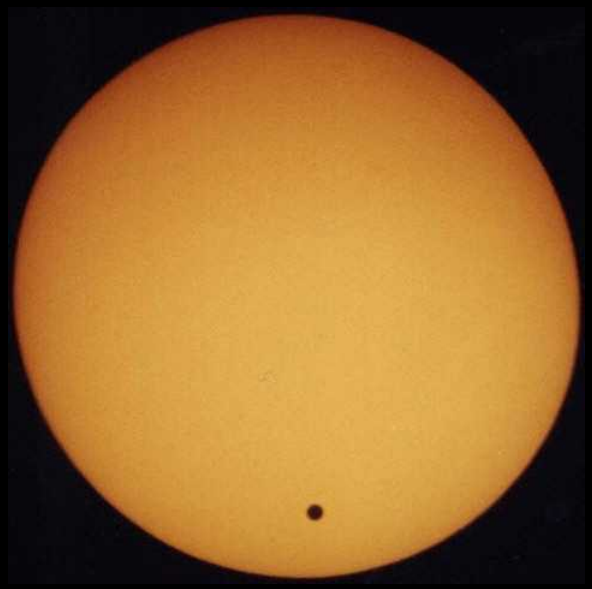
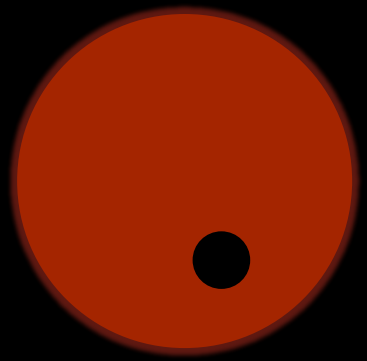
Determining Physical Parameters of M Dwarf Planet-Hosts



G2V
[Sun]



M1V
[*Kepler* 45/KOI 254]

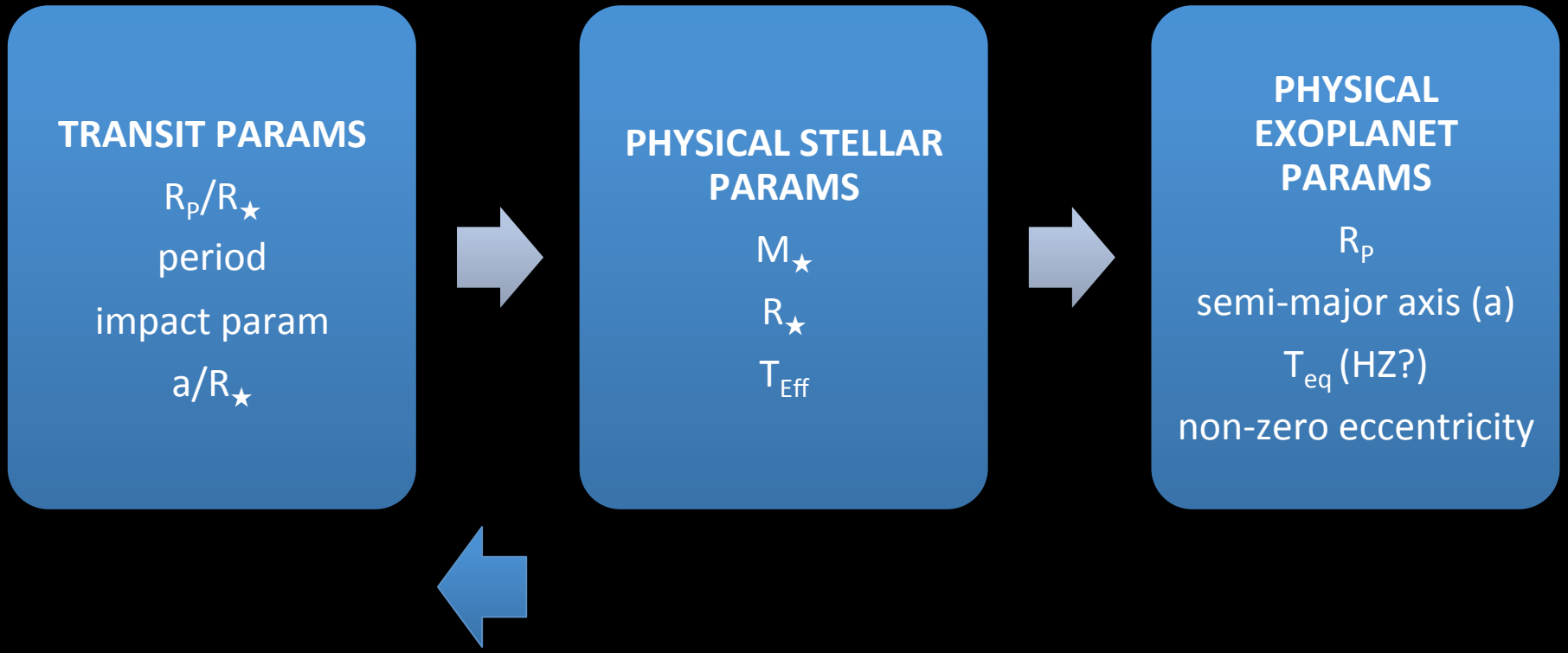
M4V
[*Kepler* 42/KOI 961]

M8V
[VB 10]

Phil Muirhead

Caltech Postdoc

Determining Physical Parameters of M Dwarf Planet-Hosts



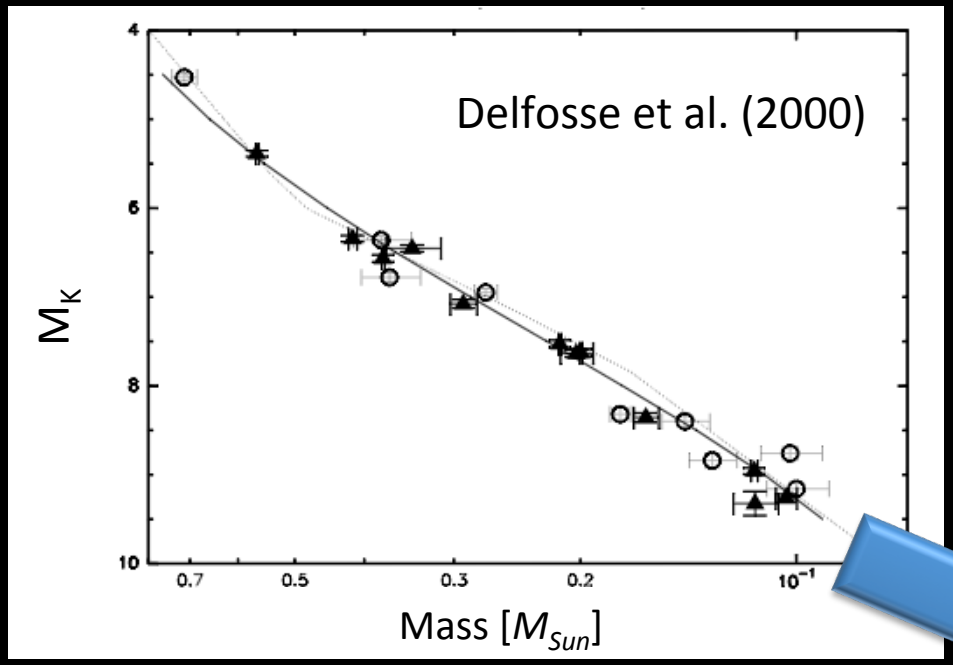
Can also use stellar params to constrain transit fit! Useful for multiple/low SNR transit light curves (J. Carter w/ KOI 961)

Determining Physical Parameters of M Dwarf Planet-Hosts

Messy combination of:

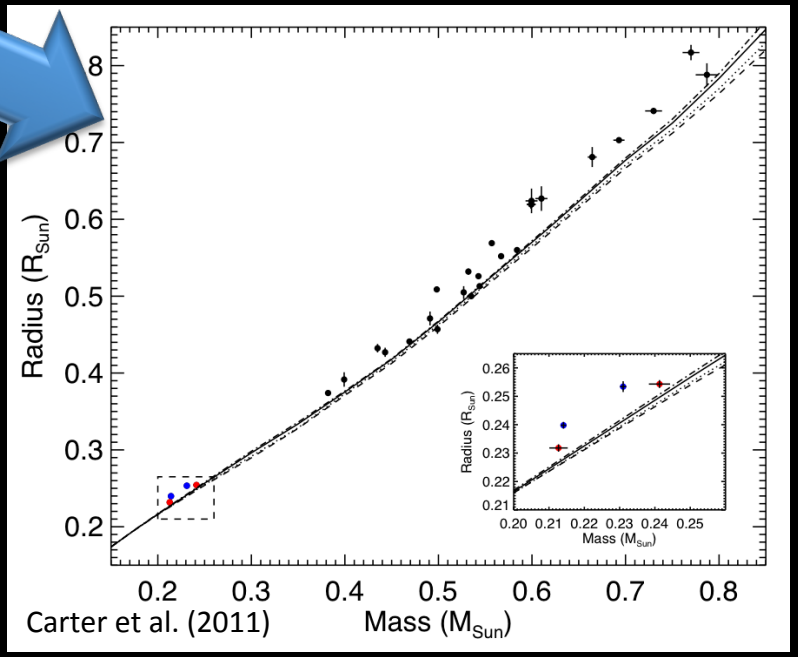
- Empirical Measurements
  - Luminosities from Parallaxes and Photometry
  - Masses from SB2 Binaries
  - Masses and Radii from Eclipsing SB2 Binaries
  - Metallicities from FGK + M Wide Binaries
  - Radii from Interferometry
  - Stellar densities from planet transits?
- Evolutionary Models
  - Predict M, R and L at a given age, metallicity
- Atmospheric Models
  - Predict spectra (and colors) at a given T_{Eff}, metallicity and logg

The Canonical Method

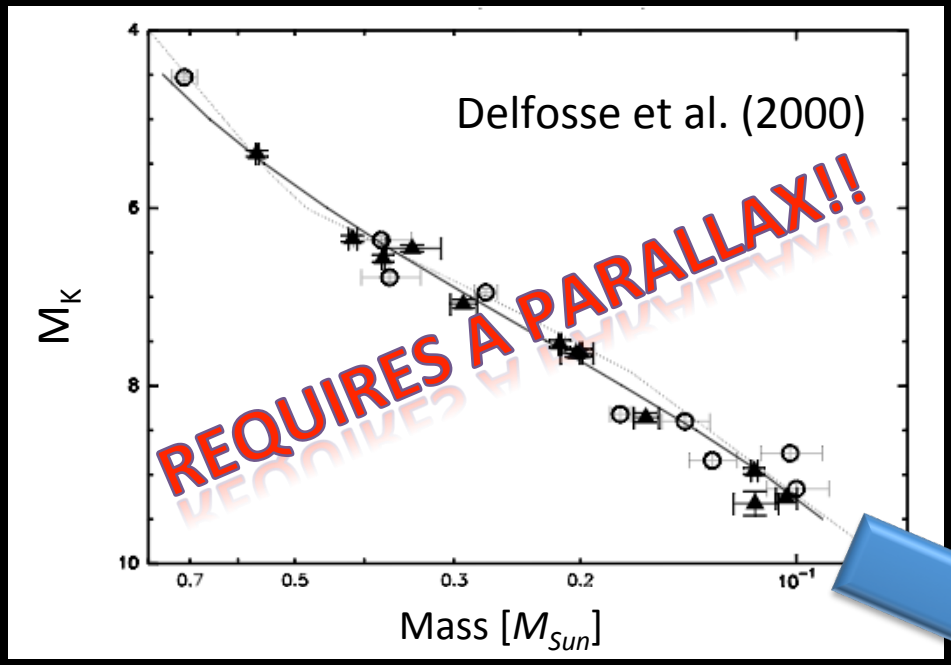


- Mass-Luminosity Relation
  - Calibrated on SB2s with parallaxes

- Mass-Radius Relation
  - Empirical from Eclipsing SB2s
    - e.g. Torres et al. (2010)
  - Or predictions from Evolutionary Models
    - e.g. Baraffe et al. (1998), Feiden et al. (2011)



The Canonical Method



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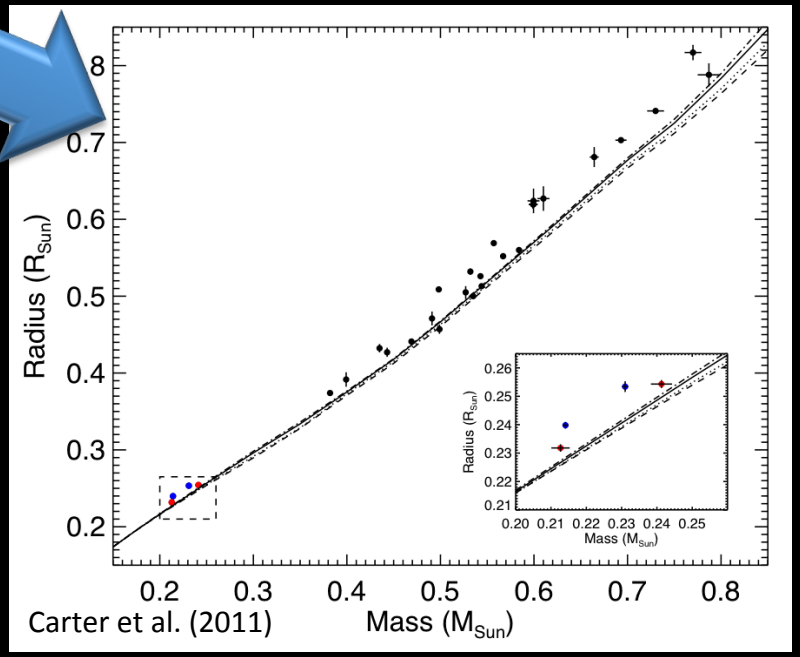
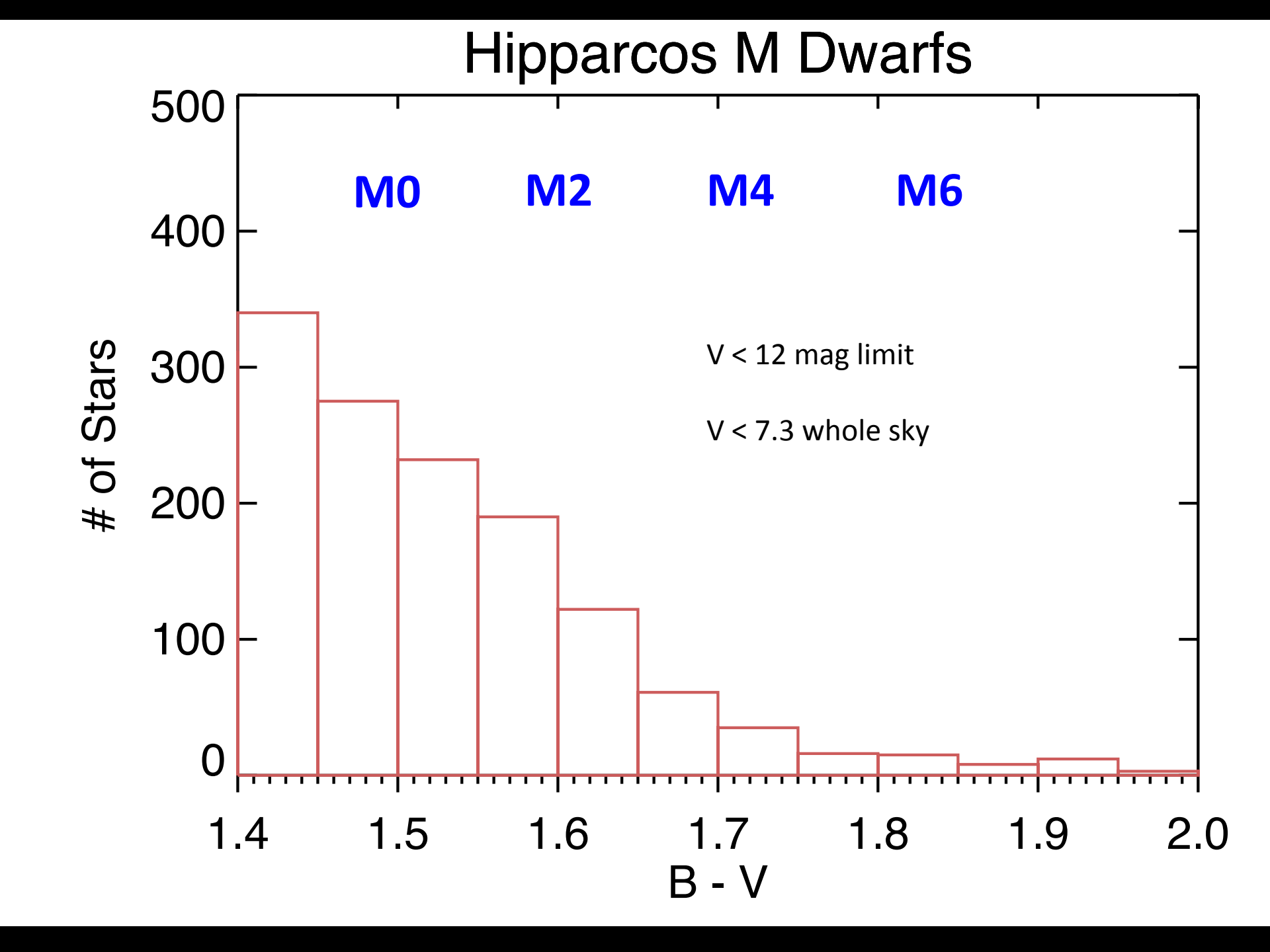
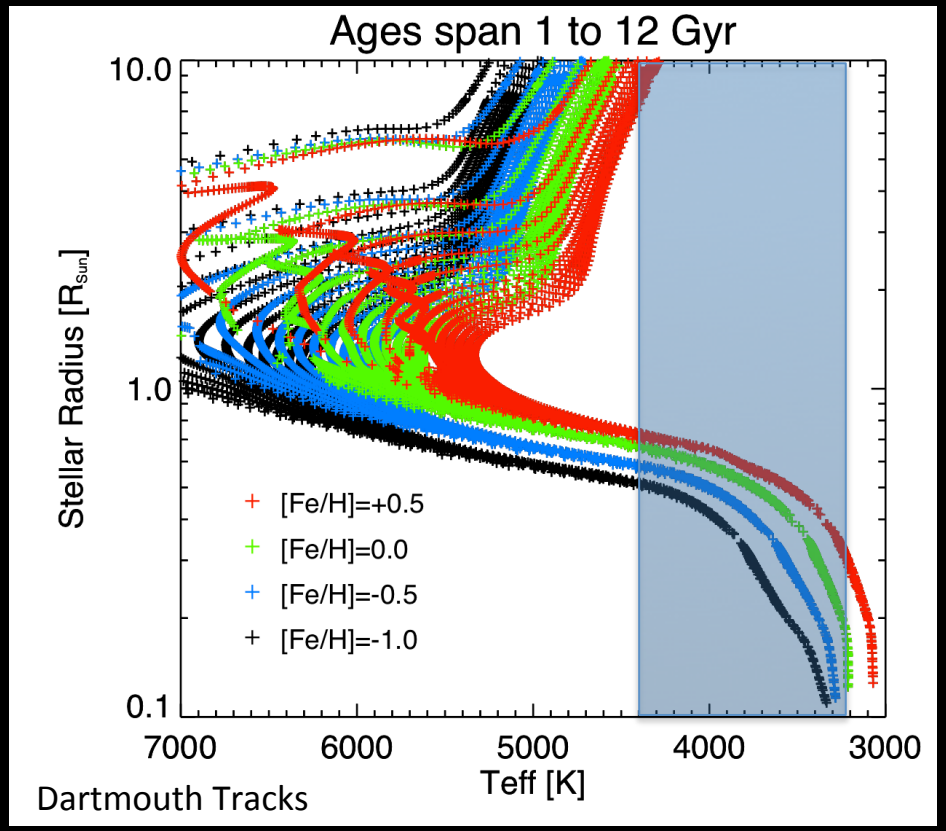
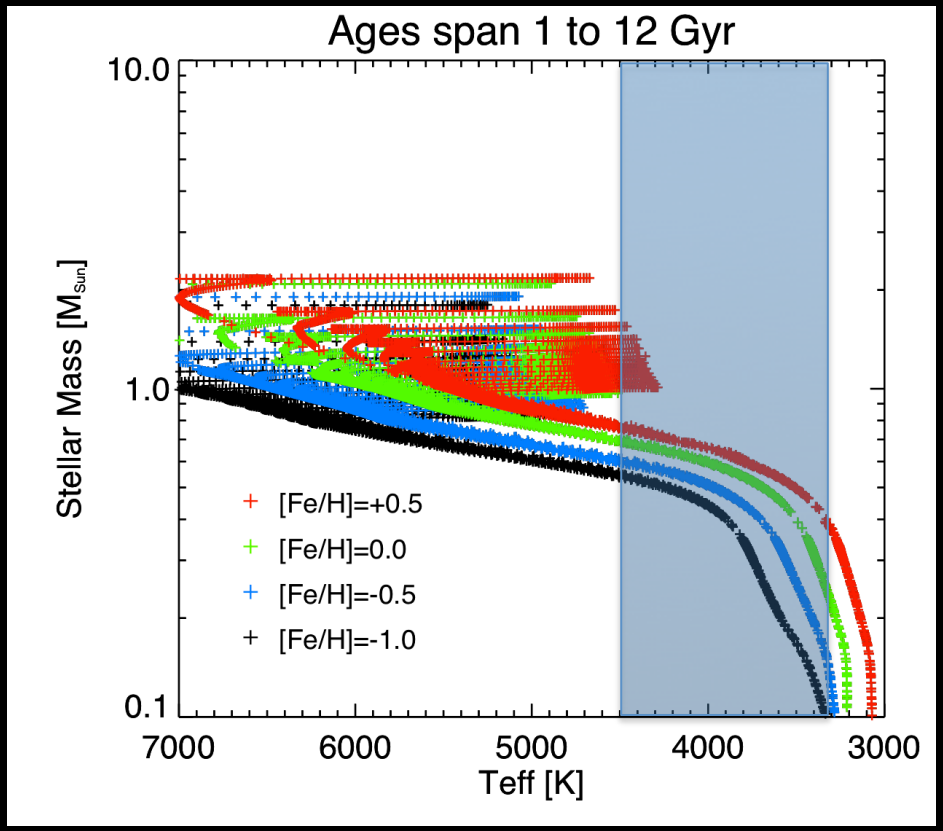



Hipparcos M Dwarfs
M0
M2
M4
M6
V < 12 mag limit
V < 7.3 whole sky
# of Stars
B - V
500
400
300
200
100
0
1.4
1.5
1.6
1.7
1.8
1.9
2.0

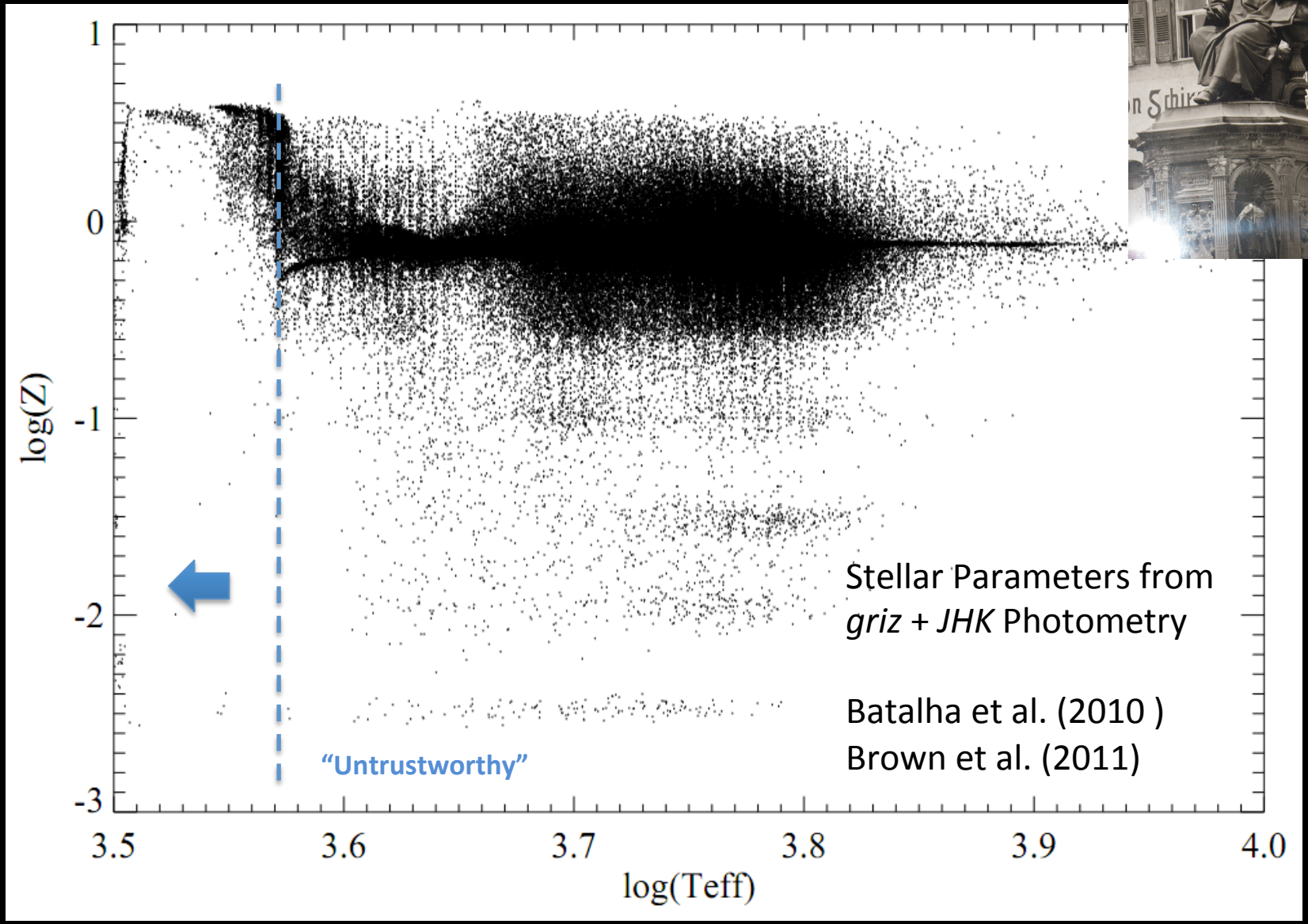
M Dwarf Mass and Radius w/o Parallax



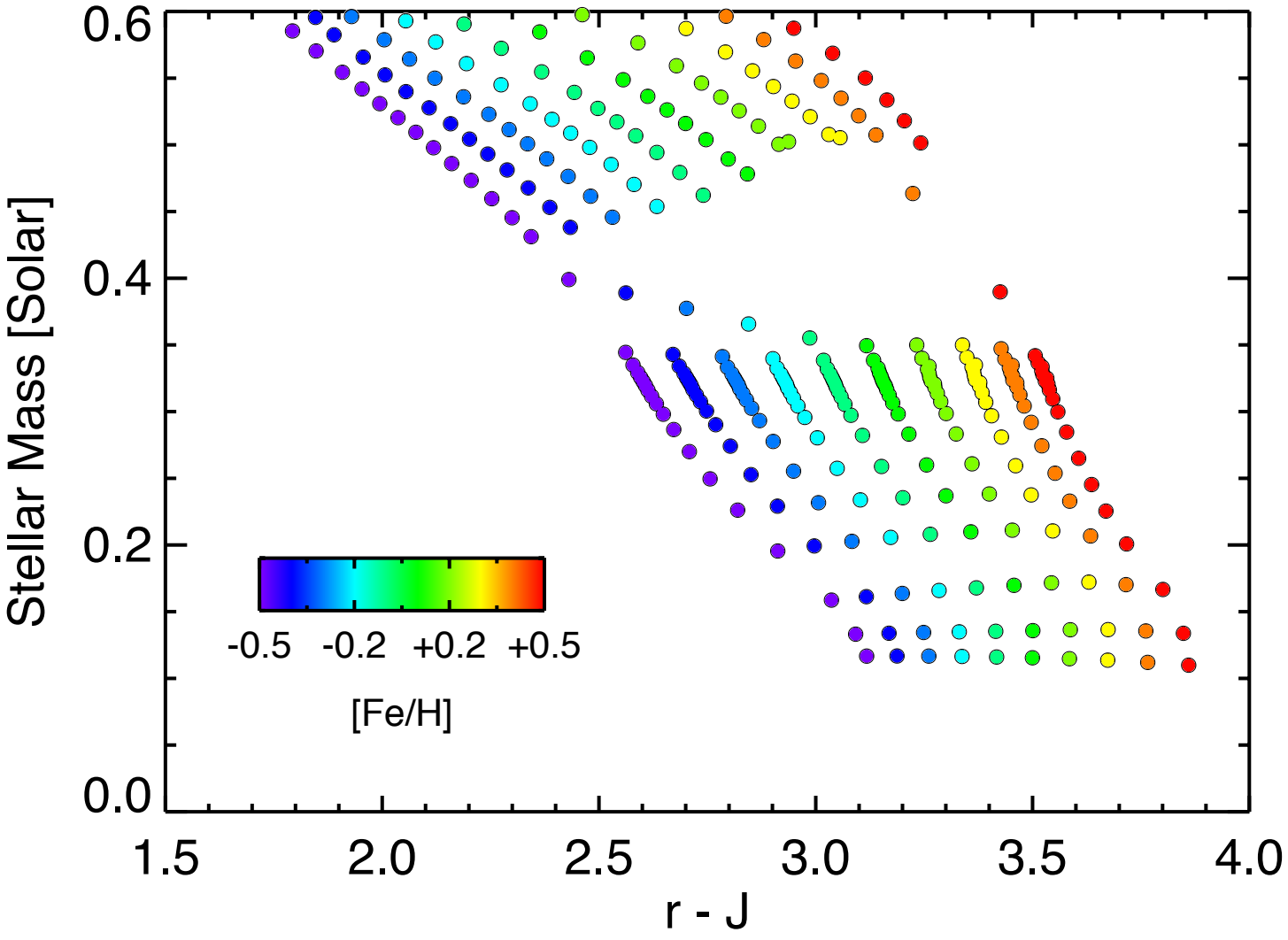


Burden falls on colors and spectra,
which trace effective temperature and metallicity.

Kepler Input Catalog



Dartmouth Isochrones (Dotter et al. 2007, Feiden et al. 2011,2012)



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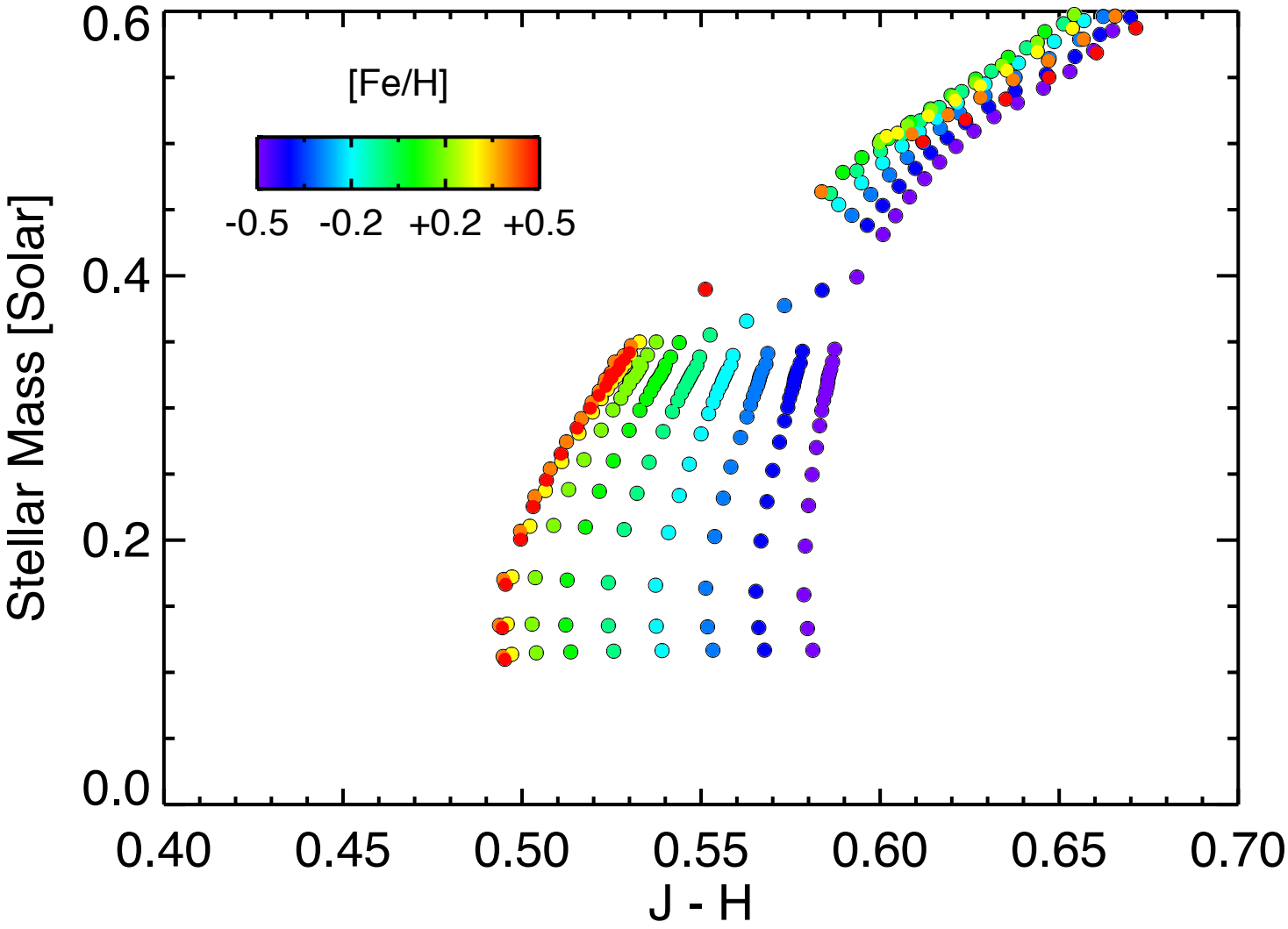

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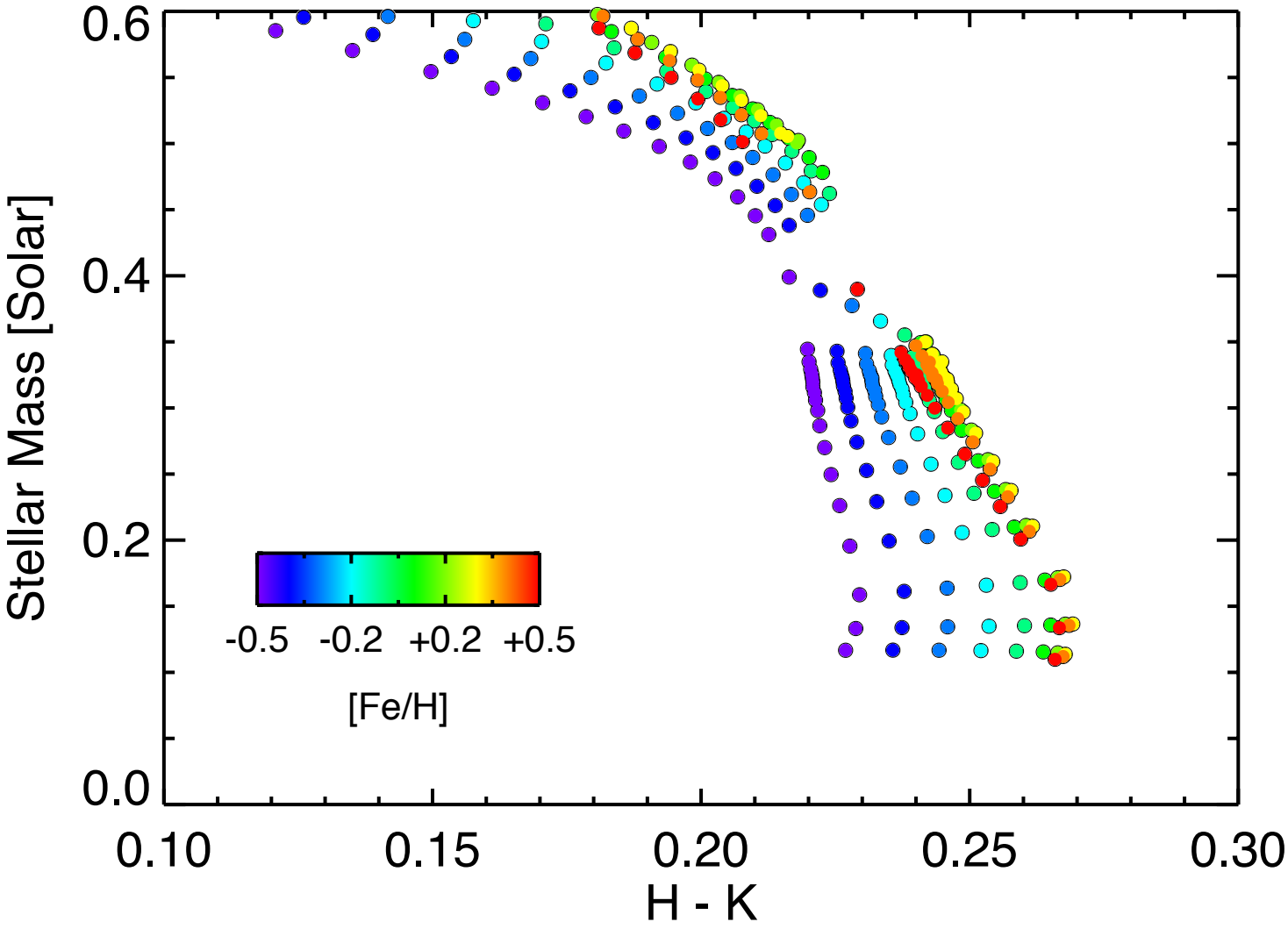
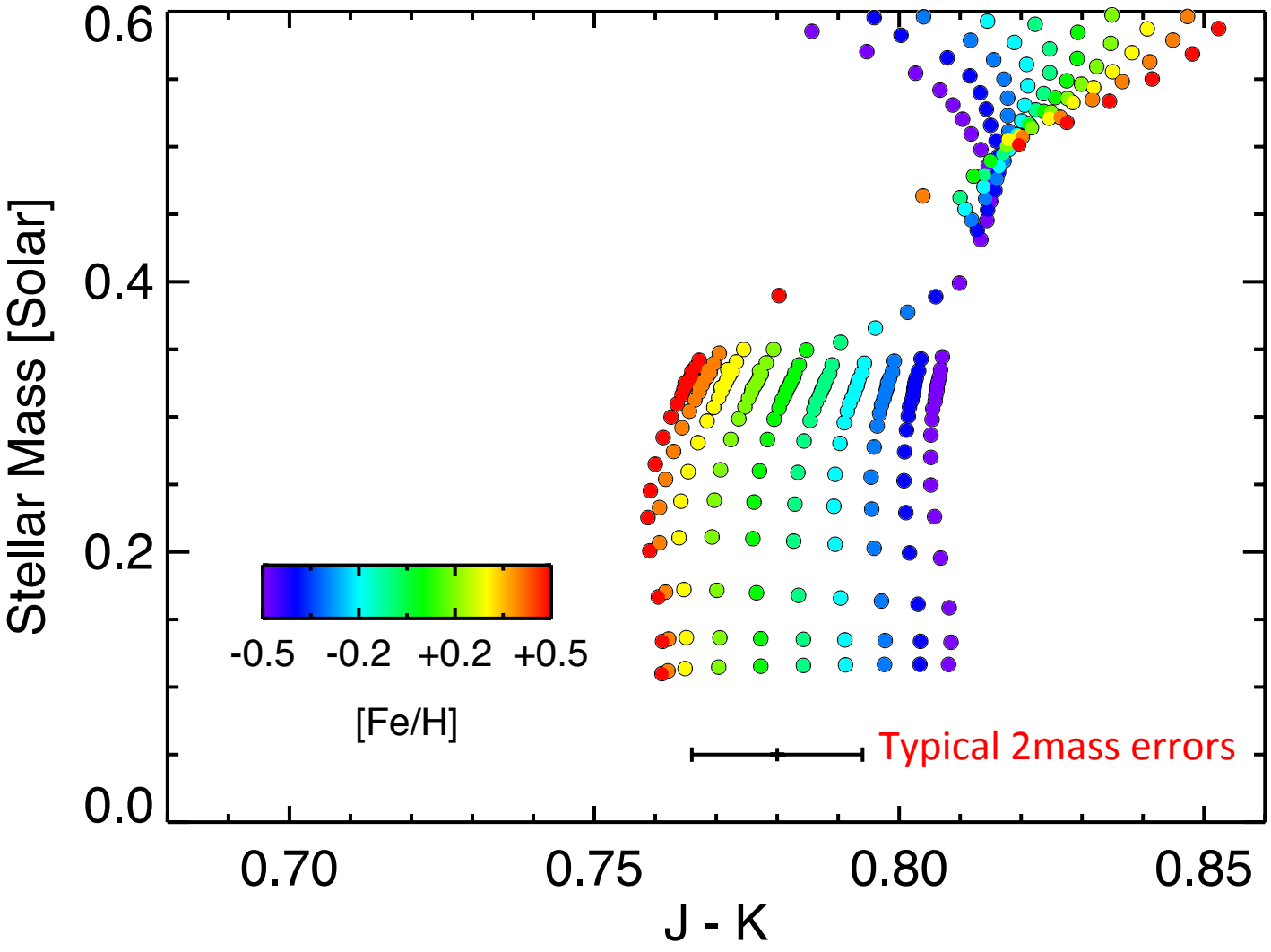
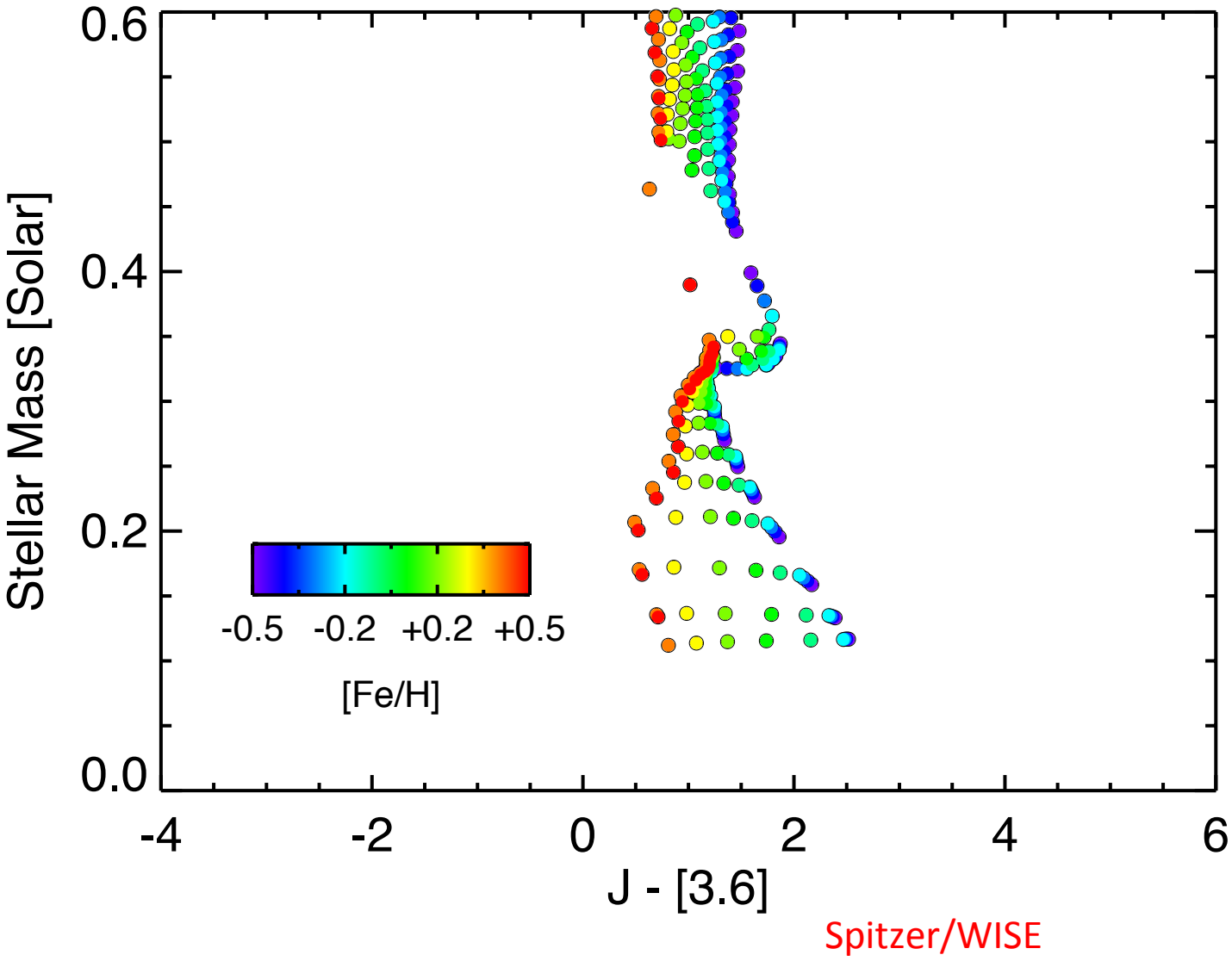


Dartmouth Isochrones (Dotter et al. 2007, Feiden et al. 2011,2012)



Dartmouth Isochrones (Dotter et al. 2007, Feiden et al. 2011,2012)



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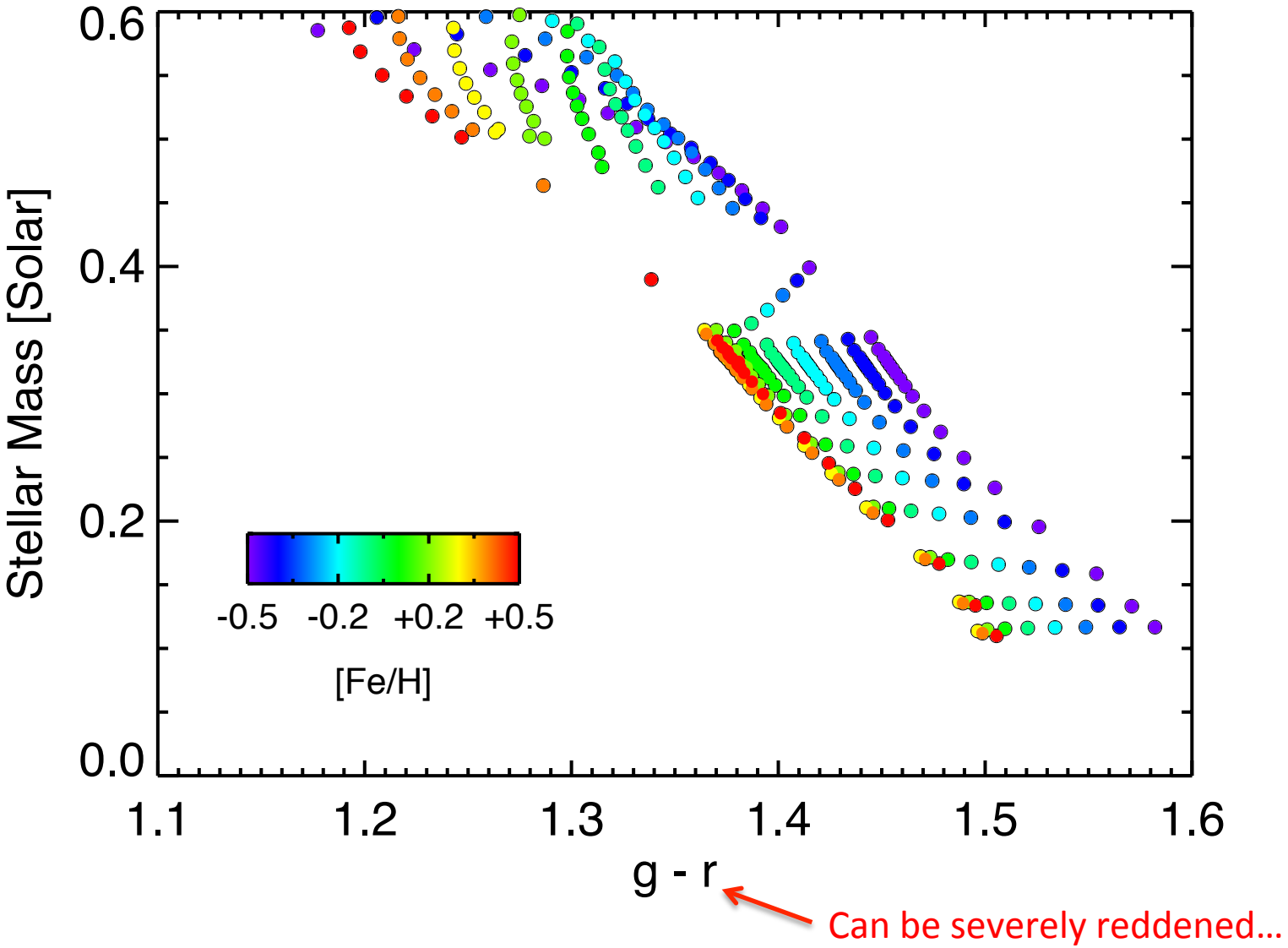
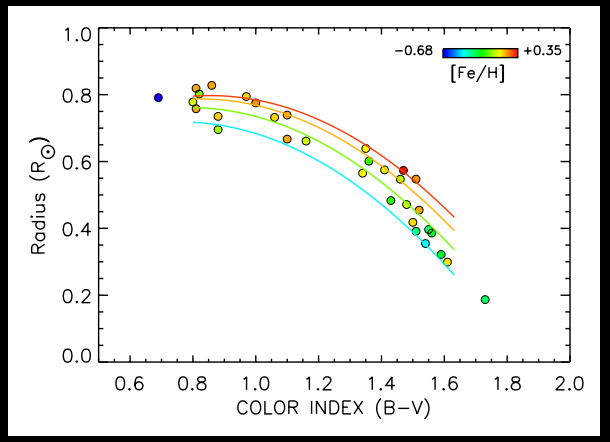


M Dwarf Parameters from Photometric Colors Alone

- Extremely important for planet occurrence statistics
  - C. Dressing (CfA)
- Bayesian approach
  - Take everything you know, find the most likely values given the data
  - Johnson et al. 2011, 2012
- Need more empirical measurements!
  - More SB2s, EBs
  - Interferometric Radii
    - Boyajian et al. (2012)

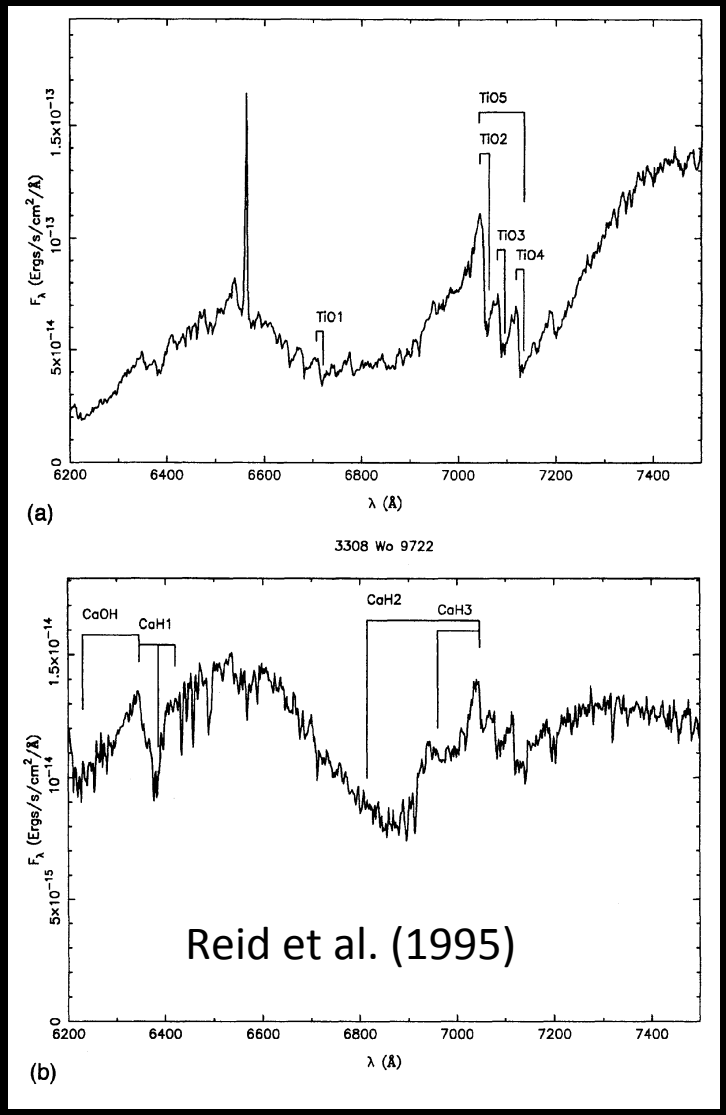
$$\chi^2_{\rm tot} = \sum_{i=1}^{3}\left(\frac{m_{i,A} - m_i(M_A, d)}{\sigma_{m_{i,A}}}\right)^2 + \sum_{i=1}^{3}\left(\frac{m_{i,B} - m_i(M_B, d)}{\sigma_{m_{i,B}}}\right)^2 + \left(\frac{V_{\rm tot} - V_{\rm tot}(M_A, M_B, d, F)}{\sigma_{V_{\rm tot}}}\right)^2 + \left(\frac{a_R - a_R(M_A, M_C, P)}{\sigma_{a_R}}\right)^2 .$$



Spectroscopy

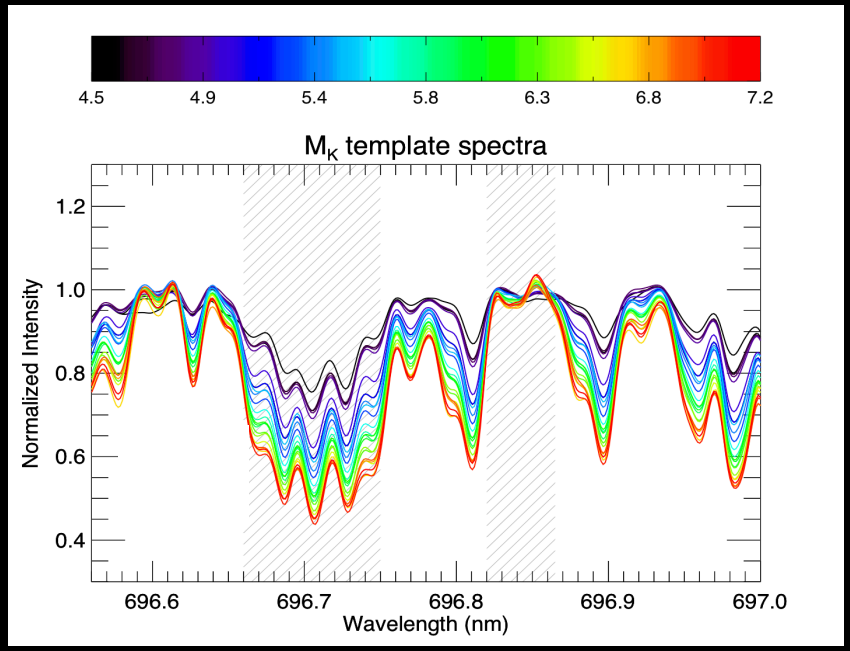
Optical Spectroscopy

- PMSU Survey
  - Reid, Hawley and Gizis
- Spectral Indices
  - TiO, CaH, CaOH
  - Useful for spectral typing, determining luminosity class
  - Not well calibrated to physical T_{Eff} or [M/H]
    - and therefore stellar mass and radius



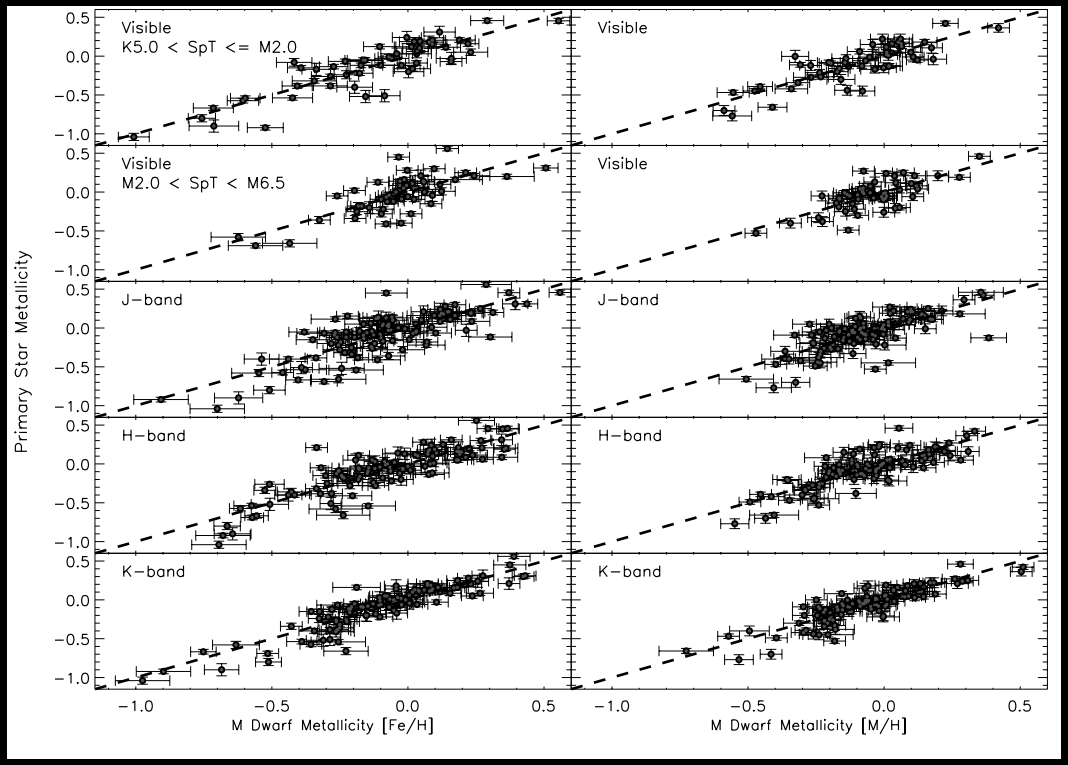
Optical Spectroscopy

- New effort by J. S. Pineda and M. Bottom (Caltech)
- Archival HIRES M dwarf spectra from the California Planet Search
- Calibrate EWs to Delfosse et al. Stellar Mass

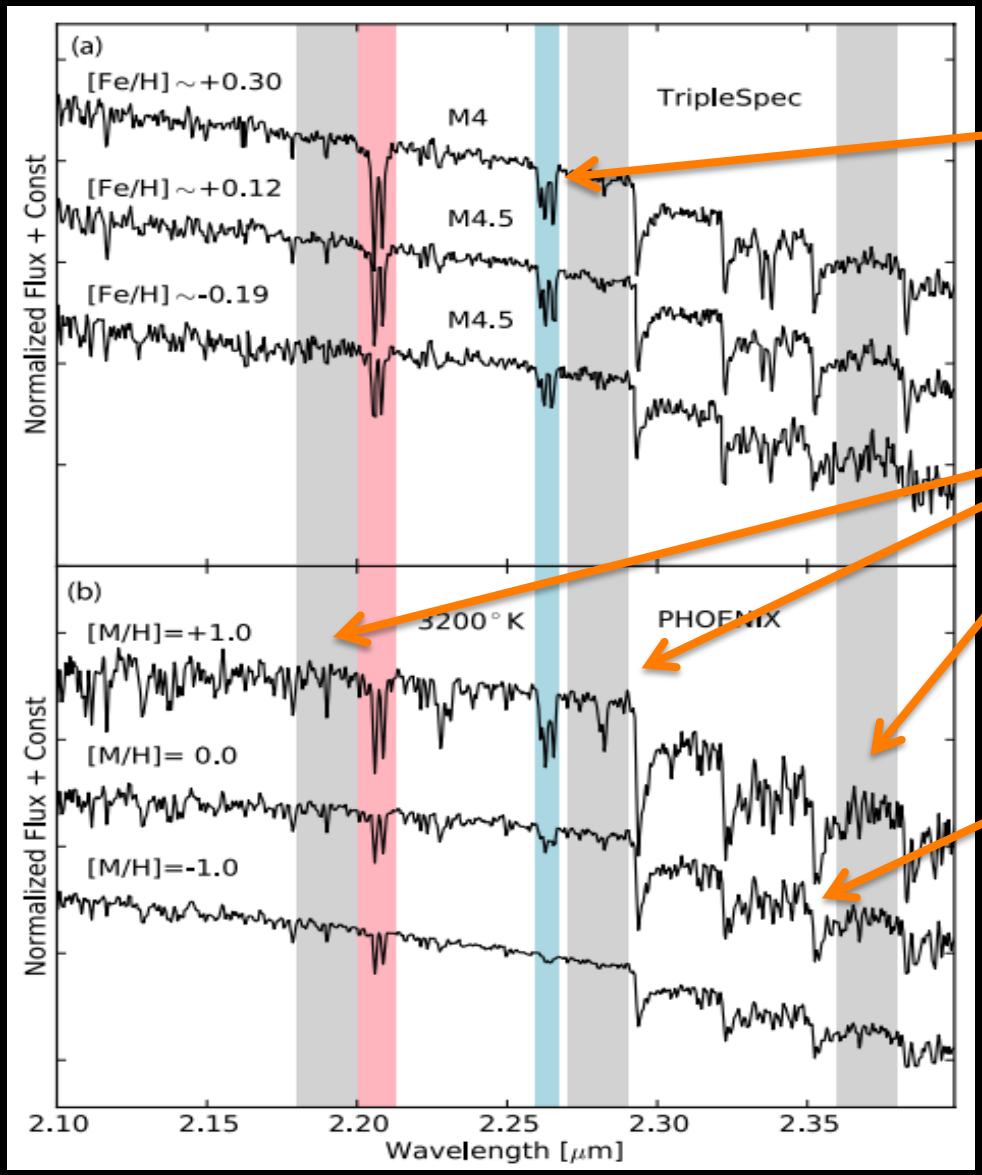


Optical Spectroscopy

- New effort by A. Mann (IfA)
- Calibrate mod-res optical spectra to physical parameters



K-Band Infrared Spectroscopy



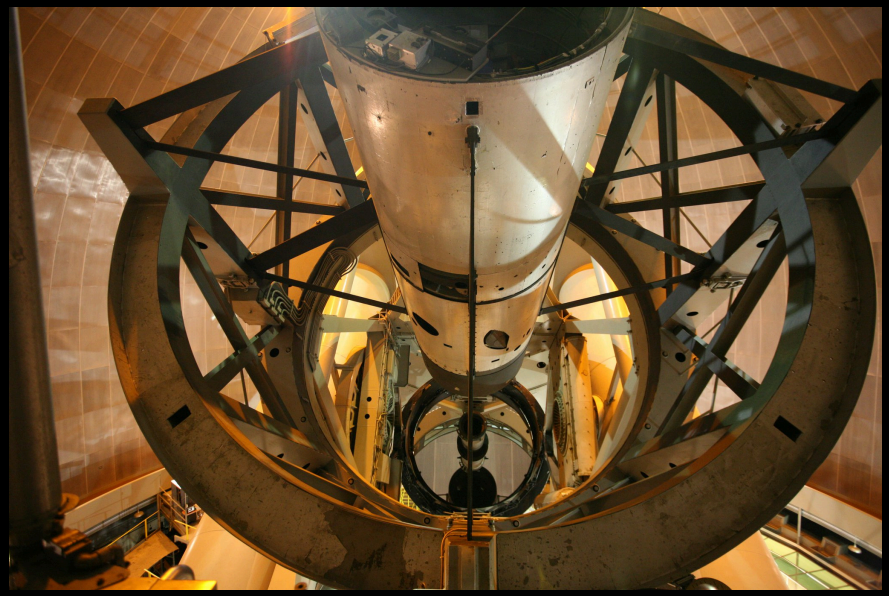
Na and Ca EW trace [Fe/H], [M/H]

Deformation from H_2O traces T_{Eff} (H_2O-K index)

CO EW determines luminosity class (V vs. III)

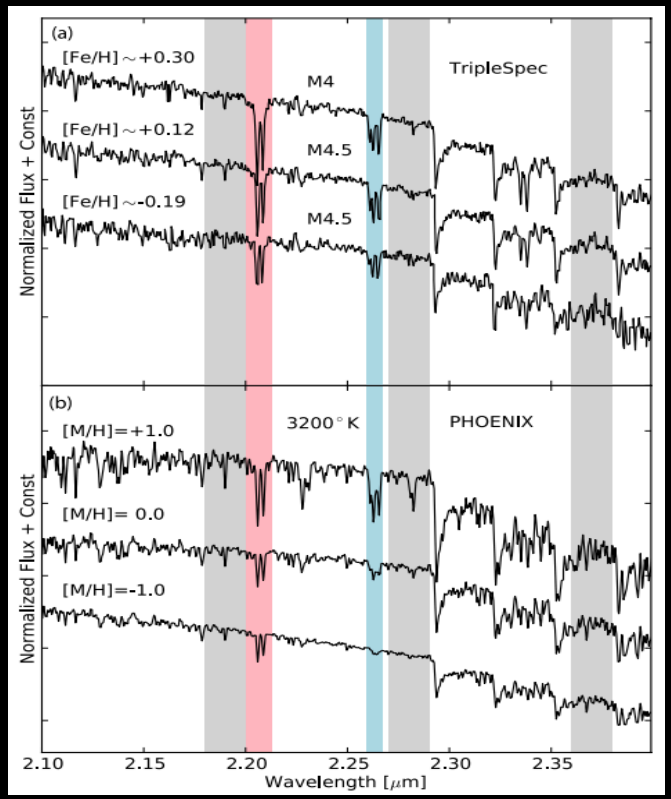
Rojas-Ayala et al. (2010, 2012)

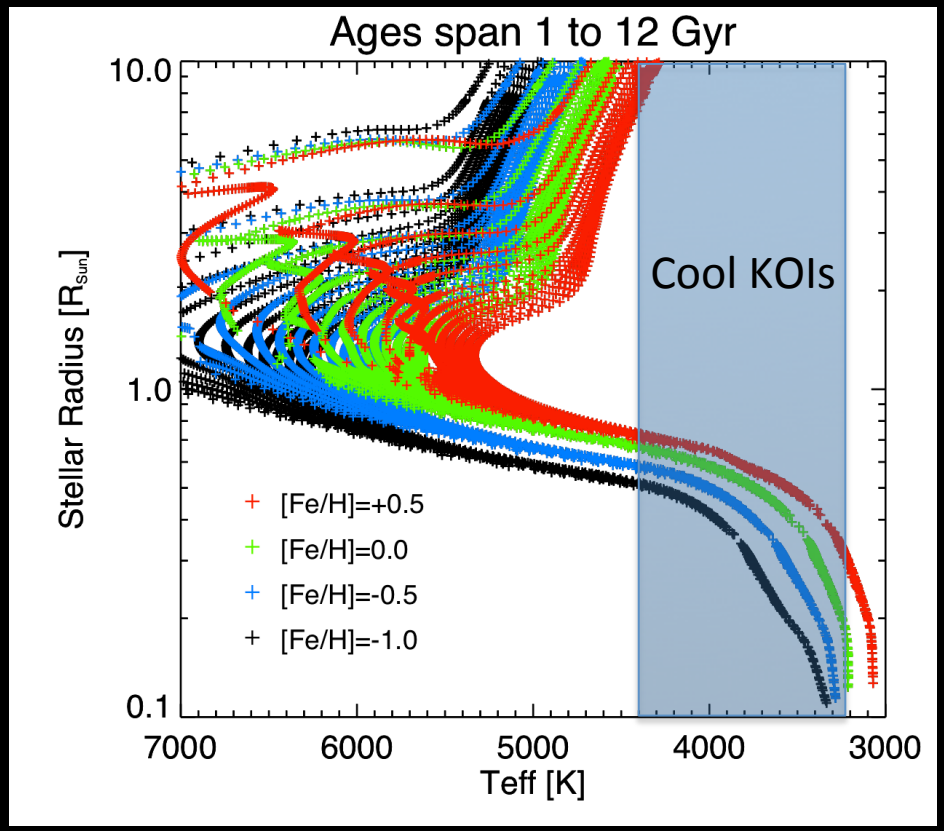
Palomar-TripleSpec



Herter et al. 2008

Interpolate T_{eff} and [M/H] onto Dartmouth Isochrones for Mass and Radius

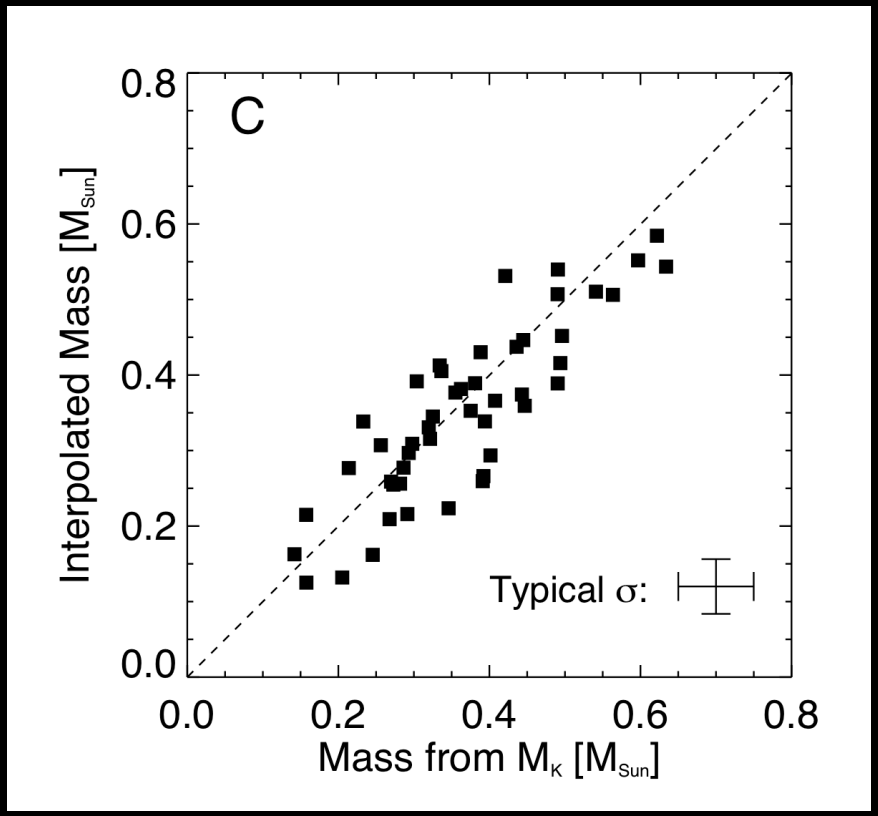




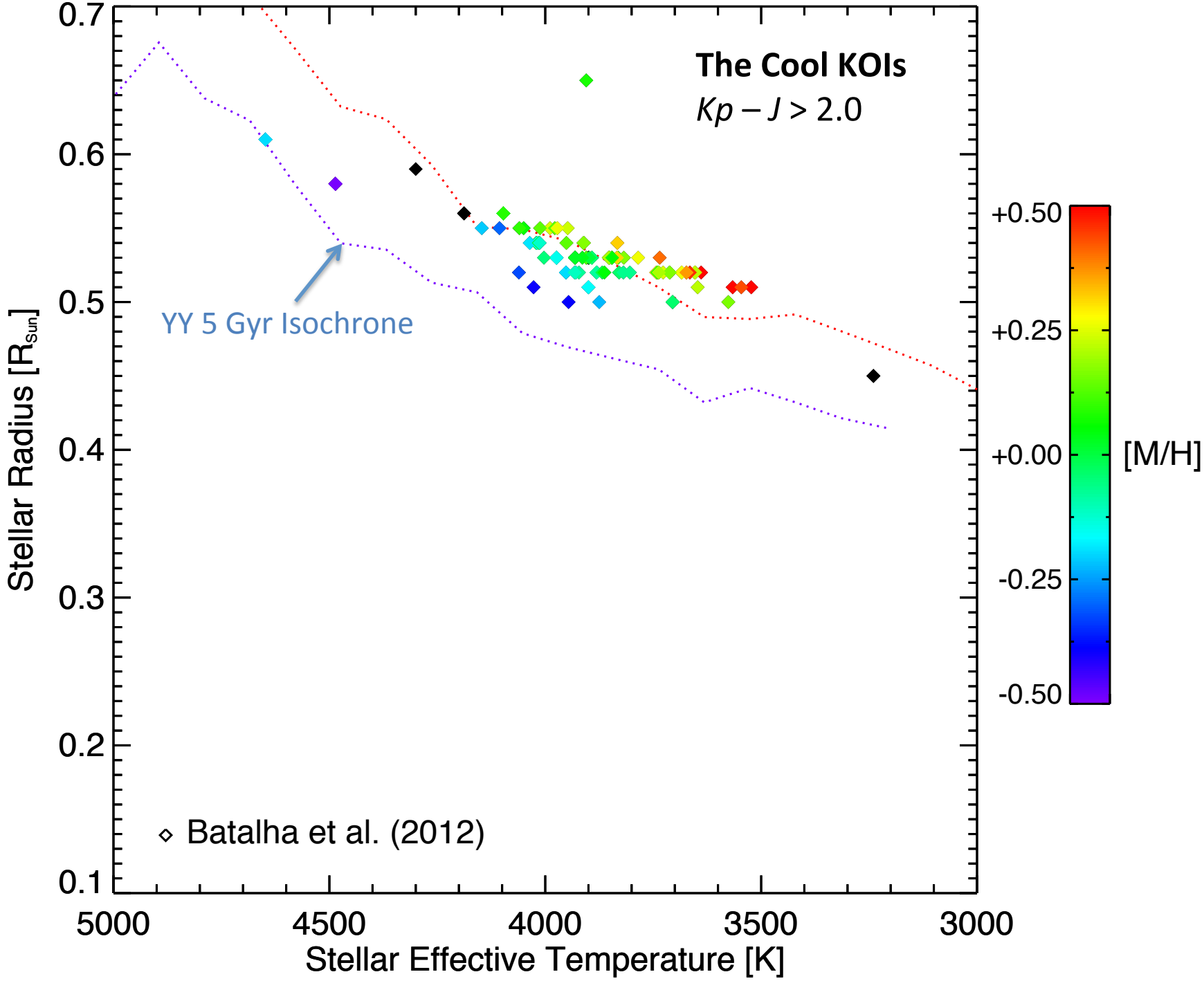
Rojas-Ayala et al. (2010, 2012)
T_{Eff} and [M/H]

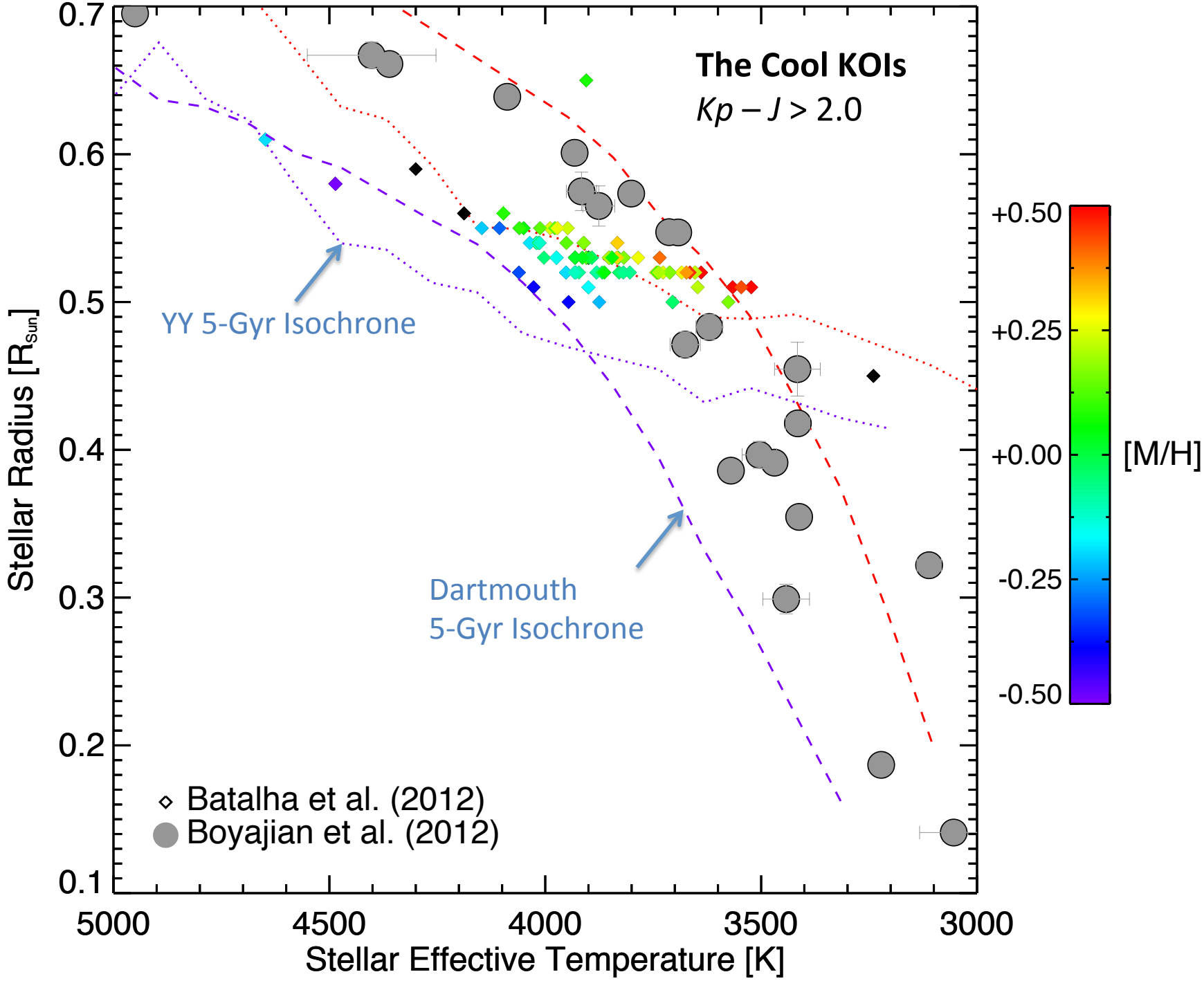
Dotter et al. (2008)
M, R, L, M_K, distance

Compare to Delfosse Masses



- Rojas-Ayala (2012) contains *K*-band spectra of 122 nearby M dwarfs.
- Compare interpolated mass to Delfosse et al. (2000) masses for stars with *Hipparcos* parallaxes.
- No systematic difference in mass estimates!


The Cool KOIs
Kp – J > 2.0
YY 5 Gyr Isochrone
Batalha et al. (2012)
Stellar Radius [R_Sun]
Stellar Effective Temperature [K]
0.7
0.6
0.5
0.4
0.3
0.2
0.1
5000
4500
4000
3500
3000
+0.50
+0.25
+0.00
-0.25
-0.50
[M/H]


The Cool KOIs
Kp – J > 2.0
YY 5-Gyr Isochrone
Dartmouth
5-Gyr Isochrone
Batalha et al. (2012)
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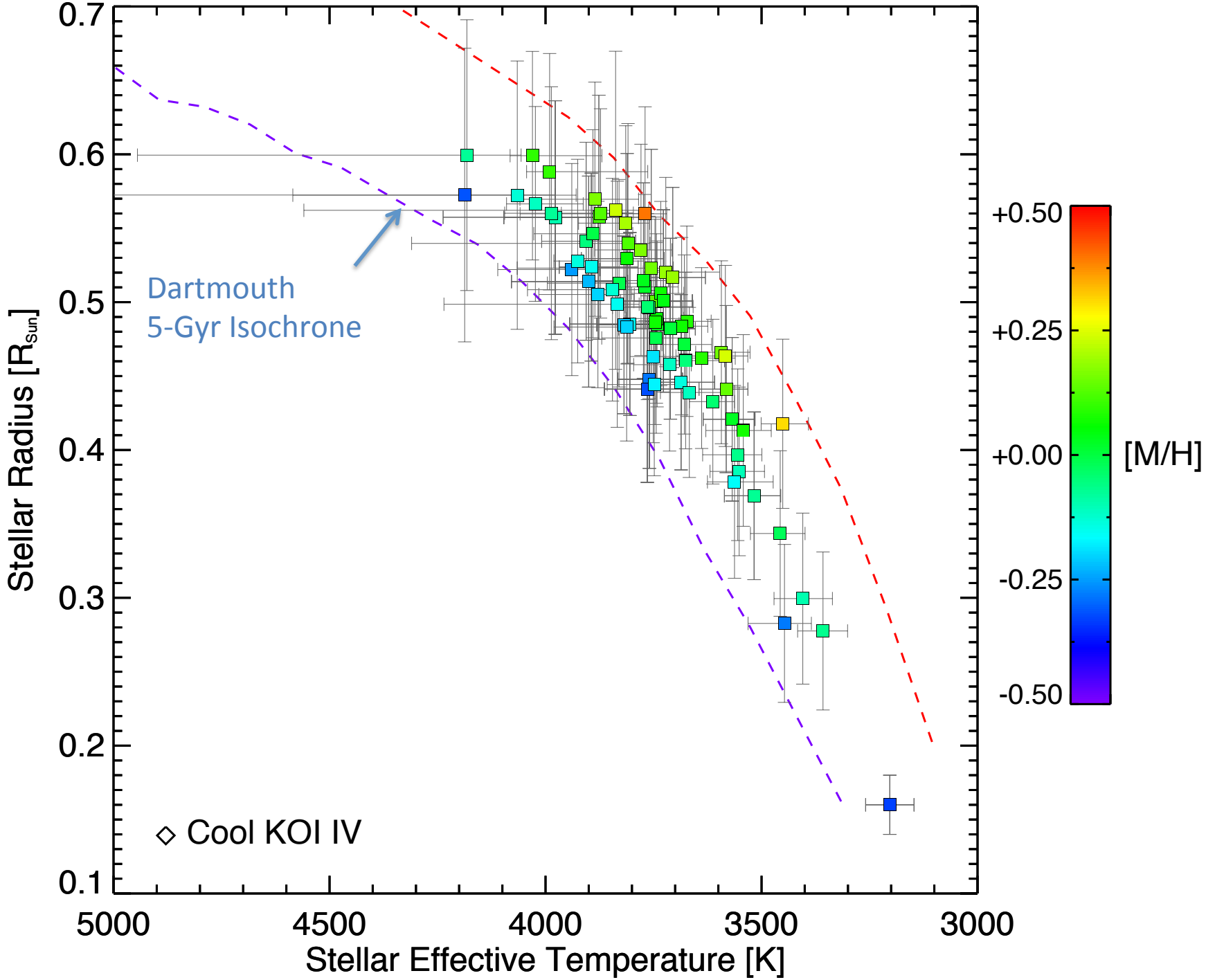
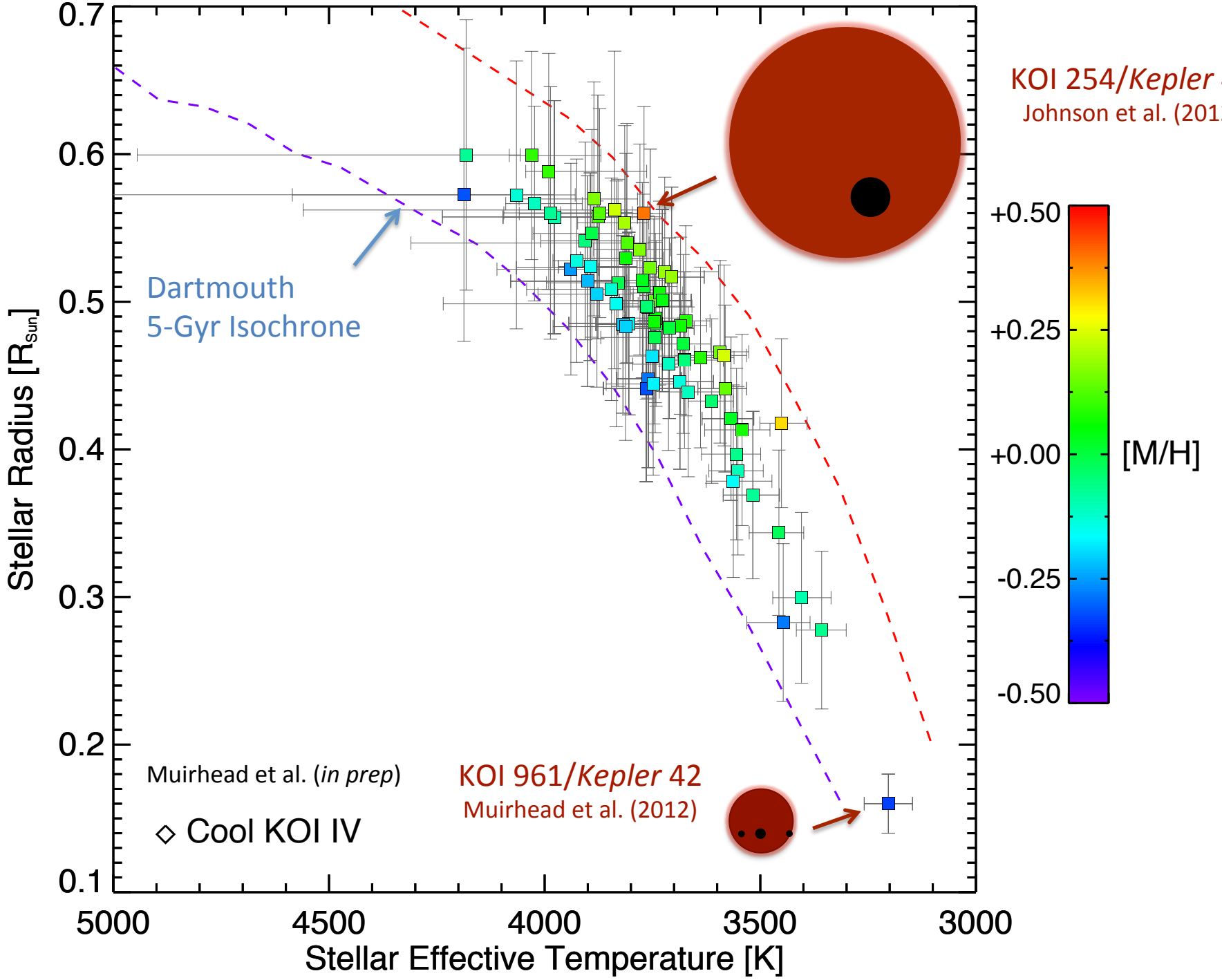
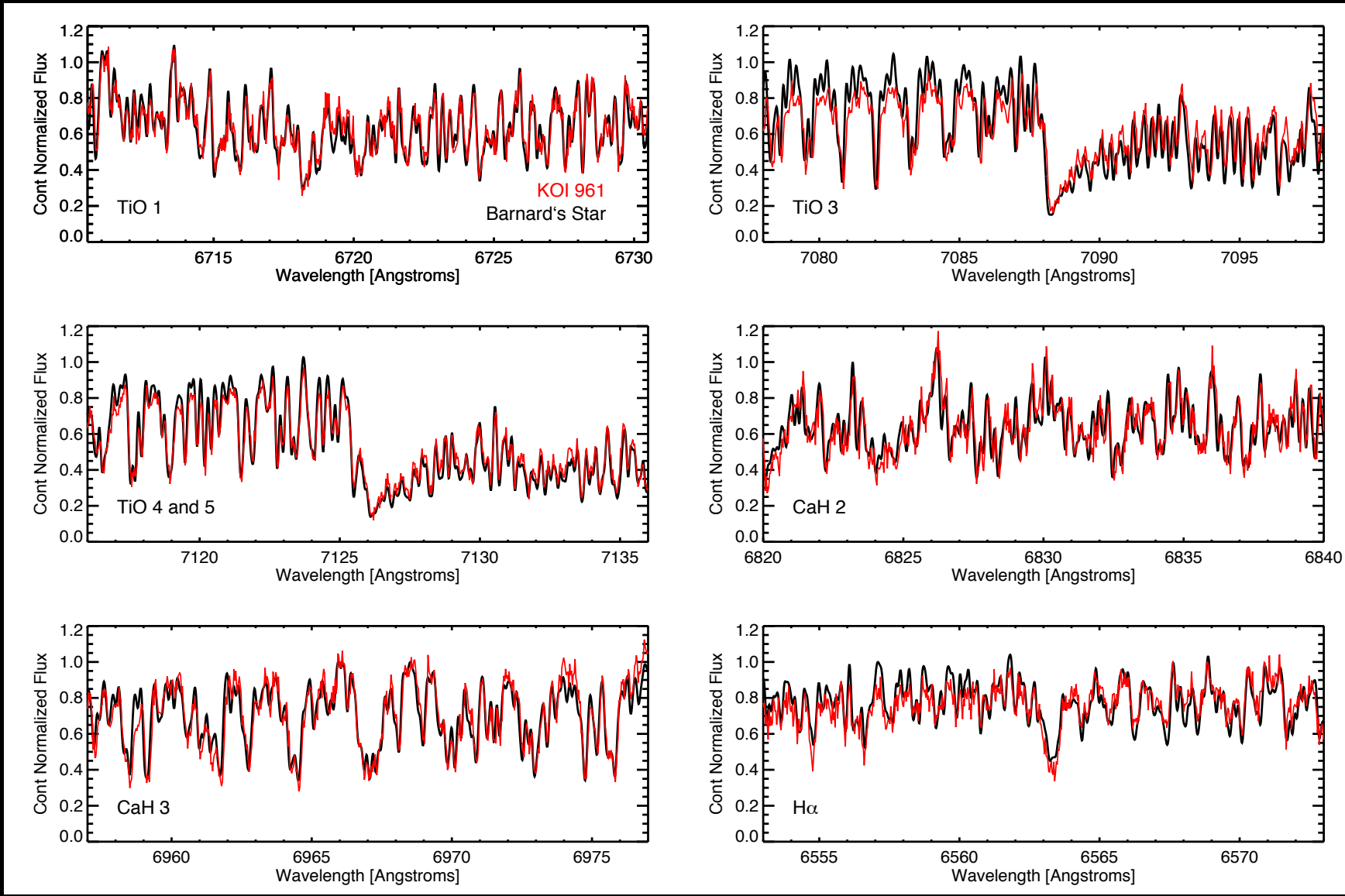
Stellar Radius [R_Sun]
Stellar Effective Temperature [K]
0.7
0.6
0.5
0.4
0.3
0.2
0.1
5000
4500
4000
3500
3000
+0.50
+0.25
+0.00
-0.25
-0.50
[M/H]


0.7
0.6
0.5
0.4
0.3
0.2
0.1
Stellar Radius [R$_{Sun}$]
5000
4500
4000
3500
3000
Stellar Effective Temperature [K]
Dartmouth
5-Gyr Isochrone
◇ Cool KOI IV
+0.50
+0.25
+0.00
-0.25
-0.50
[M/H]


0.7
0.6
0.5
0.4
0.3
0.2
0.1
Stellar Radius [R$_{Sun}$]
5000
4500
4000
3500
3000
Stellar Effective Temperature [K]
Dartmouth
5-Gyr Isochrone
KOI 254/*Kepler* 45
Johnson et al. (2012)
+0.50
+0.25
+0.00
-0.25
-0.50
[M/H]
Muirhead et al. (*in prep*)
◇ Cool KOI IV
KOI 961/*Kepler* 42
Muirhead et al. (2012)

KOI 961/*Kepler* 42 – Bootstrap off Barnard's Star

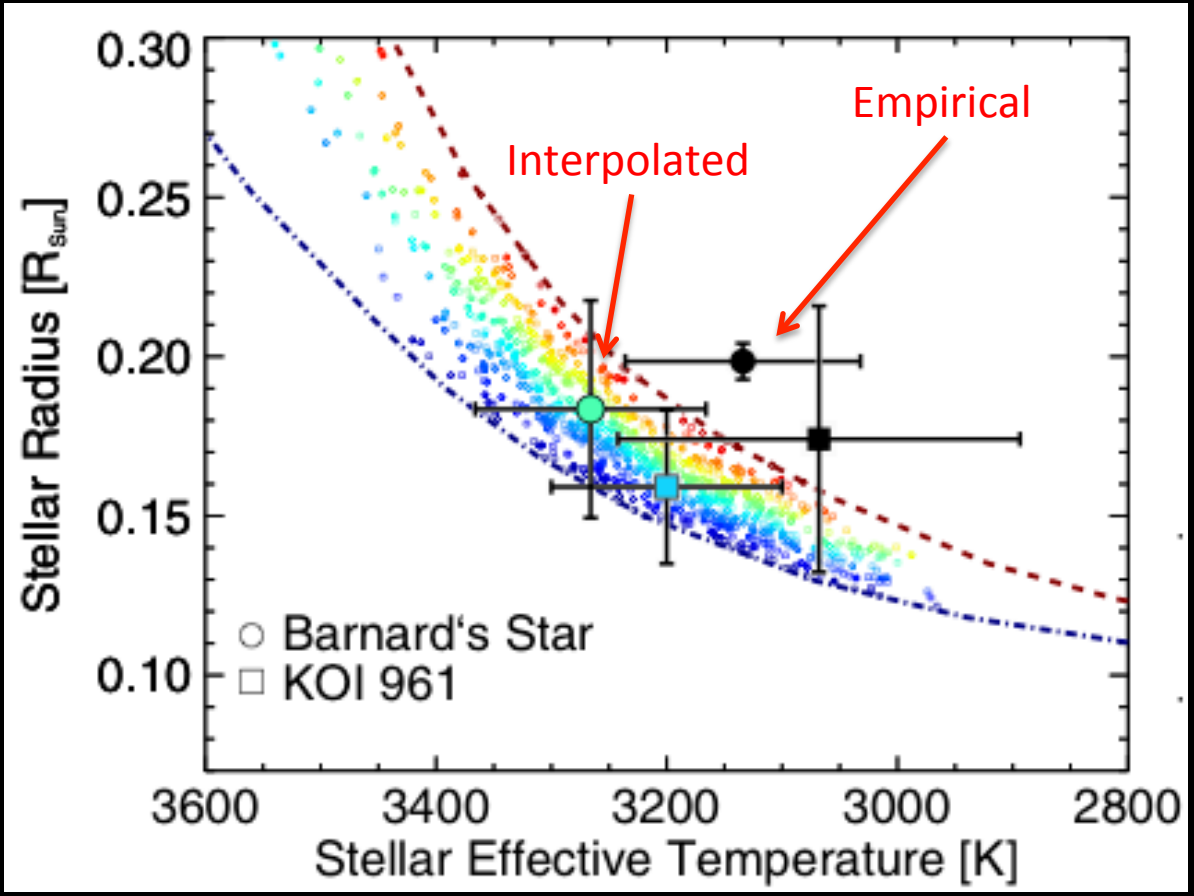


Barnard's Star

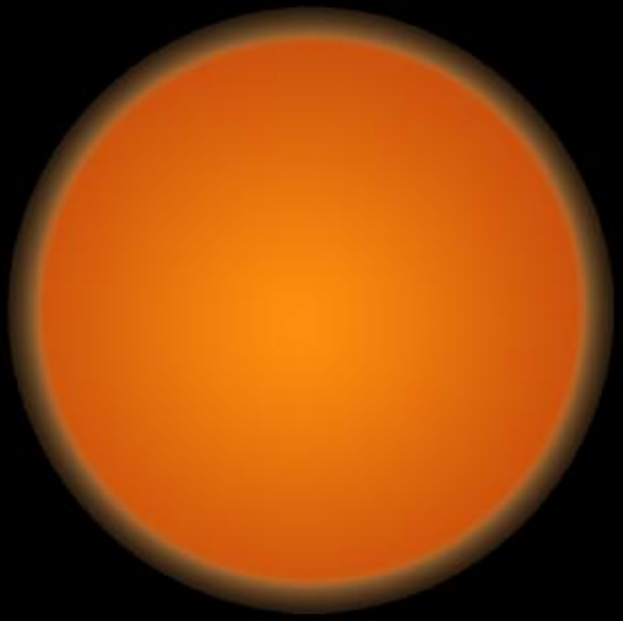
A Small Star with Large Proper Motion (Barnard 1916)

- Good *Hipparcos* parallax (d = 1.8 pc)
  - Absolute magnitude -> Mass
- Old (> 7.5 Gyr)
  - Slow rotator, no quiescent H-alpha emission, "Thick Disk" kinematics (Leggett 1992)
- Interferometric Radius! (Lane et al 2001, Boyajian et al. 2012)
- Carefully stitched spectra for bolometric luminosity (Dawson & de Robertis 2004)
  - With radius gives *empirical* Teff

KOI 961/*Kepler* 42 – Bootstrap off Barnard's Star



- Also used bootstrap method on GJ 1214 to double-check.
- Recovered parameters based on *transit* a/R_* not models!!!
  - Method A from Carter et al. 2011



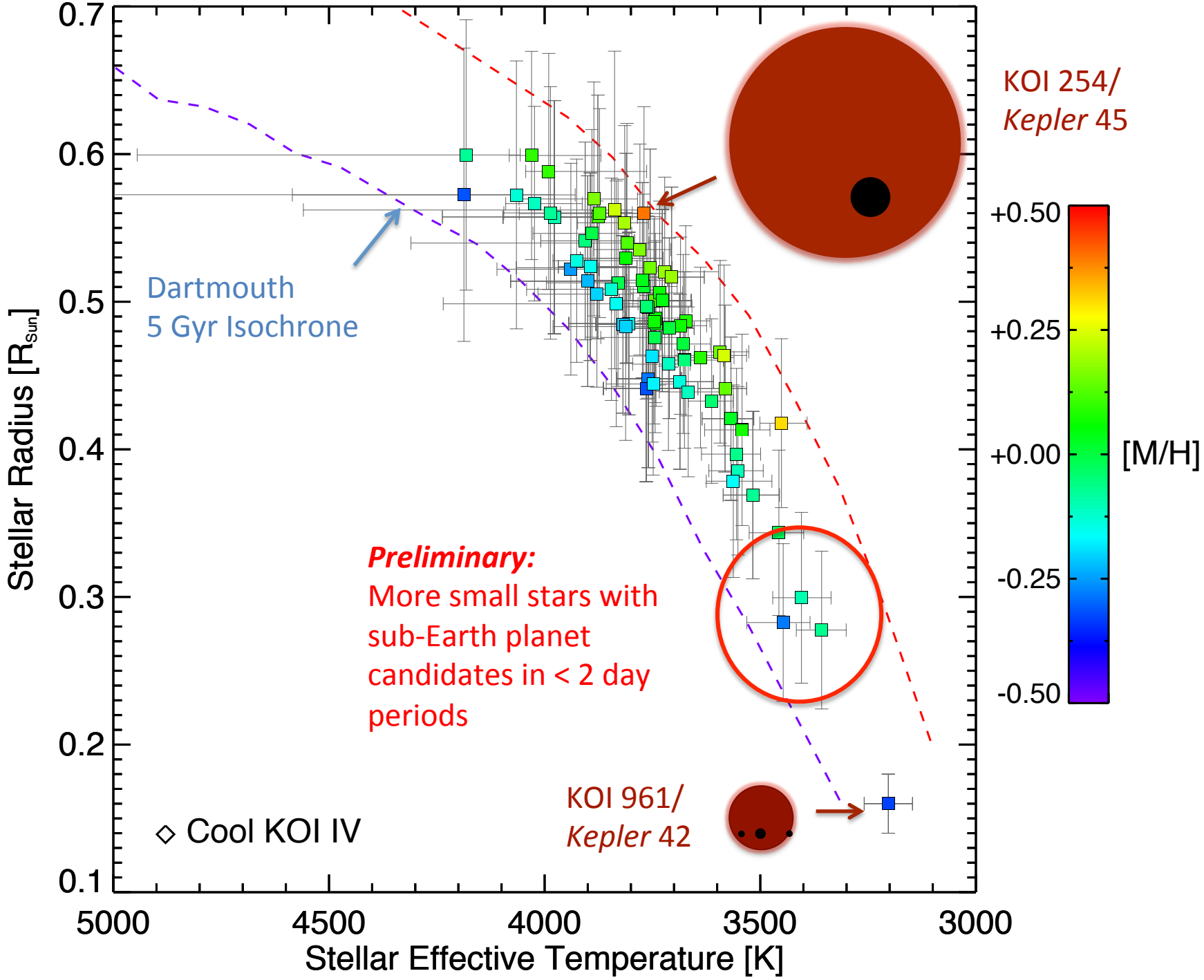
KOI-961 and Its 3 Known Planets

02 01 03

Jupiter and Its 4 Largest Moons

Io Europa Ganymede Callisto

Orbital Scale = 5 x Size Scale


0.7
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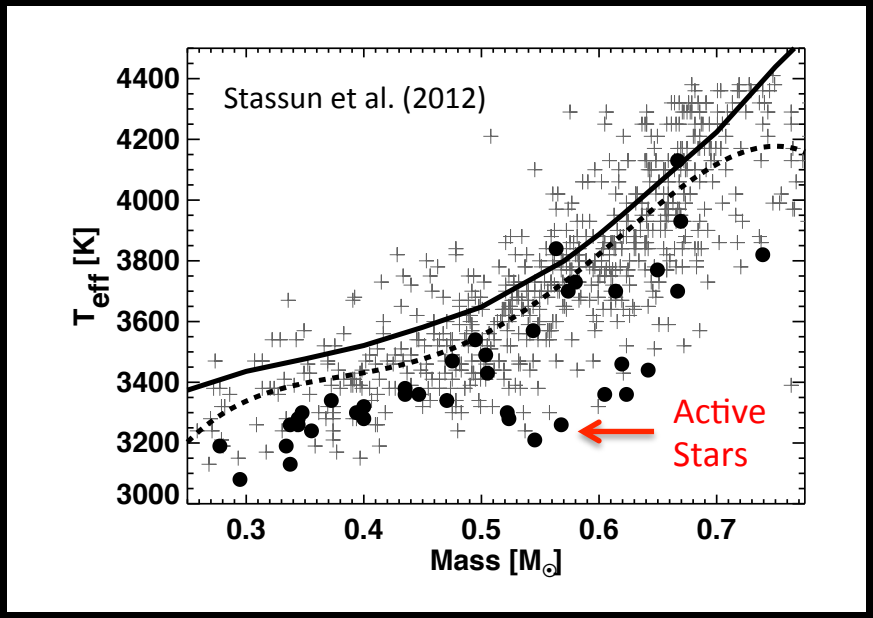
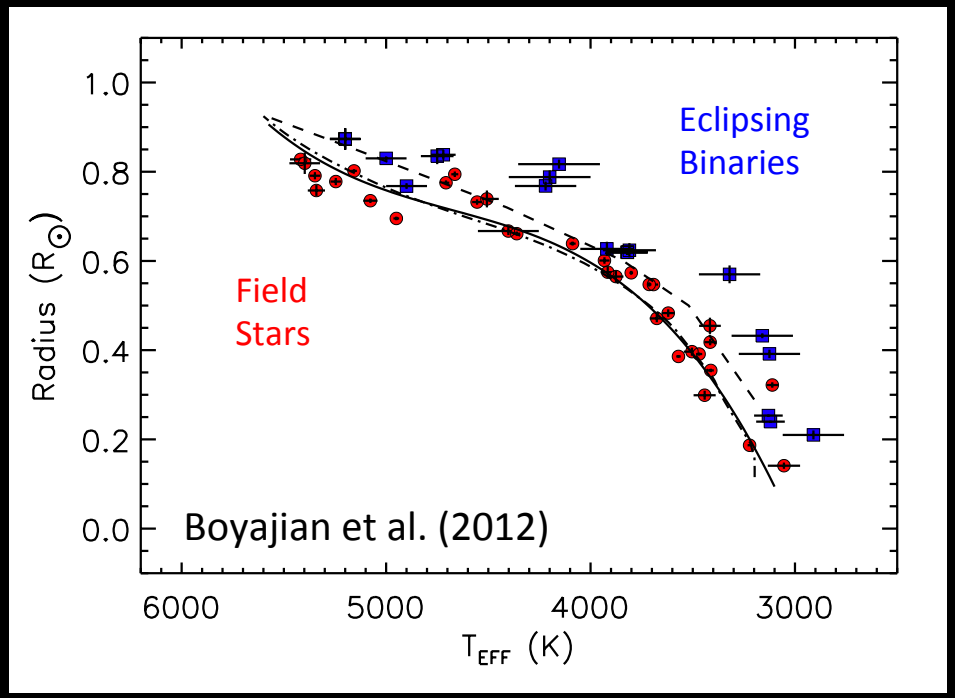
KOI 254/
Kepler 45
+0.50
+0.25
+0.00
-0.25
-0.50
[M/H]
Dartmouth
5 Gyr Isochrone
Preliminary:
More small stars with
sub-Earth planet
candidates in < 2 day
periods
KOI 961/
Kepler 42
◇ Cool KOI IV

Caveats/Research Problems



- How does activity change the connection between (Mass,Radius) and (T_{eff},[M/H])?

- AKA: What about magnetic fields!



More Research Problems

- Characterizing individual M dwarfs with exciting planets is fun…
- BUT we need physical parameters of ALL *Kepler* M dwarf targets for accurate statistics. Some possible approaches:
  - Spectra of all 3500 M dwarf targets?
    - Or a sub-sample, but how do you define it? Colors?
  - Better KIC color calibration to stellar mass and radius?
  - Parallaxes directly from *Kepler* data?
    - Few are willing to try. Crowd-source this for prize money?
  - Wait for *Gaia*… Launch next year!