Theoretical Developments in Understanding Massive Star Formation

presented at **Massive Star Formation: Observations Confront Theory**

Morse & Davidson (1996)

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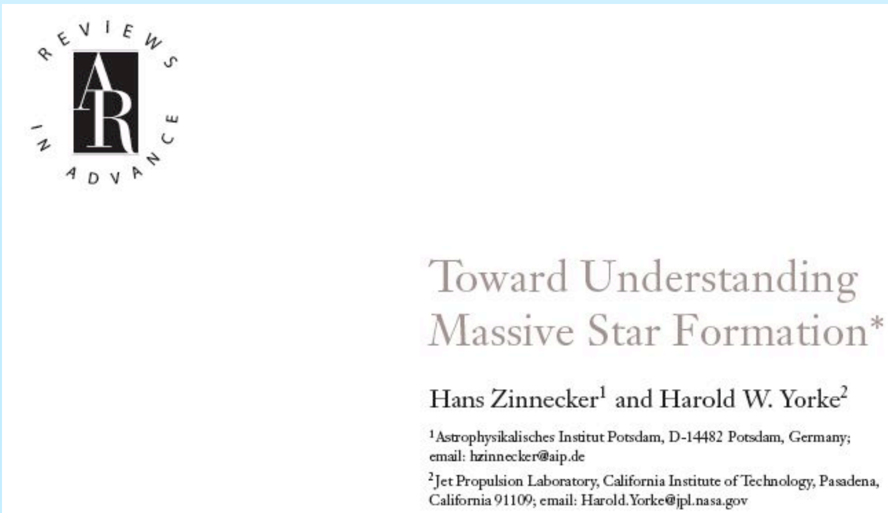
- Zinnecker & Yorke (2007) *Toward Understanding Massive Star Formation*, Ann. Rev. Astron. Astrophys. **45**: 481-563 (arXiv:0707.1279)


REVIEWS IN ADVANCE

Toward Understanding Massive Star Formation*

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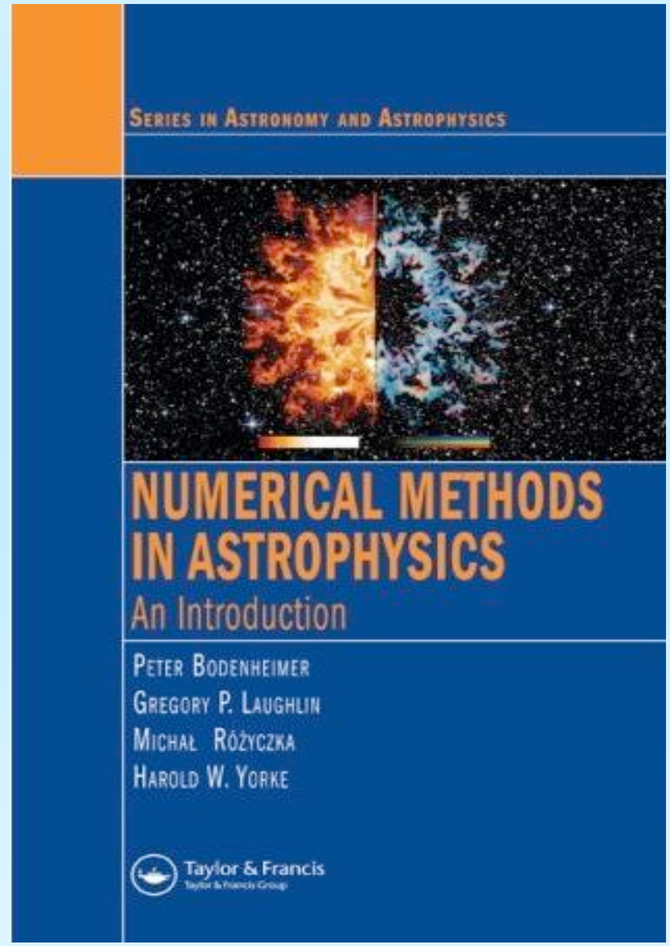
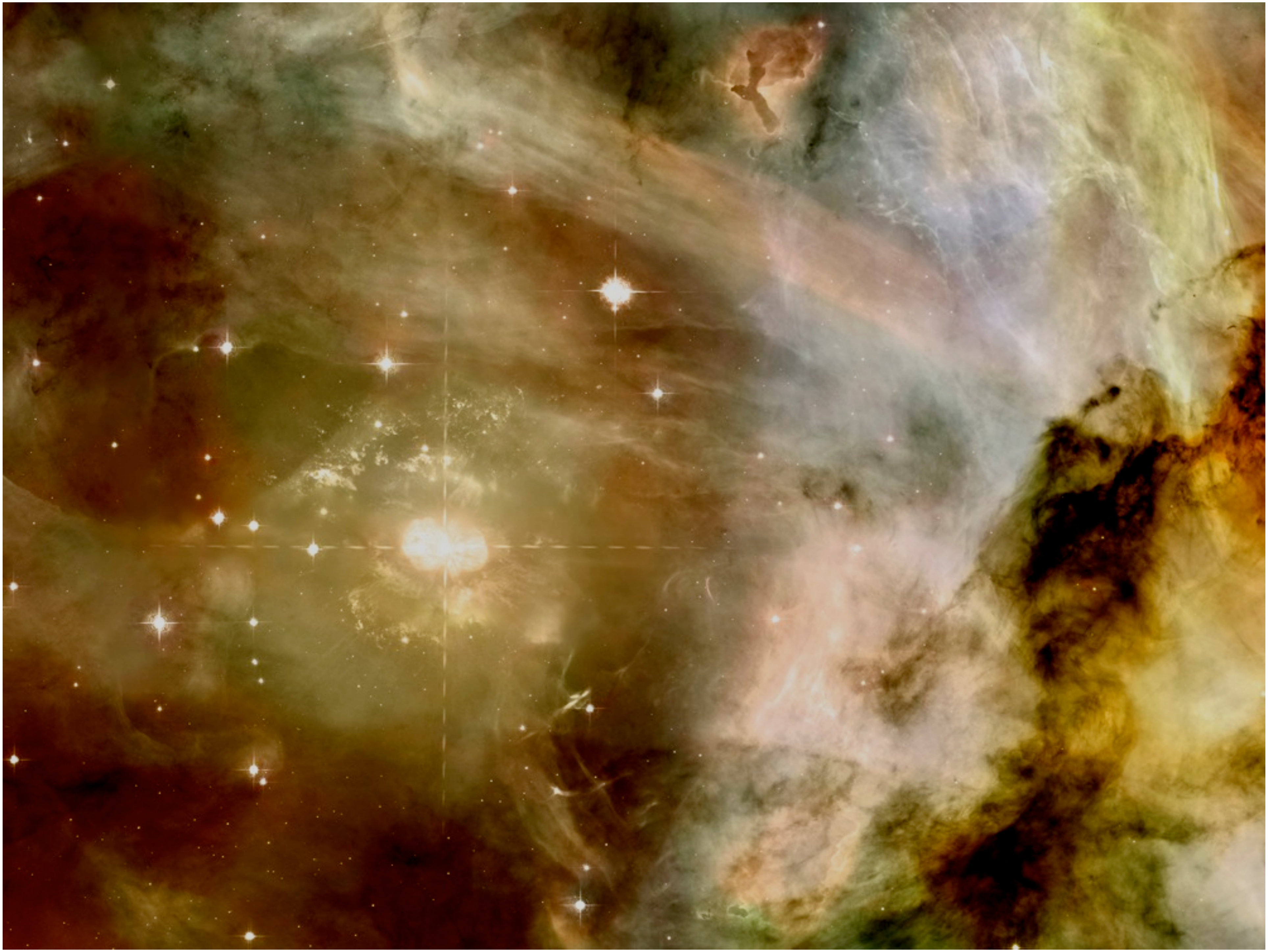
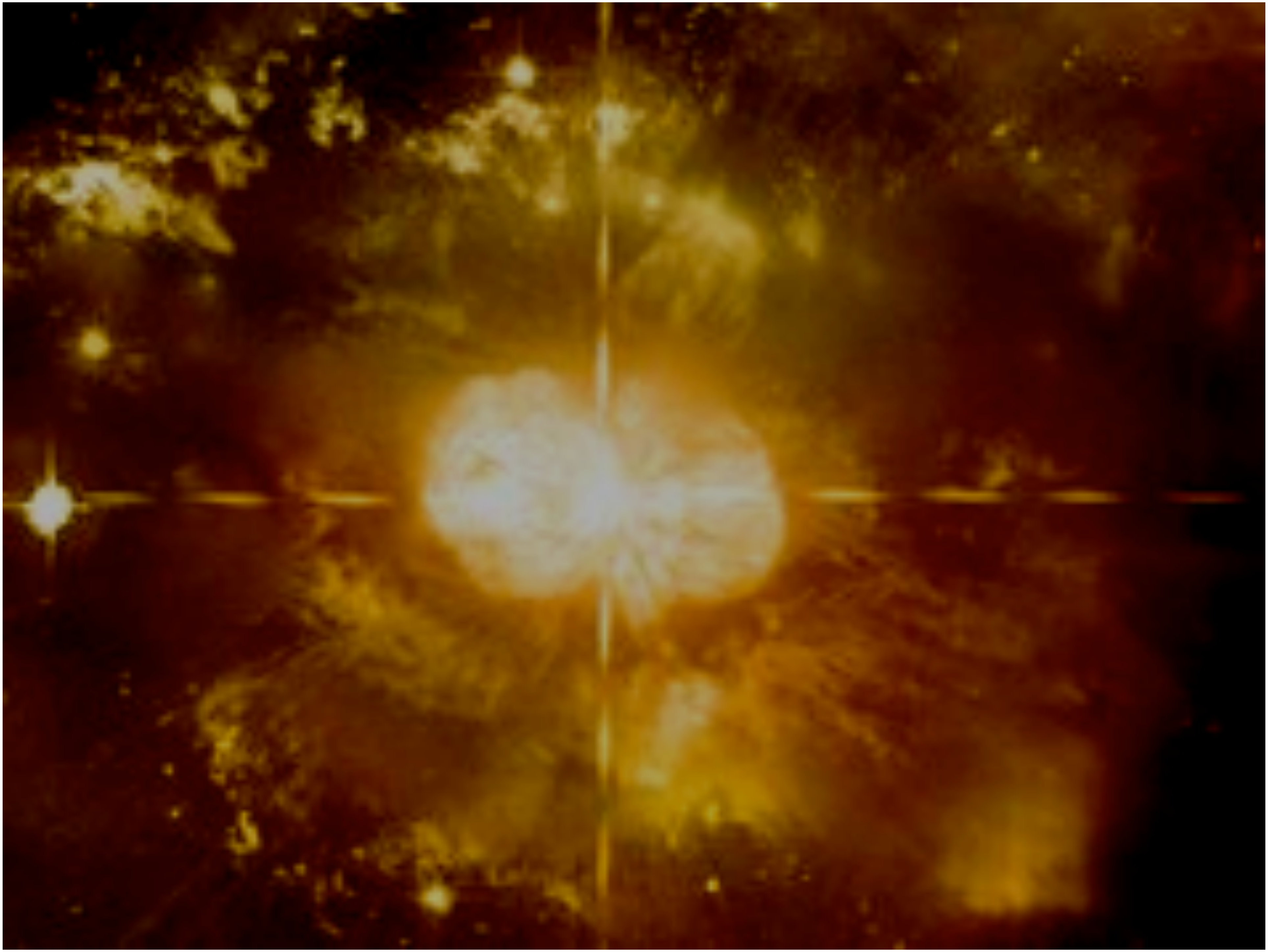
- Bodenheimer, Laughlin, Rozcyzka, Yorke (2007) Numerical Methods in Astrophysics : An Introduction, Taylor & Francis





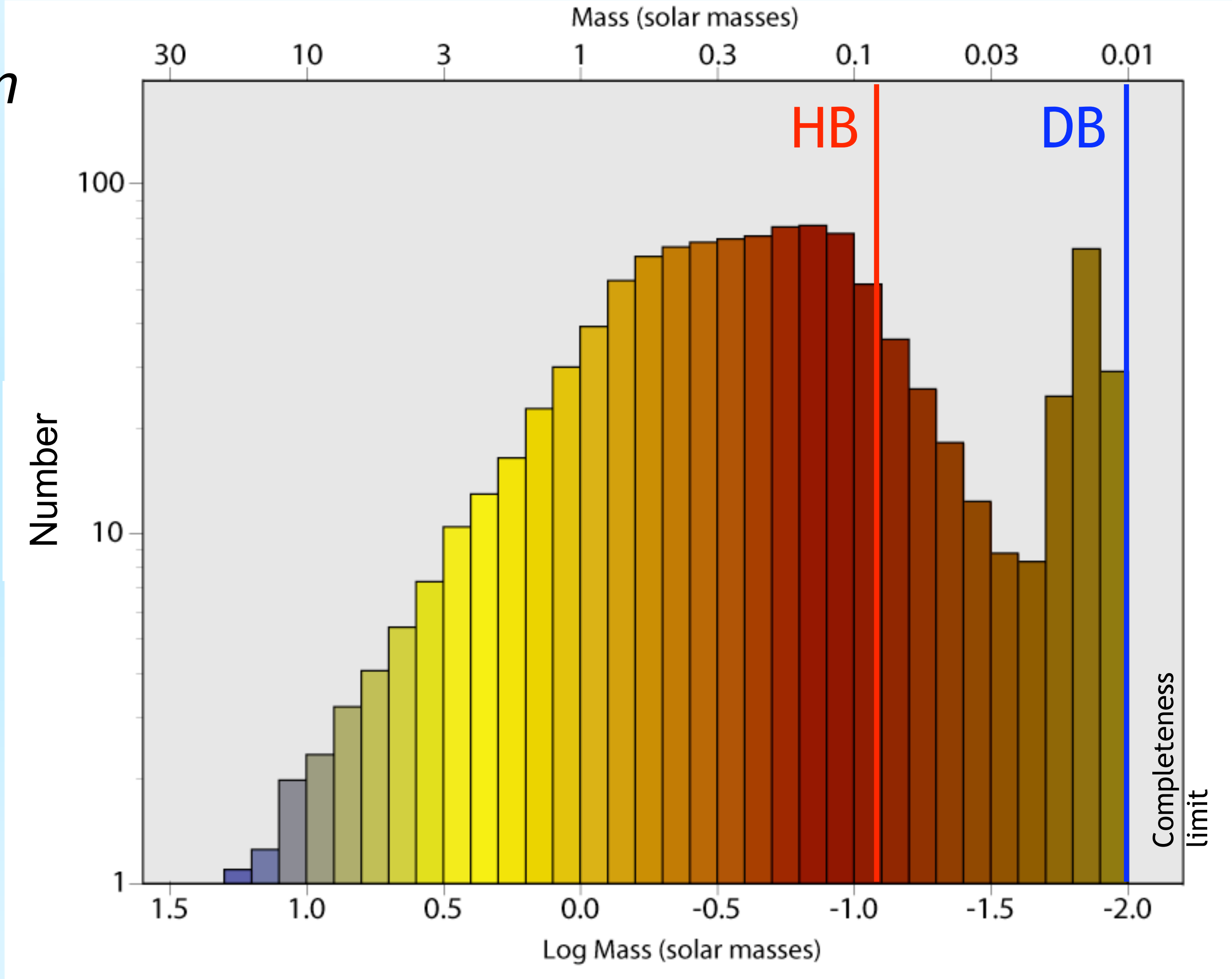


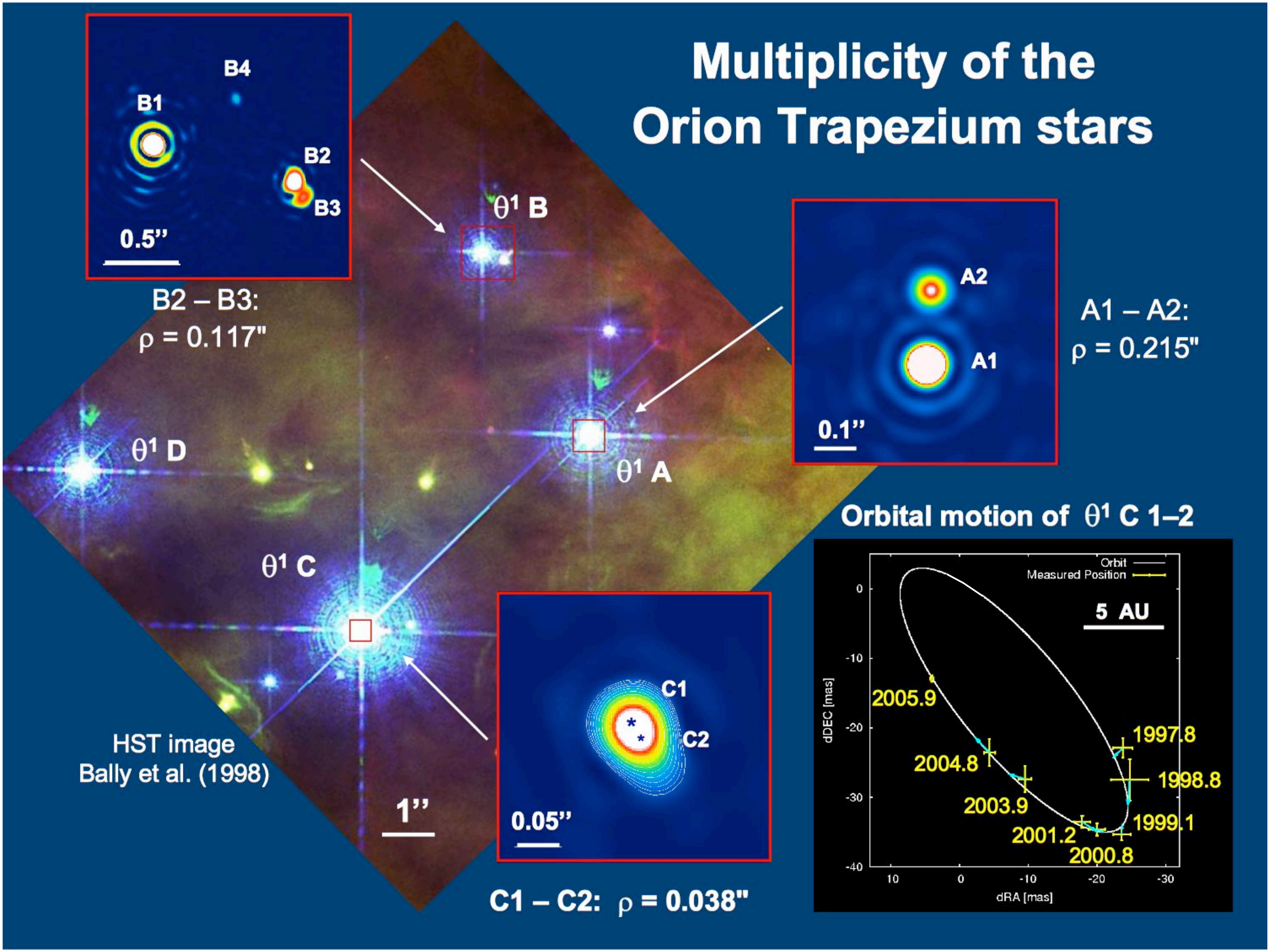
Massive Star Formation: Observations Confound Theory (1/2)

- 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

The Initial Mass Function

Trapezium cluster
(Muench et al. 2001)





Multiplicity of the Orion Trapezium stars
B4
B1
B2
B3
0.5''
B2 – B3:
ρ = 0.117"
θ1 B
A2
A1
0.1''
A1 – A2:
ρ = 0.215"
θ1 D
θ1 A
θ1 C
Orbital motion of θ1 C 1–2
Orbit
Measured Position
5 AU
dDEC [mas]
dRA [mas]
2005.9
2004.8
2003.9
2001.2
2000.8
1999.1
1998.8
1997.8
C1
C2
0.05''
HST image
Bally et al. (1998)
1''
C1 – C2: ρ = 0.038"

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

- 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 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!

The Global Picture

- 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 $M_{O\text{-star}}$ 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 $M_{O\text{-star}}$
  - Every 200 yr produce >20 $M_{O\text{-star}}$
  - Every 400 yr produce >30 $M_{O\text{-star}}$
  - Every 1000 yr produce >50 $M_{O\text{-star}}$

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

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 = 0.7%

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

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

$\Rightarrow$ 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)

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

Assume

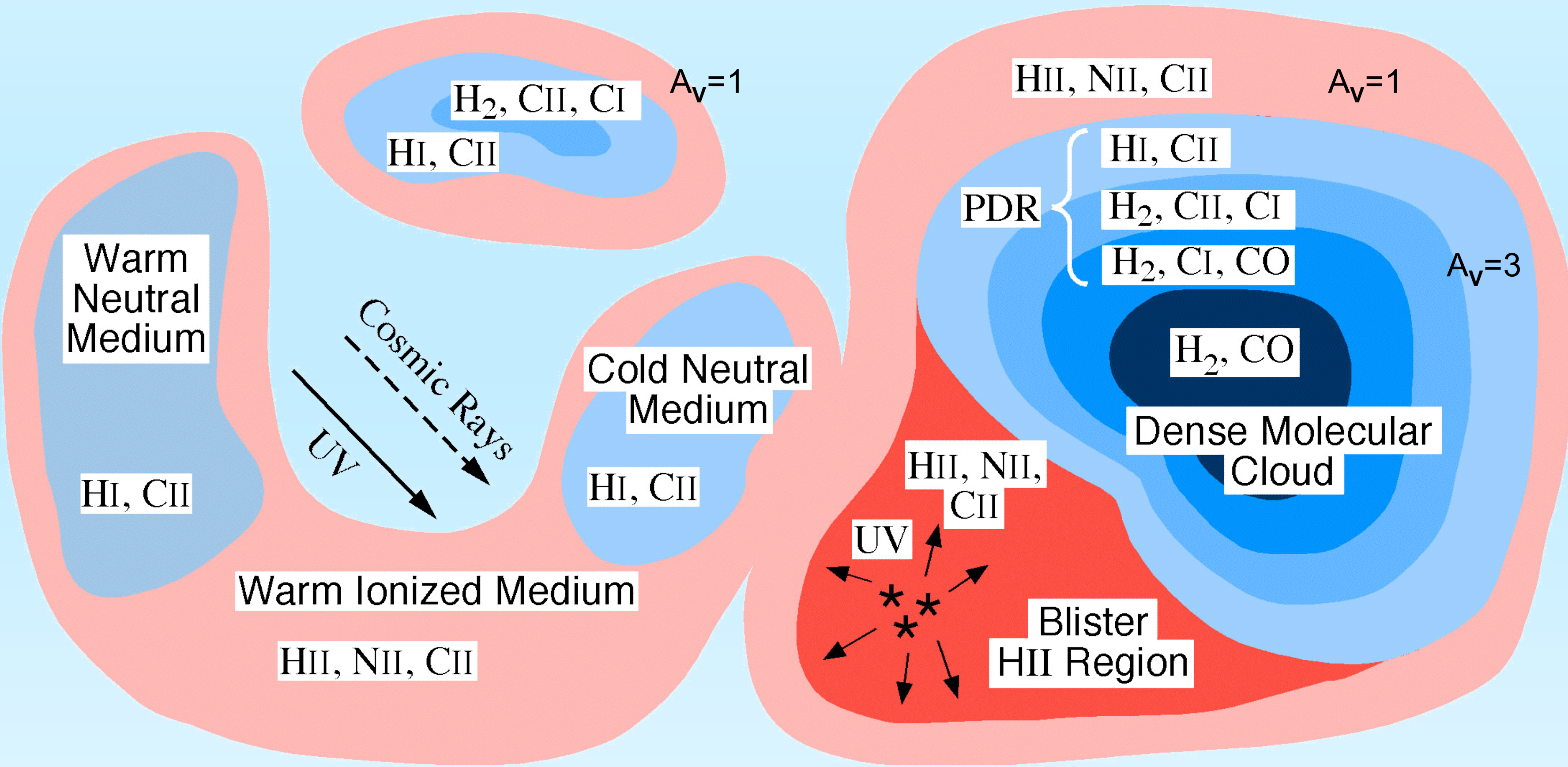
- 10^{10} M_{o} ISM, of which 40% is molecular
- Star Formation efficiency of 50%

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?



Steps to produce Massive Stars

- 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 $R_o = 2.3 \times 10^{-8}$ 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

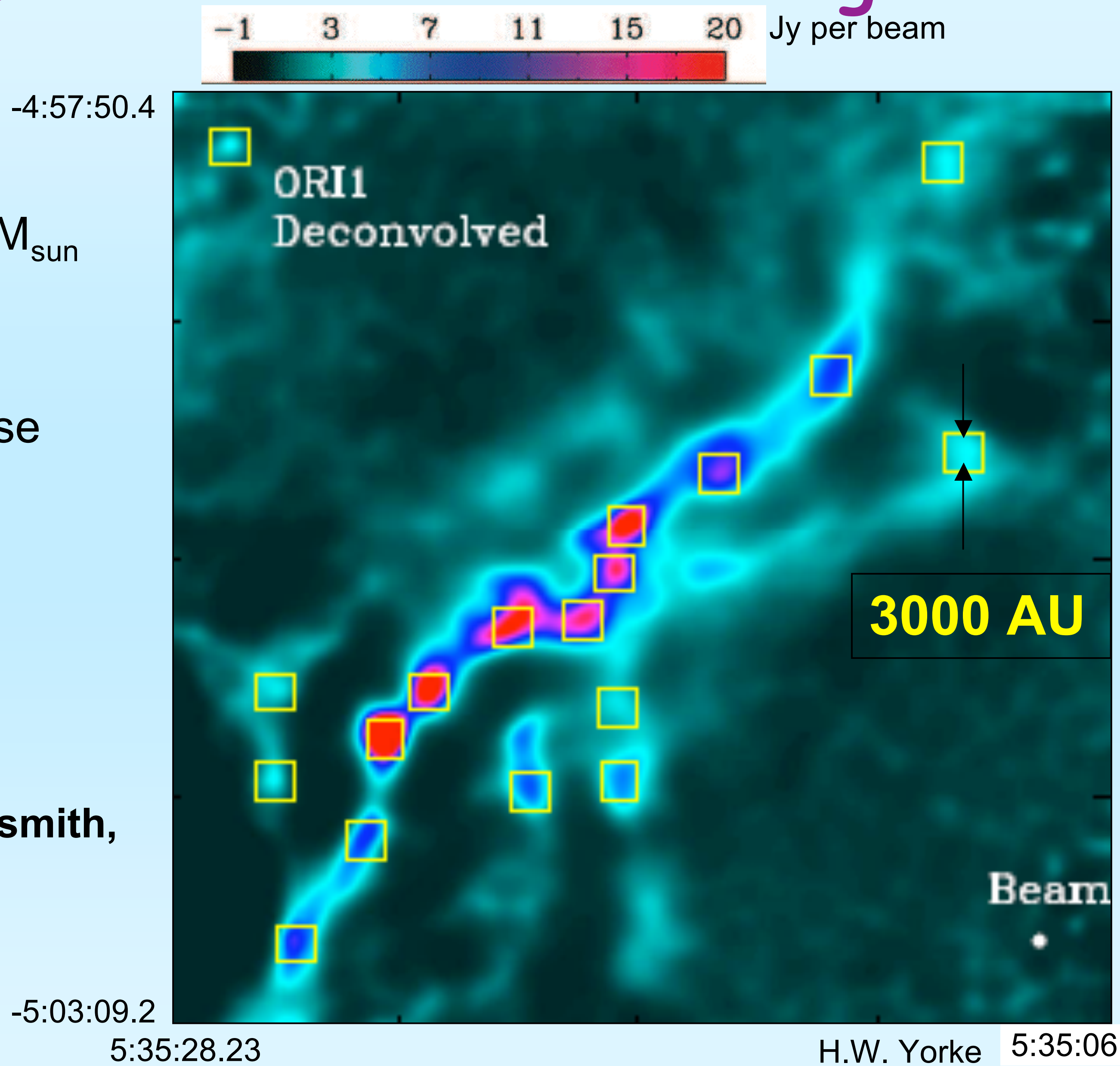
? yr

200,000 yr

350 μm Cores in the Orion Region

51 cores 0.1 to 46 M_{sun}

Many appear to be unstable against gravitational collapse



Li, Velusamy, Goldsmith, & Langer (2007)

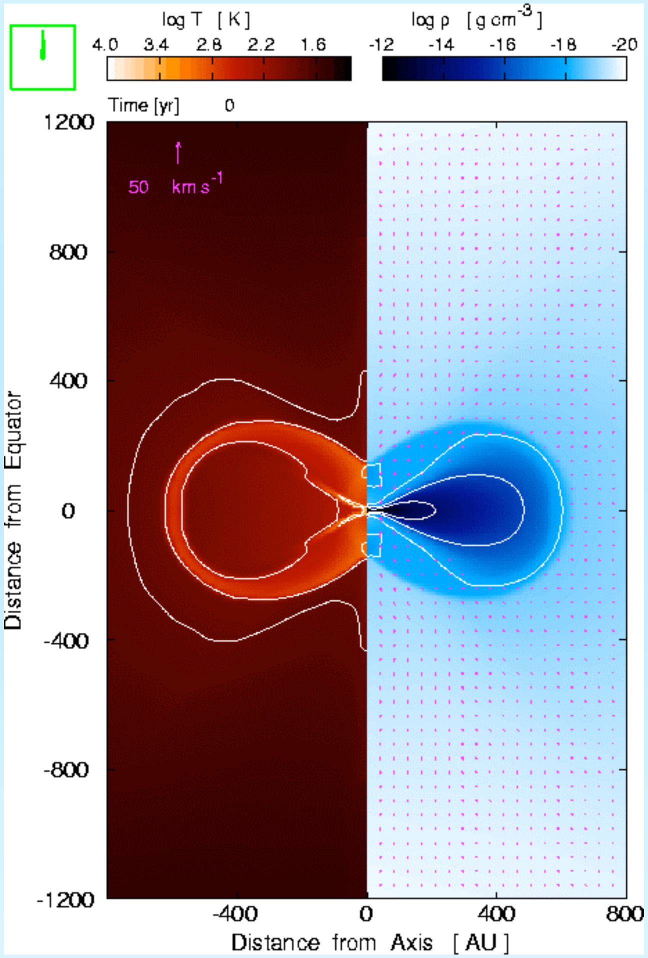
H.W. Yorke

Questions which need to be answered

- Assuming a gravitationally unstable massive clump (10^{-1} pc), how does enough material become concentrated into a sufficiently small volume (a few 10^{-8} pc) within a sufficiently short time ($\sim 10^5$ yr)?
- How does the forming massive star influence its immediate surroundings to limit its mass?
- Today I will not try to answer these questions

Destruction of circumstellar disks

- Destruction of circumstellar disk:



Initial conditions

Luminosity of star:	3550 L_o
Mass of central star:	8.3 M_o
Stellar wind:	30 km s^{-1} 10^{-8} M_o yr^{-1}
Mass of disk:	0.7 M_o
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

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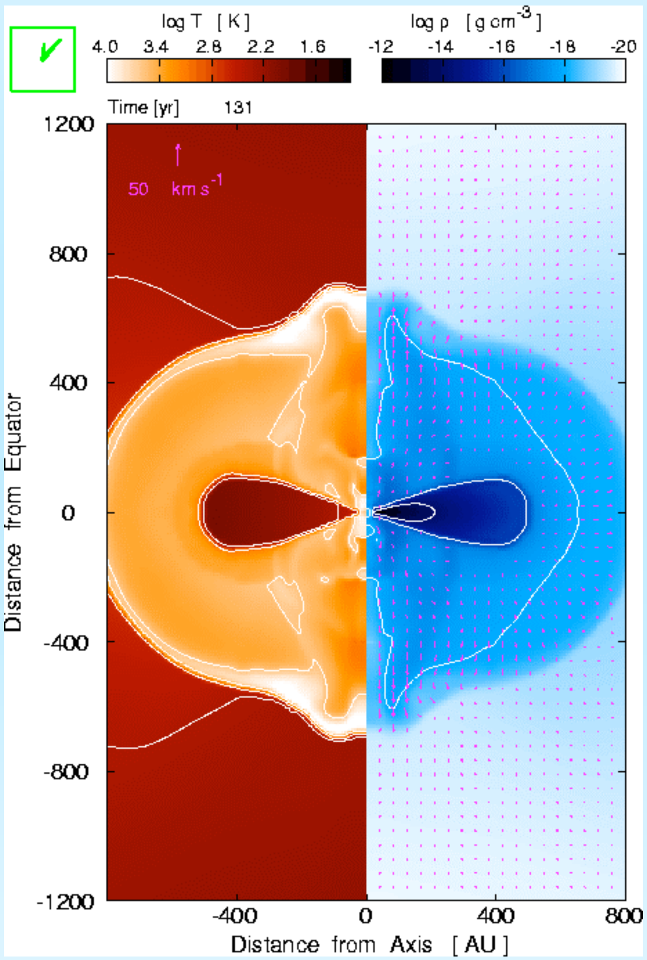

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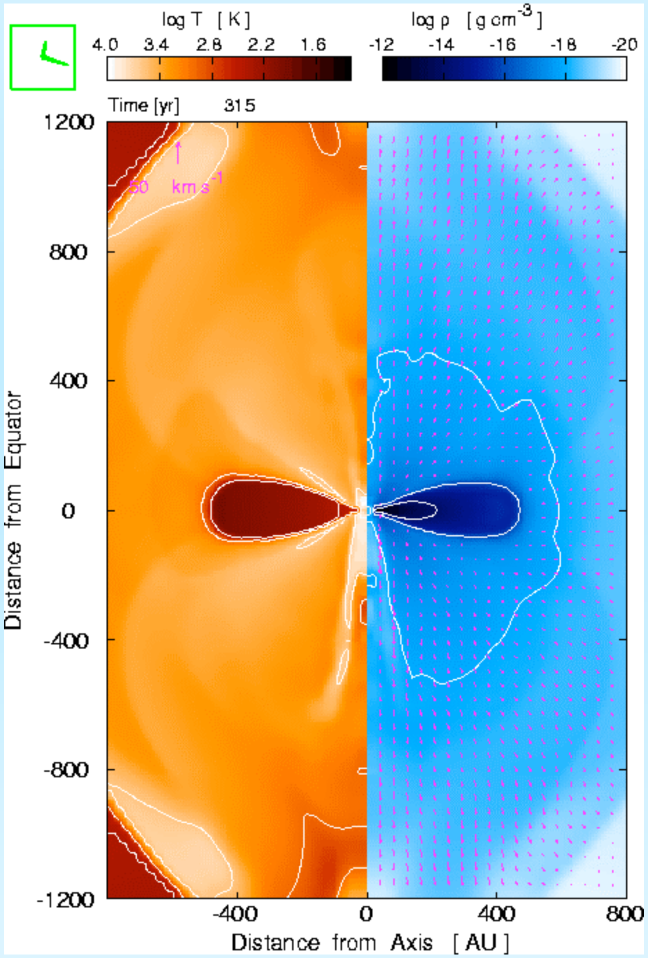

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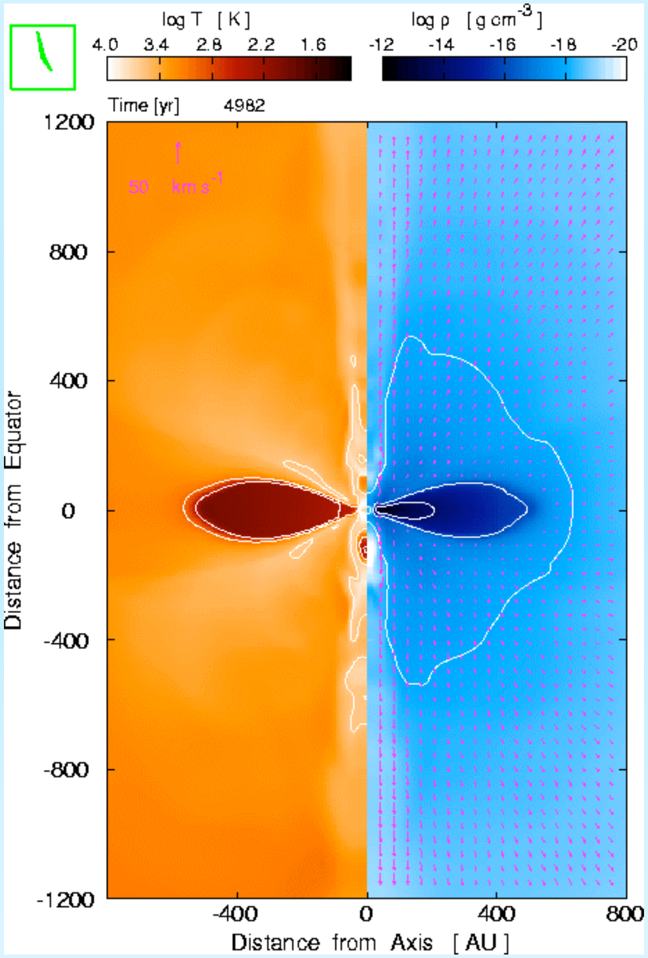

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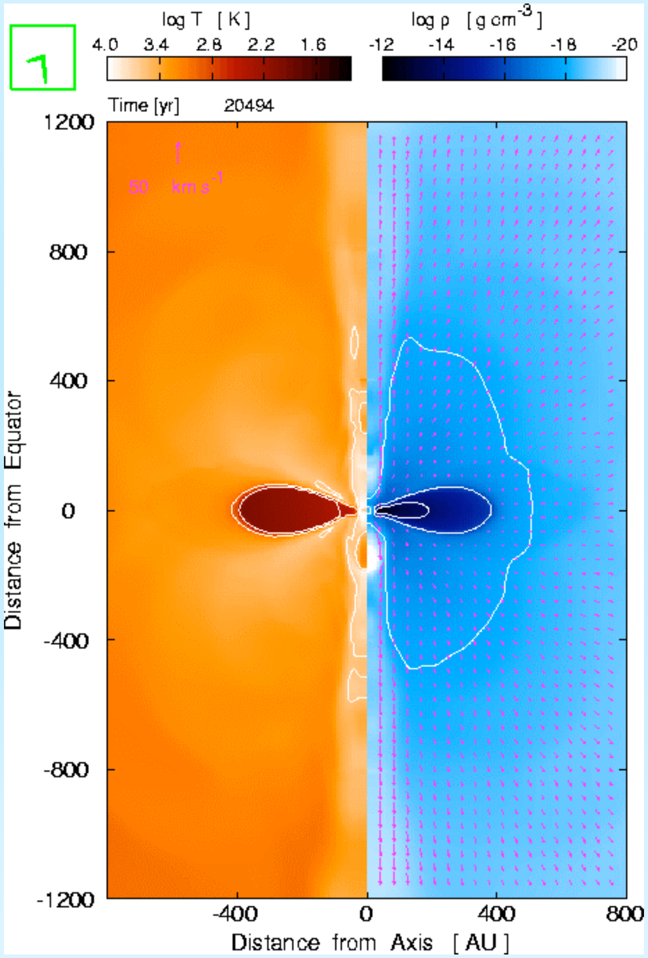

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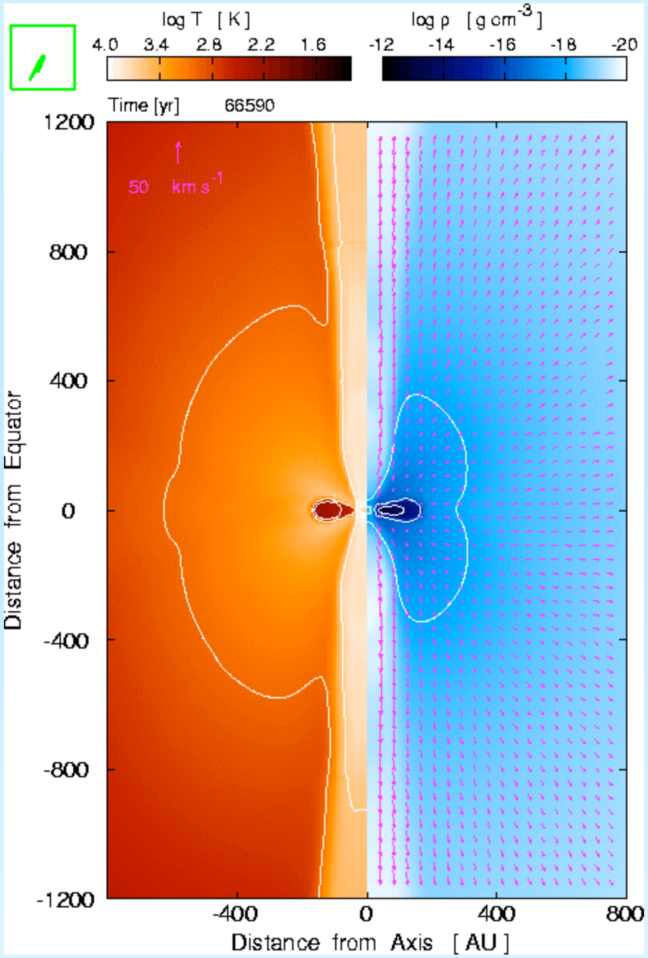

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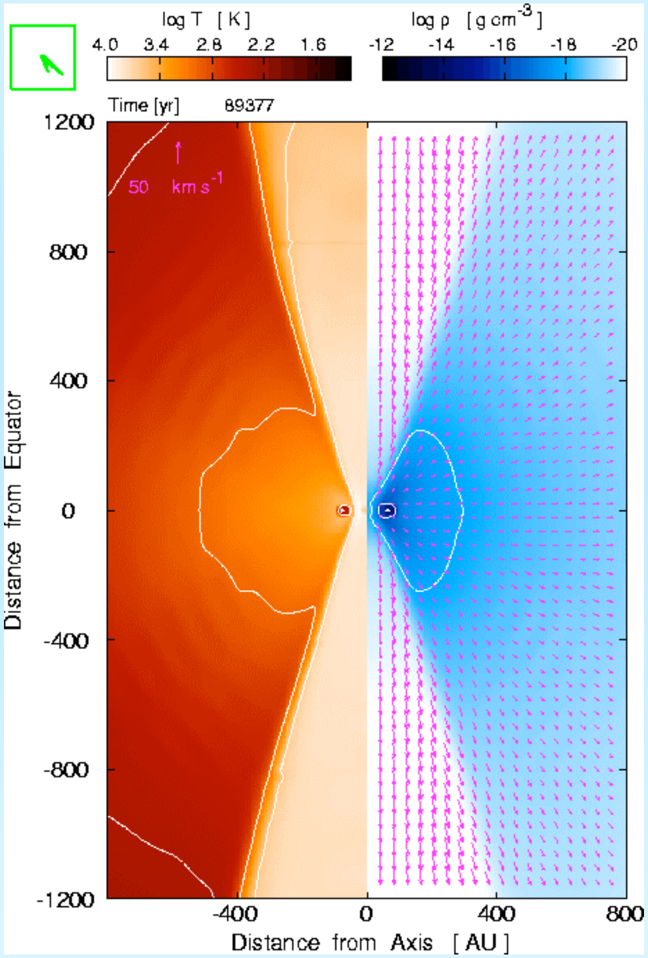

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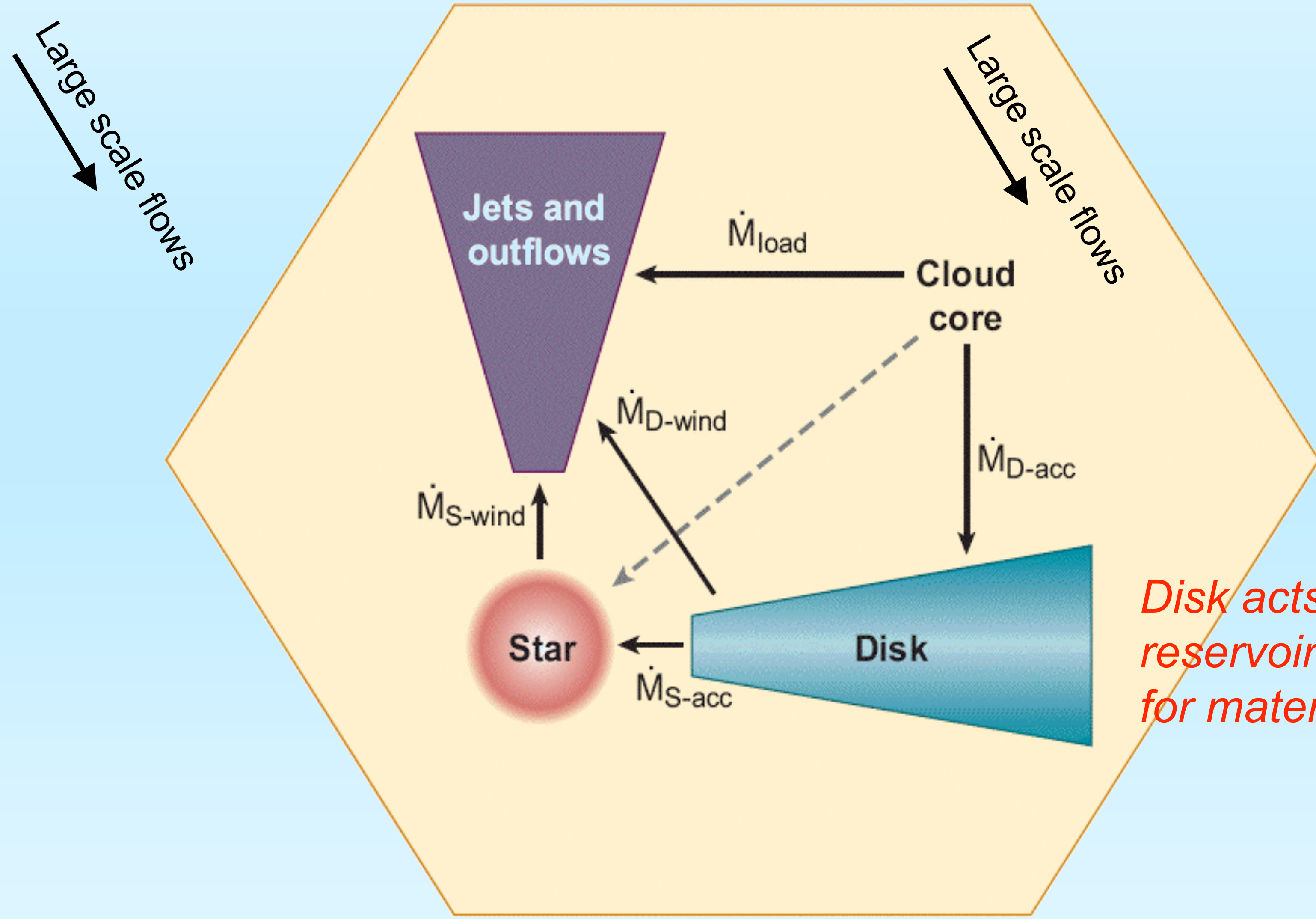
Accretion and mass loss as mass exchange between components



Disk acts as reservoir for material

Necessary conditions for forming stars by accretion

- The mass gained by accretion must exceed losses

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

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

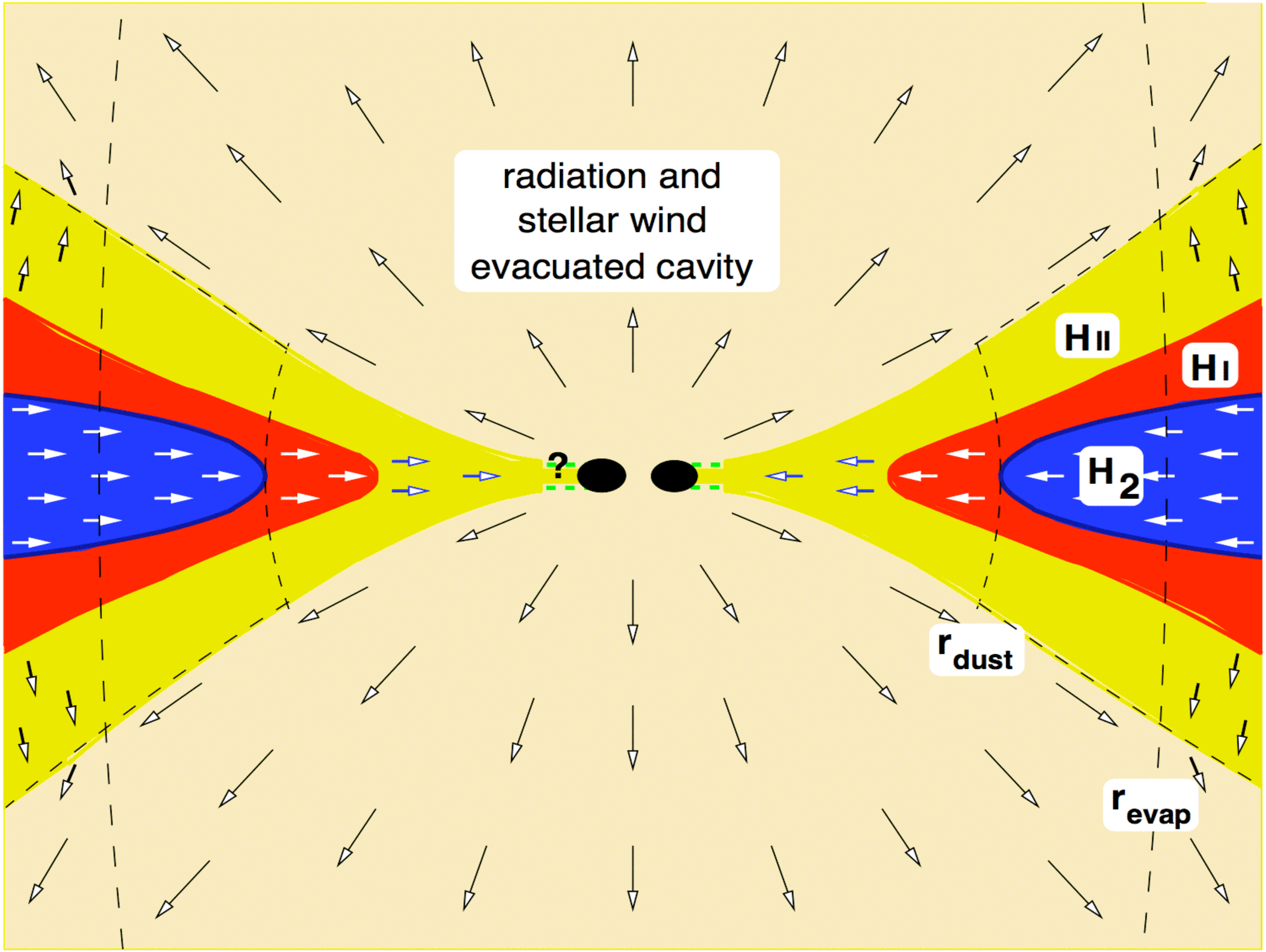
- Must accrete material within "reasonable" time

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

- Gravity must be dominant force

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

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



radiation and stellar wind evacuated cavity
H II
H I
H_2
?
r_{dust}
r_{evap}

What determines these dM/dt's?

- $\dot{M}_{disk}$ 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

Important relevant time scales

- Free-fall time scale

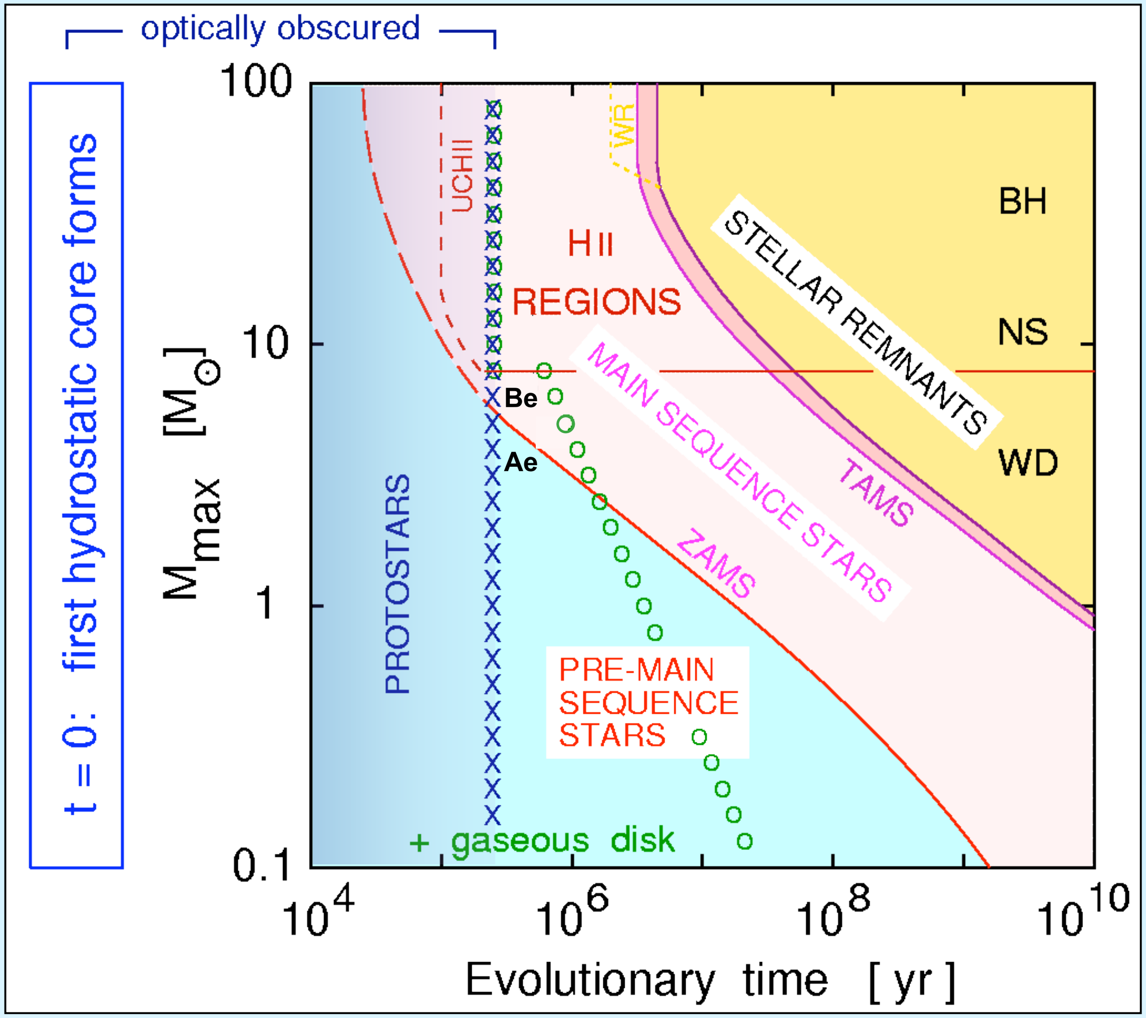
$$t_{\rm ff} \simeq 10^5\,{\rm yr}\left[\frac{n}{10^5\,{\rm cm}^{-3}}\right]^{-1/2}$$

- Accretion time scale

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

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

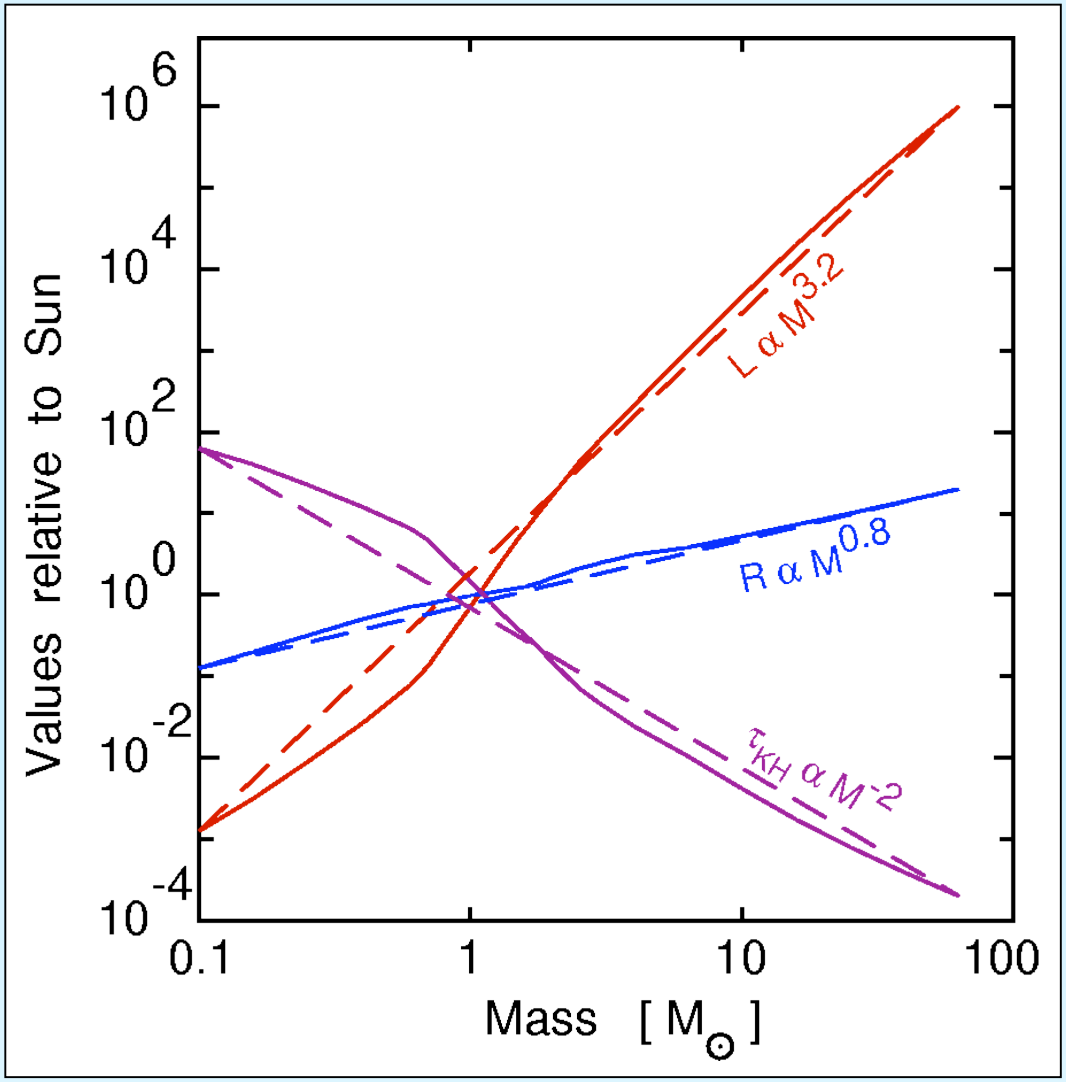
$$\tau_{\rm KH} = \frac{GM^2/R}{L} \sim M^{-2}$$



Luminosity & Radius of ZAMS star

Kelvin-Helmholtz timescale
(for thermal readjustment)

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



Sources of Luminosity of accreting Stars

- 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

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

Important relevant length scales

- 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

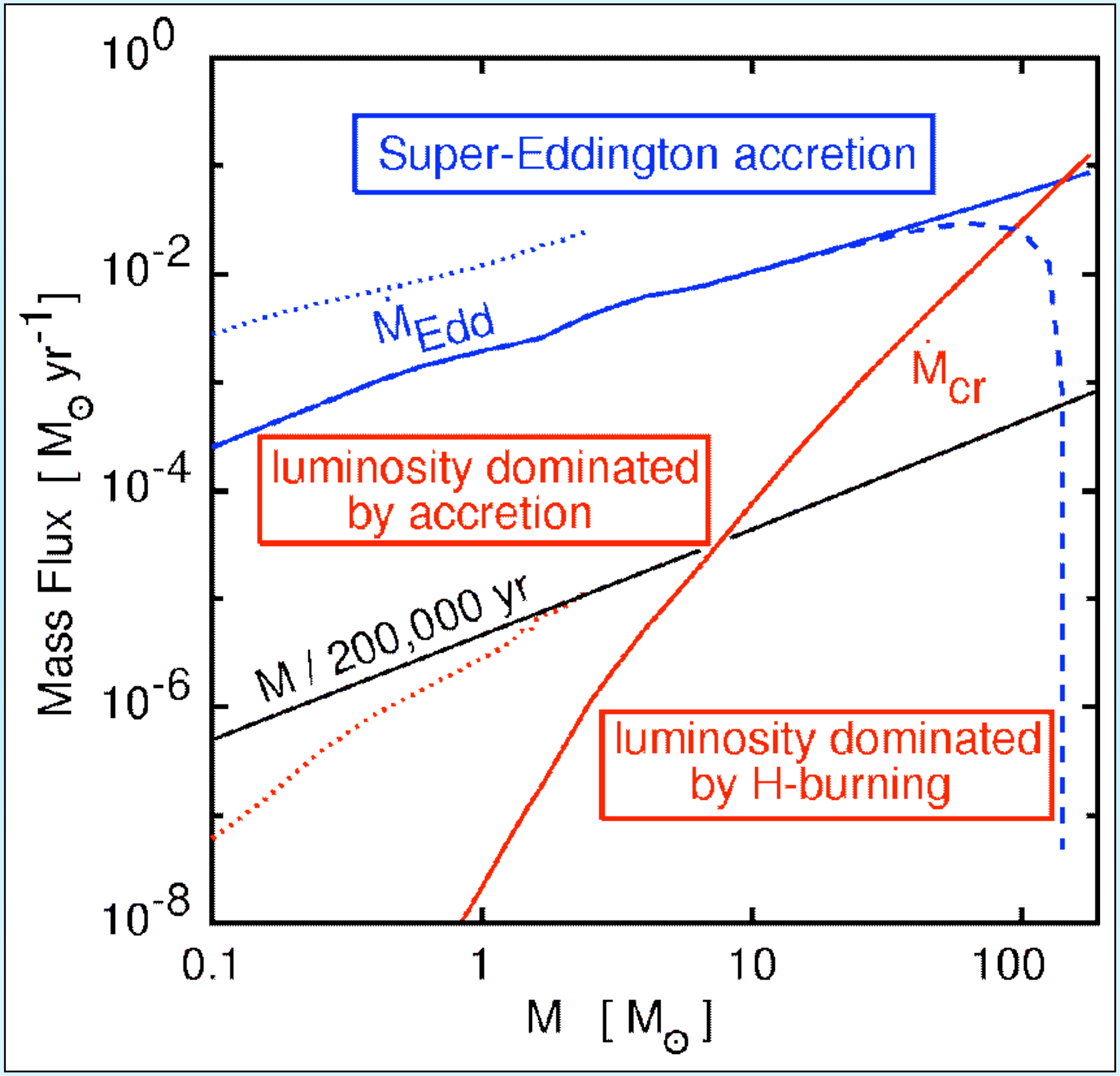
$$r_{\rm dust} \simeq 25\ {\rm AU} \left[\frac{L}{1.5 \cdot 10^5\ {\rm L_\odot}}\right]^{1/2}$$

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

- Stellar radius

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

The Eddington accretion limit



Assume electron scattering for minimum opacity...

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

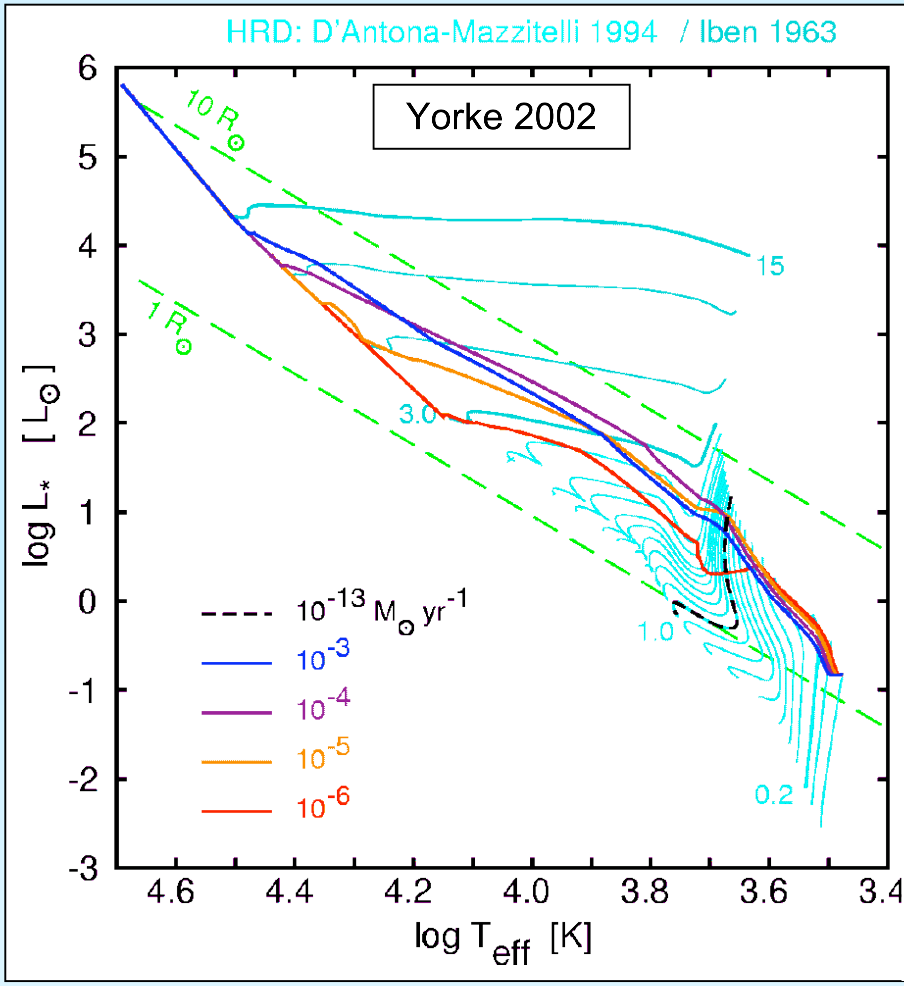
$$L_{Edd} = L_* + \frac{GM}{R}\dot{M}_{max}$$

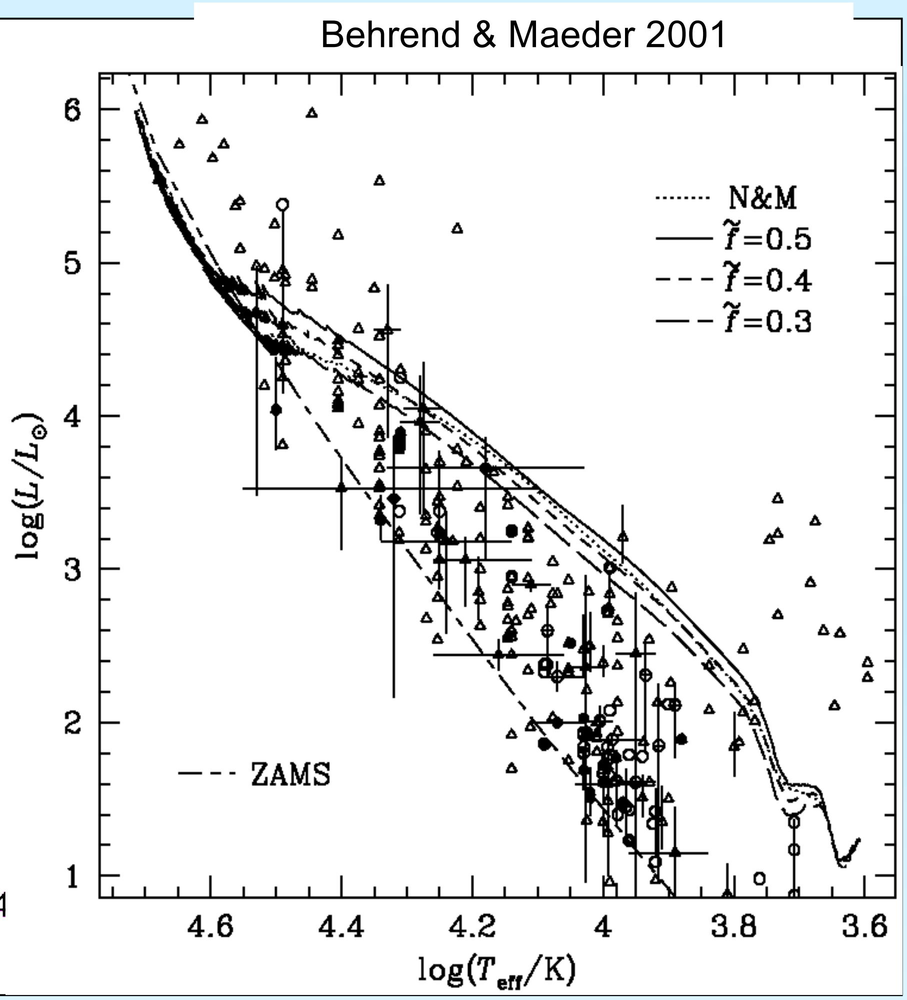
$$\dot{M}_{max} = \frac{4\pi Rc}{\kappa_e} - \frac{RL_*}{GM}$$

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

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

(Yorke 2002; Behrend & Maeder 2001)





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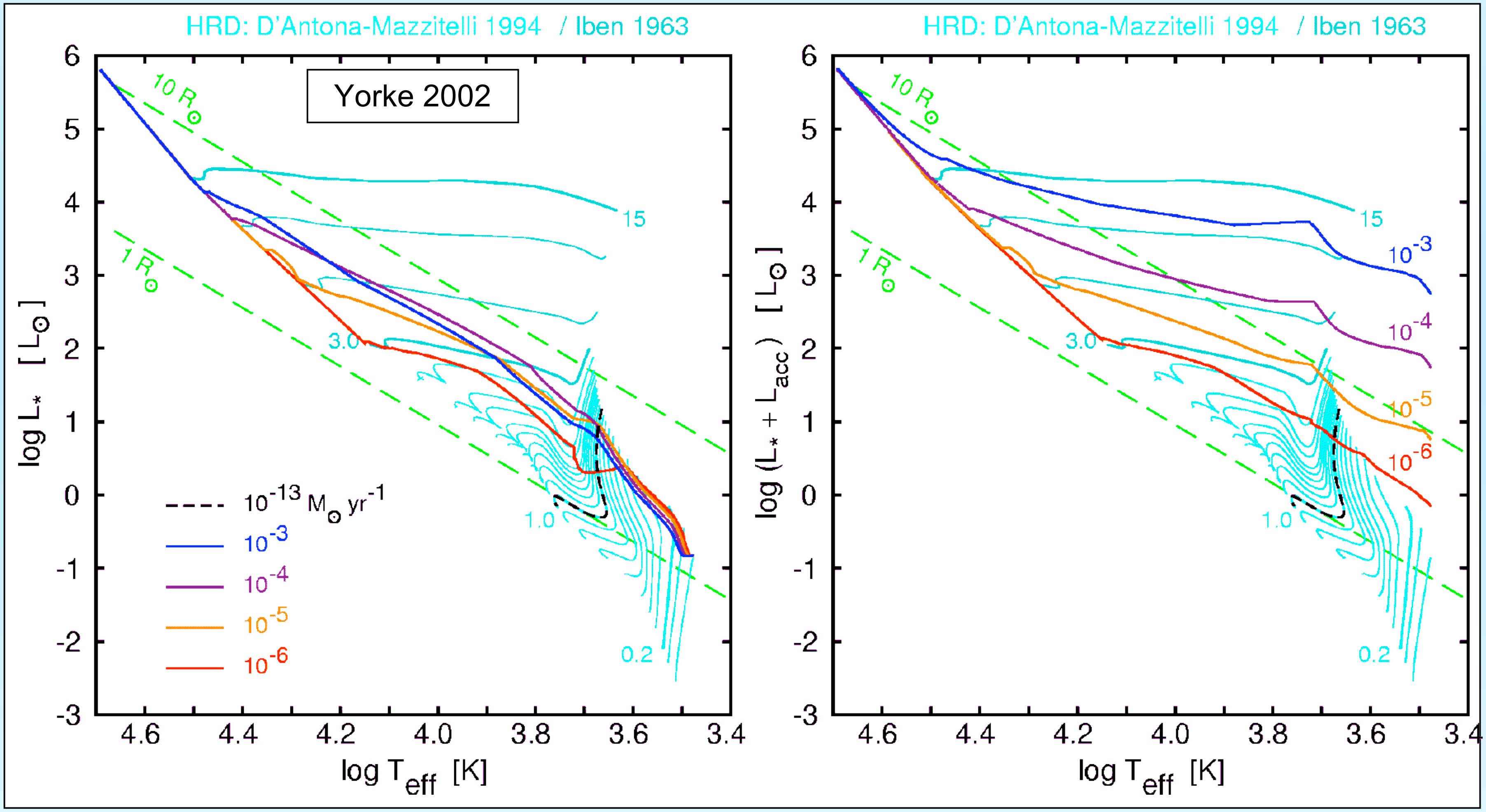

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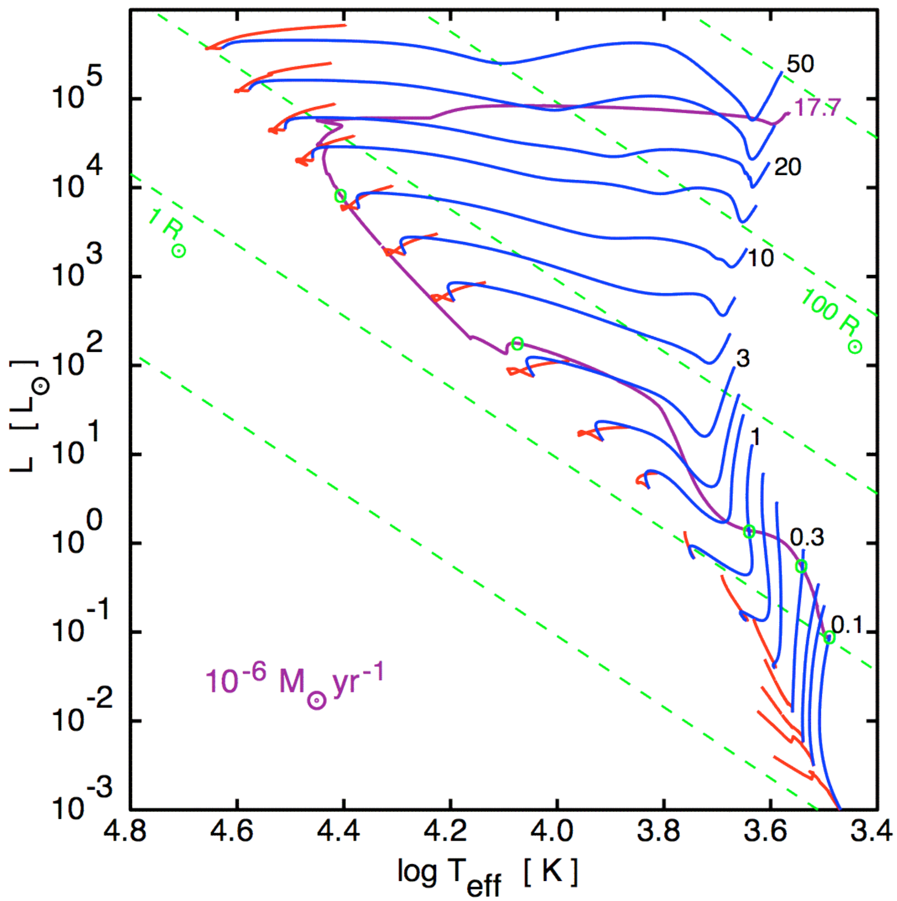

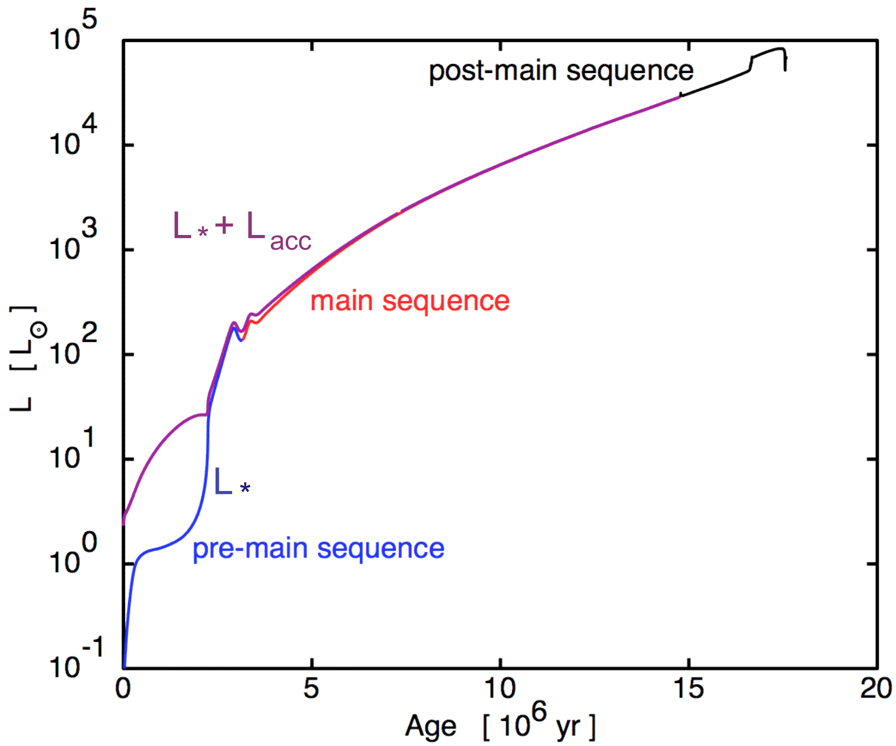

Yorke & Bodenheimer (in prep)

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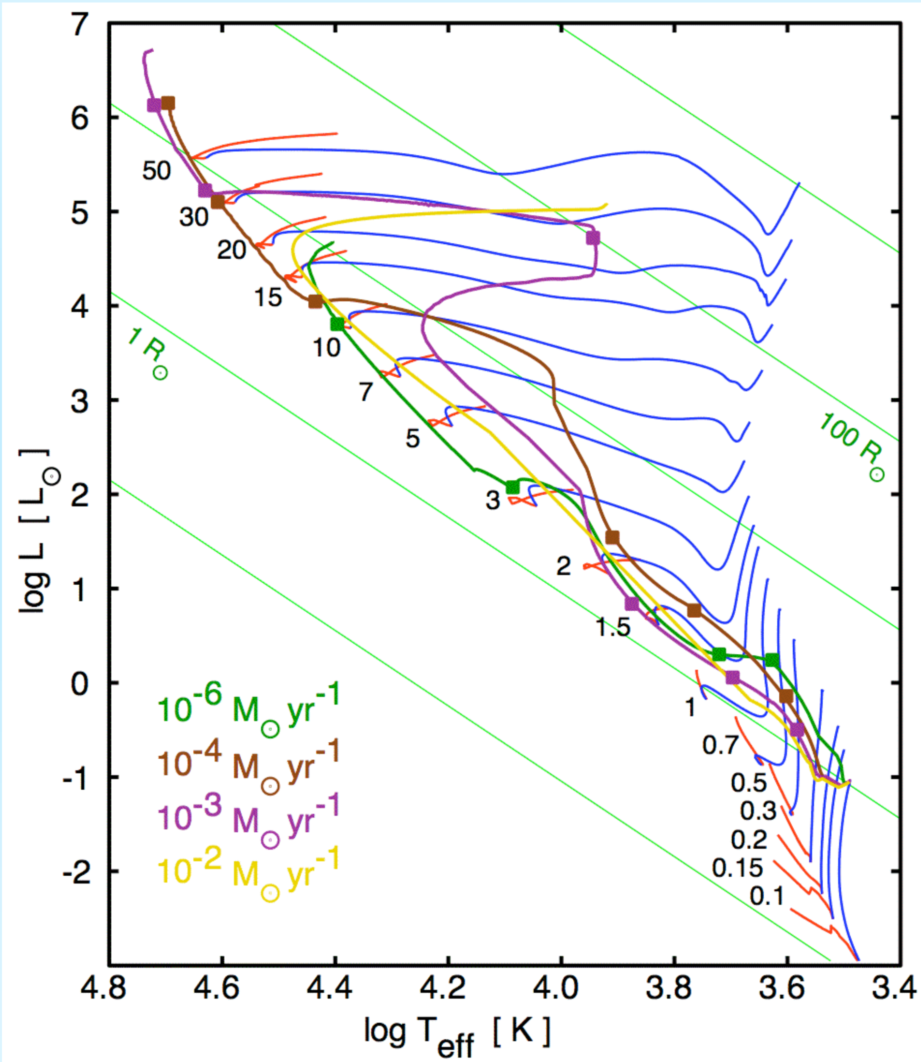

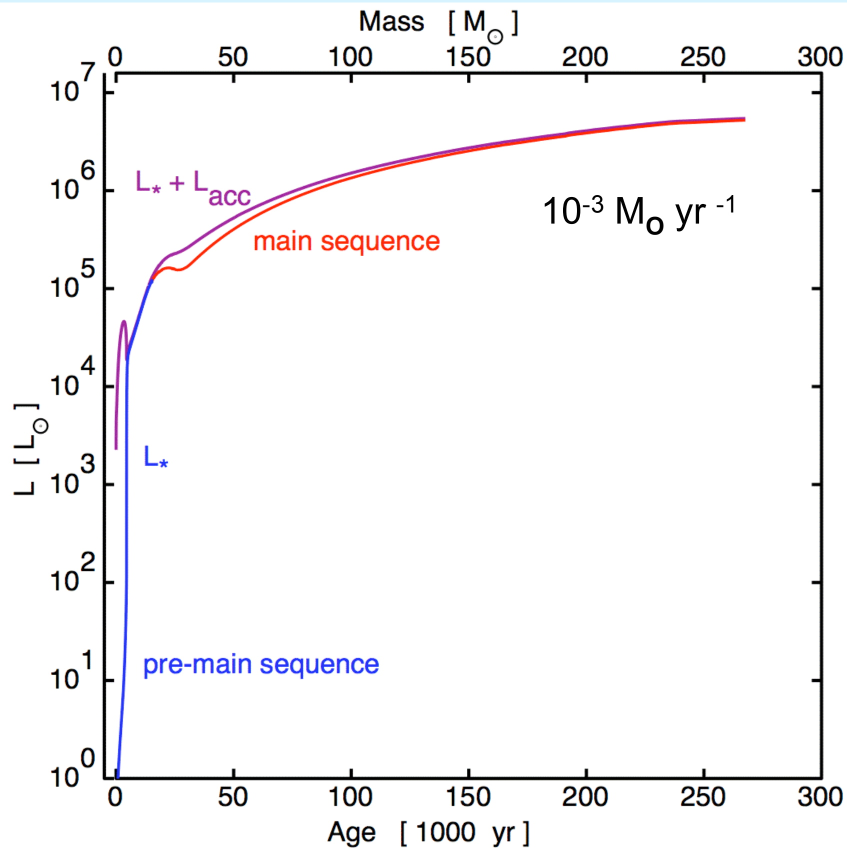

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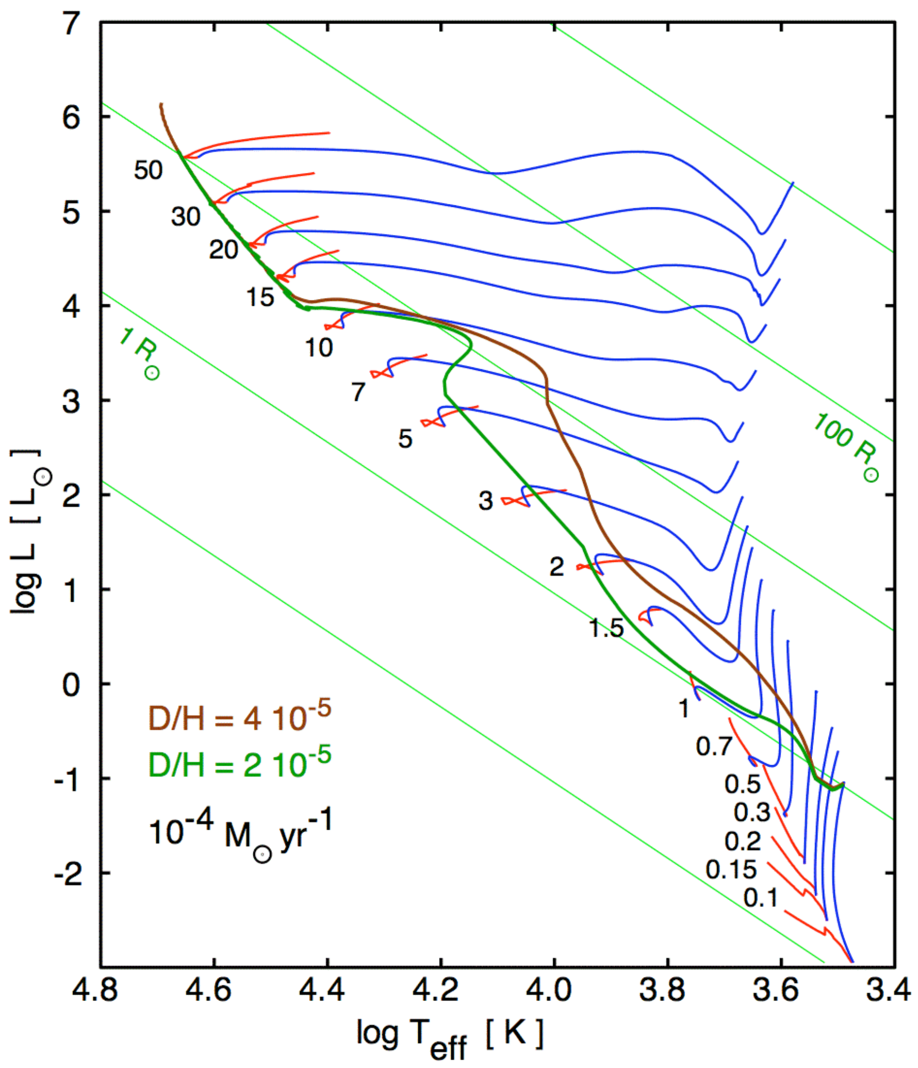
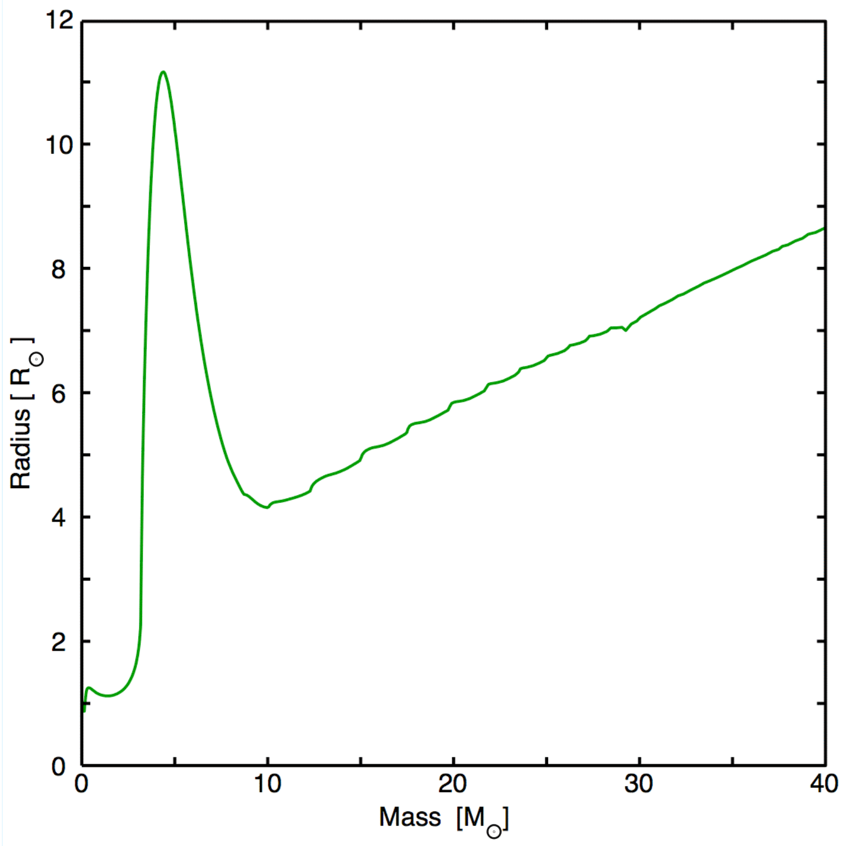
11 Sep 2007

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





Yorke & Bodenheimer (in prep)

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

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

Concluding Remarks

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

Conclusions

- 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