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Interferometric Observations of Supergiants:
Direct Measures of the Very Largest Stars

VLTI PRIMA Project

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April 7, 2008

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M Dwarfs

Interferometric Observations of Supergiants:

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Smallest

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Back of the Envelope Estimate: Supergiants

- Guesstimates (things we *think* we know):
  - Main sequence stars: 1 $M_{\odot}$, 1 $R_{\odot}$
  - Supergiant stars: : 10 $M_{\odot}$, 100 $R_{\odot}$
- Stellar lifetime T goes as $T \sim M^{-4}$
  - There are $\times 10^4$ fewer supergiants than main sequence stars
- Supergiants are $\sim 10^4$ times brighter: will be detectable at a distance 100× further than main sequence stars
  - A volume $\times 10^6$ greater
- Number of observable targets goes linearly with volume
- Ergo, 10^2 more supergiants to observe at a given apparent size
  - Most main sequence stars <1 $R_{\odot}$, and most supergiants >100 $R_{\odot}$, so things are even better than this estimate

Supergiants are obvious targets for interferometers!

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Back of the Envelope Estimate: M-Dwarfs

- Guesstimates (things we *think* we know):
  - Solar-type stars: 1 $M_\odot$, 1 $R_\odot$
  - M-dwarfs stars: : 0.4 $M_\odot$, 0.4 $R_\odot$
- Stellar lifetime T goes as $T \sim M^{-4}$
  - There are ×40 more M-dwarfs than solar-type stars
- M-dwarfs are ~100× fainter: will be resolvable at a distance 10× smaller than main sequence stars
  - A volume ×10^3 smaller
- Number of observable targets goes linearly with volume
- Ergo, 25× fewer M-dwarfs to observe at a given apparent size
  - Already difficult to resolve more massive main sequence stars (solar type) due to small size

M-dwarfs are* not *obvious targets for interferometers!

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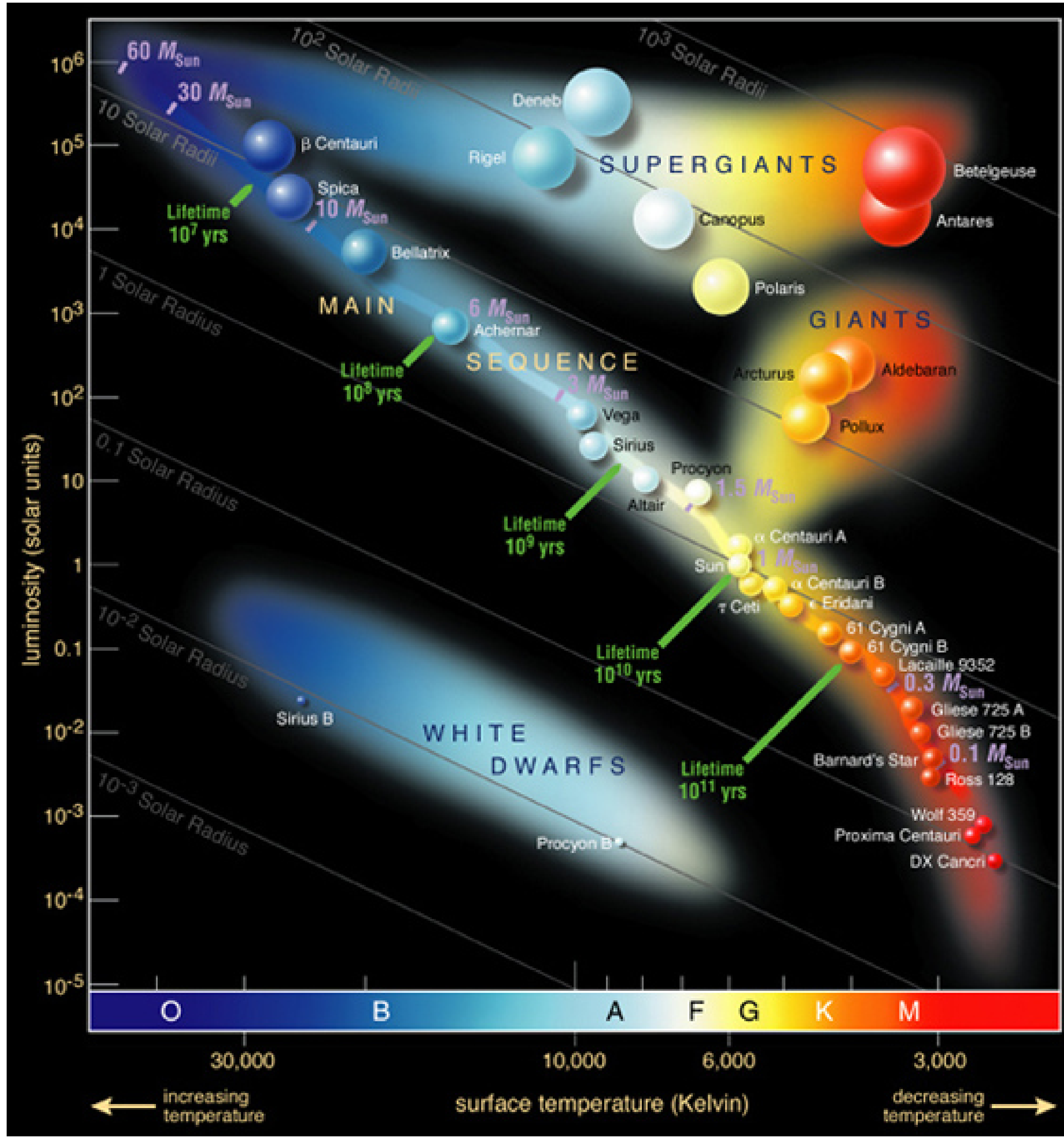
Essential Astrophysics: The HR Diagram

- Track/model stellar evolution
- Fundamental stellar properties
  - Luminosity
  - Radius
  - Temperature
- Examine properties of groups of stars
  - Clusters, associations



CHARA of Yesteryear: M-Dwarf Diameters

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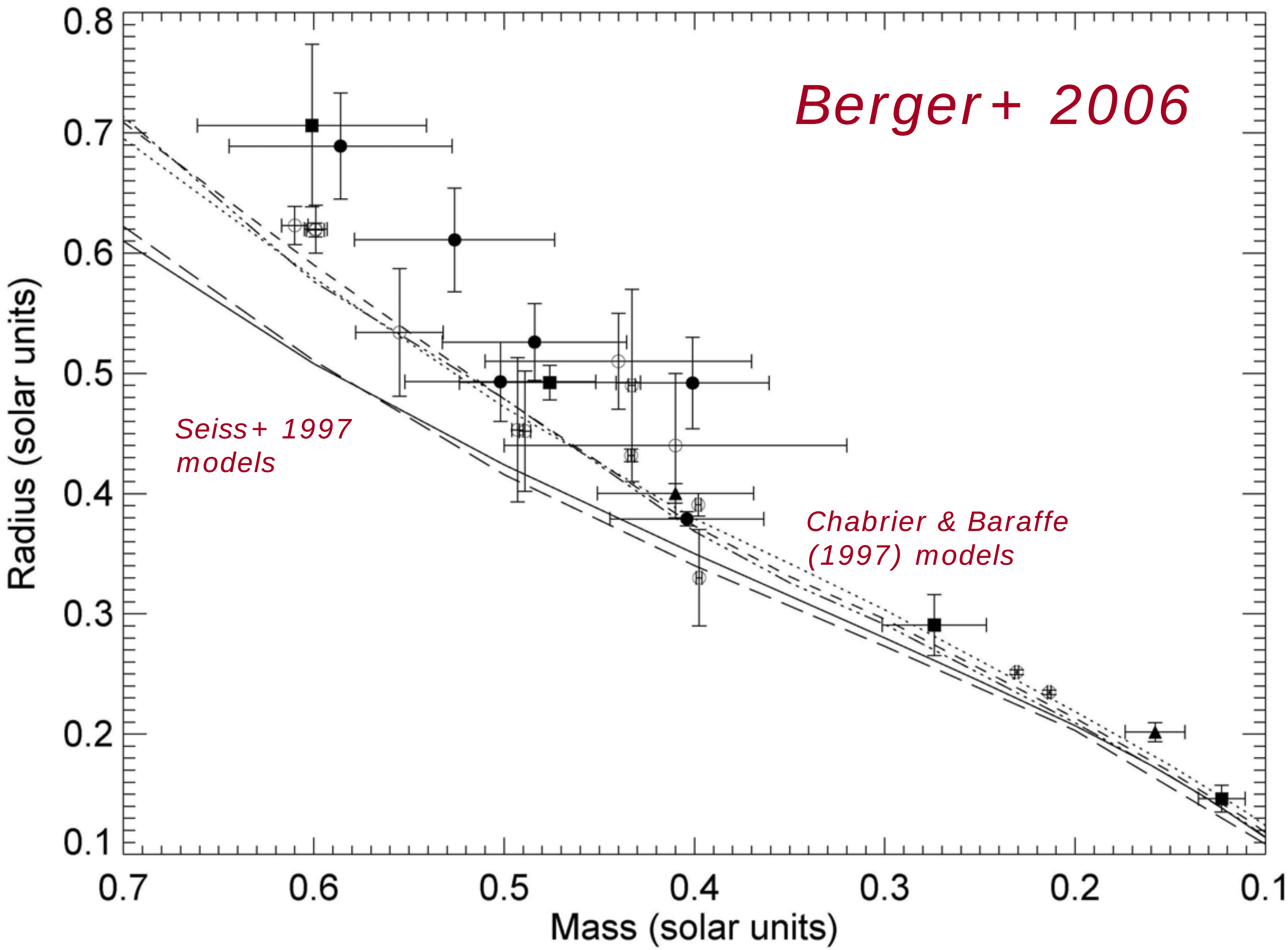

Metallicity Dependency of Diameter Deviation?

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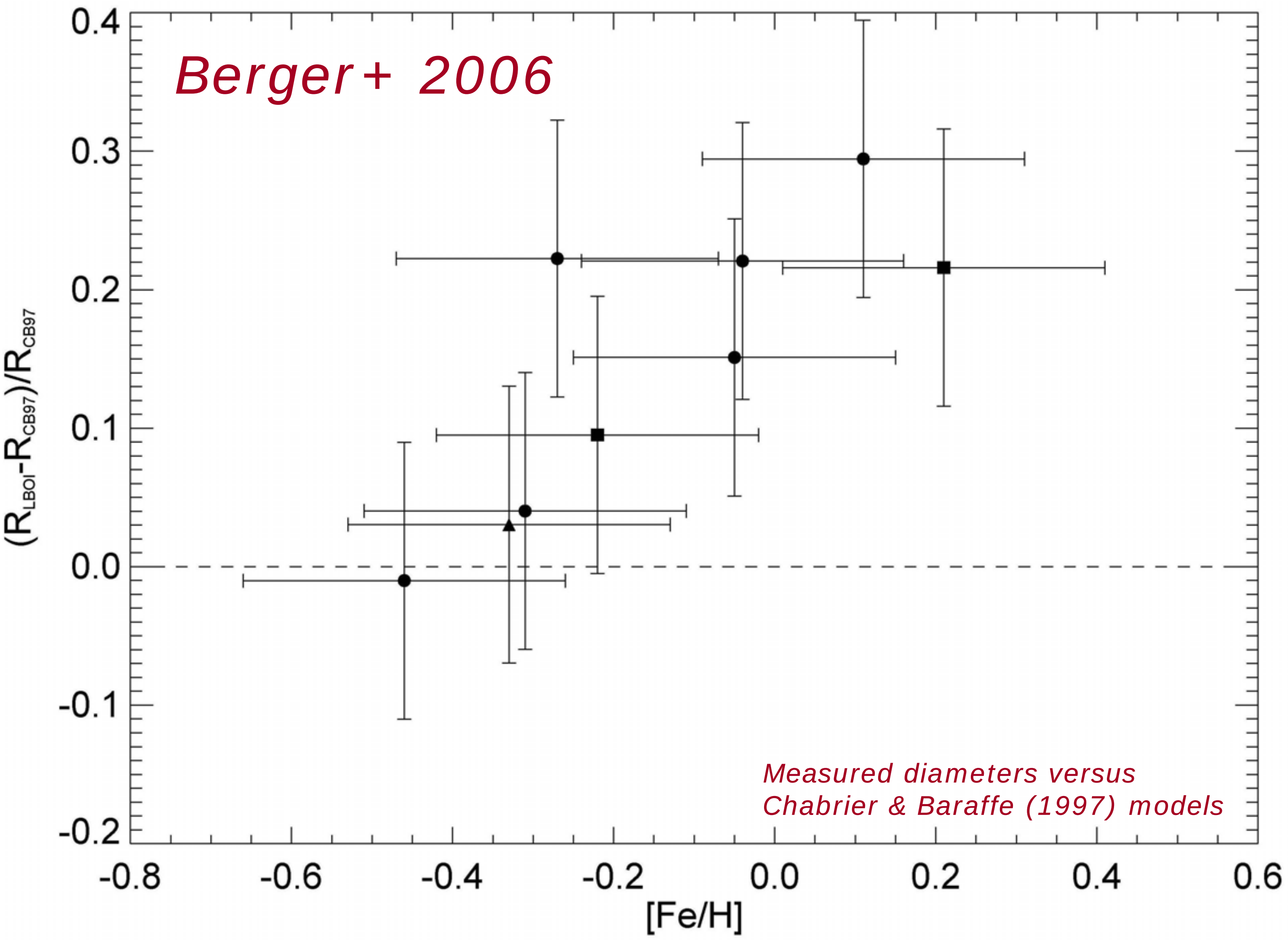

Basic Parameters from Angular Diameters (θ)

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- *Direct observation* of fundamental stellar parameters
- Effective temperature is defined as: $L = 4\pi\sigma R^2 T_{\mathrm{EFF}}^4$, which can be rewritten as:

$$T_{\mathrm{EFF}} = 1.316\times 10^7 \left(\frac{F_{\mathrm{BOL}}}{\theta_{\mathrm{R}}^2}\right)^{1/4}$$

  - F_{BOL} is the bolometric flux (W cm^{-2}), θ_{R} is the Rosseland mean stellar angular diameter (mas)
- Linear radius is simply: $R = \frac{1}{2}\theta \times d$
  - Hipparcos (Perryman et al. 1997) distances now available
  - For those M-dwarfs that are resolvable, they tend to be bright enough to have Hipparcos distances
  - But many nearby stars are too dim for good distances

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Nuances of F_{BOL} Fitting

- Stars are *not* blackbody radiators
  - Especially cool dwarfs: many features
- Spectral type estimates
  - Heterogeneous sources? By type (objective prism, slit spectroscopy, etc.) or practitioner
- Spectral type template
  - Empirical model (Pickles 1998) versus theoretical model (eg. Hauschildt's NextGen models)
- Photometry
  - Wide- and narrow-band can be used usefully
  - However, peak of flux curve at ~1μm for many M-dwarfs: most photometry here is quite poor
- Reddening
  - Can be degenerate with spectral type estimate in doing SED fitting
  - Not a significant factor for M-dwarfs

Bolometric Flux Fitting

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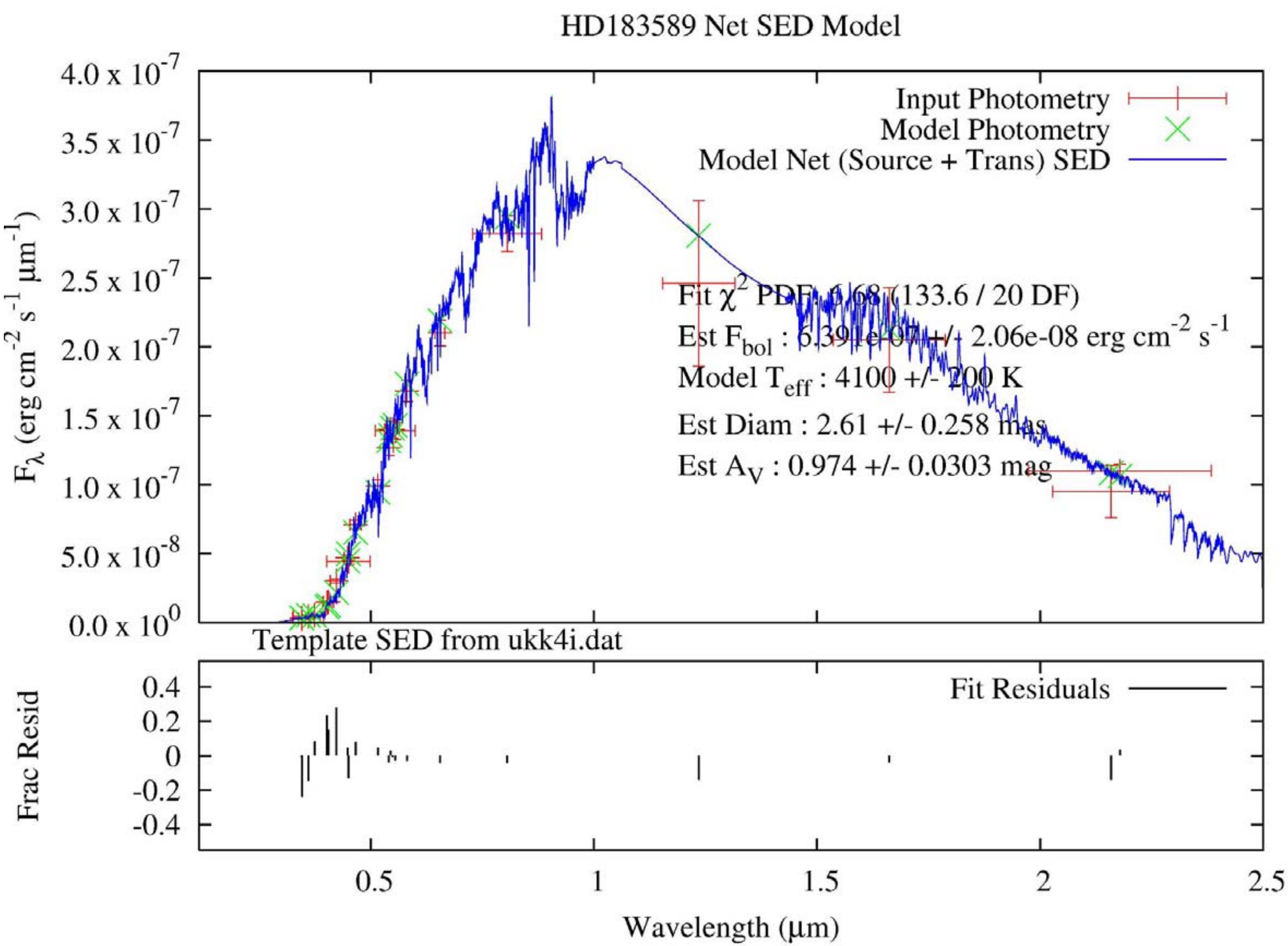

Bolometric Flux Fitting II.

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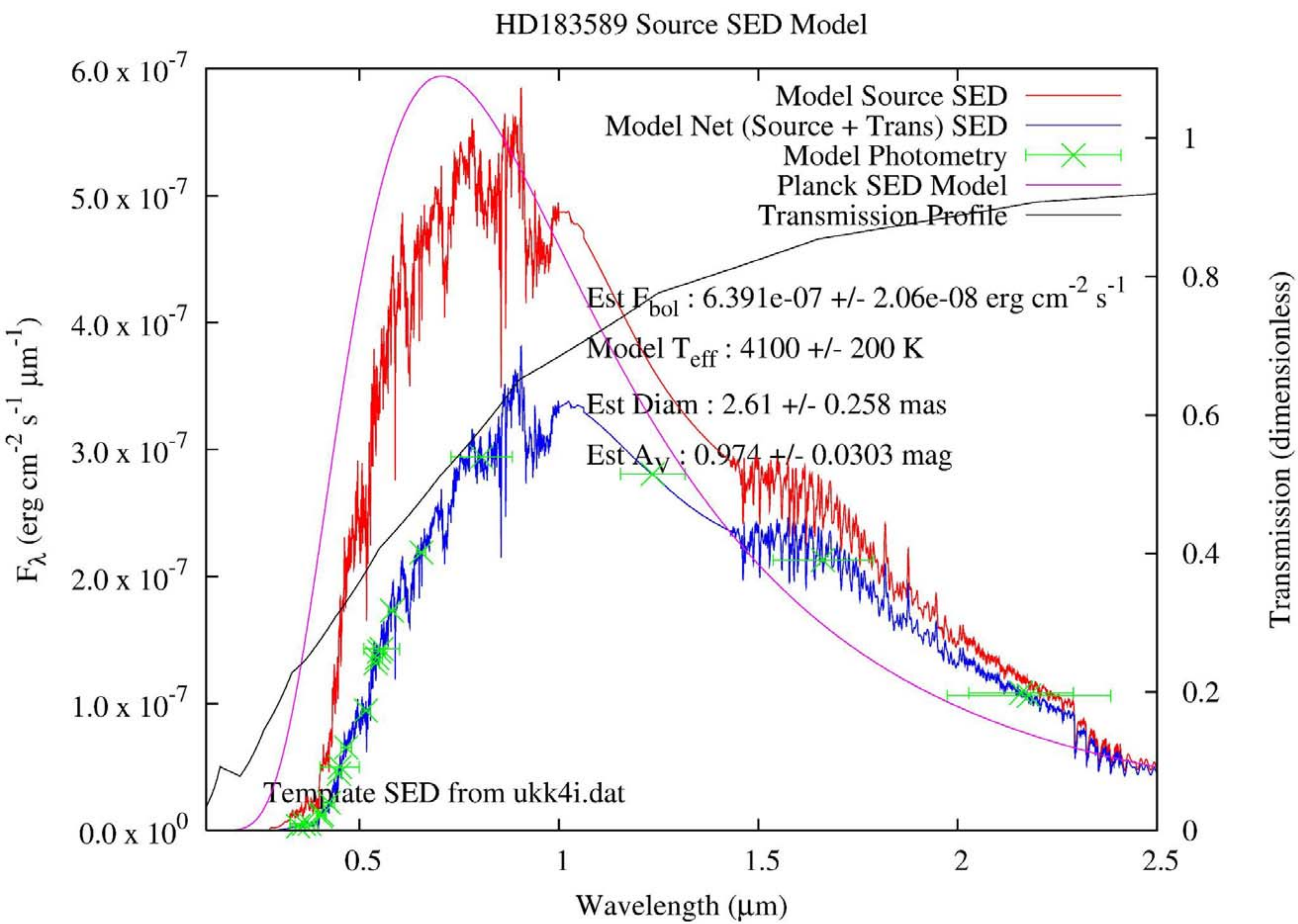

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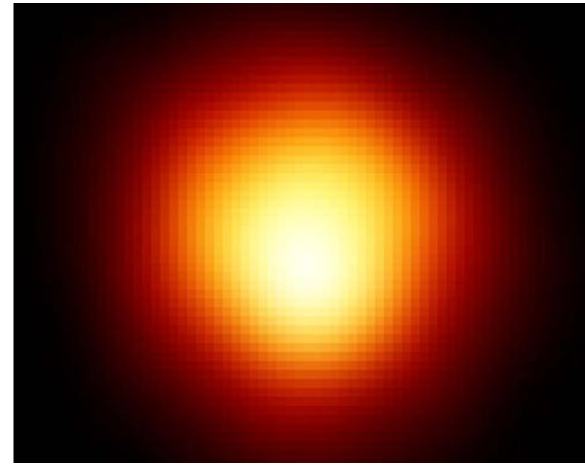
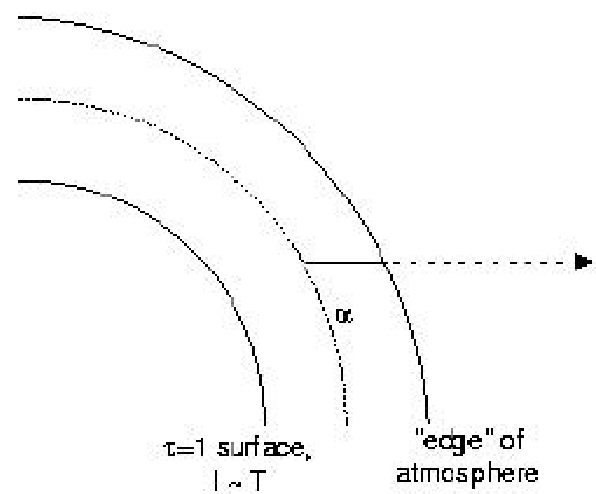
Limb darkening

- Stars are *not* uniform disks
- Gaseous, not solid, sphere
  - End up looking 'into' the star
- Good and bad
  - Have to account for this
  - Measuring this can be used to characterize internal structure of star
  - Direct probe of internal temperature structure
- For M-dwarfs, a model atmosphere will provide a correction factor from UD to LD
  - Correct account of molecular features? (Here be dragons!)



HST Image of α Ori - Betelgeuse



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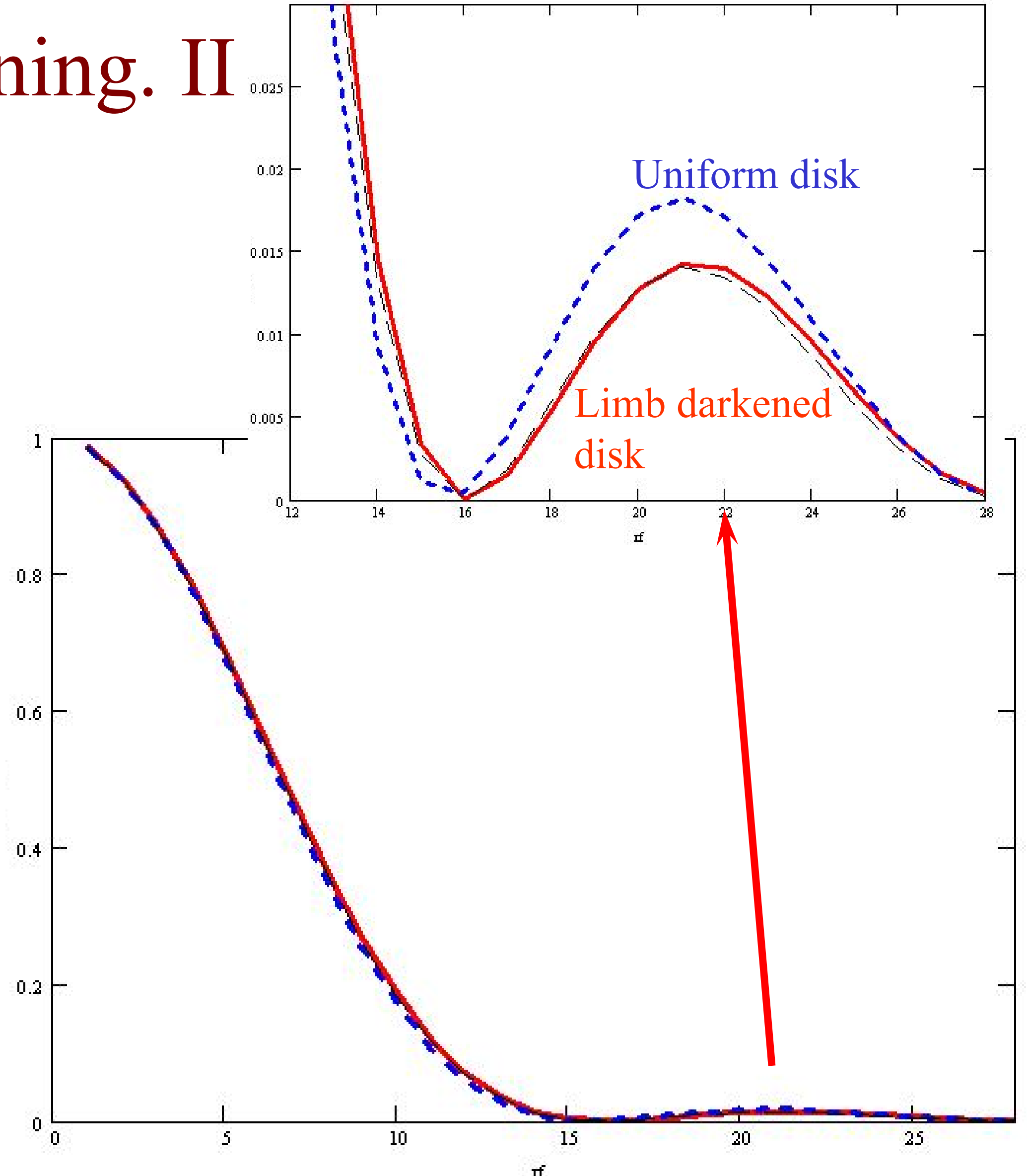
Limb darkening. II

- Effects are less striking in the near-IR
- Most of the effects are seen at the higher spatial frequencies
- Acceptable to do a UD fit, and scale
  - Gives the size of the mean radiating surface
  - Corrections are ~2% for M-dwarfs
  - *Scales with temperature*
  - Cooler → LD/UD↑



A-type Star Model (Claret et al. 1995)

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Current Stock of Results

- Borrowing from Davis (1997), increase of 145 to 340 stars in the literature (as of ~2003)
- Notable improvement: Application of interferometry to evolved stars
- Notable area for improvement: *Still* main sequence stars, **particularly late-type**, and supergiants
  - Homogenous, large datasets are absent from the literature for both

Spectral Type	I	II	III	IV	V
O	3	0	0	0	1
B0-B4	2	2	3	2	2
B5-B8	2	0	2	1	1
A0-A3	1	0	0	2	5
A5-A7	0	0	1	0	1
F0-F5	4	1	0	1	0
F8	2	0	0	0	0
G0-G5	3	1	2	3	0
G7-G9.5	2	1	22	0	0
K0-K3.5	5	16	31	0	0
K4-K7	3	1	14	0	0
M0-M4	12	13	70	0	0
M5-M8	1	2	31	0	0
Totals	40	37	176	9	10

Evolved Stars	
Carbon	22
M Miras	37
C Miras	5
S Miras	4
Total	68

Previous CHARA work : 6 Diameters

This work: 11 (and counting)

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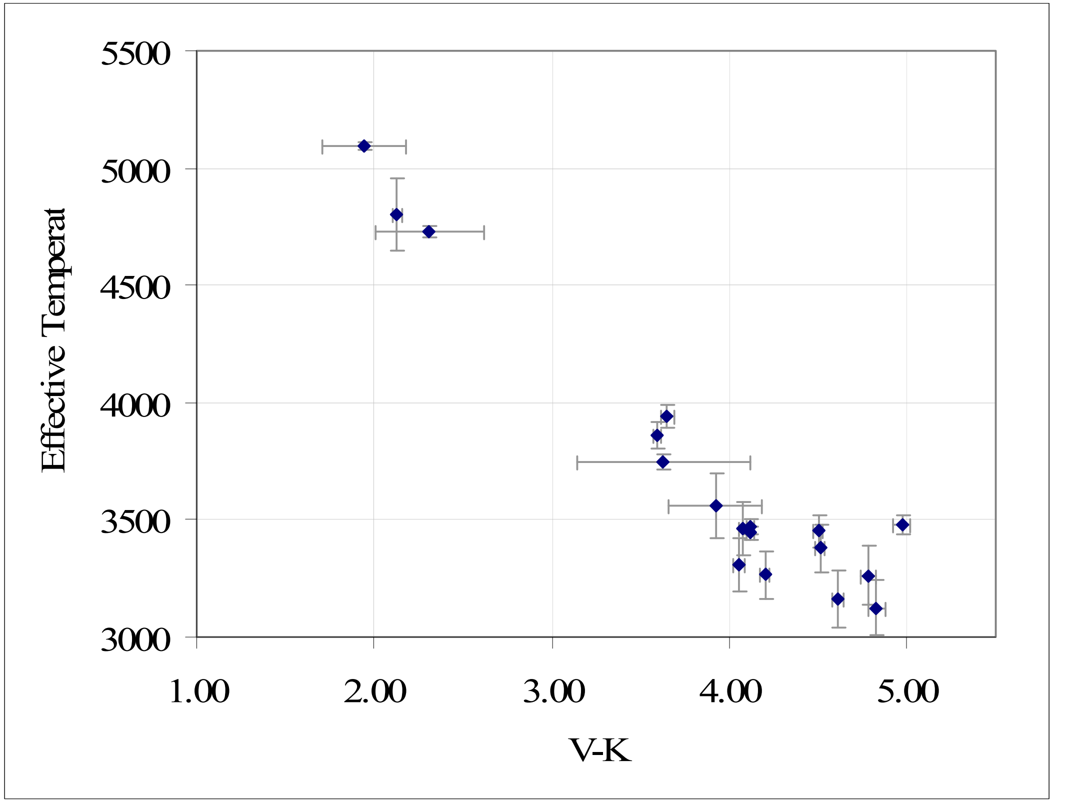
Effective Temperature versus V-K

- Most straightforward quantity: T_{EFF}
- "All V-K is good for is estimates of T_{EFF}"
  - This is not necessarily a bad thing
  - A **significantly** more robust index than spectral type
- Down to 3500K, curve seems fairly linear with V-K
- At T_{EFF}<3500K, curve seems to flatten out



Effective Temperature versus V-K

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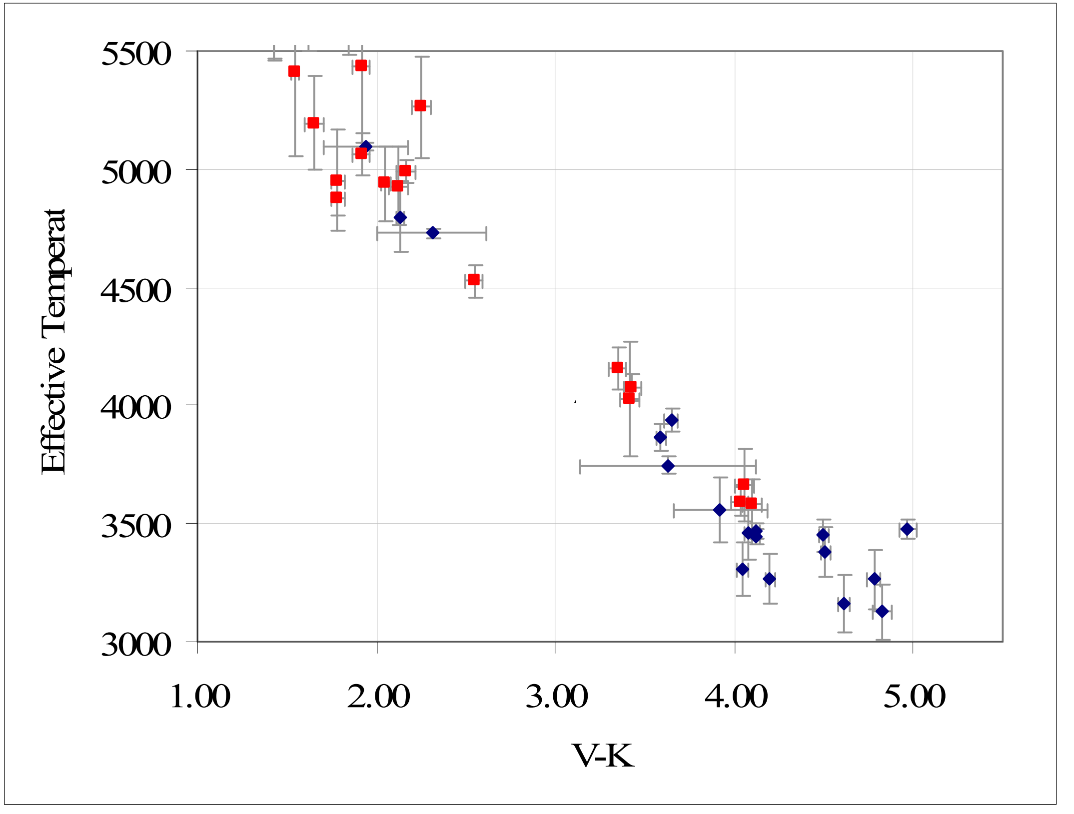
- Red points: PTI data
- Seems to bear out trend down to 3500K
  - Highlights power of CHARA, though, with smallest stars
- Low T_{EFF} versus V-K curve ‘flattening’ seen before: Miras
  - For Miras, was explained in terms of MOLsphere



Linear Radius versus V-K

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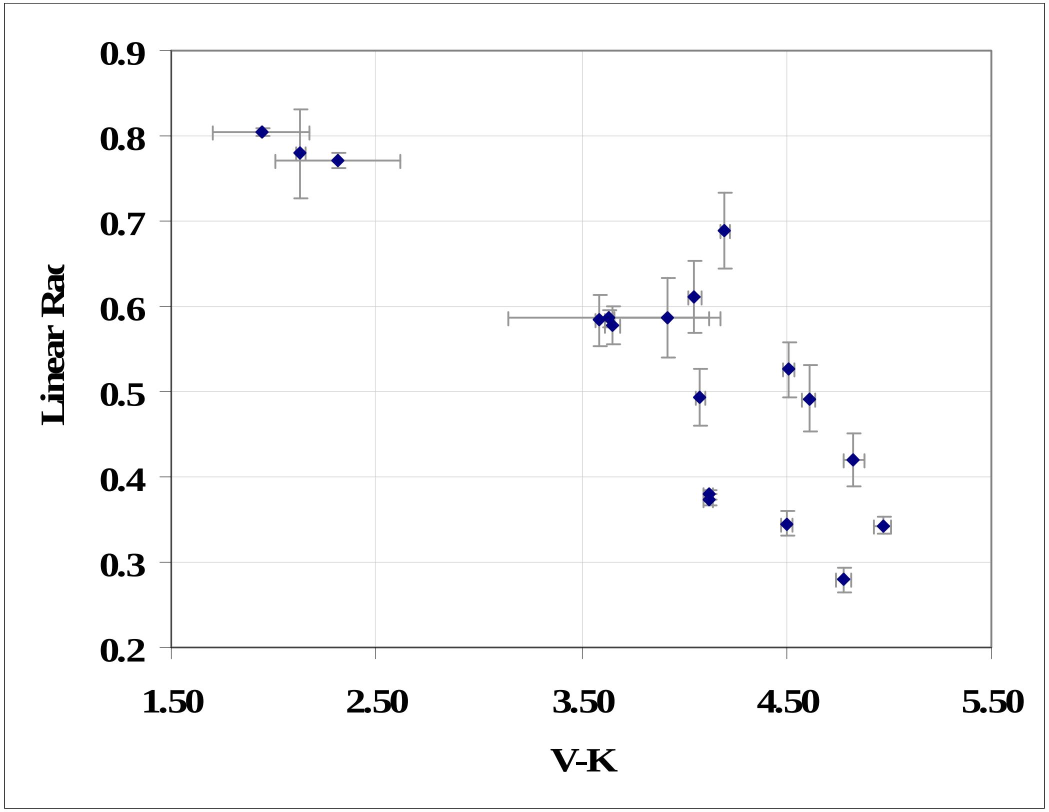
- Significant amounts of scatter seen as a function of V-K
  - eg. at V-K~4.0, factors of 2× see in linear radius
- As with T_{EFF}, starting to see 2nd order effects?
  - Age?
  - [Fe/H]?
  - Or just evidence that V-K poor proxy for *R*?



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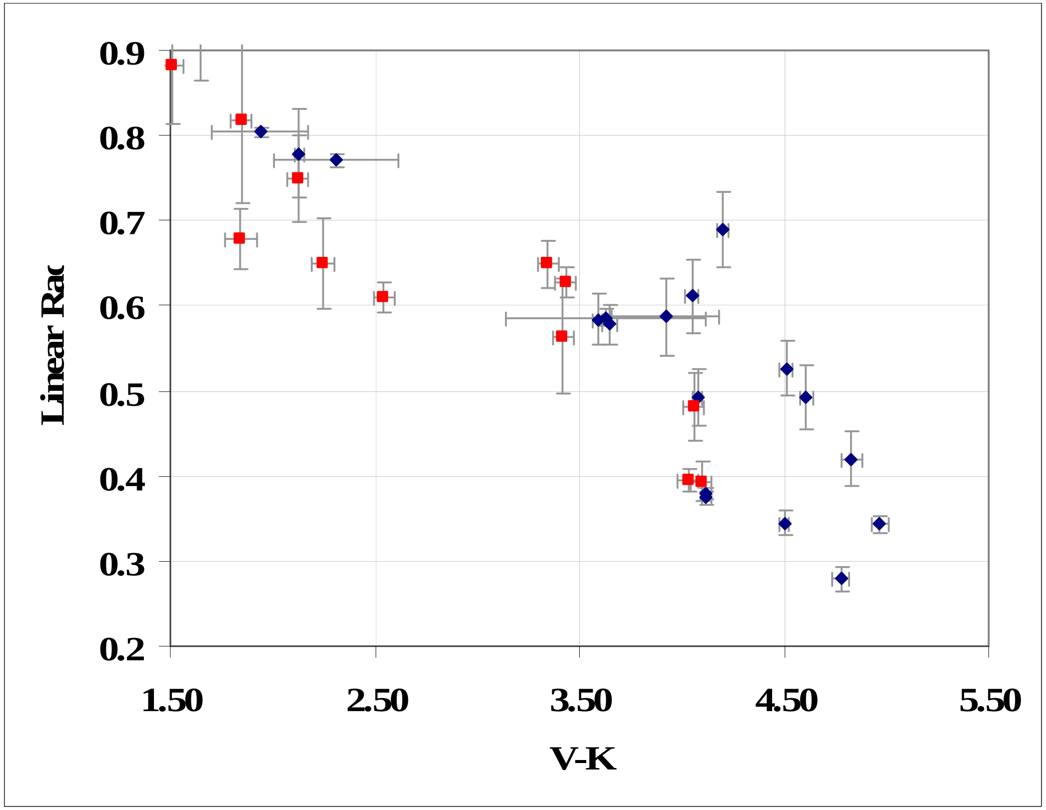
Linear Radius versus V-K

- Red points: PTI data
  - Some scatter as well (but not as much)
  - Different V-K regime



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Influence of [Fe/H] in Linear Radius?

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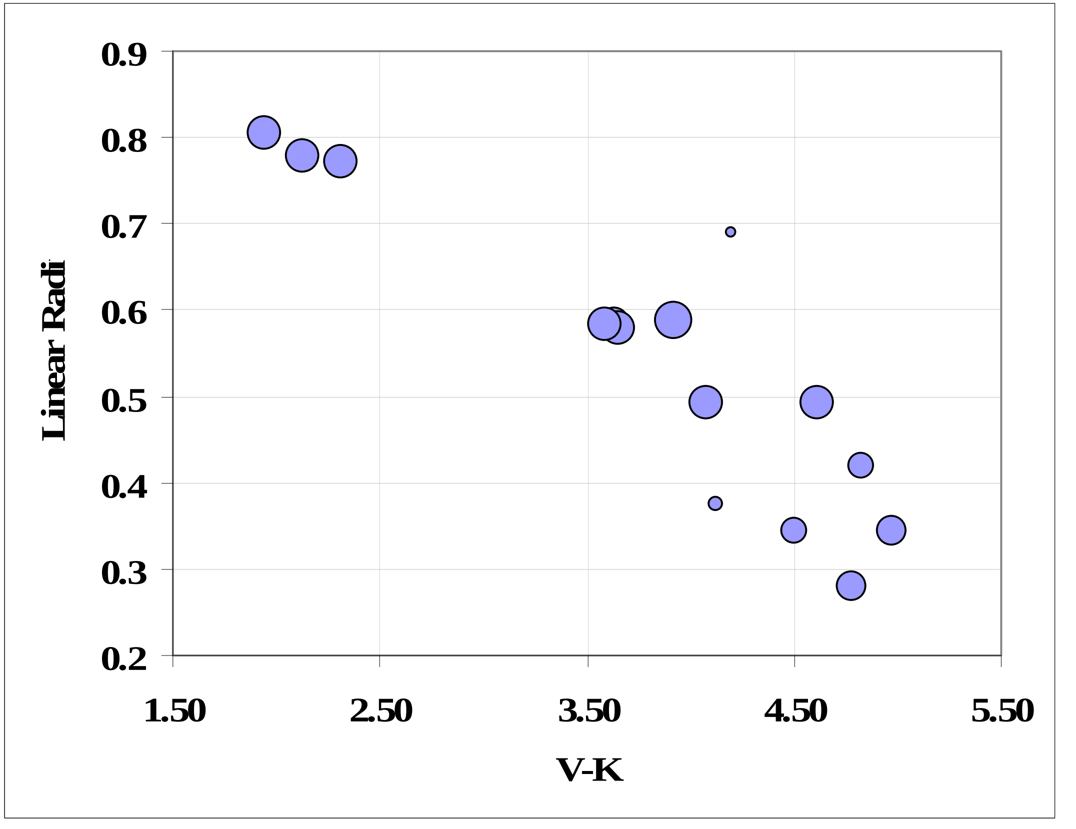
- Ranges from [Fe/H]=-1.5 (small bubble) to +0.50 (big bubble)
  - Interesting low [Fe/H] outliers at V-K~4
- Average value of -0.35
  - [Neglected to provide [Fe/H] for PTI data yet]



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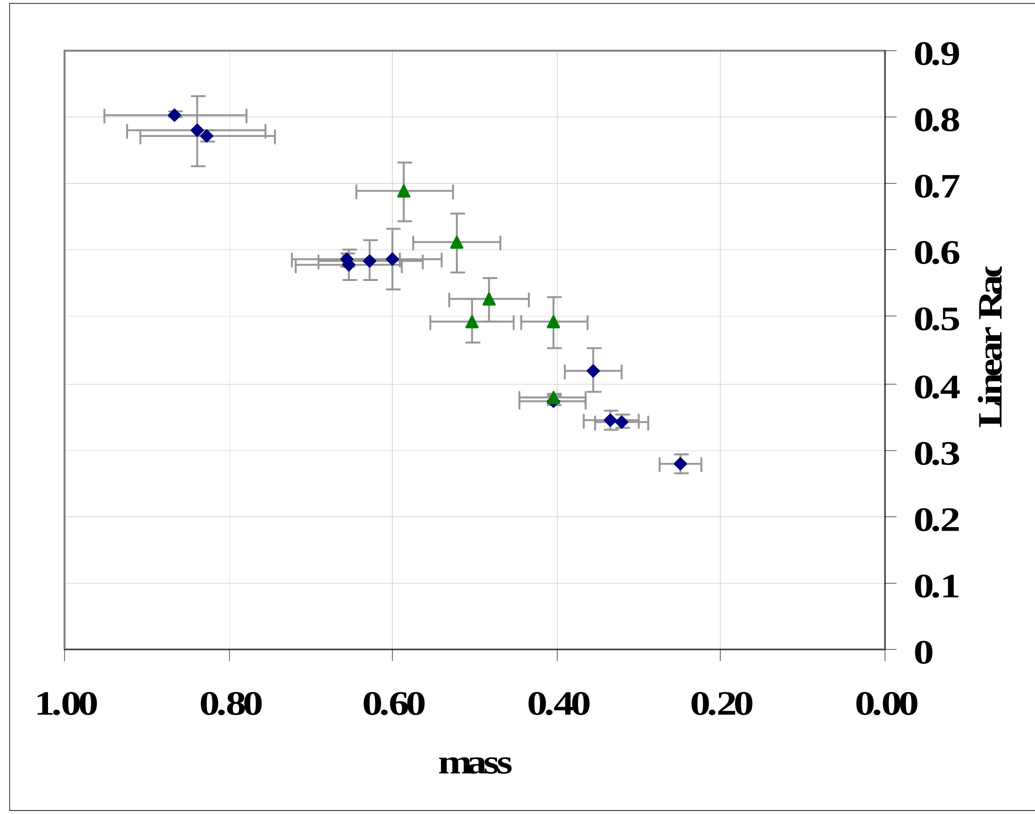
Radius versus Mass

- Mass from mass-M_K relationship found in Delfosse+ (2000)
- Green points: Berger+ (2006) CHARA
- Blue: new CHARA
- Red line: Chabrier & Baraffe (1997) model ([Fe/H]=0)
- Region of interest: 0.40-0.60 $M_\odot$
    - Convection peculiarities in models?
    - Missing from new data
    - Deviations due to **spotting**?



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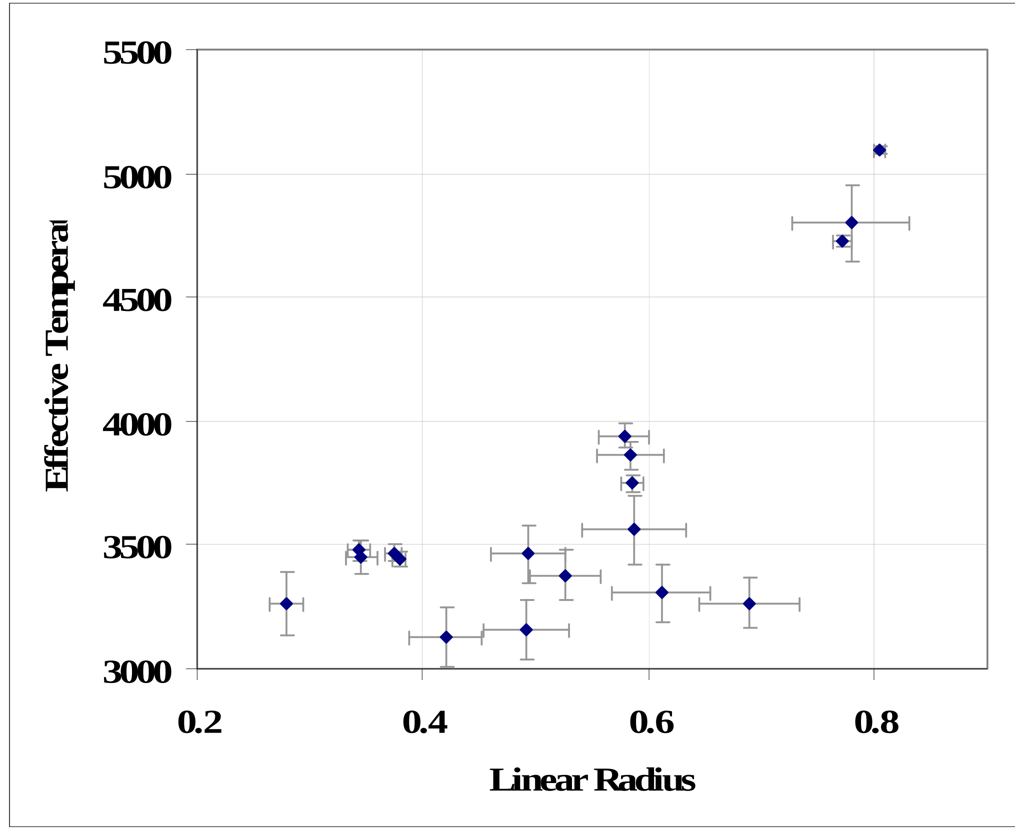
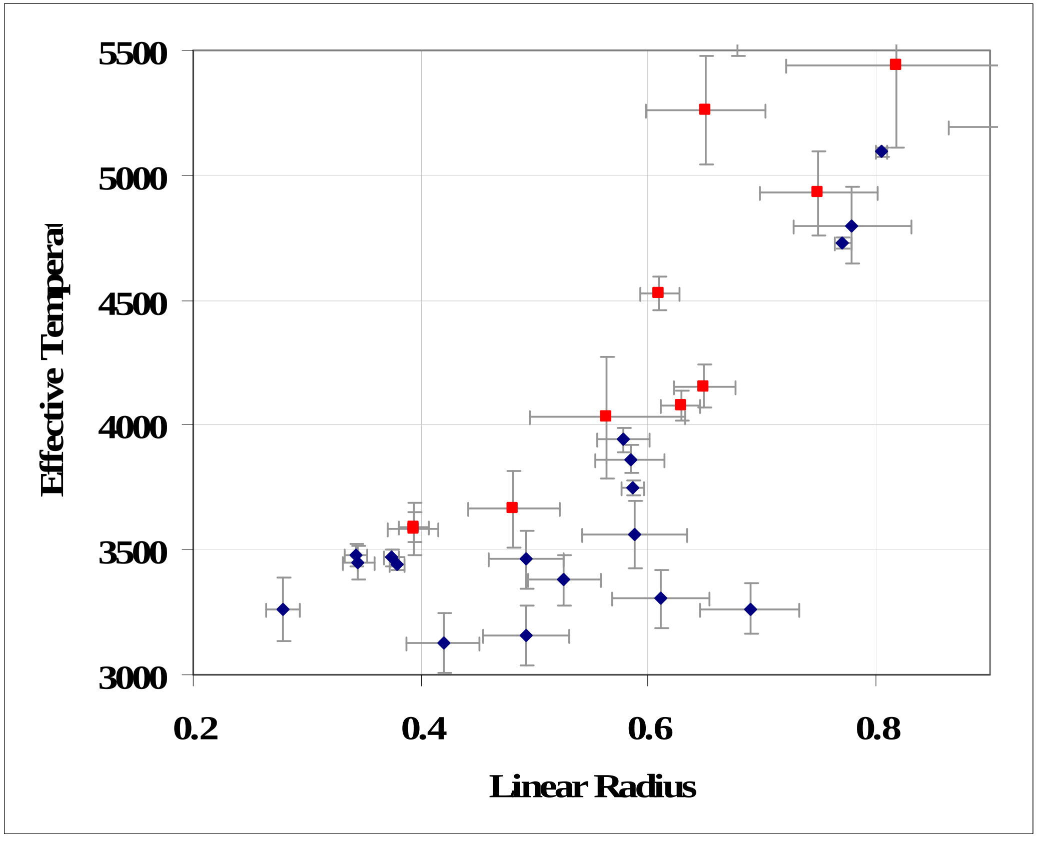
Temperature versus Radius

- More 'robust' and model-independent than measures of M, [Fe/H]
- However, a bit of plotting θ vs. θ
  - F_{BOL} data is the additional information
- As with T_{EFF} vs. V-K, linear trend down to 3500K(?) with 'pedestal' at <3500K?



Temperature versus Radius

- Red points: PTI data
- <3500K 'pedestal': 2nd order TEFF effects dominating?
  - Age, [Fe/H]?



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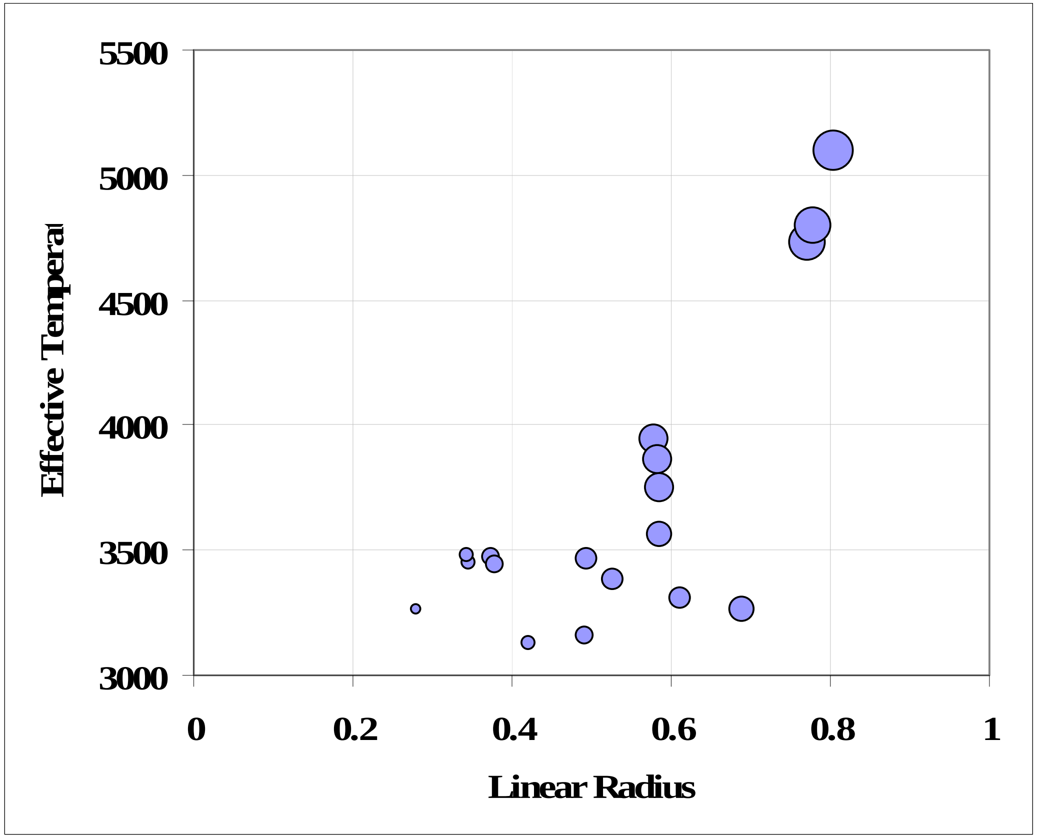
Temperature versus Radius: Relationship of Mass?

- Mass effect in T vs R?
- Bubble size a function of mass
  - 0.25-0.86 $M_{\odot}$



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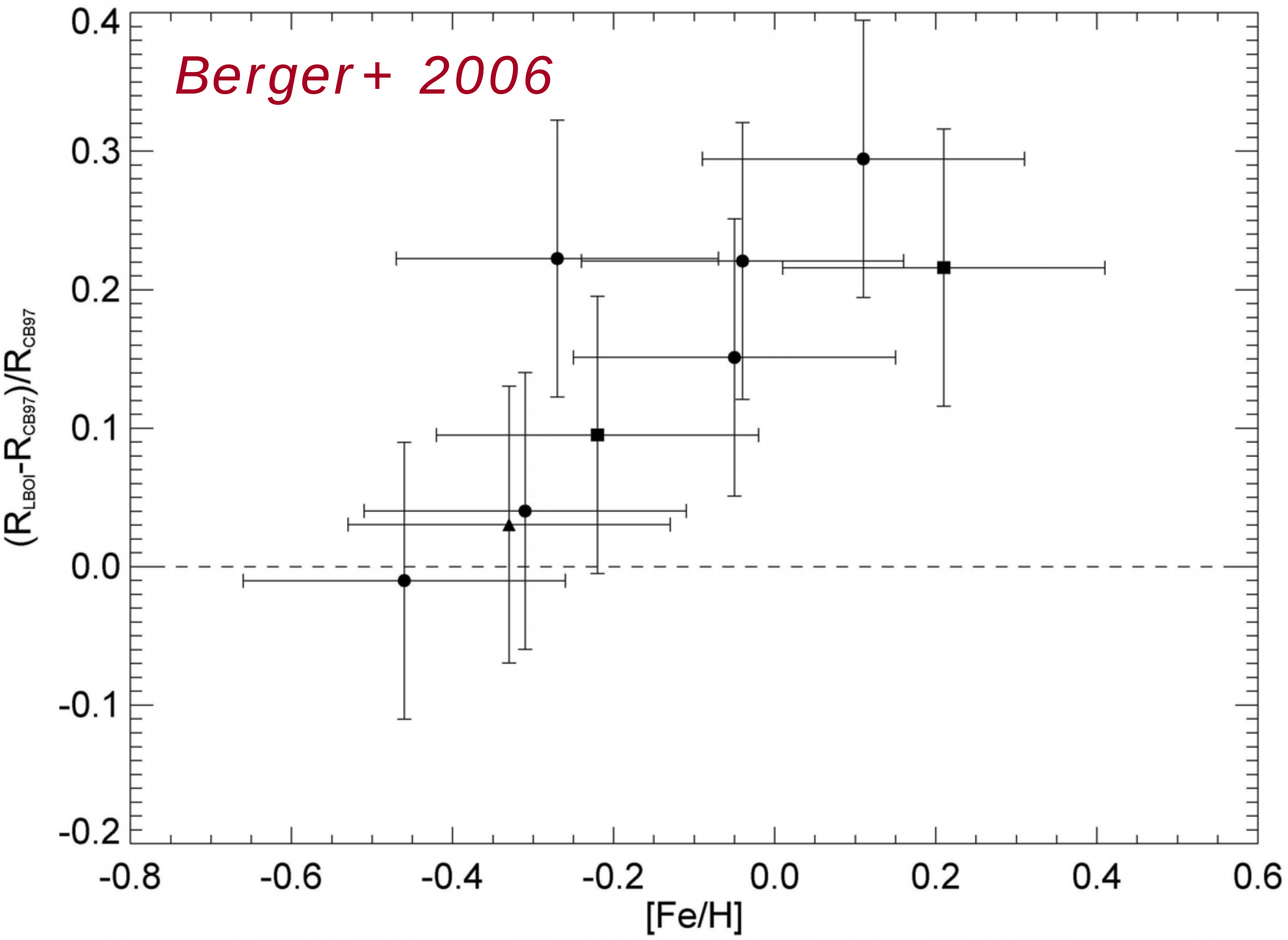
Remember this Plot?



Things Look a Little Different

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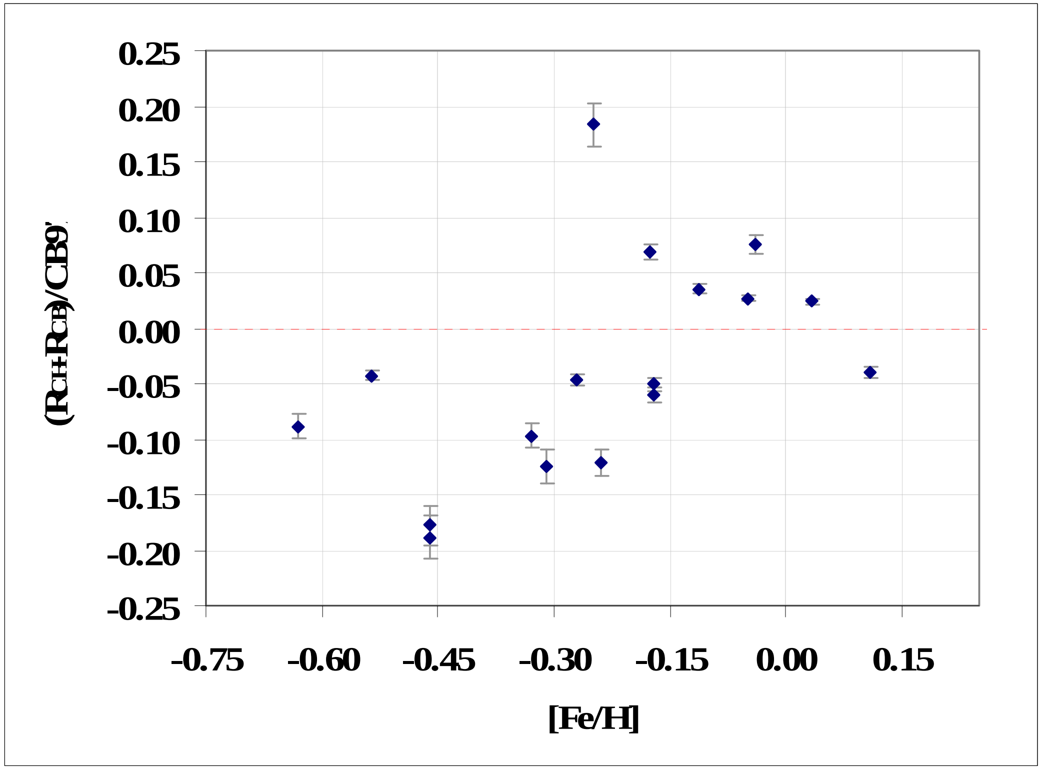
- Difficult to reproduce
  - Nominally includes Berger+ 2006 data
- How to derive 'predicted' R values from CB97?
  - $M_V \rightarrow M_{BOL}$ with $BC(T_{EFF}) \rightarrow L \rightarrow R(L)$
- Oh, and [Fe/H] values for M-dwarfs? All over the place



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The 'To-Do' List

- Further CHARA observations
  - In the 'sweet spot' of R={0.5,0.8} $R_{\odot}$, V-K={2.25,3.25}, M={0.4,0.6} $M_{\odot}$
  - Better precision?
    - Currently at $\sigma_{\theta} / \theta \sim 4.5\%$
    - Possible with repeating measures?
- Better supporting information
  - [Fe/H]
    - Homogenous measures a plus
  - Broad-band photometry: R,I (z?) bands
  - F_{BOL} errors reported at ~1%, but with $\chi_{\nu}^{2} >> 1$
- Chase after the new generation of models