Last few lectures:

- Diffuse ISM clouds
- Temperature regulation
- absorption line spectroscopy
    - measuring abundances
- Dust & reddening
- Molecules

From today (new section):

Star formation

- how does it happen?
- where?
- what are the results, what effects does it cause?
- (how) can we see it? What are the signposts?
- why? How is it triggered?

Star Formation

- Results from **collapse under gravity** of large diffuse clouds

- Lets imagine a spherical cloud
  - radius, R
  - Mass, M
  - temperature, T
  - density, n or ρ

  and look at the competing forces acting…

- inward force = GRAVITY

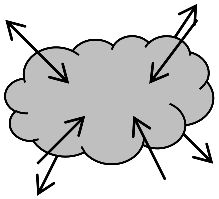
  outward force = GAS PRESSURE (caused by heat energy)

Hydrostatic Equilibrium:

GRAVITY (inward) = PRESSURE (outward)

(all main sequence stars are in HE)

However, if gravity < pressure ➔
if gravity > pressure ➔



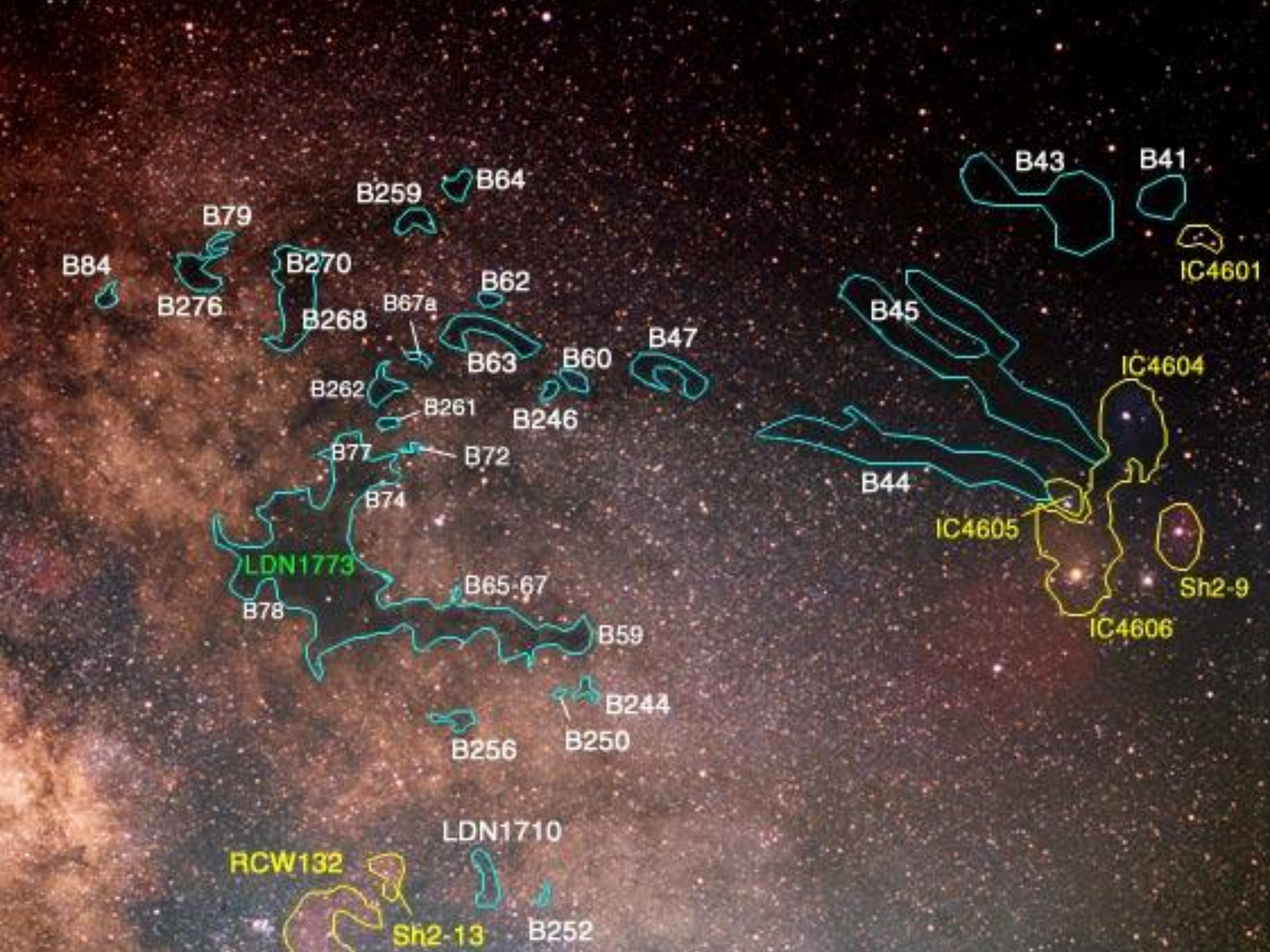
Remember: $P = nkT$ (‘ideal gas’ law)

P = pressure
n = density
k = Boltzmann’s constant
T = temperature

In order to get the highest gravity, we need lots of mass (density)

Therefore, in order to get the lowest gas pressure, we need the lowest *T*. Stars are born in very cold clouds (~10–100 K).

➔ cold dense regions = **dark clouds**



B43
B41
B64
B259
B79
B84
B270
B276
B62
IC4601
B67a
B45
B268
B47
B63
B60
IC4604
B262
B261
B246
B77
B72
B44
B74
IC4605
LDN1773
B65-67
Sh2-9
B78
IC4606
B59
B244
B256
B250
LDN1710
RCW132
Sh2-13
B252

Barnard objects:
- size ~ 10–100 pc
- mass ~ 10^3–10^4 $M_\odot$

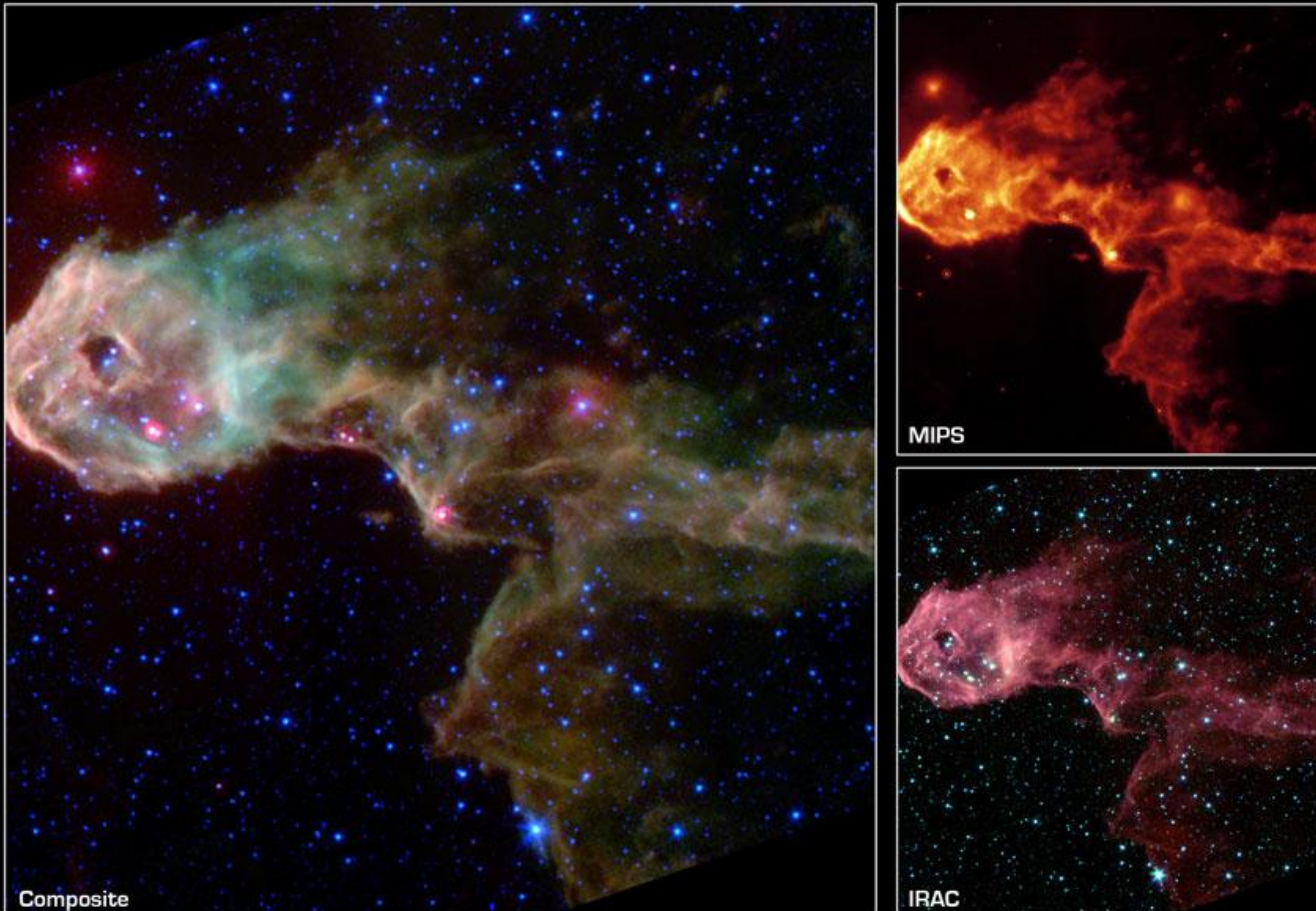
Bok globules:
- n ~ 10^4–10^9 cm^3
- T ~ 10–100 K
- size ~ 1 pc

Bok Globules in NGC 281

Hubble Heritage

Carina Nebula Details

HST•ACS/WFC



Dark Globule in IC 1396

Spitzer Space Telescope • MIPS • IRAC

NASA / JPL-Caltech / W. Reach (SSC/Caltech)

ssc2003-06b

Use eqn. of HE: can show that there is a **minimum** mass for collapse to happen (for a given ***T*** and ***ρ)***.

This is called the **JEANS' MASS (*M_J*)**:

$$M_J \sim \frac{T^{3/2}}{\sqrt{r}}$$

For typical dark cloud: $M_J = 10^5\ M_\odot$

BUT: Typical stellar masses are only 1–10 $M_\odot$

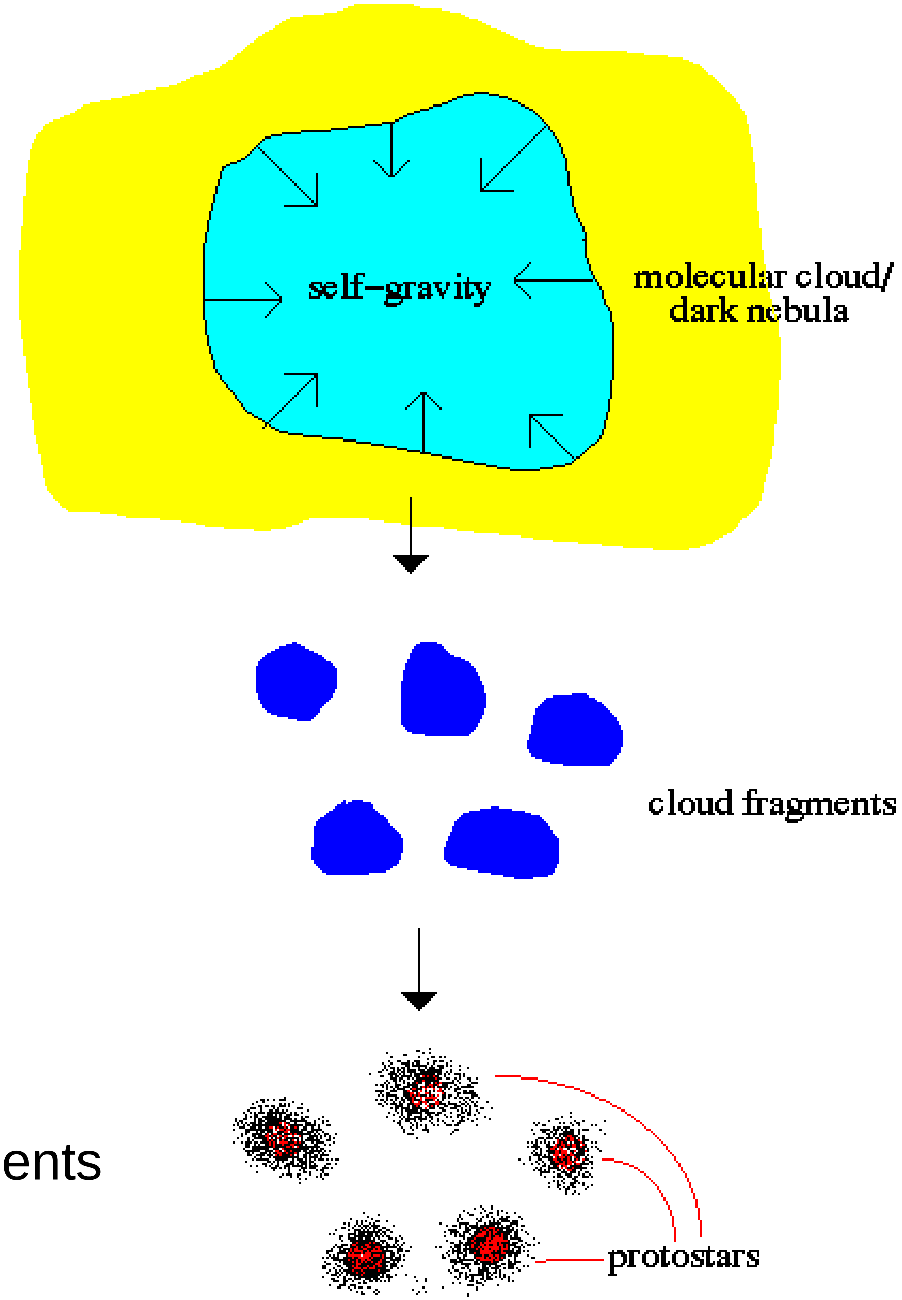
As cloud collapses, *ρ*↑ and the smaller the minimum mass, M_J, becomes.
Thus after grav. collapse cloud breaks up into smaller 'parcels' before star formation starts

FRAGMENTATION

Cloud with mass = Jeans' Mass
→ begins to collapse under grav.

Fragments further

Star formation begins in fragments



Massive **molecular clouds** fragment into many small clumps -- **stellar nursery**

Molecular cloud: gas mass = hundreds to a few millions of $M_\odot$

size: 10–100 pc

density: ~10^3 atoms/cm^3

Star formation process thought to be quite inefficient (~30%)

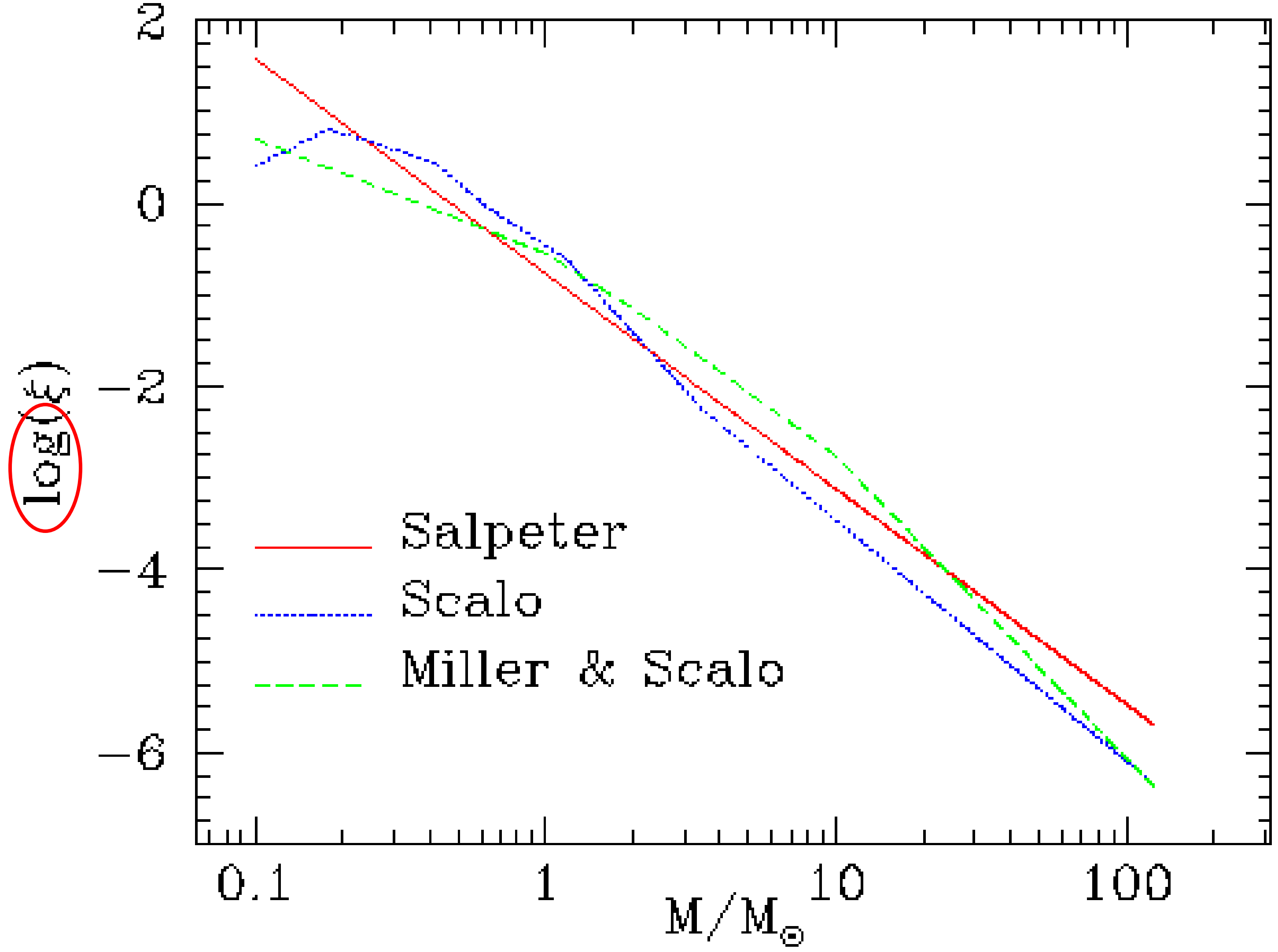
Fragmentation → range of star masses

The spread of stellar masses can be defined by the **initial mass function**:

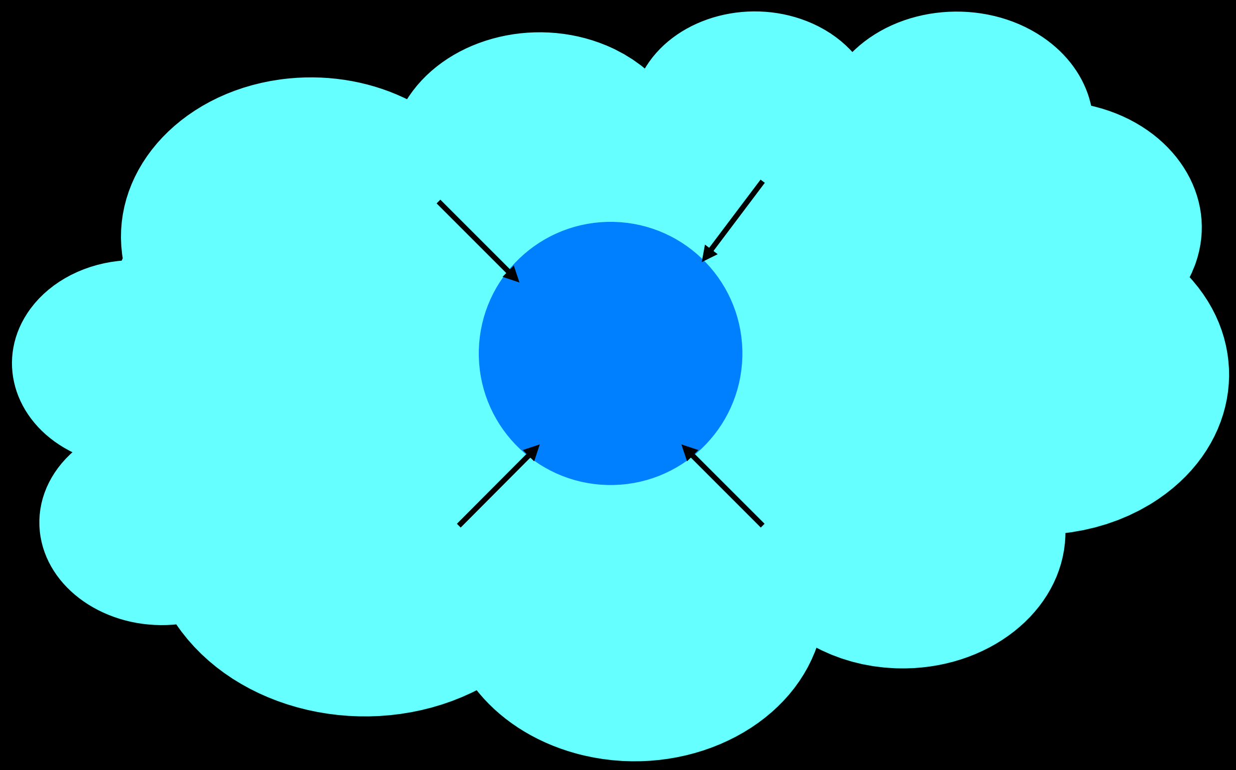
$$N(M) \sim M^{-(1+x)}$$

N(M) = no. of stars of mass *M*
M = star mass
x = constant (= slope)

Salpeter (1955) found $x = 1.35$
for lower and upper mass limits of 0.1 and 125 $M_{\odot}$

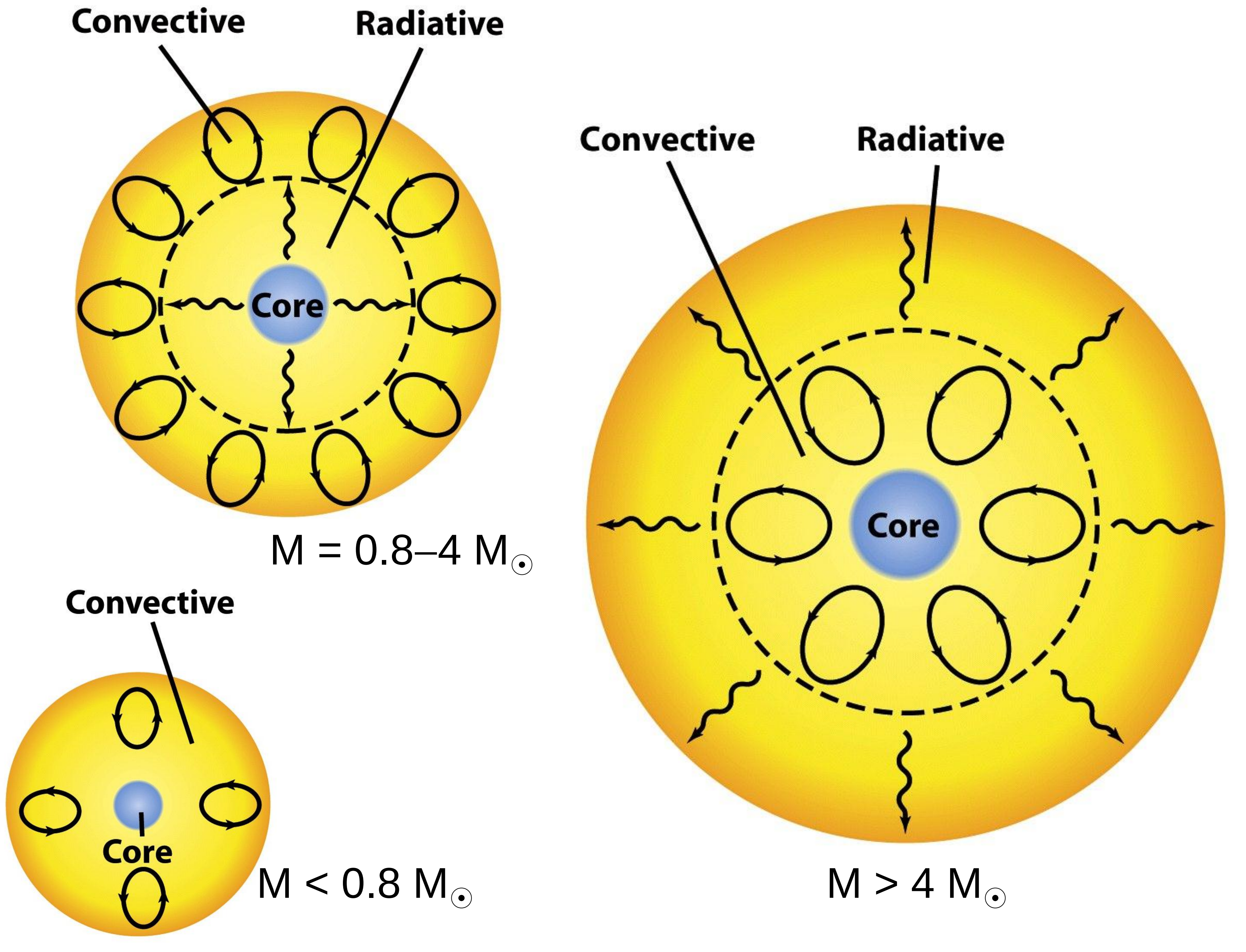


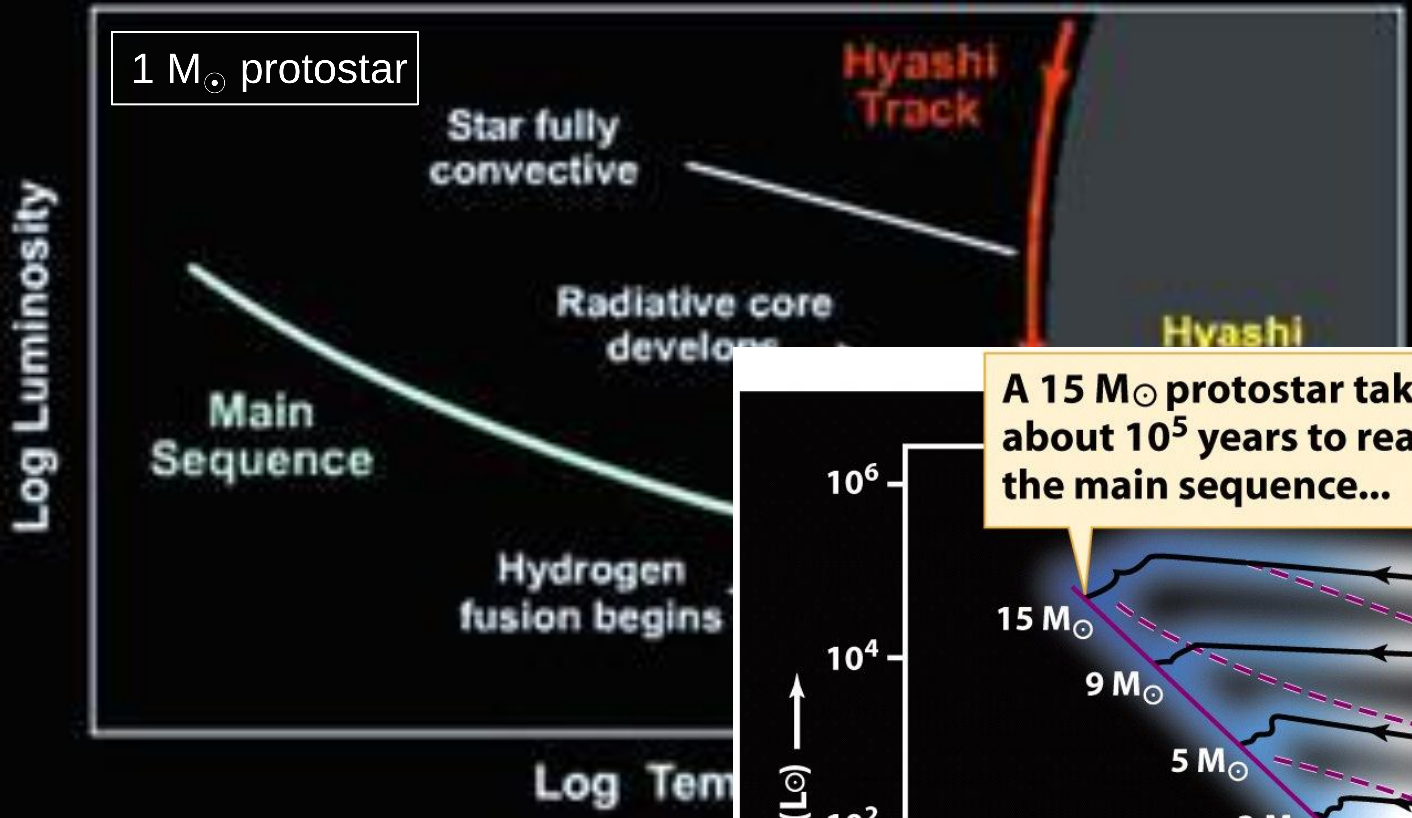
2
0
−2
−4
−6
0.1
1
10
100
M/M$_\odot$
log(ξ)
Salpeter
Scalo
Miller & Scalo

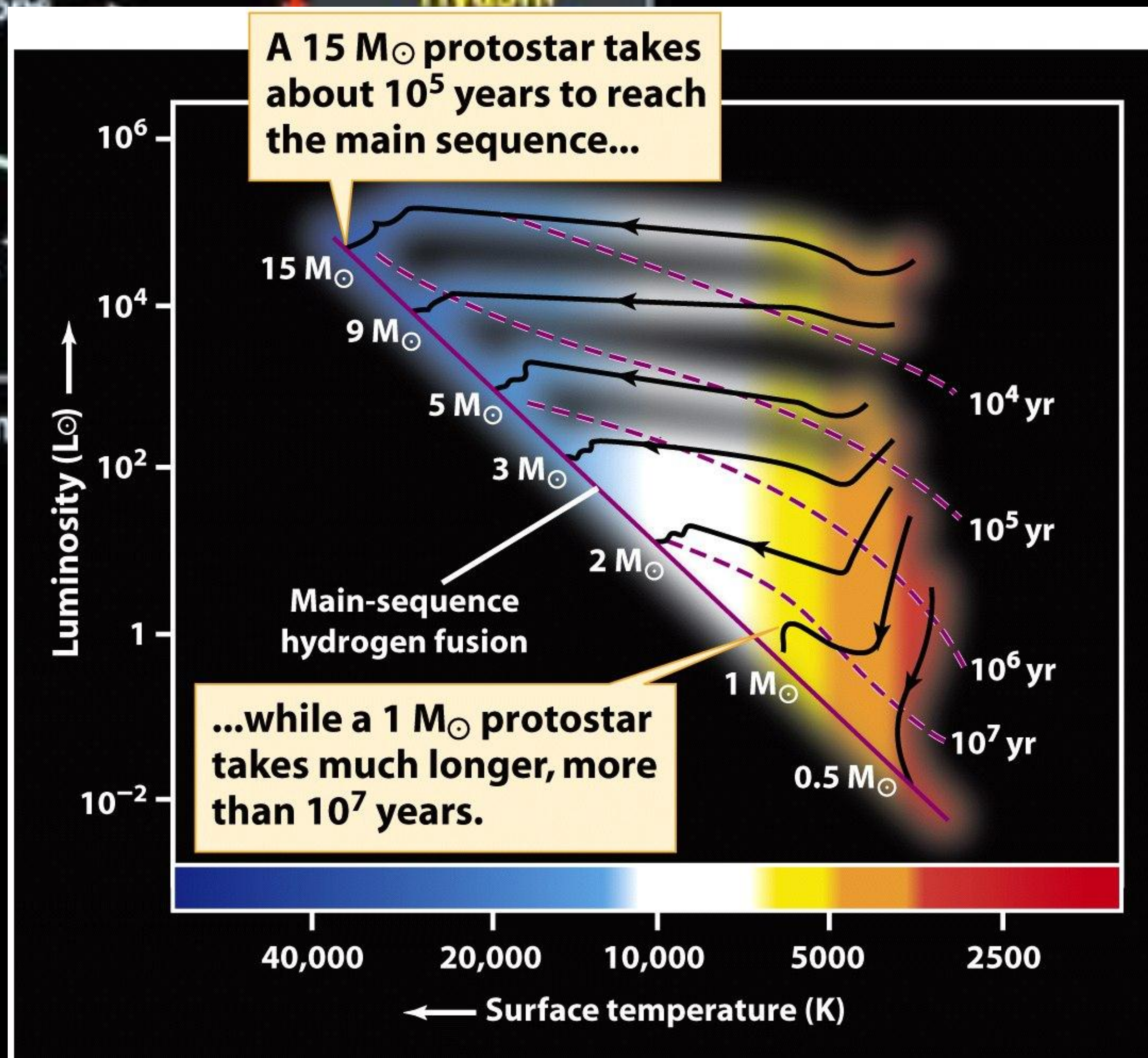


Grav energy → heat → radiation (mostly mm and far-IR)

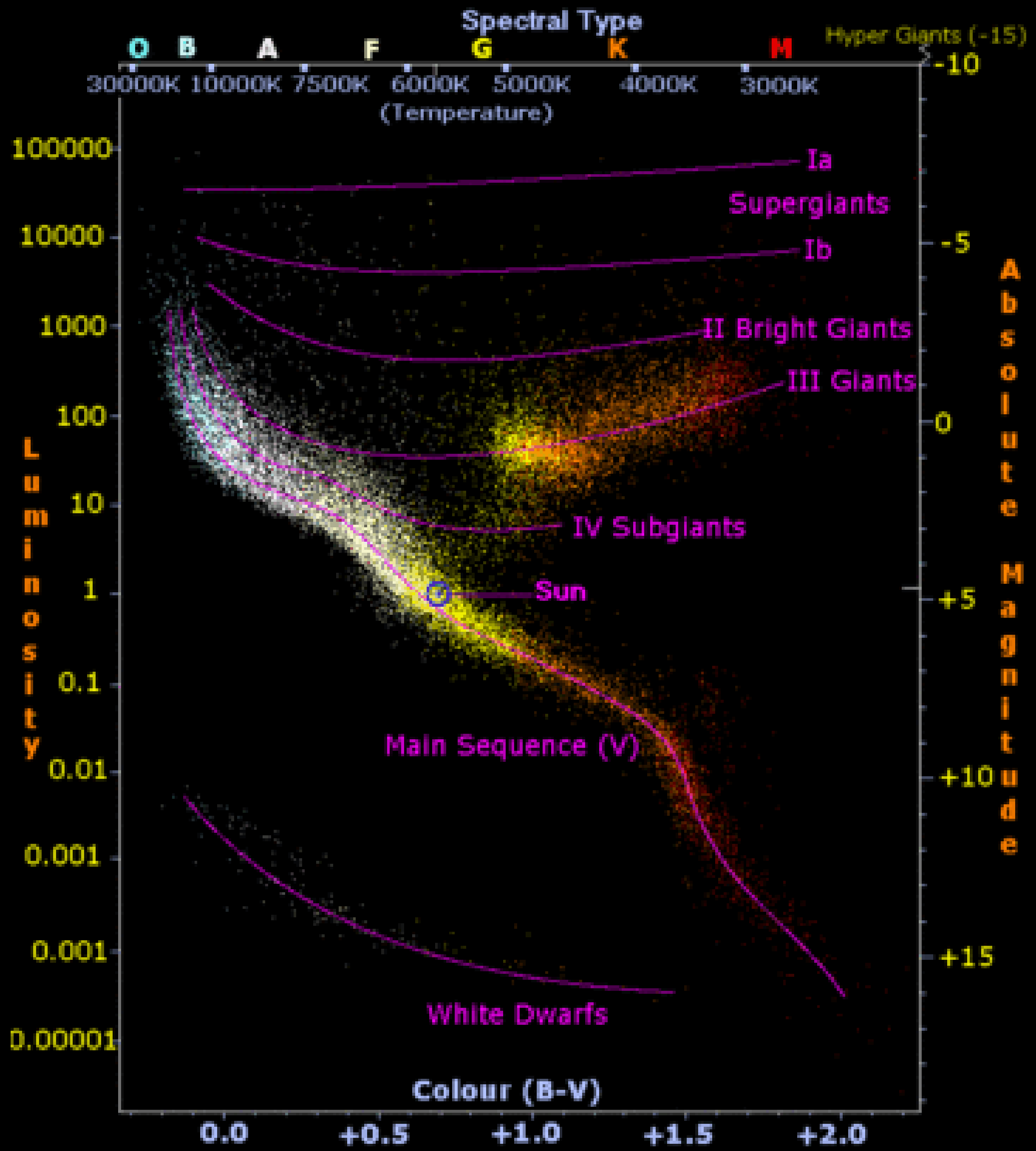
After few 1000 yrs, T~3000 K, L~1-10000 $L_\odot$


Convective
Radiative
Core
M = 0.8–4 M☉
Convective
Radiative
Core
M > 4 M☉
Convective
Core
M < 0.8 M☉



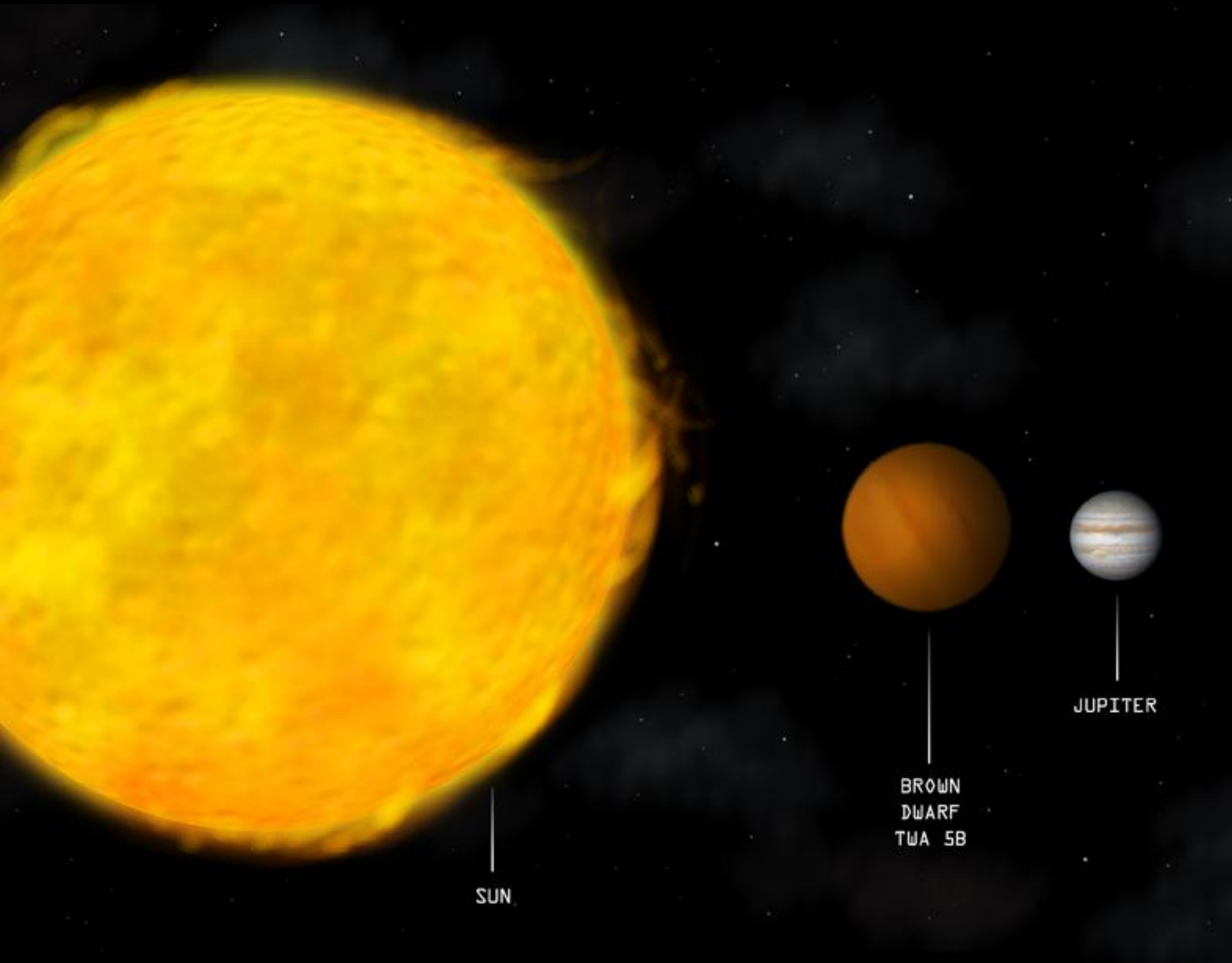


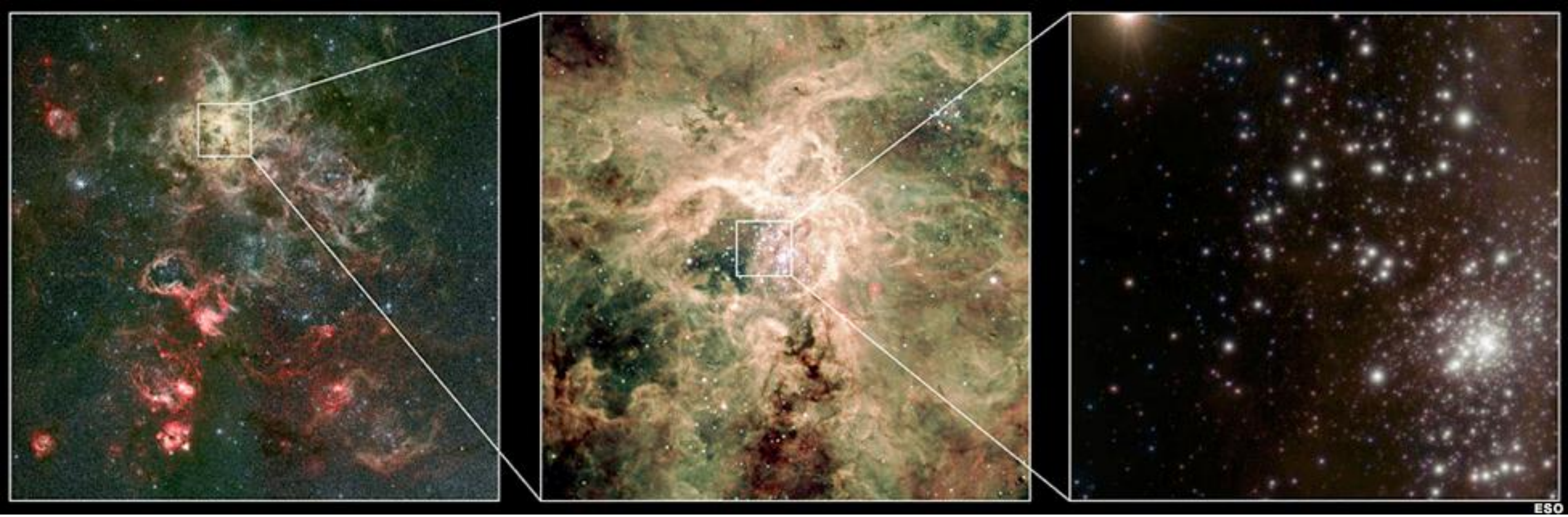
Pre-main sequence evolutionary track



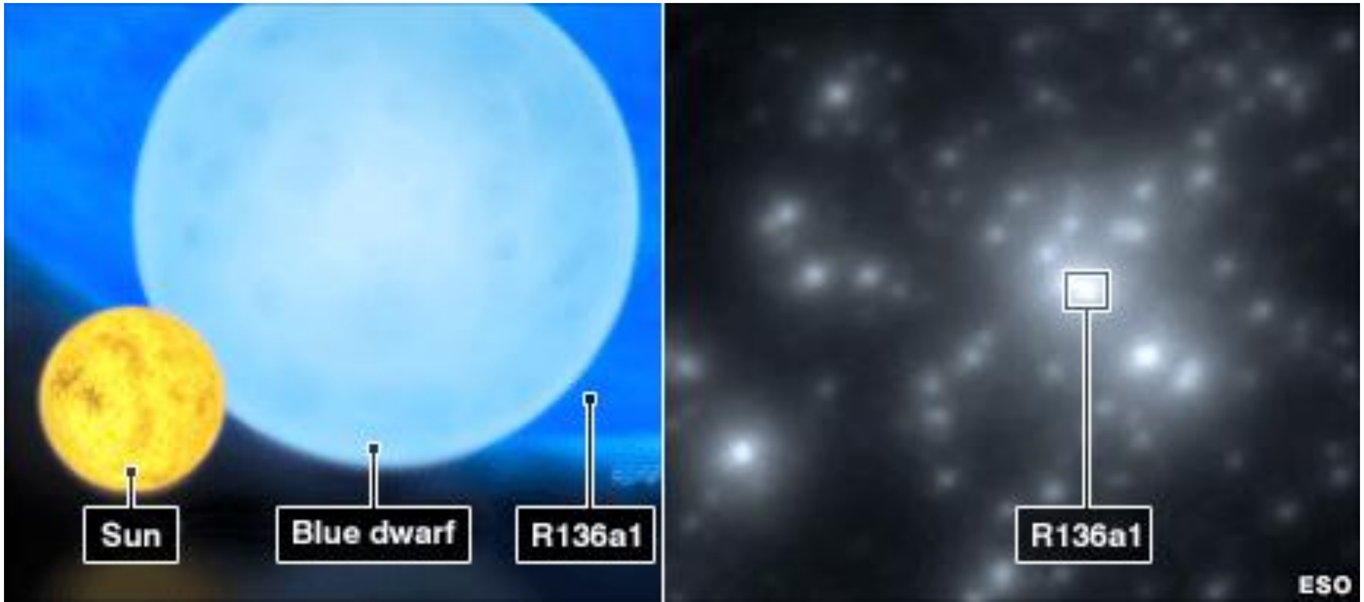
Spectral Type
O
B
A
F
G
K
M
Hyper Giants (-15)
30000K
10000K
7500K
6000K
5000K
4000K
3000K
(Temperature)
100000
10000
1000
100
10
1
0.1
0.01
0.001
0.001
0.00001
Luminosity
-10
-5
0
+5
+10
+15
Absolute Magnitude
Ia
Supergiants
Ib
II Bright Giants
III Giants
IV Subgiants
Sun
Main Sequence (V)
White Dwarfs
Colour (B-V)
0.0
+0.5
+1.0
+1.5
+2.0

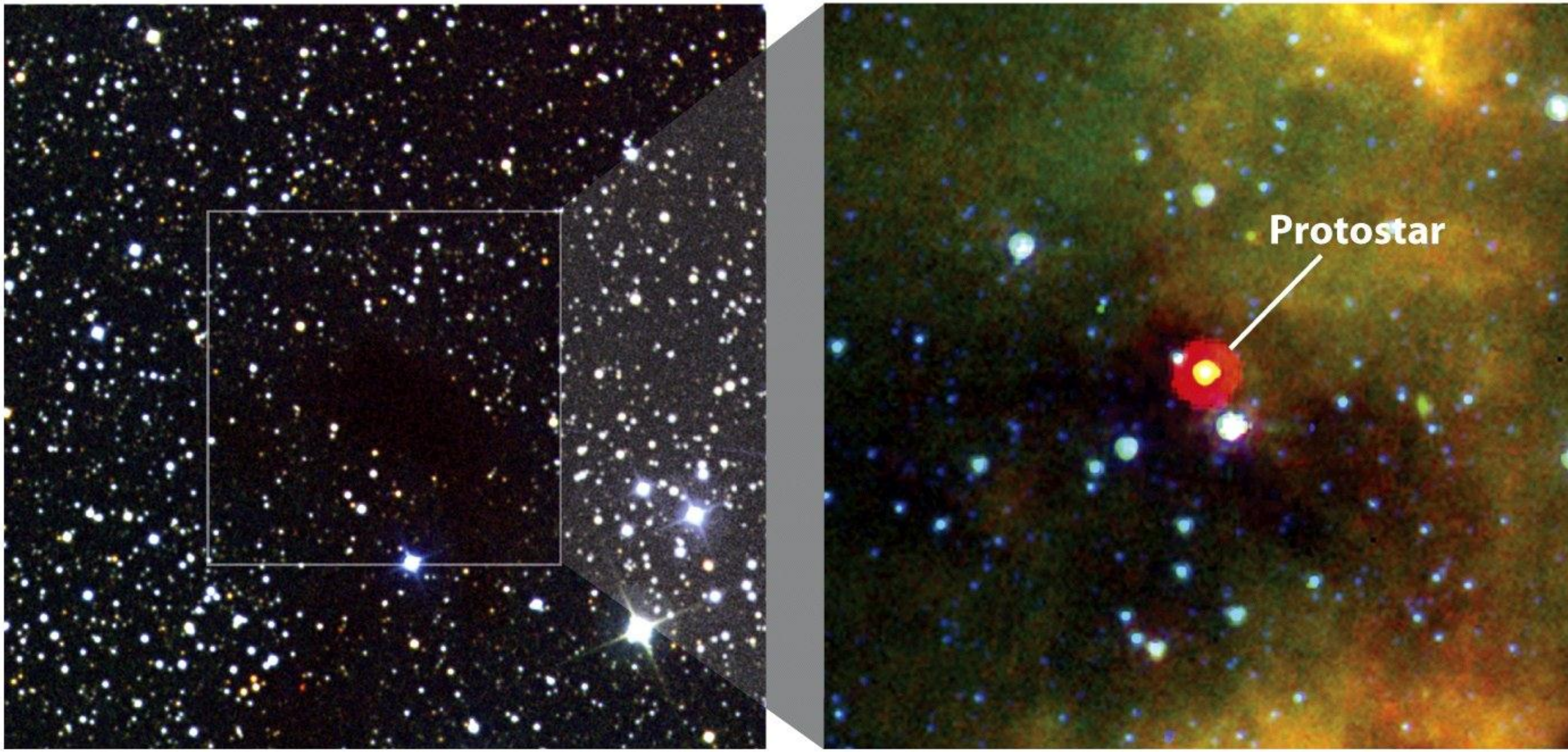
Constructing The Hertzsprung–Russell Diagram for Globular Star Cluster Omega Centauri


JUPITER
BROWN
DWARF
TWA 5B
SUN



265 solar masses (R136a1)

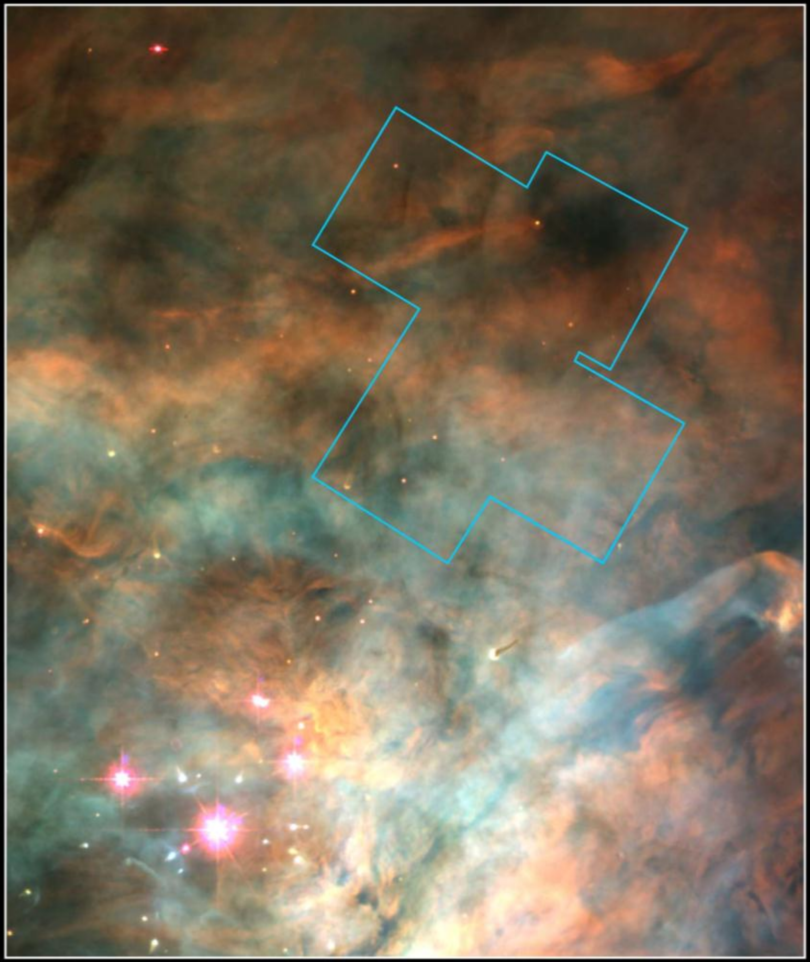


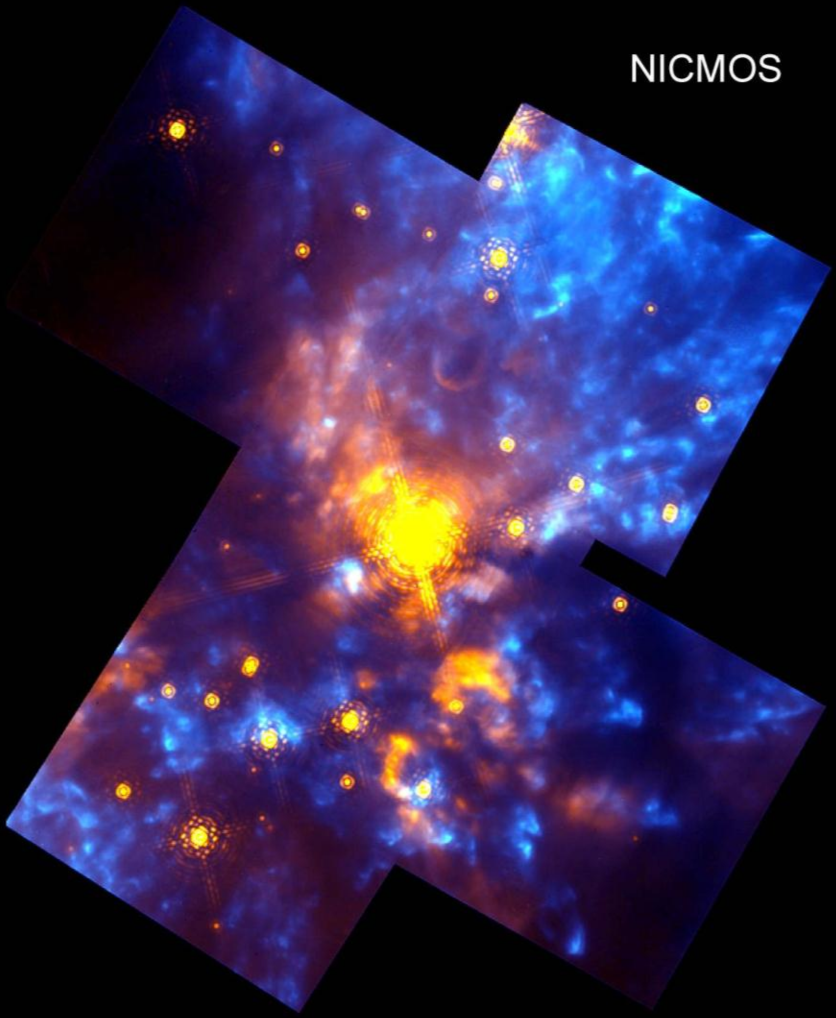


(a) A dark nebula

(b) A hidden protostar within the dark nebula

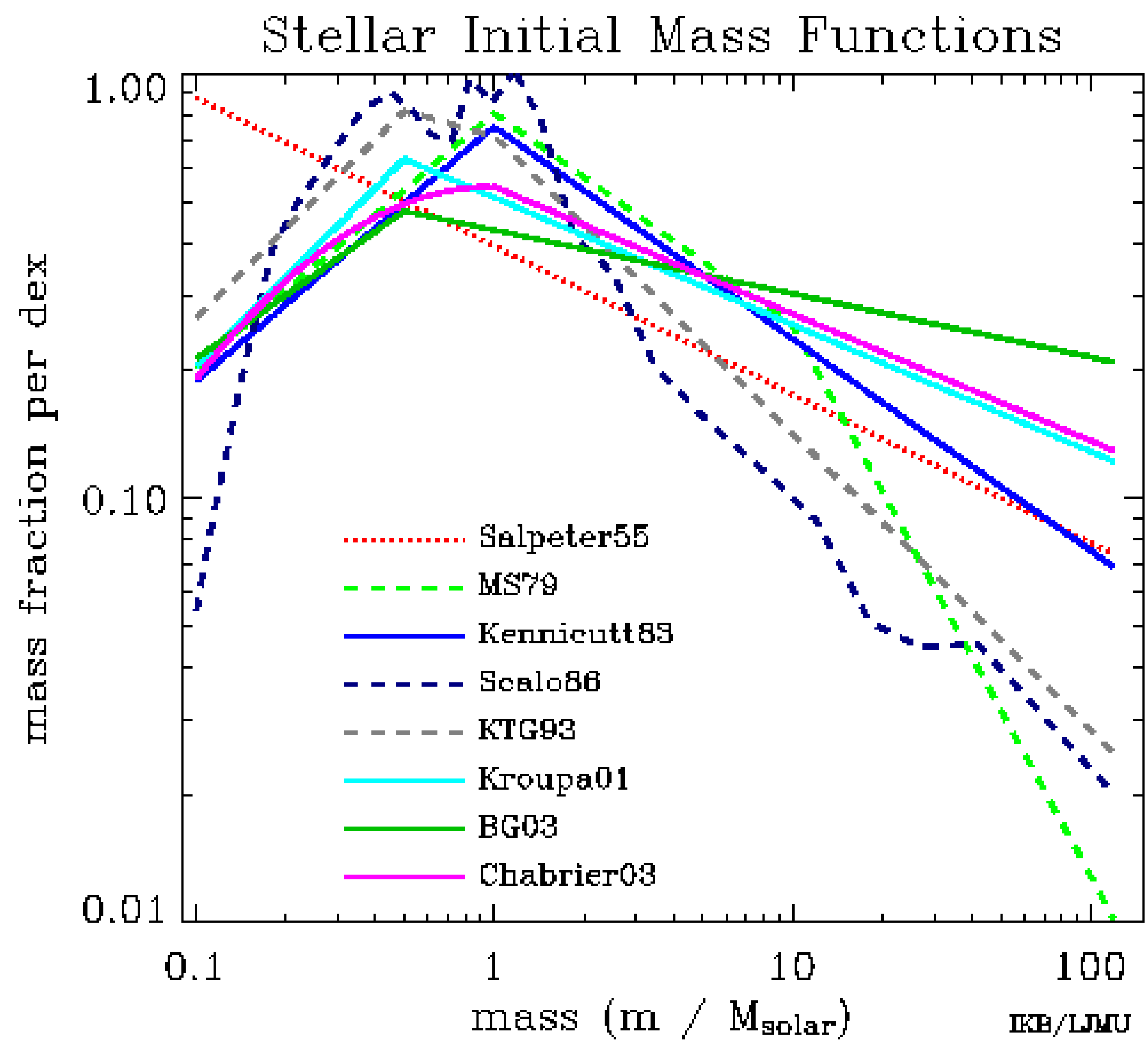
Figure 18-11
Universe, Eighth Edition


WFPC2



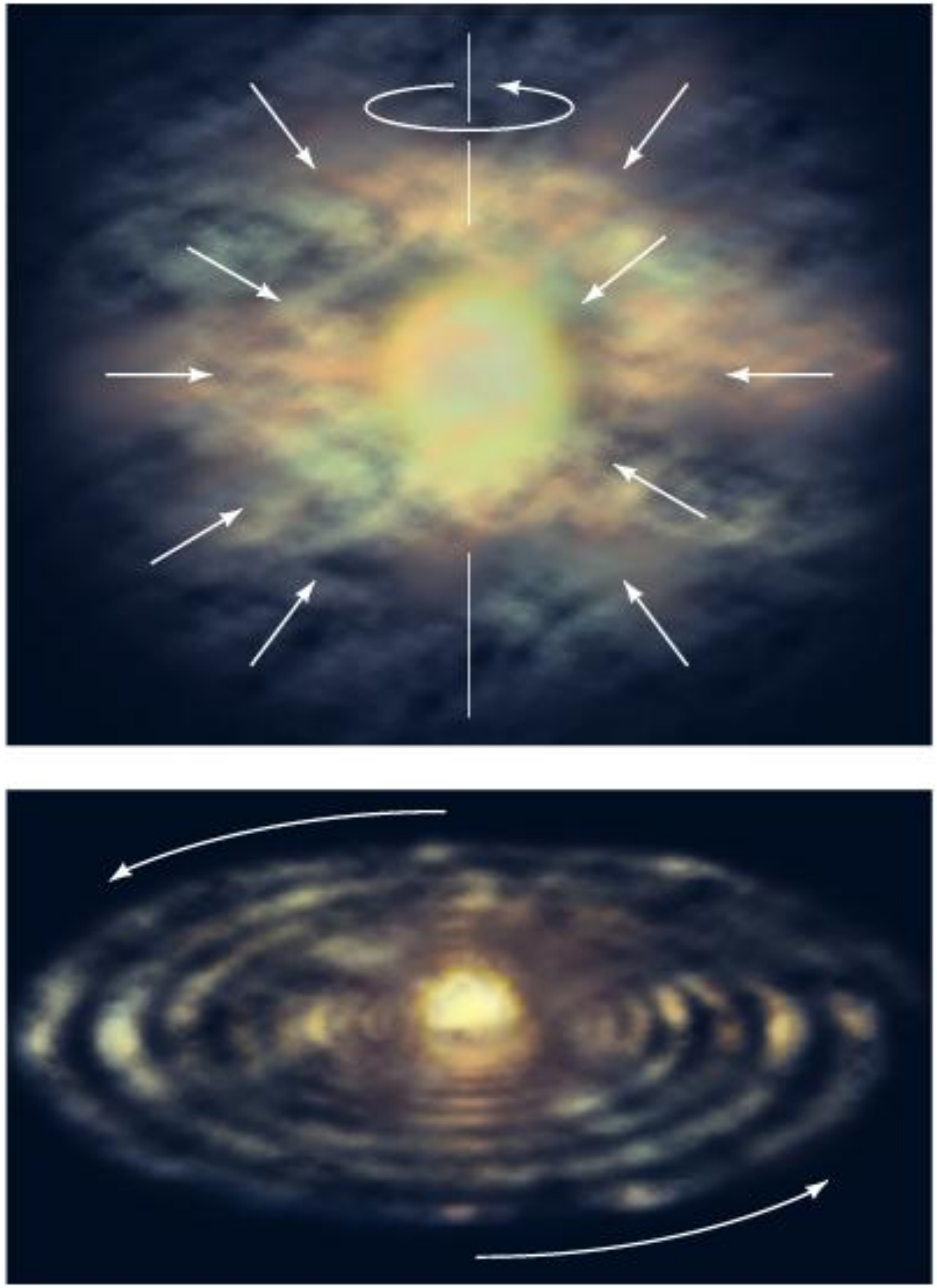
Orion Nebula • OMC-1 Region
Hubble Space Telescope • WFPC2 • NICMOS

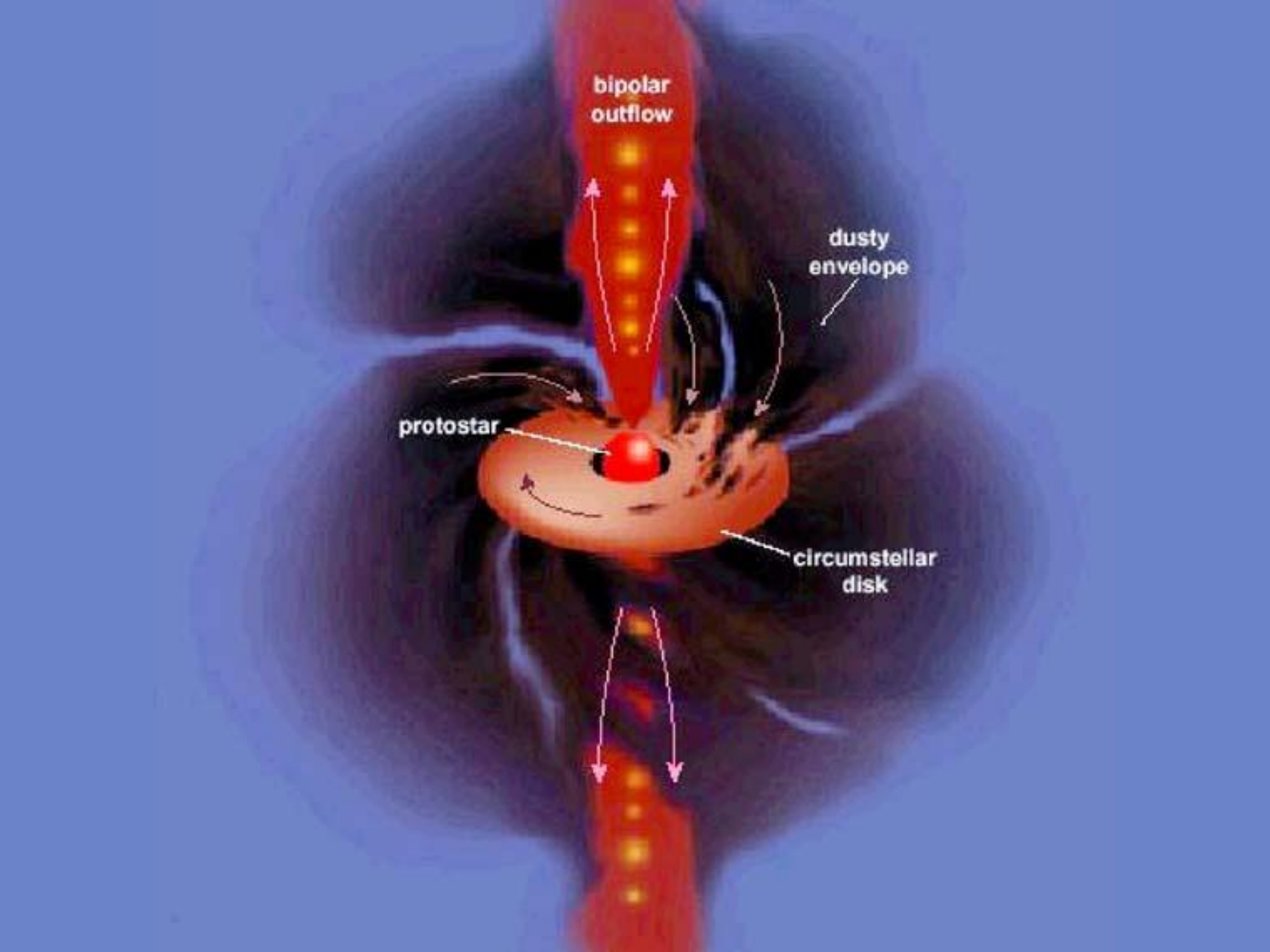
PRC97-13 • ST ScI OPO • May 12, 1997 • R. Thompson & S. Stolovy (University of Arizona), C. R. O'Dell (Rice University) and NASA



Stellar Initial Mass Functions
mass fraction per dex
1.00
0.10
0.01
0.1
1
10
100
mass (m / M_solar)
Salpeter55
MS79
Kennicutt83
Scalo86
KTG93
Kroupa01
BG03
Chabrier03
IKB/LJMU

Observational Signatures of Star Formation

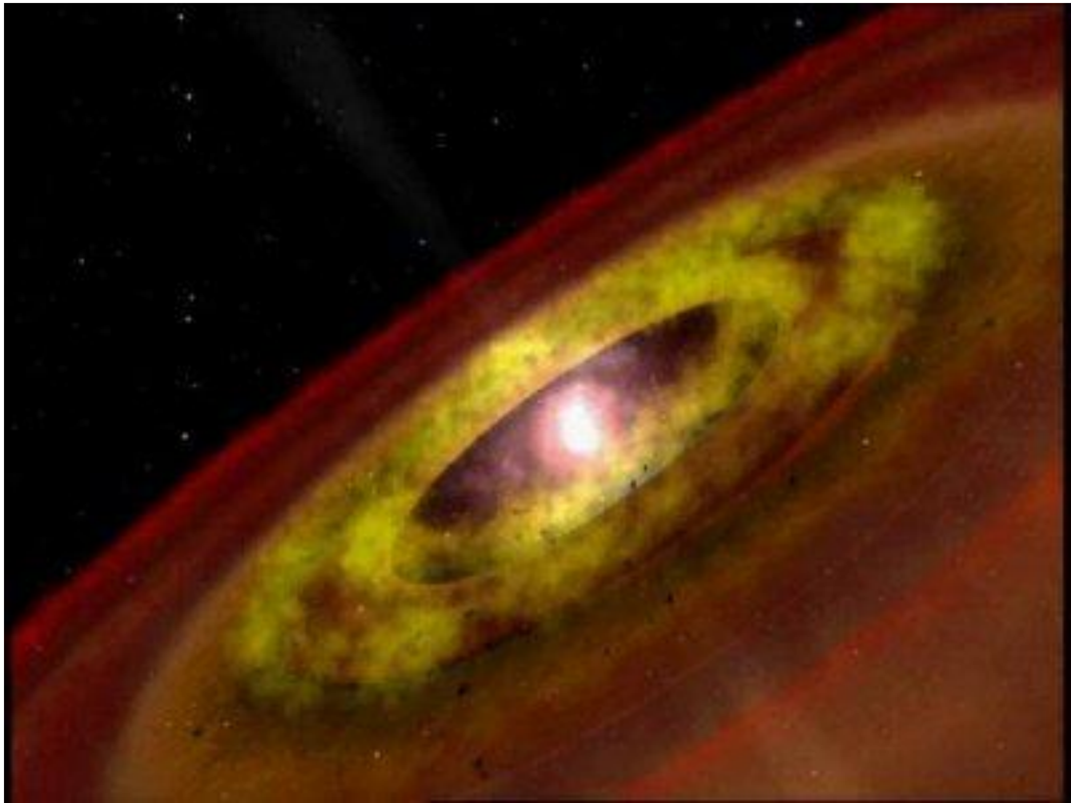


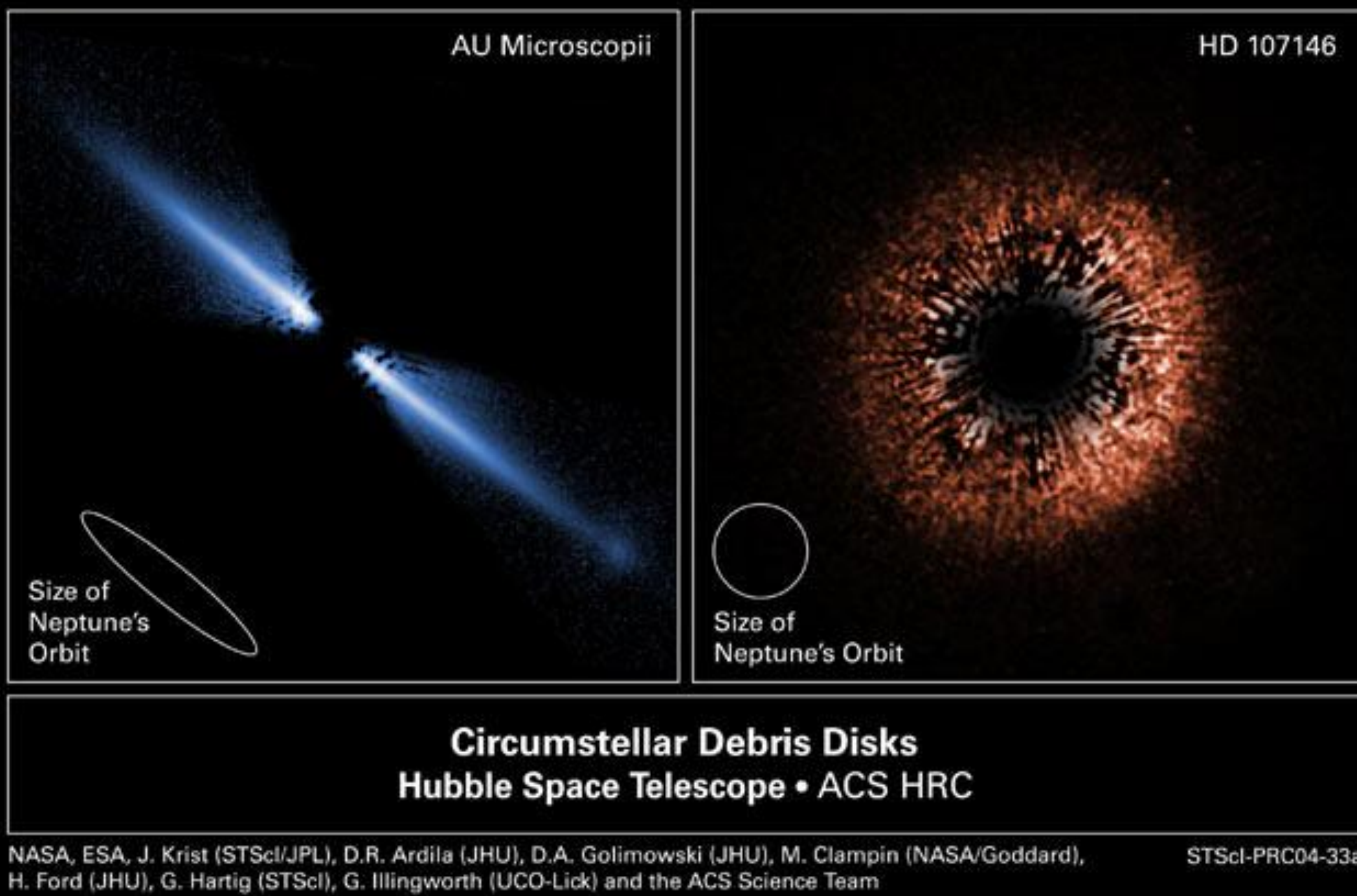

bipolar
outflow
dusty
envelope
protostar
circumstellar
disk

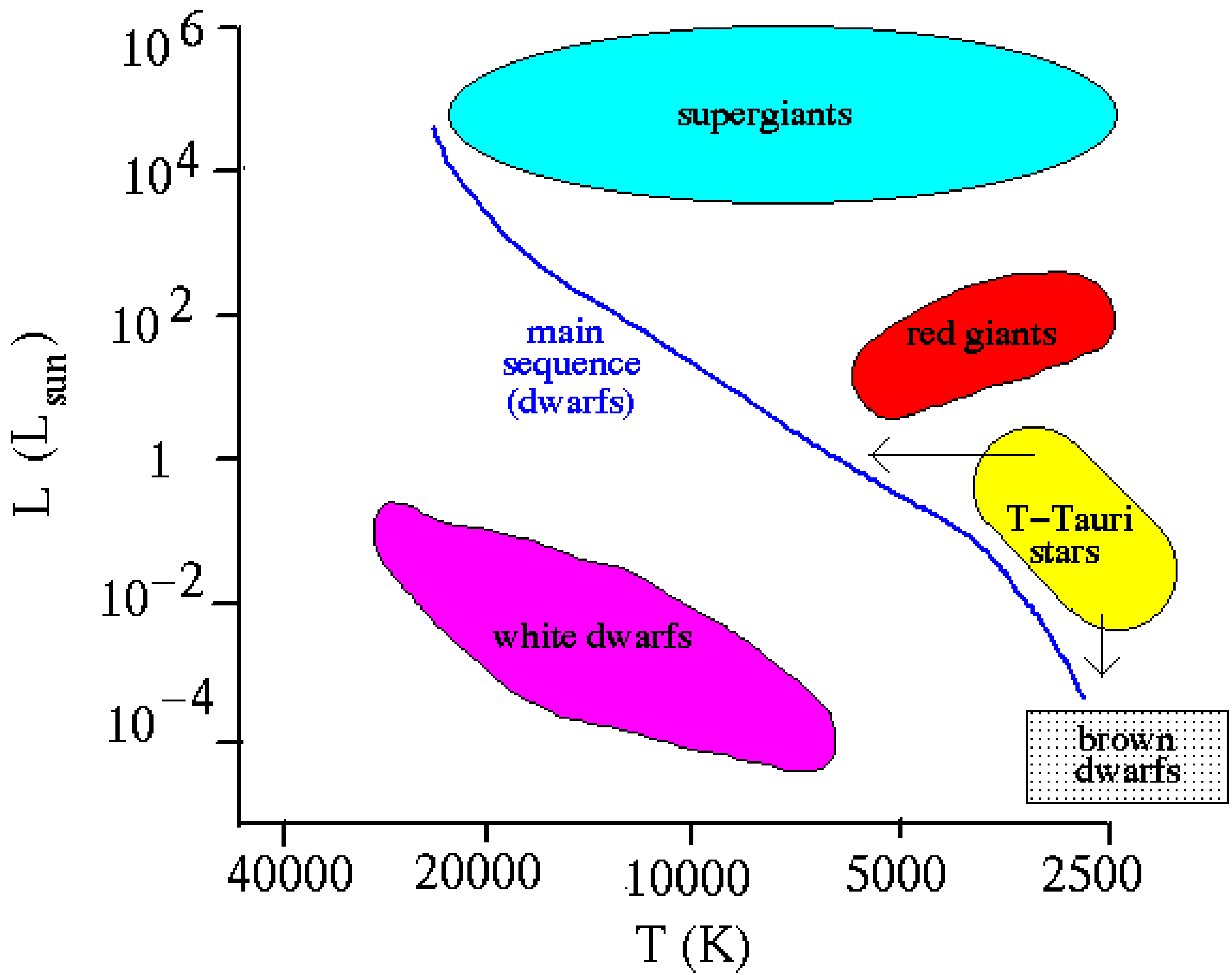
T-Tauri was the **first** star of a type found to have both disks and jet outflows…

… and we know star formation in a *fragmenting* parent cloud is a complex process, involving **competing** *mass-accretion & mass-loss* processes

➔ because of their **fast, collimated jets**, T-Tauri stars are a class of protostars that we can **observe easily**




AU Microscopii
Size of Neptune's Orbit
HD 107146
Size of Neptune's Orbit
Circumstellar Debris Disks
Hubble Space Telescope • ACS HRC
NASA, ESA, J. Krist (STScI/JPL), D.R. Ardila (JHU), D.A. Golimowski (JHU), M. Clampin (NASA/Goddard), H. Ford (JHU), G. Hartig (STScI), G. Illingworth (UCO-Lick) and the ACS Science Team
STScI-PRC04-33a



10^6
10^4
10^2
1
10^{-2}
10^{-4}
$L\ (L_{sun})$
supergiants
main
sequence
(dwarfs)
red giants
T−Tauri
stars
white dwarfs
brown
dwarfs
40000
20000
10000
5000
2500
T (K)

T-Tauri stars

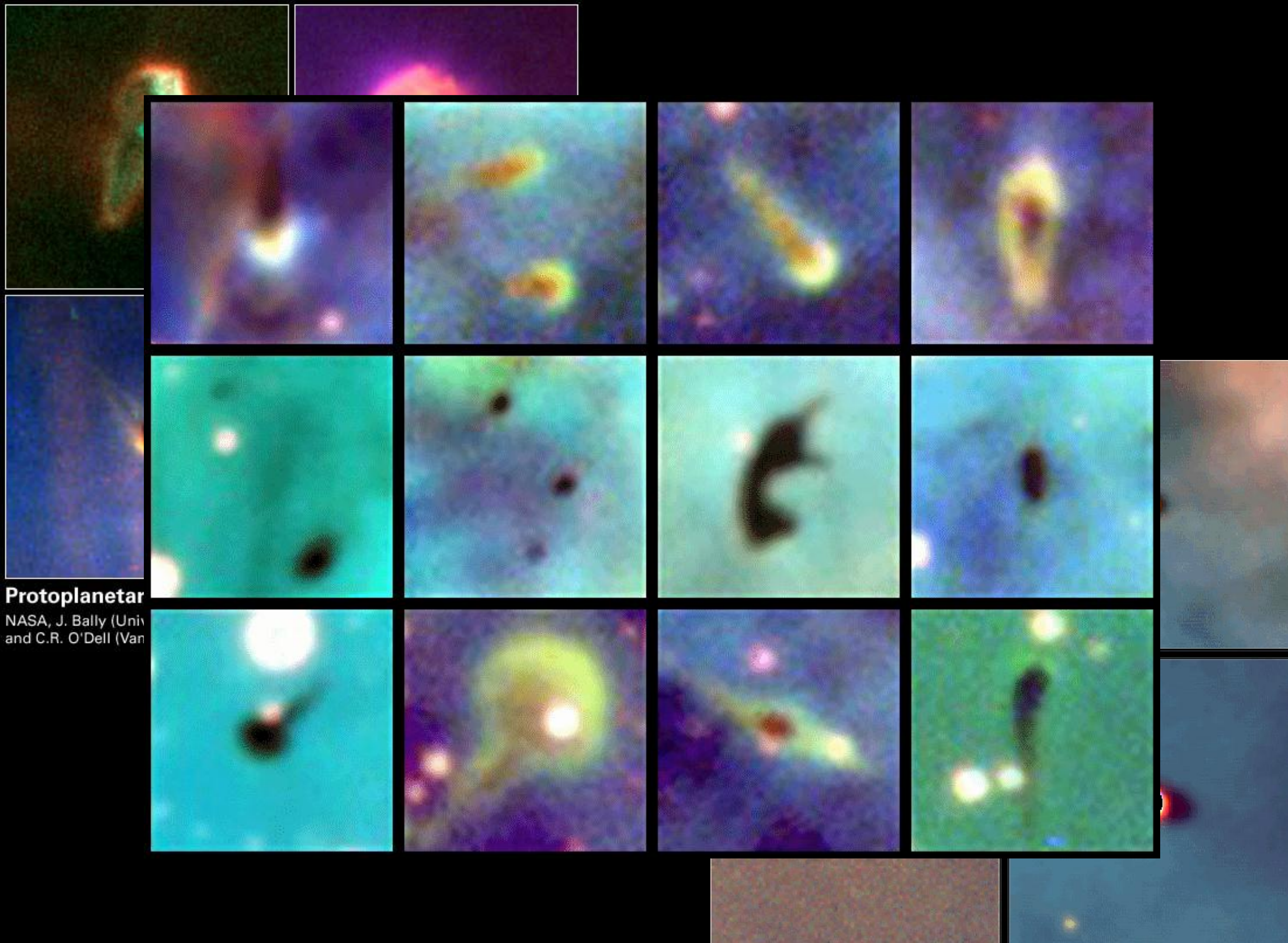
- age ~ 10^6 yr
- mid to low mass; M ~ 3 $M_\odot$.

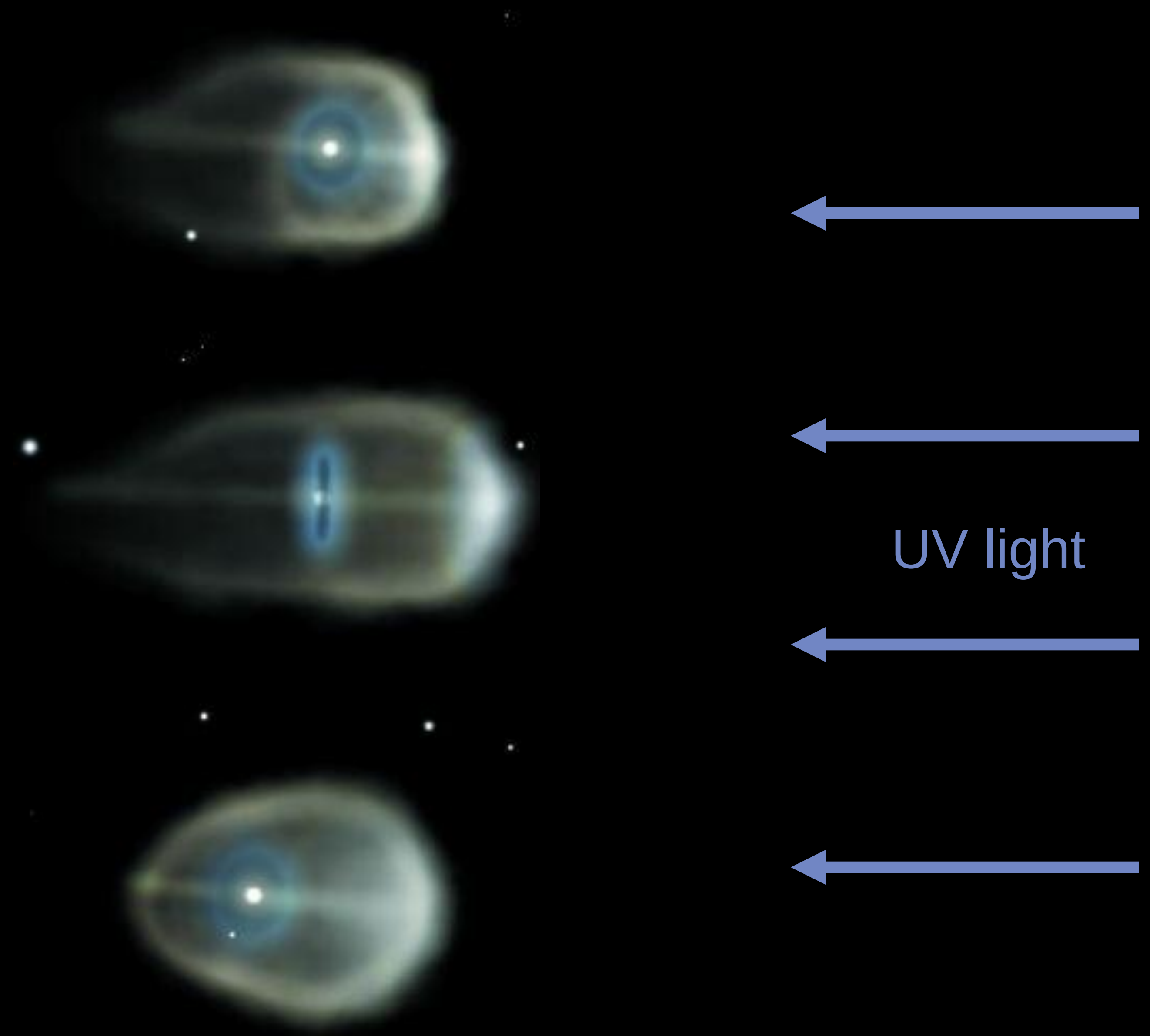
- surrounded by thin, hot gas, apparent from spectral *emission lines.*

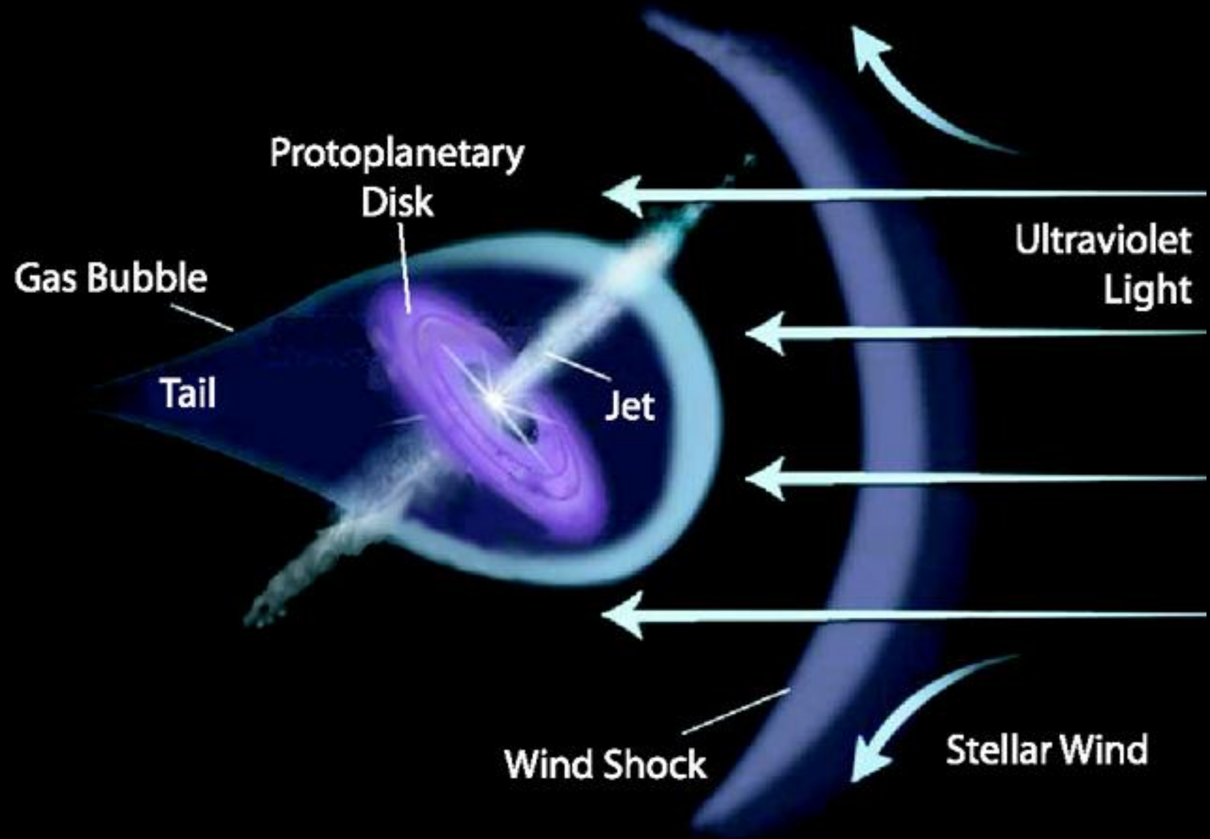
- material is being ejected at ~100 km/s in jets ➔ stars are **losing mass**.
- mass-loss rate of ~10^{-7} $M_\odot$/yr
- ➔ after reaching the MS (in ~10^7 yr) the protostar has lost ~1 $M_\odot$ of material

- this is partially lost from system, and partially incorporated into a debris disk
- debris disk is what forms a planetary system

protoplanetary disk = proplyd


Protoplanetar
NASA, J. Bally (Univ
and C.R. O'Dell (Van


UV light



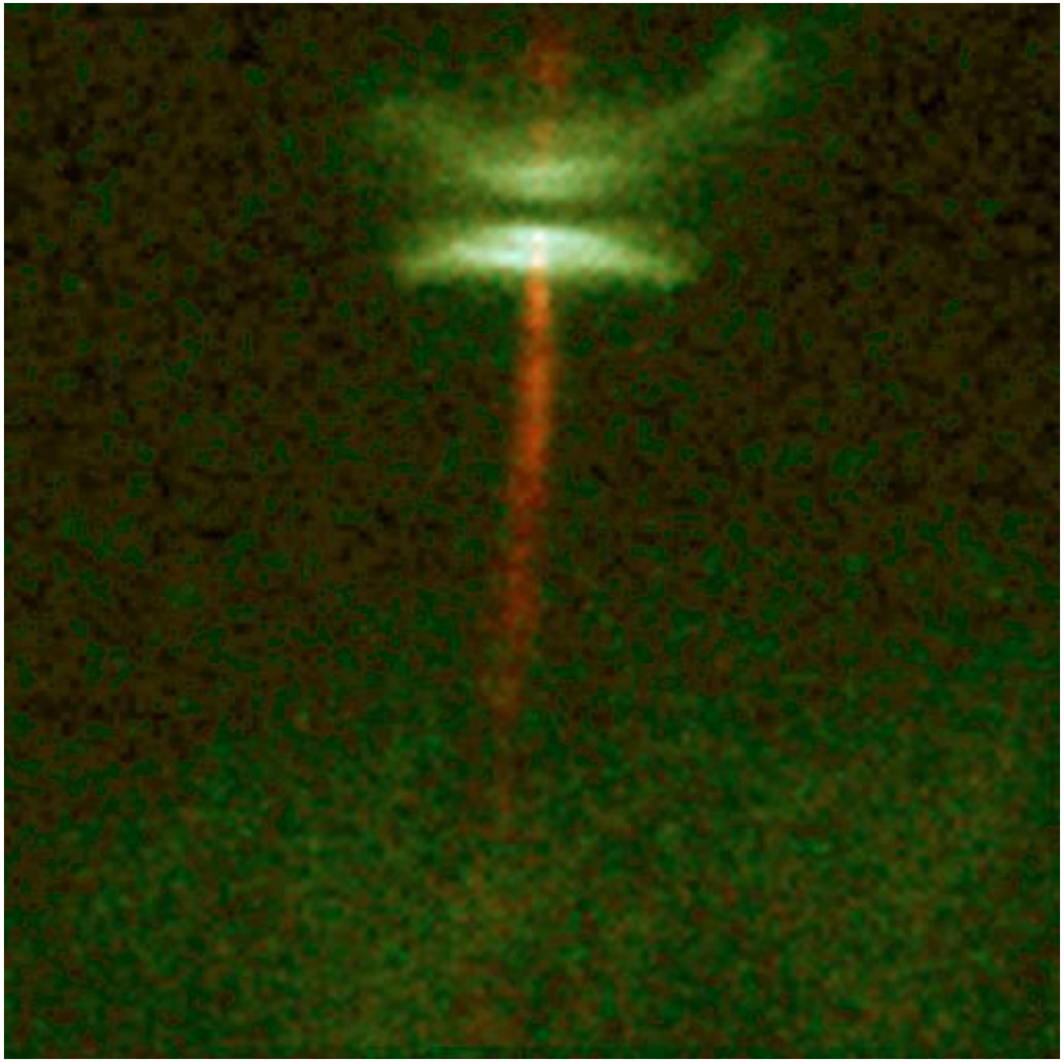
Protoplanetary
Disk
Gas Bubble
Tail
Jet
Ultraviolet
Light
Wind Shock
Stellar Wind

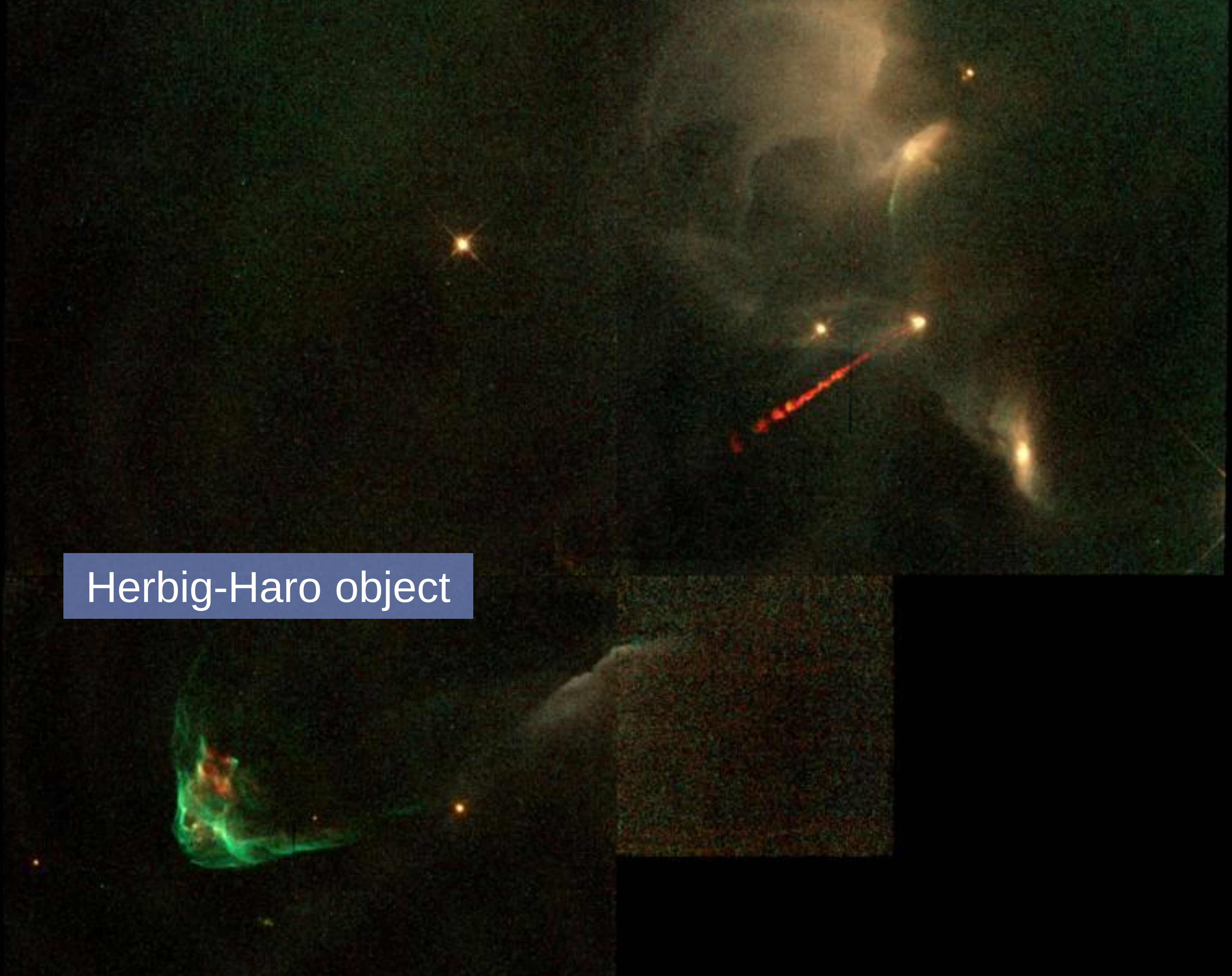
Protostar with jet called **HH-30** -- distance 140 pc (460 ly) in Taurus (*HST*/WFPC2)

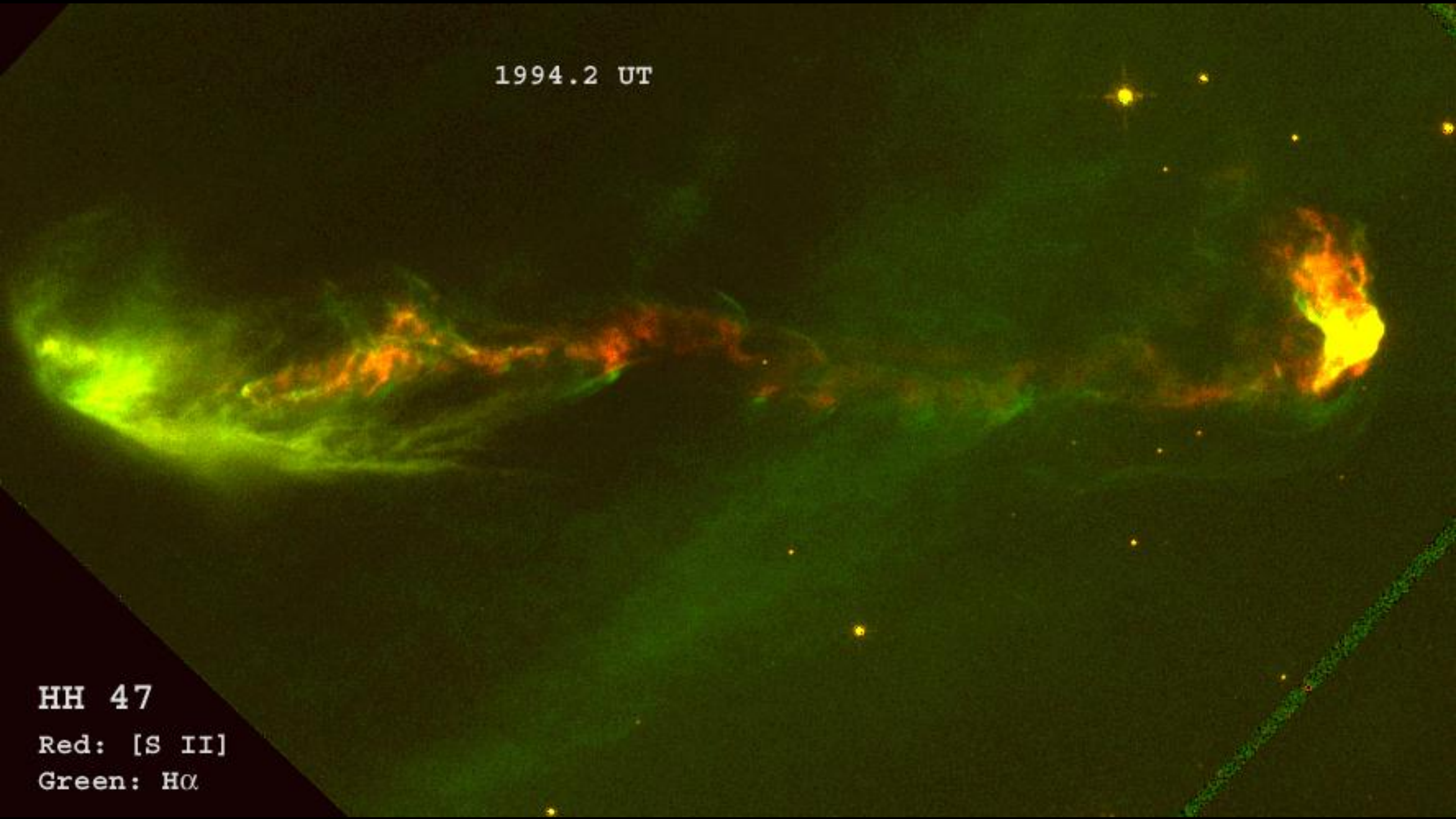
Red: ionized, bipolar **jet**

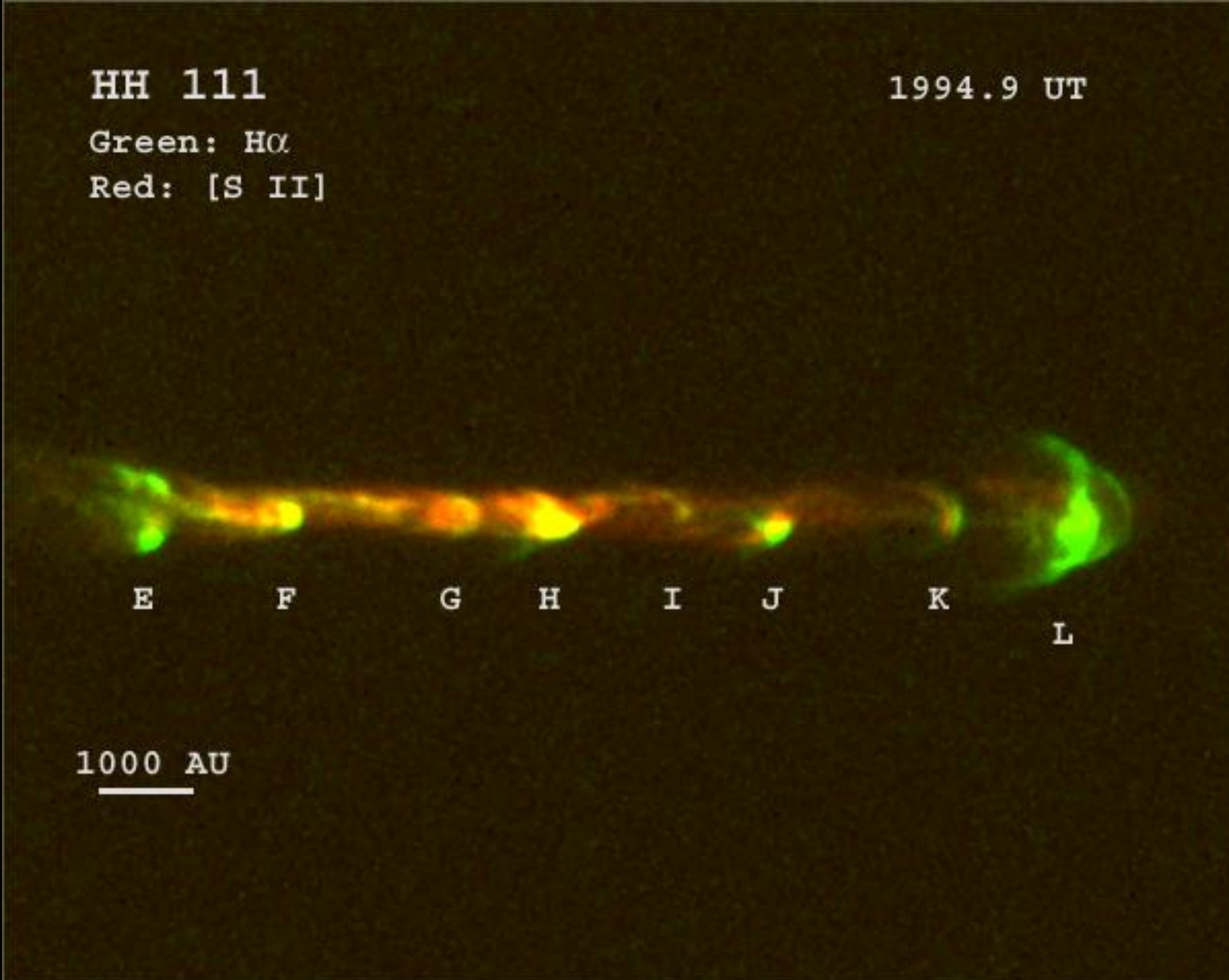
Green: light leaking vertically from the protostar and scattered from the dust particles in the circumstellar disk.

Note: opaque edge-on, **very dusty disk**, **blocking** the protostar from direct view.




Herbig-Haro object


1994.2 UT
HH 47
Red: [S II]
Green: Hα


HH 111
1994.9 UT
Green: Hα
Red: [S II]
E
F
G
H
I
J
K
L
1000 AU

Visible • WFPC2

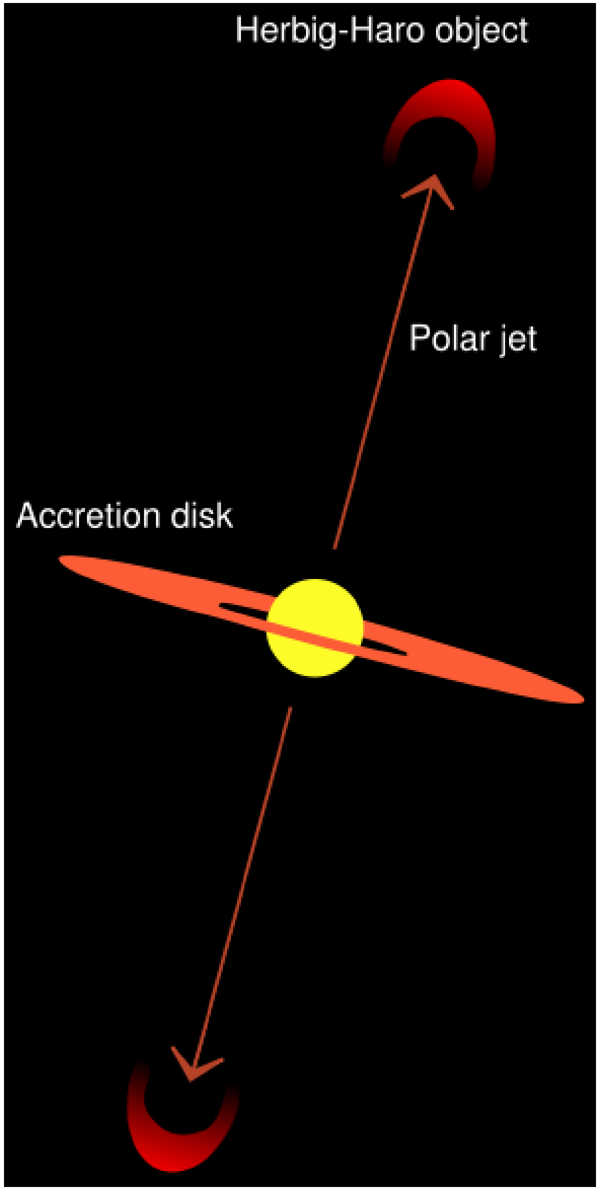
Infrared • NICMOS

HH

Hubble Spa

WFPC2 •

NASA and B. Reipurth (CASA, University of Colorado) • STScI-PRC00-05



Herbig-Haro objects: important signposts of star-formation.
Outflows/jets ejected at few 100s km/s impact the surrounding ISM and ionize it, making the jets visible.

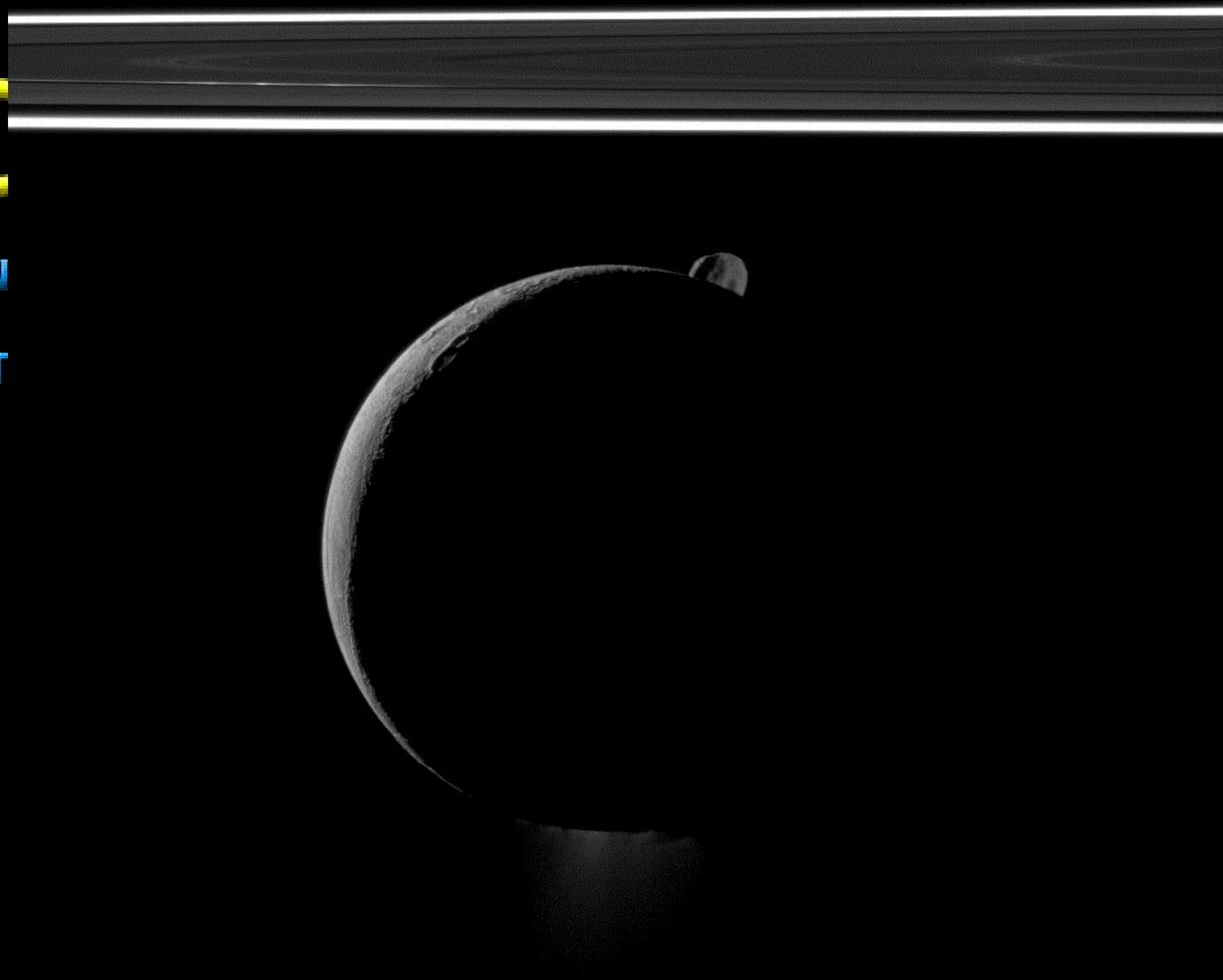
The jet creates *bow-shocks,* where the *supersonic* flow collides with the *stationary* ambient gas.
In reality, the jet 'lights up' several dense knots along its path: these knots possibly mark previous ejection episodes from the protostar. The knots emit strongly in *forbidden* emission lines.

HH objects refer to these dense lit-up knots, **not** the jet itself.

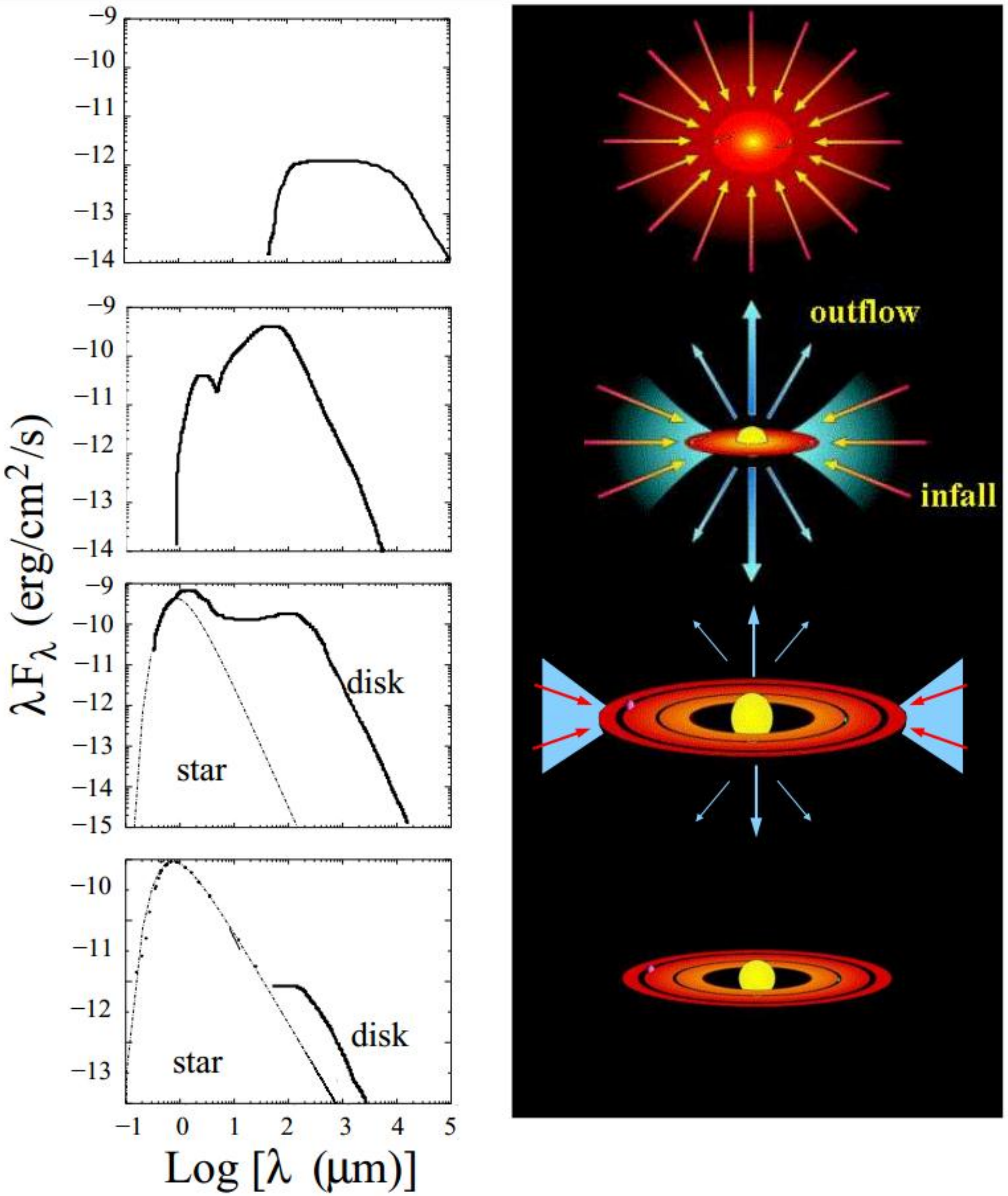
CIC

Cassin

Cent



Lack of knowledge of SF processes ➔ empirical classification of protostars



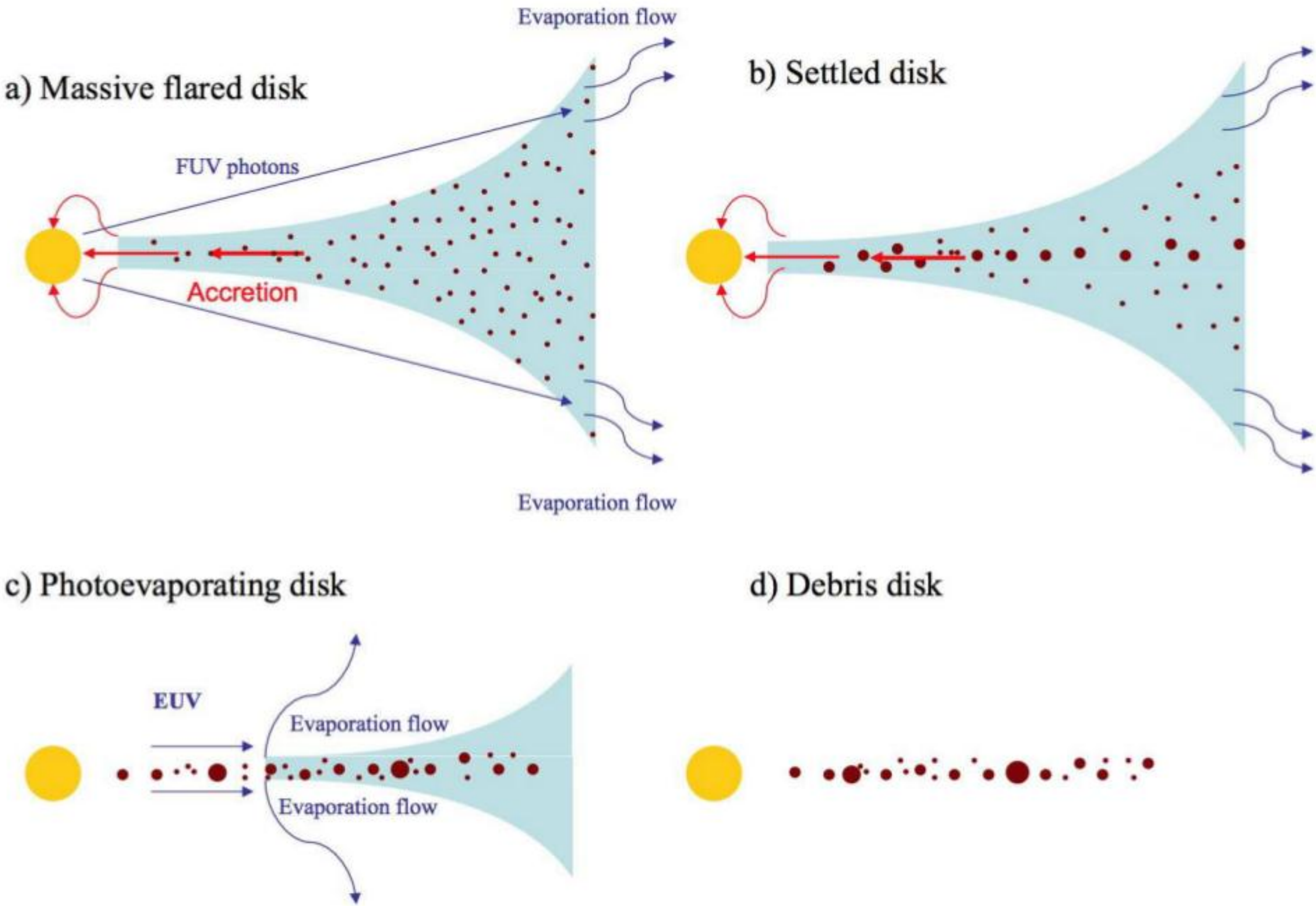
Lack of knowledge of SF processes ➔ empirical classification of protostars

Class 0: Gas infall – no protostar yet. Emission in the far-IR/mm.

Class I: protostar embedded in core; formation of outflows illuminating the surrounding dusty envelope. Shorter wavelength emission results.

Class II: The star becomes visible emitting in the UV/Opt; the disk emits in the IR (T-Tauri phase)

Class III: the infalling envelope clears, the outflow stops and the disk becomes optically thin. Debris-disks follow, and planetary formation.

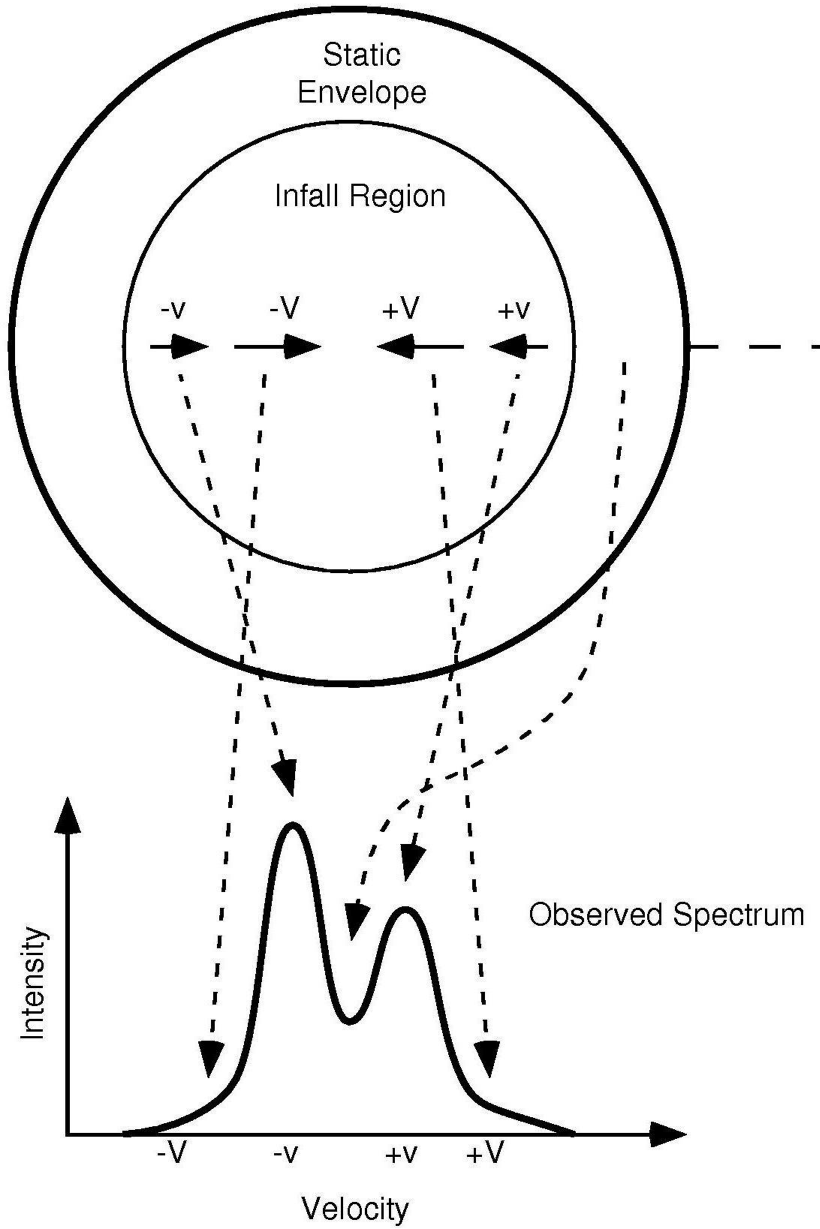

a) Massive flared disk
Evaporation flow
FUV photons
Accretion
Evaporation flow
b) Settled disk
c) Photoevaporating disk
EUV
Evaporation flow
Evaporation flow
d) Debris disk

one more class -- recently discovered…

Pre-protostellar cores: Class -1

Some dark cold clouds (e.g. ‘Bok’ globules) show signs of **infall** through sub-mm/mm observations of molecules (e.g. HCO^+, CS, NH_3).

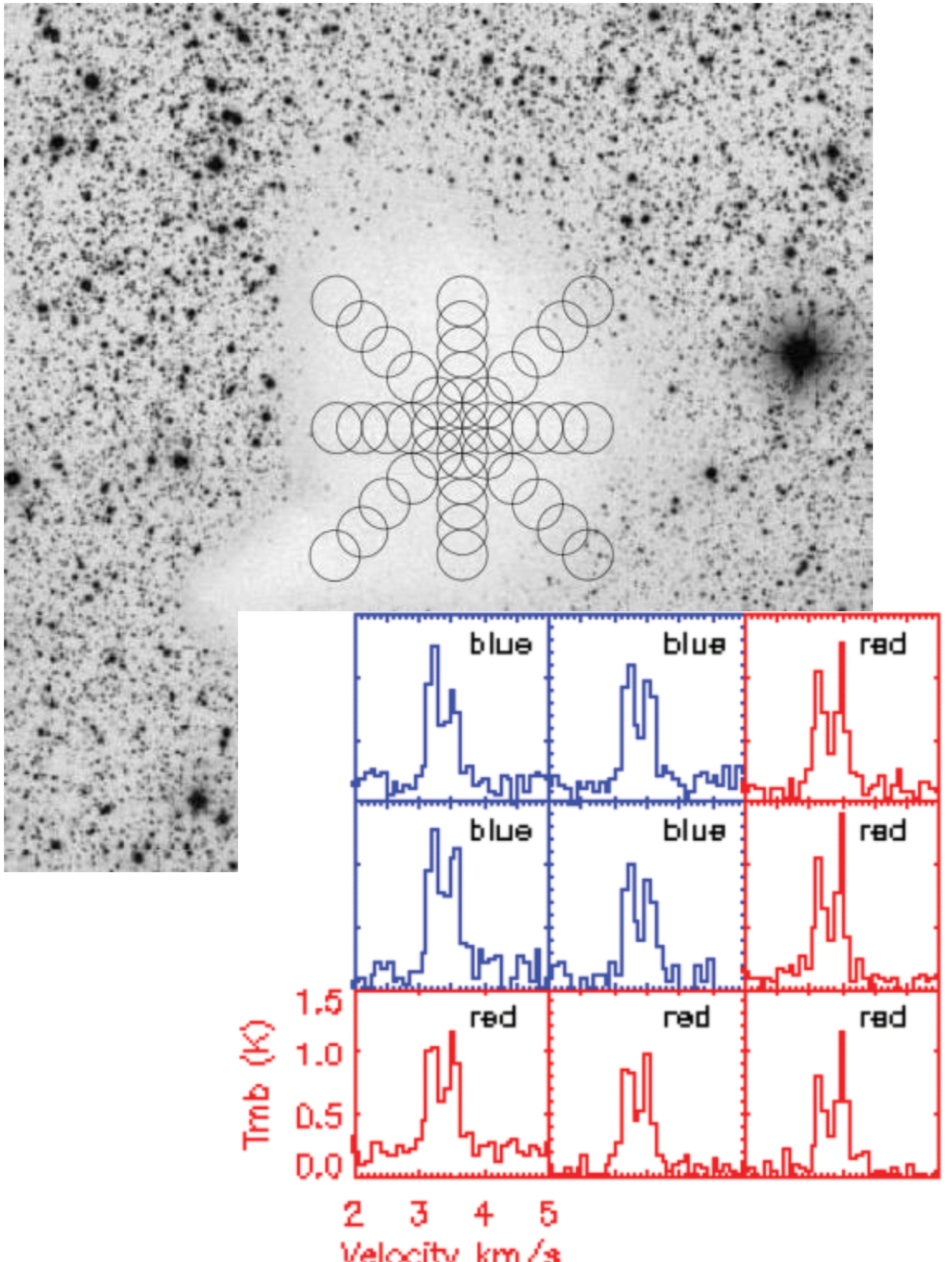
Inside-out collapse (inside of the cloud collapses first):
Signature: double-peaked line profile, where the *blue* component is stronger than the *red*…

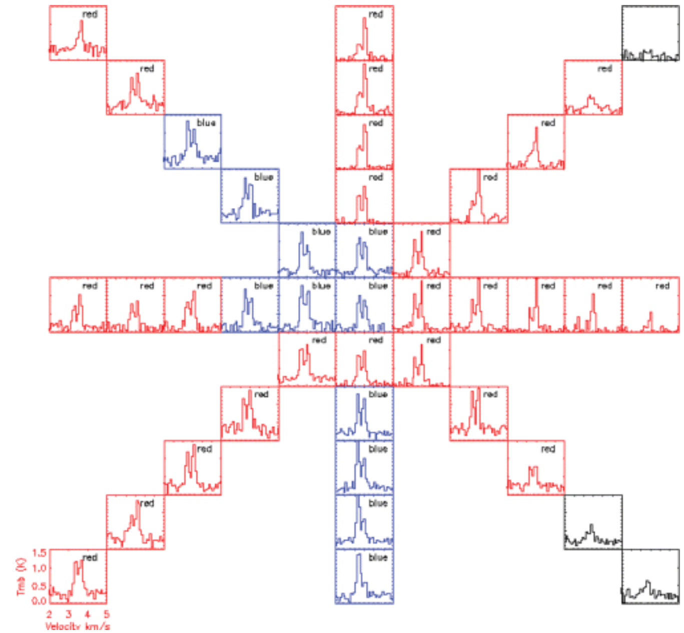


Receding velocities (redshifted):
the hot gas at +V is shielded by cooler gas at +v and the line is diminished.
Approaching velocities (blueshifted):
the hot gas at -V is not shielded by the cooler gas at +v.

The blue peak is therefore stronger than the red.


No collapse at all, just oscillation: case of B68



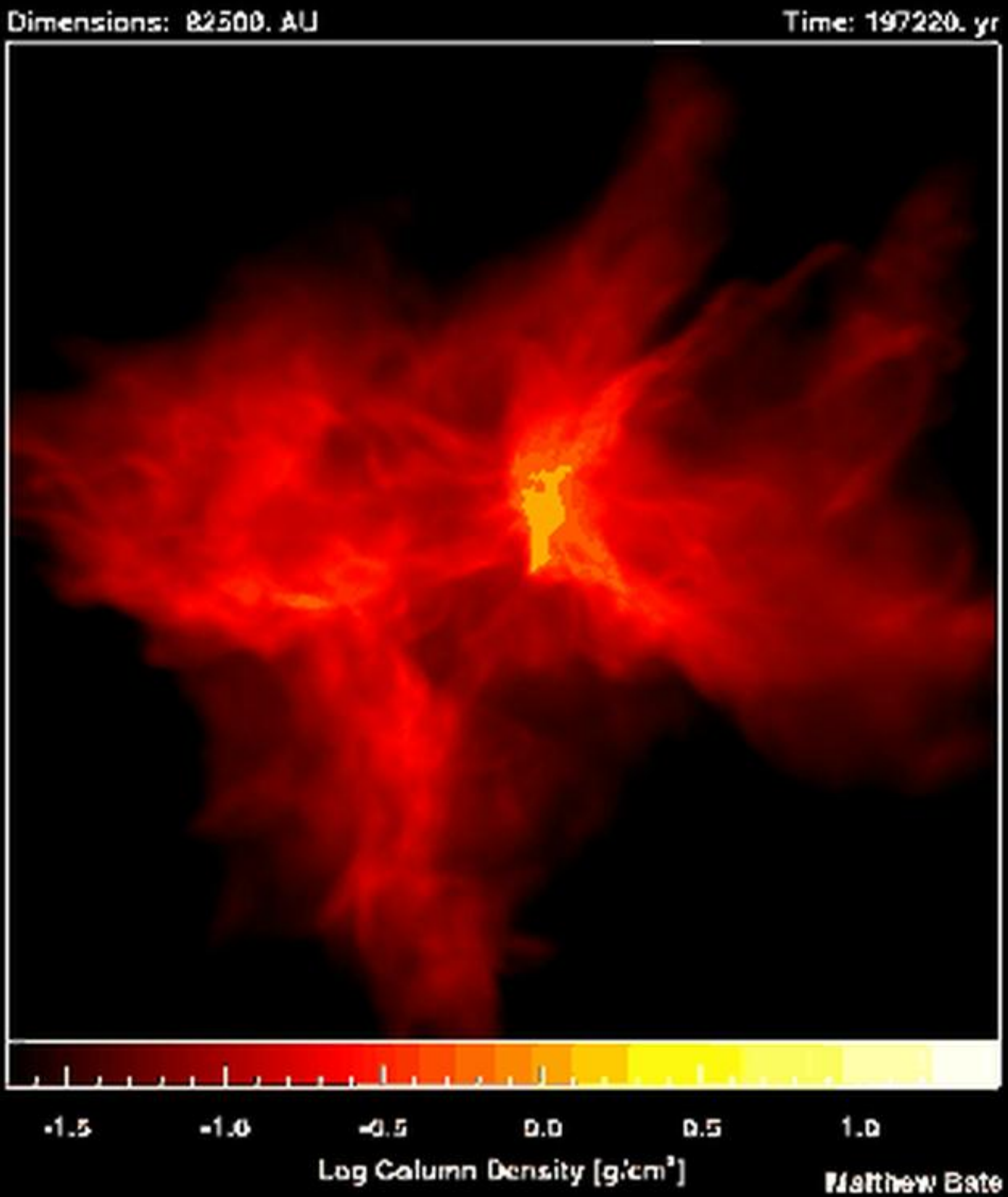


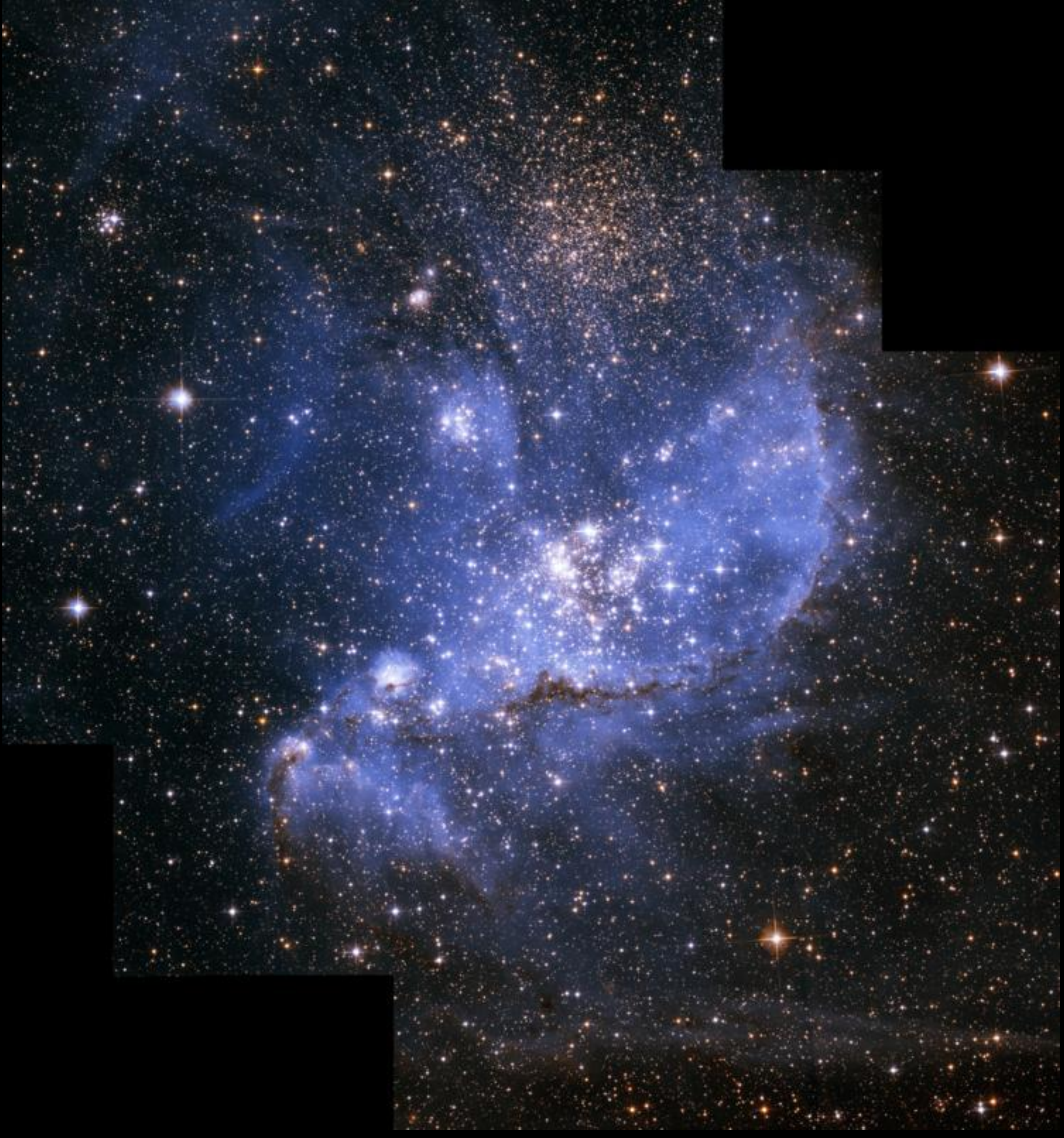
HCO$^+$ observations with JCMT

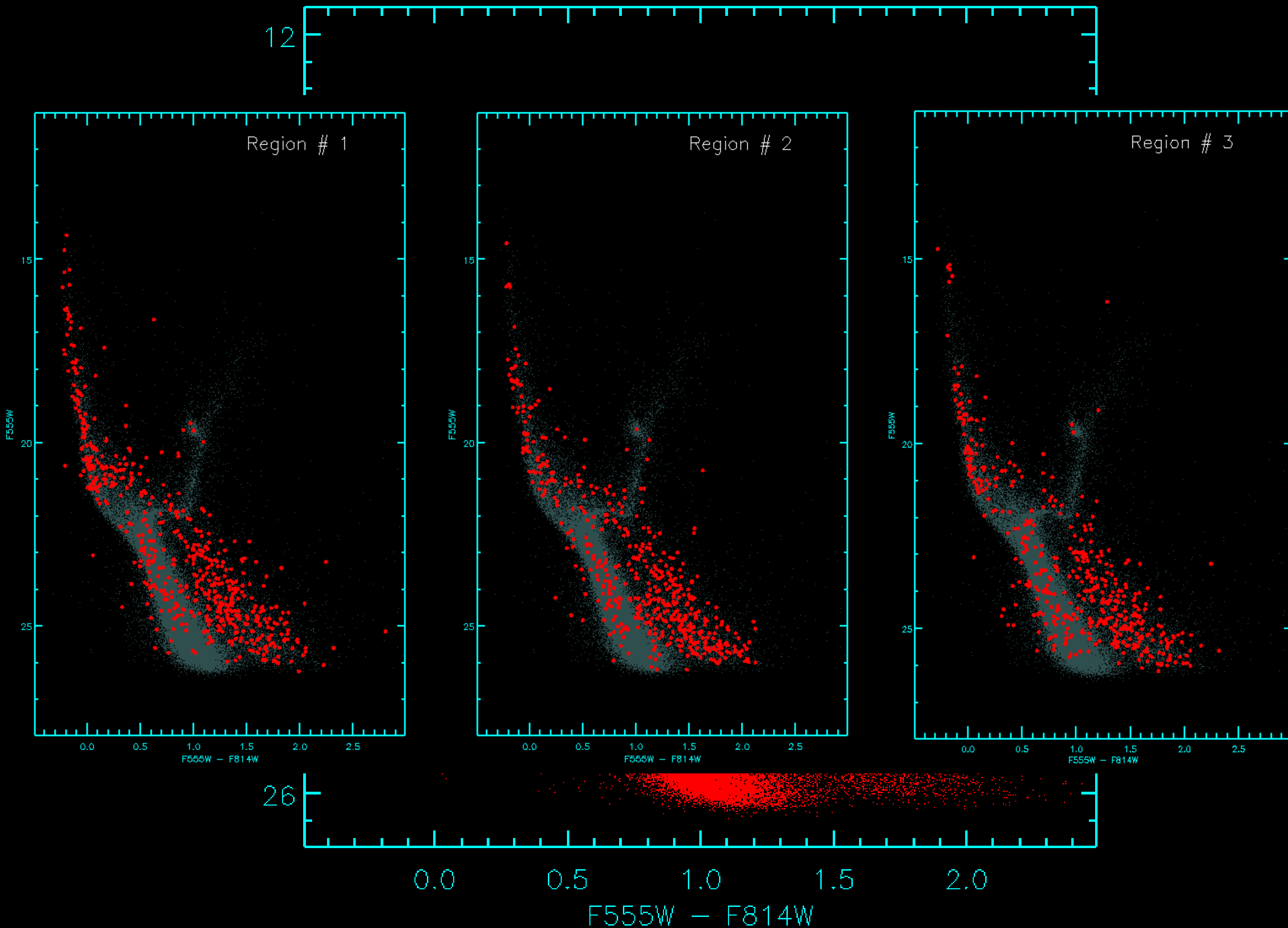
Line profiles cannot be explained by rotation, or inside-out collapse. The cloud oscillates in equilibrium

“wobbly, jelly-like nature”

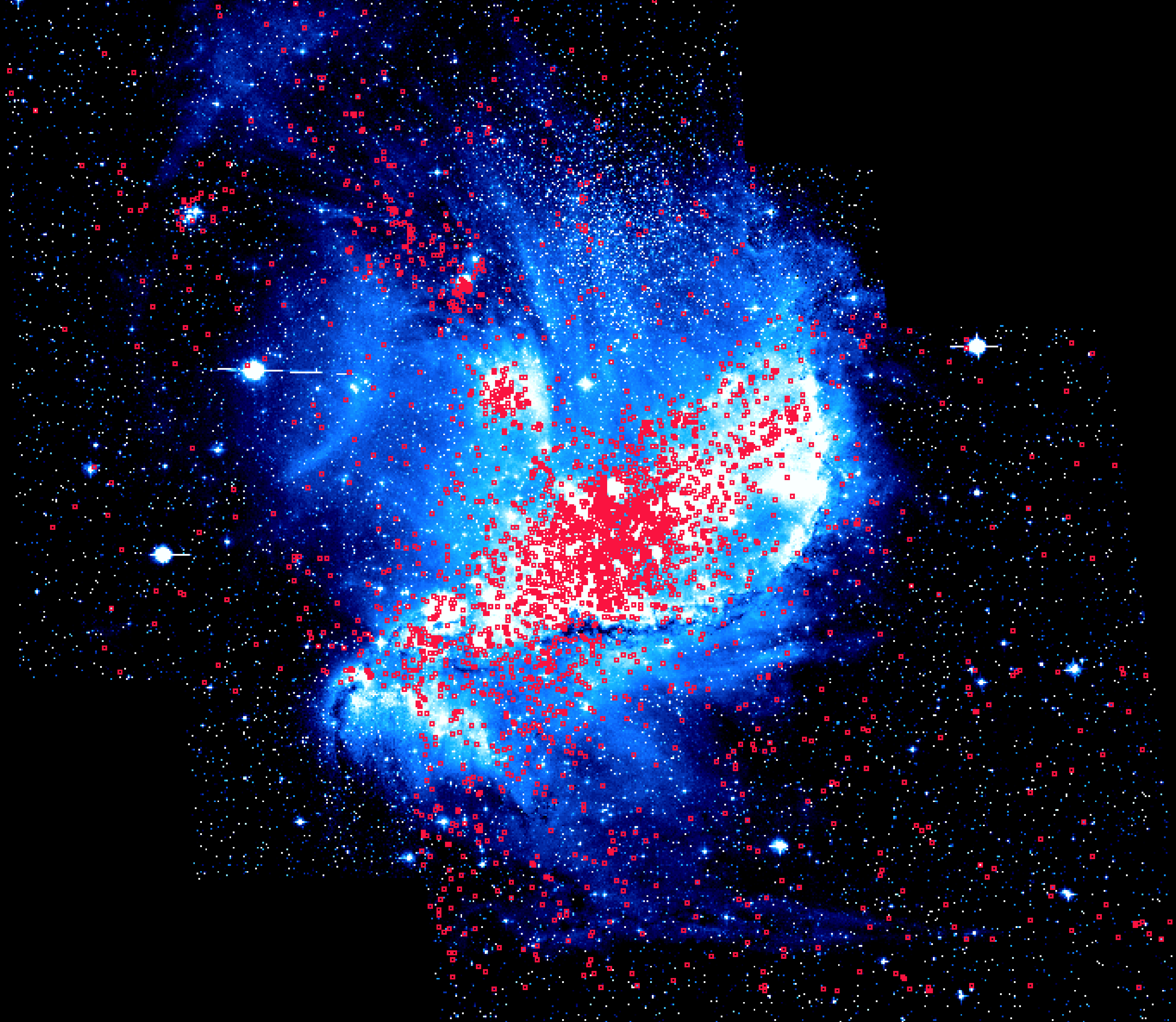
Redman et al. 2006 (MNRAS 370)


Dimensions: 82500. AU
Time: 197220. yr
-1.5
-1.0
-0.5
0.0
0.5
1.0
Log Column Density [g/cm²]
Matthew Bate





Region # 1
Region # 2
Region # 3
F555W
F555W - F814W
12
26
0.0
0.5
1.0
1.5
2.0



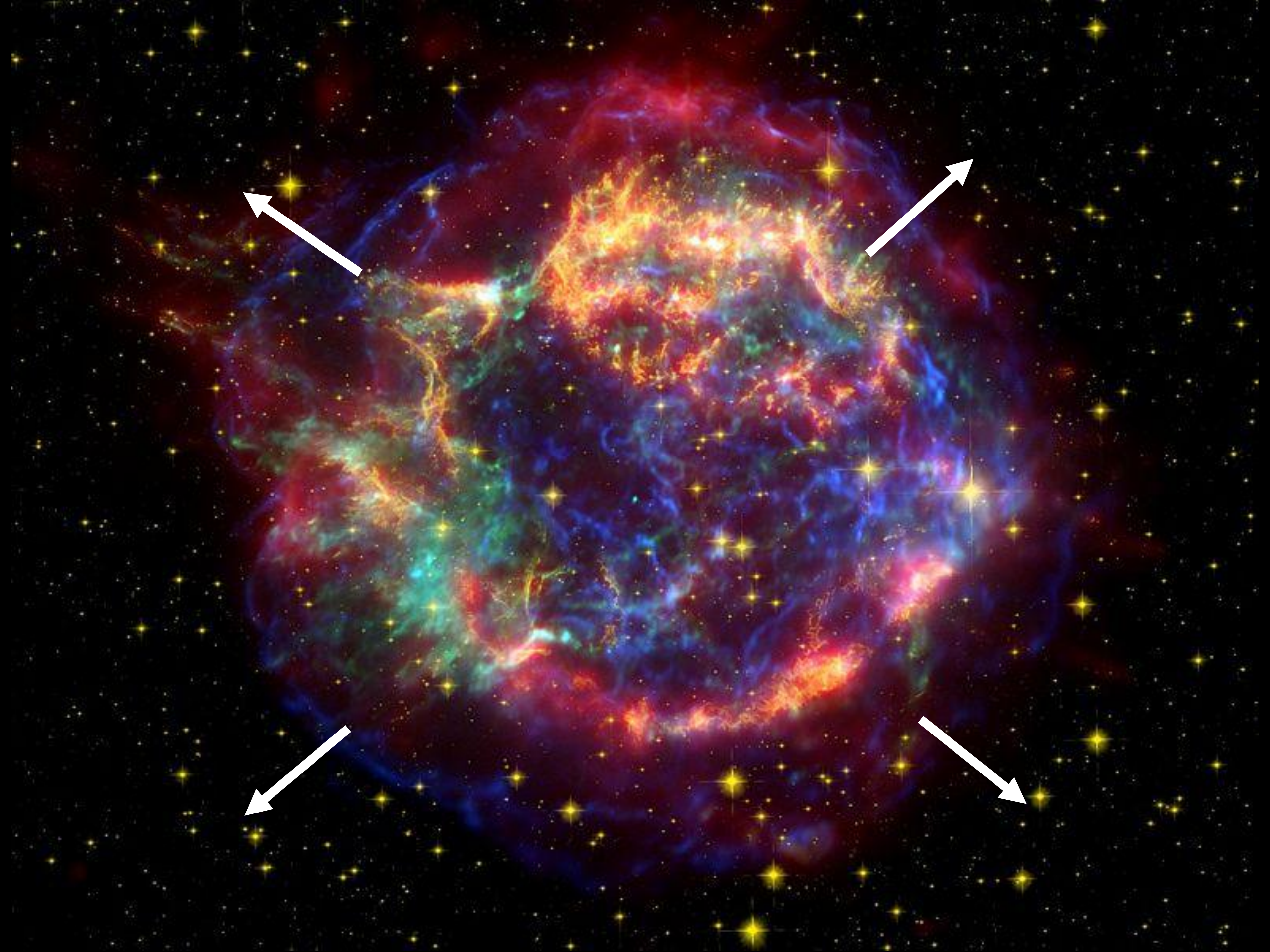
Triggering mechanisms

- Massive star winds
- SNe

} produce shock waves

- Spiral arm passage
- Collision between molecular gas clouds
– Randomly
– After galaxy interaction

compression waves



Vela Supernova Remnant

SKYFACTORY

Data from the Digitized Sky Survey
Image processing by Davide De Martin

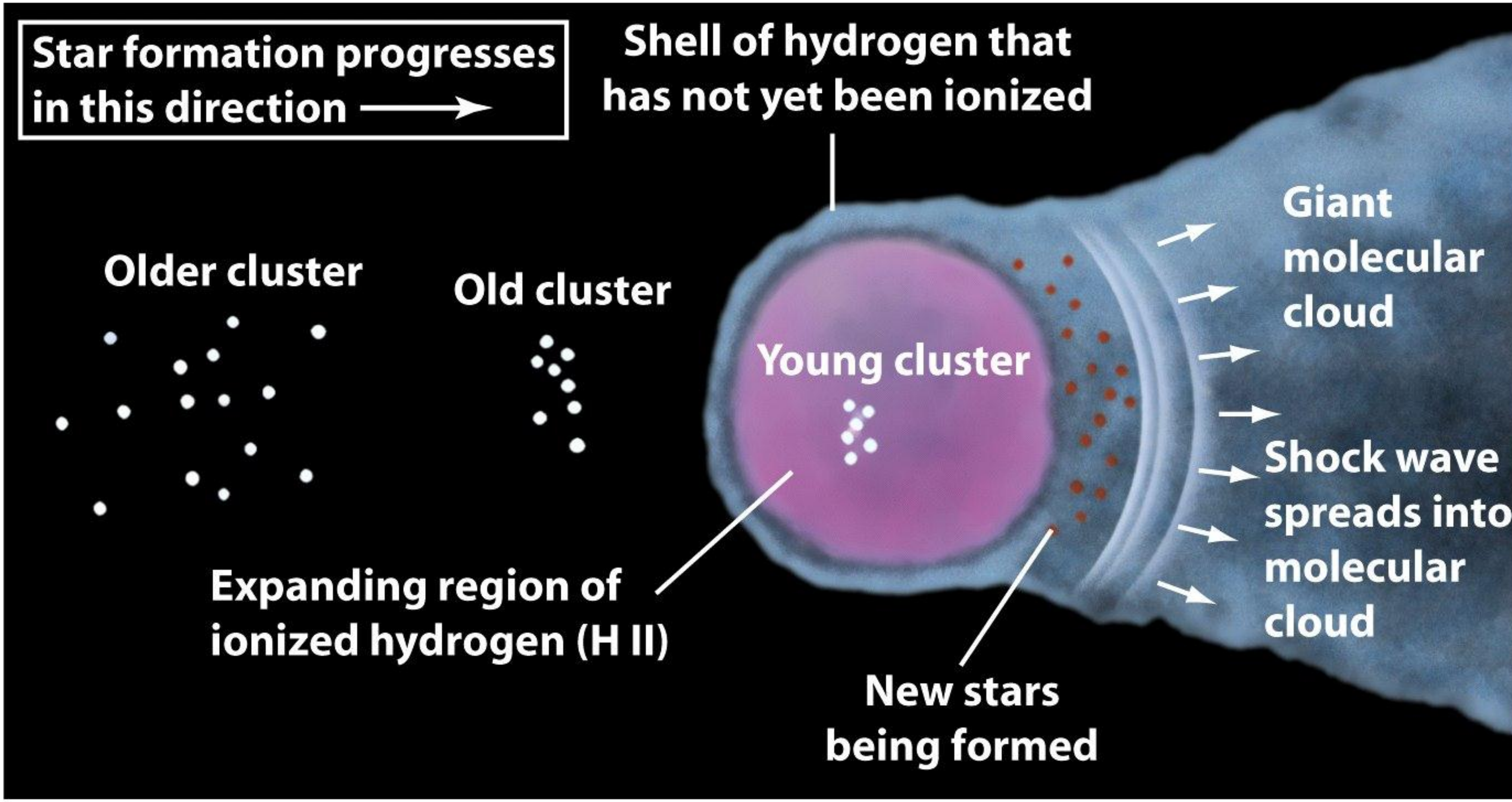
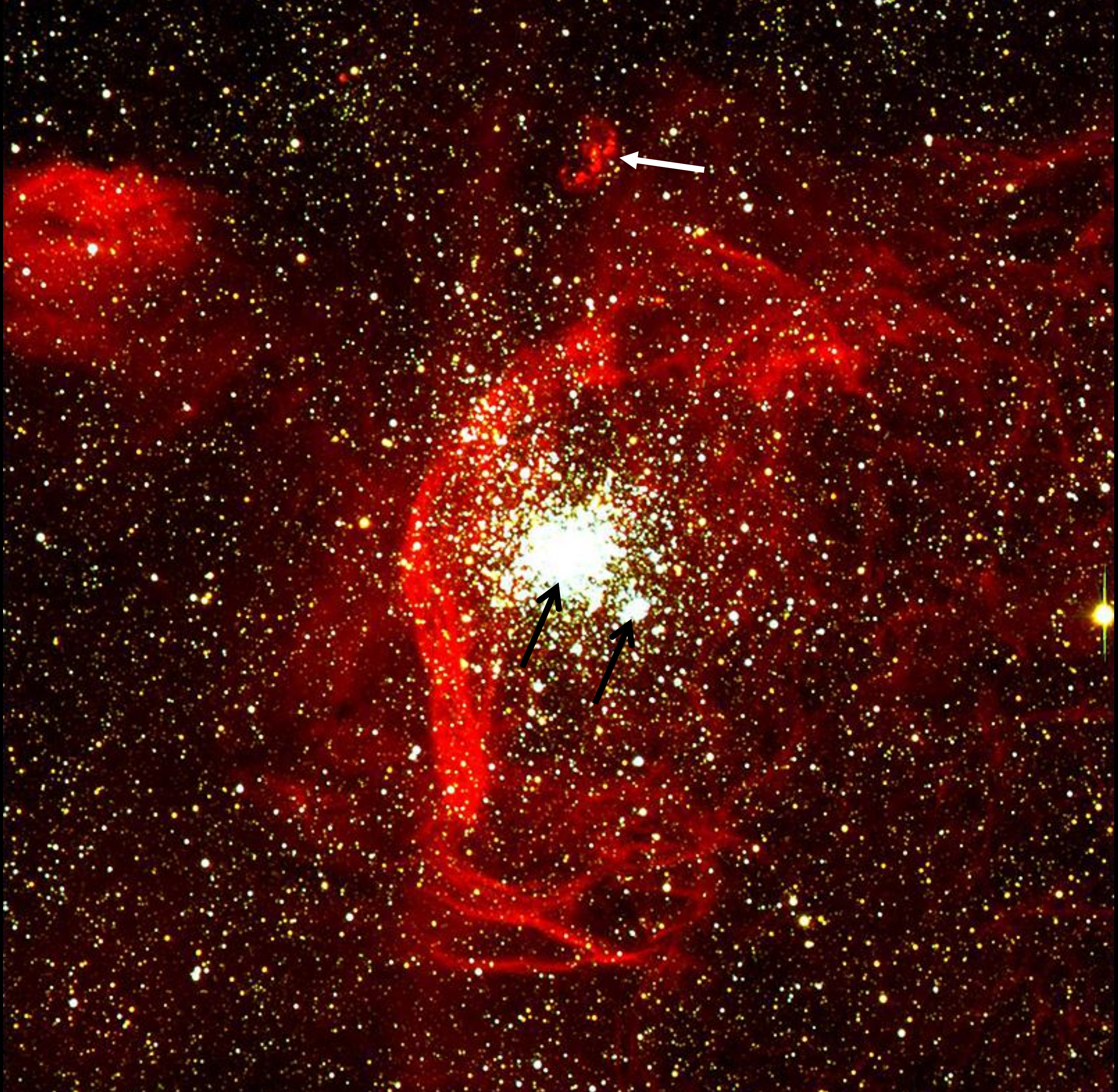
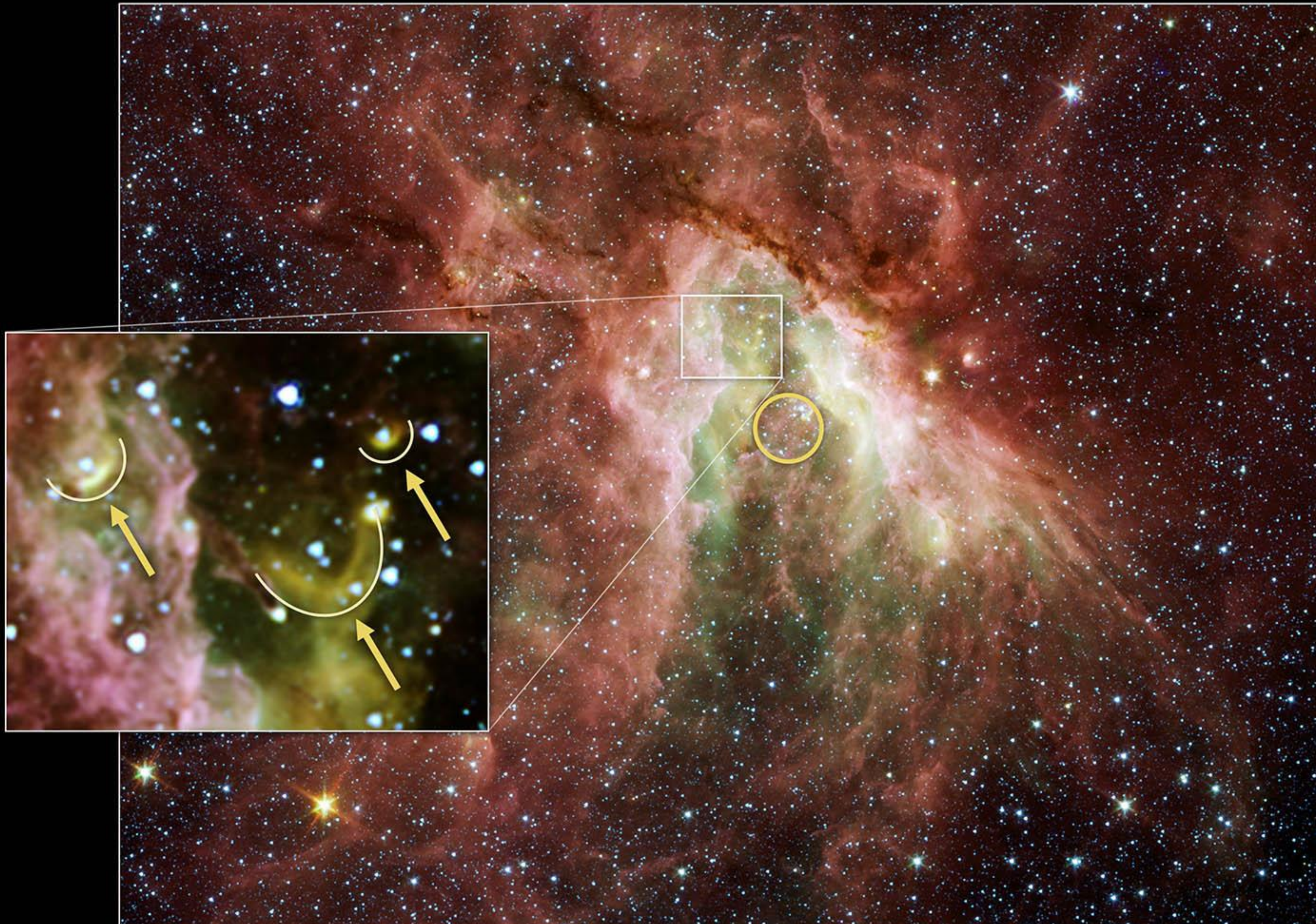


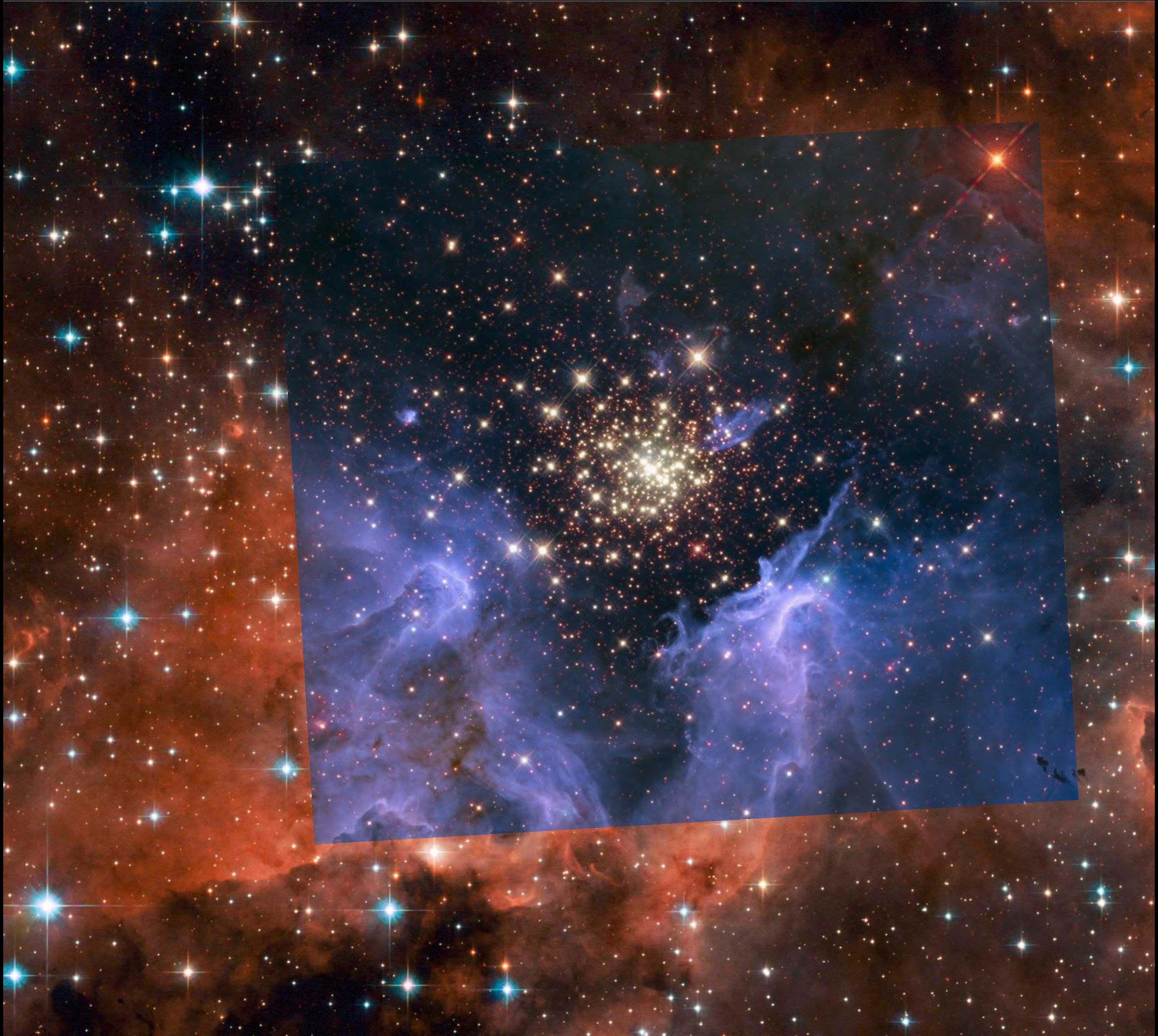
Figure 18-23 part 1
Universe, Eighth Edition

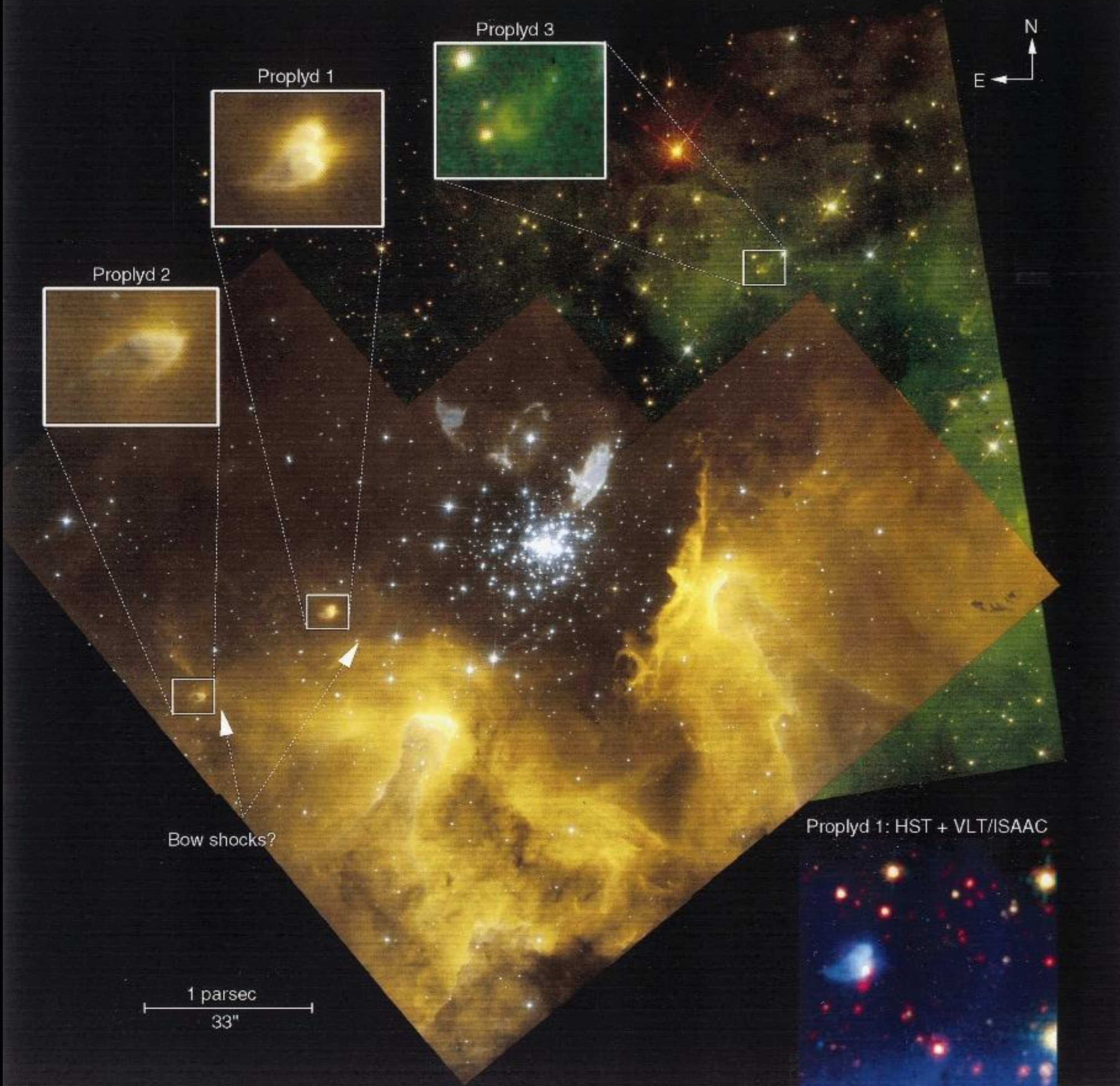




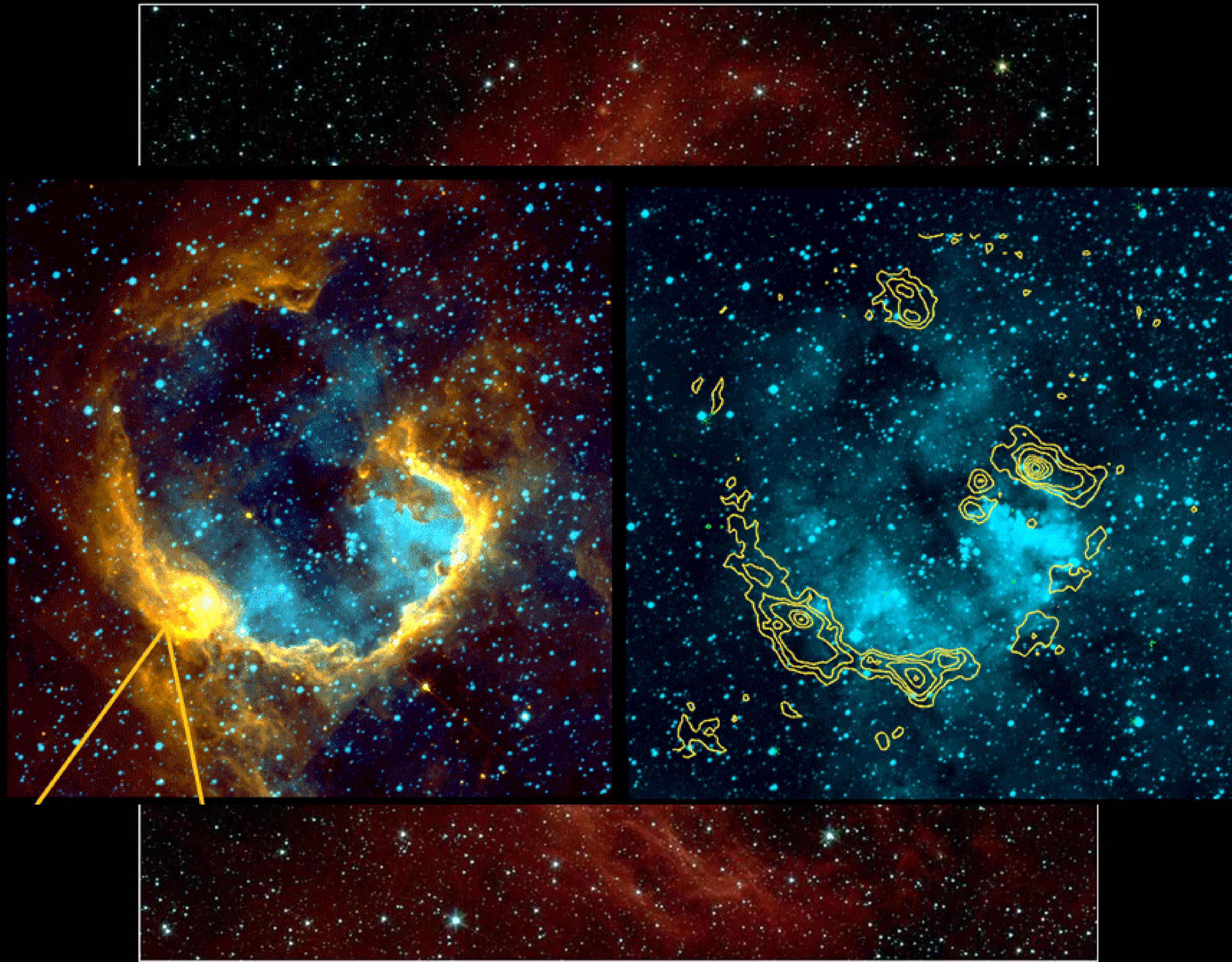
Shock Fronts in the Omega Nebula (M 17)
NASA / JPL-Caltech / M. Povich (Univ. of Wisconsin)

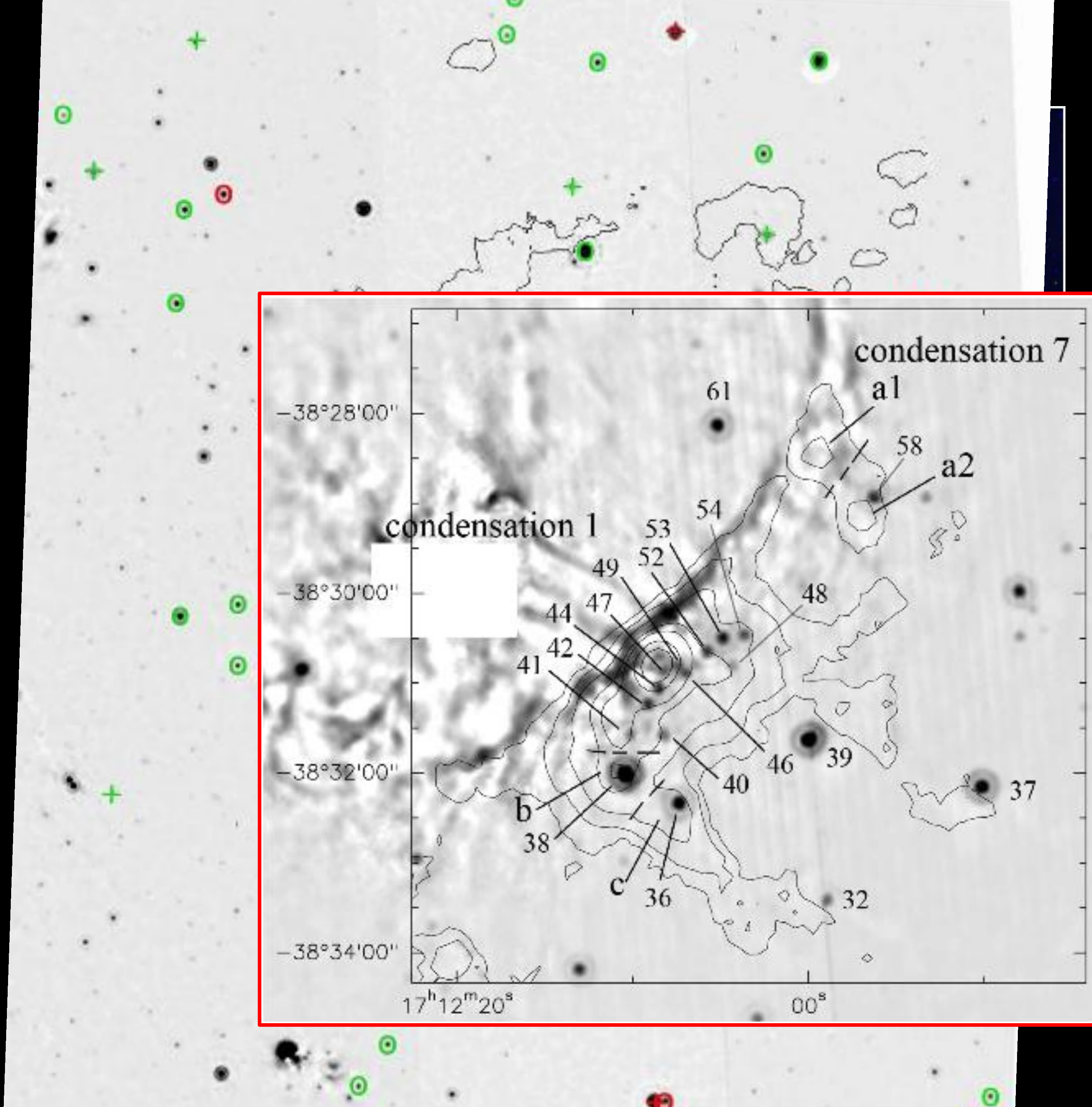
Spitzer Space Telescope • IRAC
ssc2008-21a



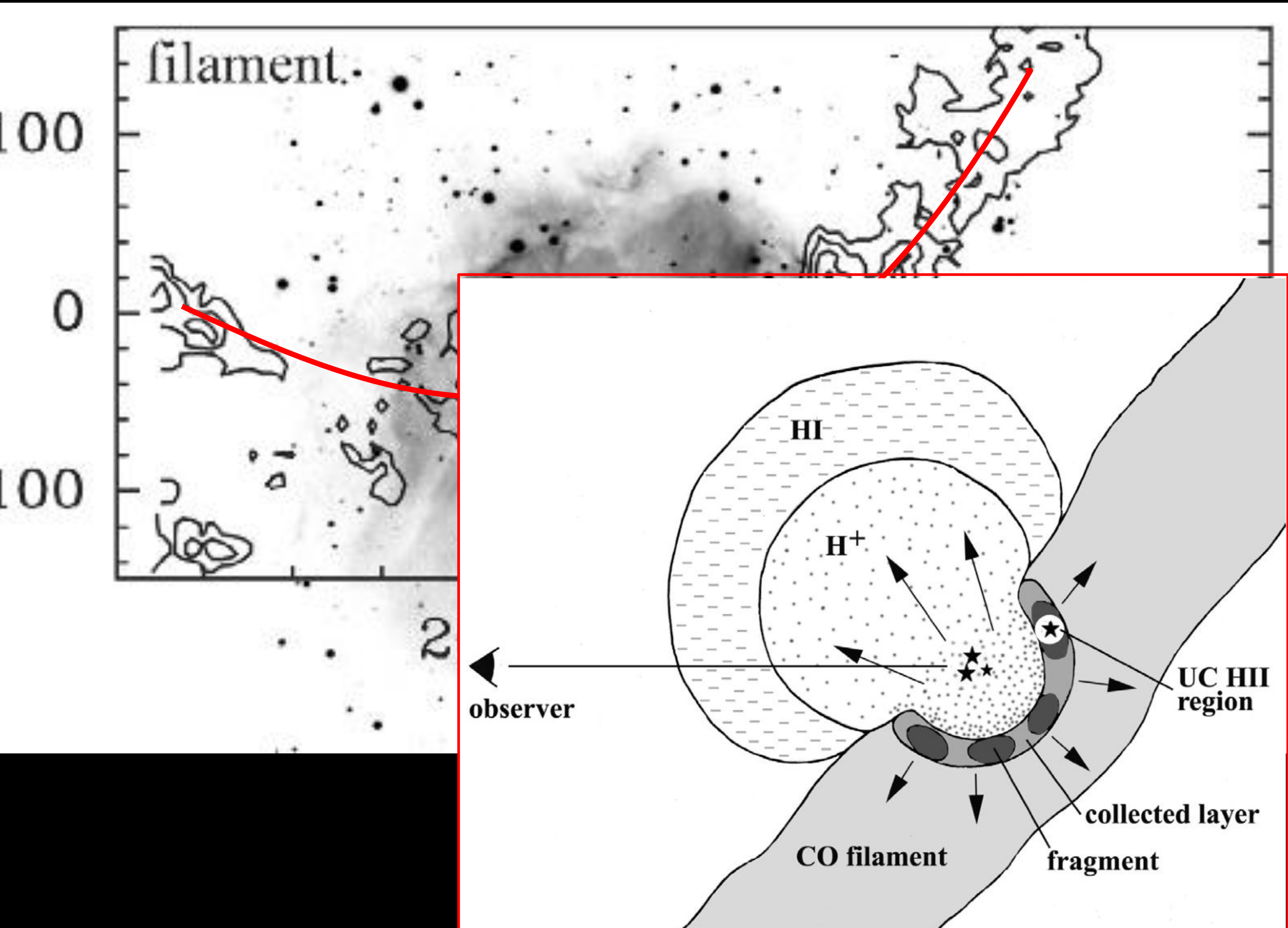

Proplyd 3
N
E
Proplyd 1
Proplyd 2
Bow shocks?
Proplyd 1: HST + VLT/ISAAC
1 parsec
33"

Latest multi-wavelength obs of HII regions showing evidence of triggered SF



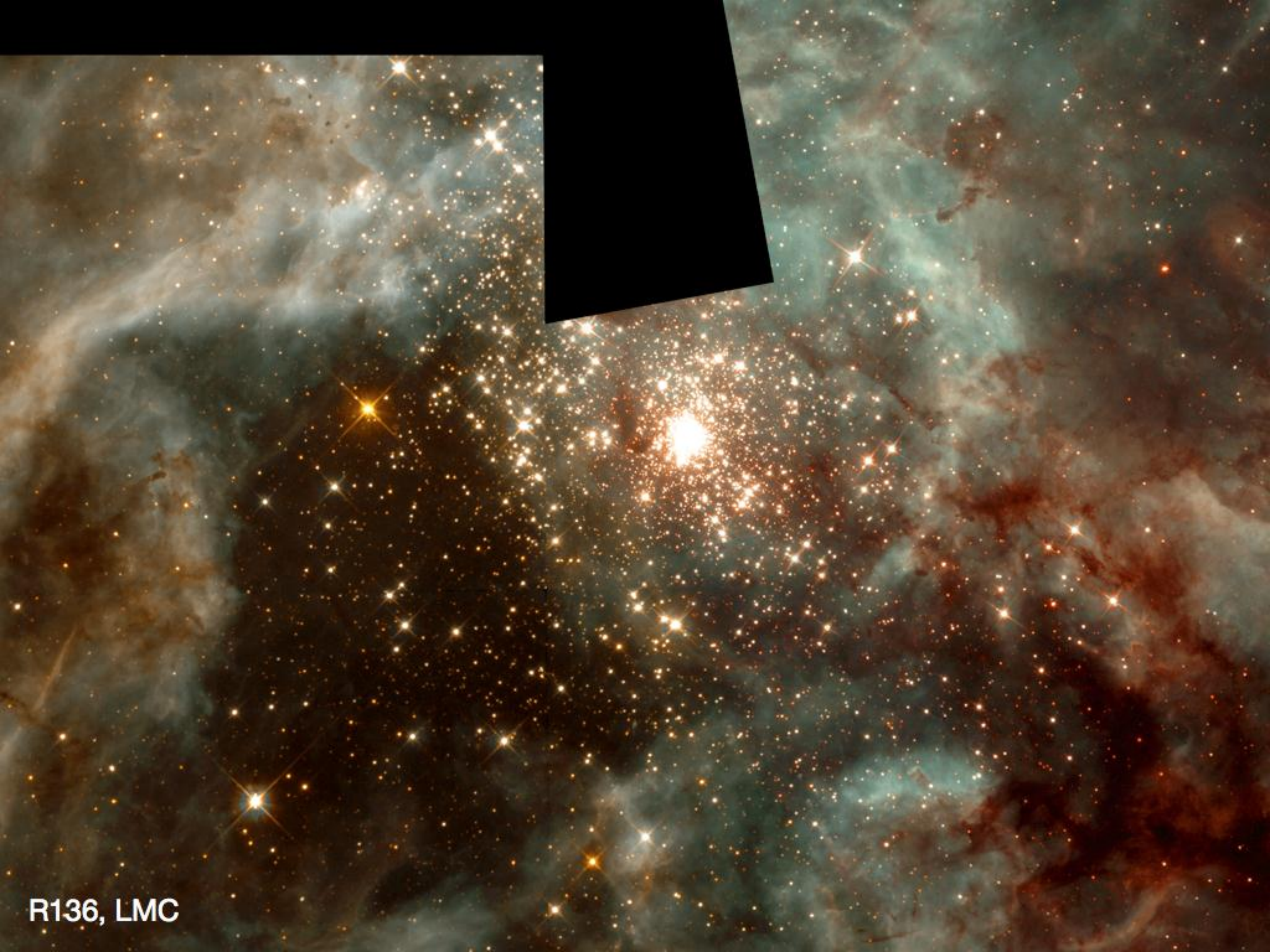


condensation 7
condensation 1
a1
a2
b
c
61
58
54
53
52
49
48
47
44
42
41
46
40
39
38
37
36
32
−38°28'00"
−38°30'00"
−38°32'00"
−38°34'00"
17h12m20s
00s


filament
100
0
100
HI
H+
observer
UC HII
region
collected layer
fragment
CO filament

Triggered SF on much larger scale

only if time


R136, LMC

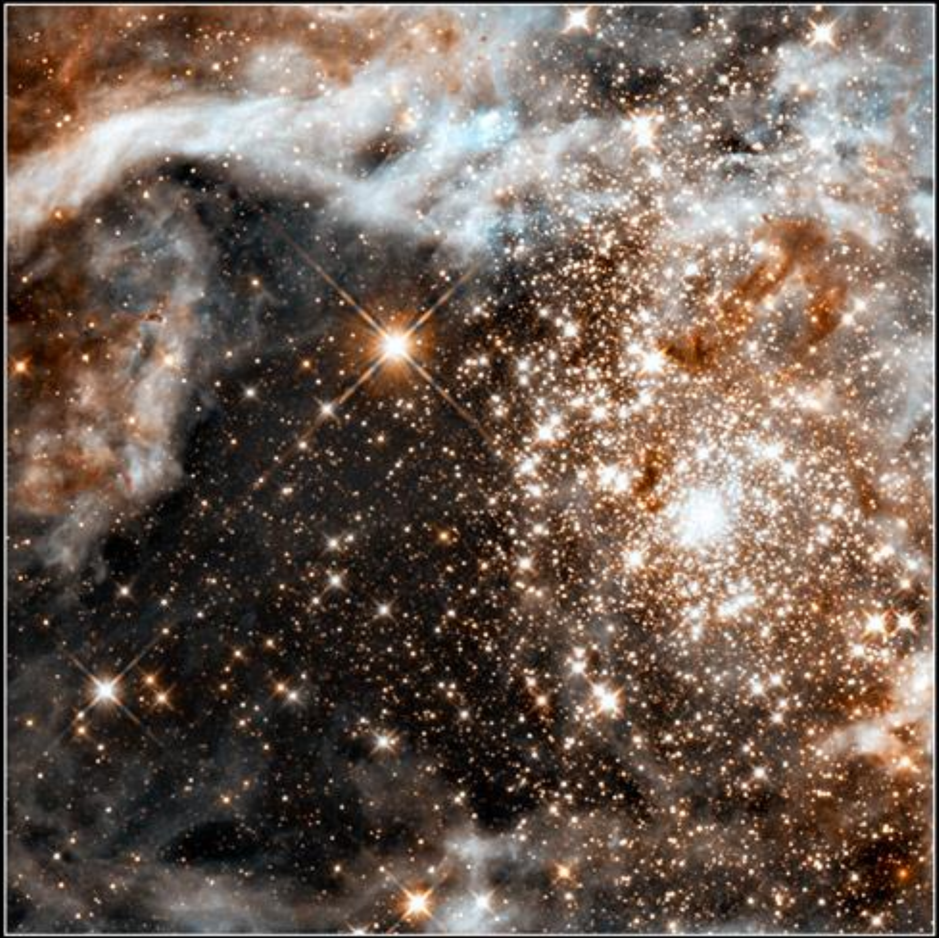
30 Doradus Nebula and Star Cluster

Hubble Space Telescope ▪ WFC3

Visible WFC3/UVIS

F336W *U* F438W *B* F555W *V* F814W *I* F656N Hα

Infrared WFC3/IR



F110W *J* F160W *H*

50 light-years

15.3 parsecs 61″

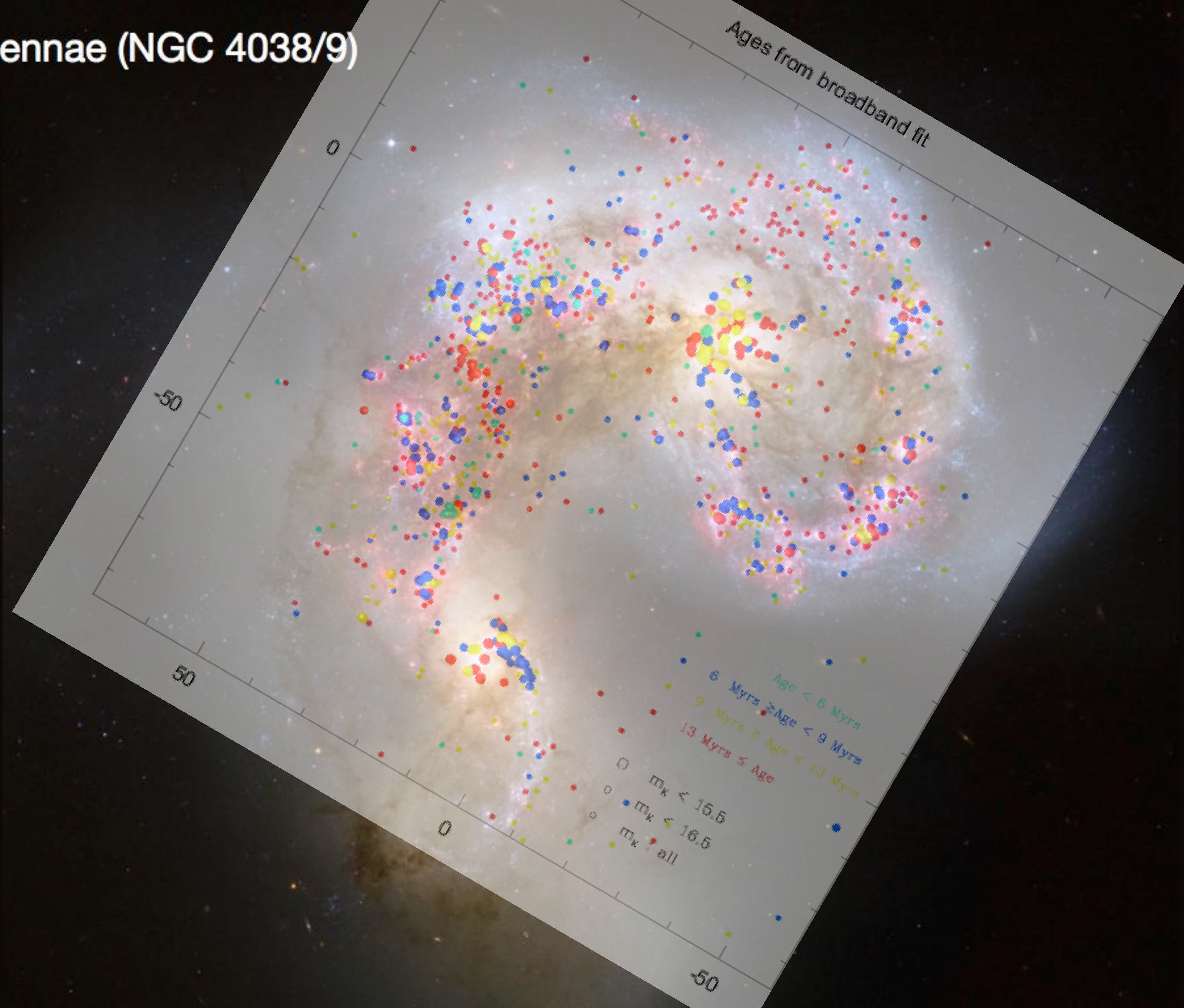
N

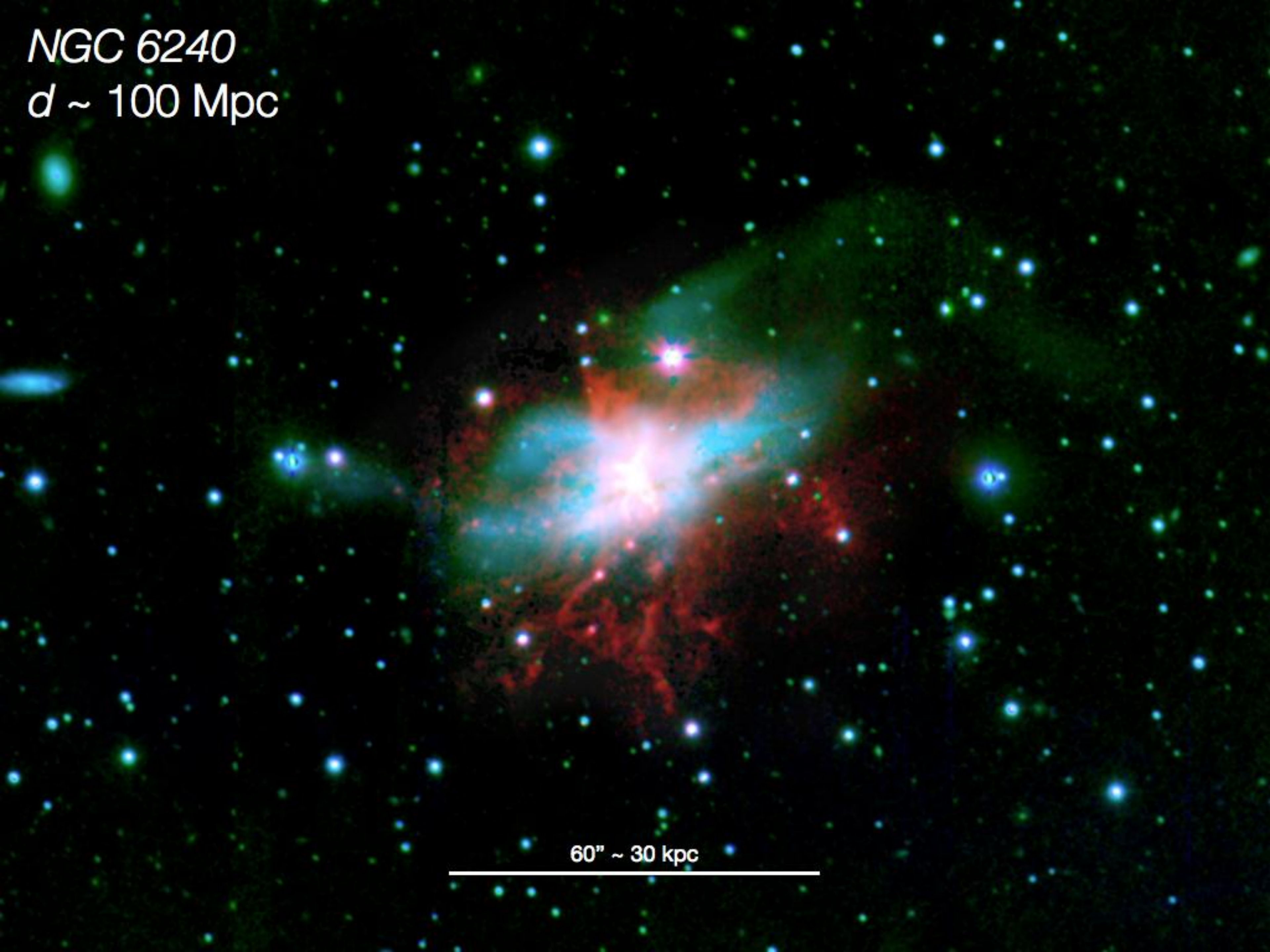
E


30 Dor
S. Points et al.
CTIO


NGC 4214
d ~ 4 Mpc

Antennae (NGC 4038/9)




NGC 6240
d ~ 100 Mpc
60" ~ 30 kpc