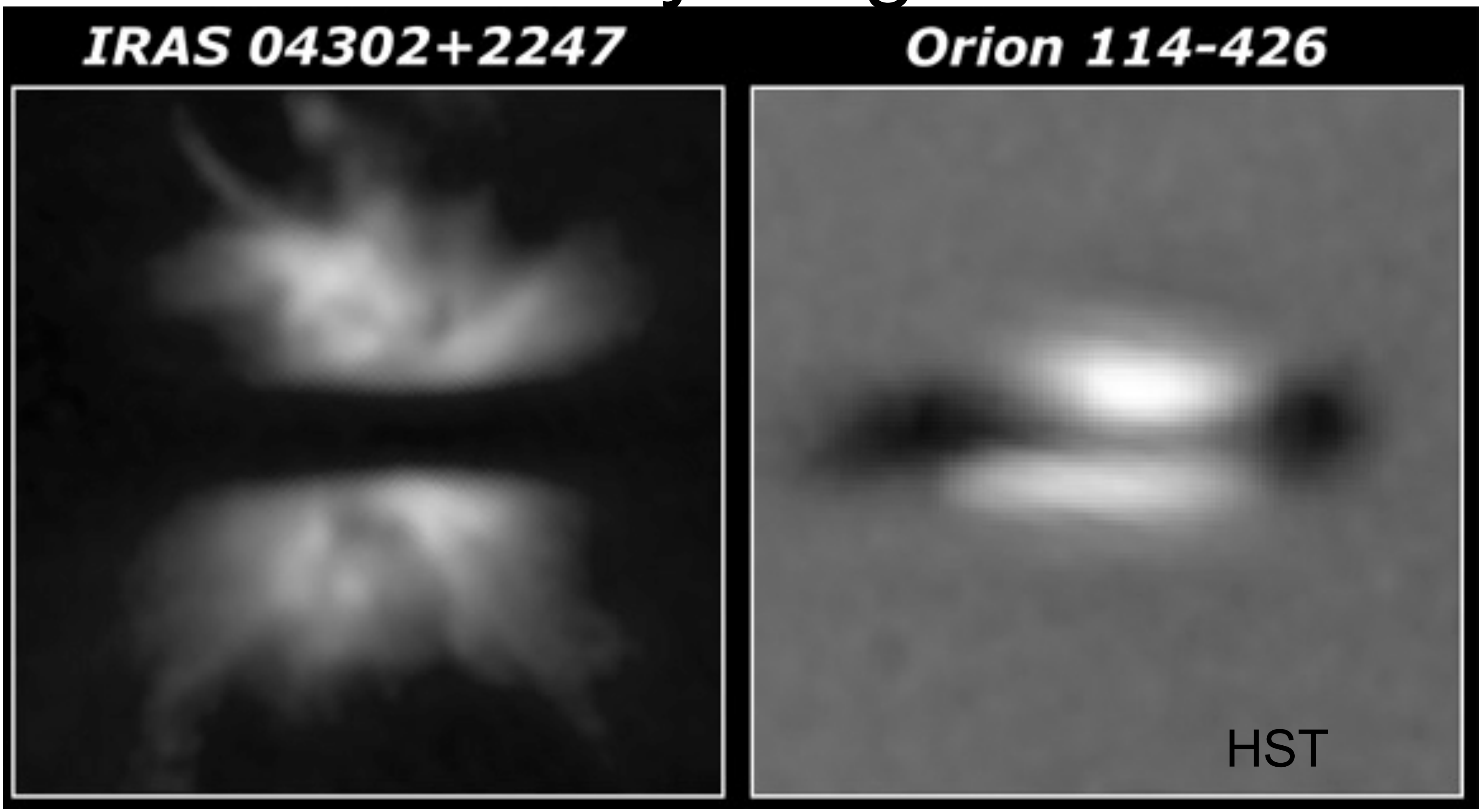
What is the name of the sequence of nuclear reactions that generates the energy in the cores of main-sequence stars that are half the mass of the Sun?

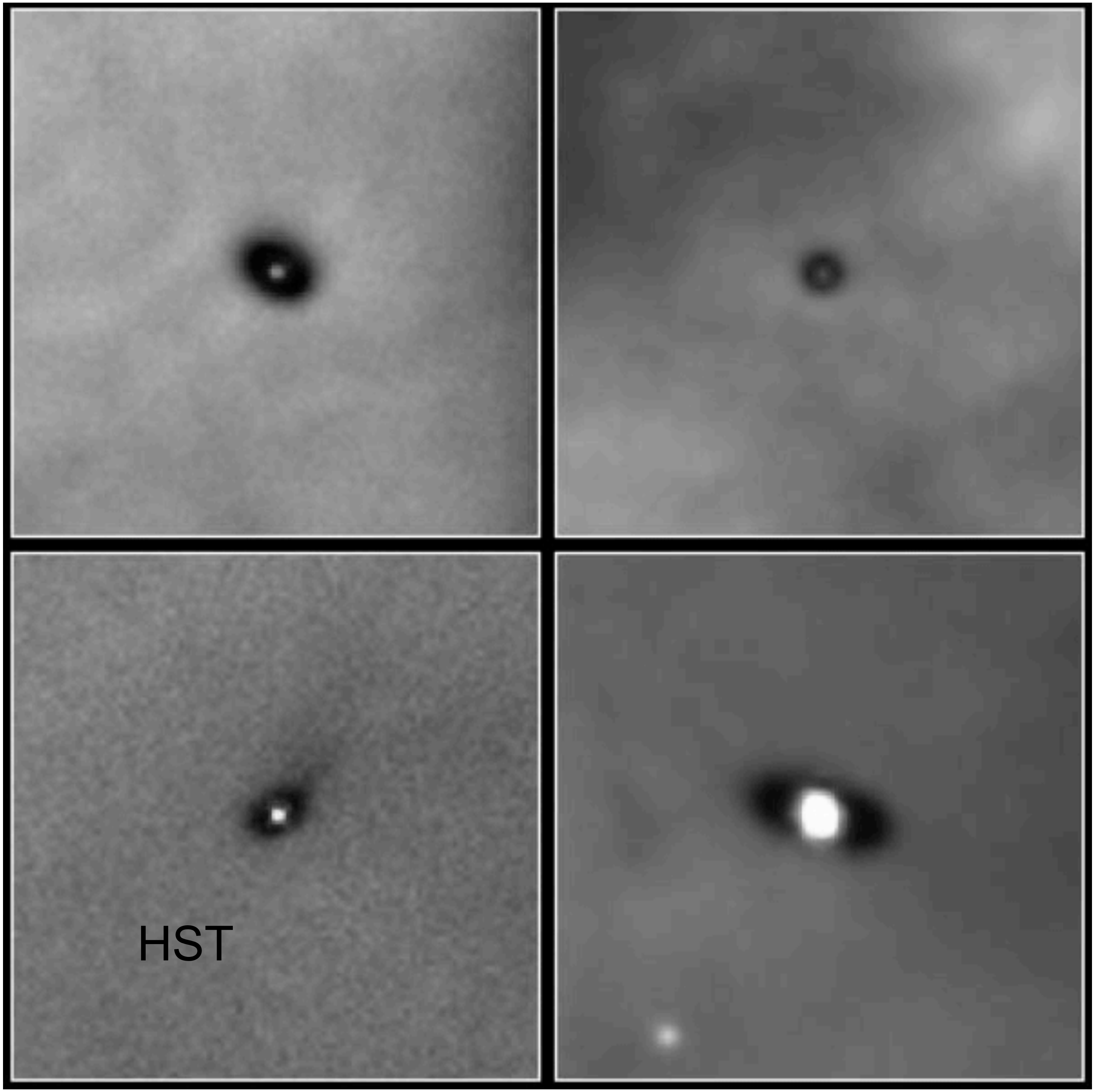
a)
b)
c)
d)
e)

The event separating the red giant phase from the horizontal branch phase of stellar evolution for low mass stars is the

a)
b)
c)
d)
e)

Gas & dust disks observed around young stars




HST

Primordial Solar Nebula

The rotating solar nebula is composed of

-
-

Starts out at several thousand K, then cools:

- ➔ when depends on their individual "*condensation temperatures*"

The “Frost Line” (Snow line)

Rock & Metals condense when gas is cooler than 1400-1300 K.

Ice condenses when the gas cools below 200 K.

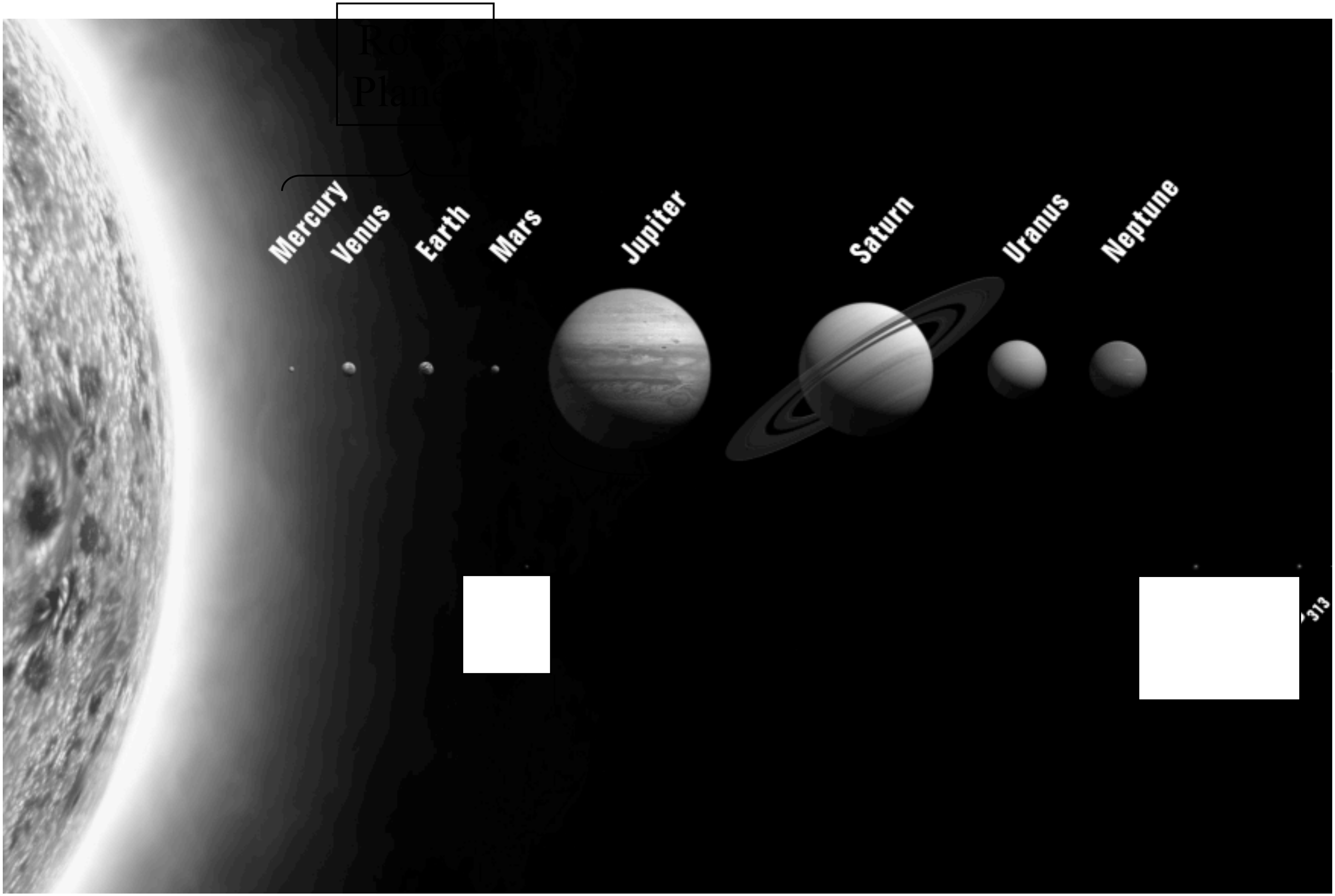
Inner Solar System:

-

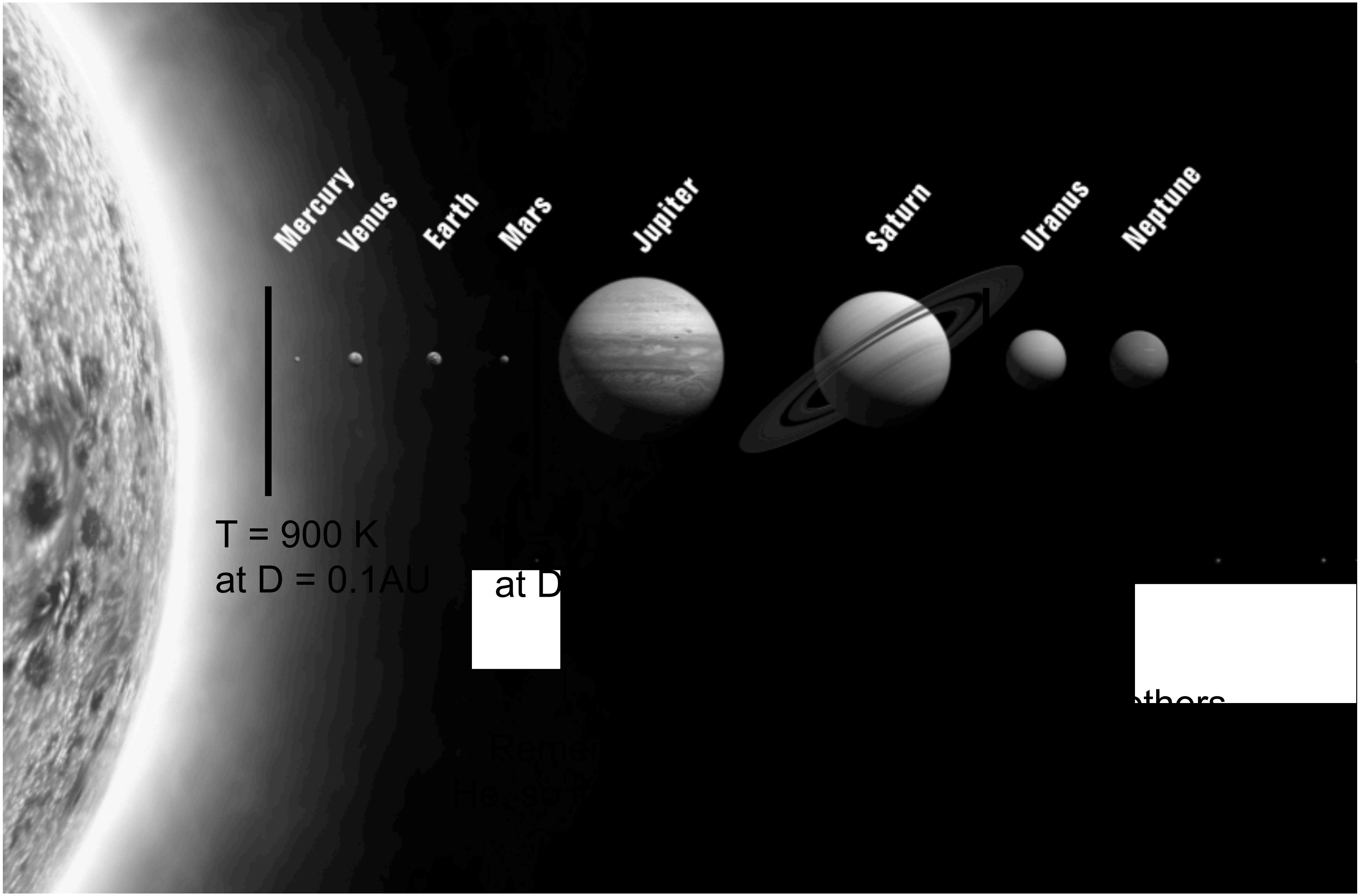
Outer Solar System:

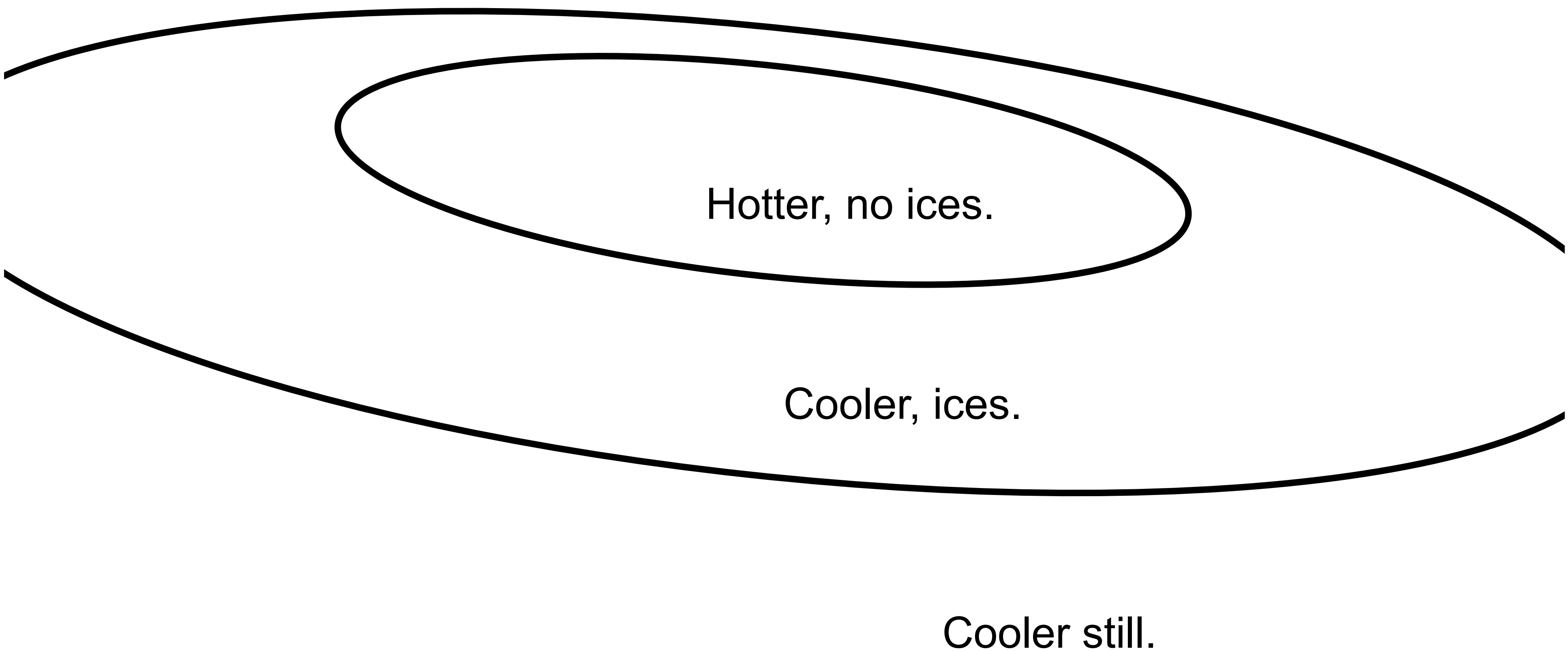
- frost line”

Temperature is determined predominantly by distance from the Sun!


Rocky
Plane
Mercury
Venus
Earth
Mars
Jupiter
Saturn
Uranus
Neptune
313

Energy In = Energy Out implies that $T = 280\ K\ (AU/D)^{1/2}$

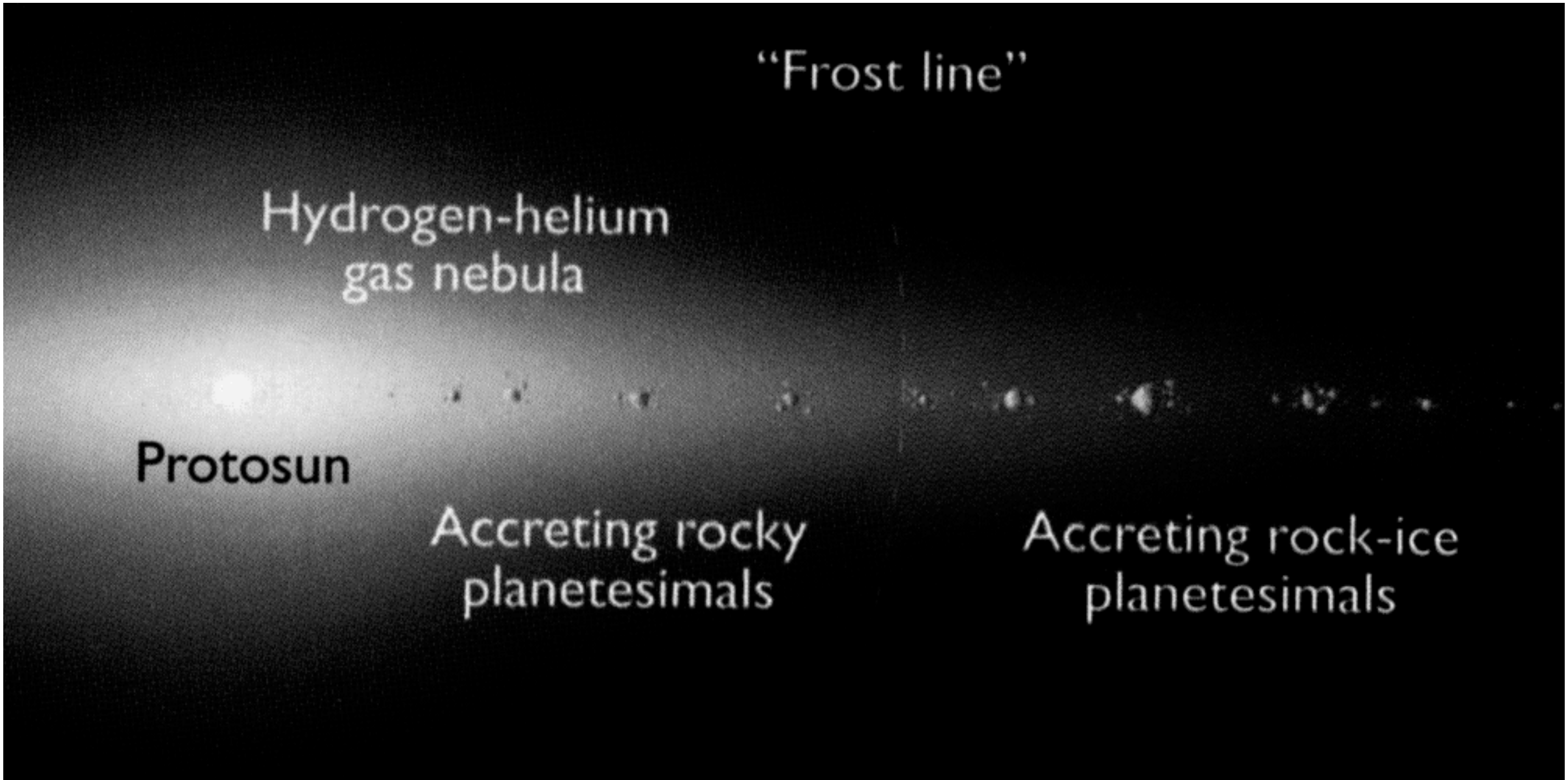



Hotter, no ices.
Cooler, ices.
Cooler still.

Dust grains form “planetesimals”

Grains have low-velocity collisions, stick, form bigger grains.

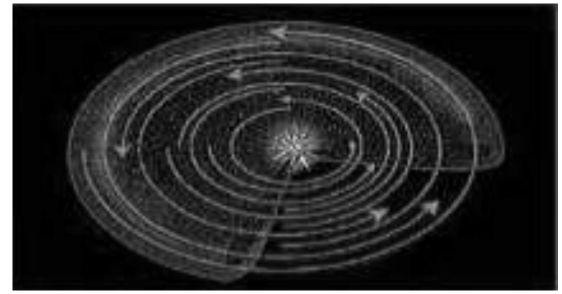
- “ ”
  condensing ices onto the grains. Lots of H!!!
- Grow into km-size *planetesimals* in few thousand years.
- Once km-sized, gravitation assists further aggregation: gravity attracts more material.
- Rapidly accelerated growth (runaway) into planets.
- Gather H and He if available. Dichotomy.



Less mass to collect.
Smaller, rocky, no ice or gas.
Terrestrial Planets

More mass.
Collect more gas!
Gas and Ice Giants

Terrestrial Planets



Only rocky planetesimals inside the frost line.

It is Hotter closer to the Sun:

- Inner planets cannot capture H & He gas, and thus do not become gas giants.
- Solar wind disperses H & He.

<u>Result</u>:

- Form rocky terrestrial planets with few ices.

Jovian Planets

Ices augment the masses of planetesimals

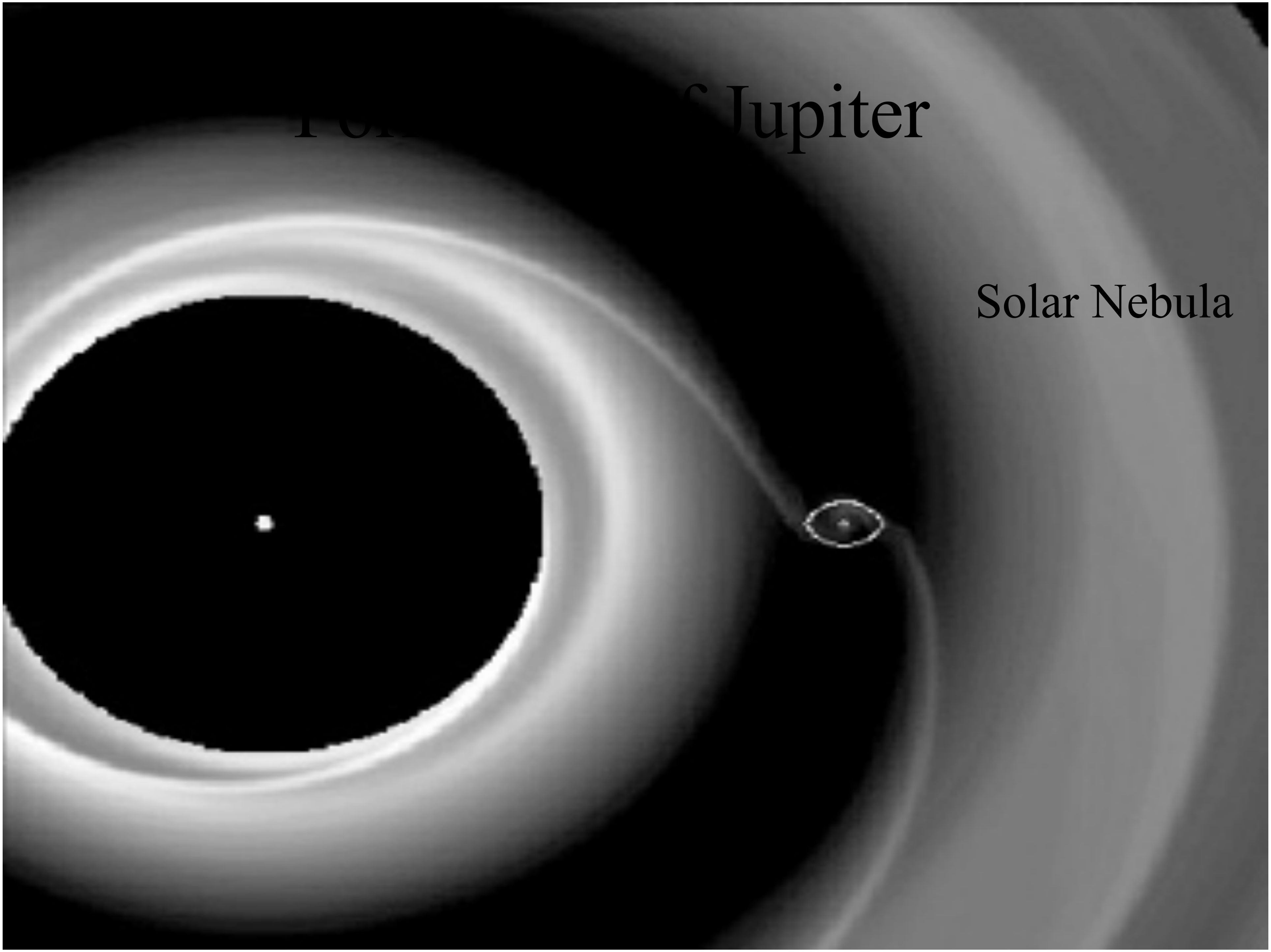
These collide to form large rock & ice cores:

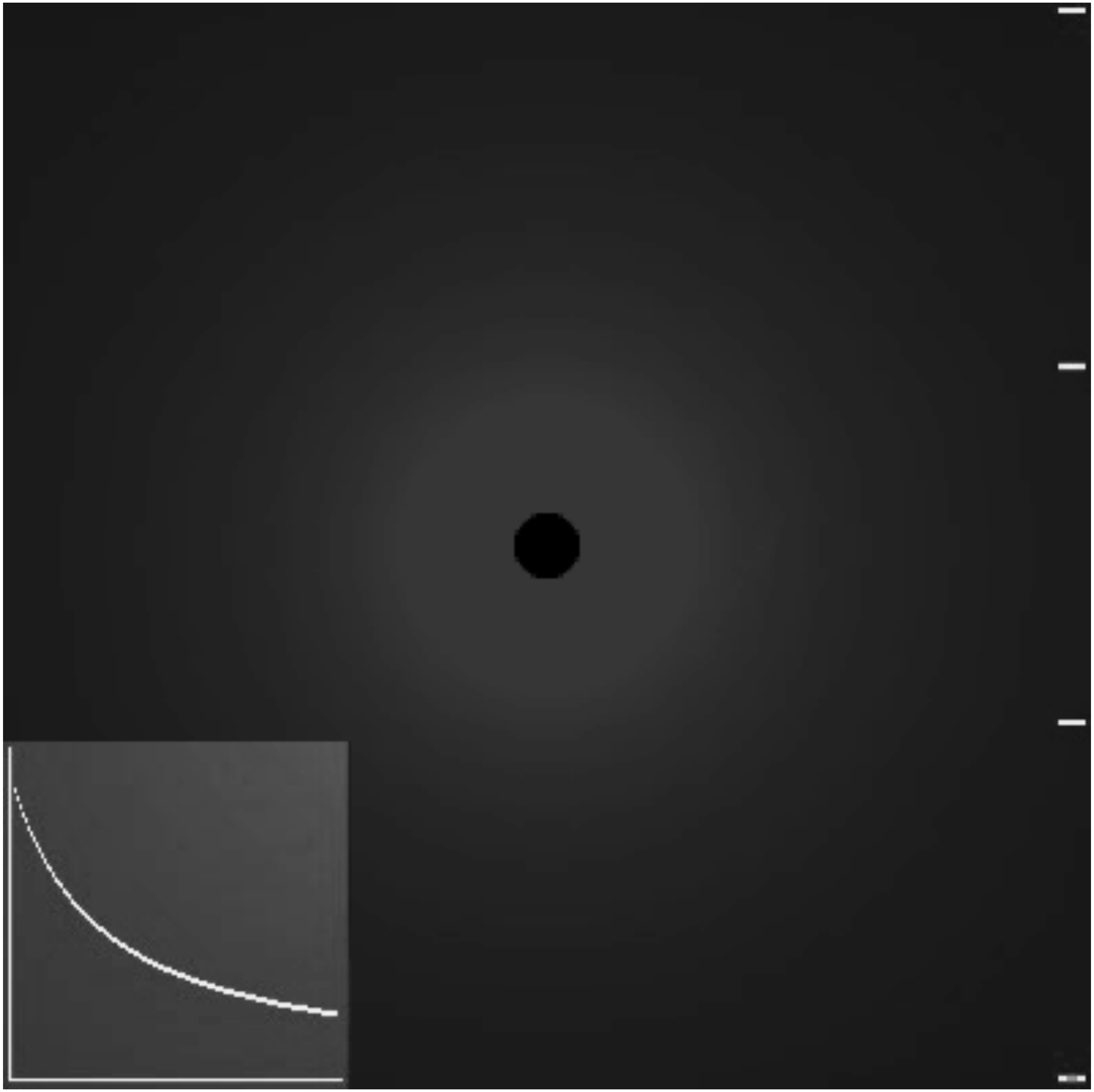
- Jupiter & Saturn: ~10 M_{Earth} rock/ice cores.
- Uranus & Neptune: ~1 M_{Earth} rock/ice cores.

Larger masses:

- Accrete (gravitationally gather) H & He gas from the surrounding disk.
- Planets with the biggest cores grow most rapidly.

Largest gas giants scatter or accrete the remaining planetesimals & protoplanets (the big get bigger, the smaller get eaten, or ejected).


Jupiter
Solar Nebula



Formation
Migration
Growth

What stops
growth?

Gap formation
Isolation mass

Migration with Gas

When a massive planet forms in a disk, couplings between the disk and the planet can make the planet "migrate" from the radius where it formed

While the details are a subject of intense research, the close-in Jupiters (100's of them) probably formed outside the frost line and then migrated inwards

Some of the details are important – for example, if this works so well, how do you keep it from sweeping all planets into the star!

The rest

Moons & Rings: Gas gets attracted to the proto-Jovians & forms rotating disks of material:

- Mini solar nebulae around the Jovians
- Rocky & icy moons form in these disks.

Asteroids:

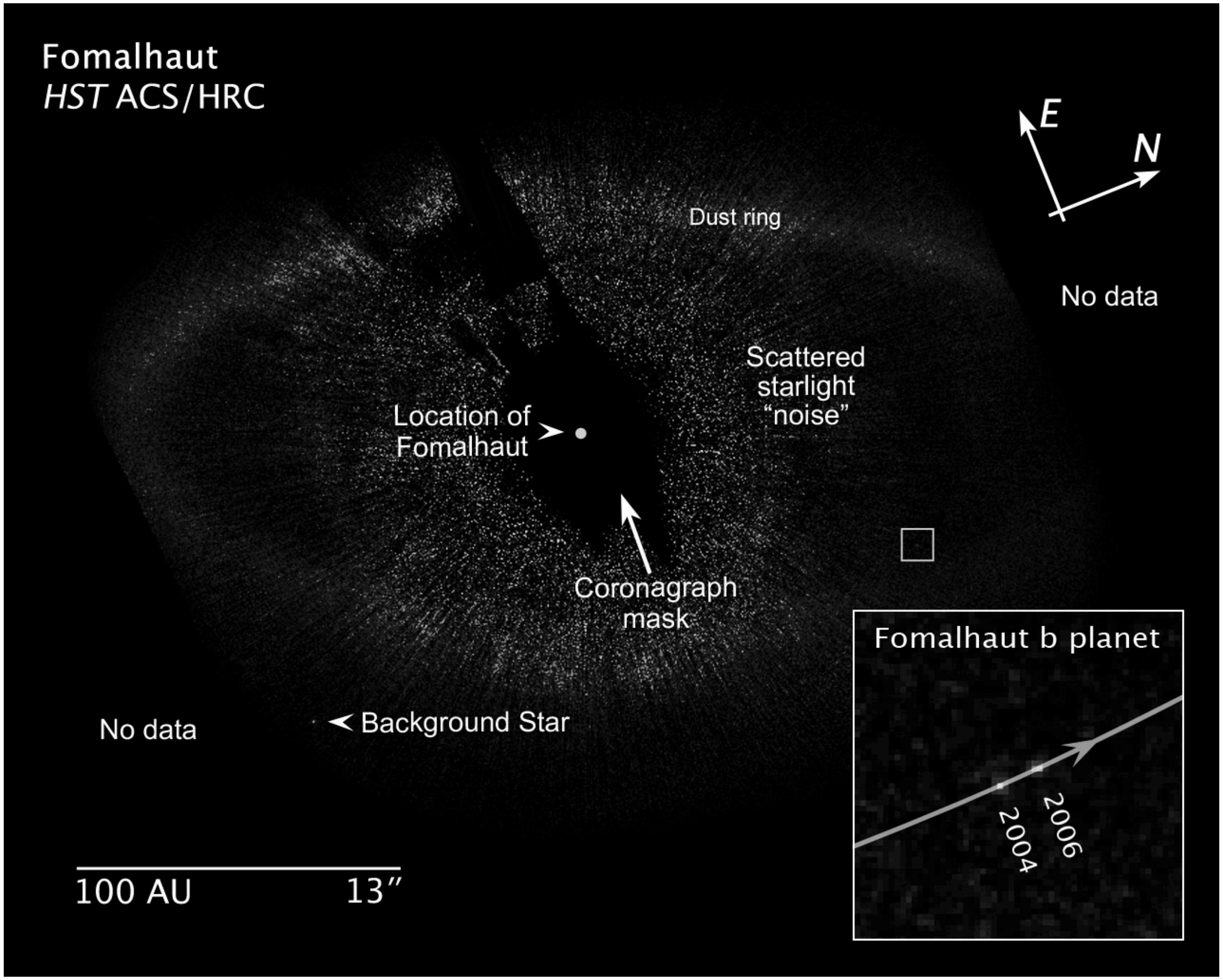
- Gravity of the proto-Jupiter keeps the planetesimals in the main belt stirred up.
- Never get to aggregate into a larger bodies.

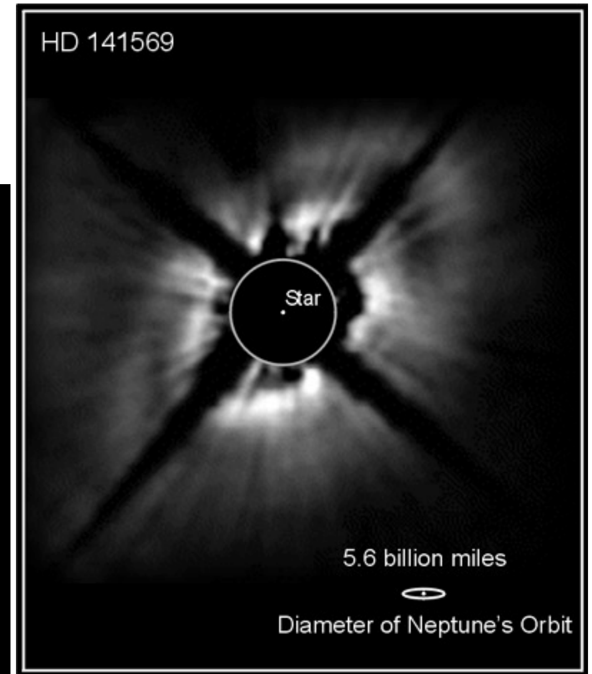
Comets:

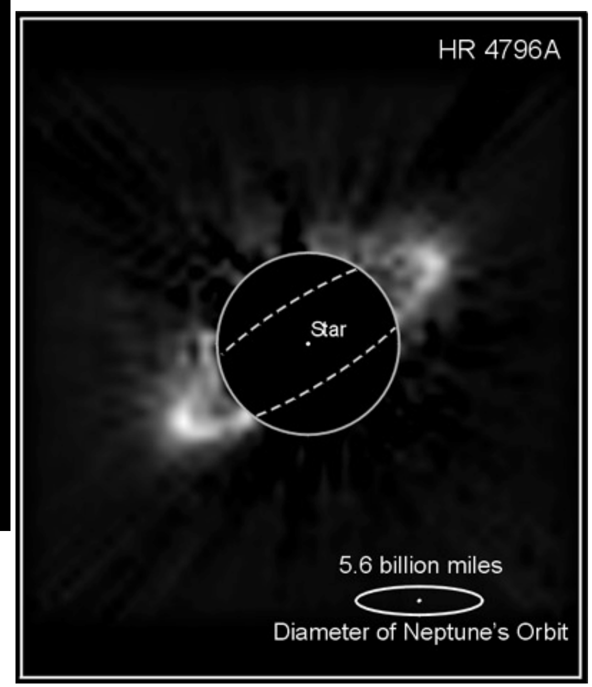
- Icy remains at the outskirts of the Solar System.

Artist’s debris disk of icy bodies

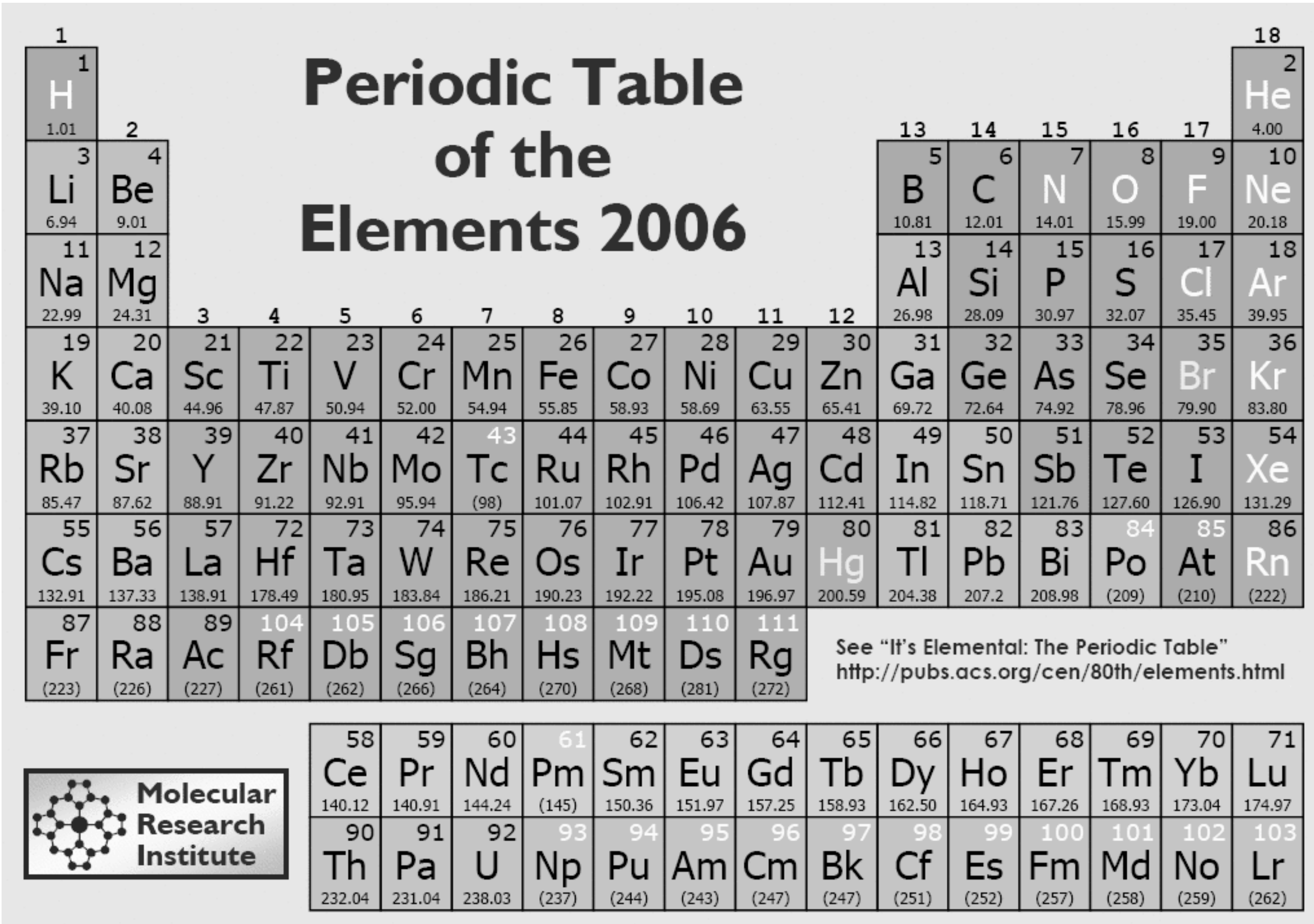
Images of debris disks







Where does all this stuff come from?



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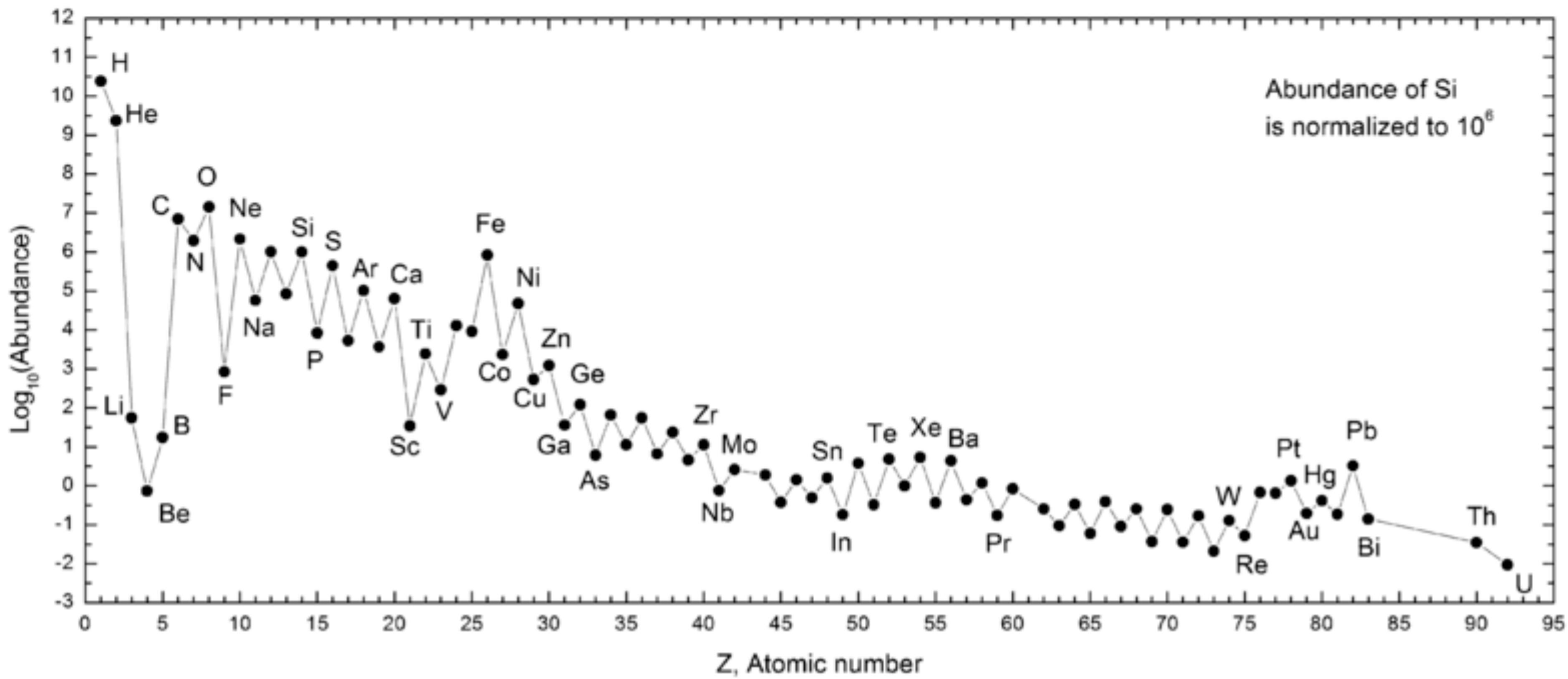


Where does all this stuff come from? Answer: Nucleosynthesis

Universe starts with mostly Hydrogen & Helium.

Almost all other elements produced by stars and stellar processes (explosions, or extreme transformations).

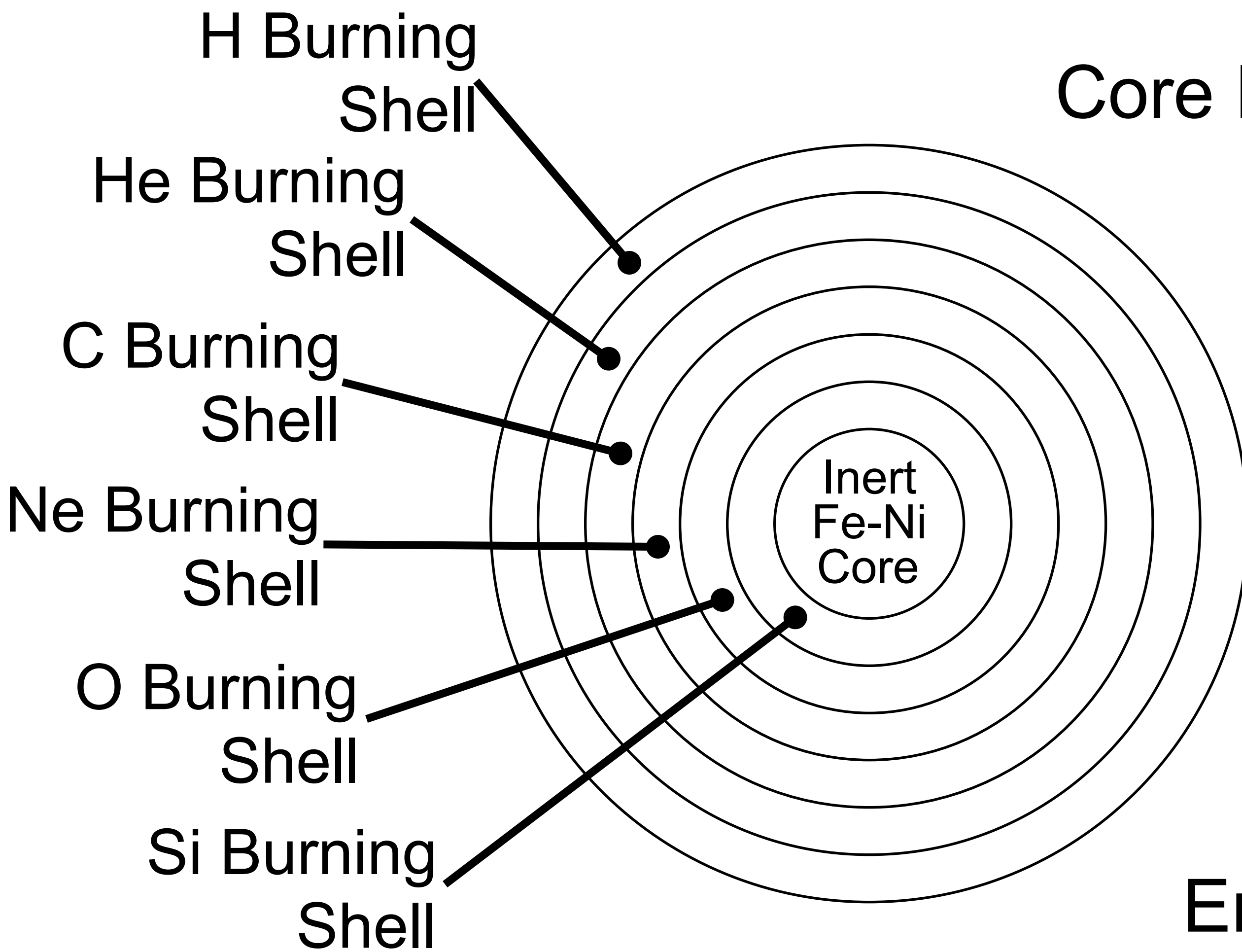
Massive stars: Fuse H into elements up to. Eject into the interstellar medium during Supernova.

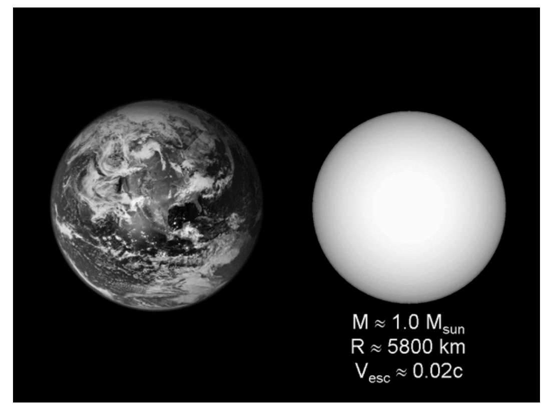
Intermediate mass stars: Eject CO, He, H

Low mass stars: Eject H, He.

End of Silicon Burning Phase:

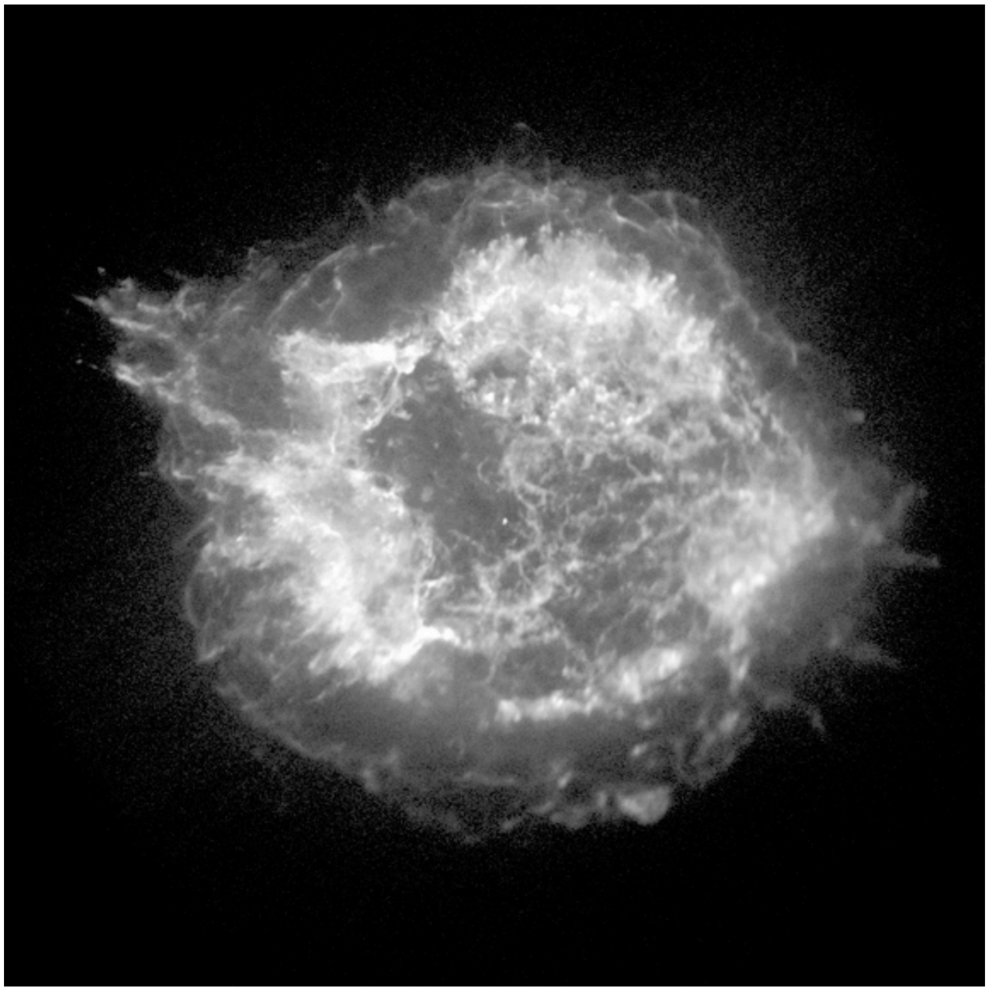
Core Radius: ~1 R_{earth}

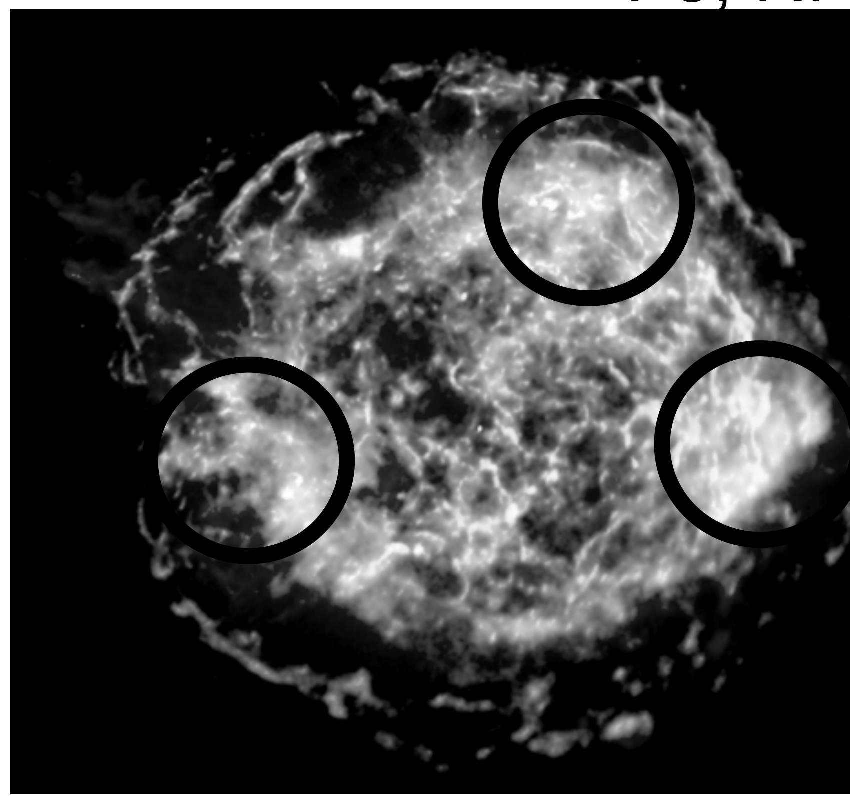




Envelope: ~ 5 AU

Massive star supernovae: 1 every 50-100 yrs in the Milky Way



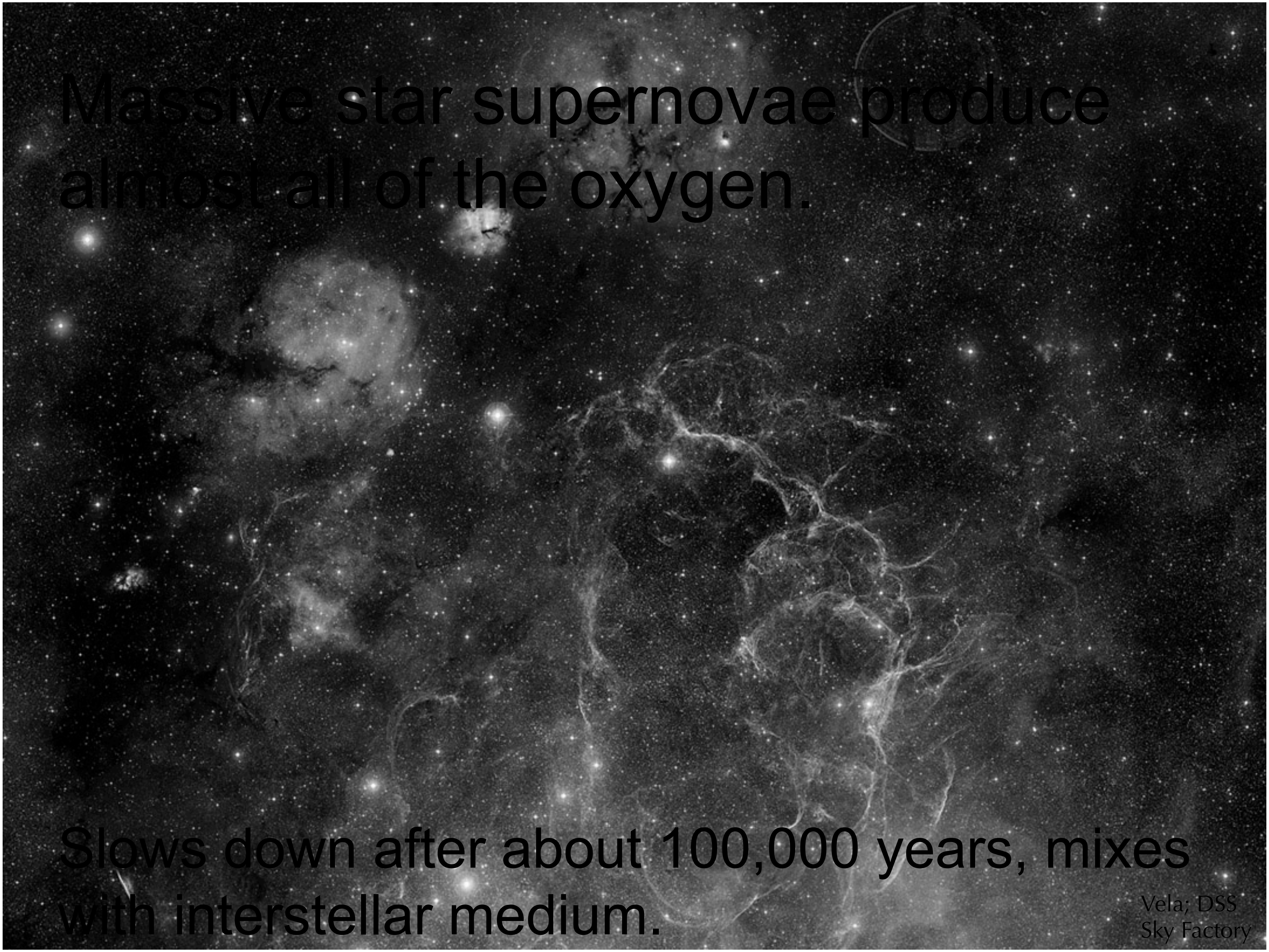


Top Ten Most Abundant Elements

10) Sulfur
9) Magnesium
8) Iron
7) Silicon
6) Nitrogen
5) Neon
4) Carbon
3) Oxygen
2) Helium
1) Hydrogen

Products
of massive star
Supernovae

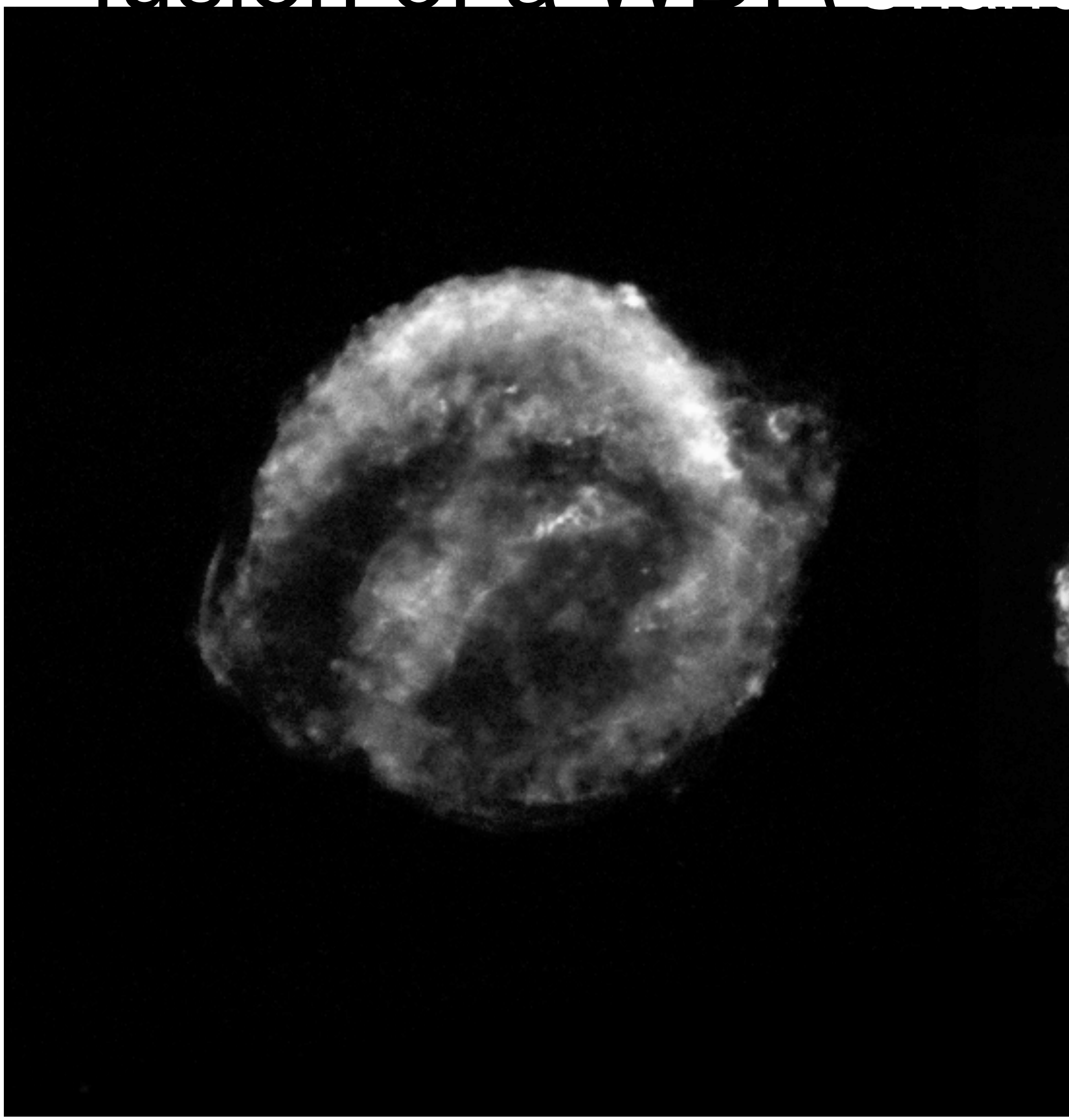
Massive star supernovae produce almost all of the oxygen.



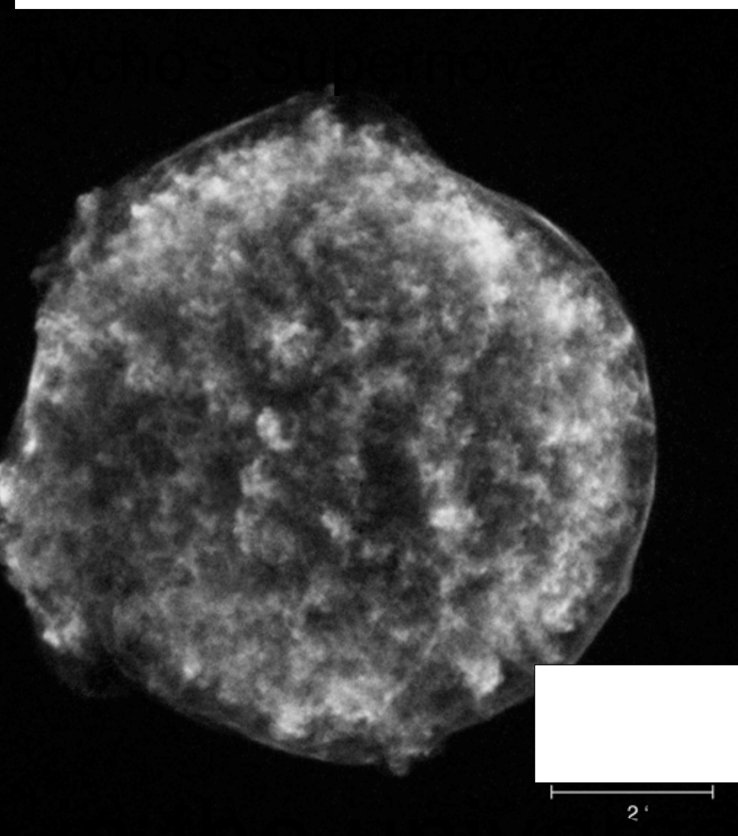
Slows down after about 100,000 years, mixes with interstellar medium.

Vela; DSS
Sky Factory

White dwarf supernovae: Unstable C fusion of a WD. (

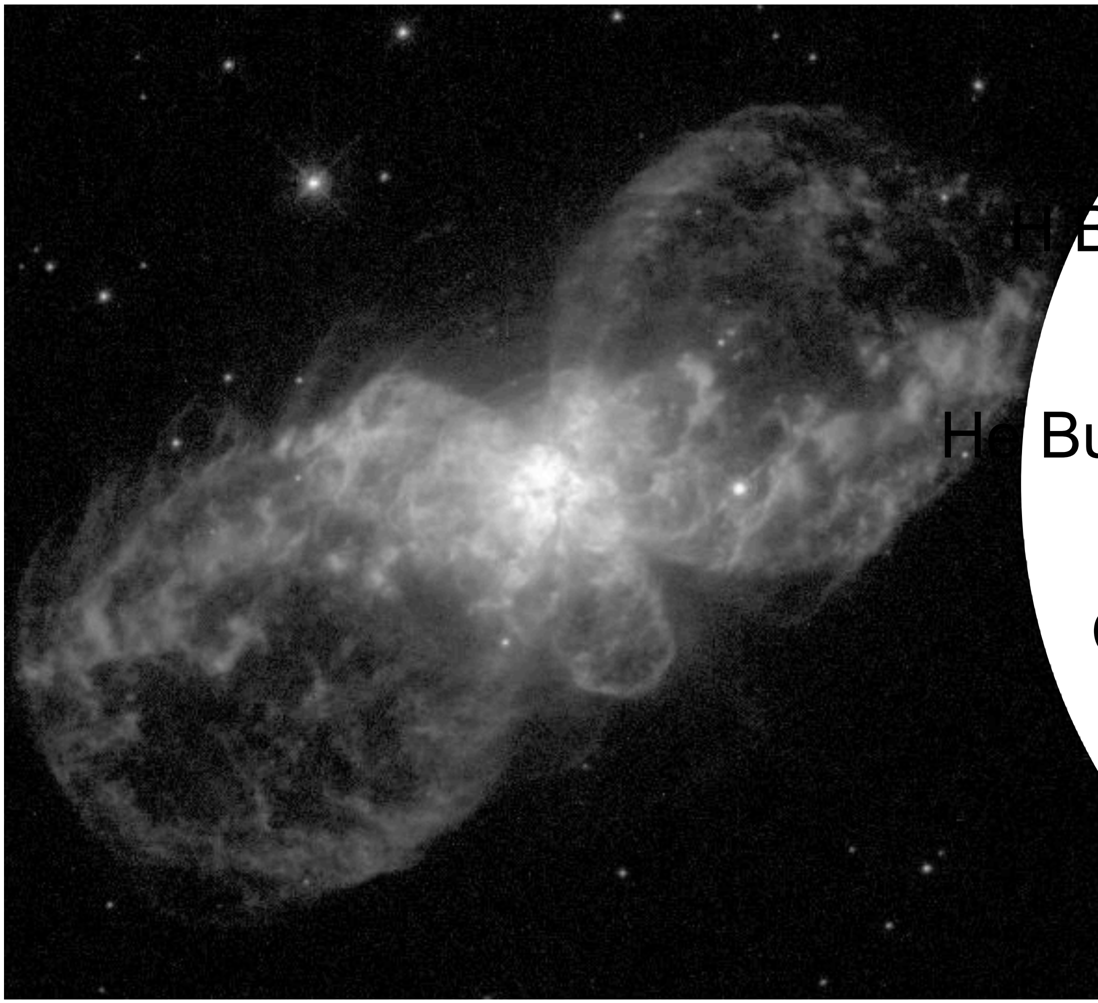


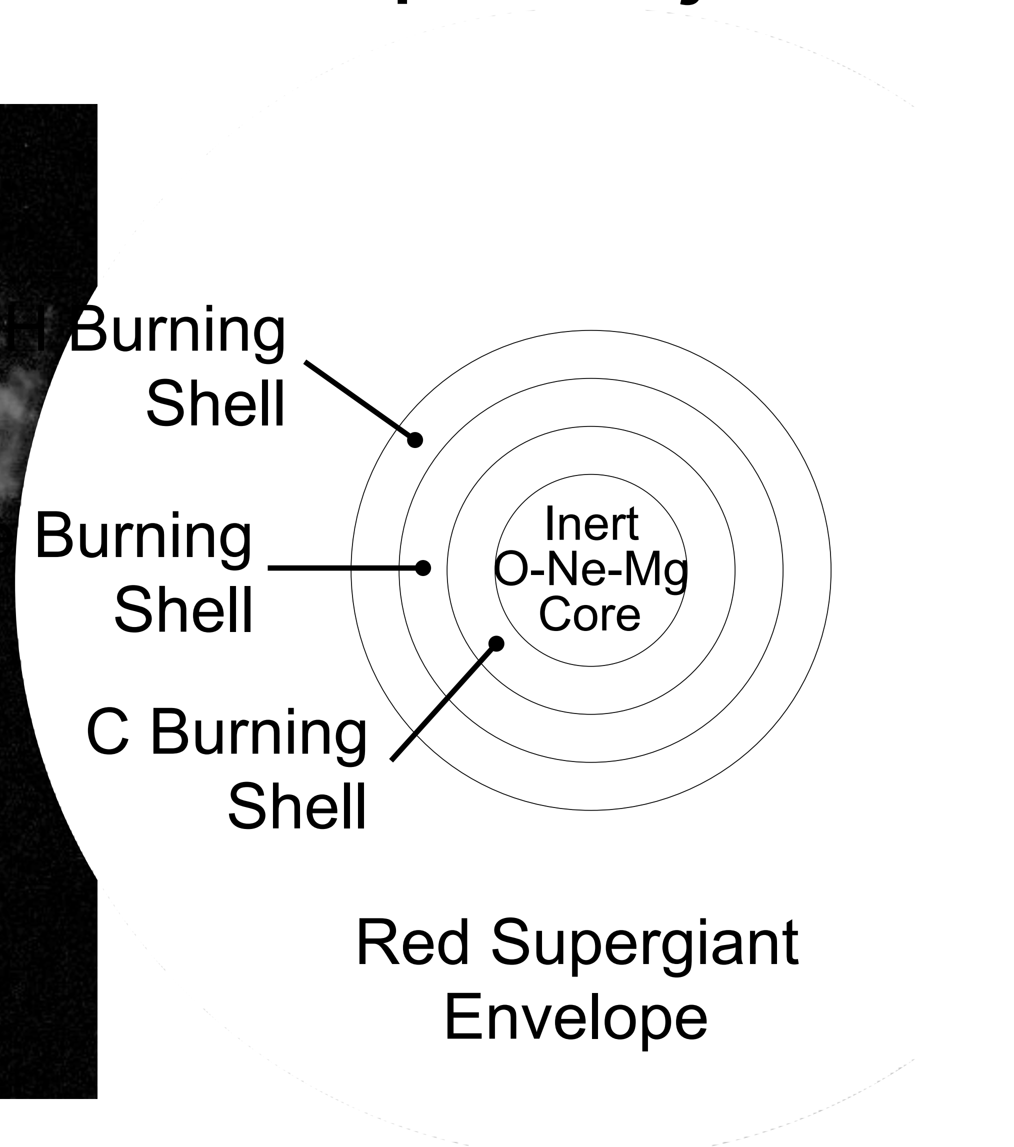
galaxy: 1 every 200yr.



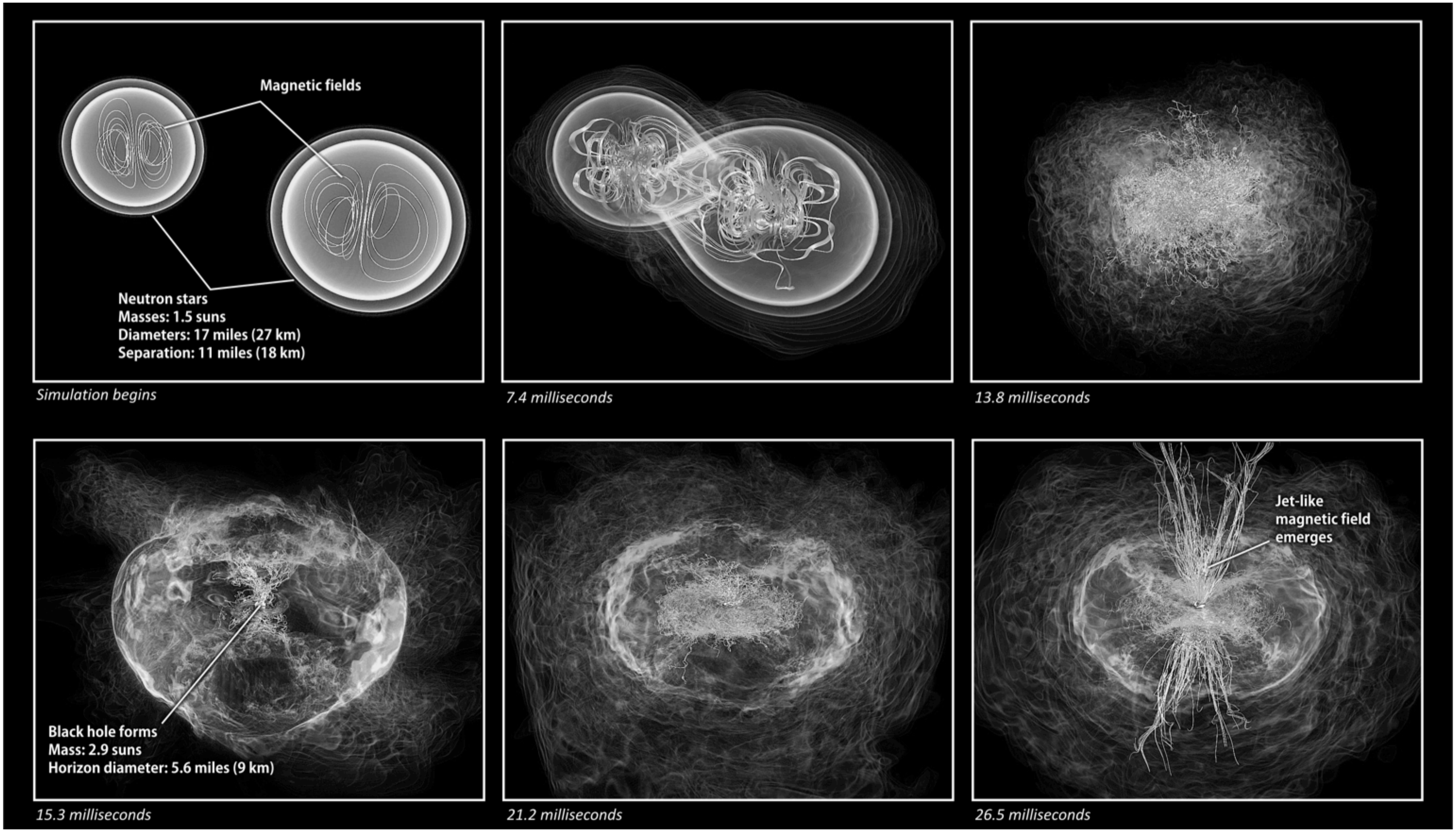
in the universe.

Nitrogen? Massive asymptotic red giants (AGB stars): Mix C + p's. Eject

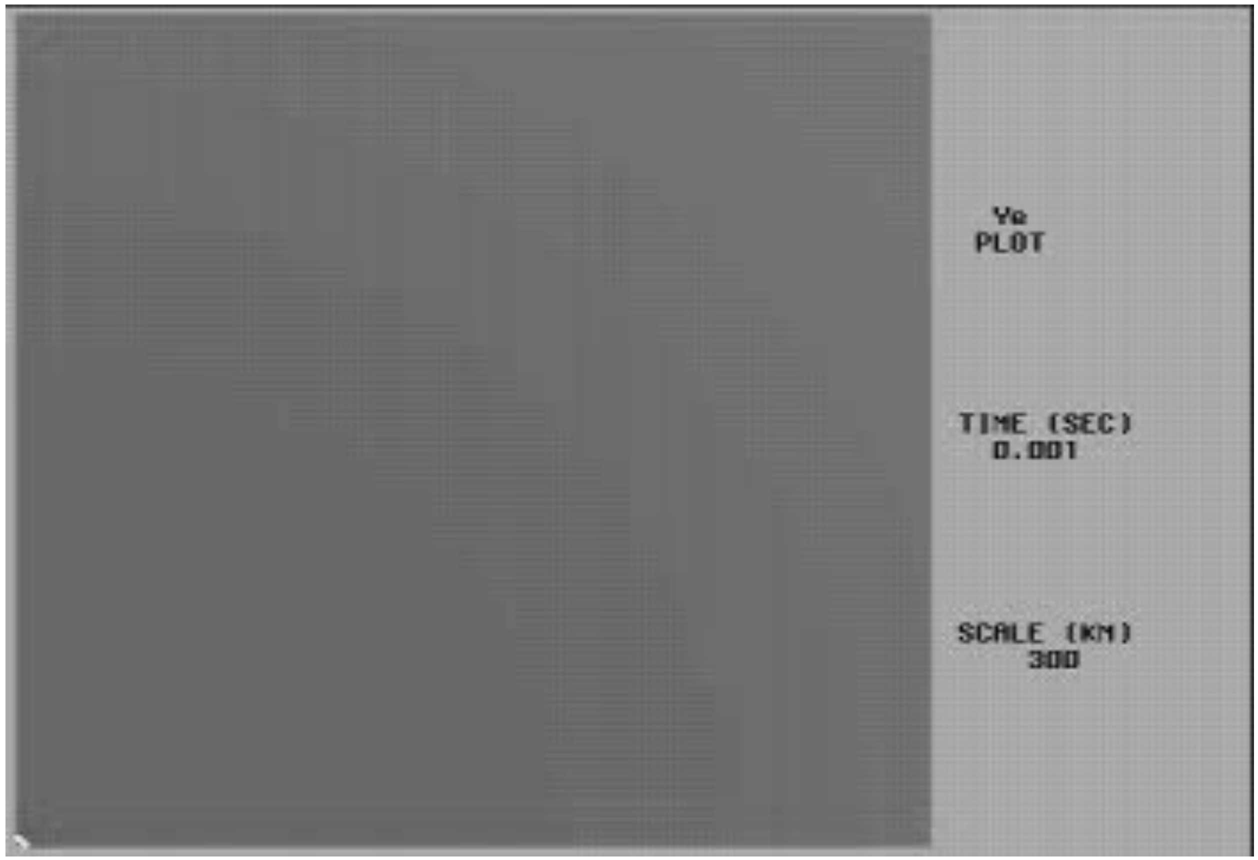




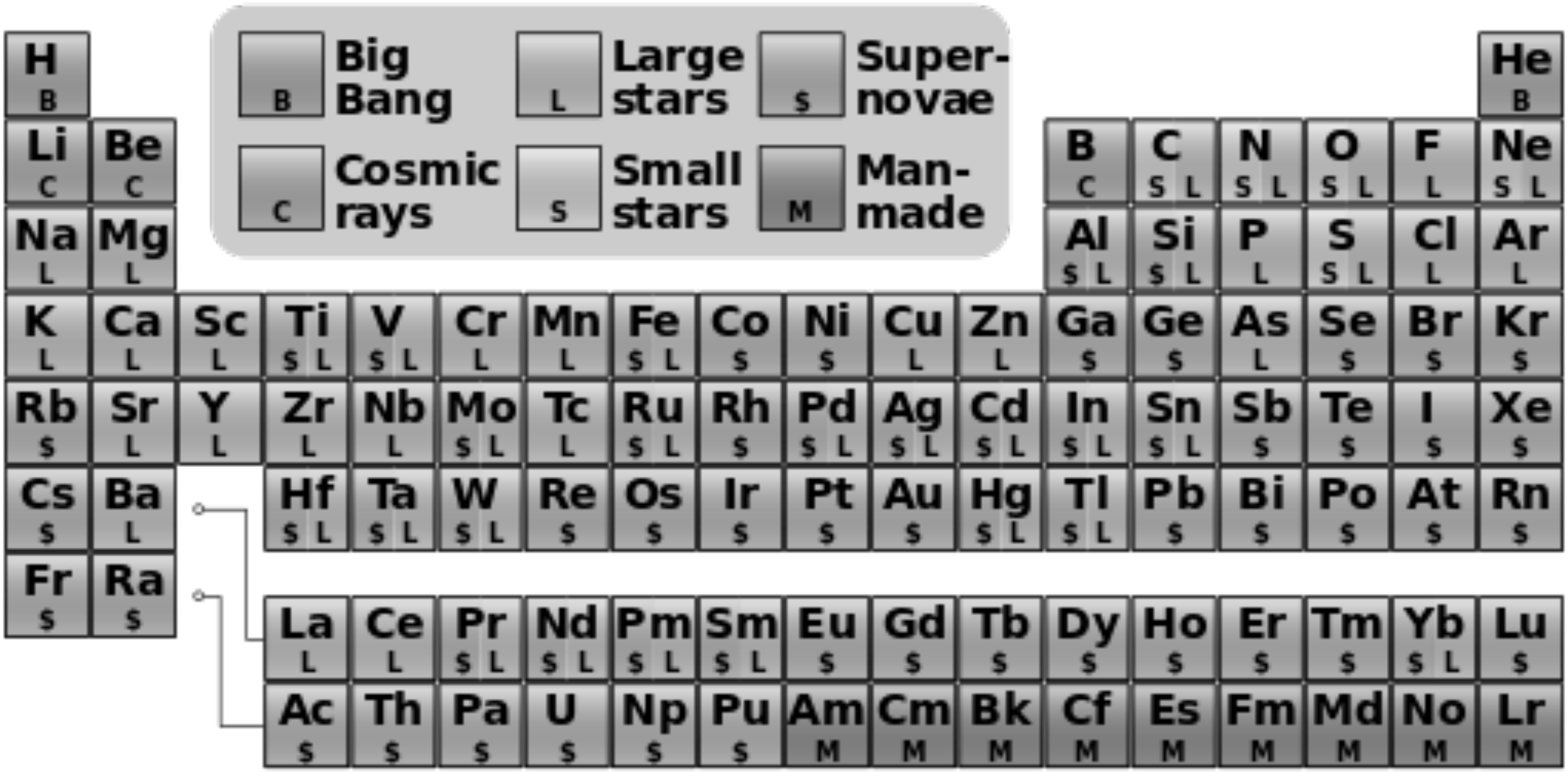
What about Gold, Platinum, Uranium? Either exotic supernova explosions of neutron star-neutron star mergers. Need super-high temps, lots of neutrons.



What about other heavy elements? Some probably produced in the super-heated wind that comes off neutron stars at birth.



Wikipedia: WRONG!



Summary

Massive star supernovae: O, C, some Fe

White dwarf (Type Ia) supernovae: Fe

Intermediate mass AGB stars: N, some heavy elements

Heavy elements like Au: maybe NS-NS mergers.

Heavy elements like Sr, Y, Zr: maybe NS winds.

Normal stars: H, He, C, O, etc.

He fusion in intermediate mass stars makes the C.

We are star stuff.

Metal-enriched gas mixes with interstellar gas

- Goes into the next generation of stars.
- Successive generations are more <u>metal rich</u>.

Sun & planets & us are about 4.5 Gyr old.

- Contain lots of metals C, N, O, Si, Fe, Mg, Au …

The Solar System formed from gas enriched by previous generations of massive stars.

Future stellar generations will form from the gas enriched by the Sun and stars we see today, but more and more of the gas will get locked into WDs, NSs, and BHs.