Early evolution of low mass stars and brown dwarfs :

News from the theoretical front

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I) Recent advancements in modelling

II) Early stages of evolution of LMS and Brown dwarfs

a) Observed spread in the HRD for young clusters
b) Lithium depletion

Conclusion

The golden age for “standard evolutionary models” (no accretion history, no rotation, no magnetic field) may have come to an end.

I) Recent advancement in modelling

Most recent/interesting idea: **effect of rotation/magnetic fields** on the inner structure of low mass stars

☛ Observations:

- Link between **magnetic activity** and **abnormally large radius** of low mass stars in eclipsing binaries *(Ribas et al. 2008)*

- Similar effect on R in **single magnetically active** late type stars *(Morales et al. 2008, Bochanski et al 2010)*

☛ Theoretical interpretation:

(i) Fast rotation and/or strong magnetic fields suppress or reduce the efficiency of interior convection *(Mullan & MacDonald 2001; Chabrier et al. 2007)*

(ii) Magnetic fields produce cool surface spots *(Chabrier et al. 2007)*

$\Rightarrow$ reduced heat flux $\Rightarrow$ **larger radii and cooler T_{eff}**

Phenomenological approach:

(1) Reduced convection efficiency can be **mimicked** by decreasing the mixing length parameter α
$\alpha = l_{mix}/H_P$ (=2 for the Sun) *CGB07*

(2) Effect of spots:

- fraction of stellar surface covered by spots $\beta = S_{spots}/S_\star$

-Total flux of the star F:

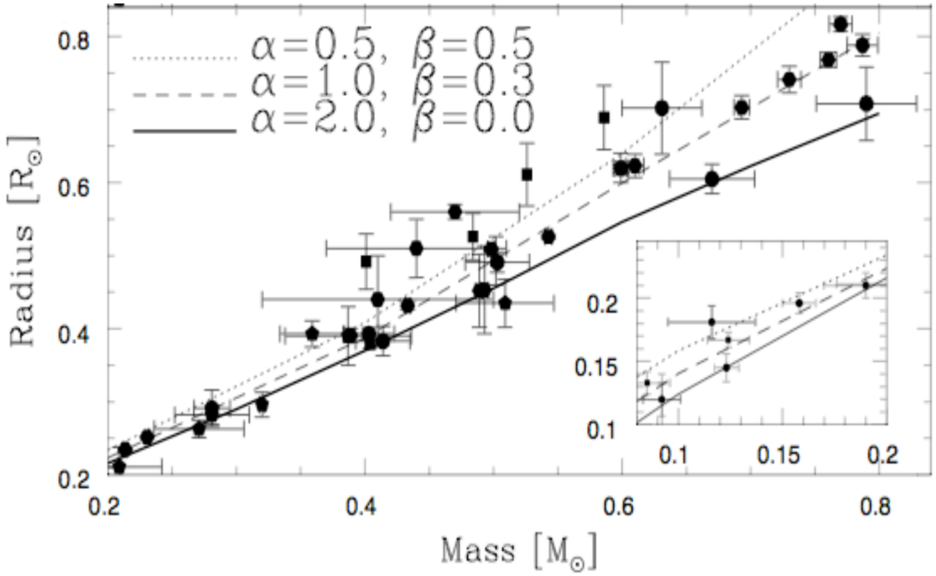
$$F = (1-\beta)\, F_\star + F_{spots}$$

where

$F_\star = \sigma T^4_{eff\star}$ (flux of spot-free star)

F_{spots}= total flux emerging from spots

Cool spots coverage $\Rightarrow T_{eff} < T_{eff\star}$



Chabrier, Gallardo, Baraffe 2007

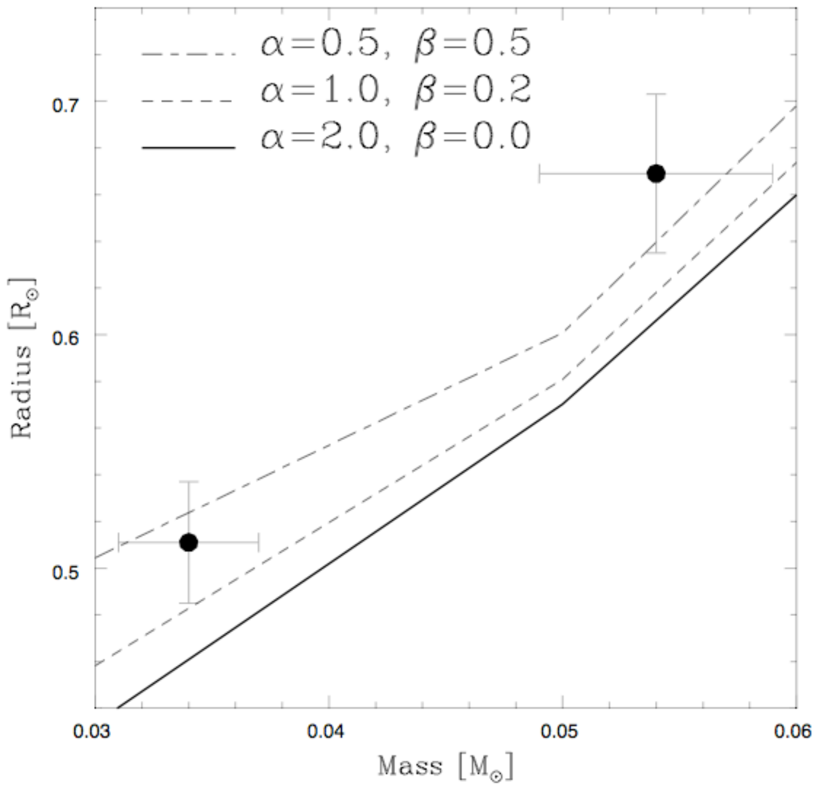
☛ Can also explain the Teff reversal of the eclipsing BD binary discovered by Stassun et al. 2006 *(Chabrier et al. 2007; MacDonald & Mullan 2009)*

☛ Chabrier et al. 2007 predict a spot coverage of 20%-50%

➜ large spot coverage required for the primary to reproduce high-resolution spectroscopy *(Mohanty et al. 2010)*

➜ Spot coverage of ~ 35% provides an overall agreement between models and observations for several EBs *(Morales et al. 2010)*

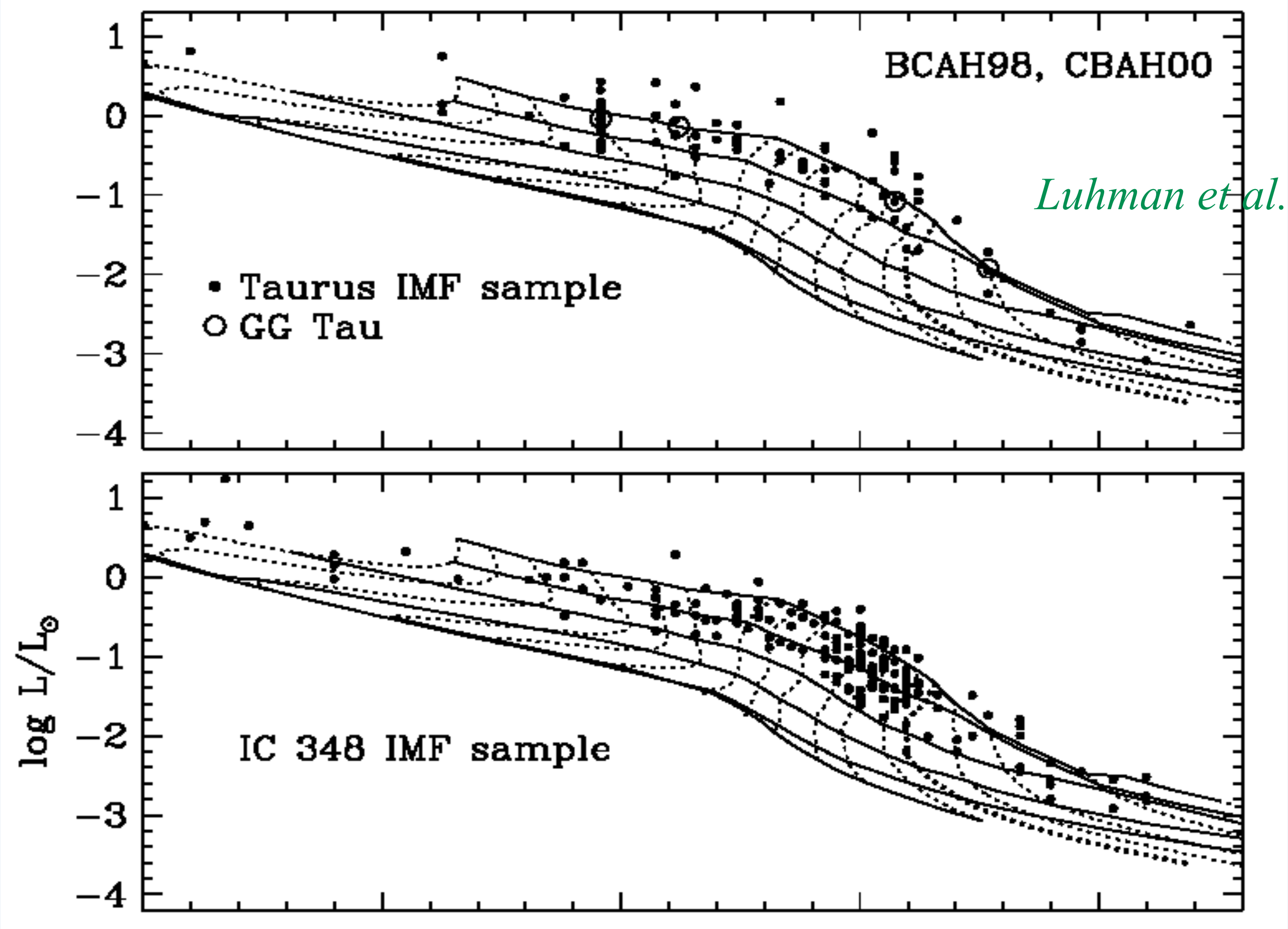
- **The future:**
  Development of 3D MHD simulations required to explore these effects *(e.g Browning 2008)*



Chabrier et al. 2007

Early stages of evolution of LMS/Brown dwarfs

a) Spread in the HRD observed in young clusters (~ 1-10Myr)



What is the explanation for this spread?

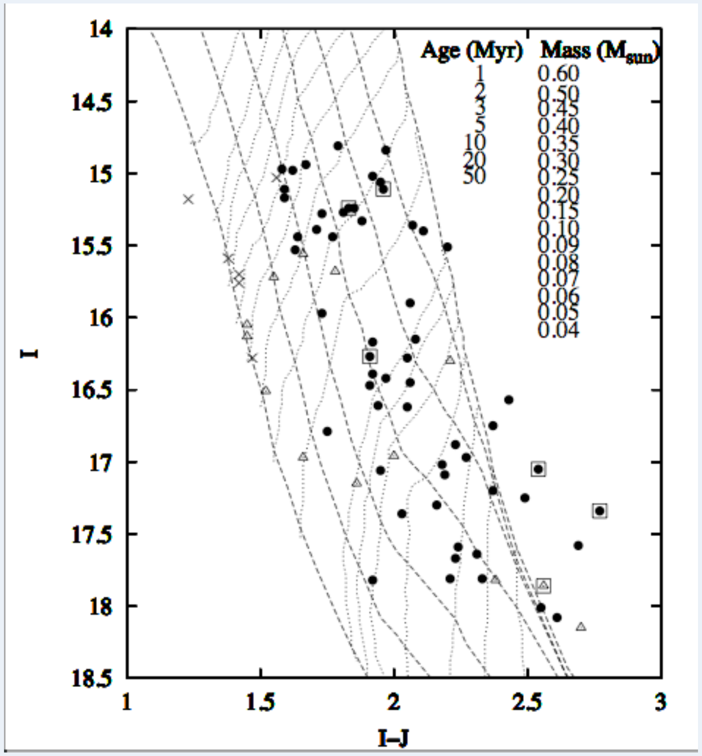
☛ Usually interpreted as an age spread:

Idea of slow star formation (quasi-static contraction of protostellar cores)

Depletion of lithium used as an argument in favor of an age spread (Palla et al. 2005)

Abundance of lithium in a few low mass stars members of clusters of mean age a few Myr (σ orionis, ONC, ...) suggest an older age for these objects (> 10 Myr).

σ ori cluster ~ 5 Myr



- lithium *(expected at this age)*

Δ no lithium

Kenyon et al. 2005

- Interpretation by an age spread due to slow star formation is strongly debated and **against** our current understanding of star formation *(dynamical picture with supersonic turbulence)*

(Hartmann 2001; Ballesteros-Paredes & Hartmann 2007; Hennebelle & Chabrier 2009,2010)

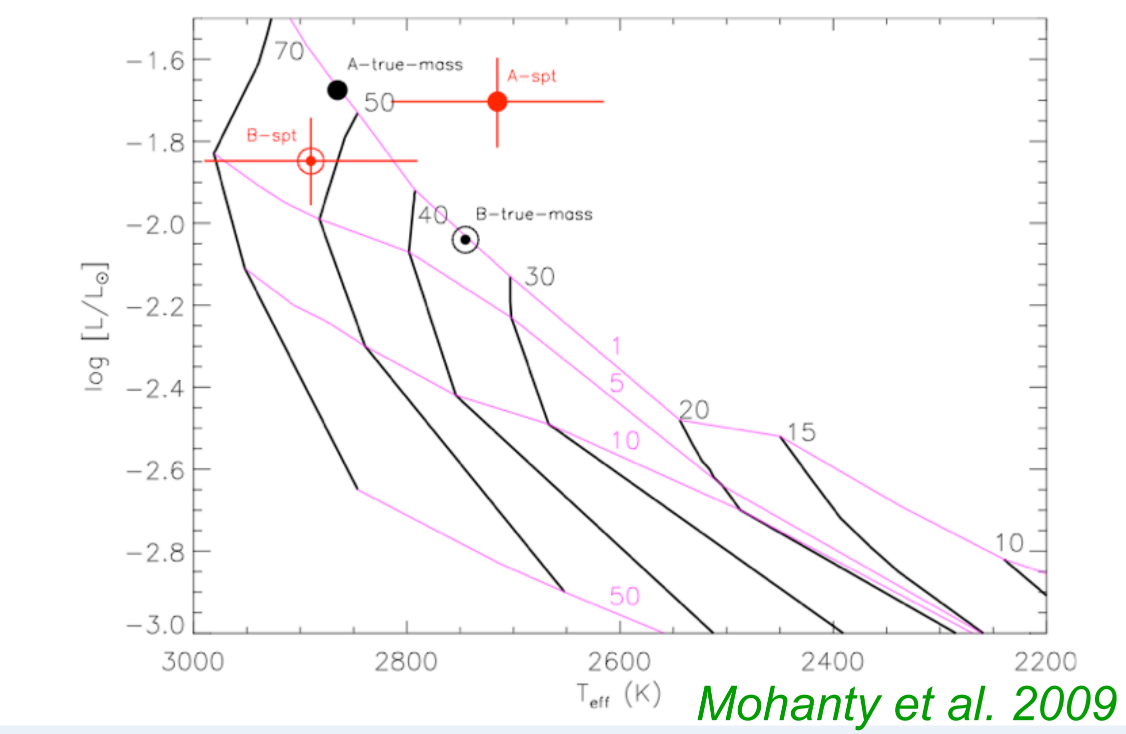
➙ Effect of magnetic fields?

Structure of the **most active young** objects affected by **spots/convection inhibition**

⇒ larger R and **cooler Teff** for given L

⇒ shift location in HRD and object would look younger

e.g the Eclipsing Binary BD2MASS 0535-0546



Mohanty et al. 2009

Evidence in **young <u>single</u> active objects?**

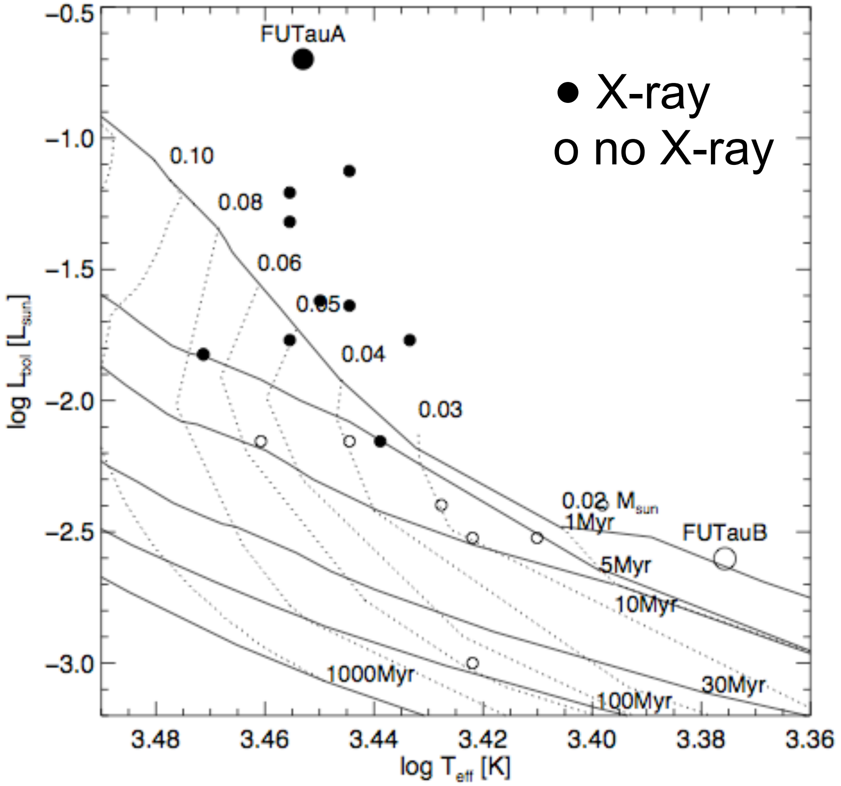


Figure 4. HR diagram for VLM objects in Taurus including BDs from Grosso et al. (2007) and the FU Tau binary on pre-main sequence models from Baraffe et al. (1998) and Chabrier et al. (2000). X-ray detections are shown as filled circles, non-detections are open circles.

Stelzer et al. 2010

➙Accretion effects at early stages of evolution?

Accretion history can affect the position in HRD even after a few Myr evolution *(Baraffe et al 2009)*

Short episods of high accretion ($M_{dot} \geq 10^{-4}\ M_{\odot}yr^{-1}$) due to disk gravitational/thermal instability *(Vorobyov & Basu 2005; Zhu et al. 2008)*

⇒ strongly affect the internal structure of the accreting proto-object: **smaller radius and less luminous than non-accreting countepart**

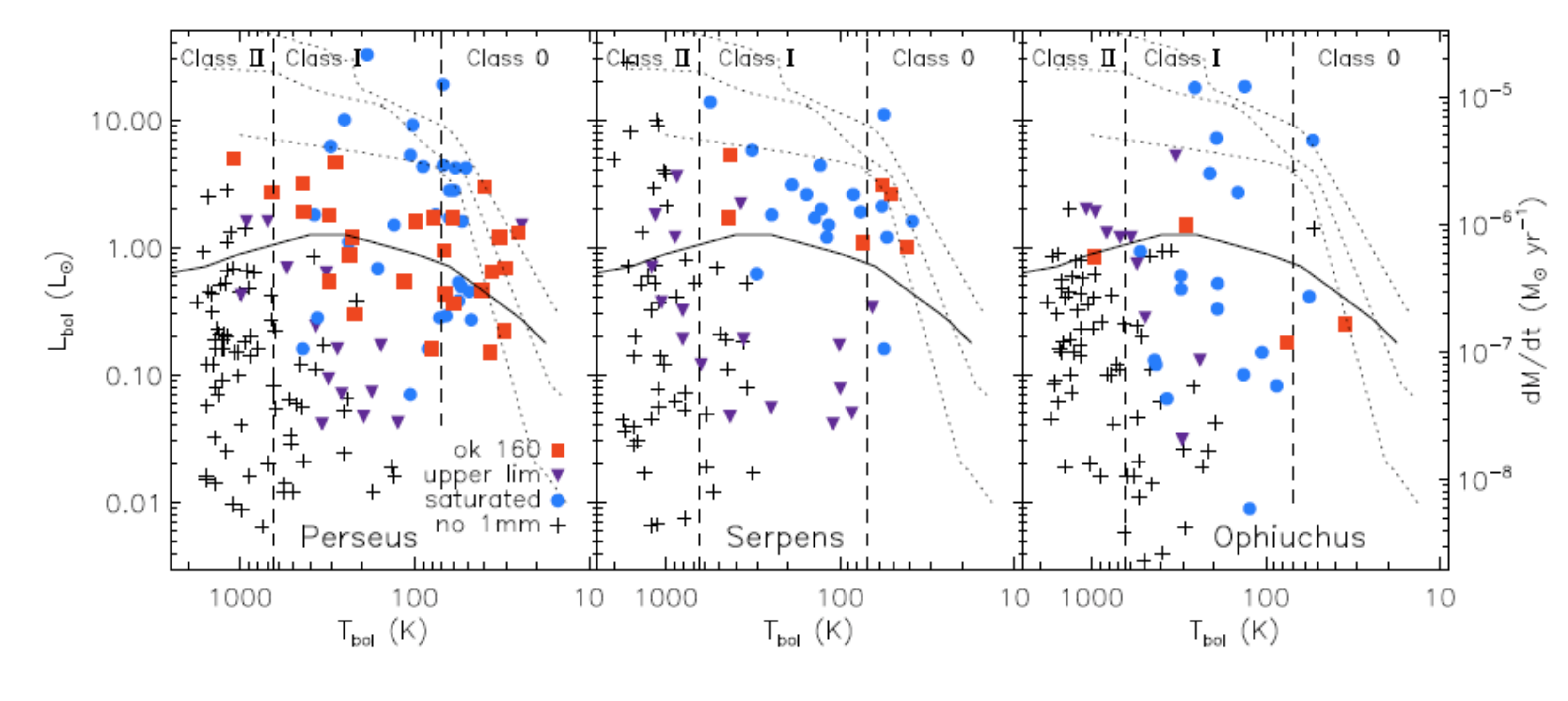
Observational evidences for episodic accretion:

- FU Ori objects provide evidences for short episodes of rapid accretion ($M_{dot} >> 10^{-5}\ M_{\odot} yr^{-1}$)

- Recent observations of embedded protostars in clouds *(Enoch et al. 2009; Evans et al. 2009)*

  ---> large population of low luminosity class I sources
  ---> small fraction of very luminous sources

Enoch et al. 2009



→ Suggest that long quiescent phases of accretion ($M_{dot} \leq 10^{-6}$ $M_{\odot}yr^{-1}$) interrupted by episods of high accretion ($M_{dot} \geq 10^{-5}$ $M_{\odot}yr^{-1}$) of short duration can explain: - large population of low luminosity class I
- small fraction of very luminous sources

→ Data rule out drastic changes in accretion rates from class 0 to class I

Theoretical scenarios for episodic accretion:

Several theoretical scenarios suggested to produce non-steady accretion

a) Constant infall from the envelope onto the disk and episodic accretion from disk to protostar due to:

- **Gravitational instabilities** *(Vorobyov & Basu 2005, 2006, 2009)*
- Combination of **gravitational and magnetorotational instabilities** *(Zhu, Hartmann, Gammie 2008)*

b) Spasmodic infall onto the disk (magnetically controlled) and consequently strong variation of accretion onto protostar *(Tassis & Mouschovias 2005)*

Both scenarios produce outbursts of rapid accretion onto the protostar

⇒ We adopt a burst mode based on models of gravitational instability in the accretion disk of Vorobyov & Basu (2005, 2006)

Initial masses m_{init} =1 M_{Jup} - 0.1 $M_\odot$

N_{burst} = 10-100

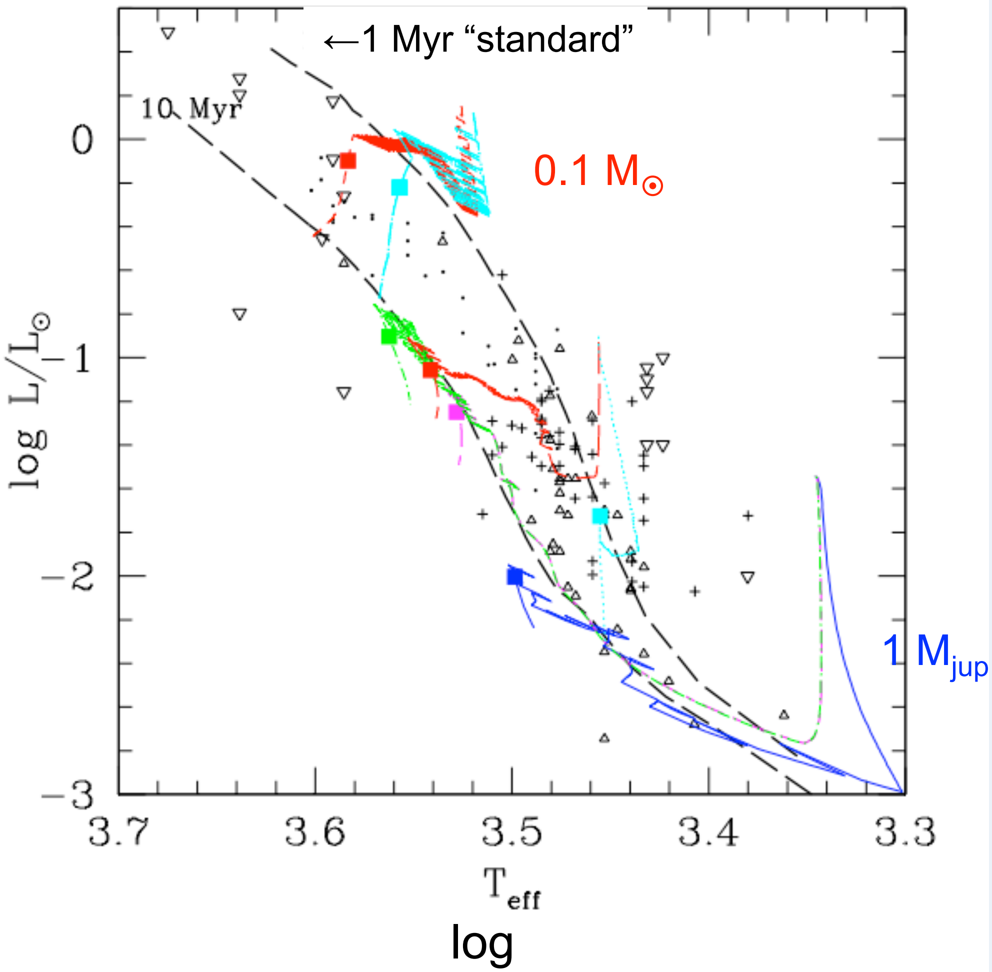
M_{dot}= 10^{-4} - 5 10^{-4} $M_\odot yr^{-1}$

Δt_{burst} = 100 yr

(Duration of burst phase ~ a few 10^5 yr)

⇒ large spread in HRD at ages of ~ Myr

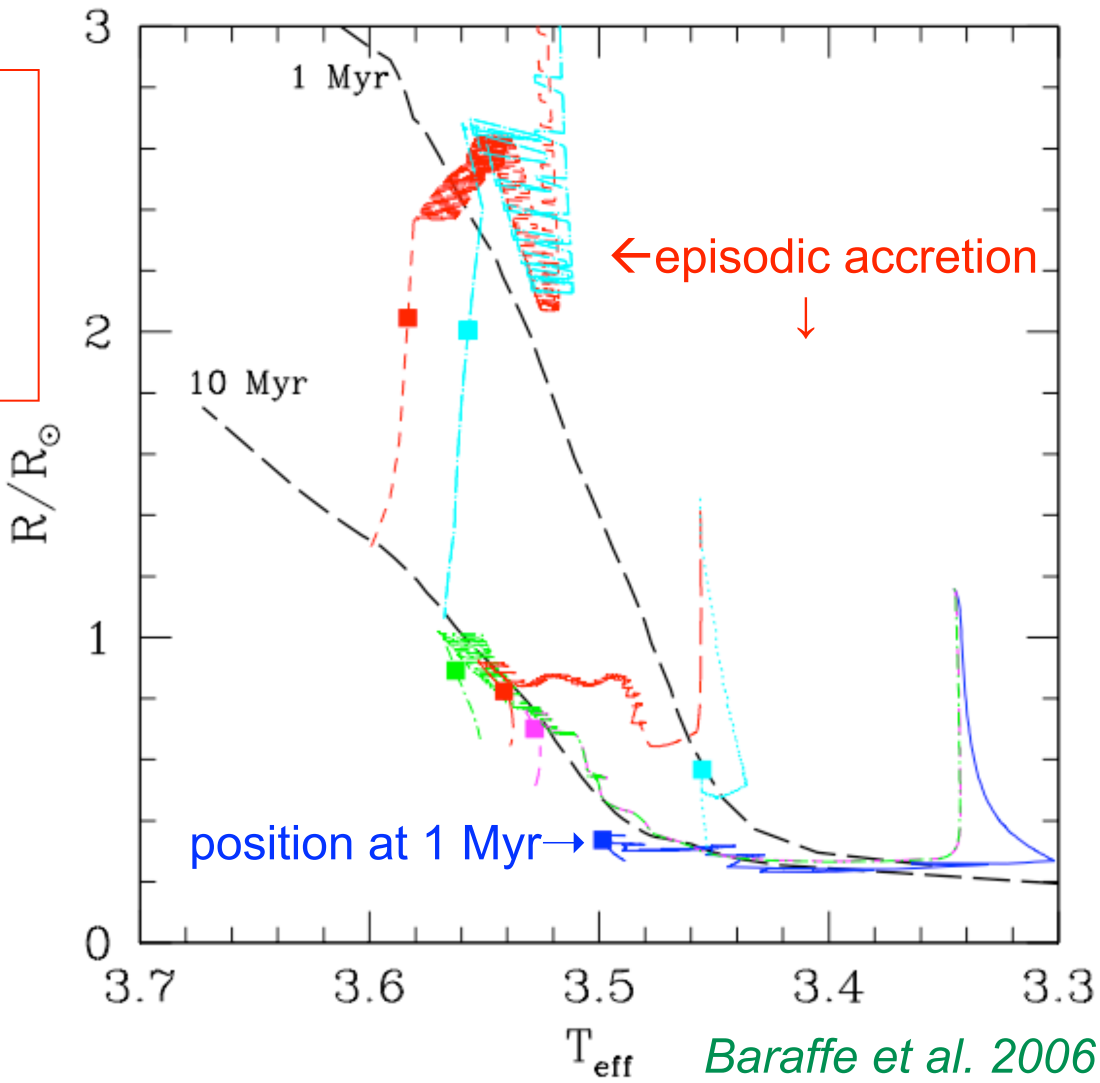
Baraffe et al. 2009



■ position at 1 Myr

⇒ **Prediction of an important spread in radius**

Jeffries 2008 suggests the existence of such a spread based on rotation periods and projected radial velocities of low mass objects in the ONC



←episodic accretion

↓

position at 1 Myr→

Baraffe et al. 2006

log

b) Lithium depletion

Several observational facts:

- Anomalous Li depletion in young cluster members of a few Myr old *(Kenyon et al. 2005; Sacco et al. 2007, 2008; Prizinsano et al. 2007)*

- Observations in IC 4665 (~ 30 Myr from isochrones or turn-off)
  Strong Li depletion in K to M-dwarfs (0.5 - 0.8 $M_\odot$)
  ⇒ ages of ~ 100 Myr ! *(Jeffries et al. 2009)*

- Large lithium scatter in clusters and associations (*da Silva et al. 2009; King et al. 2010)*

- Discrepancies between isochronal ages and LDB (Lithium depletion boundary) ages *(Yee & Jensen 2010)*

Is PMS Lithium depletion really a good age estimator for young clusters?

Possible interpretations:

•1) Rotationally-driven Li depletion

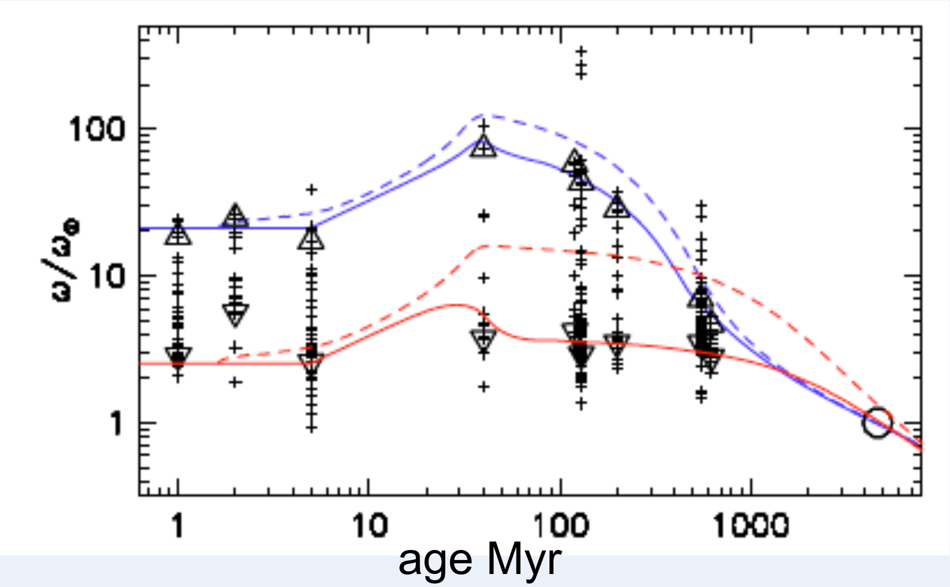
Rotationally-induced mixing due to internal differential rotation ➙ increases efficiency of Li burning Pinsonneault et al. 1989; Zahn 2007, Talon 2008, etc...

Observed relationship between rotation and Li: fast solar-type rotators in the Pleiades exhibit higher Li abundance *(Soderblom et al. 1993)*

⇒ Rotationally induced mixing appears to be more efficient in slow rotators

(Bouvier 2008)

Bouvier 2008 ➜ Core-decoupling stronger in slower rotators
(to account for the observed rotational evolution of sun-like stars from PMS to few Gyr) ➜ Slow rotators deplete more efficiently Li



☛ Idea that long-lasted disks could be the link between slow rotation on the ZAMS, Li-depletion and planet formation

Scenario can explain a Li scatter and the higher Li depletion in planet host stars (Israelian et al. 2009 *if confirmed....***)**

•2) Effect of rotation/magnetic field on the structure

(reduction of convection efficiency/spots)

Reduced heat flux ⇒ larger R and cooler T_{eff}

⇒ lower T_c and slower Li depletion at given age/mass

⇒ predict slower Li depletion and thus **older ages** based on the Lithium Depletion Boundary than using “standard models”.

Gallardo, Baraffe, Chabrier, in prep.

Scenario can explain a Li scatter (and a luminosity/T_{eff} scatter) but worsens the discrepancy between isochronal ages and LDB

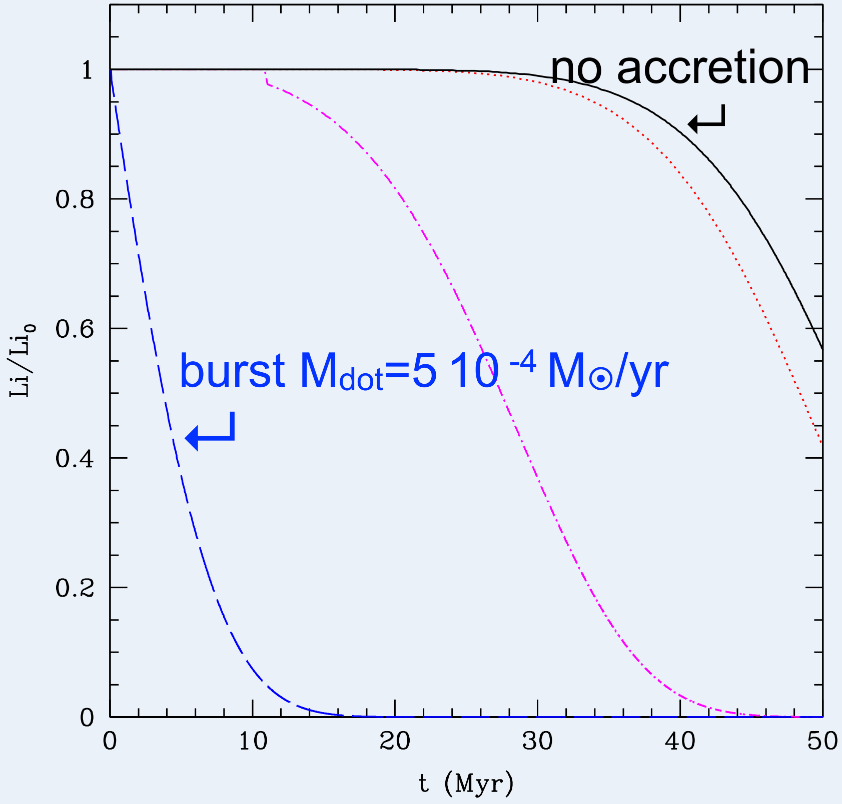
•3) Episodic accretion

Models with burst accretion are more compact ⇒ hotter T_c

⇒ faster Li depletion

(Baraffe & Chabrier 2010)

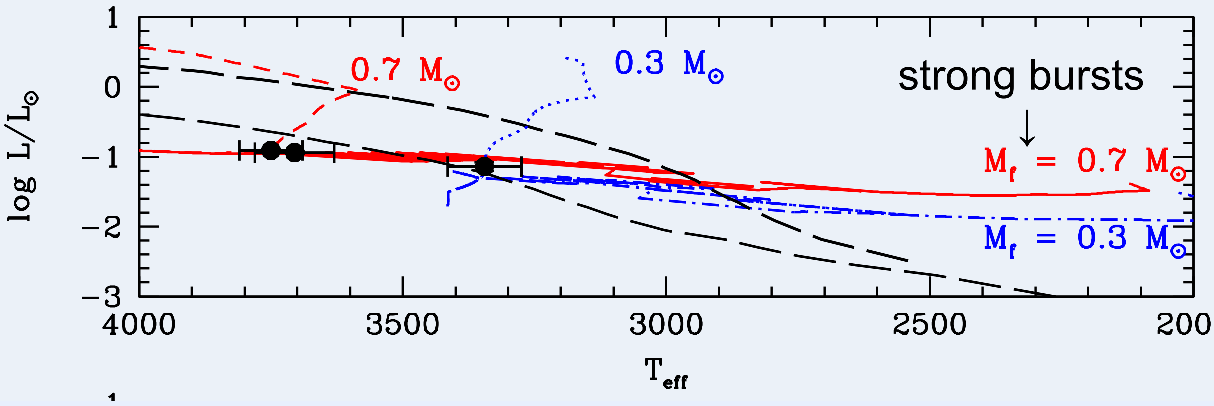
Li versus time for M_{final}=0.1 $M_\odot$



Scenario can explain a Li scatter (and a luminosity/T_{eff} scatter) + unexpected Li depleted objects in young clusters (≲ 10 Myr)

Sacco et al. 2007: 3 objects in σ Orionis (~5 Myr) with strong lithium depletion

(but with radial velocity consistent with cluster membership)



Baraffe & Chabrier 2010

- ☛ **Accreting sequences reach observed position in ~ 5 Myr**
- ☛ **Accreting sequences show strong lithium depletion**

Conclusion: the punch lines

- Increasing evidence that **rotation/magnetic field** affects the inner structure **(R,T_c)** and surface properties **(L, T_{eff})** of active stars

→ **Importance of combined observations (photometry/ spectroscopy, L_X, H_α, rotation, L_i, etc...)**

- Position in HRD may severely depend on **early accretion history** (and not only on age)

→ Inferring mass/age for young clusters (a few Myr) from non accreting models may yield wrong results

- Very limited reliability of **Li depletion** as age/cluster membership indicator

→ Re-analysis of young cluster populations since several genuine members may have been eliminated because of their high Li depletion

→ Combine with Be abundance measurement