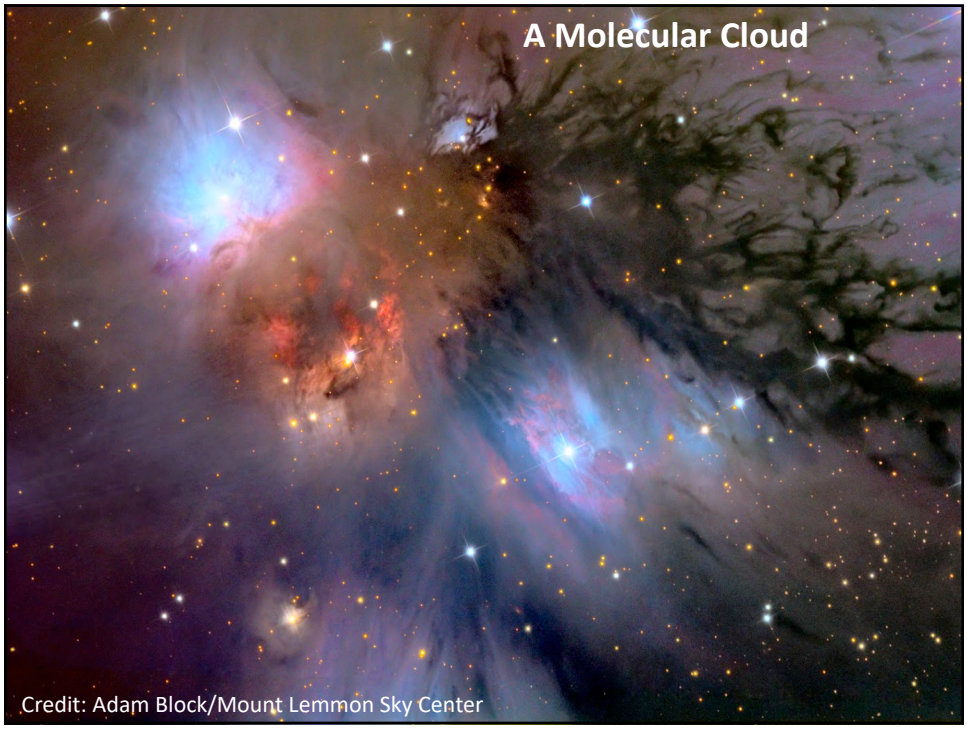
## Star Formation Occurs in Molecular Clouds ($H_2$)

- **Typical Sizes of ~10 – 100 pc**
- **Typical Masses of ~$10^2$ – $10^7$ $M_{sun}$**
- **Typical lifetime few $10^7$ years**

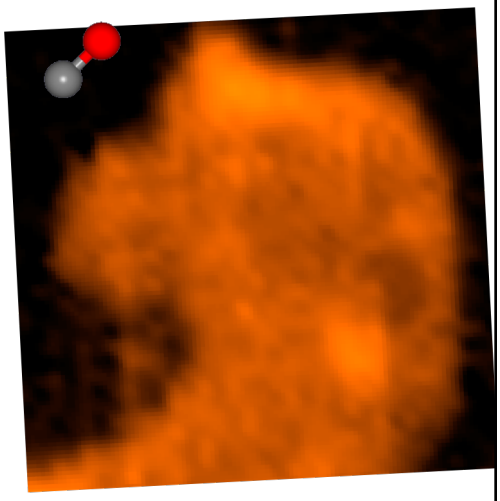
- Total molecular mass ~ few $10^9$ $M_{sun}$ in Galaxy
- Current Galactic SFR is 0.7 – 1.5 $M_{sun}$ $yr^{-1}$
  (Robitaille & Whitney 2010)
- Assuming 100% SF efficiency & free-fall collapse
  - Predicted SFR > 130 – 400 $M_{sun}$ $yr^{-1}$ (Zuckerman & Palmer 1974)
  - TOO LARGE by 2 orders of magnitude!
- SF is NOT 100% efficient in clouds
  - Efficiency is only 1 – 2% for large molecular clouds
  - Additional support against gravity: magnetic fields & turbulence

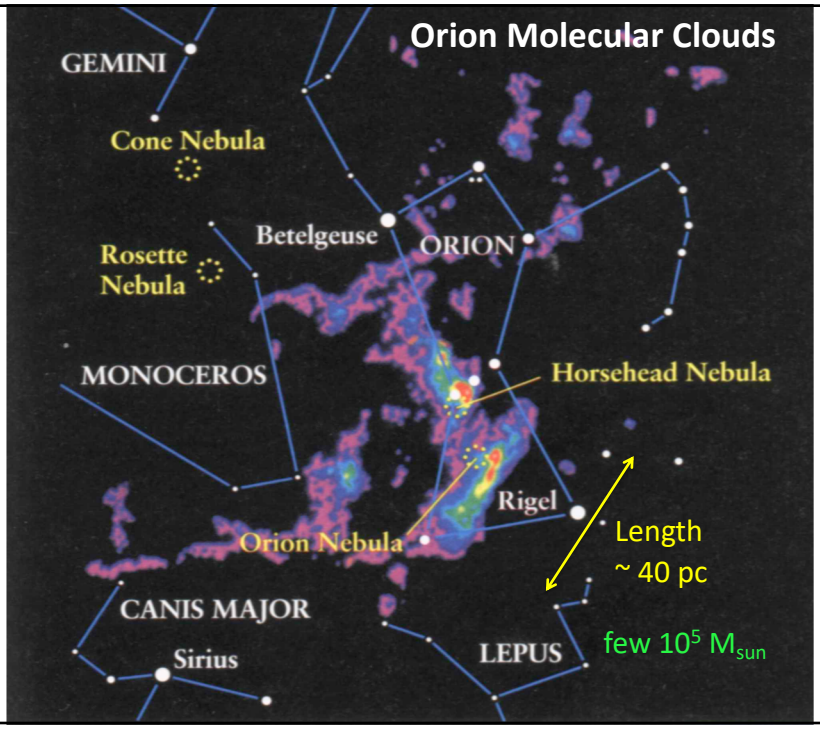


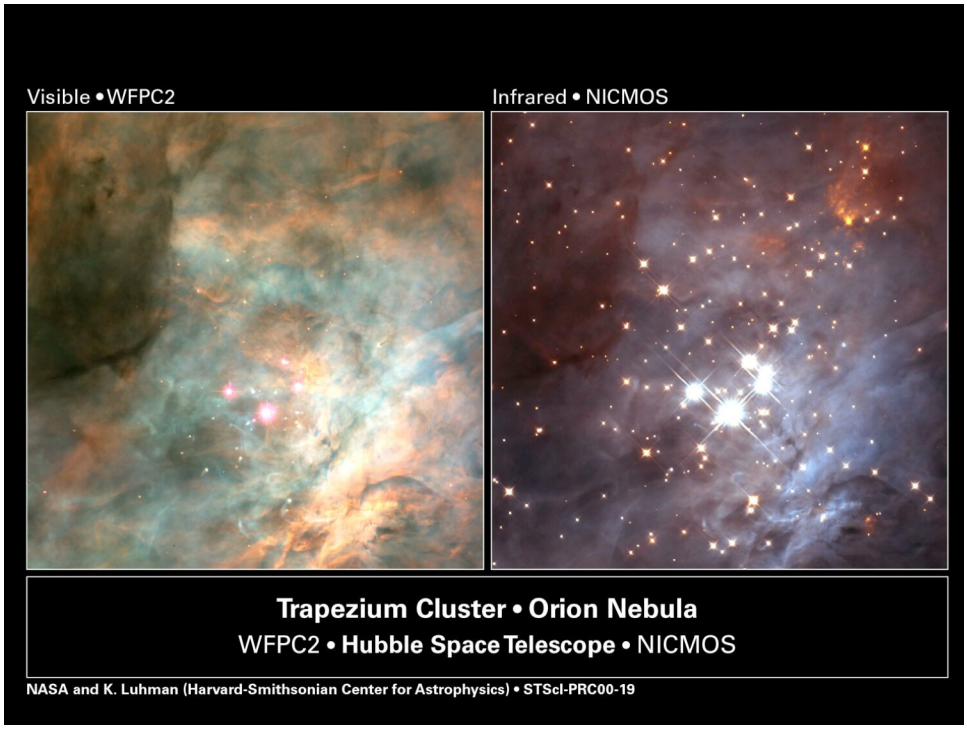
# Trace Molecular Emission with CO

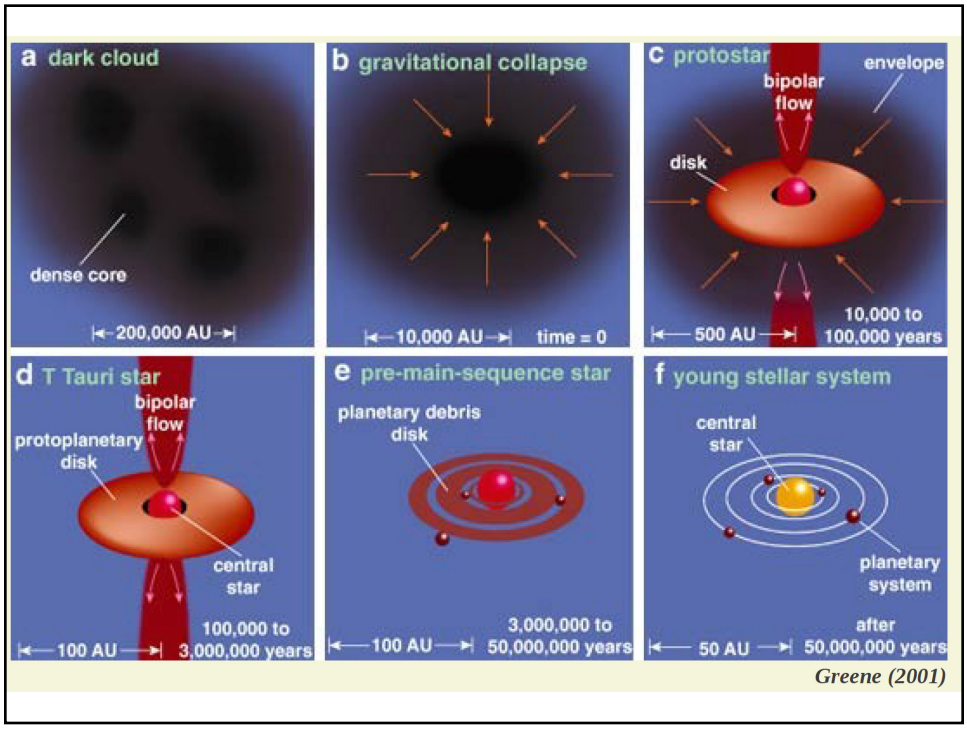
Optical

Carbon Monoxide λ = 0.87mm



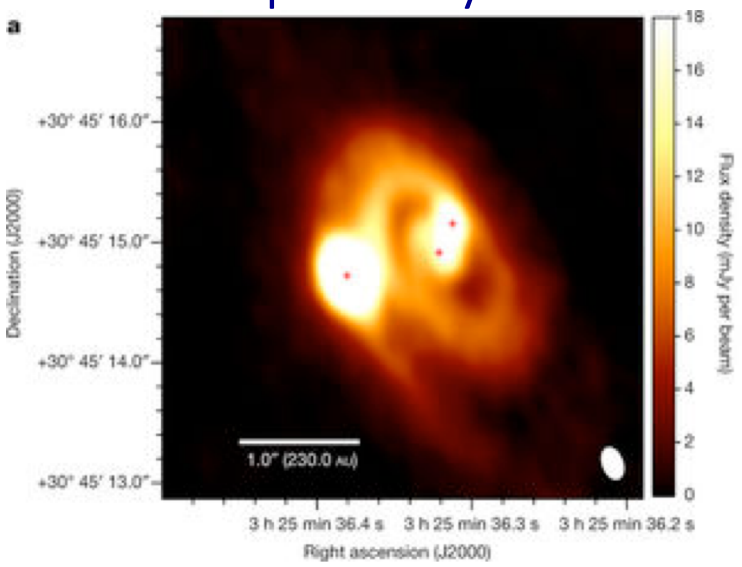



Visible • WFPC2
Infrared • NICMOS
Trapezium Cluster • Orion Nebula
WFPC2 • Hubble Space Telescope • NICMOS
NASA and K. Luhman (Harvard-Smithsonian Center for Astrophysics) • STScI-PRC00-19


a dark cloud
dense core
200,000 AU
b gravitational collapse
10,000 AU
time = 0
c protostar
bipolar flow
envelope
disk
500 AU
10,000 to 100,000 years
d T Tauri star
bipolar flow
protoplanetary disk
central star
100 AU
100,000 to 3,000,000 years
e pre-main-sequence star
planetary debris disk
100 AU
3,000,000 to 50,000,000 years
f young stellar system
central star
planetary system
50 AU
after 50,000,000 years

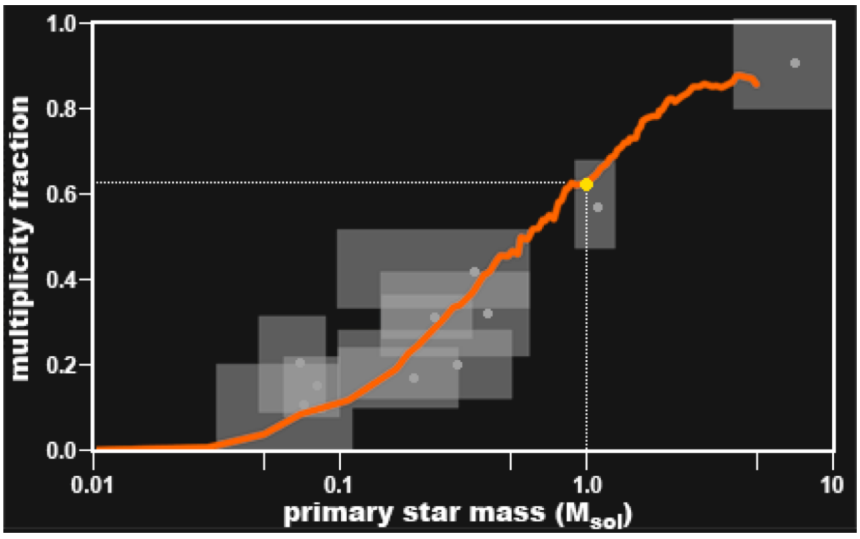
*Greene (2001)*

# Fragmentation can occur in disk forming multiple star systems




Tobin, Kratter, et al. 2016

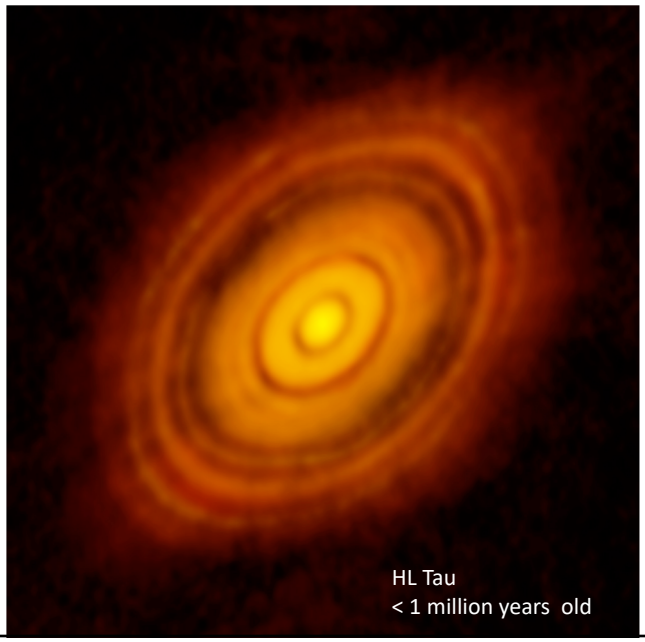
# Massive Stars more likely to be in a multiple star system

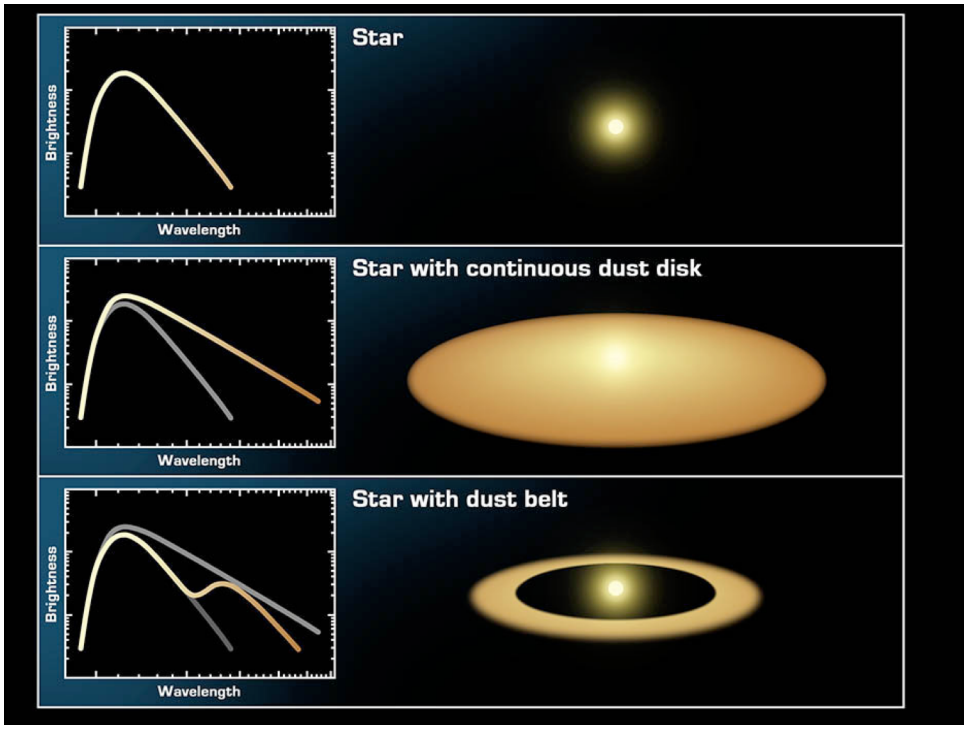


# Vast majority of stars formed are M dwarfs

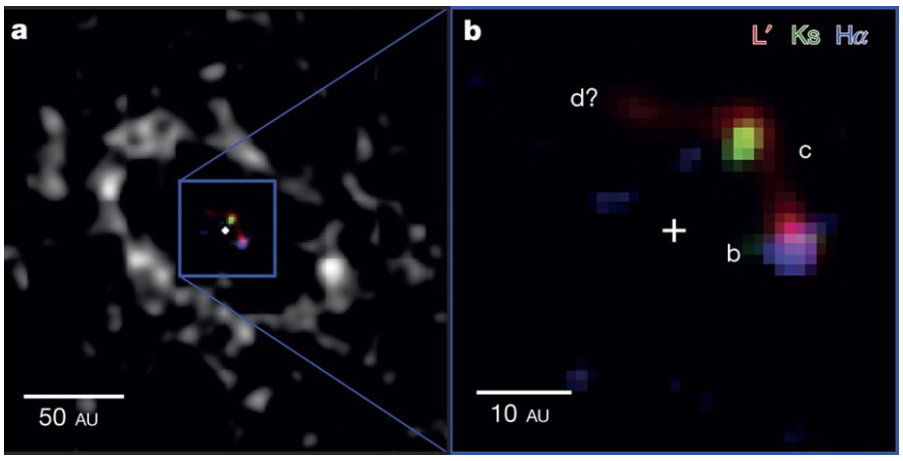
| Class | Effective temperature[1][2][3] | Vega-relative chromaticity[4][nb 1] | Main-sequence mass[1][8] (solar masses) | Main-sequence radius[1][8] (solar radii) | Main-sequence luminosity[1][8] (bolometric) | Hydrogen lines | Fraction of all main-sequence stars[9] |
|---|---|---|---|---|---|---|---|
| O | ≥ 30,000 K | blue | ≥ 16 $M_\odot$ | ≥ 6.6 $R_\odot$ | ≥ 30,000 $L_\odot$ | Weak | ~0.00003% |
| B | 10,000–30,000 K | blue white | 2.1–16 $M_\odot$ | 1.8–6.6 $R_\odot$ | 25–30,000 $L_\odot$ | Medium | 0.13% |
| A | 7,500–10,000 K | white | 1.4–2.1 $M_\odot$ | 1.4–1.8 $R_\odot$ | 5–25 $L_\odot$ | Strong | 0.6% |
| F | 6,000–7,500 K | yellow white | 1.04–1.4 $M_\odot$ | 1.15–1.4 $R_\odot$ | 1.5–5 $L_\odot$ | Medium | 3% |
| G | 5,200–6,000 K | yellow | 0.8–1.04 $M_\odot$ | 0.96–1.15 $R_\odot$ | 0.6–1.5 $L_\odot$ | Weak | 7.6% |
| K | 3,700–5,200 K | light orange | 0.45–0.8 $M_\odot$ | 0.7–0.96 $R_\odot$ | 0.08–0.6 $L_\odot$ | Very weak | 12.1% |
| M | 2,400–3,700 K | orange red | 0.08–0.45 $M_\odot$ | ≤ 0.7 $R_\odot$ | ≤ 0.08 $L_\odot$ | Very weak | 76.45% |

# Formation of Planets out of disk






# Imaging an accreting protoplanet




LkCa 15

Sallum et al. Nature 2015, 527, 342