Jet Propulsion Laboratory
California Institute of Technology

Stellar Ages and Properties

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NASA Exoplanet Exploration Program (ExEP)

Jet Propulsion Laboratory

California Institute of Technology

2018 Sagan Exoplanet Summer Workshop: Did I Really Just Find an Exoplanet?

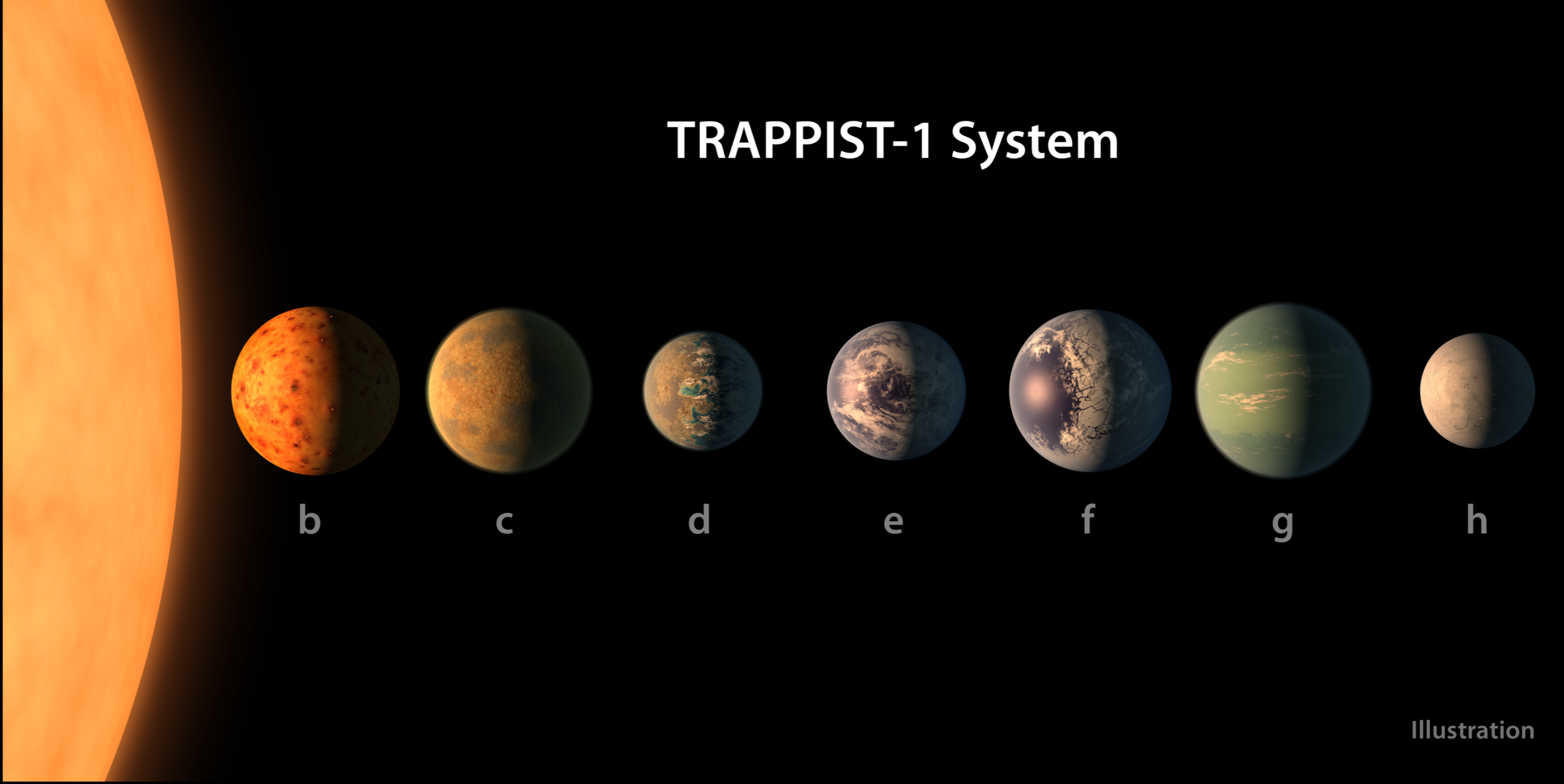
CL#18-3800

Artist concept of K2-138 (NASA-JPL/Caltech)

Why care about stellar ages?

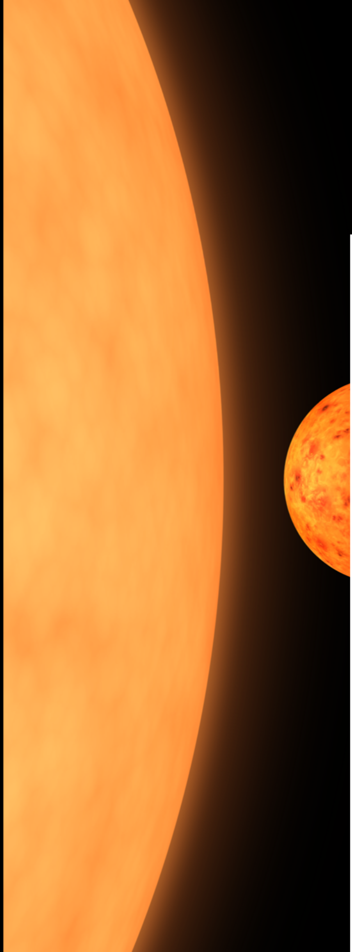
"Some day soon, we anticipate the detection of Earth-sized planets around stars. Before too long, we hope, we can expect that someone will identify a sign of life – a biomarker – on an Earth-like planet around another star. Given the need for high angular resolution to make that observation and the inherent paucity of photons to work with, the star in question will be one close to us, which is to say a field star that is unassociated with a cluster. When that claim is announced, the first question we will ask is "***How old is that star***?," so that we can assess the planet's evolution. Yet, determining its age is likely to be difficult and imprecise, and as problematic in its own way as the observation of the biomarker."

- David Soderblom (2010, ARA&A, 48, 581)



NASA/JPL-Caltech/R. Hurt, T. Pyle (IPAC)

TRAPPIST-1 System



ON THE AGE OF THE TRAPPIST-1 SYSTEM

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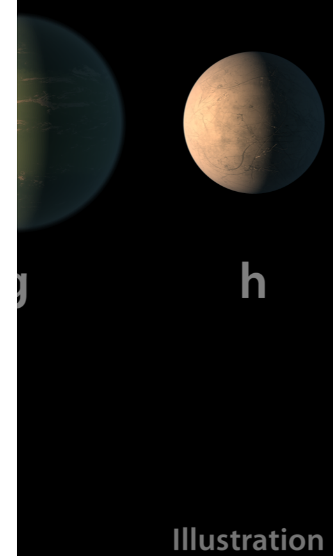
ABSTRACT

The nearby (d = 12 pc) M8 dwarf star TRAPPIST-1 (2MASS J23062928−0502285) hosts a compact system of at least seven exoplanets with sizes similar to Earth. Given its importance for testing planet formation and evolution theories, and for assessing the prospects for habitability among Earth-size exoplanets orbiting the most common type of star in the Galaxy, we present a comprehensive assessment of the age of this system. We collate empirical age constraints based on the color-absolute magnitude diagram, average density, lithium absorption, surface gravity features, metallicity, kinematics, rotation, and magnetic activity; and conclude that TRAPPIST-1 is a transitional thin/thick disk star with an age of 7.6±2.2 Gyr. The star's color-magnitude position is consistent with it being slightly metal-rich ([Fe/H] $\simeq$ +0.06), in line with its previously reported near-infrared spectroscopic metallicity; and it has a radius ($R = 0.121 \pm 0.003\ R_\odot$) that is larger by 8–14% compared to solar-metallicity evolutionary models. We discuss some implications of the old age of this system with regard to the stability and habitability of its planets.



Burgasser & Mamajek 2017, ApJ, 845, 110

NASA Exoplanet Exploration Program

Astrophysics Division, NASA Science Mission Directorate

NASA's search for habitable planets and life beyond our solar system

Program purpose described in 2014 NASA Science Plan

1. Discover planets around other stars
2. Characterize their properties
3. Identify candidates that could harbor life

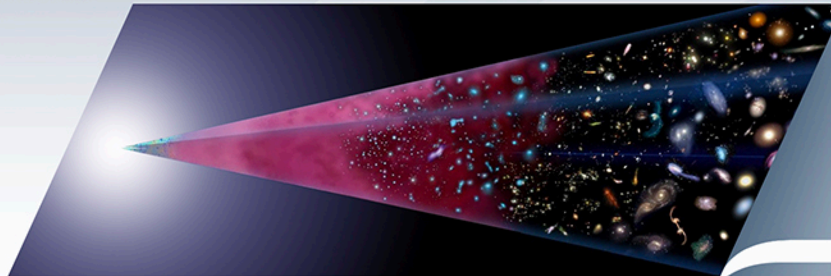
ExEP serves the science community and NASA by implementing NASA's space science vision for exoplanets

https://exoplanets.nasa.gov

Why Astrophysics?

Astrophysics is humankind's scientific endeavor to understand the universe and our place in it.

How did our universe begin and evolve?



How did galaxies, stars, and planets come to be?

Are we alone?

ExEP

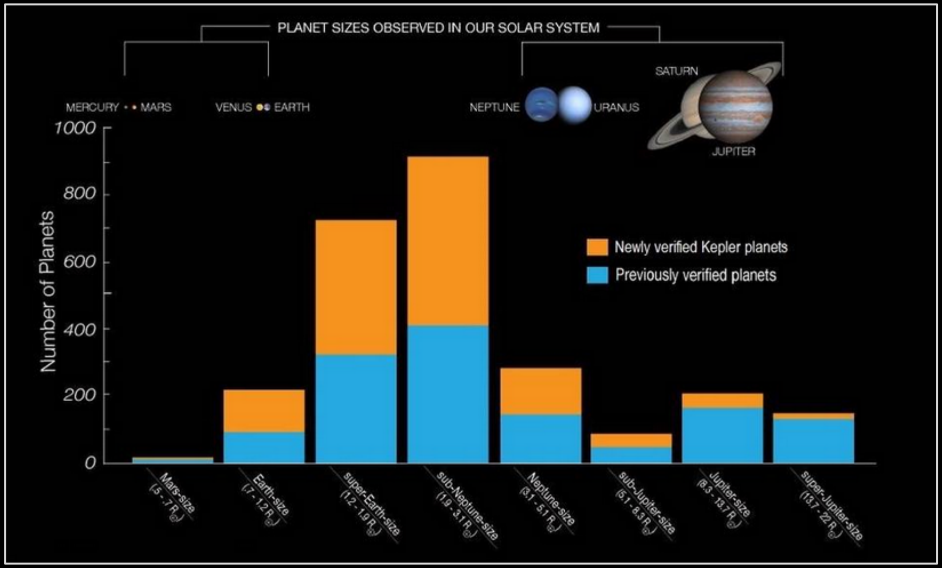
Enduring National Strategic Drivers

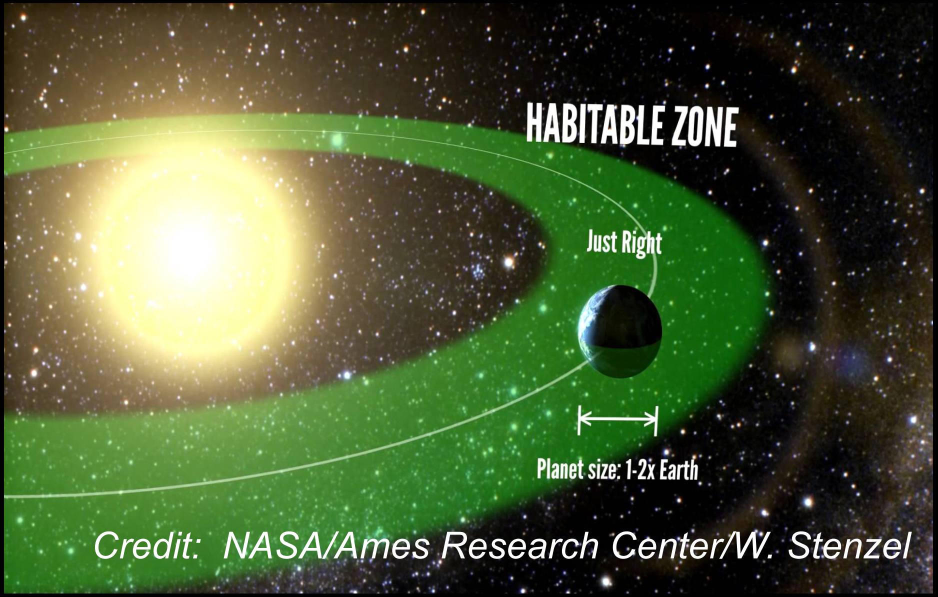
Three Key Kepler Results

1. On average there is at least one planet for each of the stars in the night sky

2. Small planets are the most common type in the Galaxy

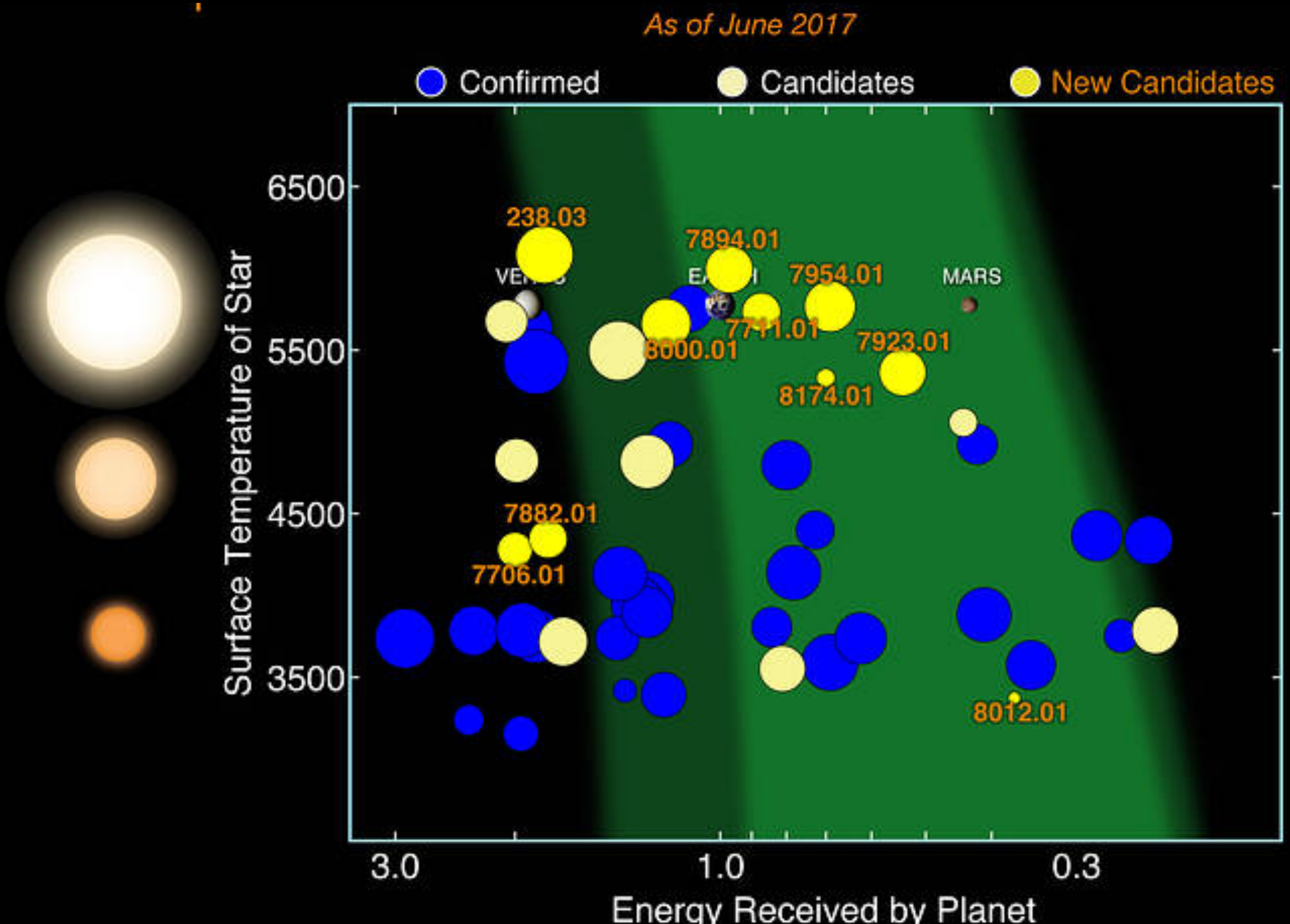
3. Earth-sized (0.5 to 2 Earth radii) planets in the Habitable Zone are common





Credit: NASA/Ames Research Center/W. Stenzel

Kepler Habitable Zone Planets



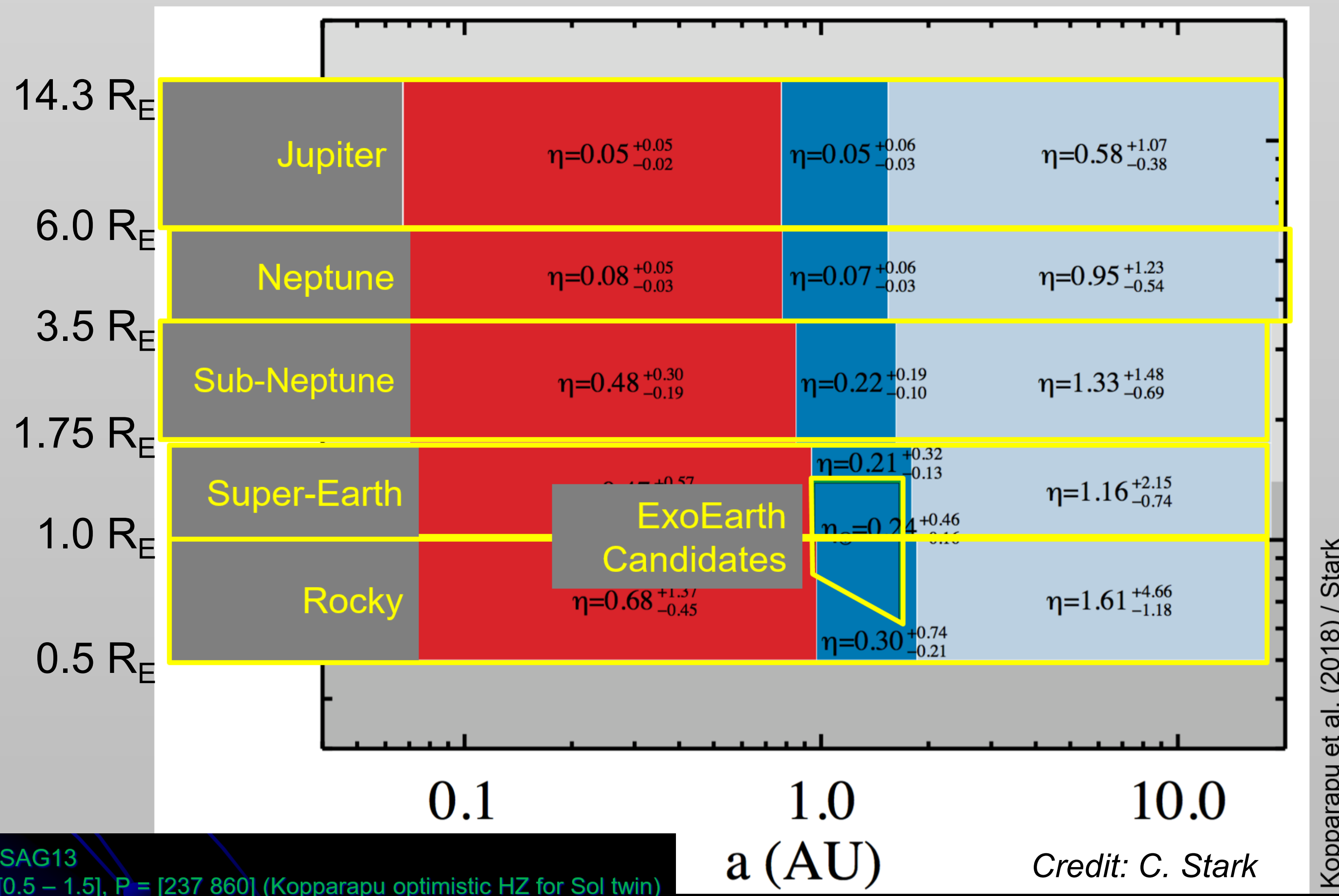
Recent DR 25 identifies additional HZ candidates and their reliability, S. Thompson et al.

Credit: NASA/Ames Research Center/W. Stenzel

Frequency of ExoEarths in Habitable Zone

Per Exoplanet Program Analysis Group

We use the SAG13 continuous distribution, but adopt coarse grid to communicate results:



$\eta_{habSol,SAG13}$

- R = [0.5 – 1.5], P = [237 860] (Kopparapu optimistic HZ for Sol twin)

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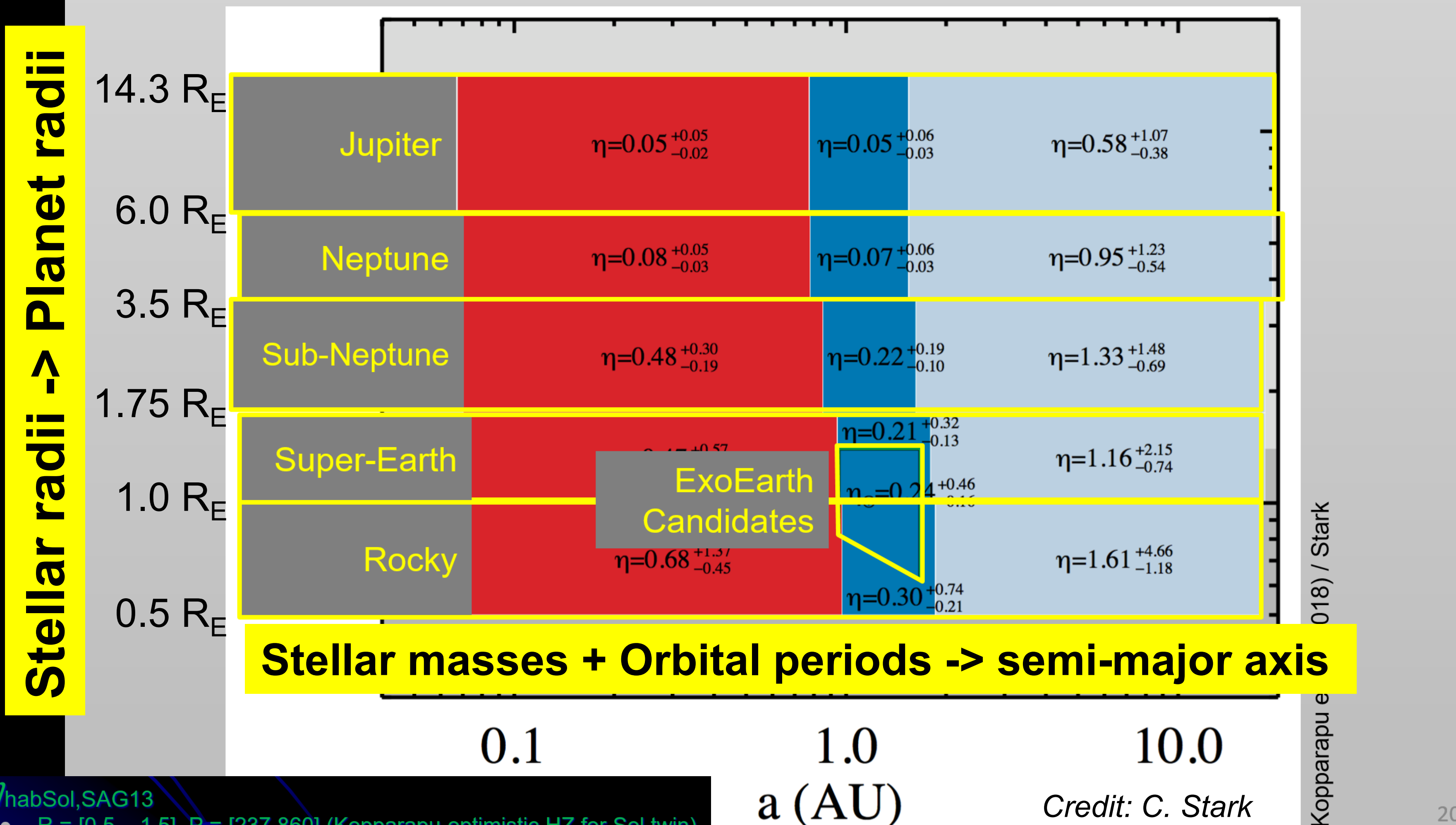

$\eta_{habSol,SAG13}$

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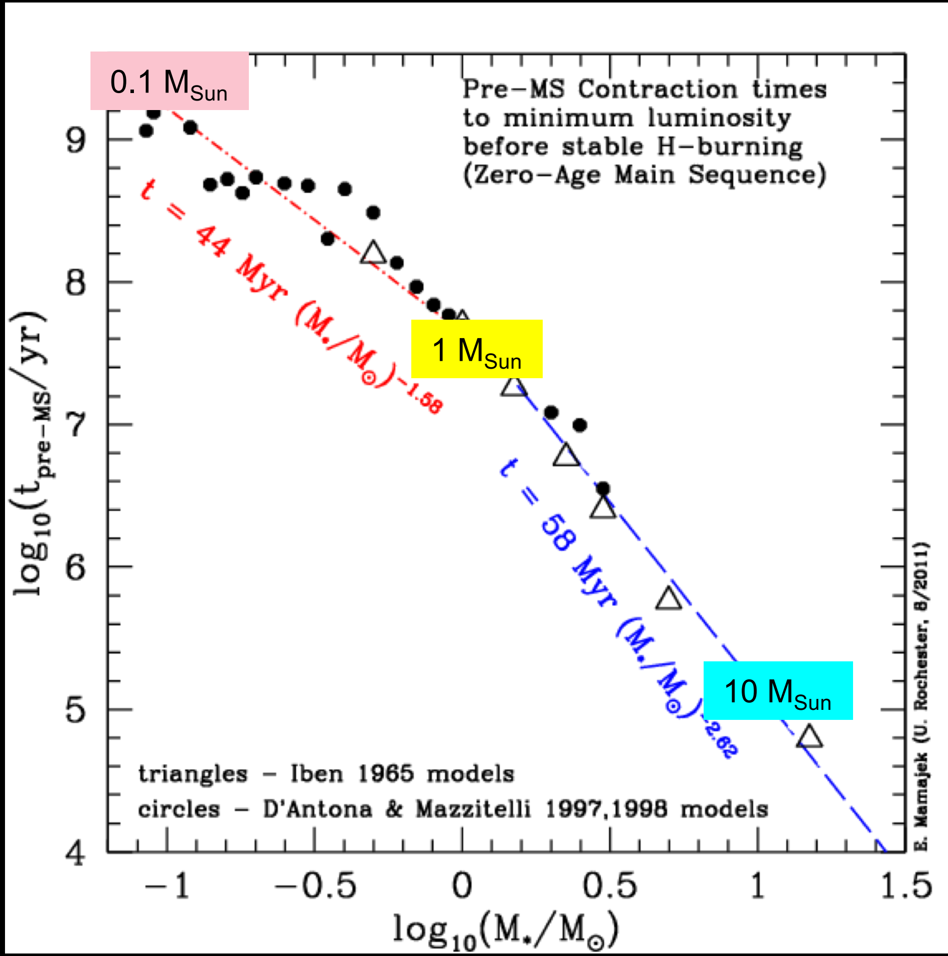
Age-dating Methods and Applicability

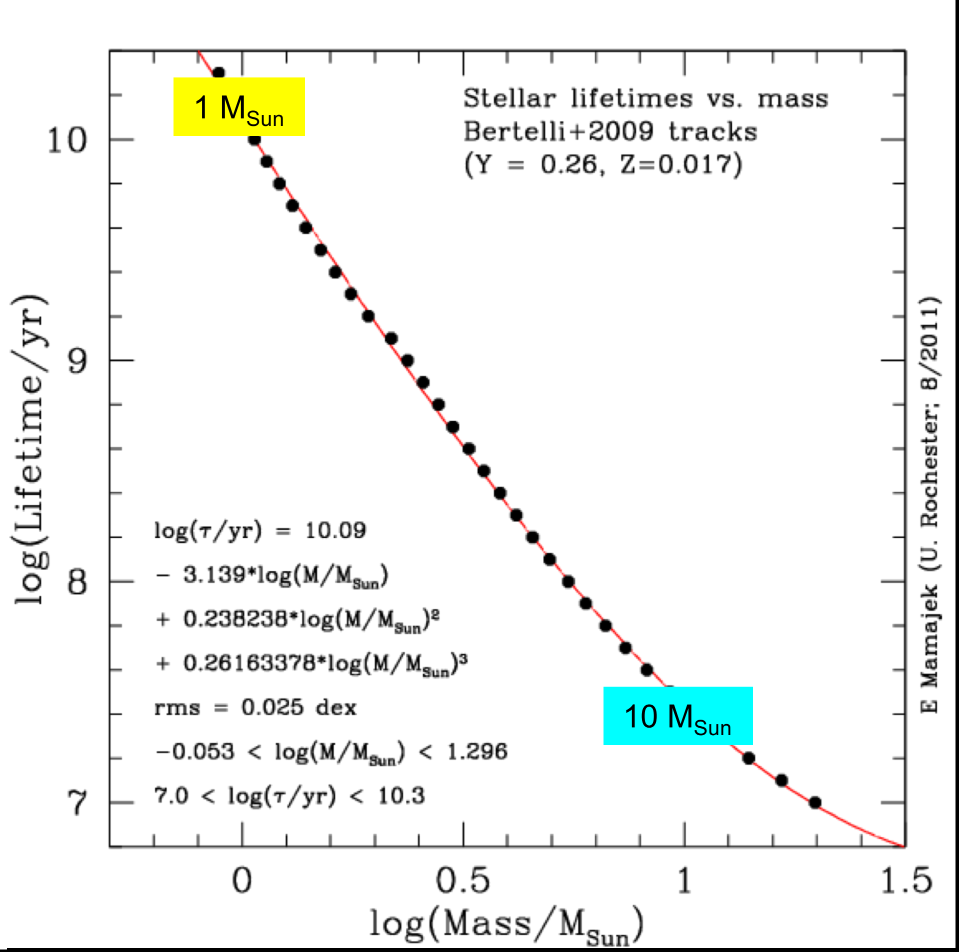
Type	Method	PMS	ZAMS	Main Sequence	Pop II
Semifundamental	nucleocosmochronometry	–	–	*E*	*I*
	kinematics	***E***	–	–	–
Model-dependent	isochrones	*E, i*	***E***	*E, i*	*E, i*
	lithium depletion boundary	***E***	***E***	–	–
	asteroseismology	–	–	***I***	*I*
Empirical	stellar spindown	*E*	*E*	***E, I***	*i*
	decay of activity	*E*	*E*	*i*	–
	decline in lithium	*E*	*E*	–	–

Note: *I* and *i* refer to individual stars, *E* and *e* to ensembles. Suitability is indicated in increasing order of usefulness by *i*, *I*, ***I***, respectively.

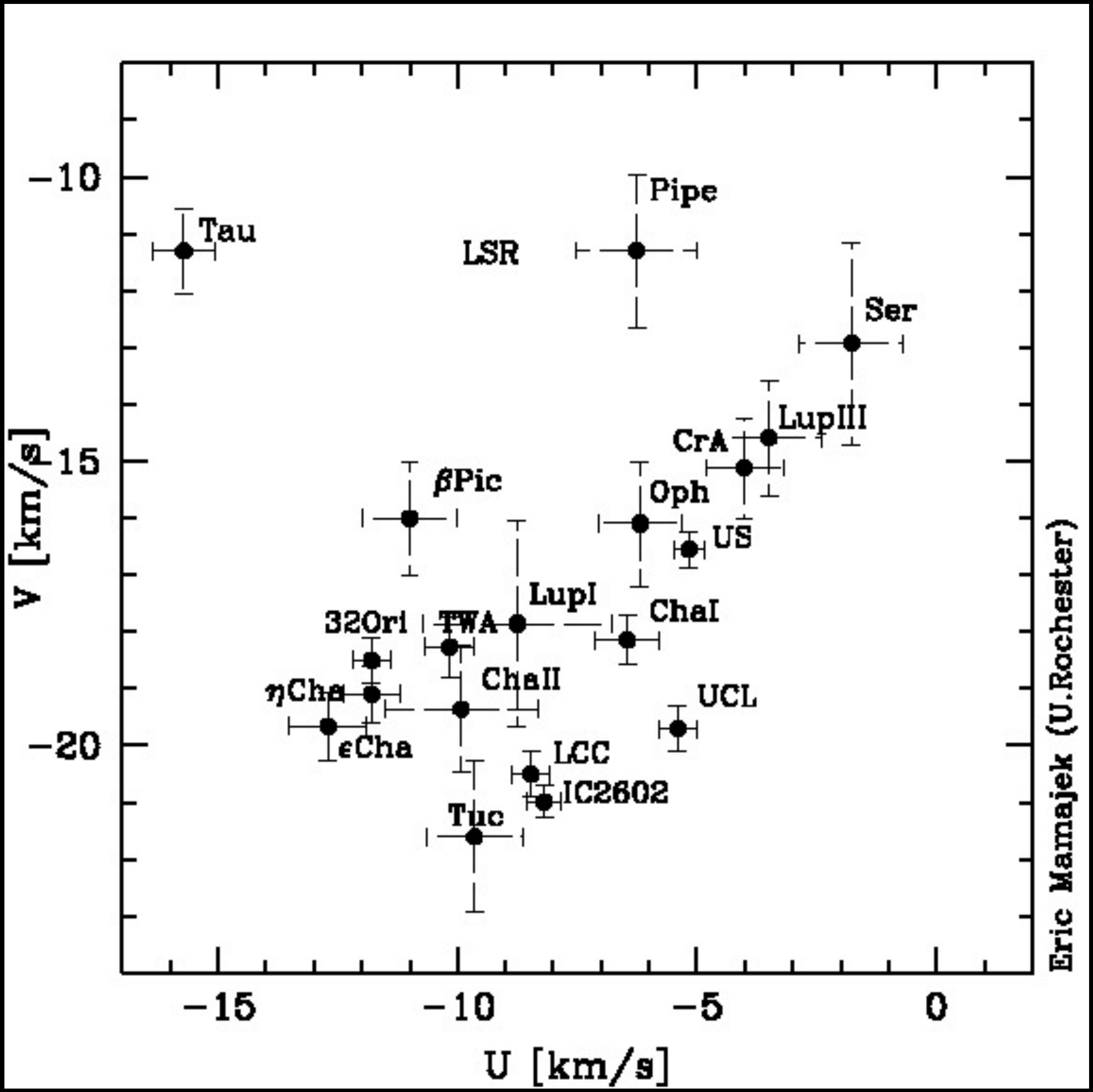
(Soderblom et al. 2010, ARA&A, 48, 581)

Pre-MS and MS/Post-MS Timescales





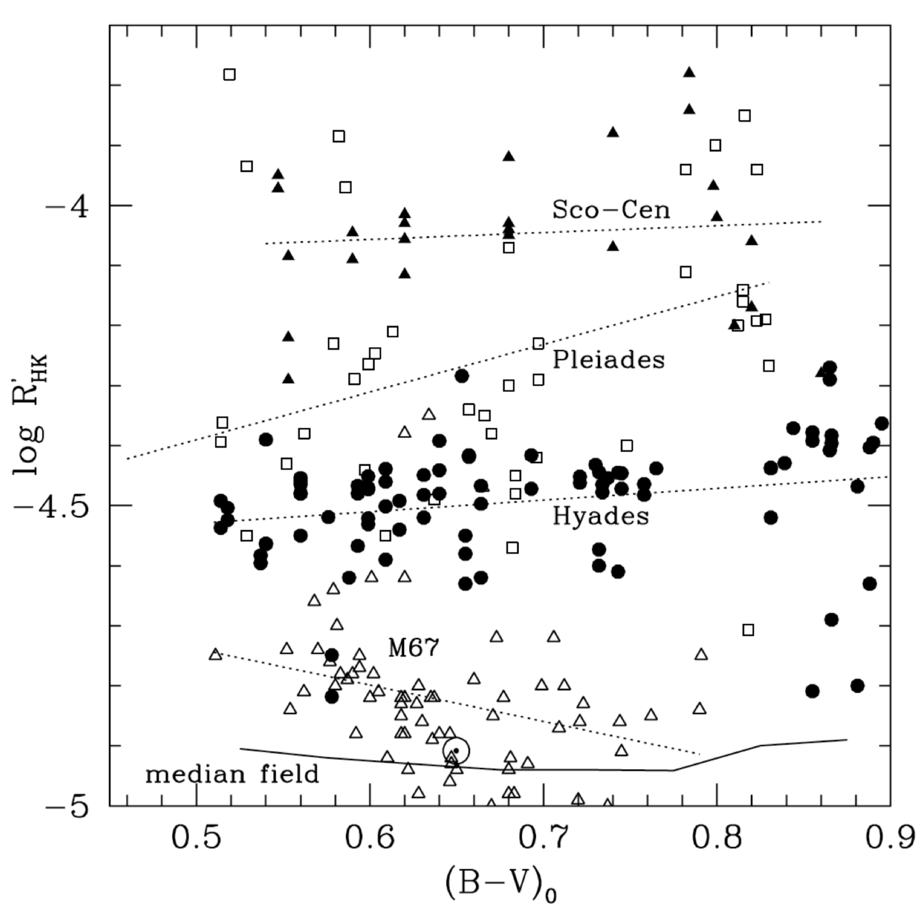
Kinematics for young stars

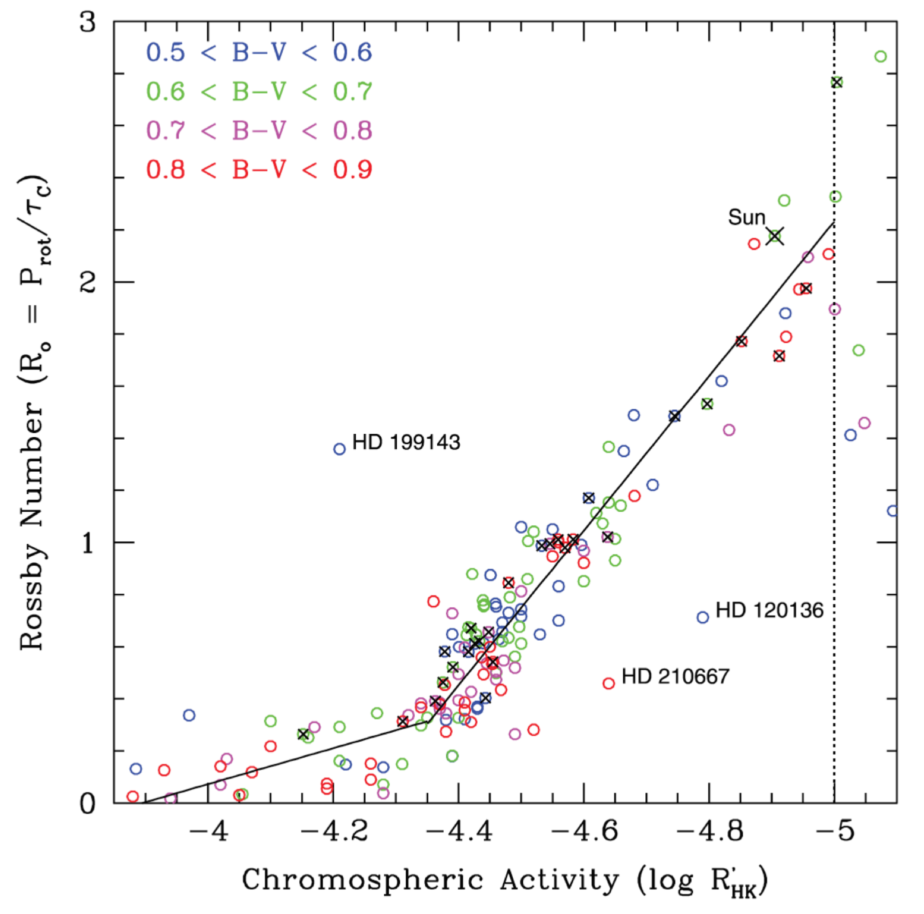


See Mamajek (2016) “Pre-Gaia census of nearby stellar groups” (IAU Symp. 314, 21)

Does it belong to a previously known nearby young stellar group?
Try Banyan Sigma tool (Jonathan Gagne et al. 2018):
http://www.exoplanetes.umontreal.ca/banyan/banyansigma.php

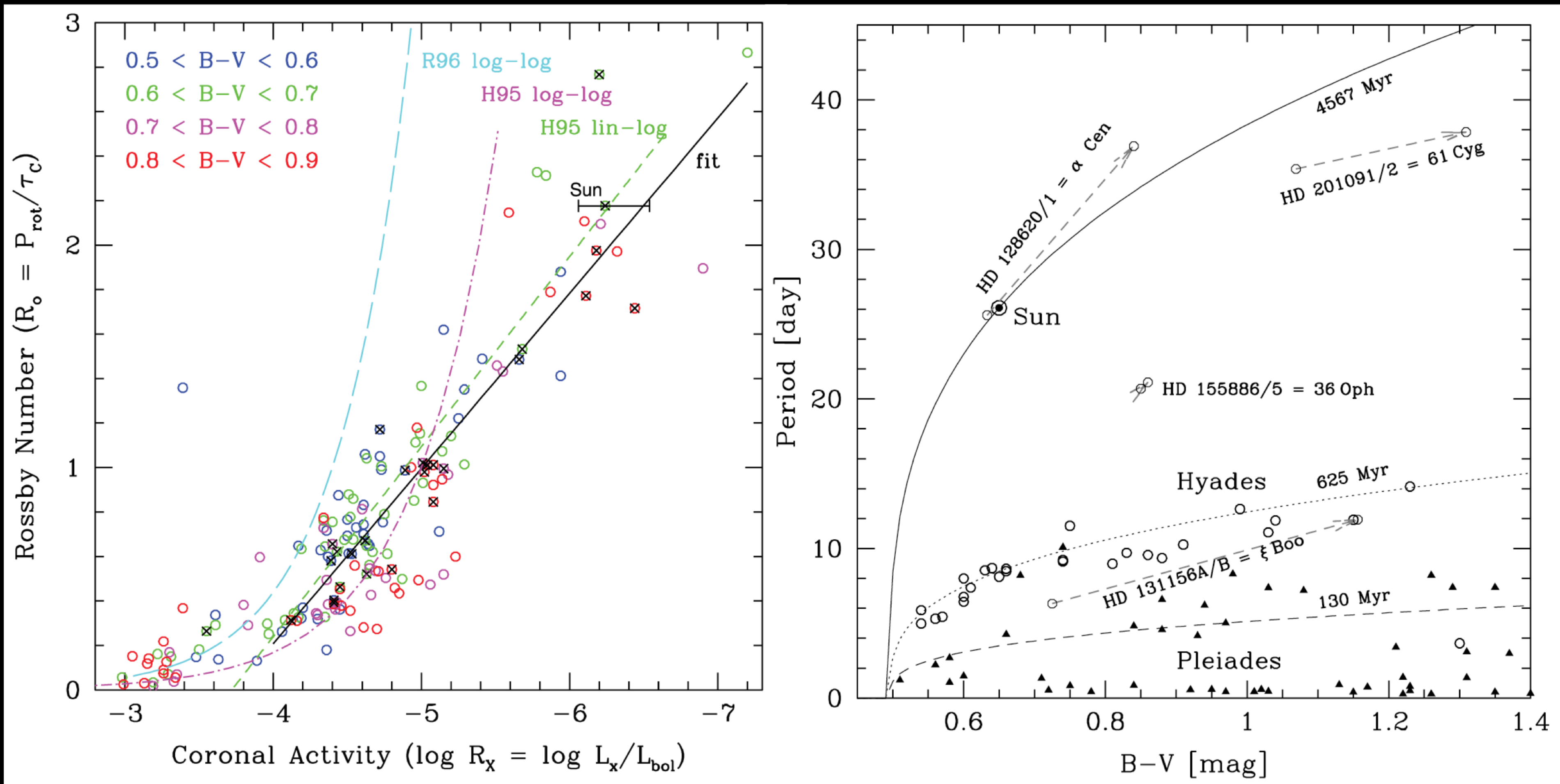
Chromospheric activity decays with rotation
Rotation slows with age (solar-type stars)





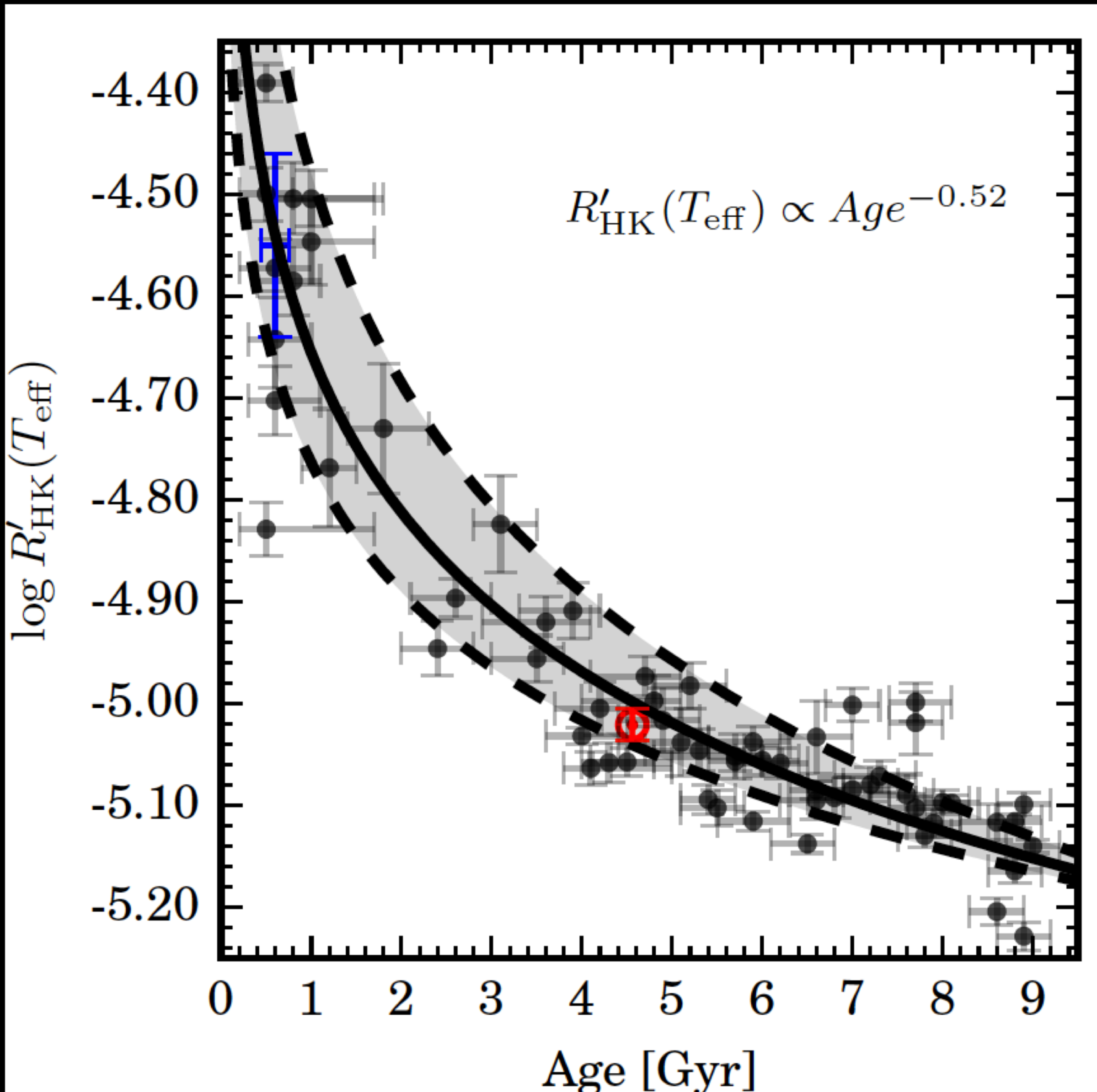
(Mamajek & Hillenbrand 2008)

Coronal (X-ray) Activity decays with Rotation slows with age ("gyrochronology")



(Mamajek & Hillenbrand 2008) – see also e.g. Barnes et al. 2010, Wright et al. 2011, Epstein & Pinsonneault 2014, Meibom et al. 2015

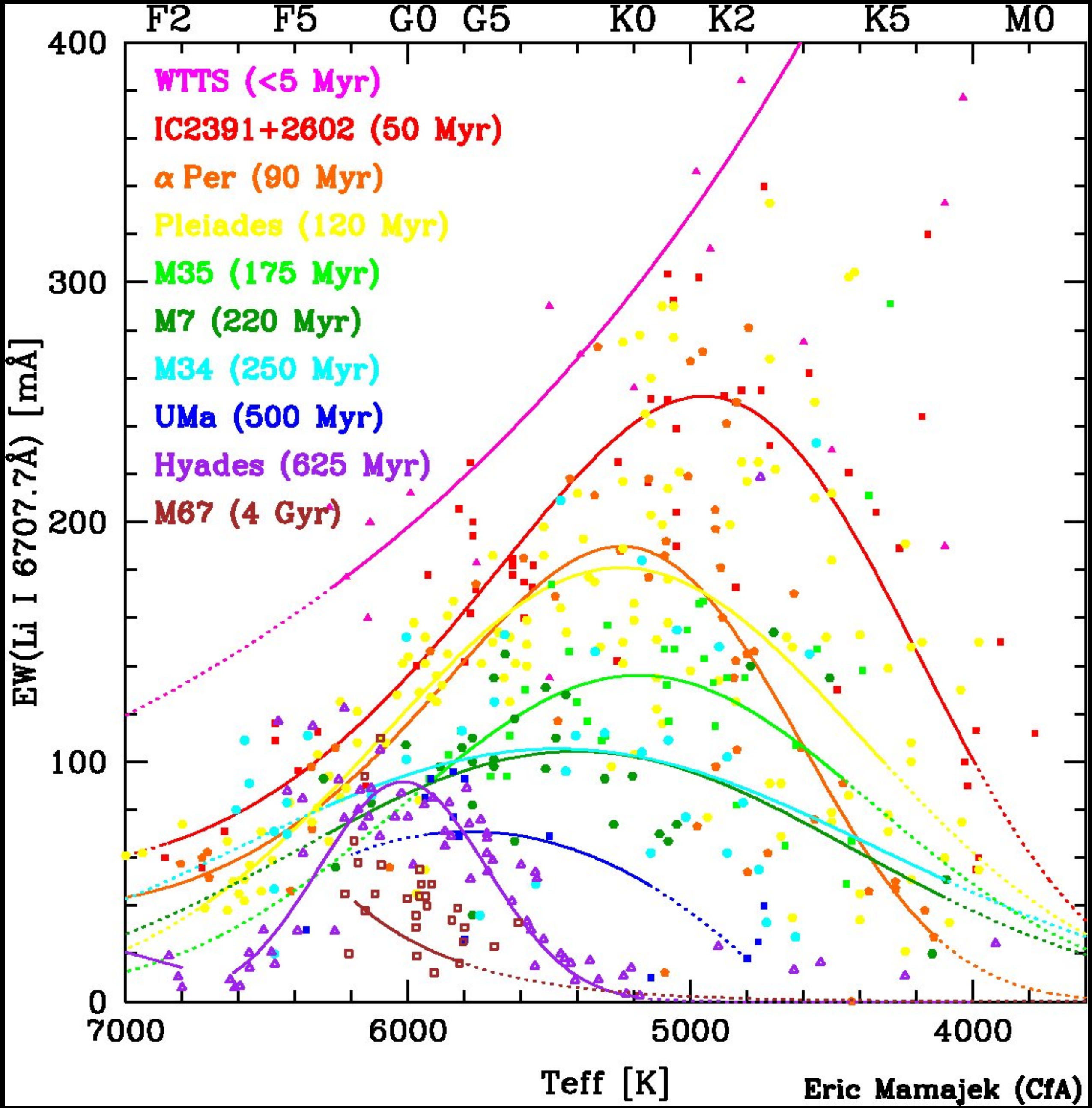
Chromospheric activity as age indicator



Decay in chromospheric activity for solar twins (isochronal ages, Ca H & K using 9000 HARPS spectra for 82 solar twins)

Lorenzo-Oliveira et al. 2018 arxiv:1806.08014, A&A, in press

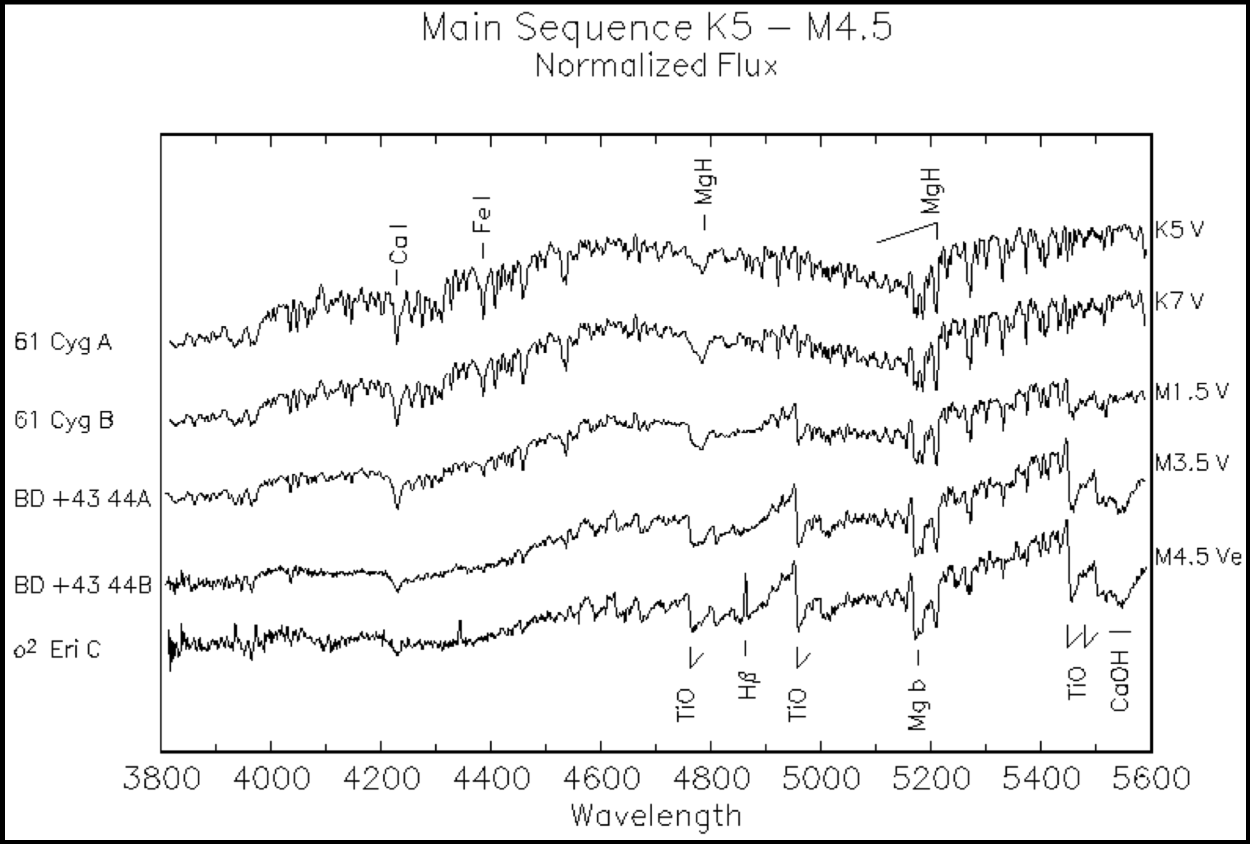
Lithium as age indicator for FGKM stars



What are spectral types?

Spectral types are defined by *appearance of spectra of standard stars*

Spectral types are NOT assigned by *colors, masses, abs. mags*



https://ned.ipac.caltech.edu/level5/Gray/frames.html

Notes on spectral standards: http://www.pas.rochester.edu/~emamajek/spt/
Compendium of mean Teff, colors, BC, properties for dwarf spectral types:
http://www.pas.rochester.edu/~emamajek/EEM_dwarf_UBVIJHK_colors_Teff.txt

What are spectral types?

Why useful?

Initial estimate of effective temperature (sans high-res high S/N spectral analysis)

Sanity check on what is the nature of star and its evolutionary status

Constraining interstellar reddening/extinction
-> improve stellar luminosity estimate
-> improve stellar radius estimate
-> improve exoplanet radius estimate
(ignore reddening/extinction at your peril)

Notes on spectral standards: http://www.pas.rochester.edu/~emamajek/spt/
Compendium of mean Teff, colors, BC, properties for dwarf spectral types:
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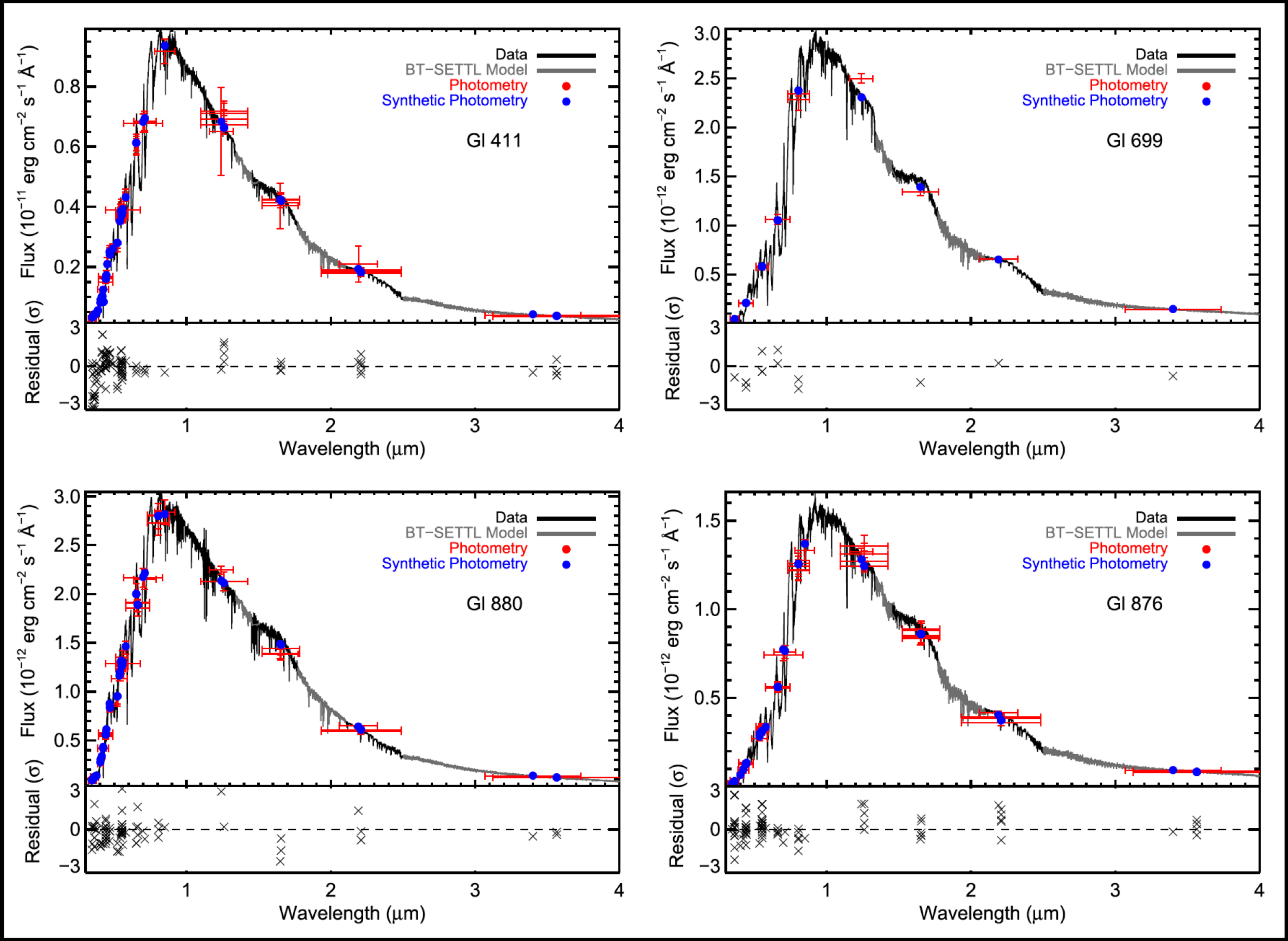
Sizing up M dwarf stars



Mann et al. 2015, ApJ, 804, 64 (see also papers on activity/kinematics by E. Newton)

Age-dating Methods and Applicability

Type	Method	PMS	ZAMS	Main Sequence	Pop II
Semifundamental	nucleocosmochronometry	–	–	*E*	*I*
	kinematics	***E***	–	–	–
Model-dependent	isochrones	*E*, *i*	***E***	*E*, *i*	*E*, *i*
	lithium depletion boundary	***E***	***E***	–	–
	asteroseismology	–	–	***I***	*I*
Empirical	stellar spindown	*E*	*E*	***E*, *I***	*i*
	decay of activity	*E*	*E*	*i*	–
	decline in lithium	*E*	*E*	–	–

Note: *I* and *i* refer to individual stars, *E* and *e* to ensembles. Suitability is indicated in increasing order of usefulness by *i*, *I*, ***I***, respectively.

(Soderblom et al. 2010, ARA&A, 48, 581)

"What is the age of HD ######?" Where to start?

- **SIMBAD** query (~2' radius): http://simbad.u-strasbg.fr/simbad/

Get lay of the land. Well studied or not? Multiple?
Star's history reflected in its designations (skim the bibliography)

- **Vizier** query (~30" radius; larger for nearby stars):

http://vizier.u-strasbg.fr/viz-bin/VizieR
Key catalogs:

  - **Astrometry**: Gaia DR2, Hipparcos (van Leeuwen 2007), UCAC5, etc.
  - **Photometry**: e.g. 2MASS, WISE, Mermilliod UBV
  - **Spectral type**: Skiff MK compendium, best types (usually since 1990)
  - **Metallicity** ([Fe/H], a-rich? e.g. LAMOST, APOGEE, RAVE, CKS, Brewer)
  - **Kinematics** (UVW, Vtan)
  - **Activity indicators** (chromospheric activity e.g. Ca H&K, coronal X-ray)
  - **Rotation** (P_{rot}, $v\sin i$)
  - Membership to stellar multiple or kinematic group (clusters and associations OK, "moving groups" be careful, "supercluster" NO)
  - Multiplicity: Washington Double Star Catalog (mix of physical & unphysical companions), SB9 (Pourbaix)
  - Infrared excess? Protoplanetary disk (likely <10 Myr), debris disk?
  - Previous age estimates: isochronal, activity, etc.

Some useful papers on ages for nearby stars

"The Ages of Stars" - Soderblom, 2010, ARA&A, 48, 581

"Ages of Young Stars" – Soderblom, Hillenbrand, Jeffries, Mamajek & Naylor, 2014, Protostars & Planets VI, 219

"Improved Age Estimation for Solar-Type Dwarfs Using Activity-Rotation Diagnostics" – Mamajek & Hillenbrand, 2008, ApJ, 687, 1264

"Intrinsic Colors, Temperatures, and Bolometric Corrections of Pre-MS stars" Pecaut & Mamajek (2013, ApJS, 208, 9) [*plenty on MS/dwarf stars also*]

"BANYAN XI: The BANYAN Sigma Multivariate Bayesian Algorithm to Identify Members of Young Associations within 150 pc" – Gagne, Mamajek, Malo et al., 2018, ApJ, 856, 23

"How to Constrain Your M Dwarf…" - Mann et al. (2015, ApJ, 804, 64)

"The Ages of Early-Type Stars…" – David & Hillenbrand (2015, ApJ, 804, 146)

"Nominal Values for Selected Solar and Planetary Quantities: IAU 2015 Resolution B3" – Prsa et al. 2016, AJ, 152, 41 (see IAU 2015 resolutions B2 and B3)

Some online resources

Basic Astronomical Data for the Sun (Mamajek):
https://sites.google.com/site/mamajeksstarnotes/basic-astronomical-data-for-the-sun

Intrinsic Colors, Temperatures, and Bolometric Corrections (Dwarfs & Pre-MS stars)
Pecaut & Mamajek (2013) http://adsabs.harvard.edu/abs/2013ApJS..208....9P
http://www.pas.rochester.edu/~emamajek/EEM_dwarf_UBVIJHK_colors_Teff.txt
http://www.pas.rochester.edu/~emamajek/spt/ (notes by spectral type)

BANYAN Sigma: Assigning membership probabilities to nearby young groups (J. Gagne):
http://www.exoplanetes.umontreal.ca/banyan/banyansigma.php

MIST: MESA Isochrones & Stellar Tracks (J. Choi, A. Dotter, C. Conroy, B. Paxton, et al.)
http://waps.cfa.harvard.edu/MIST/

IAU 2015 Resolutions B2 (Bolometric Magnitude Scale) & B3 (Nominal Units)
https://arxiv.org/abs/1510.06262
https://arxiv.org/abs/1510.07674

General Advice

Do multiple sanity checks on your star. For most stars on sky, astronomers now have e.g. Gaia DR2 parallax, 2MASS photometry, etc.
Do the colors make sense? The absolute magnitude?

Vizier query with ~30” radius – learn catalogs, strengths, weaknesses.
SIMBAD is a compilation – a starting point. Dig deeper on your star.
Search and quote values from the original literature.

Can’t ignore reddening/extinction unless within Local Bubble (d ~< 75 pc).
Check published reddening maps – does your reddening/extinction make sense?
Using near-IR photometry (e.g. 2MASS Ks band)

Direct imaging target? Beware of being biased towards young ages (which means lower planet masses!)

Luminosities: make sure you are using consistent bolometric corrections and solar values. Do you recover the Sun’s properties?

Use IAU 2015 nominal parameters for Sun (and Earth, Jupiter). Stay consistent.

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exoplanets.nasa.gov

Sign up for Exoplanet Exploration Program Analysis Group (ExoPAG) email list:

https://exoplanets.nasa.gov/exep/exopag/announcementList/

Astro2020 Decadal Survey input (due 1/2019)

http://sites.nationalacademies.org/SSB/CurrentProjects/SSB_185159

Acknowledgements

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