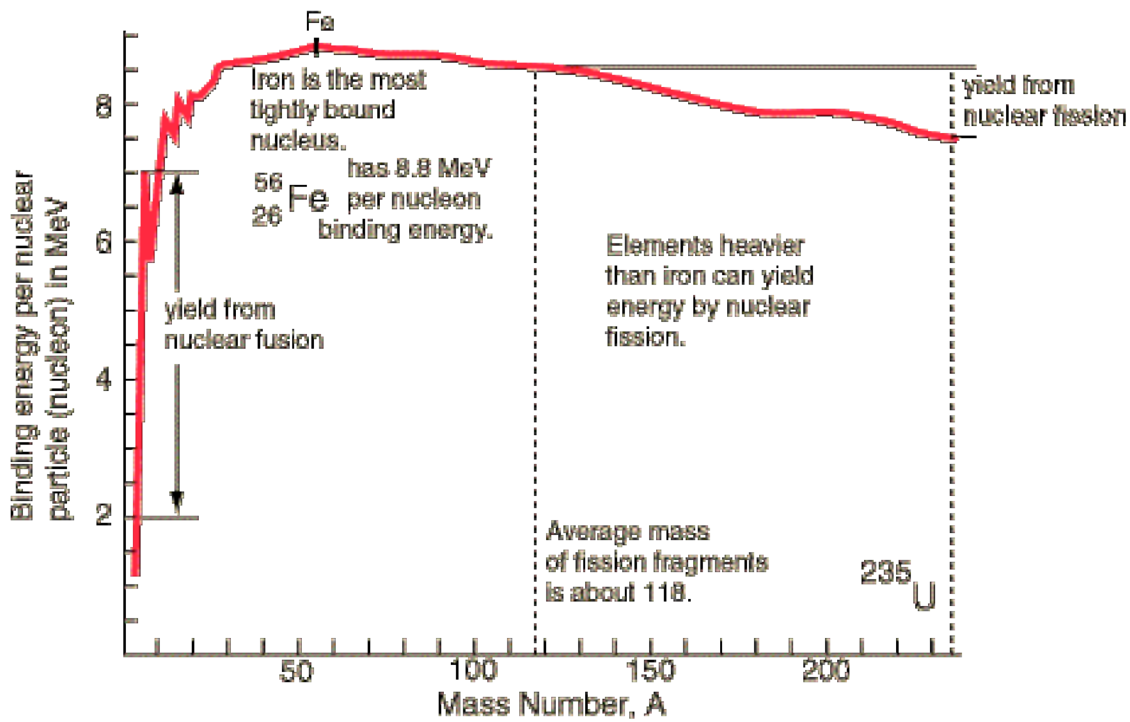




Abundance in the solar system
log cosmic abund.
12
0
H
He
C
O
Ne
Si
S
Ca
Fe
Ni
Kr
10
20
30
Atomic number

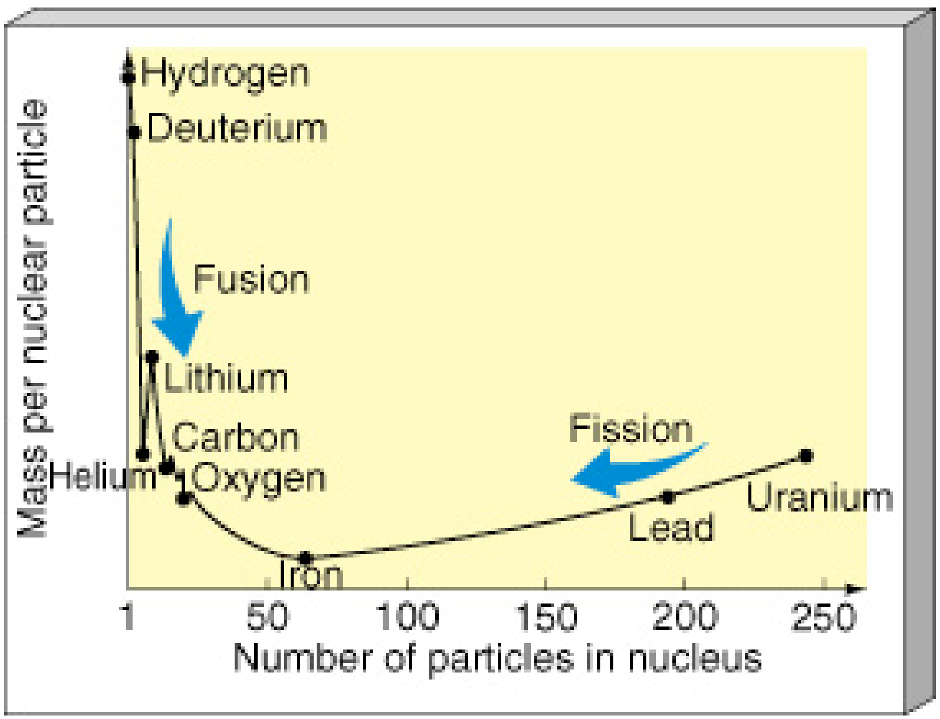
What is special about Fe?

- Fe is at the peak of the `curve of binding energy'



Fe

- An easier way to think about this is in the mass/nucleon for a given nucleus:



Nucleosynthesis

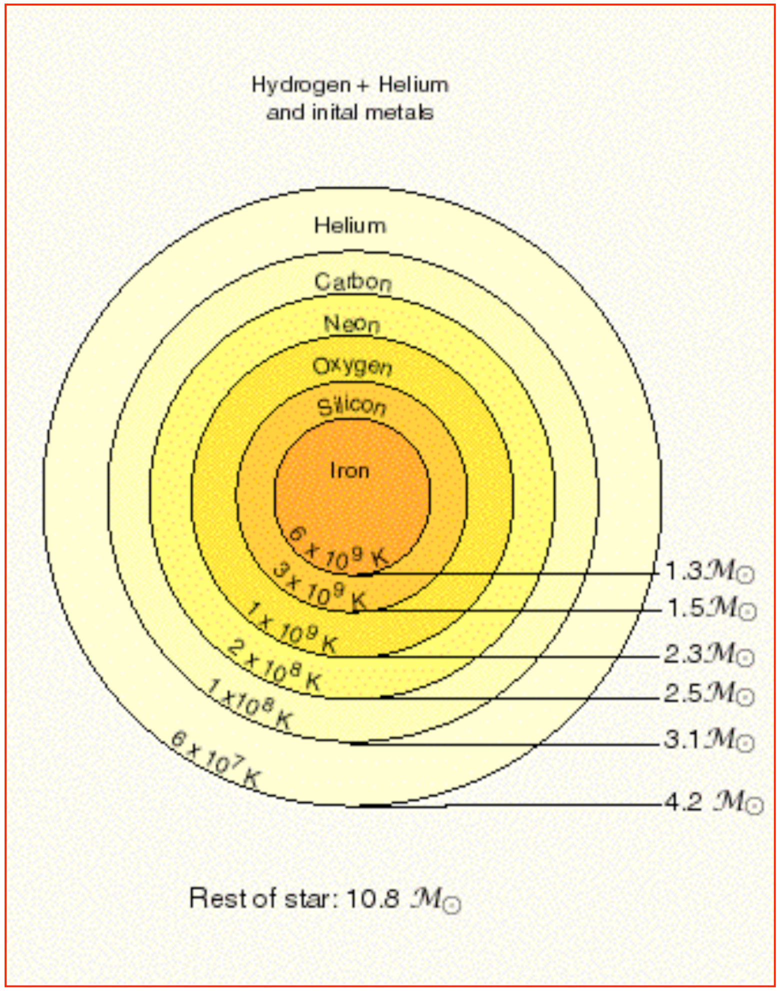
- Fusing light elements together results in more nuclear binding energy and less mass per nucleon. When the mass disappears, it is converted to energy so light-element fusion produces energy.
- But, when fusing any element to Fe, you now need to PROVIDE some energy to be converted into mass and Nature doesn't like to do this.
- On the other hand, elements heavier than Fe can break apart and go to less mass/nucleon and release energy.

Stage	Central T	Duration (yr)
H fusion	40 million K	7 million
He fusion	200 million K	500 thousand
C fusion	600 million K	600
O fusion	1.2 billion K	1
Ne fusion	1.5 billion K	6 months
Si fusion	2.7 billion K	1 day

Core Collapse

- The fusion chain stops at Fe and an Fe core very quickly builds.
- Within a day of starting to produce Fe, the core reaches the 1.4M_o Chandrasekar limit.
- On a timescale less than a second the core implodes and goes through a series of events leading to a tremendous explosion.

Massive-star Evolution



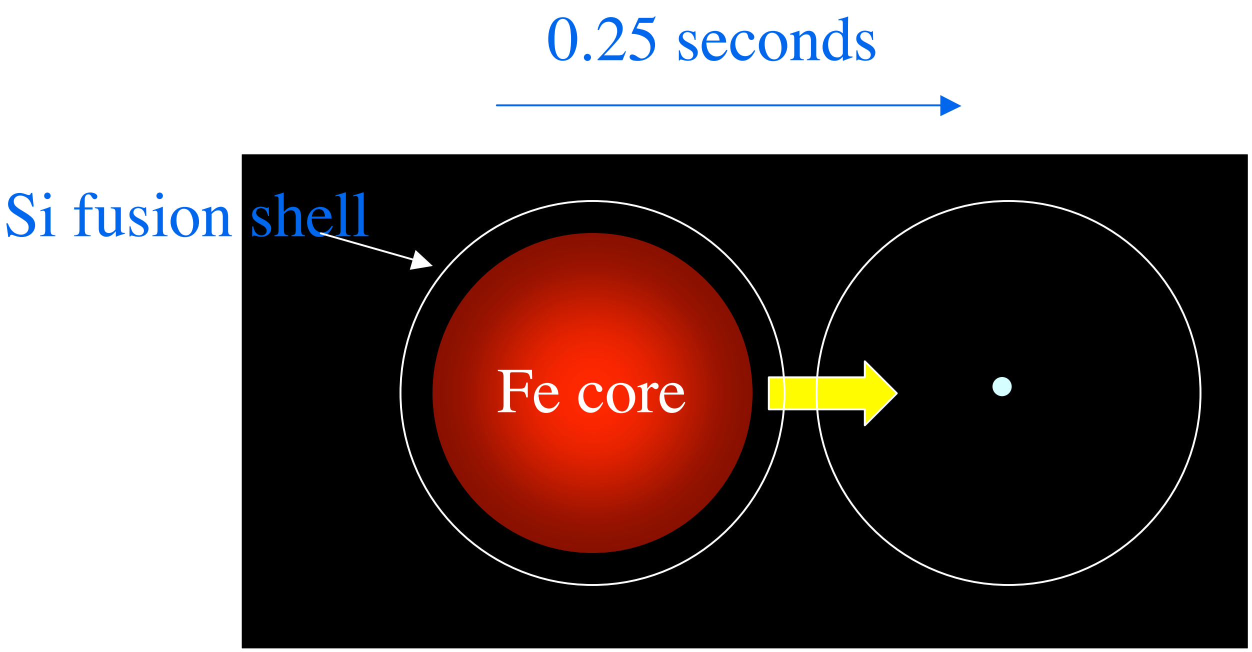
Core Collapse

1) Exceed the Chandrasekar limit
2) Temperature reaches 10 billion K
3) Fe nuclei photodisintegrate, cooling the core and speeding the collapse
4) The gravitational pressure is so high that neutronization occurs converting the electrons and protons into neutrons and releasing a blast of neutrinos

0.1 sec

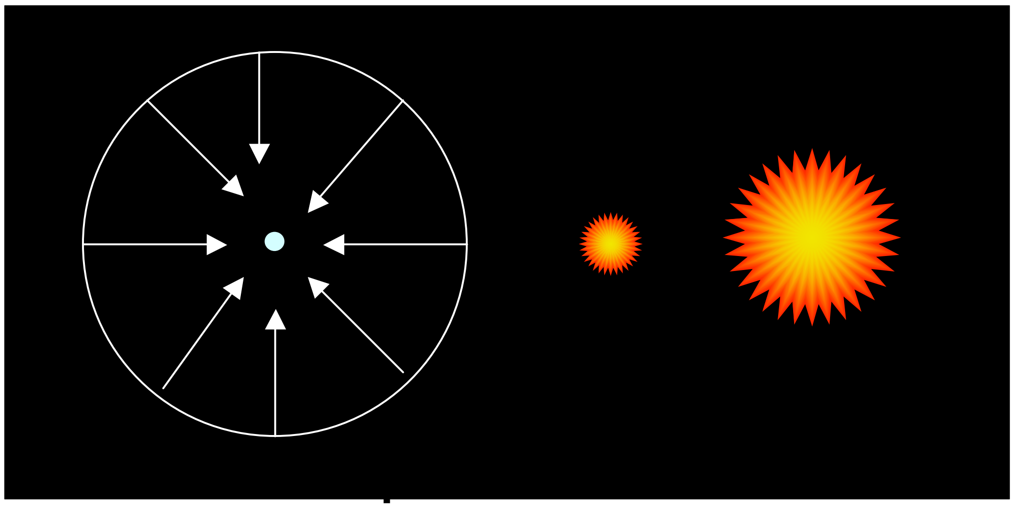
0.2 sec

Core-Collapse in Massive Stars



1) Fe core exceeds 1.4M and implodes
2) Temp reaches 5 billion K and photodisintegration begins to blast apart the Fe nuclei
3) Neutronization occurs: $e^- + p^+ \rightarrow n^0$ + neutrino

Core-Collapse in Massive Stars



4) Neutron ball is at `nuclear density' (>10^{17} kg/m^3) and is much harder than any brick wall.

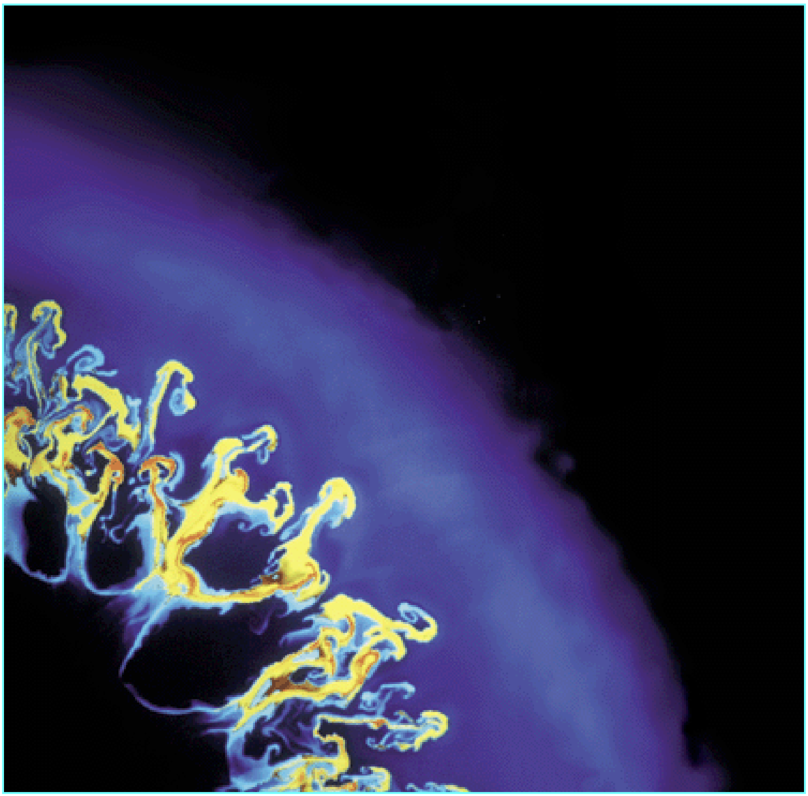
5) Infalling layers crash into neutron ball, bounce off, create a shock wave and, with help from the neutrinos, blast off the outer layers of the star at 50 million miles/hour.

SNII Bounce Shock wave

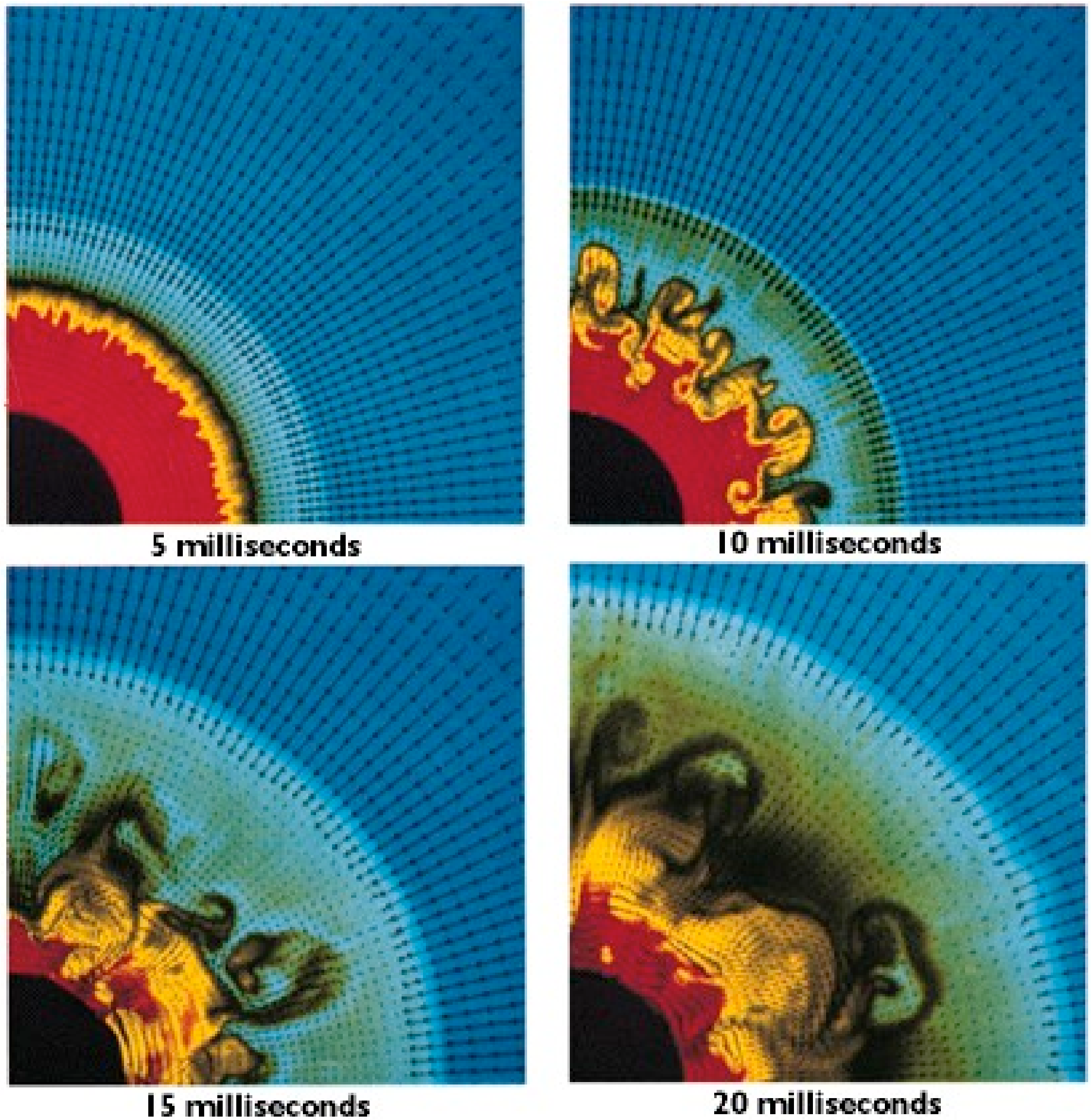
Core-collapse Supernovae

- The resulting explosion is called a SNII
- Expect:
  - Rapidly expanding debris
  - 10^8 times the optical luminosity of the Sun
  - Chemically enriched debris
  - Association with massive stars/star formation
  - Extremely dense 1.4 solar mass neutron ball

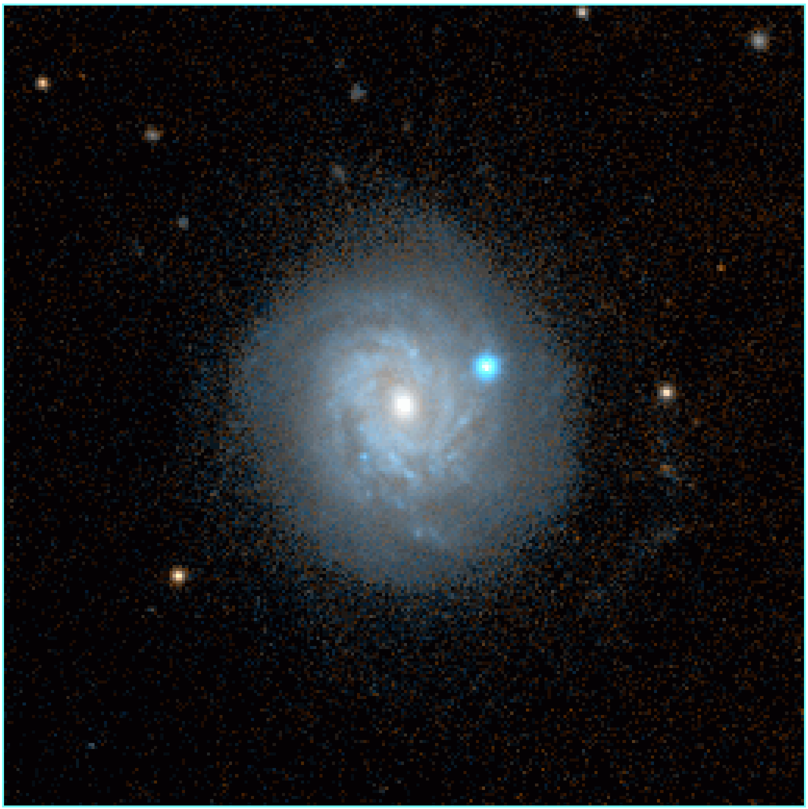
Supernova II



- This is a wild event.
- In the explosion the models predict:
- Many rare elements will be manufactured in non-equilibrium reactions
- A rapidly expanded debris shell
- An extremely dense ball of neutrons will be left behind


5 milliseconds
10 milliseconds
15 milliseconds
20 milliseconds

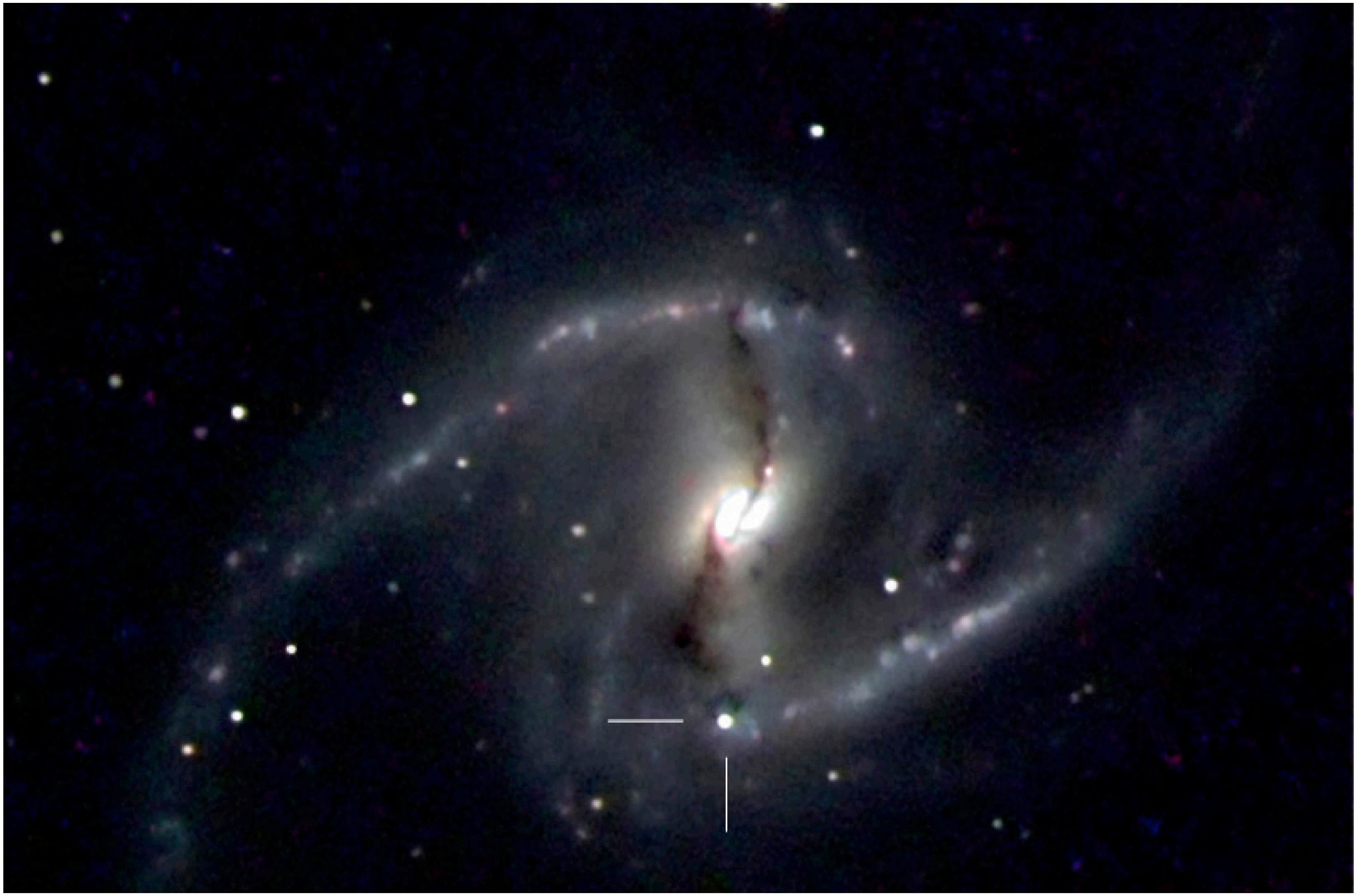
Supernova II

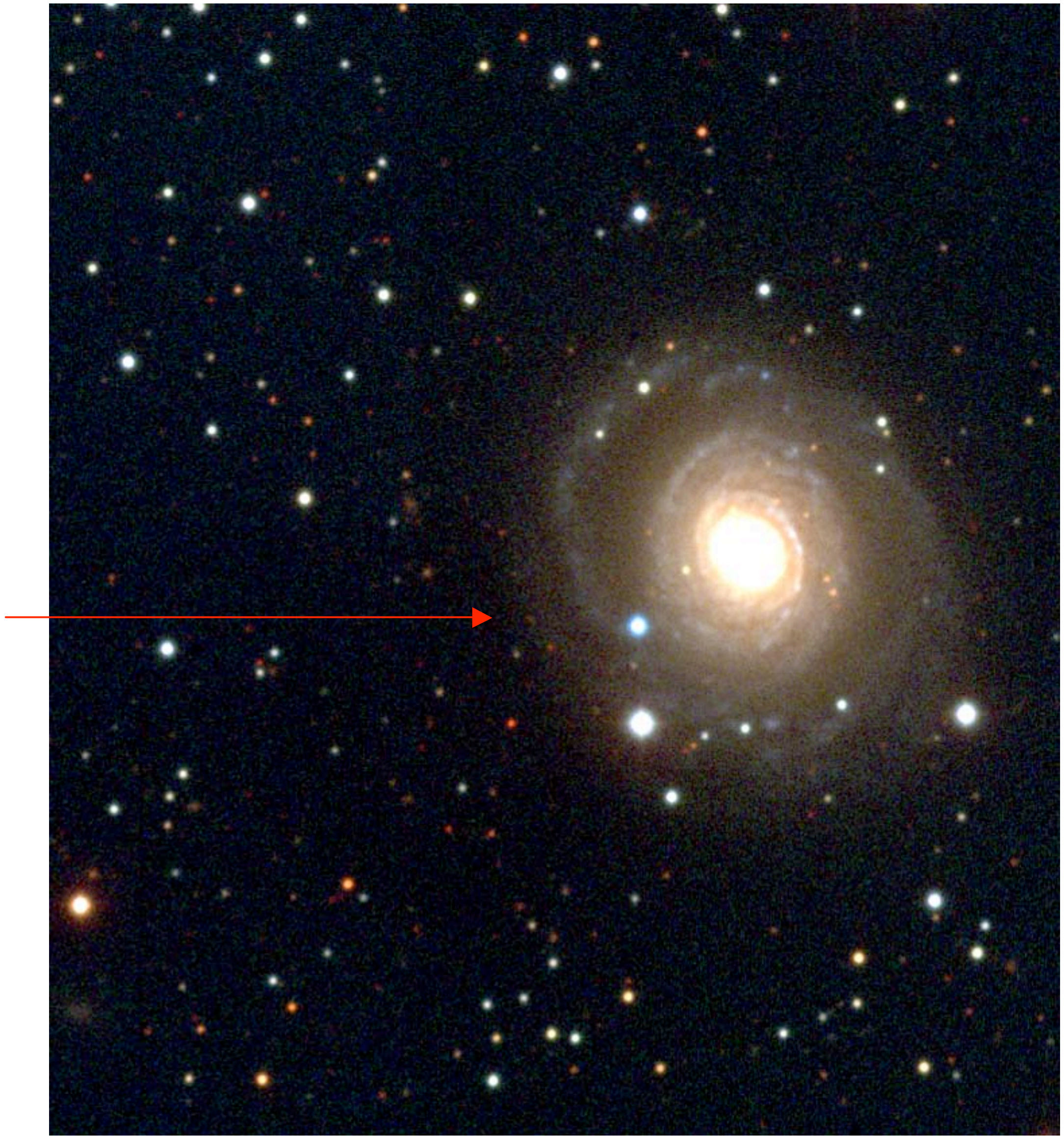


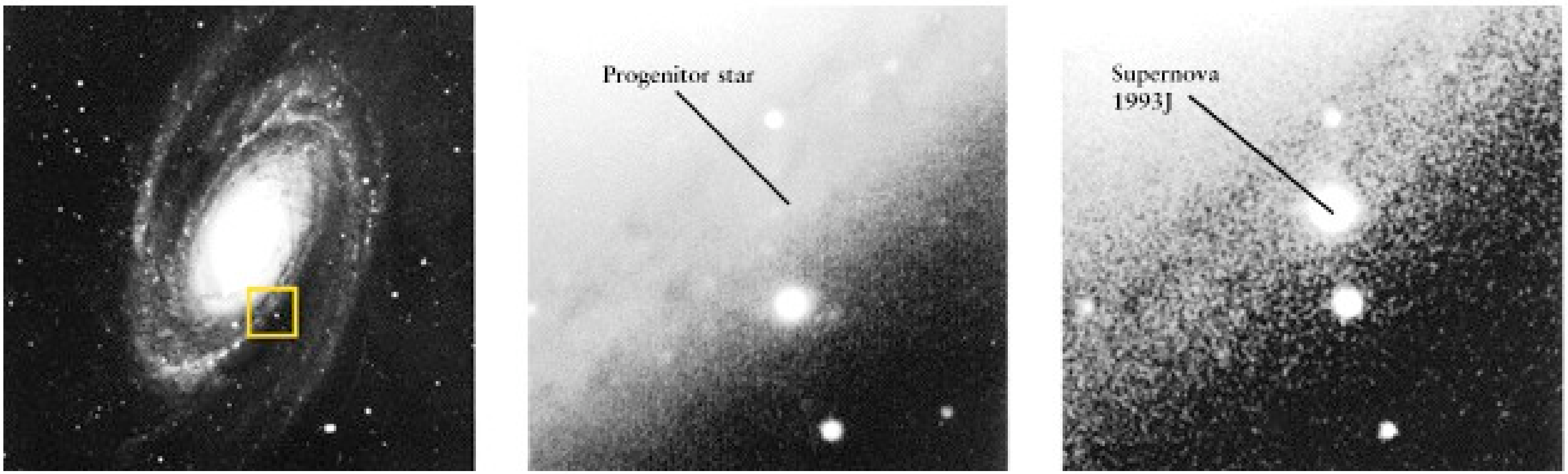
- Any reasons to believe this story?
- Many!

1) SN II have been seen in many galaxies in the last 100 years and always near star-formation regions:

Guilt by association!







a b c

SNII

2) Predicted peak luminosity of $10^8 L_o$ is observed

3) Predicted expansion velocity of 10,000 to 20,000 km/sec is observed

4) In the Galaxy, when we point our telescopes at historical SN, we see chemically-enriched, rapidly expanding shells of gas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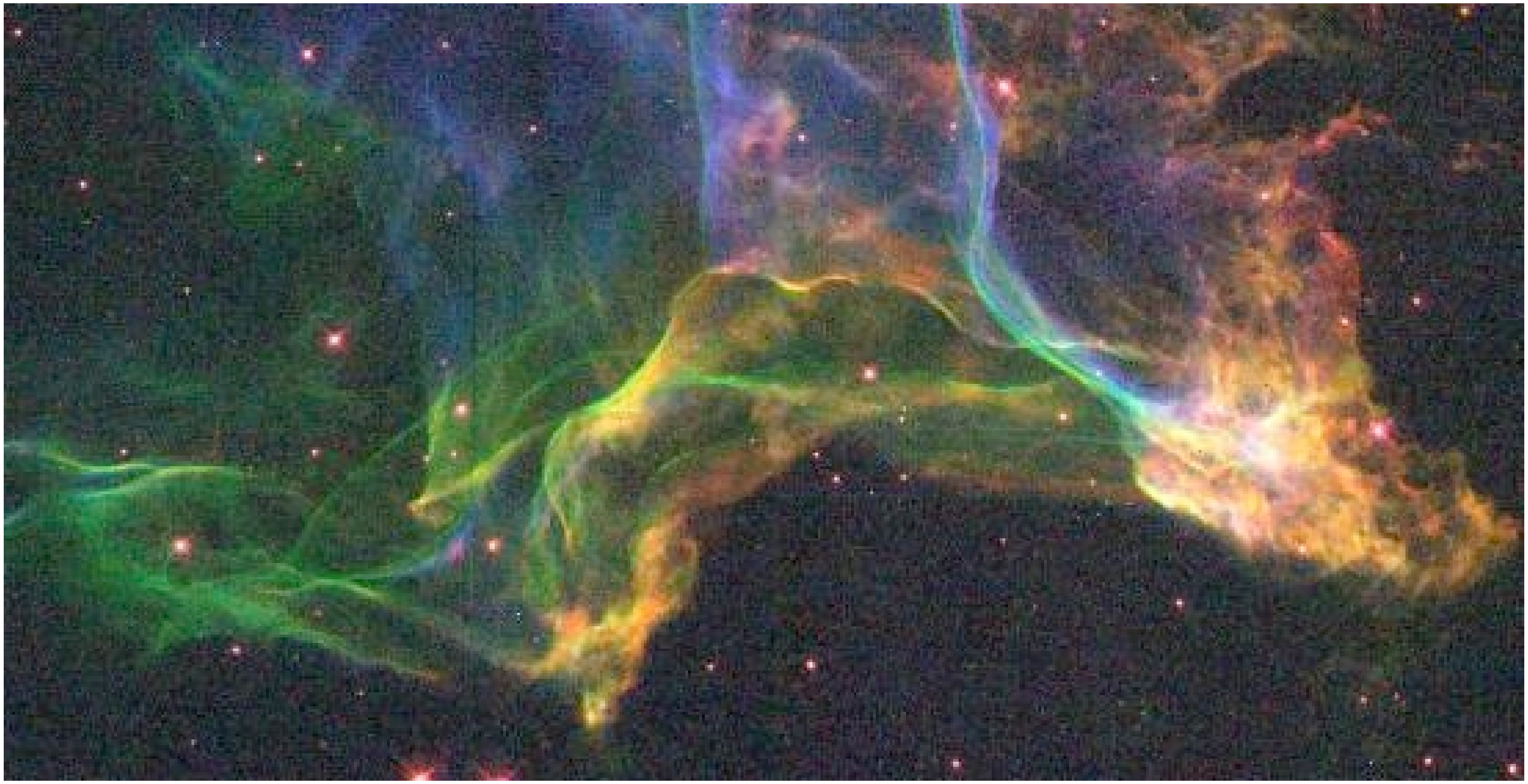


NGC 1850 in LMC

SN 1987a

- There was a major breakthrough in 1987.
- 165,000 years ago in a nearby galaxy called the Large Magellanic Cloud, a star blew up as a SNII.
- The first indication was a neutrino `burst'. About 10 billion neutrinos from SN1987a passed through every human on Earth. Neutrino detectors caught about 14 of them.
- 99% of a SNII energy is released as neutrinos.

SN1987a

- The second indication, about 4 hours after the neutrinos arrived was a new naked-eye star in the LMC

SN1987a

- For the first time, the progenitor star of a SNII was identified:

> $20M_o$ Supergiant -- bingo!

- The final prediction of SNII theory is that there should be a very dense ball of neutrons left behind in the center of a SNII remnant. More later.

Historical Supernovae

- There are more than 2500 SN that have been seen in other galaxies in the last 100 years. Based on other spiral galaxies, a big spiral like the Galaxy should have about:

0.5 SNI per century

1.8 SNII per century

Historical SN

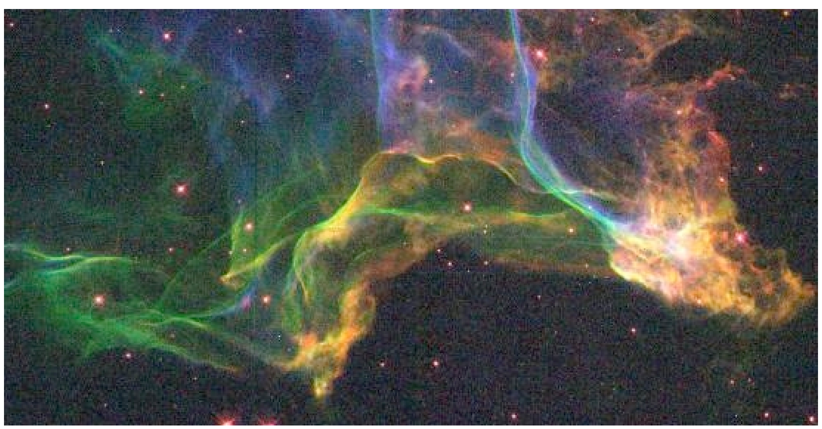
- We miss many in the Galaxy because of dust obscuration.
- From radio surveys for SN remnants, we have discovered 49 remnants for an inferred rate of 3.4 SN/century.
- There are several `historical supernovae' -- bright new stars that appeared in the sky and were recorded by various people.

Historical SN

- 1006, 1054, 1181, 1572, 1604 and 1658 were years when bright `guest stars' were widely reported

Historical SN

- For all the guest stars, point a modern telescope at the position and see a rapidly-expanding shell of material.
- In two cases, the remnant was discovered bfore the historical event



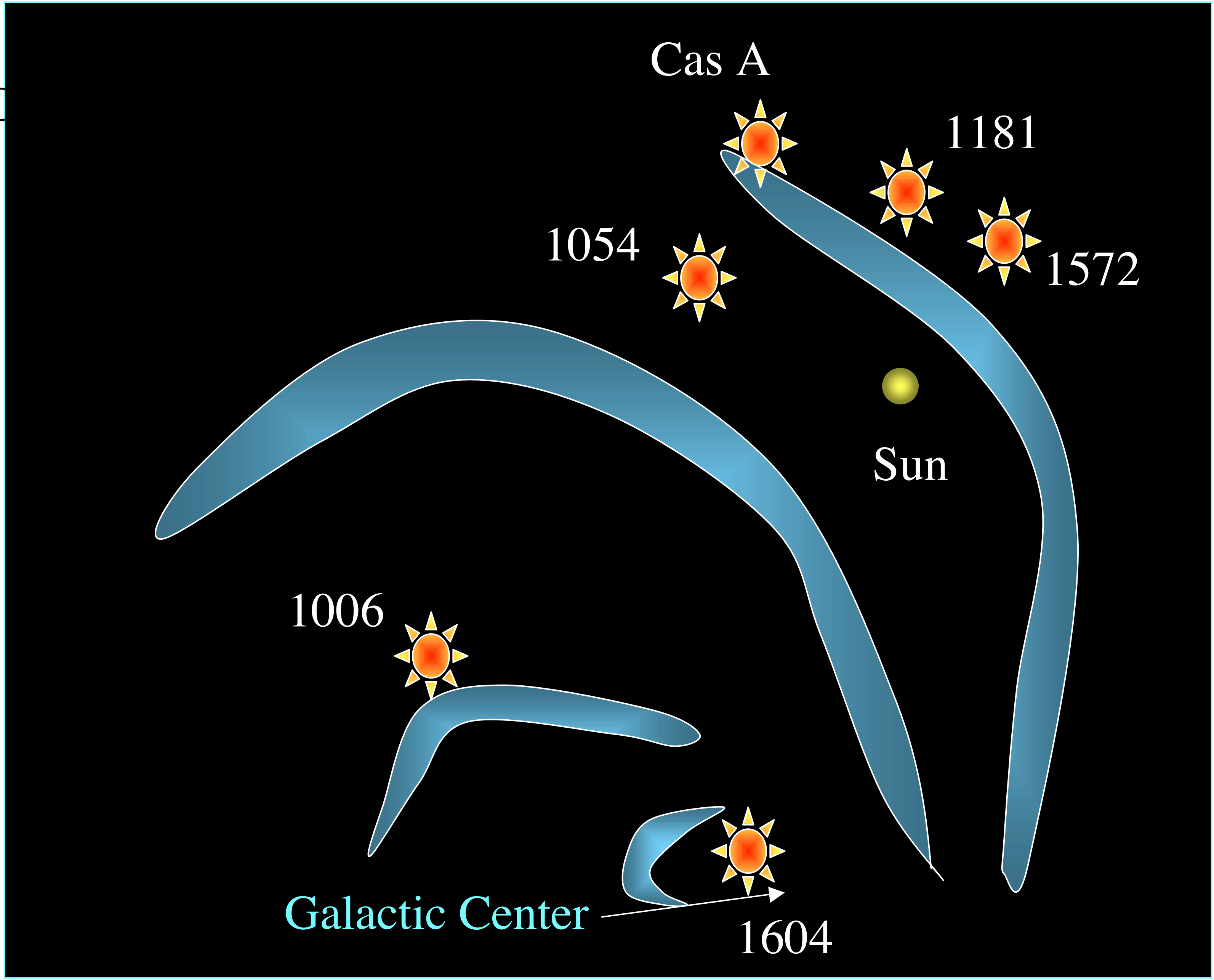
Historical SN

- The 1054AD event was so bright it cast shadows during the day -- this is the position of the Crab Nebula

Historical SN

- The nearest SN remnant is the `Gum' nebula from around 9000BC. Four times closer than the Crab, it would have been as bright as the full moon.
- A mystery is `Cas A' -- this was a SN at about 1600AD, should have been very bright, but no records of it exist.

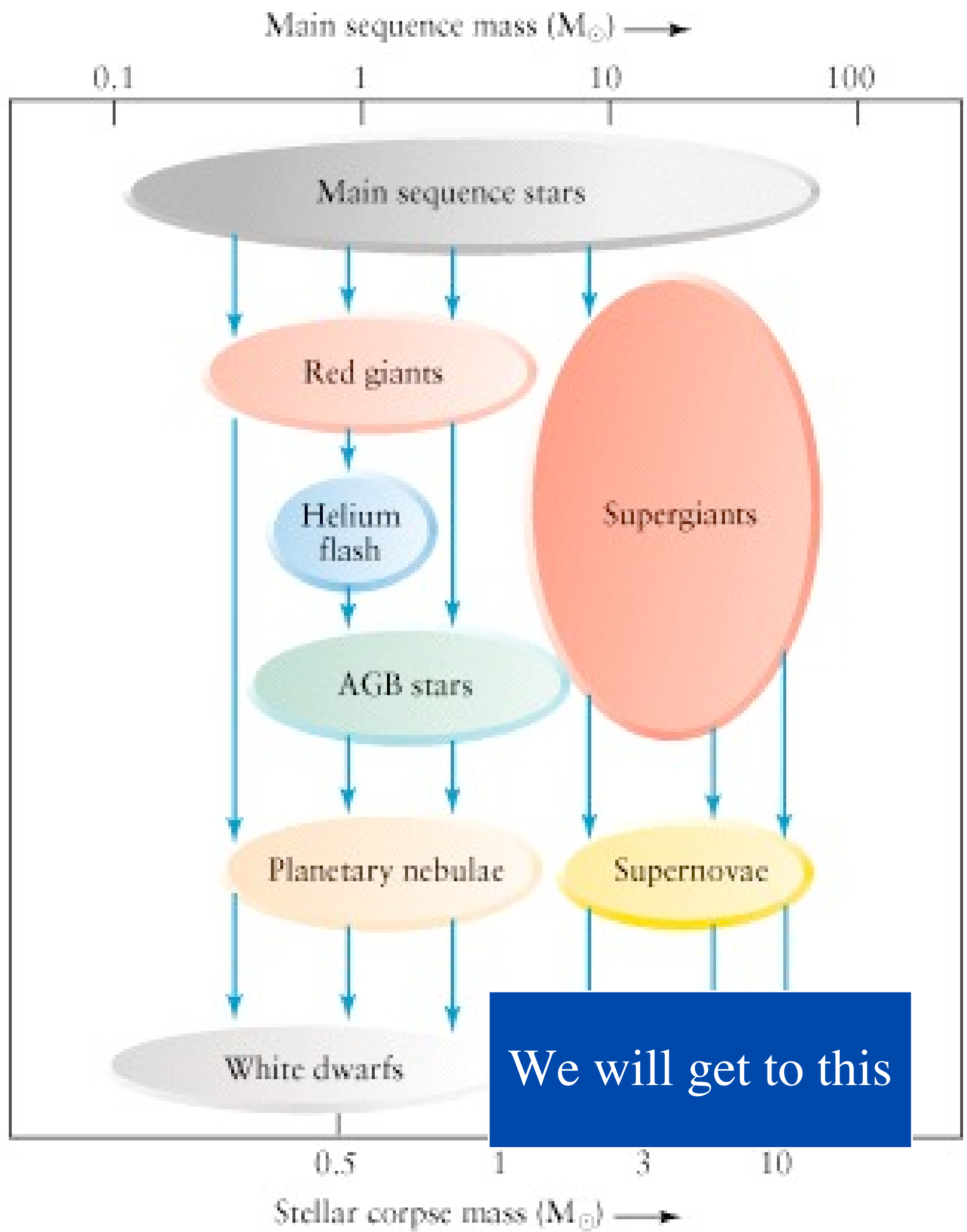
C



Supernovae in the Galaxy

- We are long overdue for a bright Galactic Supernova.
- For a while, a nearby SN was a valid candidate for the source of the demise of the dinosaurs.
- There are the products of short-lived radioactive isotopes locked up in primitive meteorites which suggest a SN in the vicinity of the Solar System about 100,000 years before the Sun formed. A SN may have triggered the collapse of the proto-Sun.

Next Galactic SN?


Main sequence mass ($M_\odot$)
0.1
1
10
100
Main sequence stars
Red giants
Helium flash
AGB stars
Supergiants
Planetary nebulae
Supernovae
White dwarfs
We will get to this
0.5
1
3
10
Stellar corpse mass ($M_\odot$)