- Do better on quizzes!
  - Know the answers to homework questions
  - Attend sections (6 per week, you can fit one in) regularly
  - LSS tutor (sokshaw@ucsc.edu) Sophie Shaw
  - Send me or TA an e-mail for office hours
  - Ask questions in class

SECTION 3

- Binary stars, nova, supernova I
- The origin of the elements
- Special relativity, General relativity, Black Holes
- The Milky Way Galaxy and other galaxies
- The distance scale of the Universe and the Hubble expansion

Evolution of Close Binary Systems

- There are many multiple star systems in the Galaxy, but for the vast majority, the separation of the stars is large enough that one star doesn't affect the evolution of the other(s).
- However, the minority of systems that are spatially close are important for several phenomena

The Algol Mystery

"Algol" is a double-lined eclipsing binary system with a period of about 3 days (very short). The two stars are:

Star A: $3.4M_{Sun}$ main-sequence star
Star B: $0.8M_{Sun}$ "subgiant" **(evolved)** star

What is wrong with this picture?

Clickr Quiz

What is wrong with this binary system and the relative evolution stages of the two stars?

3.4M_{Sun} Star A on the main sequence, 0.8M_{Sun} Star B on the Red Giant Branch

A. A star as large as 3.4M_{Sun} should have exploded as a SNII

B. A star with mass less than the Sun (0.8M_{Sun}) can not become a Red Giant

C. The more massive star should have evolved up the Red Giant Branch before the lower-mass star

D. Binary stars can only form with equal-mass components (i.e. both stars have the same mass)

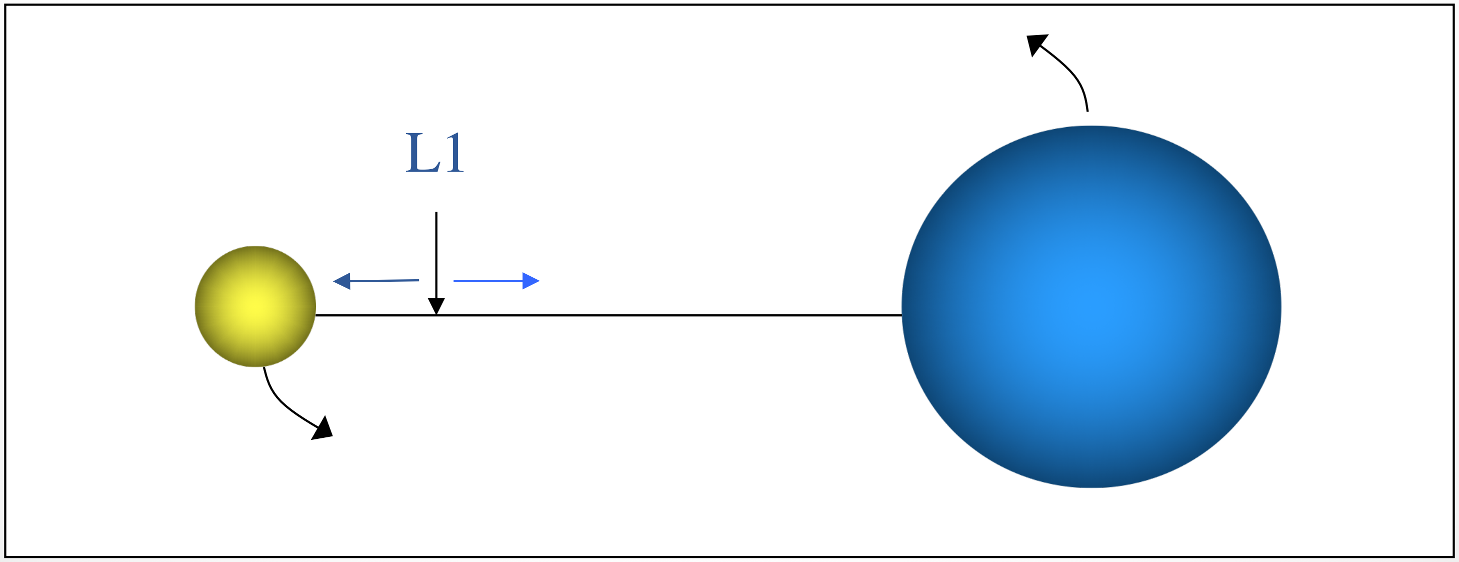
Algol

- The more massive star (A) should have left the main sequence and started up the RGB before the less massive star (B).

What is going on here?

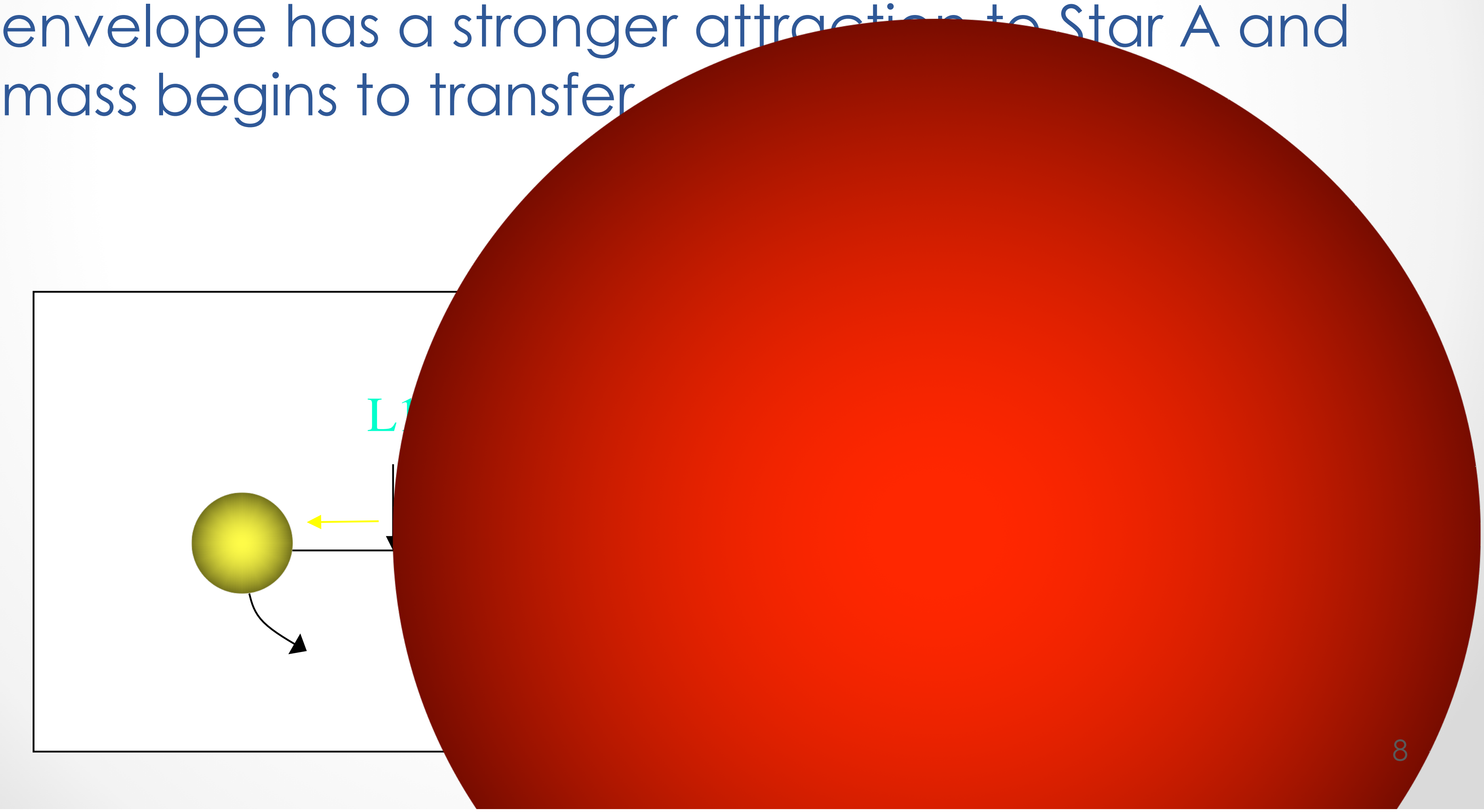
The Algol Story

- Originally the system contained Star A at $1.2M_{Sun}$ and Star B at $3.0M_{Sun}$.
- Between the two stars is a point where the gravitational forces of the two stars balance. This is called a "Lagrange point".



The Algol Story

- Star B evolves up the giant branch and eventually its radius reaches L1.
- As it continues to expand, the Star B outer envelope has a stronger attraction to Star A and mass begins to transfer



Mass Transfer in Binaries

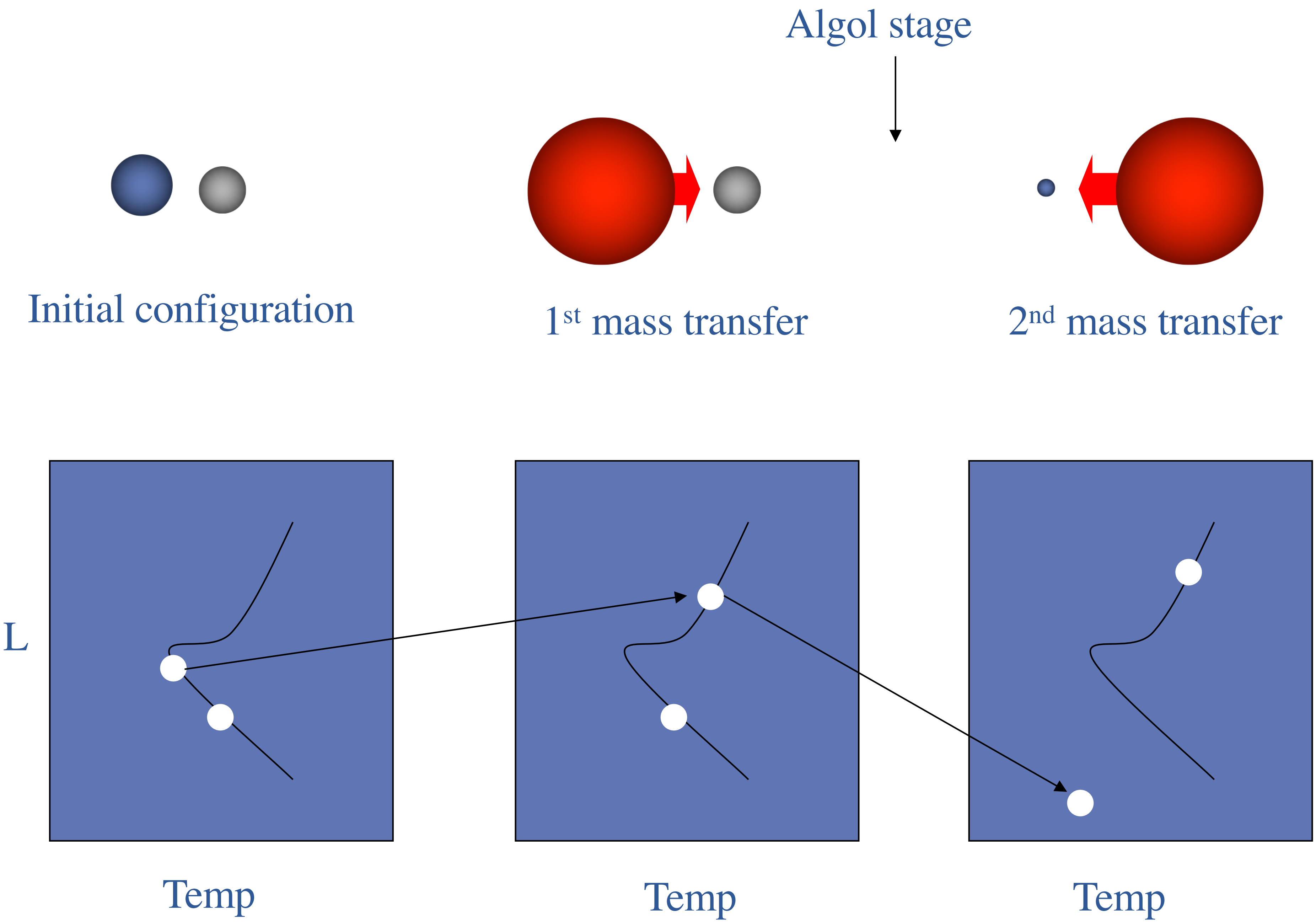
- In the case of Algol, Star B transferred $2.2M_{Sun}$ of material to Star A.

Star A: $1.2M_{Sun} \rightarrow 3.4M_{Sun}$

Star B: $3.0M_{Sun} \rightarrow 0.8M_{Sun}$

Mass Transfer Binaries

- Think about the continued evolution of Algol and you have the explanation for *novae*.
- If the original primary transfers most of its mass to the original secondary, you are left with a massive main-sequence star and a helium WD.
- When the original secondary starts to evolve up the RGB, it transfers some material back onto the helium WD.



Algol stage

Initial configuration

1st mass transfer

2nd mass transfer

L

Temp

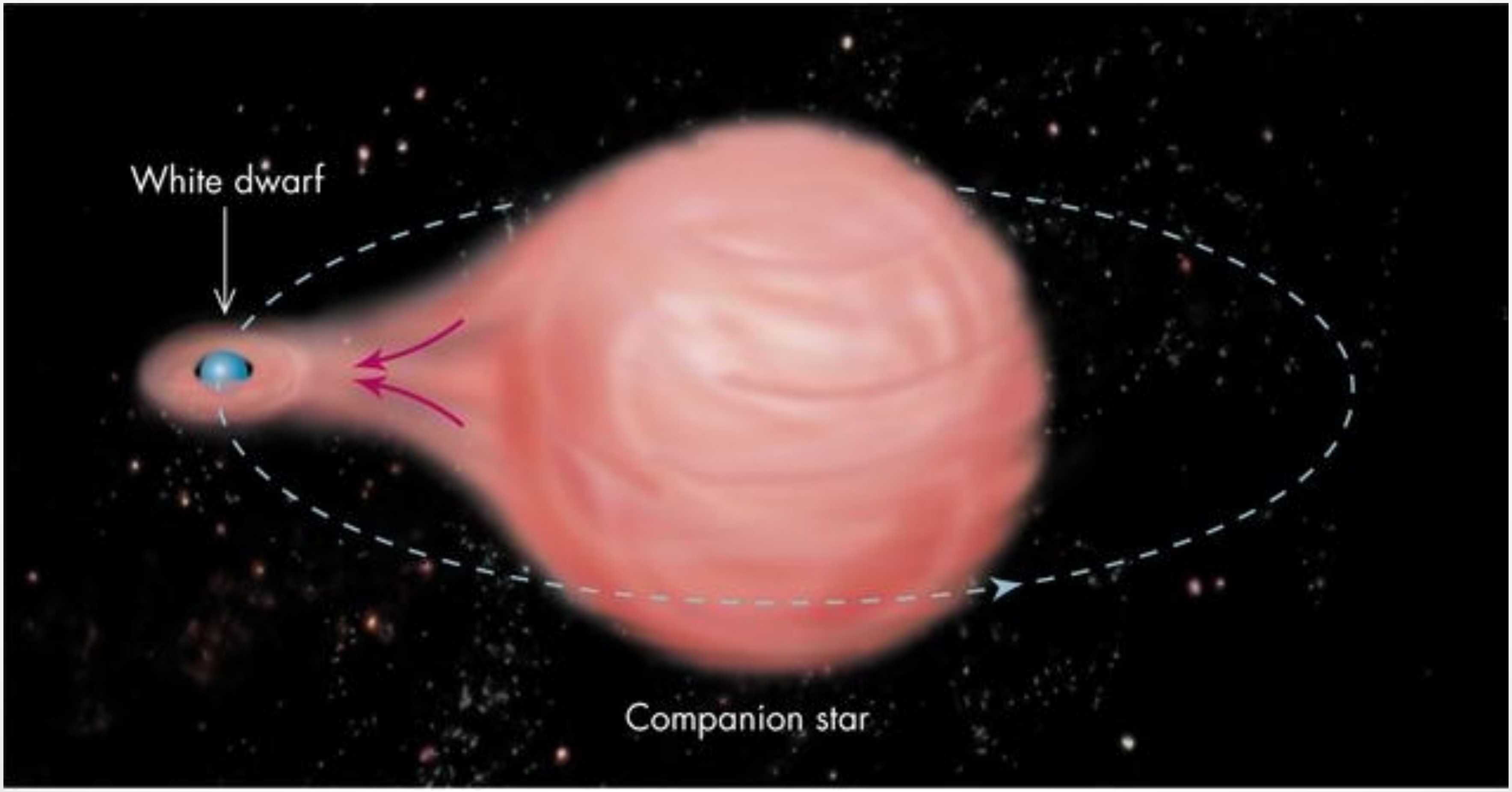
Temp

Temp

Novae

- As the fresh hydrogen accumulates on the surface of the helium WD it is like an insulating blanket -- the temperature rises to 10^7k and there is a *Hydrogen fusion explosion.*
- The star brightens by anywhere from a factor of 10 to a factor of 10,000.
- In some cases, this takes a star from too-faint to see to bright-enough to see so these objects were called Nova -- new star.

Novae/Supernovae I

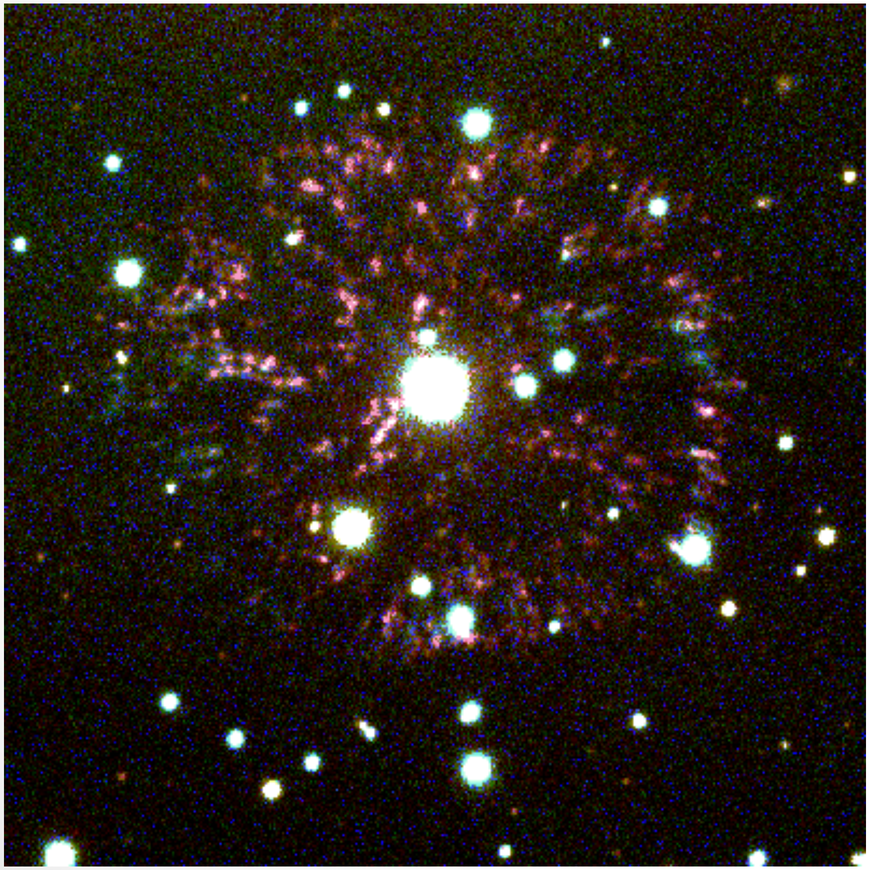


Note! Not to scale!

Novae

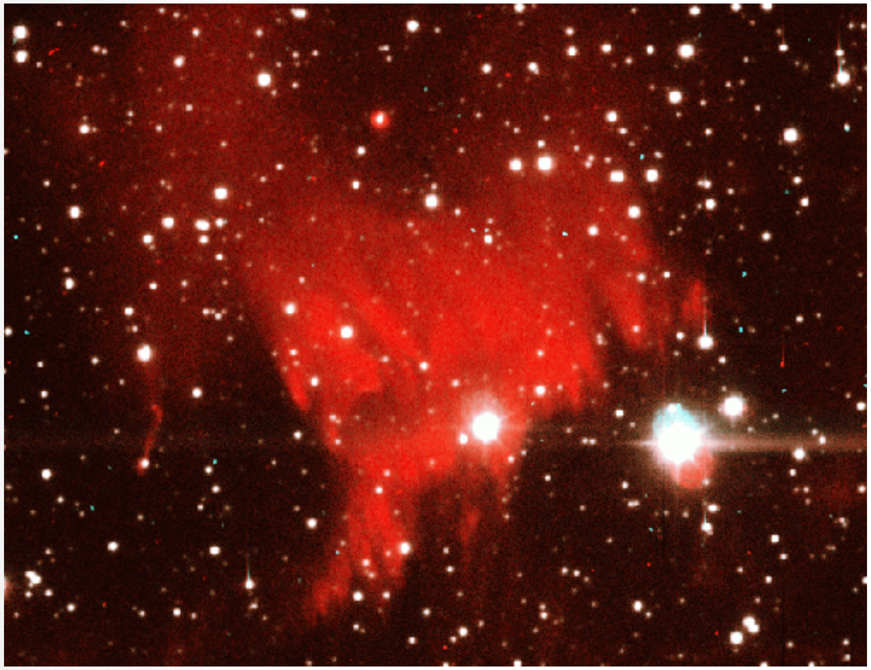
- Nova Vel 1998 (3rd magnitude)

Novae



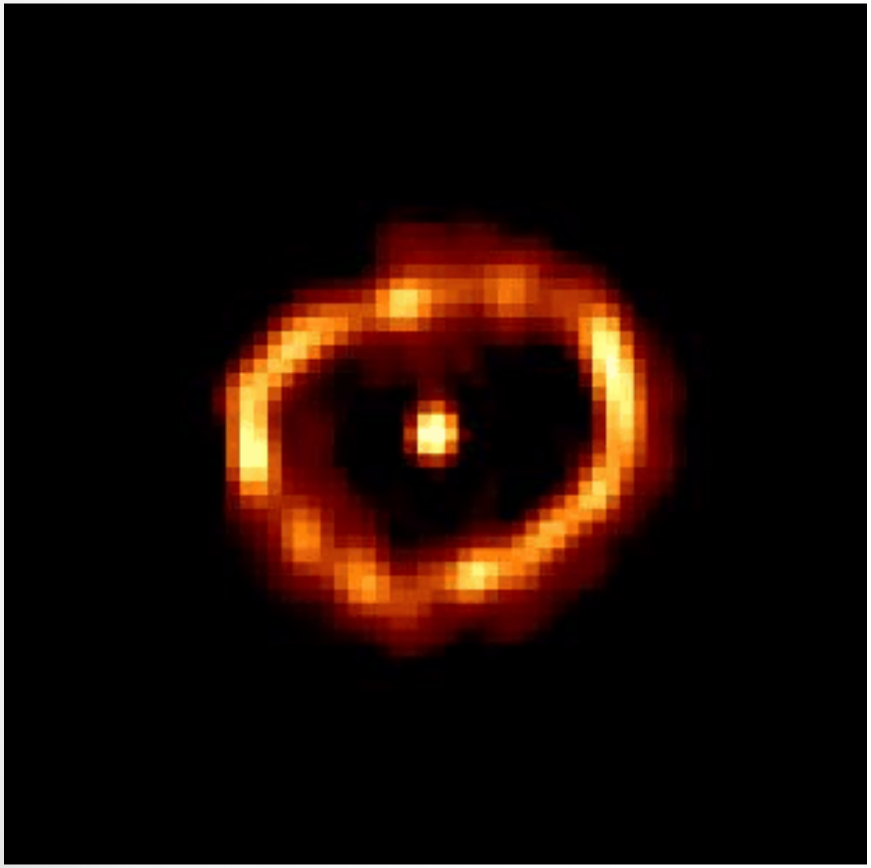
- Nova Persei became one of the brightest stars in the sky in 1901. Look there now and see the expanding shell from the explosion. The velocity of the material is ~2000km/sec

Novae



- Nova Cyg (1992) illuminated a cloud of nearby Hydrogen gas.
- The expanding shell of the nova could be seen a few years later with HST.

Novae

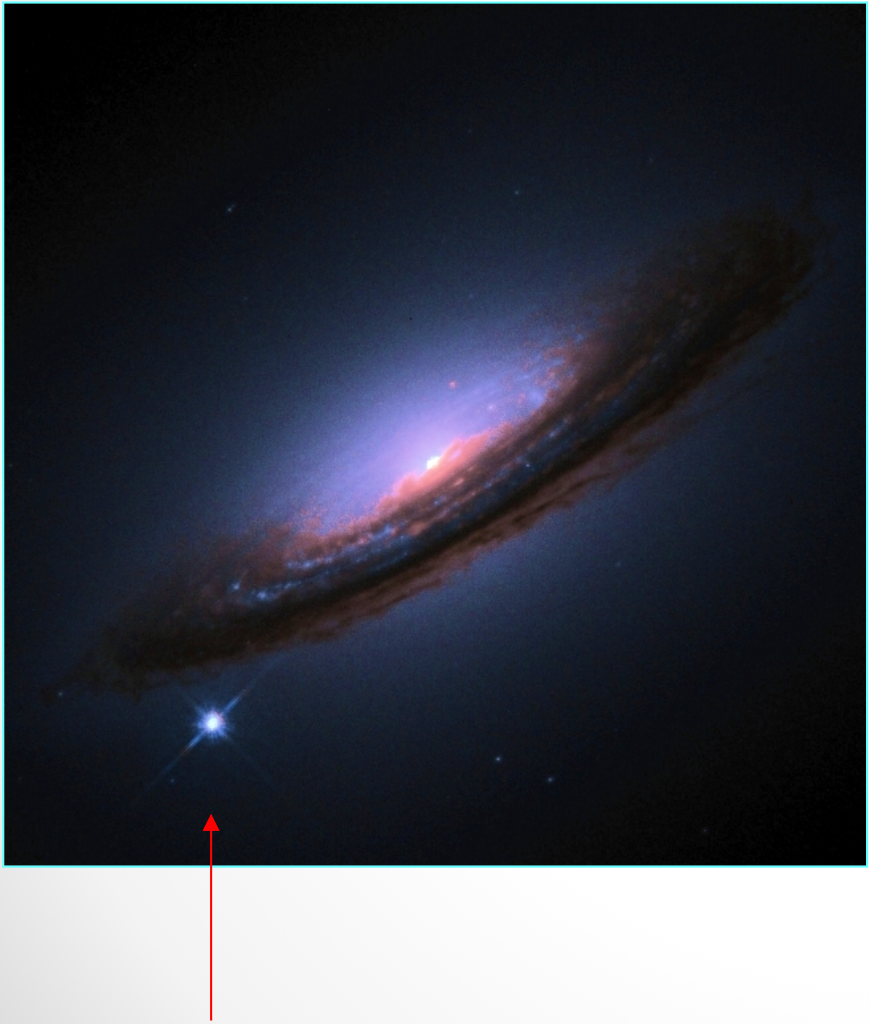


- Nova Cyg in 1994.
- Most nova are "recurrent".
- Every year there are 20 - 30 novae observed in the Galaxy. Naked eye nova occur more like one per decade.

Mass Transfer in Binaries

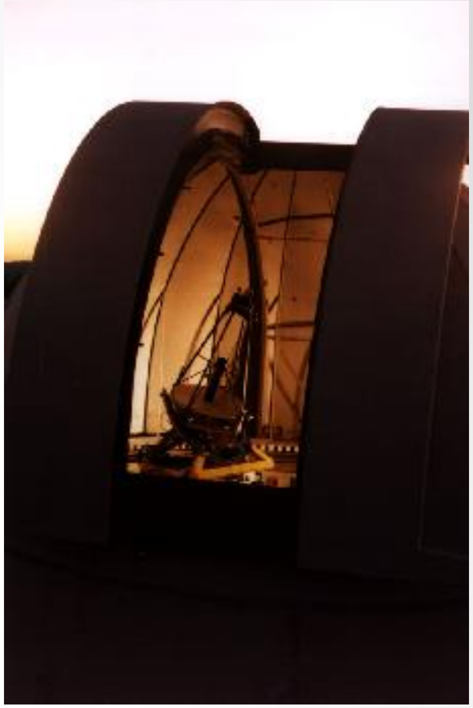
- The scenario that leads to nova explosions can produce an even wilder phenomenon.
- In the early 1900s `novae' were sometimes observed in other galaxies and were used to help set the distances to galaxies.
- But, when it became clear that even the nearest galaxies were much further away than anyone had thought this suggested that the extragalactic "nova" were much brighter than Galactic nova -- the term *supernova* was coined.

Supernova

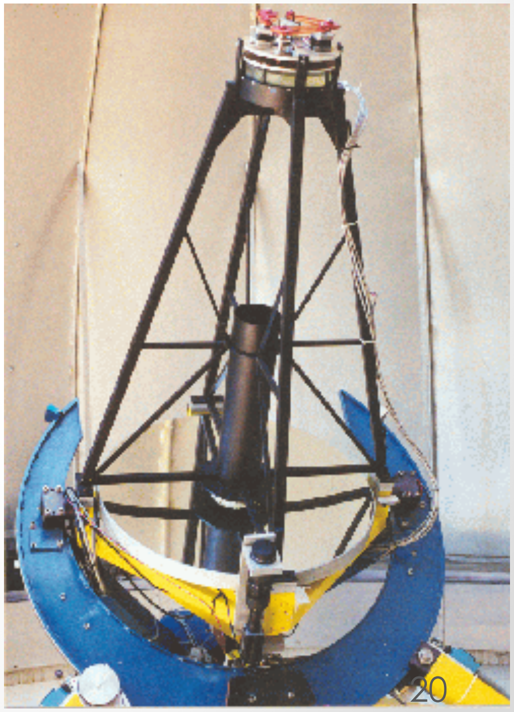


- Early on it was realized there were two distinct types of SN.
- SN I have no hydrogen in their spectra and are seen in all types of galaxies
- SN II have hydrogen and are only seen in spiral galaxies and near star-forming regions (discussed in the last section)

Supernova



- There is a robotic telescope up at Mt. Hamilton that does an automatic search for SN every clear night.
- Take images of lots of galaxies, digitally subtract them, look for any residual.
- Call grad student and start followup observations



Supernova I

- What is going on here? It took a long time to sort this out.
- Remember WD mass transfer binaries and the Chandrasekar limit.
- What would happen if mass transfer nudged the mass of a WD above the $1.4M_{Sun}$ limit for degenerate electron gas pressure?

Supernova I

- When a WD exceeds the Chandrasekar limit the electron degeneracy pressure can not support it against gravity and the WD collapses.
- The temperature skyrockets and within a second a fusion chain reaction fuses elements all the up to radioactive nickel.
- *This is a runaway thermonuclear explosion!*
- Different that the core collapse in a high-mass star Fe core (also triggered at ~$1.4M_{Sun}$) because the WD is primarily made of He.

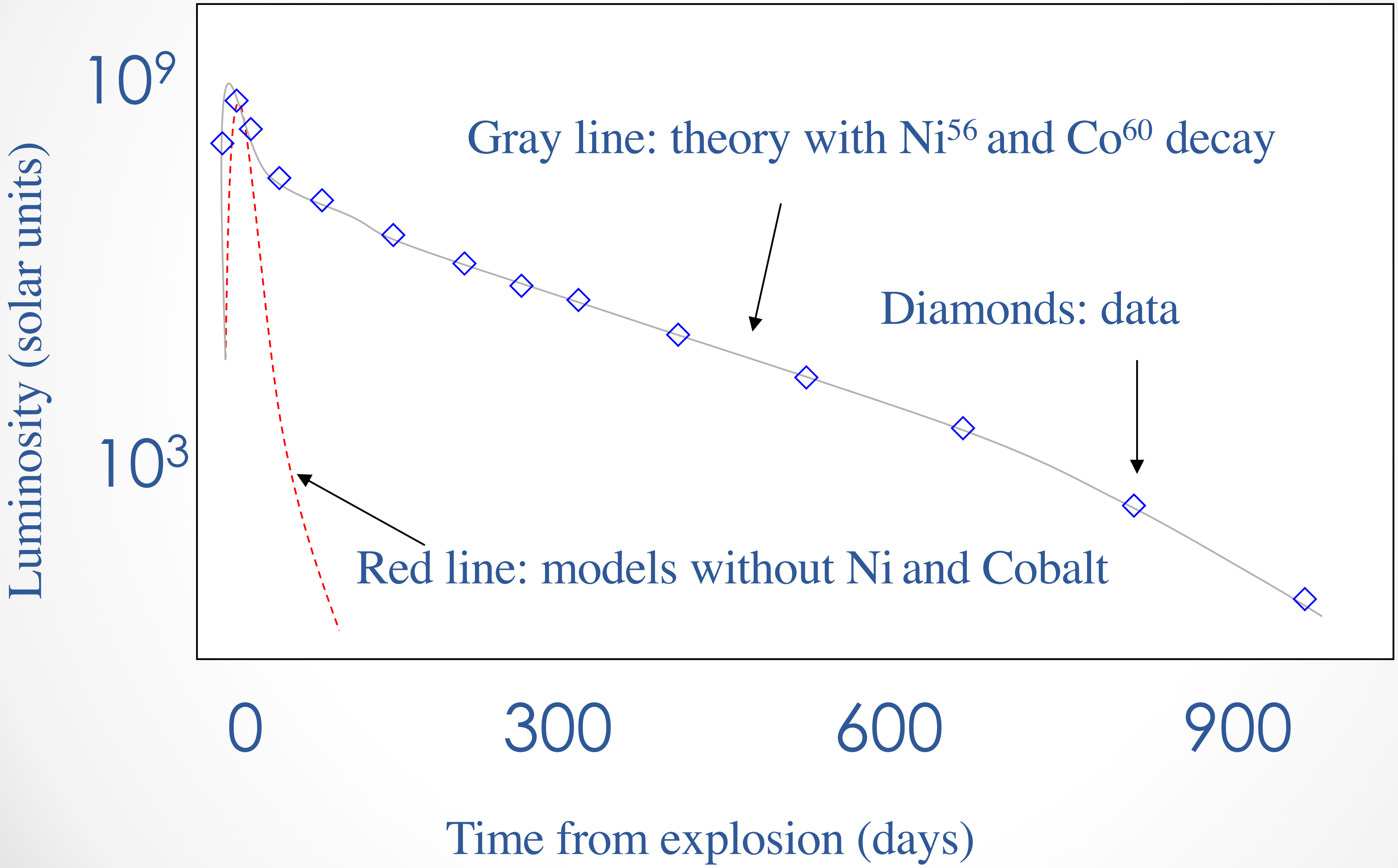
Supernova I

- What is RIGHT about this theory?

(1) Will see these objects in `old' populations.

(2) Models for the detonation of a $1.4M_o$ WD give the right total energy

(3) The predicted amount of radioactive Ni^{56} in the explosion fit the light curve perfectly



Gray line: theory with Ni^{56} and Co^{60} decay

Diamonds: data

Red line: models without Ni and Cobalt

Supernova I

- Because the explosion mechanism for SN I is the same from one to the next (WD with mass transfer that pushes it over the Chandrasekar mass), these explosions are pretty good "standard candles" and will play a roll in establishing the expansion history of the Universe.

Historical Galactic SN

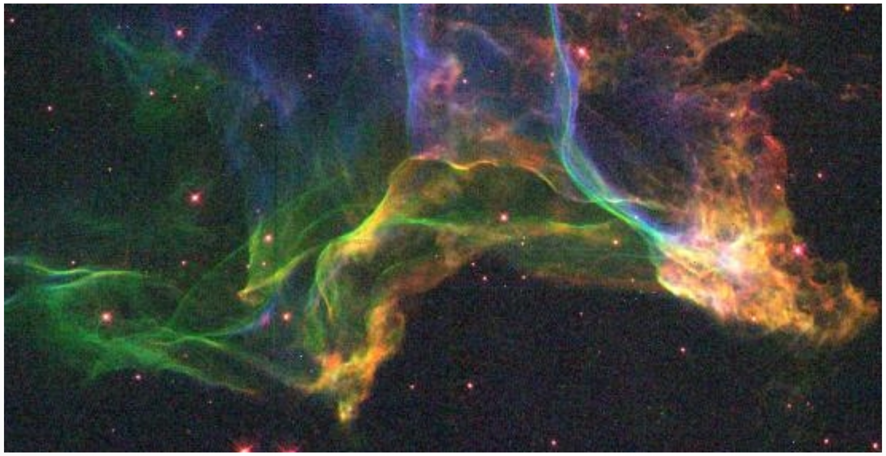
- We miss many in the Galaxy because of dust obscuration.
- From radio surveys for SN remnants, we have discovered 49 remnants for an inferred rate of 3.4 SN/century.
- There are several `historical supernovae' -- bright new stars that appeared in the sky and were recorded by various people.

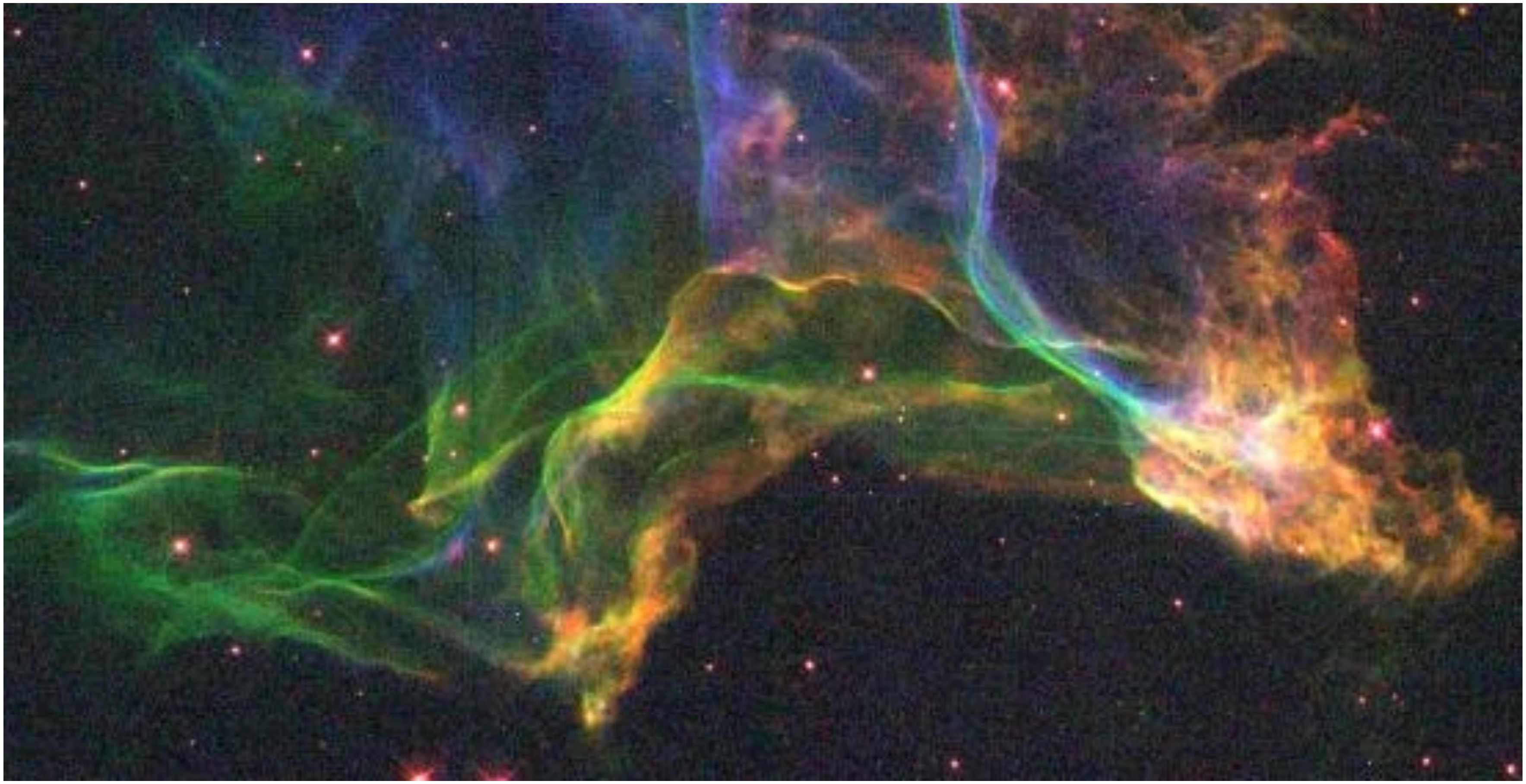
Historical SN

- 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 first





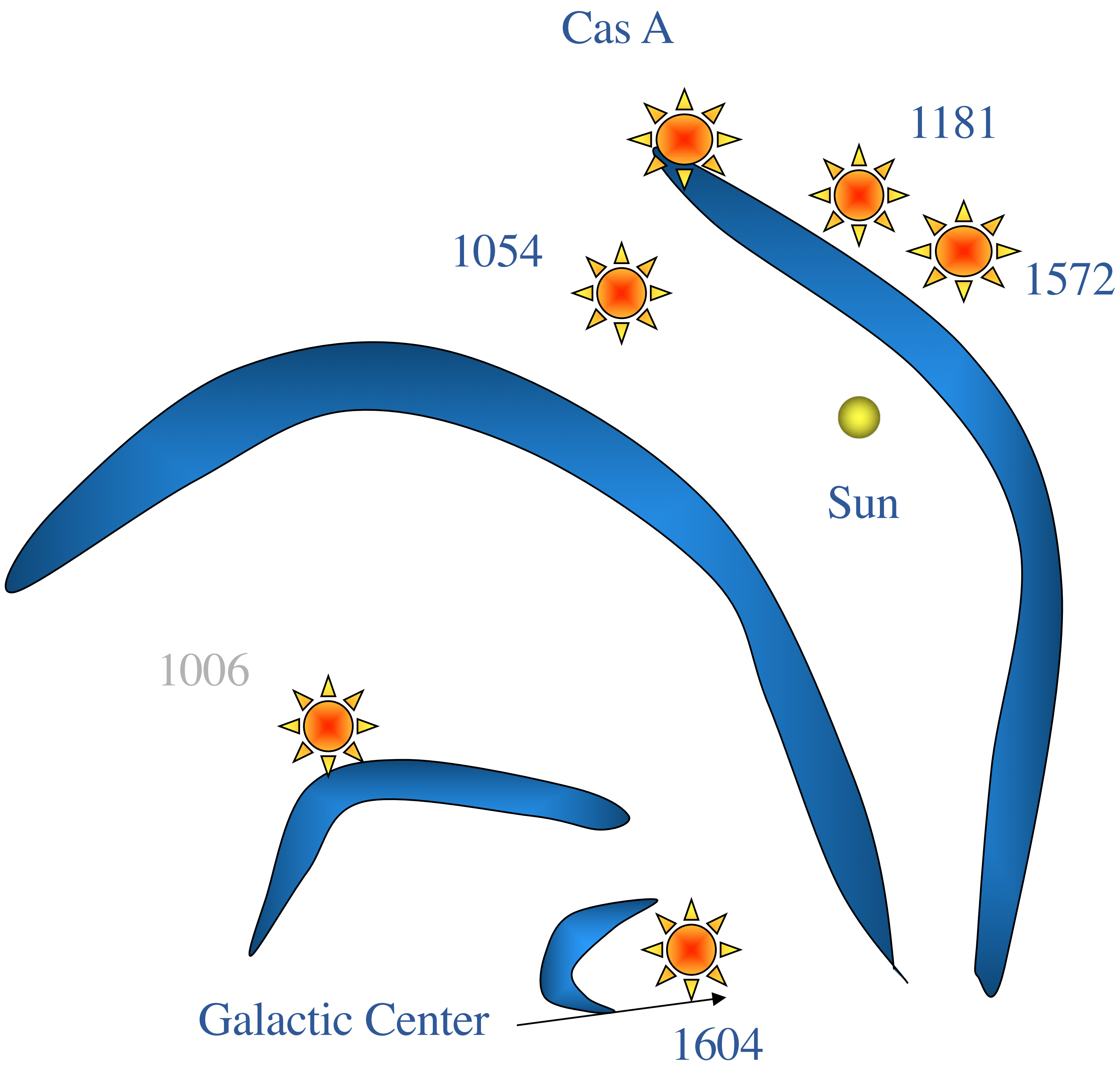
NGC 1850 in LMC

Historical SN

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

Historical SN

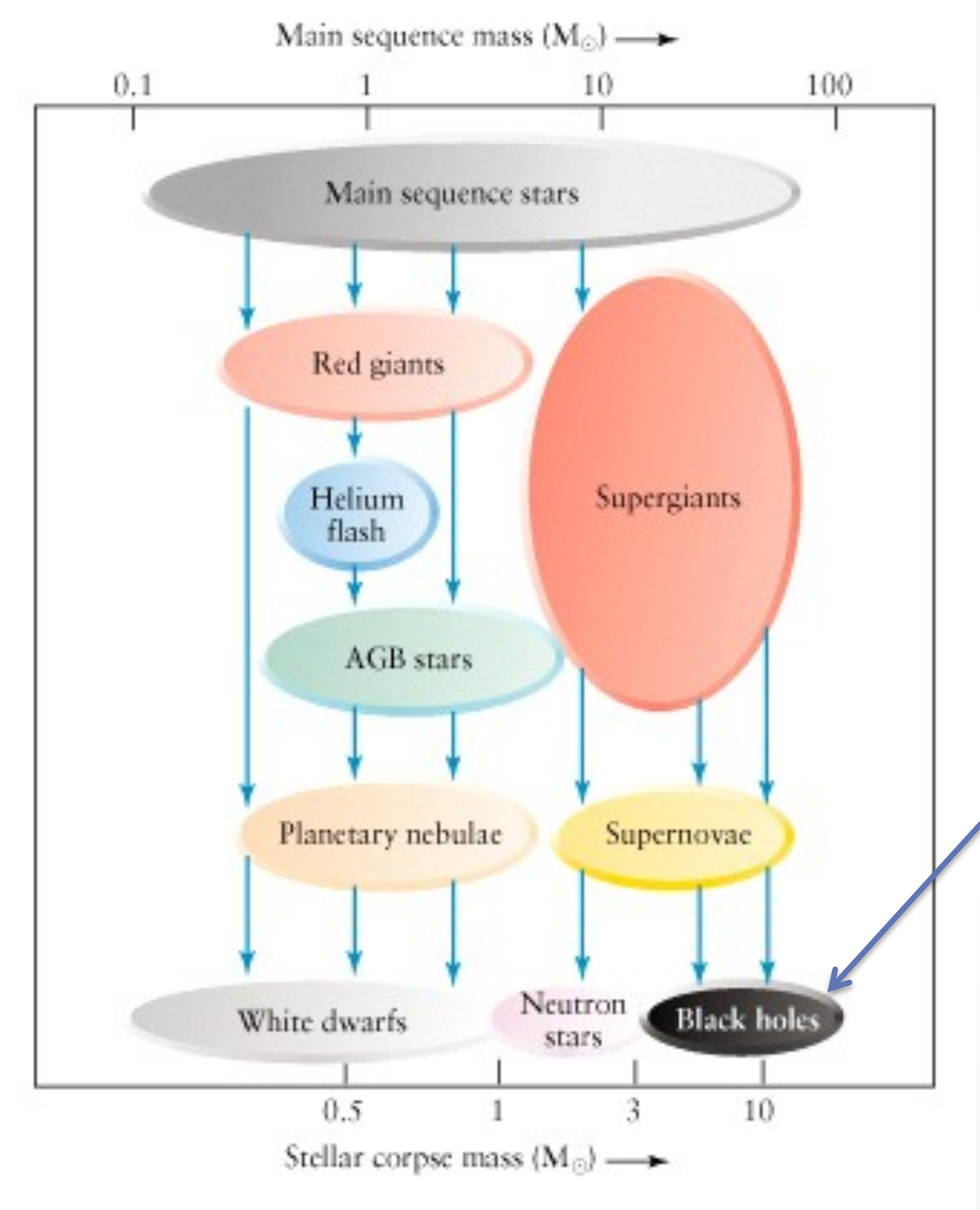
- The nearest SN remnant is the `Gum’ nebula from around 9000BC. Four times closer than the Crab, it would have been as bright as the full moon.
- A mystery is `Cas A’ -- this was a SN at about 1600AD, should have been very bright, but no records of it exist.


Cas A
1181
1054
1572
Sun
1006
Galactic Center
1604

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?



Next section

Chemical Evolution Of the Universe

- Low-mass stars synthesize "new" He, C, O, Ne, Ar, Mg during the main-sequence and giant-branch phases.
- These freshly-minted elements are brought to the surface via convection and re-distributed via stellar winds and planetary nebulae into the interstellar medium to be incorporated into later generations of stars.

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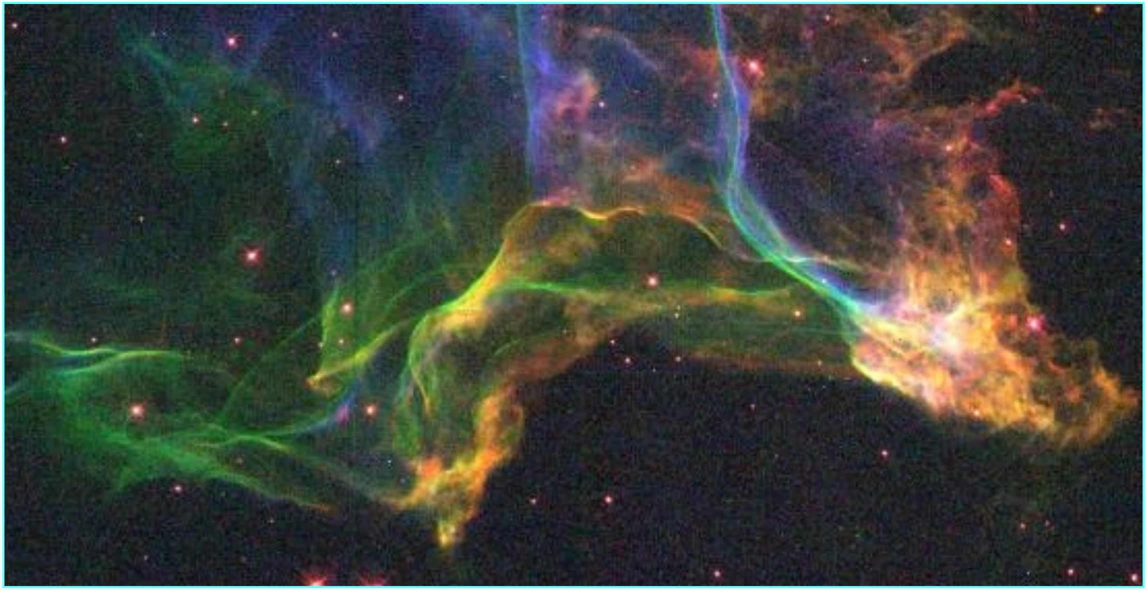
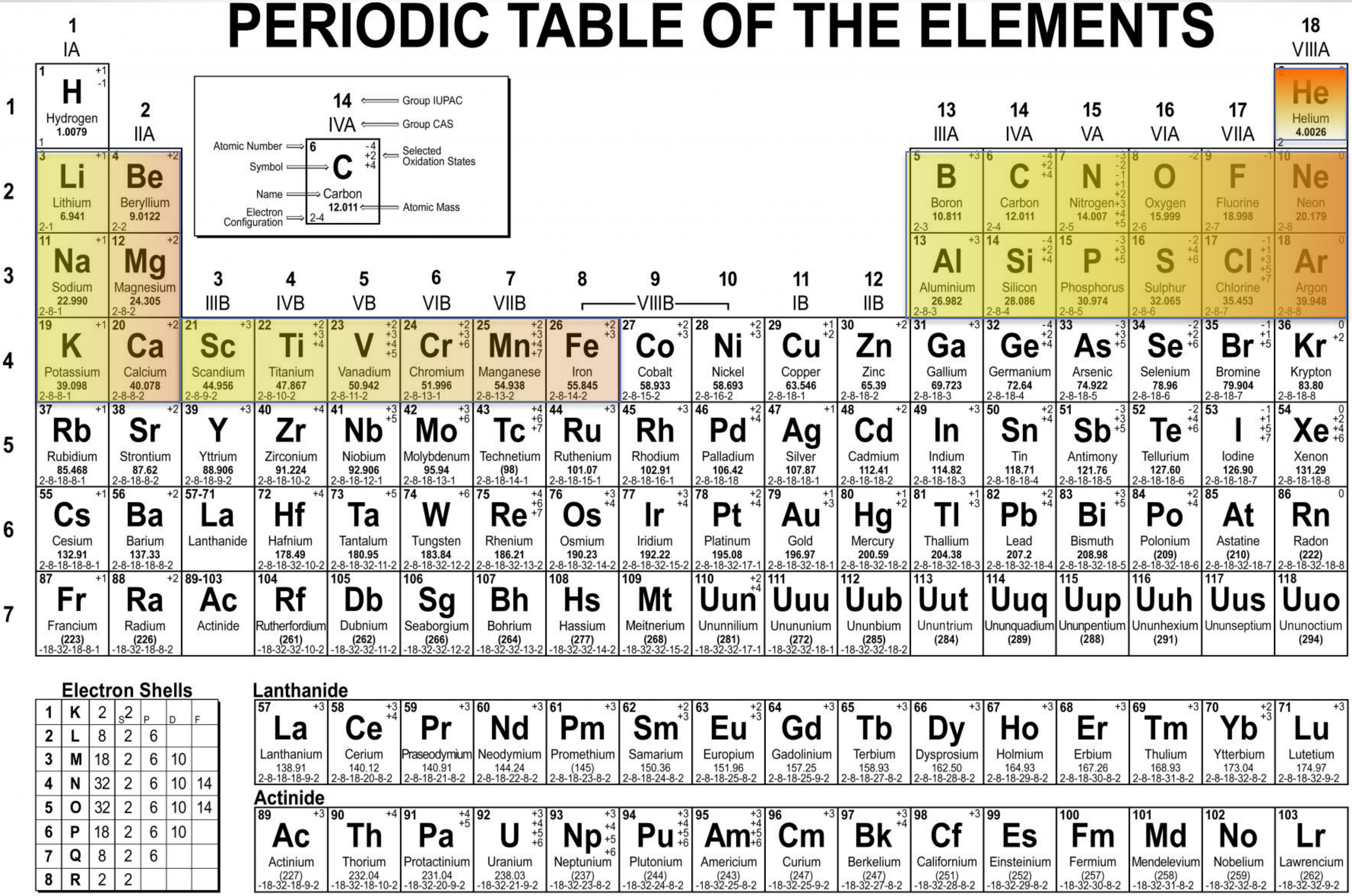
Chemical Evolution II

- For more massive stars, `equilibrium' fusion reactions produce elements all the way up to Fe.
- Freshly-made elements are delivered via stellar winds or, sometimes more spectacularly via supernova explosions



PERIODIC TABLE OF THE ELEMENTS



14 ⟸ Group IUPAC
IVA ⟸ Group CAS
Atomic Number ⟹ 6
Symbol ⟹ C
Name ⟹ Carbon
Electron Configuration ⟹ 2-4
-4 +2 +4 ⟸ Selected Oxidation States
12.011 ⟸ Atomic Mass

	1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VIIIB	9	10	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1	1 +1 -1 H Hydrogen 1.0079 1																	2 0 He Helium 4.0026 2
2	3 +1 Li Lithium 6.941 2-1	4 +2 Be Beryllium 9.0122 2-2											5 +3 B Boron 10.811 2-3	6 -4 +2 +4 C Carbon 12.011 2-4	7 -3 -2 -1 +1 +2 +3 +4 +5 N Nitrogen 14.007 2-5	8 -2 O Oxygen 15.999 2-6	9 -1 F Fluorine 18.998 2-7	10 0 Ne Neon 20.179 2-8
3	11 +1 Na Sodium 22.990 2-8-1	12 +2 Mg Magnesium 24.305 2-8-2											13 +3 Al Aluminium 26.982 2-8-3	14 -4 +2 +4 Si Silicon 28.086 2-8-4	15 -3 +3 +5 P Phosphorus 30.974 2-8-5	16 -2 +4 +6 S Sulphur 32.065 2-8-6	17 -1 +1 +3 +5 +7 Cl Chlorine 35.453 2-8-7	18 0 Ar Argon 39.948 2-8-8
4	19 +1 K Potassium 39.098 2-8-8-1	20 +2 Ca Calcium 40.078 2-8-8-2	21 +3 Sc Scandium 44.956 2-8-9-2	22 +2 +3 +4 Ti Titanium 47.867 2-8-10-2	23 +2 +3 +4 +5 V Vanadium 50.942 2-8-11-2	24 +2 +3 +6 Cr Chromium 51.996 2-8-13-1	25 +2 +3 +4 +7 Mn Manganese 54.938 2-8-13-2	26 +2 +3 Fe Iron 55.845 2-8-14-2	27 +2 +3 Co Cobalt 58.933 2-8-15-2	28 +2 +3 Ni Nickel 58.693 2-8-16-2	29 +1 +2 Cu Copper 63.546 2-8-18-1	30 +2 Zn Zinc 65.39 2-8-18-2	31 +3 Ga Gallium 69.723 2-8-18-3	32 -4 +2 +4 Ge Germanium 72.64 2-8-18-4	33 -3 +3 +5 As Arsenic 74.922 2-8-18-5	34 -2 +2 +6 Se Selenium 78.96 2-8-18-6	35 -1 +1 +5 Br Bromine 79.904 2-8-18-7	36 0 +2 Kr Krypton 83.80 2-8-18-8
5	37 +1 Rb Rubidium 85.468 2-8-18-8-1	38 +2 Sr Strontium 87.62 2-8-18-8-2	39 +3 Y Yttrium 88.906 2-8-18-9-2	40 +4 Zr Zirconium 91.224 2-8-18-10-2	41 +3 +5 Nb Niobium 92.906 2-8-18-12-1	42 +3 +6 Mo Molybdenum 95.94 2-8-18-13-1	43 +4 +6 +7 Tc Technetium (98) 2-8-18-14-1	44 +3 Ru Ruthenium 101.07 2-8-18-15-1	45 +3 Rh Rhodium 102.91 2-8-18-16-1	46 +2 +4 Pd Palladium 106.42 2-8-18-18	47 +1 Ag Silver 107.87 2-8-18-18-1	48 +2 Cd Cadmium 112.41 2-8-18-18-2	49 +3 In Indium 114.82 2-8-18-18-3	50 +2 +4 Sn Tin 118.71 2-8-18-18-4	51 -3 +3 +5 Sb Antimony 121.76 2-8-18-18-5	52 -2 +4 +6 Te Tellurium 127.60 2-8-18-18-6	53 -1 +1 +5 +7 I Iodine 126.90 2-8-18-18-7	54 0 +2 +4 +6 Xe Xenon 131.29 2-8-18-18-8
6	55 +1 Cs Cesium 132.91 2-8-18-18-8-1	56 +2 Ba Barium 137.33 2-8-18-18-8-2	57-71 La Lanthanide	72 +4 Hf Hafnium 178.49 2-8-18-32-10-2	73 +5 Ta Tantalum 180.95 2-8-18-32-11-2	74 +6 W Tungsten 183.84 2-8-18-32-12-2	75 +4 +6 +7 Re Rhenium 186.21 2-8-18-32-13-2	76 +3 +4 Os Osmium 190.23 2-8-18-32-14-2	77 +3 +4 Ir Iridium 192.22 2-8-18-32-15-2	78 +2 +4 Pt Platinum 195.08 2-8-18-32-17-1	79 +1 +3 Au Gold 196.97 2-8-18-32-18-1	80 +1 +2 Hg Mercury 200.59 2-8-18-32-18-2	81 +1 +3 Tl Thallium 204.38 2-8-18-32-18-3	82 +2 +4 Pb Lead 207.2 2-8-18-32-18-4	83 +3 +5 Bi Bismuth 208.98 2-8-18-32-18-5	84 +2 +4 Po Polonium (209) 2-8-18-32-18-6	85 At Astatine (210) 2-8-18-32-18-7	86 0 Rn Radon (222) 2-8-18-32-18-8
7	87 +1 Fr Francium (223) -18-32-18-8-1	88 +2 Ra Radium (226) -18-32-18-8-2	89-103 Ac Actinide	104 Rf Rutherfordium (261) -18-32-32-10-2	105 Db Dubnium (262) -18-32-32-11-2	106 Sg Seaborgium (266) -18-32-32-12-2	107 Bh Bohrium (264) -18-32-32-13-2	108 Hs Hassium (277) -18-32-32-14-2	109 Mt Meitnerium (268) -18-32-32-15-2	110 +2 +4 Uun Ununnilium (281) -18-32-32-17-1	111 Uuu Unununium (272) -18-32-32-18-1	112 Uub Ununbium (285) -18-32-32-18-2	113 Uut Ununtrium (284)	114 Uuq Ununquadium (289)	115 Uup Ununpentium (288)	116 Uuh Ununhexium (291)	117 Uus Ununseptium	118 Uuo Ununoctium (294)

Electron Shells

1	K	2	S 2	P	D	F
2	L	8	2	6		
3	M	18	2	6	10	
4	N	32	2	6	10	14
5	O	32	2	6	10	14
6	P	18	2	6	10	
7	Q	8	2	6		
8	R	2	2			

Lanthanide

57 +3 La Lanthanium 138.91 2-8-18-18-9-2	58 +3 +4 Ce Cerium 140.12 2-8-18-20-8-2	59 +3 Pr Praseodymium 140.91 2-8-18-21-8-2	60 +3 Nd Neodymium 144.24 2-8-18-22-8-2	61 +3 Pm Promethium (145) 2-8-18-23-8-2	62 +2 +3 Sm Samarium 150.36 2-8-18-24-8-2	63 +2 +3 Eu Europium 151.96 2-8-18-25-8-2	64 +3 Gd Gadolinium 157.25 2-8-18-25-9-2	65 +3 Tb Terbium 158.93 2-8-18-27-8-2	66 +3 Dy Dysprosium 162.50 2-8-18-28-8-2	67 +3 Ho Holmium 164.93 2-8-18-29-8-2	68 +3 Er Erbium 167.26 2-8-18-30-8-2	69 +3 Tm Thulium 168.93 2-8-18-31-8-2	70 +2 +3 Yb Ytterbium 173.04 2-8-18-32-8-2	71 +3 Lu Lutetium 174.97 2-8-18-32-9-2

Actinide

89 +3 Ac Actinium (227) -18-32-18-9-2	90 +4 Th Thorium 232.04 -18-32-18-10-2	91 +4 +5 Pa Protactinium 231.04 -18-32-20-9-2	92 +3 +4 +5 +6 U Uranium 238.03 -18-32-21-9-2	93 +3 +4 +5 +6 Np Neptunium (237) -18-32-23-8-2	94 +3 +4 +5 +6 Pu Plutonium (244) -18-32-24-8-2	95 +3 +4 +5 +6 Am Americium (243) -18-32-25-8-2	96 +3 Cm Curium (247) -18-32-25-9-2	97 +3 +4 Bk Berkelium (247) -18-32-27-8-2	98 +3 Cf Californium (251) -18-32-28-8-2	99 Es Einsteinium (252) -18-32-29-8-2	100 Fm Fermium (257) -18-32-30-8-2	101 Md Mendelevium (258) -18-32-31-8-2	102 No Nobelium (259) -18-32-32-8-2	103 Lr Lawrencium (262) -18-32-32-9-2

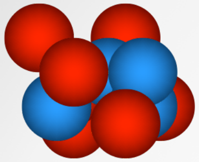
Chemical Evolution III

- What about the *trans-Fe* elements?
- *Equilibrium* fusion reactions of light elements don't proceed past Fe because of Fe's location at the peak of the curve of binding energy.
- However, in certain circumstances, supernovae for example, non-equilibrium reactions can build elements beyond Fe in the Periodic Table. Many of these are radioactive, but some are stable.

Neutron Capture Elements

There are two principle paths to building the elements heavier than Fe. Both use the addition of neutrons to existing `seed’ nuclei (neutrons have no charge so are much easier to add to positively-charged nuclei).

- S-process (slow addition of neutrons)
- R-process (rapid addition of neutrons)



The S-process

- The S-process stands for the Slow addition of neutrons to nuclei. The addition of a n° produces heavier isotope of a particular element. However, if an electron is emitted (this is called beta-decay), the nucleus moves one step up the periodic table.

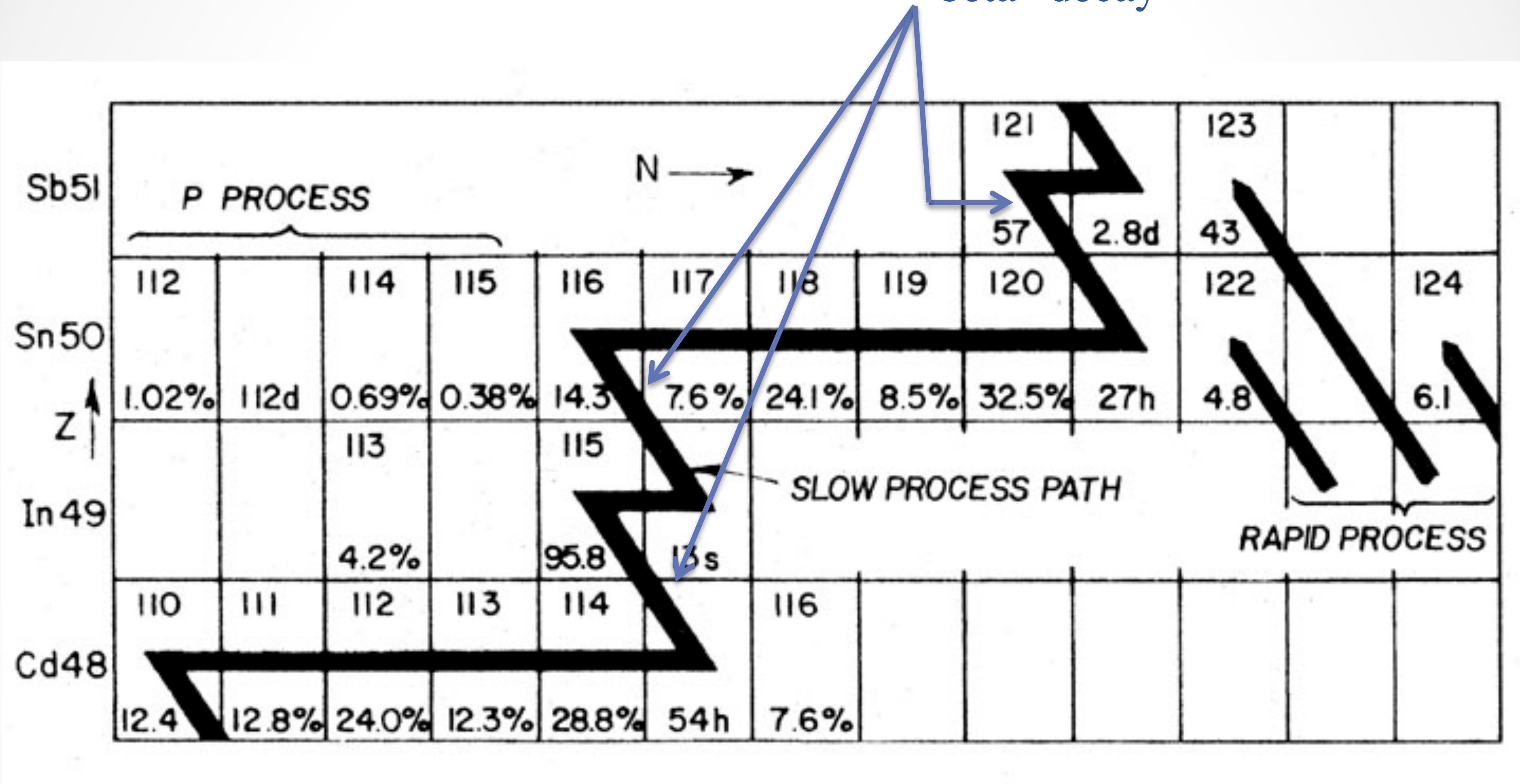
S-Process

- `Slow’ here means that rate of n° captures is low compared to the beta-decay rate.
- It really is slow, sometimes 100’s of years go by between neutron captures.

$$
\begin{array}{lll}
{}_{26}\mathrm{Fe}^{56} + n^{\circ} & \text{-->} & {}_{26}\mathrm{Fe}^{57} \\
{}_{26}\mathrm{Fe}^{57} & \text{-->} & {}_{27}\mathrm{Co}^{57} + e^{-}
\end{array}
$$

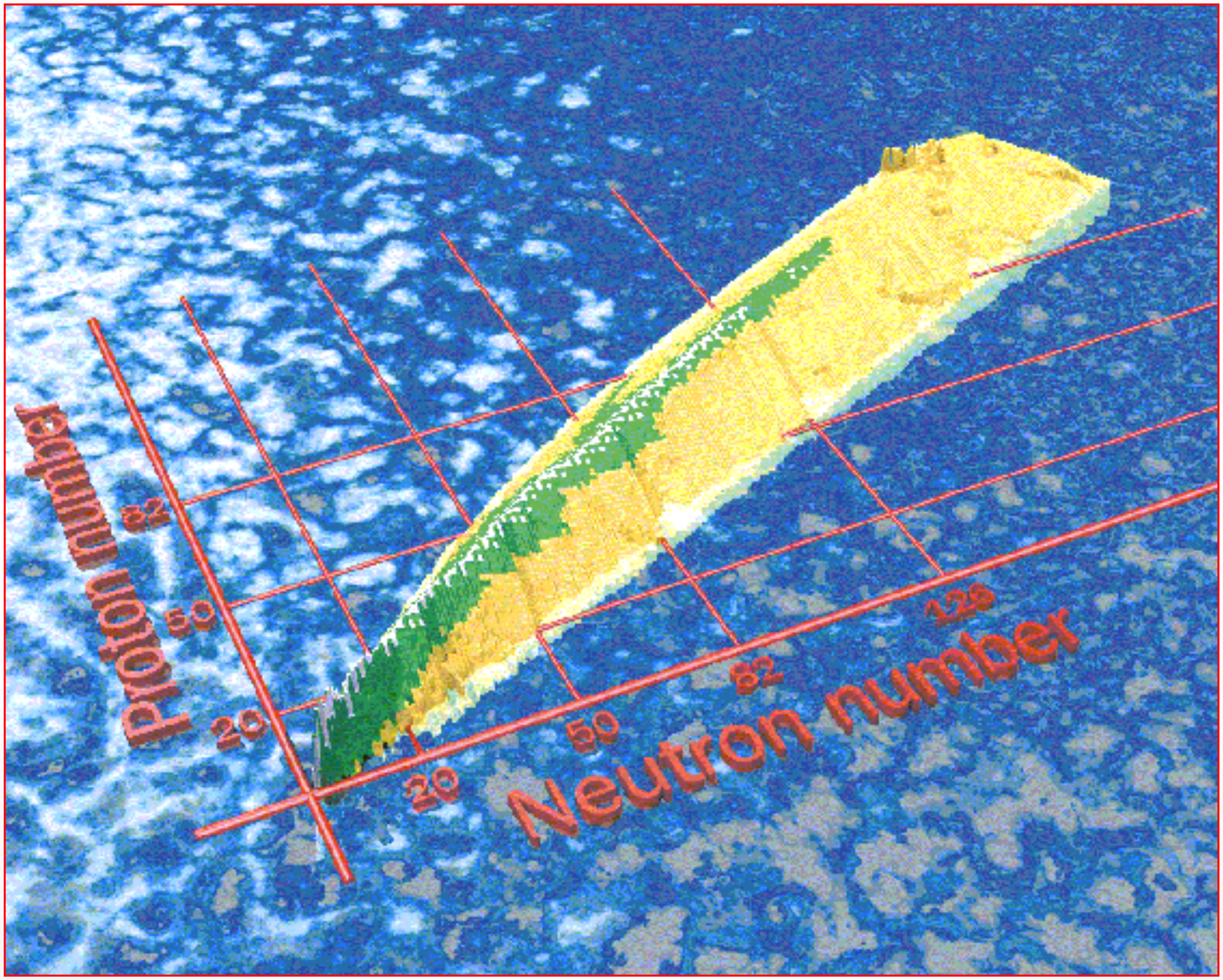
Here a neutron changed into a proton by emitting an electron

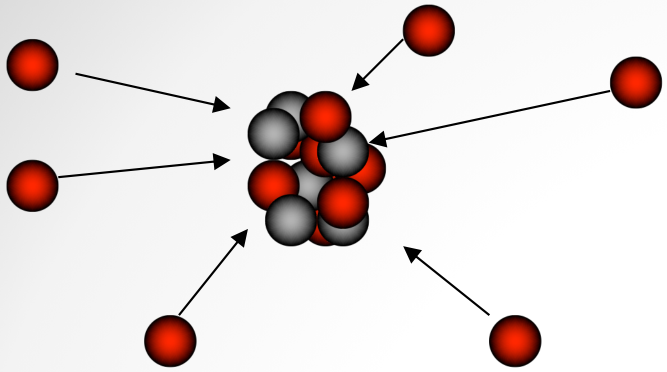
- The S-process can produce elements up to #83 - Bismuth. There are peaks in the Solar System abundance of heavy elements at ^{38}Sr, ^{56}Ba and ^{82}Pb. These are easily understood in the context of the S-process and `magic' numbers of neutrons.
- The site of the S-process is AGB stars during and between shell flashes. The n^{o} source is a by-product of $C^{13}+He^{4}$ -> O^{16}
- ^{43}Tc is an s-process nucleus and proof that it is in operation in AGB stars.



“beta” decay

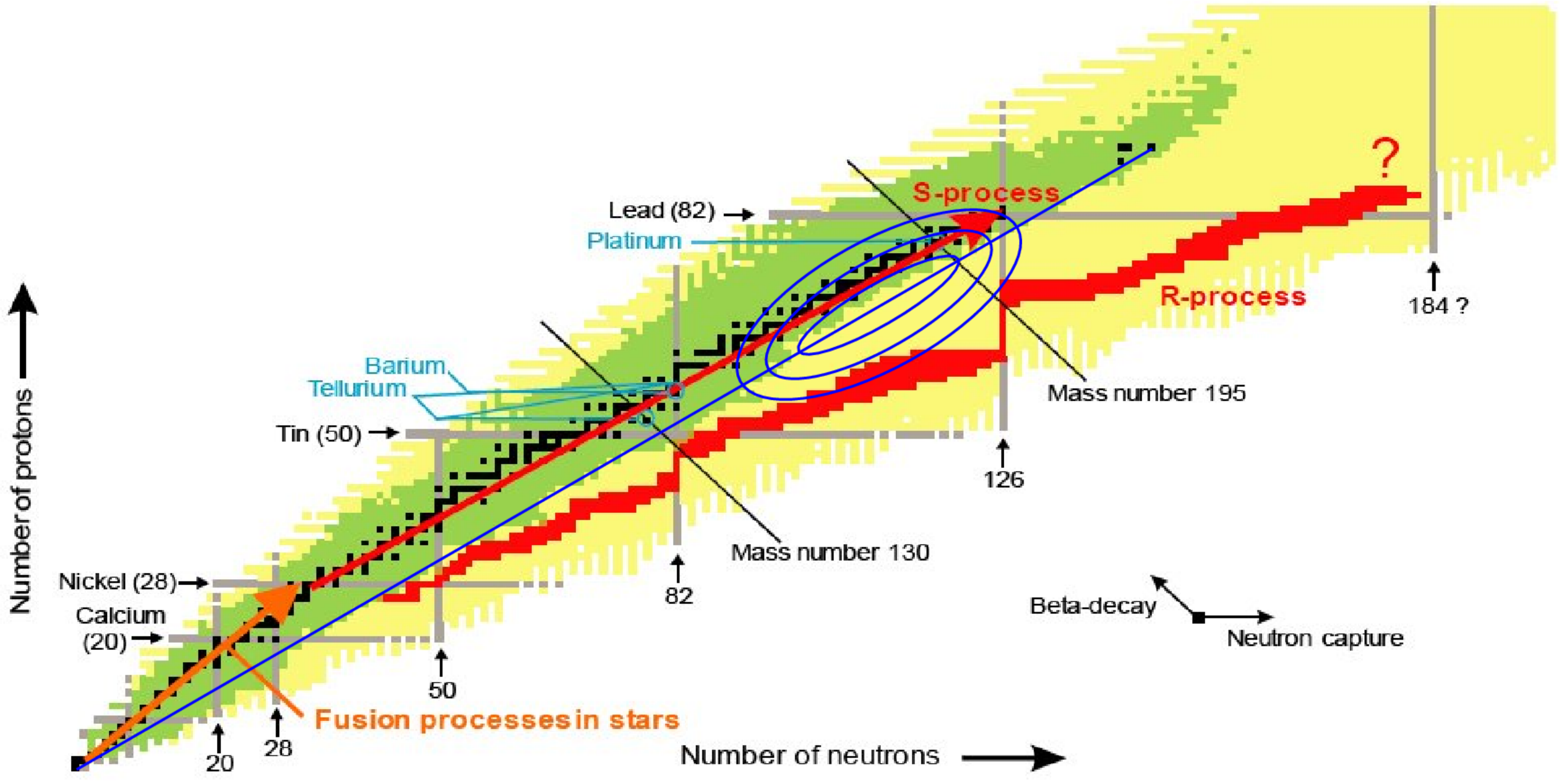
Number of neutrons


Proton number
20
50
82
Neutron number
20
50
82
126



The R-process

- The R-process is the Rapid addition of neutrons to existing nuclei. Rapid here means that many neutrons are added before a beta-decay occurs.
- First build up a VERY heavy isotope, then as beta-decays occur you march up in atomic number and produce the REALLY HEAVY STUFF.


S-process
?
Lead (82)
Platinum
R-process
184 ?
Barium
Tellurium
Mass number 195
Tin (50)
126
Mass number 130
82
Nickel (28)
Calcium
(20)
Beta-decay
Neutron capture
50
Fusion processes in stars
20
28
Number of neutrons
Number of protons

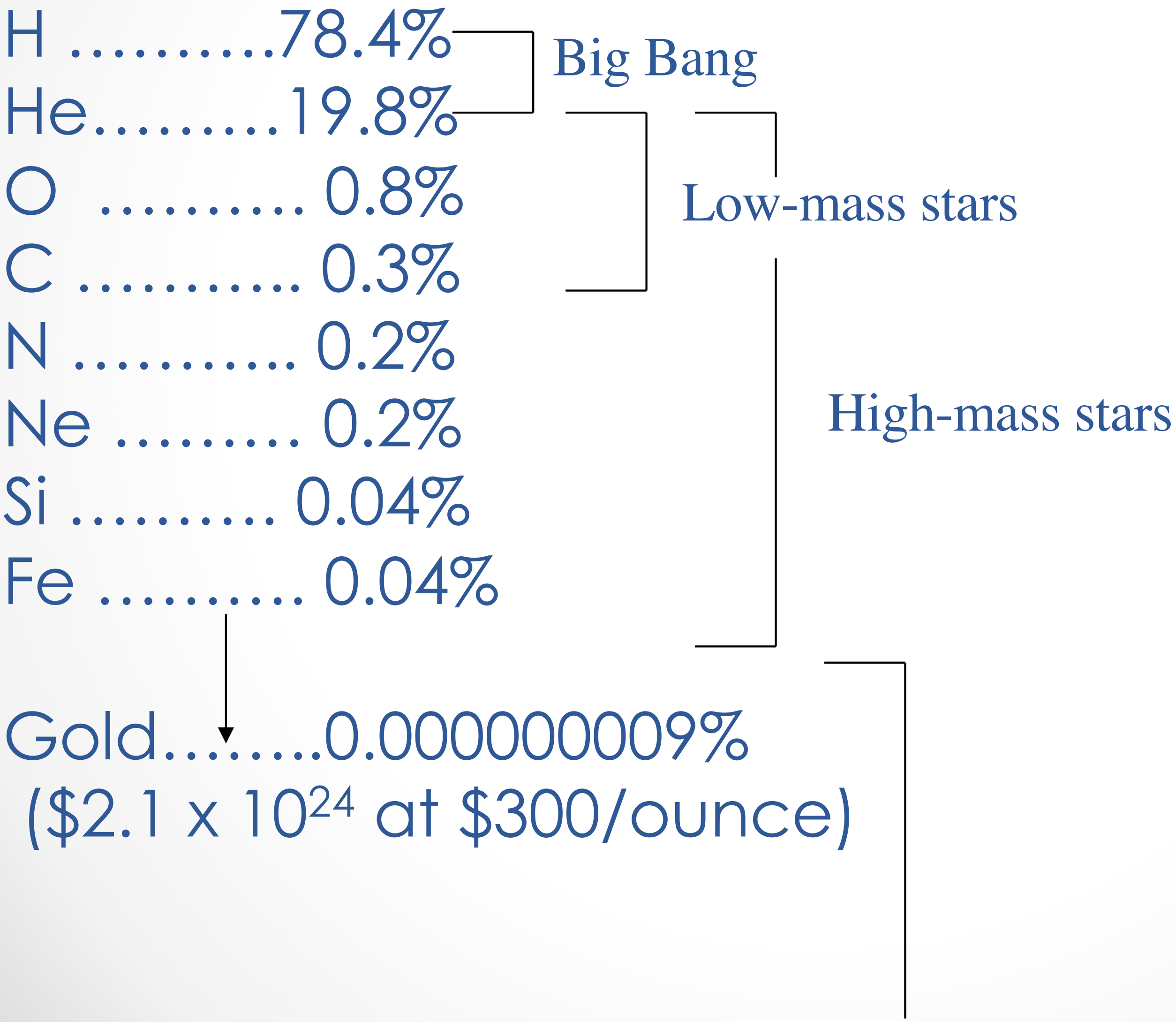
The R-process

- For this to happen need a big burst of neutrons. The right conditions are in a SNII explosion right above the collapsed core and in merging neutron stars
- Observations of one of the early gravitational wave sources demonstrated the R-process at work in merging neutron stars

R-process

- If we look at the Crab Nebula or other SNII remnants we don’t see r-process elements.
- We DO see regions of enhanced O, Si, Ne and He which appear to reflect the `onion skin’ structure of the massive star progenitor.

Solar Composition by Mass



H 78.4%

He.........19.8%

O 0.8%

C 0.3%

N 0.2%

Ne 0.2%

Si 0.04%

Fe 0.04%

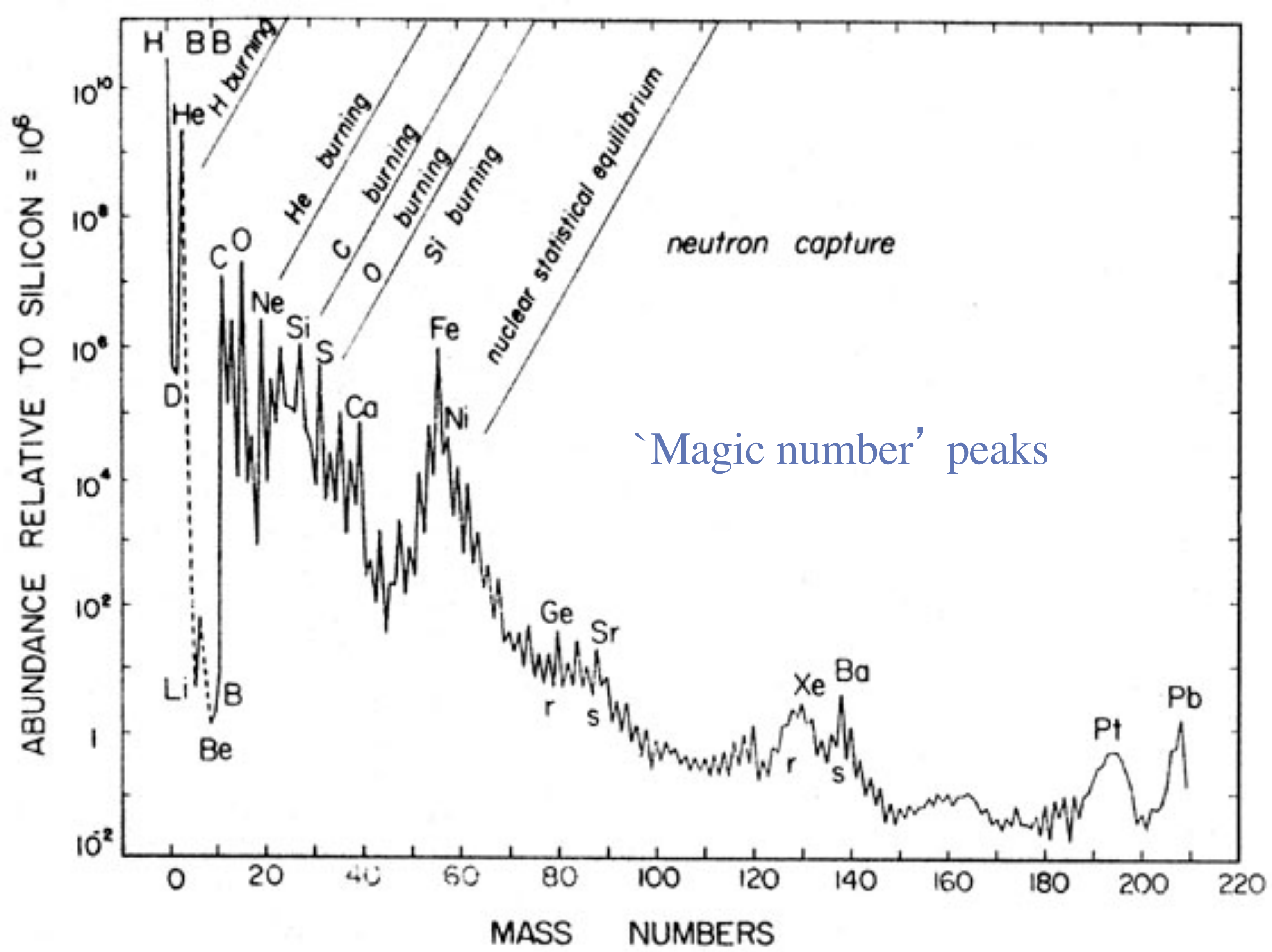
Gold.........0.000000009%

($2.1 x 10^{24} at $300/ounce)

Big Bang

Low-mass stars

High-mass stars

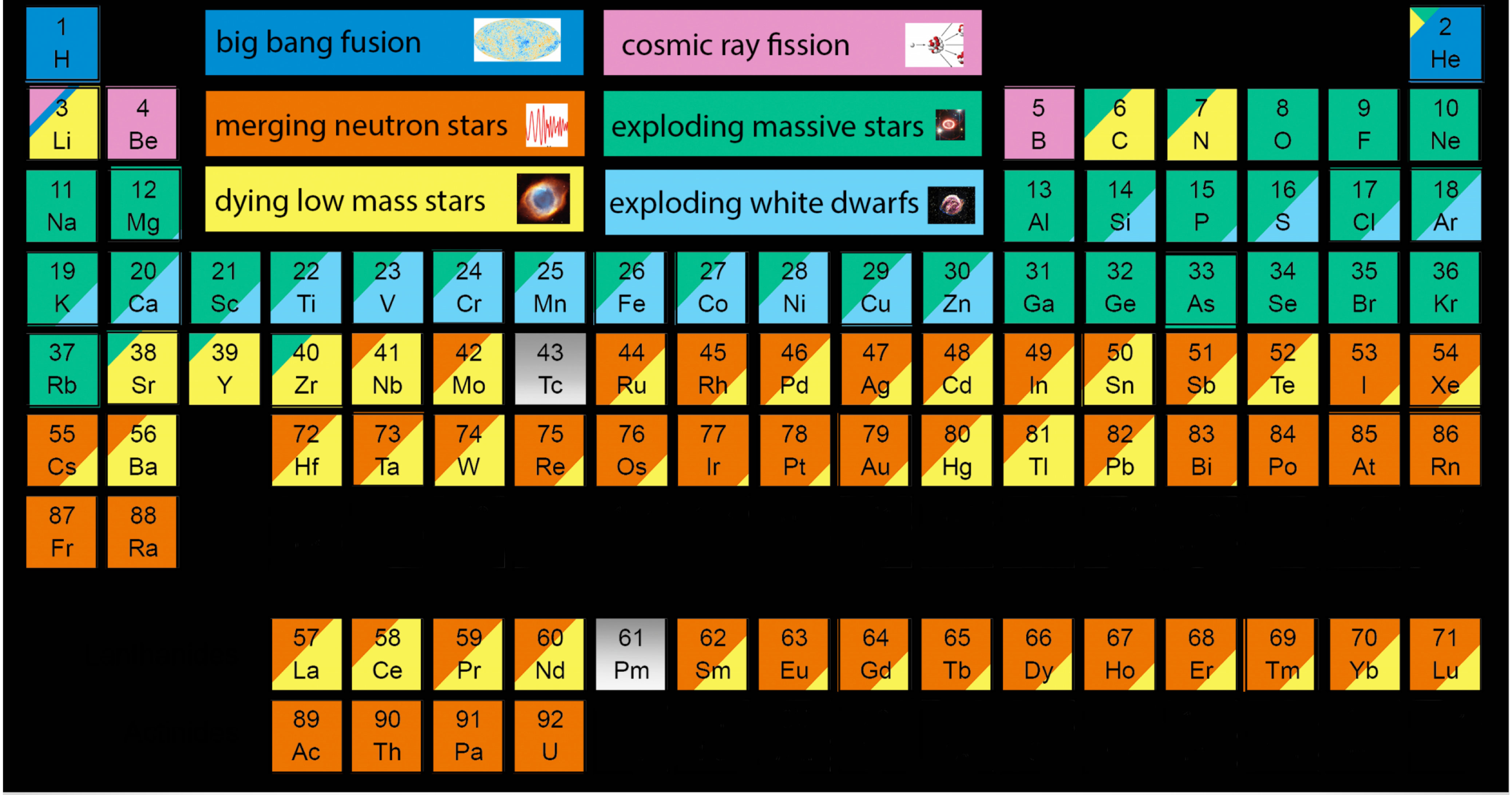


`Magic number' peaks

We are star dust

- This is literally true

The Origin of the Solar System Elements



big bang fusion

cosmic ray fission

merging neutron stars

exploding massive stars

dying low mass stars

exploding white dwarfs

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra																
			57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
			89 Ac	90 Th	91 Pa	92 U											