Ages and Age Spreads in Young Stellar Clusters

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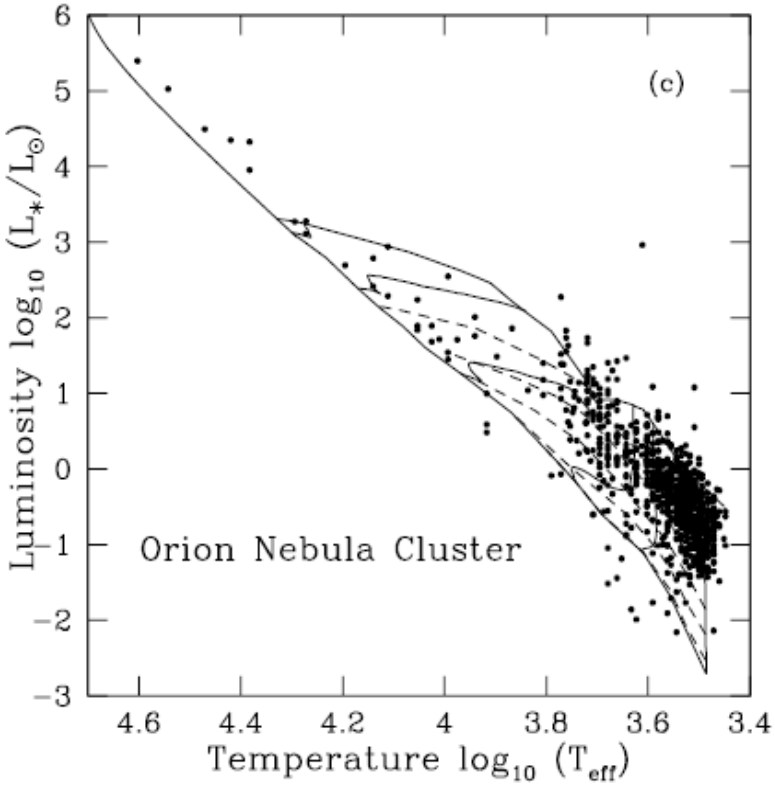
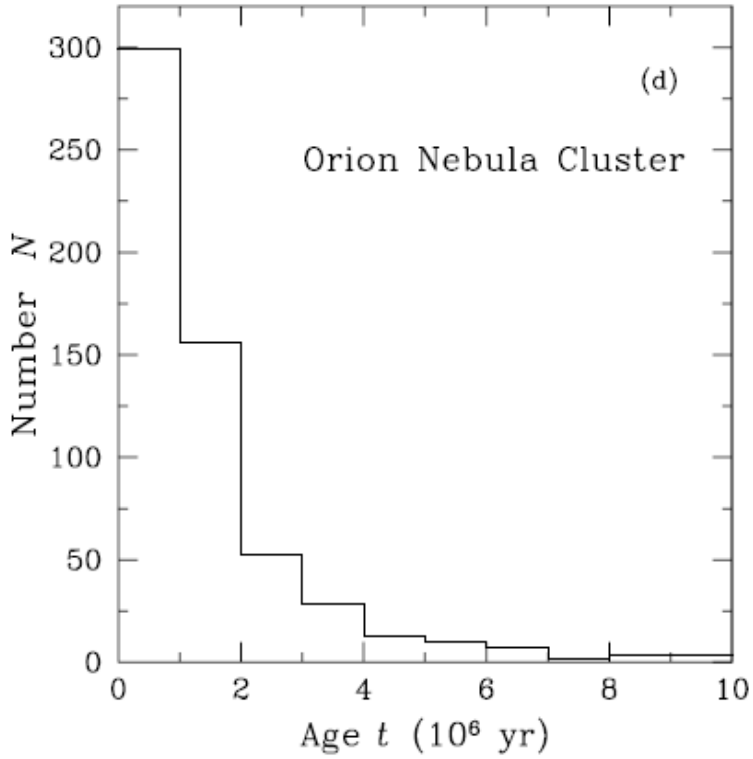
- The HR diagram and Lithium Depletion
- Evidence for luminosity and age spreads
- Absolute Ages for Young Stars

Francesco's Work

"Accelerating star formation" in several clusters

Palla & Stahler 1999, ApJ, 525, 772
Palla & Stahler 2000, ApJ, 540, 255

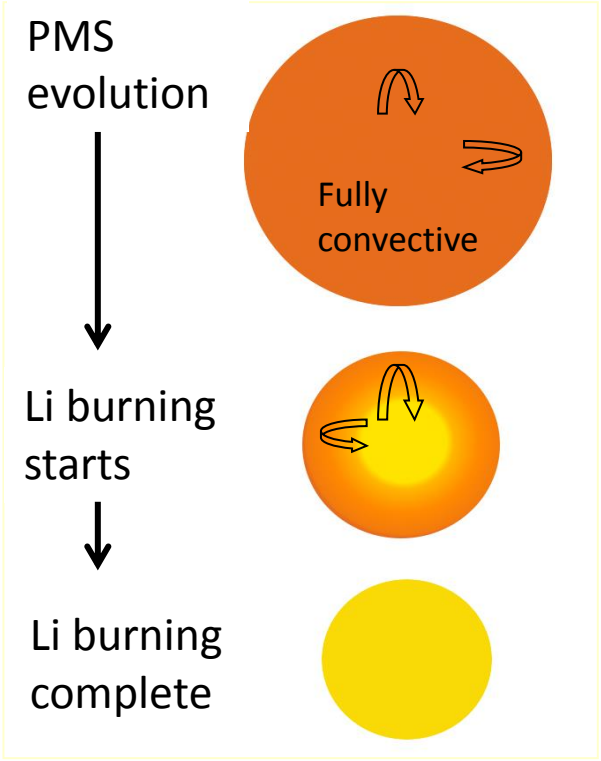


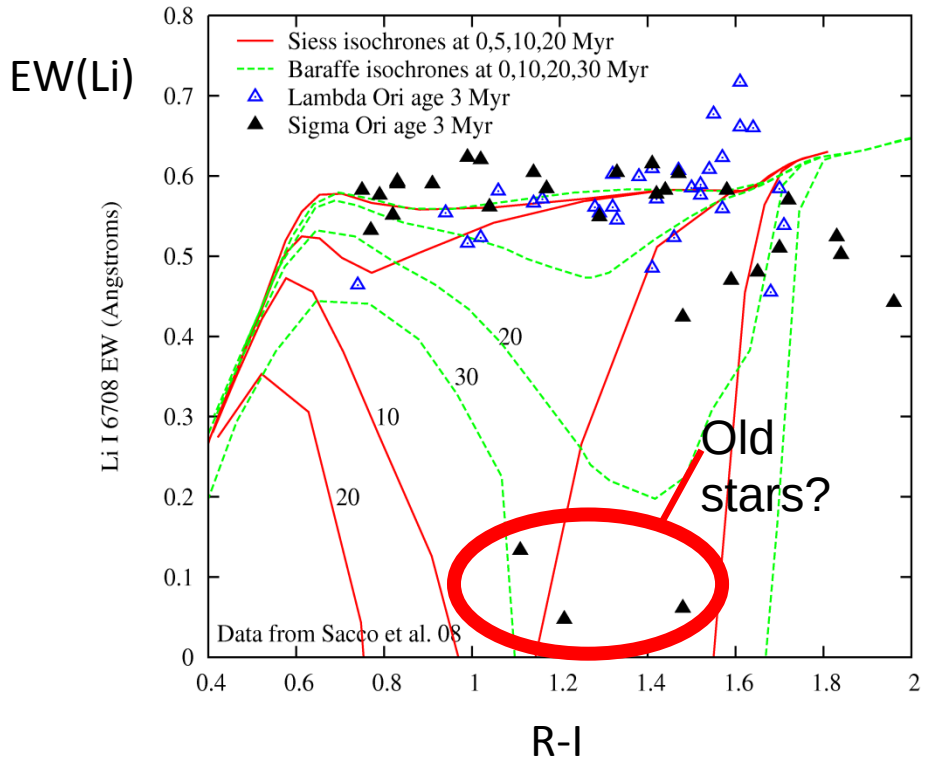


Francesco's Work

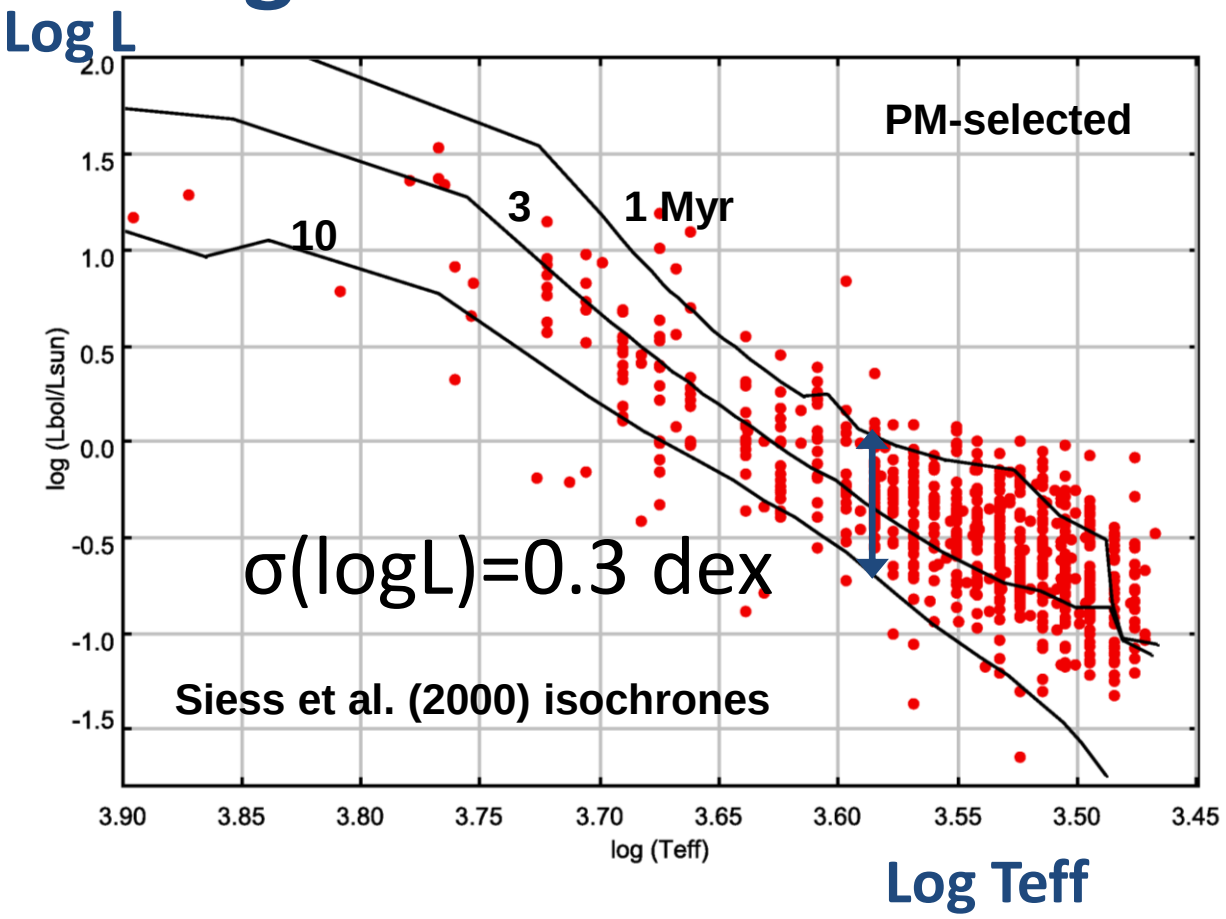
Evidence for age spreads from Li-depleted stars

Palla et al. 2005, ApJ, 626, L49
Sacco et al. 2007, ApJ, 462, L23





Age from the PMS?



BUT

1. Extinction
2. Accretion
3. Age Spread?
4. Variability
5. Binarity

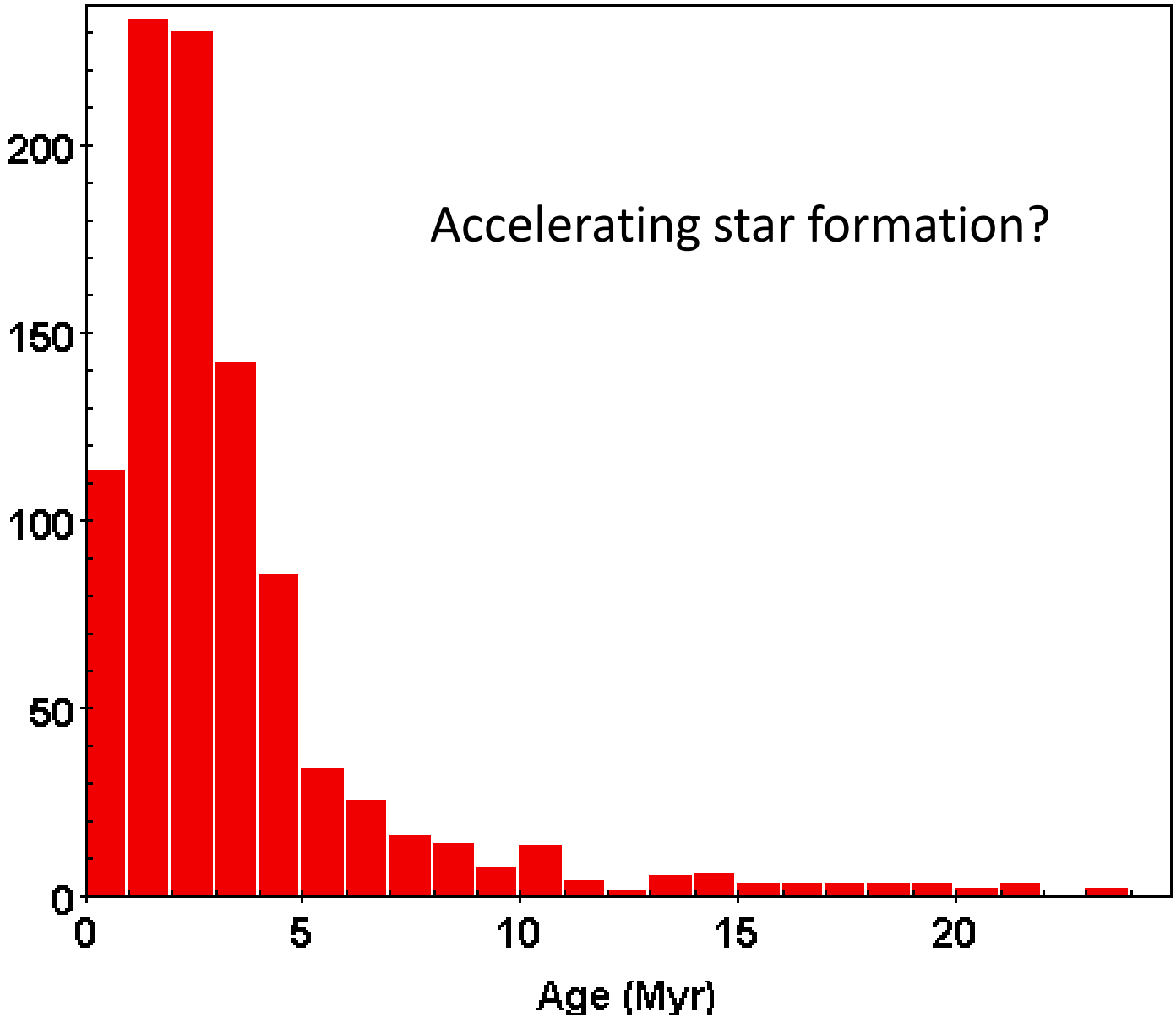
All contribute to the scatter

NB: $L \propto t^{-2/3}$

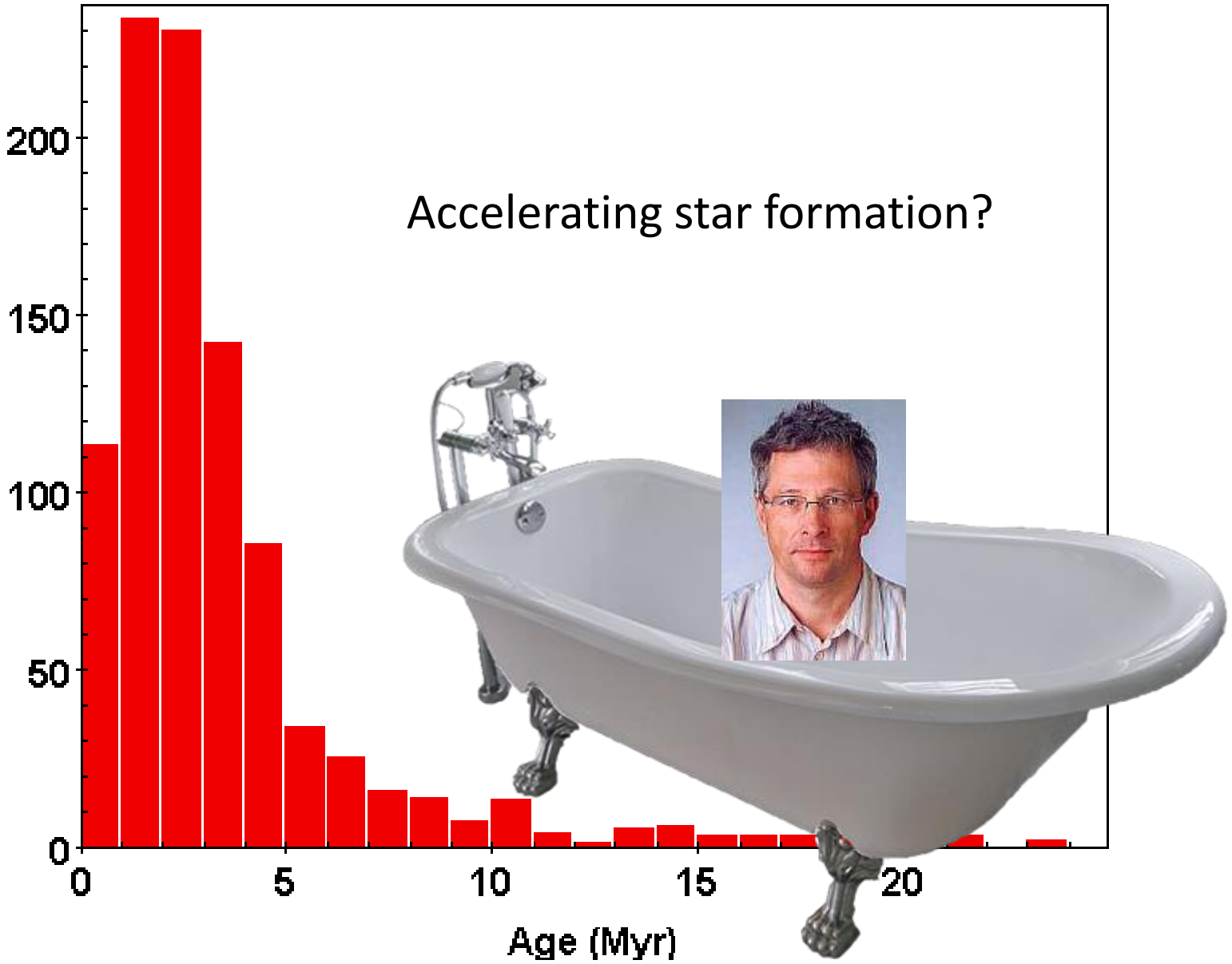
$\sigma(\log t) = 1.5\ \sigma(\log L)$

Hartmann 2001, AJ, 121, 1030

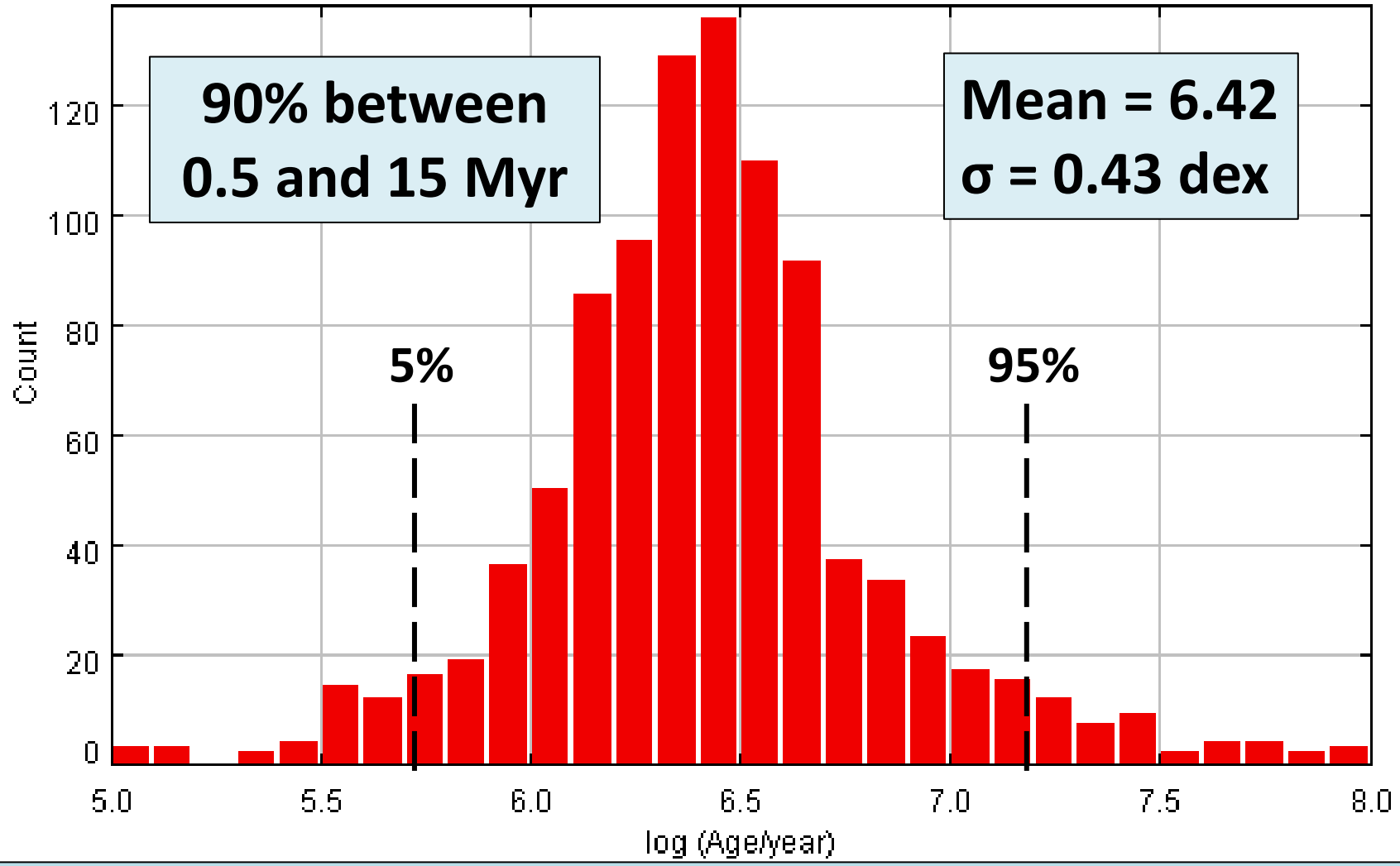
Orion Nebula Cluster: *Da Rio et al. 2010, ApJ, 722, 1092*



Orion Nebula Cluster: *Da Rio et al. 2010, ApJ, 722, 1092*



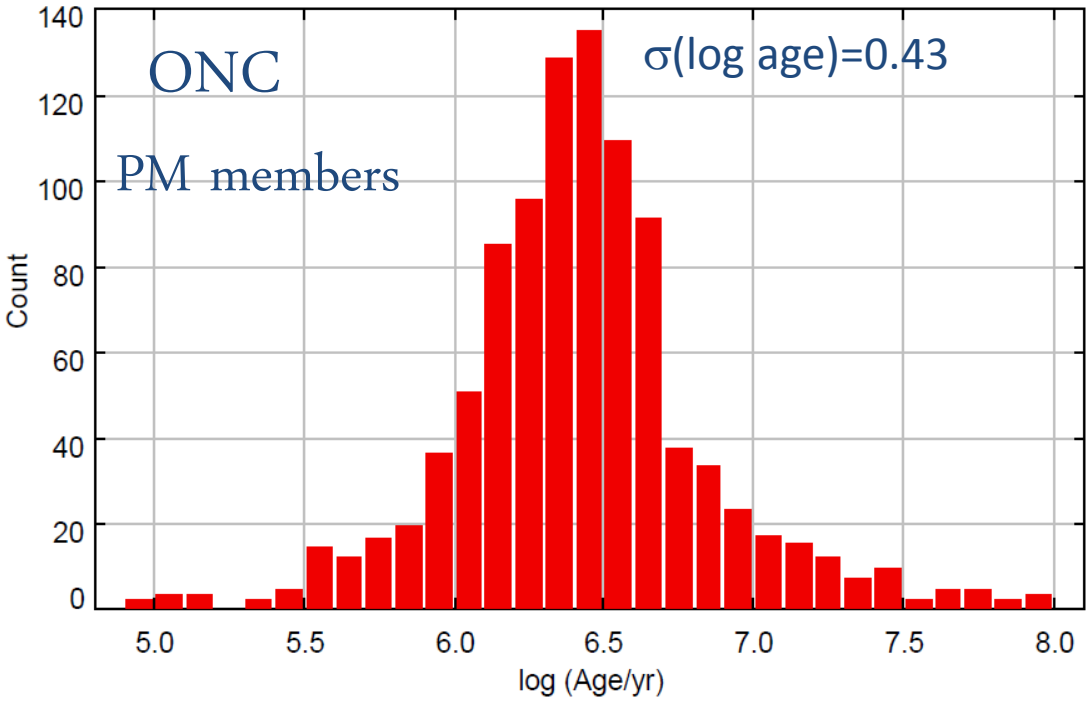
Orion Nebula Cluster: *Da Rio et al. 2010, ApJ, 722, 1092*



Are these spreads in luminosity real?
If so, do they imply large age spreads?

Estimated uncertainties from *Reggiani et al. 2011*

	σ(log L)
Variability	0.030
Distance	0.015
Extinction	0.050
Accretion	0.070
Binarity	0.10
TOTAL	0.14 dex



ONC observed age spread

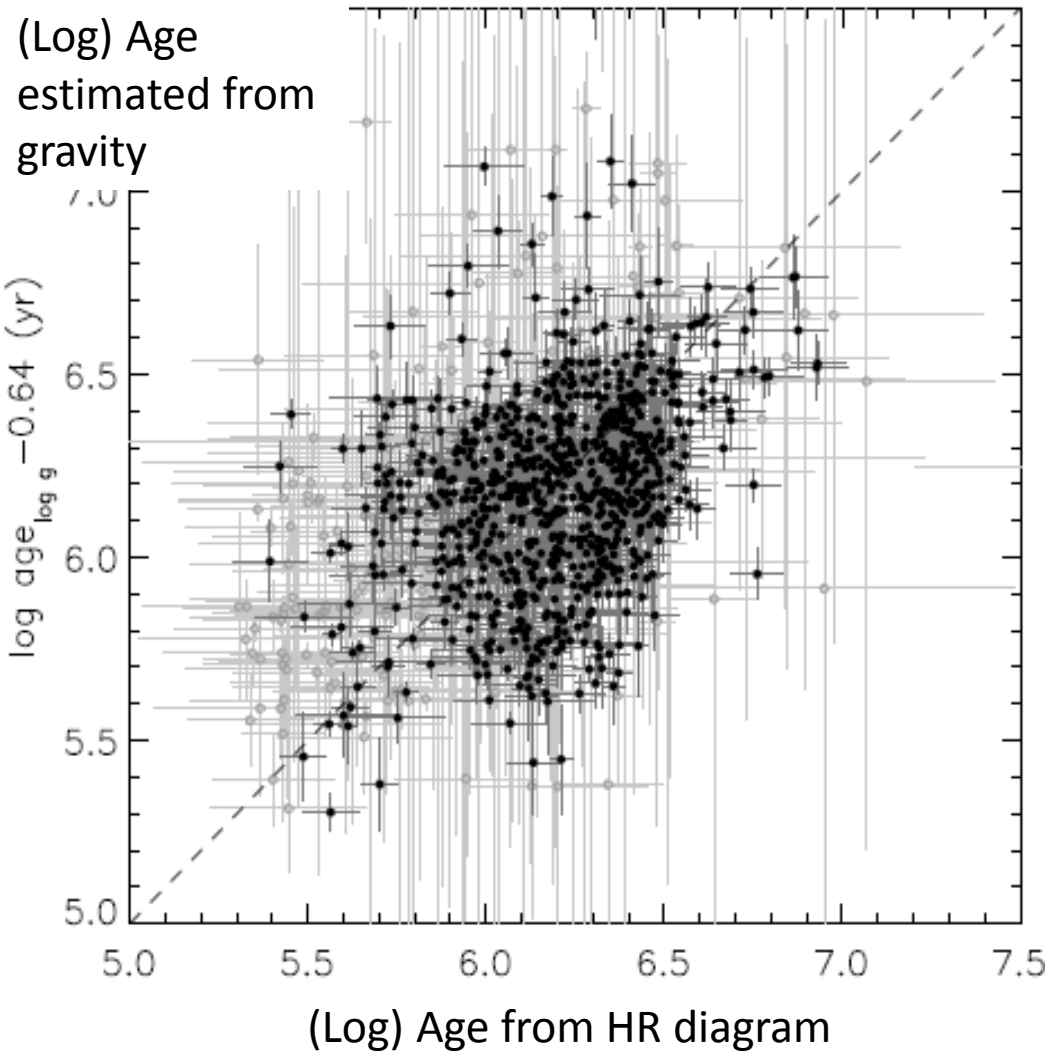
$t \propto L^{-3/2}$ so **σ(log t) ~ 0.2 dex** **c.f. σ(log age)=0.43 dex**

σ(log t)< σ(log age) - Uncertainties cannot explain spread

(unless they have been badly underestimated) *Reggiani et al. 2011, A&A, 534, A83*

See also *Hartmann 2001, AJ, 121, 1030 ; Preibisch 2012, RAA, 12, 1*

Compare spectroscopic gravity estimates with HRD position



Orion Nebula Cluster

Da Rio et al. 2016, ApJ, 818, 59

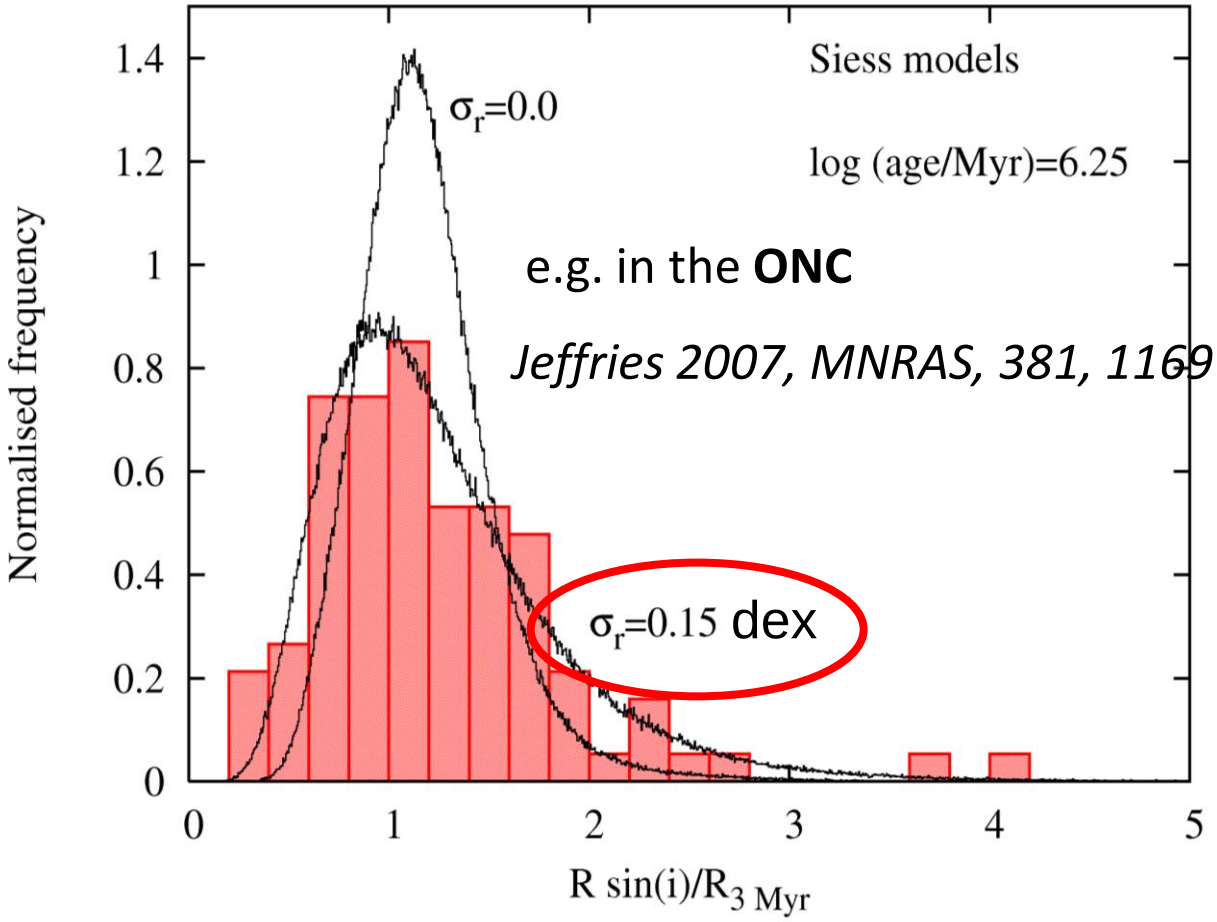
See also
Cottaar et al. 2014, ApJ, 794, 129
Similar result in IC 348

Correlation suggests a genuine spread **in radius**

Establish a radius spread:

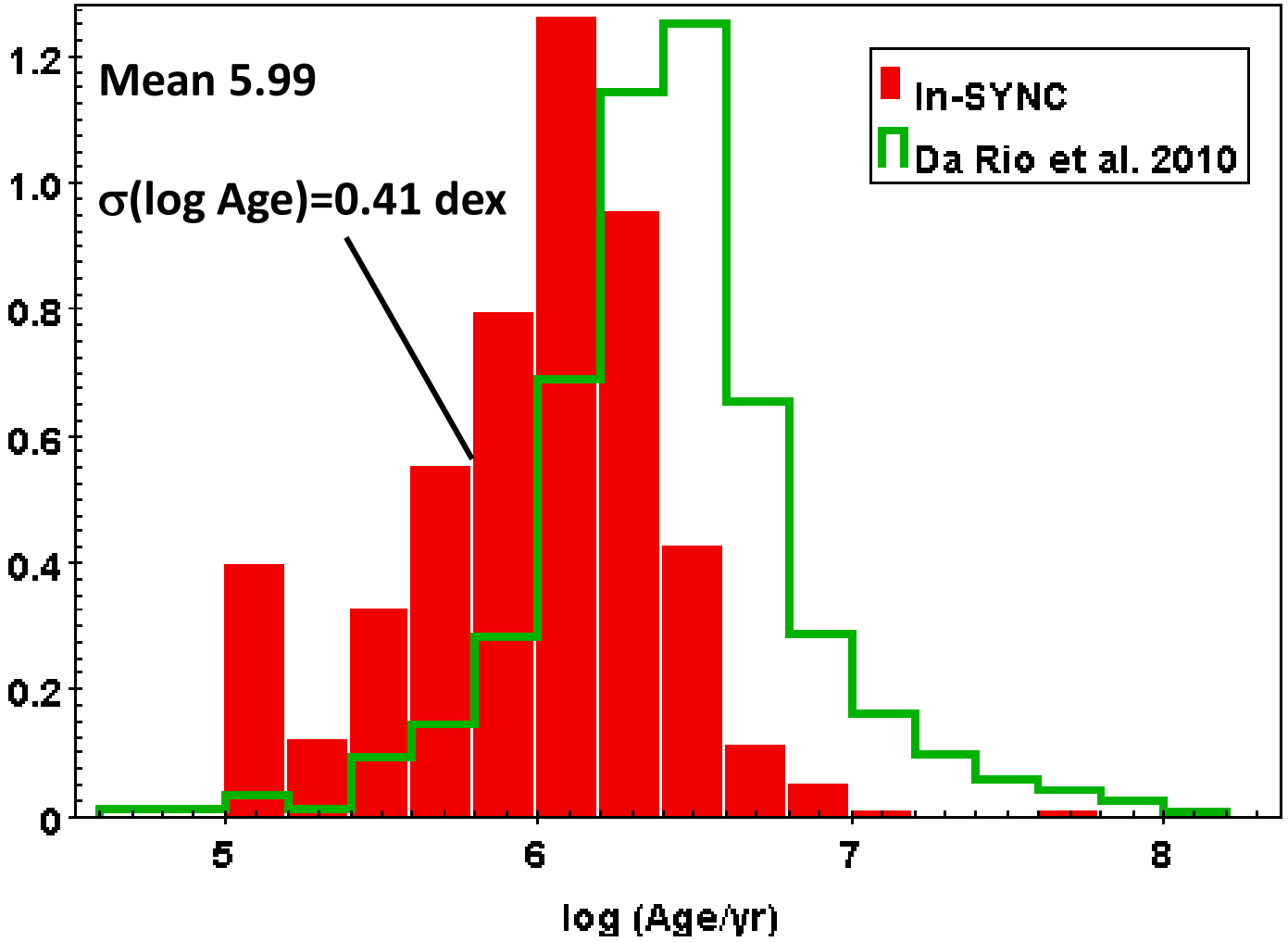
Find a sample with rotation period **P** and **v sini**

R sini = 0.02 P vsini



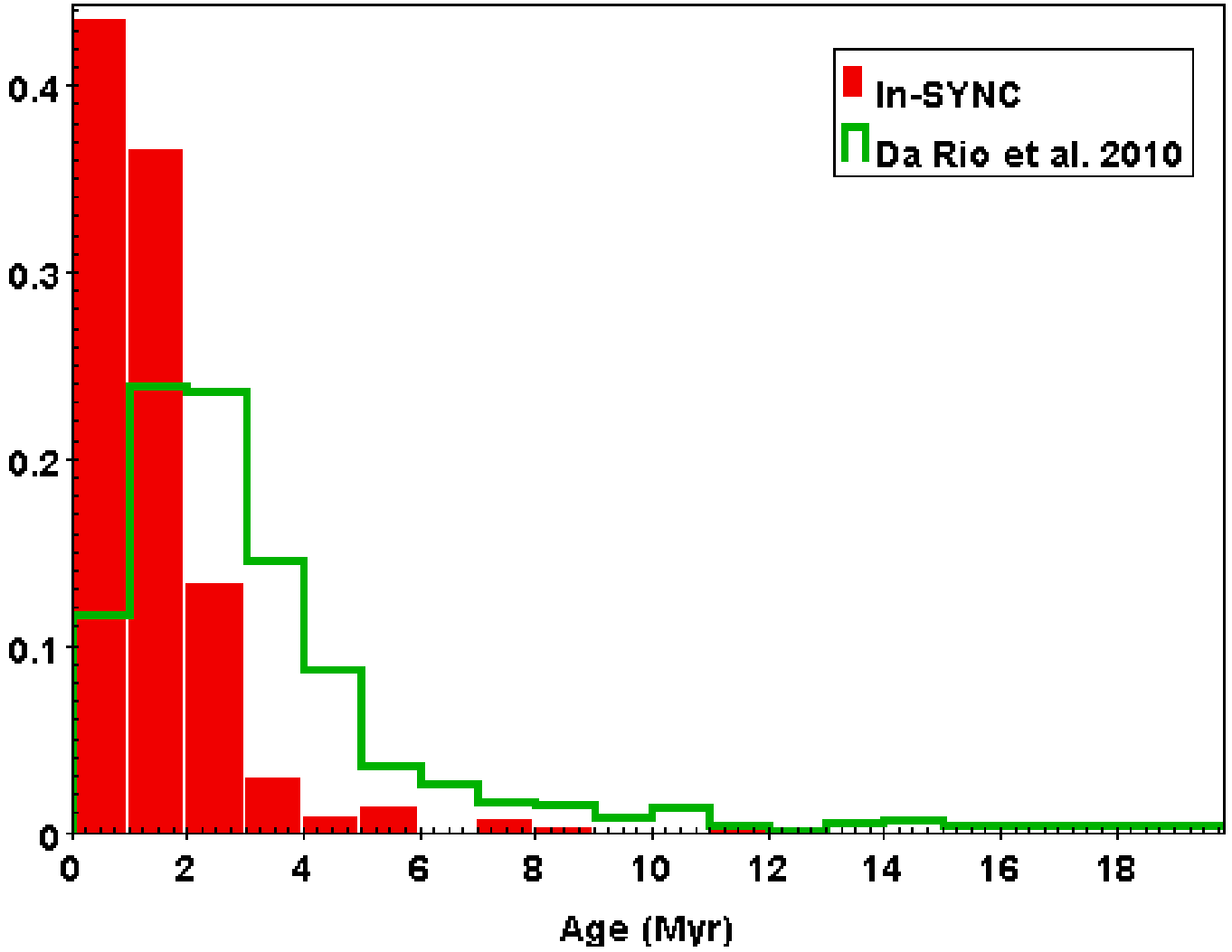
Spread in R of ×2-3 FWHM: agrees with L spread

Cottaar et al. (2014, ApJ, 794, 125) finds σ_r**= 0.10 dex in IC 348**



In-SYNC ONC data – simple change of reddening law!
(Logarithmic) age spread is the same, but mean age much lower.

Da Rio et al. 2016, ApJ, 818, 59



In-SYNC ONC data – simple change of reddening law!
Period of “acceleration” becomes <u>much</u> shorter.

Da Rio et al. 2016, ApJ, 818, 59

Are the luminosity spreads real…?

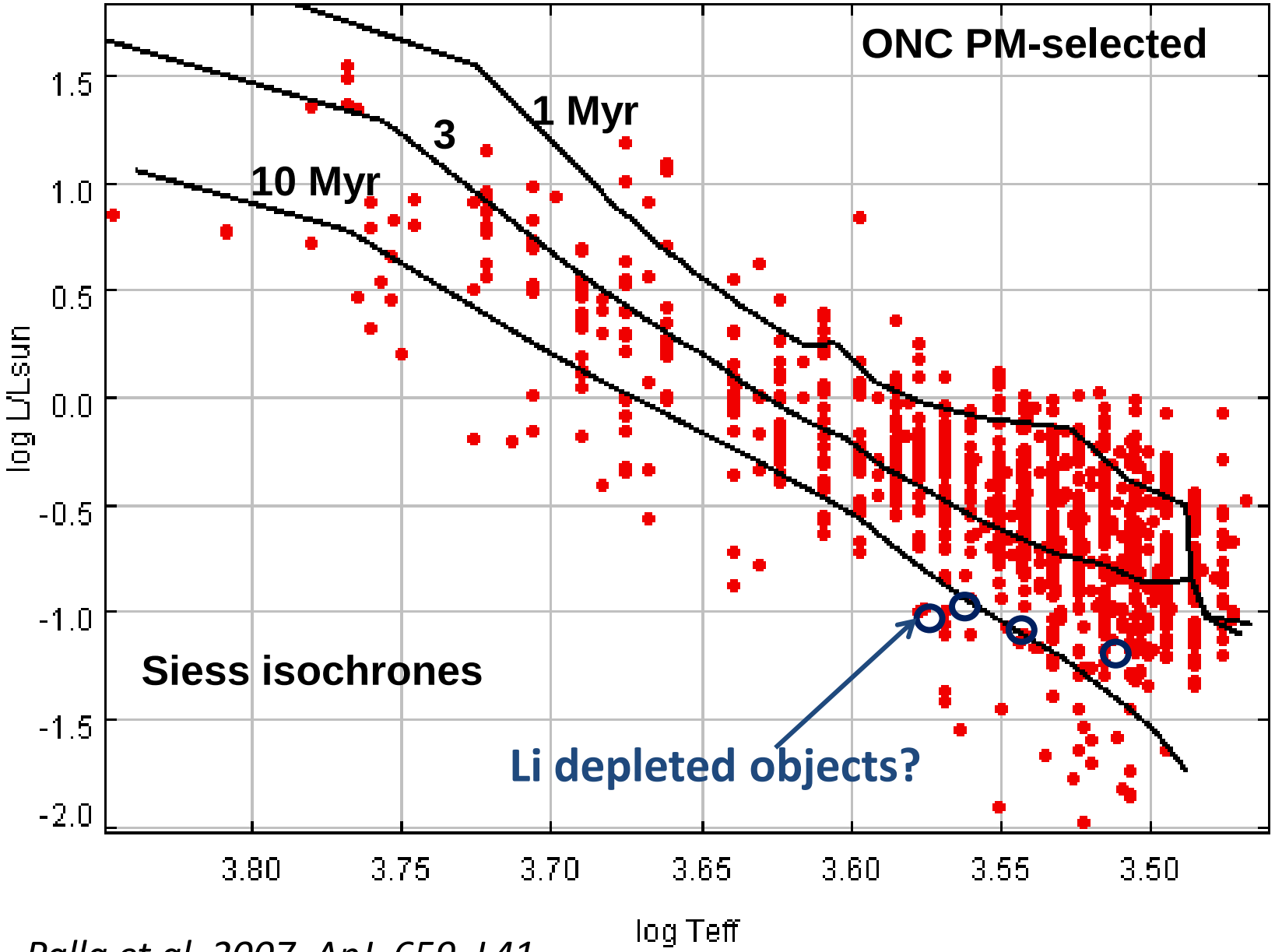
Assessment of confounding uncertainties suggests so.

Spread in stellar radii suggests so.

So… **Yes!**

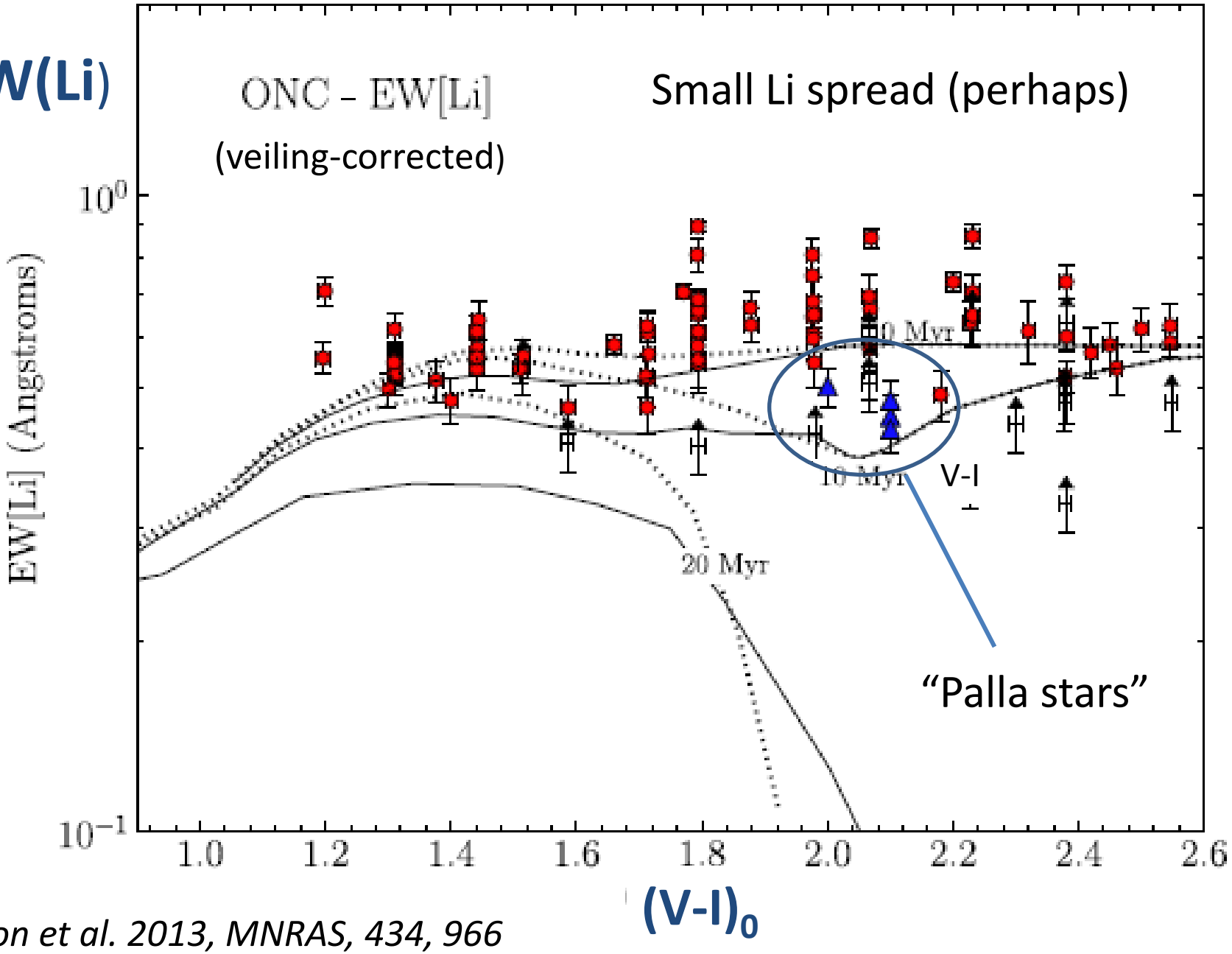
But does this imply an age spread?

We need **independent clocks** to confirm the reality of the spreads and **absolute ages** to assess their magnitude.

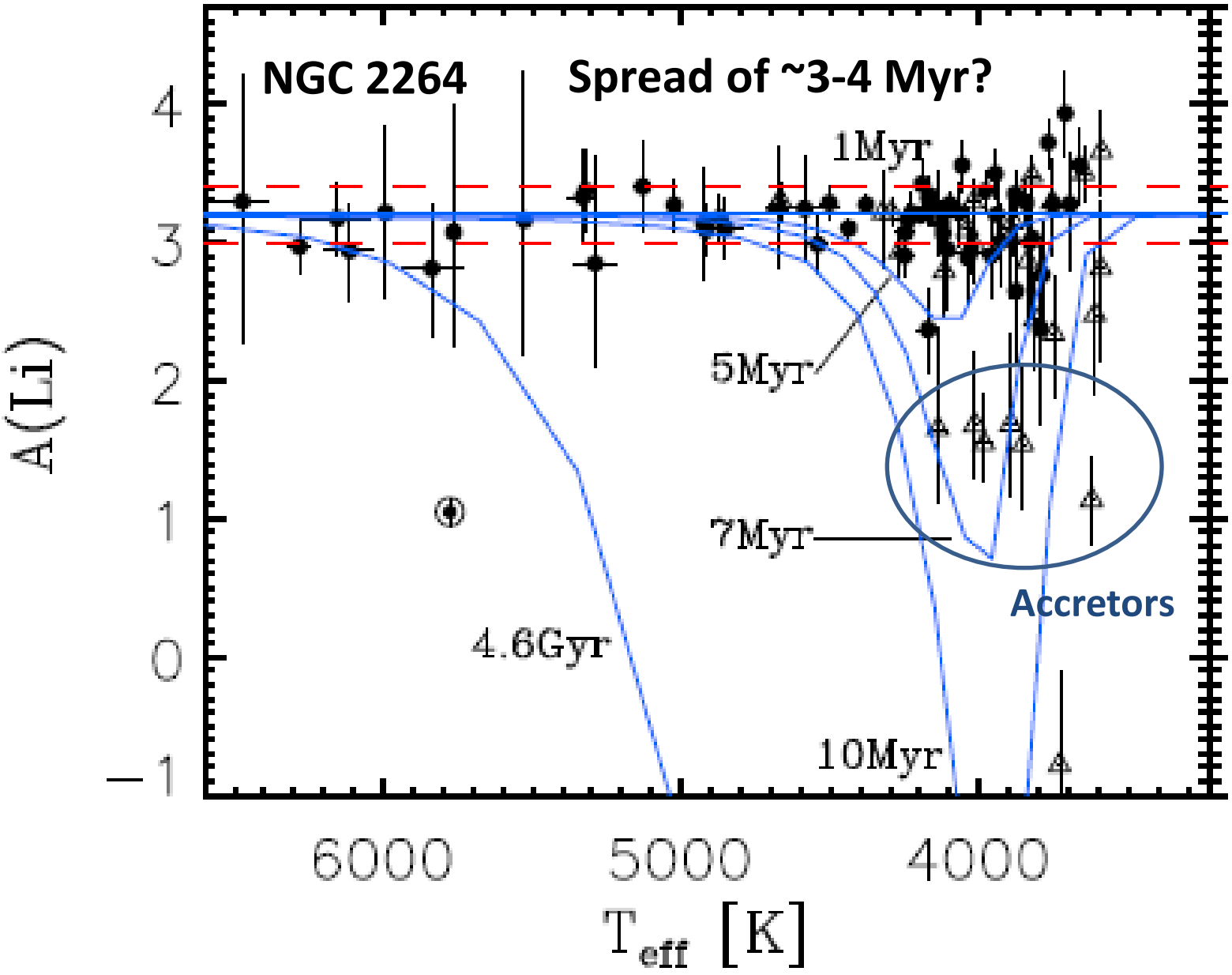


Palla et al. 2007, ApJ, 659, L41

EW(Li)



Sergison et al. 2013, MNRAS, 434, 966



Lim et al. 2016, ApJ, 831, 116 (see also poster by Venuti et al.)

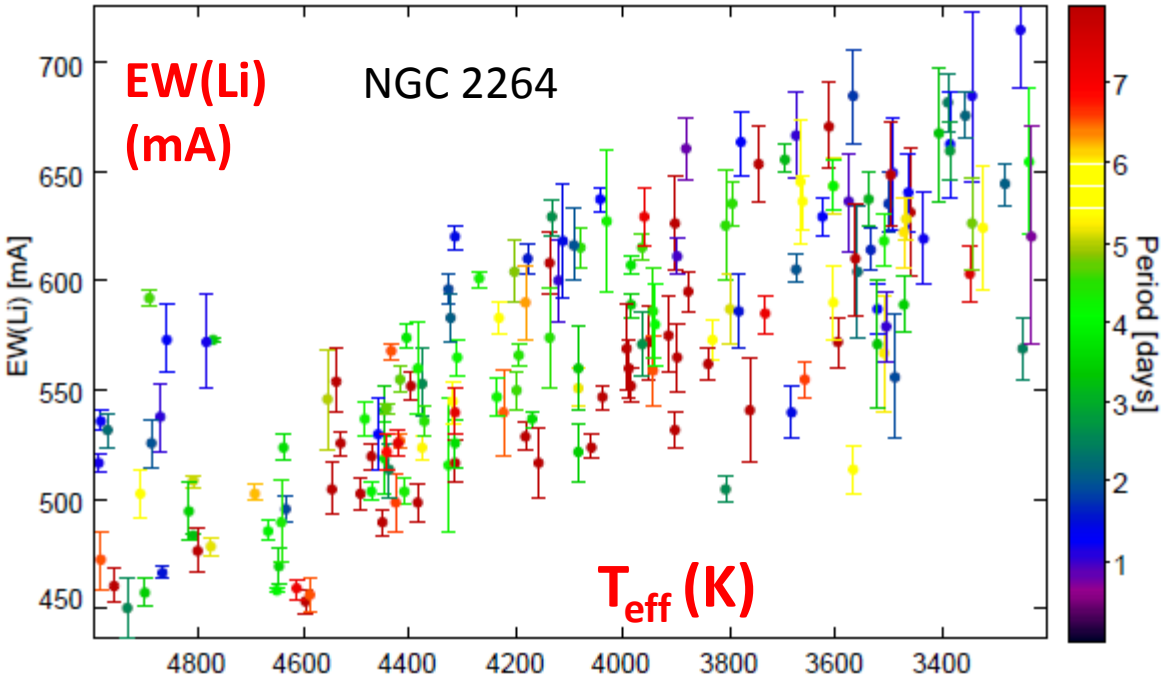
Problems with current interpretations:

But there are problems – specifically with the “vanilla “evolutionary models

- Why is Li depletion correlated with rotation and why do Li-depletion ages and isochronal ages disagree?

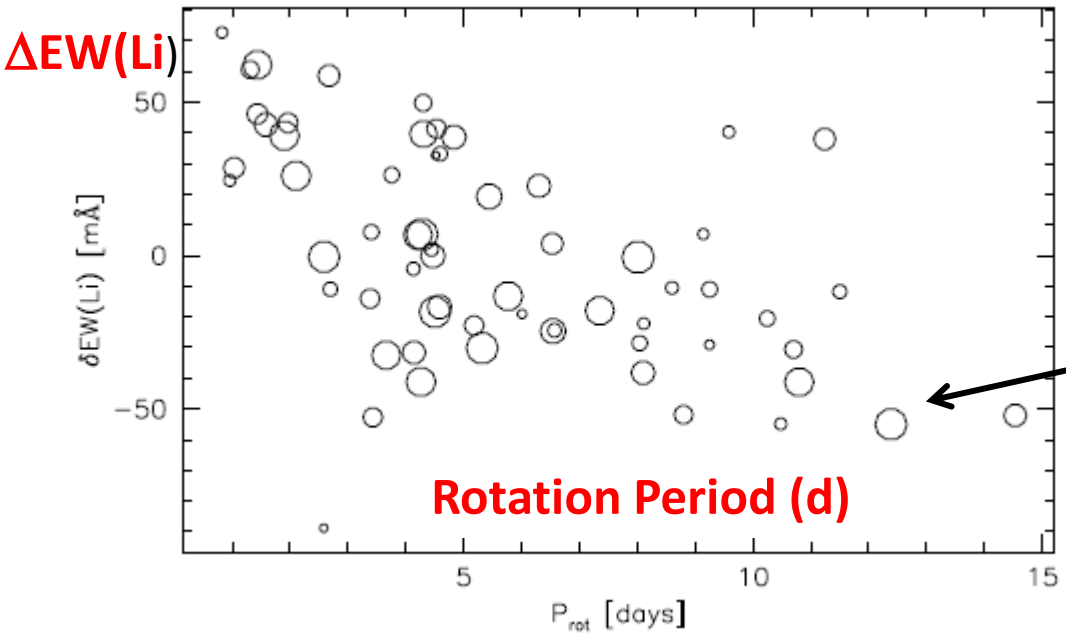
- Why are the ages of massive stars in young stars judged to be a factor of two older than those of low-mass stars?

- Why do current models fail to correctly predict the position of PMS eclipsing binaries in the HR diagram?



Extensive new data from the Gaia-ESO survey.

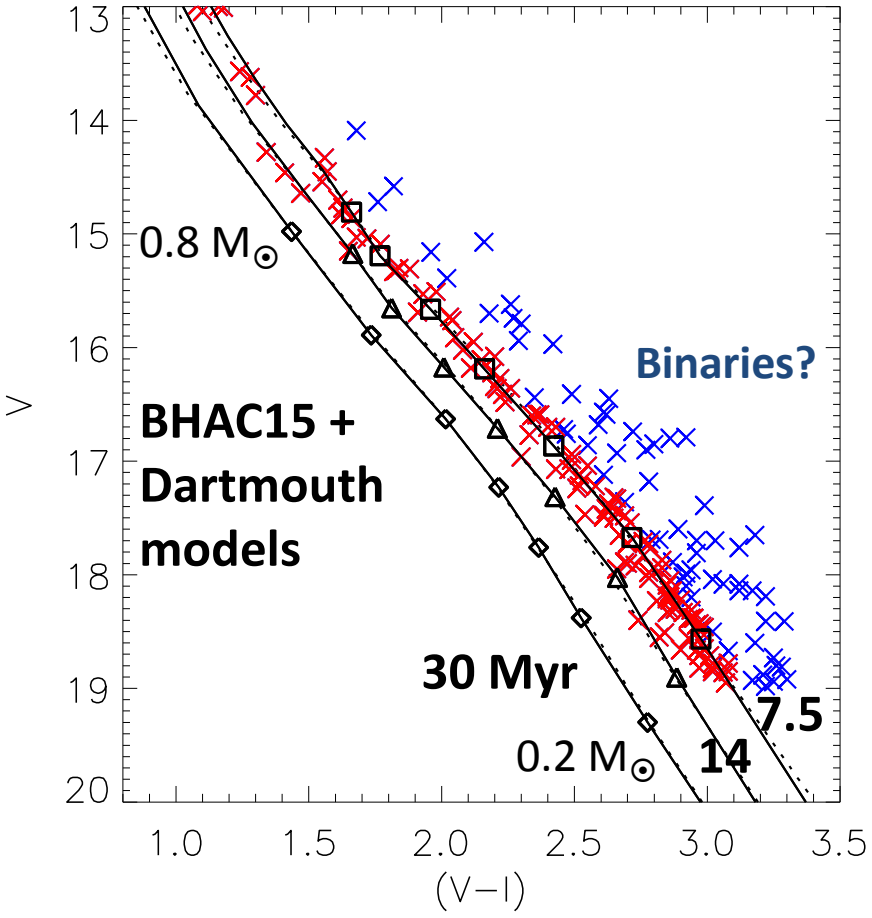
Confirms a small Li depletion spread. In NGC 2264

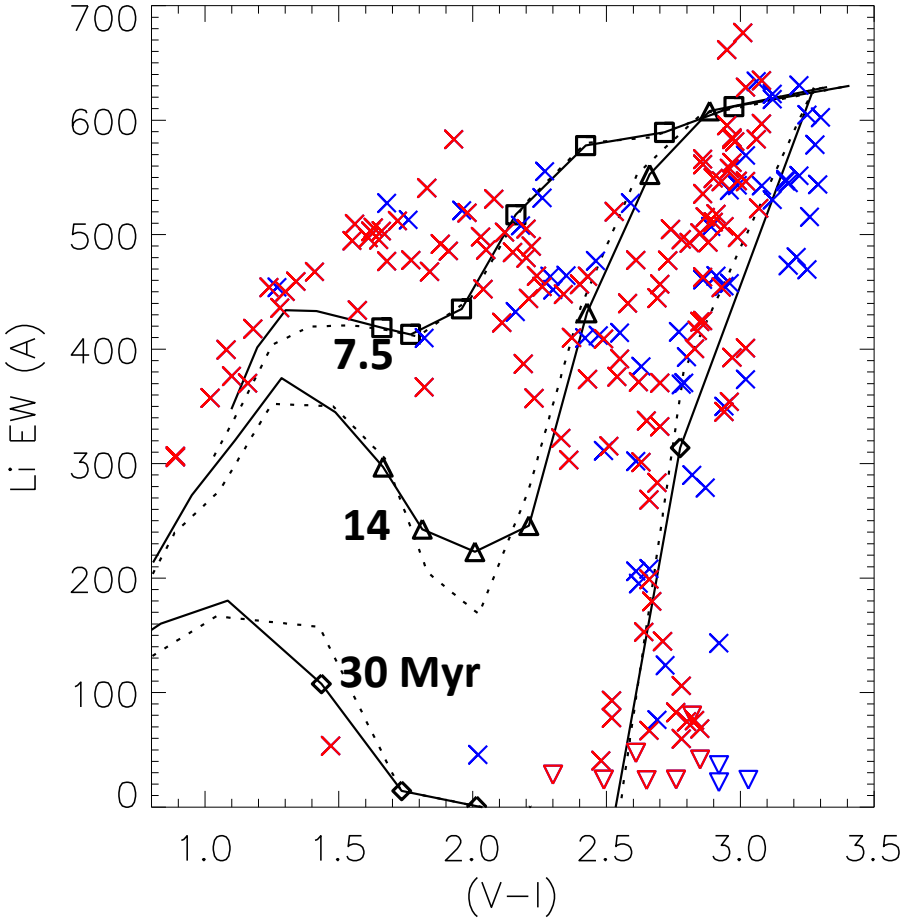


BUT – strong correlation with rotation rate.

SLOW rotators deplete more Li

Bouvier et al. 2016, A&A, 590, A78





Gaia-ESO observations of the Gamma Vel cluster

CMD **and** Li depletion cannot be explained at **ANY** age

Jeffries et al. 2017, MNRAS, 464, 1456

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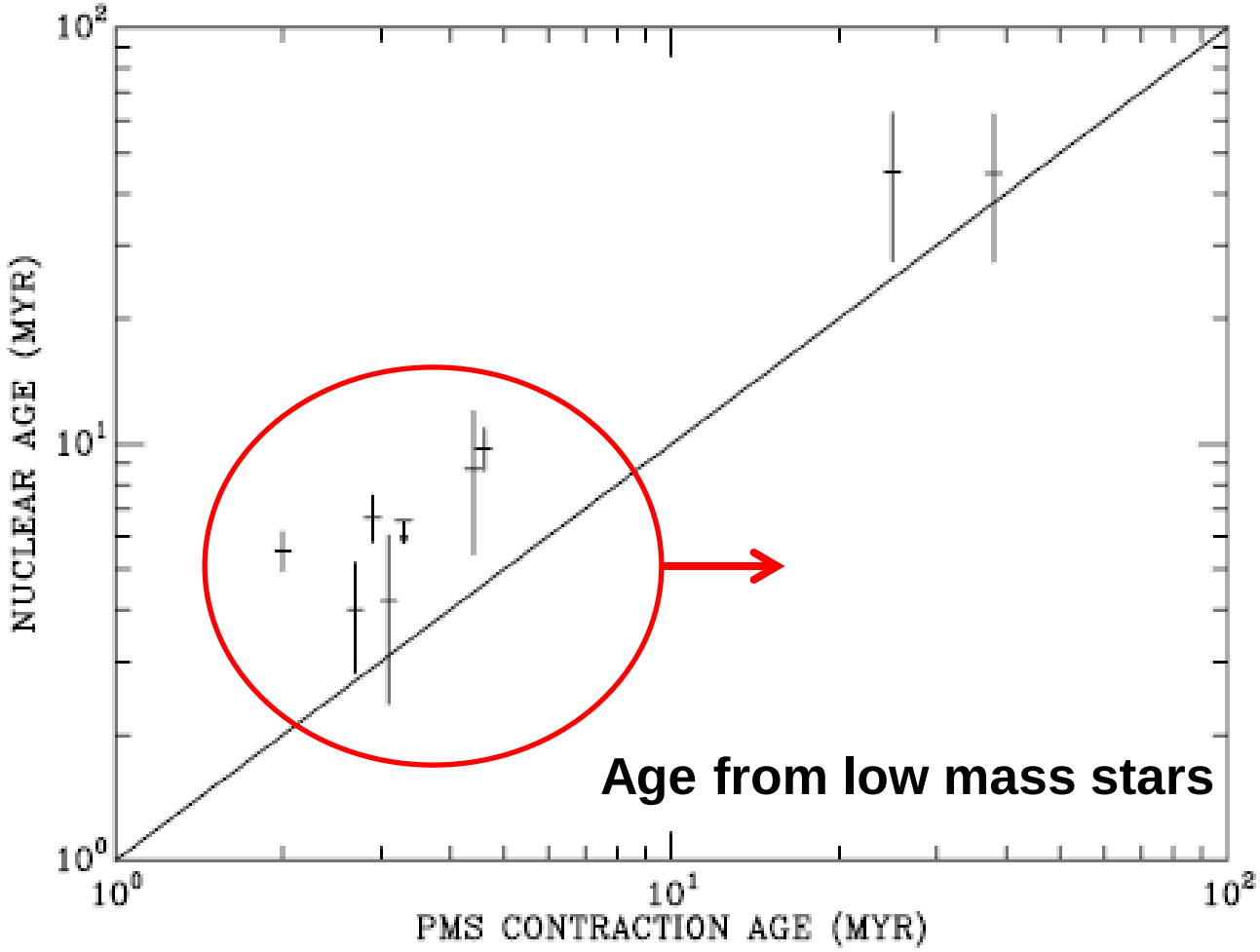
More problems: Stellar ages

PMS ages are a factor two younger than turn-off ages in young clusters

Age from high mass stars



Naylor 2009, MN, 399, 432

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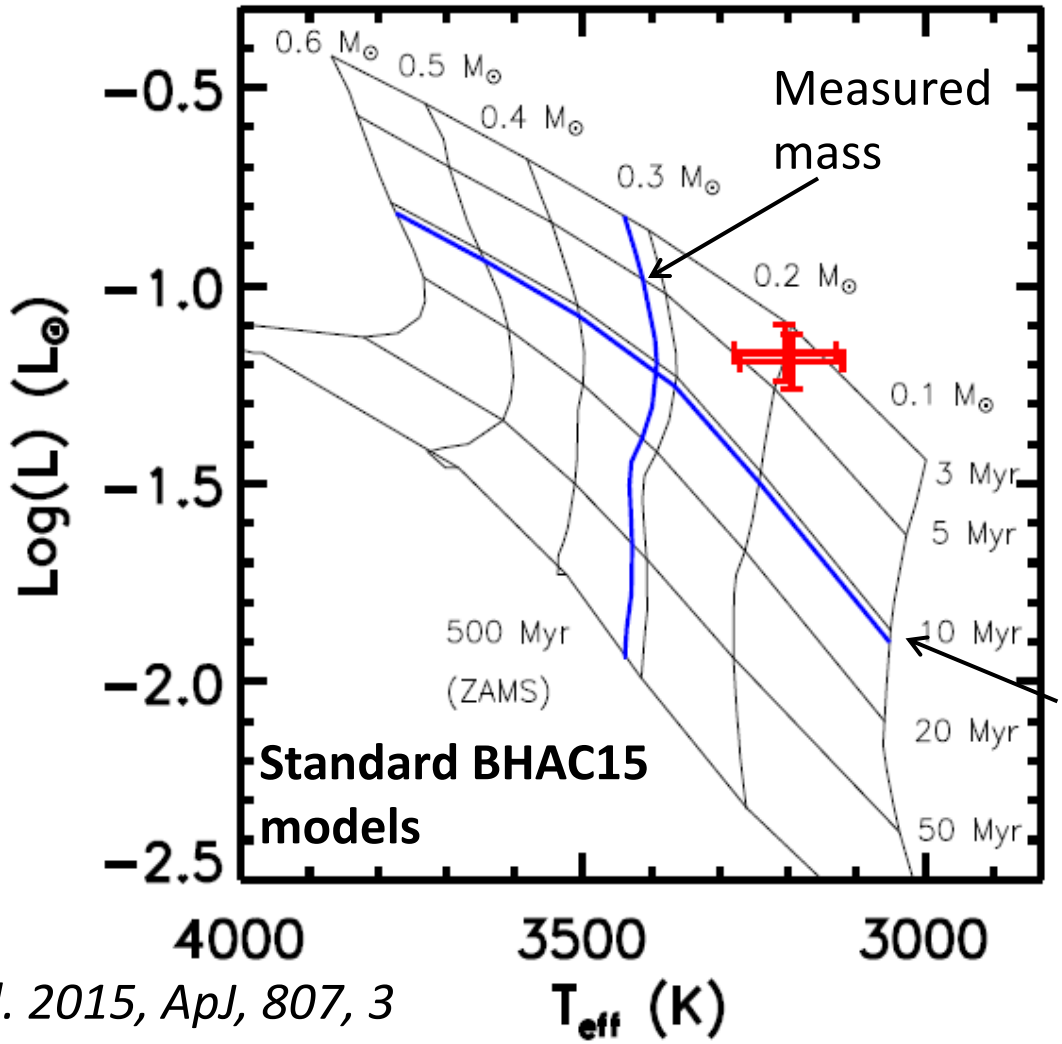
More problems: Fundamental Parameters

PMS eclipsing binaries appear <u>colder</u> than predicted by the models (or larger at the same luminosity)



Binary
In Upper Sco

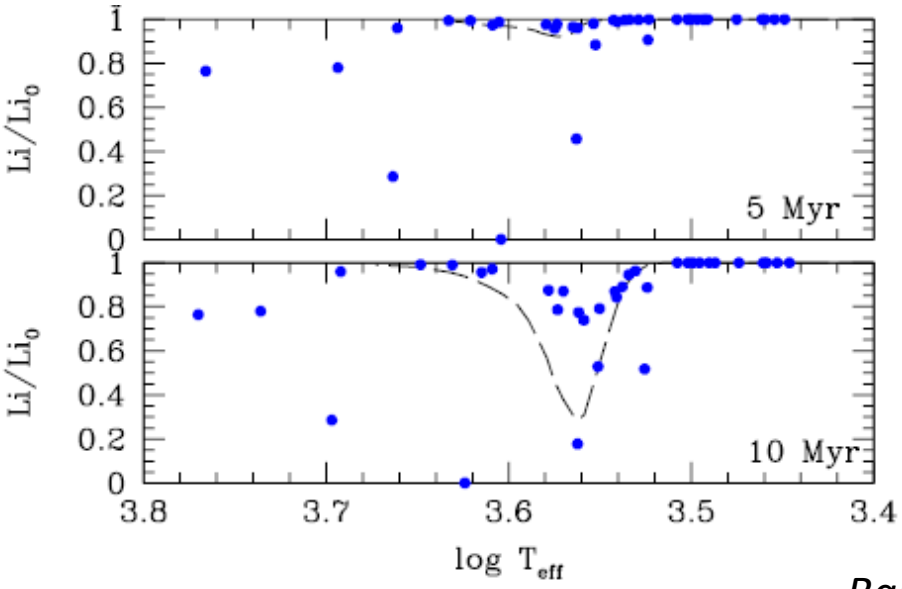
Age 11 Myr from higher mass stars

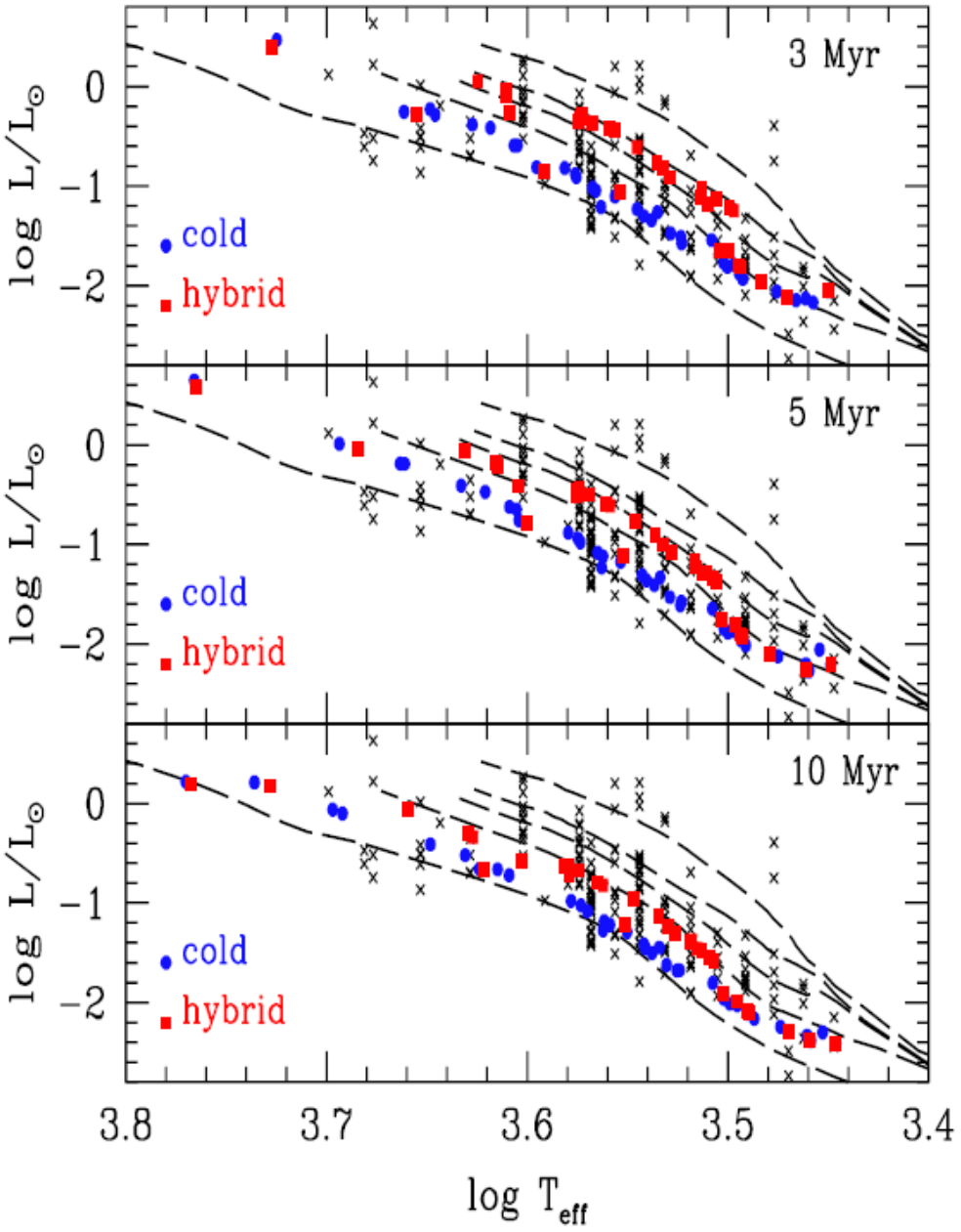
Kraus et al. 2015, ApJ, 807, 3
David et al. 2016, ApJ, 816, 21

New ideas I.

Baraffe et al. 2017, A&A, 597, A19
Baraffe et al. 2012, ApJ, 756, 118
*Vorobyov et al. 2017 arXiv:*1706.00502
Kunitomo et al. 2017, A&A, 599, A49

Early, episodic accretion can leads to spreads in the HR diagram **and** of Li depletion for **coeval** stars.





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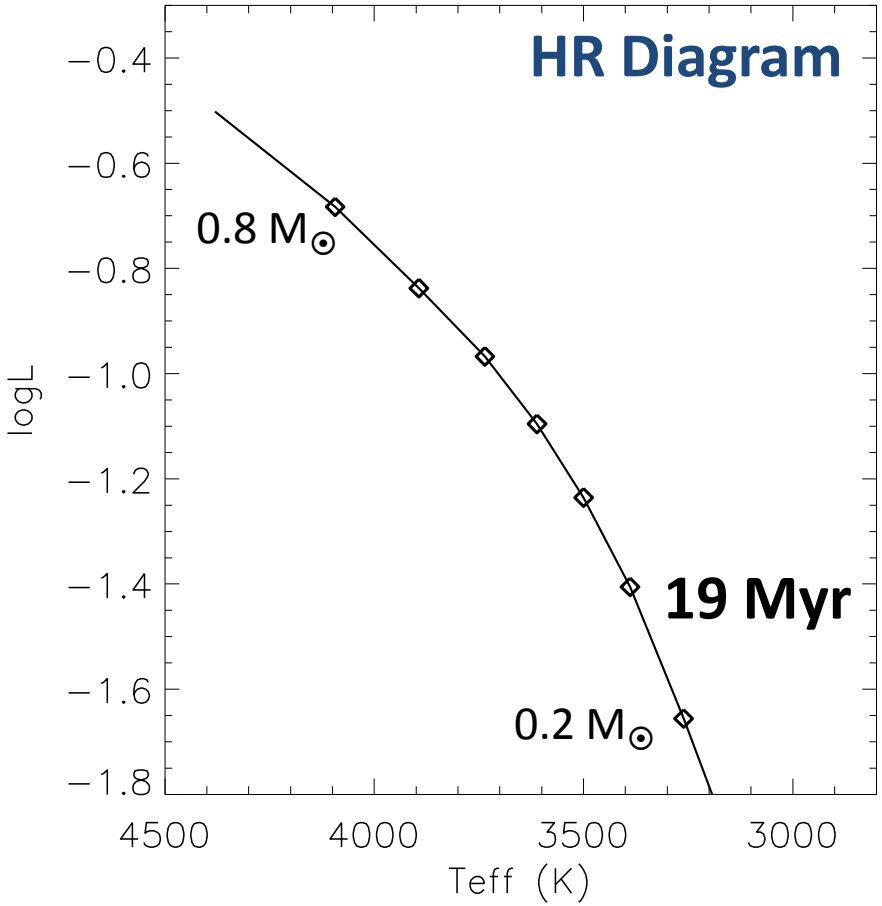
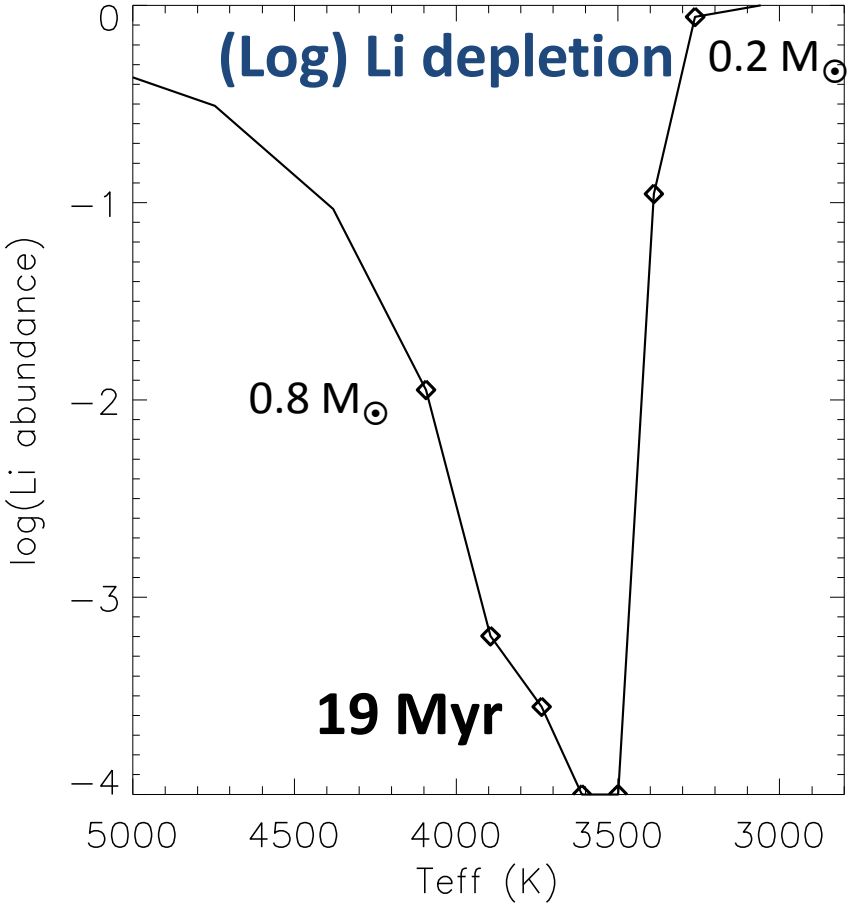
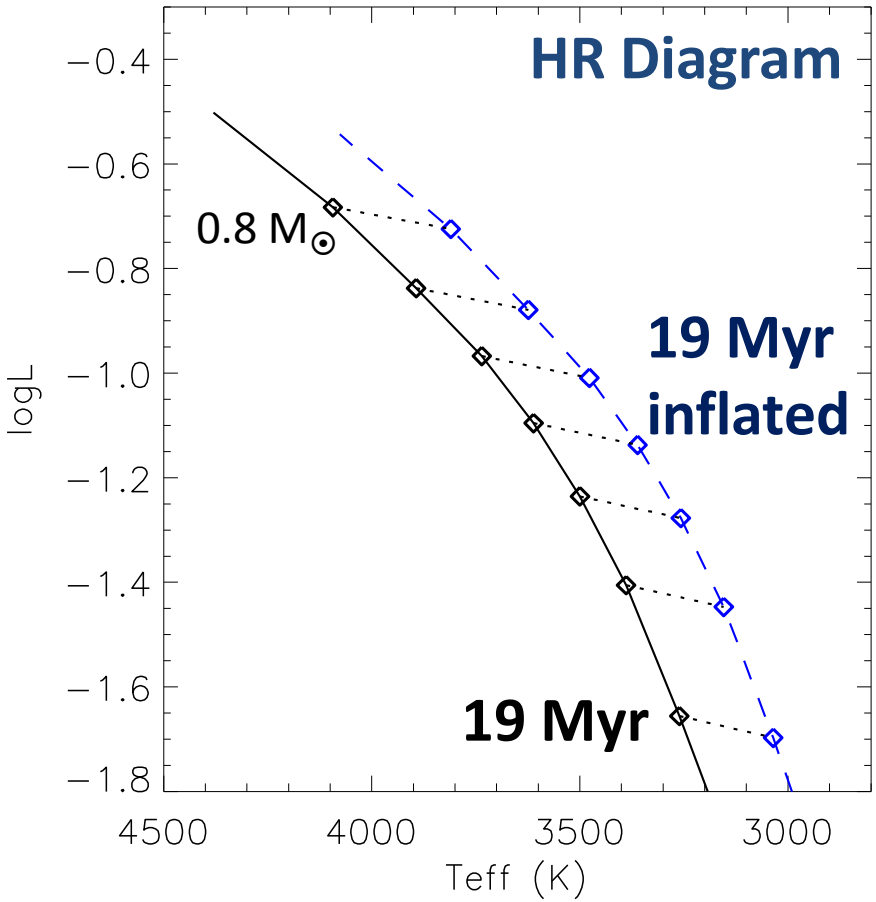


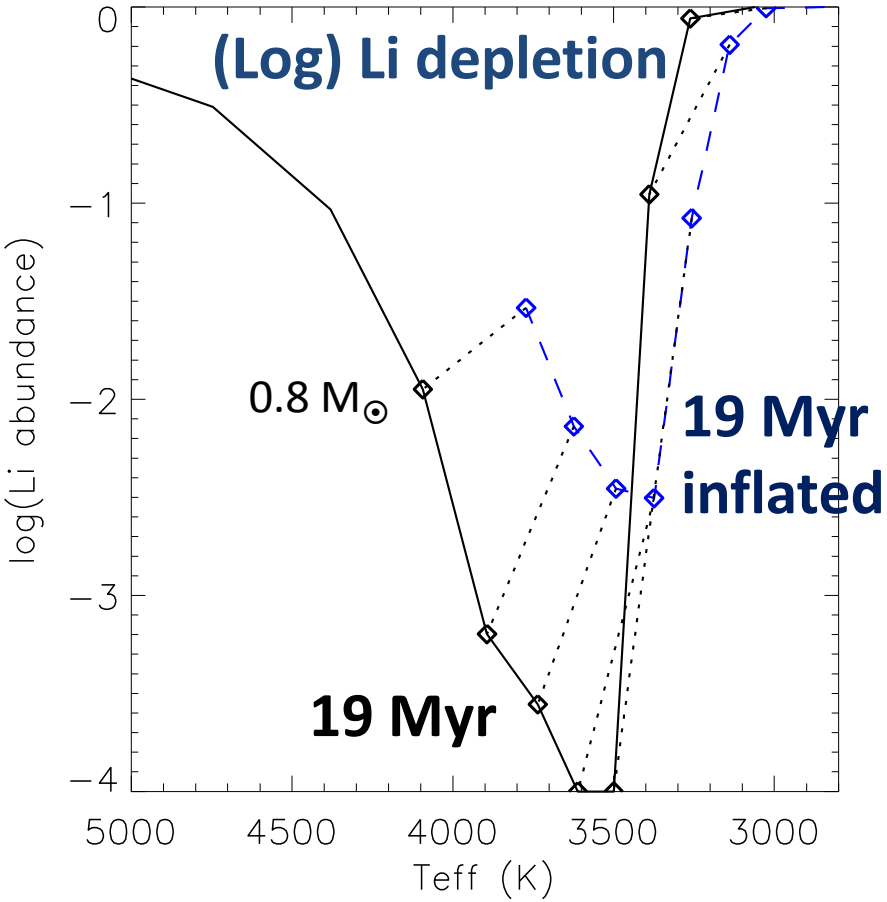


New Ideas II. Suppose stars are "inflated" by 10%

The cause could be magnetic inhibition of convection or starspots

Feiden & Chaboyer 2014, ApJ 789, 53; Jackson & Jeffries 2014, MNRAS, 441 2111; Somers & Pinsonneault 2015, ApJ, 807, 174





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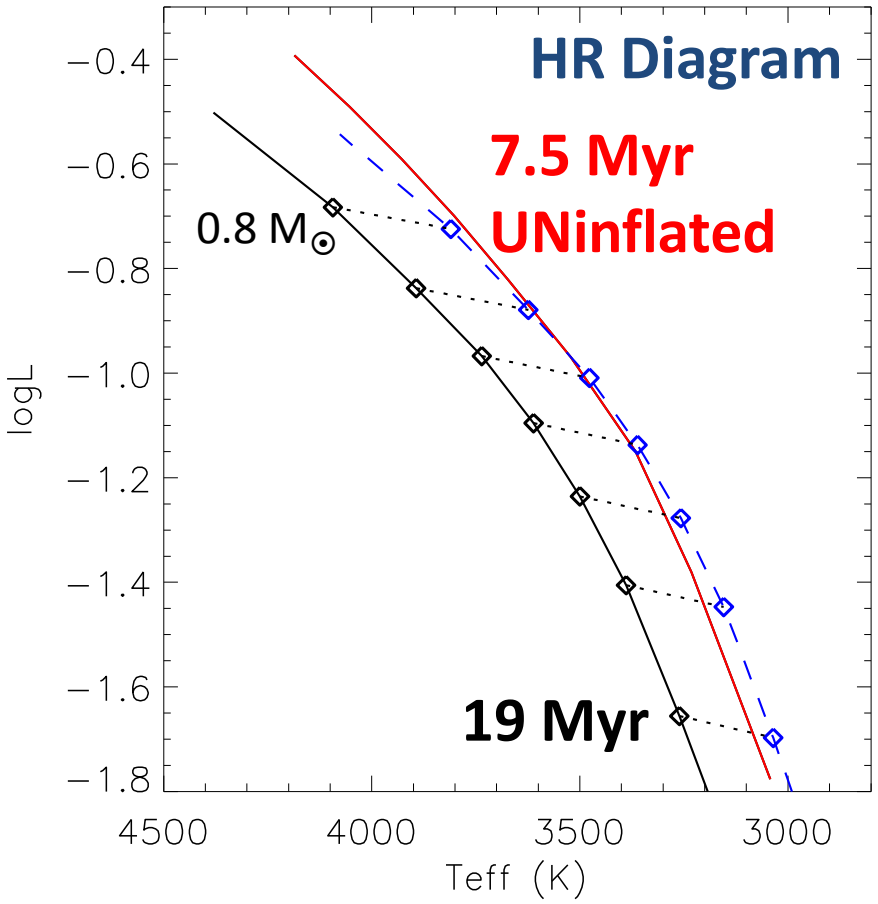
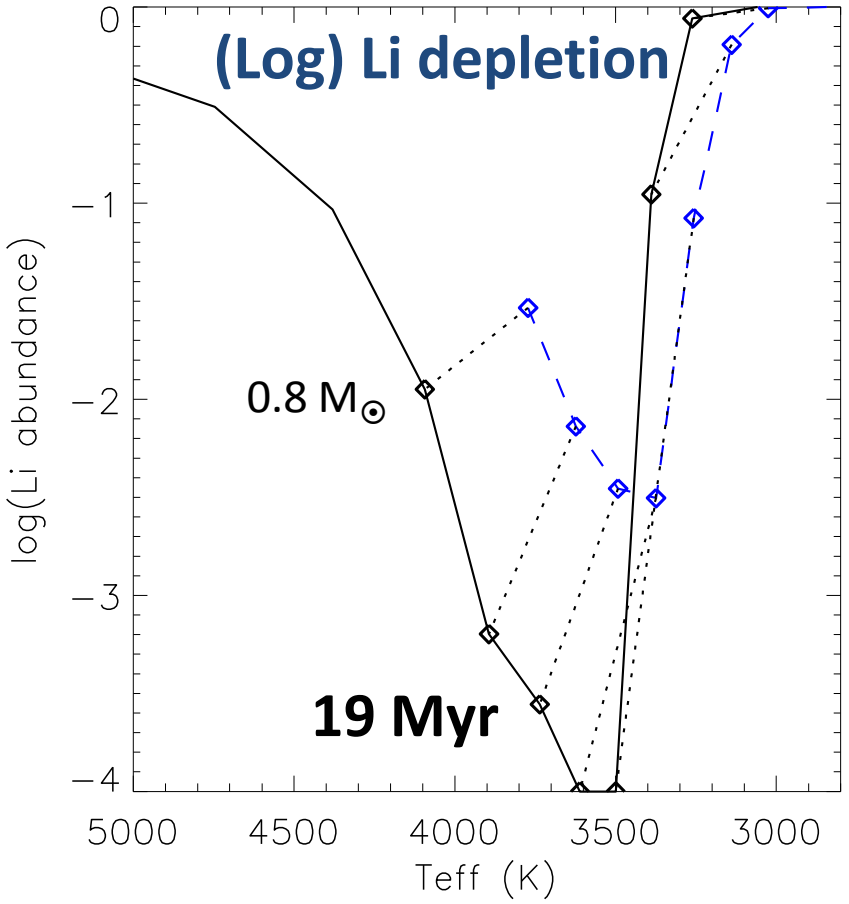




New ideas II. Suppose stars are "inflated" by 10%

An "inflated" 19 Myr isochrone in the CMD **matches** a 7.5 Myr standard isochrone and pushes Li depletion to **cooler** temperatures

Consequences

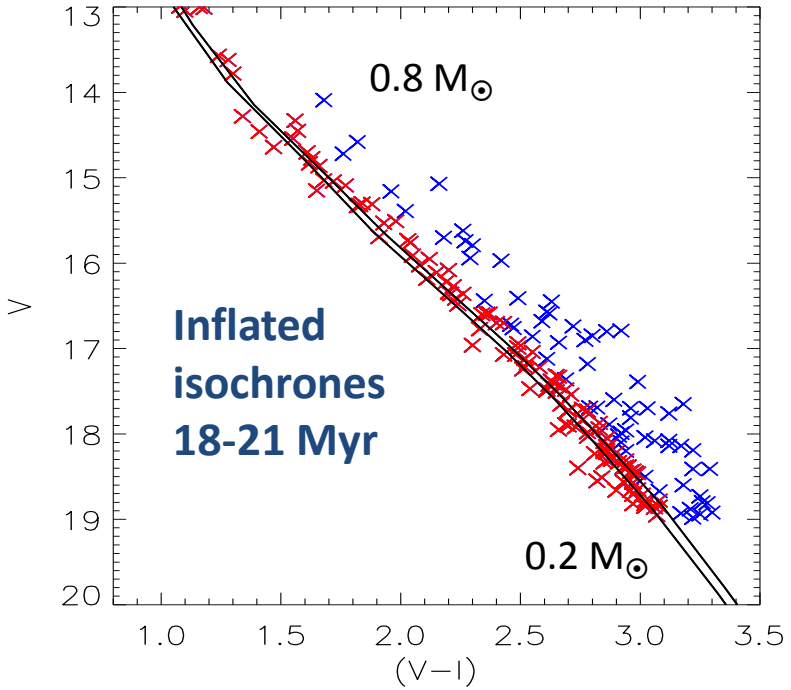
PMS stars are **OLDER** and **MORE MASSIVE** than you thought.

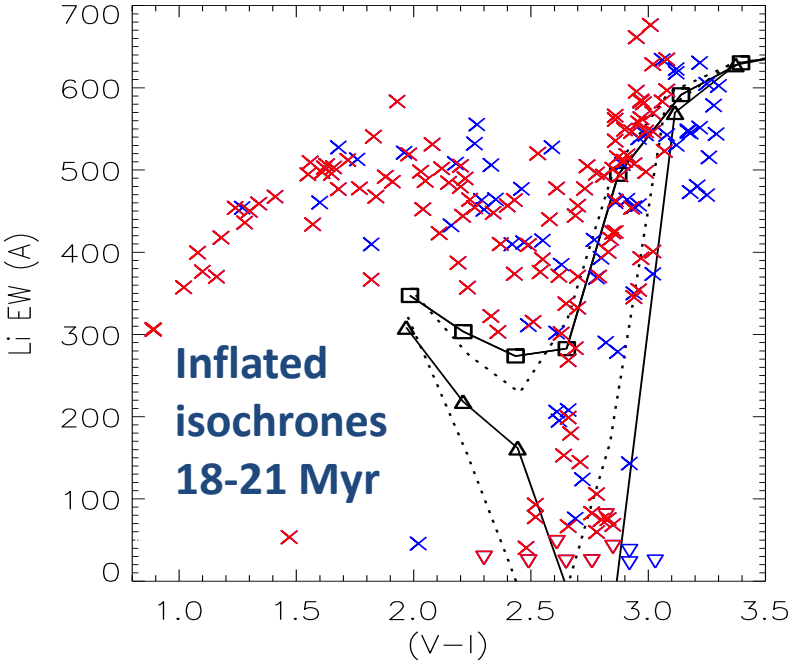
Causes additional dispersions in HRD and in Li depletion

Makes high-mass and low-mass stars coeval

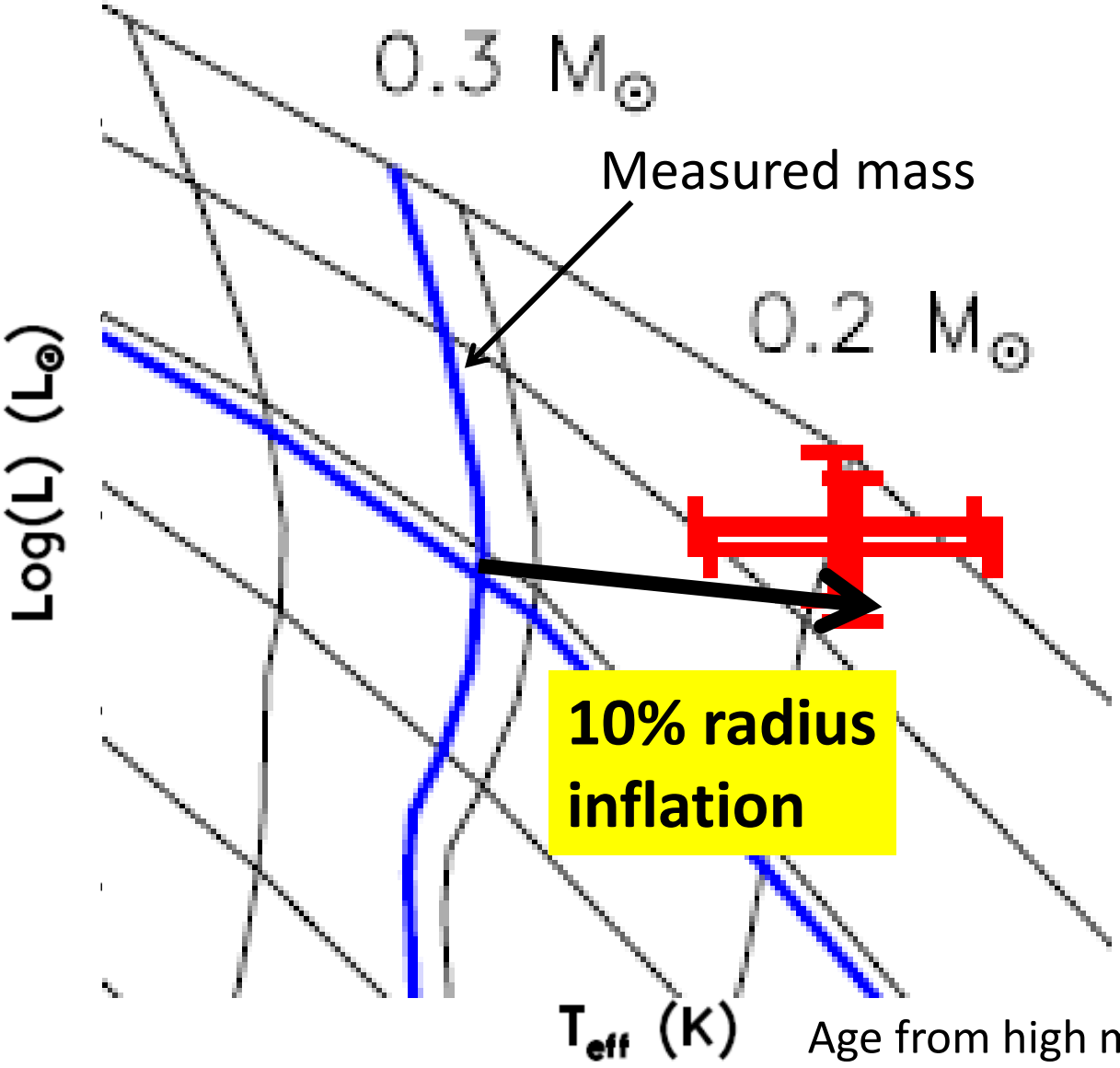
Solves eclipsing binary HR diagram problems

Feiden 2016, A&A, 593, A99
Messina et al. 2016, 596, A29
Jeffries et al. 2017, MNRAS, 464, 1456





Eclipsing binary in Upper Sco – problem solved!



Age from high mass stars

Kraus et al. 2015, ApJ, 807, 3

Summary

- Dispersions in the HR diagram and Li depletion patterns of young clusters remains a vibrant research topic.
- The majority view is that age spreads are a lot smaller than 10 Myr (within a single cluster).
- The spreads in the HR diagram cannot be explained solely in terms of observational scatter; some of the spread is due to a genuine spread in radius.
- We are now moving into a new era of more sophisticated models that question the veracity both of absolute ages and inferred age spreads.