Star Formation

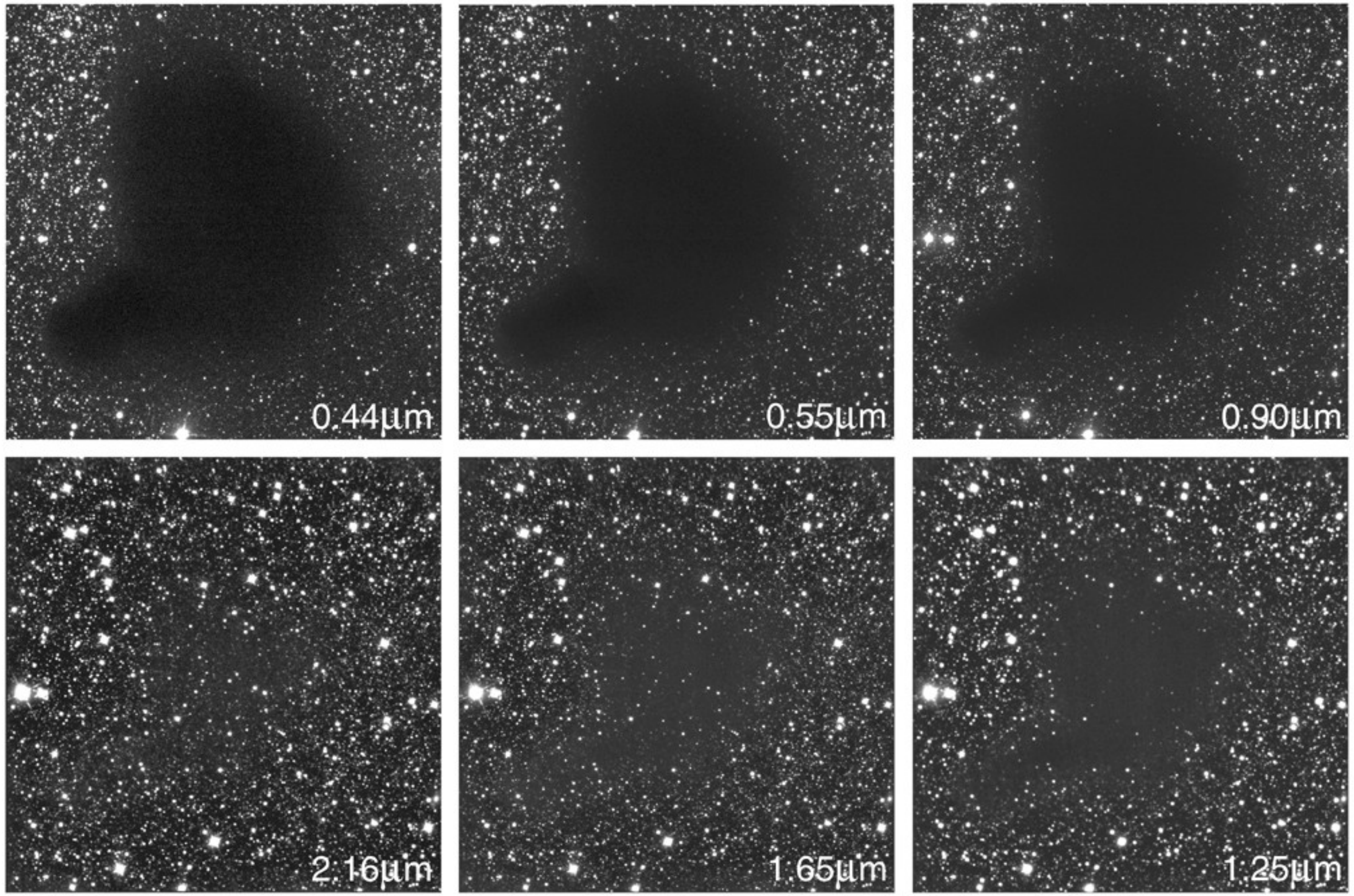
Interstellar Medium

- ISM is mostly confined to galactic disk
  - $\sim 10^9\ M_\odot$
  - $n \sim 1 - 10\ \text{cm}^{-3}$
  - Mostly H (as HI, HII, or H_2)
- Radiation is not in equilibrium with gas
- Most of ISM mass is in clouds
- Denser clouds allow molecules to form
- Stars form in the densest clouds

How Does a Star Interact with ISM?

- Star formation:
  - Stars form from clouds of gas and dust in interstellar medium
  - Large clouds collapse under their own self gravity
  - Previous generations of stars enrich gas with metals
  - We've seen how stellar structure depends on metalicity, Z
- Star Death
  - Supernova return heavy elements to the ISM
  - Low mass stars lose mass via winds, with some chemical enrichment
  - Supernova shocks may be triggers for star formation

ISM



The Dark Cloud B68 at Different Wavelengths (NTT + SOFI)

ESO PR Photo 29b/99 (2 July 1999)

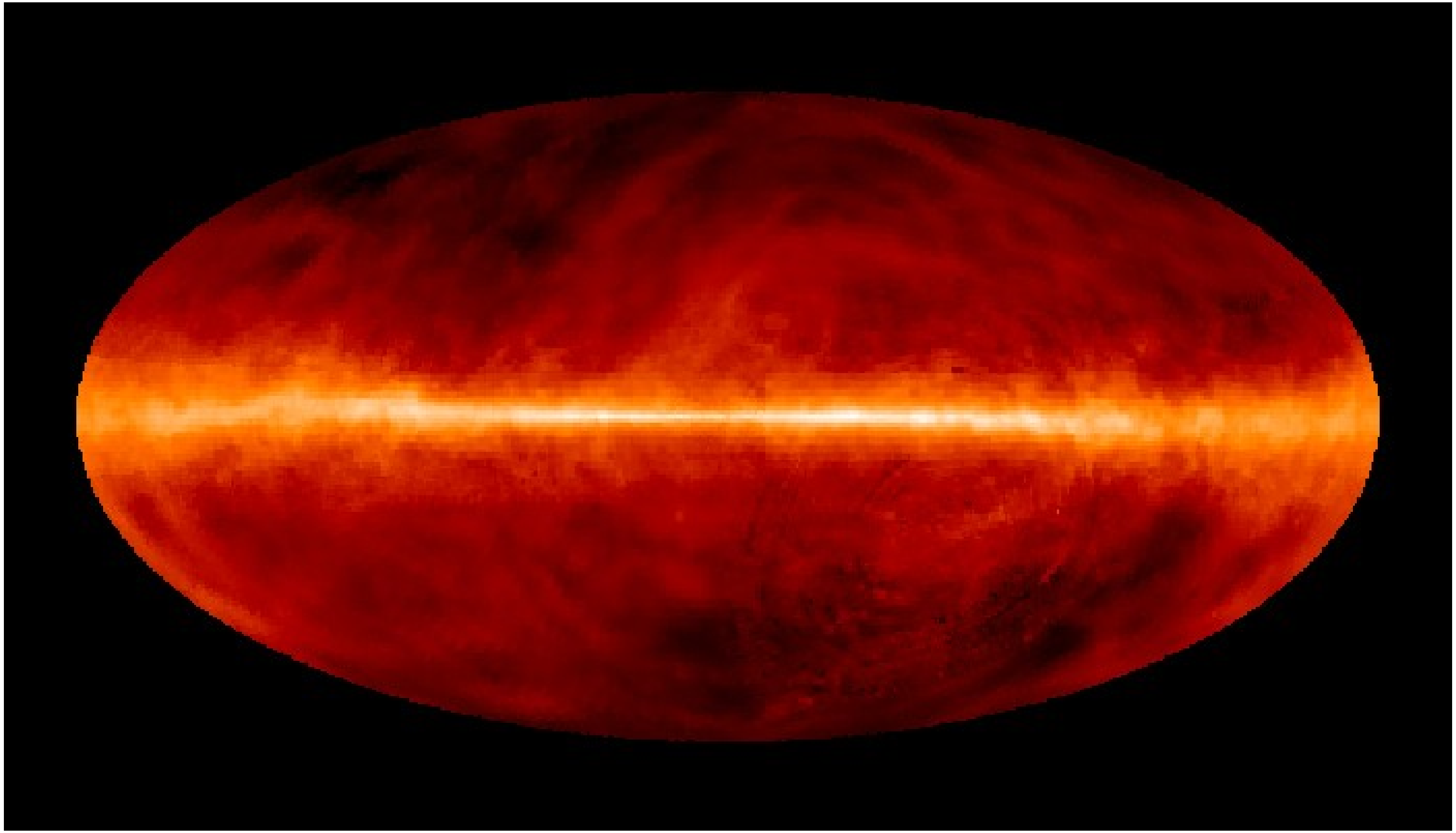
Visible vs. Infrared View of Pillar and Jets HH 901/902

Hubble Space Telescope • WFC3/UVIS/IR

NASA, ESA, and M. Livio and the Hubble 20th Anniversary Team (STScI)

STScI-PRC10-13b

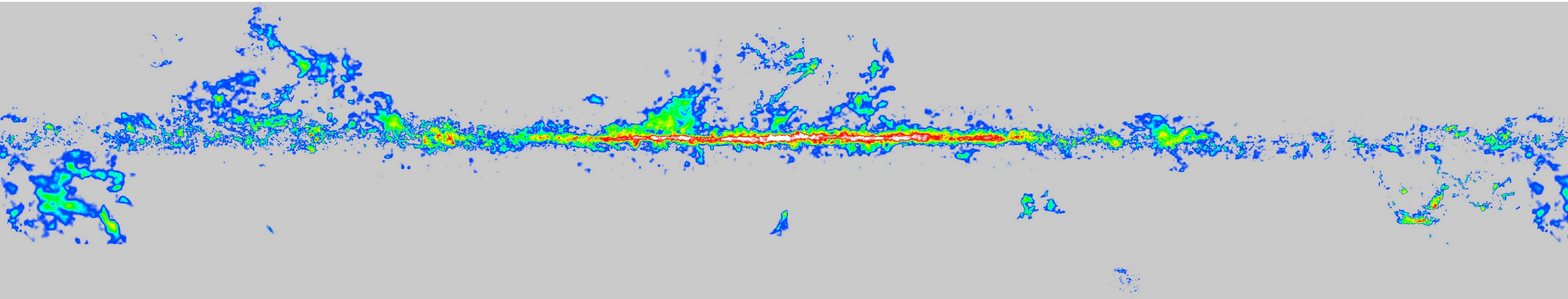
Neutral H Map



J. Dickey (UMn), F. Lockman (NRAO), SkyView

http://antwrp.gsfc.nasa.gov/apod/ap010113.html

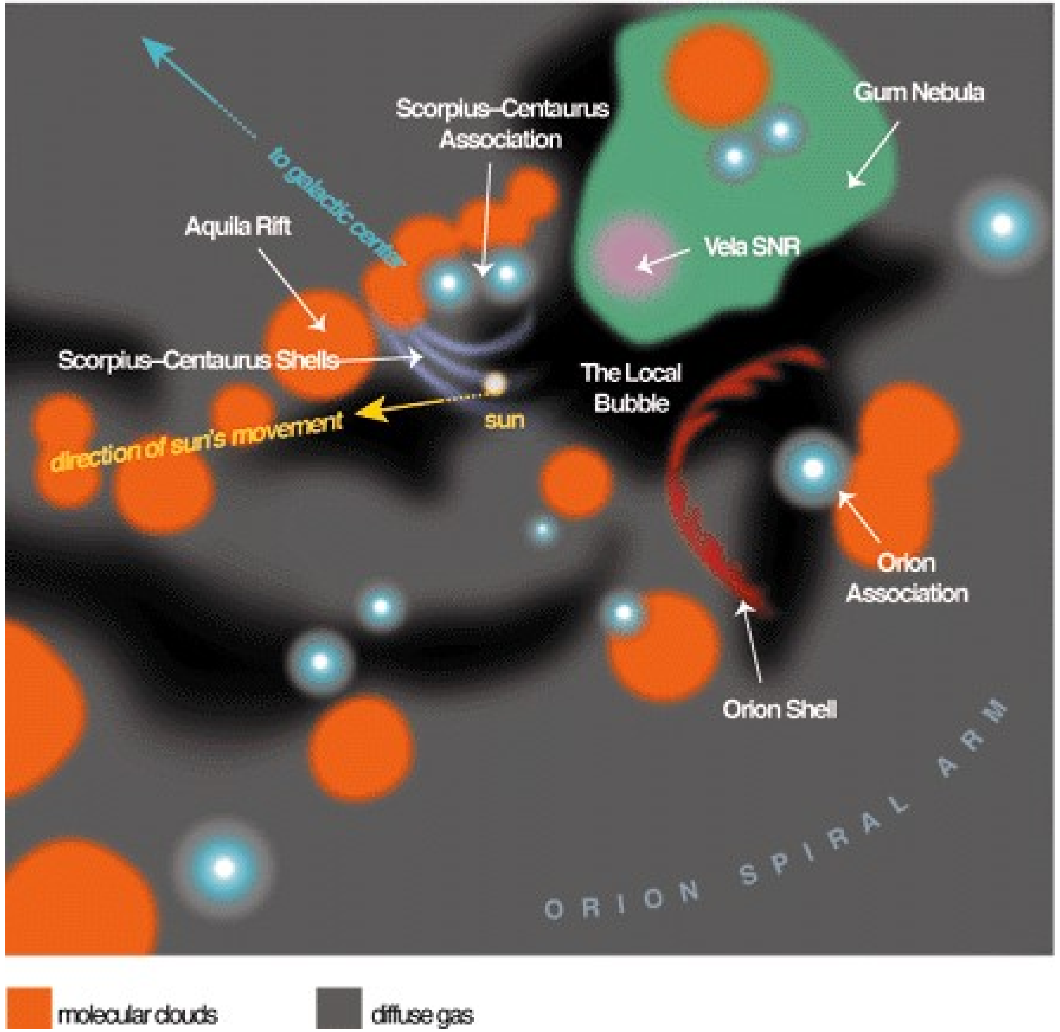
Molecular Gas Map



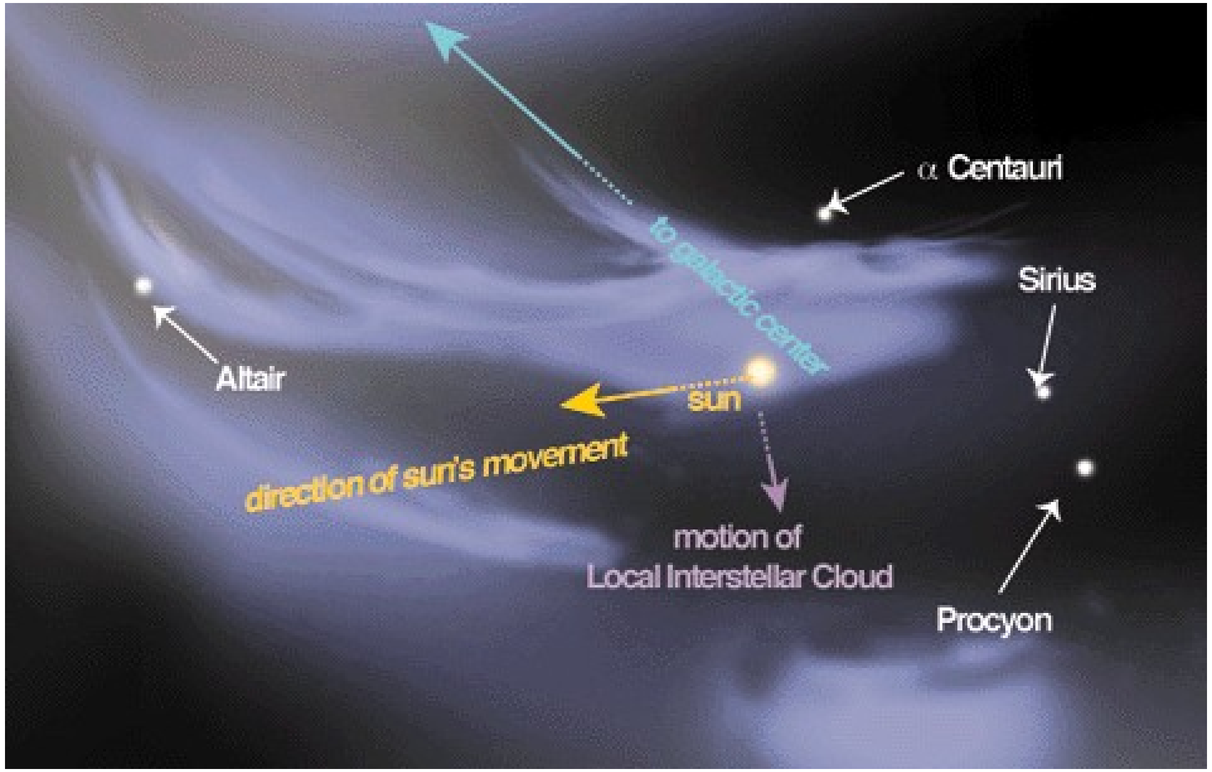
T. Dame (CfA, Harvard) et al., Columbia 1.2-m Radio Telescopes

http://antwrp.gsfc.nasa.gov/apod/ap970430.html

Local Bubble



Linda Huff (American Scientist), Priscilla Frisch (U. Chicago)
http://antwrp.gsfc.nasa.gov/apod/ap020217.html

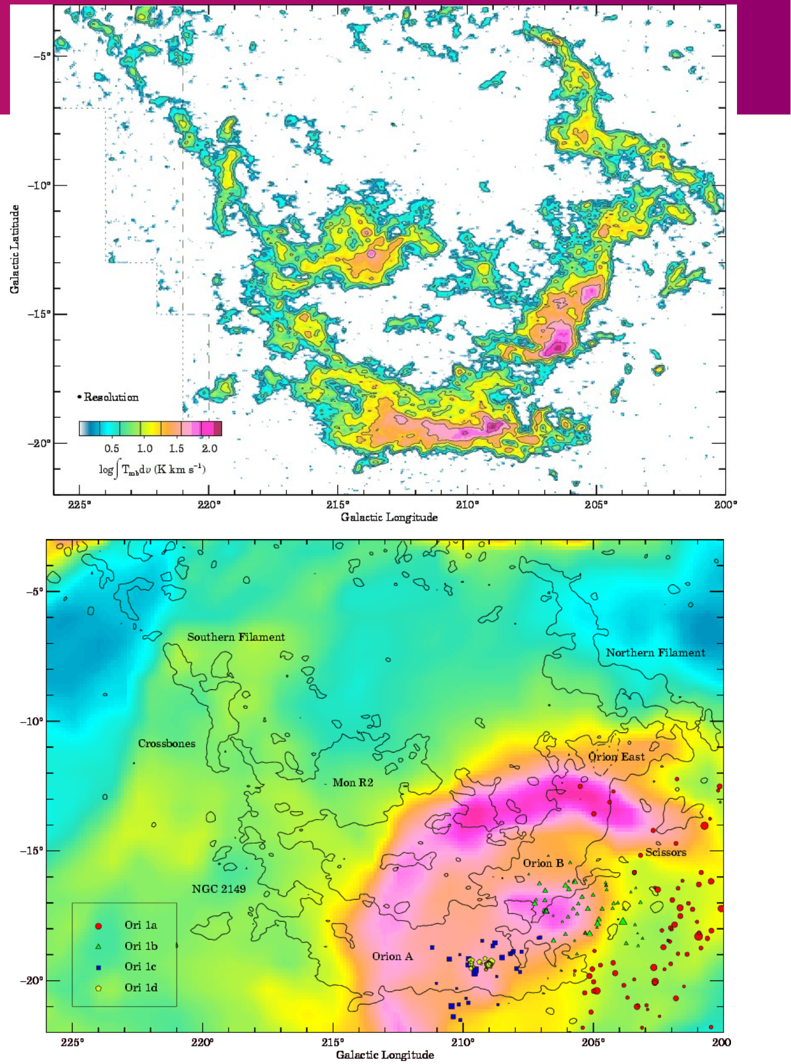


http://antwrp.gsfc.nasa.gov/apod/ap020210.html
Linda Huff (American Scientist), Priscilla Frisch (U. Chicago)

A model of the local ISM. The Sun is believed to moving through the local interstellar cloud just on the edge of the local bubble.

Star Formation

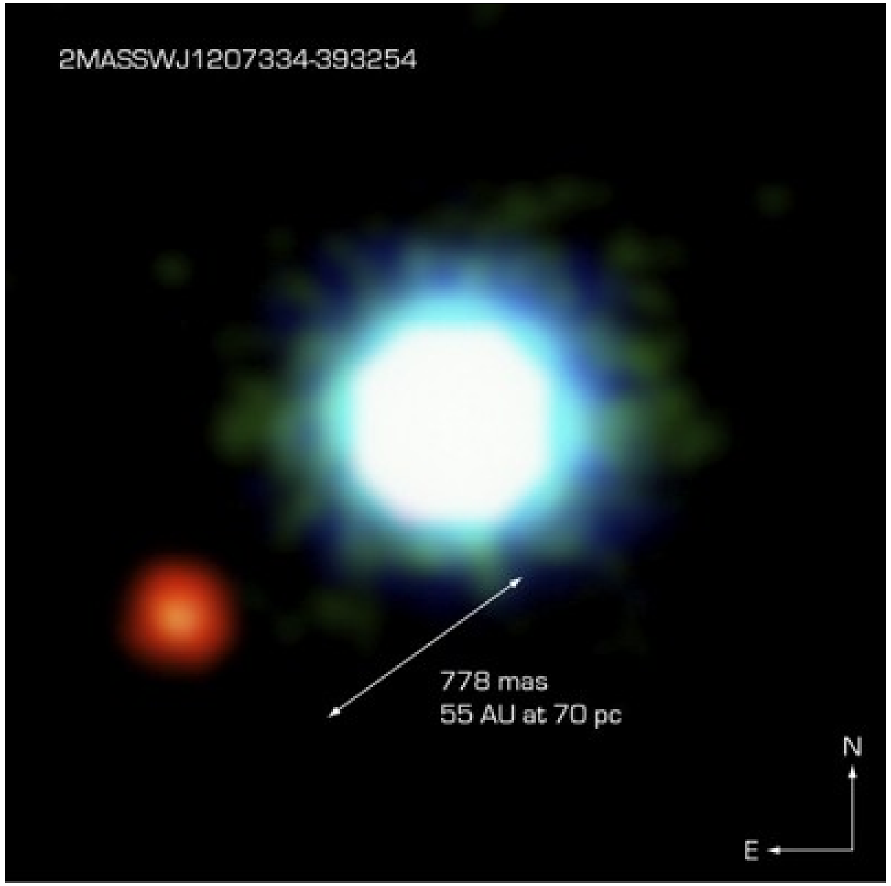
- Only the largest clouds in the ISM will collapse
- Fragmentation can occur as density increases and Jeans length shrinks



CO emission (top) and intensity of ionized gas (bottom) around Orion (B. A. Wilson - T. M. Dame - M. R. W. Masheder - P. Thaddeus, 2005)

Brown Dwarfs

- Collapse of a cloud doesn't have to make just stars
  - Lower mass objects may also form this way
- Difference depends on whether H is ignited
- Brown dwarfs have $M < 0.08\ M_\odot$
  - Still descend the Hayashi track
  - Contract and heat up (as do stars)
  - Reach degeneracy before crossing H ignition curve
- Planets formation is a different process



The Brown Dwarf 2M1207 and its Planetary Companion (VLT/NACO)

ESO PR Photo 14a/05 (30 April 2005)

Brown Dwarfs

- Brown dwarfs form like stars, cool like planets
  - Can briefly burn ^{2}H
  - Luminosity vs. time is ~constant during ^{2}H burning
  - Cool after ^{2}H exhaustion
- Planets are < 0.01 $M_\odot$
  - No ^{2}H burning
  - Luminosity continually decreases

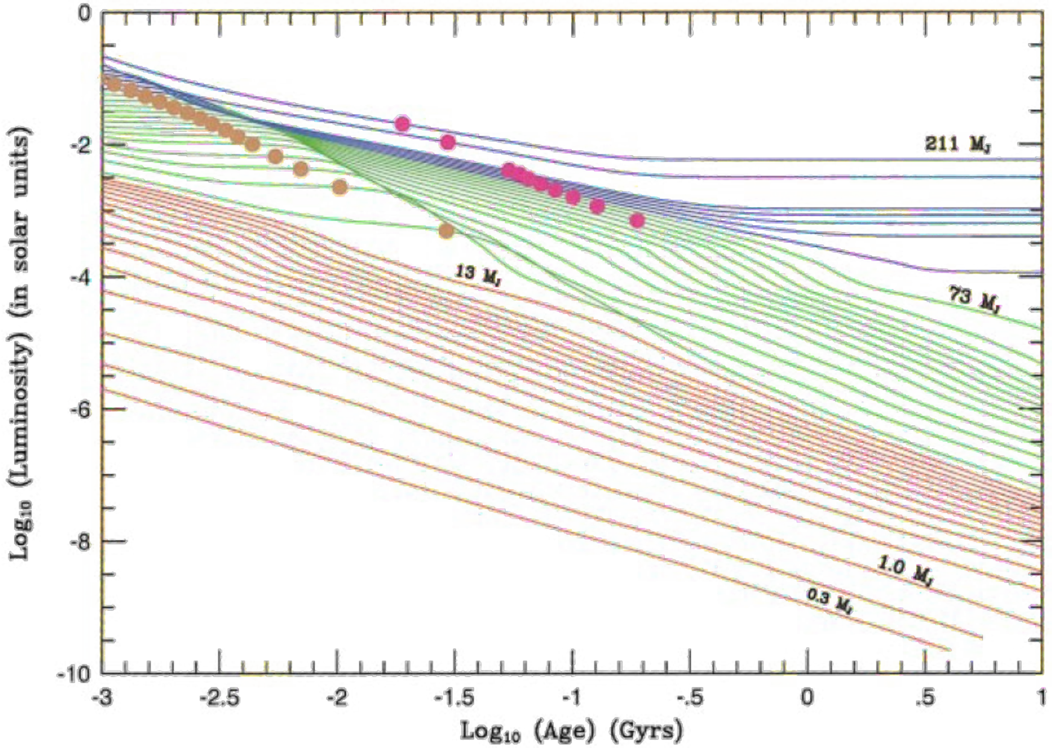
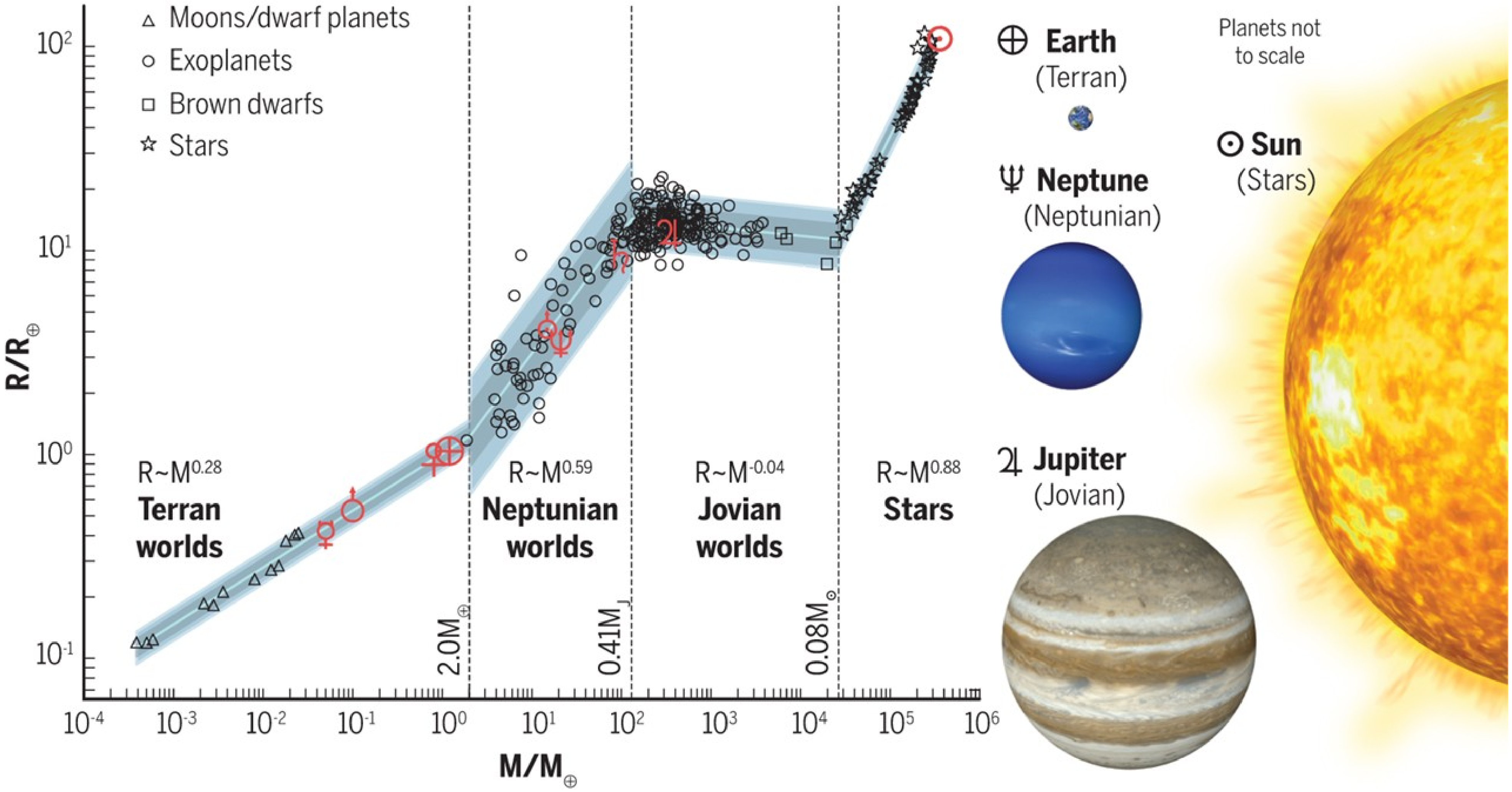


FIG. 1. Evolution of the luminosity (in $L_\odot$) of isolated solar-metallicity red dwarf stars and substellar-mass objects versus age (in years). The stars are shown in blue, those brown dwarfs above 13 M_J are shown in green, and brown dwarfs/giant planets equal to or below 13 M_J are shown in red. Though the color categories are based on deuterium or light hydrogen burning, they should be considered arbitrary *vis à vis* whether the object in question is a brown dwarf or a planet, sensibly distinguished on the basis of origin. The masses of the substeller objects/stars portrayed are 0.3, 0.5, 1.0, 2.0, 3.0, 4.0, 5.0, 6.0, 7.0, 8.0, 9.0, 10.0 11.0, 12.0, 13.0, and 15.0 M_J and 0.02, 0.025, 0.03, 0.035, 0.04, 0.045, 0.05, 0.055, 0.06, 0.065, 0.07, 0.075, 0.08, 0.085, 0.09, 0.095, 0.1, 0.15, and 0.2 $M_\odot$ (≡211 M_J). For a given object, the gold dots mark when 50% of the deuterium has burned and the magenta dots mark when 50% of the lithium has burned. Note that the lithium sequence penetrates into the brown dwarf regime near 0.065 $M_\odot$, below the HBMM. Figure based on Fig. 7 of Burrows *et al.*, 1997 [Color].

Brown Dwarfs

- Degeneracy is dominant pressure support in lowest mass stars and brown dwarfs
  - Radius increases with decreasing mass for complete degeneracy
  - Planets have more complex equations of state, with radius increasing with mass
  - Transition at some mass near Jupiter's mass
- Boundary between brown dwarf and planet is near Jupiter mass

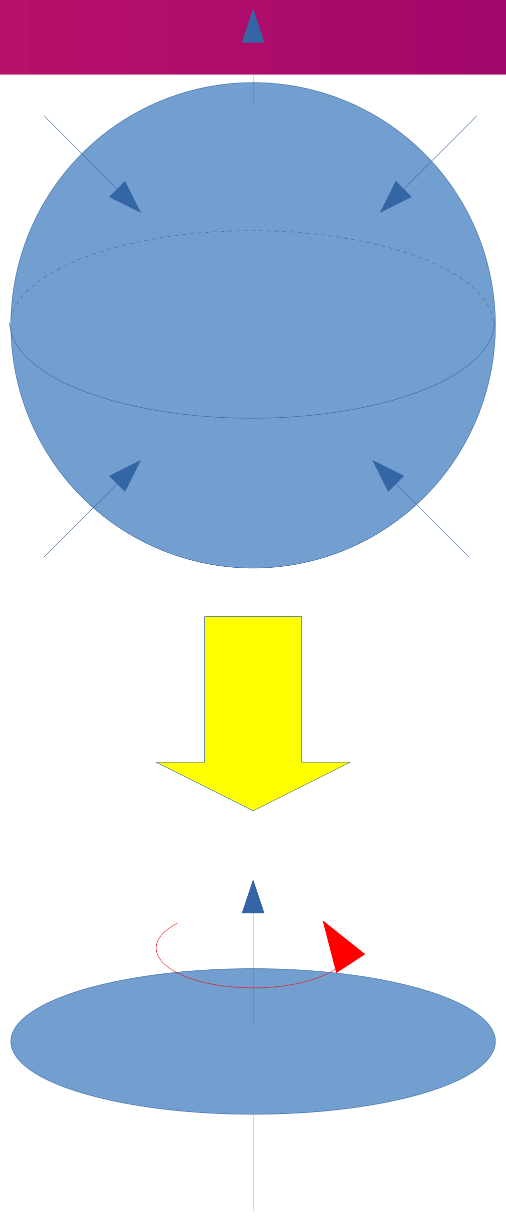
Brown Dwarfs



GRAPHIC: C. BICKEL/SCIENCE

https://science.sciencemag.org/content/353/6300/644/tab-figures-data

How It Begins



- Solar nebula: gas between stars
- Solar nebula collapsed
  - Some gravitational PE radiated away, rest heated cloud
  - Angular momentum conservation → disk forms
- Sun forms at center
  - Eventually T high enough for fusion
  - H burning began
  - Energy produced in core matched energy radiated from surface—equilibrium
- Planets form in disk
  - Orbital directions reflect spinning disk

Star Formation in Orion

More than 3000 stars are in this image amongst the gas and dust in the nebula

(NASA, ESA, M. Robberto (Space Telescope Science Institute/ESA) and the Hubble Space Telescope Orion Treasury Project Team)

(Credit: Mouser Williams)

Jeans' Mass

- A "gaseous sphere" has two influences acting on it:
  - gravity pulling it together
  - kinetic energy of particles tending to cause it to fly apart.
- Static solution: critical mass such that mass lower than this limit will disperse and mass above this limit will collapse.
  - Jeans critical mass.
- For a given density, one can also consider a Jeans radius.

- Compare sound speed to free-fall collapse
  - Collapse occurs if:

$$t_{\text{ff}} < t_{\text{sound}}$$
$$\frac{1}{\sqrt{G\rho}} < \frac{R}{c_s}$$
$$\frac{1}{\sqrt{G\rho}} < \frac{R}{\sqrt{P/\rho}}$$

  - This gives the Jeans' length

Jeans Mass from Virial

- When does a cloud collapse?
  - Consider uniform T cloud in HSE
  - If we push on it, gravity will be stronger – does the increase in pressure compensate?
  - Virial theorem:

$$\int P dV = P_s V + \frac{\alpha}{3}\frac{GM^2}{R}$$

  - Critical radius – Jeans length

$$R_J = \frac{\alpha}{3}\frac{GM\mu m_u}{kT}$$

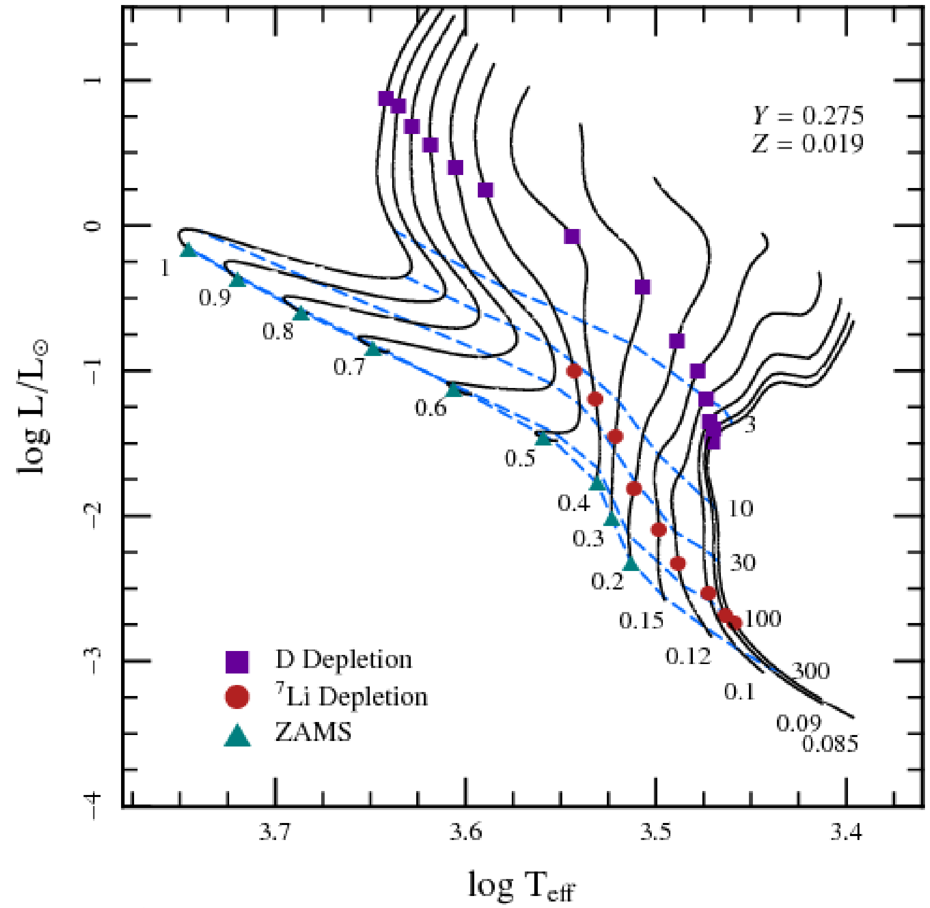
- Mass of a cloud before gravity wins – Jeans mass:

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

  - $M > M_J$ gives collapse
  - Typical value ~ $10^4\ M_\odot$

Star Formation on the HR Diagram

- Hayashi track: boundary separating convecting hydrostatic stars (left) and those that have no means of effective energy transport (right)
- Move off Hayashi track when reactions kick in
- First part of pp-chain and conversion of ^{12}C to ^{14}N via CNO
  - Low mass stars never have this happen
- Once hot enough, full H burning commences



(Paxton et al. 2010)

Fig. 15.— Location in the Hertzsprung-Russell (H-R) diagram for $0.085 M_\odot < M < 1 M_\odot$ stars as they arrive at the main sequence for $Y = 0.275$ and $Z = 0.019$. The mass of the star is noted by the values at the bottom of the line. The dashed blue lines are isochrones for ages of 3, 10, 30, 100 and 300 Myr, as noted to the right. The purple squares (red circles) show where D (^{7}Li) is depleted by a factor of 100. The green triangles show the ZAMS.

Hayashi Track

- We can derive the Hayashi track in much the same was we did WD cooling
- Consider the star to be a polytrope (very good for fully-convective protostar)
  - Connect interior structure to surface
  - Start with:

$$K = \left[\frac{4\pi}{\xi^{n+1}(-\theta'_n}^{n-1} \right]_{\xi_1}^{1/n} M_\star^{1-1/n} R_\star^{-1+3/n}$$

- From polytrope EOS:

$$P = K\rho^{1+1/n}$$

  - we get:

$$\log P_p = \left(1 - \frac{1}{n}\right) \log M_\star + \\ \left(-1 + \frac{3}{n}\right) \log R_\star + \\ \left(1 + \frac{1}{n}\right) \log \rho_p + \alpha$$

  - ‘p’ subscript for photosphere
  - α is a constant

Hayashi Track

- HSE gives:

$$\frac{dP}{d\tau} = +\frac{g_\star}{\kappa}$$

  - Integrating from the surface to the photosphere:

$$0 - P_p = \frac{g_\star}{\kappa} = -\frac{GM_\star}{\kappa R_\star^2}$$

- Take opacity as powerlaw:

$$\kappa = \kappa_0 \rho_p T_{\rm eff}^\nu$$

  - Together:

$$\begin{aligned} \log P_p = & \log M_\star - 2\log R_\star - \\ & \log \rho_p - \nu \log T_{\rm eff} + \beta \end{aligned}$$

Hayashi Track

- Ideal gas law:

$$\log P_p = \log \rho_p + \log T_{\rm eff} + \gamma$$

- Blackbody relation:

$$\log L_\star = 2\log R_\star + 4\log T_{\rm eff} + \delta$$

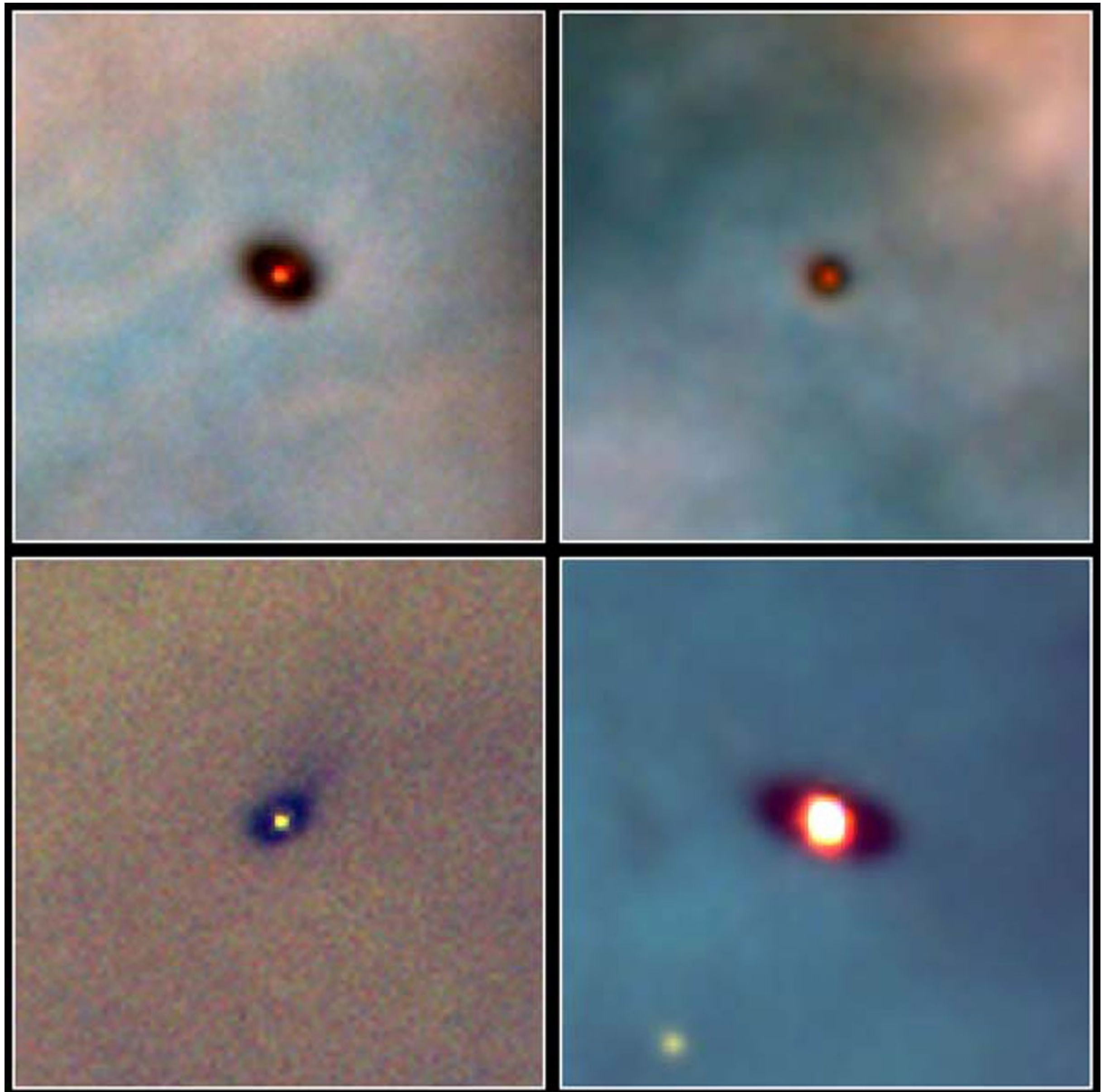
- 4 equations + 4 unknowns
- Assume H- opacity: ν = 4
- Solution:

$$\log L_\star = -4\log M_\star + 20\log T_{\rm eff} + c$$

  - This is a really steep line in the HR diagram

Protoplanetary Disks in the Orion Nebula
Hubble Space Telescope • WFPC2

NASA, J. Bally (University of Colorado), H. Throop (SWRI), and C.R. O'Dell (Vanderbilt University)
STScI-PRC01-13



Protoplanetary Disks
Orion Nebula

HST • WFPC2

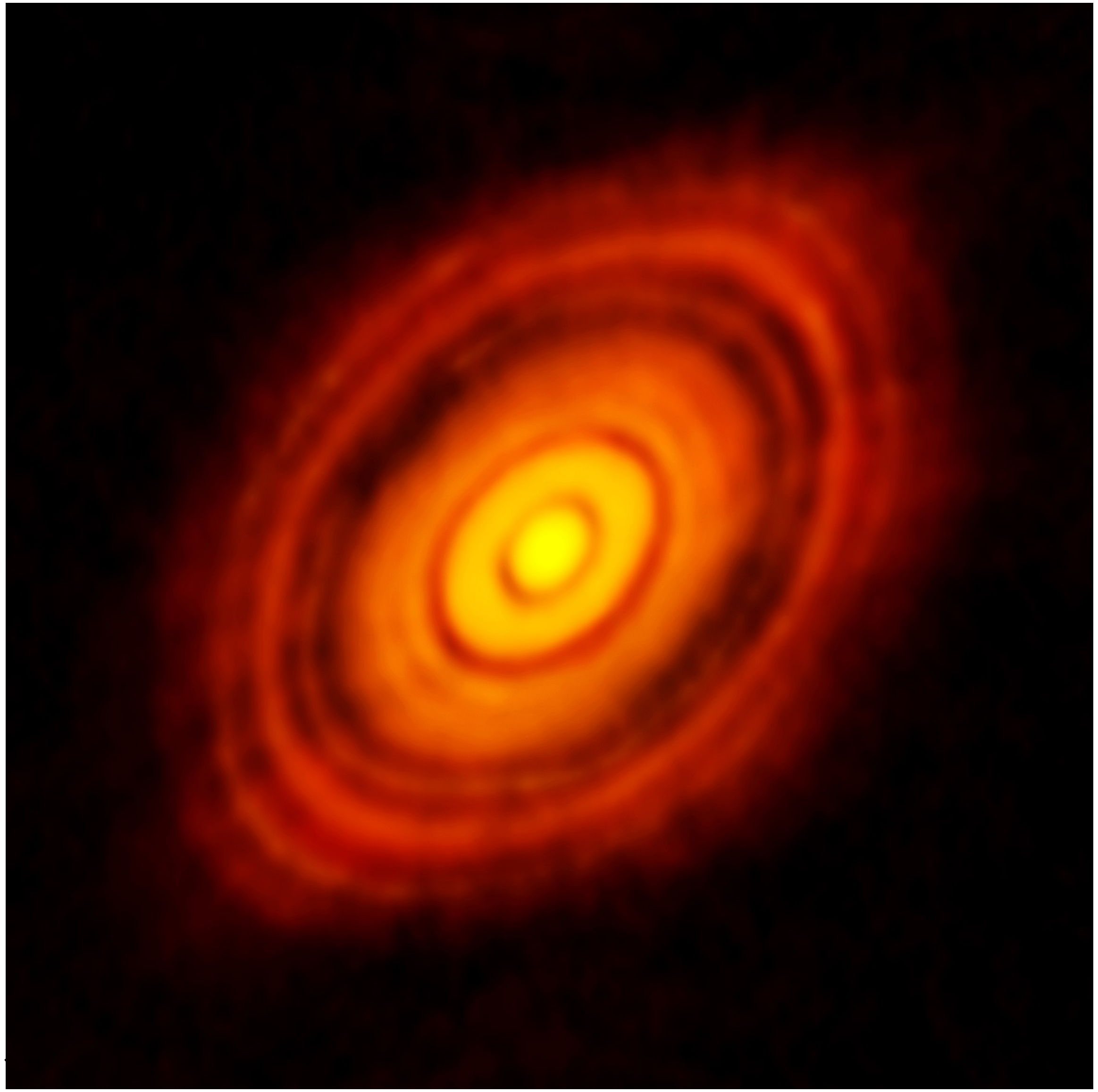
PRC95-45b • ST ScI OPO • November 20, 1995
M. J. McCaughrean (MPIA), C. R. O'Dell (Rice University), NASA

http://antwrp.gsfc.nasa.gov/apod/ap091222.html

Credit: NASA, ESA, M. Robberto (STScI/ESA), the HST Orion Treasury Project Team, & L. Ricci (ESO)

Young Disk

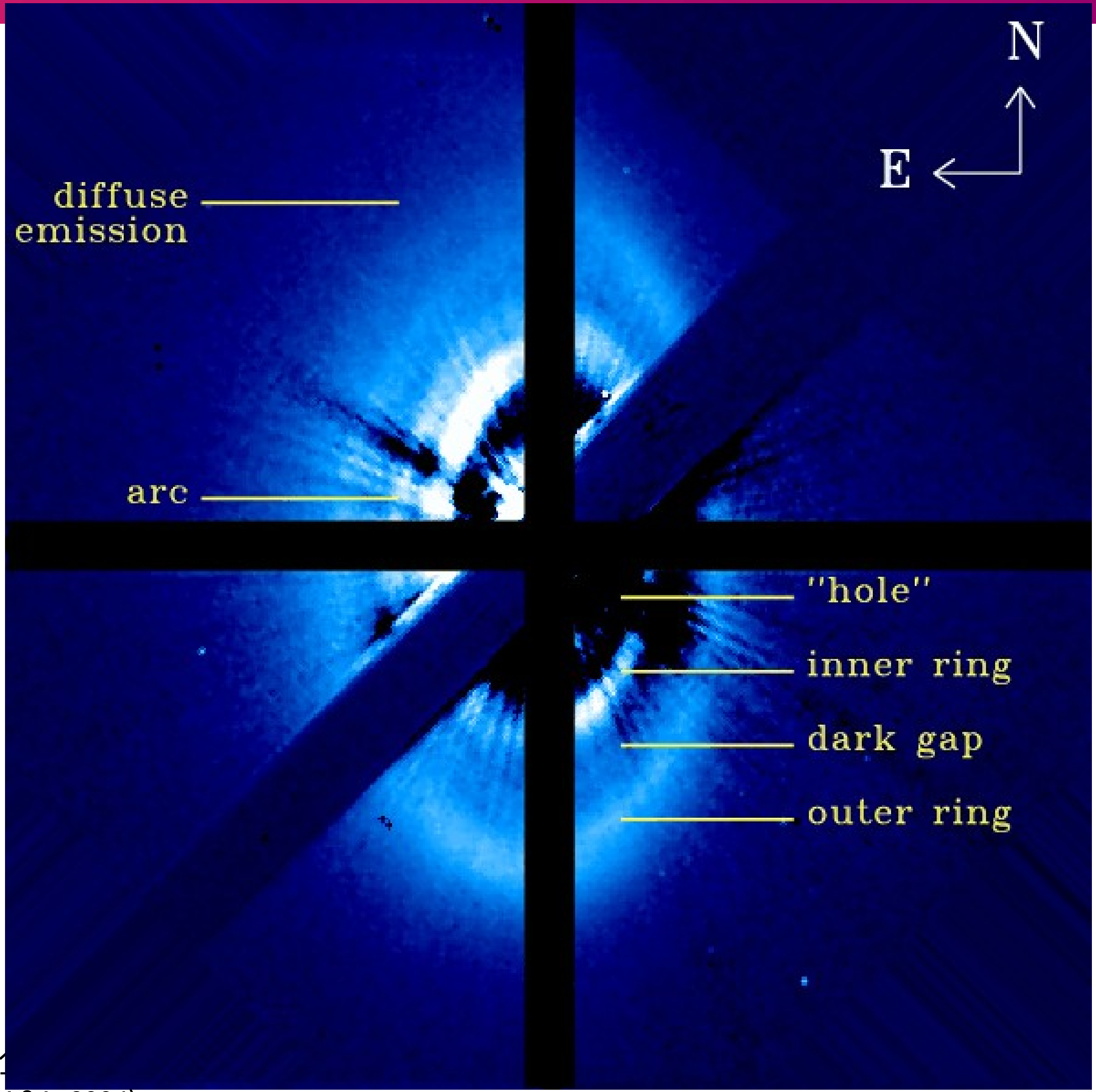
- HL Tau: < 1 Myr; 140 pc



ALMA (ESO/NAOJ/NRAO)

Slightly Older Disk

- HD 141569; 5 Myr, 98 pc

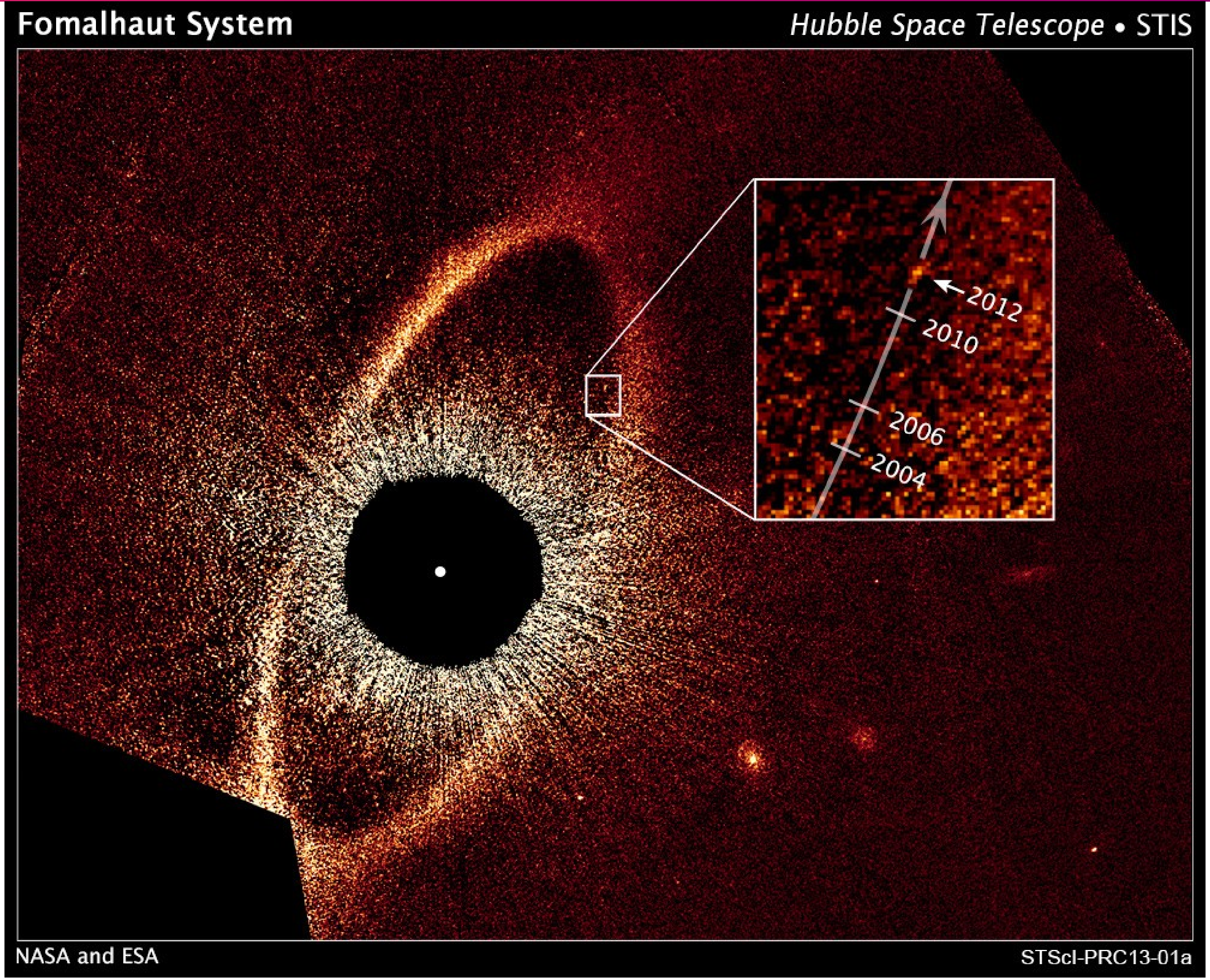


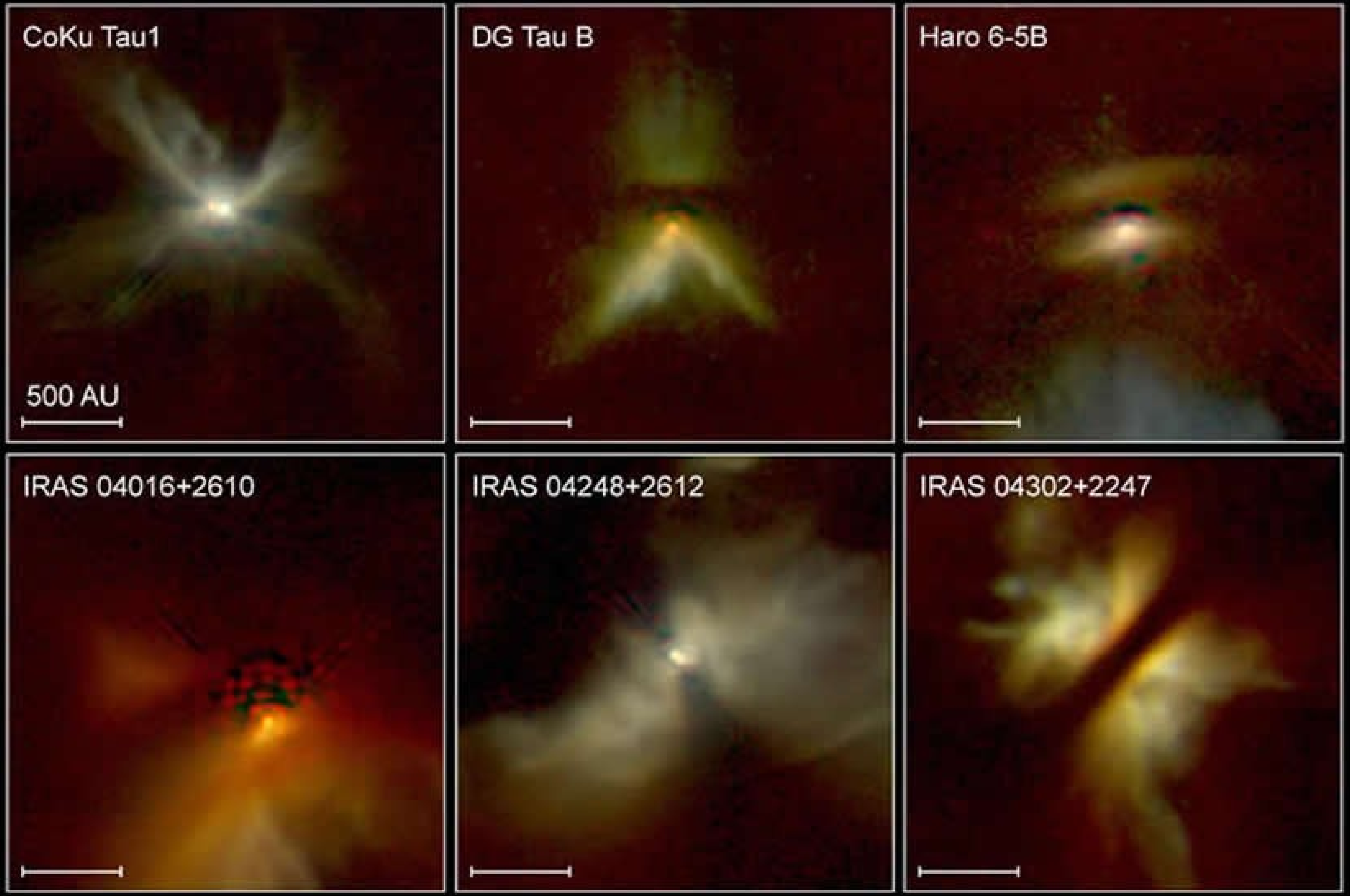
(J. C. Augereau and J. C. B. Papaloizou, A&A, 2004)

Debris Disk

- Formalhautl 440 Myr, 7.6 pc

At this stage, a planet may be actively shaping the debris





Young Stellar Disks in Infrared

Hubble Space Telescope • NICMOS

PRC99-05a • STScI OPO • D. Padgett (IPAC/Caltech), W. Brandner (IPAC), K. Stapelfeldt (JPL) and NASA

Initial Mass Function

- Number of stars formed at a given time in a volume w/ M ∈ [M, M + dM]:

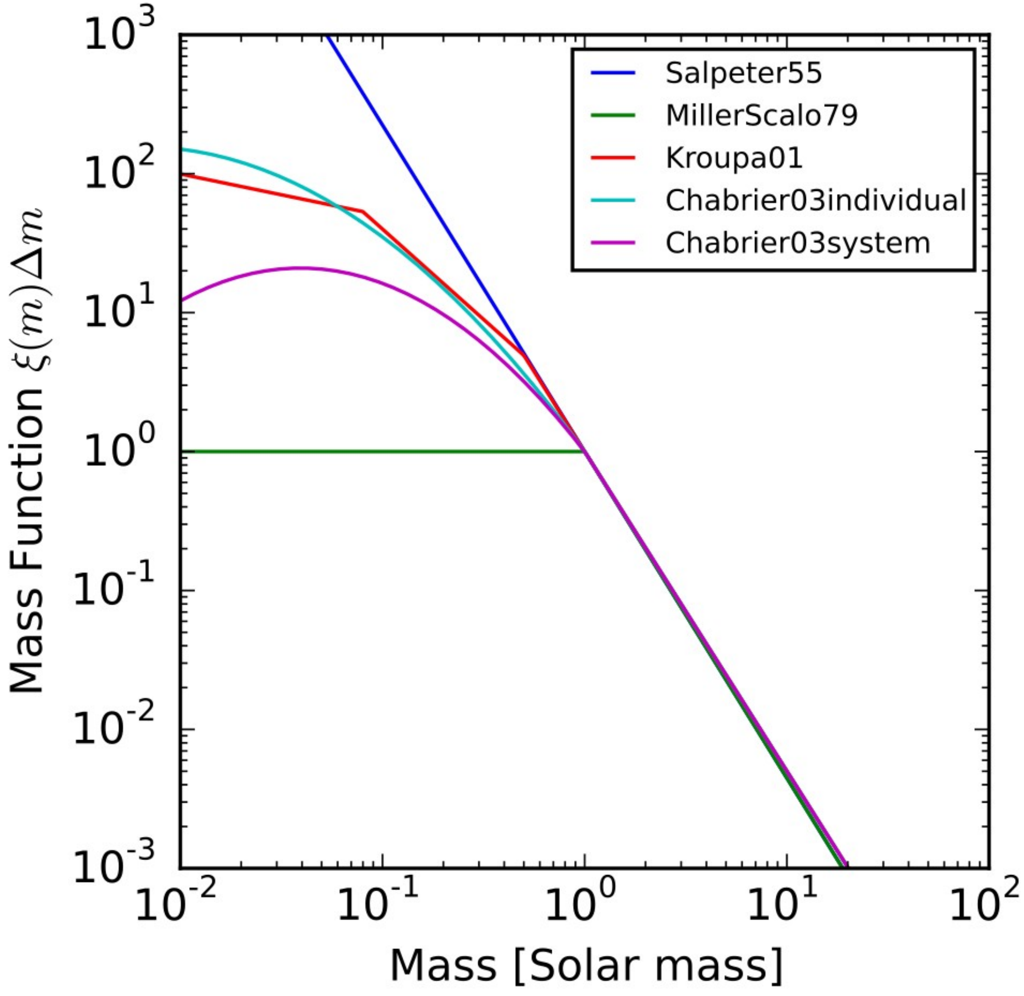
$$dN = \Phi(M)dM$$

  - ϕ(M) Is the "birth function"
  - Salpeter: ϕ(M) ~ $M^{-2.35}$
- Initial mass function:

$$MdN \equiv \xi(M)dM = \Phi(M)MdM$$

$$\xi(M) \propto \left(\frac{M}{M_\odot}\right)^{-1.35}$$

  - Empirically obtained
  - Low end is uncertain



(JohannesBuchner/ Wikipedia)

Mass Return to ISM

- Consider a generation of stars at a given time
- Mass initially locked up in stars:

$$\xi = \int_{M_{\rm min}}^{M_{\rm max}} \xi(M) dM$$

- Stars lose mass as they evolve
  - $\mathscr{R}$ is fraction of initial mass ejected by star
  - $\mathscr{R}$ depends on mass of star
- Mass returned to ISM:

$$\eta = \int_{M_{\rm min}}^{M_{\rm max}} \xi(M) \mathcal{R}(M) dM$$

- What is $\mathscr{R}$?

$$\mathcal{R} = \begin{cases} 1 & M > M_{\rm SN} \\ \frac{M - M_{\rm WD}}{M} & M_{\rm MS} < M < M_{\rm SN} \\ 0 & M M_{\rm MS} \end{cases}$$

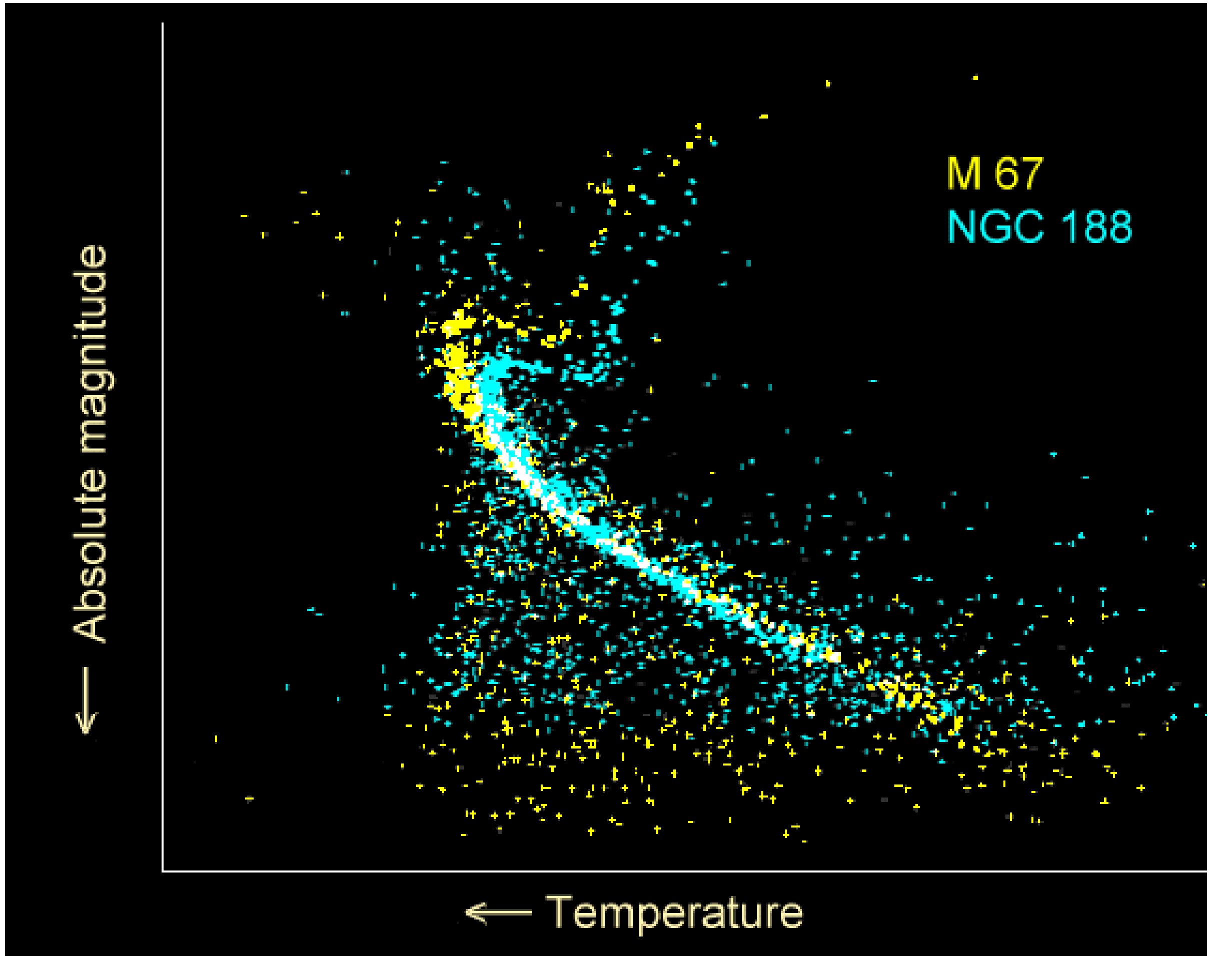
  - Stars that supernova return essentially everything
  - Stars that have evolved off the main sequence return anything above the WD mass
- Taking into account different mass losses, we find η/ξ ~ 1/3

What Fraction of Stars are WDs?

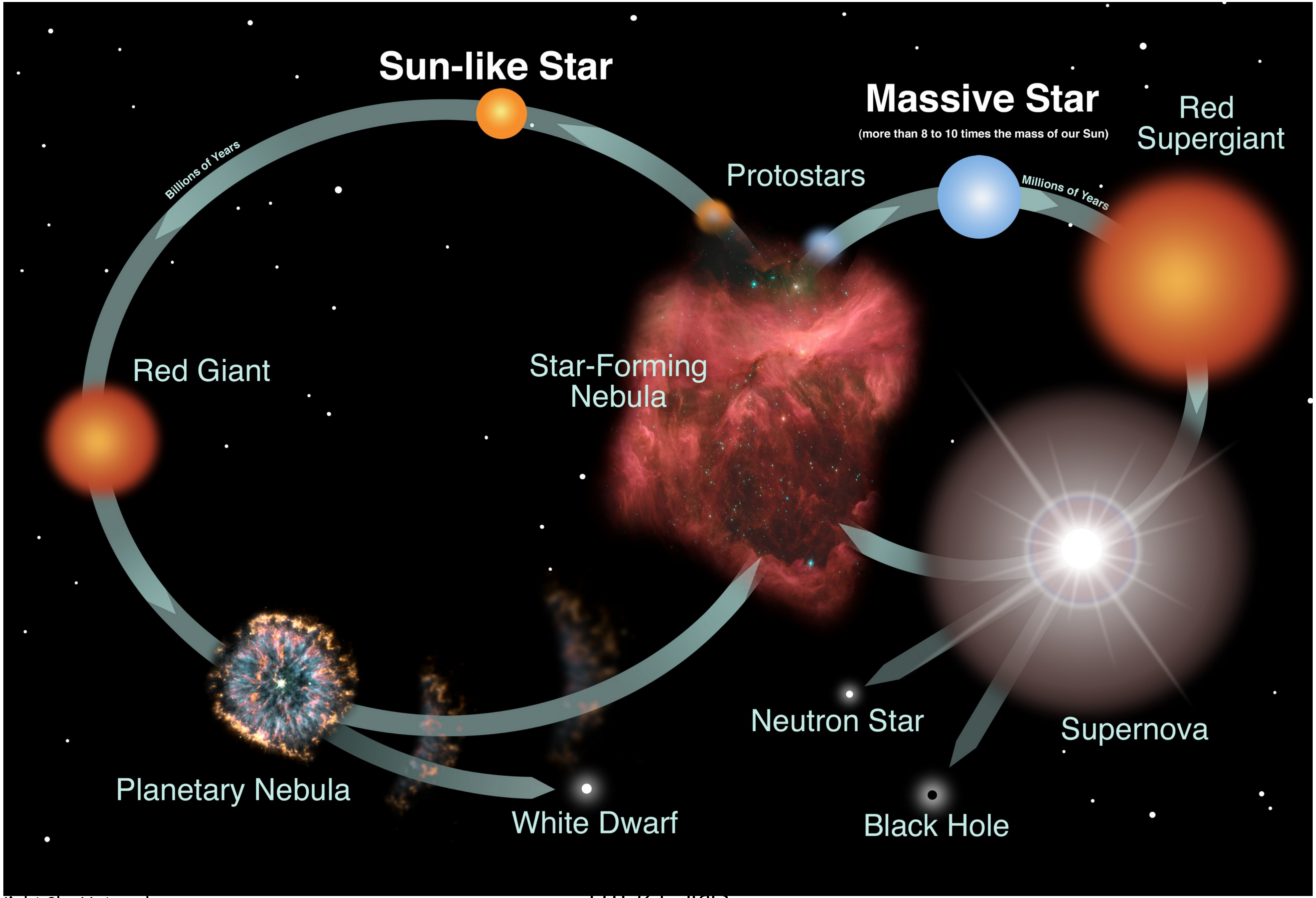
- Consider stars formed together in a cluster
- Main-sequence turnoff tells us which stars are still on the main sequence
- Fraction of stars that are WDs / MS:

$$\frac{N_{\mathrm{WD}}}{N_{\mathrm{MS}}} = \frac{\int_{M_{\mathrm{tp}}}^{M_{\mathrm{SN}}} \Phi(M)dM}{\int_{M_{\mathrm{min}}}^{M_{\mathrm{tp}}} \Phi(M)dM}$$

  - Typically a few %



(Worldtraveller /Wikipedia)



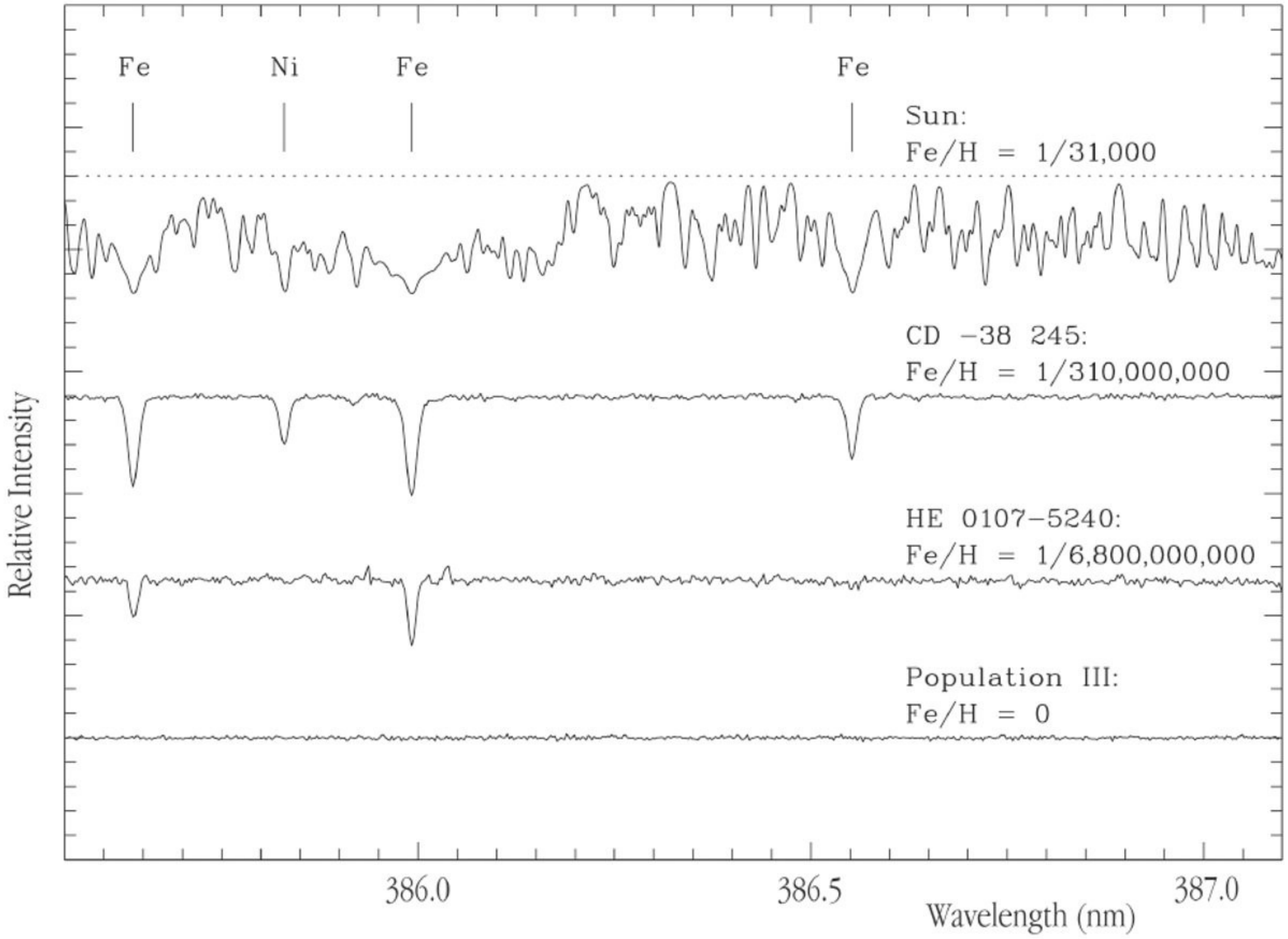
NASA and the Night Sky Network;
https://imagine.gsfc.nasa.gov/science/objects/stars1.html

Stellar Life Cycle

- First generation of stars were zero metalicity (population III)
- Next generation were metal poor (population II)
- Latest generation is metal rich (population I)

- Universe is 13.6 billion years old
- Sun formed only recently
  - Enriched by metals produced in previous generation of stars (Z ~ 0.02)
- Newest stars have Z ~ 0.04
- Lowest mass stars never evolve – lock up gas
  - Eventually these will dominate

Stellar Populations



Spectra of Stars with Different Metal Content

ESO
https://www.eso.org/public/images/eso0228b/

Stellar Life Cycle

- Evolution in our Galaxy
  - Mass of free gas decreases – fewer nebula / clouds
  - Galactic luminosity decreases (fewer massive stars)
  - Composition is enriched by metals
- Massive stars provide most of the chemical enrichment to the galaxy
  - Most enrichment happened early

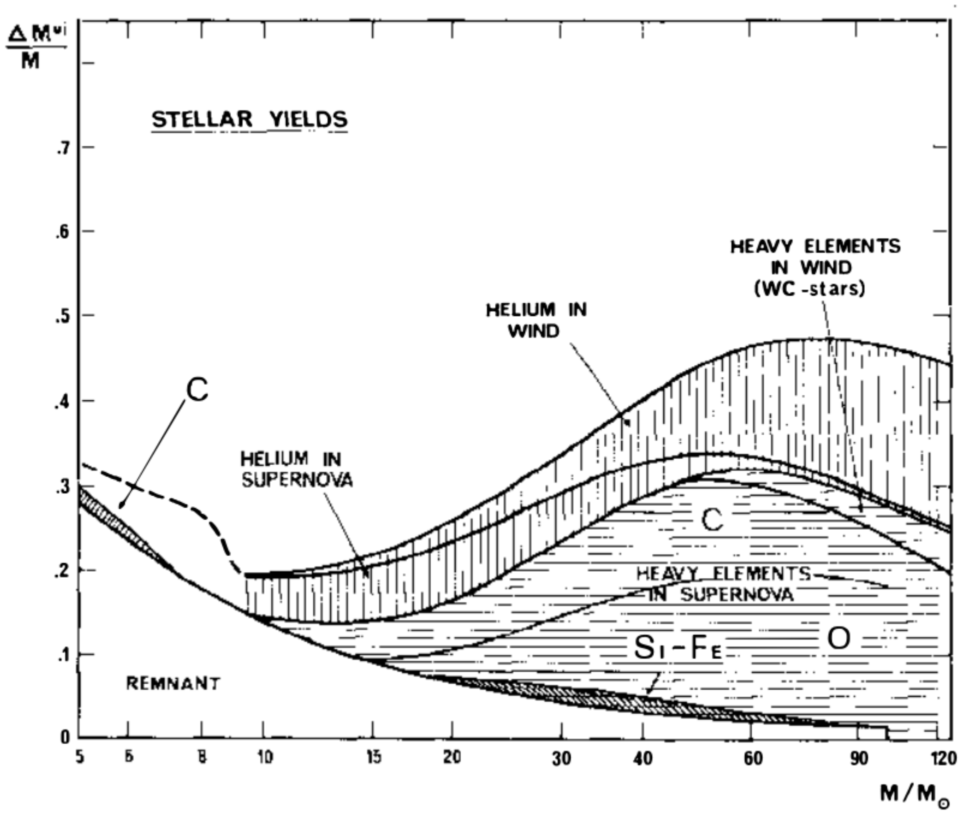


Figure 6 Mass fraction of new helium and new heavy elements ejected as a function of the initial stellar mass. Contributions from stellar winds of OB stars, supergiants, and WR stars are totaled and distinguished from the contribution from supernova explosions. The distribution of heavy elements in the supernova ejecta is based on the classic value for the $^{12}C(\alpha, \gamma)^{16}O$ reaction rate (see text). The contribution to ^{12}C by intermediate-mass stars is derived from Renzini & Voli (214) and is limited to their case A.

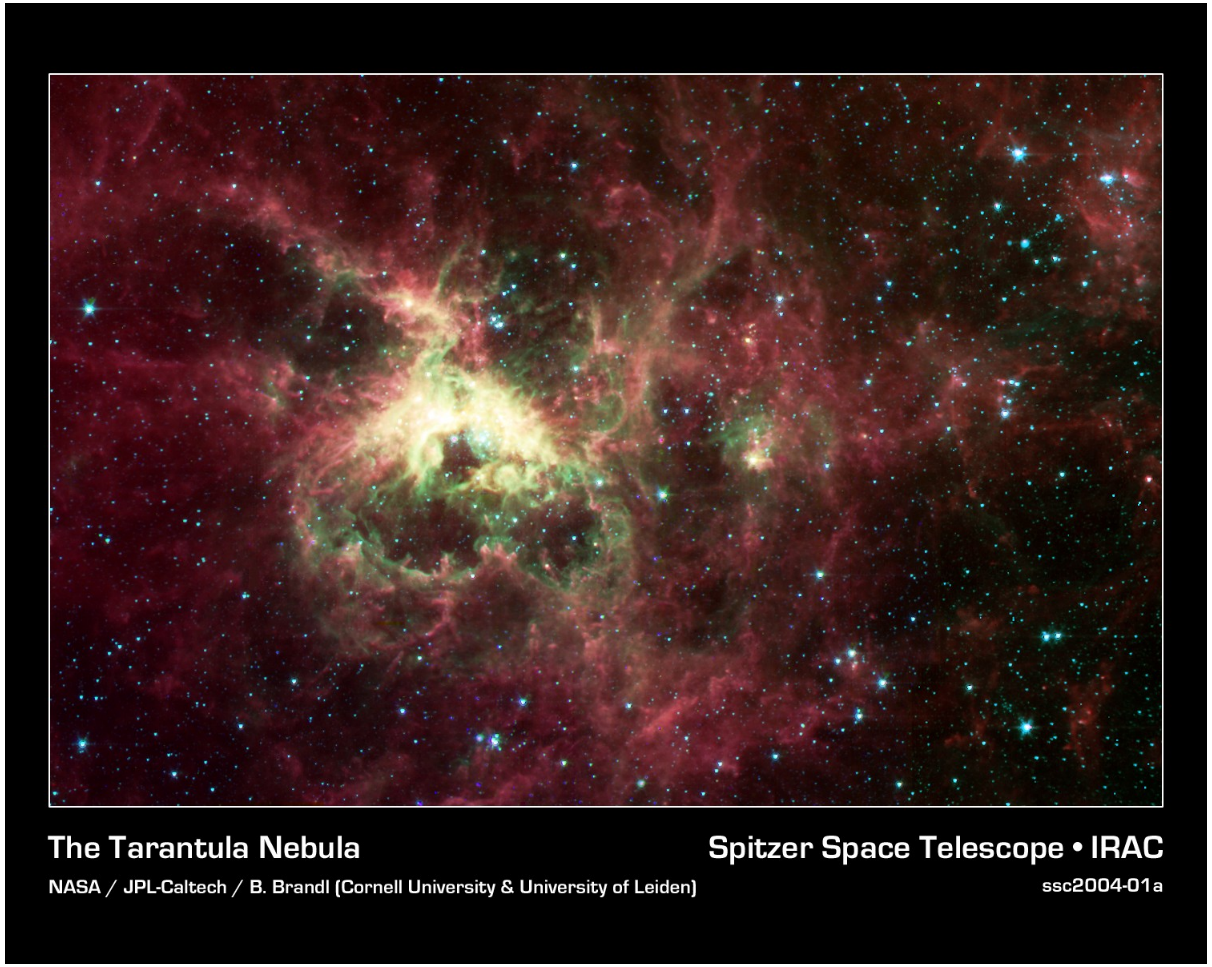
(Chiosi & Marder 1986)

Outstanding Questions

- Do we need a trigger to initiate the collapse?
  - Shock wave from nearby supernova?
  - Stellar wind from young star?
- How much of the mass of the cloud winds up in stars?
- What is the initial mass function of stars?
- OB associations: unbound stars from a bound cloud—how?
- Do high and low mass stars form in the same place?
  - High mass stars may form is bursts

HII Regions

- Hot stars (O, early B) have significant flux in UV
  - Able to ionize H
  - H II region: region surrounding star where ionization takes place—extends out to the point where ionization and recombination balance



The Tarantula Nebula

Spitzer Space Telescope • IRAC

NASA / JPL-Caltech / B. Brandl (Cornell University & University of Leiden)

ssc2004-01a

HII Regions

H II regions (red spots) in M51

(NASA, ESA, S. Beckwith (STScI), and The Hubble Heritage Team (STScI/AURA))

M33

(Chris Schur)