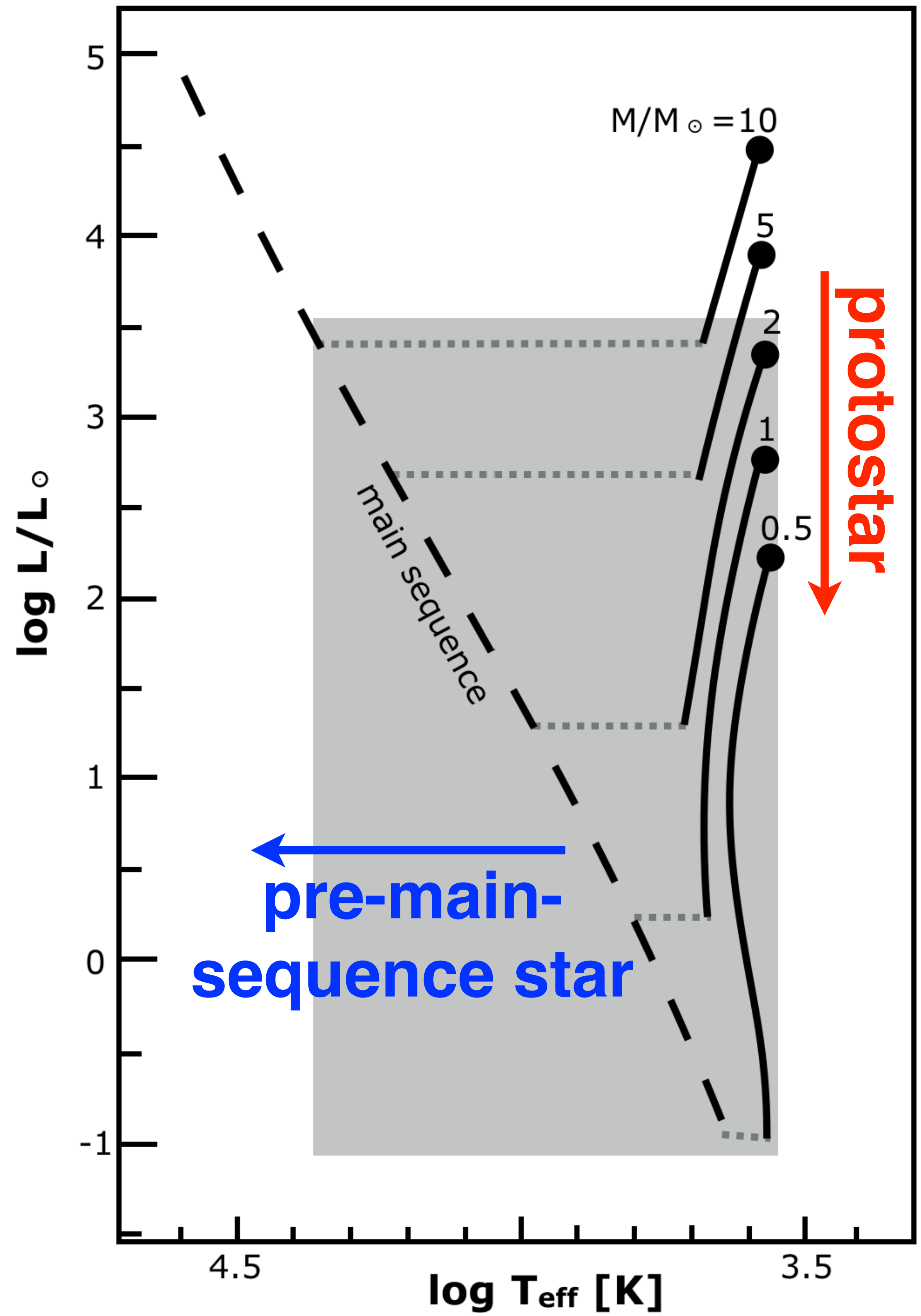
Lecture 22: Before the Main Sequence

Lamers & Levesque Ch. 12, 14.3



Star Formation

(timescales are for solar-mass objects)

Summary of star formation

last lecture

Cloud collapse ($t_{ff} \sim 10^5$-10^7 yr)

Starts when cloud exceeds Jeans mass

Ends when H2 is dissociated and H is ionized

At the end, $\langle T \rangle \sim 10^5$ K, $R/R_\odot \sim 120 M/M_\odot$

this lecture:

Proto-star ($t_{KH} \sim 2 \times 10^6$ yr) (descending Hayashi track)

Starts when collapsing cloud is dissociated/ionized

Ends when core reaches radiative equilibrium

At the end, $\langle T \rangle \sim 10^6$ K, $R/R_\odot \sim 2.5 M/M_\odot$

Pre-MS ($t_{KH} \sim 7 \times 10^6$ yr) (T Tauri, Herbig Ae/Be)

Starts when proto-star core reaches radiative equilibrium

Ends when H-fusion starts (ZAMS)

Star Formation

Collapse of a molecular cloud

1. trigger kicks off process, cloud collapses when $M > M_J$

$$t_{ff} \approx (G\rho)^{-\frac{1}{2}} \approx 1.10^8 (\mu n)^{-\frac{1}{2}} \quad yr$$

2. initial collapse is isothermal; cloud cools during collapse

Cooling by molecules: kinetic energy of molecules leads to temporary excitation, then de-excitation through emission of IR and sub-mm photons that escape the cloud

Cooling by dust: dust grains heat up through collisions and photon interactions and then emit as blackbodies with T<1000K, releasing IR photons that escape the cloud.

both of these are more efficient with more "metals"

Star Formation

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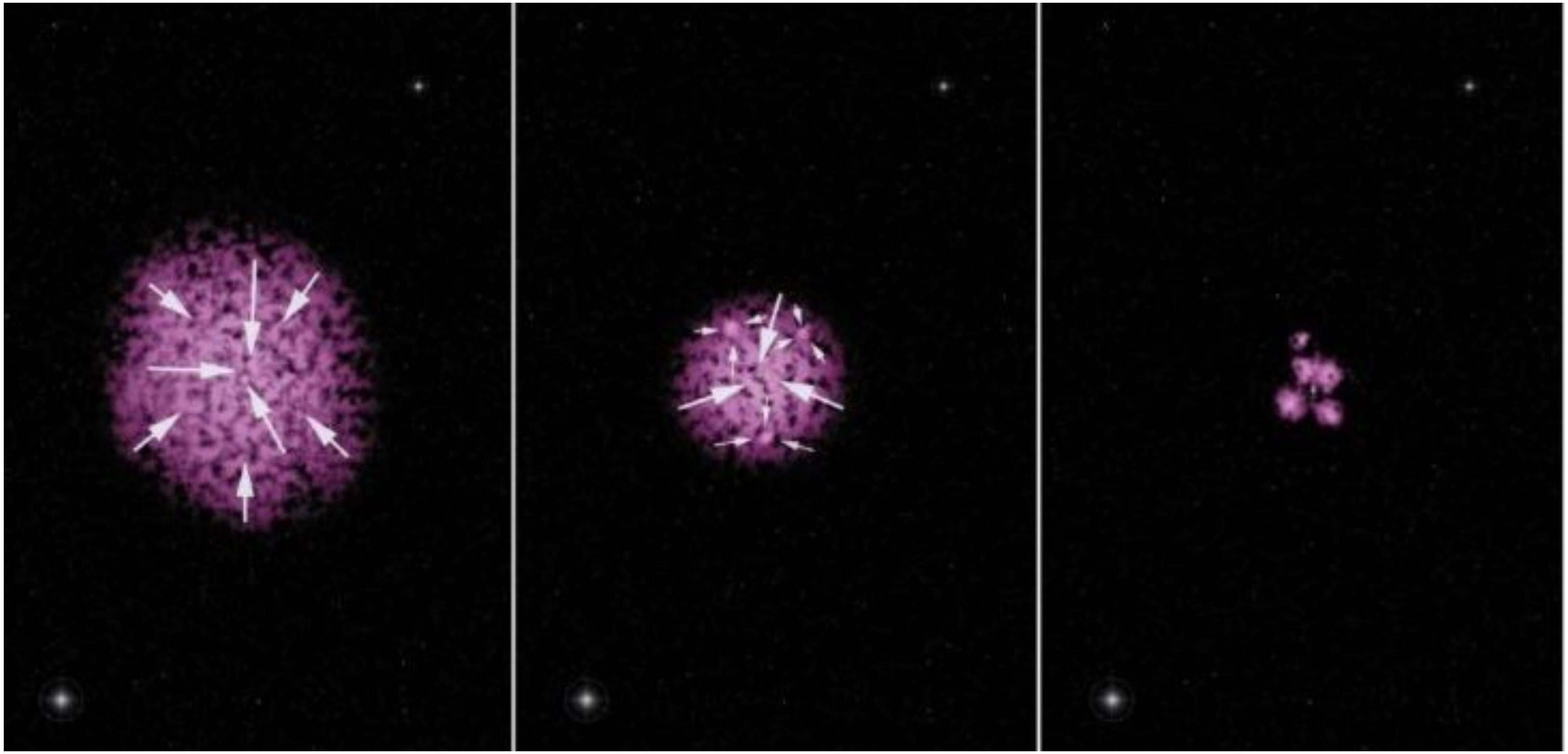

Star Formation

Collapse of a molecular cloud

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2. initial collapse is isothermal; cloud cools during collapse

3. clumps become opaque to IR; cooling switches off, collapse becomes adiabatic.

— the adiabatic collapse and rise in T raises M_J to the mass of the clump

— starting at the center, the clump can now go back to hydrostatic equilibrium, ending the free-fall phase

— **we’ve made a proto-star!**

Star Formation

Collapse of a molecular cloud

4. proto-star contraction is still accelerated by cooling through dissociating H_2 and (later) ionizing H and He

$$E_{dis} = \frac{M}{m_H}\left\{\frac{X}{2}x_{H2} + Xx_H\right\} = 1.3{\cdot}10^{58}\left(\frac{M}{M_\odot}\right)\ eV \approx 2\cdot 10^{46}\frac{M}{M_\odot}\ \text{ergs}$$

x_{H2} = 4.5 eV

x_H = **13.6 eV**

5. proto-star is eventually considered ionized and reaches hydrostatic equilibrium…

$$R/R_\odot \approx 100\ M/M_\odot$$

Now that it's back in H.E. we can estimate its mean internal temperature using the viral theorem:

$$\frac{3}{2}\frac{M}{\mu m_H}kT = \frac{A}{2}\frac{GM^2}{R} \;\rightarrow\; \bar{T} \approx \frac{A}{3}\frac{\mu m_H}{k}\cdot\frac{GM}{R} \;\rightarrow\; \bar{T} \approx 7\cdot 10^4 K$$

Star Formation

Collapse of a molecular cloud

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…proto-star is also fully convective.

Mean density is $\rho \sim 10^{-6}$ g cm^{-3}; at low T and ρ the opacity is very high and radiative energy transport is very inefficient with a high $|dT/dr|_{rad}$.

From the Schwarzschild criterion the star is convective!

Polytropic Stars

M-R relations for polytropic stars

n	γ	property	M-R relation	consequence
0	∞	incompressible	$R \sim M^{1/3}$	constant ρ
1	2	$P \sim \rho^2 \rightarrow T \sim \rho$	$R \sim M^0$	constant R
1.5	5/3	Non-relat. degeneracy Fully convective (ideal gas)	$R \sim M^{-1/3}$ -----	volume ~ $1/M$ -----
3.0	4/3	Relativ. degeneracy Constant P_{gas}/P_{rad} (ideal gas)	$R \sim M^{\infty}$ -----	$M \sim R^0$ -----
∞	1	Isothermal: $P \sim \rho$	$R \rightarrow \infty$	infinite radius

full proofs in text, follows from: $P = \dfrac{\rho k T}{\mu m_p} \propto \rho T$ ideal gas law

$$\frac{d \ln T}{d \ln P} = \frac{\gamma - 1}{\gamma} \quad \text{everywhere, fully convective}$$

Fully Convective Stars

c) the Hayashi line of fully convective stars

A fully convective star obeys the polytropic relation: $P=K\rho^{5/3}$

We've shown that all convective stars are homologous (same P/P_c, T/T_c, ρ/ρ_c as functions of r/R_*) so we can derive K's M and R dependence:

$$P_c \sim \frac{GM^2}{R^4} \quad \text{and} \quad P_c = K\,\rho_c^{5/3} \quad \text{with} \quad \rho_c \sim M/R^3$$

(H.E.) (polytrope) (homology)

So K depends on the stellar parameters as:

$$K = \frac{P_c}{\rho_c^{5/3}} \sim \frac{M^2}{R^4} / \rho^{\frac{5}{3}} \sim \frac{M^2}{R^4} / \frac{R^5}{M^{5/3}} \quad \rightarrow \quad K \sim M^{1/3} R$$

We can designate R_1 as the radius at the top of the convection zone. The polytrope expression for P is valid at all r, so:

$$\boxed{P_1^{\text{int}} = K\rho_1^{5/3} \sim M^{1/3} R_1 \rho_1^{5/3}}$$

Fully Convective Stars

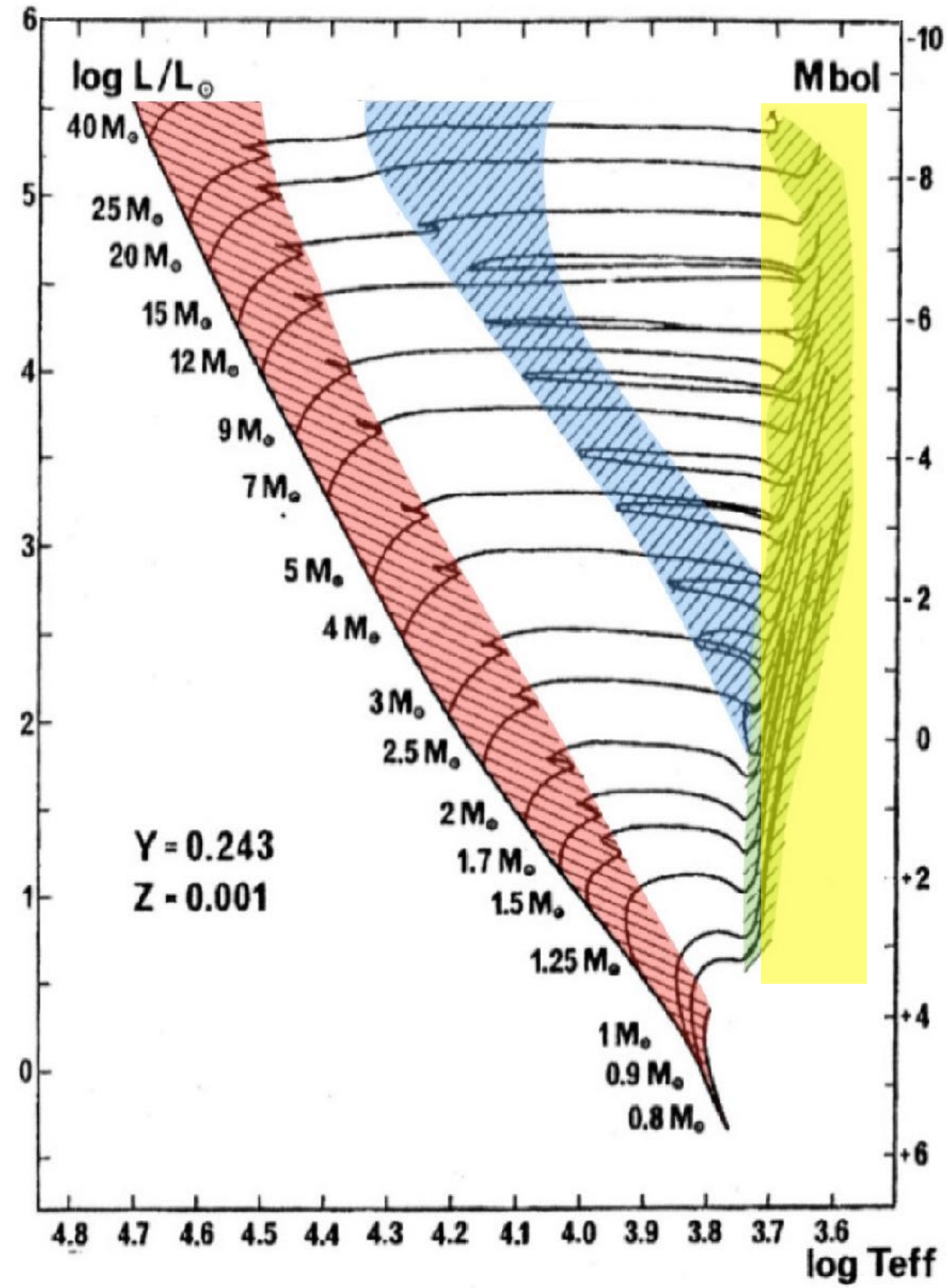
c) the Hayashi line of fully convective stars

Narrow low-T limit for convective stars applies across all mass ranges.

Result of two effects:

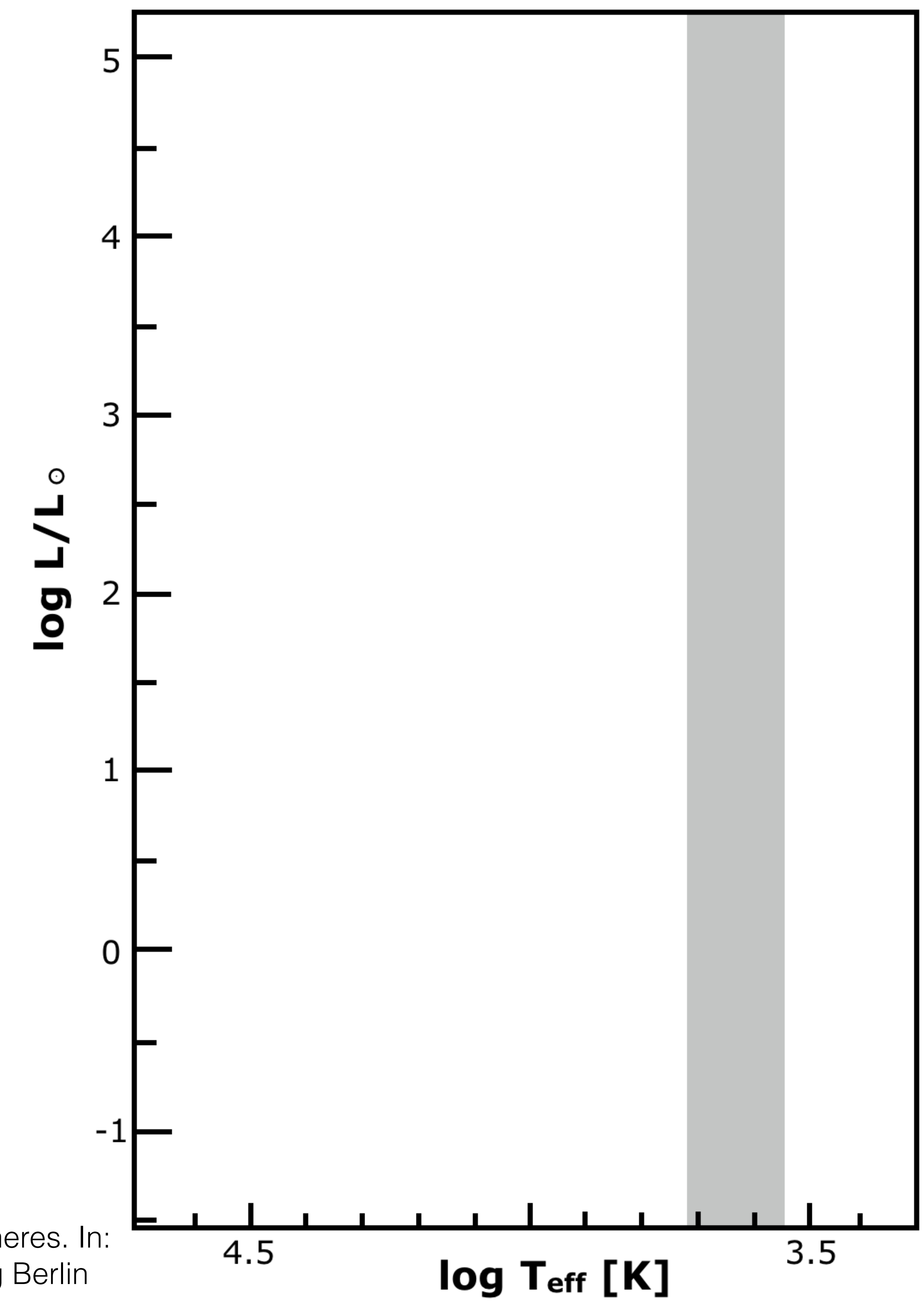
— convective stars have extended envelopes, so T_{eff} is low

— at T<3000 K the opacity in the photosphere drops steeply towards lower T_{eff}



Star Formation

Contracting proto-stars: the Hayashi tracks



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Star Formation

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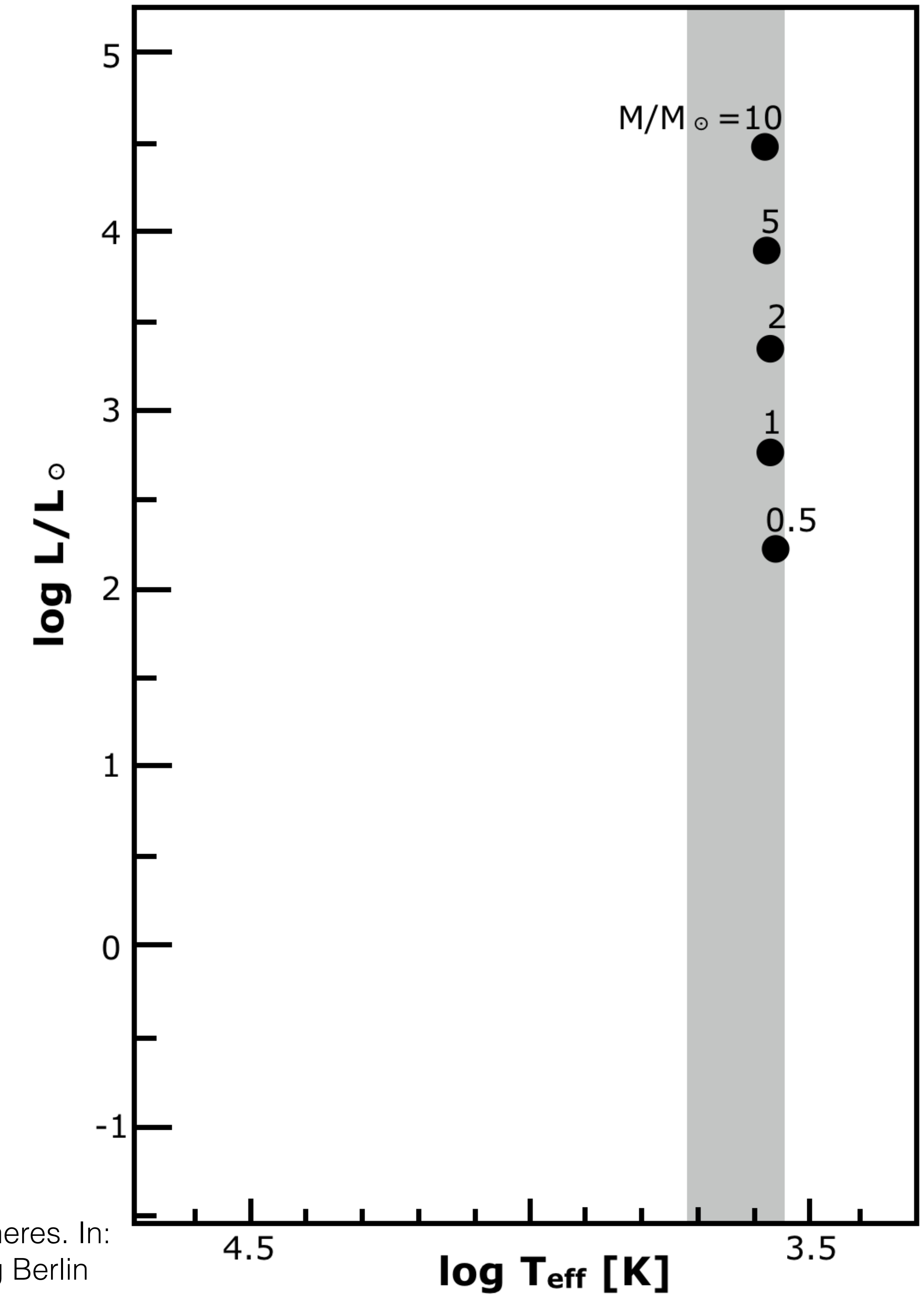

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Star Formation

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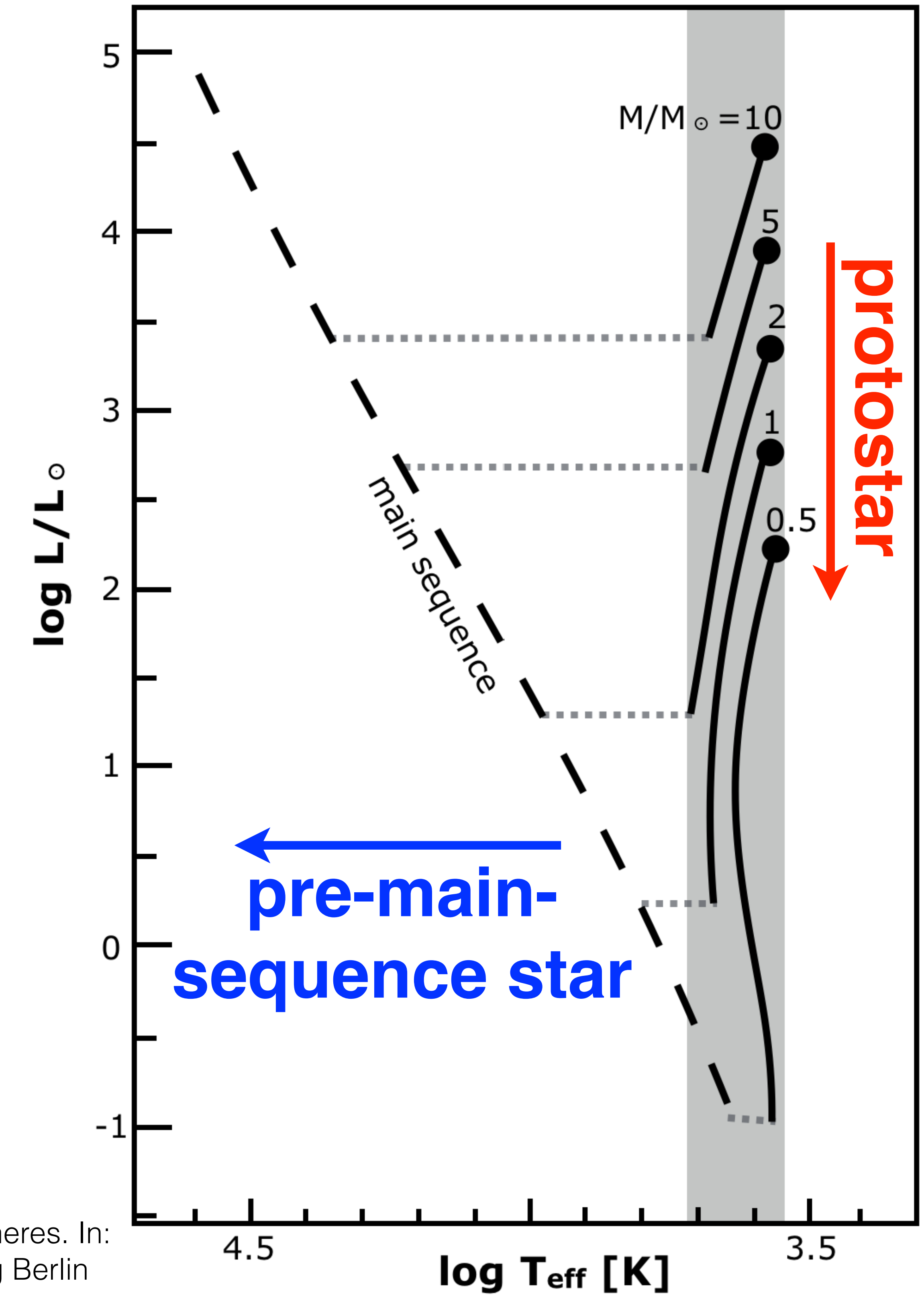

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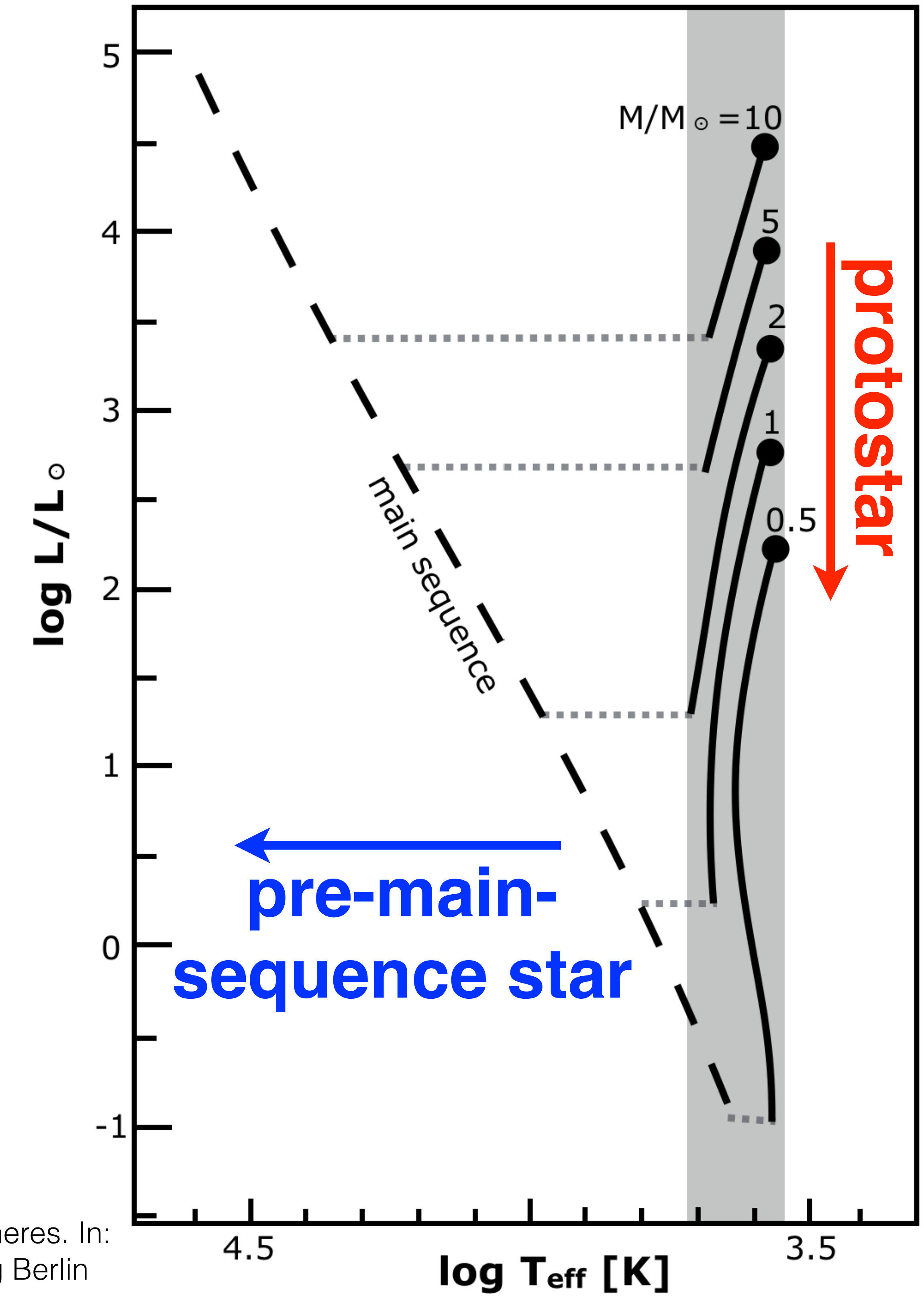
Star Formation

Contracting proto-stars: the Hayashi tracks

The contraction time for a star descending from the Hayashi track to the main sequence is given by:

$$t_{\text{Hayashi}} \approx \frac{-\Delta E_{pot}}{L} = \frac{AGM^2}{\bar{L}R_{\text{end}}}$$



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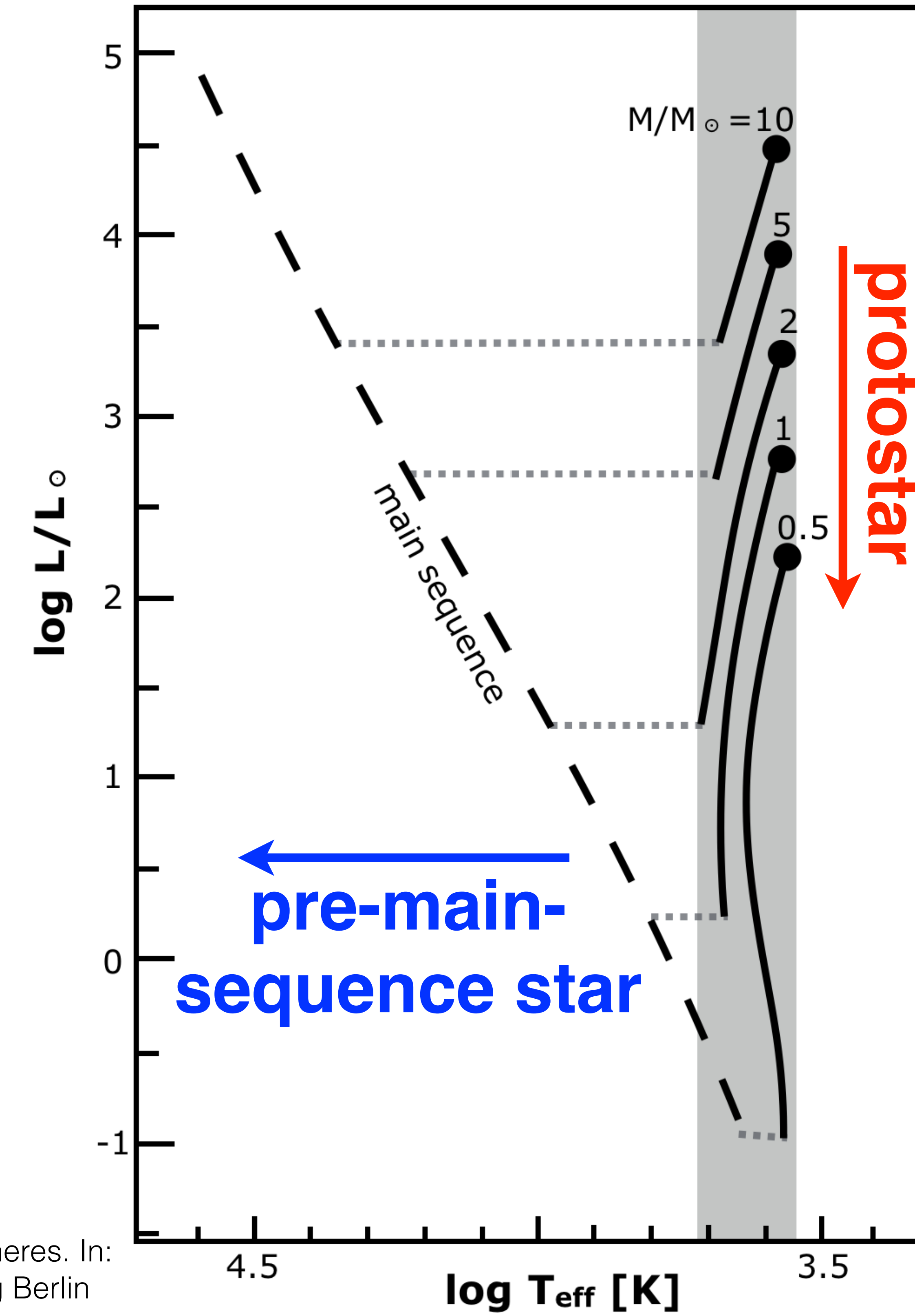
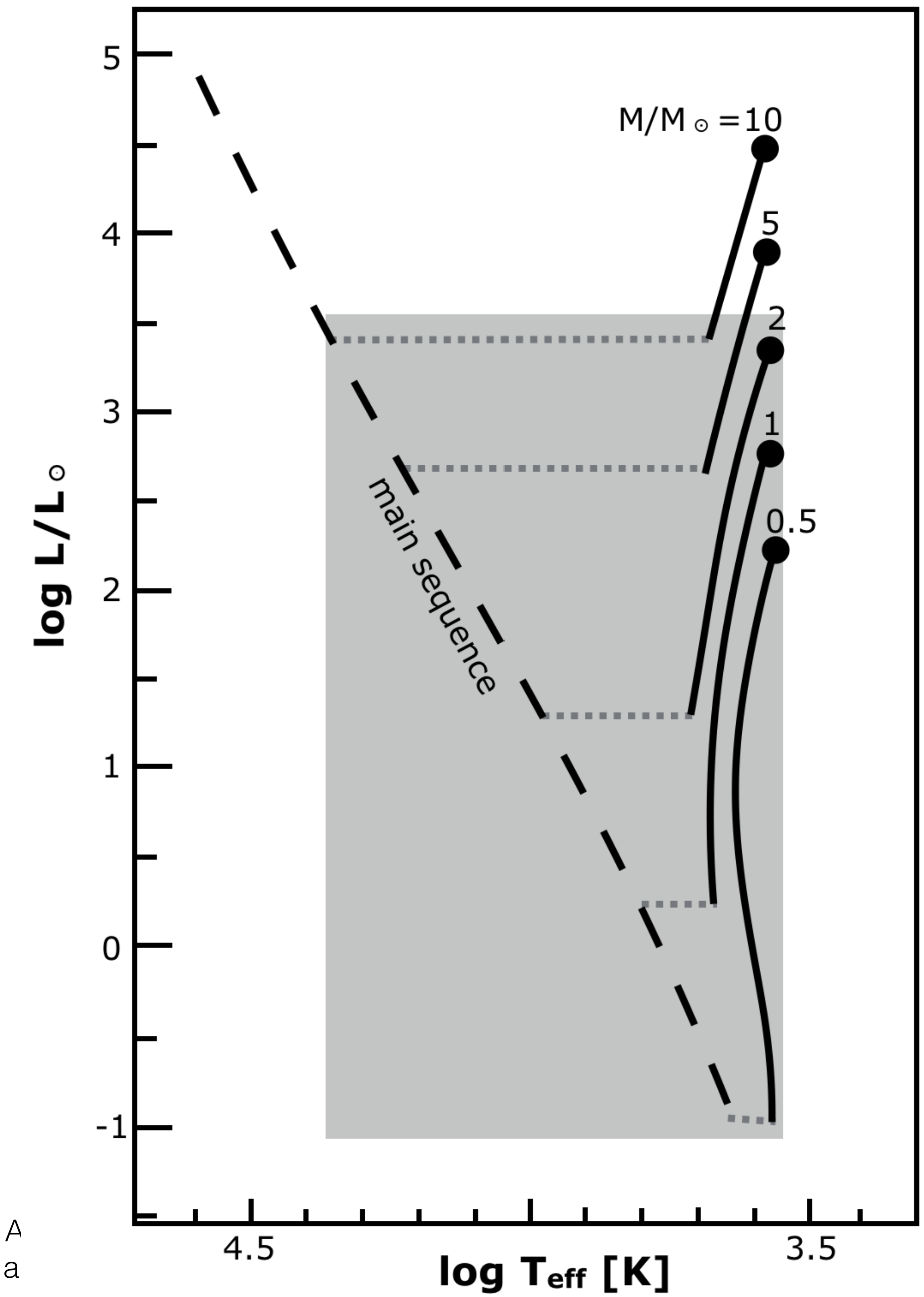
$$\bar{L} \equiv 4\pi\sigma T_{\text{eff}}^4 R^2 \cong 15 \ L_\odot$$

$$\text{if} \ \ R \cong \left(R_{\text{top}} \cdot R_{\text{bottom}}\right)^{\frac{1}{2}} \approx 15 \, R_\odot$$



Star Formation

The Hayashi track ⟶ main sequence



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Star Formation

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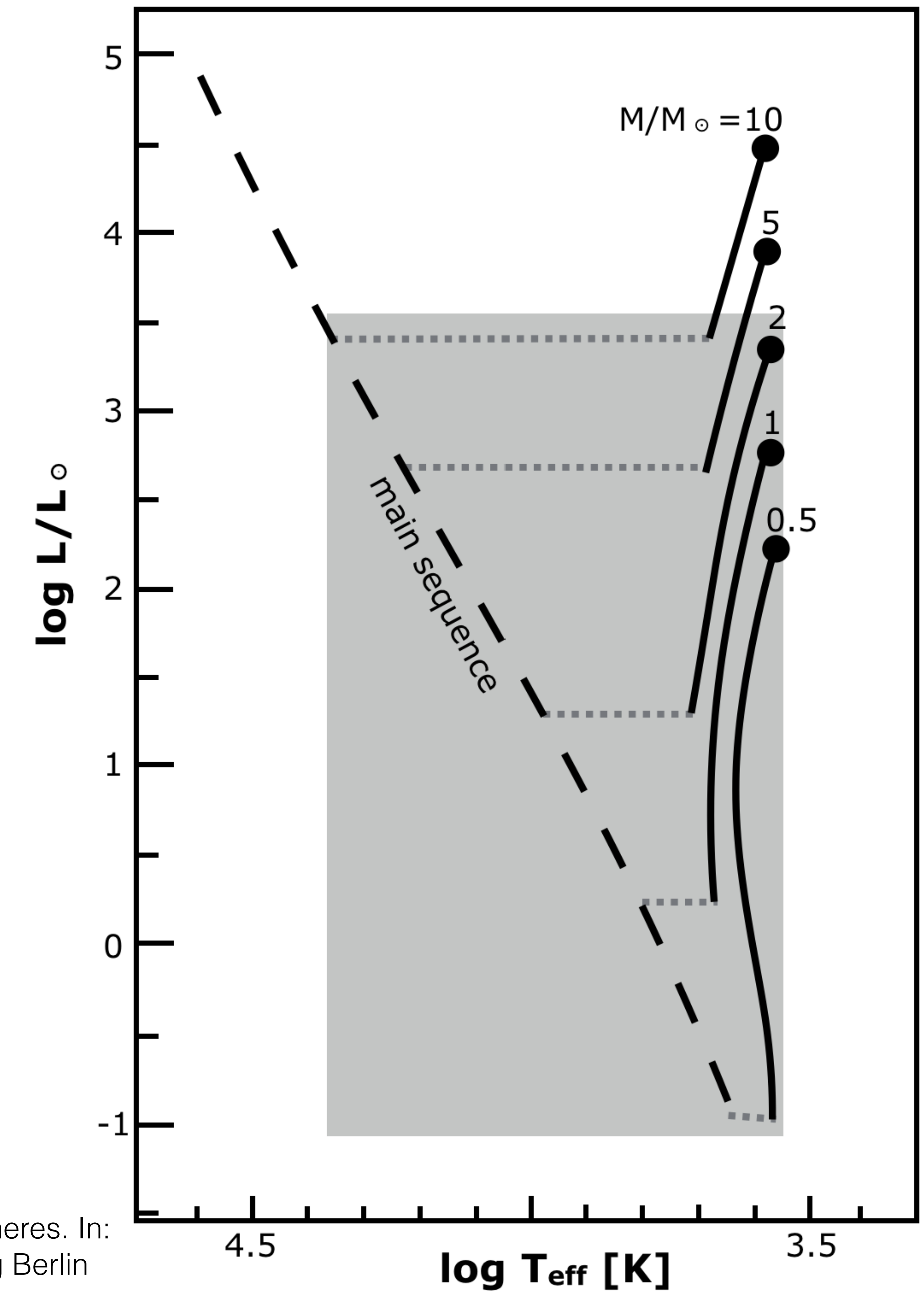
if $R \cong \left(R_{\text{top}} \cdot R_{\text{bottom}}\right)^{\frac{1}{2}} \approx 15\ R_{\odot}$

$t_{\text{Hayashi}} \approx$ 2x10⁶ yr
for a 1M$_{\odot}$ proto-star



Star Formation

The Hayashi track $\longrightarrow$ main sequence

In this final formation stage, the star has not yet started nuclear fusion (and is therefore still contracting), but it's now in hydrostatic **and** radiative equilibrium (hence the horizontal evolution on the H-R diagram...)

Taking $R_{MS}/R_{\odot} \approx (M/M_{\odot})^{0.7}$ we find:

$$t_{PMS} \approx A \frac{GM_{\odot}^2}{R_{\odot}L_{\odot}} \cdot (M/M_{\odot})^2 (R/R_{\odot})^{-1} (L/L_{\odot})^{-1} \approx 6 \times 10^7 (M/M_{\odot})^{-2.5} \text{ yrs}$$

($A = 2$, $L \sim M^{3.8}$, $R \sim M^{0.7}$)

So:

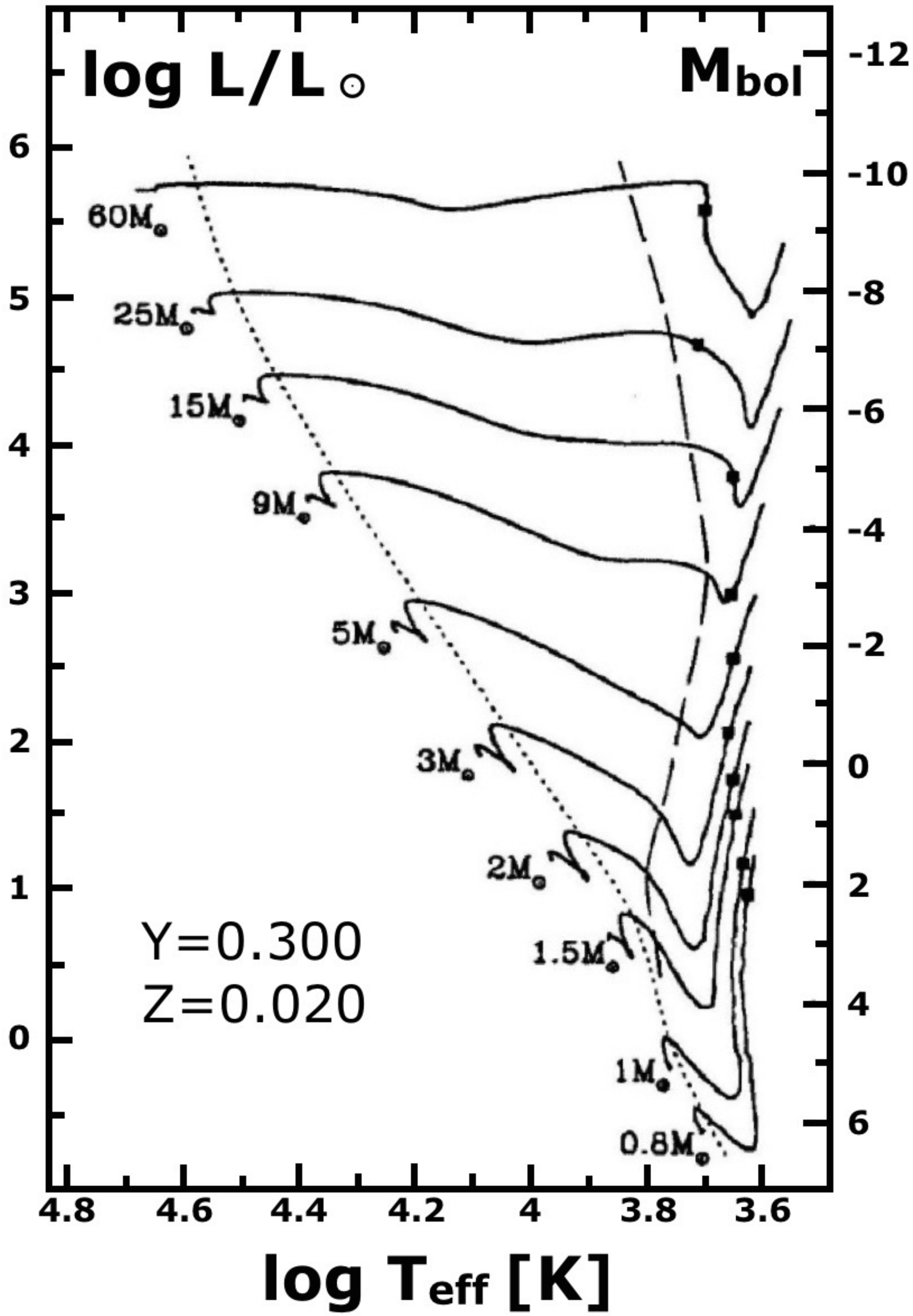
$M_{\odot}$	τ_{PMS} (estimated)	τ_{PMS} (model)
1	6×10^7	2.9×10^7
3	4×10^6	7.2×10^6
9	3×10^5	2.9×10^5
25	2×10^4	7.1×10^4
60	2×10^3	2.8×10^4

Star Formation

star-forming region NGC 2264: age ~4 Myr

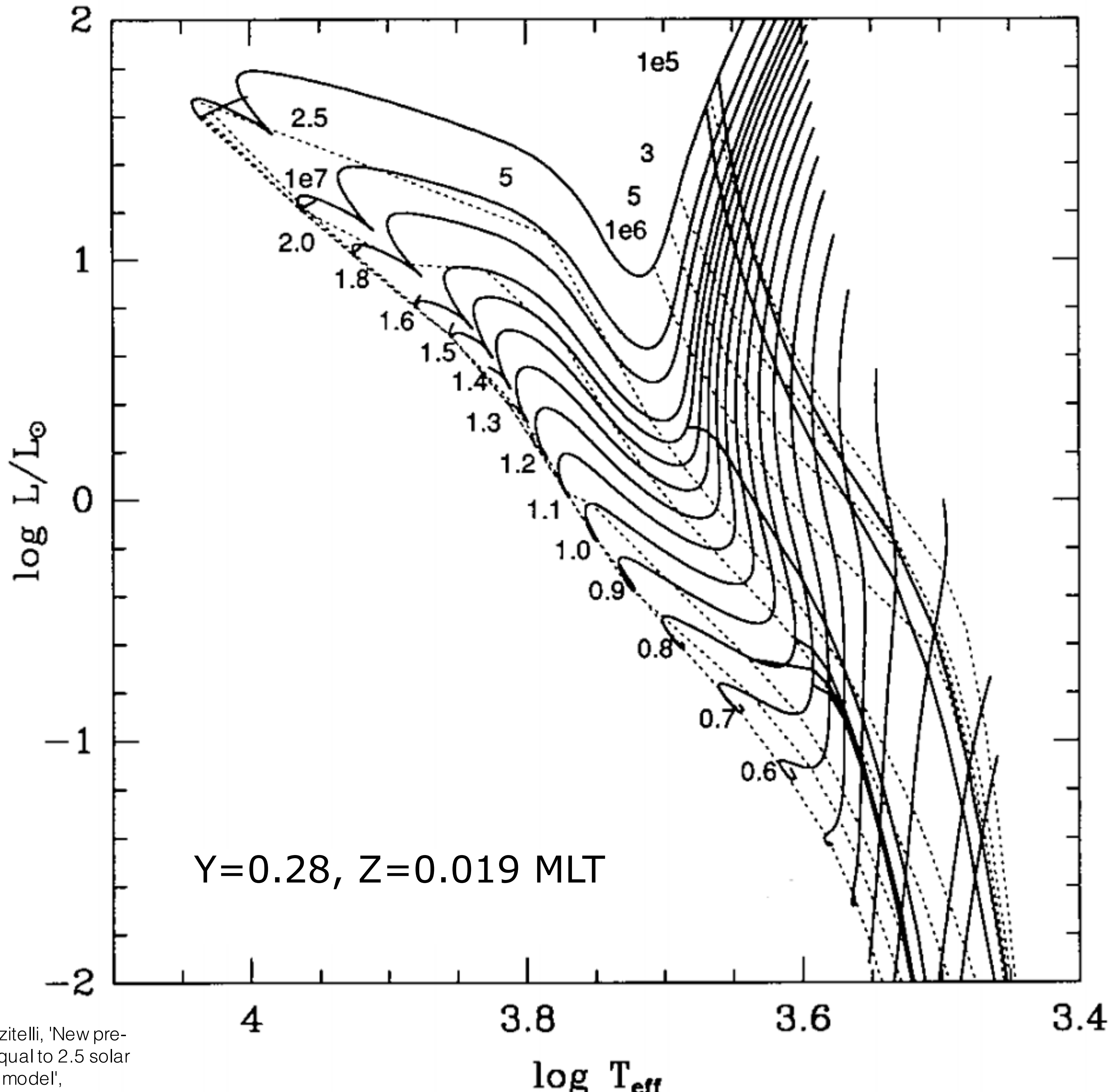
from https://apod.nasa.gov/apod/ap130806.html

Star Formation



Star Formation

The Hayashi track ⟶ main sequence



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Star Formation

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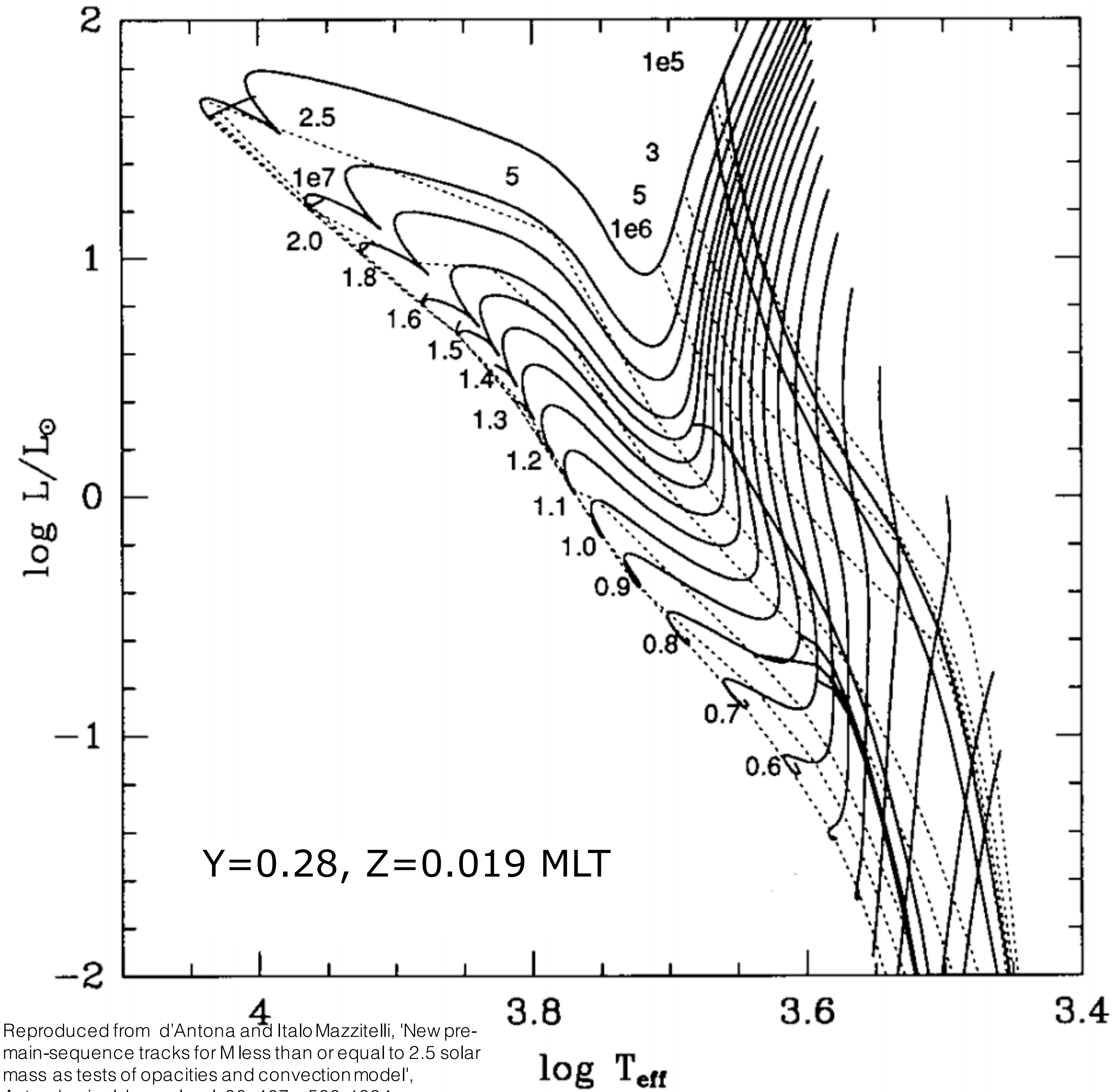

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T Tauri stars: low-mass ($M \leq 2M_\odot$) pre-MS stars

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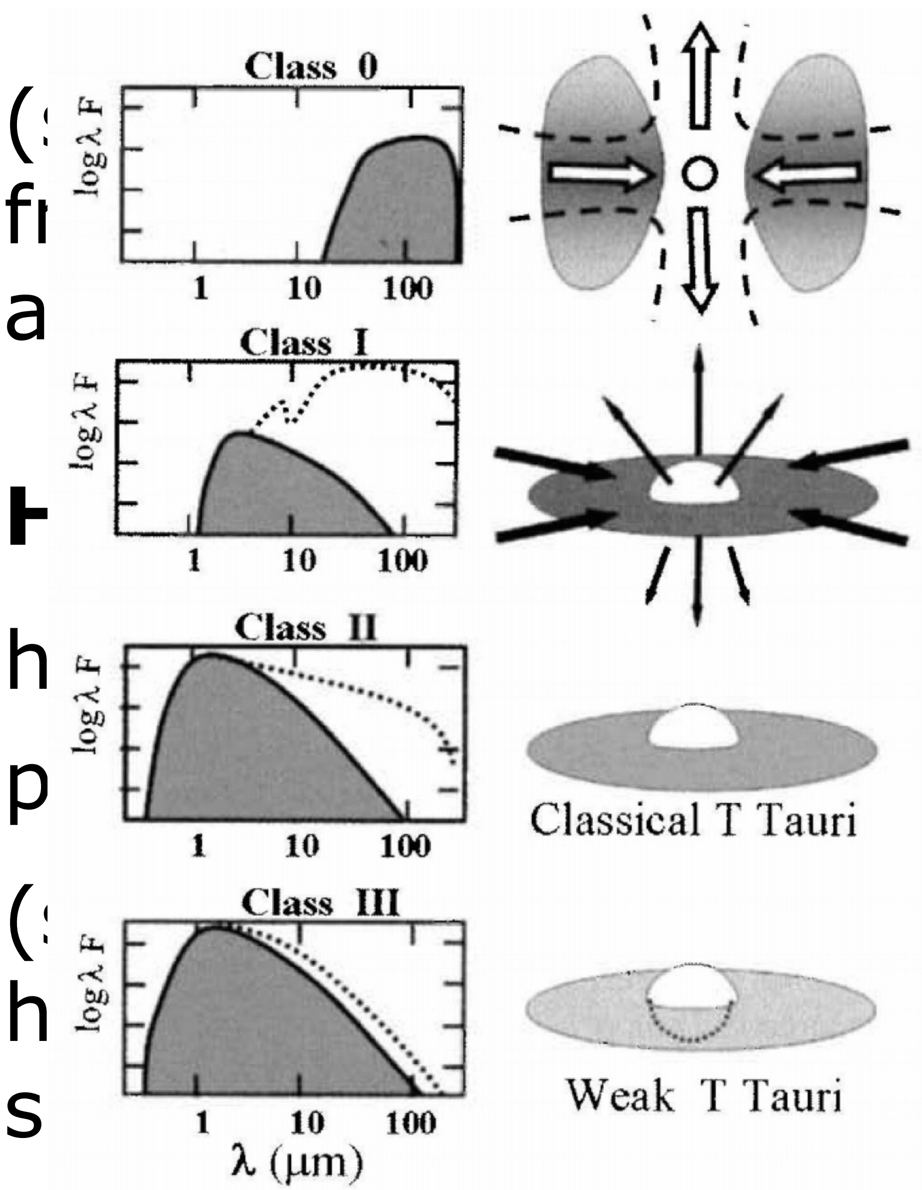

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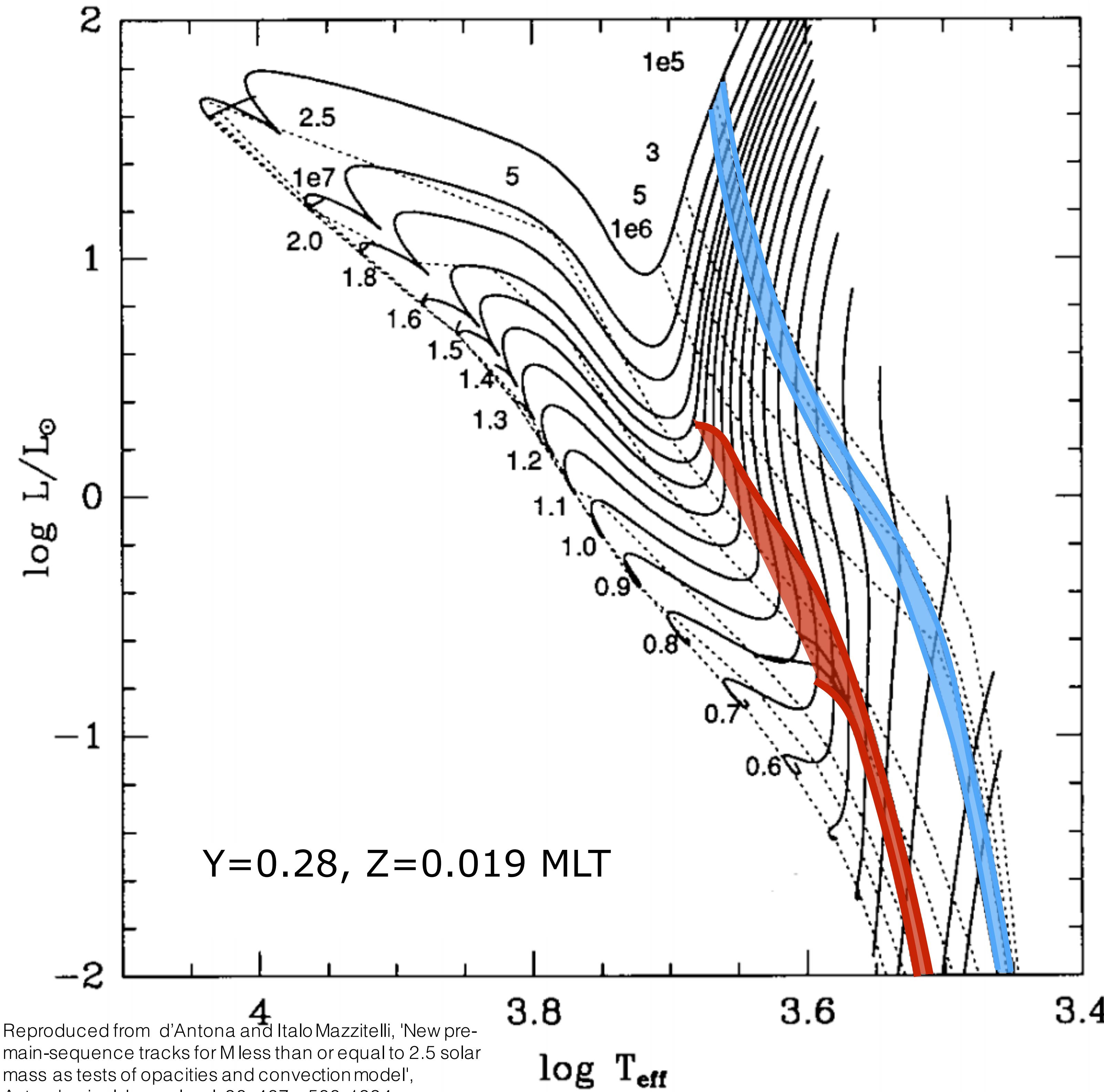
Star Formation

The Hayashi track $\longrightarrow$ main sequence



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Deuterium destruction

At ~10^6 K the initial ^{2}H in the star is destroyed by:

$$^2H + {}^1H \longrightarrow {}^3He + \gamma + 5.5\ \mathrm{MeV}$$

Lithium destruction

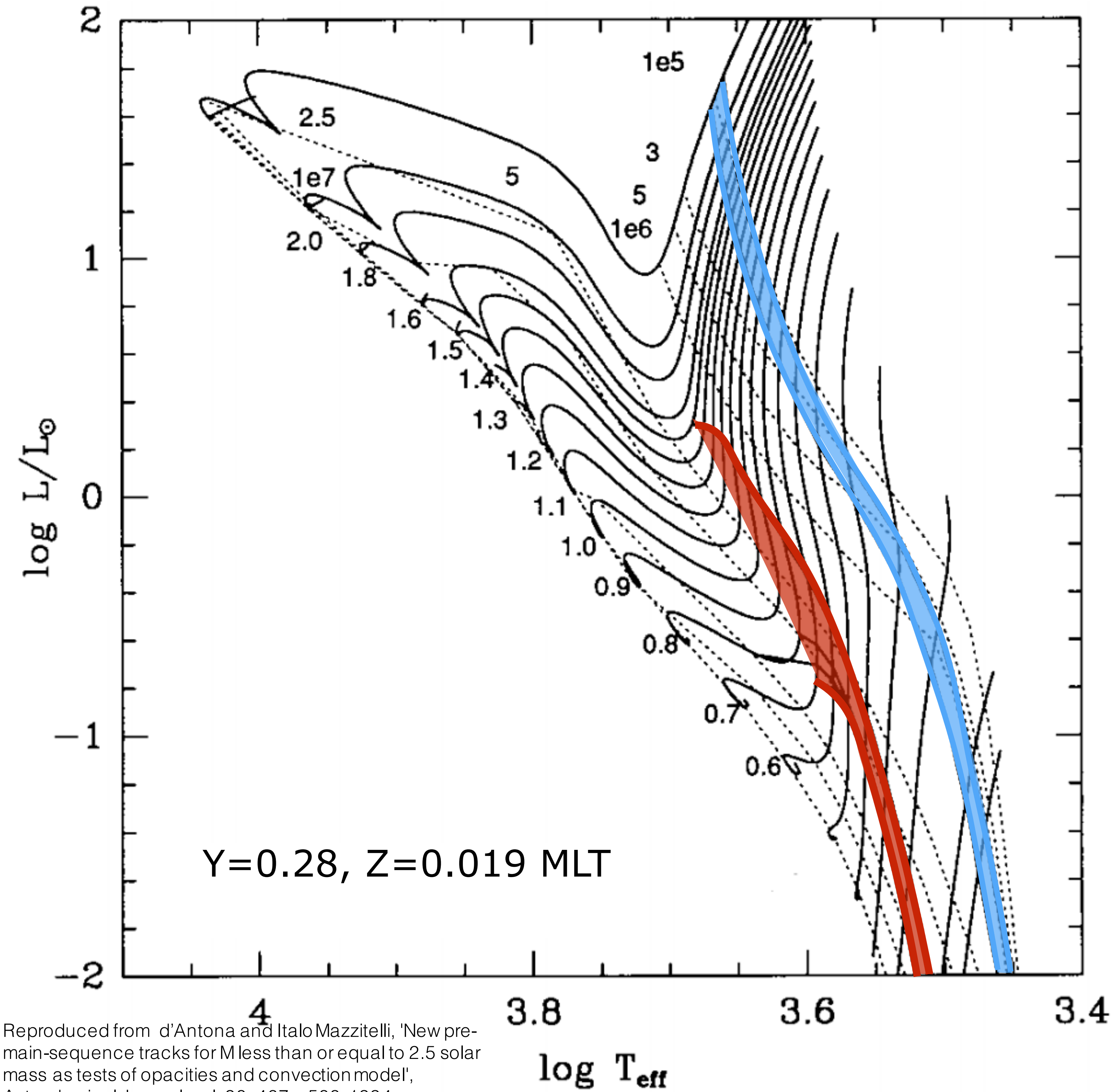
At ~2.5×10^6 K, Li is destroyed in the chain:

$$^6Li\,(p,\gamma)\,{}^7Be\,(e^-,\nu)\,{}^7Li(p,\gamma)\,{}^8Be \rightarrow 2\,{}^4He + \mathrm{energy}$$

$\therefore$ surface of Li and ^{2}H are a useful diagnostic for low-mass star formation

Star Formation

The Hayashi track ⟶ main sequence



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~0.01M$_\odot$: minimum mass for a clump to become opaque in IR

~0.08M$_\odot$: minimum mass for ignition of H-fusion

0.01M$_\odot$ ~ 0.08M$_\odot$ = brown dwarfs

Deuterium destruction

~0.01-0.08M$_\odot$

Lithium destruction

~0.06 - 0.08M$_\odot$

Star Formation

Summary of star formation

Cloud collapse (t_{ff} ~ 10^5-10^7 yr)

Starts when cloud exceeds Jeans mass
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At the end, <T> ~ 10^5 K, $R/R_\odot \sim 120 M/M_\odot$

Proto-star ($t_{KH} \sim 2\times10^6$ yr) (descending Hayashi track)

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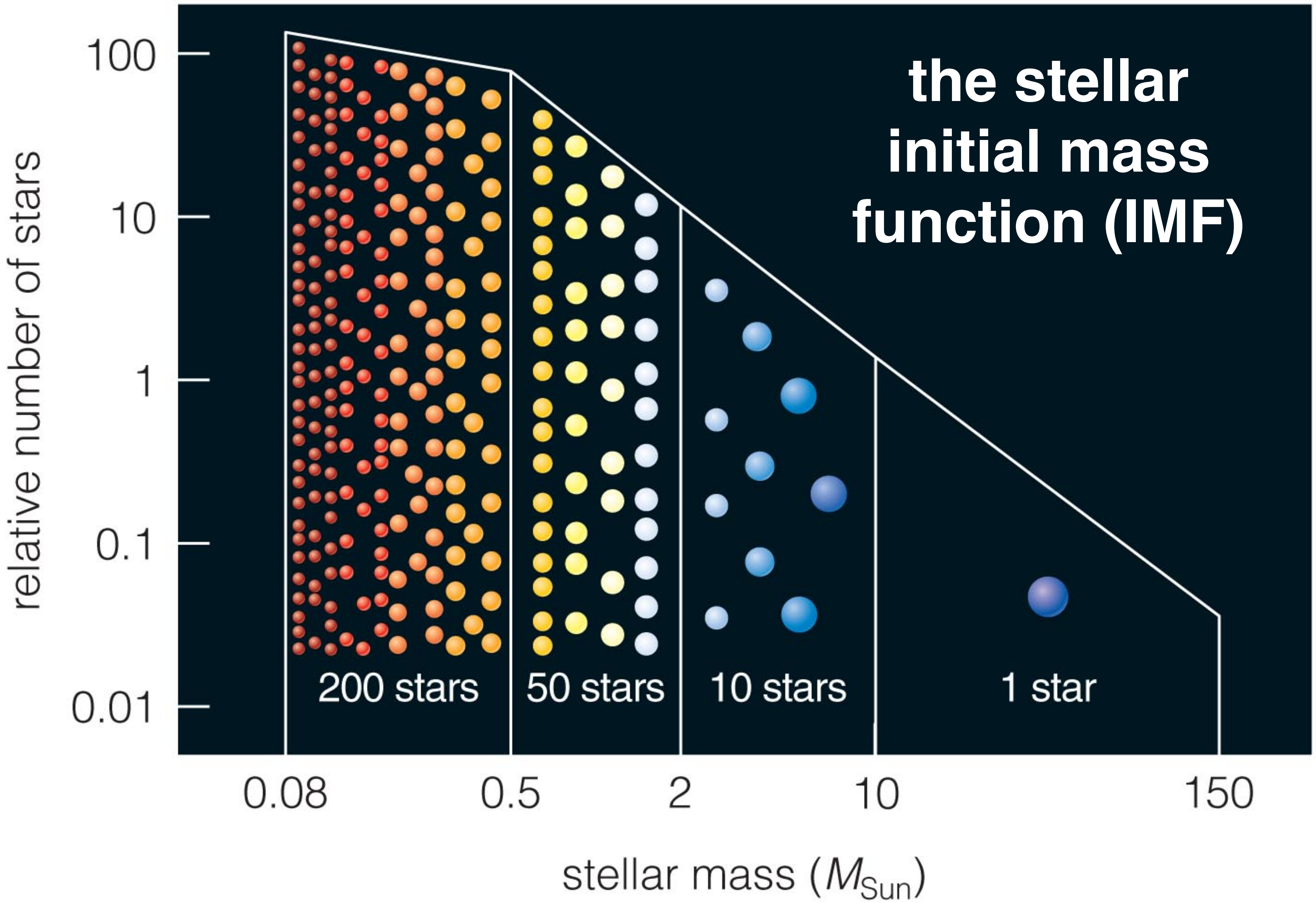
Demographics of Stars



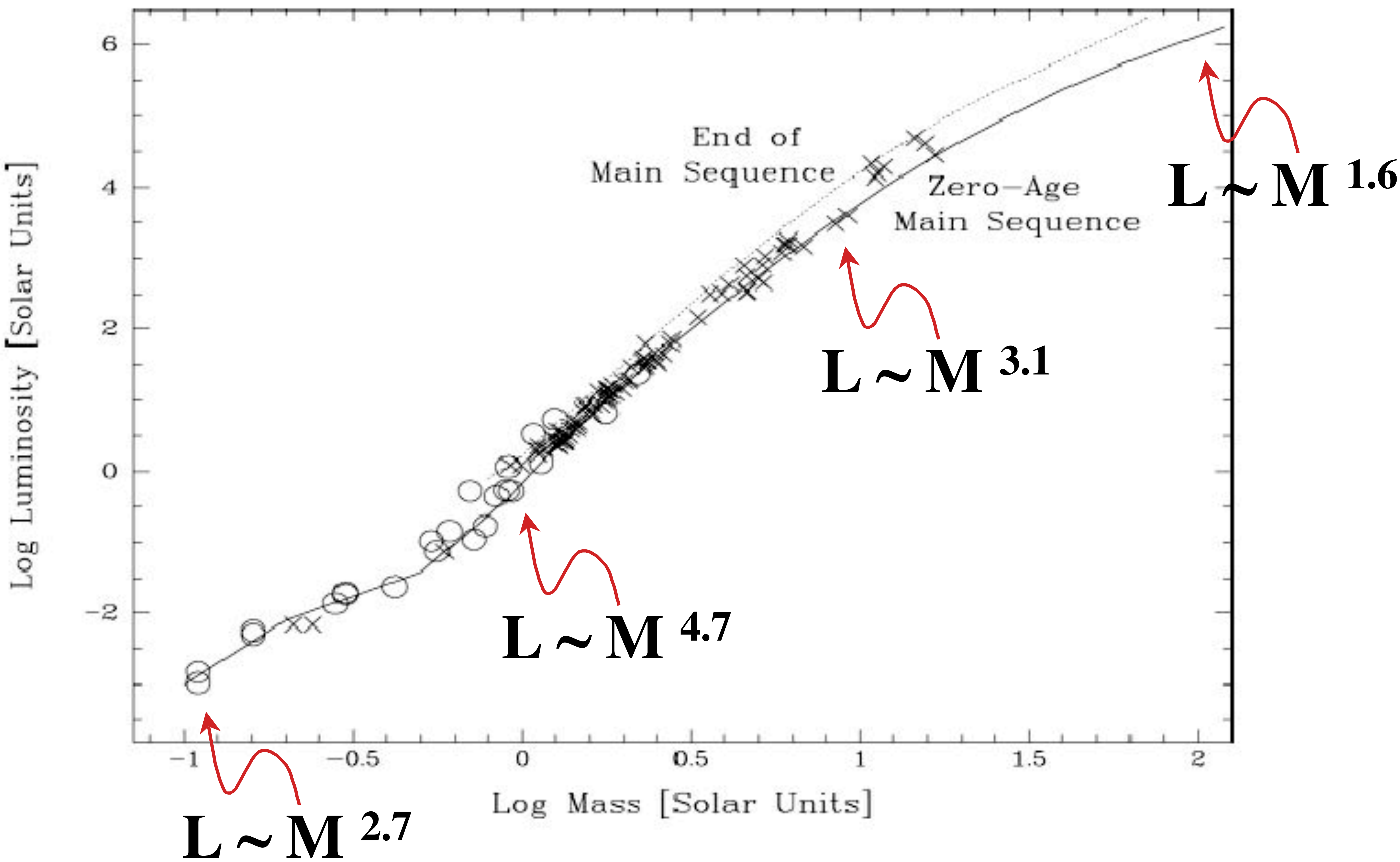
- Observations of star clusters show that star formation makes many more low-mass stars than high-mass stars.

Pleiades star cluster: why so blue?

from http://en.wikipedia.org/wiki/Pleiades_(star_cluster)

Stellar Mass-Luminosity Relation

Use it to convert stellar luminosities into masses



from Djorgovski,

Star Formation

The early universe

We've demonstrated that cooling plays a crucial role in star formation, but in the early universe with low Z there was no dust and almost no molecules; only H_2 was available for cooling.

→ higher Jeans mass

→ more massive stars
"top-heavy" initial mass function
more supernovae
faster metal enrichment

For more, see Volker Bromm Richard B. Larson, 'The First Stars', Annual Review of Astronomy and Astrophysics 2004 42:1, 79-118

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