Recent developments on the formation and evolution of young low-mass stars

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Observations of young clusters that probe:

- The influence of magnetic activity and rotation on early evolution
- The ages of young (low-mass) stars
- Precision dynamics in young clusters
- Early Gaia DR2 results

With acknowledgements to Richard Jackson, Nick Wright, the Gaia-ESO collaboration and funding from STFC and NASA

APOGEE

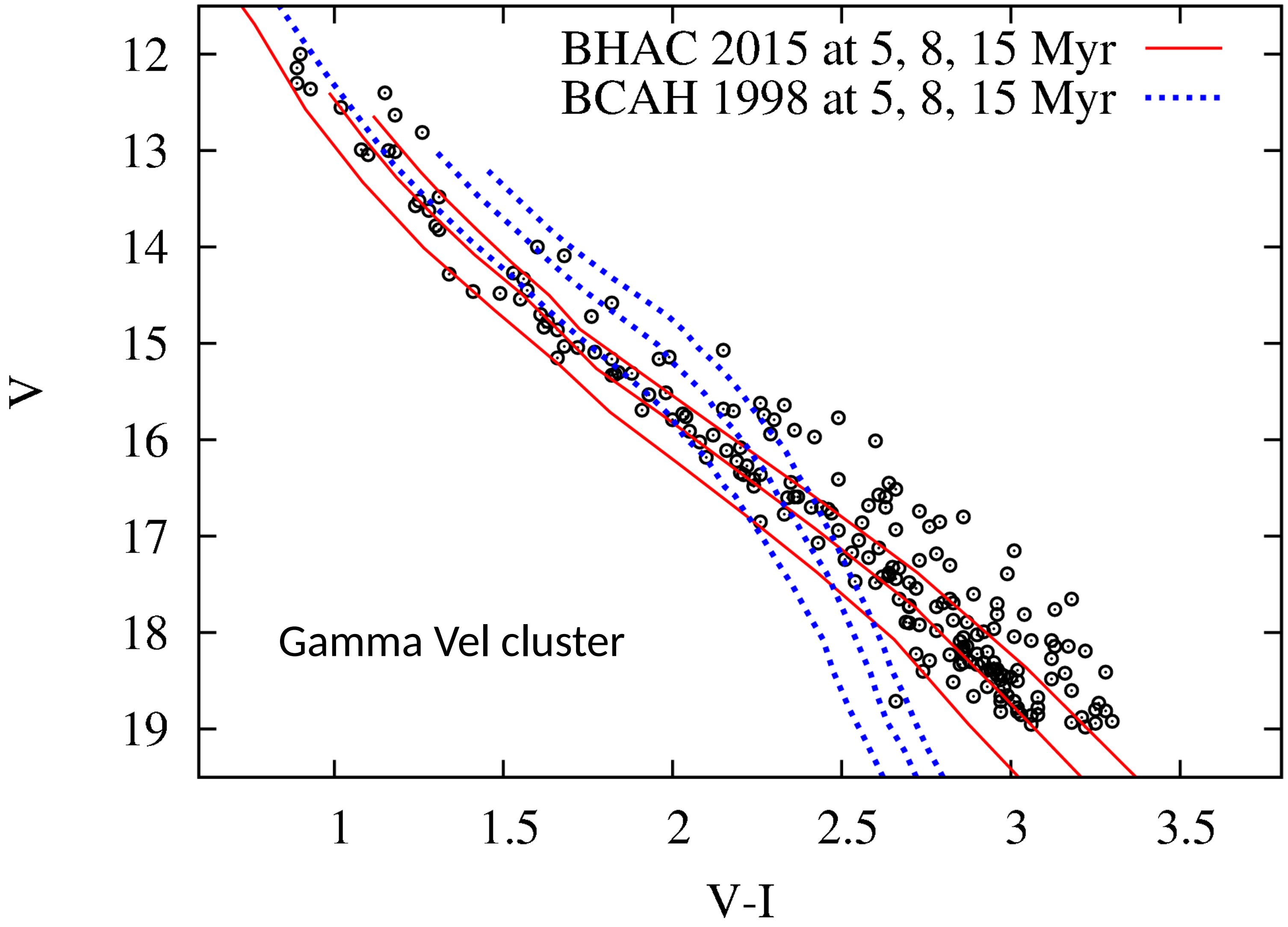
SDSSIII

gaia

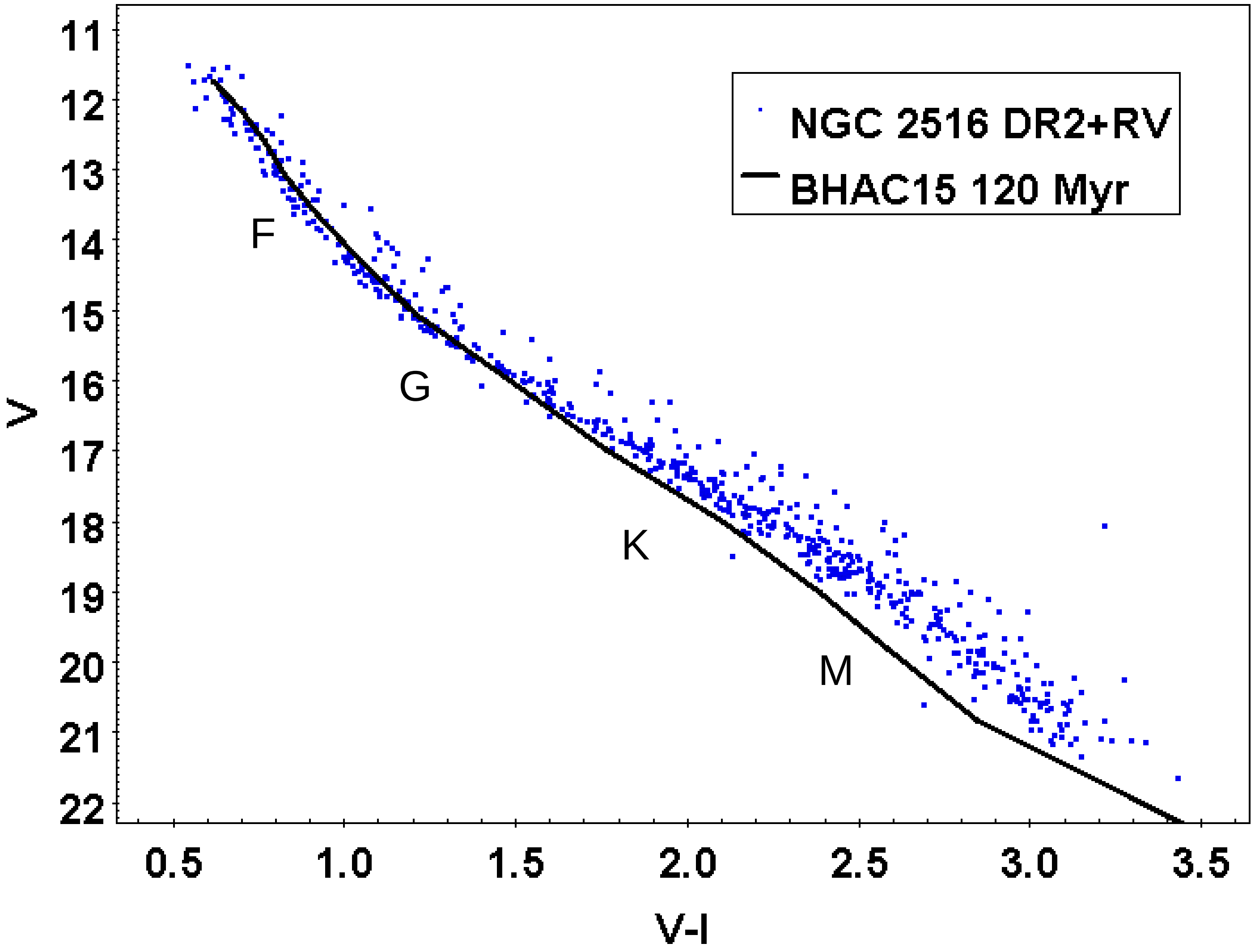
GaiaESO

K2

Improvements in stellar evolutionary models at young ages
Better match to observed colour-magnitude diagrams

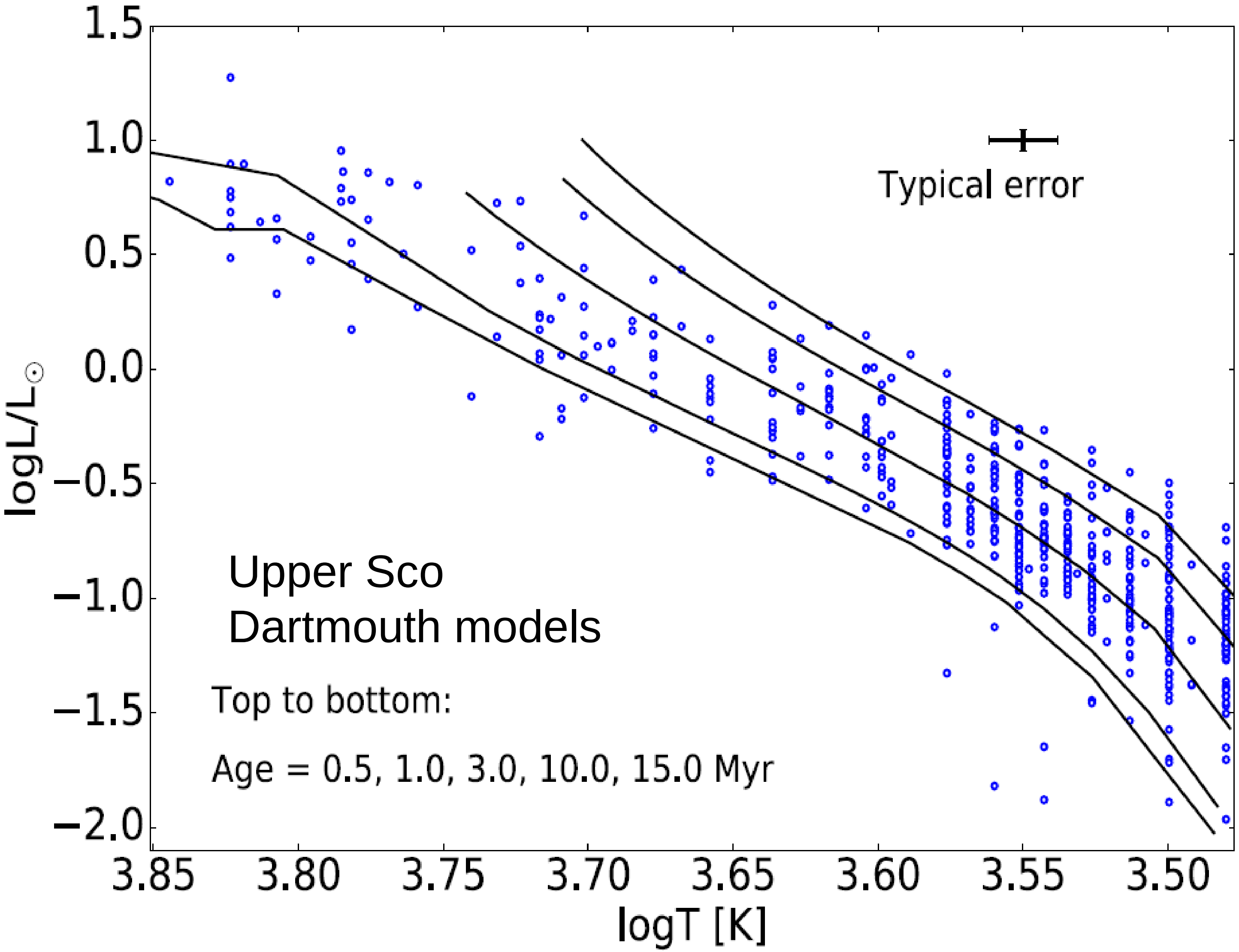


CMD: Still BIG problems for K & M stars at the ZAMS



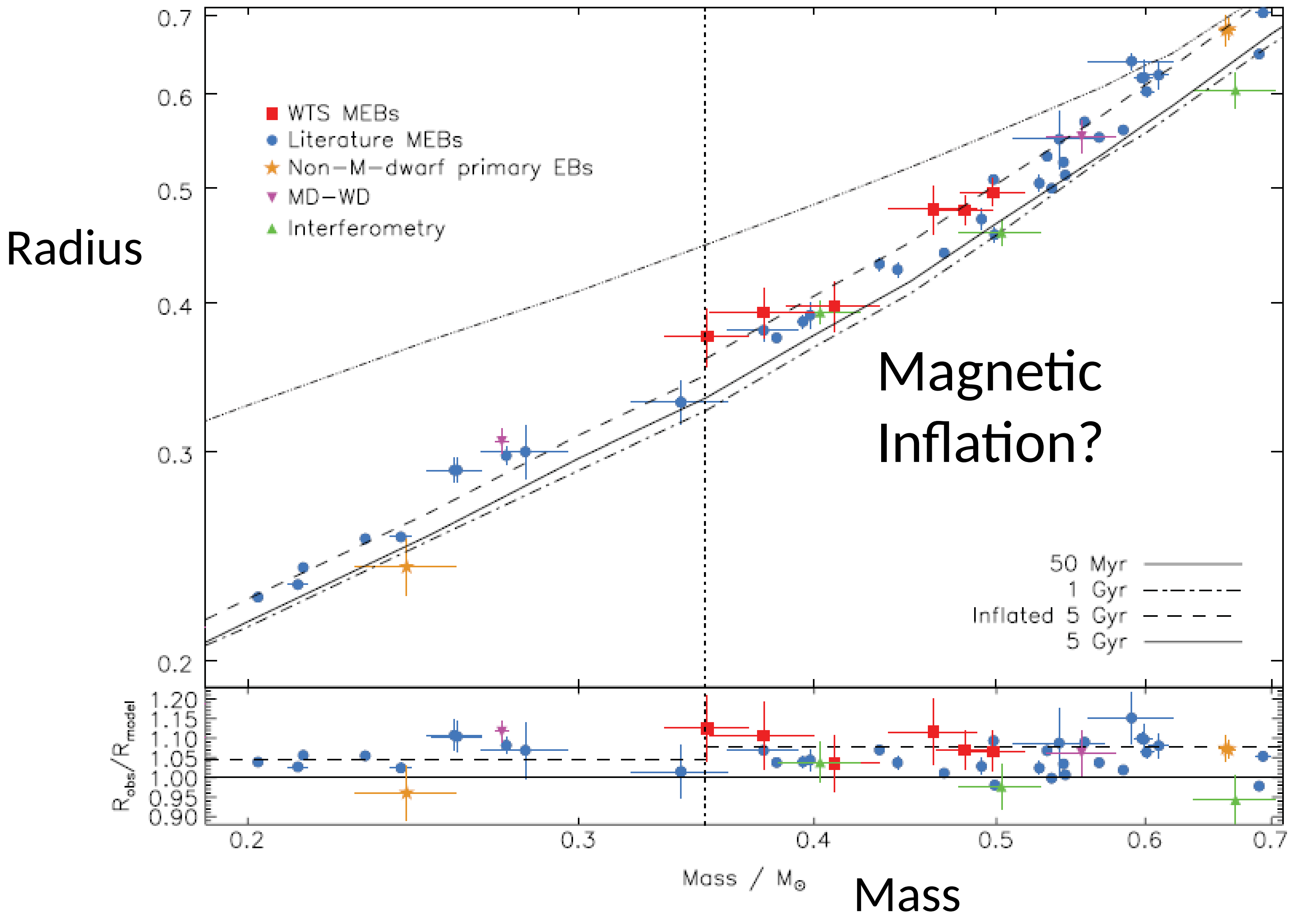
Gaia DR2 + RV selection – *Jeffries et al. in prep*

HR diagram: Ages of hotter stars older than those of cooler stars?



Fang, Herczeg & Rizutto 2017, AJ, 842, 123

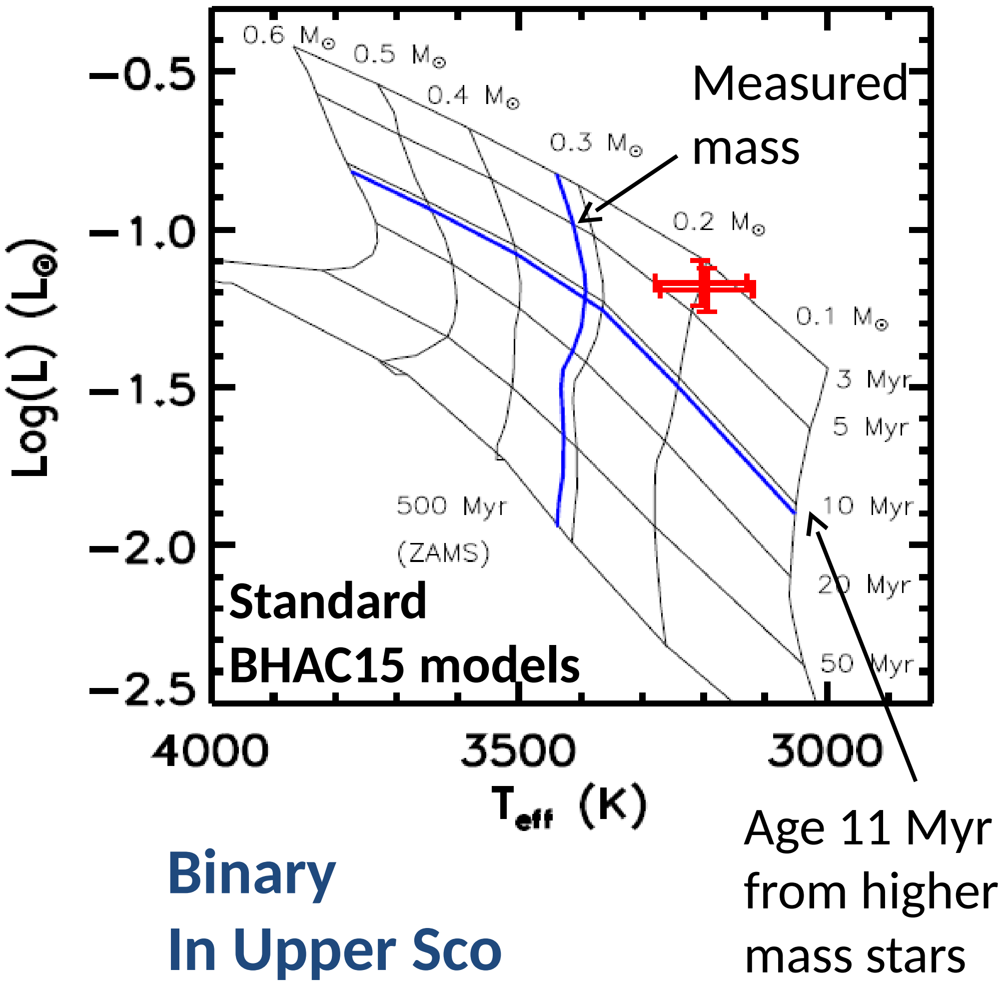
Problems with stellar evolution models



Birkby et al. 2012, MN, 426, 1507

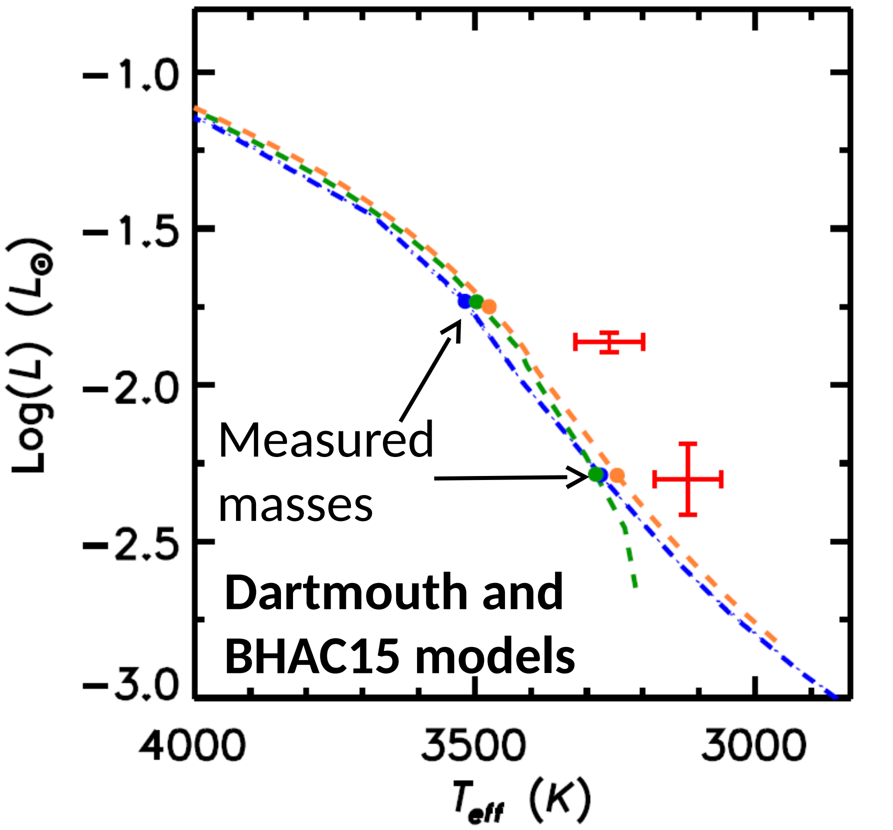
More problems: Fundamental Parameters

Low-mass PMS eclipsing binaries appear colder than predicted by the models (i.e. larger at the same mass and luminosity)



Binary In Upper Sco

Kraus et al. 2015, ApJ, 807, 3



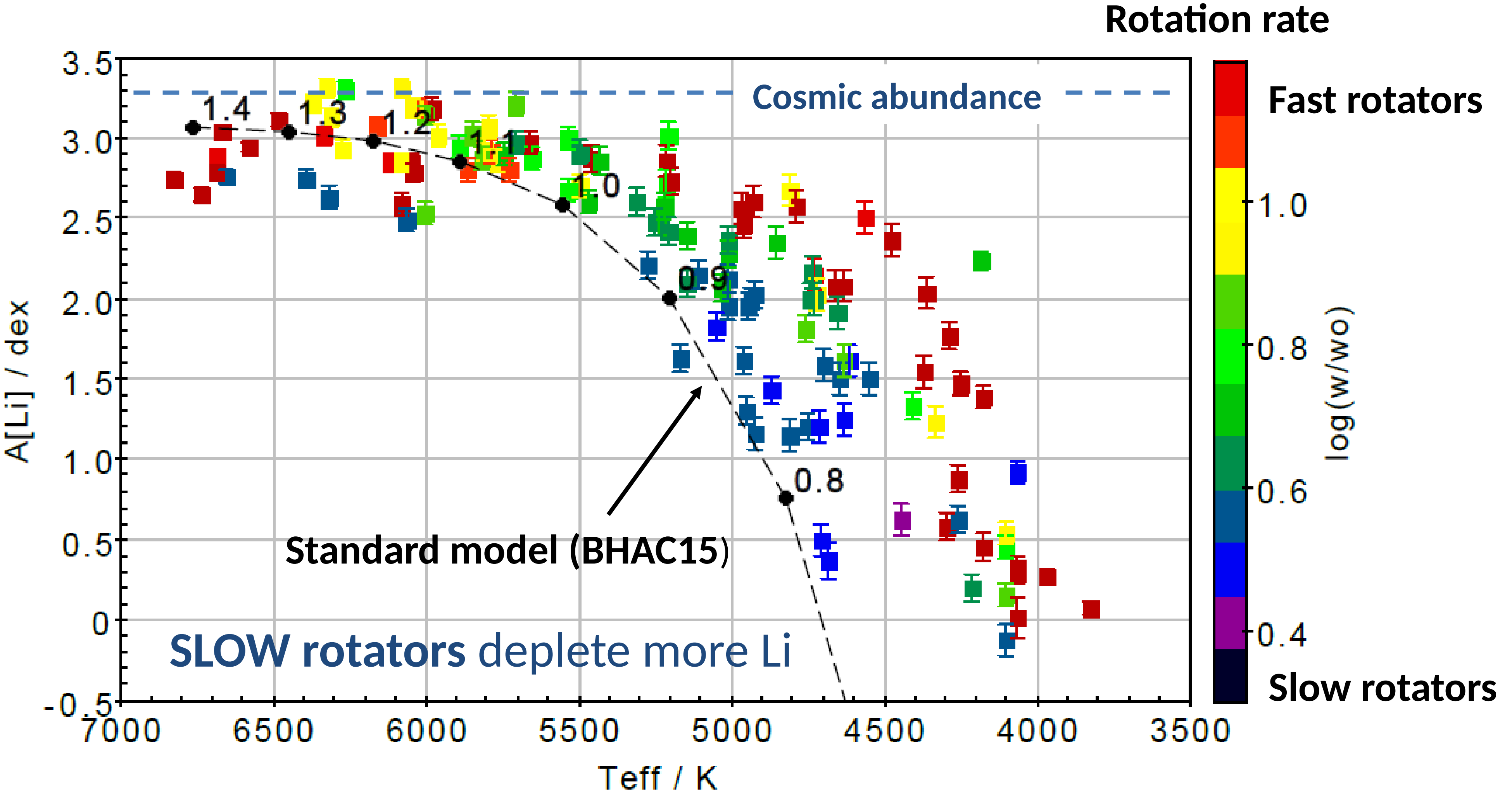
Binary In Praesepe

Kraus et al. 2017, ApJ, 845, 72

More problems: Lithium depletion

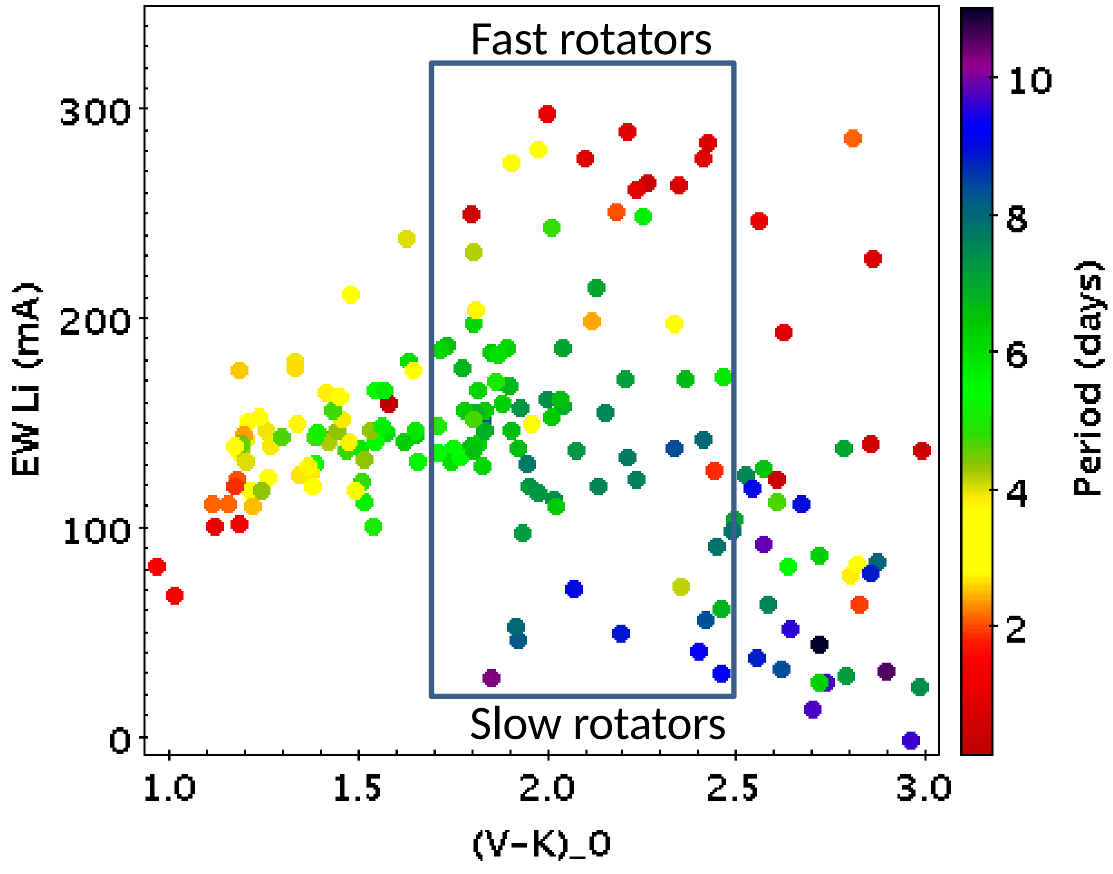
A spread of lithium depletion is apparent in young clusters

Fast rotation is correlated with less Li depletion

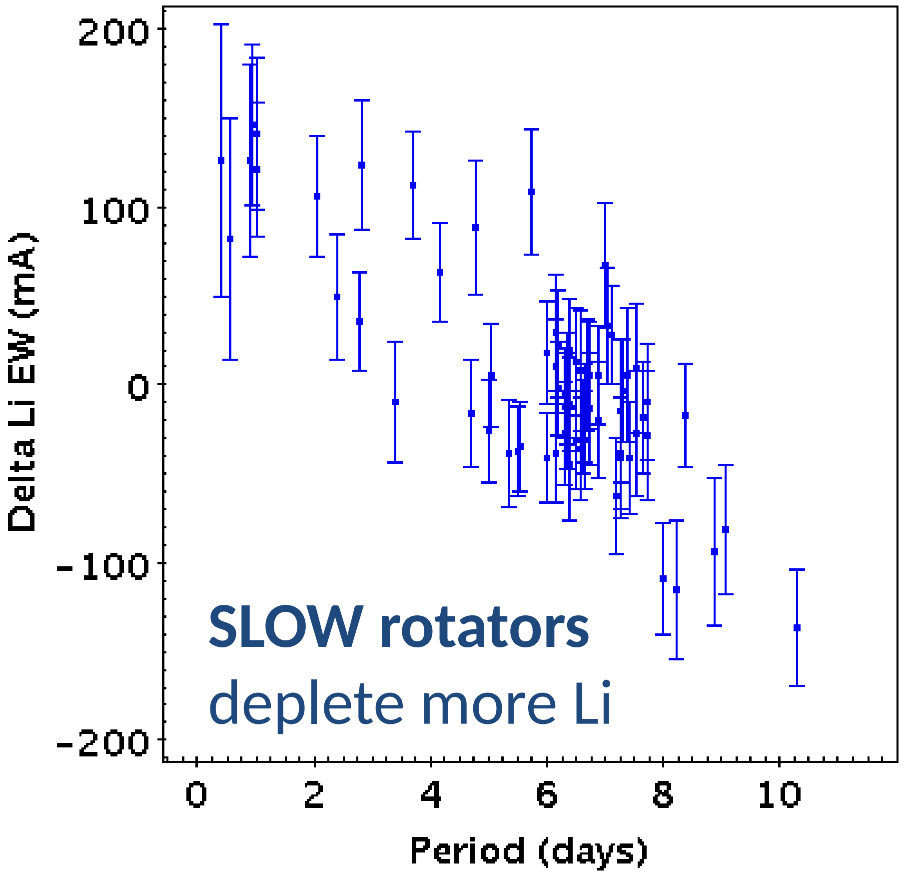


Bouvier et al. 2018, A&A, 613, 63; see also *Barrado et al. 2016, A&A, 596, 113*

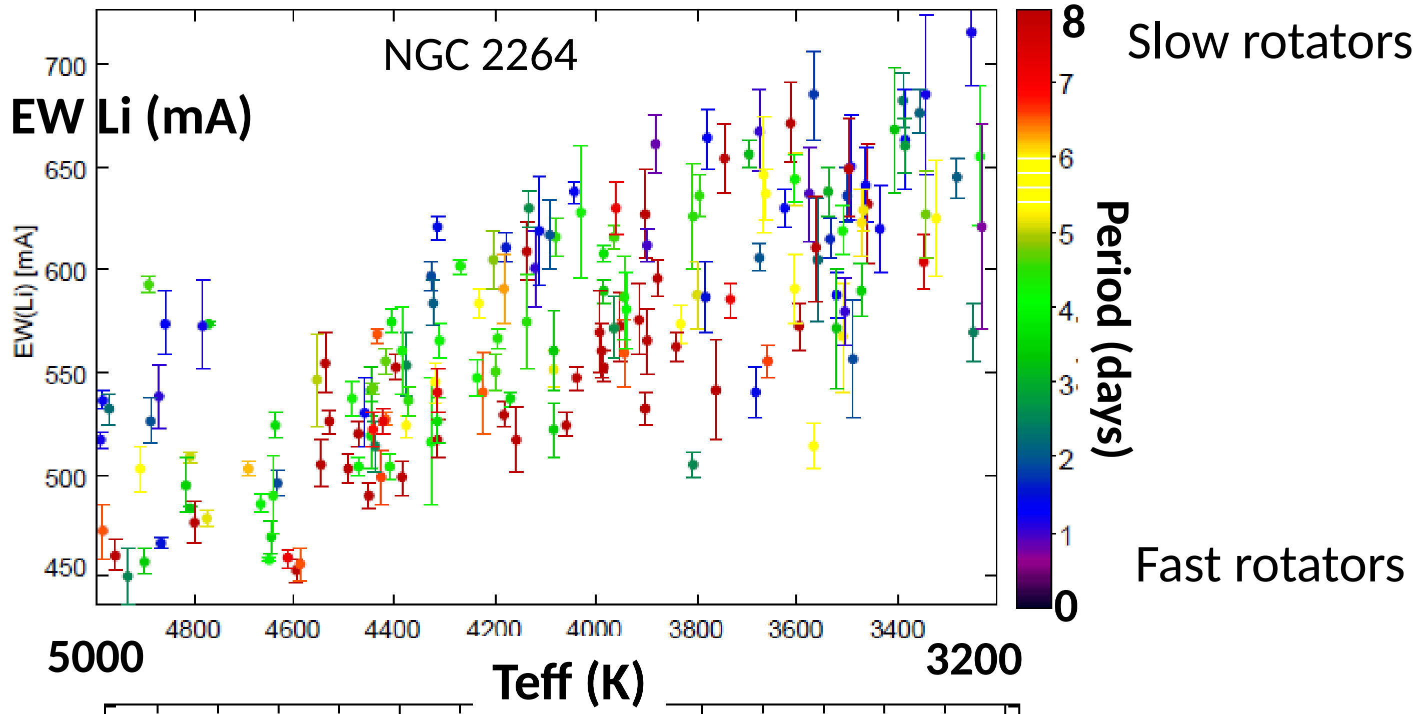
Confirmed in other clusters (with larger numbers)
K2 rotation periods + WIYN spectroscopy of M35 (age ~ 150 Myr)

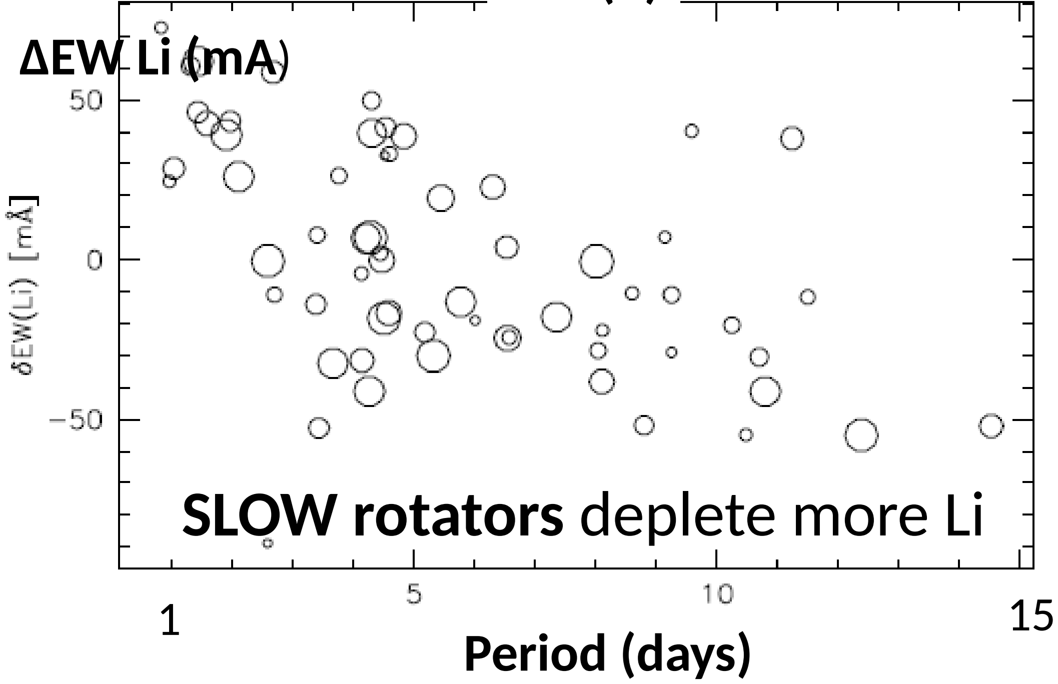


Jeffries et al. 2018 in prep.



Delta EW w.r.t median trend
$1.7 < (V-K)_0 < 2.5$



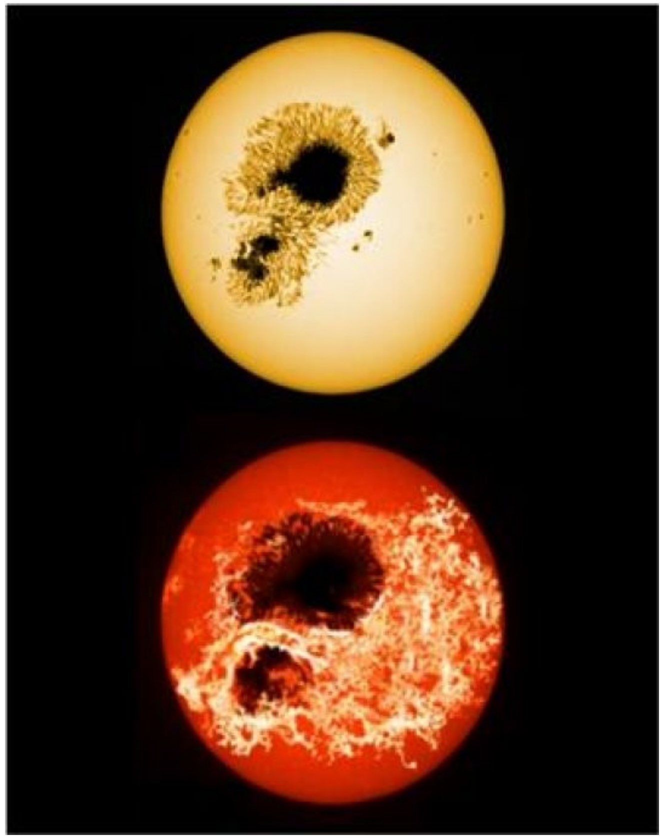


The "spreading" has already begun (with a smaller dispersion) at 5Myr in NGC 2264

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

EW Li from the Gaia-ESO survey
COROT periods from
Venuti et al. 2017, A&A, 599, A23

Magnetic fields/starspots can cause "inflation" of an active (young) star.



Inhibition of convection

Feiden & Chaboyer 2013, 2014
Feiden 2016

Macdonald & Mullan 2014, 2015, 2017

Starspots

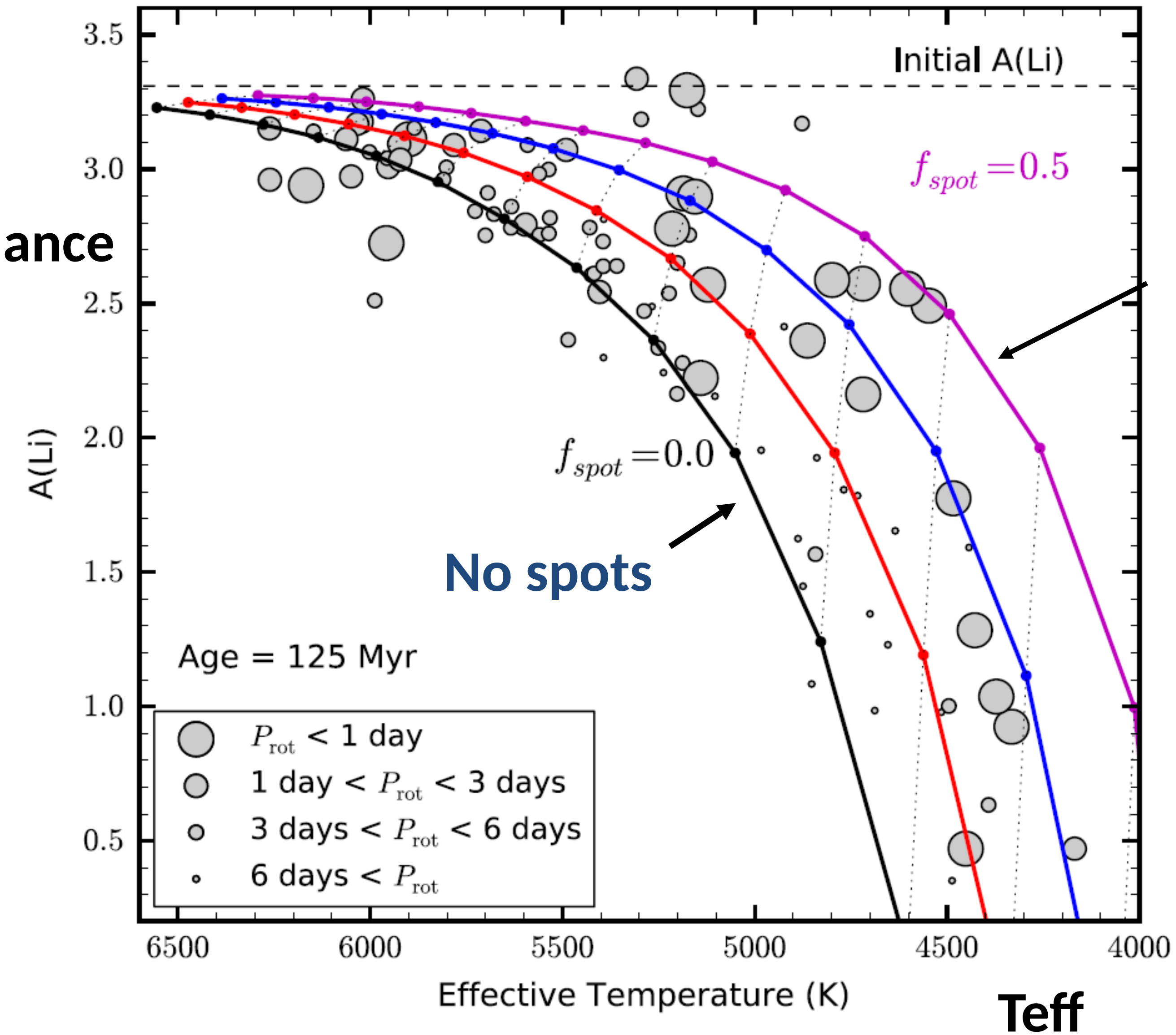
Somers & Pinsonneault 2014, 2015

Jackson & Jeffries 2014

Slows down PMS evolution.
Radii are larger, cores are cooler for a given mass/age.

Rotation dependent inflation/spot coverage can explain Li dispersion

Li Abundance



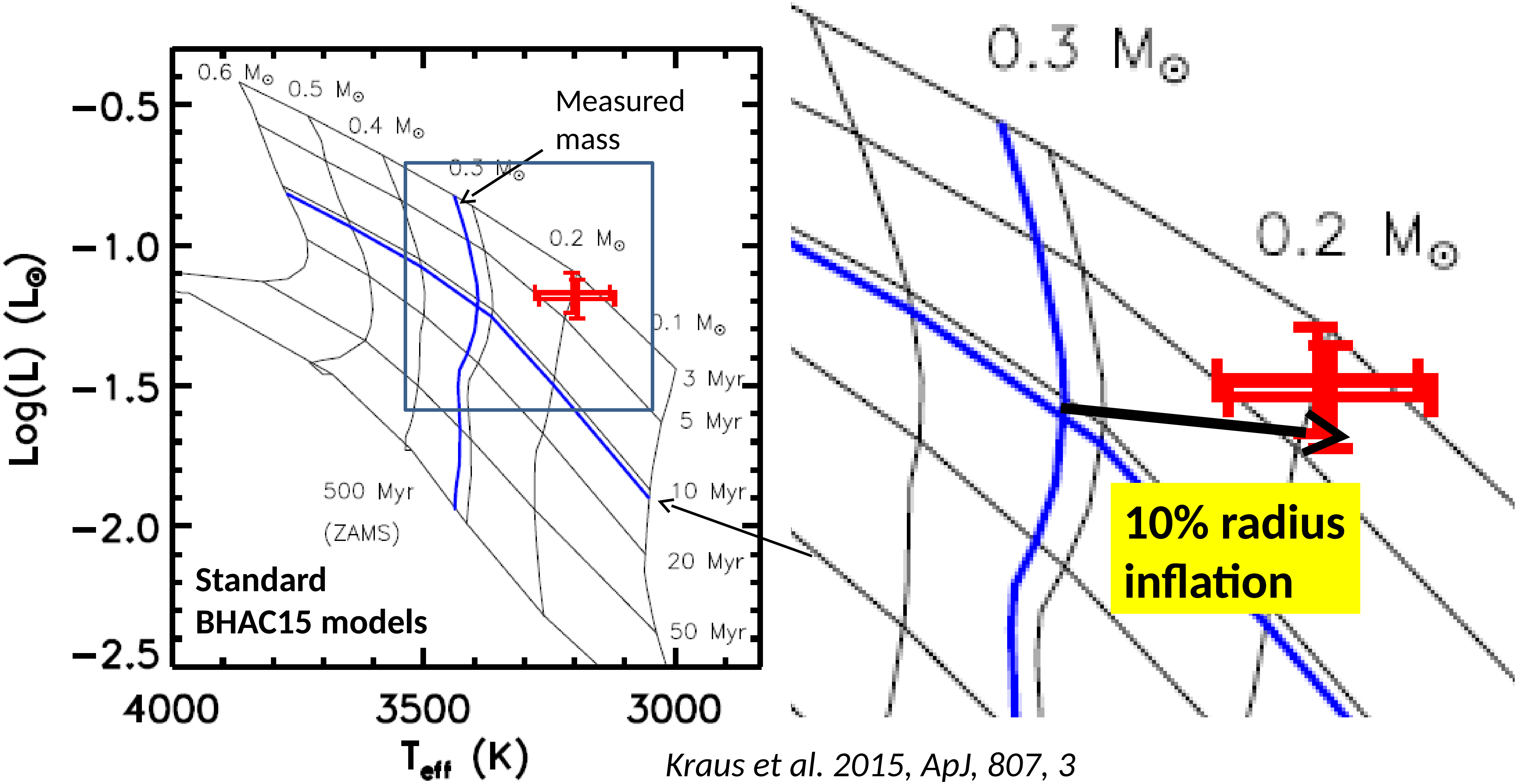
Spots block 30% of flux and inflate stars by ~10%

No spots

Teff

Somers & Pinsonneault 2015, ApJ, 807, 174

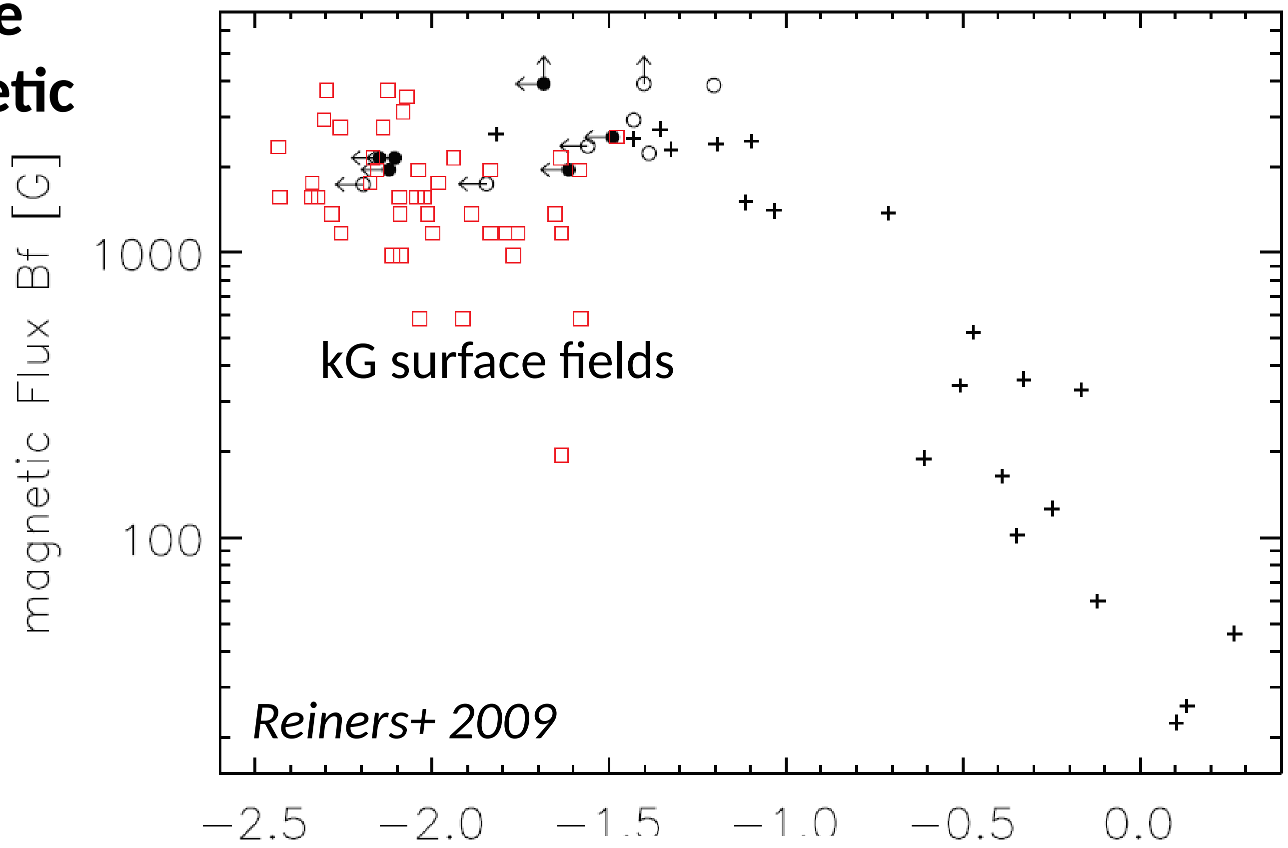
Eclipsing binary in Upper Sco – problem solved?



Kraus et al. 2015, ApJ, 807, 3

Direct evidence for magnetic fields and spots

Surface Magnetic Flux



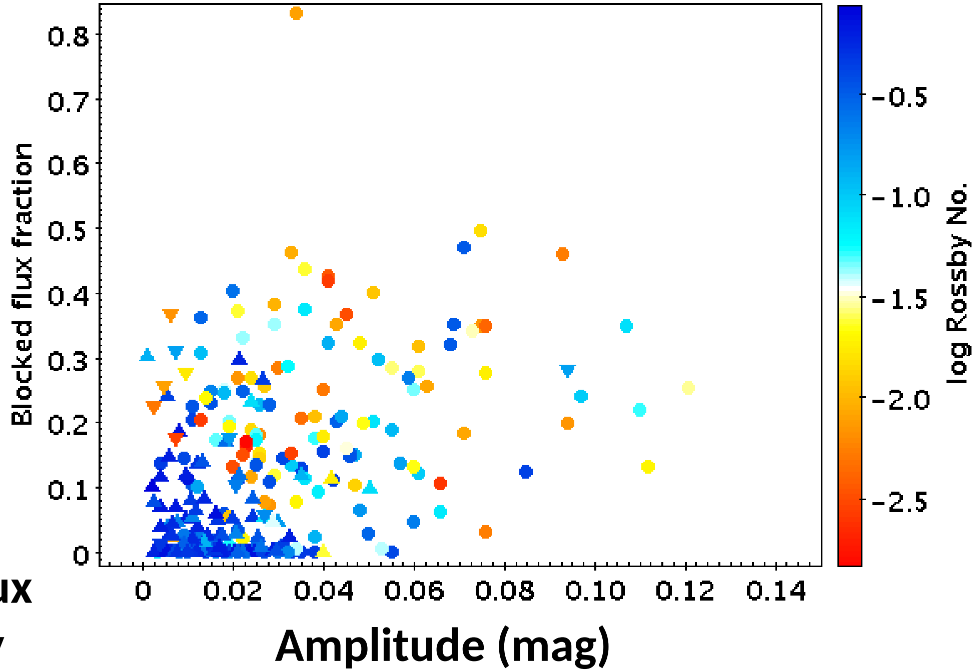
Log Rossby No.

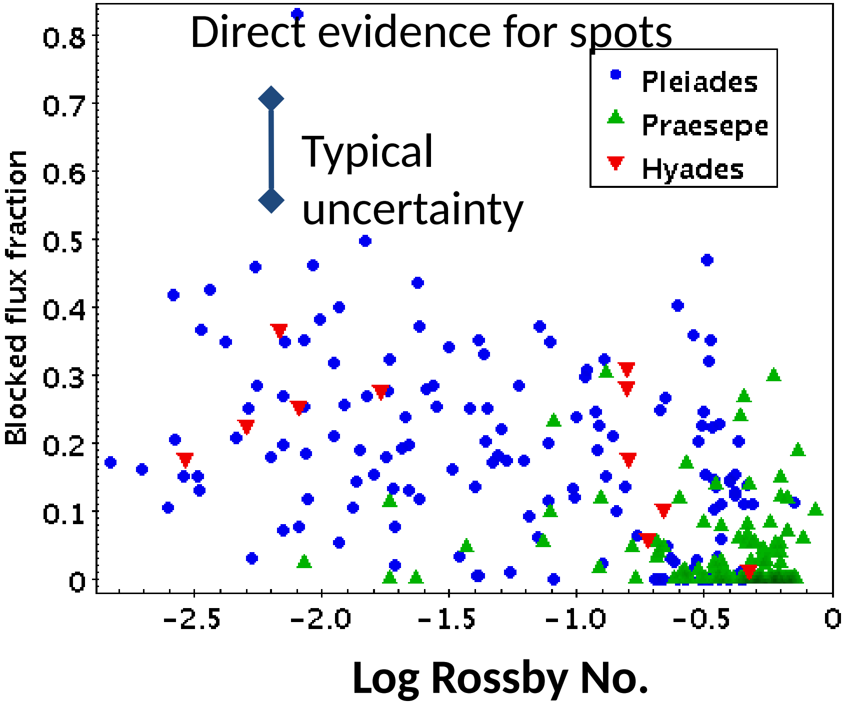
Surface magnetic flux is clearly correlated with rotation, but saturates at **2-3kG** below a Rossby number of 0.1

Magnetic flux measurements via Zeeman effect
Saar 1996, 2001;
Reiners & Basri 2007; Reiners+ 2009

Direct evidence for magnetic fields and spots

Blocked flux fraction by starspots





Spots block **10-40%** **of flux** from the most active stars. Rough correlation with Rossby Number and poor correlation with modulation amplitude suggests variable spot coverage with high levels of axial symmetry

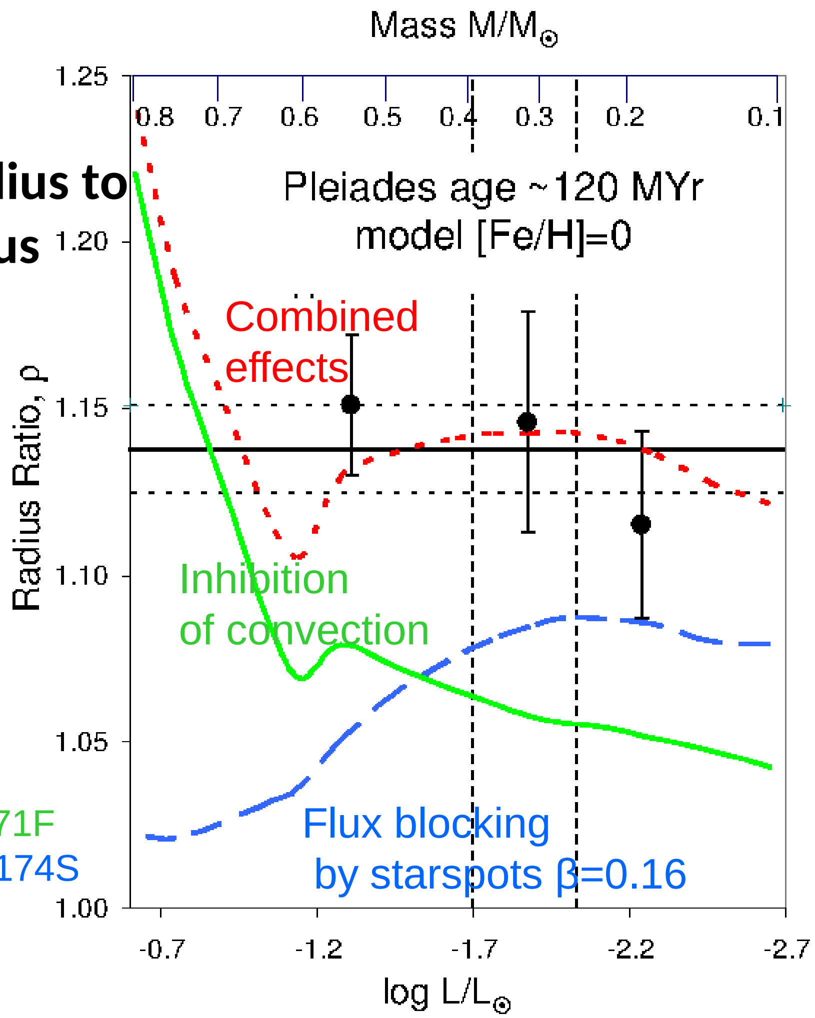
Spot coverage from LAMOST
Fang+ 2016, 2018
Rotation periods/amplitudes from K2
Rebull+ 2016; Douglas+ 2016, 2017

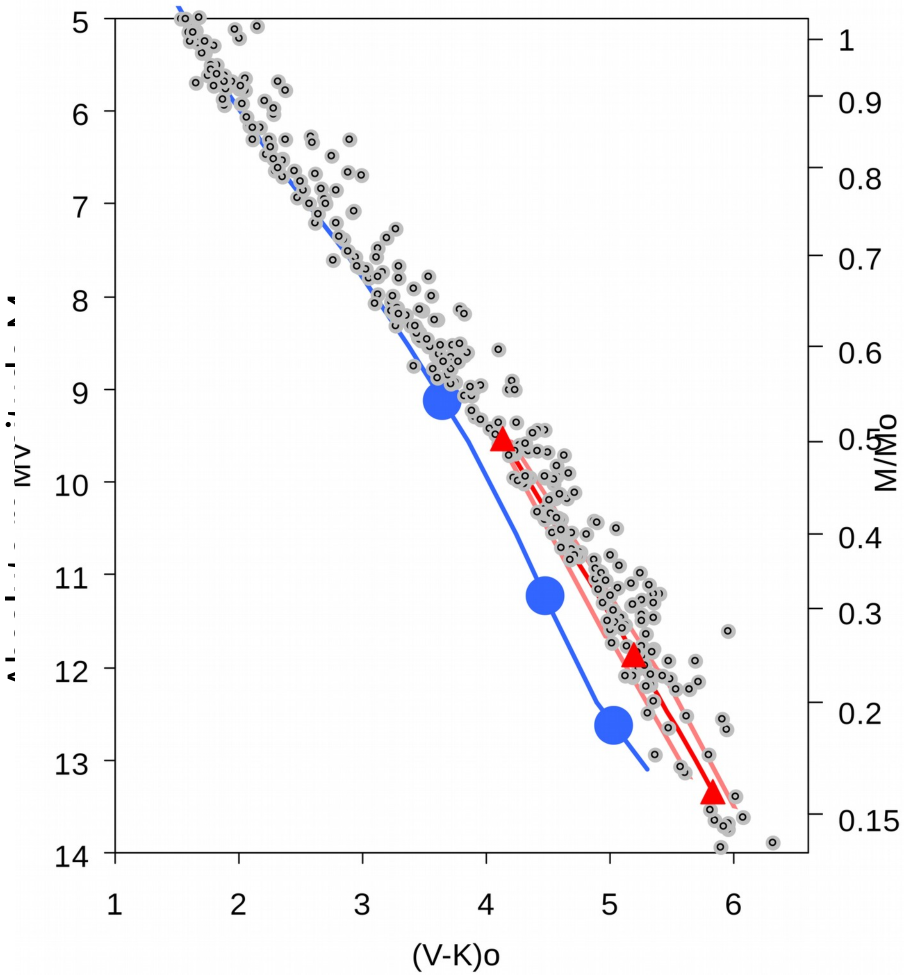
Direct evidence for radius inflation $R \sin i = 0.02\, P \times\ v \sin i$

Rotation velocities from WIYN/Hydra
Rotation periods from K2;

Ratio of radius to Model radius

14 ±2 % Inflation

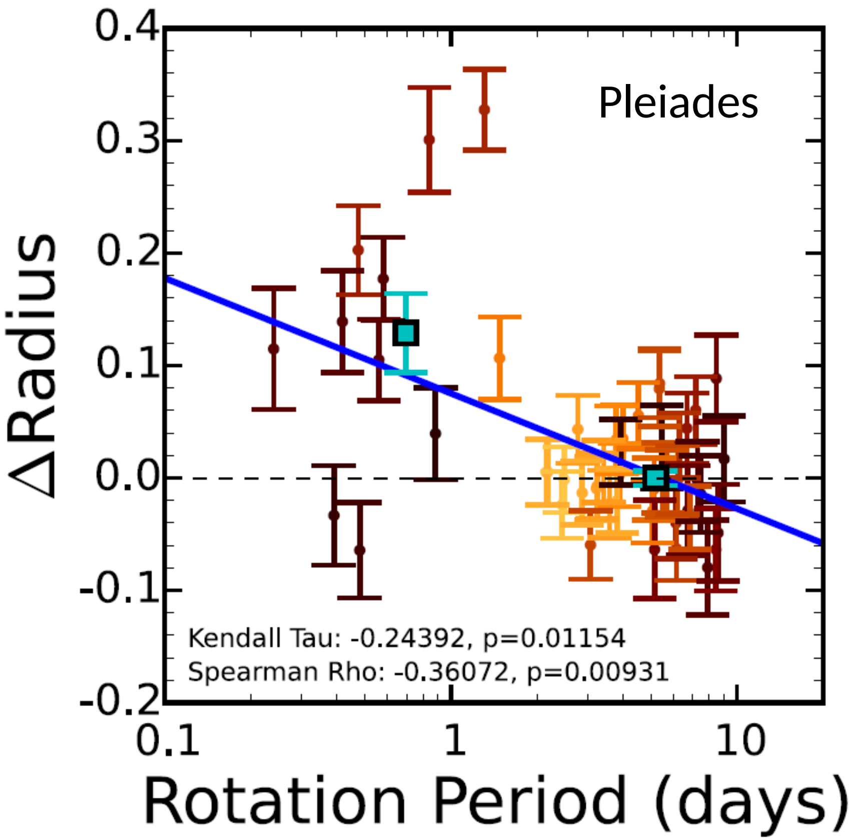




Models:
Feiden+ 2015 csss...18..171F
Somers+ 2015 ApJ...807..174S

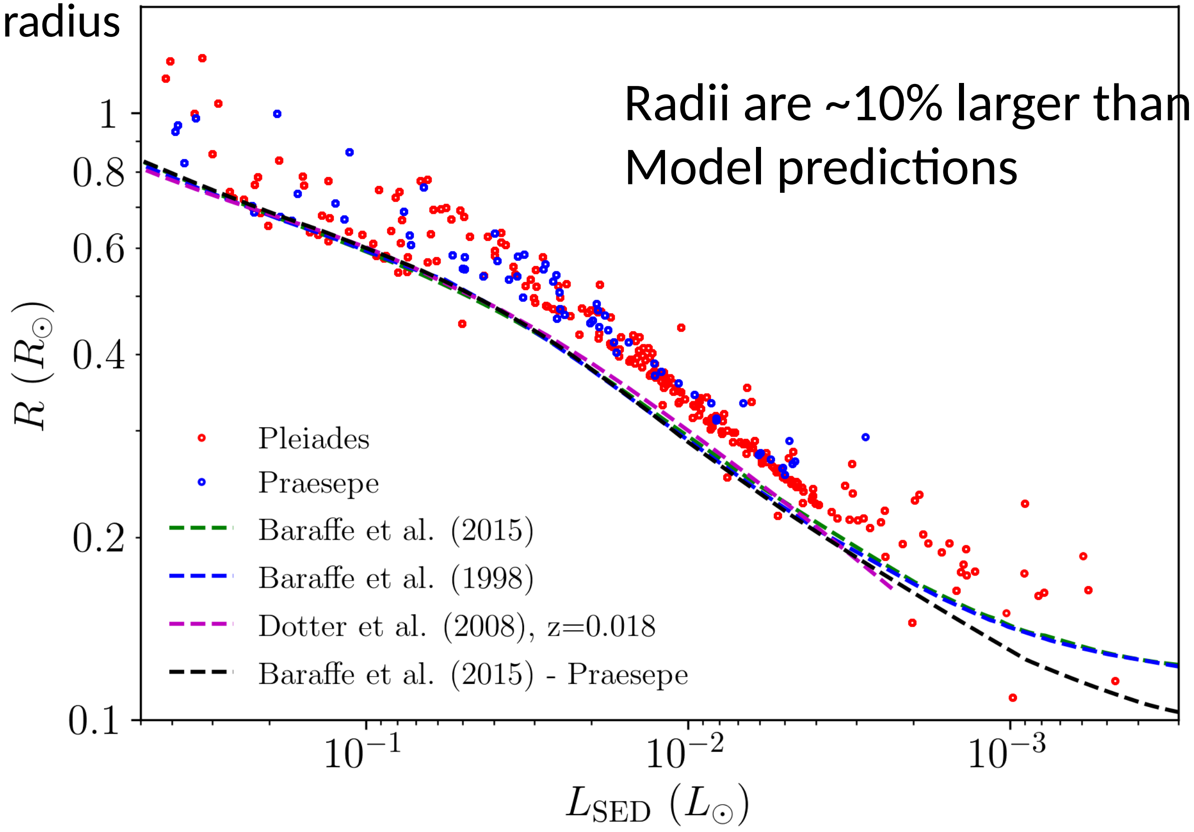
Jackson+ 2018, MN, 476, 3245
See also Jackson+ 2016; Lanzafame+ 2017; Kesseli+ 2018

SED fitting in young clusters

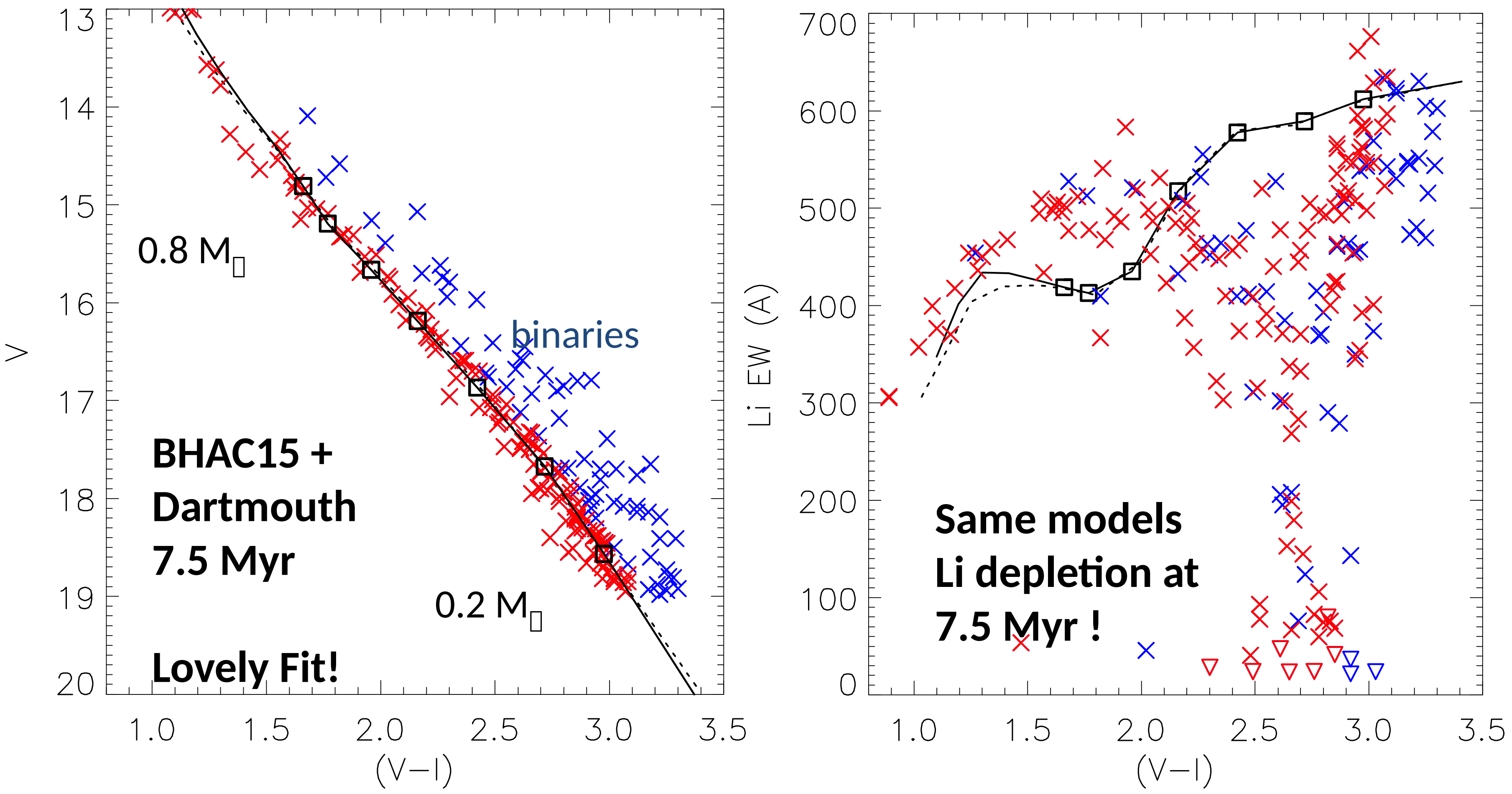


Somers & Stassun 2017, AJ, 153, 101

SED-modelled radius

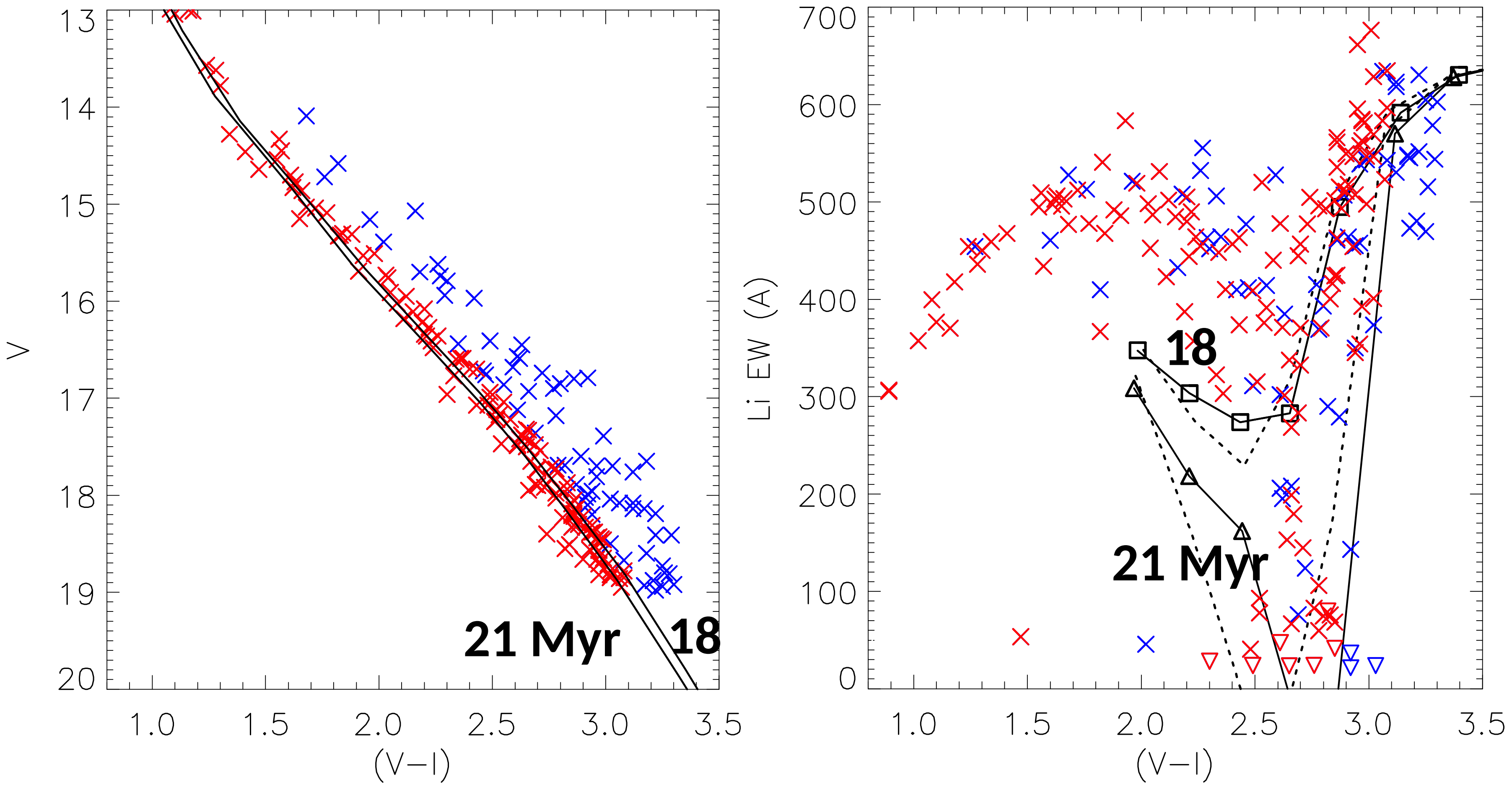


Morrell, Barnes & Naylor in prep – see poster #213



The Gaia-ESO Survey of the Gamma Vel Cluster
Examine the CMD and the Li depletion pattern

Jeffries et al. 2017, MNRAS, 464, 1456



A 10% "inflated" isochrone between 18 and 21 Myr matches the data in both diagrams

Similar results for:

the Beta Pic group at 25 Myr -- *Messina+ 2016, A&A, 596 A29*

the Upper Sco Assoc. at 10 Myr -- *Feiden 2016, A&A, 593, A99*

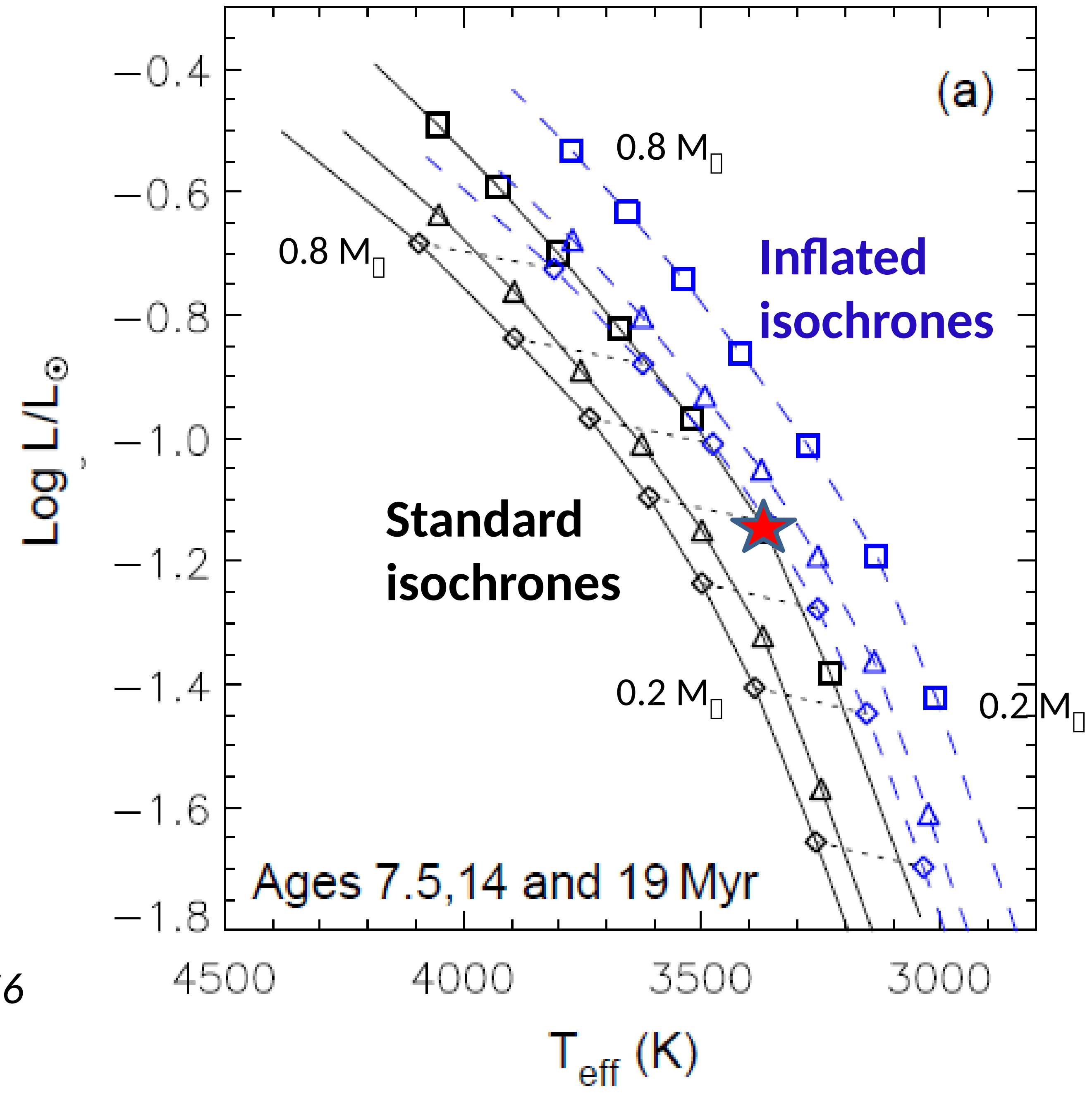
Consequences

PMS stars may be:

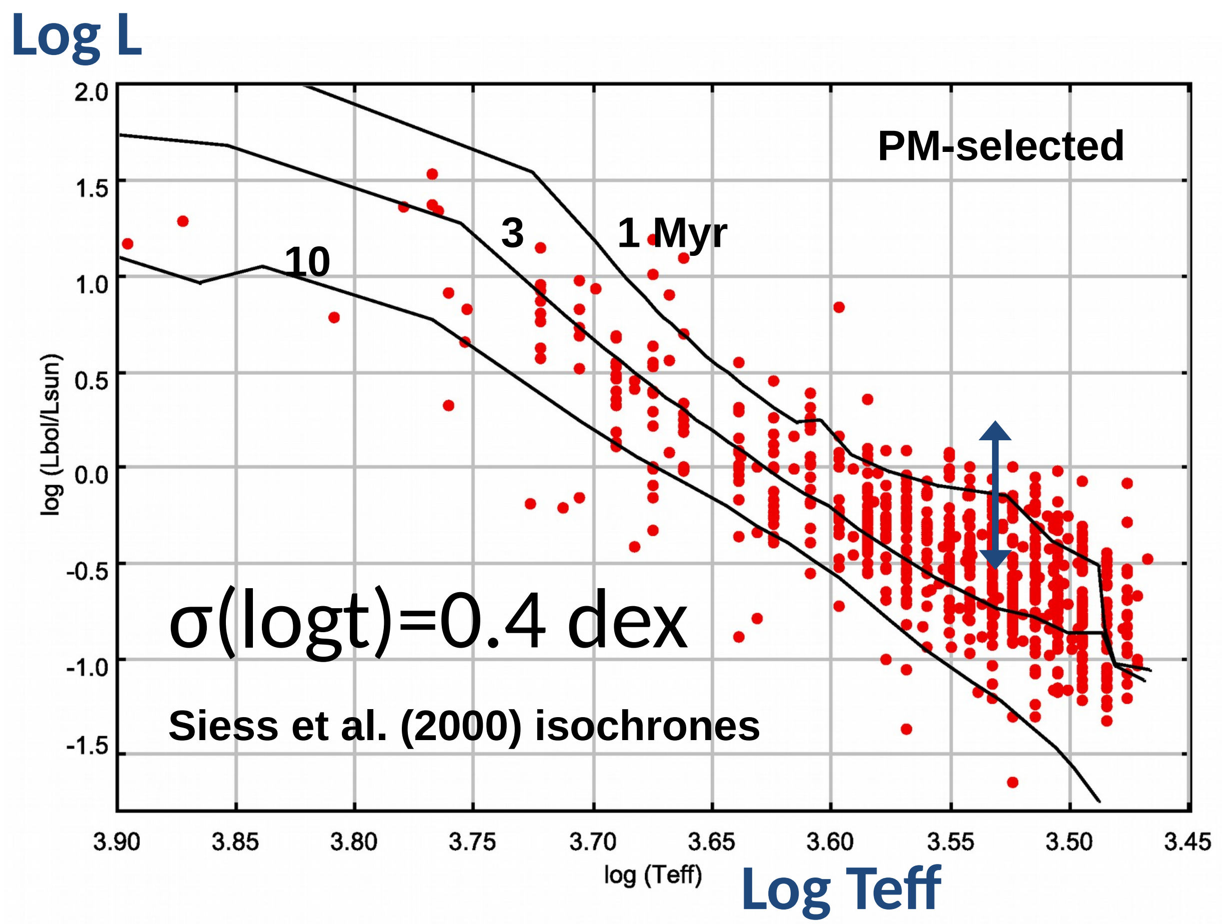
OLDER and
MORE MASSIVE than
you thought.

Cluster formation and disc dispersal lifetimes are proportional to these ages!

Jeffries et al. 2017, MNRAS, 464, 1456



Ages and formation of young stellar clusters



HR diagram implies large age spread BUT:

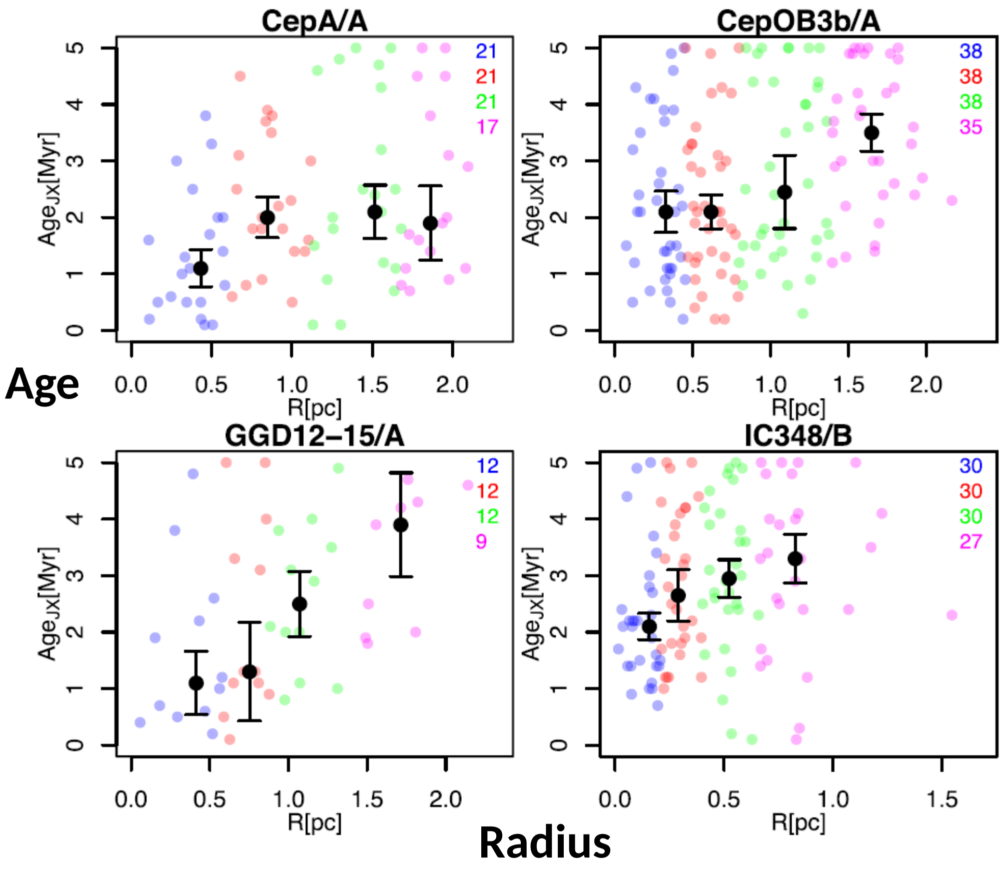
1. Extinction
2. Accretion
3. Variability
4. Binarity

All contribute to the scatter

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

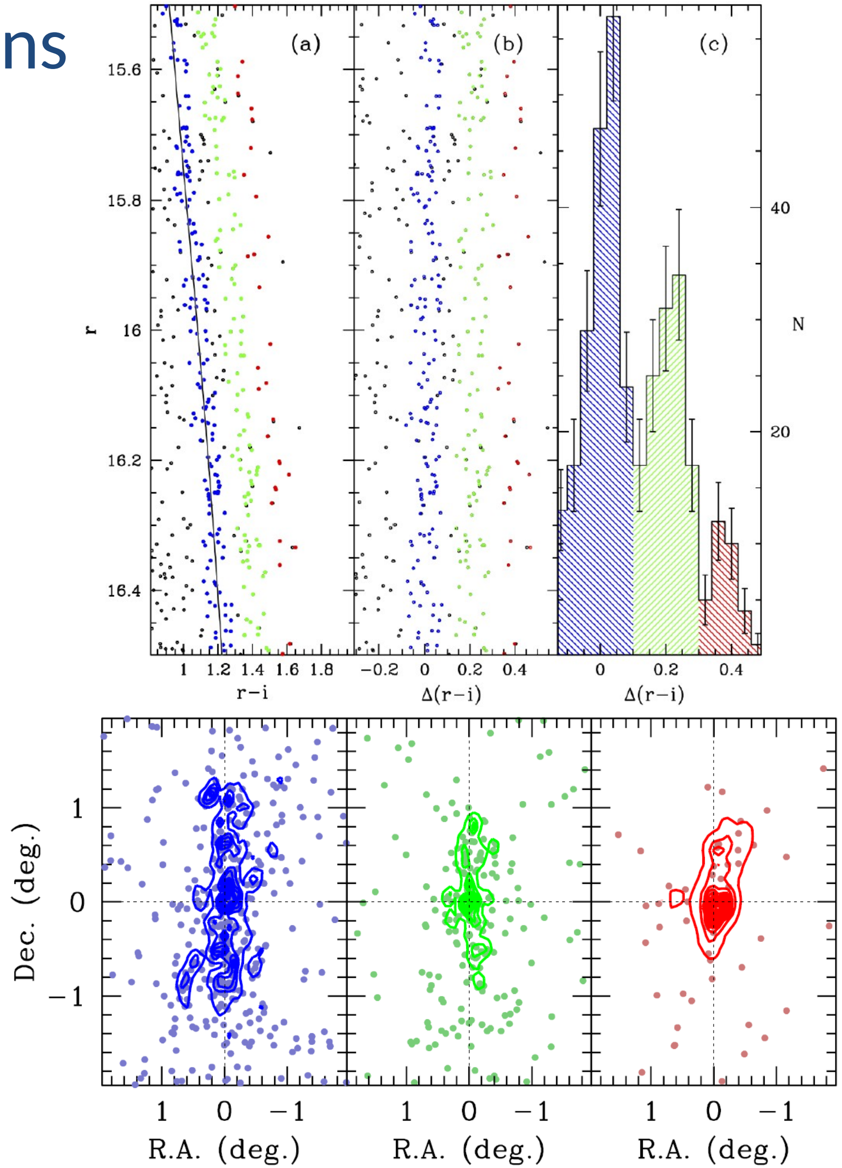
Hartmann 2001, AJ, 121, 1030

Resolving Cluster Age Distributions



Intracluster age gradients ~1 Myr/pc
with SFiNCs/MYStIX

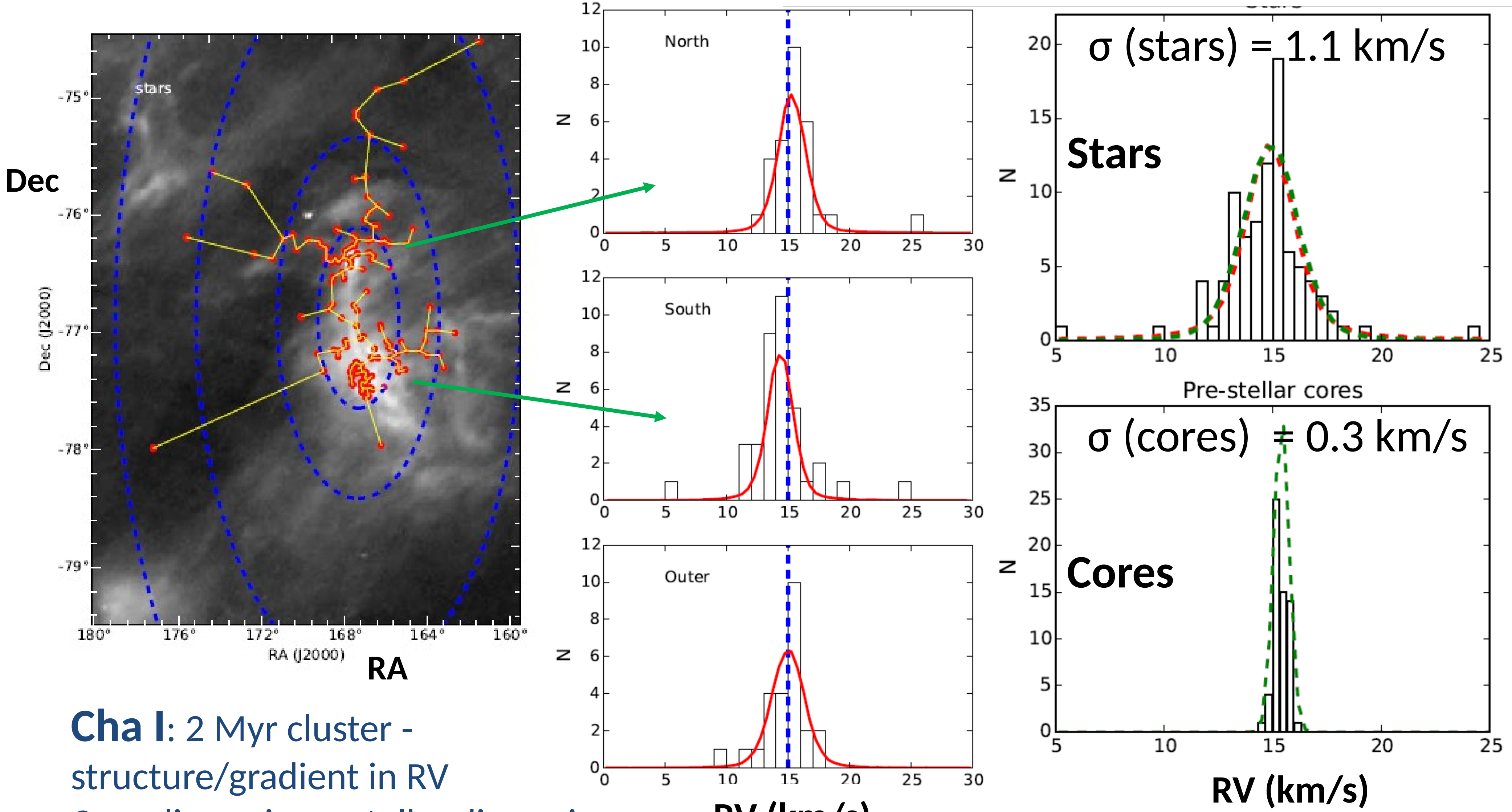
Getman+ 2018, MN, 476, 1213



Multiple sequences in the ONC
Beccari+ 2017, A&A, 604 A22

Resolving cluster dynamics

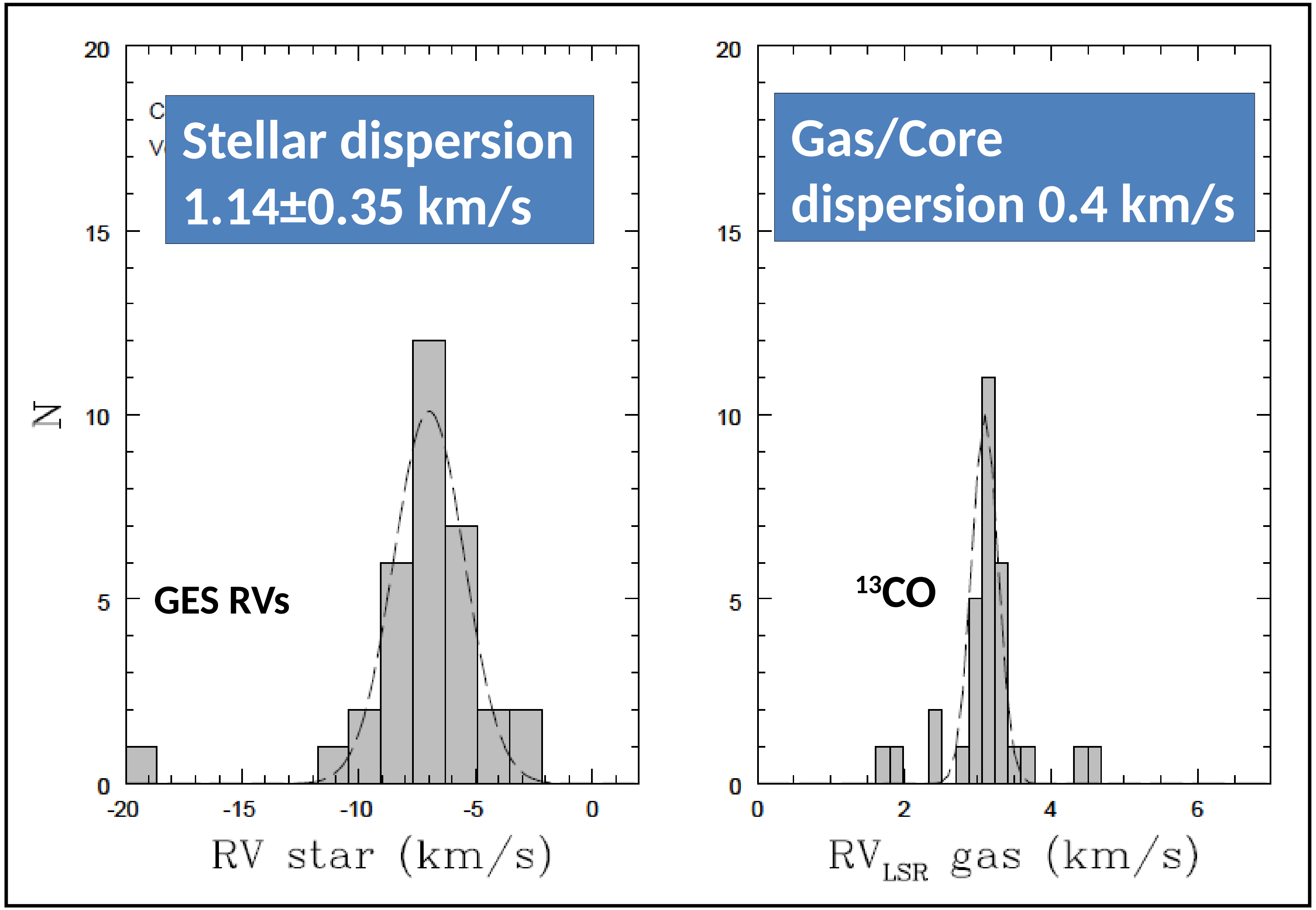
$$\sigma_{1D} \sim \mathbf{0.7} \left(\frac{M}{10^3 M_\odot}\right)^{\frac{1}{2}} \left(\frac{R}{1pc}\right)^{-\frac{1}{2}} \text{km/s}$$



Cha I: 2 Myr cluster -
structure/gradient in RV
Core dispersion < stellar dispersion

Sacco et al. 2017, A&A, 601, A97

ρ Ophiuchus: 1 Myr - Partly embedded in parental gas



Rigliaco et al. 2016, A&A, 588, A123   *see also NGC 1333 - Foster et al. 2015, ApJ, 799, 136*

Gaia DR2

$$\Delta V_T = \mathbf{0.05} \left(\frac{\Delta\mu}{0.1 mas/yr}\right)\left(\frac{d}{100pc}\right) \text{km/s}$$

$$\Delta d \approx \mathbf{1} \left(\frac{\Delta\pi}{0.1 mas}\right)\left(\frac{d}{100pc}\right)^2 \text{pc}$$

Unprecedented numbers and precision to study

- Cluster distances
- Cluster membership
- Cluster dynamics

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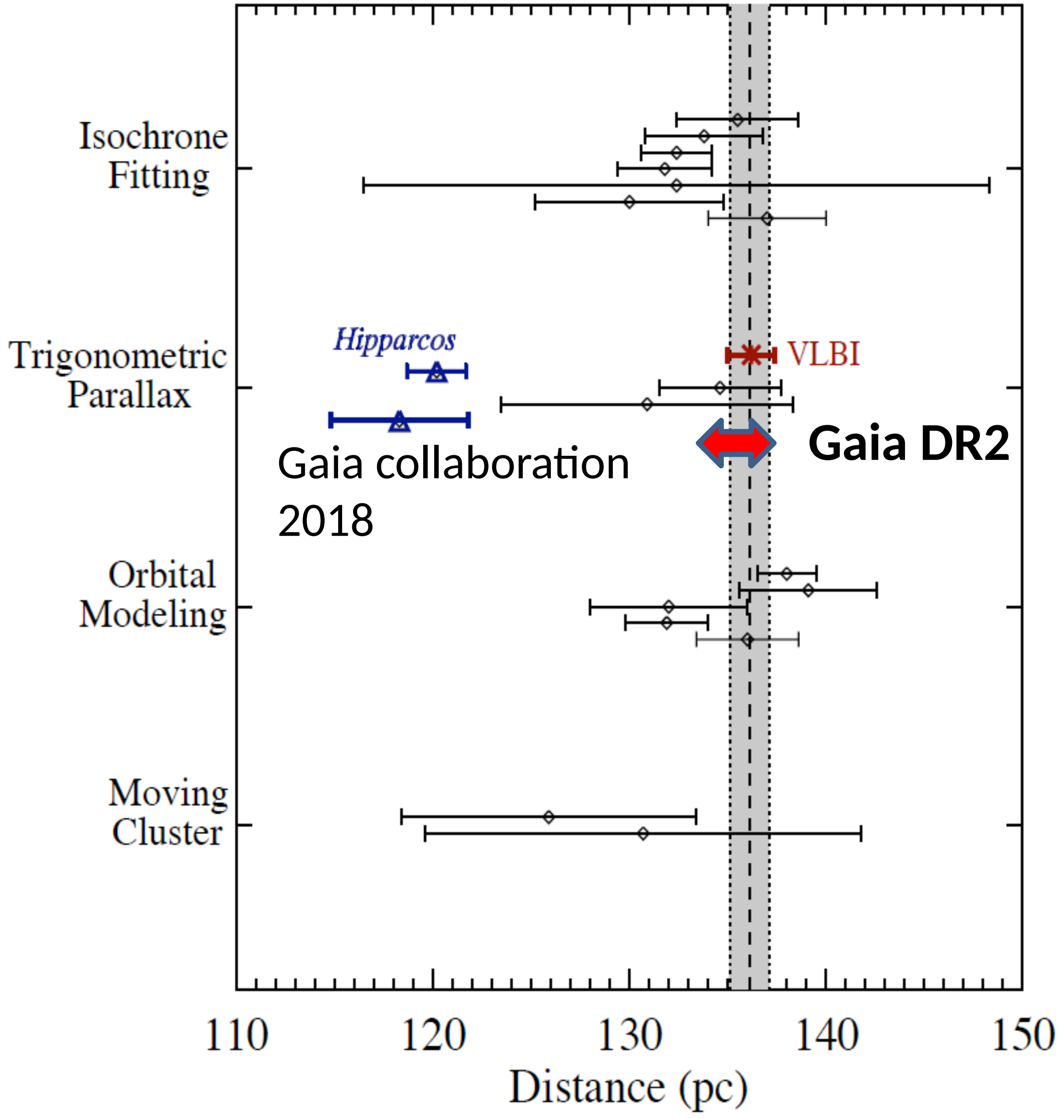
2D > 4D > 5D > 6D > 7D

Positions + PMs + Parallaxes + RVs + Ages

2D > 4D > 5D > 6D > 7D

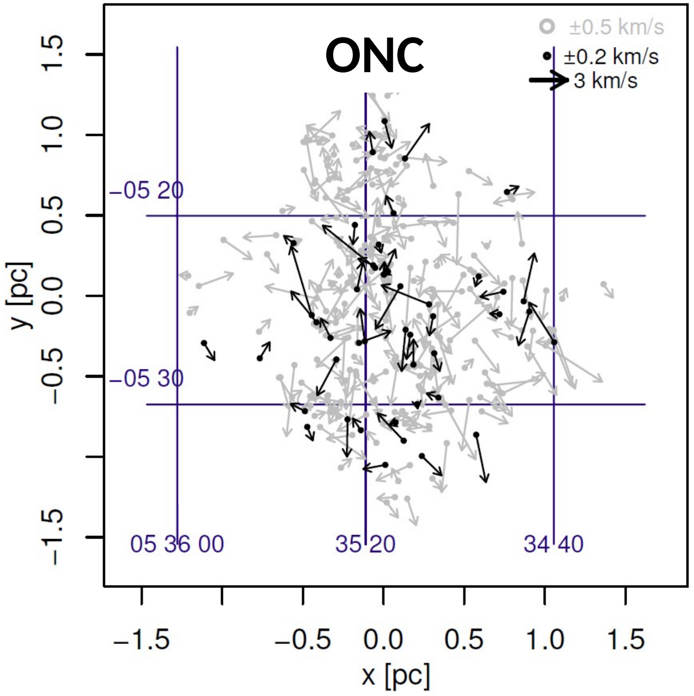
Positions + PMs + Parallaxes + RVs + Ages

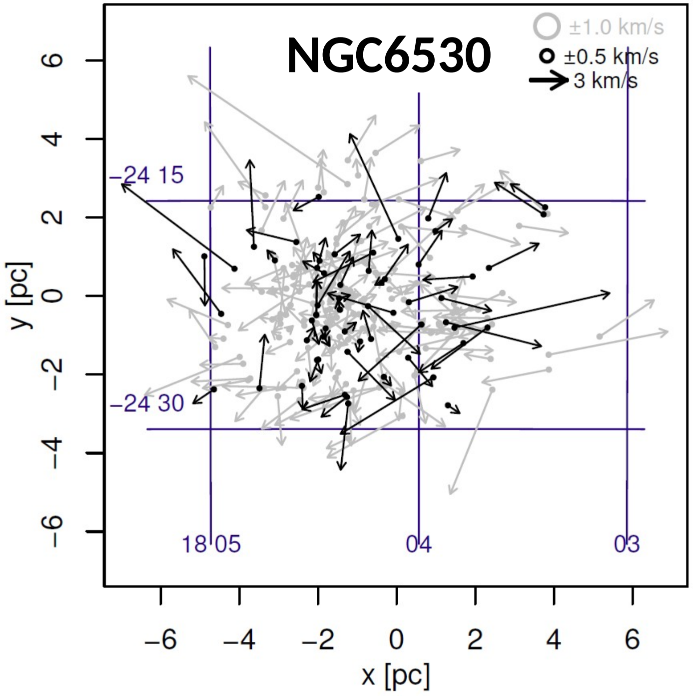
The distance to the Pleiades



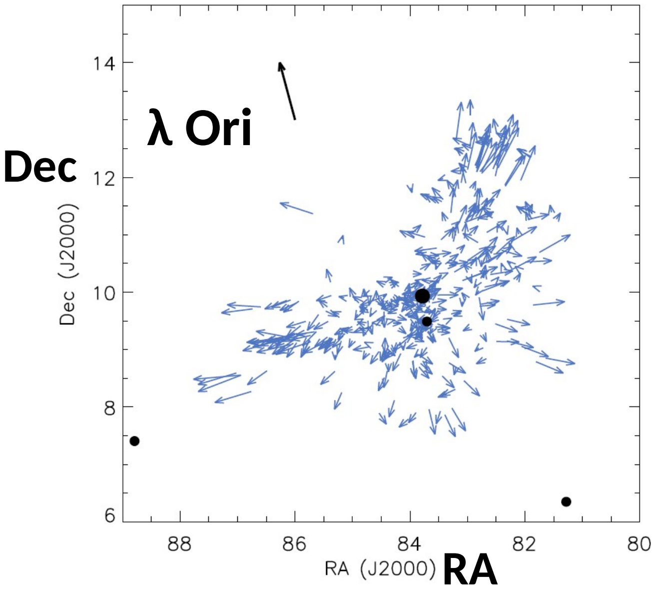
Adapted from *Melis+ 2014, Science, 345, 1029*

Gaia DR2 2D Cluster kinematics – pm vector diagrams





Kuhn et al. 2018
arXiv 1807.0211

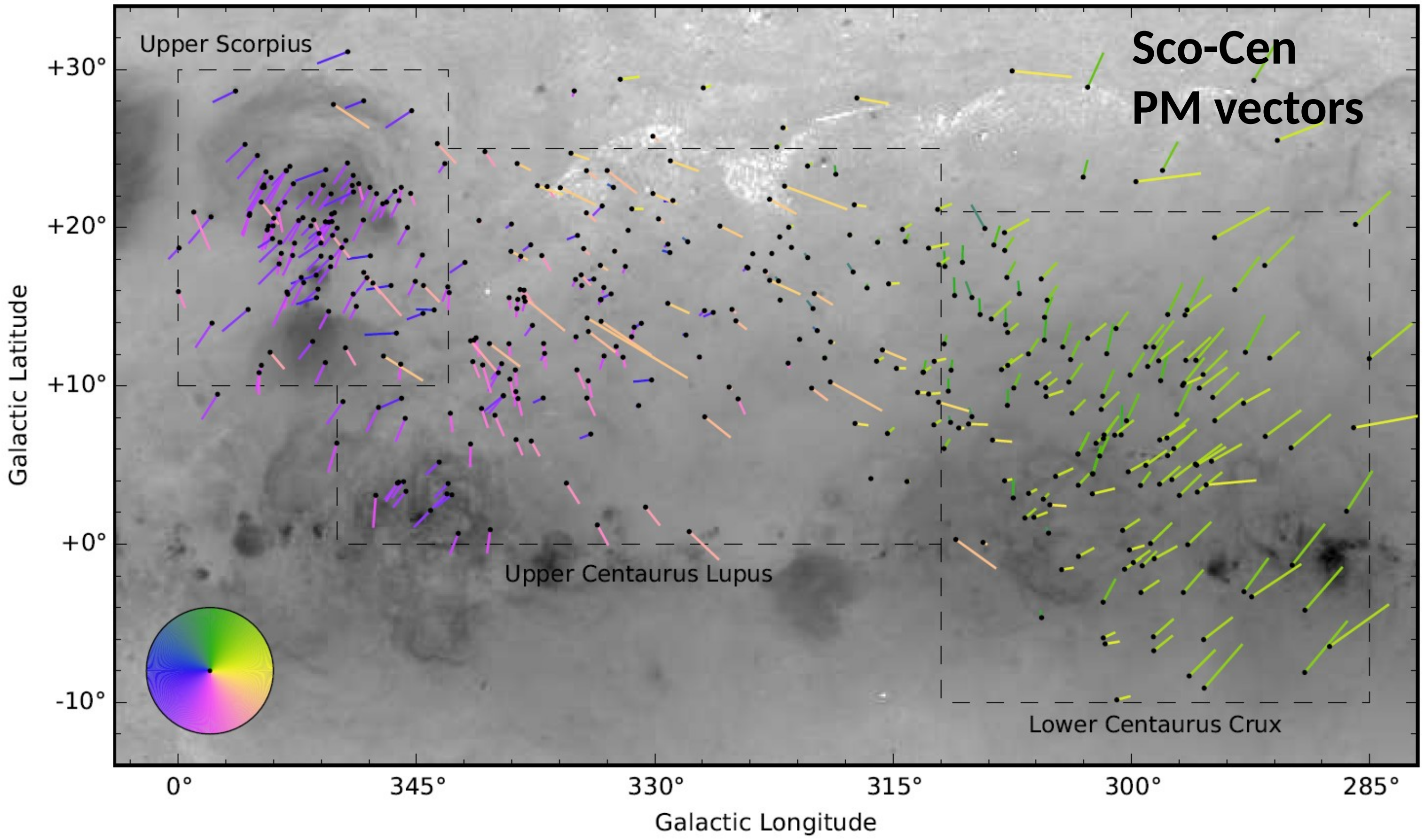


Kounkel et al. 2018
arXiv 1805.04649

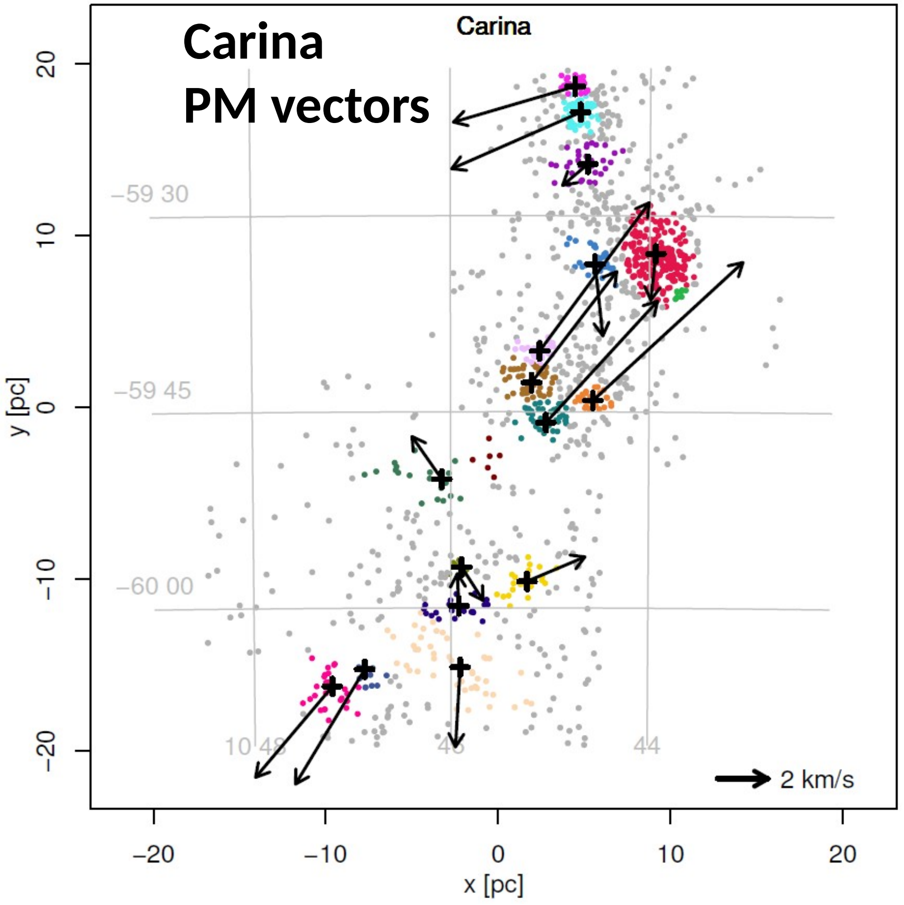
Evidence for expansion in some, but not all, young clusters

Some non-expanding clusters may be bound – e.g. the ONC, NGC2362. Rapidly expanding clusters appear unbound –e.g. λ Ori, NGC 6530.

Wright & Mamajek 2018, MN, 476, 381

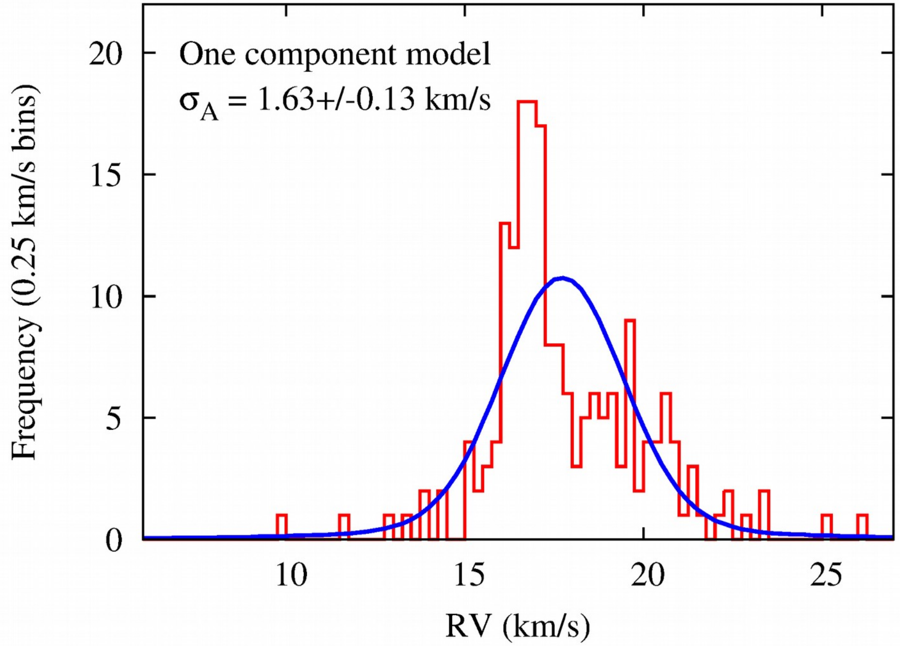


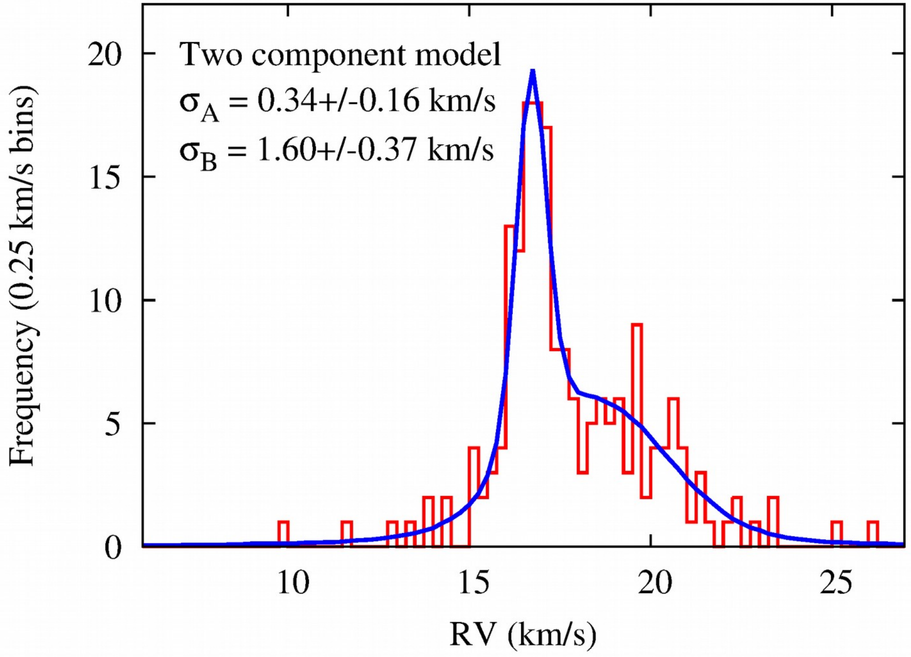
Kuhn et al. 2018 arXiv 1807.0211



Little evidence that larger clusters form by merger at later times

Kinematic substructure and lack of coherent expansion in OB associations
suggests they formed in a highly substructured manner – talks by *Wright*, *Kounkel* on Monday





The Gamma Vel Cluster

Gaia-ESO survey – RV precision 0.25 km/s

Single RV component
– poor fit

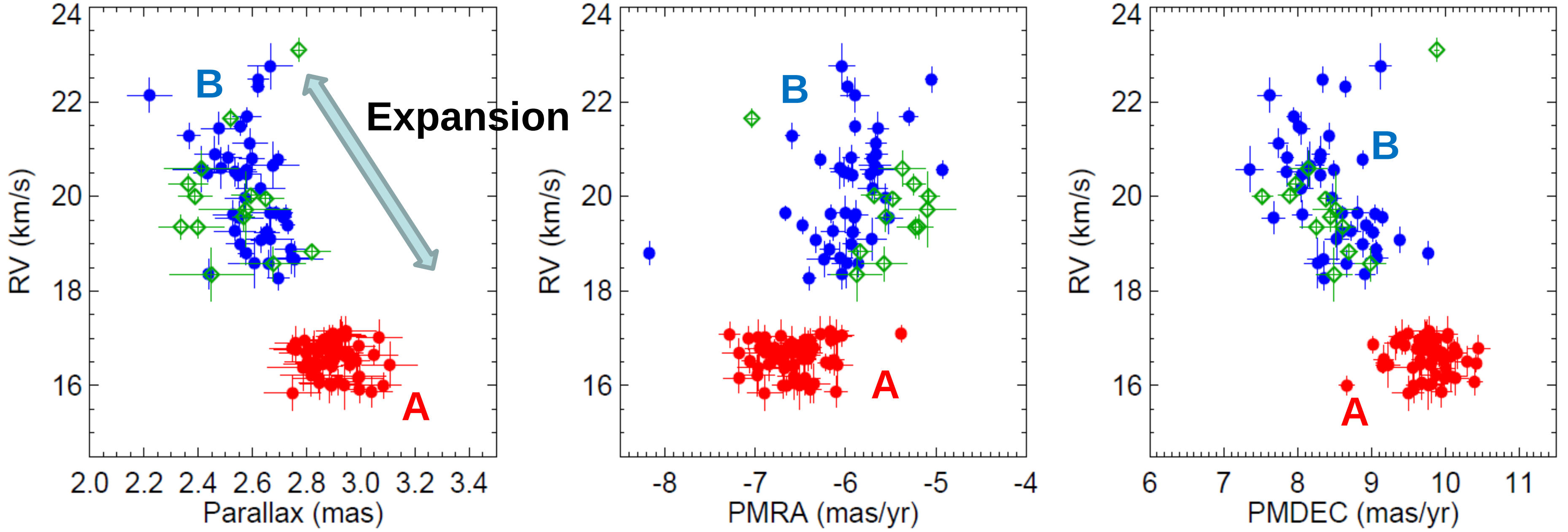
Two-component fit

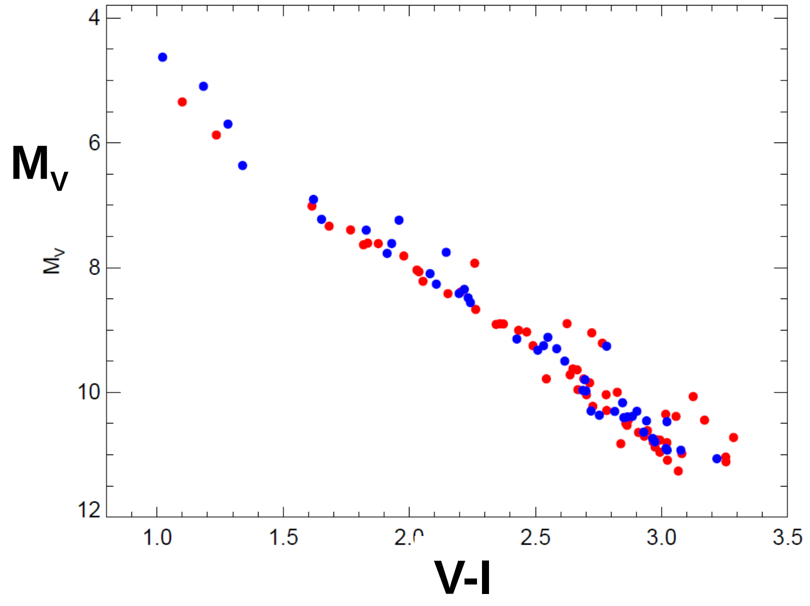
σ_A = 0.34 km/s (virial eqm.) "**Group A**"
σ_B = 1.60 km/s (unbound) "**Group B**"
ΔRV = 2 km/s

Jeffries et al. 2014, A&A, 563, A94

Gaia DR2 + RVs

Franciosini et al. 2018 arXiv 1807.0362





- Cluster(s) resolved in 7D
- **A** is closer than **B**
- **B** is expanding and moving away from **A**
- **A** and **B** are almost coeval
- **A** is bound, **B** is unbound

Recent developments on the formation and evolution of young low-mass stars

Summary

- Evidence that low-mass evolutionary models fail for PMS stars
- Magnetic activity/spots may inflate stars leading them to be older and colder than you thought
- Young clusters may have age gradients (multiple populations?), but any merging happens early-on
- Gaia will revolutionise this field – but maximum leverage comes with combined spectroscopy