Formation of Massive Stars: Theoretical Considerations

TIARA Winter School on **Star Formation**

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Morse & Davidson (1996)

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Why bother?

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- Massive stars (OB stars) are the principal source of heavy elements.
- OB stars are principal source of UV radiation.
- OB stars introduce turbulence into the ISM.
  - Stellar winds, HII champagne flows, photoevaporation flows, SN explosions
  - Turbulence + differential rotation necessary ingredients for galactic dynamos
  - Turbulence + magnetic fields lead to acceleration of cosmic rays
- OB stars profoundly influence star formation and the evolution of galaxies.
- Your extra-galactic and early universe friends always mean “formation of massive stars” when they talk about “star formation”

High mass versus low mass star formation

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- High mass star formation is not simply a scaled-up version of low mass star formation
  - Massive stars are much more seldom than low mass stars
  - Relevant time scales are extremely short
  - Radiative acceleration of dusty gas very important
  - Massive stars typically form in clusters; with a high degree of multiplicity
  - Disk dissipation must be very quick
  - Associated with UCHIIs, massive collimated outflows, H_2O masers, …

Questions to be addressed

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- Assuming a gravitationally unstable massive clump, how does enough material become concentrated into a sufficiently small volume within a sufficiently short time?

- How does the forming massive star influence its immediate surroundings to limit its mass?

The Global Picture

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- Ying: Mechanisms that drive compression
  - Gravity
  - External pressure
  - Converging gas motions
- Yang: Mechanisms that oppose compression
  - Internal pressure
  - Turbulence
  - Magnetic fields
  - Rotation
  - Radiative acceleration

Stability of gaseous clumps

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- Consider a gaseous clump of mass M, temperature T, radius R, density $\rho = 3M/4\pi R^3$, magnetic pressure $B^2/8\pi$, rotational velocity Ω_{rot} , equation of state $P = K \rho^\gamma$, immersed in an external hot medium

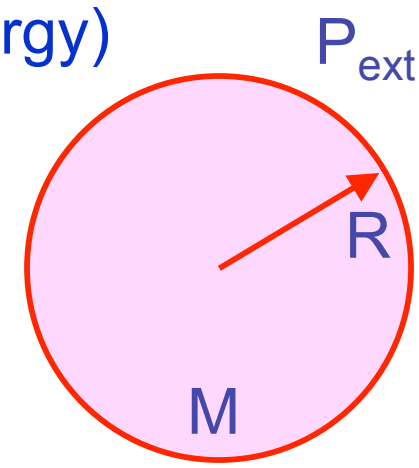
$E_G = -\alpha GM^2/R = -A_G R^{-1}$ (gravitational energy)

$E_{int} = A_{int} R^{3(1-\gamma)}$ (internal energy)

$E_{mag} = A_{mag} R^{-1}$ (magnetic energy)

$E_{rot} = A_{rot} R^{-2}$ (rotational energy)

$E_{ext} = A_{ext} R^3$ (external pressure)



Stable, Expansion or Collapse?

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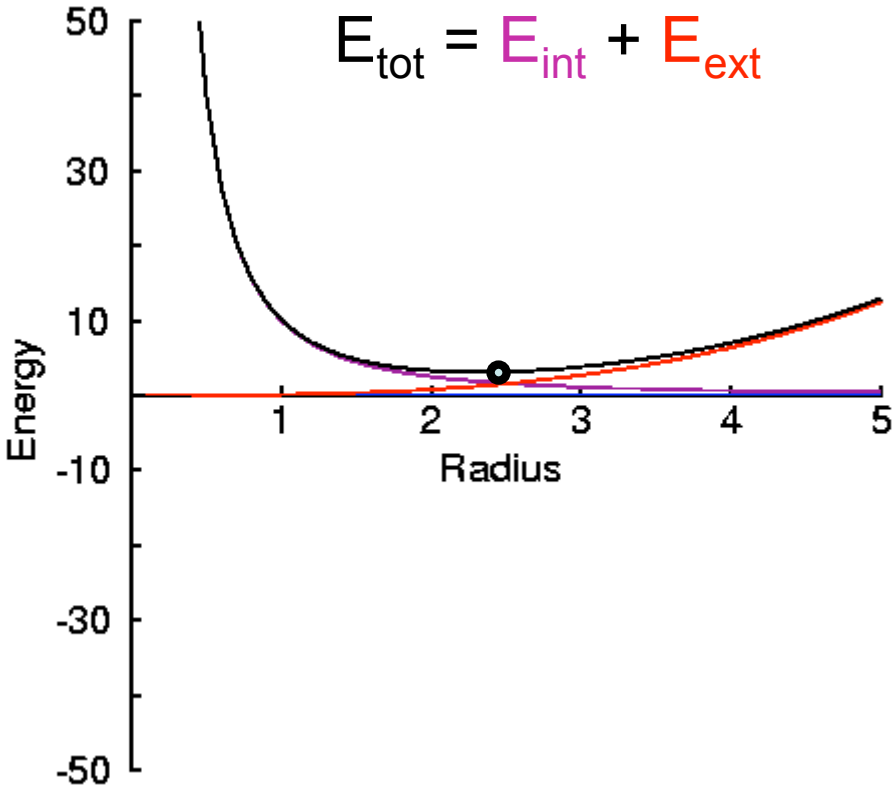

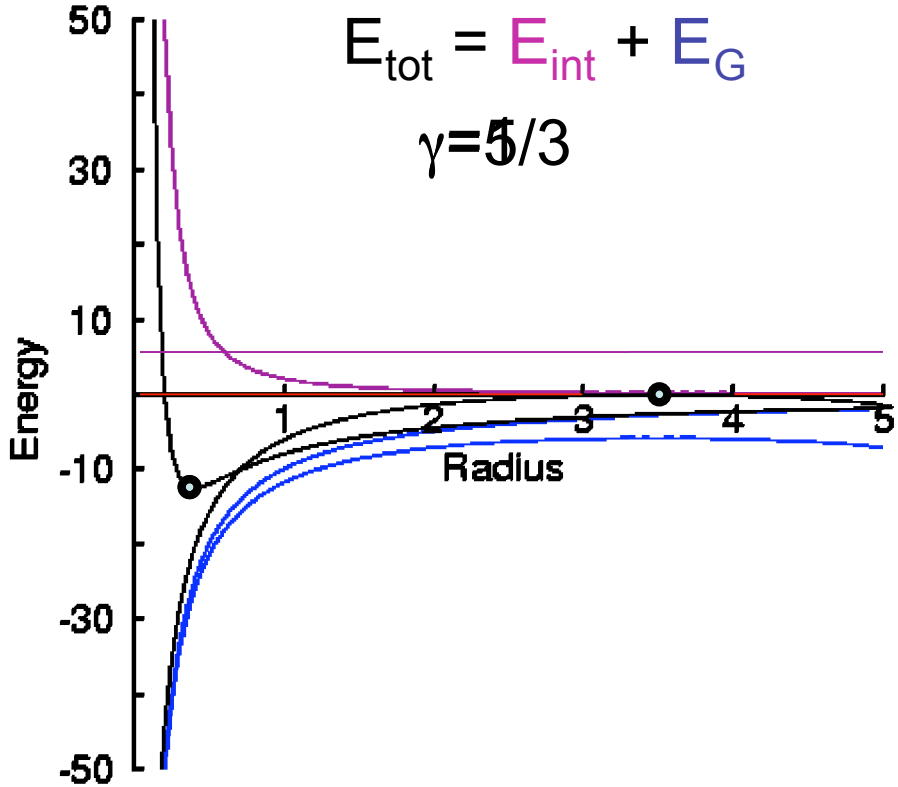

$$M_{Jeans} = 1\ M_\odot\ (T/10\ K)^{3/2}\ (n_{H_2}/10^4\ cm^{-3})^{-1/2}$$

The Initial Mass Function

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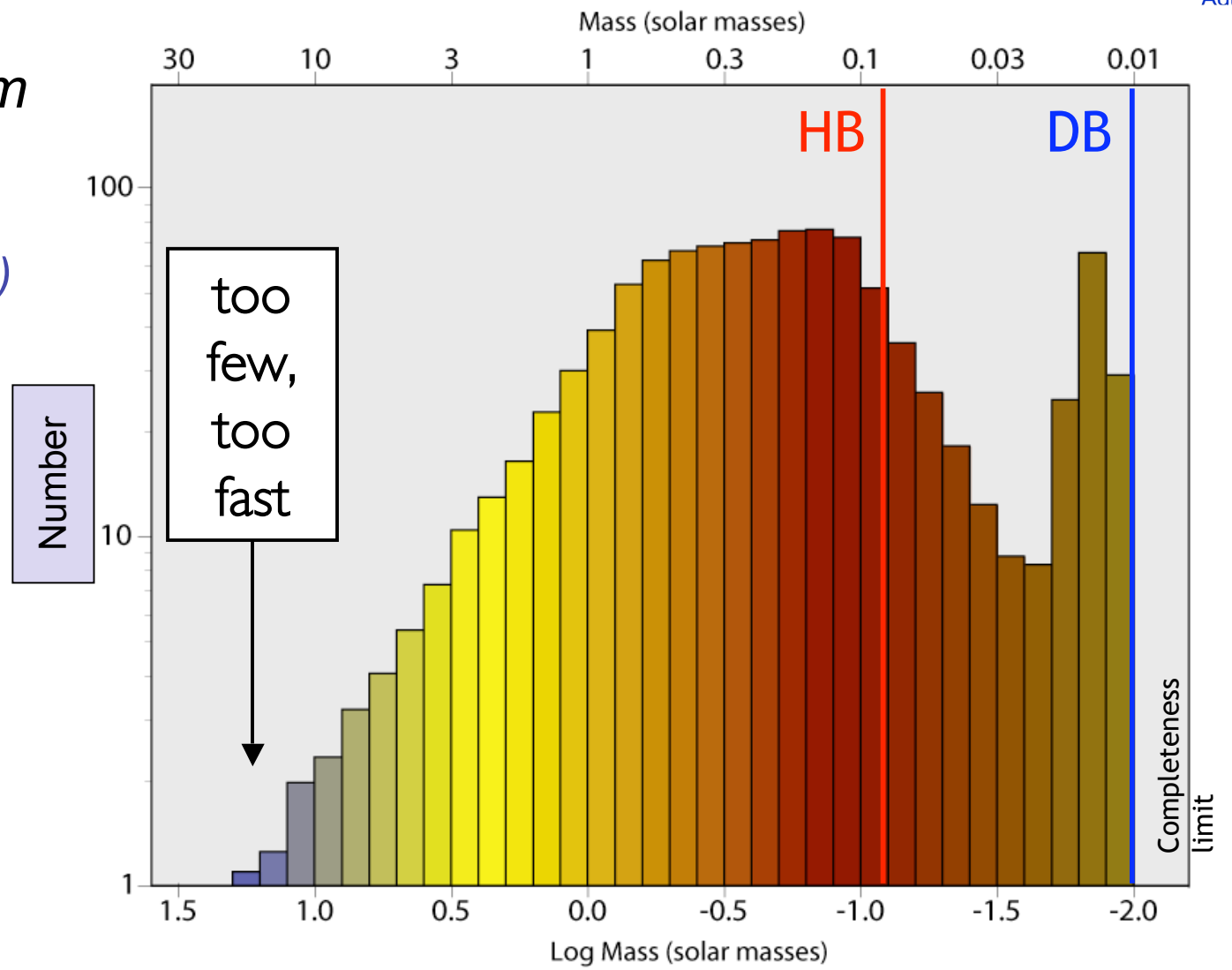
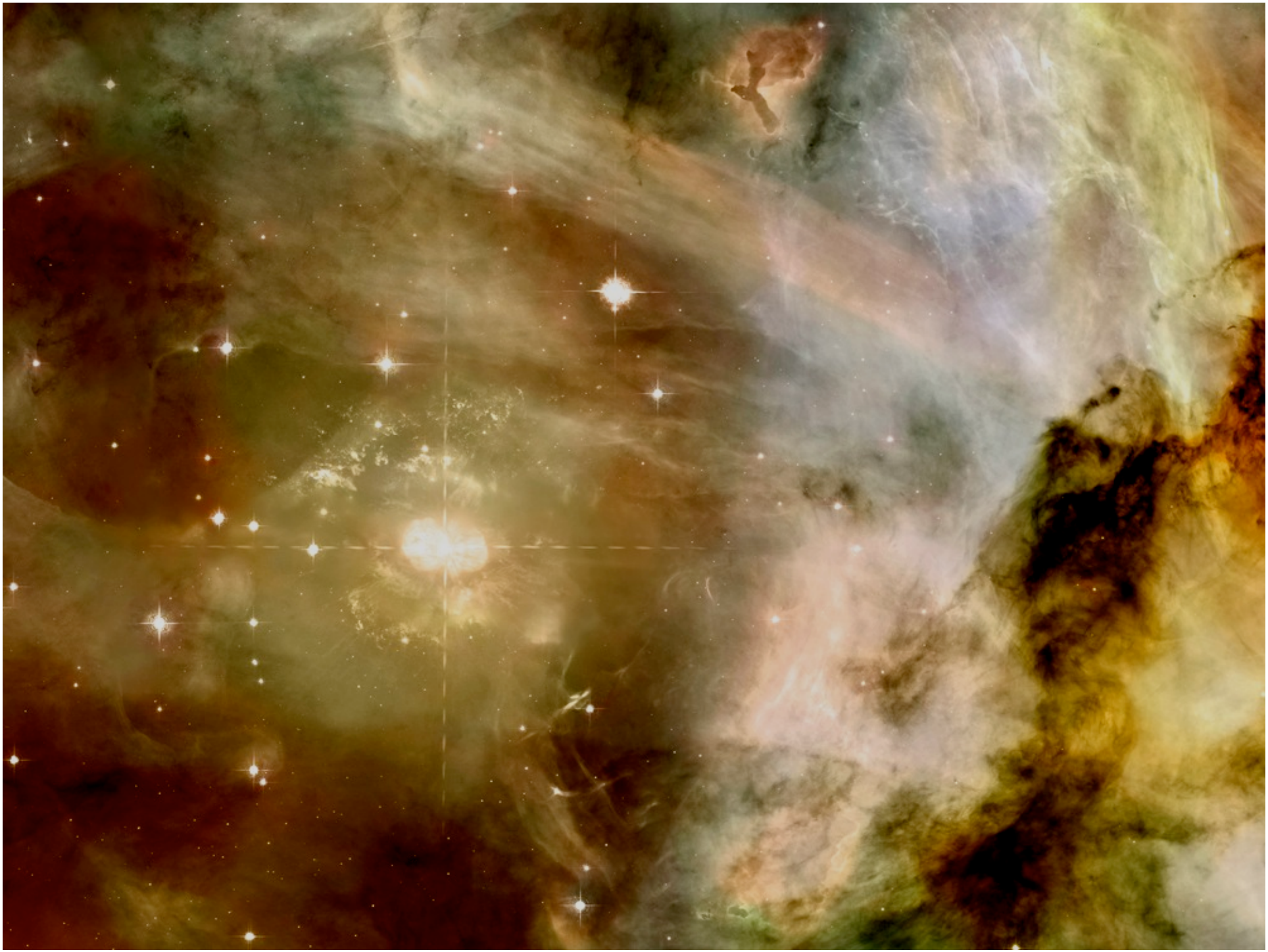
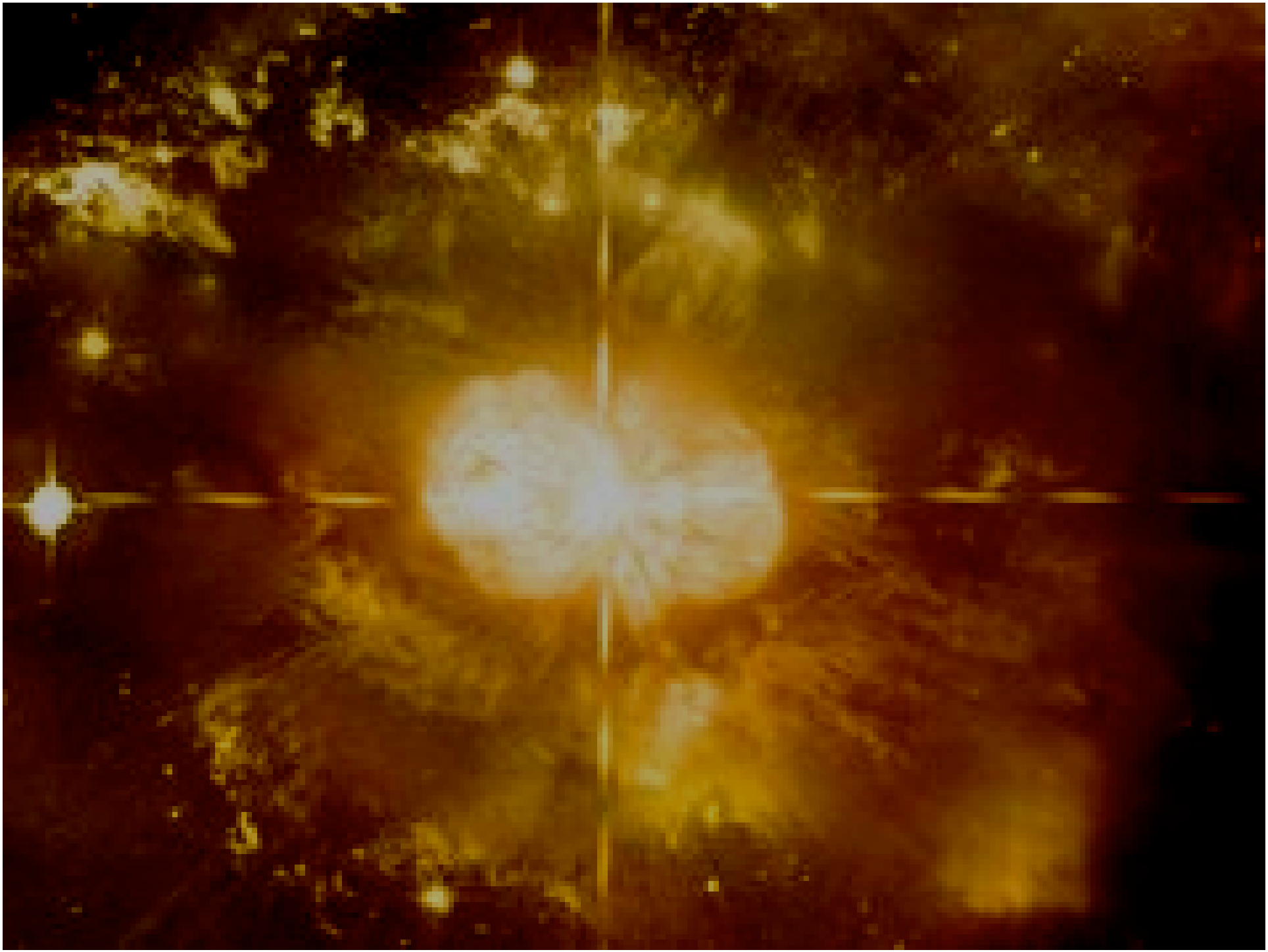
Trapezium cluster
(Muench et al. 2001)







Massive Star Formation: Observations Confront Theory (1/2)

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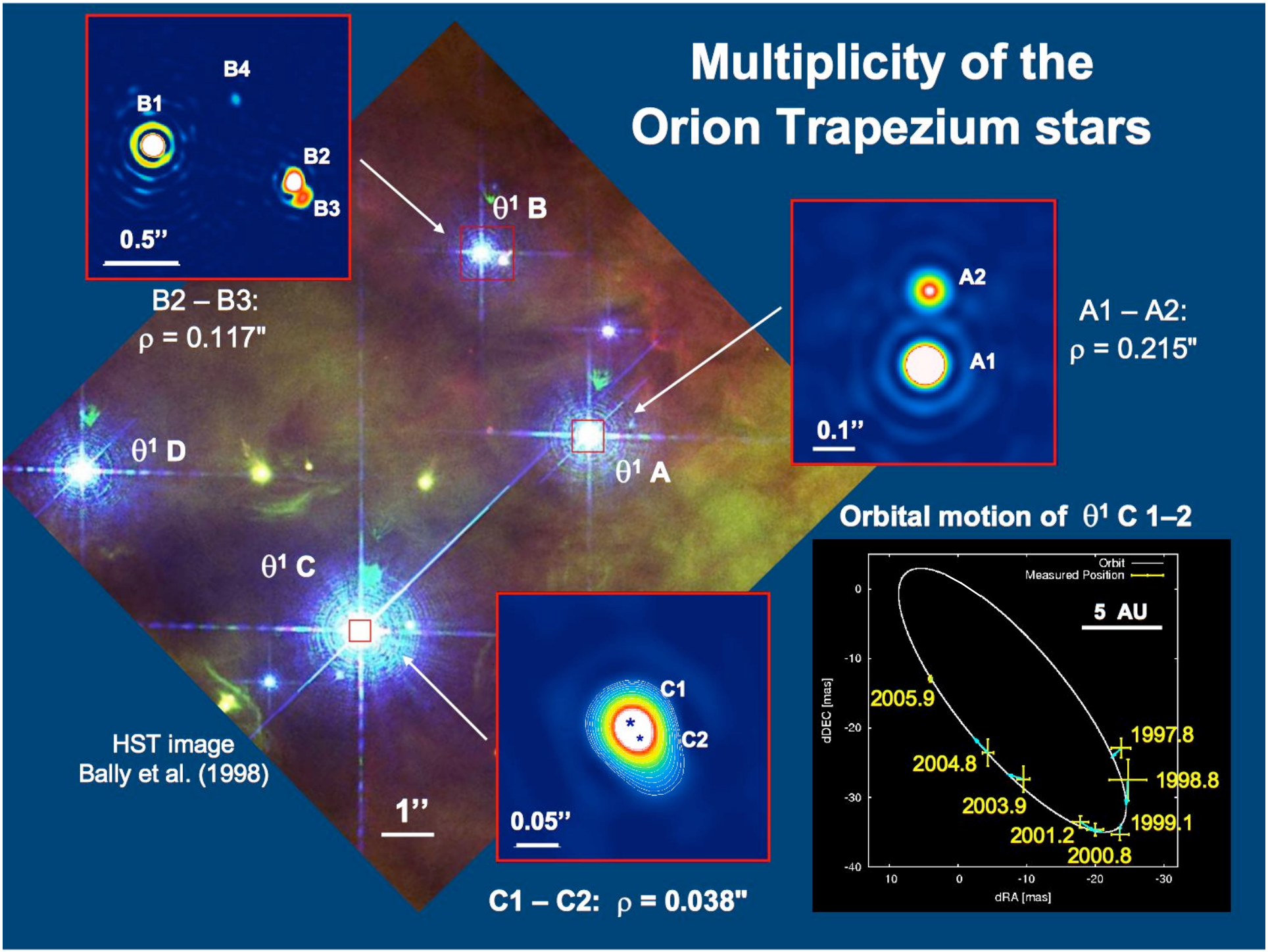
- Universality of IMF and upper mass limit
  - No clear-cut evidence of variation of slope between high mass through intermediate mass to solar-type stars
- Multiplicity, Hierarchies, Clusters, Associations
  - High mass stars generally form in clusters & associations
    - In loose OB associations (Ori OB1a,b; Sco OB2; NGC 604)
    - In dense clusters (Ori TC; NGC 3603; 30 Dor); most O-stars located in center
    - Starburst galaxies, ULIRGs
  - Higher degree of multiplicity of high mass stars than for low mass stars
    - Average number of companions ~1.5 for massive primary, whereas ~0.5 for solar-type primaries
    - O-stars have preponderance of close tight binaries with P ~ 3-5 days
    - Higher fraction of runaway O-stars than runaway B-stars
    - Reduced binarity among runaway O-stars compared to cluster O-stars

Figure 2

Hubble Space Telescope optical/IR image of the dense massive young cluster R136/30Dor (courtesy of M.J. McCaughrean; FOV ~30 arcsec × 30 arcsec or 7.5 pc × 7.5 pc). Dozens of massive O stars are found crowded within the half-light radius of 2 pc (Brandl et al. 1996). (*a*) A VLT image of NGC 3603 (Brandl et al. 1999) and (*b*) a VLT image of the Trapezium Cluster in Orion (McCaughrean 2001) are shown as these two galactic clusters would be seen if they were located at the distance of R136 in the Large Magellanic Cloud (50 kpc) and imaged with similar angular resolution (see Zinnecker 2002).

from Zinnecker & Yorke (2007) ARAA

Multiplicity of the Orion Trapezium stars



Massive Star Formation: Observations Confront Theory (2/2)

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- Characteristics of OB-star forming regions
  - Hot molecular cores in GMCs
  - Hypercompact and Ultracompact HII regions
  - Masers (OH, H_2O, SiO, CH_3OH) - in disks or in outflows?
  - Both wide-angle and collimated flows observed: jets and outflows
  - Cometary proplyds, pillars, mountains
  - Turbulence observed; enough to support clumps and cores?
- No disk around an optically visible main sequence O-star found
  - Disks around B-stars have been observed
  - There is indirect evidence of disks in early phases: collimated outflows
- There are massive molecular cores or clumps without outflows
  - There are hot cores without outflows and without radio continuum
- Some magnetic field measurements; when measurable sub/super-critical within factor 2
  - Θ1 Ori C is a magnetic star!

More on the Global Picture

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- Assume: $dN = A\, m^{-a}\, dm$ with a=2.35 (Salpeter) between m=0.1 and m=100
  - Average mass <m> = 0.35
- There is one >50 $M_{\textbf{O-star}}$ for every 7300 stars formed
- In MWG: 2 SN/100 yr (m > 8) => 8 stars/yr formed
  - 3 M_o/yr converted into stars
  - Every 50 yr produce >8 $M_{\textbf{O-star}}$
  - Every 200 yr produce >20 $M_{\textbf{O-star}}$
  - Every 400 yr produce >30 $M_{\textbf{O-star}}$
  - Every 1000 yr produce >50 $M_{\textbf{O-star}}$

Molecular Cloud Lifetime, SF Efficiency, Total Molecular Mass (1/3)

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Assume:

- 10^{10} M_o ISM, of which 40% is molecular
- 10^7 yr lifetime of molecular clouds

=> 400 M_o/yr of molecular cloud material must be dissipated and 400 M_o/yr must be newly formed

Star formation efficiency = 3/400 = 0.75%

Molecular Cloud Lifetime, SF Efficiency, Total Molecular Mass (2/3)

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Assume:

- 400 M_o/yr of molecular cloud material must be dissipated

Use >30 M_o O-stars, of which you have ~8000 in MWG

⇒ Each O-star must dissipate 0.05 M_o/yr

Champagne flows driven by O5-stars can dissipate 0.01 M_o/yr (Yorke 1986 ARAA)

Molecular Cloud Lifetime, SF Efficiency, Total Molecular Mass (3/3)

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Assume

- 10^{10} M_o ISM, of which 40% is molecular
- Star Formation efficiency of 50%

3 M_o/yr of molecular cloud material will be dissipated and 6 M_o/yr must be newly formed

Lifetime of molecular material: $4x10^9/6= 7x10^8$ yr

=> at least some molecular material is long-lived

Is there a hidden Component of H_2?

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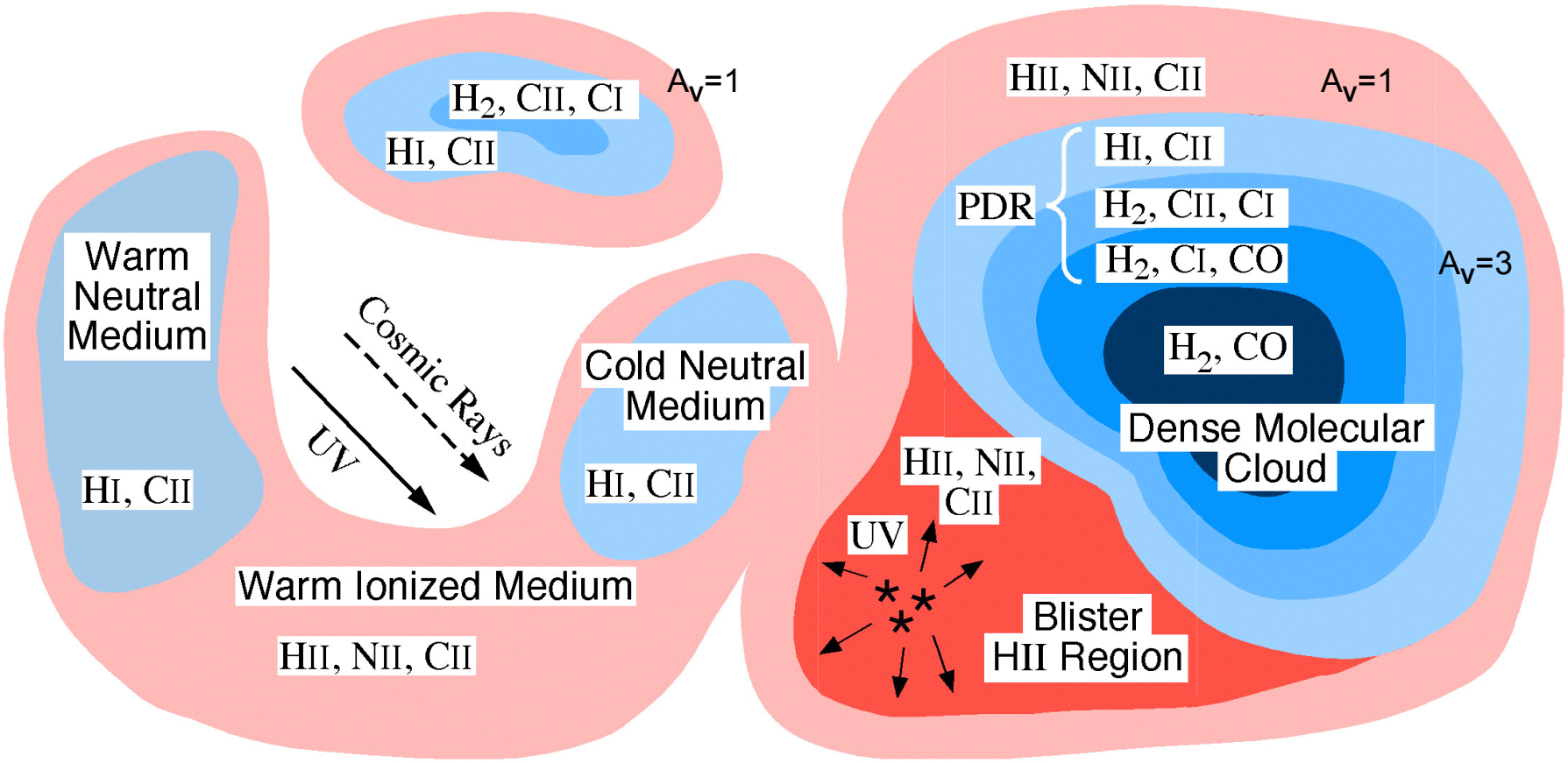

Steps to produce Massive Stars

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- Create Giant Molecular Cloud Complexes ~10-100 pc
- Create molecular cloud clumps ~1 pc and cores ~0.1 pc
- Initiate collapse of cores/filaments ~0.1 pc
- Fragment into several sub-clumps ~0.01 pc
- Create first hydrostatic cores ~1 R_o = 2.3 x 10^{-8} pc
- Accrete onto hydrostatic cores through disks, allowing them to grow in mass
  - Accretion Disks ~10^{-3} pc
  - Accretion columns << 10^{-8} pc
- Hydrostatic cores evolve quickly to H-burning, even while accreting
- Remnant disks quickly dissipate as accretion halts

? yr

200,000 yr

350 μm Cores in the Orion Region

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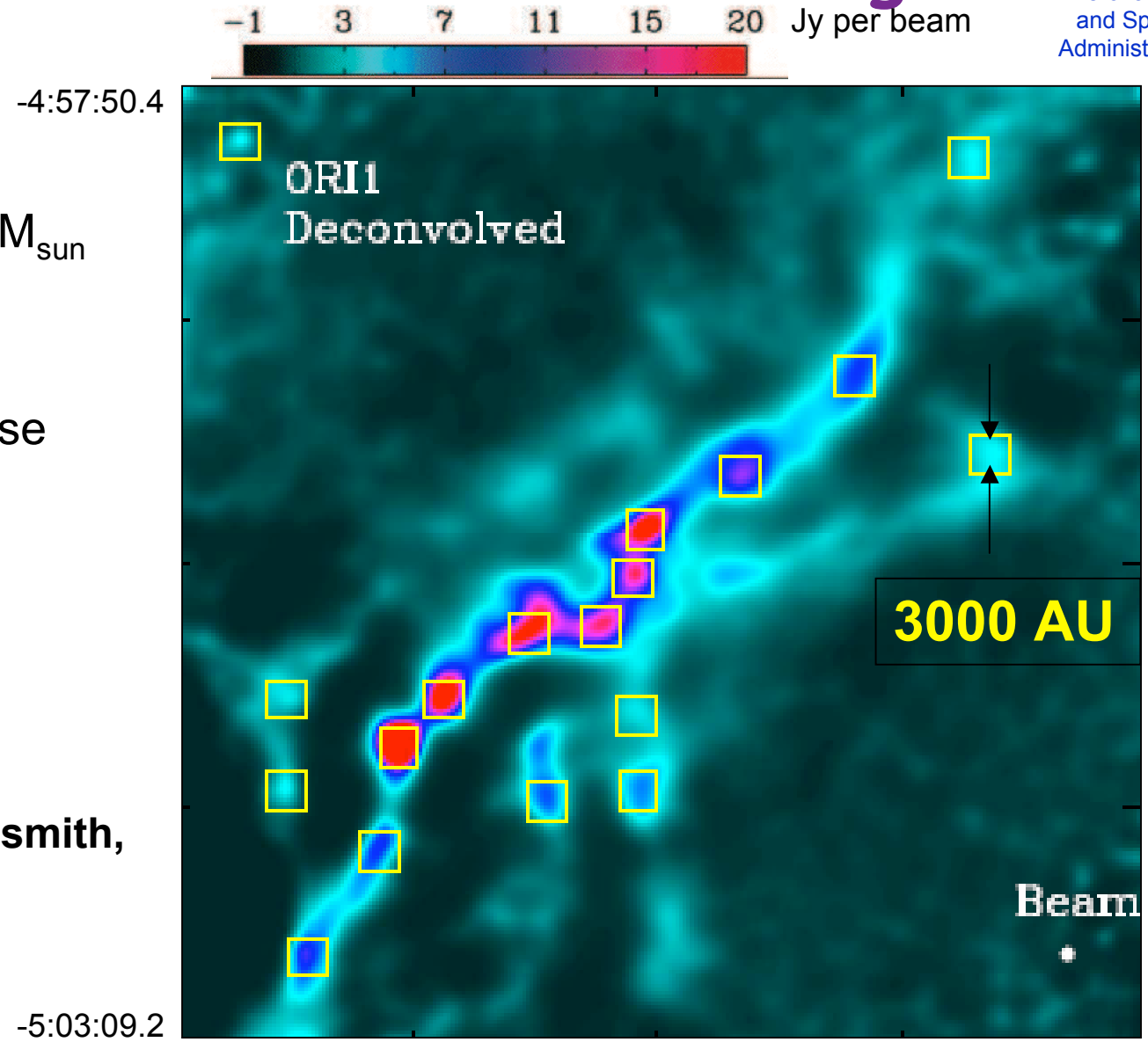
51 cores 0.1 to 46 M_{sun}

Many appear to be unstable against gravitational collapse



Li, Velusamy, Goldsmith, & Langer (2007)

Important relevant time scales

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- Free-fall time scale

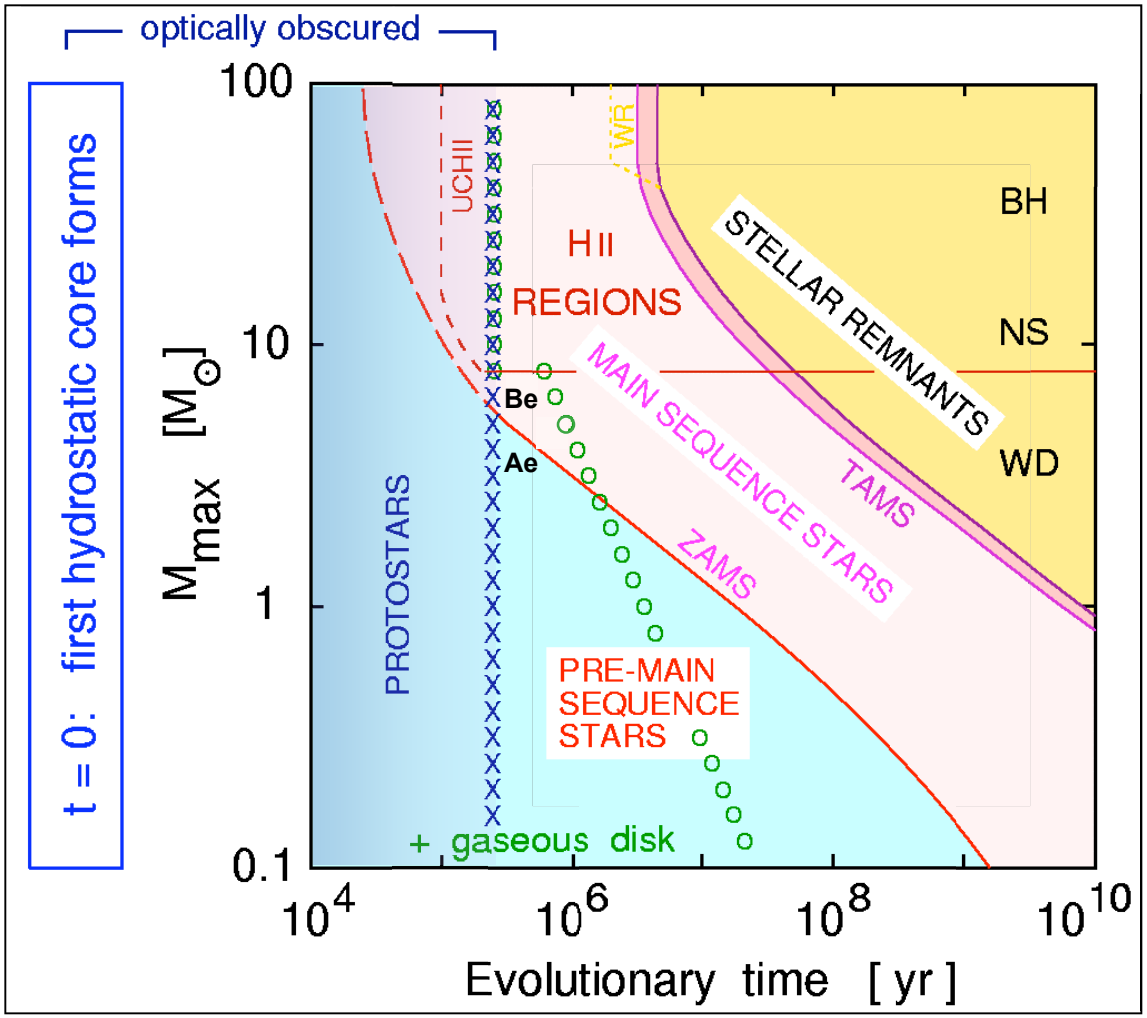
$$t_{\rm ff} \simeq 10^5\,{\rm yr}\left[\frac{n}{10^5\,{\rm cm}^{-3}}\right]^{-1/2}$$

- Accretion time scale

$$t_{\rm acc} \simeq t_{\rm ff}$$

- Kelvin-Helmholtz time scale (time to reach ZAMS)

$$\tau_{\rm KH} = \frac{GM^2/R}{L} \sim M^{-2}$$



Important relevant length scales

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- Size of clump to produce star of mass M

$$R_{\rm clump} \simeq 0.1\ {\rm pc} \left[\frac{M}{30\ {\rm M}_\odot}\right]^{1/3} \left[\frac{n}{10^5\ {\rm cm}^{-3}}\right]^{-1/3}$$

- Photoevaporation radius

$$r_{\rm evap} \simeq 130\ {\rm AU} \left[\frac{M}{30\ {\rm M}_\odot}\right]$$

- Dust destruction radius

$$r_{\rm dust} \simeq 25\ {\rm AU} \left[\frac{L}{1.5 \cdot 10^5\ {\rm L}_\odot}\right]^{1/2}$$

$$r_{\rm dust} \simeq 25\ {\rm AU} \left[\frac{M}{30\ {\rm M}_\odot}\right]^{1.6}$$

- Stellar radius

$$R_* \simeq 12\ {\rm R}_\odot \left[\frac{M}{30\ {\rm M}_\odot}\right]^{0.8}$$

Competitive Accretion?

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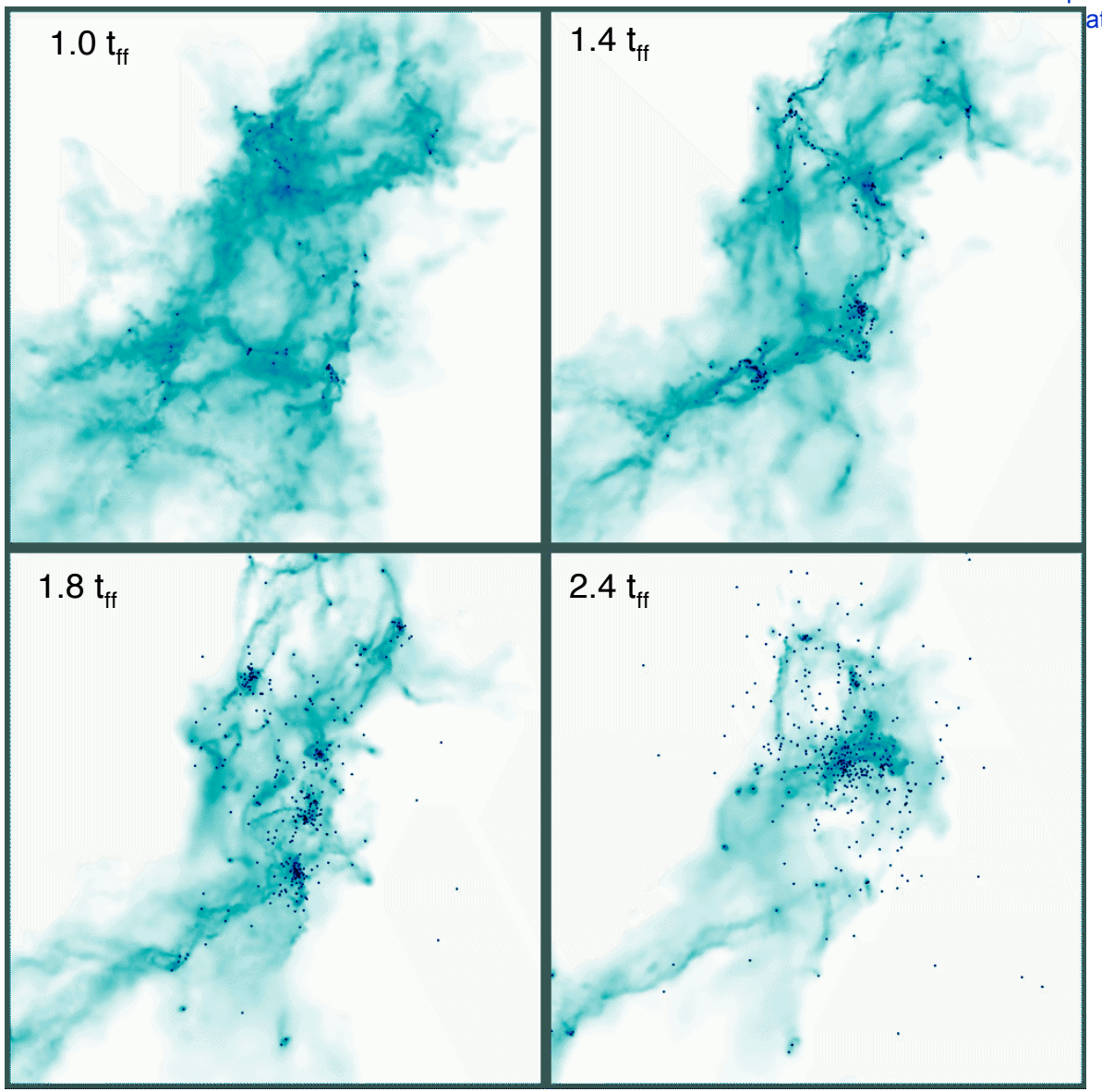
Time-dependent evolution of a turbulent, self-gravitating 1000-M_{sun} cloud showing the formation of sheets, filaments, and cores, the latter of which become gravitationally unstable. Newly formed stars are shown in dark blue, the gas is shown in blue-green. Stars tend to cluster, and they continue to accrete material in competition with other stars. Times shown are 1.0, 1.4, 1.8, and 2.4 initial free-fall times (t_{ff}), from left to right and top to bottom. [Adapted from Bonnell, Bate & Vine (2003)].



Accretion and mass loss as mass exchange between components

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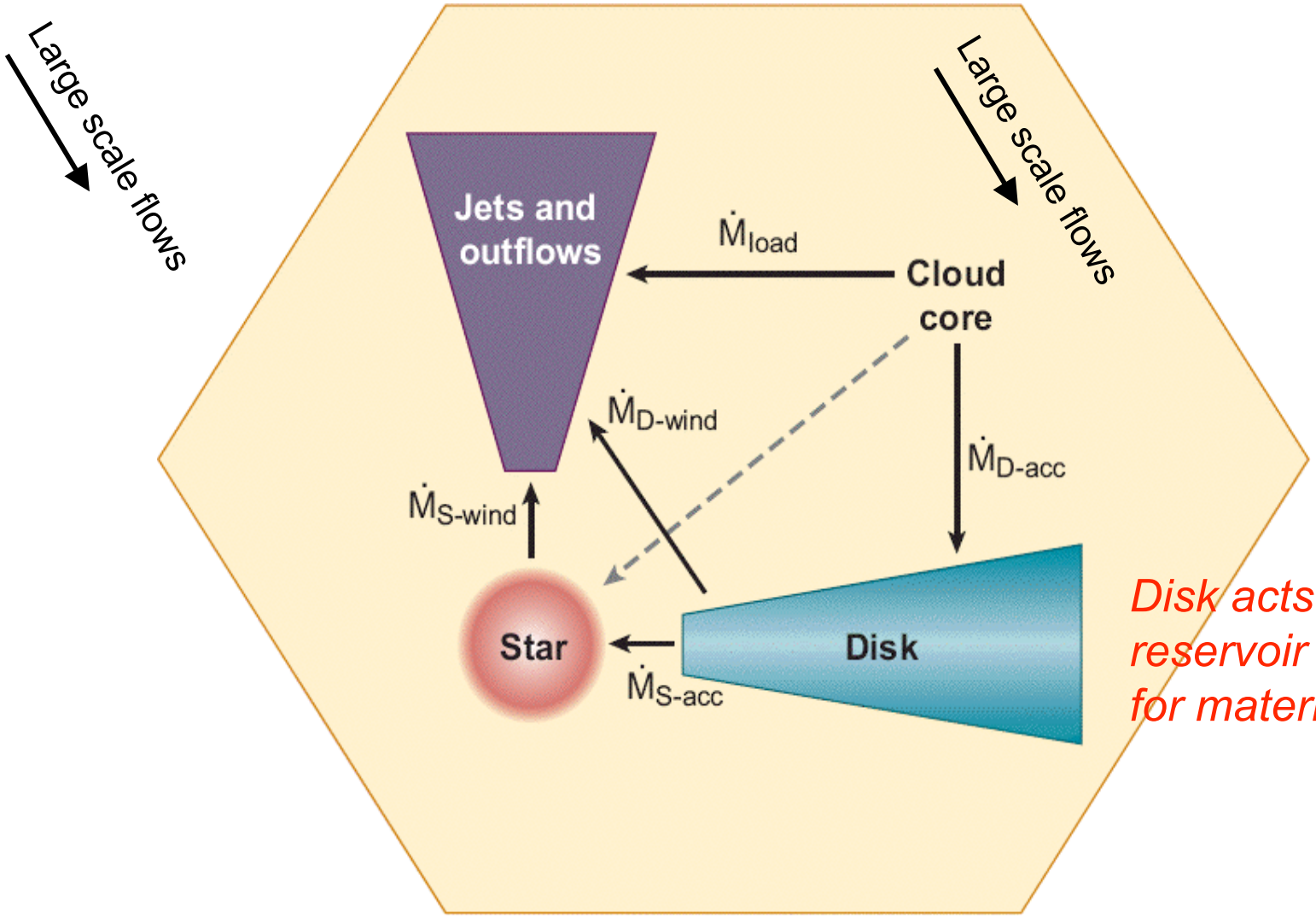

Disk acts as reservoir for material

What determines these dM/dt's?

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- $\dot{M}_{disk}$ related to angular momentum transport within disk
  - Magnetic fields
  - Tidal effects (bars, spiral arms)
  - Turbulence (photon bubbles: Turner, Quataert, Yorke 2007)
- $\dot{M}_{acc}$ determined by cloud core parameters, competitive accretion
  - $t_{acc} \sim t_{ff} \sim t_{cross}$
- $\dot{M}_{D\text{-}wind}$ has contributions from jets and photoevaporation
  - $\dot{M}_{jet} \sim f(\dot{M}_{disk})$
  - $\dot{M}_{photoevap} \sim f(F_v)$
- $\dot{M}_{S\text{-}wind}$ related to stellar parameters

Necessary conditions for forming stars by accretion

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- The mass gained by accretion must exceed losses

$$M_* (t) = \int^t [\, \dot{M}_{disk}(t') - \dot{M}_{S\text{-}wind}(t') \,]\, dt'$$

$$M_{disk} (t) = \int^t [\, \dot{M}_{acc}(t') - \dot{M}_{disk}(t') - \dot{M}_{D\text{-}wind}(t') \,]\, dt'$$

- Must accrete material within "reasonable" time

$$\dot{M}_{acc} - \dot{M}_{S\text{-}wind} - \dot{M}_{D\text{-}wind} \sim M_* / t_{acc}$$

- Gravity must be dominant force

$$\frac{GM}{r^2} > \frac{\kappa_{\rm eff} L}{4\pi r^2\, c}\,, \qquad \text{where} \qquad L = L_* + L_{\rm acc}$$

$$\kappa_{\rm eff} < 130\ {\rm cm}^2\,{\rm g}^{-1} \left[\frac{M}{10\ {\rm M}_\odot}\right] \left[\frac{L}{1000\ {\rm L}_\odot}\right]^{-1}$$

How you form massive stars in the present epoch?

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- Reduce κ_{eff}
  - Modify optical properties of absorbing and scattering material
    - Dust destruction
    - Dust coagulation
    - Slippage of dust and gas (dust is left behind)
  - Accrete optically thick "blobs" of material $\kappa_{\rm eff} = \frac{\pi R_{\rm blob}^2}{M_{\rm blob}}$
- Reduce radiative flux
  - Accrete during quiescent phases
  - "Flashlight" effect of disks
- Increase gravity
  - Force material on star from its sheer weight (and external pressure)
  - Form massive stars within a dense cluster of not so brightly radiating objects $\rho_{\rm objects} \geq \rho_{\rm gas}$

Luminosity & Radius of ZAMS star

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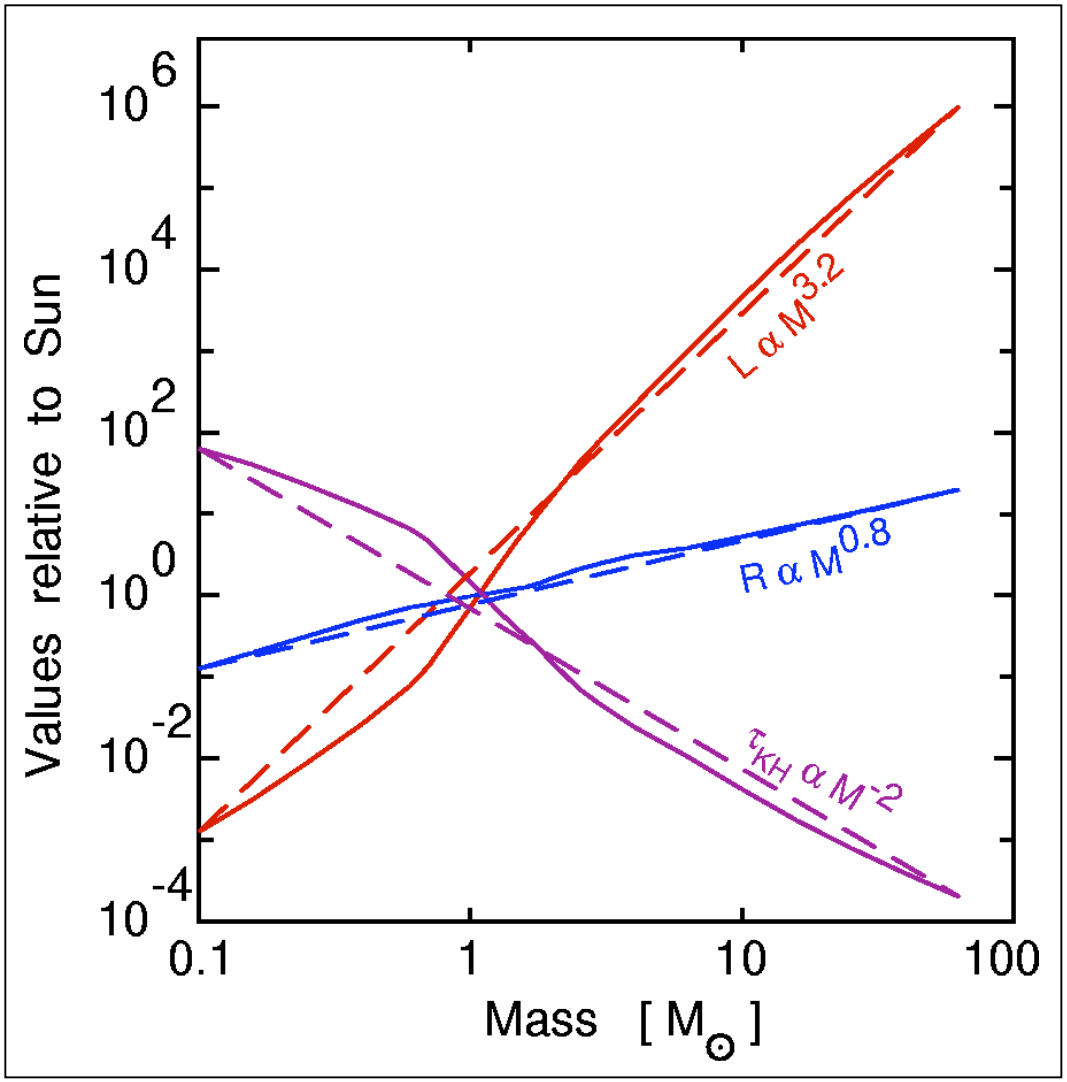
Kelvin-Helmholtz timescale
(for thermal readjustment)

$$\tau_{\rm KH} = \frac{GM^2/R}{L}$$



Accretion onto main sequence stars

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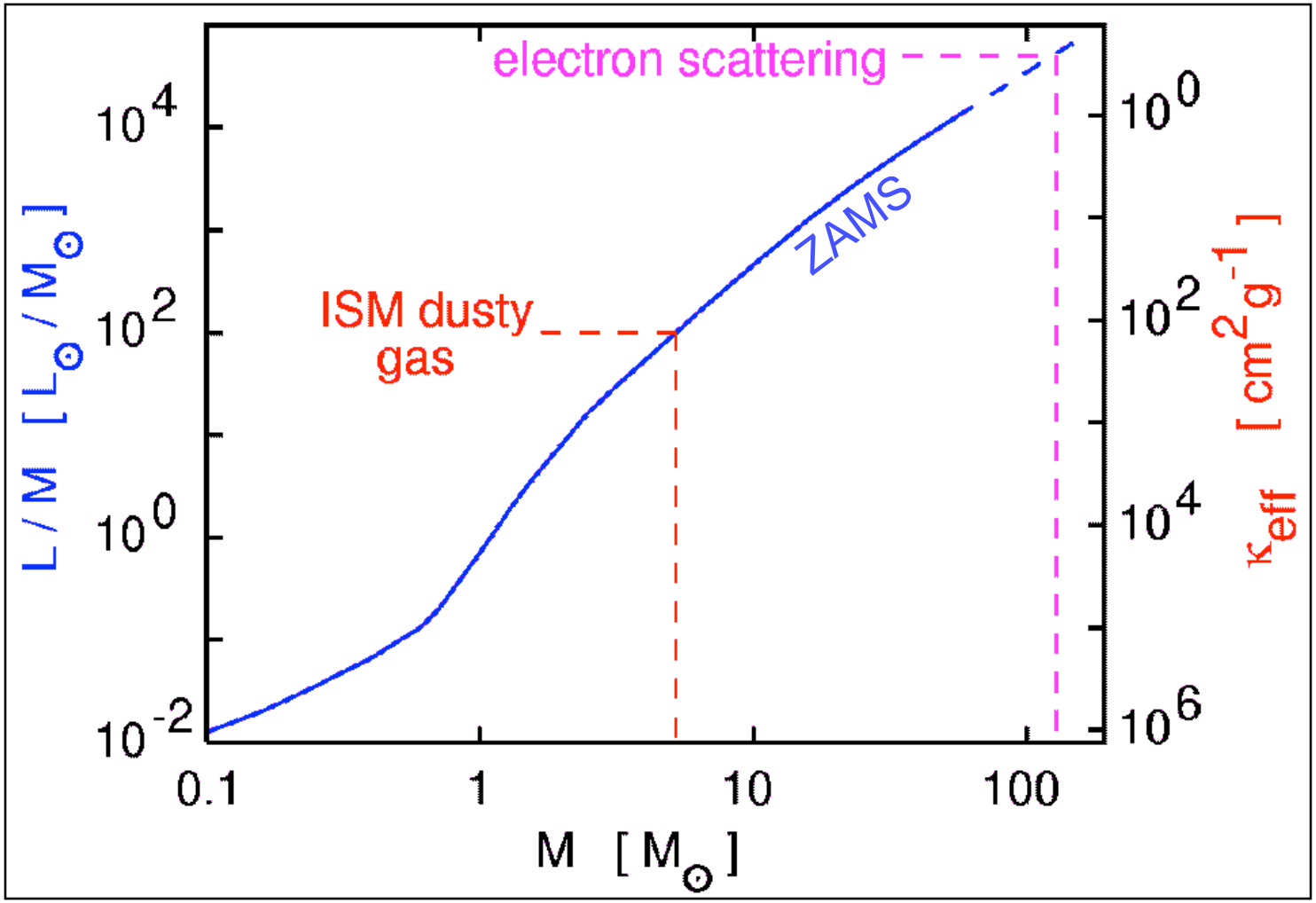

Opacity of dusty gas

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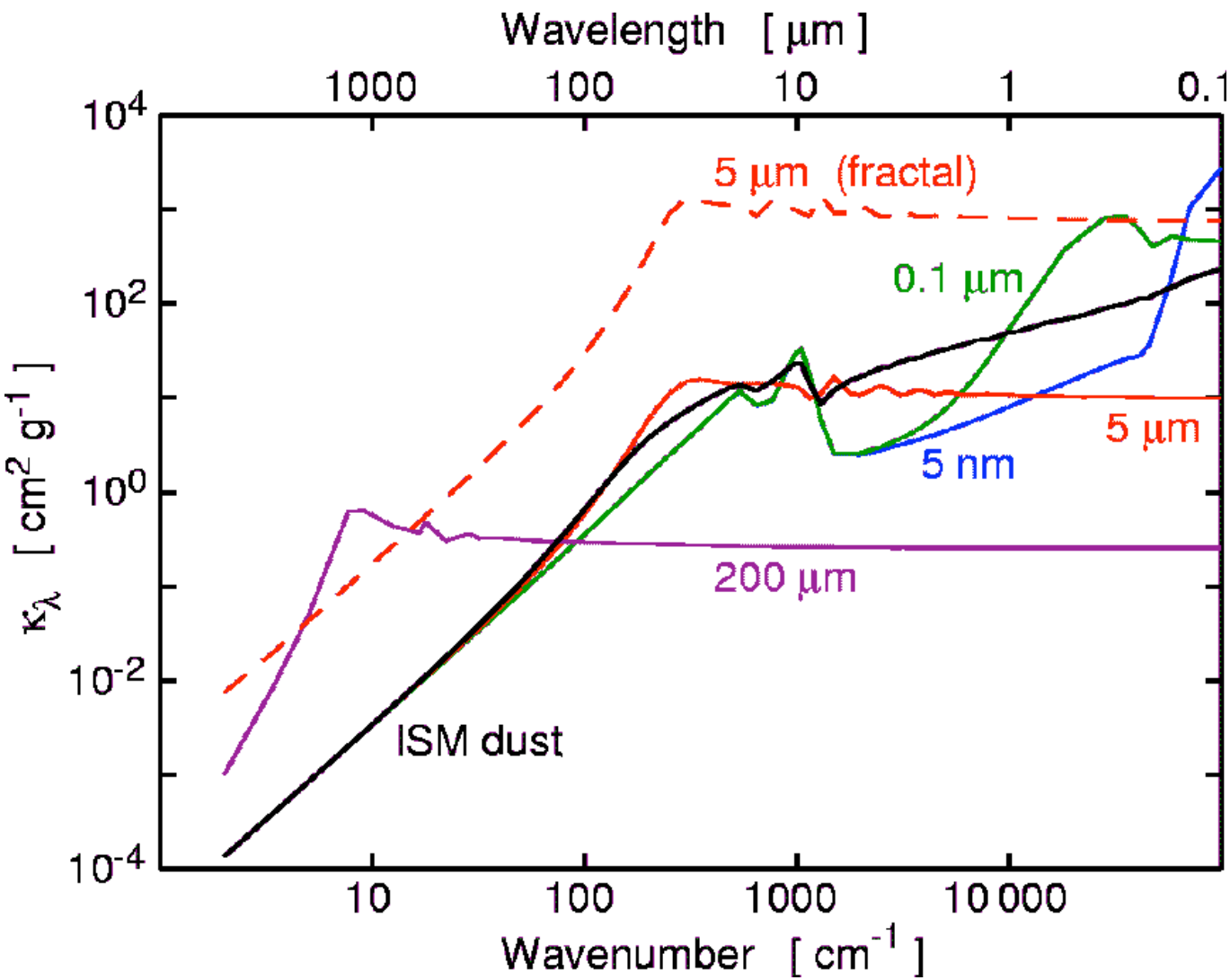

ISM Dust (mixture of silicates, SiC, carbons, ice-coated grains)

compared to

Silicates of given sizes (colored lines)

The Eddington accretion limit

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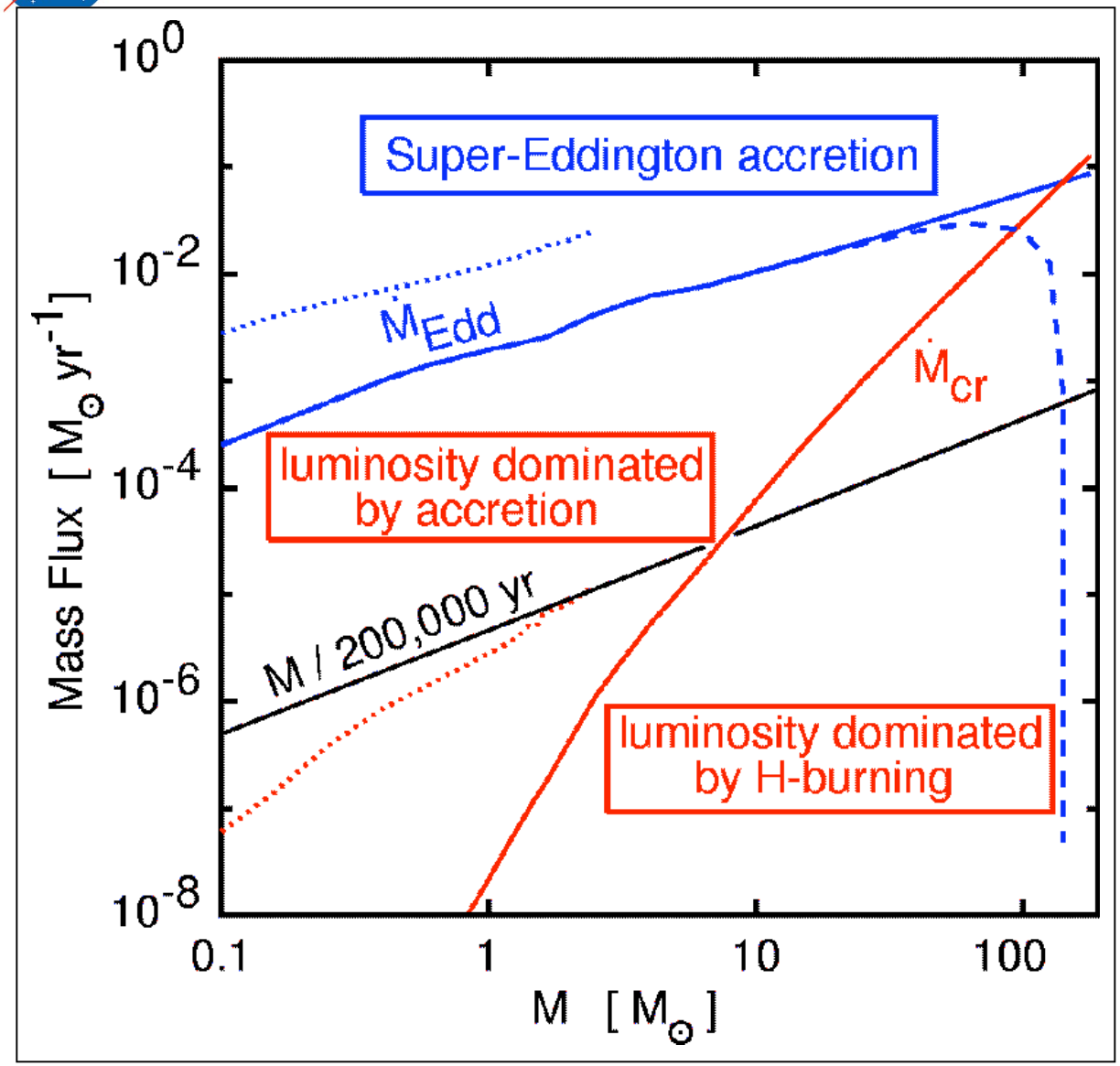

Assume electron scattering for minimum opacity…

$$\frac{\kappa_e L_{Edd}}{4\pi r^2 c} = \frac{GM}{r^2}$$

$$L_{Edd} = L_* + \frac{GM}{R}\dot{M}_{max}$$

$$\dot{M}_{max} = \frac{4\pi Rc}{\kappa_e} - \frac{RL_*}{GM}$$

$$\dot{M}_{max} = \dot{M}_{Edd} - \dot{M}_{cr}$$

How likely is it to observe high mass stars during accretion?

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Assume:

- Galactic star formation rate: 5 M_o/yr
- $t_{acc} = 2 \times 10^5$ yr
- Salpeter IMF
  - $N(M)\, dM = A\, M^{-\alpha}\, dM$
  - $0.1\, M_o < M < 100\, M_o$

Note that the local Galaxy (r < 500 pc) contains ~10^{-3} of Galactic star forming volume

=> 10^6 M_o in stars

M_* [M_o]	N_* $\alpha = 2.35$	N_* $\alpha = 2.3$
>10	5400	6300
>20	2000	2400
>30	950	1200
>50	390	480

Numerical Simulations of Physical Processes

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Collapsing Envelopes

- 2D Hydrodynamics (axial symmetry)
- 2D Radiation transport of non-ionizing radiation ("grey" FLD approximation) => dust temperature
- Self gravity
- Angular momentum transport (Shakura-Sunyaev "alpha")
- Evolution of central protostar in HRD
- Time dependent heating/cooling of gas
- No evolution of the dust (coagulation/cratering/shattering)
- No magnetic fields

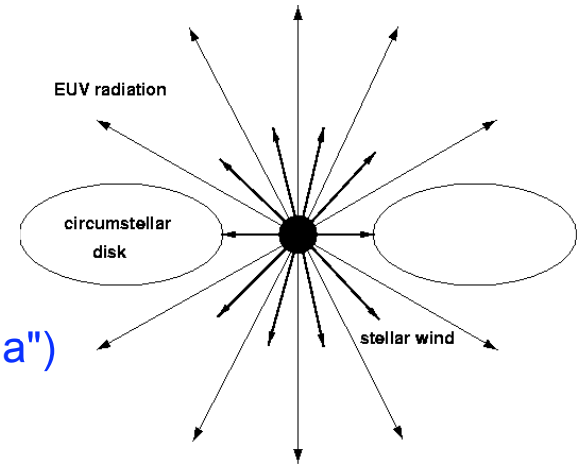
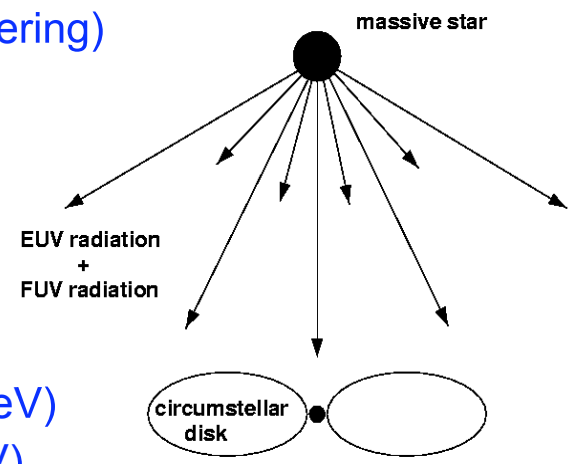


Photo-ionized Envelopes

- Central stellar wind + UV
- Time dependent ionization/recombination
- Transport of stellar EUV photons ($h\nu$ > 13.6 eV)
- Transport of stellar FUV photons (6 eV < $h\nu$ < 13.6 eV)
- Transport of H-recombination photons ($h\nu$ ~ 14.2 eV)
- Transport of UV photons scattered by dust



Emission from Star Forming Regions

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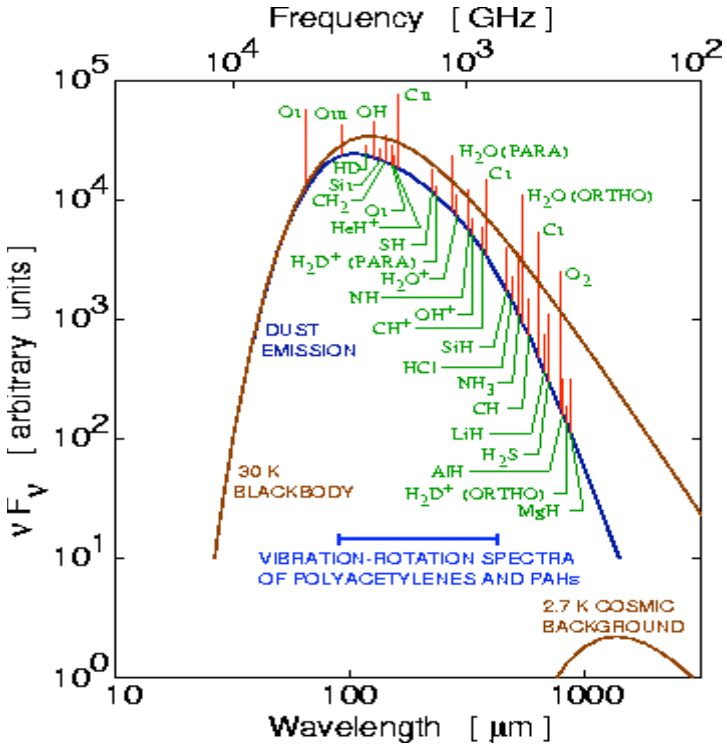
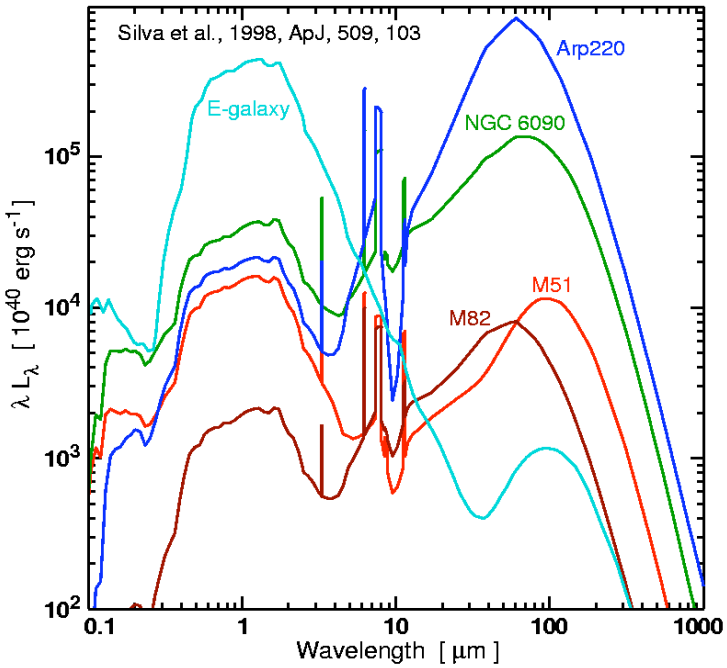


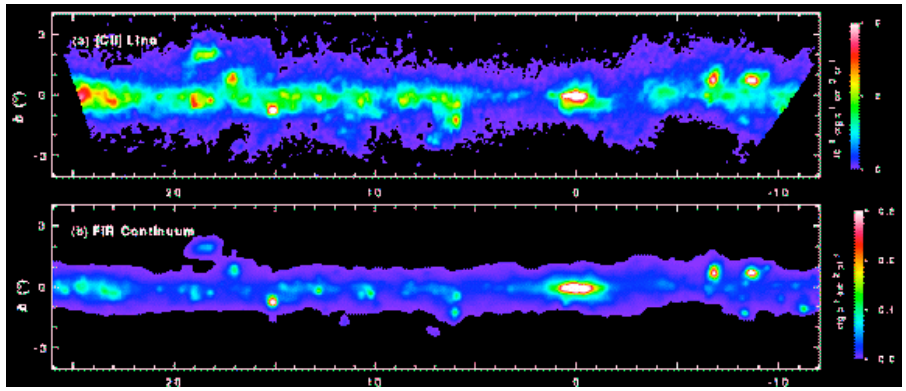
Dusty galaxies emit mostly in the far-IR.

These wave-lengths probe their star formation properties and evolution



Emission from a star forming region (~70K) with spectral lines imposed on the dust continuum.

CII at 158 μm, the strongest cooling line in the ISM. BICE Galactic maps of CII at very low spectral resolution (top) and dust emission (bottom).



Modeling Protostar + Disk Formation

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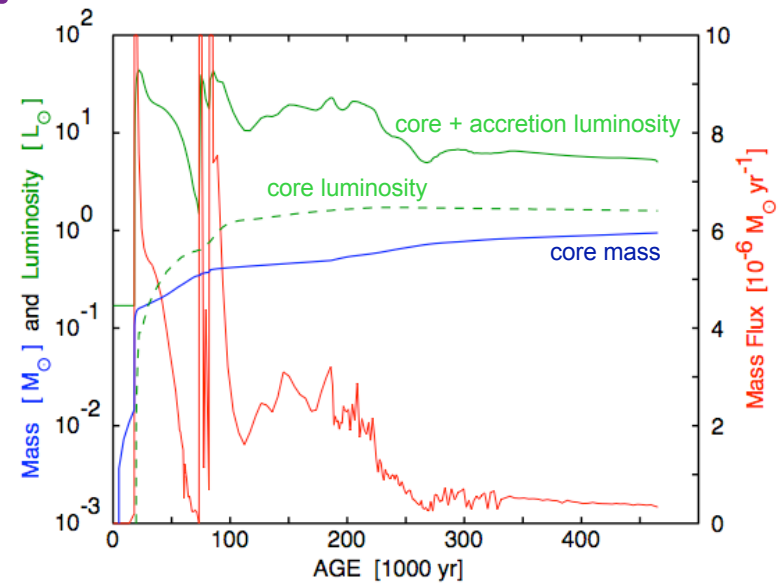

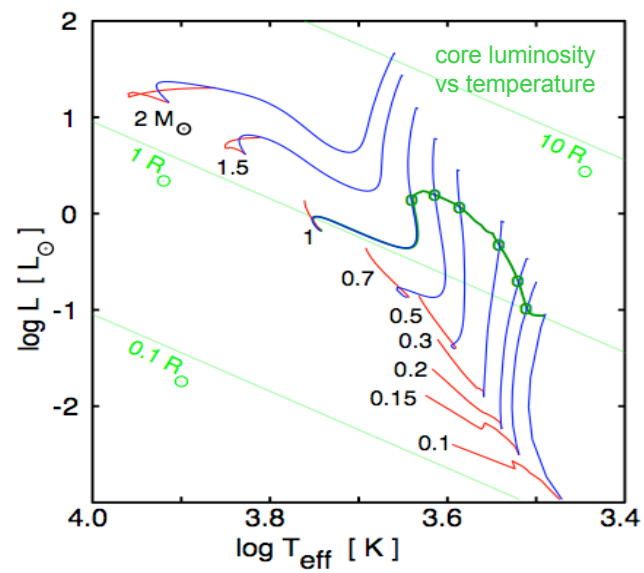

Modeling Protostar + Disk Formation

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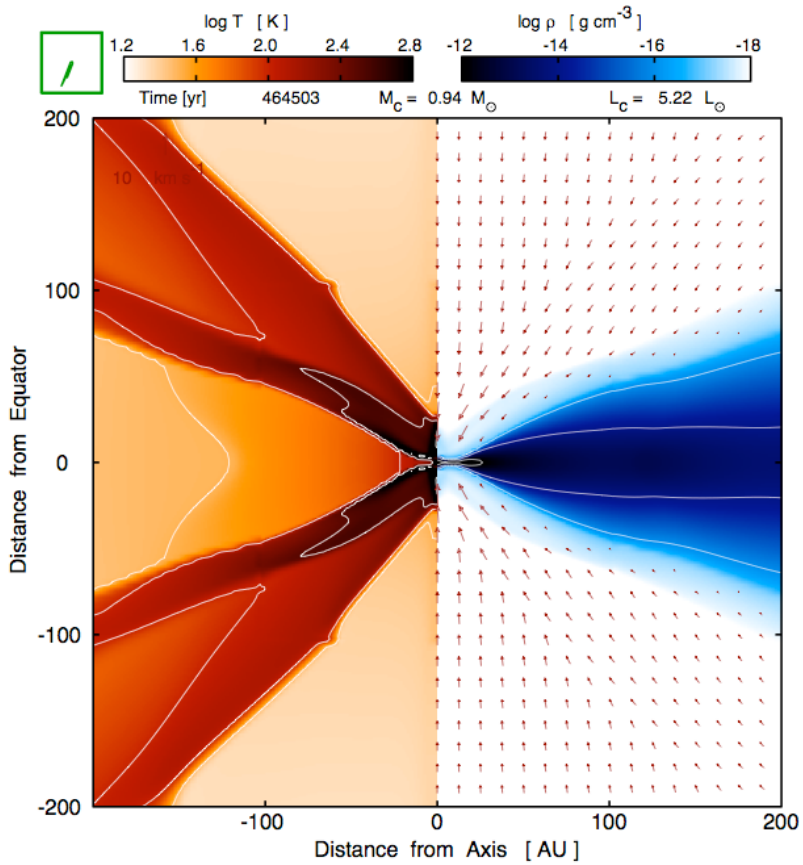

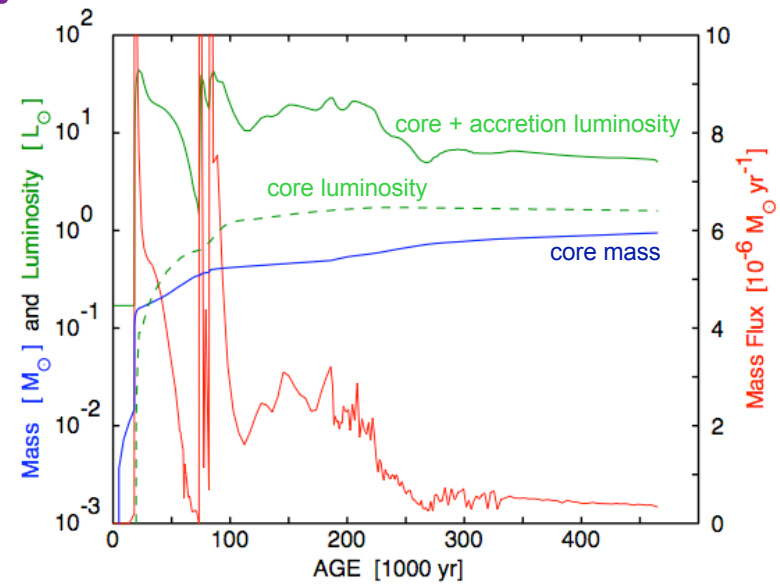

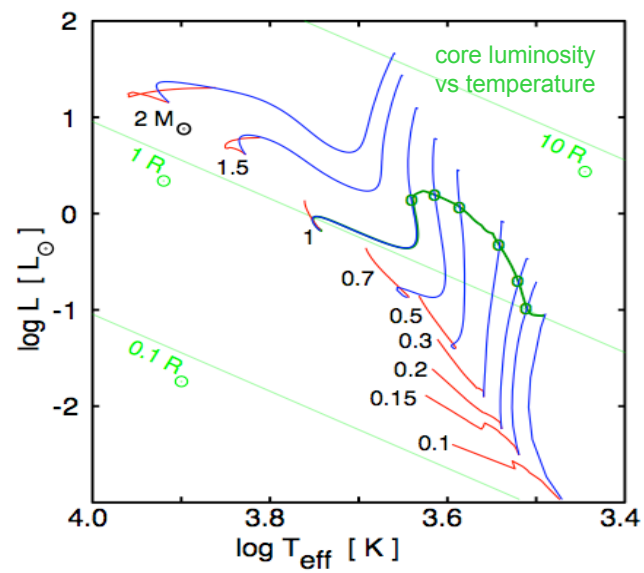

Modeling Protostar + Disk Formation

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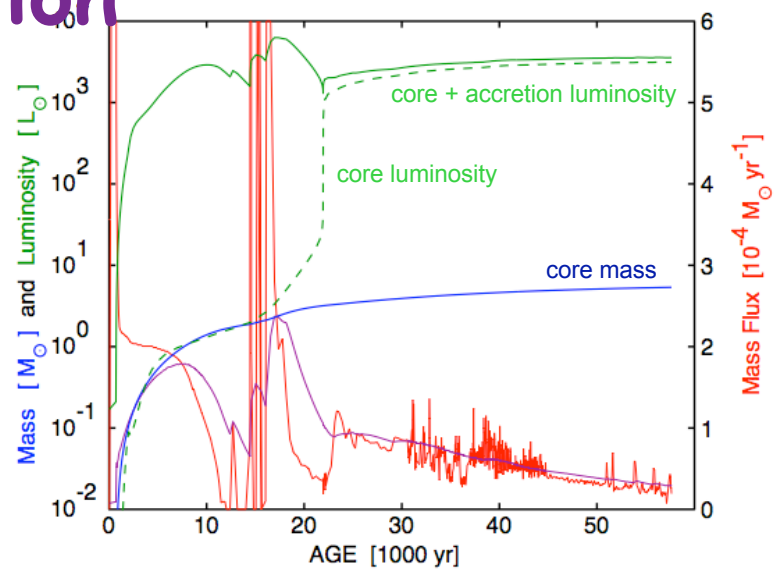

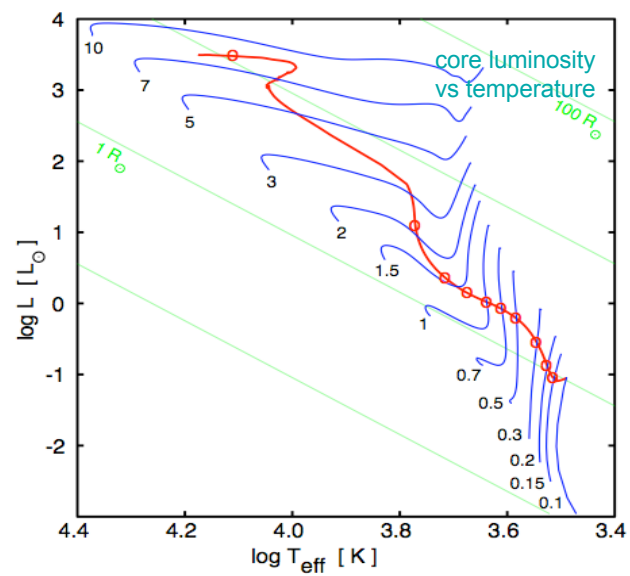

Modeling Protostar + Disk Formation

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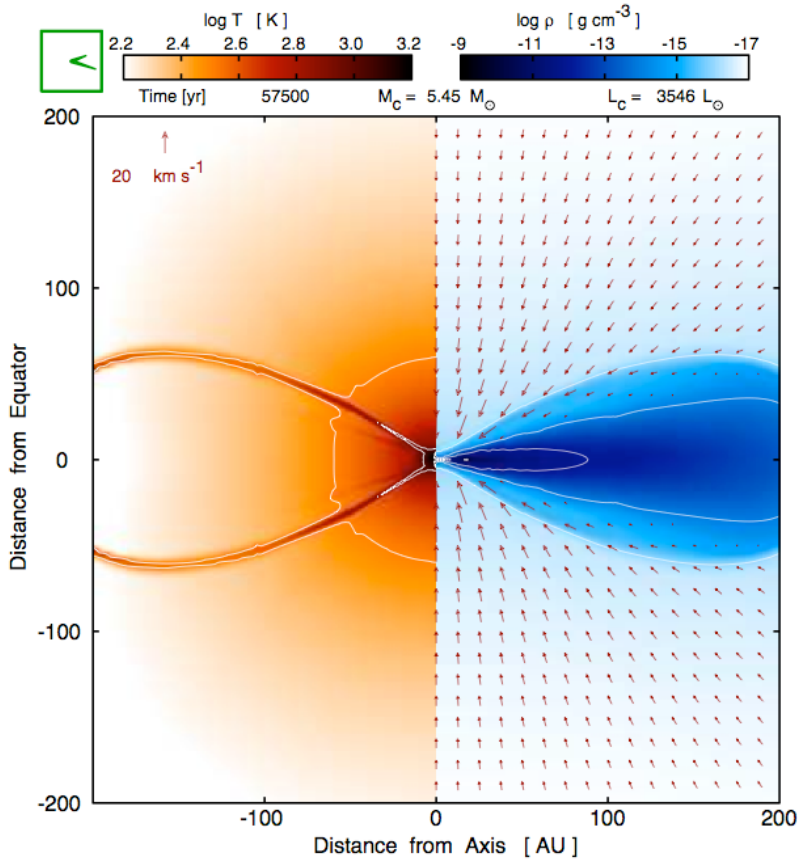

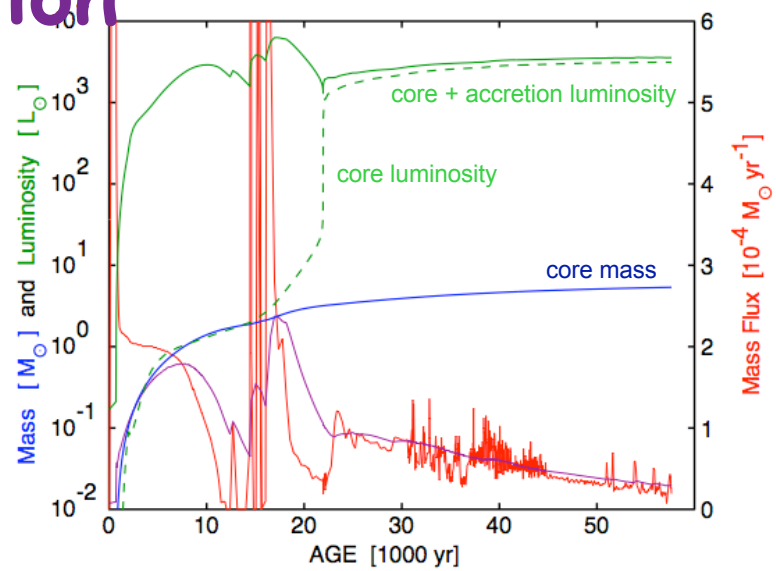

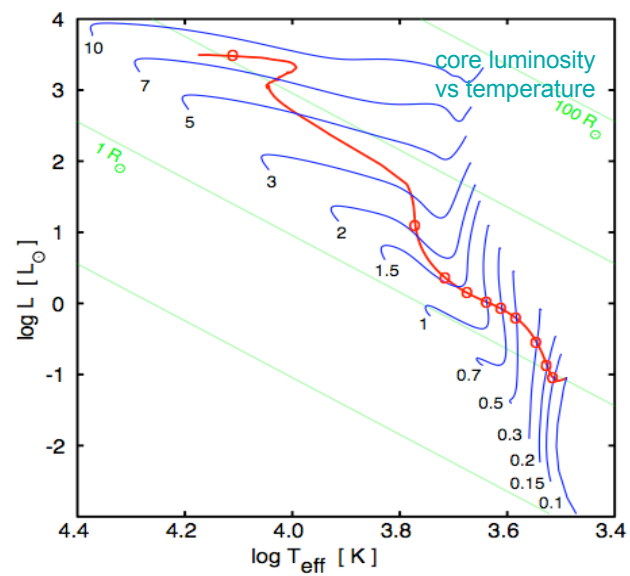

Spectral Energy Distributions

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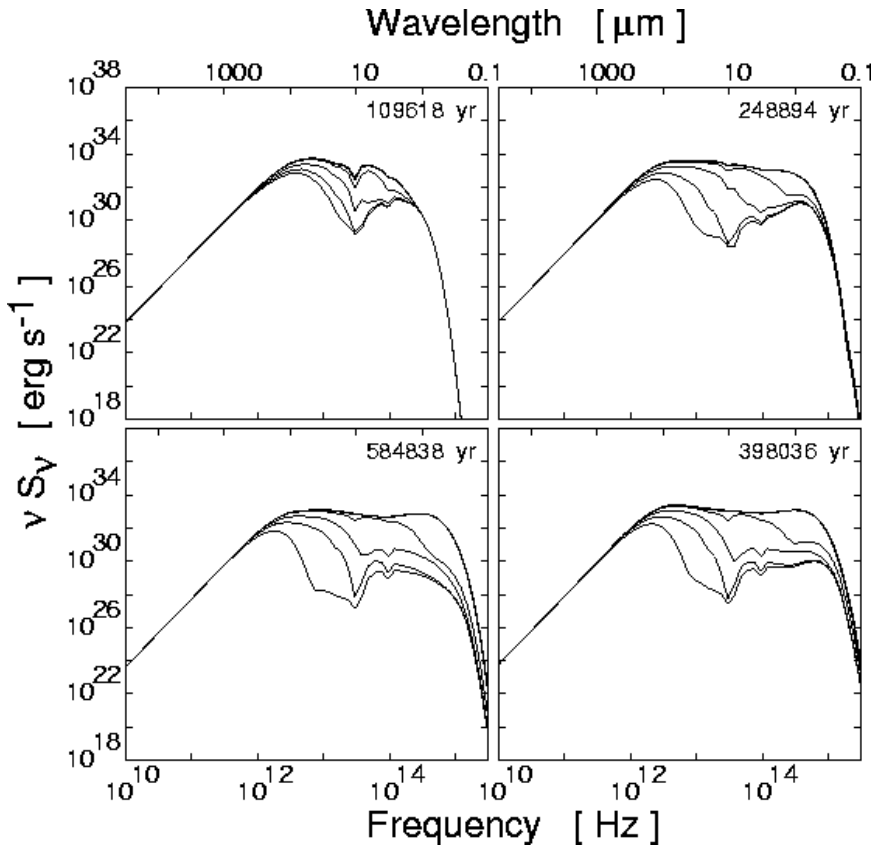
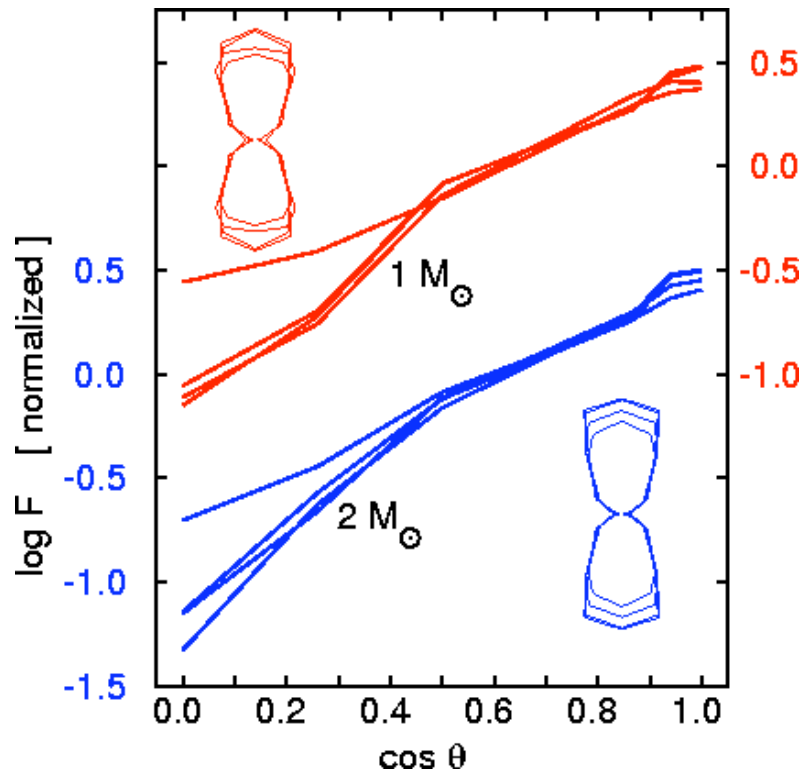


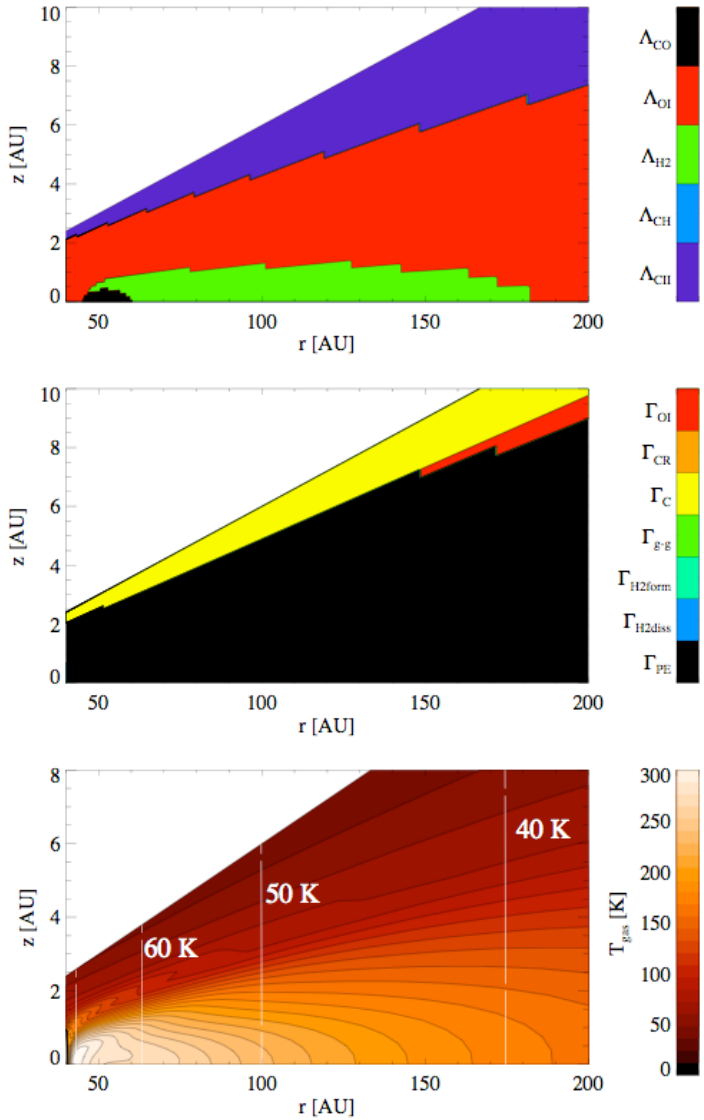
SEDs as a function of time and orientation (0º, 30º, 45º, 60º, 90º from pole-on view)



The "flashlight" effect: bolometric luminosity as a function of orientation

Using Line Emission to Resolve Internal disk Structure

National Aeronautics and Space Administration



A RESOLVED MOLECULAR GAS DISK AROUND THE NEARBY A STAR 49 CETI

A. M. Hughes [1], D. J. Wilner [1], I. Kamp [2], M. R. Hogerheijde [3]

Accepted for publication in ApJ: March 20, 2008

ABSTRACT

The A star 49 Ceti, at a distance of 61 pc, is unusual in retaining a substantial quantity of molecular gas while exhibiting dust properties similar to those of a debris disk. We present resolved observations of the disk around 49 Ceti from the Submillimeter Array in the J=2-1 rotational transition of CO with a resolution of 1.0×1.2 arcsec. The observed emission reveals an extended rotating structure viewed approximately edge-on and clear of detectable CO emission out to a distance of ∼ 90 AU from the star. No 1.3 millimeter continuum emission is detected at a 3σ sensitivity of 2.1 mJy/beam. Models of disk structure and chemistry indicate that the inner disk is devoid of molecular gas, while the outer gas disk between 40 and 200 AU from the star is dominated by photochemistry from stellar and interstellar radiation. We determine parameters for a model that reproduces the basic features of the spatially resolved CO J=2-1 emission, the spectral energy distribution, and the unresolved CO J=3-2 spectrum. We investigate variations in disk chemistry and observable properties for a range of structural parameters. 49 Ceti appears to be a rare example of a system in a late stage of transition between a gas-rich protoplanetary disk and a tenuous, virtually gas-free debris disk.

Subject headings: astrochemistry — circumstellar matter — planetary systems: protoplanetary disks — stars:individual (49 Ceti)

Envelopes of accreting Stars

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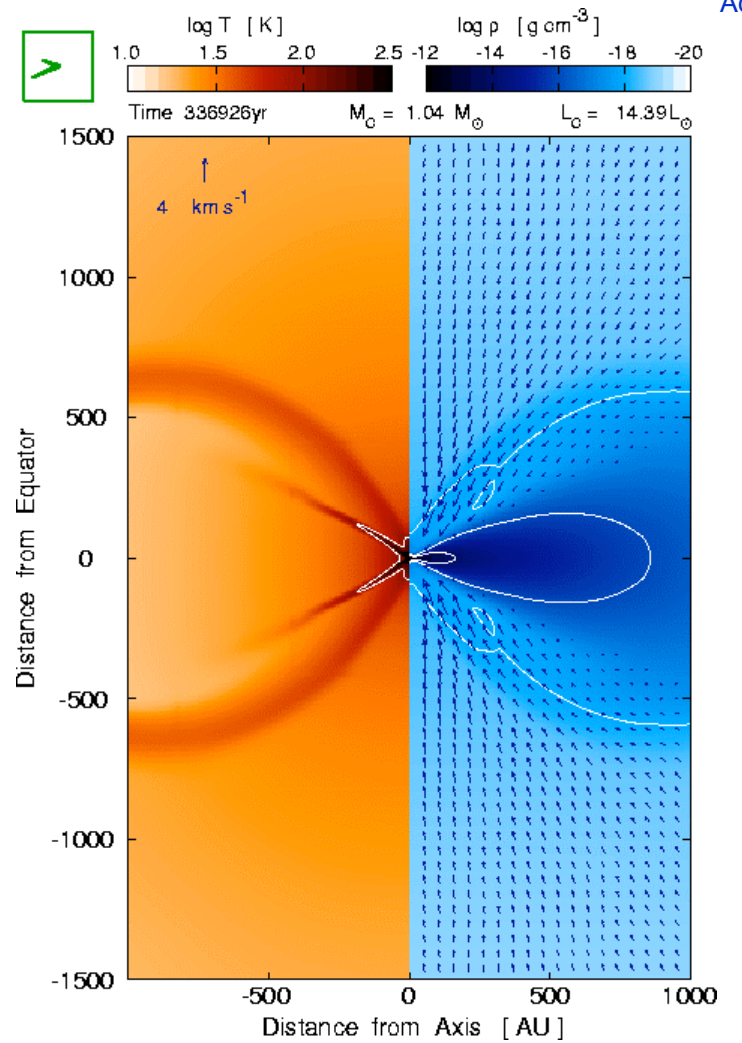
Yorke & Bodenheimer 1999

- 2 M_o cloud, diameter 0.13 pc
- $\langle n_{H2} \rangle = 3\ 10^4\ cm^{-3}$, T = 10 K
- $n_{H2} = A\ r^{-2}$ (density peaked)
- $\Omega = 5\ 10^{-14}\ s^{-1}$, $v_{rot} = 10$ m/s



Formation of a $1M_o$ Star with accretion disk

Accretion during quiescent phases

(Suttner et al. 1999, ApJ, 524, 857)

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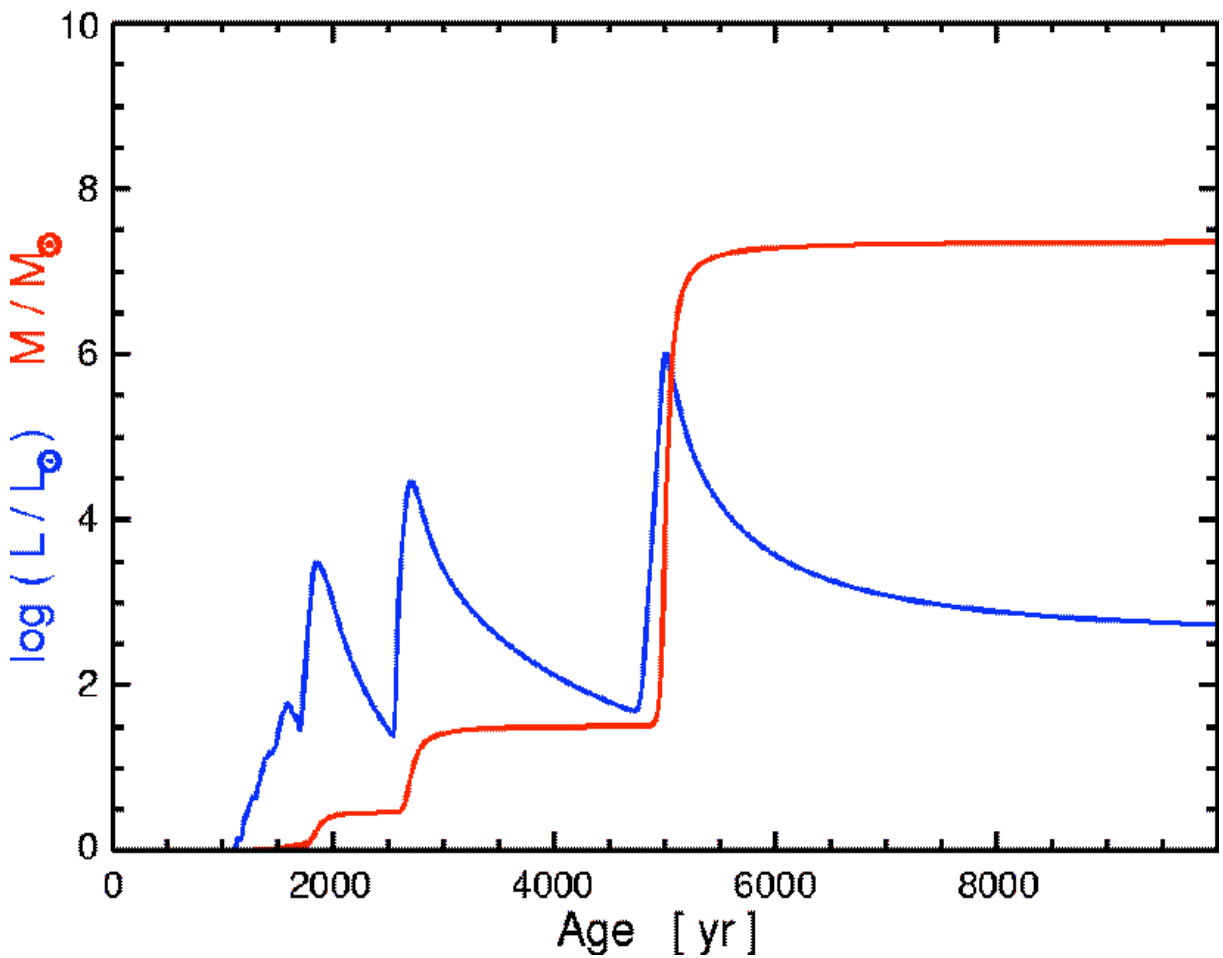

10 M_o case

Time dependent spherical (1-D) accretion + grain coagulation, cratering, and shattering

⇒ Episodic accretion

M_{final} = 7.4 M_o

Time dependent accretion through disk

(Yorke & Sonnhalter, 2002, ApJ, 569, 846)

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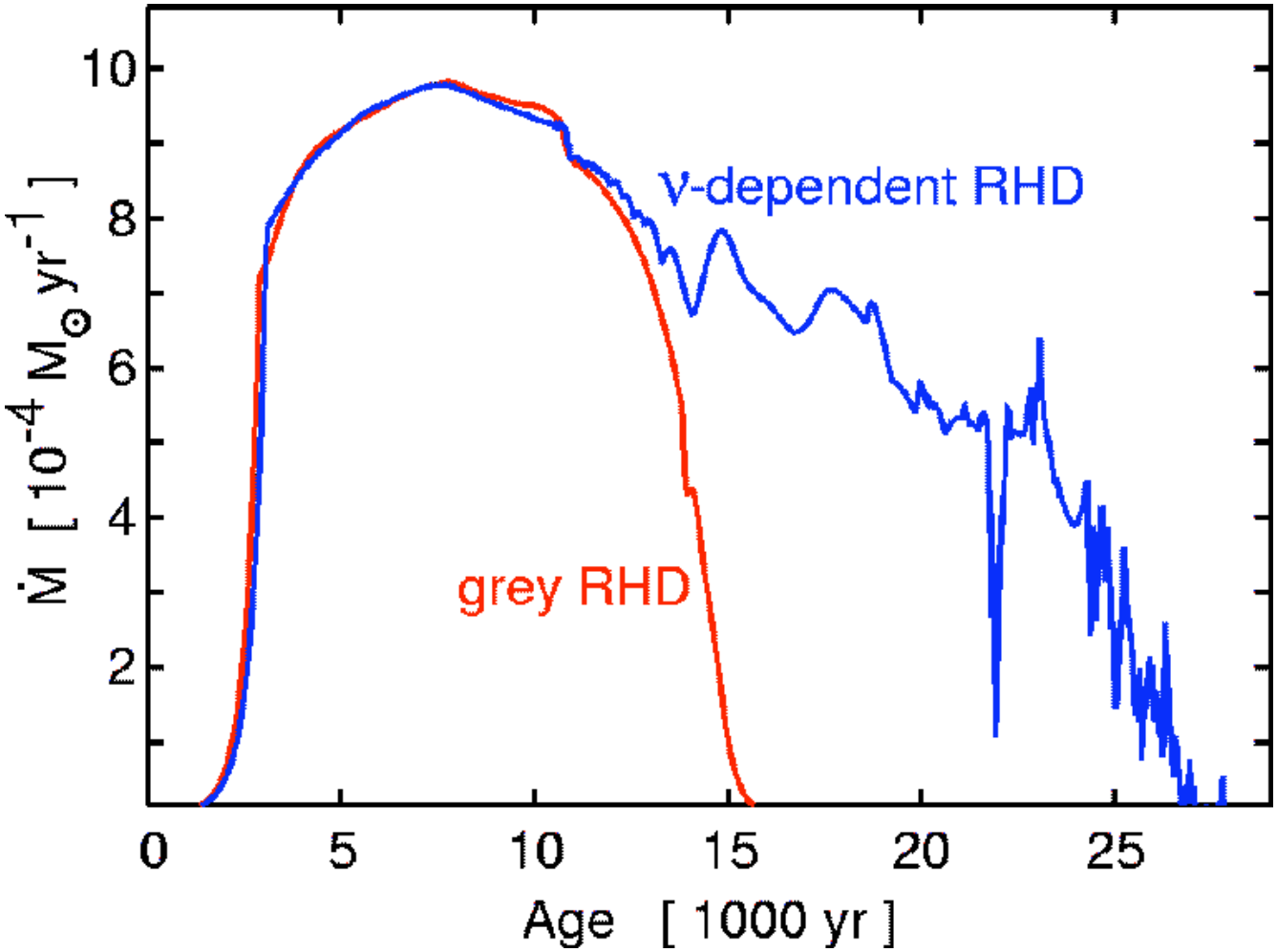

Ω [s^{-1}]	$5\ 10^{-13}$
R_{max} [pc]	0.1 0.2
M_0 [M_o]	60 / 60 120
M_{final} [M_o]	34 43
M_{final} [M_o]	21 (grey)

ν-Dependent Radiation Hydrodynamics of Collapse

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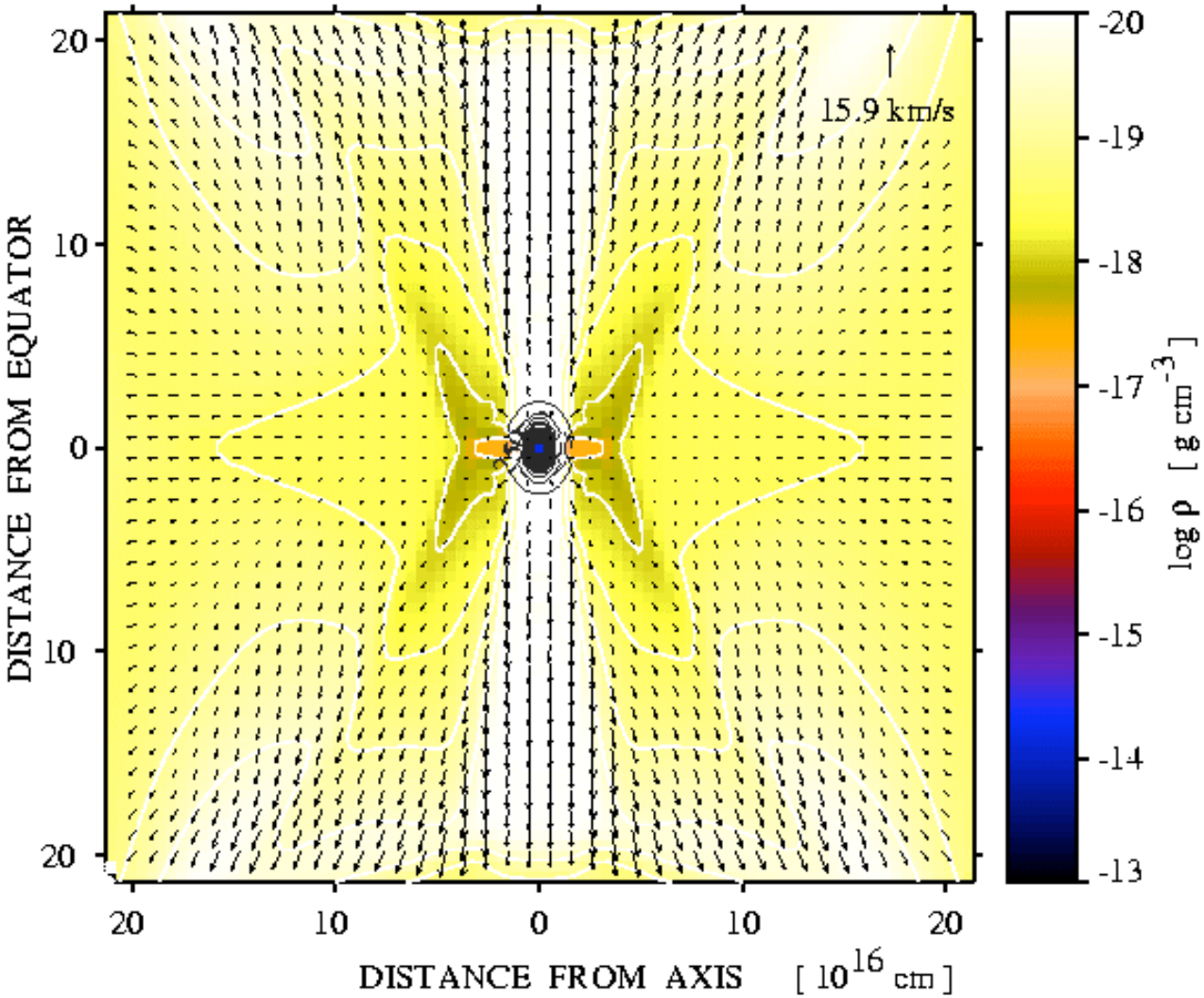
Yorke & Sonnhalter, 2002, ApJ, 569, 846

35,000 yr 33.6 M_o



60 M_o case
120 M_o case

Ω [s^{-1}]	5 10^{-13}
R_{max} [pc]	0.1 0.2
M_0 [M_o]	60 120
M_{final} [M_o]	34 43
M_{final} [M_o]	21 (grey)

The "flashlight" Effect

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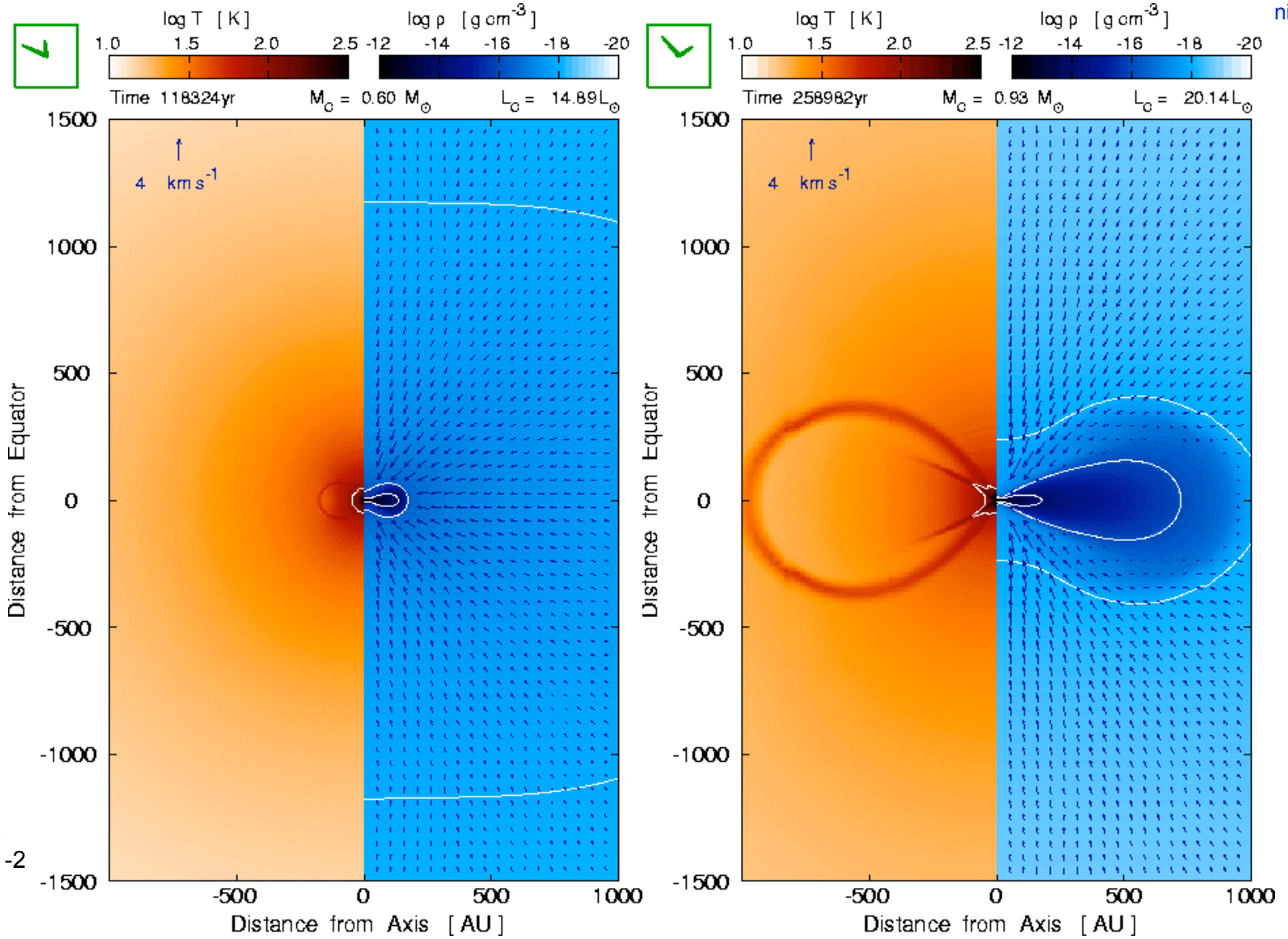
(Yorke & Bodenheimer 1999, ApJ, 525, 330)

$2\ M_\odot$

$\rho \sim r^{-2}$



The Growth of Stellar Mass by Accretion

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- Calculations of molecular core collapse show that infall motions are halted in the central region when it becomes optically thick (~ several Jupiter masses)
- This quasi-hydrostatic core contracts on Kelvin-Helmholtz time scale towards H-burning (and main sequence) while still accreting material from surrounding infalling optically thin envelope

Accretion and mass loss as mass exchange between components

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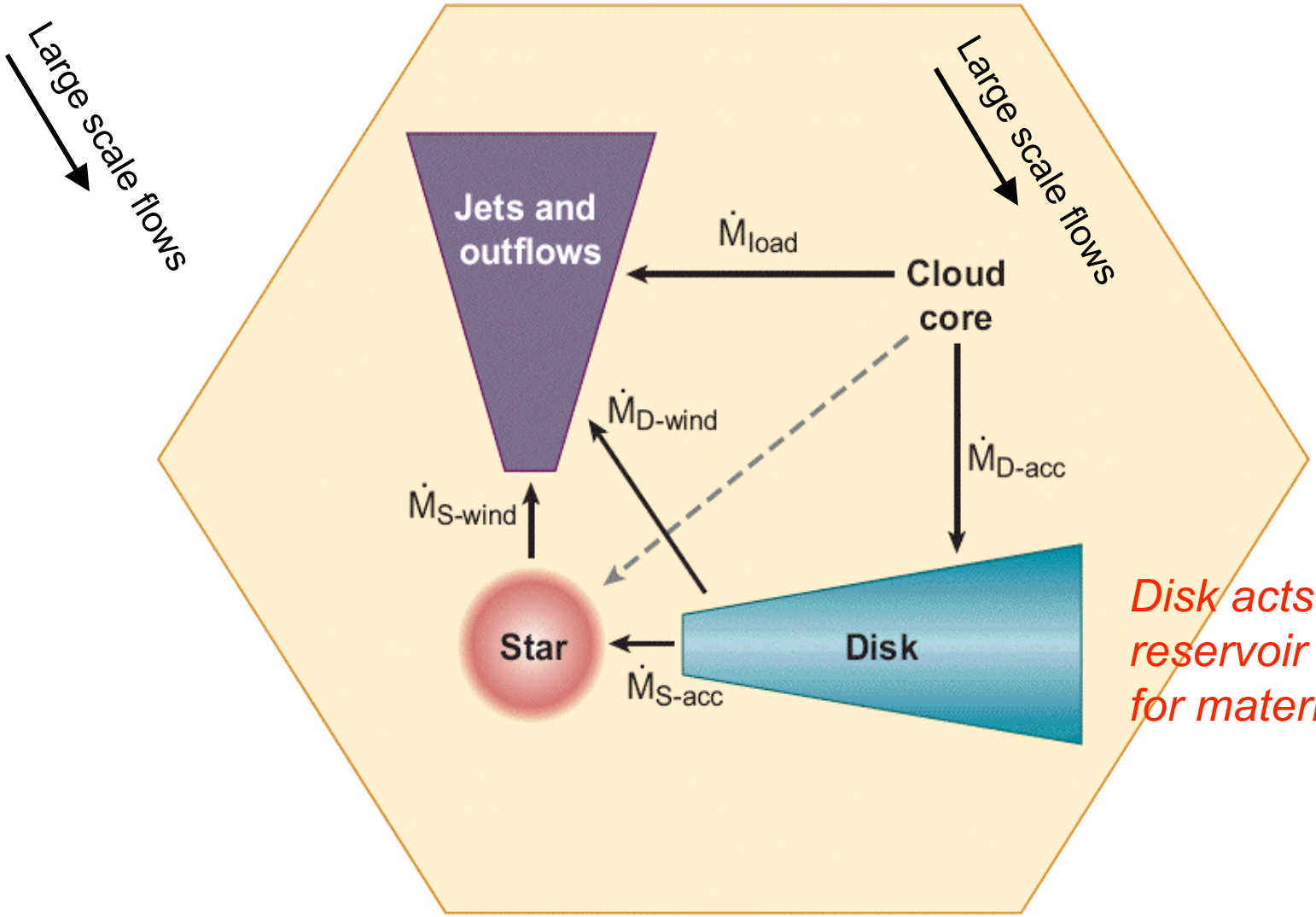

Disk acts as reservoir for material

Sources of Luminosity of accreting Stars

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- Accretion luminosity: $L_{acc} = GM_*/R_*\ dM/dt$

  $L_{acc} = 6000\ L_\odot\ [M_*/30\ M_\odot]^{0.2}\ [dM/dt\ /\ 10^{-4}\ M_\odot/yr]$

- Deuterium burning

  $L_D = 400\ L_\odot\ [dM/dt\ /\ 10^{-4}\ M_\odot/yr]$

- PMS Contraction

  $L_{KH} = GM_*^2/R_*^2\ dR/dt$

- Hydrogen burning

  $L_* = 10^5\ L_\odot\ [M_*/30\ M_\odot]^{3.2}$

Evolution of accreting stars in the HRD ($dM_*/dt > 0$)

(Yorke 2002; Behrend & Maeder 2001)

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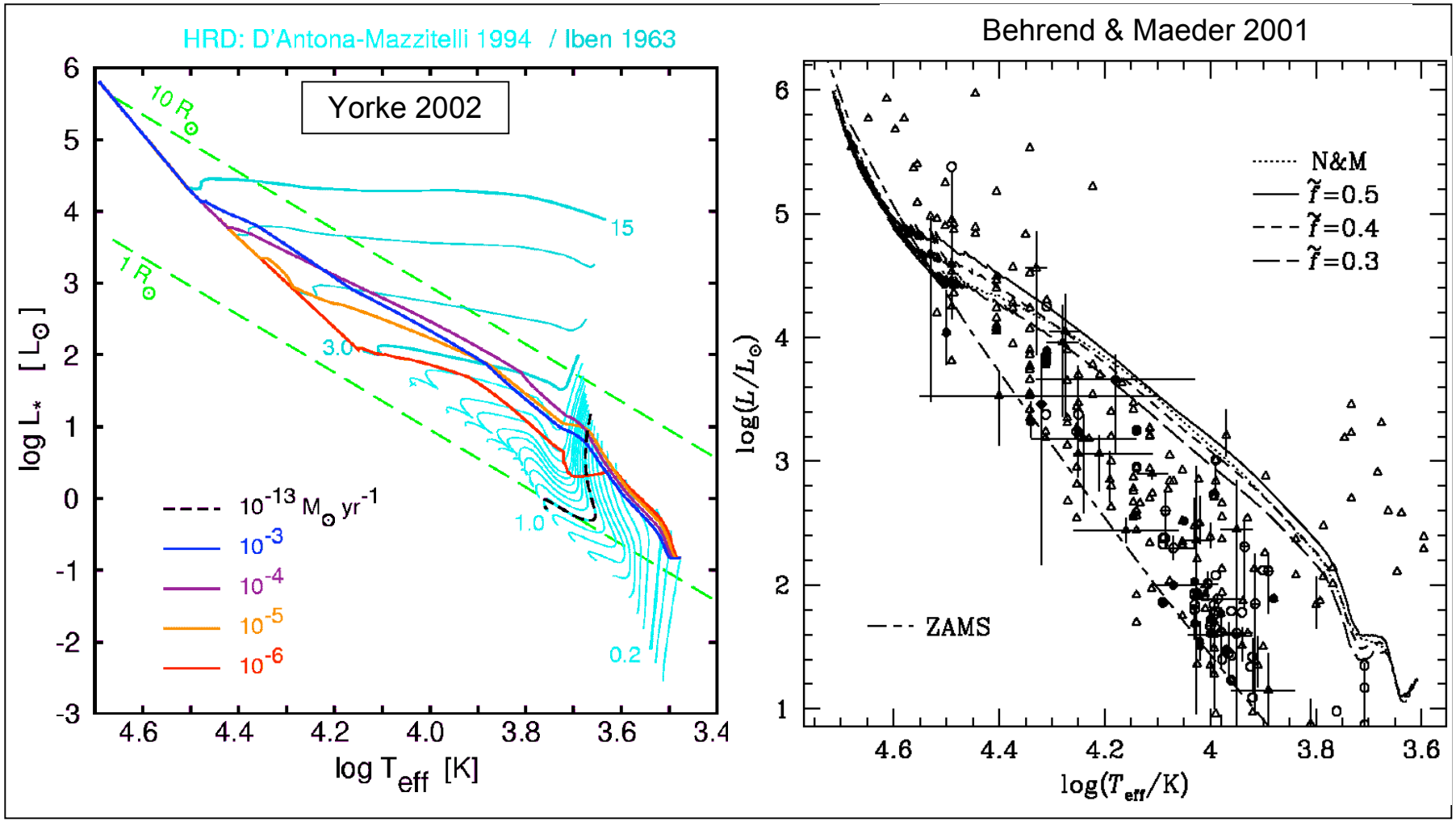

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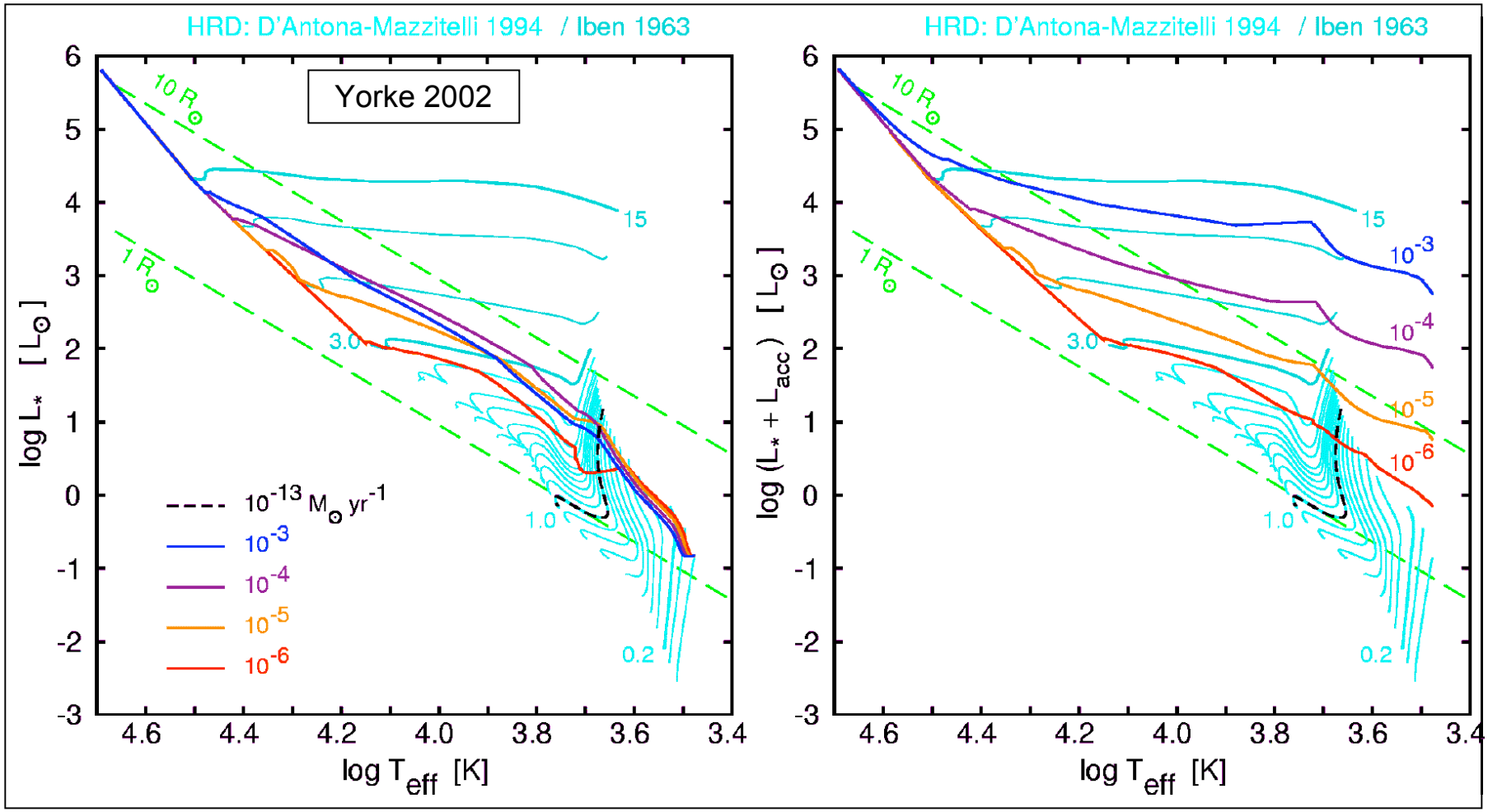
National Aeronautics and Space Administration



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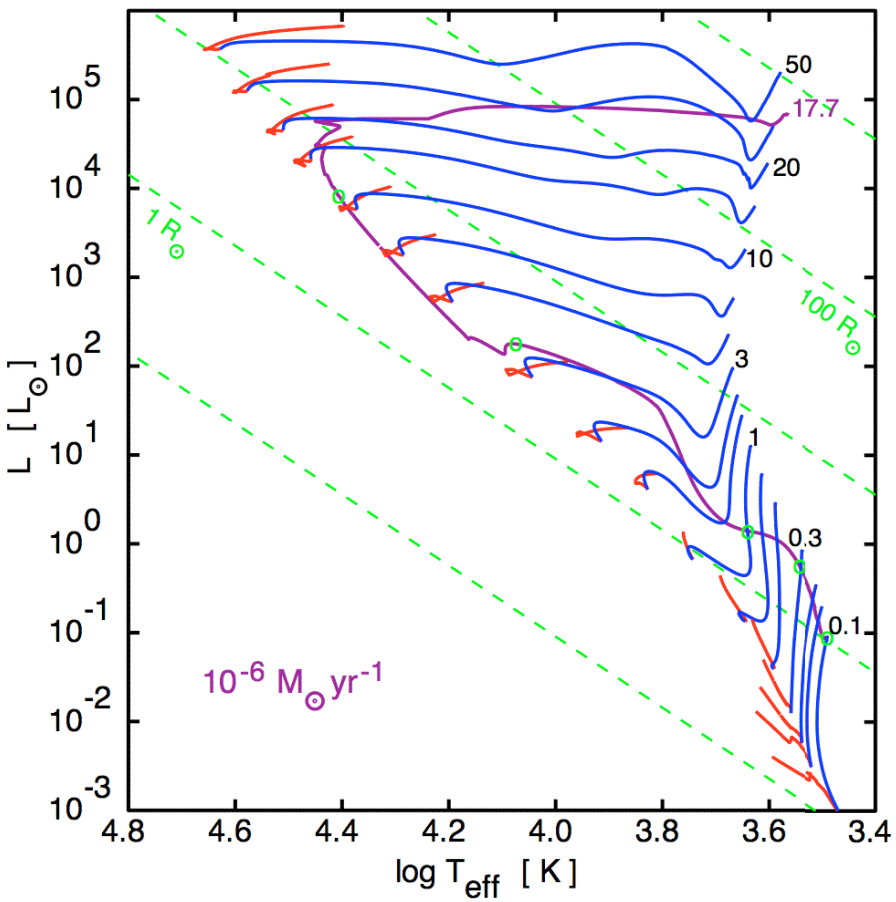
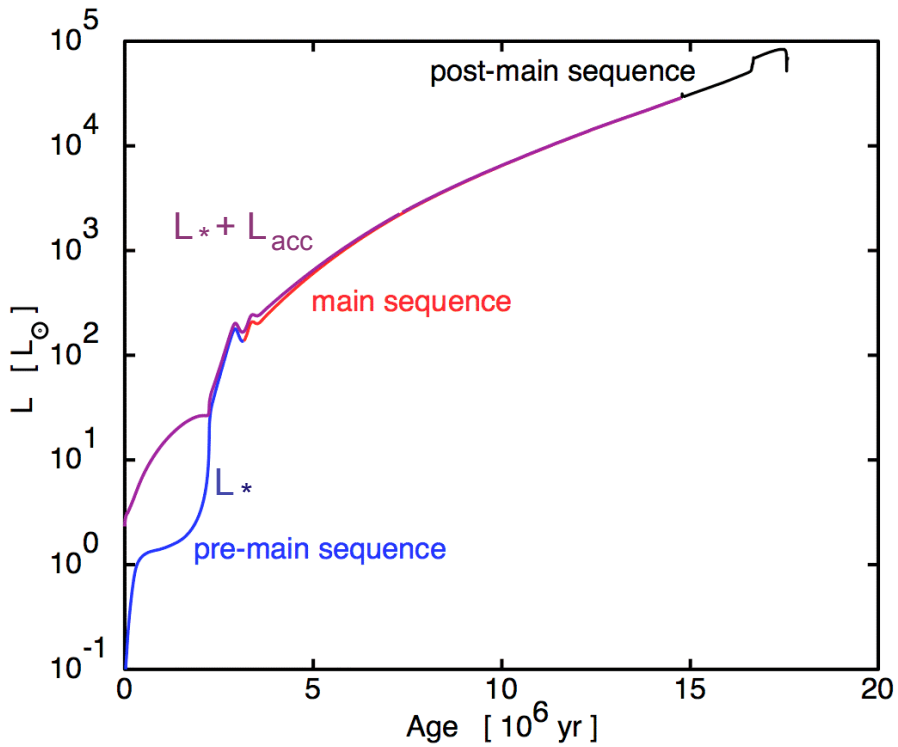
National Aeronautics and Space Administration

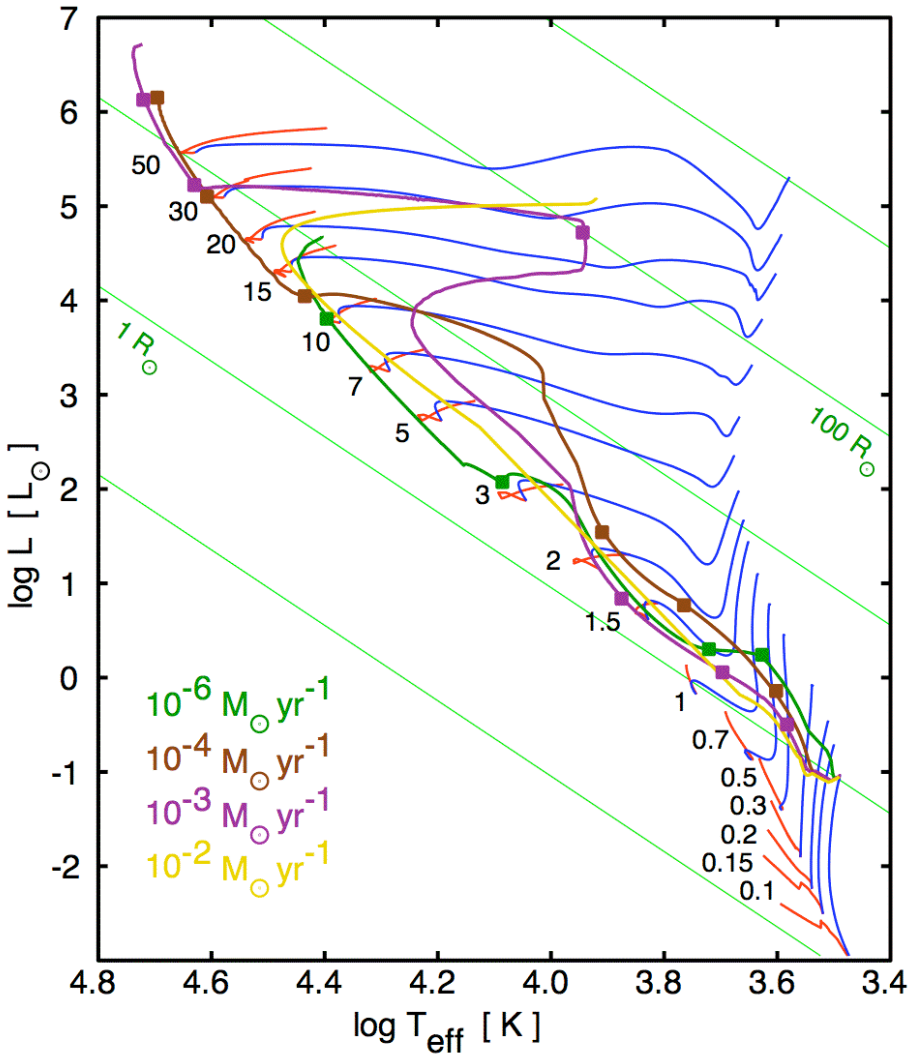


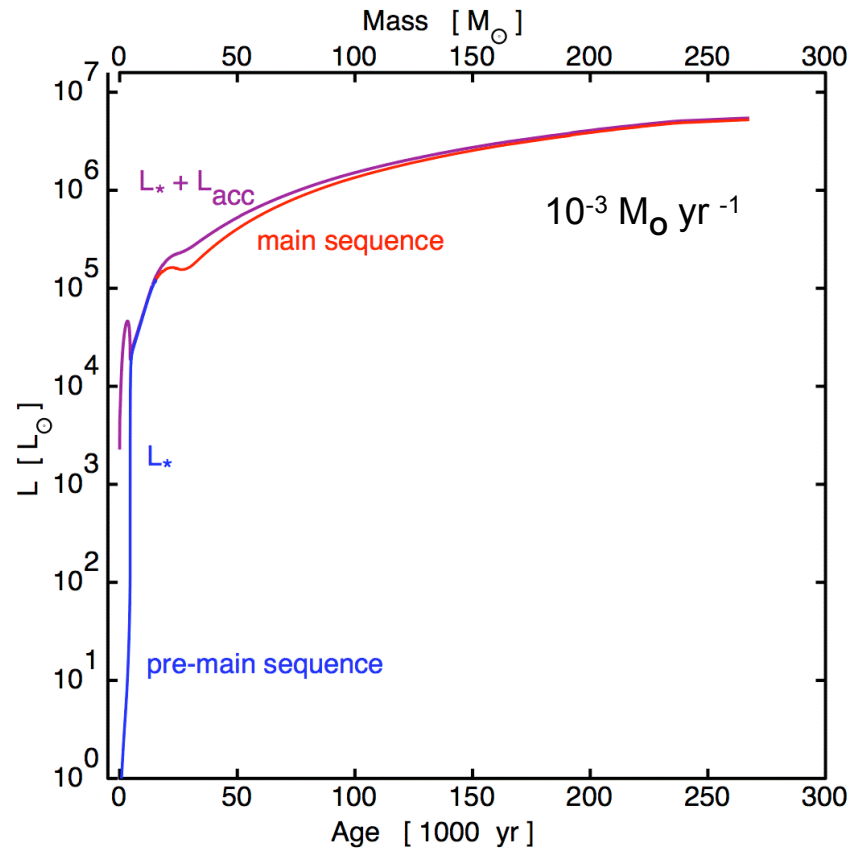


Yorke & Bodenheimer (2008)

Evolution of accreting stars in the HRD ($dM_*/dt > 0$)

National Aeronautics and Space Administration





Yorke & Bodenheimer (2008)

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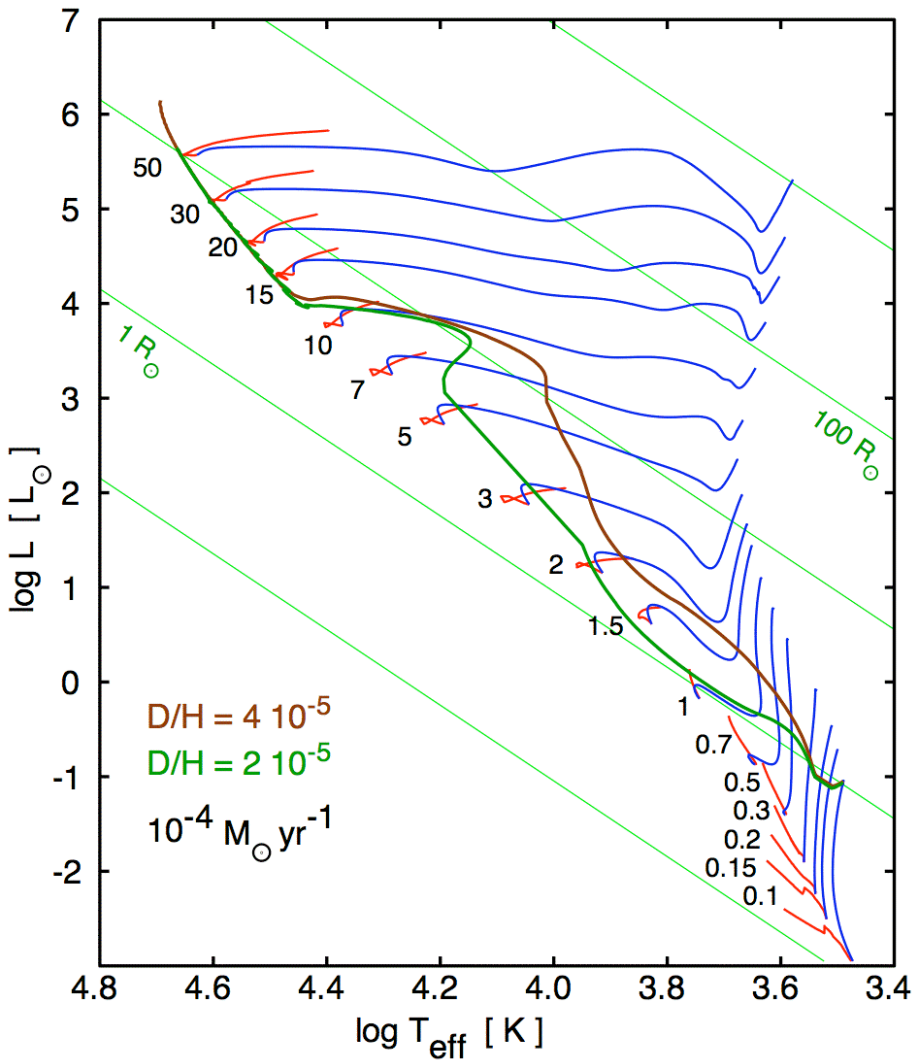

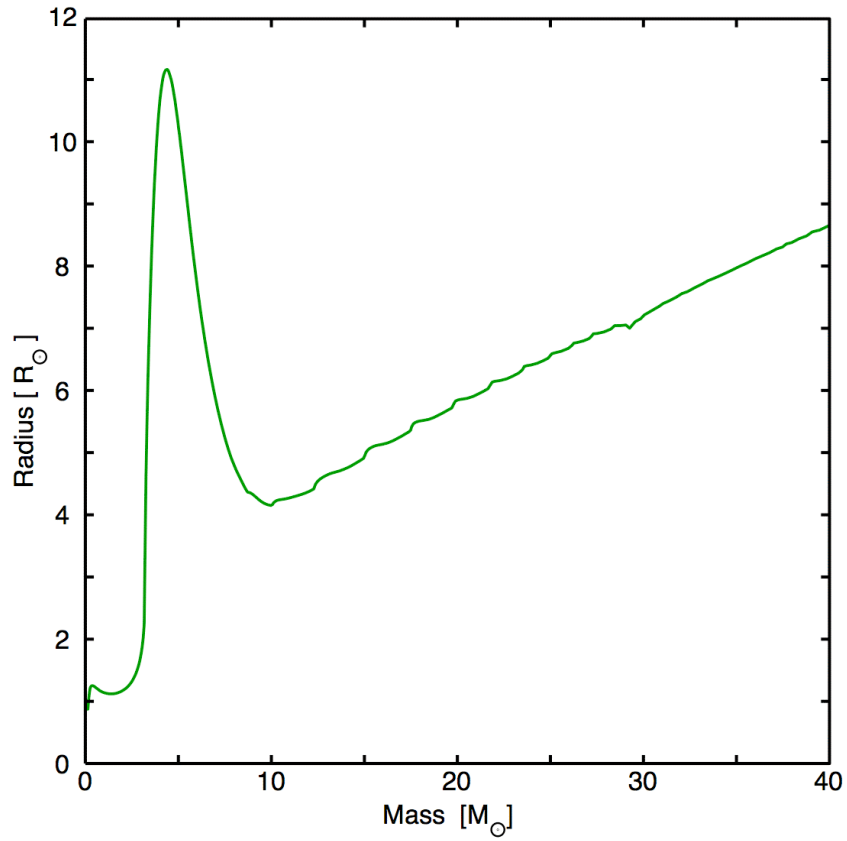

Yorke & Bodenheimer (2008)

A few Remarks

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- Accretion physics will be key to understanding formation of massive stars
- Stellar evolution is not dead

The Destruction of Disks around newly formed massive Stars

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- Disks have not been observed around main sequence O-stars, so either…
  - There were no disks during formation

  or…
  - Disks around O-stars are destroyed on a short time scale

Photodissociation Regions (PDRs)

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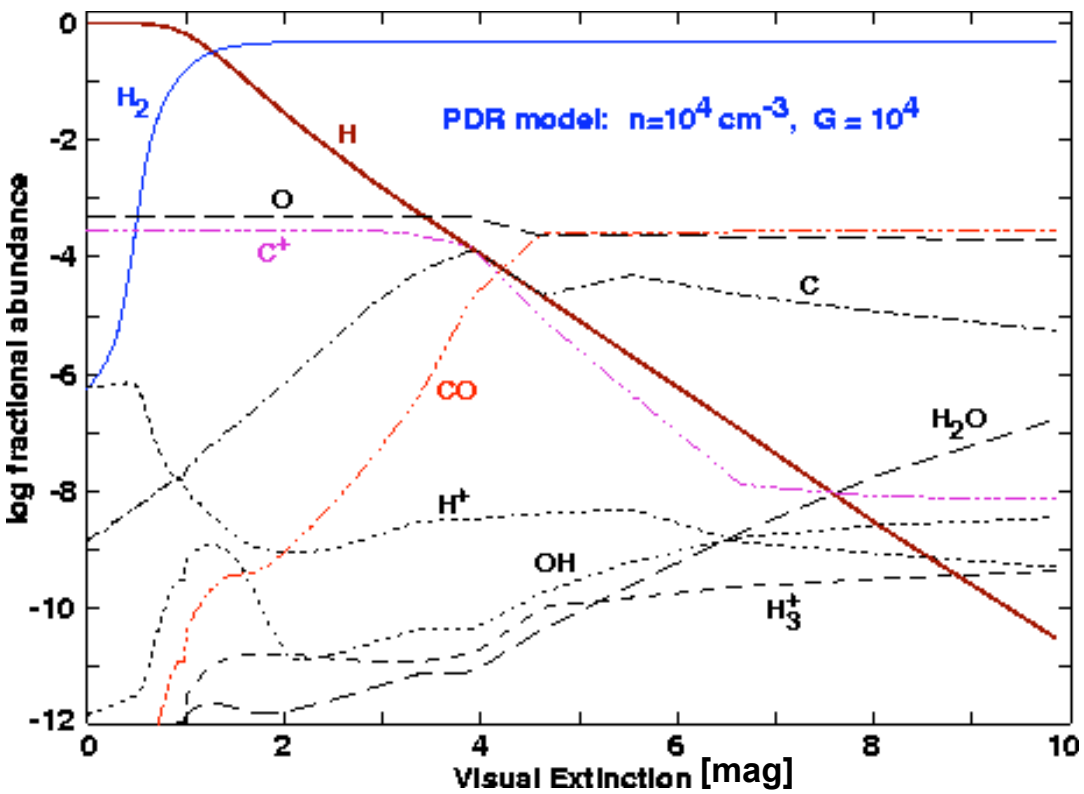
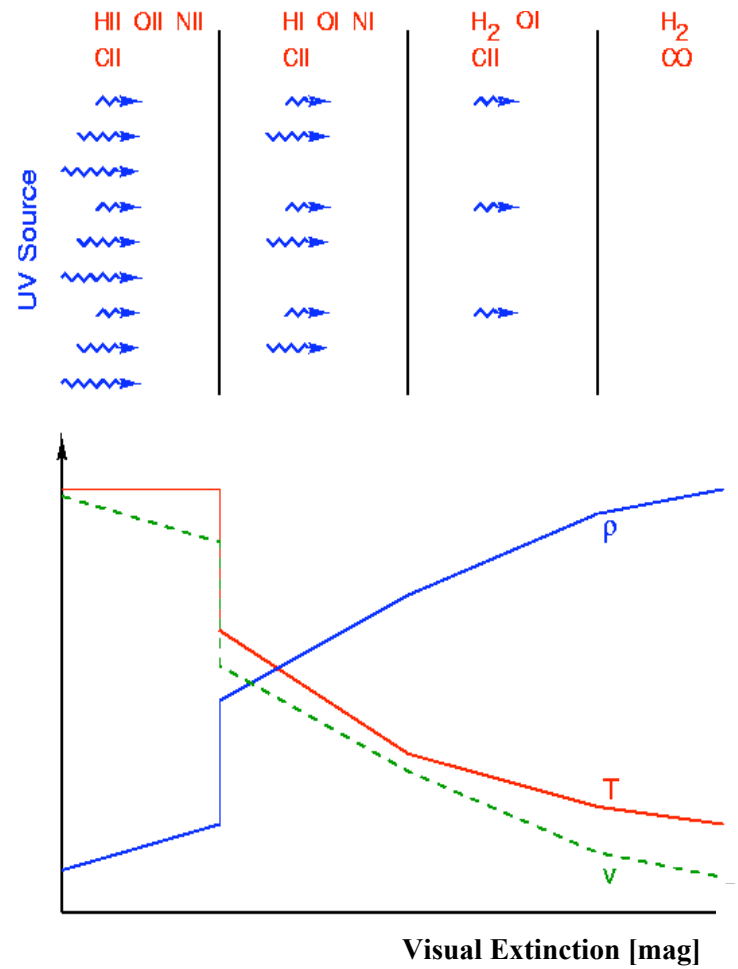
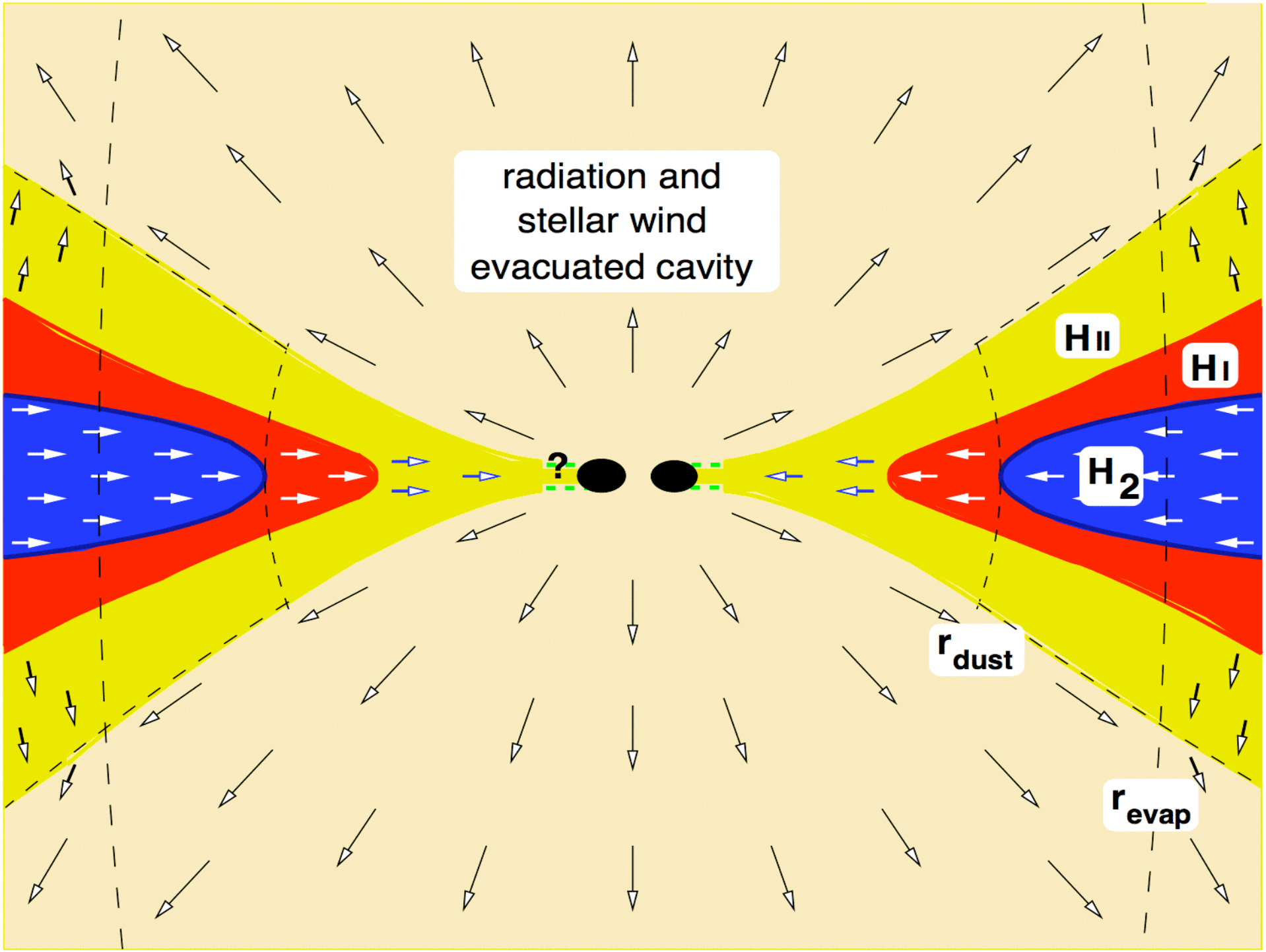
- Illumination of interstellar material (ISM) by UV photons affects its composition and thermal properties.
- This in turn affects the dynamics of the ISM.
- Many important lines for analyzing ISM and the UV sources are accessible to Herschel's HIFI.






radiation and
stellar wind
evacuated cavity
H II
H I
H 2
?
r dust
r evap

Destruction of circumstellar disks

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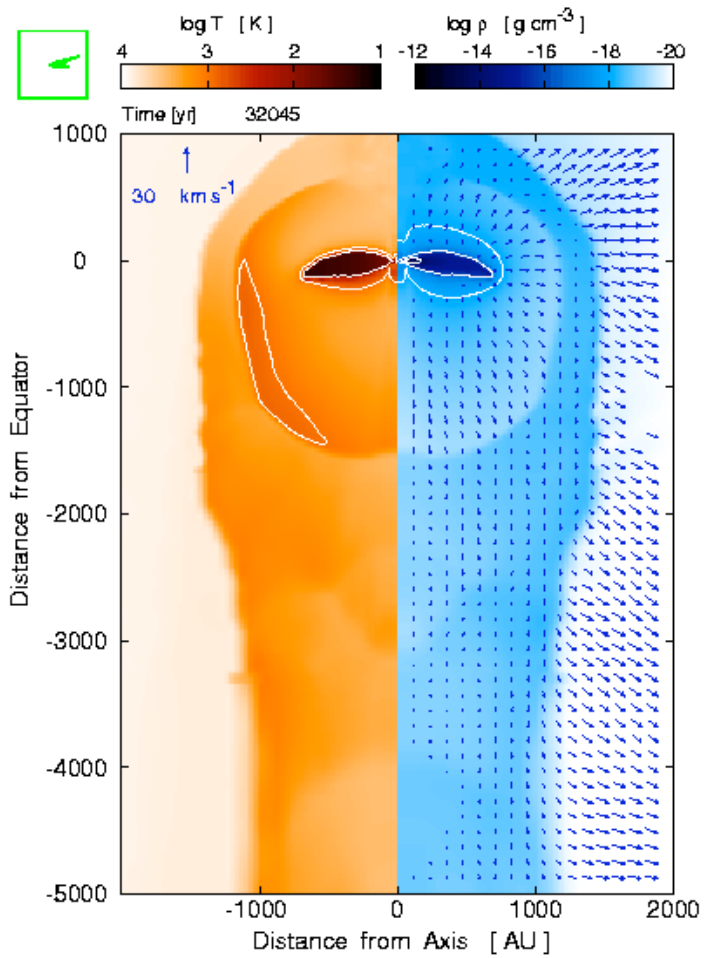
- Destruction of nearby disk: 1, 2, 3, 4



Initial conditions

Mass of star: 1.2 $M_\odot$
Mass of disk: 0.5 $M_\odot$

External O5 star
Distance from disk: 0.1 pc

Results

0 … 400 years:
400 … 40,000 years:
40,000 … 100,000 years:
100,000 … 220,000 years:

Destruction of circumstellar disks

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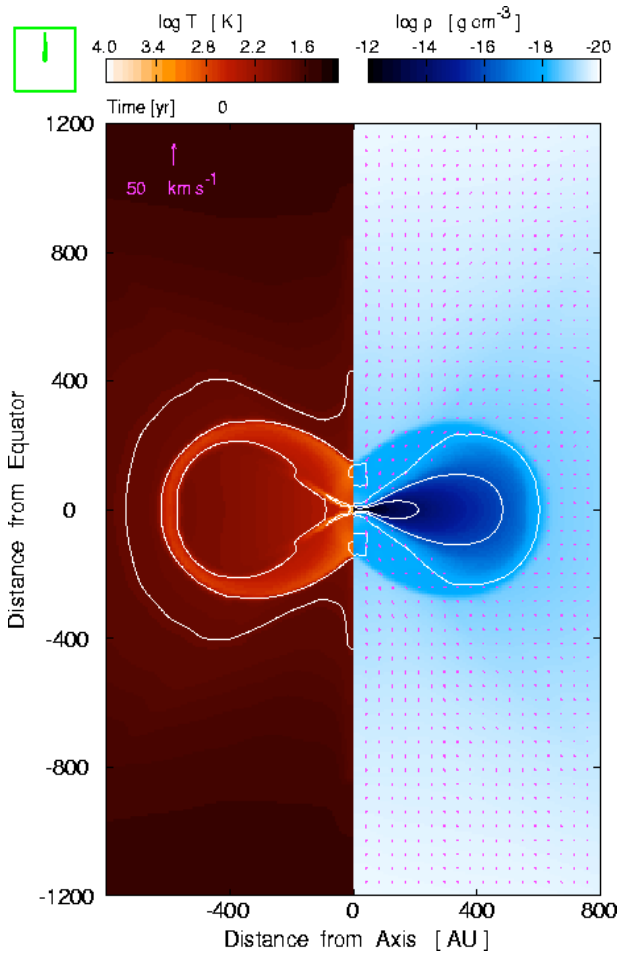
- Destruction of circumstellar disk: 1, 2



Initial conditions

Luminosity of star:	3550 $L_\odot$
Mass of central star:	8.3 $M_\odot$
Stellar wind:	30 km s^{-1} 10^{-7} $M_\odot$ yr^{-1}
Mass of disk:	0.7 $M_\odot$
H-ionizing flux:	7 x 10^{44} s^{-1}
Net UV flux:	2 x 10^{48} s^{-1}

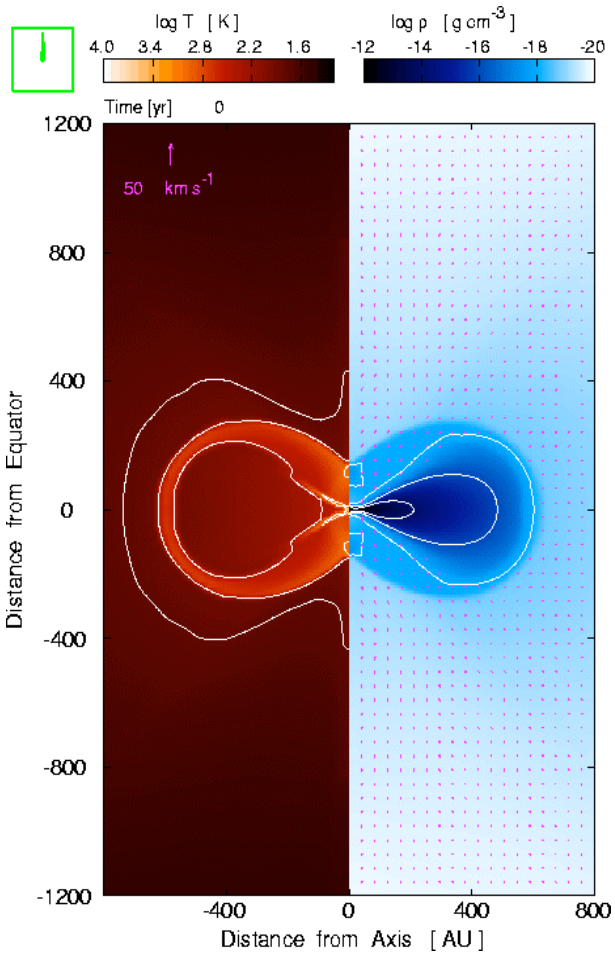
Results

Disk wind via “external” UV heating
Stellar wind focused through polar cavity
Photoevaporation of disk within 10^5 years

Destruction of circumstellar disks

National Aeronautics and Space Administration

- Destruction of circumstellar disk:



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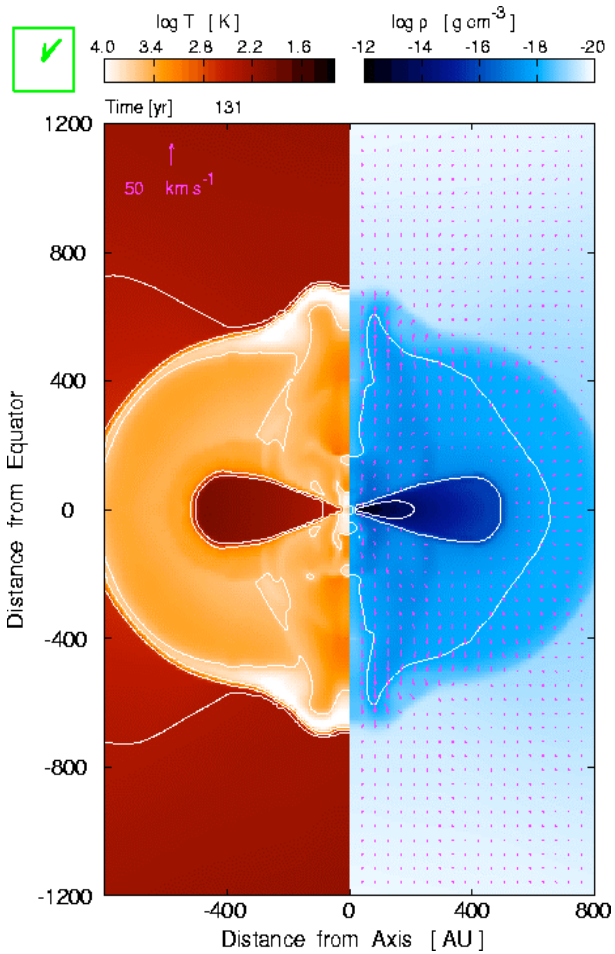

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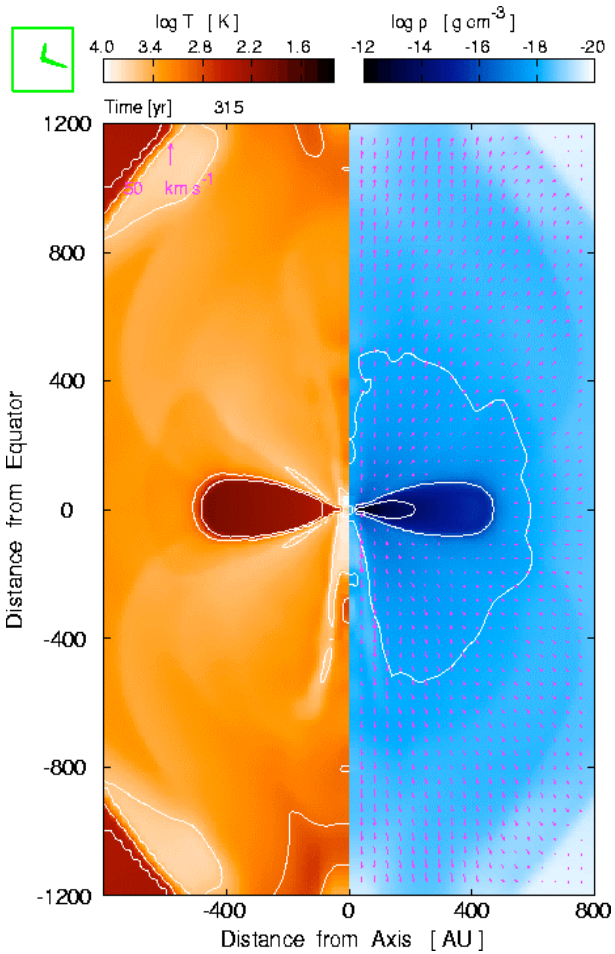

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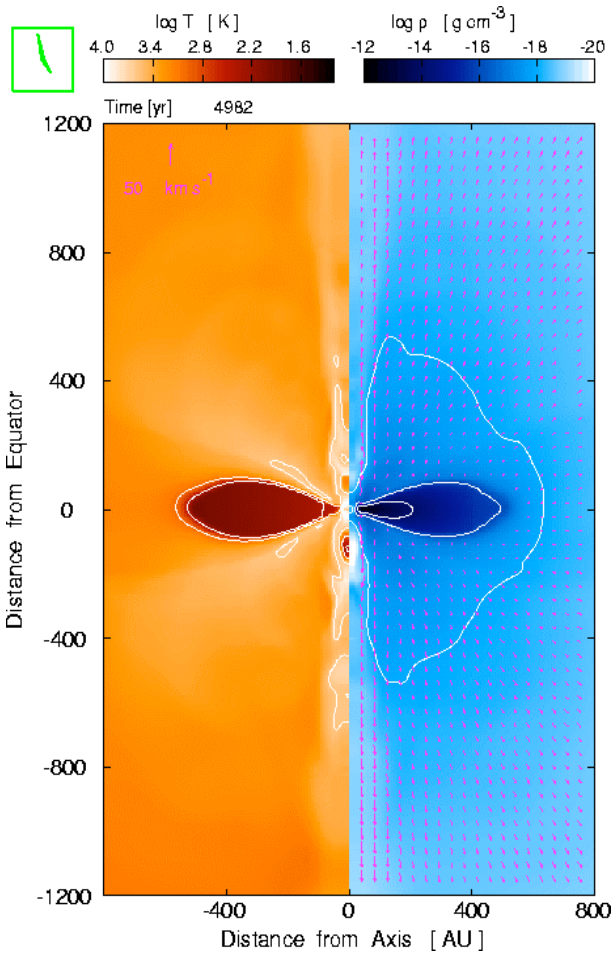

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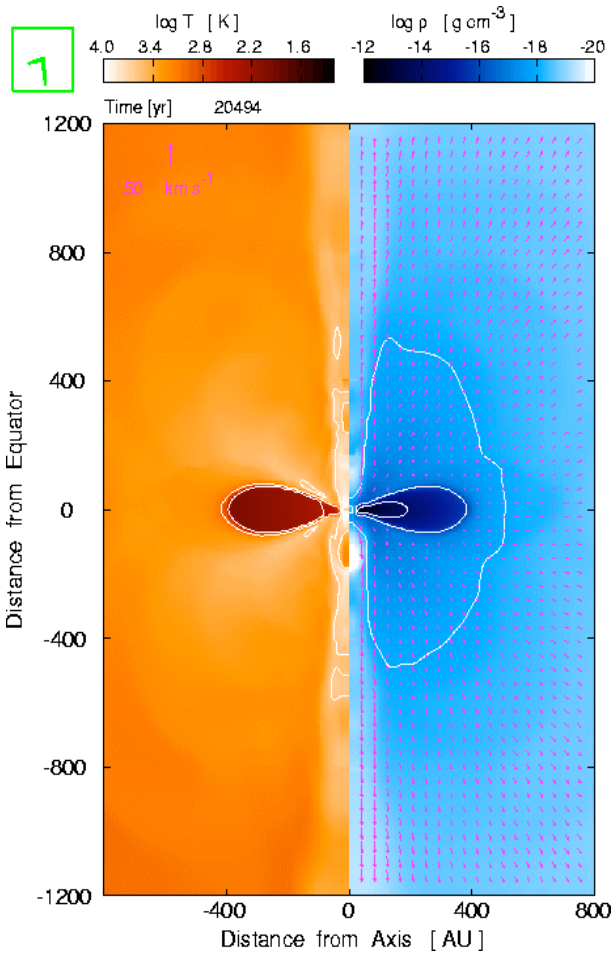

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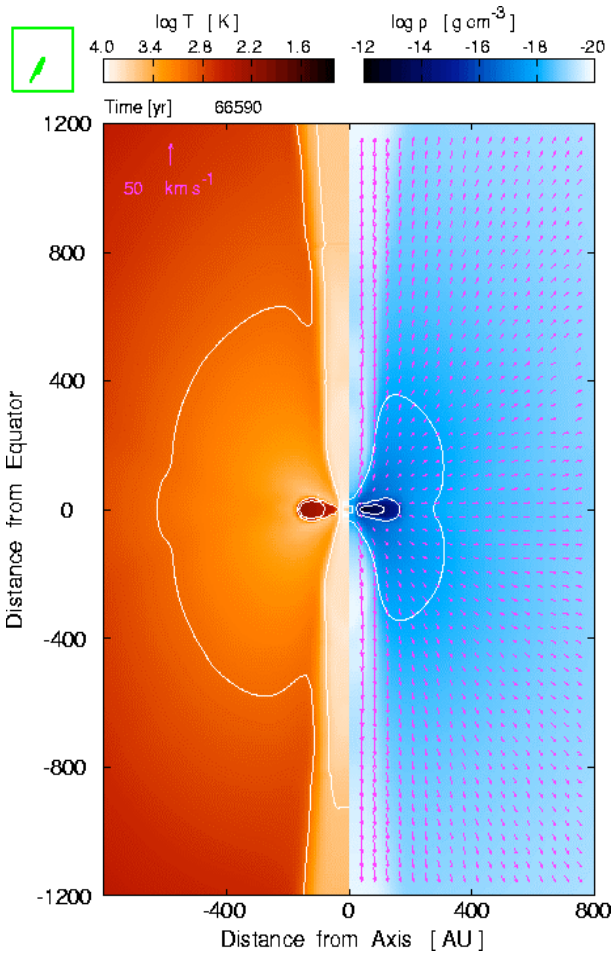

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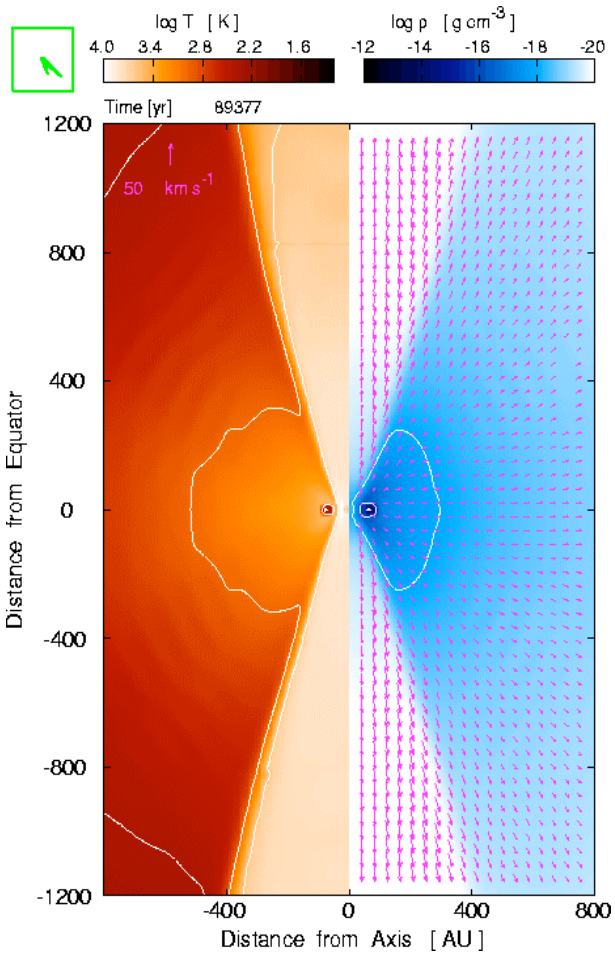

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"Known" Massive Accretion Disks

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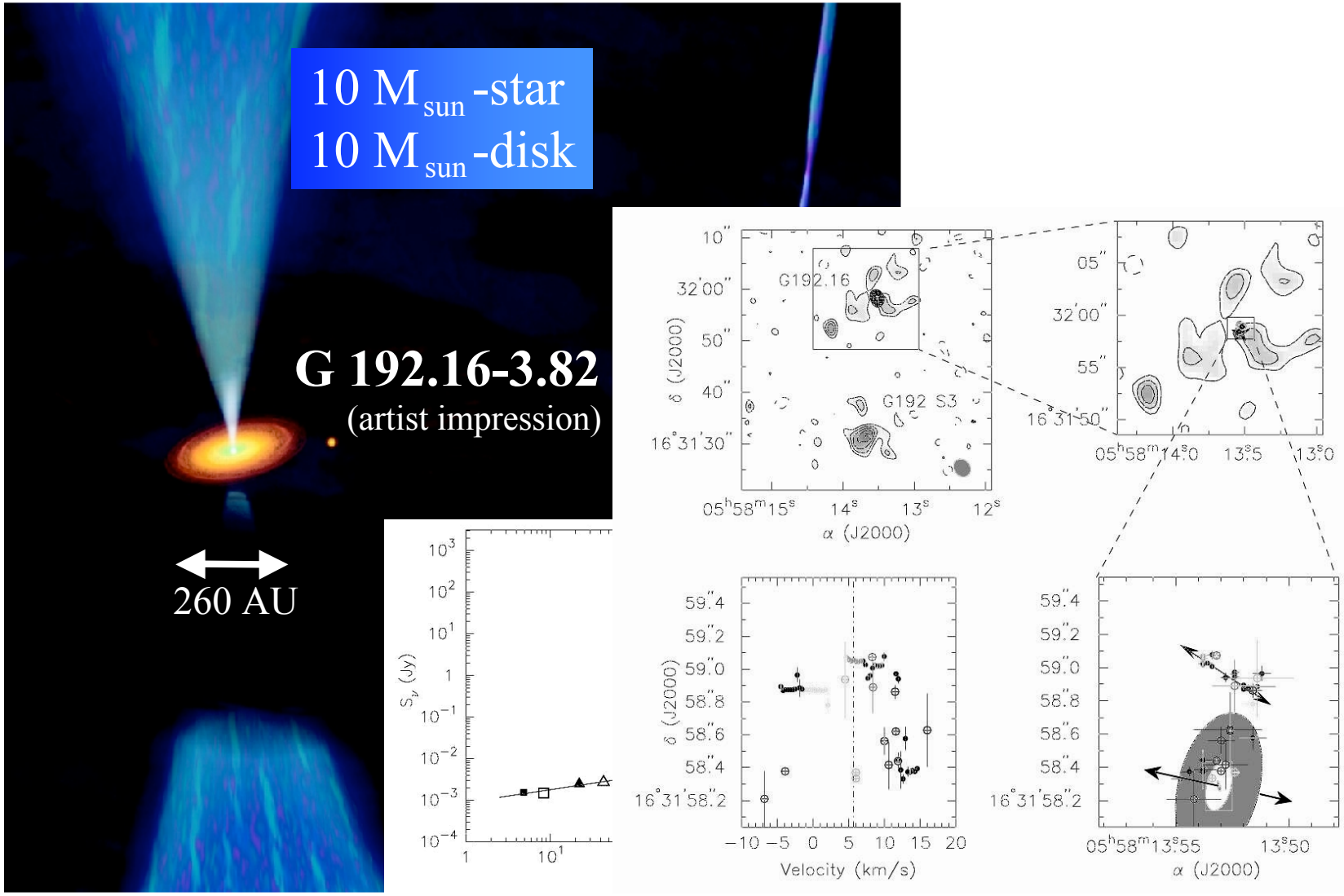

Star Formation: The first Generation

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- Stars in the distant past (Pop III) are probably formed non-homologously through accretion => disks?
- Without magnetic fields angular momentum transport in disks occurs via…
  - Tidal forces (bars & spirals)
  - Turbulence (?)
- Massive stars photoionize nearby disks (including their own), eventually destroying the disks.
  - The accretion and disk destruction processes close to massive stars operate on similar timescales.
  - Photoionization can limit the final mass of the star

First protostars

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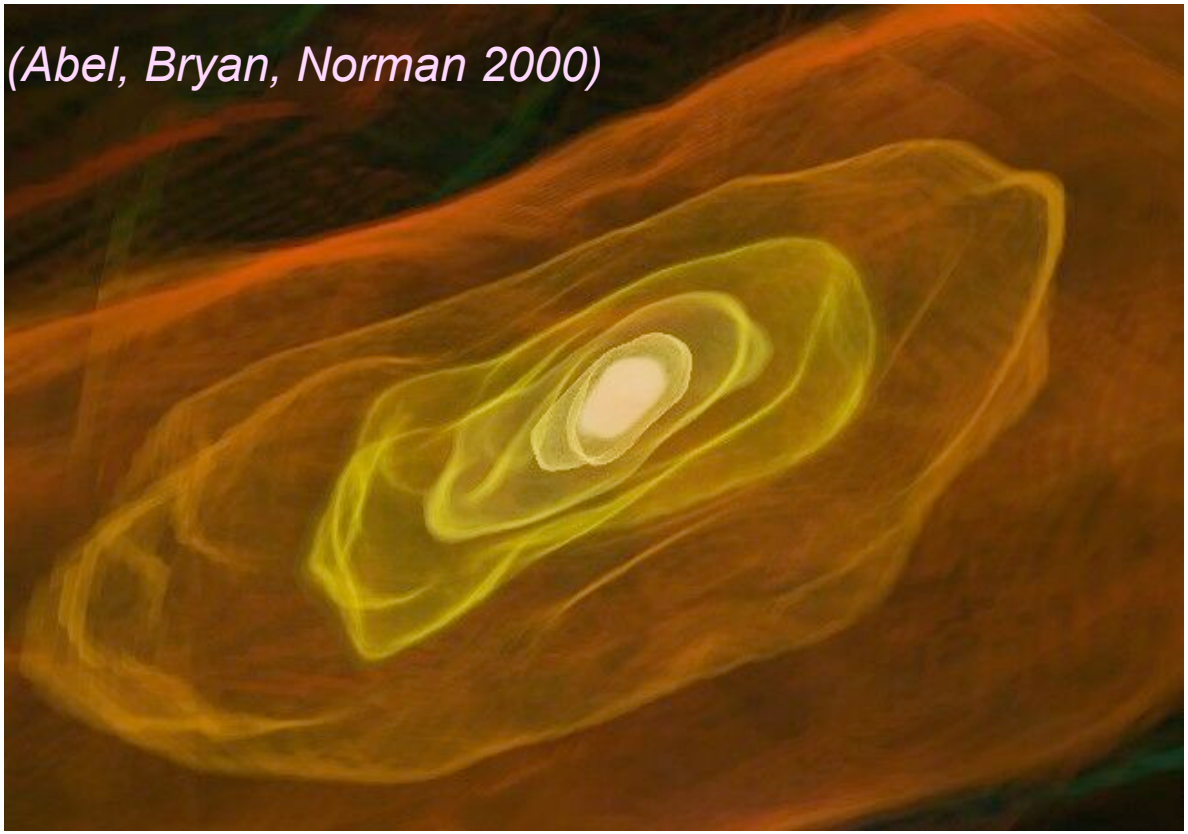
Rotation will play an important role …



Star Formation in the Distant Past – Standard Wisdom

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- Star formation in the earliest epochs (metal-free) is an "easy" theoretical problem
  - No magnetic fields
  - Equation of state relatively simple
  - Merely collect mass in gravitational troughs and allow it to evolve to central hydrogen burning
  - Once they form, the first stars have negligible winds
  - Once they form, the first stars inhibit further star formation in the immediate vicinity (radiation, SN explosions)

- The greatest difficulty: no direct observations of these Pop III stars

More Star Formation Wisdom

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- Massive star formation today is by contrast a difficult theoretical problem
  - Magnetic, radiative forces on dust important
  - Complex microphysics (dust, degree of ionization, …)
  - Generally form in groups and clusters and their winds, ionizing radiation, and supernova explosions strongly affect ongoing star formation
- There are direct observations
- What we don't know about massive star formation today may indicate what we don't really know about star formation in the distant past.

Speculation about the first Stars

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- Pop III stars probably formed in clusters.
  - Pop I/II analogy: “triggered star formation”
  - Photoionization, winds, and SN shocks can help compress nearby clumps, initiating secondary star formation
- Pop III stars were probably multiple systems.
  - Because of lack of magnetic fields in their early phases, fission in rapidly rotating Pop III stars can produce close binaries

More Speculation about the first Stars

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- Unable to support themselves through pp-burning, Pop III stars immediately produced C (via 3-α process) which then allowed central CNO H-burning
- Meridianal circulation (Goldreich-Schubert-Fricke) in rapidly rotating Pop III stars mixed interiors on a timescale of 10^6 years, bringing metals to the surface.
- Radiation driven mass loss probably created Wolf-Rayet Pop III stars.

Conclusions

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- Massive star formation is a difficult theoretical problem
  - Magnetic, radiative forces on dust important
  - Complex microphysics (dust, degree of ionization, …)
  - Massive stars form in groups/clusters and their winds, ionizing radiation, and supernova explosions strongly affect ongoing star formation.
- Massive stars photoionize nearby disks (including their own), eventually destroying the disks.
  - The accretion and disk destruction processes close to massive stars operate on similar timescales.
  - Photoionization can limit the final mass of the star.
- Observations continue to confound theorists

Thank you