# Formazione stellare

**thanks to**
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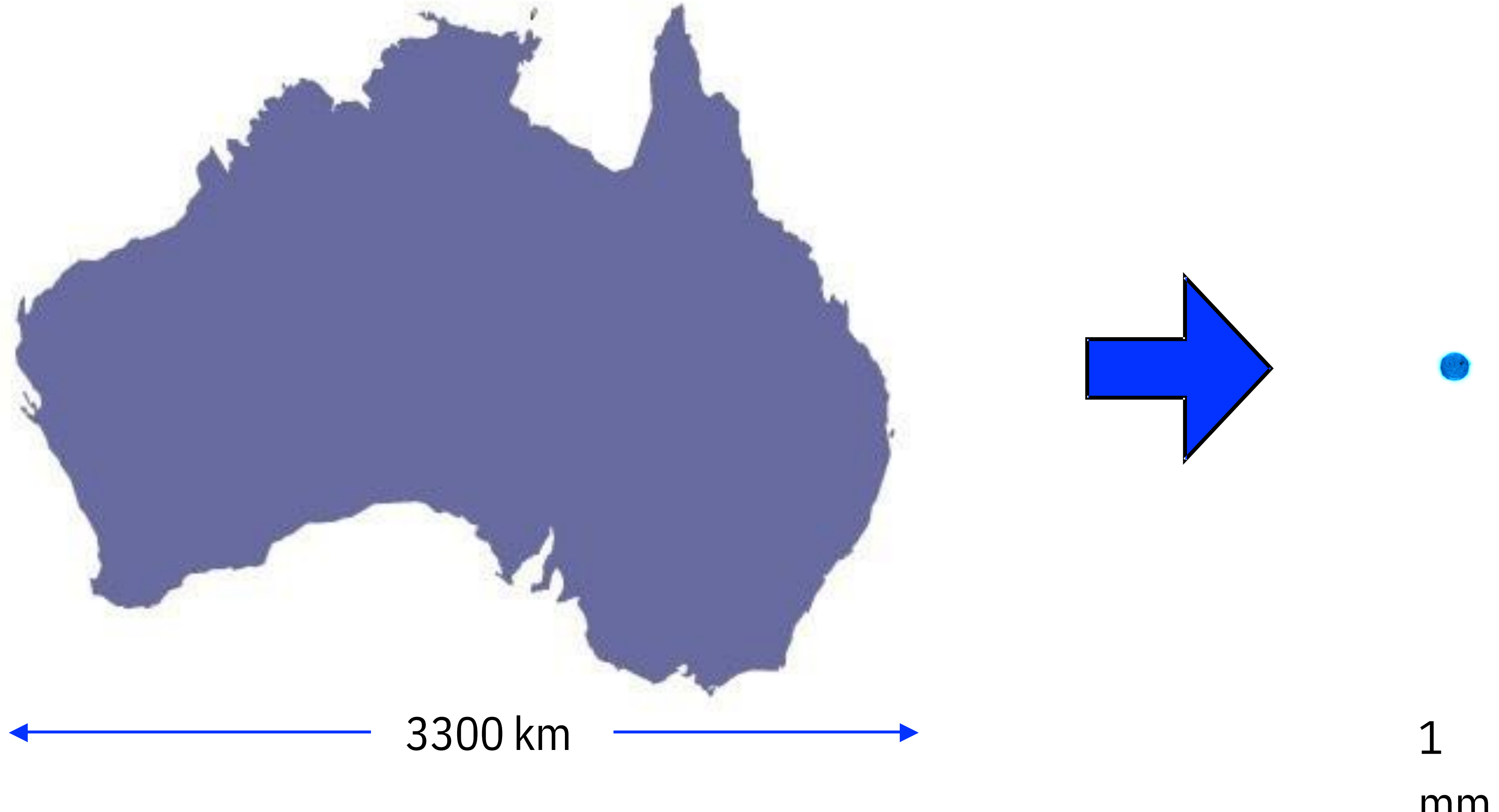
There are a lot of things we really don't understand about how stars form.

Part of the problem is that stars form in the interiors of dense dark clouds, and it is only recently that we've been able to see through the clouds using infrared telescopes to understand what's going on.

Jet from an embedded star in the dust- darkened Bok Globule BHR 71

The other problem is the enormous range of scales over which star formation takes place. An interstellar cloud 30 pc across collapses to form stars the size of our Sun.

If the original cloud were the size of Australia, the final stars would be about 1 mm across.



# In this lecture

- Where do stars form?
  - the interstellar medium and molecular clouds
- How do stars form?
  - gravitational collapse
- Why do stars form?
  - spontaneous or triggered?
- Extra (mostly unanswered) questions
  - binary & multiple stars?

# Where do stars form?

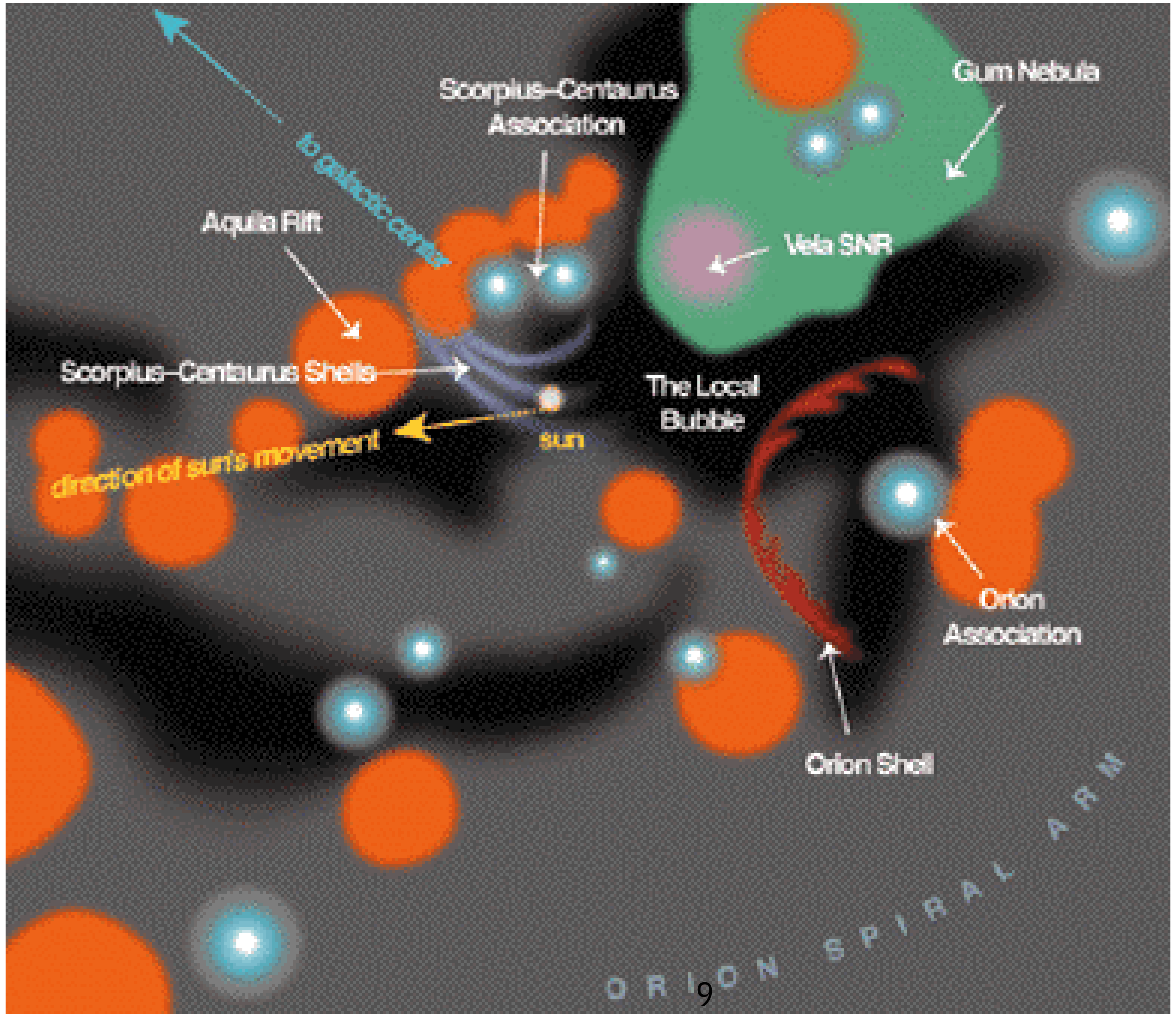
We can find where stars form by looking to see where we find young stars.
Young stars congregate together in loose groups, and always in association with giant molecular clouds.

The space between the stars is filled with gas at extremely low densities: collectively, this is called the interstellar medium.

Most of this gas is atomic, often ionised by the radiation from hot stars.

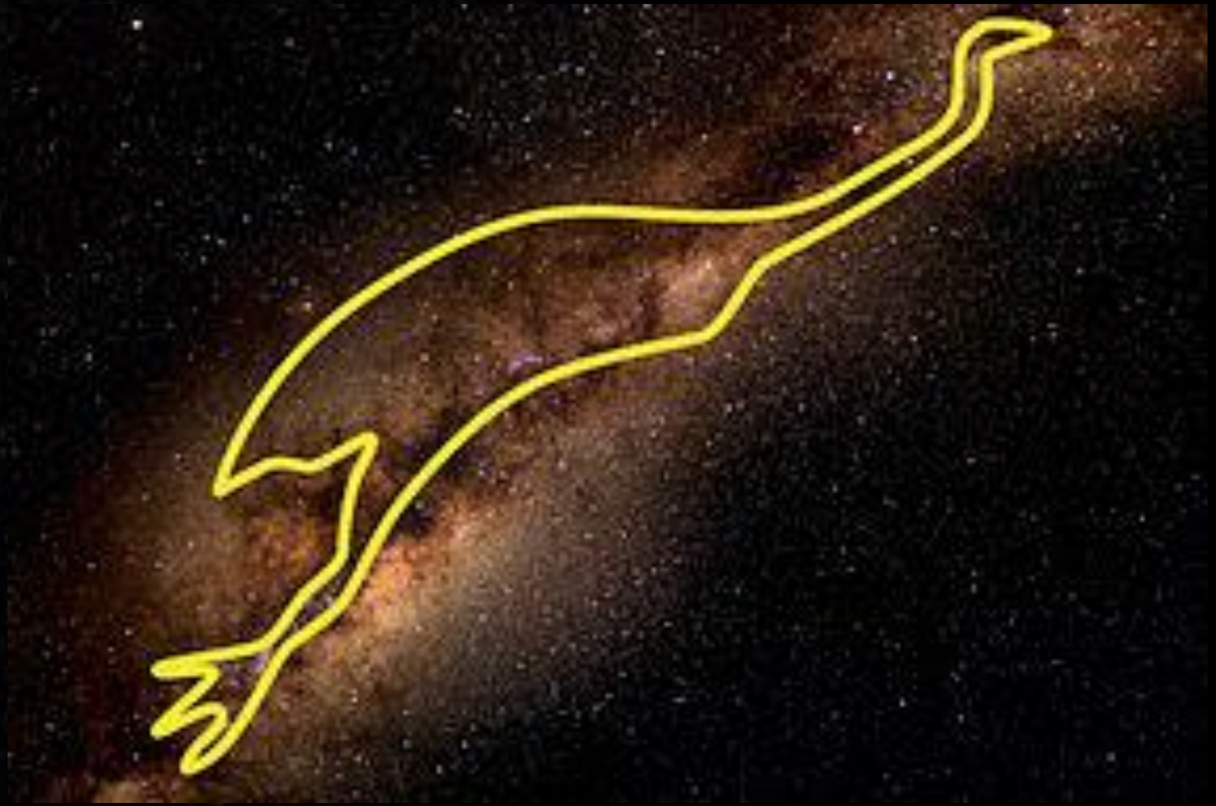
However, about 1% of the volumes is occupied by gas which is cool enough and dense enough to form molecules.

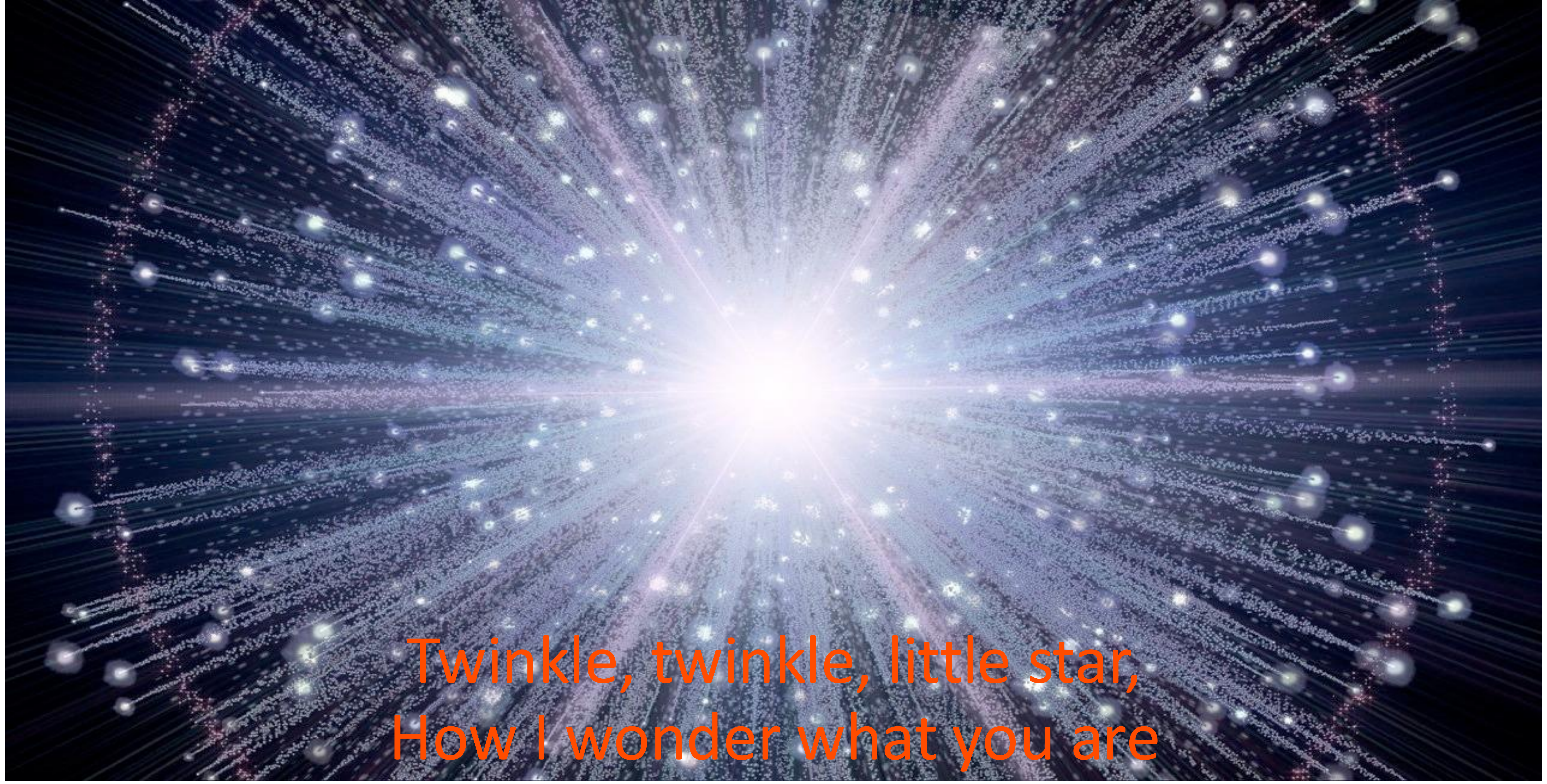
The molecular gas is clumped in regions called clouds, with masses of up to a million solar masses and sizes typically a few tens of parsecs. The clouds near the Sun are shown in orange in this illustration.



# Here is a giant molecular cloud you can see.

The Coal Sack Nebula appears as a dark patch in the bright Milky Way. It is actually, a dense cloud of dust and gas, and appears dark because it blocks the light behind.

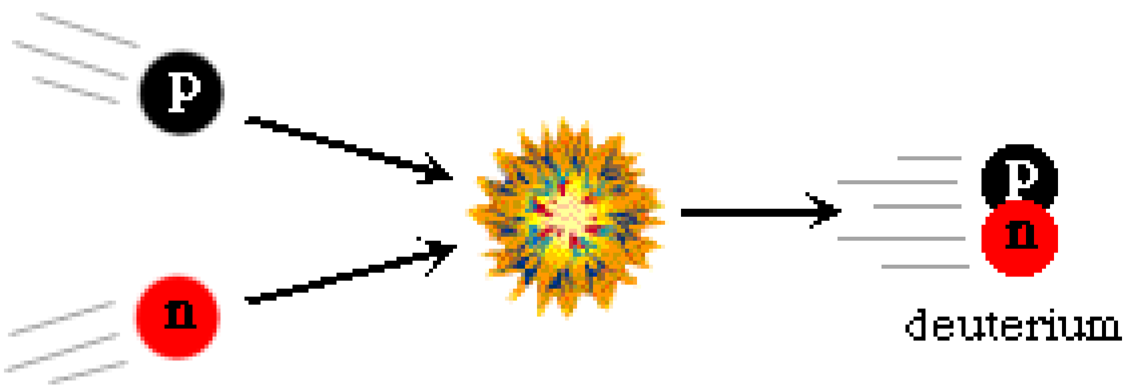




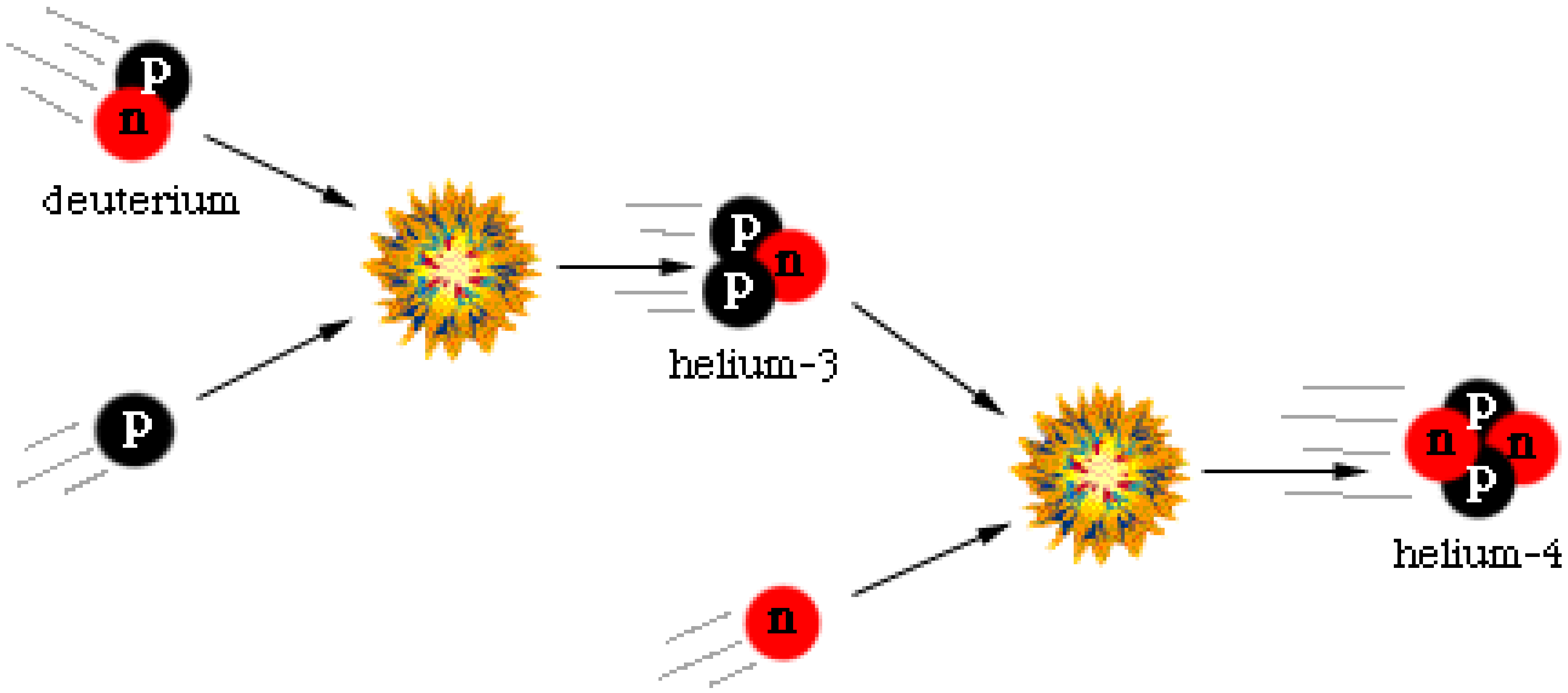

Before we begin asking how a star forms, let us ask a more basic question: what does it form out of, and how did that stuff get here?

To answer that properly, we have to go all the way back to the formation of the Universe in the Big Bang.

About 3 minutes after the Big Bang, the temperature of the Universe had cooled from 100 billion degrees to about 1 billion degrees. As the temperature dropped, protons and neutrons began combining to form a deuterium nucleus: prior to this they had too much energy to built up heavier nuclei



Nearly all the nuclei with a few protons and neutrons are unstable or easily destroyed. Helium-4 is the only really stable one, so lots of Helium-4 was formed in the next few seconds. But apart from tiny amounts of Lithium-7, no other element can be easily formed. So, when the era of fusion ended, about 3½ minutes after the Big Bang, the universe consisted of lots of hydrogen, some helium, tiny amounts of deuterium and lithium-7, and not much else.



The first stars to form in the universe would have been very different from our own Sun: they had no heavy elements. With no heavy elements, there can have been no rocky planets (no silicon, carbon, etc.).

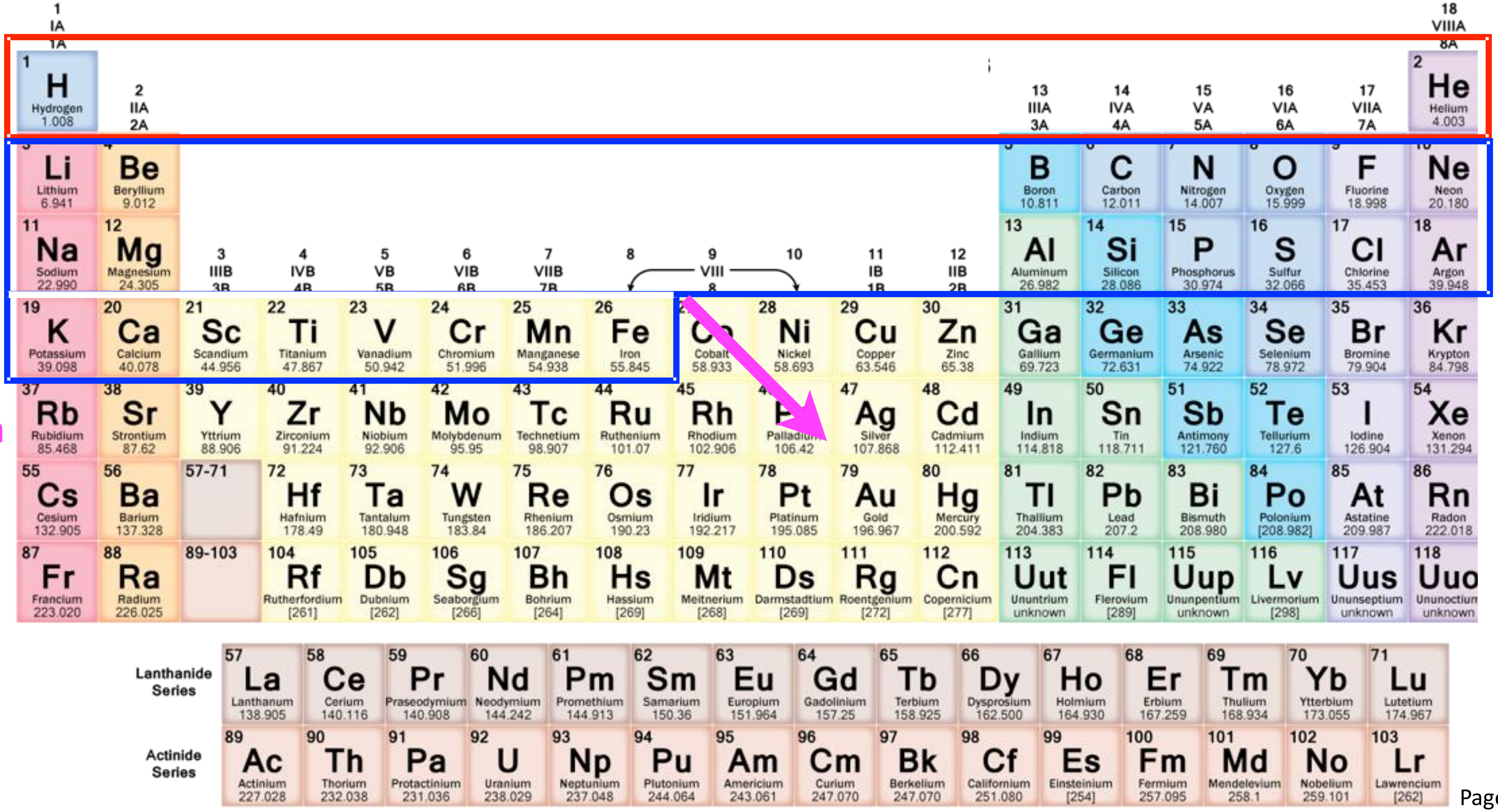
So where did the heavy elements come from?

# As we you have seen few weeks ago, all the other elements in the periodic table were formed inside stars, or during the death of stars.

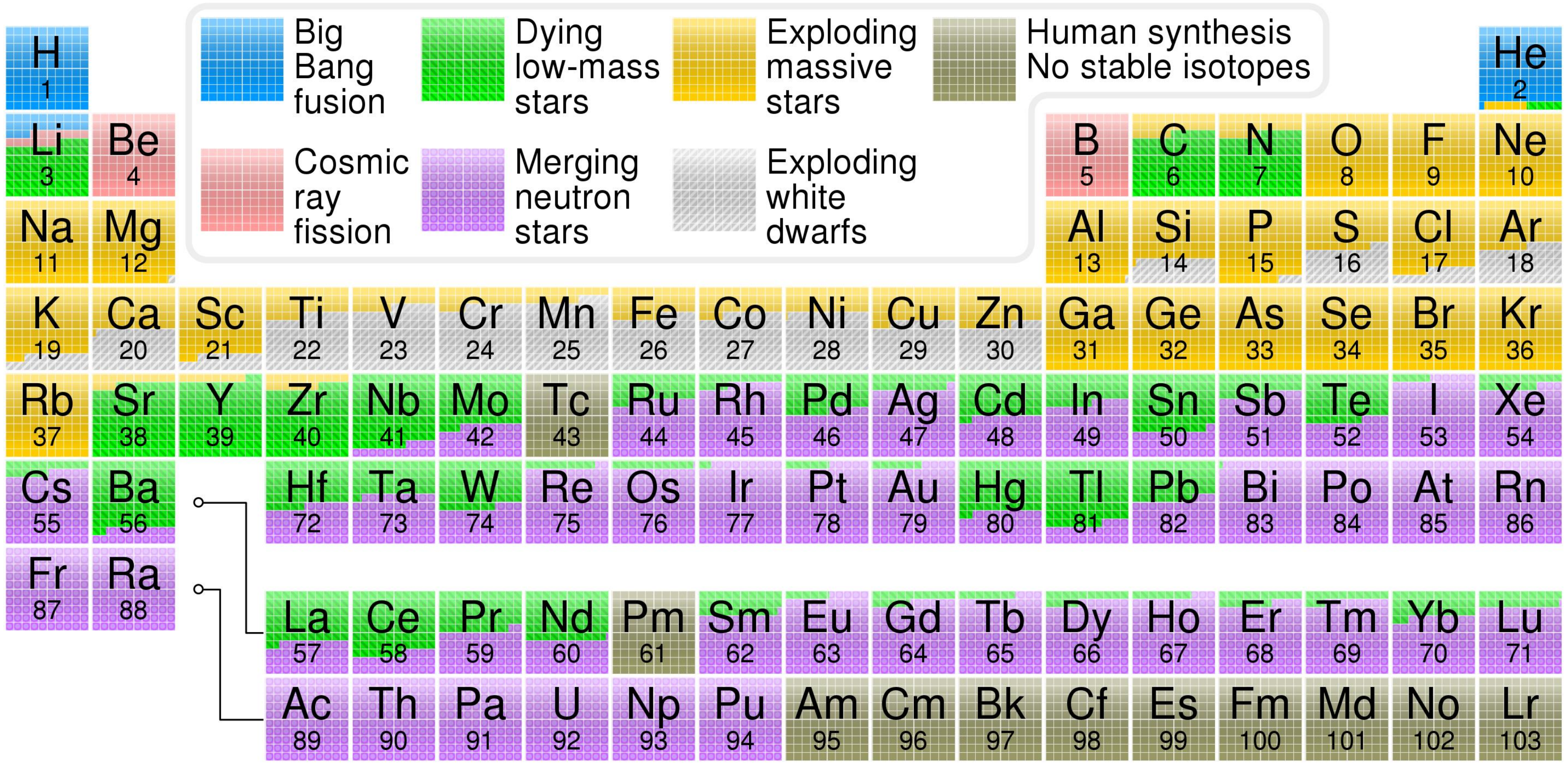
produced in the Big Bang

produced in stars

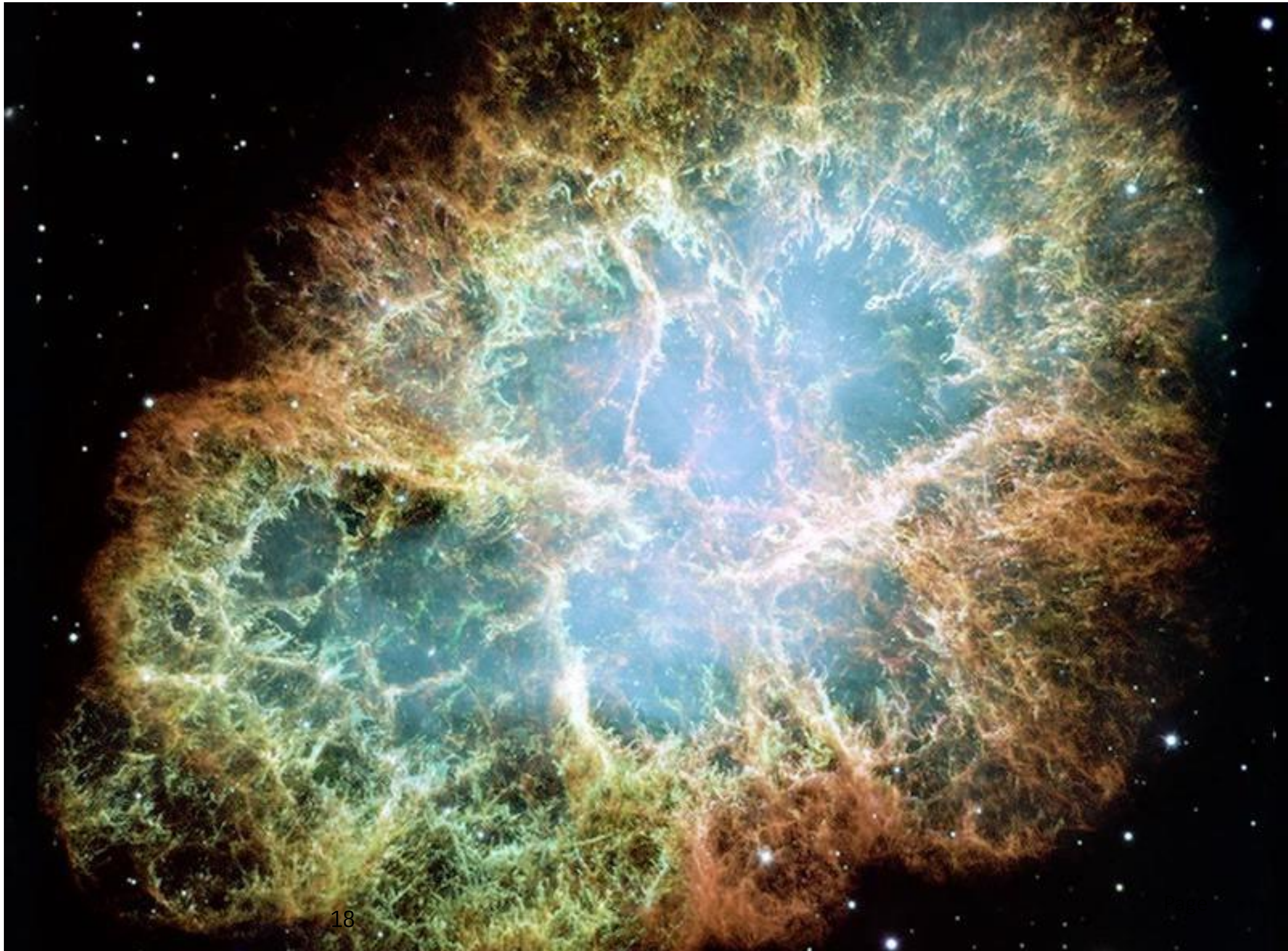
produced in supernova explosions



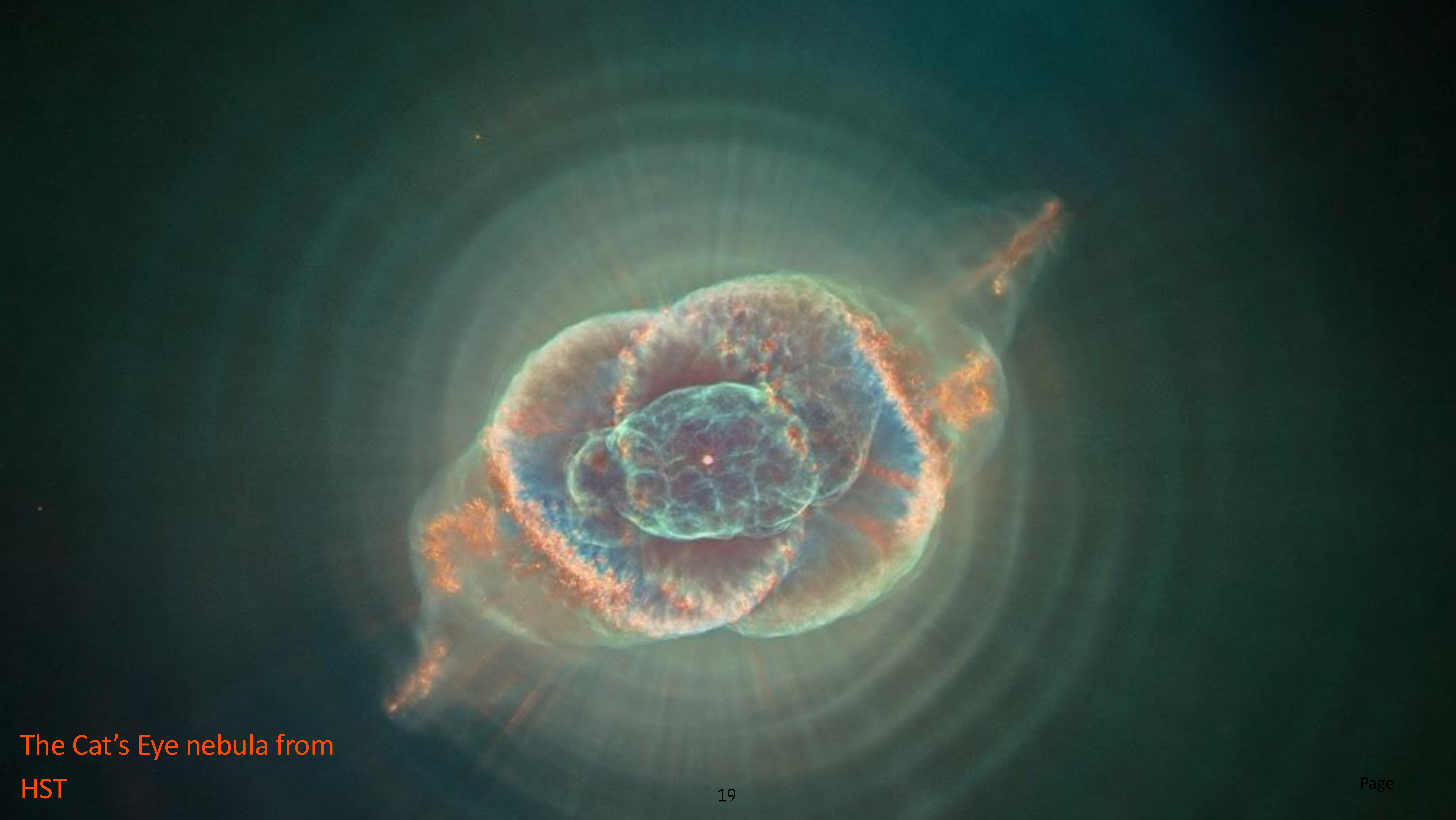
# More detailed table from J.Johnson (Ohio University)
# we will learn more in the next week… it is all chemical evolution!



Star material does not stay locked in stars forever; vast quantities are erupted back into space in a variety of ways: nova and supernova explosions, planetary nebulae, stellar winds.

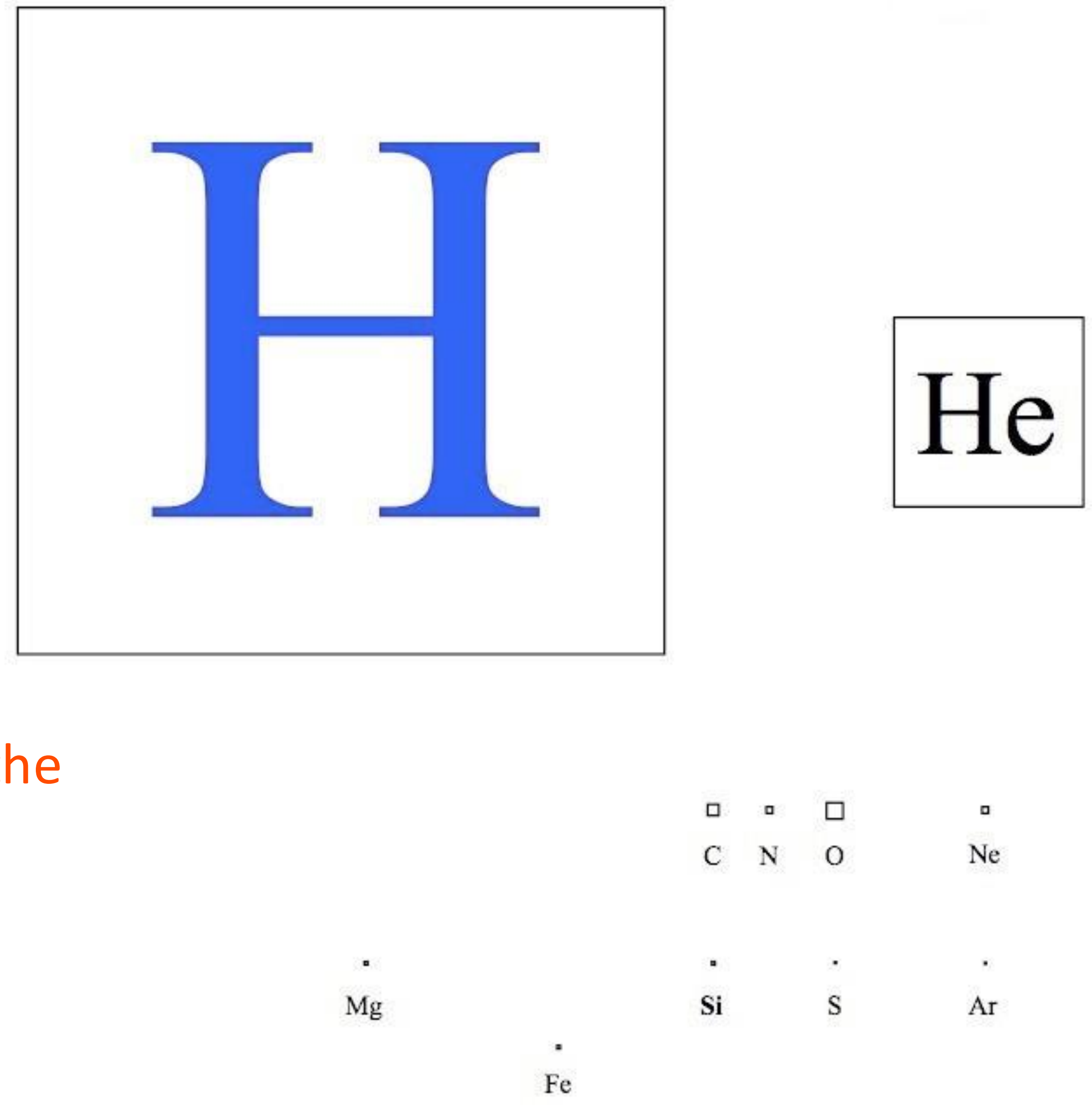


Mosaic of the Crab Nebula from HST



The Cat’s Eye nebula from HST

These other elements, however, only make up a tiny fraction of interstellar material. The gas from which stars form consists mostly of hydrogen and helium, with other elements less than one-thousandth as abundant as hydrogen.




The "Astronomer's Periodic table", with the size of the element indicating its abundance by weight . (Figure by Ben McCall)

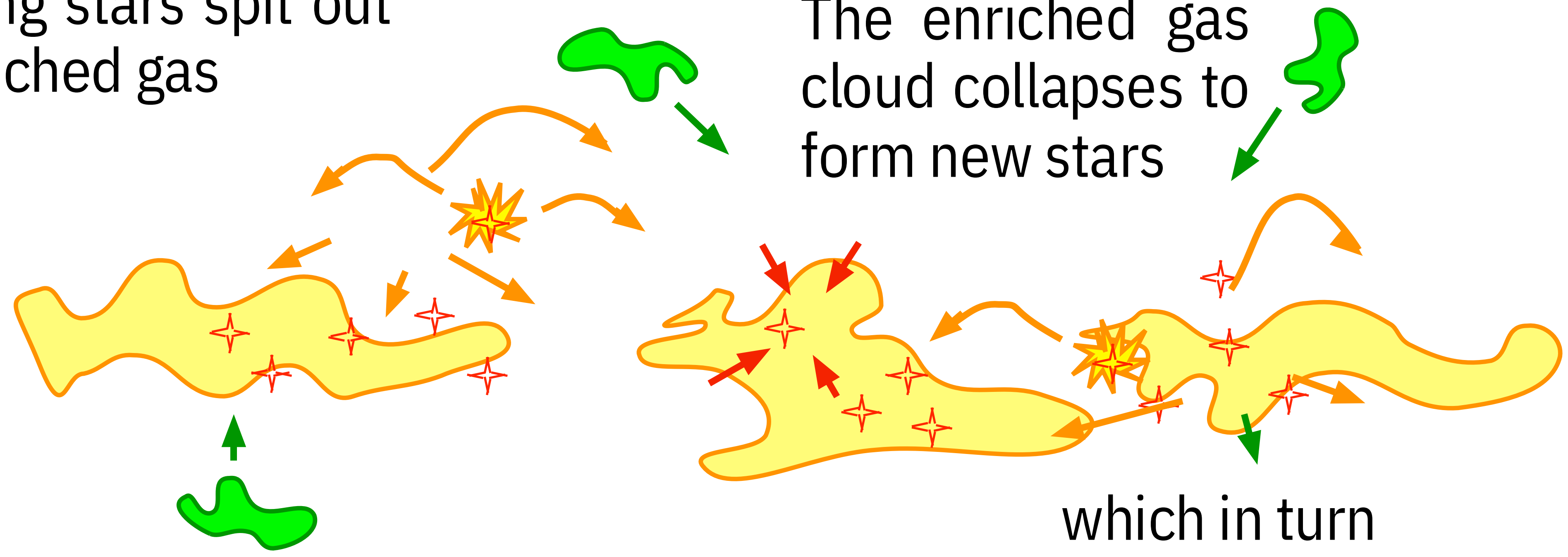
The gas swirls around in space and collects in dense clouds. These clouds mix with the remaining primordial gas and coalesce into the clouds we call giant molecular clouds.

These clouds are the sites of star formation. Here you can see the new-born stars in NGC 281 lighting up the wispy remnants of the cloud which gave them birth.

The dark blobs are Bok globules, small sub-clouds which are currently forming stars.

Dark globules in IC2944

# These stars will in their turn age, die, and release their gas back to the interstellar clouds, in a giant cycle of stellar birth and death.



This is how molecular clouds form. How do they collapse to form stars? Gravity, which attracts everything to everything else, tries to make the whole cloud collapse. But this inward force is resisted by gas pressure, which pushes outward against gravity.

It turns out the cloud will only collapse if its mass exceeds a critical mass called the Jeans mass, which depends on the density and type of gas. Low density clouds with large mass may collapse to form galaxies, while smaller but denser clouds collapse to form star clusters or single stars.

Se consideriamo una nube sferica di densità uniforme $\rho$

temperatura uniforme T e massa M

$$\text{Egrav} = \Omega = -0.6GM^2/R$$

(0.6 per configurazione sferica)

L'energia interna della nube sarà:

$E_{int} = \frac{3}{2}NkT = 1.5R_{gas}TM/\mu$ con

$\mu = \frac{\langle m \rangle}{m_H} peso\ molecolare\ medio$ e $R_{gas} = \text{costante dei gas}$

Il collasso avrà dunque luogo solo se

$$Egrav = |\Omega| > E_{int}$$

$$\frac{0.6GM^2}{R} > 1.5R_{gas}TM/\mu$$

$$R < R_{Jeans} = \frac{2}{5}GM\mu/R_{gas}T$$

con $R_{Jeans} = Raggio\ di\ Jeans$

Eliminando il raggio a favore della densità si ottiene la massa di Jeans,

la minima massa che la nube deve avere per collassare

$$M_{Jeans} > \left(\frac{5R_{gas}T}{2\mu G}\right)^{\frac{3}{2}} (4/3\Pi\rho)^{-1/2}$$

La condizione della massa di Jeans è molto restrittiva:

una tipica nube di HI ha T~ 50 K , $\rho$~ 1.7 $10^{-23}$ g/cm$^3$ $\mu$ ~ 1

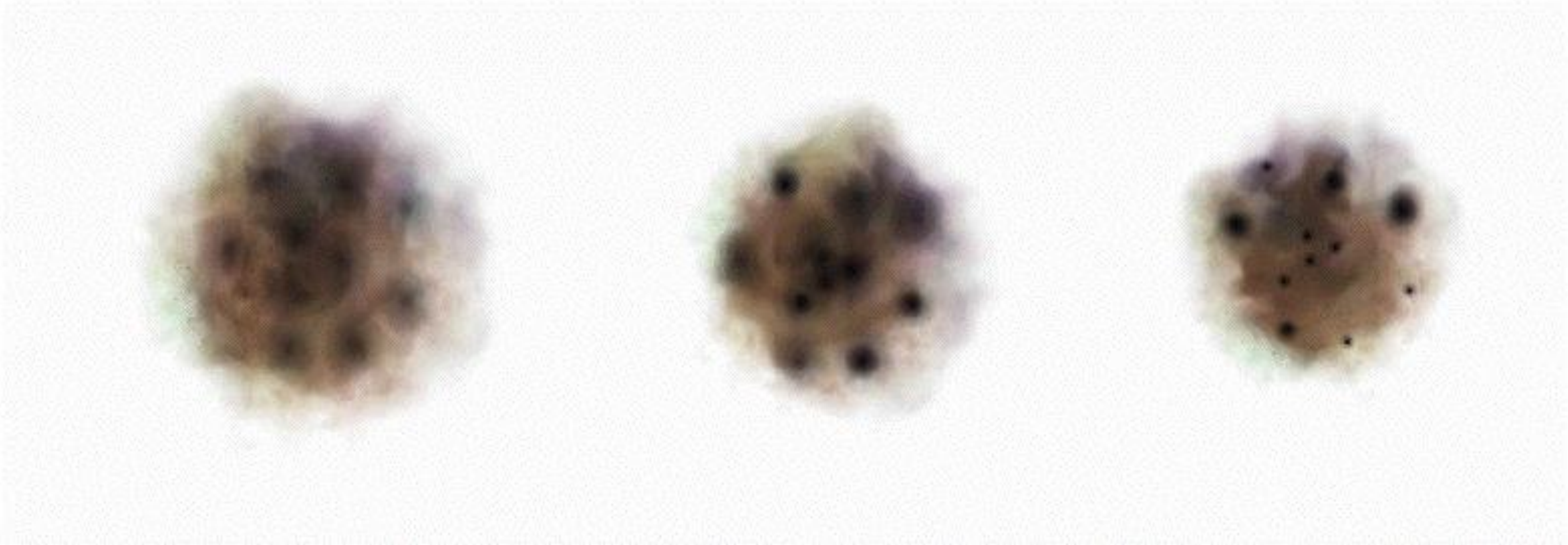
$$M_{Jeans} = 3600 M_{\odot}$$

Le condizioni di una tipica massa di una nube molecolare

T~ 10 K , $\rho$~ 1.7 $10^{-21}$ g/cm$^3$ $\mu$ ~ 2

$$M_{Jeans} = 8 M_{\odot}$$

Le nubi molecolari hanno masse dell'ordine di $10^4$-$10^5$ masse solari. Questo suggerisce che possano avvenire delle frammentazioni nel collasso con quindi il  collasso di frammenti di massa delle ordine di quelle stellari, formando svariarate proto-stelle.



As the cloud contracts, its speed of rotation increases. The law of conservation of angular momentum says that as rotating things get smaller, they rotate faster.

To be precise, angular momentum is equal to

mass x velocity x distance from axis

If no outside forces act on the body, this number remains the same, so if the distance gets smaller, the velocity must increase.

Il momento angolare delle nubi interstellari rappresenta un ostacolo alla formazione stellare;

il momento angolare minimo di una nube lo si puo' calcolare assumendo che la nube ruoti alla stessa velocita' angolare che e' associata al suo moto di rotazione attorno al centro galattico

$$\simeq 10^{-15} rad/sec.$$

Il momento angolare per unita' di massa e' pertanto

$$J/M = 10^{24} cm^2 sec^{-1}$$

COME LO SI CALCOLA?

Però la rotazione tipica di una stella è dell’ordine di

$$J/M = 10^{17} cm^2 sec^{-1}$$

quindi 7 ORDINI di grandezza in meno. Come è possibile perdere tutto questo momento angolare?

**Una parte è disperso tramite onde di Alven.**

se la materia e' accoppiata al campo magnetico B, l'avvitamento delle linee di forza del campo puo' dare origine ad onde di Alfven che trasferiscono momento angolare dalla nube al mezzo esterno. Si pensa che una riduzione significativa di momento angolare avvenga in $10^6$ - $10^7$ anni. Questo meccanismo e'
valido fino a = $10^{-19}$g/cm$^3$, poiche' a tale densita' il campo magnetico non e' piu' accoppiato alla materia, cioe' la densita' di particelle cariche diventa molto bassa.

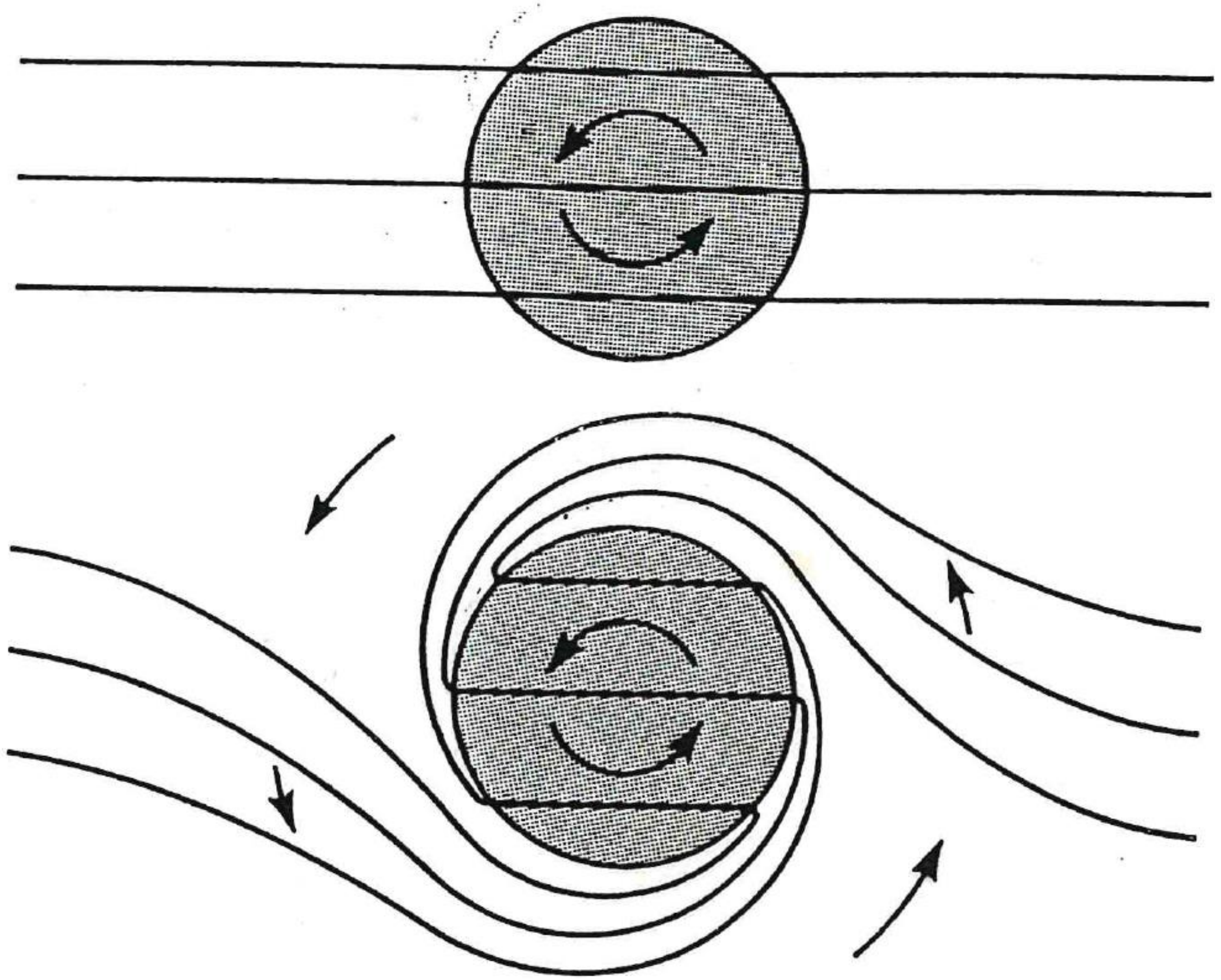


**Figure 11.46.** Magnetic-field lines which thread a rotating interstellar cloud may help to remove angular momentum from the cloud by transferring it to the surrounding medium. The frozen-in field lines wrap up as the cloud turns, and the resulting curved field lines tend to spin up the surrounding gas. More and more of the ambient gas is set into motion as the rotating disturbance propagates away from the gas cloud as an Alfven wave.

Al procedere del collasso la densità cresce ma la temperatura diminuisce o rimane costante (collasso isotermo). La nube tende a scaldarsi a causa della compressione gravitazionale ma l'energia interna viene convertita in parte in radiazione che può facilmente uscire dalla nube grazie alla ancor bassa densità (in seguito entreremo in qualche dettaglio)

Pertanto la massa di Jeans tende a diminuire facilitando la frammentazione.

Dopo la frammentazione, ogni frammento trattiene del momento angolare di spin ma è piccolo a sufficienza da lasciar collassare il frammento.

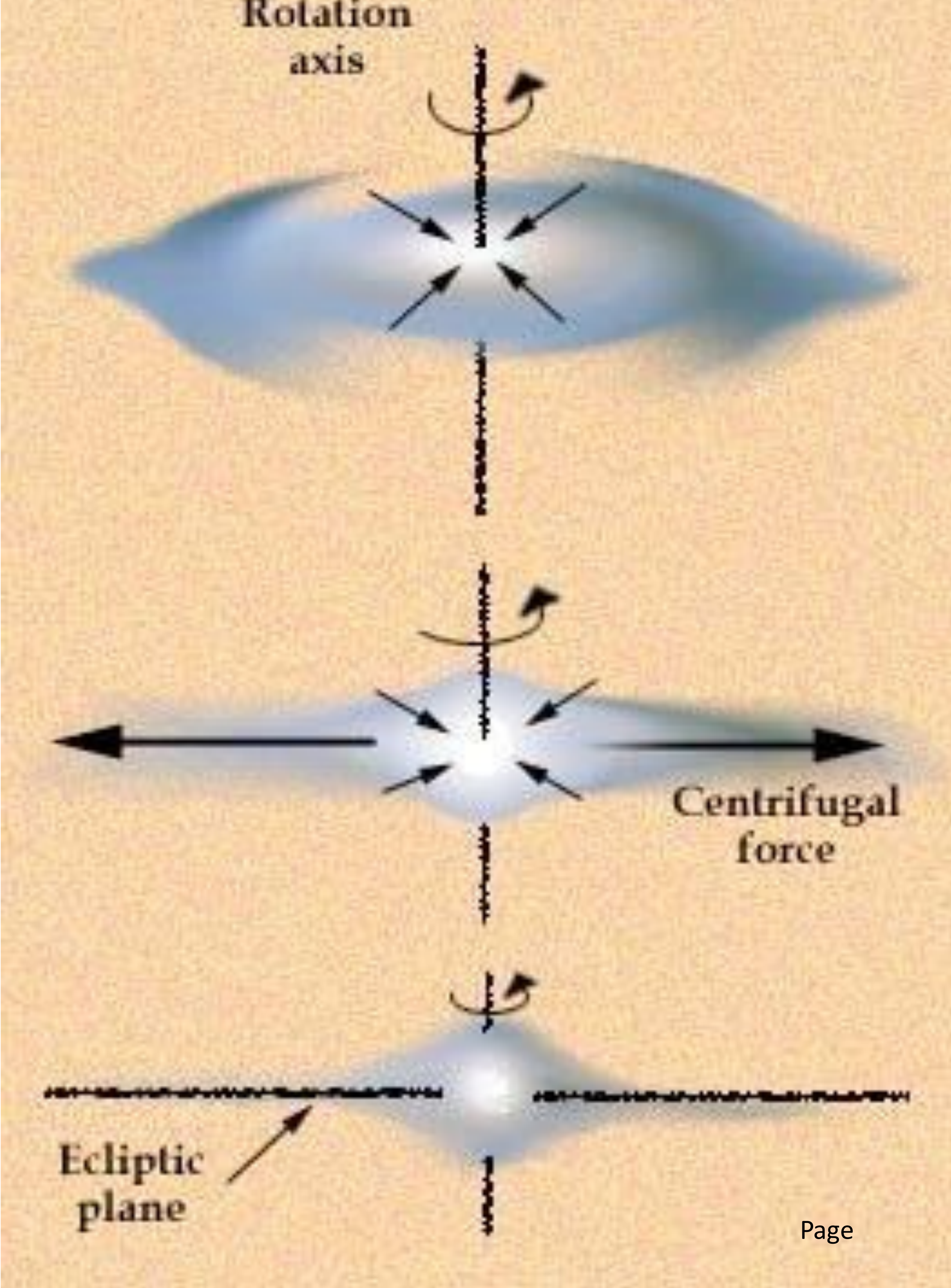
I frammenti  si possono ulteriormente spezzare in altri frammenti convertendo momento angolare di spin in moto orbitale.
Dopo, il momento angolare può  essersi ridotto di alcuni ordini di grandezza. Una sequenza di frammentazioni è un evento molto probabile durante il processo di formazione stellare. Il fatto che la massa di Jeans nelle nubi molecolari sia maggiore della tipica massa stellare (1Msun  ) indica che si hanno frammentazioni successive.

La frammentazione continua fino a quando la densità non è cresciuta al punto da rendere la nube opaca alla radiazione per

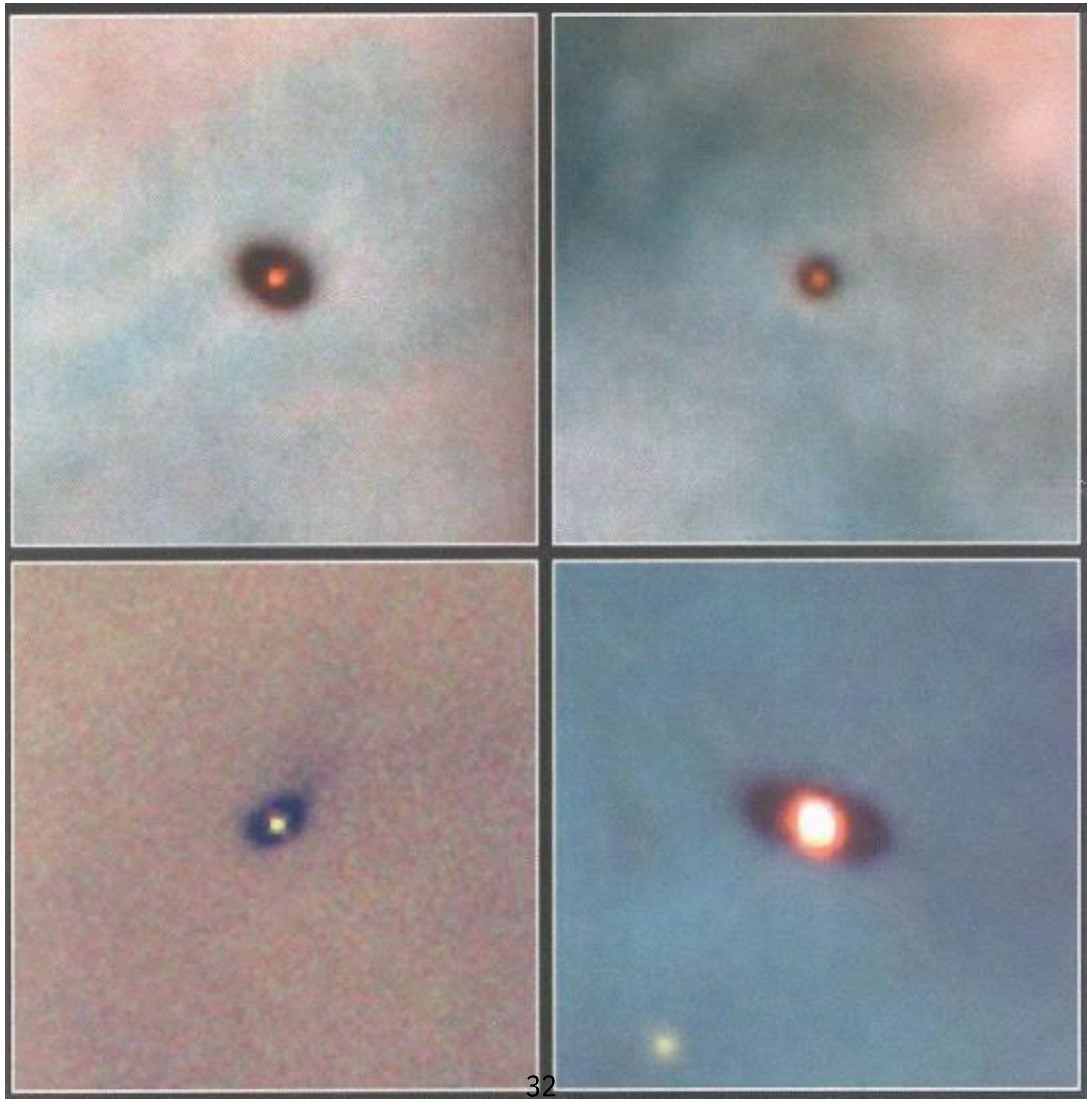
$$\rho \simeq 10^{-13} - 10^{-14} gr/cm^3,$$

Che corrisponde alla massa di Jeans di $M_J(T = 10K) = 0.005 M_\odot$

Moreover the fragmented collapsing cloud will be end up as a disk, because while angular momentum makes it hard to collapse to the centre, there is nothing to stop the gravitational collapse to the plane.



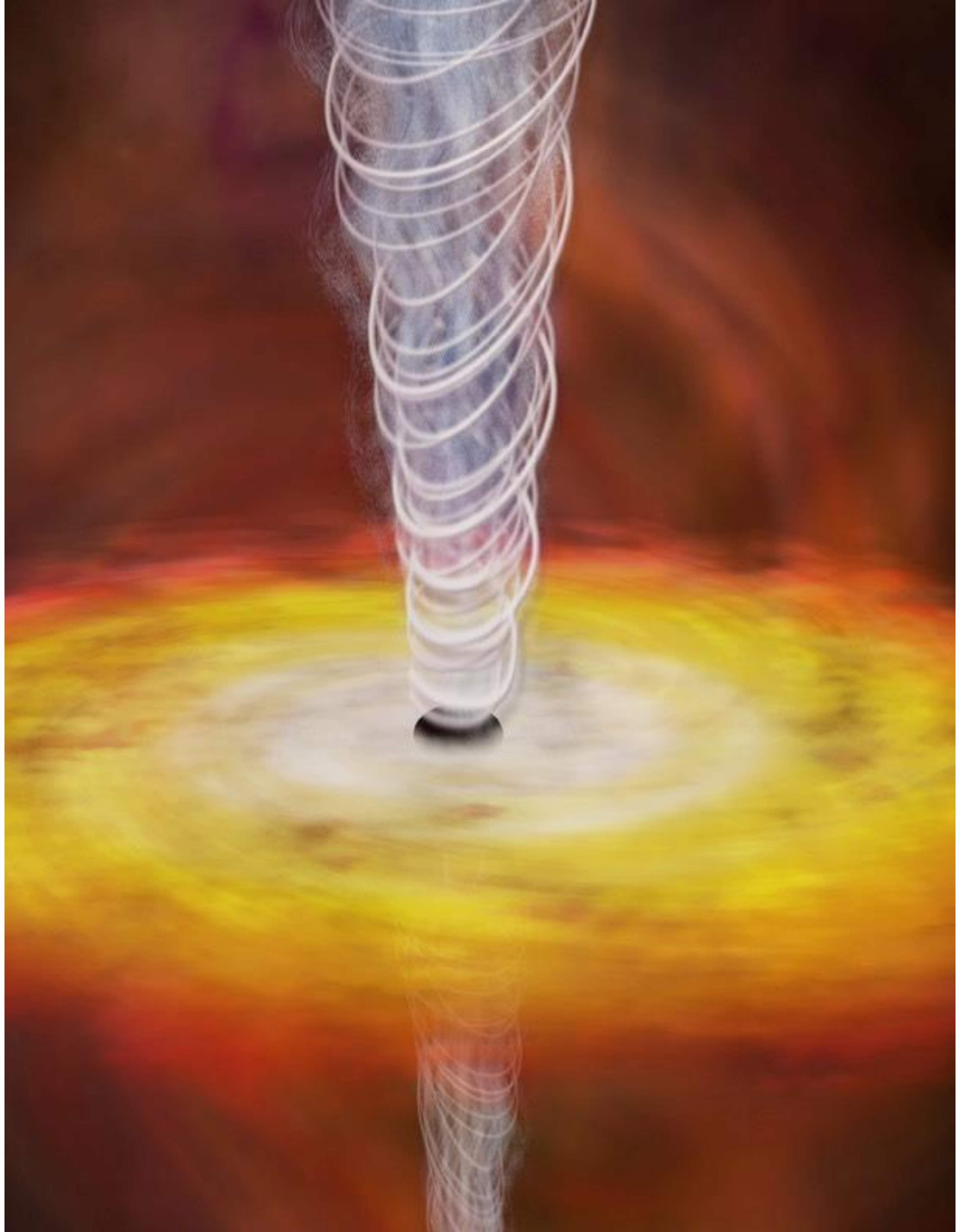
# We can actually see these disks around newborn stars.



Hubble images of proto-planetary disks in the Orion nebula

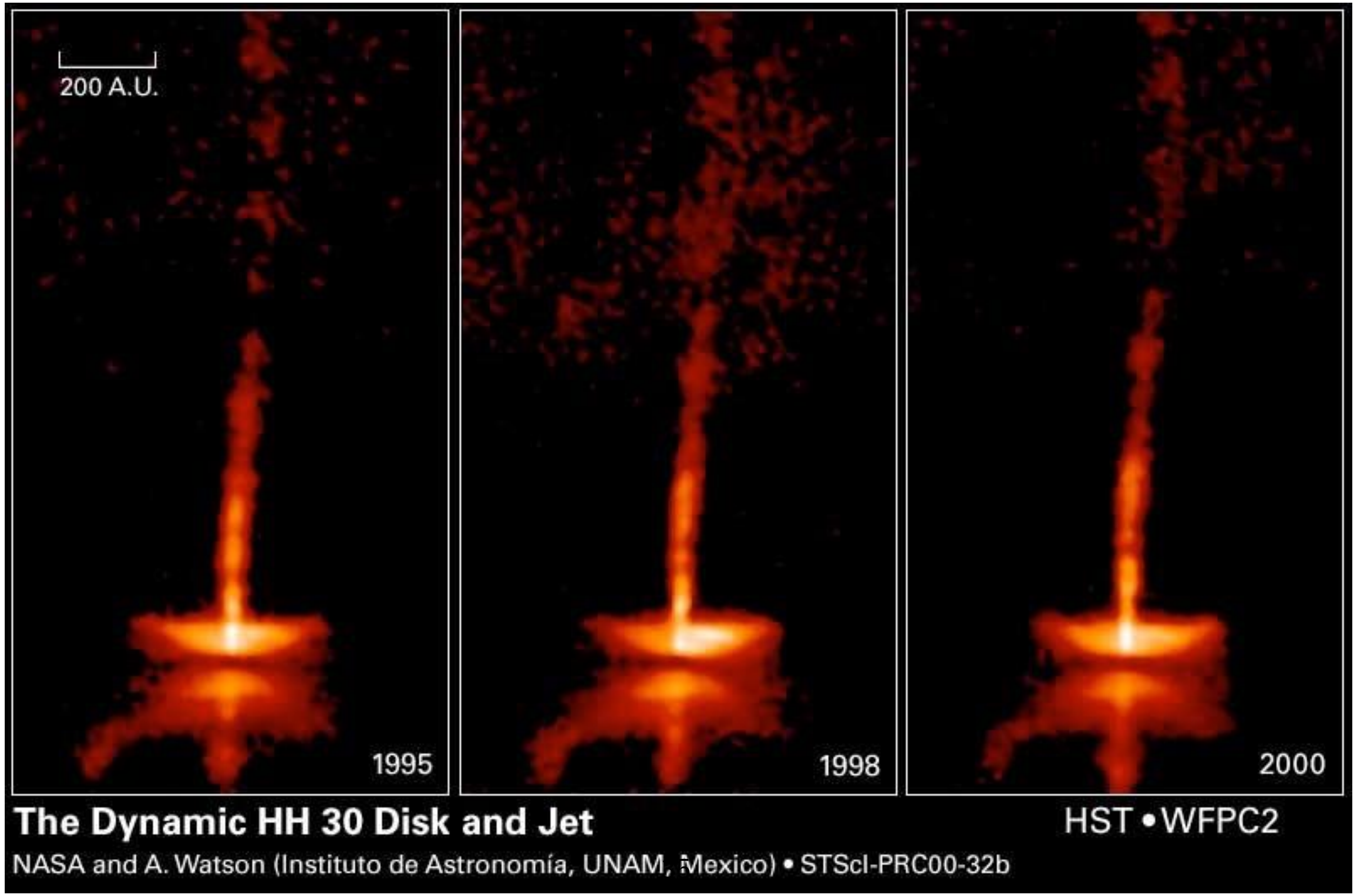
As the central regions get denser, the collapse speeds up, so that the cloud collapses from the inside. As the density increases, the cloud becomes opaque, trapping the heat within the cloud. This then causes both the temperature and pressure to rise rapidly – the collapsing cloud is now a protostar.

The protostar, surrounded by an orbiting disk of gas, is still deeply embedded in the gas envelope, which continues to fall inwards.

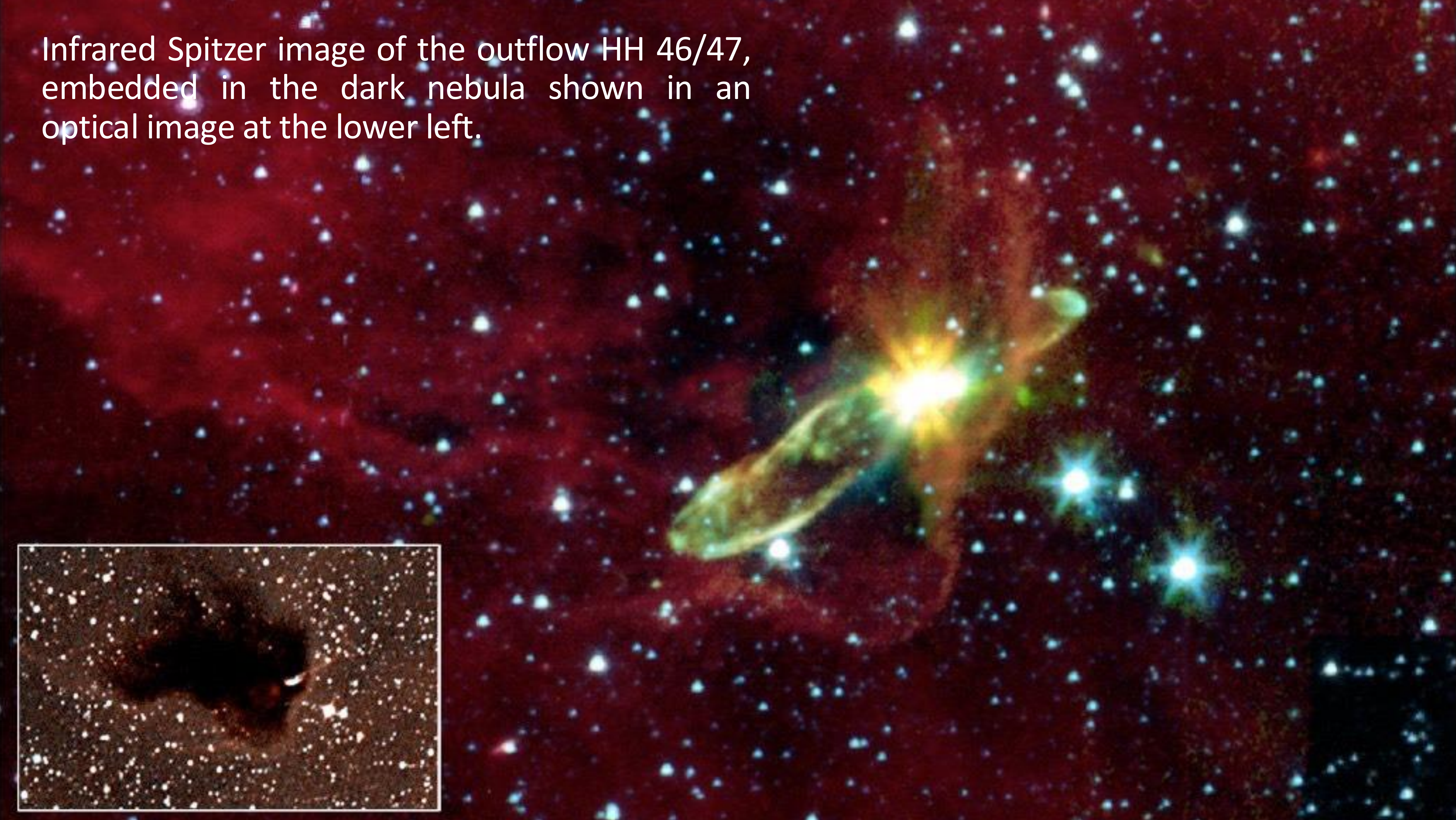


Somehow, infalling material gets tangled with magnetic fields generated by the protostar, and large plumes of gas get ejected in an enormous bipolar outflow. The details of how this happens are still sketchy, but the results are plain to see.

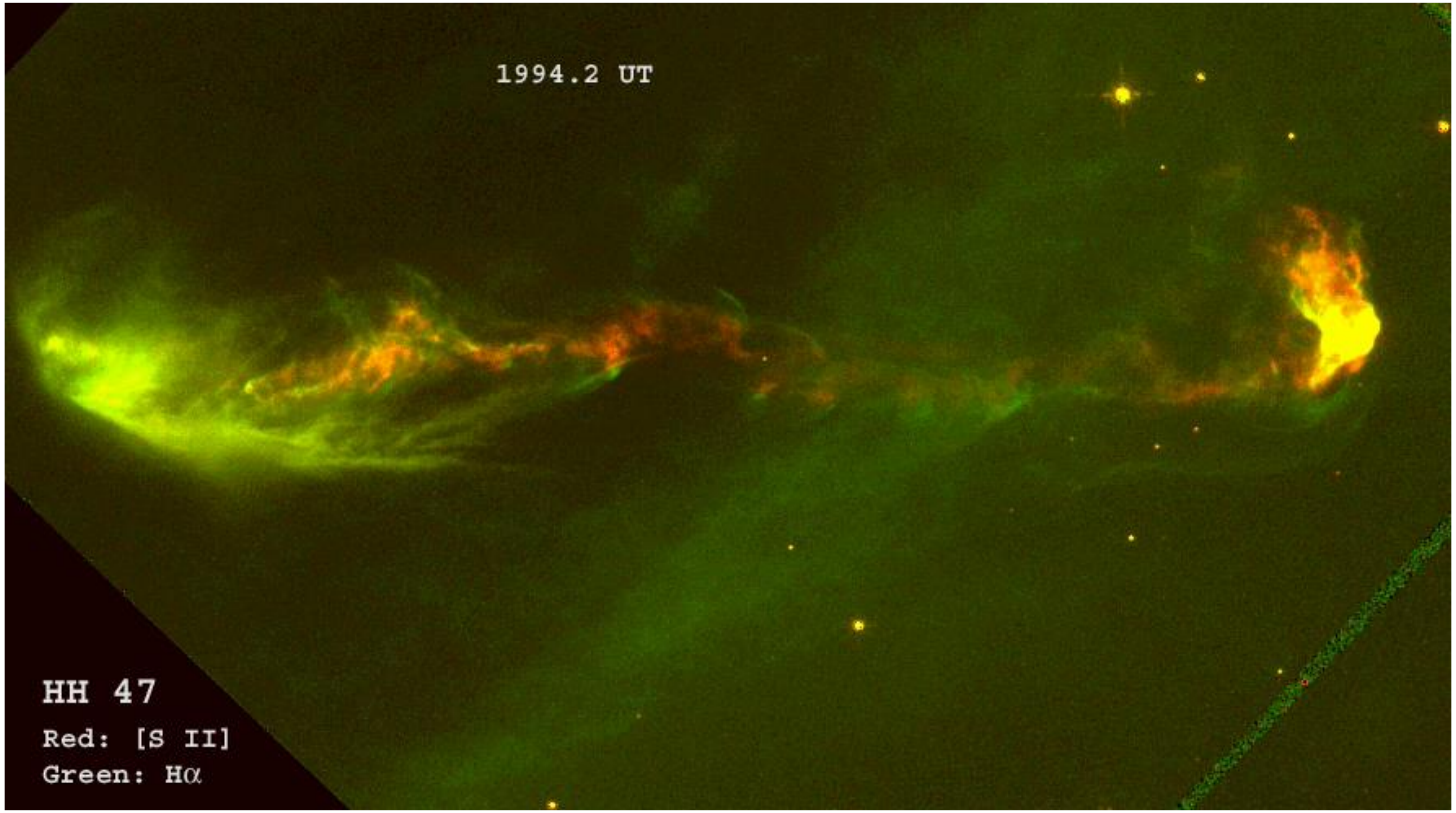
The jets are moving at speeds of 100–1000 km/s and can extend for several light years. When they collide with the interstellar medium, they form bright nebulae known as Herbig-Haro objects.




Spitzer image of the “cosmic tornado” HH 49/50. The star responsible for the jet is just off the top of the picture.



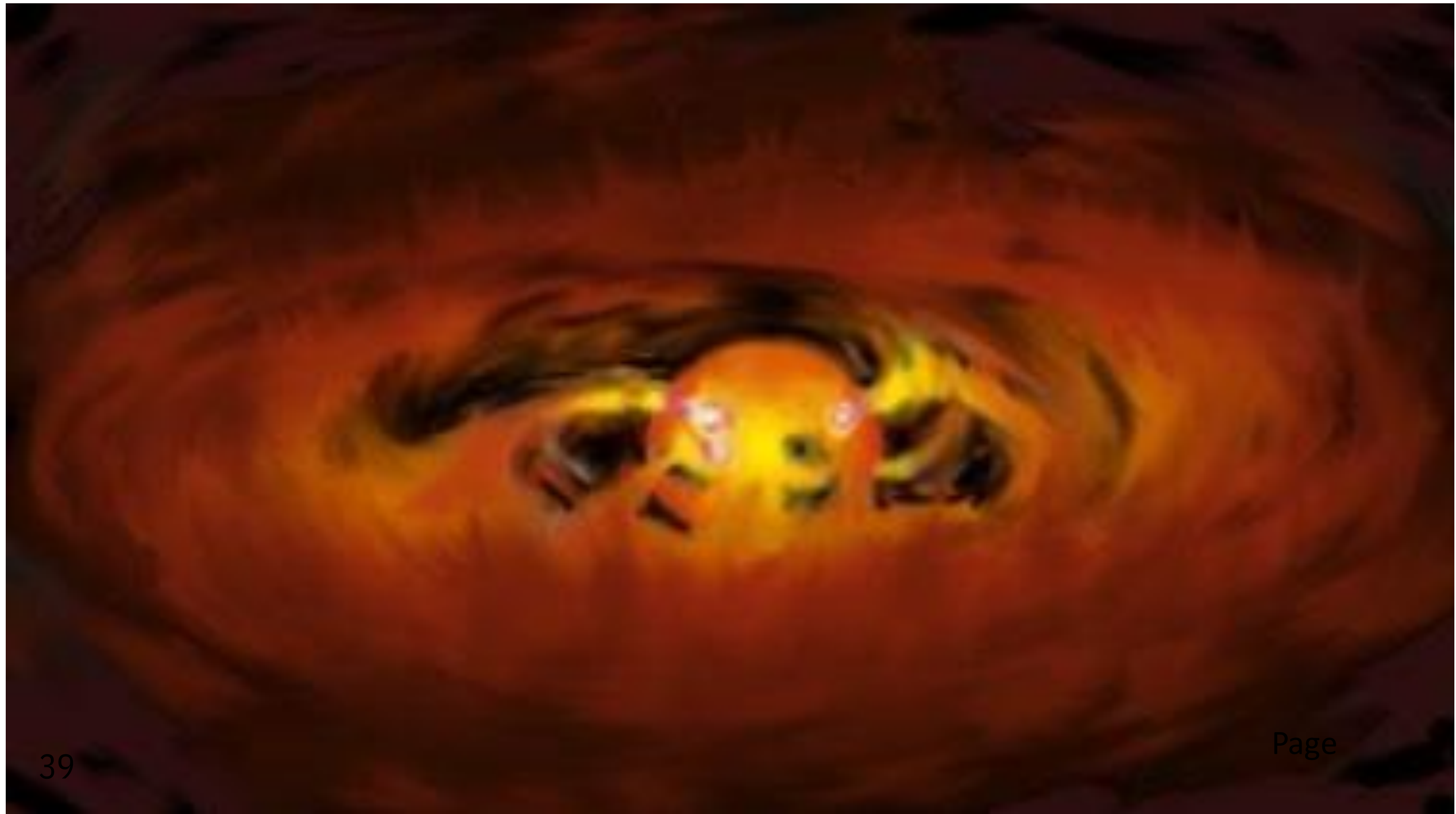
Infrared Spitzer image of the outflow HH 46/47, embedded in the dark nebula shown in an optical image at the lower left.




HST images taken over five years reveal the motion of material in the Herbig-Haro object HH47

More and more material falls onto the disk instead of the star, which continues to contract. When most of the gas has been accreted, we can see the nearly completed star properly for the first time as a T Tauri star.

When the central temperature gets high enough to start fusing hydrogen into helium, the collapse is halted and the mature main-sequence star has been born.



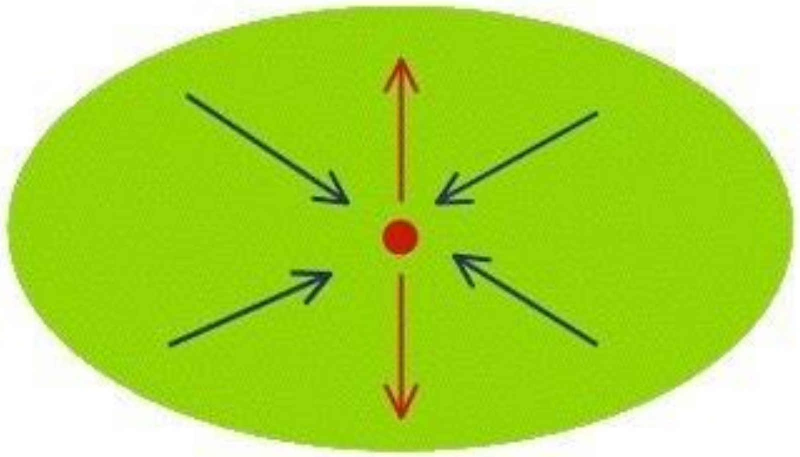
Artist's impression of a T Tauri star, still accreting from its dense disk of dust and gas.

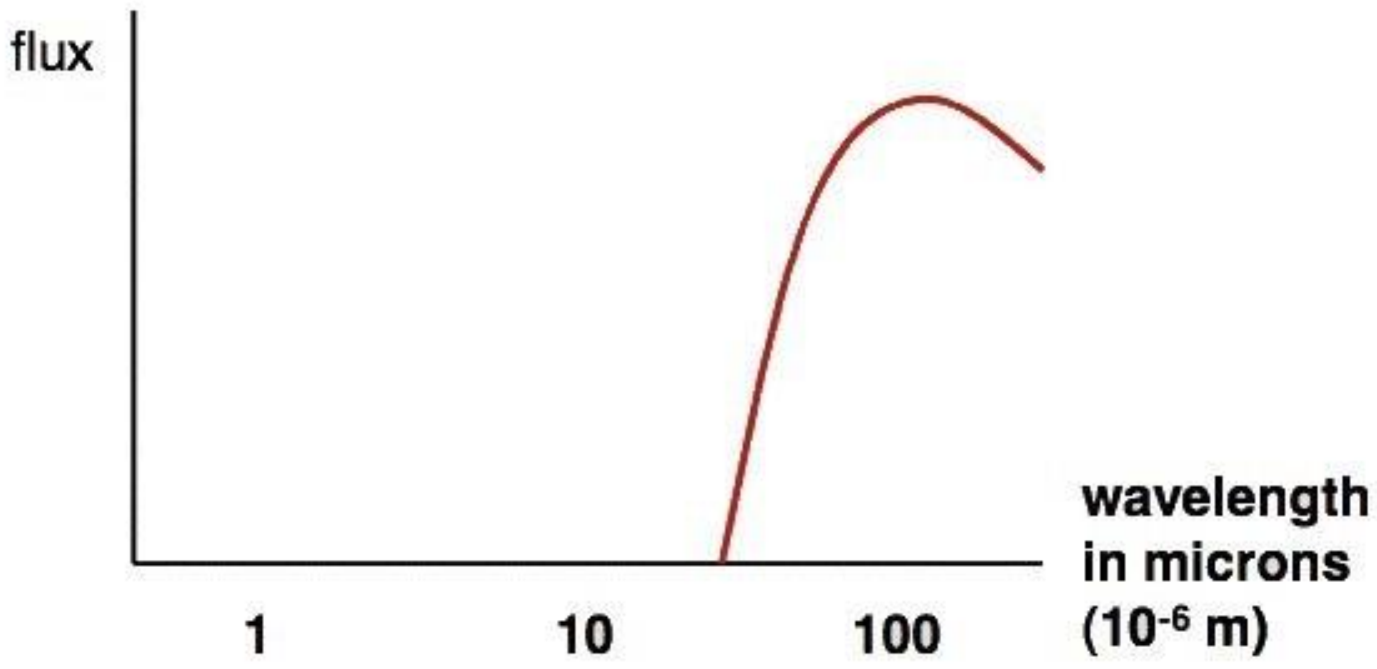
The young star RY Tau, emerging from its birth cloud of dust and gas. The region shown is about 2/3 of a light year across.

T Tauri is the orange star at the centre of this image.

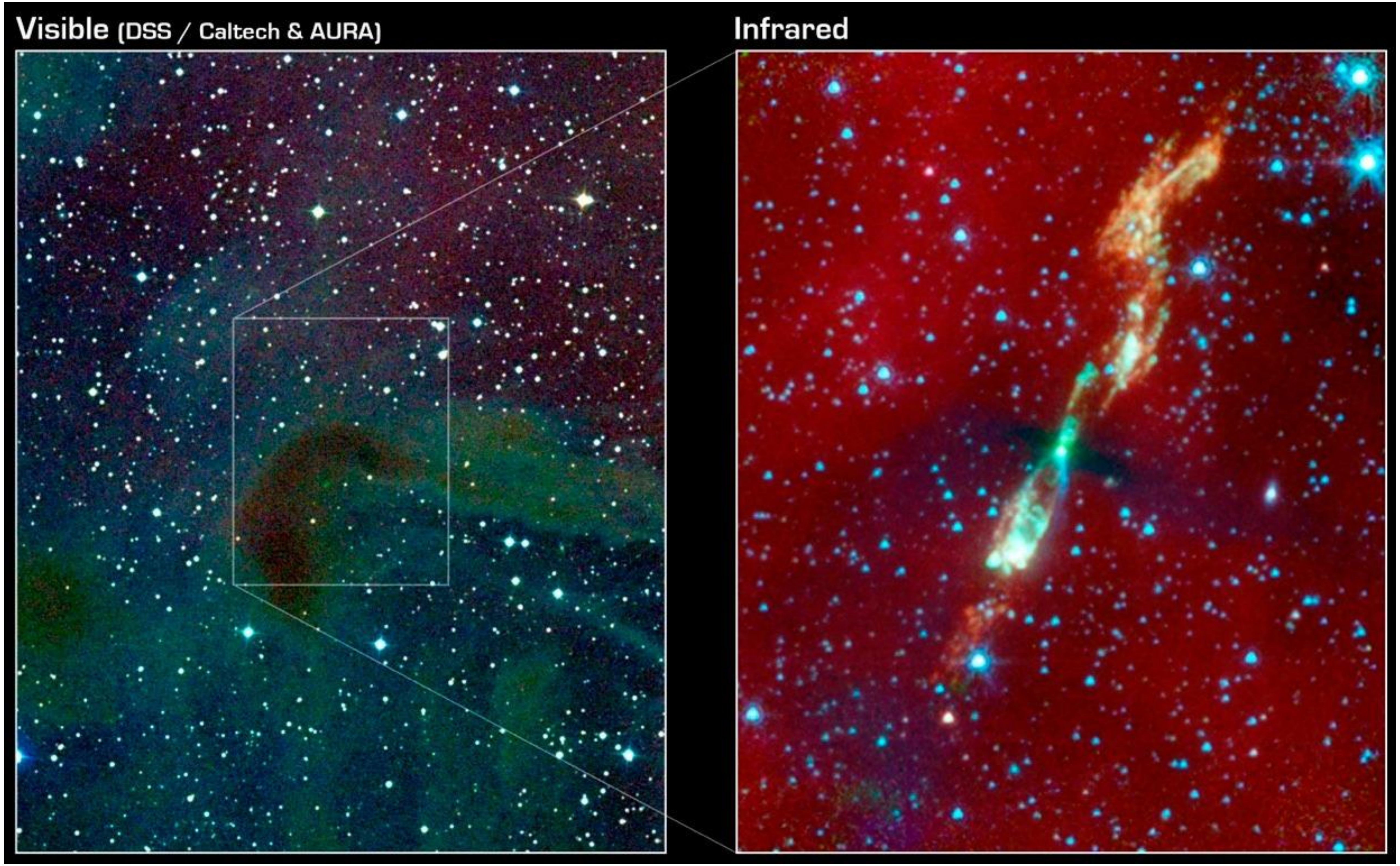
We observe several different types of young stellar objects (YSO), which represent different stages in the collapse.

- Class 0 sources have no emission in the optical or infrared. They are still deeply embedded in gas and dust, and are very cool – not much warmer than the surrounding cloud. Outflows suggest a protostar is forming.



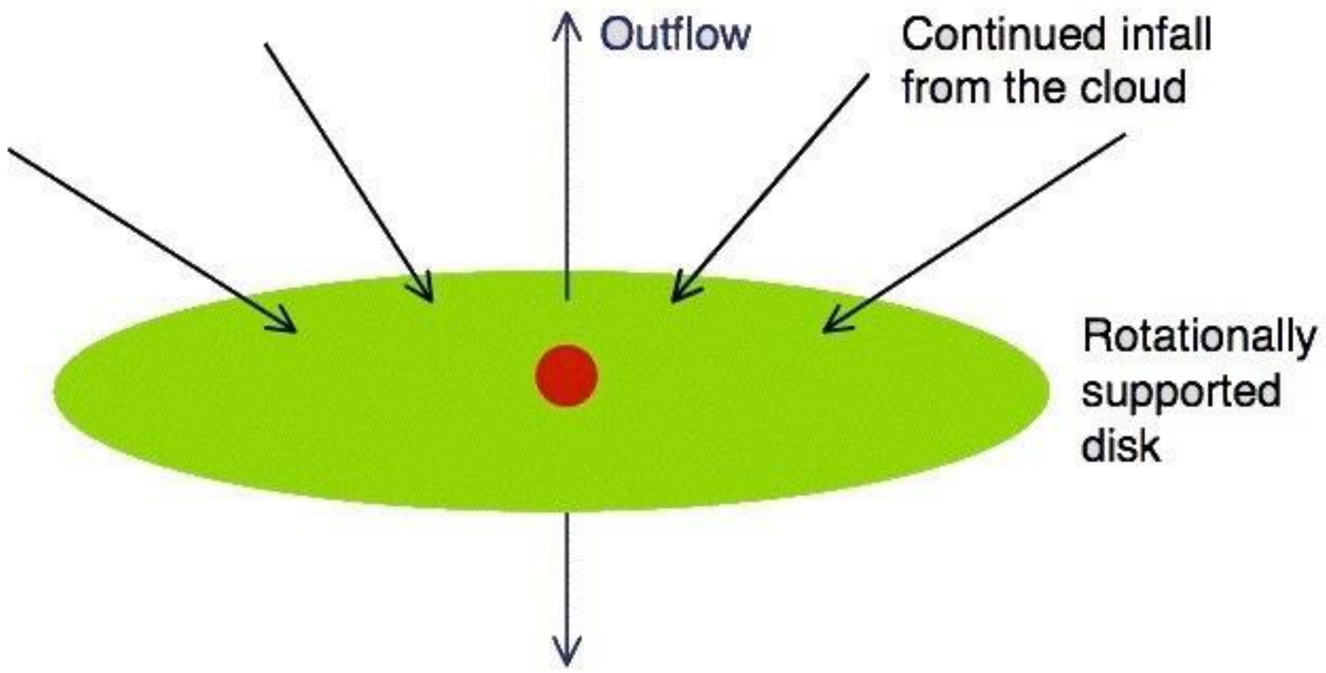


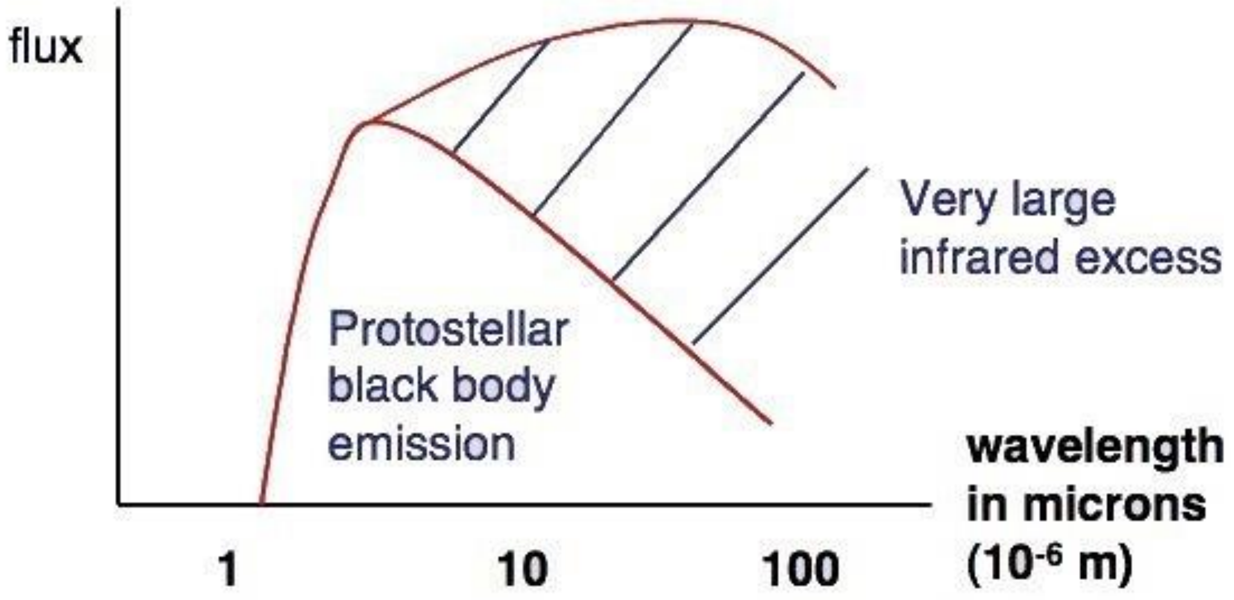

optical IR sub-mm




The Class 0 protostar L1157, imaged by Spitzer. The protostar is hidden by the flattened envelope of dust, while giant jets stream outward.

•Class I sources are much brighter in the infrared, but still invisible at optical wavelengths. We still can't see the star itself, but enough dust has cleared away to see the hot gas and dust near the star.

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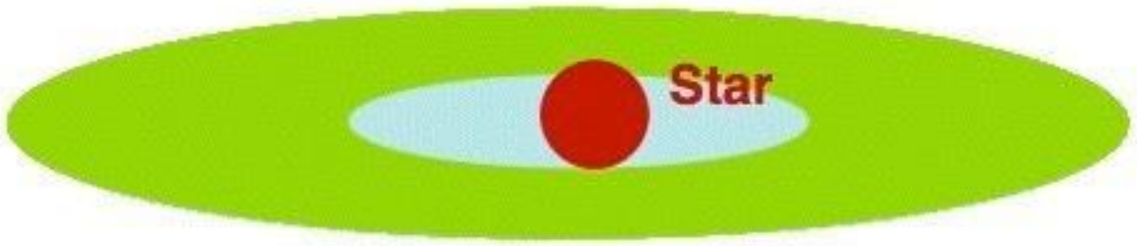
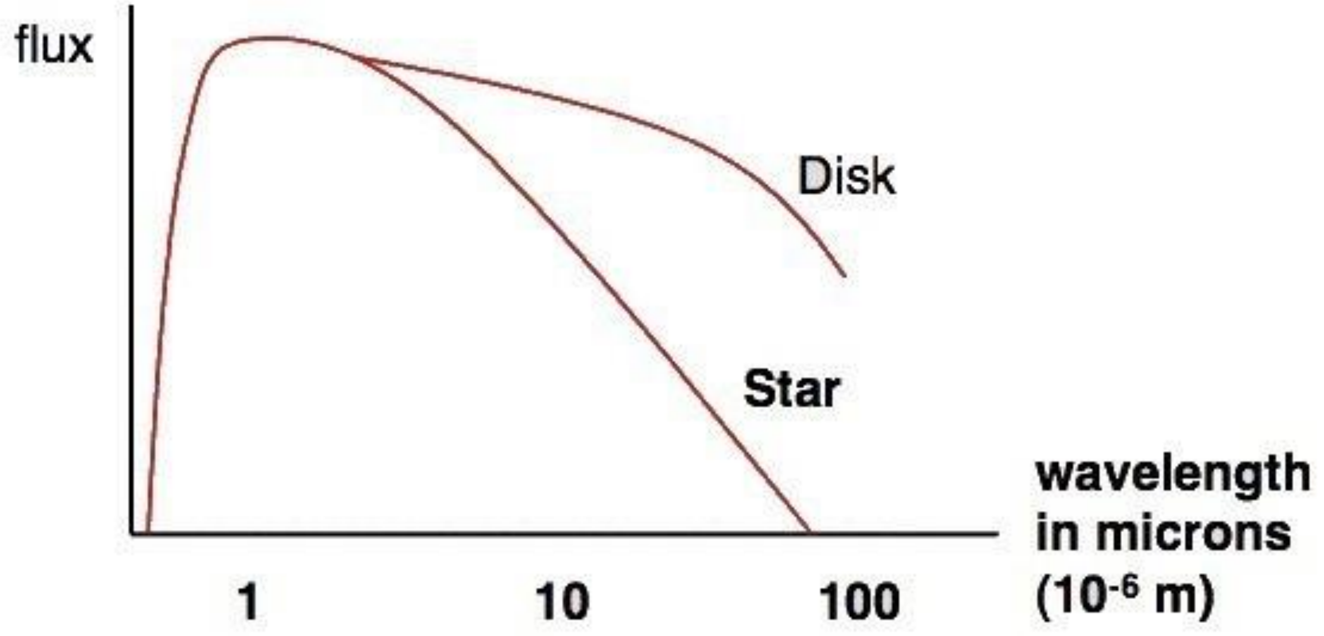
•Class II sources are finally visible at optical wavelengths. The star has emerged from its birth material; most of the collapsing cloud has settled on to the star or its disk. From most angles we can see the star directly. These are the T Tauri stars.

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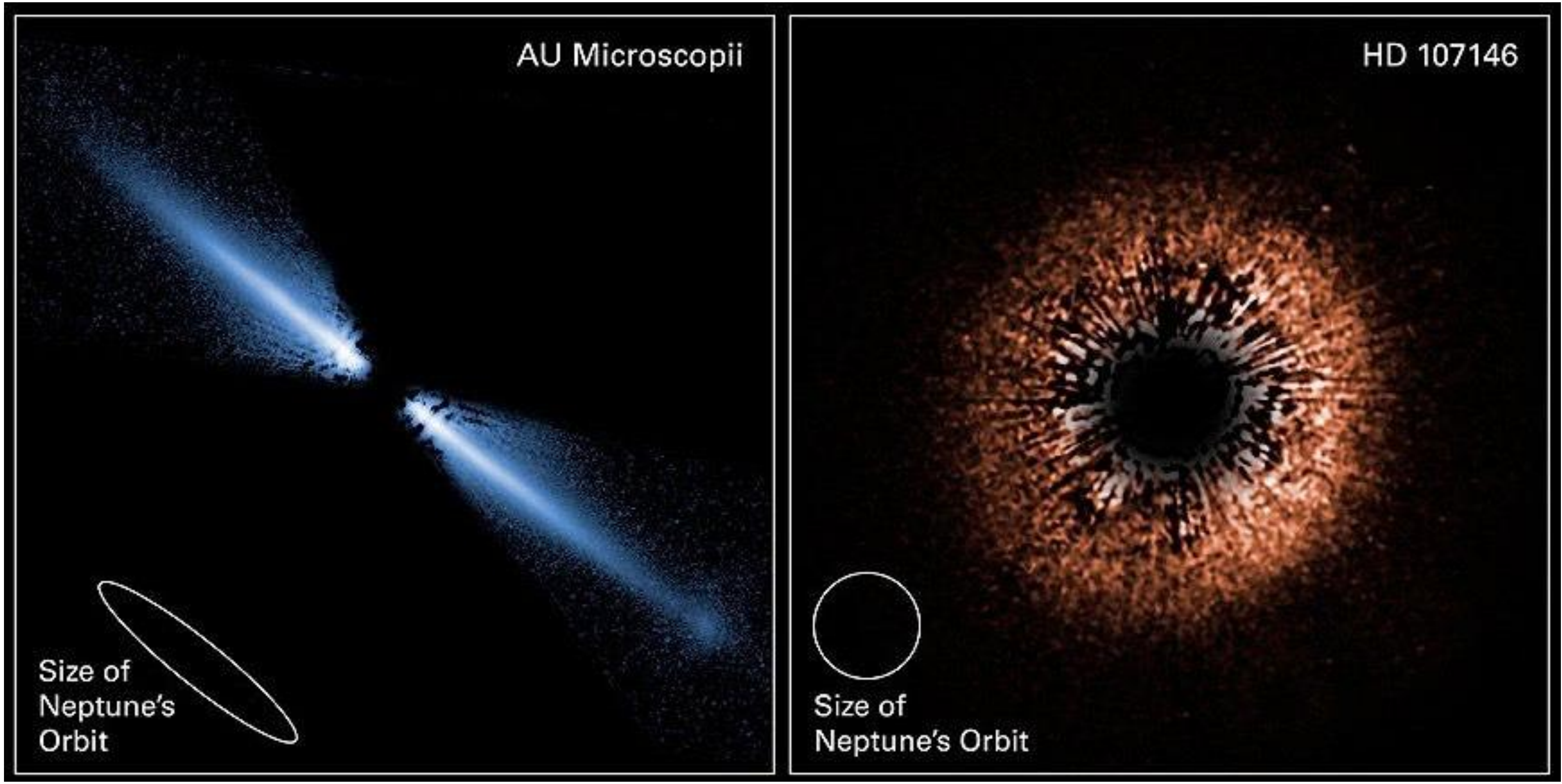
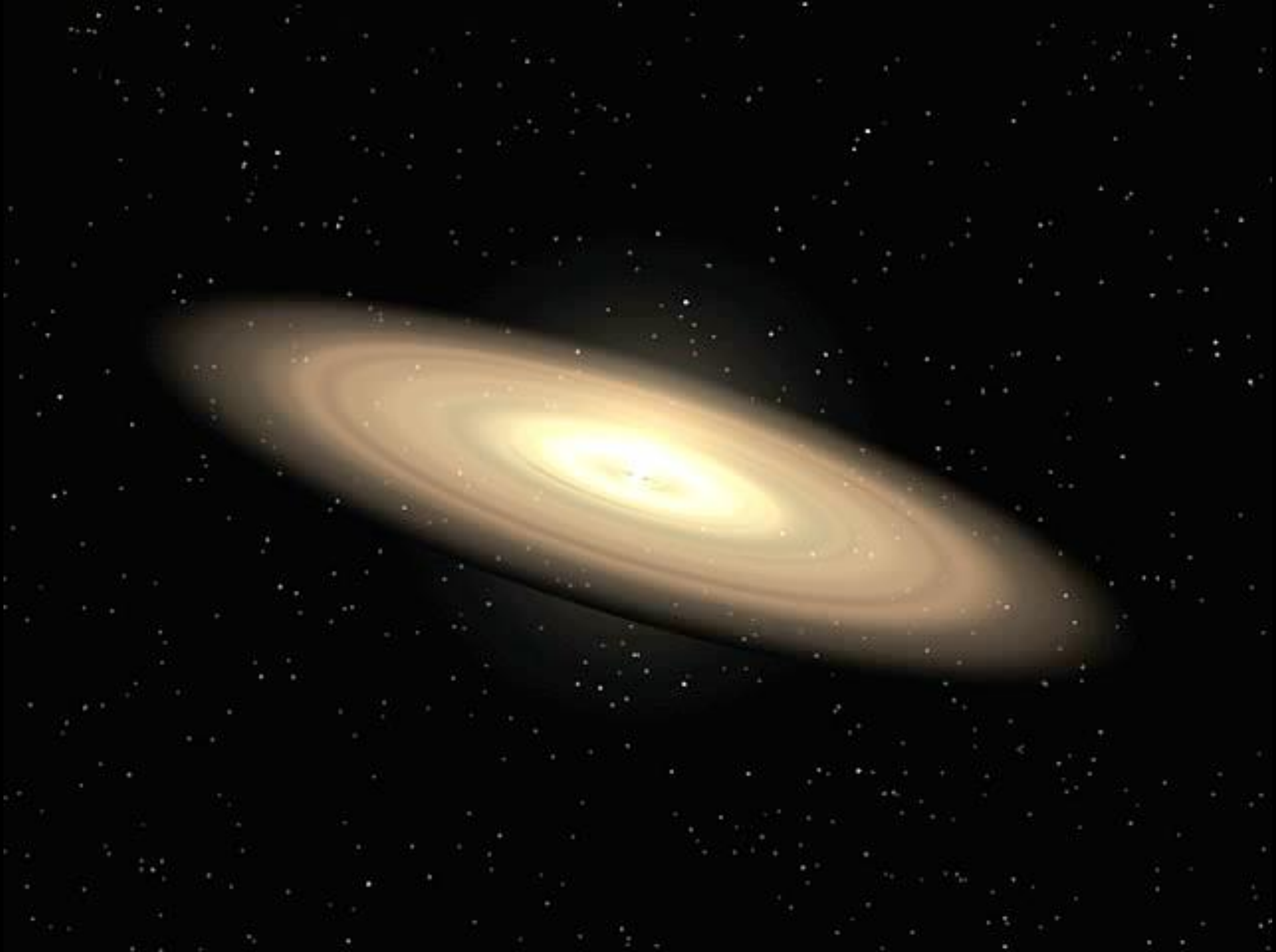
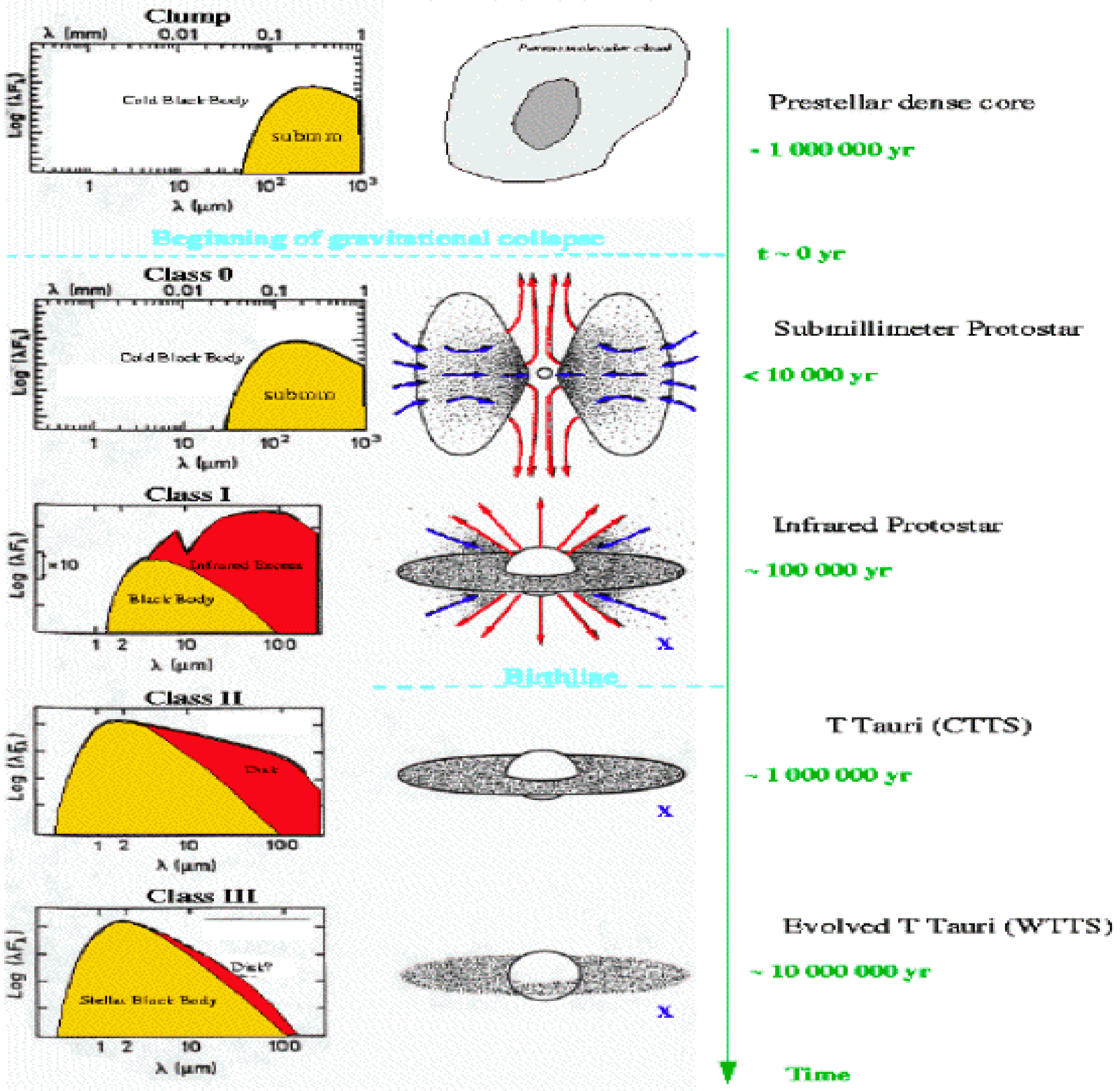
As T Tauri stars age, their disks disappear. The disk material has either fed onto the star, or coagulated into larger bodies i.e. begun to form the building blocks for planets.

HST images of debris disks around two nearby stars






Clump
λ (mm)
0.01
0.1
1
Log (λF_λ)
Cold Black Body
submm
1
10
10²
10³
λ (µm)
Prestellar dense core
~ 1 000 000 yr
t ~ 0 yr
Class 0
Cold Black Body
submm
Submillimeter Protostar
< 10 000 yr
Class I
Infrared Excess
Black Body
×10
2
100
Infrared Protostar
~ 100 000 yr
X
Class II
Disk
T Tauri (CTTS)
~ 1 000 000 yr
Class III
Disk?
Stellar Black Body
Evolved T Tauri (WTTS)
~ 10 000 000 yr
Time

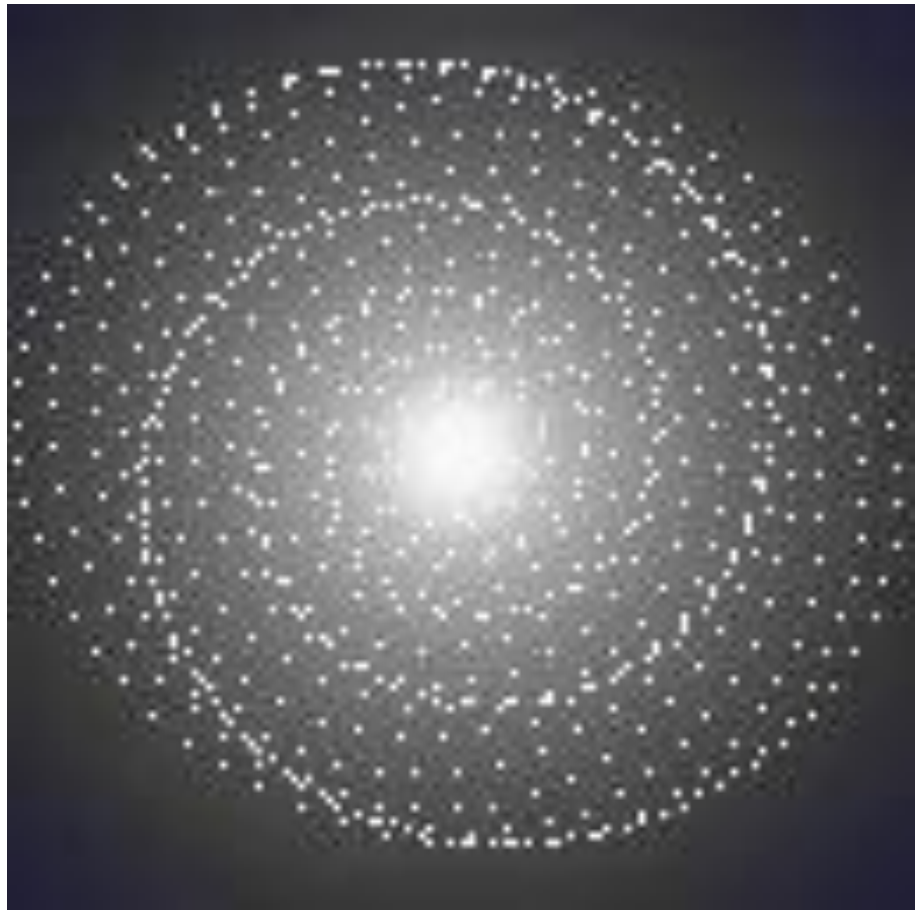
# Why do stars form?

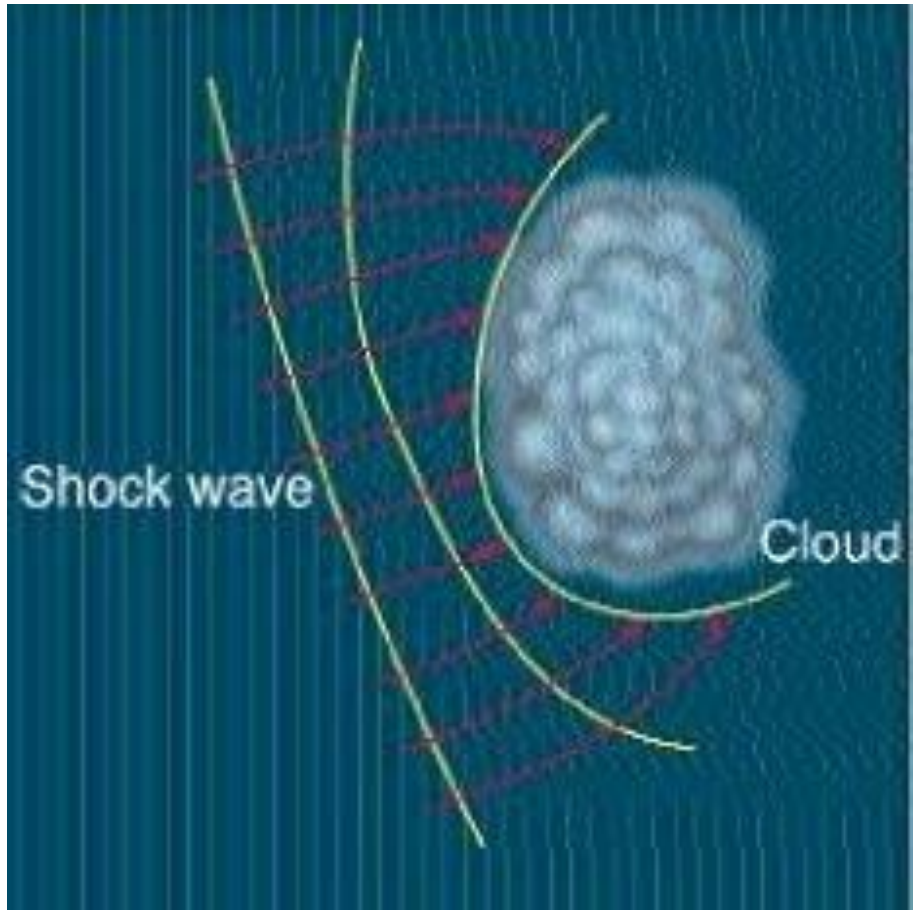
One important question is: does a cloud collapse spontaneously to form stars, or does it require a trigger?

Hot stars, which are the youngest stars, are associated with the arms of spiral galaxies. Yet the gas can't be rotating with the arms.

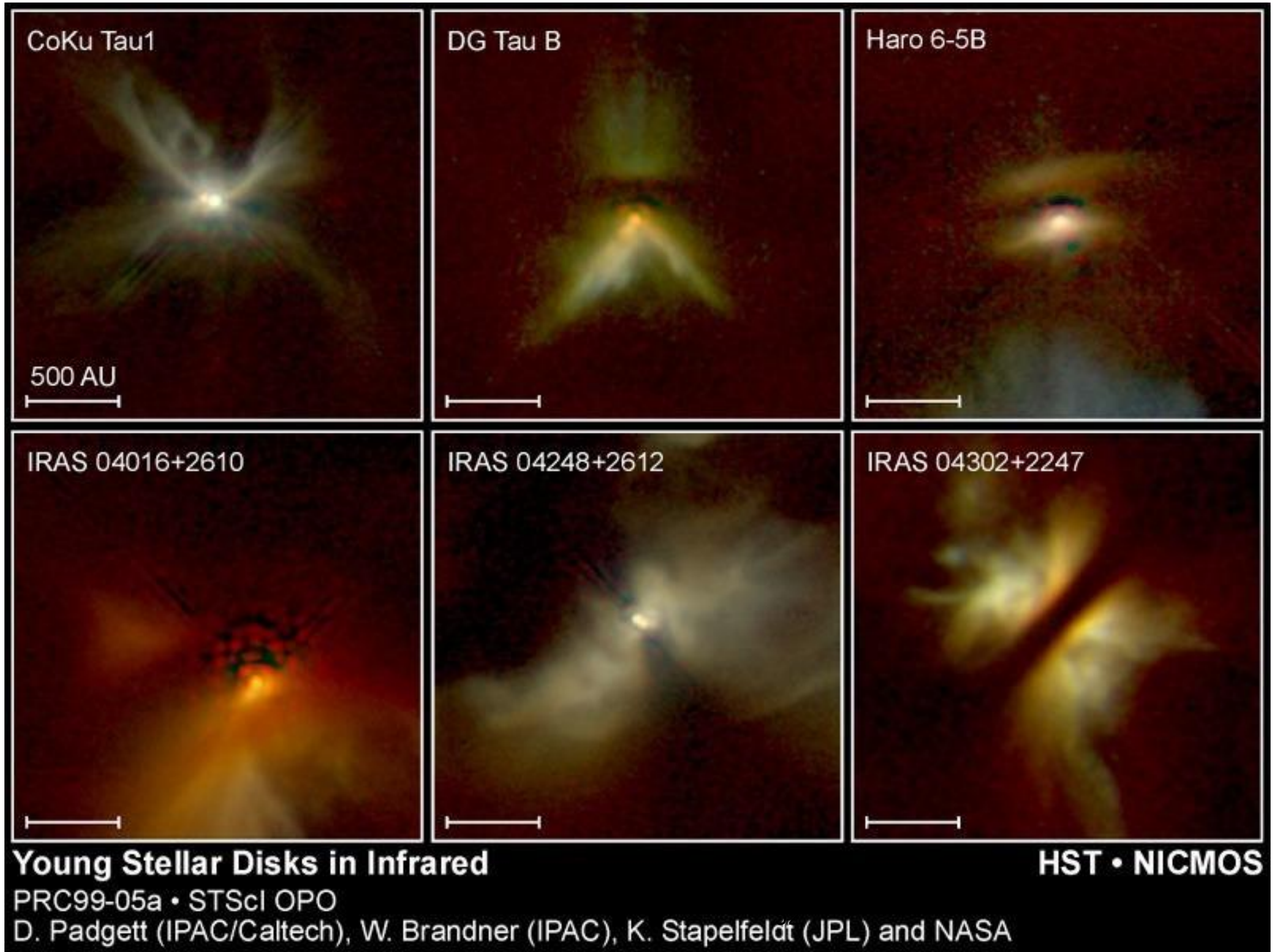
Perhaps the collapse of the clouds and the birth of the stars is triggered by the passage of the spiral density wave through the cloud.

Or perhaps nearby supernova explosions, or winds from massive stars, are enough to trigger the collapse of a cloud.





Where do young stars like our Sun form? One of the best-studied regions of star formation is the Taurus-Auriga region, only 140 pc distant and forming lots of low-mass stars.



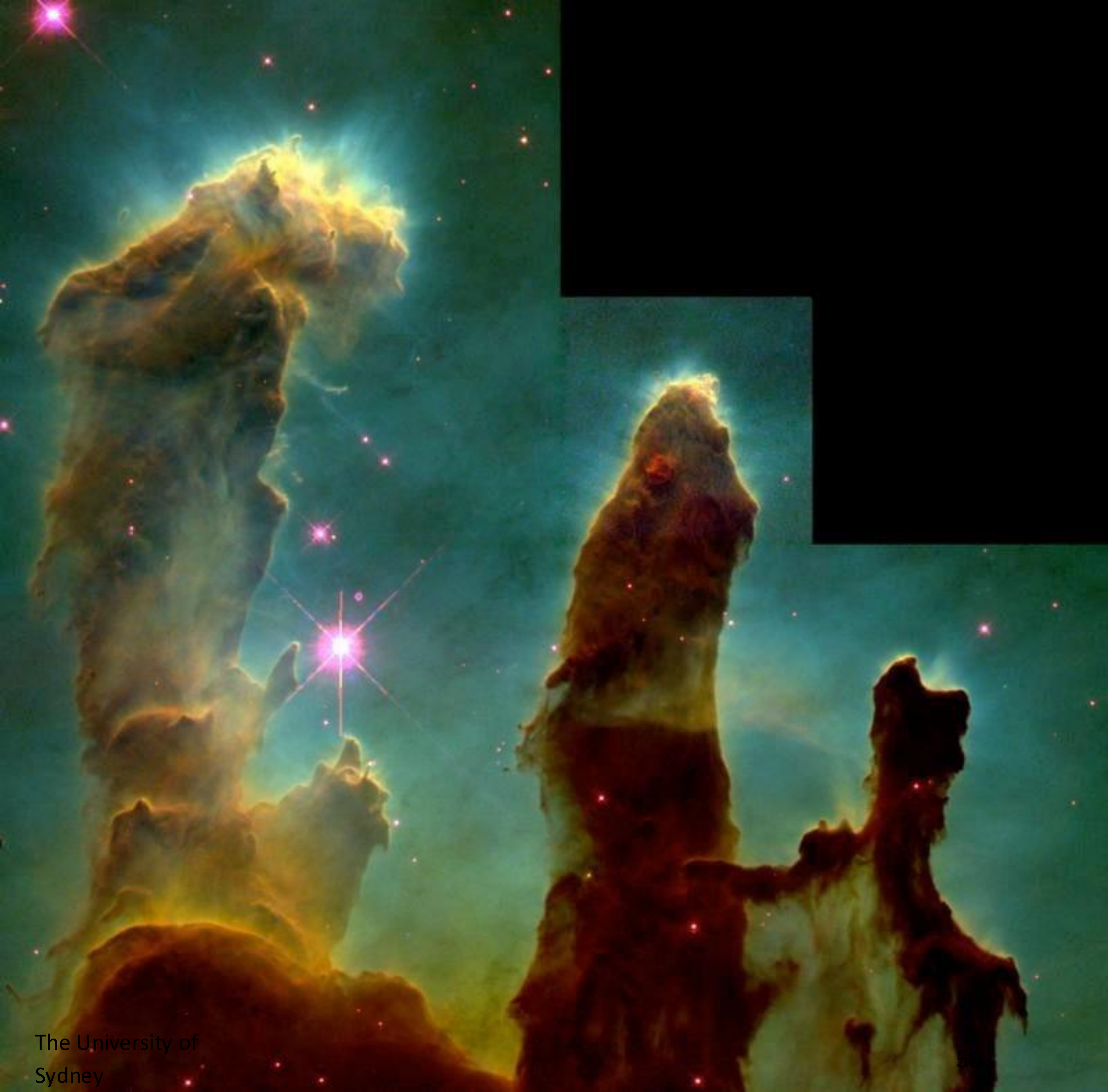

HST images of disks around young stars in Taurus.

The Orion star-forming region, on the other hand, appears to be forming both low- and high-mass stars.

The conditions for a young star forming in Orion must be very different for a star forming in the relative quiet of Taurus-Auriga.

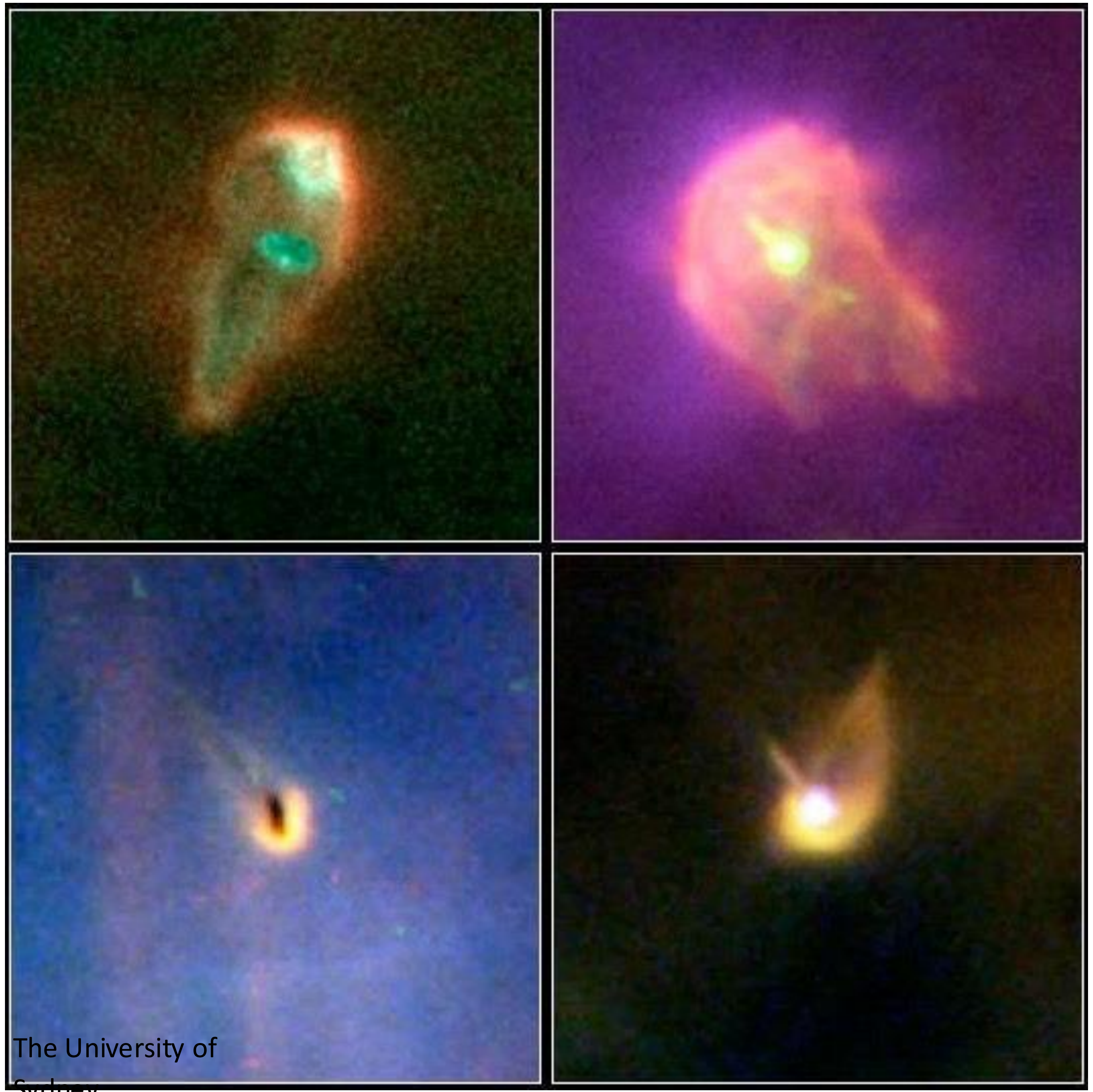
As soon as massive stars form, you get intense radiation, powerful winds, and supernova explosions. The hot stars reshape their own environment.

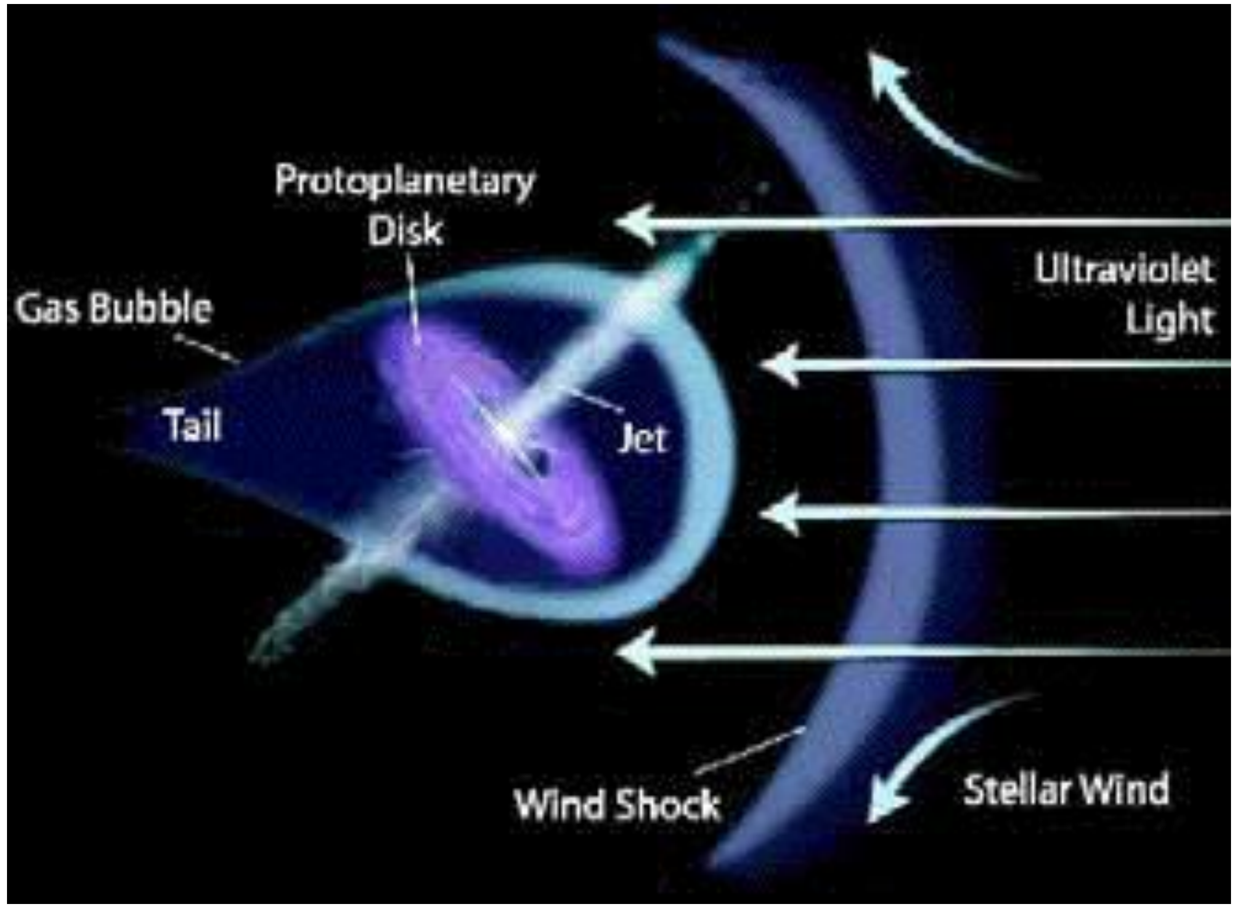
The Great Nebula in Orion, M42



This image of the Eagle Nebula shows even more dramatic evidence of the effect that massive stars have on their environment.

# HST images of disks around young stars show that they look very different to their counterparts in Taurus-Auriga.

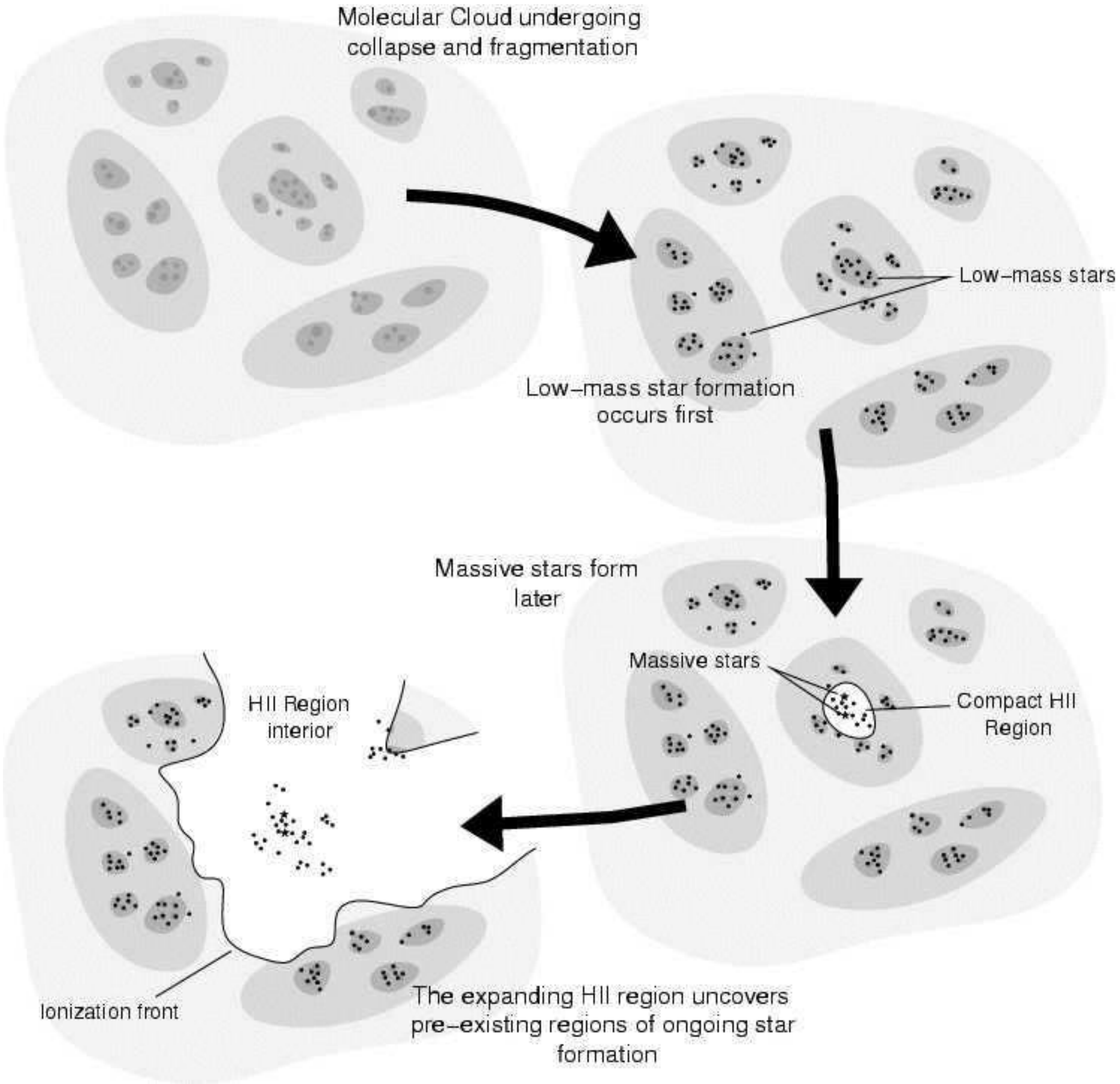


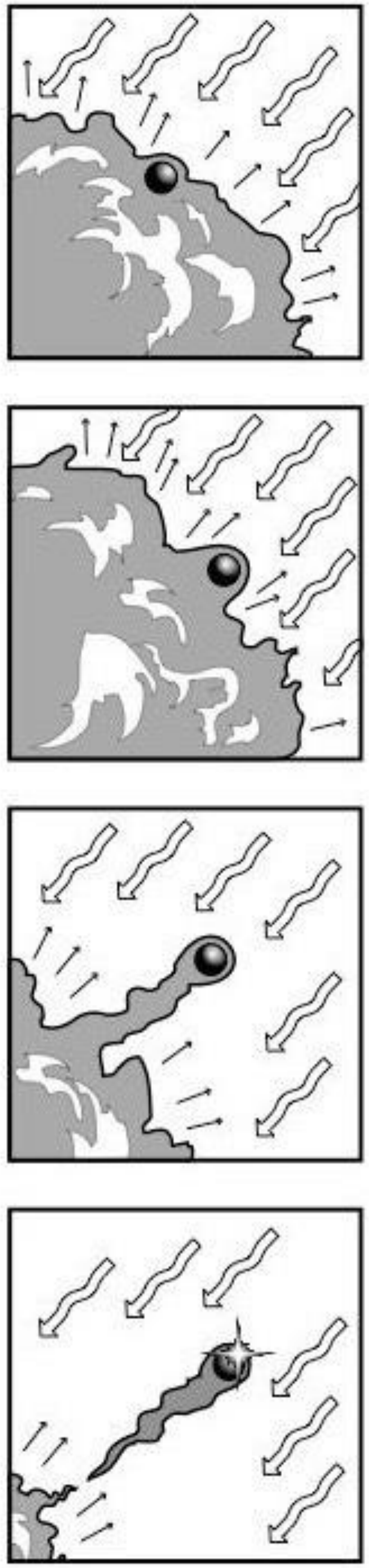



HST images show dust disks around embryonic stars in the Orion Nebula being "blowtorched" by a blistering flood of ultraviolet radiation from the region's brightest star.

The young stars are in tenuous, low-density regions which have been ionised by hot stars. The gas is much too thin and hot for stars to have formed there.

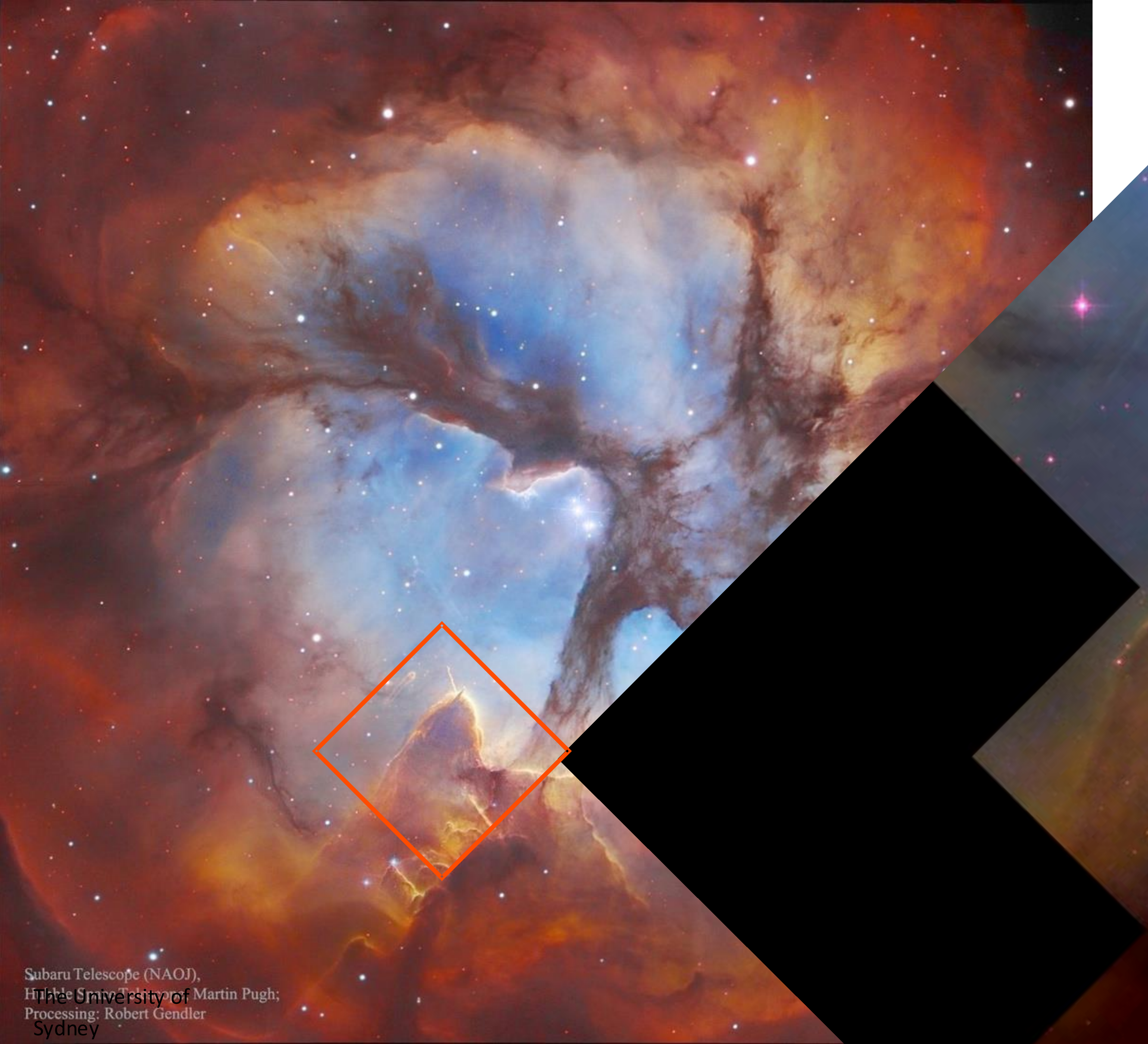
Probably the stars formed in the dense molecular gas around the ionised regions, and were uncovered by photo-evaporation of the dense gas.





A close-up of the end of the pillar shows numerous “EGGs” – evaporating gaseous globules. The denser gas resists evaporation and protects a column of gas behind it, giving a finger-like appearance.

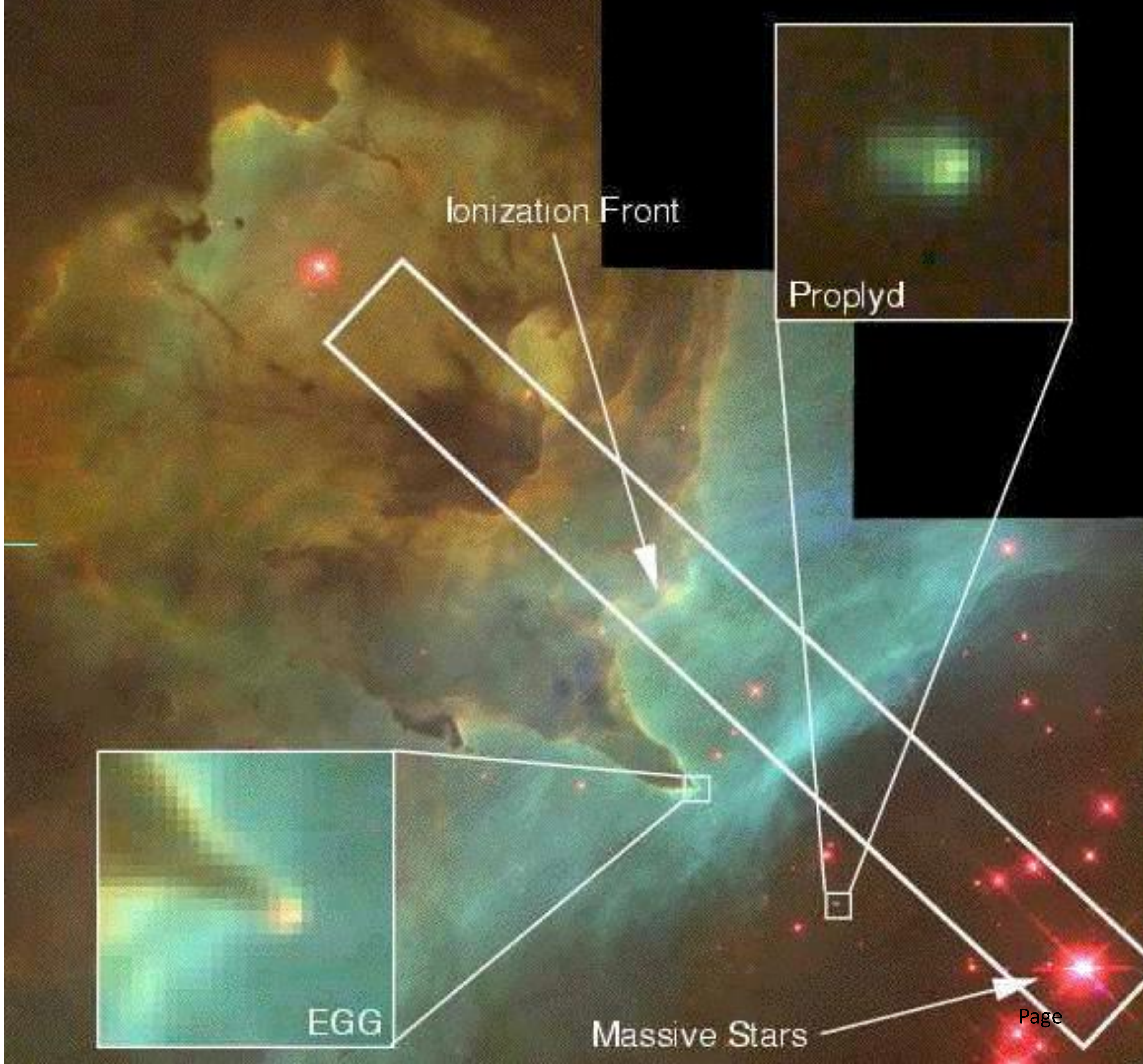
# Trifid nebula




The University of Sydney

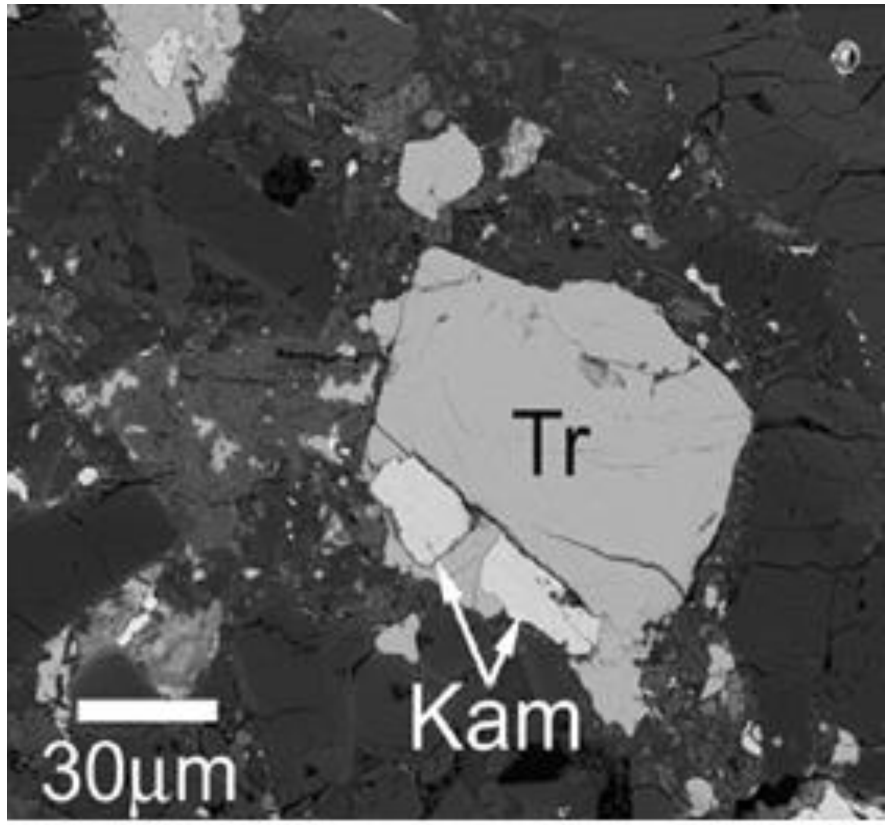
# In the Triffid Nebula, we see more EGGS, including one which appears to be turning into a proplyd.

Here is another region illustrating the same sequence of events: the ionisation front from massive stars erodes the edge of the molecular cloud, uncovering EGGs which then erode to proplyds.




An HST image of the G353.2+0.9 region in NGC 6357.

Evidence that the Sun did indeed form in a region containing massive stars comes from the discovery of the decay products of 60Fe when they were formed. 60Fe is a short-lived (half-life 1.5 million years) isotope, which must have been produced in a supernova explosion. This means that our Sun formed in a region where massive stars were ending their lives.



(Courtesy of S. Tachibana and G. Huss, Arizona State Univ.)

Polished piece of the meteorite Bishunpur. The mineral labelled "Tr" is troilite (FeS), in which the ratio of 60Fe to 56Fe was measured.

**Spitzer** infrared images of Orion show large numbers of low-mass stars and brown dwarfs, invisible in the optical image (left), surrounding the central massive stars of the Trapezium cluster.

# What about binaries?

As we know, most star systems contain at least two stars. Why and how do they form?

The why is easier to explain. It comes down to angular momentum again. Star-forming clumps contain large amounts of angular momentum: much more than can be contained in a single star, even if it is rotating at break-up speed. But stars like the Sun are almost non-rotating, and so contain very little angular momentum.

Where has all the angular momentum gone?

In the case of the Solar System, most of the angular momentum is carried by the orbits of the planets: the spin of the Sun contains only about 1% of the total angular momentum of the Solar System.

Remember that

angular momentum = mass x velocity x distance

so, to have large angular momentum, you need to have either large mass, large velocity or large distance from the centre. The Sun contains 99.9% of the mass of the Solar System, but the larger planets are at such large distances that they contain most of the angular momentum.

For interest, here is the rough distribution of angular momentum in the Solar System:

Sun 3%
Mercury 0.003%

Venus 0.05%
Earth 0.1%

Mars 0.01%
Jupiter 60%

Saturn 24%
Uranus 5%

Neptune 8%
Pluto 0.001%

Similarly, in binary systems most of the angular momentum is carried by the orbits of the stars.

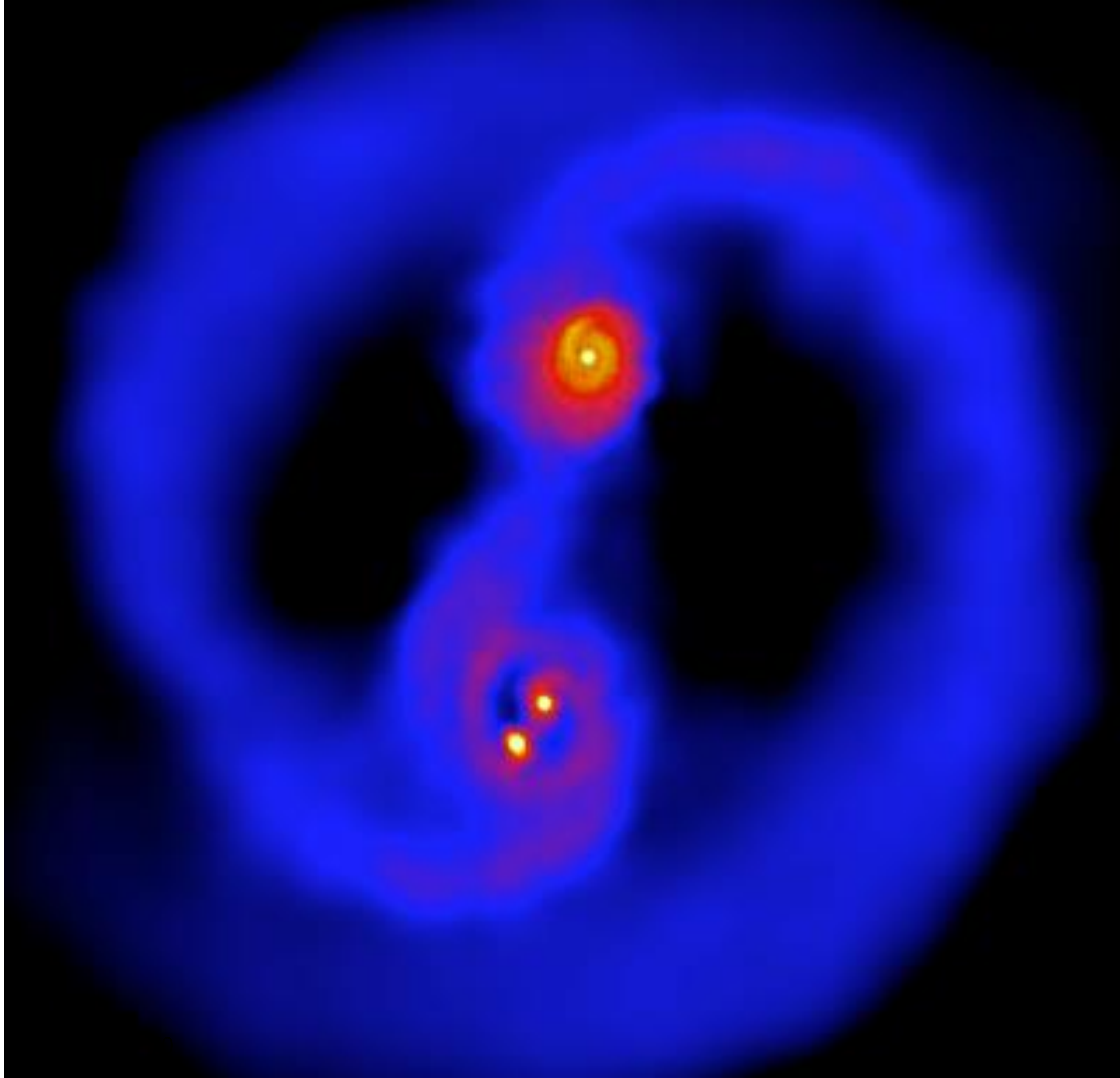
So, forming either a binary companion or a planetary system is the obvious solution to the angular momentum problem. This may imply that
binary companions and/or planetary systems are the norm, not the exception.

But how do you form a binary companion?

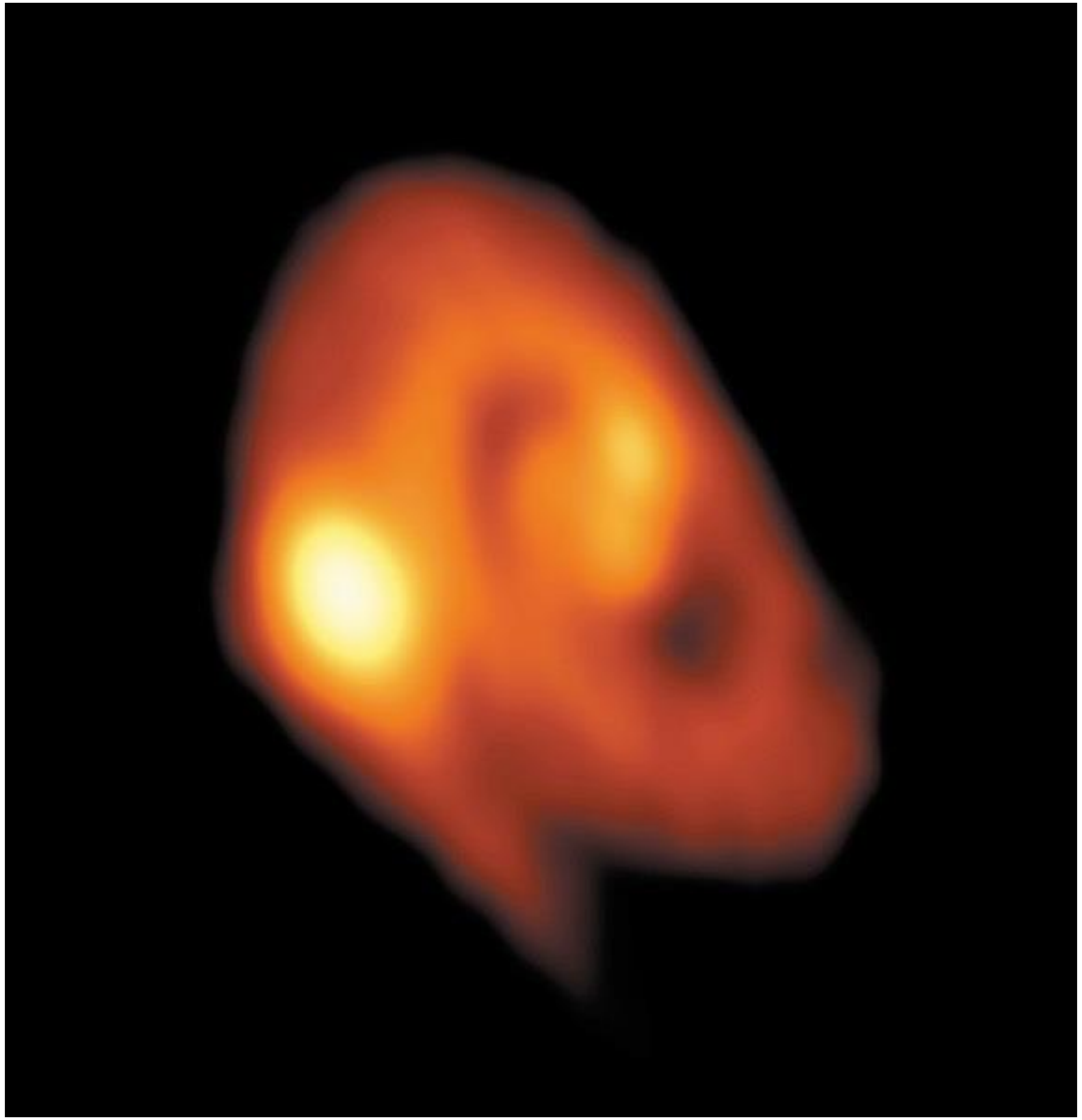
This is still not understood. It is suspected that there are two very different mechanisms:

- wide binaries form by fragmentation:

the collapsing cloud splits into separate pieces, each of which then collapses to form  a star



Simulation of the collapse and fragmentation of a molecular cloud, forming a triple system. (From Bate, Bonnet & Price 1 995)

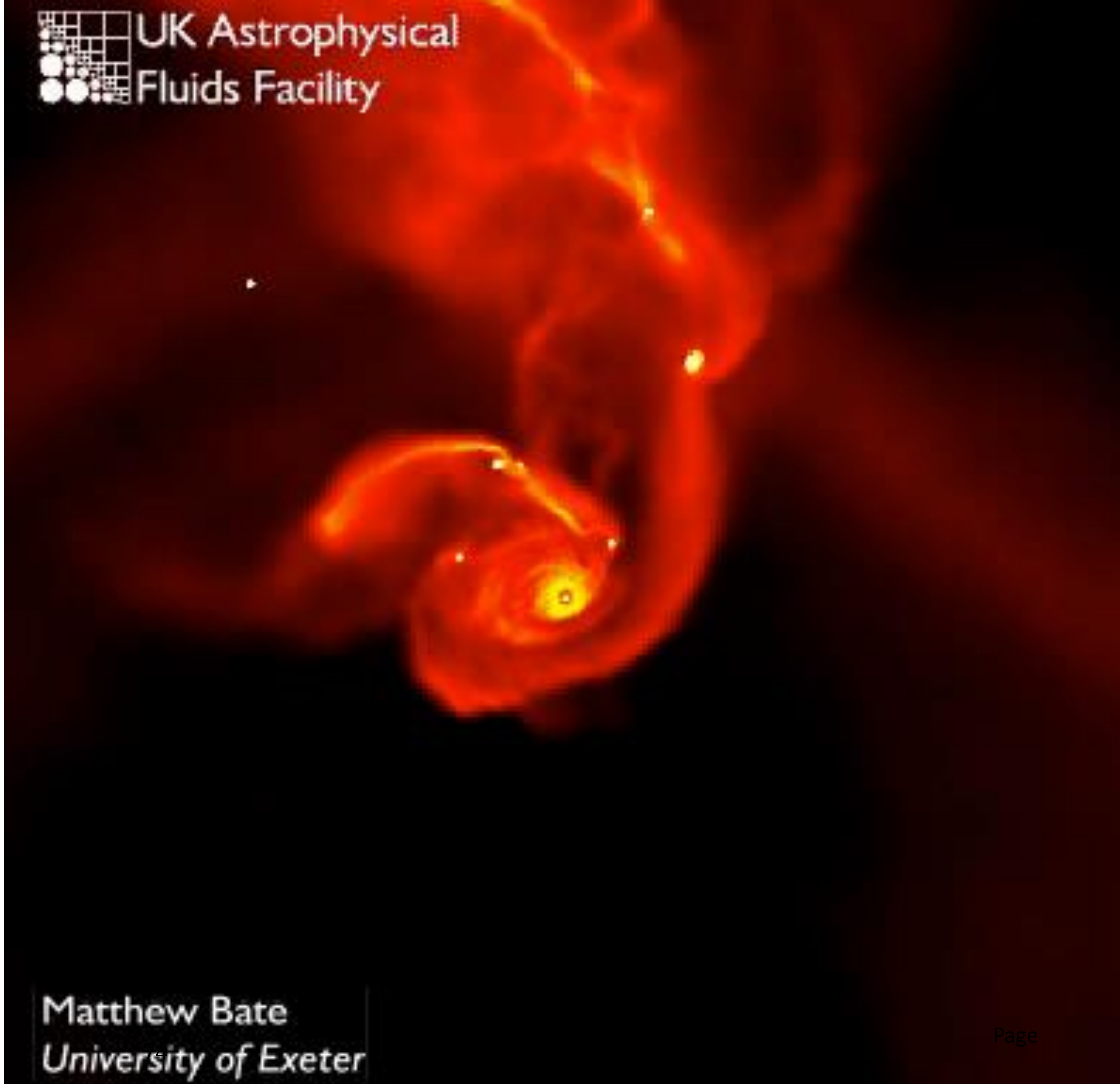


ALMA radio image of L1448 IRS3B, a star-forming disk harbouring three protostars. The central two protostars are separated by 61 AU; following a spiral arm outward, the third member resides at a distance of 183 AU from the central- most protostar.

- close binaries form by fission: the forming star elongates, then splits into two

The following pictures of a rotating water drop in zero-gravity (on the Space Shuttle) shows it fissioning into two drops.

However, computer models can’t yet get stars to form binaries like this.
Newer work suggests that stars form together in subgroups, and within these groups binary and multiple systems are continually formed and disrupted. If this is true, then stable disks like the one which we think formed our own Solar System may not be very common, as they are usually disturbed by a companion star during formation.
Or perhaps our own solar system was also disturbed by  a binary companion (the 8 degrees tilt between the ecliptic and the Sun’s equator?).




A simulation of the collapse of a 50 solar mass gas cloud, 1 light-year across, eventually forming a cluster of about 50 stars (Bate et al 2002)

And of course, some time during this process the planets must form, before the gas is swept away by the newborn star. In our solar system, the gas would have dispersed about 3–10 million years after the Sun became a T Tauri star.