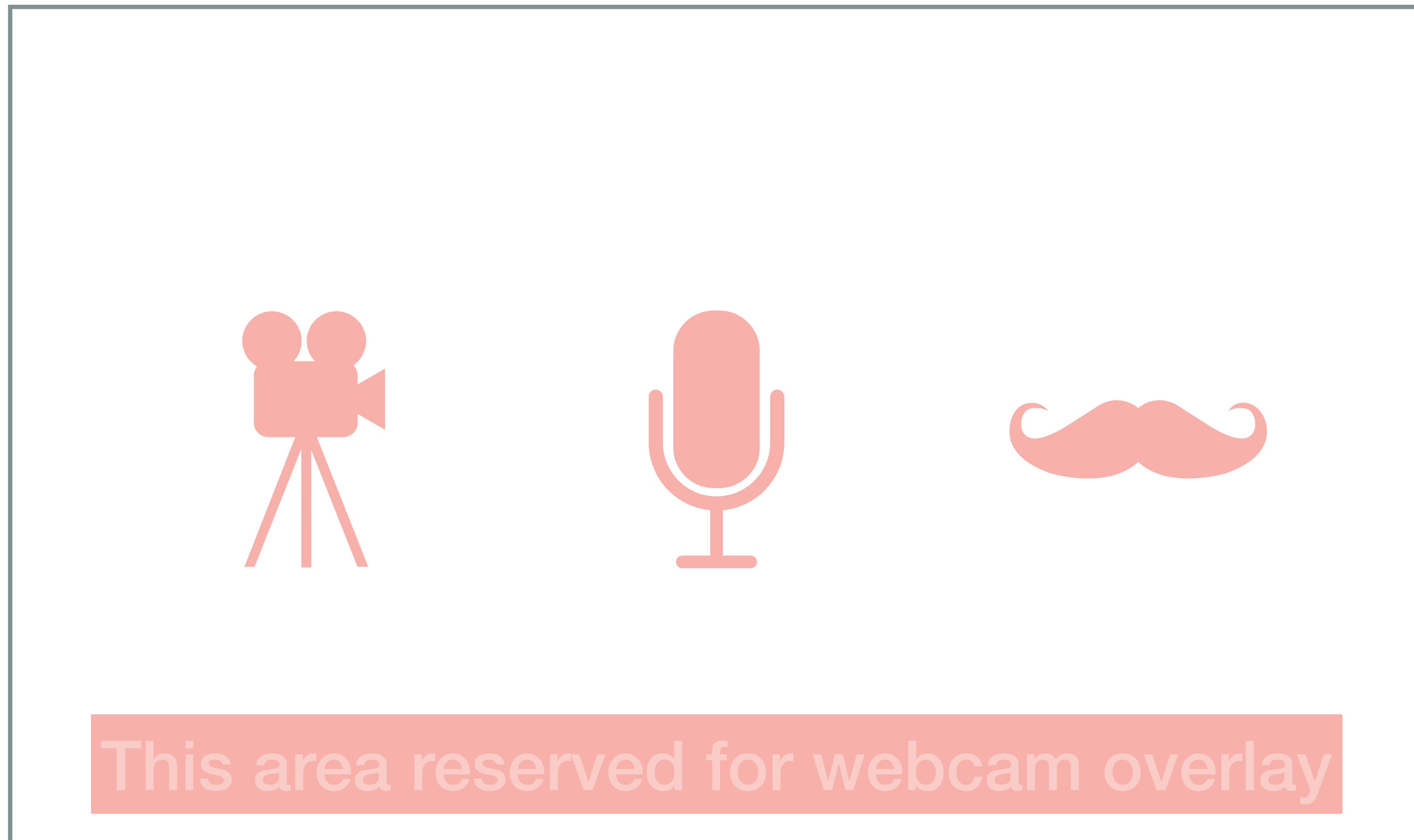
ASTR 421

Stellar Observations and Theory

Lecture 15
Stellar Evolution: I

Prof. James Davenport (UW)



This Week

- Working towards HW6: MESA evolution models for two stars: 1 & 25 $M_\odot$
- So far we've talked lots about stars on the main sequence
- We'll be discussing stellar evolution, their formation and destruction

  "Birth" and "Death"
- Reminder: MESA (Modules for Experiments in Stellar Astrophysics)

MESA

https://docs.mesastar.org/en/release-r21.12.1/

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Today

- Reminder of Stellar Structure Eqns & Timescales
- Star Formation, Pre-Main Sequence Evolution
- YSOs

- BOB, Ch 12.2+

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Stellar Structure Equations

$$\frac{dP}{dr} = -G\frac{M_r\rho}{r^2} = -\rho g$$

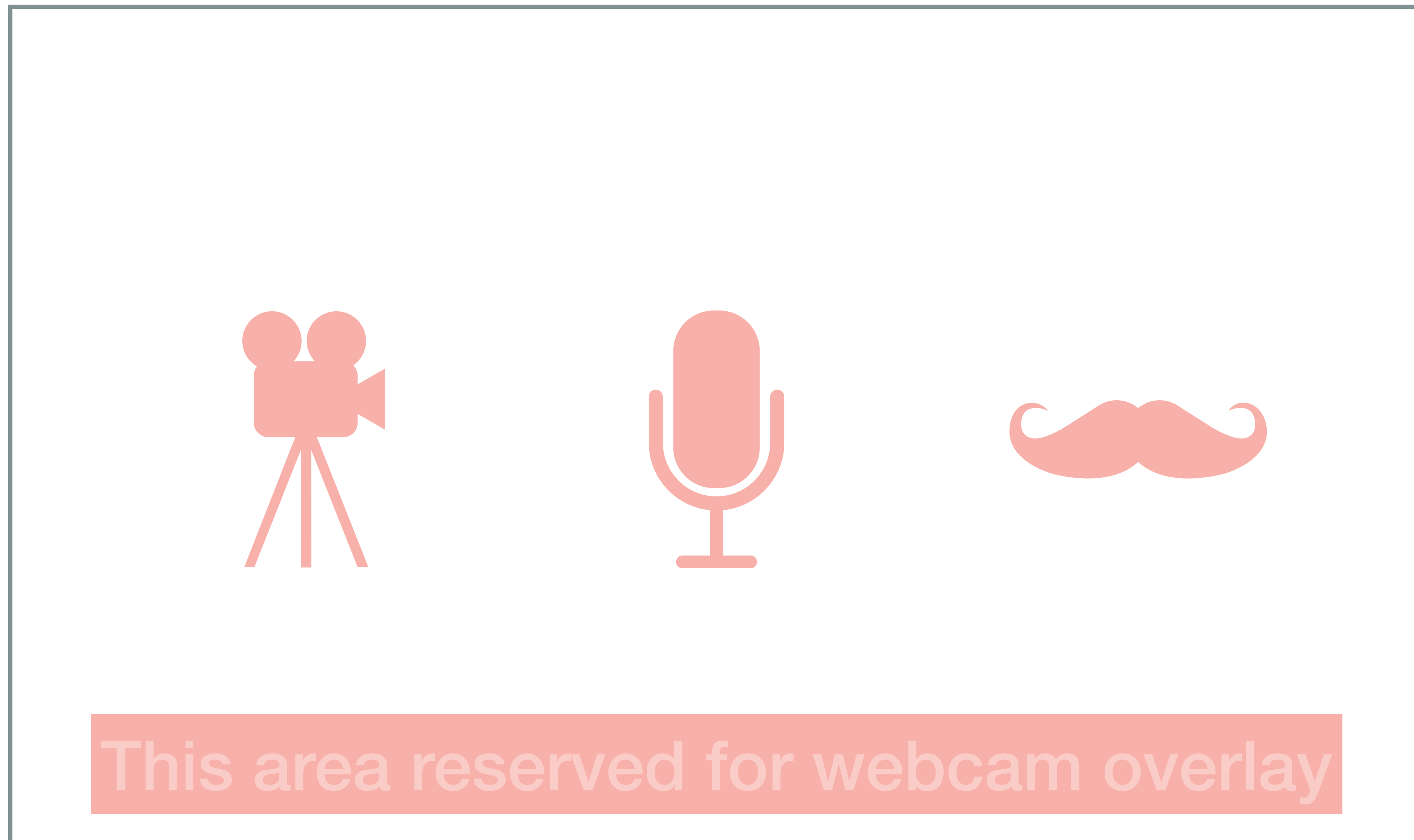
$$\frac{dM}{dr} = 4\pi r^2 \rho$$

$$\frac{dL}{dr} = 4\pi r^2 \rho\ \epsilon$$

$$\frac{dT}{dr} = \frac{3\bar{\kappa}\rho L}{64\pi r^2 \sigma T^3} \qquad \frac{dT}{dr} = -\frac{g}{C_P}$$

These eqns govern structure *assuming* HSE, don't apply to all phases of pre-MS evolution

(Especially early proto-star formation)

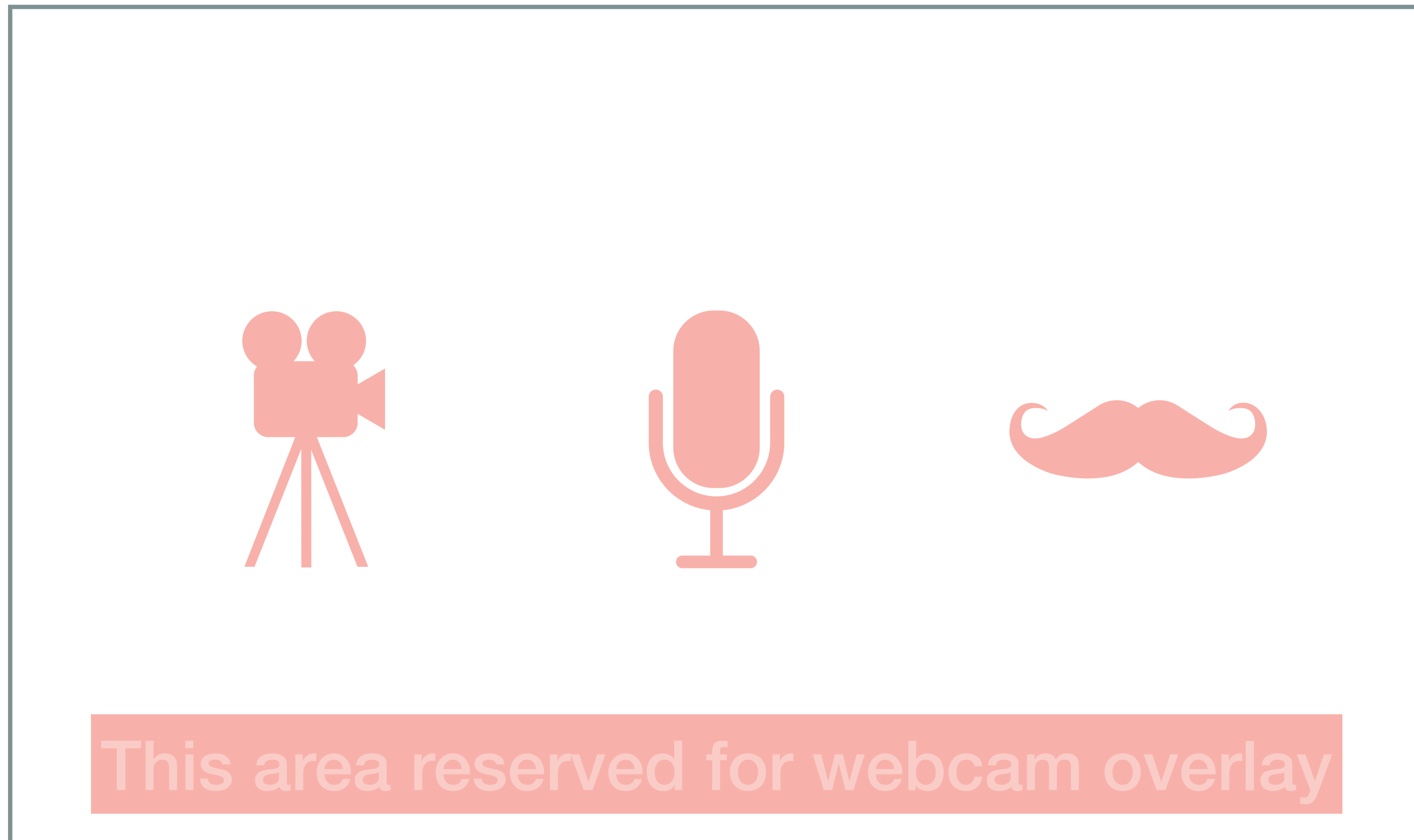


Stellar Timescales

- $t_{ff} = \frac{1}{2}\sqrt{\frac{R^3}{GM}}$ ~27 min (for the Sun)
- $t_{KH} \approx \frac{GM^2}{RL}$ ~30 Myr
- $t_{nuc} = \frac{E_{nuc}}{L}$ ~10^{10} yr

Pre-MS (star formation) Timescales!

Main Sequence Timescale



Star formation

- It begins in dense, cold clouds
- Bok globules, small molecular clouds
- **Giant Molecular Clouds (GMC)**
- Temps ~10-20K
- Densities ~$10^2 - 10^6$ / cm^3

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Star formation

- A portion reaches the "Jean's Mass"
  - cloud begins to collapse (at least in places)

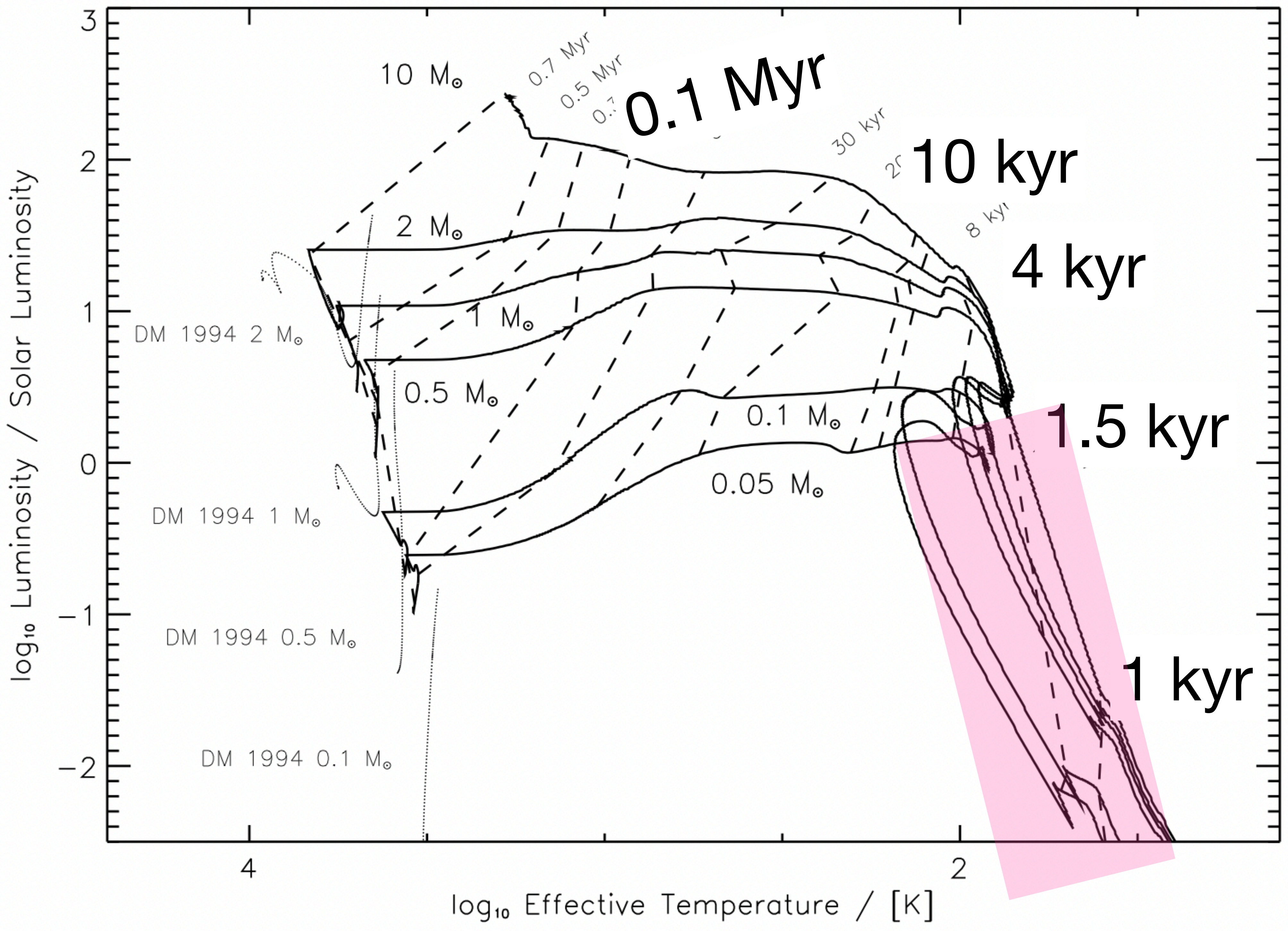
- **Why?** What causes initial GMC collapse? Many possible things: turbulence & gas compression, HII and SNe induced compression, colliding GMCs…
  - All are happening, a nice review by Elmegreen (1998)

Protostar formation

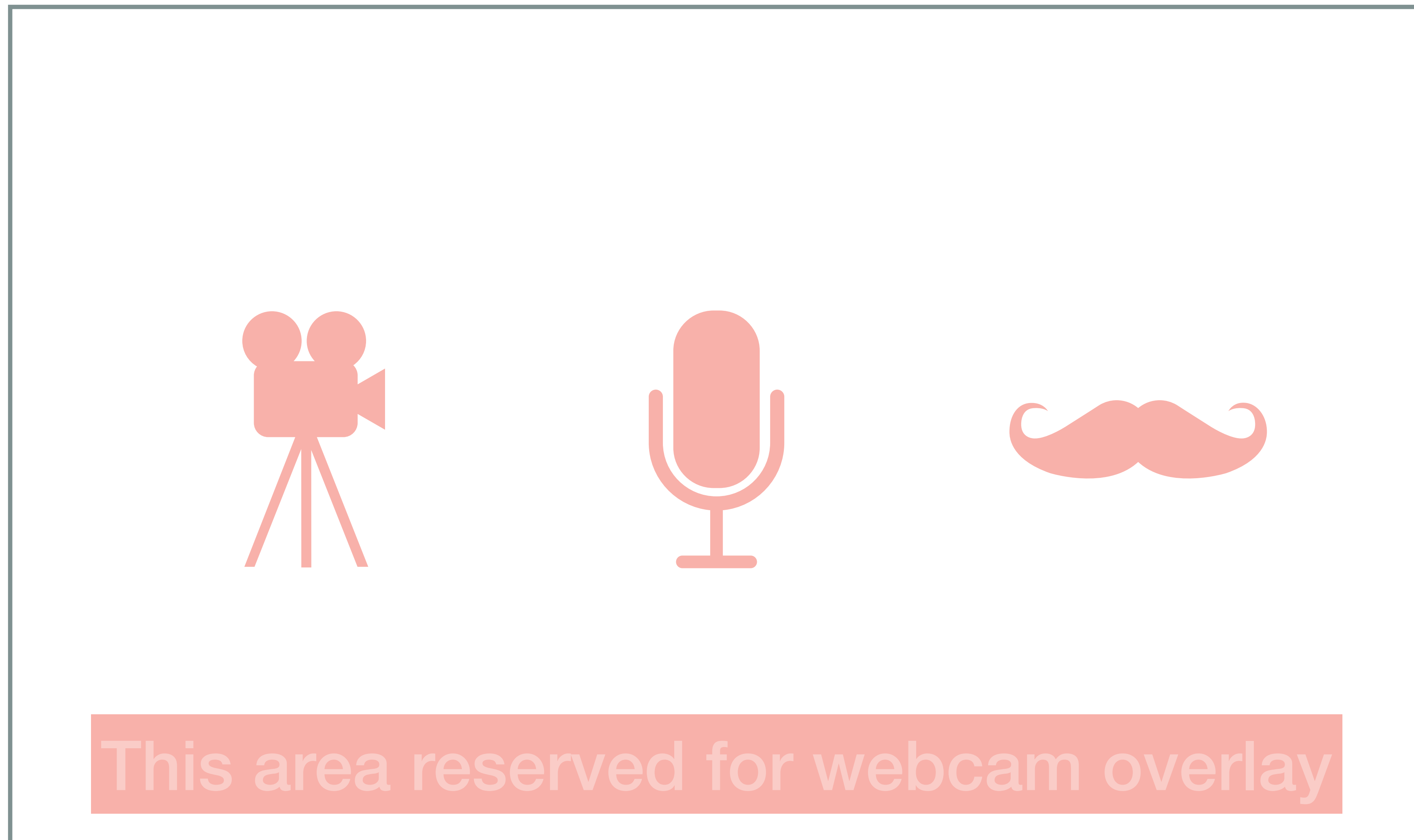
- **Initial collapse** is approximately *isothermal*, density is low enough the gas isn't thermalizing (colliding) yet.
    - optically thin!
- So gas collapses on roughly the free-fall timescale (i.e. FAST)

$$t_{ff} = \frac{1}{2}\sqrt{\frac{R^3}{GM}} \approx \sqrt{\frac{1}{G\rho}}$$

- Can get "inside out" collapse here, lots of interesting shocks & structure here as "core" forms

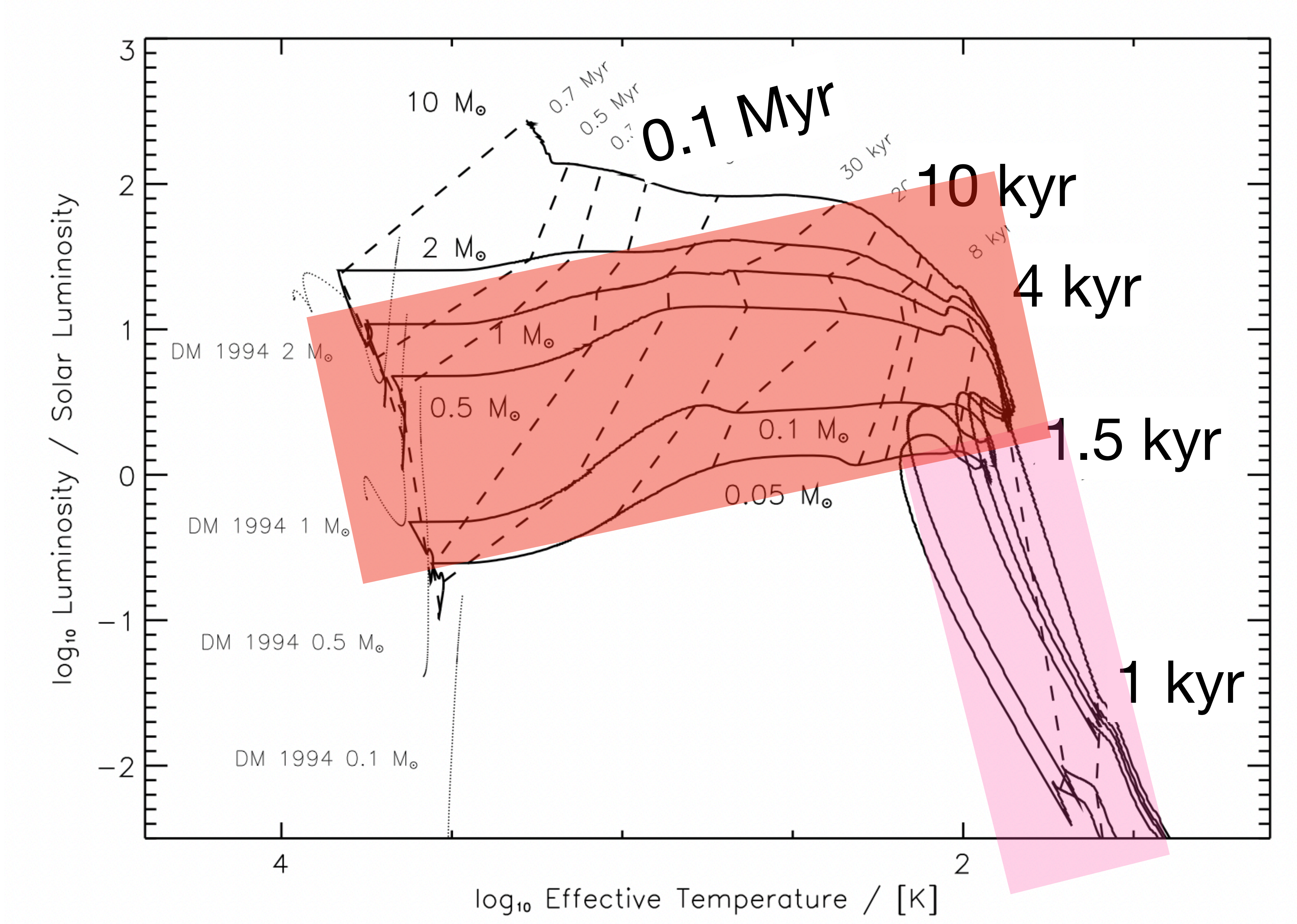


Wuchterl & Tscharnuter (2003)



Protostar formation

- **Free-fall** collapse continues until gas becomes optically thick
- Lots of mass has "arrived" near the protostar, but needs to collapse & accrete
- Disk forms
- Protostar has to actually *cool* to contract
- **Cools adiabatically**, temp increases but SO much gas and dust around it doesn't radiate
- Hydrostatic equilibrium begins



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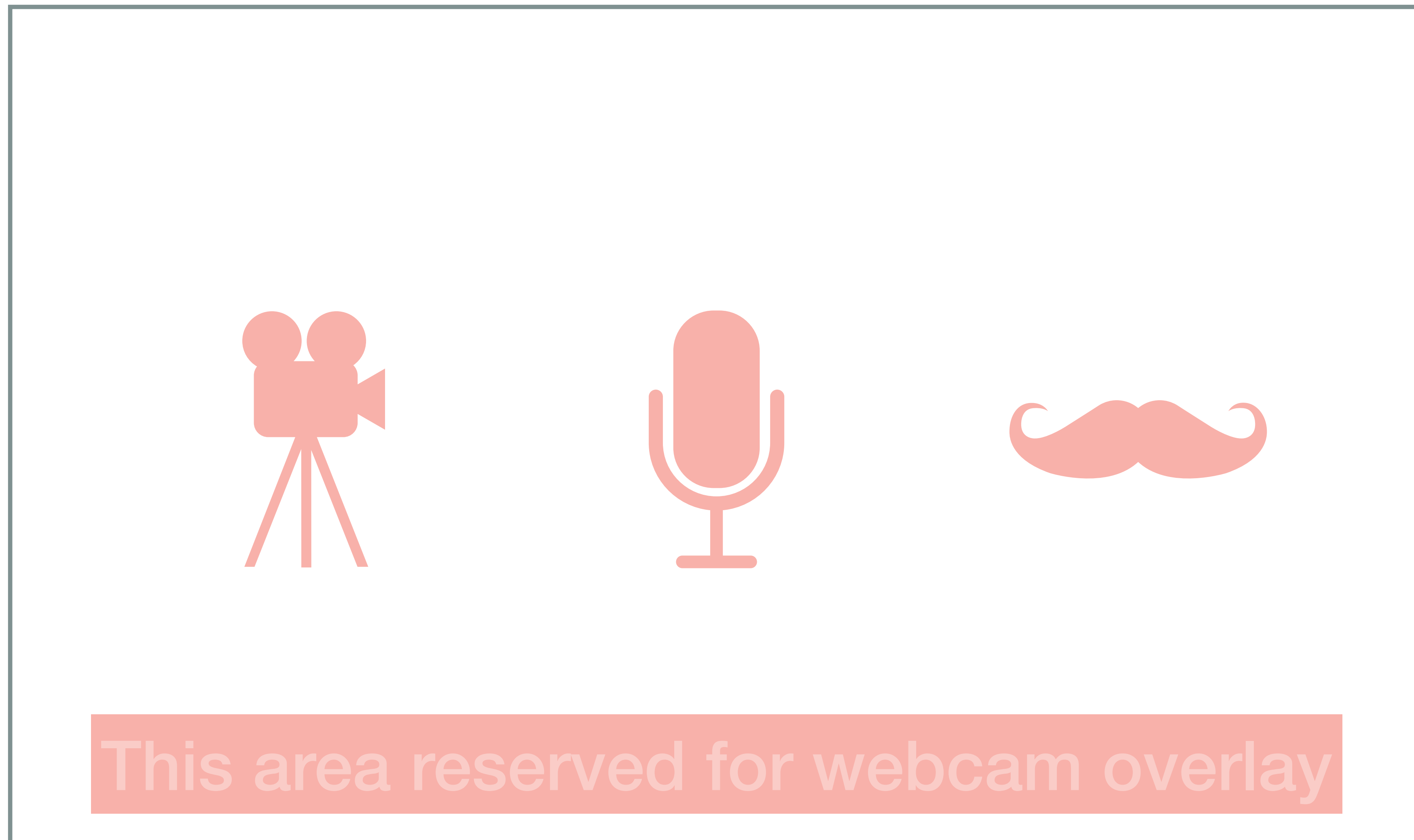

Protostars

- When they finally “emerge”, highly variable!
- Very turbulent phase, accretion is amazing
- (Planets get started around here too)
- Need IR, mm, or radio to see protostars
- IMO, one of the most *photogenic* areas of astronomy

https://public.nrao.edu/news/new-look-bright-stellar-nursery/

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Protostars

- They’re often partially “enshrouded” in gas/dust
- Winds blow open holes
- Typically in big star forming “complexes”


http://spacetelescope.org/images/potw1509a/

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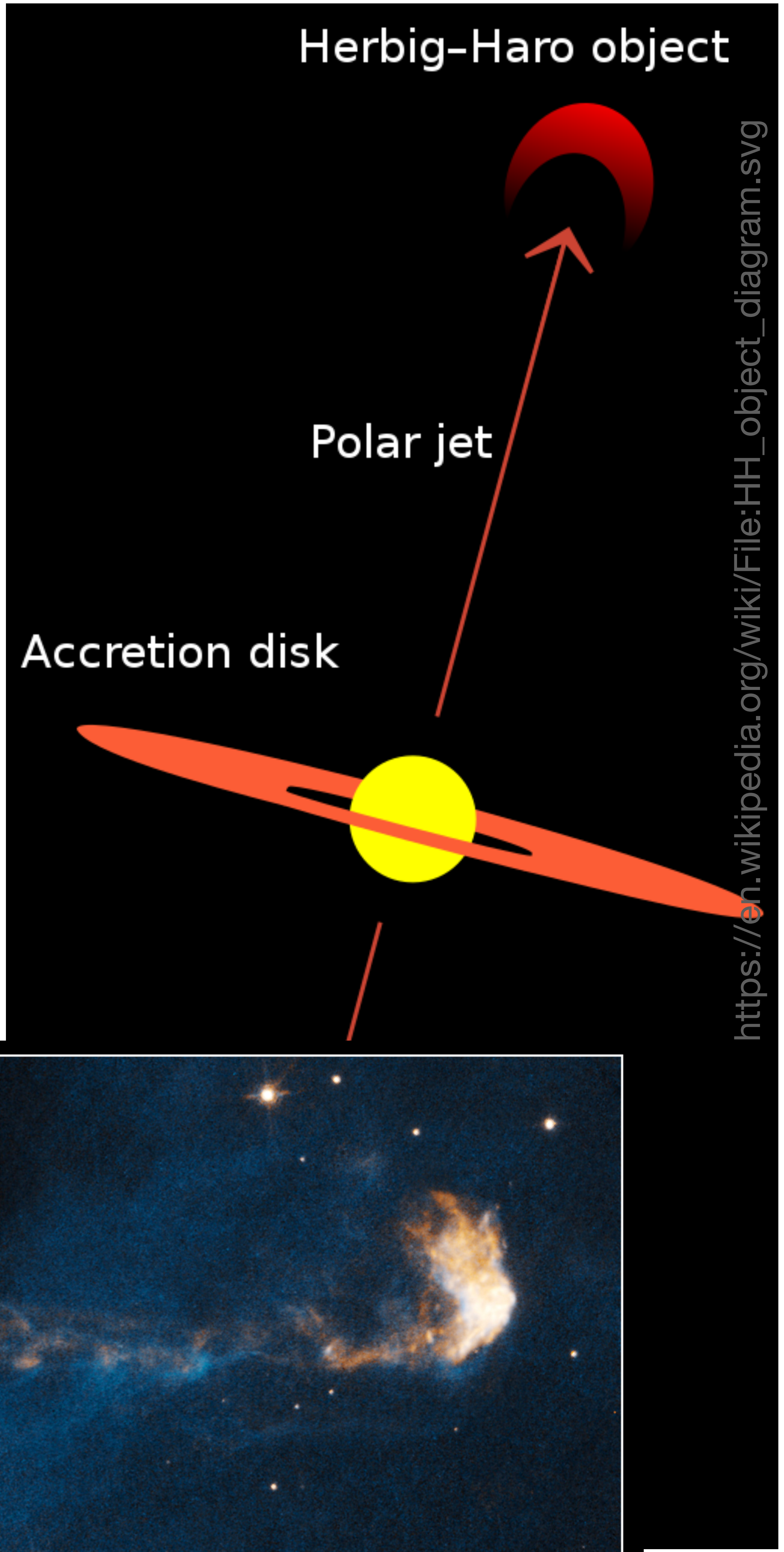
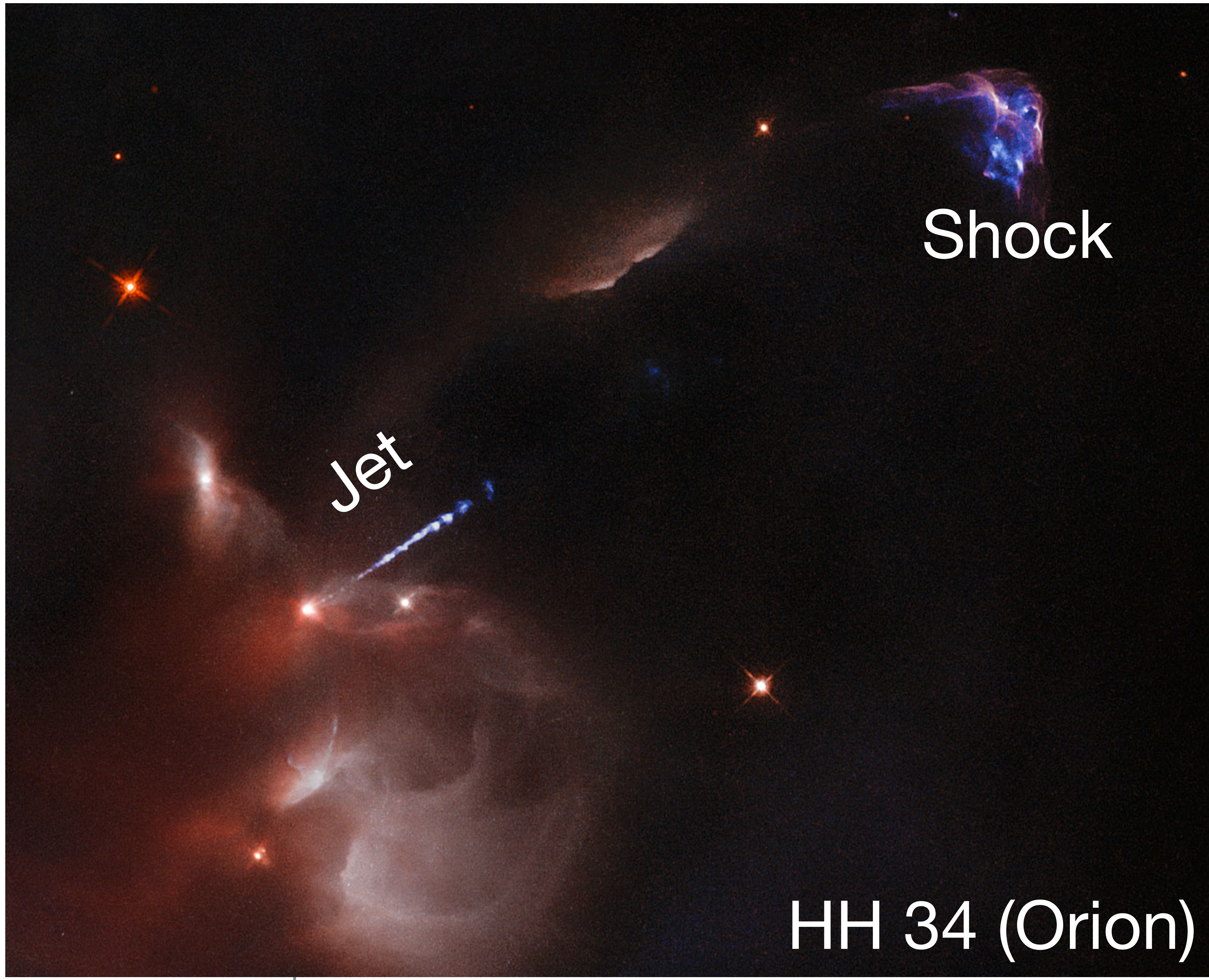
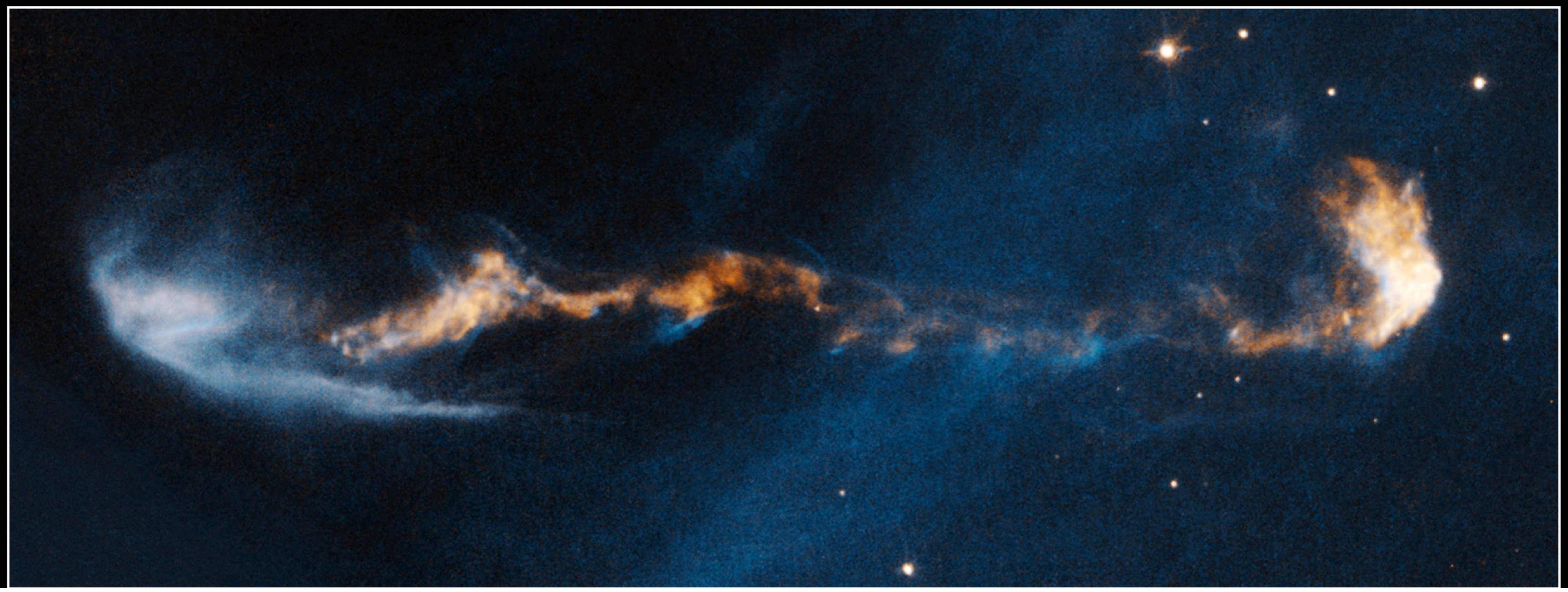
Jets

- Accretion + **B** fields from the protostar = launching jets
- Herbig-Haro (HH) objects
- Enormous, seen all over!







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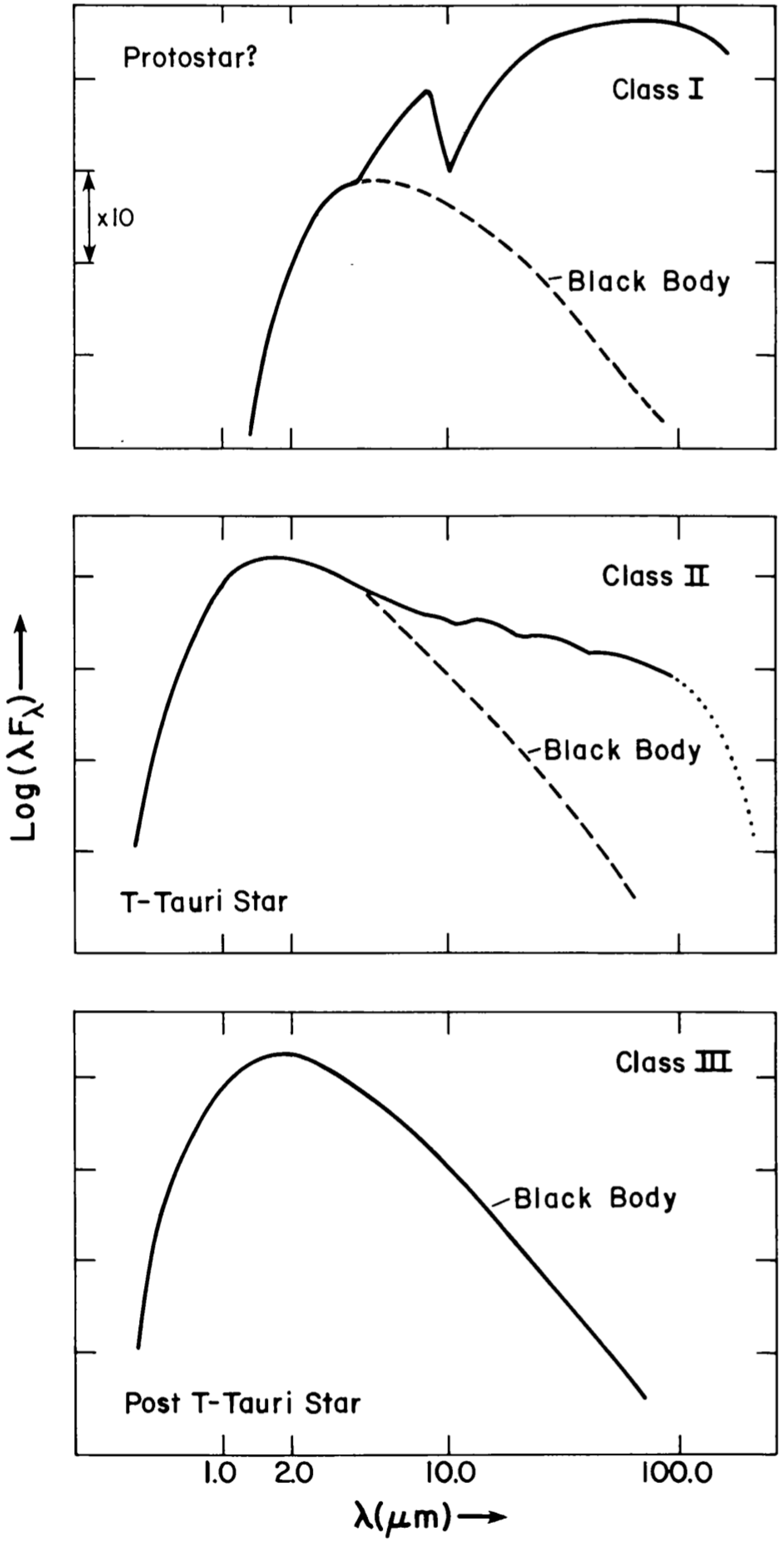
HH 34 (Orion)
1994 - 2007
https://esahubble.org/videos/heic1113d/

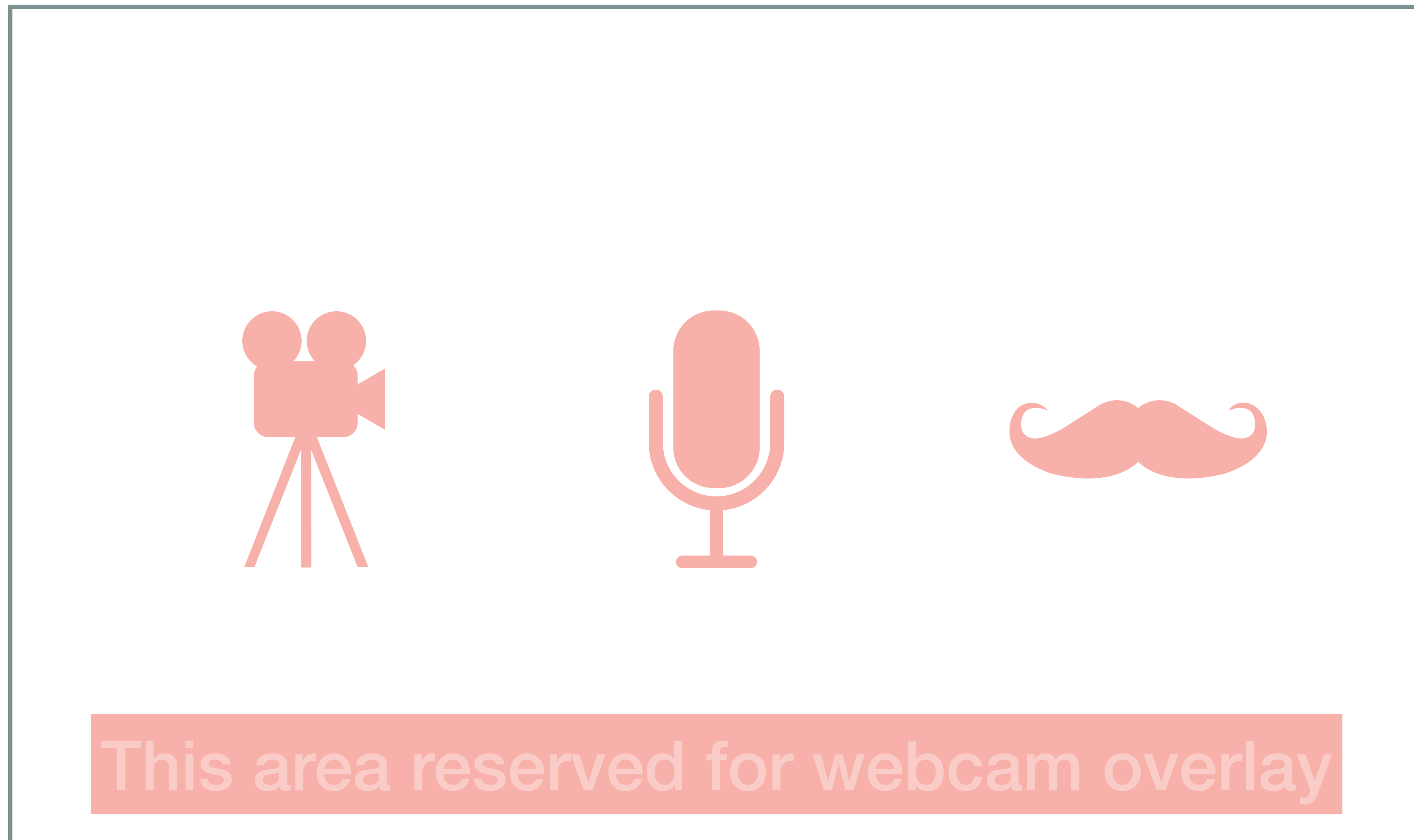
Protostars & Pre-Main Sequence



- Class 0: pre-stellar clump
- Class I: Disk-dominated

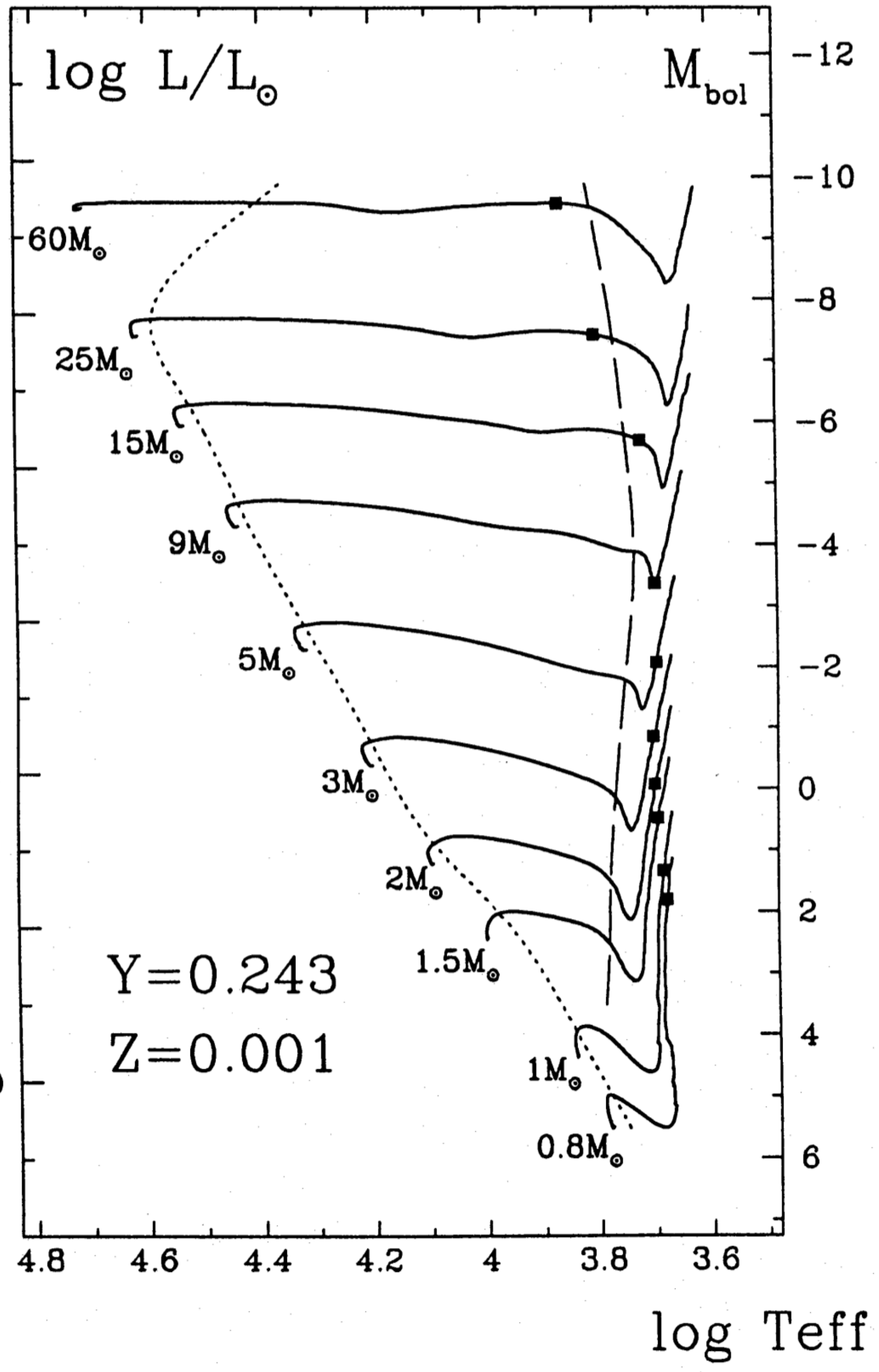
- Class II: T-Tauri stars, strong disks
- Class III: Weak T-Tauri, thin disks, transition objects towards main sequence

Lada (1987)



Pre-Main Sequence Evolution

- The protostar has formed, *most* of the mass is in place
- It's not a star yet, fusion not happening in the core
- Protostar is giant (low core density), bright
- Surface is cool (as cool as can be!), strong *temperature gradient* throughout
  - This means *convection* throughout protostar!



Bernasconi & Maeder (1996)

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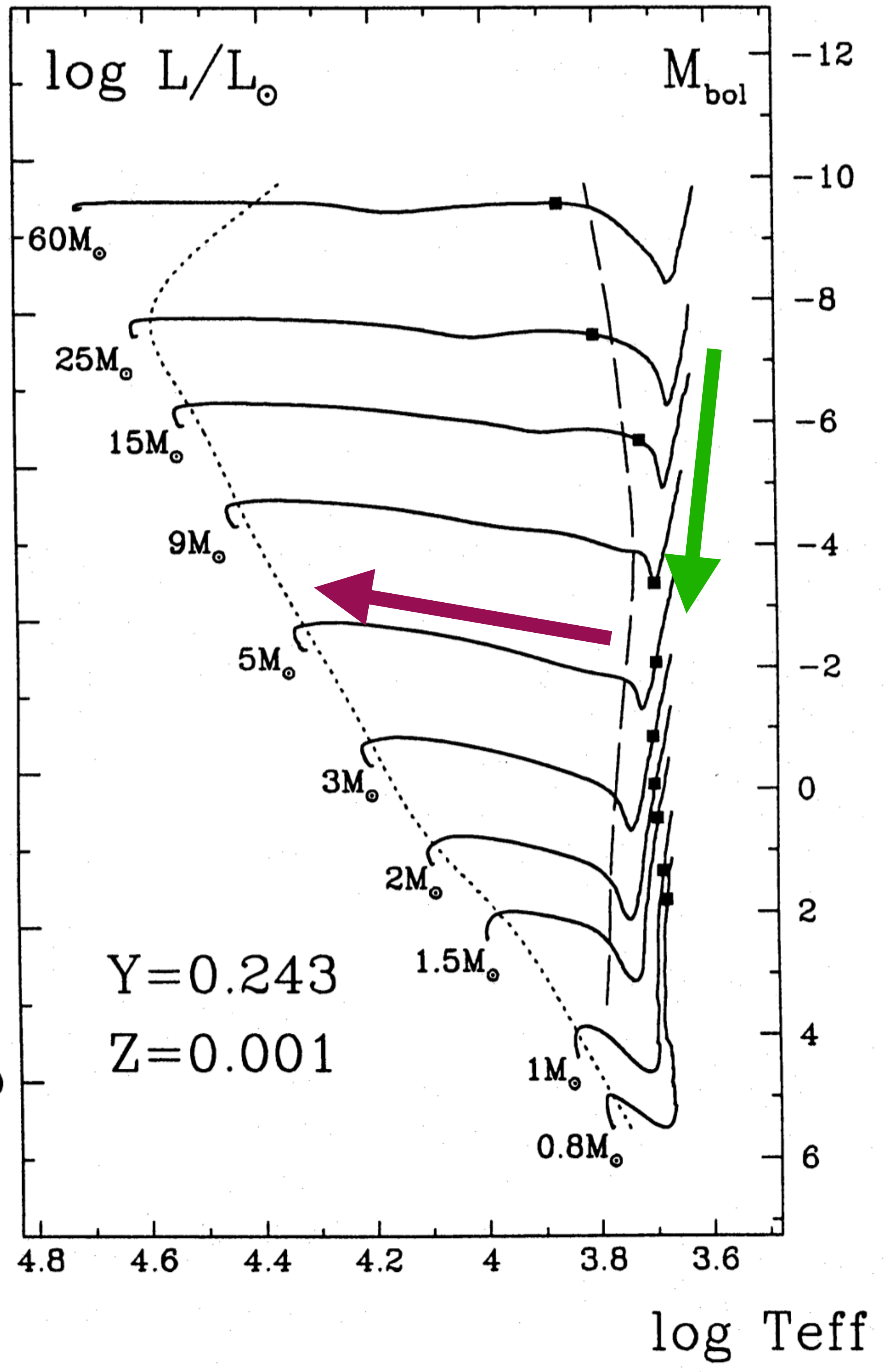
Pre-Main Sequence Evolution

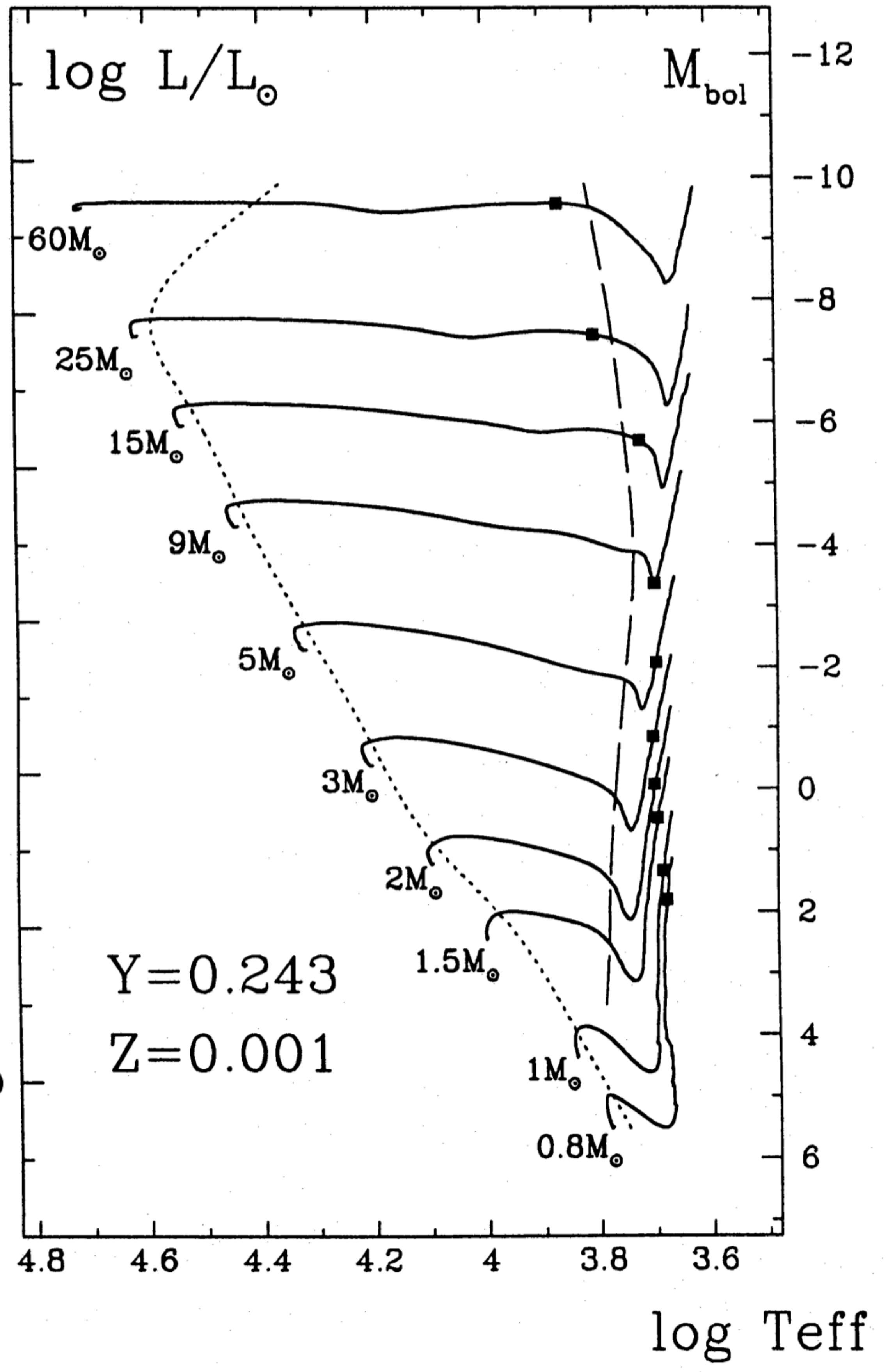
- 2 phases of this evolution:
  - Convective contraction (the **Hayashi Track**)
    - Up against the “Hayashi limit” temperature
    - Vertical motion on H-R diagram
  - Radiative contraction (**Henyey Track**)
    - Core forms, luminosity ~fixed near HSE
    - Horizontal motion on H-R diagram



Bernasconi & Maeder (1996)

Pre-Main Sequence Evolution

- <u>Interesting edge cases:</u>
- Low-mass stars never form a radiative core, no Henyey track
- High-mass stars ~never support convection, almost no Hayashi track



Bernasconi & Maeder (1996)

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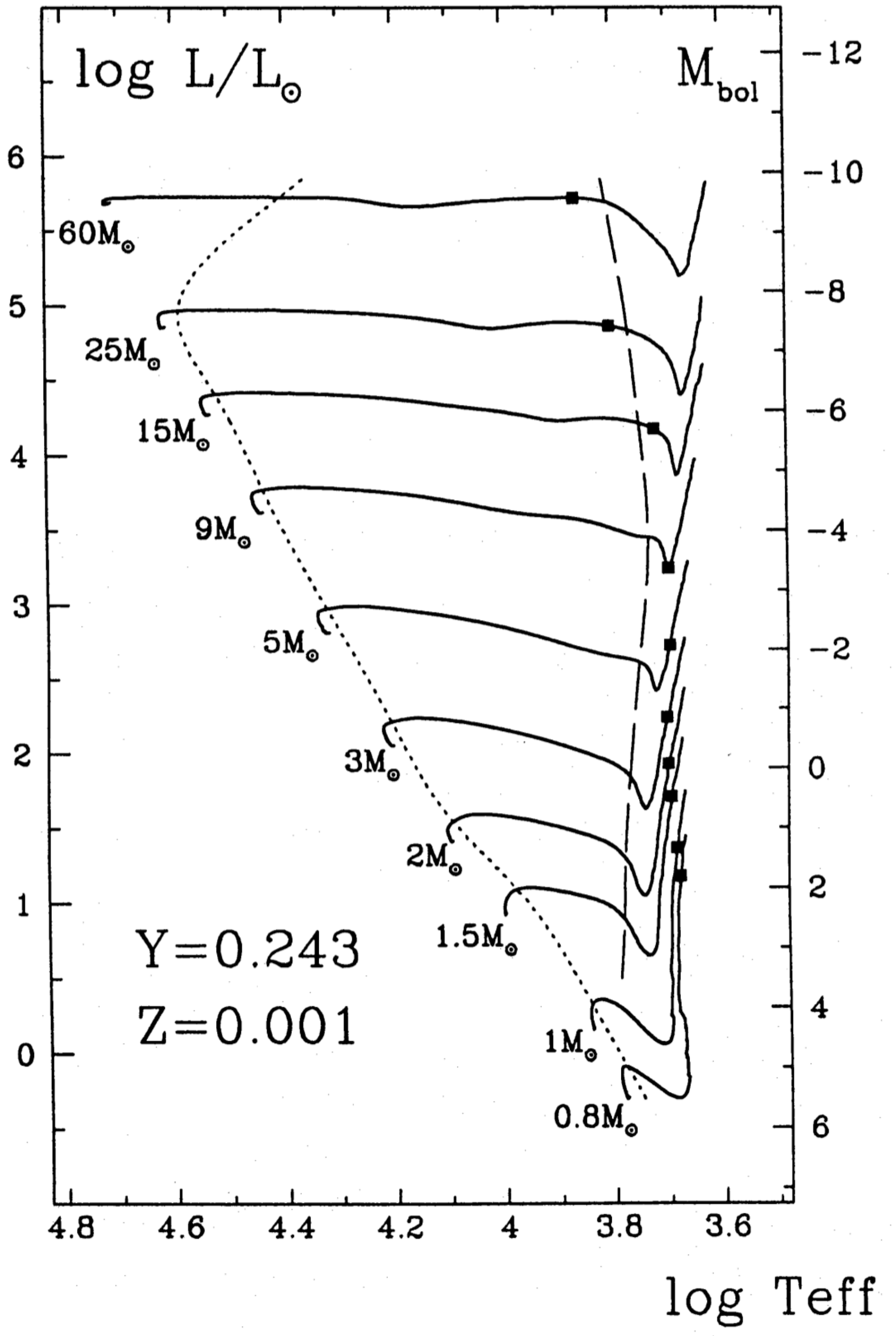
Pre-Main Sequence Evolution

- This phase (especially Hayashi Track) governed by thermal timescale

- Protostar is collapsing via Kelvin-Helmholtz Contraction

$$t_{KH} \approx \frac{GM^2}{RL}$$

~2Myr for a $1M_\odot$ protostar



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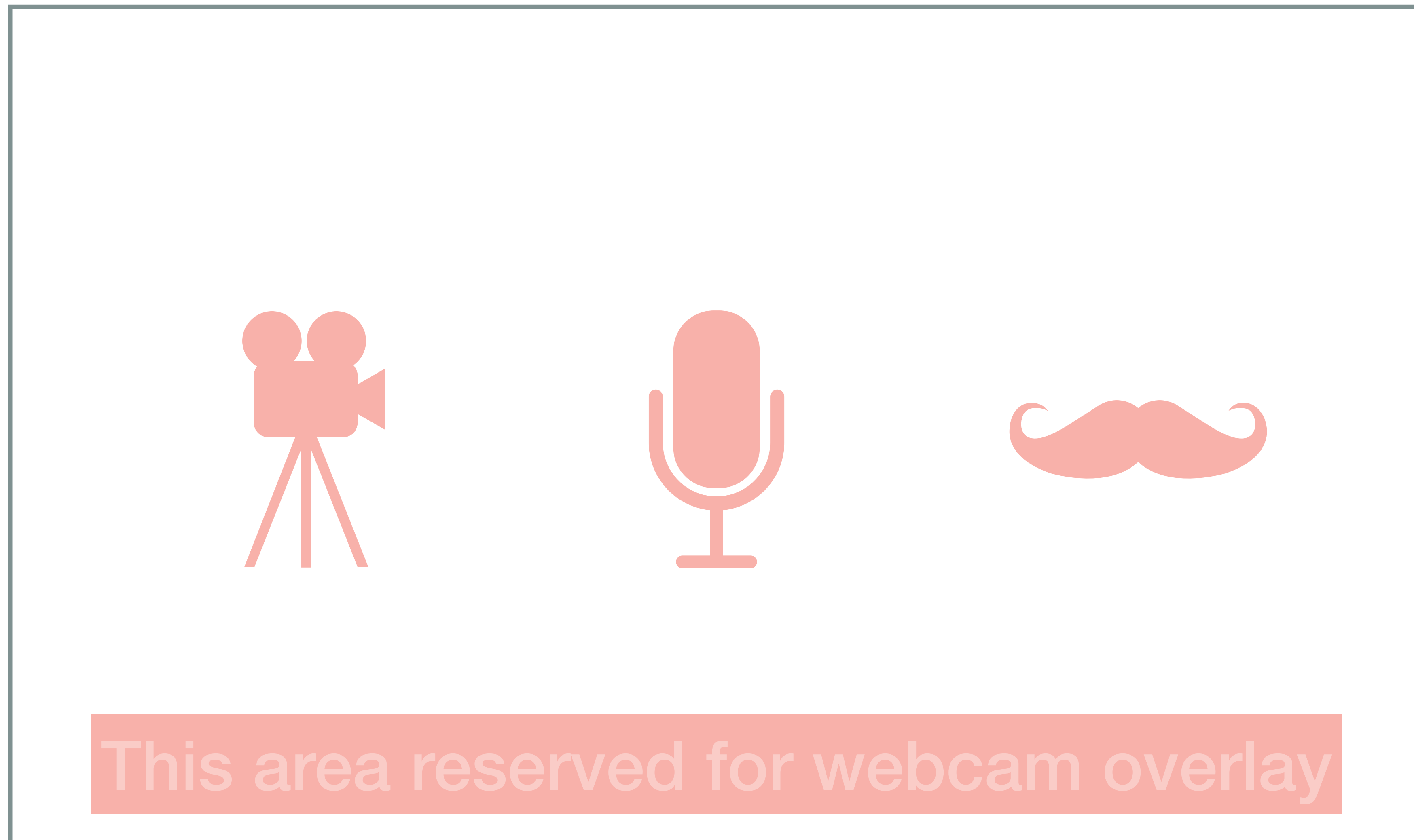
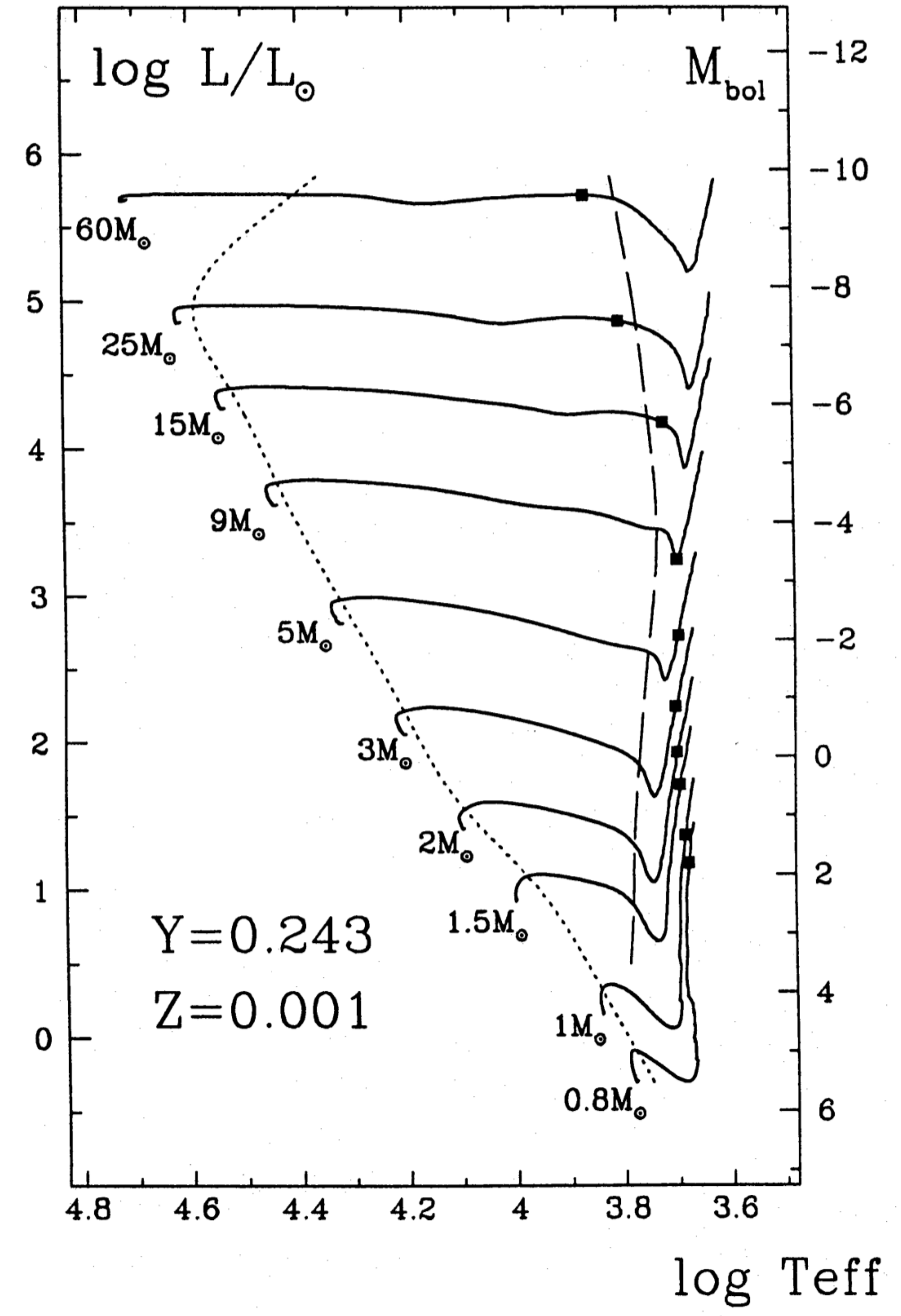


Pre-Main Sequence Evolution

- If we adopt some general scaling relations, can est. the total pre-MS timescale…
  - $L \propto M^{3.5}, R \propto M^{0.7}$

$$t_{KH} \approx \frac{GM^2}{RL} \approx 6 \times 10^6 \; (M/M_{\odot})^{\sim(-2.5)} \text{ yrs}$$

- So massive stars contract *faster*!
  - 50 $M_{\odot}$: few 10^4 yrs
  - 10 $M_{\odot}$: 0.1 Myr
  - 1 $M_{\odot}$: 30-40 Myr



Bernasconi & Maeder (1996)

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Pre-Main Sequence Evolution

- Somewhere in the initial collapse, the GMC fragments into many pre-stellar clumps
- Clumps have big range of masses, follow a ~powerlaw mass distribution
- This *must* be the origin of the stellar "initial mass function" (IMF)
- **High mass stars form faster, lower slower**
- No ONE age to a cluster (intrinsic age spread here, already within few Myr)
- One more reason we never see a "true IMF"

https://public.nrao.edu/news/new-look-bright-stellar-nursery/

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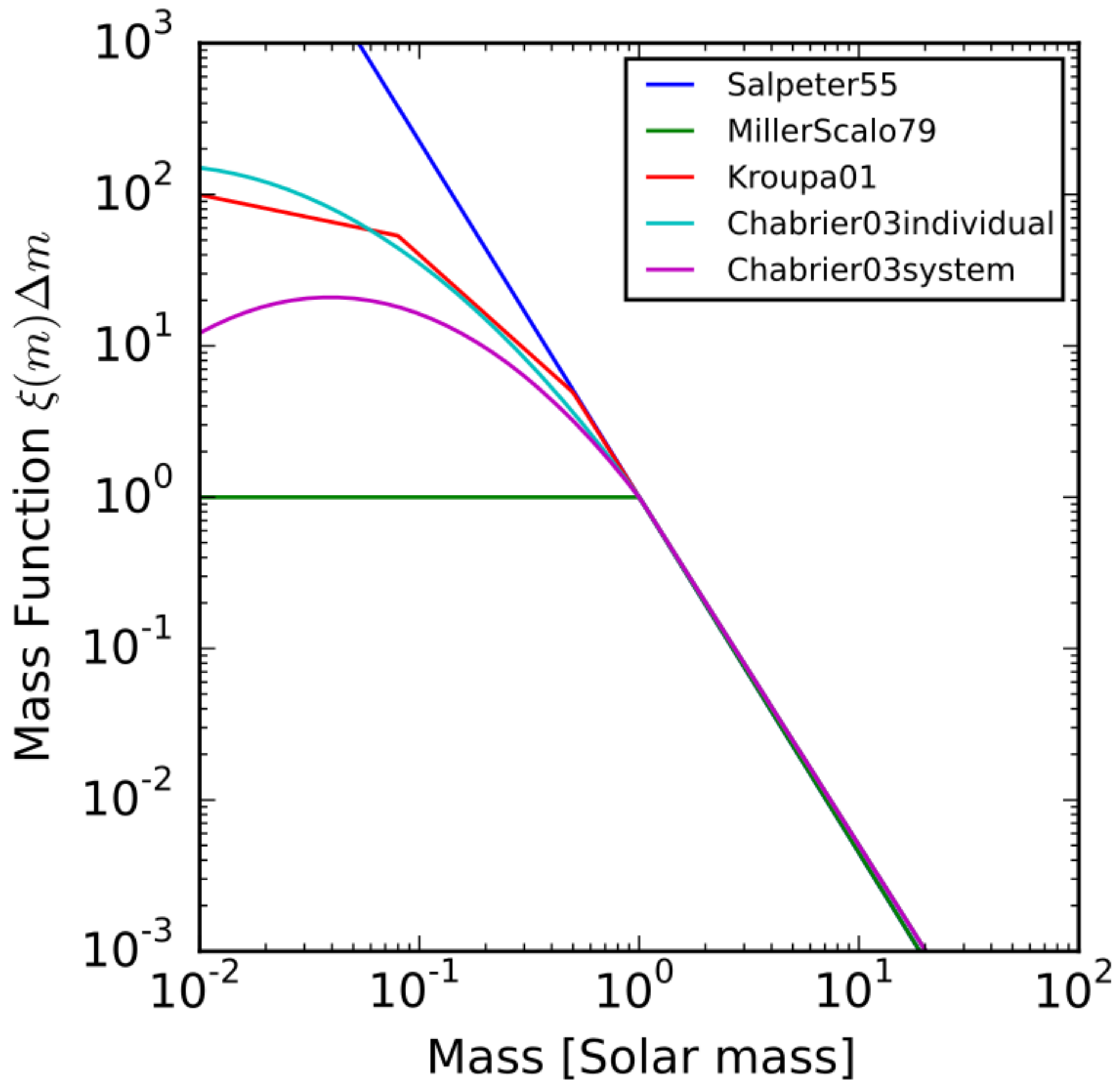
Pre-Main Sequence Evolution

- The stellar IMF is a long-studied, & still hot topic

- - Is it "universal"? (Probably not)
  - What does [m/H] do to the IMF?
  - When do binary stars form, how do they impact the IMF?
  - How low does it go?

- "Salpeter" is the classic IMF form



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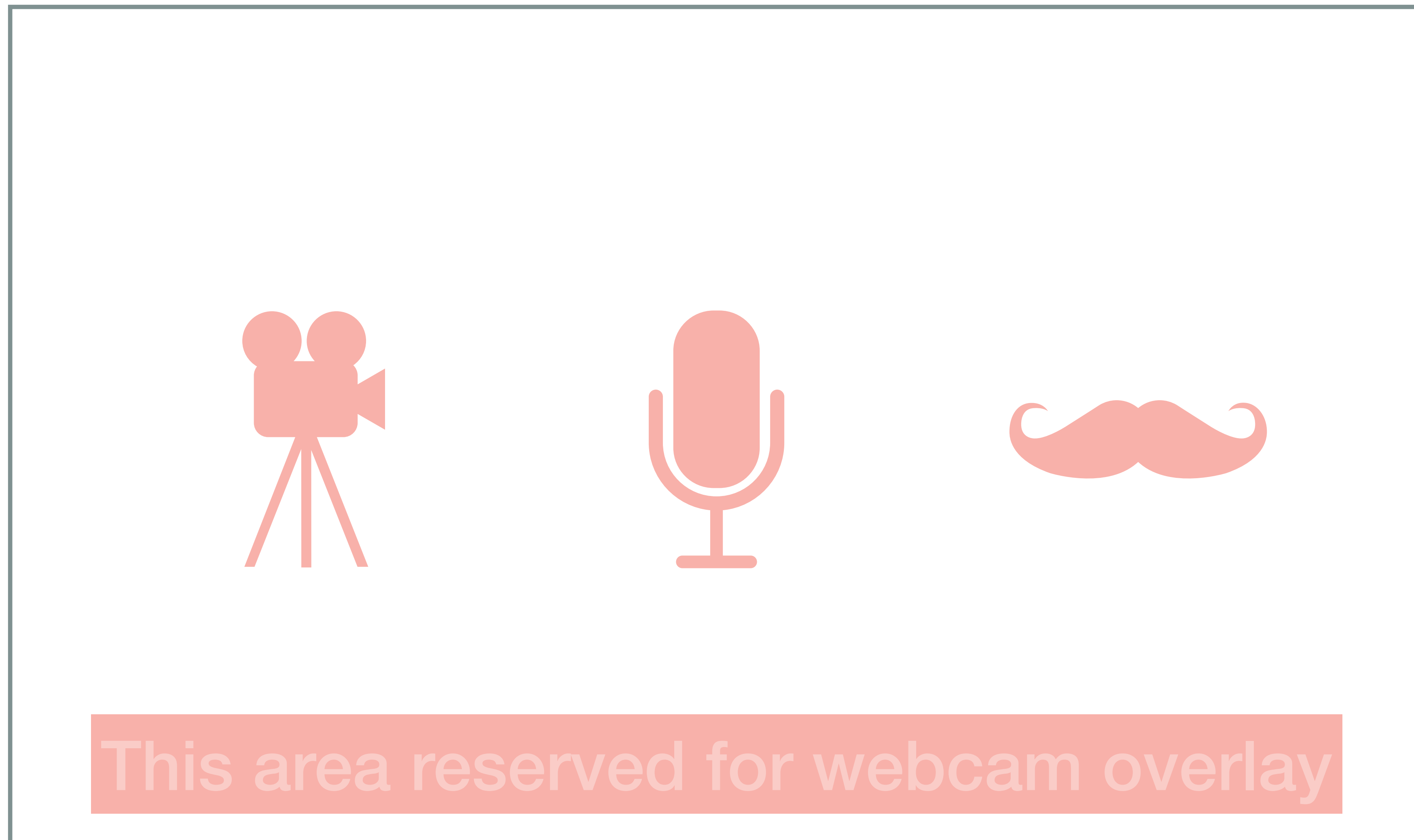

Pre-Main Sequence Evolution

- What sets the “top” end of the mass function? How BIG can you make a star?

- Somewhere around 120-150 $M_\odot$, protostar hits the “Eddington Limit”, super winds would drive off mass

  - Super-Eddington accretion is *possible,* also binary stars can merge…

  - but no single-star candidates with $M > 150 M_\odot$ are super certain

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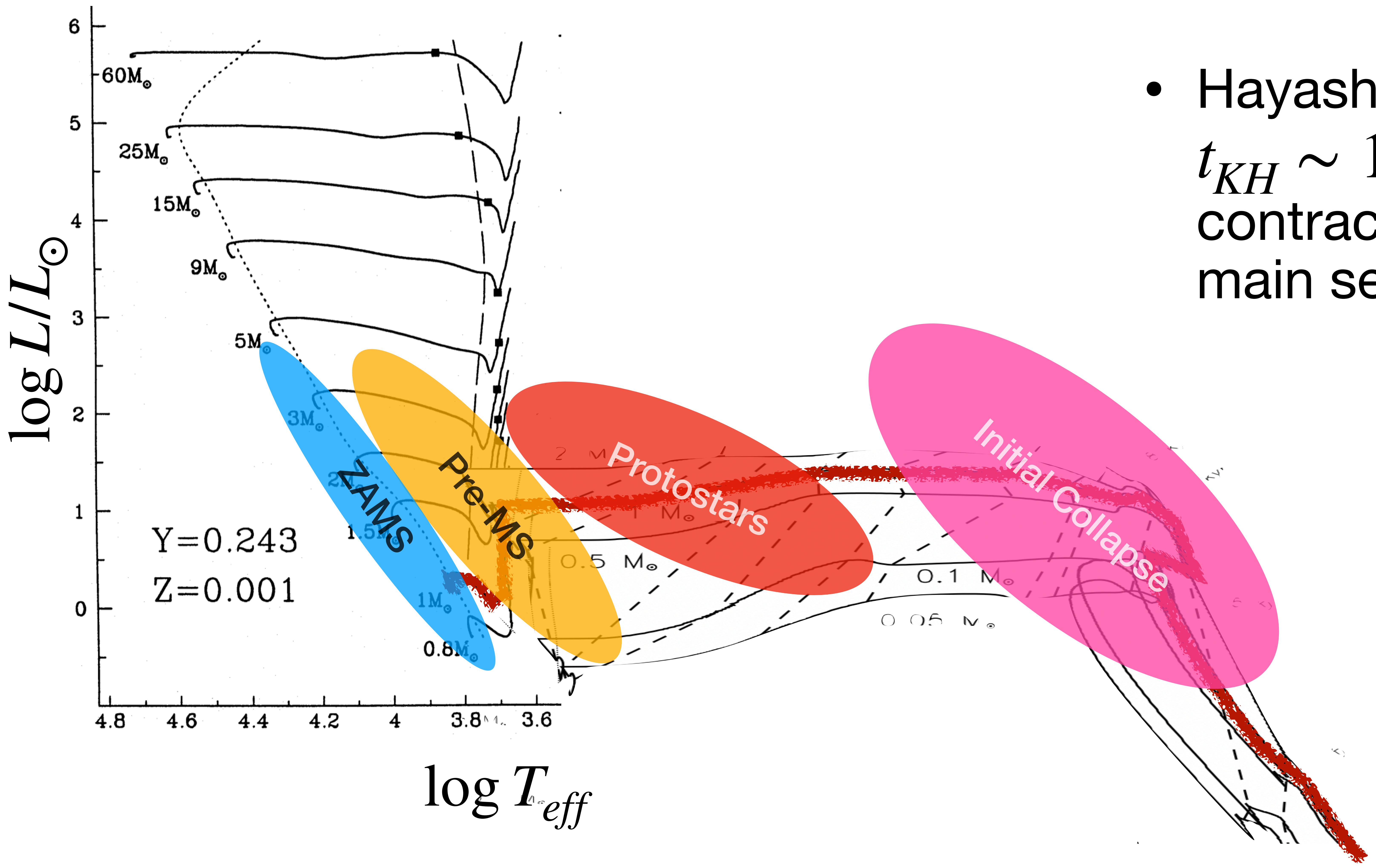
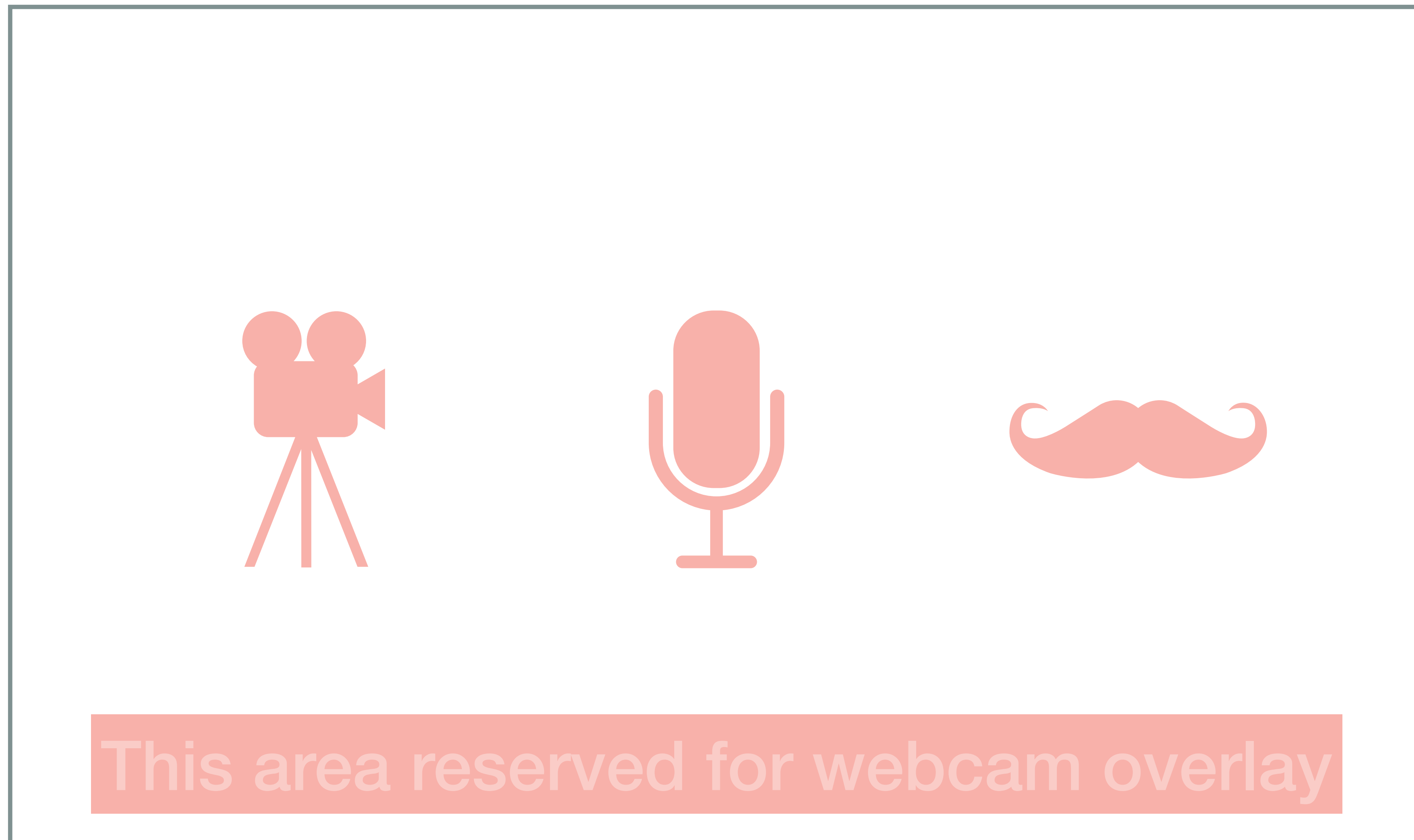
Putting it all together

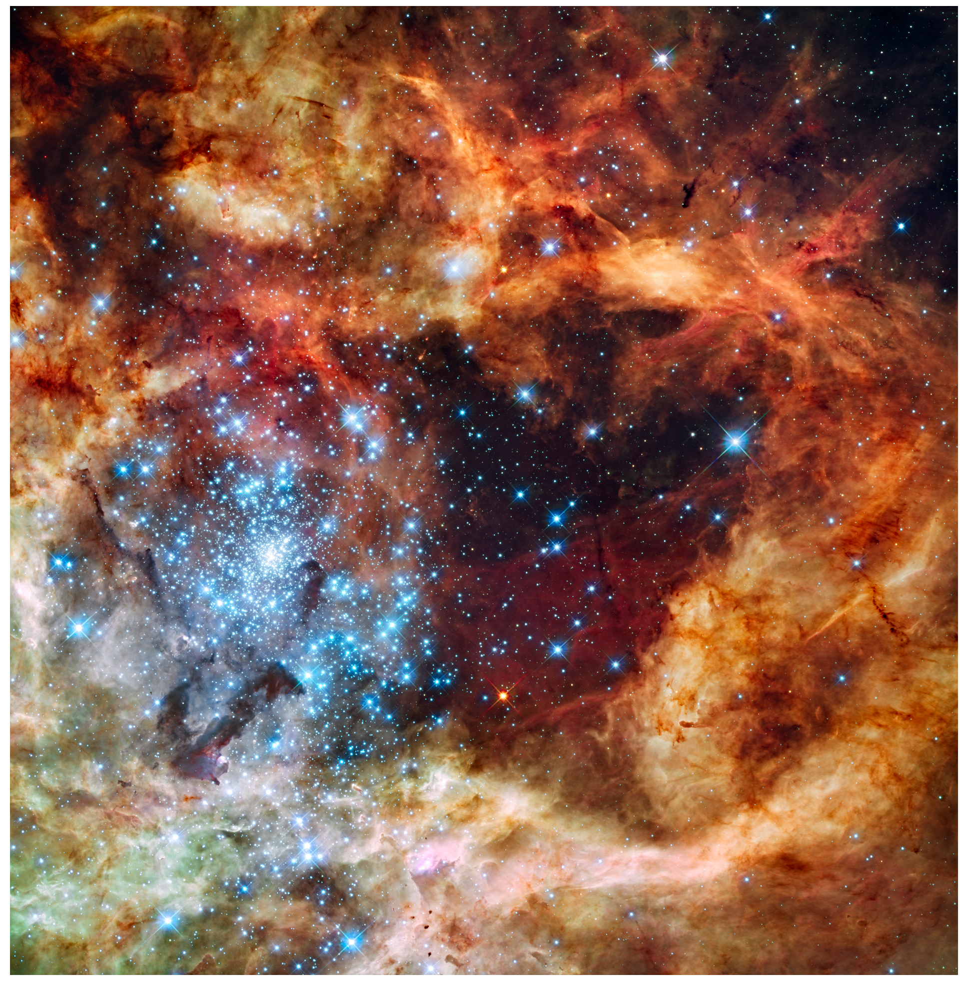


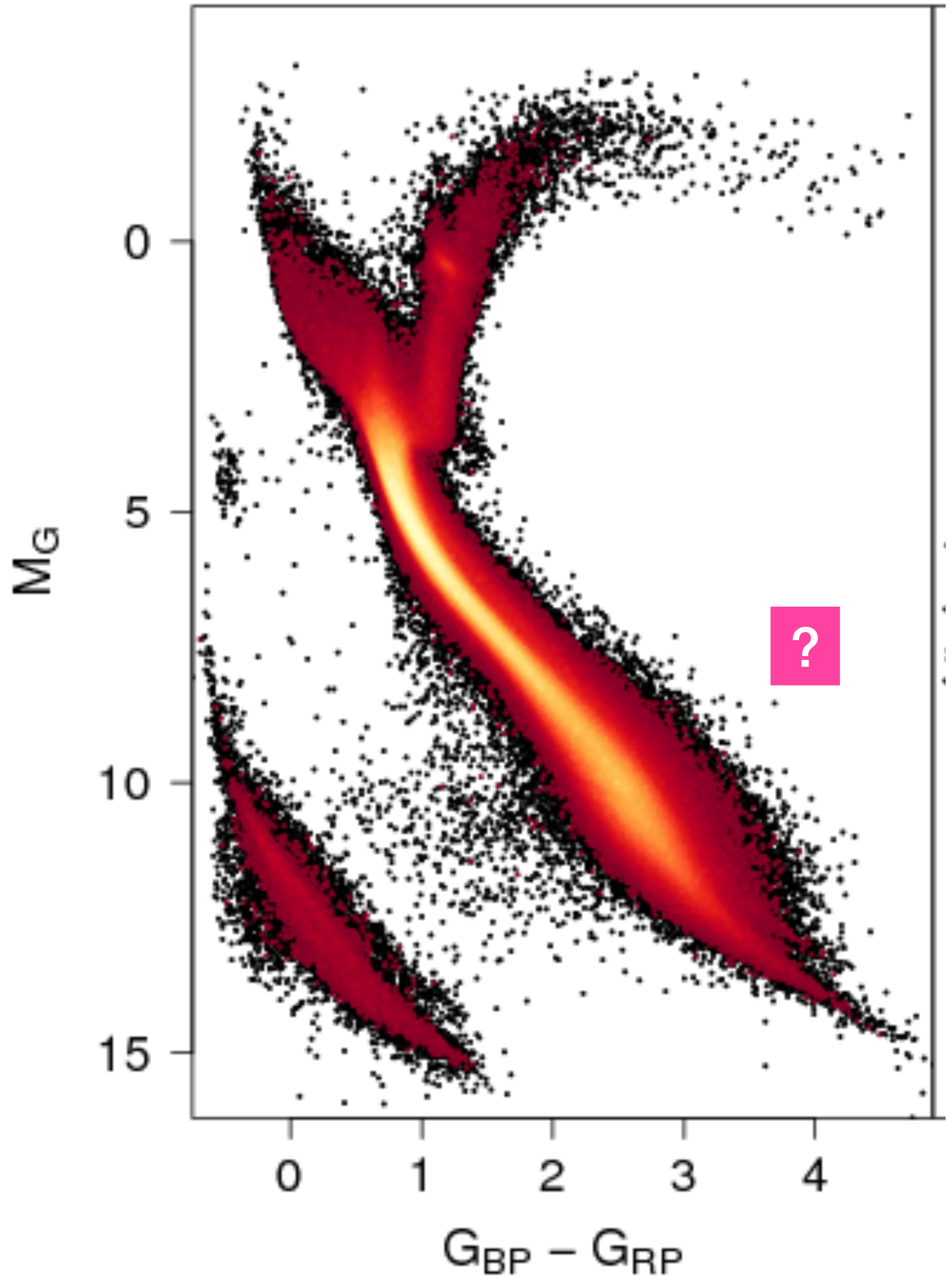
- Cloud collapse: $t_{ff} \sim 10^5 - 10^6$ yr forms a protostar, creates the IMF
- Hayashi and Henyey tracks: $t_{KH} \sim 10^4 - 10^7$ yr contraction of protostar towards main sequence

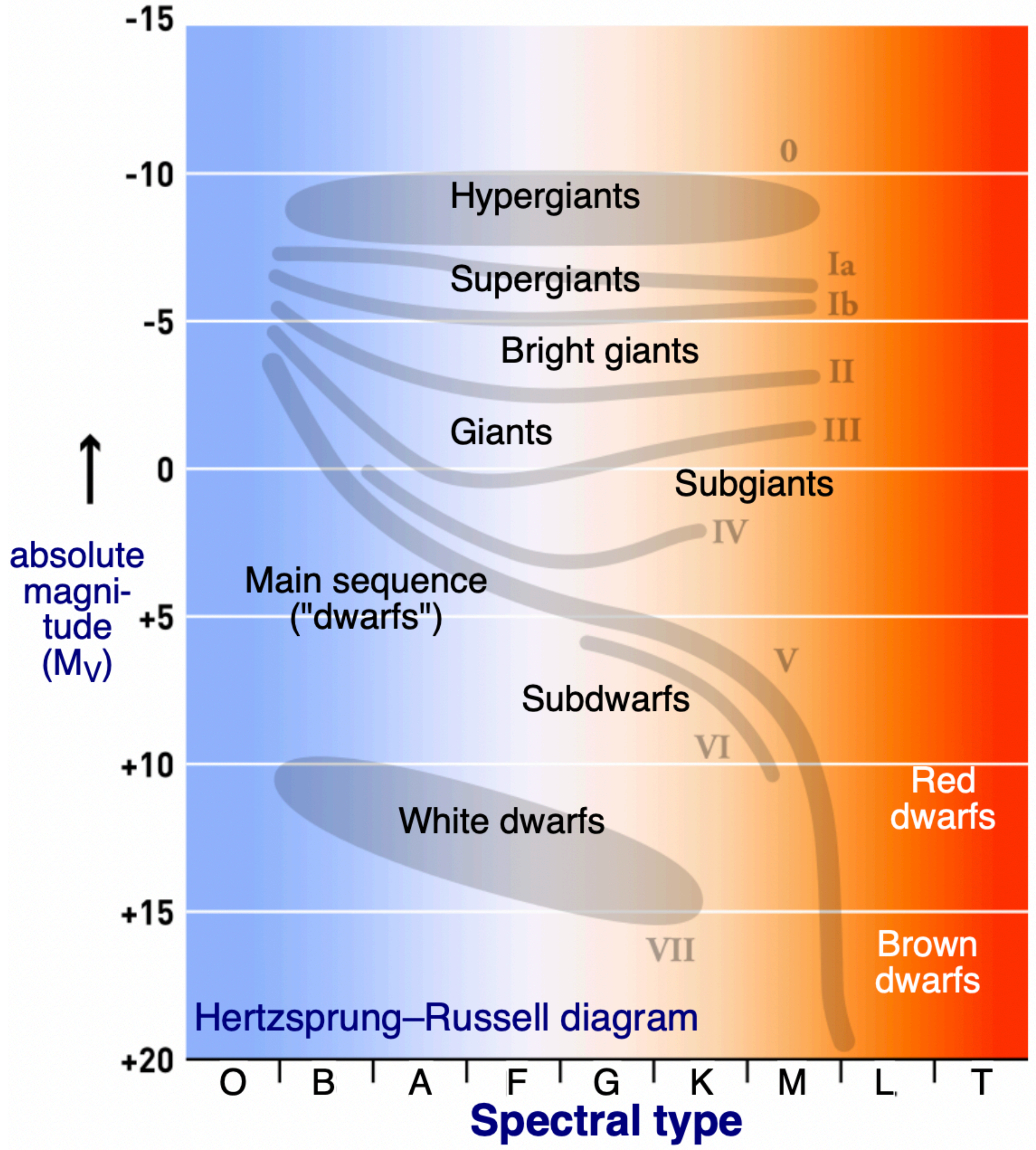


Where are all the protostars?

- They're buried in dust, super high extinction.
- Star forming regions tend to be near the "galactic mid-plane", very dense, lots of source confusion







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Next time…

- Post Main Sequence evolution!
- BOB, Ch 13