The Ages of Young Stars

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Aims and Scope

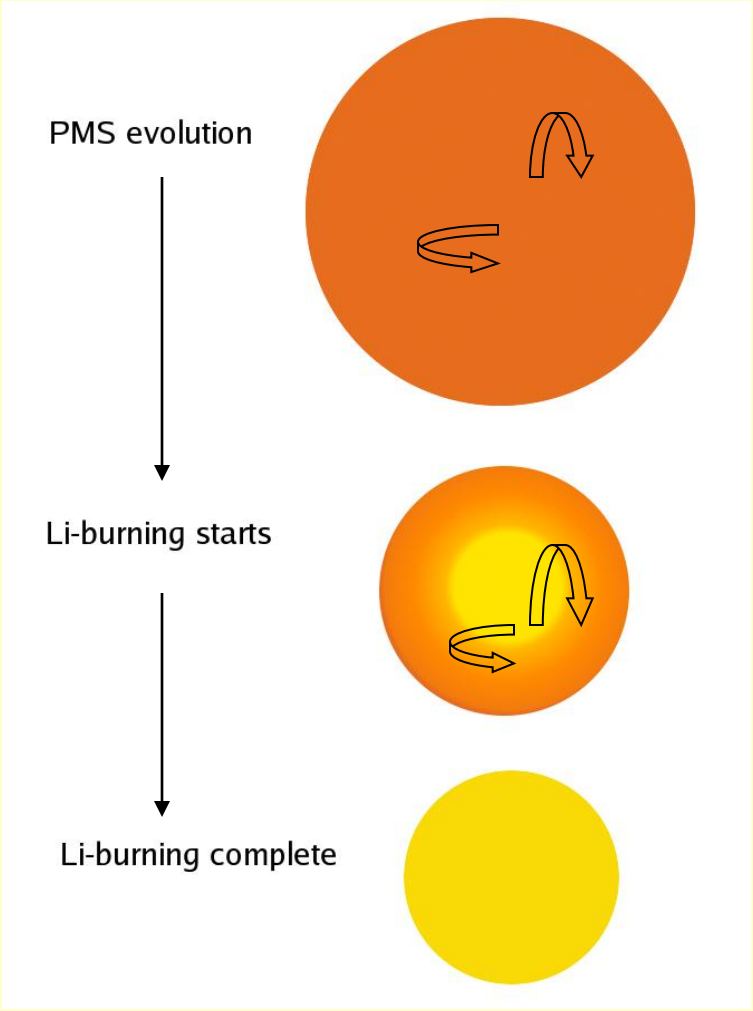
For young stars up to the age of **~100 Myr**:

- Can we categorise stars?
- Can we put them in age order?
- Can we estimate age ratios or age differences?
- Can we estimate absolute ages?

A hierarchy of methods

Fundamental	None available
Semi-Fundamental	Lithium Depletion Boundary Kinematic Traceback
Model-Dependent	Isochrone fitting, Asteroseismology Surface gravity, Radii, Radiative-convective gap
Empirical	Rotation, activity, disks, lithium
Statistical	Metallicity, Kinematics - not useful

The Lithium Depletion Boundary



In low mass stars <0.4 $M_\odot$

Fully convective

Li burns at **T_C= 3x10^6 K**

When core reaches T_C, Li is **rapidly** burned.

Little dependence on convection treatment, nuclear rate, opacities; **some dependence** on atmosphere, equation of state.

LDB - the luminosity at which Li remains unburned

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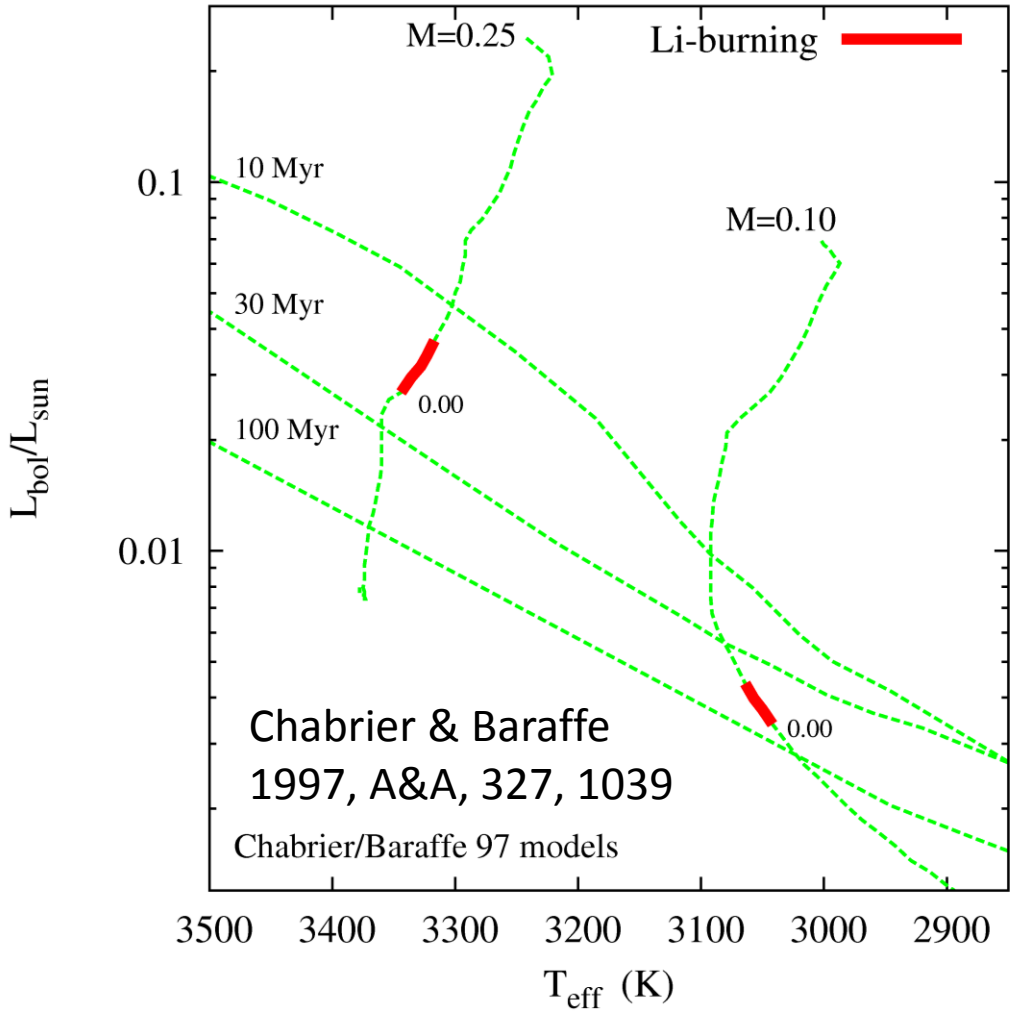

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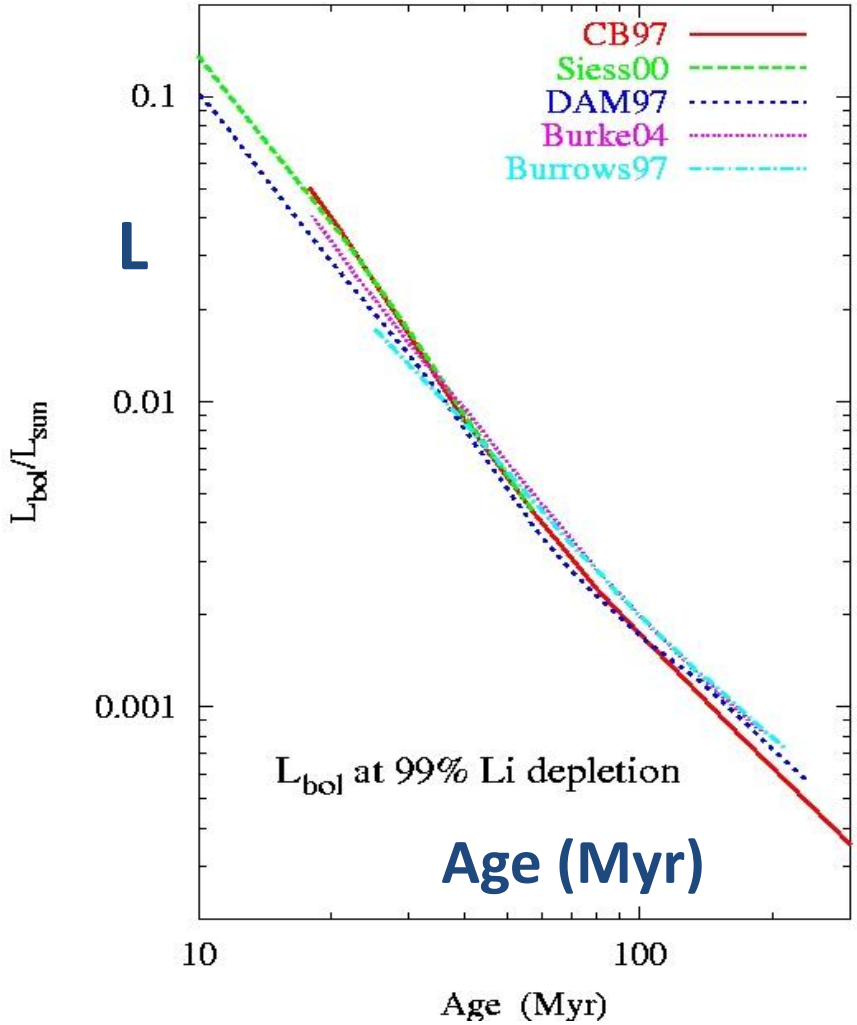
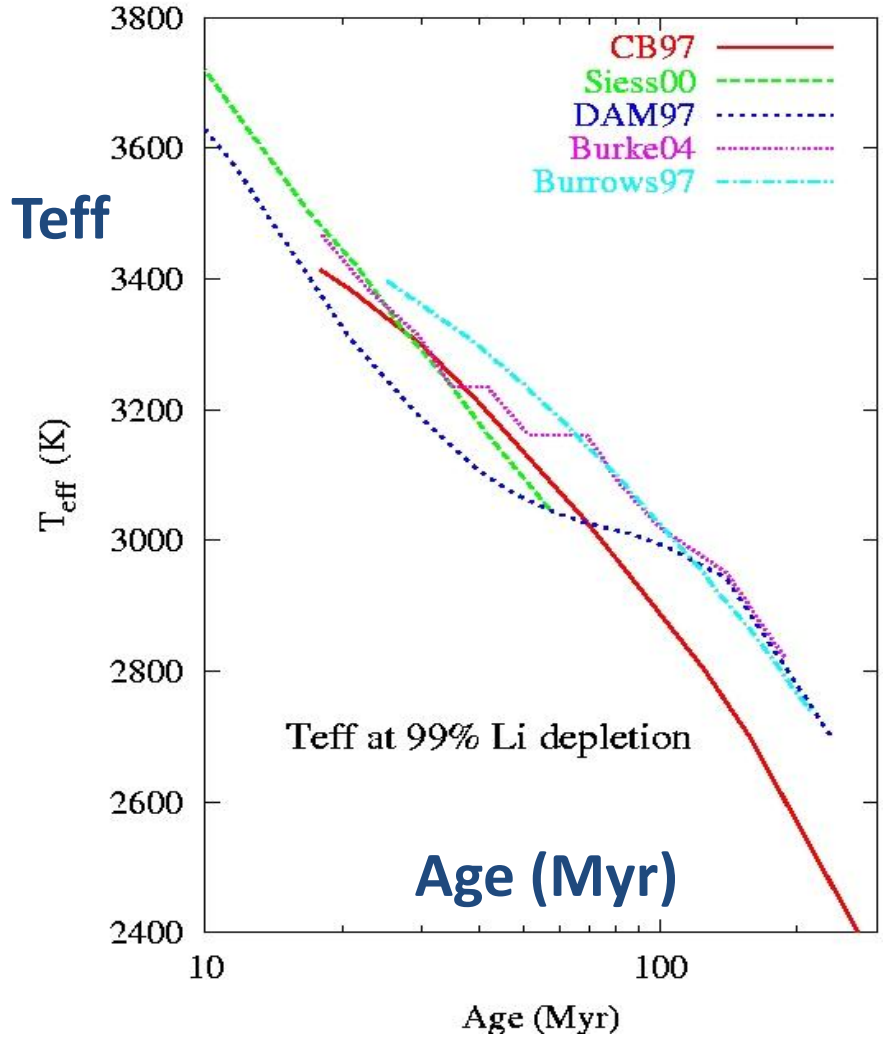




L_{bol} when depletion occurs is **model <u>in</u>sensitive (20-200 Myr)**

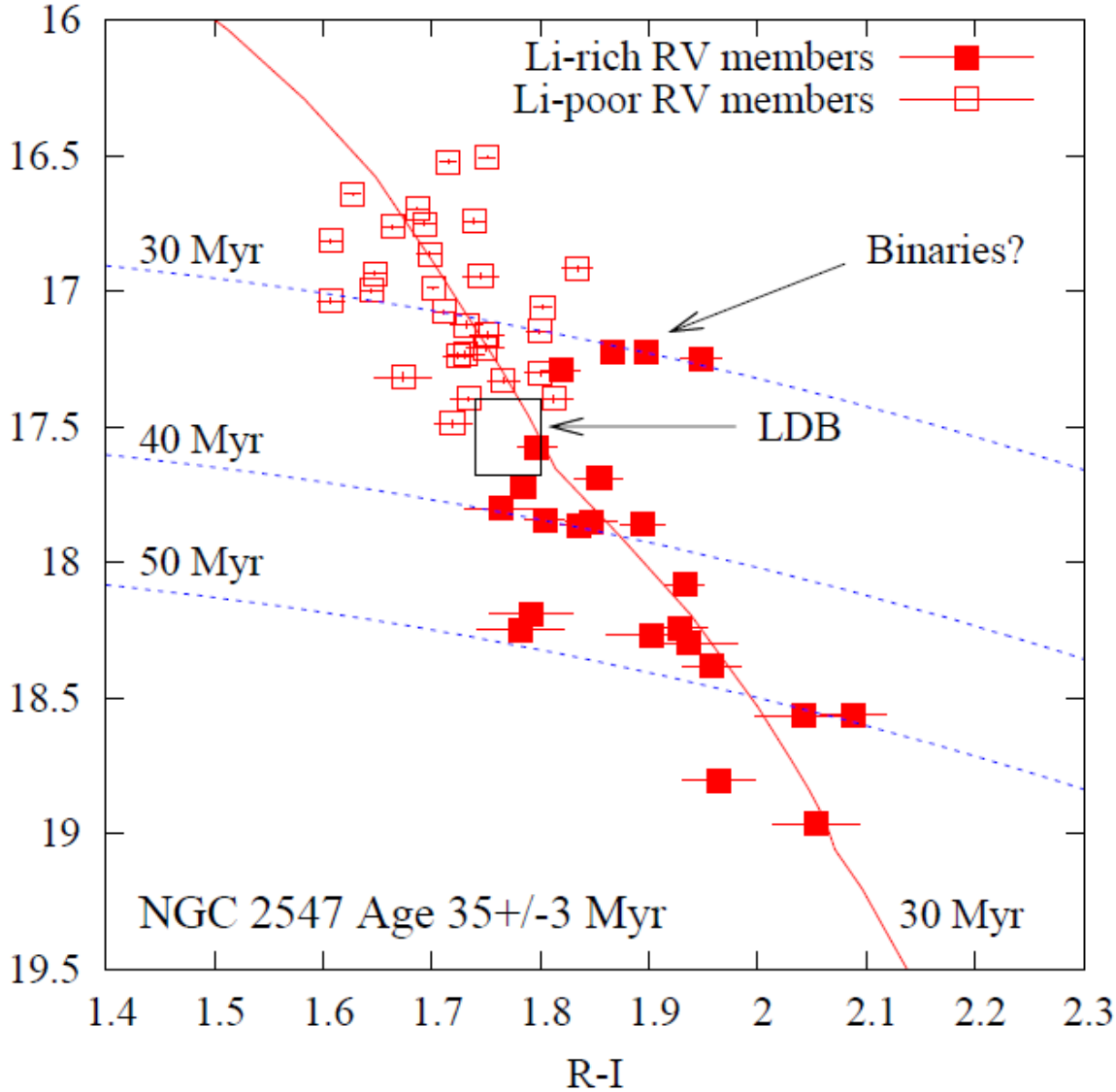
T_{eff} when depletion occurs is atmosphere dependent

Insensitive to measurement uncertainties – distance, extinction etc.

Requires good spectroscopy and photometry of faint stars

Difficult to locate LDB – binarity, variability, age spreads?

8 CLUSTERS HAVE MEASURED LDB 22-132 Myr



Jeffries & Oliveira 2005, MNRAS, 358, 13

Kinematic Ages

"Traceback Ages" – tracing orbits of group members to a past minimum dispersion/size.

"Expansion Ages" – measuring velocity vs. position trends (age = 1/slope)

"Flyby Ages" – time of min. separation between star-group, group-group (star/group from same cloud?)

"Runaway Ages" – flyby age where either a binary-supernova or dynamical ejection likely occurred.

- **Conceptually simple, though require excellent astrometry,**
- **But these techniques have checkered histories.**

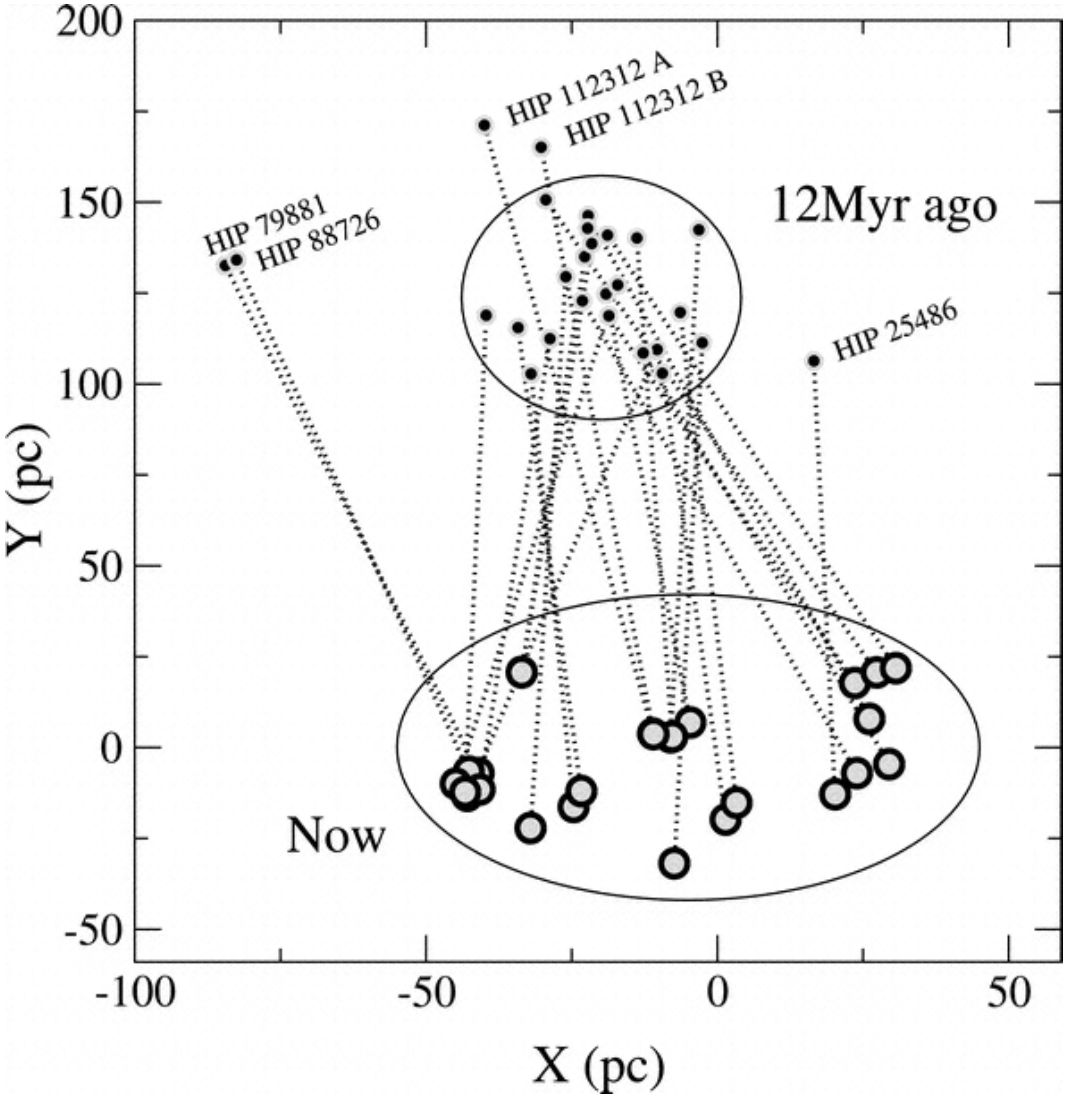
Brown et al. 1997 MNRAS, 285, 479

Ortega et al. 2002, ApJ, 575, L75

Hoogerwerf et al. 2001 A&A 365, 49

Soderblom 2010 ARA&A 48, 581

Traceback Ages

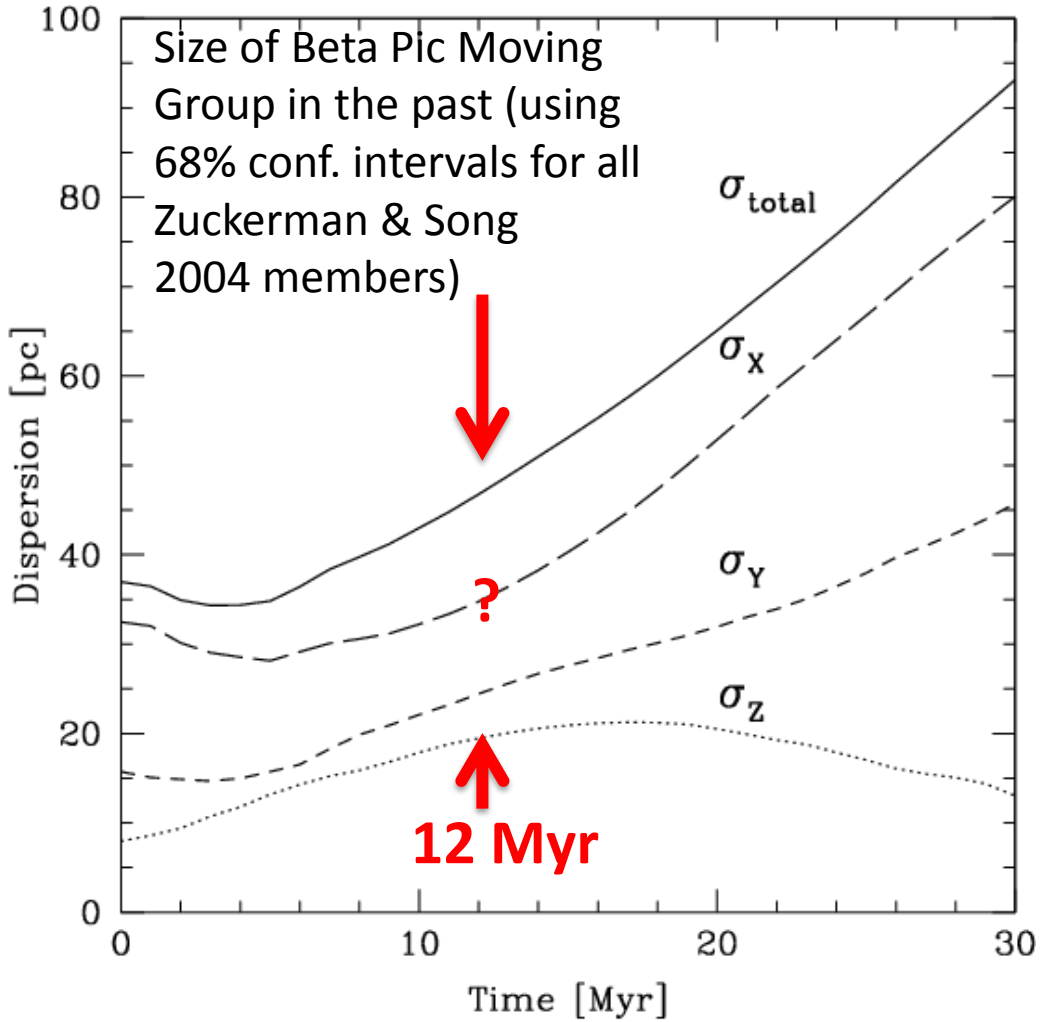


- **Famous example: Beta Pic Moving Group**
- **Isochronal age 12^{+8}_{-4} Myr (Zuckerman et al. 2001 ApJ, 562, L87)**
- **Using Hipparcos astrometry and published radial velocities, 3 subsequent studies estimate traceback age of ~11-12 Myr.**

Song et al. 2003 ApJ 599, 342

(see also Ortega et al. 2002, ApJ, 575, L75; Ortega et al. 2004, ApJ, 609, 243)

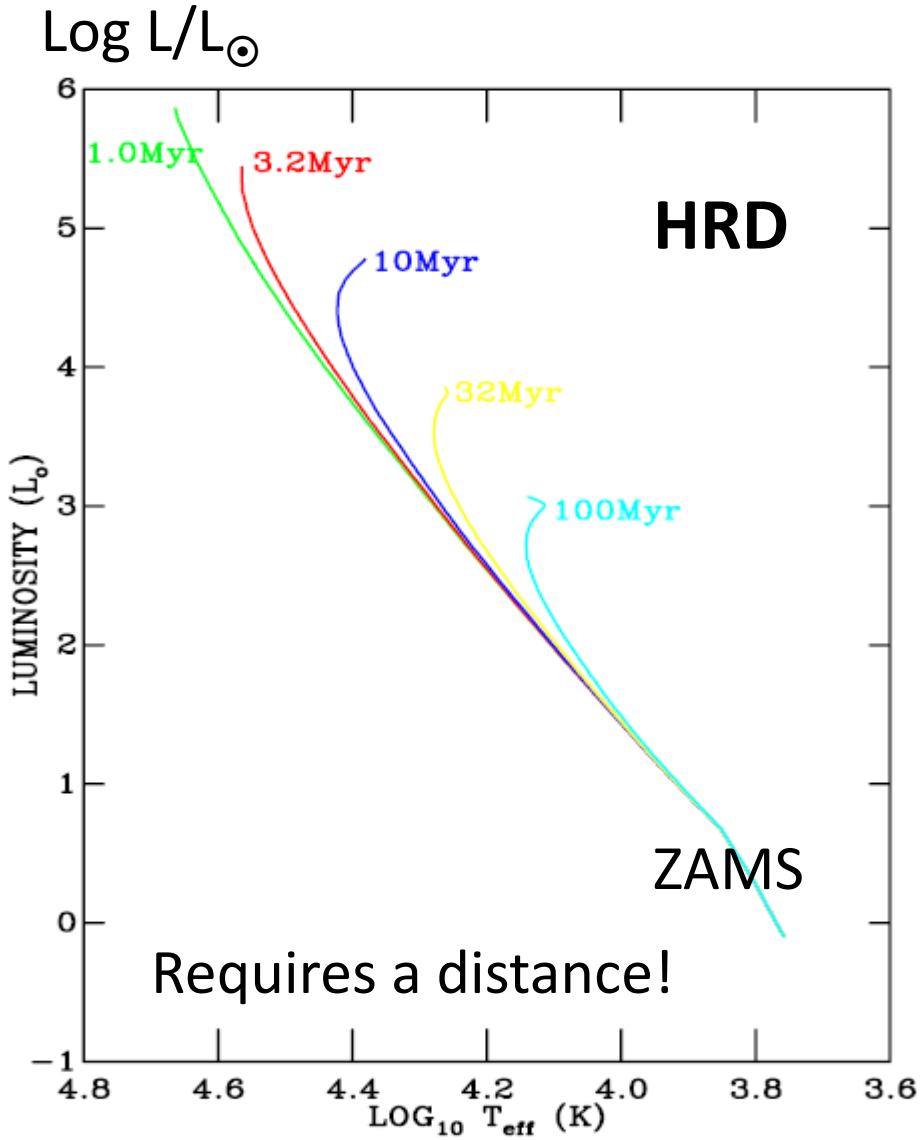
Traceback Ages

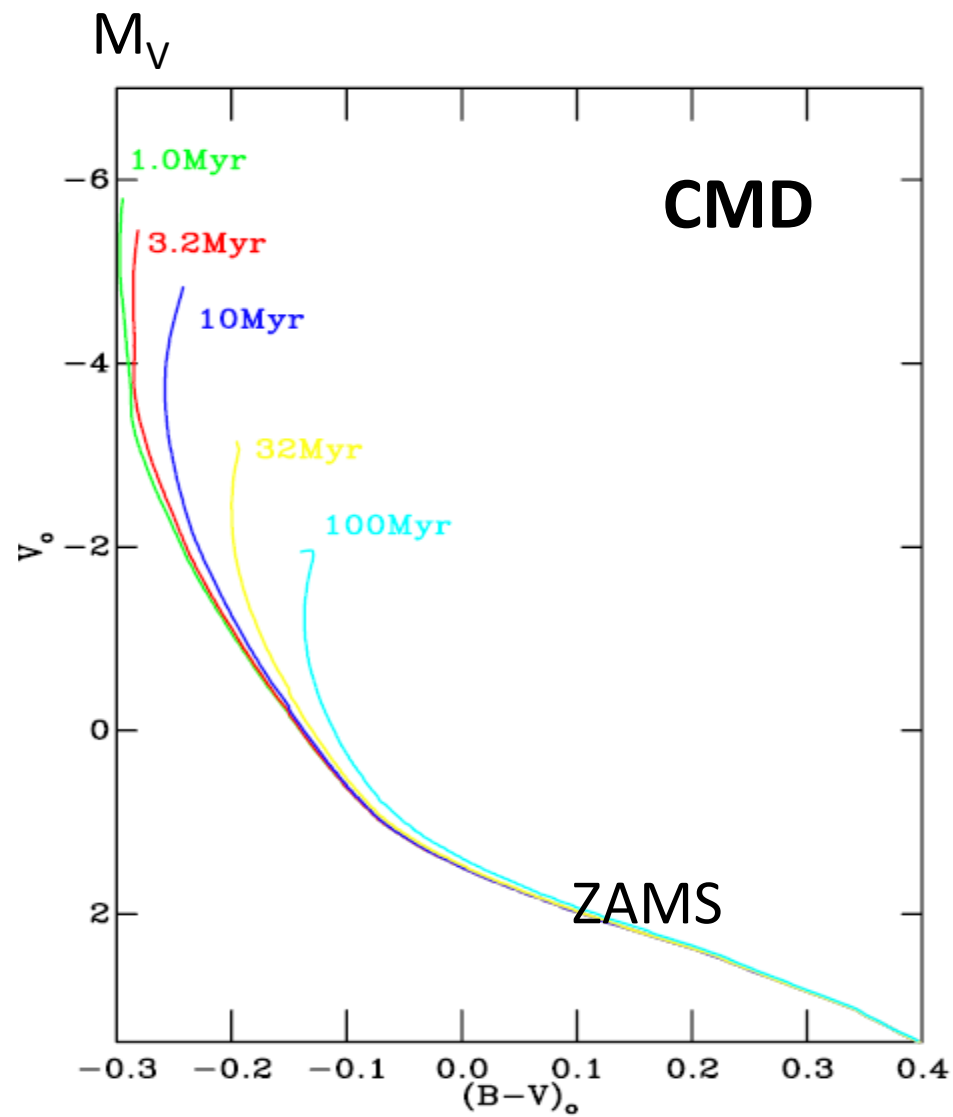


- **But… results hinge on inclusion/exclusion of particular stars.**
- **Using revised Hipparcos astrometry, the group is *not* smaller in the past**
- **Expansion rate inconsistent with 12 Myr at >3σ**

Mamajek, in prep. (using van Leeuwen's revised Hipparcos astrometry)

Ages from the UMS



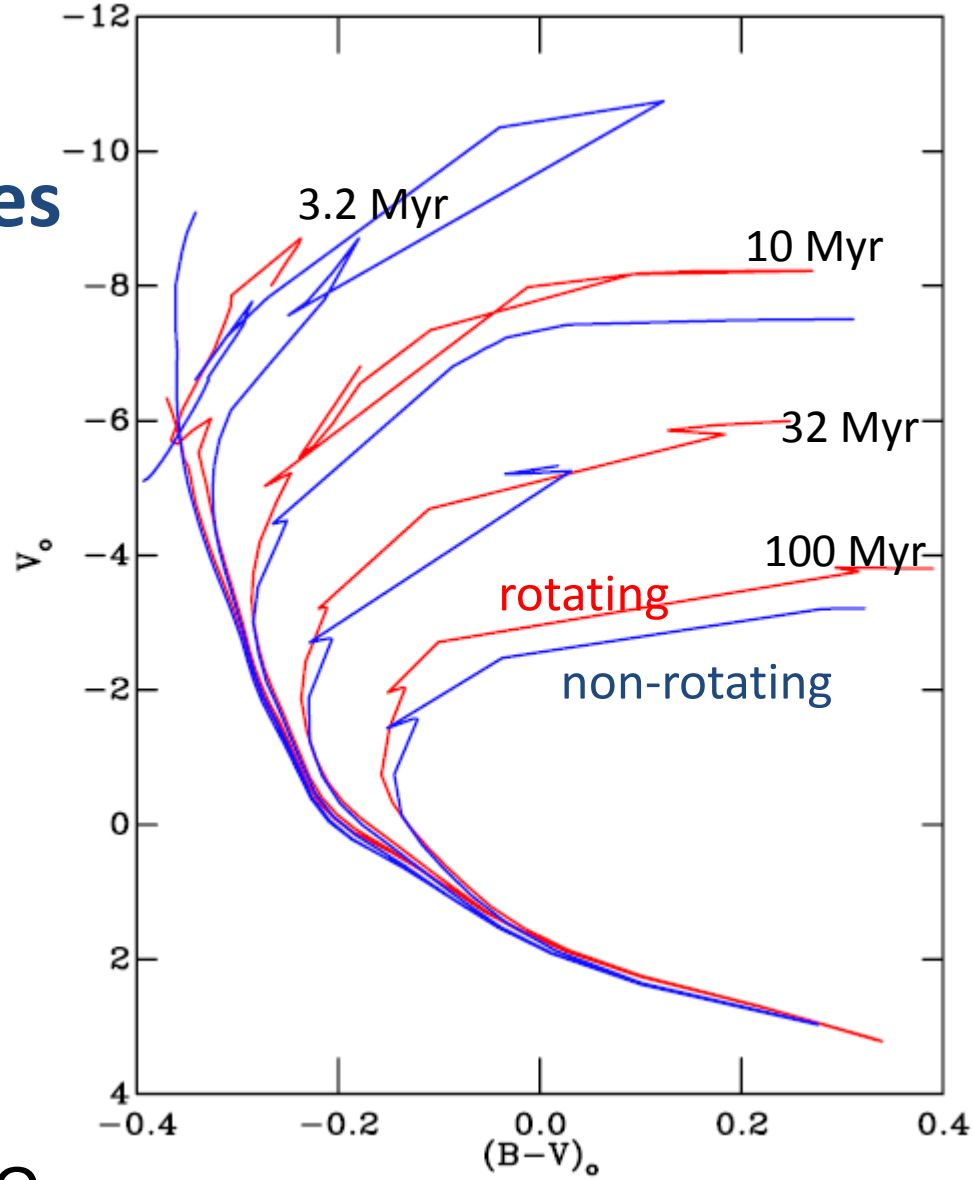


Physical uncertainties in high mass isochrones

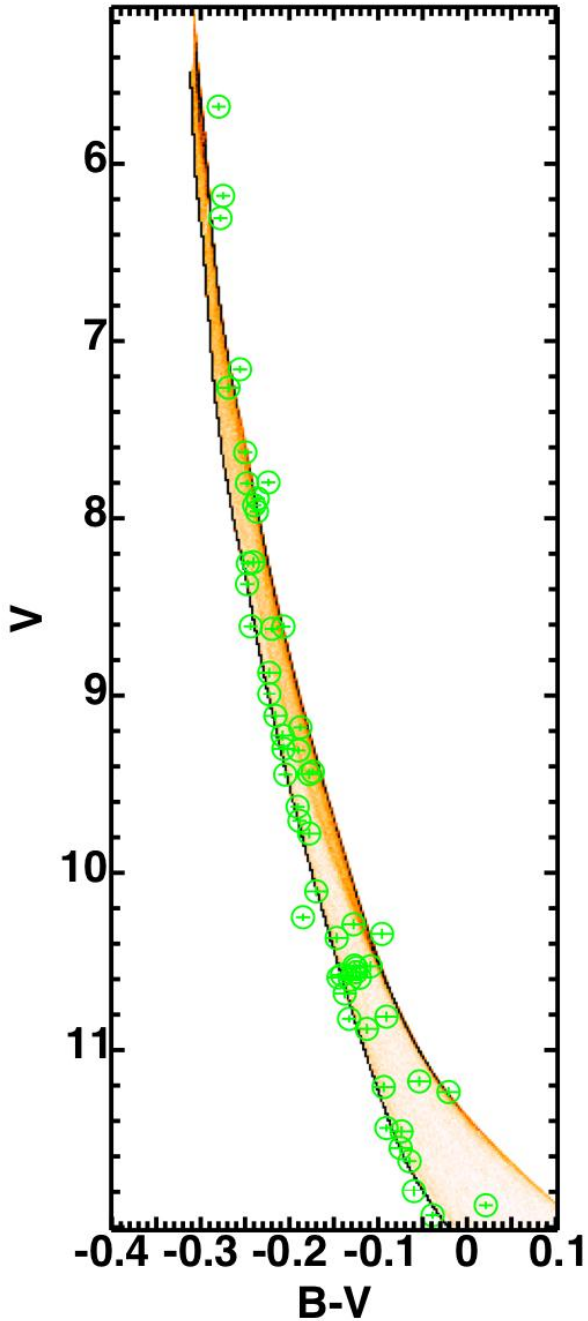
1. Rotation
2. Overshooting

Both increase main sequence lifetimes

Introducing rotation or overshoot increases estimated ages from MSTO



Ekström et al. 2012, A&A, 537, 146

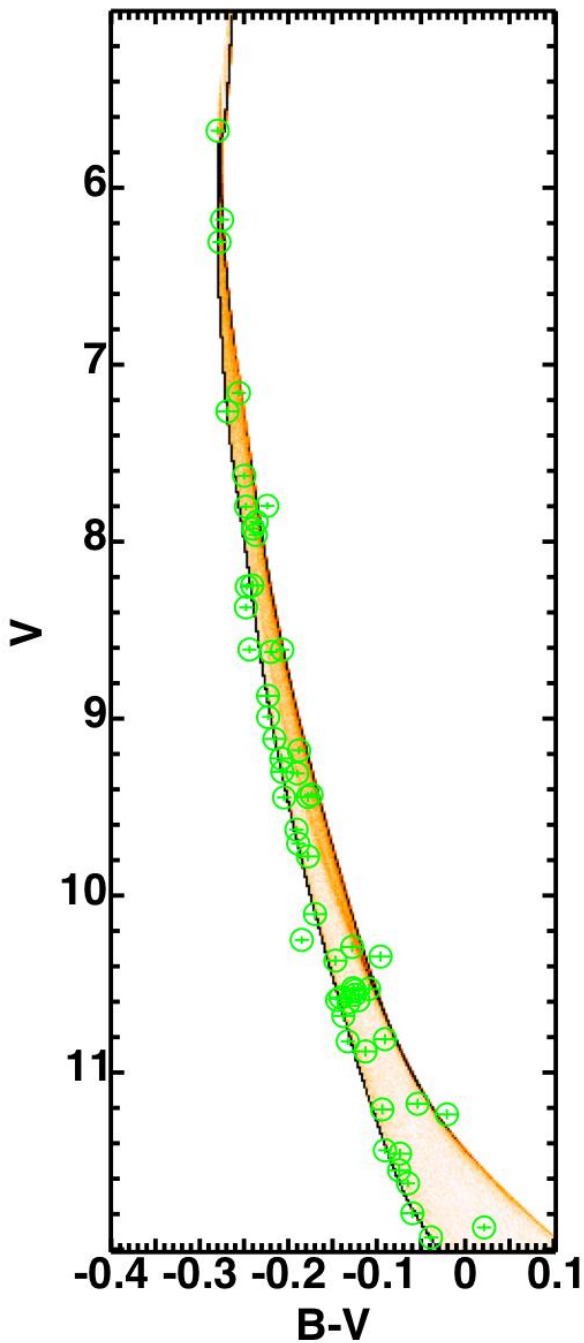


Upper M-S fitting

NGC 6530 0.25 Myr (Geneva-Bessell)

Pr(τ^2)=0.03

A poor fit to the ZAMS



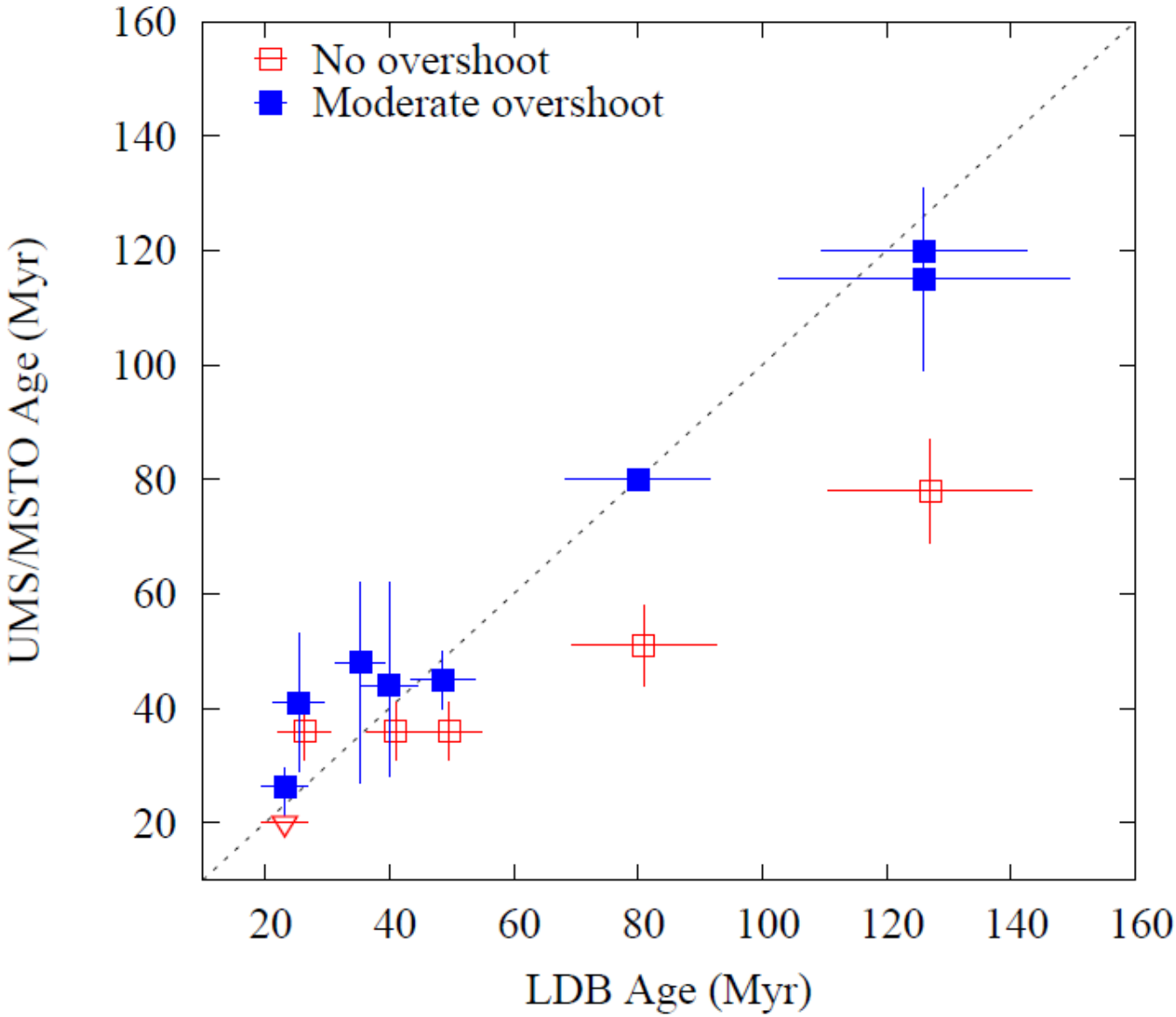
Upper M-S fitting

NGC 6530 5.50 +/- 0.6 Myr (Geneva-Bessell)

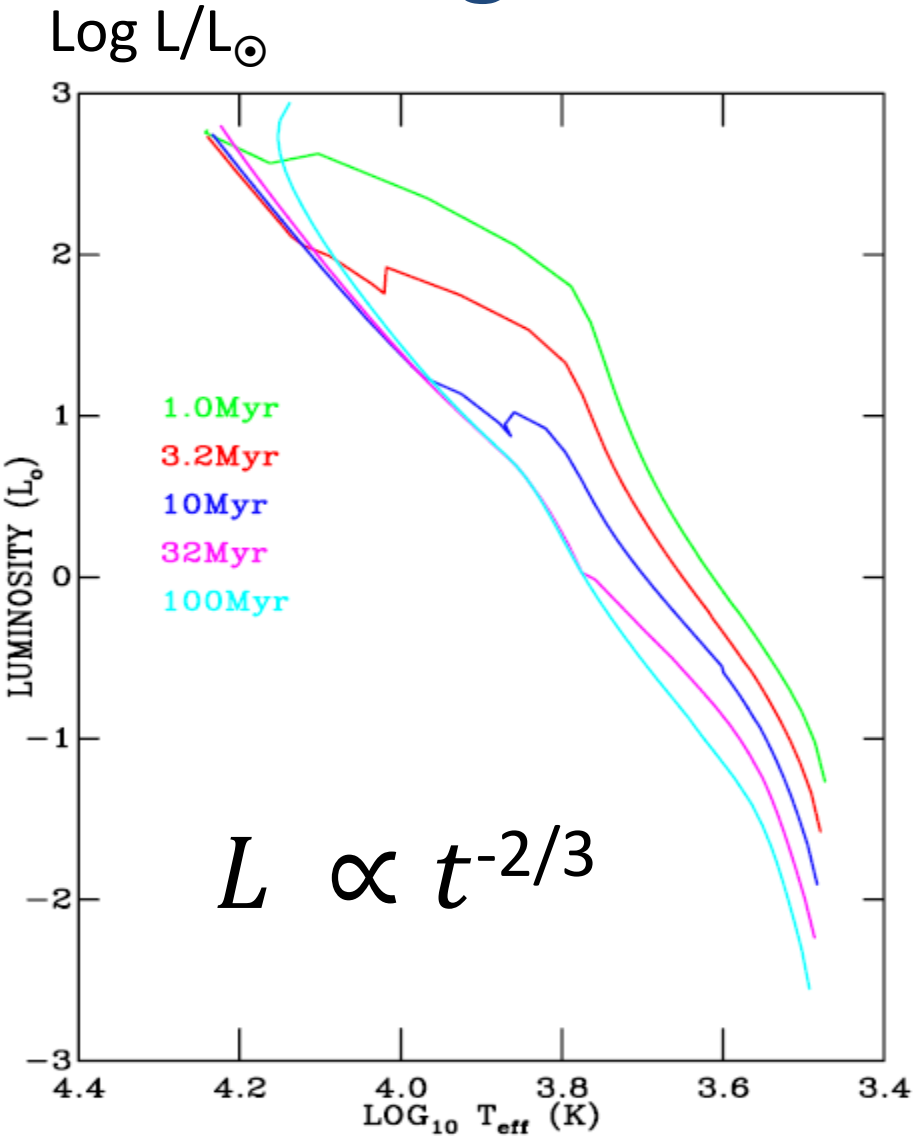
Pr(τ^2)=0.67

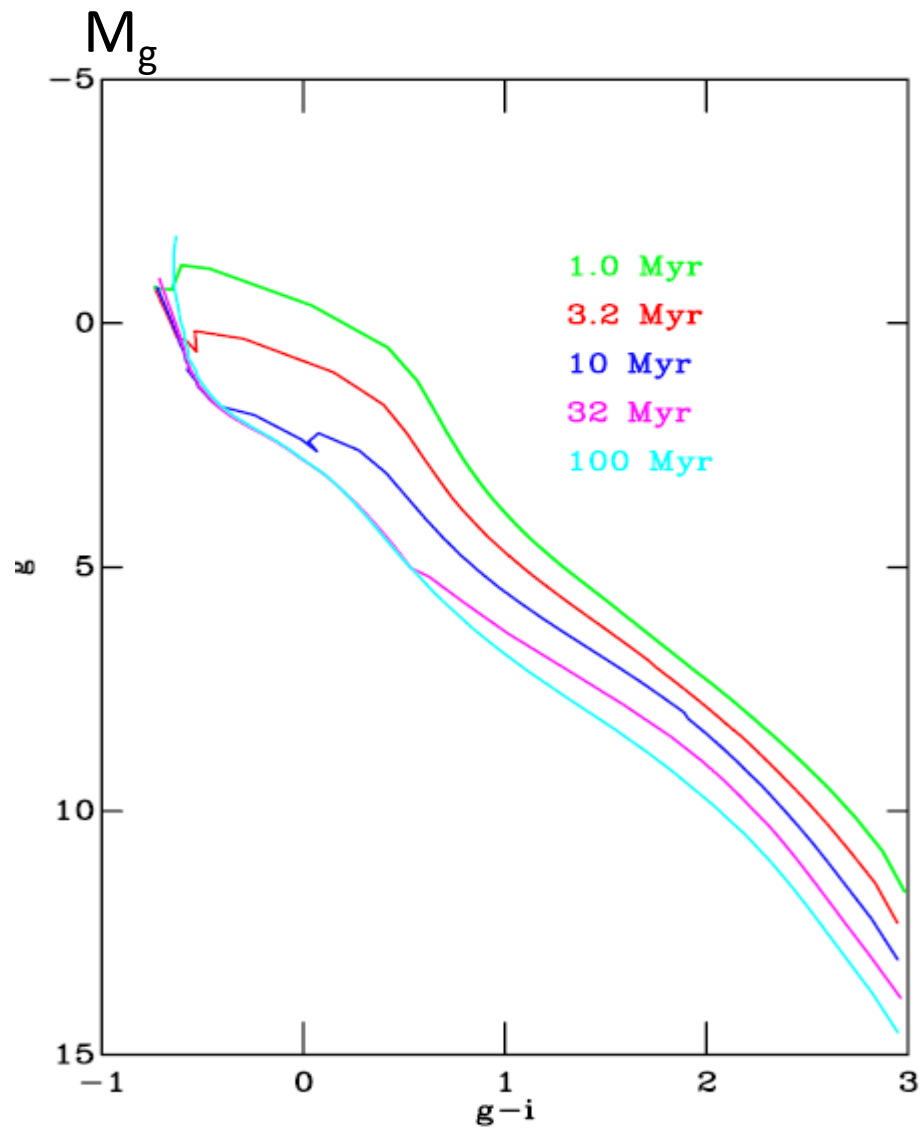
A much better fit achieved allowing the age to go free

LDB vs UMS comparison

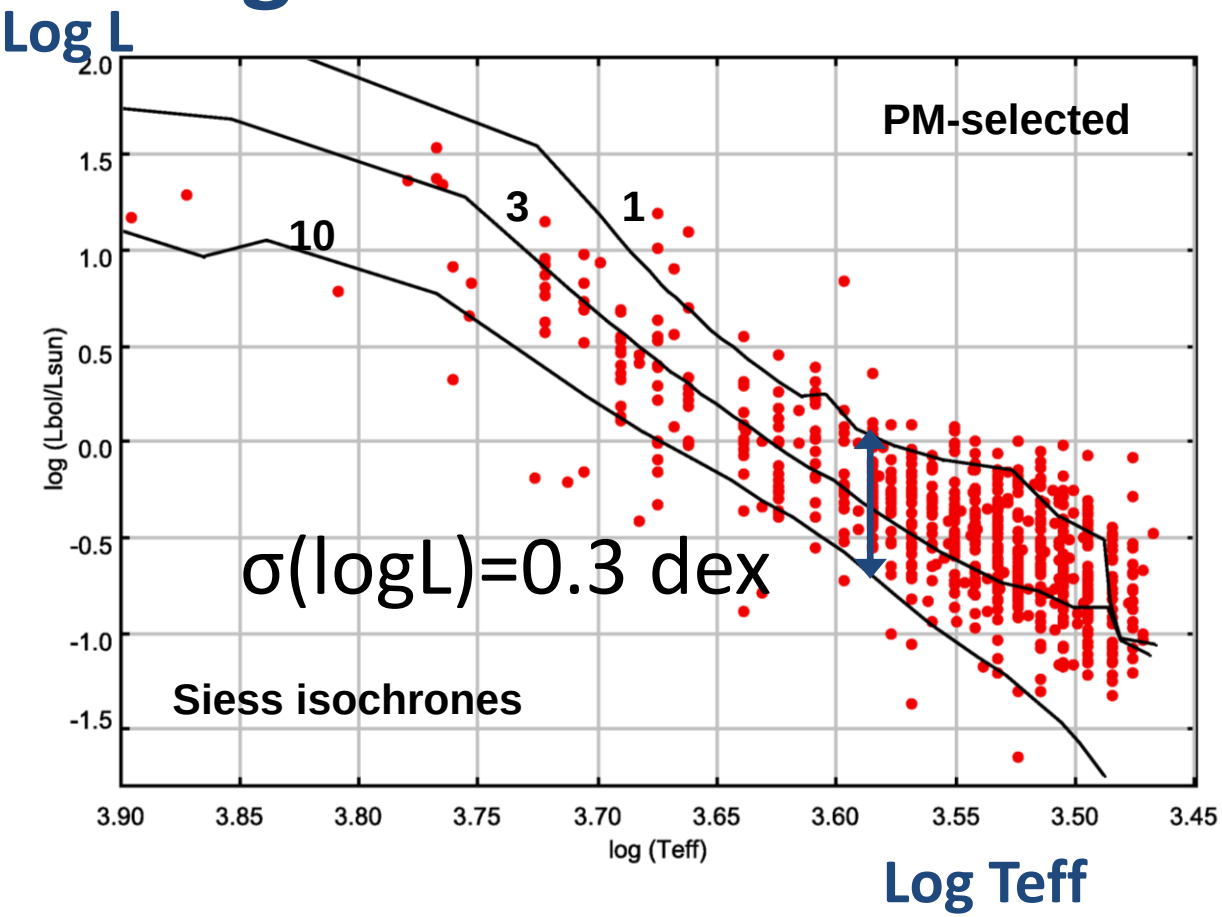


Ages from the PMS





Age from the PMS?

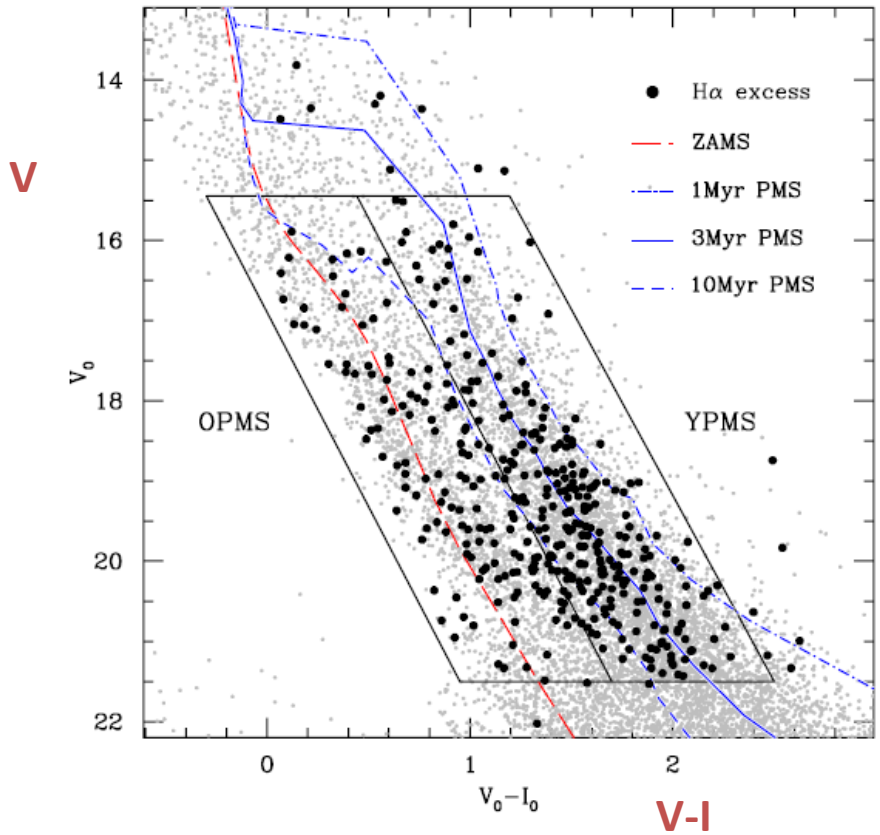


1. Extinction
2. Accretion
3. Age Spread?
4. Variability
5. Binarity

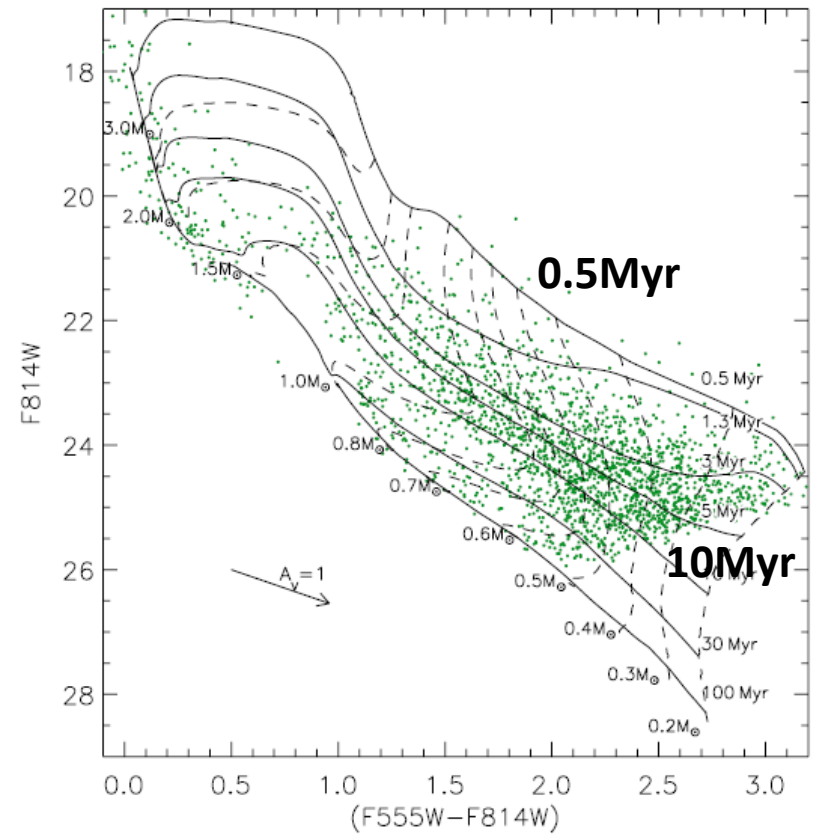
All contribute to the scatter

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

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



NGC 3603: Beccari et al. 2010, ApJ, 720, 1108

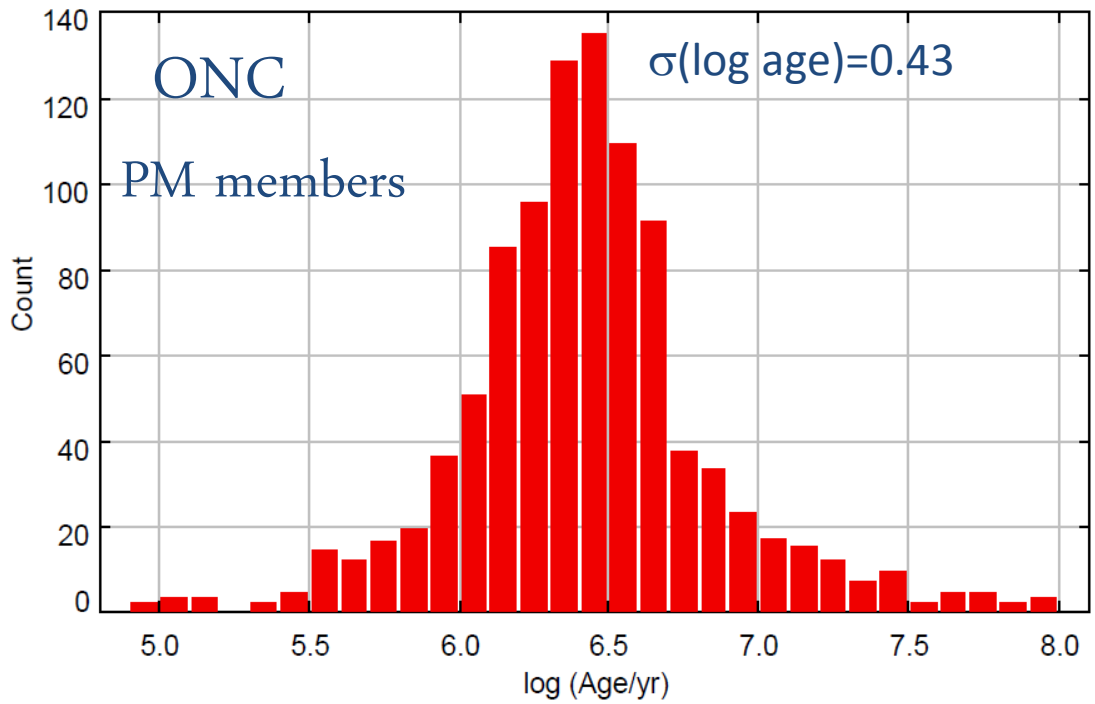


LH 95 in the LMC: Da Rio et al. 2010, ApJ, 723, 166

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	0.016
TOTAL	0.10



ONC observed age spread

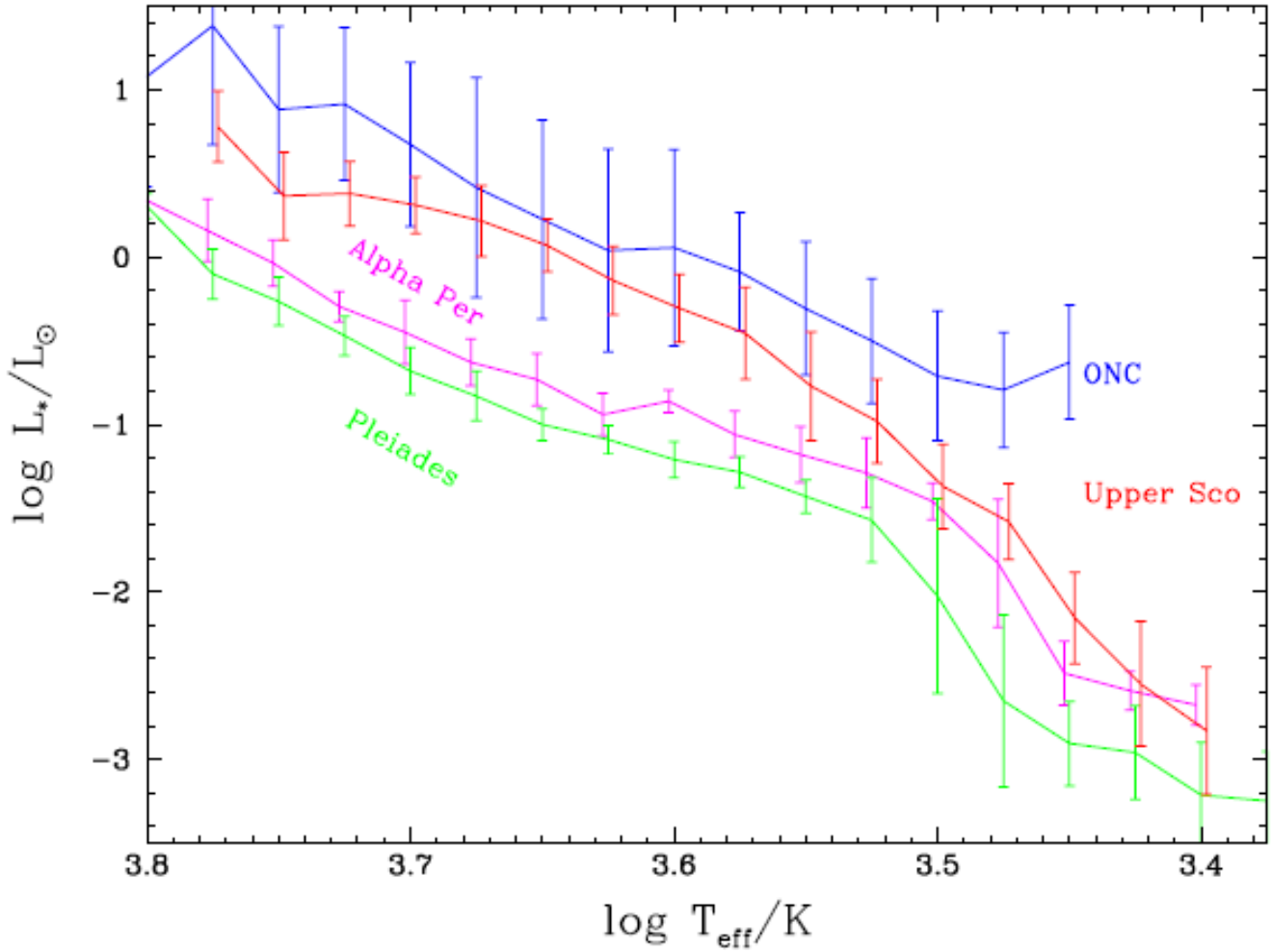
σ(log age)=0.4 dex

(More typically 0.15 dex)

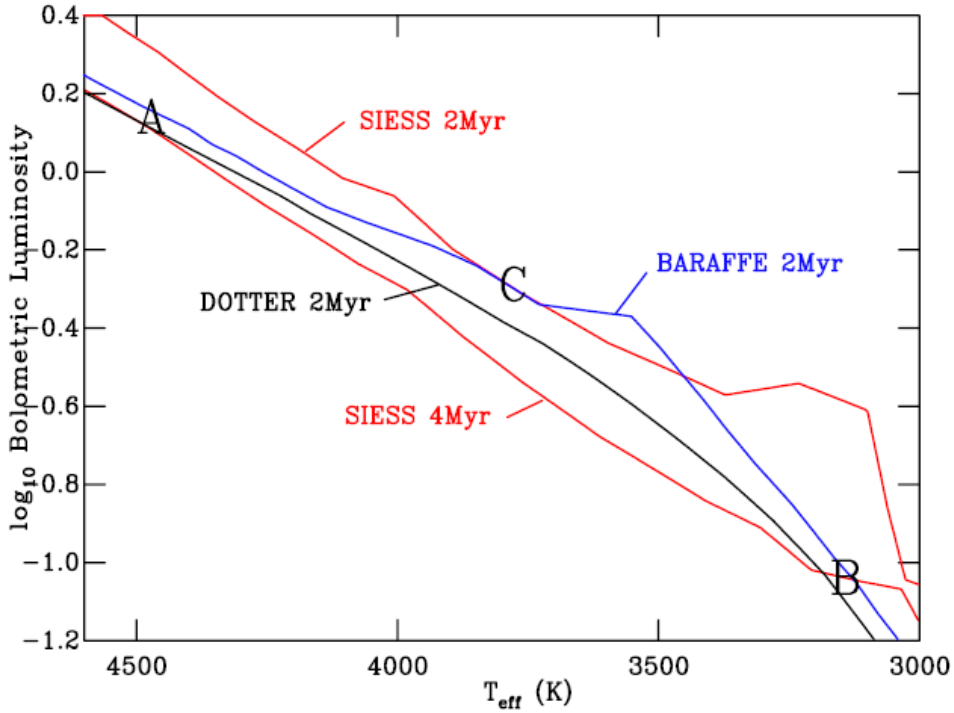
$t \propto L^{-3/2}$ so **σ(log t)=0.15-0.2 dex**

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

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

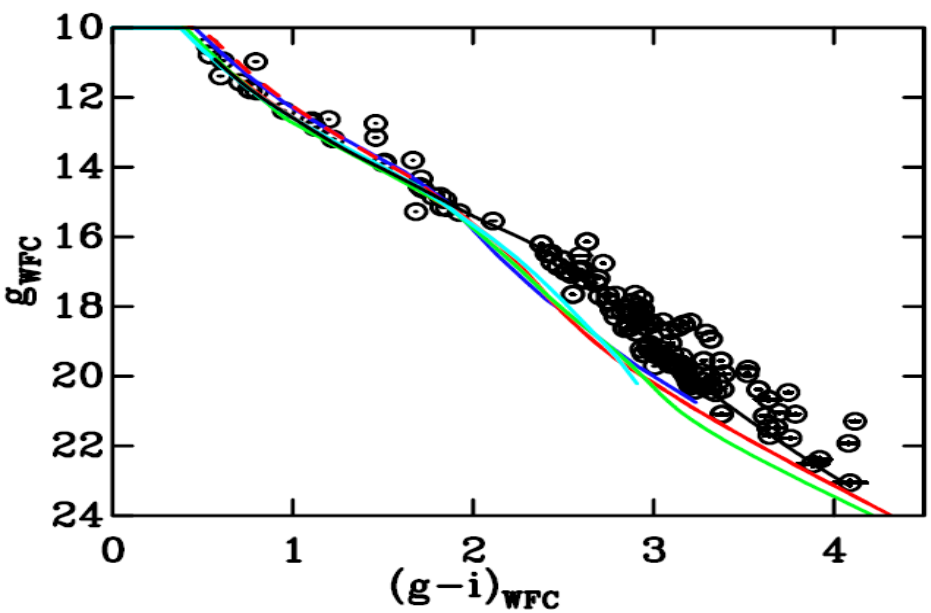


Astrophysical scatter in logL diminishes at age>10 Myr to ~0.15 dex in G/K/early M stars



Model isochrones do not agree and not in a consistent sense!

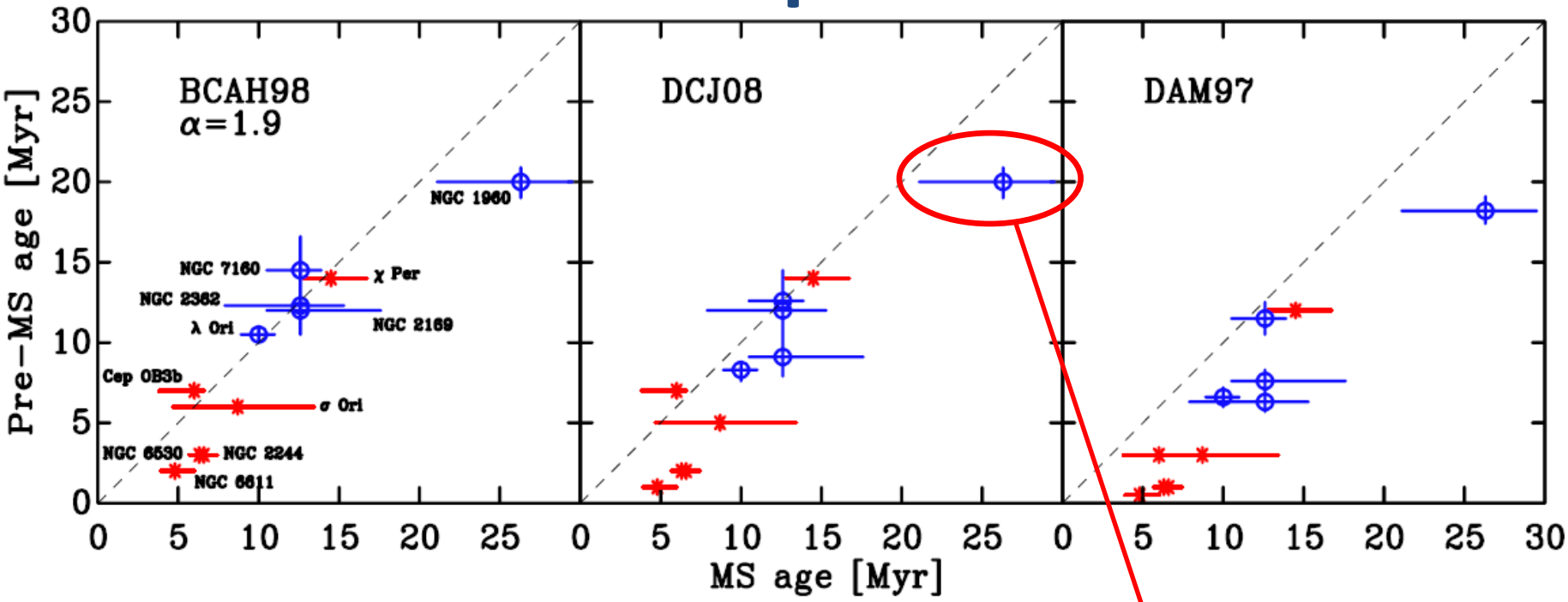
Factor of 2 differences at <10 Myr, smaller differences at older ages



130 Myr isochrone and BT-Settl atmospheres do not match the Pleiades for T<4000K

Bell et al. 2012, MNRAS, 424 3178

PMS vs UMS comparison



Bell et al 2013, arXiv 1306.3273

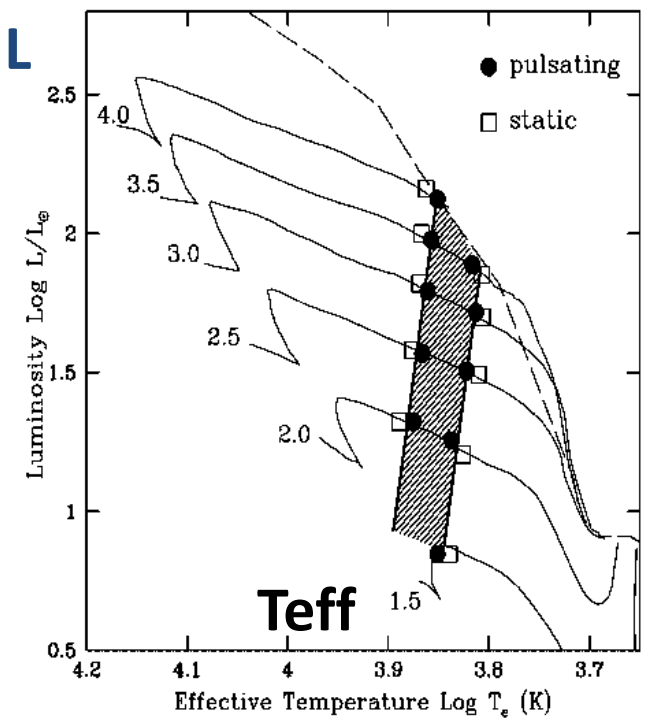
Has an LDB age of 22+/-4 Myr

Reasonable agreement between UMS and PMS ages

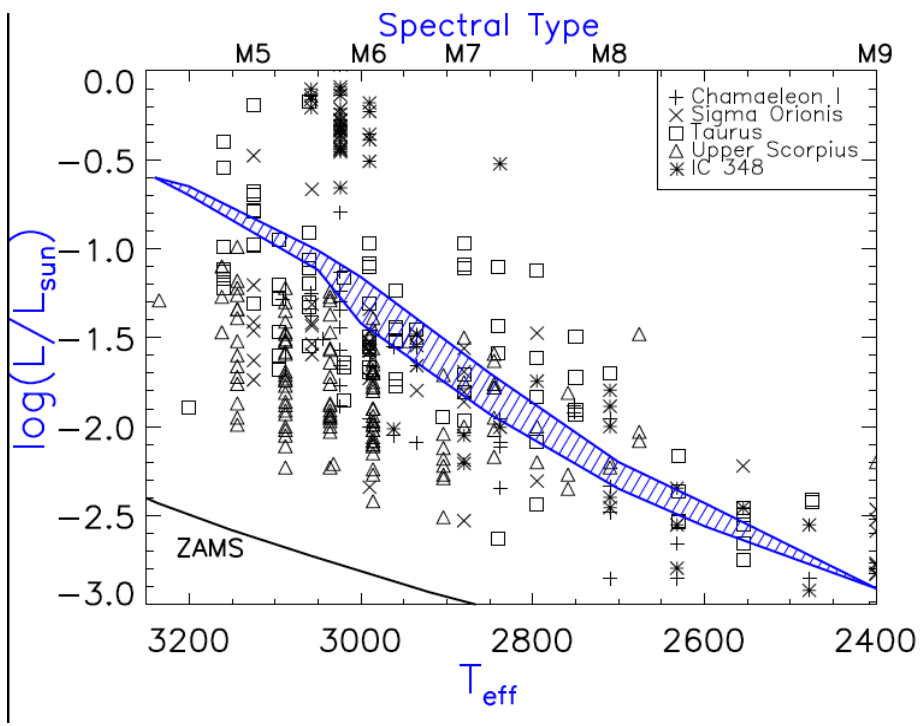
Also see
Lyra et al. 2006, A&A, 453, 101
Pecaut et al. 2012, ApJ, 746, 154

Pre-Main Sequence Stellar Pulsation

- Higher-mass pre-ms evolutionary tracks cross the classical instability strip in the δ-Scuti region (kappa mechanism)
- Lower-mass stars very early in pre-ms evolution may cross a deuterium-burning instability strip (epsilon mechanism)
- Pulsations predicted on a dynamical timescale -- few hours



Marconi & Palla 1998, ApJ, 507, L141



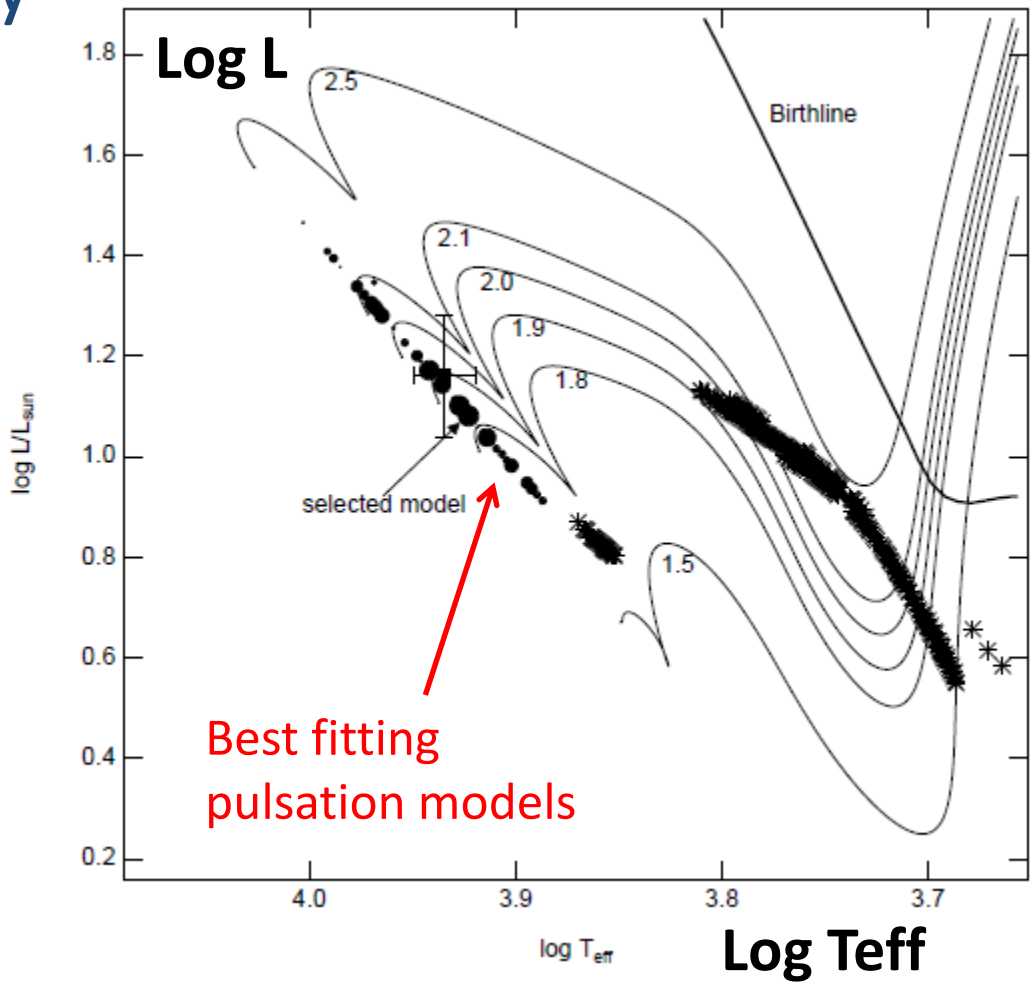
Palla & Baraffe 2005, A&A, 432, L57; Cody PhD 2012

Seismology potentially more precise

COROT and MOST monitoring in NGC 2264

Age of <u>this star</u> from HR diagram: **<u>6-10 Myr</u>**

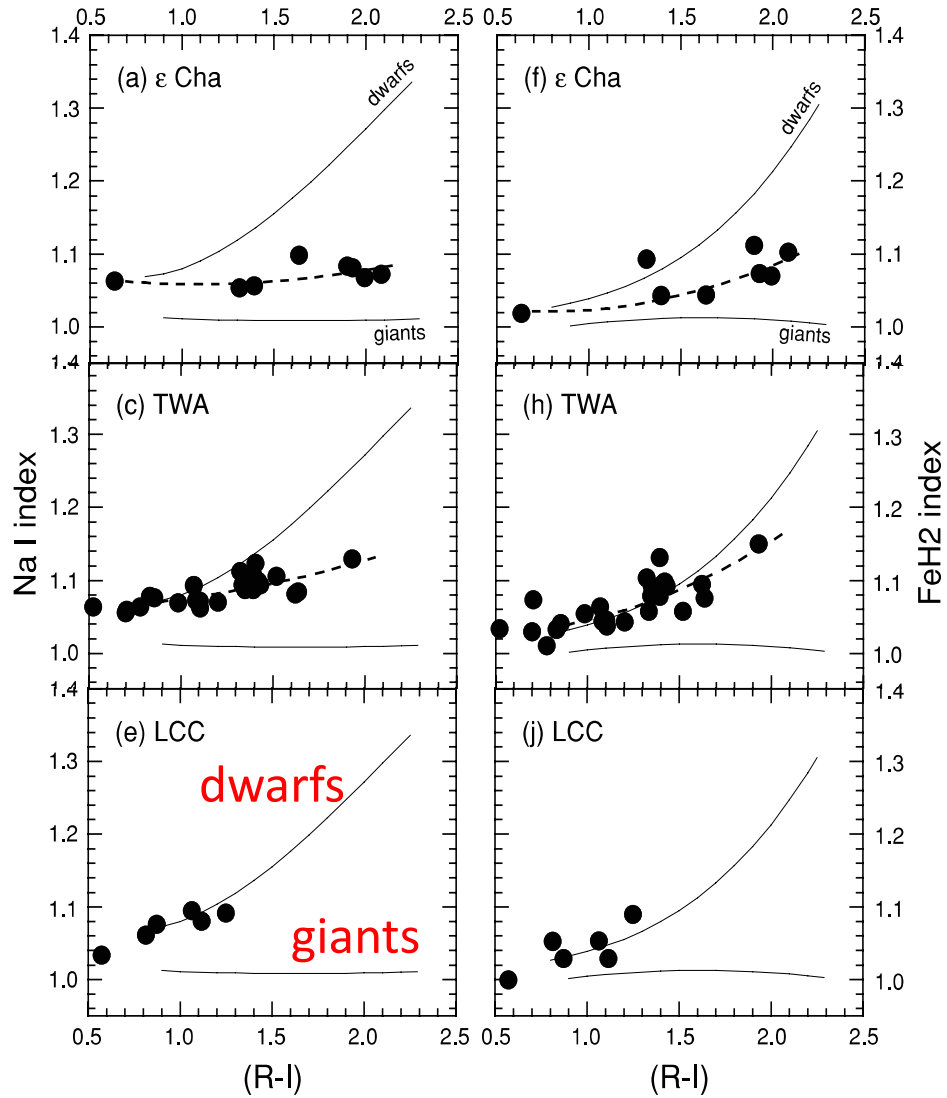
Age from seismology: **<u>10-11 Myr</u>**



Zwintz et al. 2013, A&A, 552, A68

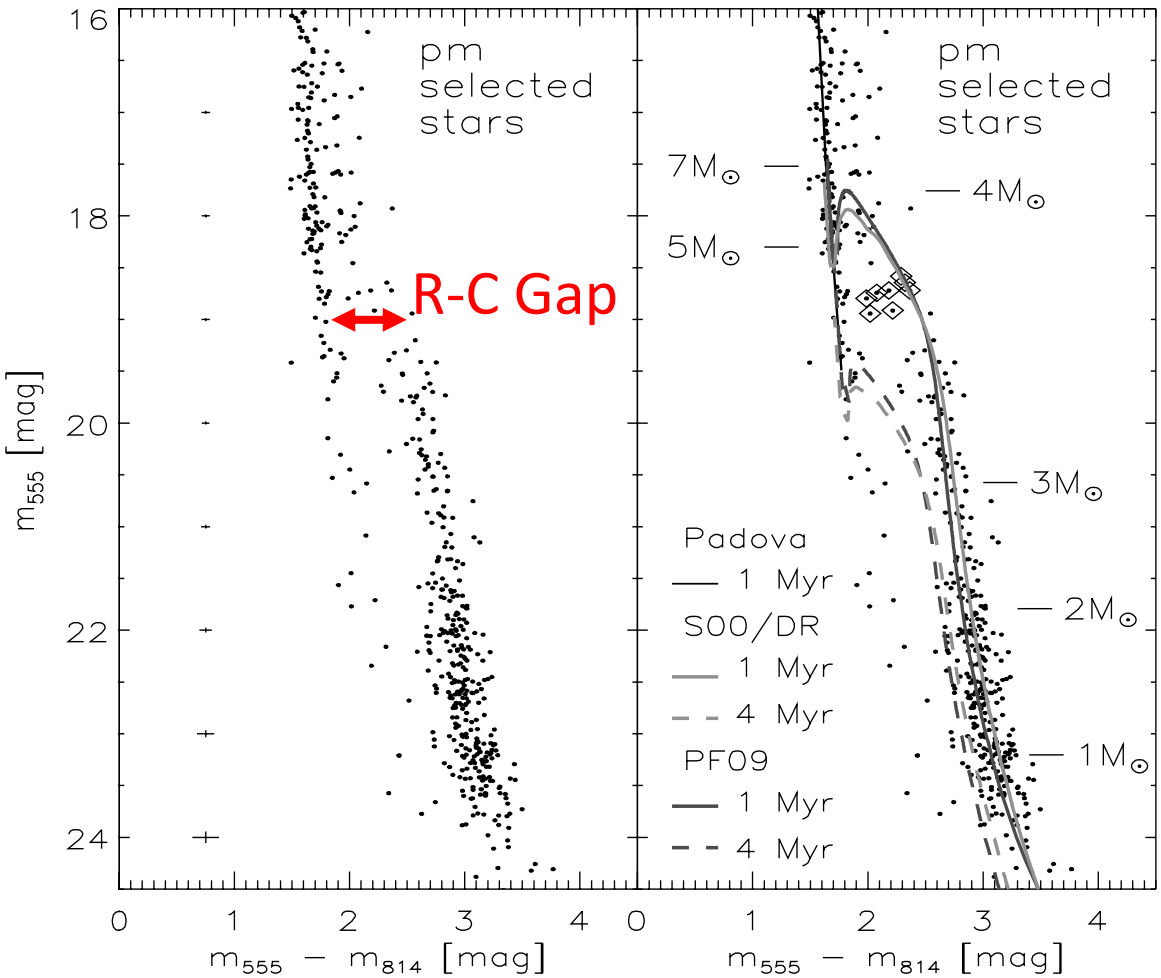
Gravity diagnostics

- Require a 2-dimensional classification
- Little hope of absolute accuracy
- Capable of providing the rank order of ages and separating them with a resolution of a few Myr at **<u>5-20 Myr</u>**



Lawson et al. 2009, MNRAS, 400 ,L29

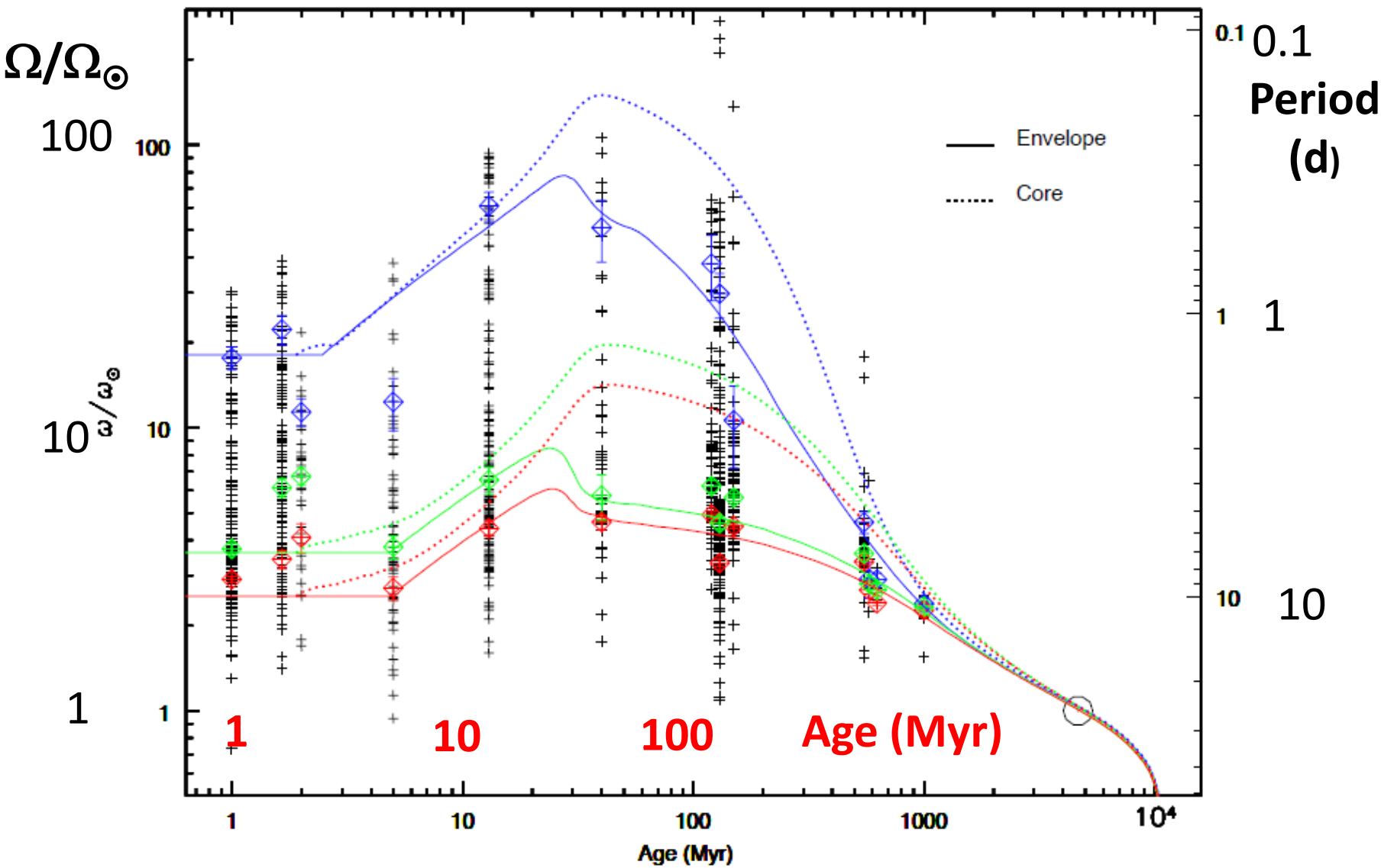
The radiative-convective gap



- Rapid evolution in HRD caused by development of a radiative core .
- Opens up an R-C Gap with an age-dependent width and color <15 Myr
- Independent of distance and extinction

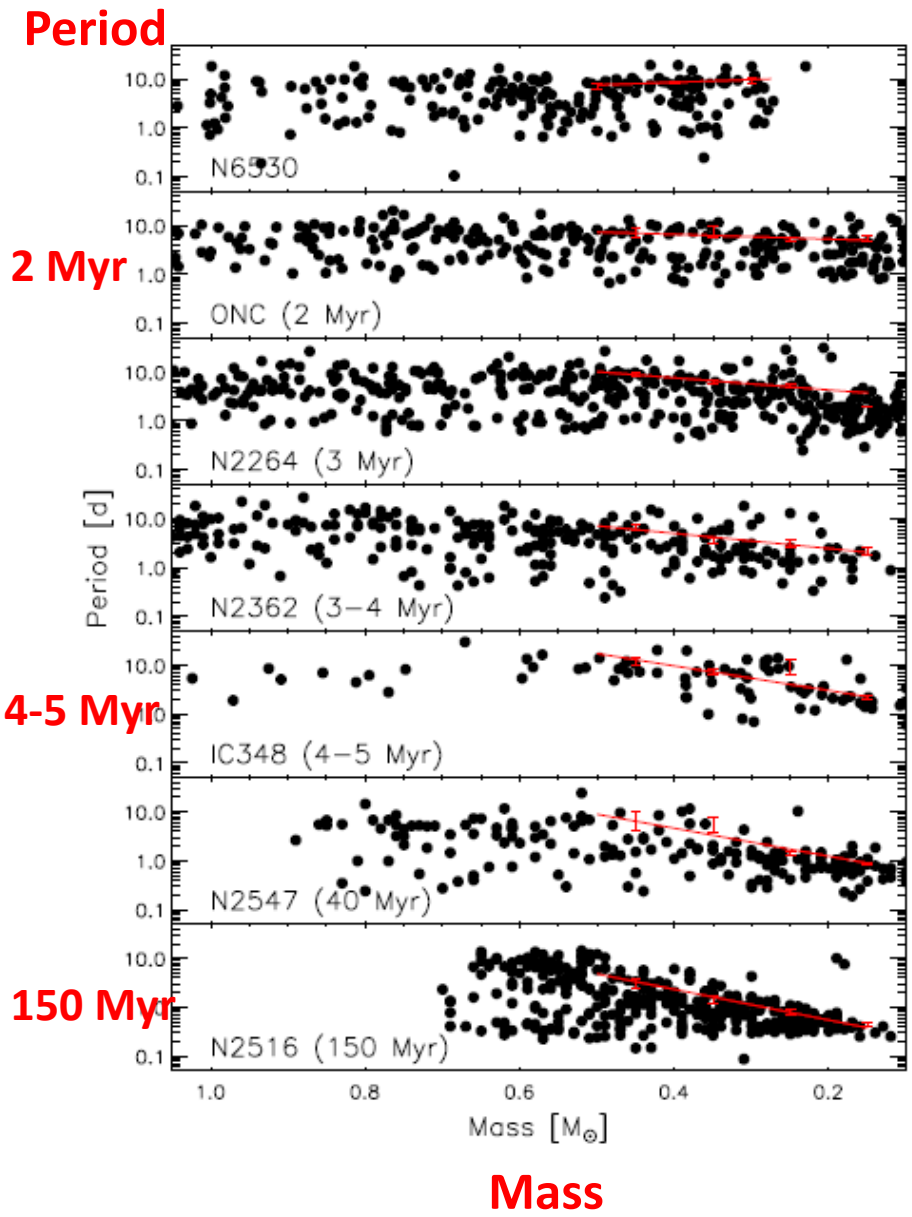
Adapted from Rochau et al. 2010, ApJ, 716, L90

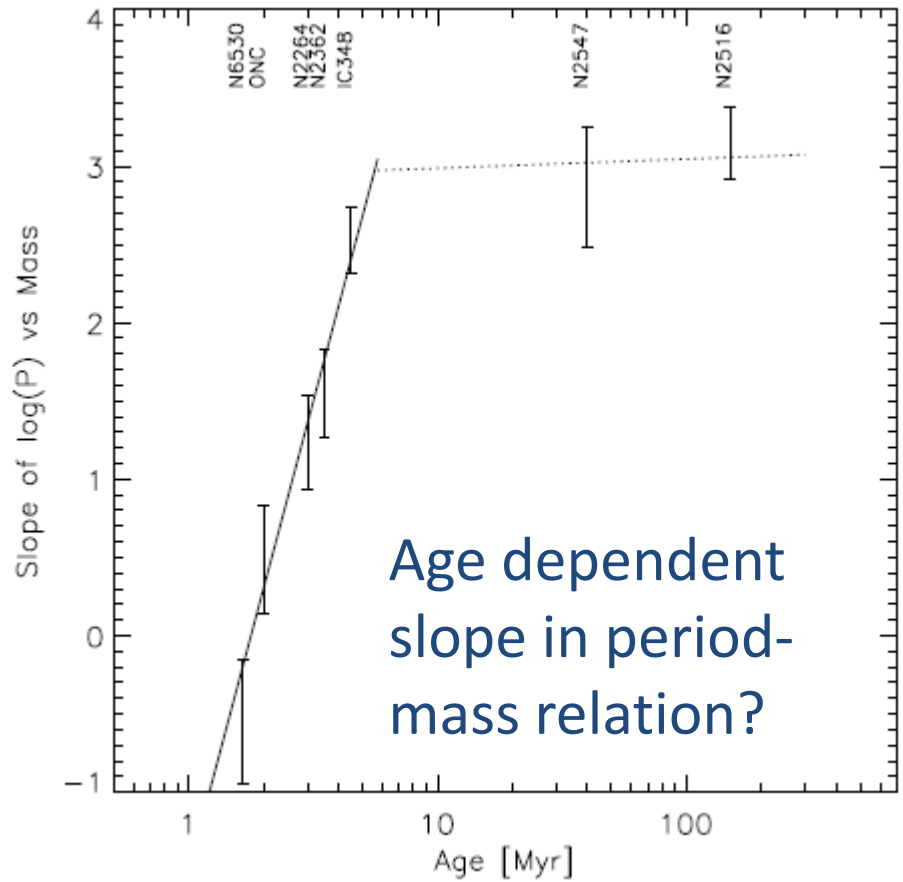
Rotation and activity



Gallet & Bouvier 2013, arXiv 1306.2130

Rotation and activity

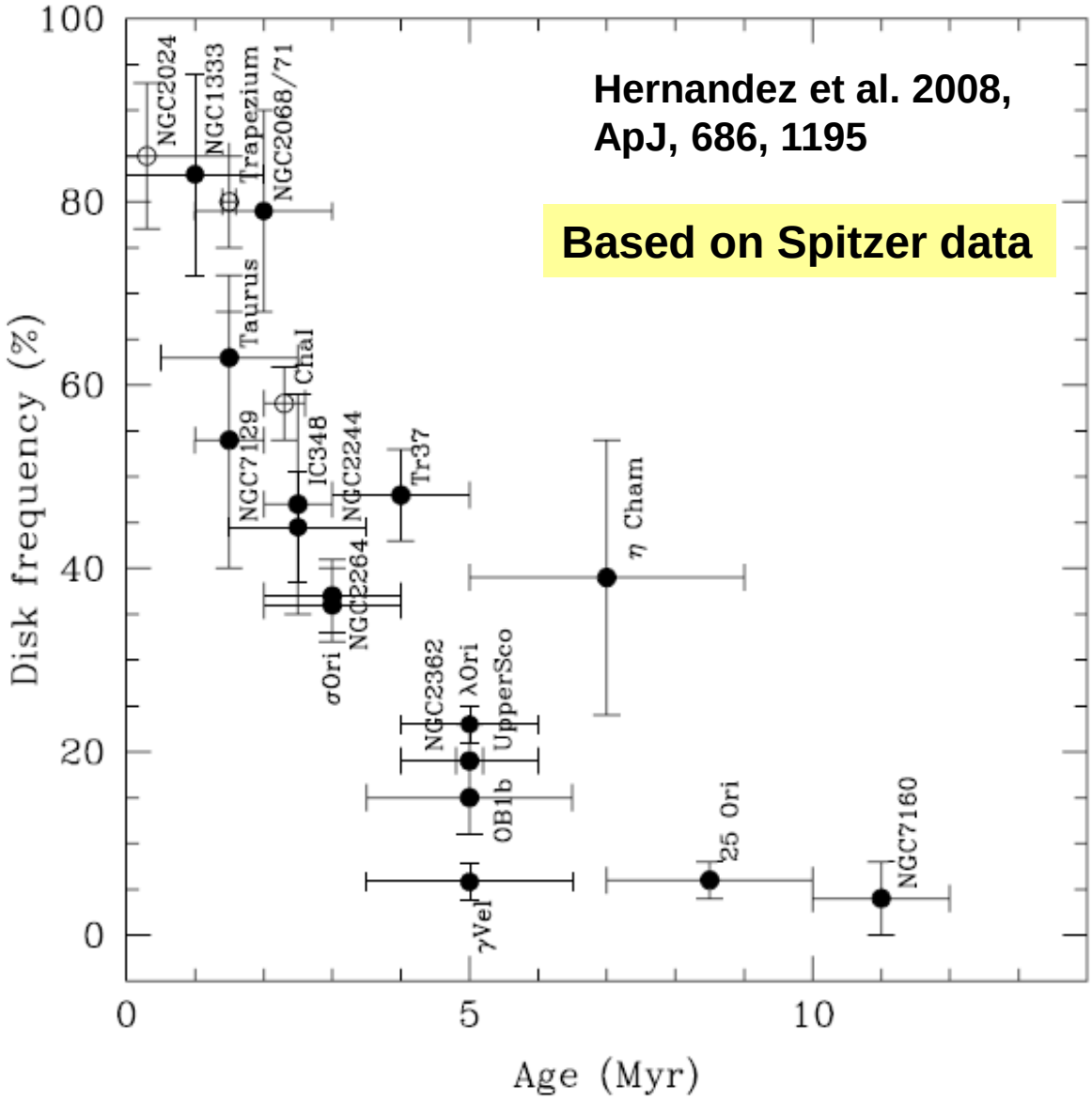




Age dependent slope in period-mass relation?

Henderson & Stassun 2012, ApJ, 747, 51

Disc presence as an independent clock?

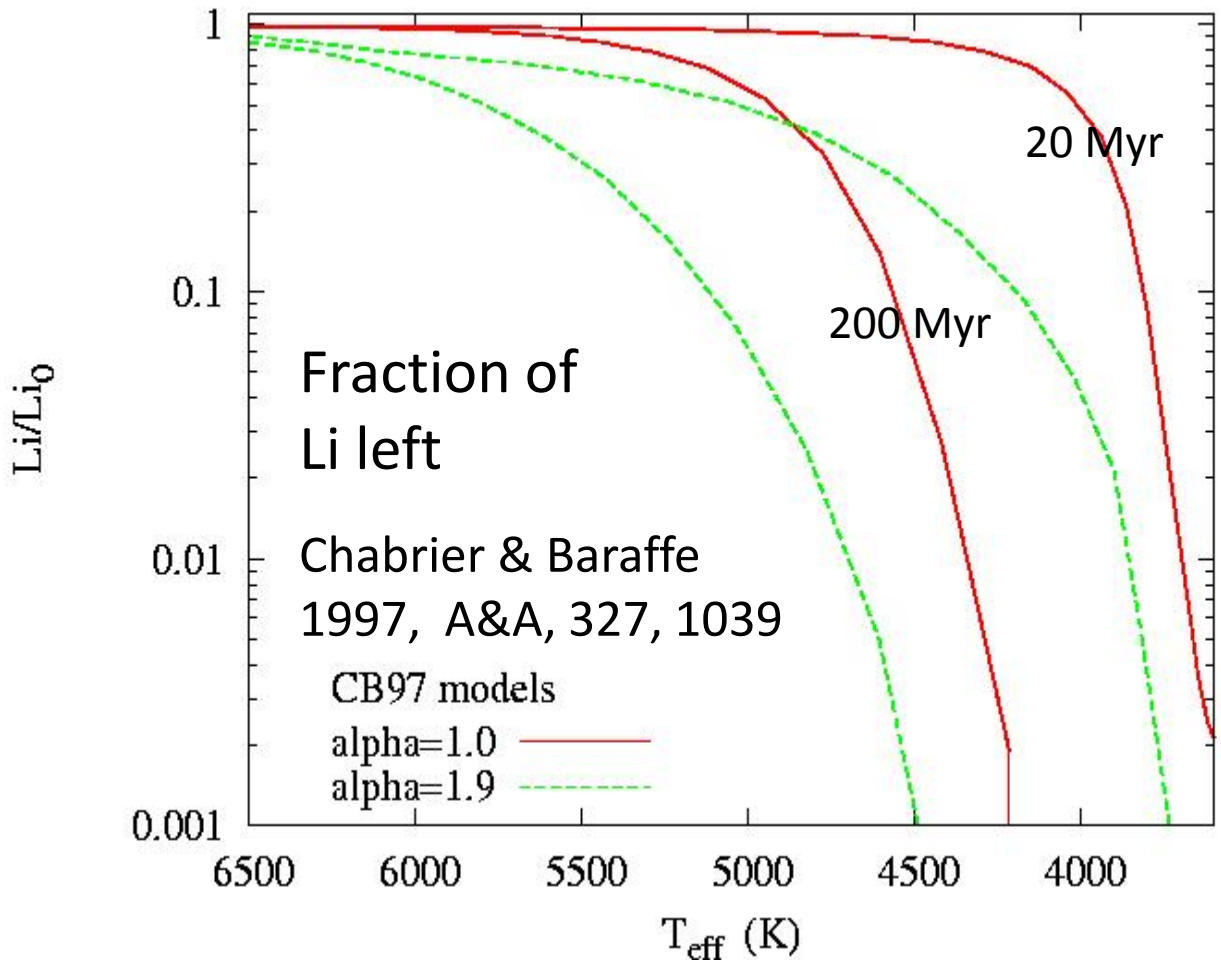


Lithium depletion – is age dependent

But also depends on convective efficiency, composition, magnetic fields, rotation…

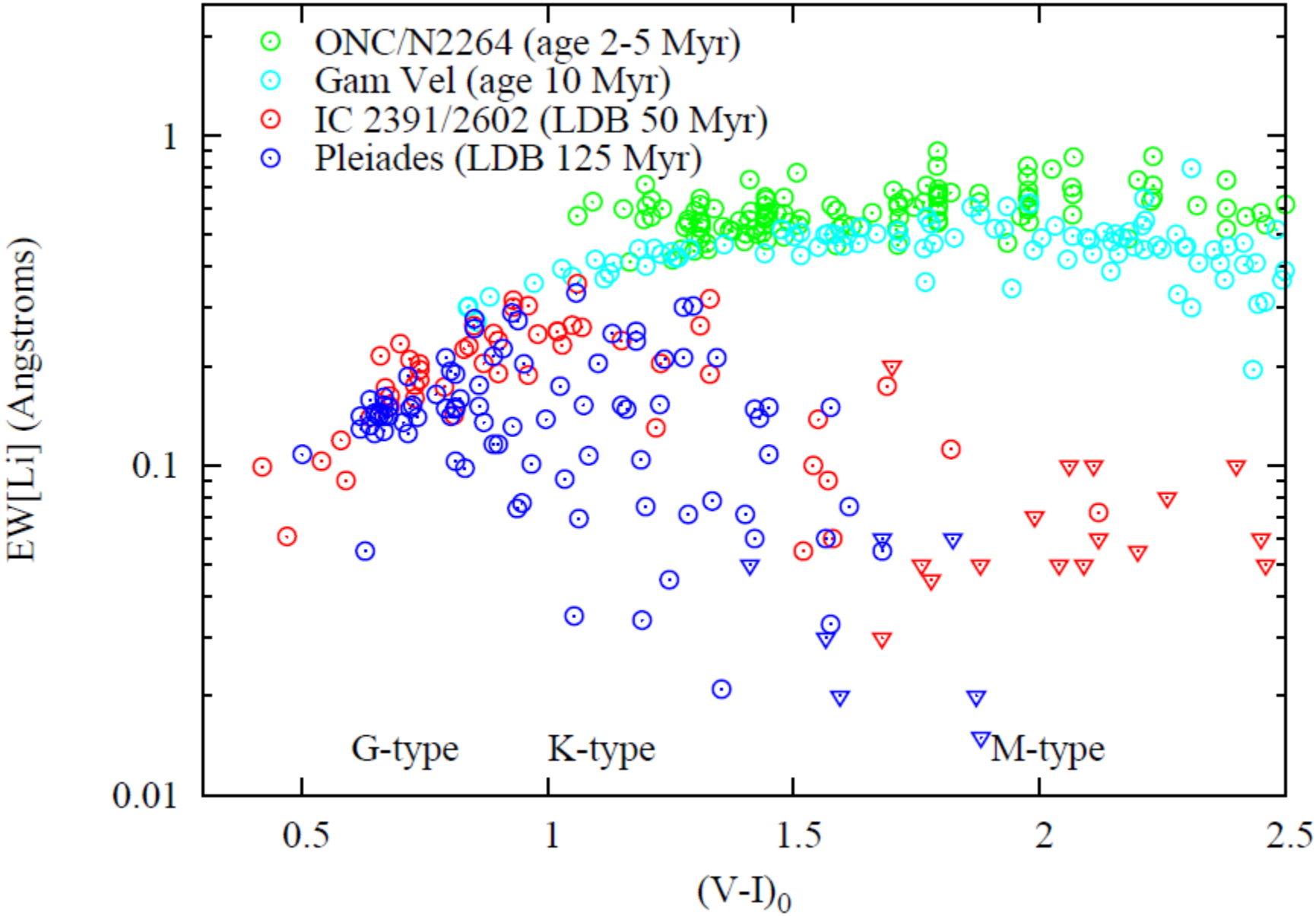
Many uncertainties in the models.

Cannot be used to derive absolute ages



Two convective efficiencies. Isochrones of Li depletion at 20 and 200 Myr.

Empirical Li depletion



The Key Points

Semi-Fundamental Ages

LDB: Luminosity at the LDB.

- Works well for 20-200 Myr,
- Gives ages to 10-20%.
- Establishes a set of calibration clusters.

Kinematics: Not recommended yet.

- Problems with precision, membership and locating the origin of runaways.
- Gaia will help!

The Key Points

Model-Dependent Ages

UMS and PMS isochrones can rank clusters in age order.

- UMS: theoretically robust, but poor precision
- PMS: precise, but factor 2-3 absolute uncertainties and observationally difficult at <10 Myr; better at older ages.
- Age spreads a complicating factor?

Pulsations, R-C gap, Gravity indicators – show promise as **distance-independent methods**

The Key Points

Empirical Ages

Lithium: sensitive for K/M dwarfs 10-100 Myr

- Factor 2 precision for 1 such star

Disks/Accretion: ~50% precision at 1-15 Myr

- But significant hazards – known unknowns!

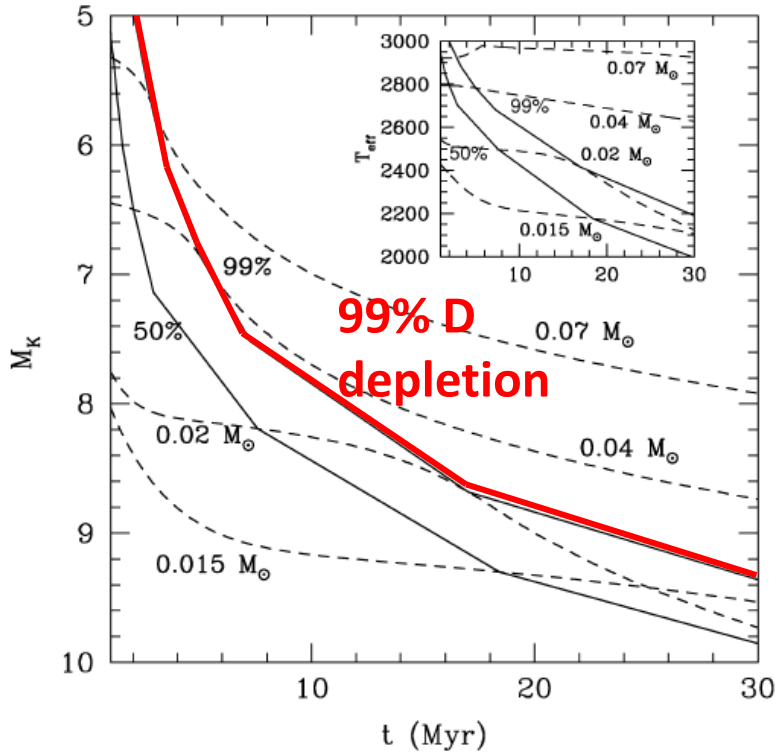
Rotation/Activity: hopeless at 10-100 Myr.

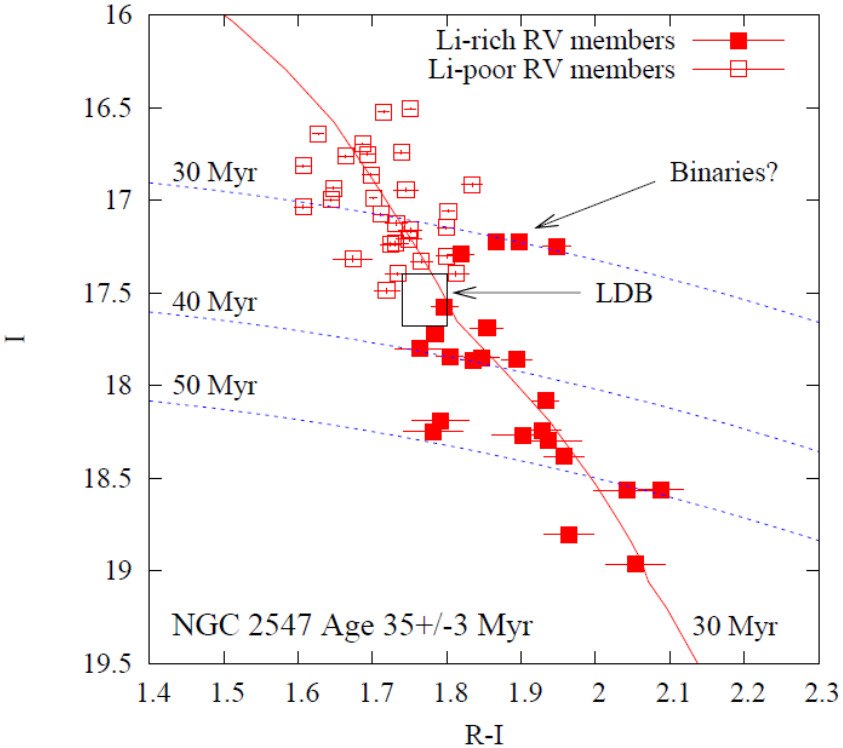
- Possible use for M-stars at 1-10 Myr

Final Thought

DDB ? ← LDB →

1 Myr | 10 Myr | 100 Myr





Chabrier et al. 2000, ApJ, 542, L119