Fundamental stellar parameters & the fine structure of the Low Main Sequence

Luca Casagrande

Max Planck Institute for Astrophysics

MPA: I. Ramírez, M. Asplund
CAUP: J. Meléndez
ANU: M. Bessell

Casagrande et al. (2010, A&A - in press; arXiv:1001.3142)

✓ Effective Temperatures
✓ Bolometric Luminosities
✓ Angular diameters

&

the fine structure of the Low Main Sequence

Luca Casagrande

Max Planck Institute
for Astrophysics

MPA: I. Ramírez, M. Asplund
CAUP: J. Meléndez
ANU: M. Bessell

Casagrande et al. (2010, A&A - in press; arXiv:1001.3142)

Effective Temperature

Direct: interferometry (Hanbury Brown et al. 1974, van Belle & von Braun 2009)

- ✓ precise & accurate
- \- nearby stars (limited range)
- \- uniform disk

$$\mathcal{F}_{Bol}(\mathrm{Earth}) = \left(\frac{\theta}{2}\right)^2 \sigma T_{\mathrm{eff}}^4$$

UD → LD

Allende Prieto et al. (2002)
Bigot et al. (2006)
Koesterke et al. (2008)

Allende Prieto et al. (2002)

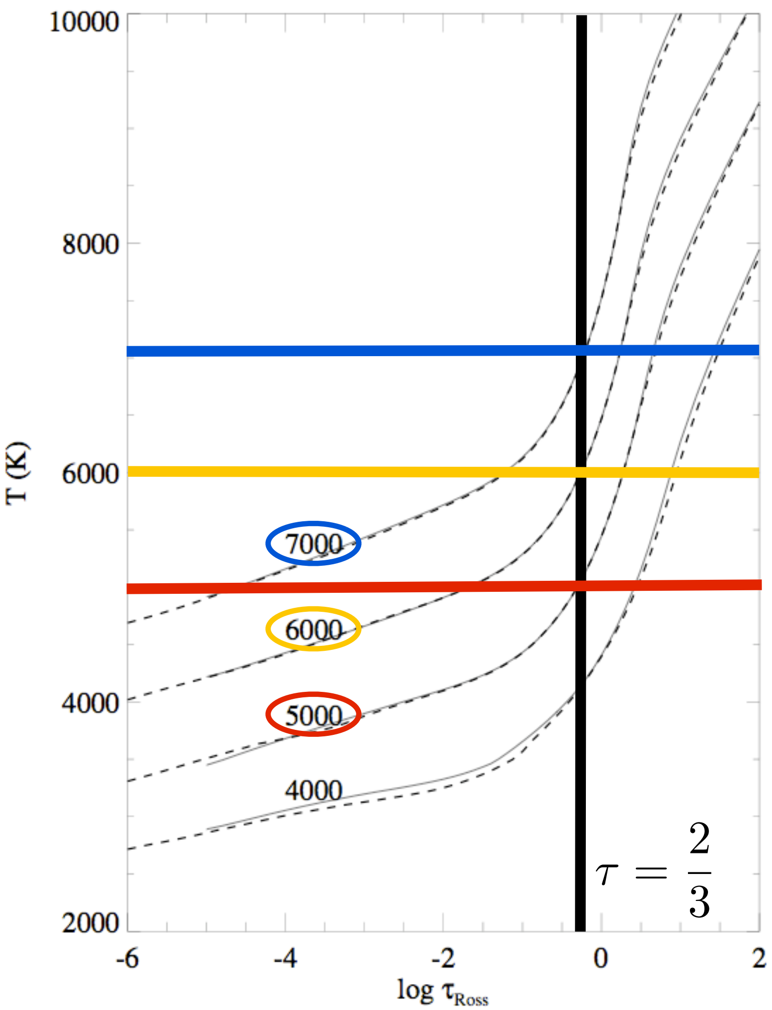
Semi-Direct: InfraRed Flux Method

$$\frac{\mathcal{F}_{Bol}(\mathrm{Earth})}{\mathcal{F}_{\mathrm{IR}}(\mathrm{Earth})} = \frac{\sigma T_{\mathrm{eff}}^4}{\mathcal{F}_{\mathrm{IR}}(\mathrm{model})}$$

- ✓ precise
- ✓ ~ model-independent
- ✓ any star (photometry)
- \- reddening
- \- accuracy: absolute calibration

Indirect: ionization/excitation, Balmer lines, line-depth ratio

- ✓ precise
- ✓ any stars (spectra)
- \- model dependent (NLTE, inhomogeneity, e.g. Asplund 2005, Ludwig et al. 2009)



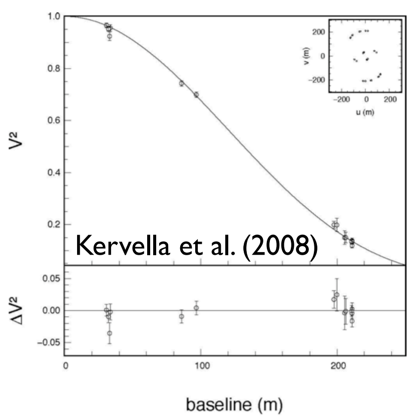
Gustafsson et al. (2008)

Effective Temperature

Direct: interferometry (Hanbury Brown et al. 1974, van Belle & von Braun 2009)

- ✓ **precise & accurate**
- \- **nearby stars (limited range)**
- \- **uniform disk**

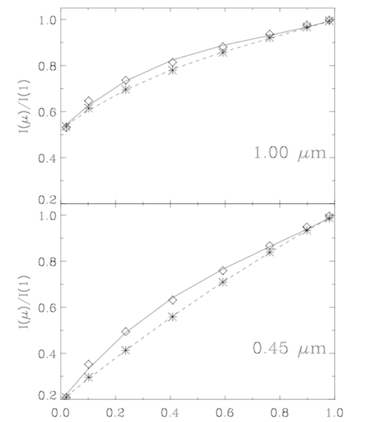
$$\mathcal{F}_{Bol}(\mathrm{Earth}) = \left(\frac{\theta}{2}\right)^2 \sigma T_{\mathrm{eff}}^4$$



Kervella et al. (2008)

UD → LD

Allende Prieto et al. (2002)
Bigot et al. (2006)
Koesterke et al. (2008)

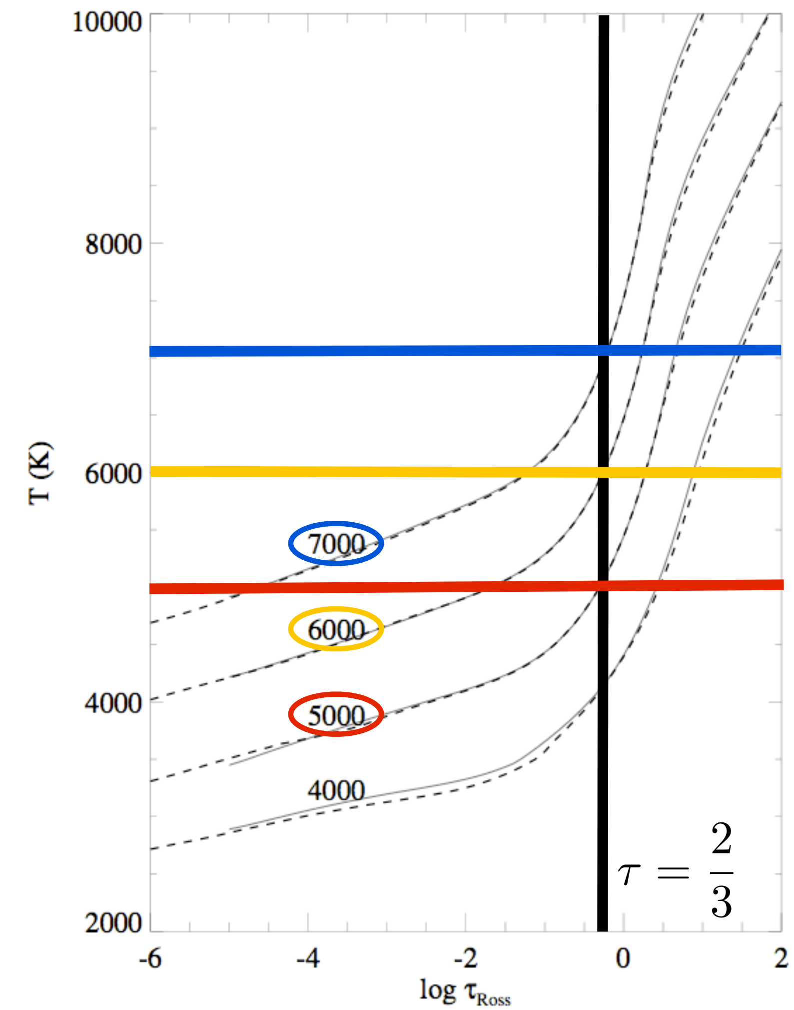


Allende Prieto et al. (2002)

Semi-Direct: InfraRed Flux Method

- ✓ **precise**
- ✓ **~ model-independent**
- ✓ **any star** (photometry)
- \- **reddening**
- \- **accuracy: absolute calibration**

$$\frac{\mathcal{F}_{Bol}(\mathrm{Earth})}{\mathcal{F}_{\mathrm{IR}}(\mathrm{Earth})} = \frac{\sigma T_{\mathrm{eff}}^4}{\mathcal{F}_{\mathrm{IR}}(\mathrm{model})}$$



Gustafsson et al. (2008)

Indirect: ionization/excitation, Balmer lines, line-depth ratio

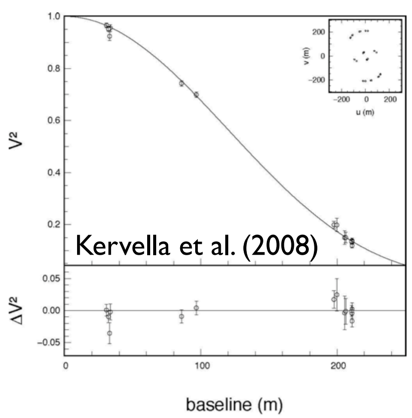
- ✓ **precise**
- ✓ **any stars** (spectra)
- \- **model dependent** (NLTE, inhomogeneity, e.g. Asplund 2005, Ludwig et al. 2009)

Effective Temperature

Direct: interferometry (Hanbury Brown et al. 1974, van Belle & von Braun 2009)

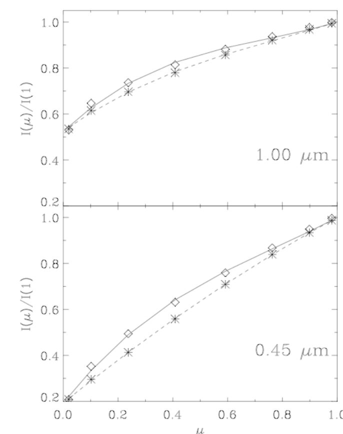
- ✓ **precise & accurate**
- - **nearby stars (limited range)**
- - **uniform disk**

$$\mathcal{F}_{Bol}(\text{Earth}) = \left(\frac{\theta}{2}\right)^2 \sigma T_{\text{eff}}^4$$



UD → LD

Allende Prieto et al. (2002)
Bigot et al. (2006)
Koesterke et al. (2008)



Allende Prieto et al. (2002)

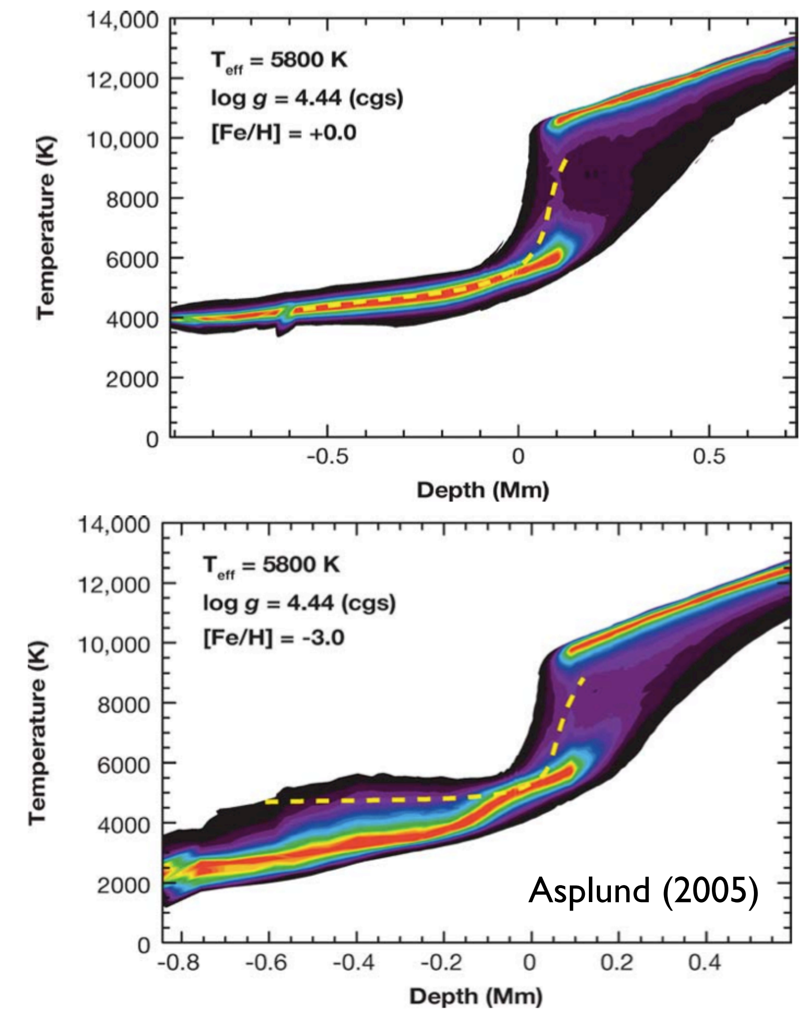
Semi-Direct: InfraRed Flux Method

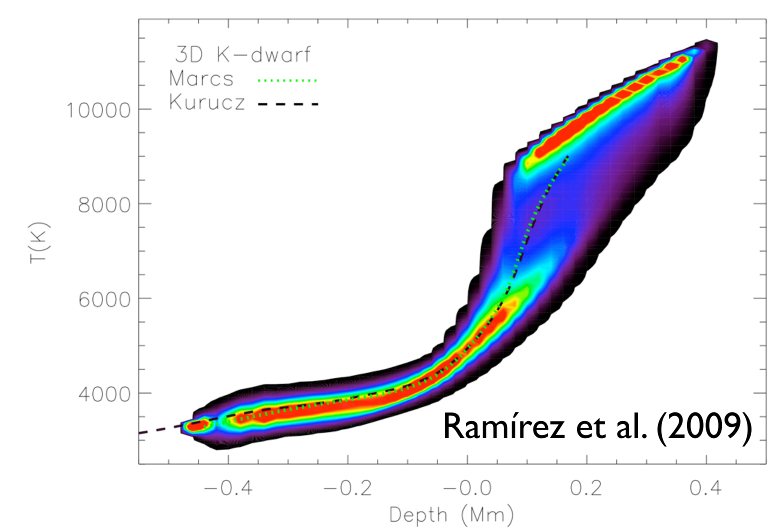
- ✓ precise
- ✓ ~ model-independent
- ✓ any star (photometry)
- - reddening
- - accuracy: absolute calibration

$$\frac{\mathcal{F}_{Bol}(\text{Earth})}{\mathcal{F}_{\text{IR}}(\text{Earth})} = \frac{\sigma T_{\text{eff}}^4}{\mathcal{F}_{\text{IR}}(\text{model})}$$

Indirect: ionization/excitation, Balmer lines, line-depth ratio

- ✓ precise
- ✓ any stars (spectra)
- - model dependent (NLTE, inhomogeneity, e.g. Asplund 2005, Ludwig et al. 2009)



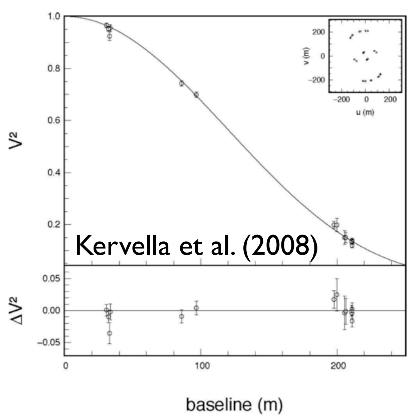


Effective Temperature

Direct: interferometry (Hanbury Brown et al. 1974, van Belle & von Braun 2009)

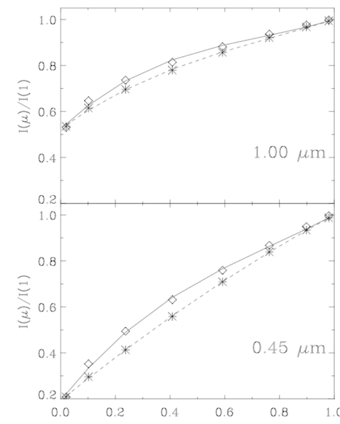
- ✓ precise & accurate
- \- nearby stars (limited range)
- \- uniform disk

$$\mathcal{F}_{Bol}(\mathrm{Earth}) = \left(\frac{\theta}{2}\right)^2 \sigma T_{\mathrm{eff}}^4$$



UD → LD

Allende Prieto et al. (2002)
Bigot et al. (2006)
Koesterke et al. (2008)

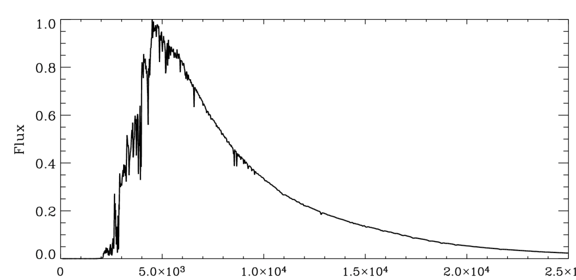


Allende Prieto et al. (2002)

Semi-Direct: InfraRed Flux Method

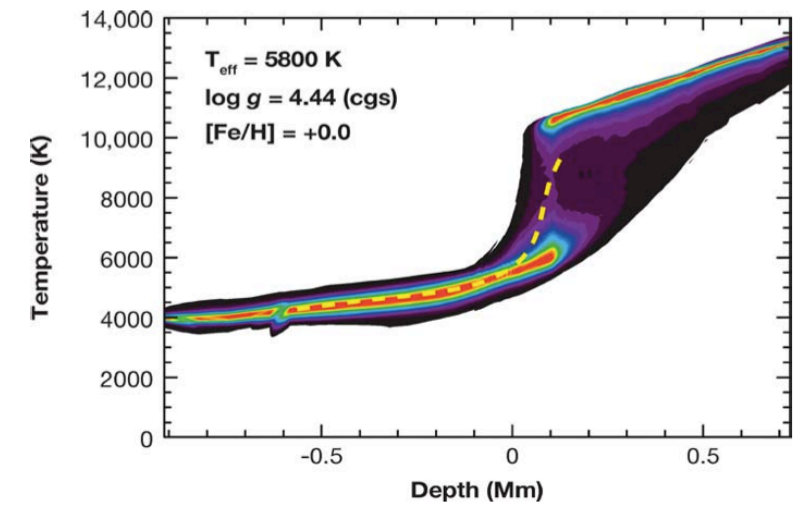
- ✓ precise
- ✓ ~ model-independent
- ✓ any star (photometry)
- \- reddening
- \- accuracy: absolute calibration

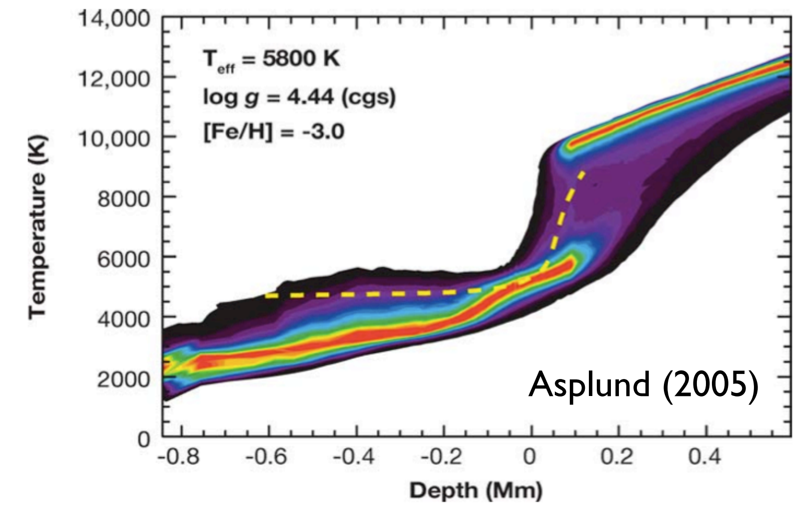
$$\frac{\mathcal{F}_{Bol}(\mathrm{Earth})}{\mathcal{F}_{\mathrm{IR}}(\mathrm{Earth})} = \frac{\sigma T_{\mathrm{eff}}^4}{\mathcal{F}_{\mathrm{IR}}(\mathrm{model})}$$

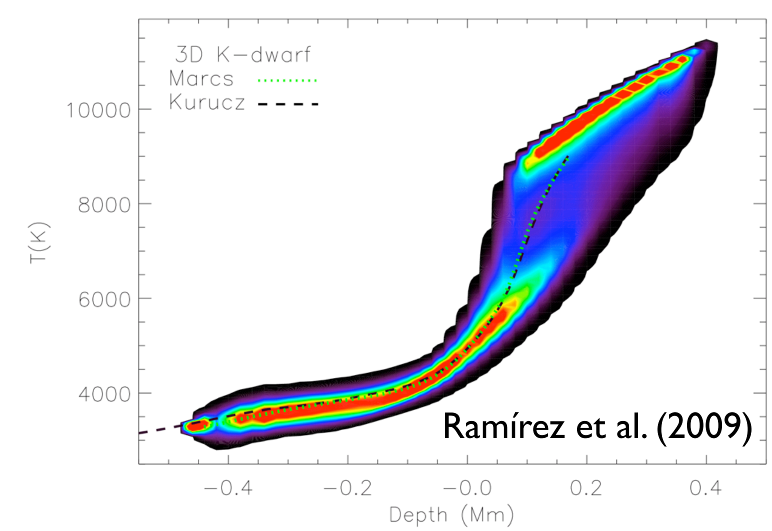


Indirect: ionization/excitation, Balmer lines, line-depth ratio

- ✓ precise
- ✓ any stars (spectra)
- \- model dependent (NLTE, inhomogeneity, e.g. Asplund 2005, Ludwig et al. 2009)





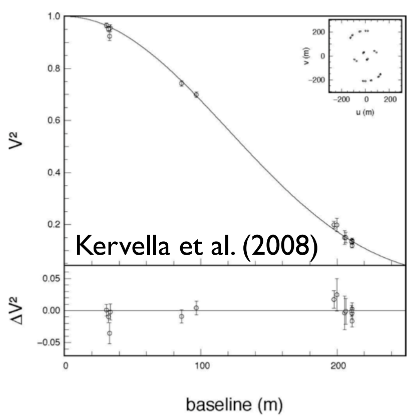


Effective Temperature

Direct: interferometry (Hanbury Brown et al. 1974, van Belle & von Braun 2009)

- ✓ **precise & accurate**
- \- **nearby stars (limited range)**
- \- **uniform disk**

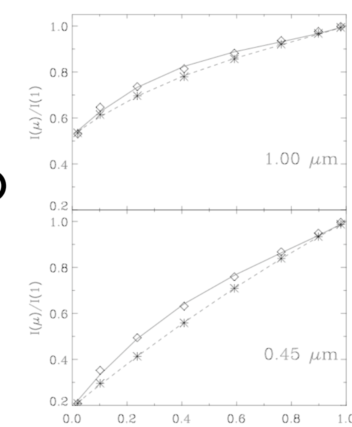
$$\mathcal{F}_{Bol}(\mathrm{Earth}) = \left(\frac{\theta}{2}\right)^2 \sigma T_{\mathrm{eff}}^4$$



Kervella et al. (2008)

UD → LD

Allende Prieto et al. (2002)
Bigot et al. (2006)
Koesterke et al. (2008)

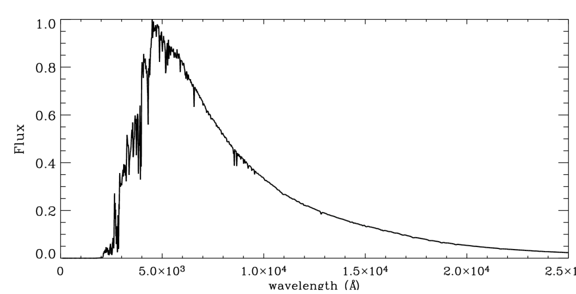


Allende Prieto et al. (2002)

Semi-Direct: InfraRed Flux Method

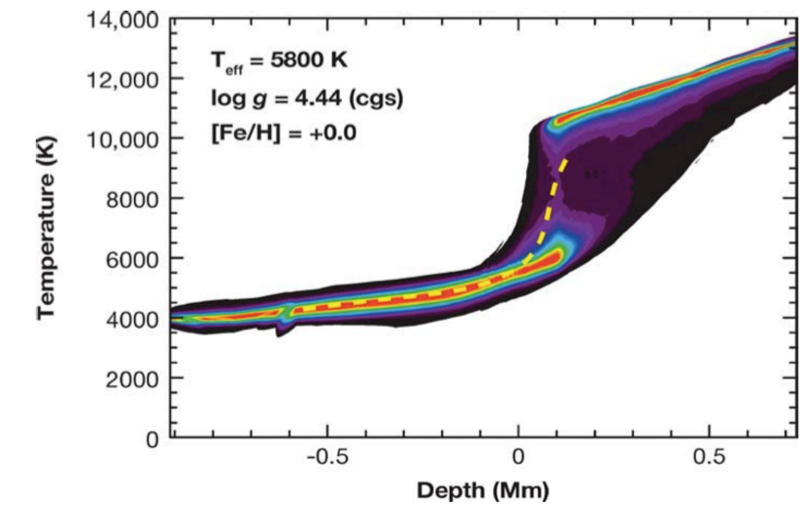
- ✓ **precise**
- ✓ **~ model-independent**
- ✓ **any star (photometry)**
- \- **reddening**
- \- **accuracy: absolute calibration**

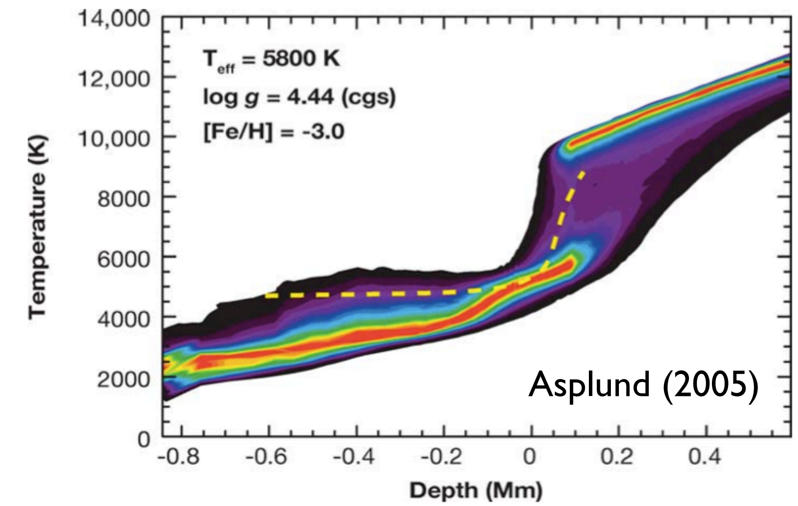
$$\frac{\mathcal{F}_{Bol}(\mathrm{Earth})}{\mathcal{F}_{\mathrm{IR}}(\mathrm{Earth})} = \frac{\sigma T_{\mathrm{eff}}^4}{\mathcal{F}_{\mathrm{IR}}(\mathrm{model})}$$



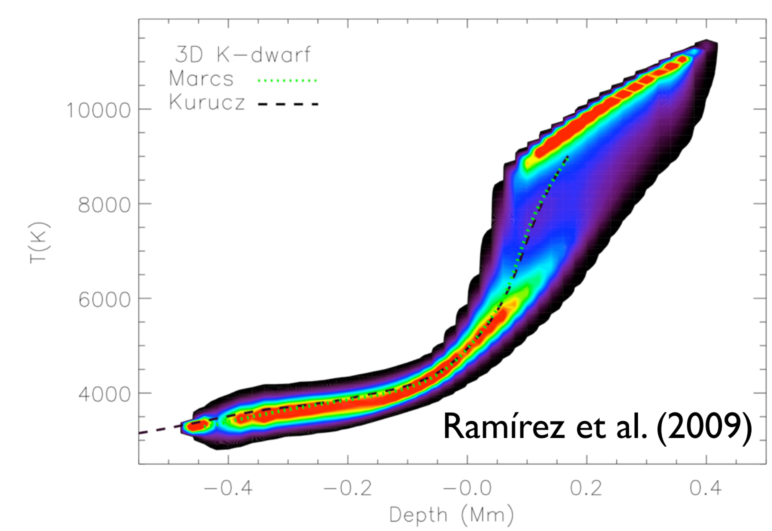
Indirect: ionization/excitation, Balmer lines, line-depth ratio

- ✓ **precise**
- ✓ **any stars (spectra)**
- \- **model dependent (NLTE, inhomogeneity, e.g. Asplund 2005, Ludwig et al. 2009)**





Asplund (2005)



Ramírez et al. (2009)

Effective Temperature

Direct: interferometry (Hanbury Brown et al. 1974, van Belle & von Braun 2009)

- ✓ precise & accurate
- \- nearby stars (limited range)
- \- uniform disk

$$\mathcal{F}_{Bol}(\mathrm{Earth}) = \left(\frac{\theta}{2}\right)^2 \sigma T_{\mathrm{eff}}^4$$

UD → LD

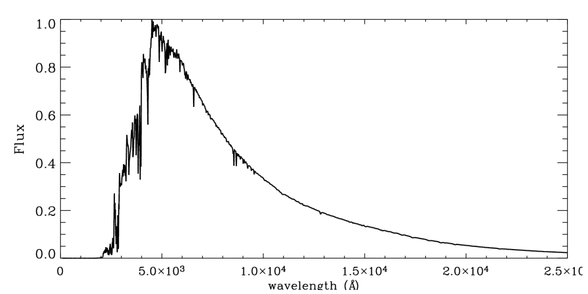
Allende Prieto et al. (2002)
Bigot et al. (2006)
Koesterke et al. (2008)

Allende Prieto et al. (2002)

Semi-Direct: InfraRed Flux Method

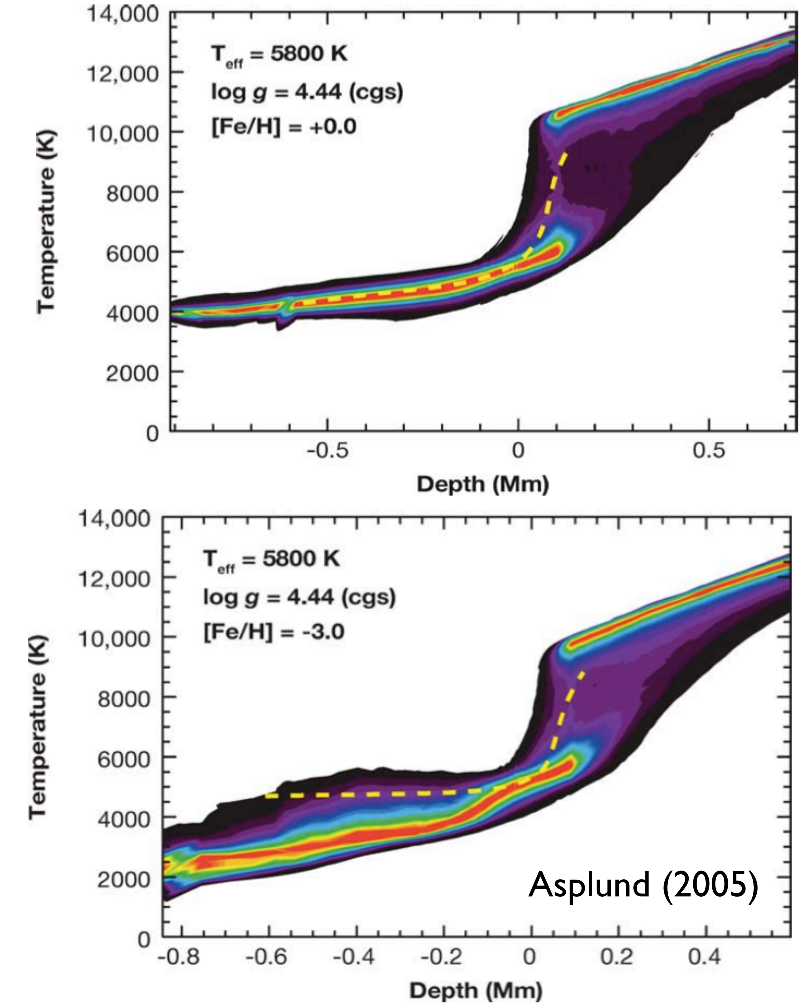
- ✓ precise
- ✓ ~ model-independent
- ✓ any star (photometry)
- \- reddening
- \- accuracy: absolute calibration

$$\frac{\mathcal{F}_{Bol}(\mathrm{Earth})}{\mathcal{F}_{\mathrm{IR}}(\mathrm{Earth})} = \frac{\sigma T_{\mathrm{eff}}^4}{\mathcal{F}_{\mathrm{IR}}(\mathrm{model})}$$

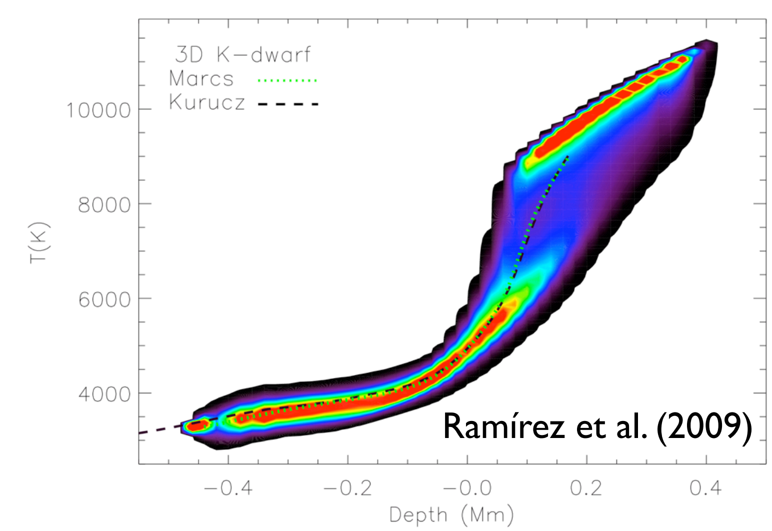


Indirect: ionization/excitation, Balmer lines, line-depth ratio

- ✓ precise
- ✓ any stars (spectra)
- \- model dependent (NLTE, inhomogeneity, e.g. Asplund 2005, Ludwig et al. 2009)



Asplund (2005)

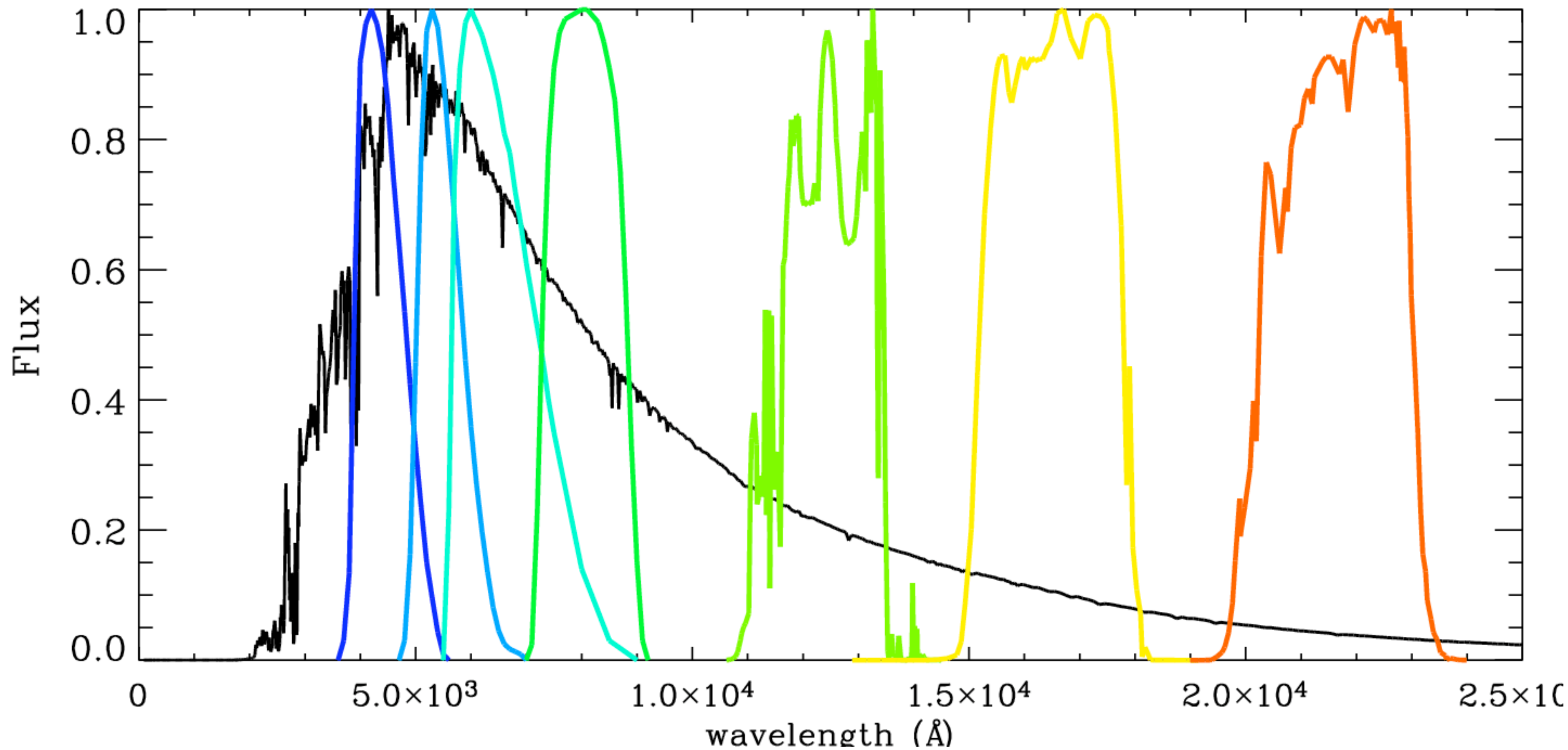


Ramírez et al. (2009)

InfraRed Flux Method

Blackwell et al. (1977,1978,1979)

$$\frac{\mathcal{F}_{Bol}(\mathrm{Earth})}{\mathcal{F}_{\mathrm{IR}}(\mathrm{Earth})} = \frac{\sigma T_{\mathrm{eff}}^4}{\mathcal{F}_{\mathrm{IR}}(\mathrm{model})}$$

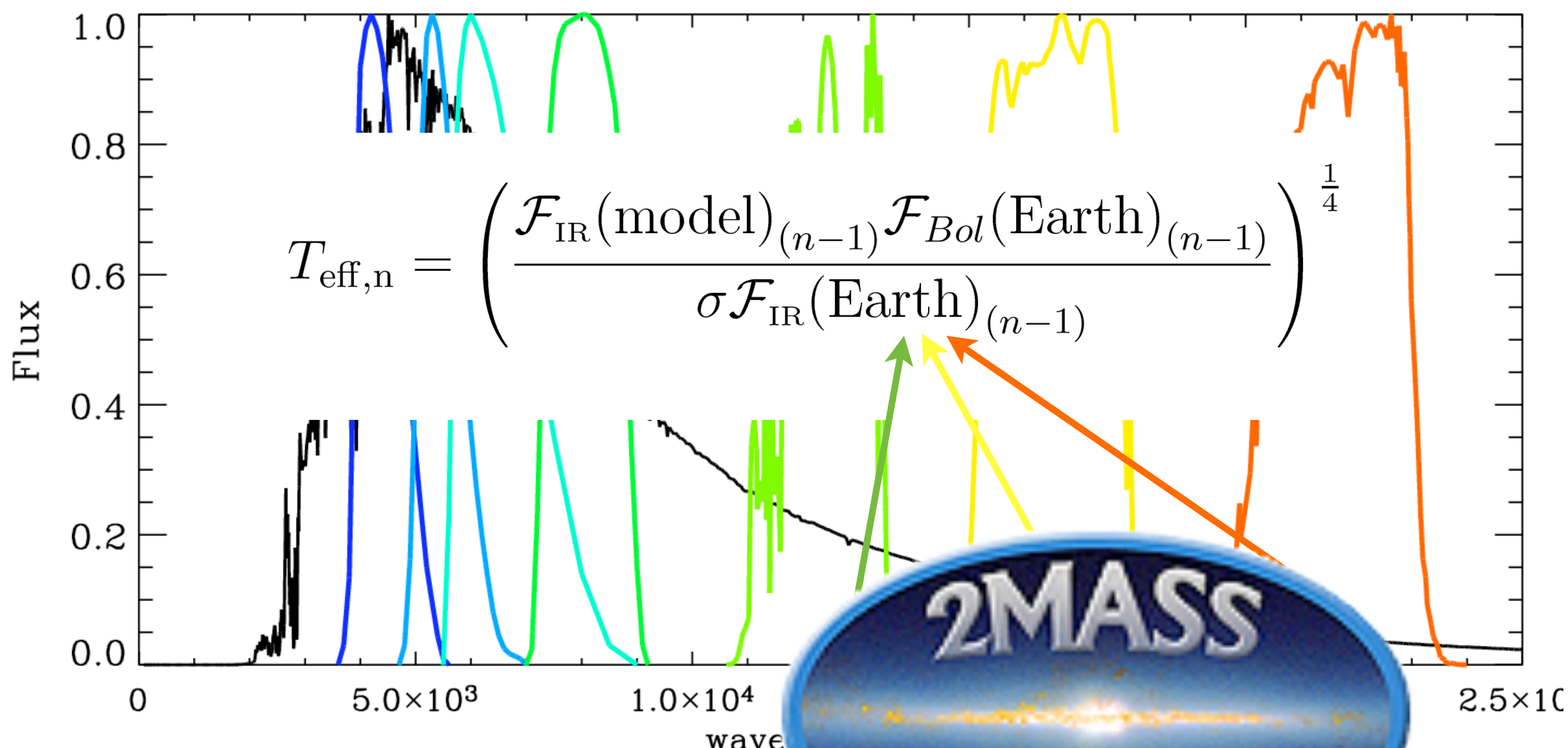


Casagrande et al. (2006, 2010)

InfraRed Flux Method

Blackwell et al. (1977,1978,1979)

$$\frac{\mathcal{F}_{Bol}(\mathrm{Earth})}{\mathcal{F}_{\mathrm{IR}}(\mathrm{Earth})} = \frac{\sigma T_{\mathrm{eff}}^4}{\mathcal{F}_{\mathrm{IR}}(\mathrm{model})}$$

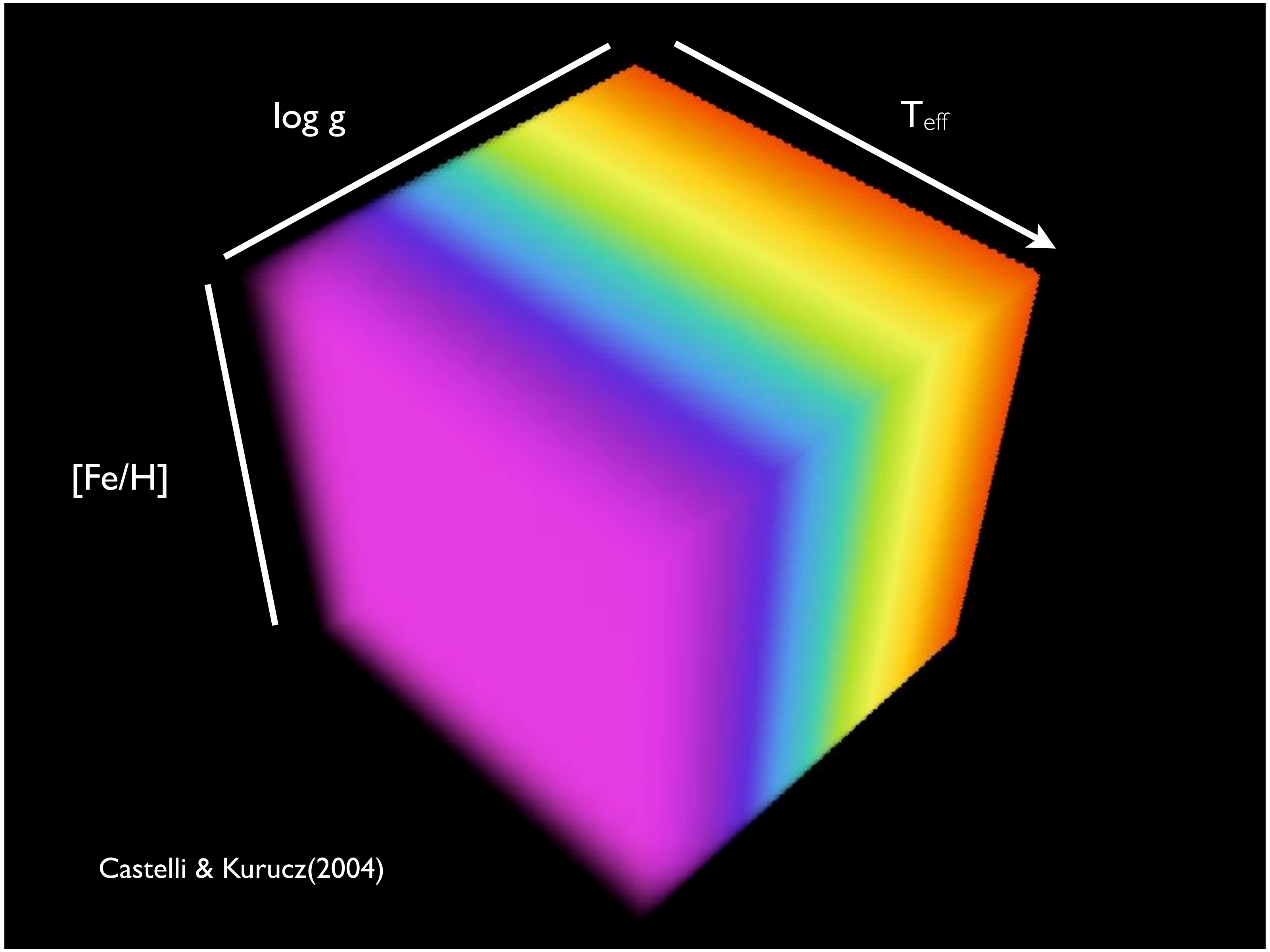


$$T_{\mathrm{eff,n}} = \left(\frac{\mathcal{F}_{\mathrm{IR}}(\mathrm{model})_{(n-1)} \mathcal{F}_{Bol}(\mathrm{Earth})_{(n-1)}}{\sigma \mathcal{F}_{\mathrm{IR}}(\mathrm{Earth})_{(n-1)}} \right)^{\frac{1}{4}}$$

Casagrande et al. (2006, 2010)

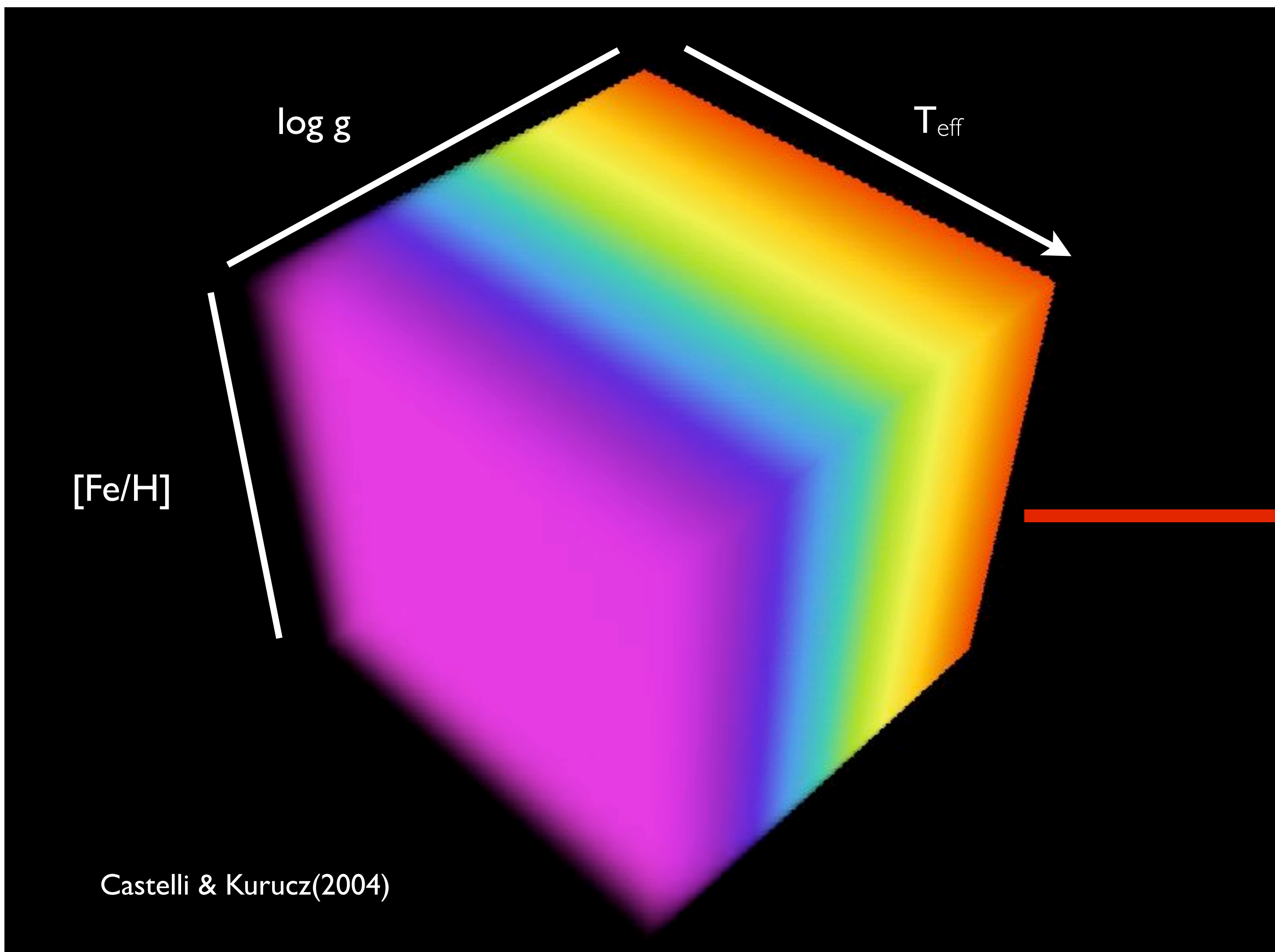
InfraRed Flux Method

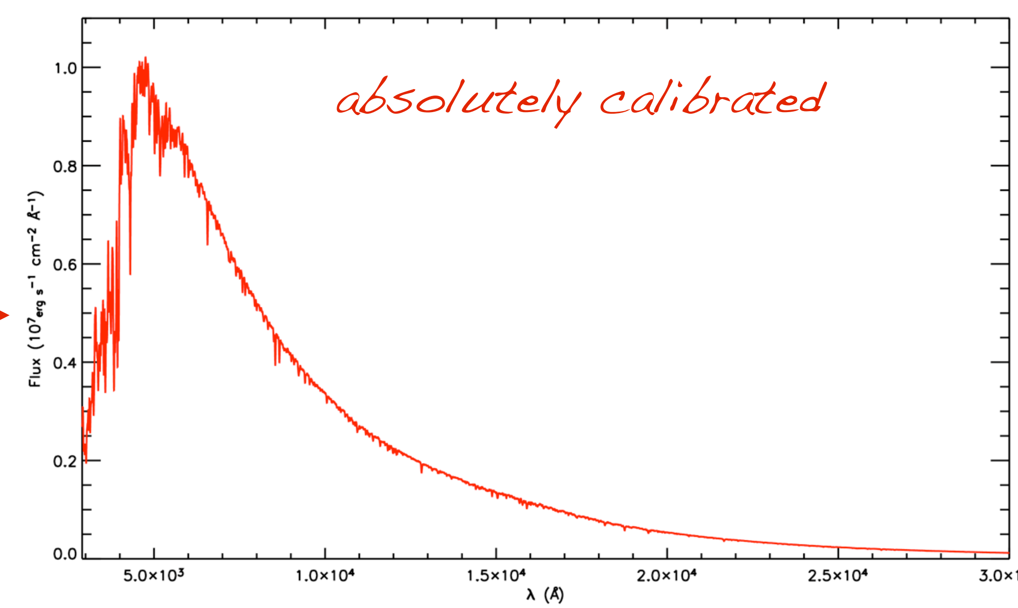
$$\frac{\mathcal{F}_{Bol}(\mathrm{Earth})}{\mathcal{F}_{\mathrm{IR}}(\mathrm{Earth})} = \frac{\sigma T_{\mathrm{eff}}^4}{\mathcal{F}_{\mathrm{IR}}(\mathrm{model})}$$



InfraRed Flux Method

$$\frac{\mathcal{F}_{Bol}(\mathrm{Earth})}{\mathcal{F}_{\mathrm{IR}}(\mathrm{Earth})} = \frac{\sigma T_{\mathrm{eff}}^{4}}{\mathcal{F}_{\mathrm{IR}}(\mathrm{model})}$$

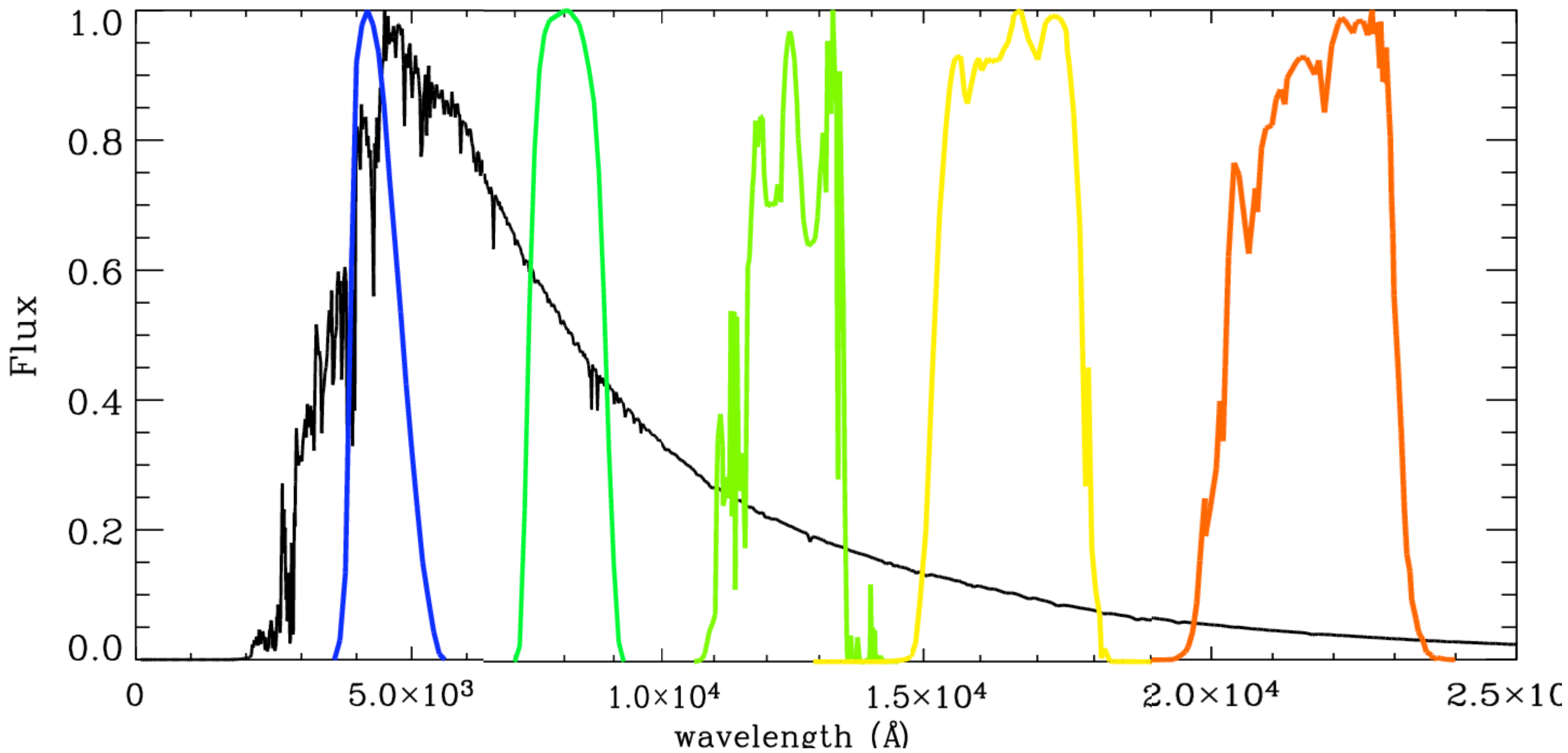




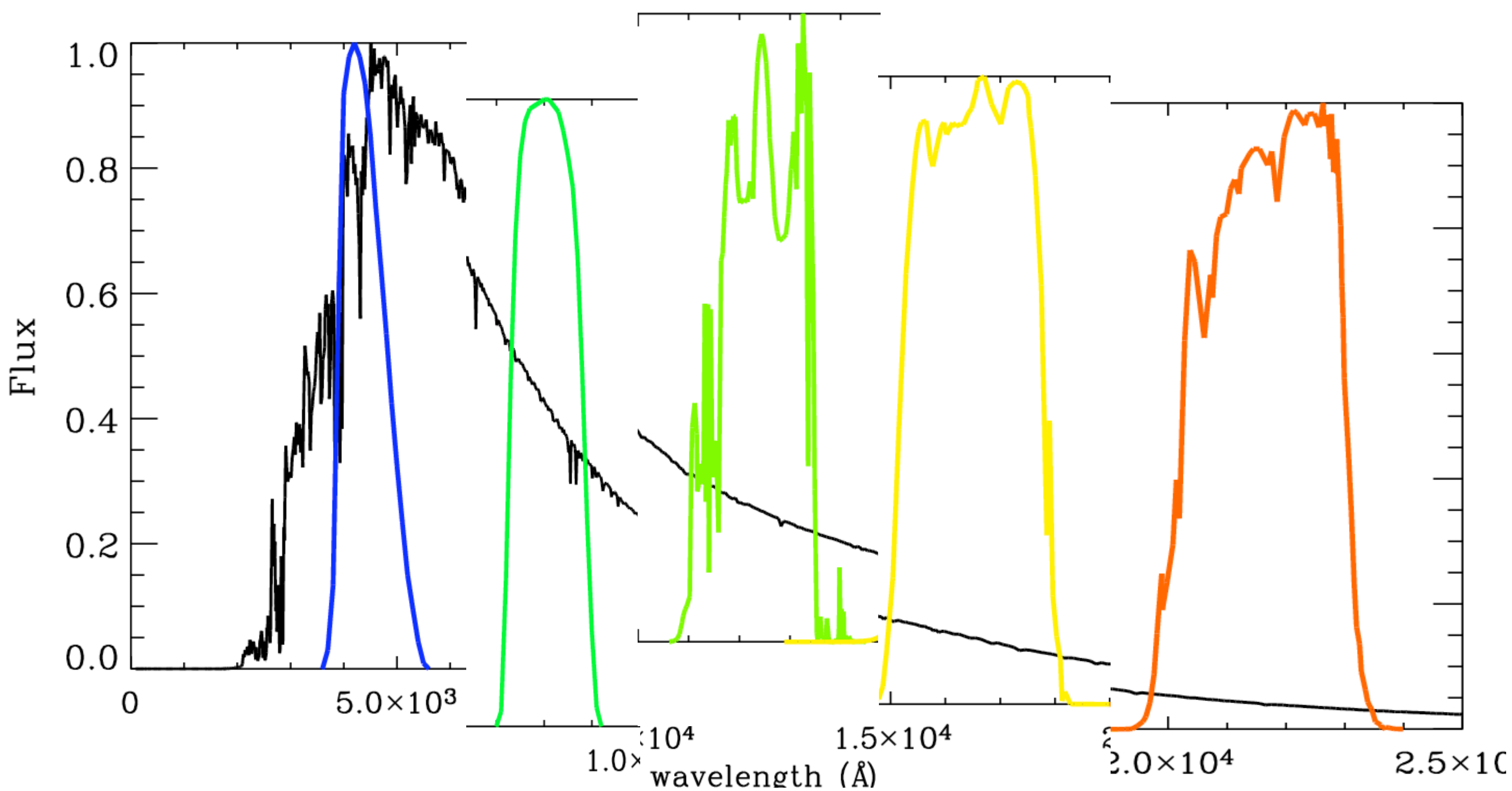
flux scale: overall absolute calibration

shape: spectral library

IRFM: Pros & Cons

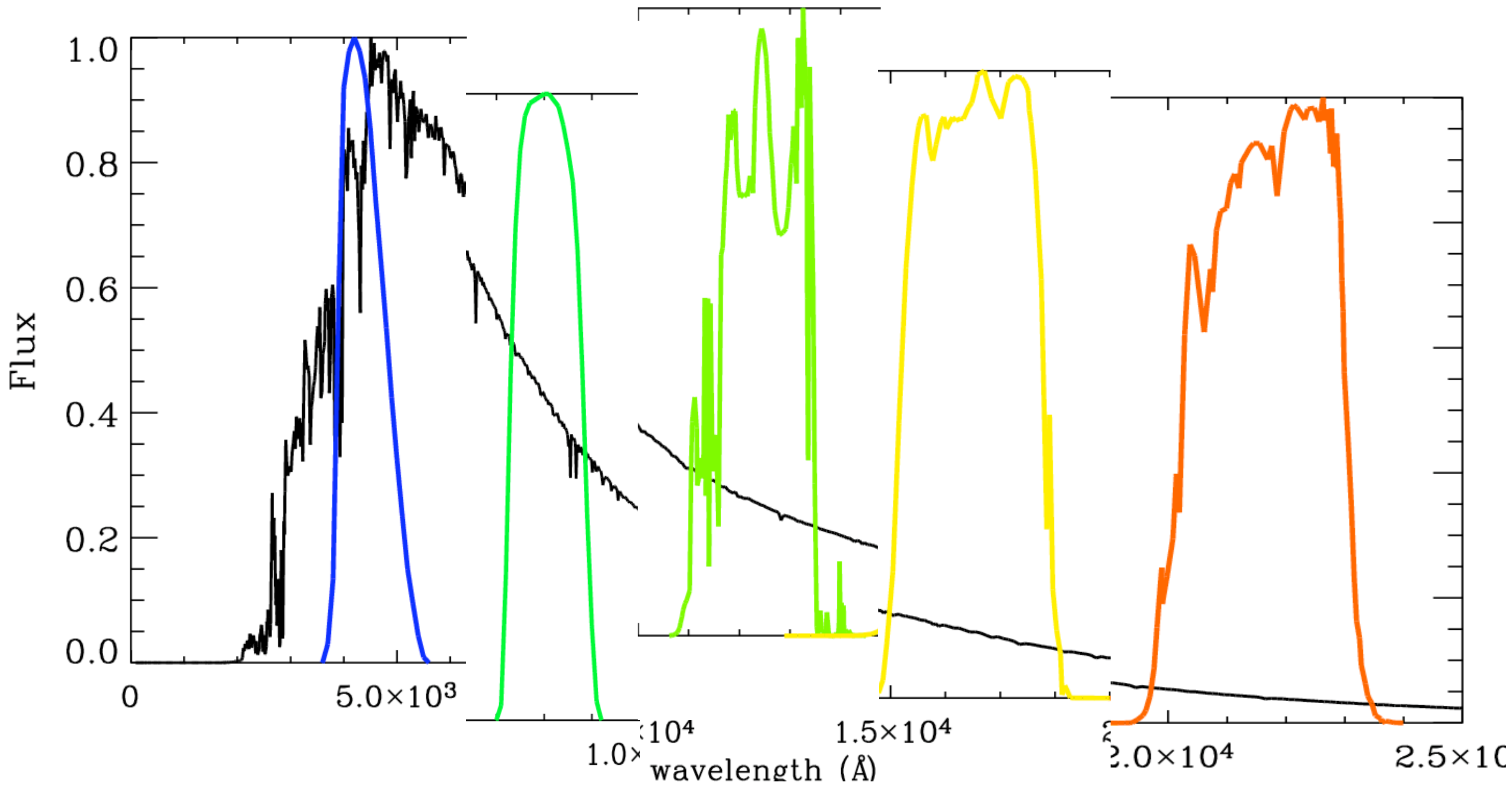


IRFM: Pros & Cons



IRFM: Pros & Cons

$$\mathcal{F}_\lambda(\text{Earth}) = \mathcal{F}_\lambda^{\text{std}}(\text{Earth})10^{-0.4(m_\lambda - m_\lambda^{\text{std}})}$$

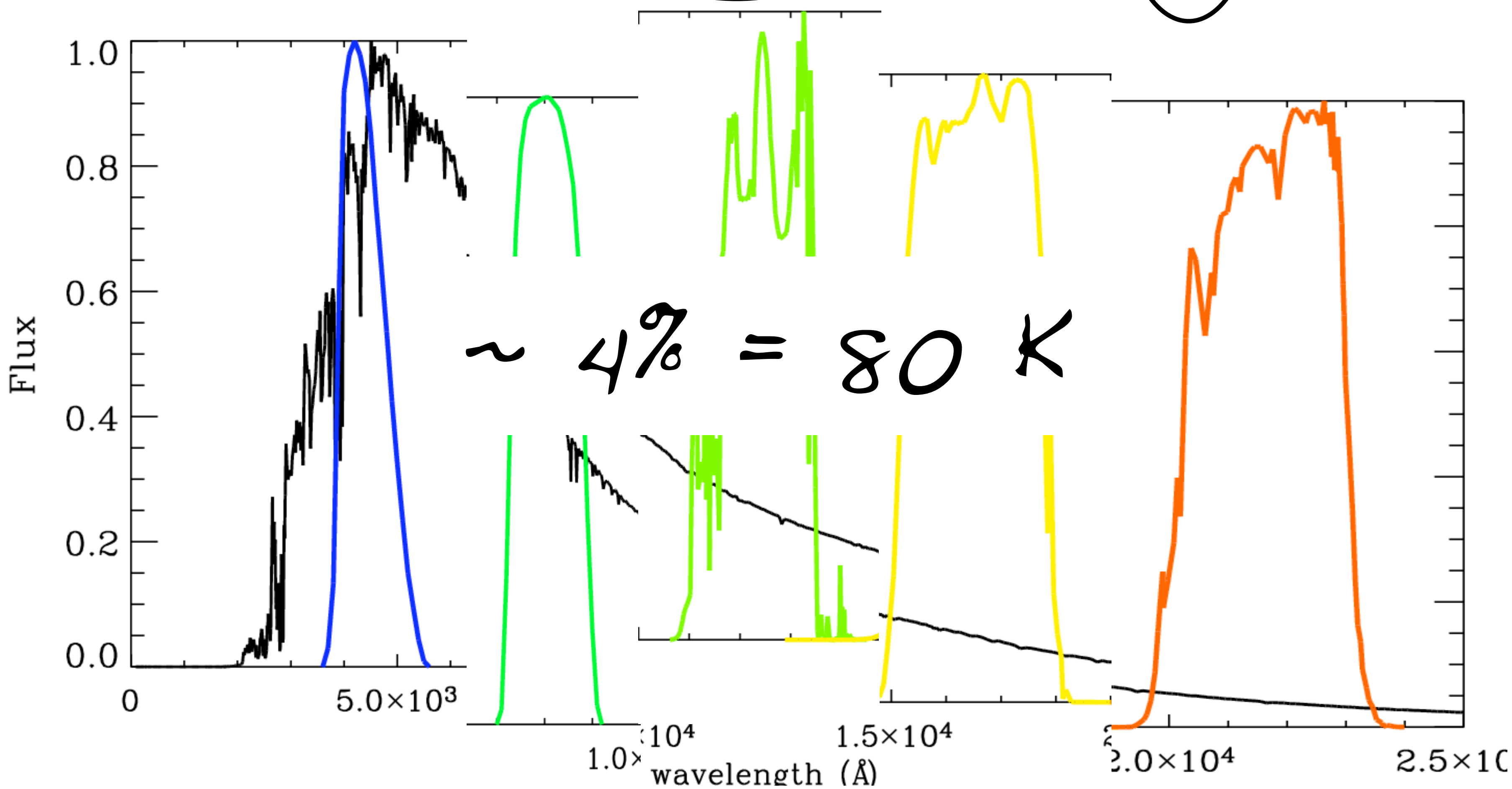


IRFM: Pros & Cons

$$\mathcal{F}_\lambda(\mathrm{Earth}) = \mathcal{F}_\lambda^{\mathrm{std}}(\mathrm{Earth})10^{-0.4(m_\lambda - m_\lambda^{\mathrm{std}})}$$

~2/3%

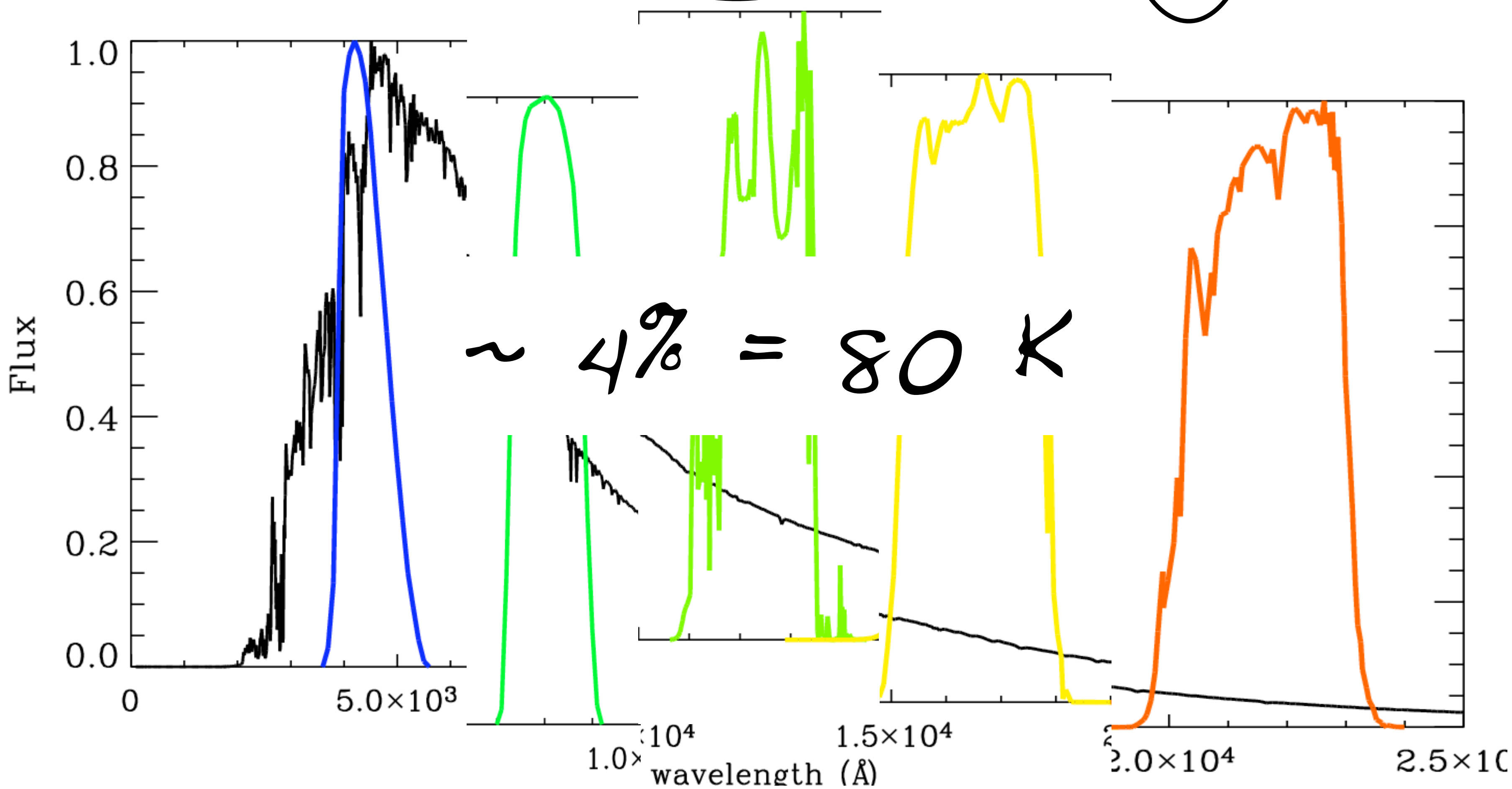
~0.01 mag



IRFM: Pros & Cons

$$\mathcal{F}_\lambda(\text{Earth}) = \mathcal{F}_\lambda^{\text{std}}(\text{Earth})\, 10^{-0.4(m_\lambda - m_\lambda^{\text{std}})}$$

~2/3% ~0.01 mag

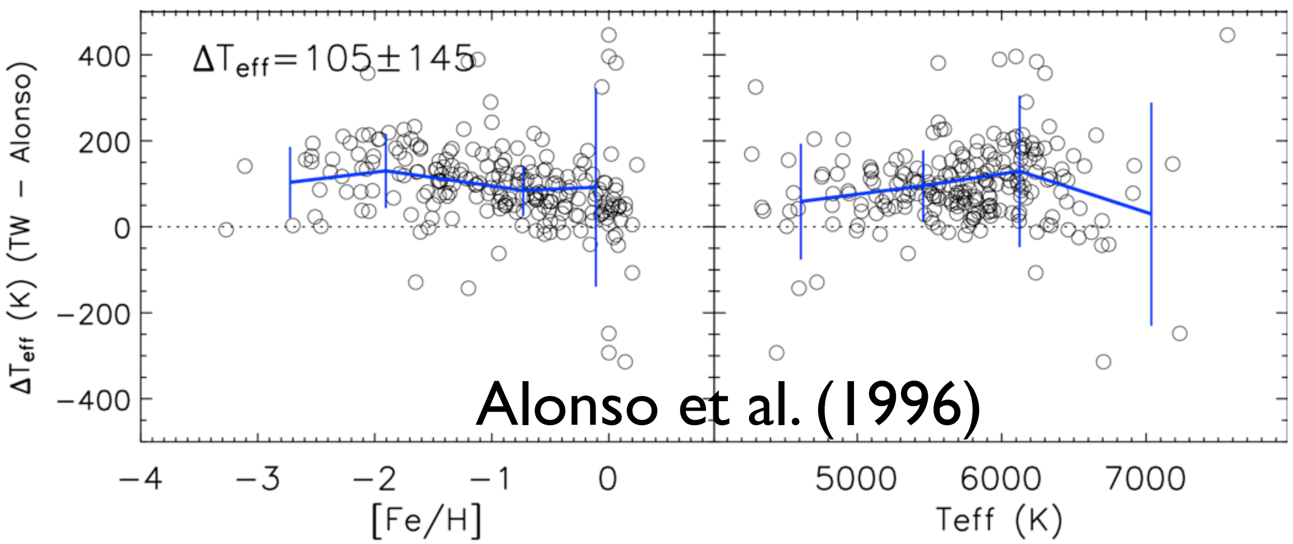


~ 4% = 80 K

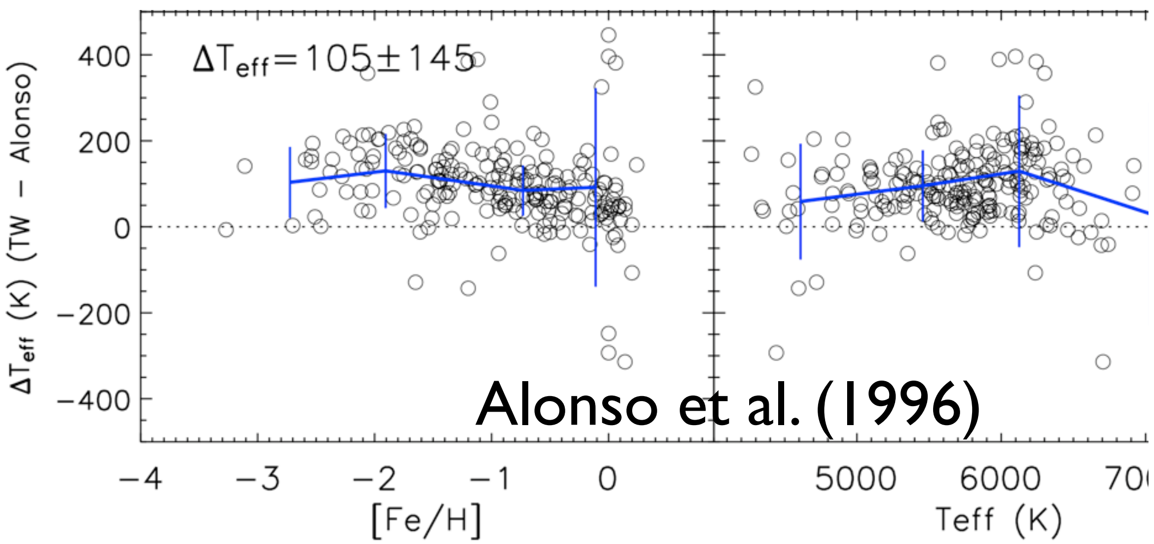
But recently, towards 1% accuracy :

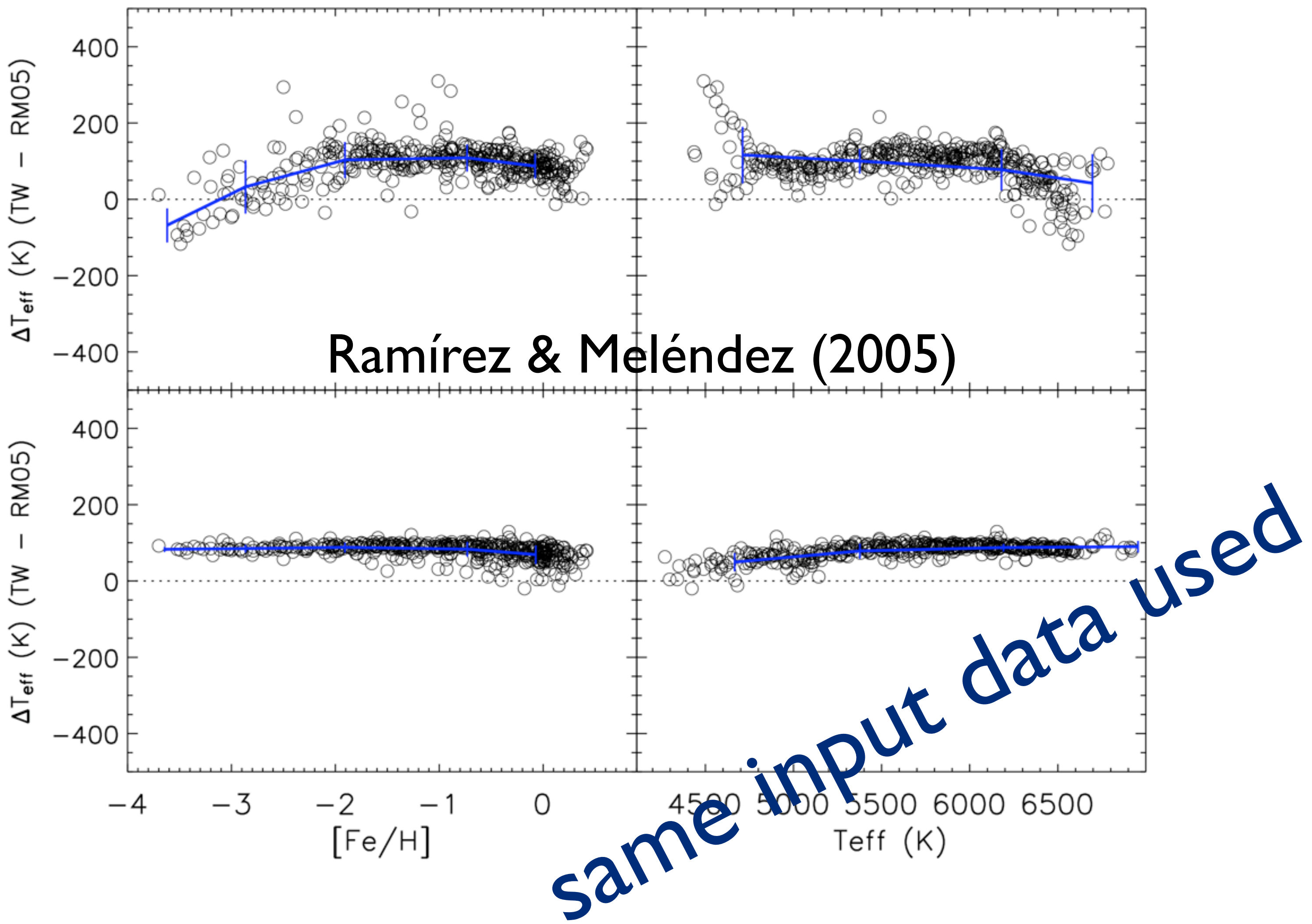
Bohlin (2007)
Apellaniz (2007)
Bohlin & Cohen (2008)
Rieke et al. (2008)

Comparing different versions

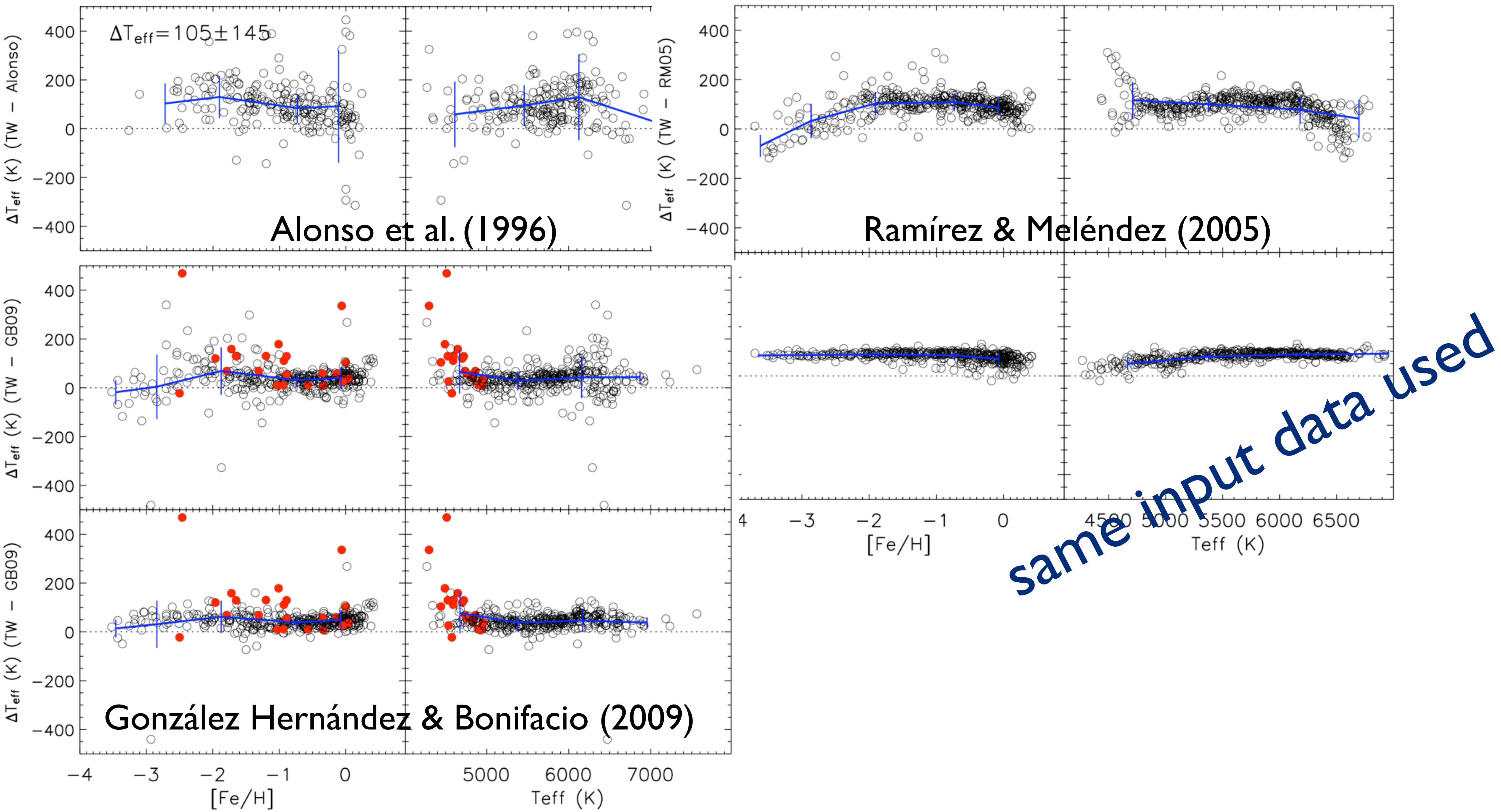


Comparing different versions





Comparing different versions



Comparing different versions

IRFM can accommodate any T_{eff} scale

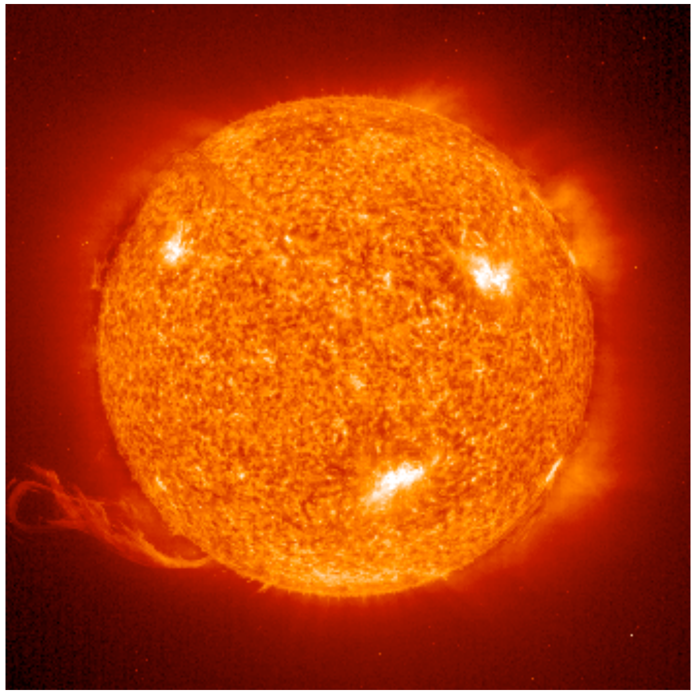
We understand the differences

Which one do we choose?

Resolving different versions

photometry

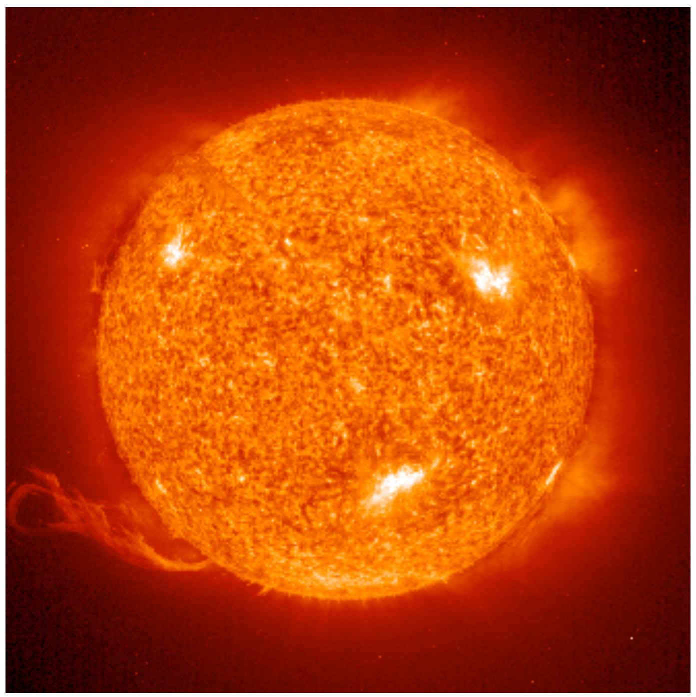
T_{eff}



Resolving different versions

photometry

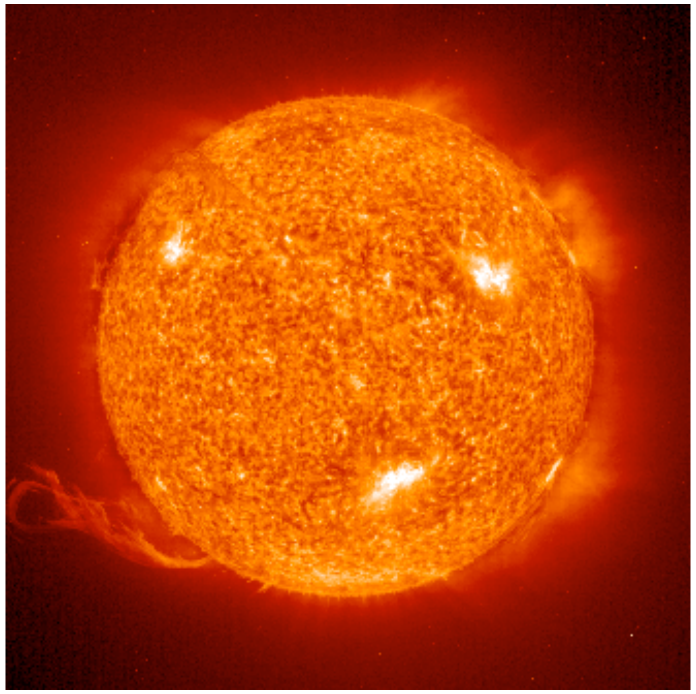
T_{eff}



Solar Twins

photometry

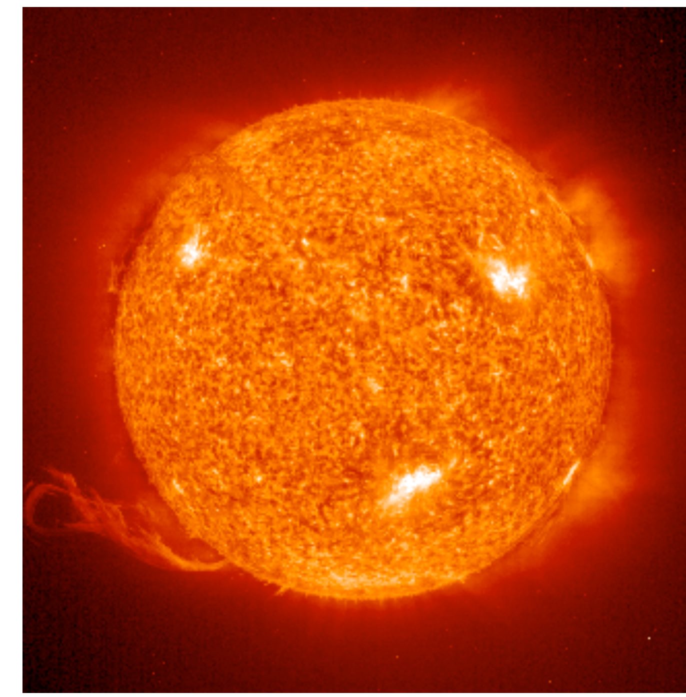
T_{eff}



Solar Twins

photometry

T_{eff}



Meléndez et al. (2009)
Ramírez et al. (2009) → R~65000, S/N >450 → ΔEW same instrument → ~~NLTE, granulation~~

high-quality

no *a priori*

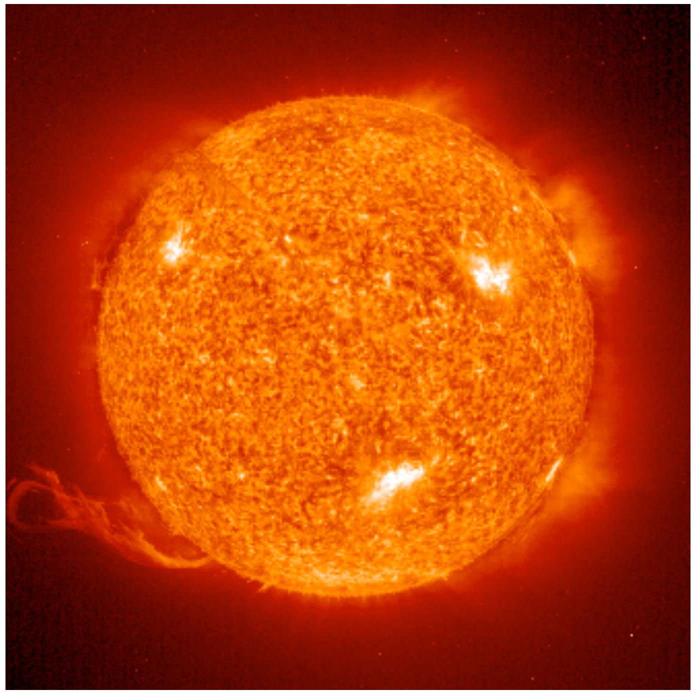
model-independent
high-accuracy

Solar Twins

photometry

~15-20 K

T_{eff}



Meléndez et al. (2009)
Ramírez et al. (2009) → R~65000, S/N >450 → ΔEW same instrument → ~~NLTE, granulation~~

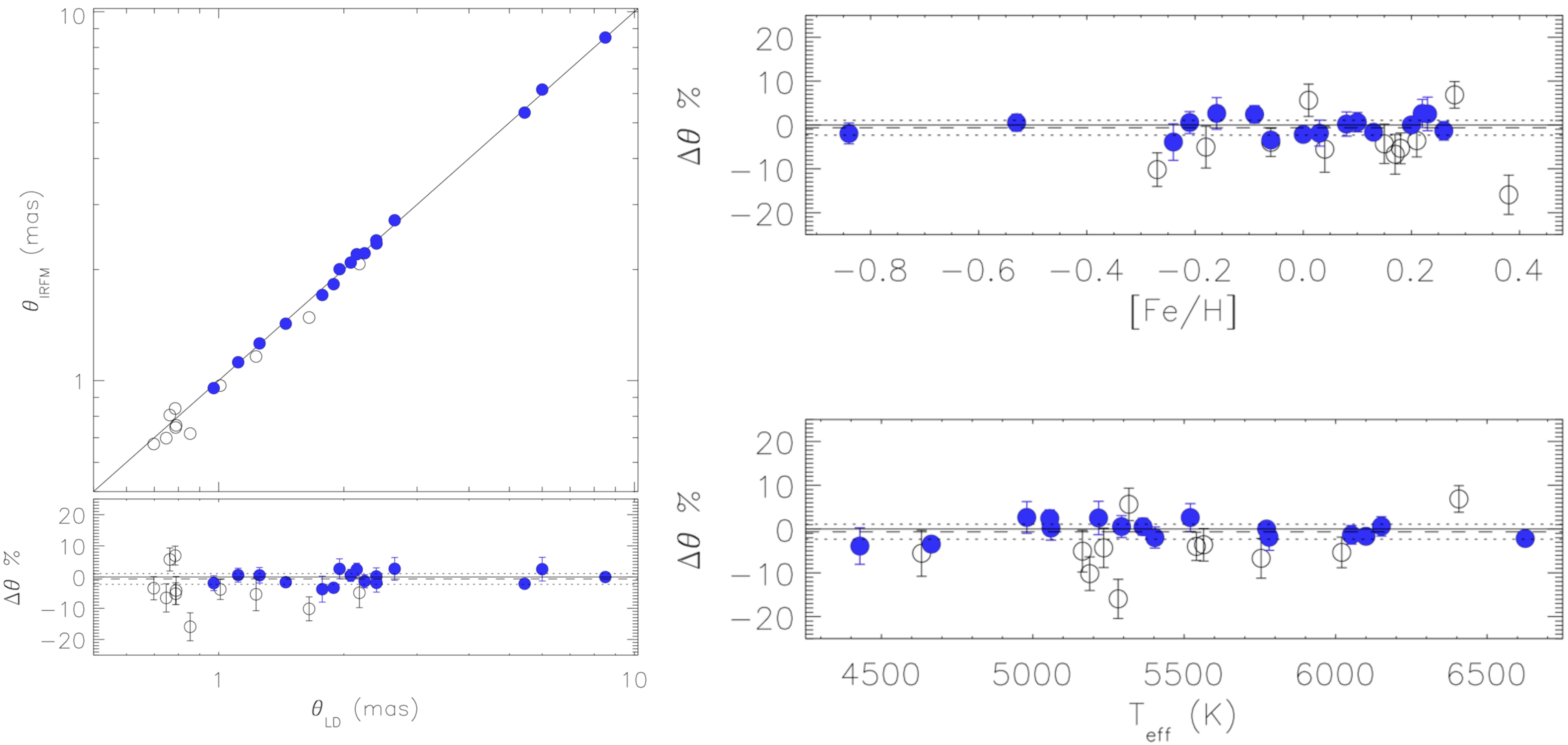
high-quality

no *a priori*

model-independent
high-accuracy

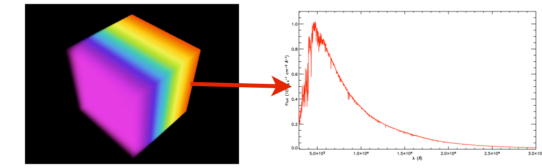
Angular diameters

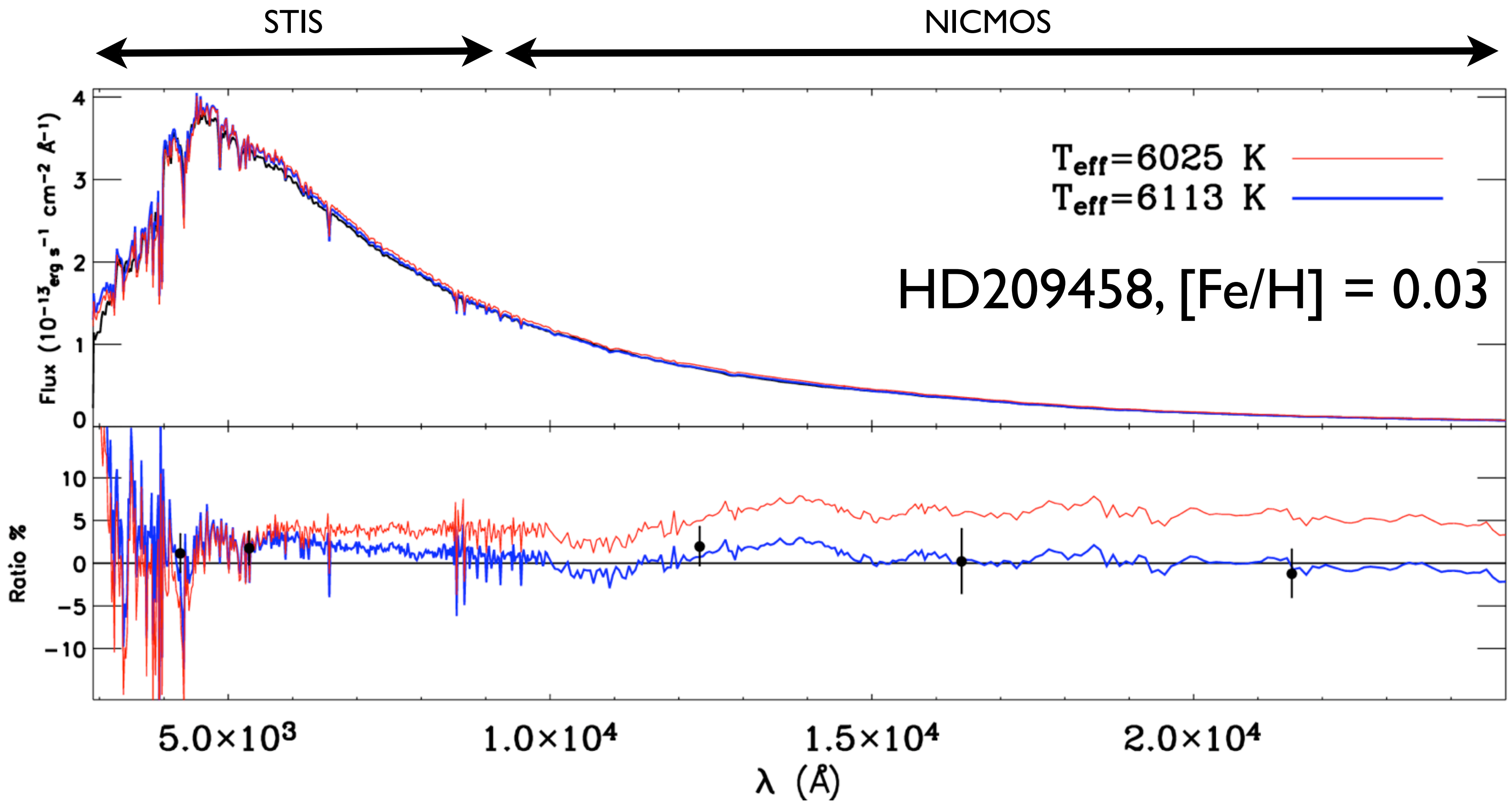
$$\mathcal{F}_{\rm Bol} = \left(\frac{\theta}{2}\right)^2 T_{\rm eff}$$

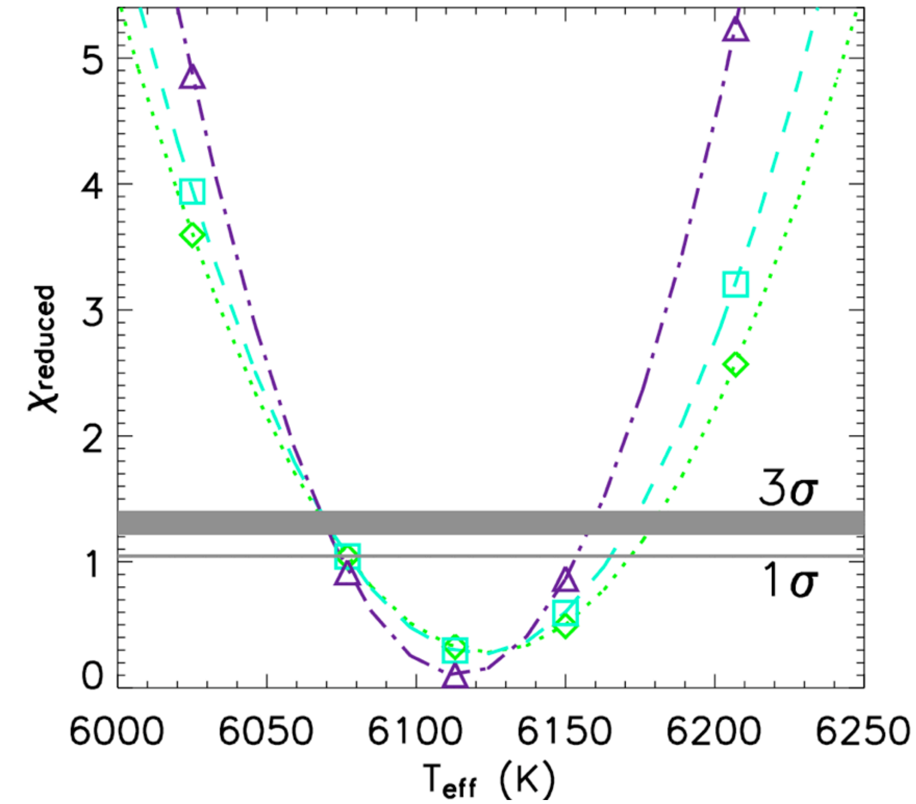


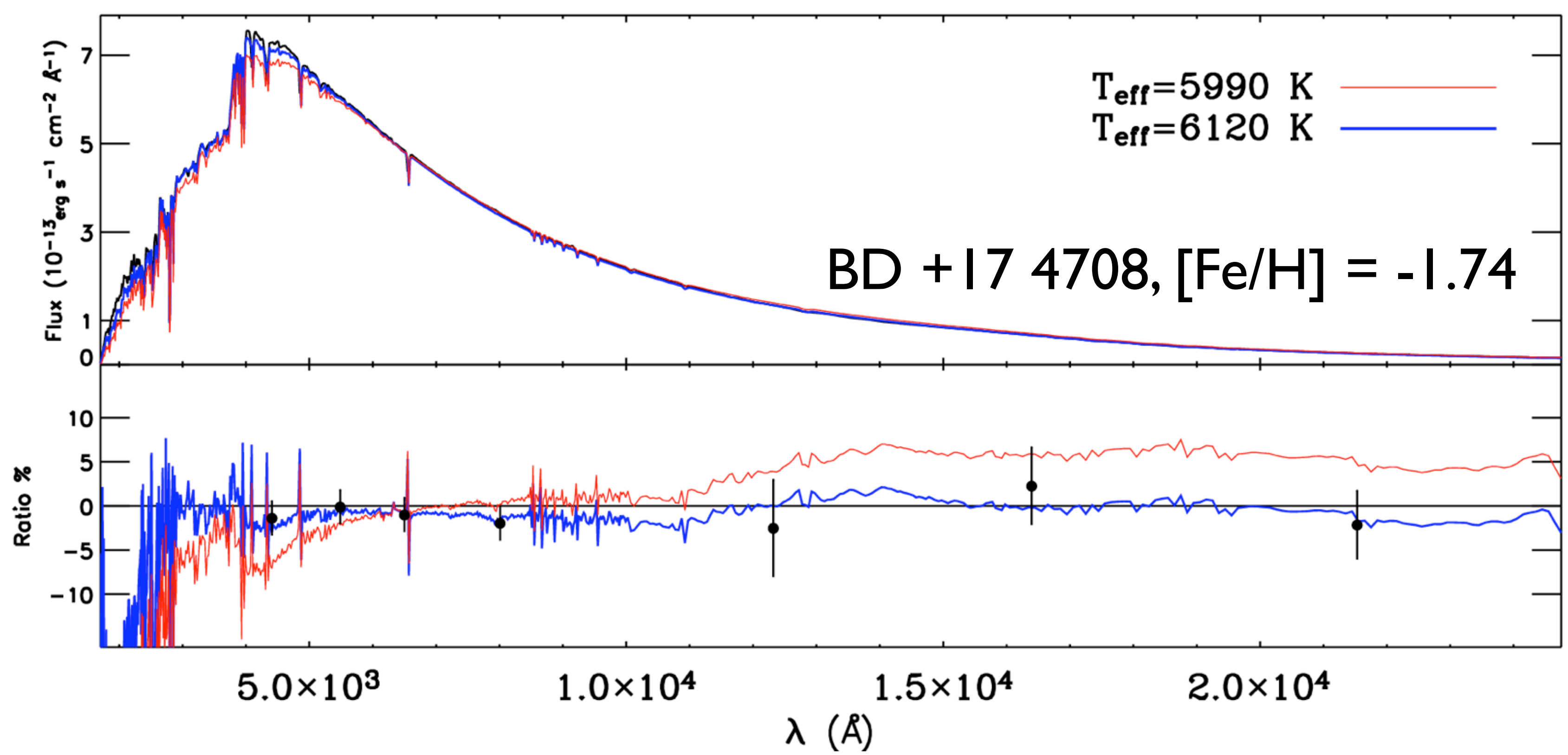
$$\Delta\theta = -0.6 \pm 1.7\% \longrightarrow \Delta T_{\rm eff} = 18 \pm 50\mathrm{K}$$

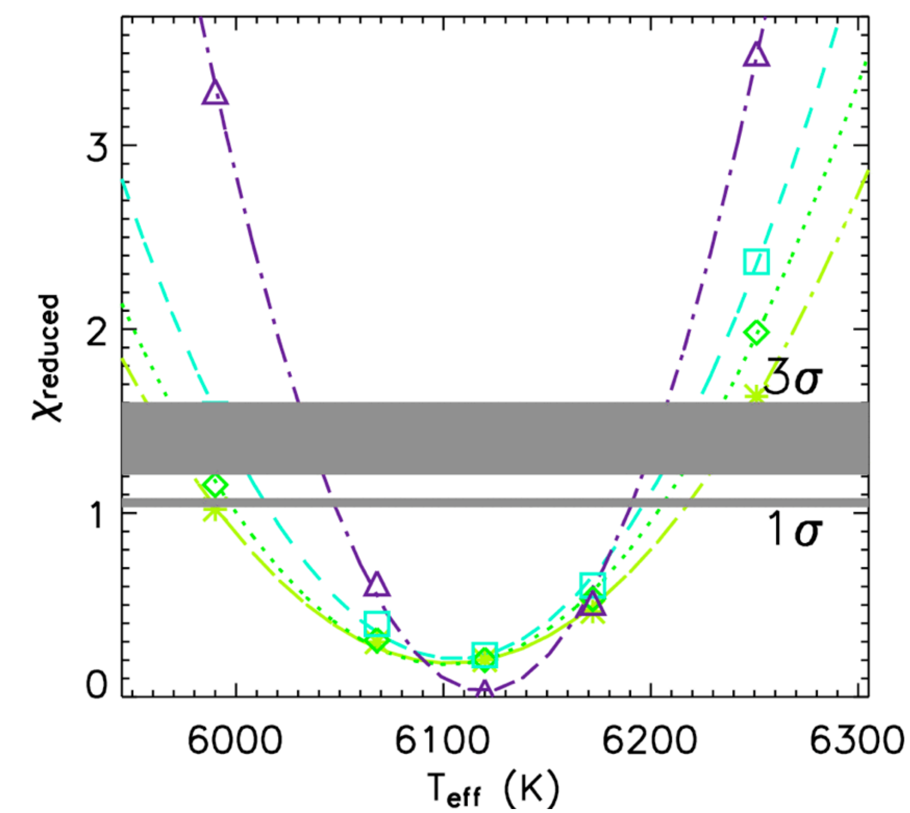
HST Spectro-photometry



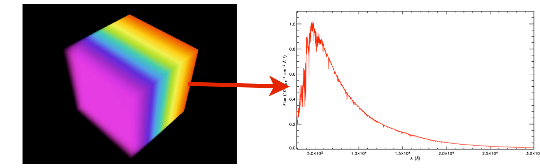


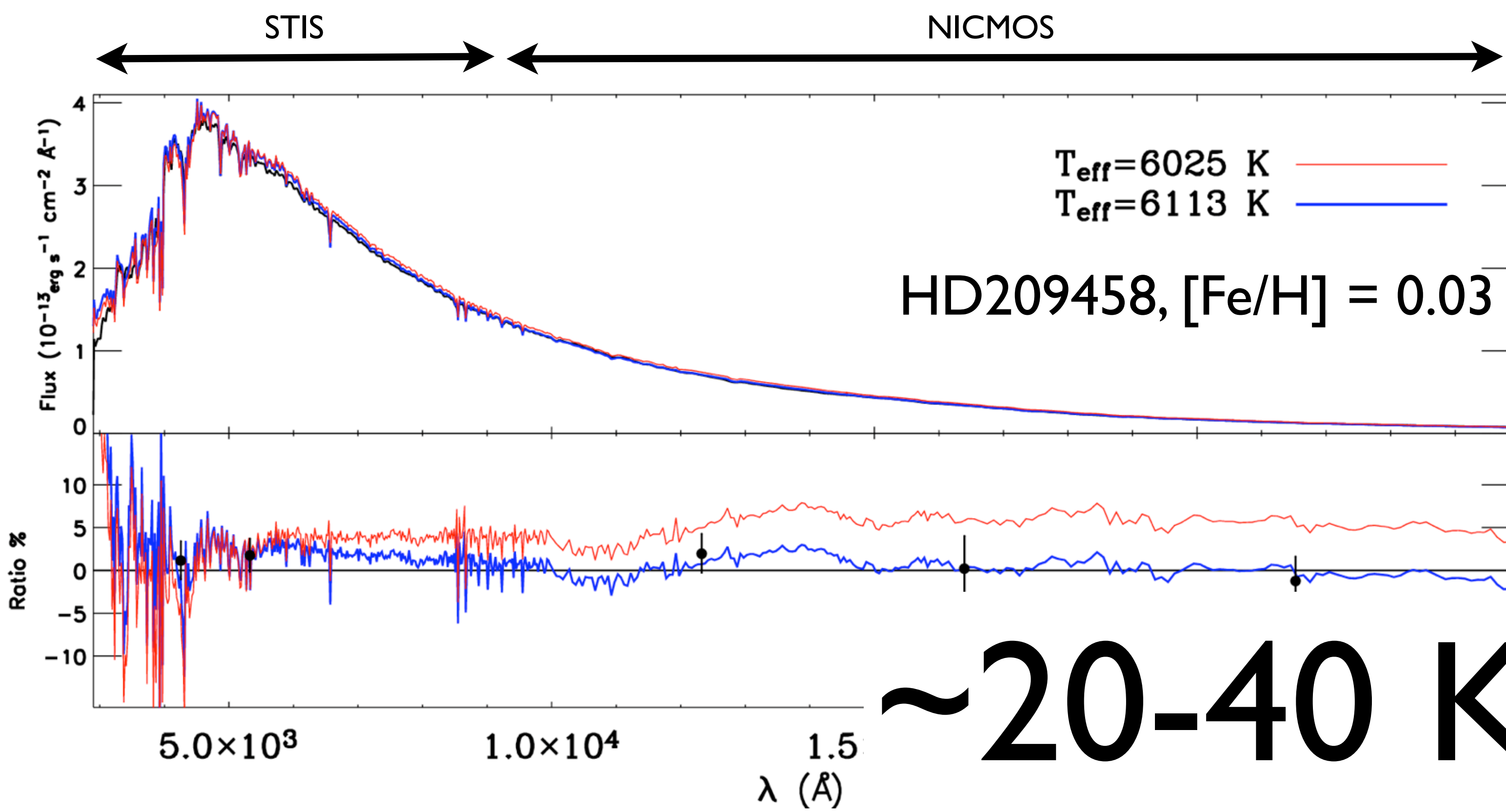




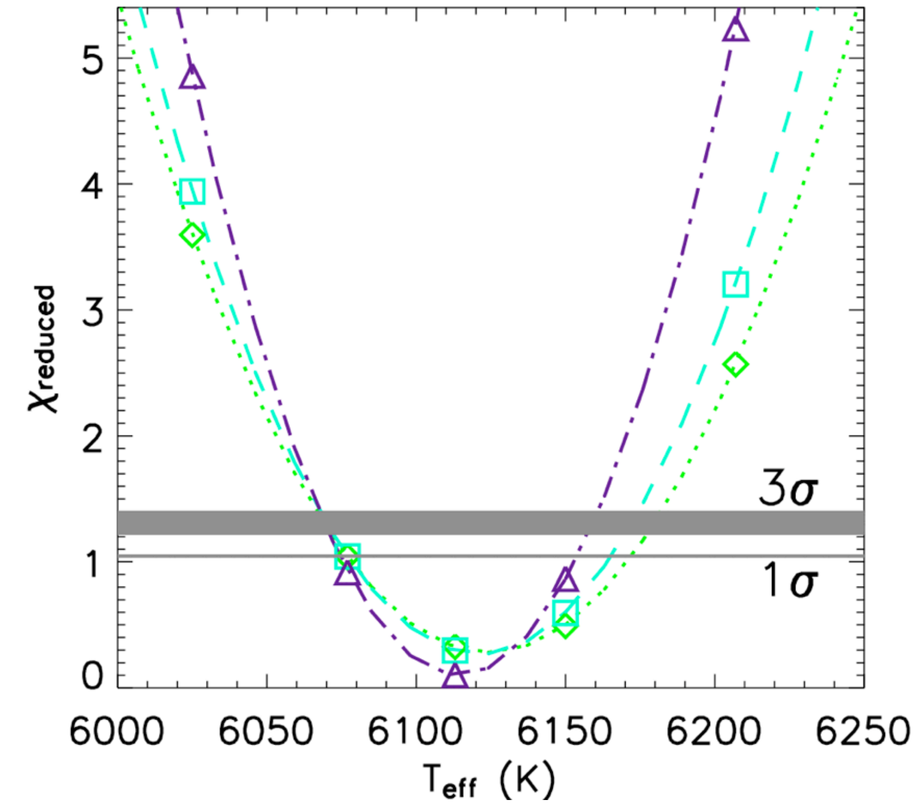


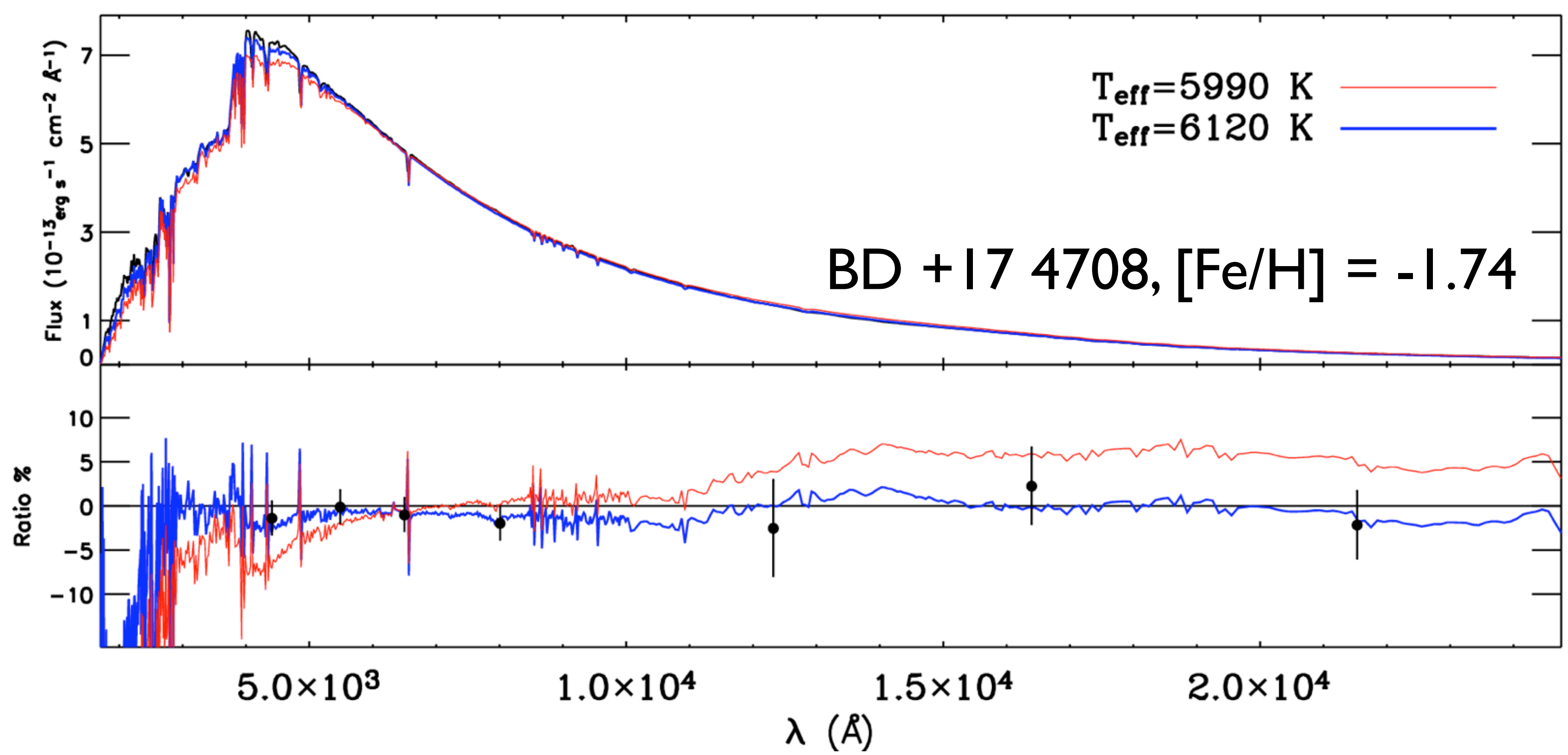
HST Spectro-photometry

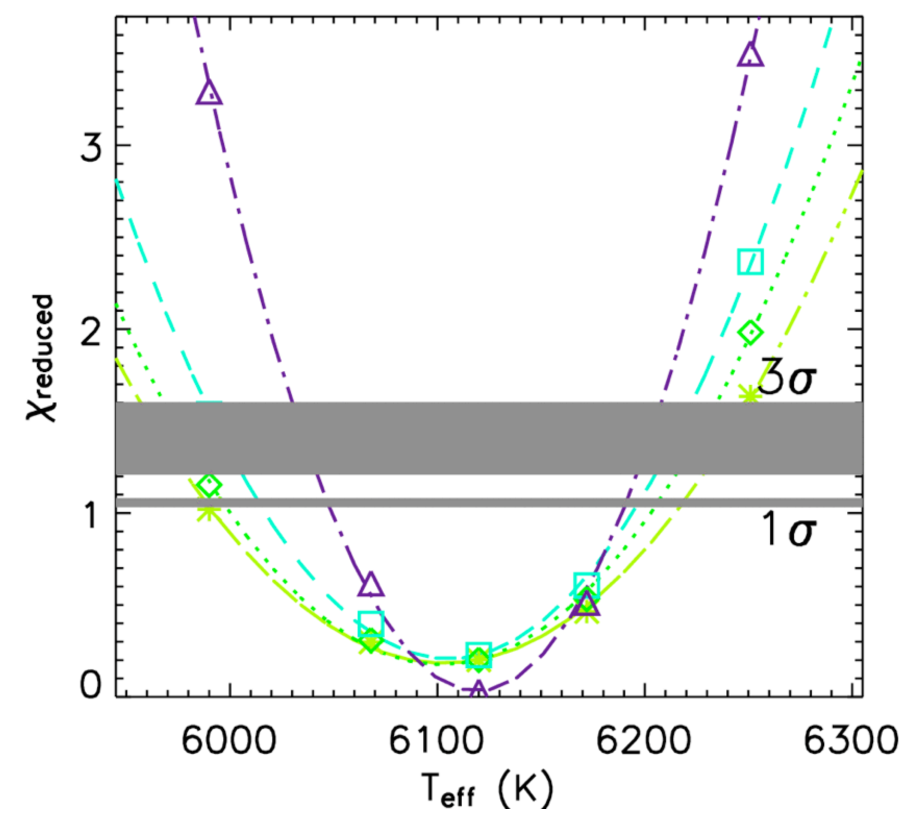




~20-40 K

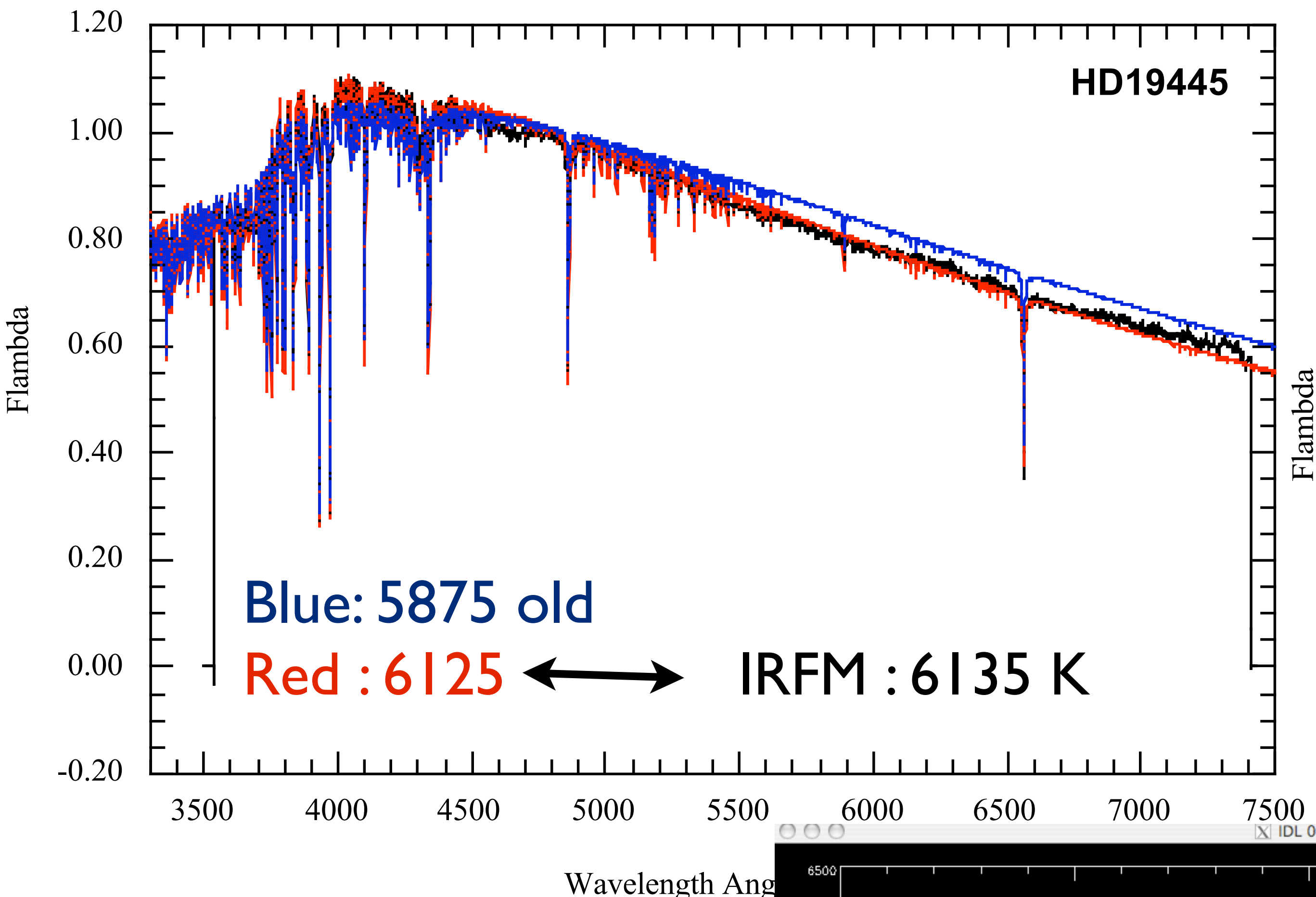


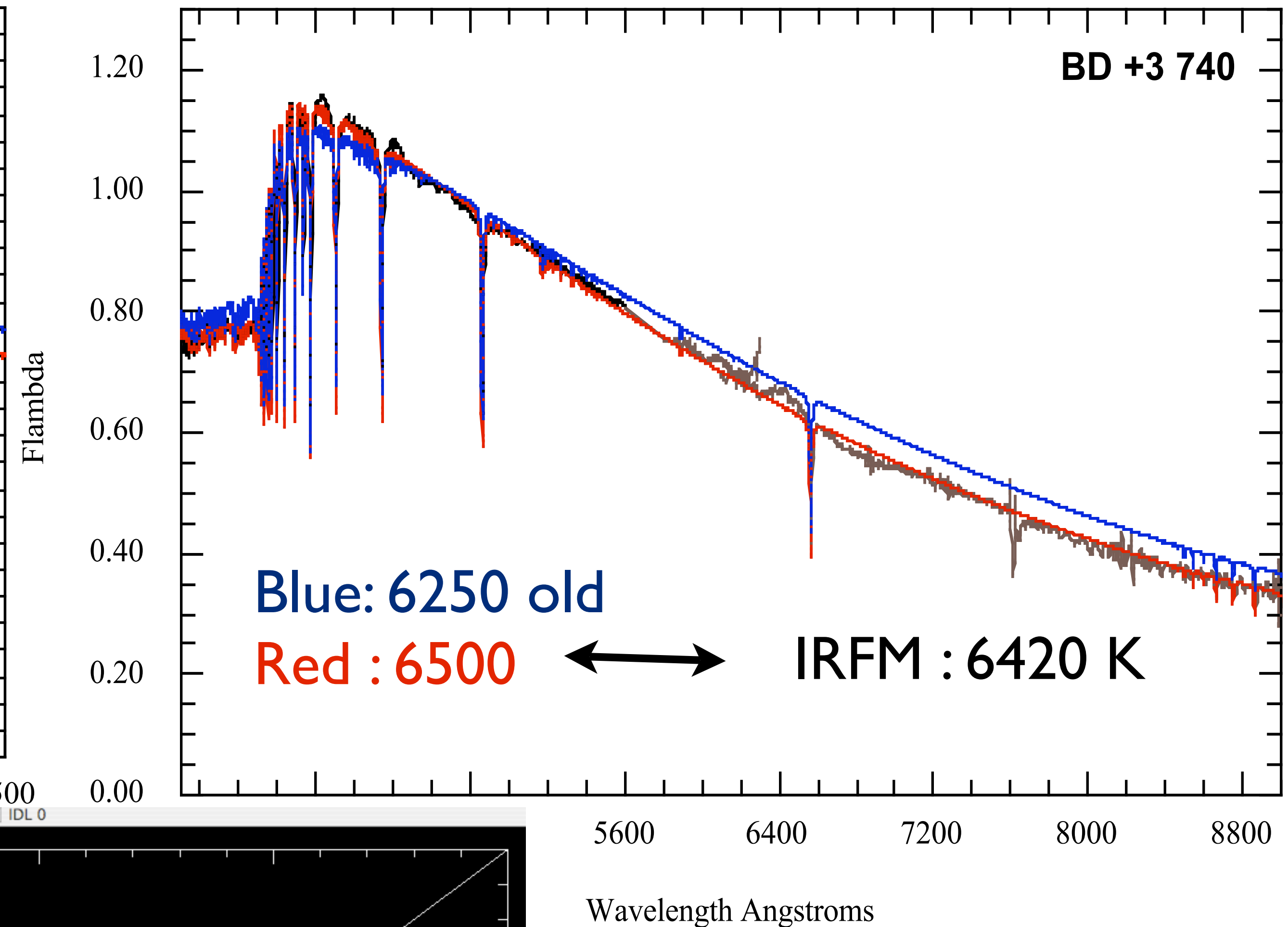


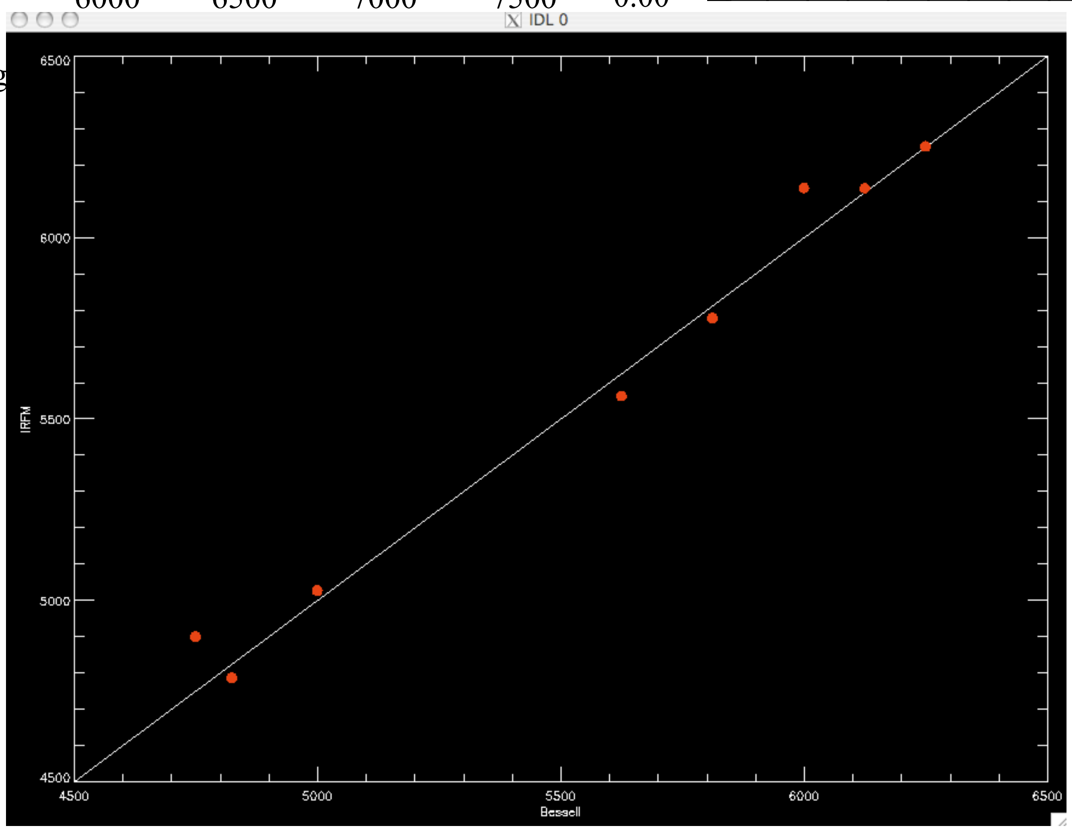


More Spectro-photometry

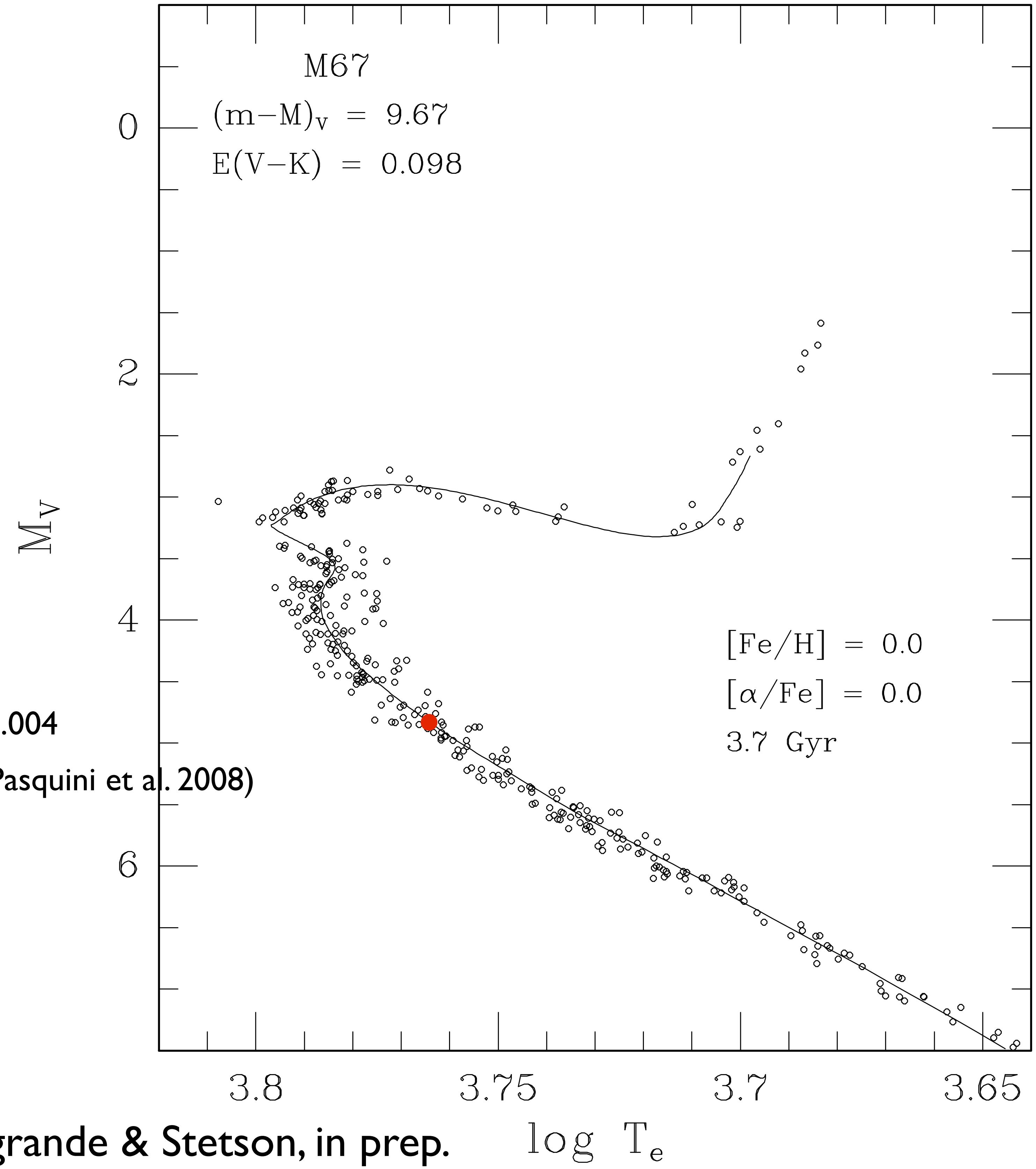
M. Bessell (private comm.)







Solar like stars: CMD

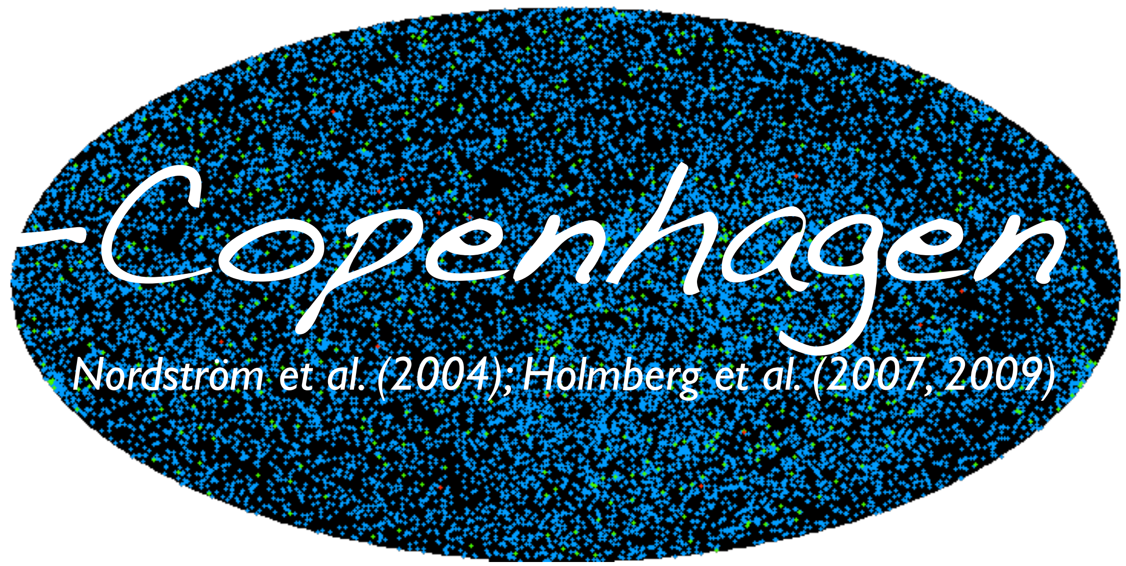


B-V = 0.641± 0.024±0.004

B-V = 0.649±0.016 (Pasquini et al. 2008)

Vandenberg, Casagrande & Stetson, in prep.

Solar like stars: field



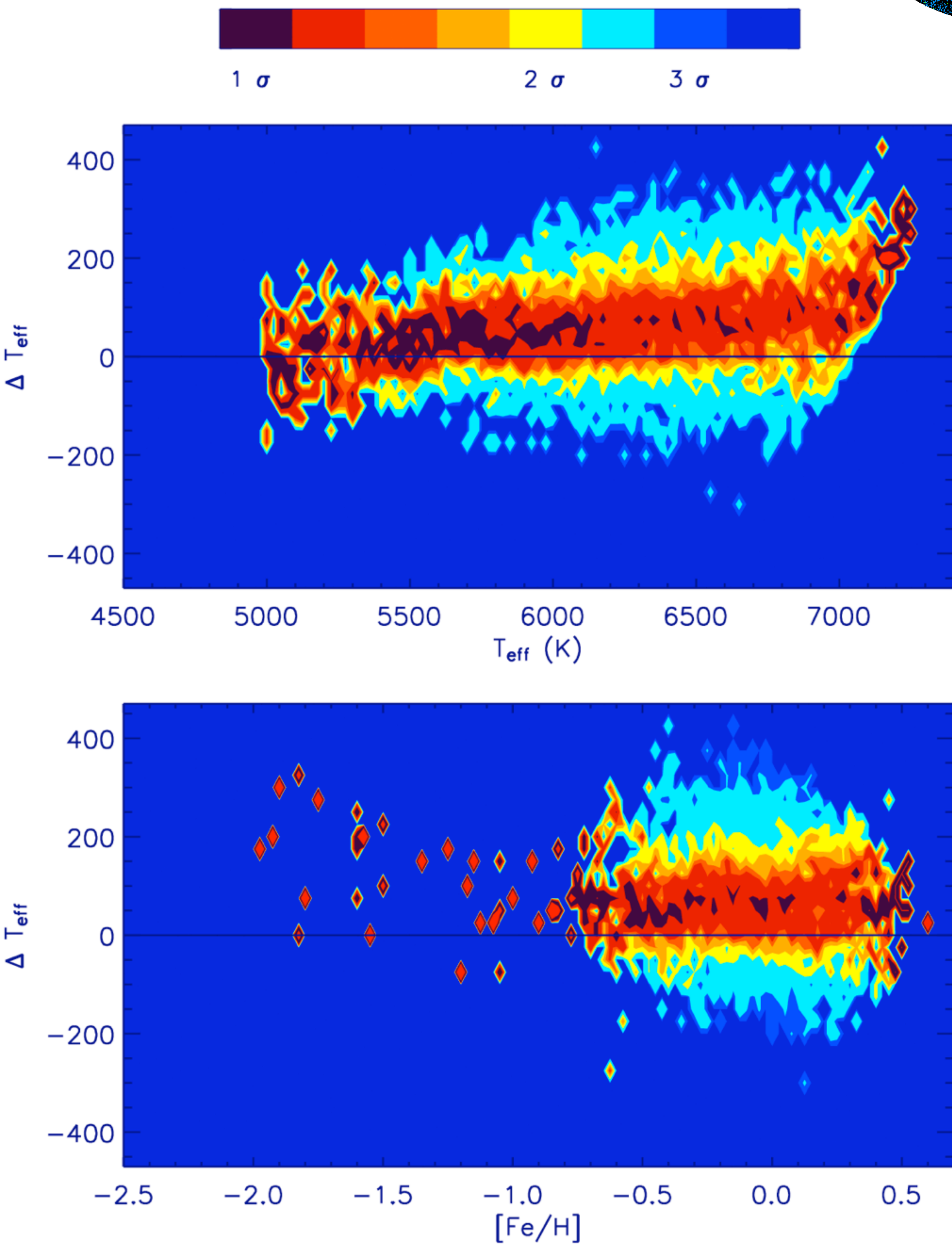
Geneva-Copenhagen Survey

Nordström et al. (2004); Holmberg et al. (2007, 2009)

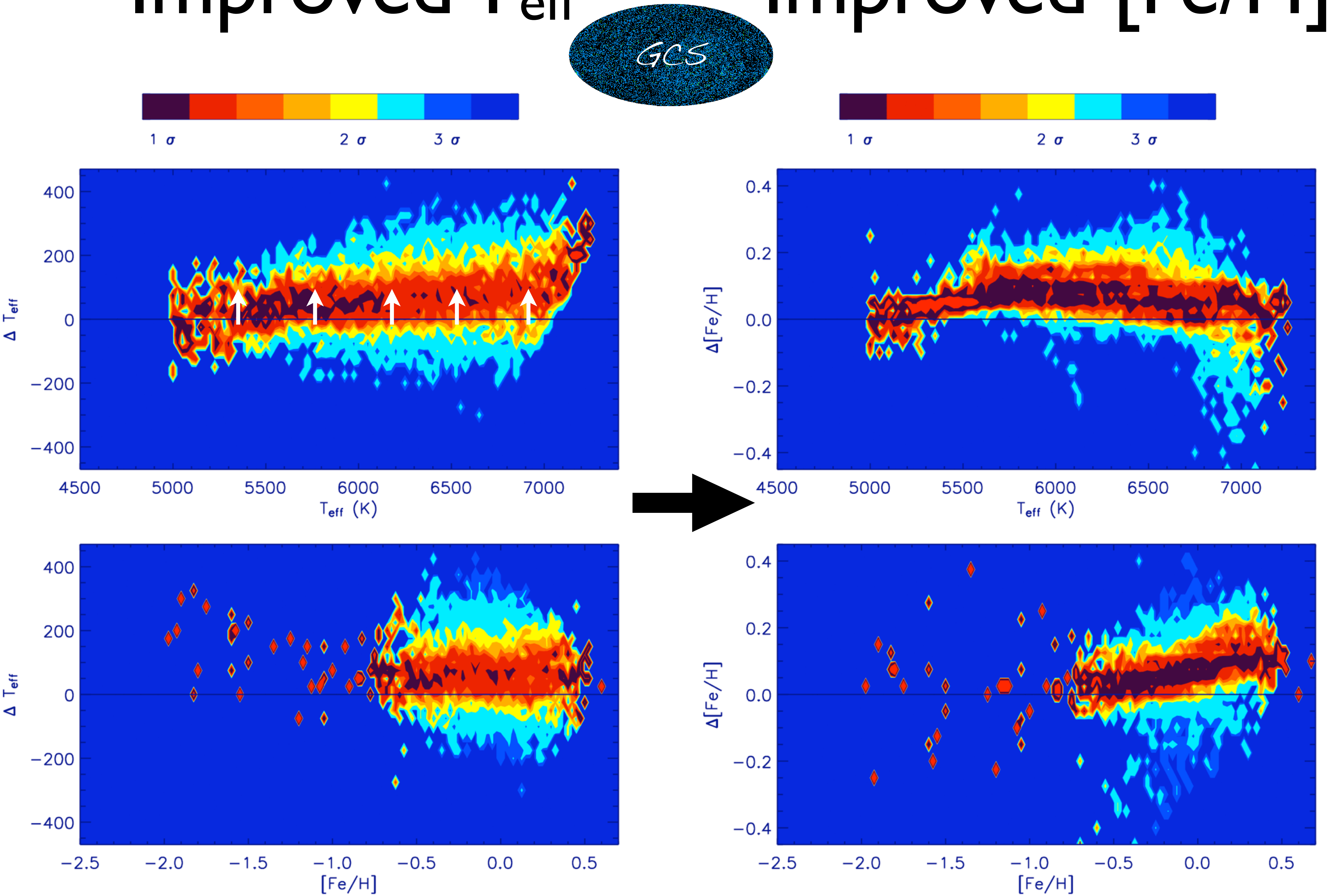
Revisiting the Geneva-Copenhagen Survey :

Casagrande, Schönrich, Asplund, Ramírez, Meléndez, Bensby (2010)

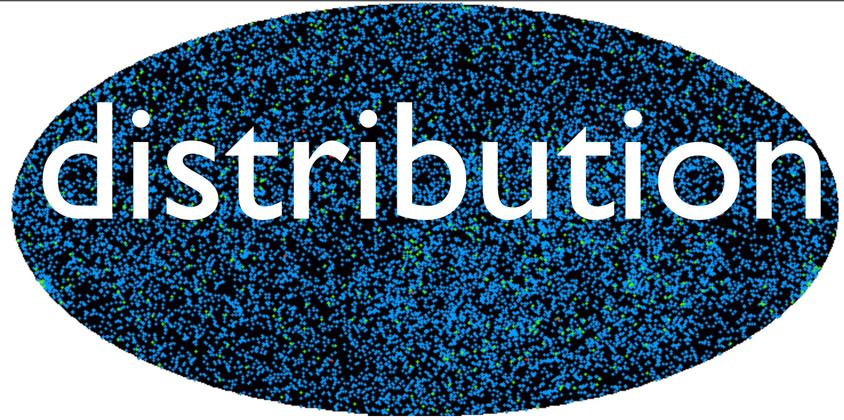
Improved T_{eff}



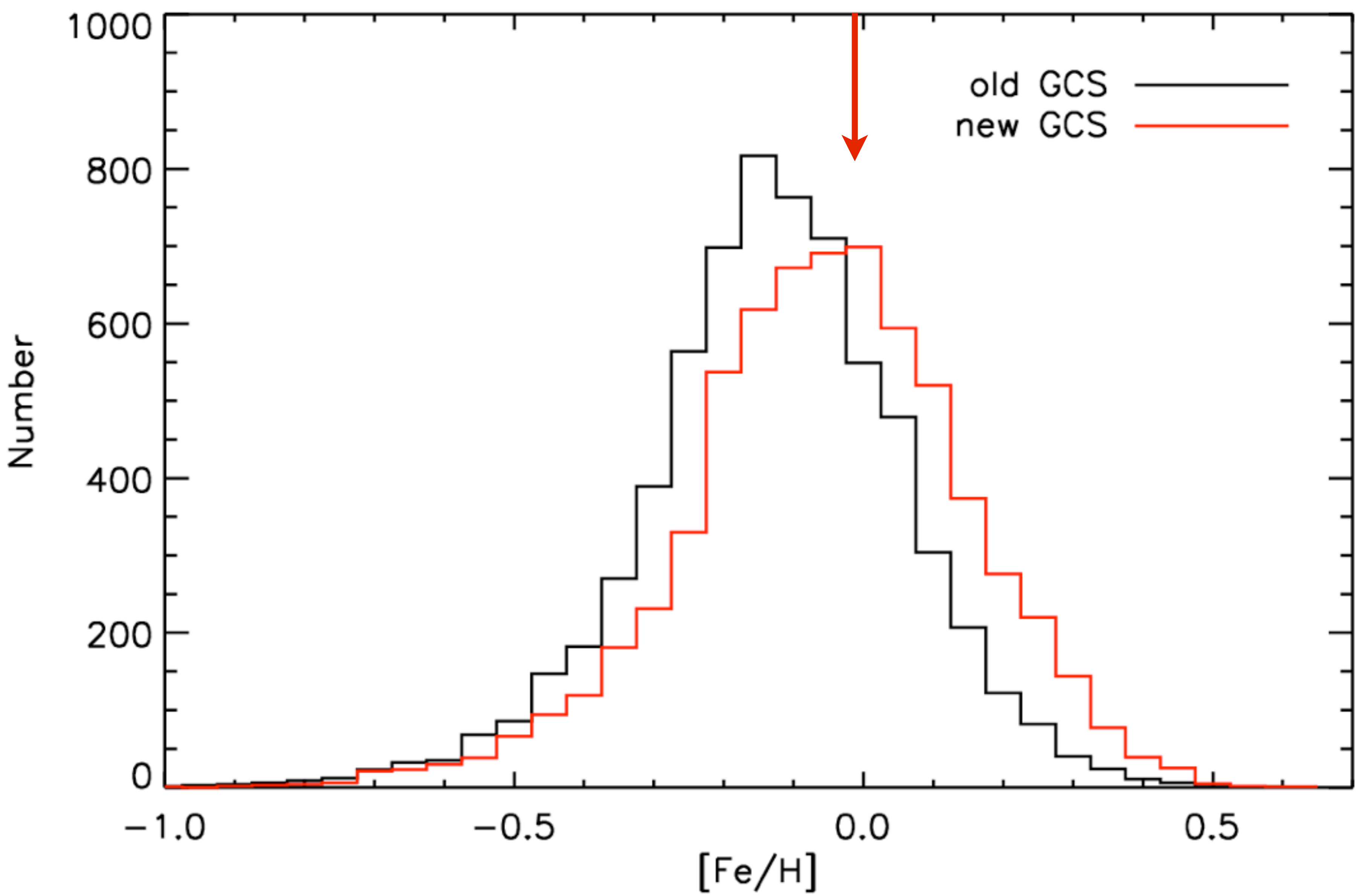
Improved T_{eff} Improved [Fe/H]



Metallicity distribution function



Peaks ~ solar

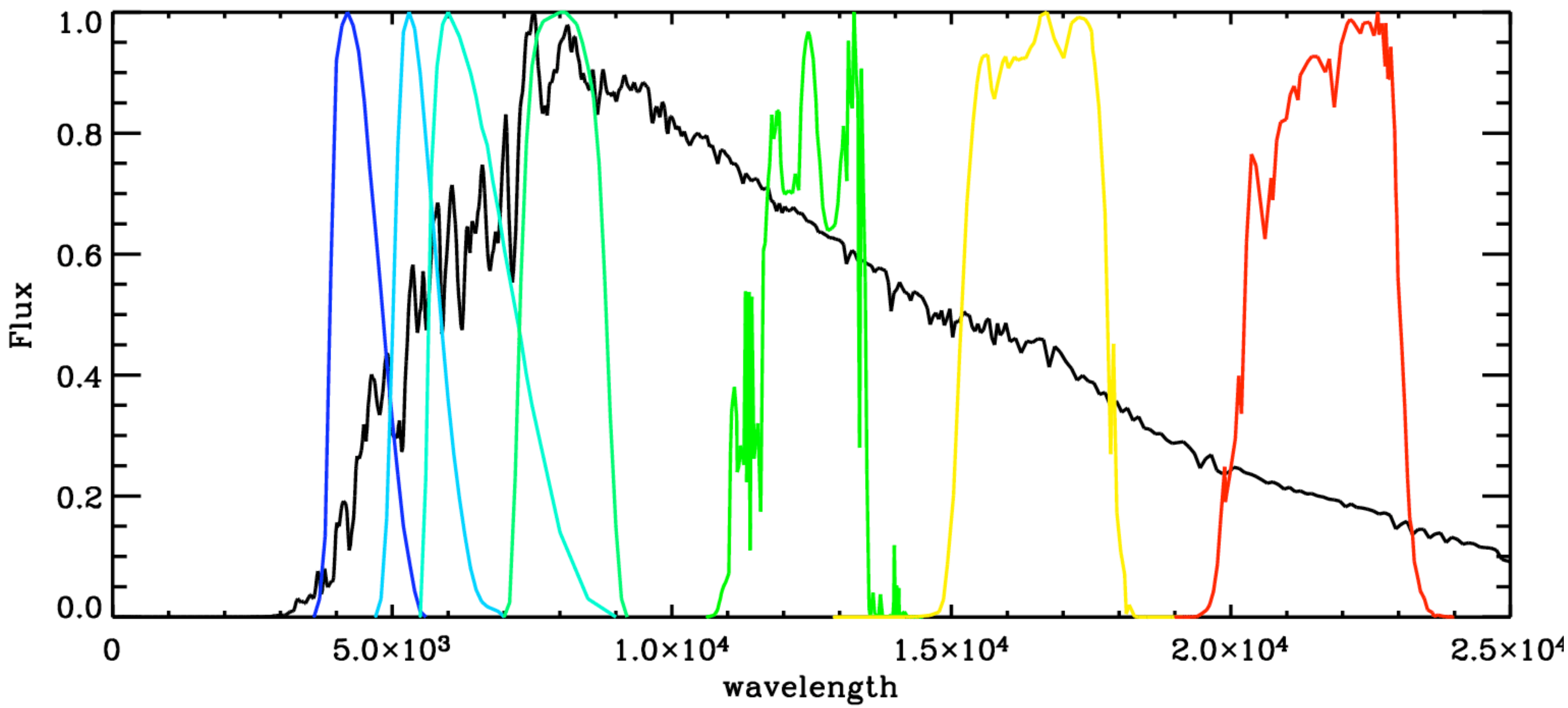


but see Meléndez et al. (2009), Ramírez et al. (2009) for the peculiar solar chemical composition

Something new under the Sun

IRFM goes cool

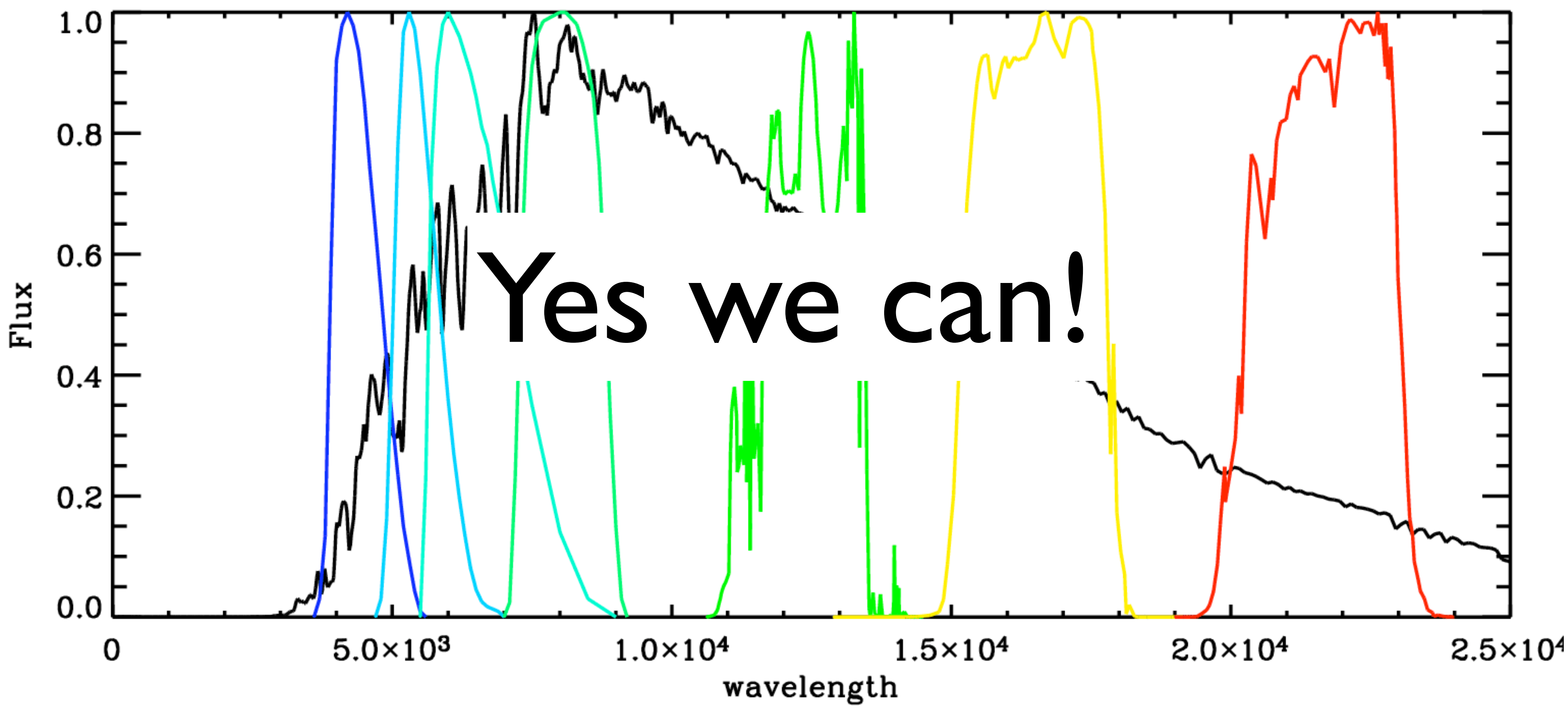
$$\frac{\mathcal{F}_{Bol}(\mathrm{Earth})}{\mathcal{F}_{\mathrm{IR}}(\mathrm{Earth})} = \frac{\sigma T_{\mathrm{eff}}^4}{\mathcal{F}_{\mathrm{IR}}(\mathrm{model})}$$



Casagrande, Flynn & Bessell (2008)

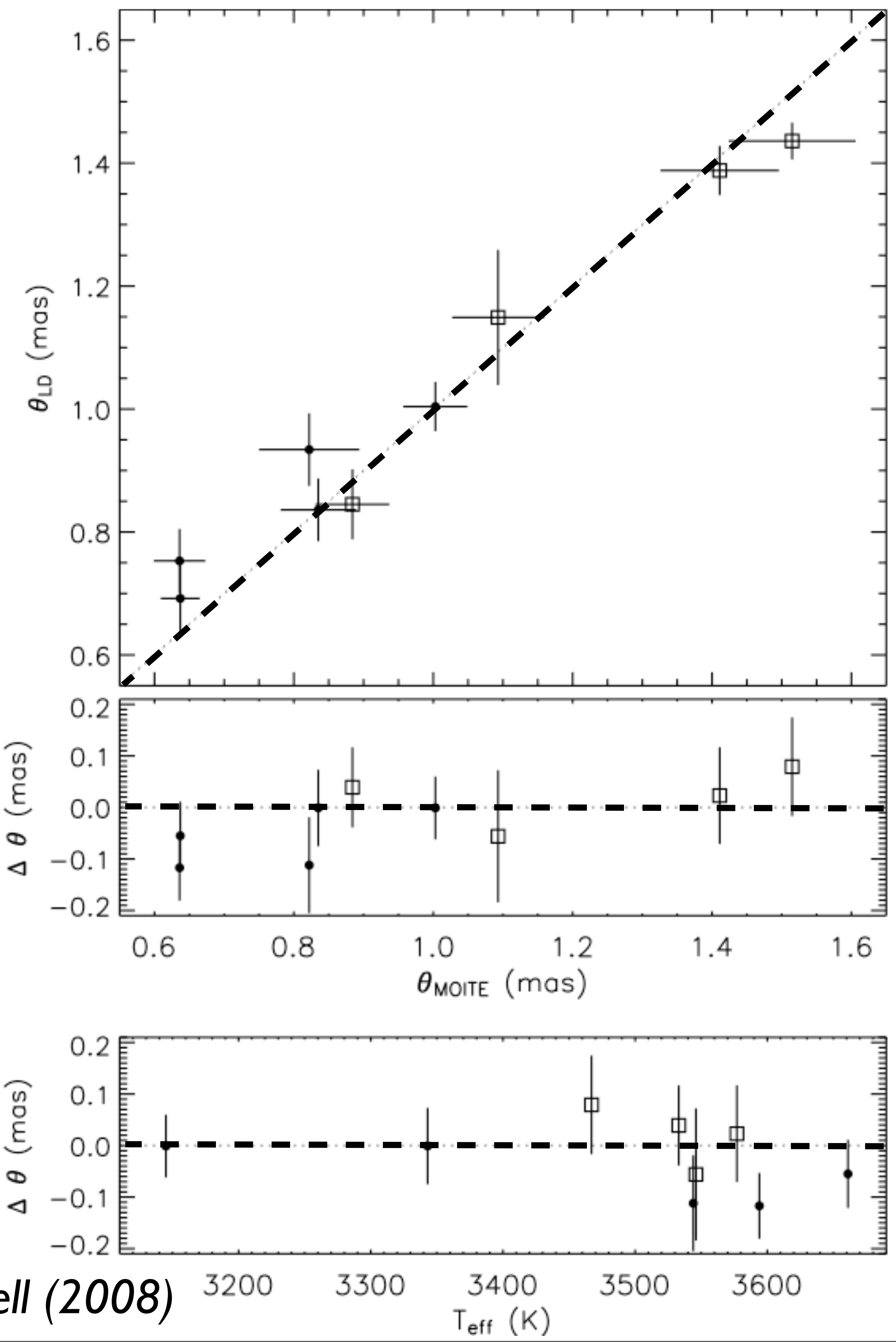
IRFM goes cool

$$\frac{\mathcal{F}_{Bol}(\mathrm{Earth})}{\mathcal{F}_{\mathrm{IR}}(\mathrm{Earth})} = \frac{\sigma T_{\mathrm{eff}}^4}{\mathcal{F}_{\mathrm{IR}}(\mathrm{model})}$$



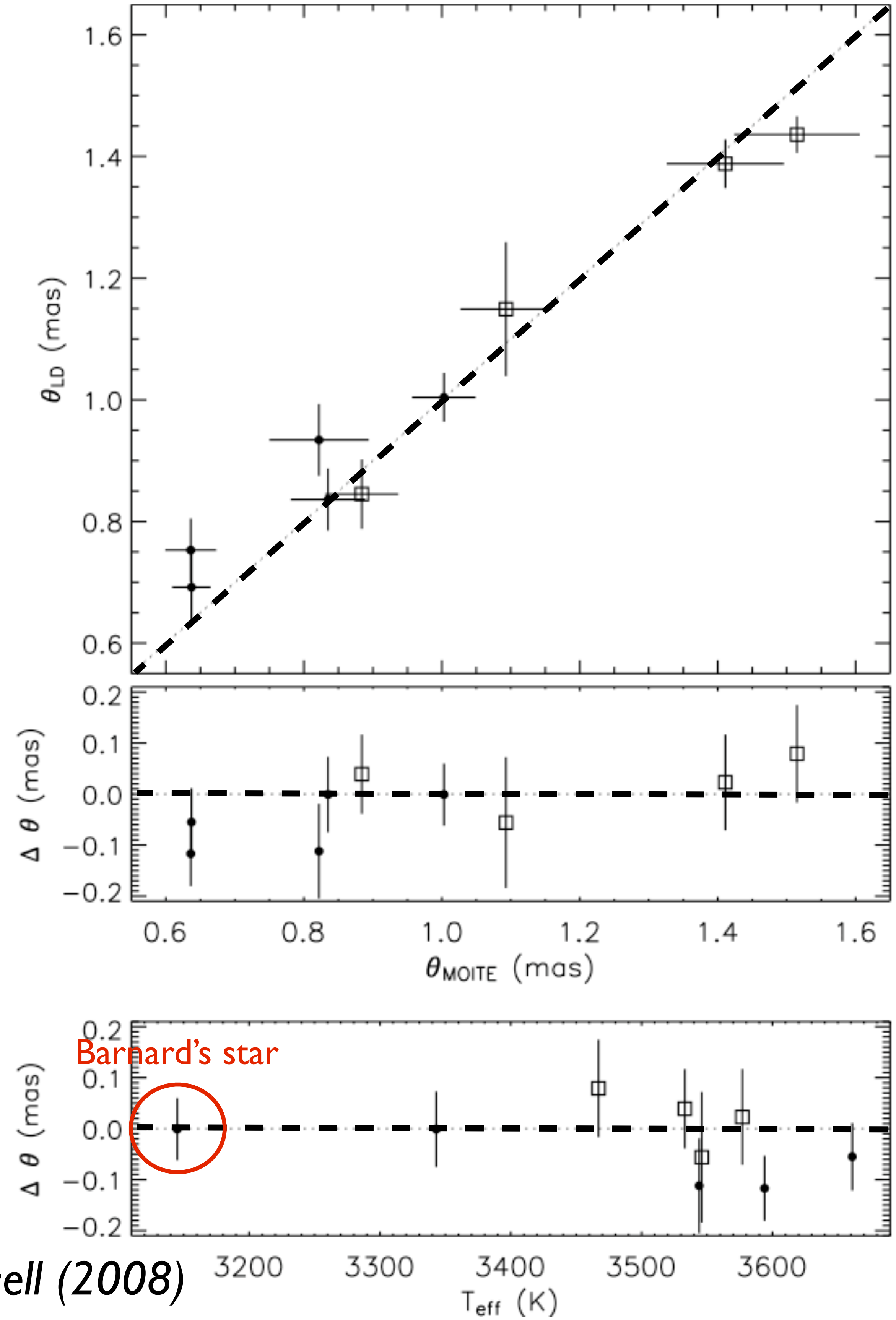
Casagrande, Flynn & Bessell (2008)

M dwarfs angular diameters



Casagrande, Flynn & Bessell (2008)

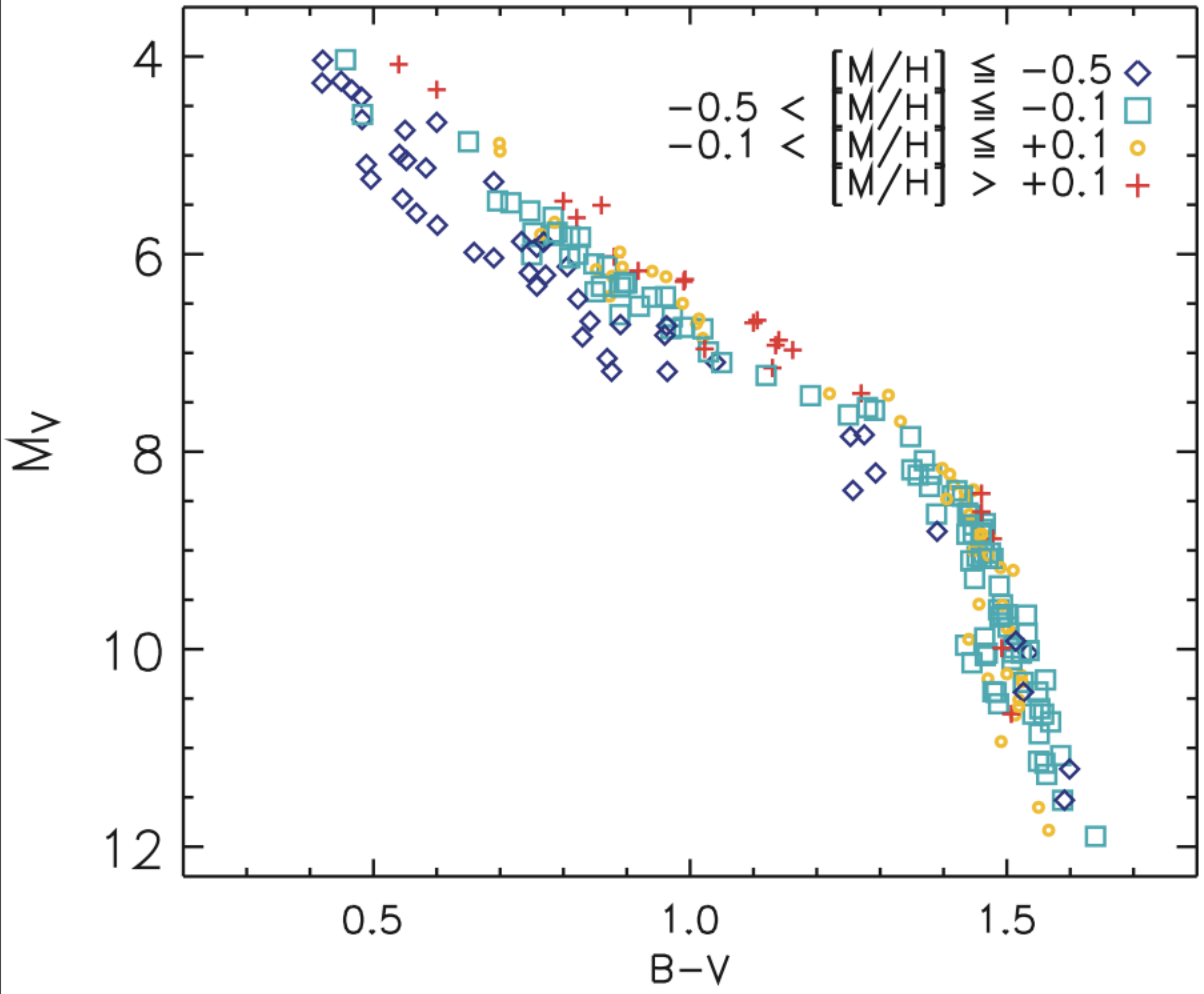
M dwarfs angular diameters



Test on
CM Draconis
(Morales et al. 2009)

Casagrande, Flynn & Bessell (2008)

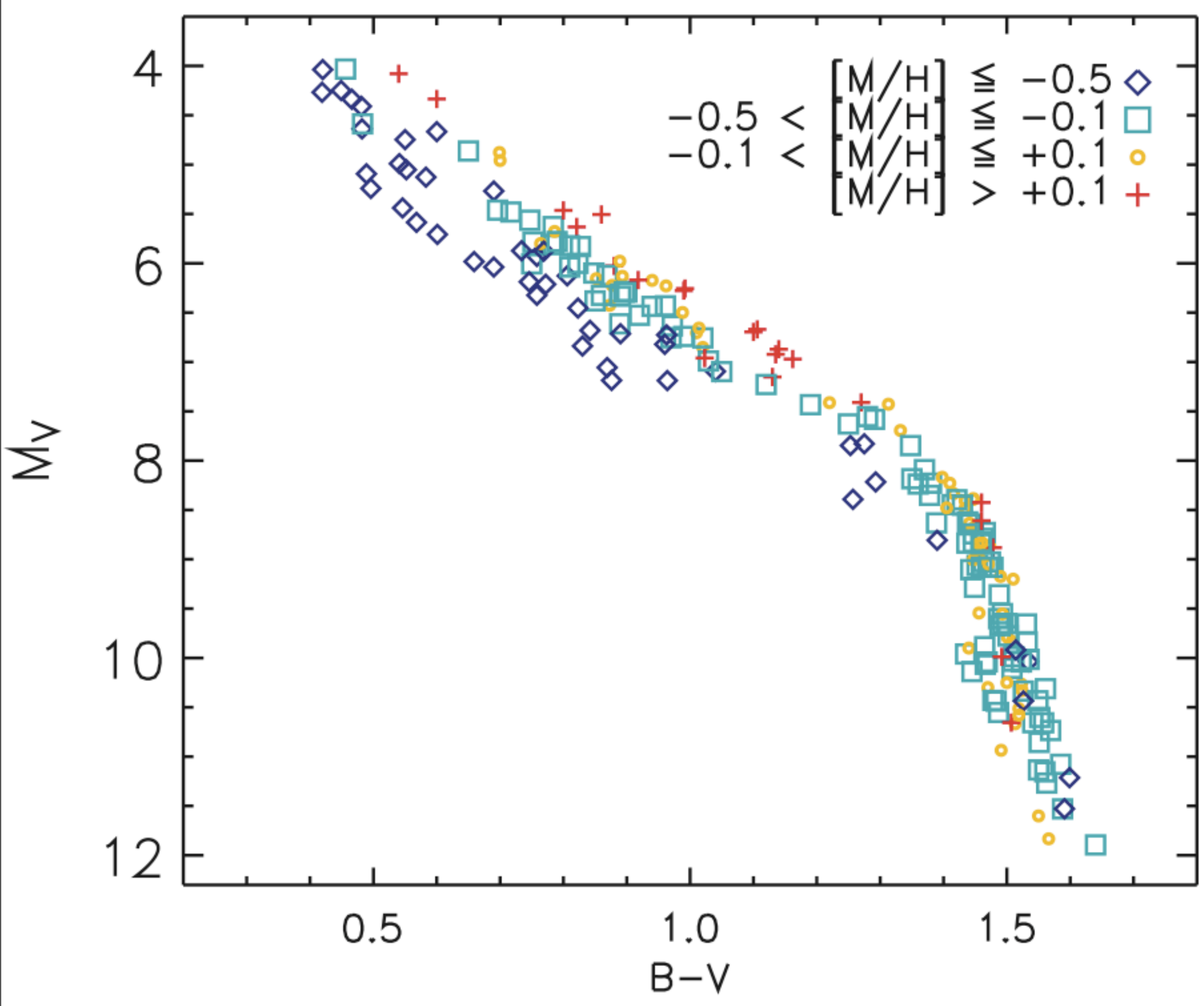
Fine Structure



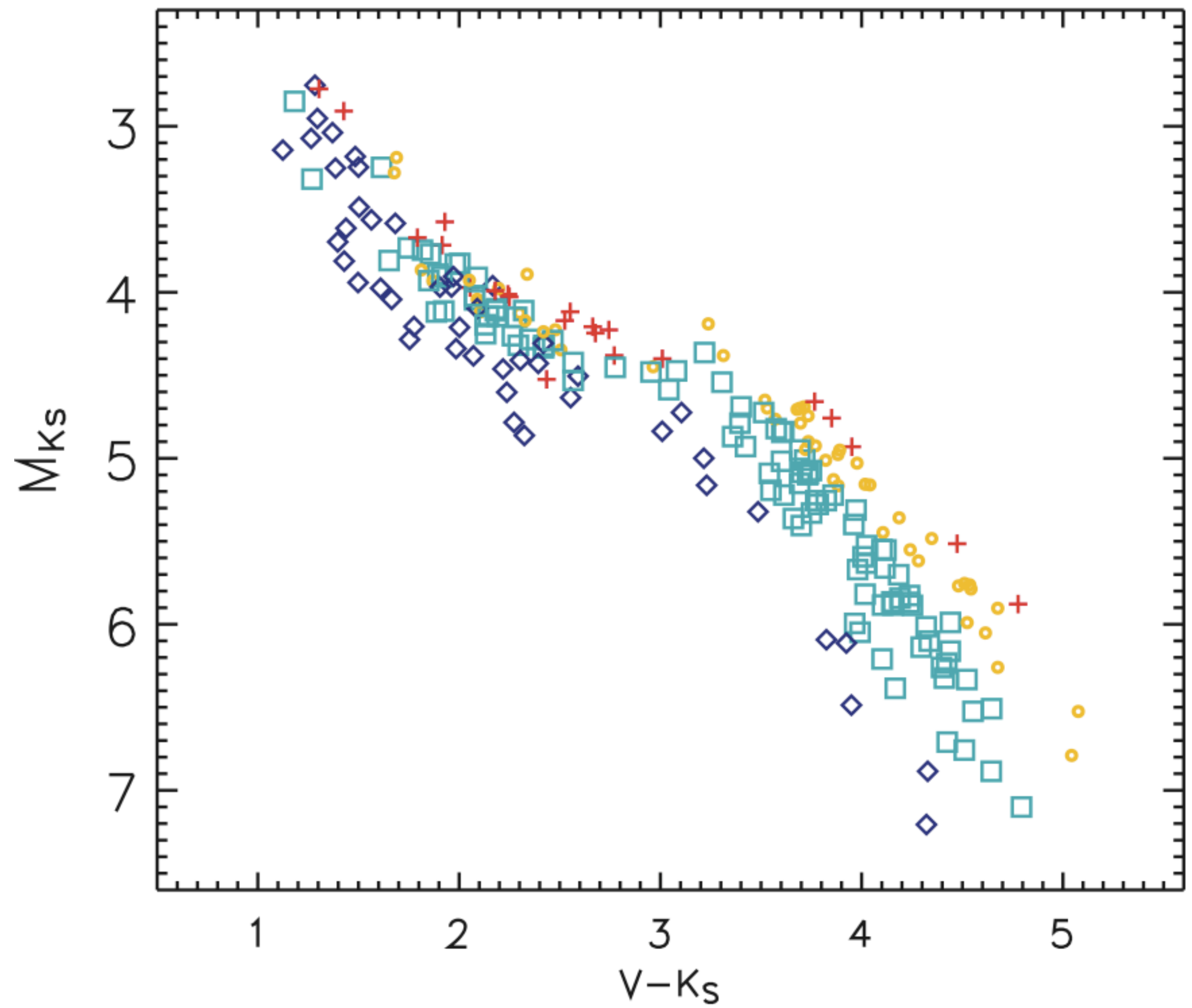
- 222 GKM dwarfs
- σ parallaxes better 15%
- Hipparcos to remove variables/binaries

Casagrande, Flynn & Bessell (2008)

Fine Structure

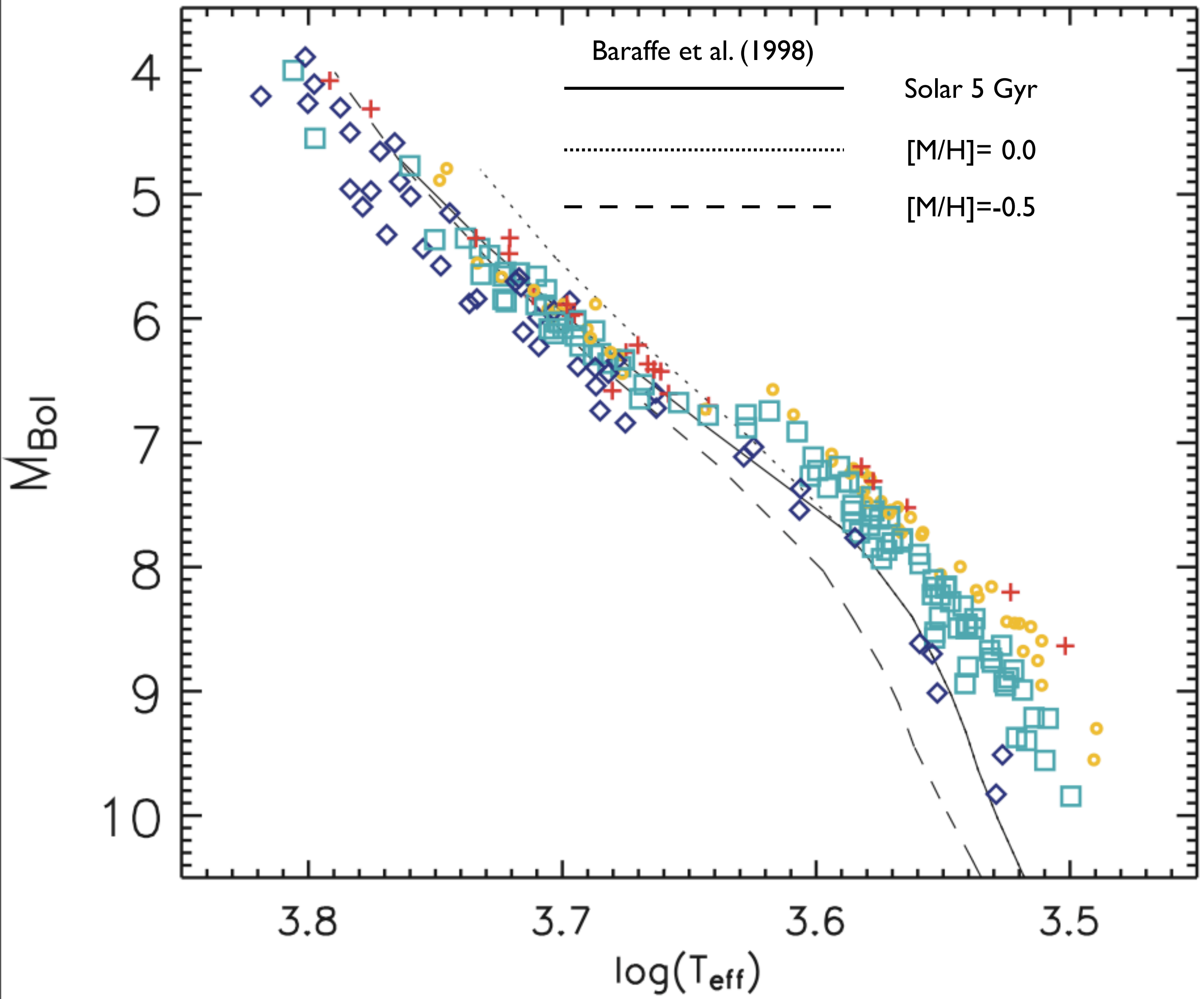


- 222 GKM dwarfs
- σ parallaxes better 15%
- Hipparcos to remove variables/binaries

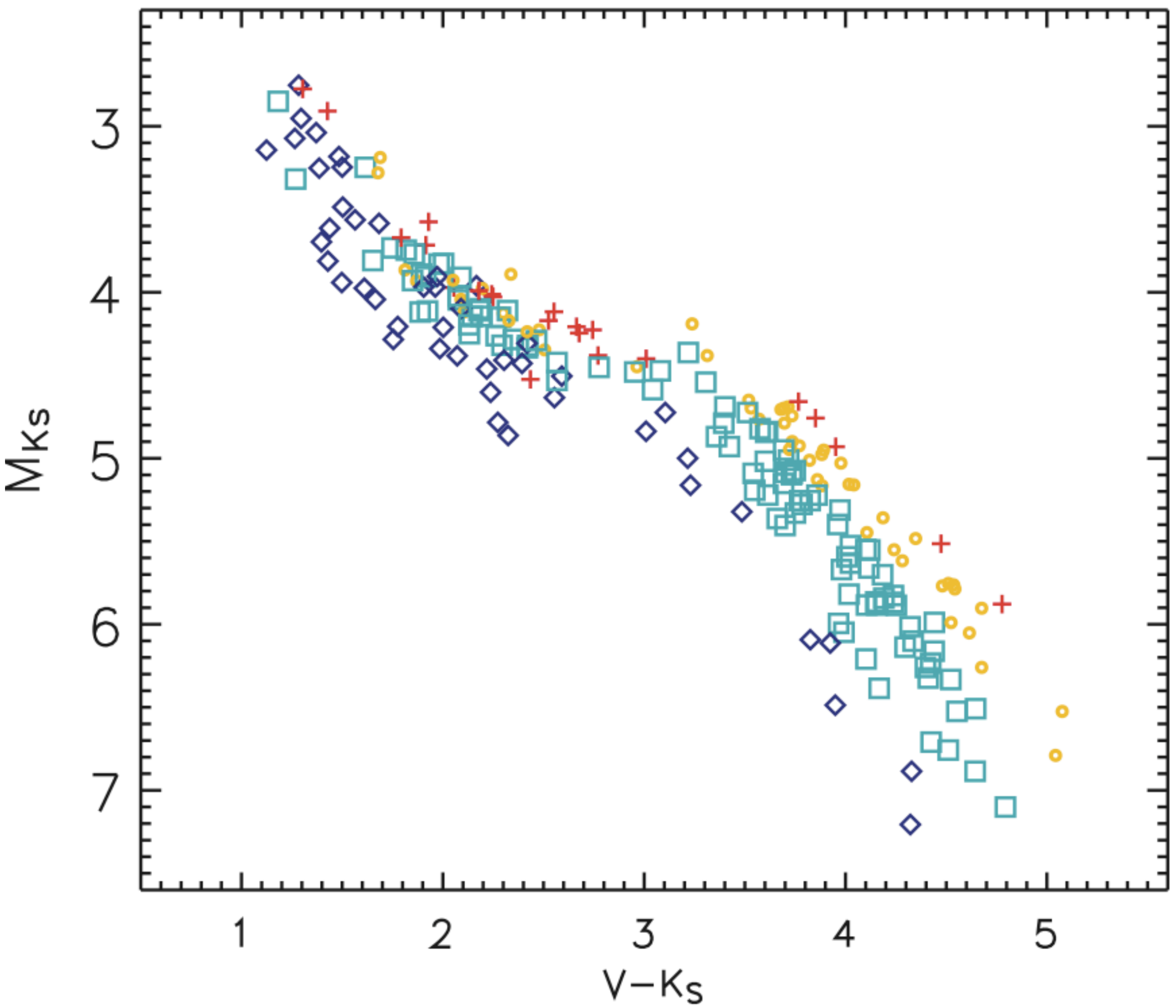


Casagrande, Flynn & Bessell (2008)

Fine Structure

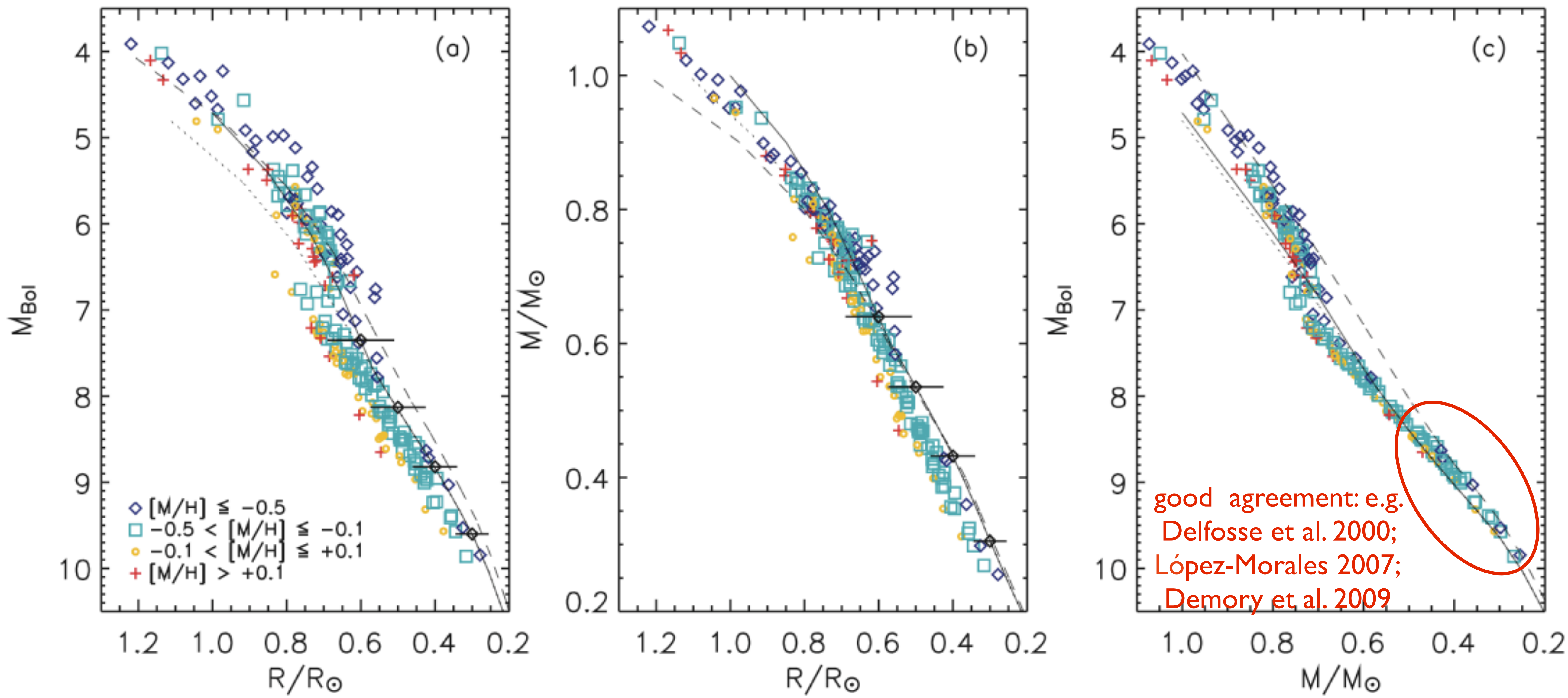


- 222 GKM dwarfs
- σ parallaxes better 15%
- Hipparcos to remove variables/binaries



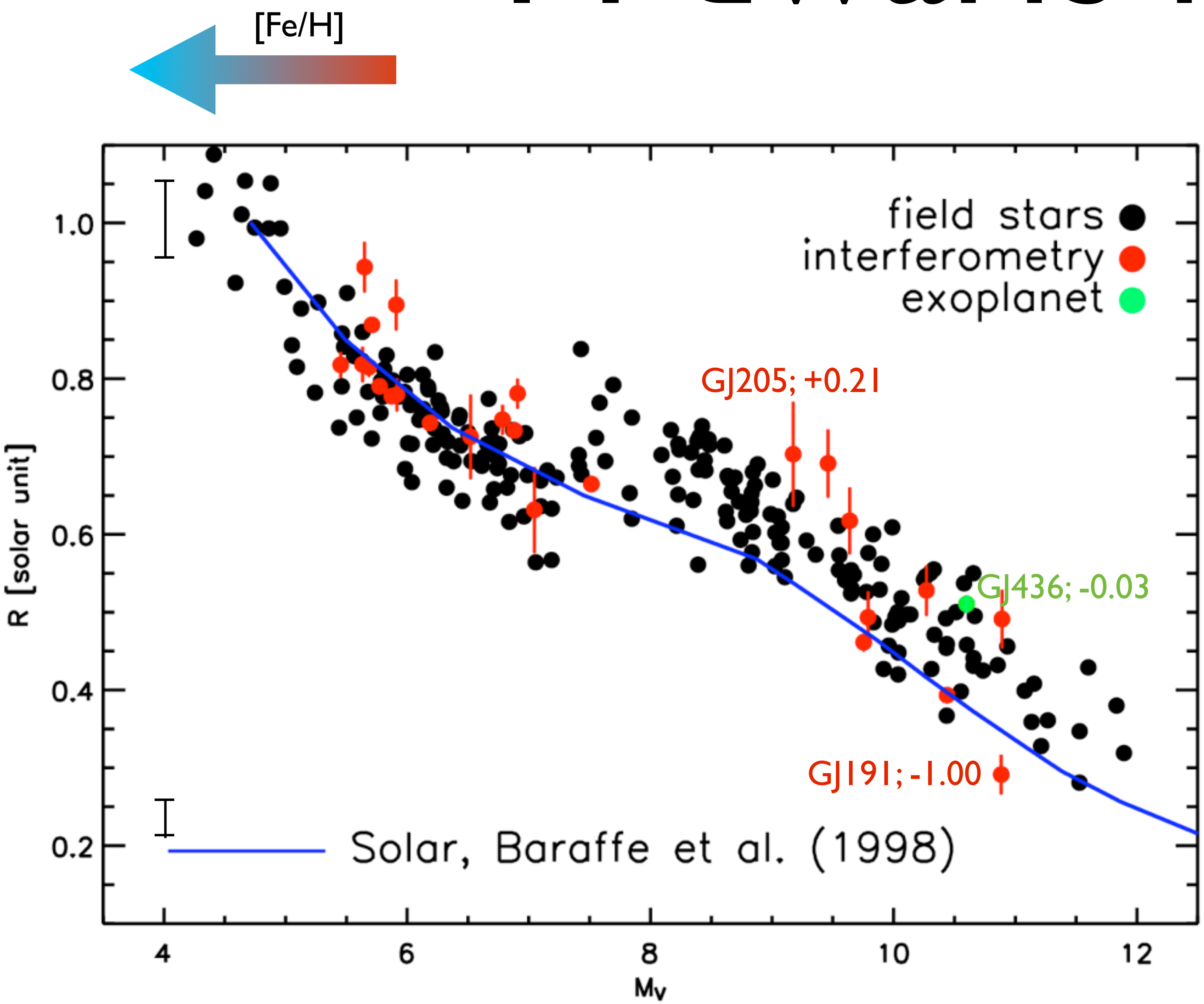
Casagrande, Flynn & Bessell (2008)

M dwarfs radii



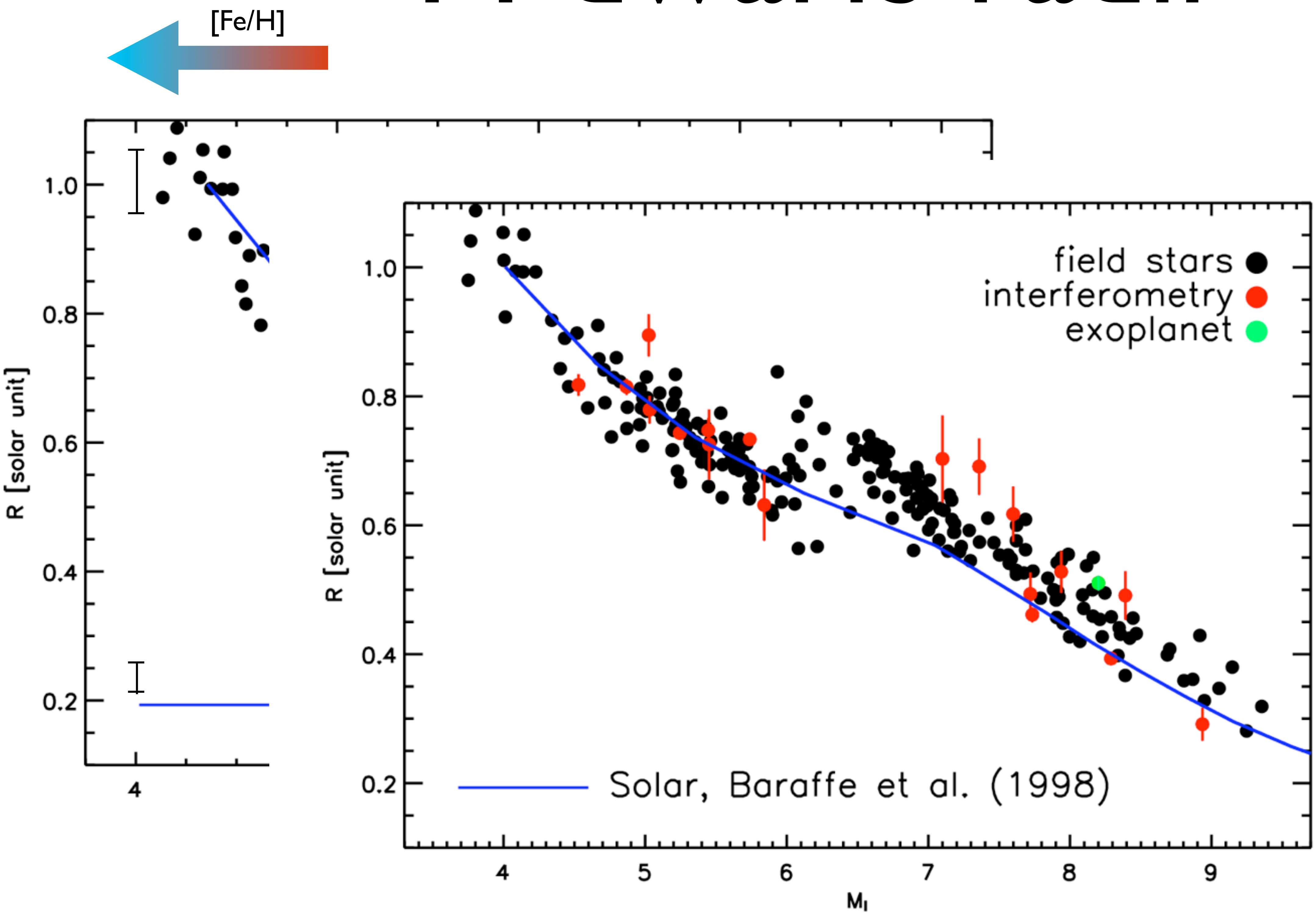
Casagrande, Flynn & Bessell (2008)

M dwarfs radii



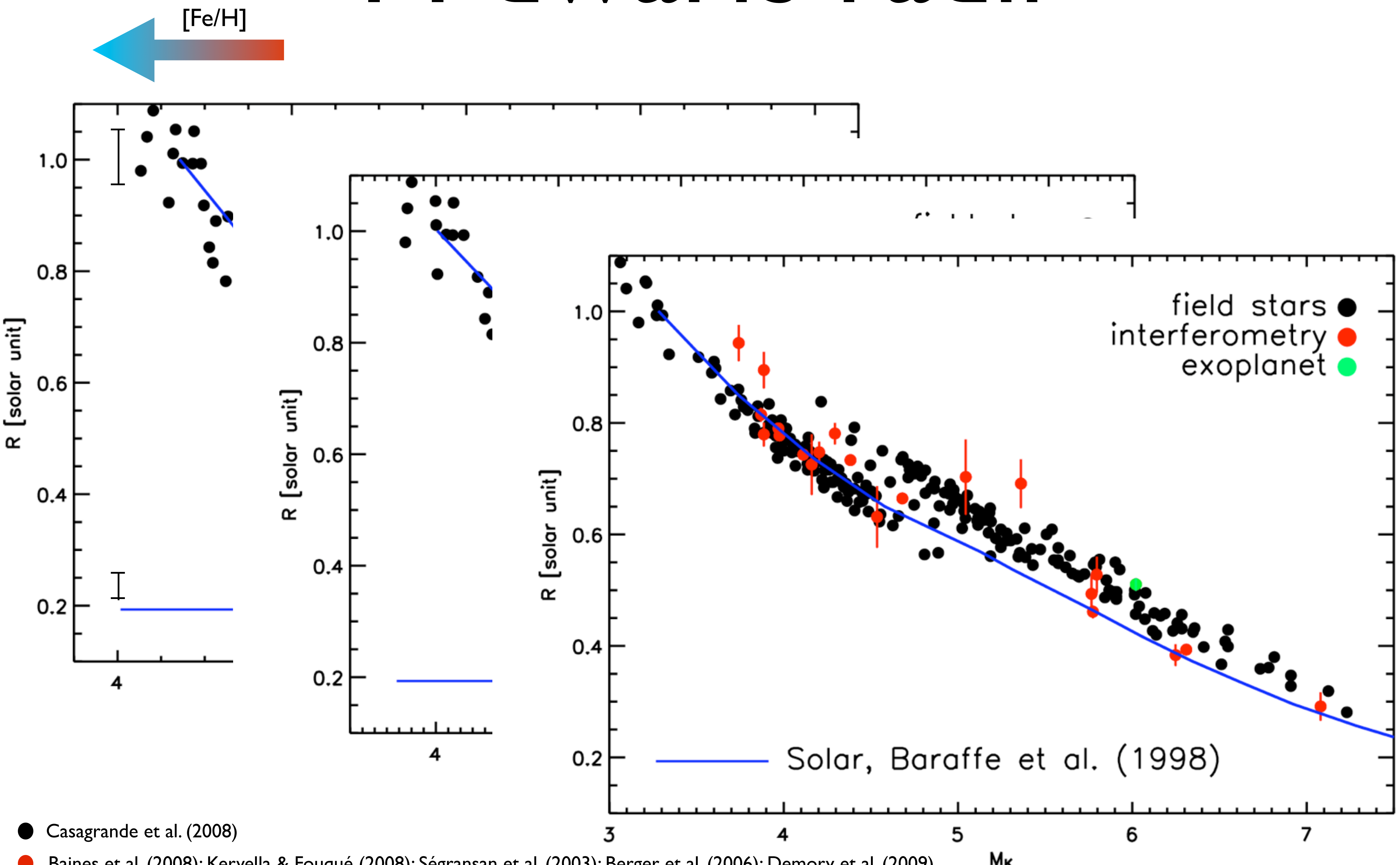
- Casagrande et al. (2008)
- Baines et al. (2008); Kervella & Fouqué (2008); Ségransan et al. (2003); Berger et al. (2006); Demory et al. (2009)
- Gillon et al. (2007); Torres (2007)

M dwarfs radii



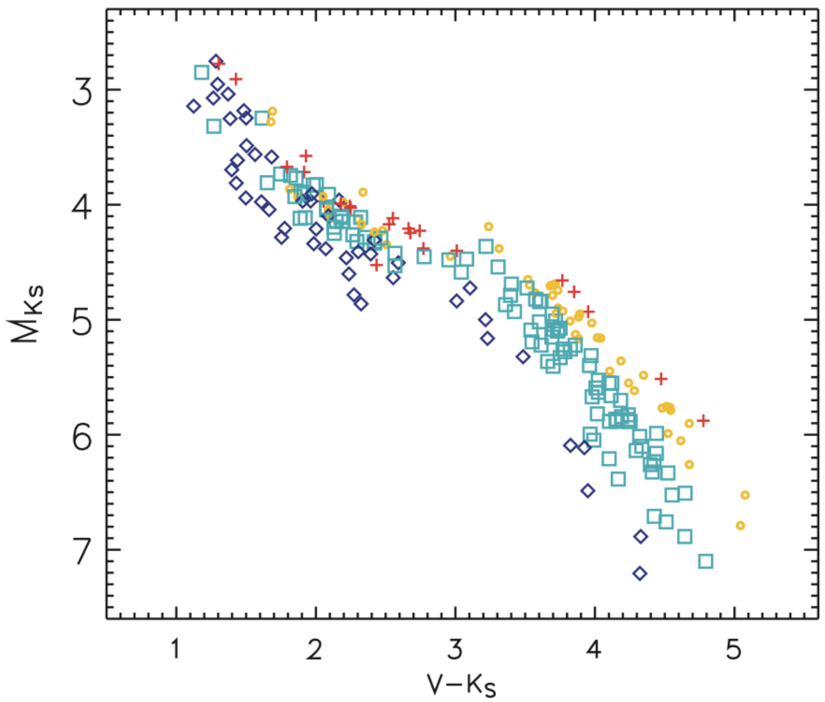
- Casagrande et al. (2008)
- Baines et al. (2008); Kervella & Fouqué (2008); Ségransan et al. (2003); Berger et al. (2006); Demory et al. (2009)
- Gillon et al. (2007); Torres (2007)

M dwarfs radii



- Casagrande et al. (2008)
- Baines et al. (2008); Kervella & Fouqué (2008); Ségransan et al. (2003); Berger et al. (2006); Demory et al. (2009)
- Gillon et al. (2007); Torres (2007)

3 characters in search of an author



→ inflated radii in M dwarfs not only in **eclipsing binaries**, also **single field stars**

- Mixing Length (e.g. Chabrier et al. 2007)

- Magnetic activity (e.g. Mullan & MacDonald 2001; López-Morales & Ribas 2005)

- Opacity (e.g. Berger et al. 2006)

The Epilogue

- **T_{eff} : FGK dwarfs**
  - **understand the differences among scales**
  - **settle the issue**
    - solar twins
    - HST spectro-photometry
    - angular diameters

    } **~ 20 K**
  - **chemical evolution Solar Neighbourhood**
- **T_{eff} : M dwarfs**
  - T_{eff} scale robust down to 3000 K
  - discontinuity in obs. plane! ⟶ inflated radii ?!?