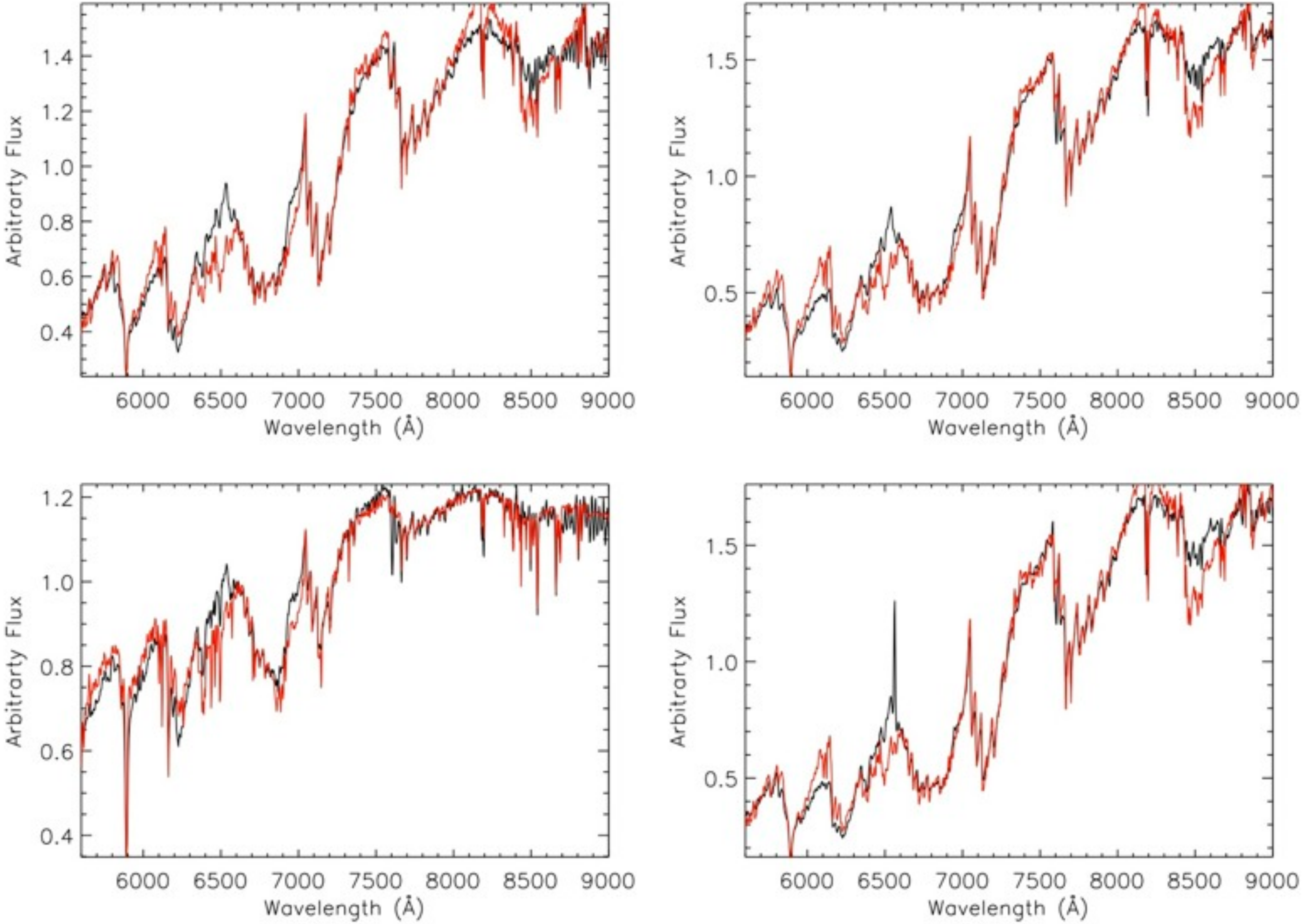
Full Metal Bracket:

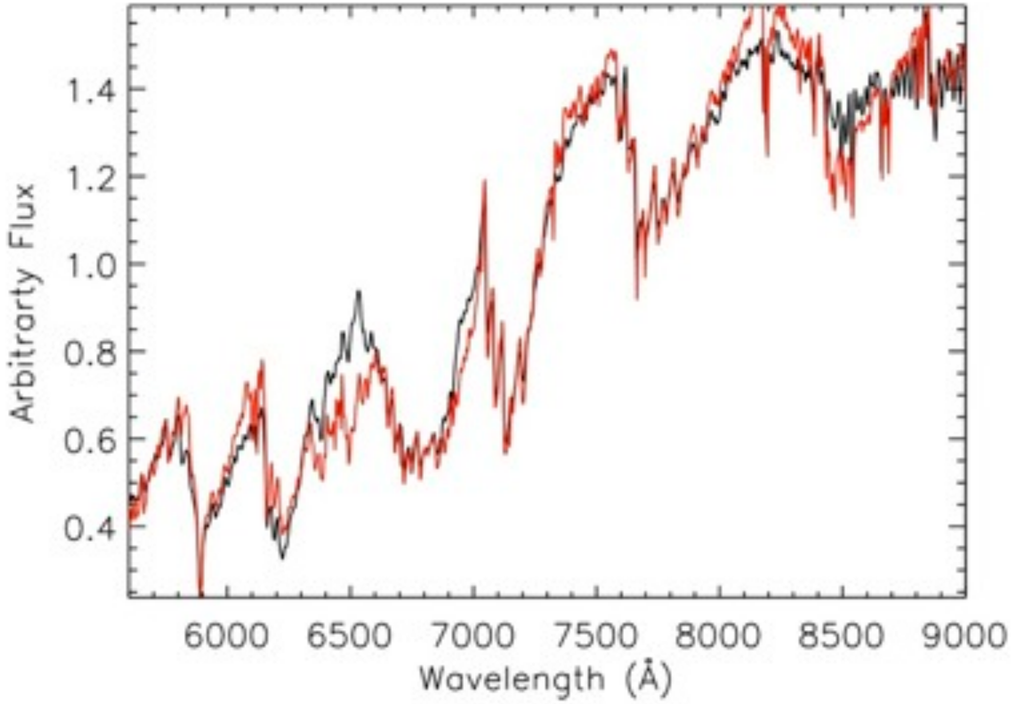
a calibration of infrared and optical spectroscopic metallicities of M dwarfs over 1.5 dex

Andrew W. Mann, John Brewer, Eric Gaidos,
Sebastien Lepine, & Eric Hilton

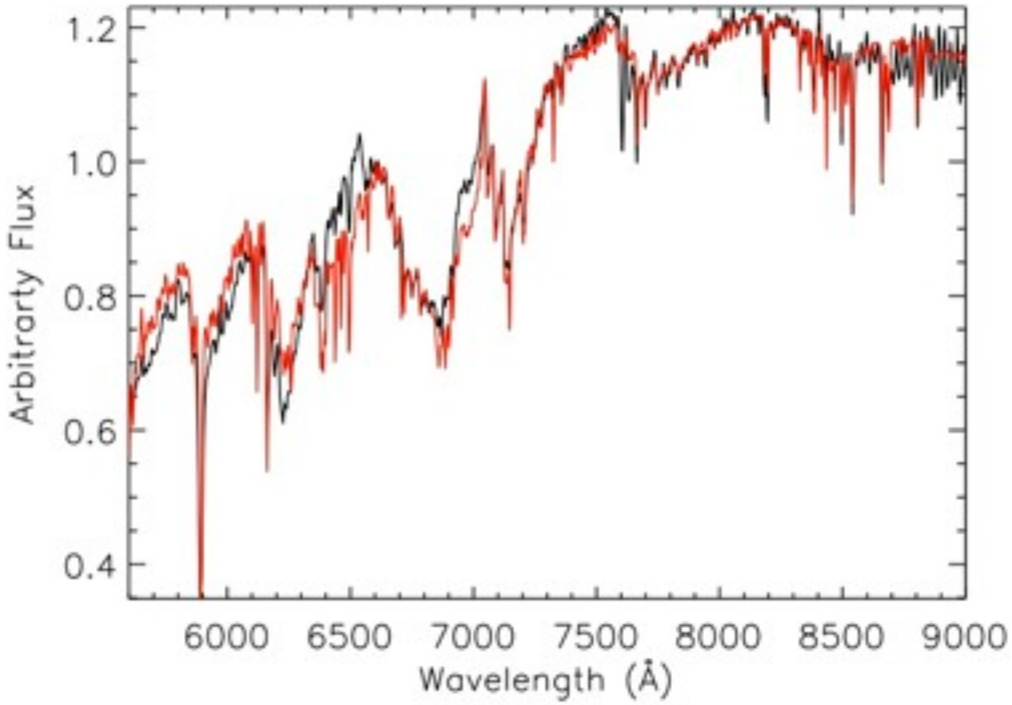
M Dwarf Metallicities

- Chemical analysis of M dwarfs is extraordinarily difficult:
  - Their spectra are dominated by complex bands of diatomic and triatomic molecules.
  - Spectral synthesis techniques do not match well with observed spectra.
- Instead we can take advantage of FGK-M dwarf wide binary systems. (Bonfils et al 2005)


Arbitrarty Flux
Wavelength (Å)



[Fe/H] = +0.38
[Fe/H] = -0.40



[Fe/H] = -0.89
[Fe/H] = +0.10

M Dwarf Metallicities

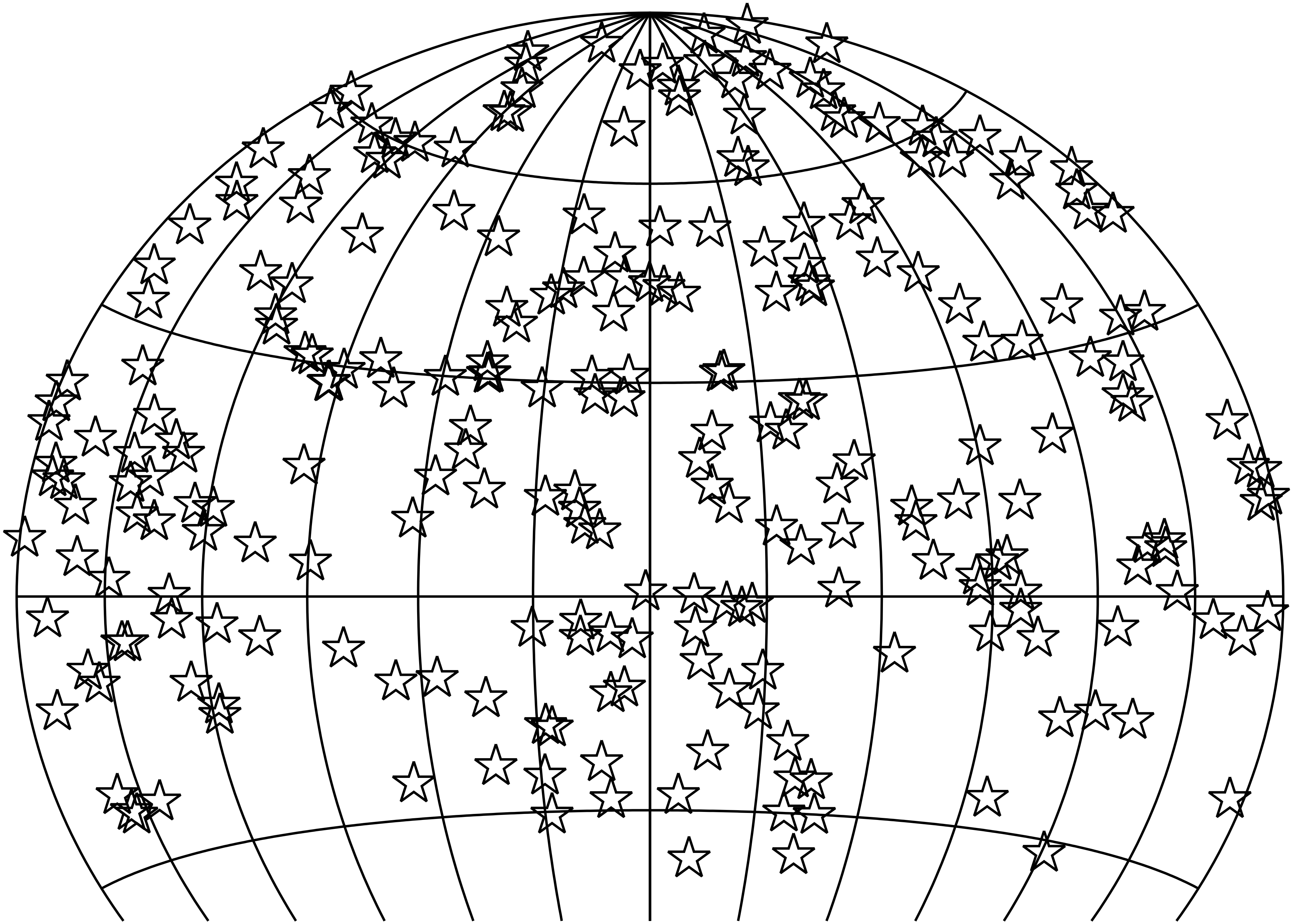
- Chemical analysis of M dwarfs is extraordinarily difficult:
  - Their spectra are dominated by complex bands of diatomic and triatomic molecules.
  - Spectral synthesis techniques do not match well with observed spectra.
- Instead we can take advantage of FGK-M dwarf wide binary systems (Bonfils et al 2005).

The FMB program

- Identify new FGK-M pairs.
- Expand the sample of FGK stars with reliable metallicities.
- Extend existing metallicity calibrations to metal-poor M dwarfs.
- Identify new metal-sensitive features, including in visible and J-band wavelengths.

The FMB program

- Identify new FGK-M pairs.
- Expand the sample of FGK stars with reliable metallicities.
- Extend existing metallicity calibrations to metal-poor M dwarfs.
- Identify new metal-sensitive features, including in visible and J-band wavelengths.



The FMB program

- Identify new FGK-M pairs.
- Expand the sample of FGK stars with reliable metallicities.
- Extend existing metallicity calibrations to metal-poor M dwarfs.
- Identify new metal-sensitive features, including in visible and J-band wavelengths.

FGK Star Metallicities

- 105 objects with metallicities of the primary star:
  - 31 stars in SPOCS (Fischer & Valenti 2005).
  - 12 from Casagrande et al. (2011), derived from photometry (higher errors).
  - 18 from other literature sources of high-resolution spectra (may have small systematic differences).
  - 44 from our own CFHT/ESPaDOnS program.

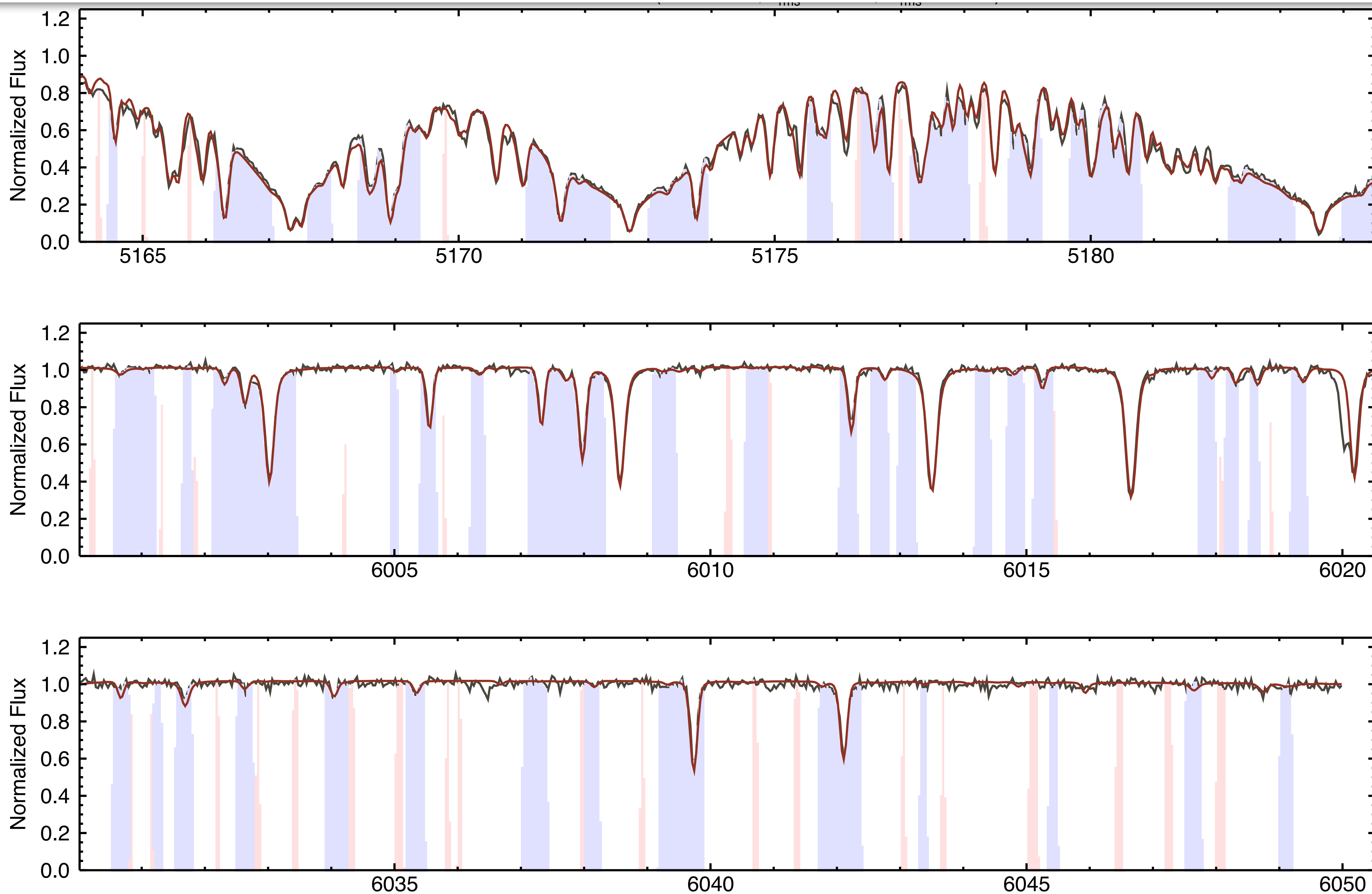
FGK Star Metallicities

- 105 objects with metallicities of the primary star:
  - 31 stars in SPOCS (Fischer & Valenti 2005).
  - 12 from Casagrande et al. (2011), derived from photometry (higher errors).
  - 18 from other literature sources of high-resolution spectra (may have small systematic differences).
  - 44 from our own CFHT/ESPaDOnS program.

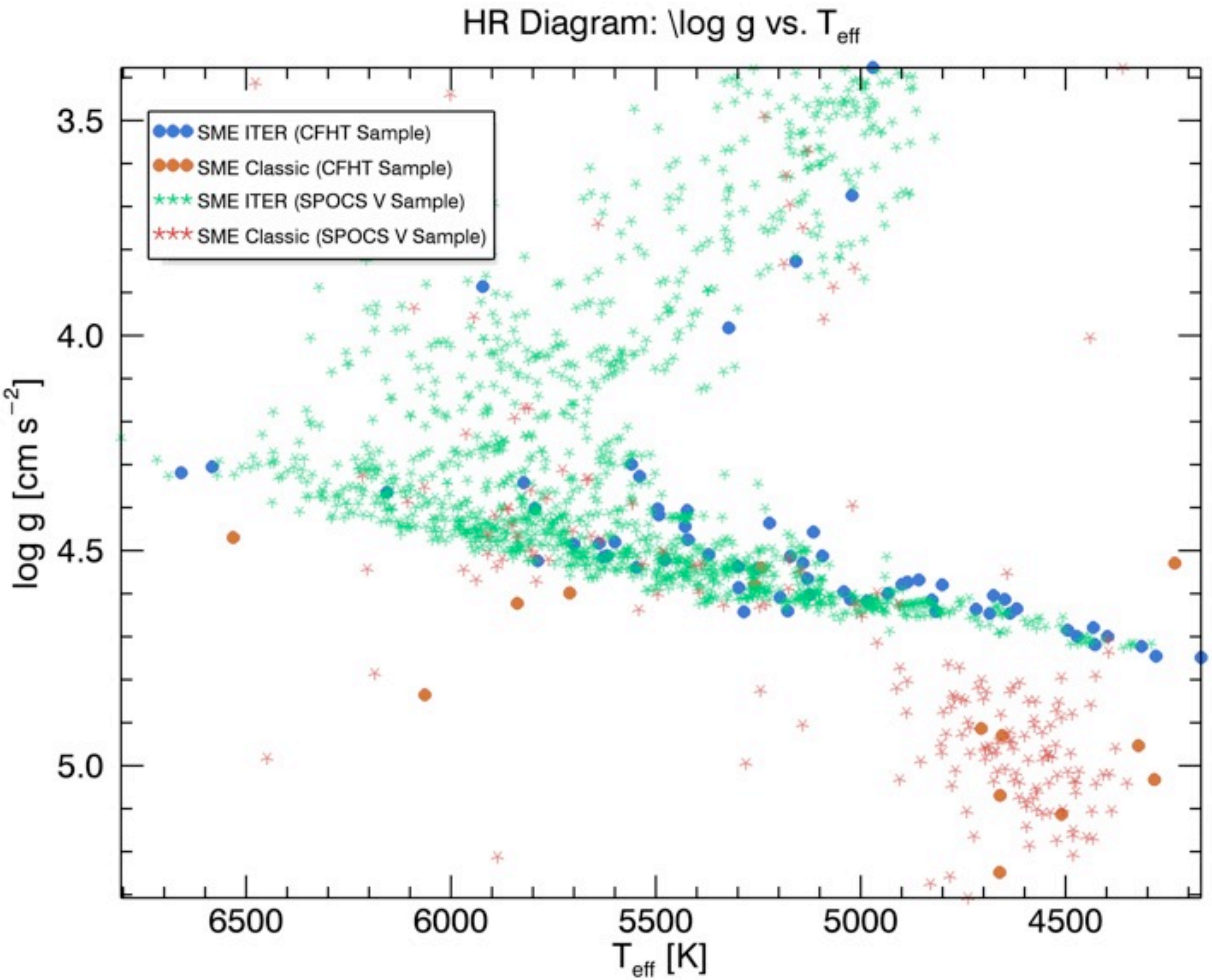
CFHT/ESPaDOnS

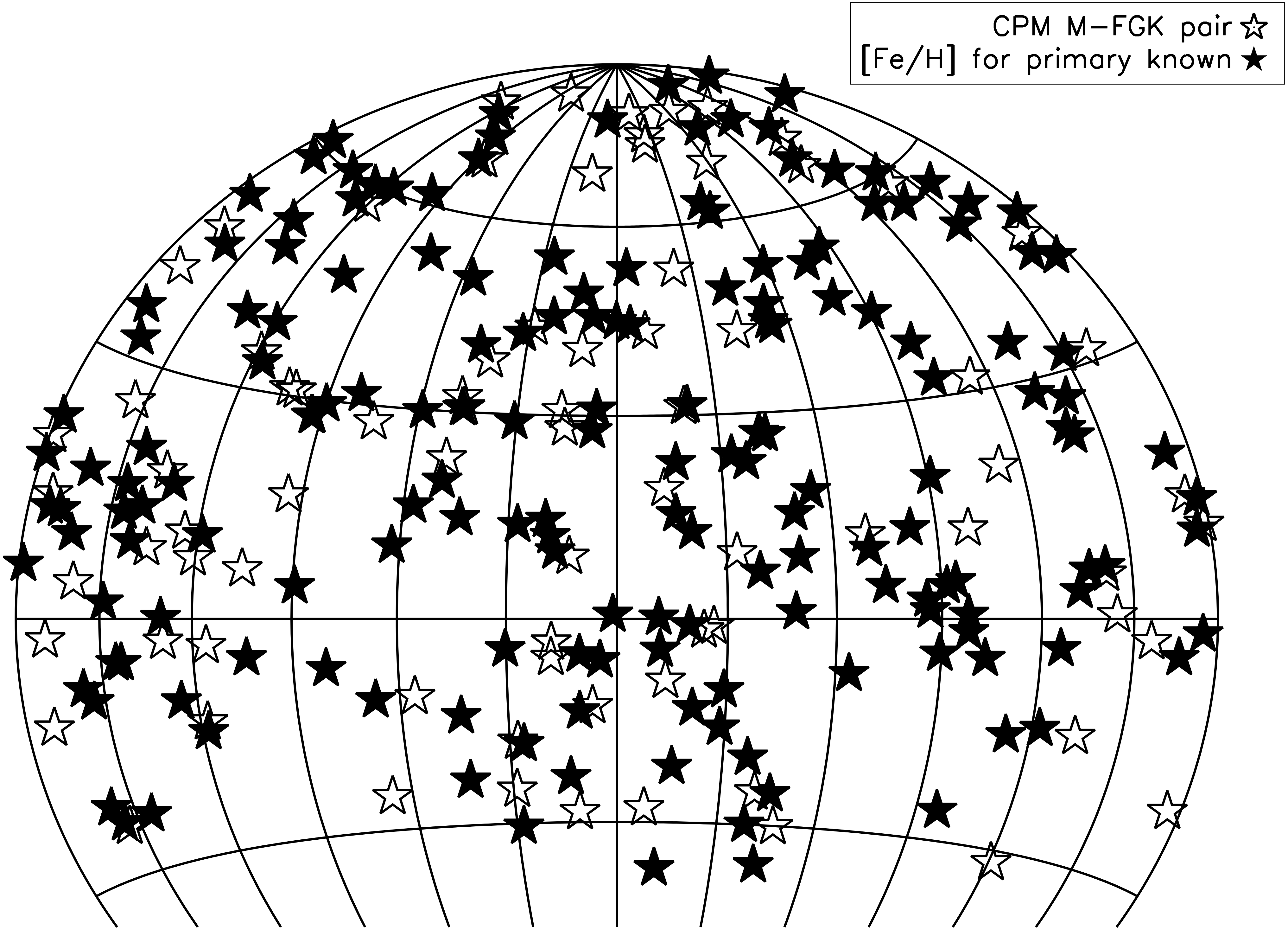
High-resolution (R~65,000) spectrograph

Spectroscopy Made Easy



Valenti & Piskunov (1996)

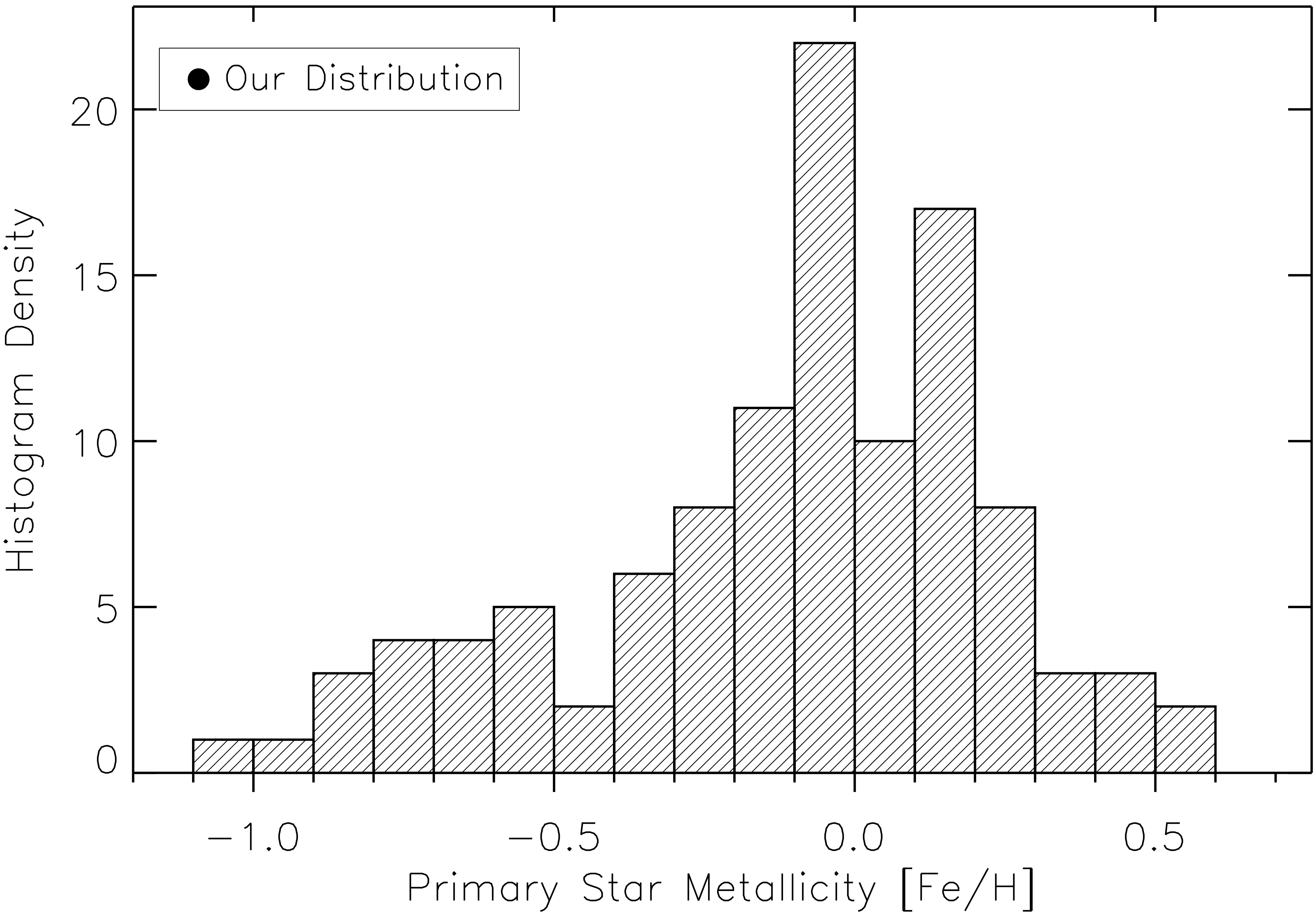

HR Diagram: \log g vs. T_eff
SME ITER (CFHT Sample)
SME Classic (CFHT Sample)
SME ITER (SPOCS V Sample)
SME Classic (SPOCS V Sample)
log g [cm s^-2]
3.5
4.0
4.5
5.0
6500
6000
5500
5000
4500
T_eff [K]



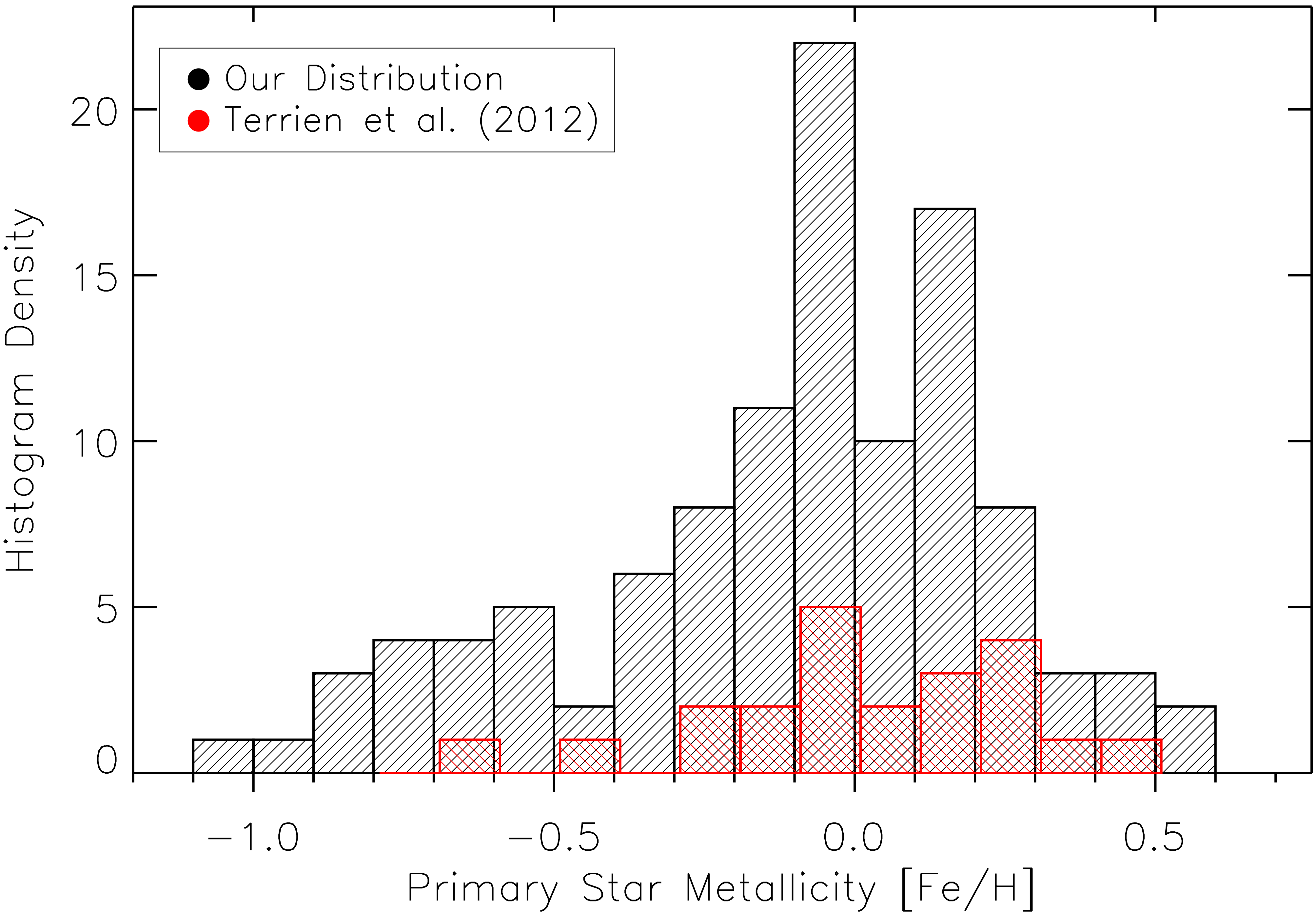
CPM M–FGK pair
[Fe/H] for primary known

The FMB program

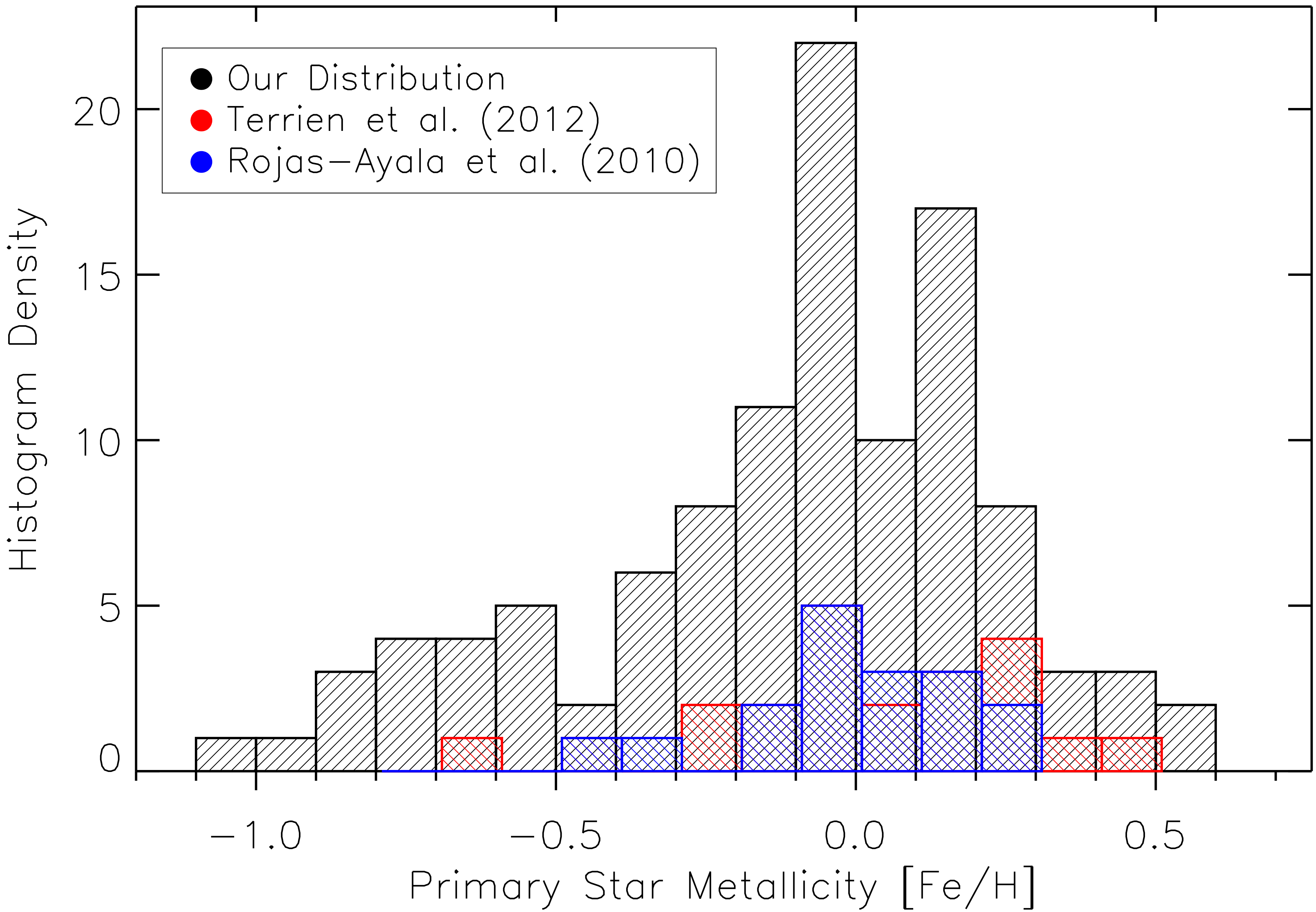
- Identify new FGK-M pairs.
- Expand the sample of FGK stars with reliable metallicities.
- Extend existing metallicity calibrations to metal-poor M dwarfs.
- Identify new metal-sensitive features, including in visible and J-band wavelengths.



Our Distribution
Histogram Density
20
15
10
5
0
−1.0
−0.5
0.0
0.5
Primary Star Metallicity [Fe/H]



Our Distribution
Terrien et al. (2012)
Histogram Density
0
5
10
15
20
−1.0
−0.5
0.0
0.5
Primary Star Metallicity [Fe/H]



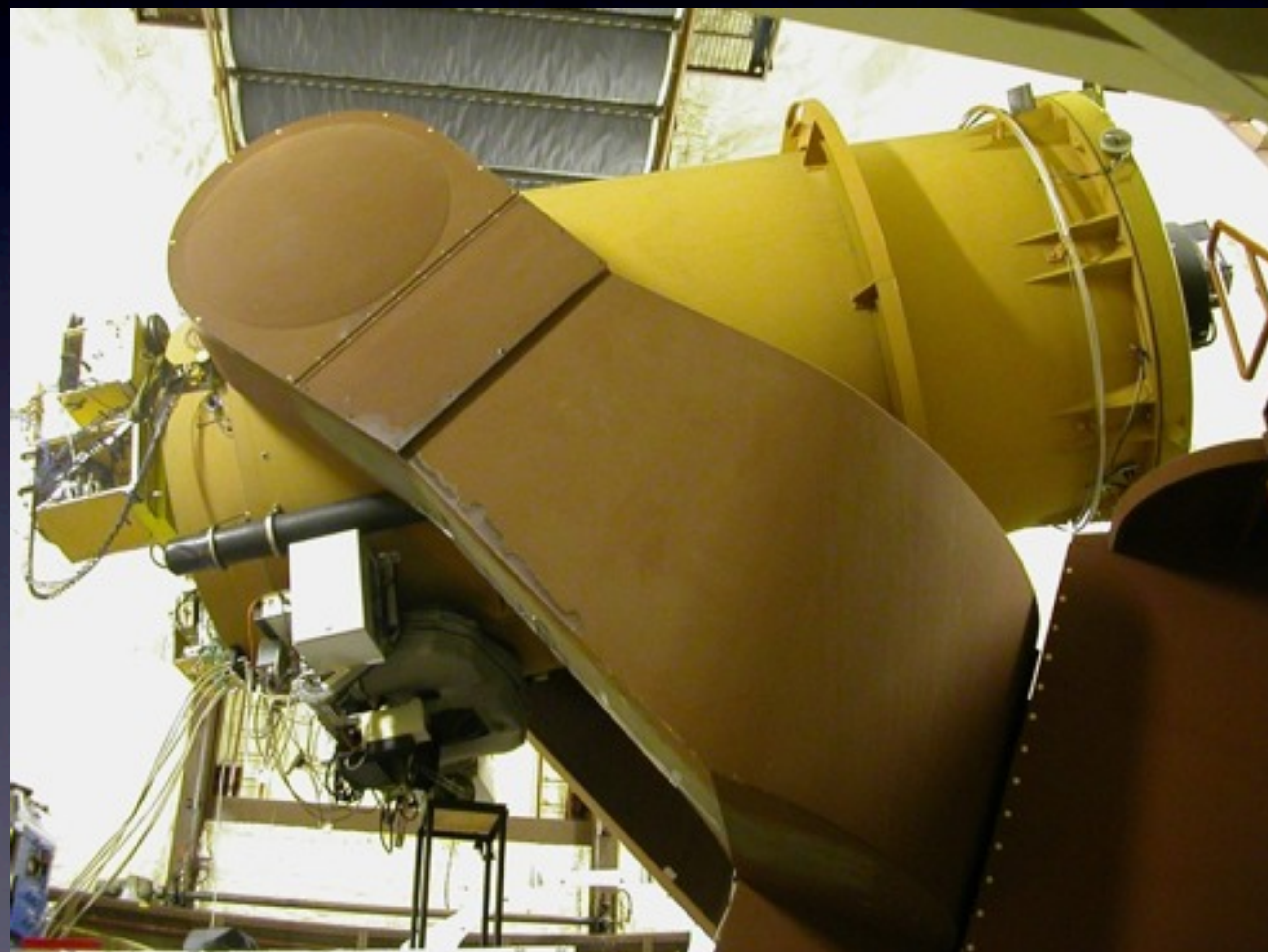
Our Distribution
Terrien et al. (2012)
Rojas–Ayala et al. (2010)
Histogram Density
0
5
10
15
20
−1.0
−0.5
0.0
0.5
Primary Star Metallicity [Fe/H]

The FMB program

- Identify new FGK-M pairs.
- Extend existing calibrations to metal-poor M dwarfs.
- Refine existing techniques to estimate M dwarf metallicities.
- Identify new metal-sensitive features, including in visible and J-band wavelengths.

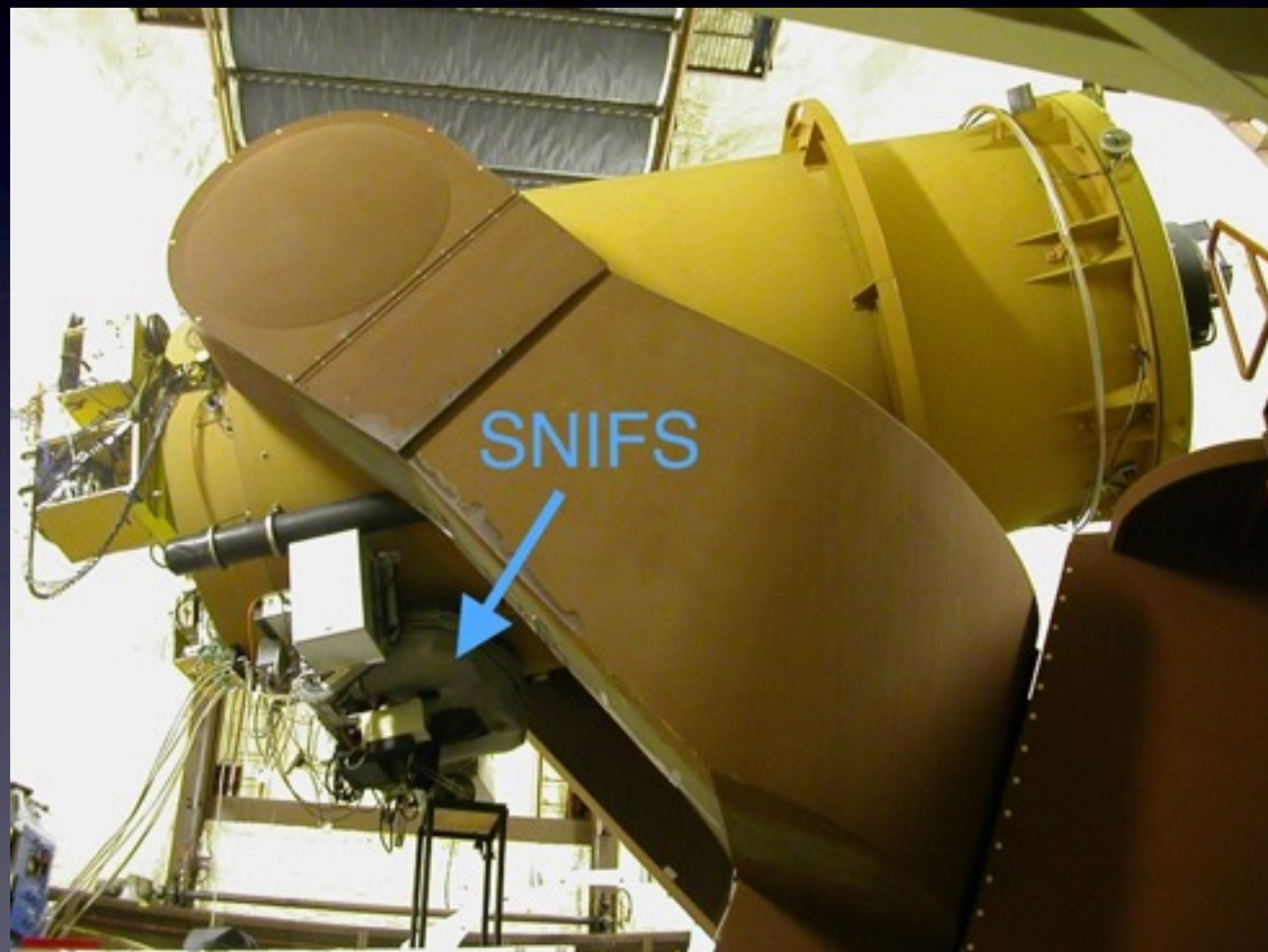
M dwarf Observations

- Visible wavelength spectra from SNIFS/UH2.2m (R~1300)



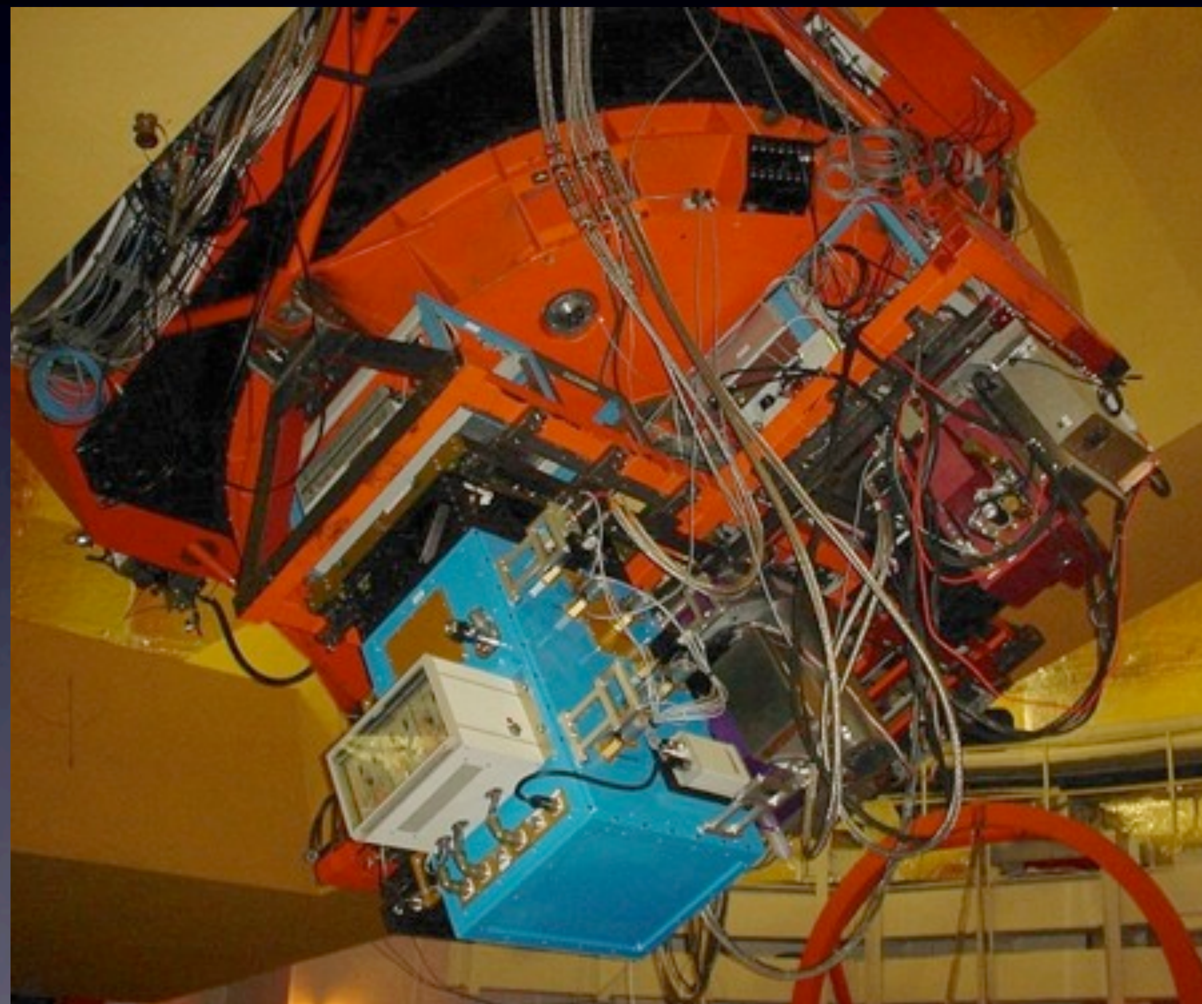
M dwarf Observations

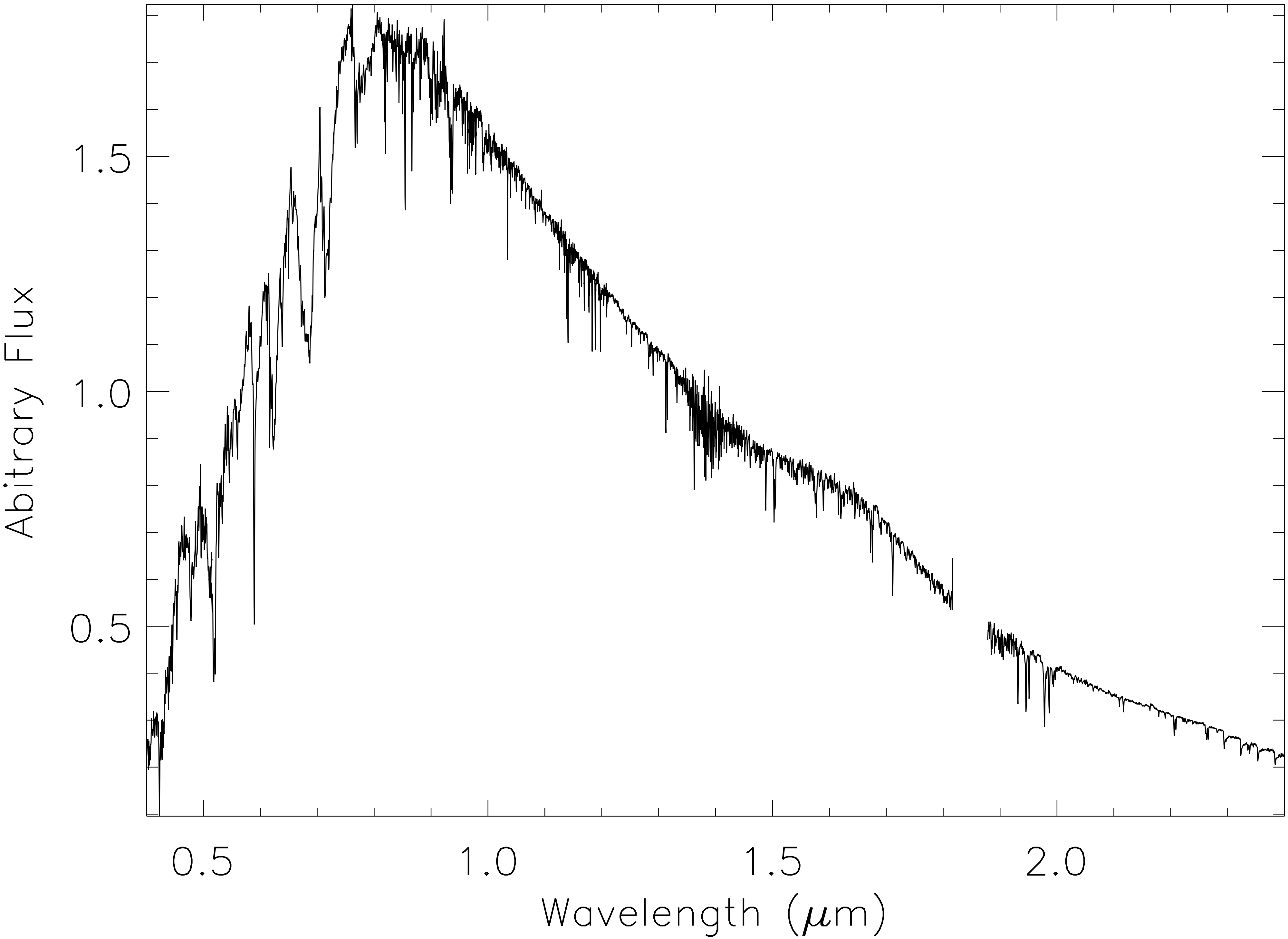
- Visible wavelength spectra from SNIFS/UH2.2m (R~1300)



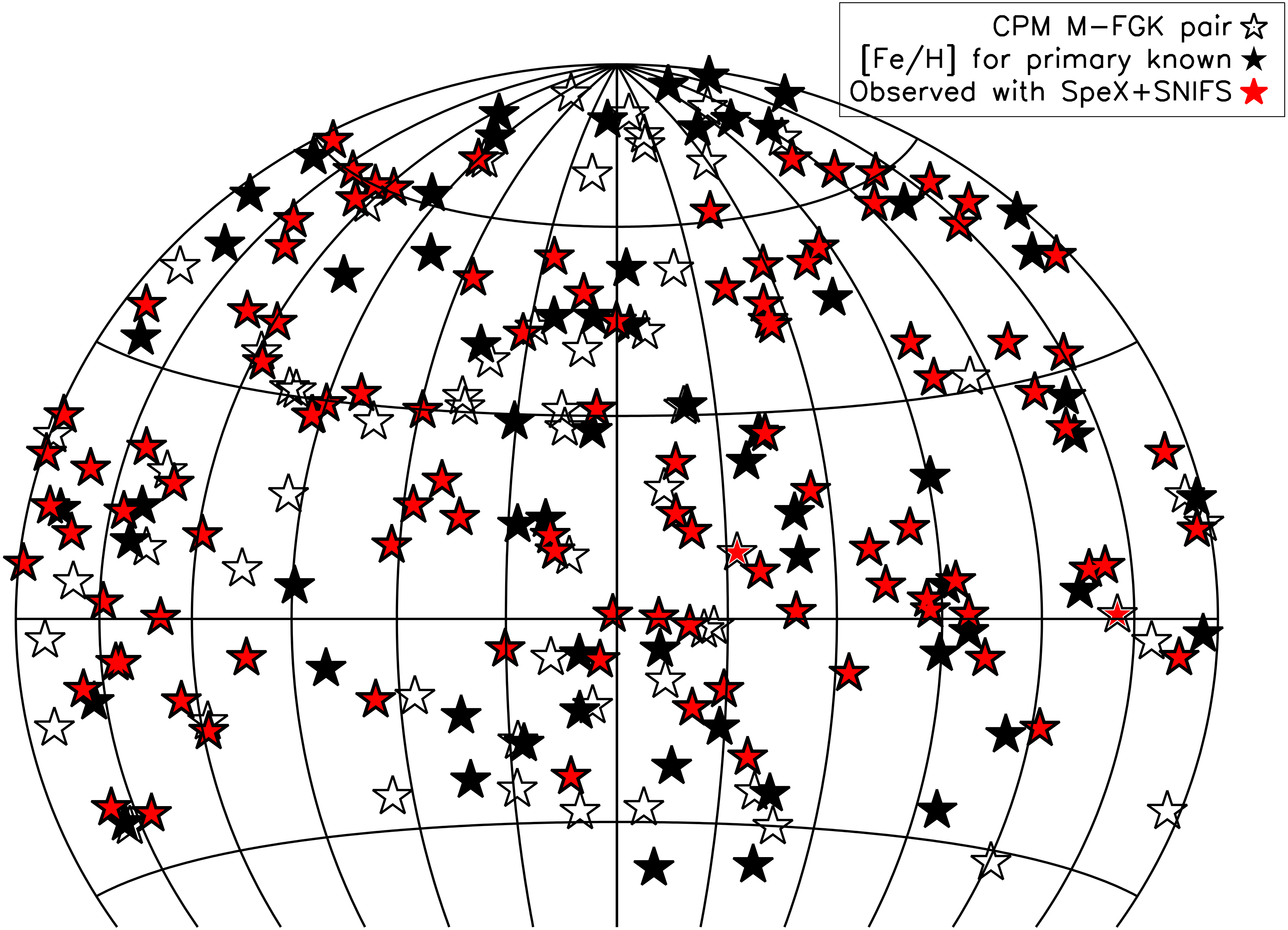
M dwarf Observations

- Visible wavelength spectra from SNIFS/UH2.2m (R~1300)
- NIR spectra from SpeX/IRTF (R~2000)





Abitrary Flux
1.5
1.0
0.5
0.5
1.0
1.5
2.0
Wavelength (μm)


CPM M−FGK pair
[Fe/H] for primary known
Observed with SpeX+SNIFS

Prospecting

Moderate Resolution Spectra

Prospecting

Moderate Resolution Spectra

Metallicities!

Prospecting

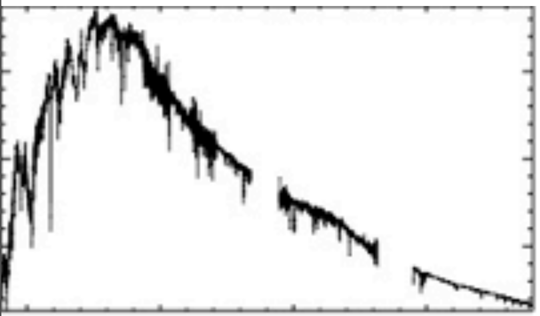
Moderate Resolution Spectra

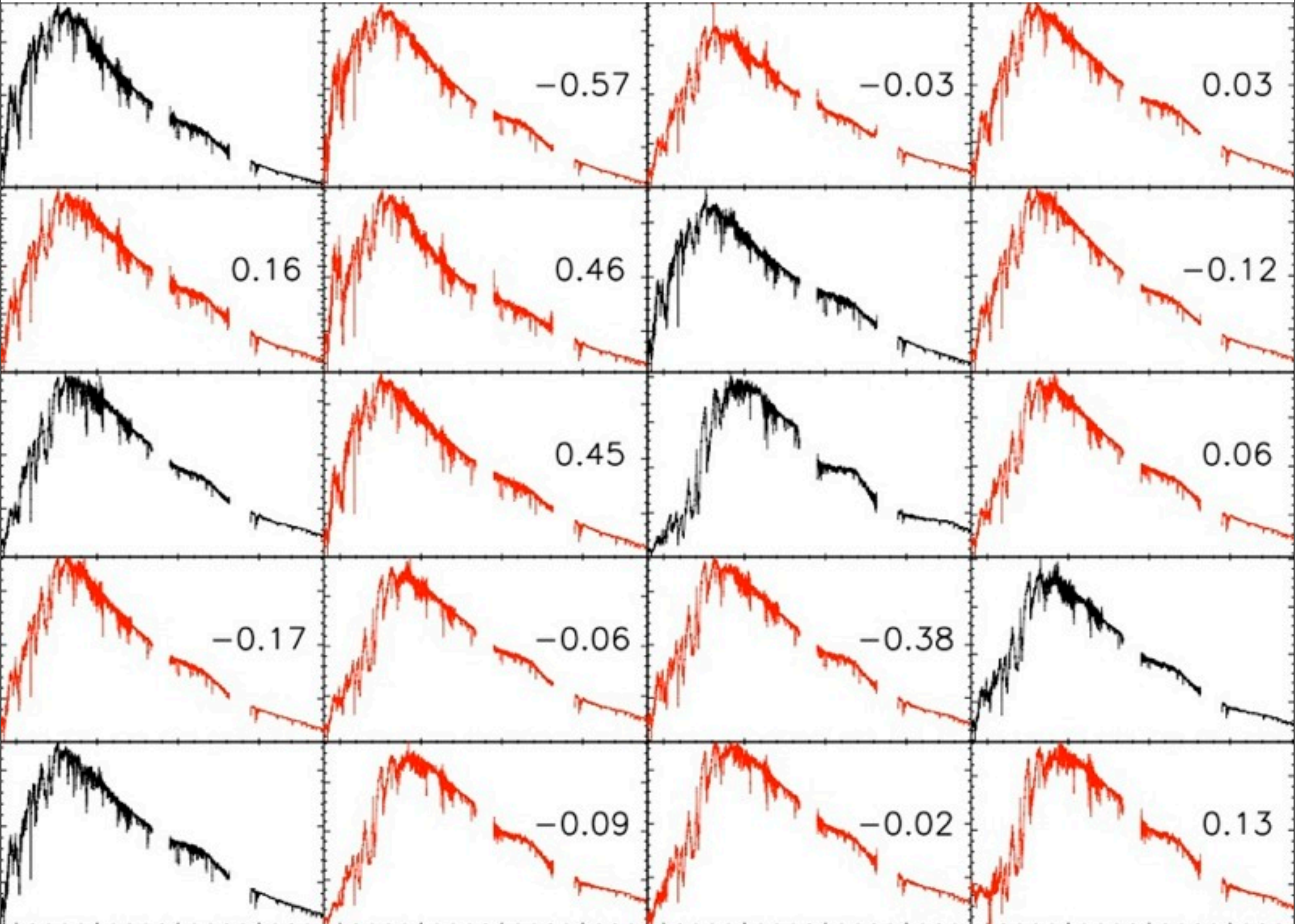
?????????

Metallicities!

Prospecting

- Pick a random subset of our wide binaries. Add Poisson noise to spectra and perturb primary star [Fe/H] values according to Gaussian errors.
- Pick a random wavelength center and width in this range.
- Compute the equivalent width of the selected ‘feature’.
- Calculate the best linear fit (by least squares) between the feature strength and the metallicity of the star.
- Repeat ~100,000 times.
- Perform the same calculation with random metallicities.

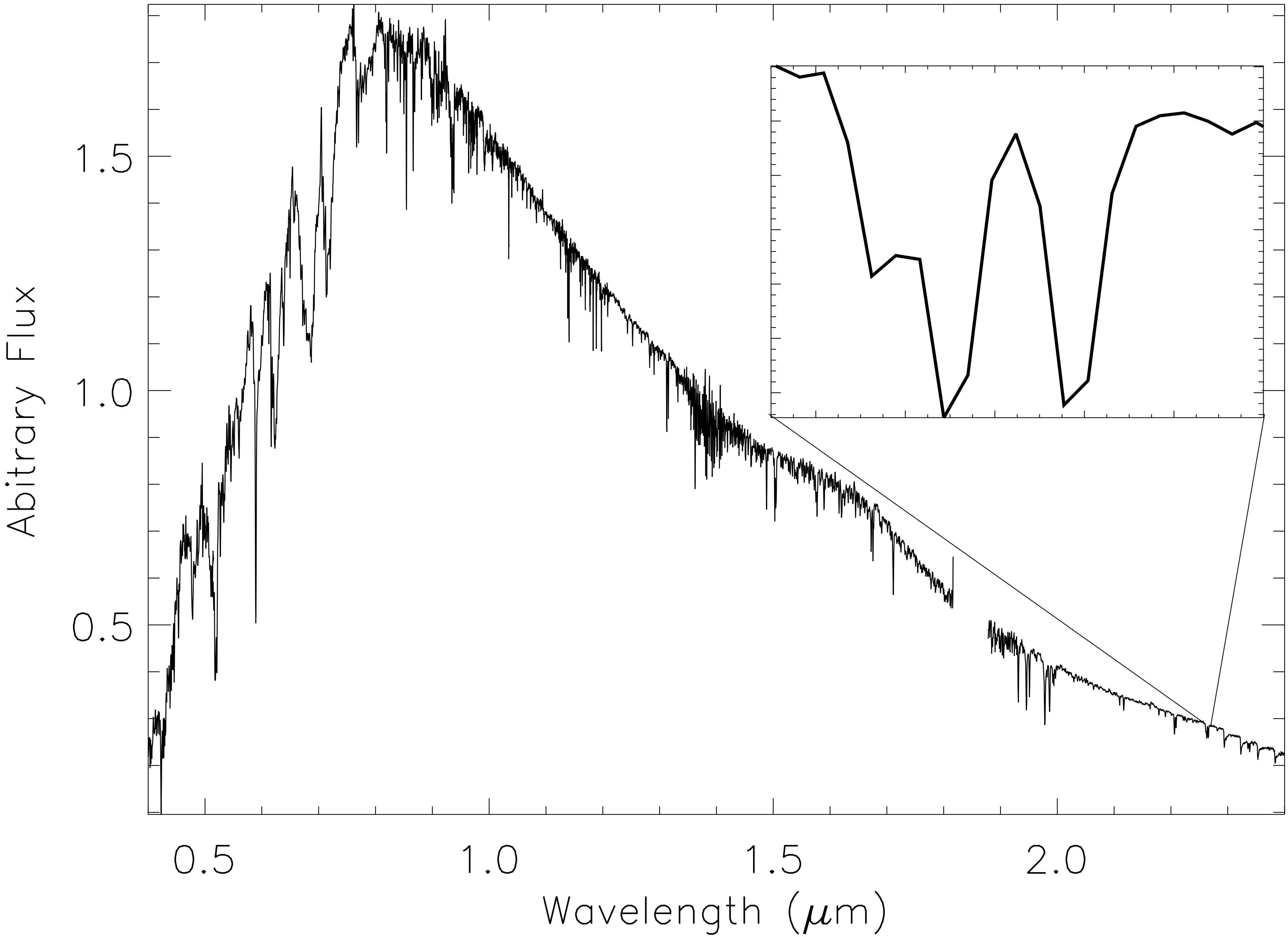




−0.57
−0.03
0.03
0.16
0.46
−0.12
0.45
0.06
−0.17
−0.06
−0.38
−0.09
−0.02
0.13

Prospecting

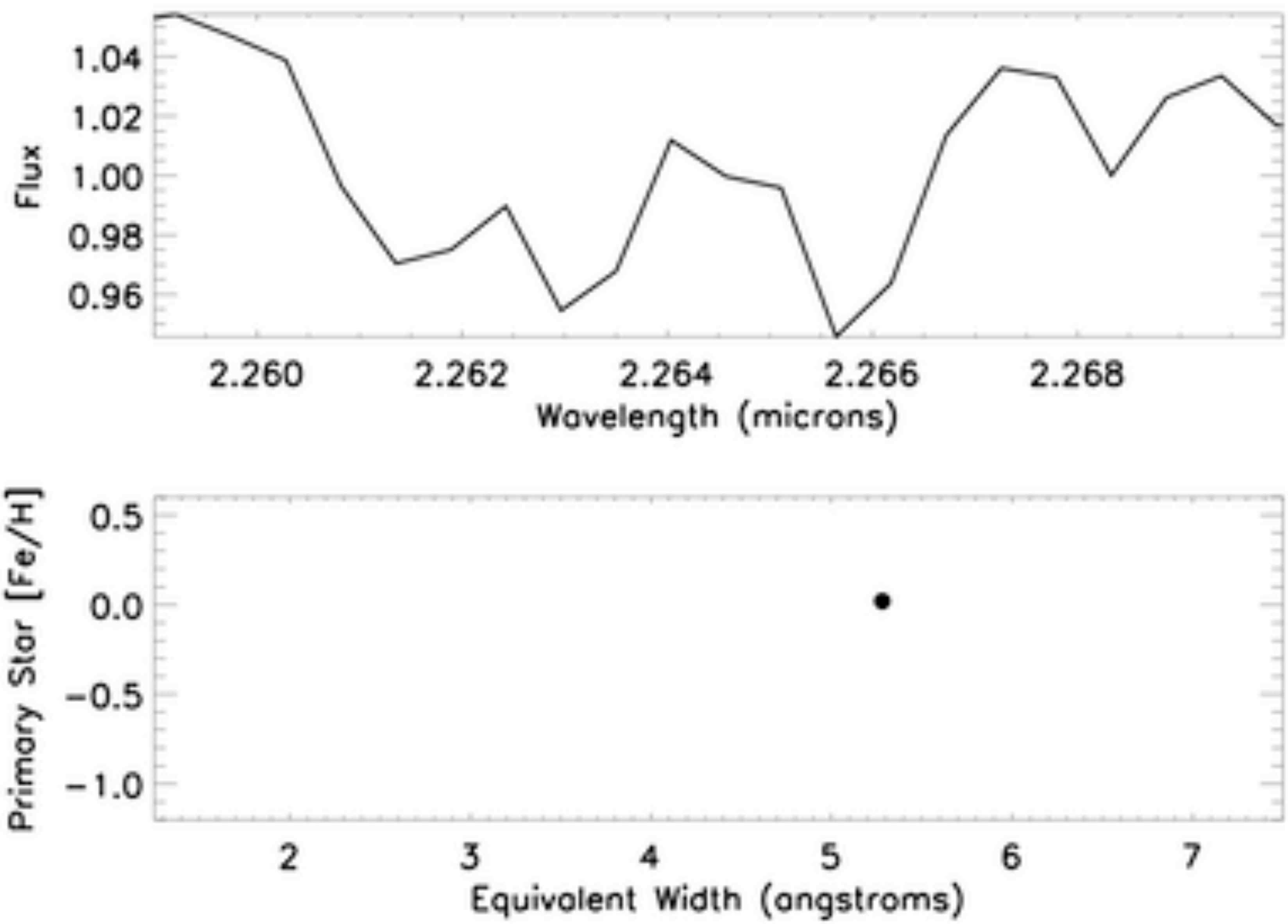
- Pick a random subset of our wide binaries. Add Poisson noise to spectra and perturb primary star [Fe/H] values according to Gaussian errors.
- Pick a random wavelength center and width in this range.
- Compute the equivalent width of the selected ‘feature’.
- Calculate the best linear fit (by least squares) between the feature strength and the metallicity of the star.
- Repeat ~100,000 times.
- Perform the same calculation with random metallicities.



Abitrary Flux
1.5
1.0
0.5
0.5
1.0
1.5
2.0
Wavelength (μm)

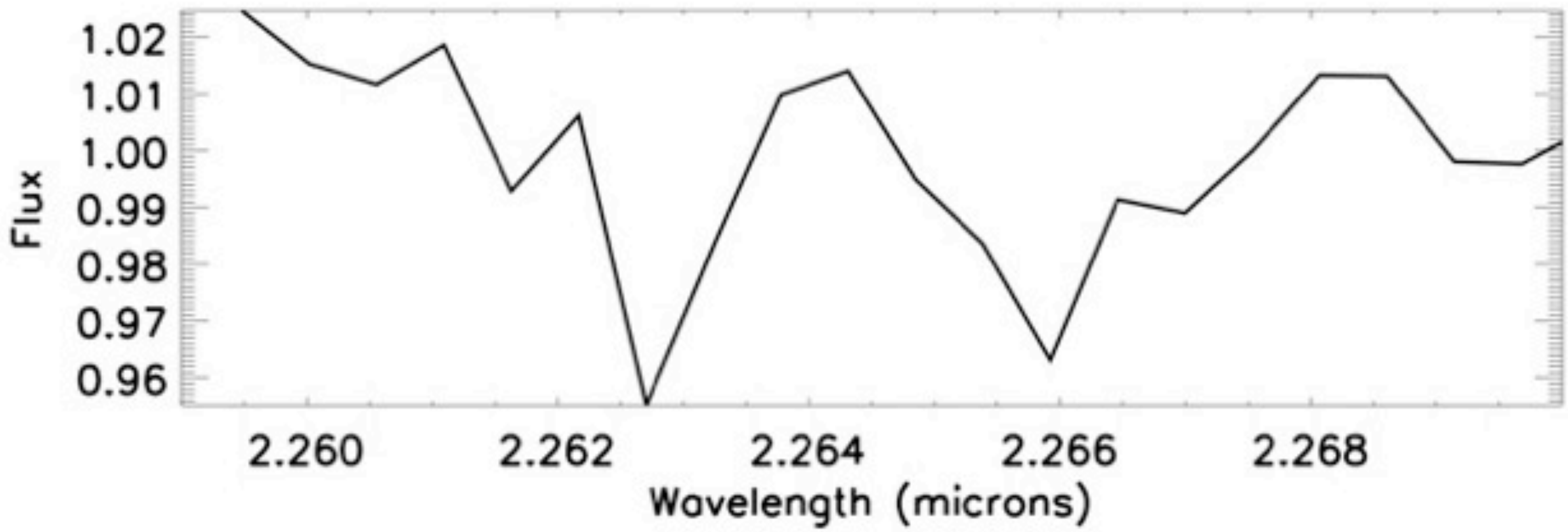
Prospecting

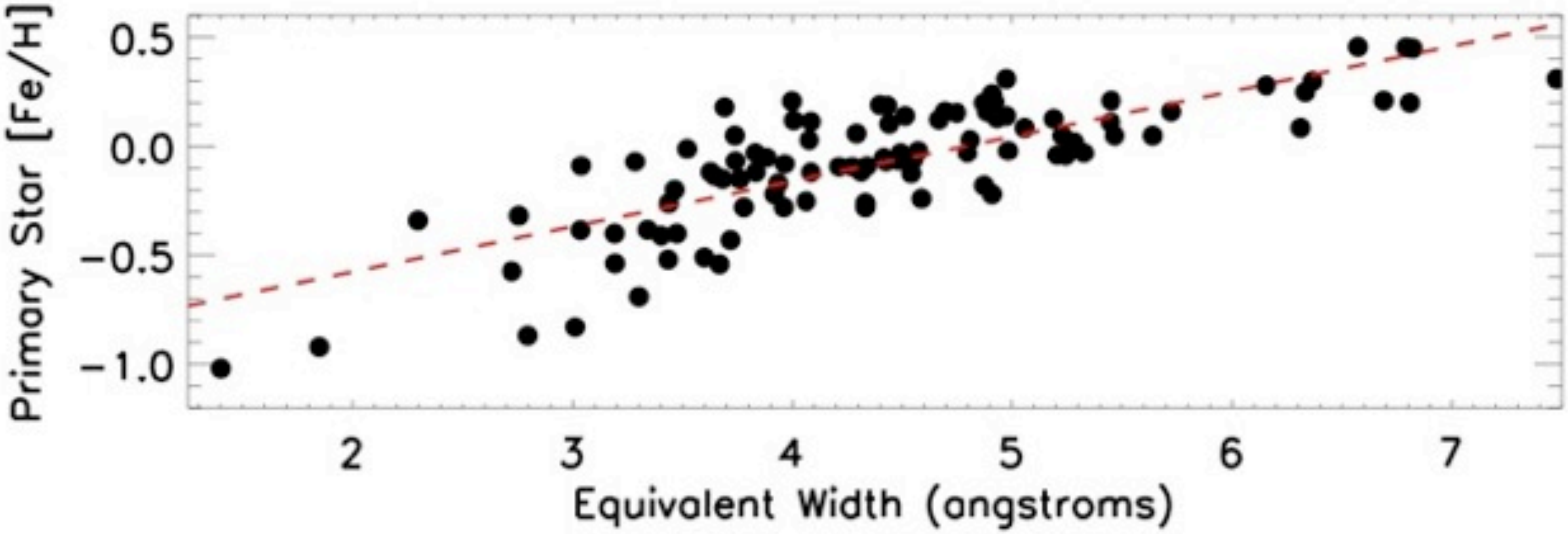
- Pick a random subset of our wide binaries. Add Poisson noise to spectra and perturb primary star [Fe/H] values according to Gaussian errors.
- Pick a random wavelength center and width in this range.
- Compute the equivalent width of the selected 'feature'.
- Calculate the best linear fit (by least squares) between the feature strength and the metallicity of the star.
- Repeat ~100,000 times.
- Perform the same calculation with random metallicities.


Flux
1.04
1.02
1.00
0.98
0.96
2.260
2.262
2.264
2.266
2.268
Wavelength (microns)
Primary Star [Fe/H]
0.5
0.0
−0.5
−1.0
2
3
4
5
6
7
Equivalent Width (angstroms)

Prospecting

- Pick a random subset of our wide binaries. Add Poisson noise to spectra and perturb primary star [Fe/H] values according to Gaussian errors.
- Pick a random wavelength center and width in this range.
- Compute the equivalent width of the selected 'feature'.
- Calculate the best linear fit (by least squares) between the feature strength and the metallicity of the star.
- Repeat ~100,000 times.
- Perform the same calculation with random metallicities.





$$[Fe/H] = a(EW_{Na}) + b(T_{\lambda}) + c$$

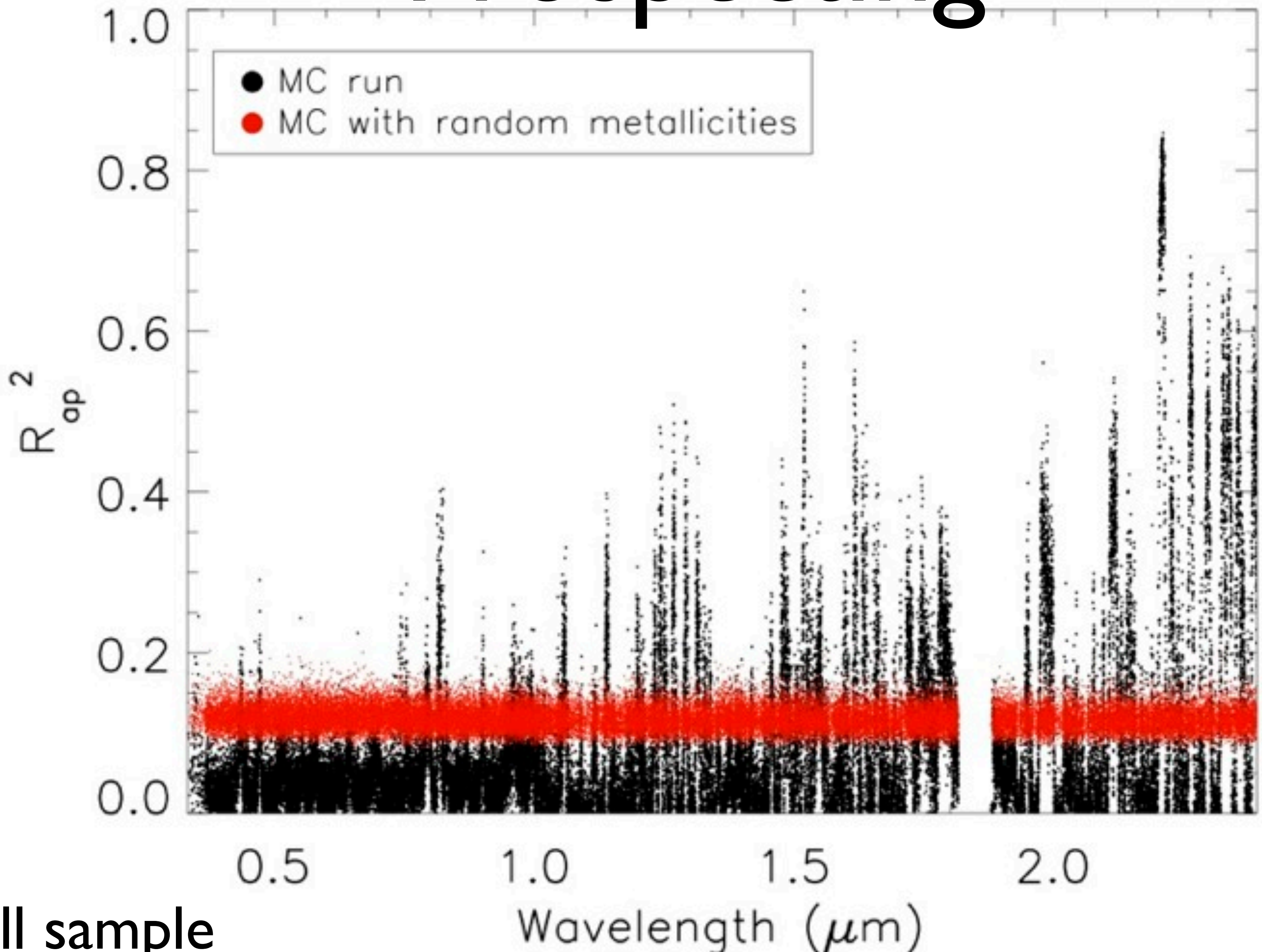
Temperature sensitive index
e.g. H_2O-K Rojas-Ayala et al. (2010)

$$[Fe/H] = a(EW_{Na}) + b(T_{\lambda}) + c$$

Prospecting

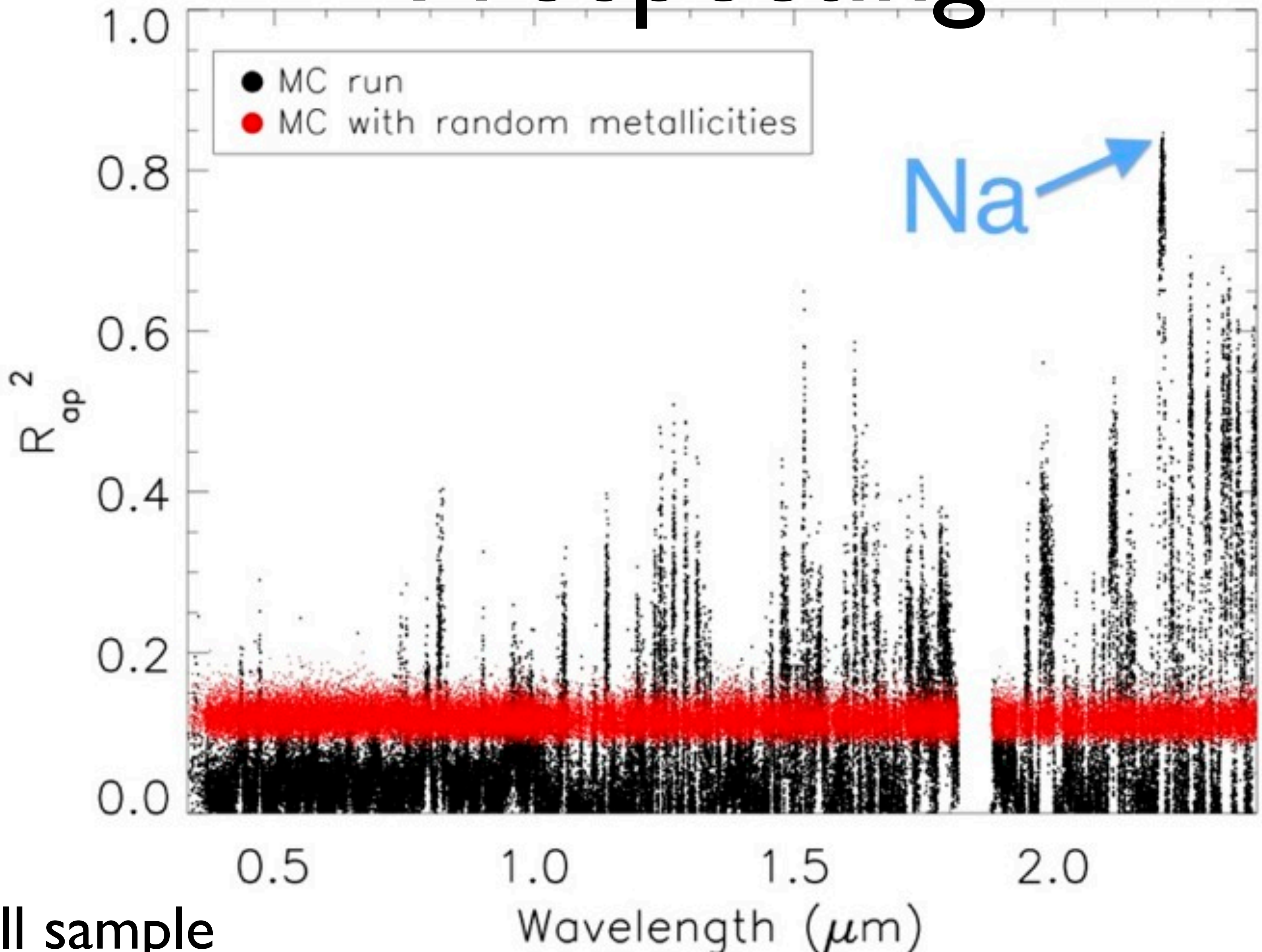
- Pick a random subset of our wide binaries. Add Poisson noise to spectra and perturb primary star [Fe/H] values according to Gaussian errors.
- Pick a random wavelength center and width in this range.
- Compute the equivalent width of the selected 'feature'.
- Calculate the best linear fit (by least squares) between the feature strength and the metallicity of the star.
- Repeat ~100,000 times.
- Perform the same calculation with random metallicities.

Prospecting



Full sample

Prospecting



Full sample

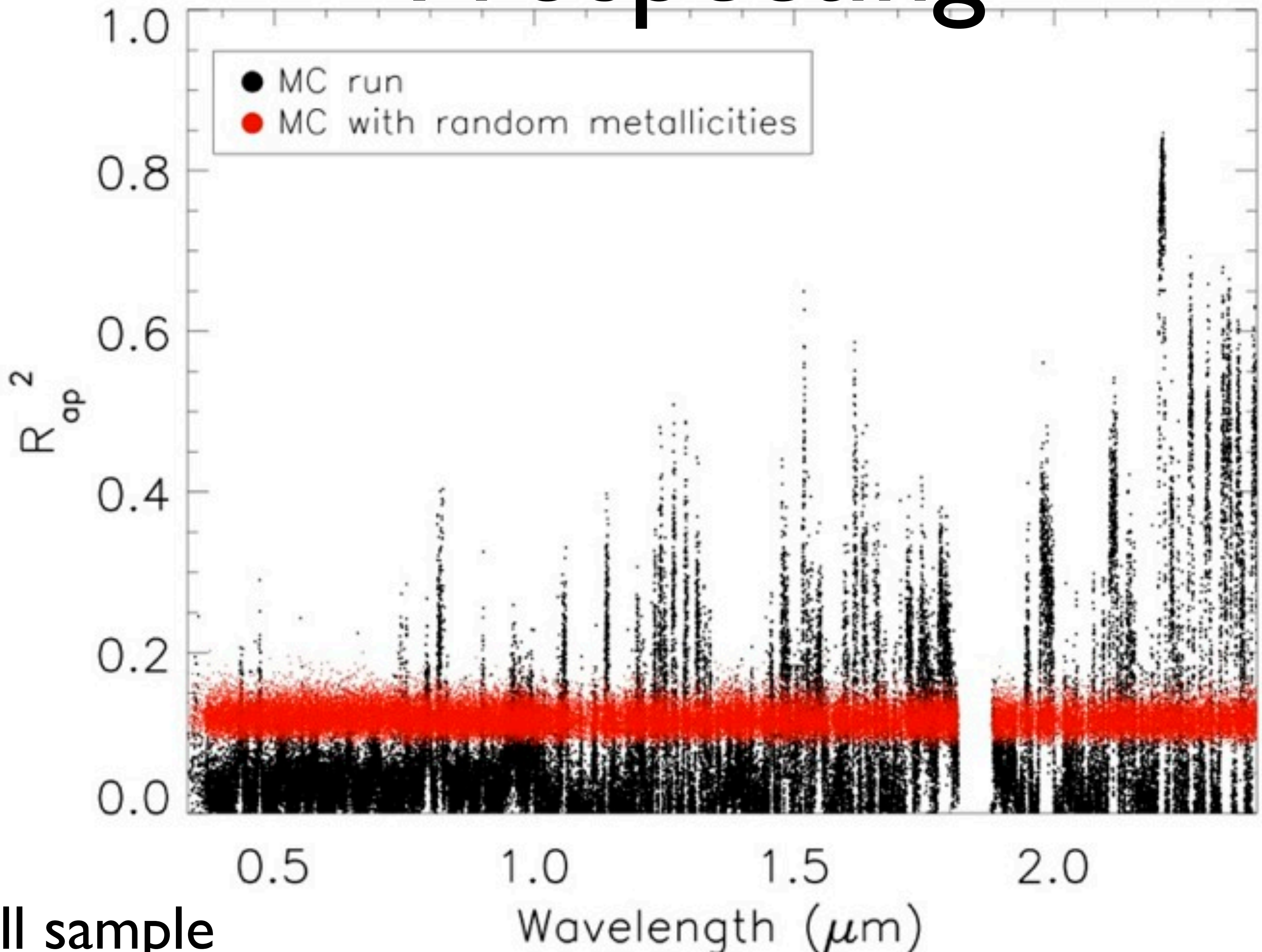
Prospecting

- We can take advantage of our sample size and distribution as well as information about the primary star to learn even more:
  - How do our results vary with spectral type?
  - How do results depend on [M/H], [α/Fe], etc?
  - What is the best we can do in any given wavelength range at our resolution?

Prospecting

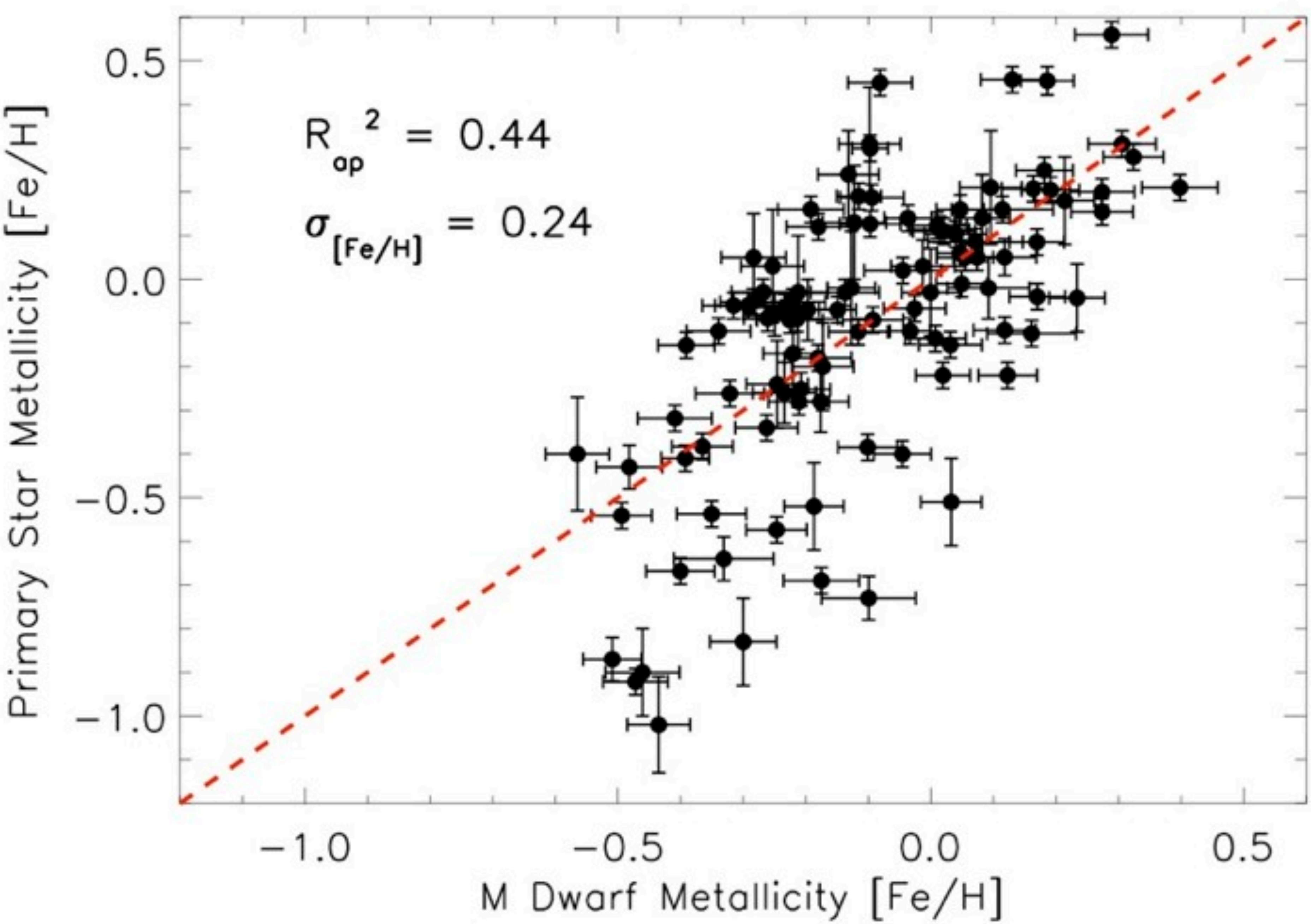
- We can take advantage of our sample size and distribution as well as information about the primary star to learn even more:
  - How do our results vary with spectral type?
  - How do results depend on [M/H], [α/Fe], etc?
  - What is the best we can do in any given wavelength range at our resolution?

Prospecting



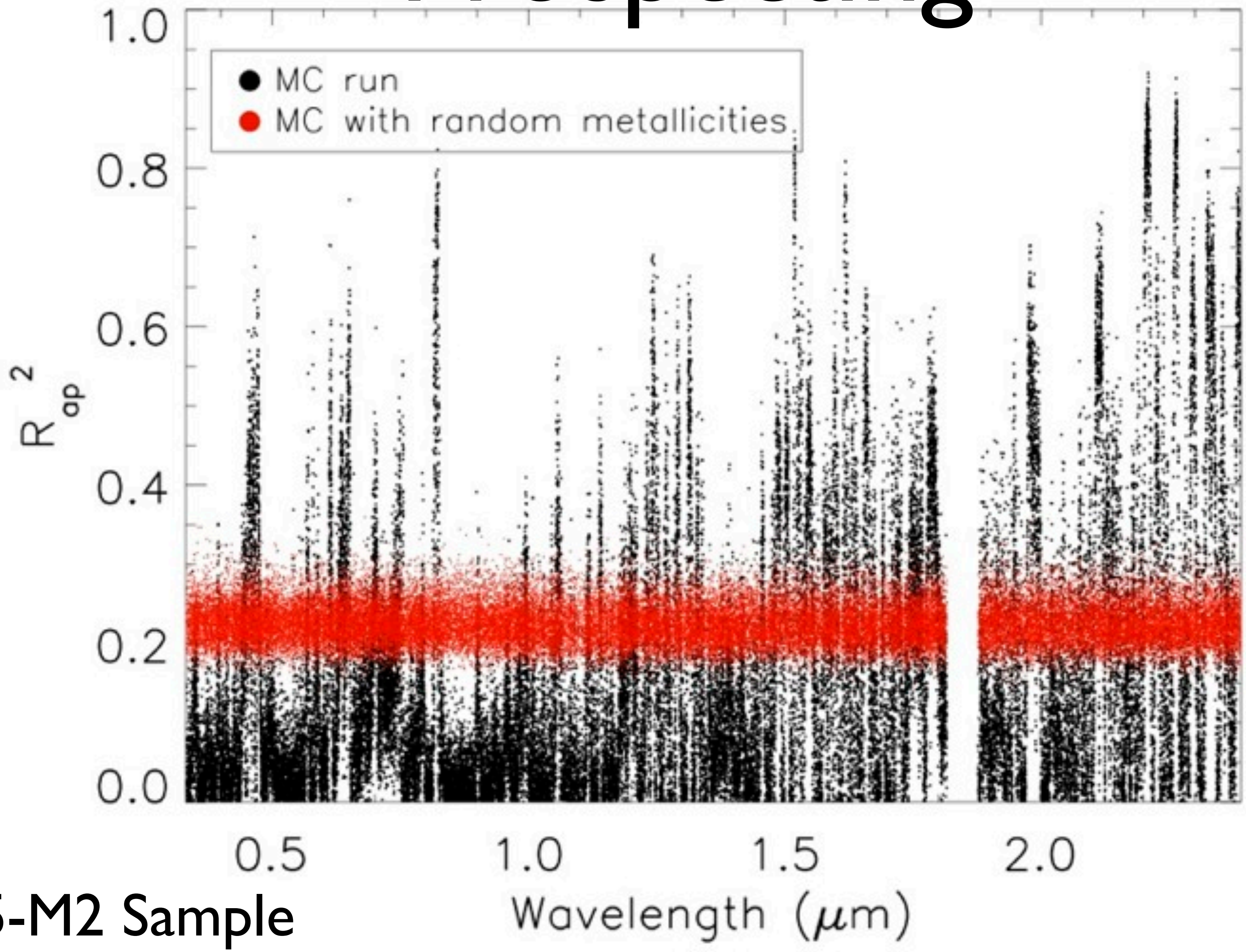
Full sample

Visible



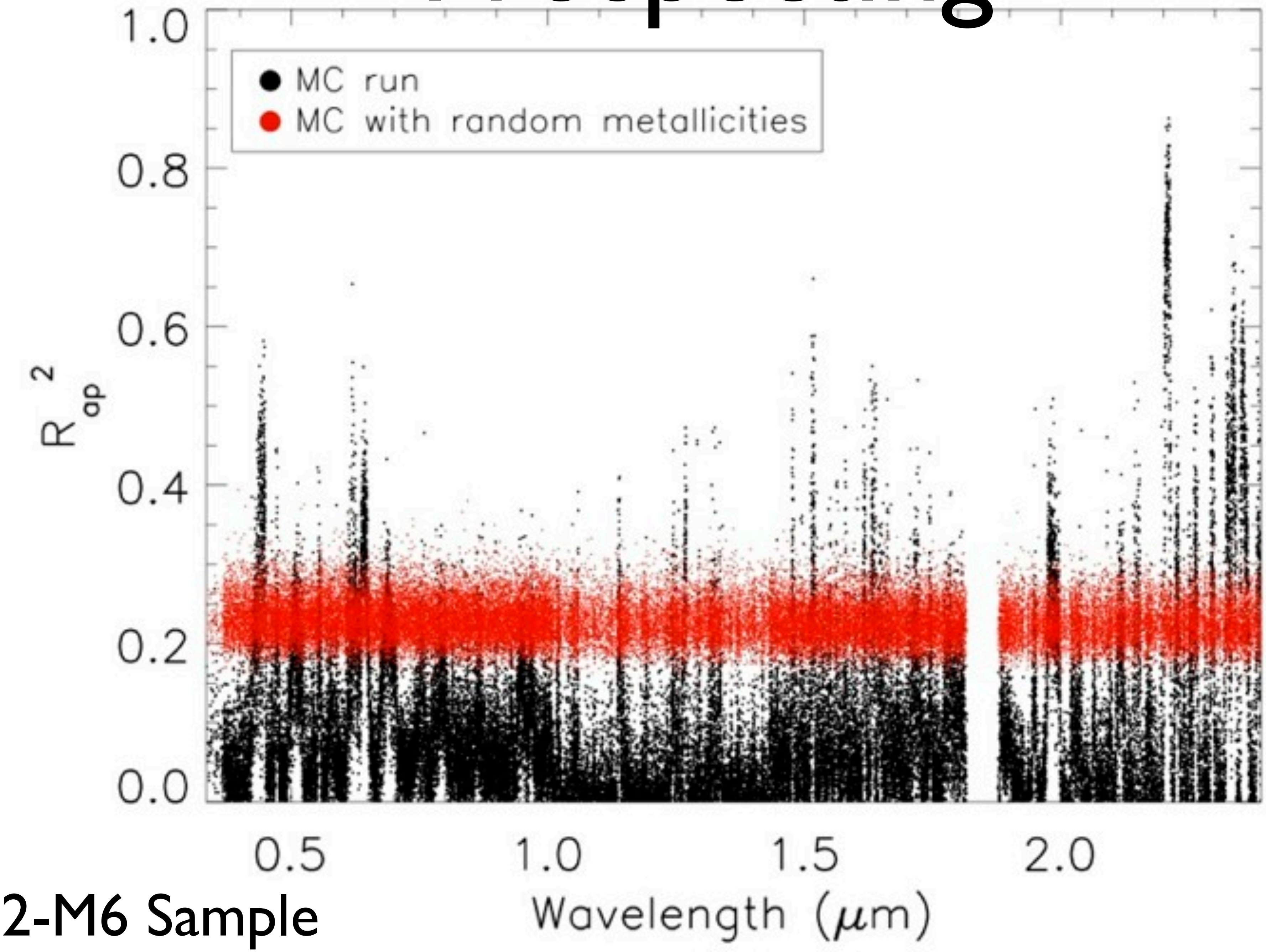
$R_{ap}^2 = 0.44$
$\sigma_{[Fe/H]} = 0.24$
Primary Star Metallicity [Fe/H]
M Dwarf Metallicity [Fe/H]
0.5
0.0
−0.5
−1.0
−1.0
−0.5
0.0
0.5

Prospecting



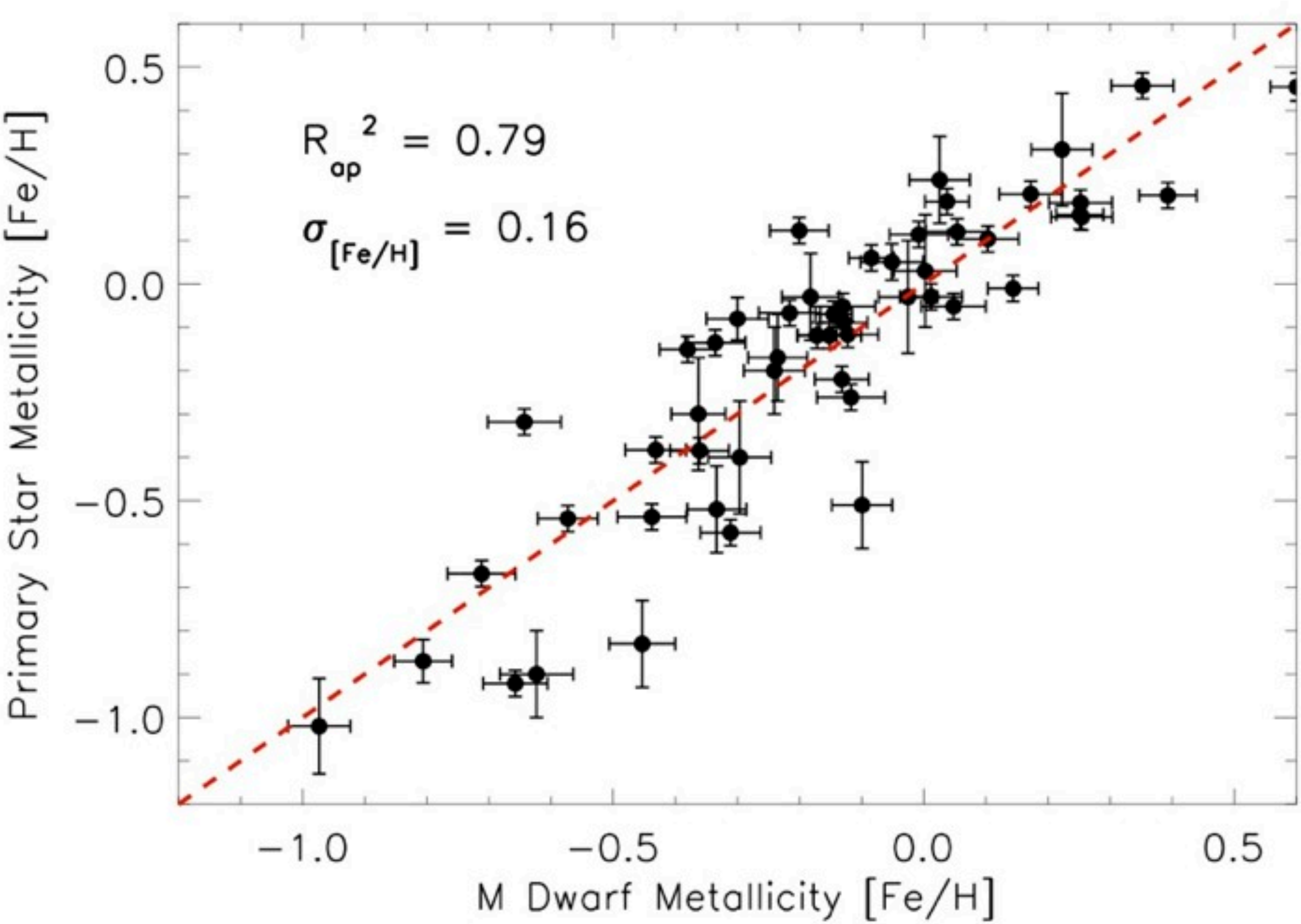
K5-M2 Sample

Prospecting

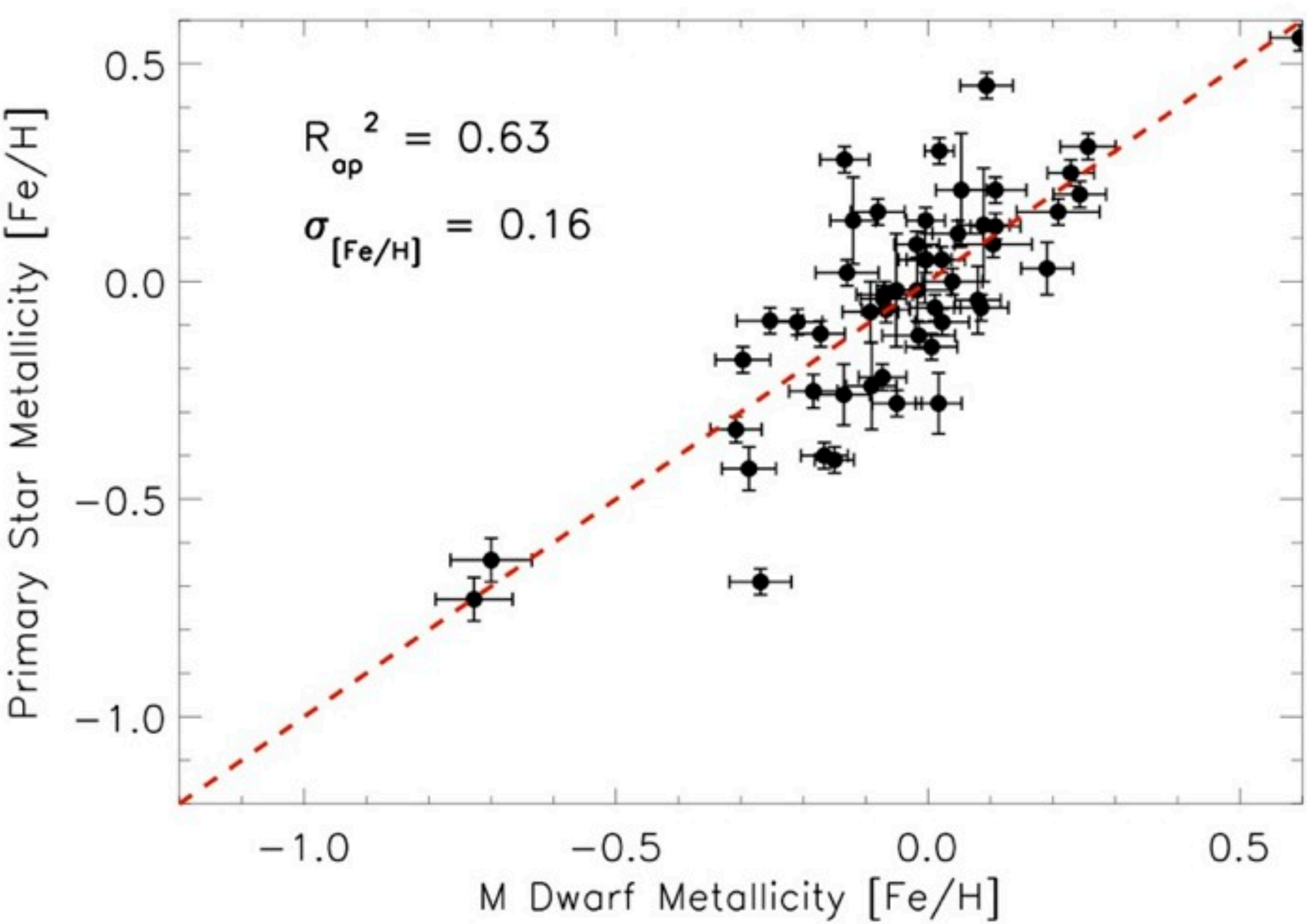


M2-M6 Sample

Visible (K5-M2)



Visible (M2-M6)

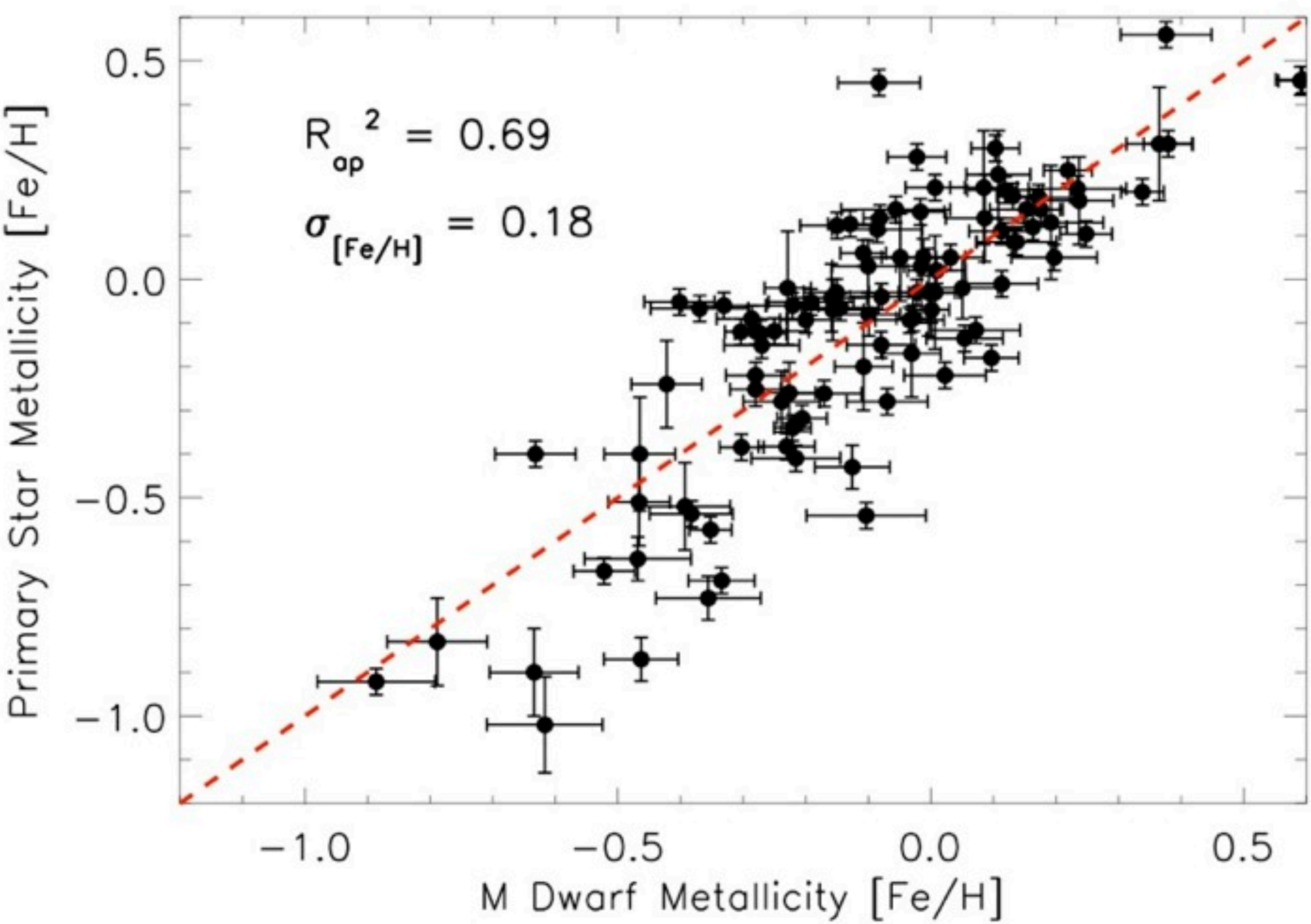


Conclusions

- It is possible to determine the metallicity of M dwarfs using a range of different wavelengths. You can optimize based on your own setup.
- The 'best' technique for determining a given M dwarf's metallicity depends on its spectral type (especially in the visible).
- We're rapidly approaching the limit of what is possible at moderate resolution.

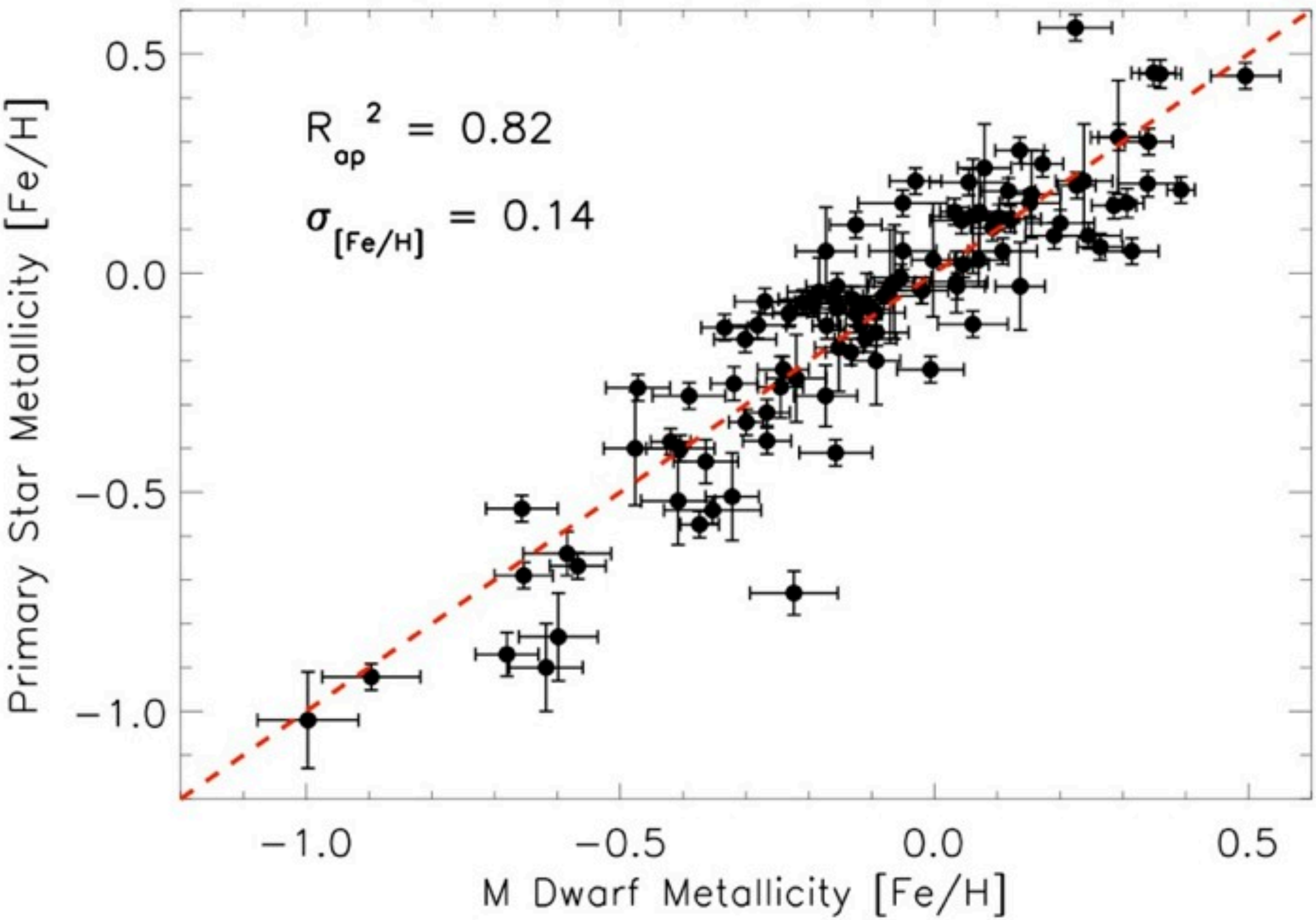
Begin Bonus Slides

J-band

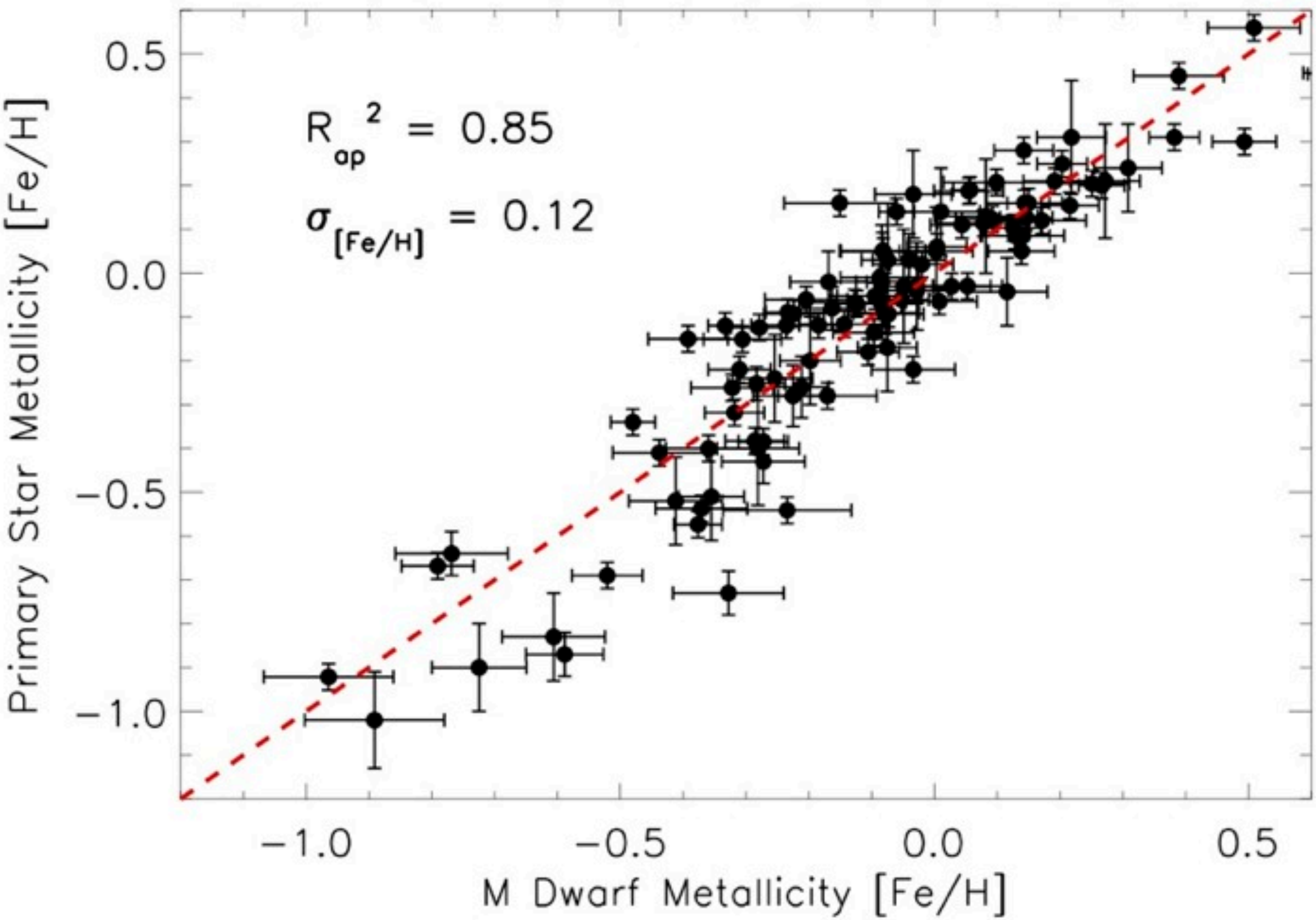


$R_{op}^2 = 0.69$
$\sigma_{[Fe/H]} = 0.18$
Primary Star Metallicity [Fe/H]
M Dwarf Metallicity [Fe/H]
0.5
0.0
−0.5
−1.0
−1.0
−0.5
0.0
0.5

H-band


R_{ap}^2 = 0.82
$\sigma_{[Fe/H]}$ = 0.14
Primary Star Metallicity [Fe/H]
M Dwarf Metallicity [Fe/H]
0.5
0.0
−0.5
−1.0
−1.0
−0.5
0.0
0.5

K-band

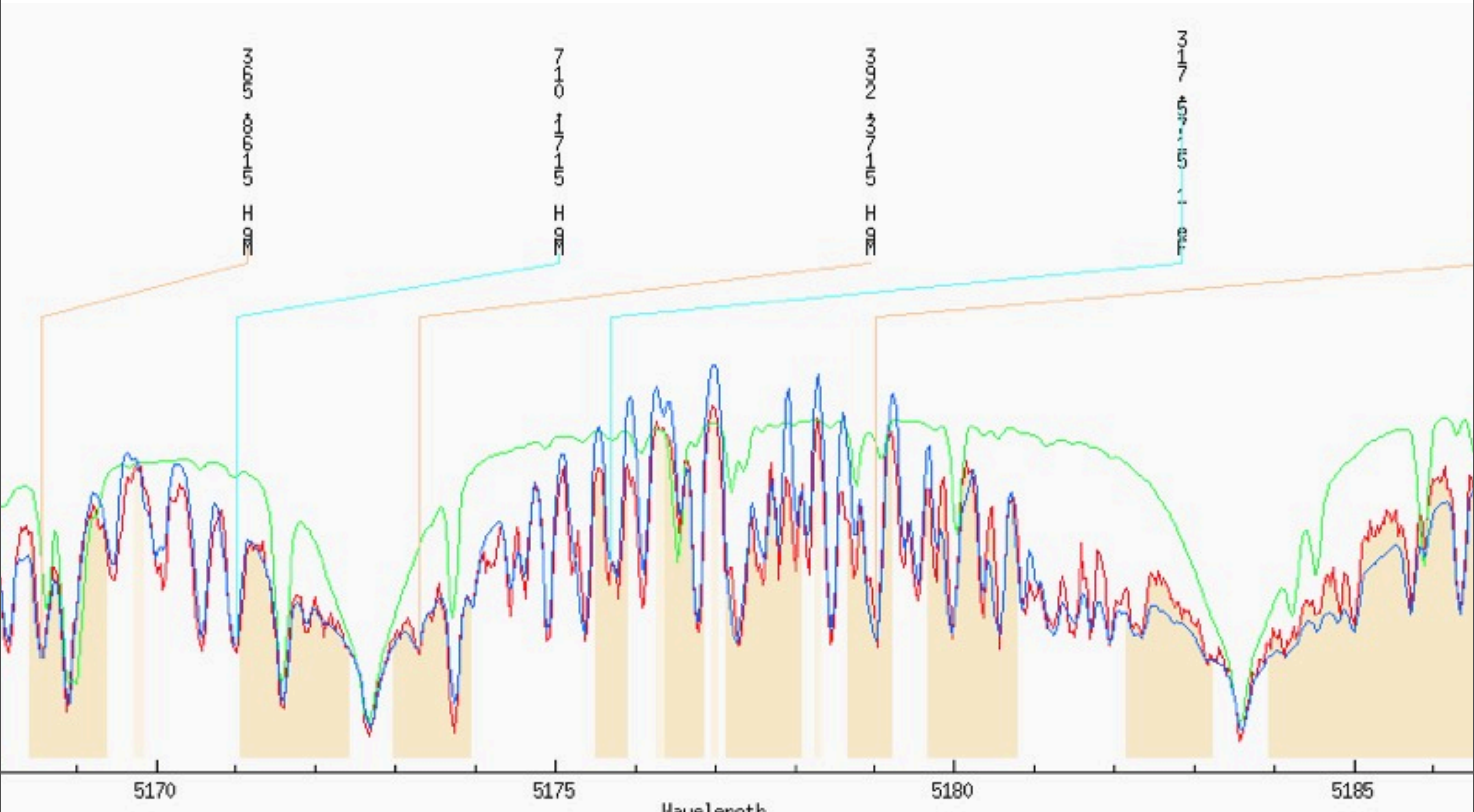


$R_{ap}^2 = 0.85$
$\sigma_{[Fe/H]} = 0.12$
0.5
0.0
−0.5
−1.0
Primary Star Metallicity [Fe/H]
−1.0
−0.5
0.0
0.5
M Dwarf Metallicity [Fe/H]

Prospecting

- Be careful in the interpretation of our results:
  - Our resolution and SNR is not the same across all wavelengths.
  - Our J-band data has lower SNR than visible and H/K bands.
  - Our visible wavelength data have from lower resolution (R~1300) than NIR data (R~2000).

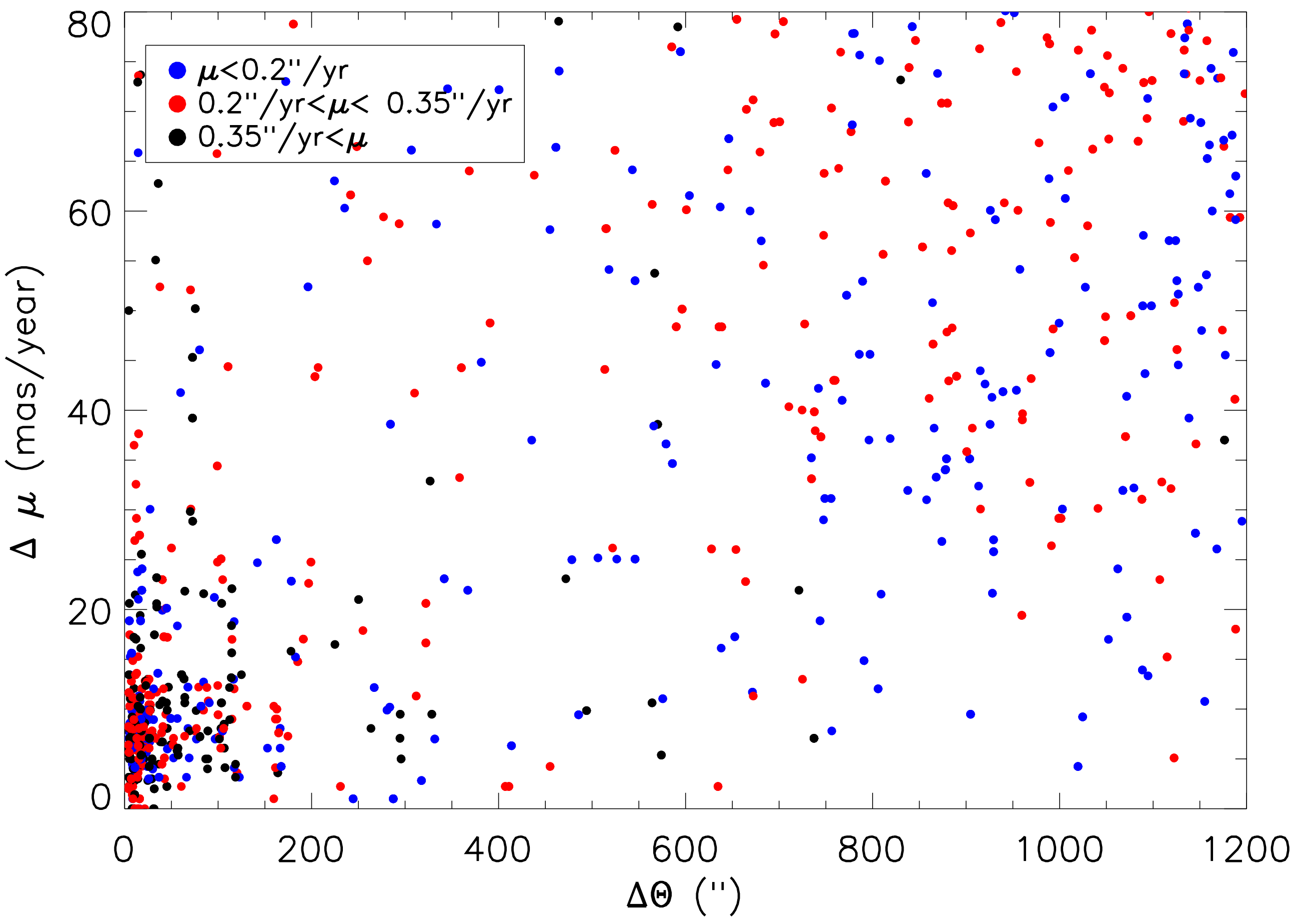
Spectroscopy Made Easy



Valenti & Piskunov (1996)

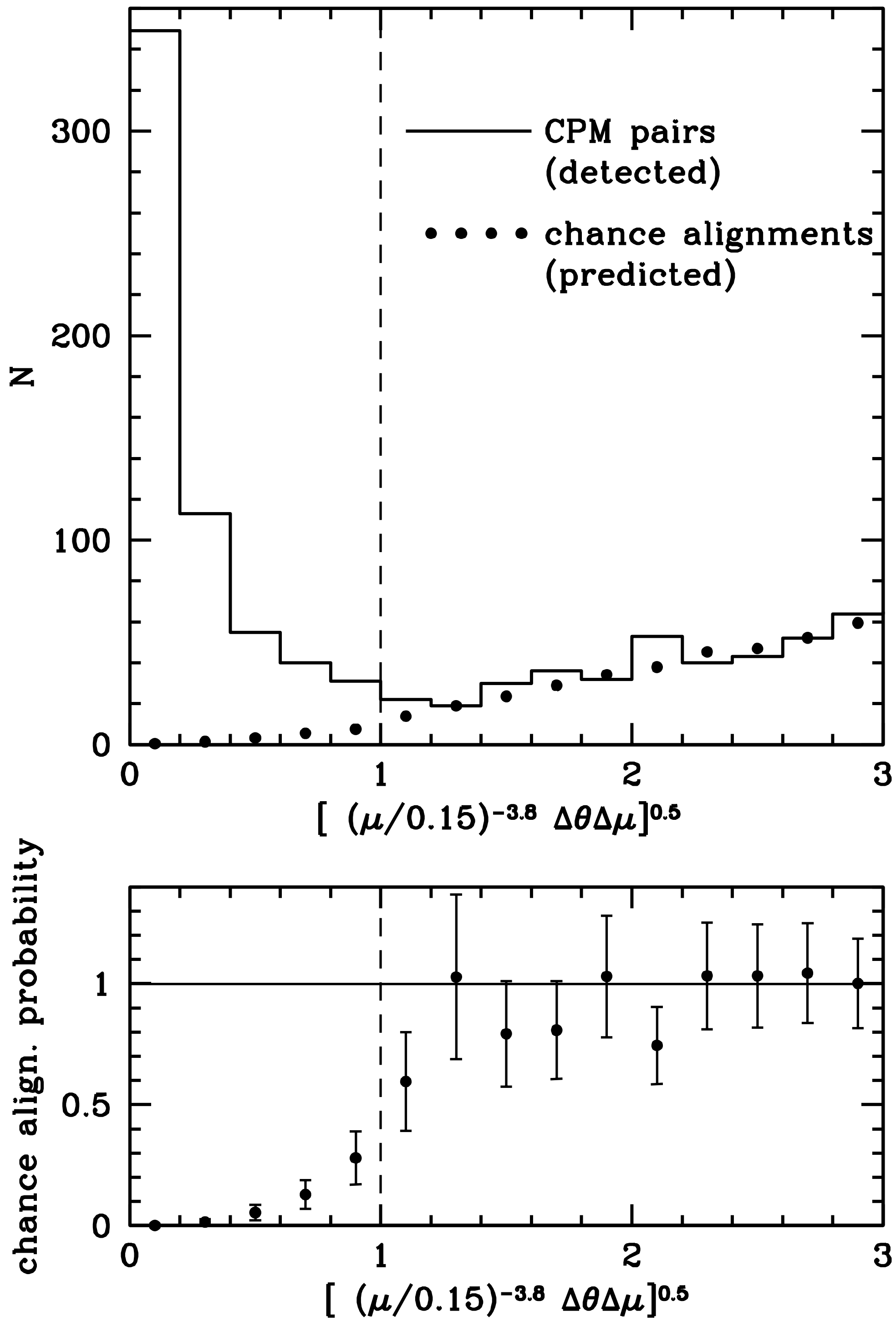
Identifying FGK-M Pairs

Combine proper motions, photometry, and parallaxes (if available) to identify a set of *bright* FGK-M pairs.

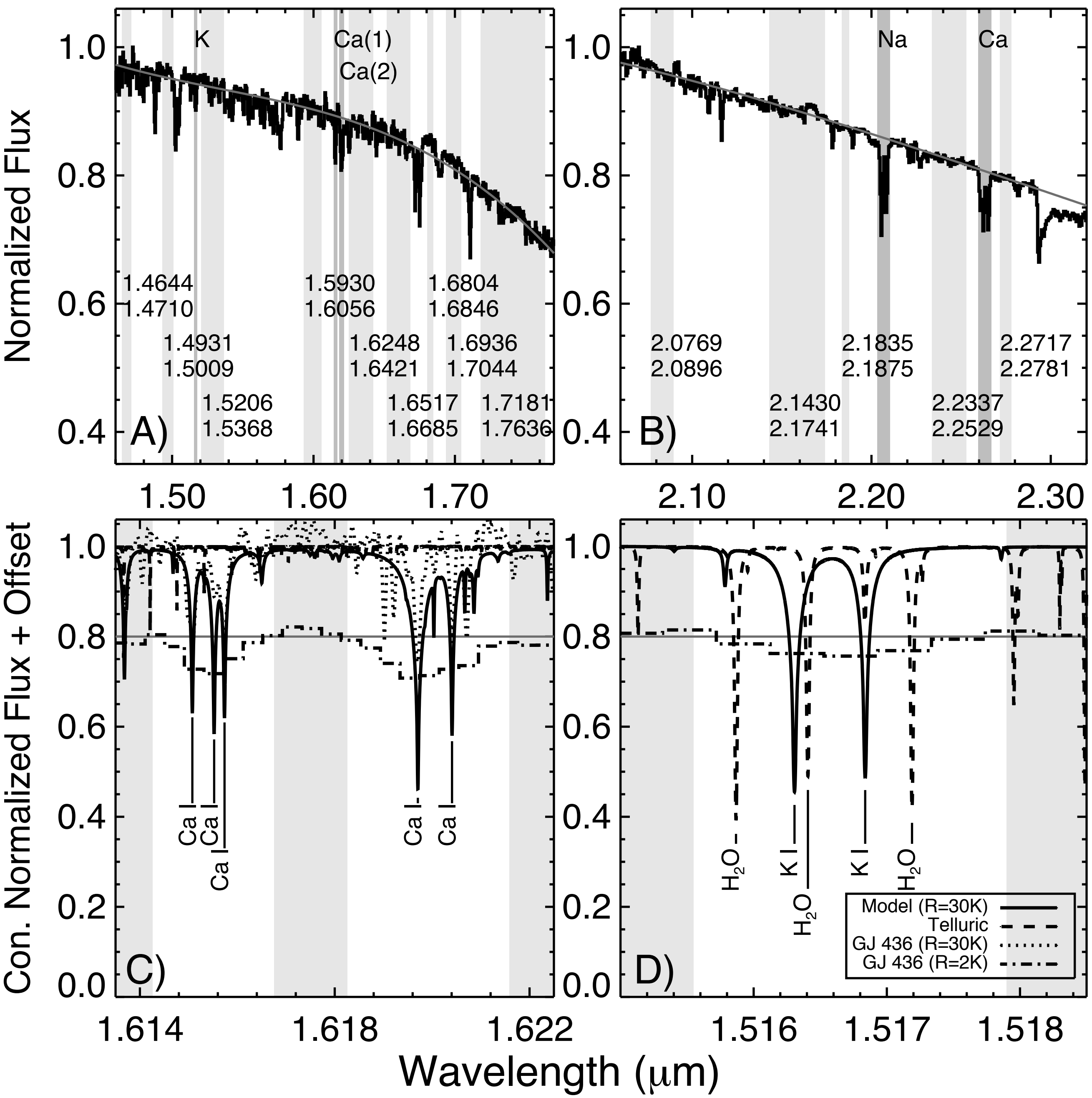


Lepine & Bongiorno (2007)
Dhital et al. (2012)

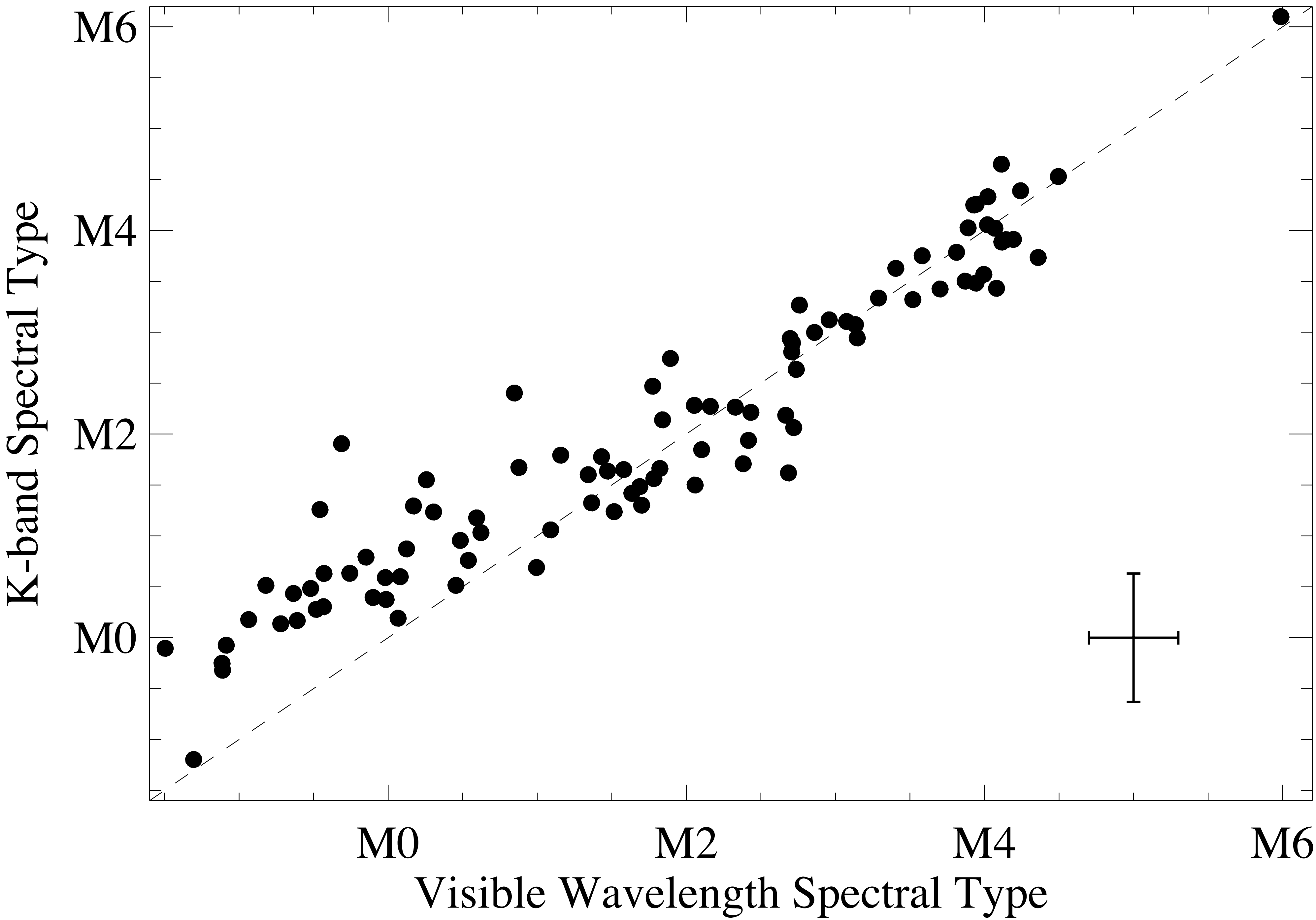
- Compare proper motion distribution to a Galactic model.
- Yields a likelihood that a given pair is a true CPM pair or just a chance alignment.
- Combine with all available photometry and parallax information.



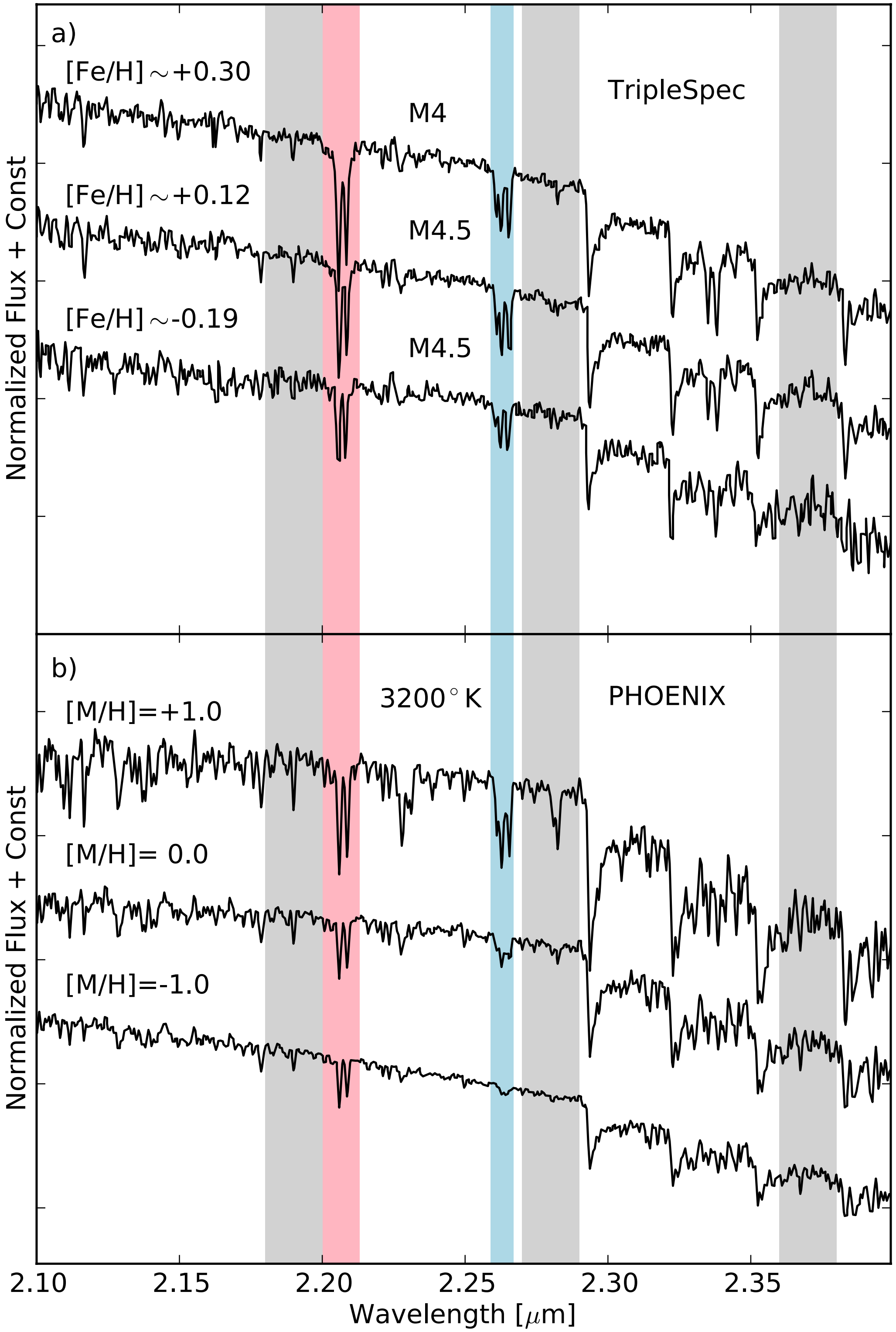
Lepine & Bongiorno (2007)
Dhital et al. (2012)



Terrien et al. (2012)



M6
M4
M2
M0
K-band Spectral Type
M0
M2
M4
M6
Visible Wavelength Spectral Type

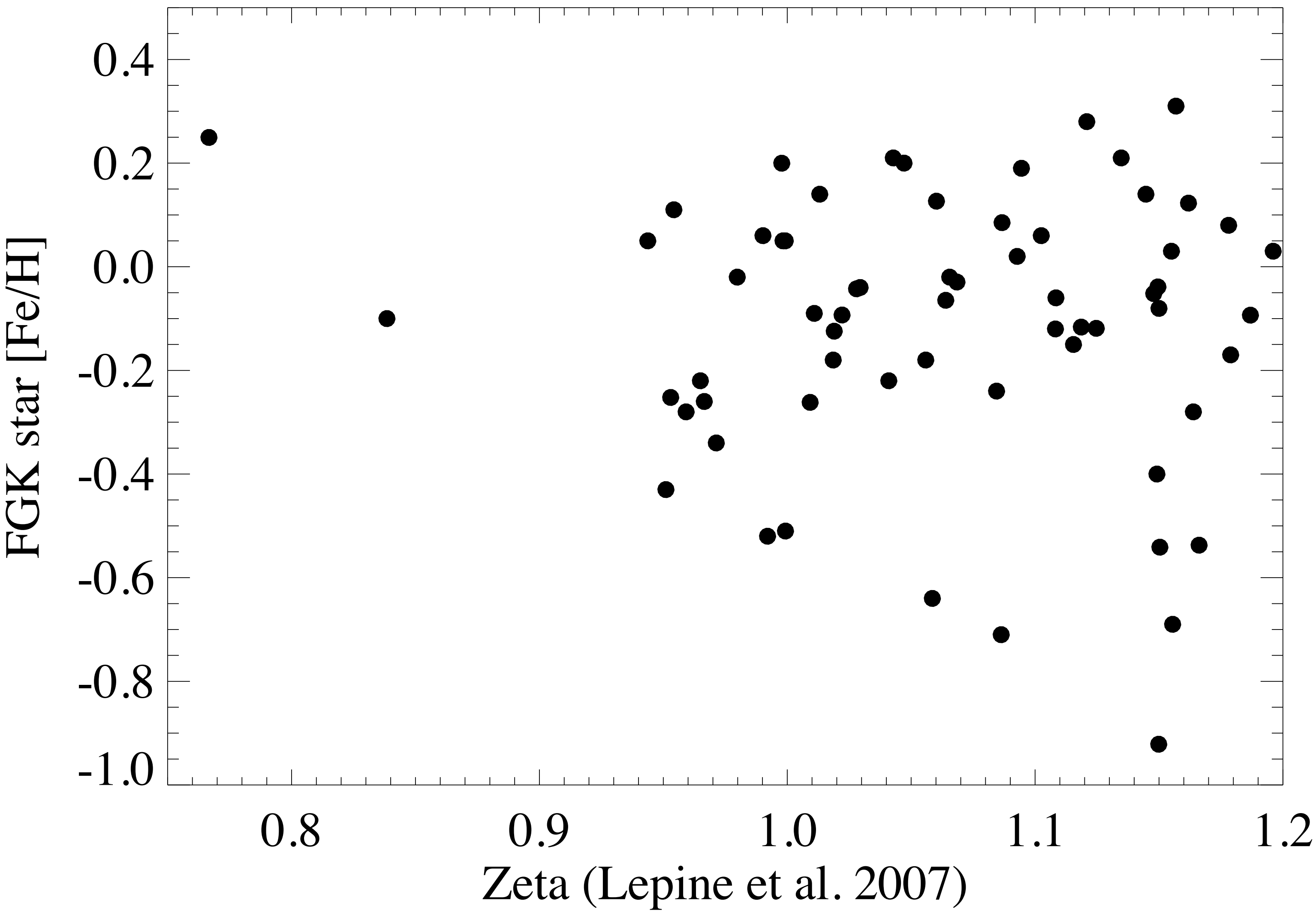


Rojas-Ayala et al. (2010)

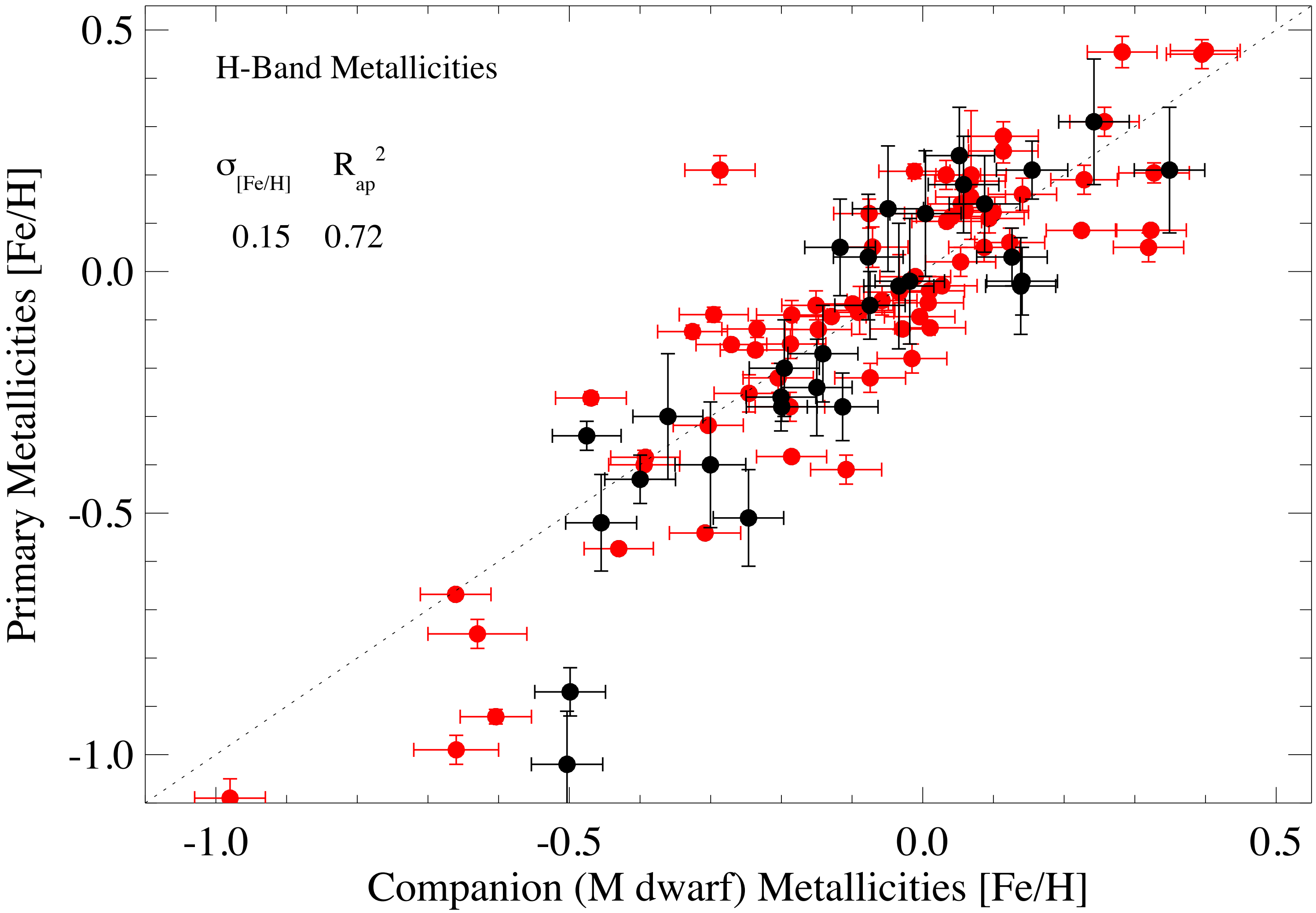
Testing Existing Techniques

- Current methods of determining M dwarf metallicities:
  - TiO, CaH bands in the optical (zeta)
  - Na I, Ca I equivalent widths in the K-band
  - K I, Ca I equivalent widths in the H-band

Testing Existing Techniques

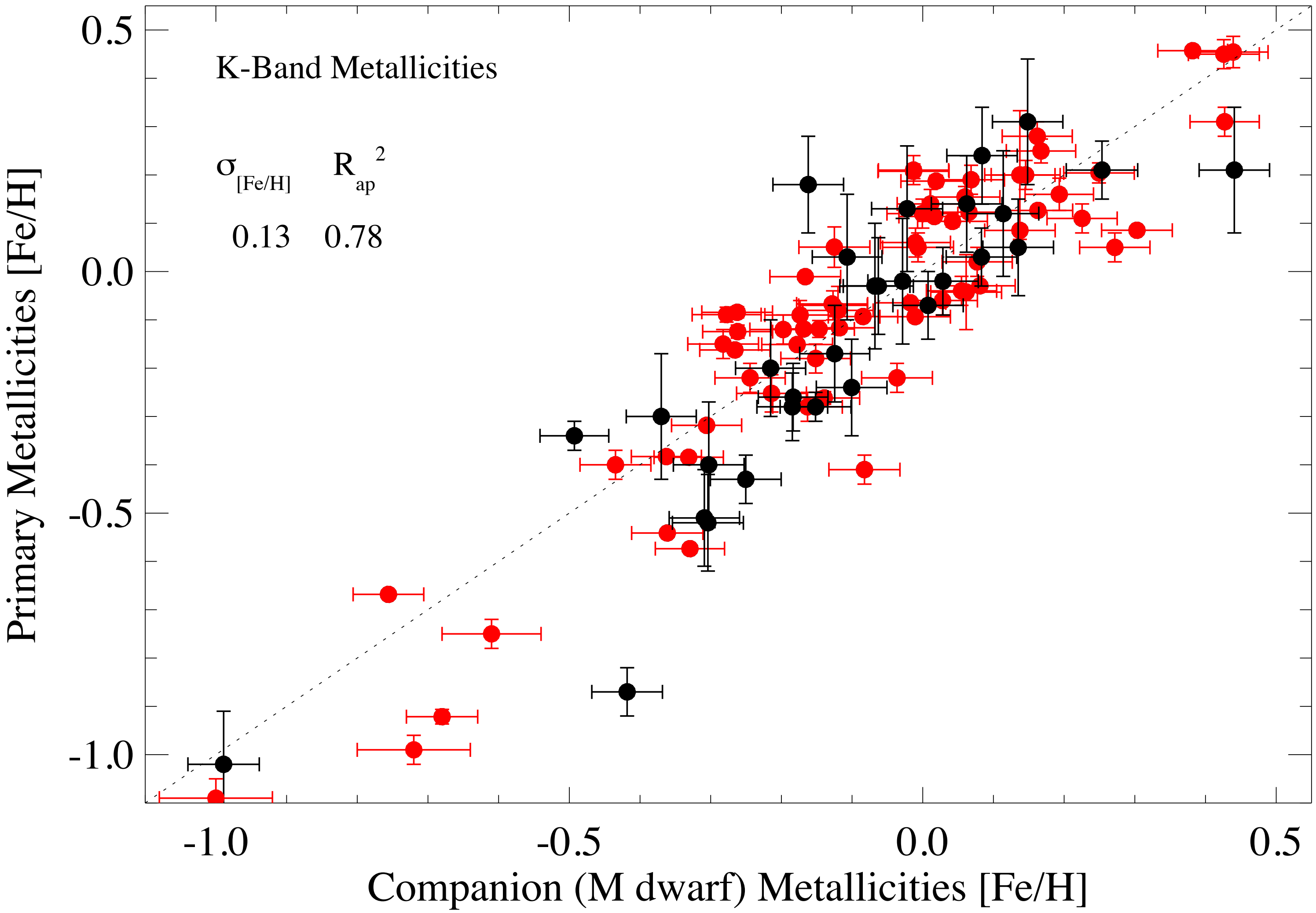


Testing Existing Techniques



Terrien et al. (2012)

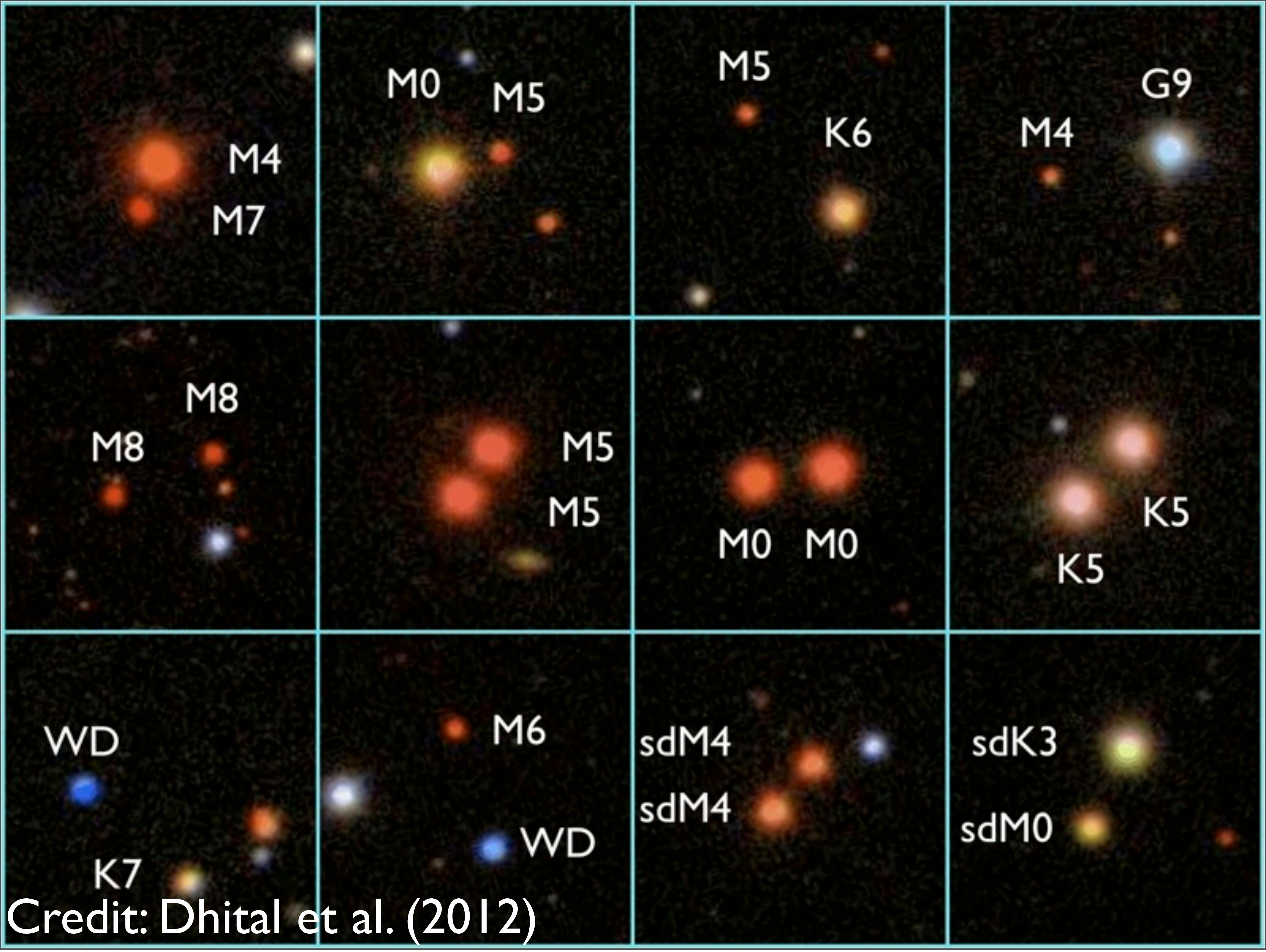
Testing Existing Techniques

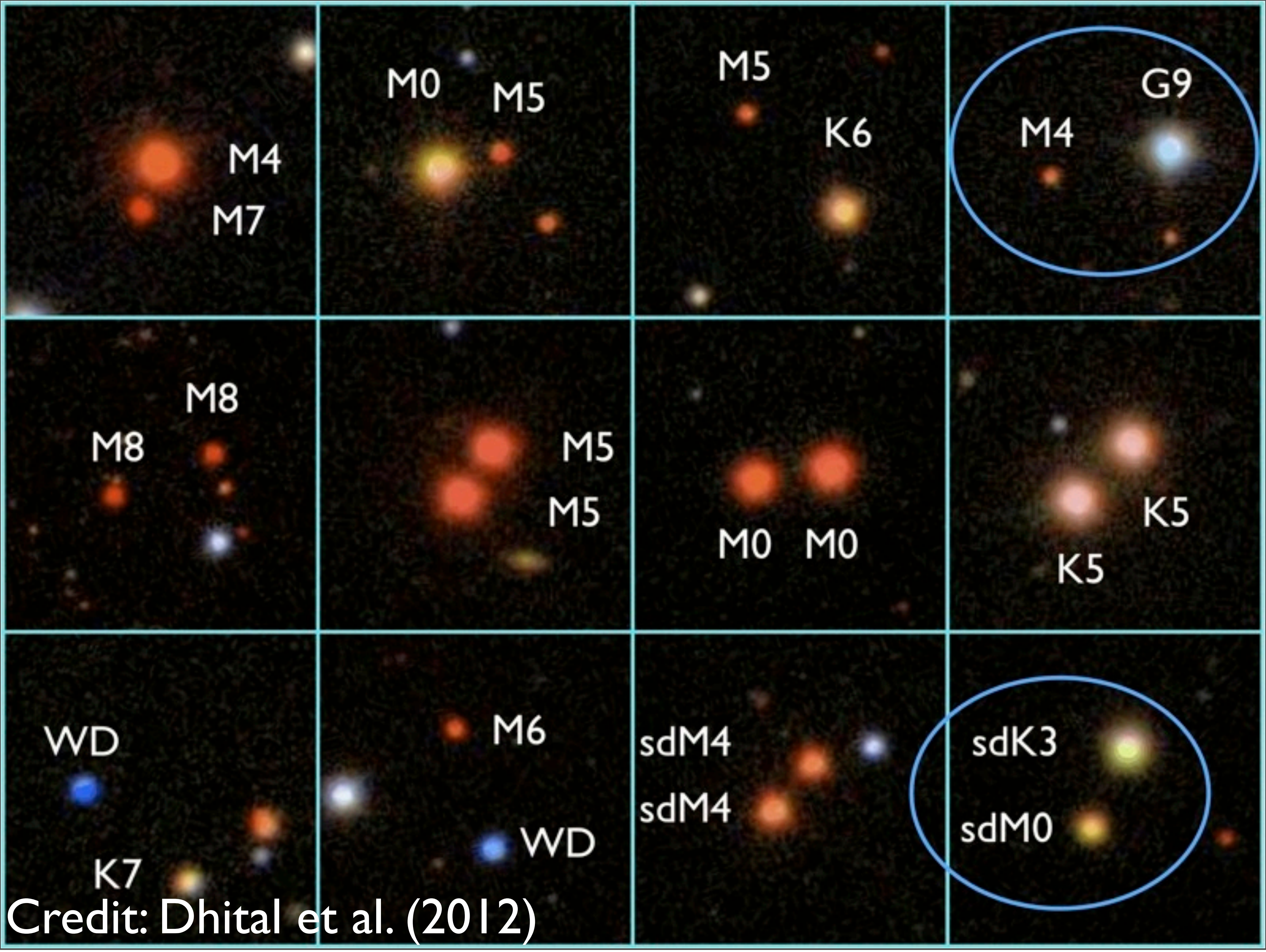


Rojas-Ayala et al. (2011)

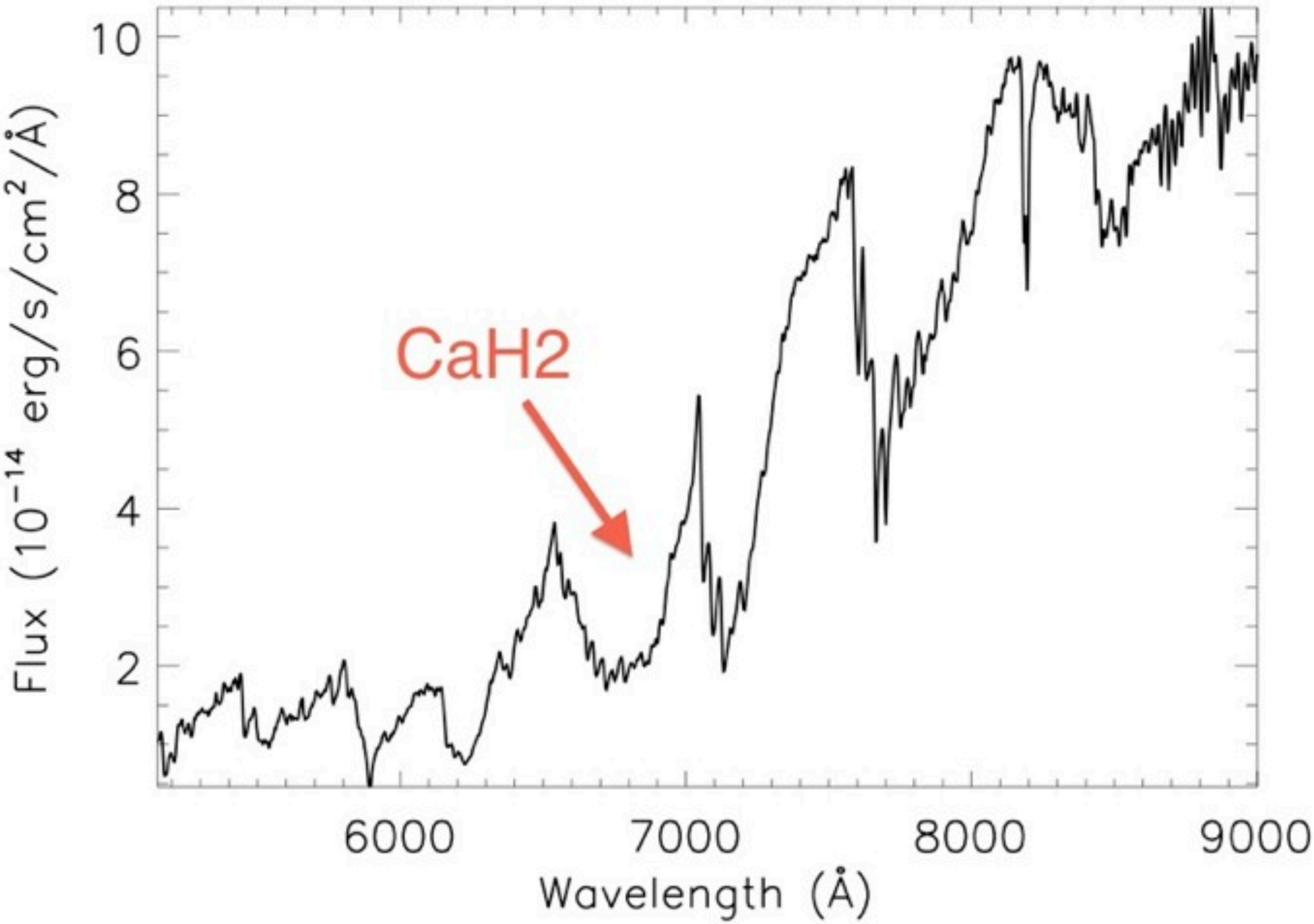
Previous Programs:

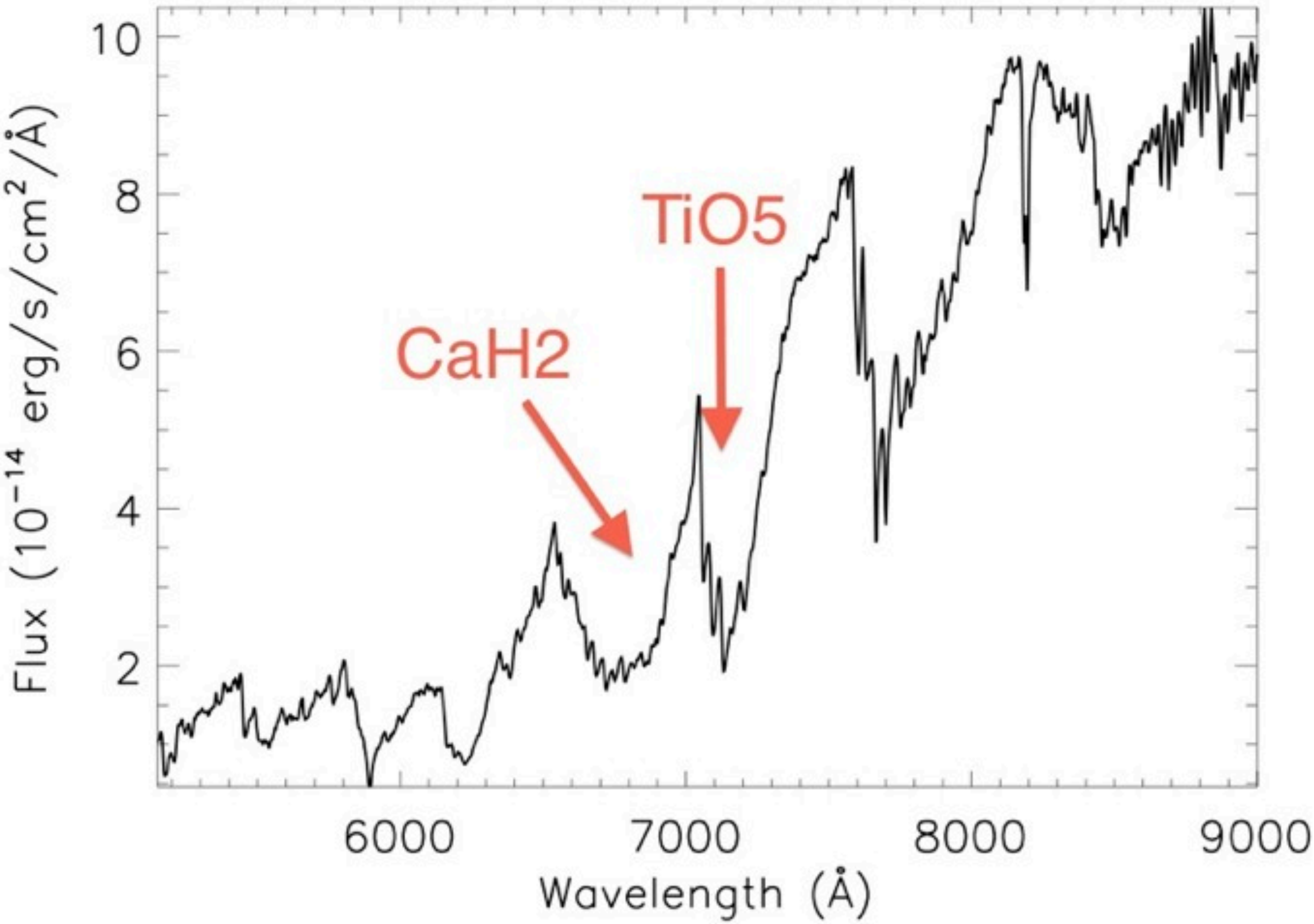
- Current techniques to estimate M-dwarf metallicities are limited:
  - Based on relatively few FGK-M pairs (10-30).
  - Narrow range of metallicities (-0.4 < [Fe/H] < +0.4).
  - Narrow range of spectral types (K7 to M4).

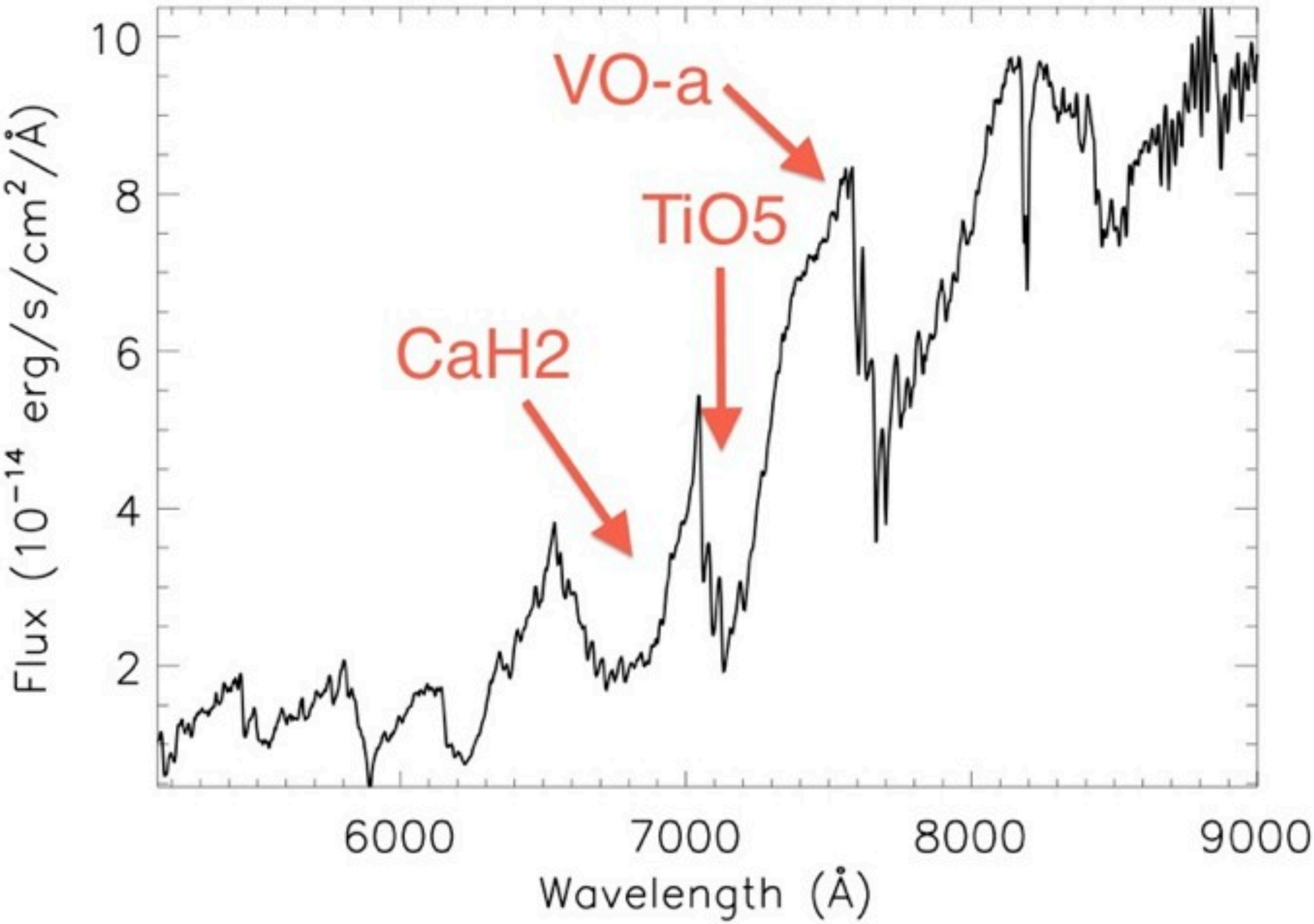

M4
M7
M0
M5
M5
K6
G9
M4
M8
M8
M5
M5
M0
M0
K5
K5
WD
K7
M6
WD
sdM4
sdM4
sdK3
sdM0
Credit: Dhital et al. (2012)

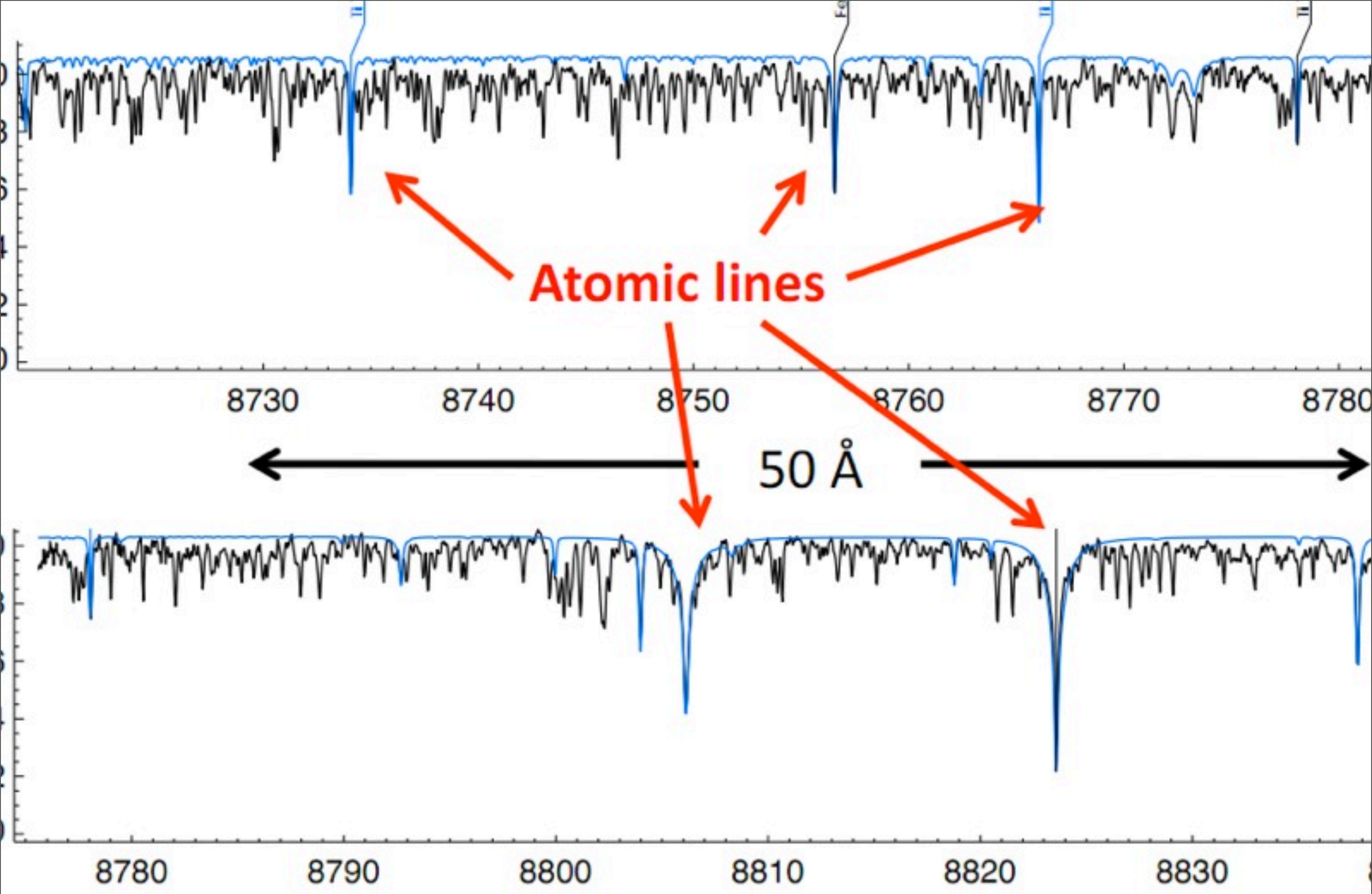


Credit: Dhital et al. (2012)


CaH2
Flux (10^{-14} erg/s/cm^2/Å)
10
8
6
4
2
6000
7000
8000
9000
Wavelength (Å)


TiO5
CaH2
Flux (10^{-14} erg/s/cm^2/Å)
Wavelength (Å)
10
8
6
4
2
6000
7000
8000
9000


VO-a
TiO5
CaH2
10
8
6
4
2
Flux (10^{-14} erg/s/cm^2/Å)
6000
7000
8000
9000
Wavelength (Å)



Atomic lines
8730
8740
8750
8760
8770
8780
50 Å
8780
8790
8800
8810
8820
8830