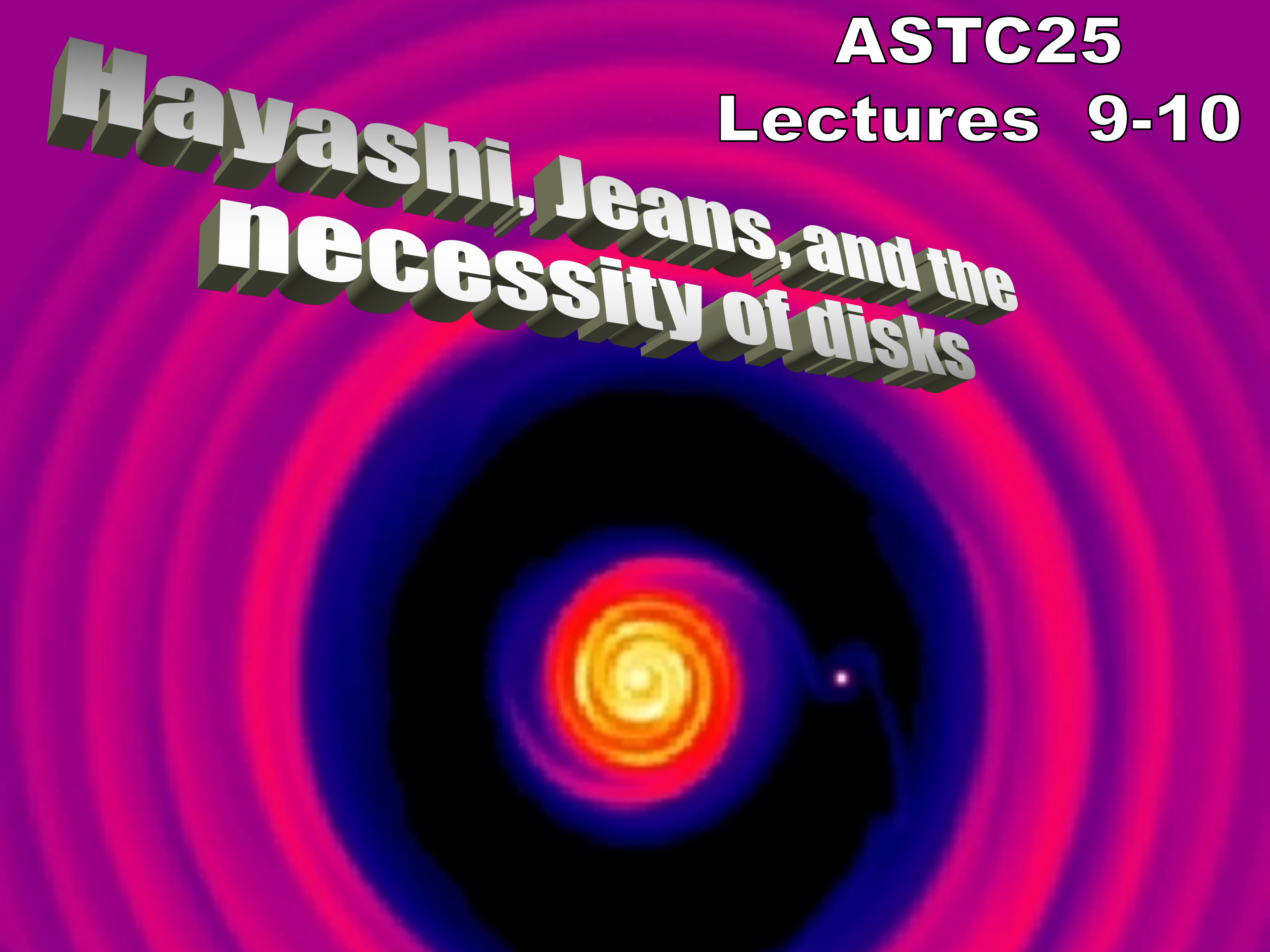
ASTC25
Lectures 9-10

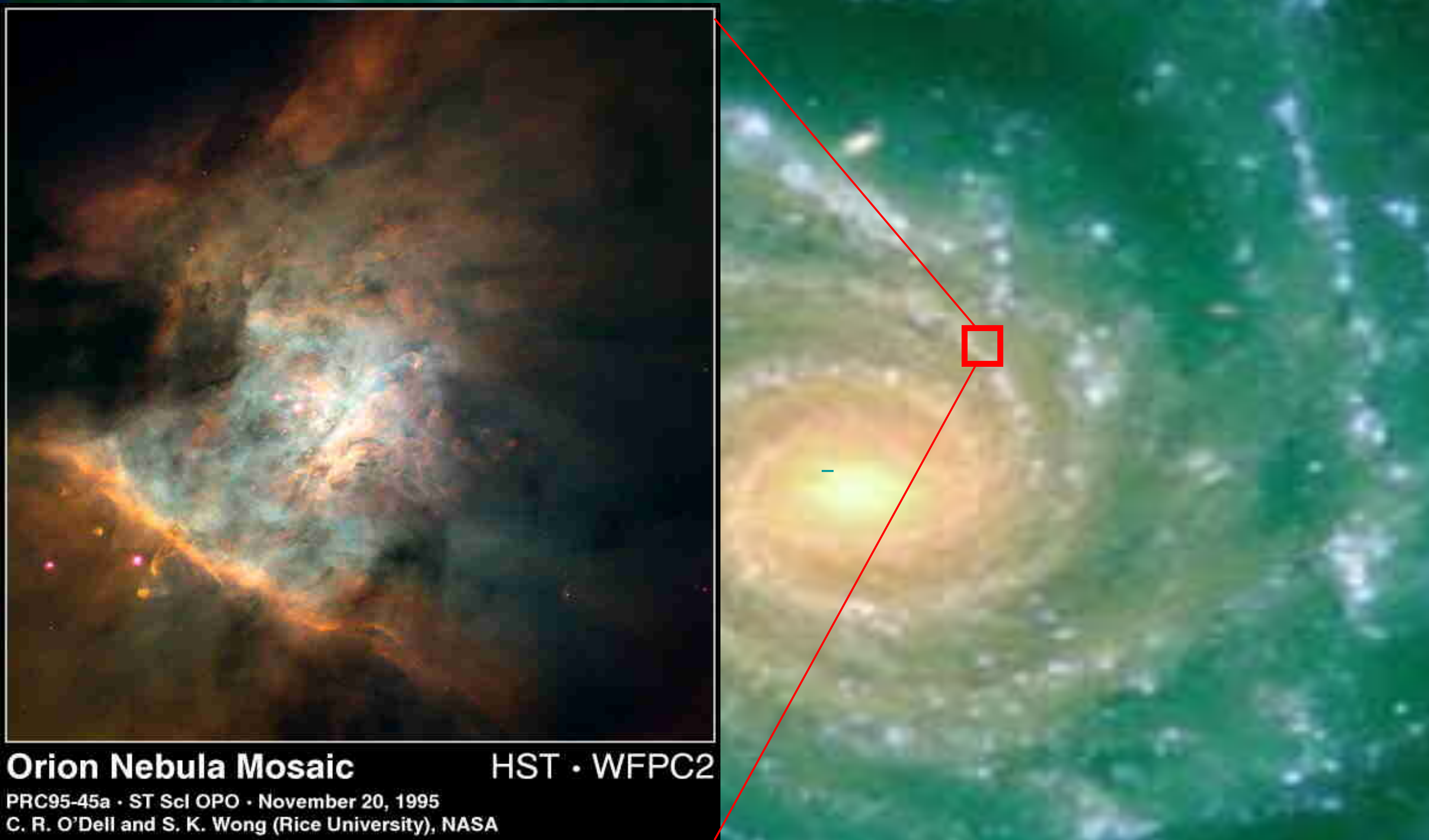
Hayashi, Jeans, and the necessity of disks



Jeans instability & the collapse of molecular clouds

James Hopwood Jeans
(1877-1946)

How Do Stars Form?

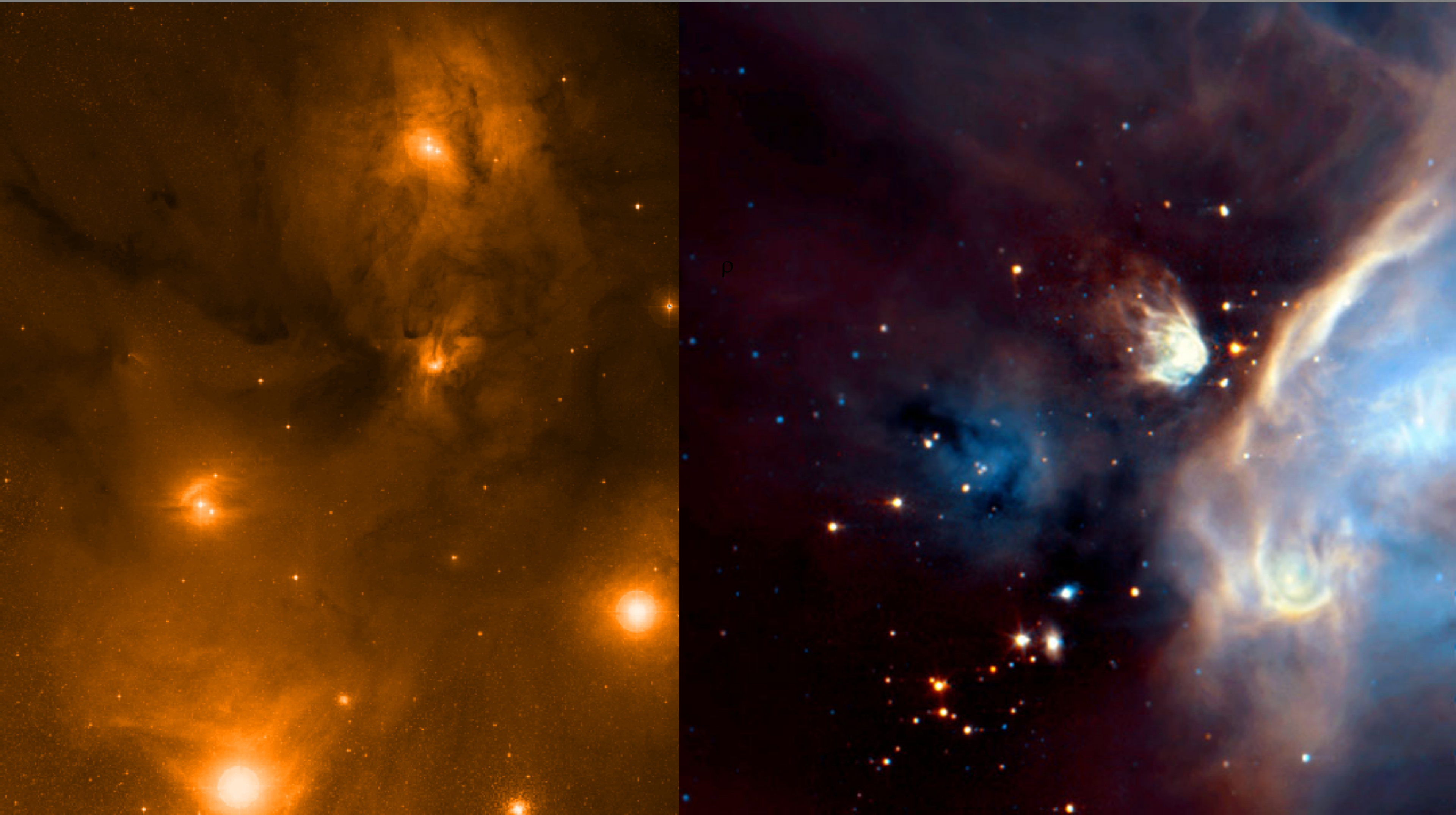


Orion Nebula Mosaic HST • WFPC2

PRC95-45a • ST ScI OPO • November 20, 1995
C. R. O'Dell and S. K. Wong (Rice University), NASA

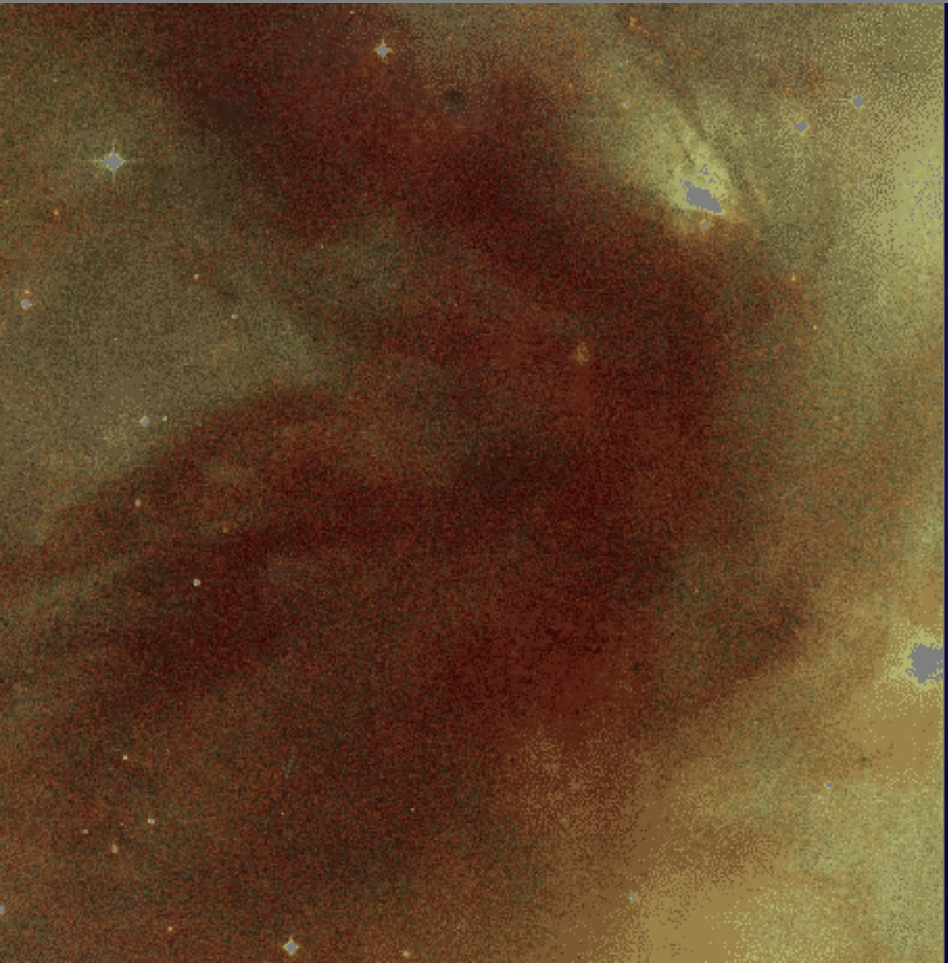
ρ Oph

Giant Molecular Cloud, 160 pc away contains numerous dark clouds



GMCs contain: dark clouds, cores, Bok globules
GMC mass = ~ 10^5 solar masses

ρ Oph



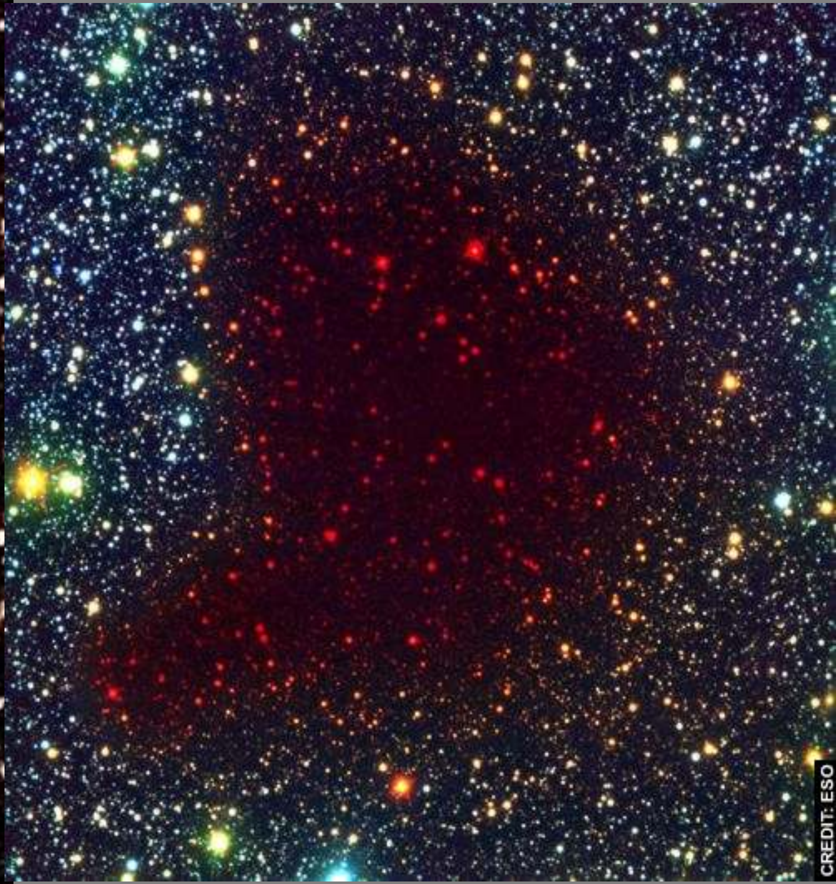
V380 Ori + NGC1999

NASA

Dark clouds

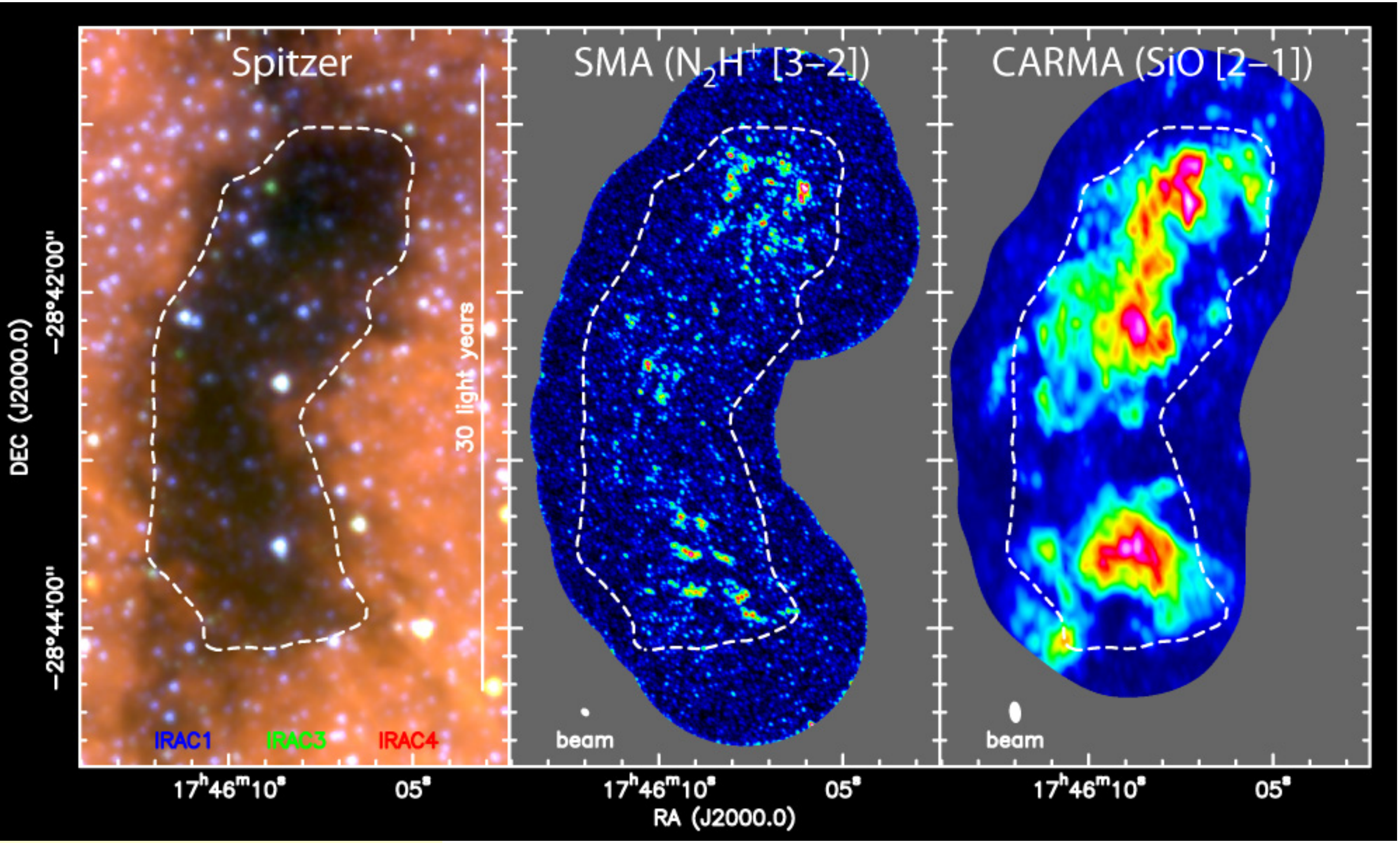
L57

Barnard 68



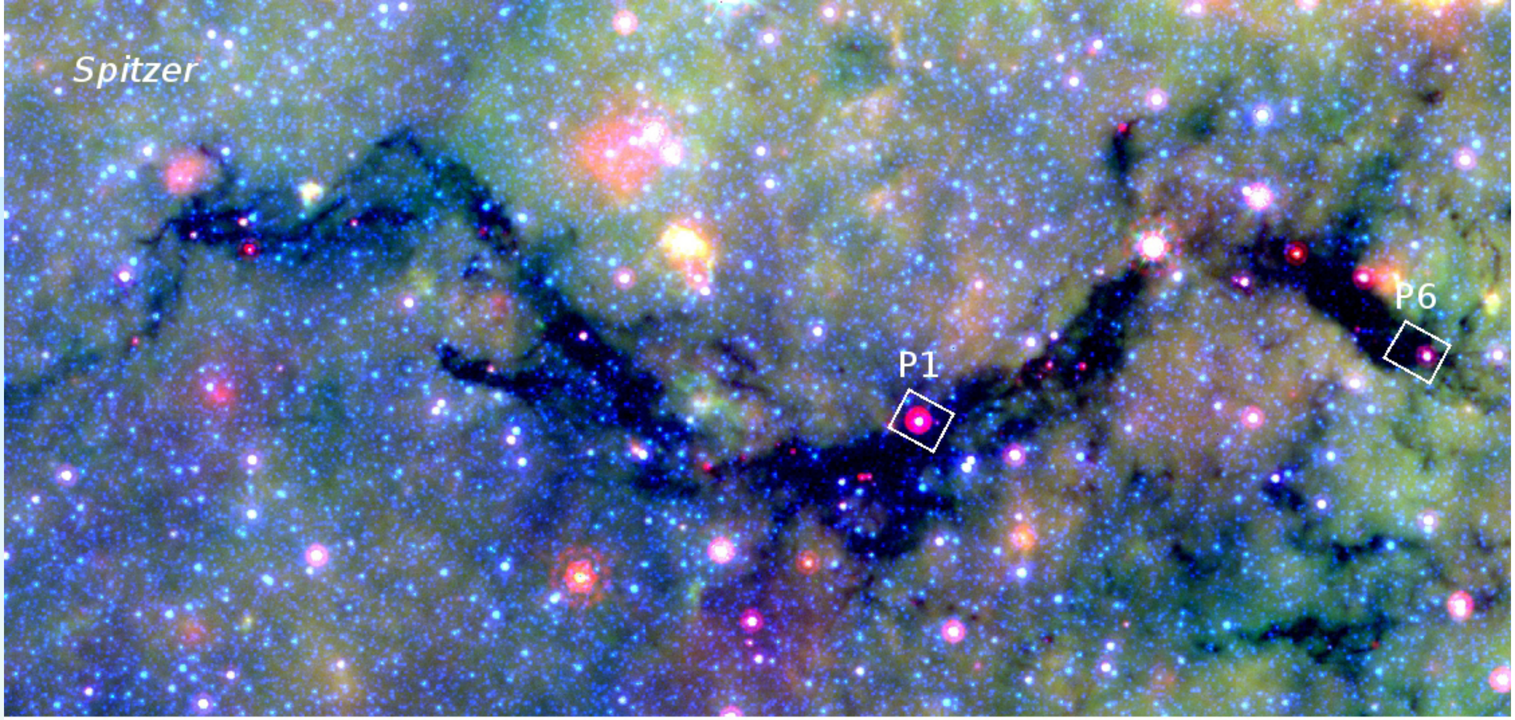
CREDIT: ESO

Different instruments: Spitzer telescope, SMA (Sub-mm Array) and CARMA observe the dark cloud in different wavelengths



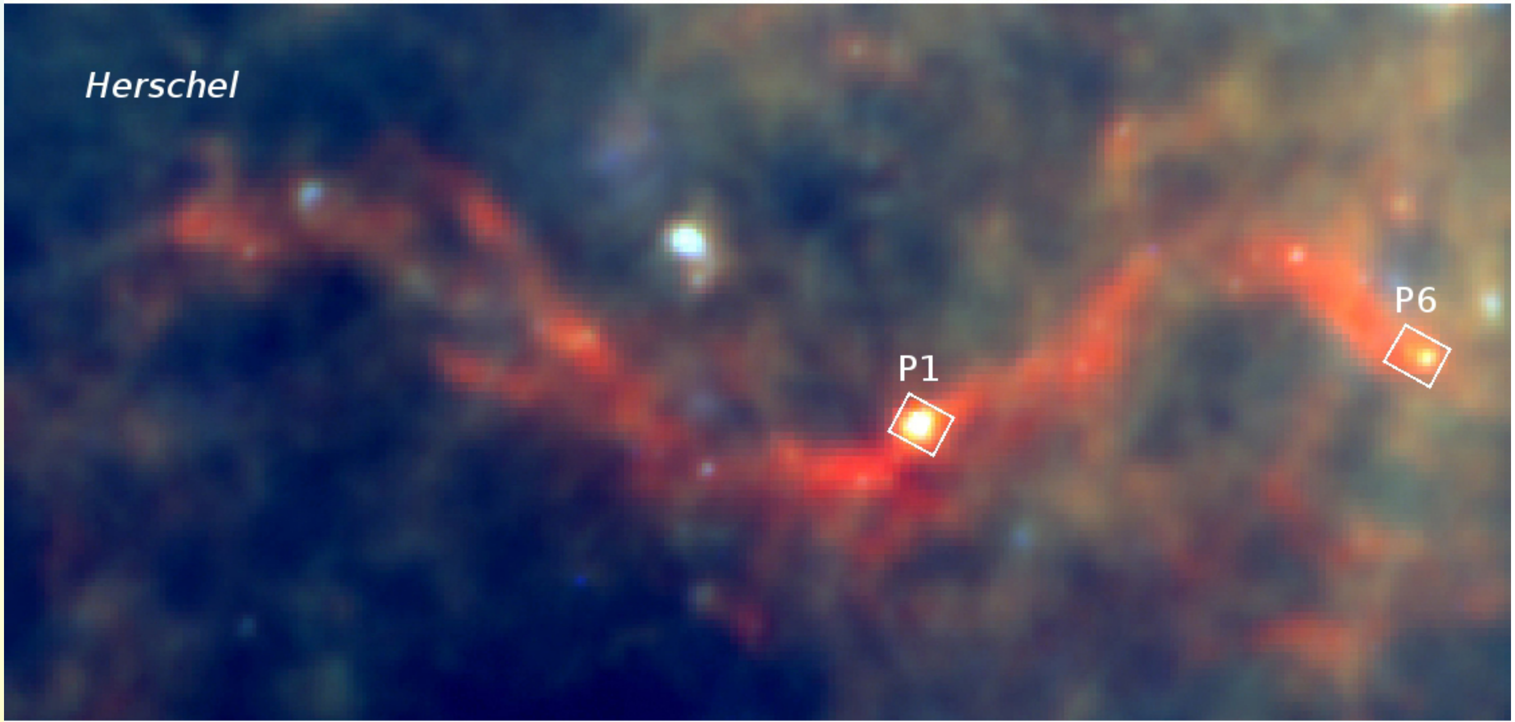
The central molecular zone of Galactic Center

Snake nebula



mid-IR
(λ=20-50μm)

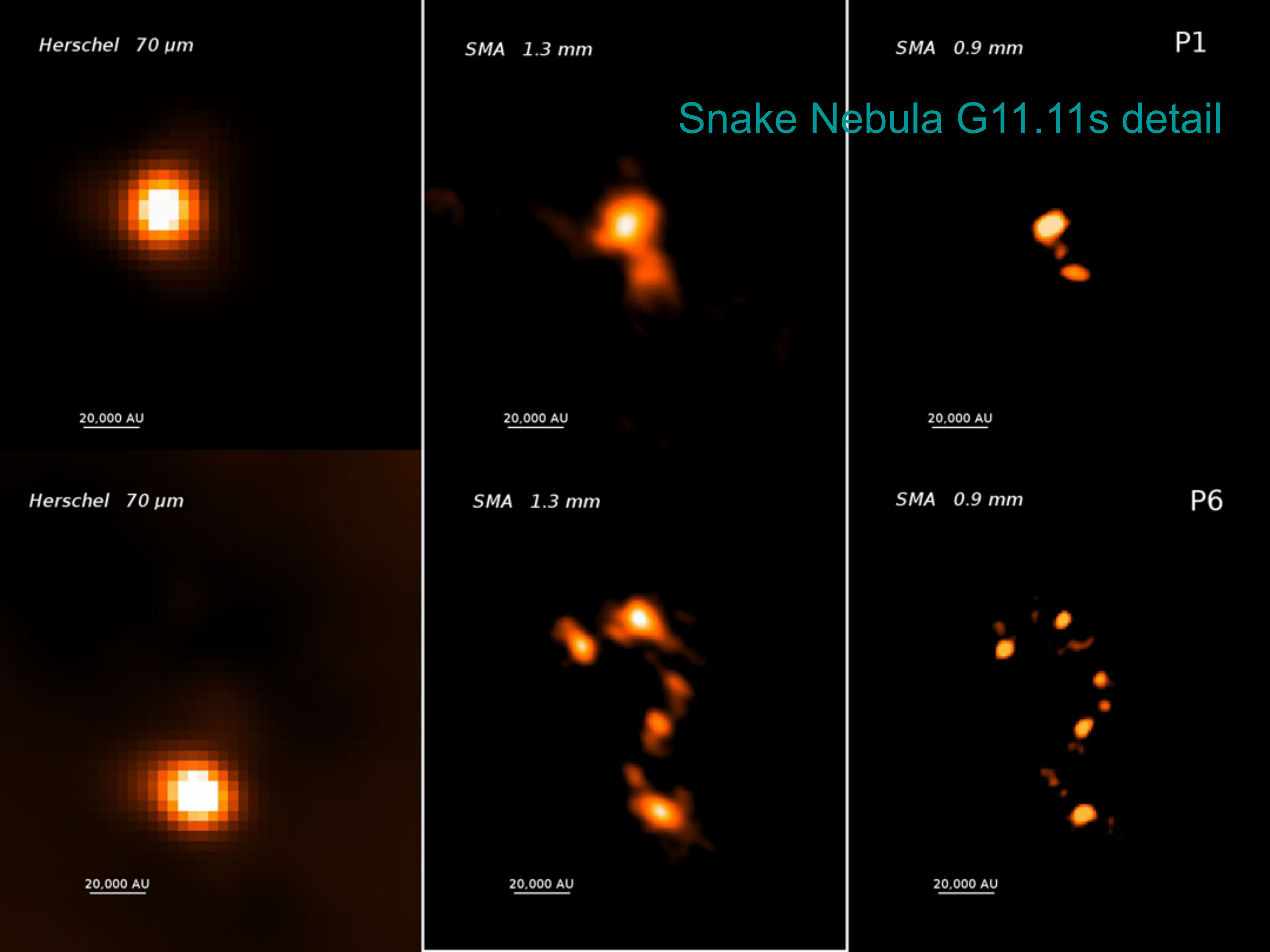
Spitzer
Space
Telescope

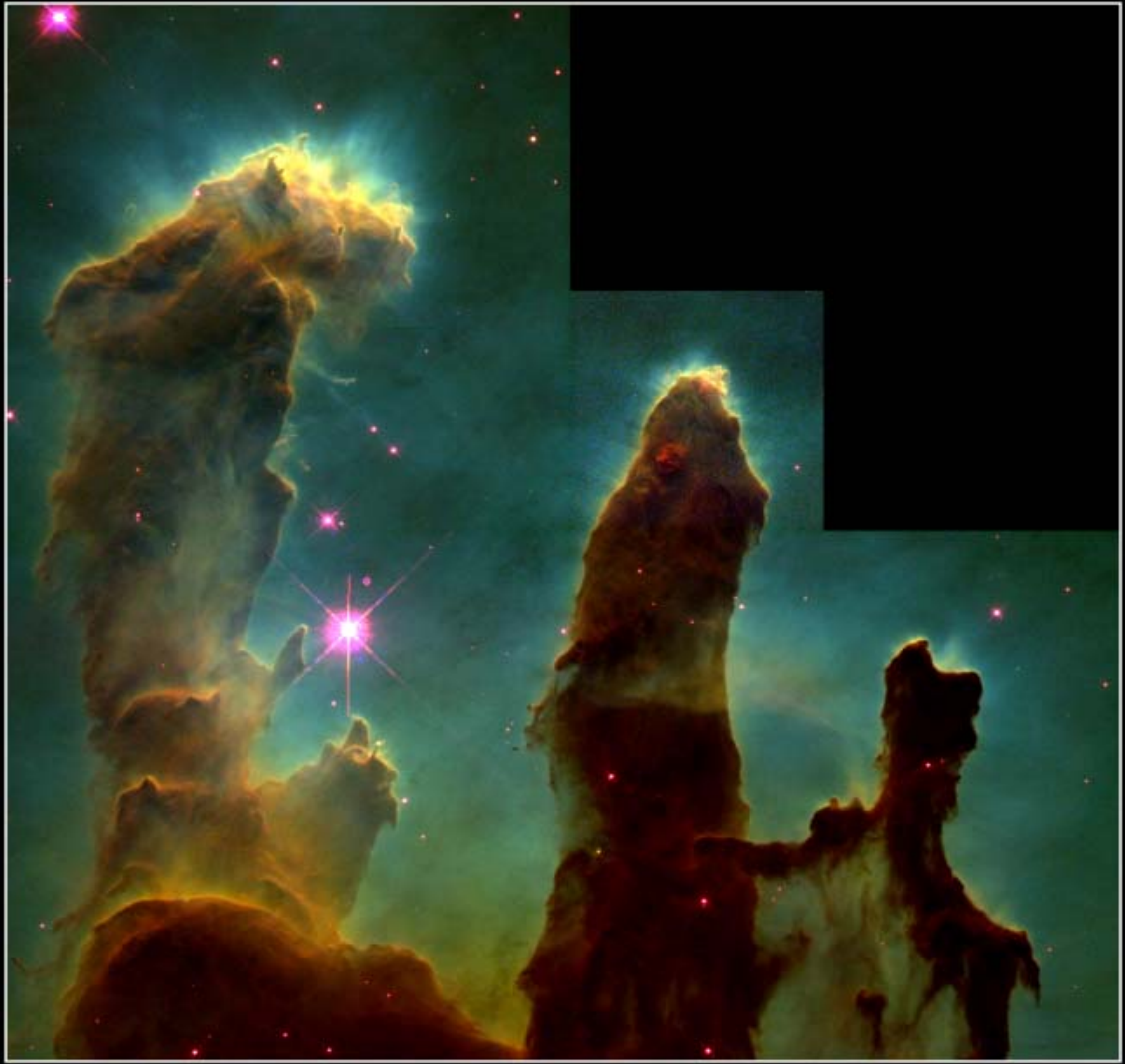


far-IR
λ = 70 μm

Herschel
Space
Telescope

Snake Nebula G11.11s detail





Gaseous Pillars · M16 HST · WFPC2

PRC95-44a · ST ScI OPO · November 2, 1995
J. Hester and P. Scowen (AZ State Univ.), NASA

Comparison of Hubble and Webb Space Telescope images of M16 (star forming region in Serpent constellation)

TheTrapezium cluster in the center of Orion Nebula

NASA, ESA, CSA,
Processing: M. McCaughrean & S. Pearson

Jeans Mass in molecular clouds

J.H. Jeans (1902)

$$\frac{dP}{dr} = -\varrho \frac{Gm}{r^2}$$ hydrostatic eq. $\Big| \cdot \underbrace{\frac{4}{3}\pi r^3}_{V}$

$$V dP = -\frac{1}{3}\frac{Gm\,dm}{r}$$

$(dm = 4\pi r^2 \varrho\, dr)$

$(dm = \varrho\, dV)$

$$d(PV) = VdP + PdV$$

Integrate :

$$\int d(PV) - \int P dV = -\frac{1}{3}\int \frac{Gm\,dm}{r}$$

(*) $$\underbrace{\int P\, dV}_{\int \frac{dm\, P}{\varrho}} = \Big[PV\Big]_0^R + \frac{1}{3}\int \frac{Gm\,dm}{r}$$

Integrate :

$$\int d(PV) - \int P\,dV = -\frac{1}{3}\int\frac{Gm\,dm}{r}$$

(*) $$\underbrace{\int P\,dV}_{\int\frac{dm\,P}{\rho}} = \left[PV\right]_0^R + \frac{1}{3}\int\frac{Gm\,dm}{r}$$

$$\left\{\begin{array}{l}\text{Ideal e.o.s.} \Rightarrow \quad P = \rho\frac{kT}{\mu m_H} =: \frac{\rho R_B T}{\mu} \qquad ; \; R_B = \frac{k}{m_H}\\ \int dV\,P = \frac{R_B}{\mu}\int T\rho\,dV \underset{\substack{\uparrow\\ T=\text{const}}}{=} \frac{R_B T}{\mu}M\end{array}\right.$$

Substituting into (*) we get

$$\frac{R_B}{\mu}TM = PV\Big|_{\substack{\text{boundary}\\ \text{of cloud}}} + \frac{1}{3}\underbrace{\int\frac{Gm\,dm}{r}}_{\alpha\frac{GM^2}{R}}$$

where $\alpha \sim 1$

$$\frac{R_B}{\mu} T M = P V \Big|_{\substack{\text{boundary}\\ \text{of cloud}}} + \frac{1}{3} \underbrace{\int \frac{G m \, dm}{r}}_{\alpha \frac{GM^2}{R}}$$

where $\alpha \sim 1$

$$\frac{R_B}{\mu} T \cancel{M} \geqslant \frac{1}{3} \alpha \frac{G M^{\cancel{2}}}{R} \quad \text{or} \quad \boxed{kT \geqslant \frac{\alpha}{3} \frac{G M \mu m_H}{R}}$$

~ thermal energy   ~ grav. binding energy

$$R \geqslant \frac{\alpha}{3} \frac{\mu G M}{R_B T}$$

or $R \geqslant R_J$ (Jeans radius)

R_J = lower limit on cloud size, given cloud mass M and temperature T.

$3\, k_B T$ energy

or $R \geqslant R_J$ (Jeans radius)

R_J = lower limit on cloud size, given cloud mass M and temperature T.

Conversely, if R & T are known, $M \leqslant M_J$

Jeans mass $\boxed{M_J := \frac{3}{\alpha} \frac{k_B T R}{\mu G}}$ (upper limit of stable cloud)

$$M_J \approx 10^5 M_\odot \left(\frac{T}{K}\right)^{3/2} \left(\frac{n}{m^{-3}}\right)^{-\frac{1}{2}} = 100\, M_\odot \left(\frac{T}{K}\right)^{3/2} \left(\frac{n}{cm^{-3}}\right)^{-1/2}$$

(we obtain this form by expressing R through mean density $\rho_{av} = M/V = M/(\frac{4}{3}\pi R^3)$, or the mean number density $n = \rho_{av}/(\mu m_H)$)

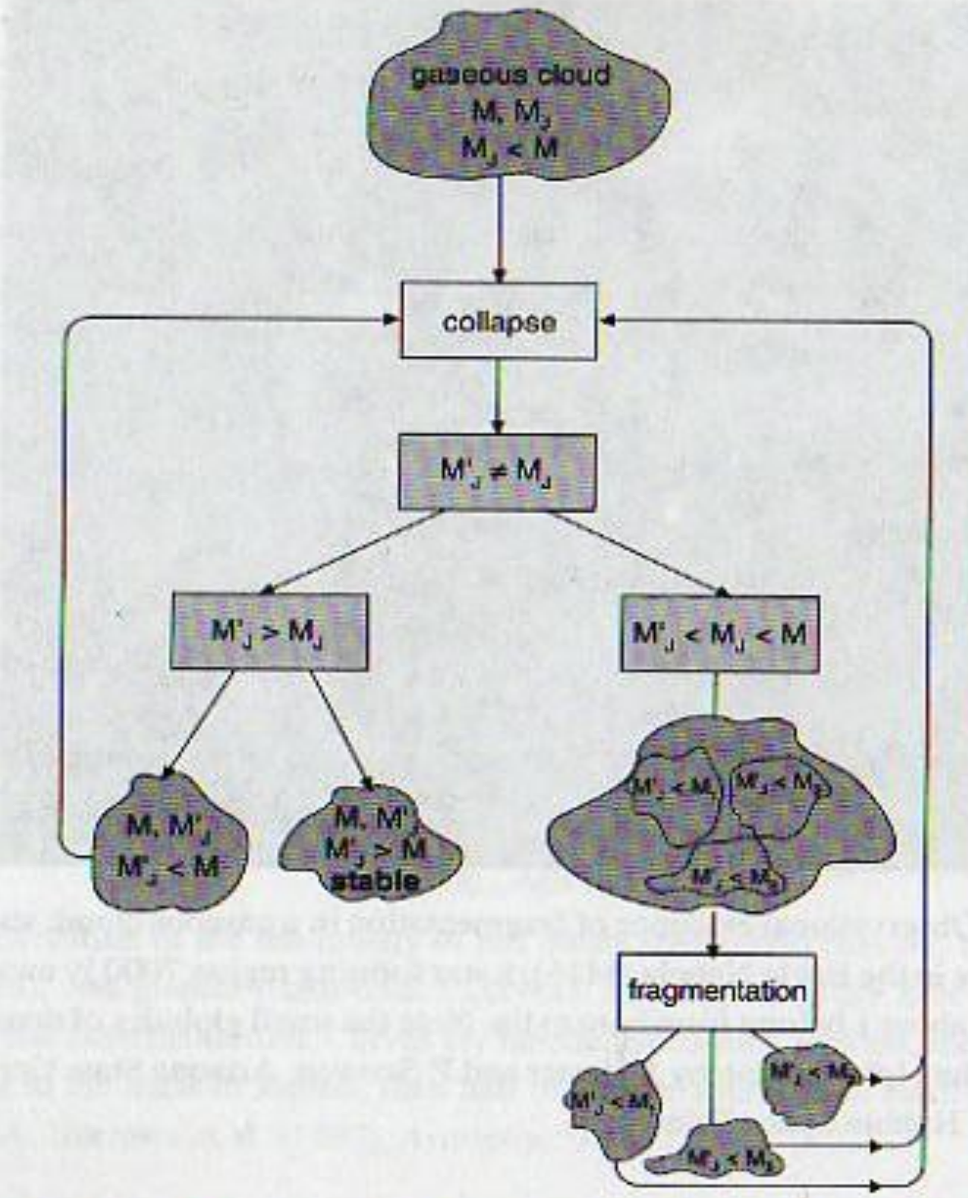


Figure 10.1 Schematic illustration of the fragmentation of a gas cloud.

Following the fragmentation history, and tracking the way M_{Jeans} changes w.r.t. the fragment mass,

F. Hoyle (1953) arrived at a concept of opacity-limited fragmentation.

When heat gets trapped by opacity, Jeans mass increases because T rises.

The smallest mass of a fragment is $\sim 0.01\ M_\odot = 10\ m_{Jup}$

This theory recently encountered possible observational challenges that we will consider below

Chushiro Hayashi
(1920-2010)

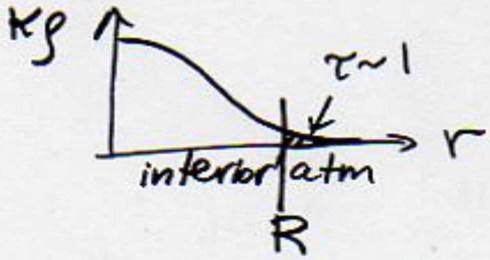
Hayashi tracks
and the
Pre-Main Sequence evolution of stars

Hayashi zone and the Pre-Main-Sequence phase (sect. 8.1 Prialnik)

Polytropes ⇒ $P = K \rho^{1+\frac{1}{n}}$ to describe convective star

$$K^n = C_n G^n M^{n-1} R^{3-n}$$

Joining convective interior and radiative atmosphere (photosphere) at $r = R$



$$\kappa = \kappa_0 \rho^a T^b$$

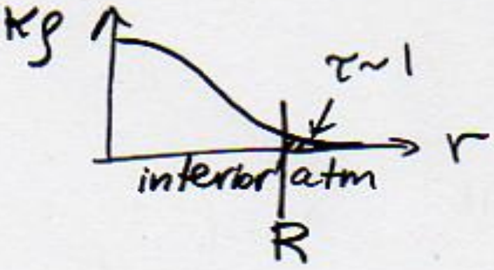
$(a,b,n) \rightarrow$ determine the relationship between

L, T_{eff}, M

(H–R diagram tracks)

One often takes $a=1$, $n = 1.5 \ldots 3$, then

Hayashi theory gives a nice explanation for nearly vertical tracks of PMS objects in the H-R diagram, under certain assumptions/guesses



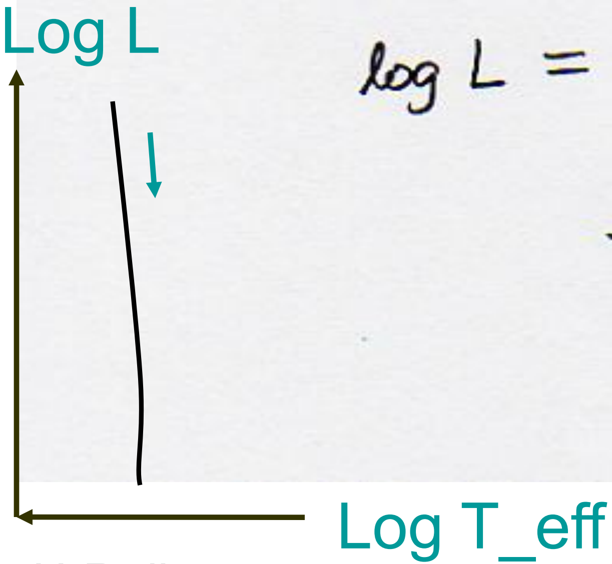
$$\kappa = \kappa_0 \rho^a T^b$$

$(a,b,n) \rightarrow$ determine the relationship between L, T_{eff}, M (H-R diagram tracks)

One often takes $a=1$, $n = 1.5 \ldots 3$, then

$$\log L = \underbrace{\left(\frac{9-2n+b}{2-n}\right)}_{\text{for } b\approx 4 \text{ this is } \approx 20} \log T_{eff} + \left(\frac{1-2n}{2-n}\right) \log M + \text{const.}$$

$\Rightarrow$ almost vertical tracks on H-R diagram



H-R diagram

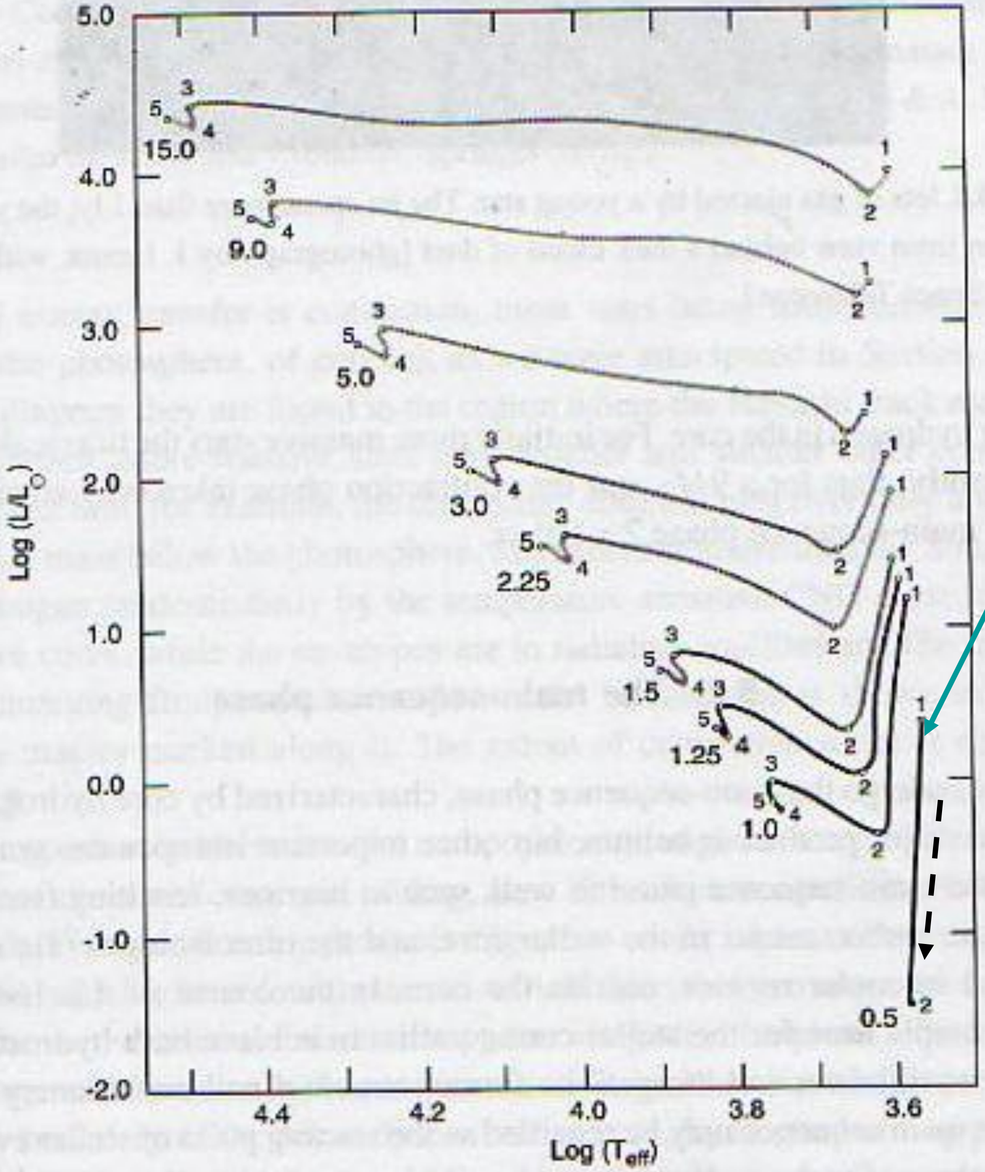


Figure 8.1 Evolutionary paths in the H–R diagram for stars of different initial mass (as marked) during the pre-main-sequence phase. The shade of segments is indicative of the time spent in each phase, ranging from less than 10^3 yr (light) to more than 10^7 yr (dark), as given in Table 8.1 [adapted from I. Iben Jr. (1965), *Astrophys. J.*, 141].

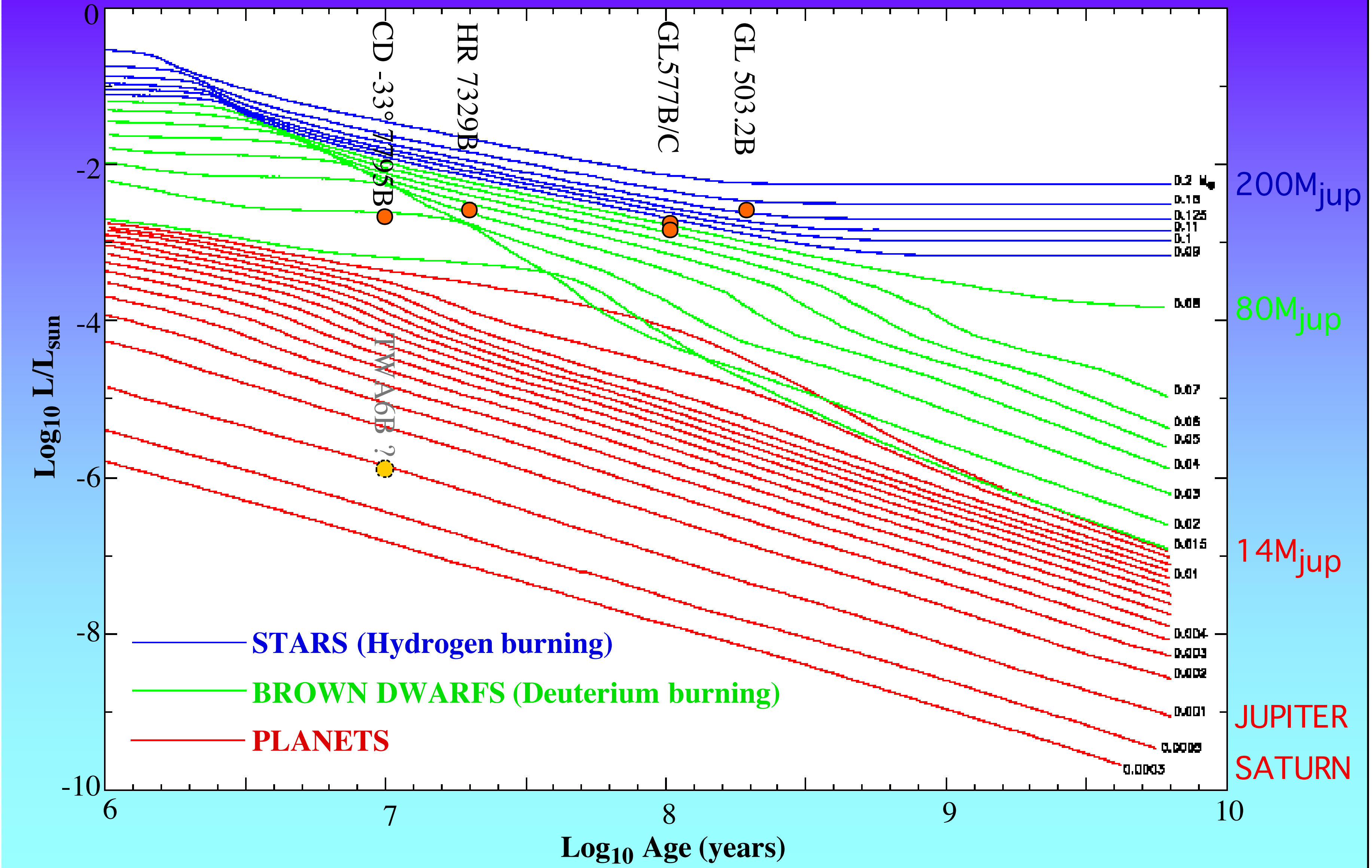
Hayashi phase of protostar contraction

Star formation in reality is a bit different: e.g., no spherical symmetry!

Evolution of M Dwarf Stars, Brown Dwarfs and Giant Planets (from Adam Burrows)

Glenn Schneider

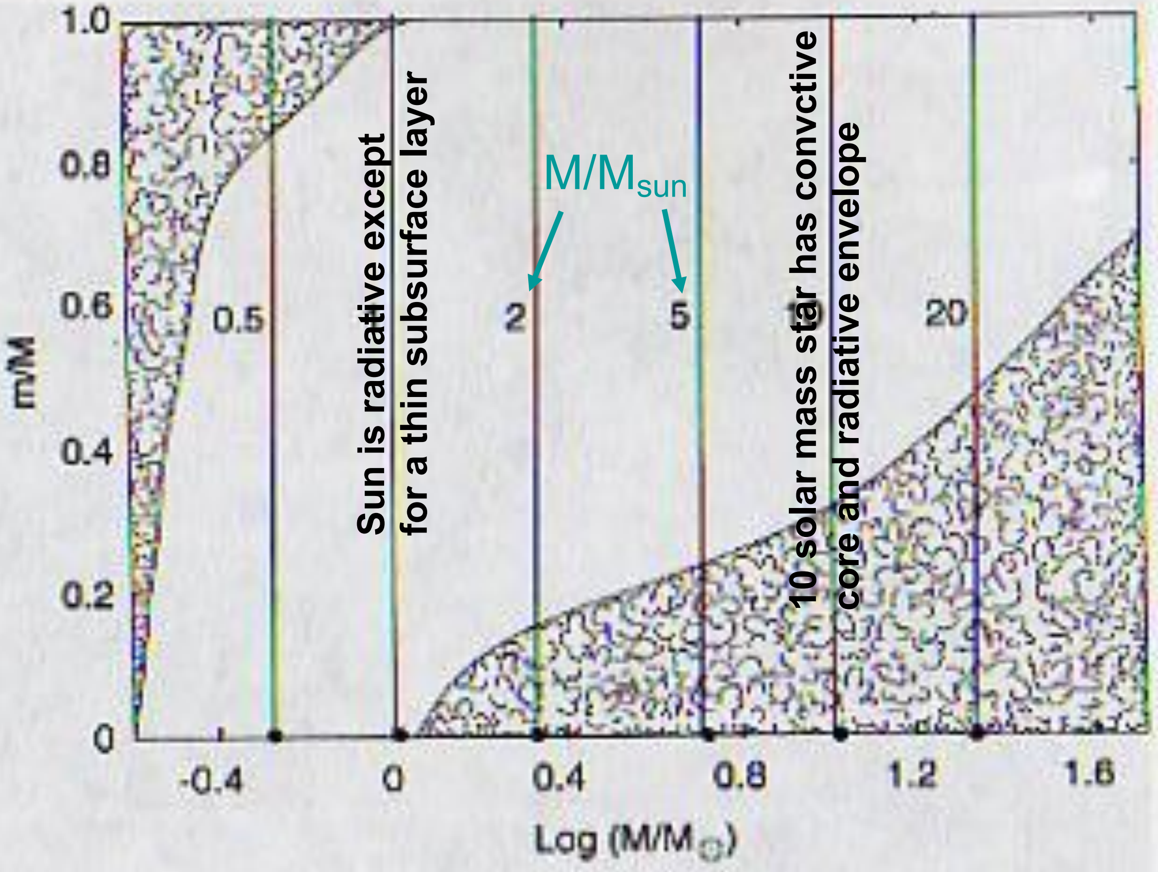
NICMOS Project
Steward Observatory



Which regions of a star are convective and which radiative?

140 8 The evolution of stars – a detailed picture

That depends on mass...



M/M_{sun}

Sun is radiative except for a thin subsurface layer

10 solar mass star has convctive core and radiative envelope

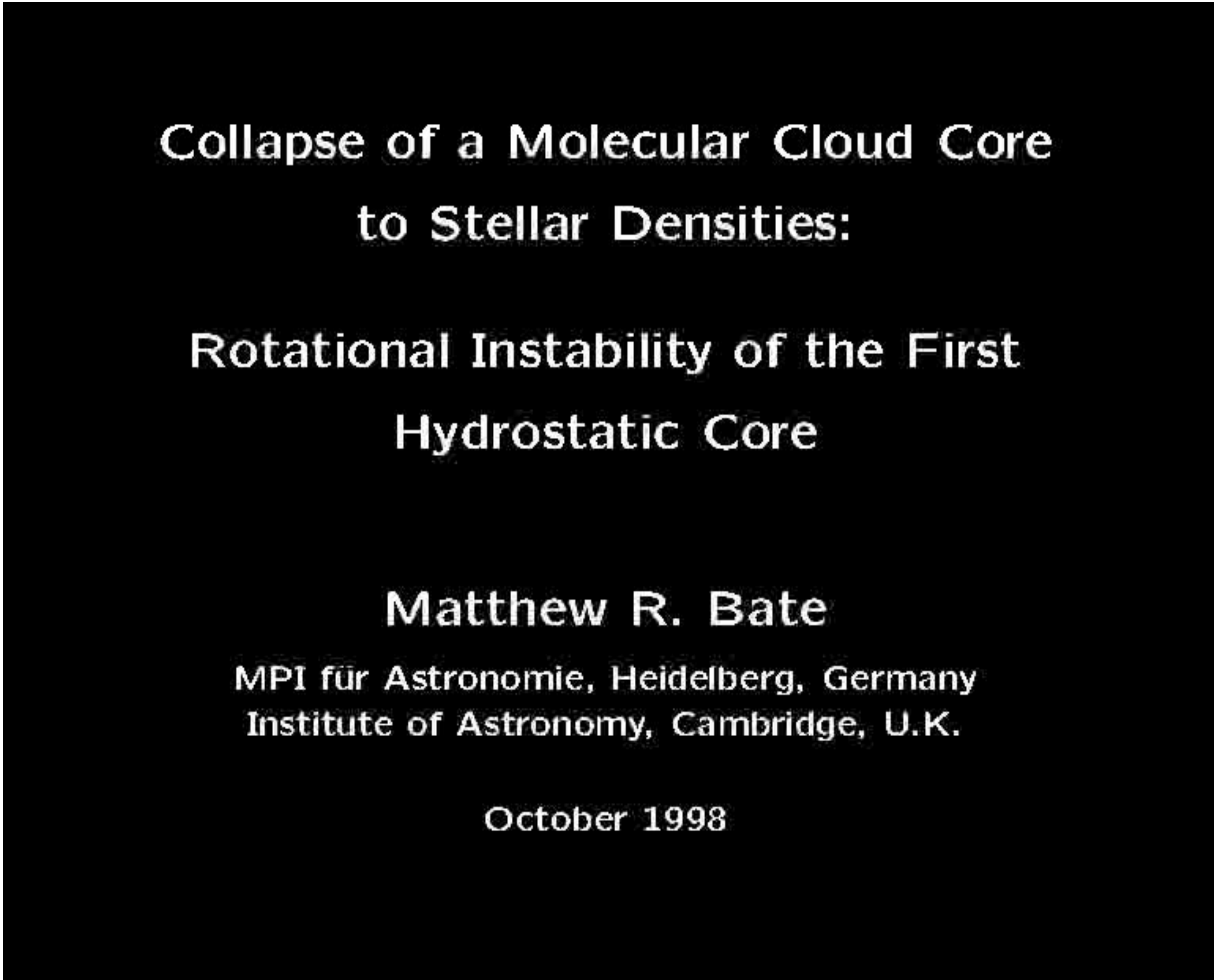
Figure 8.4 The extent of convective zones (shaded areas) in main-sequence star models as a function of the stellar mass [adapted from R. Kippenhahn & A. Weigert (1990), *Stellar Structure and Evolution*, Springer-Verlag].

UK Astroph. Fluids Facility supercomputer (parallel computer)

Stars are forming in…
these racks

Matthew
Bate
(1998)

Symmetric initial conditions



Collapse of a Molecular Cloud Core
to Stellar Densities:

Rotational Instability of the First
Hydrostatic Core

Matthew R. Bate

MPI für Astronomie, Heidelberg, Germany
Institute of Astronomy, Cambridge, U.K.

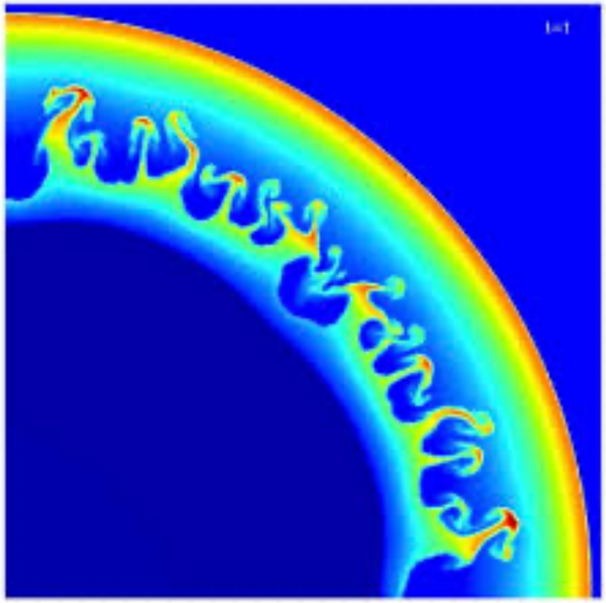
October 1998

Realistic star formation simulations using **S**moothed **P**article **H**ydrodynamics (SPH) became possible at the end of the 20th century.

Millions of particles represent a moving, irregular, 3-D grid, and can be thought of as gas clouds that partially overlap. Each particle interacts with 10…50 neighbors to represent pressure forces with good accuracy.

A somewhat ad hoc treatment also simulates gas with viscosity, although not in the form found in Navier-Stokes eq. of viscous fluid.

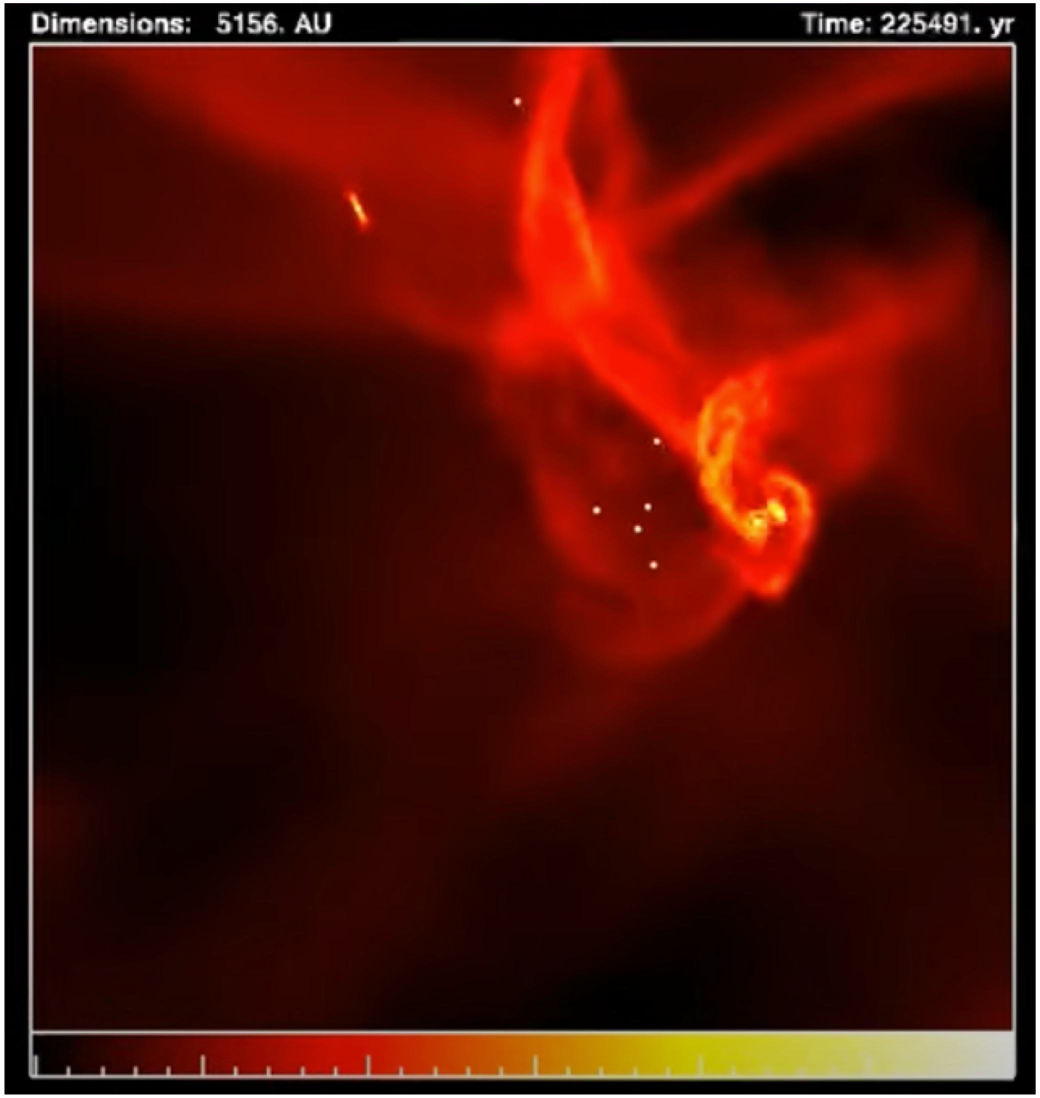
SPH has been used for supernova simulations.



Matthew Bate (2003),
Bate and Benz (2003)
SPH method (Smoothed Particles Hydrodynamics) with 1.5M particles

Starting from turbulent, self-gravitating gas cloud

Collapse starts after turbulence dies down and Jeans mass drops below the cloud mass



A link to animation
is shown on the course web page +here:
https://www.youtube.com/watch?v=YbdwTwB8jtc&t=78s

Or here https://www.youtube.com/watch?v=YbdwTwB8jtc

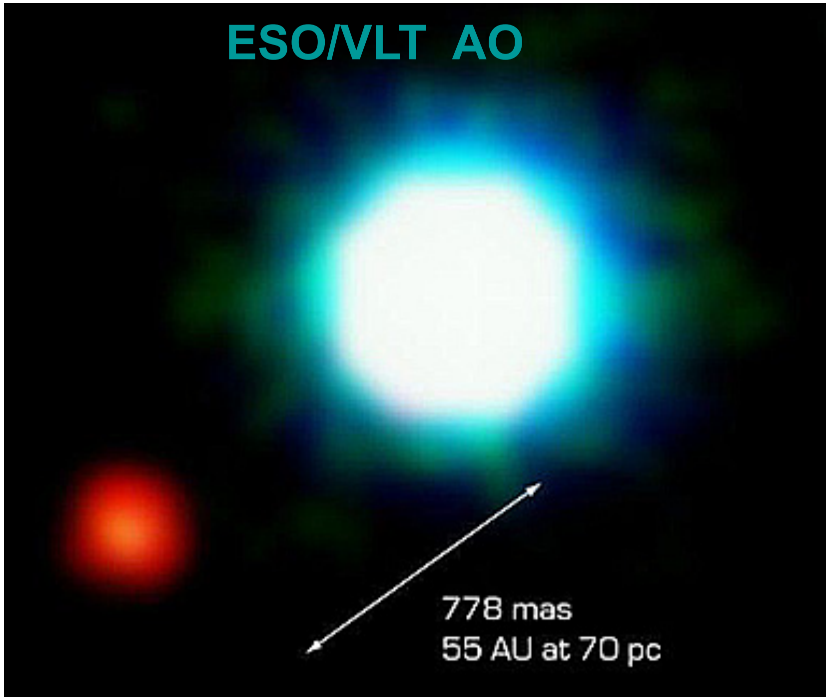
Brown dwarfs, or a failed attempt at stardom

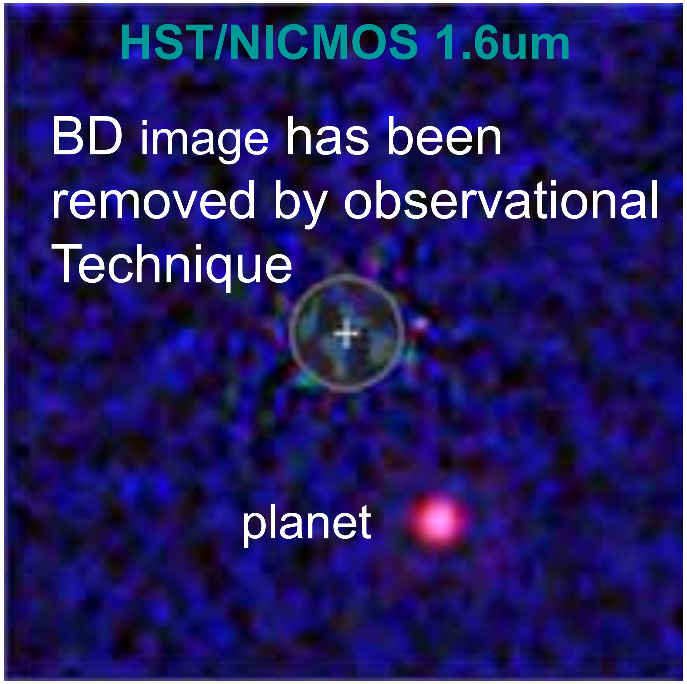
As seen in the SPH simulation of molecular cloud fragmentation, brown dwarfs (smallest objects simulated as white points) form in large numbers, and are mostly dispersed throughout the Galaxy afterwards. Sometimes, they are found as orbital companions to stars (not frequently, hence the term "brown dwarf desert" as opposed to a large numbers of planetary companions to stars.)

And there is even one BD with it's own companion of only 5 Jupiter masses!

A strange system **2MASS1207** *discovered in 2003 (among other by UofT professor Ray Jayawardhana) :*

5 M_{Jup} planet around a 25 M_{Jup} Brown Dwarf

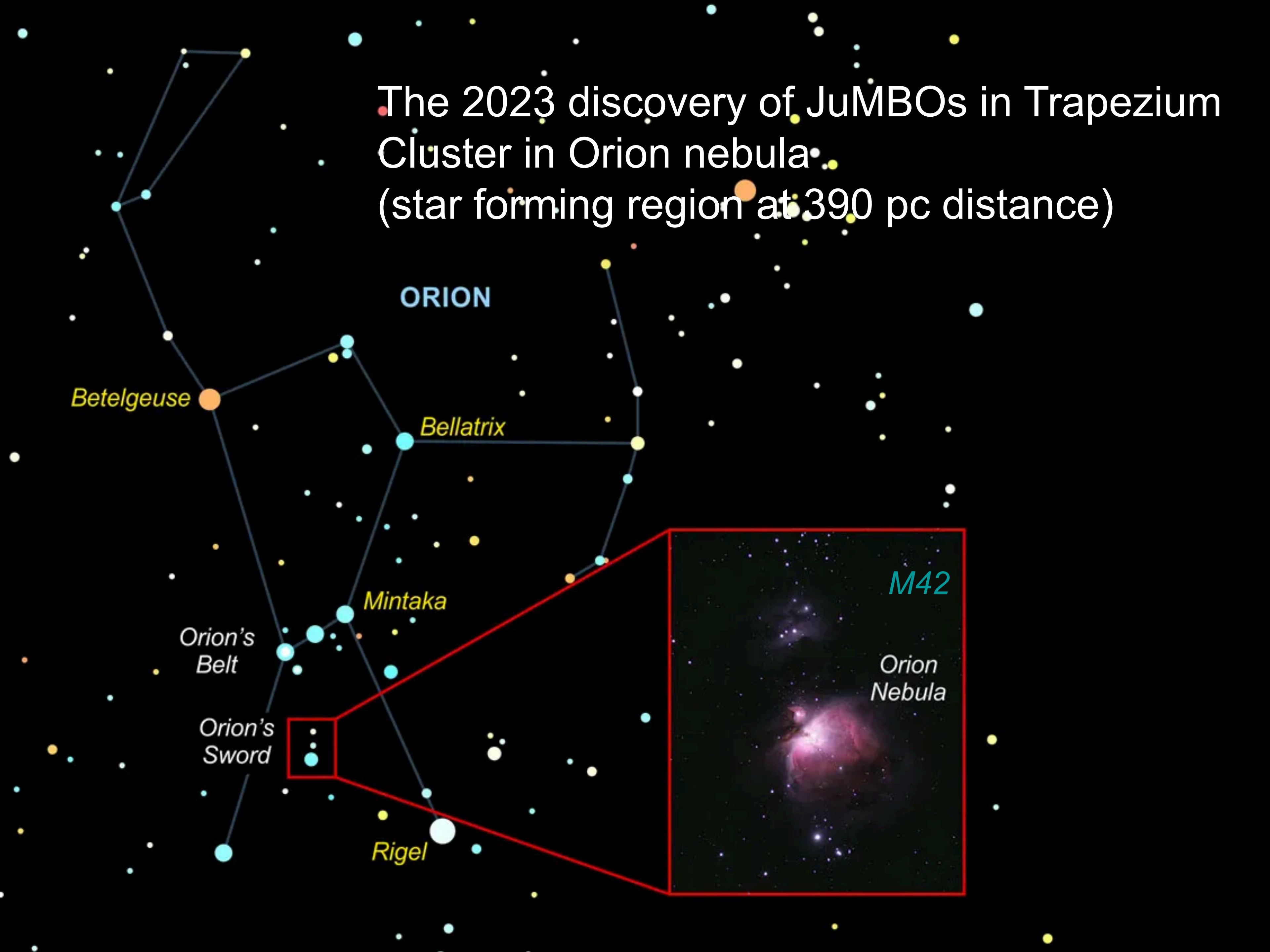




BD image has been removed by observational Technique

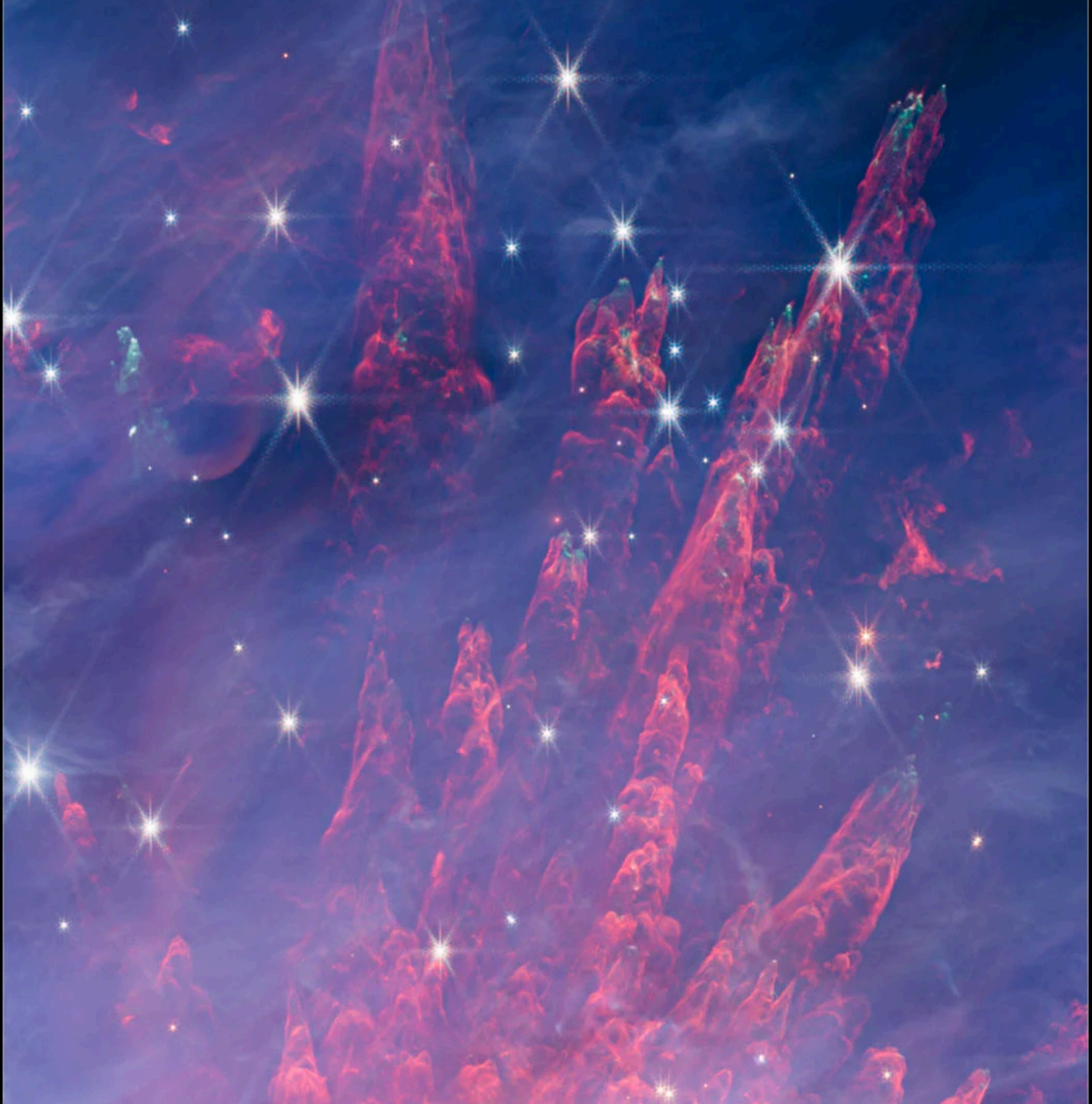
Such object challenge the distinction between failed stars and planets (conventionally, mass of 13 Jupiters is a demarcation line). Also, star formation theory predicts that objects of 0.5-5 Jupiter mass *cannot* form in collapsing cloud cores in the process of opacity-limited fragmentation. Yet, quite possibly, they actually form like/together with brown dwarfs. **James Webb Space Telescope in 2023 unexpectedly found 42 JuMBOs**, Jupiter-mass Binary Objects, free floating (not associated with stars) in Orion Nebula

The 2023 discovery of JuMBOs in Trapezium Cluster in Orion nebula
(star forming region at 390 pc distance)



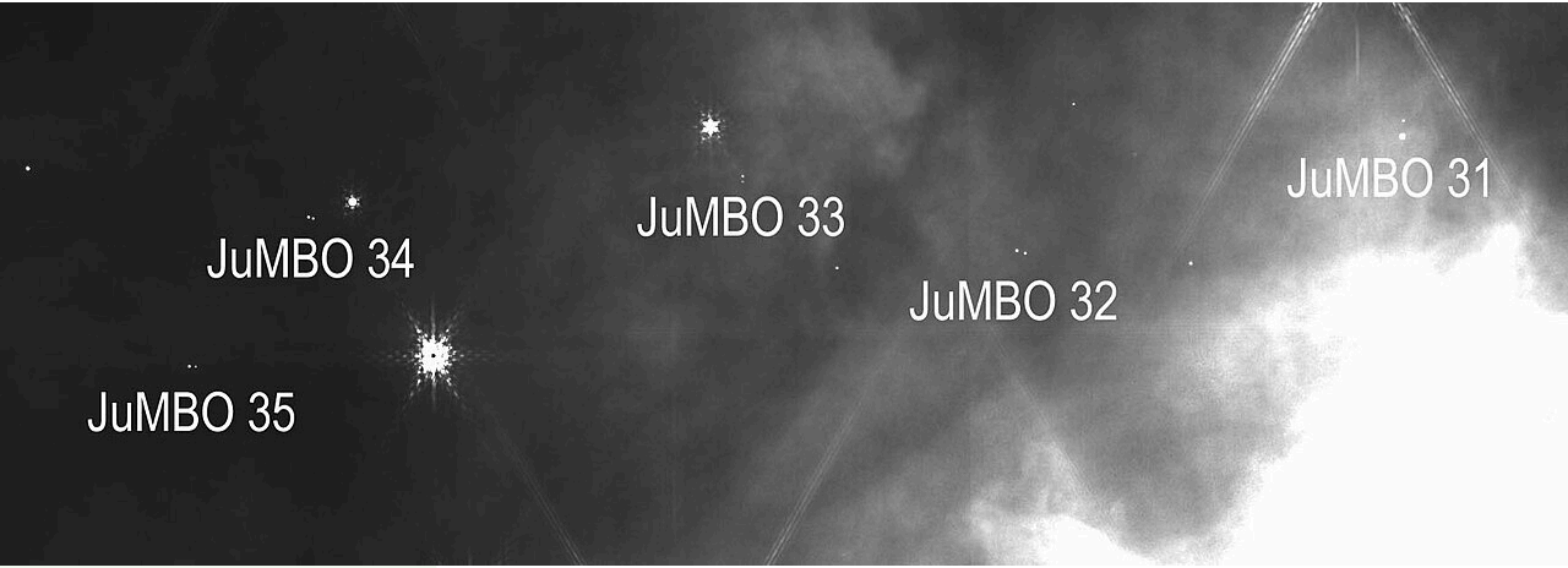
Amateur astrography today returns beautiful Pictures of Orion nebula M42

JWST



Possibly a result of two young stars colliding in Trapezium Cluster of Orion nebula

JuMBOs



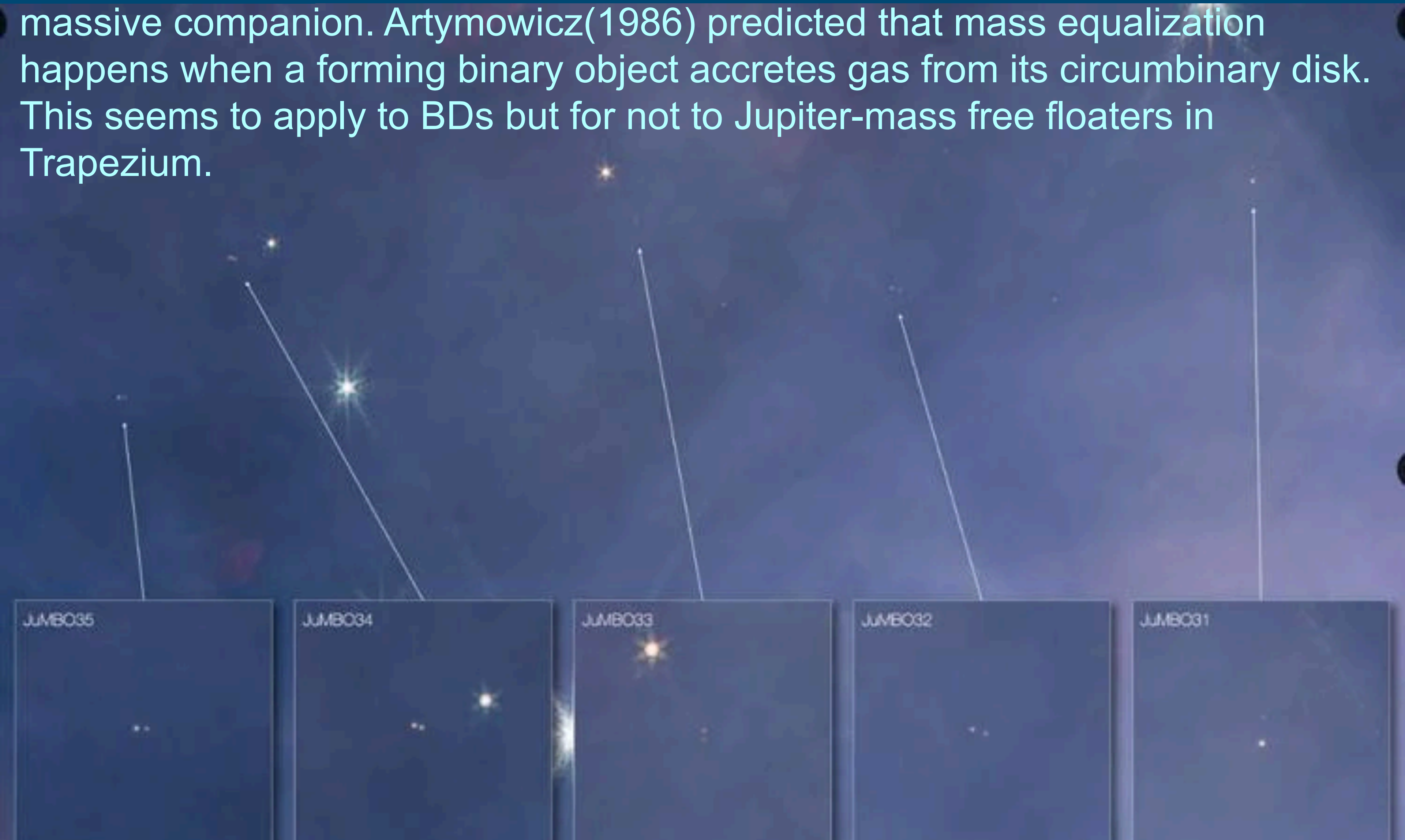
540 free floating planets have been imaged in M42 with JWST.
9% of them (48) are in Jupiter Mass Binary Objects

S. Pearson and M. McCaugherin (Nov. 2023) https://arxiv.org/pdf/2310.01231.pdf

> ”We have discovered and characterised a sample of 540 planetary-mass candidates with masses down to 0.6 Jupiter masses, demonstrating that there is indeed no sharp cut-off in the mass function. Furthermore, we find that 9% of the planetary-mass objects are in wide binaries, a result that is highly unexpected and which challenges current theories of both star and planet formation”

A lane of JuMBOs in Trapezium Cluster of Orion nebula, JWST NIRcam.

The pictured planetary-mass objects have $m < 7\ M_{jup,}$ Projected distances: 25 to 390 AU, most are thus wide binaries. Average mass ratio $m_2/m_1 = 0.66$, with distribution unlike binary BDs, which strongly prefer to have an equally massive companion. Artymowicz(1986) predicted that mass equalization happens when a forming binary object accretes gas from its circumbinary disk. This seems to apply to BDs but for not to Jupiter-mass free floaters in Trapezium.



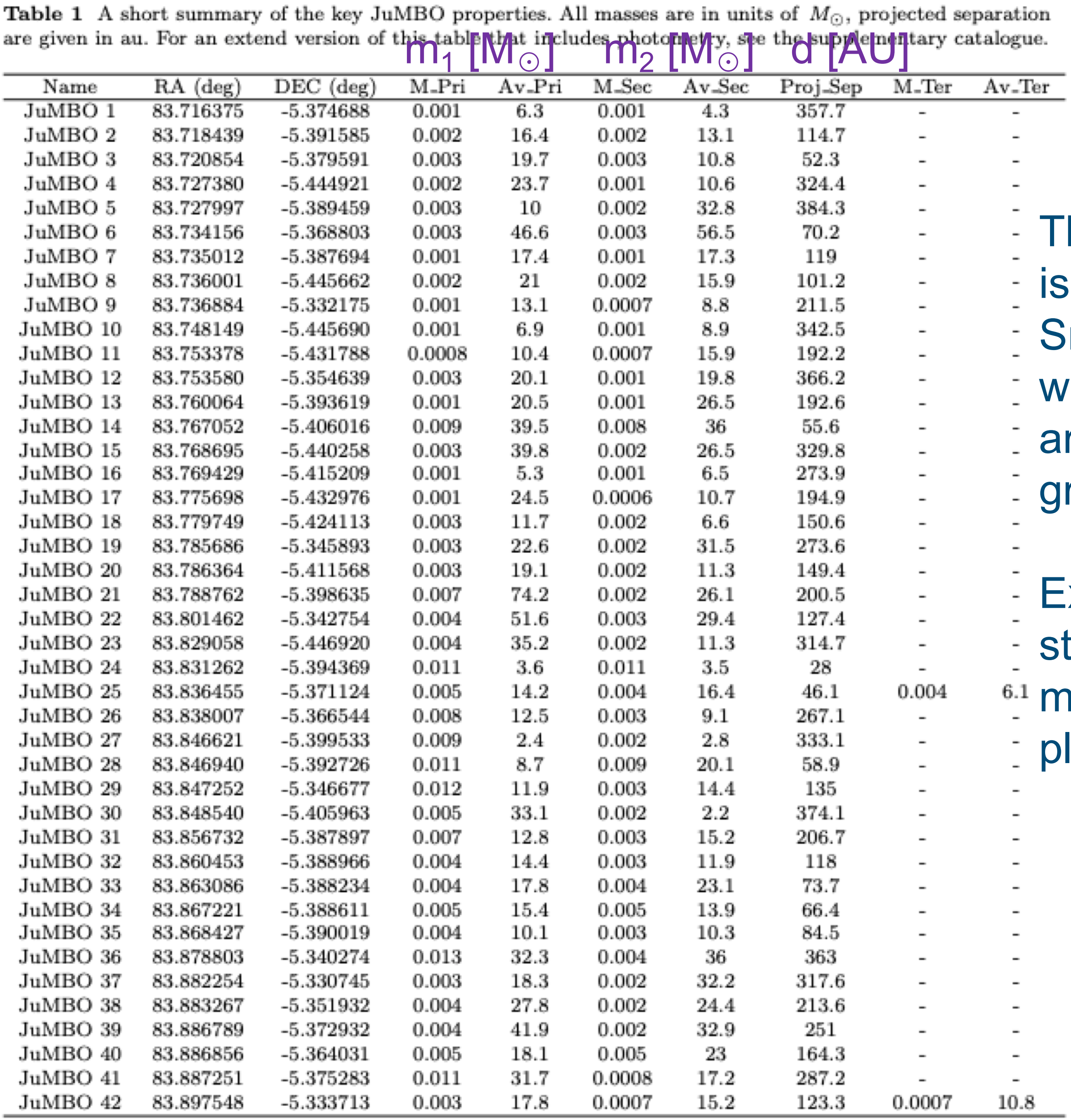


Table 1 A short summary of the key JuMBO properties. All masses are in units of $M_\odot$, projected separation are given in au. For an extend version of this table that includes photometry, see the supplementary catalogue.

m_1 [$M_\odot$] m_2 [$M_\odot$] d [AU]

Name	RA (deg)	DEC (deg)	M_Pri	Av_Pri	M_Sec	Av_Sec	Proj_Sep	M_Ter	Av_Ter
JuMBO 1	83.716375	-5.374688	0.001	6.3	0.001	4.3	357.7	-	-
JuMBO 2	83.718439	-5.391585	0.002	16.4	0.002	13.1	114.7	-	-
JuMBO 3	83.720854	-5.379591	0.003	19.7	0.003	10.8	52.3	-	-
JuMBO 4	83.727380	-5.444921	0.002	23.7	0.001	10.6	324.4	-	-
JuMBO 5	83.727997	-5.389459	0.003	10	0.002	32.8	384.3	-	-
JuMBO 6	83.734156	-5.368803	0.003	46.6	0.003	56.5	70.2	-	-
JuMBO 7	83.735012	-5.387694	0.001	17.4	0.001	17.3	119	-	-
JuMBO 8	83.736001	-5.445662	0.002	21	0.002	15.9	101.2	-	-
JuMBO 9	83.736884	-5.332175	0.001	13.1	0.0007	8.8	211.5	-	-
JuMBO 10	83.748149	-5.445690	0.001	6.9	0.001	8.9	342.5	-	-
JuMBO 11	83.753378	-5.431788	0.0008	10.4	0.0007	15.9	192.2	-	-
JuMBO 12	83.753580	-5.354639	0.003	20.1	0.001	19.8	366.2	-	-
JuMBO 13	83.760064	-5.393619	0.001	20.5	0.001	26.5	192.6	-	-
JuMBO 14	83.767052	-5.406016	0.009	39.5	0.008	36	55.6	-	-
JuMBO 15	83.768695	-5.440258	0.003	39.8	0.002	26.5	329.8	-	-
JuMBO 16	83.769429	-5.415209	0.001	5.3	0.001	6.5	273.9	-	-
JuMBO 17	83.775698	-5.432976	0.001	24.5	0.0006	10.7	194.9	-	-
JuMBO 18	83.779749	-5.424113	0.003	11.7	0.002	6.6	150.6	-	-
JuMBO 19	83.785686	-5.345893	0.003	22.6	0.002	31.5	273.6	-	-
JuMBO 20	83.786364	-5.411568	0.003	19.1	0.002	11.3	149.4	-	-
JuMBO 21	83.788762	-5.398635	0.007	74.2	0.002	26.1	200.5	-	-
JuMBO 22	83.801462	-5.342754	0.004	51.6	0.003	29.4	127.4	-	-
JuMBO 23	83.829058	-5.446920	0.004	35.2	0.002	11.3	314.7	-	-
JuMBO 24	83.831262	-5.394369	0.011	3.6	0.011	3.5	28	-	-
JuMBO 25	83.836455	-5.371124	0.005	14.2	0.004	16.4	46.1	0.004	6.1
JuMBO 26	83.838007	-5.366544	0.008	12.5	0.003	9.1	267.1	-	-
JuMBO 27	83.846621	-5.399533	0.009	2.4	0.002	2.8	333.1	-	-
JuMBO 28	83.846940	-5.392726	0.011	8.7	0.009	20.1	58.9	-	-
JuMBO 29	83.847252	-5.346677	0.012	11.9	0.003	14.4	135	-	-
JuMBO 30	83.848540	-5.405963	0.005	33.1	0.002	2.2	374.1	-	-
JuMBO 31	83.856732	-5.387897	0.007	12.8	0.003	15.2	206.7	-	-
JuMBO 32	83.860453	-5.388966	0.004	14.4	0.003	11.9	118	-	-
JuMBO 33	83.863086	-5.388234	0.004	17.8	0.004	23.1	73.7	-	-
JuMBO 34	83.867221	-5.388611	0.005	15.4	0.005	13.9	66.4	-	-
JuMBO 35	83.868427	-5.390019	0.004	10.1	0.003	10.3	84.5	-	-
JuMBO 36	83.878803	-5.340274	0.013	32.3	0.004	36	363	-	-
JuMBO 37	83.882254	-5.330745	0.003	18.3	0.002	32.2	317.6	-	-
JuMBO 38	83.883267	-5.351932	0.004	27.8	0.002	24.4	213.6	-	-
JuMBO 39	83.886789	-5.372932	0.004	41.9	0.002	32.9	251	-	-
JuMBO 40	83.886856	-5.364031	0.005	18.1	0.005	23	164.3	-	-
JuMBO 41	83.887251	-5.375283	0.011	31.7	0.0008	17.2	287.2	-	-
JuMBO 42	83.897548	-5.333713	0.003	17.8	0.0007	15.2	123.3	0.0007	10.8

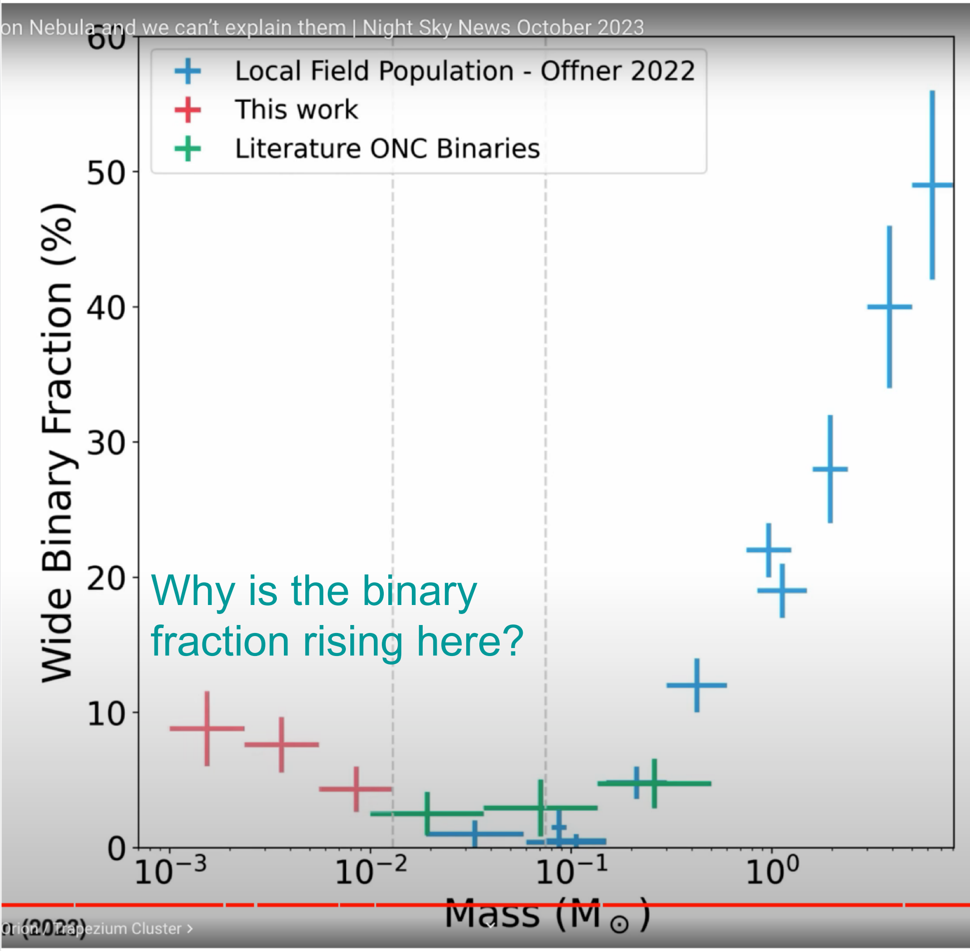
The origin of JuMBOs is enigmatic, having Small masses and wide separations, they are weakly bound gravitationally.

Existing theories of star and planet formation do not have place for such JuMBOs.

It is a JuMBO surprise

A century ago David Hilbert said (about mathematics): “We must know, we will know”. (Then he was proven wrong by Kurt Gödel.)

How long will the JuMBO puzzle last?



Why is the binary fraction rising here?

(This star is much further away)

The orange dot is the coldest exoplanet ever directly imaged:
WISE J0830+2837 is about 11 pc away, much closer than M42.
It was imaged at 3.6 and 4.5 μm by Spitzer Space Telescope.

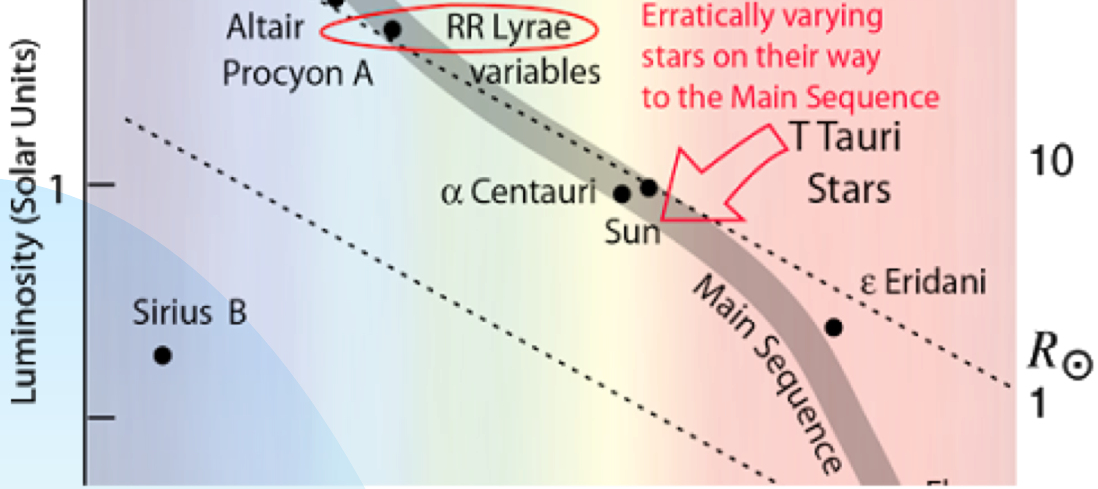
T =300-350 K, or 27-77 ℃.

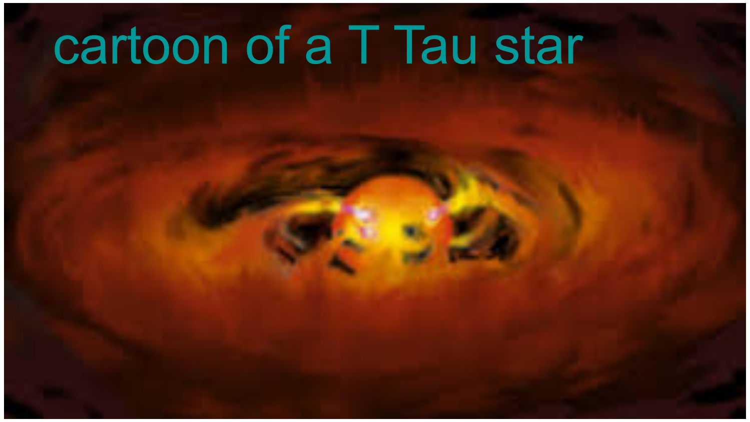
Disks

a natural way to stardom

As seen in the simulation of molecular cloud fragmentation, star formation is very non-spherical and not even very axisymmetric: it is 3-D and leads to protostars surrounded by accretion disks.

The main physical reason is the angular momentum (L) conservation: before L is transferred outward (e.g. by viscosity), the gas cannot approach the rotation axis; but it has no such restriction on approaching the equatorial plane (or midplane), where it gathers in the form of a rotationally-supported thin disk.




cartoon of a T Tau star

T Tau = T Tauri stars

[Taurus = Ox, a constellation]

Herbig-Haro 212 object,   VLT (ESA),Mt Paranal, Chile)

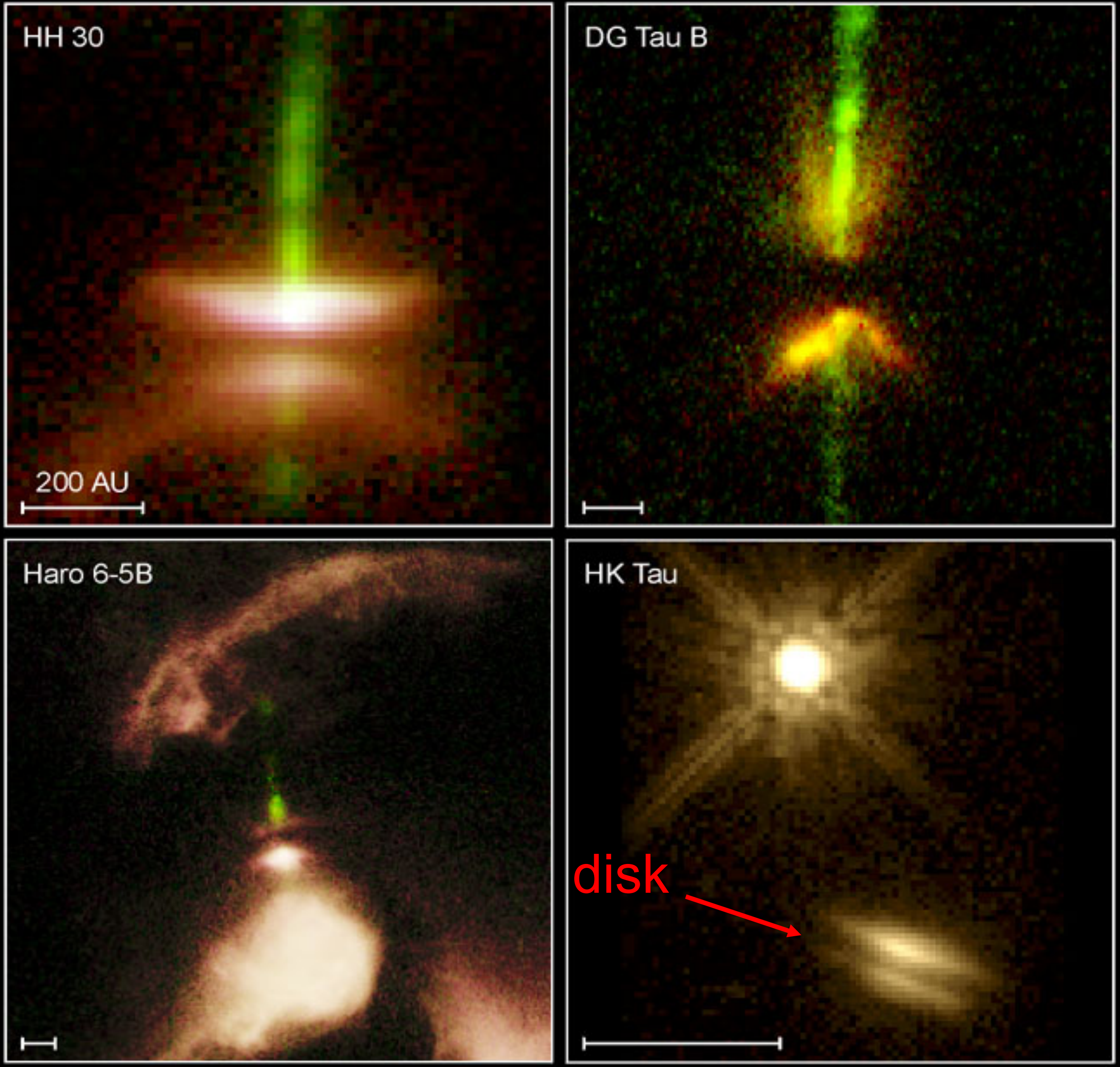
age = a few * 10^5 yr

Classical T Tau stars

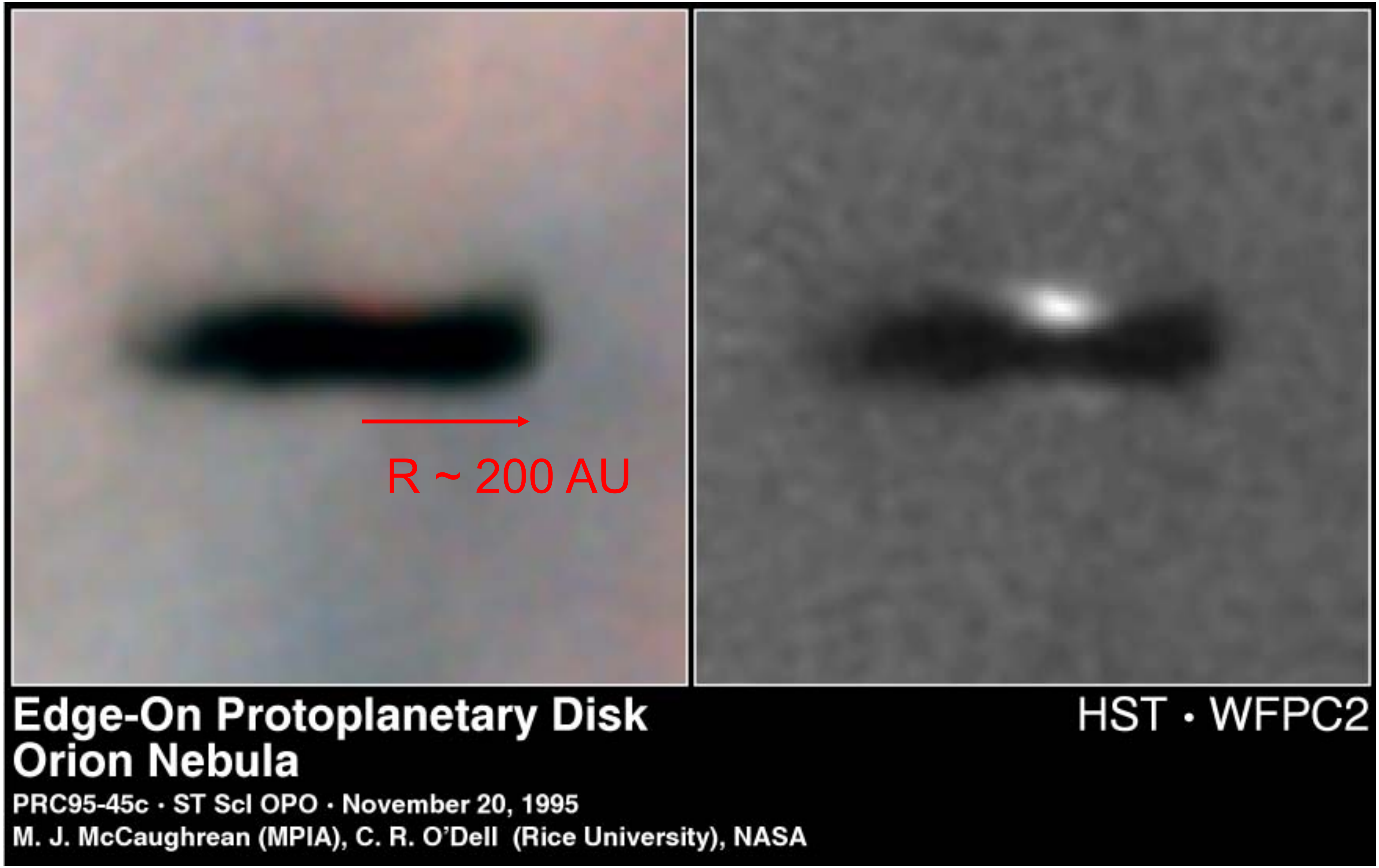
with massive H-He disks and jets
age = a few * 10^5 yr

They evolve later, at several Myr of age, into the *weak-lined* T Tau star class with low-mass disks, no gas in the vicinity of the star

age = 10^6 - 10^5 yr



Disks around Young Stars **HST • WFPC2**
PRC99-05b • STScI OPO
C. Burrows and J. Krist (STScI), K. Stapelfeldt (JPL) and NASA



Edge-On Protoplanetary Disk
Orion Nebula

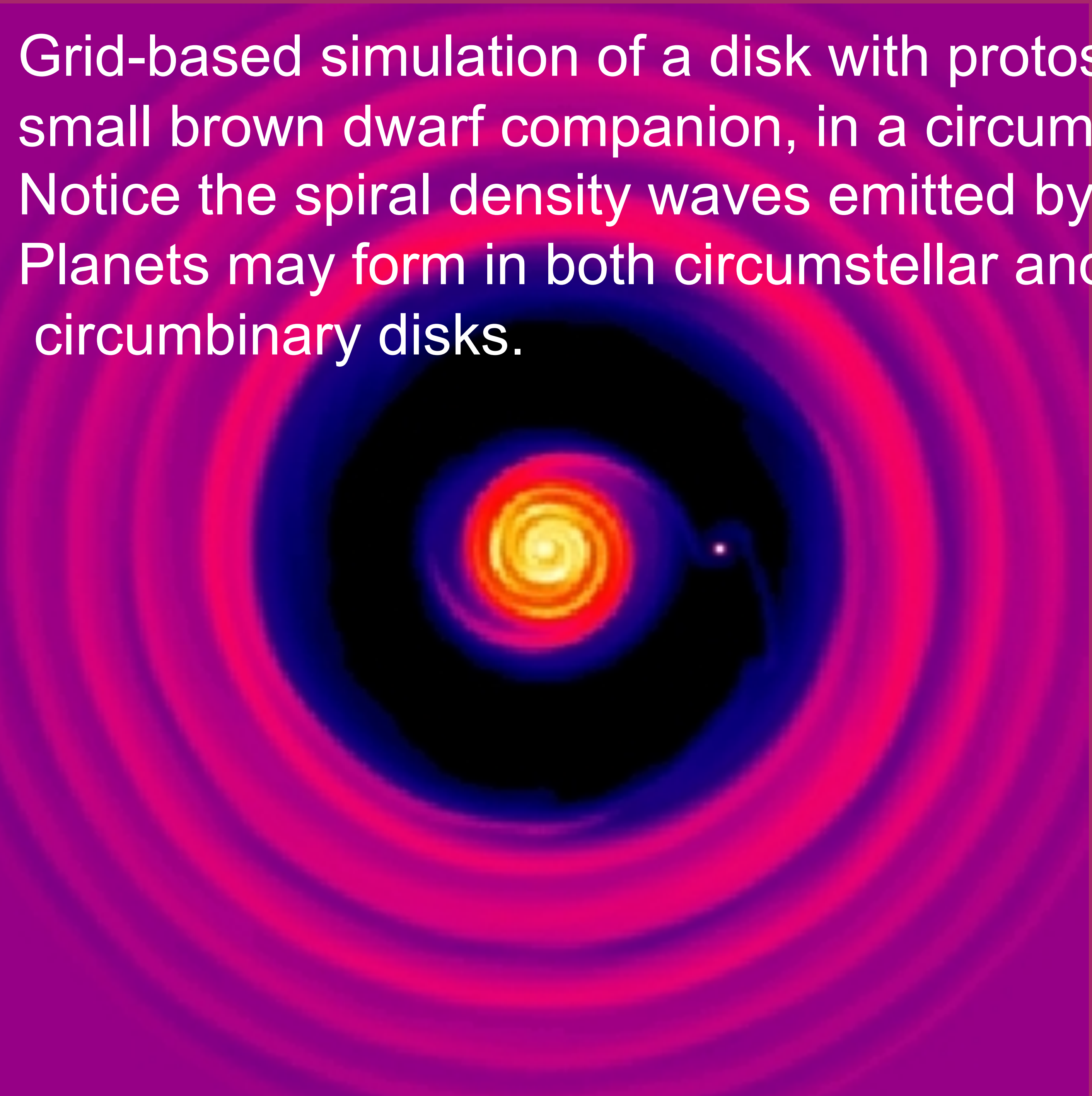
HST • WFPC2

PRC95-45c • ST ScI OPO • November 20, 1995
M. J. McCaughrean (MPIA), C. R. O'Dell (Rice University), NASA

The size is similar to, but larger than of our primordial Solar Nebula (limited to $R < 100$ AU, which is shown by the paucity of objects beyond 50 AU radius)

JWST images of Orion disks in infrared (NIRcam)

Grid-based simulation of a disk with protostar and a small brown dwarf companion, in a circumbinary gap. Notice the spiral density waves emitted by the system. Planets may form in both circumstellar and circumbinary disks.



Gas density is color-coded:

bright = dense

Dusty disks, often much older than T Tau disks

JWST found LONE planets in the Orion Nebula and we can't explain them | Night Sky News October 2023