Disks and the Formation of the Most Massive Stars

Presented at the ESO-MPA-MPA-USM Workshop on:

From Circumstellar Disks to Planetary Systems

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Outline

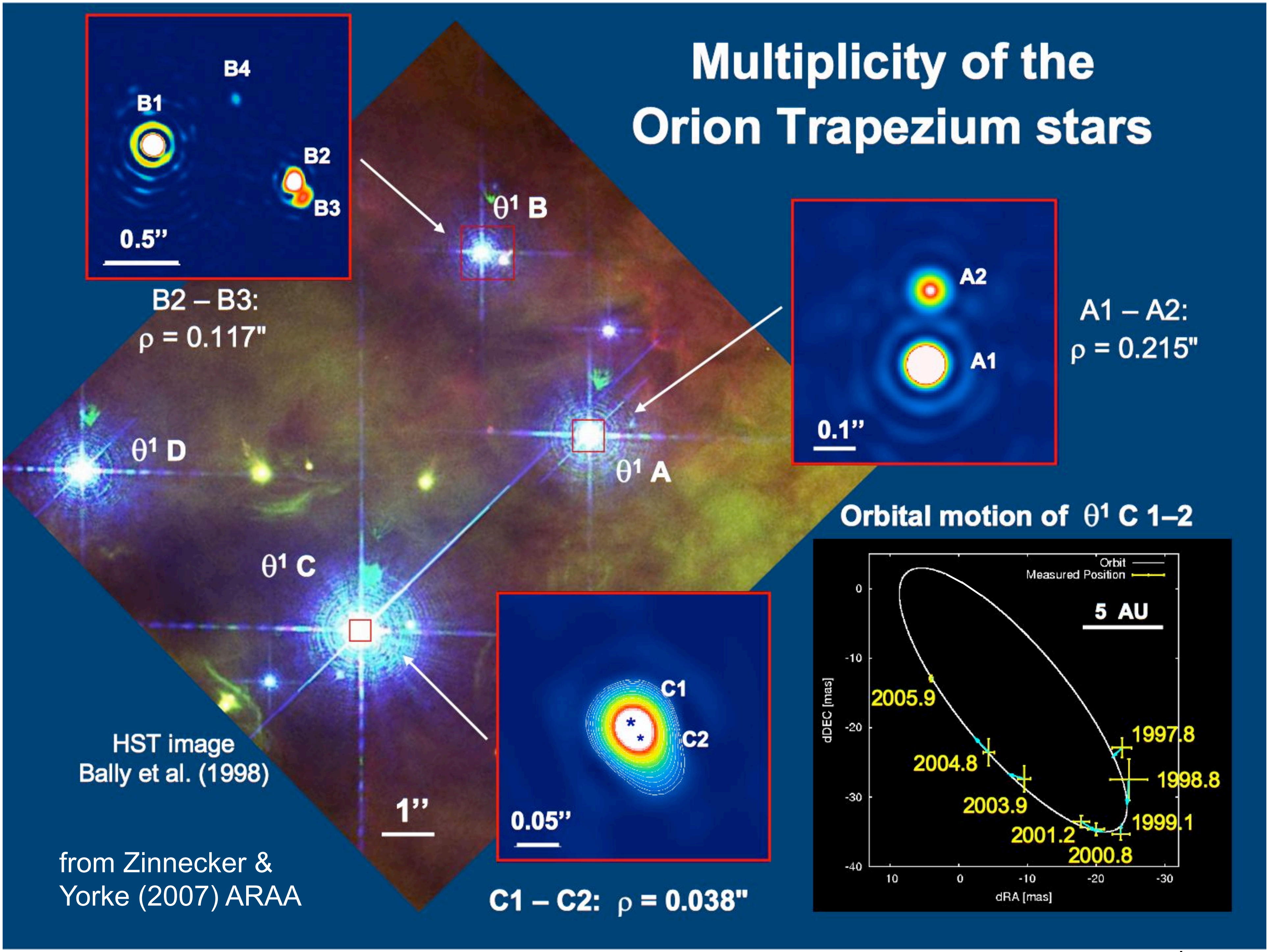
- Introduction
- The evolution of accreting (proto-)stars at high accretion rates
- Destruction and dissipation of cores & disks
- Discussion & Conclusions

Disks and Massive Star Formation: A few selected observational facts

- No disk yet found around an optically visible main sequence O-star
  - Disks around B-stars have been observed
  - There is indirect evidence of disks in early phases: (poorly) collimated outflows
- There are massive molecular cores 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 an O5 magnetic star!

Why is the study of disks around high mass stars so difficult?

- Direct imaging of high mass star forming regions difficult
  - High mass stars are rare (few and far between)
  - High mass stars evolve relatively quickly
  - High mass star forming regions are highly confused
  - High mass star forming regions are highly obscured
- High mass stars generally form in dense clusters with a high degree of multiplicity
  - Examples: Ori TC; NGC 3603; 30 Dor
  - Most O-stars located in center
  - m=1.5 for high mass stars compared to m=0.5 for solar stars
  - O-stars often in close binary systems (P ~ 3-5 d) with a high percentage of double-lined spectroscopic binaries

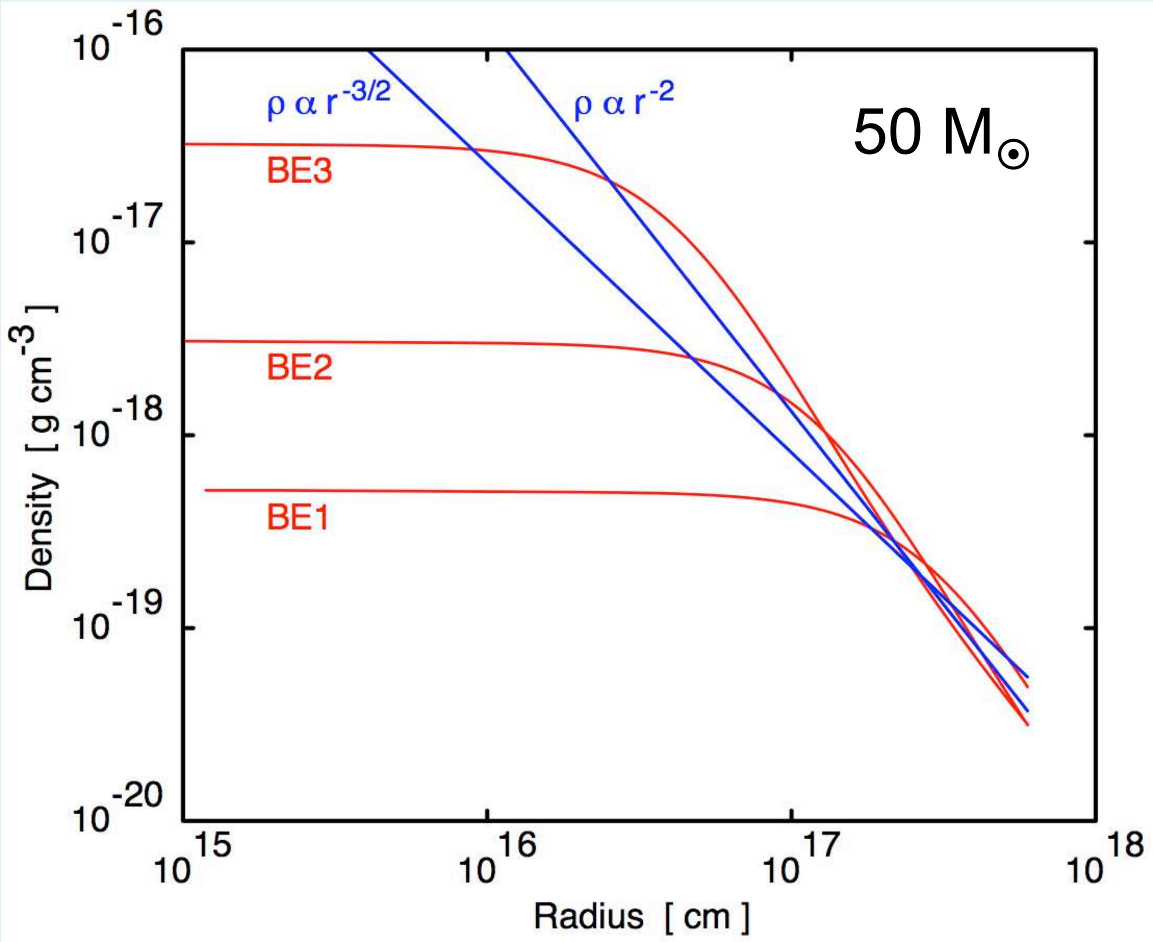


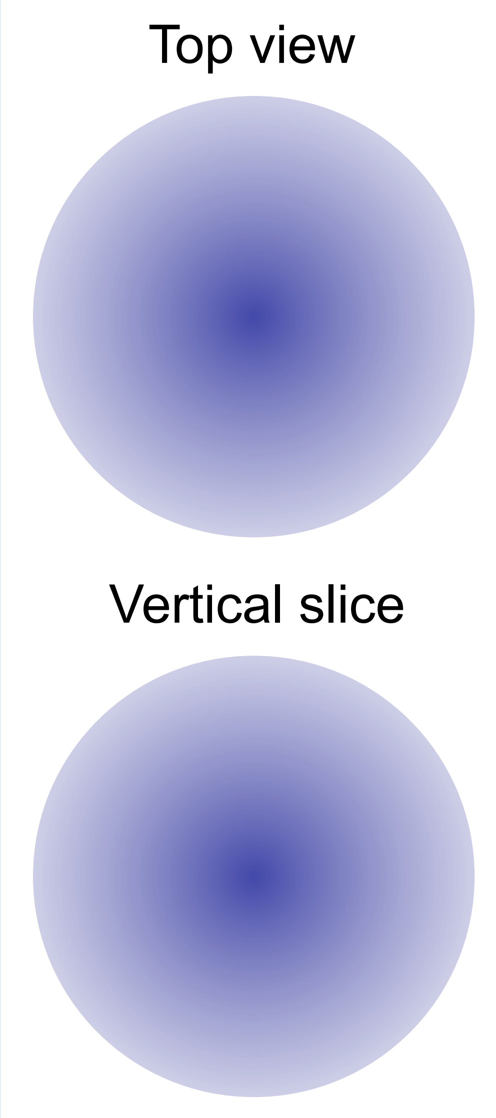
Multiplicity of the Orion Trapezium stars
B4
B1
B2
B3
0.5''
B2 – B3:
ρ = 0.117"
θ^1 B
A2
A1
0.1''
A1 – A2:
ρ = 0.215"
θ^1 D
θ^1 A
θ^1 C
Orbital motion of θ^1 C 1–2
Orbit
Measured Position
5 AU
2005.9
2004.8
2003.9
2001.2
2000.8
1999.1
1998.8
1997.8
dDEC [mas]
dRA [mas]
C1
C2
0.05''
HST image
Bally et al. (1998)
1''
from Zinnecker & Yorke (2007) ARAA
C1 – C2: ρ = 0.038"

Disks are a crucial ingredient of high mass star formation

- Help get rid of angular momentum
  - Multiplicity of high mass stars converts spin angular momentum of contracting/collapsing molecular core into orbital angular momentum
- Allow accretion onto compact high mass star precursors of high luminosity
  - Disk self-shields against radiative acceleration
  - "Flashlight effect" (Yorke & Bodenheimer 1999; Yorke & Sonnhalter 2002) allows most radiation to escape in a direction perpendicular to disk
  - Disk casts shadow of luminous central source, allowing infall of molecular core material onto disks

Rotating Molecular Cores: The "Centripetal Radius"





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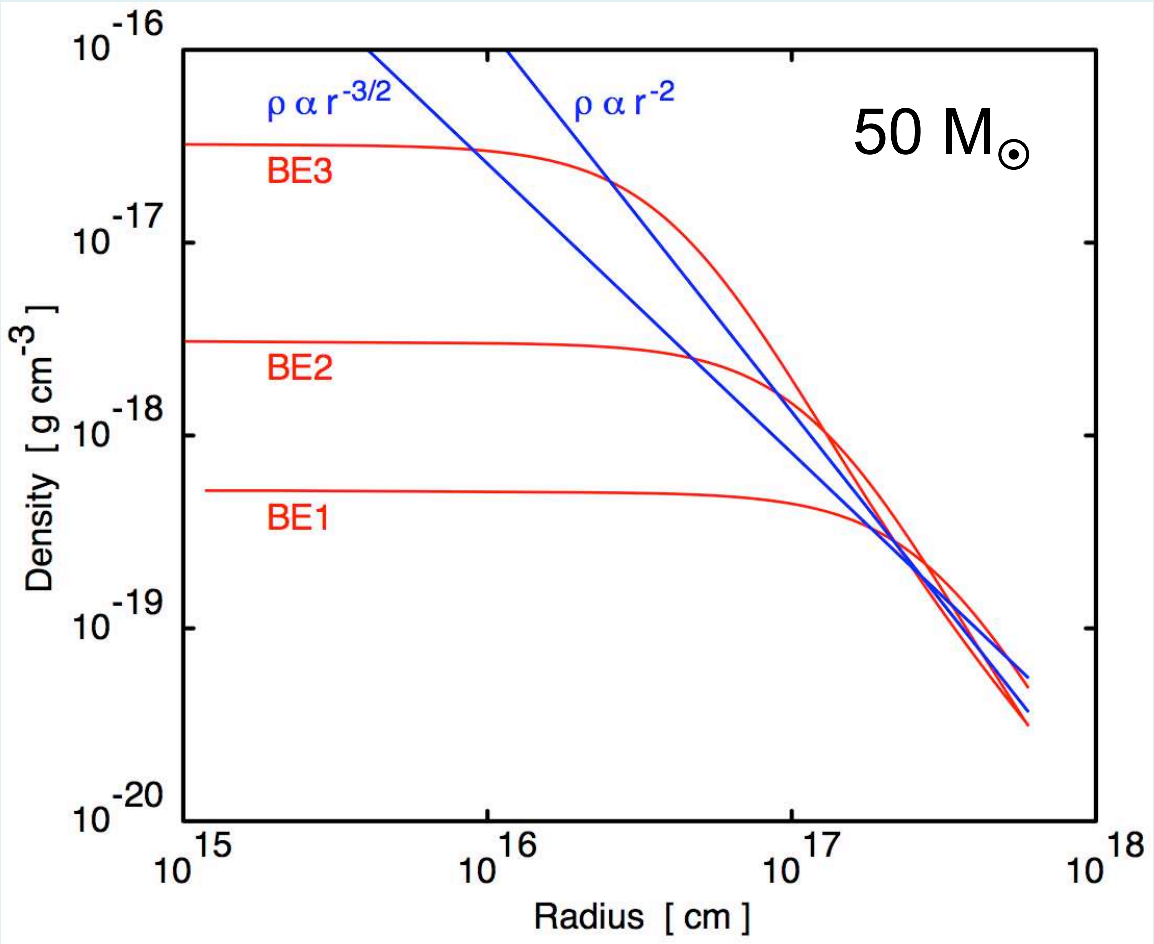

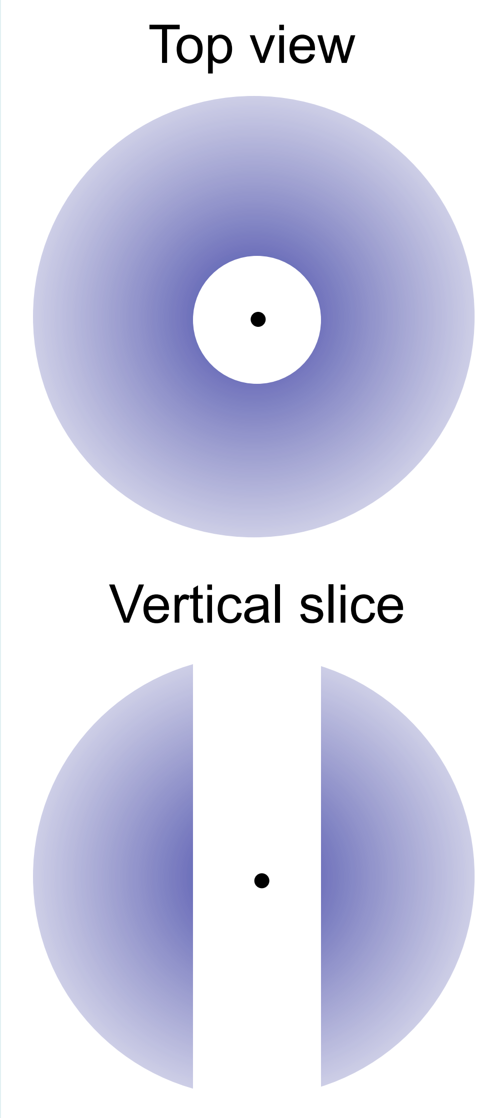

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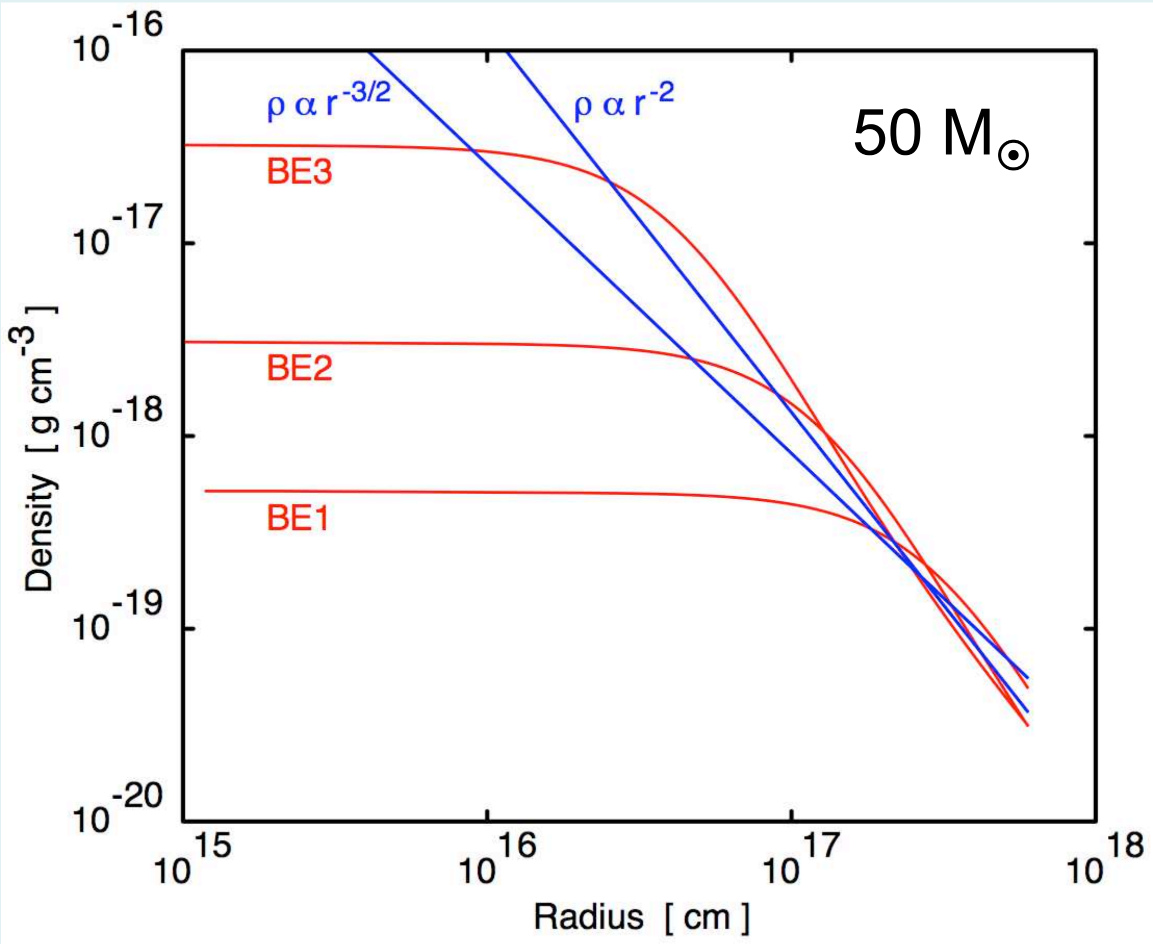

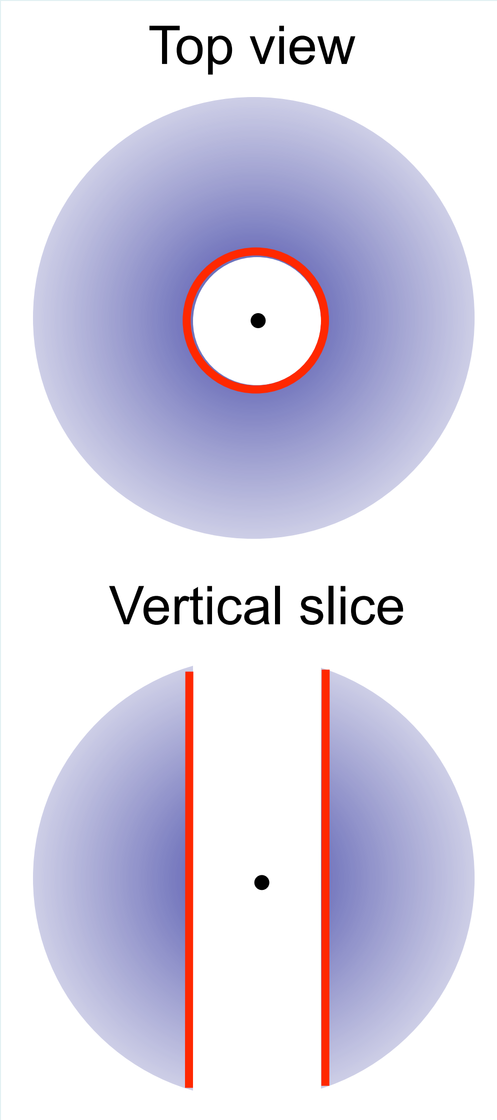

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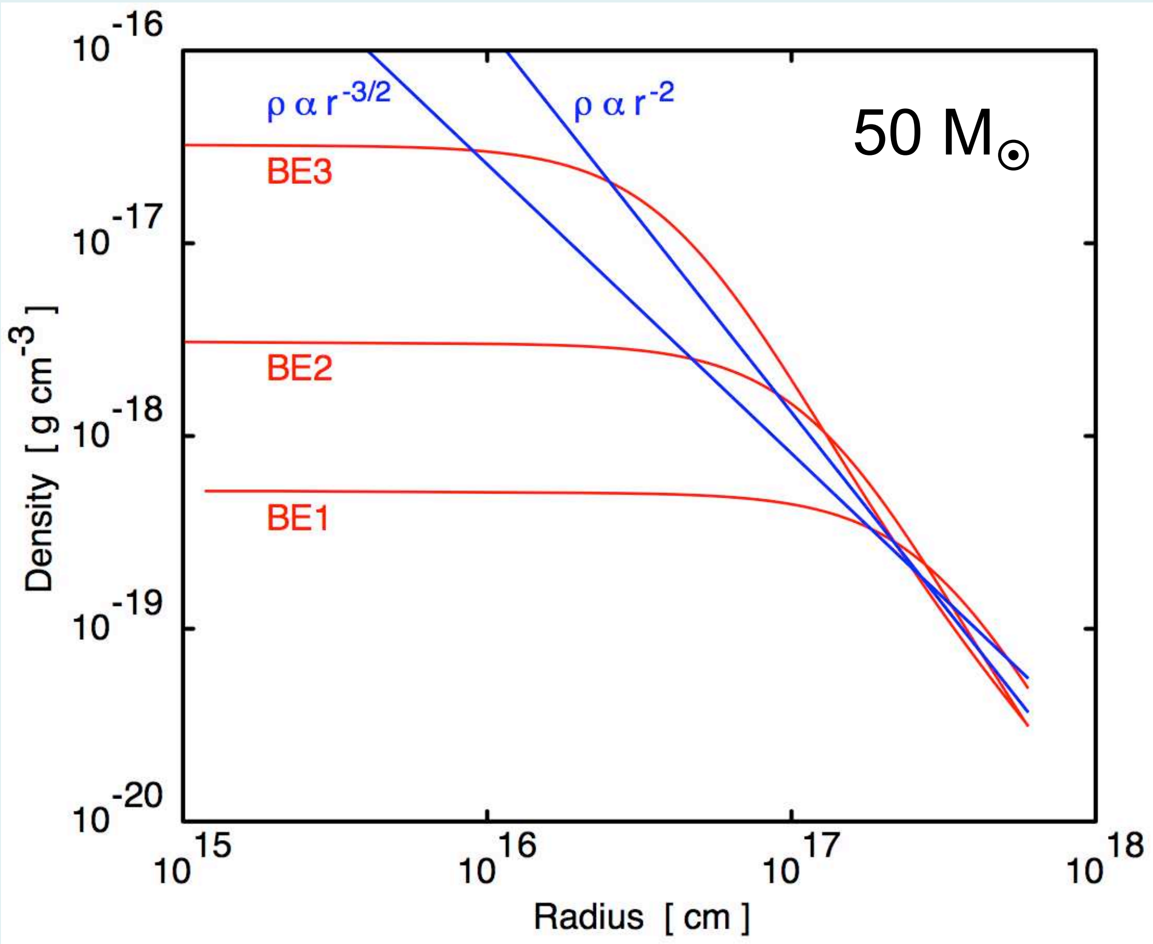
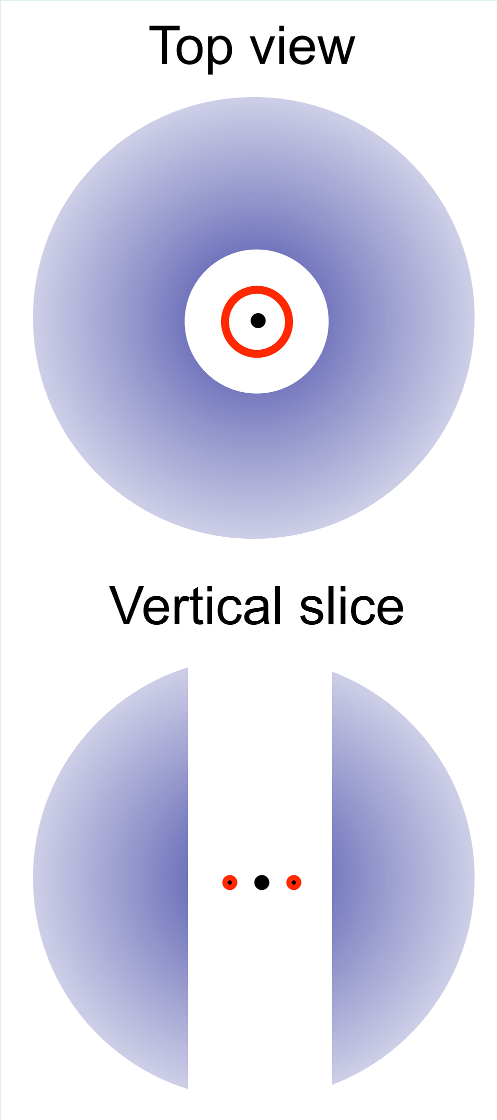
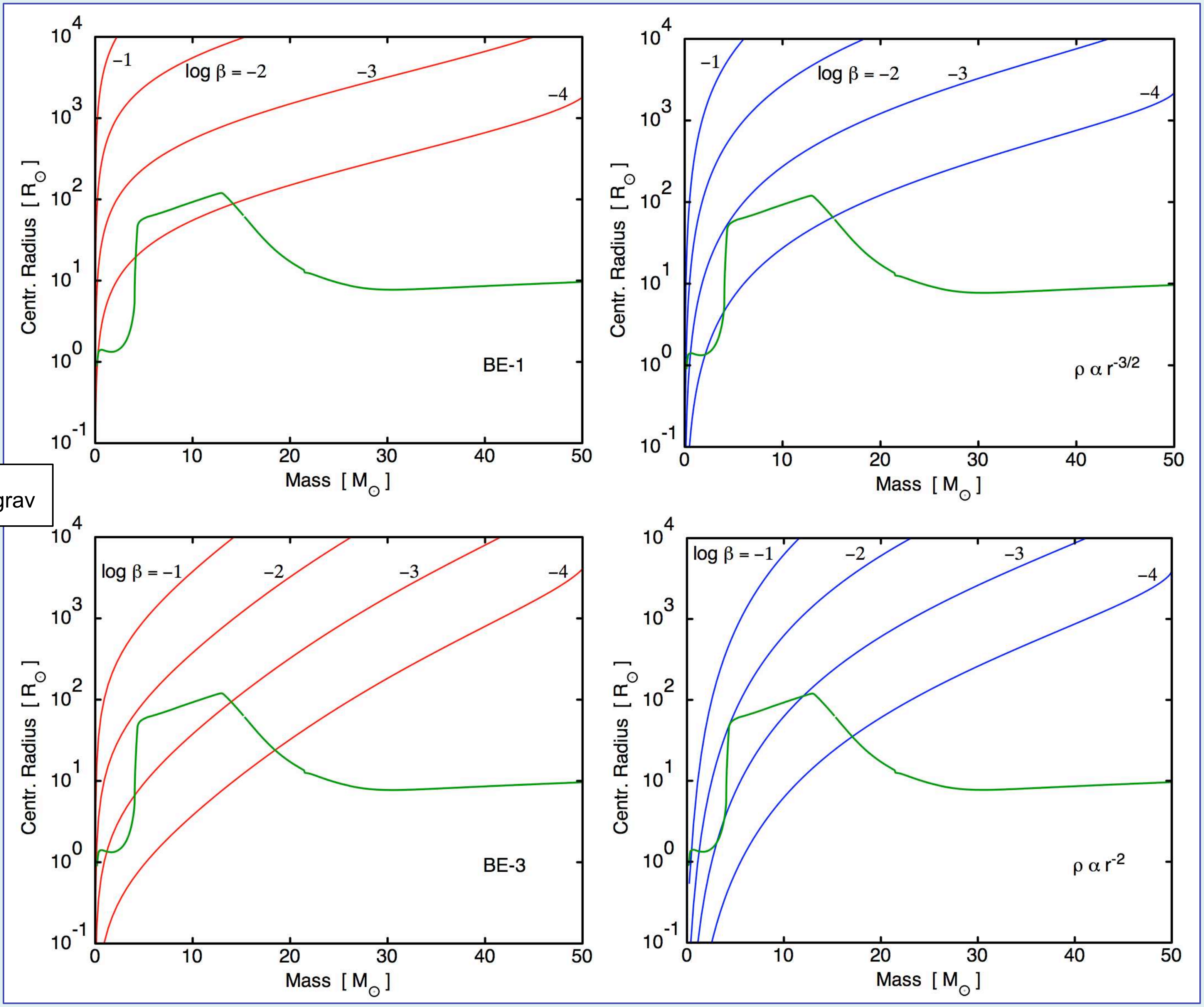




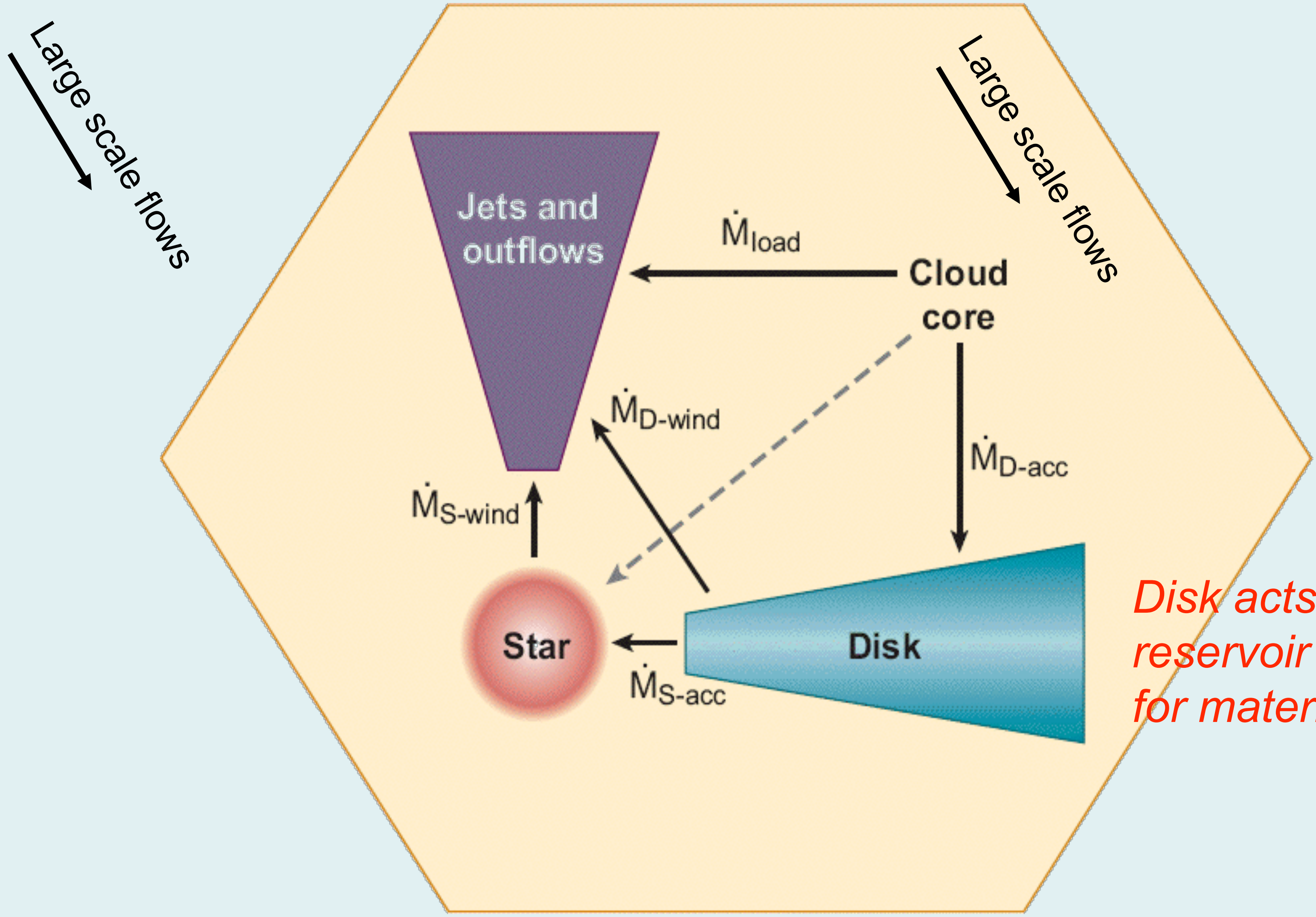


$\beta = E_{rot}/E_{grav}$

The Growth of Stellar Mass by Accretion

- Calculations of molecular core collapse show that infall motions are halted in the central region when it becomes optically thick (several Jupiter masses); when H^- opacity dominates $R \sim R_\odot$
- 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
- Evolution of accreting main sequence stars first considered by Meyer-Hofmeister & Kippenhahn (1977)
- Palla & Stahler (1990) considered accreting pre-main sequence stars (importance of deuterium burning) at modest rates

Accretion and mass loss as mass exchange between components



Disk acts as reservoir for material

Sources of Luminosity of accreting Stars

- Accretion luminosity: $L_{acc} = \xi G M_* / R_* \, dM/dt$

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

- Deuterium burning

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

- PMS Contraction

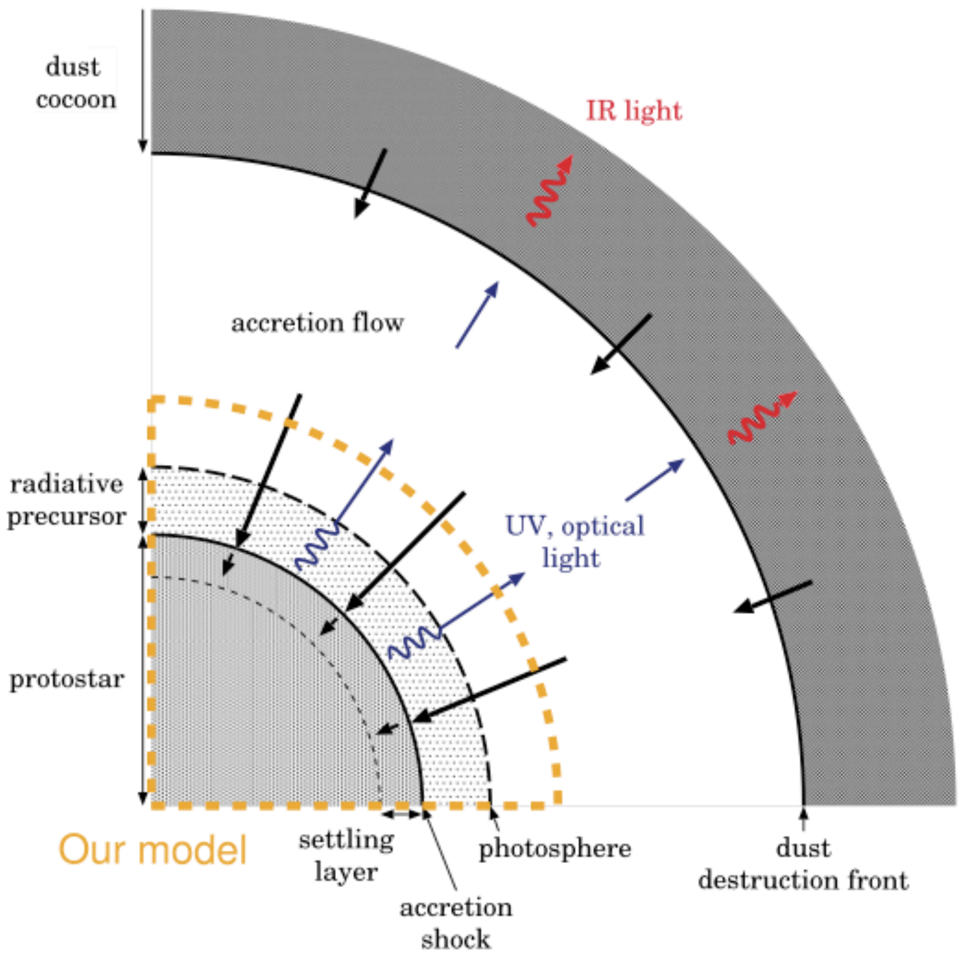
  $L_{KH} = G M_*^2 / R_*^2 \, dR/dt$

- Hydrogen burning

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

Evolution of accreting stars

(Hosokawa & Omukai 2009)



In the model of Hosokawa & Omukai (2009) the stellar photosphere is **outside** of the accretion shock

Evolution of accreting stars

(Hosokawa & Omukai 2009)

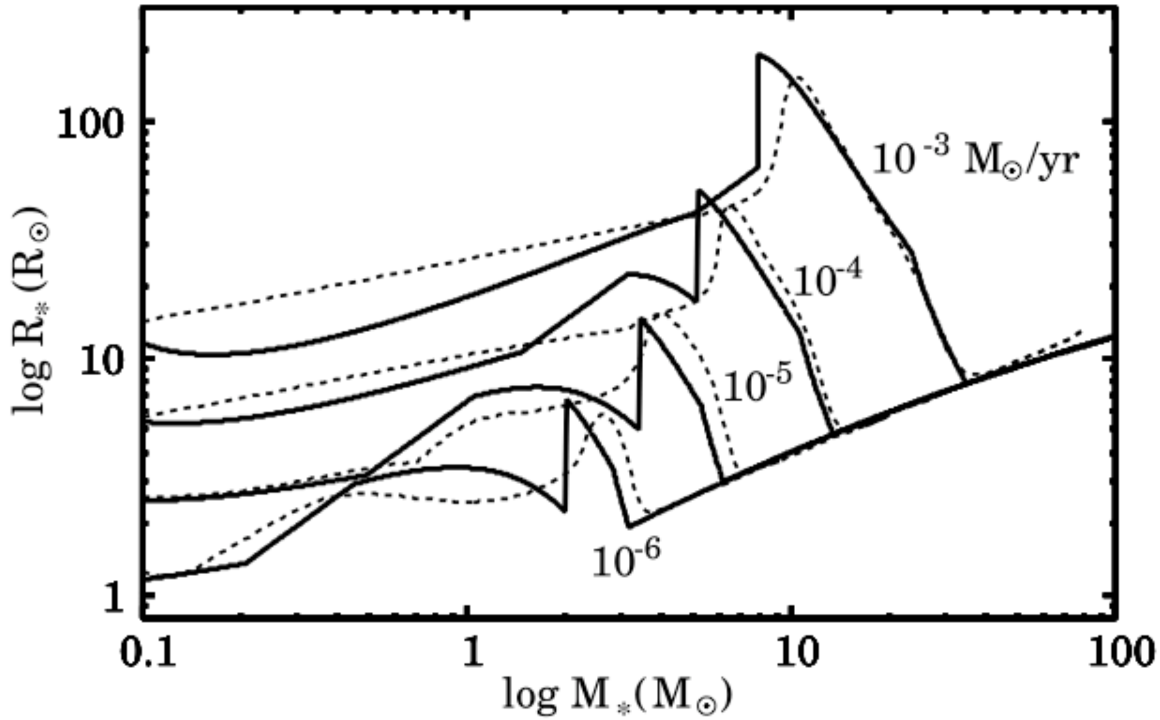
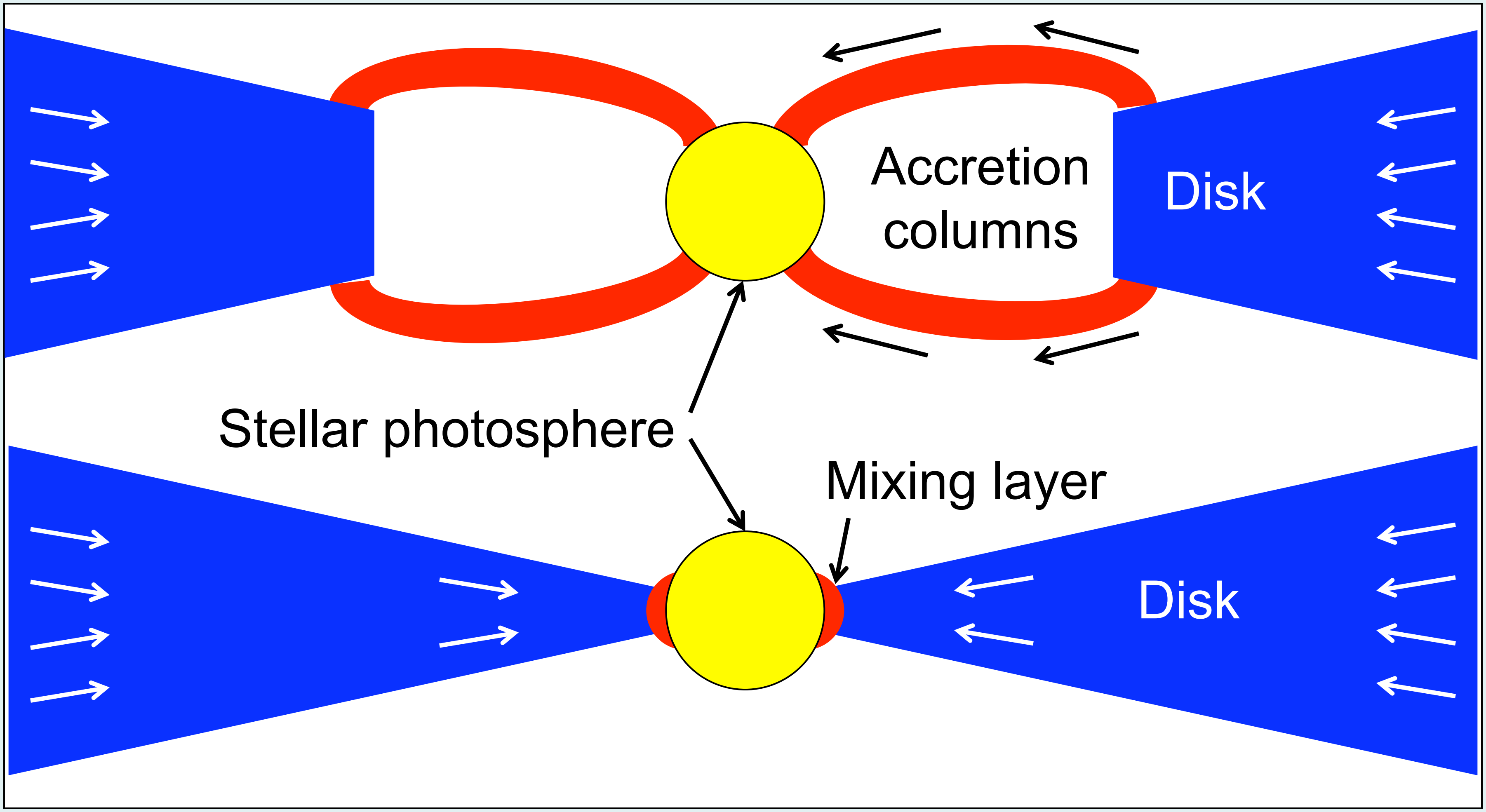
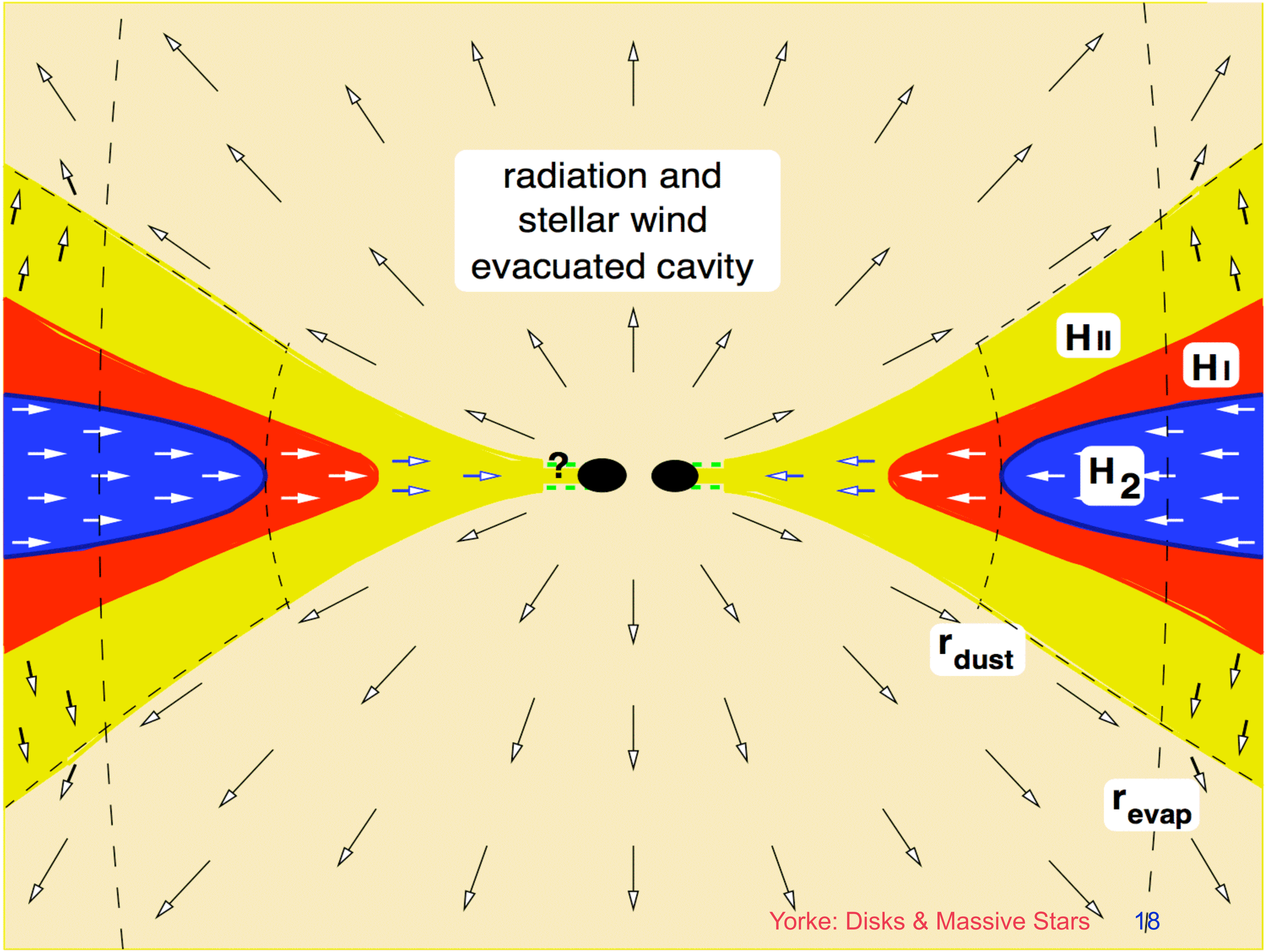


Figure 24. Comparison between the protostellar radii calculated by the one-zone models based on McKee & Tan (2003) but with parameters calibrated as in Appendix C (solid) and by our numerical models (dotted). The cases with the accretion rates from 10^{-6} to 10^{-3} $M_\odot$ yr^{-1} are shown.

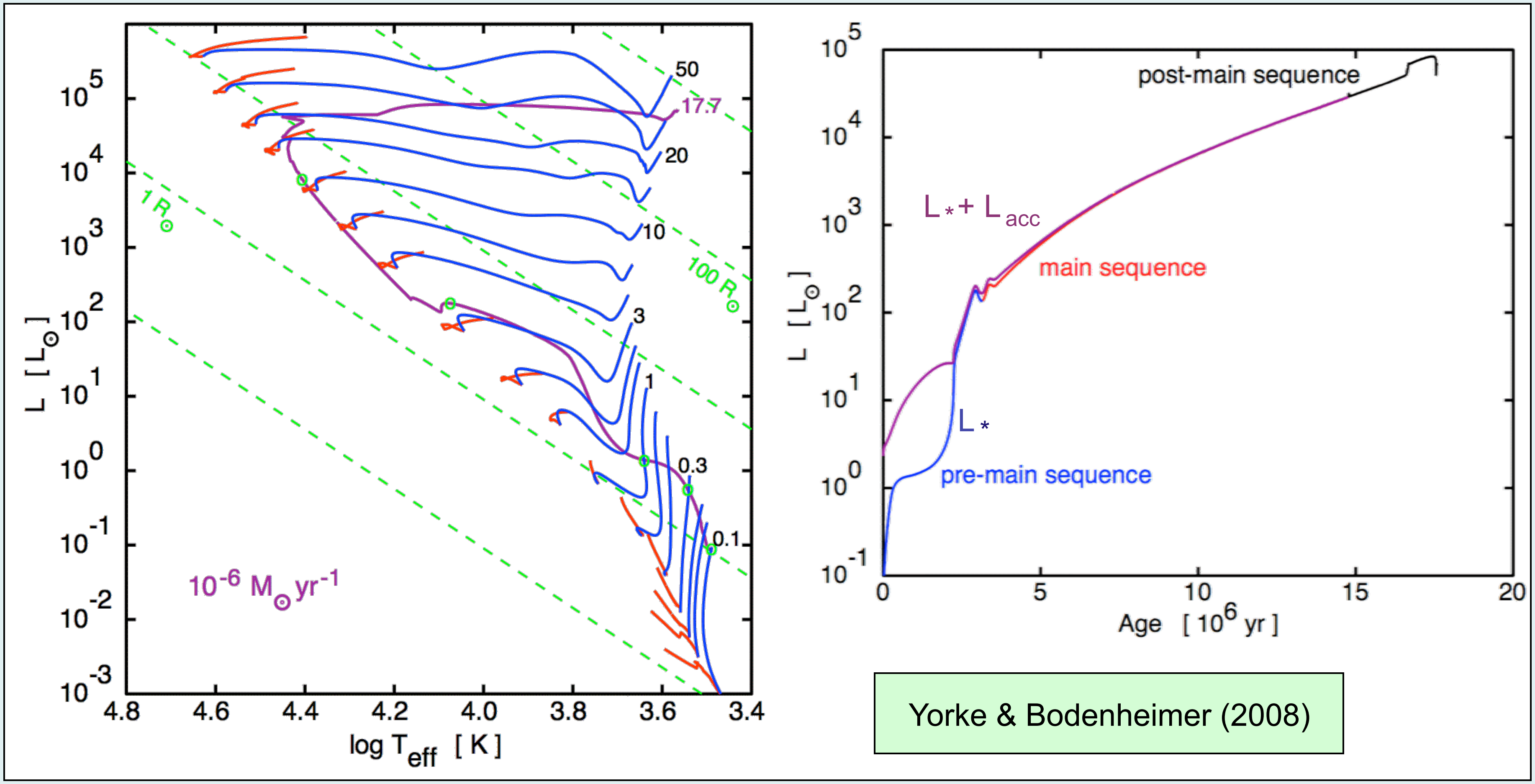
Evolution of accreting stars

Yorke & Bodenheimer (2008): stellar photosphere is at stellar surface



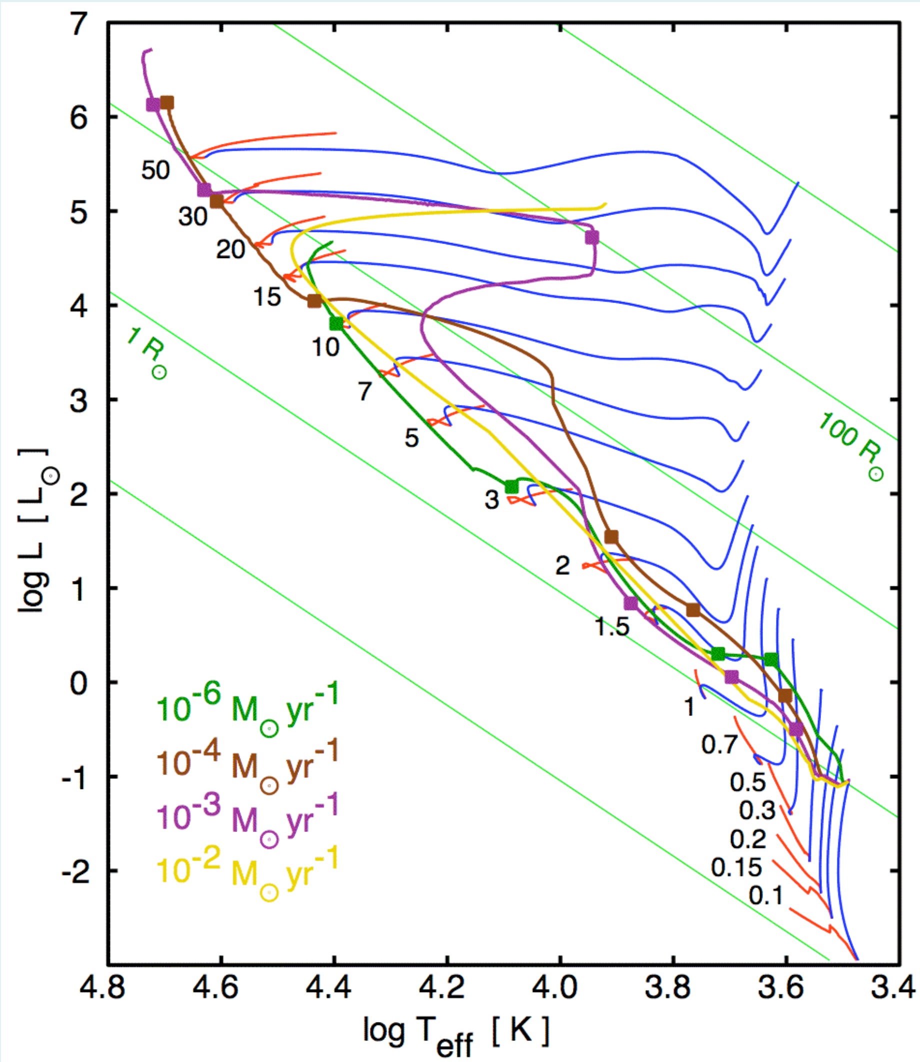

radiation and
stellar wind
evacuated cavity
?
H II
H I
H_2
r_{dust}
r_{evap}

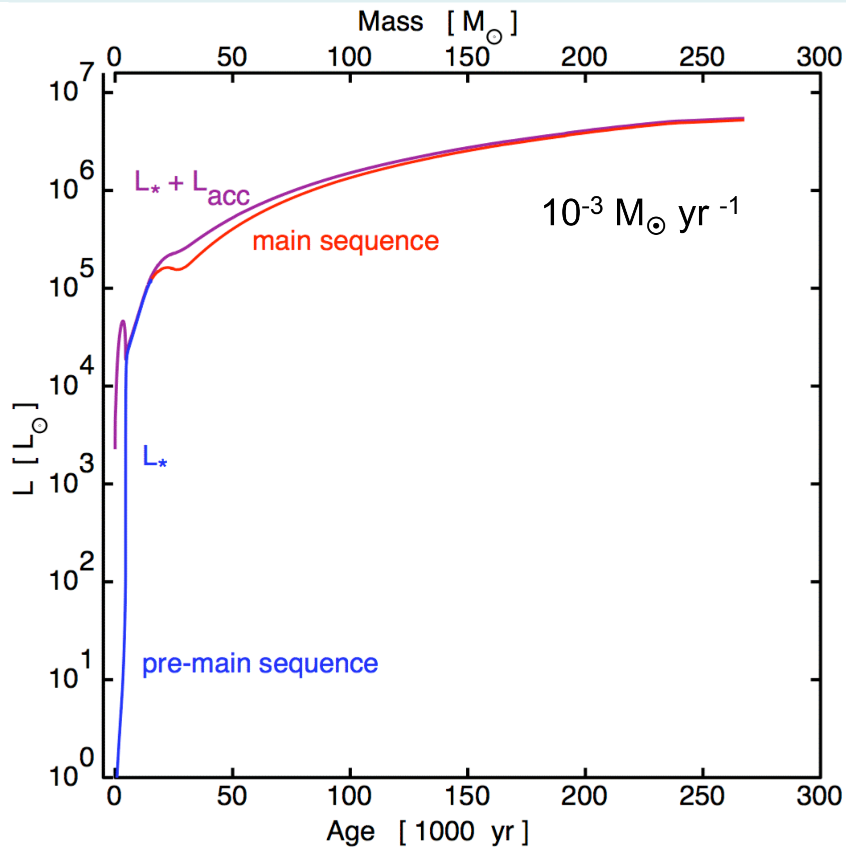
Evolution of accreting stars in the HRD ($dM_*/dt > 0$)



Yorke & Bodenheimer (2008)

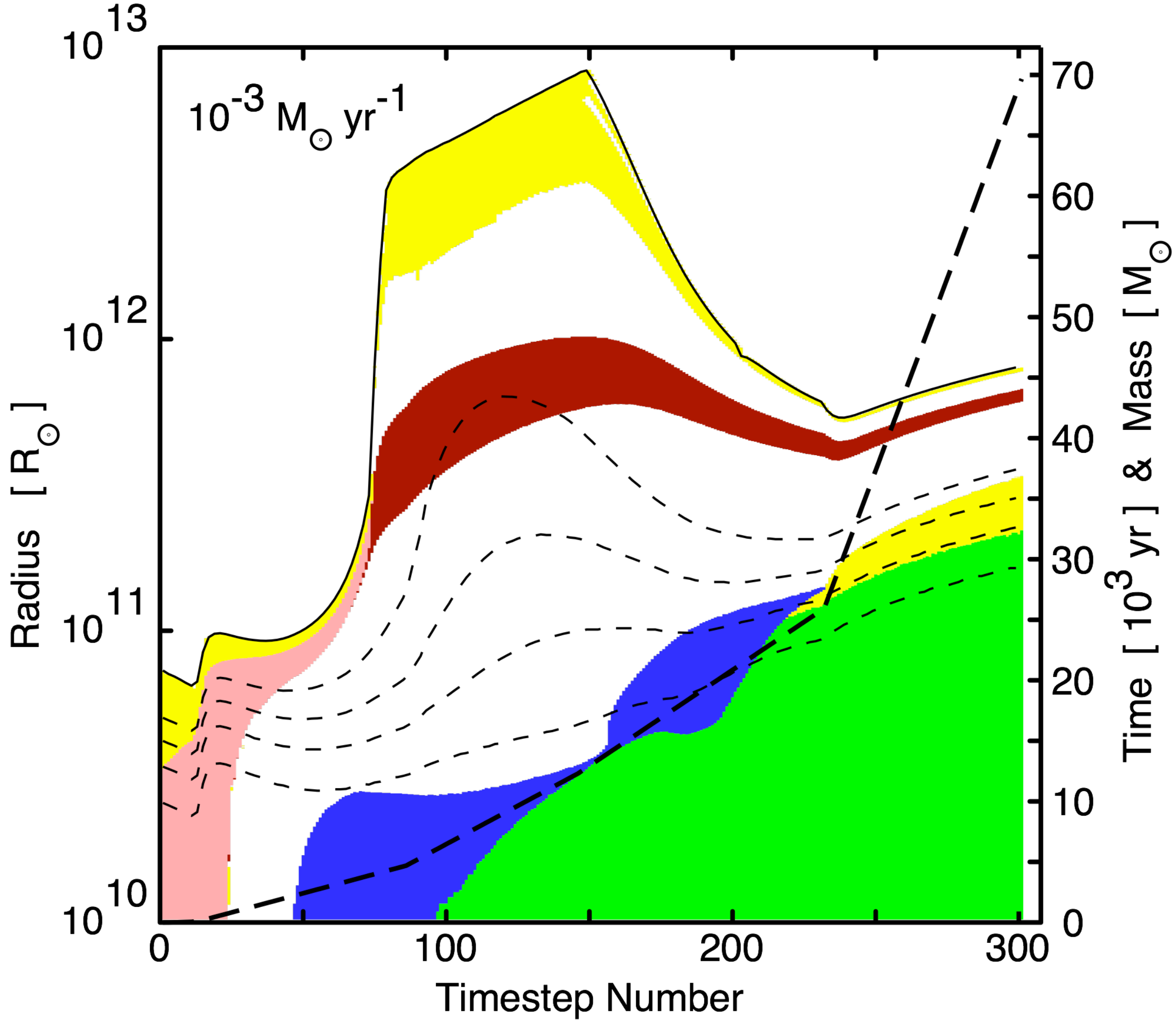
Evolution of accreting stars in the HRD ($dM_*/dt > 0$)





Yorke & Bodenheimer (2008)

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



Dashed line: Timestep vs. Mass and Time

Light dashed & solid lines: Radii at which M_r = 0.2, 0.4, 0.6,0.8, and 1 (stellar surface)

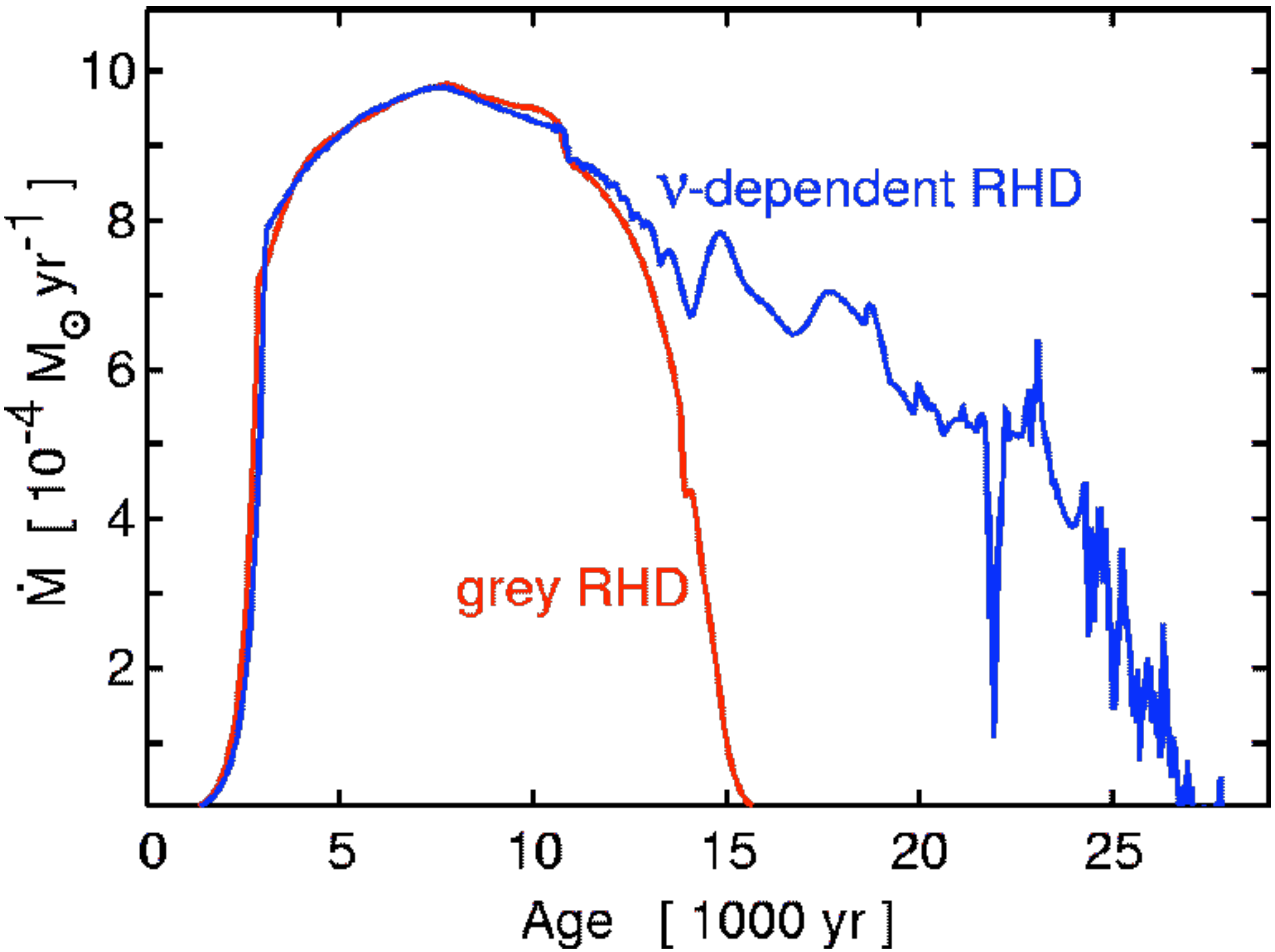
- convection
- convective D-burning
- D-burning
- H-burning
- convective H-burning

A few Remarks

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

Time dependent accretion through disk

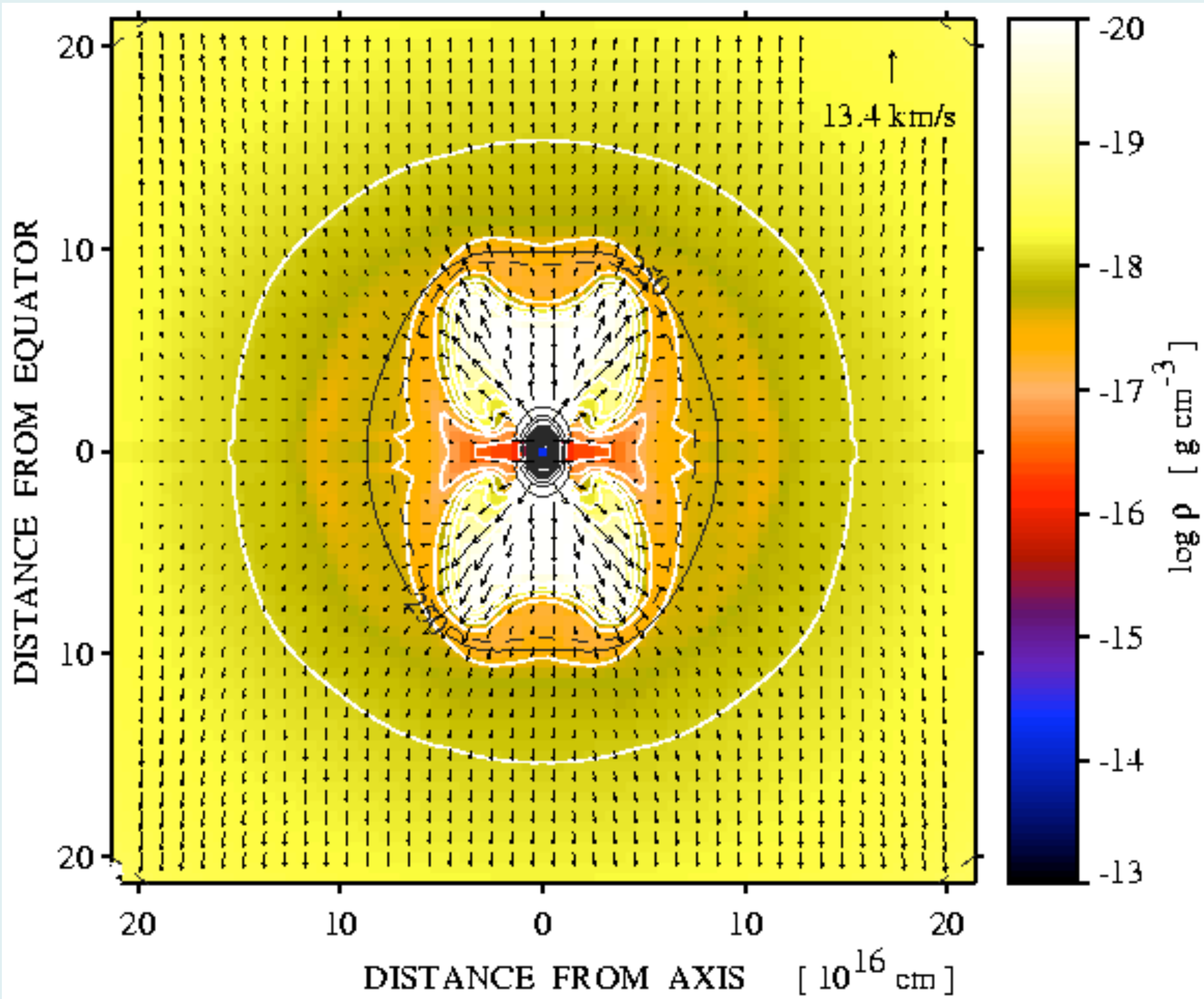
(Yorke & Sonnhalter, 2002, ApJ, 569, 846)



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

ν-Dependent Radiation Hydrodynamics of Collapse

35,000 yr   33.6 $M_\odot$

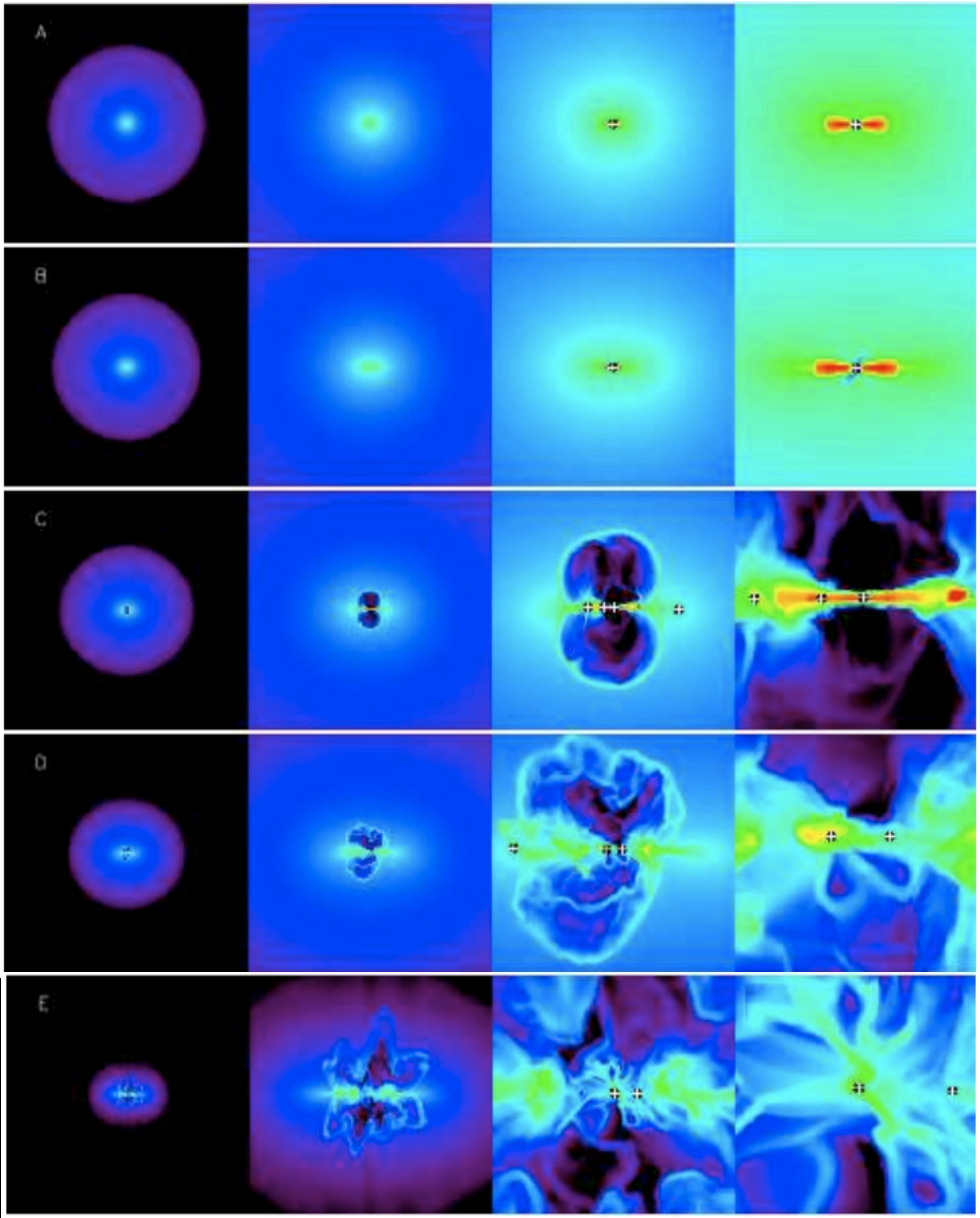


Yorke & Sonnhalter, 2002, ApJ, 569, 846

60 $M_\odot$ case

120 $M_\odot$ case

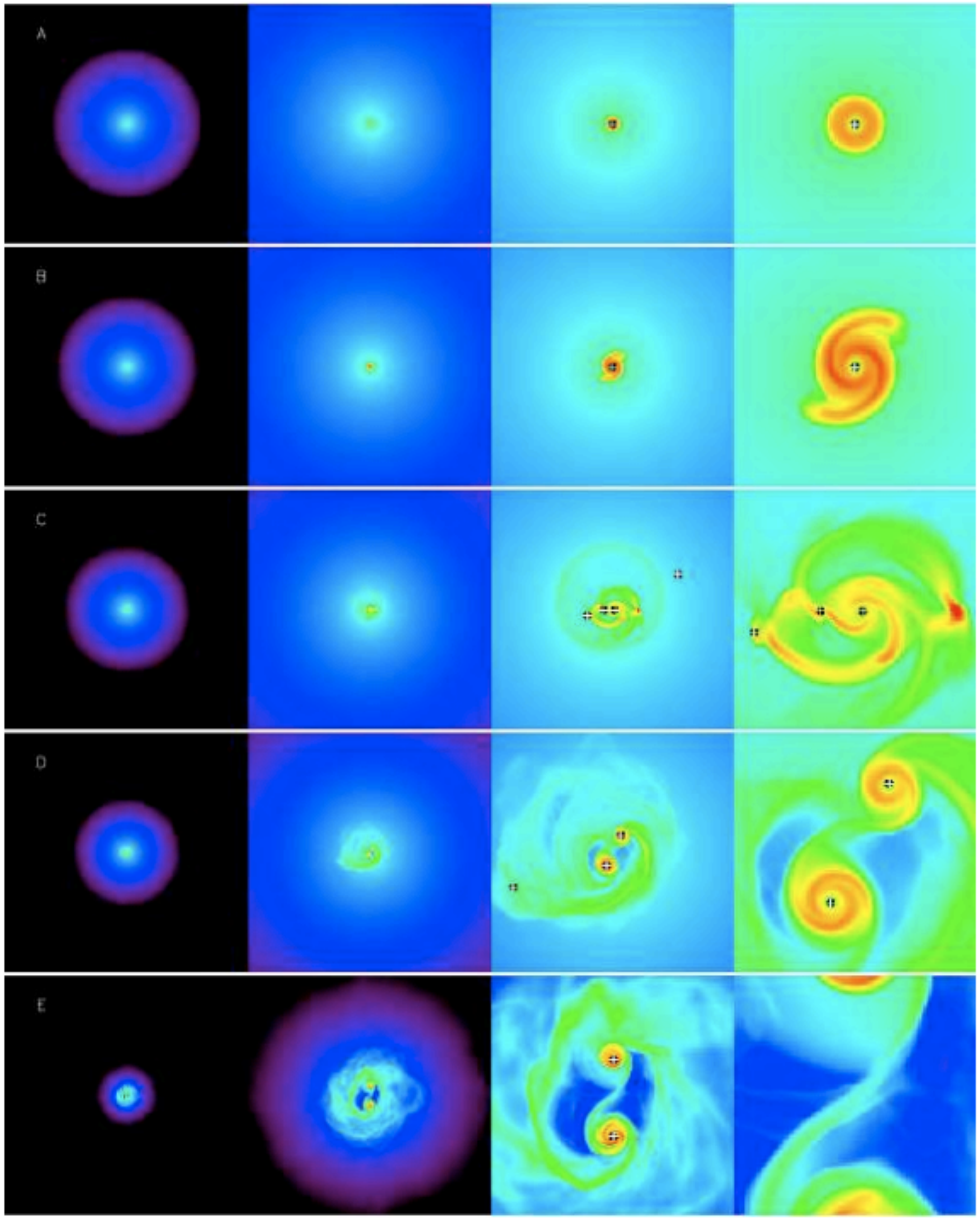
Ω [s^{-1}]	5 10^{-13}
R_{max} [pc]	0.1 0.2
M_o [$M_\odot$]	60 120
M_{final} [$M_\odot$]	34 43
M_{final} [$M_\odot$]	21 (grey)



3D Models of Massive Star Formation
(Krumholz et al 2009, Science)

100 $M_{\odot}$ cloud, 20 K, 0.1 pc, $\rho \sim r^{-3/2}$

Edge-on views of density at: 17.5, 25.0, 34.0, 41.7 and 55.9 kyr. The leftmost frames show a (0.3 pc)^2 region, and each step to the right reduces the size of the region shown by a factor of 4; the rightmost box shows a region (966 AU)^2 in size. The color scale is logarithmic, running from 10^{-19} to 10^{-12} g cm^{-3}.



3D Models of Massive Star Formation

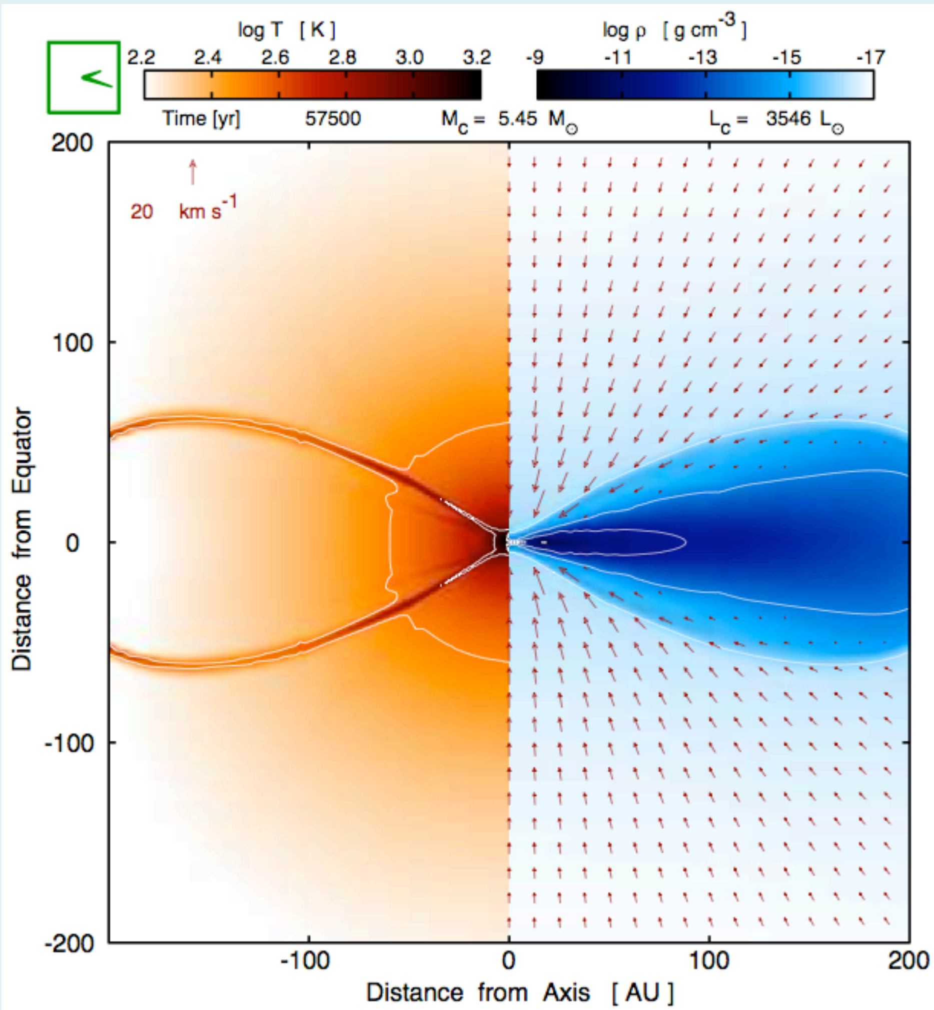
(Krumholz et al 2009, Science)

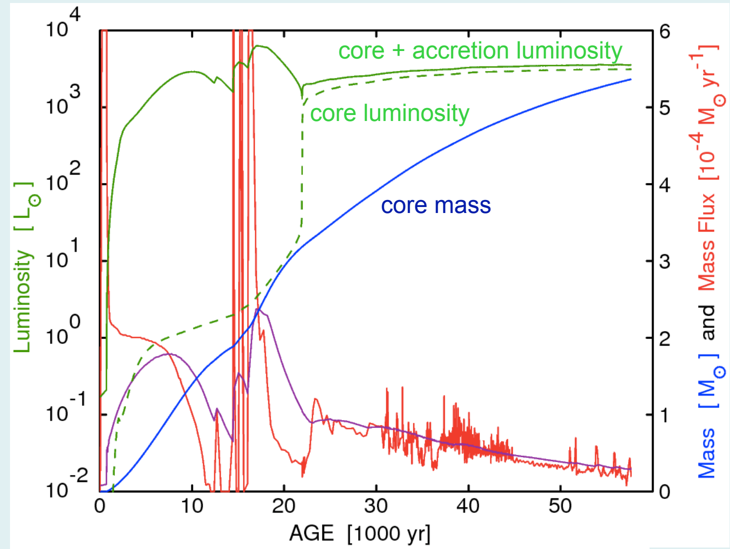
Pole-on views of column density at:17.5, 25.0, 34.0, 41.7 and 55.9 kyr. The color scale is logarithmic, running from 10^{-1} to 10^{3} g cm^{-2}.

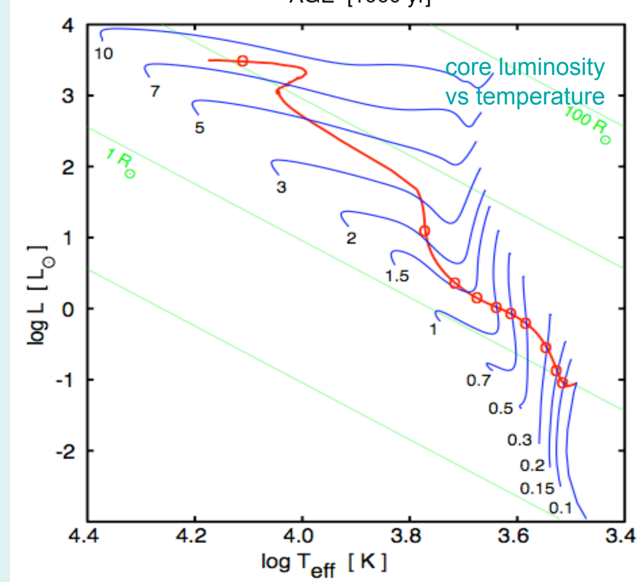
=> Stars of mass 41.5 $M_{\odot}$ and 29.2 $M_{\odot}$ with 1590 AU separation

Step 1: Collapse of a (slowly) rotating 10 $M_\odot$ molecular core (2/2)

10 $M_\odot$ clump; R=0.07 pc; T_{out} = 100 K





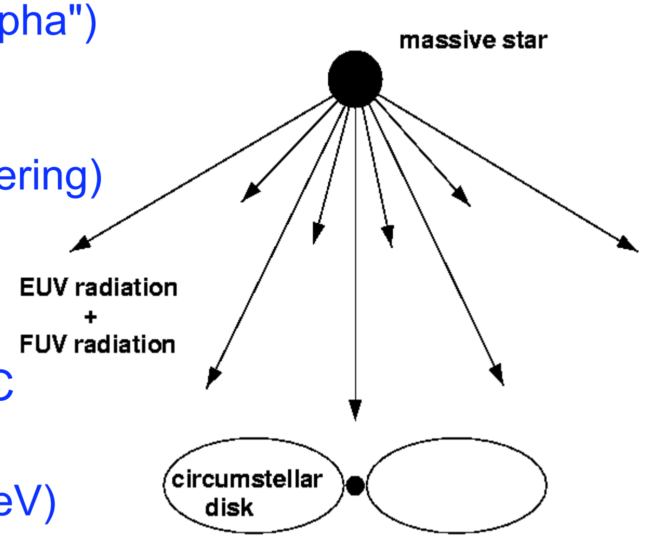


Step 2: Photoevaporation of molecular core and disk by nearby O star (1/2)

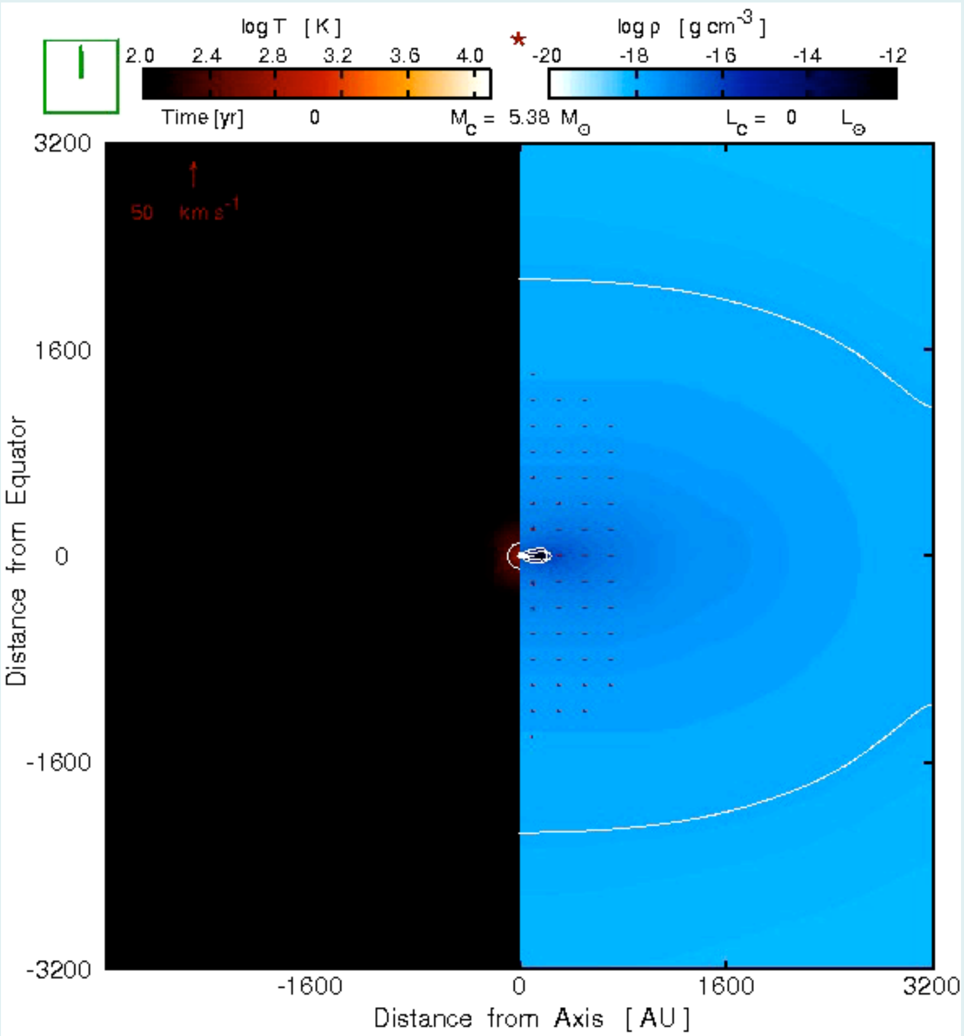
Use of Richling & Yorke (2000) ApJ 539, 258 computer code

- 2.5D 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

- Central stellar wind + EUV / FUV
- Time dependent ionization/recombination of H and C
- Transport of stellar EUV photons ($h\nu > 13.6$ eV)
- Transport of stellar FUV photons ($6 \text{ eV} < h\nu < 13.6$ eV)
- Transport of H-recombination photons ($h\nu \sim 14.2$ eV)
- Transport of EUV & FUV photons scattered by dust



Step 2: Photoevaporation of molecular core and disk by nearby O star (2/2)



Initial conditions

Mass of star: 5.4 $M_\odot$
Mass of disk: 1.9 $M_\odot$

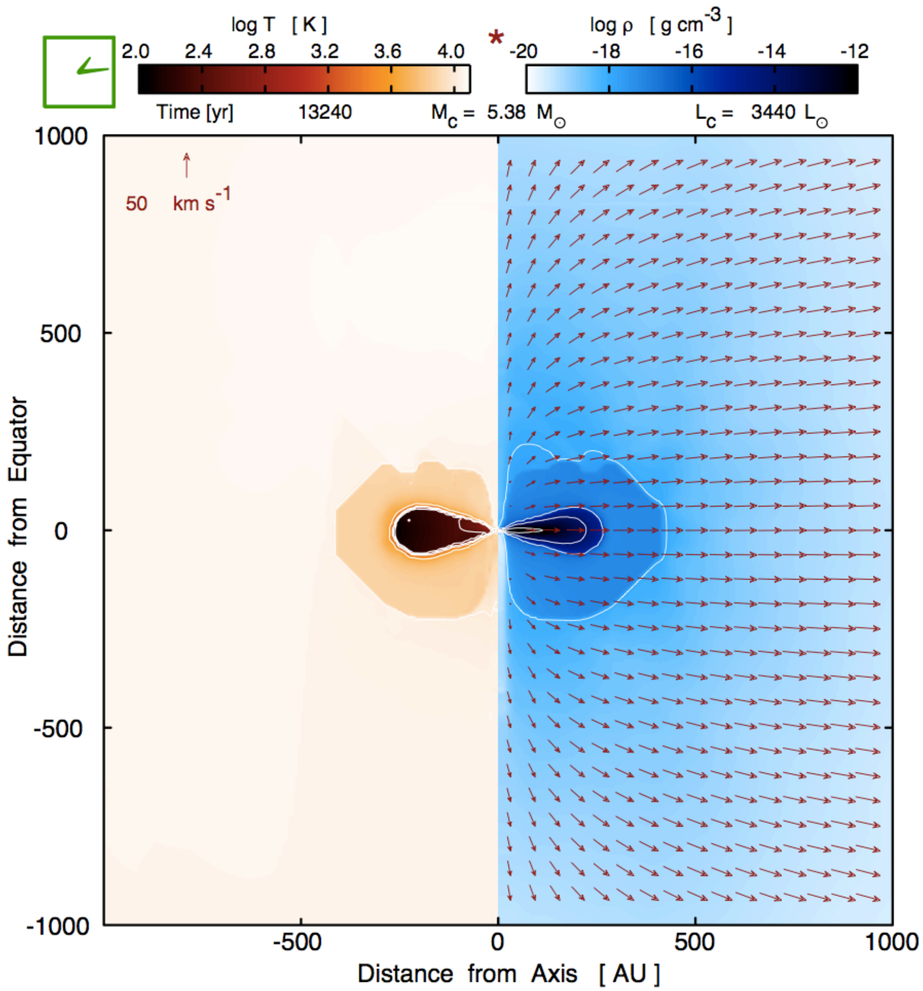
External O5 star
Distance from disk: 4000 AU

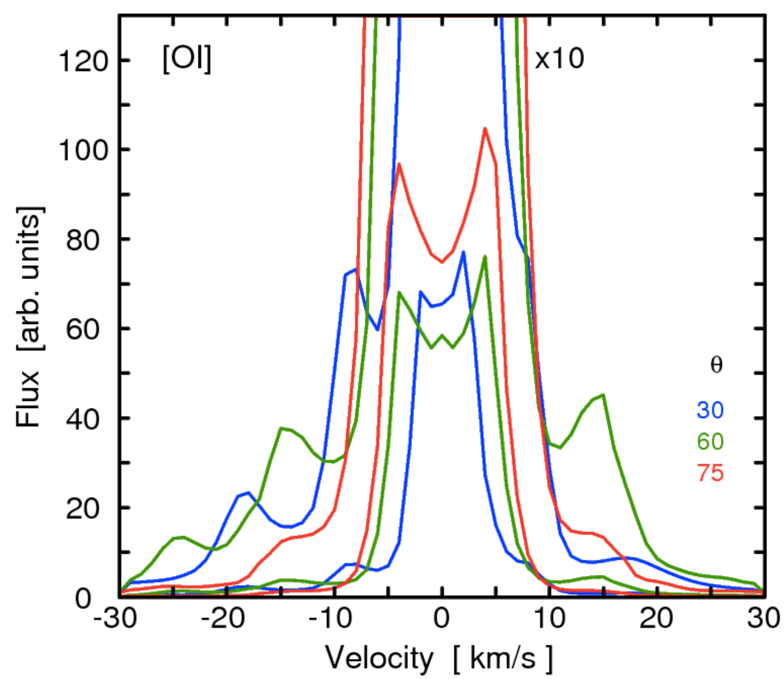
Results

Dissipation of molecular core in 8,000 years
Dissipation of disk in 100,000 years

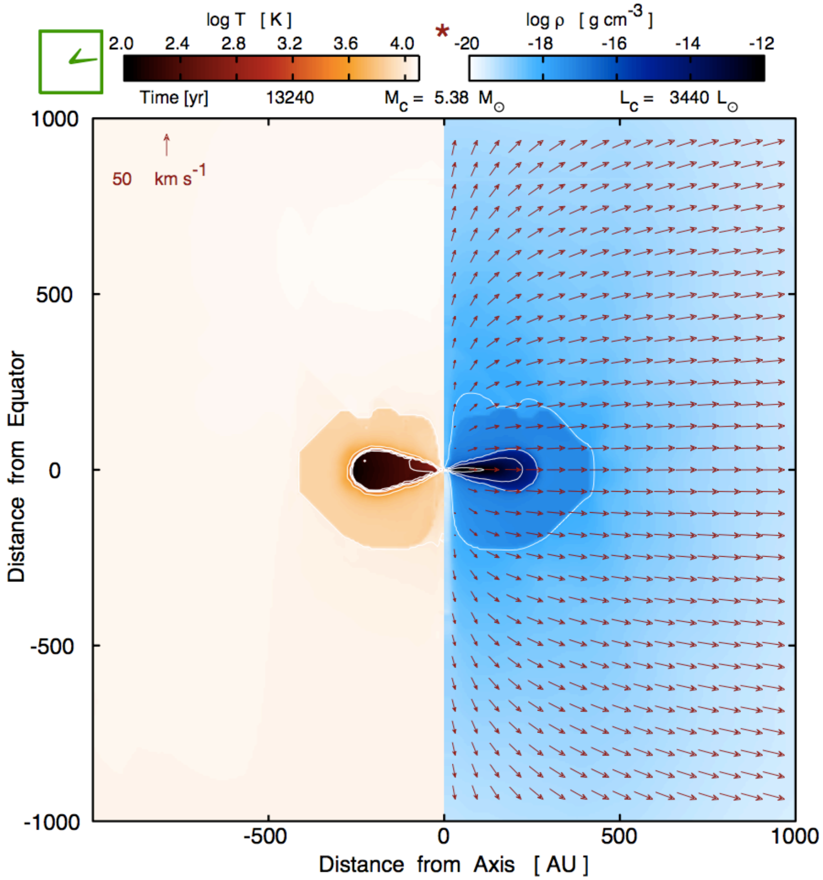
Step 3: Line transfer calculations of [CII] 158um and [OI] 63um radiation

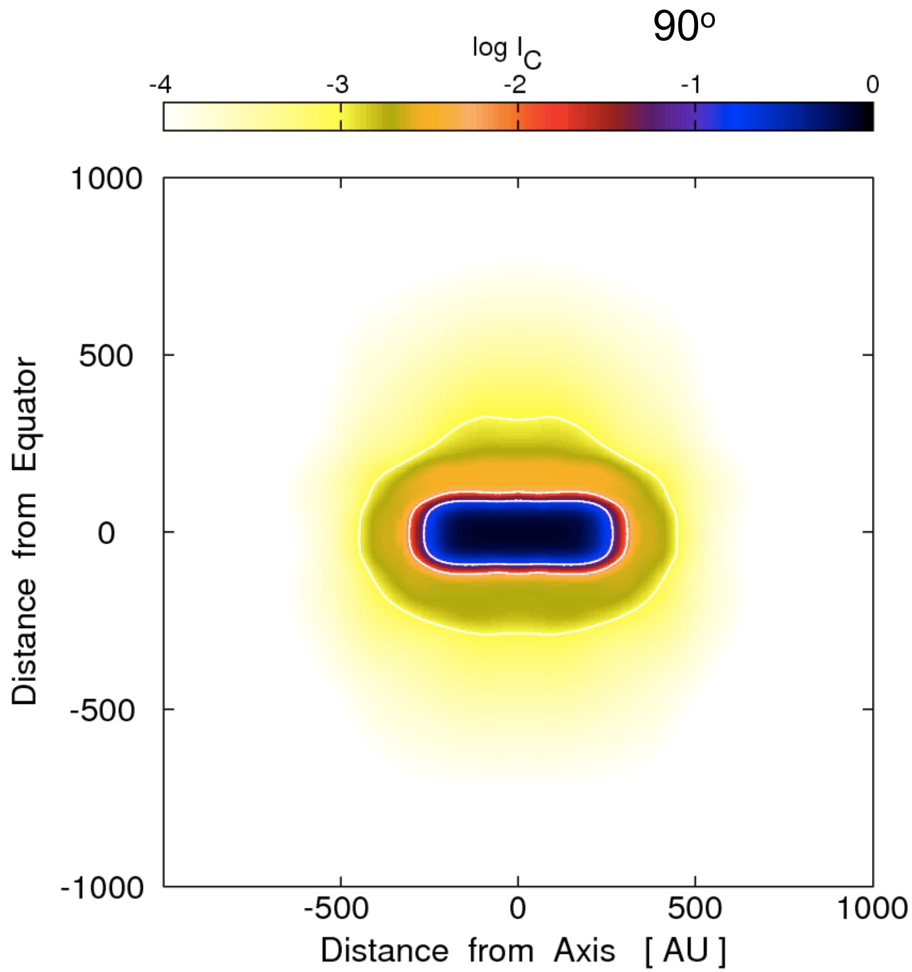
Line transfer along a grid of LOS at various angles of view



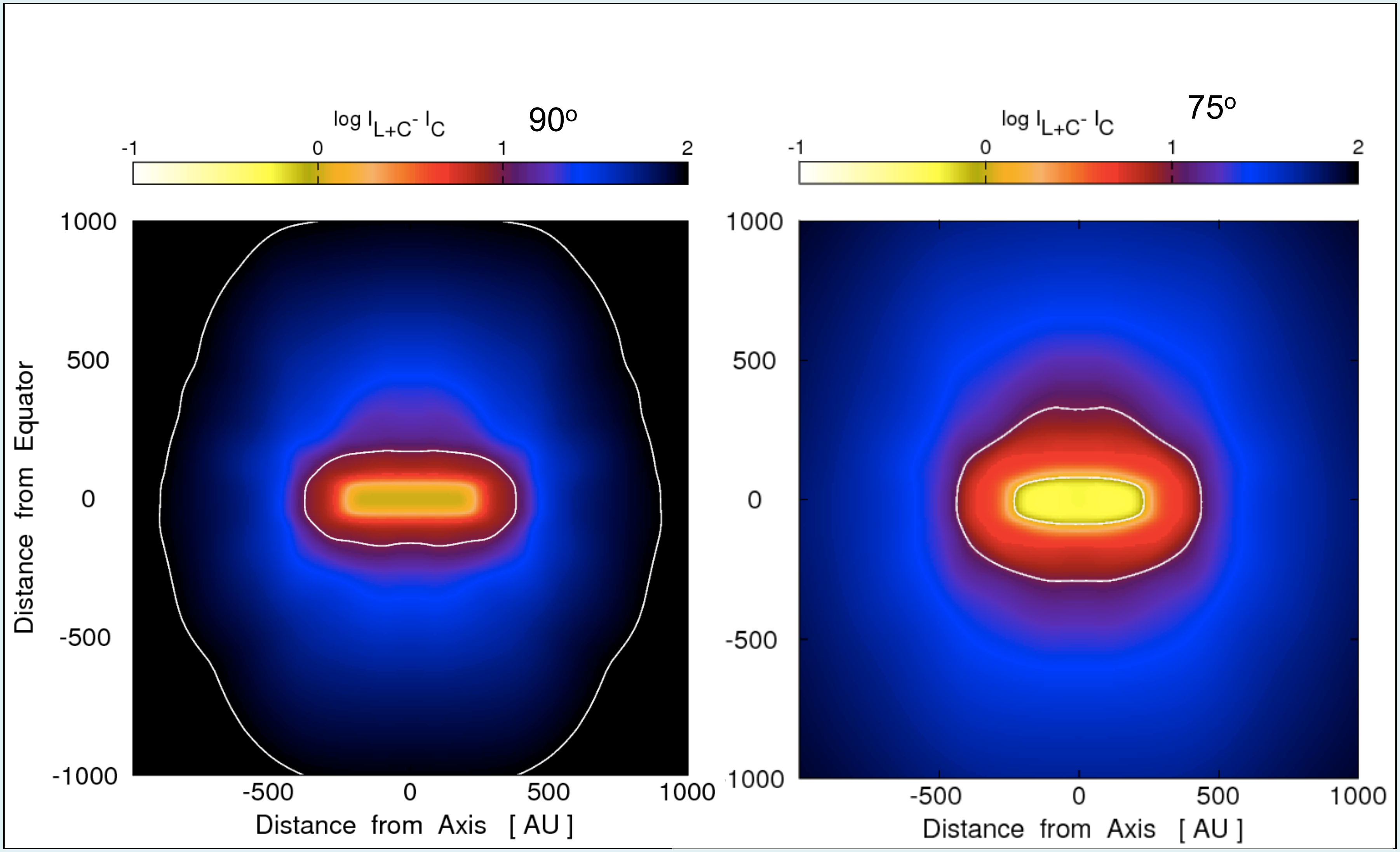


Continuum at 158um

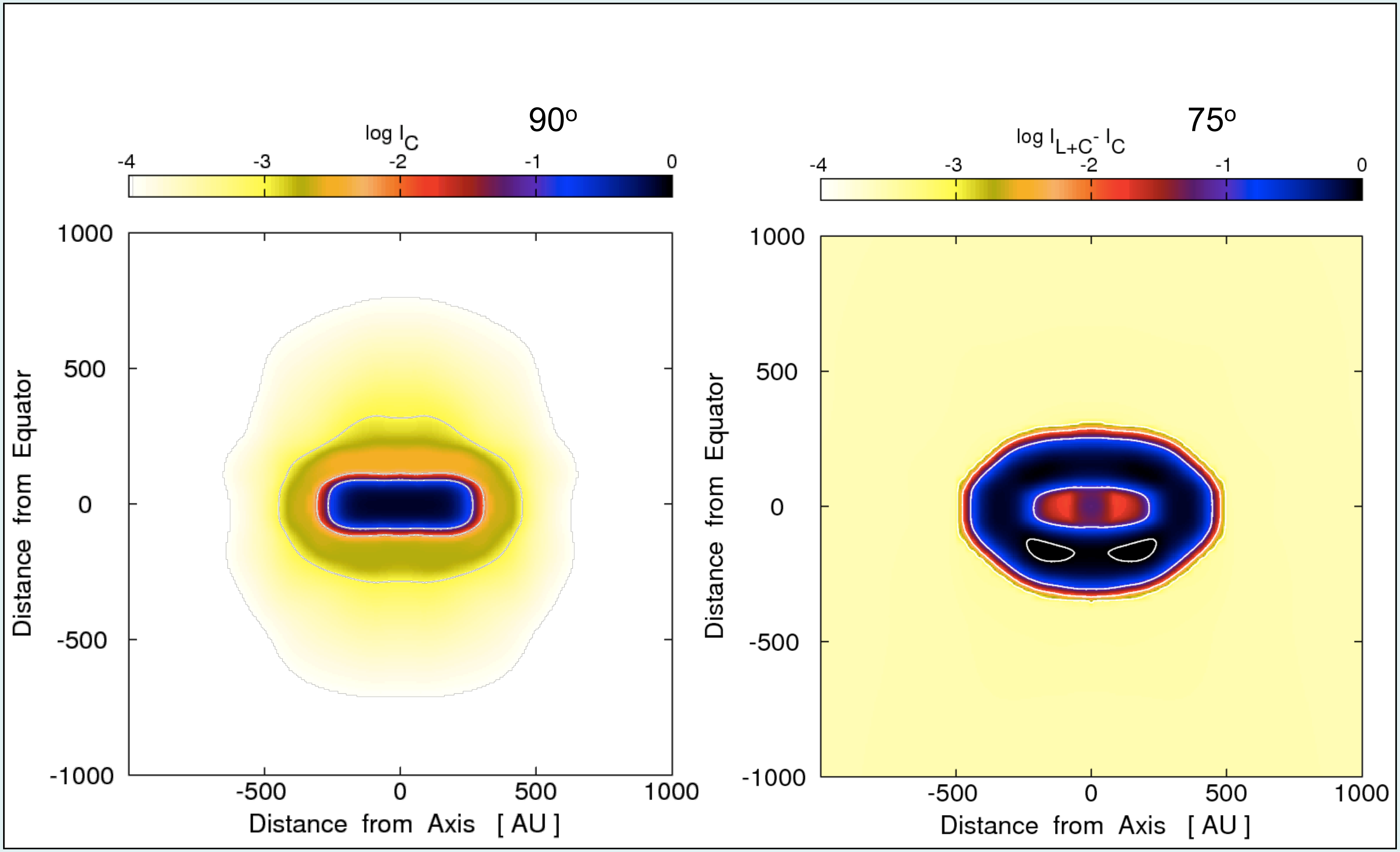




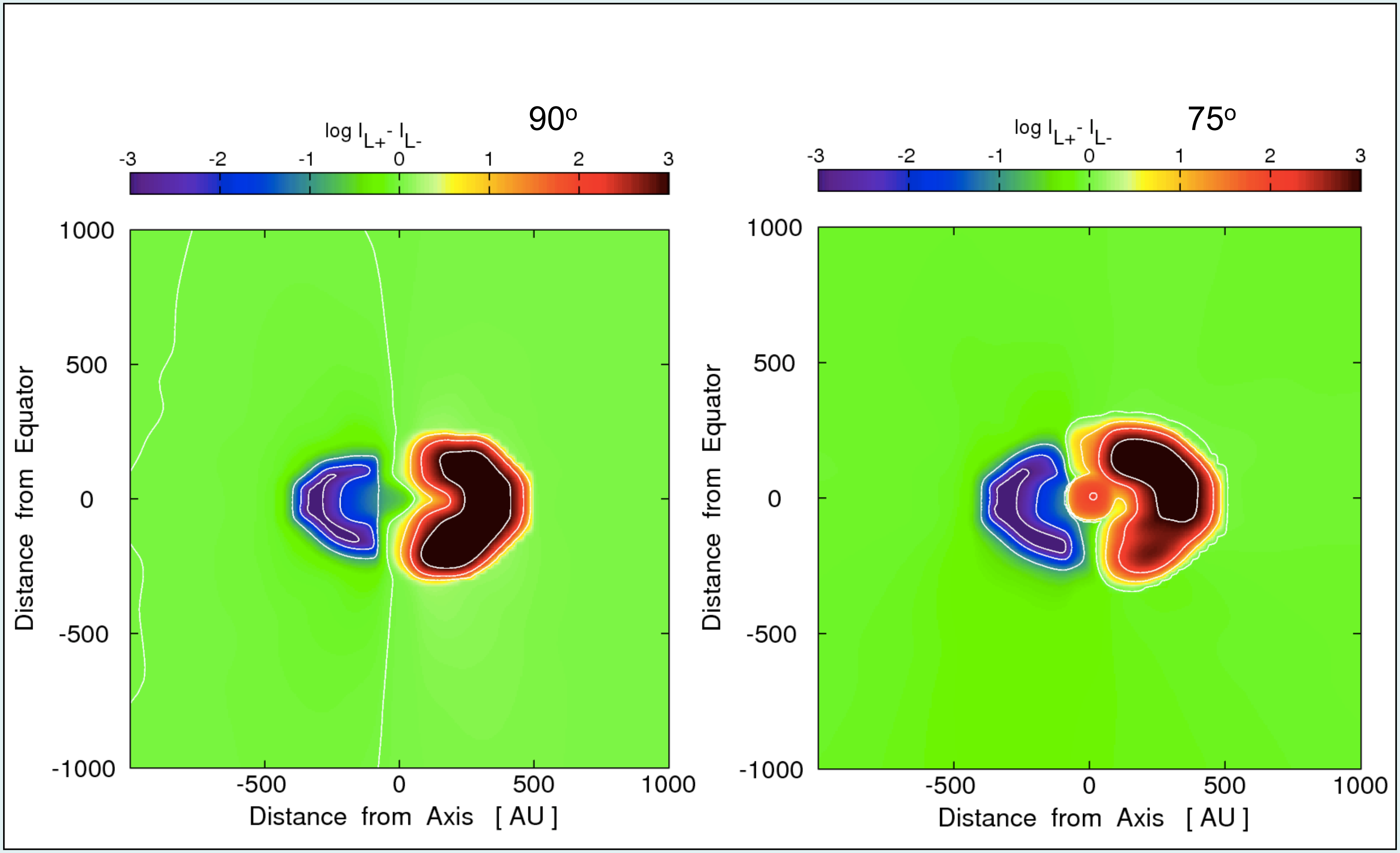
Line - Continuum of [CII] 158um



Line - Continuum of [OI] 63um



Velocity structure of [OI] 63um



Conclusions and Discussion

- Disks are an important (but short-lived) ingredient of massive star formation – they allow accretion at high rates onto (proto-)stars
- Details of accretion onto (proto-)star effect its appearance and evolution
- Molecular cores can be photoevaporated by a nearby O star in a 10^4 years
- Circumstellar disks in the immediate vicinity of O stars can survive 10^5 years (and only 10^5 years)
- The future: ALMA, Herschel, SOFIA, …

Thank you