The Lives and Deaths of Stars and the Stellar Explosions That Made Us

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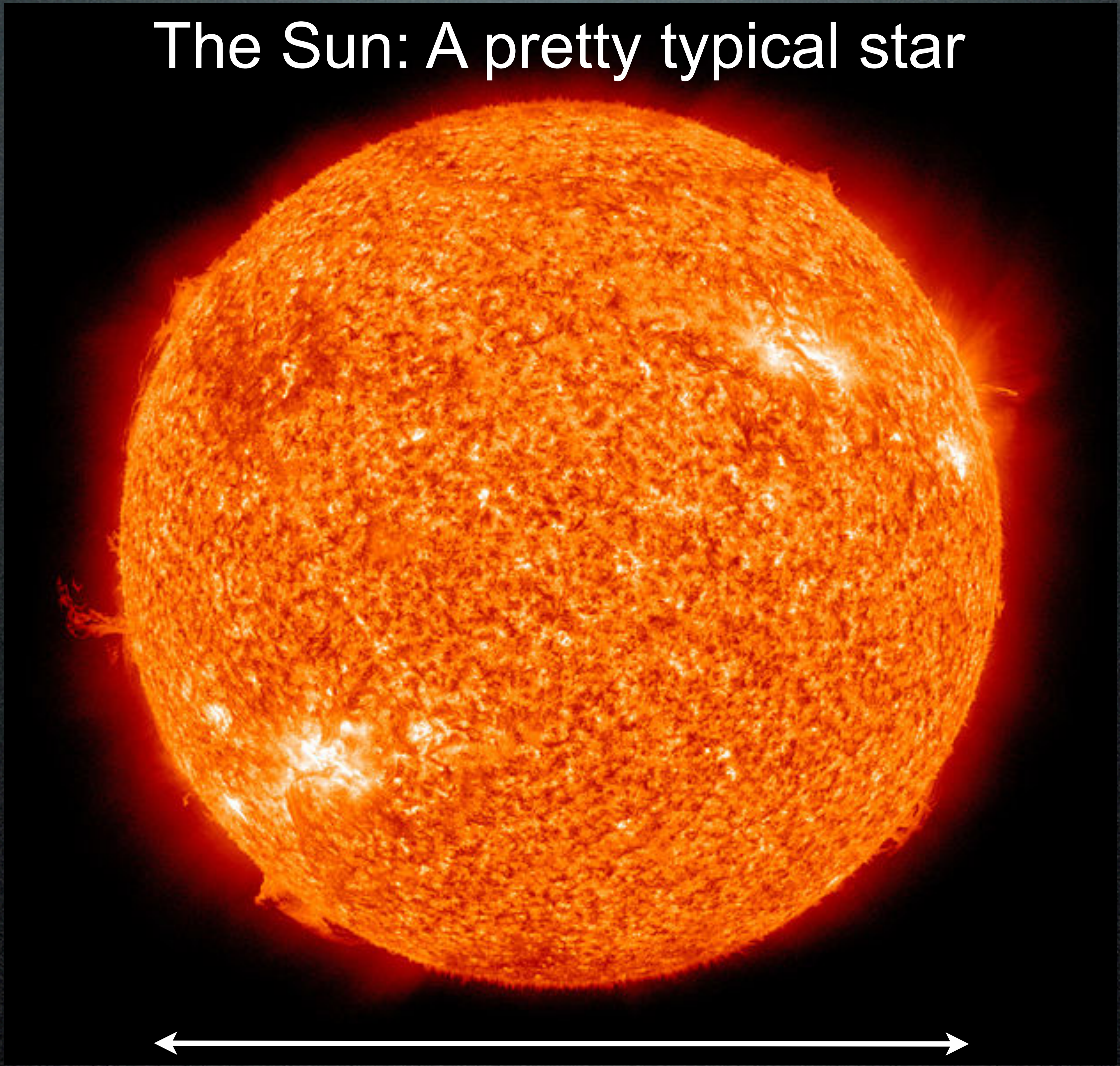
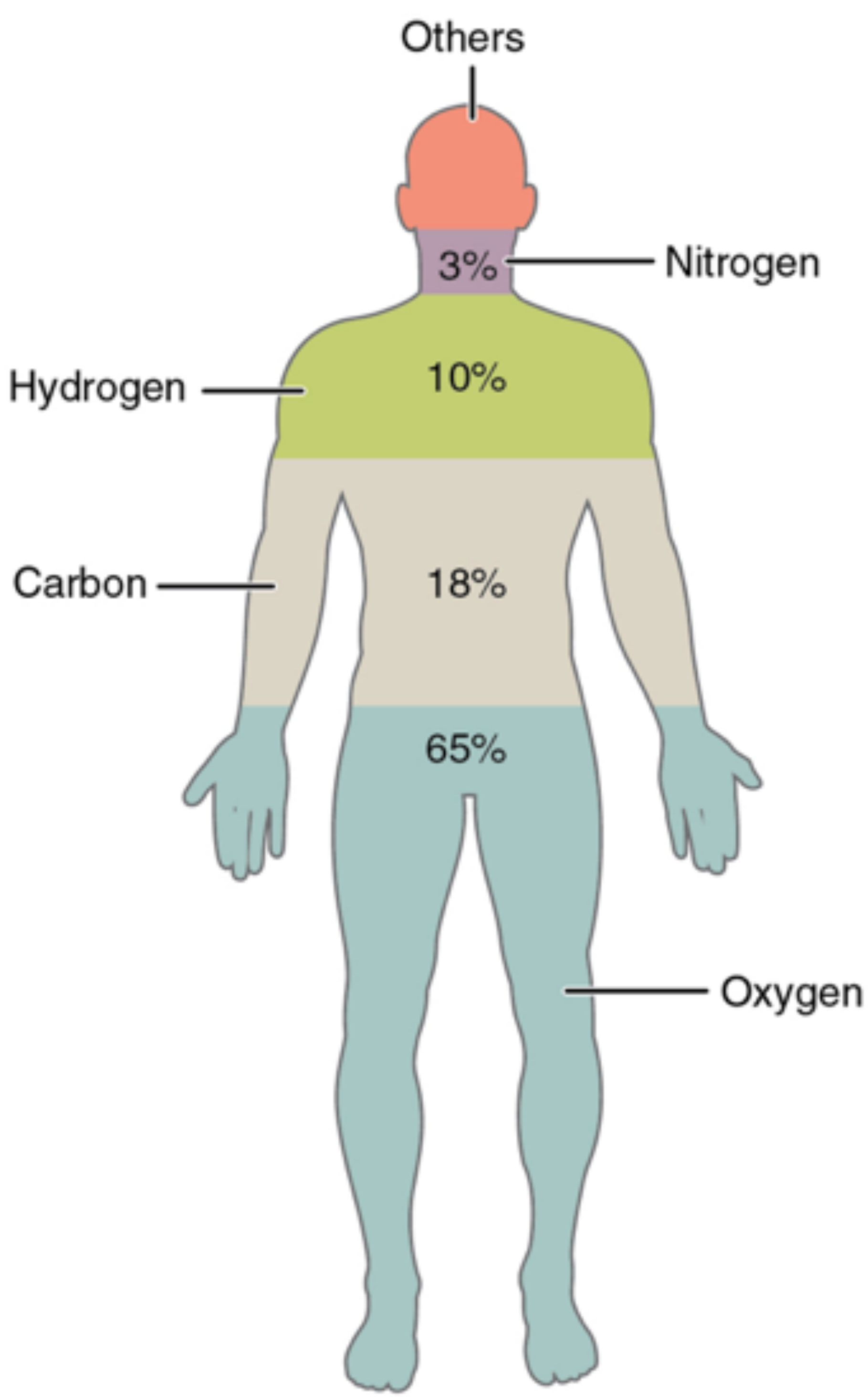
Stars: Big Nuclear Furnaces



1,400,000 km

You Are Star Stuff!



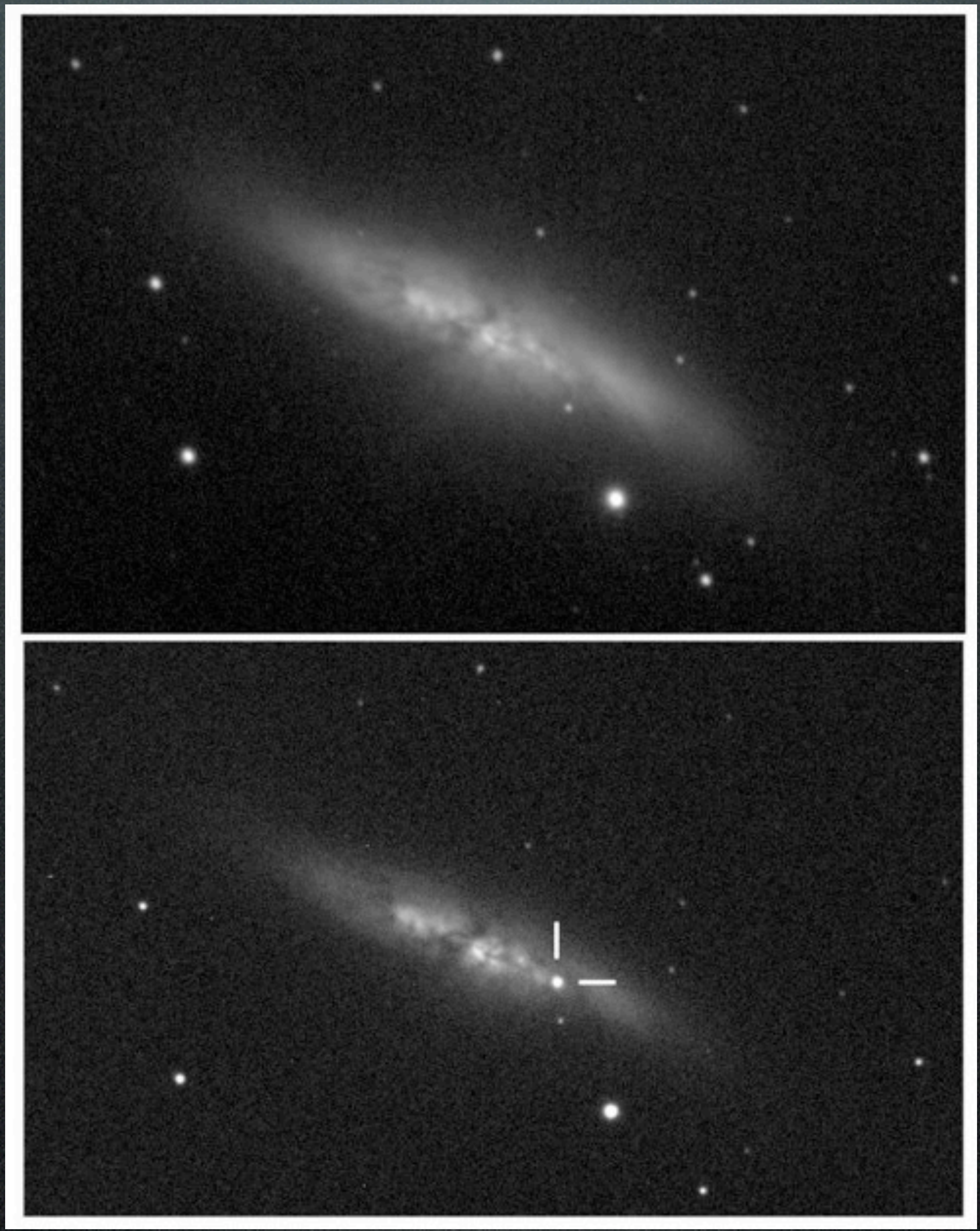
Element	Symbol	Percentage in Body
Oxygen	O	65.0
Carbon	C	18.5
Hydrogen	H	9.5
Nitrogen	N	3.2
Calcium	Ca	1.5
Phosphorus	P	1.0
Potassium	K	0.4
Sulfur	S	0.3
Sodium	Na	0.2
Chlorine	Cl	0.2
Magnesium	Mg	0.1
Trace elements include boron (B), chromium (Cr), cobalt (Co), copper (Cu), fluorine (F), iodine (I), iron (Fe), manganese (Mn), molybdenum (Mo), selenium (Se), silicon (Si), tin (Sn), vanadium (V), and zinc (Zn).		less than 1.0

A Supernova (i.e., Massive Star) is one of your ancestors!

Stars and Supernovae

- The life of “normal” stars, like the sun.
- The fast and furious lives and big stars.
- The fates of the stars and supernovae.

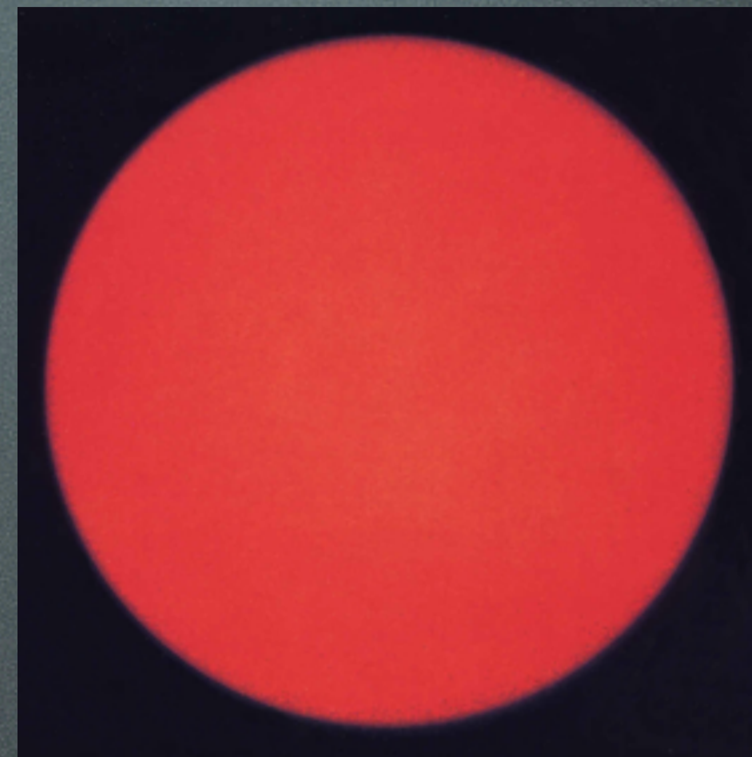
Bright Transients in the Sky



Astronomical Scales

Earth,
1 R_E

Sun,
110 R_E



Red Giant,
5000 R_E

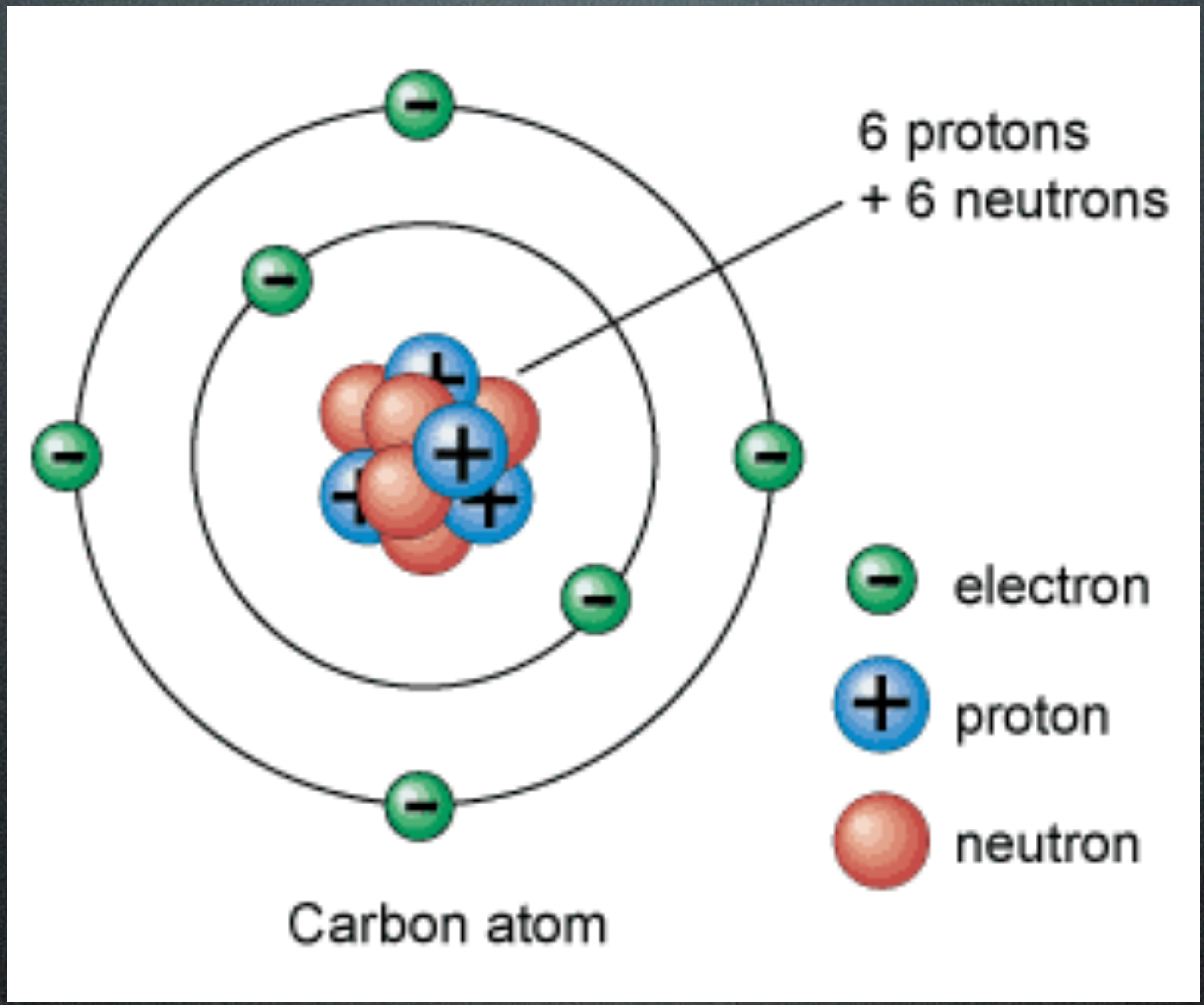
Galaxy,
100 Trillion R_E

Molecular Cloud,
100 Billion R_E

Stars: Basic Unit of Astronomy

1 Million Trillion km

Nuclei: Basic Unit of Matter



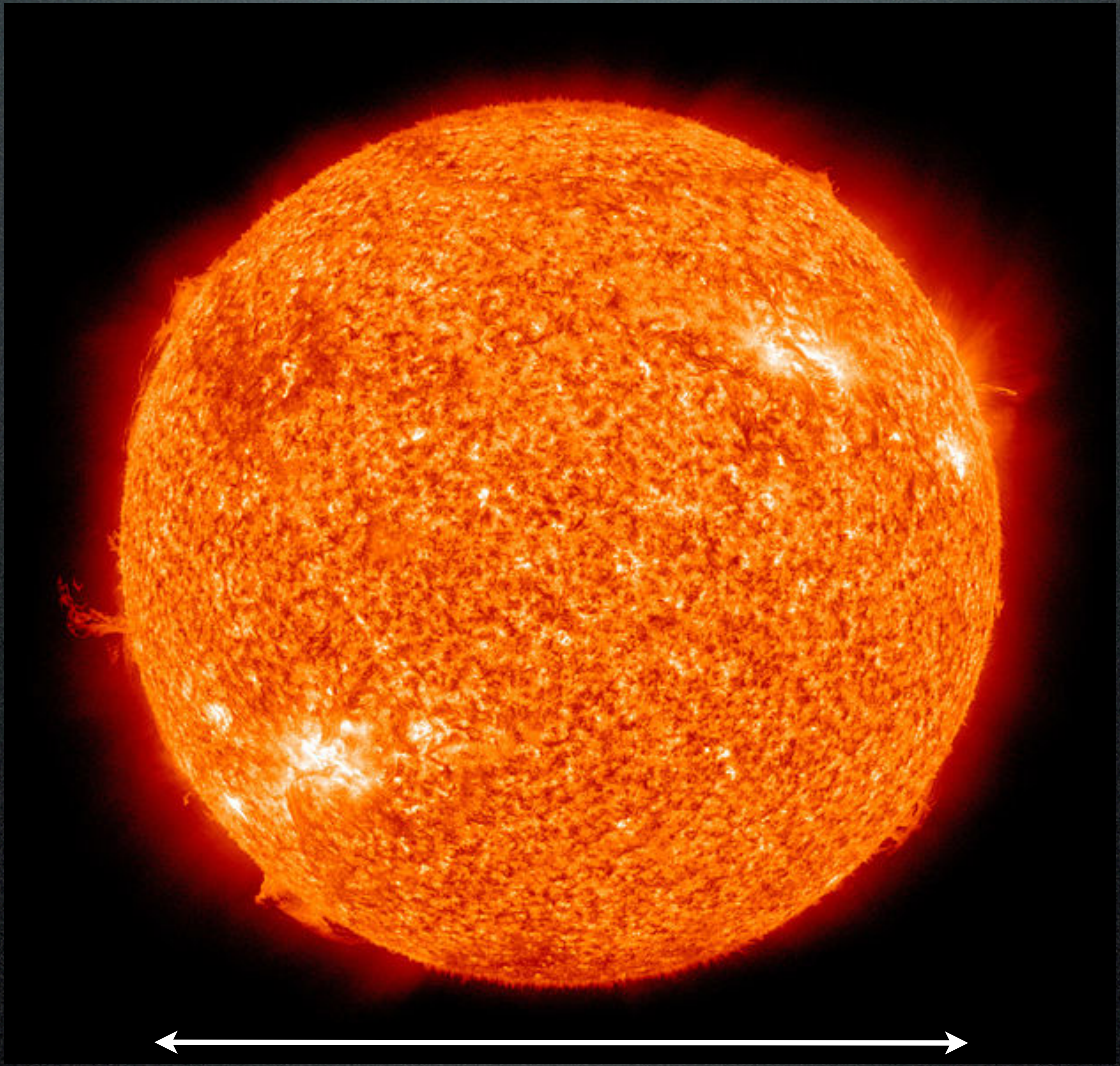
1 Hundred-Trillionth km

Nucleosynthesis

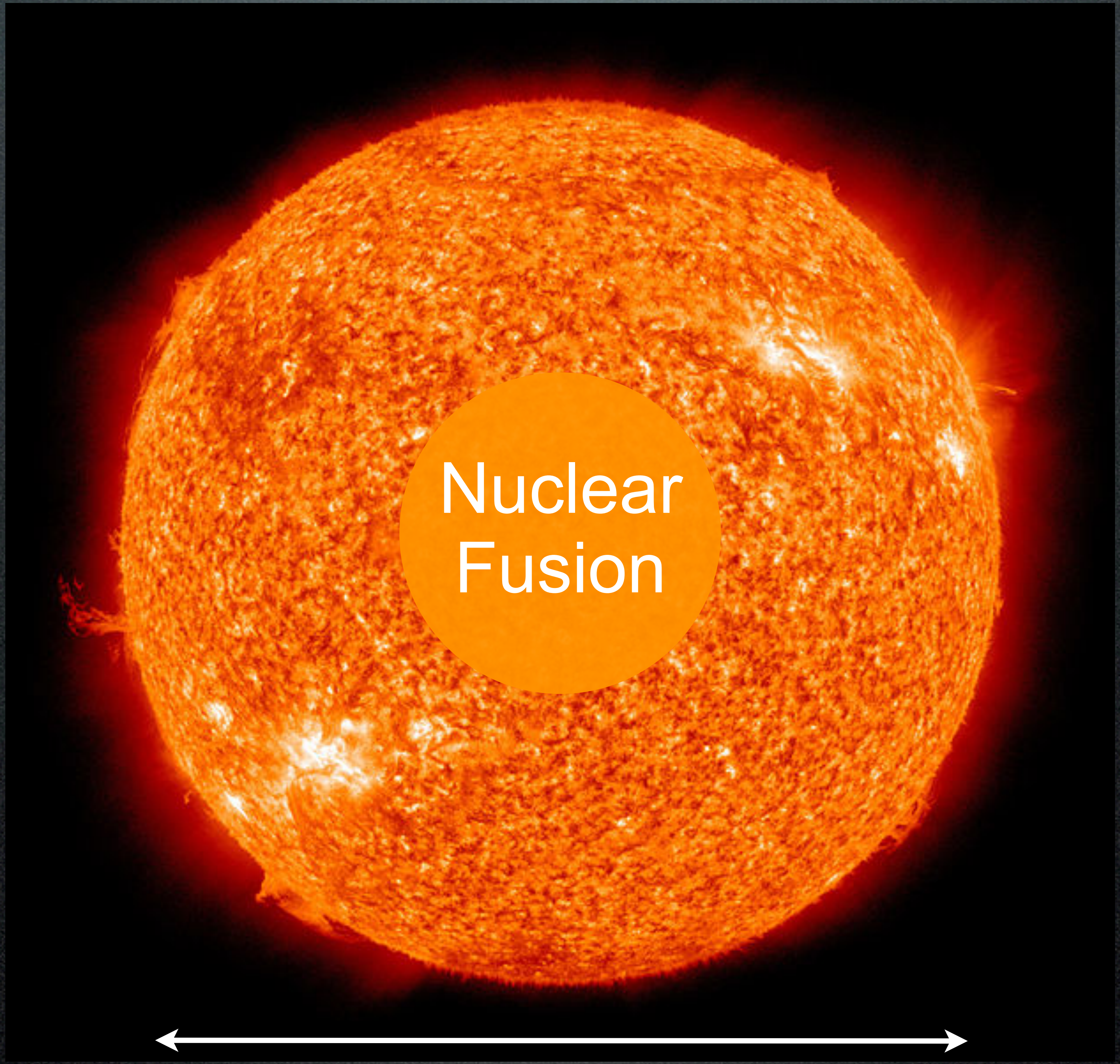
hydrogen 1 **H** 1.0079																		helium 2 **He** 4.0026
lithium 3 **Li** 6.941	beryllium 4 **Be** 9.0122												boron 5 **B** 10.811	carbon 6 **C** 12.011	nitrogen 7 **N** 14.007	oxygen 8 **O** 15.999	fluorine 9 **F** 18.998	neon 10 **Ne** 20.180
sodium 11 **Na** 22.990	magnesium 12 **Mg** 24.305												aluminium 13 **Al** 26.982	silicon 14 **Si** 28.086	phosphorus 15 **P** 30.974	sulfur 16 **S** 32.065	chlorine 17 **Cl** 35.453	argon 18 **Ar** 39.948
potassium 19 **K** 39.098	calcium 20 **Ca** 40.078		scandium 21 **Sc** 44.956	titanium 22 **Ti** 47.867	vanadium 23 **V** 50.942	chromium 24 **Cr** 51.996	manganese 25 **Mn** 54.938	iron 26 **Fe** 55.845	cobalt 27 **Co** 58.933	nickel 28 **Ni** 58.693	copper 29 **Cu** 63.546	zinc 30 **Zn** 65.39	gallium 31 **Ga** 69.723	germanium 32 **Ge** 72.61	arsenic 33 **As** 74.922	selenium 34 **Se** 78.96	bromine 35 **Br** 79.904	krypton 36 **Kr** 83.80
rubidium 37 **Rb** 85.468	strontium 38 **Sr** 87.62		yttrium 39 **Y** 88.906	zirconium 40 **Zr** 91.224	niobium 41 **Nb** 92.906	molybdenum 42 **Mo** 95.94	technetium 43 **Tc** [98]	ruthenium 44 **Ru** 101.07	rhodium 45 **Rh** 102.91	palladium 46 **Pd** 106.42	silver 47 **Ag** 107.87	cadmium 48 **Cd** 112.41	indium 49 **In** 114.82	tin 50 **Sn** 118.71	antimony 51 **Sb** 121.76	tellurium 52 **Te** 127.60	iodine 53 **I** 126.90	xenon 54 **Xe** 131.29
caesium 55 **Cs** 132.91	barium 56 **Ba** 137.33	57-70 *	lutetium 71 **Lu** 174.97	hafnium 72 **Hf** 178.49	tantalum 73 **Ta** 180.95	tungsten 74 **W** 183.84	rhenium 75 **Re** 186.21	osmium 76 **Os** 190.23	iridium 77 **Ir** 192.22	platinum 78 **Pt** 195.08	gold 79 **Au** 196.97	mercury 80 **Hg** 200.59	thallium 81 **Tl** 204.38	lead 82 **Pb** 207.2	bismuth 83 **Bi** 208.98	polonium 84 **Po** [209]	astatine 85 **At** [210]	radon 86 **Rn** [222]
francium 87 **Fr** [223]	radium 88 **Ra** [226]	89-102 * *	lawrencium 103 **Lr** [262]	rutherfordium 104 **Rf** [261]	dubnium 105 **Db** [262]	seaborgium 106 **Sg** [266]	bohrium 107 **Bh** [264]	hassium 108 **Hs** [269]	meitnerium 109 **Mt** [268]	ununnilium 110 **Uun** [271]	unununium 111 **Uuu** [272]	ununbium 112 **Uub** [277]		ununquadium 114 **Uuq** [289]				

* Lanthanide series	lanthanum 57 **La** 138.91	cerium 58 **Ce** 140.12	praseodymium 59 **Pr** 140.91	neodymium 60 **Nd** 144.24	promethium 61 **Pm** [145]	samarium 62 **Sm** 150.36	europium 63 **Eu** 151.96	gadolinium 64 **Gd** 157.25	terbium 65 **Tb** 158.93	dysprosium 66 **Dy** 162.50	holmium 67 **Ho** 164.93	erbium 68 **Er** 167.26	thulium 69 **Tm** 168.93	ytterbium 70 **Yb** 173.04
* * Actinide series	actinium 89 **Ac** [227]	thorium 90 **Th** 232.04	protactinium 91 **Pa** 231.04	uranium 92 **U** 238.03	neptunium 93 **Np** [237]	plutonium 94 **Pu** [244]	americium 95 **Am** [243]	curium 96 **Cm** [247]	berkelium 97 **Bk** [247]	californium 98 **Cf** [251]	einsteinium 99 **Es** [252]	fermium 100 **Fm** [257]	mendelevium 101 **Md** [258]	nobelium 102 **No** [259]

Stars: Big Nuclear Furnaces

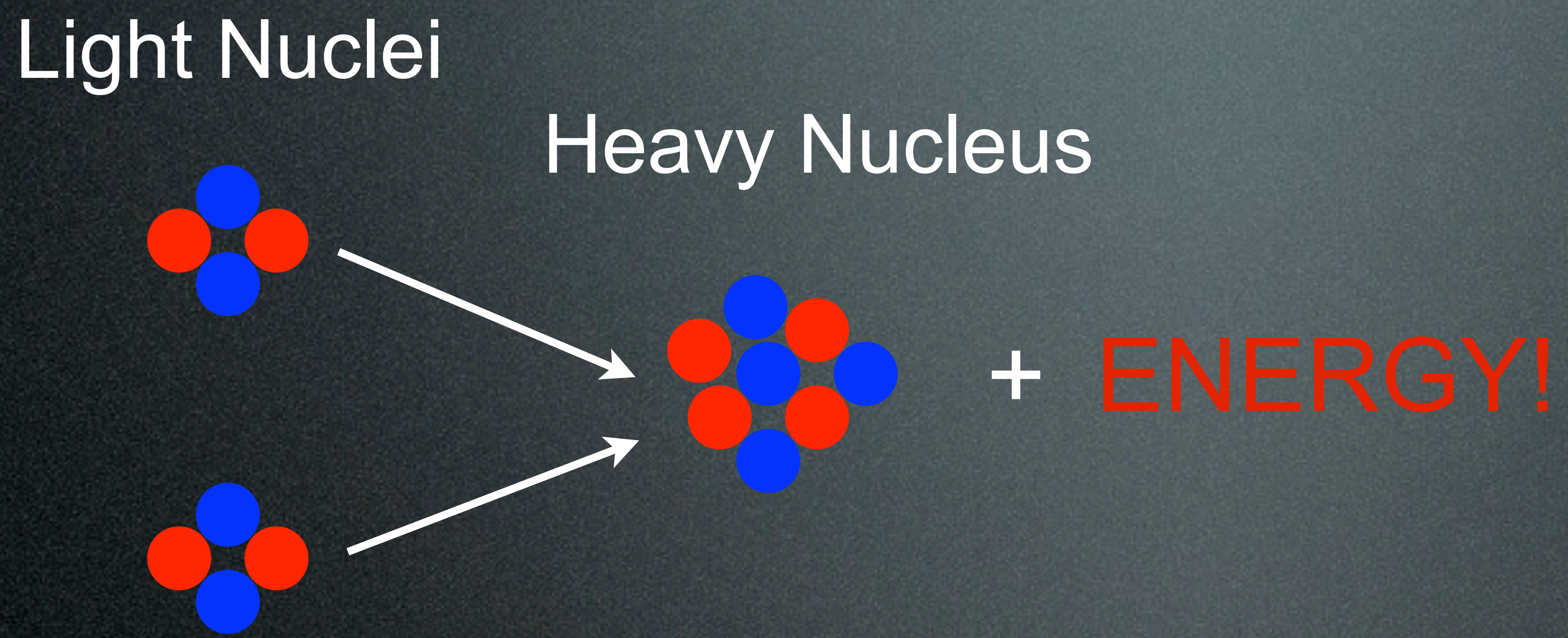


Stars: Big Nuclear Furnaces



1,400,000 km

Nuclear Fusion

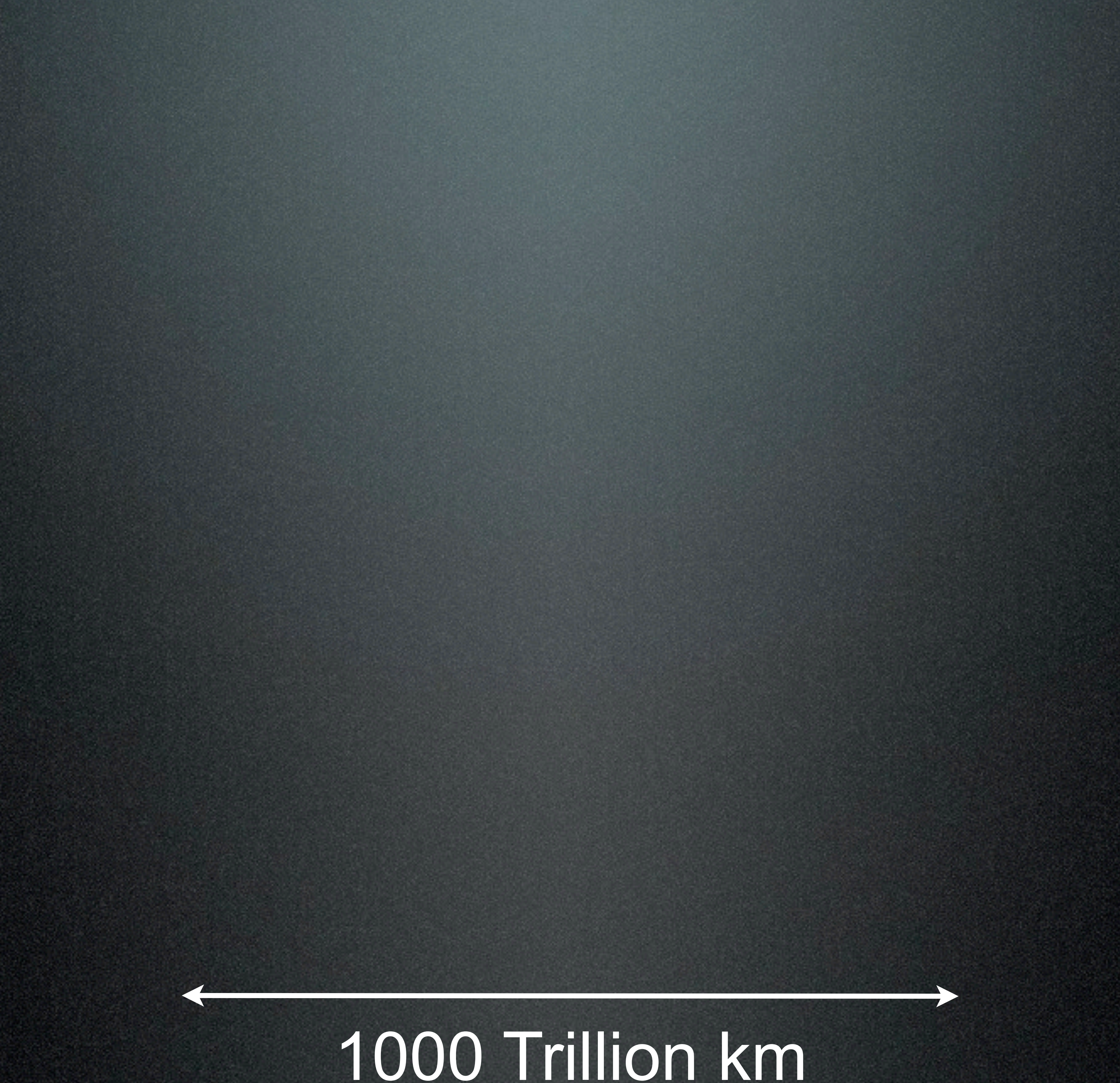


Very sensitive to temperature!

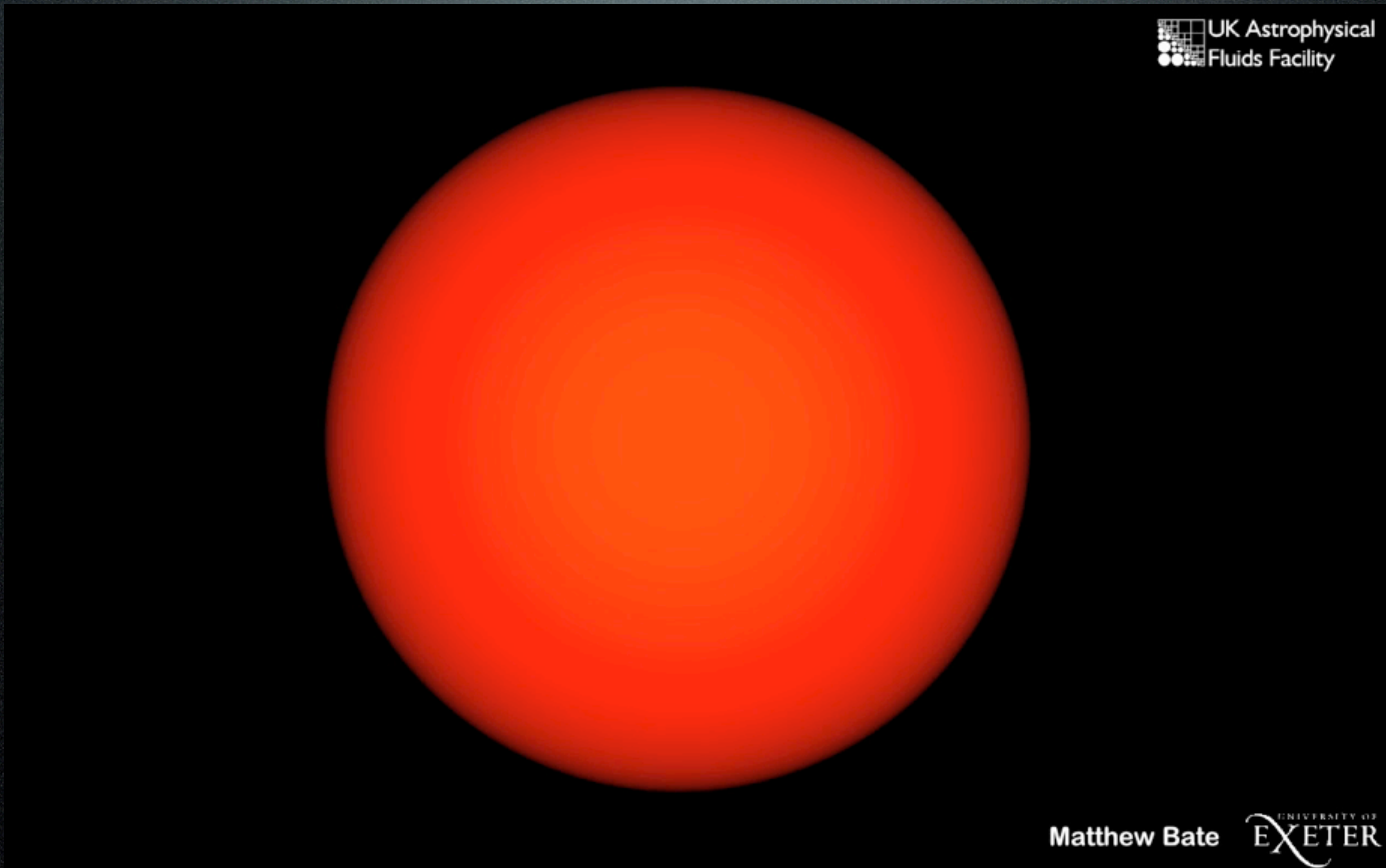
Fusion of heavier and heavier elements requires higher and higher *threshold* temperatures.


Stellar Birth

Star Formation

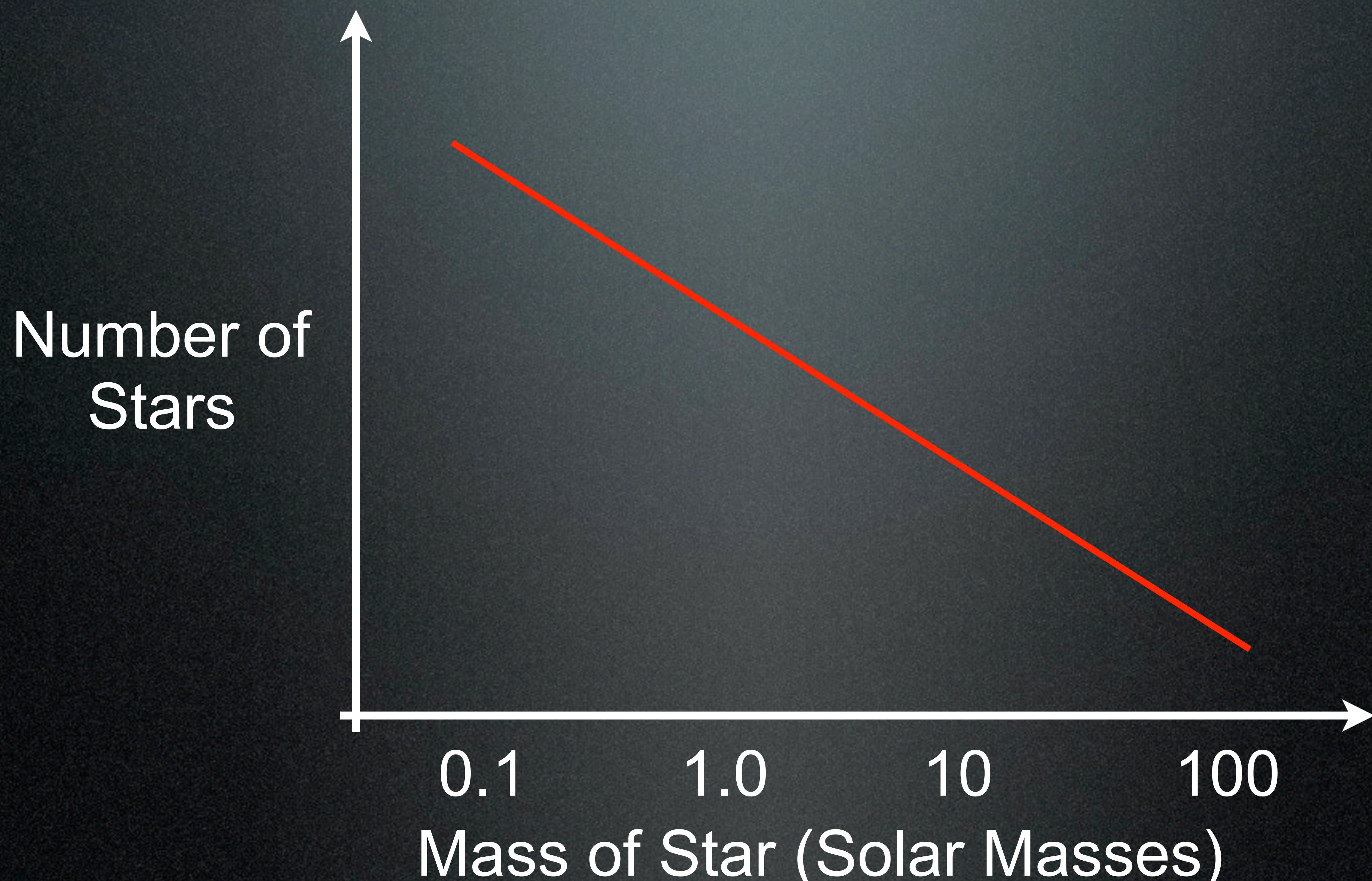


Star Formation

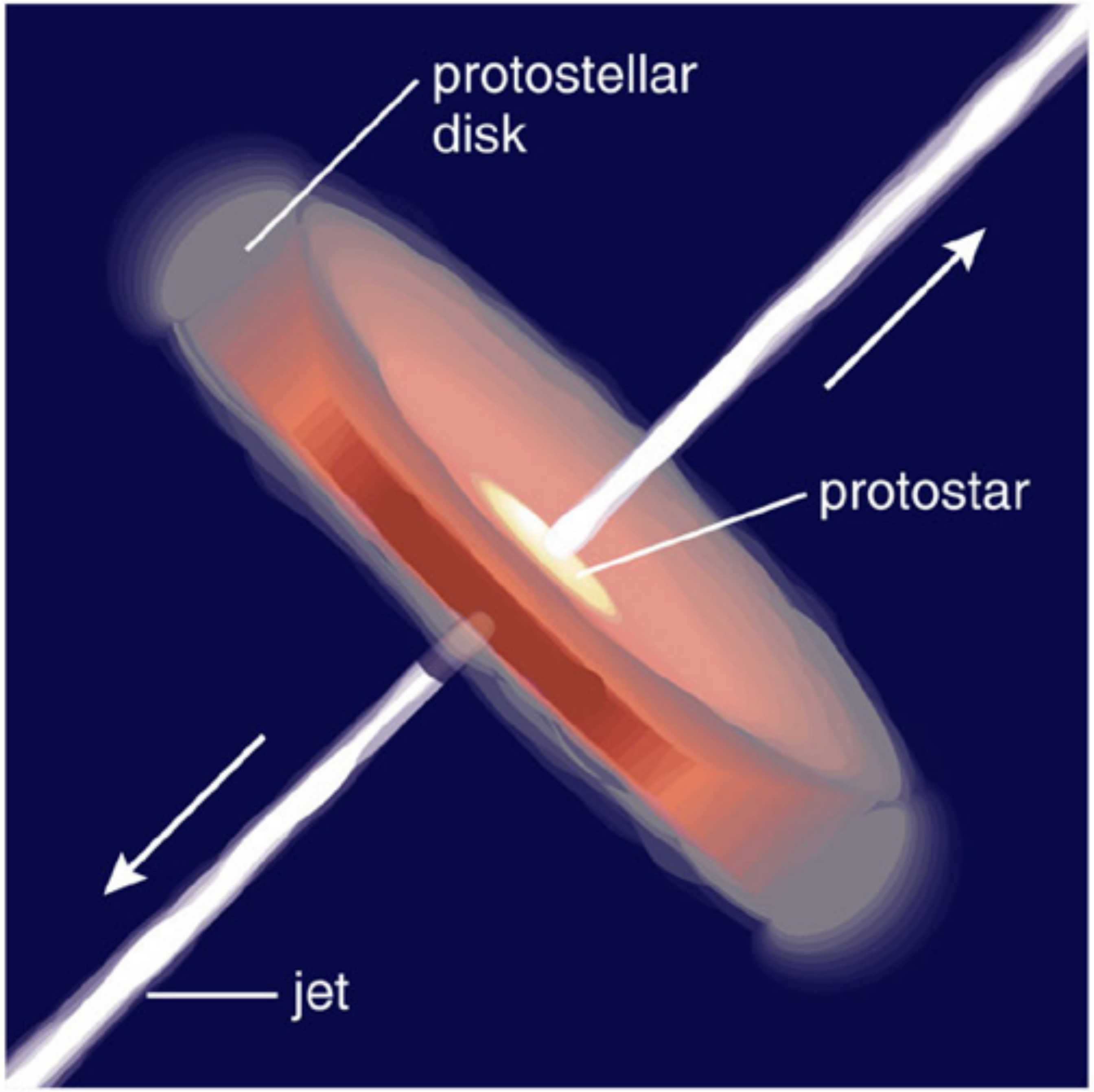


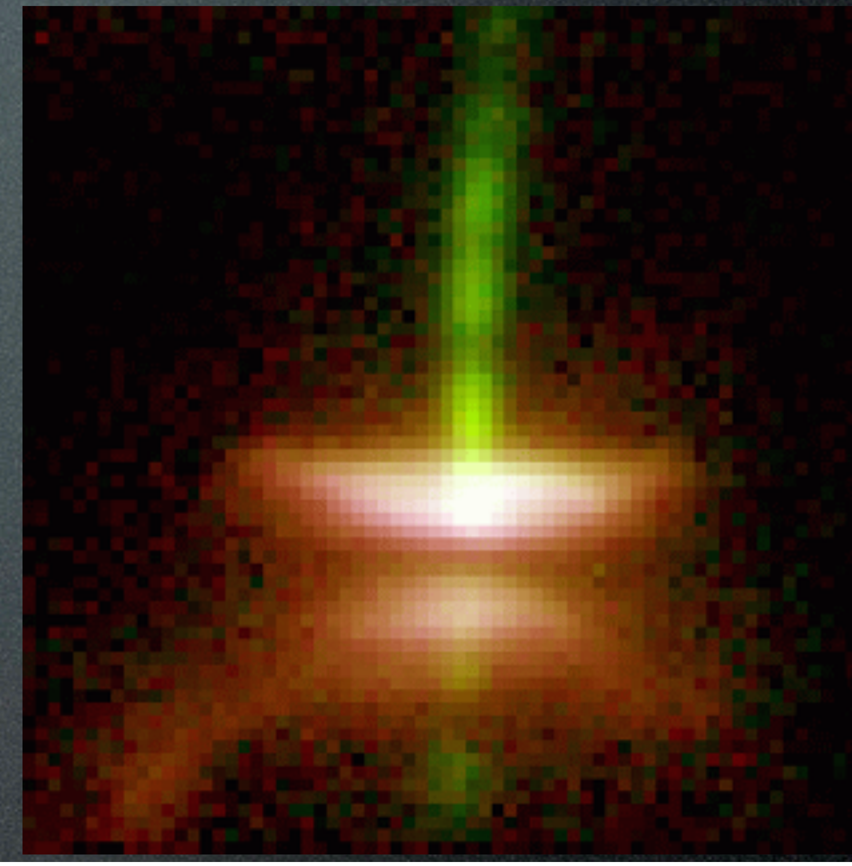
1000 Trillion km

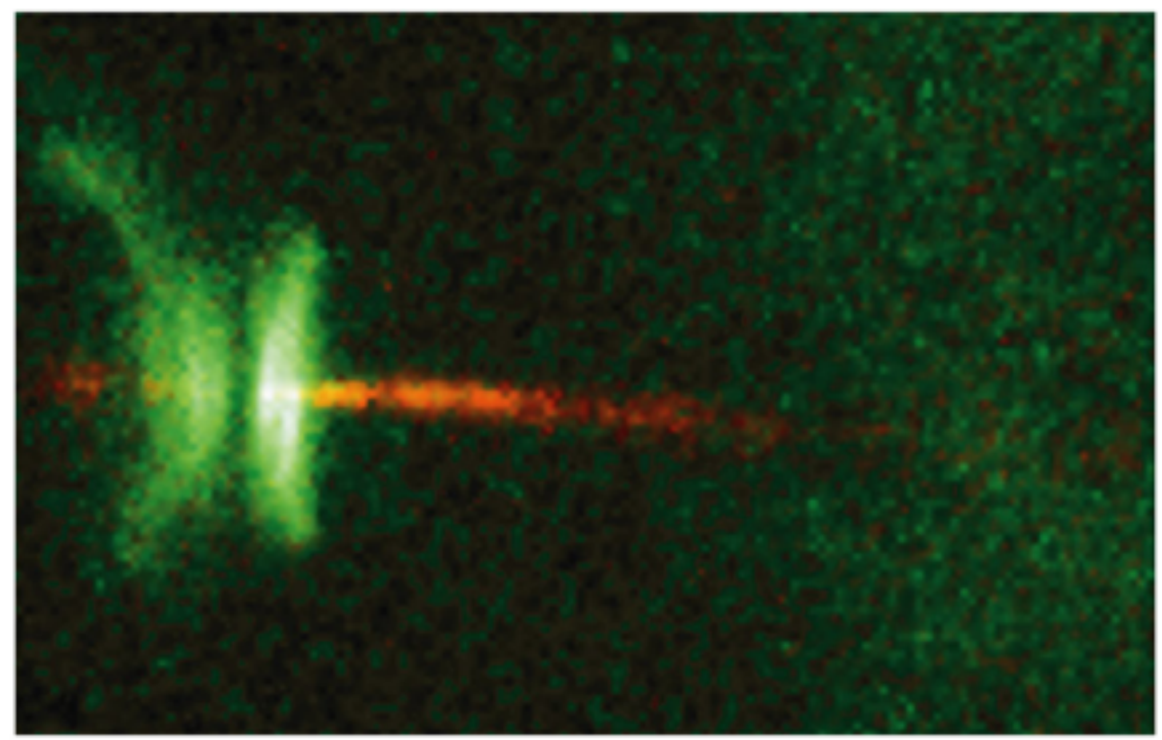
More Small Stars than Big



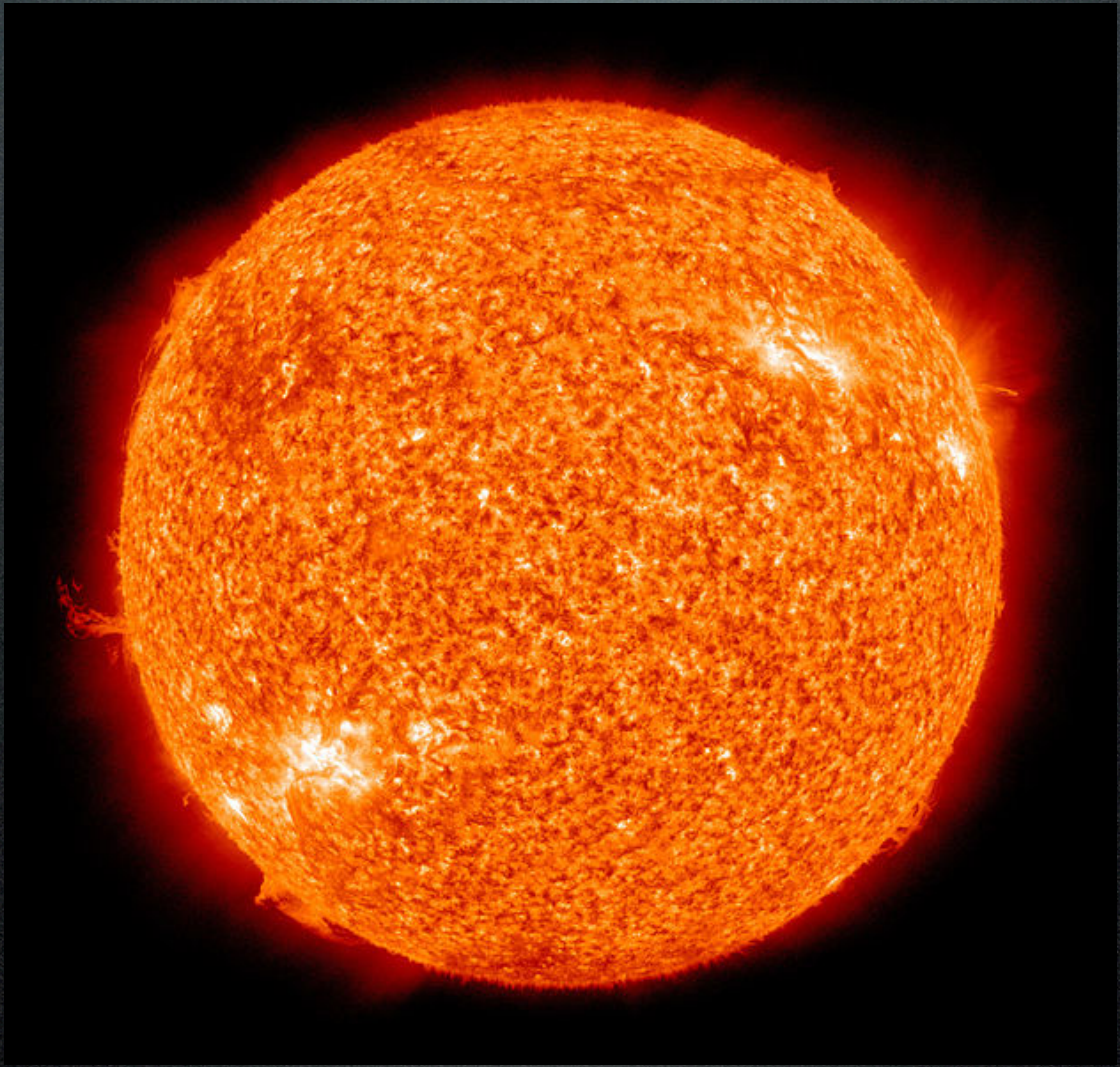
Newborn Stars Have Disks



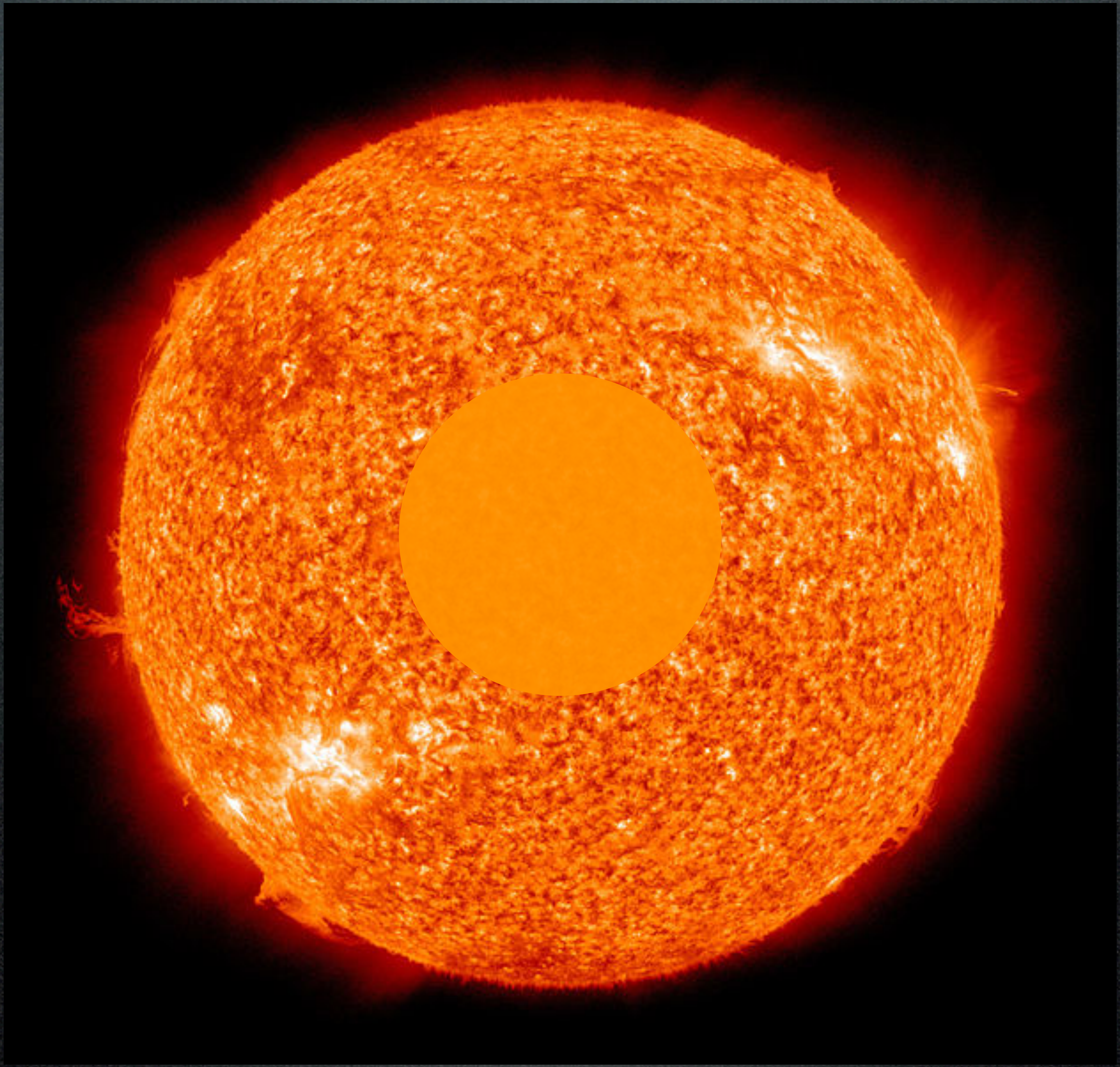




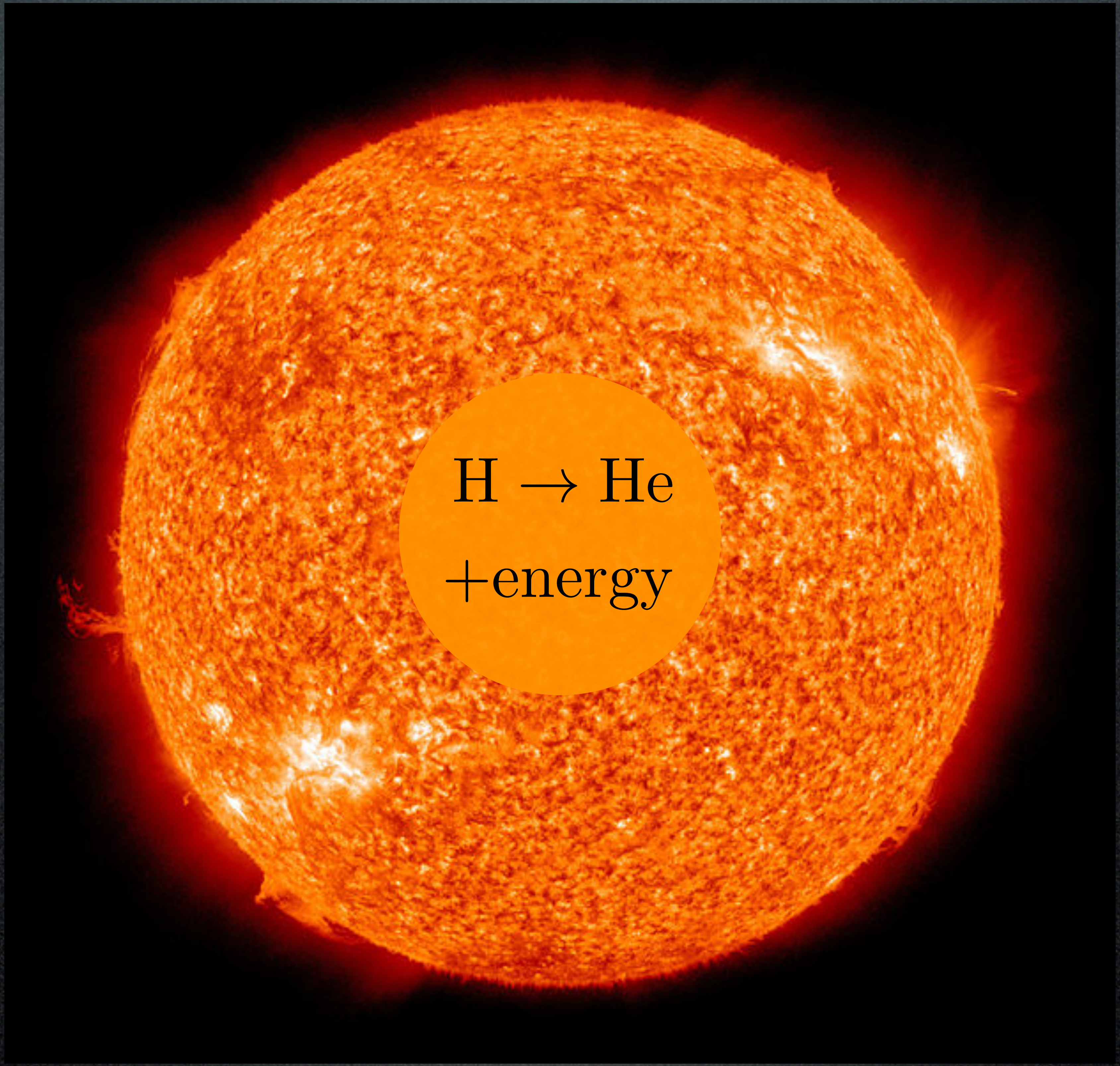
Hydrogen Ignition: Main Sequence



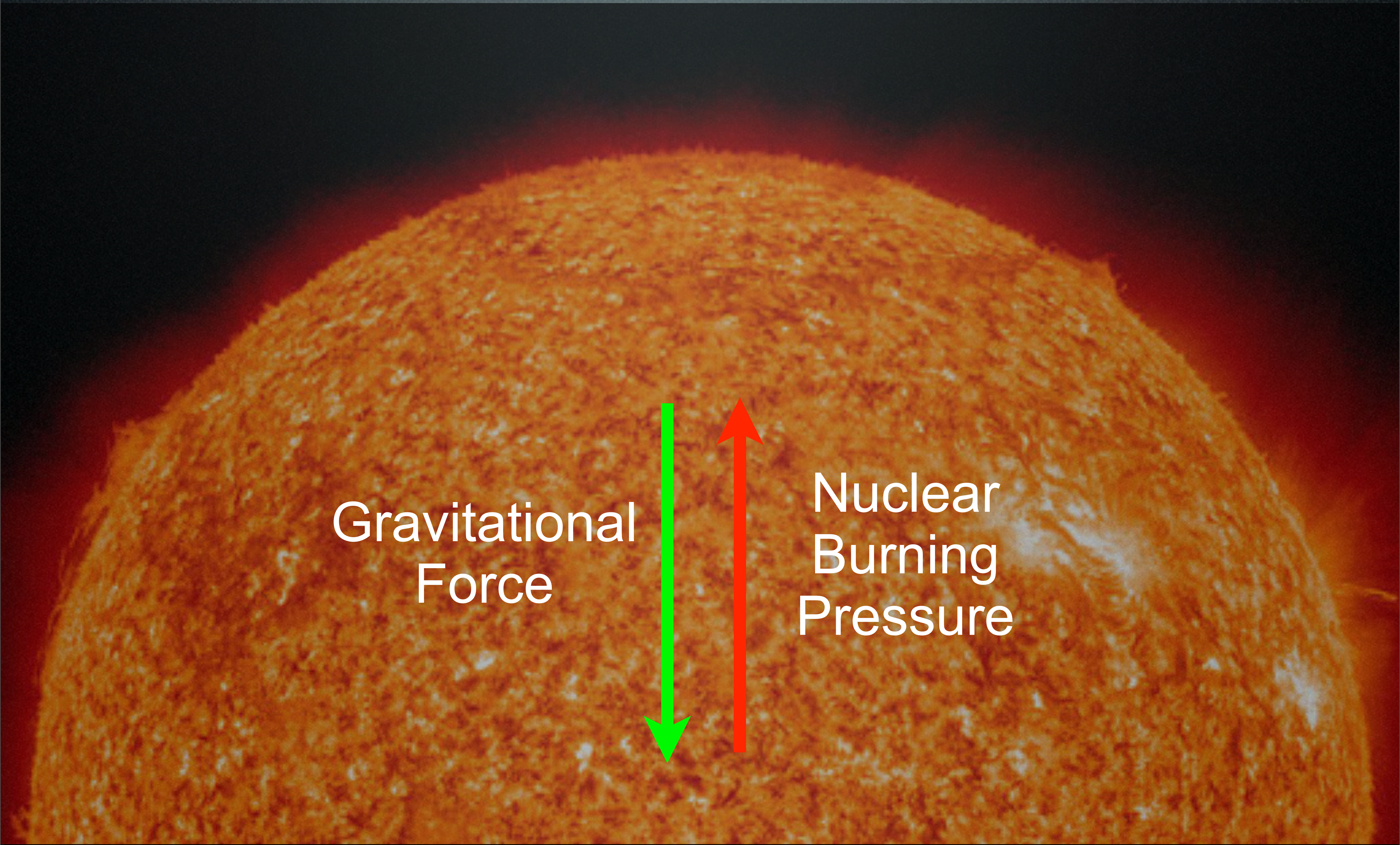
Hydrogen Ignition: Main Sequence



Hydrogen Ignition: Main Sequence

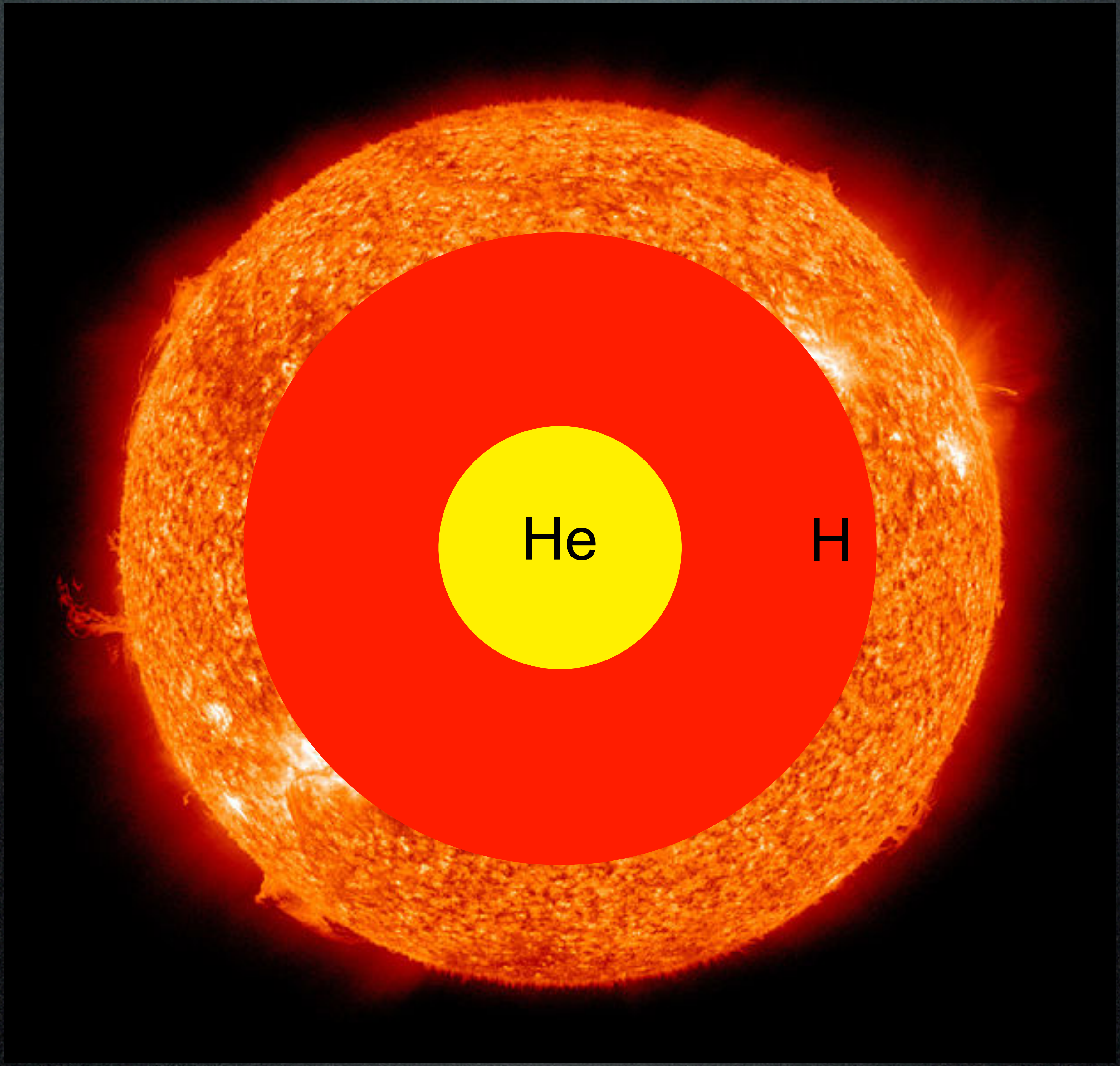


Struggle Against Gravity

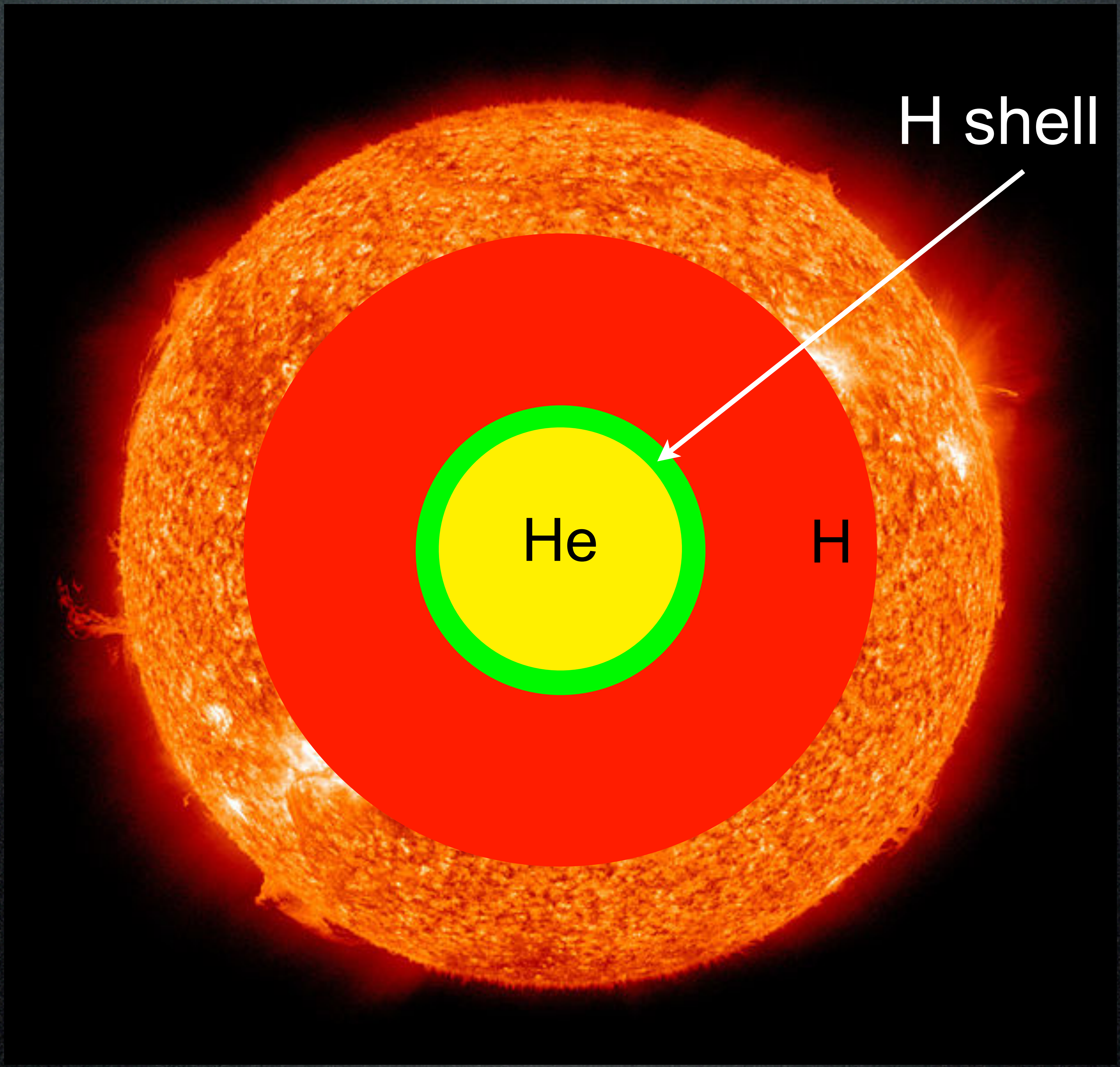


What is Pressure?

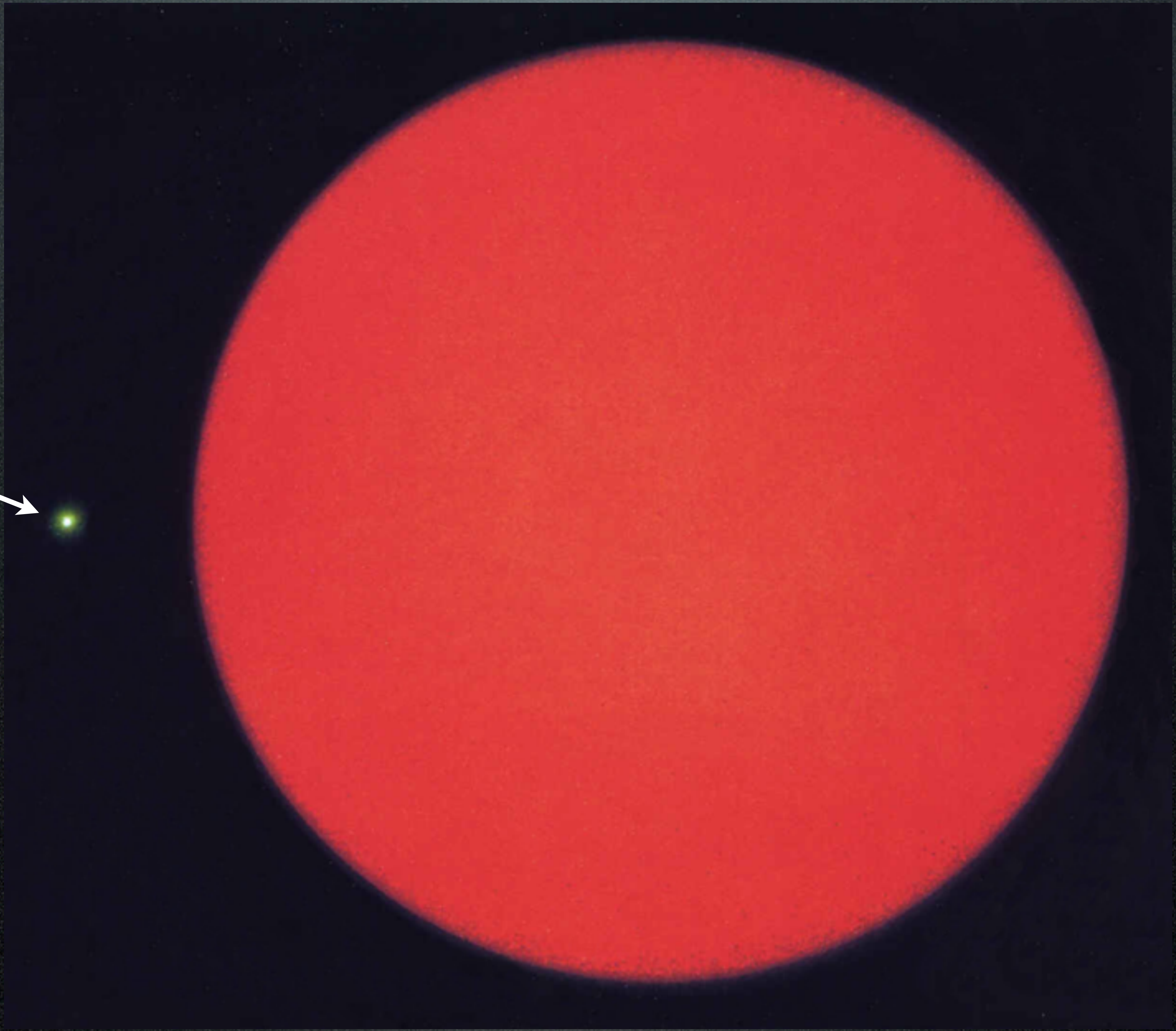
Core Hydrogen Exhaustion



Core Hydrogen Exhaustion

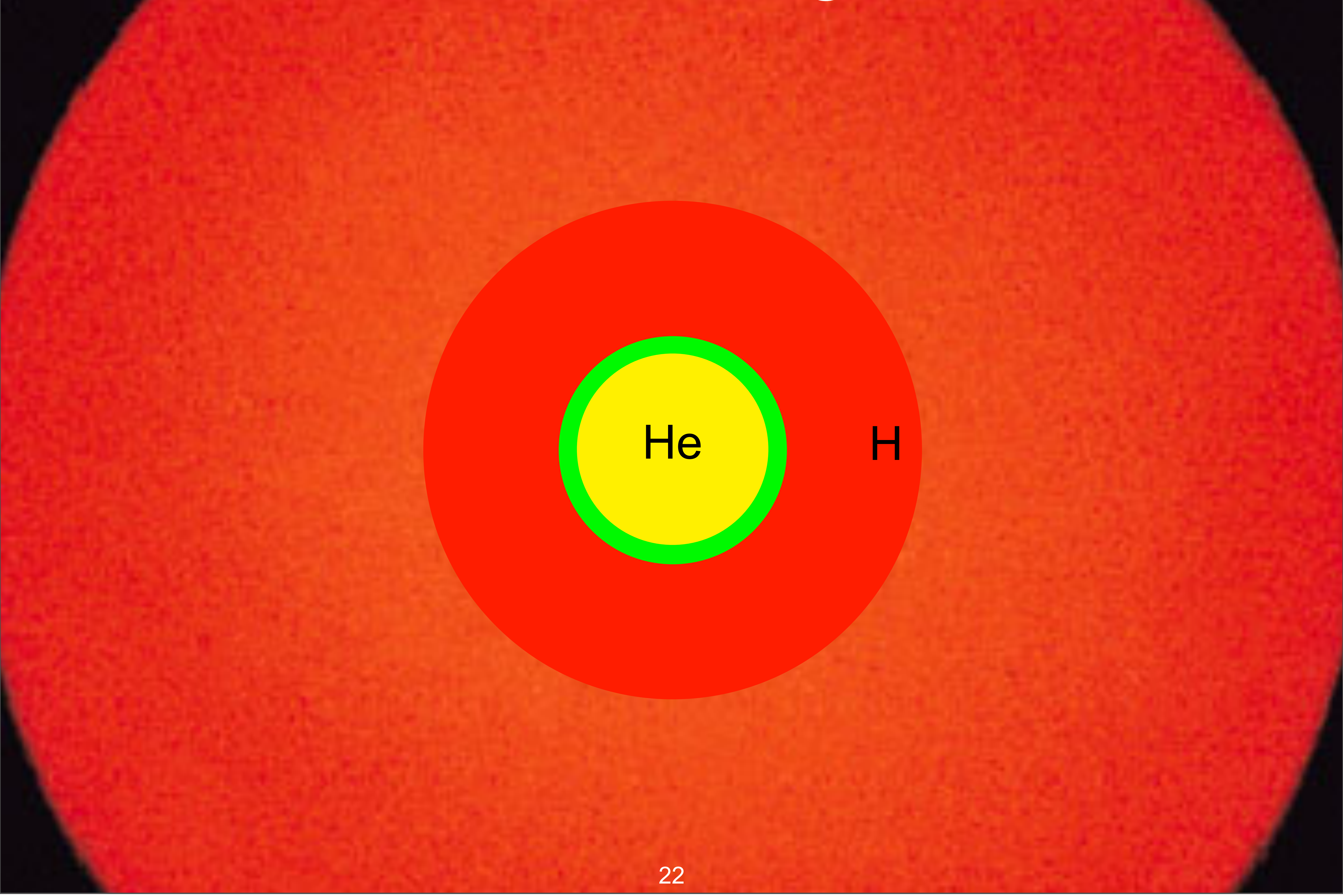


Red Giant Phase

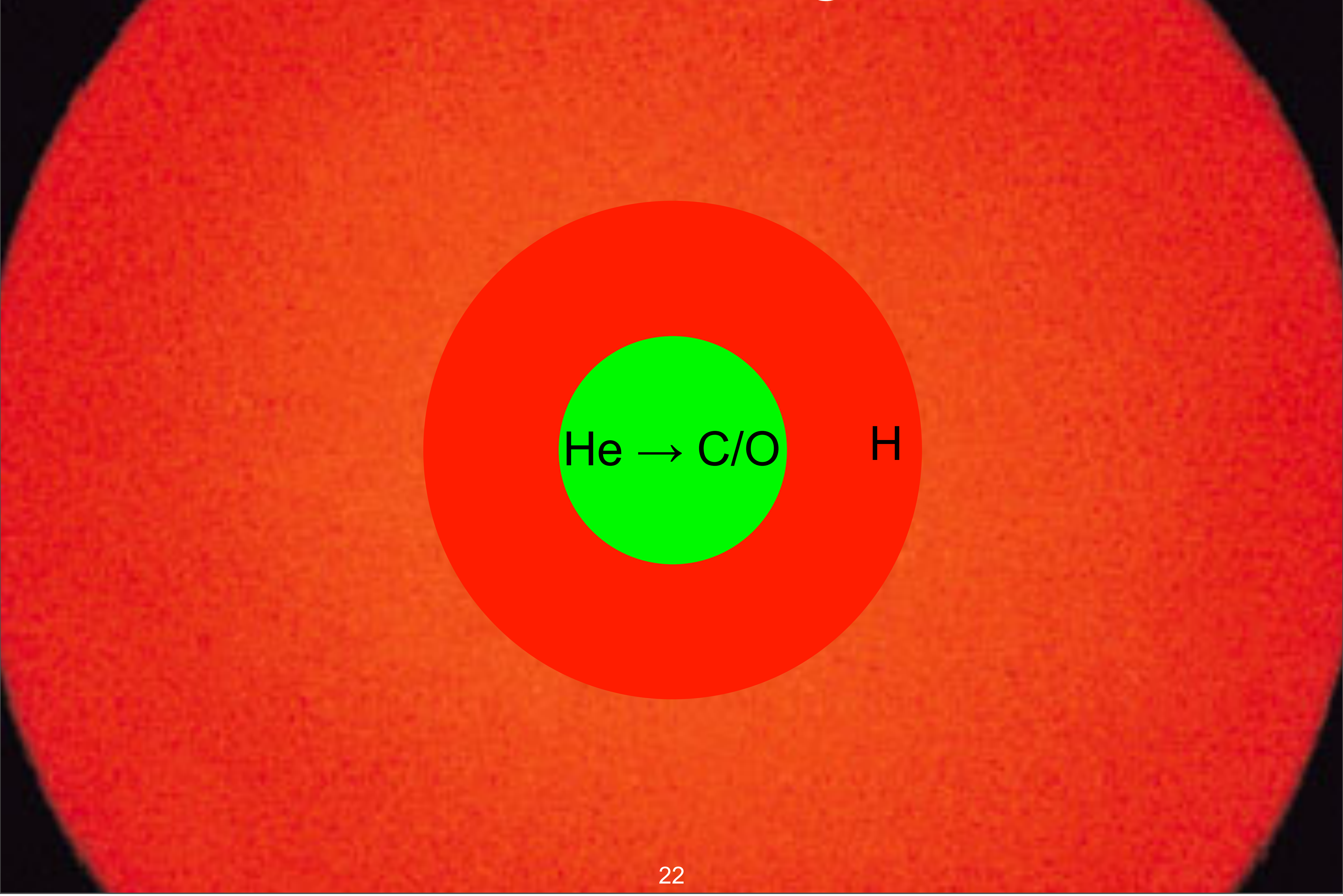


Red Giant Phase

Core Helium Ignition



Core Helium Ignition

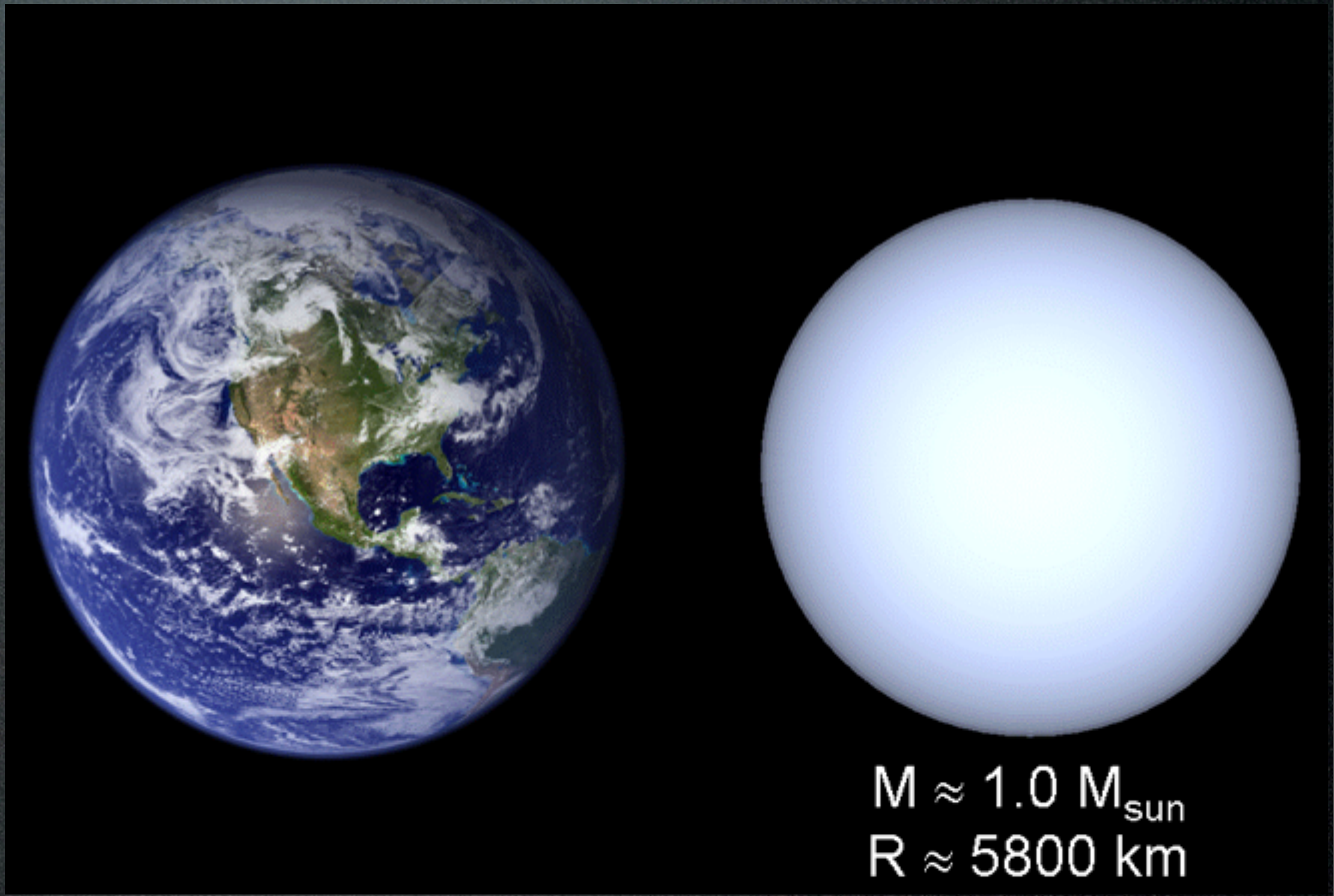


White Dwarfs and Nebulae

The Fate of the Sun

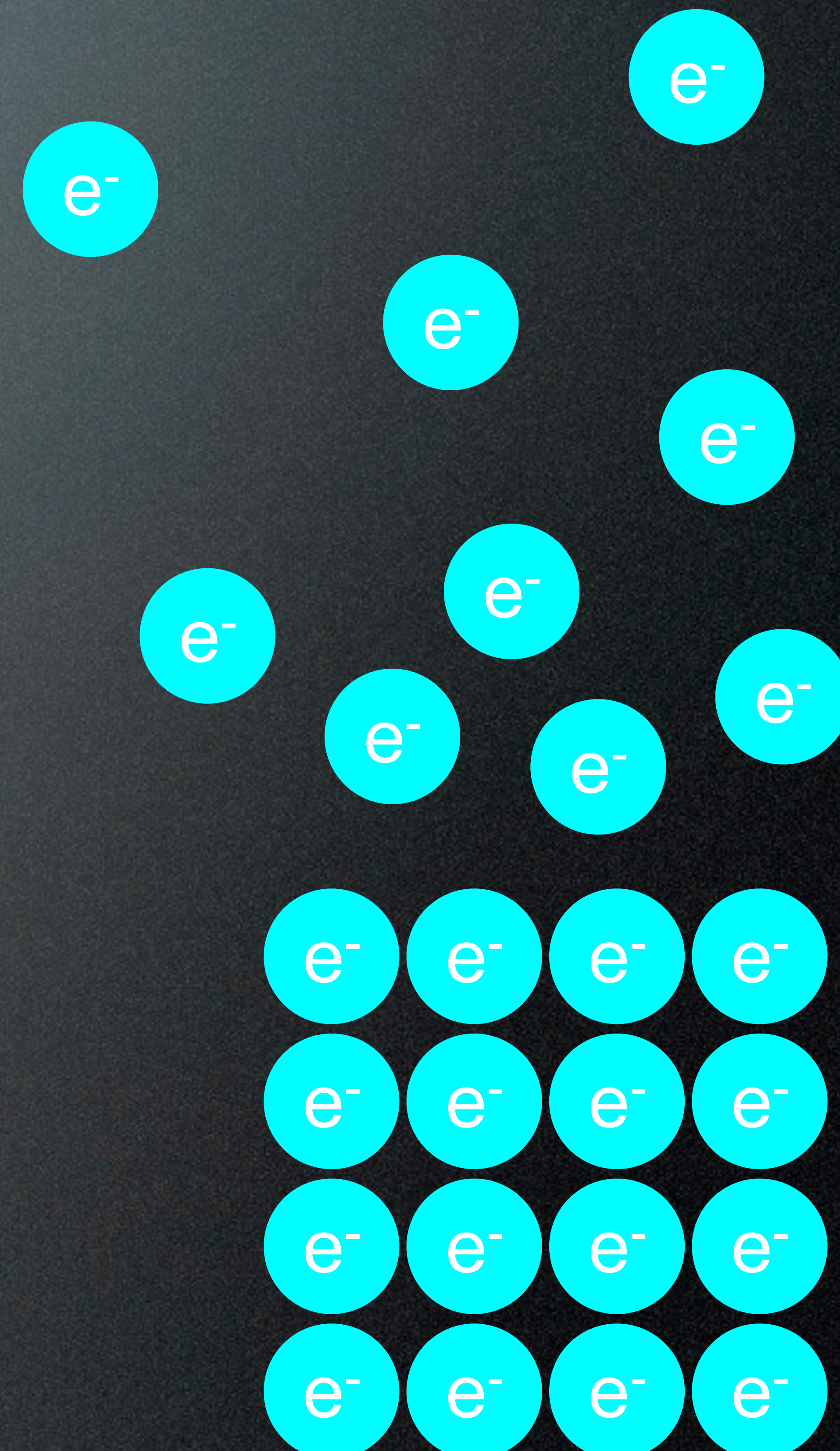
- After running out of Hydrogen fuel, the sun will burn Helium into Carbon and Oxygen.

Sun will stop nuclear burning, expel it's outer envelope and become a White Dwarf Star.



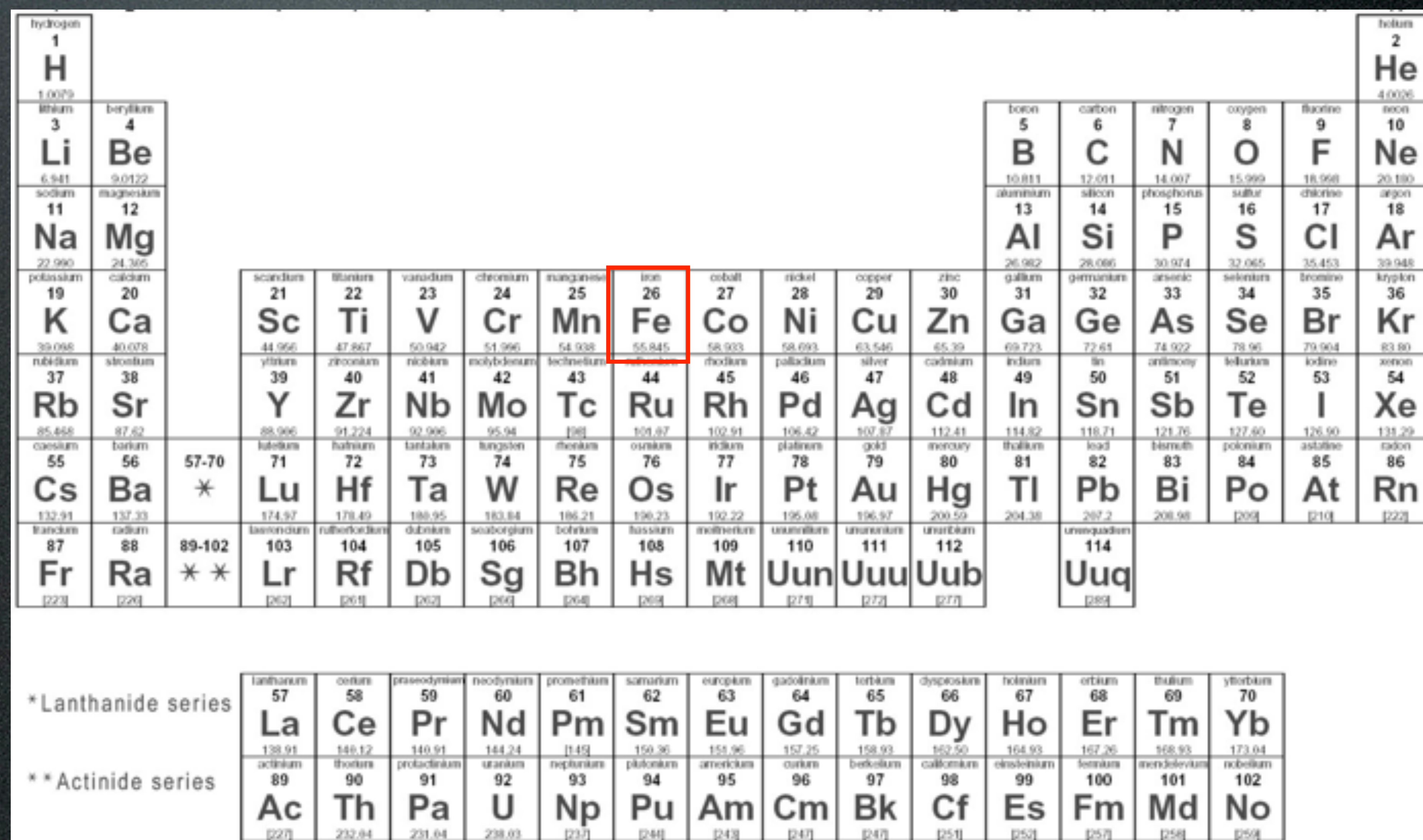
White Dwarfs & Pressure

- No nuclear burning a WD.
- Held up against gravity by *electron degeneracy* pressure.
- Pressure demo:

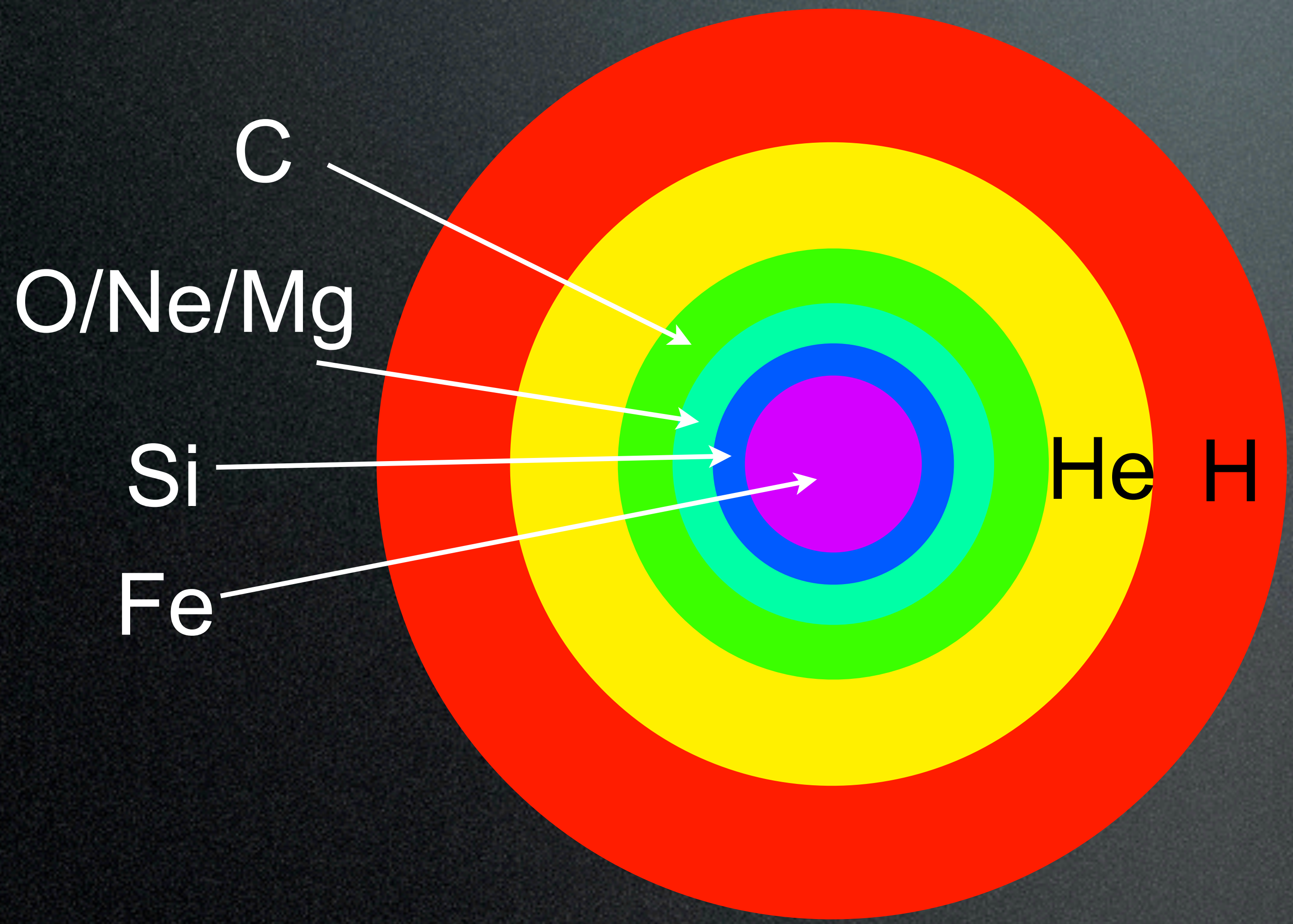


What about Bigger Stars?

- More massive stars than the sun can burn elements beyond Helium (Carbon, Oxygen, etc.).
- Stars more than about 10 times the sun's mass can burn nuclear fuel all the way to iron.
- Iron won't burn!



Burning in Big Stars



Iron is most tightly-bound nucleus.

Nuclear reactions with iron *absorb* energy.

Nuclear Burning is Violent!

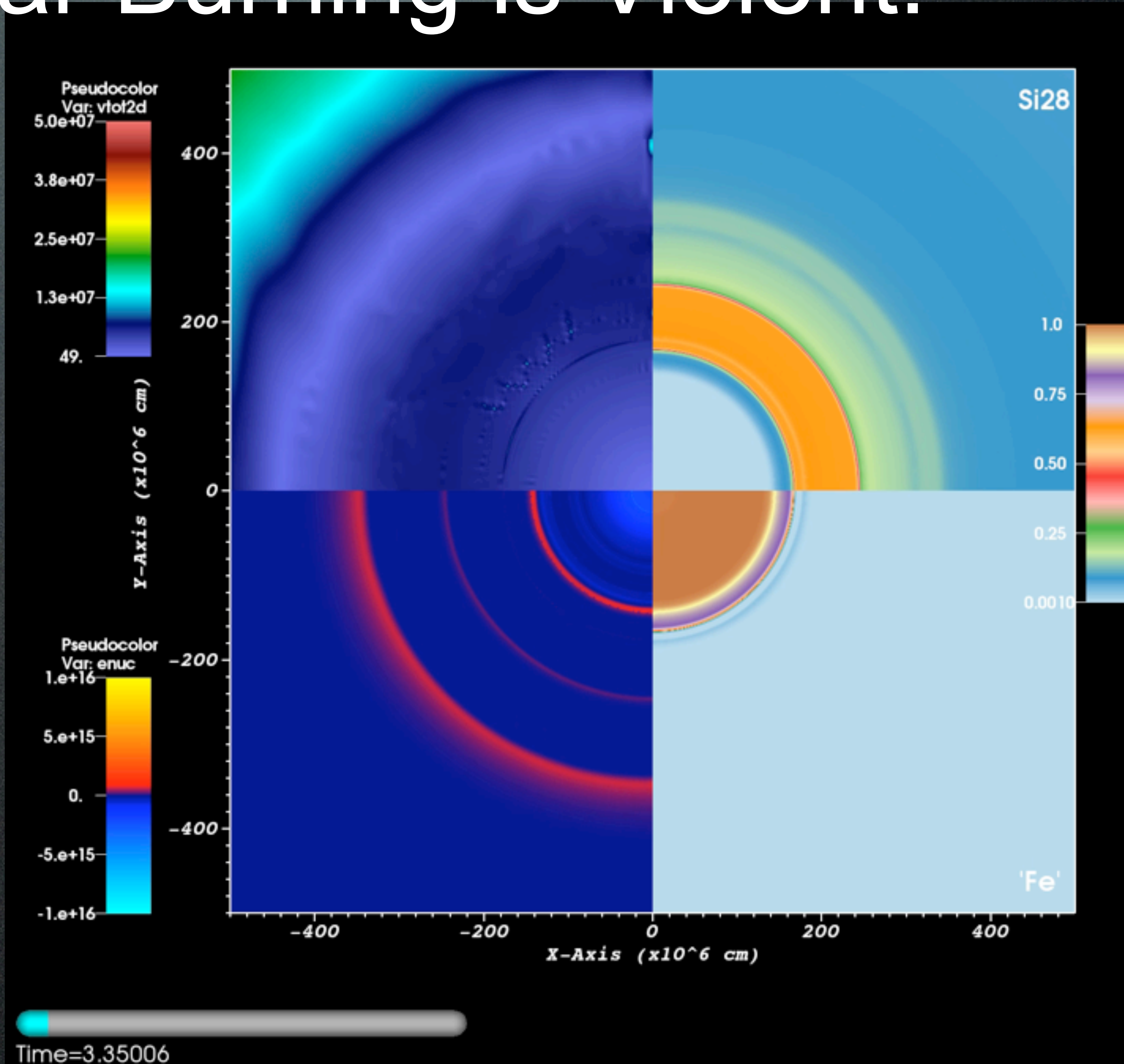
Nuclear Burning Convection: Like boiling a pot of water!

Stars are not (perfectly) spherical!

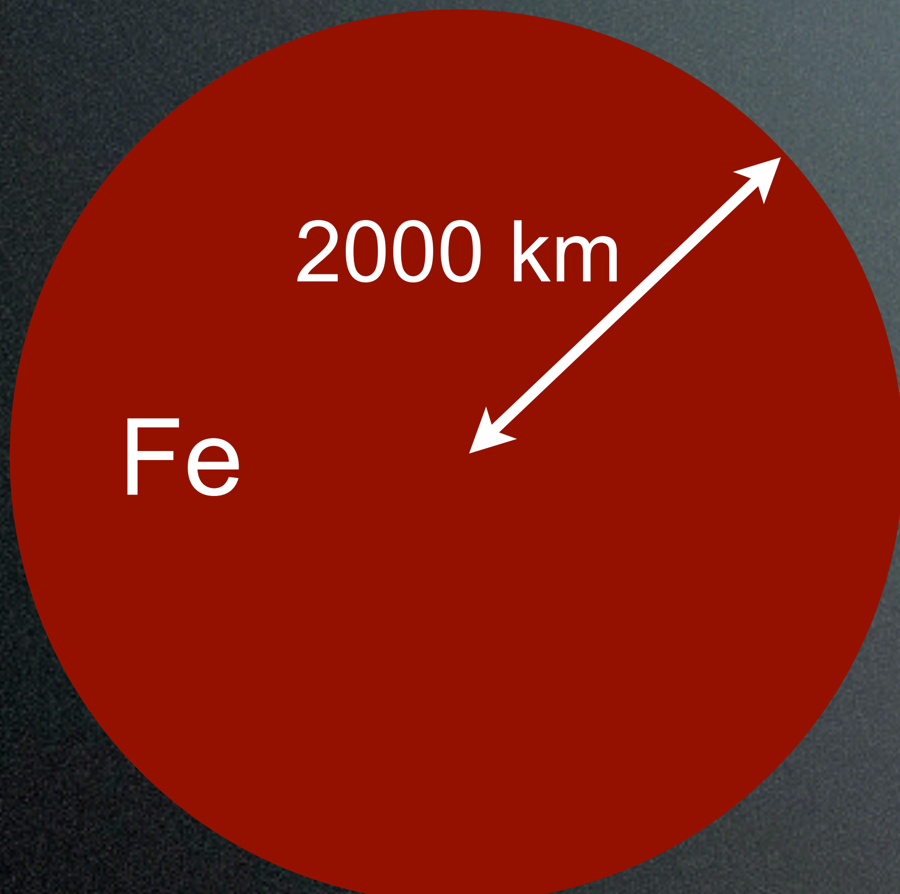
Nuclear Burning is Violent!

Nuclear Burning Convection: Like boiling a pot of water!

Stars are not (perfectly) spherical!



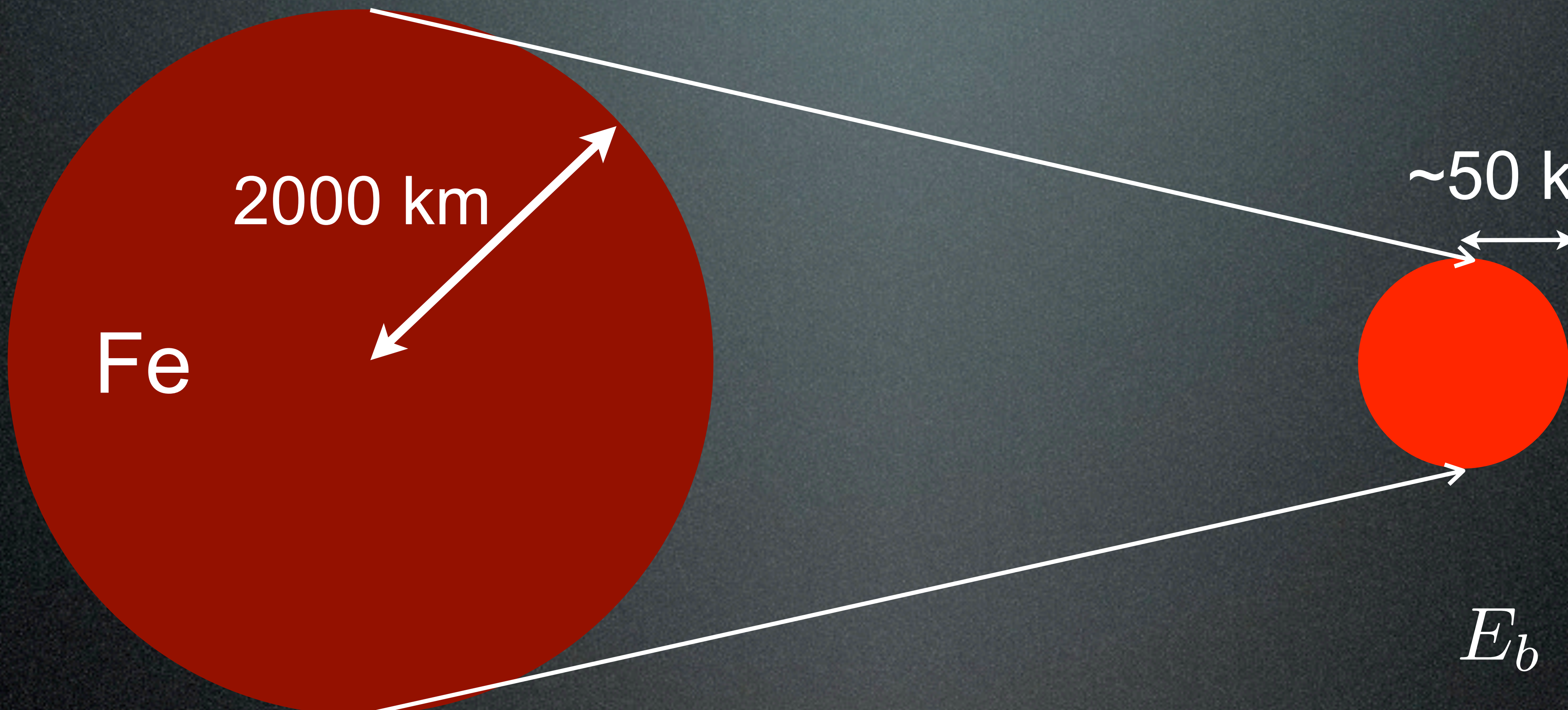
Stellar Core Collapse



$$M_{Fe} \sim M_{\rm Ch} \sim 1.4\ M_{\odot}$$

$$\rho_c \sim 10^{10}\ {\rm g\ cm}^{-3}$$

Stellar Core Collapse



$$E_b > 10^{53}\ \mathrm{erg}$$

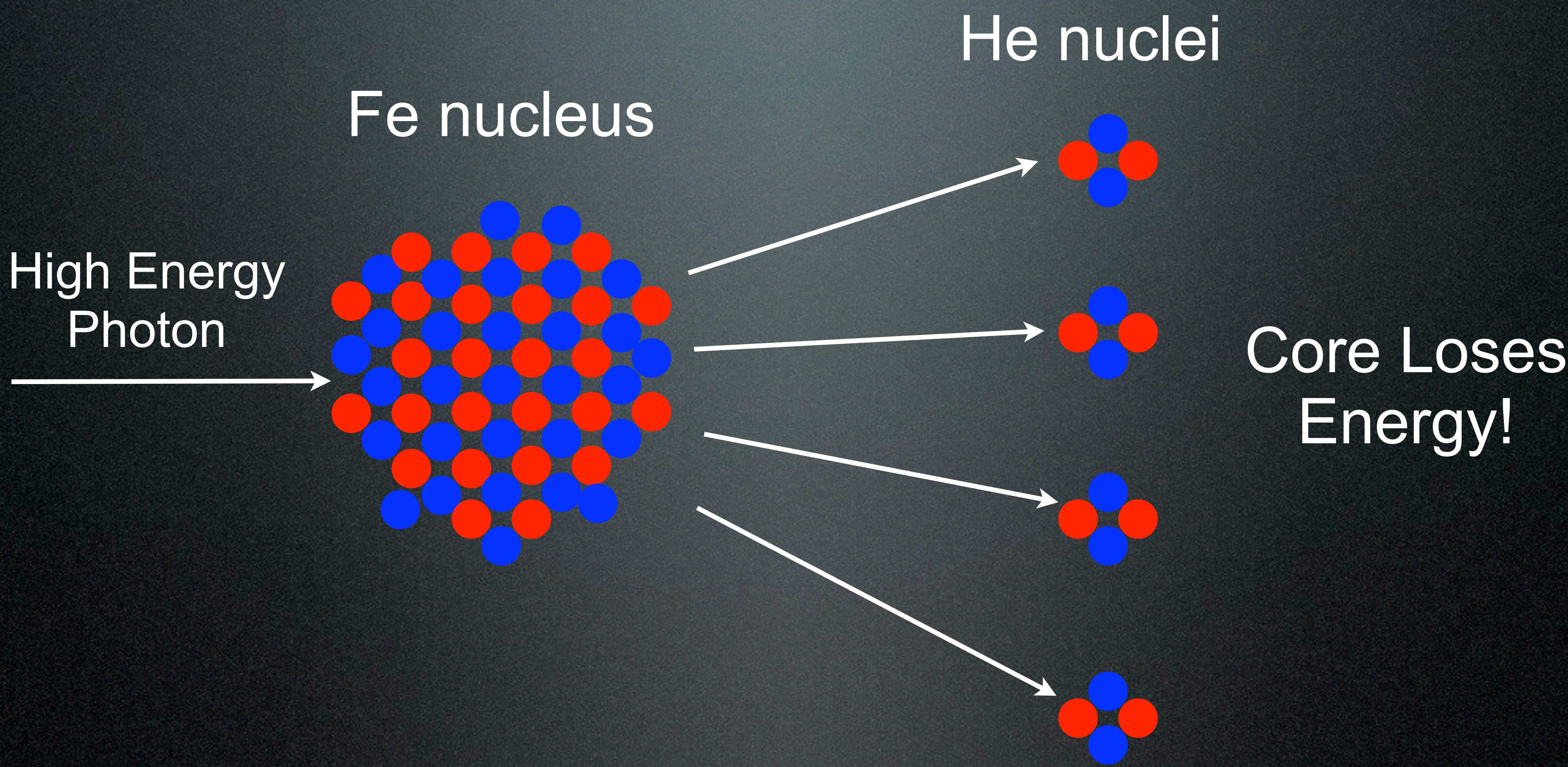
$$M_{Fe} \sim M_{\mathrm{Ch}} \sim 1.4\ M_\odot$$

$$\rho_c > 10^{14}\ \mathrm{g\ cm^{-3}}$$

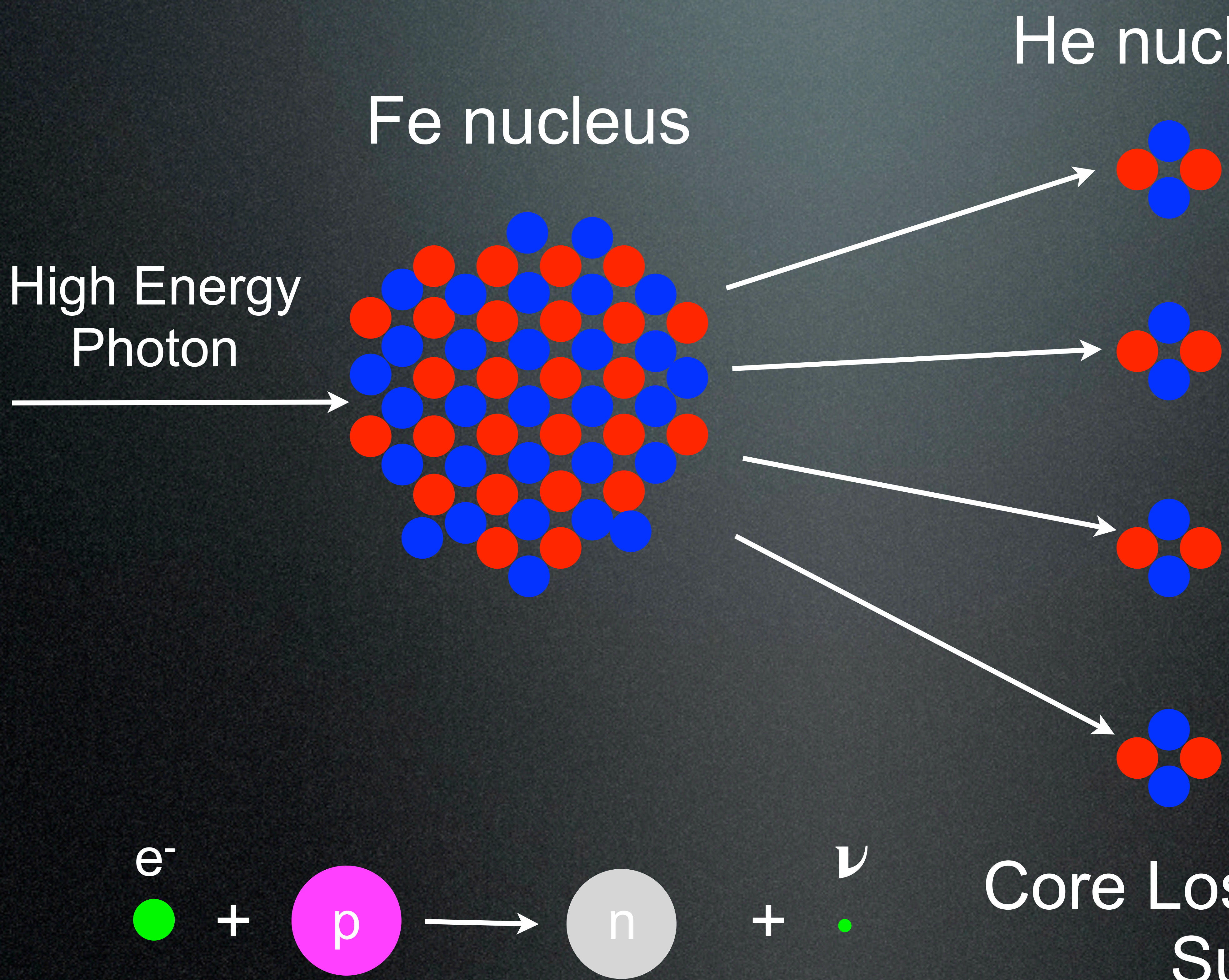
$$\rho_c \sim 10^{10}\ \mathrm{g\ cm^{-3}}$$

10^{57} neutrinos released!!

Stellar Core Collapse



Stellar Core Collapse

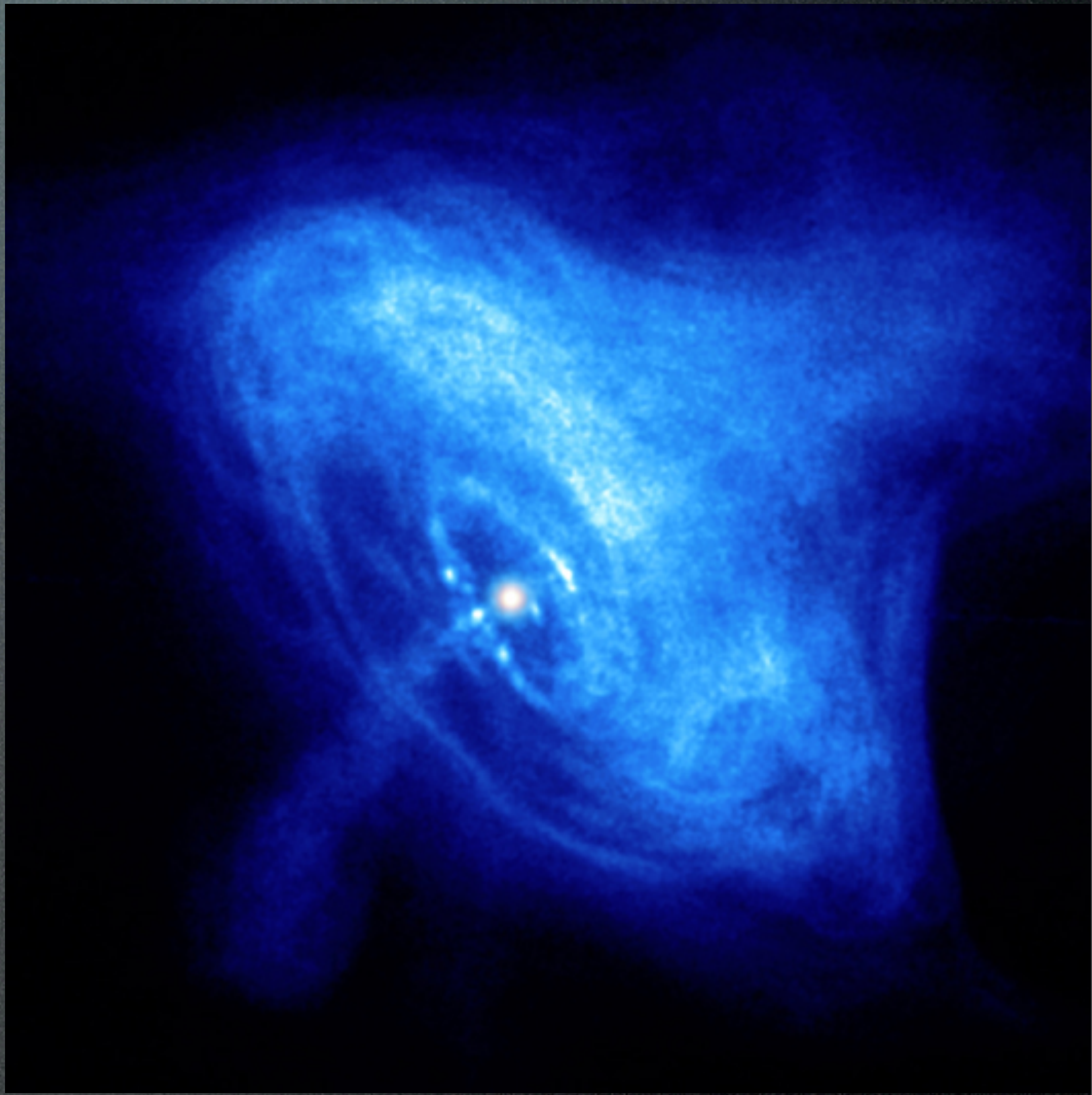


Core Loses Energy!

Core Loses Pressure Support!

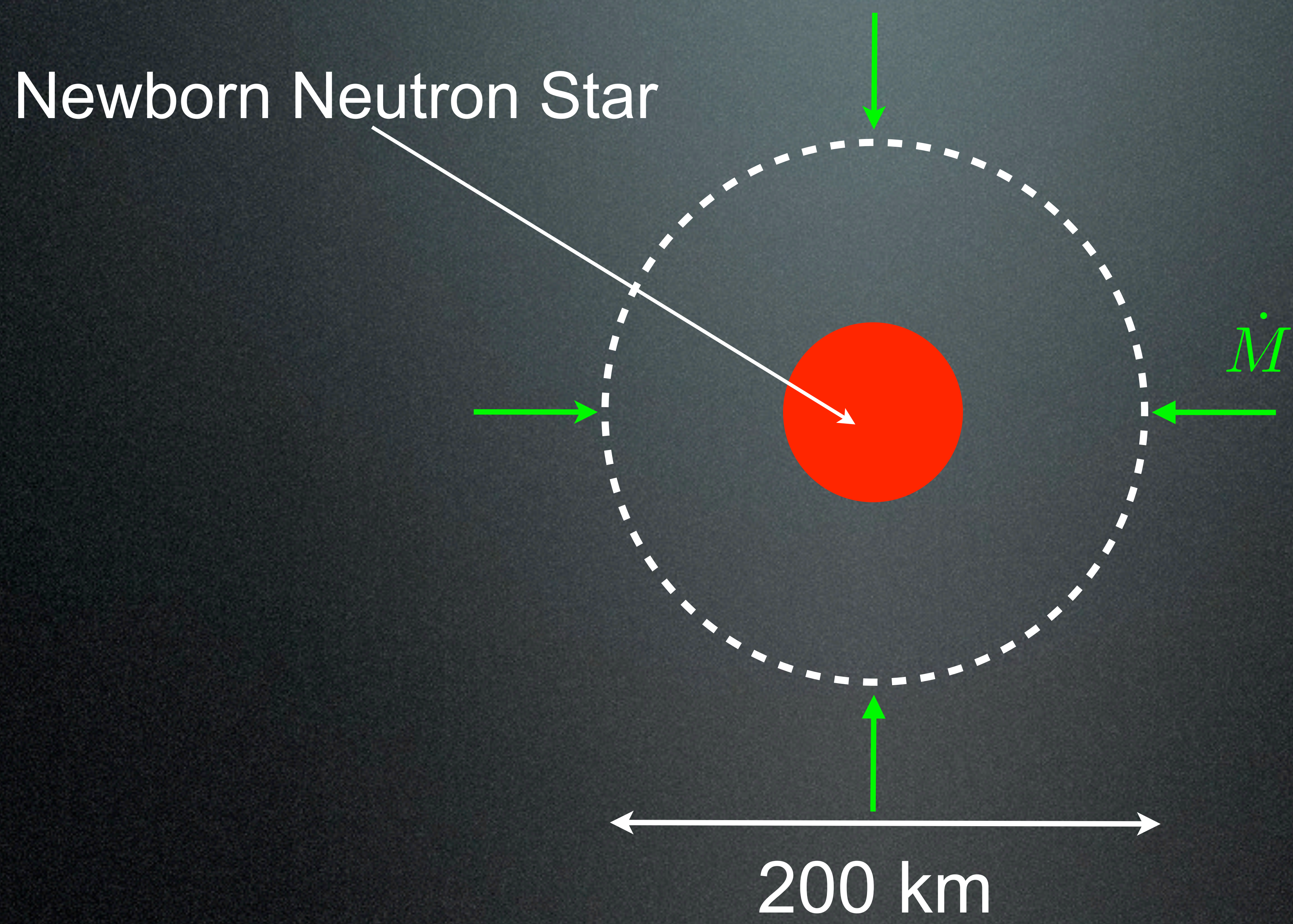
Neutron Stars

- All neutrons! Nuclear densities! Giant atomic nuclei in space.
- Like White Dwarfs, only held up by *neutron* degeneracy pressure.
- Mass of sun, size of Chicago!

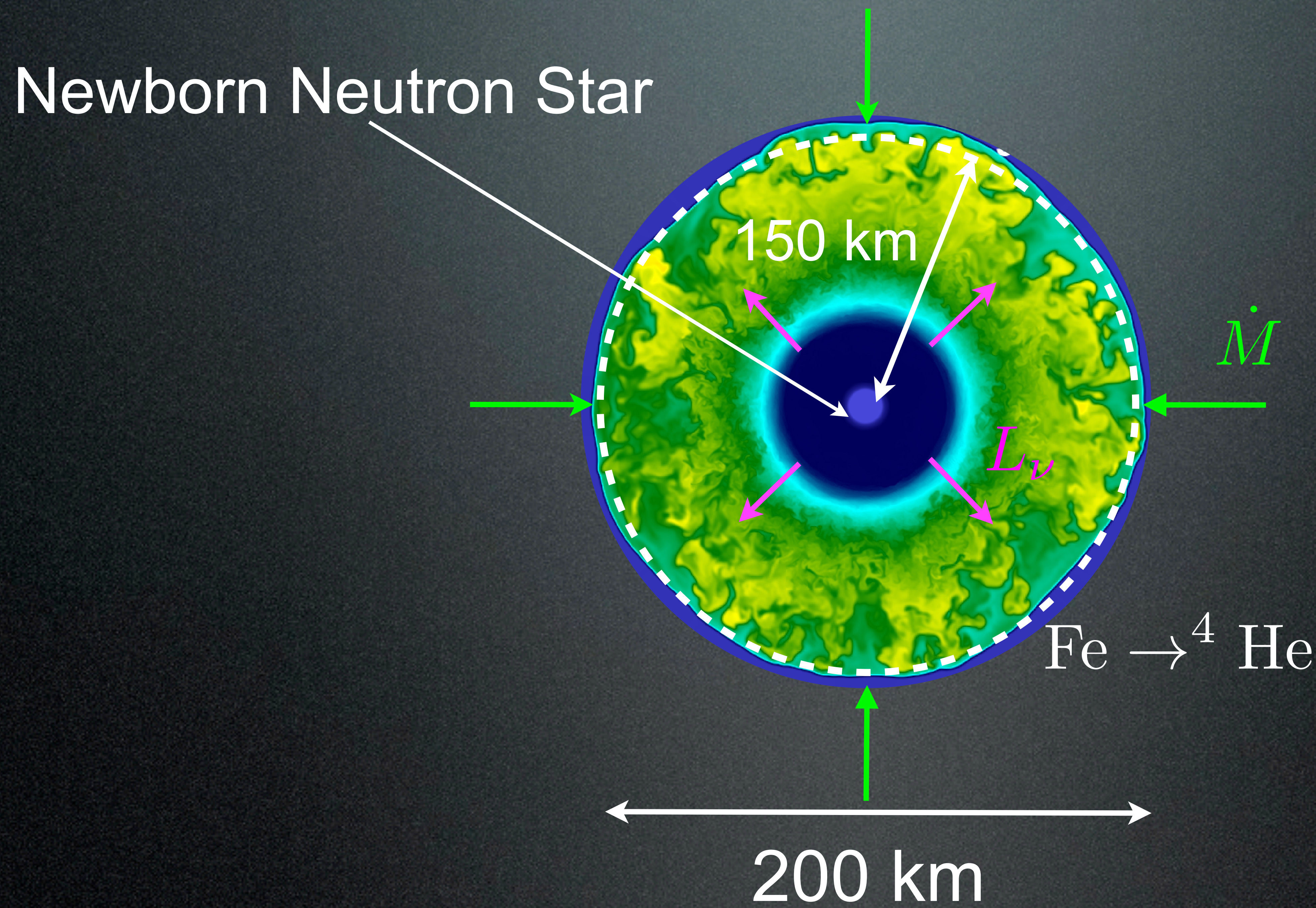


Crab Pulsar

The Supernova Problem



The Supernova Problem

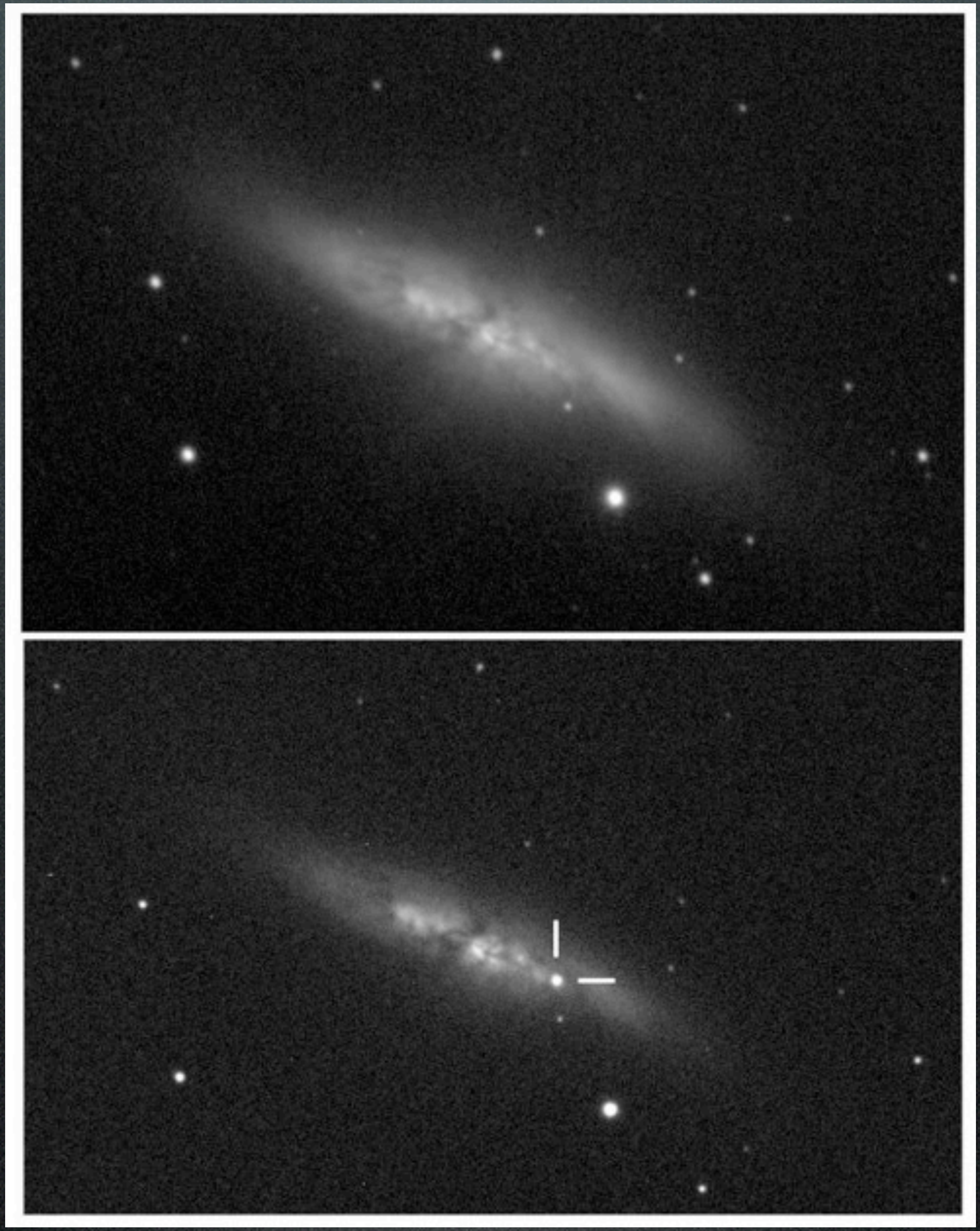


Shock stalls... What revives it??

Observational Facts

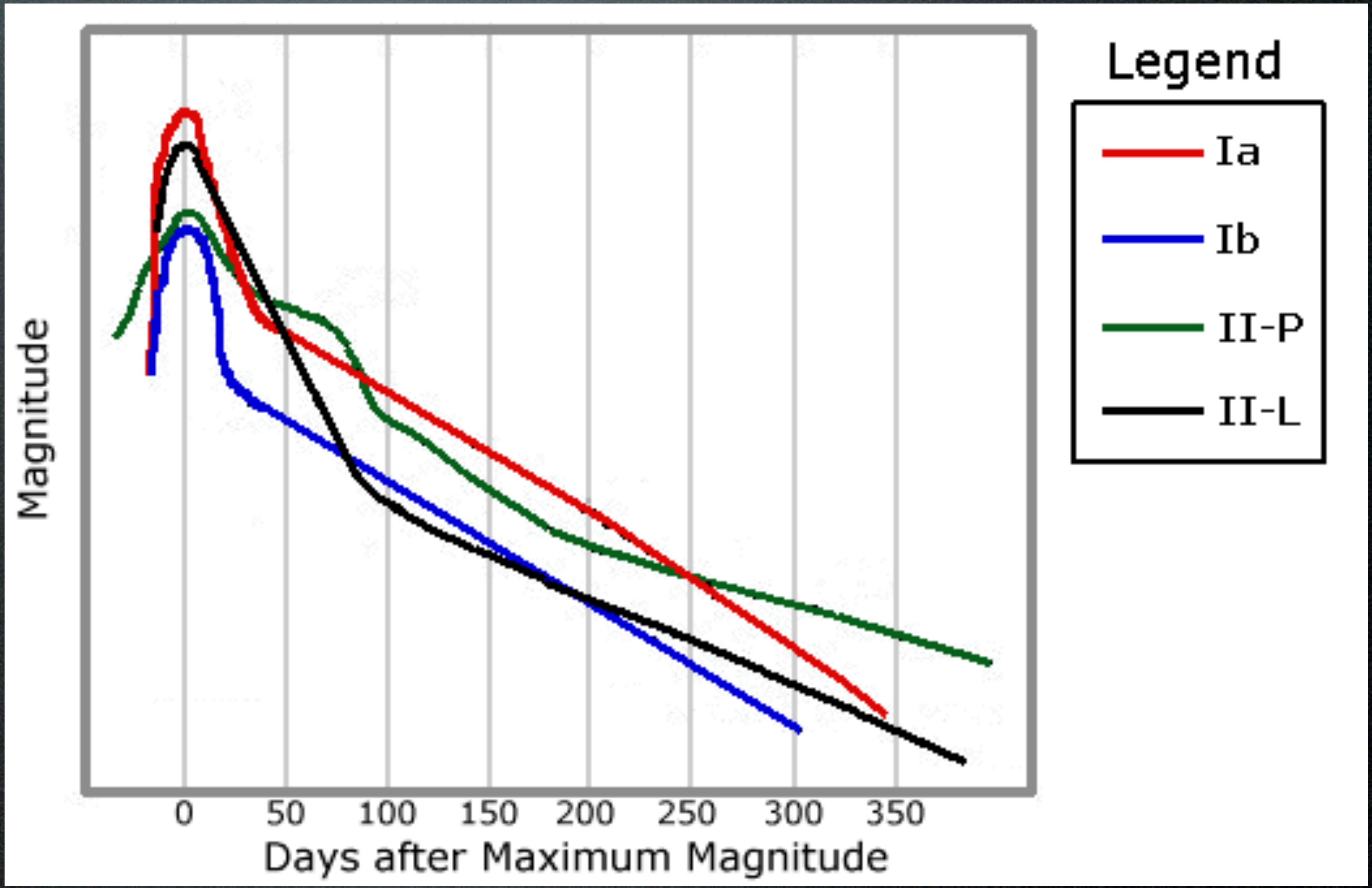
- Explode 5 s^{-1} in universe, about 1 per day observed; 4x the number of Ia's.
- Have large kinetic energies, $\sim 10^{51}$ erg.
- Have massive star progenitors: direct observation!
- Remnants have kicks $\lesssim 1000$ km s^{-1}.
- Radiate neutrinos: create neutron stars.
- Are fundamentally 3D.

Bright Transients in the Sky

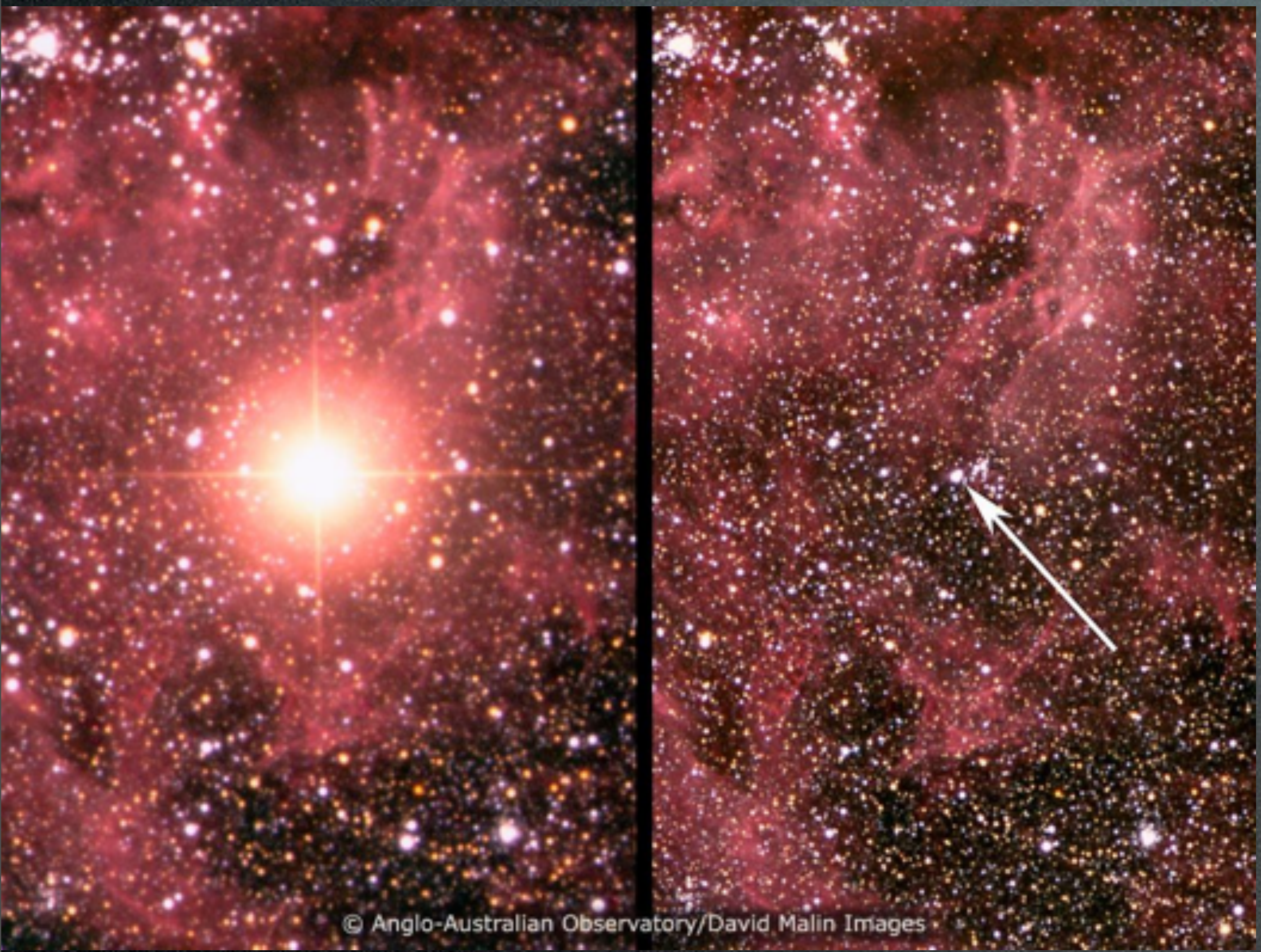


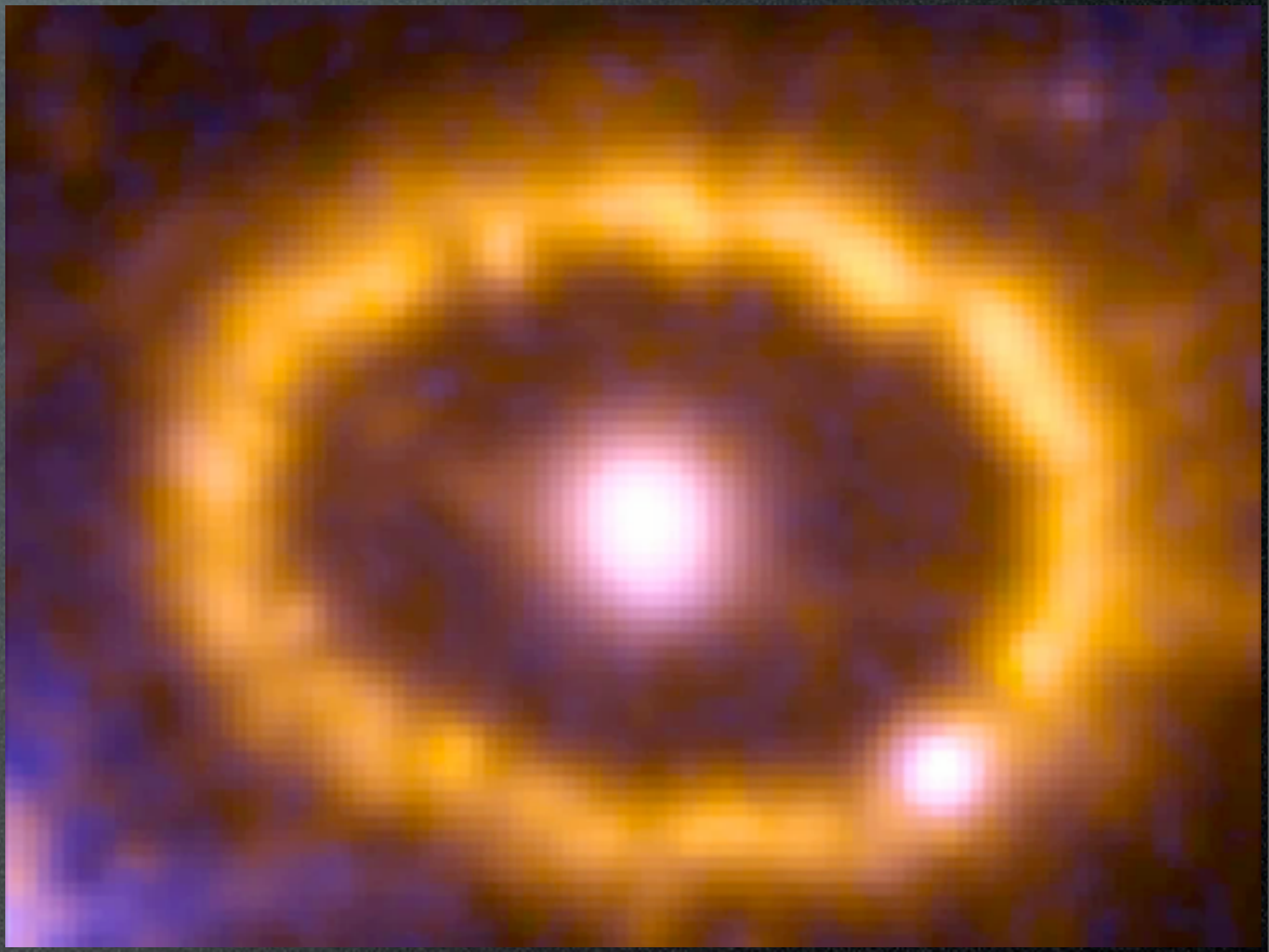
Bright Transients in the Sky

More than a billion times brighter than the sun!



Supernova 1987A

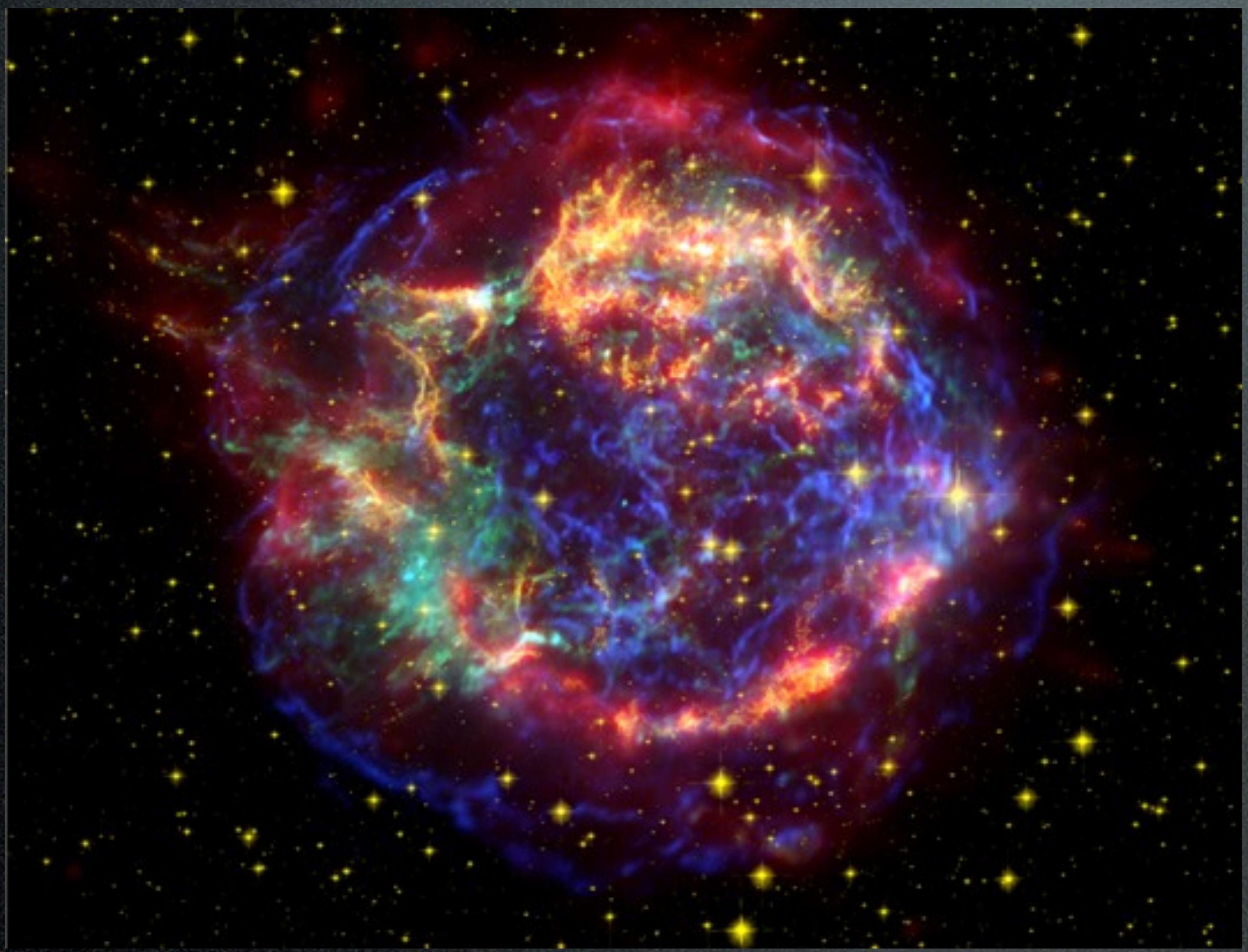




1.5 Million Trillion km away!
Closest SN in >300 years!

Cas A

Hubble, Chandra, Spitzer



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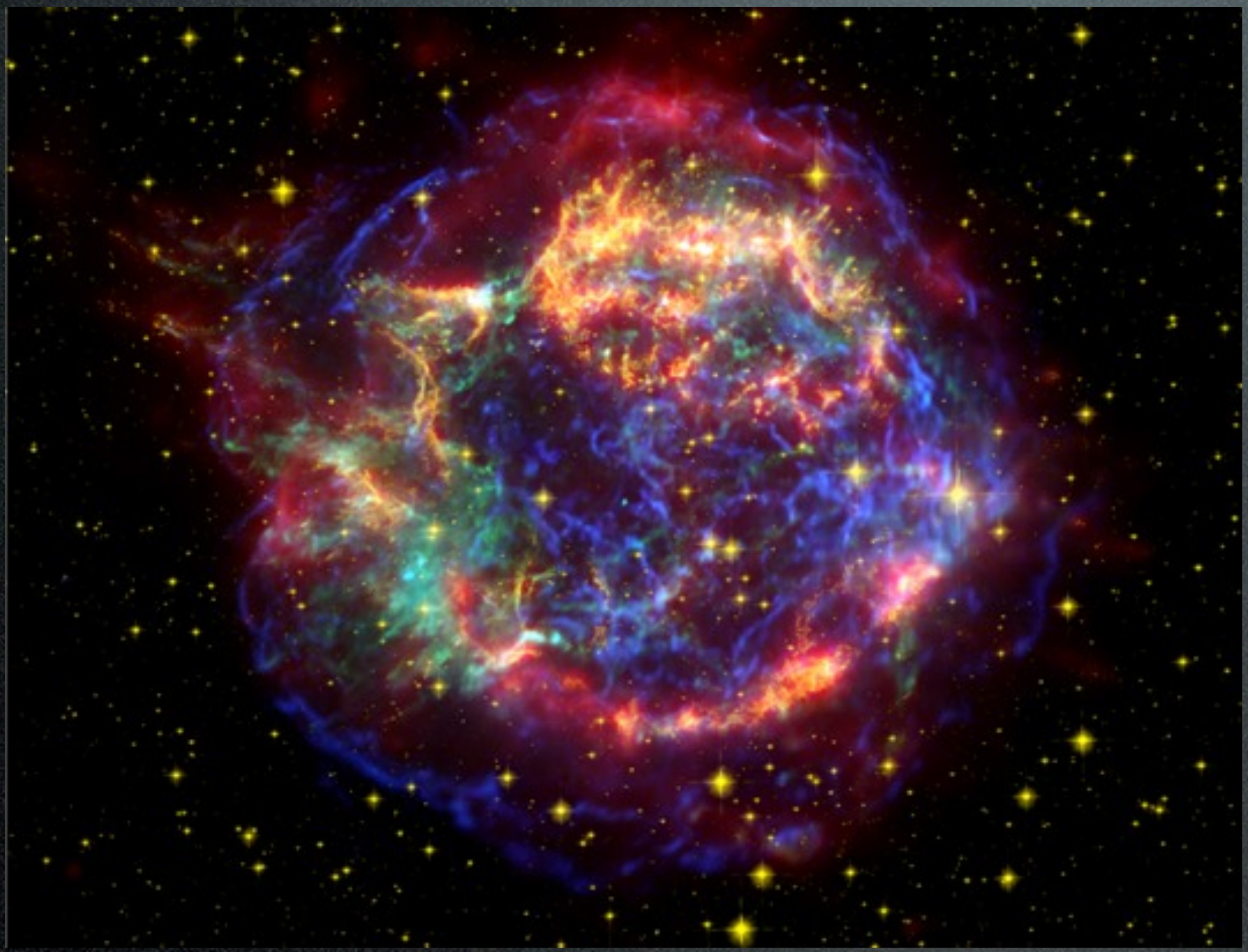
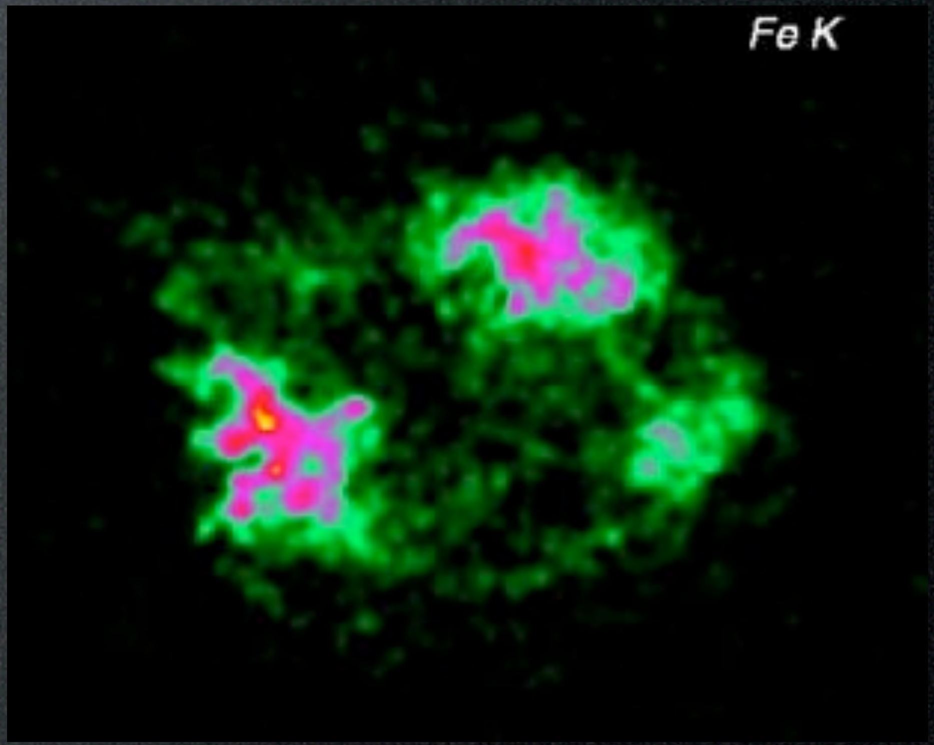
Hubble, Chandra, Spitzer

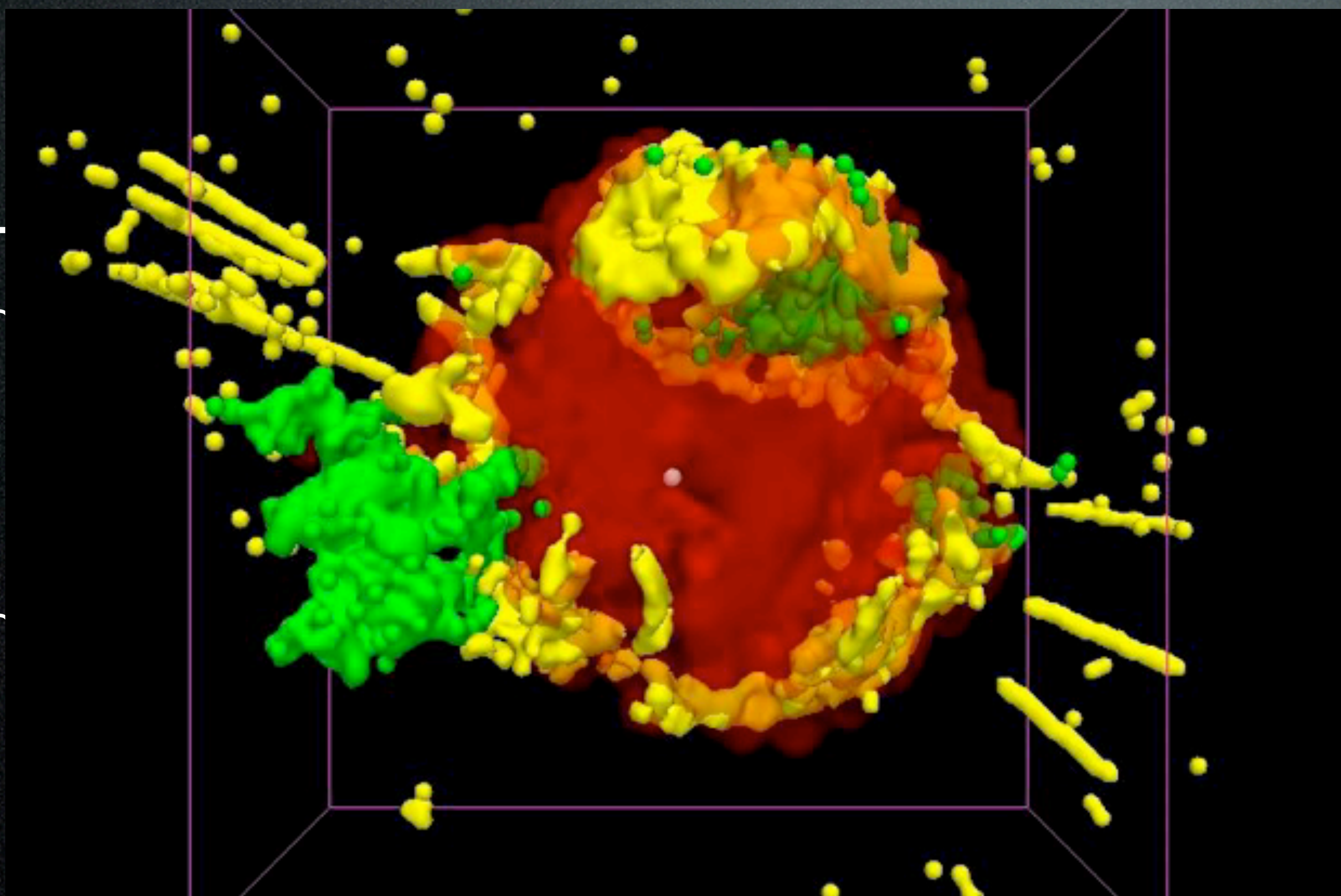


Chandra



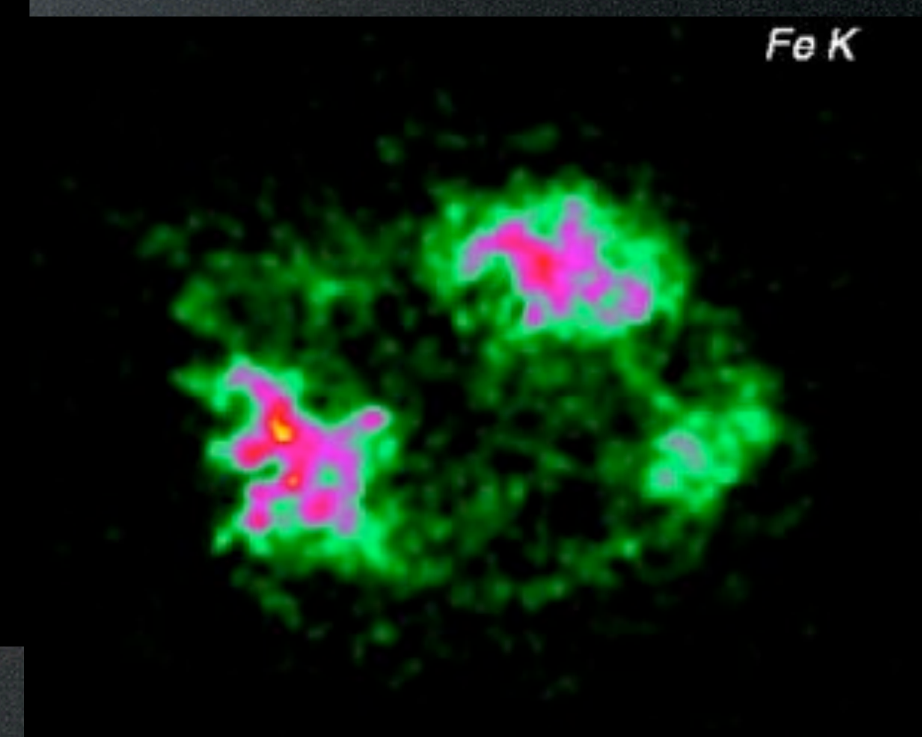
Cas A

Hubble, Chandra, Spitzer



T. Delaney et al.

Chandra



Why Do Stars Explode?

- Investigate using sophisticated computer simulations.

What is Scientific Simulation?

- Many physical problems are too complex to find simple solutions or equations that describe the system.
- Simulation: Solve the basic physical equations (there's lots of them!) to evolve the system in time.

Multiphysics Challenges

3D Magnetohydrodynamics

General Relativity

Boltzmann ν-transport

Microphysics
(Nuclear EOS, ν-interactions/
cross sections)

Multiphysics Challenges

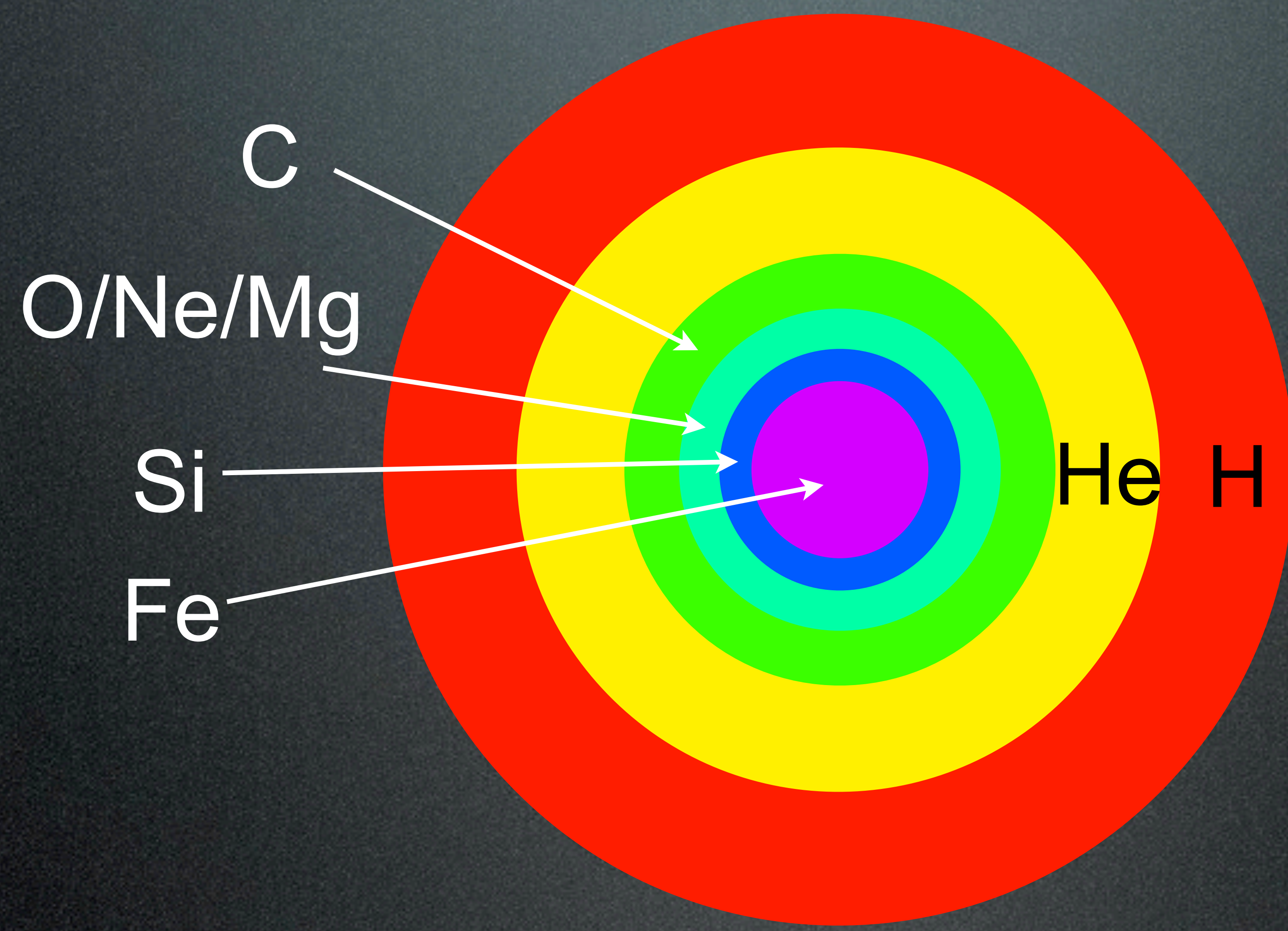
Require Approximations

3D Magnetohydrodynamics
- 1D, 2D
- Pure Hydro
- Low-resolution

General Relativity
- Monopole Newtonian
- Multipole Newtonian
- GR Monopole
- Conformally-flat

Boltzmann ν-transport
- Lightbulb heating/cooling
- Leakage
- Gray vs. Spectral
- Ray-by-Ray vs. Multi-angle
- FLD, VET, M1, MC

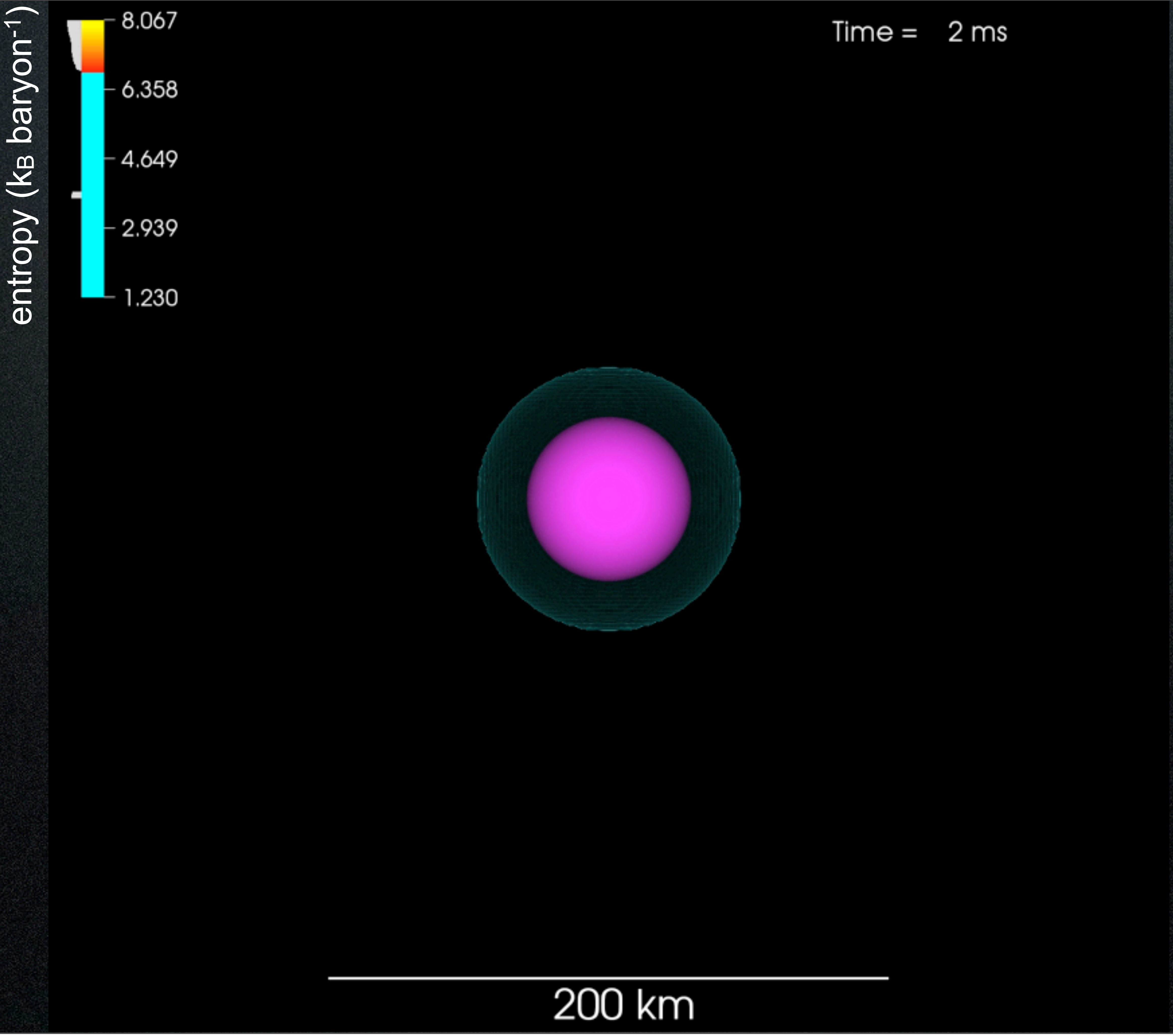
Microphysics (Nuclear EOS, ν-interactions/ cross sections)
- Simplified ν-reactions



Whole star: 100 Million km

I simulation only the inner 10,000 km!

entropy (k_B baryon^{-1})


entropy (k_B baryon^{-1})
8.067
6.358
4.649
2.939
1.230
Time = 2 ms
200 km

Stars and Supernovae

- All the elements that made the planets and us came from stars.
- Supernovae spread these elements throughout the universe.
- Massive stars die as bright explosions, but we don’t yet fully understand the physics of this process.
- Computer simulation is an important approach for solving this problem.