

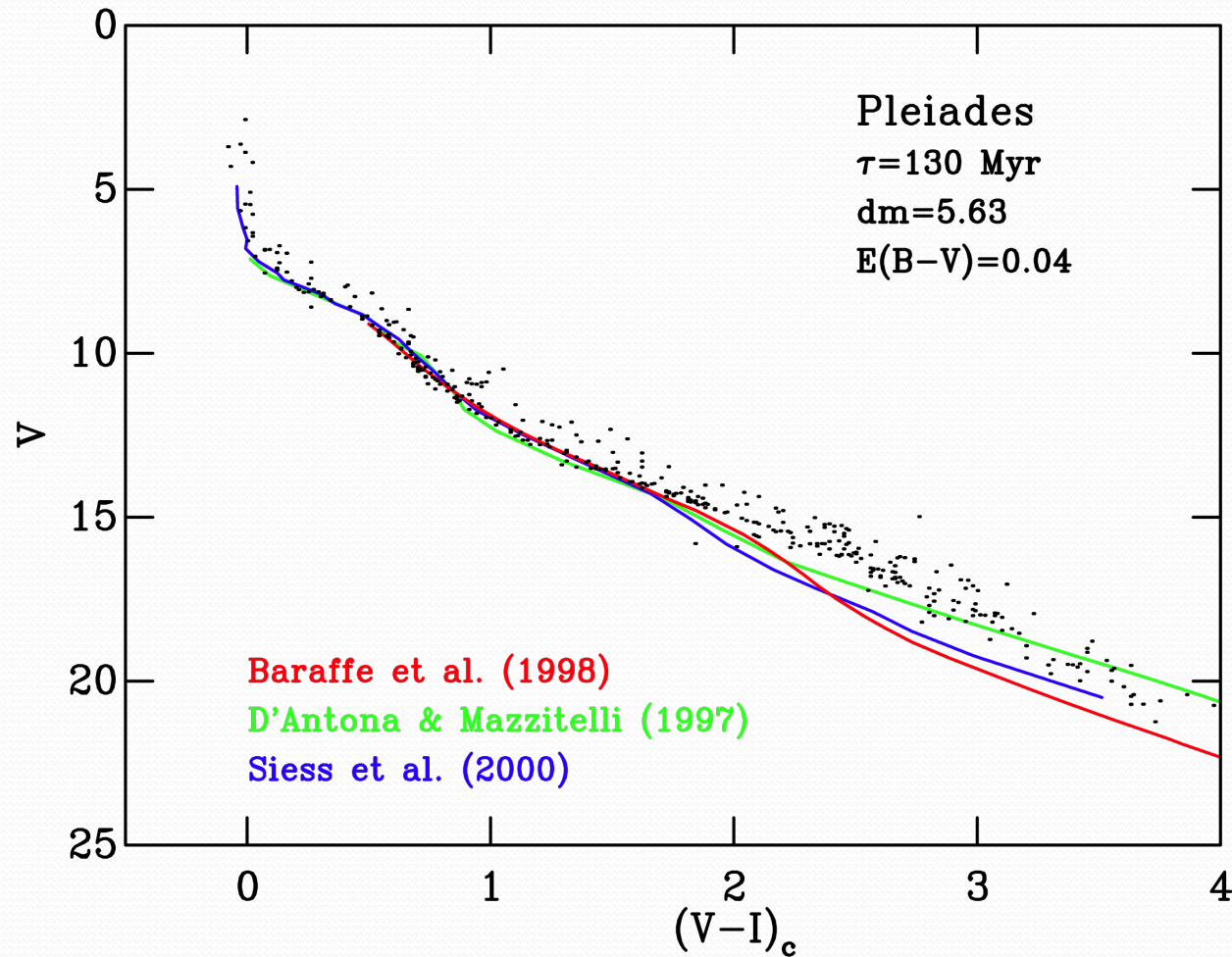


Pre-Main-Sequence Stars: Older Than We Thought?

Cameron Bell¹, Tim Naylor¹, N. J. Mayne¹, R. D. Jeffries², S. P. Littlefair³

1 – University of Exeter, 2 – Keele University, 3 – University of Sheffield

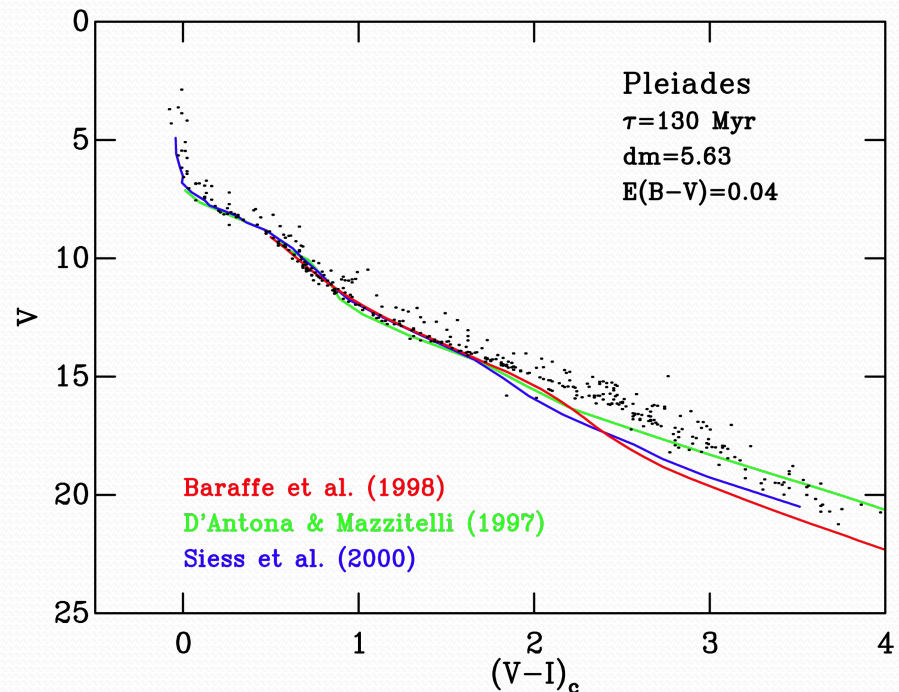
Setting the scene



Photometric data from Stauffer et al. (2007)

Setting the scene

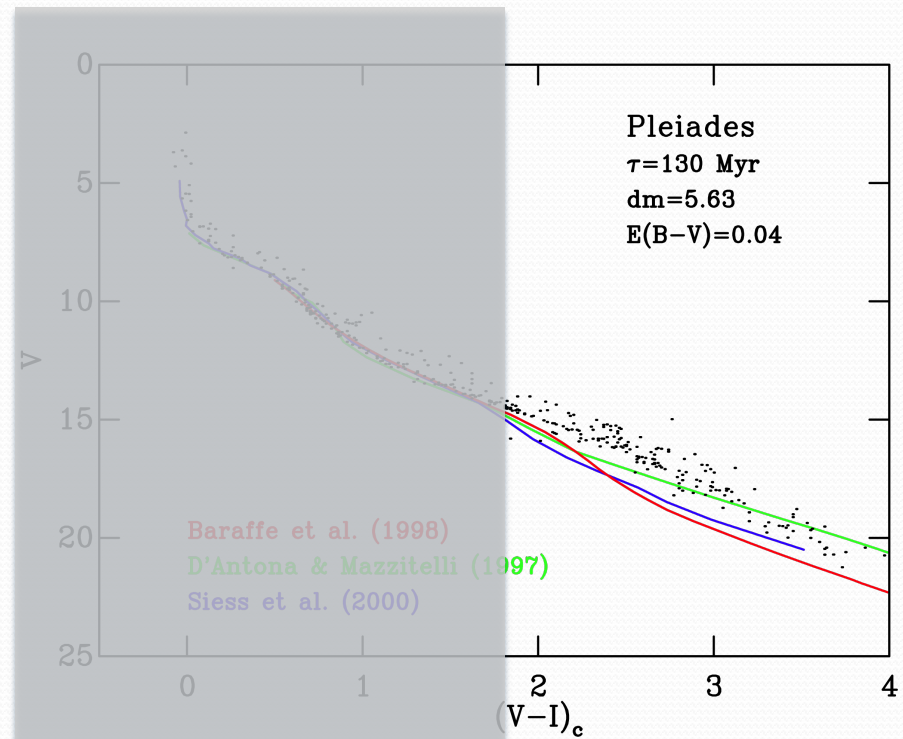
- Why the poor fit in the pre-MS regime?
 - photometric calibration?
 - transformation from H-R to CMD?
 - problems with models themselves?



Photometric data from Stauffer et al. (2007)

Setting the scene

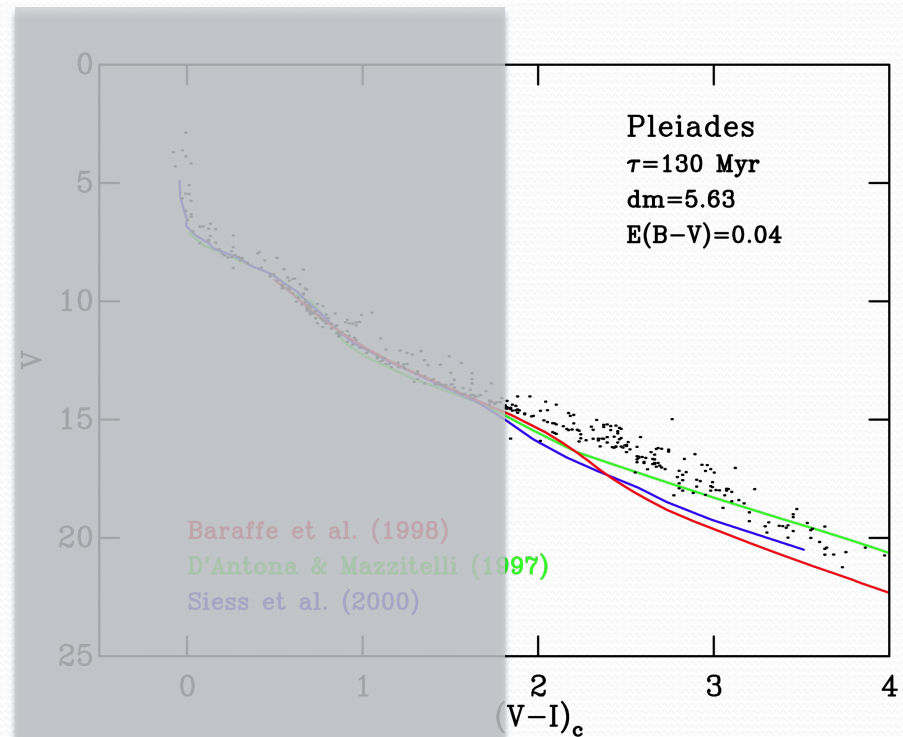
- Why the poor fit in the pre-MS regime?
 - photometric calibration?
 - transformation from H-R to CMD?
 - problems with models themselves?
- ⇒ spread in pre-MS ages for a given region!



Photometric data from Stauffer et al. (2007)

Setting the scene

- Why the poor fit in the pre-MS regime?
 - photometric calibration?
 - transformation from H-R to CMD?
 - problems with models themselves?
- ⇒ spread in pre-MS ages for a given region!
- ⇒ how reliable are ages for young pre-MS stars?



Photometric data from Stauffer et al. (2007)

Photometric calibration

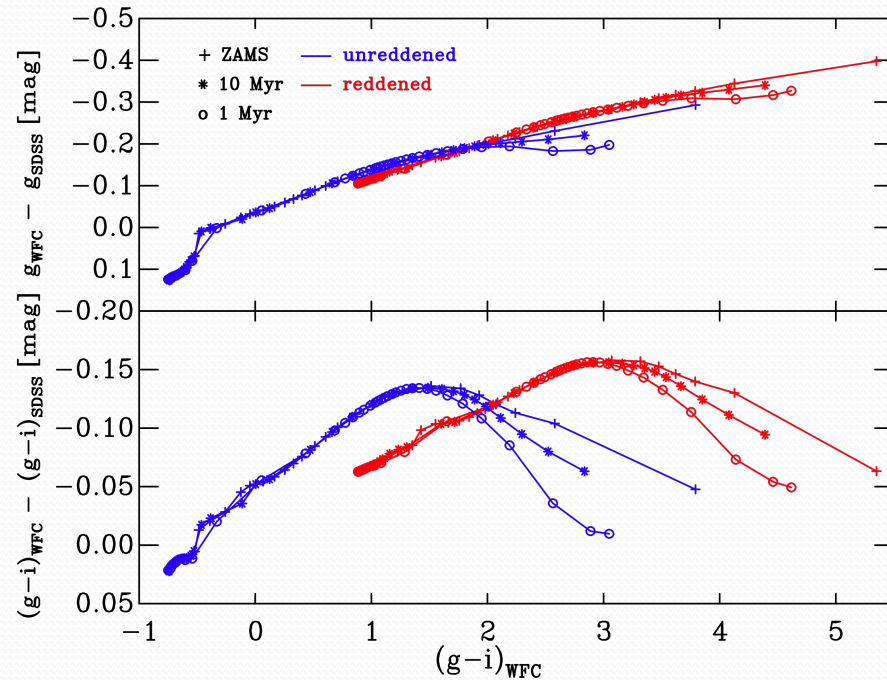
- Like to convert INT-WFC survey to SDSS

- $g_{\text{stand}} = \varphi_g (g-i)_{\text{inst}} - k_g \chi + z_g.$

- Model INT-WFC system responses

- transformations.

Cep OB3b, χ Per, IC 348, IC 5146, λ Ori, NGC 1960, NGC 2169, NGC 2244, NGC 2362, NGC 6530, NGC 6611, NGC 7160, ONC, Pleiades, σ Ori



Photometric calibration

- Like to convert INT-WFC survey to SDSS

$$\bullet g_{\text{stand}} = \varphi_g (g-i)_{\text{inst}} - k_g \chi + z_g.$$

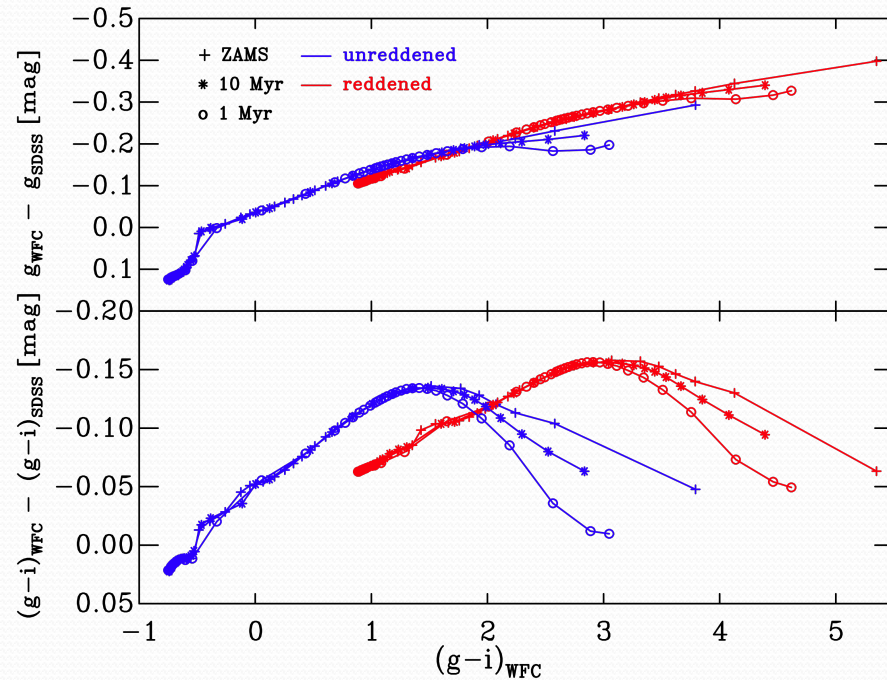
- Model INT-WFC system responses

- transformations.

- Traditional calibration would place pre-MS stars in wrong position in CMD space

⇒ leave photometry in natural INT-WFC system.

Cep OB3b, χ Per, IC 348, IC 5146, λ Ori, NGC 1960, NGC 2169, NGC 2244, NGC 2362, NGC 6530, NGC 6611, NGC 7160, ONC, Pleiades, σ Ori



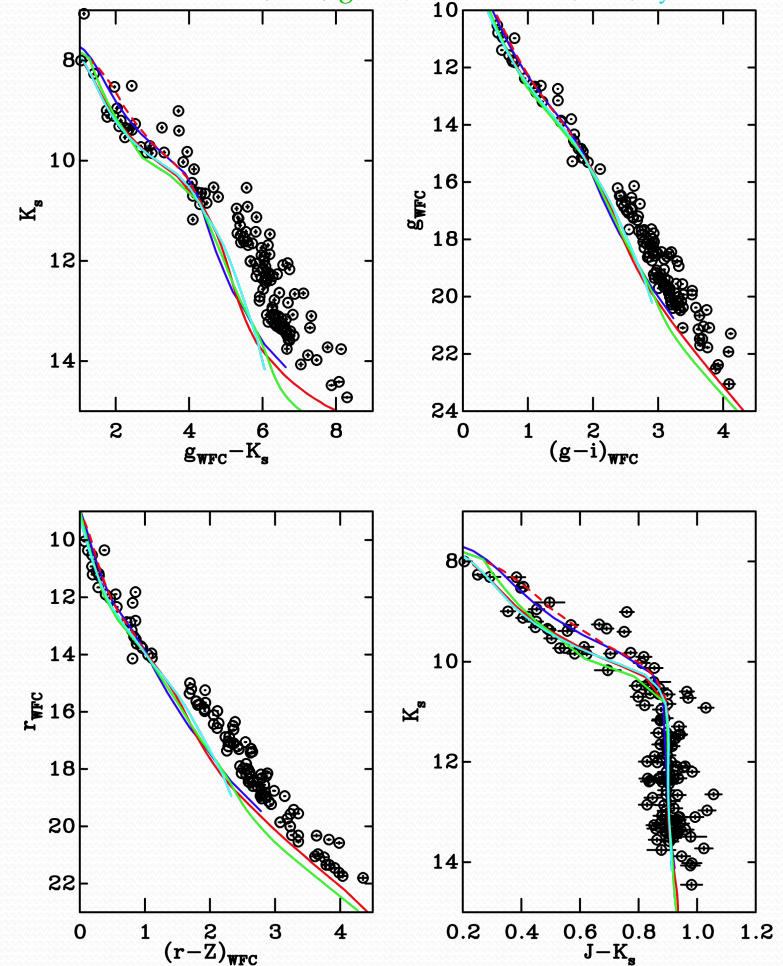
A simple test

- A simple test is to take our Pleiades dataset in the natural photometric system and see if we can match the observed pre-MS.
- Working in the natural system we require atmospheric models to transform isochrones into CMD space.

A simple test

Baraffe et al. (1998) red; Siess et al. (2000) blue; D'Antona & Mazzitelli (1997) green; Dotter et al. (2008) cyan

- Models still do not fit the Pleiades pre-MS population
 - missing sources of opacity?
 - treatment of convection?
 - missing physics?
- Can we then quantify this mismatch?



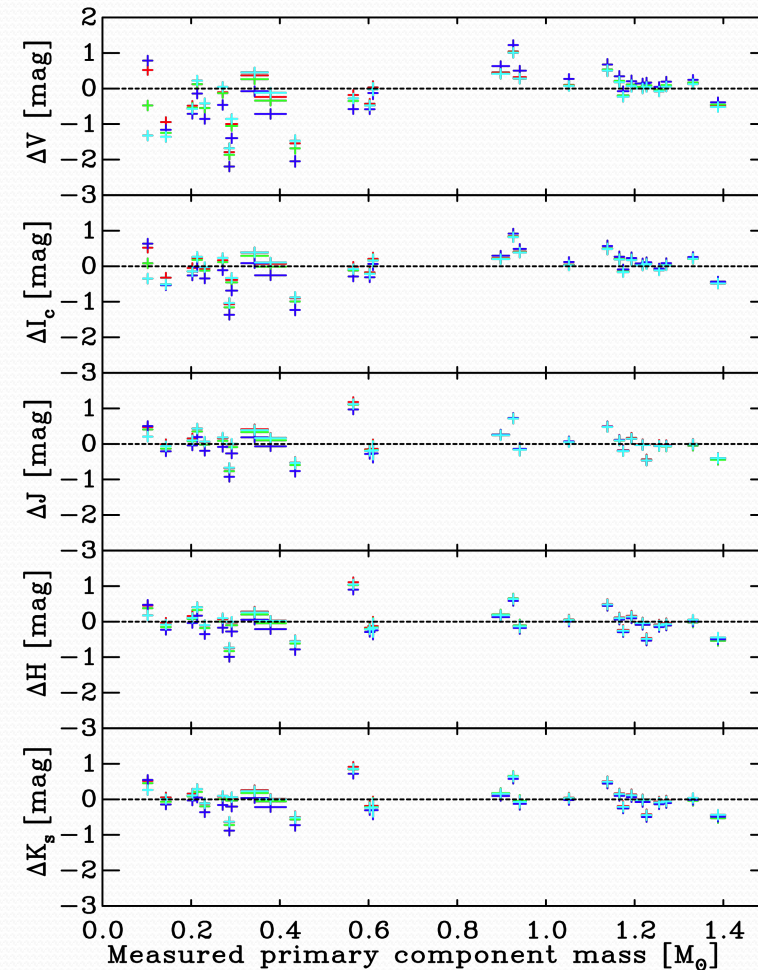
Bell et al. (2012)

Utilising binaries

- To be quantitative, we must measure the mismatch in each photometric bandpass, *not* as a function of colour.
- Find a bandpass where the discrepancy is the smallest and create colours with respect to that band.
- Equivalent to using this band as a T_{eff} indicator.
- Study mass-luminosity relation in individual bandpasses using binaries.
- These data do not exist for the Pleiades, so we use main-sequence binaries.

Main-sequence binaries

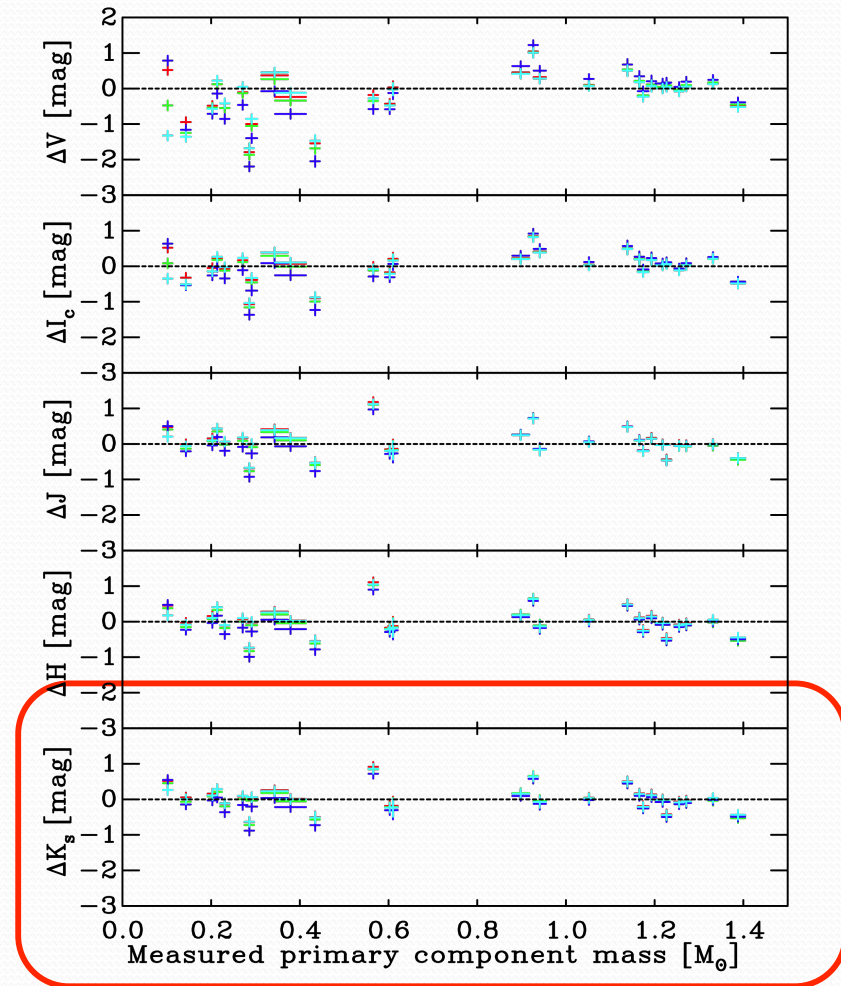
- Eclipsing and spectroscopic binaries give system magnitude
 - $q \rightarrow 1$ (same mass)
 - $q \rightarrow 0$ (mass = primary)



Bell et al. (2012)

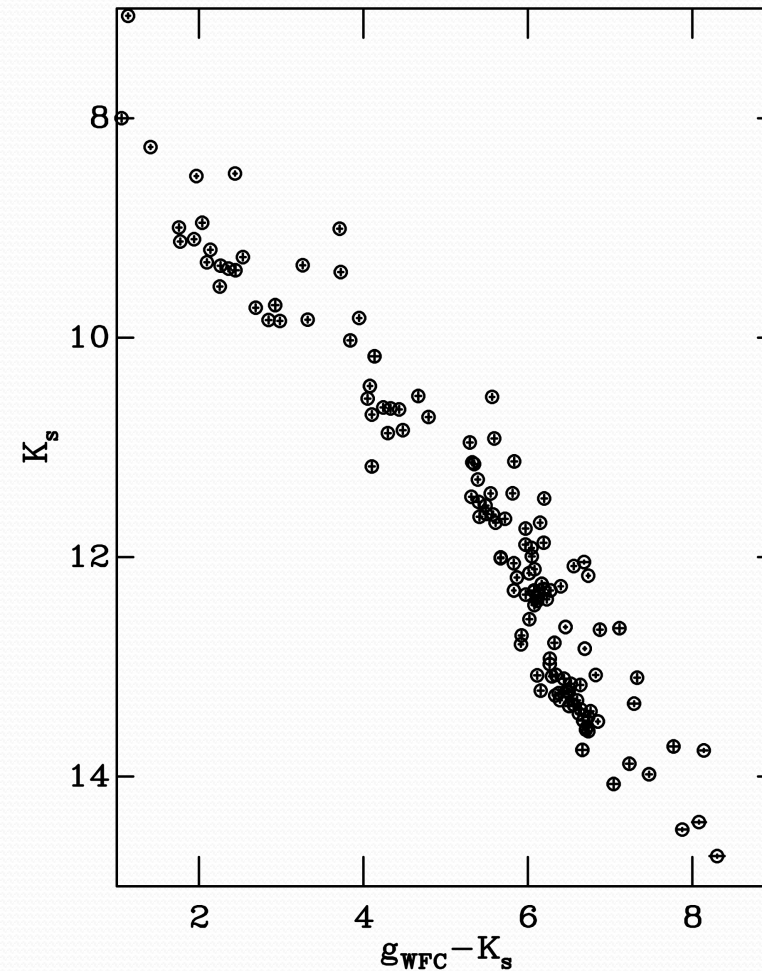
Main-sequence binaries

- Eclipsing and spectroscopic binaries give system magnitude
 - $q \rightarrow 1$ (same mass)
 - $q \rightarrow 0$ (mass = primary)
- K_s -band magnitude is closest to that predicted by the models
 - \Rightarrow use this as our T_{eff} indicator.



Bell et al. (2012)

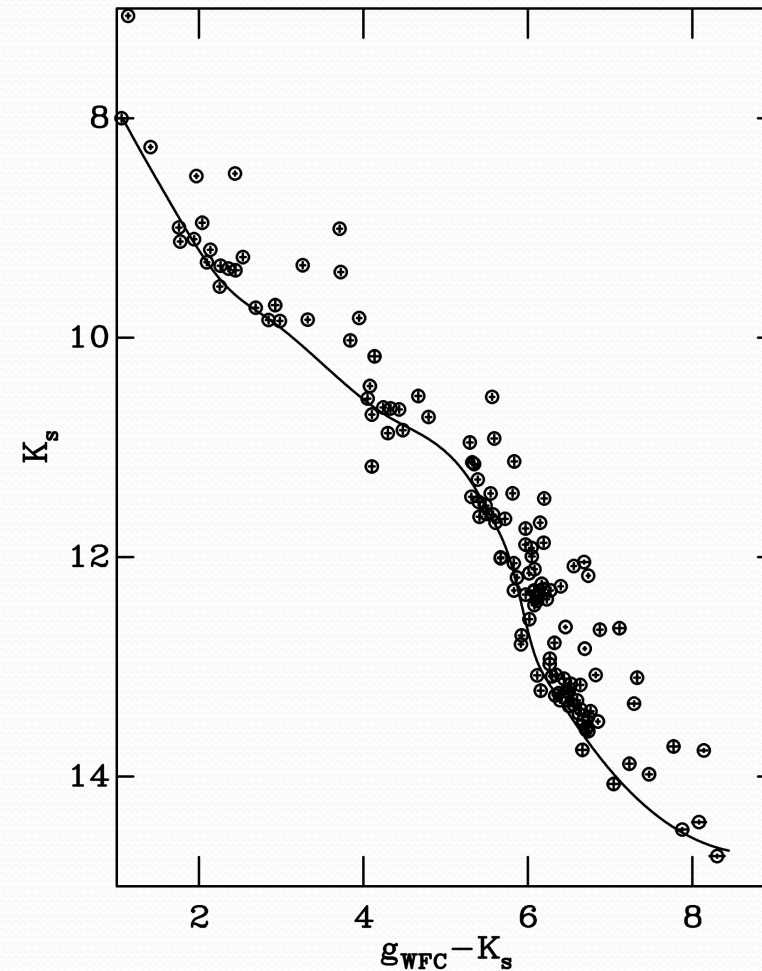
Quantifying the discrepancy



Bell et al. (2012)

Quantifying the discrepancy

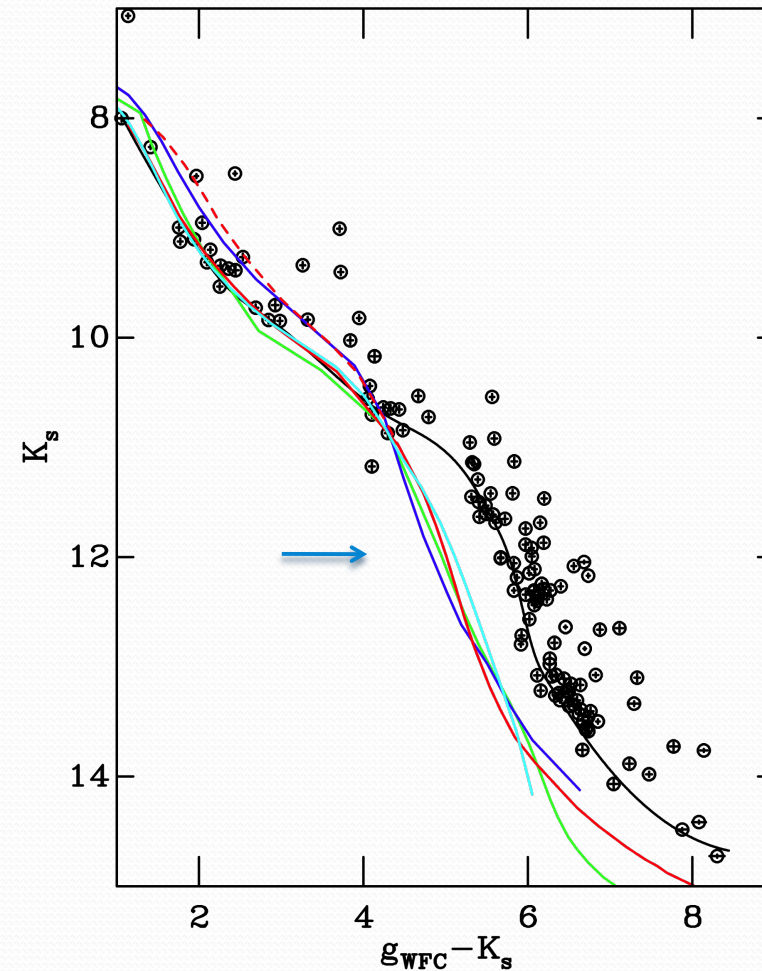
- Empirical spline fitted to observed sequence.



Bell et al. (2012)

Quantifying the discrepancy

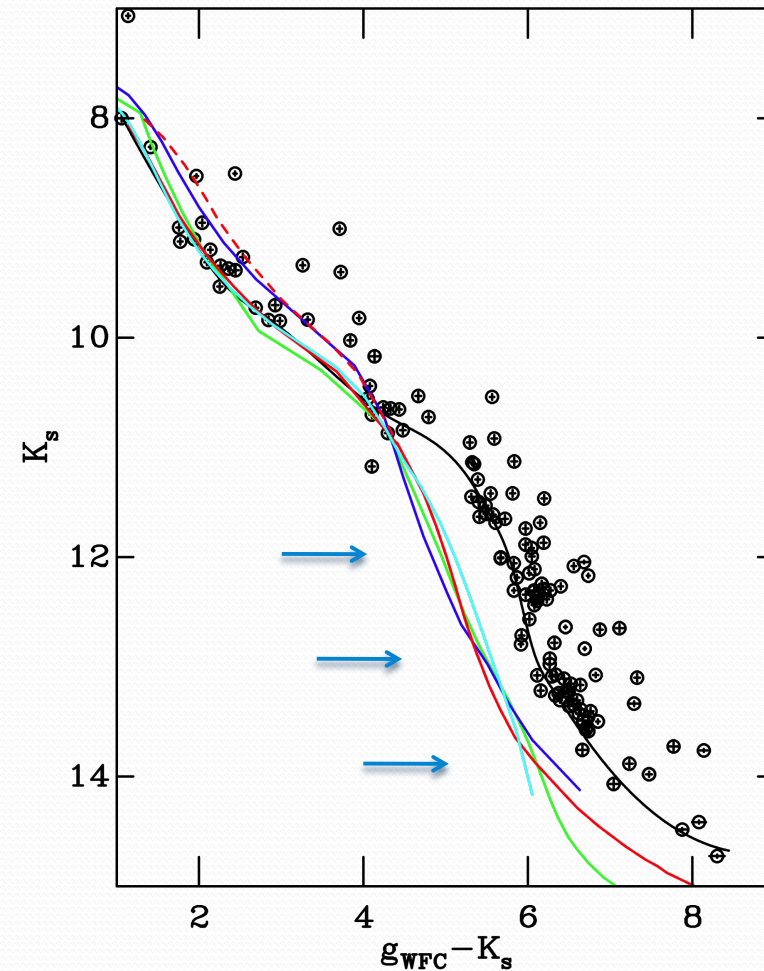
- Empirical spline fitted to observed sequence.
- Assuming $K_{\text{obs}} = K_{\text{calc}}$, calculate mismatch at a given T_{eff} .



Bell et al. (2012)

Quantifying the discrepancy

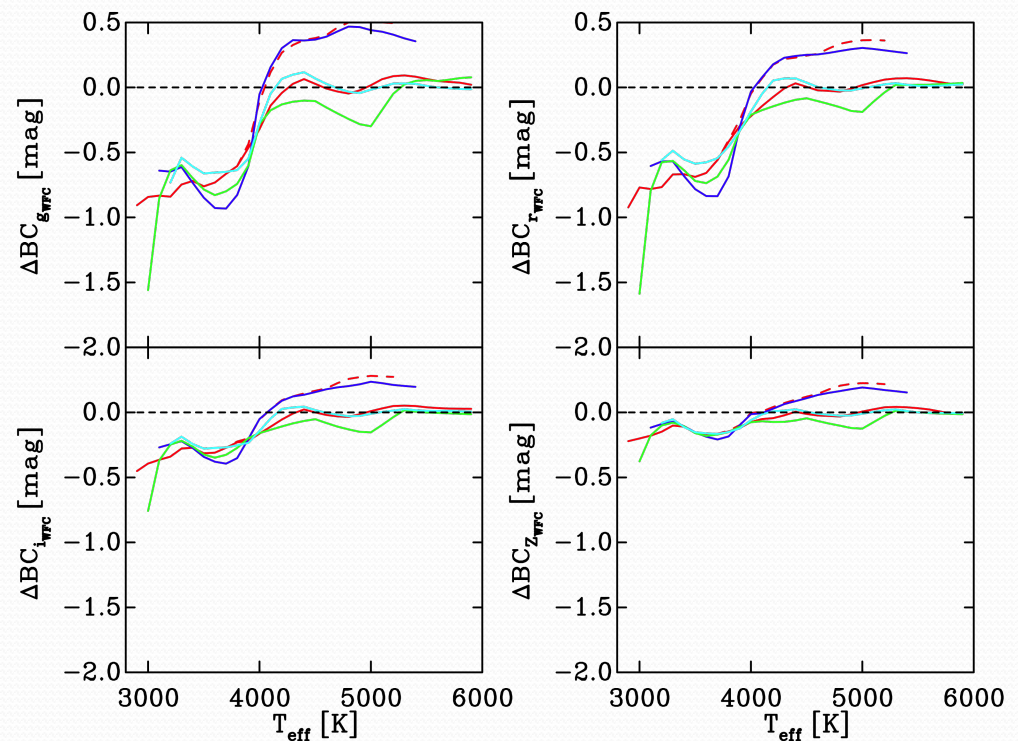
- Empirical spline fitted to observed sequence.
- Assuming $K_{\text{obs}} = K_{\text{calc}}$, calculate mismatch at a given T_{eff} .
- Repeat for all T_{eff} along isochrone.



Bell et al. (2012)

Quantifying the discrepancy

- This process can be repeated for all optical/near-IR photometric bandpasses.
- Below 4000K, models overestimate flux by a factor 2 at $0.5\mu\text{m}$, becoming negligible at $2.2\mu\text{m}$.
- Define an empirical model-dependent adjustment to BCs required to fit Pleiades at 130 Myr.



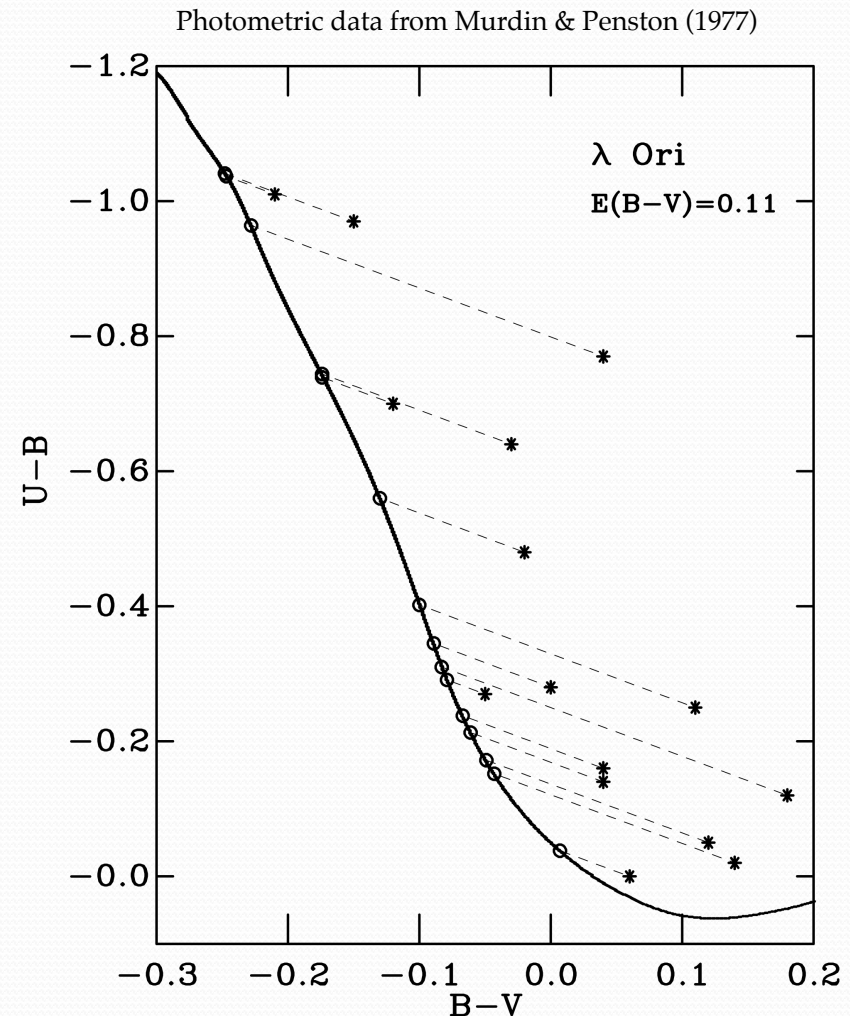
Bell et al. (2012)

Prior to fitting the pre-MS

- Before fitting the pre-MS with model isochrones we require a distance (due to an age-distance degeneracy) as well as a robust reddening measurement.
- *UBV* photometry of high-mass members can give both of these
 - standard main-sequence distance fitting
 - reddening from the colour-colour diagram
- Added bonus of deriving an age from stars between the ZAMS and TAMS.

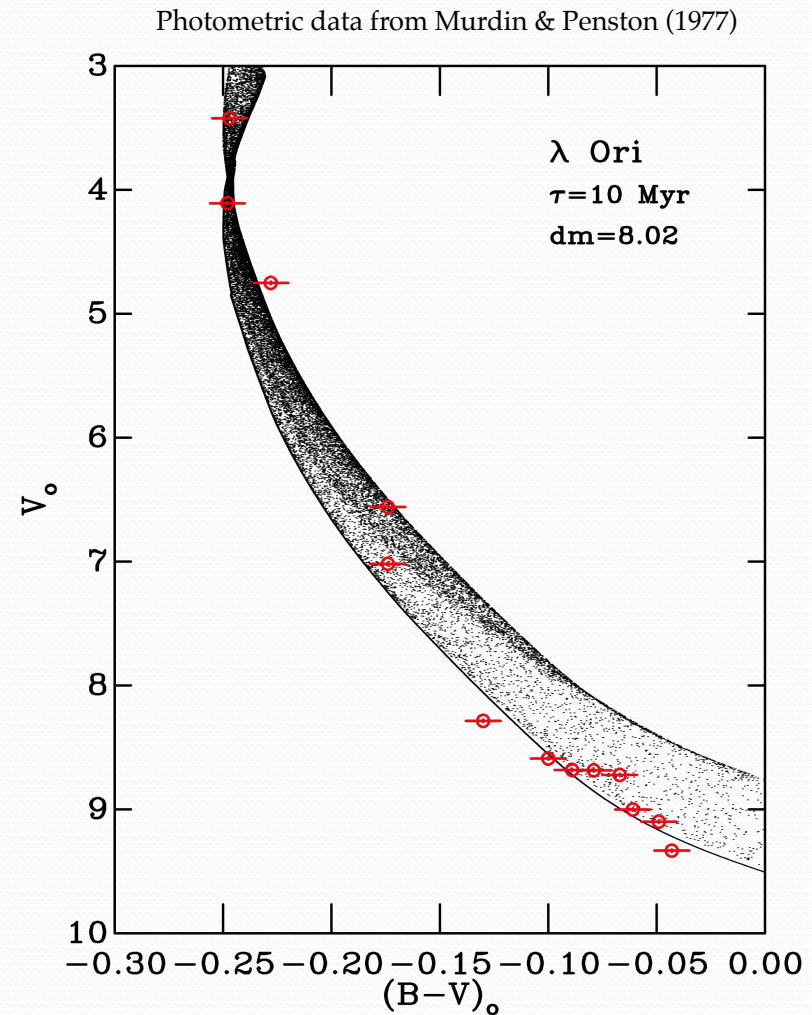
Fitting the main-sequence

- Use a revised Q-method to deredden each object individually.



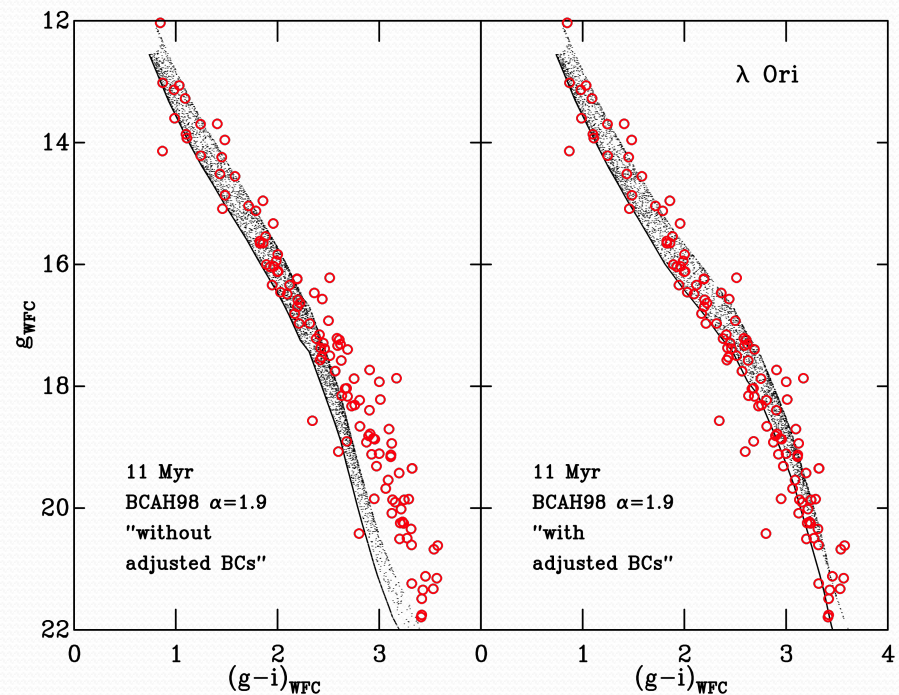
Fitting the main-sequence

- Use a revised Q-method to deredden each object individually.
- Calculate an age and distance from the dereddened CMD.
- Use the τ^2 fitting statistic (Naylor & Jeffries 2006)
 - 10^6 stars (interior models)
 - intrinsic binary fraction 50%



Fitting the pre-MS

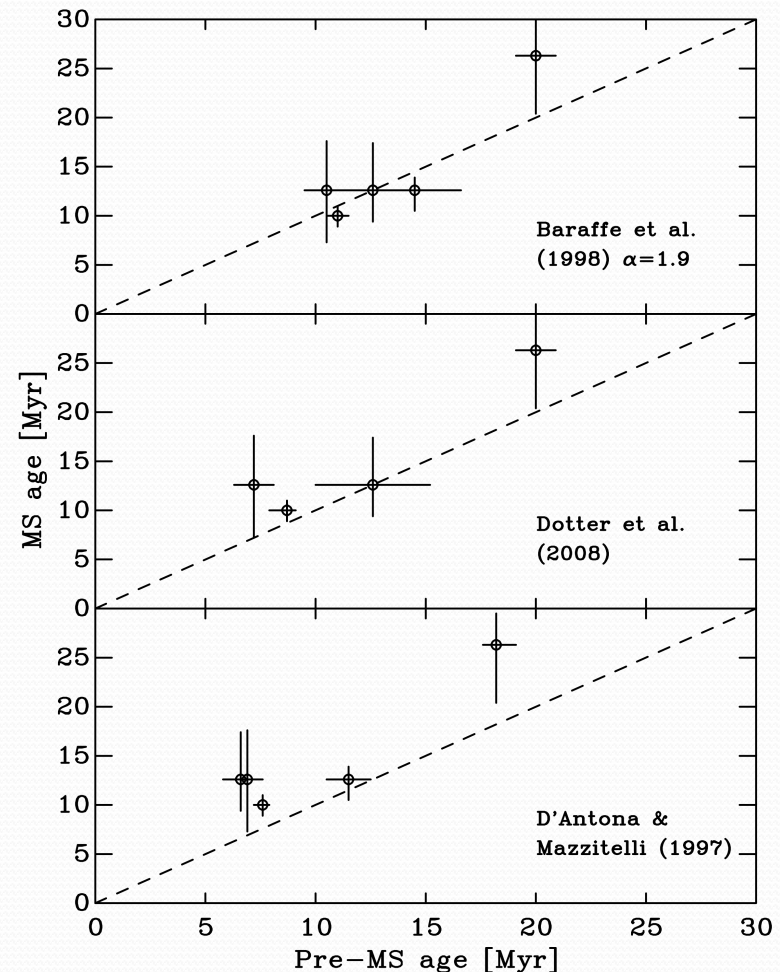
- We posit that the *absolute* adjustment as a function of T_{eff} required for the Pleiades is valid for *all* ages.
- Again use the τ^2 fitting statistic. Allow age to float as a free parameter with main-sequence distance fixed.



Spectroscopically confirmed members of the λ Ori association from Bayo et al. (2011).

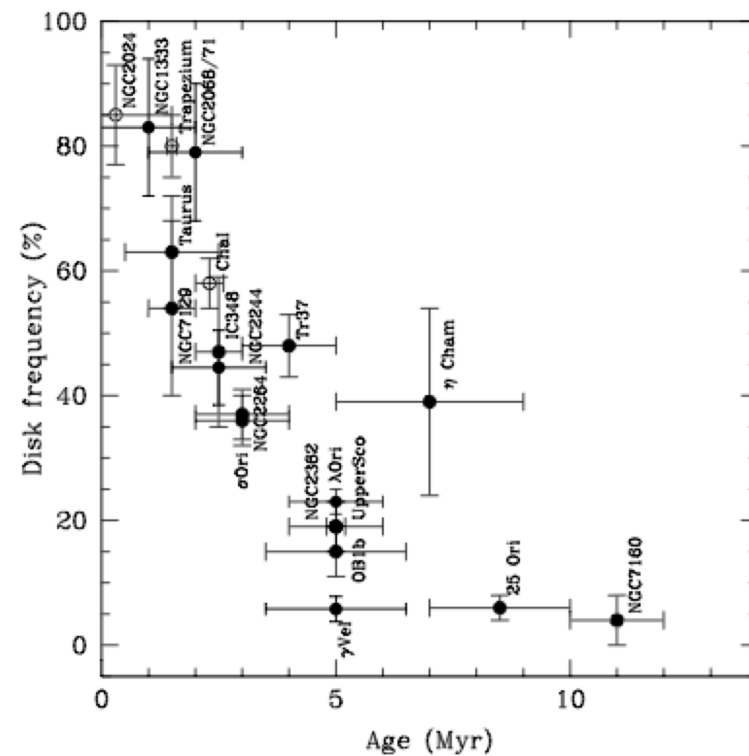
Revised pre-MS age scale?

- Consistent main-sequence and pre-MS ages for regions < 50 Myr.
- Adopting the BCAH98 $\alpha=1.9$ models
 - λ Ori ~ 11 Myr
 - NGC 2169 ~ 11 Myr
 - NGC 2362 ~ 12 Myr
 - NGC 7160 ~ 14 Myr
 - NGC 1960 ~ 20 Myr



Circumstellar disc lifetimes

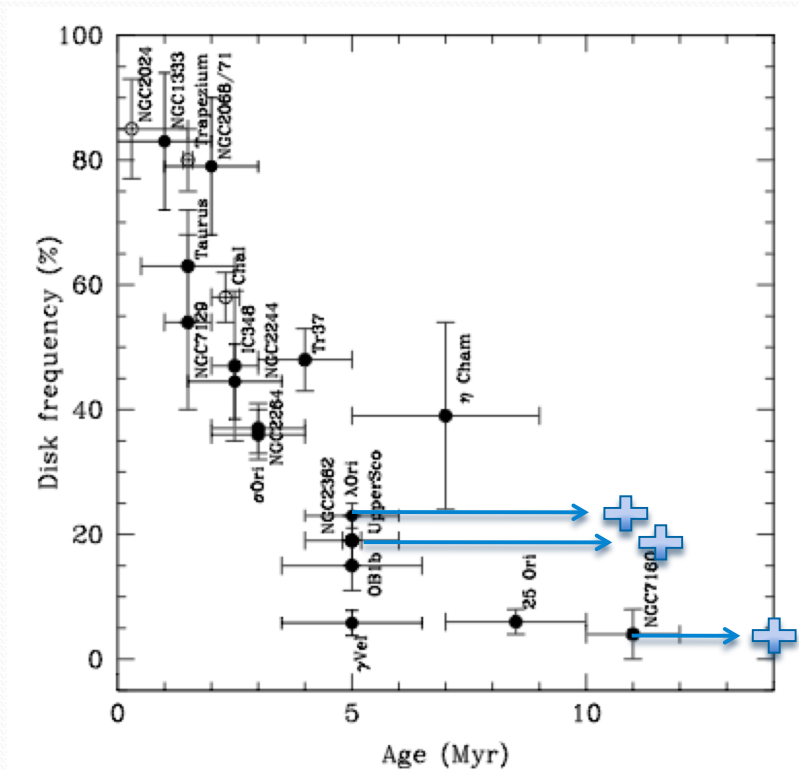
- Two independent age estimates for λ Ori that suggests an age of 10-11 Myr.
- Compare with Upper Sco and the recent age estimate of 11 Myr (Pecaut et al. 2012)



Hernandez et al. (2008)

Circumstellar disc lifetimes

- Two independent age estimates for λ Ori that suggests an age of 10-11 Myr.
- Compare with Upper Sco and the recent age estimate of 11 Myr (Pecaut et al. 2012)
 - ⇒ pre-MS ages could be a factor of 2 too young.
 - ⇒ disc dissipation timescales may be underestimated.



Hernandez et al. (2008)

Conclusions

- Transforming data into standard system using main-sequence star observations can place pre-MS in wrong position in CMD
 - compare models to data in natural photometric system.
- Models do not match Pleiades pre-MS in optical regime
 - recalibrate the transformation from H-R to CMD.
- Strong evidence that pre-MS ages are underestimated by up to a factor of 2
 - obvious implications for circumstellar disc lifetimes.