The Gaia-ESO survey and the empirical determination of stellar ages
(Improving stellar age estimates)

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- Why we need empirical methods
- Rotation, activity and lithium depletion
- A role for the Gaia-ESO survey

A hierarchy of methods

Fundamental	Radio-isotope dating (solar system)
Semi-Fundamental	Lithium Depletion Boundary Kinematic Traceback
Model-Dependent	Isochrone fitting, Asteroseismology Surface gravity
Empirical	Rotation, activity, lithium,
Statistical	Metallicity, Kinematics

See Soderblom 2010, ARAA, 48, 581

A hierarchy of methods

Fundamental	Radio-isotope dating (solar system)
Semi-Fundamental	Lithiun Kinema
Model-Dependent	Isochrone fitting, Asteroseismology Surface gravity
Empirical	Rotation, activity, lithium,
Statistical	Me

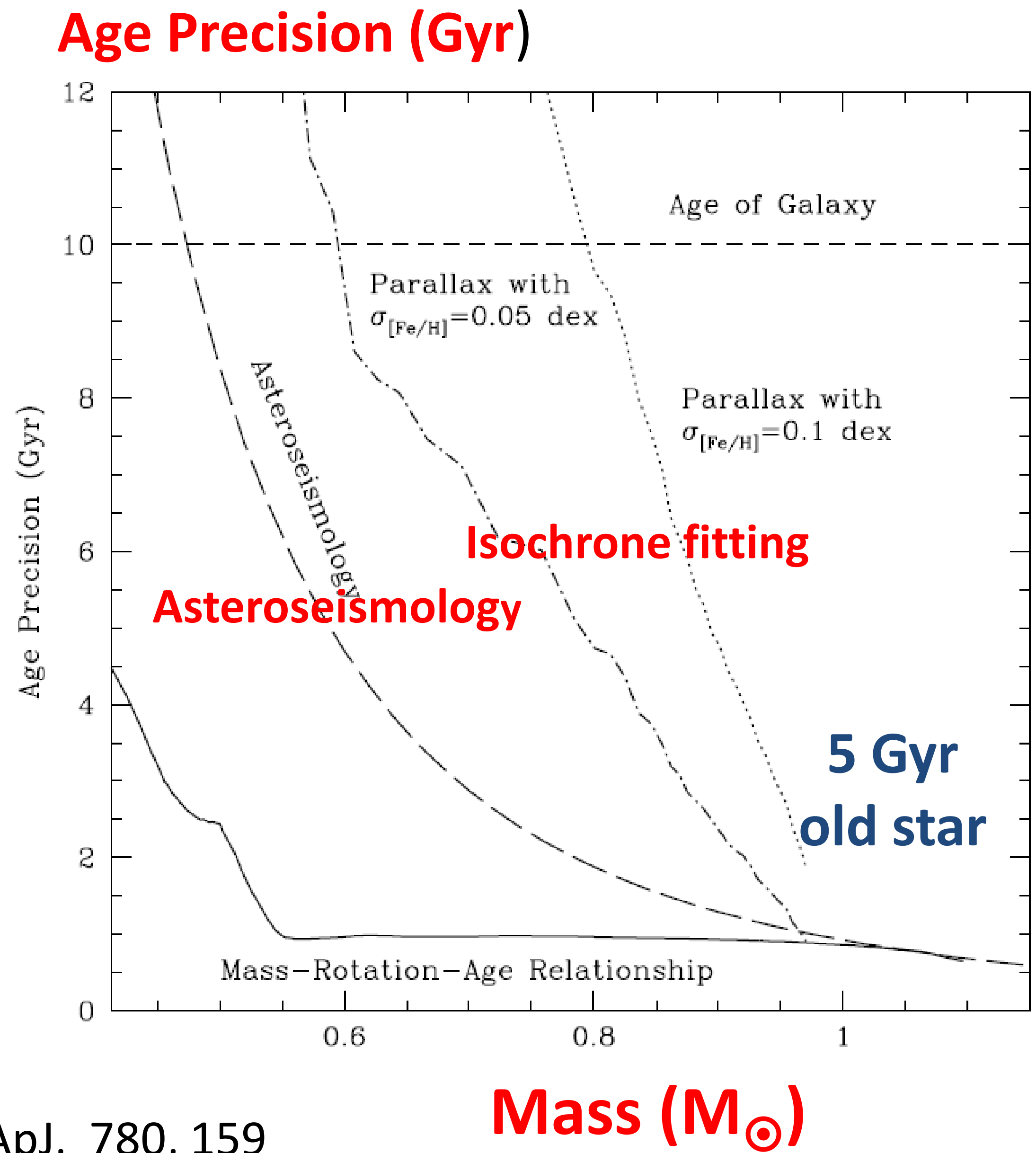
Groups Only

Want to test these!

See Soderblom 2010, ARAA, 48, 581

Problems with asteroseismology and HR diagram for <u>main-sequence</u> stars.

Precision ~10% of H-burning lifetime.



Epstein & Pinsonneault 2014, ApJ, 780, 159

A hierarchy of methods

Fundamental — Radio-isotope dating (solar system)

Semi-Fundamental — Lithiun
Kinema

Groups Only

Model-Depend
Surface gravity

Too Model Dependent or Imprecise

Empirical — Rotation, activity, lithium

Statistical — Me

Want to test these!

See Soderblom 2010, ARAA, 48, 581

What makes a good empirical age indicator?

(see Barnes 2007, ApJ, 669, 1167)

Essential:

- Sensitive to age
- Can be calibrated

Desirable:

- Measurable in single stars
- Insensitive to other parameters
- Can be inverted to find a unique age (single valued)
- Distance independent

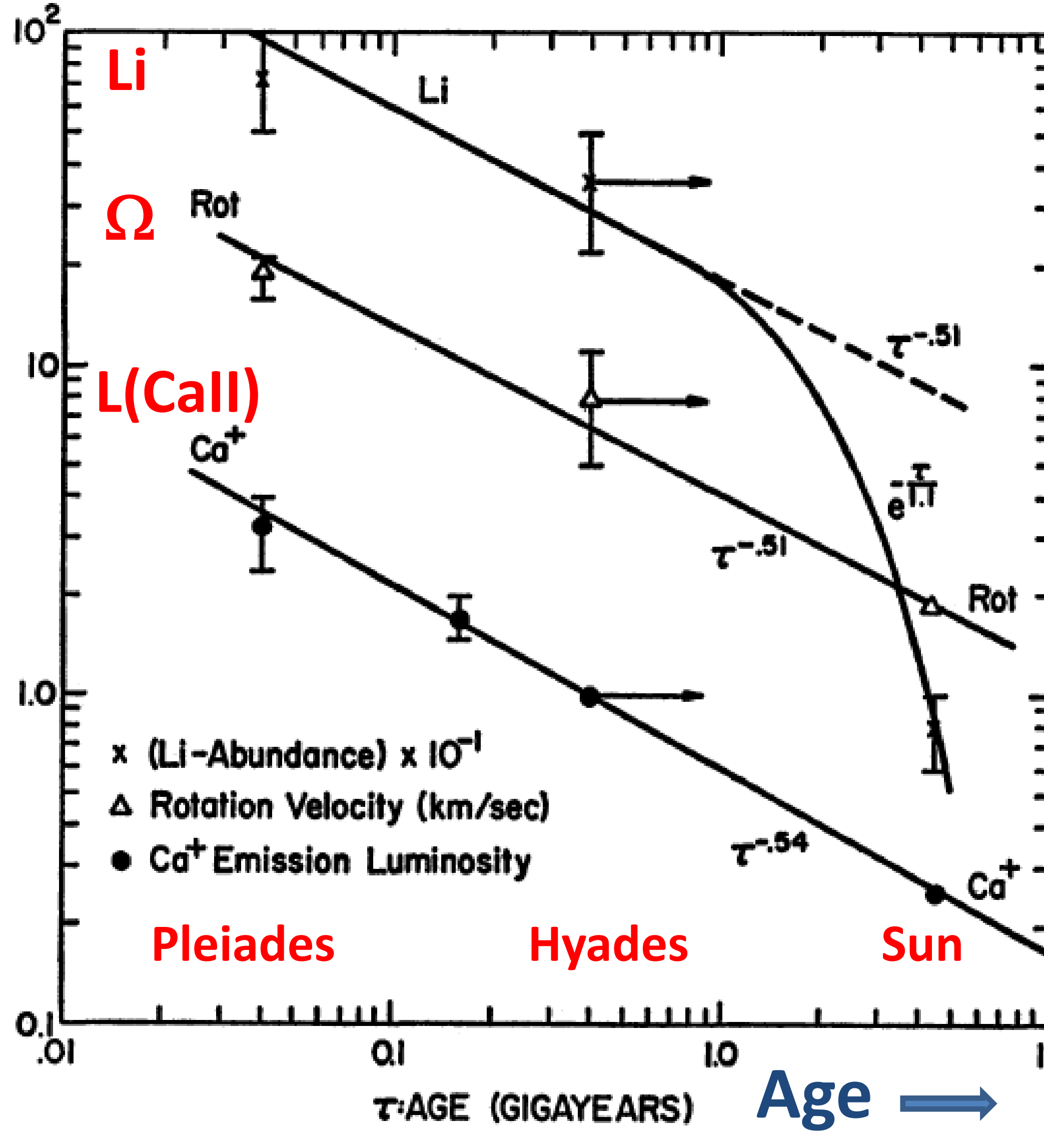
Jeffries (2014), EAS Review: **bit.ly/empiricalages**

Where it all started: Skumanich 1972, ApJ, 171, 565

$\Omega \propto t^{-1/2}$

$L(CaII) \propto t^{-1/2}$

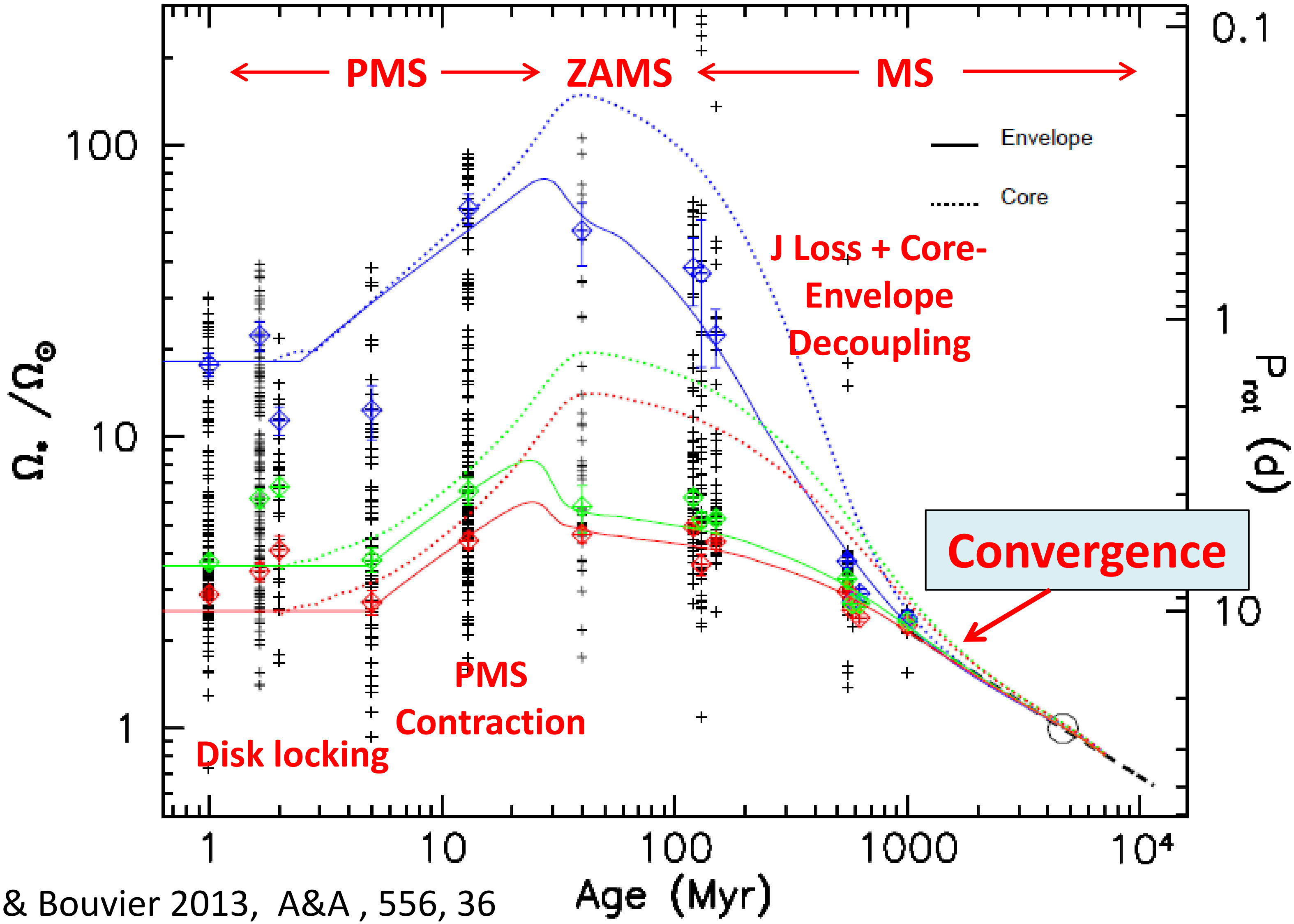
$A(Li) \sim t^{-1/2}$



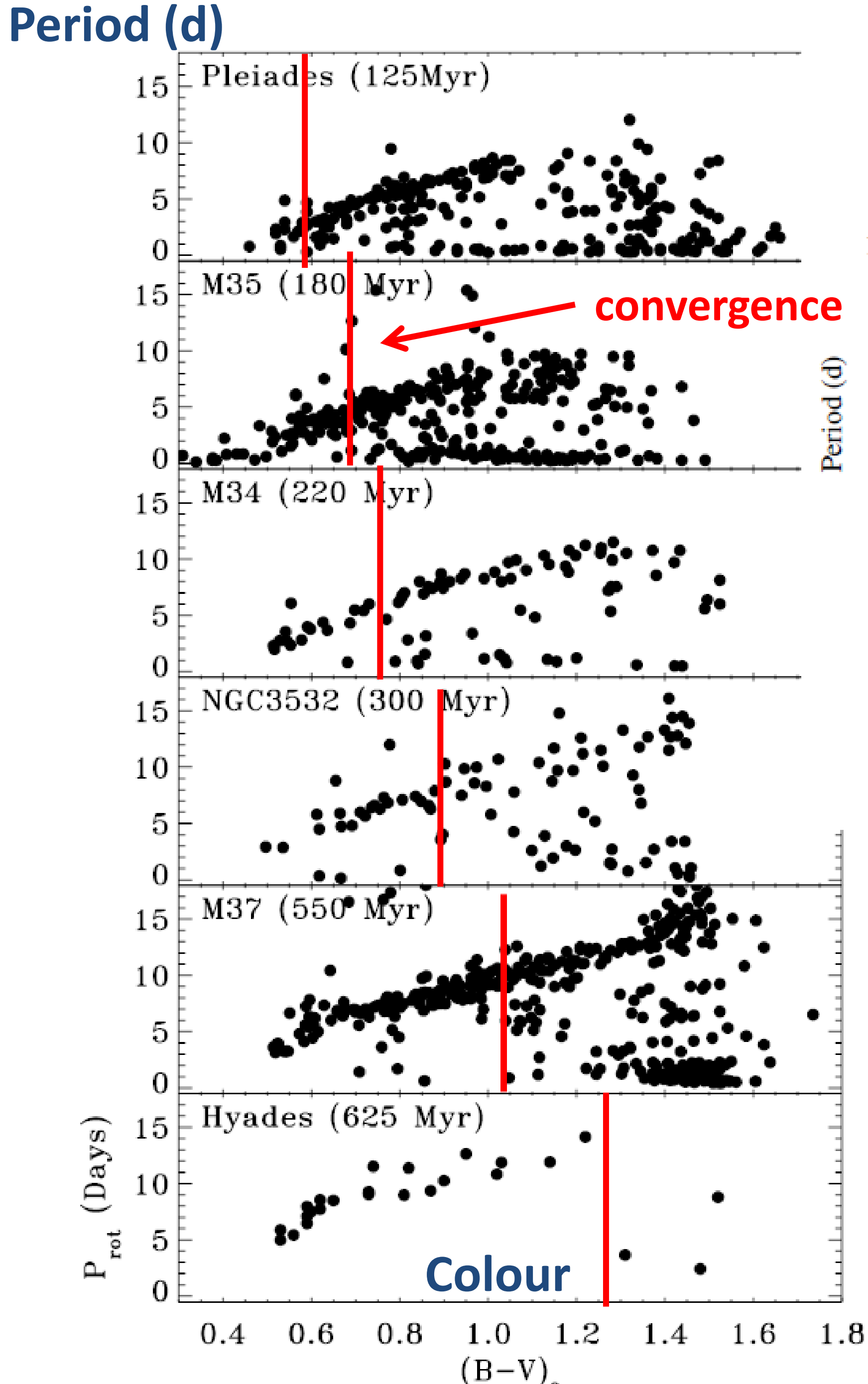
The connection?

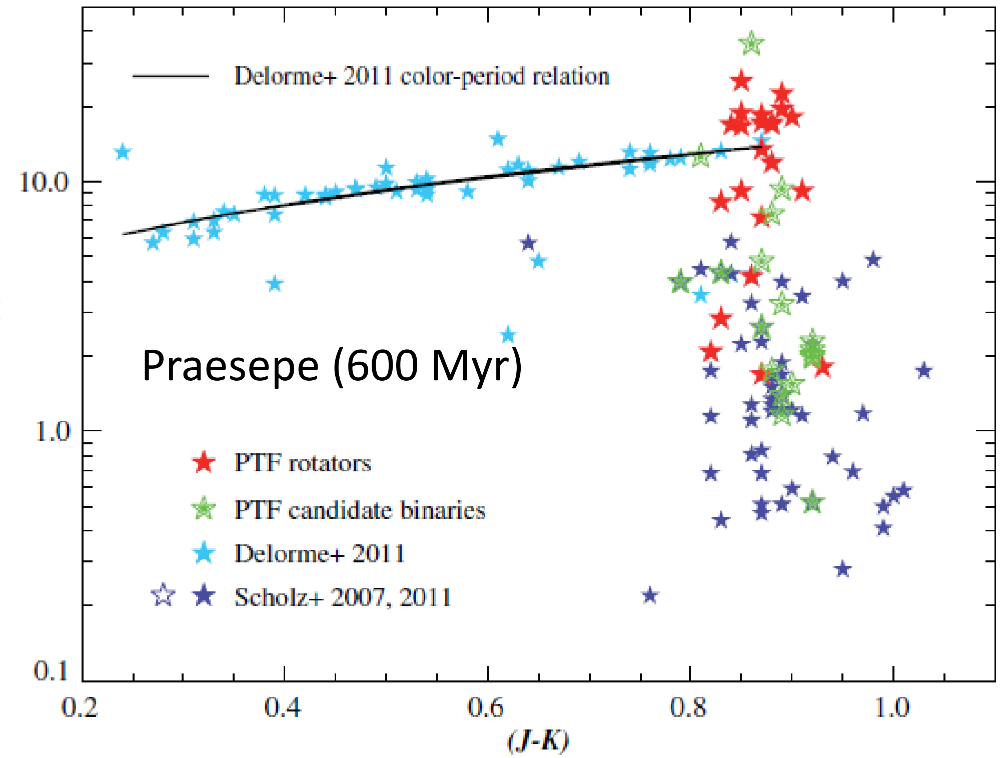
Stars with convection zones – rotation and magnetic activity

The rotation – age connection: Solar type stars



Gallet & Bouvier 2013, A&A , 556, 36





Agueros et al. 2011, ApJ, 740, 110

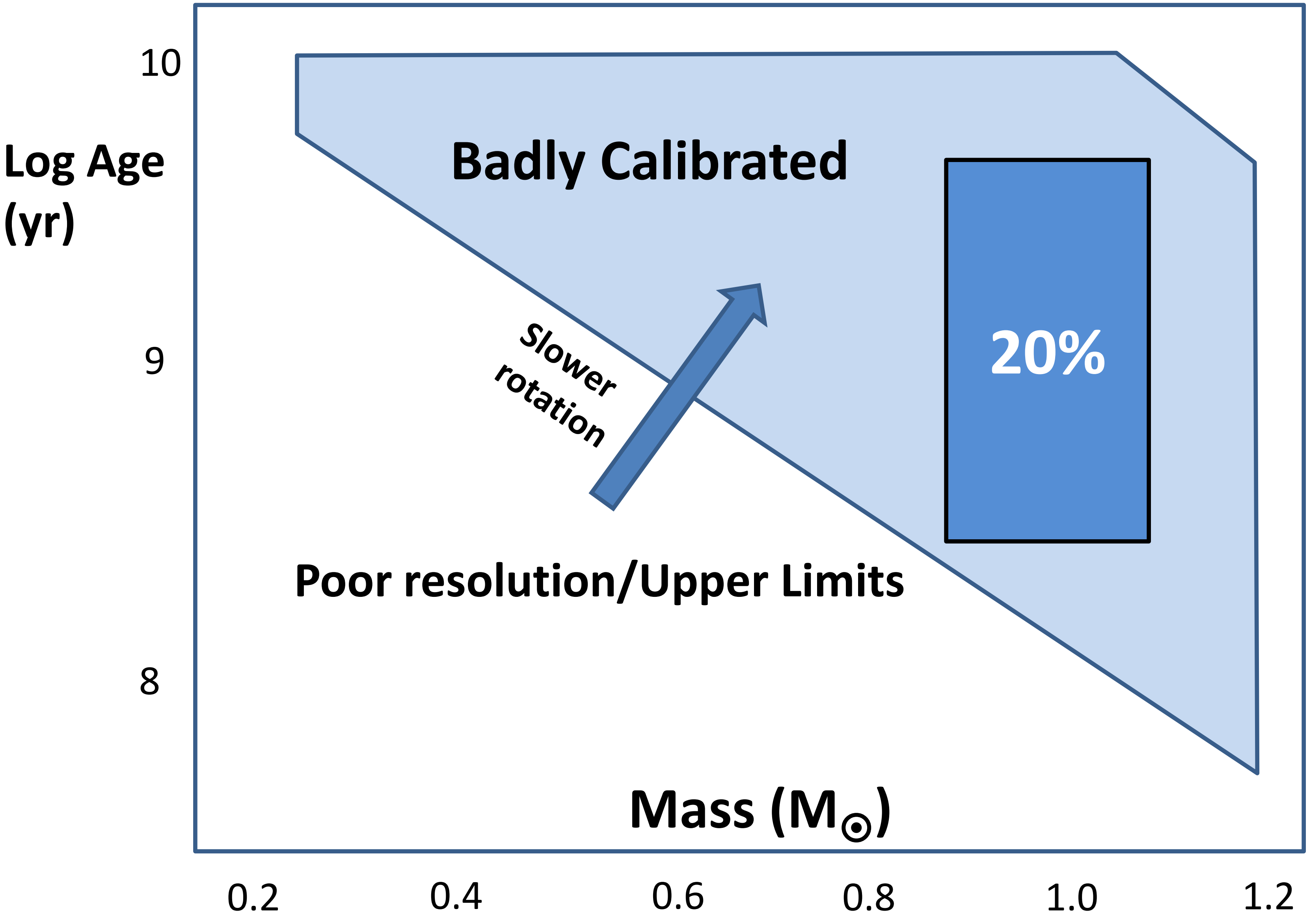
- **Lower mass stars take longer to converge**
- **Converged rotation trend is a function of age and mass**

Meibom et al. 2011, ApJ, 733, 115

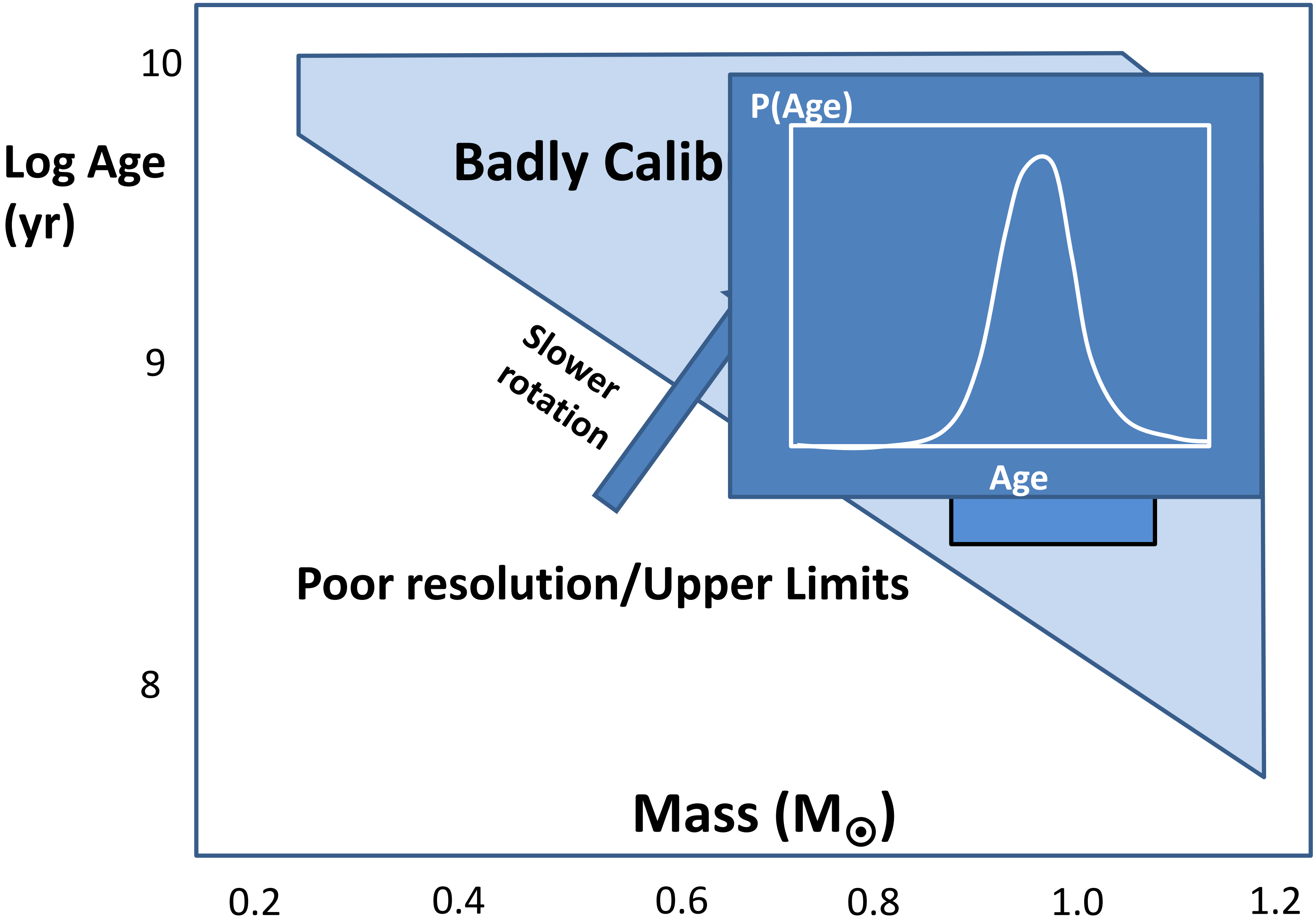
Summary for rotation as an empirical age indicator

- Rotational evolution not fully understood
- Rotation is good indicator below at >0.1 Gyr for early G-stars to >1 Gyr for M-stars
- Precision limited by rotation spreads at a given age in younger stars and differential rotation in older stars.
- Age **precisions of 20%** are feasible, but **hard to measure** rotation (esp. vsini) in old (>1 Gyr) stars.
- **Accuracy**! We need other older and cooler calibrators.

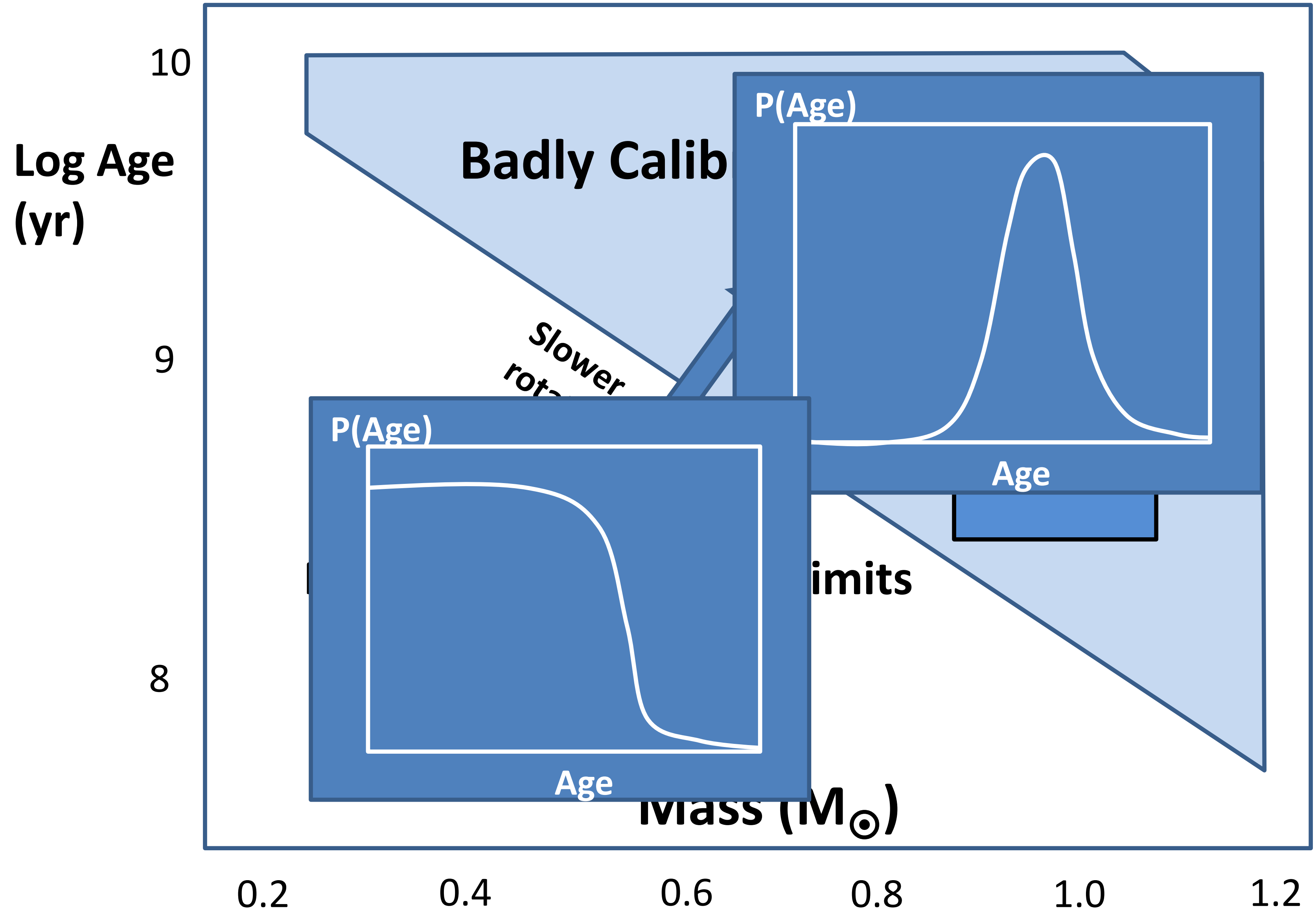
Applicability of Rotation



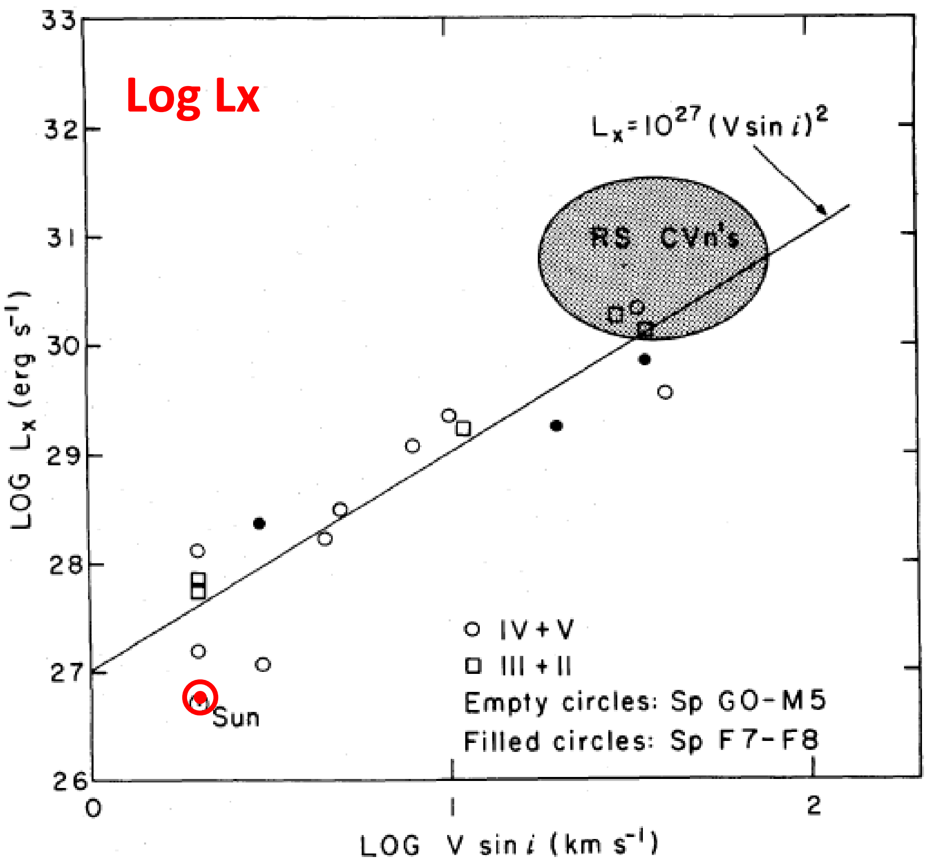
Applicability of Rotation



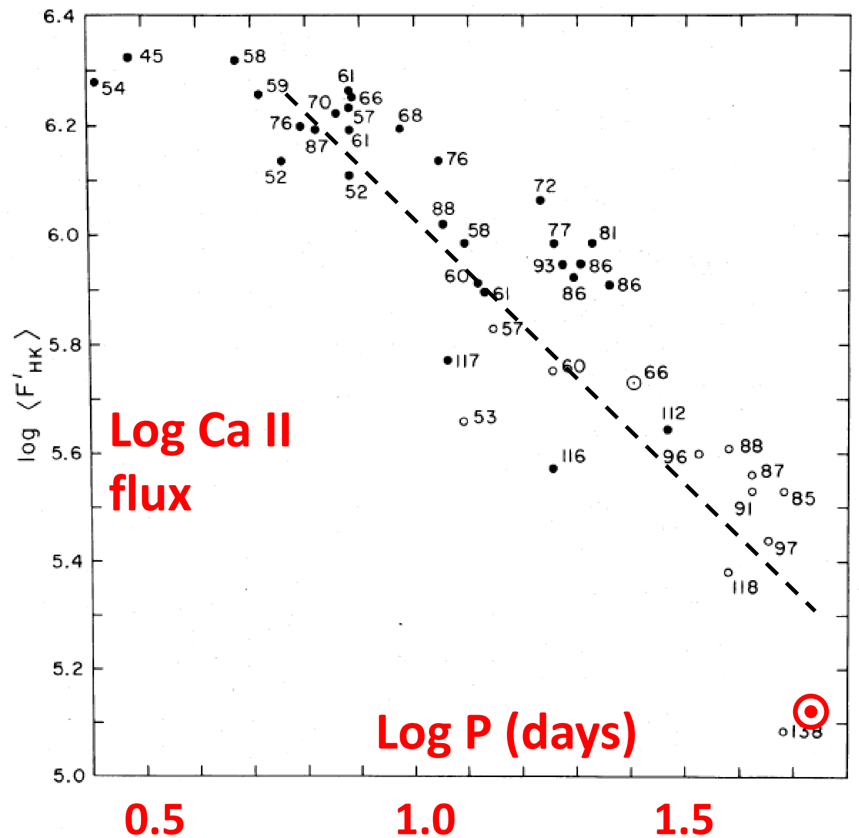
Applicability of Rotation



The rotation-activity connection



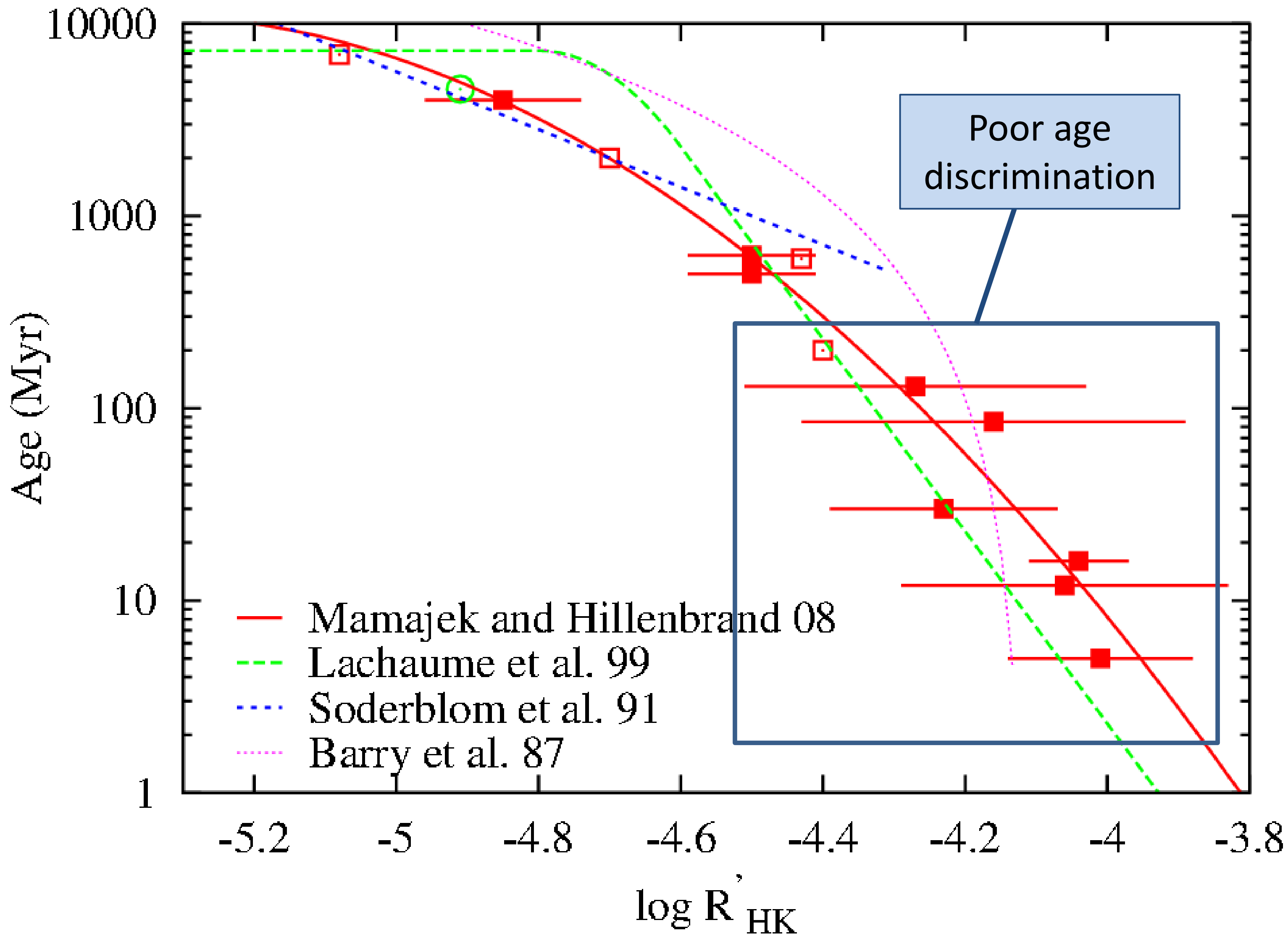
Pallavicini et al. 1981, ApJ, 248, 279



Noyes et al. 1984, ApJ, 279 763

Magnetic activity <u>can</u> be easier to measure than rotation – but old stars are less active

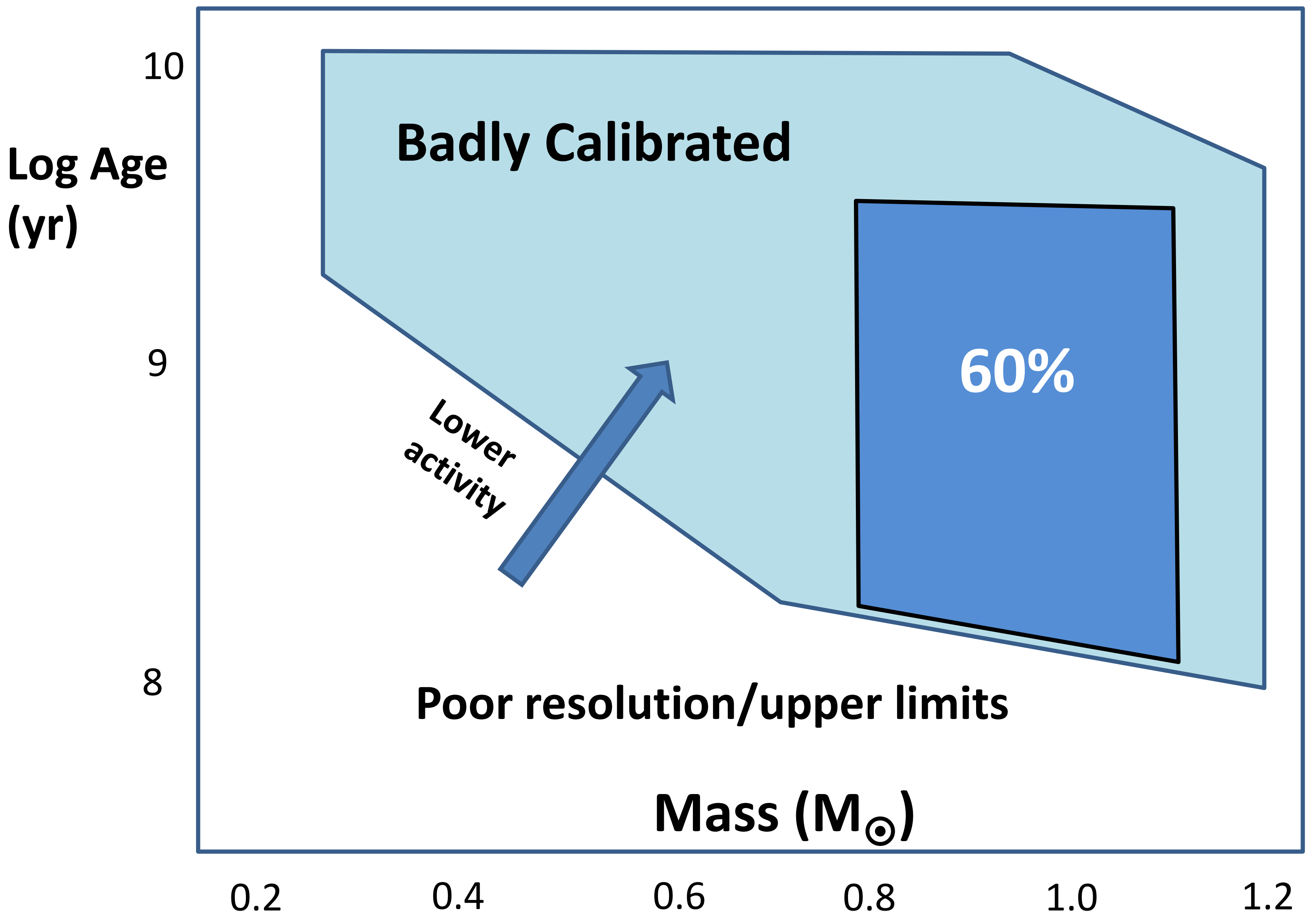
Activity-age relationships



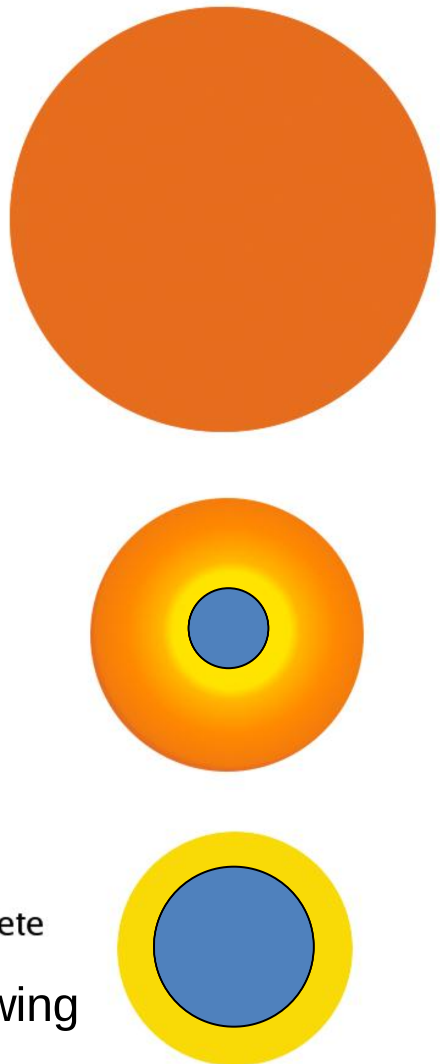
Summary for activity as an empirical age indicator

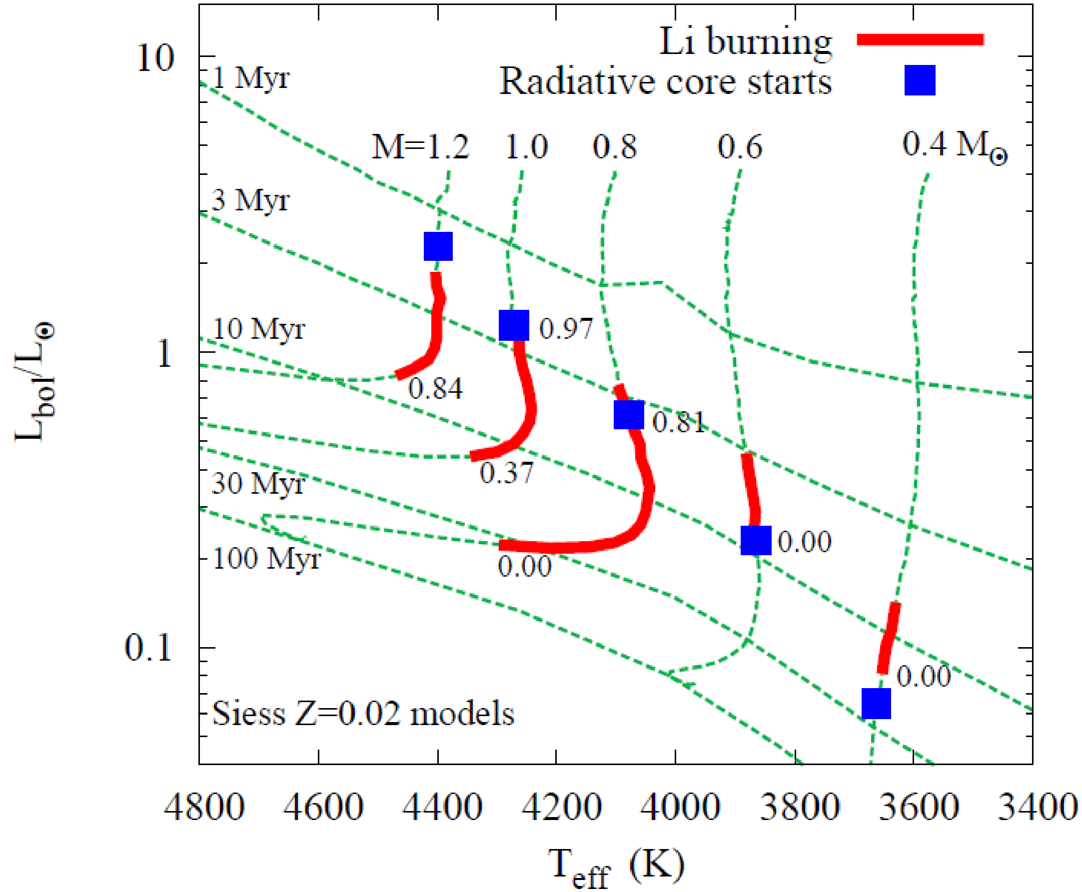
- Activity a good indicator at >0.1 Gyr in solar type stars and older for lower masses.
- **Precision +/- 60%** for older stars; poorer at lower masses
- Confused by rotation spreads at young ages and activity cycles at older ages
- Easier to measure than rotation
- Poorly calibrated for cooler stars and at older ages (>5 Gyr)

Applicability of Activity-Age Relations



Lithium depletion in F-,G-,K- and early-M stars





Halted by growing radiative core

$^{7}Li + p \longrightarrow {}^{4}He + {}^{4}He$ at 2.5×10^{6} K

^{6}Li destroyed at lower temperatures

The Pleiades (125 Myr) and the Sun

For the Sun

A(Li) = 1.1

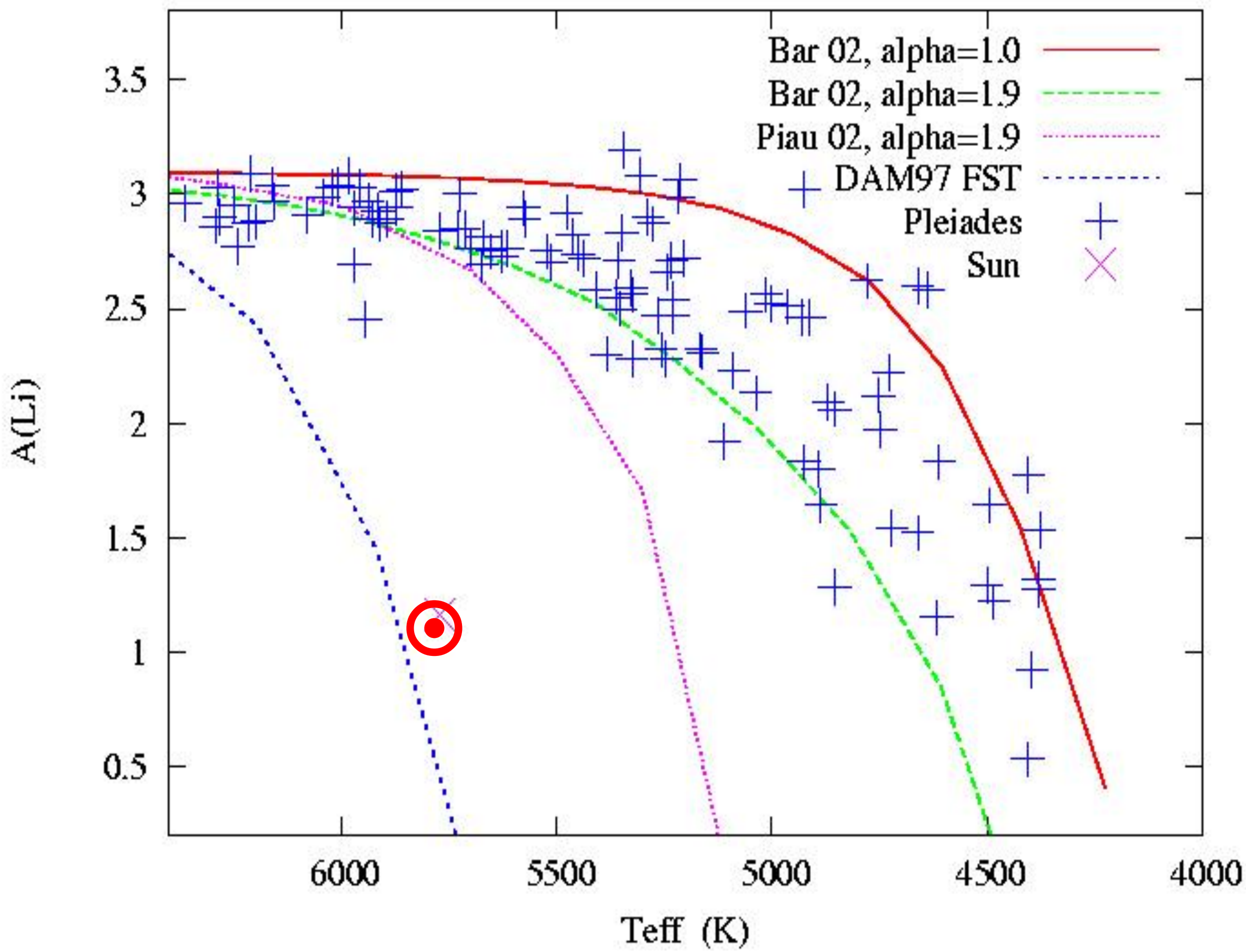
Pleiades G-stars

A(Li) = 3.0

There is <=0.3 dex of PMS Li depletion in F/G stars.

Depletion increases and a **SCATTER** develops among K-stars.

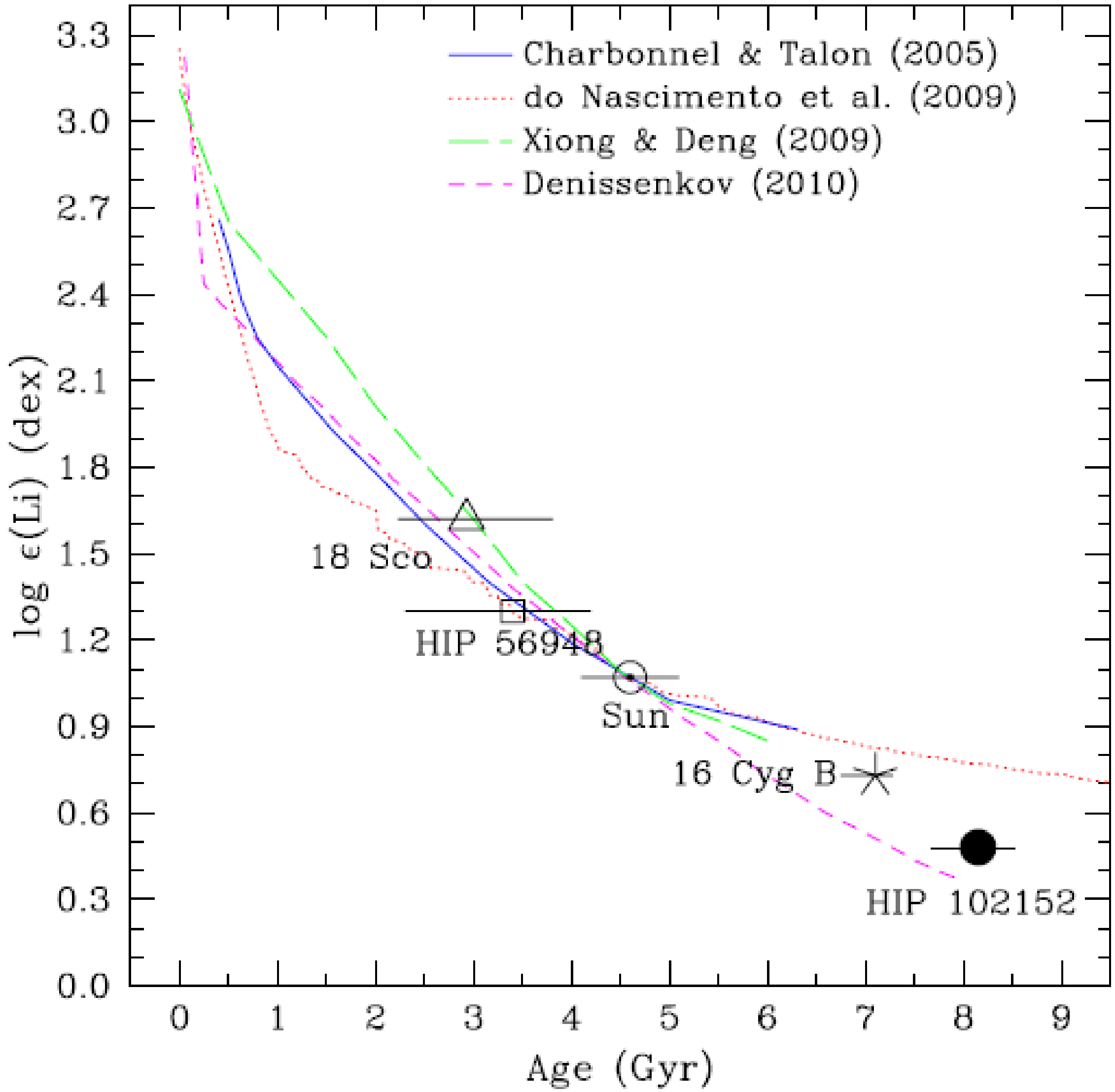
$A(Li) = 12 + \log(N_{li}/N_H)$



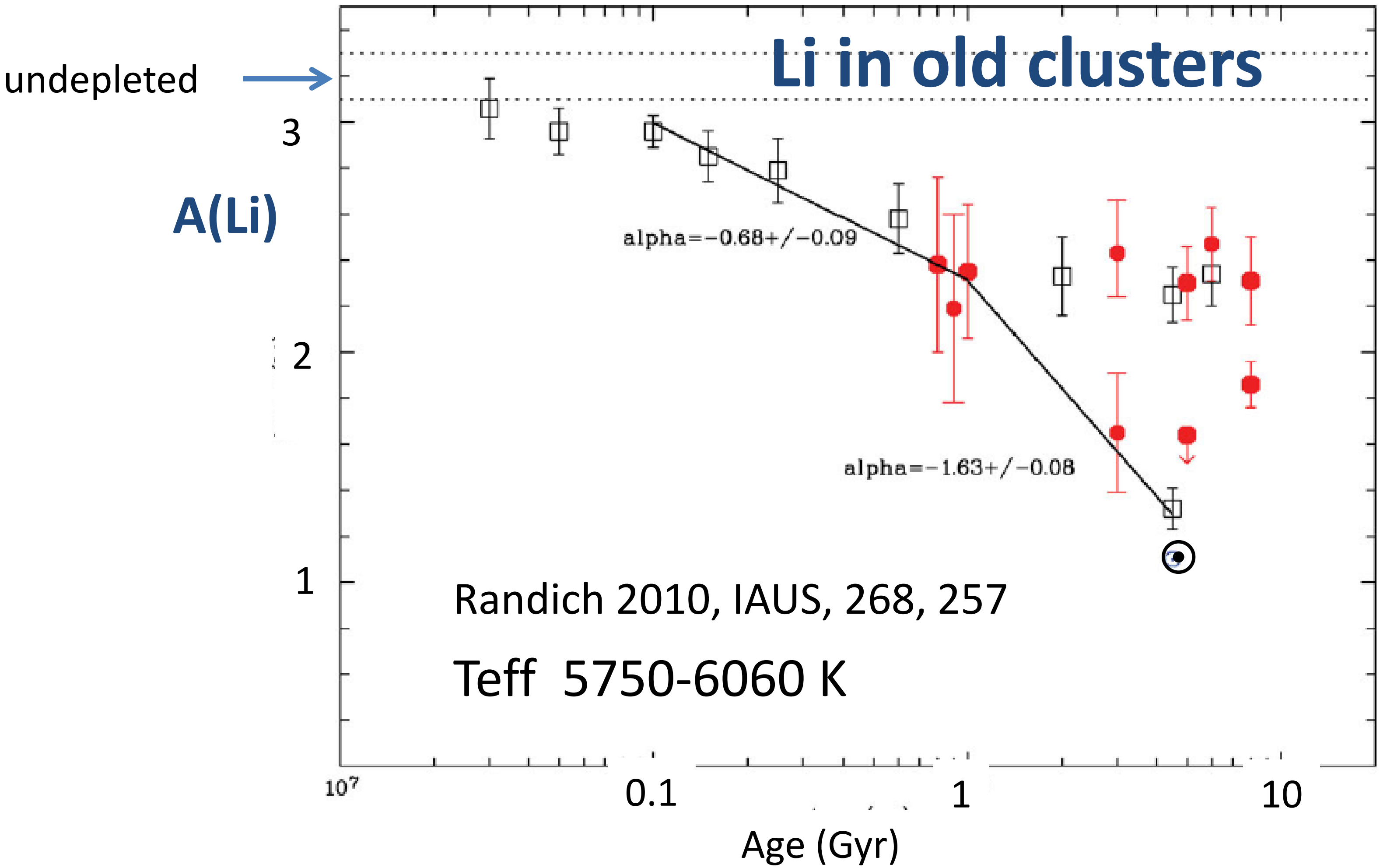
Pleiades data from Soderblom et al. 1993, AJ, 106, 1059

Models: D'Antona & Mazzitelli 1997, MmSAI, 68, 807; Baraffe et al. 2002, A&A, 382, 563; Piau & Turck-Chieze 2002, ApJ, 566, 419

Solar Twins



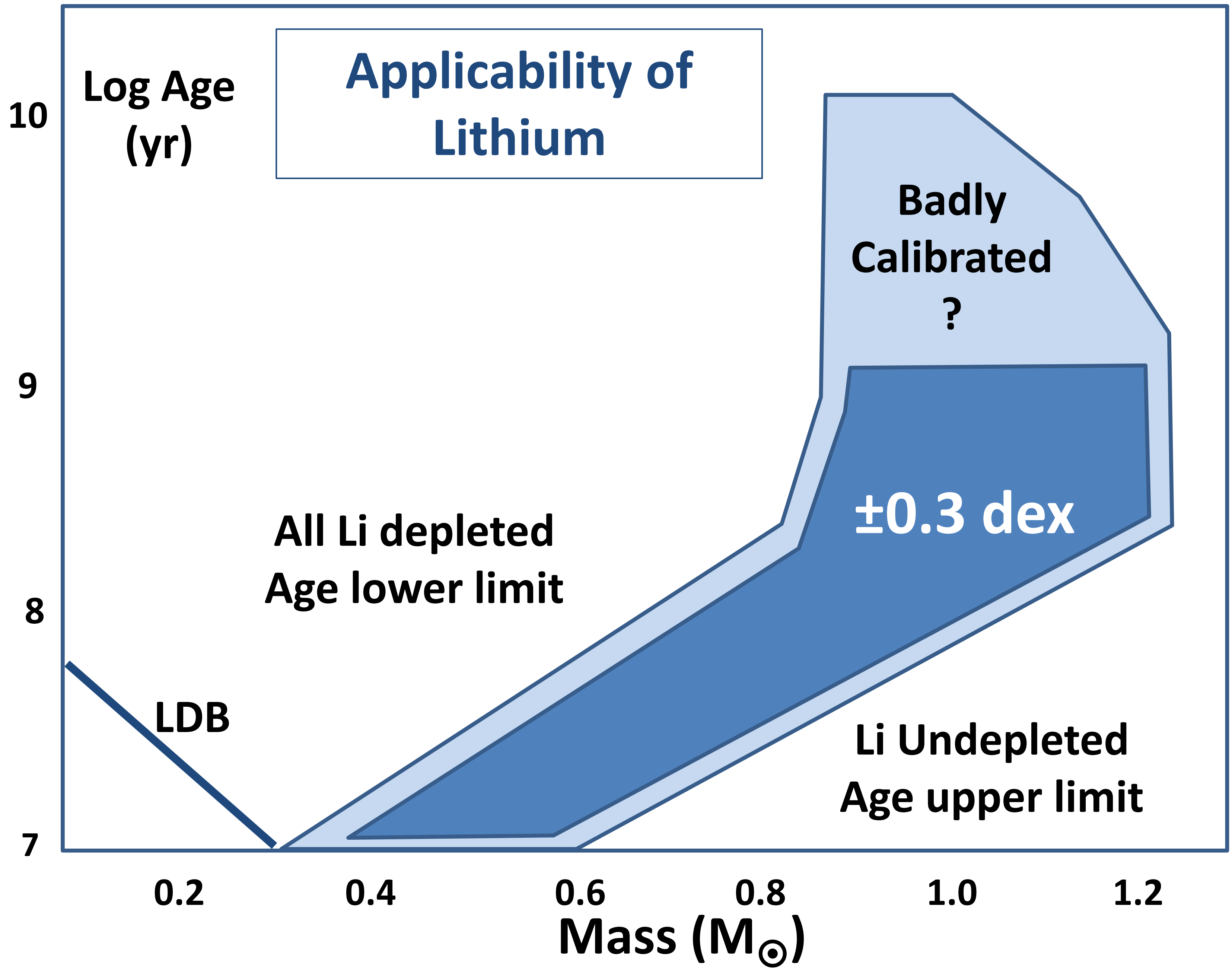
Monroe et al. 2013, ApJ, 774, L32



1. Sun appears LOW
2. Correlation with [Fe/H] is not obvious
3. Empirical ages may be inaccurate beyond 1 Gyr

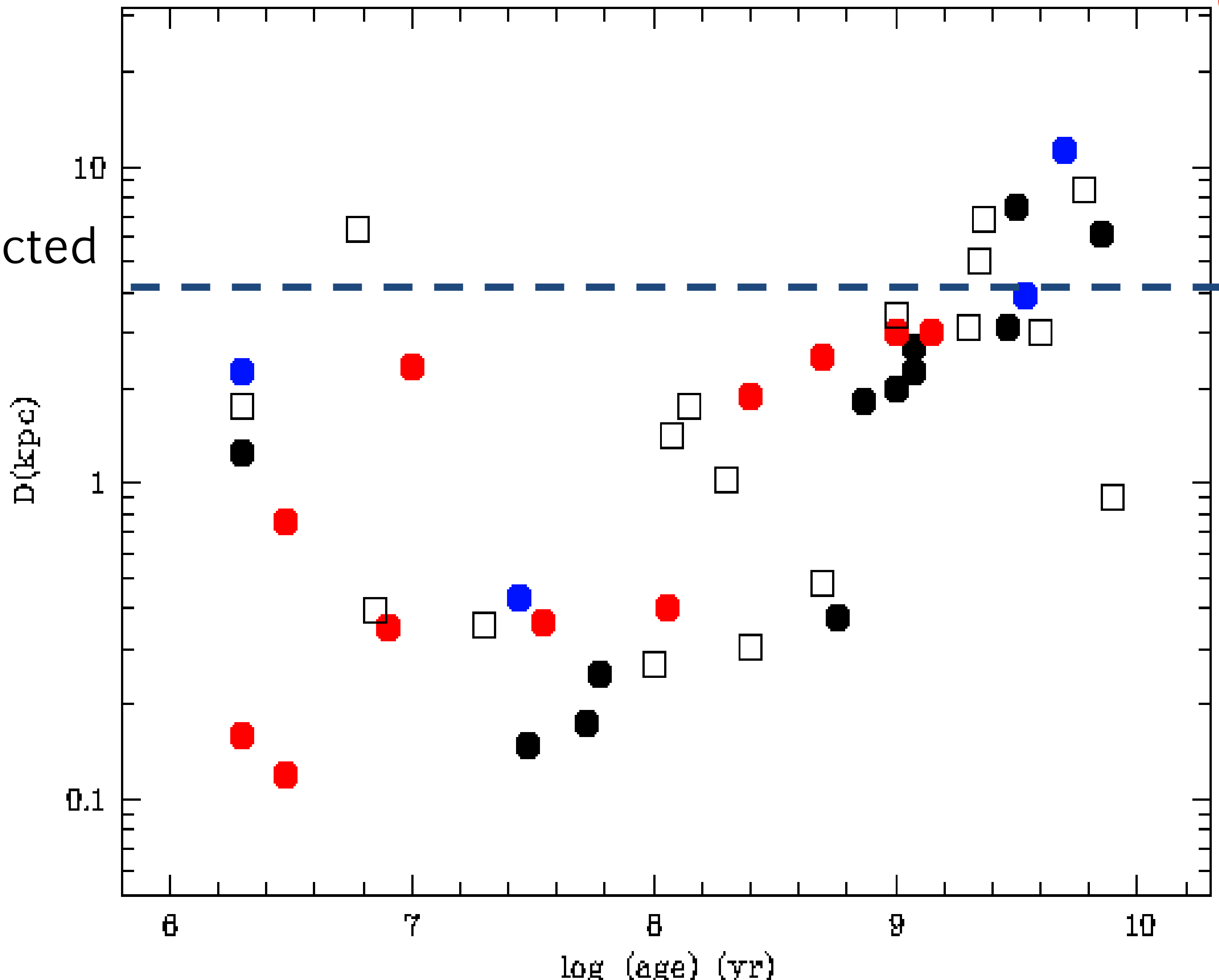
Summary of Li Abundance as an Age Indicator

- Li depletion is strongly age-dependent on the PMS – distance-independent age indicator for K/M stars with **precision of ~50%**
- Older, solar-type MS stars continue to deplete Li – precise measurements yield ages out to 1 Gyr.
- Contradictory evidence from field and clusters – Li depletion may halt after 1 Gyr in some stars.
- No/undepleted Li provides firm lower/upper limit to age


Applicability of Lithium
Log Age (yr)
10
9
8
7
Badly Calibrated ?
±0.3 dex
All Li depleted
Age lower limit
LDB
Li Undepleted
Age upper limit
0.2
0.4
0.6
0.8
1.0
1.2
Mass ($M_\odot$)

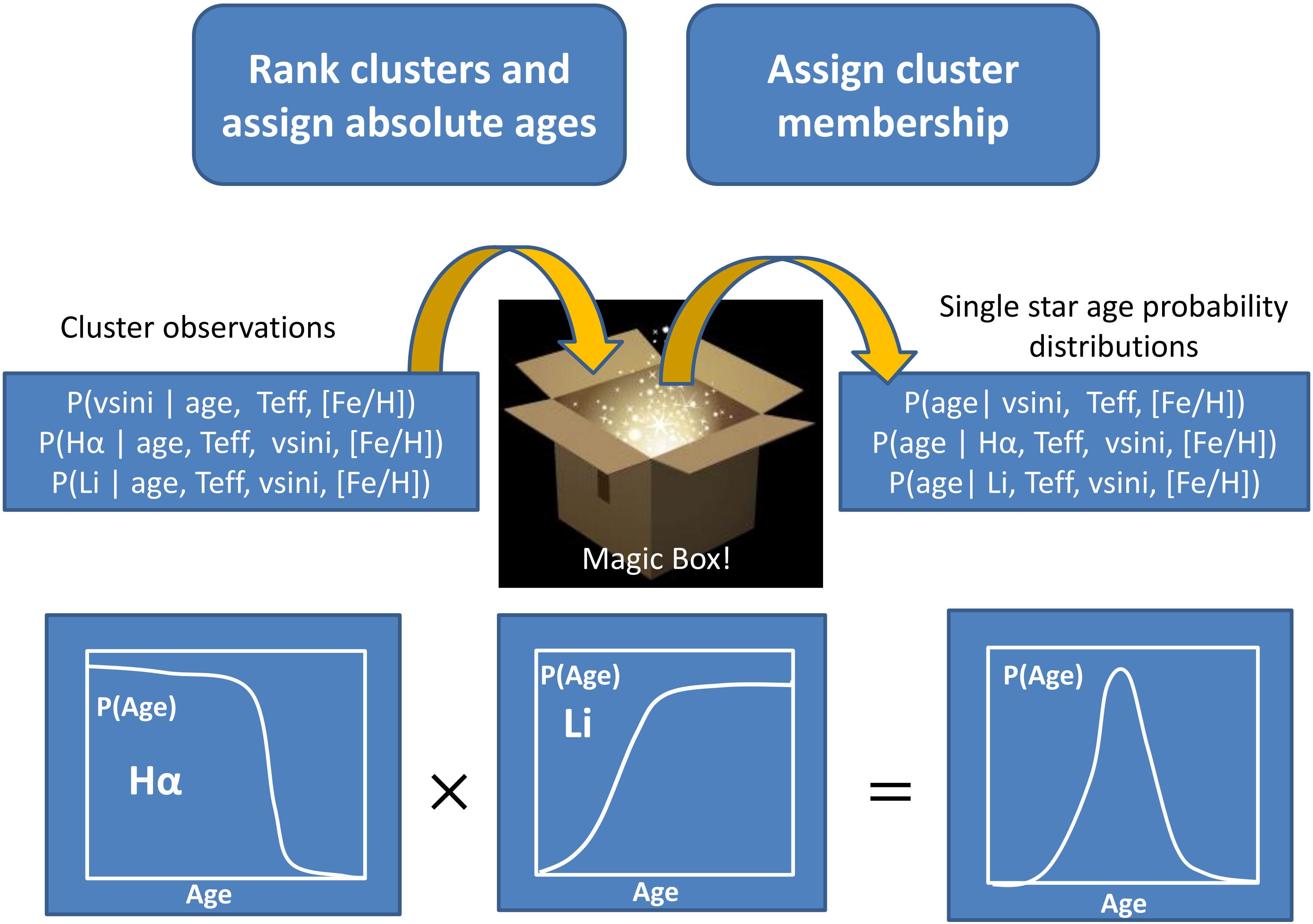
GES cluster sample

- iDR2
- iDR3
- iDR4
- protected



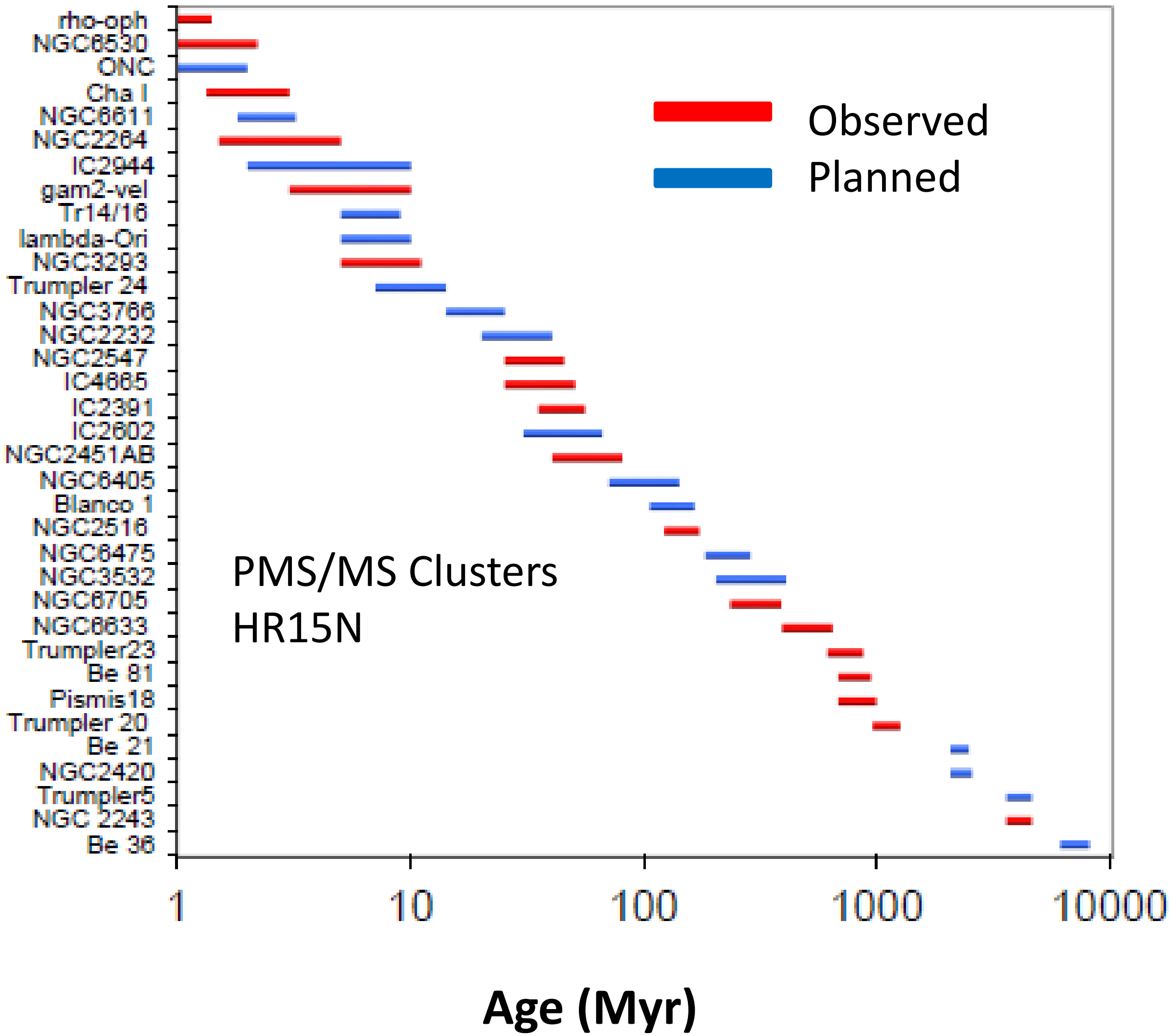
G2 MS star @V=19

S. Randich



Rank clusters and assign absolute ages
Assign cluster membership
Cluster observations
P(vsini | age, Teff, [Fe/H])
P(Hα | age, Teff, vsini, [Fe/H])
P(Li | age, Teff, vsini, [Fe/H])
Magic Box!
Single star age probability distributions
P(age| vsini, Teff, [Fe/H])
P(age | Hα, Teff, vsini, [Fe/H])
P(age| Li, Teff, vsini, [Fe/H])
P(Age)
Hα
Age
×
P(Age)
Li
Age
=
P(Age)
Age

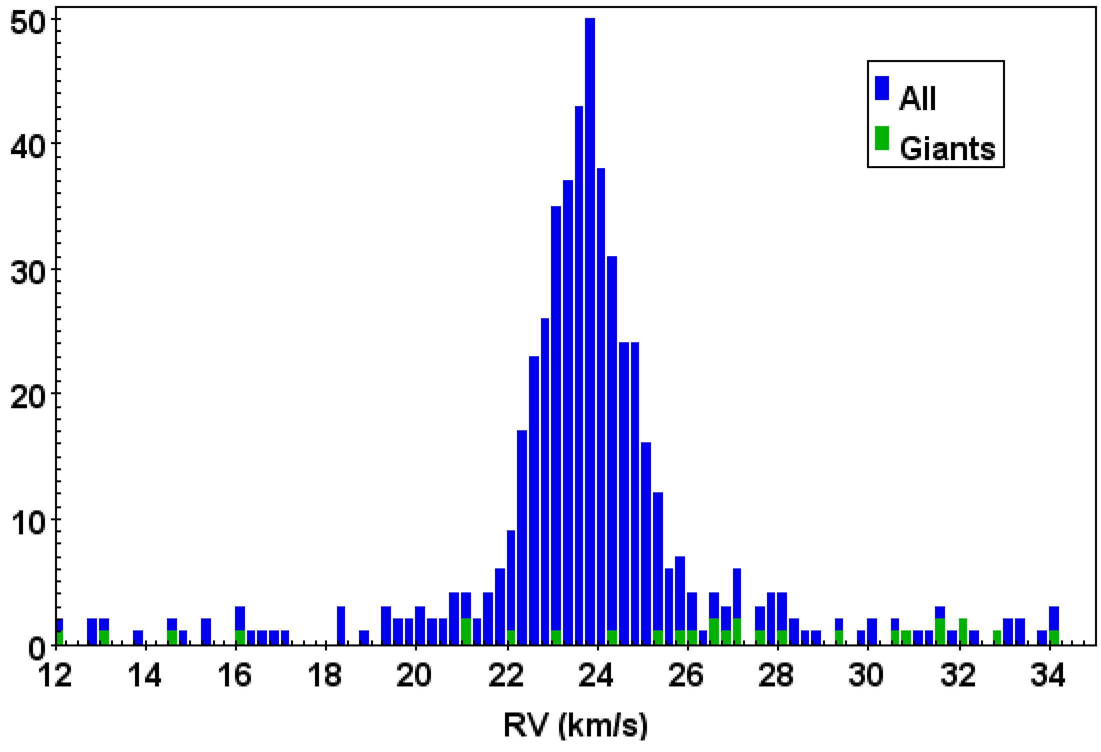
How can GES help?



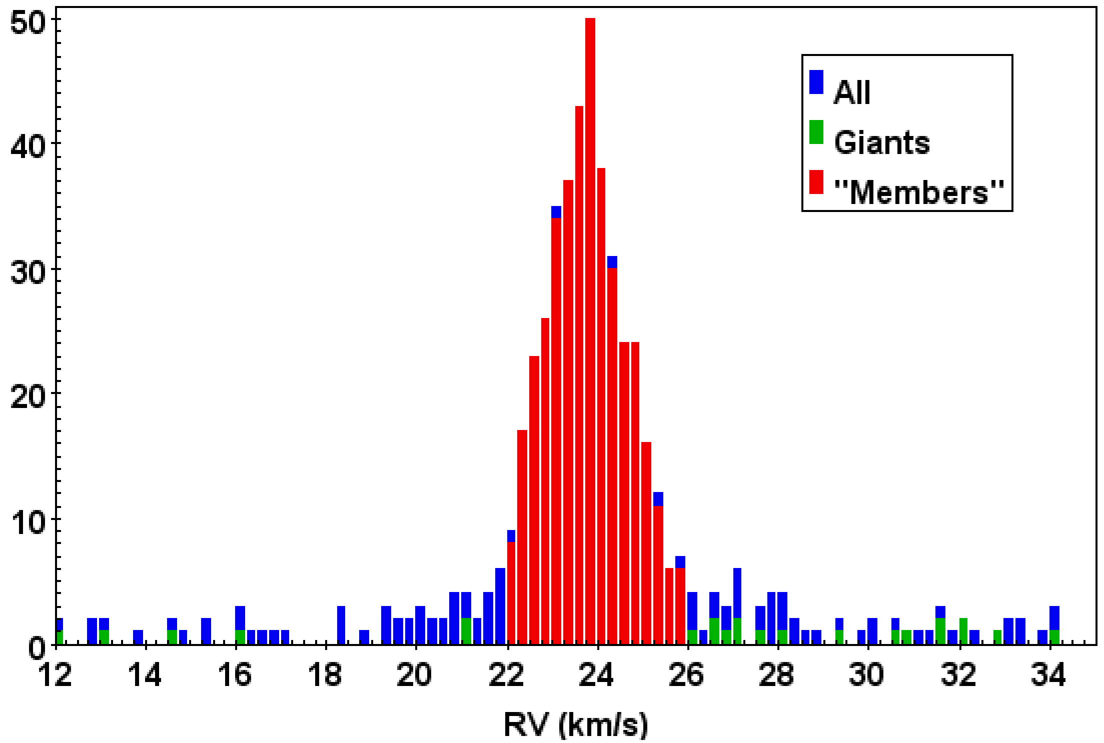
<u>Homogeneous data</u>

- Membership
- Teff, log g
- Metallicity
- Rotation (vsini)
- Activity (H-alpha)
- Accretion
- Lithium

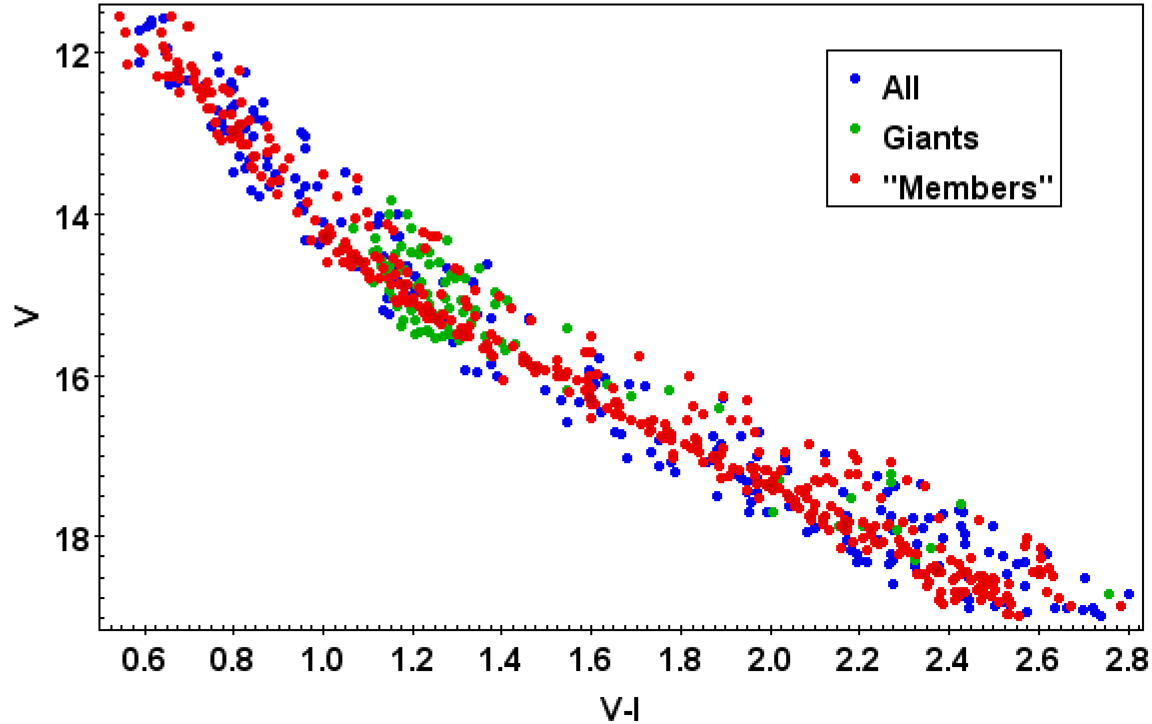
Membership Selection: e.g. NGC 2516 Age 140 Myr.



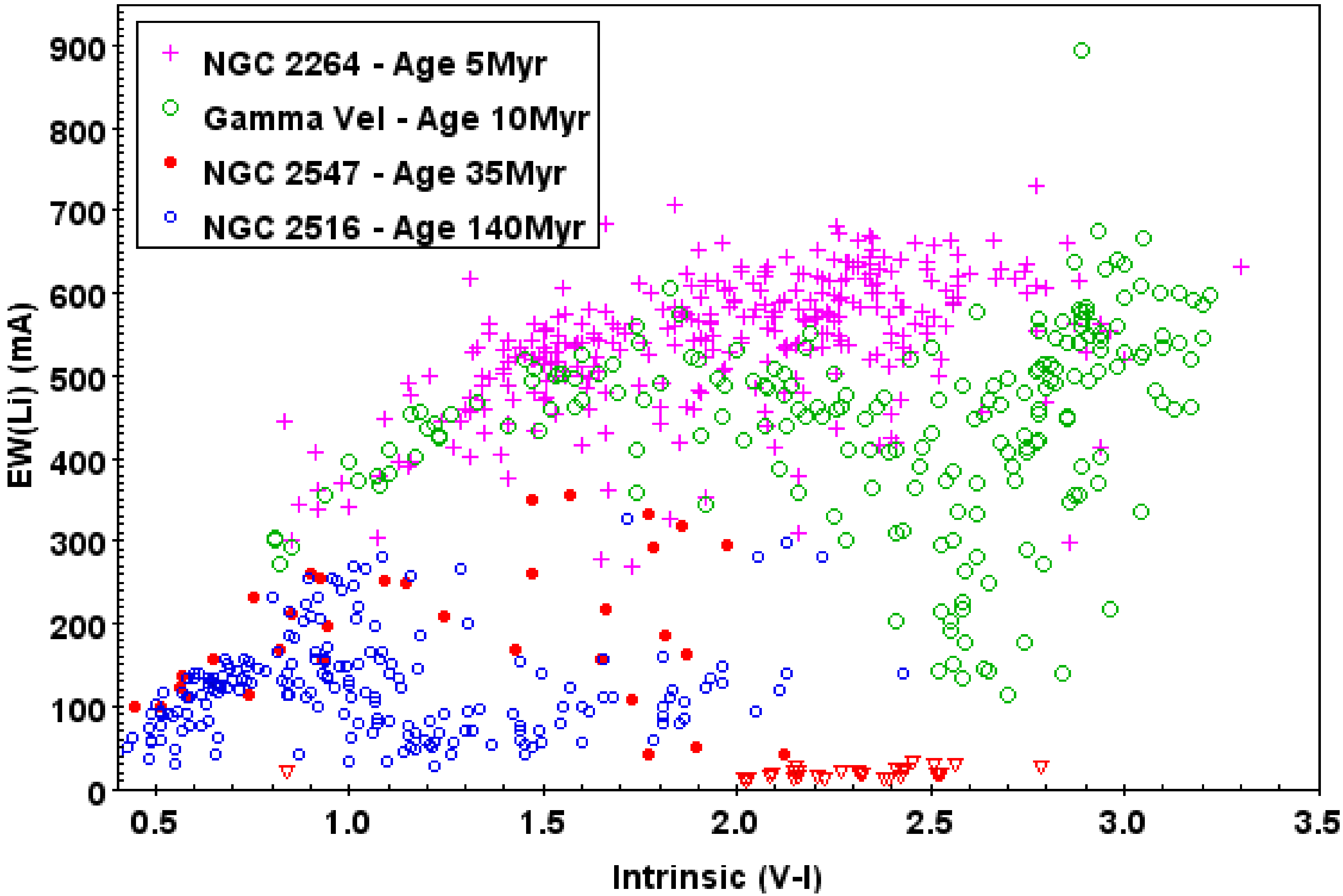
Simple kinematic +gravity selection – very clean
May be improved with proper motions



Probably no need to trim further in the CMD – though this is also possible



GES Lithium measurements EWLi(Age)

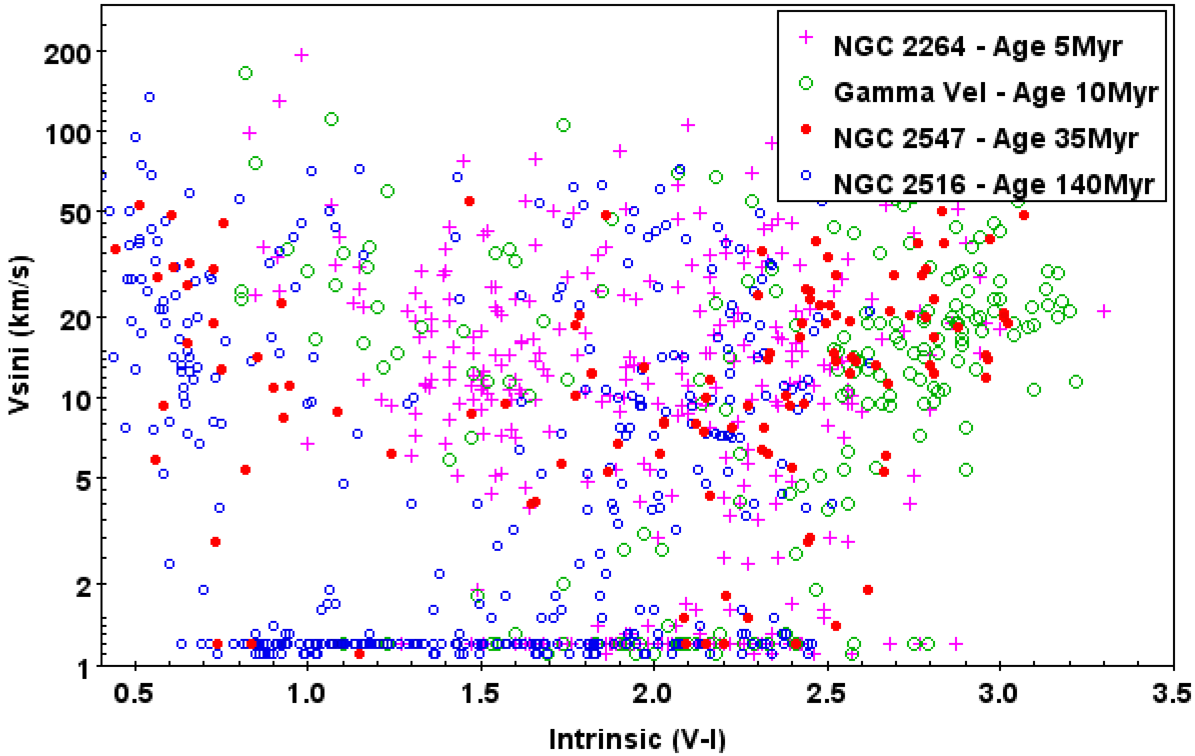


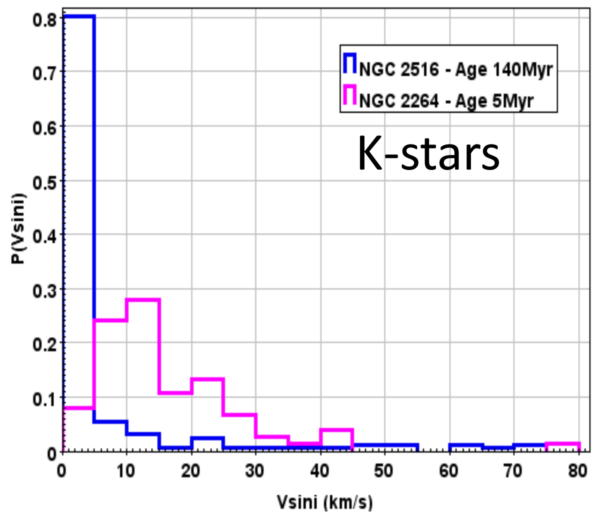
Extremely promising 5-200 Myr

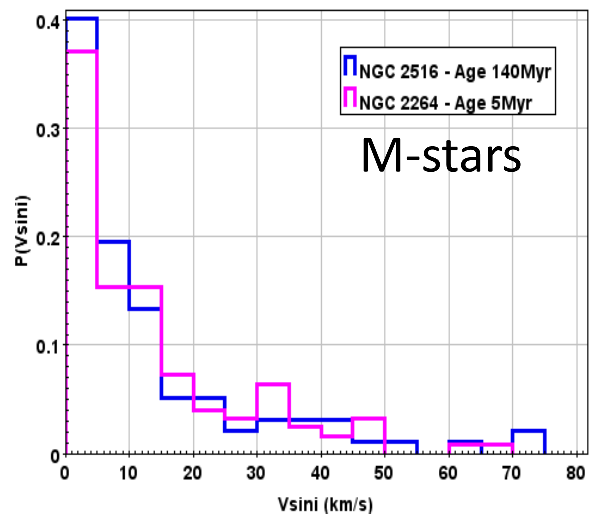
Rotation - Vsini(age)

More messy

But still clear, spectral-type-dependent variations with age







The Gaia-ESO survey and the empirical determination of stellar ages

Summary

- Empirical methods can (substantially) improve stellar age estimates
- Calibration can be provided by homogeneous analysis of GES clusters
- Lasting legacy – many applications; GES field stars; population selection; GALAH, WEAVE etc.; "priors" for Gaia isochrone fitting