

From protostellar to pre-main-sequence evolution

A summary remembering Francesco

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Palermo 1997



Firenze, June 5-9 2017 - Francesco's legacy - Star formation in space and time

Outline

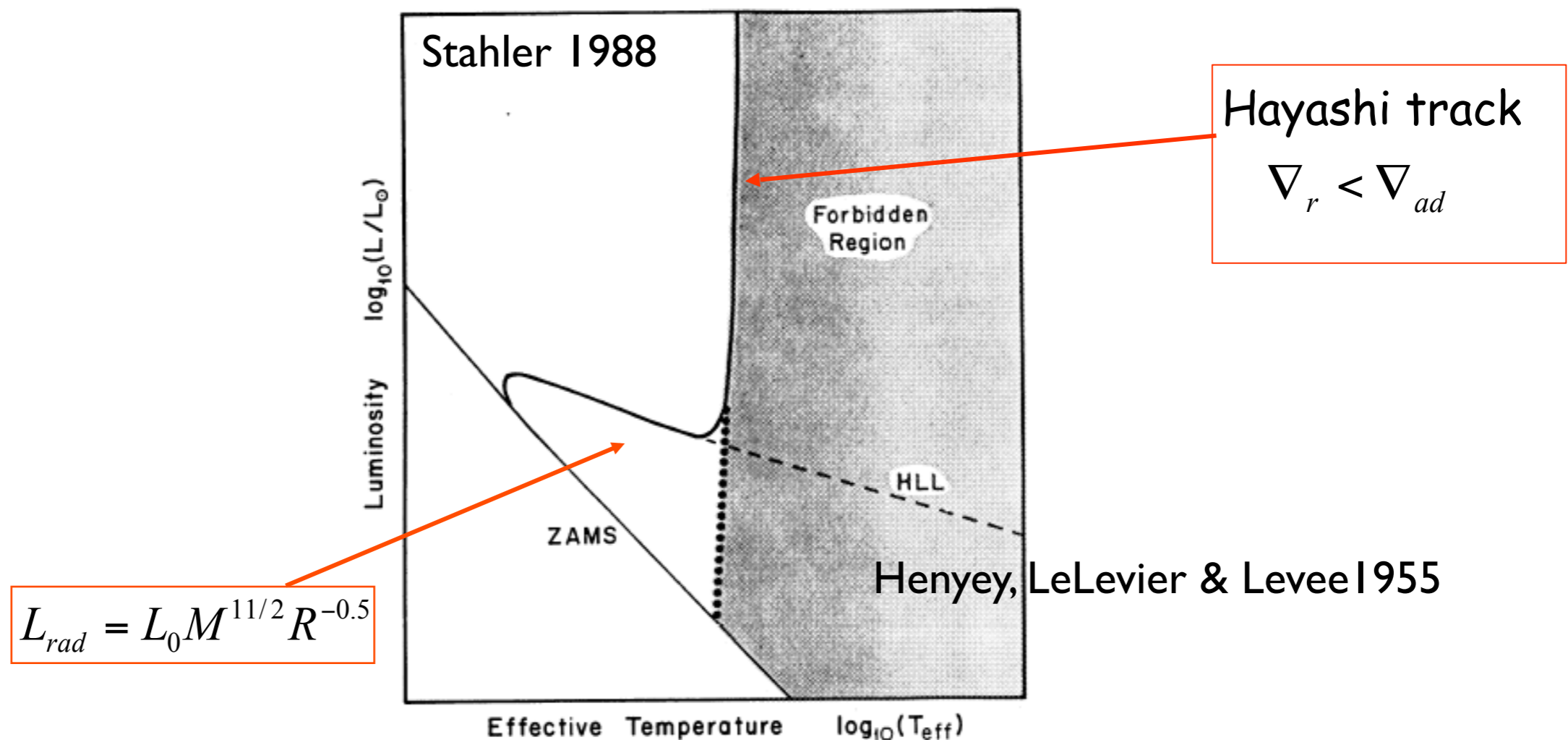
- The first steps in the approach: the Hayashi track, and the evolution through hydrostatic contraction
- the dynamical protostellar phase, the inside-out collapse
- Reconciling protostellar evolution and “standard” pre-MS evolution at the stellar birth line?
- Disk accretion
- Limitations and uncertainties of mass - age determinations from models
- Burning of light elements: still a powerful signature

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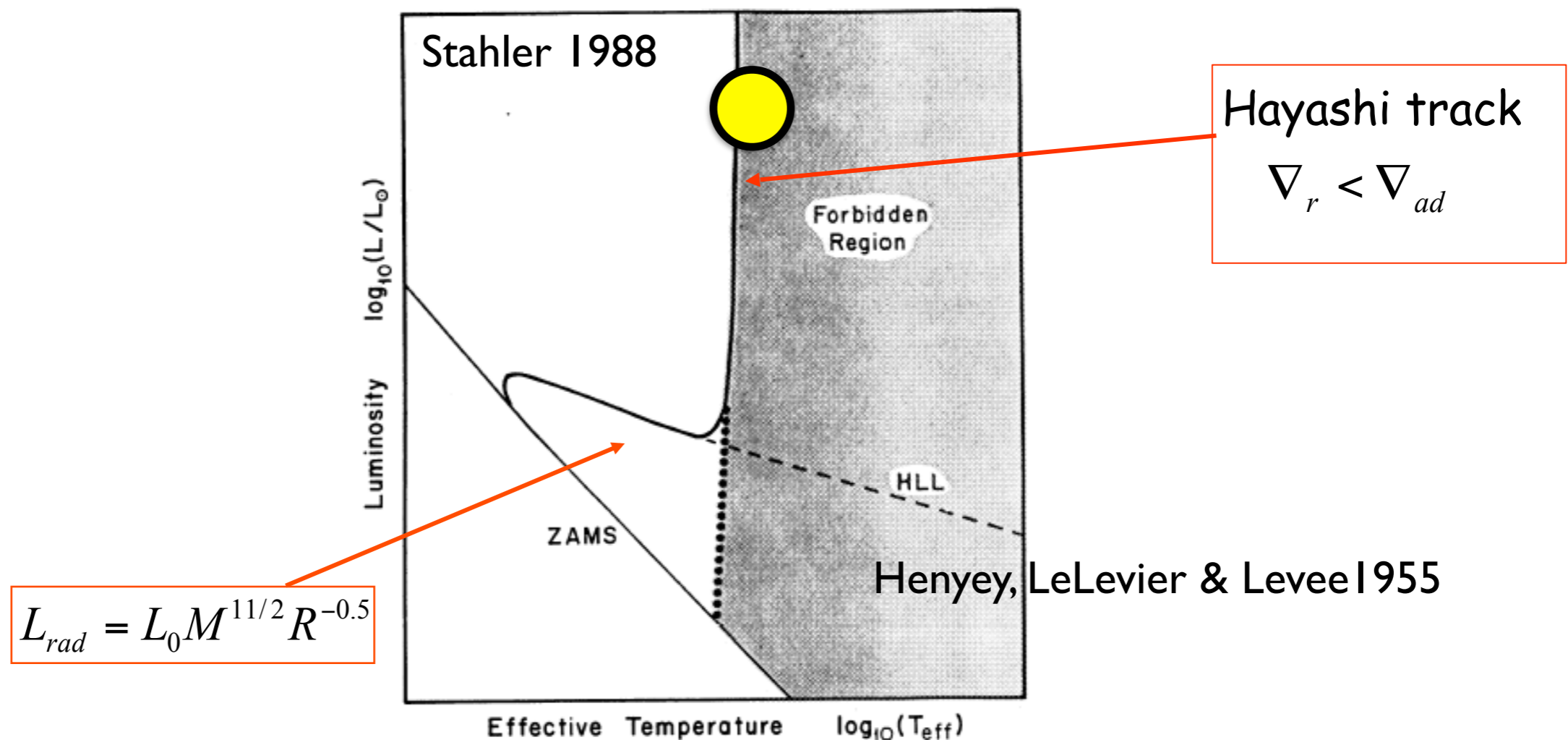
The Hayashi tracks

- In the sixties: no idea of the protostellar phase! Hayashi (1966) - the molecular cloud contracts hydrostatically from very high radii and luminosities



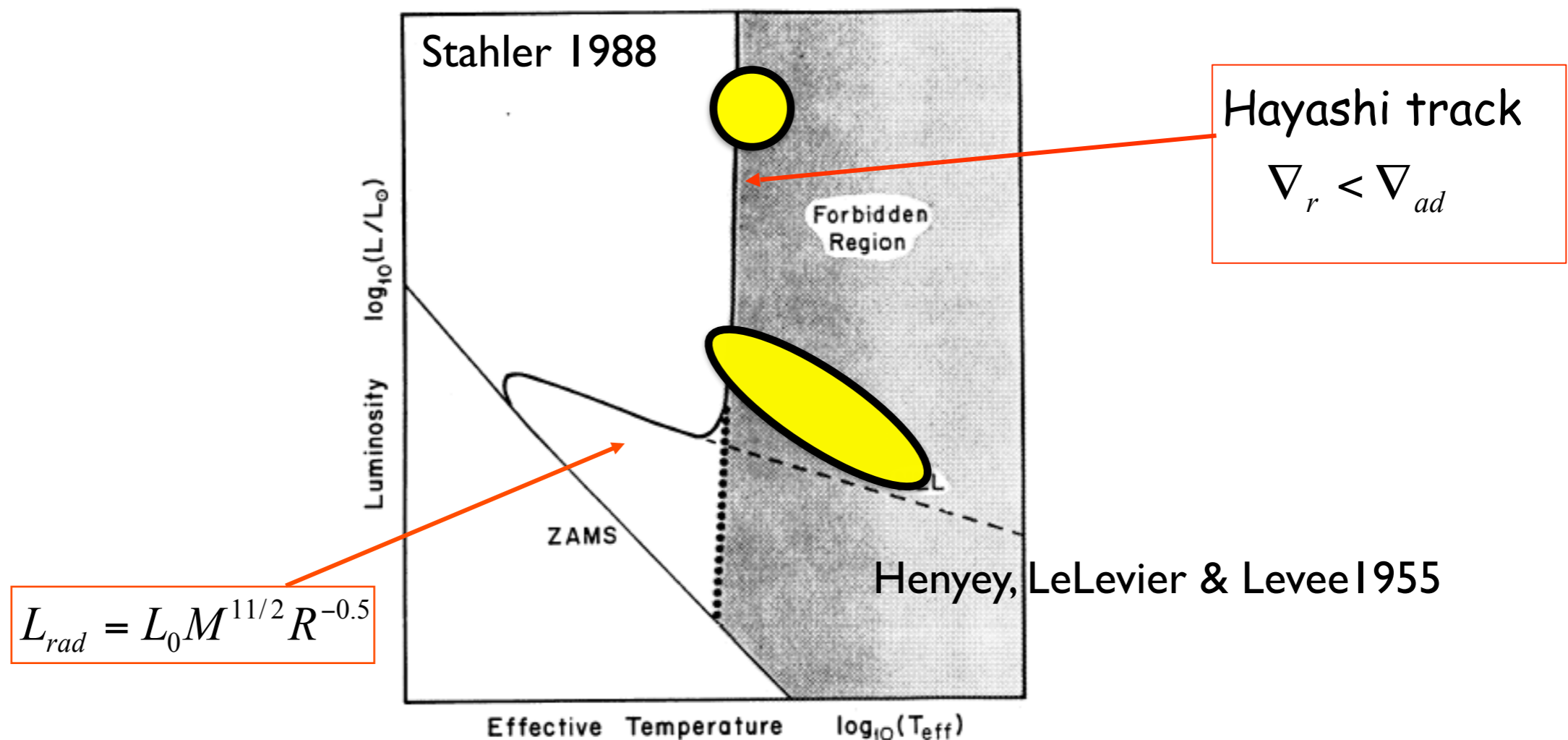
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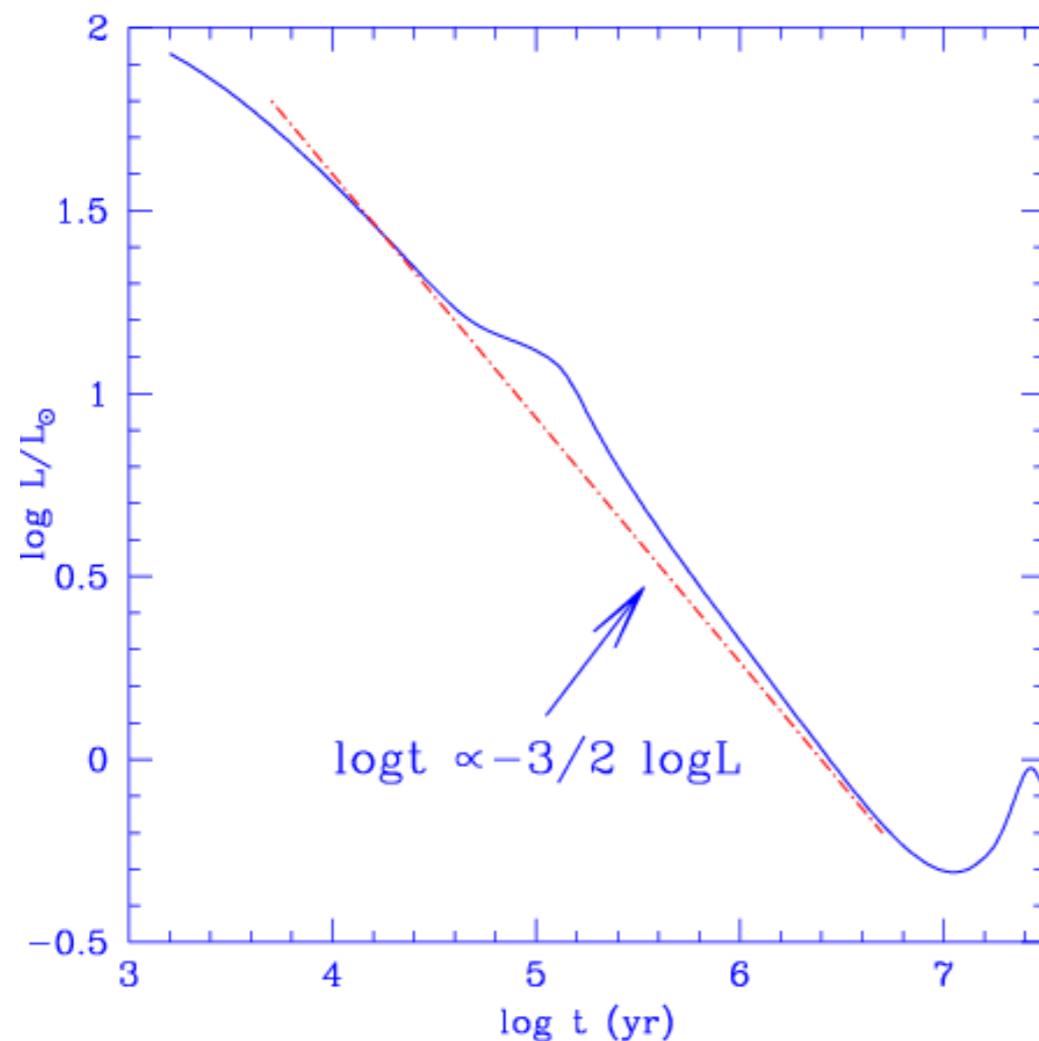
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estimating the evolution timescale

- Contraction is the main driver of evolution. By the Virial theorem, half of the gravitational energy released is radiated and half goes to increase the thermal energy



$$E_g = -\frac{6}{7} \frac{GM^2}{R} \quad Ldt = -\frac{1}{2} dE_g = -\frac{1}{2} \frac{6}{7} \frac{GM^2}{R^2} dR$$

- Adding Stefan-Boltzmann and $T_{\text{eff}} \sim \text{const}$ along the Hayashi line

$$\frac{dt}{dL} = -\frac{3}{14} GM^2 (4\pi\sigma)^{1/2} T_{\text{eff}}^2 L^{-5/2}$$

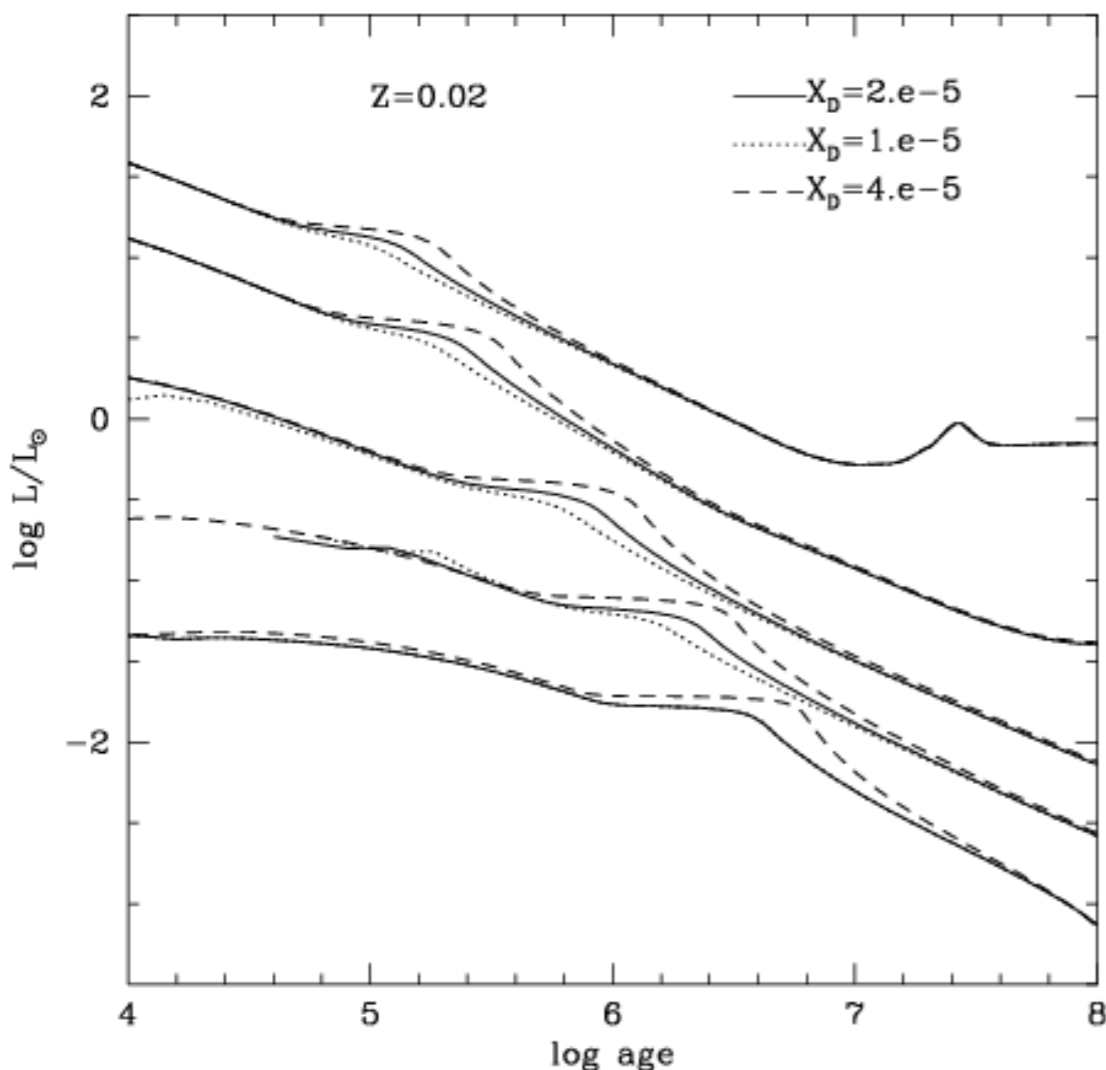
$$t = 0.2 \left(\frac{M}{M_{\odot}} \right)^2 T_{\text{eff}}^2 \left(\frac{L}{L_{\odot}} \right)^{-3/2} \text{ anni}$$

the advantage of KH timescale

- The equation defines the “characteristic lifetime” of a structure at luminosity L sustained only by gravitational contraction (thermal or Kelvin-Helmoltz timescale)

$$L dt = -\frac{1}{2} dE_g = -\frac{1}{2} \frac{6 GM^2}{7 R^2} dR$$

$$t_{KH} = -\frac{1}{2} \frac{E_g}{L} = \frac{3}{7} \frac{GM^2}{RL} \sim \frac{GM^2}{RL}$$

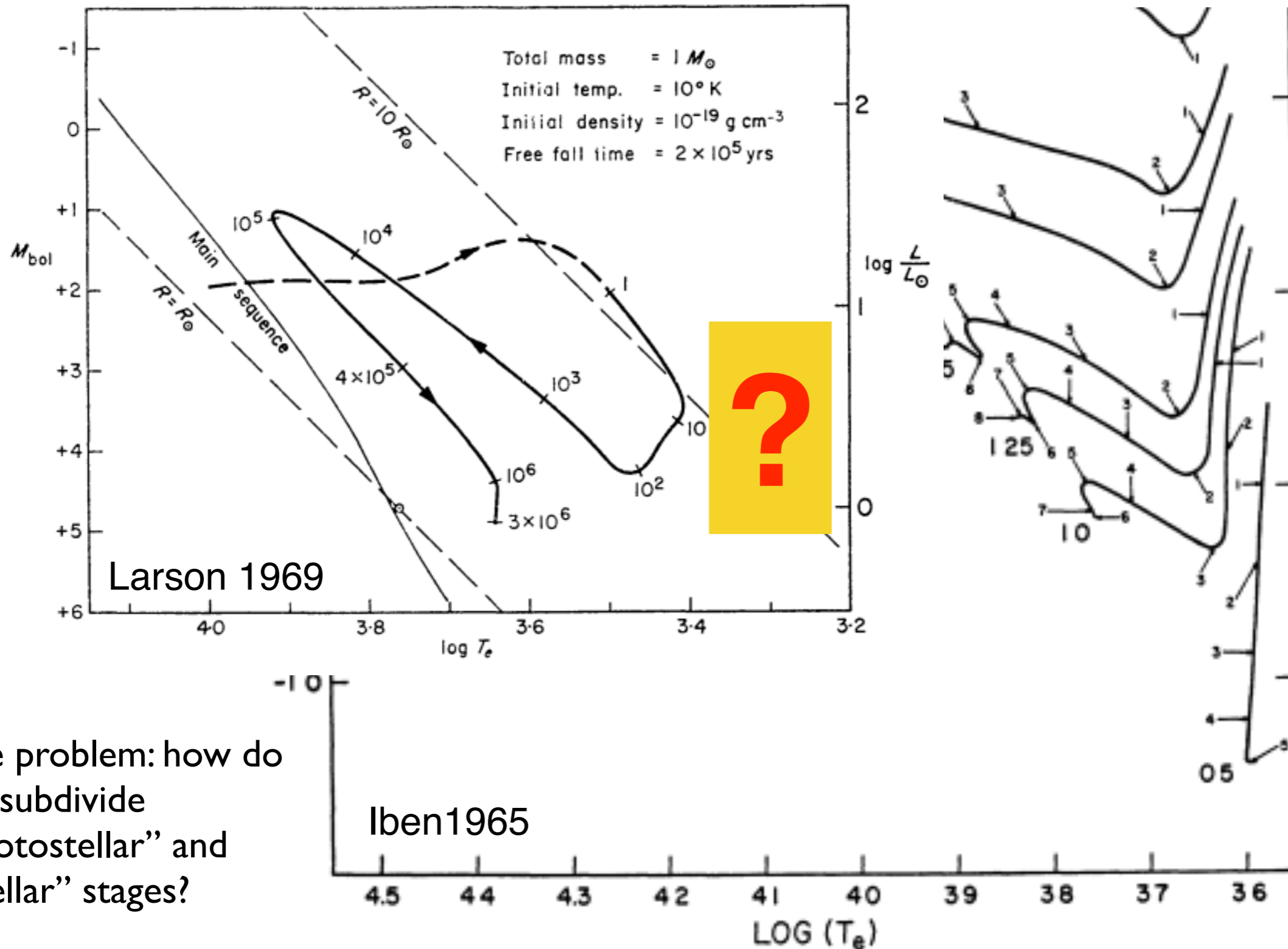


- Thermal timescale is the relevant timescale in the hydrostatic evolution
- Perturbation factors (nuclear burning of deuterium, accretion, rotation) *in the end* can not alter the result significantly, when you attempt to date stars which are not perturbed any longer → any previous difference is easily forgot
- This is a simplification, but... other much more relevant factors are hanging on the preMS evolution!

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Dynamics of a collapsing protostars



- The problem: how do we subdivide “protostellar” and “stellar” stages?

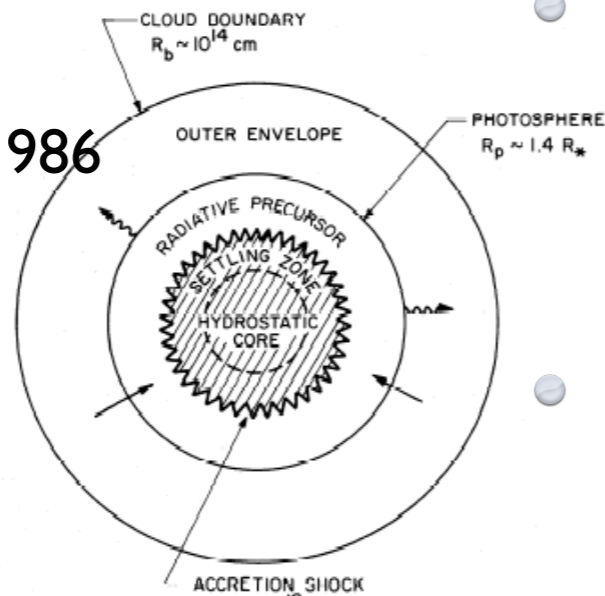
the D-burning thermostat

-Stahler Shu Taam 1980a & b

-Stahler 1983

-Stahler Palla Salpeter 1986

-Palla Stahler 91, 92, 93



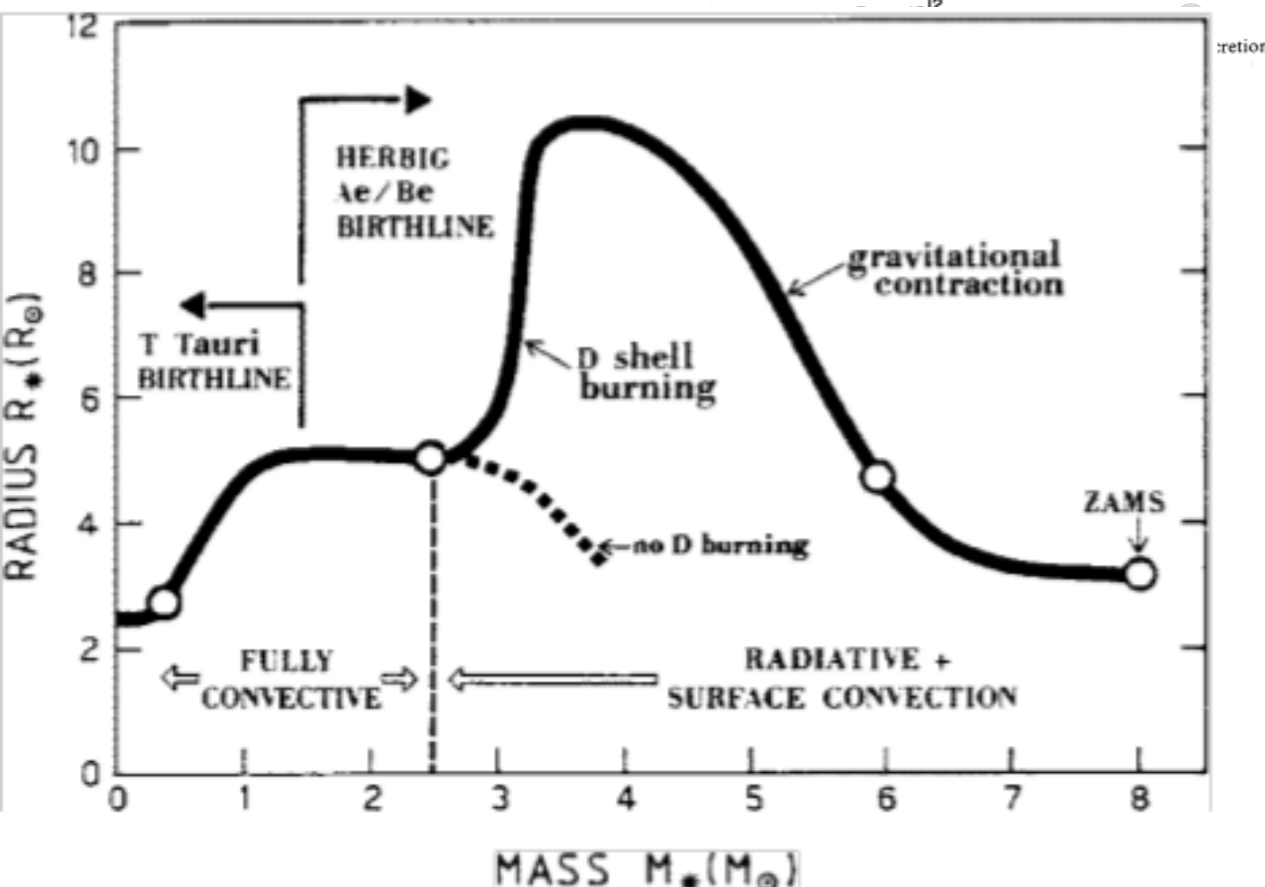
- The core and envelope evolution are decoupled: accretion on the hydrostatic core characterizes the main phase of proto-star evolution (spherical symmetry) and defines the Mass-Radius relation
- In $M < 1 M_{\text{sun}}$ - the onset of D-burning during the main accretion phase...

—halts the hydrostatic core contraction

—The core becomes fully convective

—When the main accretion phase ends the star appears on the track of its final mass, at the D-burning line (birthline)

This simple model reconciles hydrostatic and dynamic evolution “where it matters”, at the T-Tauri stage



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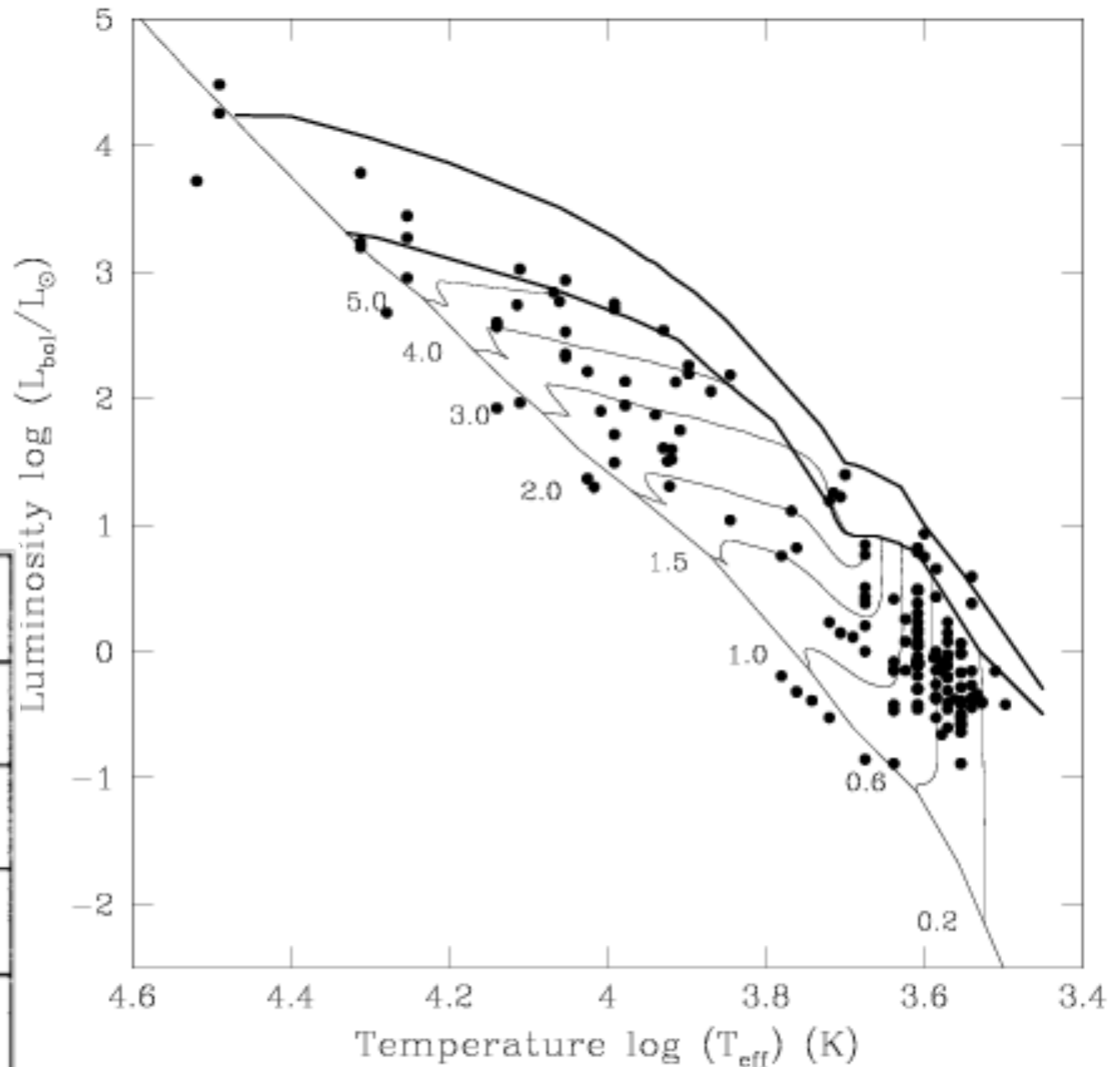
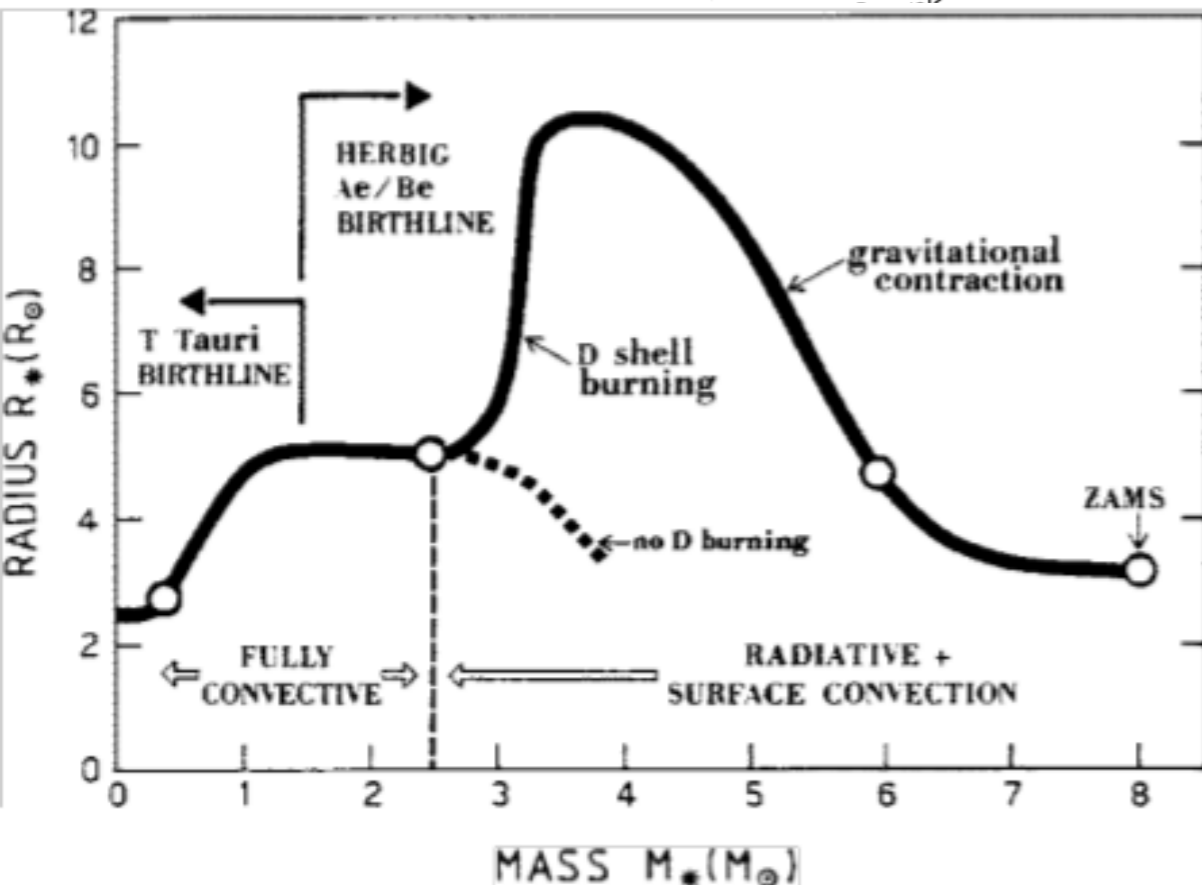
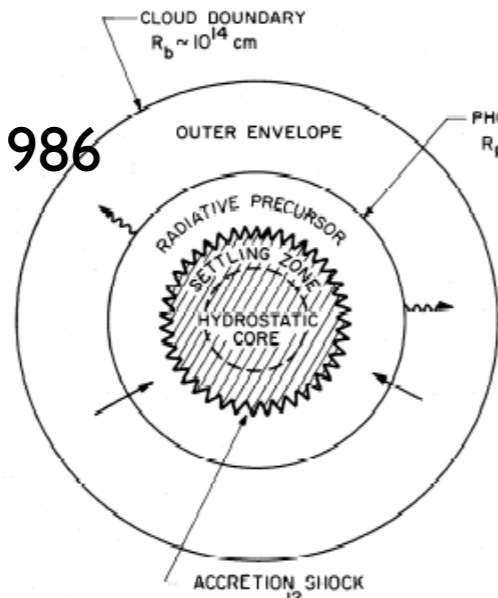


fig. 7. Location of the stellar birthline in the H-R diagram for accretion rates of 10^{-5} (lower heavy curve) and 10^{-4} (upper heavy curve) $M_\odot \text{yr}^{-1}$. Symbols give the positions of young PMS stars. Labeled curves are PMS evolutionary tracks for the indicated stellar mass. (From Palla & Stahler [41])

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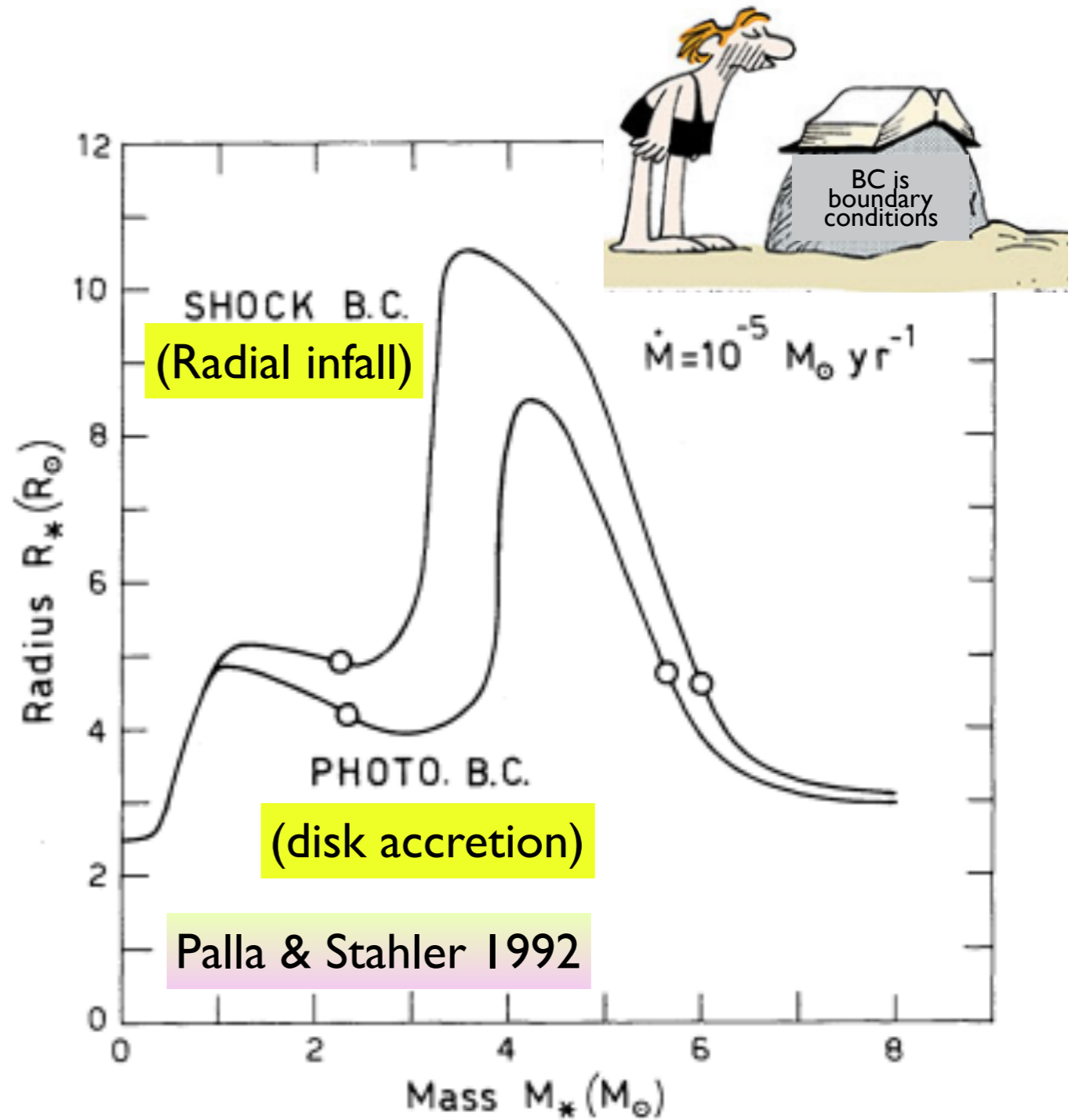
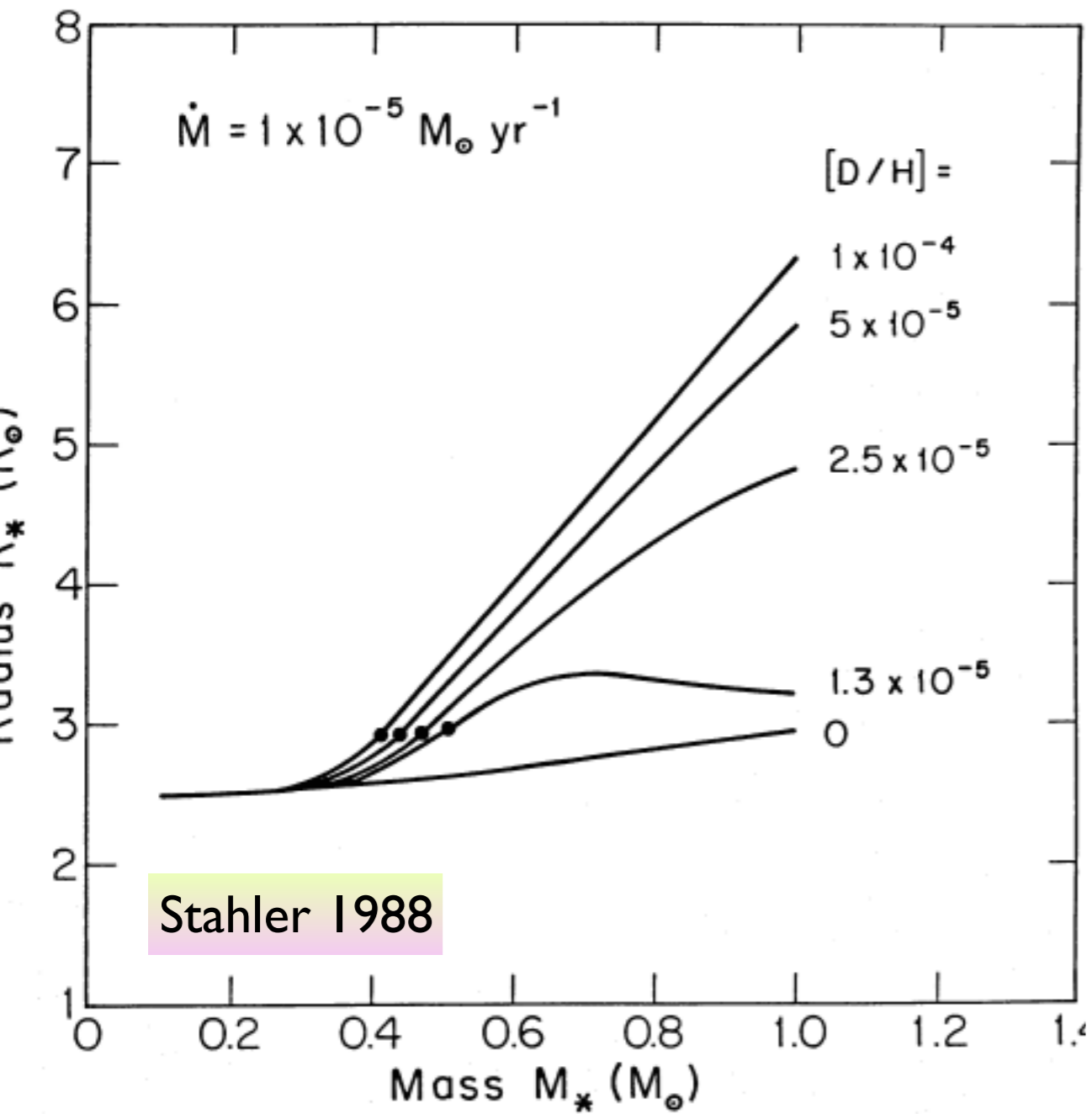
standard evolution is back...

- Palla & Stahler's thermostat view is the way we may (might?) appreciate back the usefulness of standard evolutionary tracks for low mass stars:
- Apart from a zero age problem —depending on the duration of the protostellar phase— standard evolution along the convective pre-main sequence is a reasonable approximation following the D—burning stage
- This means we can use standard tracks to date young populations (possibly not very young) if their stars have finished the rapid protostellar accretion phase
- But...
 - location of the birth line depends on the details of accretion
 - disk accretion may change everything (?)
 - accretion is not uniform in time
 - location of standard tracks in the HR diagram is far from settled

Blurry definition of the birth line

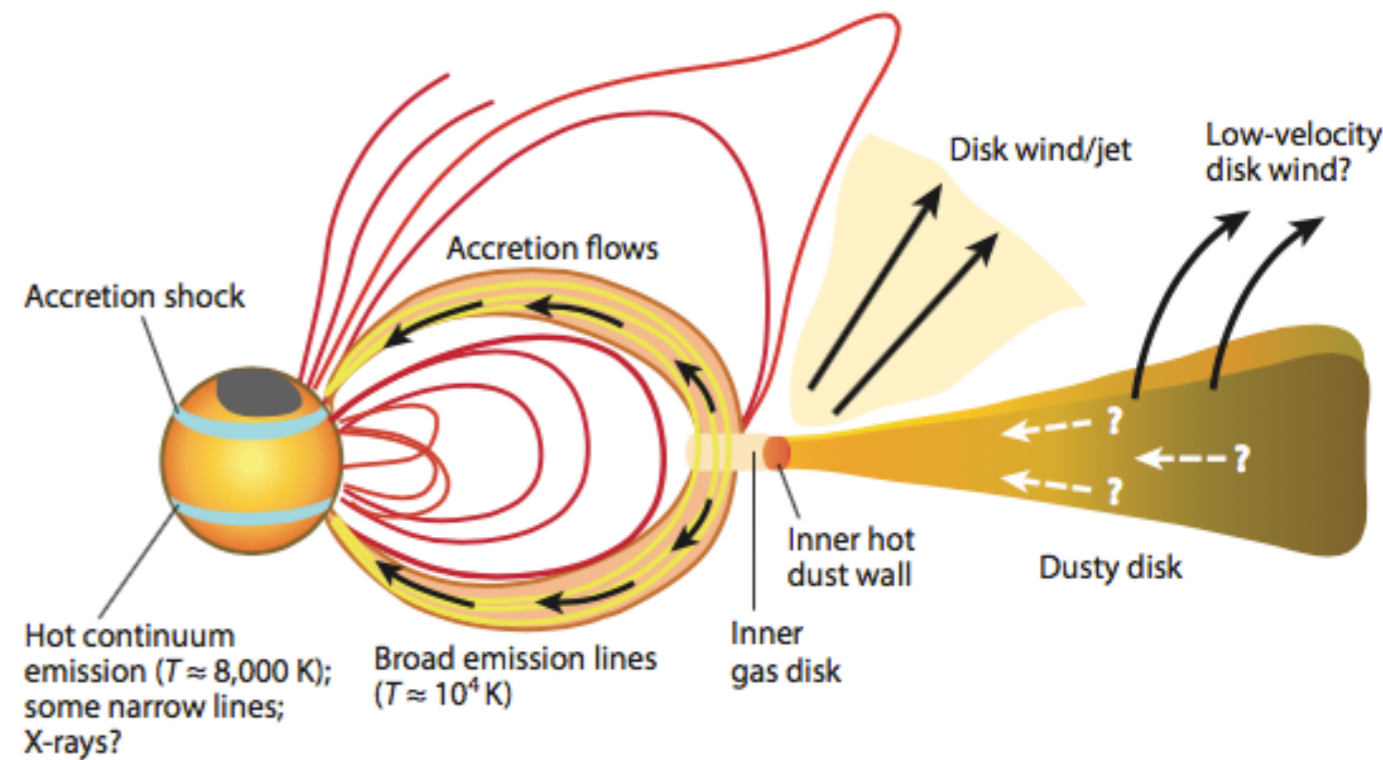
- Existence of FU Ori outbursts (Herbig 1977) and, mainly, of EXors with close repeated variability (Herbig 1989) requires the mediation of an accretion circumstellar disk
- it is possible that intermittent (disk) accretion is the way stars acquire the bulk of the mass, starting during the protostar phase (Baraffe+2009, Vorobyov-Basu 2005)
- Stahler's talk (EXors are present both at late TTauri stage and in class I objects) and Vorobyov talk (evolution with disk accretion)
- The D-abundance in the accreting matter modifies the radius evolution (Kunitomo talk)
- The accretion modeling leads to a *more uncertain definition* of stellar “zero age”, and to spread of luminosity in coeval low mass stars (Baraffe+2009)

the birthline (the mass-radius relation) depends on X_D , dM_{acc}/dt and BC



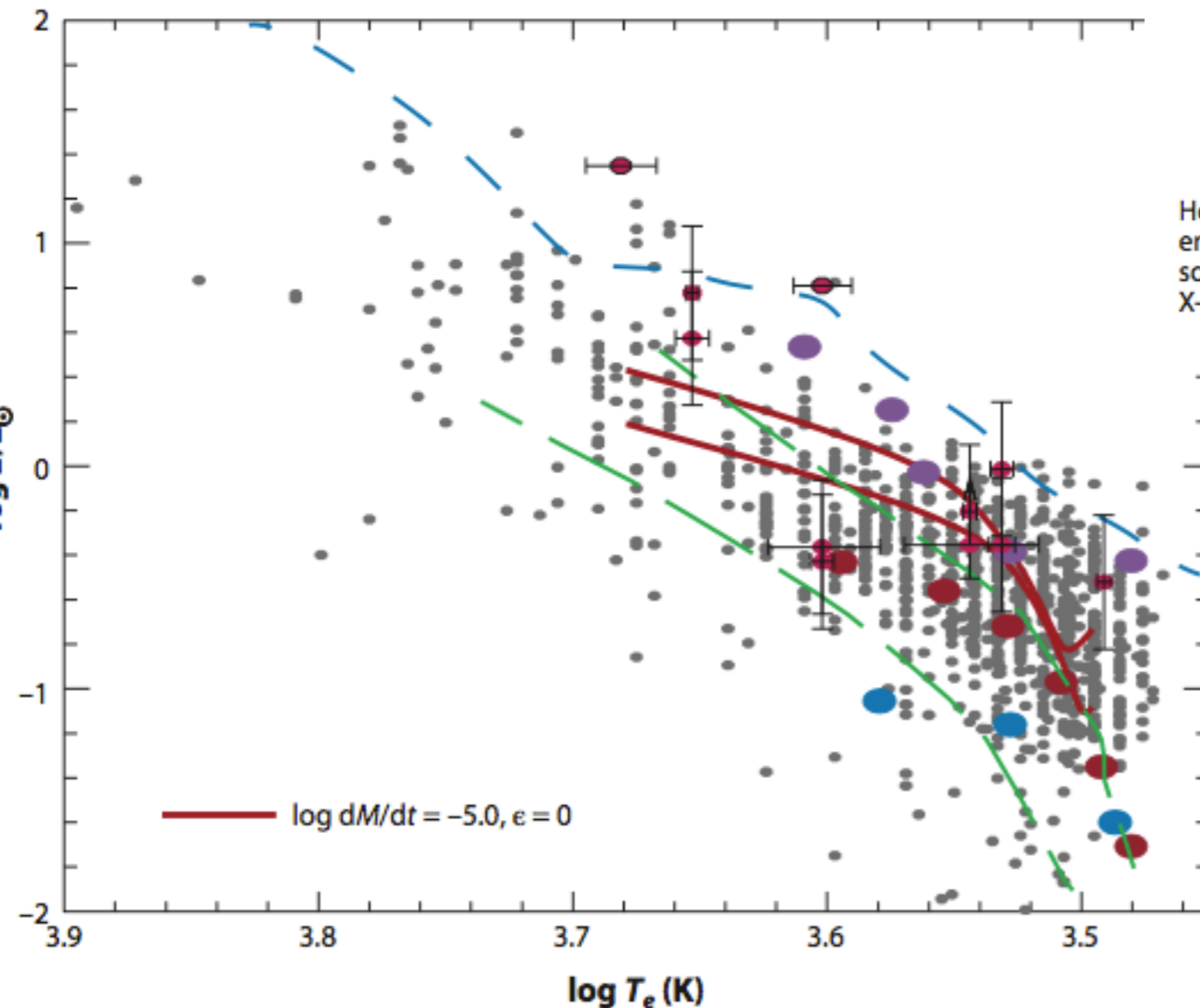
Disk accretion

- Disk accretion alters the model of protostellar evolution, and also the CTTS phase (Mercer-Smith+1984, Hartmann+1997)



Hartmann+2014 ARAA

- Accretion from disk should be mostly “cold”
- In this case, the evolution after the main accretion phase begins at smaller radii than the birth line



Radius evolution

(Hartmann+2014 ARAA)

$$\frac{\dot{R}_*}{R_*} \approx \frac{7}{3} \frac{R_*}{GM_*^2} \left[-L_* + \left(\beta_D - \frac{GM_*}{7R_*} \right) \dot{M} \right]$$

Standard PMS contraction

expansion related to mass accretion, if D-burning is concomitant.
 β_D energy release per gram from D-burning

contraction due to mass accretion, in absence of D

How “cold” is disk accretion?

$$L_{\text{add}} = \xi GM_* \dot{M} / R_*$$

And “where” is the additional energy released?

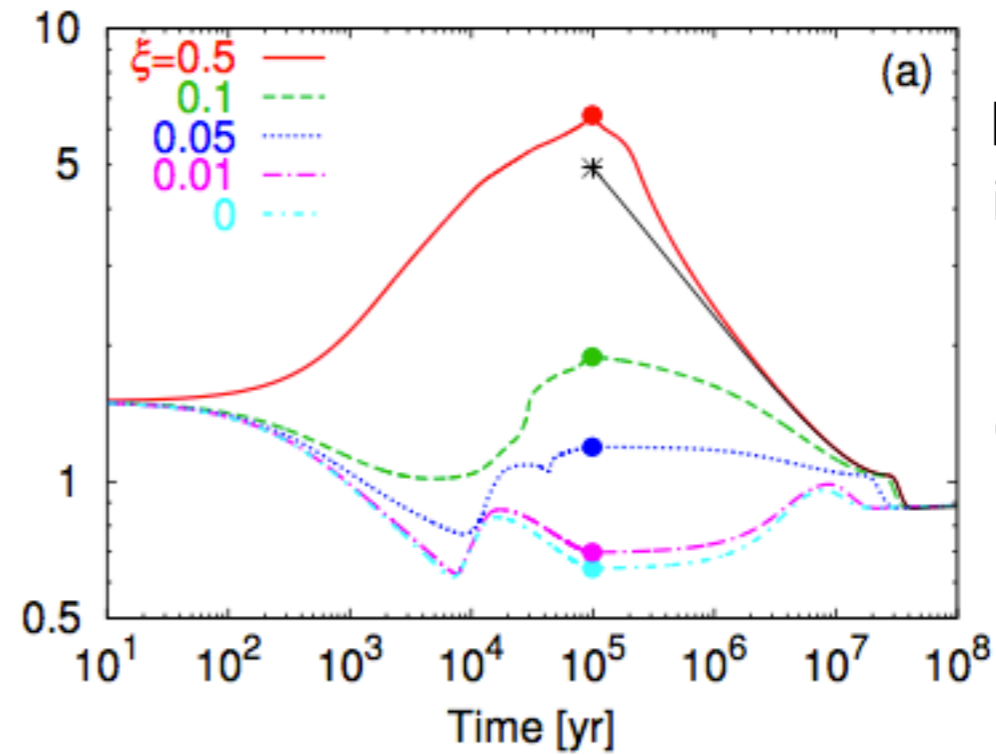
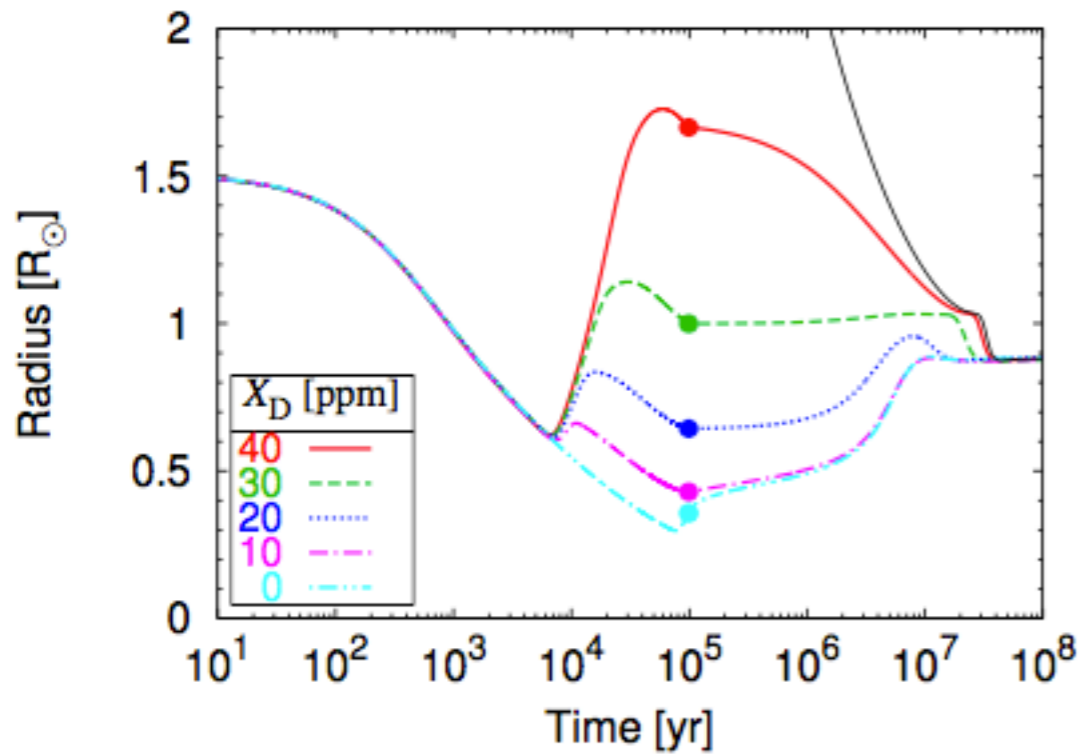
—“Uniform” model (e.g. Baraffe+Chabrier 2010) L_{add} is distributed uniformly and instantaneously within the entire star

$$\epsilon_{\text{add}}^{(\text{uniform})} = \frac{L_{\text{add}}}{M_*}$$

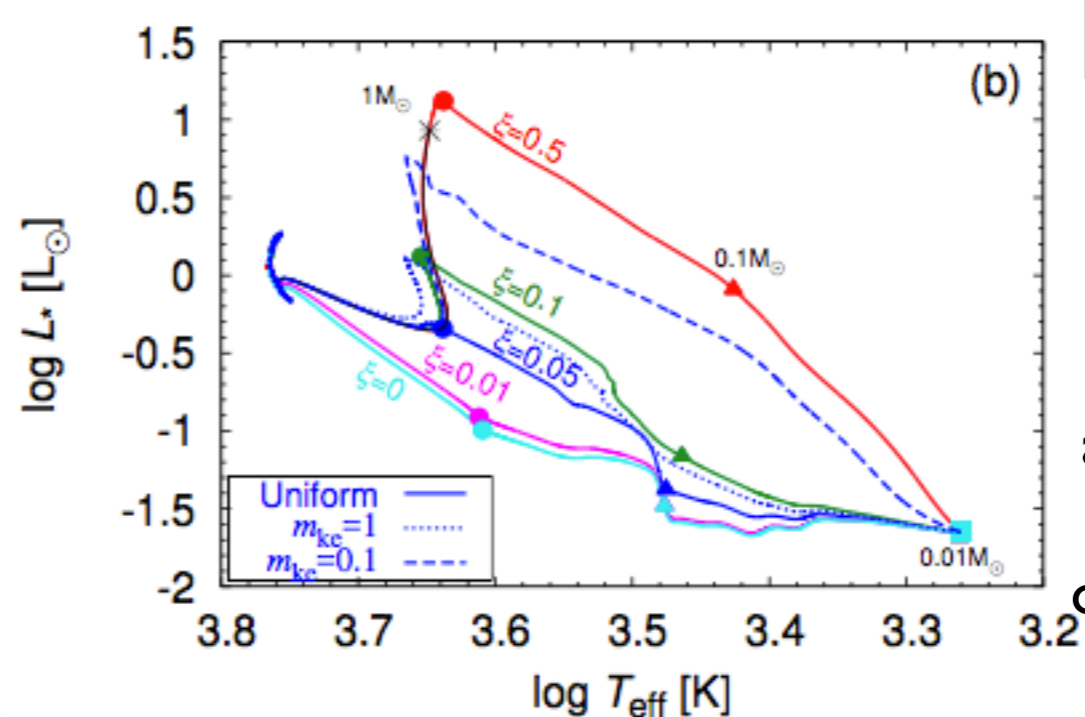
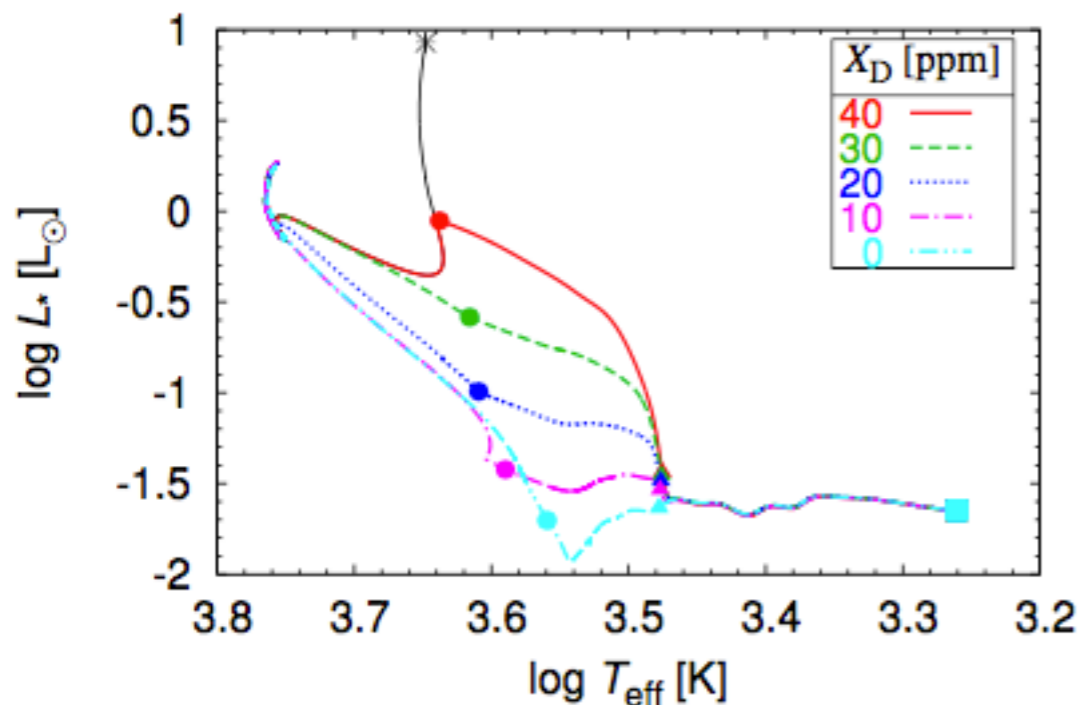
—“Linear” (Kunitomo+2017): an outer layer m_{ke} is affected

$$\epsilon_{\text{add}}^{(\text{linear})} = \frac{L_{\text{add}}}{M_*} \text{Max} \left[0, \frac{2}{m_{\text{ke}}^2} \left(\frac{M_r}{M_*} - 1 + m_{\text{ke}} \right) \right]$$

Radius evolution



LEFT: D abundance is important, also if there is no accretion energy (but anyway a total energy release $E_D = q_D X_D M_{\text{fin}}$)



$$L_{\text{add}} = \xi GM_{\star} \dot{M} / R_{\star}$$

RIGHT: If ξ is not zero, the radius becomes larger, especially if the accretion energy is released in the outer parts (dashed blue line, $\xi = 0.05$ and $m_{\text{ke}} = 0.1$)

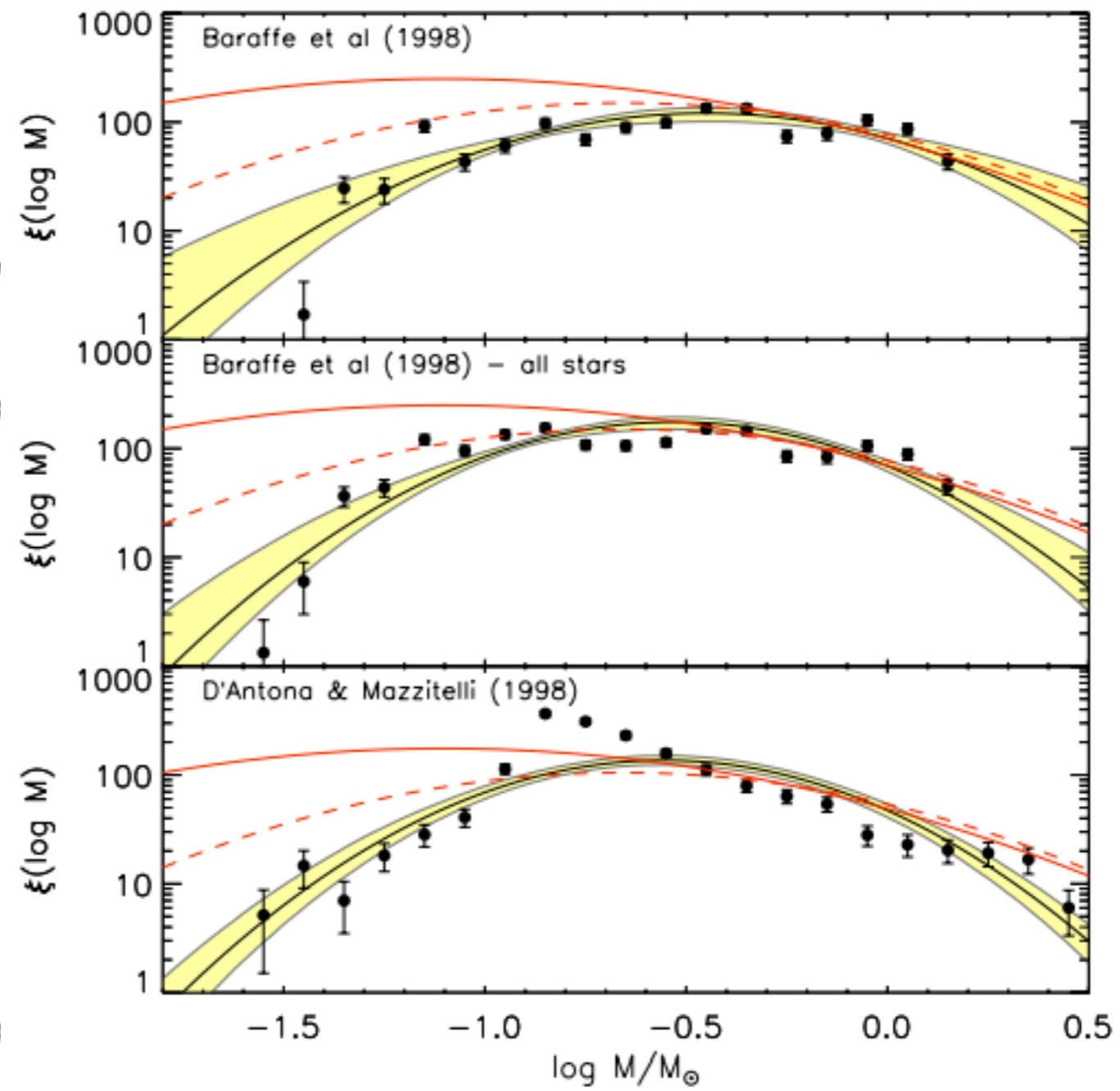
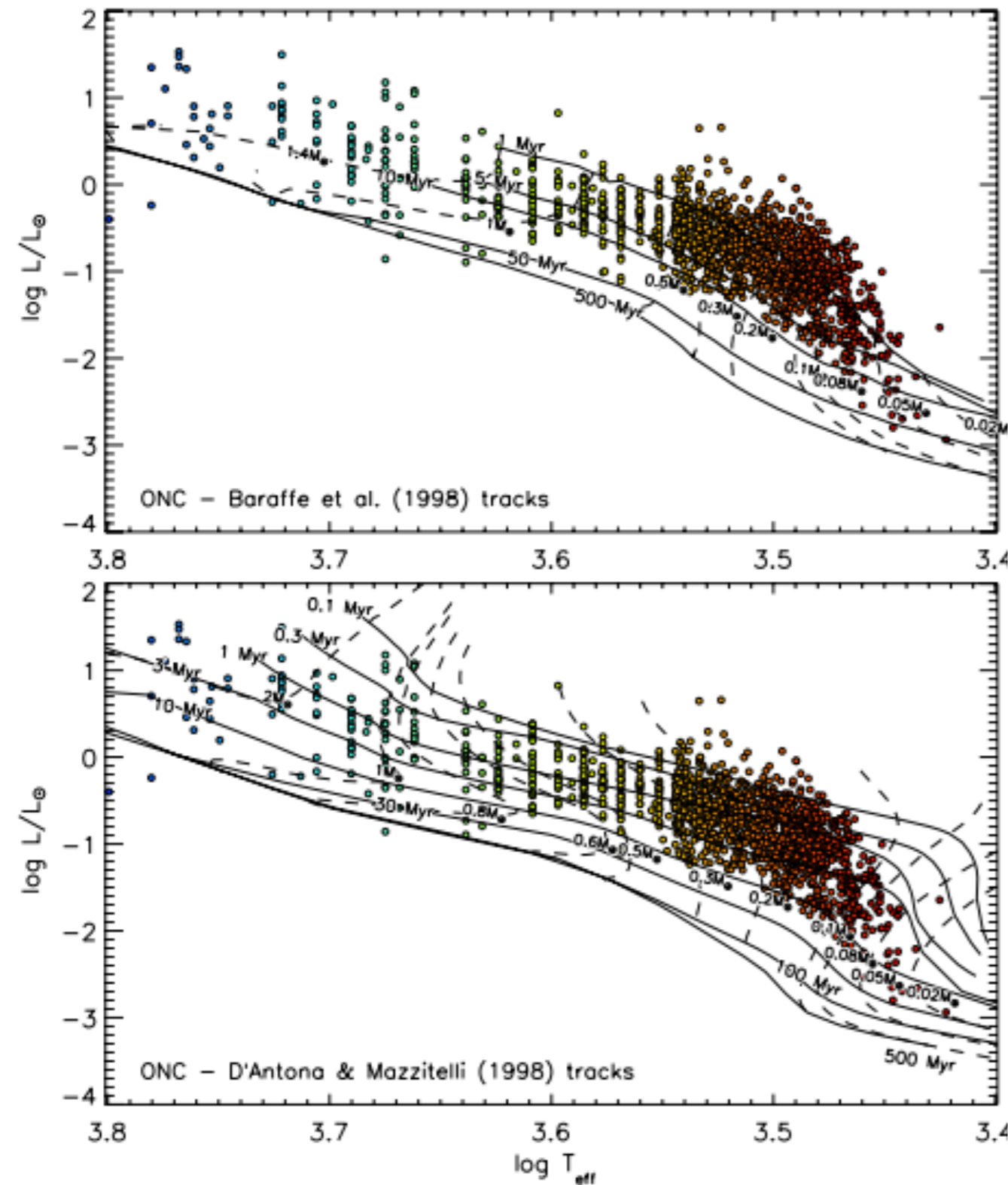
(Kunitomo+2017)

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HST Treasury program of ONC (PI Robberto)

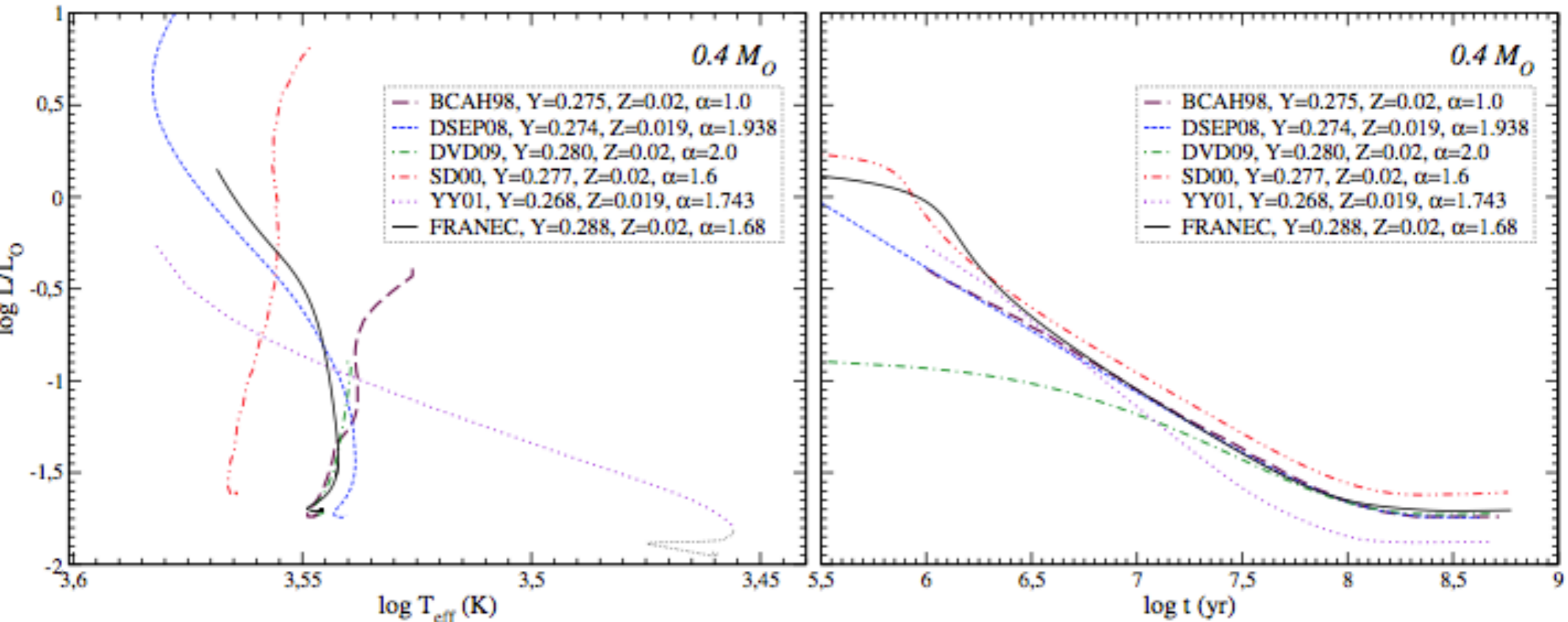
DaRio+2012 - dating and mass determination of the ONC sample



Dating and assigning masses to young populations with standard models

- Computing pre-MS standard evolution is “simple”: flourishing of models in the 90’s (Swenson & Faulkner, D’Antona-Mazzitelli 1994 -1998, Baraffe+1998, Siess 2000) but also in the last decade (Montalbán+2004, Dotter+2007, Tognelli+2011, Baraffe+2015)
- Initial efforts: equation of state (especially needed for the very low masses) and opacities
- main improvement: use of non-grey boundary conditions (small caveat, see later); use of improved molecular line lists for various atmospheric absorbers (see DUSTY and COND models by Allard+2001, Baraffe+2003)
- Main uncertainty at $M \geq 0.5 M_{\text{sun}}$: the Teff location of the Hayashi track depends on the convection model!
- —“Standard” Mixing Length Theory (MLT) description - parameter $\alpha = l/H_p$ (often chosen by imposing reproduction of solar Teff for the solar model)
- —“Full Spectrum of Turbulence” (FST) convection model by Canuto-Mazzitelli 2001, Canuto+2006 has been used in the D’Antona & Mazzitelli 1994 set

Model comparison



- Comparison of different sets for the $0.4M_{\odot}$ track (Tognelli+2011)
- (skipping YY01), the main difference here is the use of Haushildt+1999 or Allard & Hauschildt boundary conditions in all sets but SD00 (hotter)

- **At low masses, boundary conditions are the important input**

SD00 Siess+2000

YY01: Yi+2001

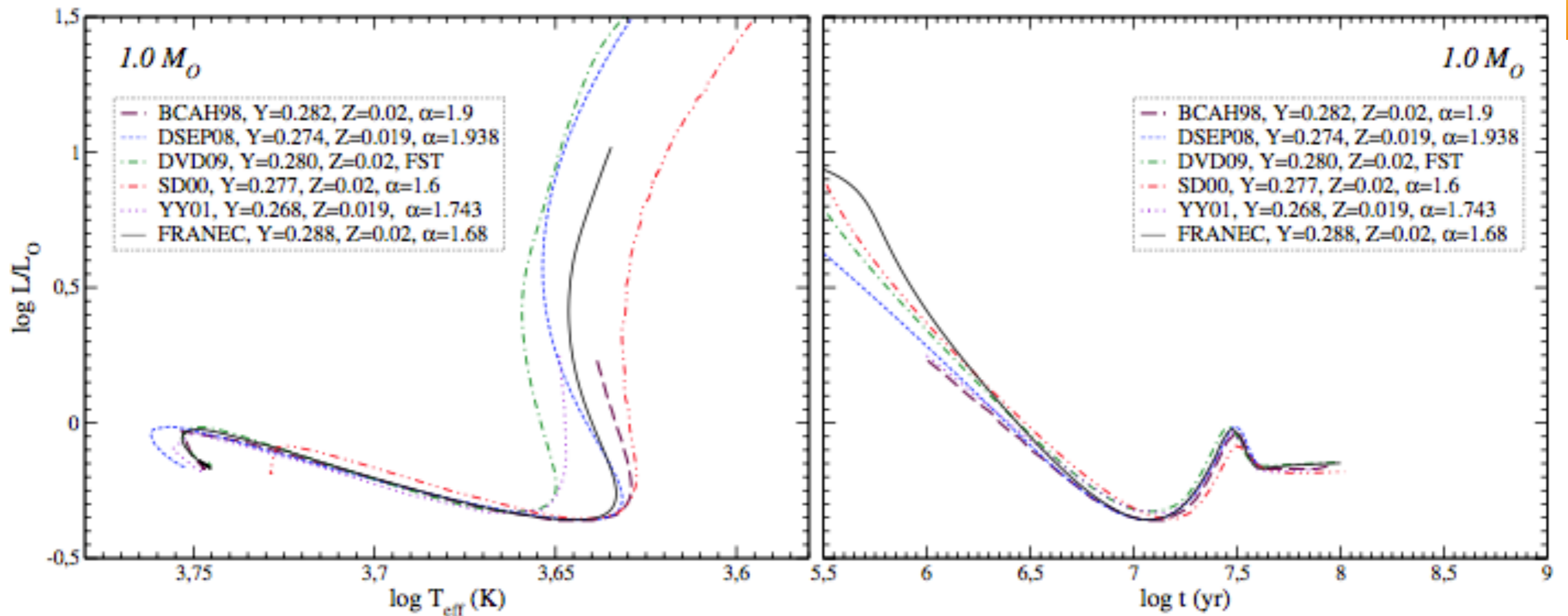
DSEP08 Dotter+2008

DVD09 DiCriscienzo+2009

BCAH98 Baraffe+2008

FRANEC Tognelli+2011

Model comparison



- Comparison of different sets for the $1 M_{\odot}$ track (Tognelli+2011)
- Here the BCAH track is the coolest! the problem is not the non grey BC, but the mixing length of the atmosphere (0.5 down to $\tau=100$)

- **At larger masses ($M \gtrsim 0.5 M_{\text{sun}}$), convection is the important input (super-adiabaticity is high)**

SD00 Siess+2000

YY01: Yi+2001

DSEP08 Dotter+2008

DVD09 DiCriscienzo+2009

BCAH98 Baraffe+2008

FRANEC Tognelli+2011

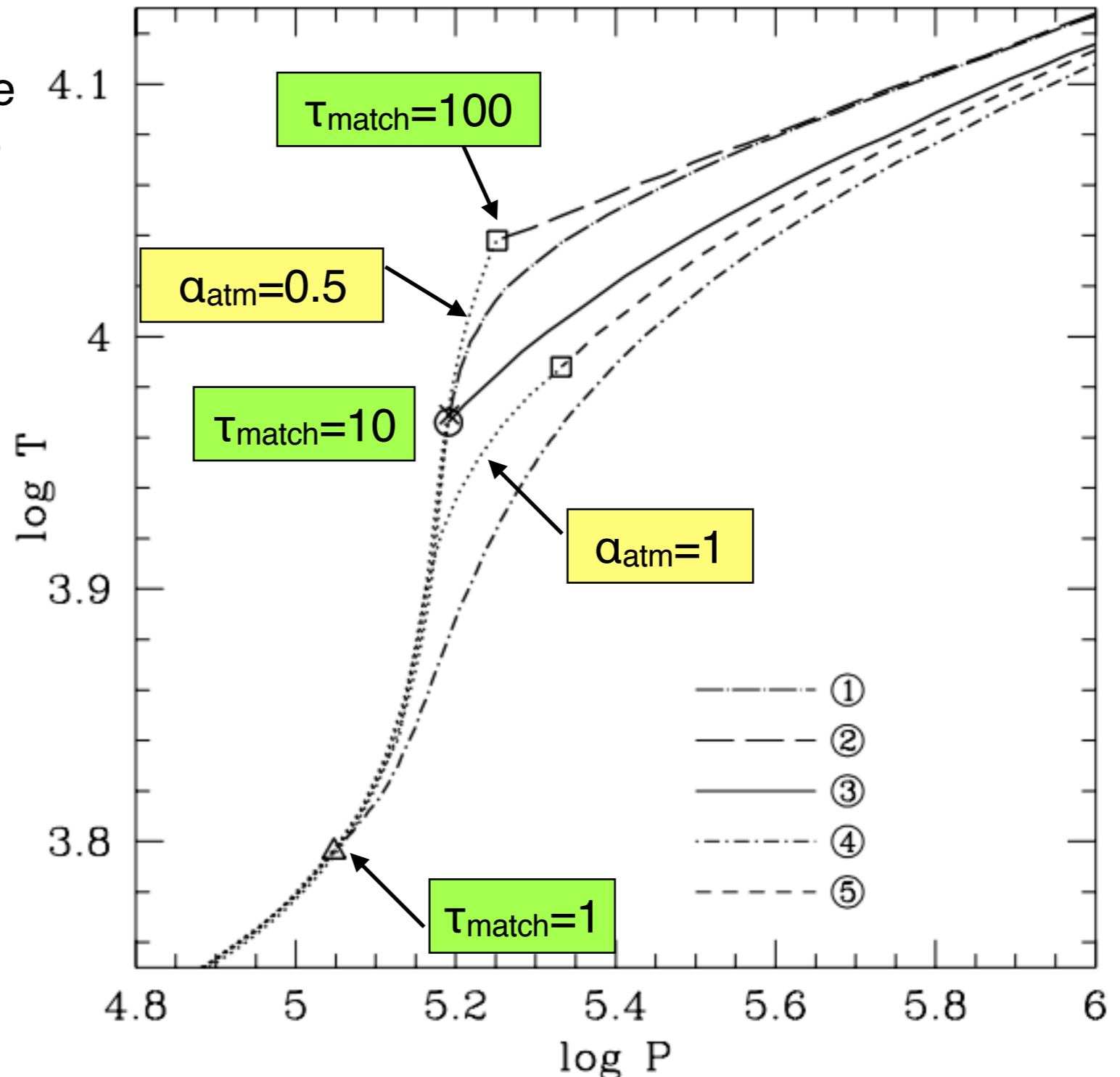
matching atmosphere and interior

- The Temperature gradient (and the resulting T_{eff}) depends on the choice of convection model in the atmosphere (boundary condition) and in the interior, and on the matching point between the two computations (Montalban+2006)

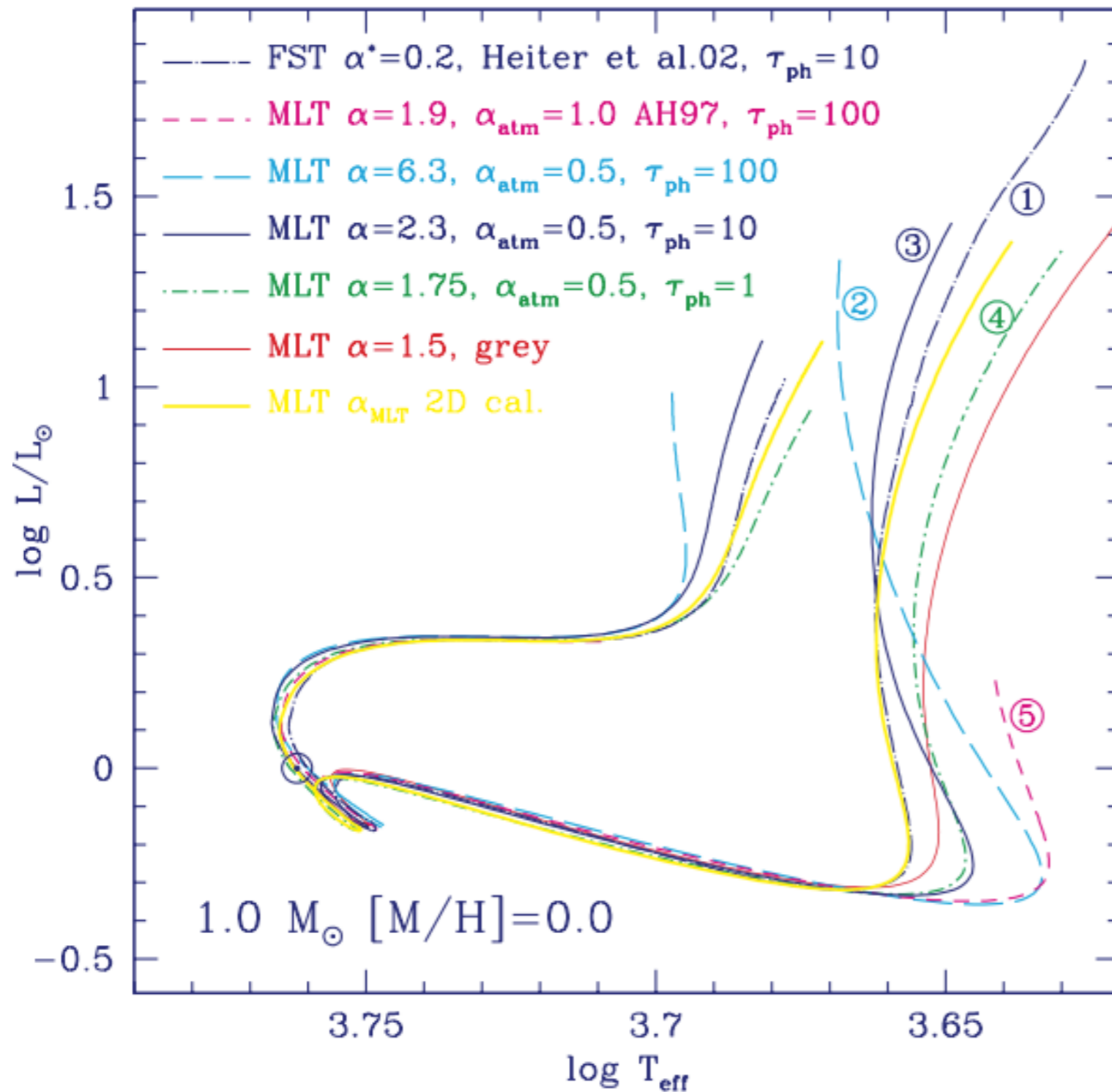
- Parameters: α_{atm} , α_{in} , τ_{match}

- Use of FST in both atmosphere (Heiter+2002) and interior provides a smooth transition

- BCAH1997 models were the coolest because they employed $\alpha_{\text{atm}}=0.5$ and $\tau_{\text{match}}=100$, a very inefficient convection (large T gradient) (now different choice in Baraffe+2015)



matching atmosphere and interior



Montalbán+2004

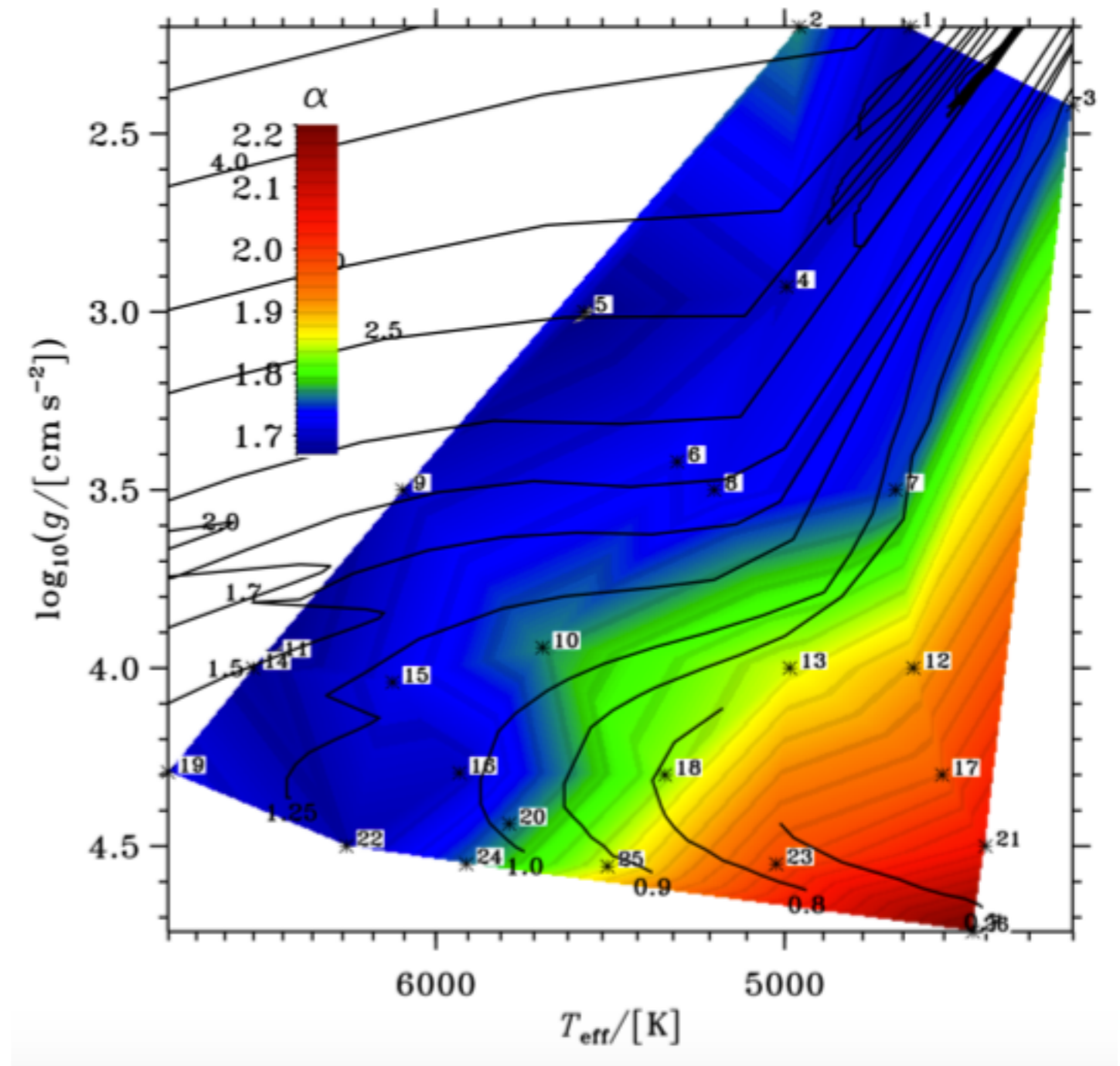
Parameters: α_{atm} , α_{in} , T_{match}

Uncertainty of $\sim 200\text{K}$ in the preMS location of $1 M_{\odot}$, in spite of **fitting the solar T_{eff}** (a paradigm of uncertain meaning)

• (comparison includes models computed with NEMO non grey atmospheric grid by Heiter+2002)

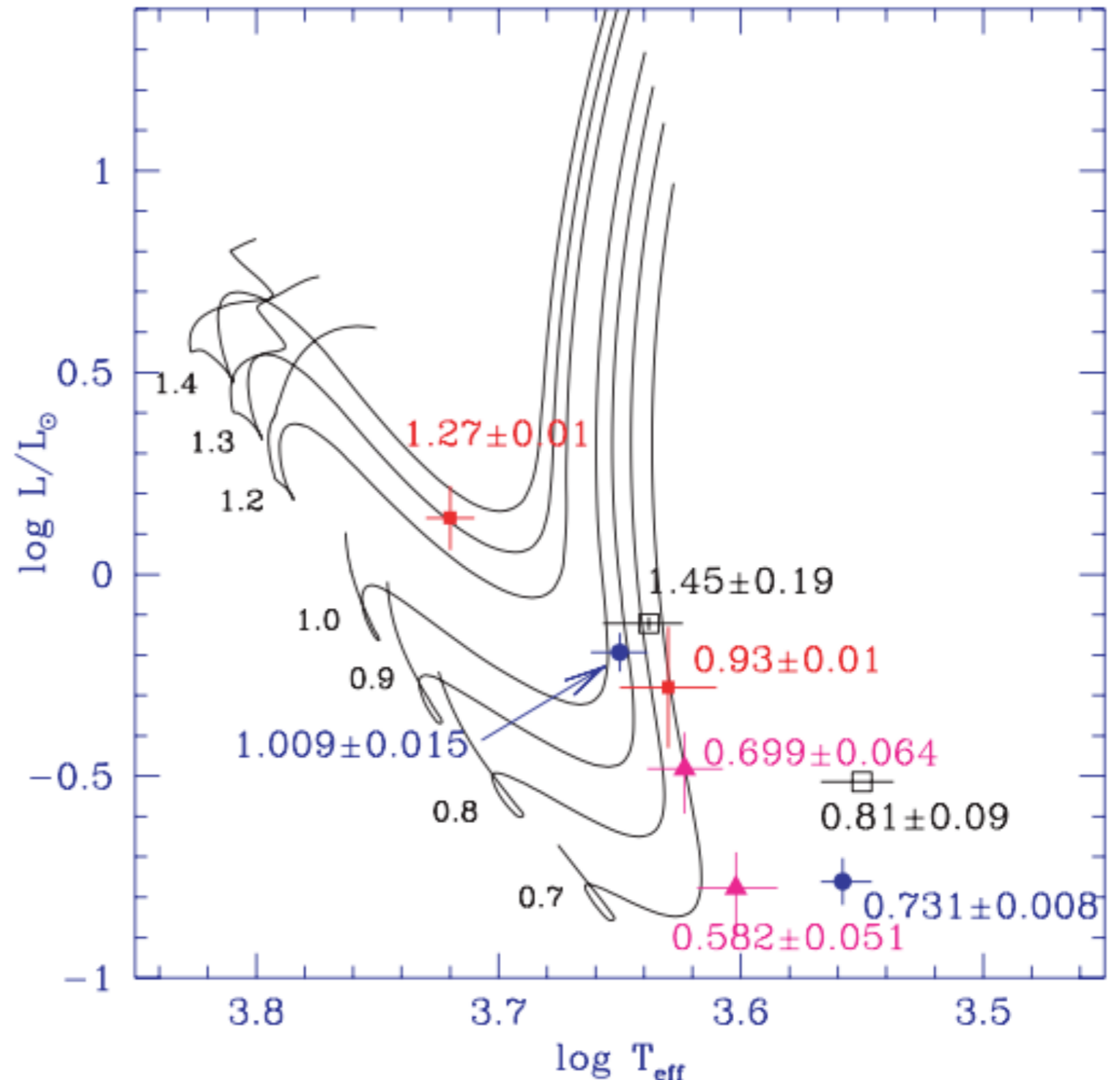
use of 2-3D RHD simulations of convection

- Partial attempt to improve knowledge of convection efficiency: 2–3D radiative-hydrodynamical (RHD) simulations of stellar surface convection (e.g. Freytag, Ludwig & Steffen 1996; Stein & Nordlund 1998; Asplund et al. 2000; Ludwig, Allard & Hauschildt 2002).
- The idea is: approximate the gradient in the whole convective region with the value of mixing length which provides the same average gradient found by simulations → *This does not say anything about the “true” gradient along the structure, but allows computation of “calibrated MLT” models.*



MLT— α^{2D} stellar models: problems remain

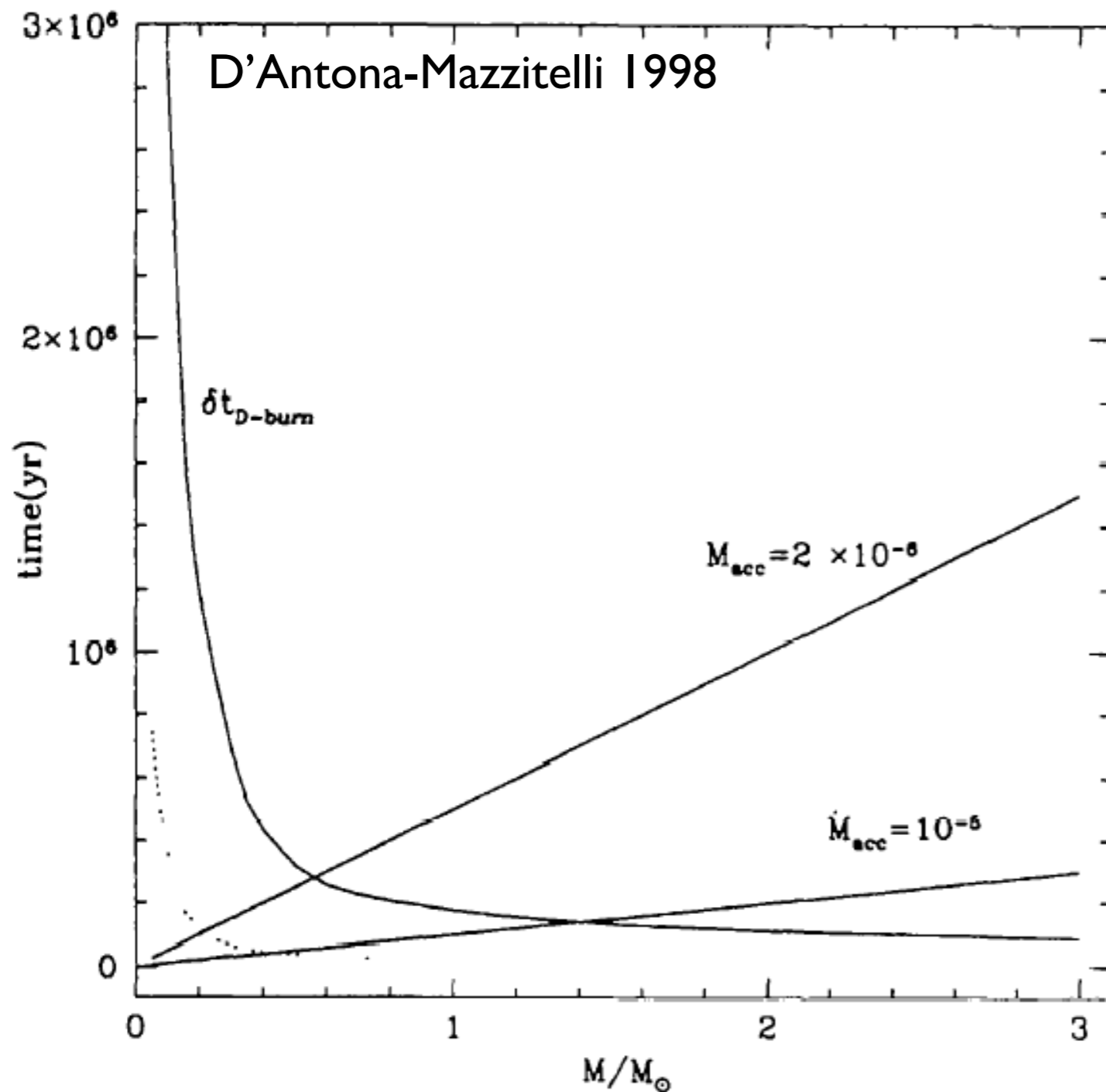
- (Montalbán+2006)
- Results similar to those of FST models
- BUT two problems are shown to be left:
 - 1) —Fit requires lower T_{eff} 's for some binary data
 - 2) — Too strong Lithium preMS depletion!
- Do we need modification of models in some non standard way? (See at the end)



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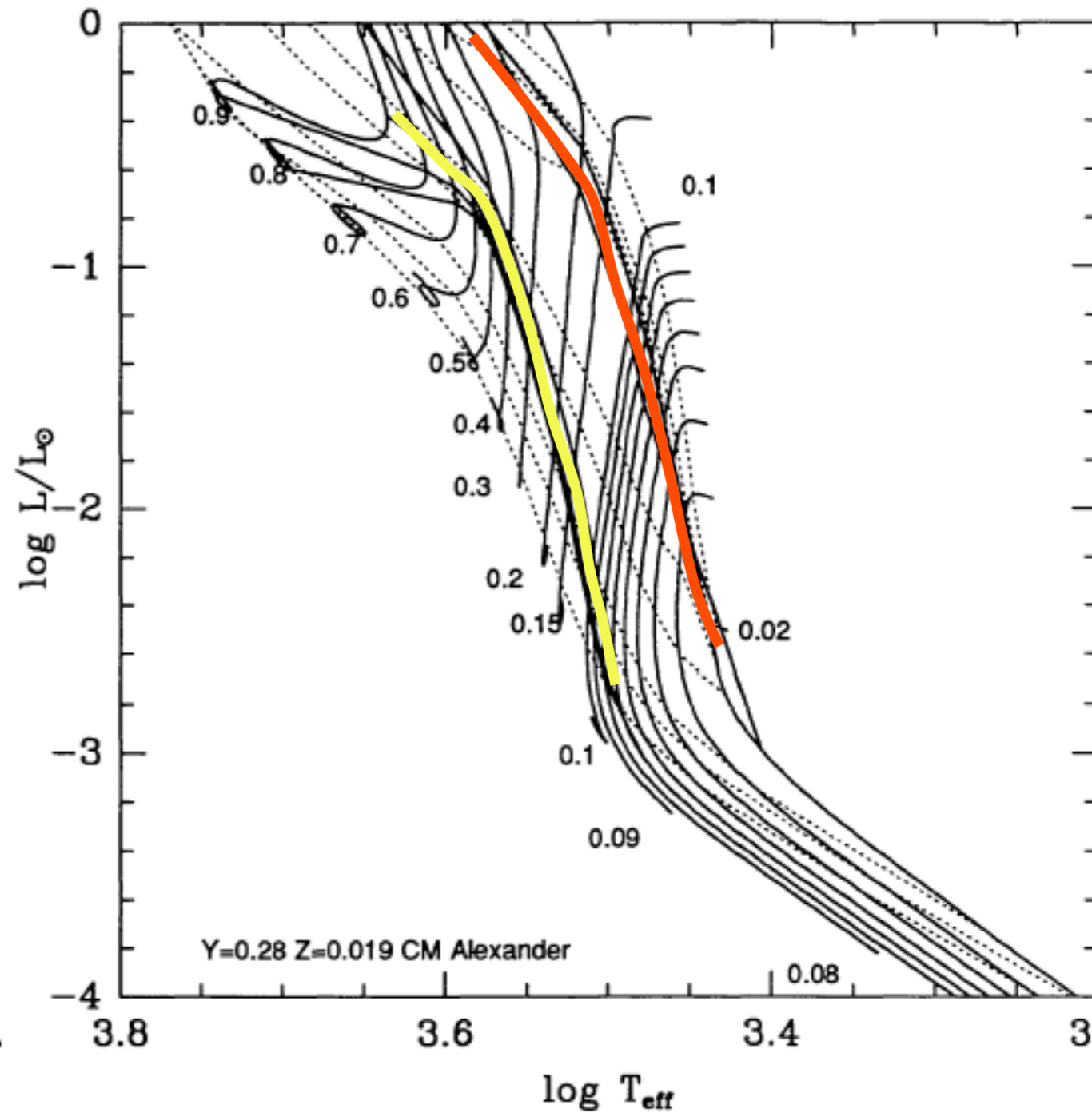
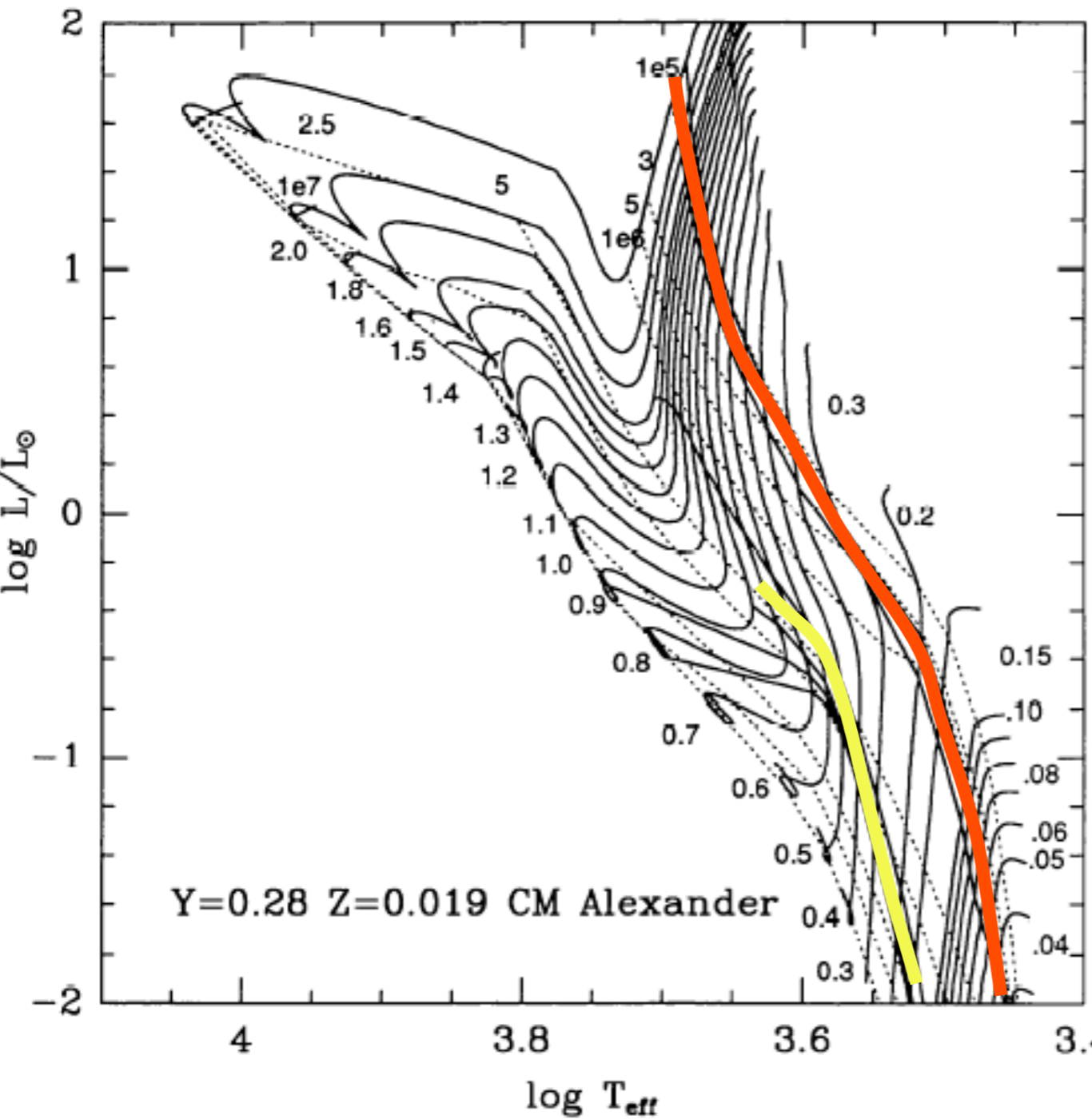
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Do we see D-burning in the T-Tauri stage of the lowest masses?

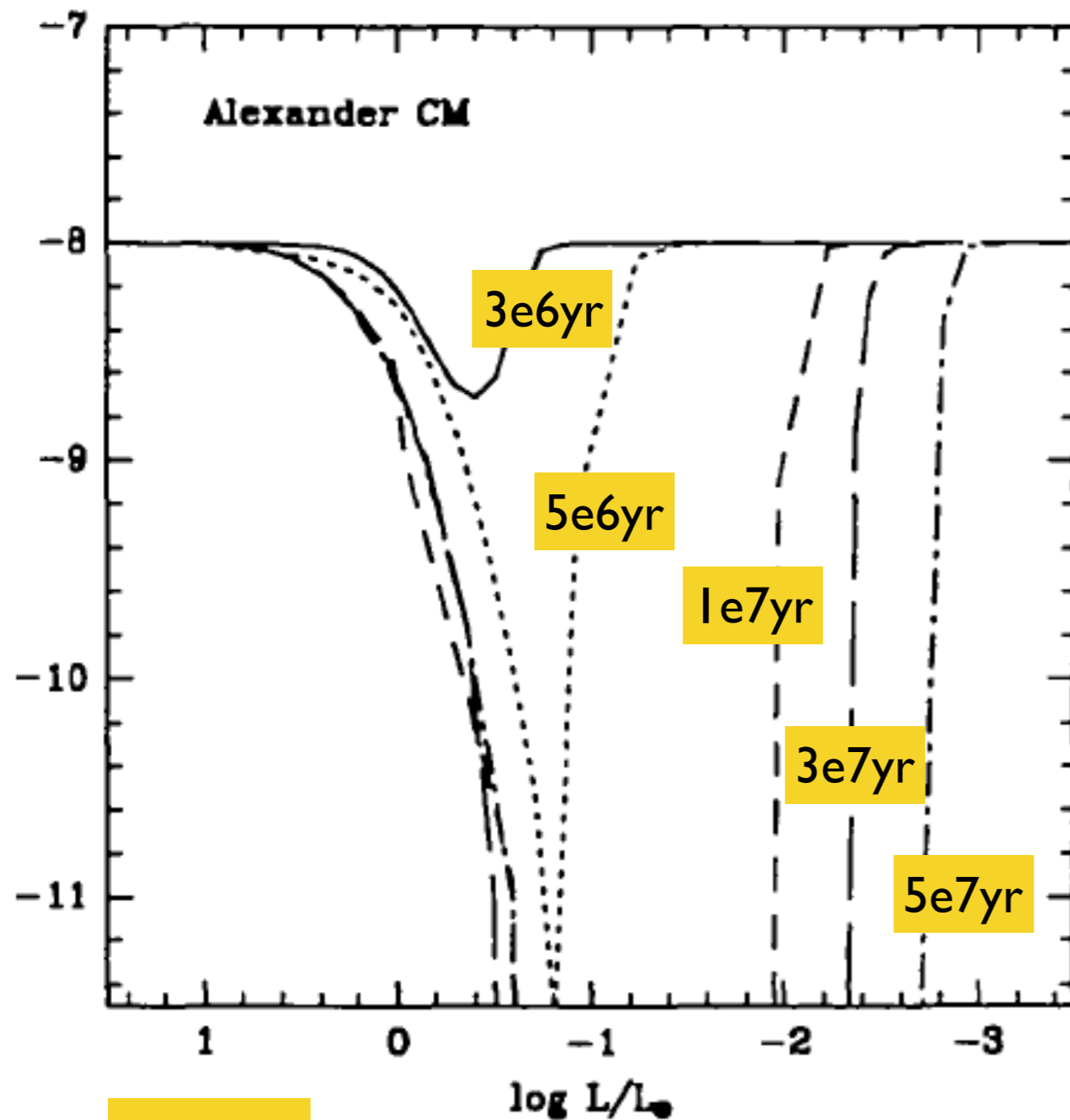


- The accretion timescale and the Deuterium burning timescale become comparable below $1 M_{\odot}$ (for accretion rates of $10^{-5} M_{\odot}/\text{yr}$)
- low masses burn Deuterium in the visible phase?
- (In -some- models with disk accretion it is even possible that Lithium is burned very early during the protostellar phase)

Relevant benchmarks along preMS



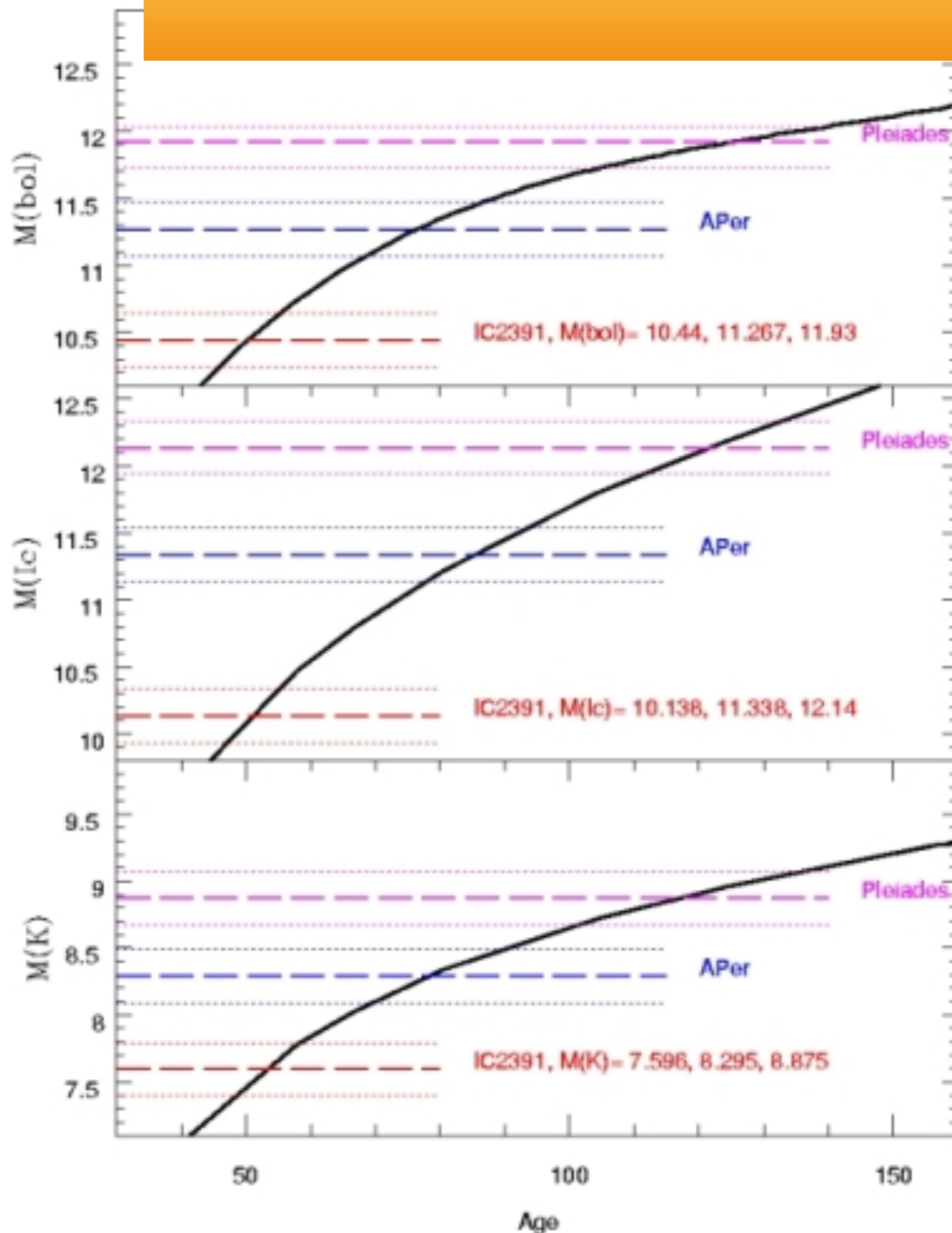
The lithium “chasm” and the LDB



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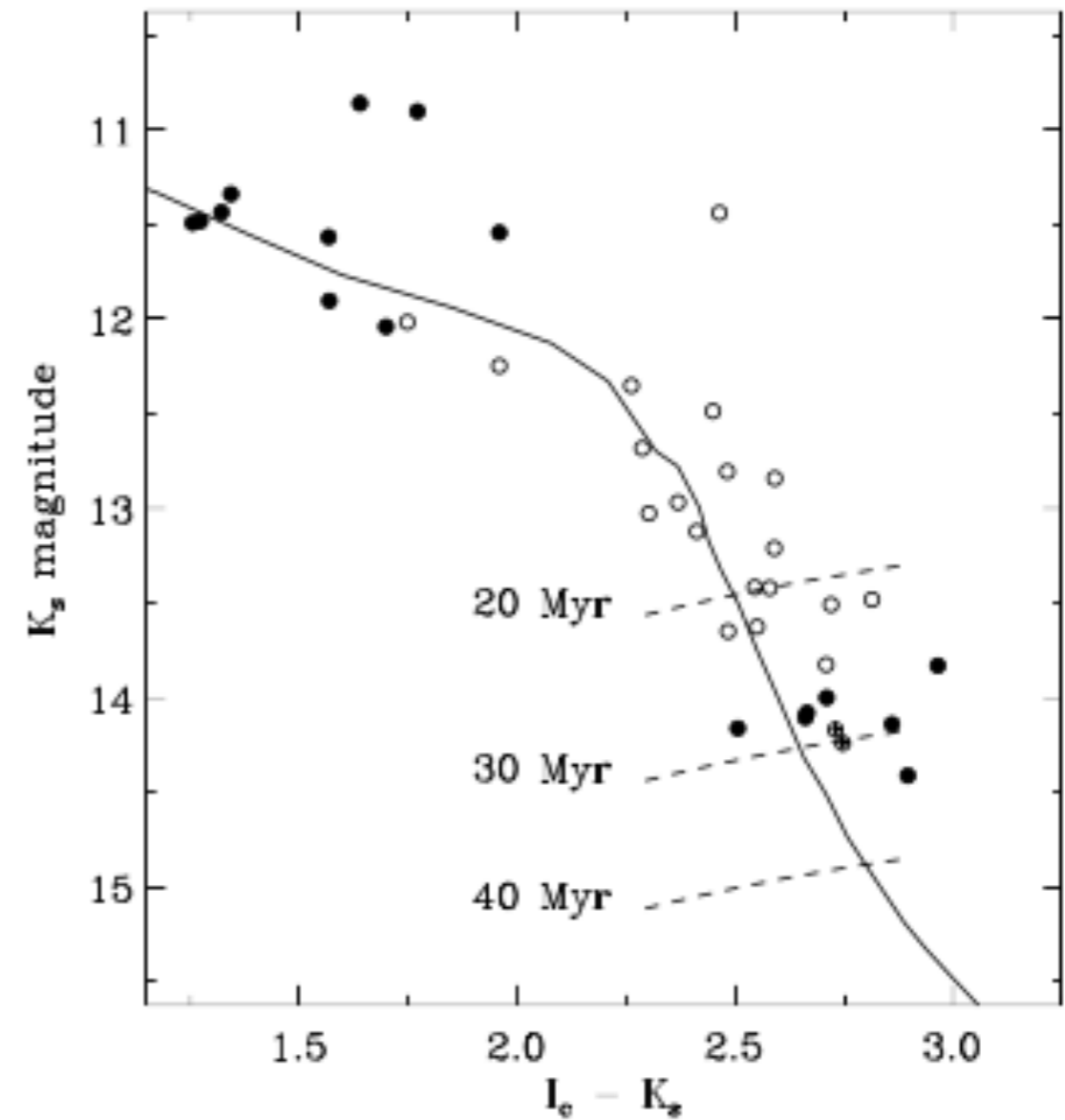
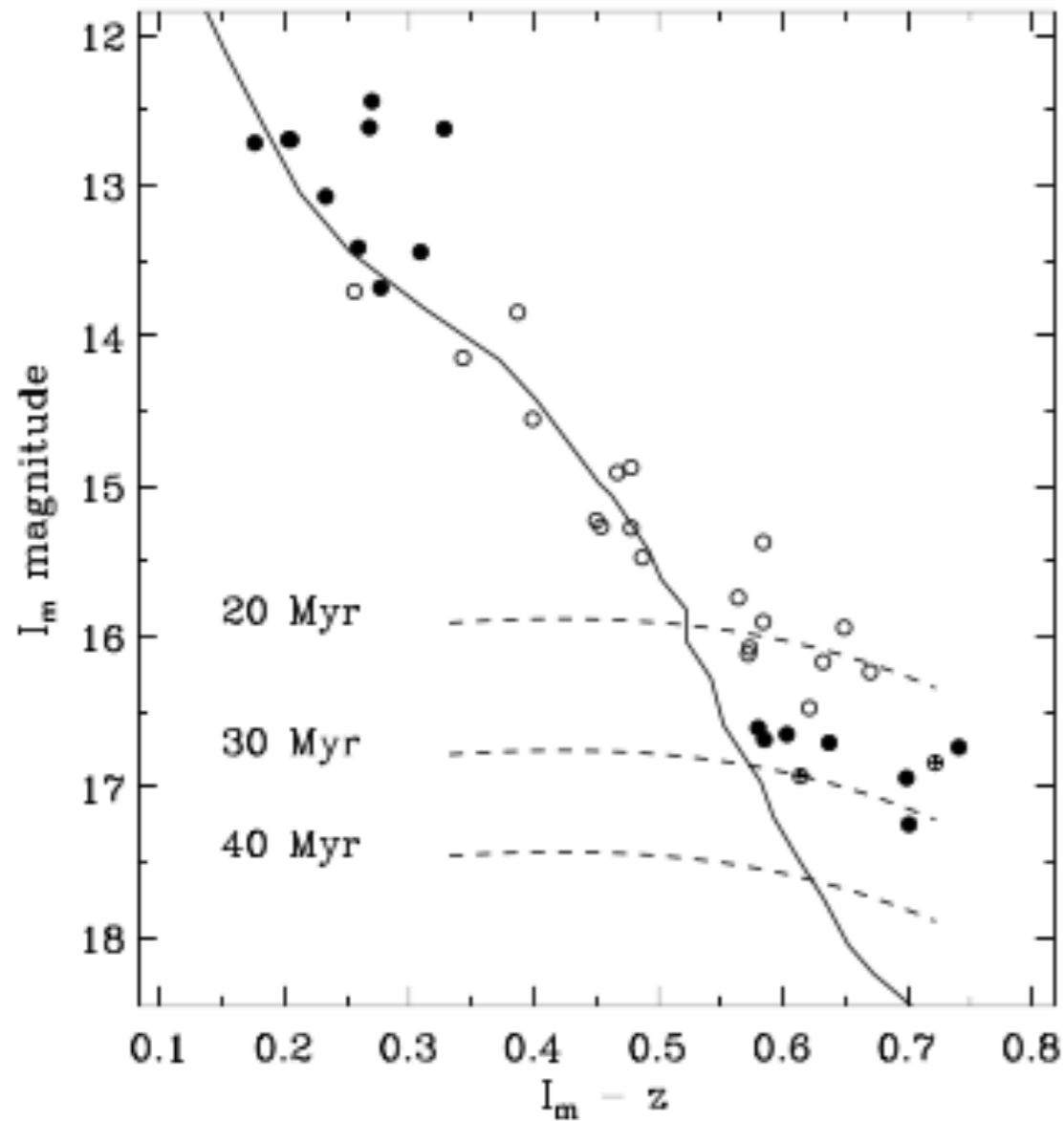
- Lithium burning T ($\sim 2.5e6K$) is reached later for smaller masses: in clusters this produces a region where Lithium is reduced or absent.
- The right boundary of the “chasm” can be used as an independent way to date clusters
- The left boundary (the “standard” pre-MS Lithium depletion) poses strong problems to models, discussed later on

The lithium “chasm” and the LDB



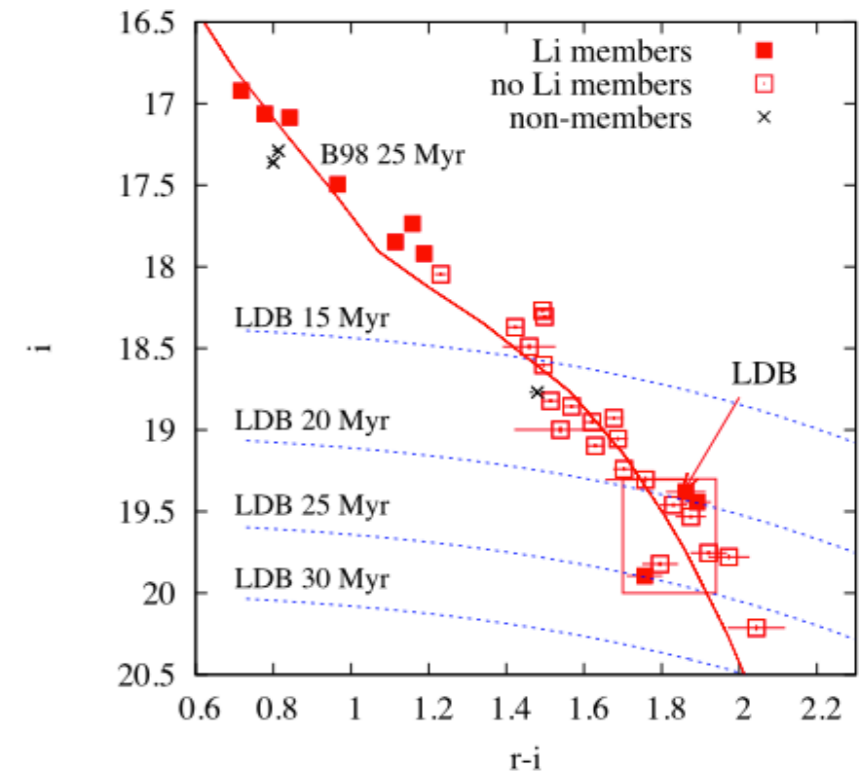
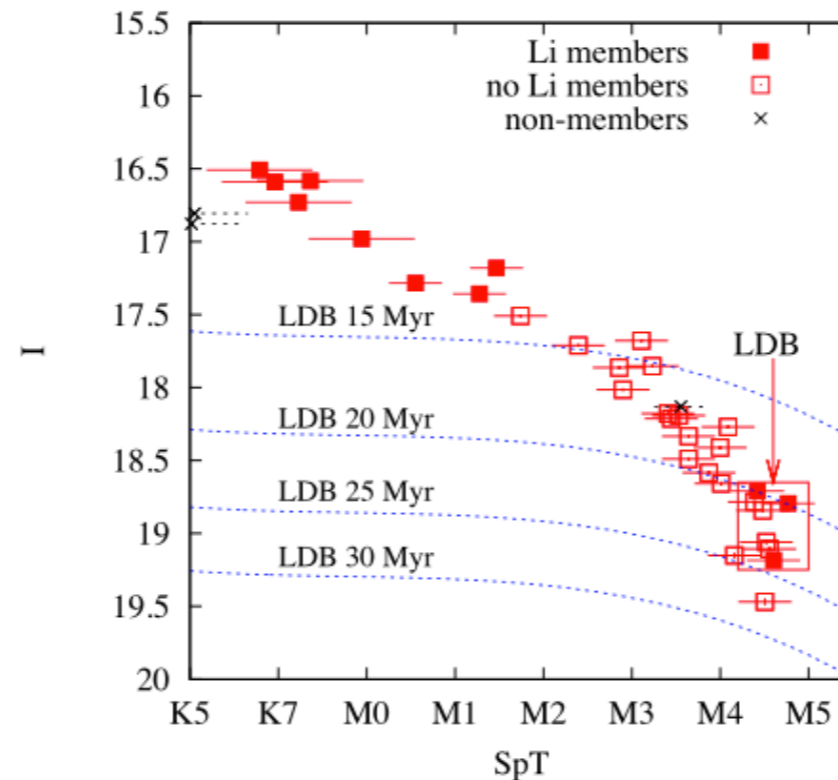
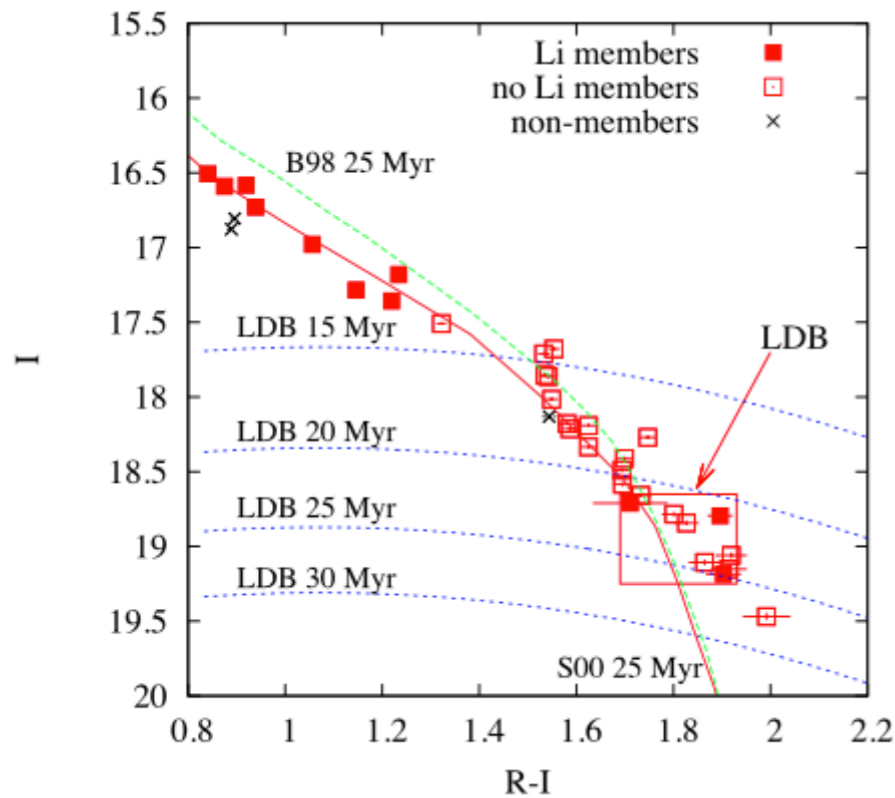
- Lithium burning T ($\sim 2.5 \times 10^6 \text{K}$) is reached later for smaller masses: in clusters this produces a region where Lithium is reduced or absent.
- The right boundary (Lithium Depletion Boundary, LDB) of the “chasm” can be used as an independent way to date clusters
- *Recent attempts to determine the uncertainty in the LDB — see Jeffries 2013, Tognelli+2015*

The lithium “chasm” and the LDB



- Manzi, Randich, deWit & Palla 2008 - LDB for the cluster IC 4665
- Age determination $27.7_{-3.5}^{+4.2} \pm 1.1 \pm 2$ Myr.

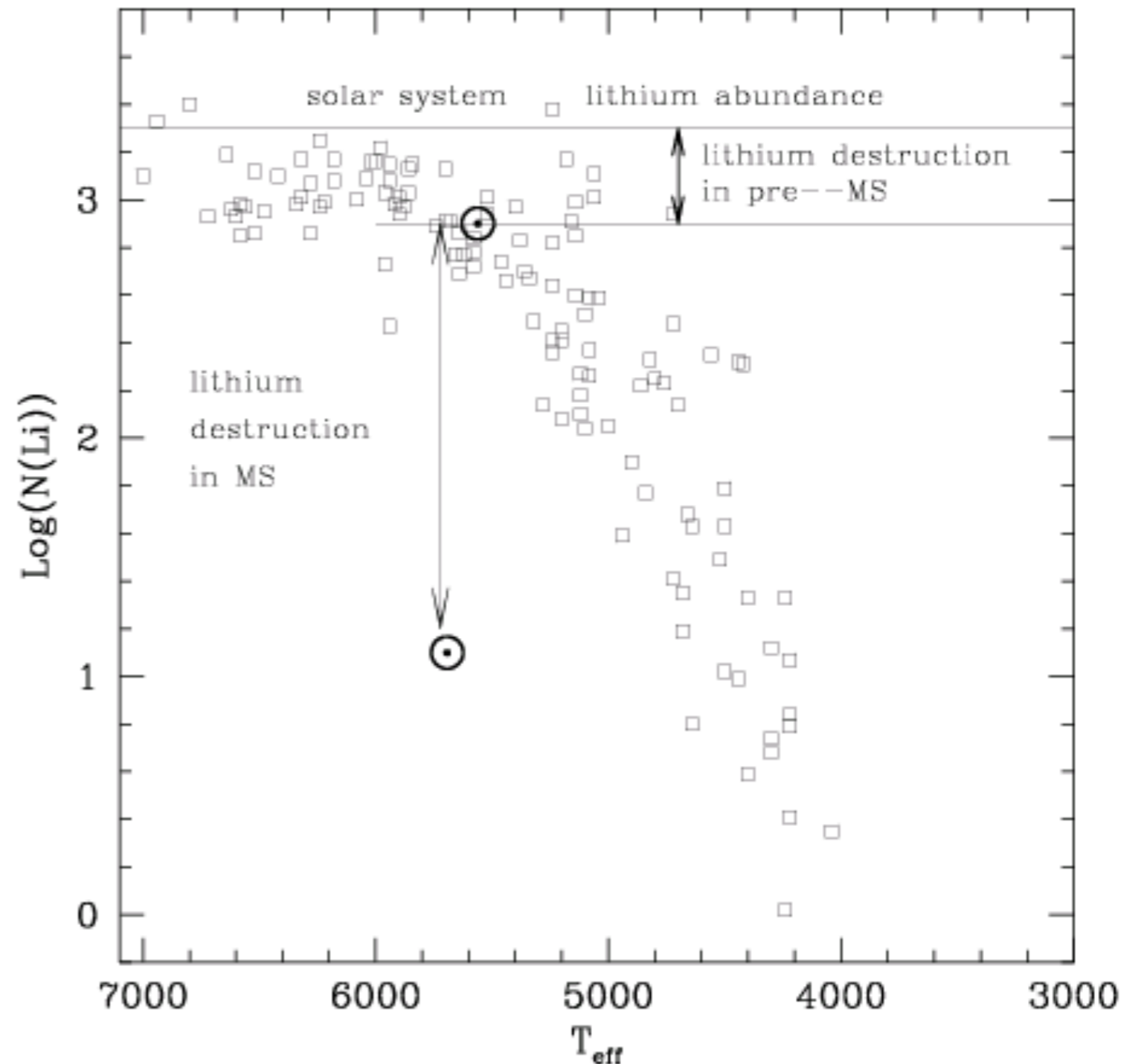
The lithium “chasm” and the LDB



- Jeffries+2013 determination of age of NGC 1960 from LBD (22 ± 4 Myr) using semi empirical isochrones transformations.
- *Age from the LBD consistent with turnoff age for isochrones including moderate overshooting — larger indetermination in the turnoff age than in LDB*

the lithium problem in time

- Pre-MS Li-depletion can be inferred by the Lithium abundance of solar mass stars in open clusters
- This depends on the cluster age, showing that the solar present abundance results from “long term” depletion mechanisms
- Long literature from the sixties
- Recent models compatible with open clusters data only for not very efficient convection (small α) or solar initial metallicity at the lowest value



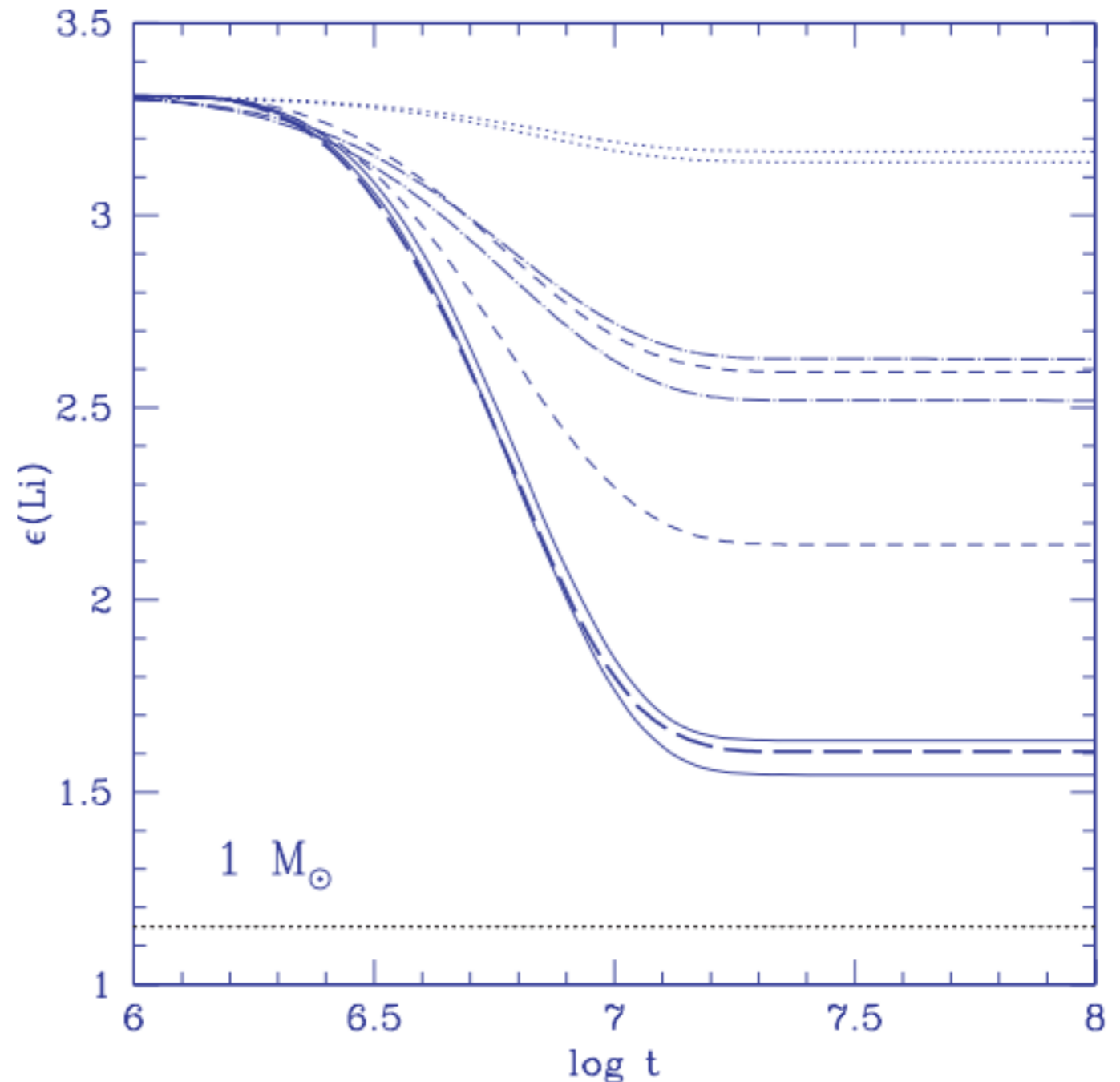
MLT— α^{2D} stellar models: the lithium problem!

The rate of Li burning is extremely sensitive to temperature ($\propto T^{20}$ — Bildsten et al. 1997)

small changes in the T boundary of the convection zone in the pre-MS may have large effects on the magnitude of Li depletion predicted

(Montalbán+2006)

2) — Too strong Lithium preMS depletion! —> this means that not even simulations describe correctly the temperature gradient in the solar envelope?

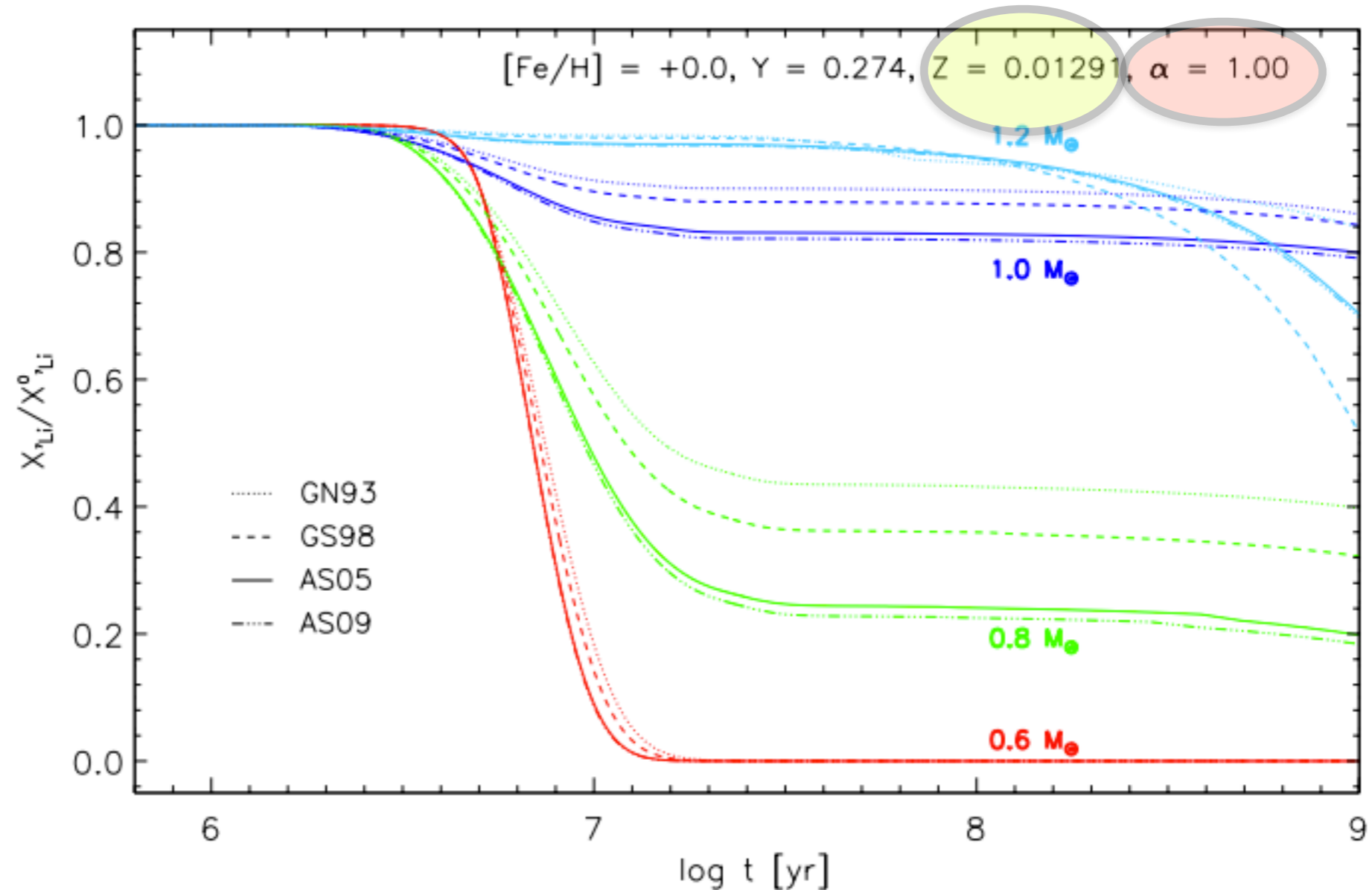


other recent models: the lithium problem!

Warning:

the problem is less severe if updated solar abundances are used (Asplund+2005, 2009), as smaller opacities imply smaller convective extension and reduced Li —burning

Nevertheless, Tognelli+2012 can not fit the young open clusters Li-Teff data using the same mixing length necessary to fit the main sequence

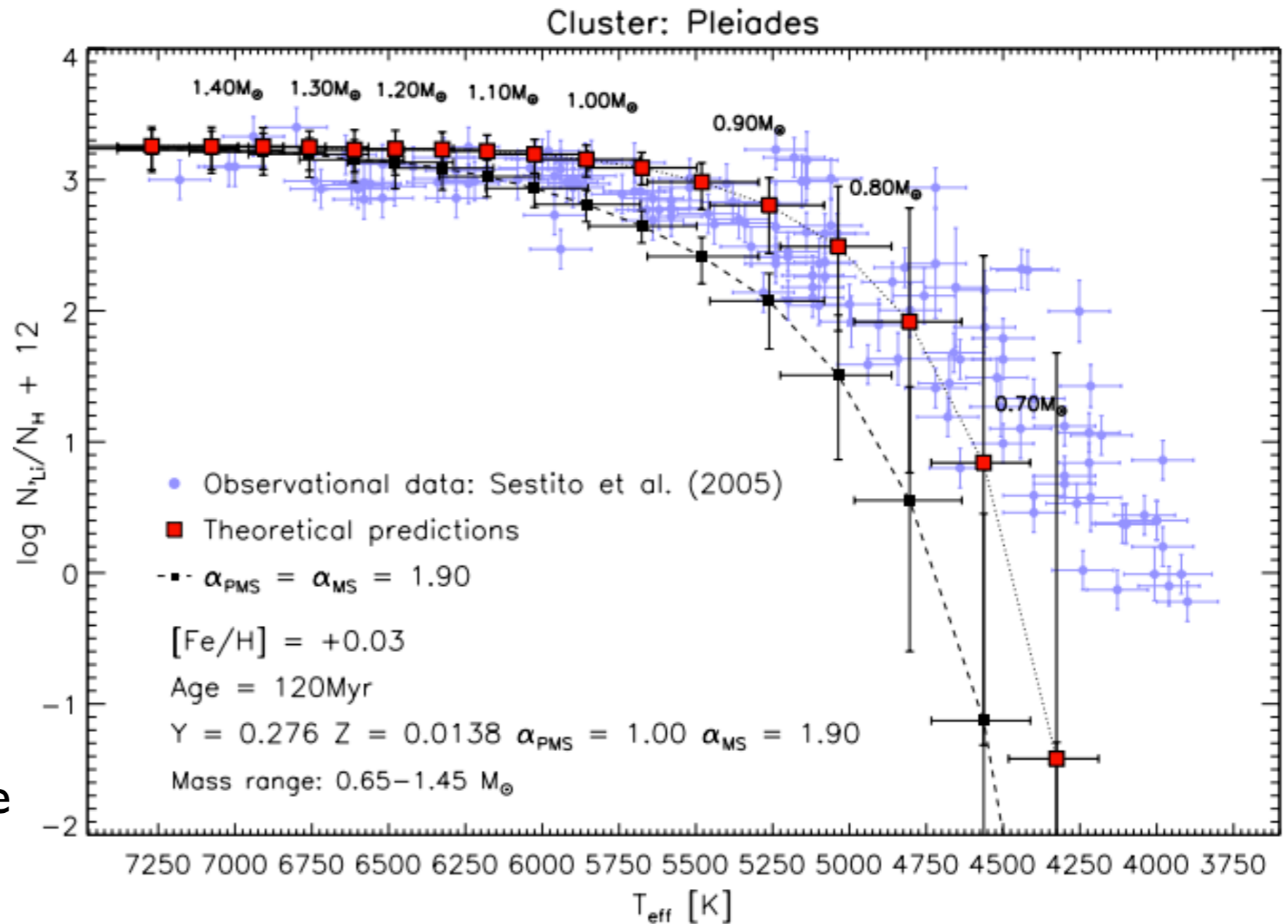


other recent models: the lithium problem!

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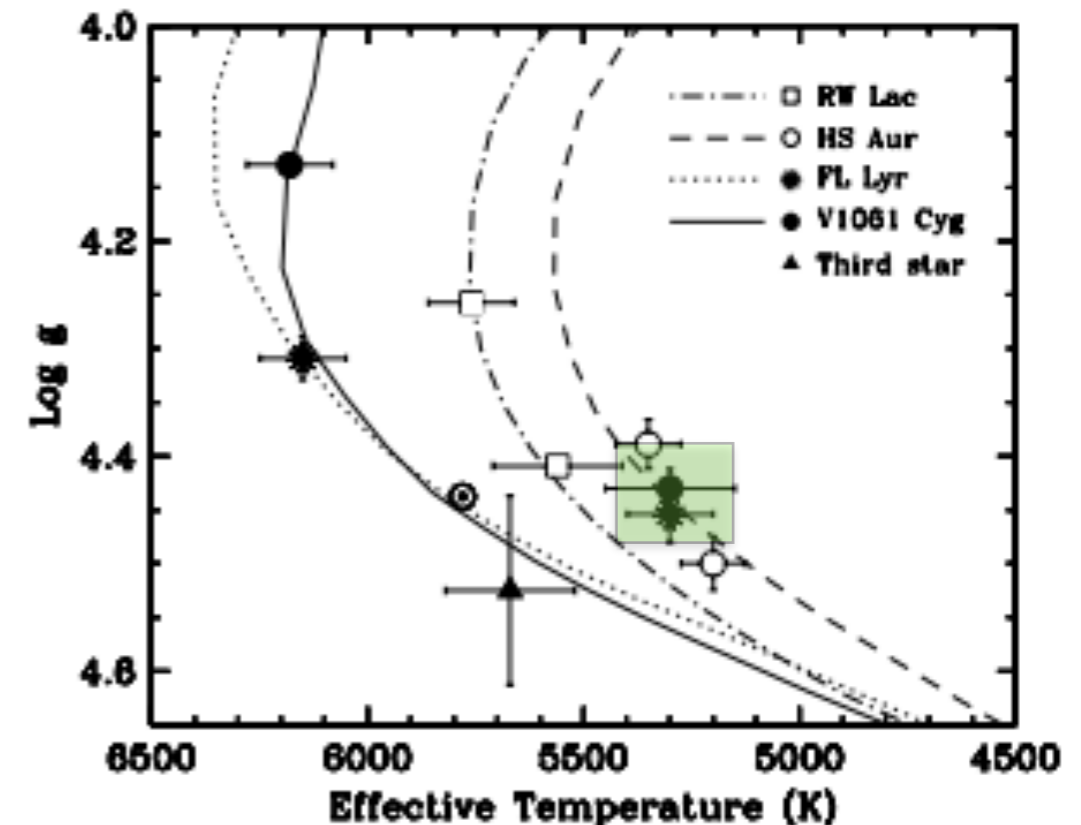
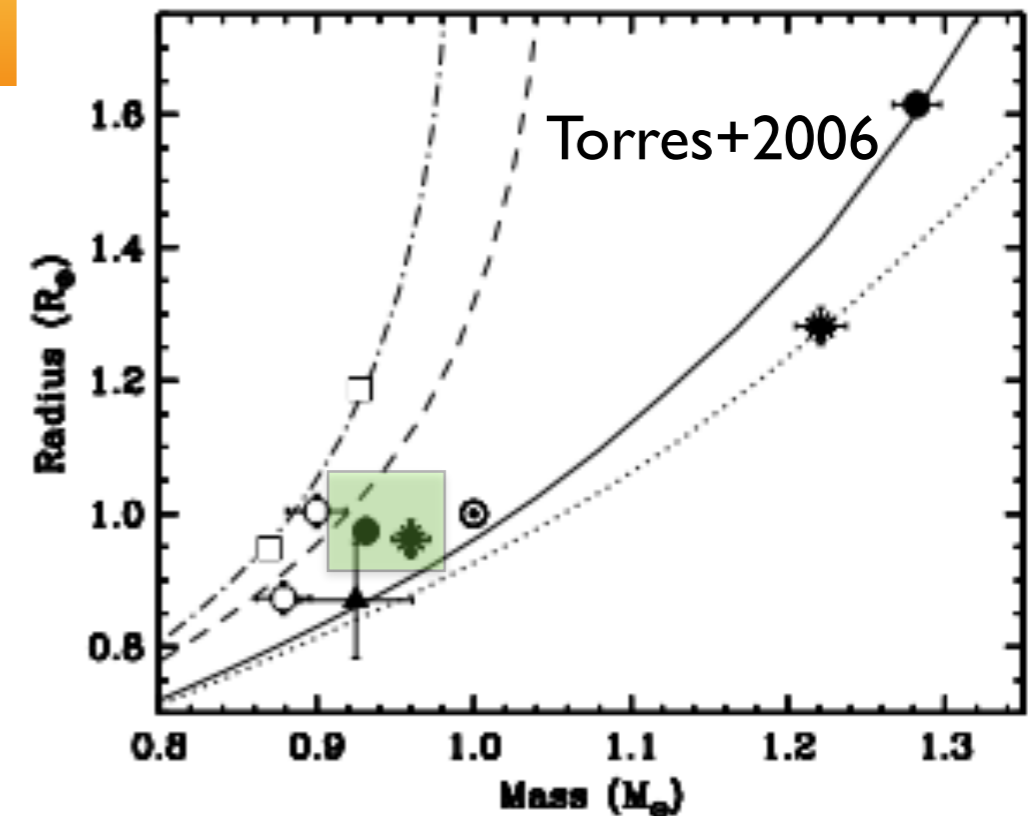
the problem is less severe if updated solar abundances are used (Asplund+2005, 2009), as smaller opacities imply smaller convective extension and reduced Li —burning

Nevertheless, Tognelli+2012 can not fit the young open clusters Li-Teff data using the same mixing length necessary to fit the main sequence



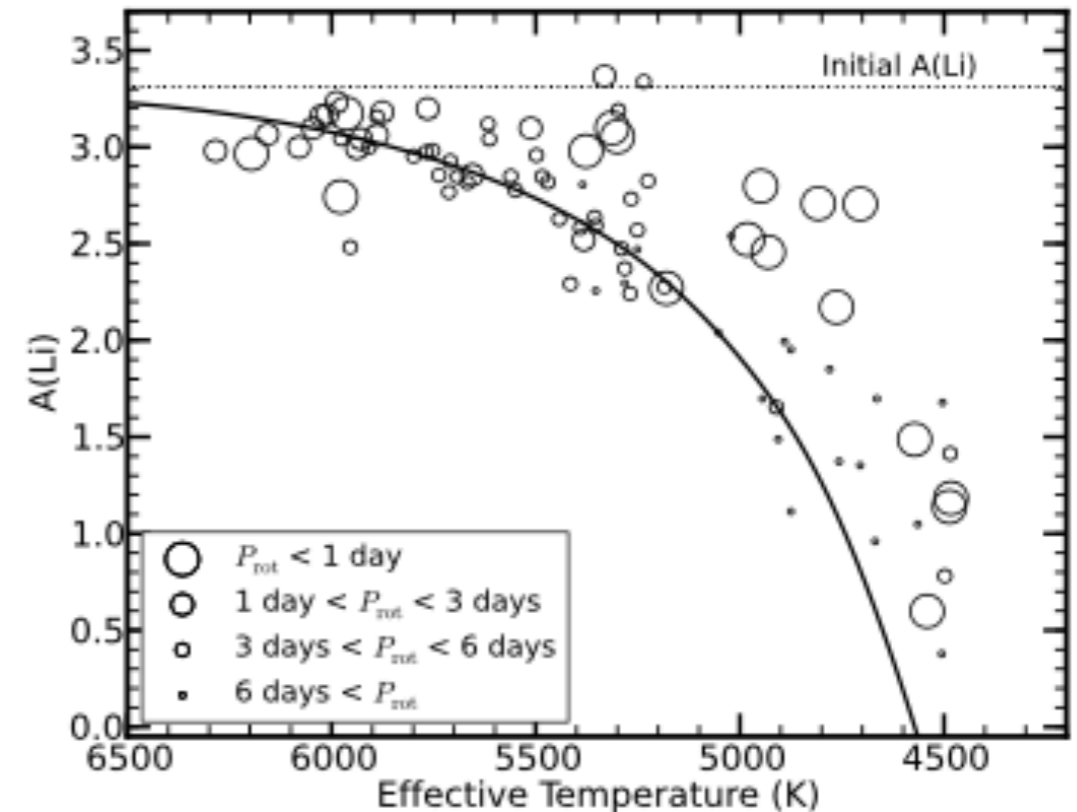
lower efficiency of convection due to magnetic field?

- Torres+2006 attributes the larger radii to stellar activity (rotation) in eclipsing binaries
- Pre-MS stars are generally active anyway
- Ventura+1998 and D'Antona+ 2000 show that the presence of a magnetic field may inhibit convection in pre-MS and provide larger radii at $\sim 1 M_{\odot}$, and models consistent with scarce lithium depletion
- Chabrier+2007 reach similar conclusions for low mass M and brown dwarfs in eclipsing binaries
- *If inhibition of convection is an important parameter in preMS, not even at low masses we have reliable models* 😞

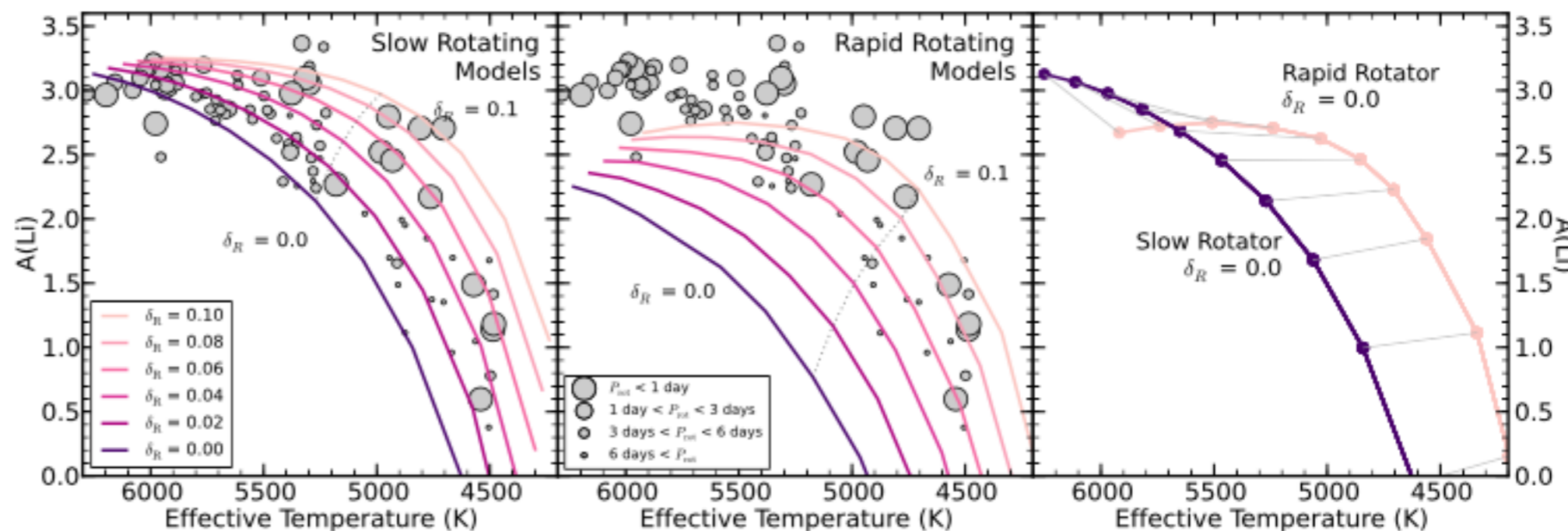


Rotation, spotting and inflated radii

- a different approach is taken by Somers & Pinsonneault 2014
- Rotating stars have inflated radii \rightarrow lower Li-depletion
- This explains the correlation Li-rotation and the spread in the Pleiades abundances



- (but note: rotation with no radius inflation increases Li-depletion- Somers&Pinsonneault 2015)



Summary

- The hydrostatic contraction models are still of some value for age - mass determinations at “reasonable” ages (above 10^6 yr?) — but disk accretion must be better modeled
- the role of Deuterium burning may still be the key to understand the observed location of T Tauri stars
- Still the uncertainties in the mass - age determinations from models are large. At small masses ($<0.4M_{\text{sun}}$?) it is mostly necessary to determine good atmospheric BCs, but problems at larger masses are still due to the convection modeling. Radii of preMS stars are larger than computed taking into account only standard physics (no magnetic field)
- Burning of light elements is a powerful signature of hydrostatic evolution