Star formation

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Based on scripts by Peter Schilke and Bringfried Stecklum

Exercises: Markus Röllig

http://www.ph1.uni-koeln.de/~ossk/Myself/star-formation.html

Overview

- Motivation and historical approach
- The starting point: The physics and chemistry of the interstellar medium
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- Protostars
- The IMF and multiplicity
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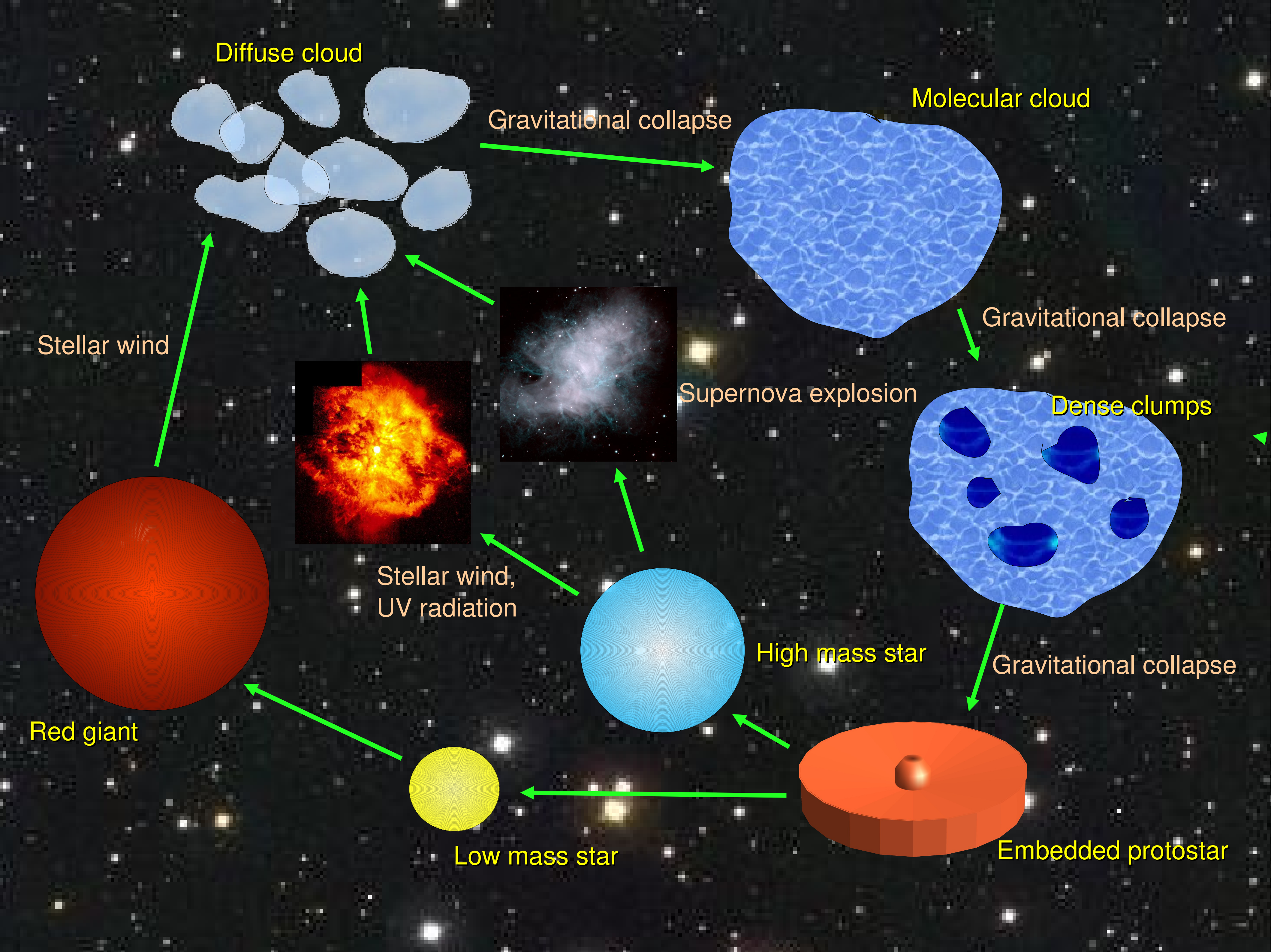
- Pre-main sequence stars
- Formation of massive stars
- The formation of planets
- Feedback and the structure of Galaxies: Shocks and PDRs
- Starburst Galaxies
- Star Formation History of the Universe


Diffuse cloud
Gravitational collapse
Molecular cloud
Gravitational collapse
Stellar wind
Supernova explosion
Dense clumps
Stellar wind,
UV radiation
High mass star
Gravitational collapse
Red giant
Low mass star
Embedded protostar

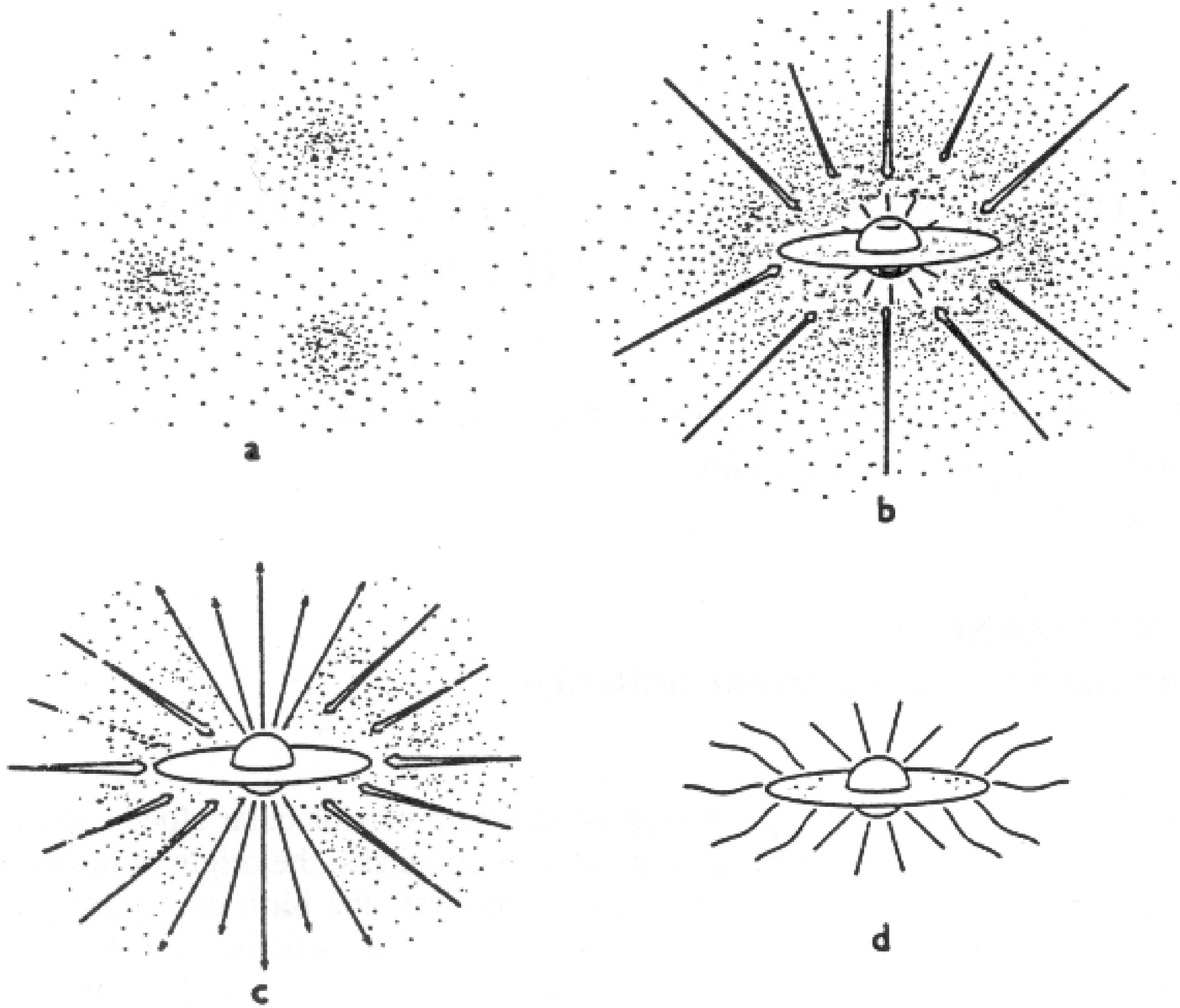


Figure 1. The four stages of star formation. (a) Cores form within molecular cloud envelopes as magnetic and turbulent support is lost through ambipolar diffusion. (b) Protostar with a surrounding nebular disk forms at the center of a cloud core collapsing from inside-out. (c) A stellar wind breaks out along the rotational axis of the system, creating a bipolar flow. (d) The infall terminates, revealing a newly formed star with a circumstellar disk (figure from Shu et al. 1987*a*).

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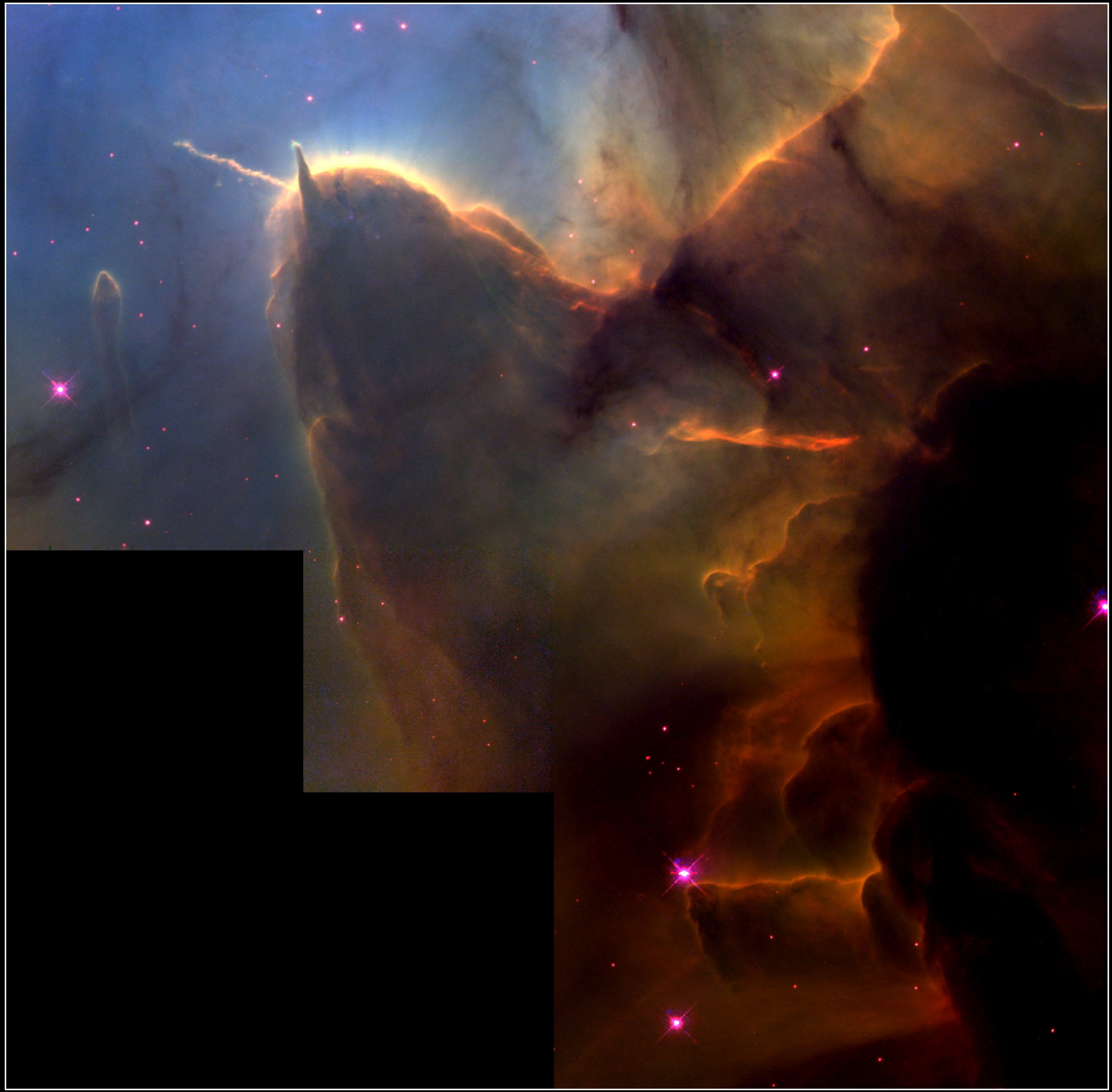

Trifid Nebula • M20

Hubble Space Telescope • WFPC2

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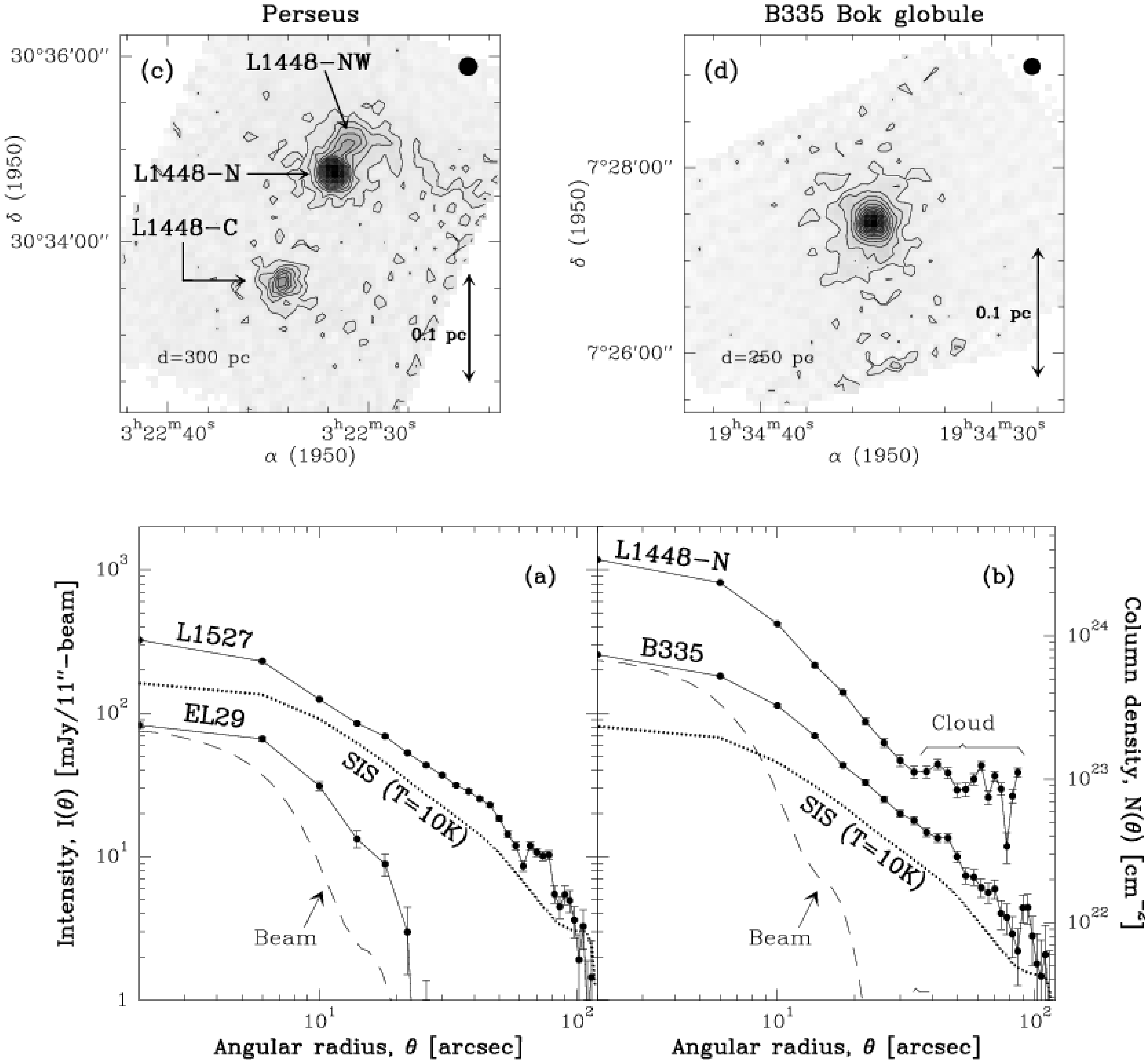

Perseus
B335 Bok globule
(c)
(d)
L1448-NW
L1448-N
L1448-C
0.1 pc
d=300 pc
d=250 pc
30°36′00″
30°34′00″
7°28′00″
7°26′00″
δ (1950)
3h22m40s
3h22m30s
19h34m40s
19h34m30s
α (1950)
(a)
(b)
L1527
EL29
L1448-N
B335
SIS (T=10K)
Beam
Cloud
Intensity, I(θ) [mJy/11″-beam]
Column density, N(θ) [cm⁻²]
Angular radius, θ [arcsec]

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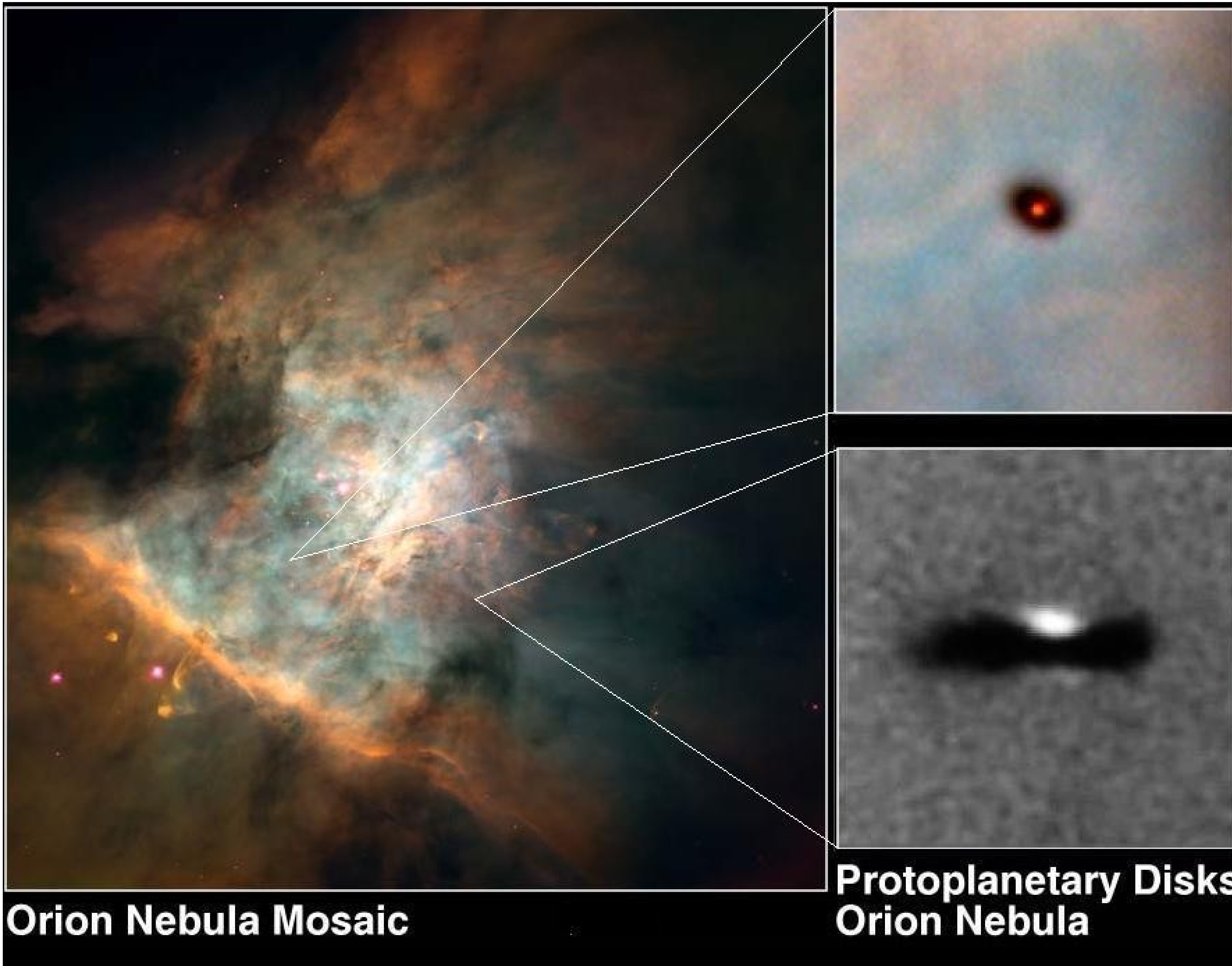
Orion Nebula Mosaic
Protoplanetary Disks
Orion Nebula

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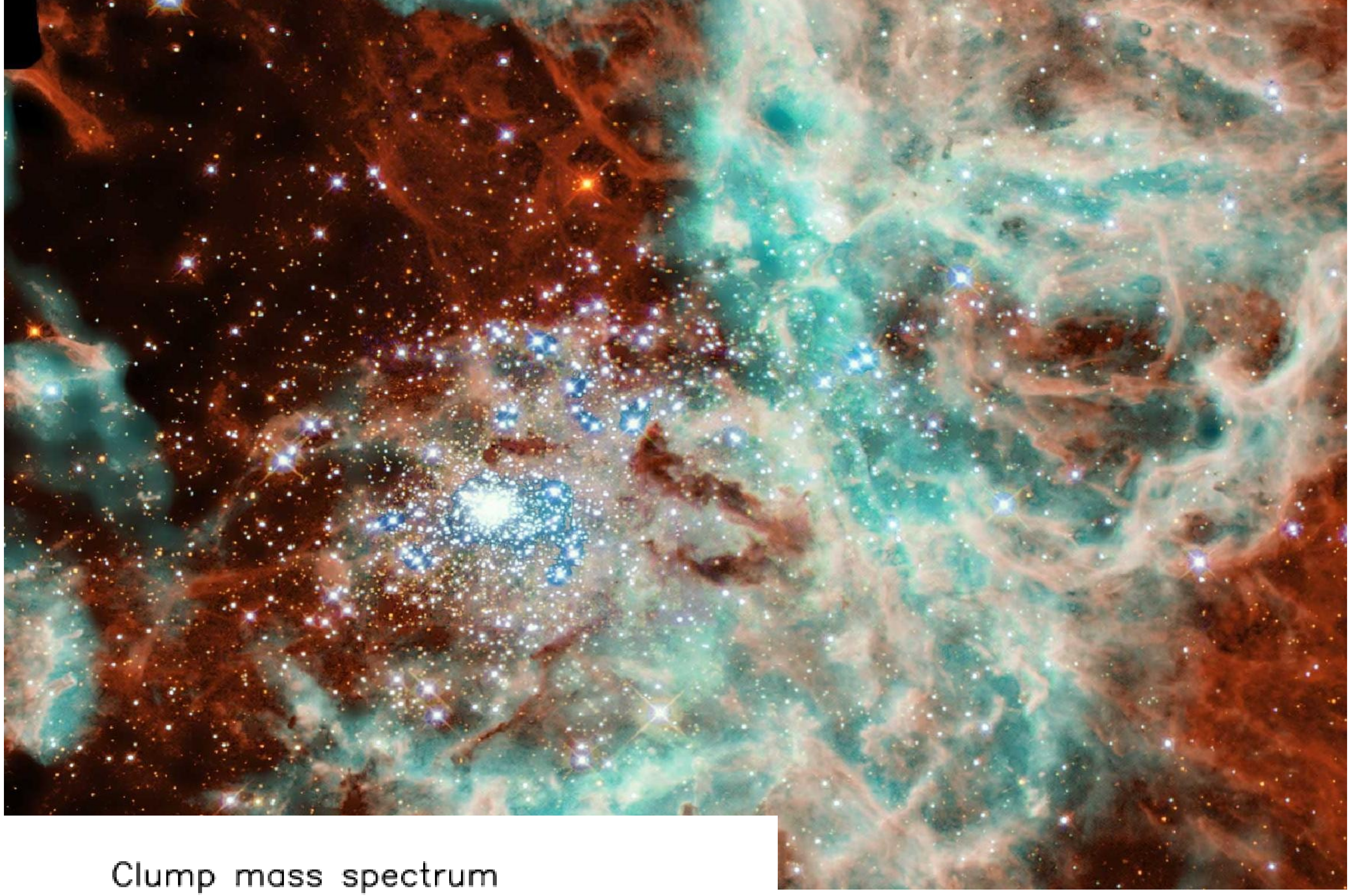

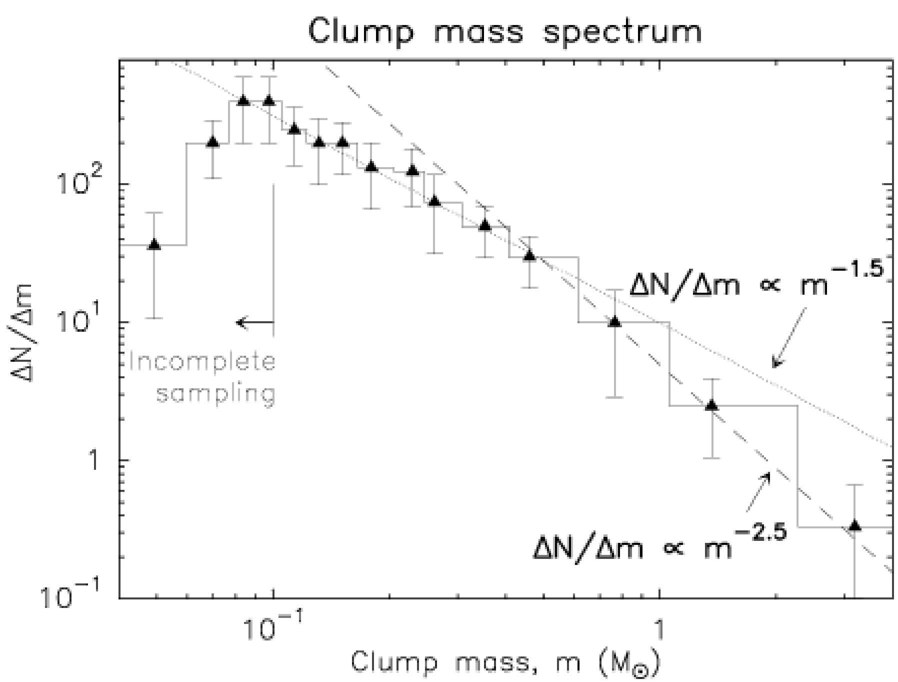

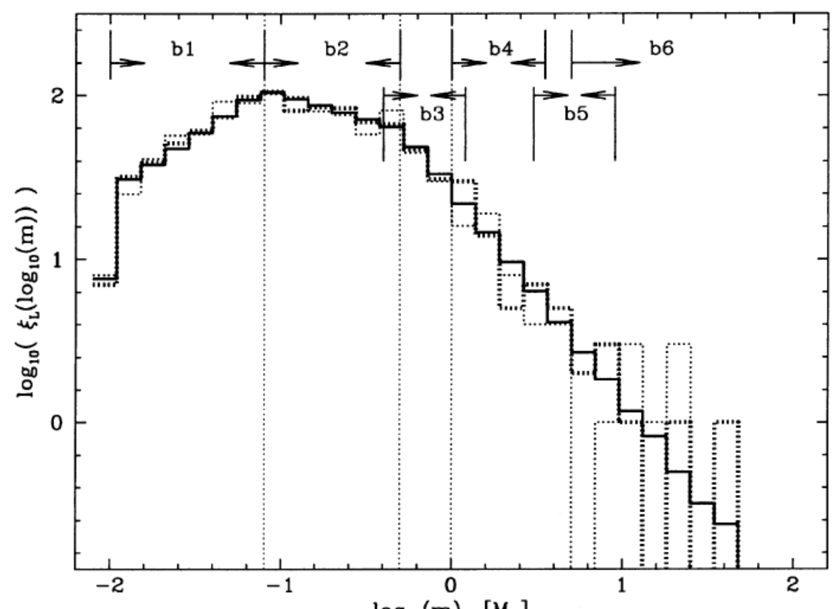

Fig 5. Frequency distribution of masses for 60 small-scale clumps

Figure 2. The adopted logarithmic IMF (equations 2 and 3), ξ_L (10^3, for

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200 A.U.
2000
NASA and A. Watso
Herbig-Haro 32
Hubble Heritage
PRC99-35 • Space Telescope Science Institute • Hubble Heritage Team (AURA/STScI/NASA)

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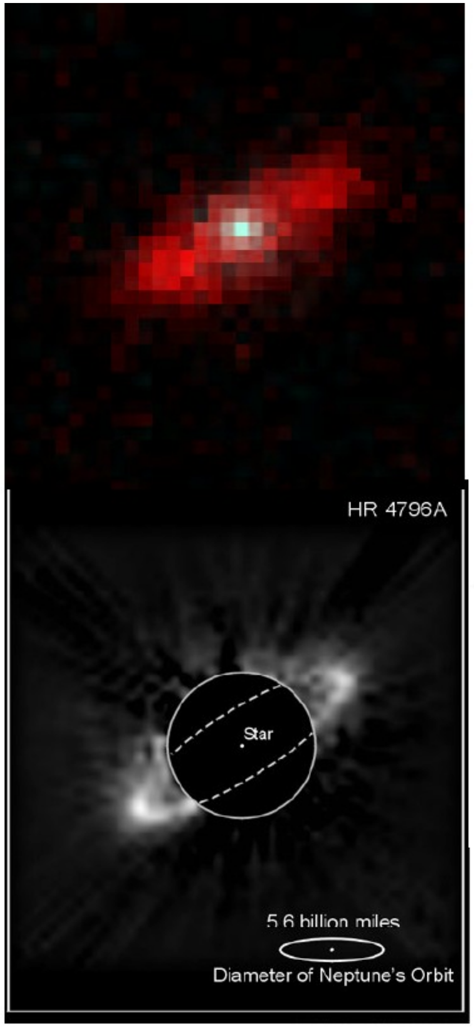

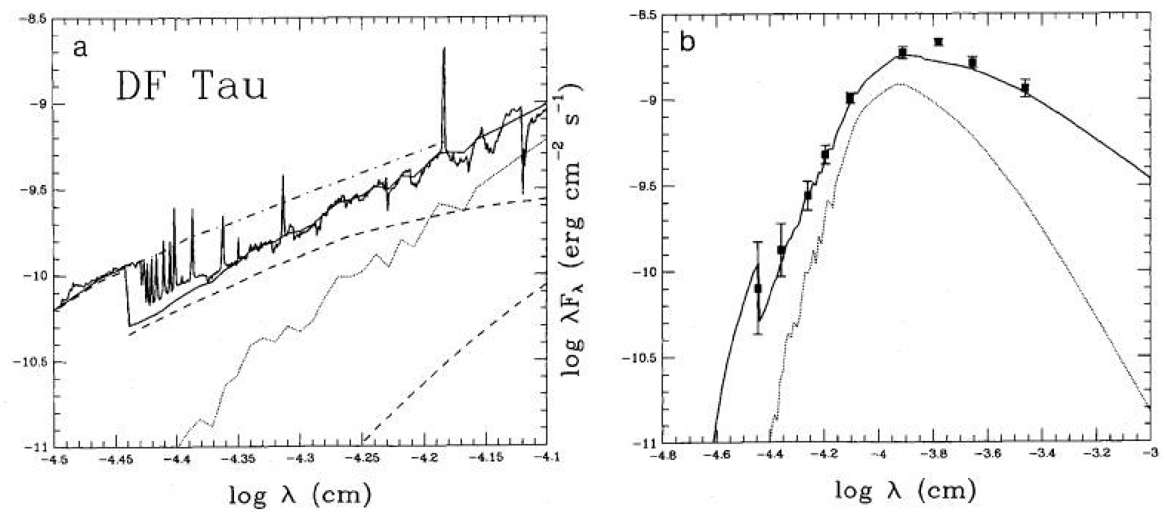

Staub-Ring um den Vega-ähnlichen Stern HR4796A.
Farbbild aus 12µm und 21µm Keck-Aufnahmen (oben)
und HST-Bild bei 1,1µm (unten).

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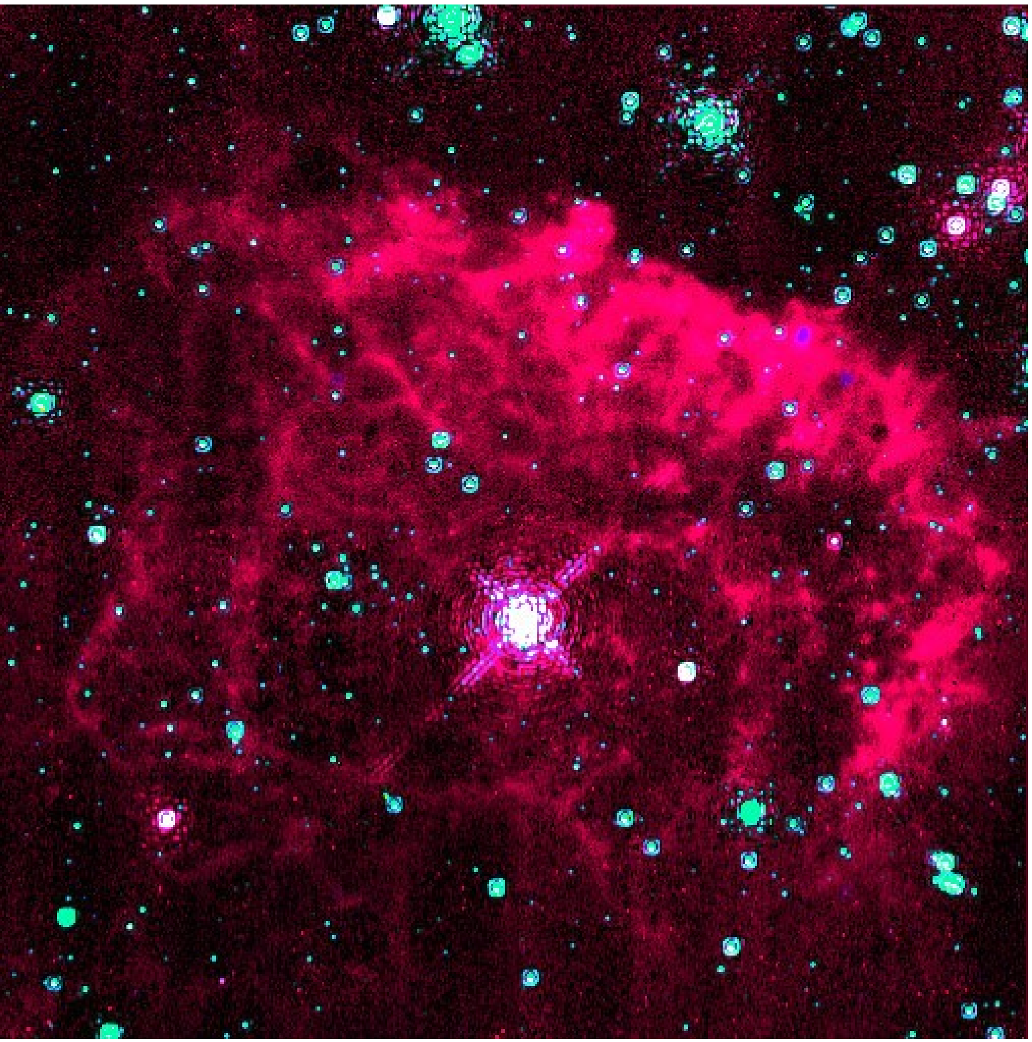

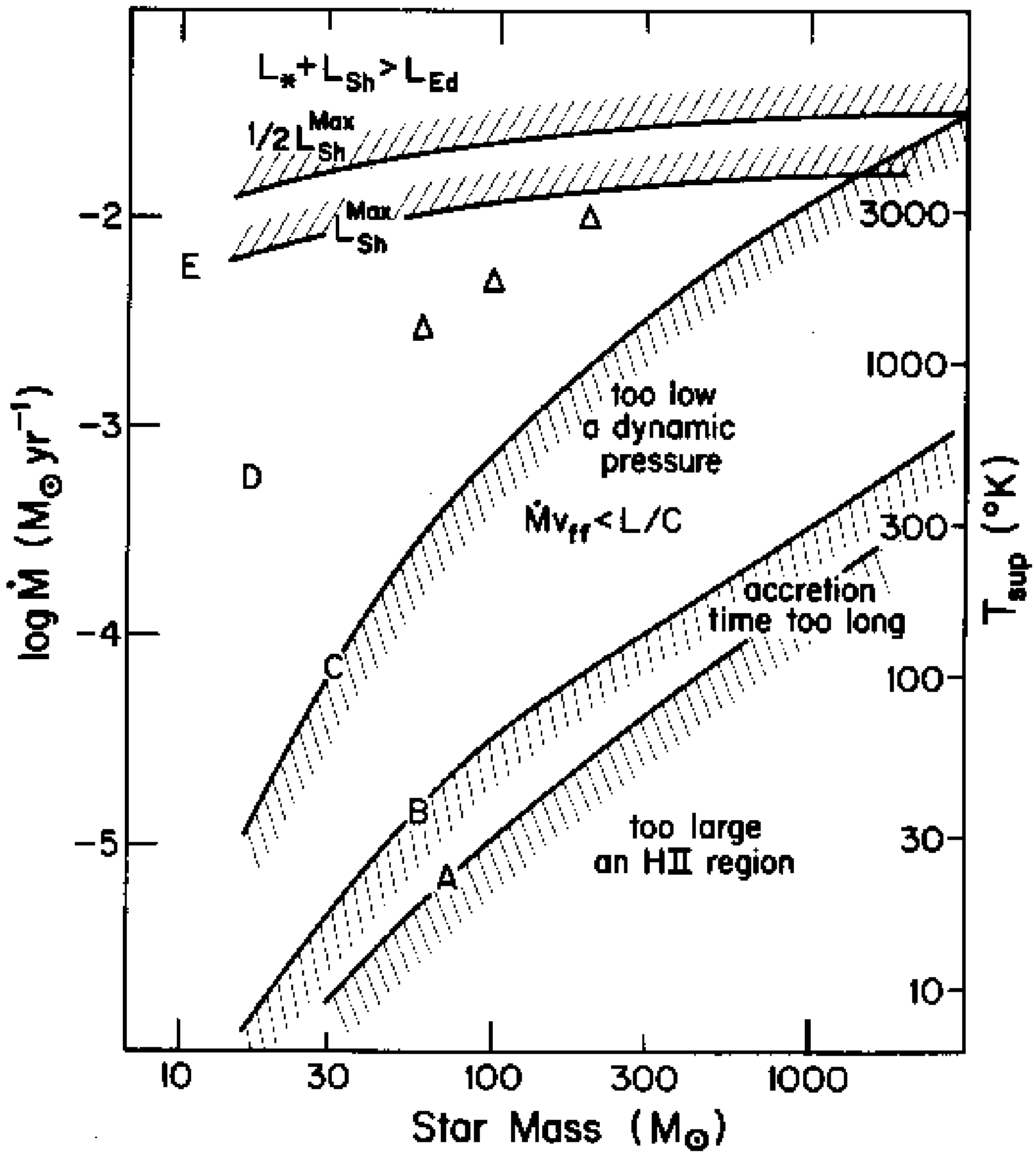

$L_* + L_{Sh} > L_{Ed}$
$1/2\,L_{Sh}^{Max}$
L_{Sh}^{Max}
E
D
C
B
A
too low
a dynamic
pressure
$\dot{M}v_{ff} < L/C$
accretion
time too long
too large
an HII region
$\log \dot{M}\ (M_\odot\ yr^{-1})$
−2
−3
−4
−5
T_{sup} (°K)
3000
1000
300
100
30
10
Star Mass ($M_\odot$)

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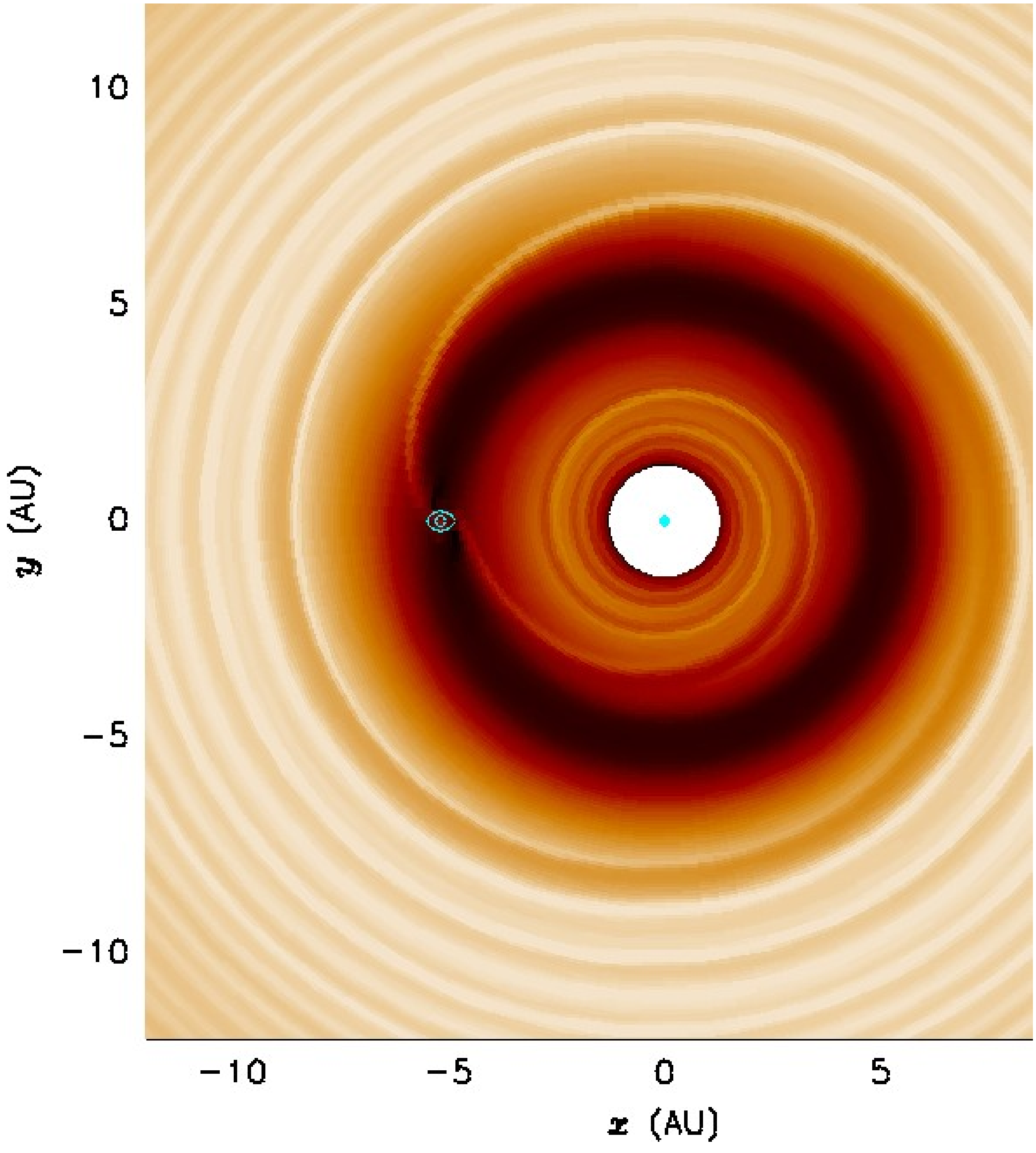

10
5
0
−5
−10
y (AU)
−10
−5
0
5
x (AU)

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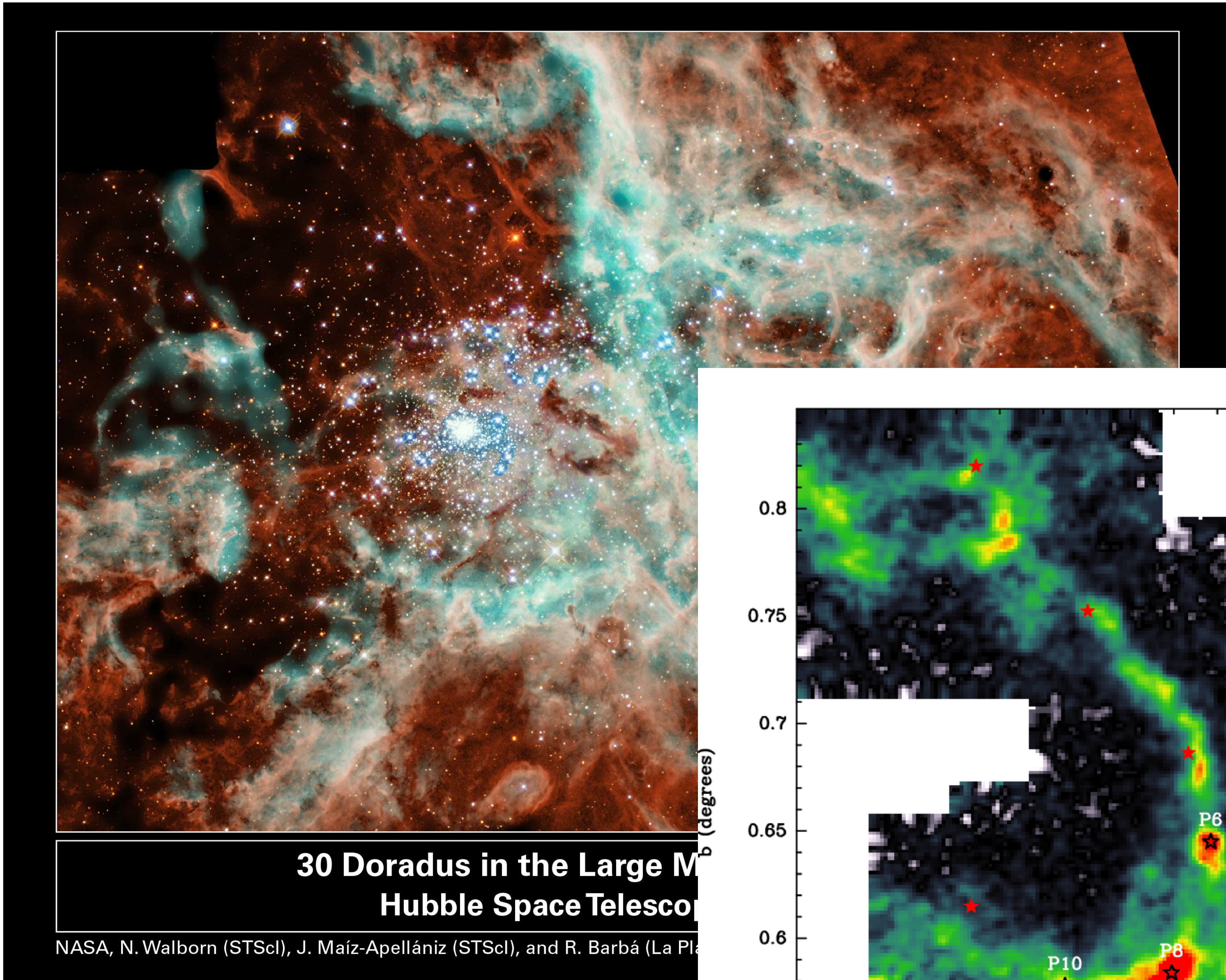
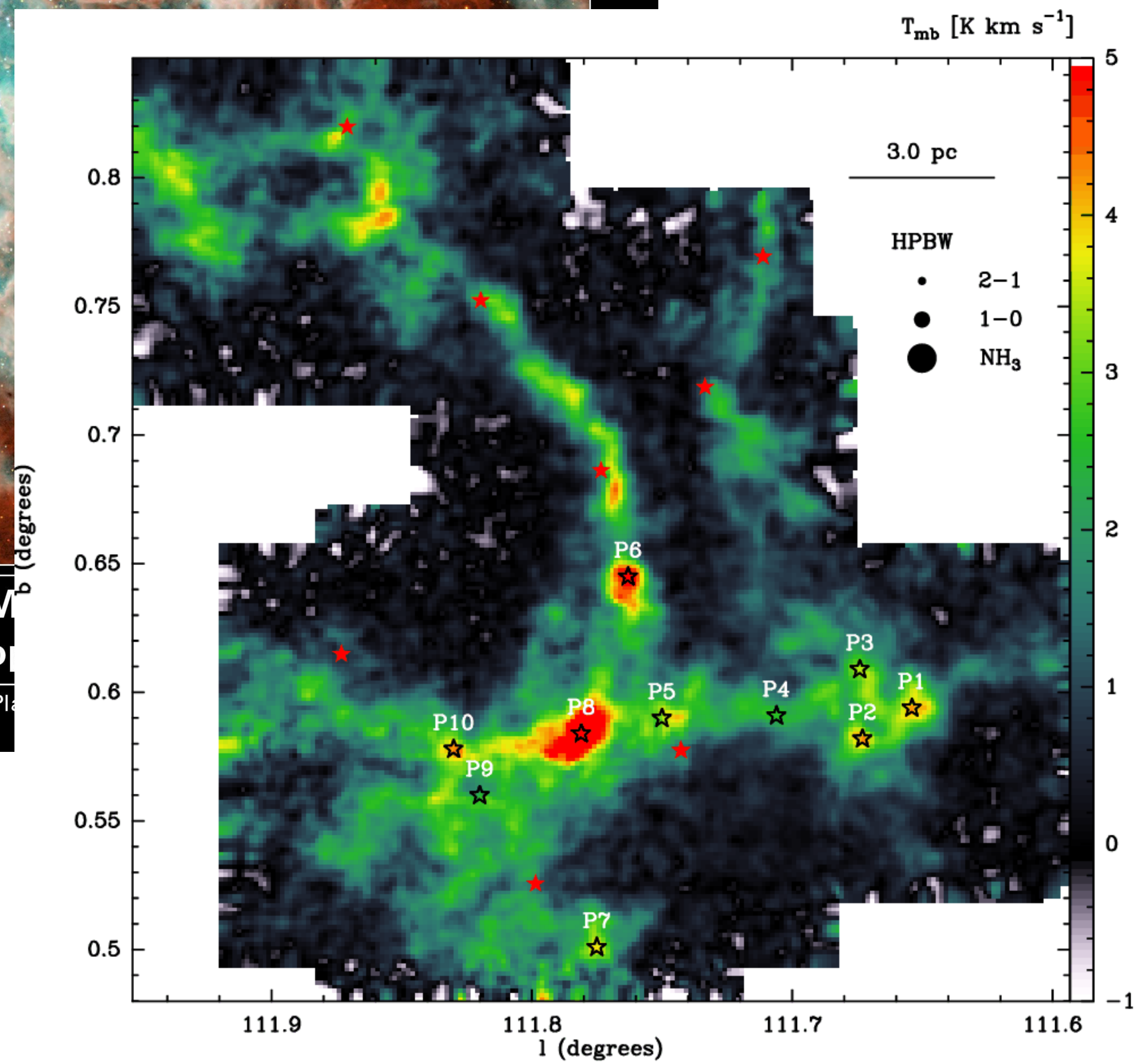


30 Doradus in the Large M
Hubble Space Telescop
NASA, N. Walborn (STScI), J. Maíz-Apellániz (STScI), and R. Barbá (La Pla



T_{mb} [K km s^{-1}]
5
4
3
2
1
0
−1
3.0 pc
HPBW
2−1
1−0
NH_3
P1
P2
P3
P4
P5
P6
P7
P8
P9
P10
b (degrees)
0.8
0.75
0.7
0.65
0.6
0.55
0.5
111.9
111.8
111.7
111.6
l (degrees)

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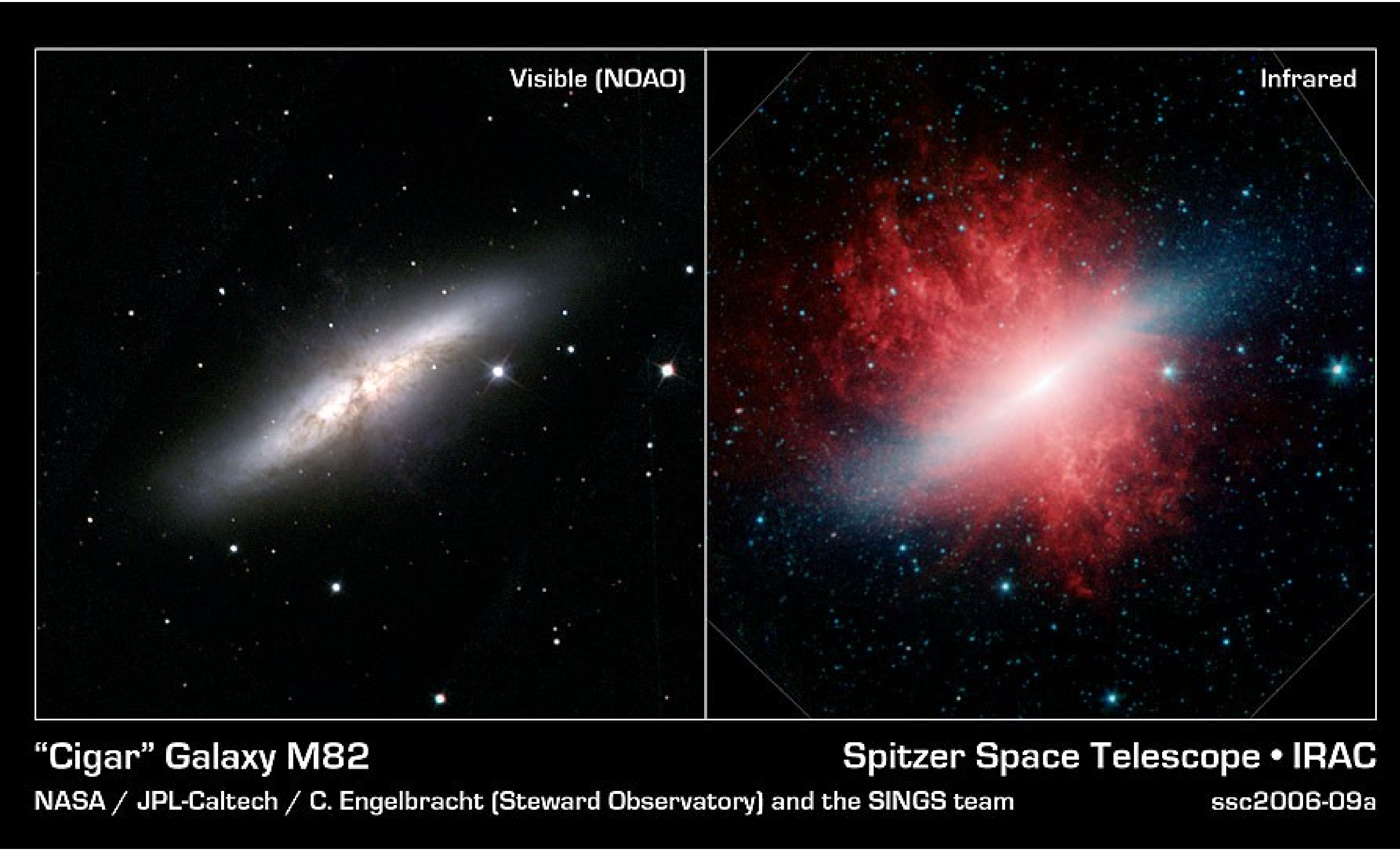
Visible (NOAO)
Infrared
"Cigar" Galaxy M82
Spitzer Space Telescope • IRAC
NASA / JPL-Caltech / C. Engelbracht (Steward Observatory) and the SINGS team
ssc2006-09a

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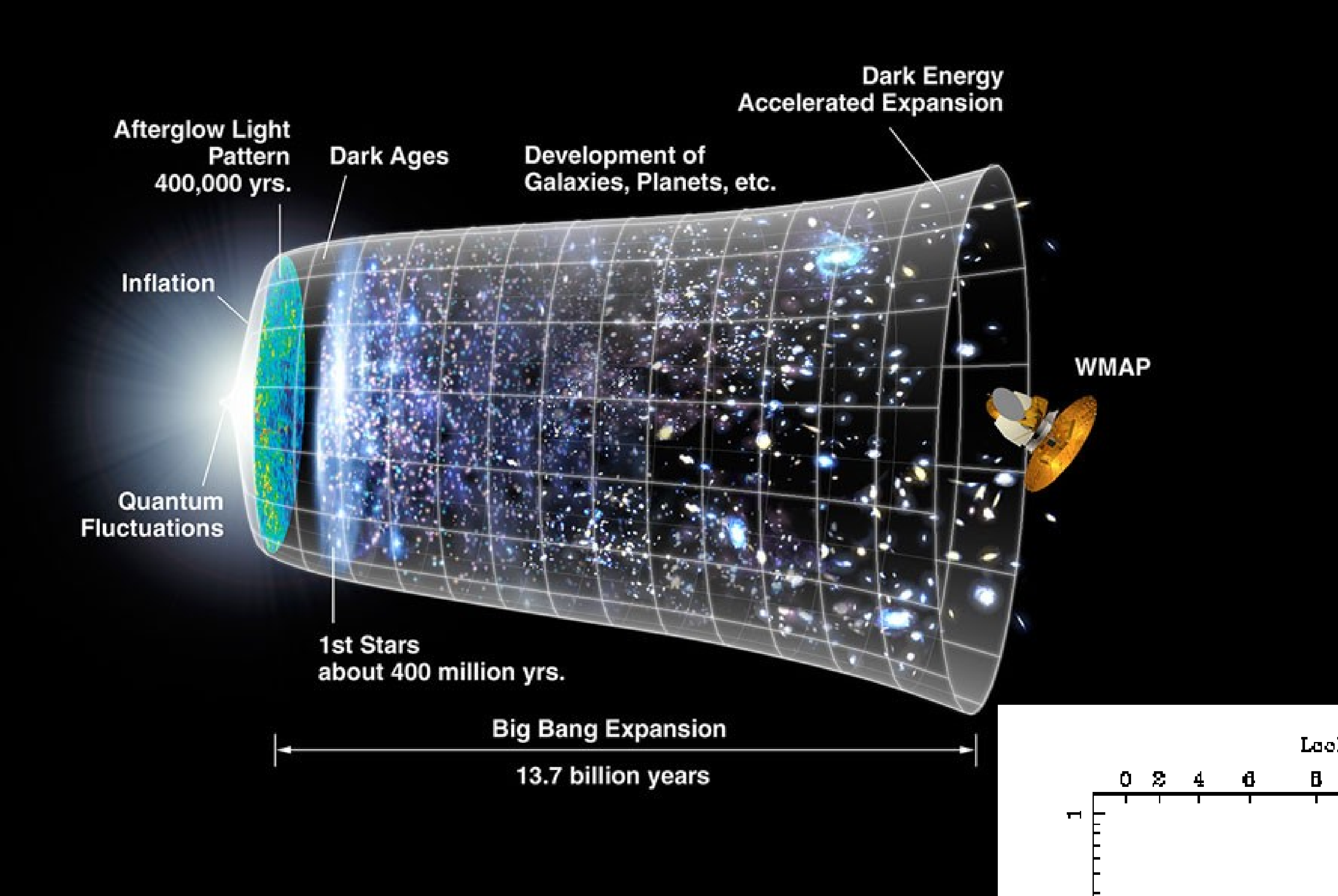
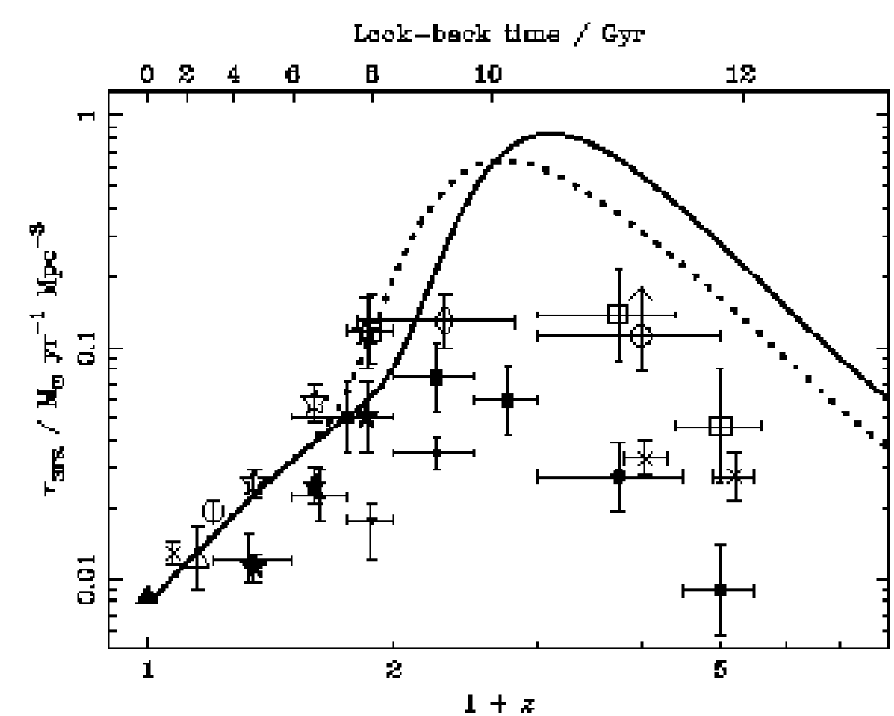

Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years


Look-back time / Gyr
0 2 4 6 8 10 12
1
0.1
0.01
1 2 5
1 + z

Recommended reading

- Physics of Star Formation in Galaxies
  Palla & Zinnecker (Springer)
  Broad overview of theory and observations

- "The formation of Stars"
  Stahler & Palla (Wiley-VCH)
  Covers most topics of this lecture.

- Protostars and Planets V
  Bo Reipurth, David Jewitt, & Klaus Keil (Univ. of Arizona Press)
  A collection of review articles on recent progress in star formation research.

- Die Entstehung von Sonnensystemen
  Fahr & Willerding (Spektrum)

- The Physics and Chemistry of the Interstellar Medium
  A. G. G. M. Tielens (Cambridge University Press)

- Physical processes in the interstellar medium
  L. Spitzer (Wiley-VCH)

Historical approach

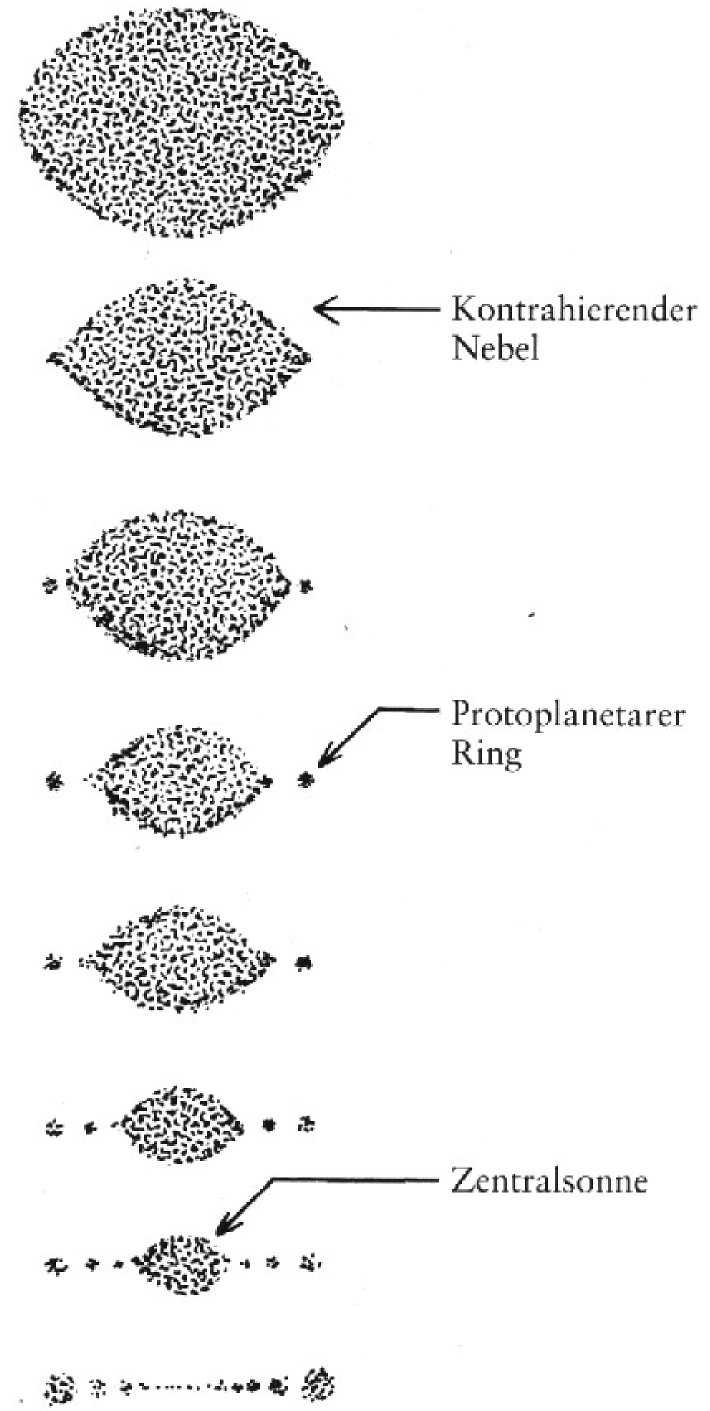
- Until ~ 1920 the universe and all stars were believed to be static and eternal
- Only some deviating arguments:

... the matter on ye outside of this space would by its gravity tend towards all ye matter on the inside & by consequence fall down to ye middle of the whole space & there compose one great spherical mass. But if the matter was eavenly diffused through an infinite space, it would never convene into one mass but some of it convene into one mass & some into another so as to make an infinite number of great masses scattered at great distances from one to another throughout all ye infinite space. And thus might ye Sun and Fixt stars be formed supposing the matter were of a lucid nature.

Isaac Newton (10.12.1692):
Letter to minister Richard Bentley

Historical approach

- Application of hydrodynamics and angular momentum

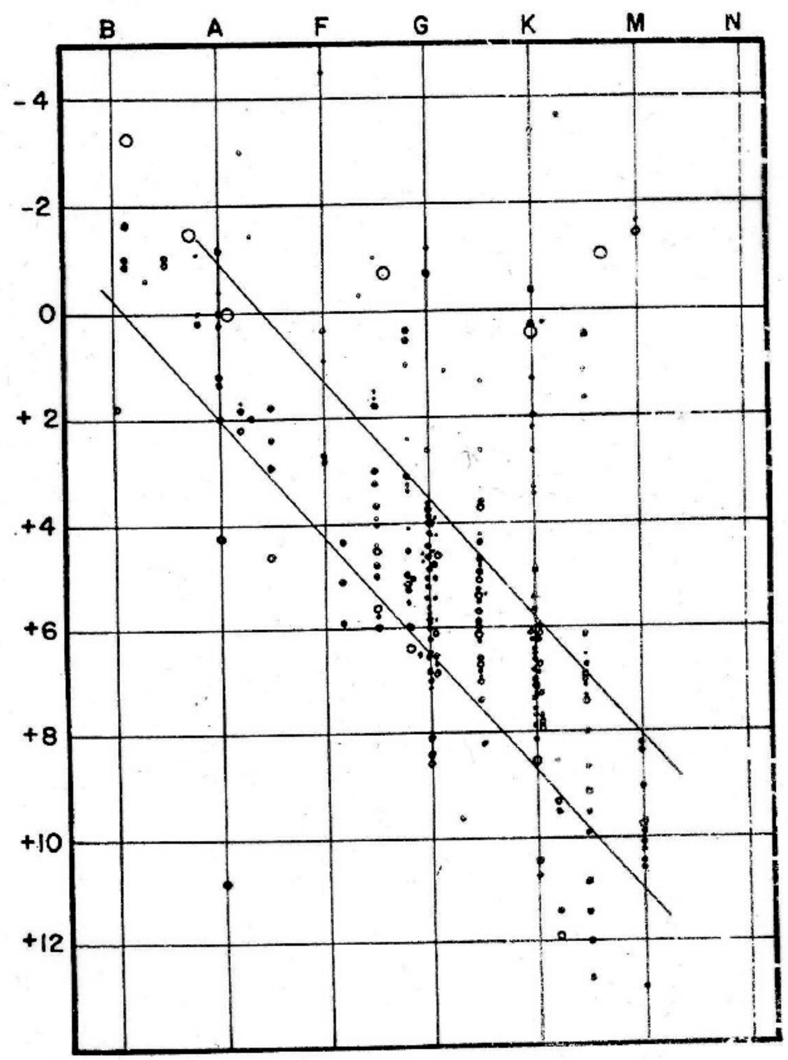


Pierre Simon de Laplace (1796):
"Exposition de Système du Monde"

Historical approach

- Stars are not all the same
- Different position in HR-diagram might indicate a different age

Ejnar Hertzsprung & Henry Norris Russell (1910-1913):
Mass-temperature relation



H.N. Russell's 1913 diagram correlating the absolute magnitudes of stars with their spectral types. The Harvard spectral classifiers had noted subtle differences between otherwise identical spectra; in particular, in the later spectral types some stars had very narrow lines. In 1905 Ejnar Hertzsprung noted that these stars tended to have very small proper motions, and so were probably distant and highly luminous. This first indication of the existence of what later became known as 'giant' and 'dwarf' stars was strengthened by the distribution shown in Russell's diagram.

Historical approach

- Clusters of stars (same origin, same position on sky) show widespread of HR properties

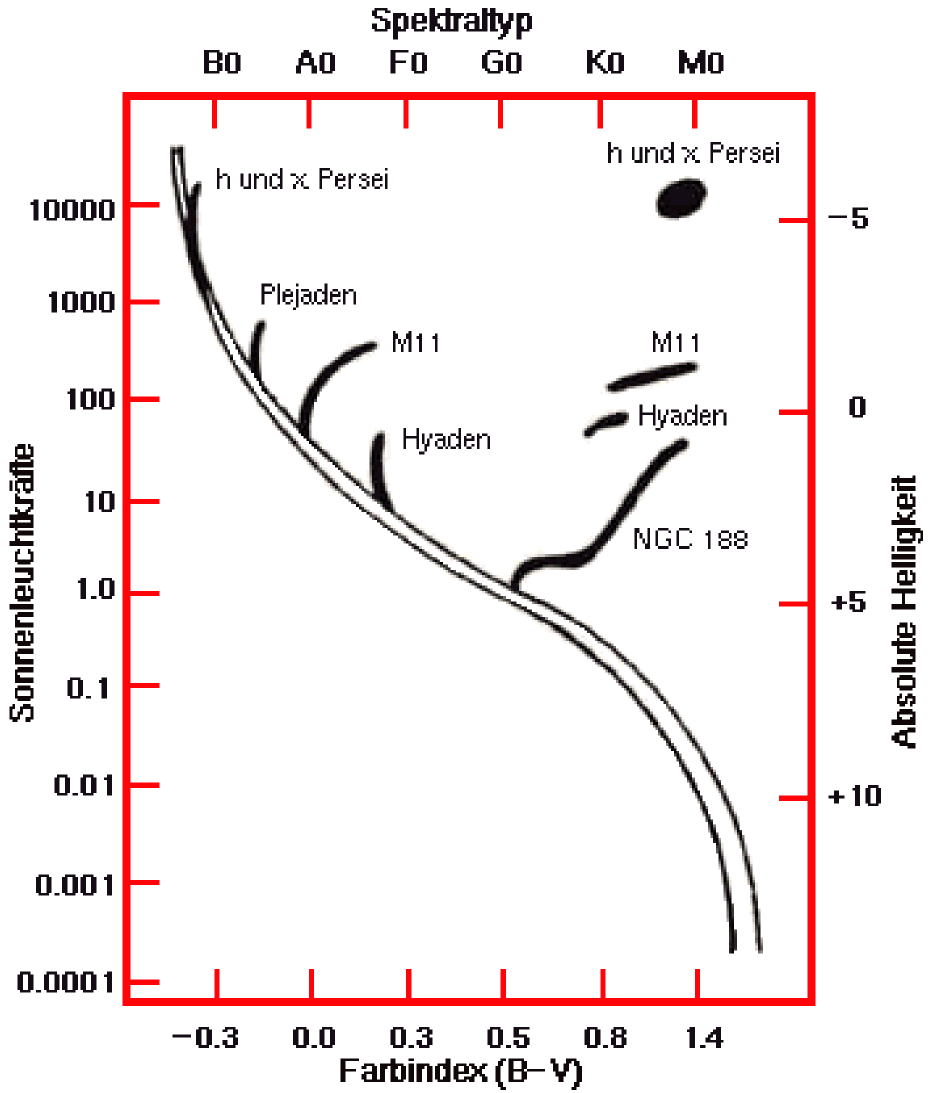
- Explanation: aging

- Physics:

  Bethe & Weizäcker (1938):

  H fusion = source of luminosity

→ finite age → stars must be born

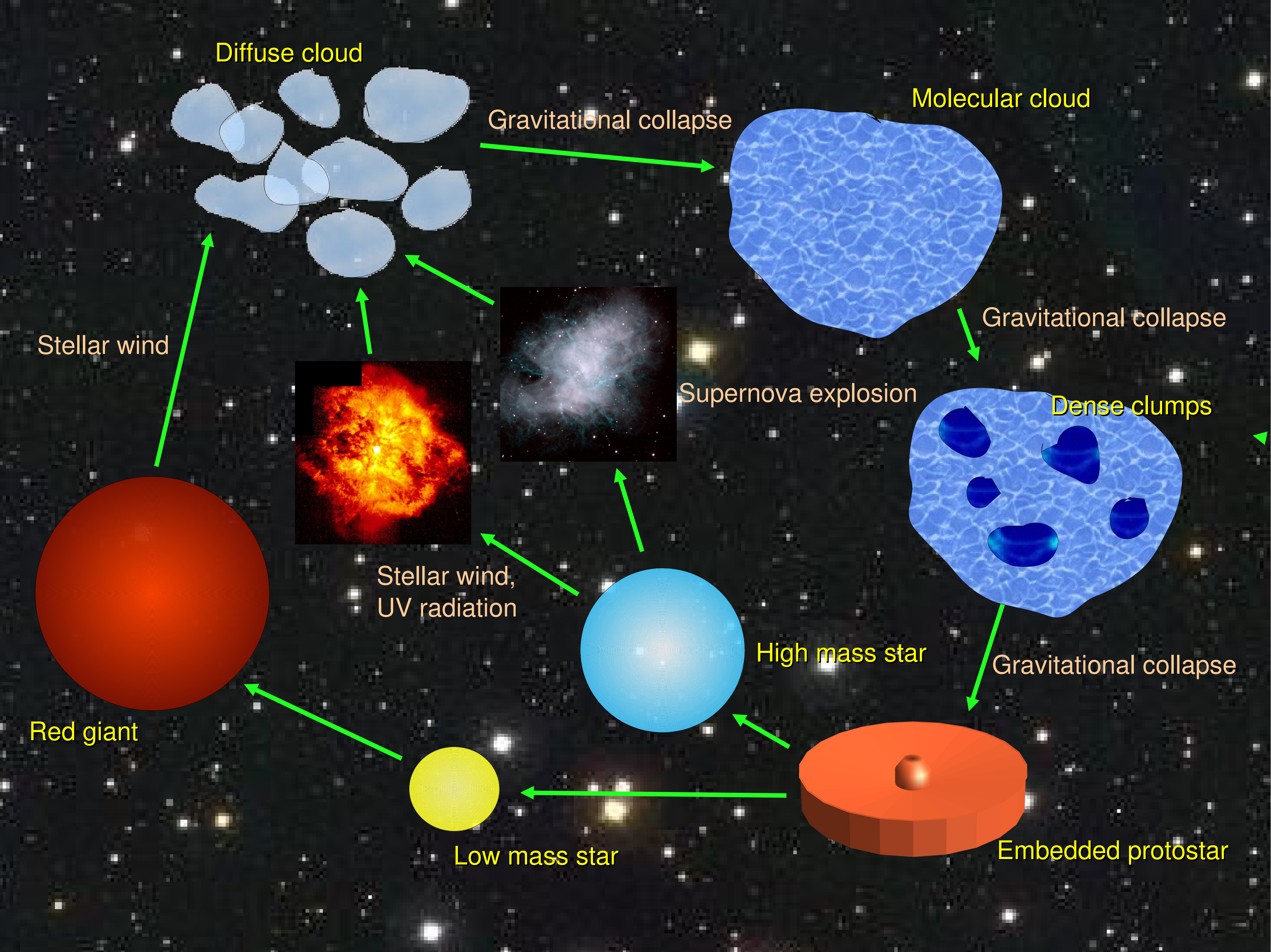


Historical approach

- Observation of young stars and associations:
  - Cecilia Payne-Gaposchkin (1952): T Tauri stars

    variability, emission lines, too bright for their mass
  - Viktor Ambartsumian (1953): dynamics of open clusters

    unbound associations → must have recently formed
  - Georg Herbig (1954): T Tauri stars in young clusters (IC348)
- Observation of the interstellar medium: 1912-today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Questions in star formation

- How do molecular clouds form and what is their lifetime?
- What are the triggering mechanisms of star formation?
- What is the origin of the IMF (Initial Mass Function)?
- How do protostellar cores evolve (for all masses)?
- Which role play accompanying phenomena (jets, outflows, variability?)
- Are there massive disks?
- How do planets form?
- How do starbursts work?
- How were the first stars formed ?