Lives of the Stars Lecture 5: Star birth

Presented by
Dr Helen Johnston
School of Physics

Spring 2016

THE UNIVERSITY OF SYDNEY

Rooftop night-viewing evening

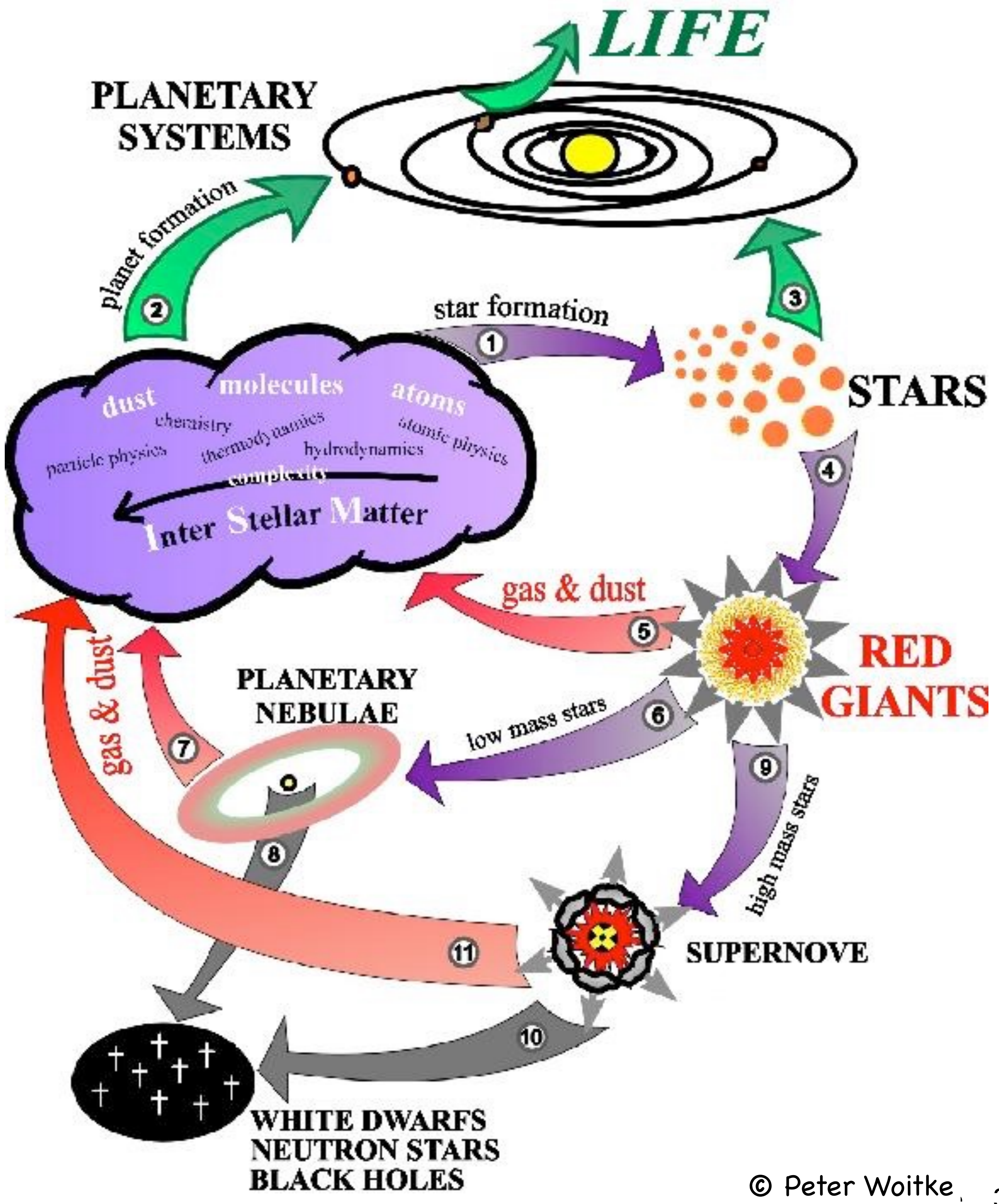
We will have our star-viewing evening from our rooftop observatory

NEXT week 16 November.

Weather permitting, we will spend the first hour talking about binary stars, then go up to the roof to look through the telescope.

If the weather is *not* good, we will revert to the original plan of talking about stellar evolution, and postpone the viewing for one more week.

The cycle of matter



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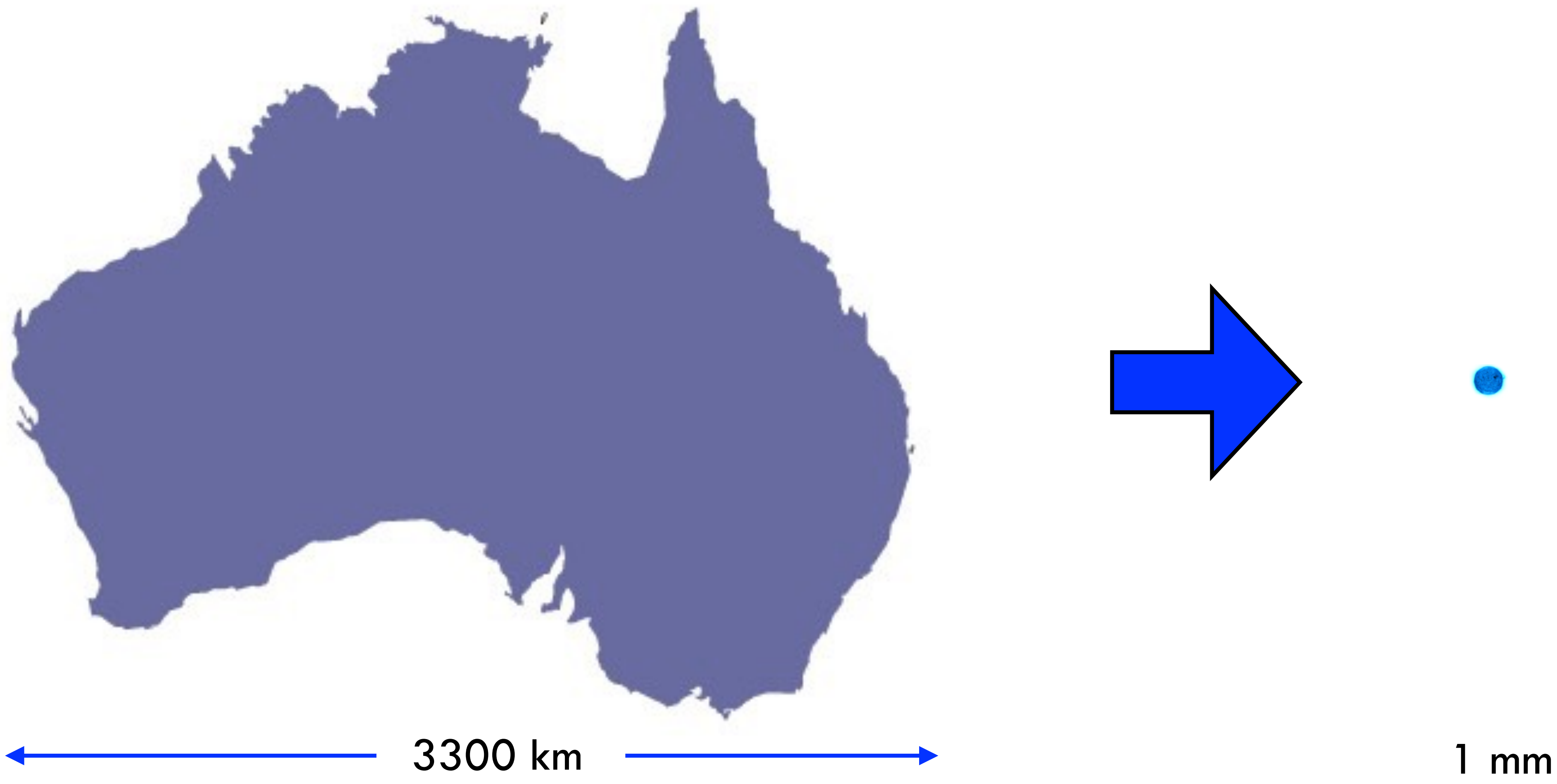
There are a lot of things we really don't understand about how stars form.

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 tonight's 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.

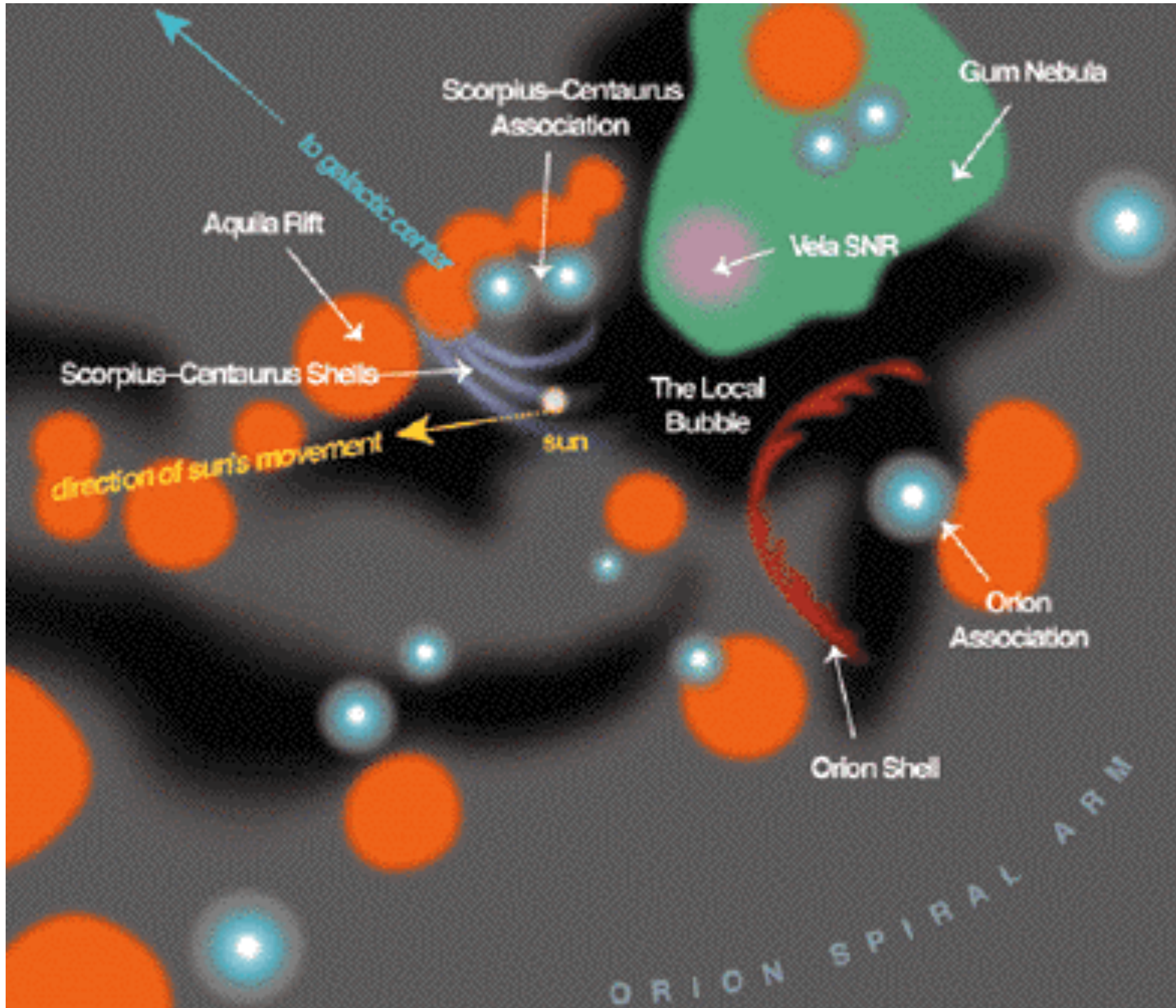
Young stars congregate together in loose groups, and always in association with *giant molecular clouds*.

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.

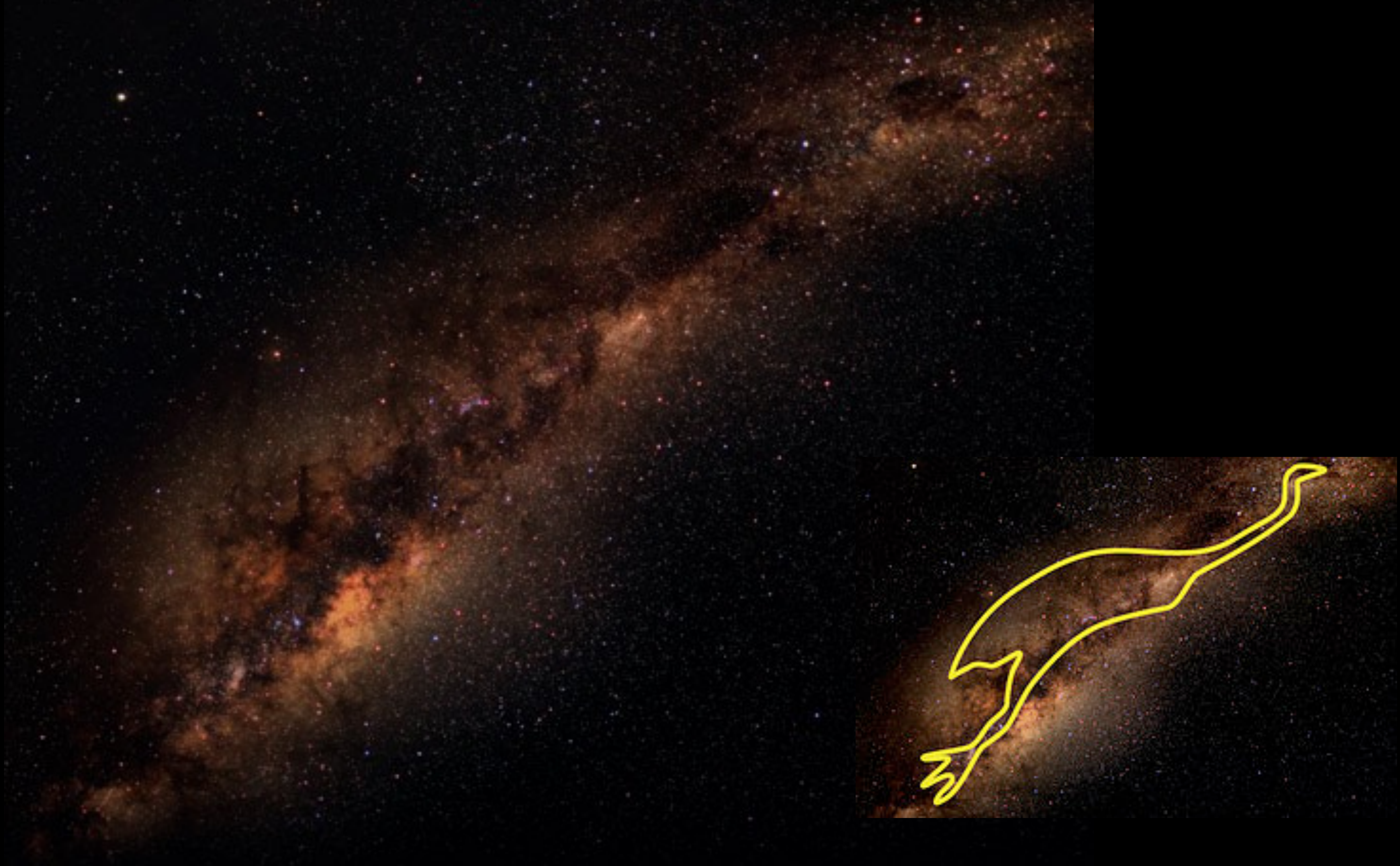
However, about 1% of the volumes is occupied by gas which is cool enough and dense enough to form molecules.

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.

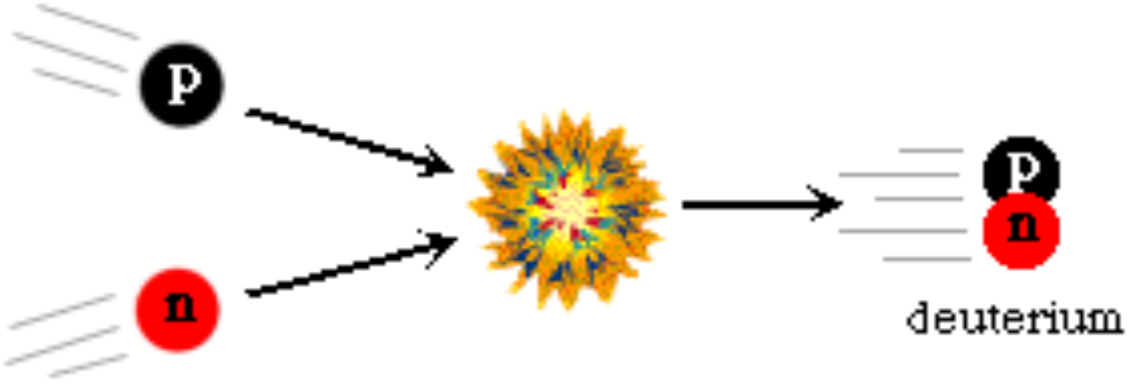
The *Coal Sack Nebula* appears as a dark patch in the bright Milky Way. It is actually a dense cloud of dust and gas, and appears dark because it blocks the light behind.



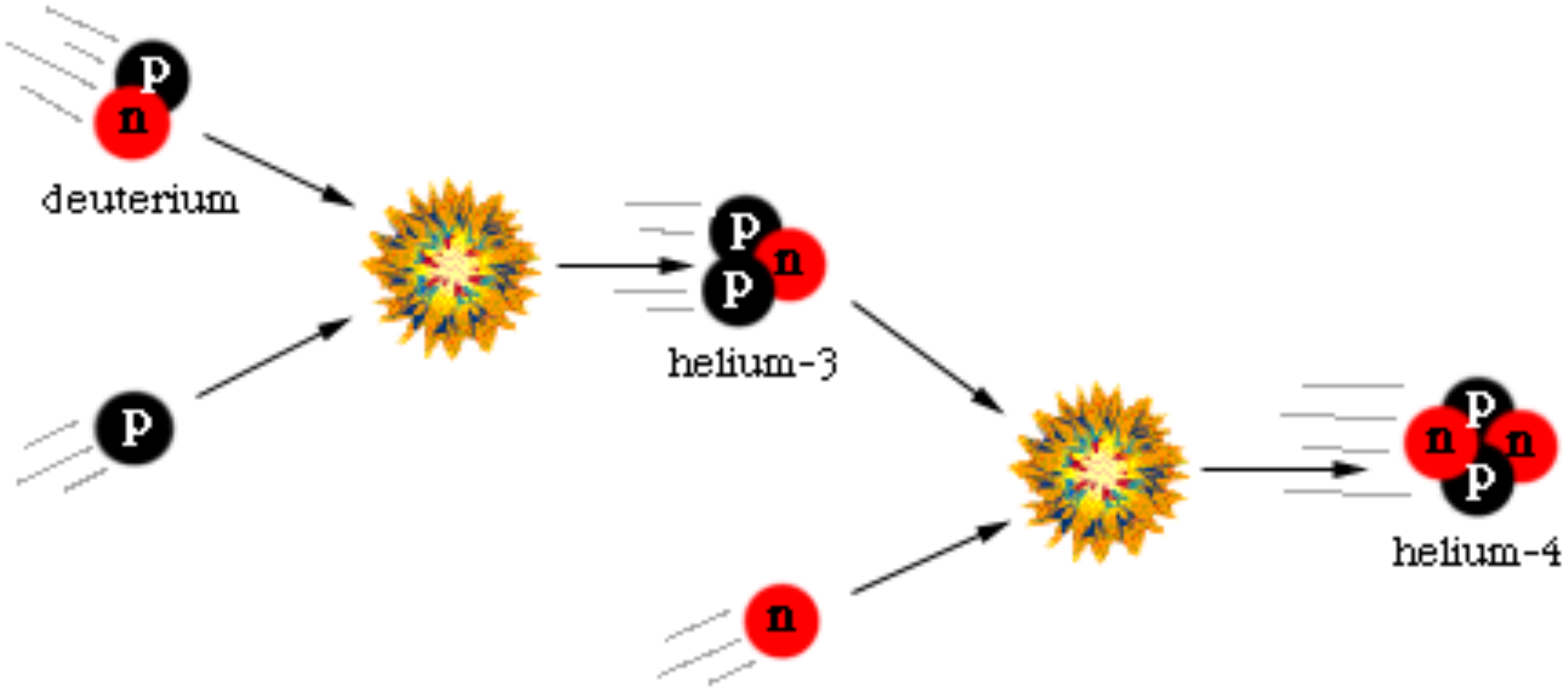
© Barnaby Norris 2007

Barnaby Norris' photograph shows a formation of dust lanes in the Milky Way that make the shape of an emu, rising above an ancient rock engraving of an emu in Ku-ring-gai Chase National Park, north of Sydney.

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, and didn't "stick".



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.).

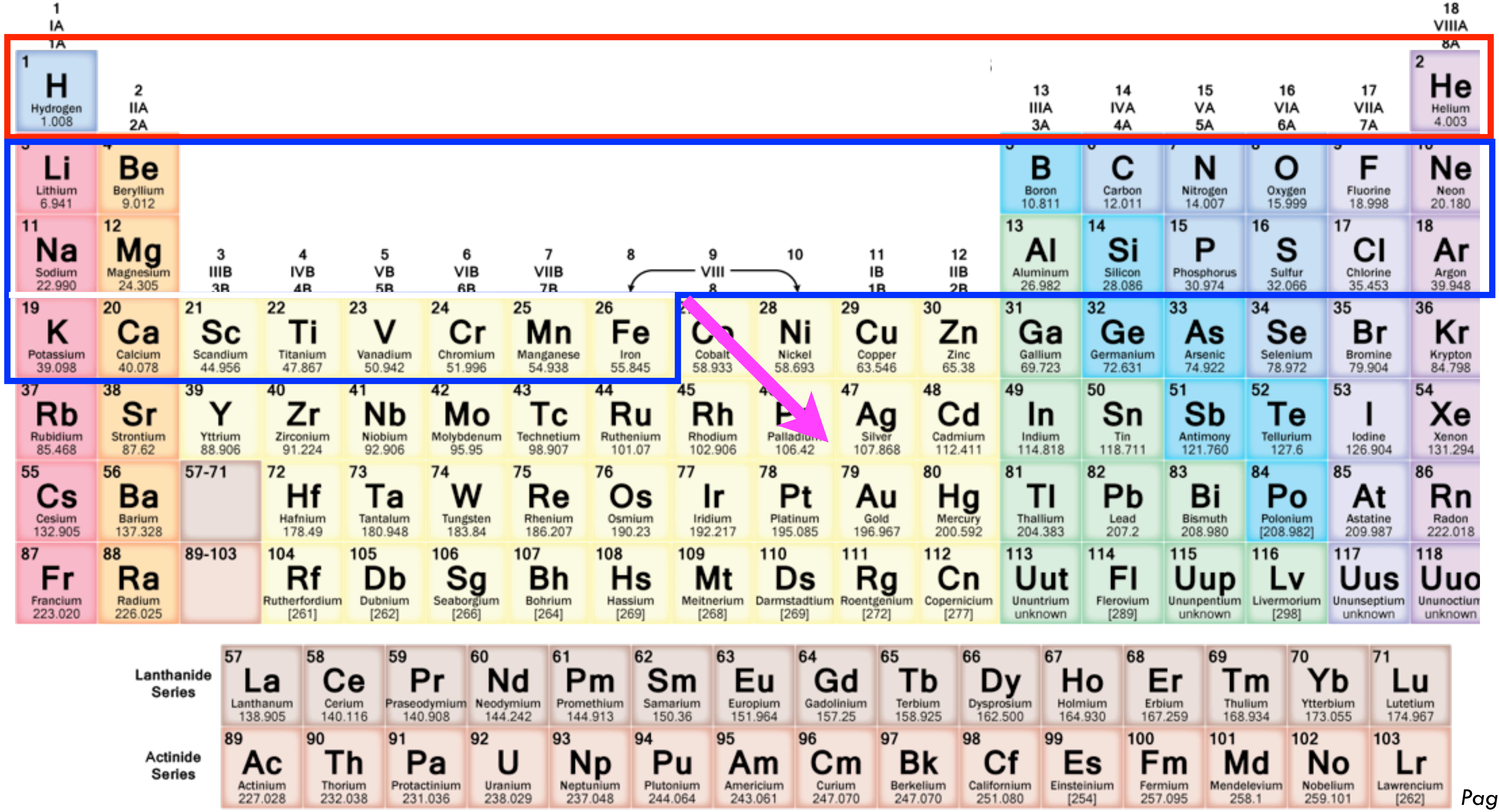
So where did the heavy elements come from?

As we will see in the next few weeks, 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



1 IA 1A	2 IIA 2A	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8	9 VIII 8	10	11 IB 1B	12 IIB 2B	13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A
1 H Hydrogen 1.008																	2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
11 Na Sodium 22.990	12 Mg Magnesium 24.305											13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.867	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.845	2 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.631	33 As Arsenic 74.922	34 Se Selenium 78.972	35 Br Bromine 79.904	36 Kr Krypton 84.798
37 Rb Rubidium 85.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.95	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	4 P Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.711	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.294
55 Cs Cesium 132.905	56 Ba Barium 137.328	57-71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.085	79 Au Gold 196.967	80 Hg Mercury 200.592	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [208.982]	85 At Astatine 209.987	86 Rn Radon 222.018
87 Fr Francium 223.020	88 Ra Radium 226.025	89-103	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Uut Ununtrium unknown	114 Fl Flerovium [289]	115 Uup Ununpentium unknown	116 Lv Livermorium [298]	117 Uus Ununseptium unknown	118 Uuo Ununoctium unknown

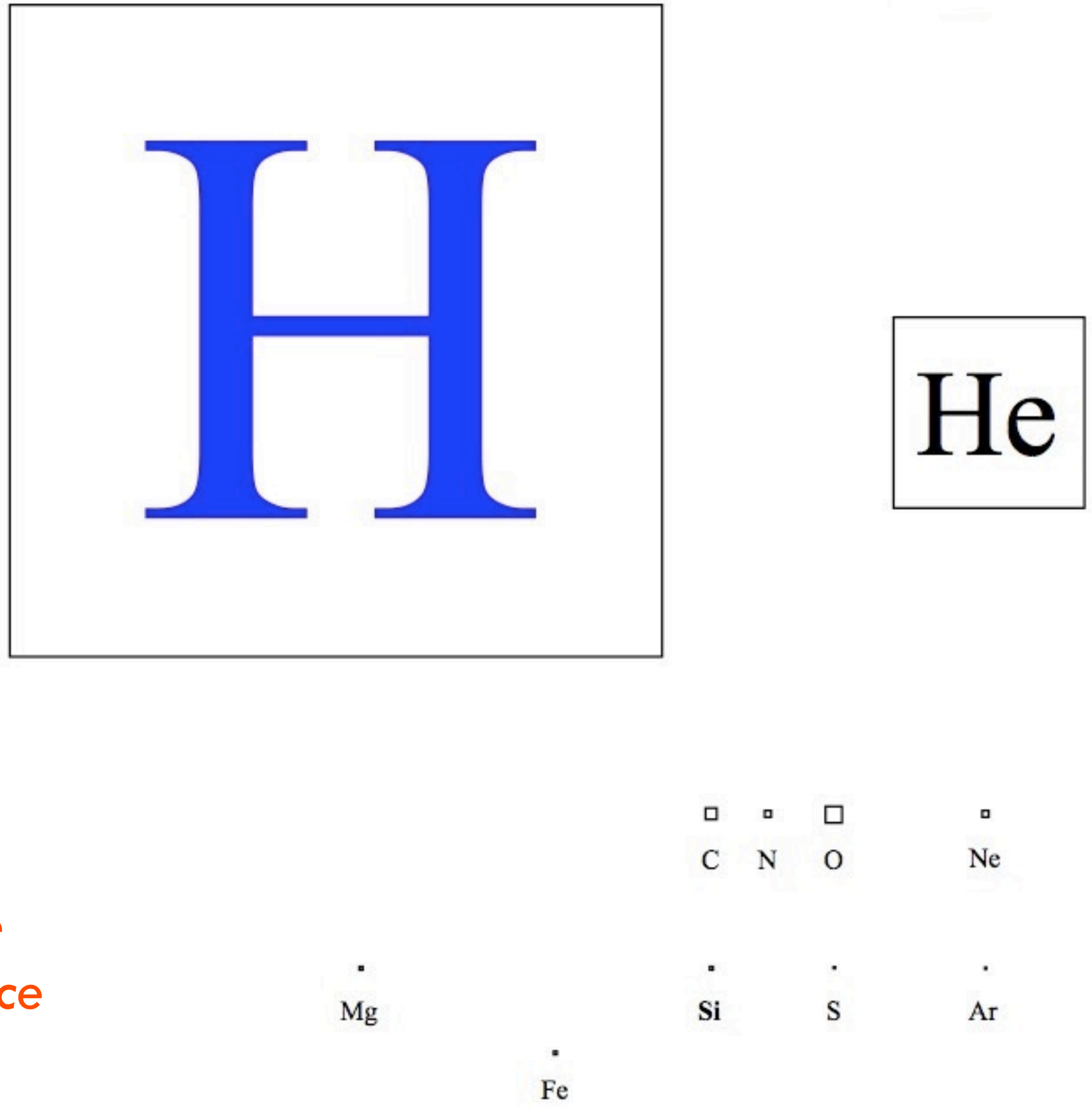
Lanthanide Series	57 La Lanthanum 138.905	58 Ce Cerium 140.116	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.242	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.500	67 Ho Holmium 164.930	68 Er Erbium 167.259	69 Tm Thulium 168.934	70 Yb Ytterbium 173.055	71 Lu Lutetium 174.967
Actinide Series	89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [254]	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium [262]

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)

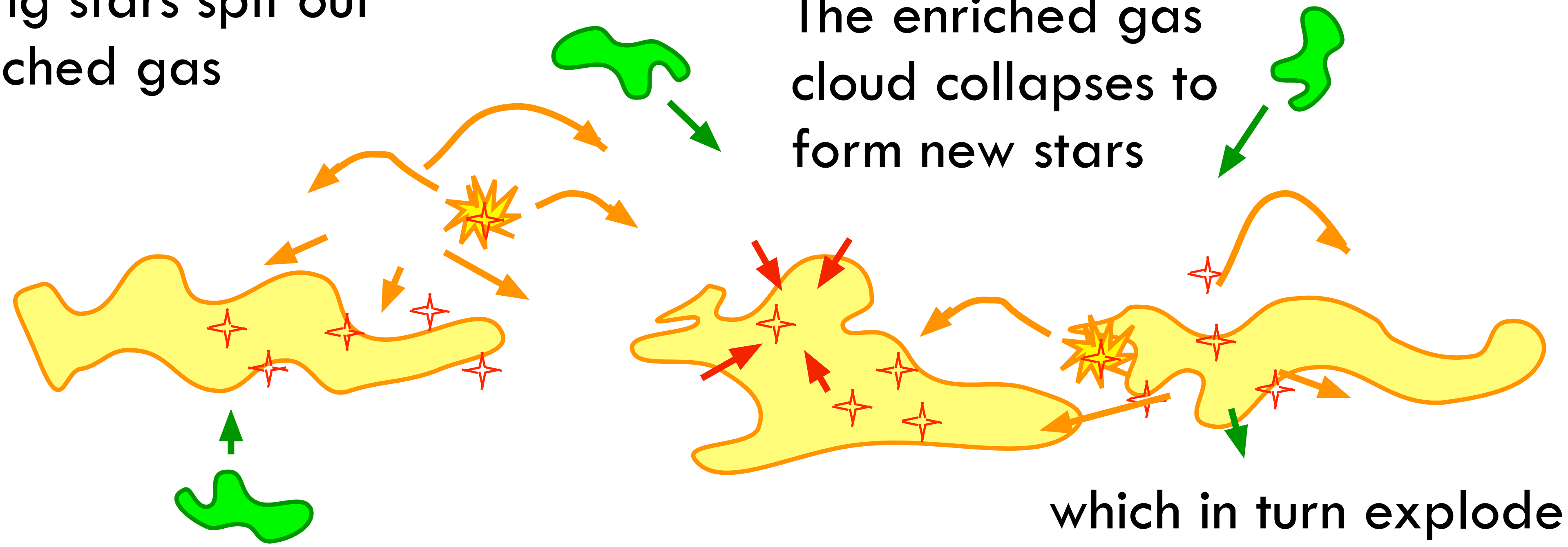
The gas swirls around in space and collects in dense clouds. These clouds mix with the remaining primordial gas, and coalesce into the clouds we call *giant molecular clouds*.

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.



Dying stars spit out enriched gas

The enriched gas cloud collapses to form new stars

which in turn explode

Meanwhile, clouds of primordial gas are constantly raining down

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.

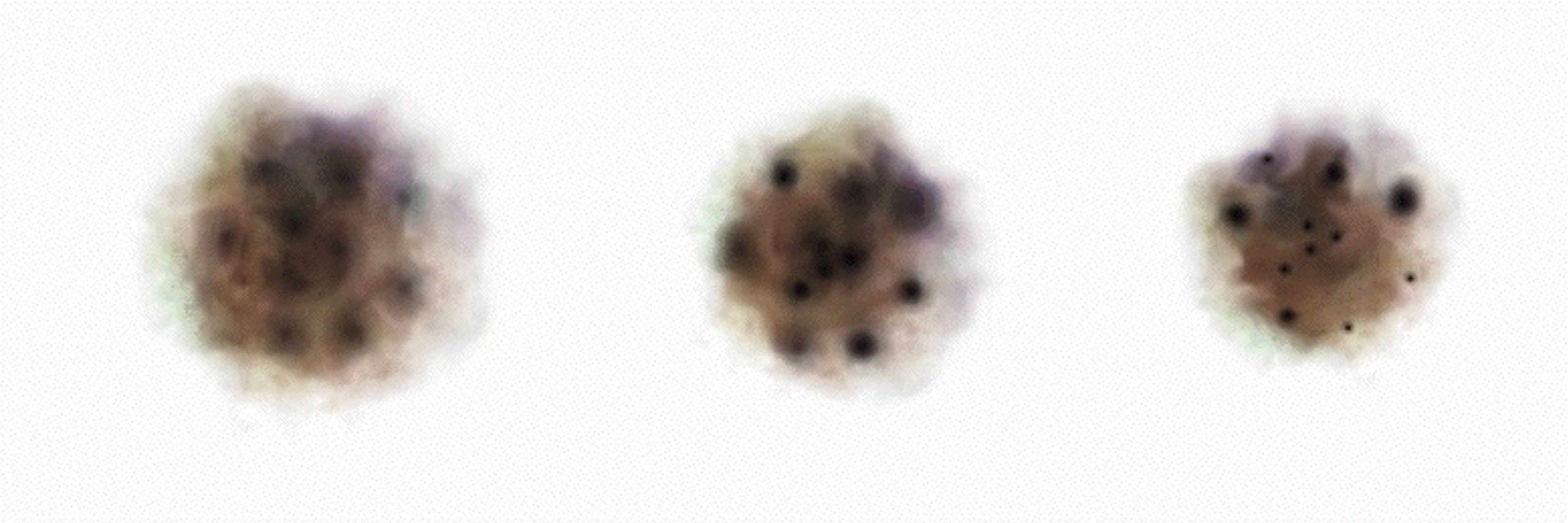
The greater the *mass* of the cloud, the smaller its *size*, and the colder its *temperature*, the more unstable it will be to gravitational collapse.

The Jeans criterion is easier to meet if the mass of the cloud is *large*.

For example, a cloud of 1000 solar masses, with a temperature of 20 K can condense if it reaches a density of 10^{-22} kg m^{-3}, or about 100,000 molecules per cubic metre.

The density threshold for a 1 solar mass cloud is a million times higher.

This suggests that the condensation of a cloud takes place in several steps. First a very large cloud (1000s of solar masses) starts to contract. When it has contracted enough that its density is high enough, smaller parts of it will be able to contract independently. Eventually the cloud will be able to fragment into many parts, each of which can form its own proto-star.



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.

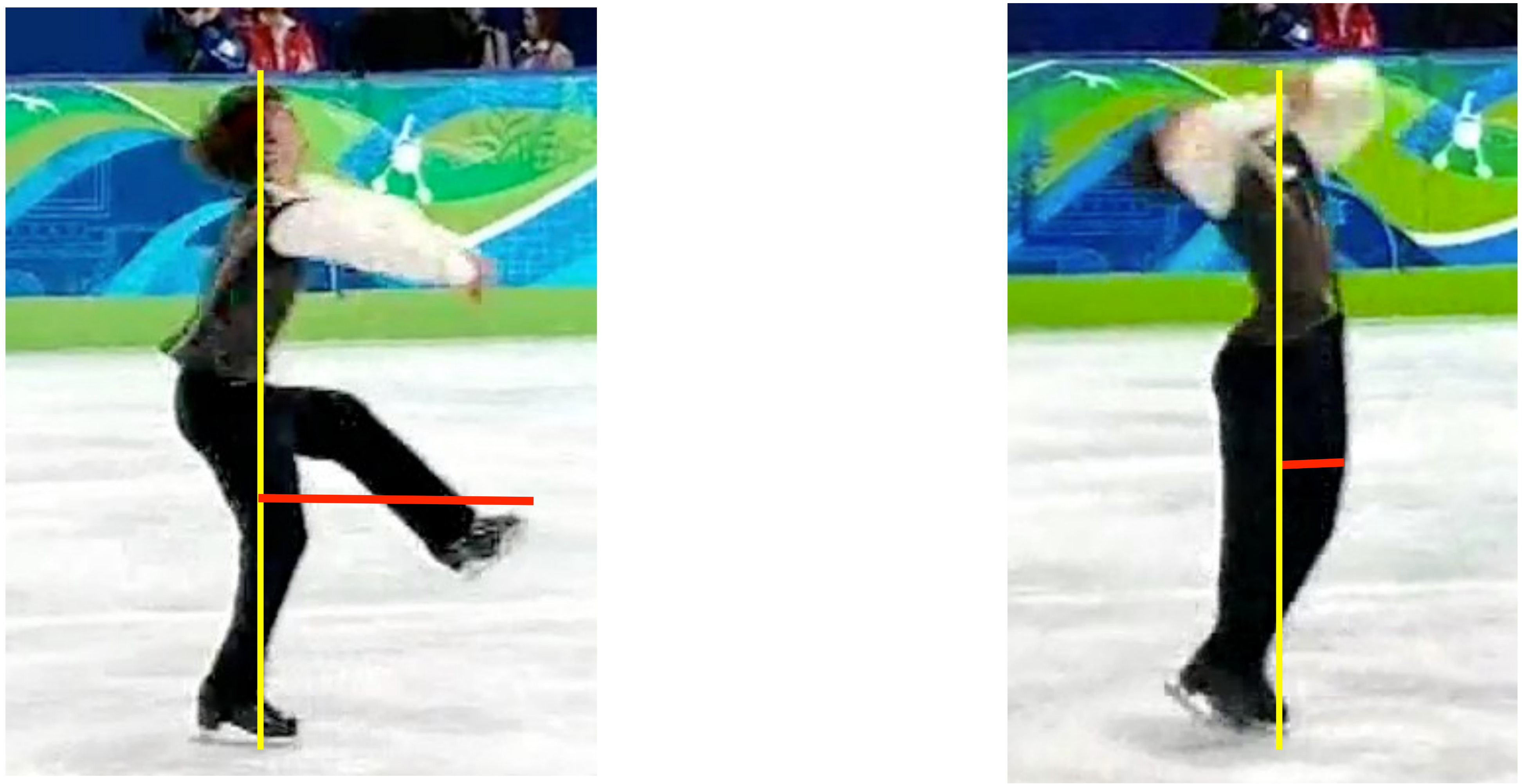
To be precise, angular momentum is equal to

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.

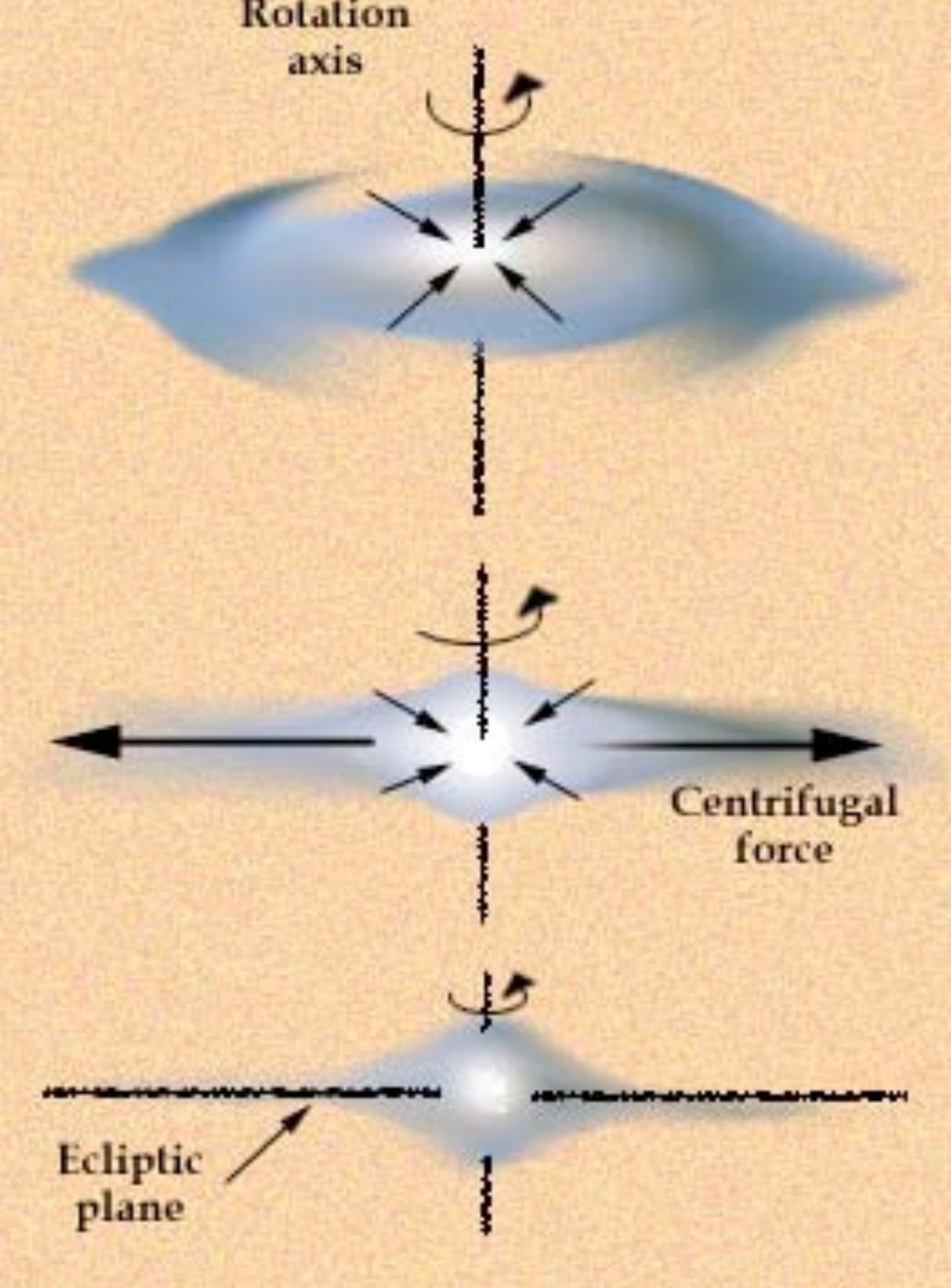
Conservation of angular momentum is what ice skaters use when they speed up a spin.

Conservation of angular momentum is what ice skaters use when they speed up a spin. By bringing his arms and legs into line, the skater reduces the average distance of his mass from the axis of rotation, so the rate of spin must increase.



The collapsing cloud will be rotating slightly, even if only due to Galactic rotation. The cloud shrinks by a factor of 10,000 or more, so any slight rotation is greatly amplified and the cloud will end up rotating rapidly.

What's more, it will 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.

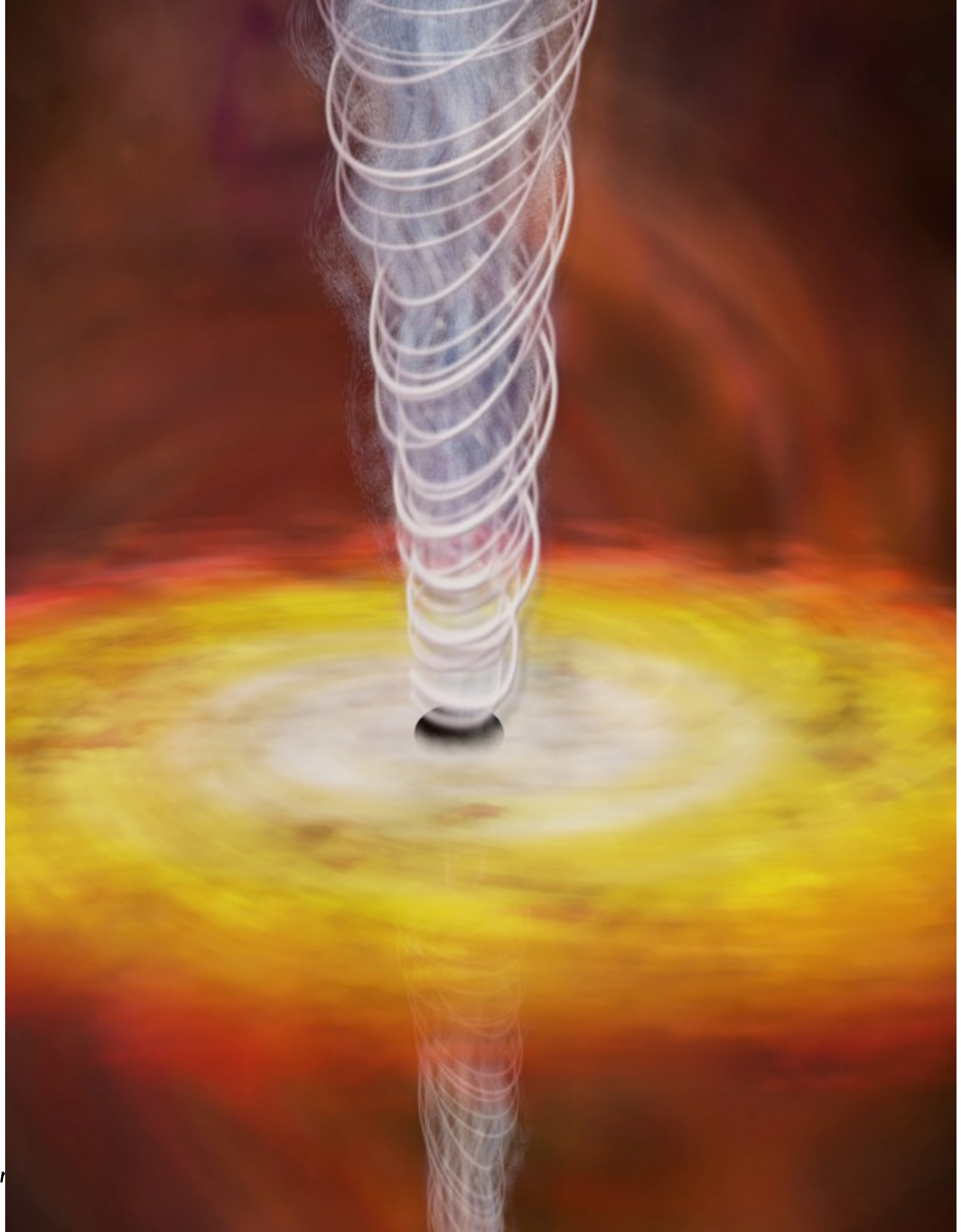


We can actually see these disks around newborn stars.

Hubble images of proto-planetary disks in the Orion nebula

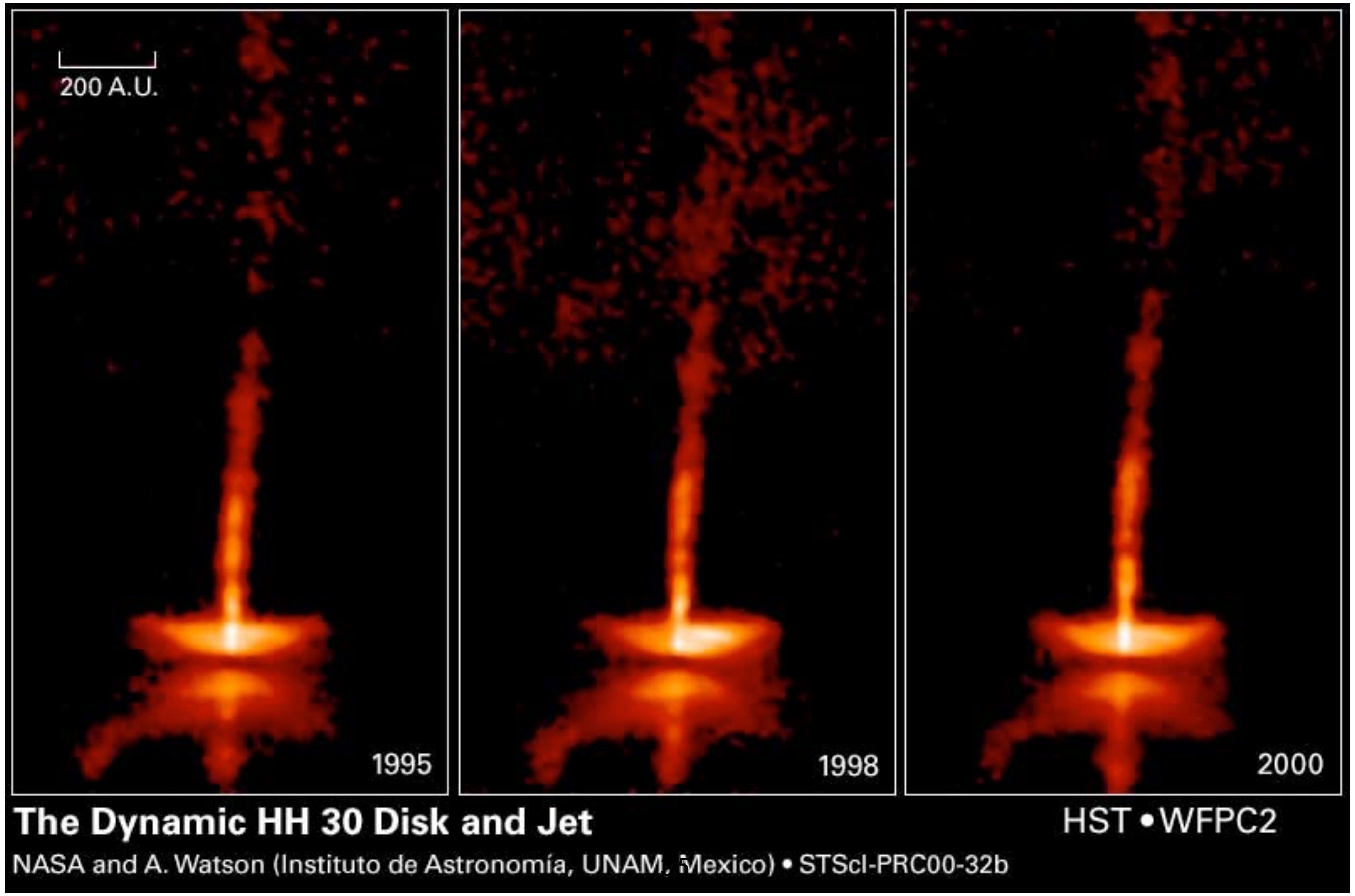
As the central regions get denser, the collapse speeds up, so that the cloud collapses from the inside. As the density increases, the cloud becomes opaque, trapping the heat within the cloud. This then causes both the temperature and pressure to rise rapidly – the collapsing cloud is now a *protostar*.

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*.



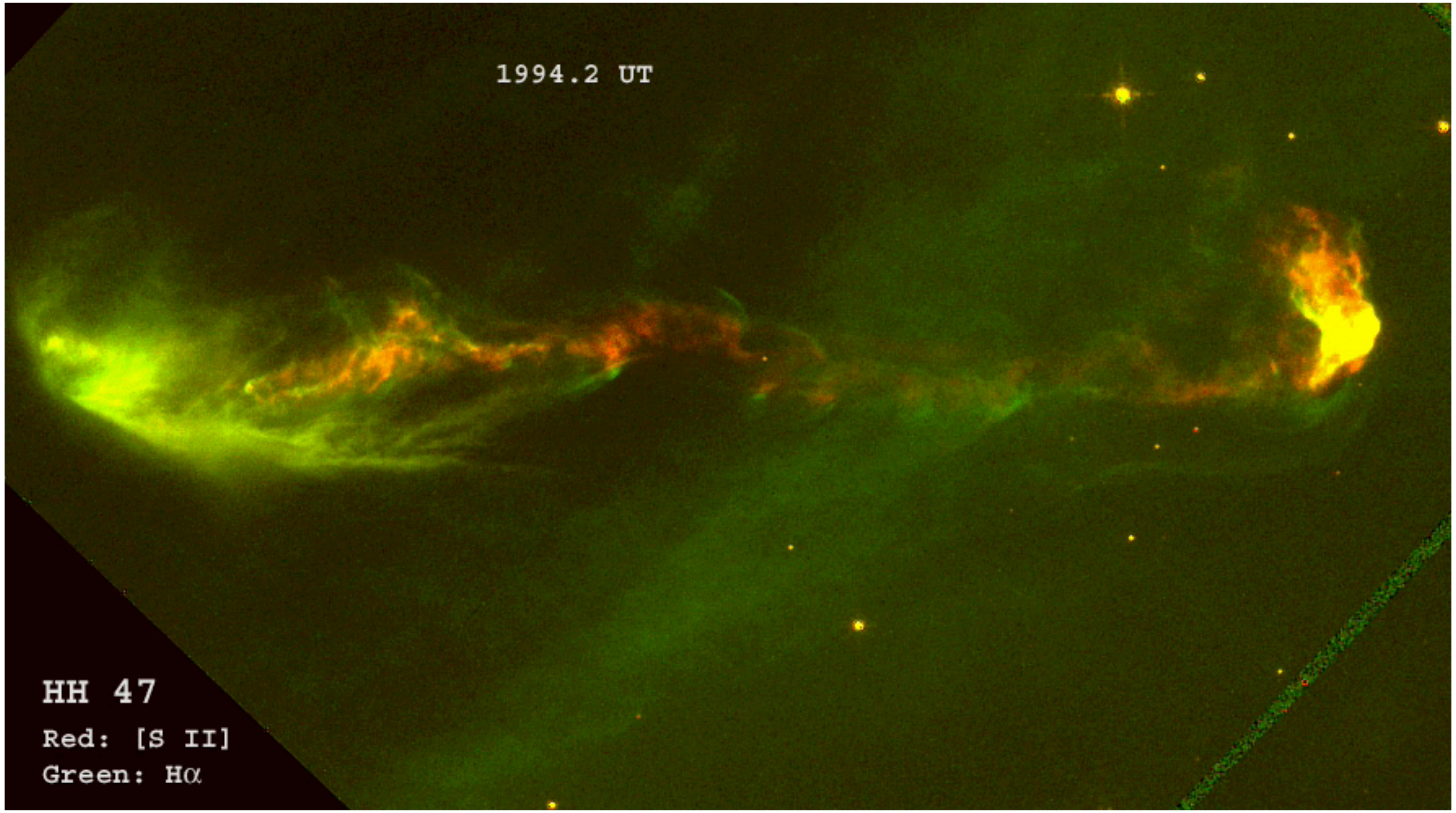
The Dynamic HH 30 Disk and Jet

HST • WFPC2

NASA and A. Watson (Instituto de Astronomía, UNAM, Mexico) • STScI-PRC00-32b

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

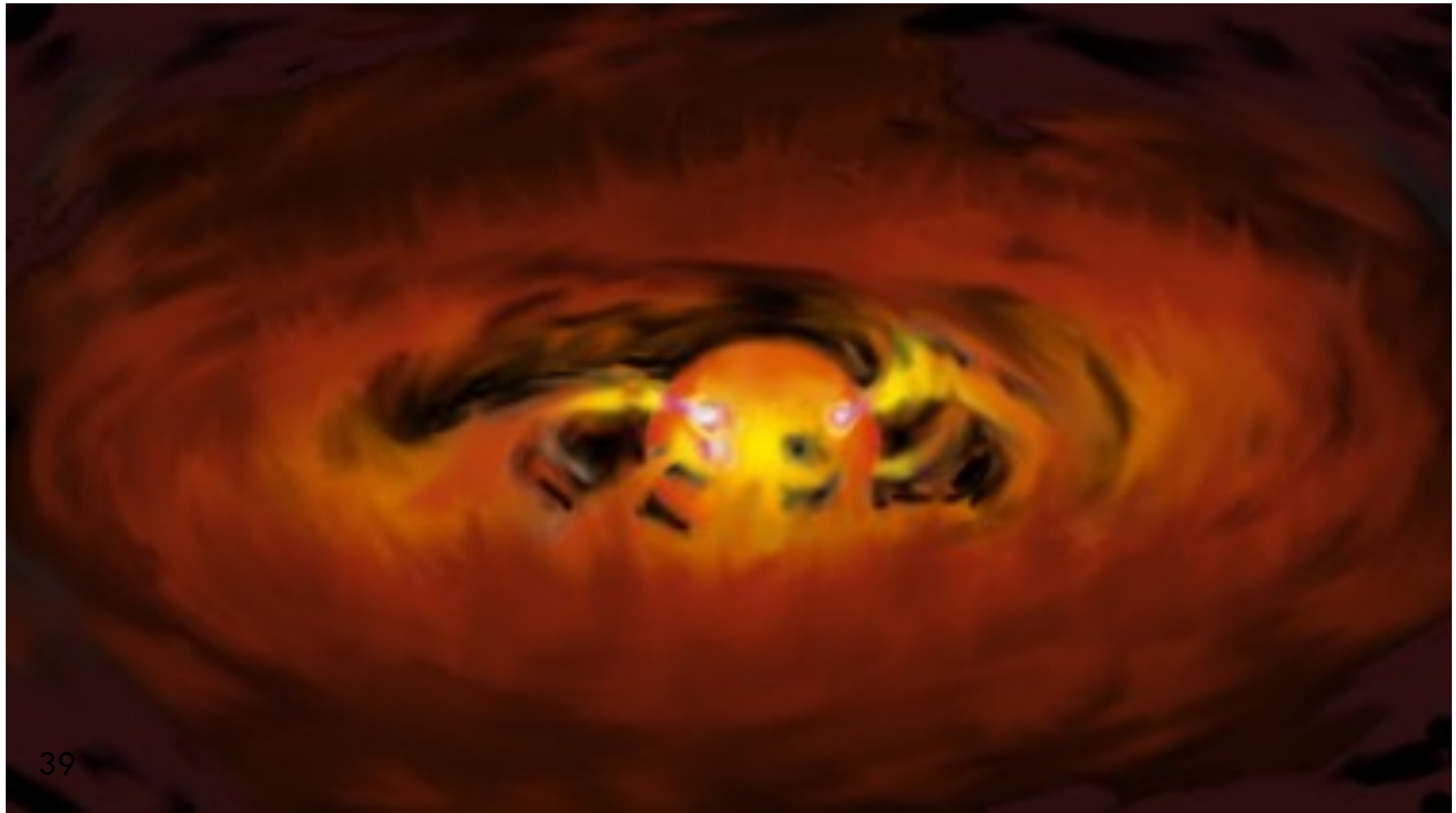
Infrared Spitzer image of the outflow HH 46/47, embedded in the dark nebula shown in an optical image at the lower left.



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.



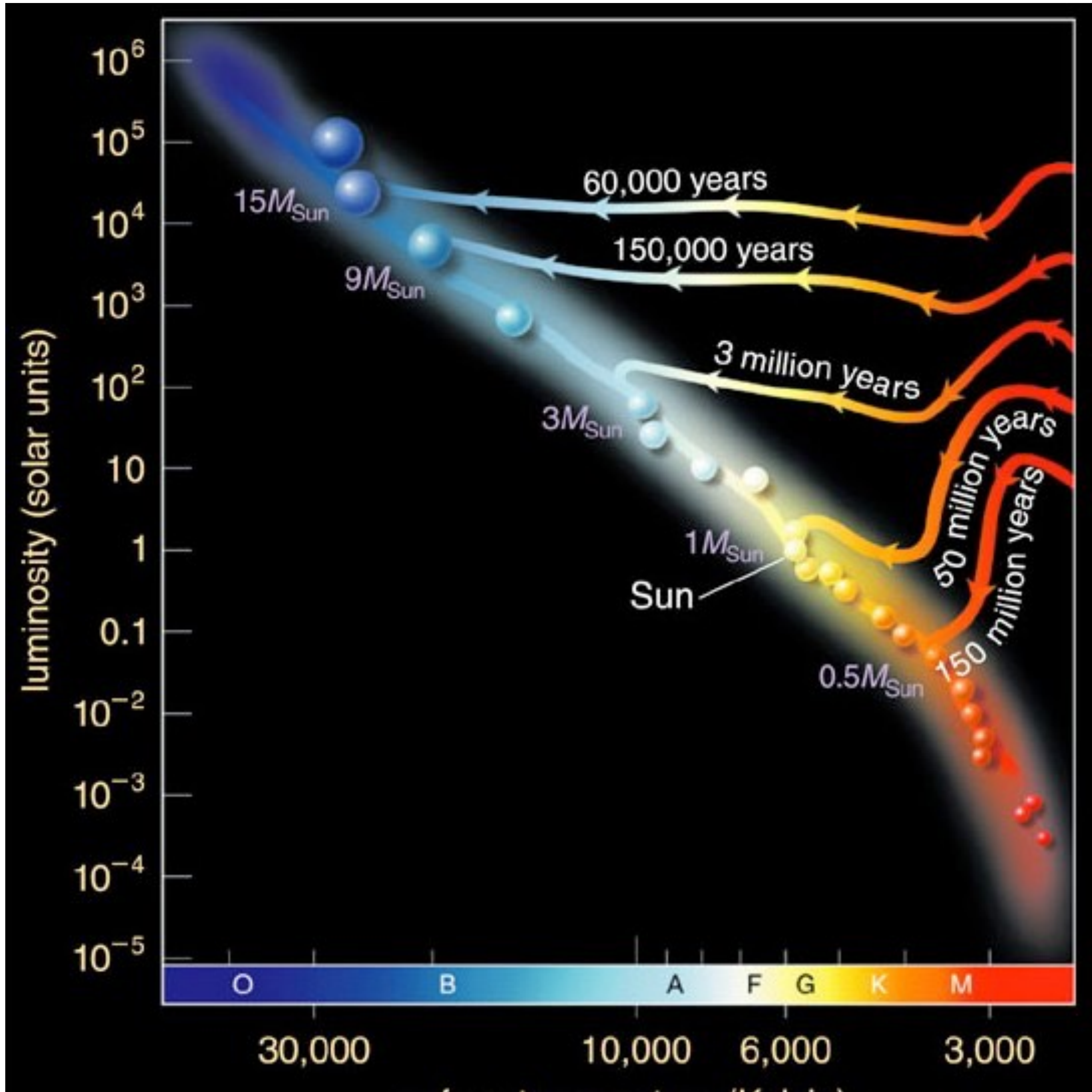
Artist's impression of a T Tauri star, still accreting from its dense disk of dust and gas.

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.

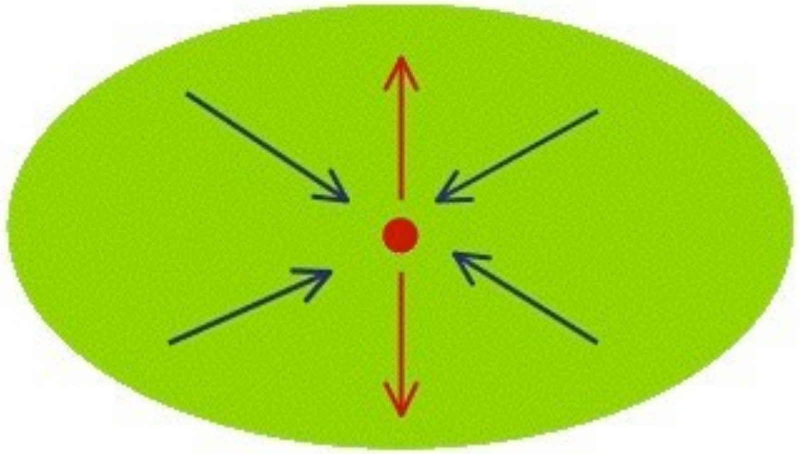
How long this collapse takes depends on the mass of the forming star. A 15 solar mass protostar may collapse in only 60,000 years while a star half the mass of the Sun would take around 150 million years.

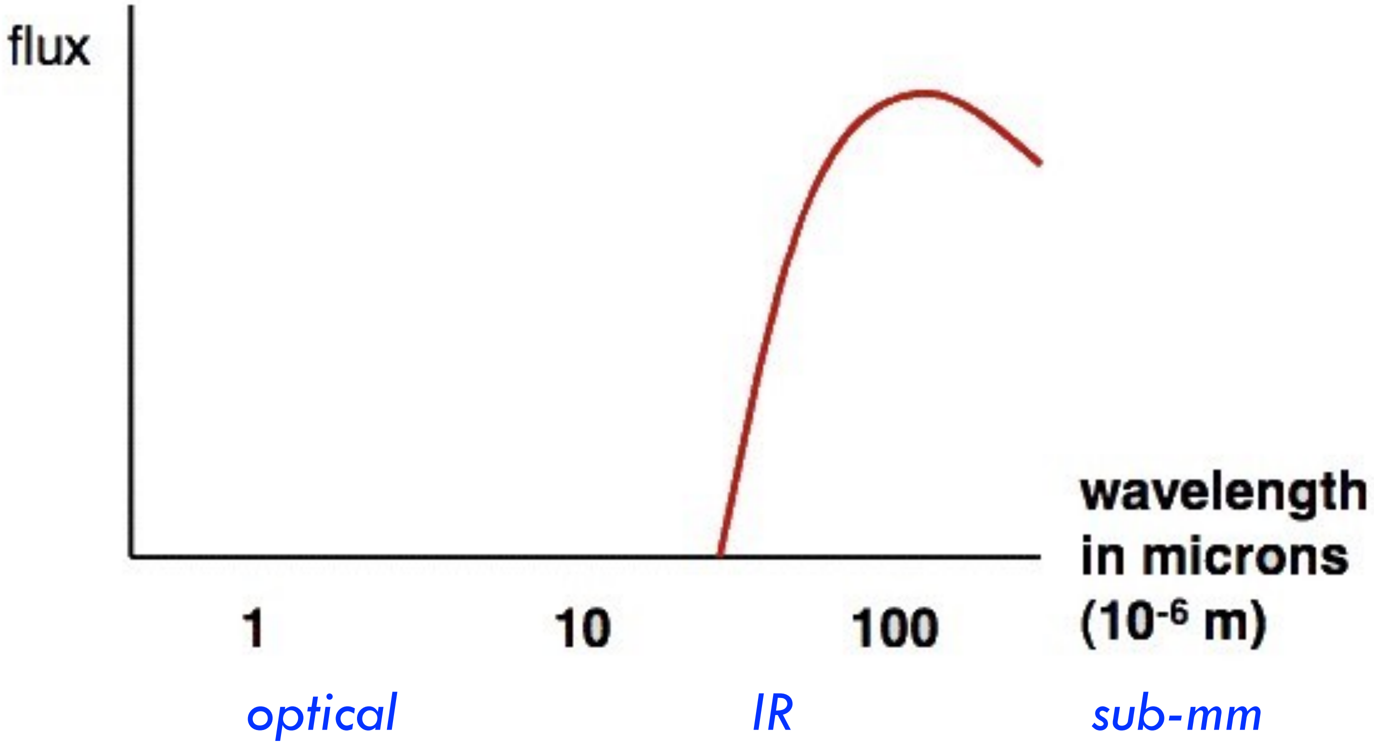
As we will see next week, this is longer than the lifetimes of massive stars, which means that massive stars forming in a cluster can collapse onto the main sequence, complete their hydrogen burning and finish their lives before a low mass star has even made it onto the main sequence.

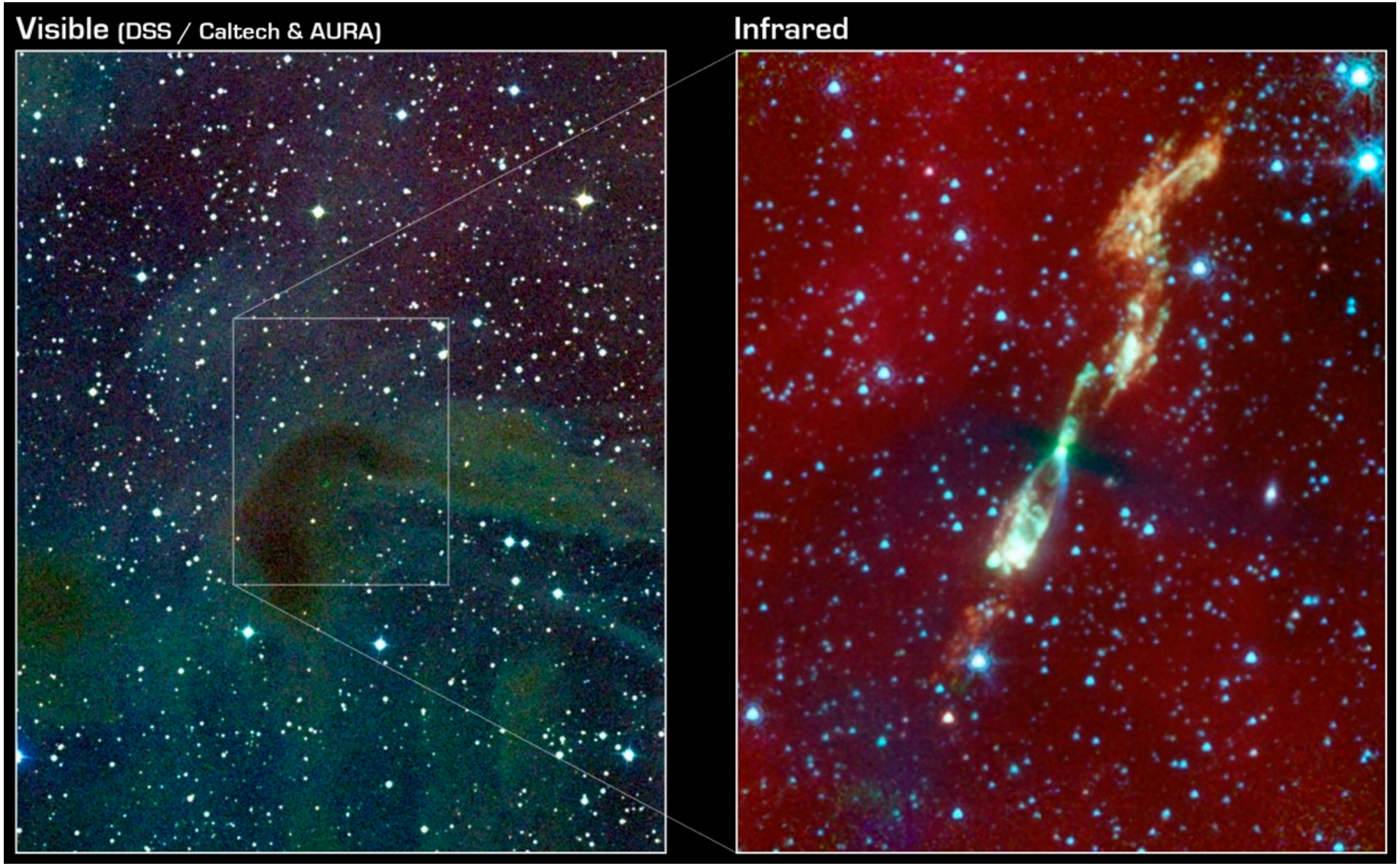


We observe several different types of young stellar objects, which represent different stages in the collapse.

- 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.

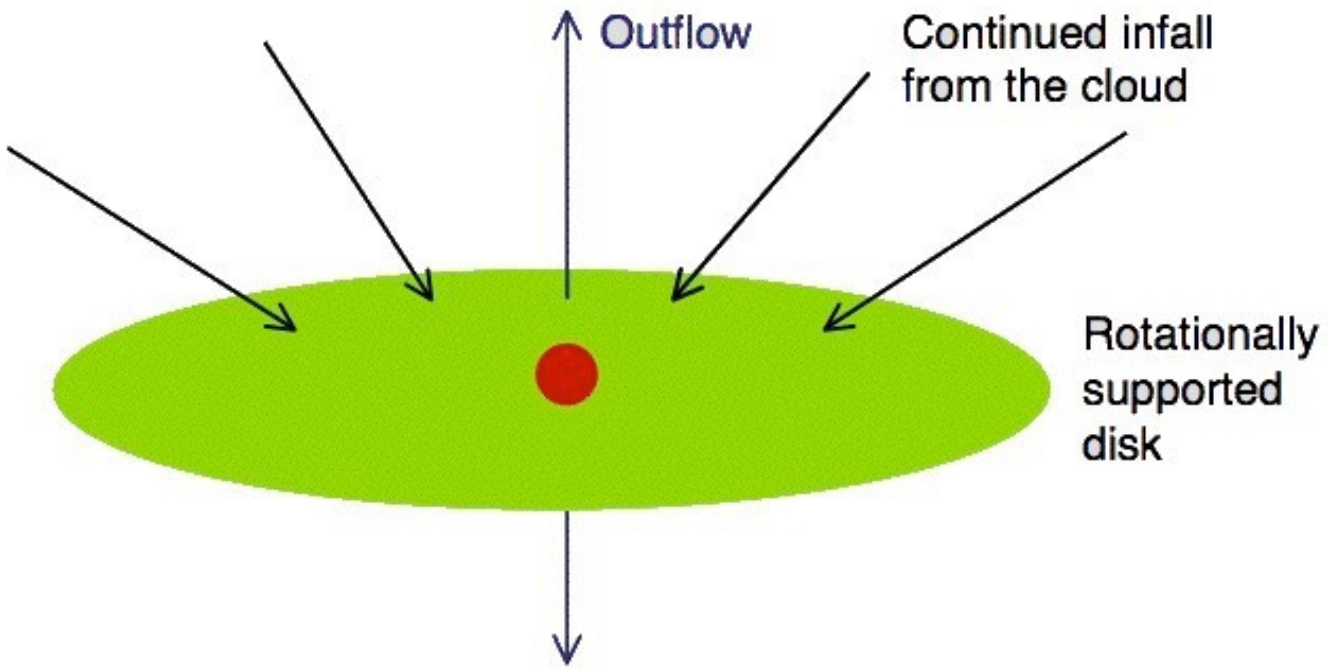


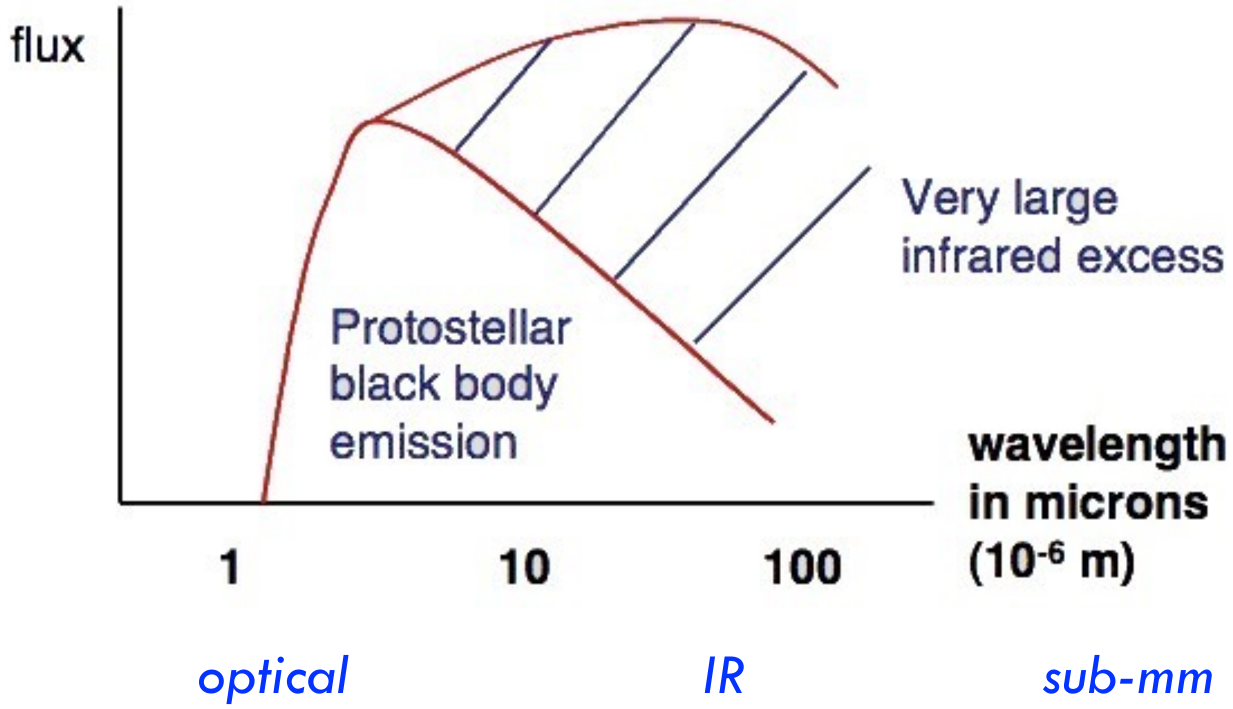




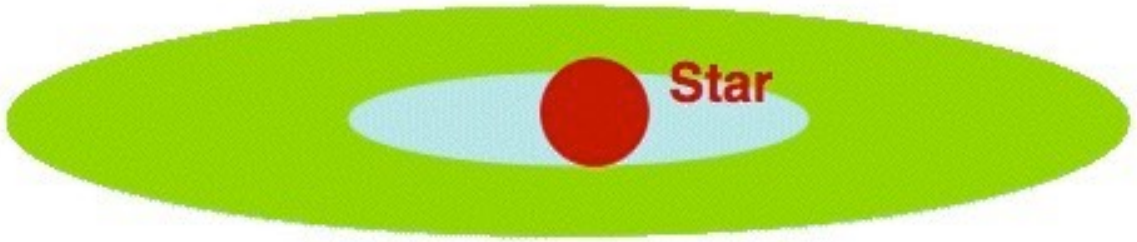
The Class 0 protostar L1157, imaged by Spitzer. The protostar is hidden by the flattened envelope of dust, while giant jets stream outward.

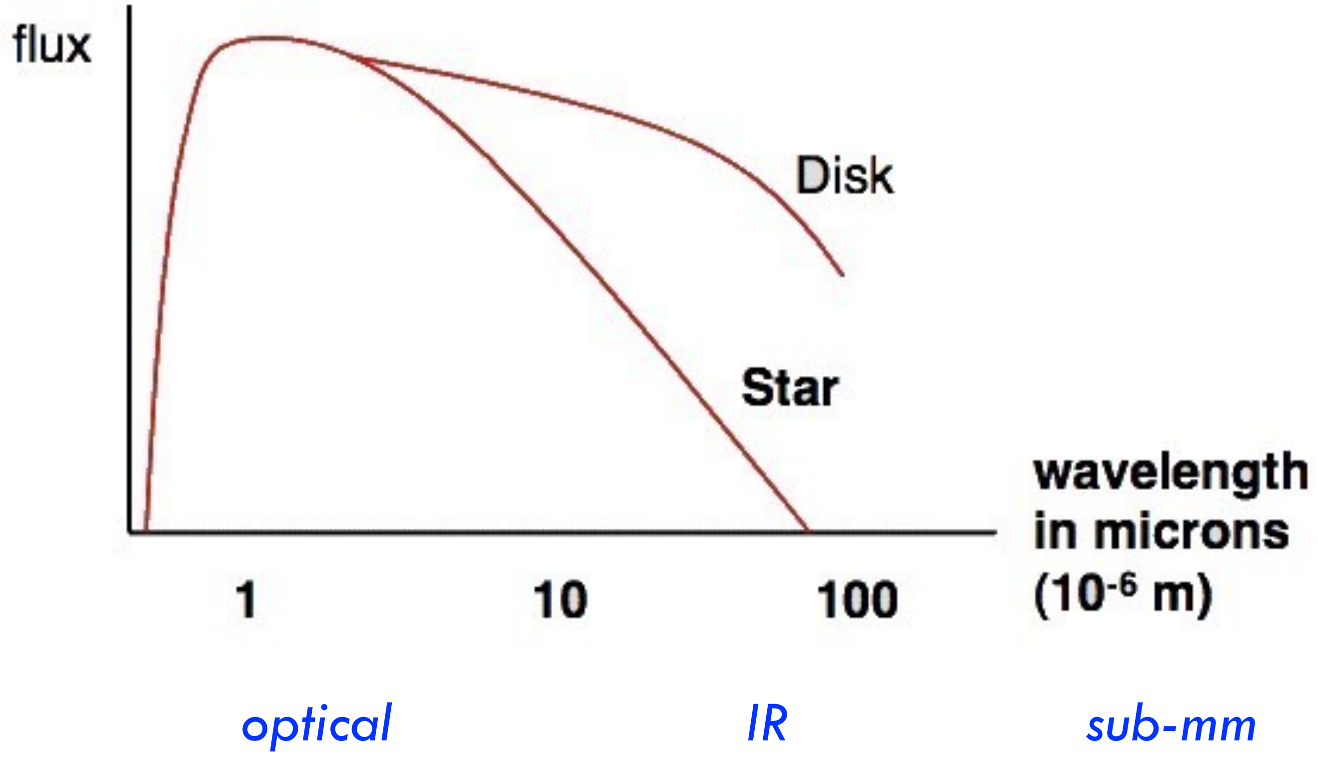
- Class I sources are much brighter in the infrared, but still invisible at optical wavelengths. We still can't see the star itself, but enough dust has cleared away to see the hot gas and dust near the star.



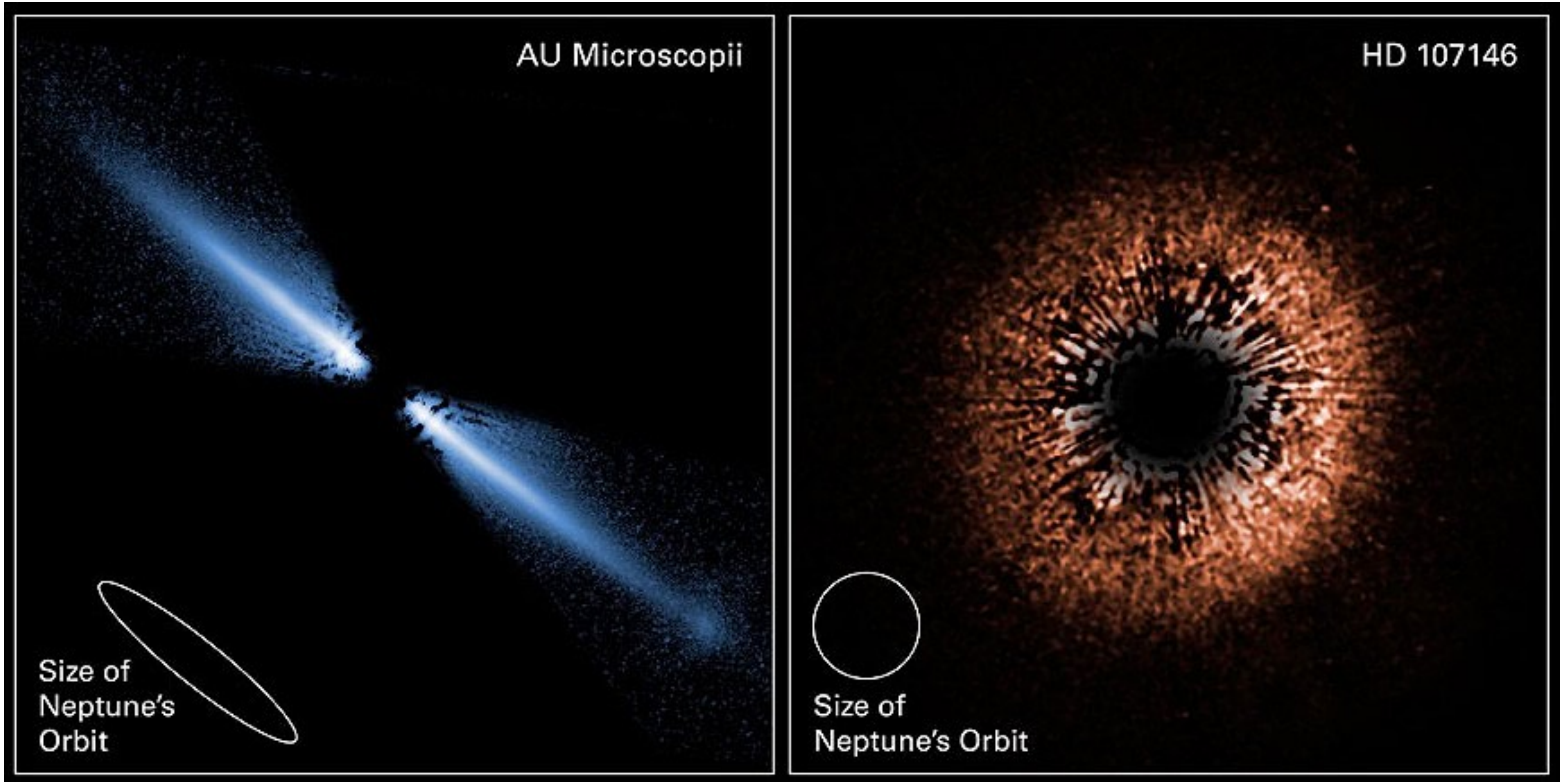


- Class II sources are finally visible at optical wavelengths. The star has emerged from its birth material; most of the collapsing cloud has settled on to the star or its disk. From most angles we can see the star directly. These are the *T Tauri stars*.

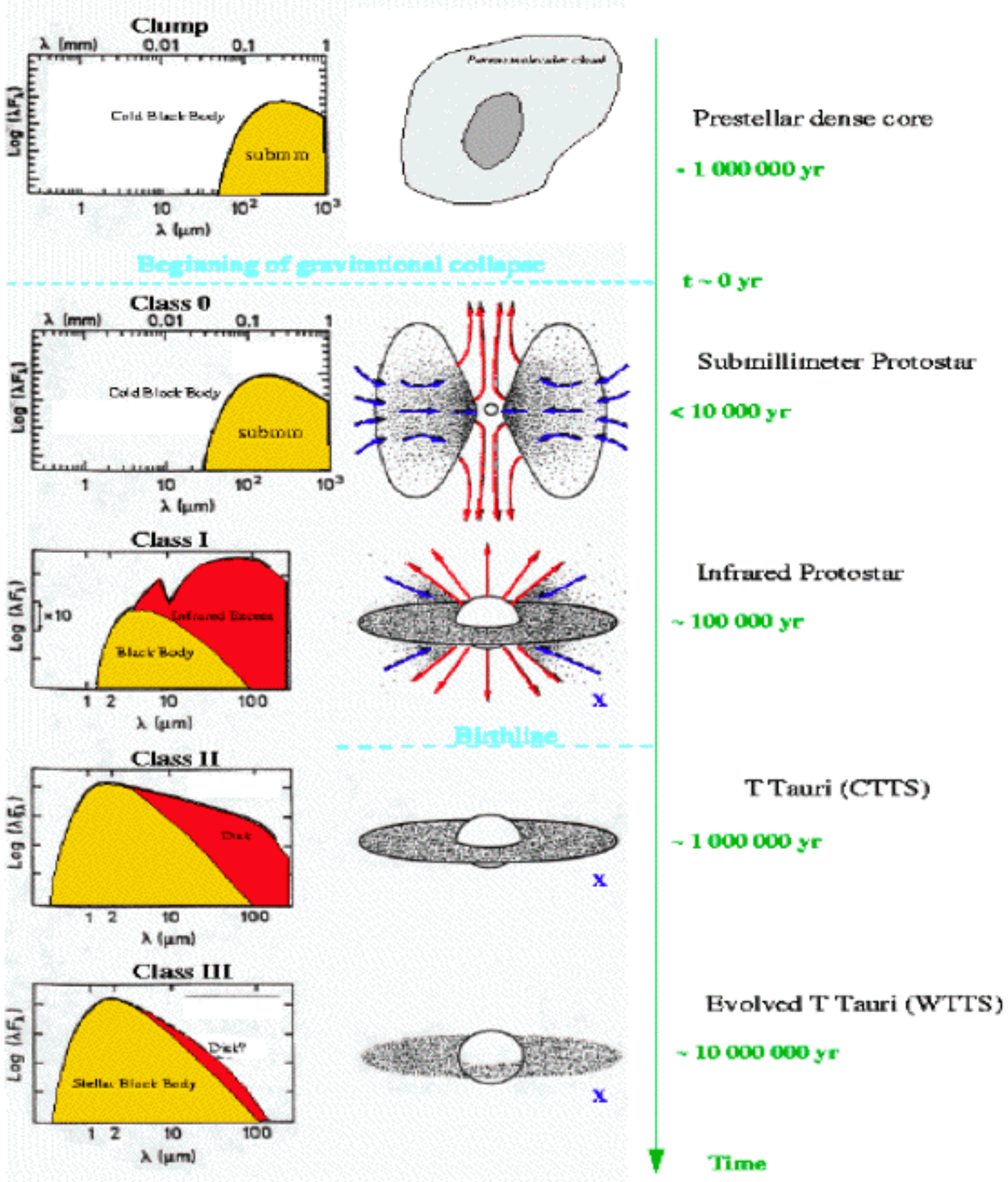




As T Tauri stars age, their disks disappear. The disk material has either fed onto the star, or coagulated into larger bodies i.e. begun to form the building blocks for planets.



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

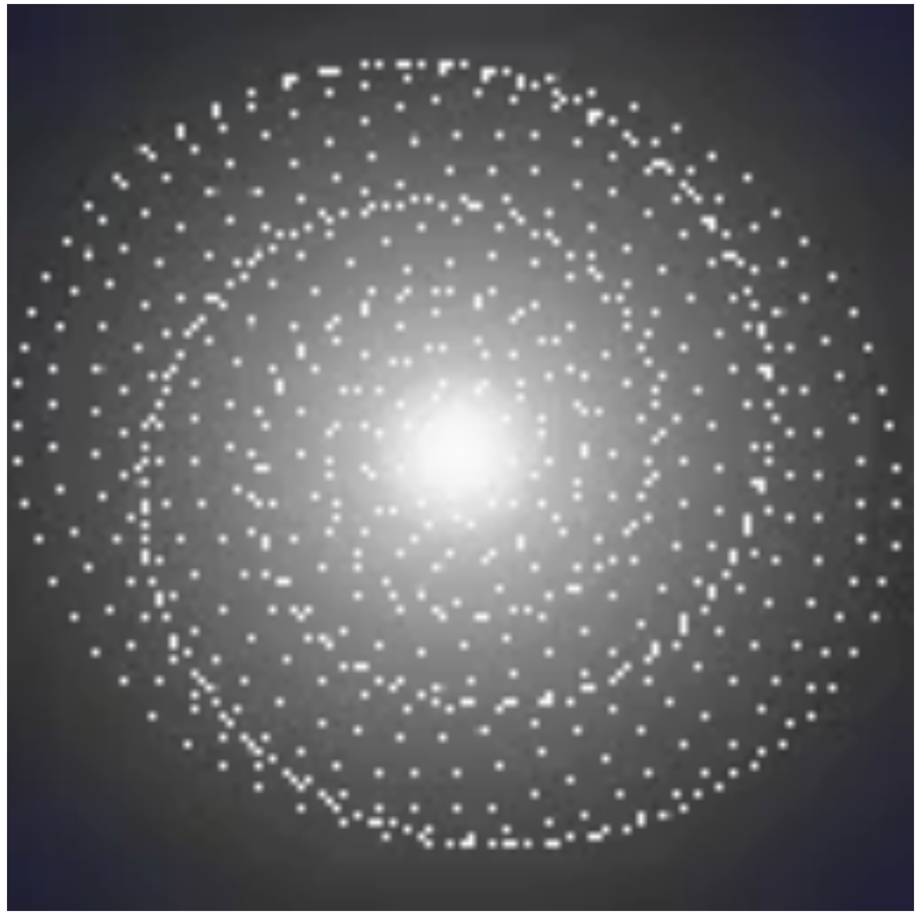
Why do stars form?

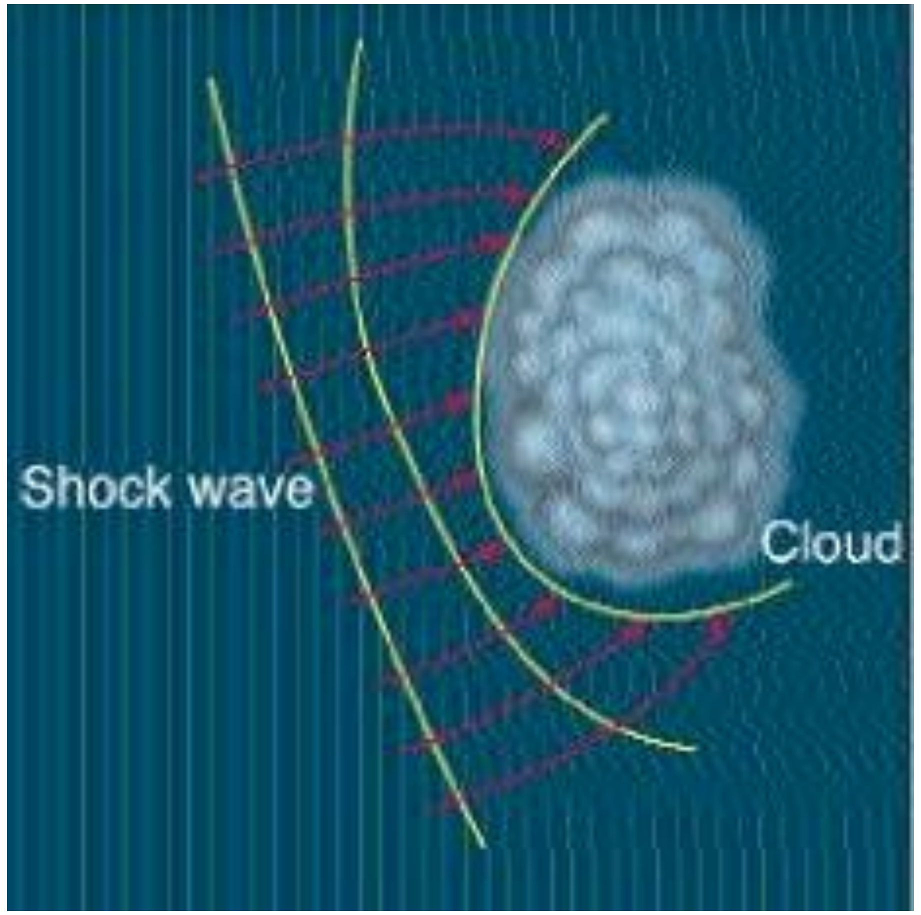
One important question is: does a cloud collapse spontaneously to form stars, or does it require a trigger?

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.

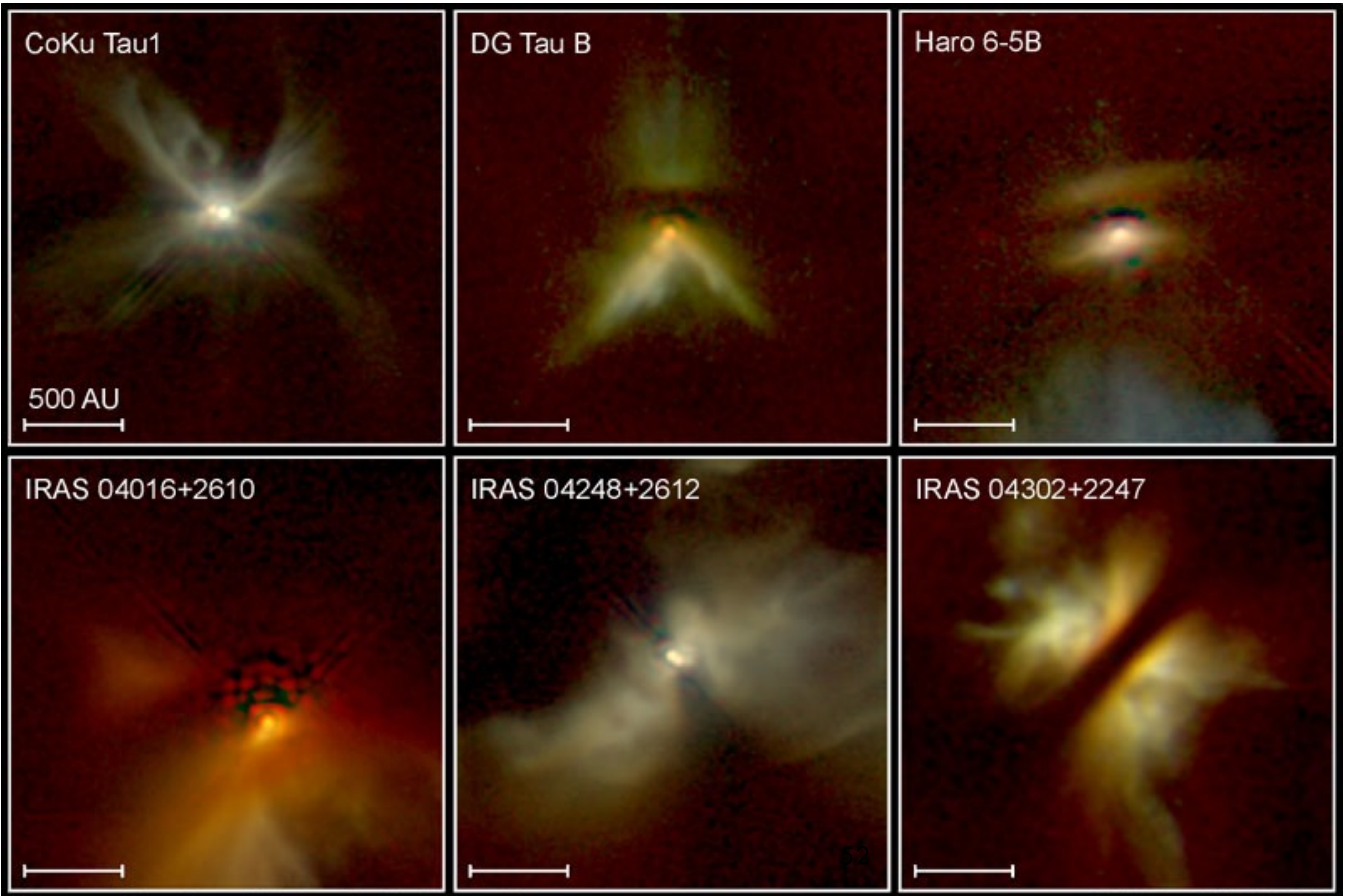
Perhaps the collapse of the clouds and the birth of the stars is *triggered* by the passage of the spiral density wave through the cloud.

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.



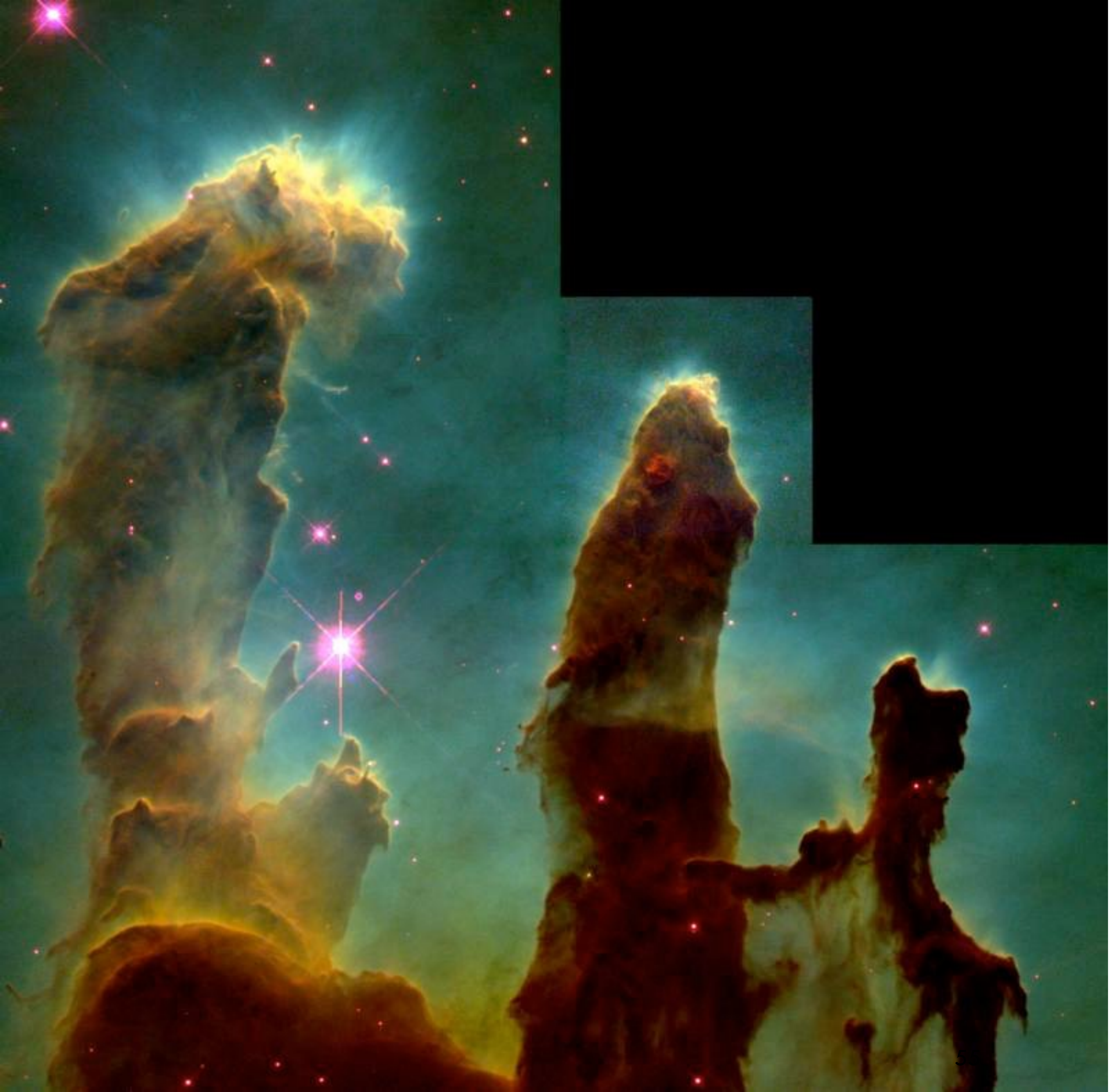
HST images of disks around young stars in Taurus.

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.

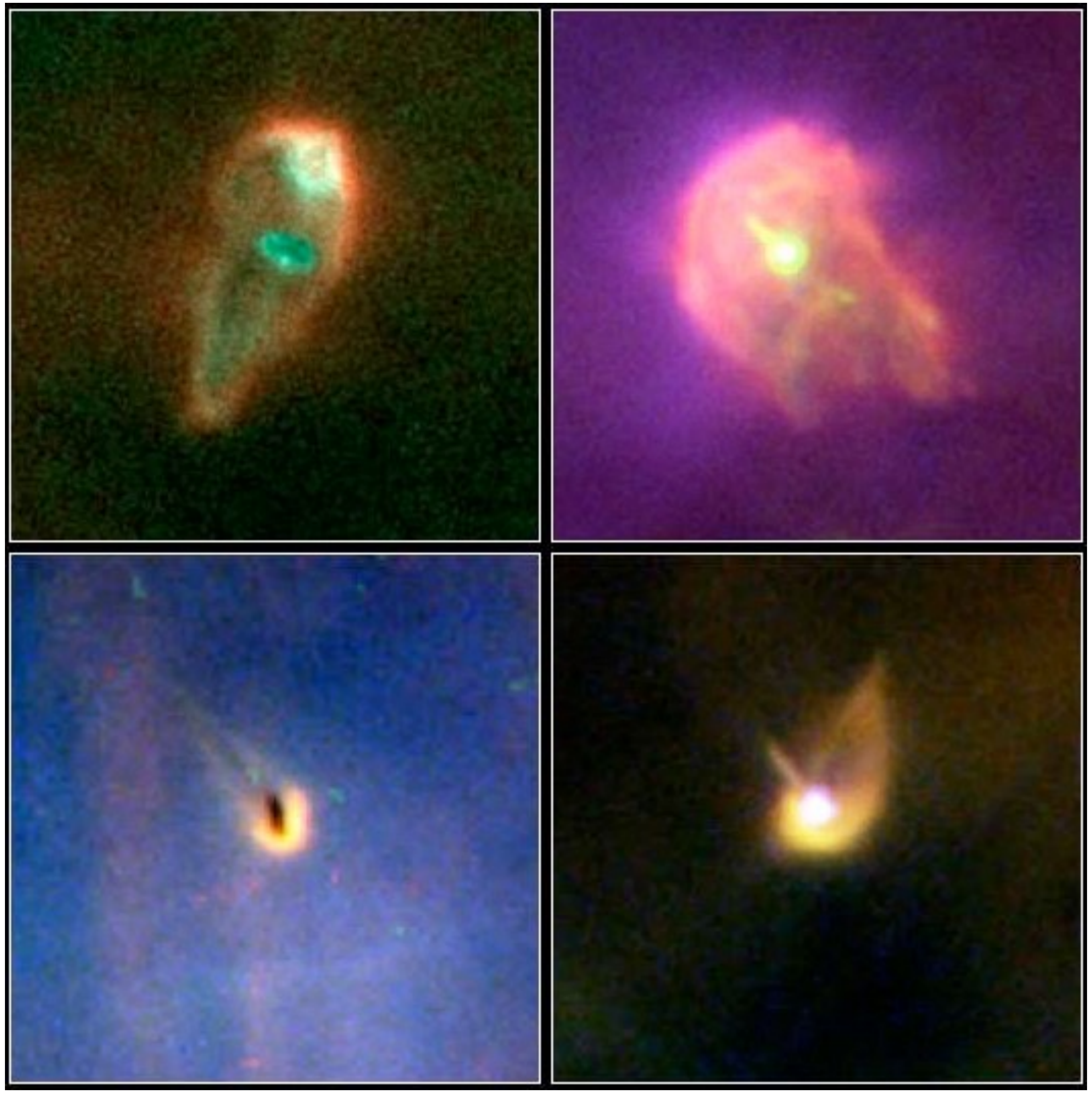
As soon as massive stars form, you get intense radiation, powerful winds, and supernova explosions. The hot stars reshape their own environment.

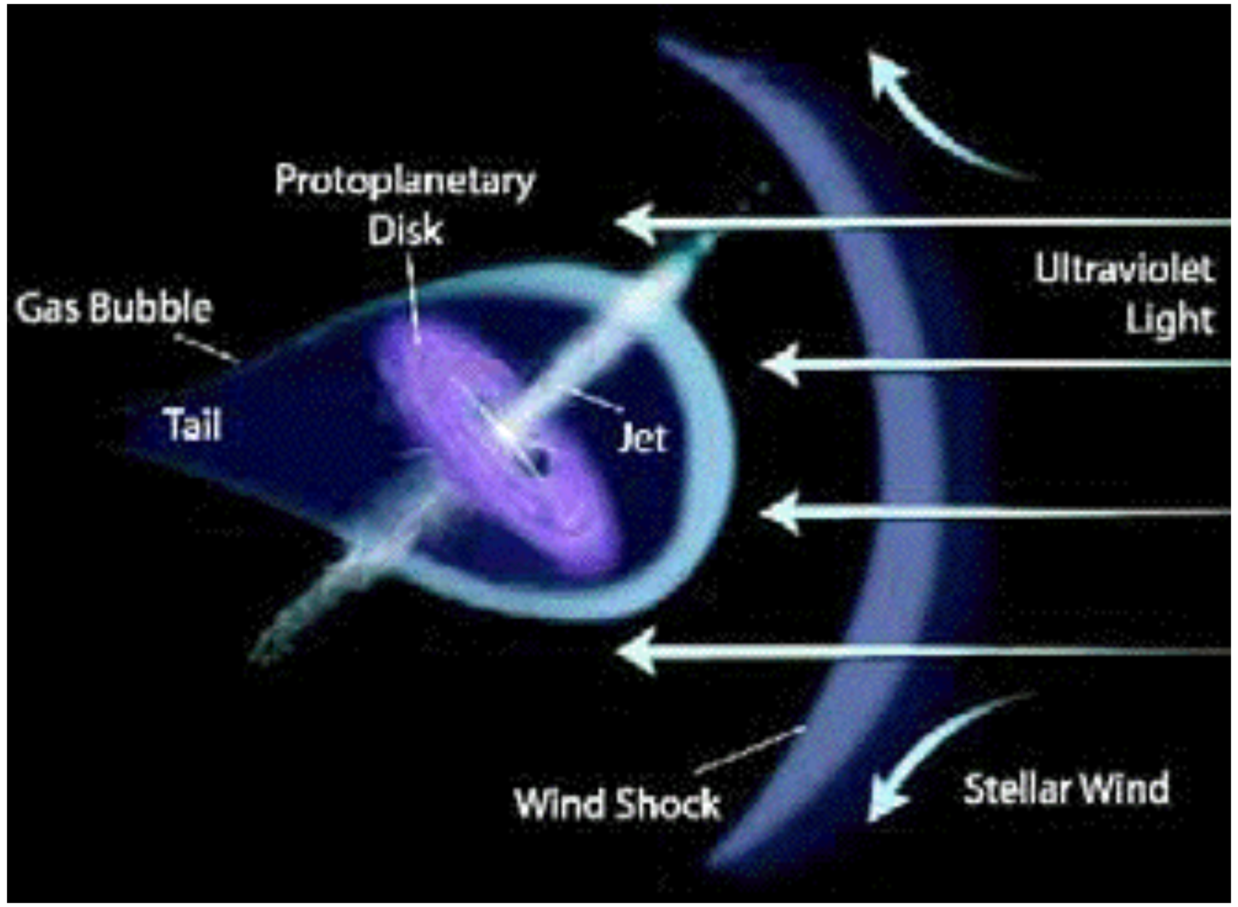
The Great Nebula in Orion, M42



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.

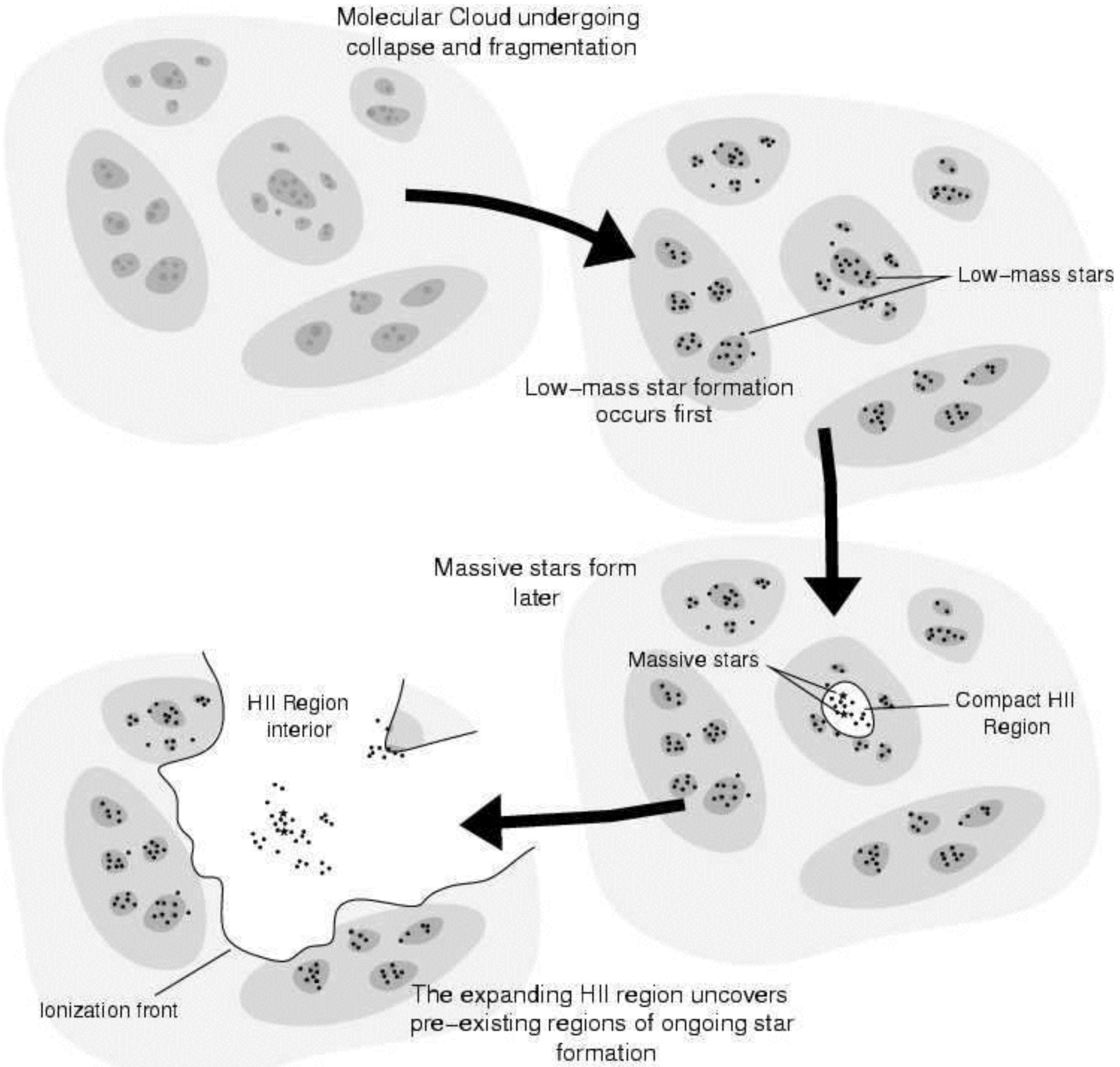




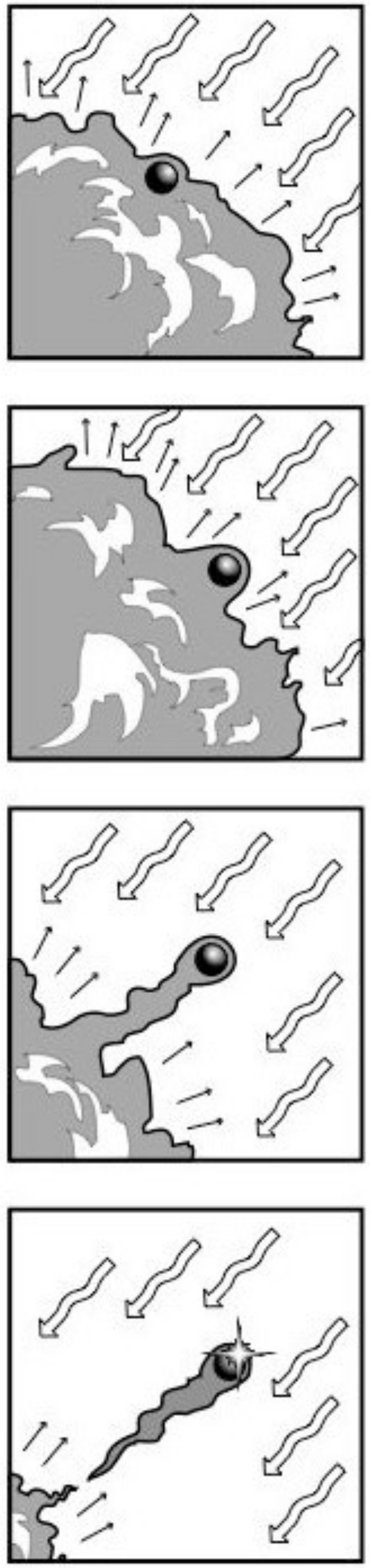
HST images show dust disks around embryonic stars in the Orion Nebula being "blowtorched" by a blistering flood of ultraviolet radiation from the region's brightest star.

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.

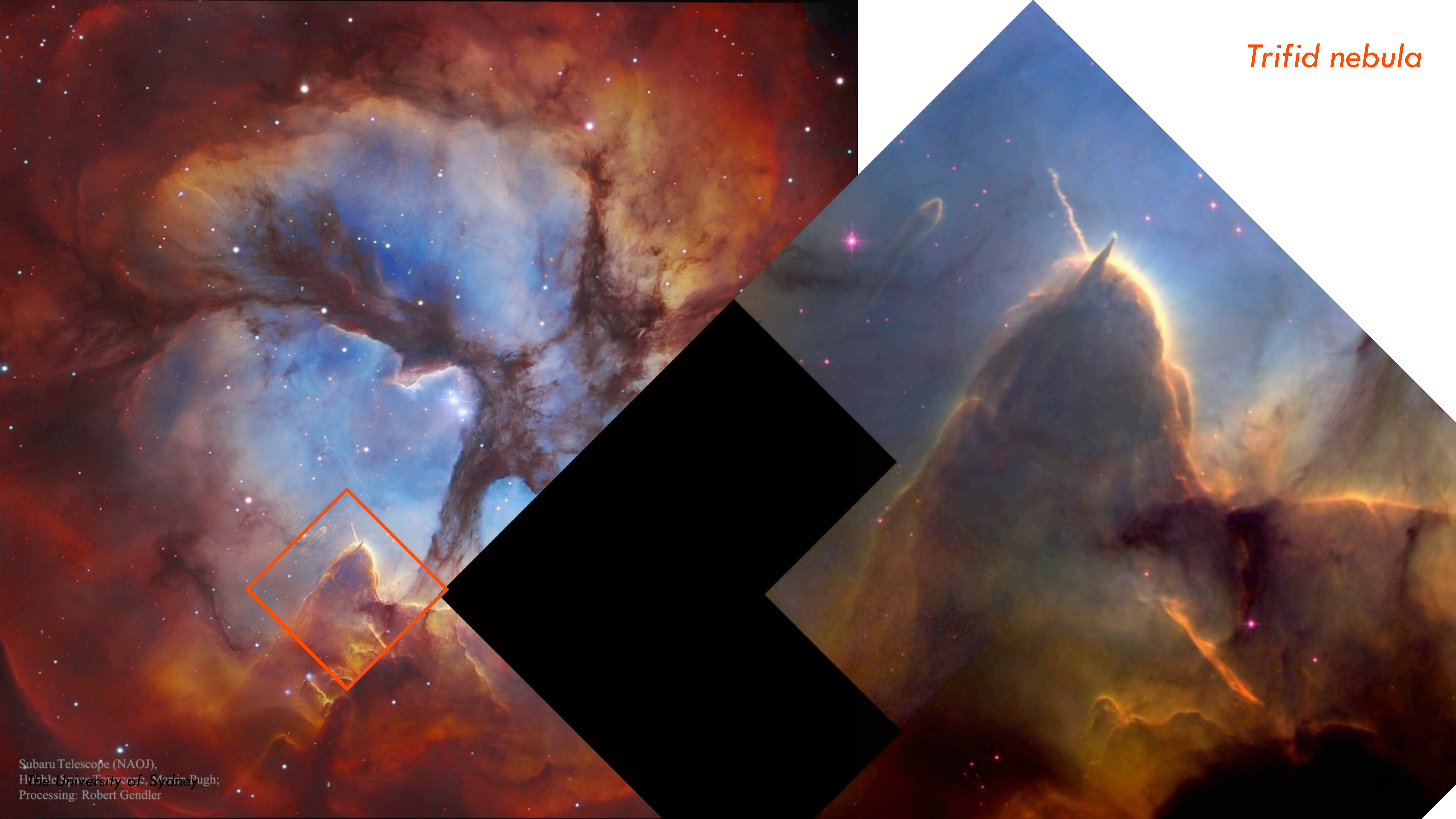
Probably the stars formed in the dense molecular gas around the ionised regions, and were uncovered by photo-evaporation of the dense gas.



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

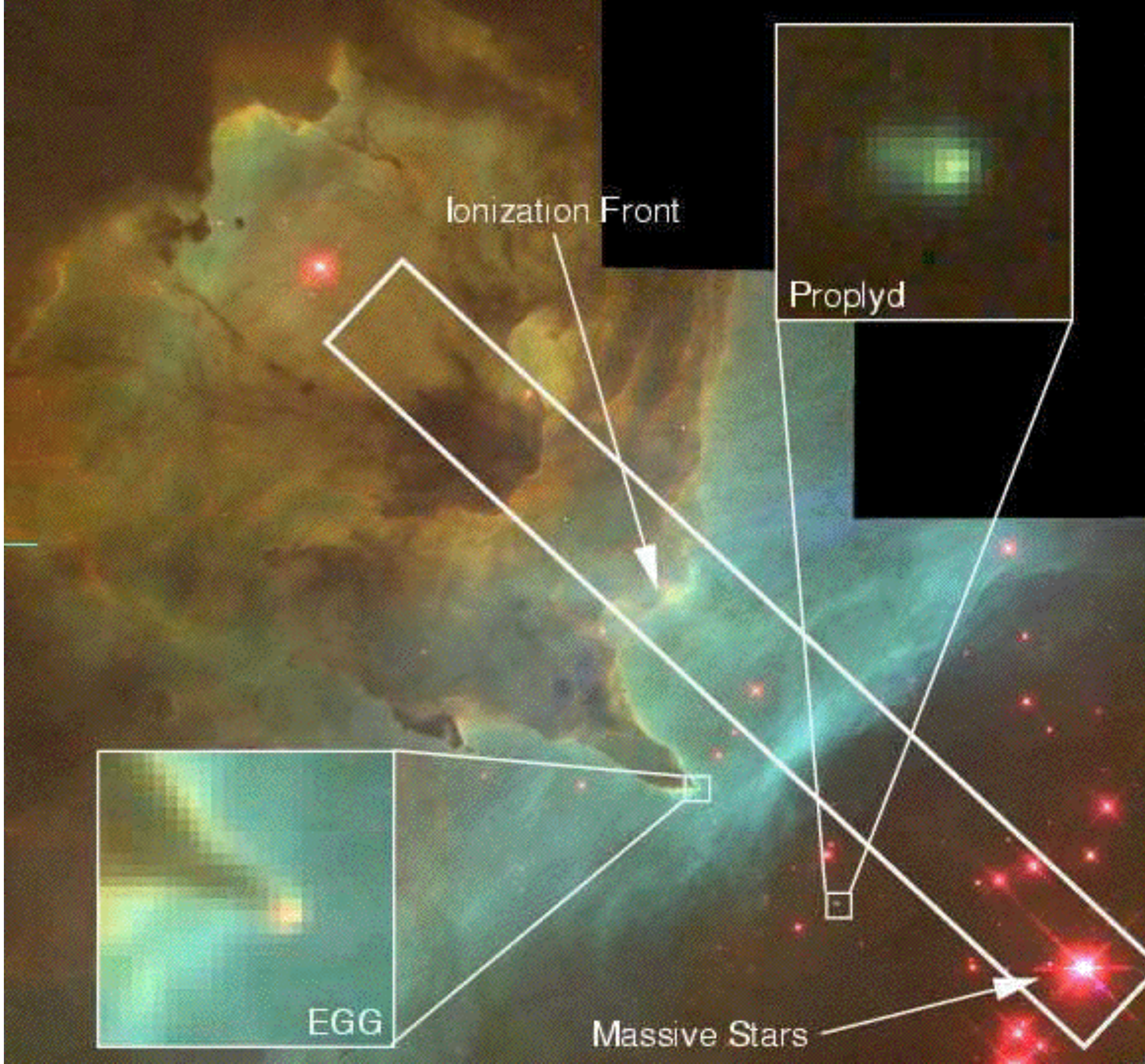


Subaru Telescope (NAOJ),
Hubble Space Telescope, Martin Pugh;
Processing: Robert Gendler

The University of Sydney

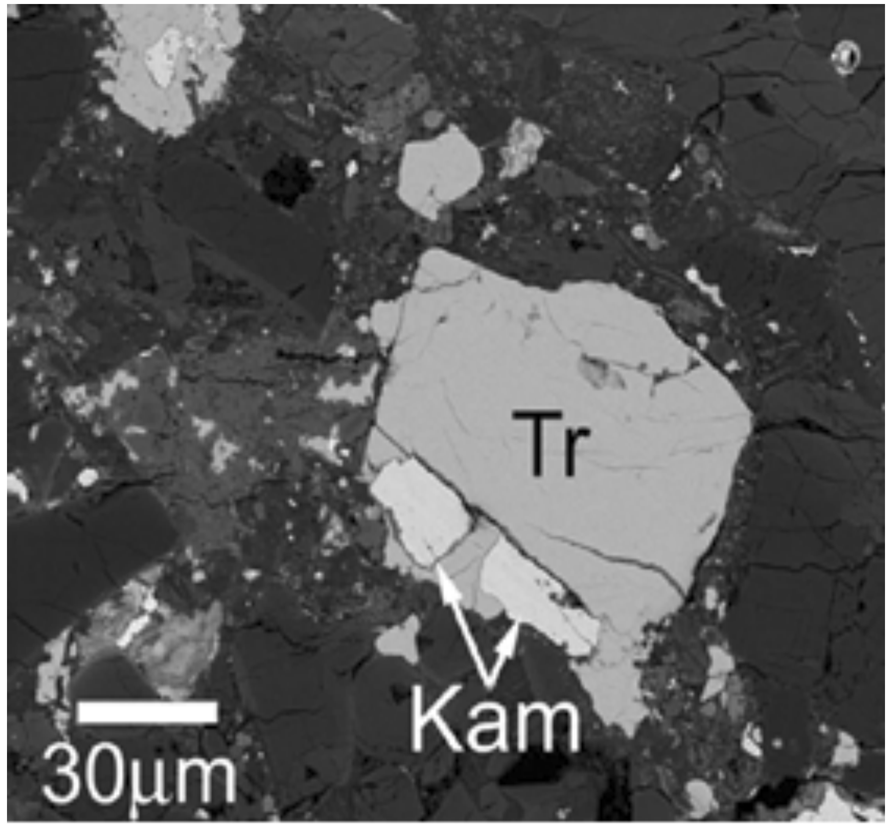
In the Triffid Nebula, we see more EGGS, including one which appears to be turning into a proplyd.

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.

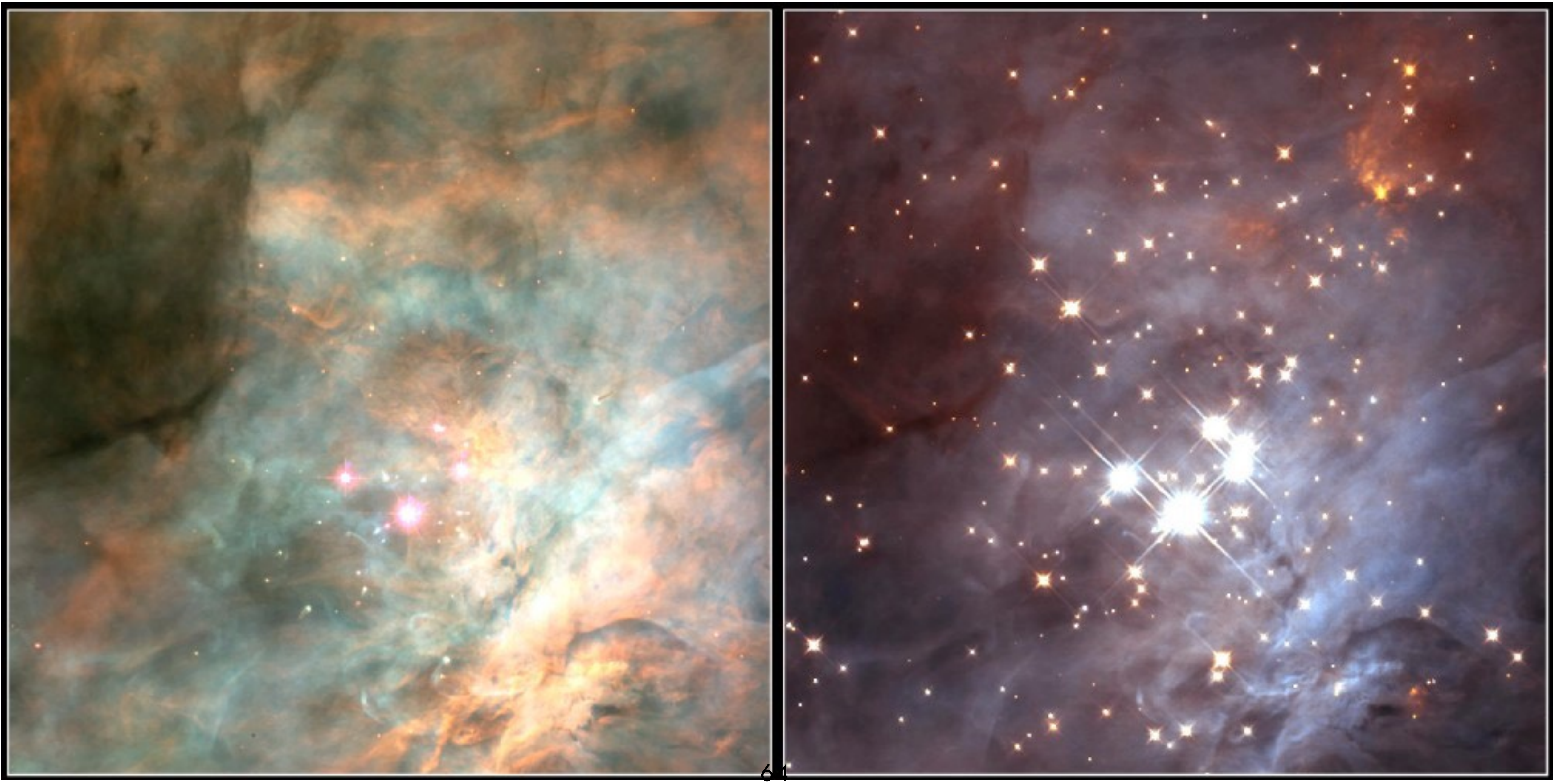
Evidence that the Sun did indeed form in a region containing massive stars comes from the discovery of the decay products of ^{60}Fe when they were formed. ^{60}Fe is a short-lived (half-life 1.5 million years) isotope, which must have been produced in a supernova explosion. This means that our Sun formed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

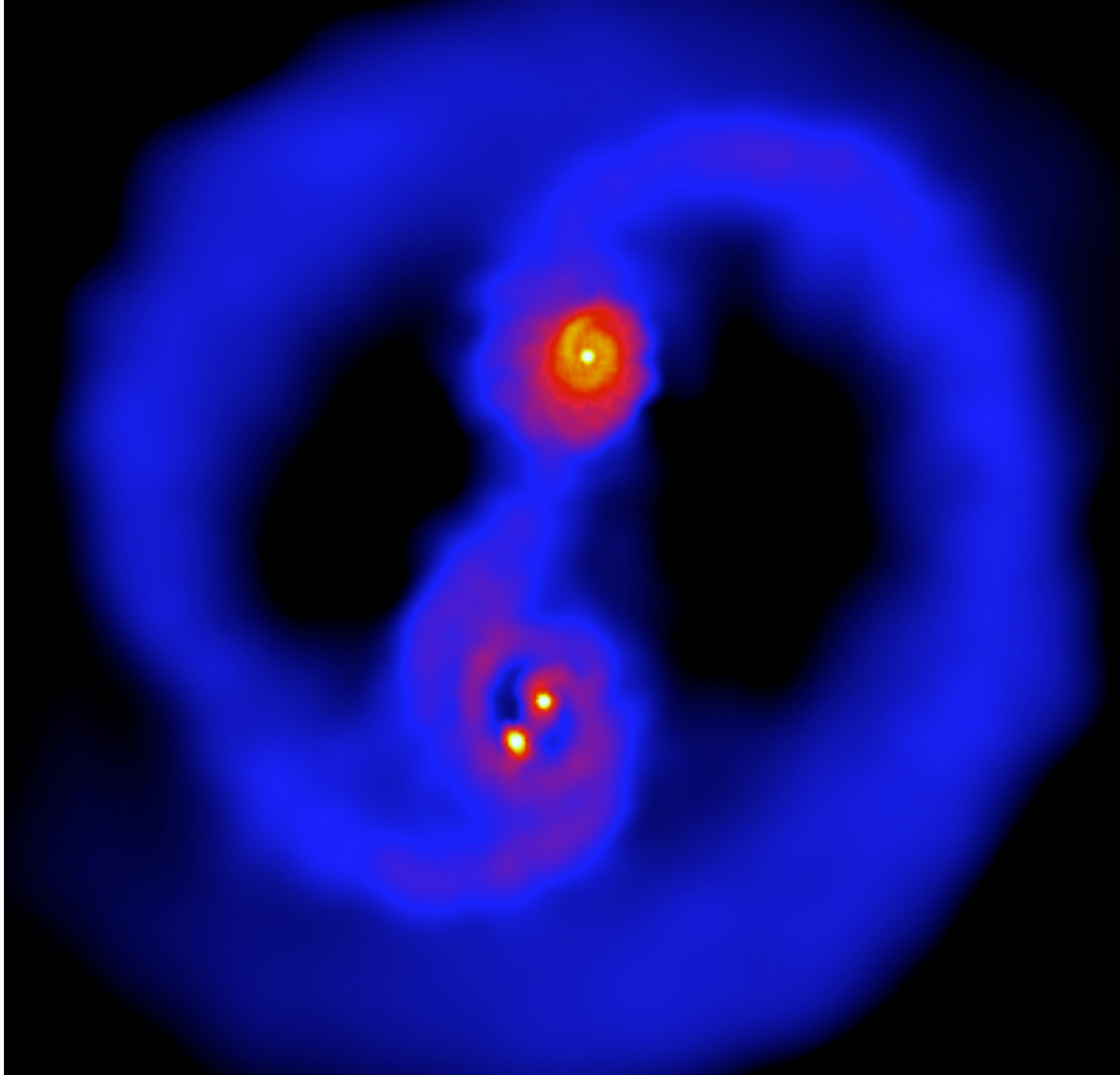
Similarly, in binary systems most of the angular momentum is carried by the orbits of the stars.

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.

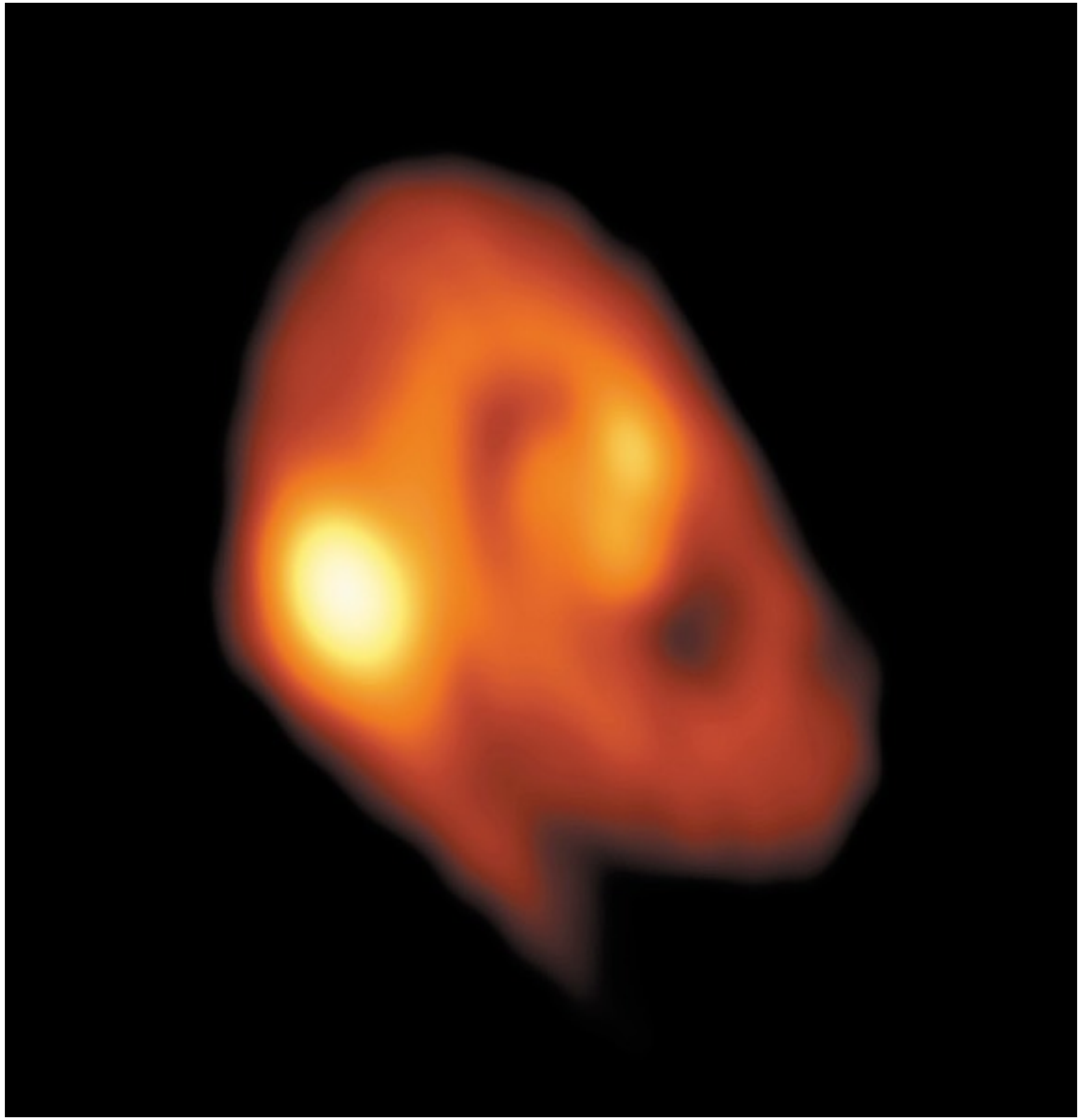
But *how* do you form a binary companion?

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



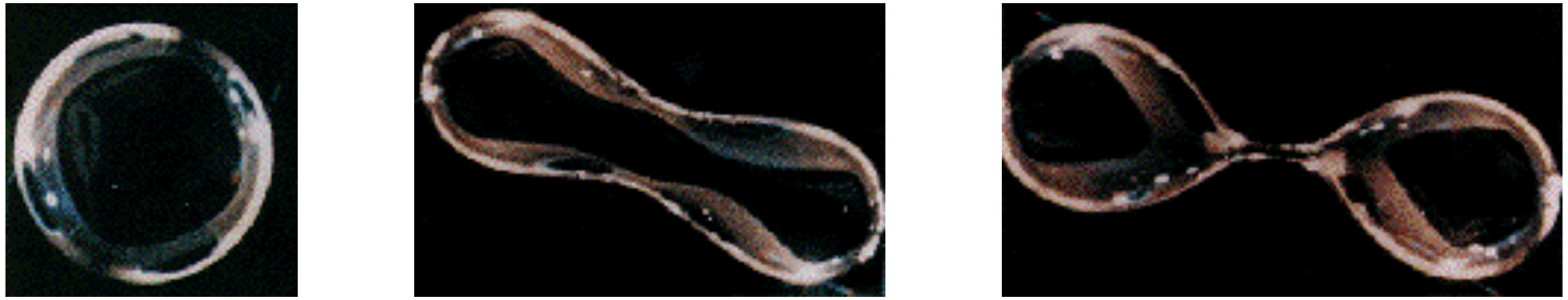
Simulation of the collapse and fragmentation of a molecular cloud, forming a triple system. (From Bate, Bonnet & Price 1995)



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

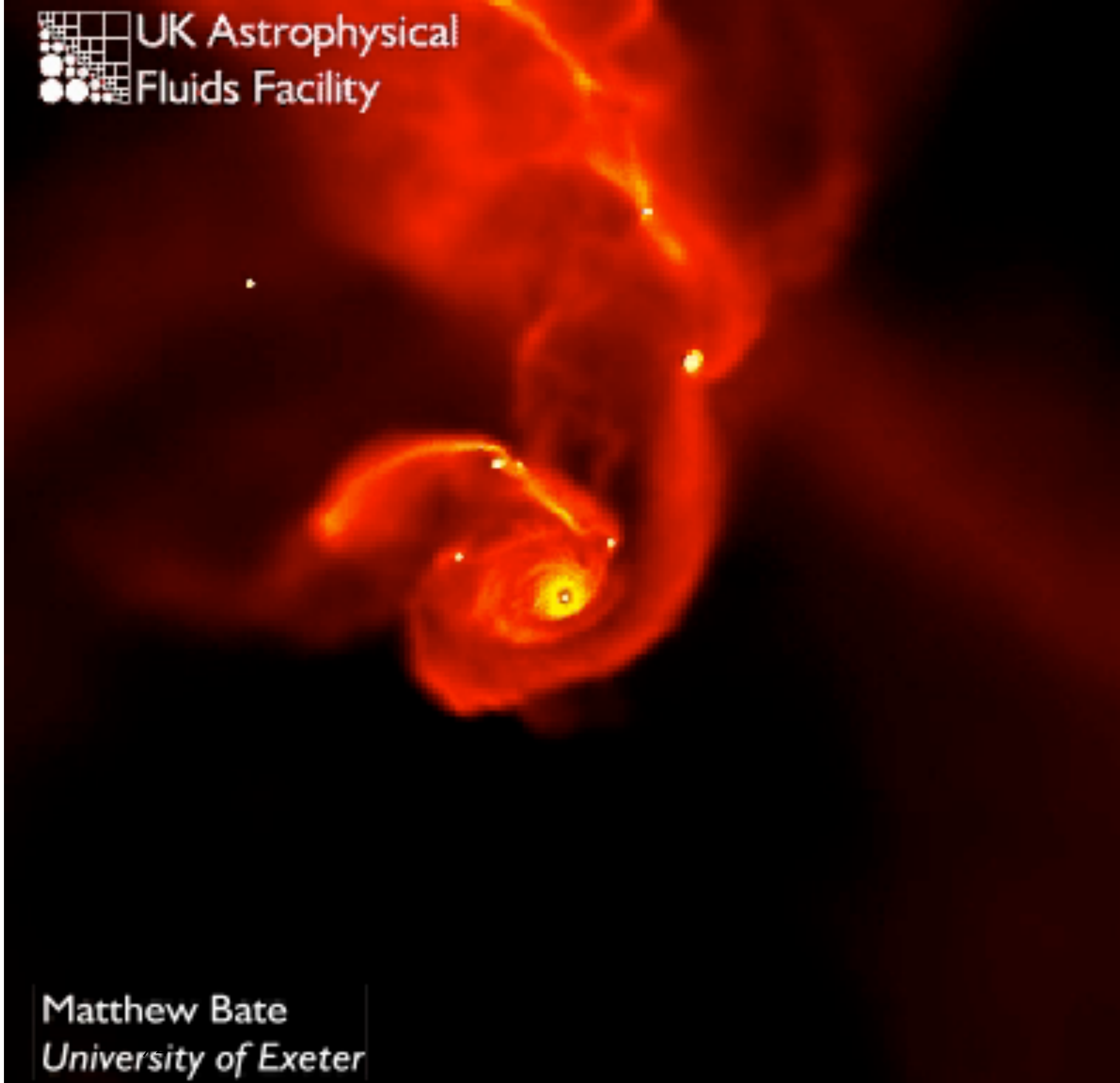
The following pictures of a rotating water drop in zero-gravity (on the Space Shuttle) shows it fissioning into two drops.



However, computer models can’t yet get stars to form binaries like this.

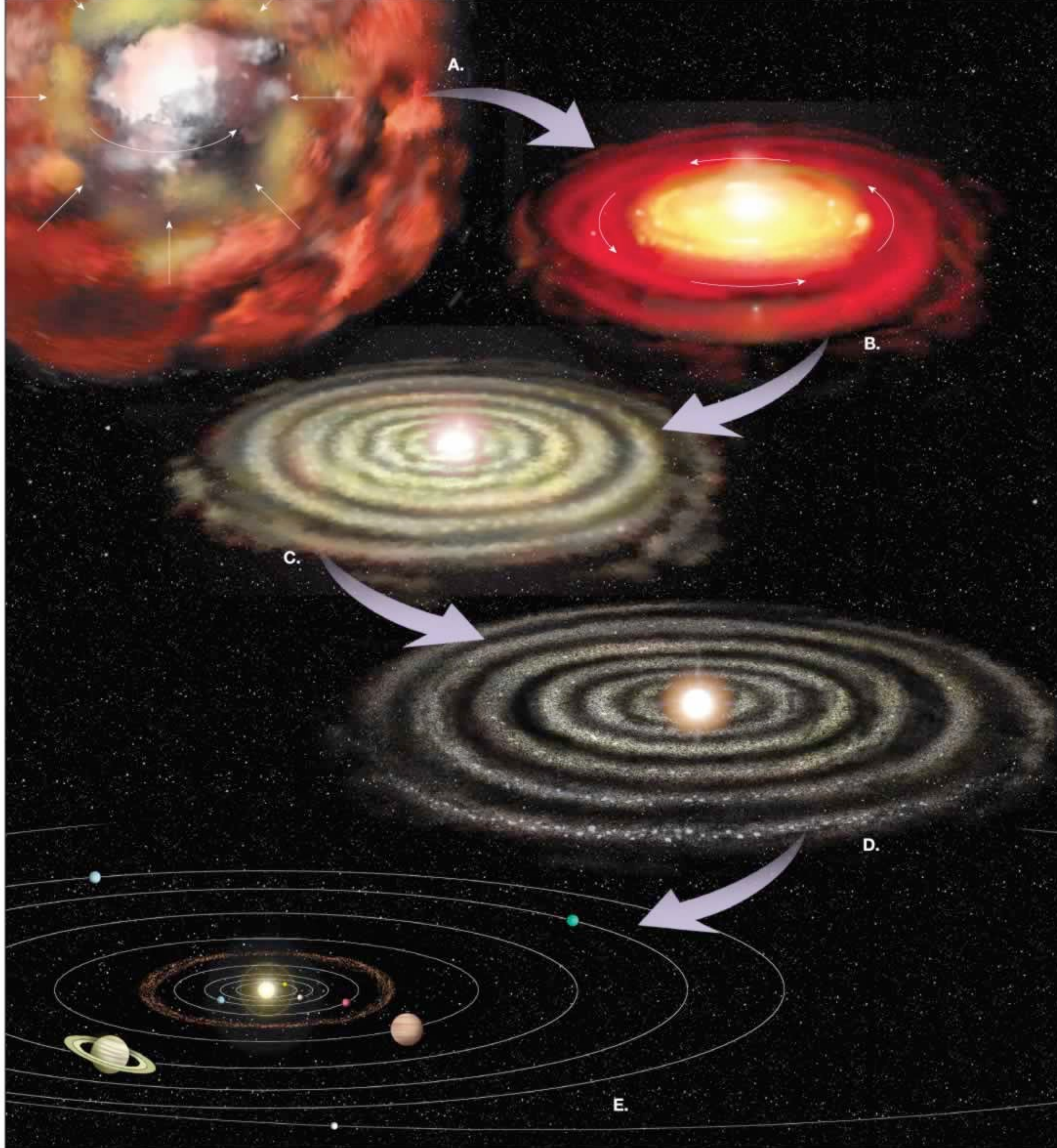
Newer work suggests that stars form together in subgroups, and within these groups binary and multiple systems are continually formed and disrupted. If this is true, then stable disks like the one which we think formed our own Solar System may not be very common, as they are usually disturbed by a companion star during formation. Or perhaps our own solar system was also disturbed by a binary companion (the 8° 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.

But those details are for another time…



Next week

… we'll talk about binary stars, and do some star-viewing (if the weather's good).

If not,we'll talk about how stars change as they age, after finishing life on the main sequence.

Further reading

- Finally, after several years of looking for a decent popular book, a good one has come out: “**The Birth of Stars and Planets**” by John Bally and Bo Reipurth (Cambridge UP, 2006). Written by two experts in the field, it is an excellent description of a very complicated field, as well as being a really beautiful book, full of many fabulous pictures from Hubble, Spitzer and ground-based telescopes.

- You can keep up with the latest Spitzer images at the Spitzer site http://www.spitzer.caltech.edu/spitzer/index.shtml

- The Australia Telescope Outreach and Education site has a good description of star formation, at http://outreach.atnf.csiro.au/education/senior/astrophysics/stellarevolution_formation.html

Sources for images used:

- Cycle of matter: from The Chaotic Winds of Cool Giants by Peter Woitke http://www.strw.leidenuniv.nl/~woitke/Bilder/Cycle_of_matter_small.jpg
- Bok Globule BHR 71: from Astronomy Picture of the Day 2003 January 27, http://apod.nasa.gov/apod/ap030127.html
- Spitzer image of Rho Ophiuchi dark cloud: from “Spitzer Catches Young Stars in Their Baby Blanket of Dust”, Spitzer Press Release 2008-03 http://www.spitzer.caltech.edu/Media/releases/ssc2008-03/
- Orion Nebula and Horsehead Nebula: image by Emmanuel Mallart, from Astronomy Picture of the Day 2002 May 30, http://apod.nasa.gov/apod/ap020530.html
- Map of solar neighbourhood: illustration by Linda Huff and Priscilla Frisch, from Astronomy Picture of the Day 2002 February 17, http://apod.nasa.gov/apod/ap020217.html
- The Milky Way near the Southern Cross: image by Yuri Beletsky, from APOD 2007 May 17 http://apod.nasa.gov/apod/ap070517.html
- Emu dreaming: photo by Barnaby Norris, from http://www.atnf.csiro.au/research/AboriginalAstronomy/Examples/emu.htm
- Big Bang: from "Faith and Reason": The Big Bang http://www.pbs.org/faithandreason/media/bbang-body.html
- Big Bang nucleosynthesis: from Formation of the Elements by Kipp Penovich http://aether.lbl.gov/www/tour/elements/early/early_a.html
- Periodic table: from http://sciencenotes.org/printable-periodic-table/
- Crab nebula: from Astronomy Picture of the Day 2008 Feb 17 http://apod.nasa.gov/apod/ap080217.html
- Cat’s Eye Nebula: from Astronomy Picture of the Day 2008 Mar 22 http://apod.nasa.gov/apod/ap080322.html
- Astronomer’s periodic table: Ben McCall http://rsta.royalsocietypublishing.org/content/364/1848/2953
- Dark nebula Barnard 68: from Astronomy Picture of the Day 2003 February 2, http://apod.nasa.gov/apod/ap030202.html
- Bok globules in NGC 281: from APOD 2003 April 7 http://apod.nasa.gov/apod/ap030407.html
- Dark globules in IC2944: from APOD 2012 June 12 http://apod.nasa.gov/apod/ap120612.html
- Star birth cycle: after diagram by Paul Francis, http://www.mso.anu.edu.au/~pfrancis/roleplay_copies.html
- Fragmentation of a cloud: from Jill Bechtold http://boojum.as.arizona.edu/~jill/NS102_2004/Lectures/Edo3/edo3.html
- Rotation and collapse: from STARS AND GALAXIES A Hypertext Course by Richard McCray http://cosmos.colorado.edu/cw2/courses/astr1120/text/chapter9/l9S3.htm
- Disks in the Orion Nebula: from Herschel Space Observatory: Stars, http://herschel.jpl.nasa.gov/science/stars01.html
- Formation of jet: from Chandra resources: Black holes http://chandra.harvard.edu/photo/2006/bhcen/bhe_closeup.jpg
- Cosmic tornado HH 49/50: from APOD 2006 February 3, http://apod.nasa.gov/apod/ap060203.html
- HH 46/47: from APOD 2003 December 26 http://apod.nasa.gov/apod/ap031226.html
- Movie of HH47 proper motion: from Patrick Hartigan http://sparky.rice.edu/~hartigan/movies.html
- Artist’s impression of protostar: from Rice University Physics and Astronomy Research: Galactic Astronomy http://www.physics.rice.edu/astro.cfm
- RY Tau: Gemini image, from APOD 2005 September 23 http://apod.nasa.gov/apod/ap050923.html
- T Tauri: T. A. Rector & H. Schweiker, NOAO, from APOD 2009 August 3 http://apod.nasa.gov/apod/ap090803.html
- Time to reach the main sequence: from Jill Bechtold http://boojum.as.arizona.edu/~jill/NS102_2004/Lectures/Edo3/edo3.html
- Stages in the life of a protostar: from Astr3730 lecture notes by Phil Armitage, Lecture 25 http://jilawww.colorado.edu/~pja/astr3730/index.html and “Jets and Molecular Outflows” by Hsien Shang https://www.tiara.sinica.edu.tw/activities/workshop/2007/presentation/shang.pdf
- Jets from L1157: from “Embryonic Star Captured with Jets Flaring”, Spitzer Press Release 2007-19 http://www.spitzer.caltech.edu/Media/releases/ssc2007-19/index.shtml
- Debris disks and animation: from “Spitzer and Hubble Capture Evolving Planetary Systems” http://www.spitzer.caltech.edu/Media/releases/ssc2004-22/index.shtml

- Hubble image of M51: from Hubblesite, http://hubblesite.org/gallery/album/entire_collection/pr2005012a/
- Spiral density wave animation: from Rolf Schröder http://www.rschr.de/Htm/Astro.htm; triggered collapse, from http://www.olemiss.edu/courses/astr104/Topics/Formation-N.html
- Proplyds in Taurus: from Hubblesite http://hubblesite.org/newscenter/newsdesk/archive/releases/1999/05/
- Orion: from APOD 2006 January 19 http://apod.nasa.gov/apod/ap060119.html
- Pillars in the Eagle Nebula: from Hubblesite http://hubblesite.org/newscenter/newsdesk/archive/releases/1995/44/
- Proplyds in Orion: from Hubblesite http://hubblesite.org/newscenter/newsdesk/archive/releases/2001/13/
- The Eagle Nebula: image by T. Rector, NOAO/AURA, from APOD 2004 October 24, http://apod.nasa.gov/apod/ap041024.html
- Fragmentation of molecular cloud: from "Understanding our Origins: Star Formation in H II Region Environments," J. J. Hester & S. J. Desch 2005, ASP Conference Series vol. 341, "Chondrules and the Protoplanetary Disk," p. 107 http://eagle.la.asu.edu/hester/star_formation/kauai_hester_final.pdf
- Trifid nebula: from http://apod.nasa.gov/apod/ap151011.html and http://hubblesite.org/newscenter/archive/releases/1999/42/
- EGGs in the Trifid Nebula: from Jeff Hester http://eagle.la.asu.edu/hester/trifid.html
- Star formation in NGC 6357: from "Understanding our Origins: Star Formation in H II Region Environments," J. J. Hester & S. J. Desch 2005, ASP Conference Series vol. 341, "Chondrules and the Protoplanetary Disk," p. 107 http://eagle.la.asu.edu/hester/star_formation/kauai_hester_final.pdf
- Meteorite section: from “Triggering the Formation of the Solar System” by G. Jeffrey Taylor, Planetary Science Research Discoveries, May 2003, http://www.psrd.hawaii.edu/May03/SolarSystemTrigger.html
- Stars in the Trapezium cluster: from Hubblesite http://hubblesite.org/newscenter/newsdesk/archive/releases/2000/19/
- Binary formation by fragmentation: from SciTech Daily, “New Research Boosts Binary-Star Formation Theory”, 2 Jan 2014, http://scitechdaily.com/new-research-boosts-binary-star-formation-theory/
- Fragmentation of molecular cloud: from Matthew Bate’s Animations, http://www.astro.ex.ac.uk/people/mbate/animations.html
- Triple protostar system L1448 IRS3B, from Tobin et al. 2016, “A triple protostar system formed via fragmentation of a gravitationally unstable disk”, http://www.nature.com/nature/journal/v538/n7626/full/nature20094.html
- Fission of water droplet in microgravity: from USML-2 Drop Physics Module, http://liftoff.msfc.nasa.gov/Shuttle/USML2/science/dpm.html
- Simulation of molecular cloud collapse: from Matthew Bate’s Animations, http://www.astro.ex.ac.uk/people/mbate/animations.html
- Nebula hypothesis: from http://astronomyonline.org/Exoplanets/ExoplanetDynamics.asp#I1
- Stellar evolution image: from Wikipedia https://en.wikipedia.org/wiki/Stellar_evolution