# Diameters and Temperatures of Main-Sequence Stars:

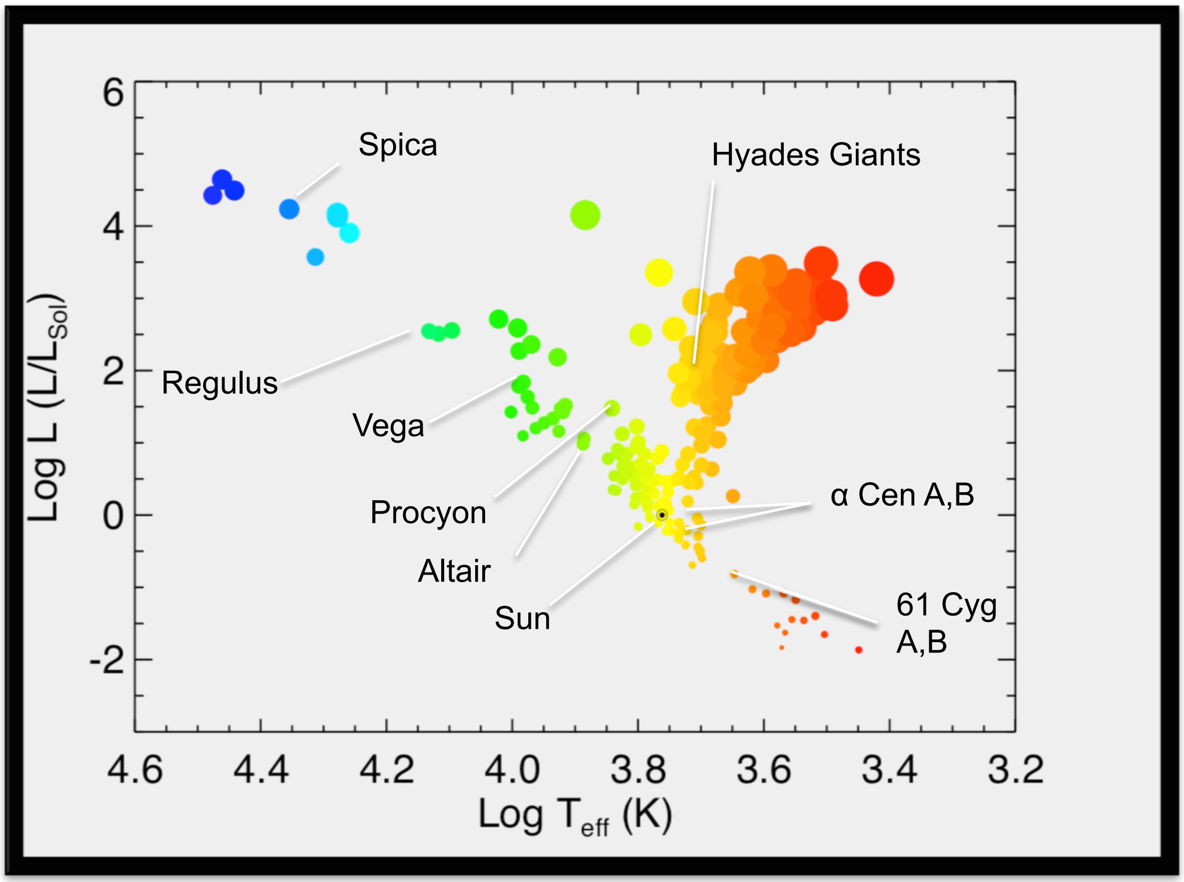
# **The Big Picture**

Tabetha Boyajian

Yale University

# Big Picture:

Empirically determined H-R diagram from interferometric measurements



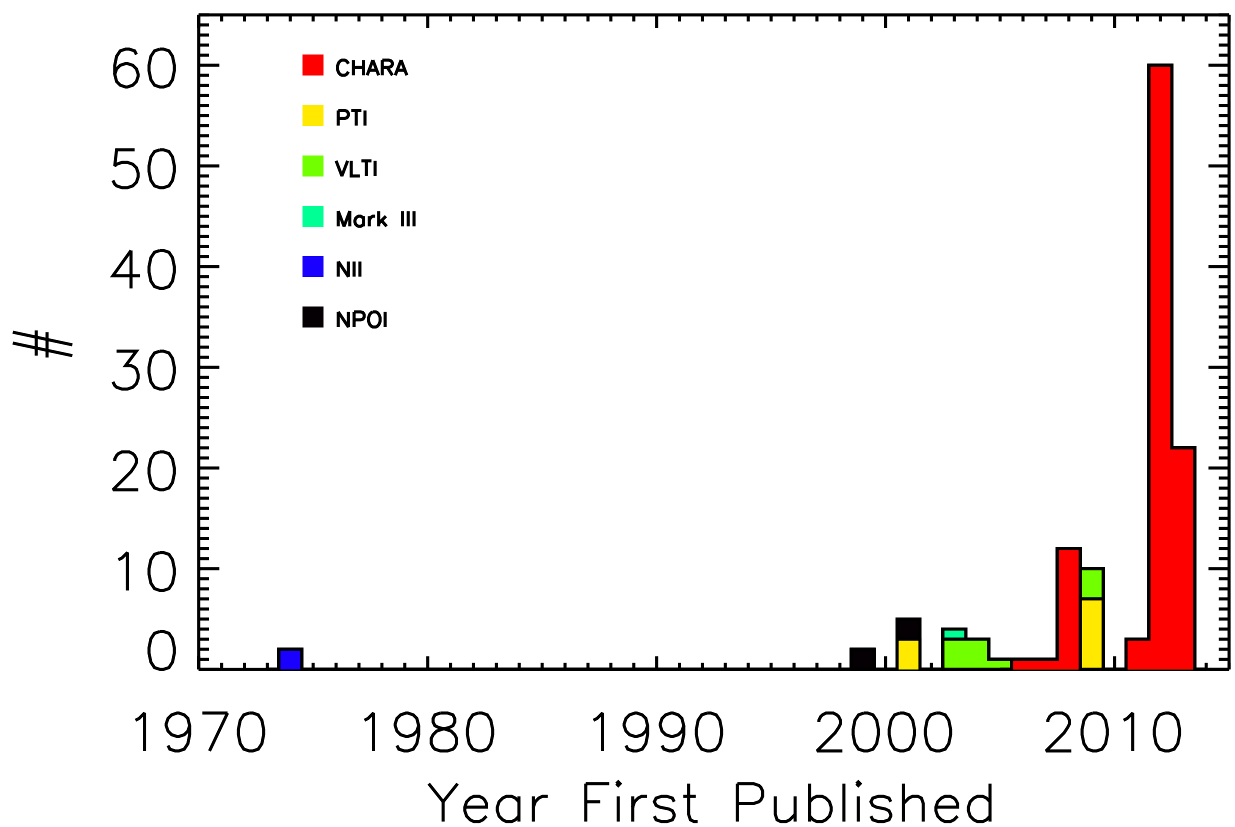

**An interferometer measures the angular diameter (θ) of a star. (yields the effective temperature and L with distance and flux)**

# Progress

*Heigh Ho...*

| | 1997 | 2004 | |
|---|---|---|---|
| Total # of stars with angular diameter measurement | 145 | 458 | (~3) |
| Stars with σθ < 5% | 45 | 242 | (~5.5) |
| Stars with σθ < 5% and on main-sequence | 6 | 24 | (4) |
| | Source: Davis 1997 | Source: Richichi et al. 2005 (CHARM2 Catalogue) | |

# Current 2013 count: **127!**



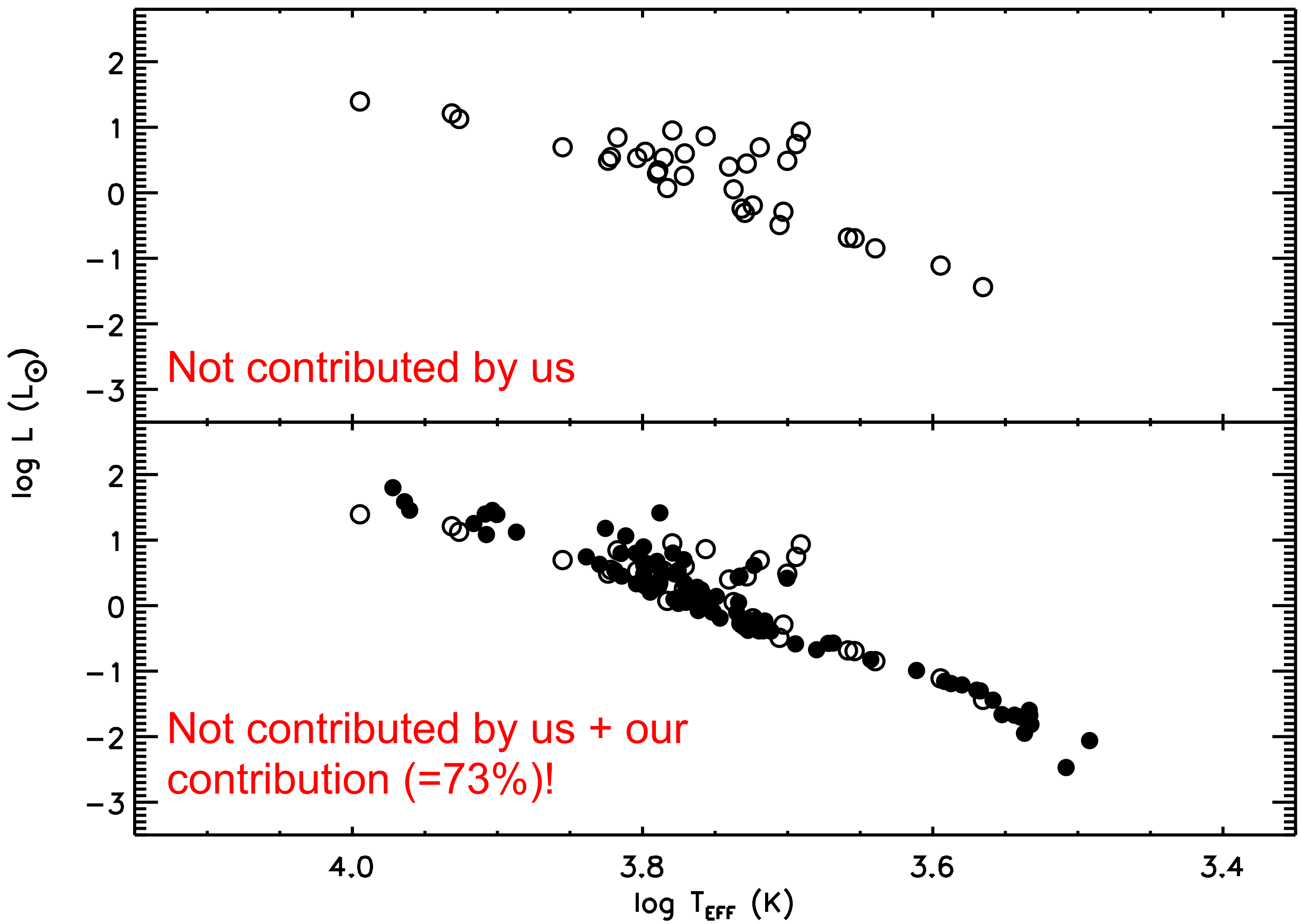

Above: Number of MS stars with diameters measured to better than 5%

# The Boyajian/von Braun Survey:

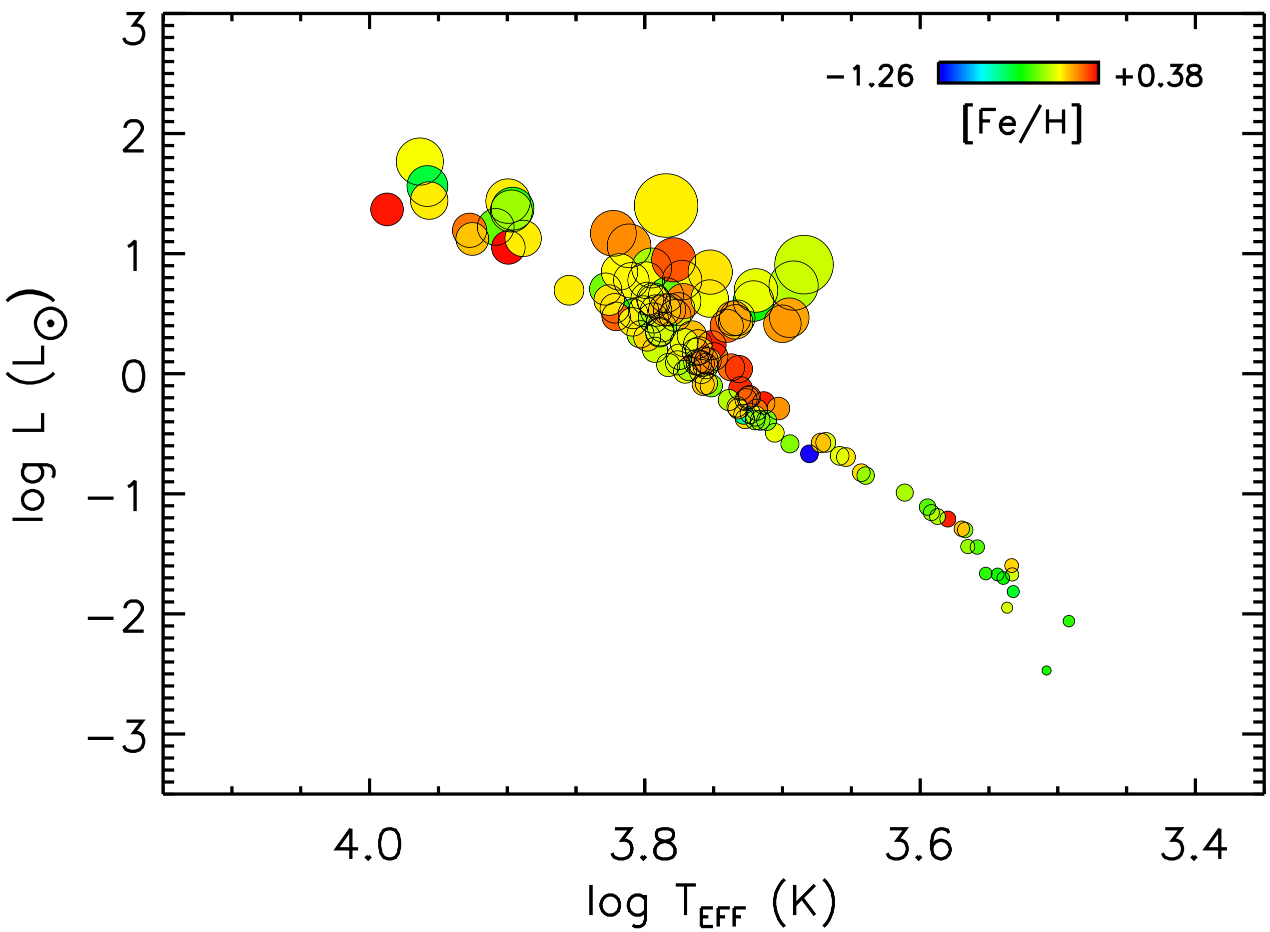
## Update from 2012

- Stellar Diameters and Temperatures II. Main Sequence K- and M- stars (Boyajian et al. 2012)
- Stellar Diameters and Temperatures III. Main Sequence A, F, G, & K stars: Additional high precision measurements and empirical relations (Boyajian et al. 2013, submitted)

# The Boyajian/von Braun Survey



# Empirical HRD: 2013



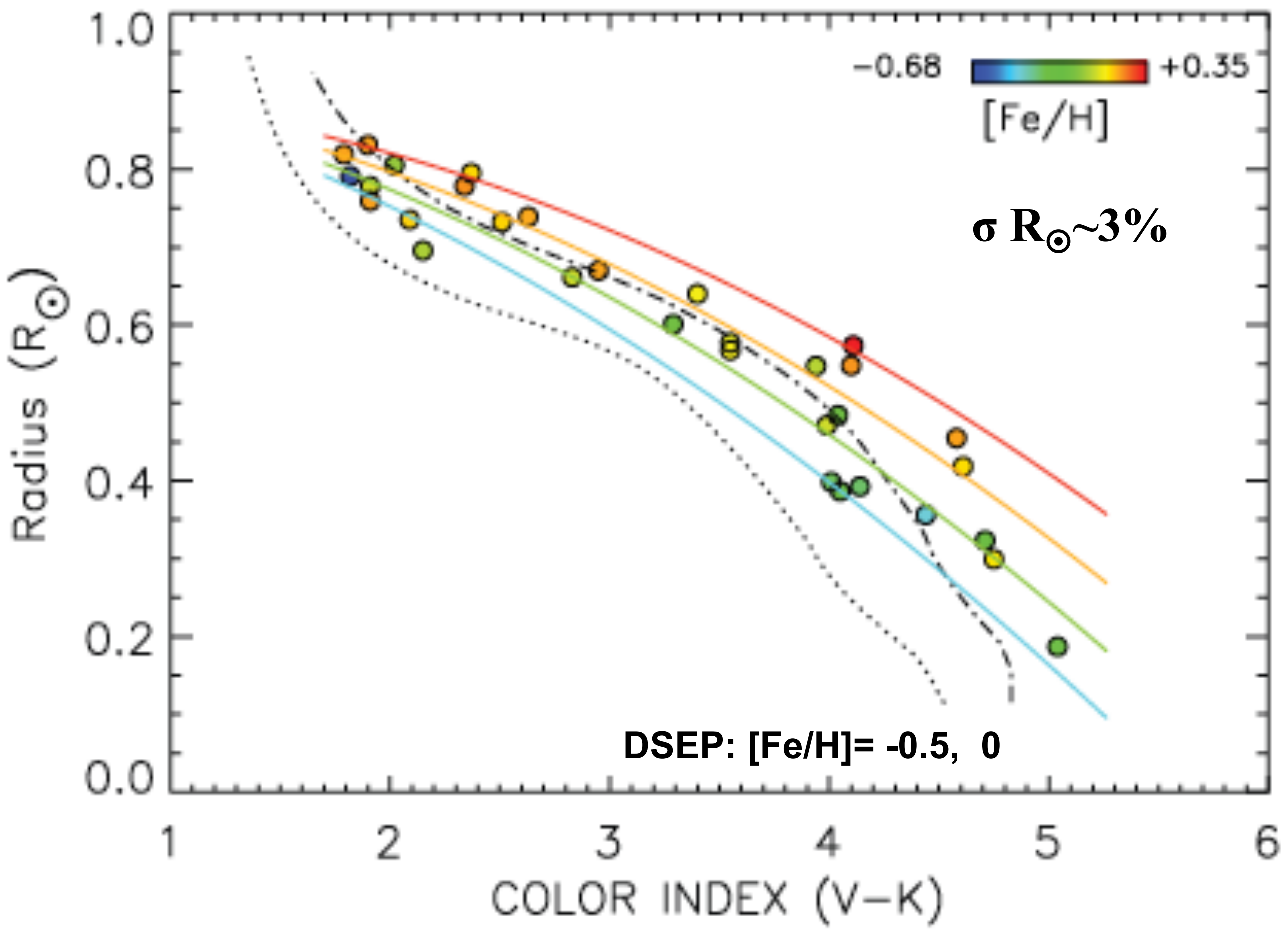

Boyajian et al. (2013, submitted)

Includes only **MS stars** with diameter precision <**5%**

# Highlights: KM dwarfs

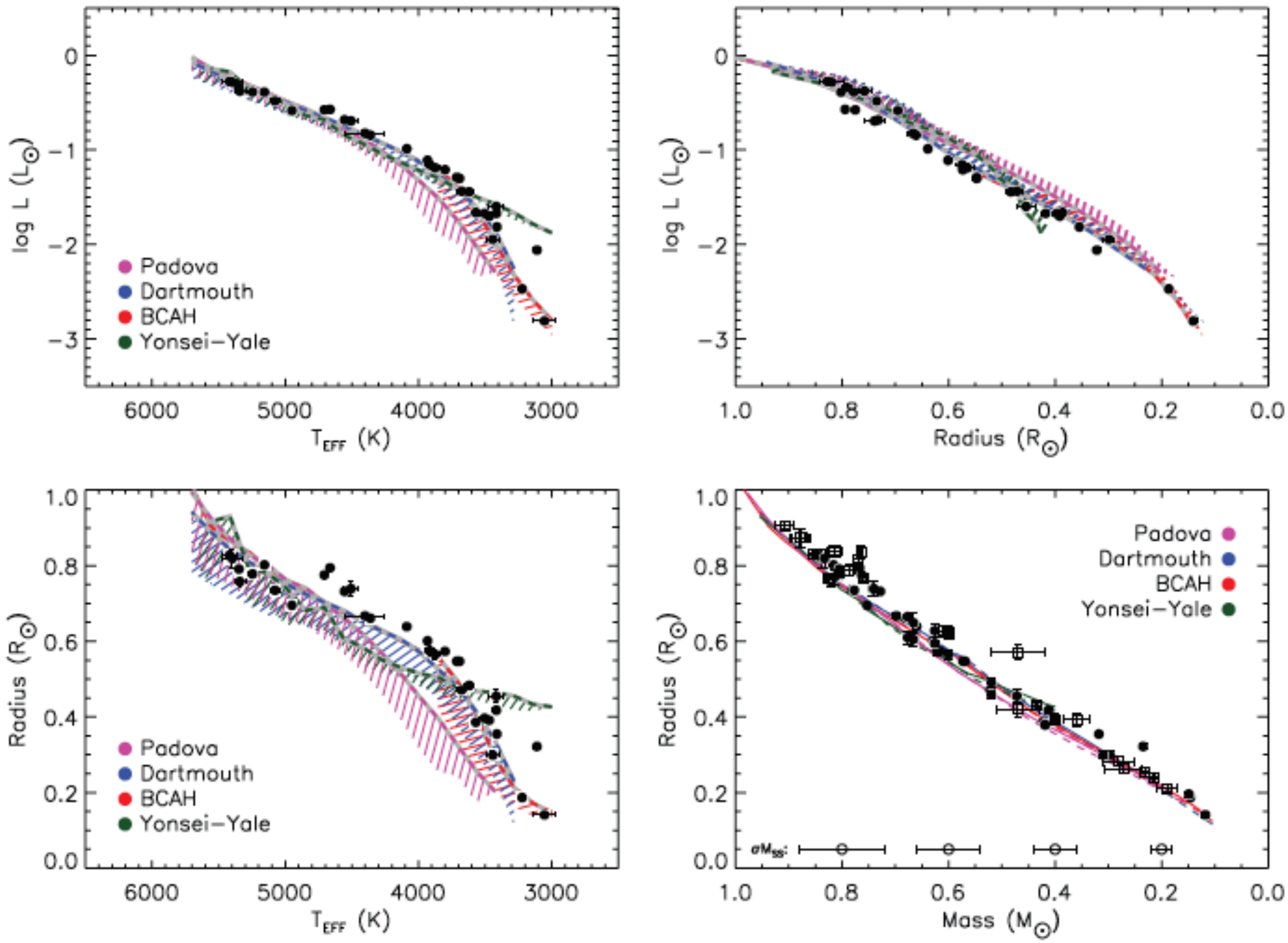
## Color - metallicity - radius

$$R(R_\odot) = a_0 + a_1X + a_2X^2 + a_3XY + a_4Y + a_5Y^2$$

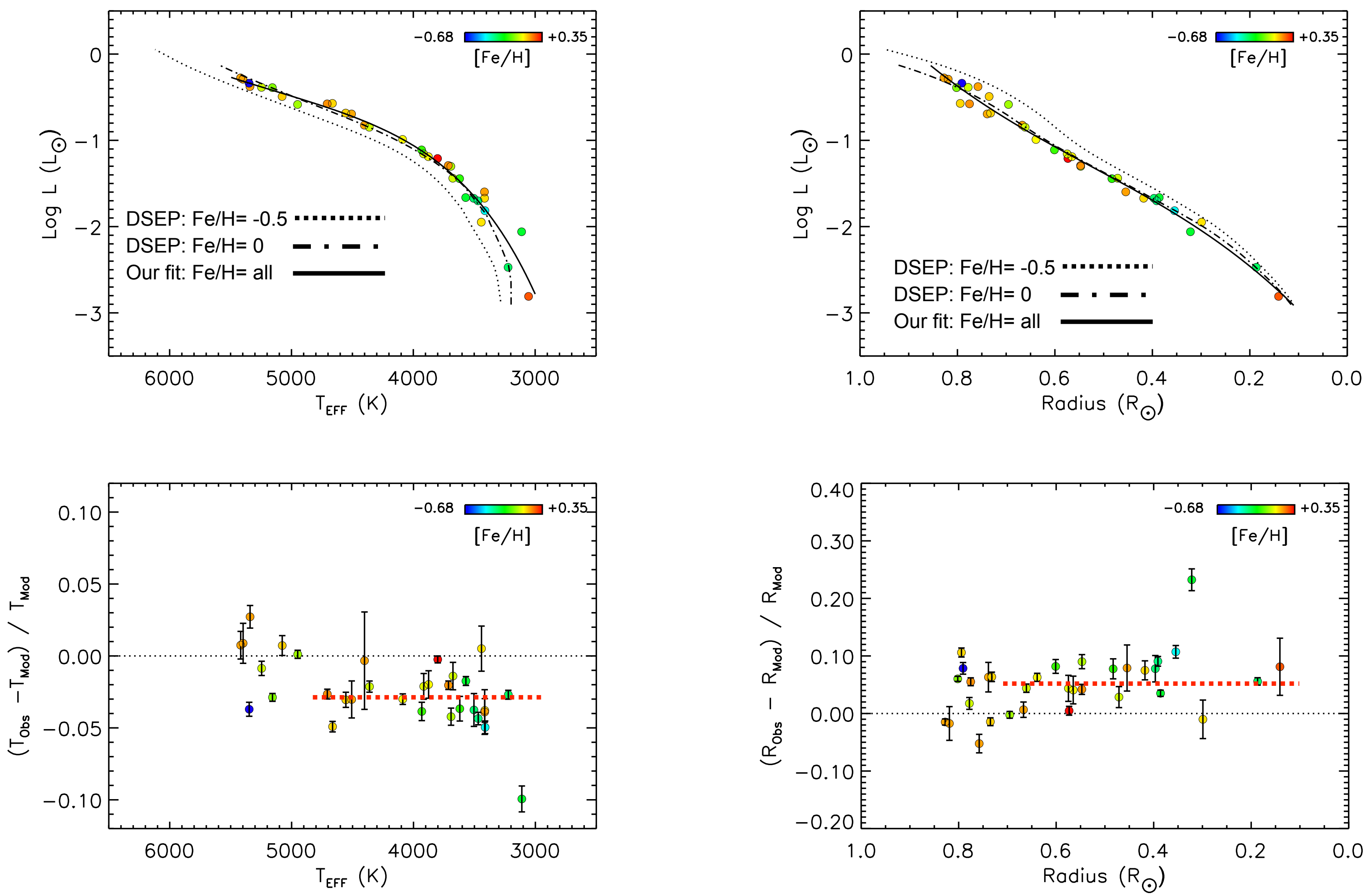



This is done with Teff and luminosity too, producing relations precise to 2% (Teff) and 4% (L).

The Astrophysical Journal, 756:1 (31pp), 2012 ??? Boyajian et al.



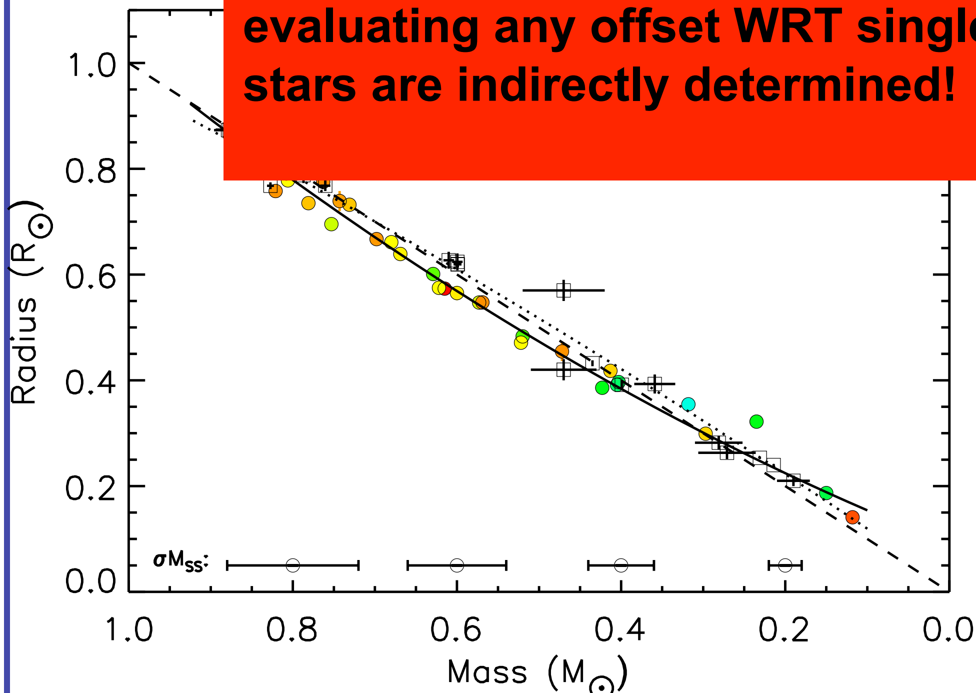
# Modeling low-mass stars

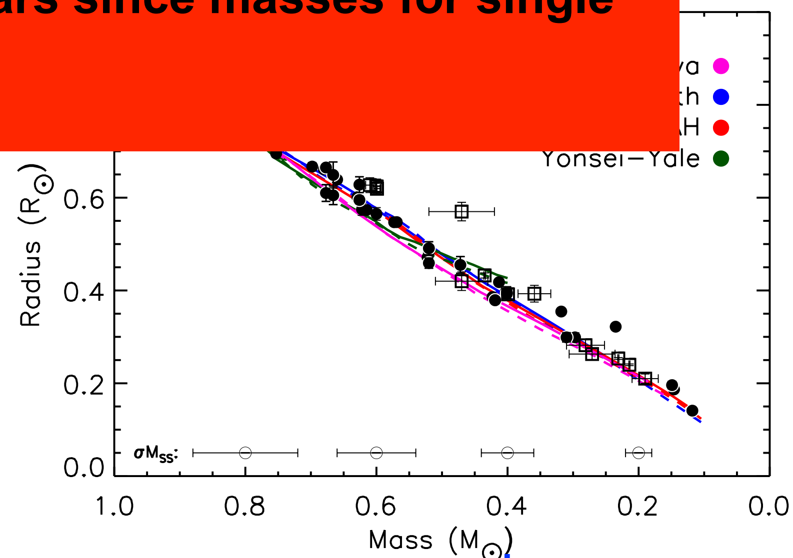


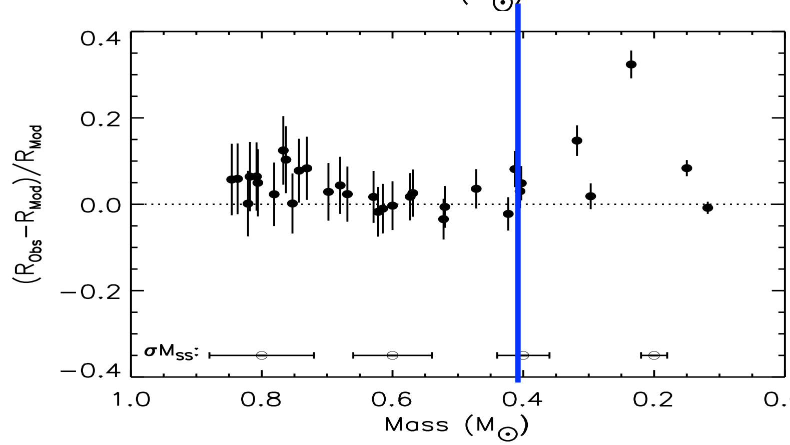

**At a given luminosity, for stars <5000K models are over estimating Teff by ~3% and for stars <0.7$R_\odot$ models under estimating radii by ~5%**

# Mass-Radius: Models & Single VS binary stars

**NOTE: This is not the best approach to the problem when evaluating any offset WRT single stars since masses for single stars are indirectly determined!**



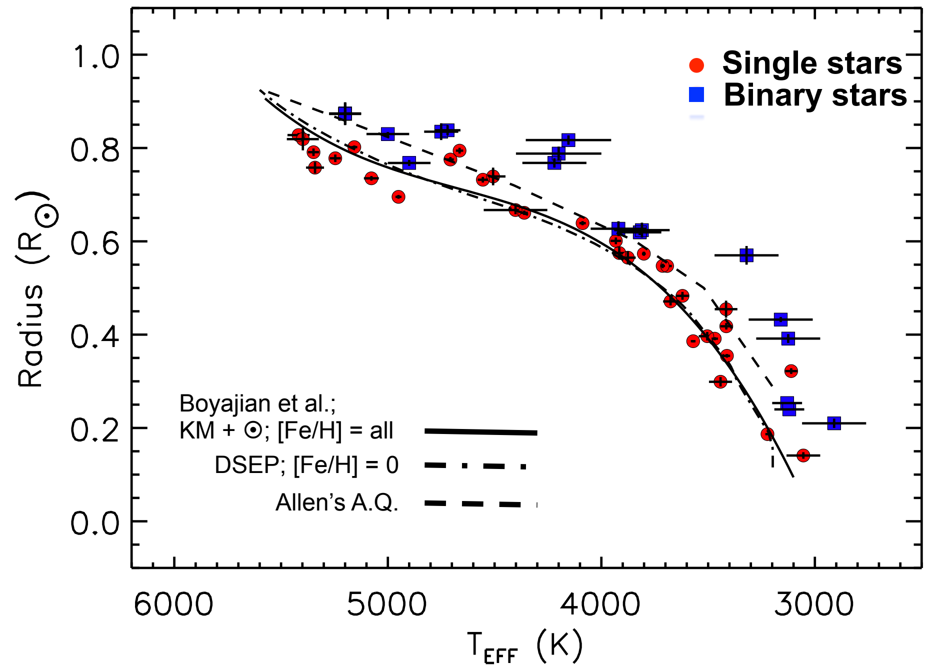




$R_{Mod}$= Dartmouth model radius at estimated mass.

- **Single and binary stars have comparable radii, and ~1:1 relation**
- **Models under estimate radii for stars <~0.4$M_\odot$**

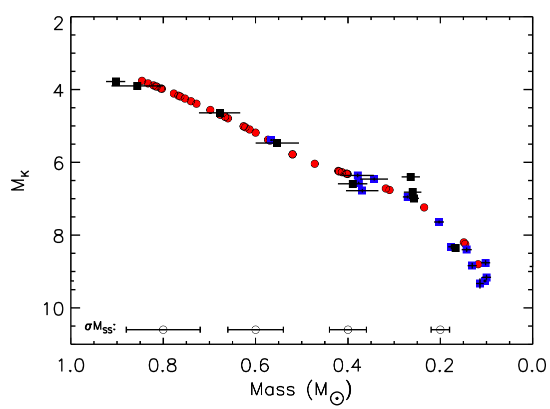
# Validating eclipsing binary Teff

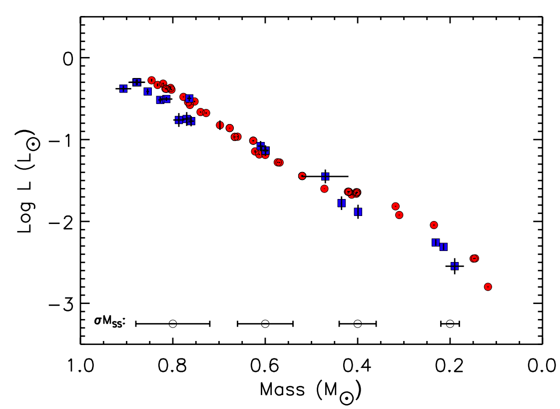
**If the radii are comparable, the temperature is offset by several 100K!**



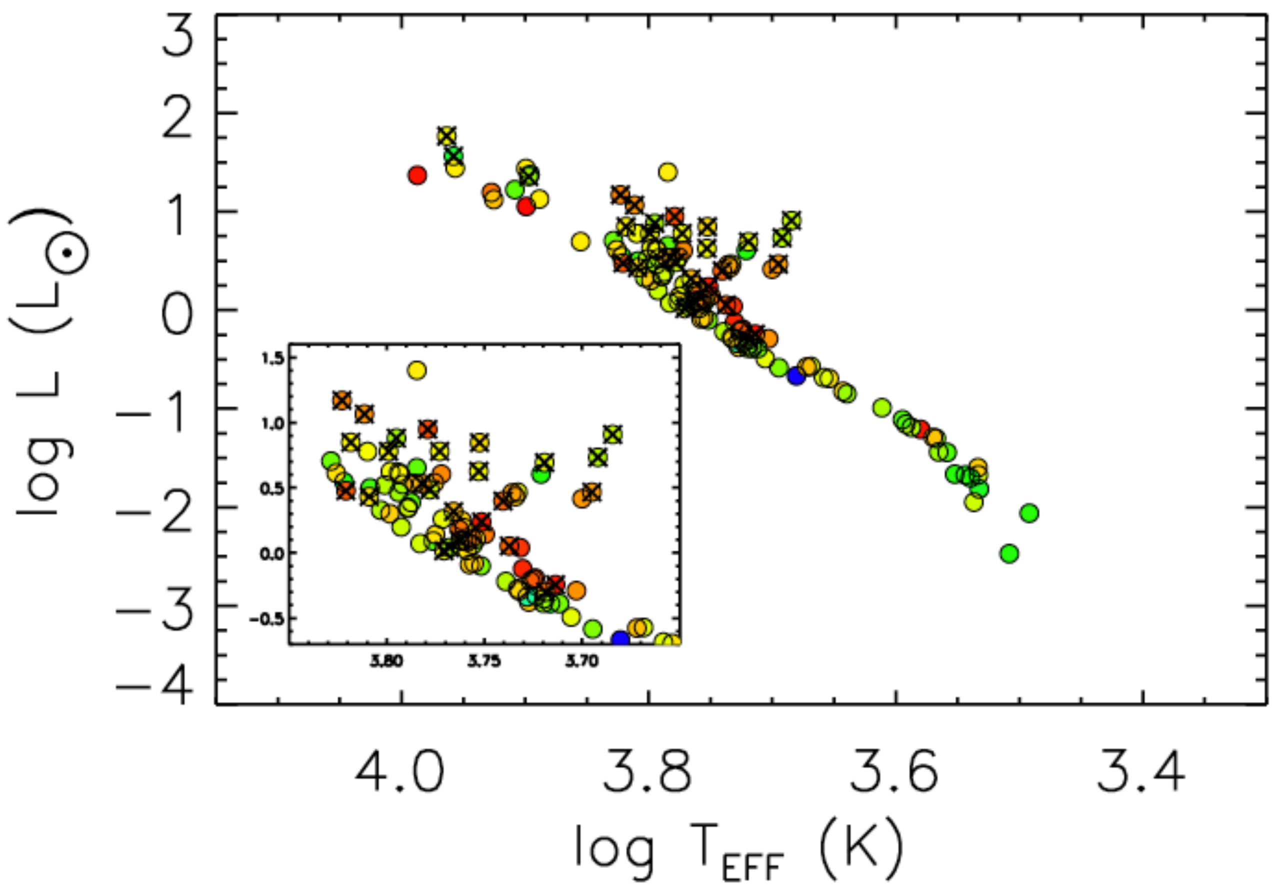

**IS IT REAL??**
**1)Binary $T_{eff}$ are wrong or**
**2)Binary $T_{eff}$ is correct, and the effect is a consequence of higher activity rates in binary stars**

- **Additional supporting evidence:**
  - **Mass-$M_K$ is perfect (as expected)**
  - **Mass-L shows EB L ↓ thus adopted EB T must be ↓ ($L \sim R^2T^4$)**



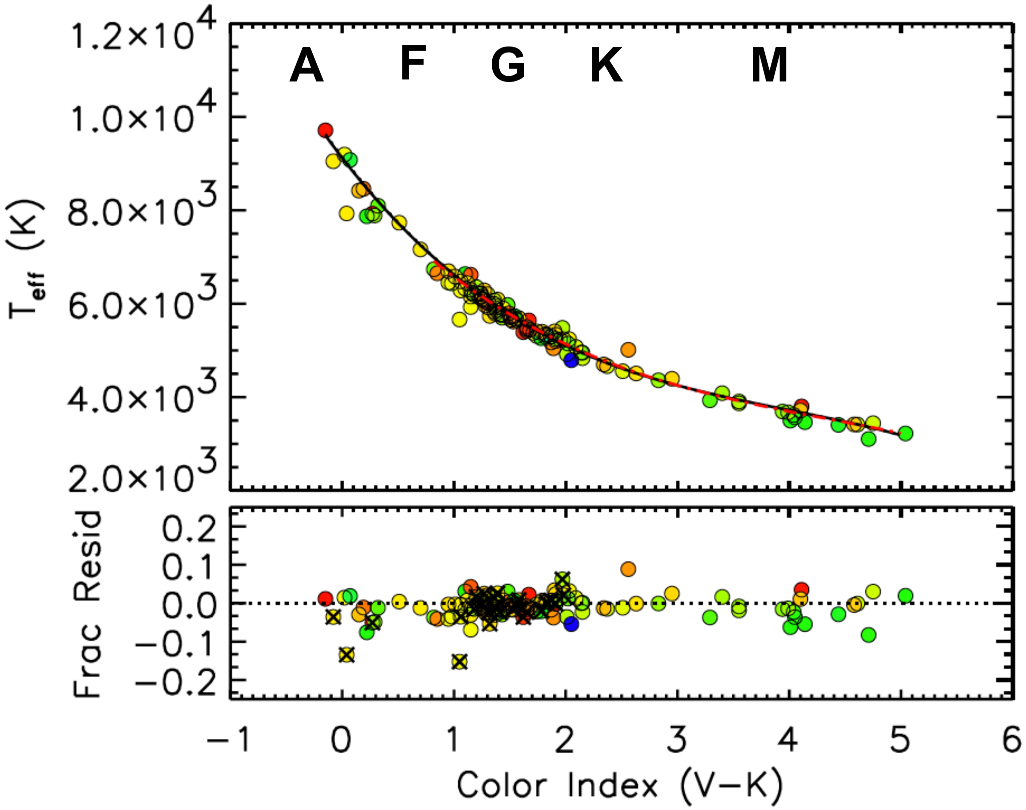



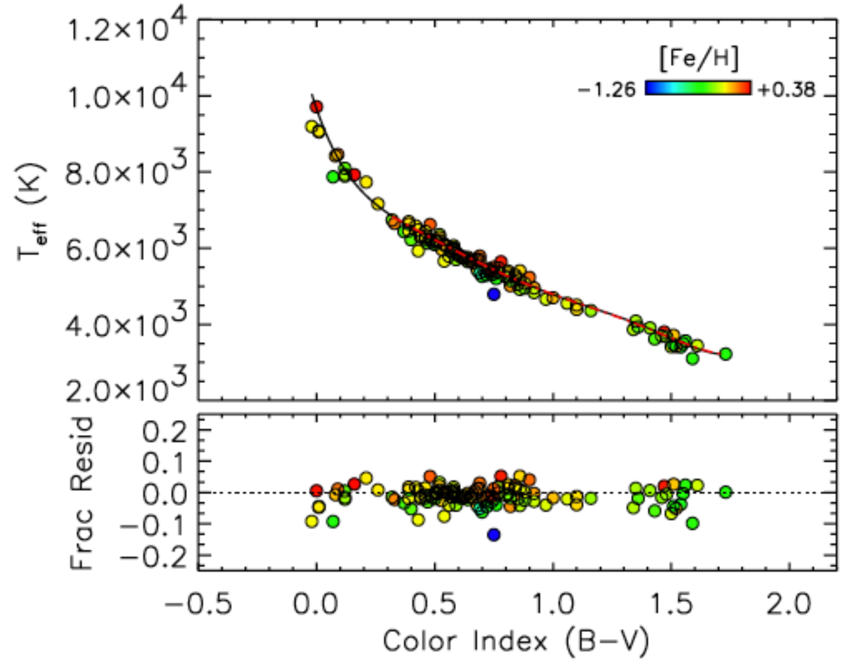
# Highlights on A-M main sequence stars: Bridging the gap

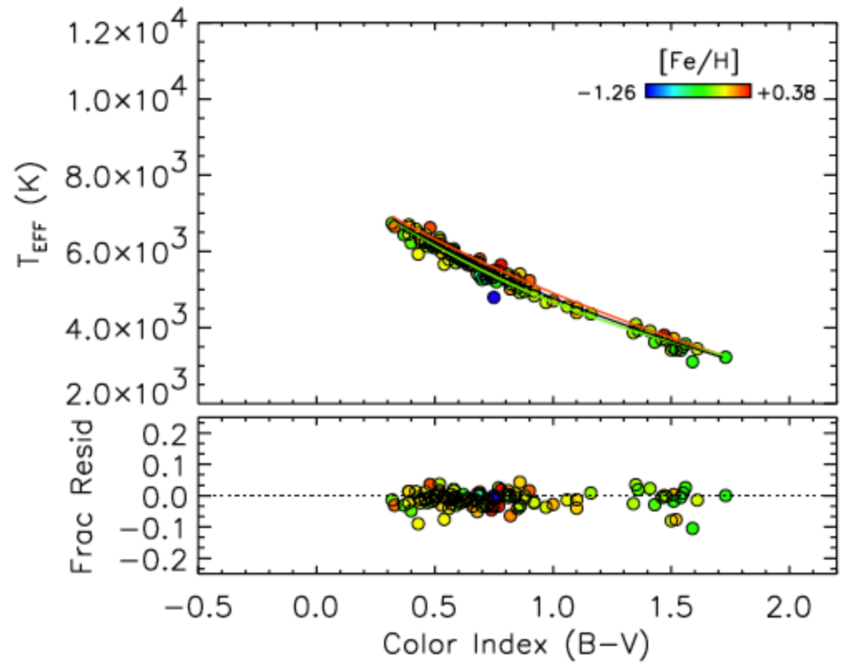



**Note: Its probably not so great an idea to use spectral typing as an indicator of stellar evolution for LC IV and V stars**

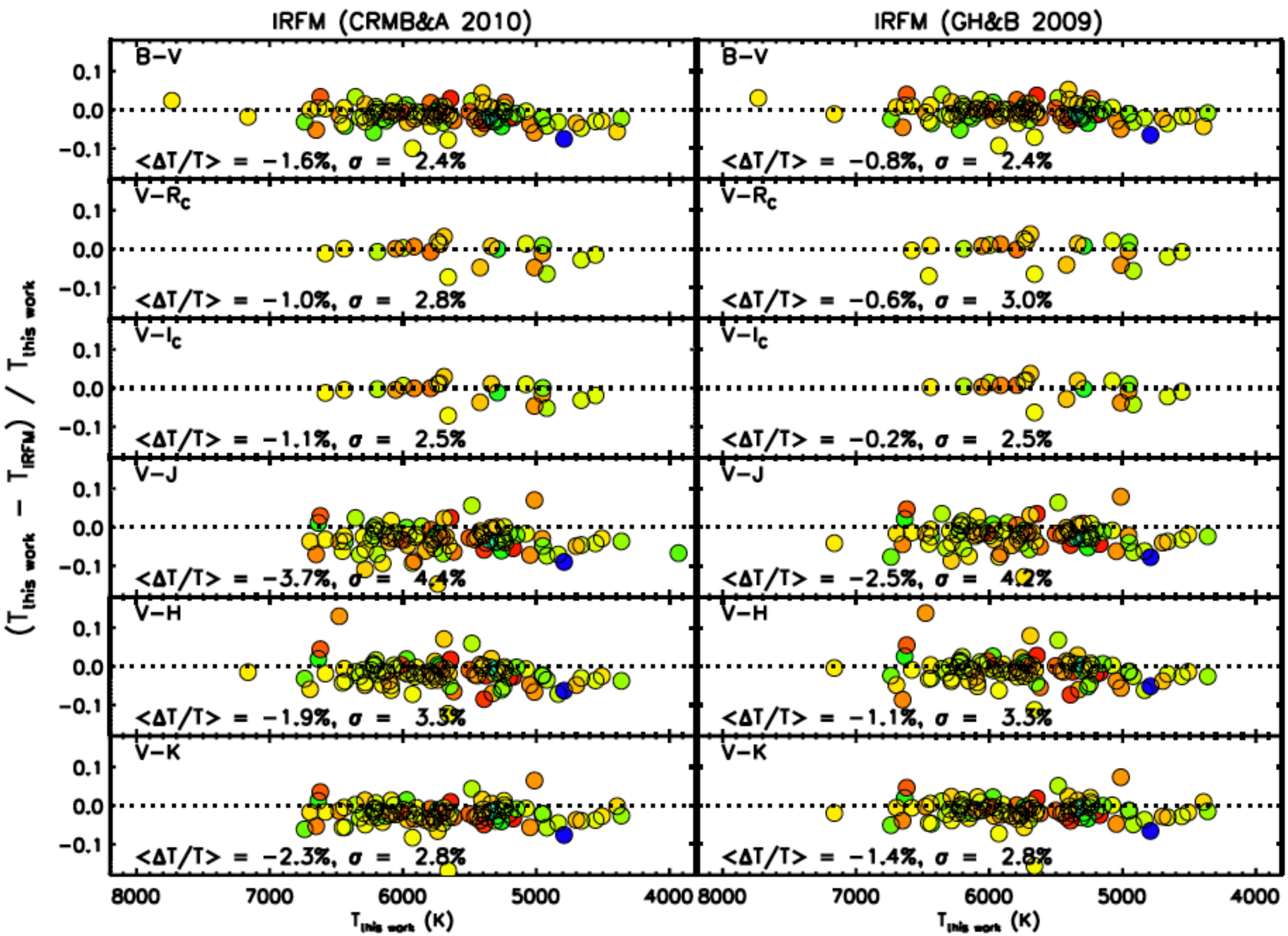
# Color –Teff relations: σT~2%

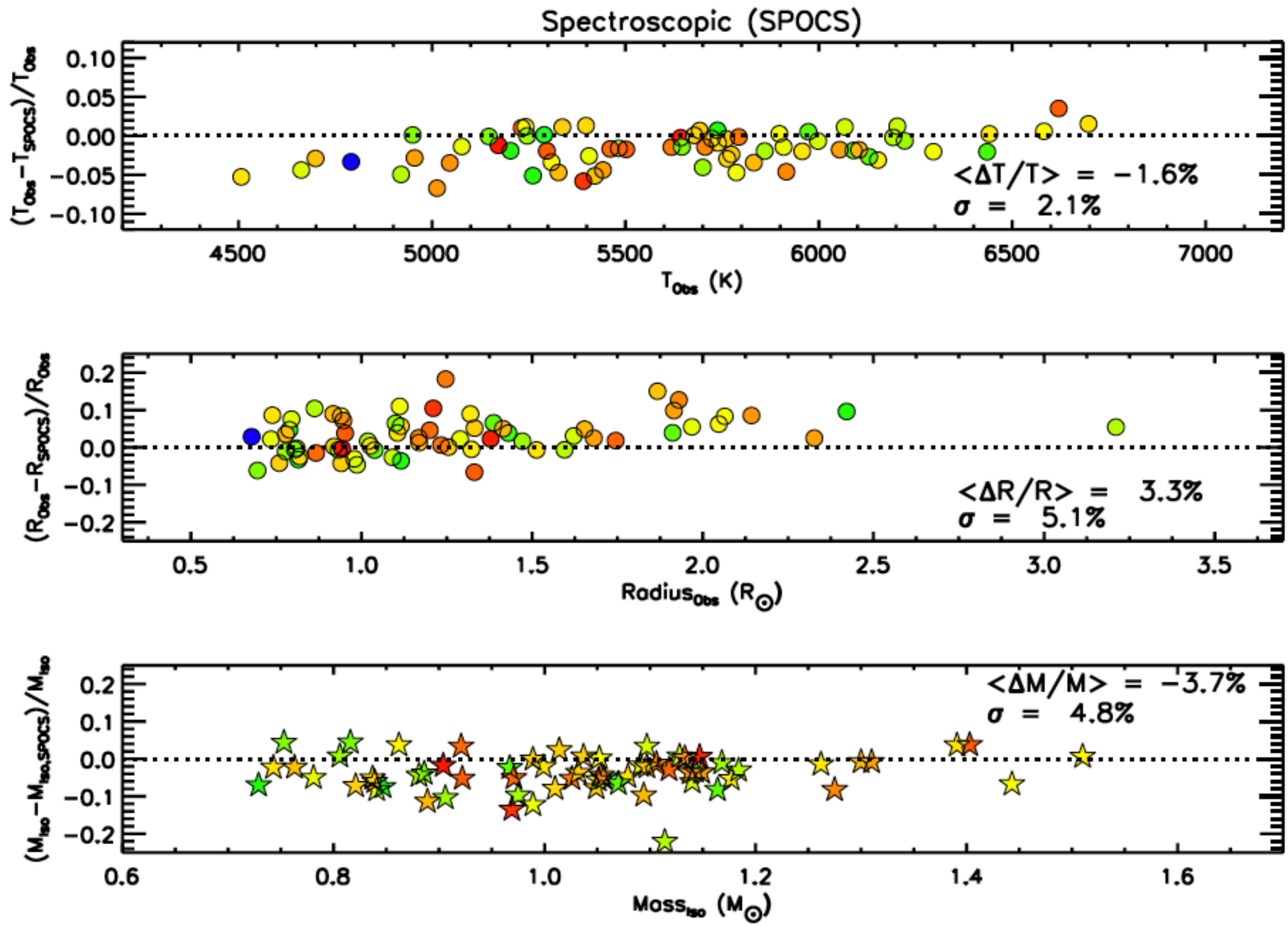


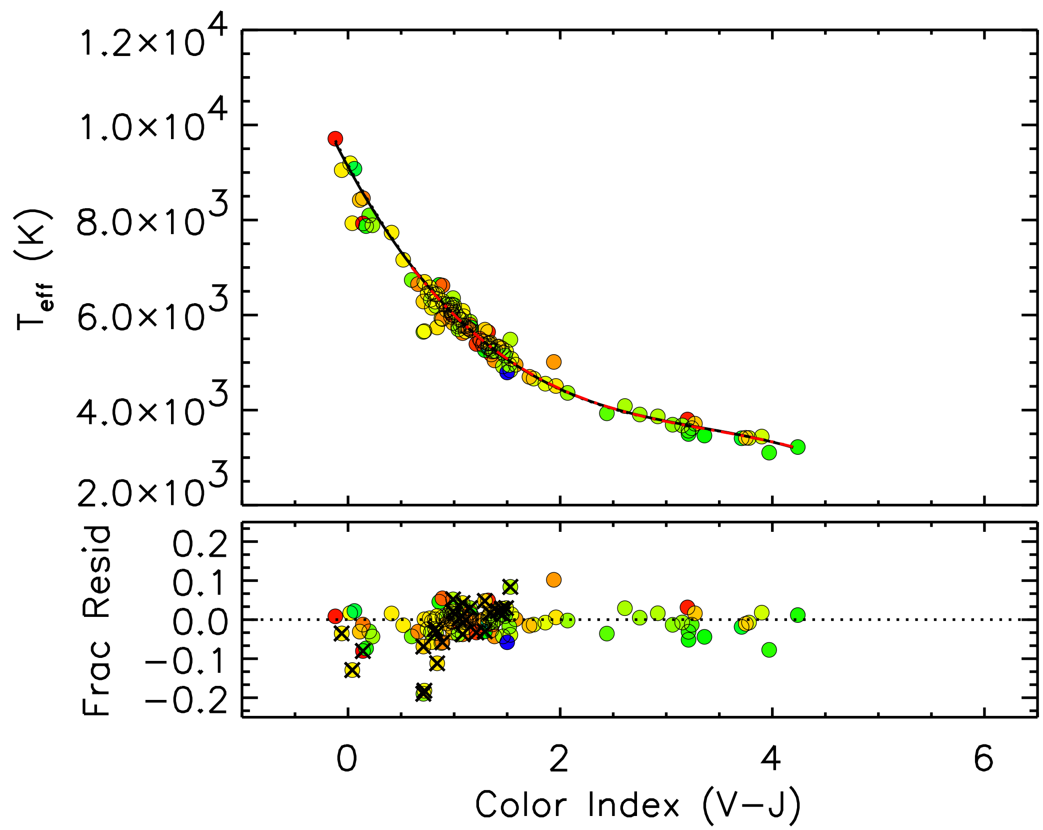

Boyajian et al. (2013; submitted)


IRFM (CRMB&A 2010)
IRFM (GH&B 2009)
B−V
V−Rc
V−Ic
V−J
V−H
V−K
<ΔT/T> = −1.6%, σ = 2.4%
<ΔT/T> = −0.8%, σ = 2.4%
<ΔT/T> = −1.0%, σ = 2.8%
<ΔT/T> = −0.6%, σ = 3.0%
<ΔT/T> = −1.1%, σ = 2.5%
<ΔT/T> = −0.2%, σ = 2.5%
<ΔT/T> = −3.7%, σ = 4.4%
<ΔT/T> = −2.5%, σ = 4.2%
<ΔT/T> = −1.9%, σ = 3.3%
<ΔT/T> = −1.1%, σ = 3.3%
<ΔT/T> = −2.3%, σ = 2.8%
<ΔT/T> = −1.4%, σ = 2.8%
(T_this work − T_IRFM) / T_this work
T_this work (K)
0.1
0.0
−0.1
8000
7000
6000
5000
4000


Spectroscopic (SPOCS)
(T_Obs−T_SPOCS)/T_Obs
0.10
0.05
0.00
−0.05
−0.10
4500
5000
5500
6000
6500
7000
T_Obs (K)
<ΔT/T> = −1.6%
σ = 2.1%
(R_Obs−R_SPOCS)/R_Obs
0.2
0.1
0.0
−0.1
−0.2
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Radius_Obs (R⊙)
<ΔR/R> = 3.3%
σ = 5.1%
(M_iso−M_iso,SPOCS)/M_iso
0.2
0.1
0.0
−0.1
−0.2
0.6
0.8
1.0
1.2
1.4
1.6
Mass_iso (M⊙)
<ΔM/M> = −3.7%
σ = 4.8%

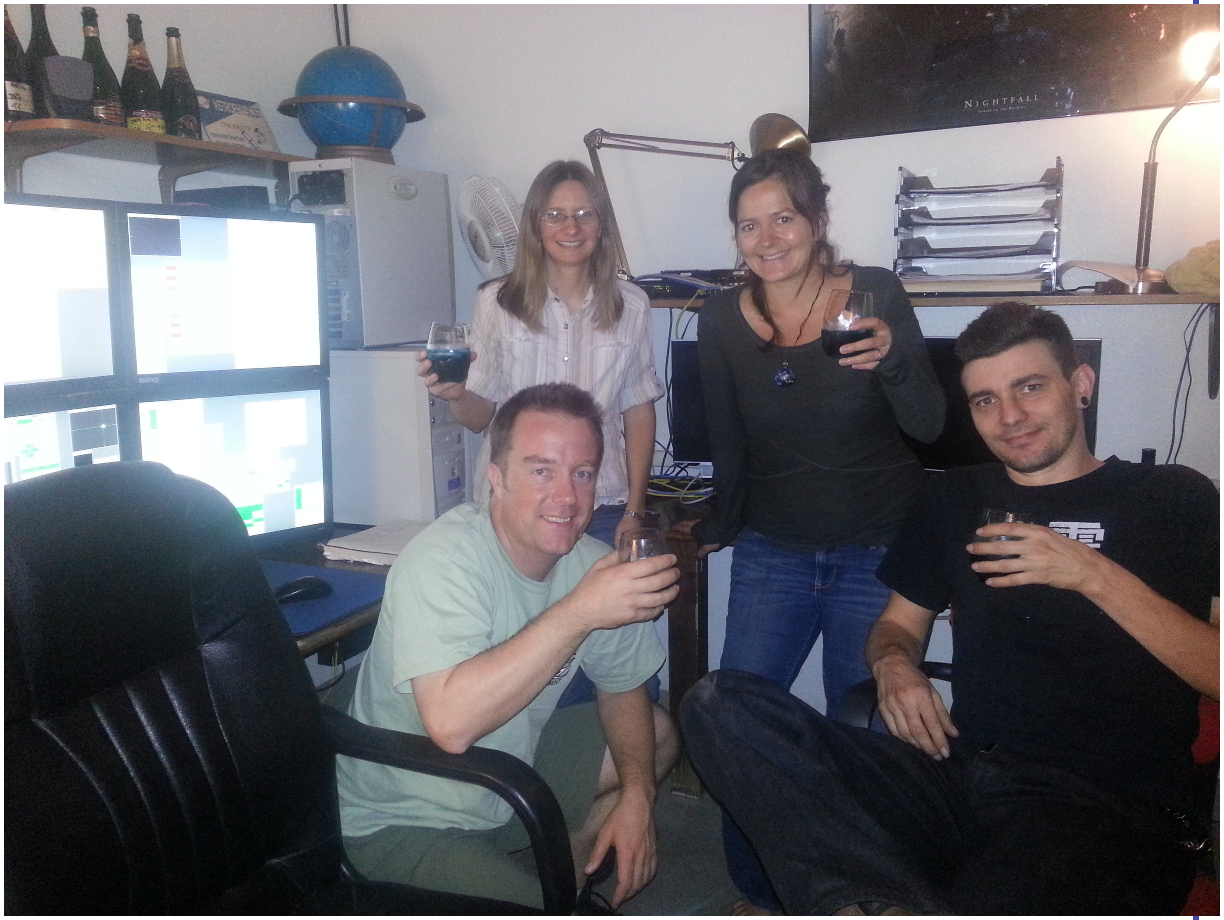
# Punch list: How to make things better

- Minimizing scatter in color relations
  - Get uniform measures of metallicity
    - Incorporate iterative method with spectroscopy, interferometry and model isochrones
  - Get better broad-band photometry of sample
  - Get spectrophotometry of sample
- Focus on broadening parameter space
  - Higher range in metallicity
  - Later-type stars
  - Presently known as well as perspective exoplanet host stars



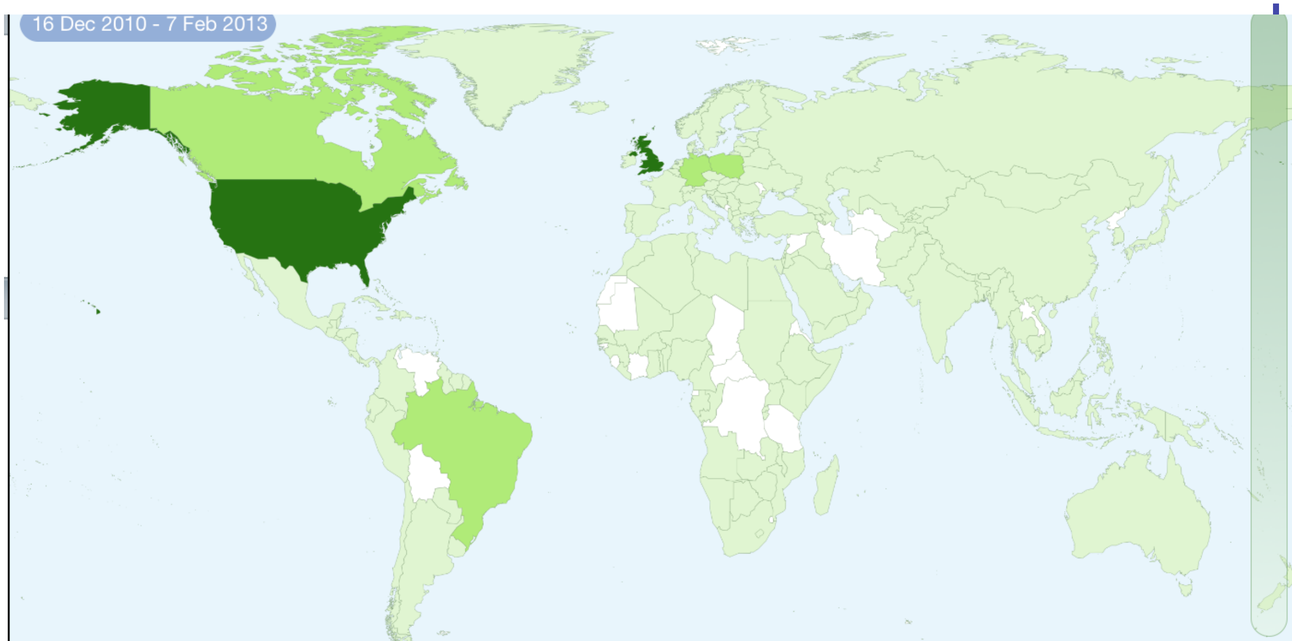
# Plug for current work

- I am funded by a winning NASA/ ADAP proposal
  - Planet Hunters: a citizen science group
  - M2K: Doppler searches for planets around nearby K-dwarfs
  - Eclipsing binaries: a bulk characterization



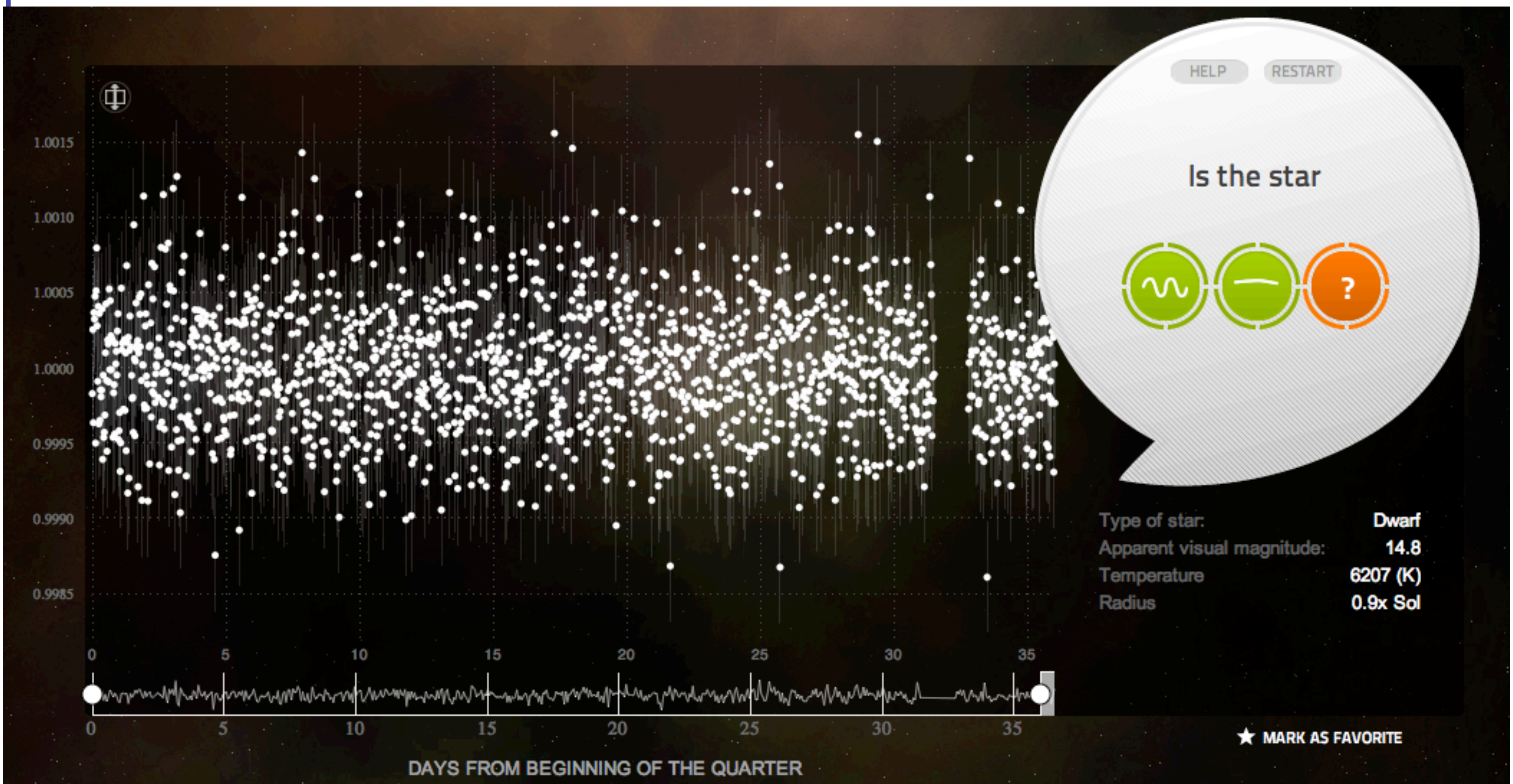
# Planethunters.org

Citizen science project in collaboration with Yale University (PI Debra Fischer) and Zooniverse Citizen Science Alliance (PI Chris Lintott)

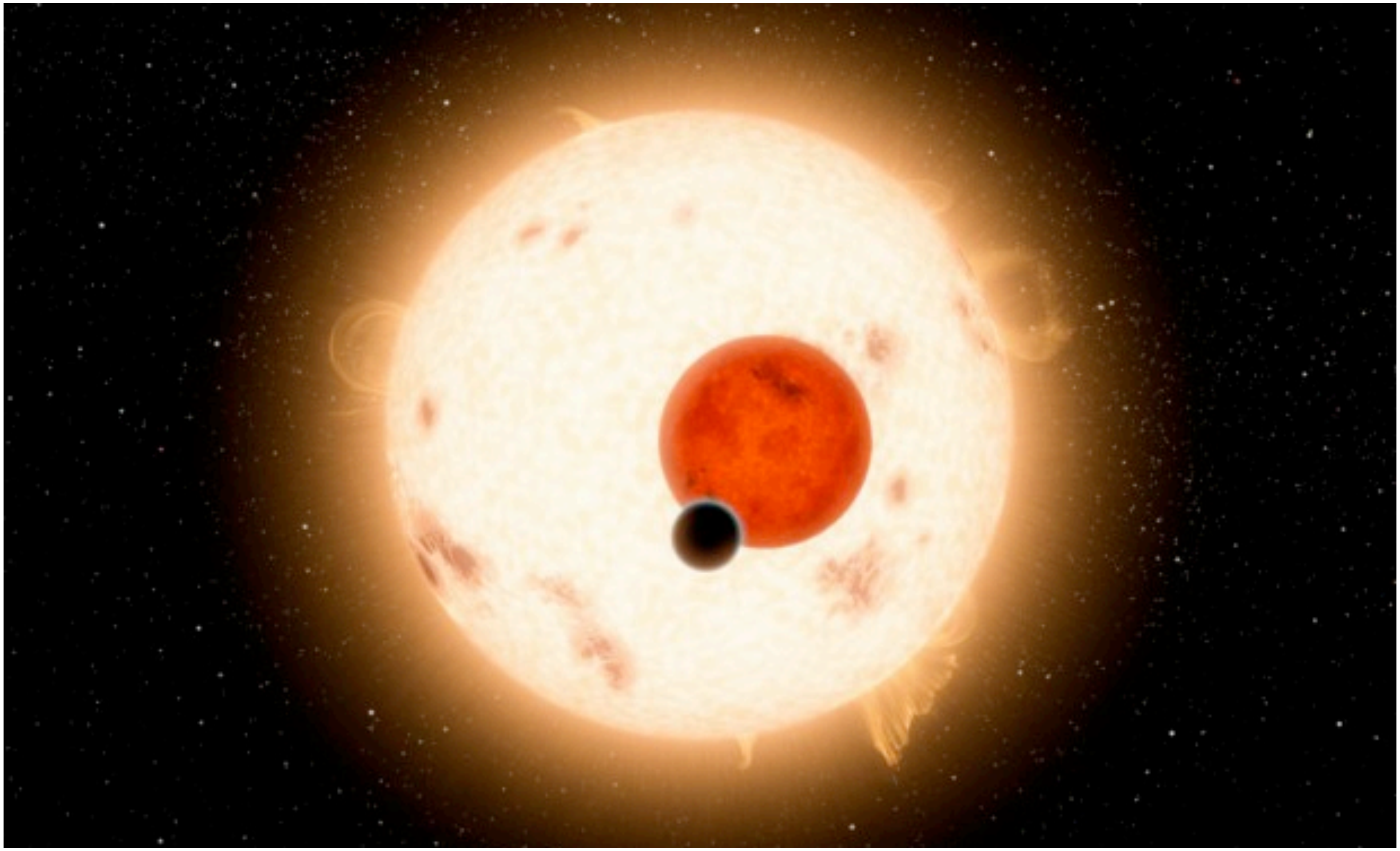



| Country | Visits | Pages | Time | Bounce |
|---|---|---|---|---|
| United States | 457713 | 13.0 | 10:49 | 40% |
| United Kingdom | 400200 | 14.7 | 11:41 | 36% |
| Poland | 55500 | 13.8 | 11:13 | 36% |
| Canada | 52758 | 12.6 | 9:33 | 36% |
| Germany | 52297 | 14.4 | 12:03 | 34% |
| Brazil | 46260 | 6.4 | 7:13 | 37% |
| France | 45200 | 13.9 | 12:44 | 33% |

# User interface



# Discoveries



***Artistic rendition of Tatooine (Doyle et al. 2011), posing in front of the two stars that it orbits. Image credit: NASA/JPL-Caltech/R. Hurt. Planet Hunters identified this system four months before the Kepler team announced it.***

# Discoveries: PH1-b; Schwamb et al.

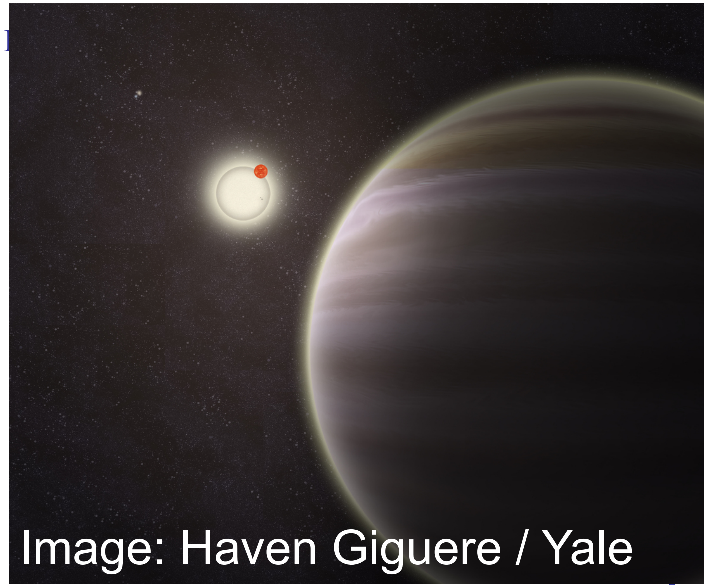
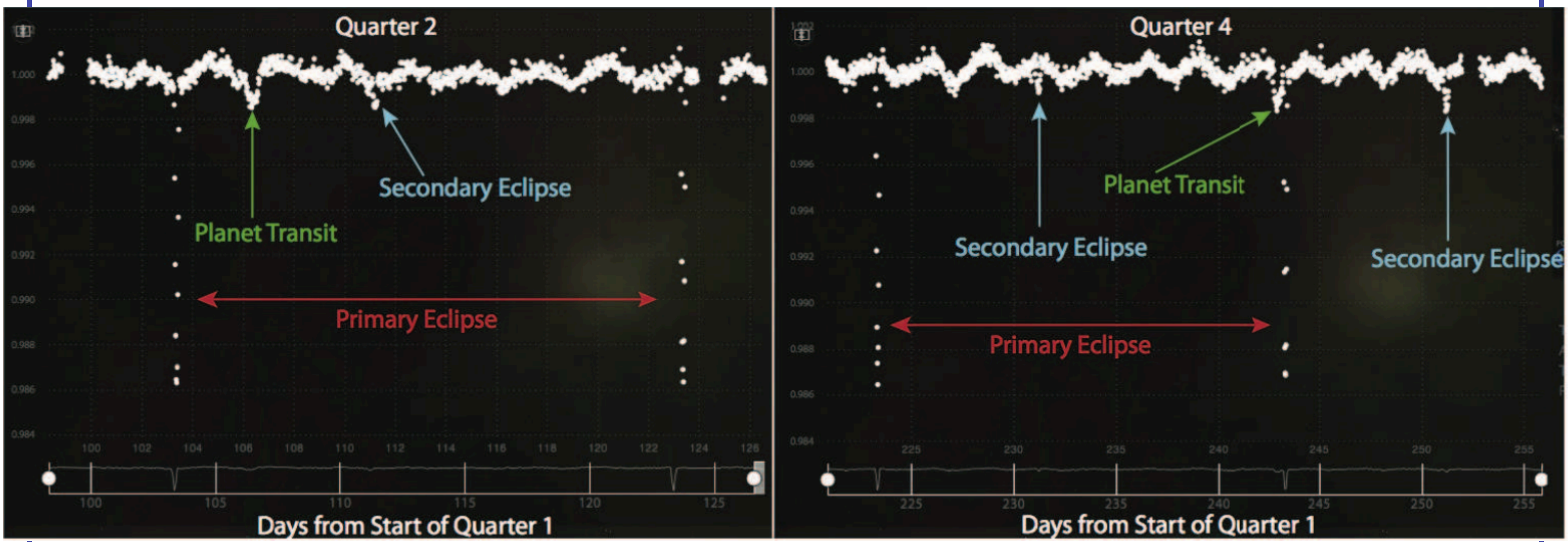
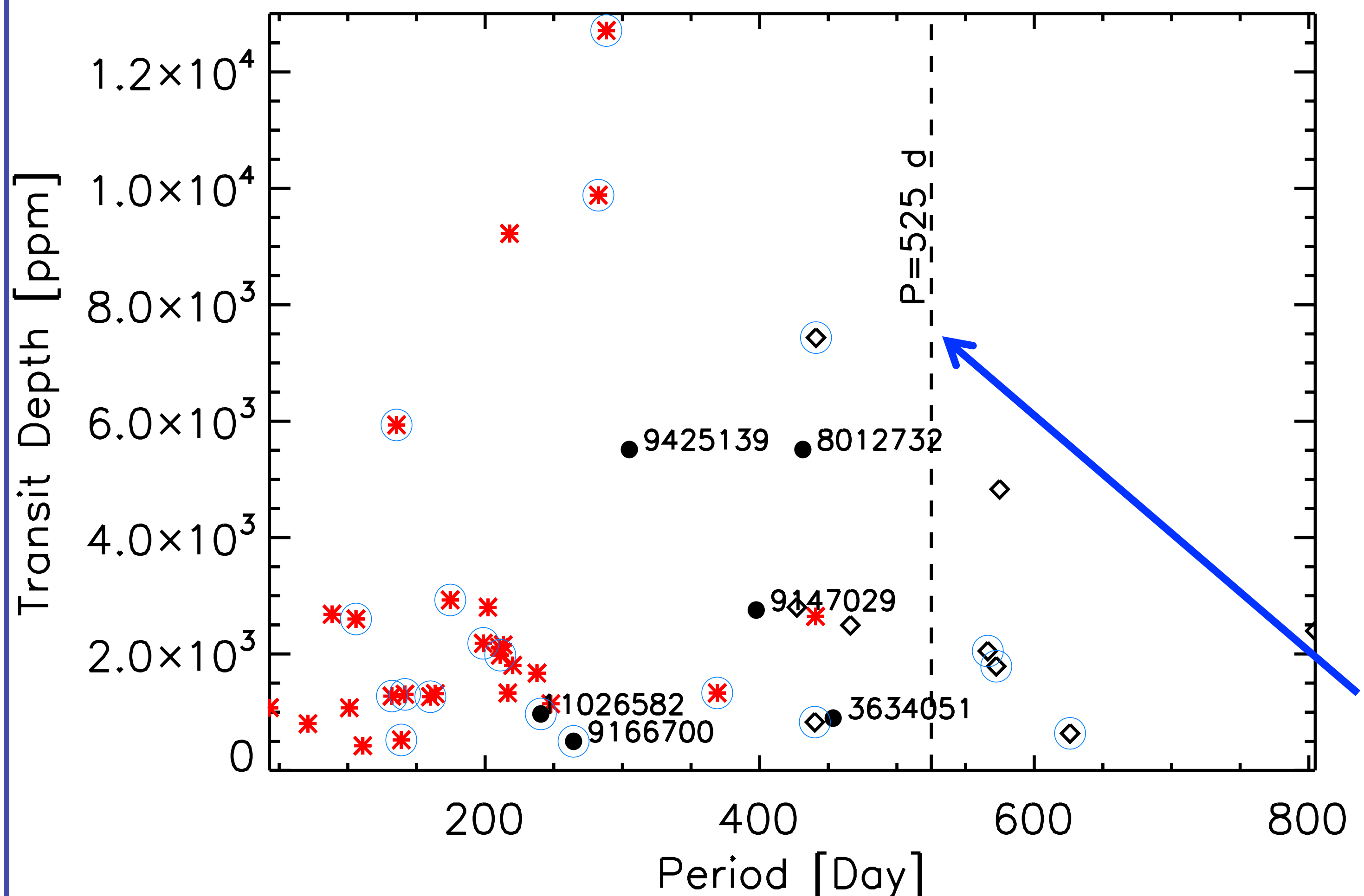


Image: Haven Giguere / Yale




Planetary transits in addition to binary-star eclipses identified by Planet Hunters volunteers in KIC 4862[illegible]5 as viewed in the Planet Hunters interface.

# Discoveries: Wang et al.

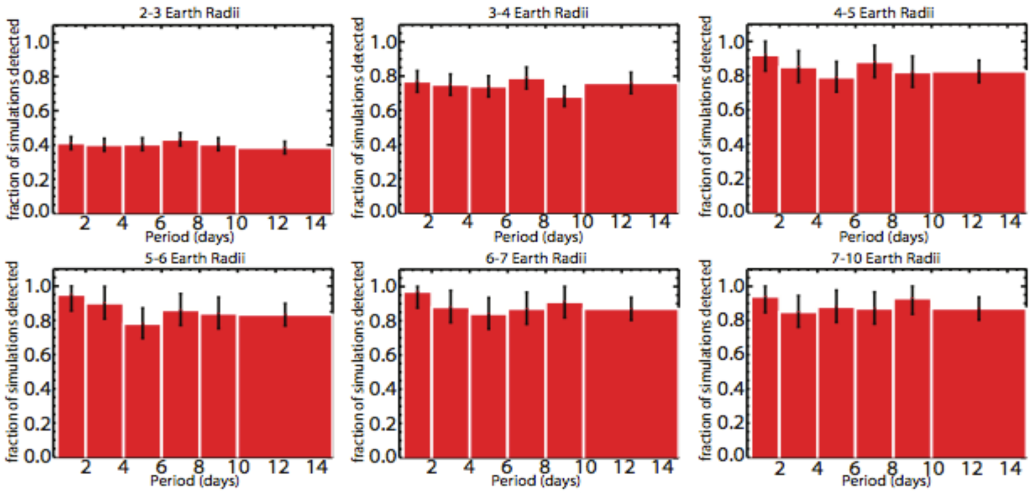



Nearly doubled the number of planet candidates with radii from 4 – 10 $R_{EARTH}$ residing at habitable zone distances

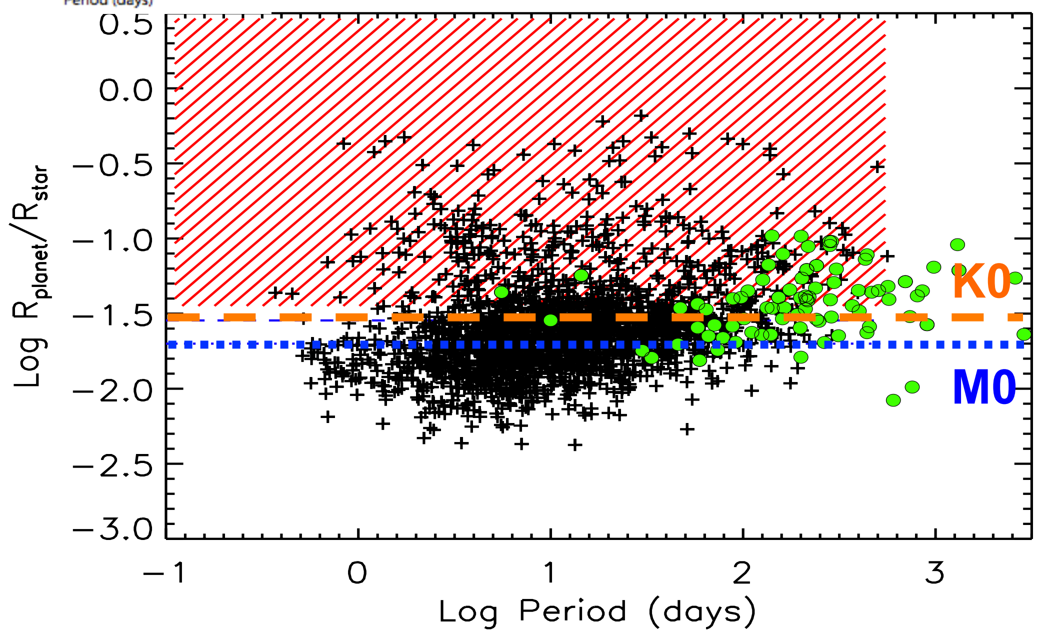
Imposed boundary of Kepler pipeline

*Transit depth and orbital period scatter plot for 43 planet candidates presented Wang et al. (2013). Red asterisks are candidates also included by the Kepler TCEs list (Tenenbaum et al. 2012). Black solid circles marked with KIC numbers are discoveries not included on the TCEs list but with at least 3 transits identified by Planet Hunter participants. Diamonds are long period candidates where only two transits were found by Planet Hunter volunteers. Planet candidates that appear to reside in the habitable zone are circled in blue.*

# Discoveries: Detection efficiency



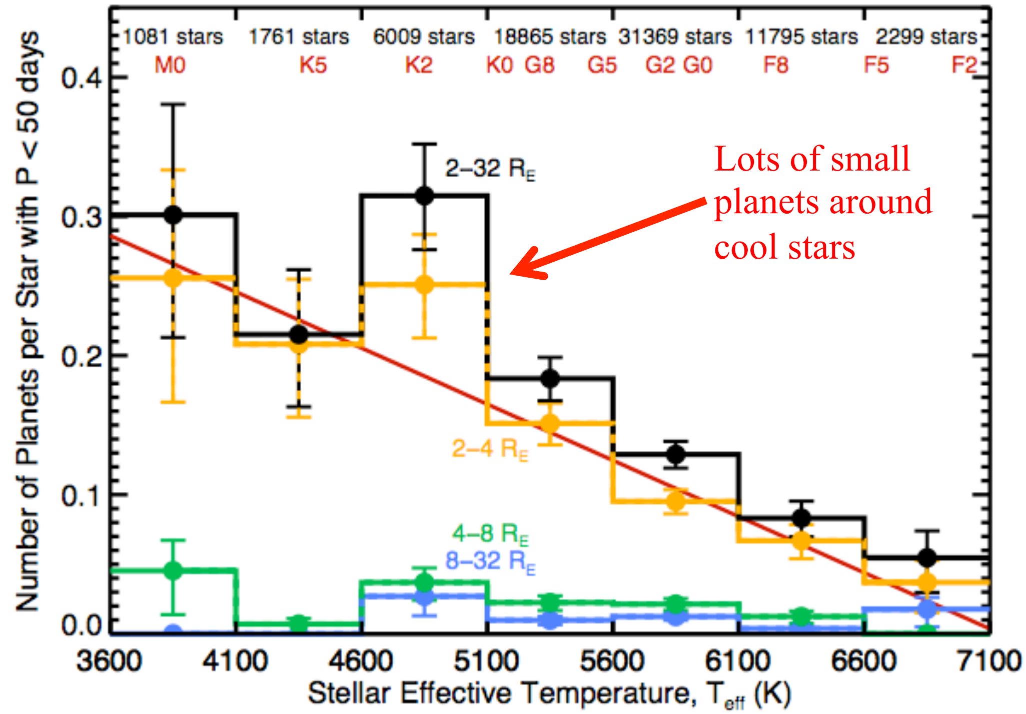

Analysis from Schwamb et al. statistics for Q1

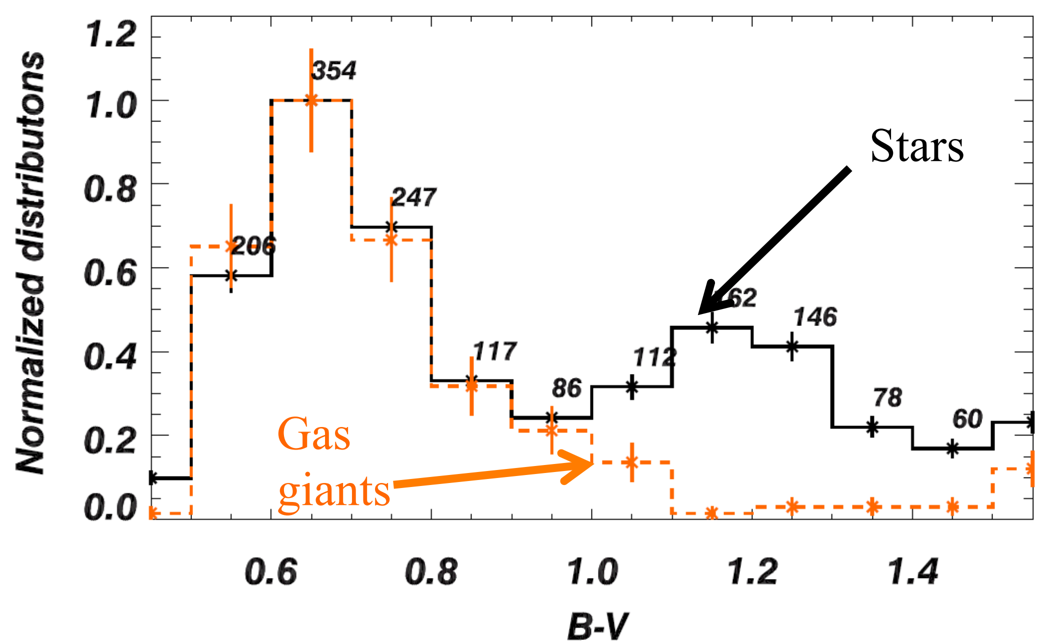



- Current PH candidates not identified as KOIs or TCEs by Kepler pipeline (**green**)
- KOIs (**black**)

# M2K

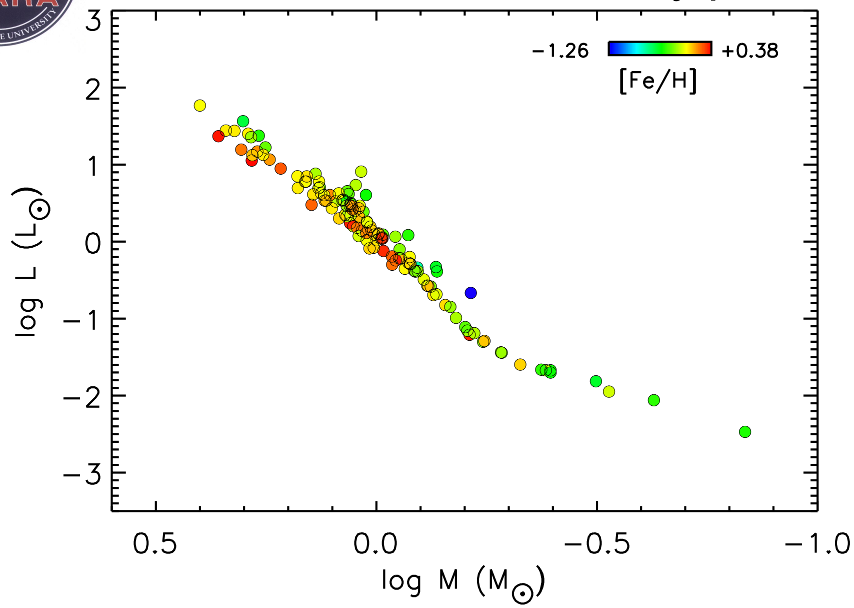
- Idealness of K-stars:
  - Lower mass = higher RV shifts
  - Lower luminosity = closer HZ
  - Stellar noise at minimum
  - Simpler spectral modeling (compared to Ms)
  - Smaller radii = larger signal for transiting systems
  - Low mass planets are common and members of multi-planet systems
- Systems are nearby, follow-up imaging, astrometry, interferometry is do-able (not a quality of any KOIs!)
- **Dramatic increase in fraction of planets around cooler, low-mass stars**

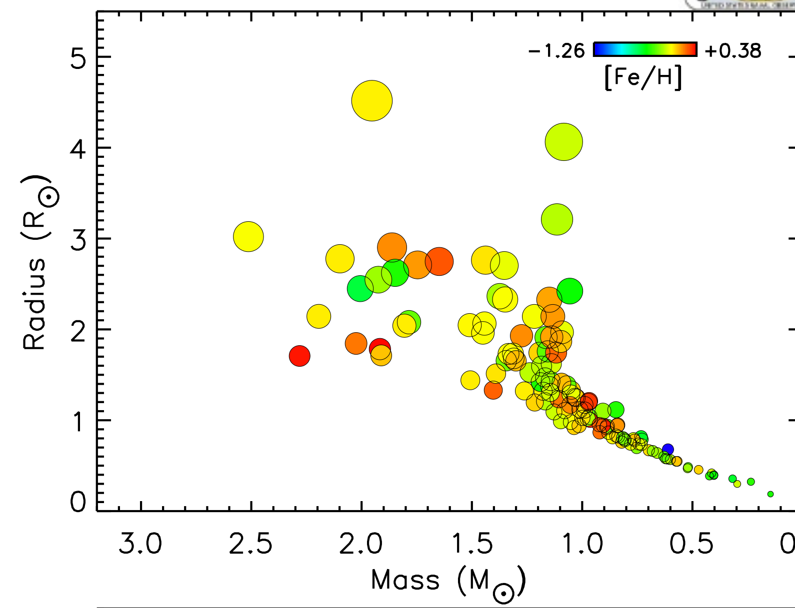


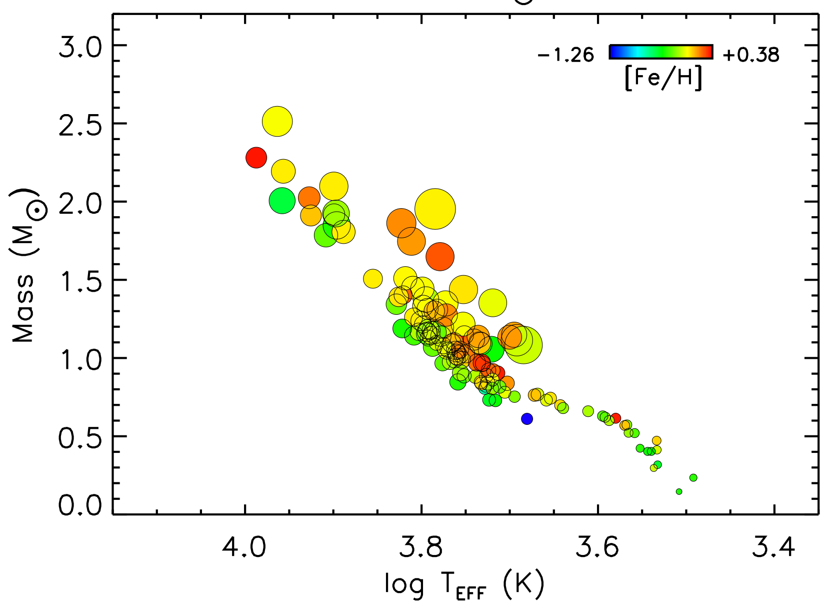



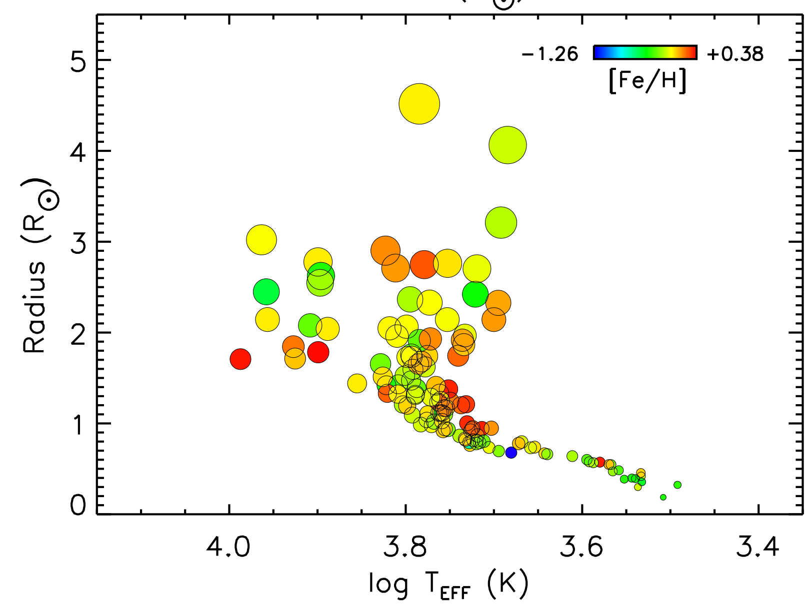

Howard et al. 2011 (top);
Fischer et al. 2011 (bottom)

# Pretty plots to enjoy. Questions?

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