# Diameters and Temperatures of Main Sequence Stars

Tabetha Boyajian (GSU / Hubble Fellow)

…and a whole lot of y'all

# Interest and motivation

- Fundamental properties of stars

  Radius: $f(\theta, \pi)$

  Temperature: $f(\theta, F_{BOL})$

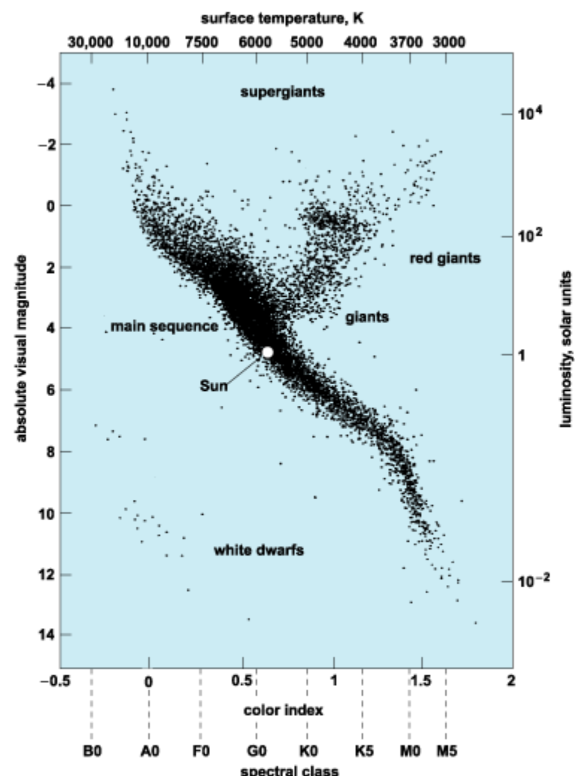
  Luminosity: $f(F_{BOL}, \pi)$

  Mass

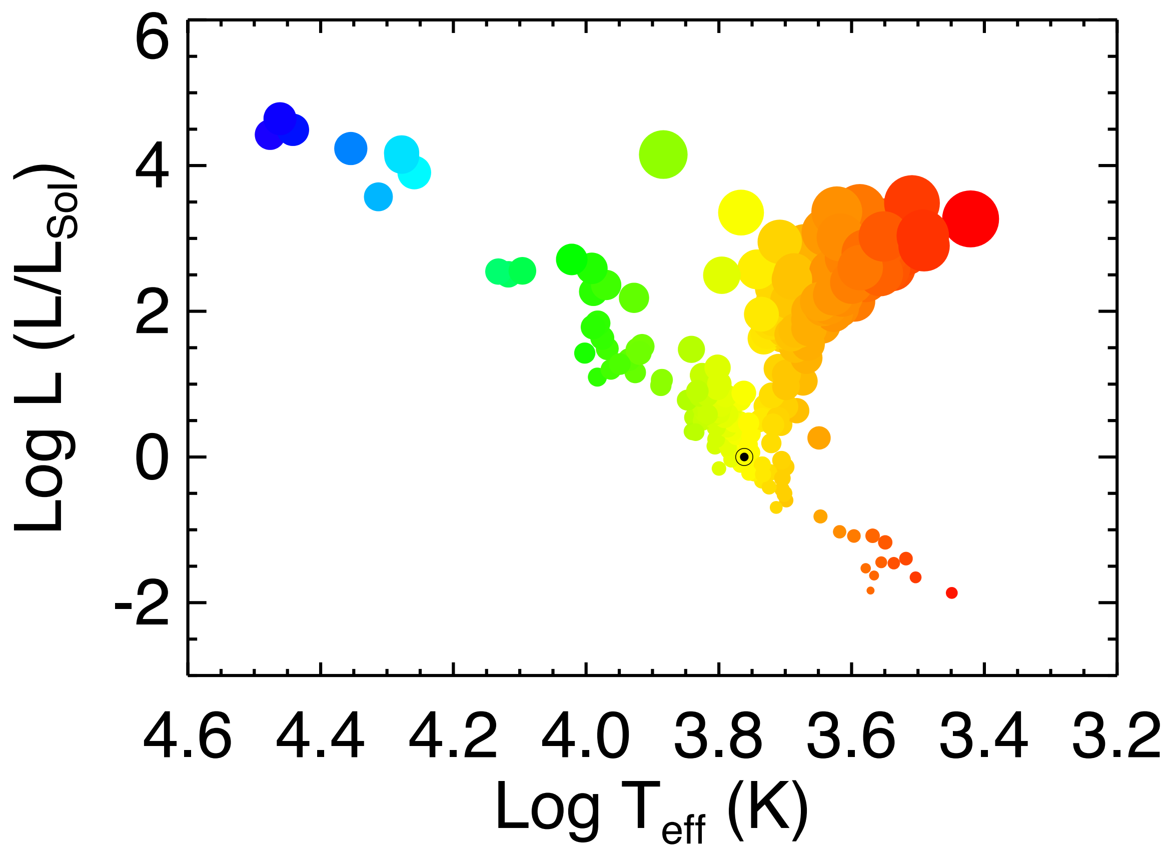
  Age

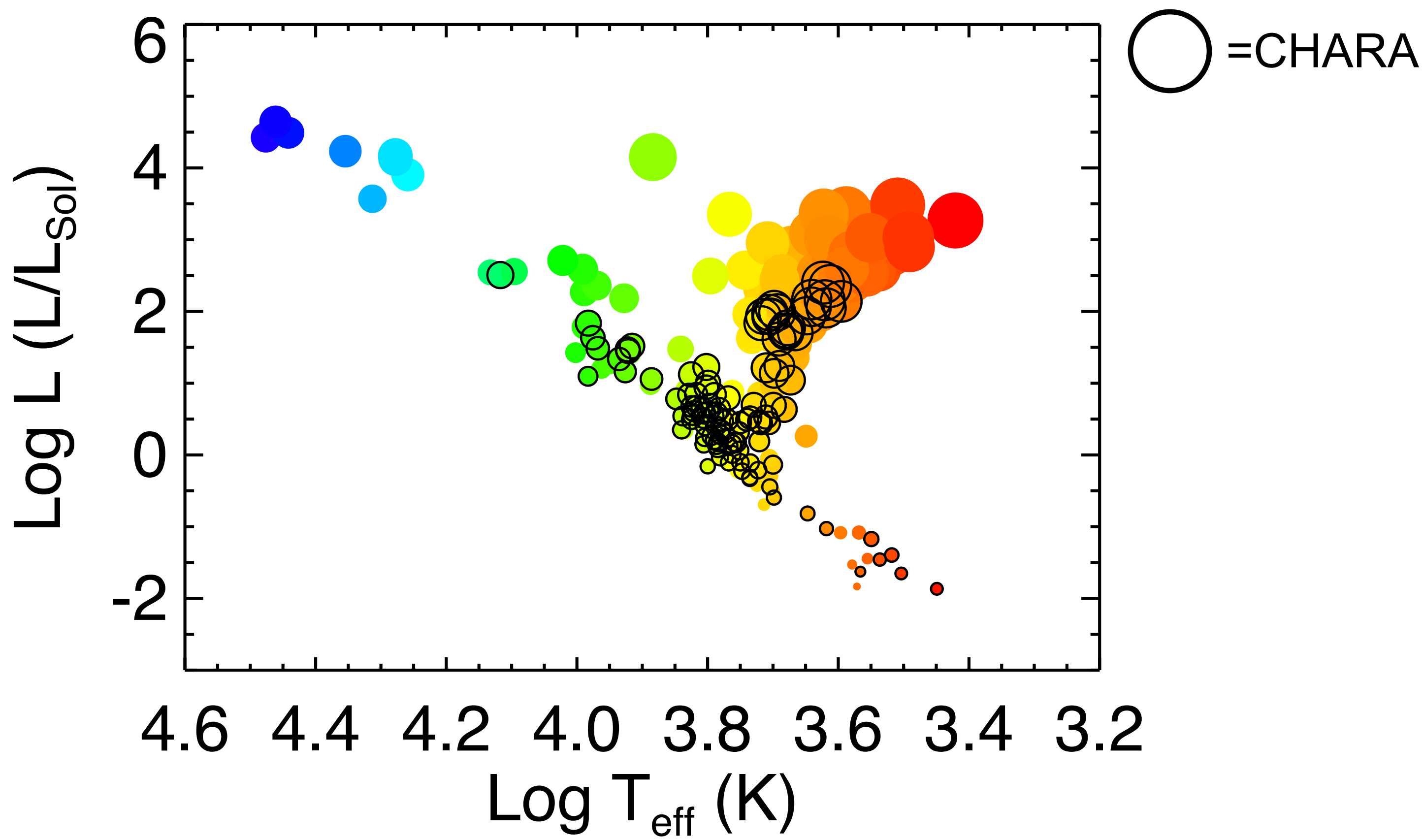
- A large, accurate, homogenous set of data
  - Building empirical calibrations/transformations
  - Test atmosphere/evolutionary models
- Exoplanet environments (see KvB talk)

θ = angular diameter
π = parallax
$F_{BOL}$ = bolometric flux



# The HRD



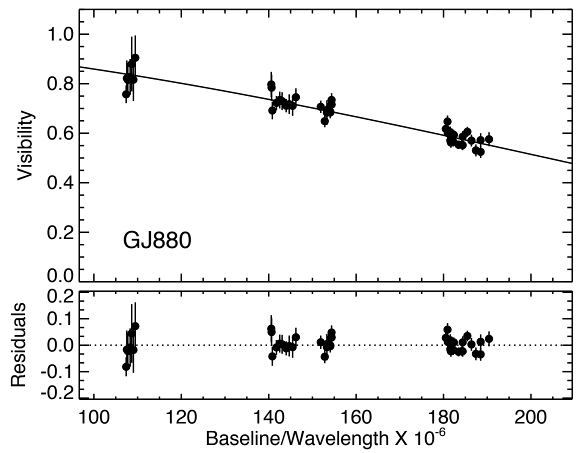

=CHARA
6
4
2
0
-2
Log L (L/L$_{Sol}$)
4.6 4.4 4.2 4.0 3.8 3.6 3.4 3.2
Log T$_{eff}$ (K)

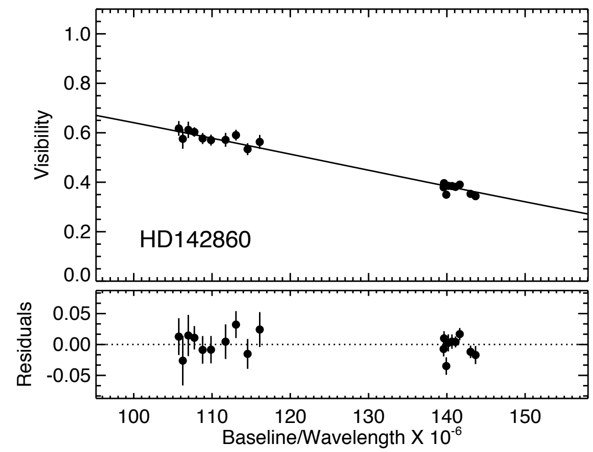
# Identifying the sample

- Choose a non-biased sample of normal, main sequence stars to observe
  - Limited to declination >-10 deg
  - Volume limited based on color index
- Qualities of these bright nearby stars are known very well??
  - Distances, photometry (right on, man)
  - Spectral typing, duplicity (so-so)
  - Composition/metallicity, (iffy… but best of all studied bc nearby and bright.) IR photometry (not so much ☹)

# Interferometric observations

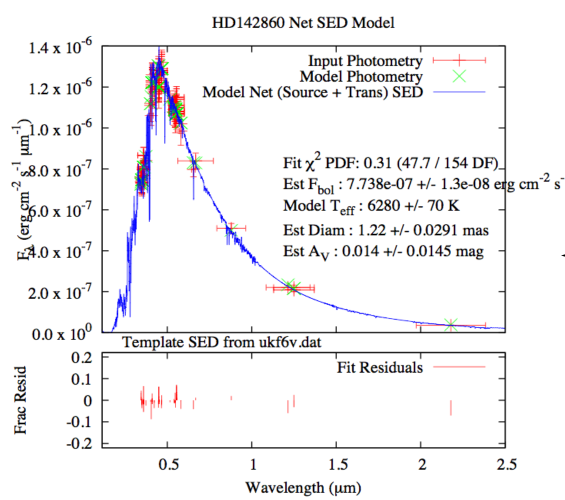
- Use multiple wavelengths, baselines and calibrators over several nights
- Fit calibrated visibilities to get ***angular diameter***




# Spectral Energy Distribution (SED) fits

- Collect flux calibrated photometry from literature and fit to spectral template to get ***bolometric flux*** and reddening





Georgia State University · NSF · NOAO · l'Observatoire de Paris · LESIA · The University of Michigan 1817 · NExScI NASA Exoplanet Science Institute · SUSI Sydney University Stellar Interferometer Australia · Observatoire de la Côte d'Azur

# Status

- How many we have measured in each category?
  - 9 A stars
  - 25 F stars
  - 18 G stars
  - 9 K stars
  - 14 M stars

  **= 75, and counting…**
- How good are the measurements?
  - This data has an average δθ (or δR)~1.5-2% -> δT~1%
  - In the IR, can resolve star of ~0.45 mas to ~4% error
- What is the efficiency of the observing program(s)? I.e., are getting really good at it, but will we ever run out of targets?)

# Ours versus theirs

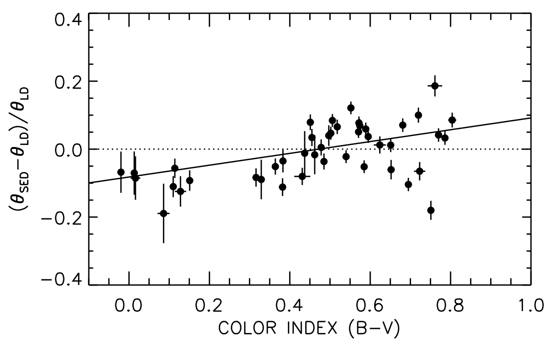
Table 3:: Comparison of Angular Diameters

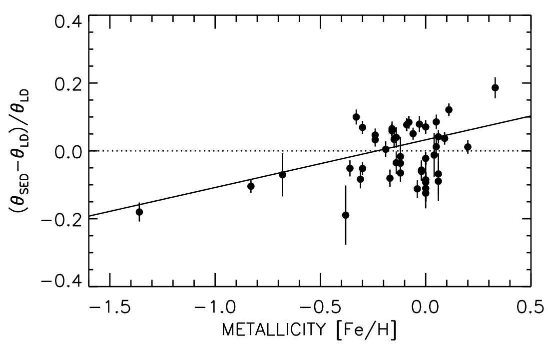
| Star Name | $\theta_{LD} \pm \sigma$ (mas) | Reference | Insturment | Spectral Type | $\Delta\theta_{LD}/\sigma_C^{\dagger}$ |
|---|---|---|---|---|---|
| GJ 15A | 0.998 ± 0.007 | This work | CHARA | M1.5 V | 0.0 |
| | 0.988 ± 0.016 | Berger et al. (2006) | CHARA* | | 0.6 |
| | 1.027 ± 0.059 | van Belle & von Braun (2009) | PTI | | −0.5 |
| GJ 33 | 0.858 ± 0.005 | This work | CHARA | K2 V | 0.0 |
| | 0.933 ± 0.064 | van Belle & von Braun (2009) | PTI | | −1.2 |
| GJ 105 | 1.011 ± 0.009 | This work | CHARA | K3 V | 0.0 |
| | 0.936 ± 0.070 | Lane et al. (2001) | PTI | | 1.1 |
| GJ 166A | 1.483 ± 0.006 | This work | CHARA | K1 Ve | 0.0 |
| | 1.437 ± 0.039 | Demory et al. (2009) | VLTI | | 1.2 |
| GJ 380 | 1.198 ± 0.008 | This work | CHARA | K7.0 V | 0.0 |
| | 1.155 ± 0.040$^{\dagger\dagger}$ | Lane et al. (2001) | PTI | | 1.1 |
| | 1.238 ± 0.053 | van Belle & von Braun (2009) | PTI | | −0.7 |
| GJ 411 | 1.405 ± 0.013 | This work | CHARA | M2.0 V | 0.0 |
| | 1.436 ± 0.030 | Lane et al. (2001) | PTI | | −0.9 |
| | 1.439 ± 0.048 | van Belle & von Braun (2009) | PTI | | −0.7 |
| GJ 526 | 0.829 ± 0.014 | This work | CHARA | M1.5 V | 0.0 |
| | 0.845 ± 0.057 | Berger et al. (2006) | CHARA | | −0.3 |
| GJ 614 | 0.458 ± 0.018 | This work | CHARA | K0 | 0.0 |
| | 0.371 ± 0.044 | Baines et al. (2008) | CHARA | | 1.8 |
| GJ 631 | 0.717 ± 0.011 | This work | CHARA | K0 V | 0.0 |
| | 0.888 ± 0.066 | van Belle & von Braun (2009) | PTI | | −2.6 |
| GJ 699 | 0.954 ± 0.005 | This work | CHARA | M4.0 V | 0.0 |
| | 1.004 ± 0.040 | Lane et al. (2001) | PTI | | −1.2 |
| GJ 880 | 0.726 ± 0.005 | This work | CHARA | M1.5 V | 0.0 |
| | 0.934 ± 0.059 | Berger et al. (2006) | CHARA | | −3.5 |

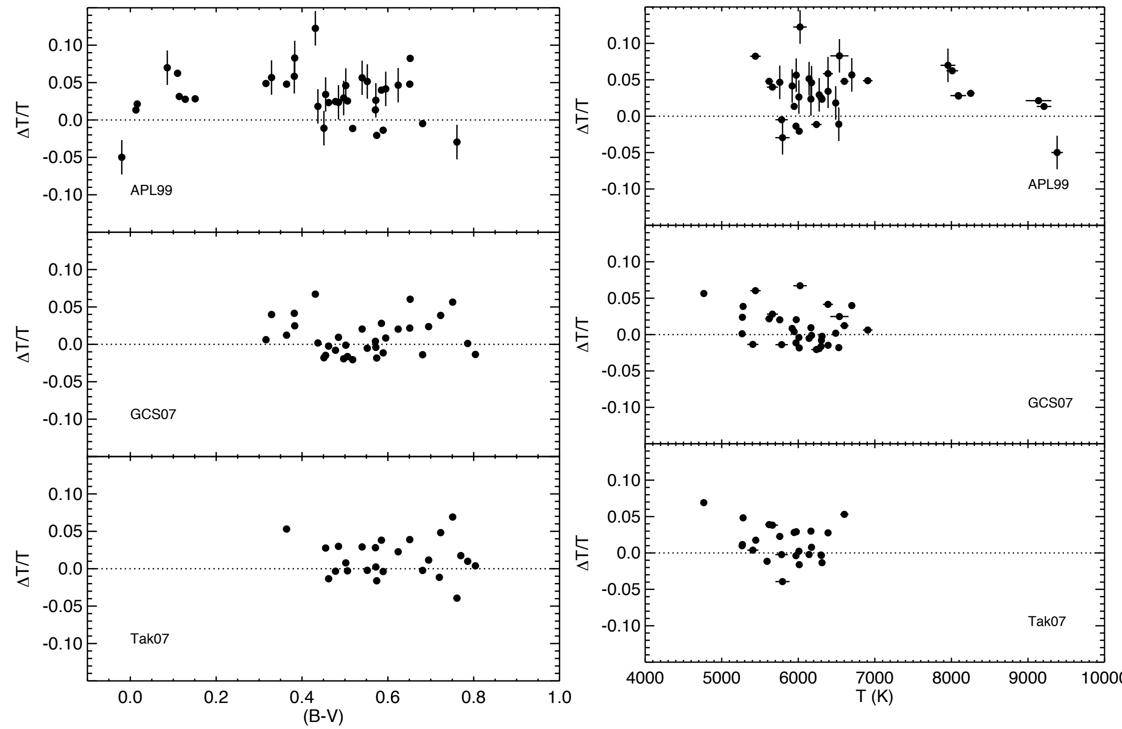
CHARA* = CHARA/FLUOR
All other CHARA = Classic

Boyajian et al., in prep.

# Ours versus non-direct approaches
# Solar-type stars




No obvious correlation between predicted diameter and metallicity or color index.

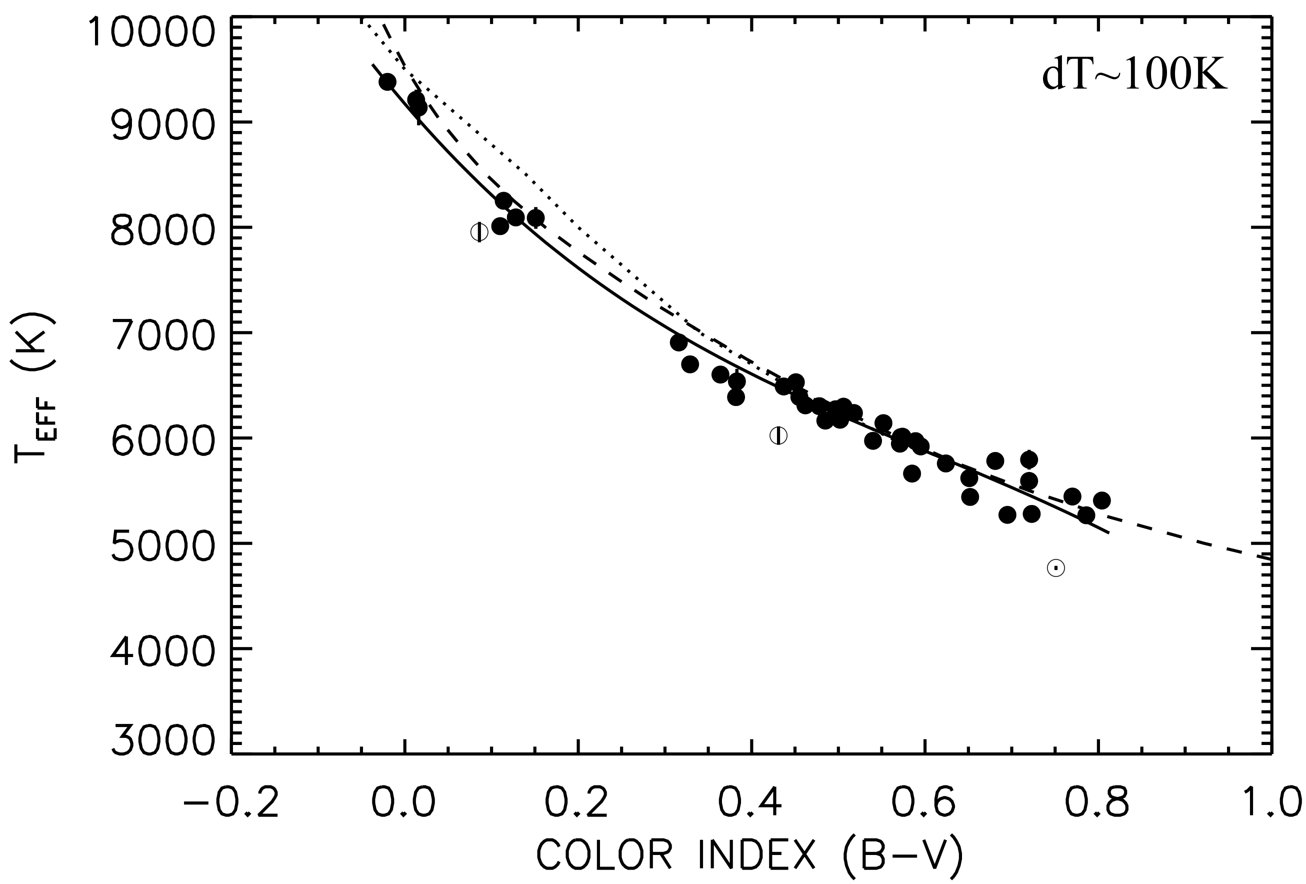
Also seen when comparing these values to semi-empirical ones from the literature.

*APL99 = Allende Prieto & Lambert 1999; GCS07 = Holmberg et al. 2007, Tak07 = Takeda 2007*

Boyajian et al., in prep.

# Empirical relations:

## Solar-type stars



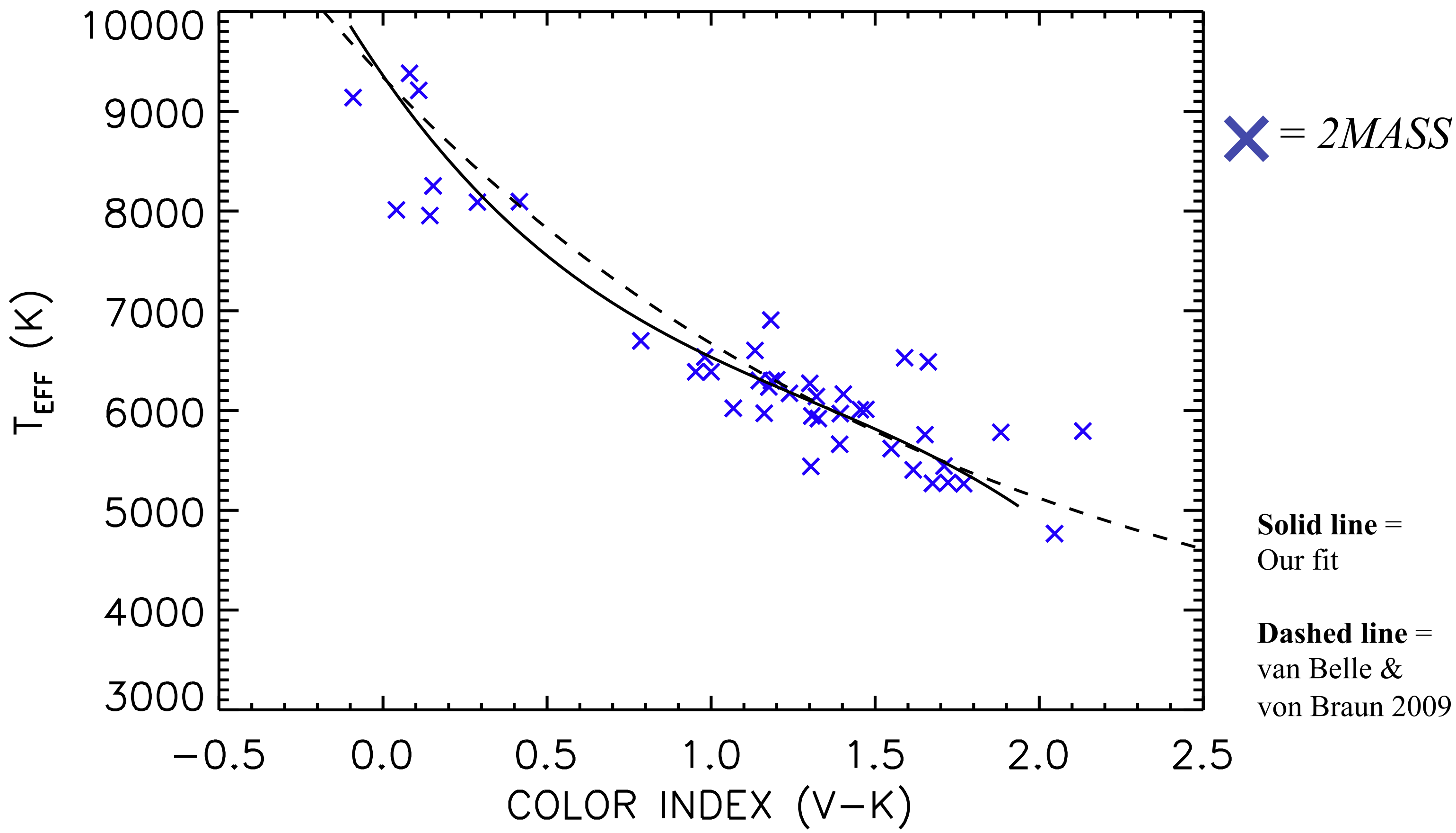

**Solid line** =
Our fit

**Dashed line** =
Lejeune 1998

**Dotted line** =
Code et al. 1976

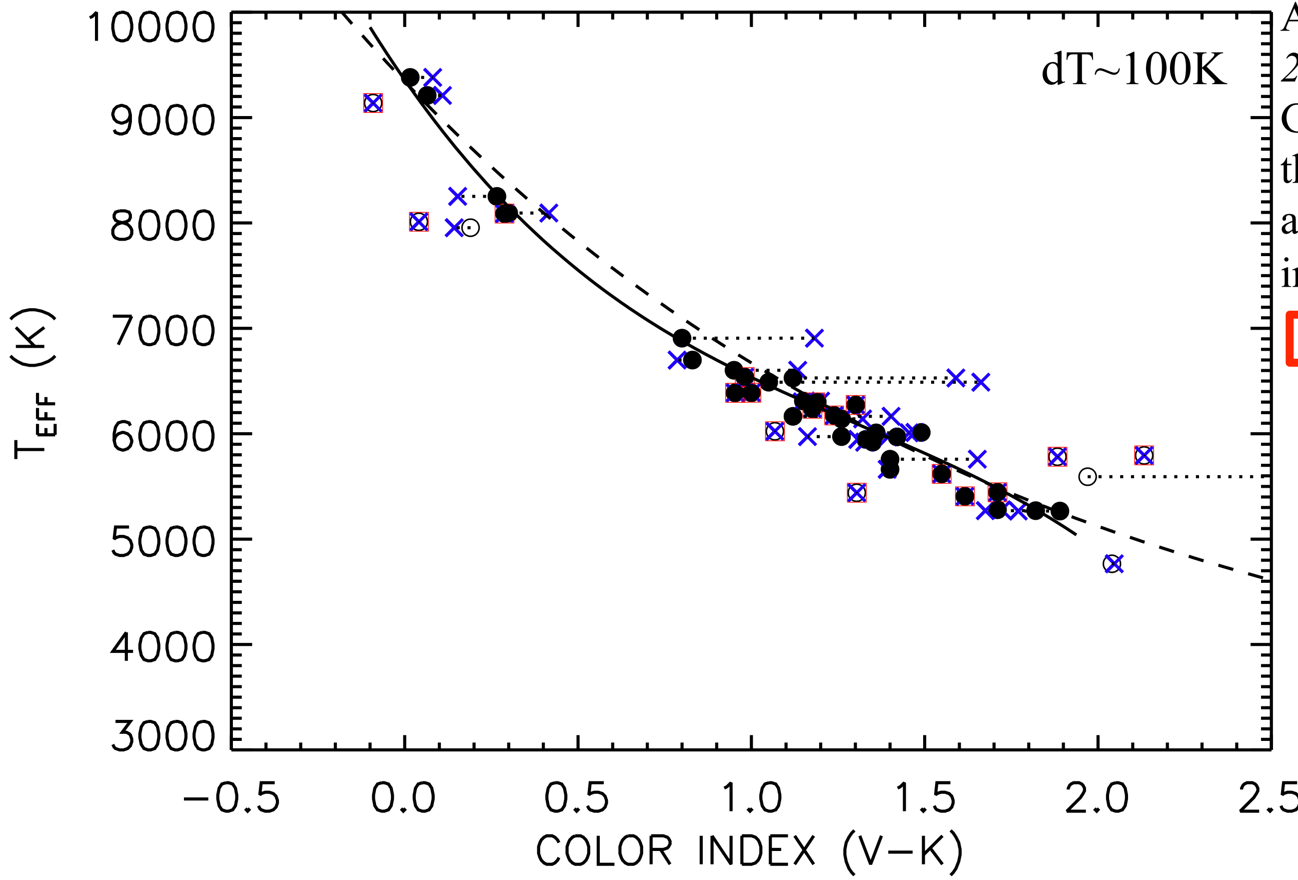
# Empirical relations:

## Solar-type stars



# Empirical relations:

## Solar-type stars




A ▪▪▪▪▪ connects *2MASS* ✕ to GCPD* values that are used ●, and not used ○, in the final fit.

□ = No GCPD entry

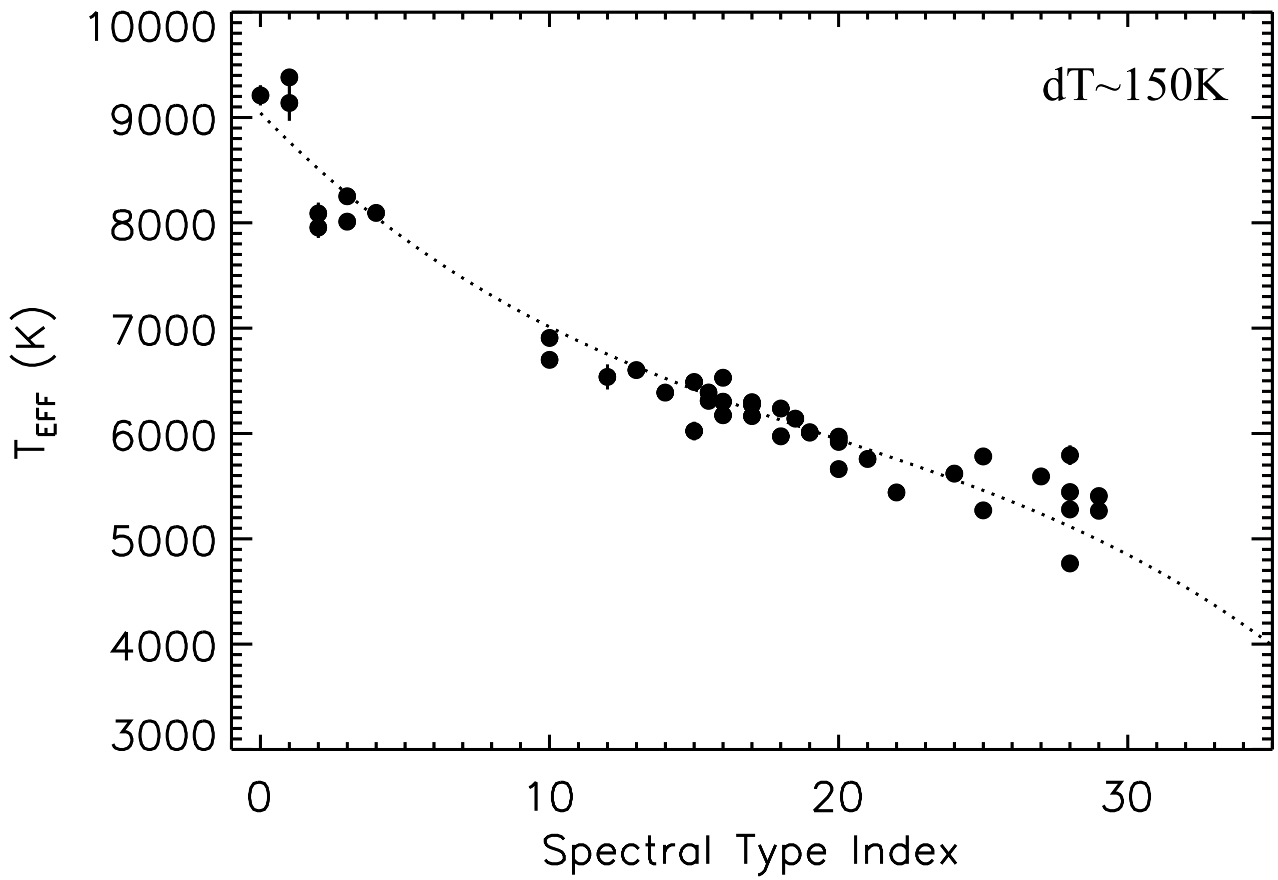
**Solid line** = Our fit

**Dashed line** = Van Belle & von Braun 2009

*GCPD: The General Catalogue of Photometric Data, Mermilliod, Mermilliod & Hauck 1997, A&AS, 124, 349

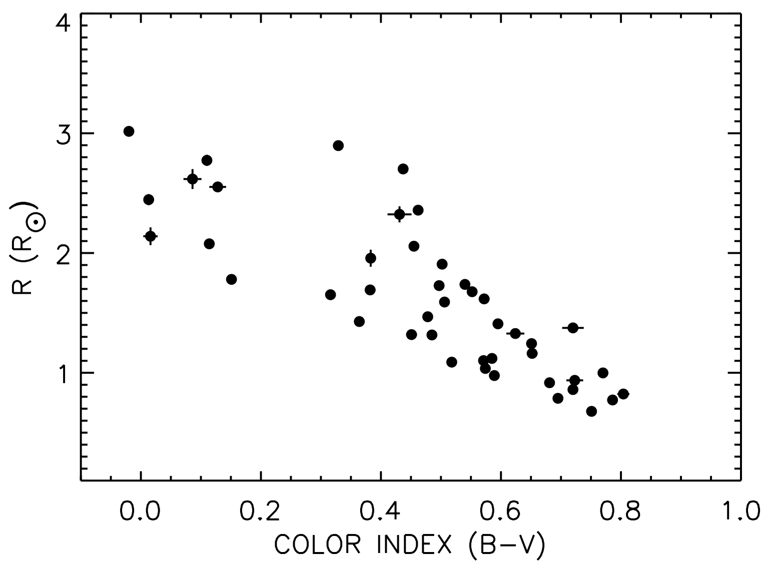
# Empirical relations:

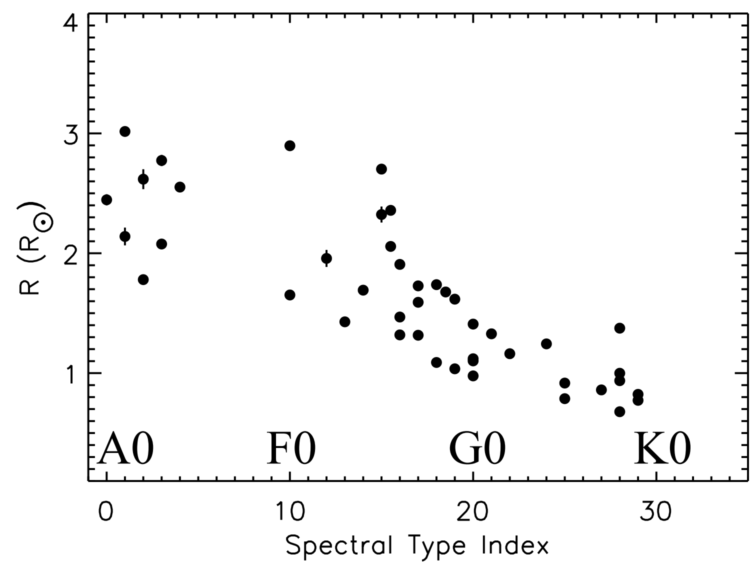
## Solar-type stars



# Empirical relations:

## Solar-type stars



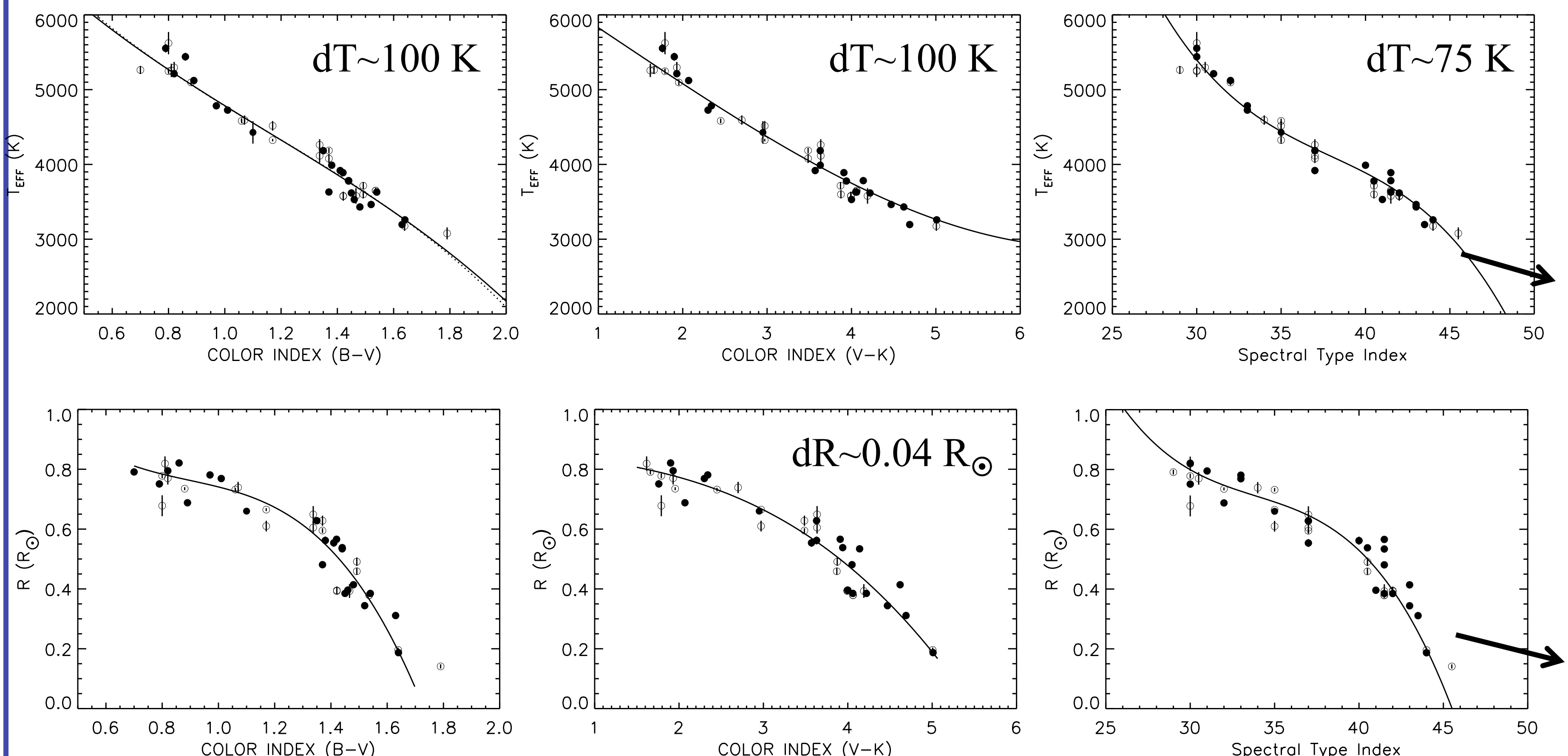




dR~0.25 $R_\odot$. Not useful, mainly due to evolution within main sequence.

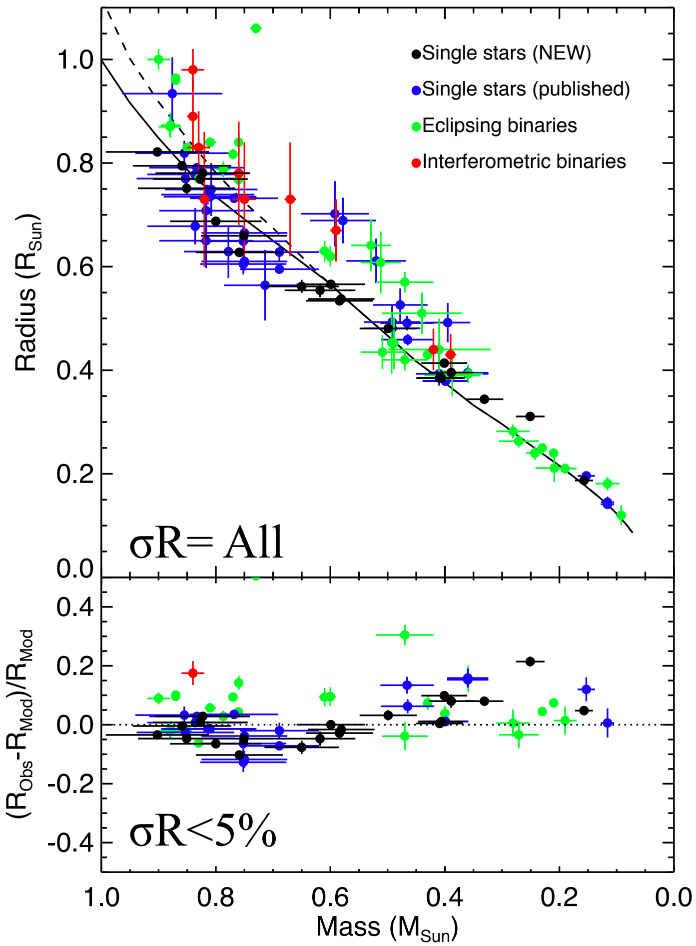
# Empirical relations:

## KM dwarfs

Filled = new; Open = published



# Theory versus observation




- Theory predicts the radius of M-dwarf to be smaller by ~10-15% of what we observe for both single and binary stars.

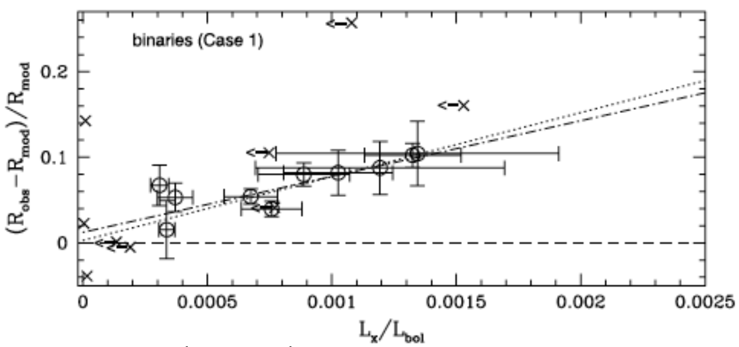
LEGEND

- Masses for single stars are derived from the K-band mass-luminosity relationship from Delfosse et al. 2000, and assume a 10% error.
- (TOP) The solid black line is a 5 Gyr isochrone from the BCAH98 models (Baraffe et al. 1998) for $L_{mix}=H_p$. In the K-star regime, the dashed lines are $L_{mix}= 1.9\ H_p$ and solid line $L_{mix}= H_p$ .
- (BOTTOM) dotted line signifies zero deviation between observation and model.

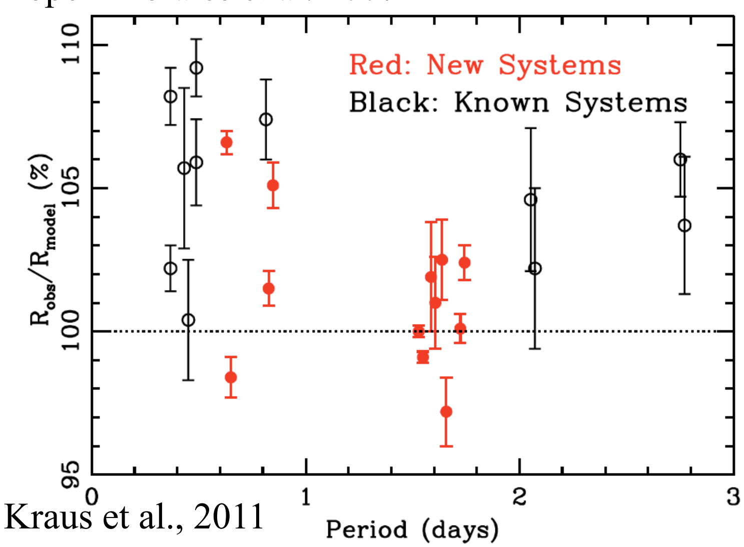
# Resistance to an easy solution?

## Binary Stars

Actvity ($L_X/L_{BOL}$) & Rotation



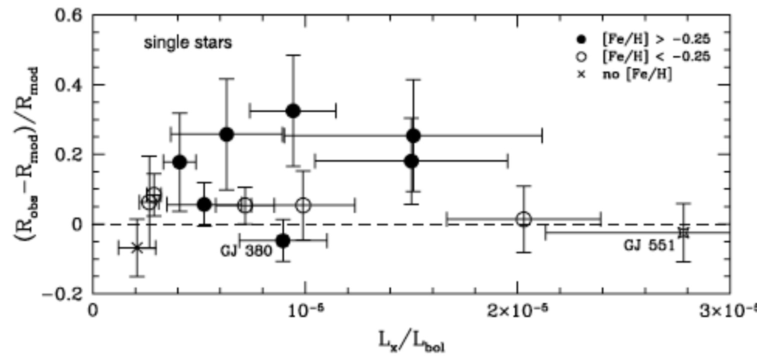

Lopez-Morales et al. 2007



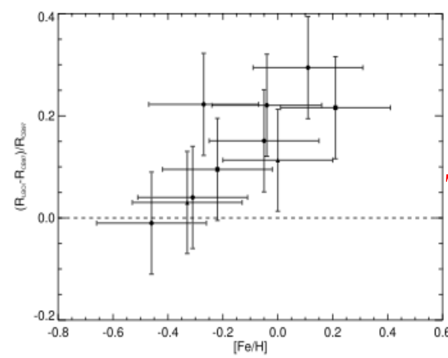

Kraus et al., 2011

## Single Stars

**Not:** Active / Rapidly Rotating

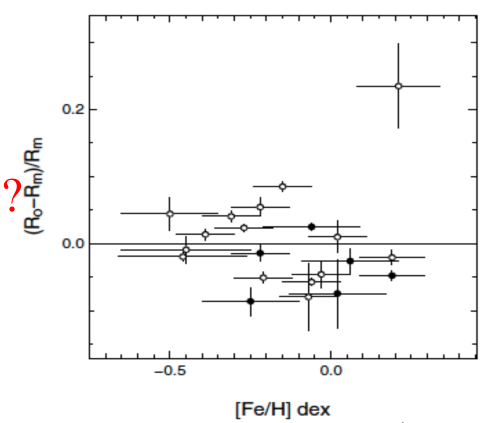



Lopez-Morales et al. 2007

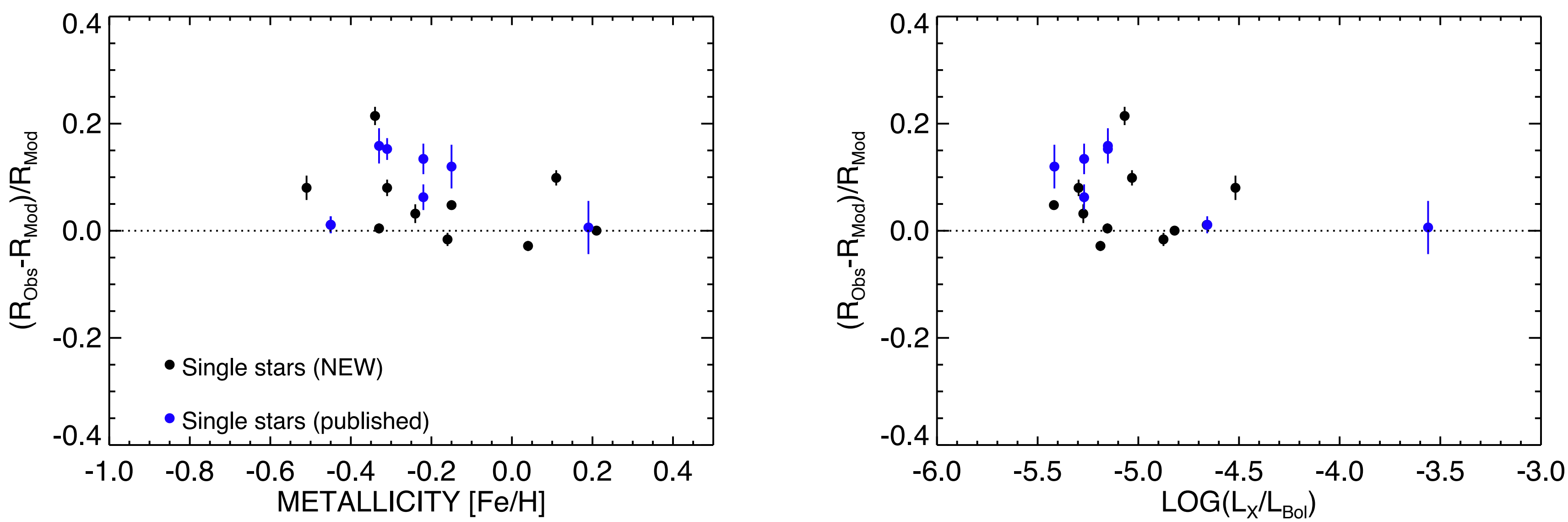



Berger et al. 2006

OR THIS?




Demory et al. 2009




SINGLE stars between ~0.65-0.35 $M_{\odot}$, we do not neither metallicity or activity explains this discrepancy with model predictions (~10%).

# Summary

- This work demonstrates impact interferometry has now on fundamental parameters across the HR diagram in both sensitivity and resolution
  - Limits for precise fundamental parameters main sequence stars lie in their photometry and abundances.
- These two surveys have just begun to establish a foundation for empirical relationships of solar-type dwarfs at the 1% level and late-type dwarfs at the 2% level
- Testing models
  - Models predict properties of solar type stars decently
  - A significant disagreement between models and observations still exist on either side of this boundary where models under predict the radii and over predict the temperatures