Theoretical Considerations of Massive Star Formation

presented at the Ringberg Conference on

Early Stage of Star Formation

28 August 2006

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Morse & Davidson (1996)

High mass versus low mass star formation

- High mass star formation is not simply a scaled-up version of low mass star formation
  - Relevant time scales are extremely short
  - Radiative acceleration of dusty gas very important
  - Disk dissipation must be very quick
  - Associated with UCHIIs, massive collimated outflows, H_2O masers, …
- High mass star formation is not merely a scaled-down version of accretion disks around super-massive black holes
- High mass star formation lies somewhere in between

Questions to be addressed

- 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?

Stability of gaseous clumps

- 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

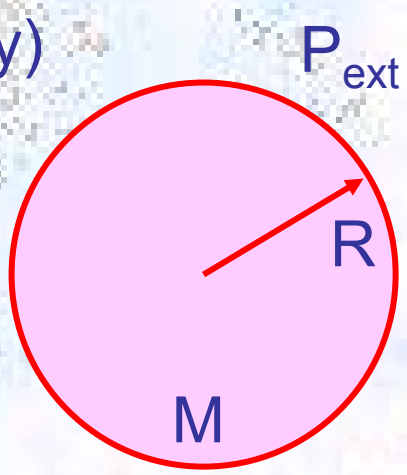
$E_G = -\alpha GM^2/R = -A_G R^{-1}$ (gravitational energy)

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

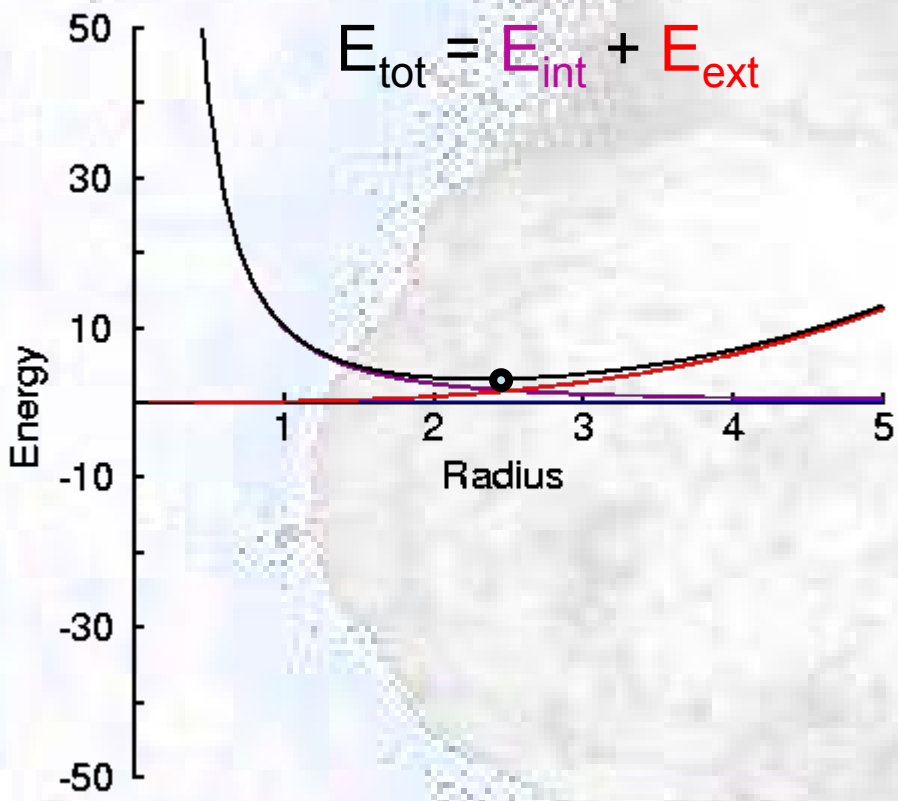
$E_{mag} = A_{mag} R^{-1}$ (magnetic energy)

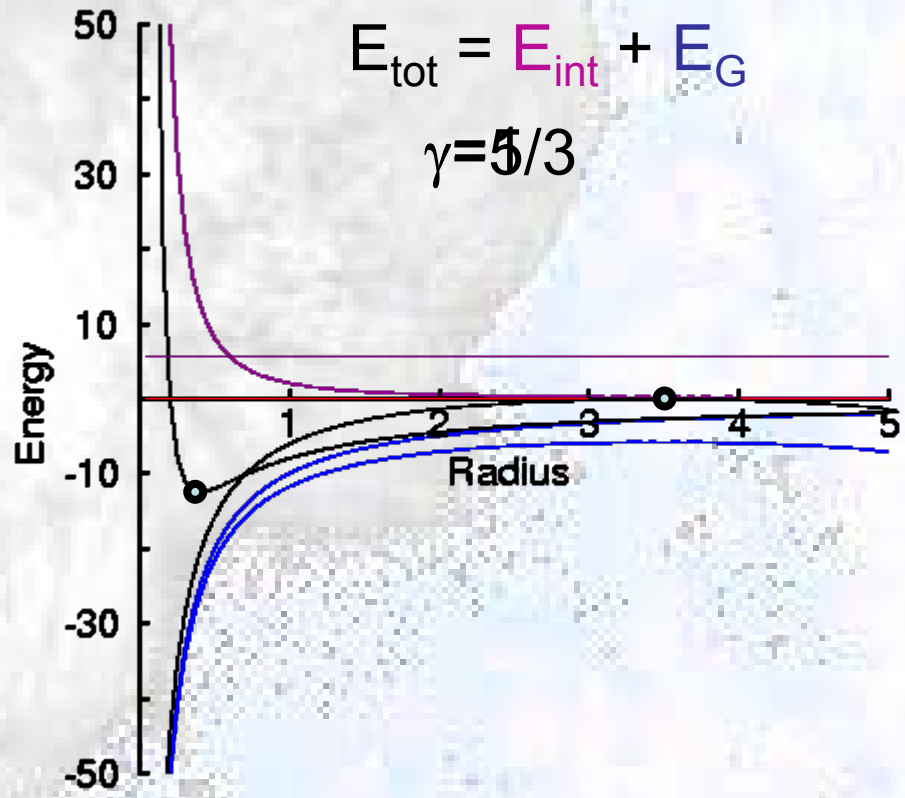
$E_{rot} = A_{rot} R^{-2}$ (rotational energy)

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



Stable, Expansion or Collapse?

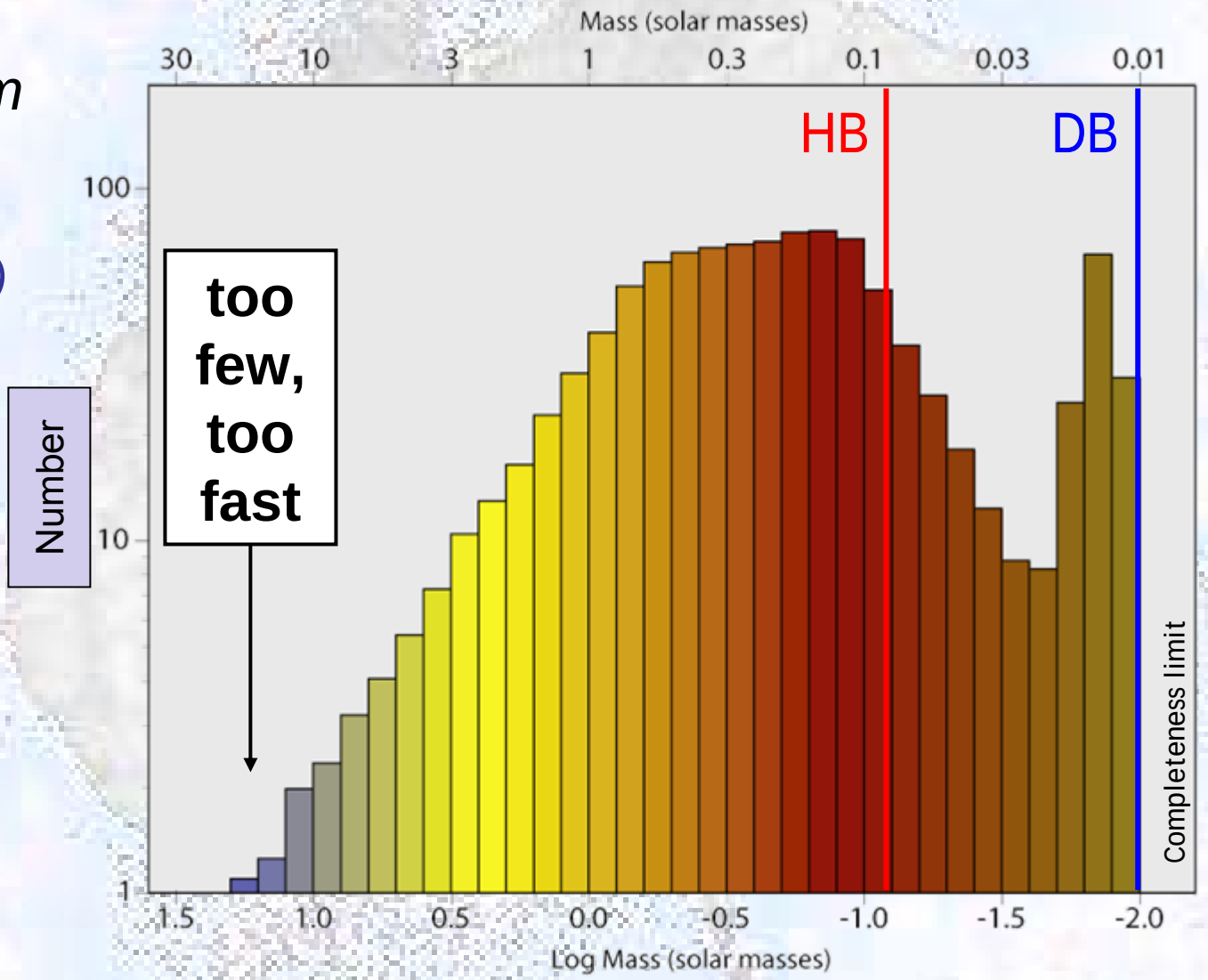




$$M_{Jeans} = 1\ M_{\odot}\ (T/10K)^{3/2}\ (n_{H2}/10^4\ cm^{-3})^{-1/2}$$

The Initial Mass Function

Trapezium cluster
(Muench et al. 2001)



Early Universe Analogy

- Rather than a single isolated star of a "characteristic mass" we can expect a spectrum of mass scales (an IMF) ranging from…
  - Lower mass limit: $M_{min} > 1\ M_{\odot}$ (solution to G-dwarf problem?)
  - Upper mass limit? Slope/Shape?
  - Cluster, multiple systems?

- Note: clustered star formation is primary mode in present epoch and past out to z~3

Important relevant time scales (today)

- Free-fall time scale

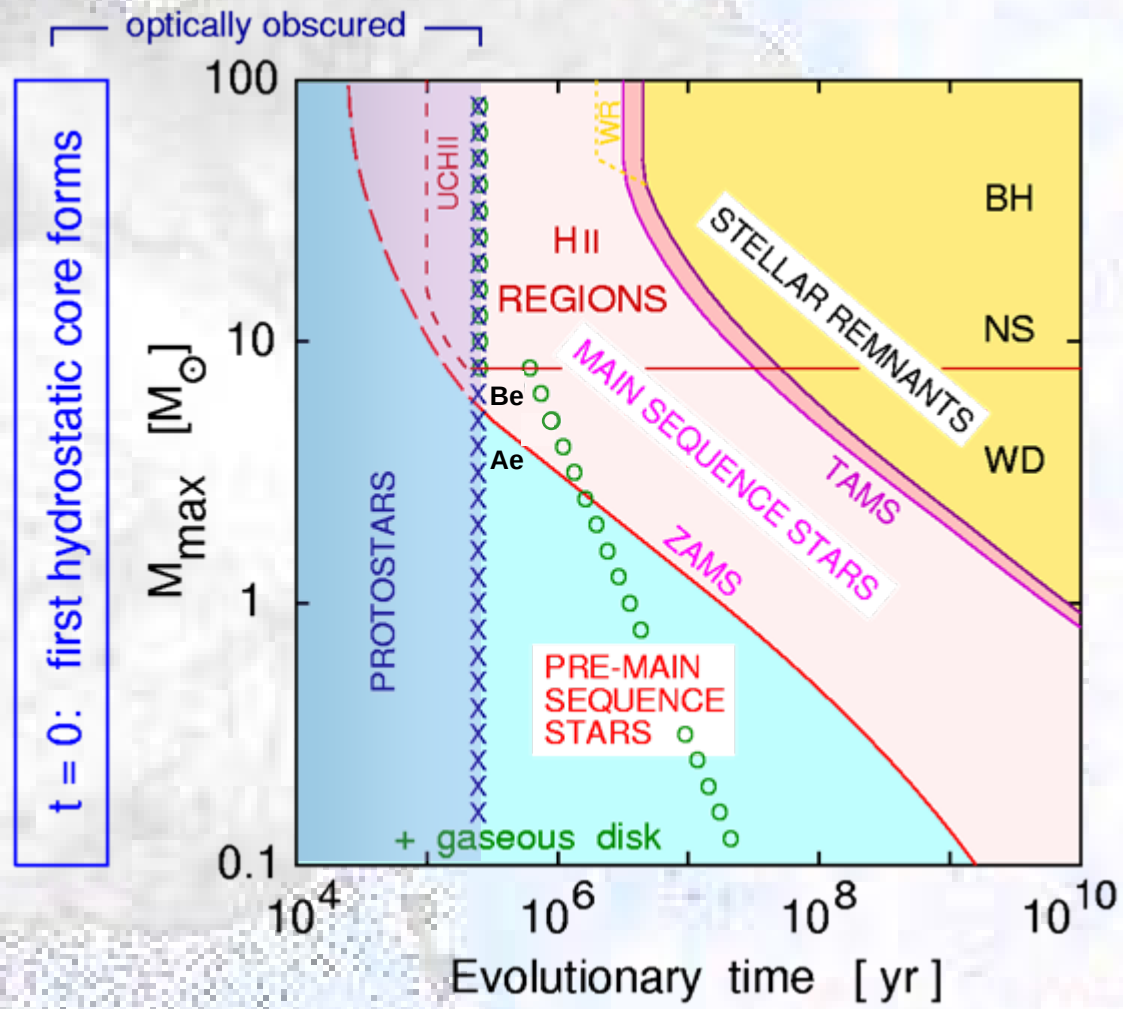
$$t_{\rm ff} \simeq 10^5\,{\rm yr}\left[\frac{n}{10^5\,{\rm cm}^{-3}}\right]^{-1/2}$$

- 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

- 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

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

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

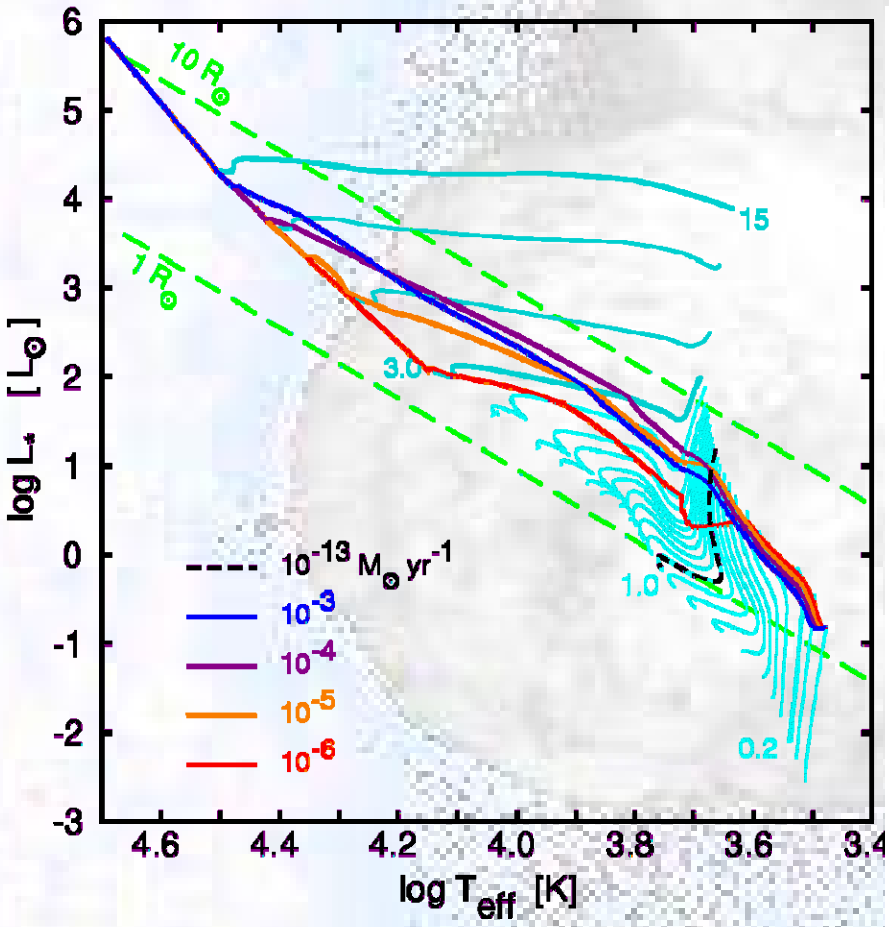
- Stellar radius

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

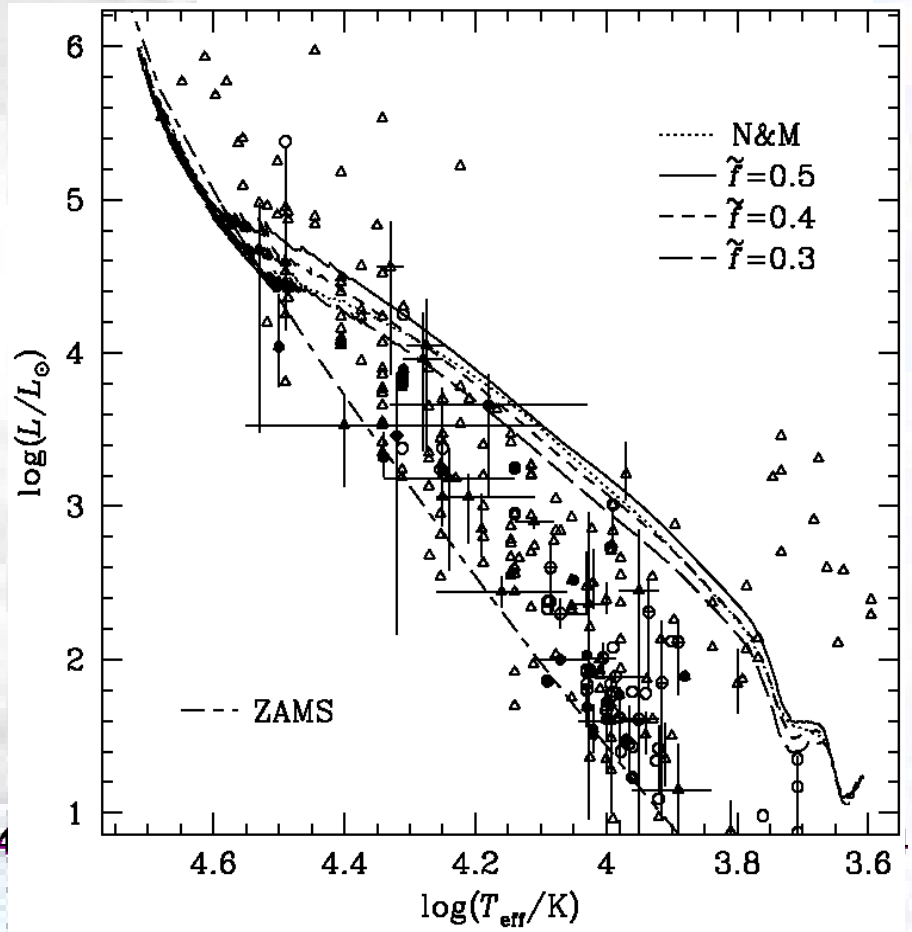
Evolution of accreting stars in the HRD ($dM_*/dt > 0$)

(Yorke 2002; Behrend & Maeder 2001)

HRD: D'Antona-Mazzitelli 1994 / Iben 1963



Behrend & Maeder 2001



Necessary conditions for forming stars by accretion

- The mass gained by accretion must exceed losses

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

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

- Must accrete material within "reasonable" time

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

- Gravity must be dominant force

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

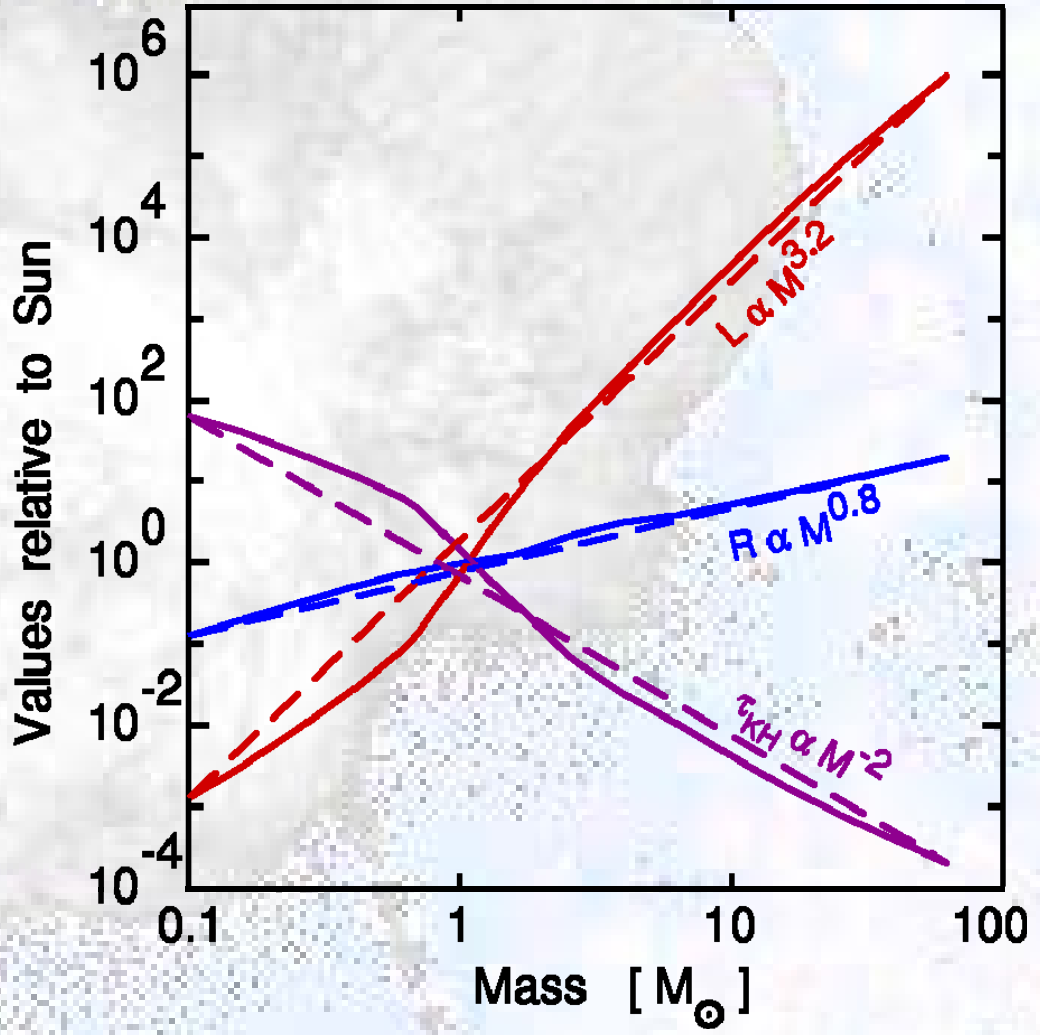
$$\kappa_{\rm eff} < 130\ {\rm cm^2\,g^{-1}} \left[\frac{M}{10\ {\rm M_\odot}}\right]\left[\frac{L}{1000\ {\rm L_\odot}}\right]^{-1}$$

Luminosity & Radius of ZAMS star

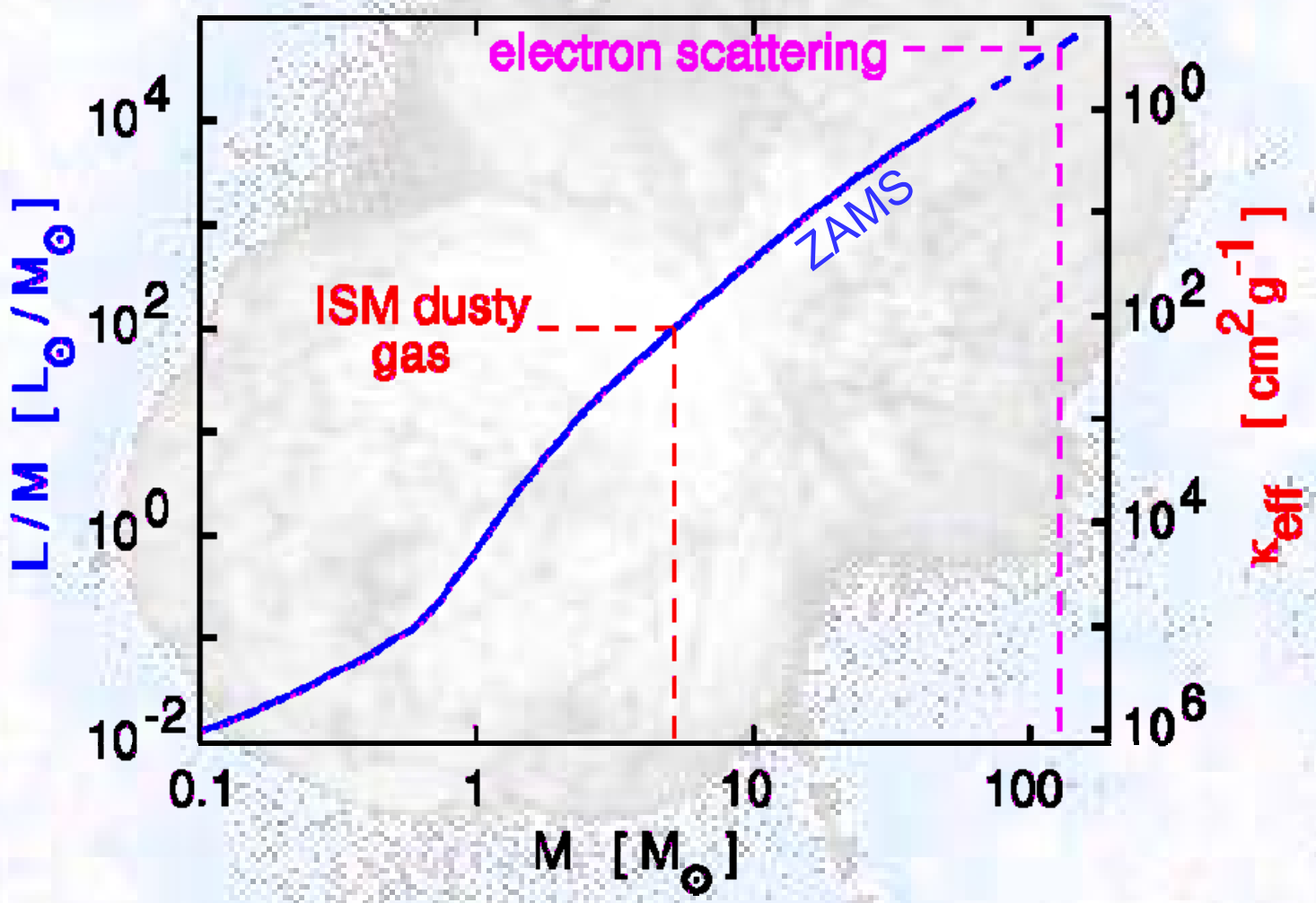
Kelvin-Helmholtz timescale

(for thermal readjustment)

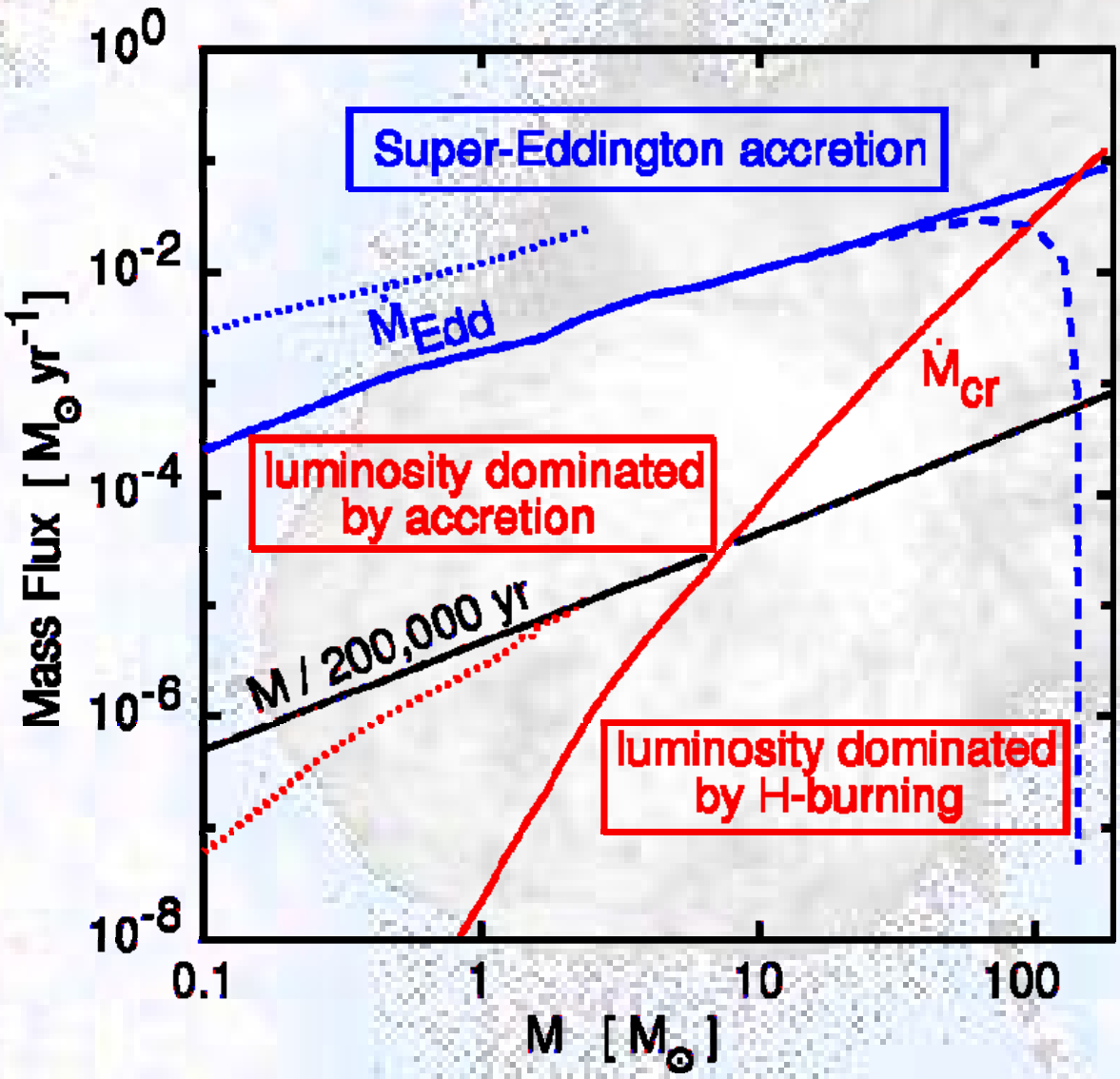
$$\tau_{\mathrm{KH}} = \frac{GM^2/R}{L}$$



Accretion onto main sequence stars



The Eddington accretion limit



Assume electron scattering for minimum opacity...

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

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

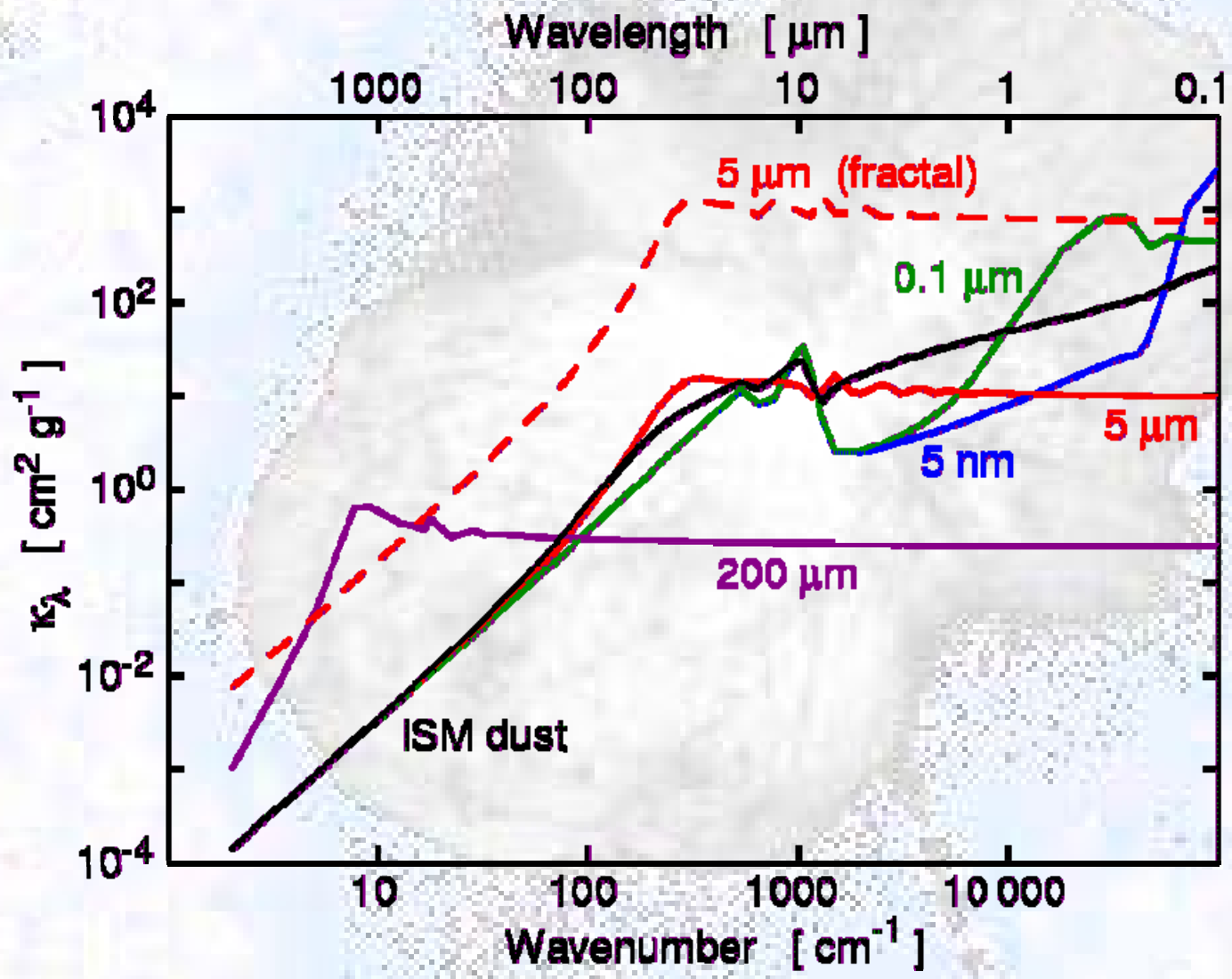
$$\dot{M}_{max} = \frac{4\pi Rc}{\kappa_e} - \frac{RL_*}{GM}$$

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

How you form massive stars in the present epoch?

- 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 $\kappa_{eff} = \frac{\pi R_{blob}^2}{M_{blob}}$
- 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 $\rho_{objects} \geq \rho_{gas}$

Opacity of dusty gas



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

compared to

Silicates of given sizes (colored lines)

Numerical Simulations of Physical Processes

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

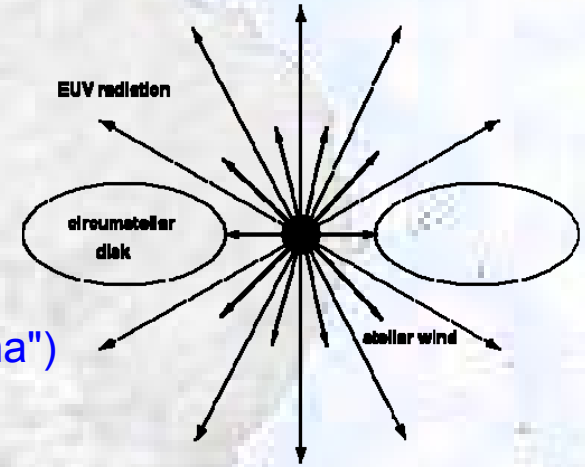
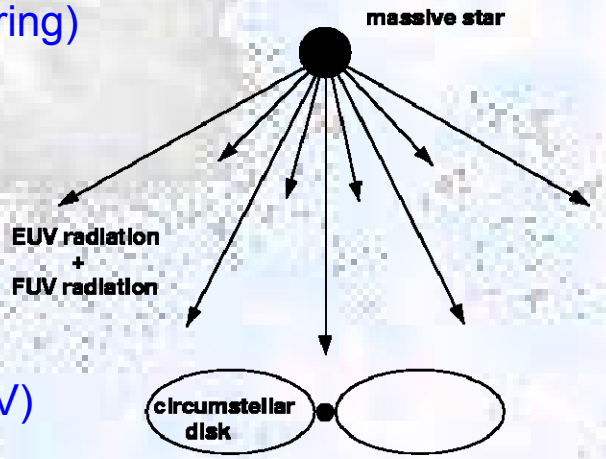


Photo-ionized Envelopes

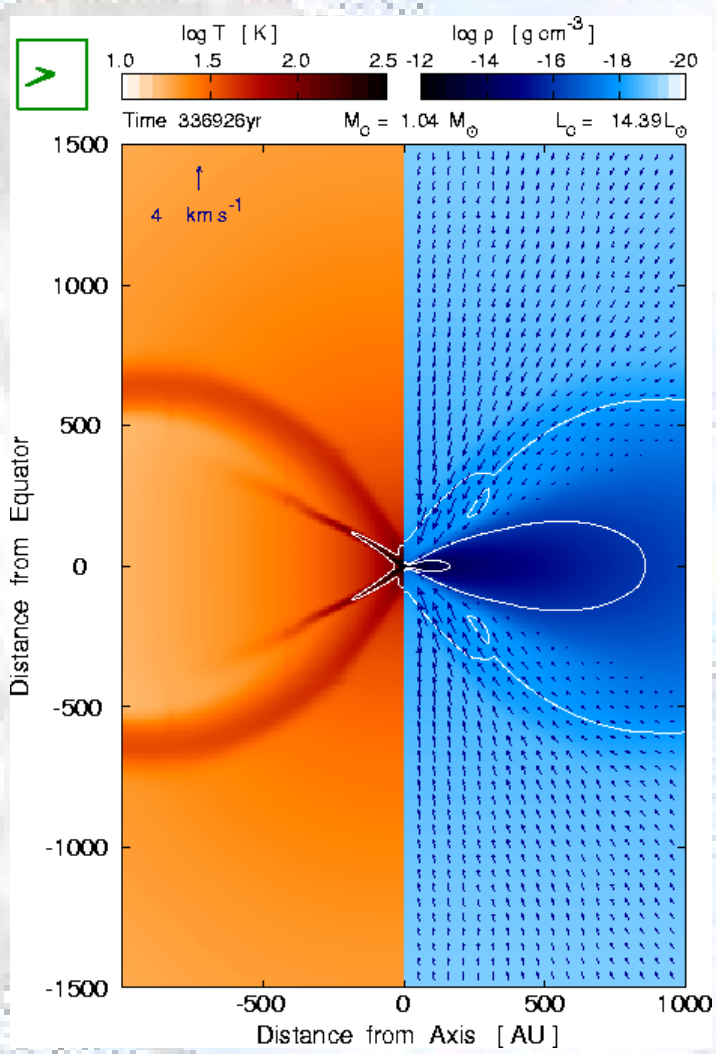
- Central stellar wind + UV
- Time dependent ionization/recombination
- Transport of stellar EUV photons ($h\nu > 13.6$ eV)
- Transport of stellar FUV photons (6 eV $< h\nu <$ 13.6 eV)
- Transport of H-recombination photons ($h\nu \sim 14.2$ eV)
- Transport of UV photons scattered by dust



Envelopes of accreting Stars

Yorke & Bodenheimer 1999

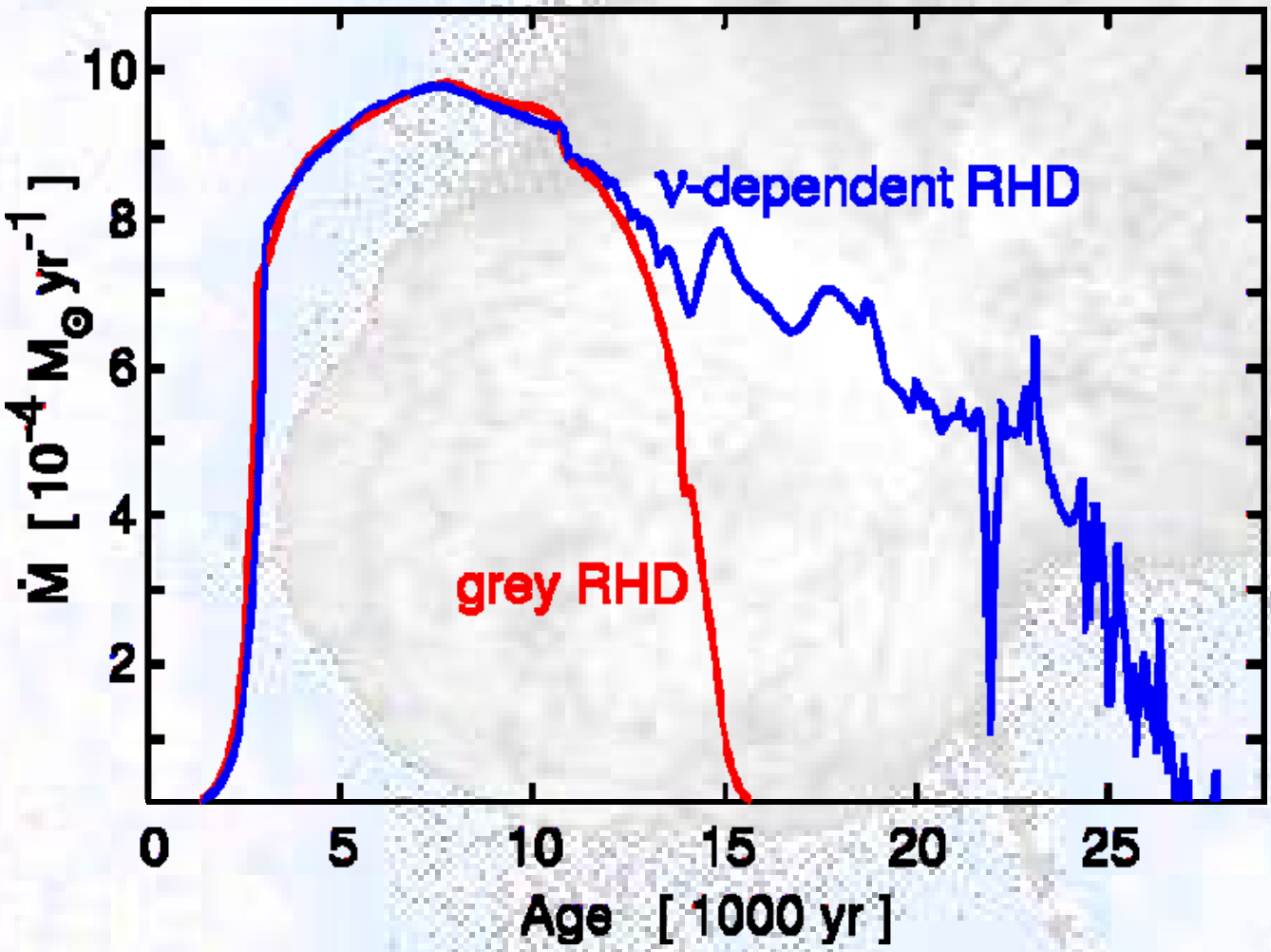
- 2 M_o cloud, diameter 0.13 pc
- $\langle n_{H2} \rangle = 3\ 10^4\ cm^{-3}$, T = 10 K
- $n_{H2} = A\ r^{-2}$ (density peaked)
- $\Omega = 5\ 10^{-14}\ s^{-1}$, $v_{rot} = 10$ m/s



Formation of a $1M_o$ Star with accretion disk

Time dependent accretion through disk

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

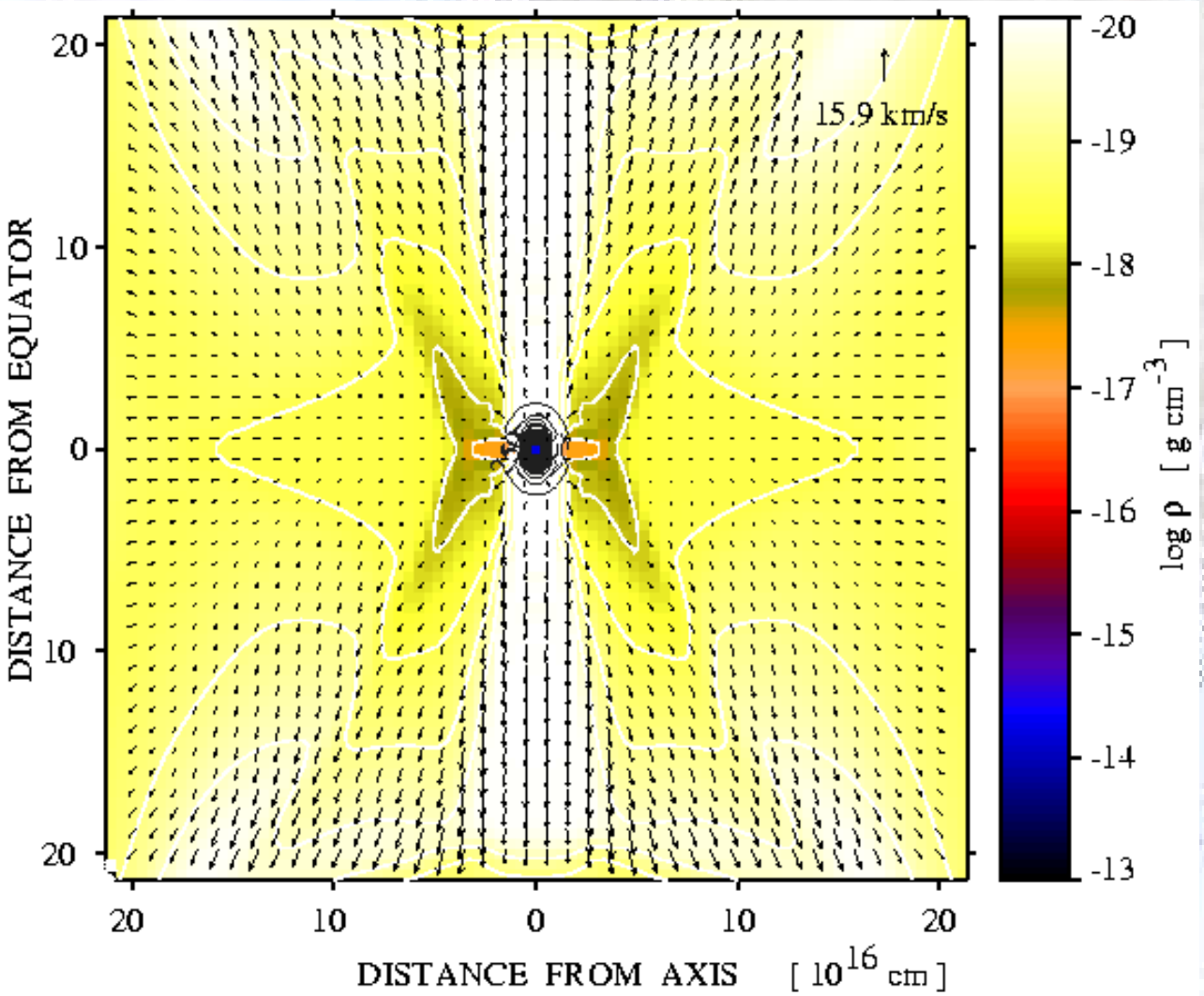


Ω [s^{-1}]	$5\ 10^{-13}$
R_{max} [pc]	0.1 0.2
M_0 [M_o]	60 / 60 120
M_{final} [M_o]	34 43
M_{final} [M_o]	21 (grey)

ν-Dependent Radiation Hydrodynamics of Collapse

35,000 yr 33.6 M_o

Yorke & Sonnhalter, 2002, ApJ, 569, 846

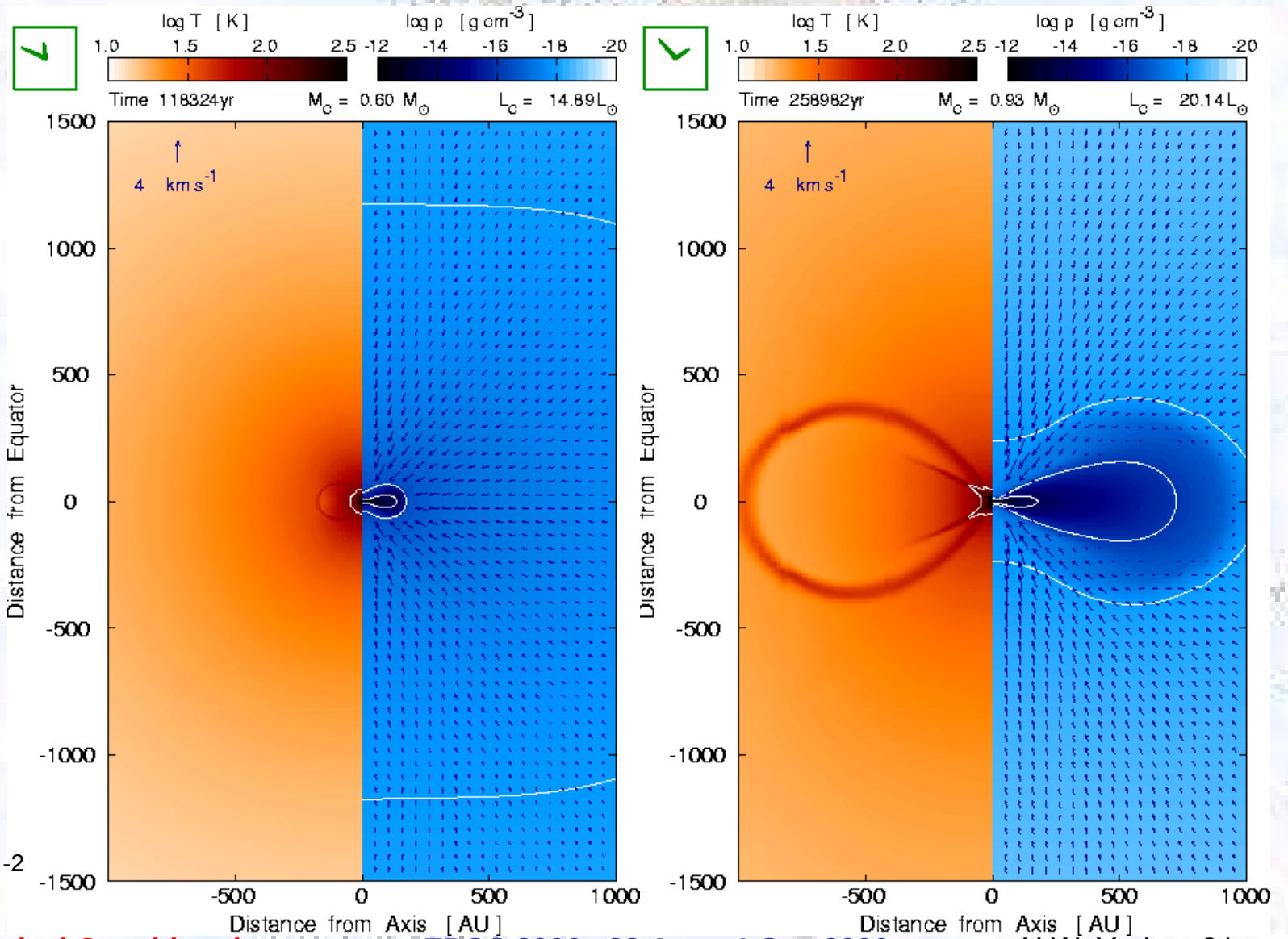


60 M_o case
120 M_o case

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)

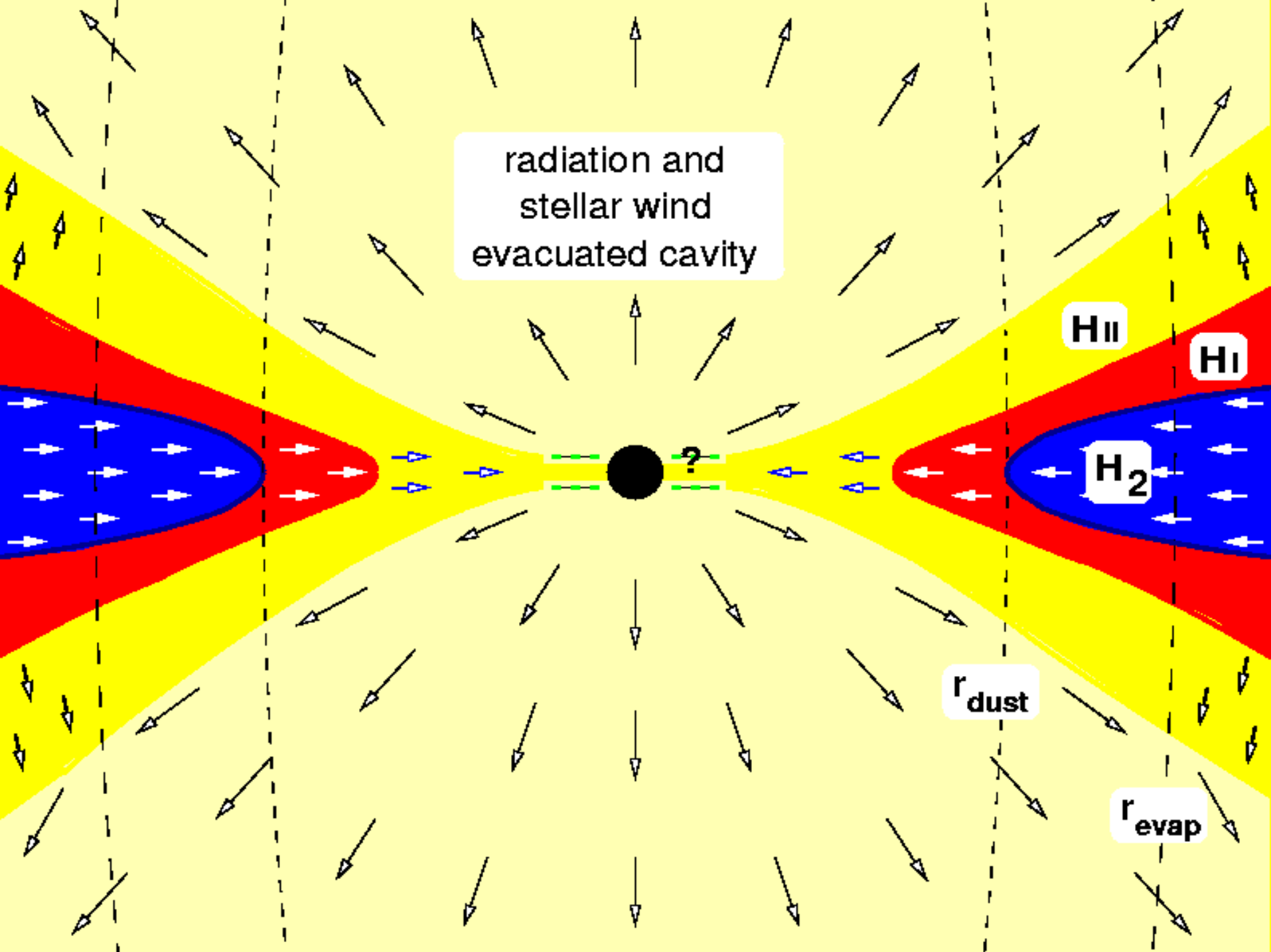
The "flashlight" Effect

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



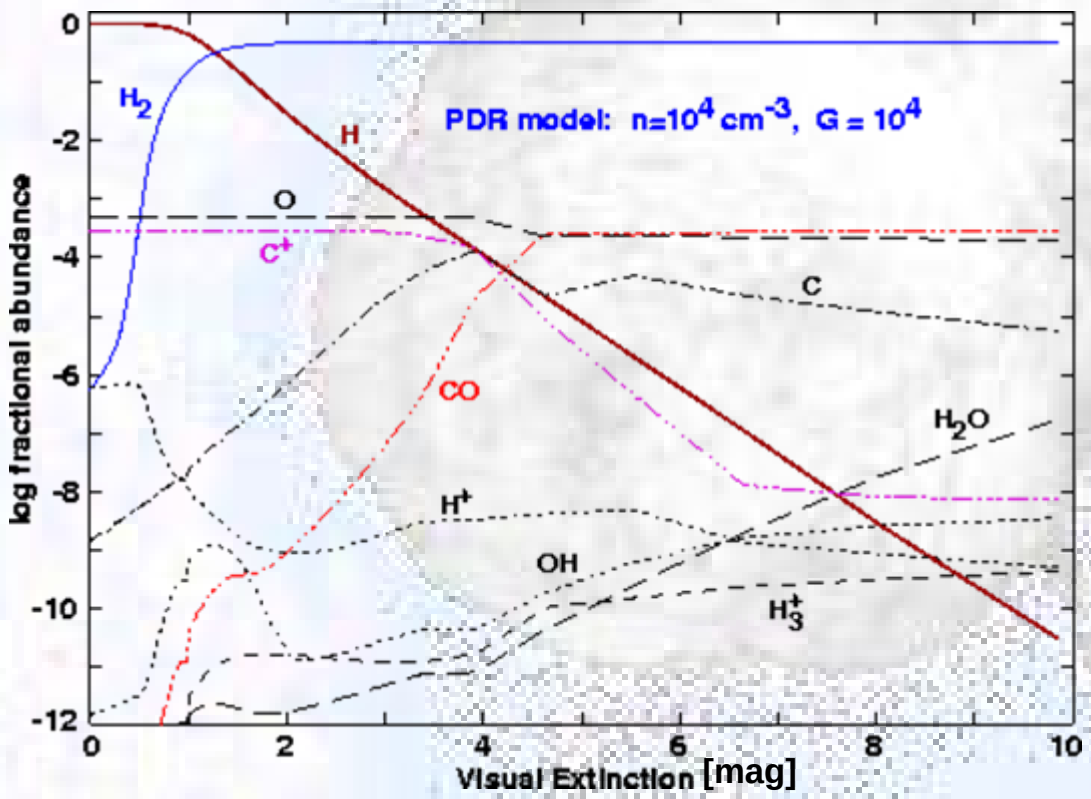
2 M_o

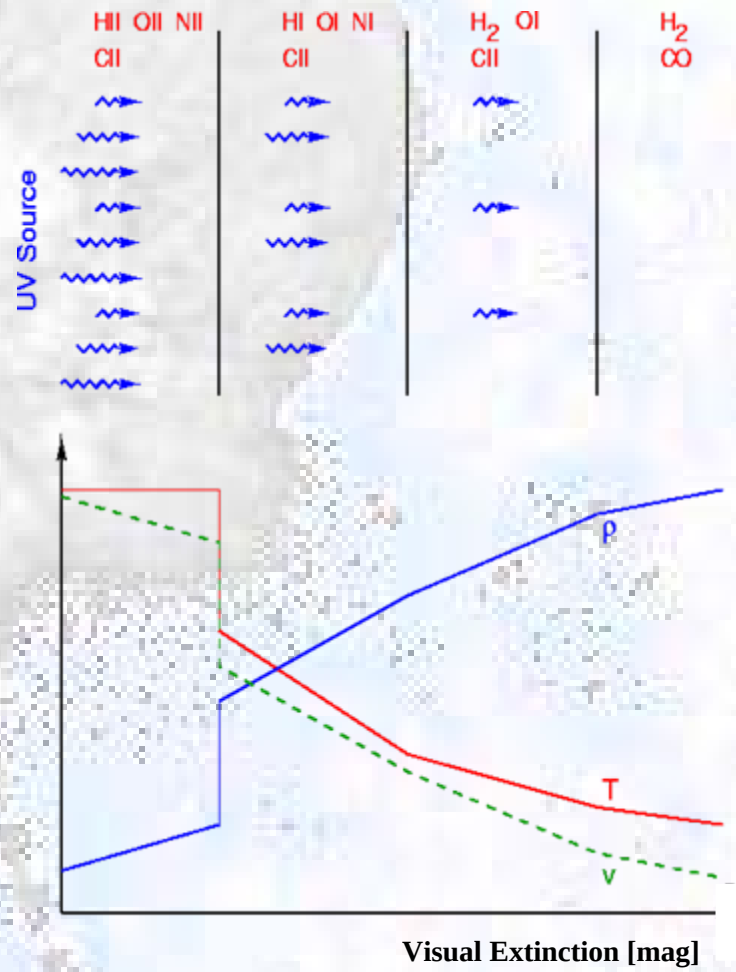
$\rho \sim r^{-2}$


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

Photodissociation Regions (PDRs)

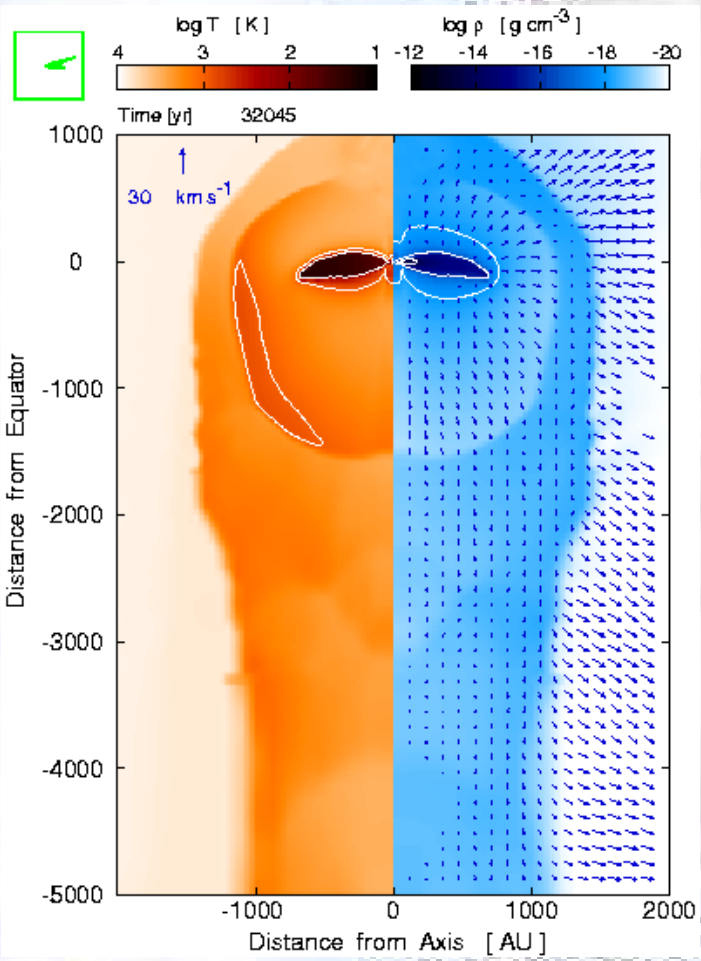
- Illumination of interstellar material (ISM) by UV photons affects its composition and thermal properties.
- This in turn affects the dynamics of the ISM.
- Many important lines for analyzing ISM and the UV sources are accessible to Herschel's HIFI.





Destruction of circumstellar disks

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



Initial conditions

Mass of star: 1.2 M_o
Mass of disk: 0.5 M_o

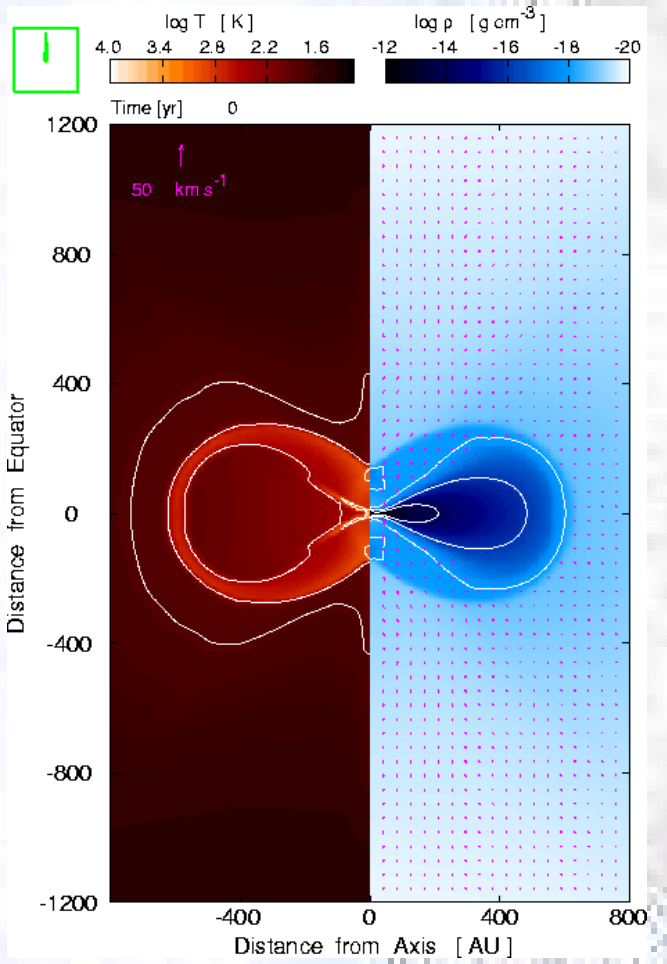
External O5 star
Distance from disk: 0.1 pc

Results

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

Destruction of circumstellar disks

- Destruction of circumstellar disk: 1, 2



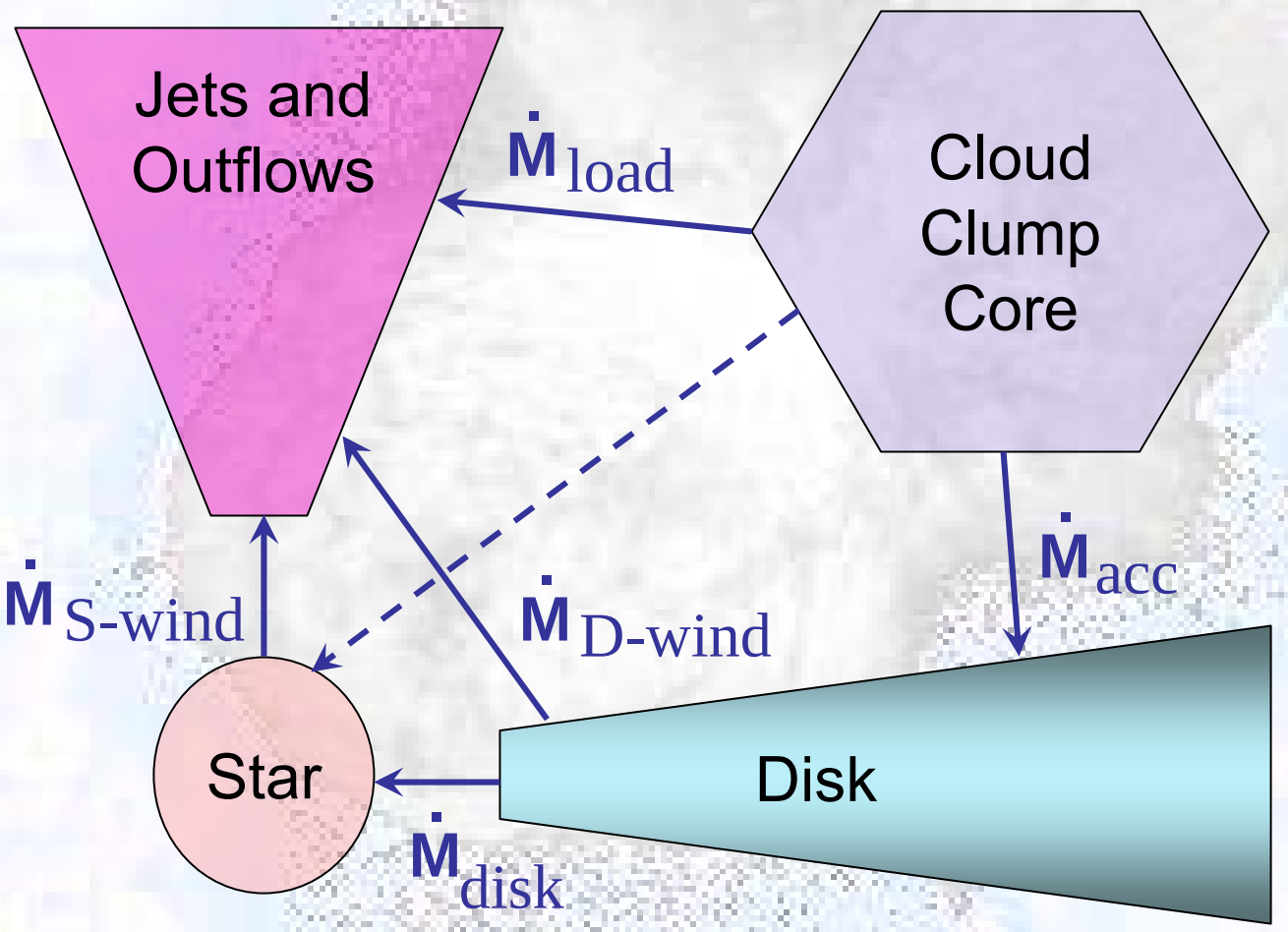
Initial conditions

Luminosity of star:	3550 L_o
Mass of central star:	8.3 M_o
Stellar wind:	30 km s^{-1} 10^{-7} 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

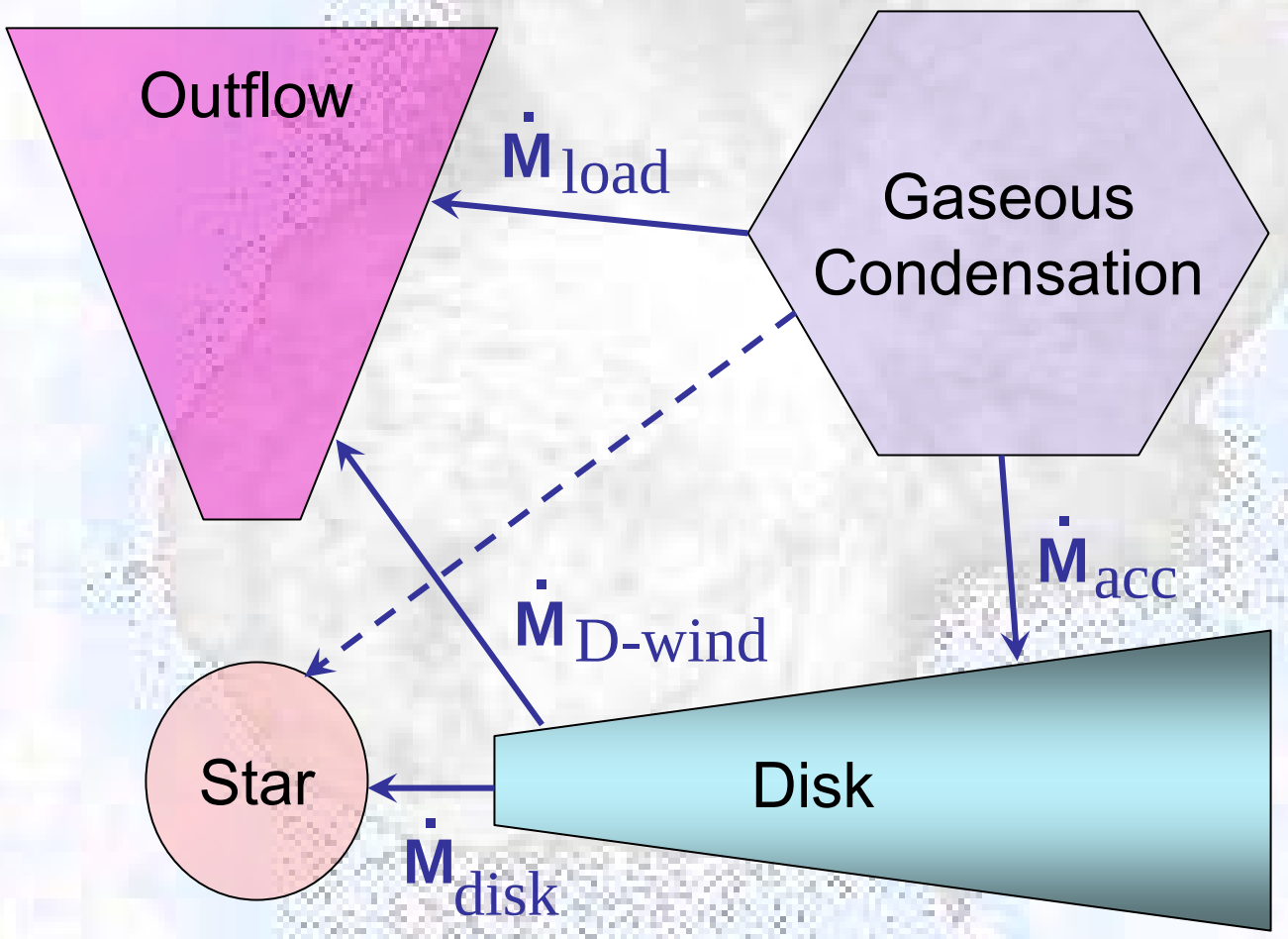
Disk wind via “external” UV heating
Stellar wind focused through polar cavity
Photoevaporation of disk within 10^5 years

Accretion and mass loss as mass exchange between components



Disk acts as reservoir for material

Pop III: Accretion and mass loss as mass exchange between components



Disk acts as reservoir for material

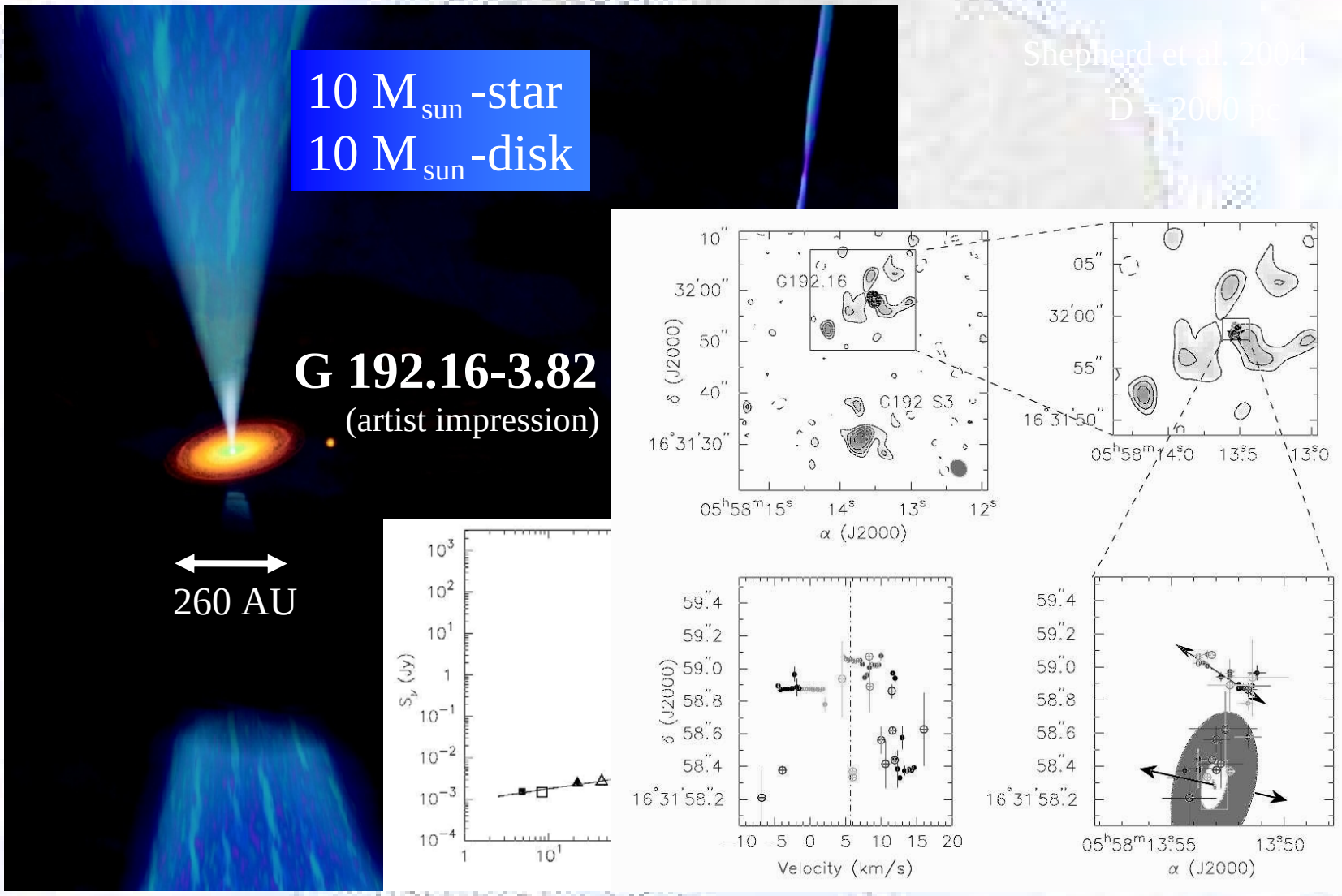
What determines these dM/dt's?

- $\dot{M}_{disk}$ related to angular momentum transport within disk
  - Magnetic fields (important for current star formation)
  - Turbulence
  - Tidal effects (bars, spiral arms)
- $\dot{M}_{acc}$ determined by cloud core parameters
  - $t_{acc} \sim t_{ff} \sim t_{cross}$
- $\dot{M}_{D\text{-}wind}$ 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 (stellar winds won't happen for young Pop III stars but may occur later)

"Known" Massive Accretion Disks

Shepherd et al. 2004

D = 2000 pc



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

Star Formation in the Distant Past – Standard Wisdom

- 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

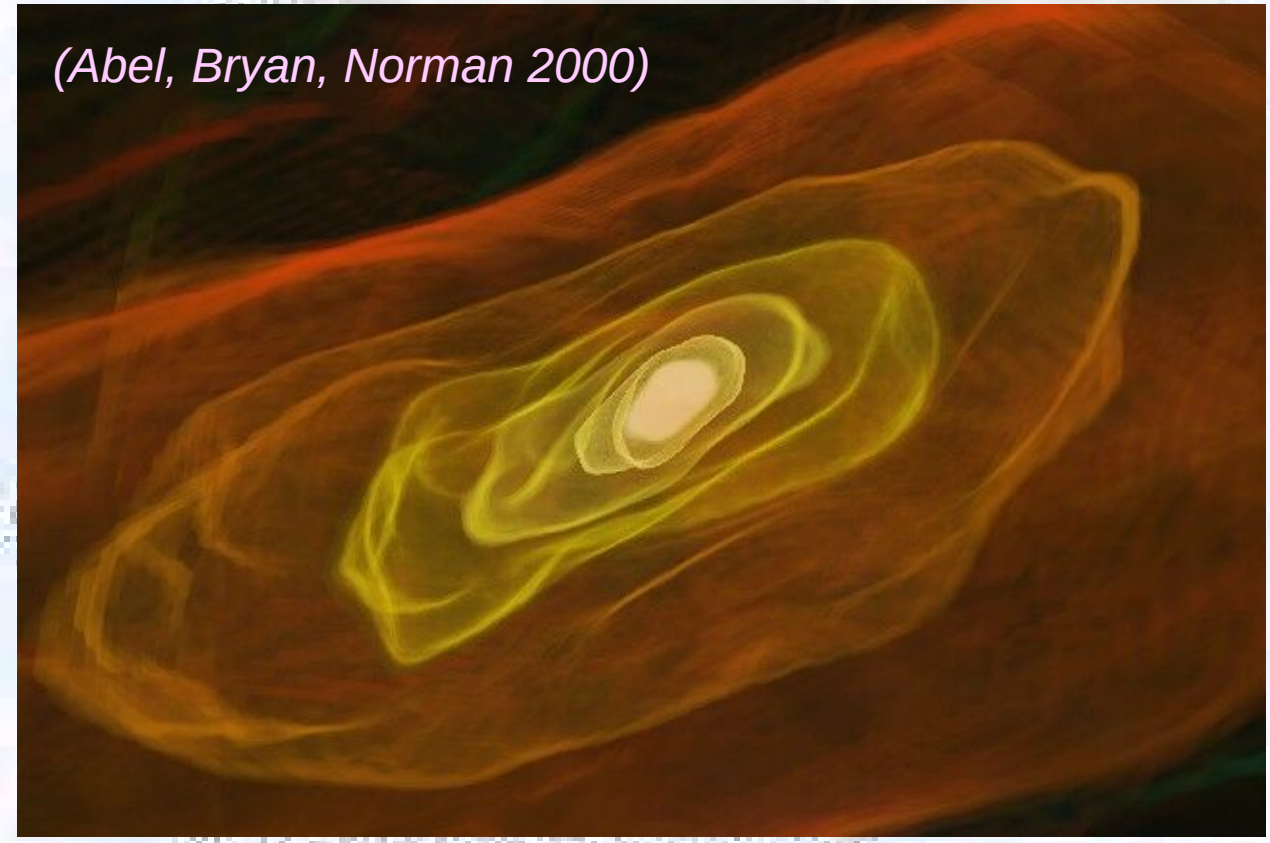
More Star Formation Wisdom

- 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.

First protostars

Rotation will play an important role …



Concluding Remarks 1

- 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

Concluding Remarks 2

- Pop III stars probably form 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 are probably multiple systems.
  - Because of lack of magnetic fields in their early phases, fission in rapidly rotating Pop III stars can produce close binaries

Concluding Remarks 3

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