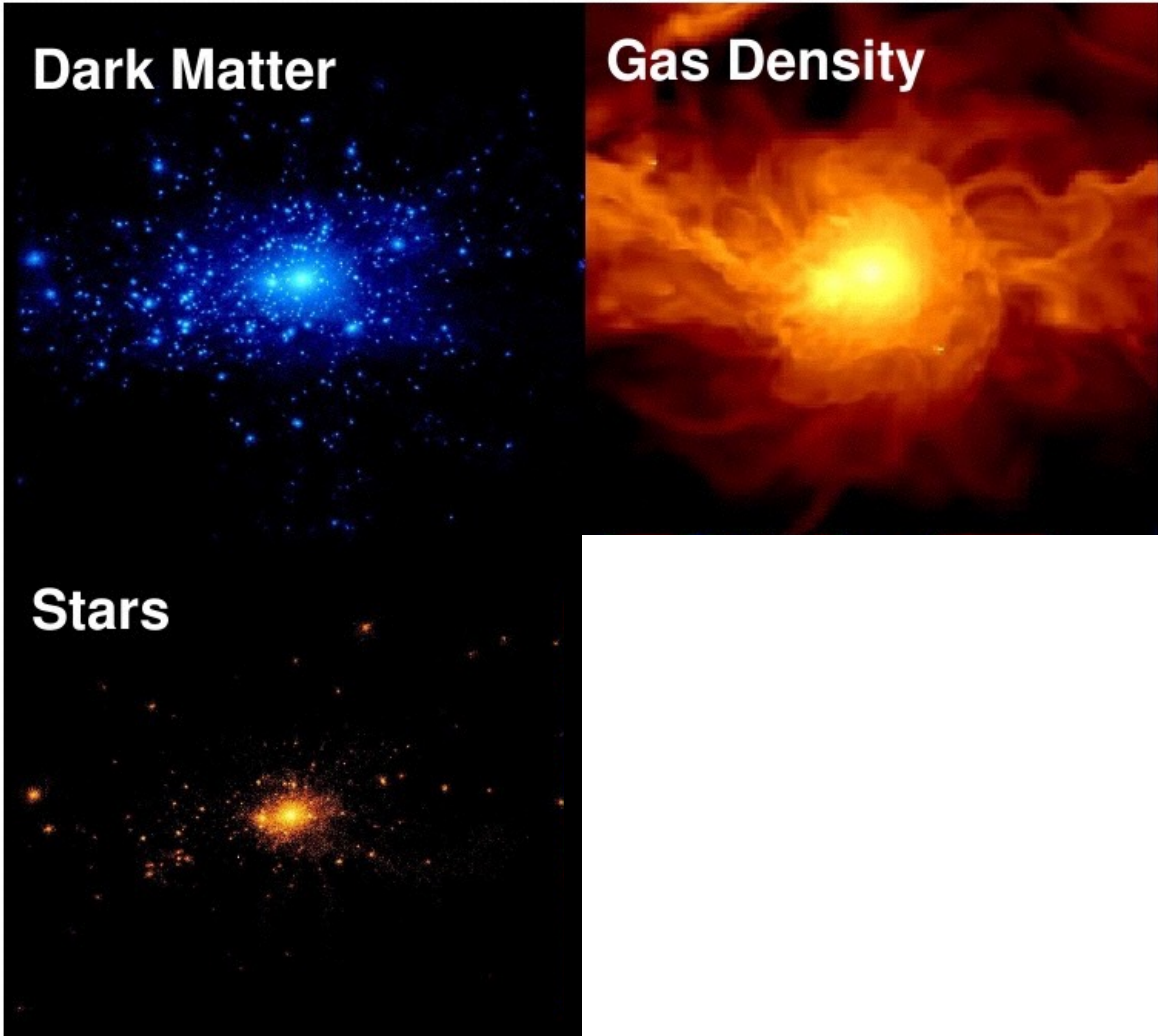
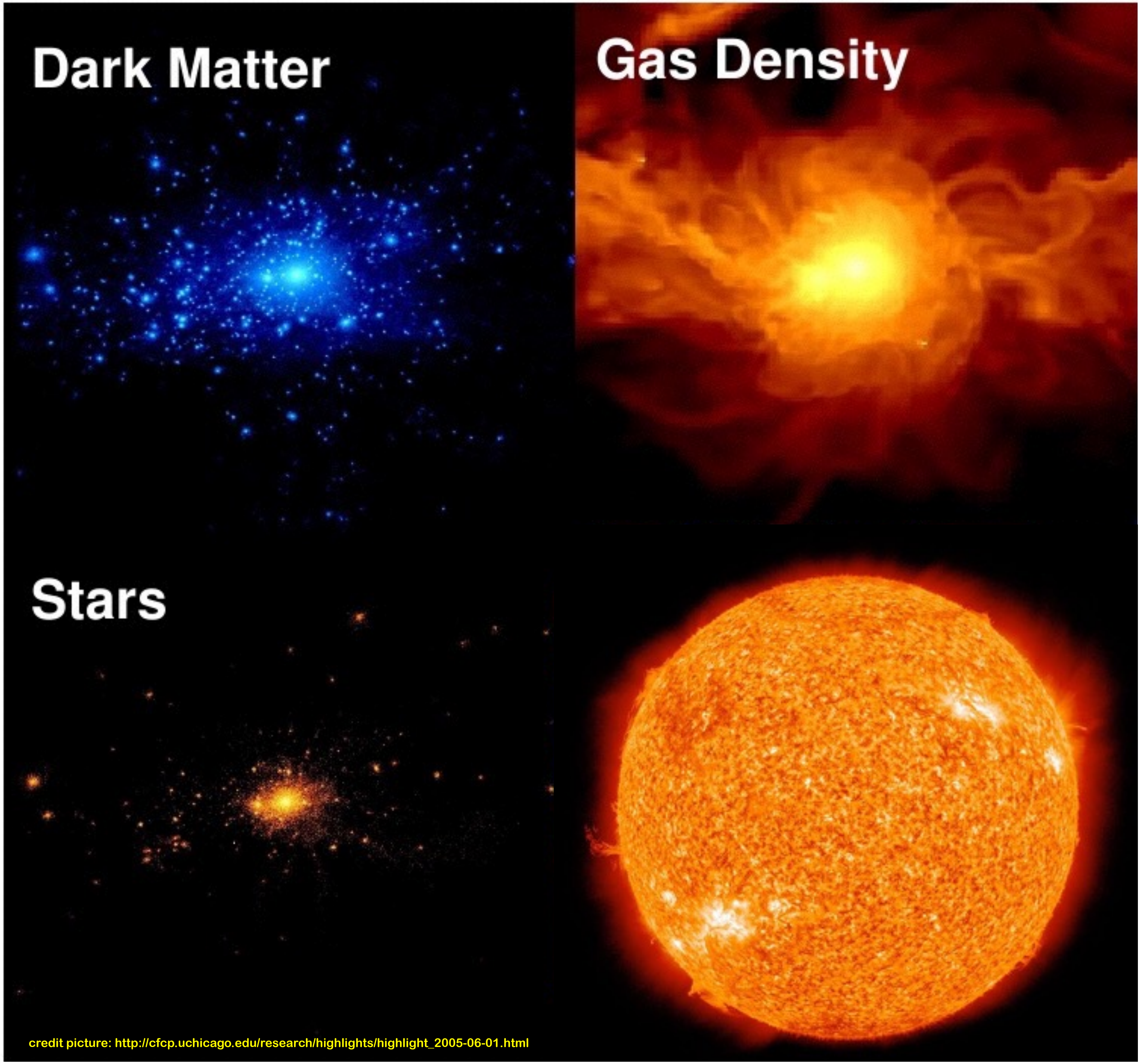
One for All
All for One:
stellar parameters for Galactic studies

Luca Casagrande

Australian National University



credit picture: http://cfcp.uchicago.edu/research/highlights/highlight_2005-06-01.html


Dark Matter
Gas Density
Stars
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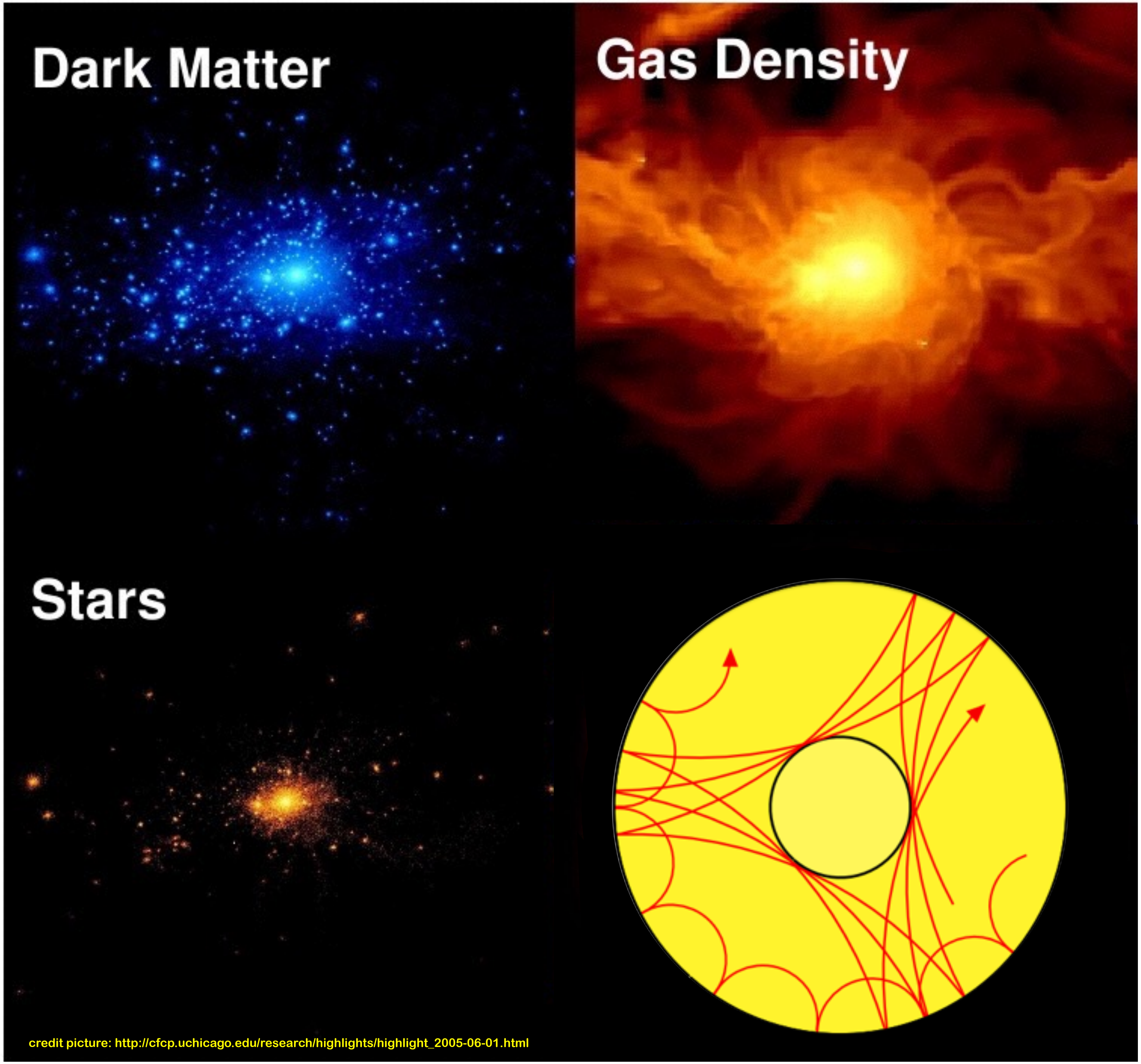
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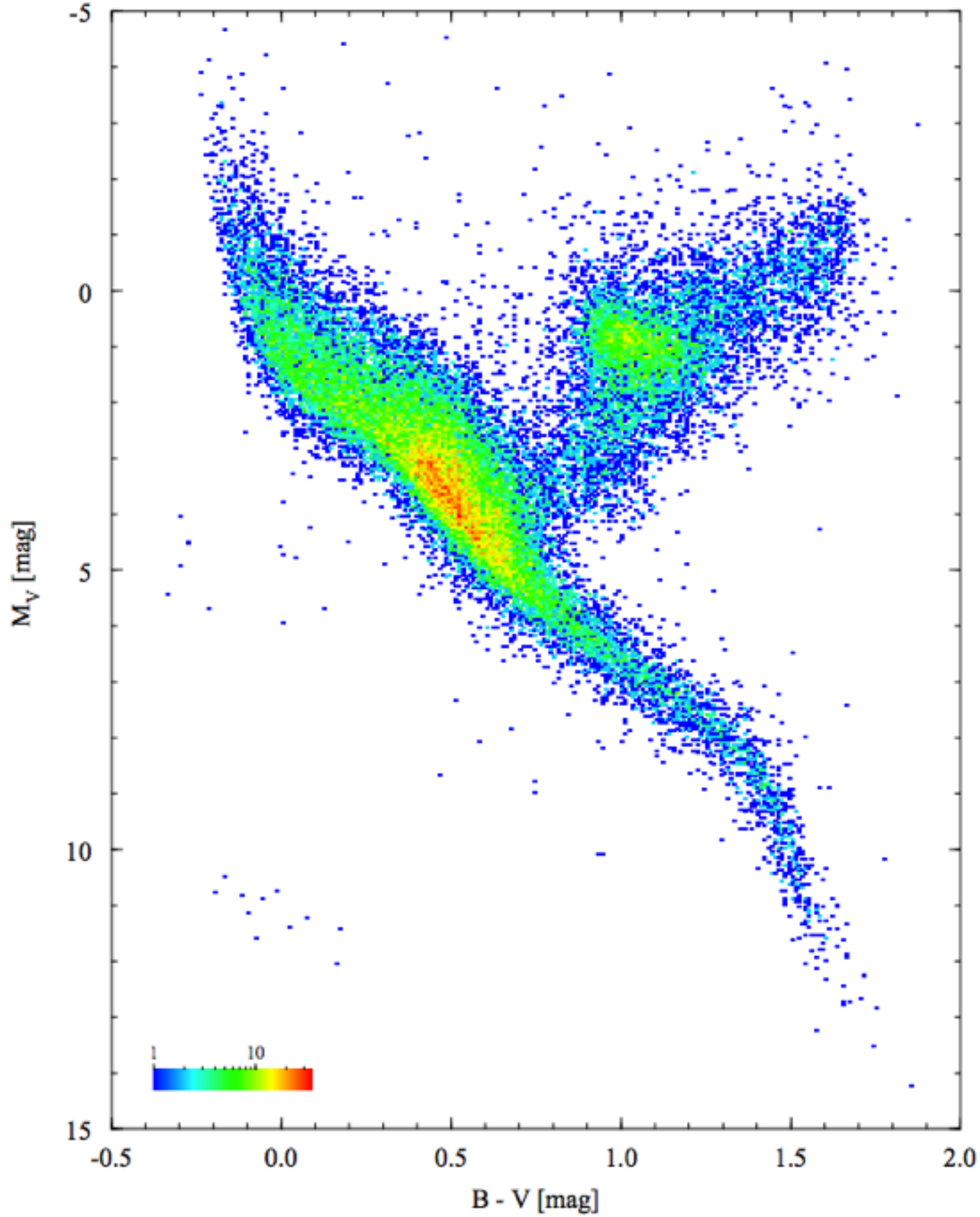
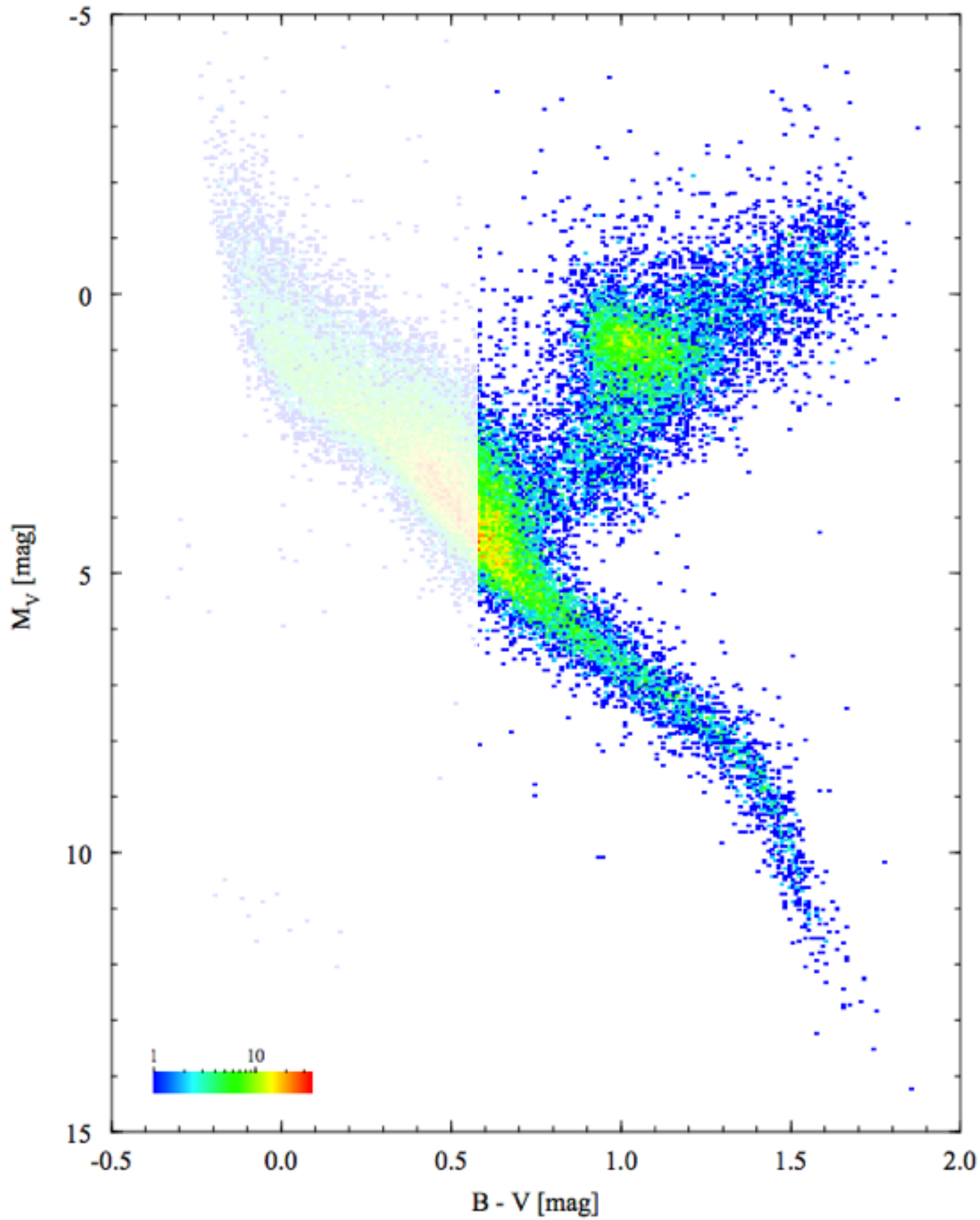
Fossils

chemical composition: ISM at the time and place of their formation
orbits: encode residual information on dynamical history



http://www.rssd.esa.int/SA-general/Projects/Hipparcos/images/f3_5_005.pdf



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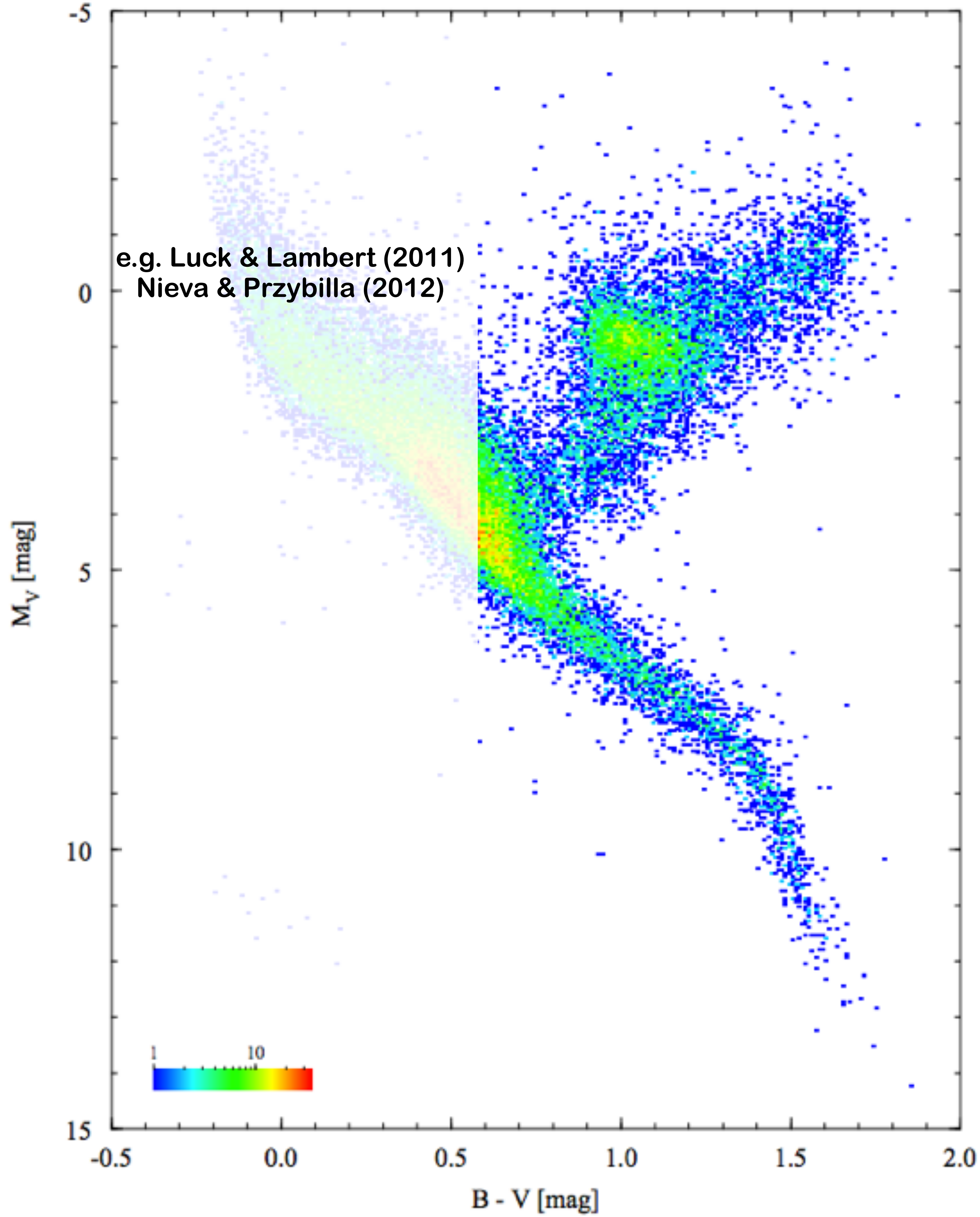

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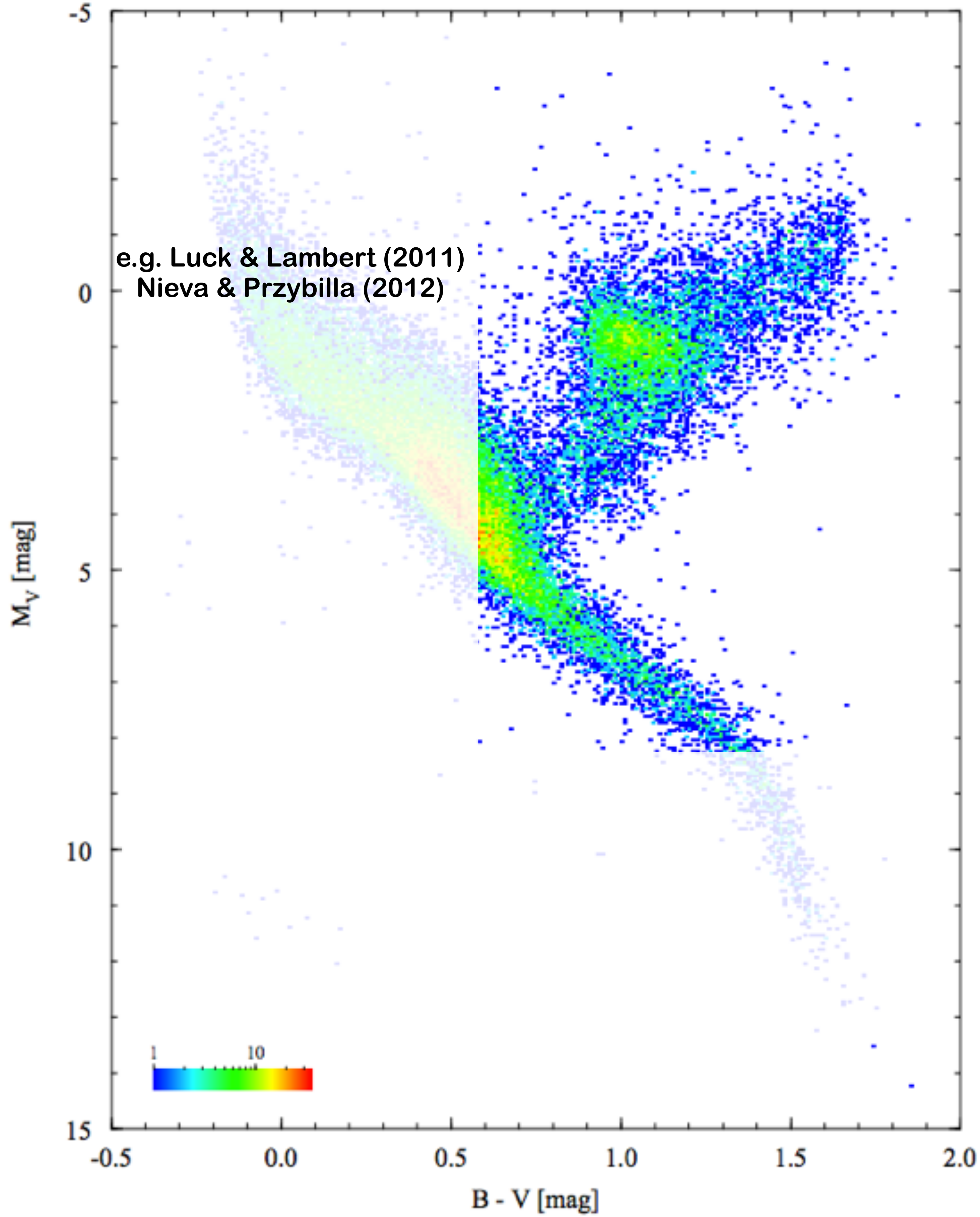

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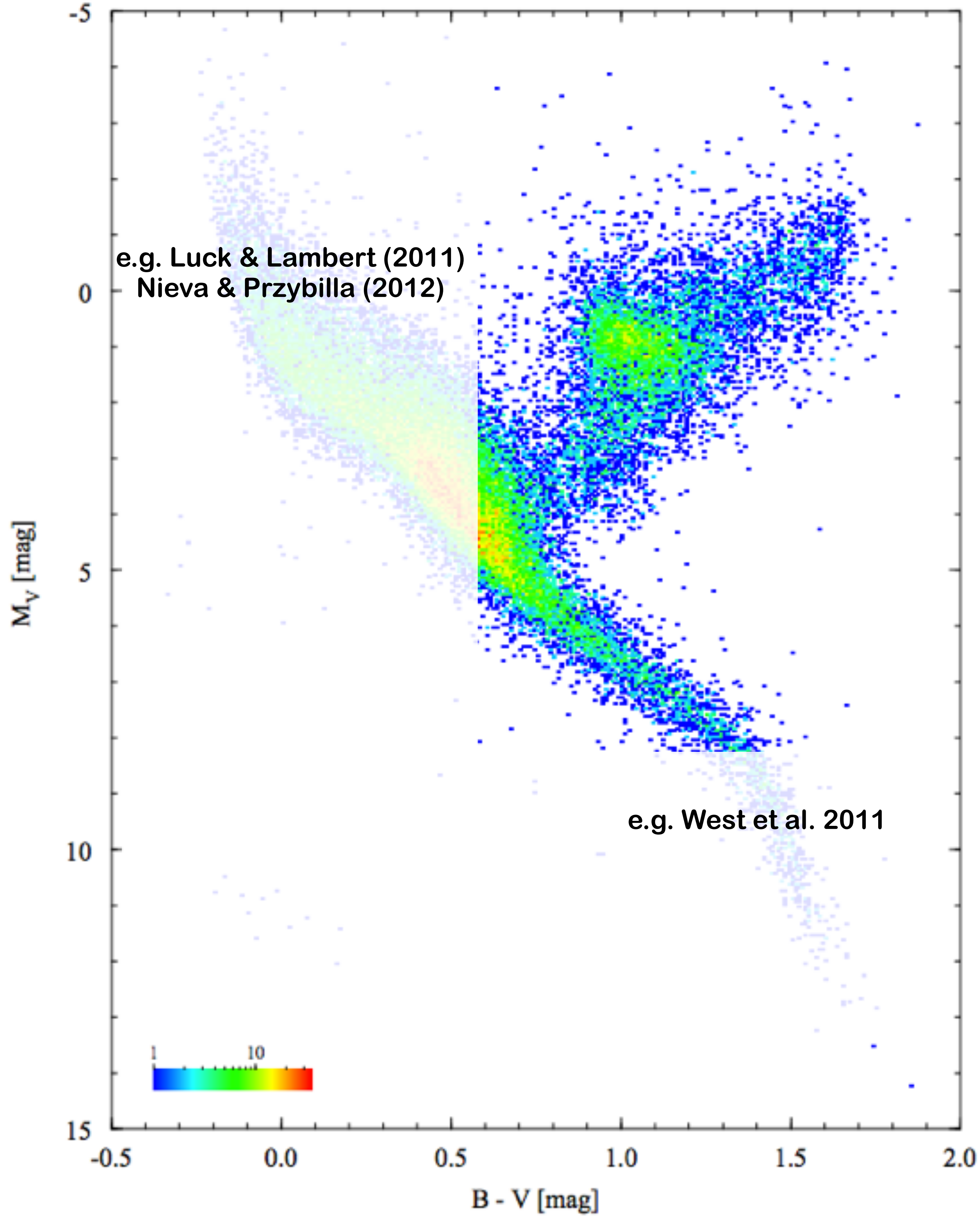

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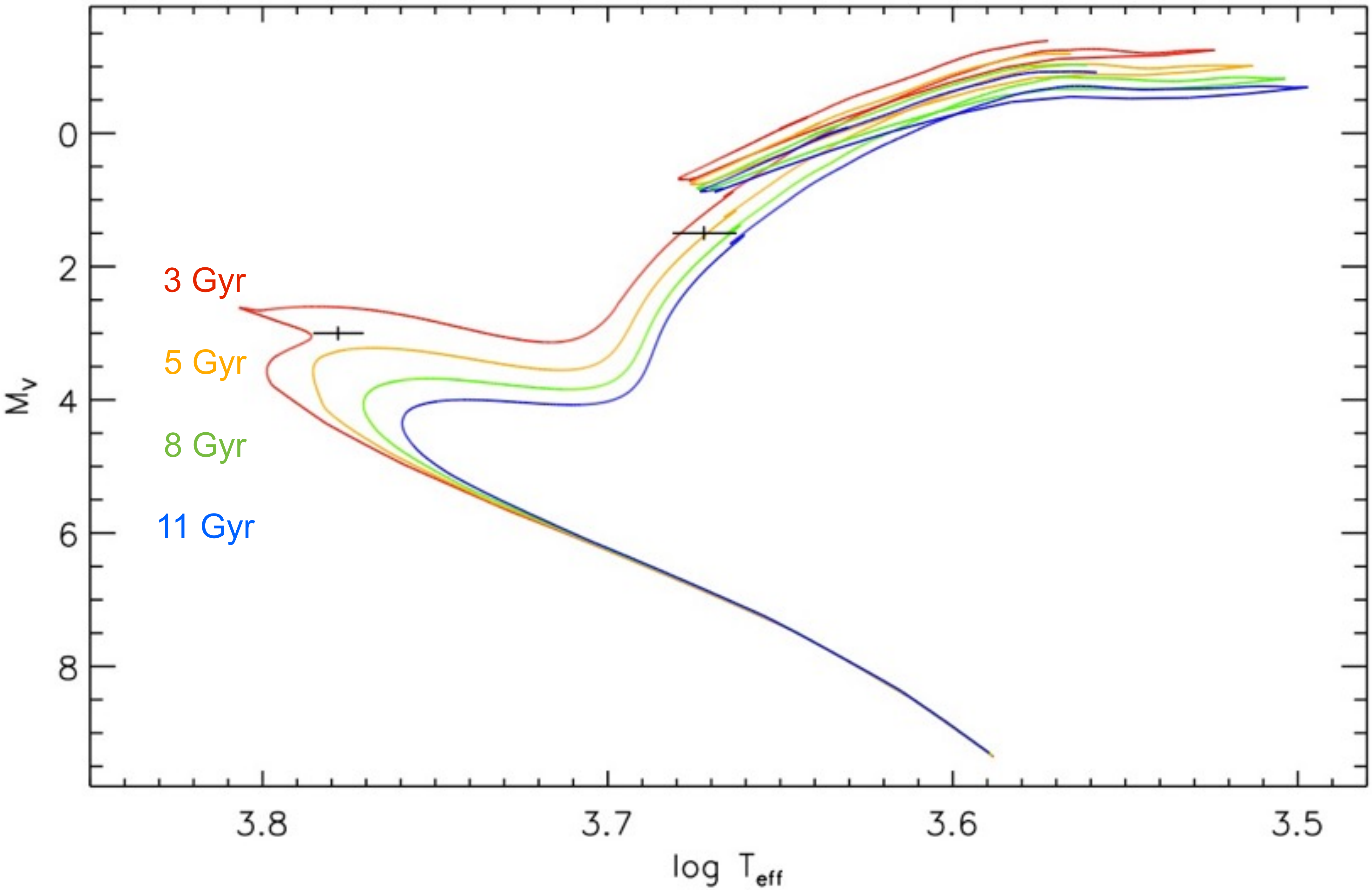

e.g. Soderblom (2010, ARAA)

Ways to stellar parameters

Spectroscopy $f(\lambda)$: lots of info, but also model dependent

Photometry $\int f(\lambda) T \, d\lambda$: info is more degenerate, "less" model dependent

Interferometry θ : fundamental, but "**calibrate calibrate calibrate**"

Asteroseismology $\Delta\nu$, ν_{max} : Mass and Radius (solar-like oscillations)

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Asteroseismology $\Delta\nu$, ν_{max} : Mass and Radius (solar-like oscillations)

$T_{\rm eff}$ ⟶ L, R

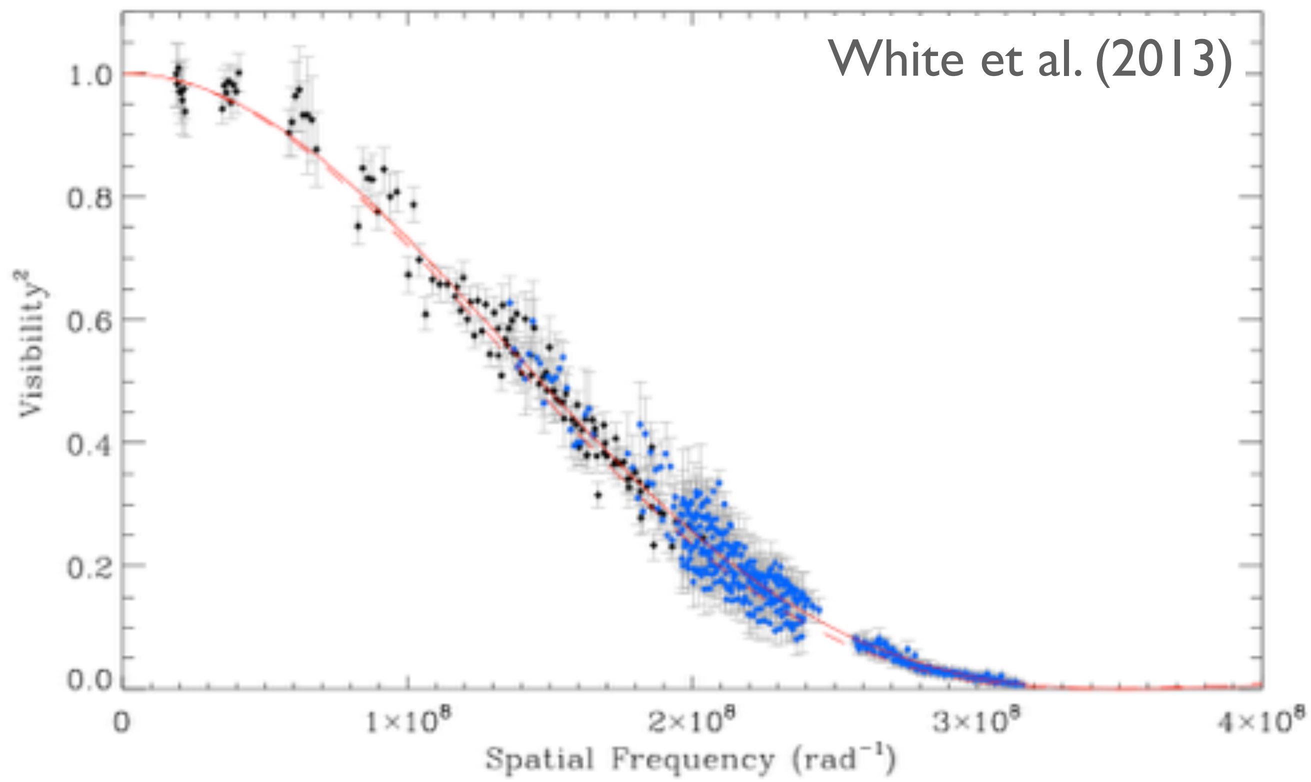
$[Fe/H]$ ⟶ X, Y, Z

$\log(g)$ ⟶ M, R

+ distances

+ ages

Not JUST a technicality!



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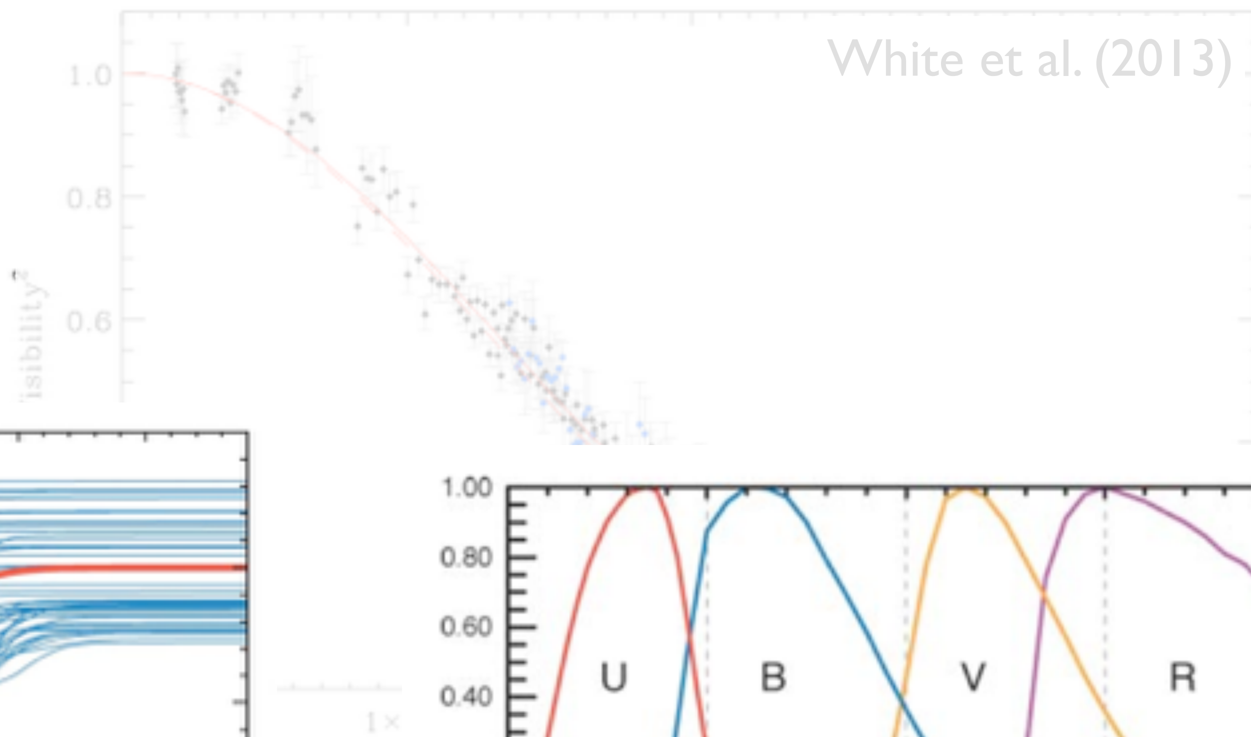

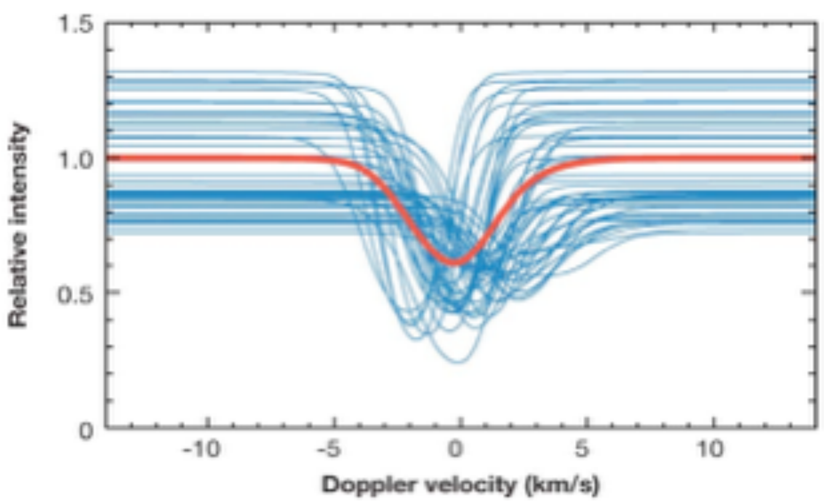

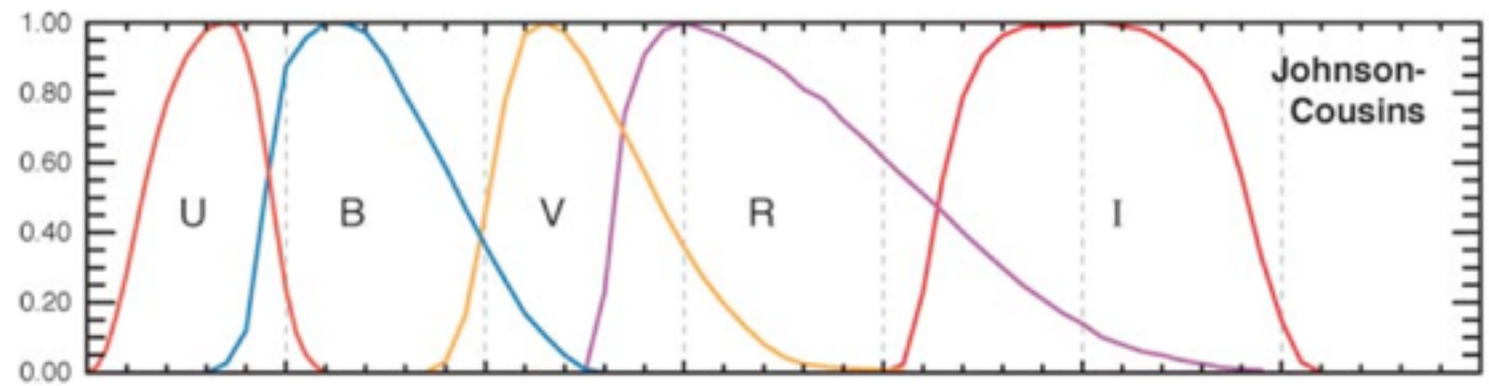

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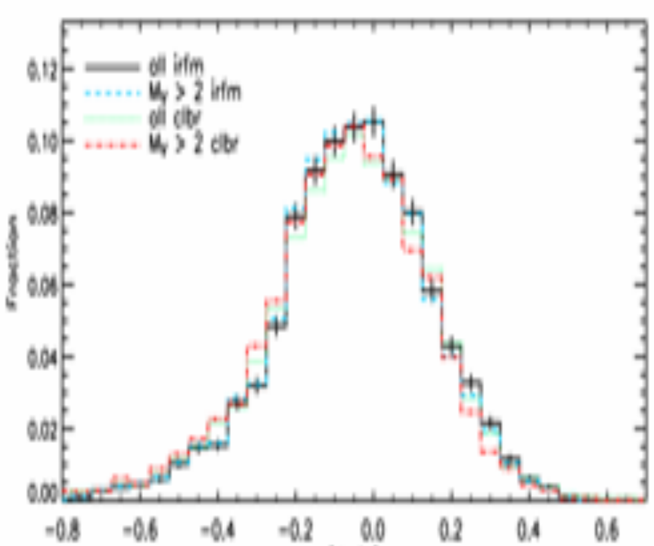
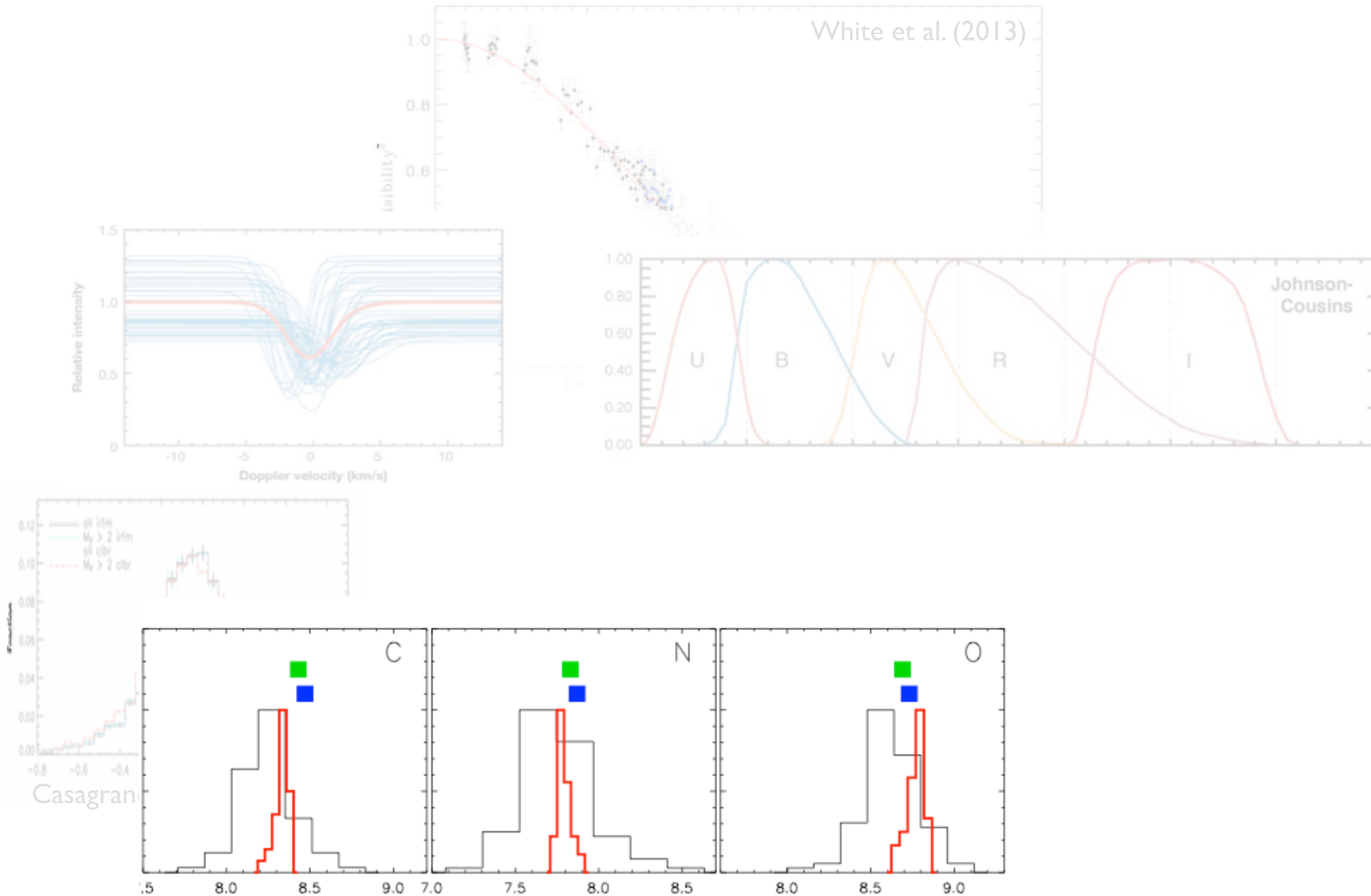


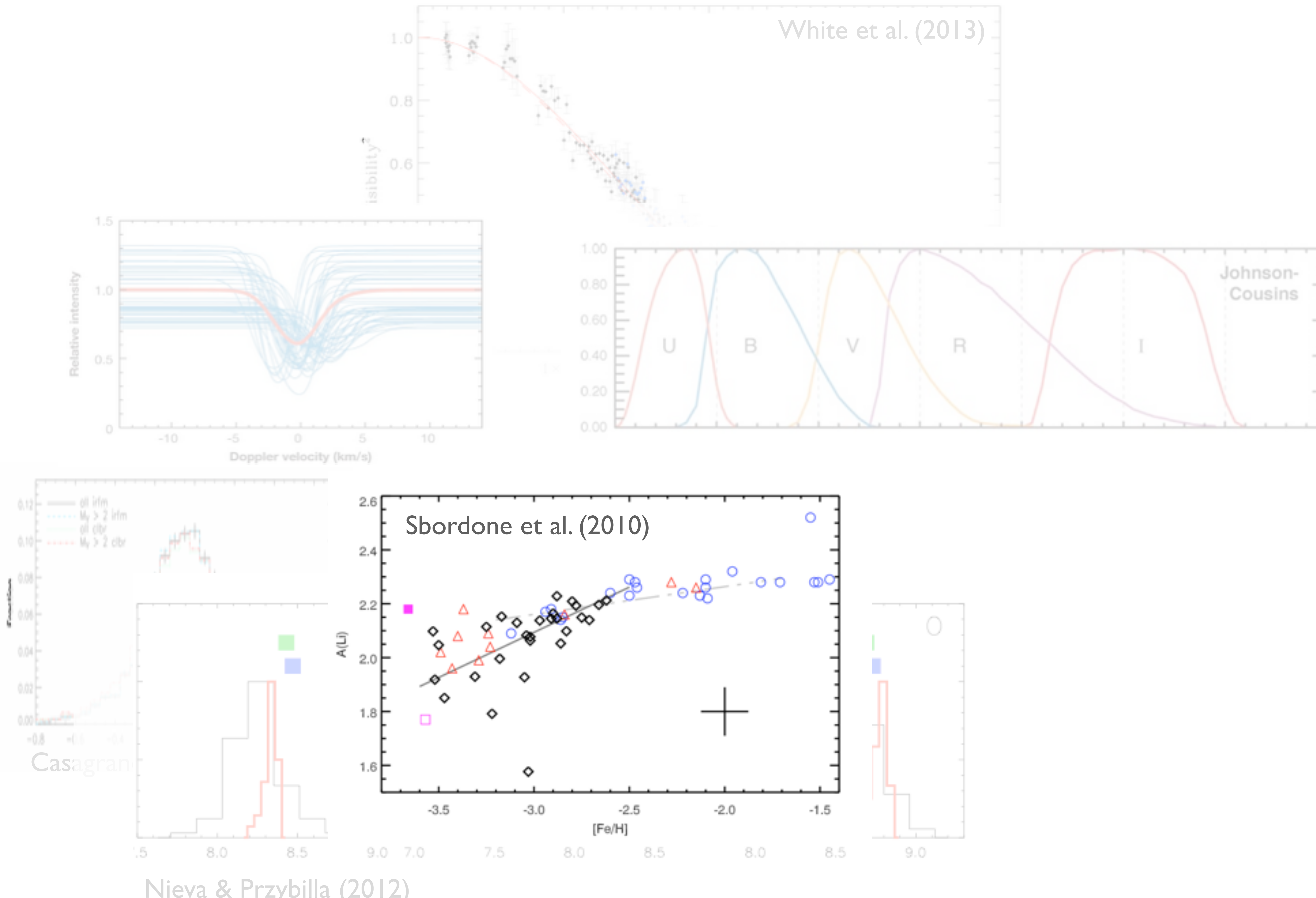
Casagrande et al. (2011)

Not JUST a technicality!



Nieva & Przybilla (2012)

Not JUST a technicality!



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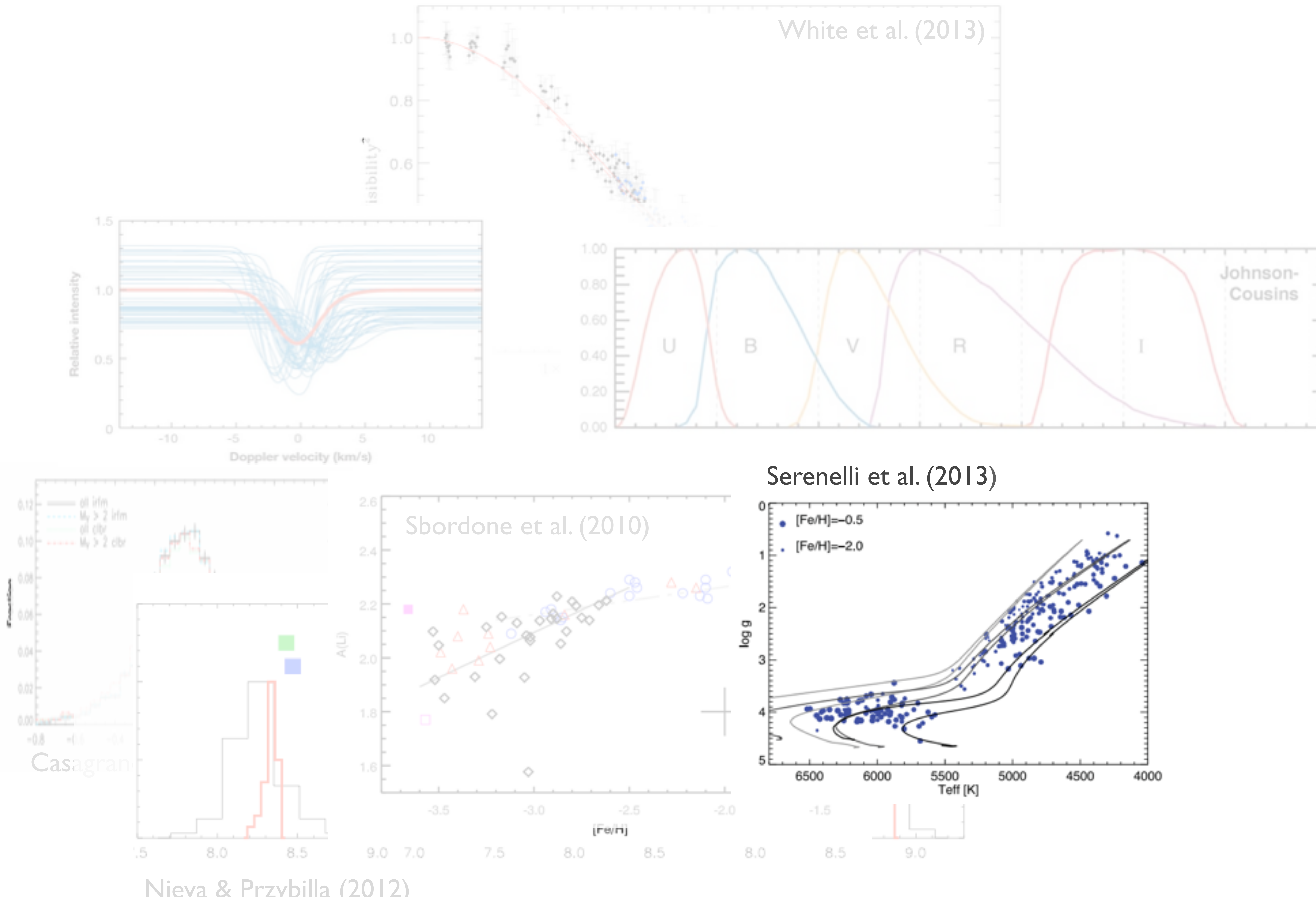

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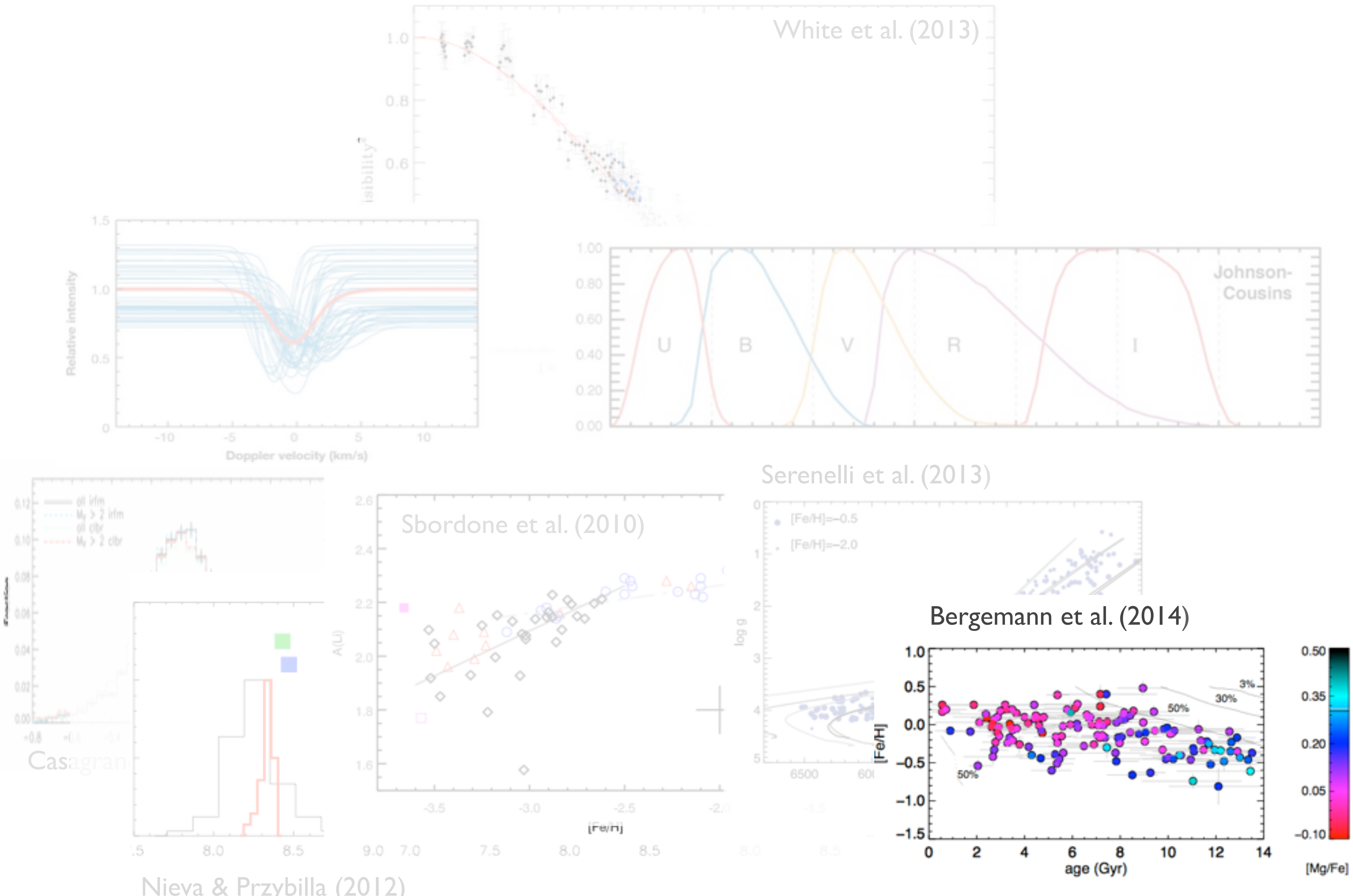
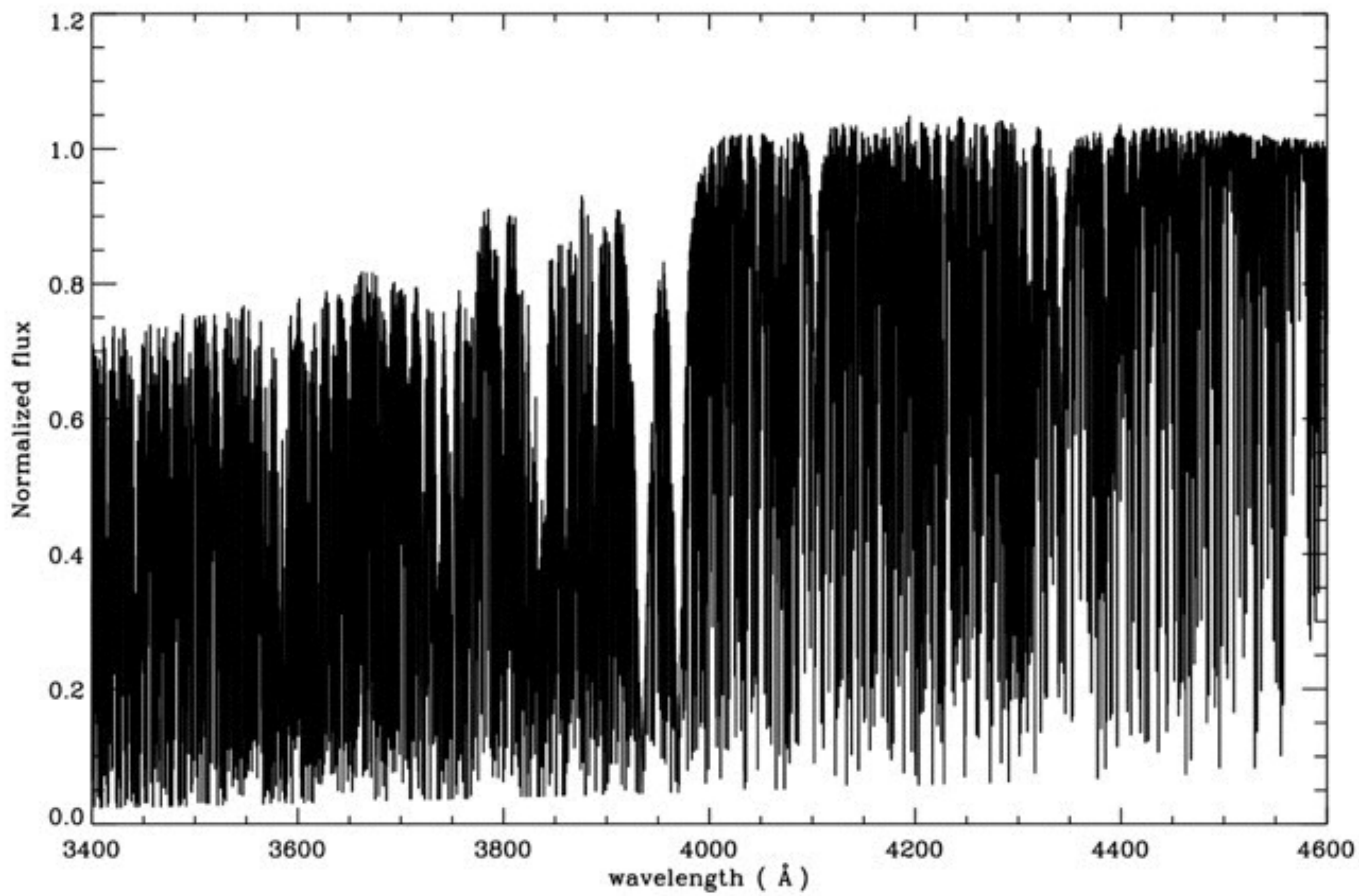


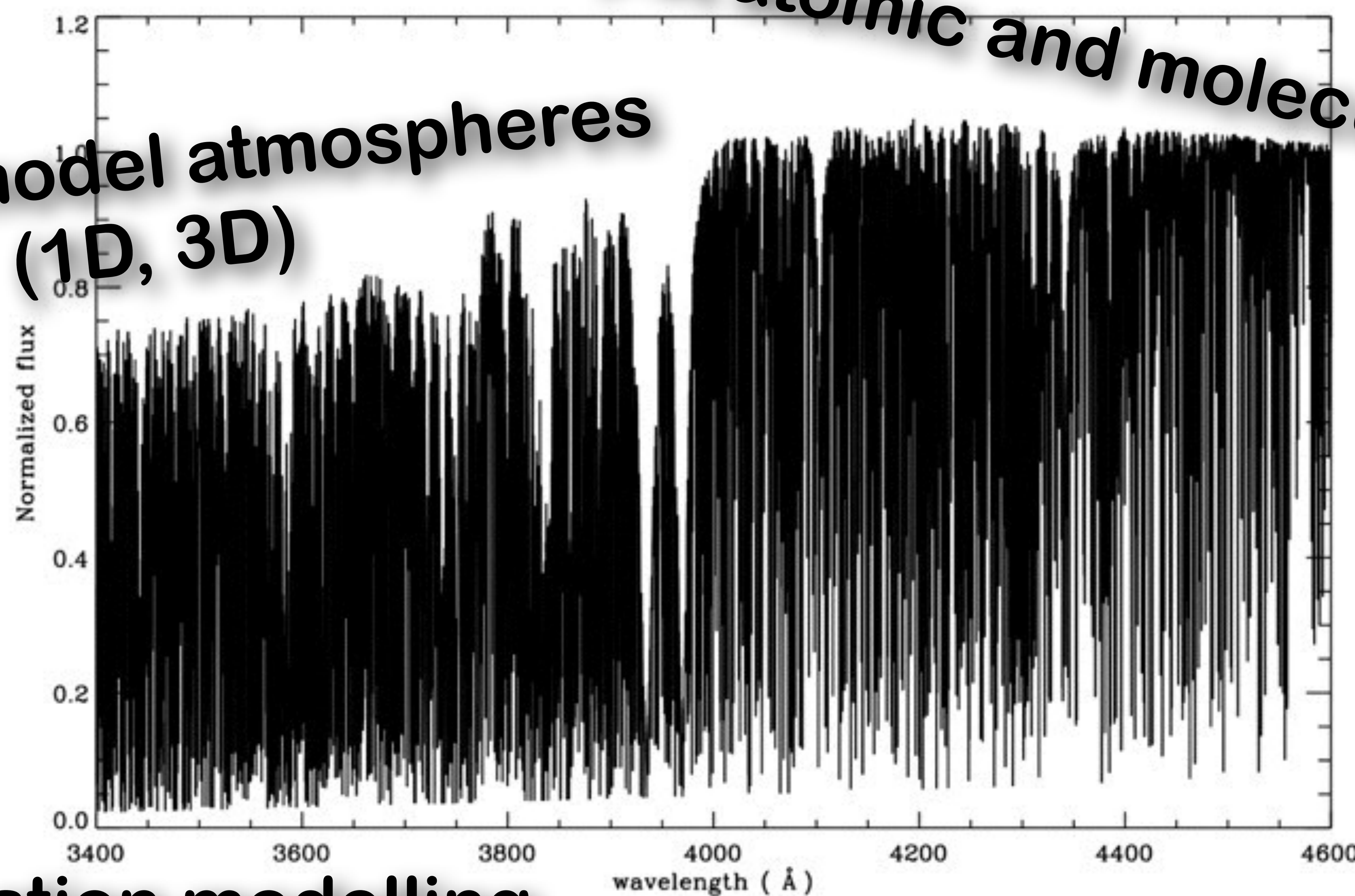
Measure for measure



Measure for measure

input atomic and molecular physics

realistic model atmospheres
(1D, 3D)



line formation modelling
(LTE, NLTE)

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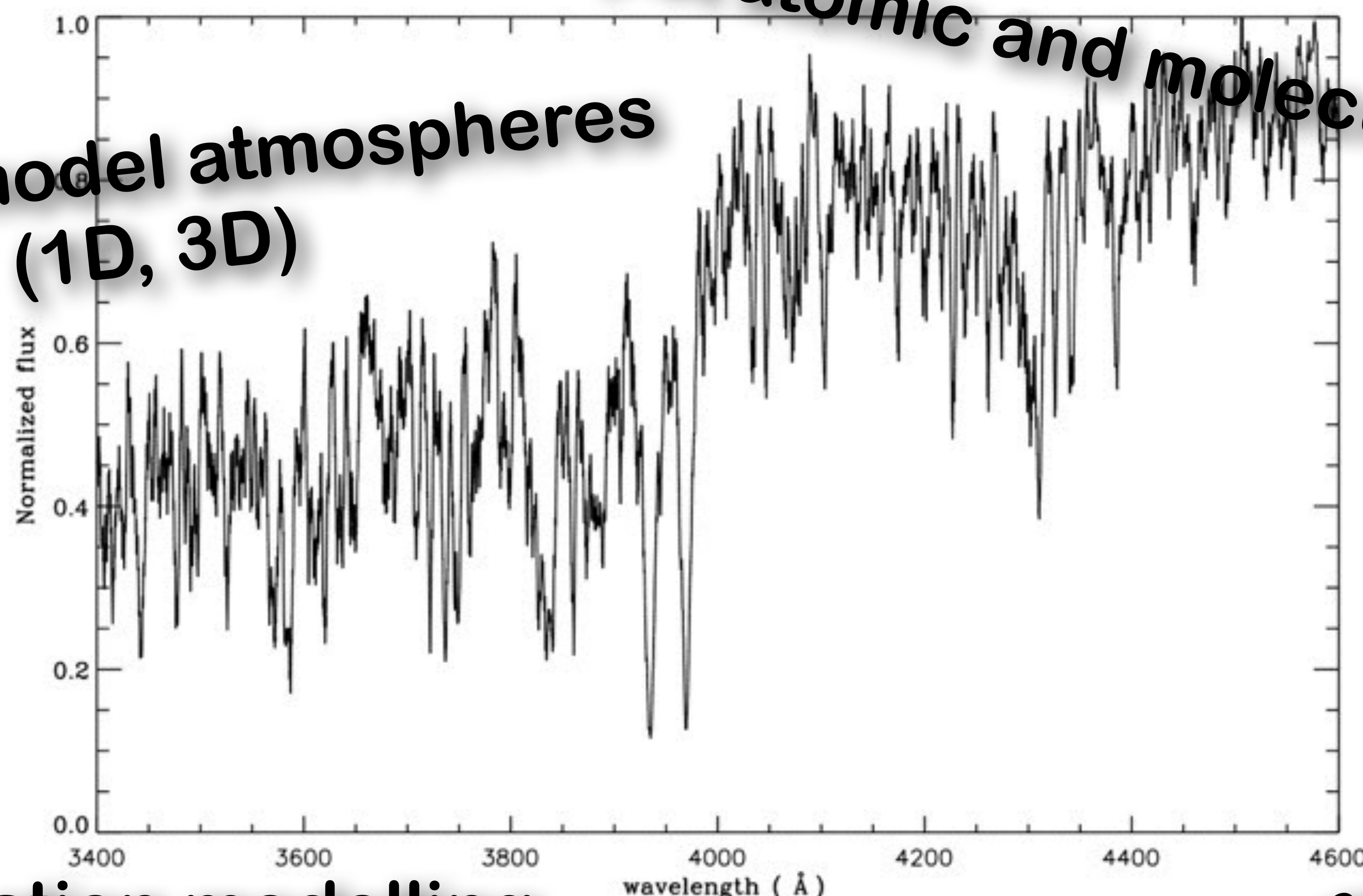

input atomic and molecular physics

realistic model atmospheres
(1D, 3D)

line formation modelling
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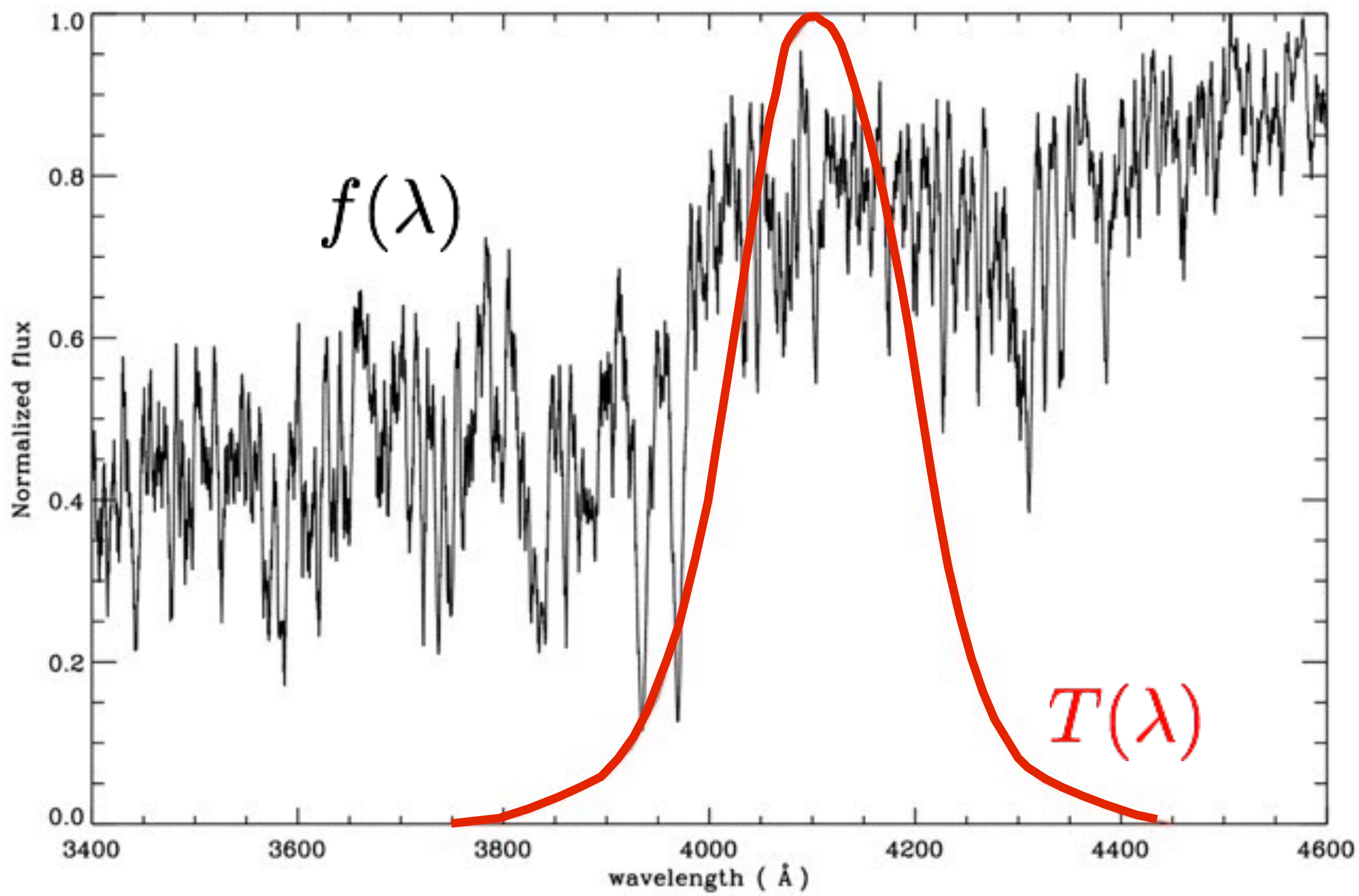
resolution and signal-to-noise

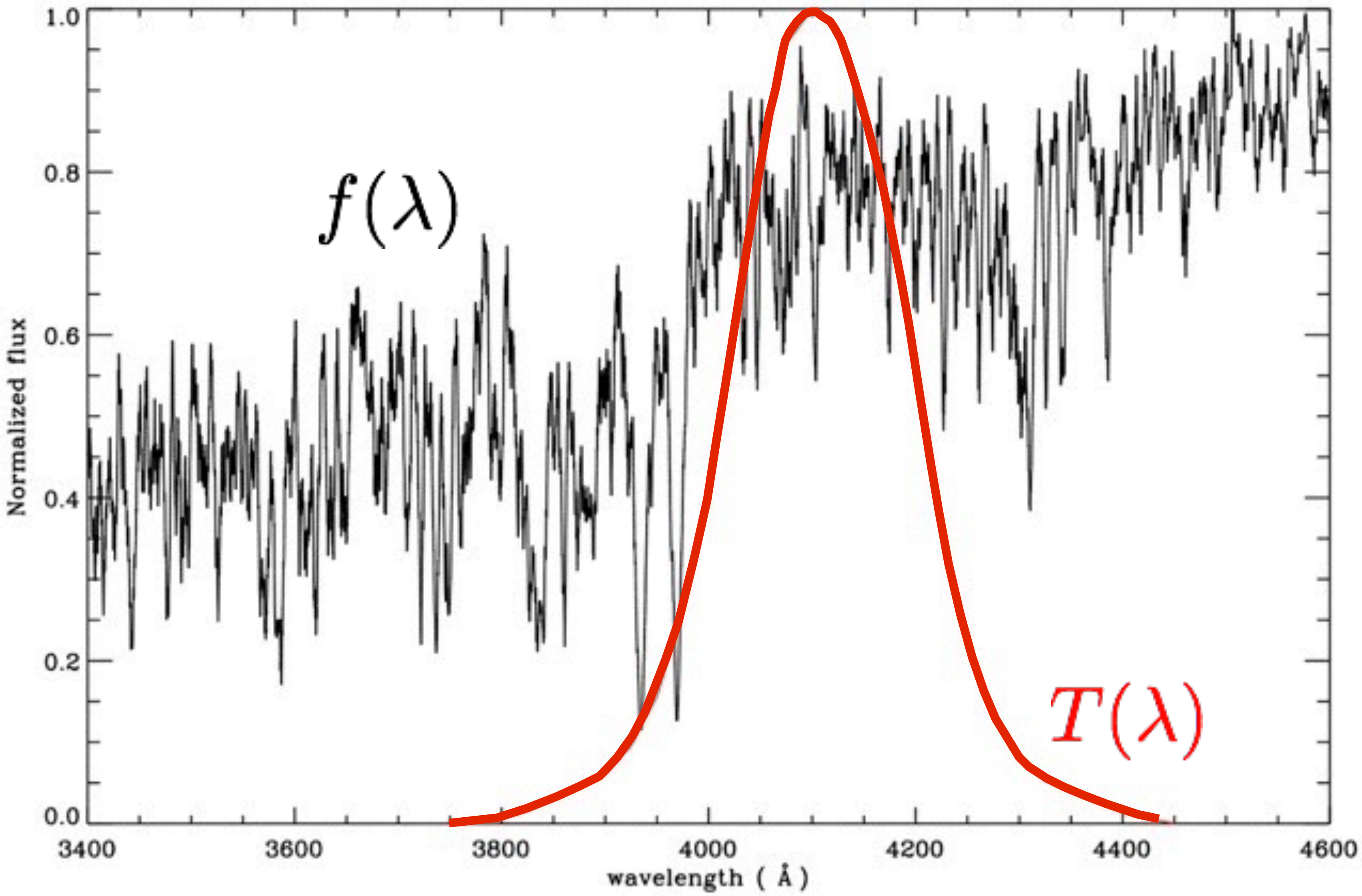
e.g., **Asplund (2005, ARAA), Bergemann 2014, arXiv1403:3089**

Measure for measure



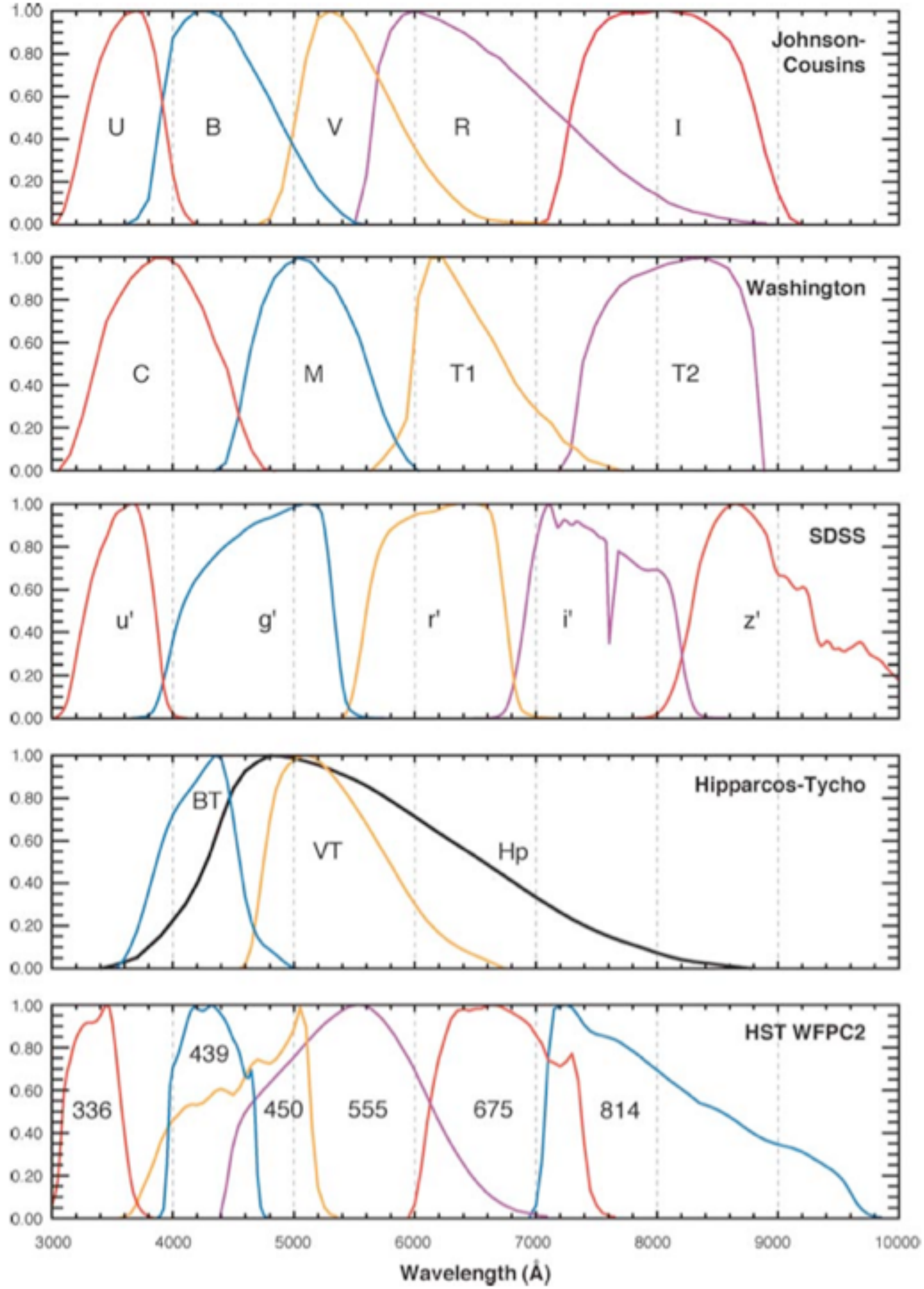
$$\int f(\lambda)T(\lambda)\mathrm{d}\lambda$$

Measure for measure

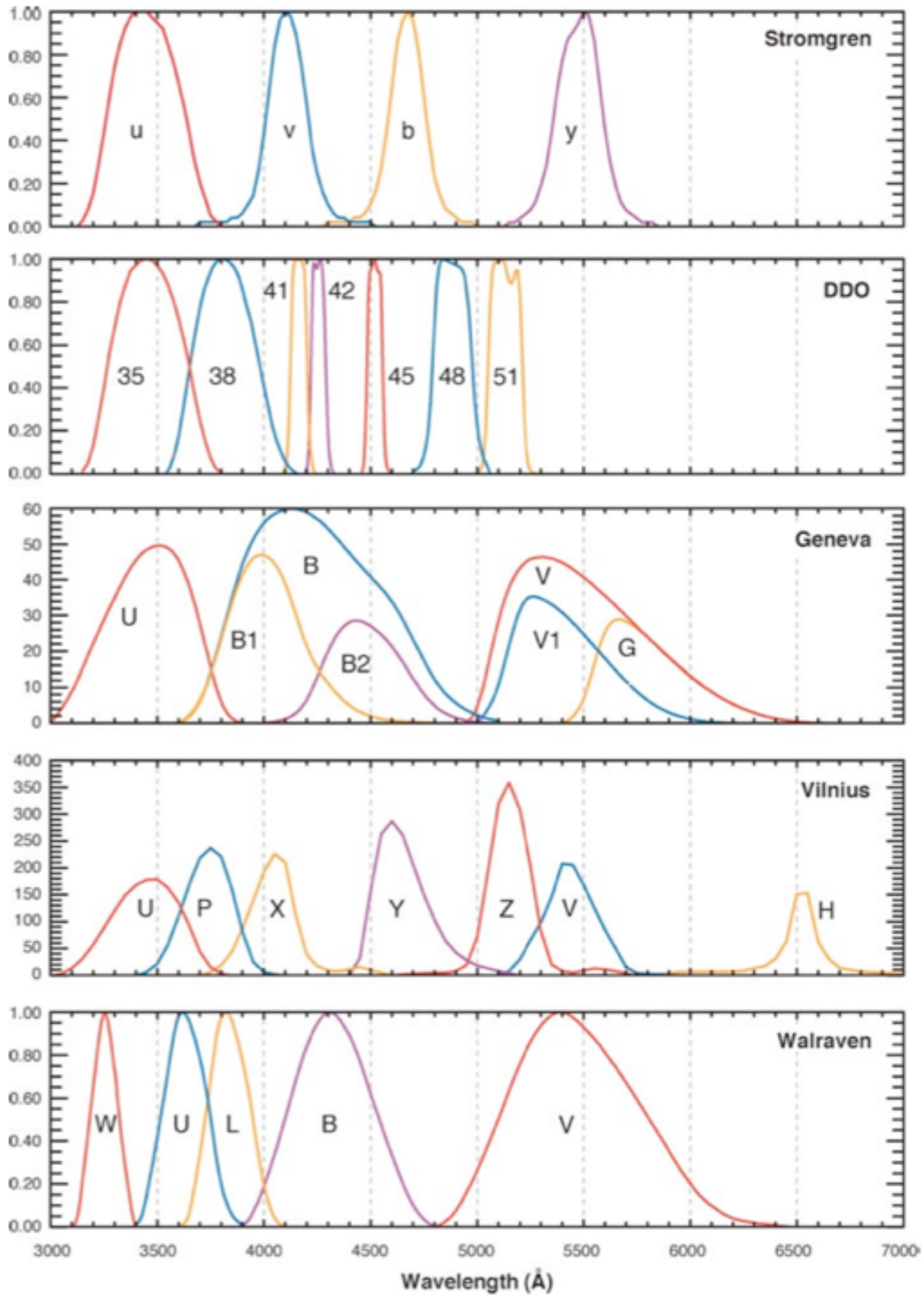


$$\int f(\lambda)T(\lambda)\mathrm{d}\lambda$$

e.g., **Bessell (2005, ARAA),**
Casagrande & VandenBerg (2014)



Bessell (2005)



Bessell (2005)

Some basic definitions

energy-integration (for photo-counting $T_\zeta \rightarrow \lambda T_\zeta$ or $T_\zeta \rightarrow T_\zeta/\nu$)

$$m \propto \frac{\int f_x T_\zeta \, \mathrm{dx}}{\int T_\zeta \, \mathrm{dx}}$$

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$$m_{ST} \propto \frac{\int f_\lambda T_\zeta \,\mathrm{d}\lambda}{f^0_\lambda \int T_\zeta \,\mathrm{d}\lambda}$$

$$f^0_\lambda = 3.631 \times 10^{-9} \mathrm{erg\,s^{-1}\,cm^{-2}\,\AA^{-1}}$$

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$$f_\lambda^0 = 3.631 \times 10^{-9} \mathrm{erg\, s^{-1}\, cm^{-2}\, \mathring{A}^{-1}}$$

$$f_\nu^0 = 3.631 \times 10^{-20} \mathrm{erg\, s^{-1}\, cm^{-2}\, Hz^{-1}}$$

Some basic definitions

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$$m_{\mathrm{VEGA}} \propto \frac{\int f_\lambda T_\zeta \,\mathrm{d}\lambda}{\int T_\zeta \,\mathrm{d}\lambda} + ZP_\zeta$$

$$m_{AB} \propto \frac{\int f_\nu T_\zeta \,\mathrm{d}\nu}{f^0_\nu \int T_\zeta \,\mathrm{d}\nu}$$

$$f^0_\lambda = 3.631 \times 10^{-9} \mathrm{erg\,s^{-1}\,cm^{-2}\,\AA^{-1}}$$

$$ZP_\zeta = m_{\star,\zeta} + 2.5 \log \frac{\int f_\star T_\zeta \,\mathrm{d}\lambda}{\int T_\zeta \mathrm{d}\lambda}$$

$$f^0_\nu = 3.631 \times 10^{-20} \mathrm{erg\,s^{-1}\,cm^{-2}\,Hz^{-1}}$$

absolute calibration

$\mathrm{erg\,s^{-1}\,cm^{-2}\,\AA^{-1}}$

e.g., **Golay 1974, Girardi et al. 2002, Bessell & Murphy (2012), Casagrande & VandenBerg (2014)**

In practice

Even if the definition of a photometric system is sound:

- its actual realisation at the telescope is non-trivial,
- converting magnitudes back into fluxes is non-trivial.

As a matter of fact, we always introduce some zero-point correction(s) trying to satisfy the original definition:

$$m_{ST} \propto \frac{\int f_\lambda T_\zeta \, \mathrm{d}\lambda}{f_\lambda^0 \int T_\zeta \, \mathrm{d}\lambda} \qquad m_{\mathtt{VEGA}} \propto \frac{\int f_\lambda T_\zeta \, \mathrm{d}\lambda}{\int T_\zeta \, \mathrm{d}\lambda} + ZP_\zeta \qquad m_{AB} \propto \frac{\int f_\nu T_\zeta \, \mathrm{d}\nu}{f_\nu^0 \int T_\zeta \, \mathrm{d}\nu}$$

e.g. 2MASS: **Cohen et al. (2003)**; SLOAN: **Eisenstein et al. (2006), Holberg & Bergeron (2006)**

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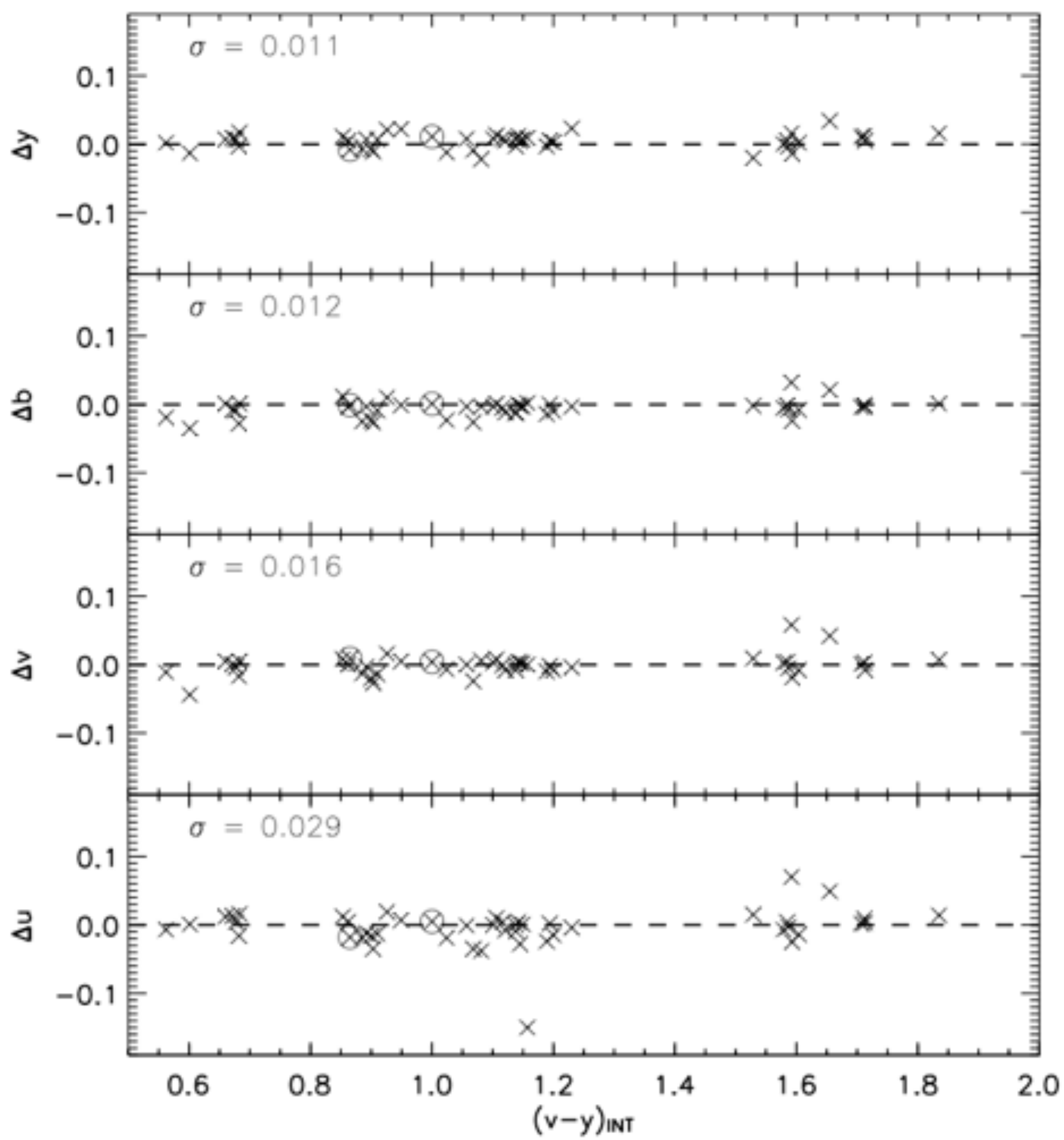
$$m_{ST} \propto \frac{\int f_\lambda T_\zeta \, \mathrm{d}\lambda}{f_\lambda^0 \int T_\zeta \, \mathrm{d}\lambda} + \epsilon \qquad m_{\mathtt{VEGA}} \propto \frac{\int f_\lambda T_\zeta \, \mathrm{d}\lambda}{\int T_\zeta \, \mathrm{d}\lambda} + ZP_\zeta + \epsilon \qquad m_{AB} \propto \frac{\int f_\nu T_\zeta \, \mathrm{d}\nu}{f_\nu^0 \int T_\zeta \, \mathrm{d}\nu} + \epsilon$$

e.g. 2MASS: **Cohen et al. (2003)**; SLOAN: **Eisenstein et al. (2006), Holberg & Bergeron (2006)**

When you observe

$$m = m_{\text{inst}} + a_0 Z_{\text{airmass}} + a_1 X_{color} + k$$



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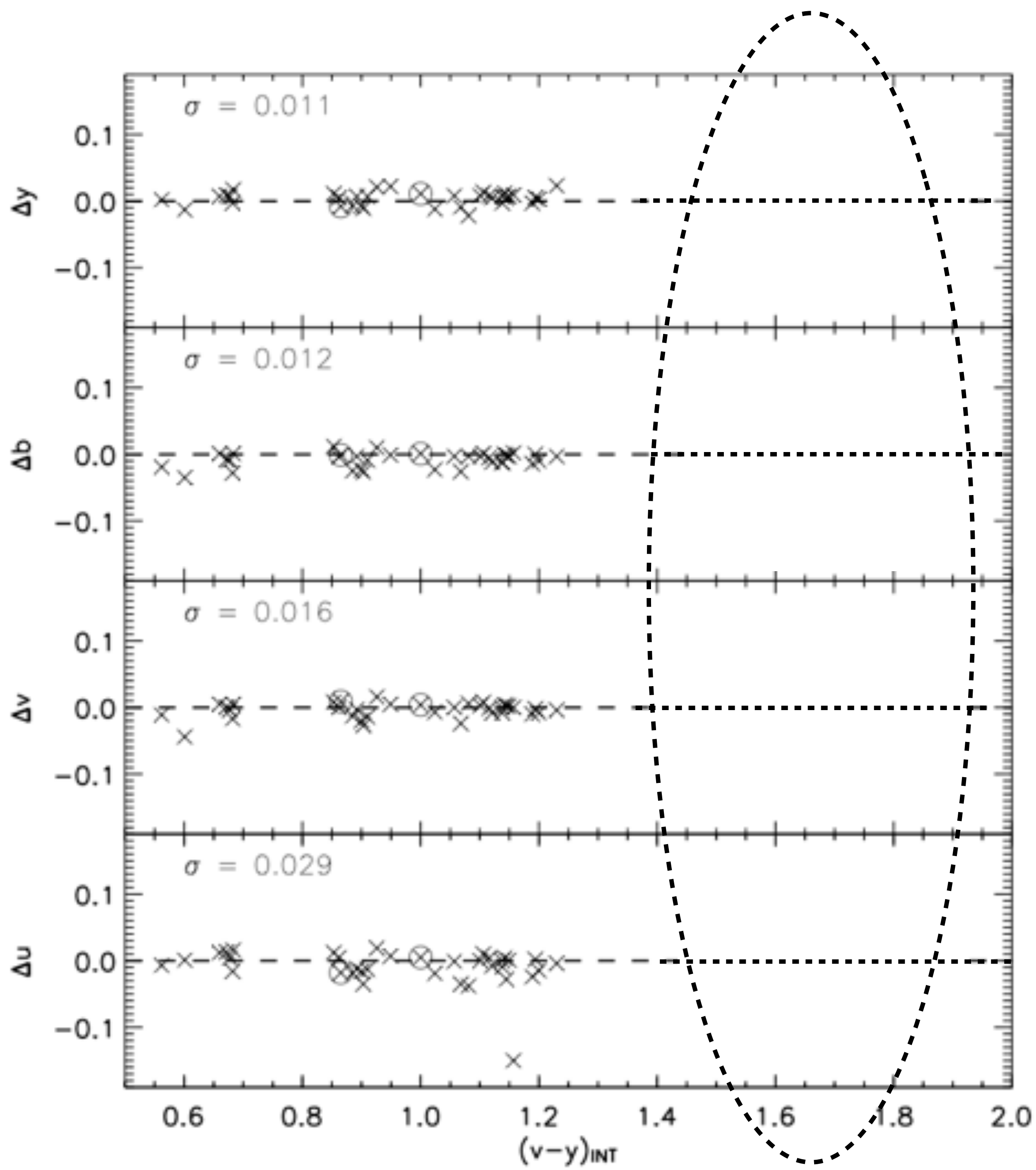

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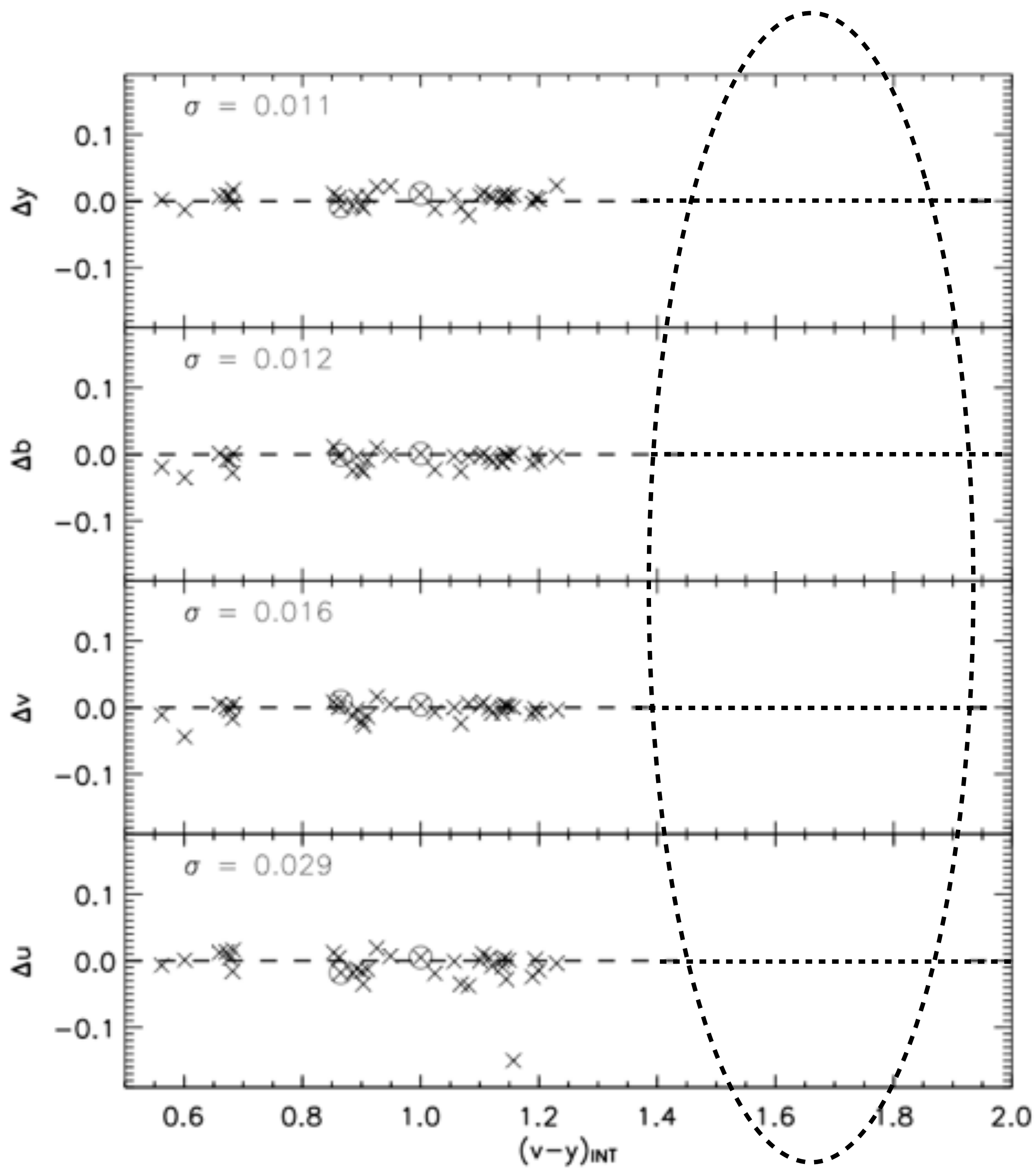

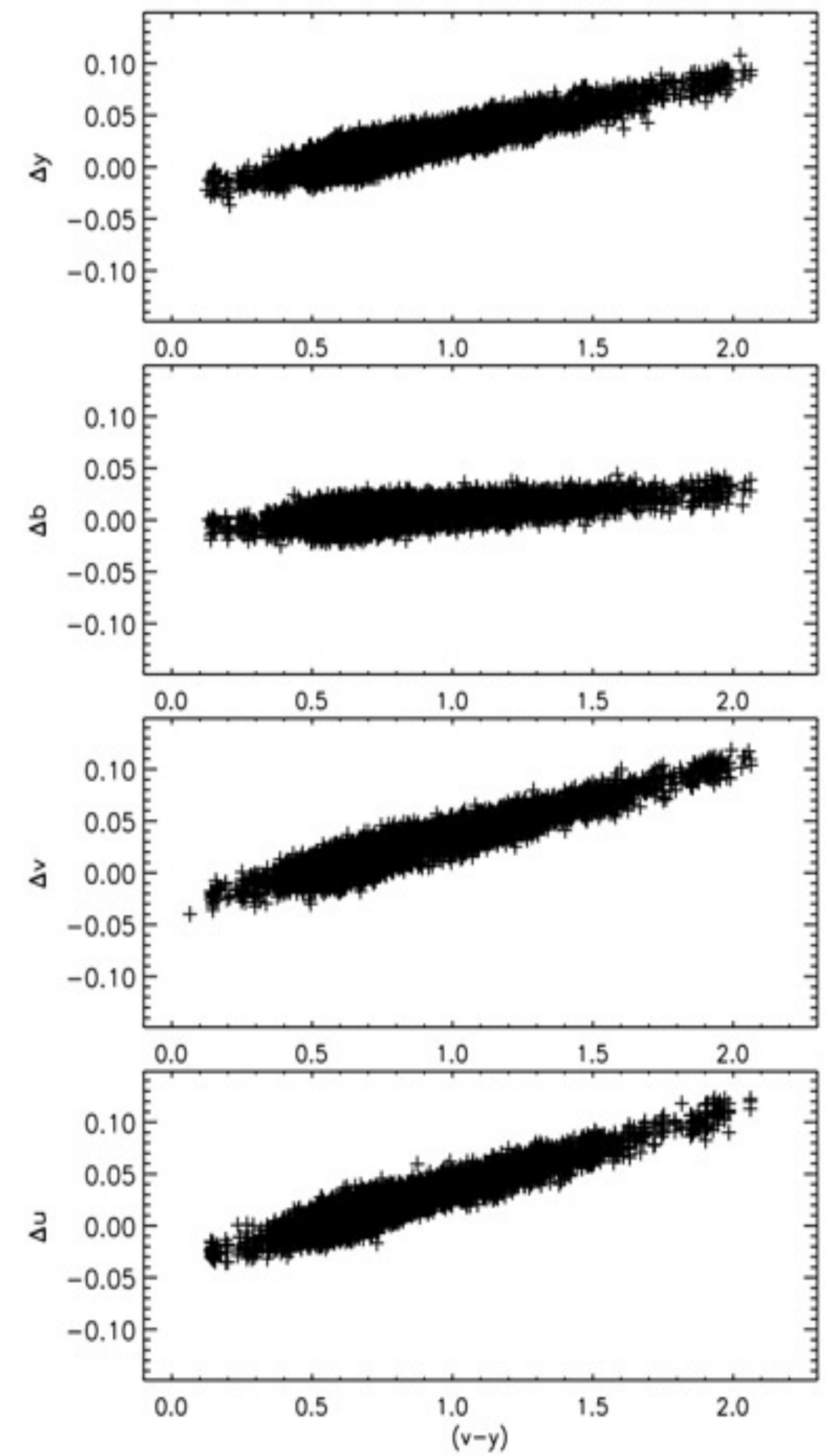

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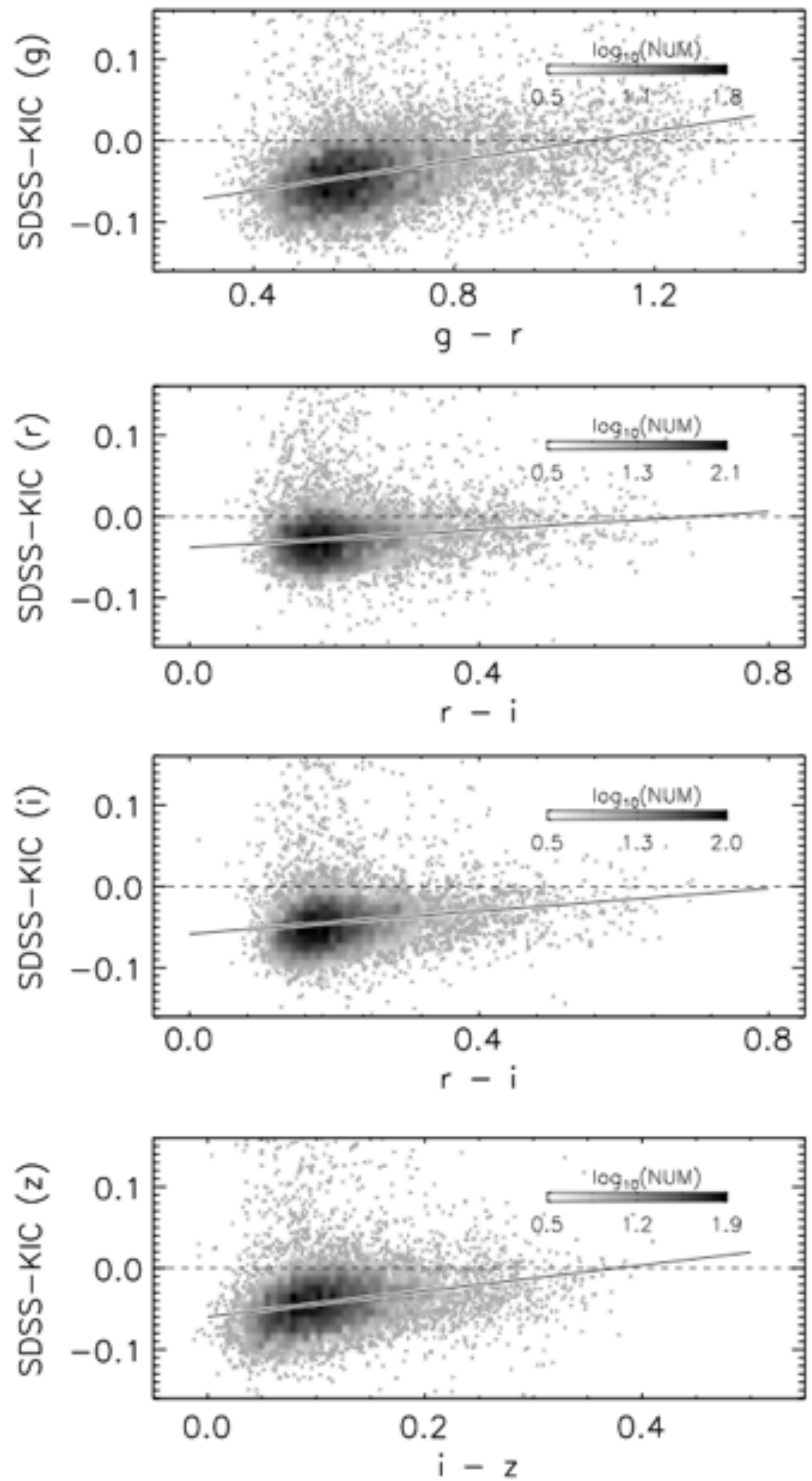
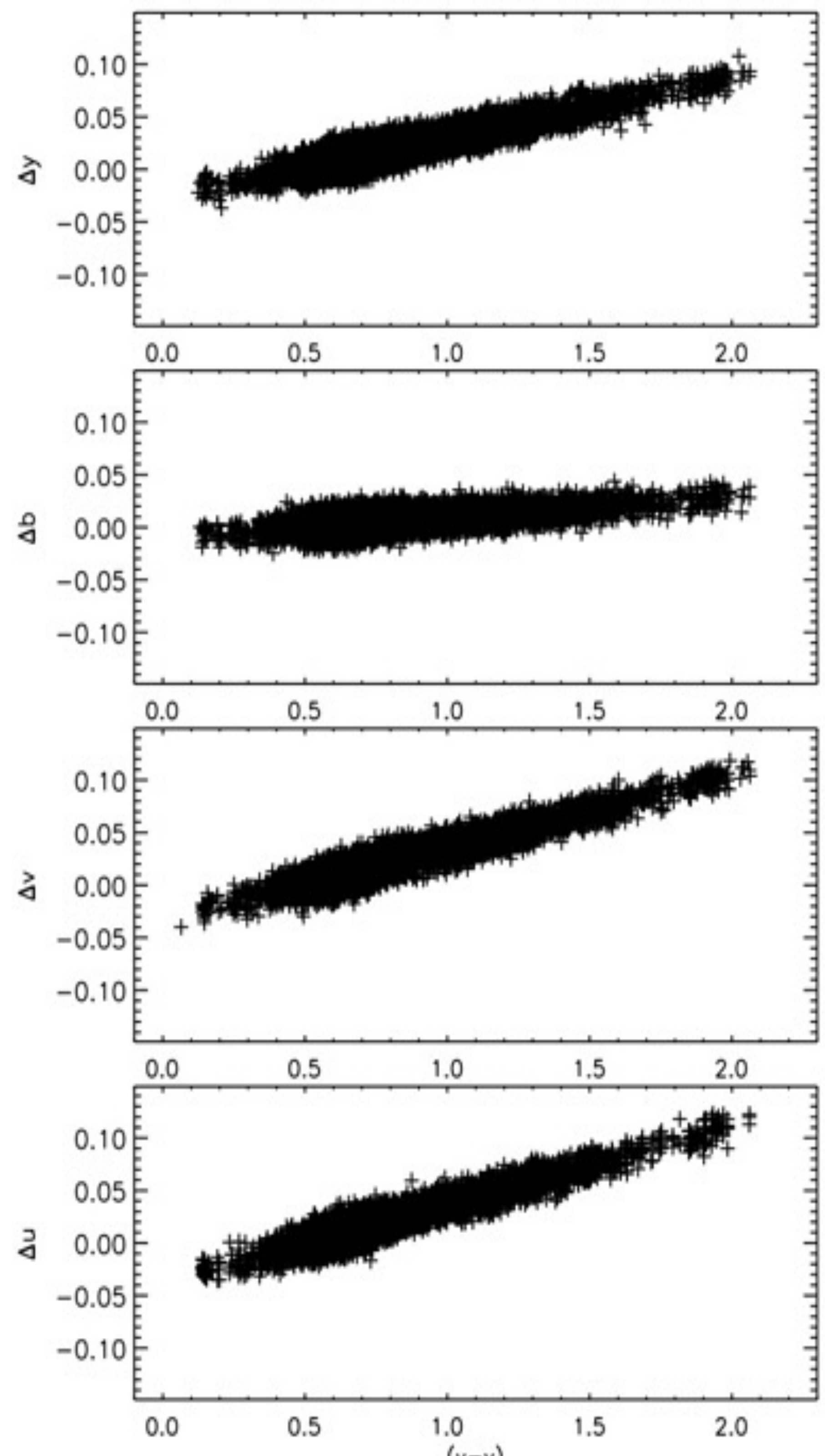
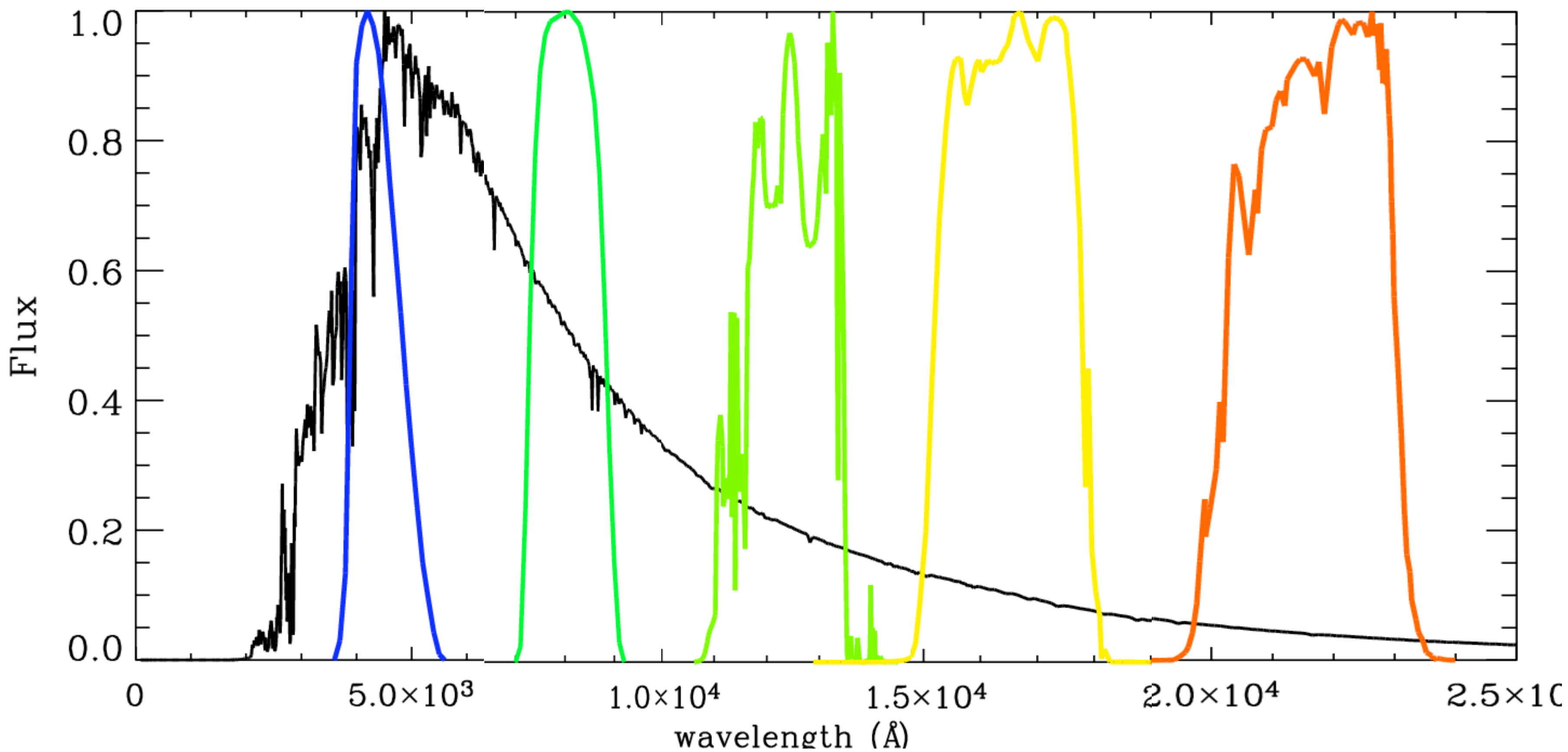


This is likely the reason for the colour trends when *ugriz* photometry from the Kepler Input Catalogue (**Brown et al. 2011**) is compared to properly standardised SLOAN photometry **(Pinsonneault et al. 2012)**



When you use observations

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



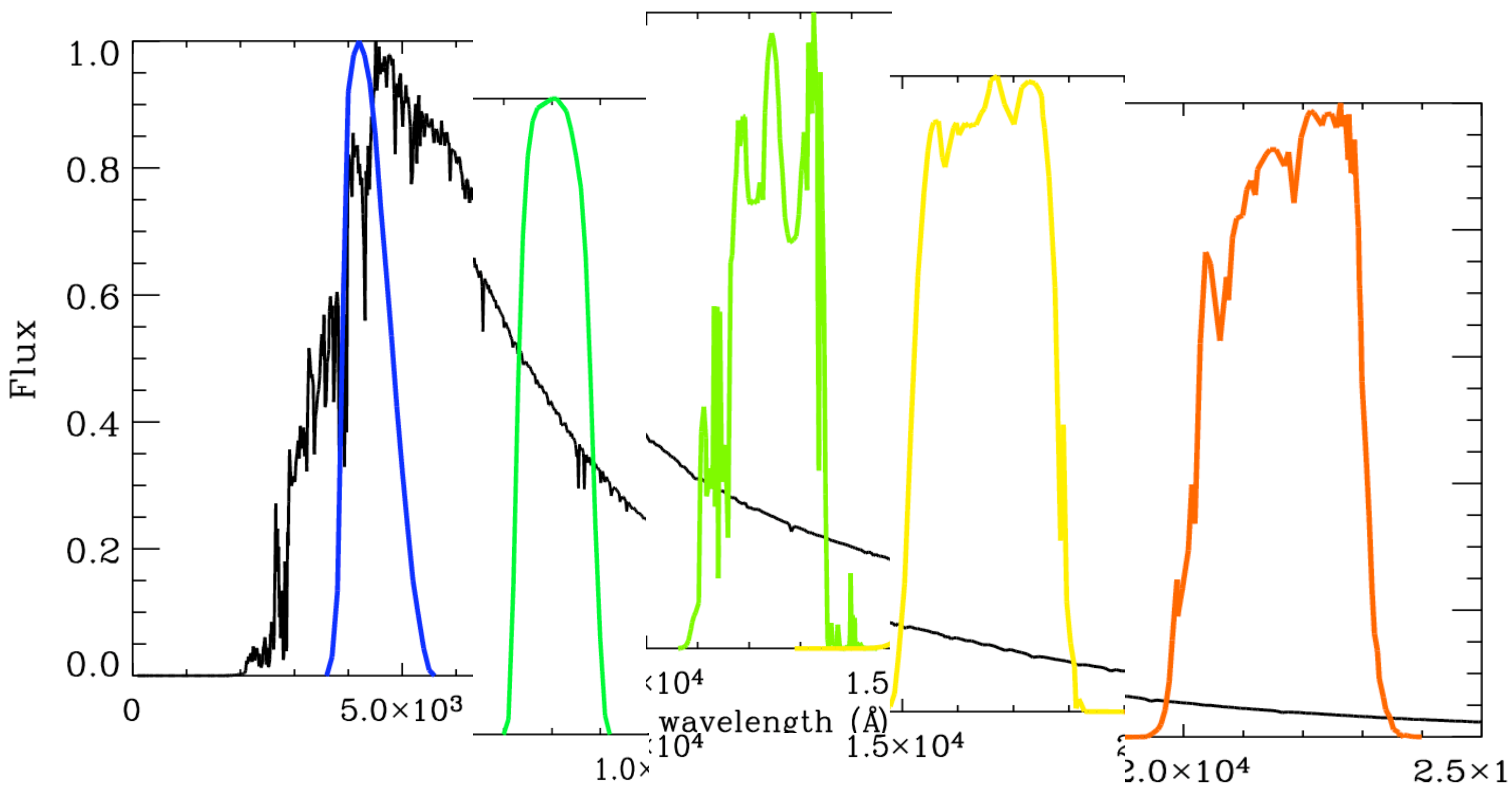
When you use observations

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

≃2 or 3%

≃ 0.01 mag

≃ 4% ≃ 80K



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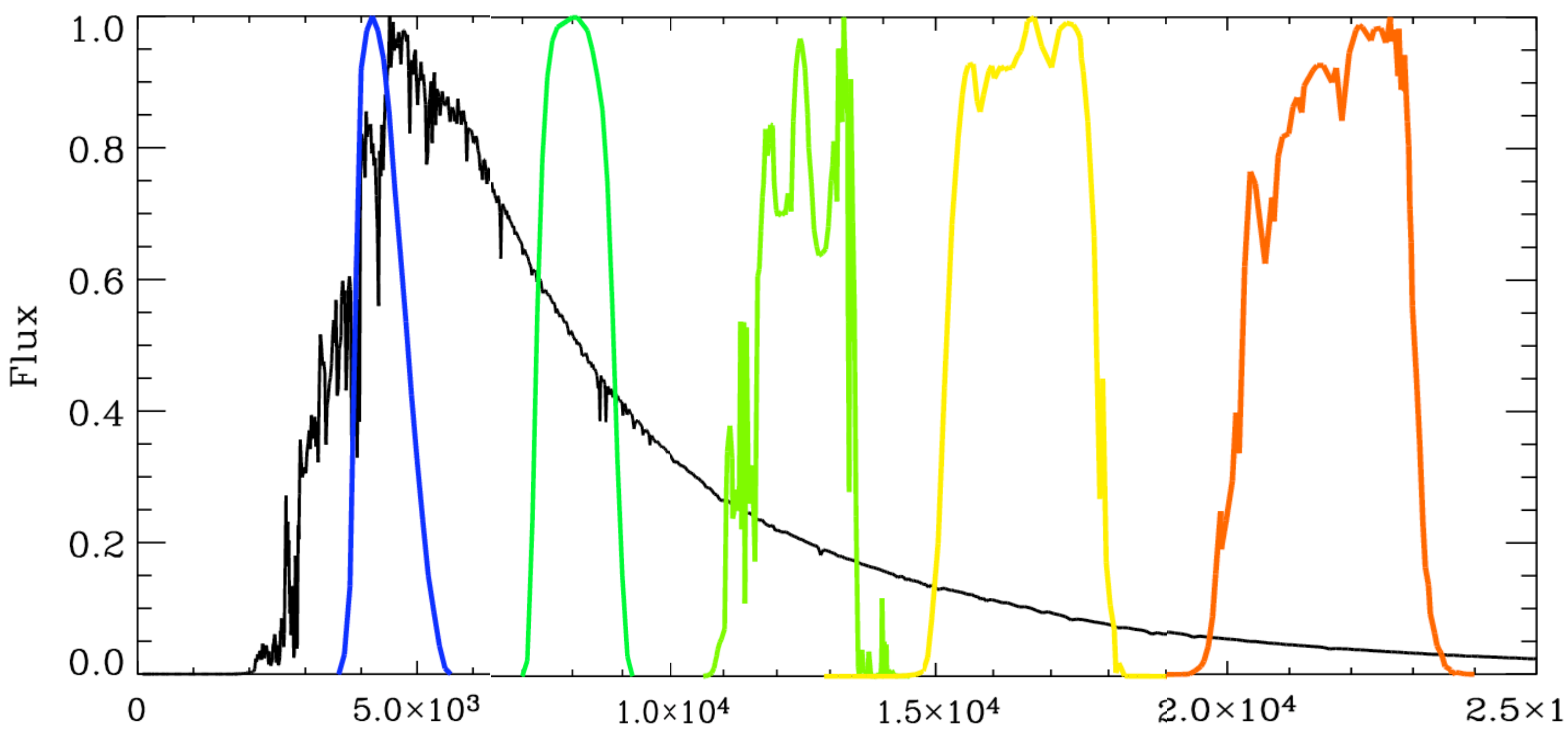
≃ 1% ≃ 20K



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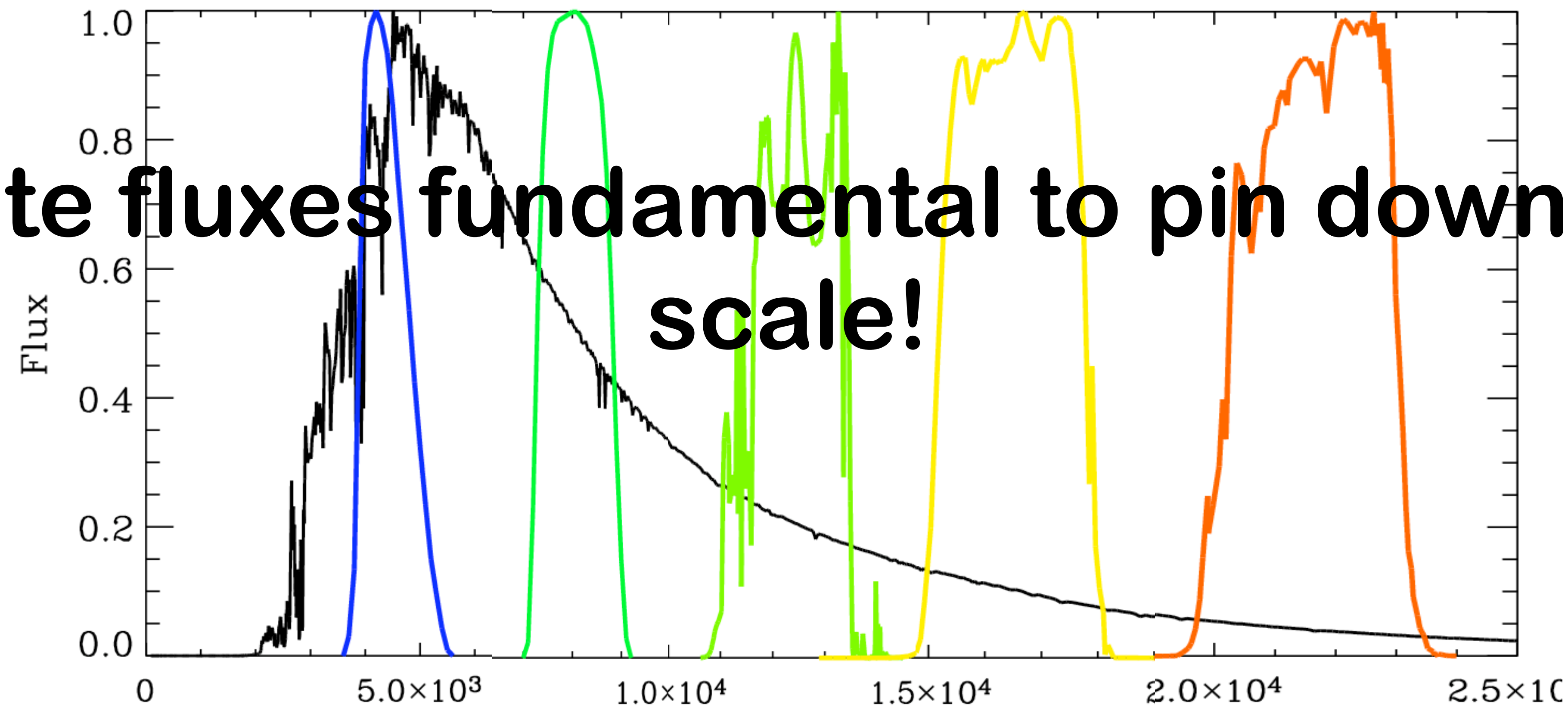
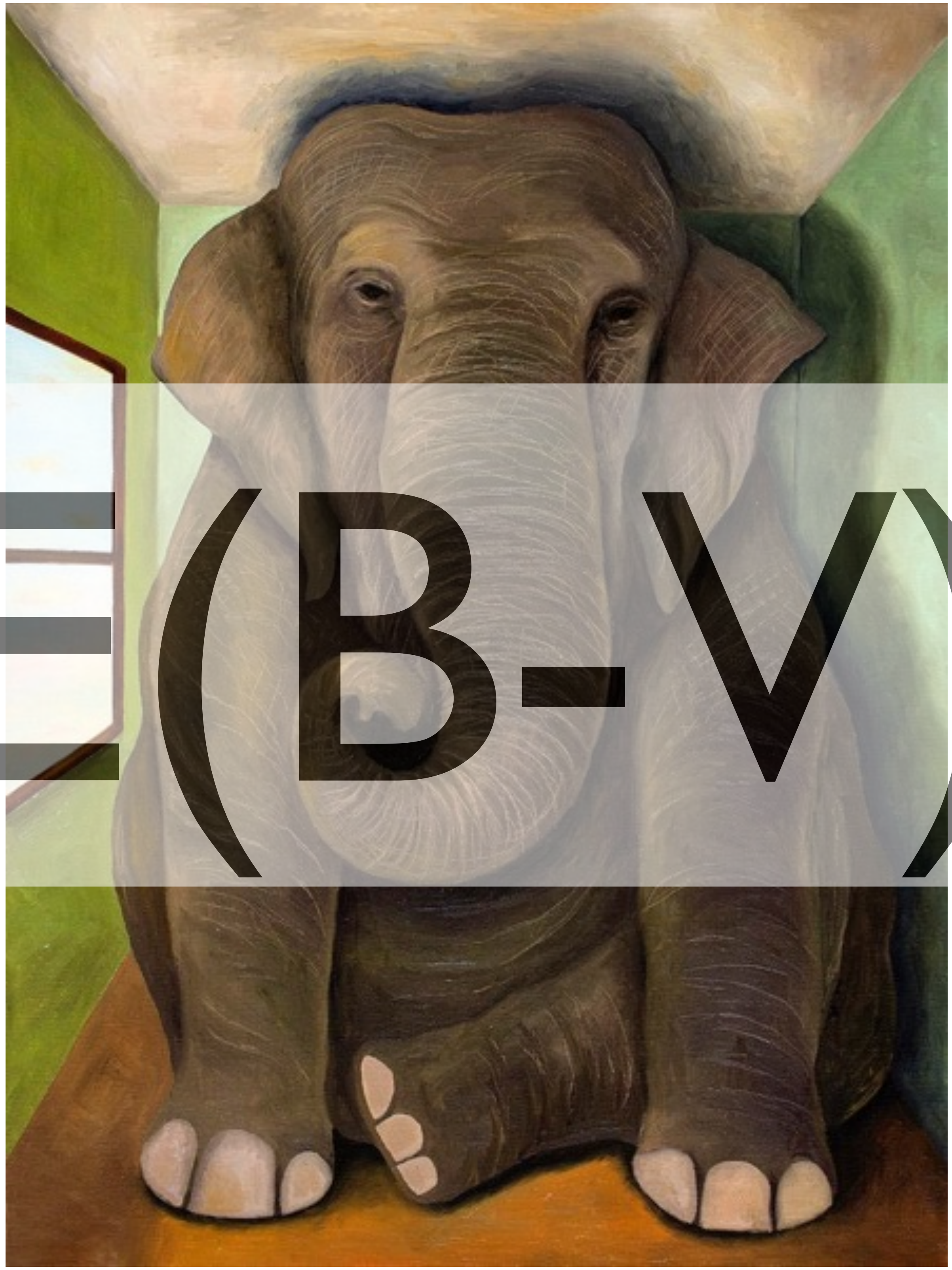
$\simeq 1\% \simeq 20\mathrm{K}$



Absolute fluxes fundamental to pin down the T_{eff} scale!

IRFM: Blackwell et al. (1977, 1979), Alonso et al. (1996, 1999), Gonzalez-Hernandez & Bonifacio (2009), Casagrande et al. (2010)


E(B-V)

More definitions

Heterochromatic measurement

$$\frac{\int f_\lambda T_\zeta \,\mathrm{d}\lambda}{\int T_\zeta \,\mathrm{d}\lambda}$$

→

Effective wavelength

$$\frac{\int \lambda f_\lambda T_\zeta \,\mathrm{d}\lambda}{\int f_\lambda T_\zeta \,\mathrm{d}\lambda}$$

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In presence of reddening

$$A_\lambda = R_V E(B-V)[\ldots\lambda\ldots]$$

(this is the extinction, or attenuation)

More definitions

Heterochromatic measurement

$$\frac{\int f_\lambda T_\varsigma \, \mathrm{d}\lambda}{\int T_\varsigma \, \mathrm{d}\lambda}$$

$\longrightarrow$

Effective wavelength

$$\frac{\int \lambda f_\lambda T_\varsigma \, \mathrm{d}\lambda}{\int f_\lambda T_\varsigma \, \mathrm{d}\lambda}$$

In presence of reddening

$$A_\lambda = R_V E(B-V)[\ldots\lambda\ldots]$$

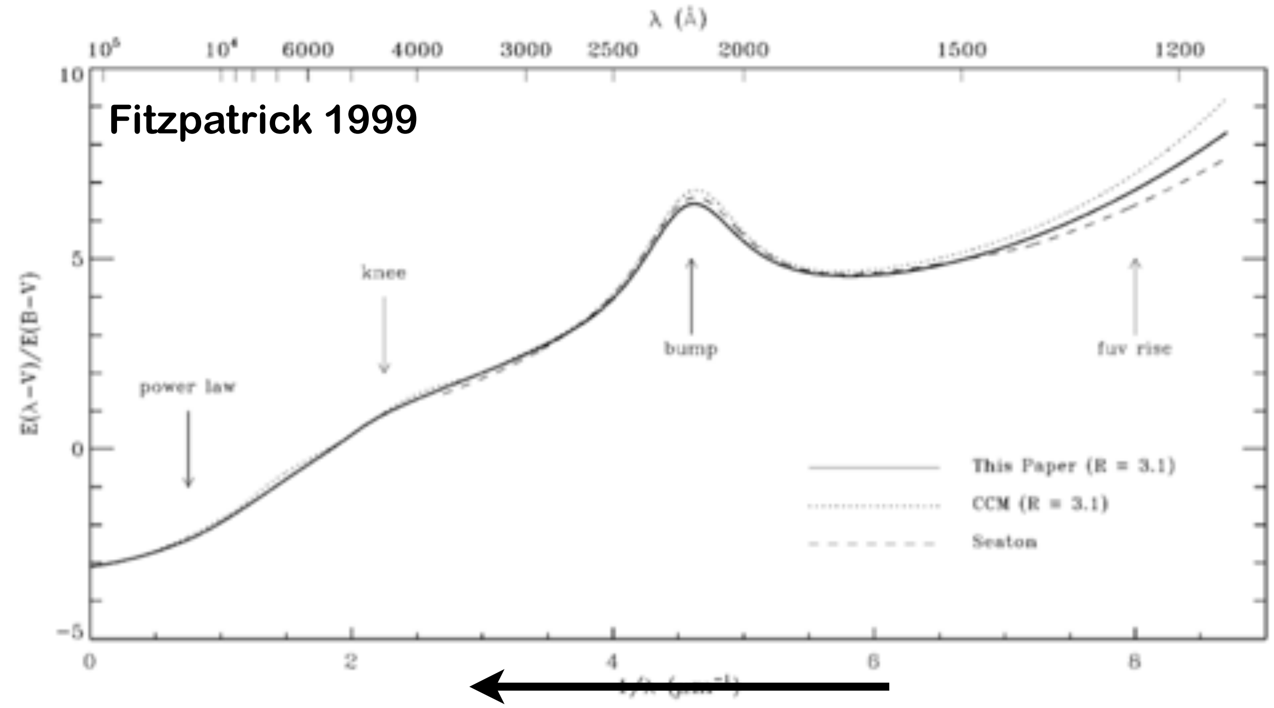
(this is the extinction, or attenuation)

$$f_\lambda \longrightarrow f_\lambda 10^{-0.4 A_\lambda}$$

In presence of extinction, the flux changes, and so does the effective wavelength of a filter

$$A_\lambda = R_V E(B-V)[\ldots\lambda\ldots]$$

derived using early type OB stars (e.g. Cardelli et al. 1989, Fitzpatrick et al. 1999)



decreasing attenuation for increasing λ

$$R_\zeta = \frac{A_\zeta}{E(B-V)} = \frac{A_\zeta}{A_B - A_V}$$

input:

$E(B-V) = 0.6$

$R_V = 3.1$

$$A_\lambda = R_V E(B-V)[\ldots\lambda\ldots]$$

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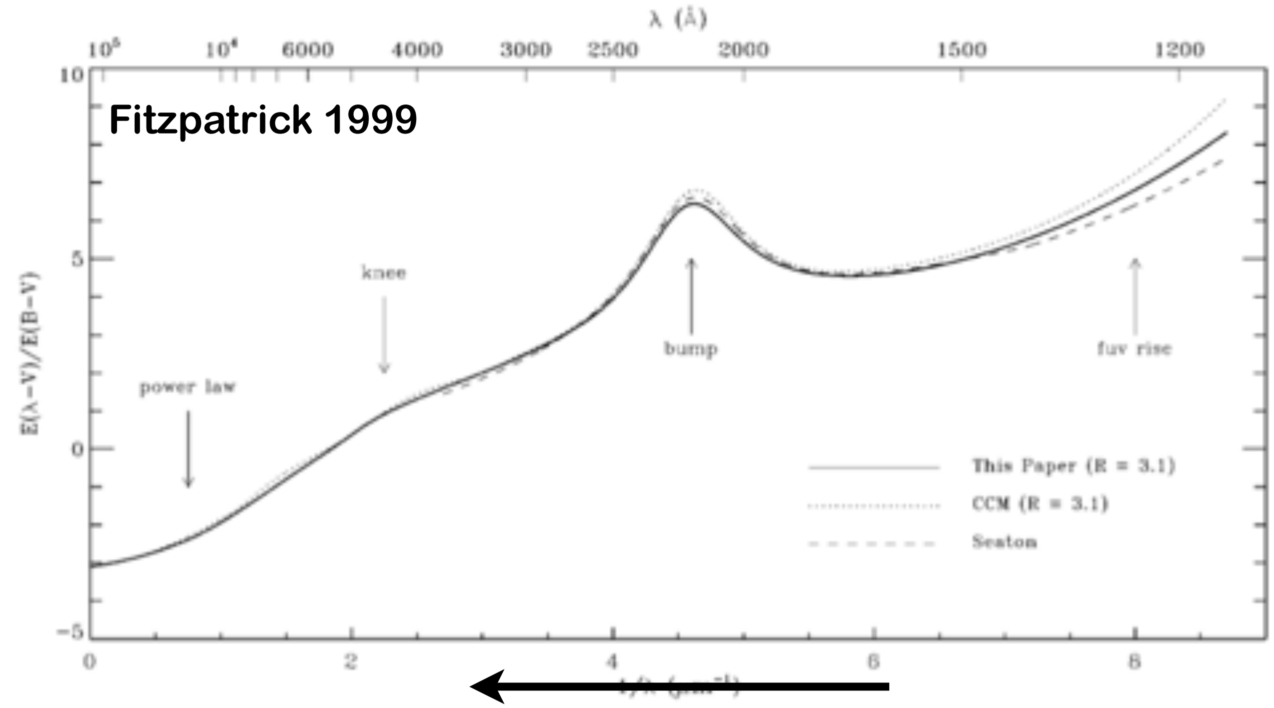

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→

TO star:
T_{eff} ≃ 6000 K
[Fe/H] ≃ -0.8 dex
log(g) ≃ 4.0 dex

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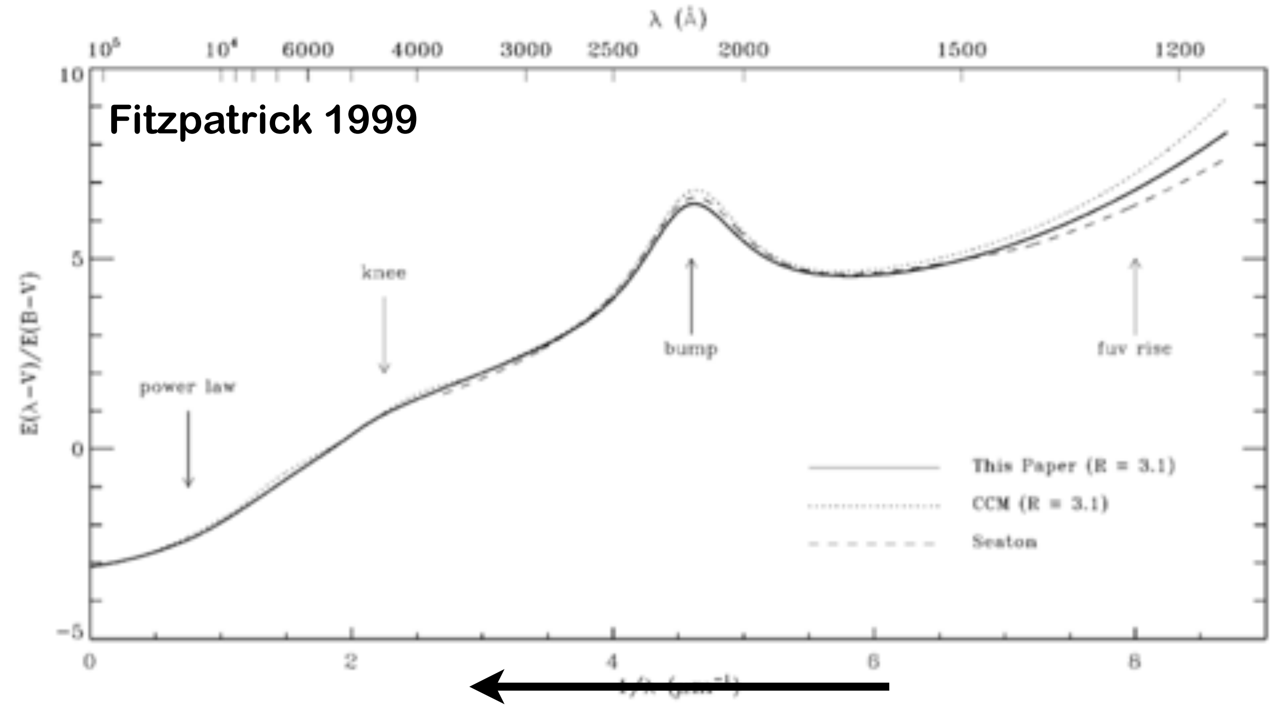

decreasing attenuation for increasing λ

$$R_\zeta = \frac{A_\zeta}{E(B-V)} = \frac{A_\zeta}{A_B - A_V}$$

E(B-V)=0.55

R_B=4.40

R_V=3.40

R_B-R_V = 1

$m_{V,0}$=$m_{V,0}$-3.40 x 0.55

input:
E(B-V) = 0.6
R_V = 3.1

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T_{eff} ≃ 6000 K
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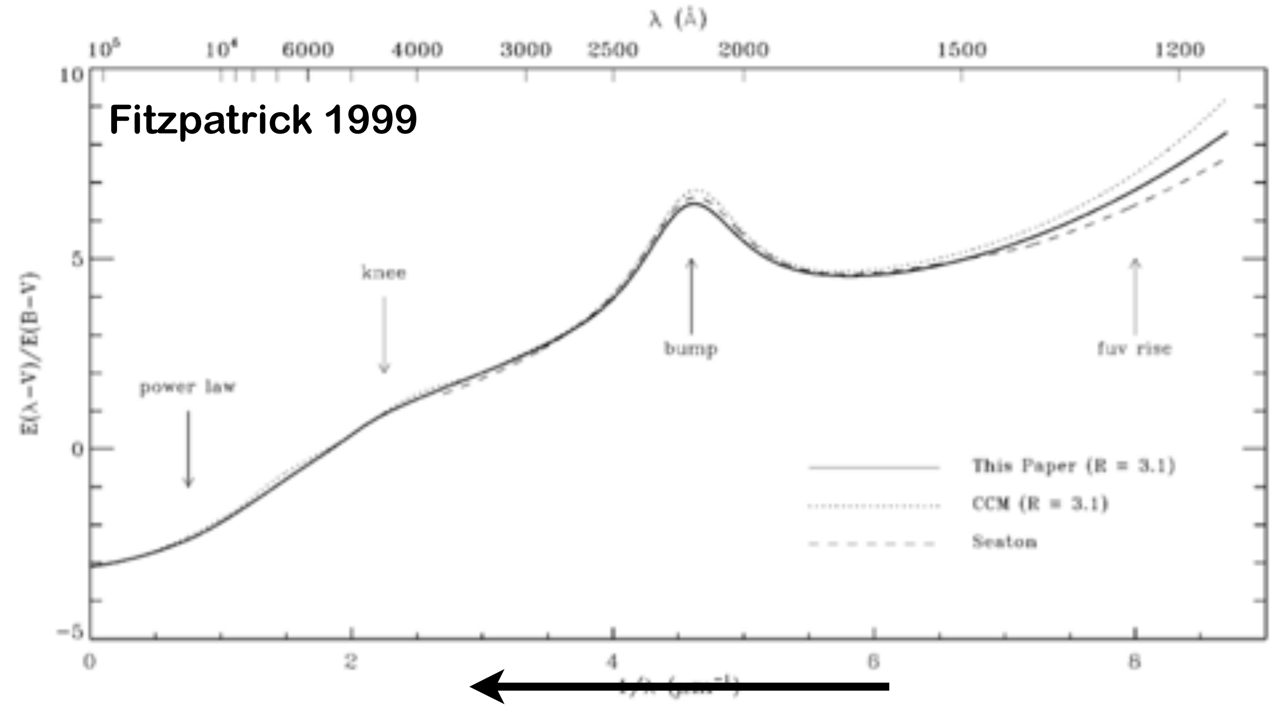

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R_V = 3.1

TO star:
$T_{eff} \simeq 6000$ K
[Fe/H] ≃ -0.8 dex
log(g) ≃ 4.0 dex

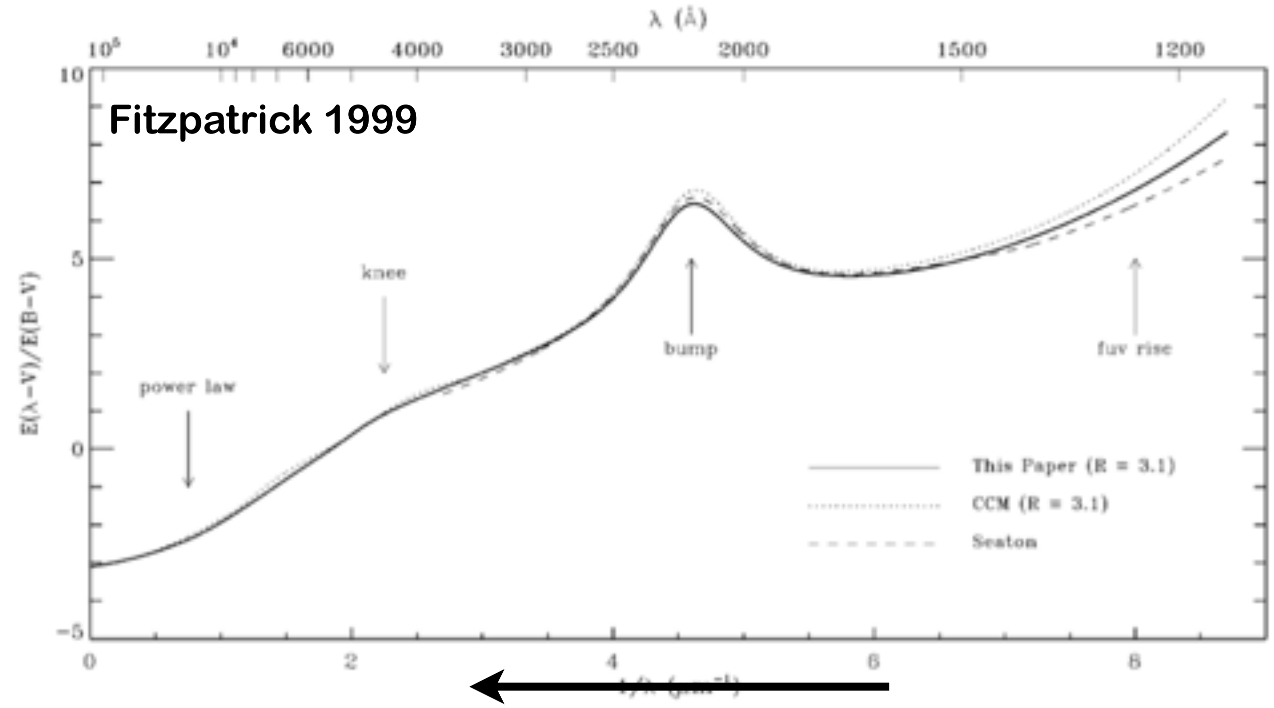
E(B-V)=0.55
R_B=4.40
R_V=3.40
R_B-R_V = 1
$m_{V,0}=m_{V,0}-3.40 \times 0.55$

E(B-V)=0.60
R_B=4.02
R_V=3.10
R_B-R_V = 0.92
thus **0.60 x 0.92 = 0.55**
$m_{V,0}=m_{V,0}-3.10 \times 0.60$

Both approaches are correct, as long as things are done self-consistently

$$A_\lambda = R_V E(B-V)[\ldots\lambda\ldots]$$

derived using early type OB stars (e.g. Cardelli et al. 1989, Fitzpatrick et al. 1999)



decreasing attenuation for increasing λ

$$R_\zeta = \frac{A_\zeta}{E(B-V)} = \frac{A_\zeta}{A_B - A_V}$$

input:
E(B-V) = 0.6
R_V = 3.1

→

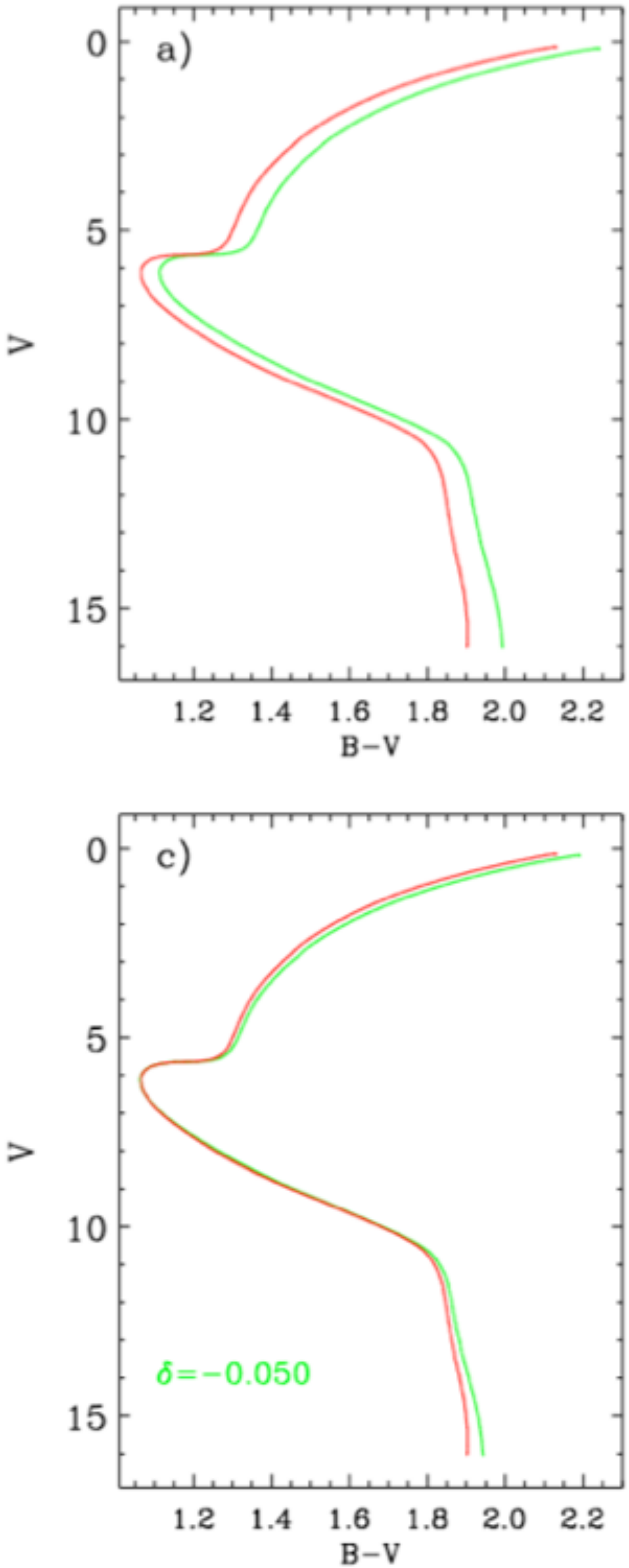
TO star:
$T_{eff} \simeq$ 6000 K
[Fe/H] ≃ -0.8 dex
log(g) ≃ 4.0 dex

E(B-V)=0.55
R_B=4.40
R_V=3.40
R_B-R_V = 1
$m_{V,0}$=$m_{V,0}$-3.40 x 0.55

E(B-V)=0.60
R_B=4.02
R_V=3.10
R_B-R_V = 0.92
thus **0.60 x 0.92 = 0.55**
$m_{V,0}$=$m_{V,0}$-3.10 x 0.60

Both approaches are correct, as long as things are done self-consistently

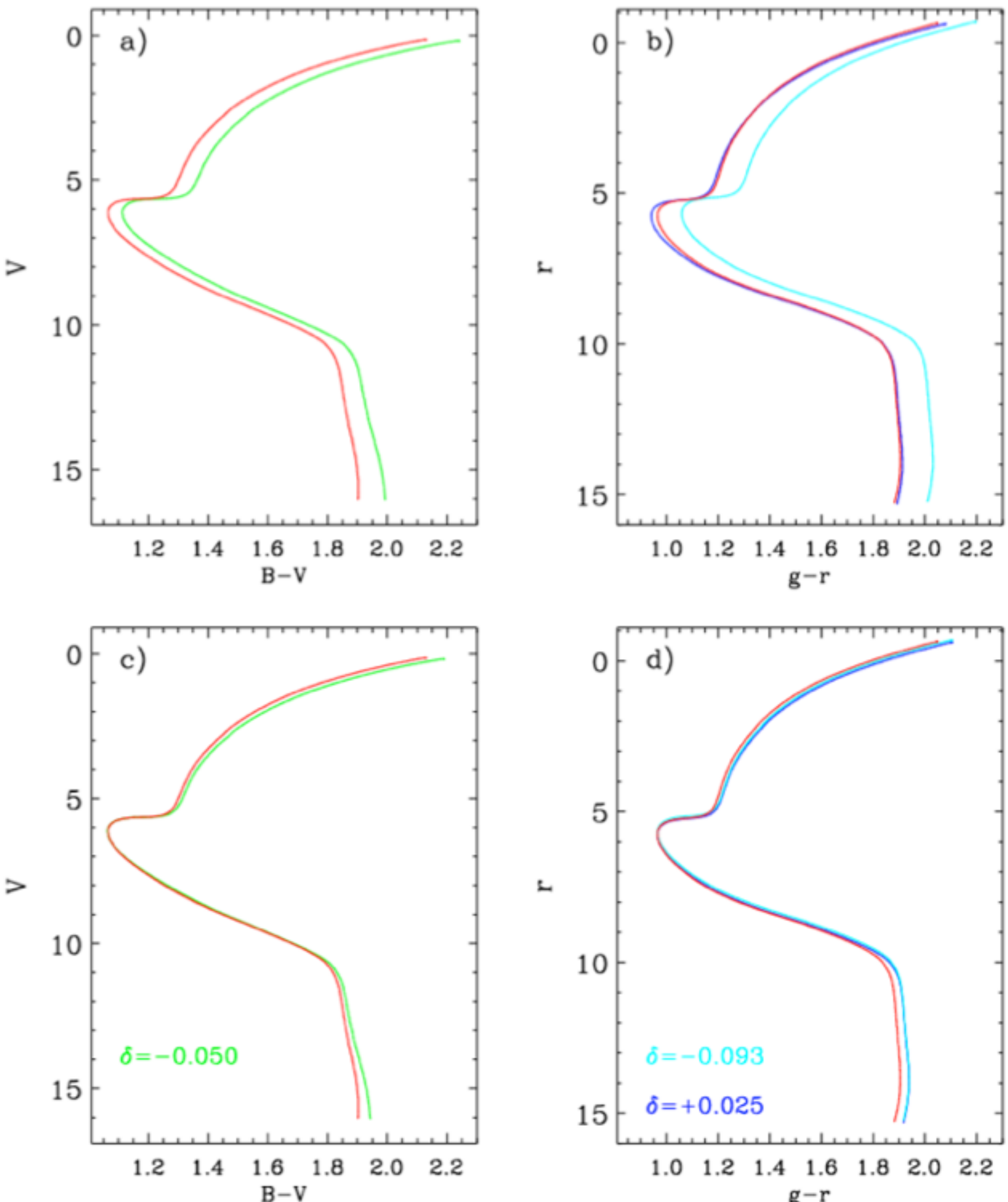
BE CAREFUL: changes in extinction coefficients (e.g. R_V) might stem either from shifts in effective wavelength, or changes in the nature of the dust (see e.g. excellent discussion in McCall 2004) !!!



Self-consistent E(B-V)=0.6, R_V=3.1

Using E(B-V)=0.6 and R_V=3.1

Casagrande & VandenBerg (2014)



Self-consistent E(B-V)=0.6, Rv=3.1

Using E(B-V)=0.6 and Rv=3.1

Using E(B-V)=0.6 with An et al (2009) coefficients

Using E(B-V)=0.6 with McCall (2004) coefficients

all these coefficients are correct for the spectral types they have been derived for! They cannot be applied at their face value to every stars (unfortunately this is often done)

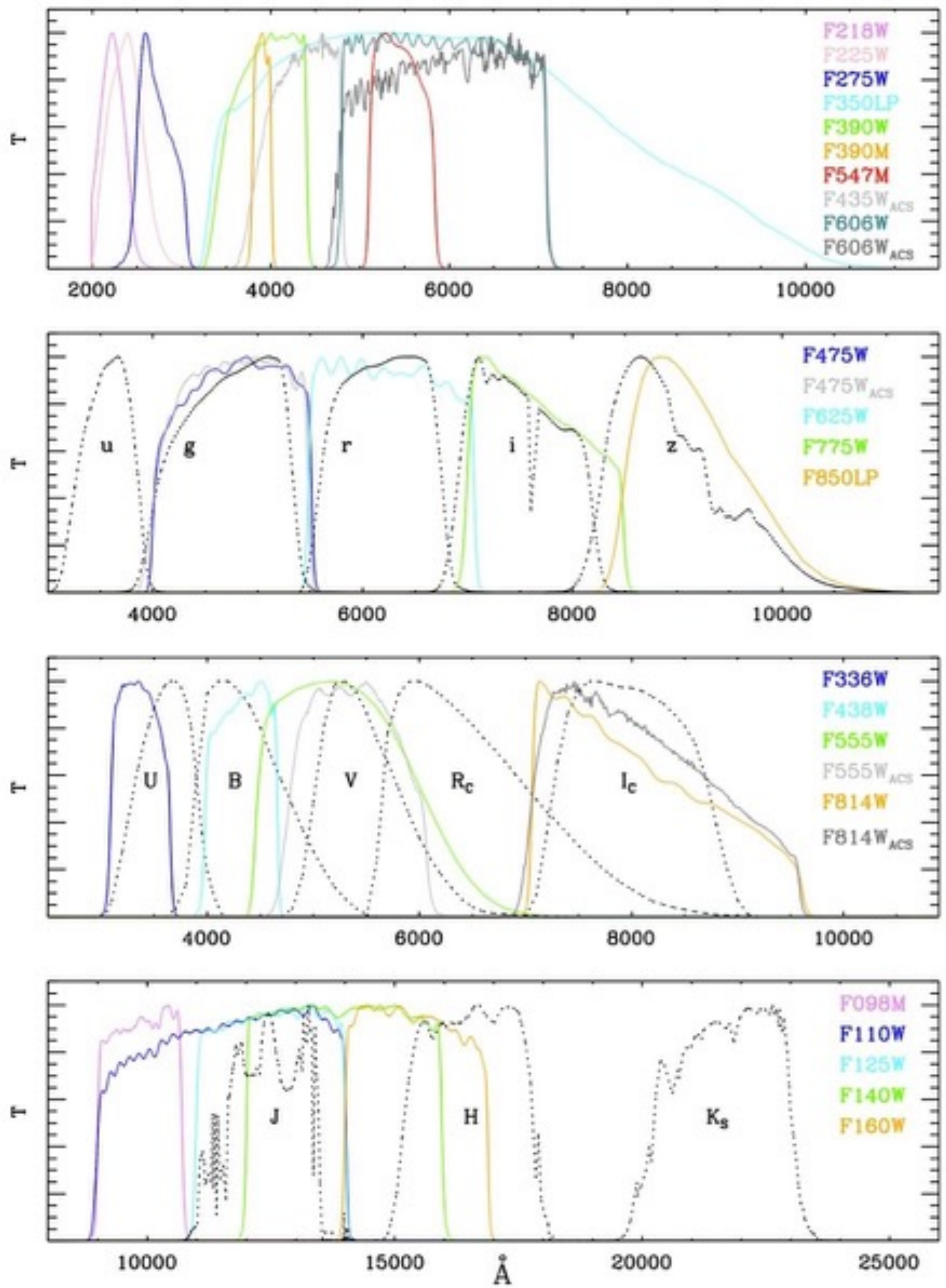
Casagrande & VandenBerg (2014)

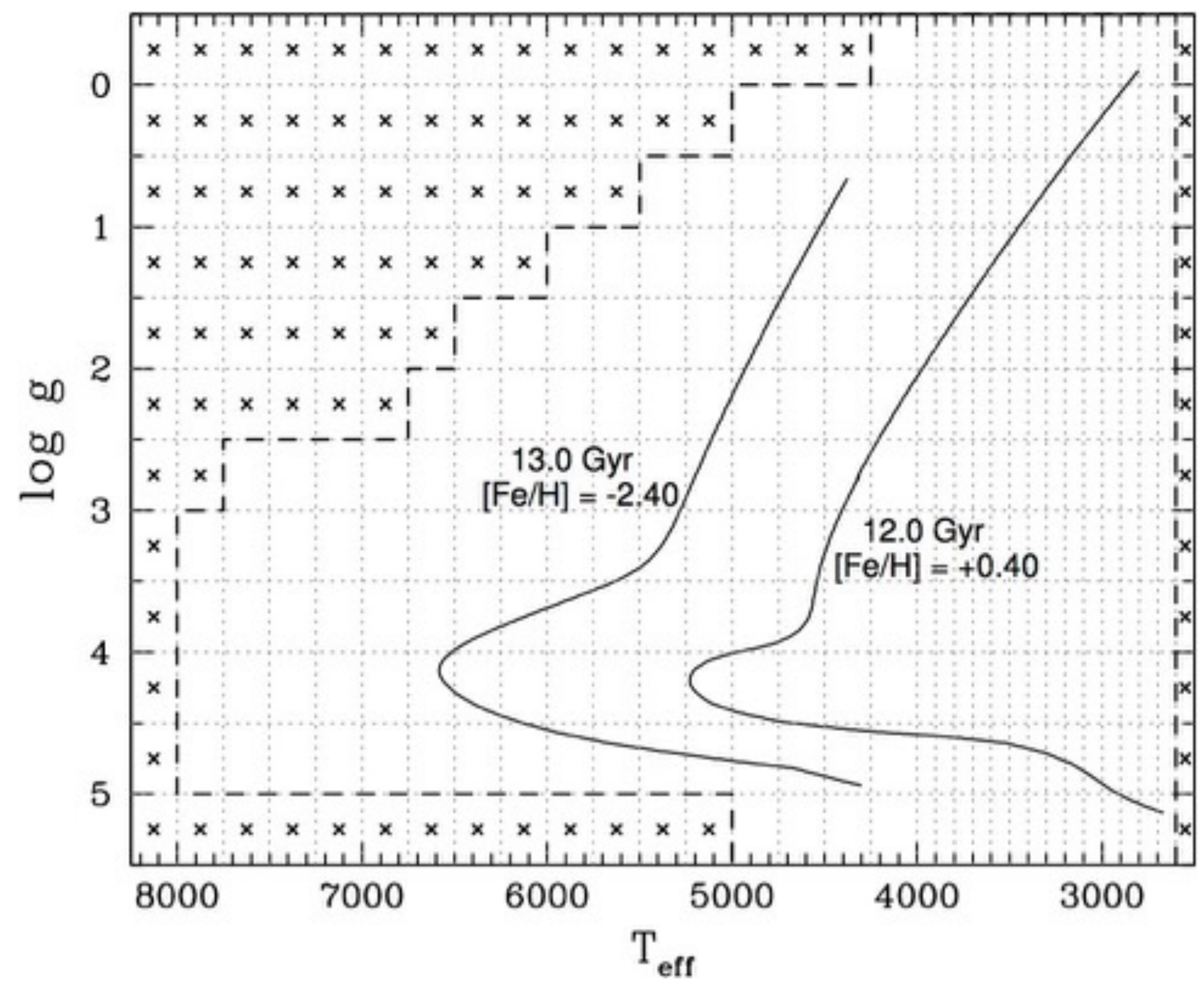
Where everything comes (wrongly) together!

Reddening must (and can!) be properly treated. Many (most of the) times, what happens is instead:

- assume a reddening law derived from early-type stars (CCM89, F99, etc ..)
- with reddening coefficients derived for yet some other spectral type
- using reddening values derived from background galaxies (Schlegel et al. 1998) to study late-type stars

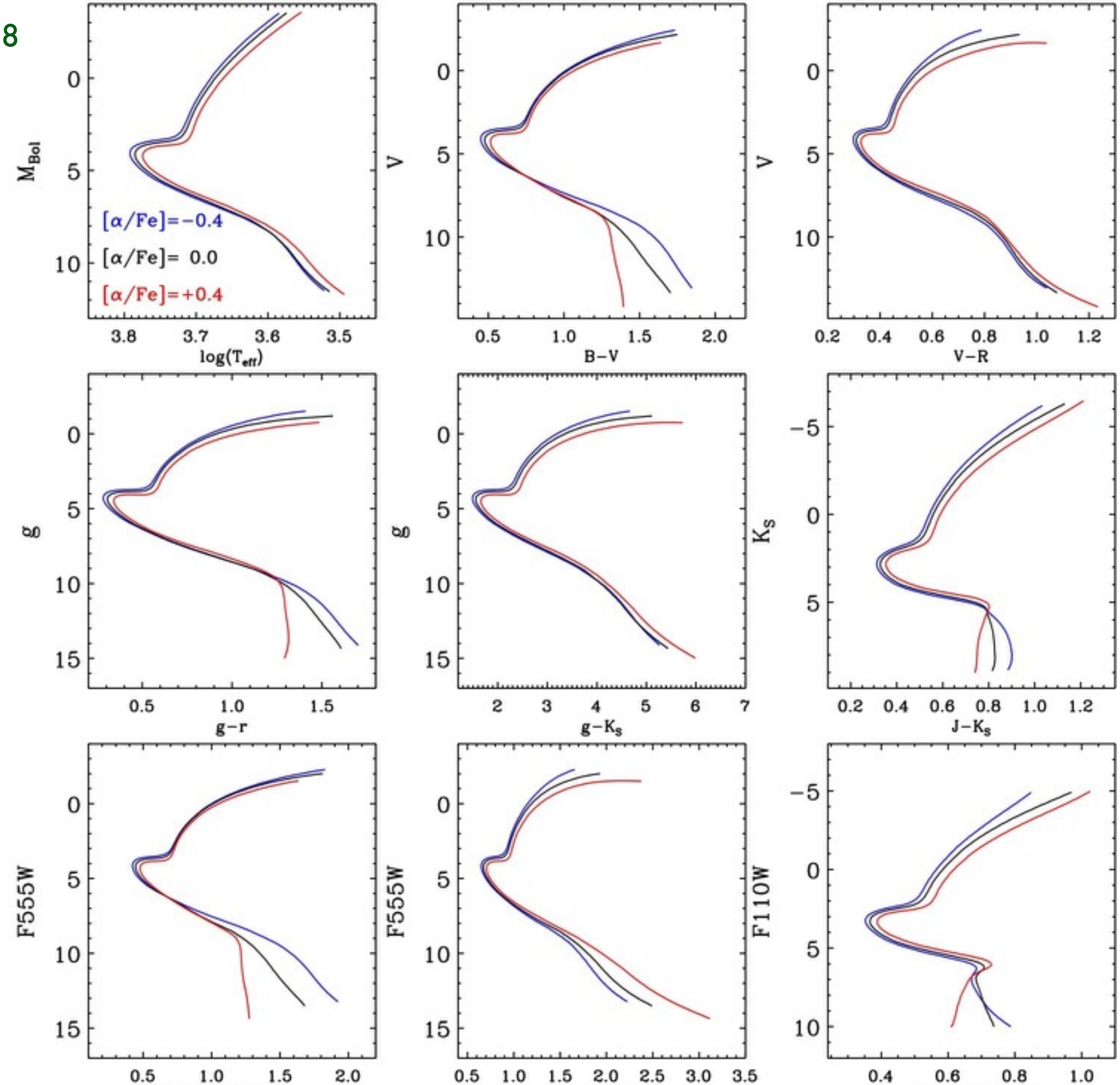
Self-consistent synthetic photometry (BC) + reddening





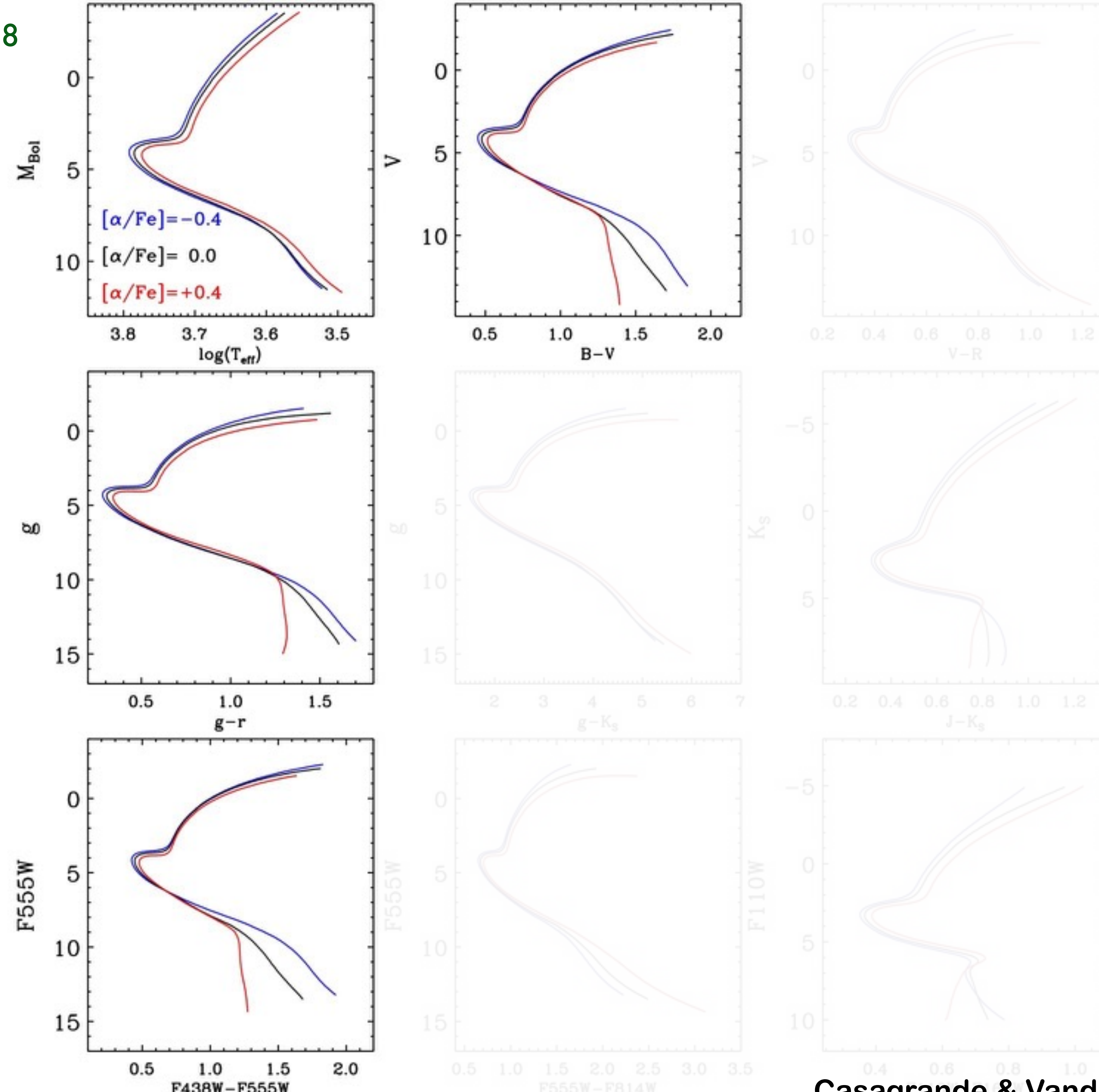
Casagrande & VandenBerg (2014)
Vizier/CDS at J/MNRAS/444/392

[Fe/H]= -0.8



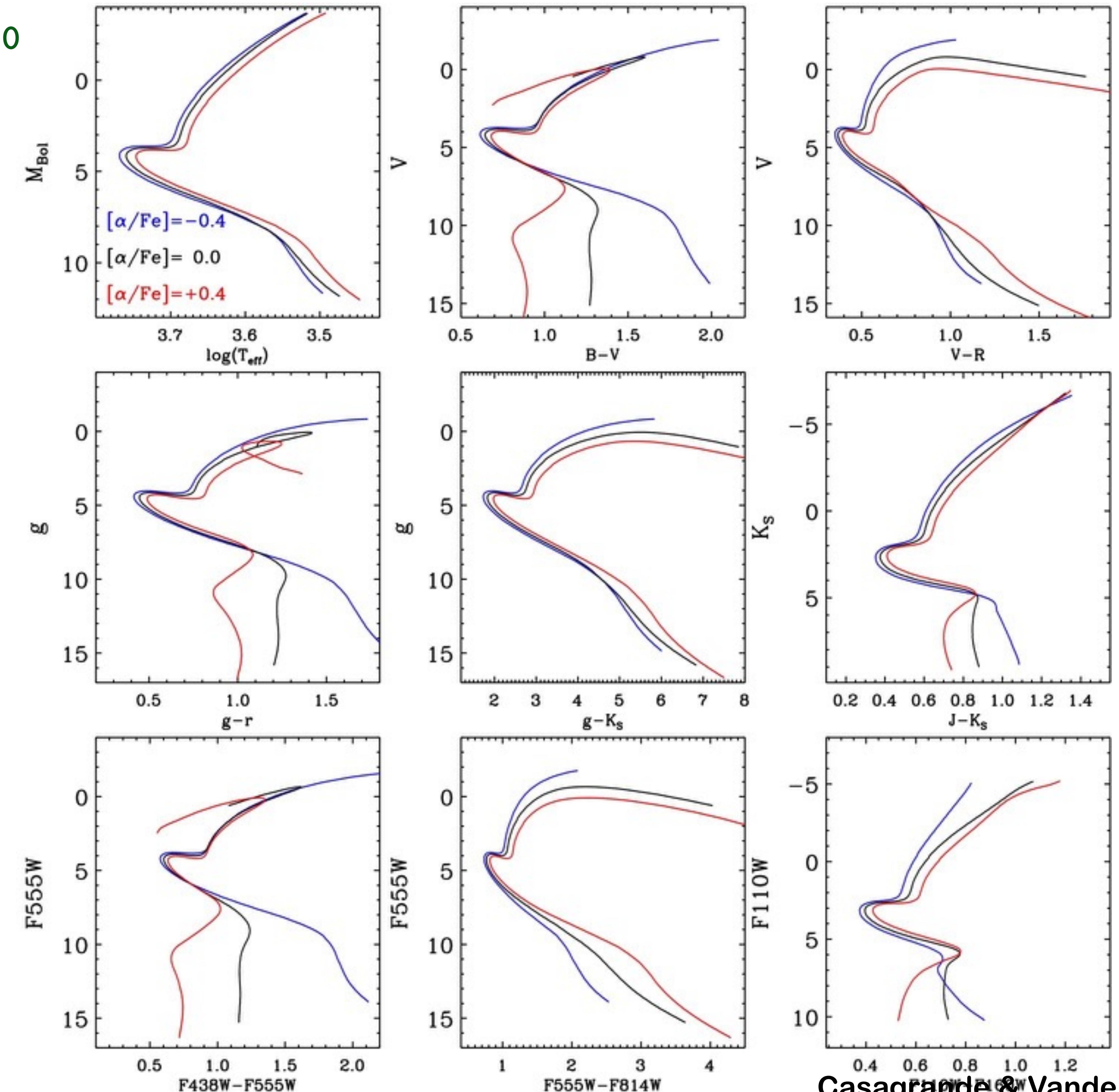
Casagrande & VandenBerg (2014)

[Fe/H]= -0.8



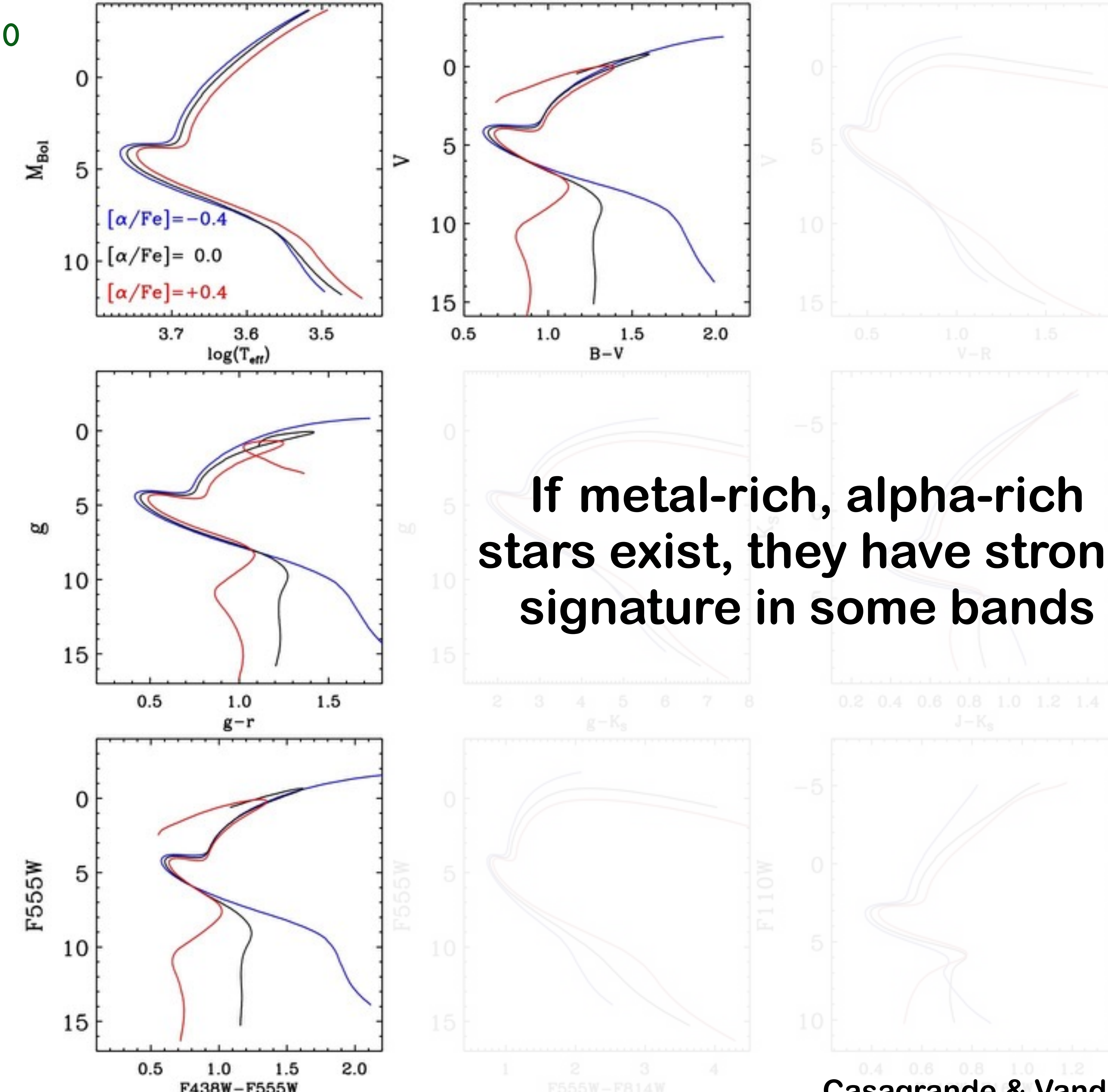
Casagrande & VandenBerg (2014)

[Fe/H]=0.0



Casagrande & VandenBerg (2014)

[Fe/H]=0.0

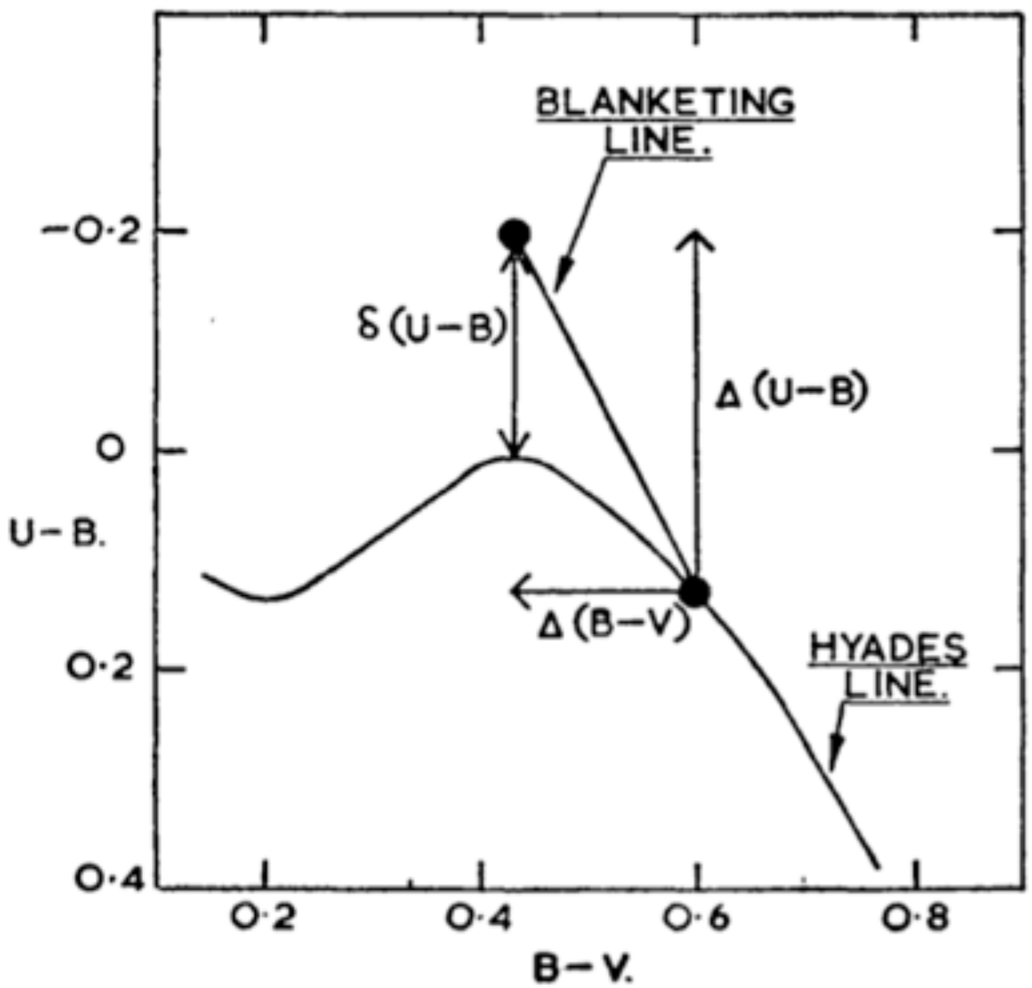


If metal-rich, alpha-rich stars exist, they have strong signature in some bands

Casagrande & VandenBerg (2014)

Photometric metallicities Known from the '60

Sandage & Eggen (1959)



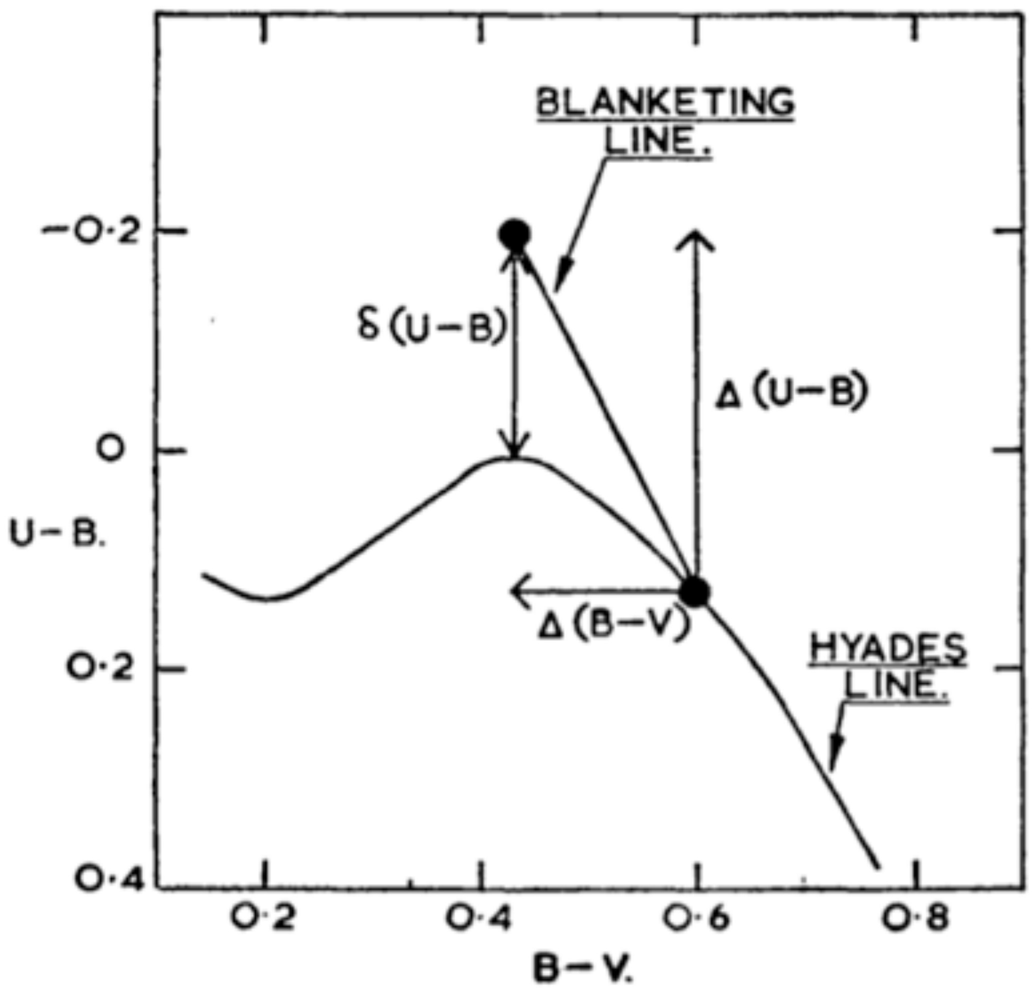
Calibrate a consistent/homogeneous photometric dataset

vs

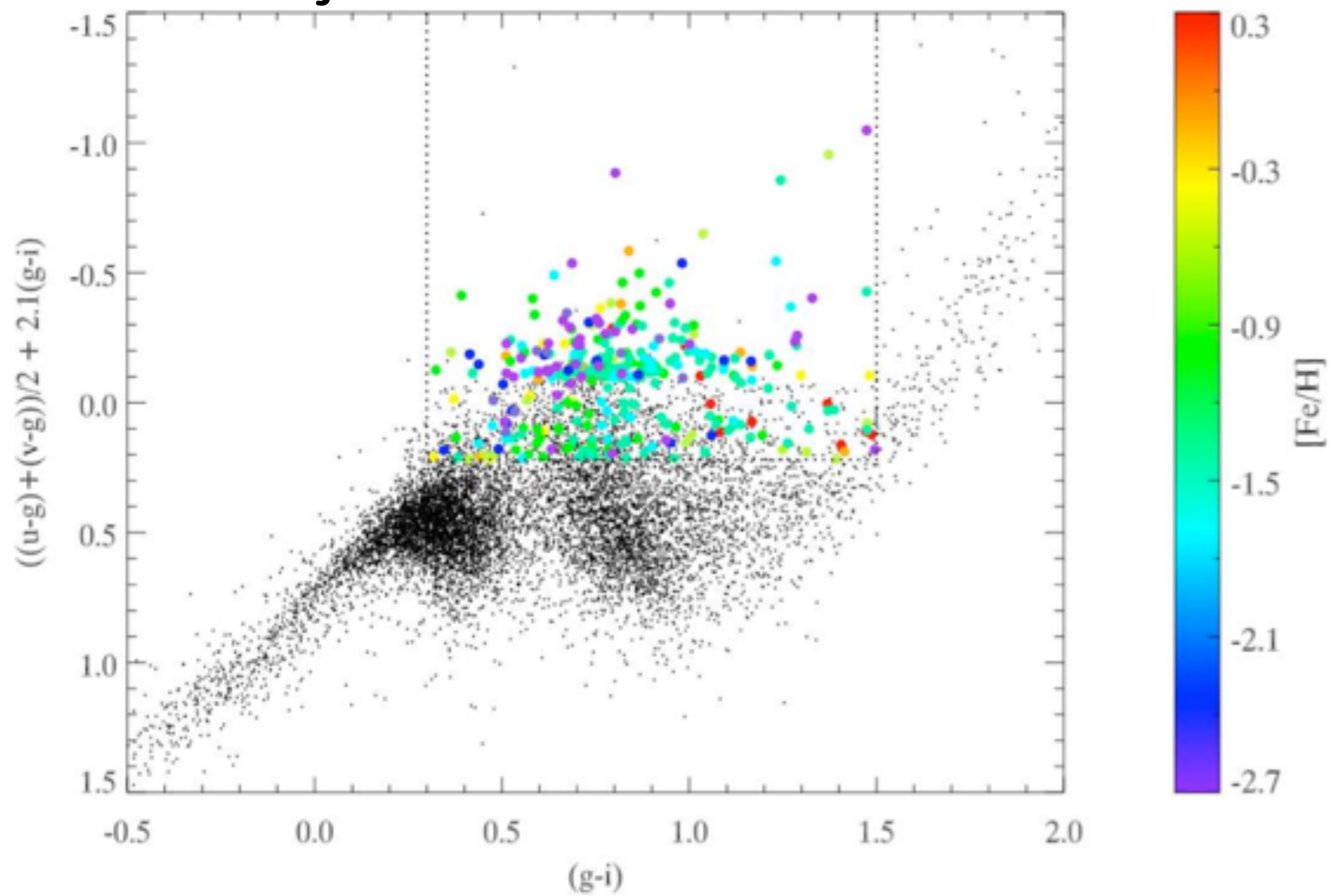
a consistent/homogeneous set of metallicities

Photometric metallicities Known from the '60

Sandage & Eggen (1959)



Courtesy of S. Keller

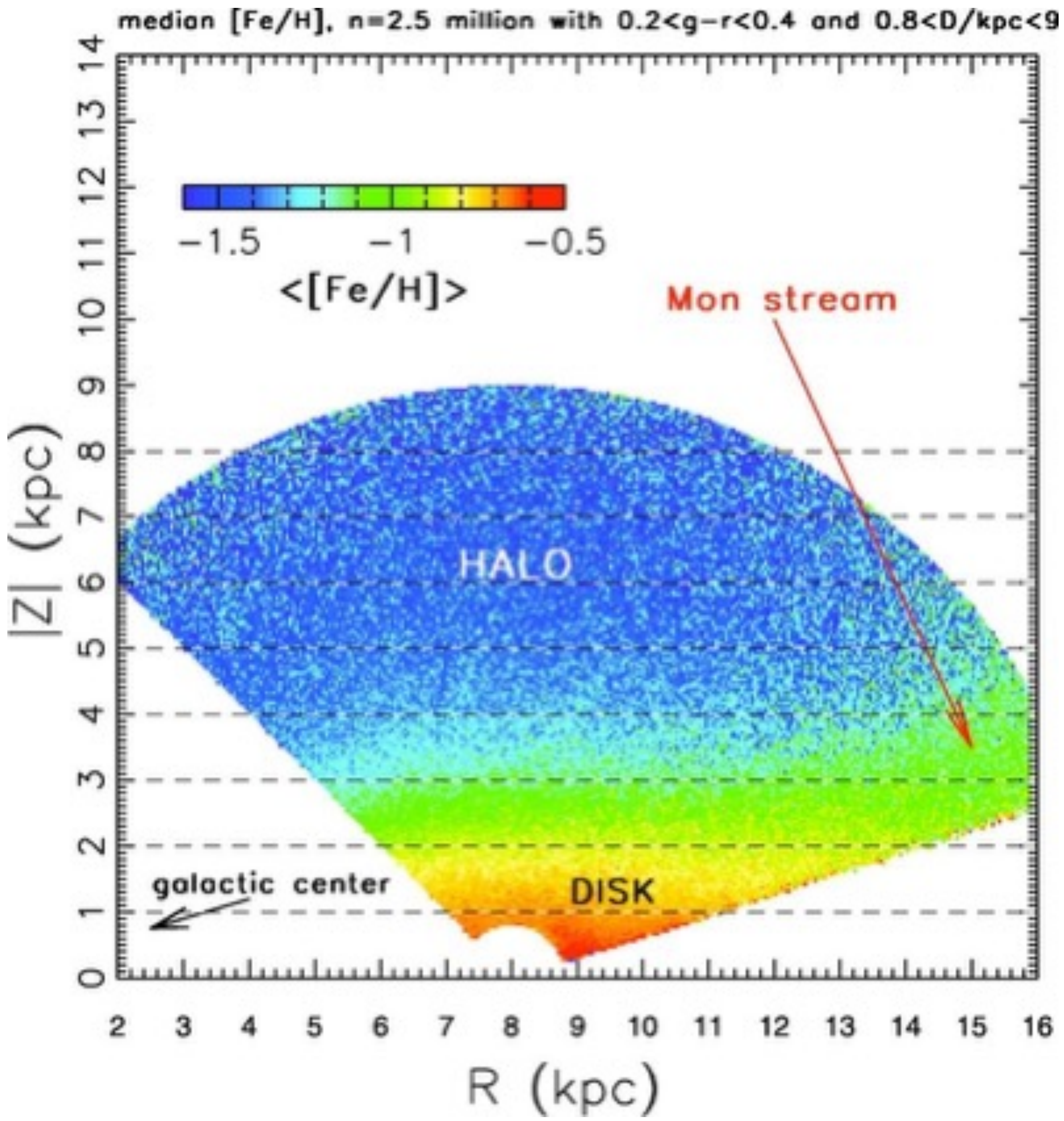


Calibrate a consistent/homogeneous photometric dataset

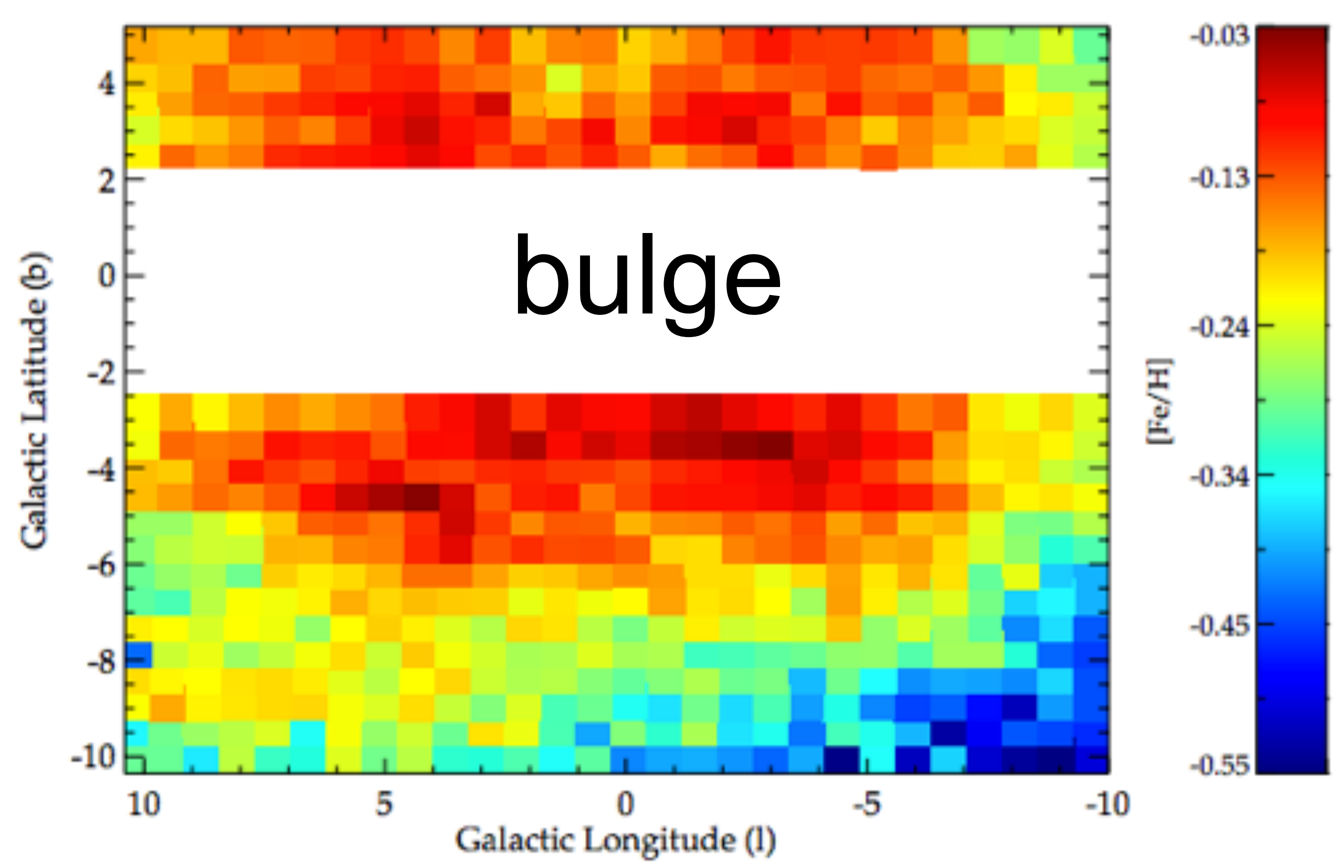
vs

a consistent/homogeneous set of metallicities

Metallicity maps

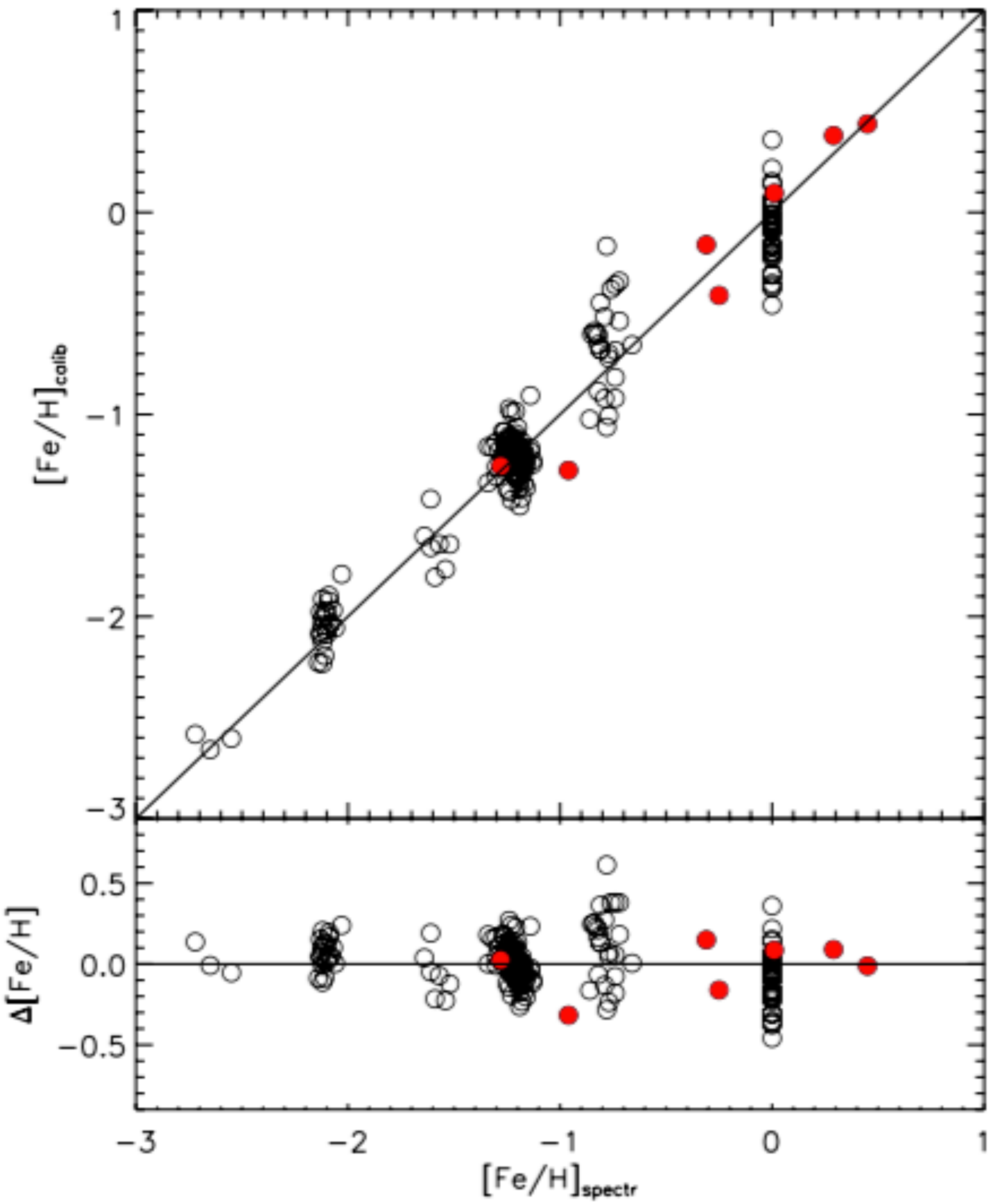


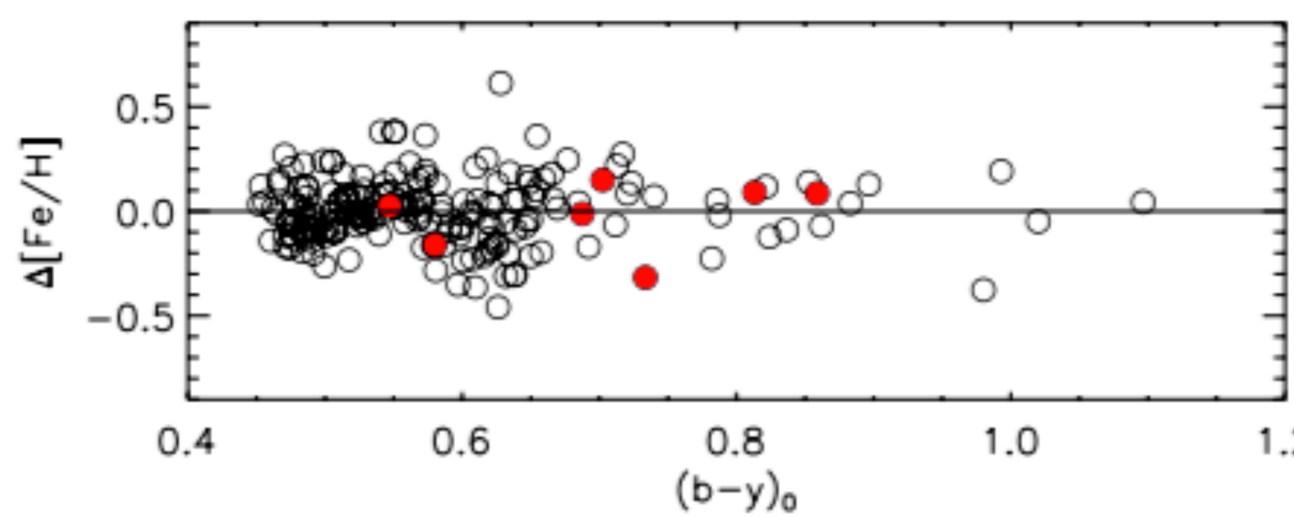
Ivezic et al. 2008
see also An et al. 2013



Gonzalez et al. (2013)

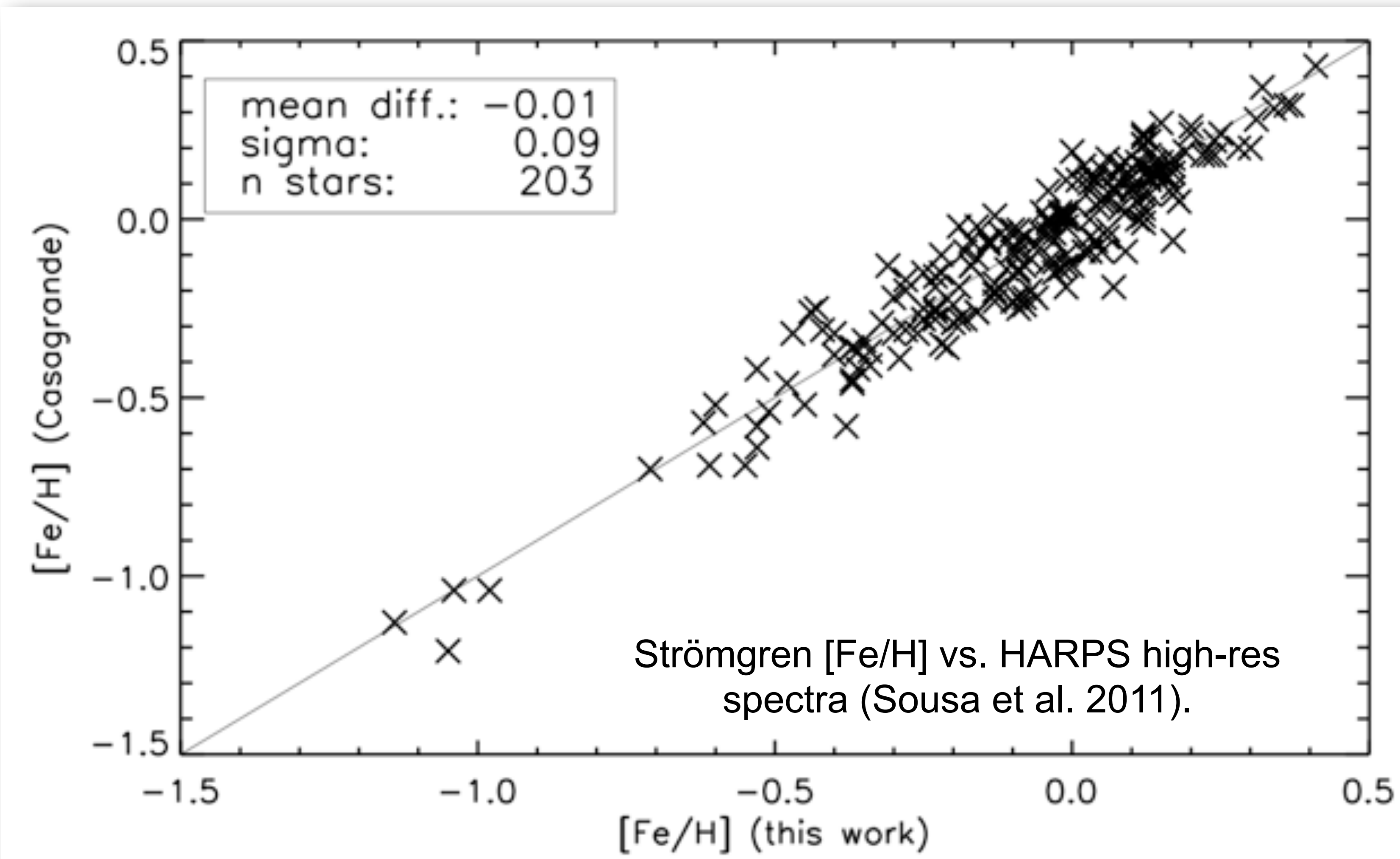
Photometric metallicities: Strömgren



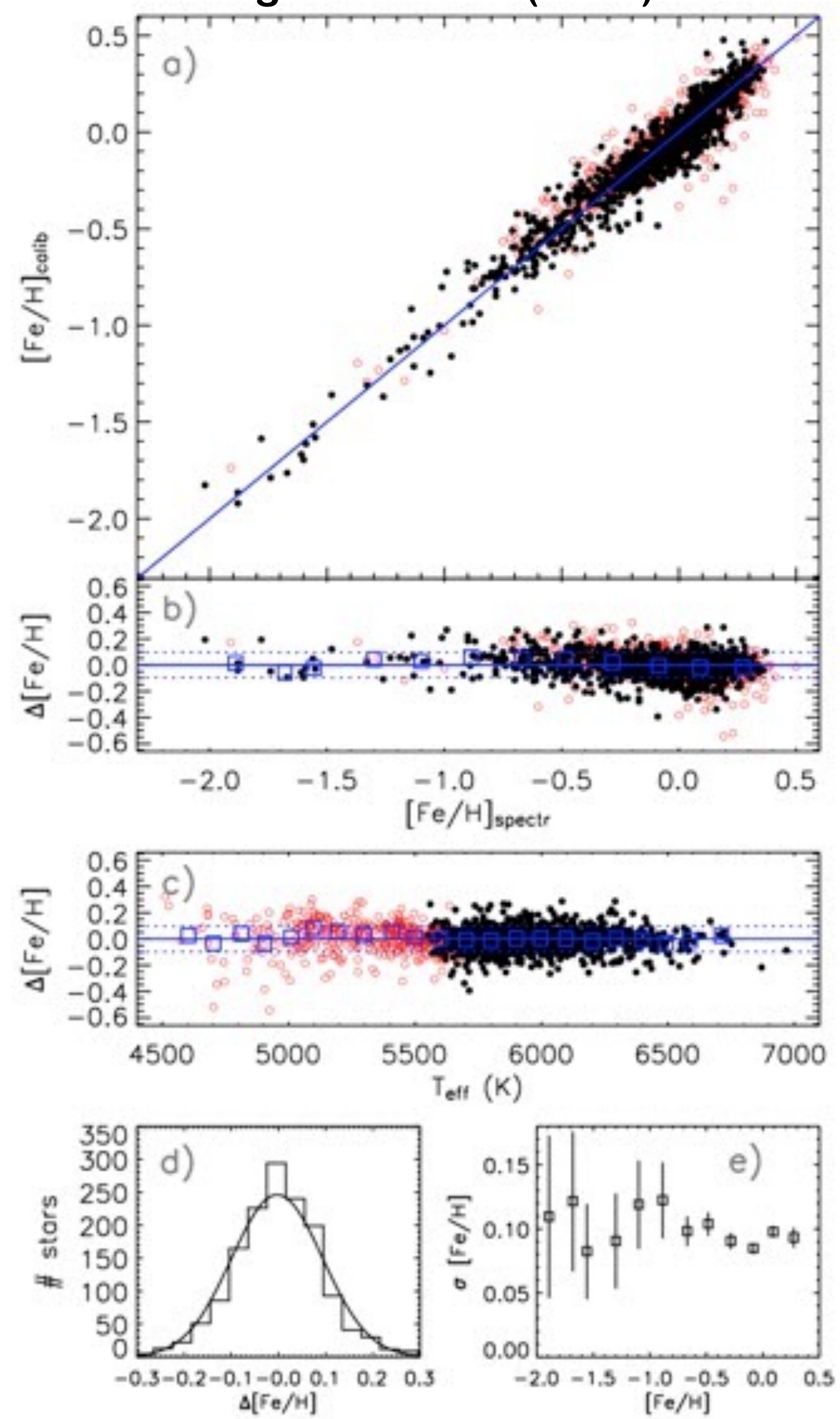


Casagrande, Silva Aguirre, Stello et al. (2014)

Photometric metallicities: Strömgren

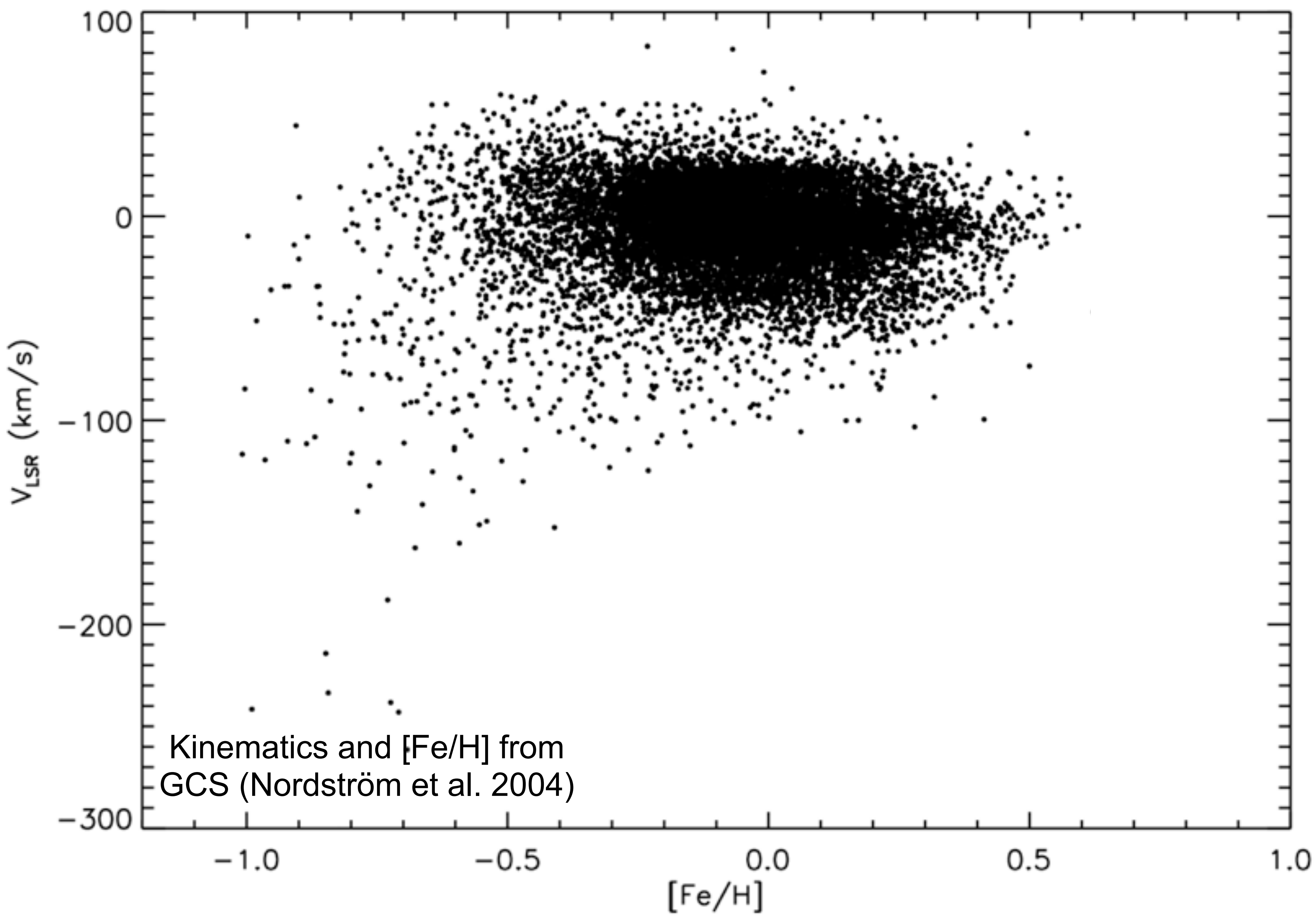


Casagrande et al. (2011)



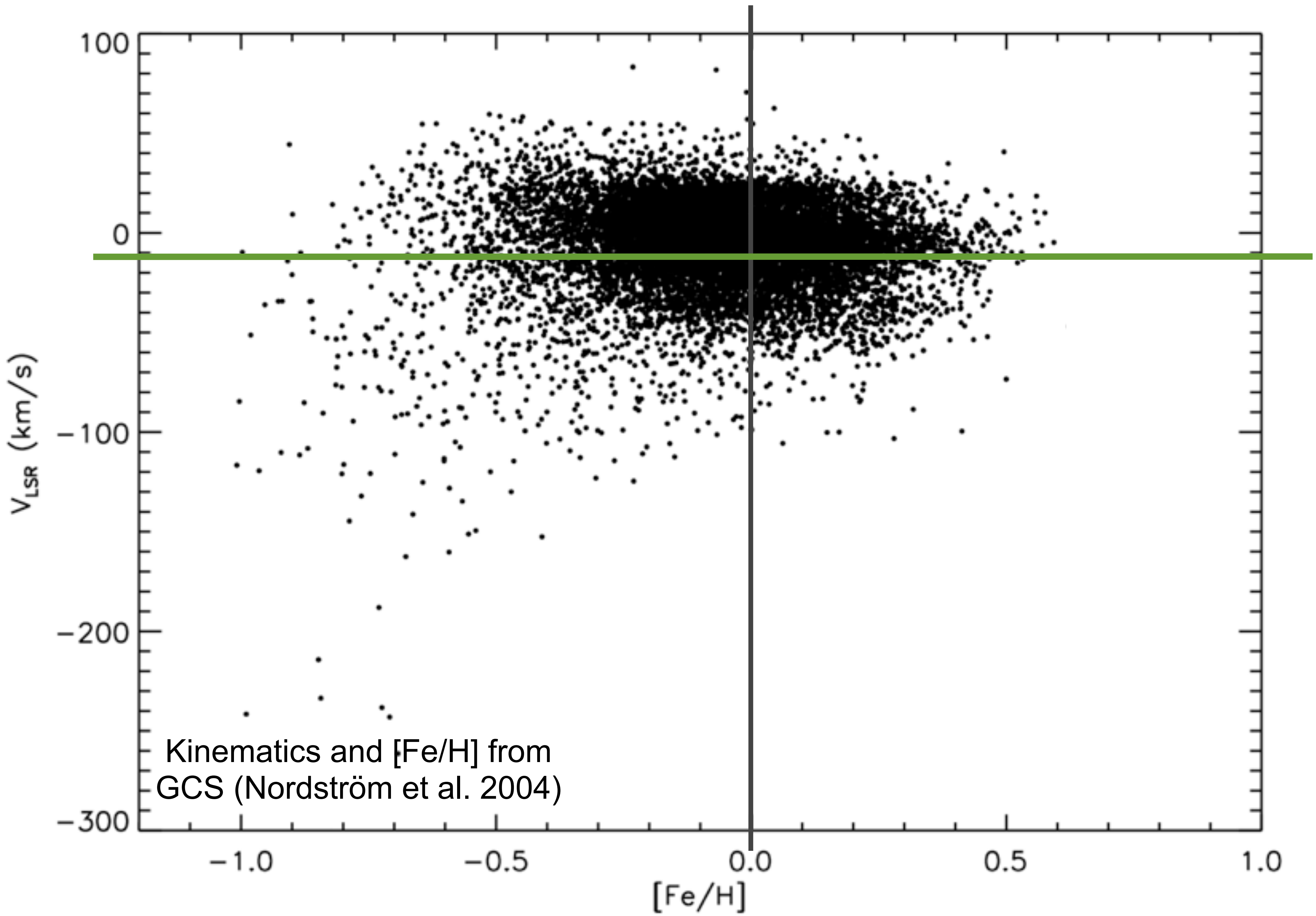
many calibration in literature: Schuster & Nissen (1989), Haywood (2002), Martell & Smith (2004), Holmberg et al. (2007), Ramirez & Melendez (2005)

(as) UNBIASED
(as possible)



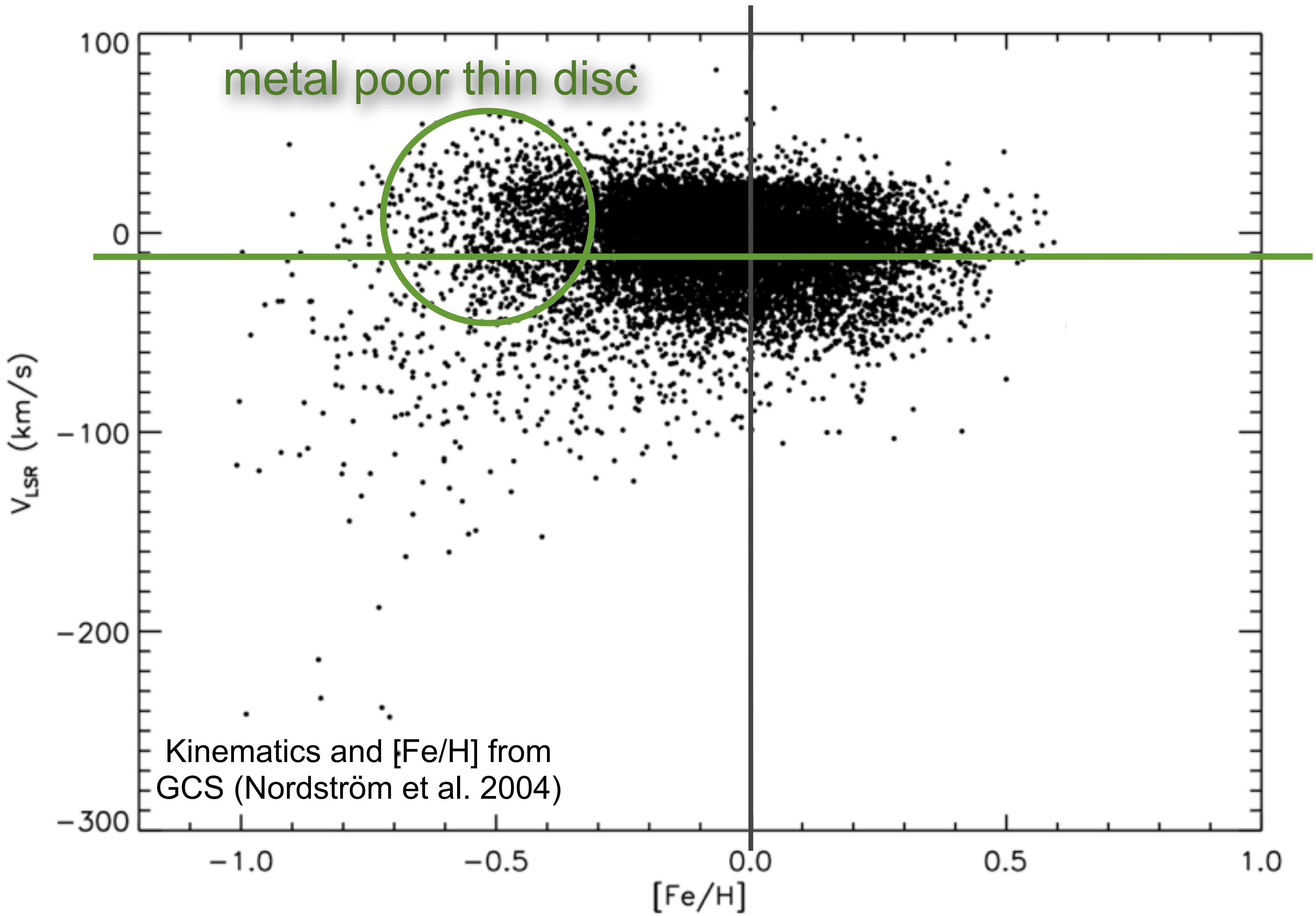
(as) UNBIASED

(as possible)



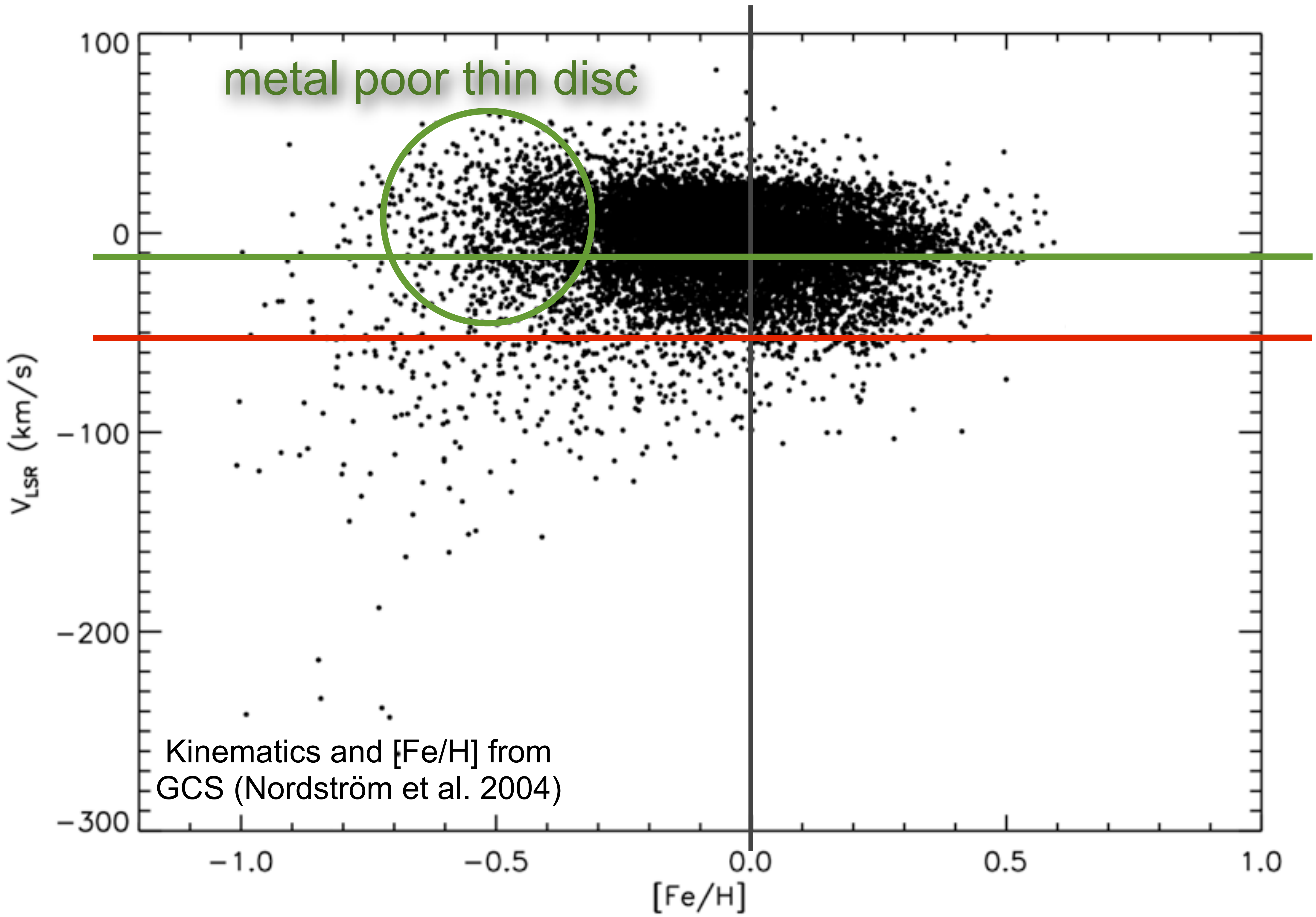
(as) UNBIASED

(as possible)



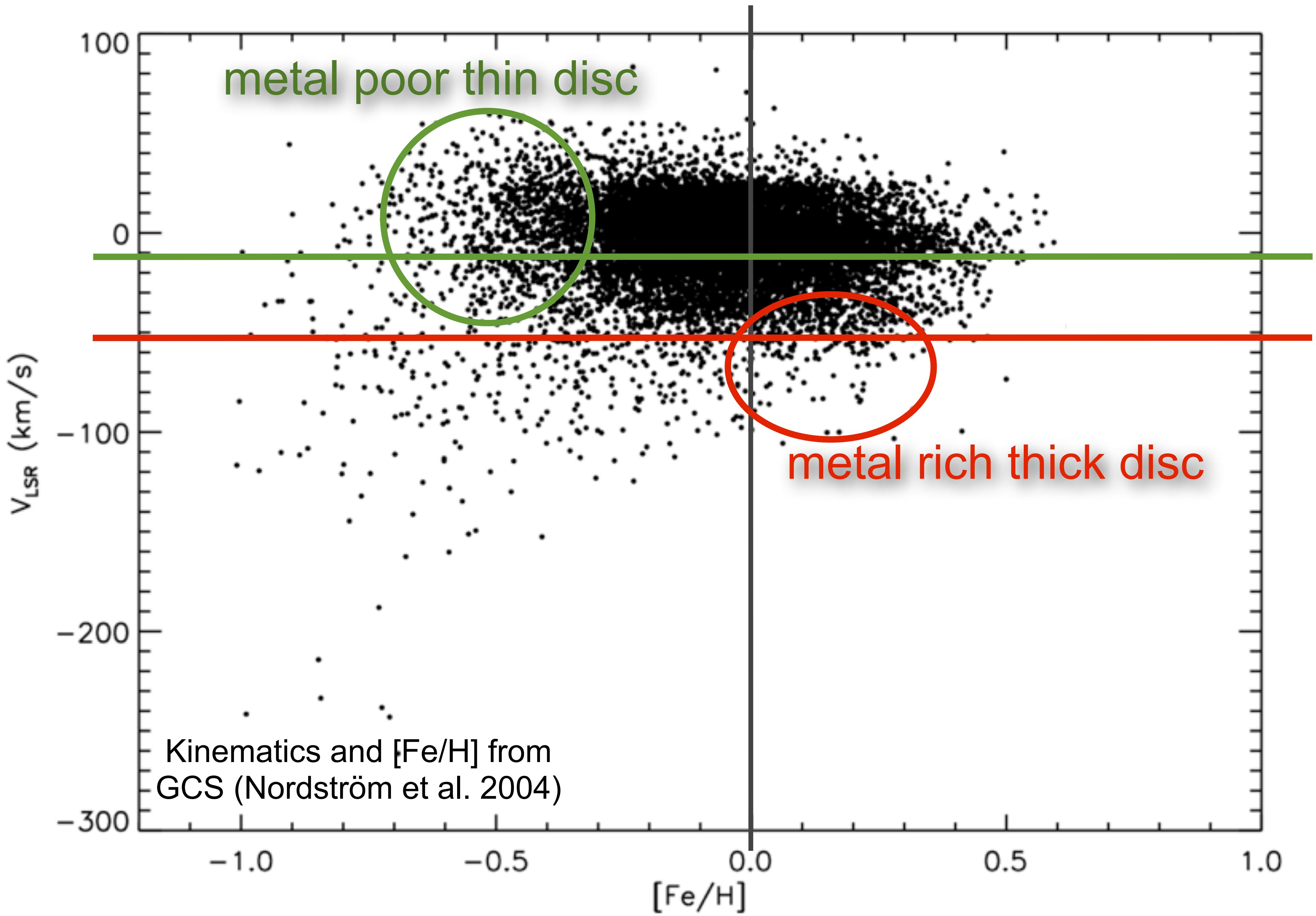
(as) UNBIASED

(as possible)



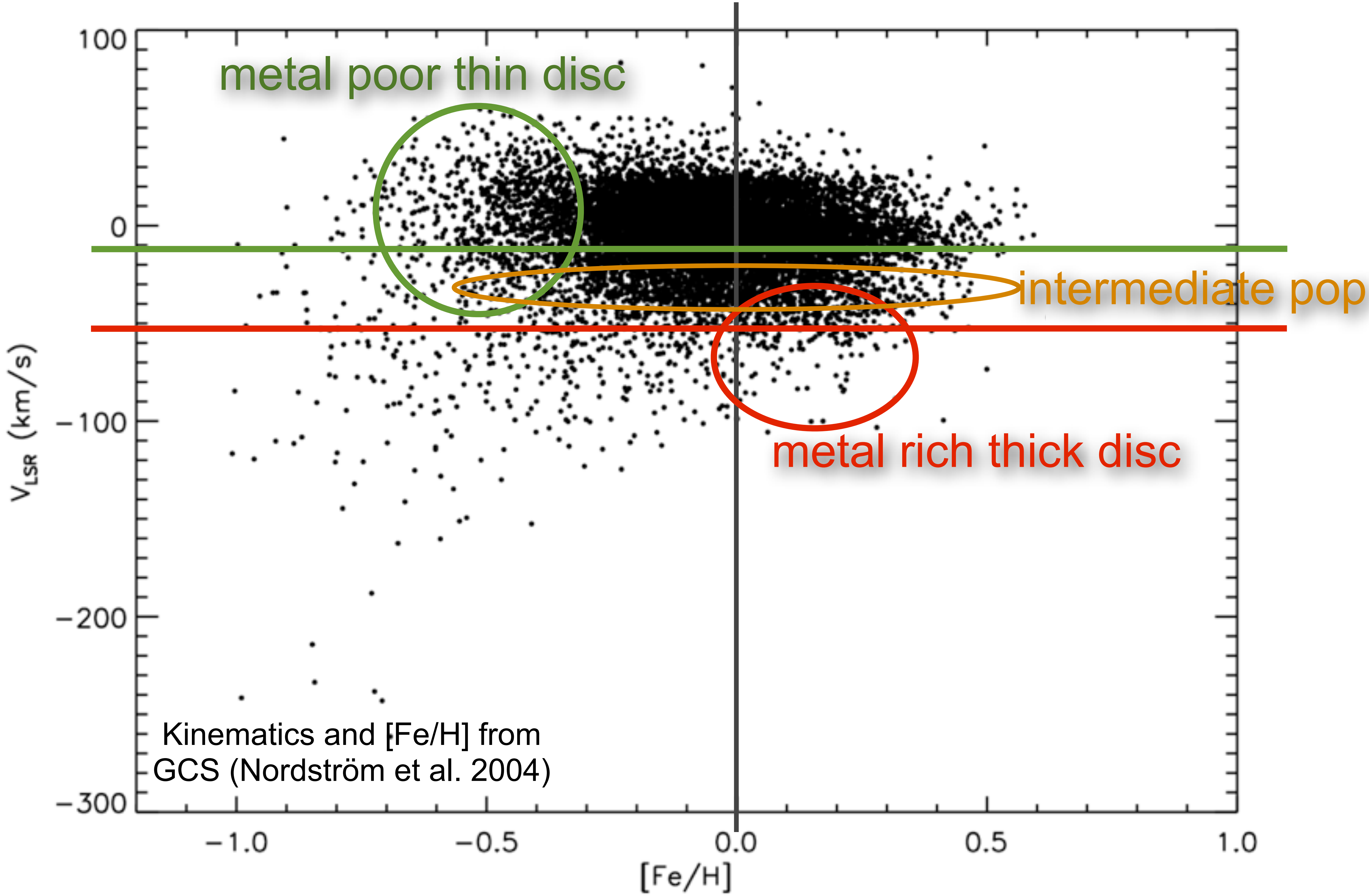
(as) UNBIASED

(as possible)



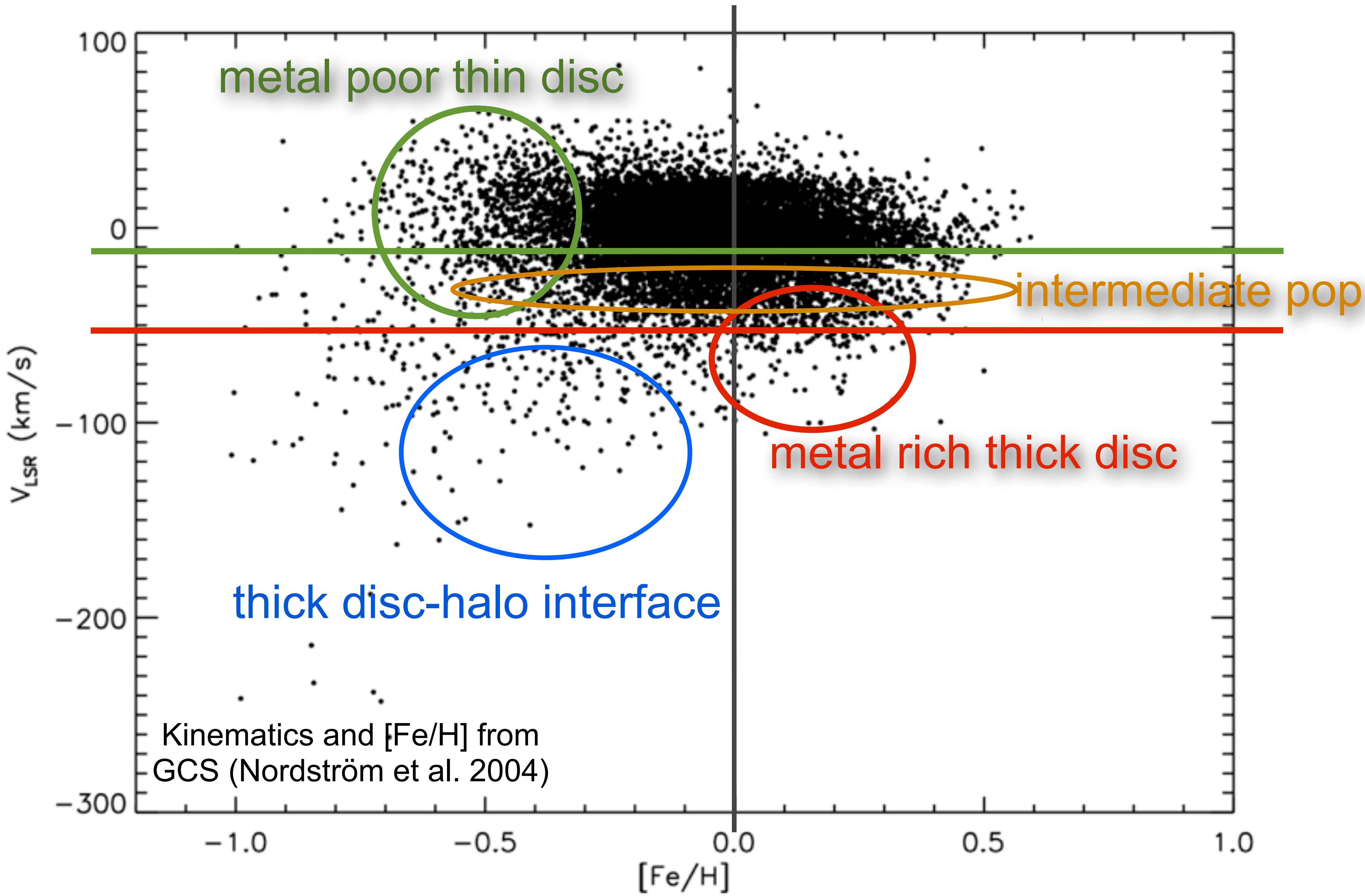
(as) **UNBIASED**

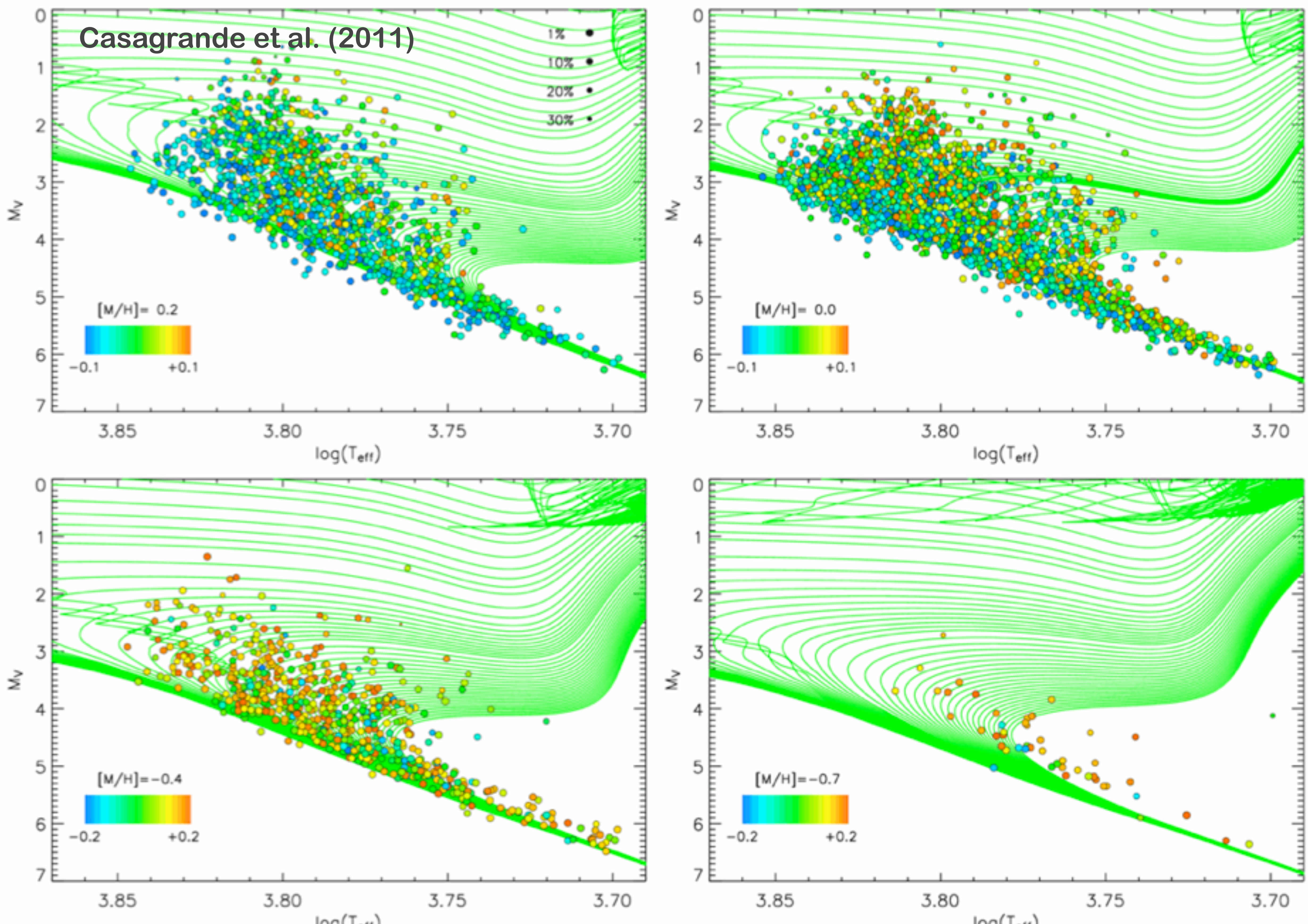
(as possible)



(as) UNBIASED

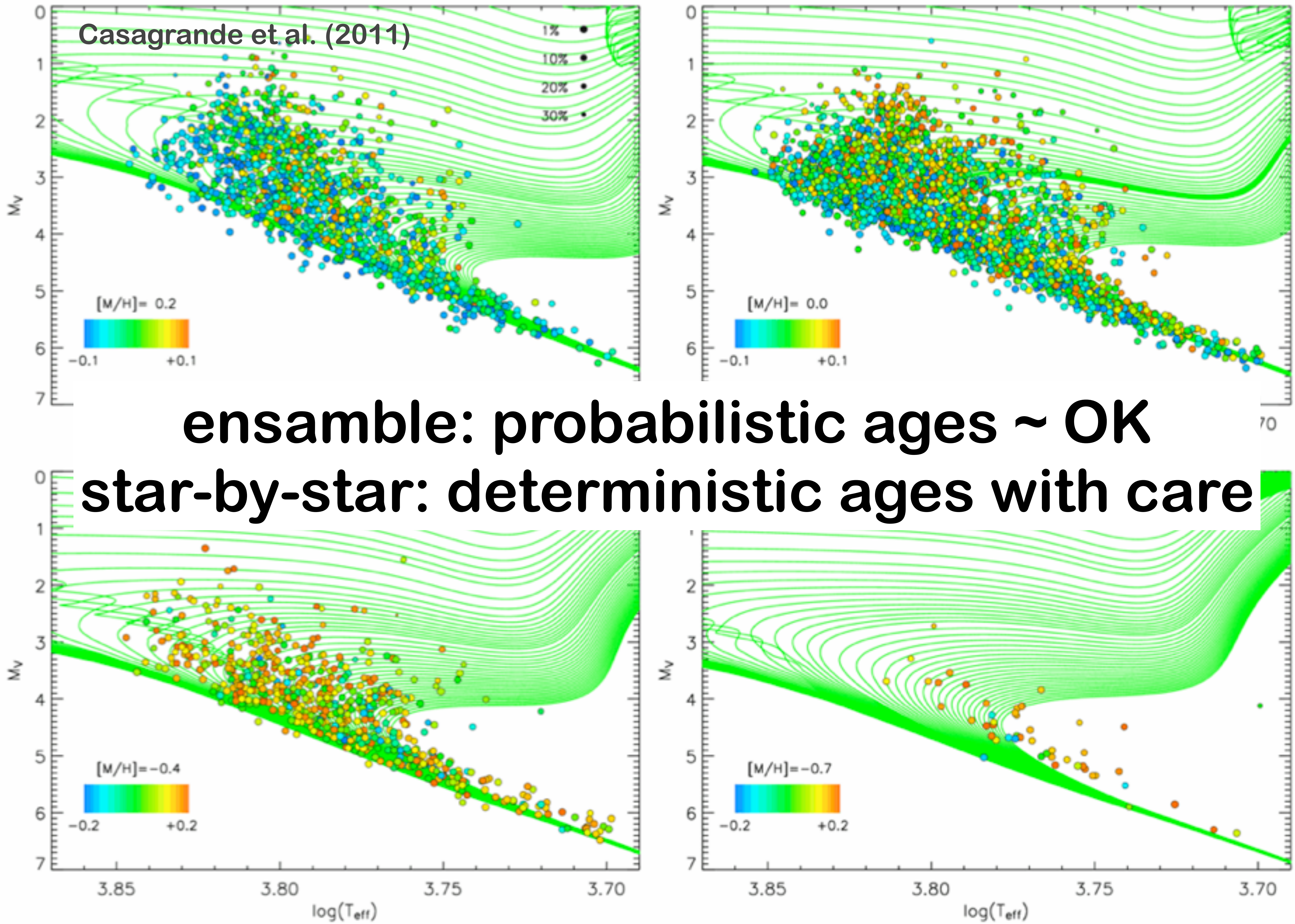
(as possible)





cf. e.g. Pont & Eyer (2004), Jørgensen & Lindegren (2005), Burnett & Binney (2010)

Sweeping (many things) under the rug



ensamble: probabilistic ages ~ OK

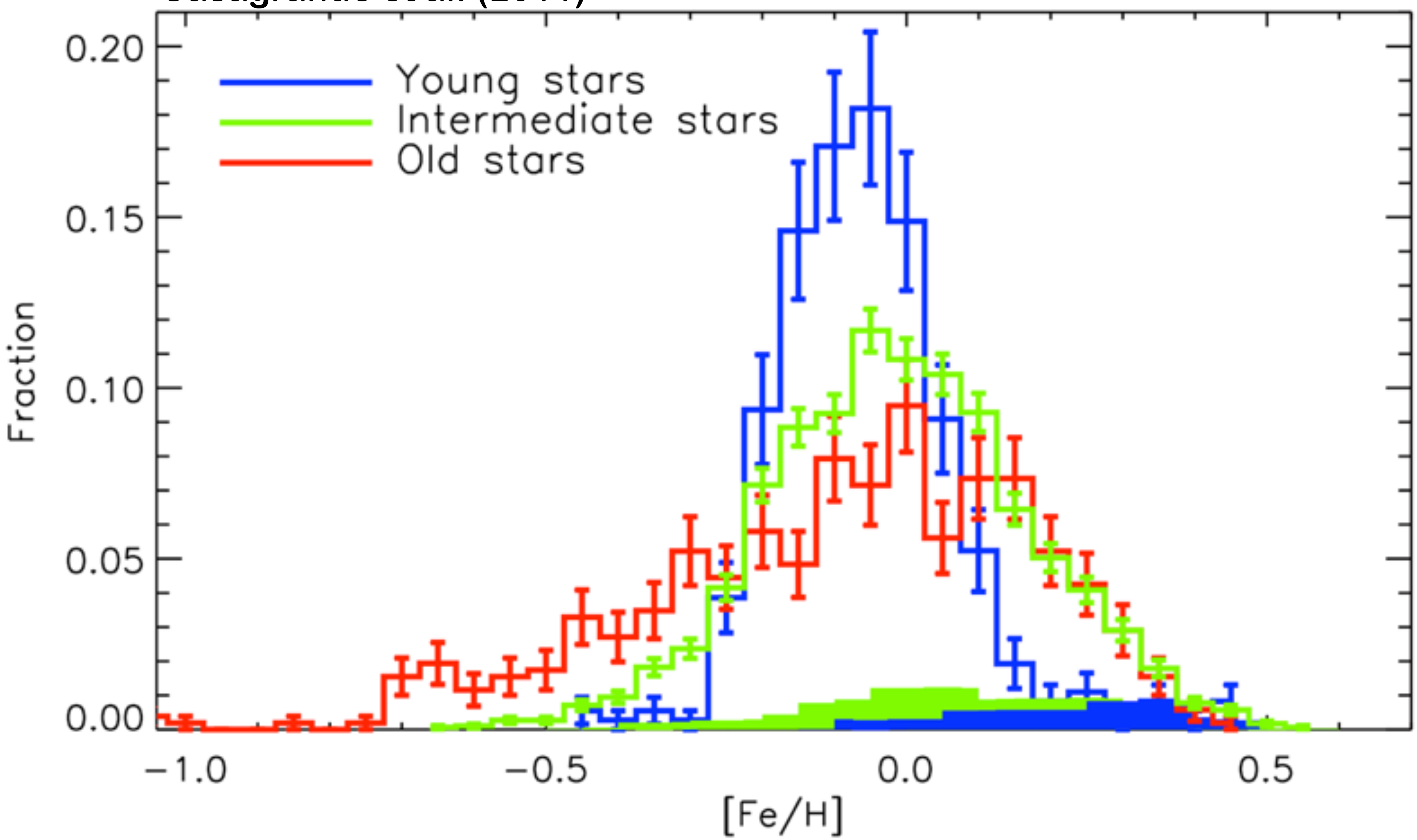
star-by-star: deterministic ages with care

cf. e.g. Pont & Eyer (2004), Jørgensen & Lindegren (2005), Burnett & Binney (2010)

Age-Metallicity Distribution Function (Solar Neighbourhood)

from isochrones

Casagrande et al. (2011)

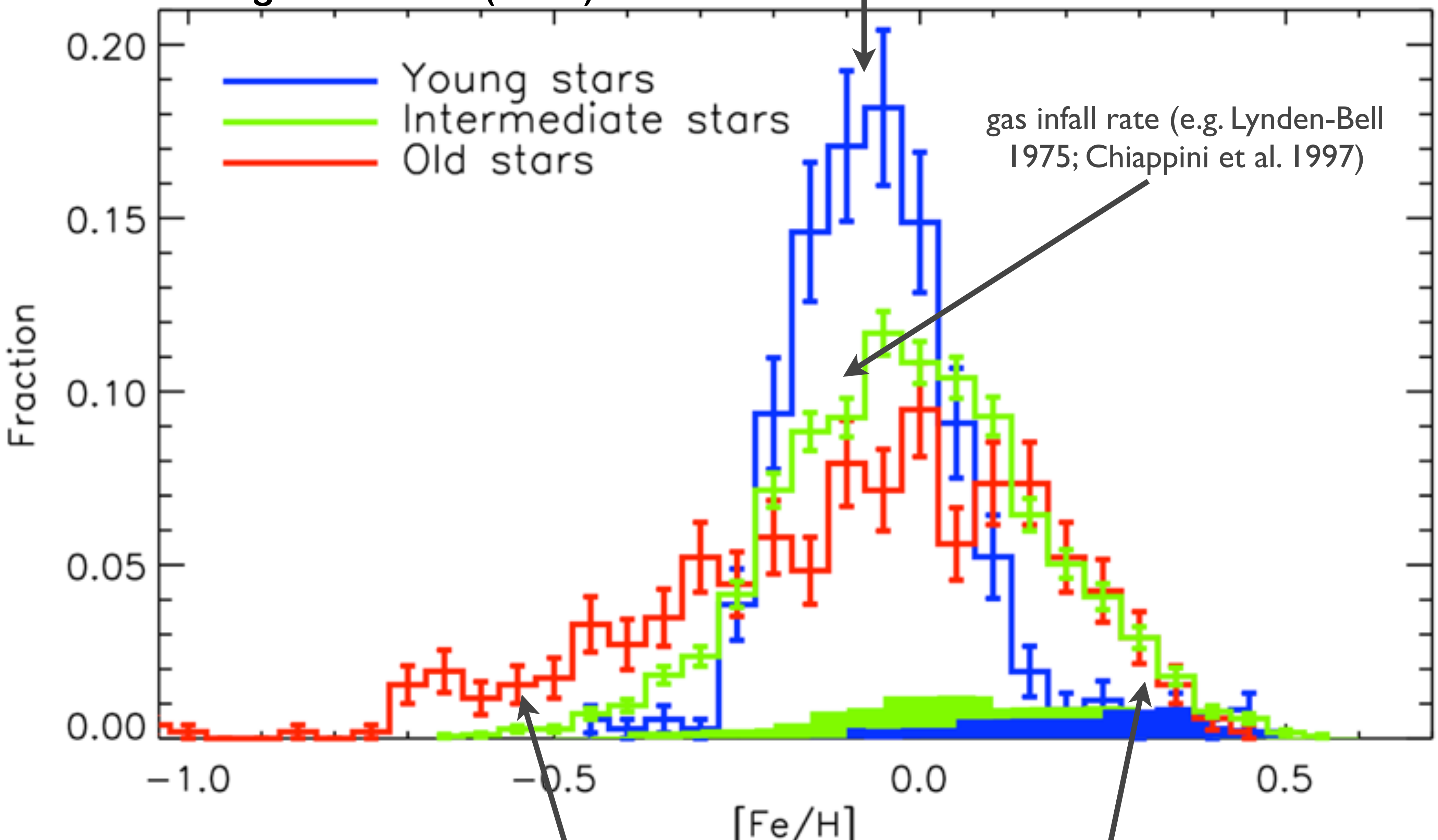


Age-Metallicity Distribution Function (Solar Neighbourhood)

from isochrones

how typical is the Sun?

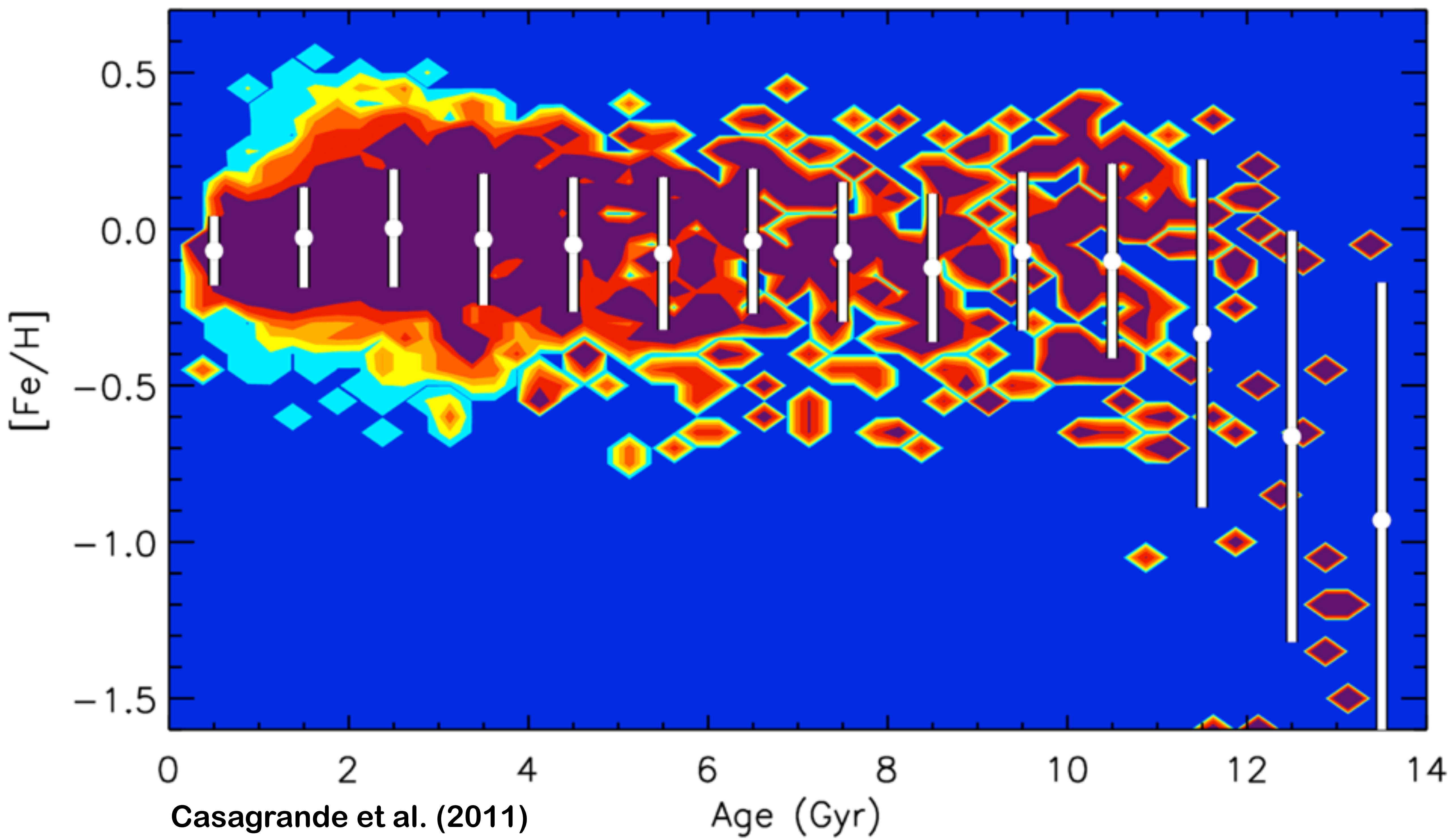
Casagrande et al. (2011)



gas infall rate (e.g. Lynden-Bell 1975; Chiappini et al. 1997)

stellar radial migration in the disc (e.g. Sellwood & Binney 2002, Roskar et al. 2008, Schönrich & Binney 2009, Yu et al. 2012)

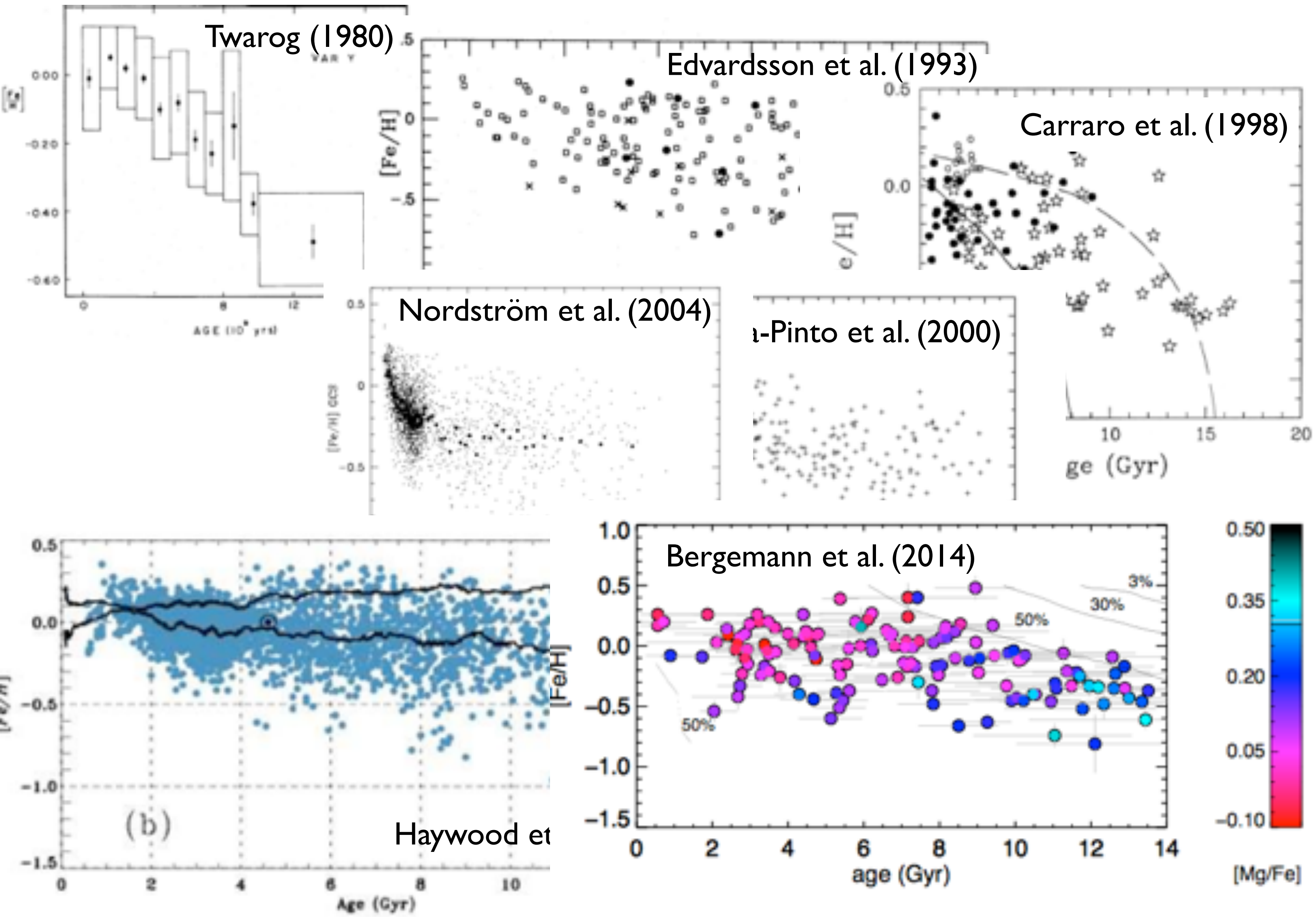
Age-Metallicity Relation



Casagrande et al. (2011)

Age-Metallicity Relation

(does it exist? Feltzing et al. 2001)

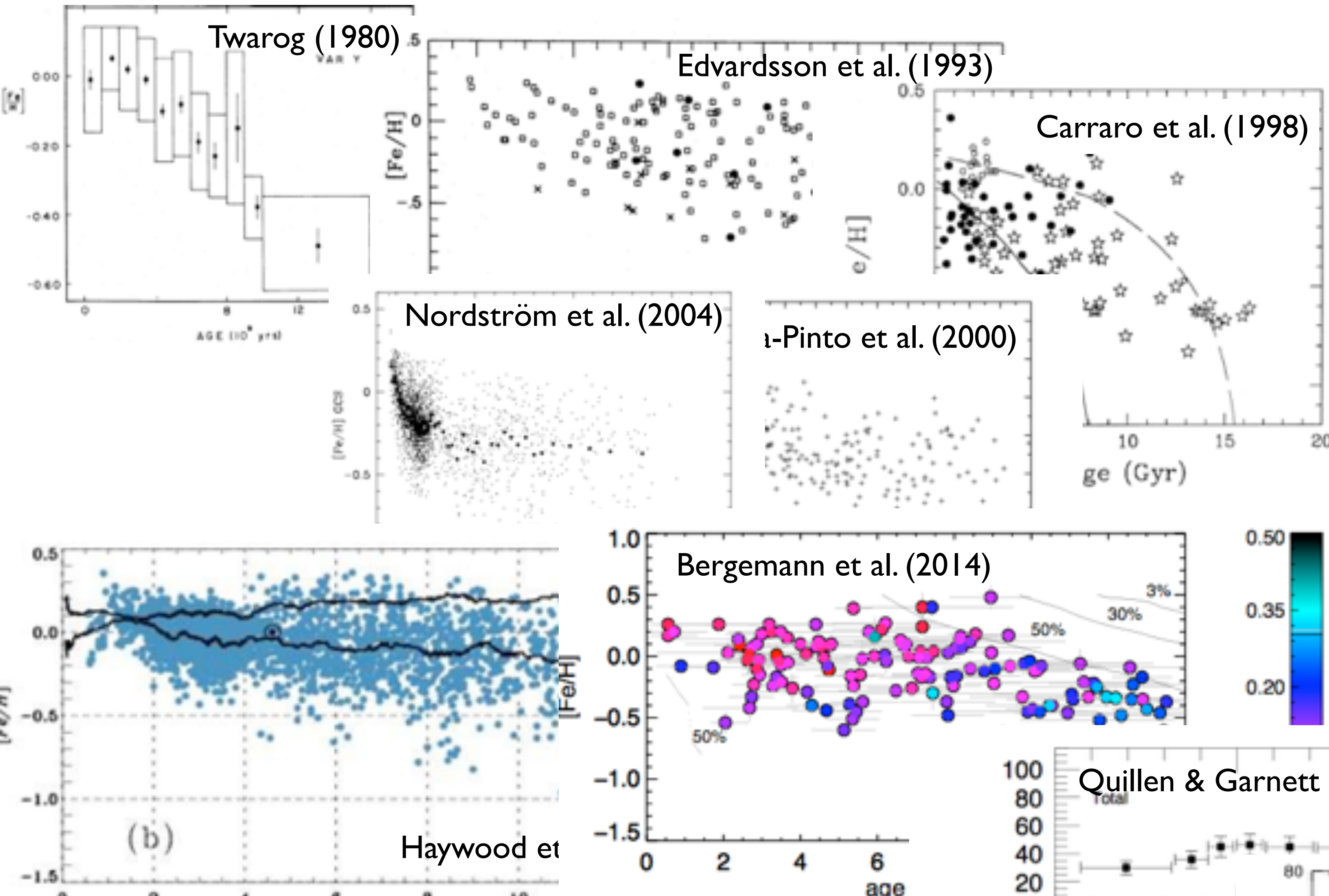


Age-Metallicity Relation

(does it exist? Feltzing et al. 2001)

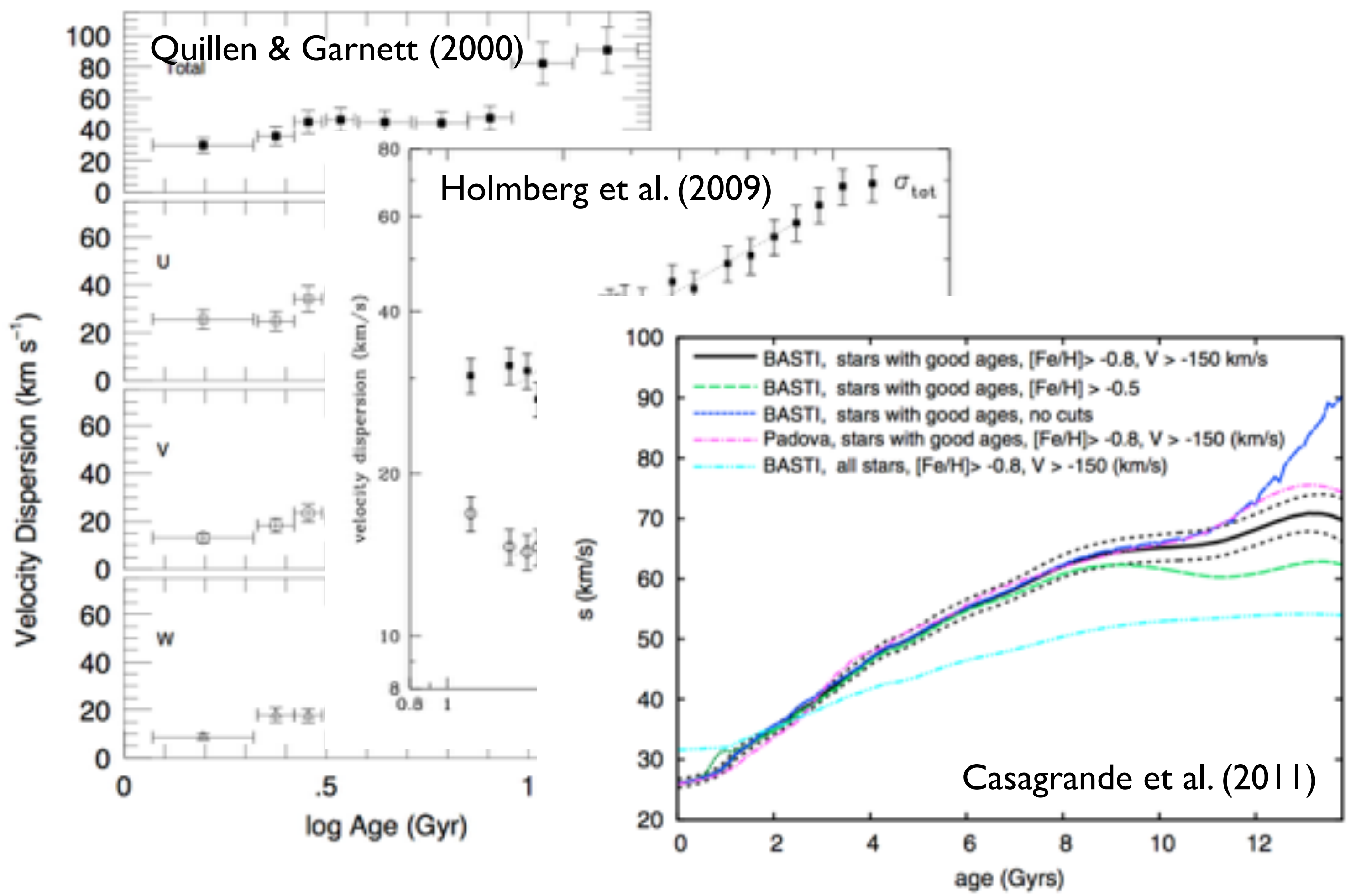
Age-Metallicity Relation

(does it exist? Feltzing et al. 2001)

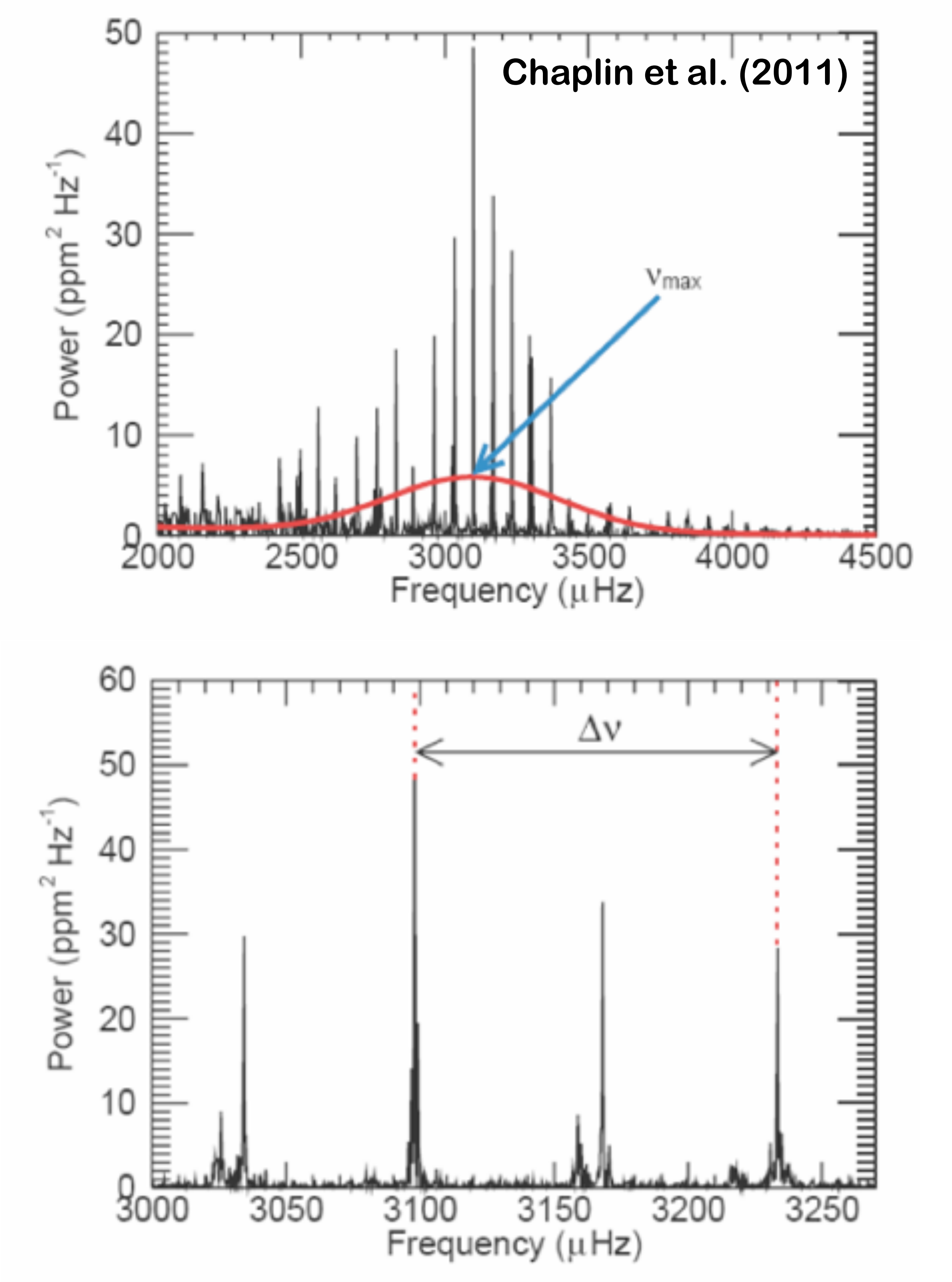


Age-Dispersion Relation

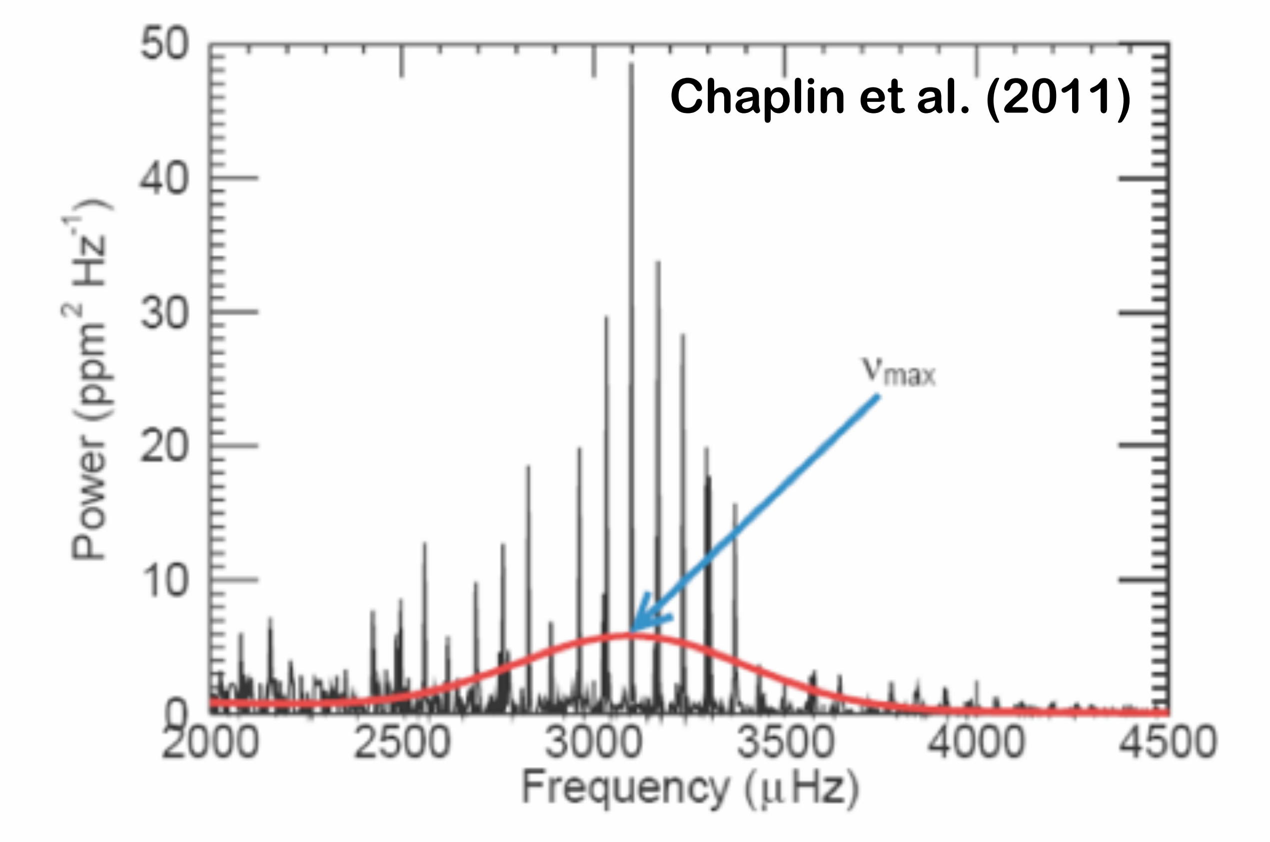
(rise or saturate?)

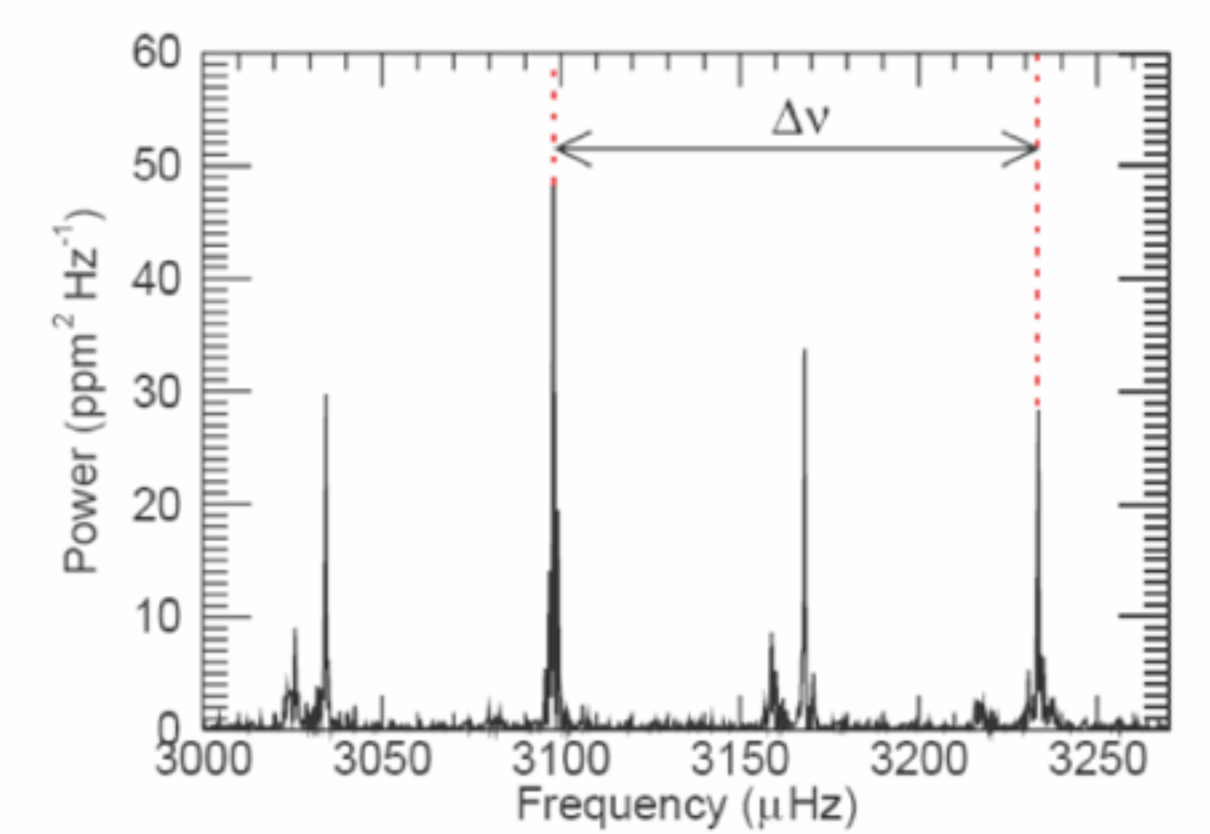


Asteroseismology



Asteroseismology





Ages

$$\frac{M}{M_\odot} \simeq \left(\frac{\nu_{\rm max}}{\nu_{\rm max,\odot}}\right)^3 \left(\frac{\Delta\nu}{\Delta\nu_\odot}\right)^{-4} \left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}}\right)^{3/2}$$

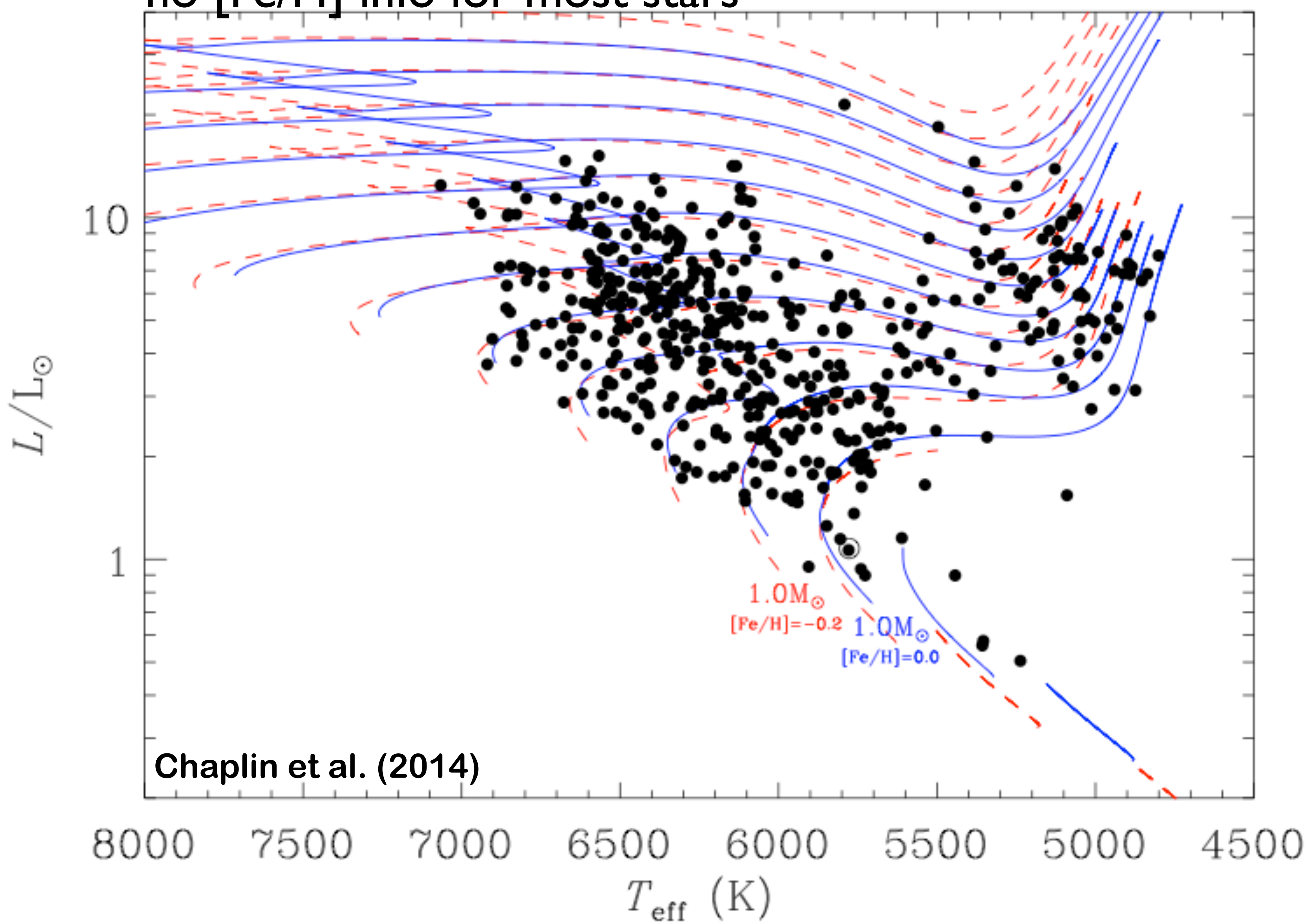
Distances

$$\frac{R}{R_\odot} \simeq \left(\frac{\nu_{\rm max}}{\nu_{\rm max,\odot}}\right) \left(\frac{\Delta\nu}{\Delta\nu_\odot}\right)^{-2} \left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}}\right)^{1/2}$$

e.g., Hekker et al. 2009, 2011, Stello et al. 2009, and exceedingly precise log(g) values (e.g. Gai et al. 2011, Chaplin et al. 2014)

Ages: Main Sequence

no [Fe/H] info for most stars

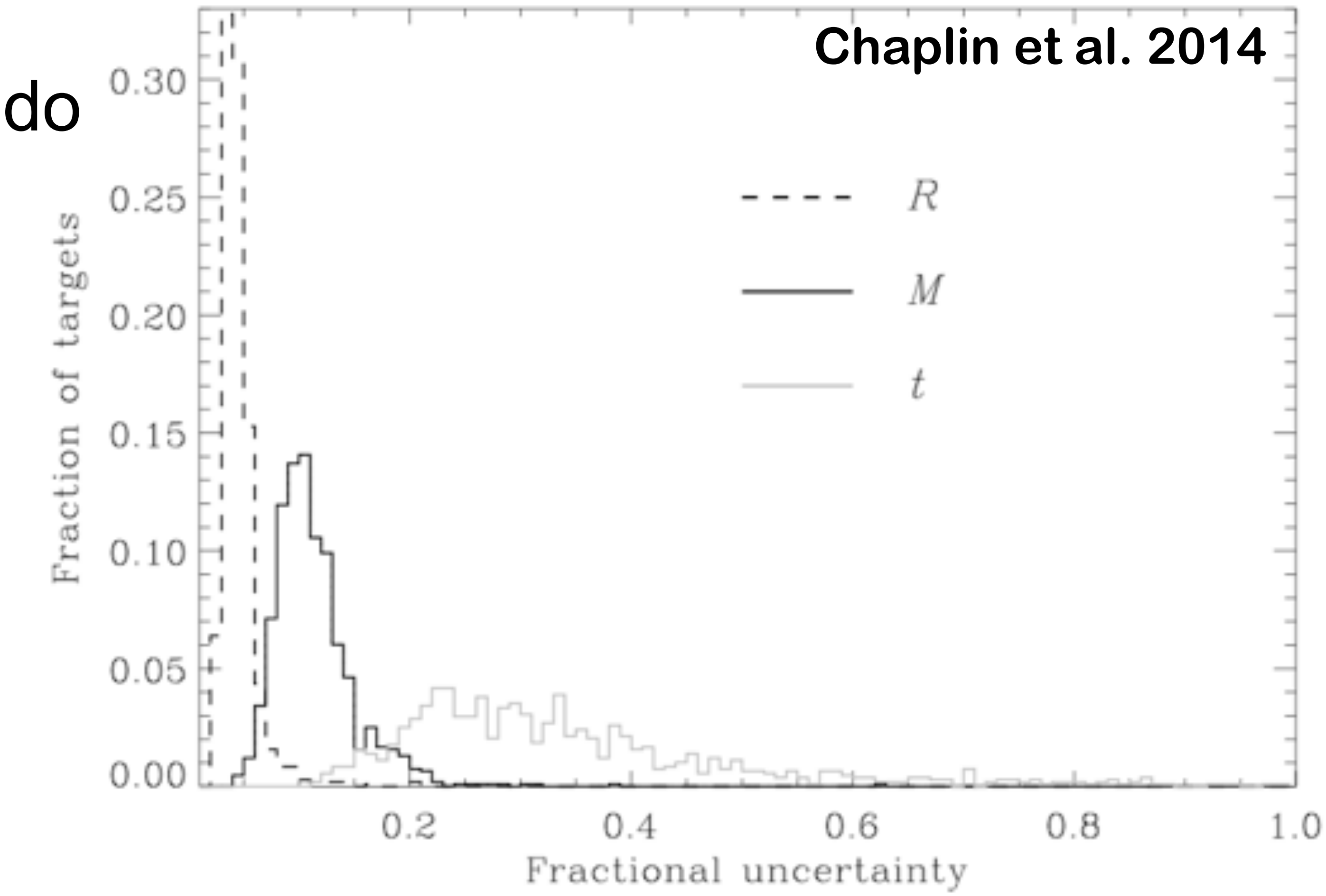


asteroseismology: the least we can do

$\nu_{\max}$

$\Delta\nu$

$T_{\rm eff}$

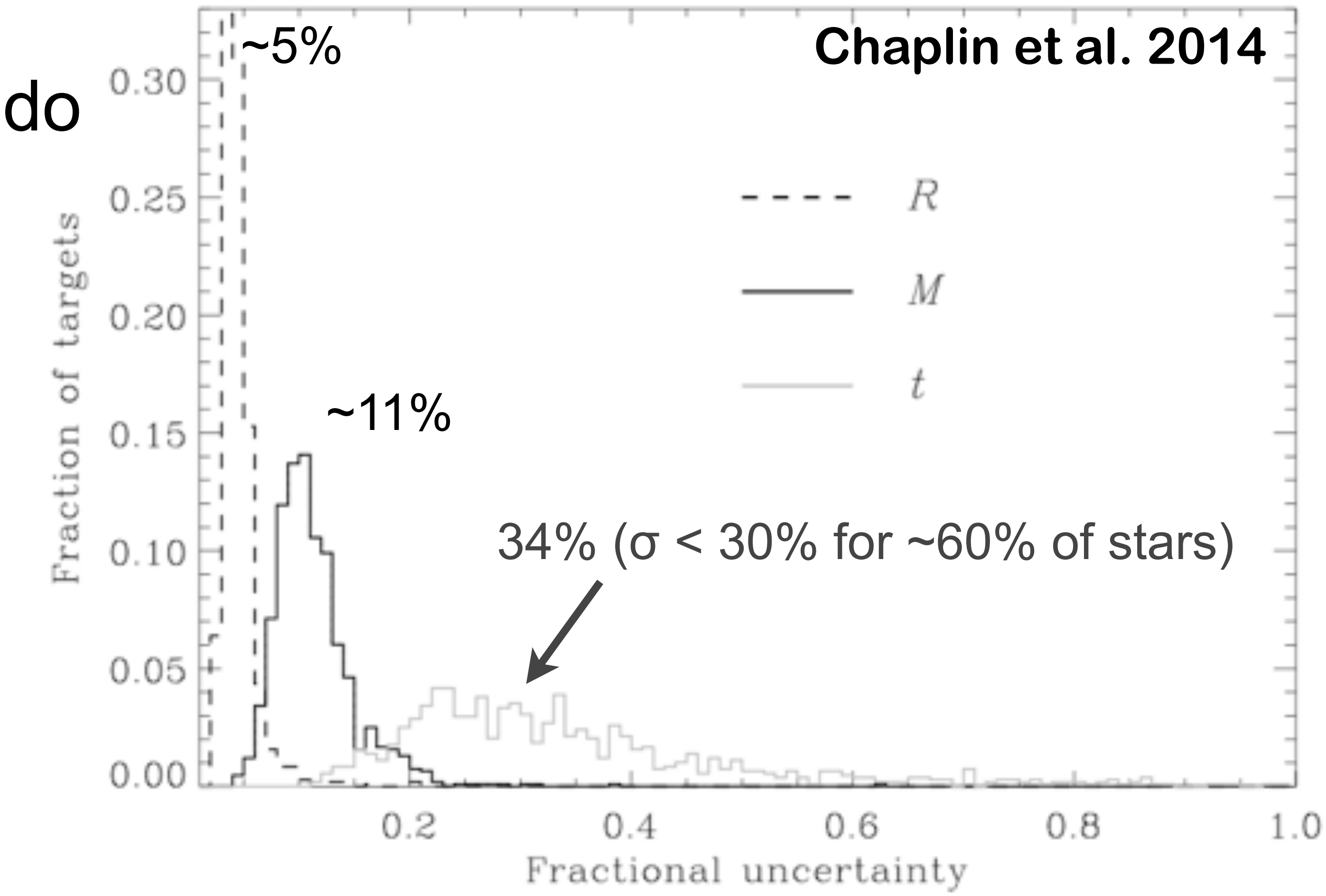


asteroseismology: the least we can do

$$\nu_{\rm max}$$

$$\Delta\nu$$

$$T_{\rm eff}$$

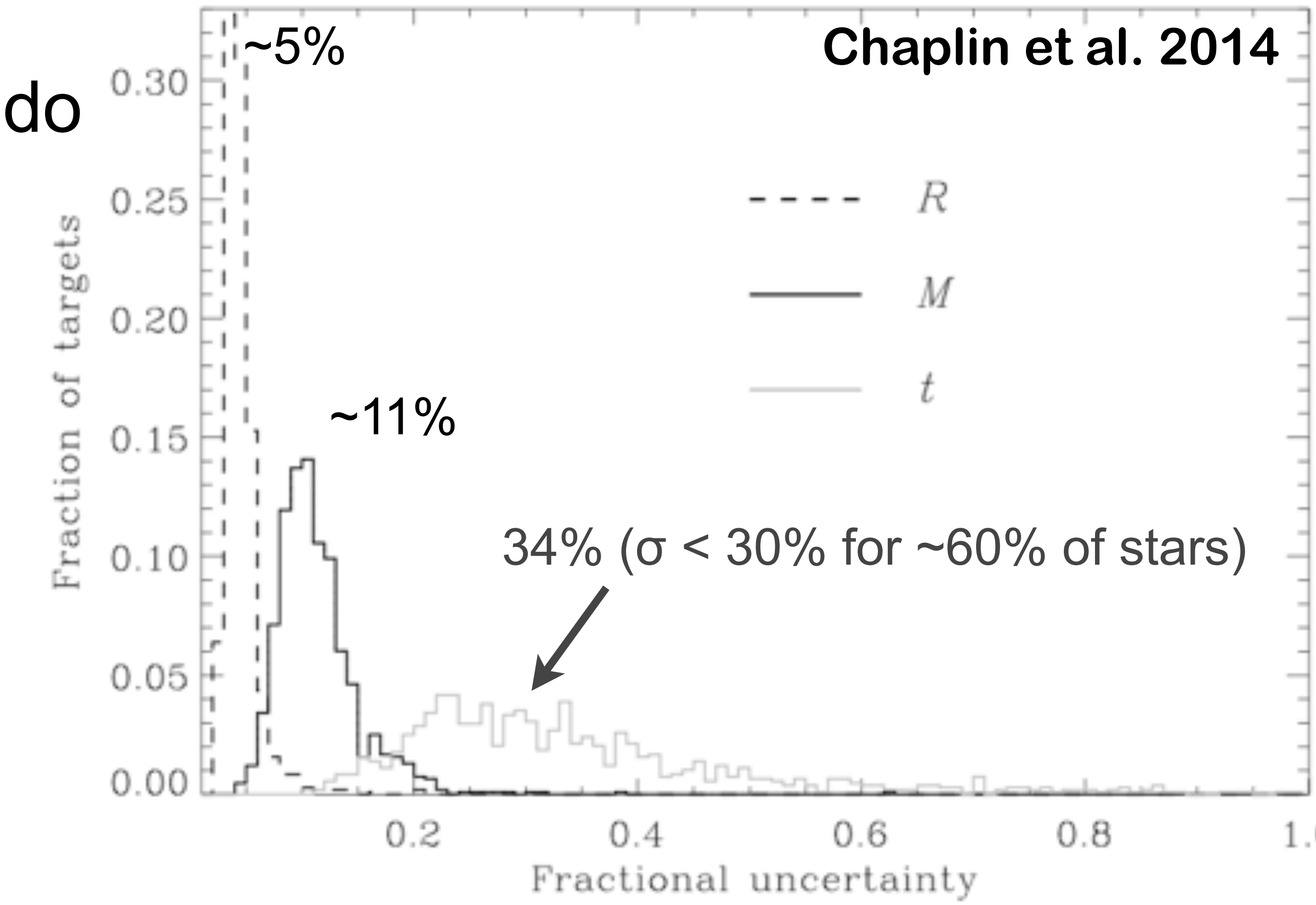


asteroseismology: the least we can do

$$\nu_{\max}$$

$$\Delta\nu$$

$$T_{\mathrm{eff}}$$

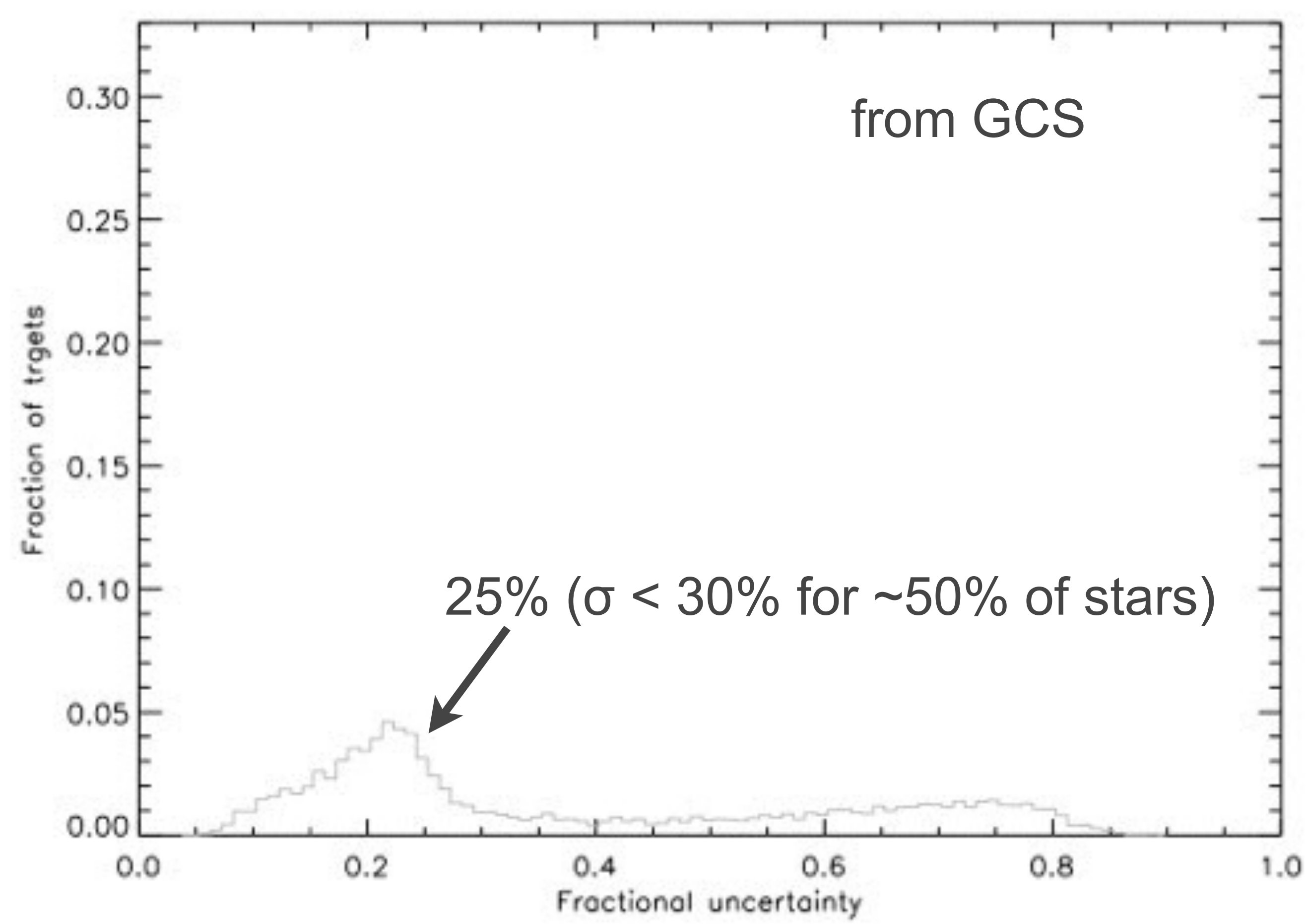


isochrone fitting: the best we can do

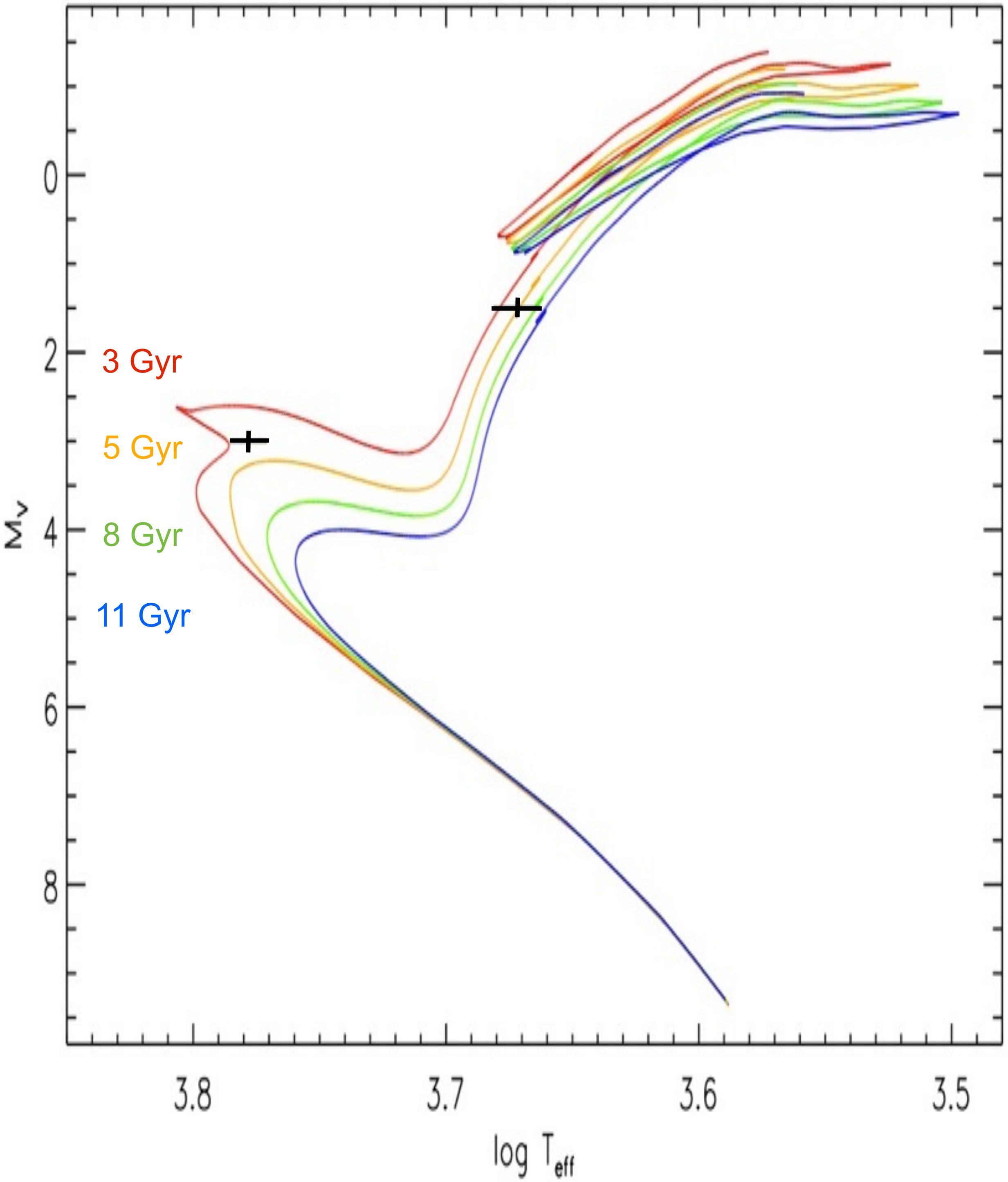
$$[Fe/H]$$

$$\pi$$

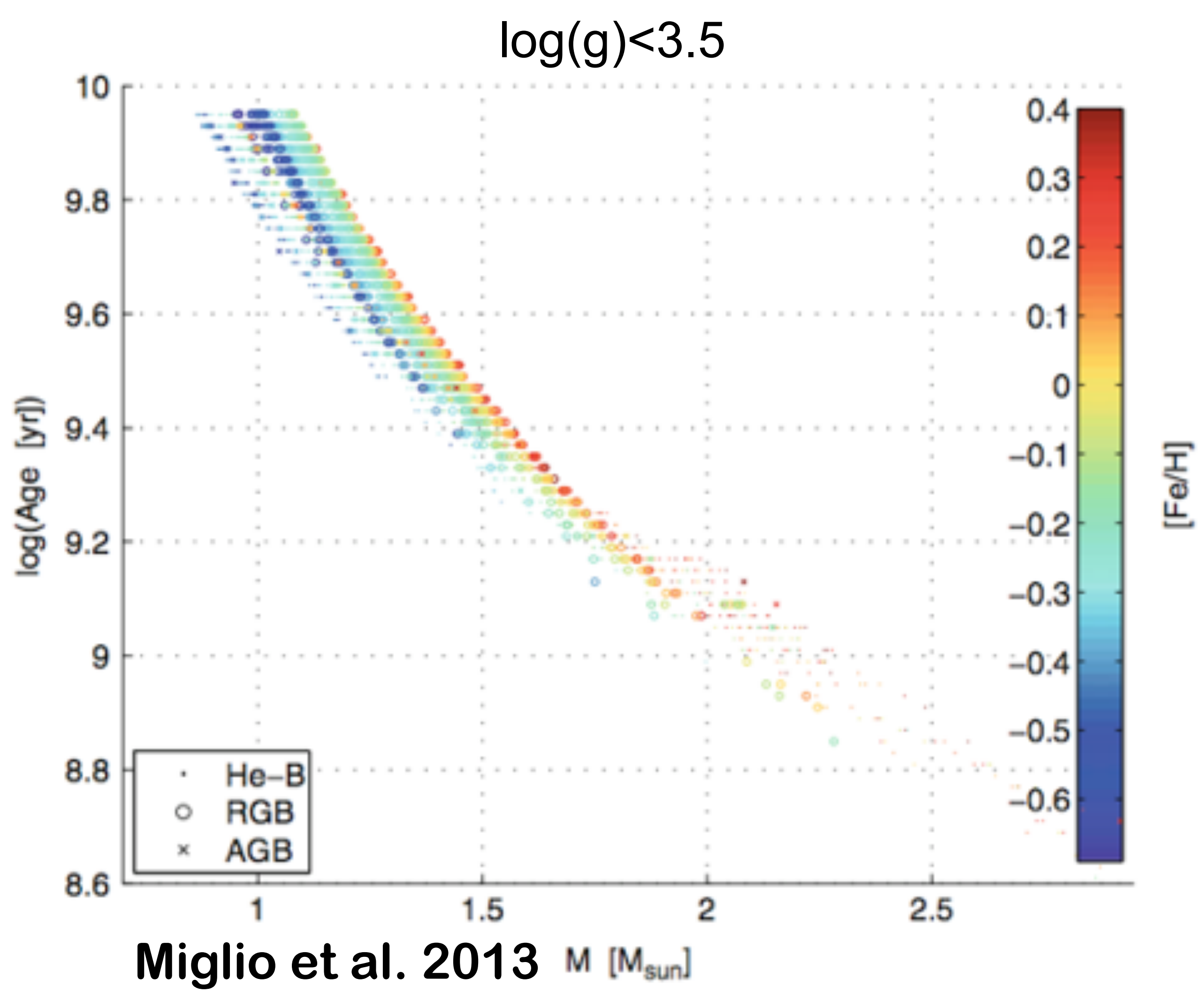
$$T_{\mathrm{eff}}$$



Red Giants

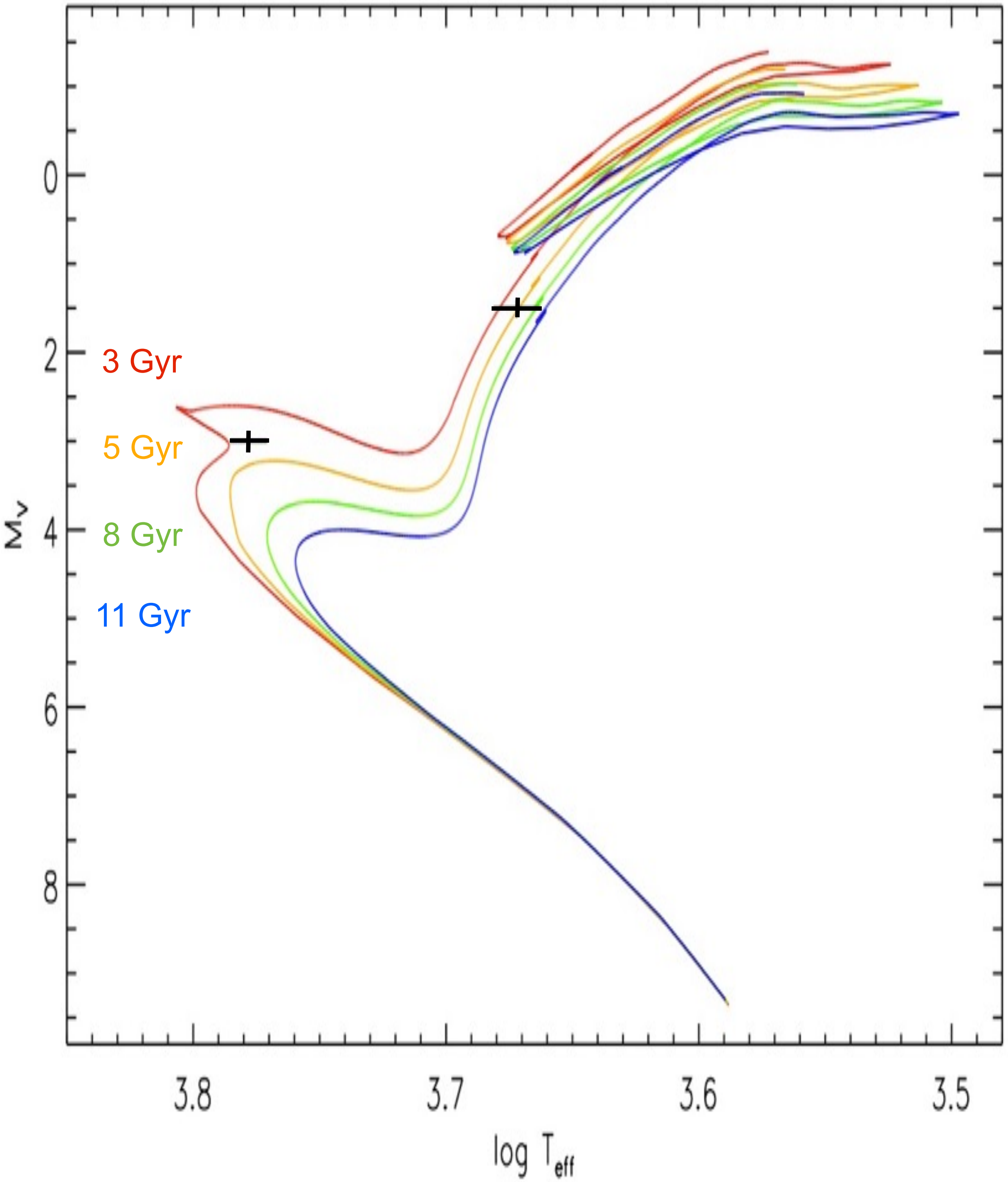


RGB : Once a star has evolved to the red-giant phase, its age is determined to good approximation by the time spent in the core-hydrogen burning phase, and this is predominantly a function of mass.

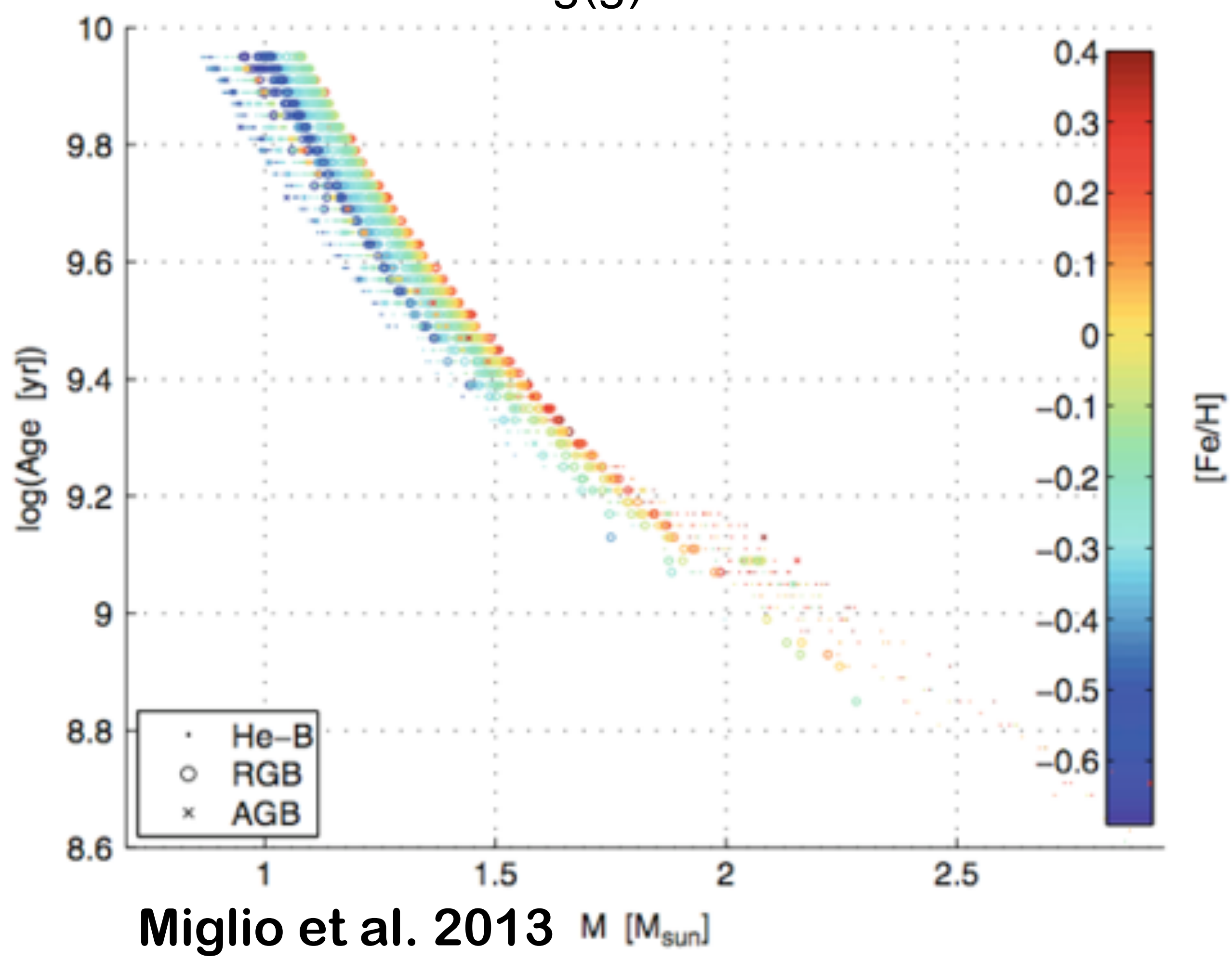


Miglio et al. 2013

Ages of intrinsically bright and long lived stars



RGB : Once a star has evolved to the red-giant phase, its age is determined to good approximation by the time spent in the core-hydrogen burning phase, and this is predominantly a function of mass.



Miglio et al. 2013

Coupling classical and seismic parameters

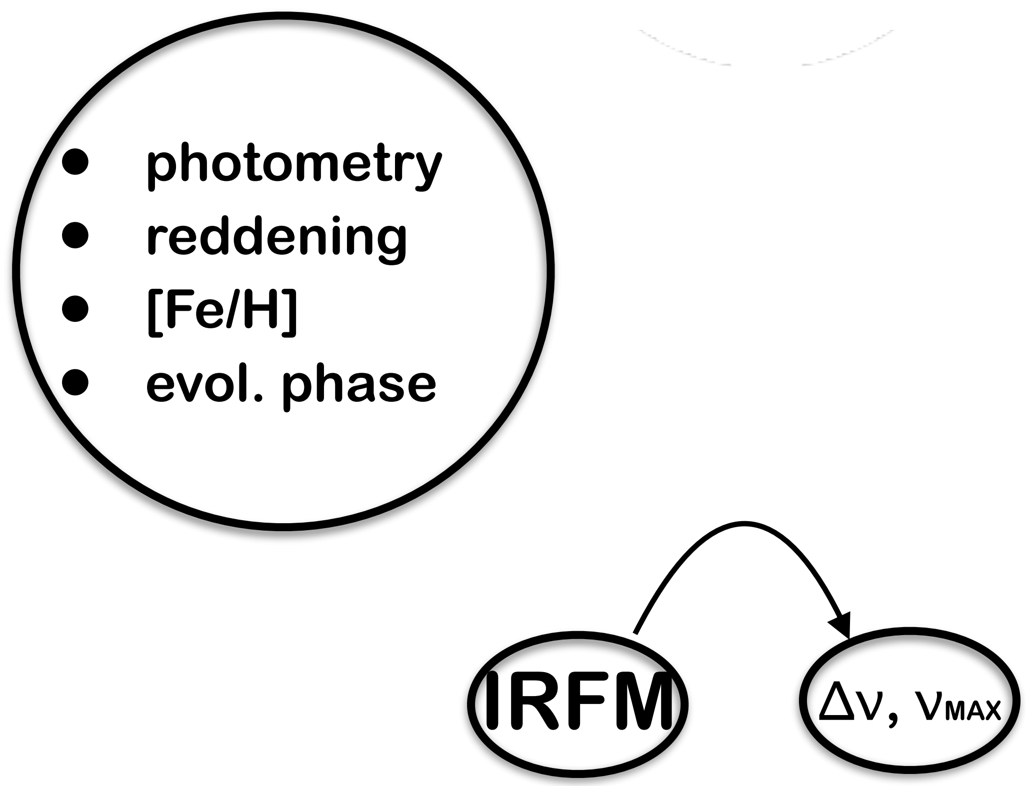
- photometry
- reddening
- [Fe/H]
- evol. phase

Coupling classical and seismic parameters

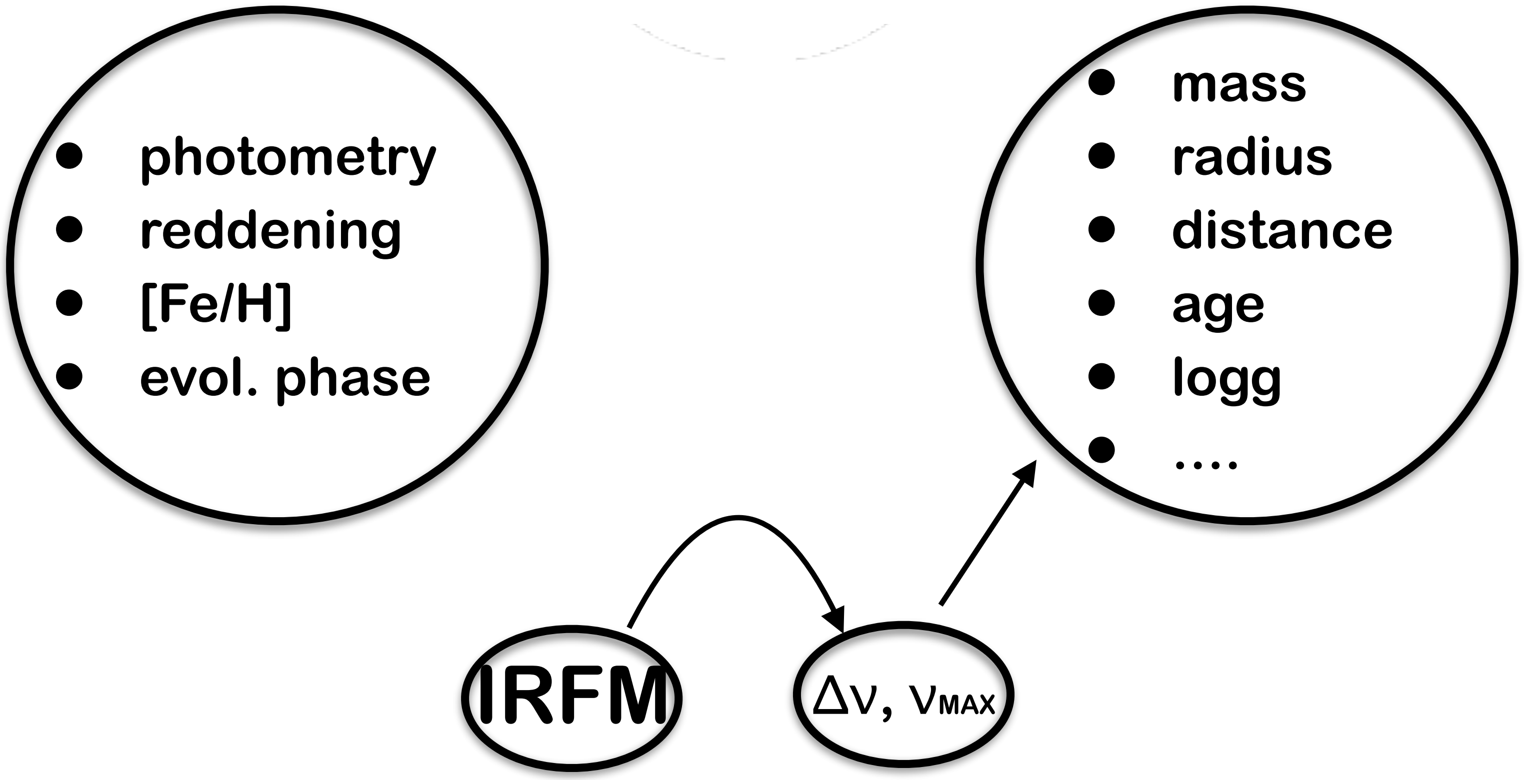
- photometry
- reddening
- [Fe/H]
- evol. phase

IRFM

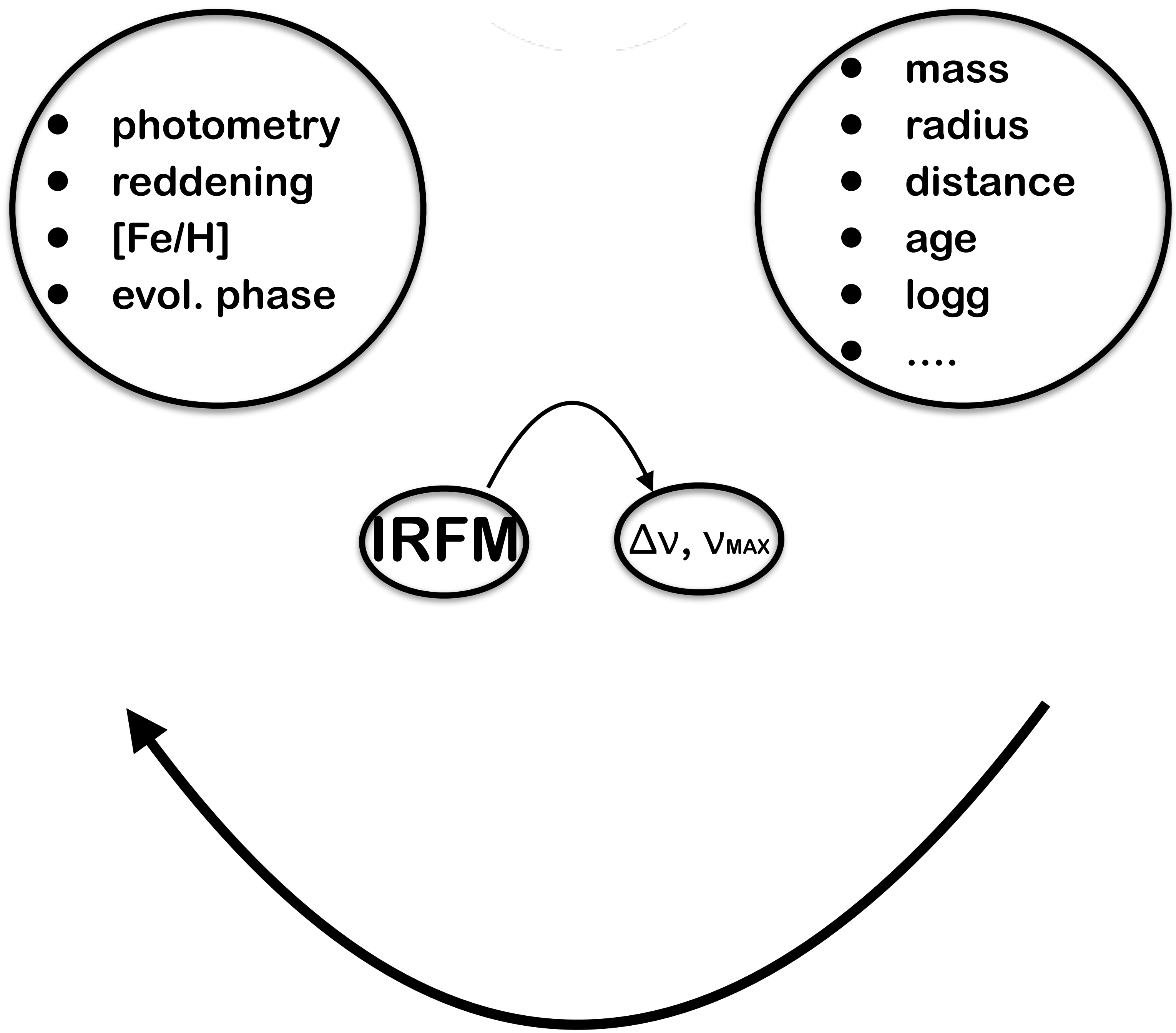
Coupling classical and seismic parameters

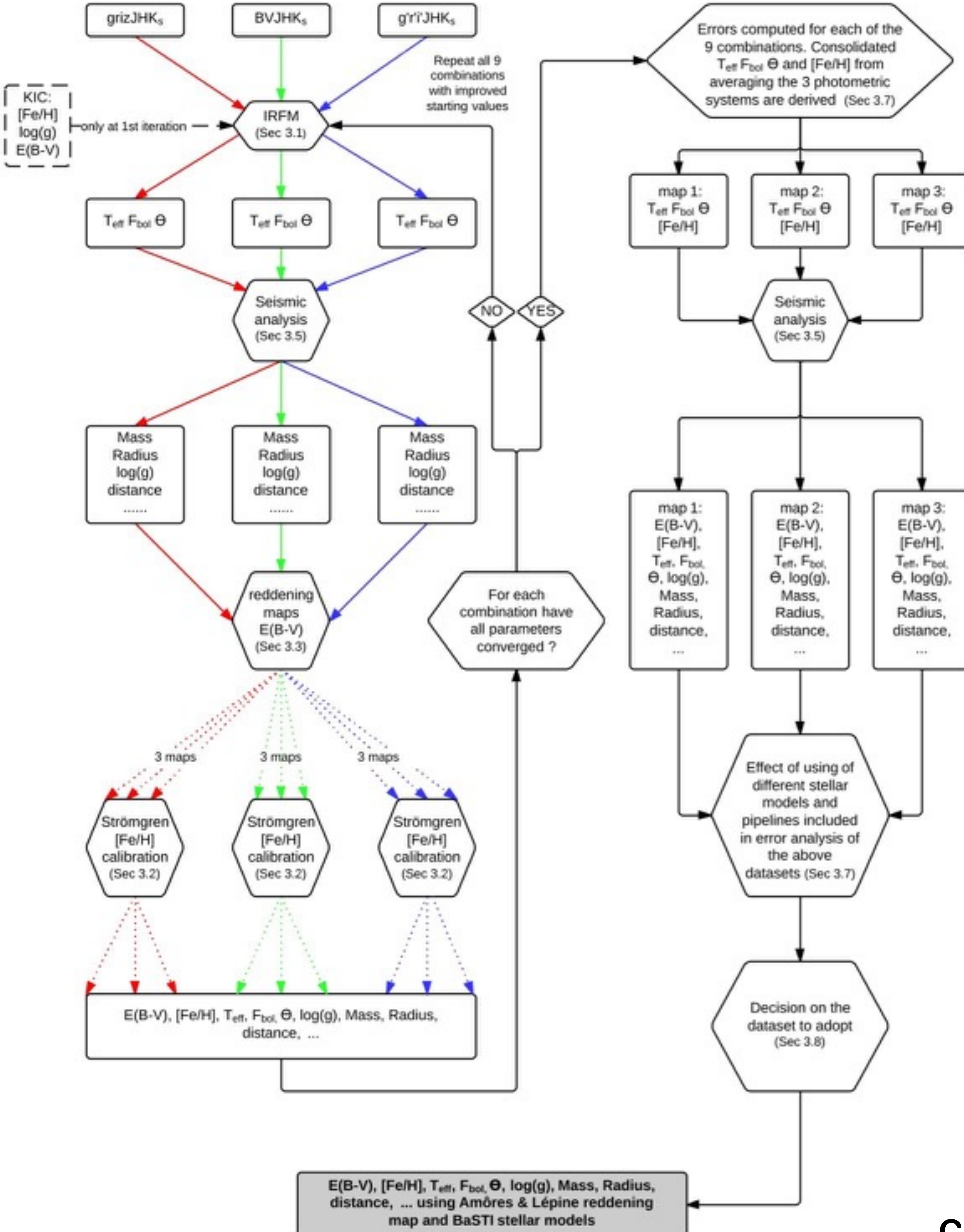


Coupling classical and seismic parameters



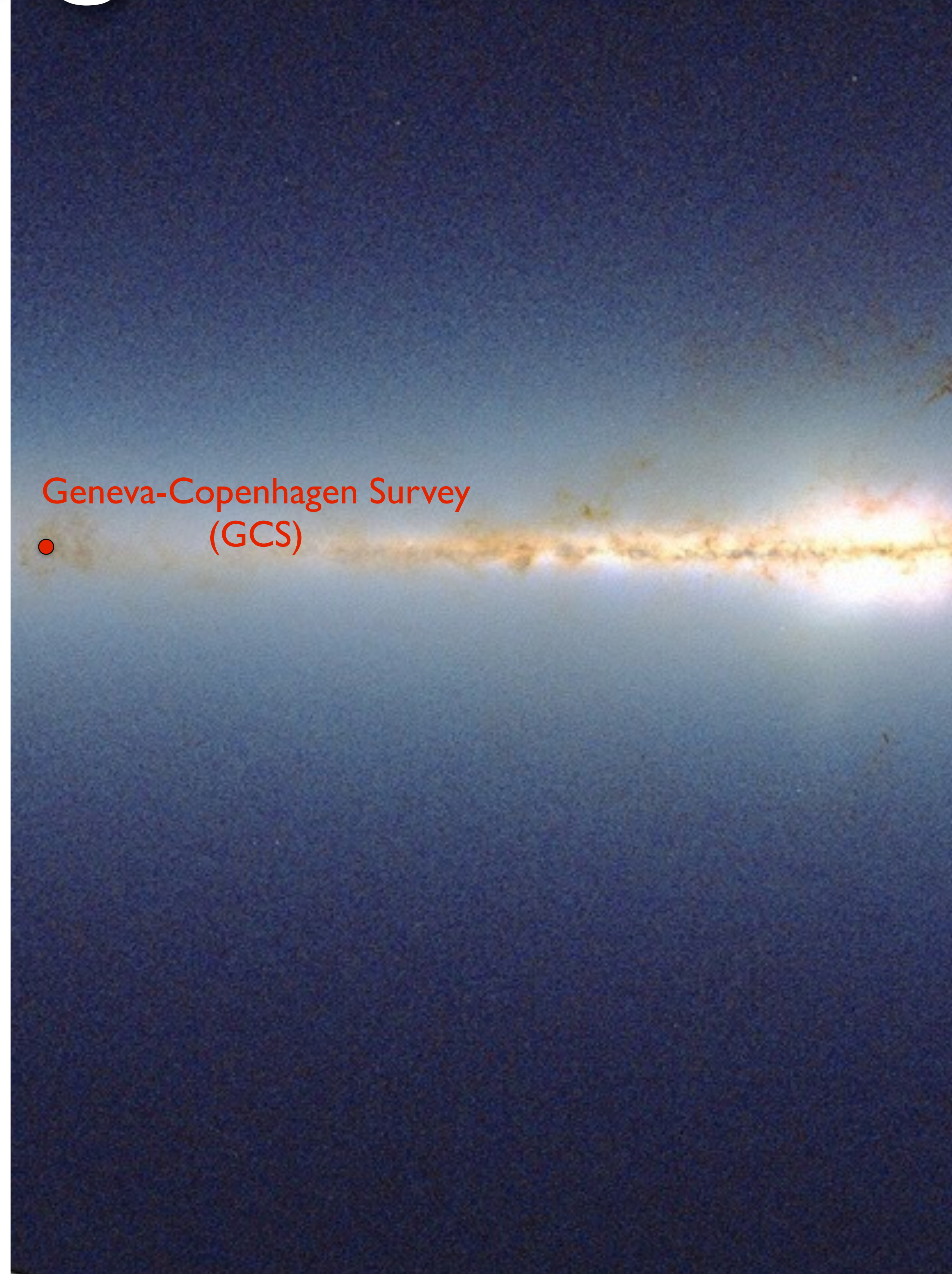
Coupling classical and seismic parameters



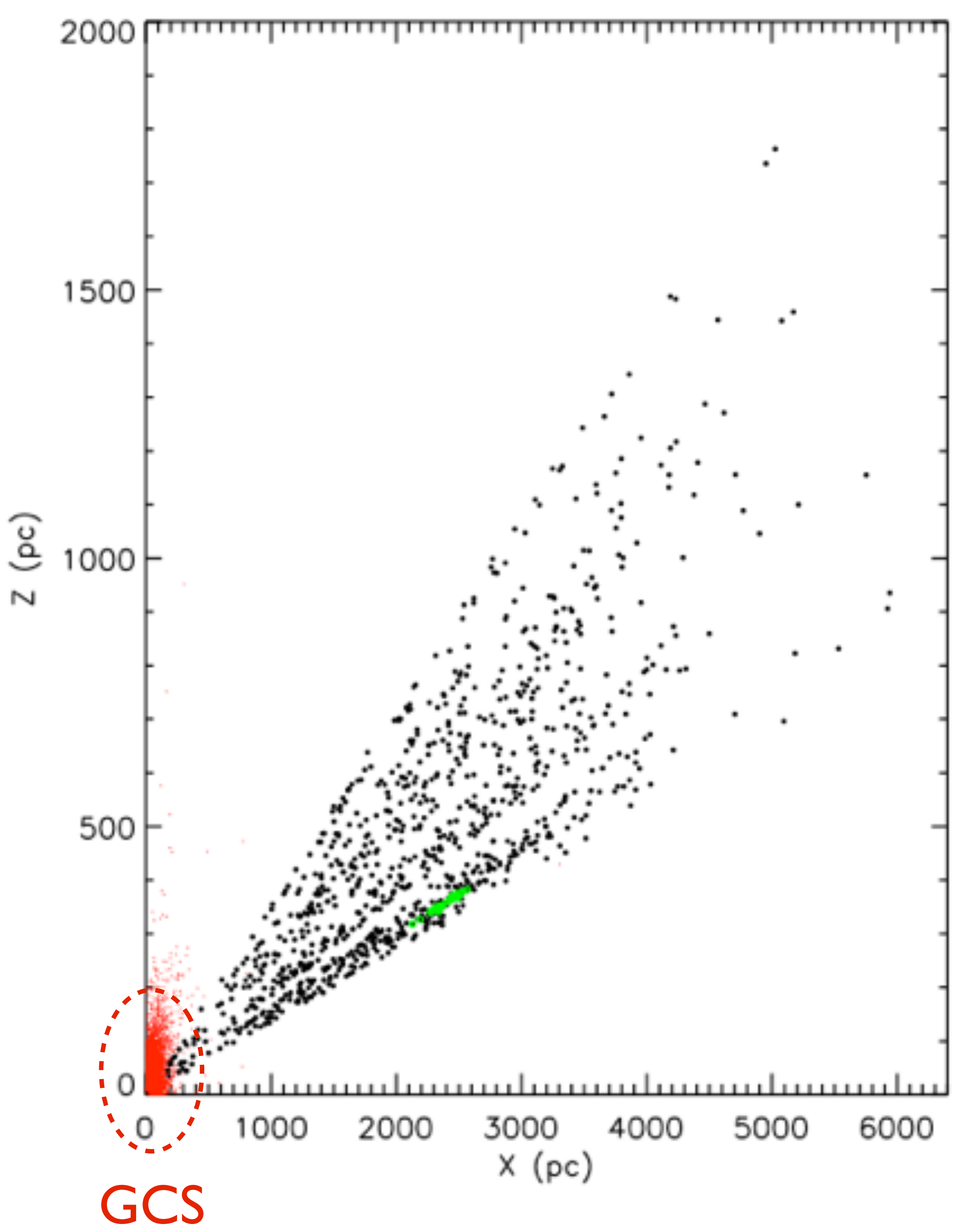


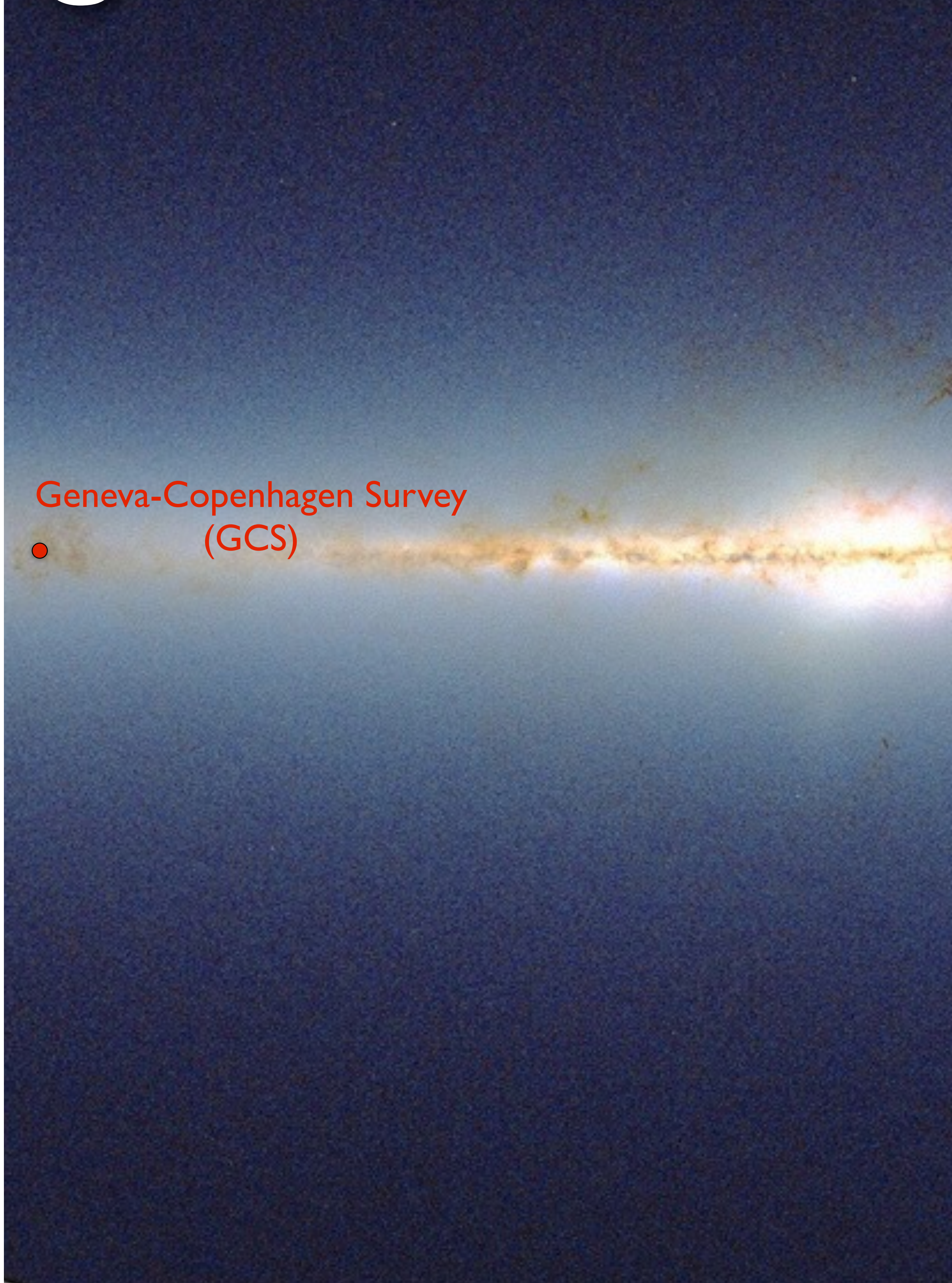
Casagrande et al. (2014)

Leaving the Neighbourhood

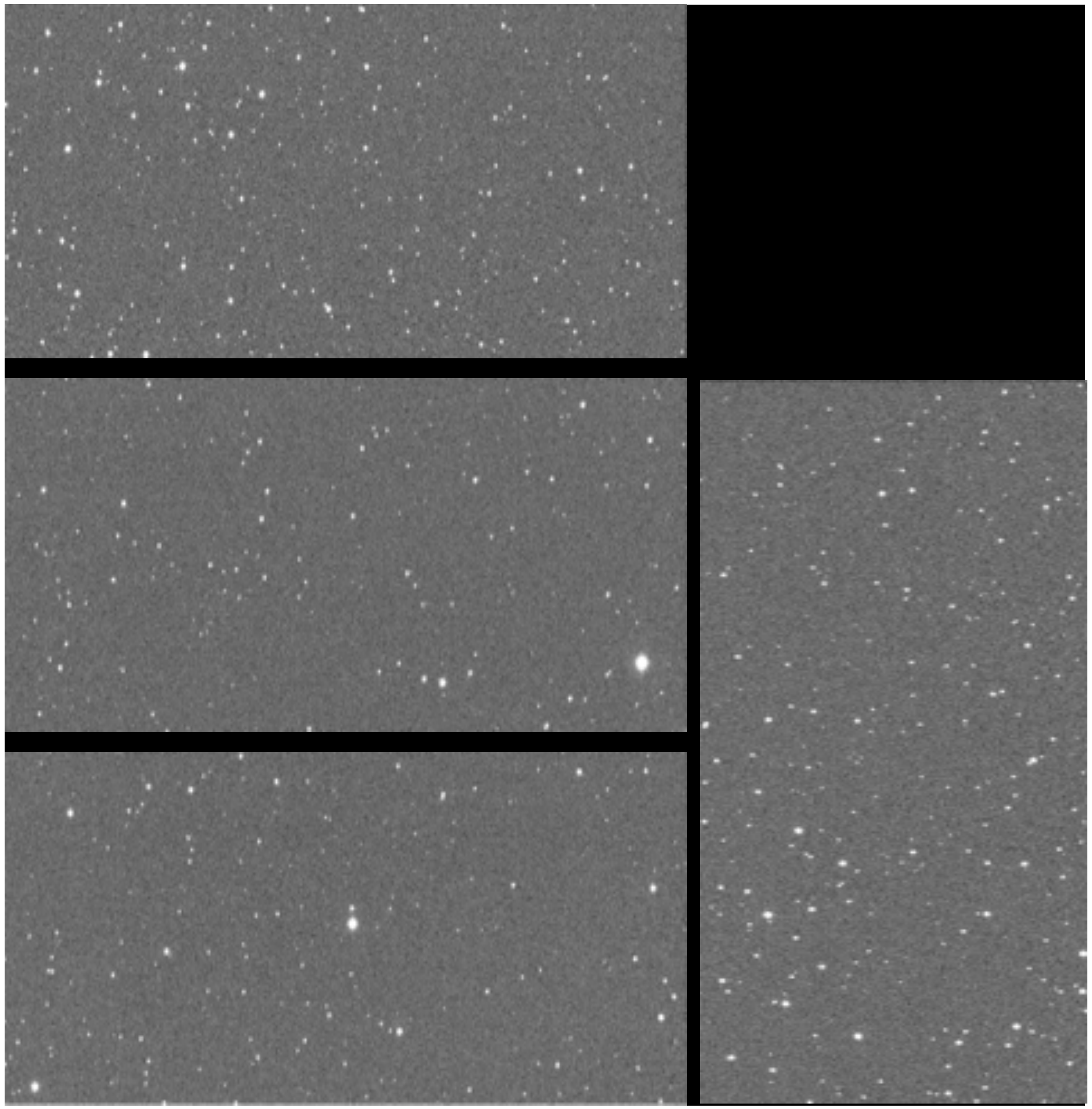


Leaving the Neighbourhood

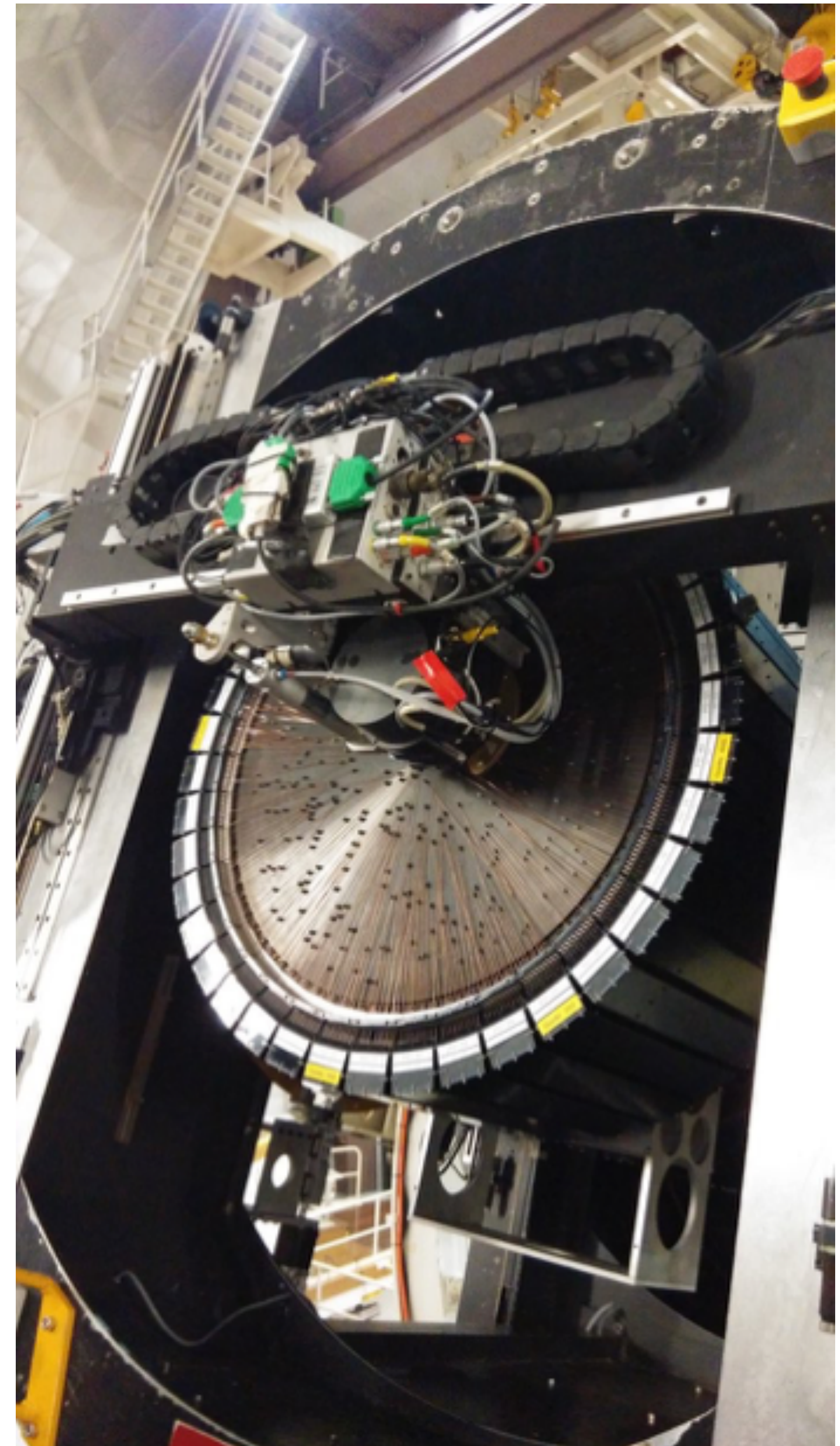




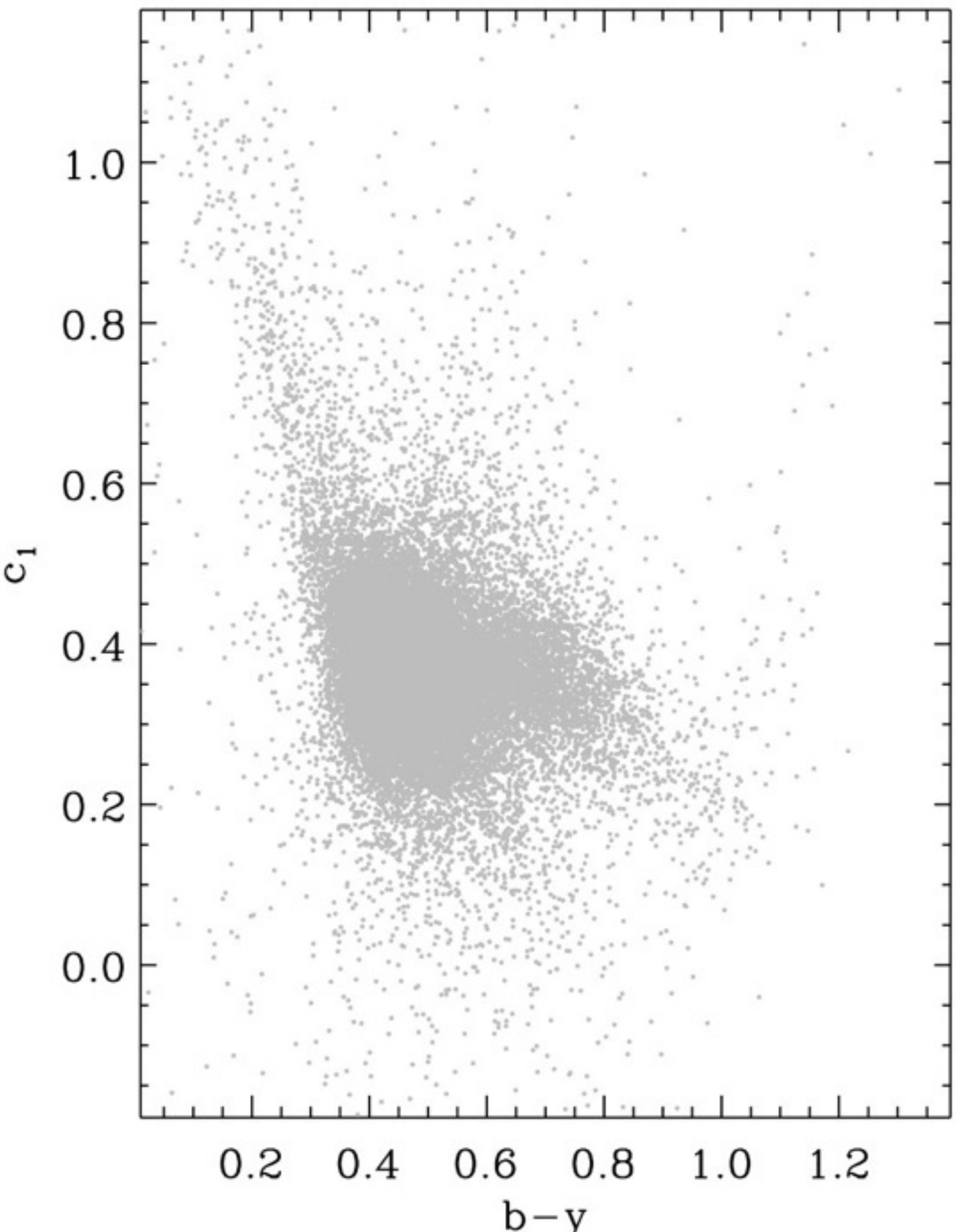
WFC @ INT



2dF @ AAO

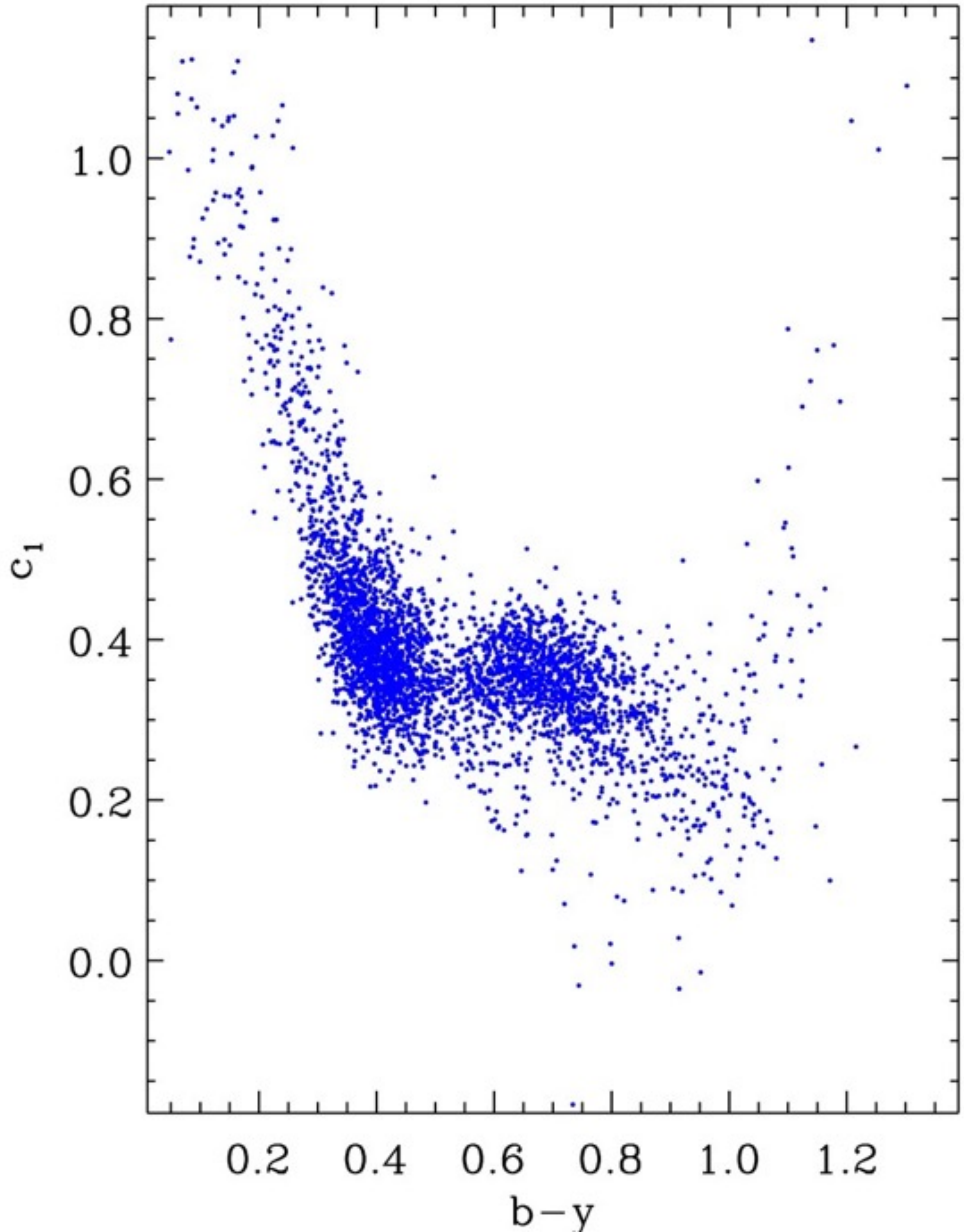


Benchmarking



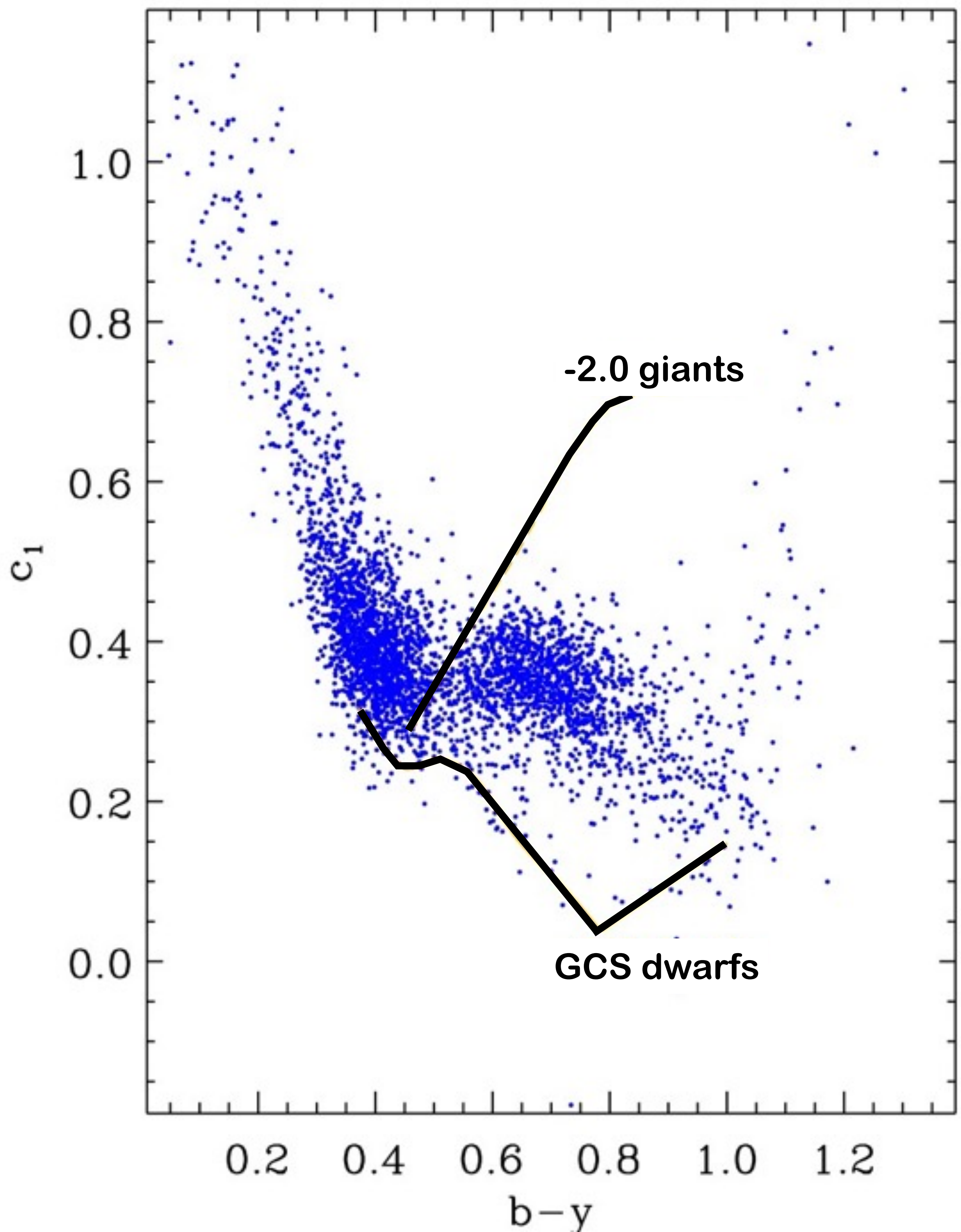
all stars

Benchmarking

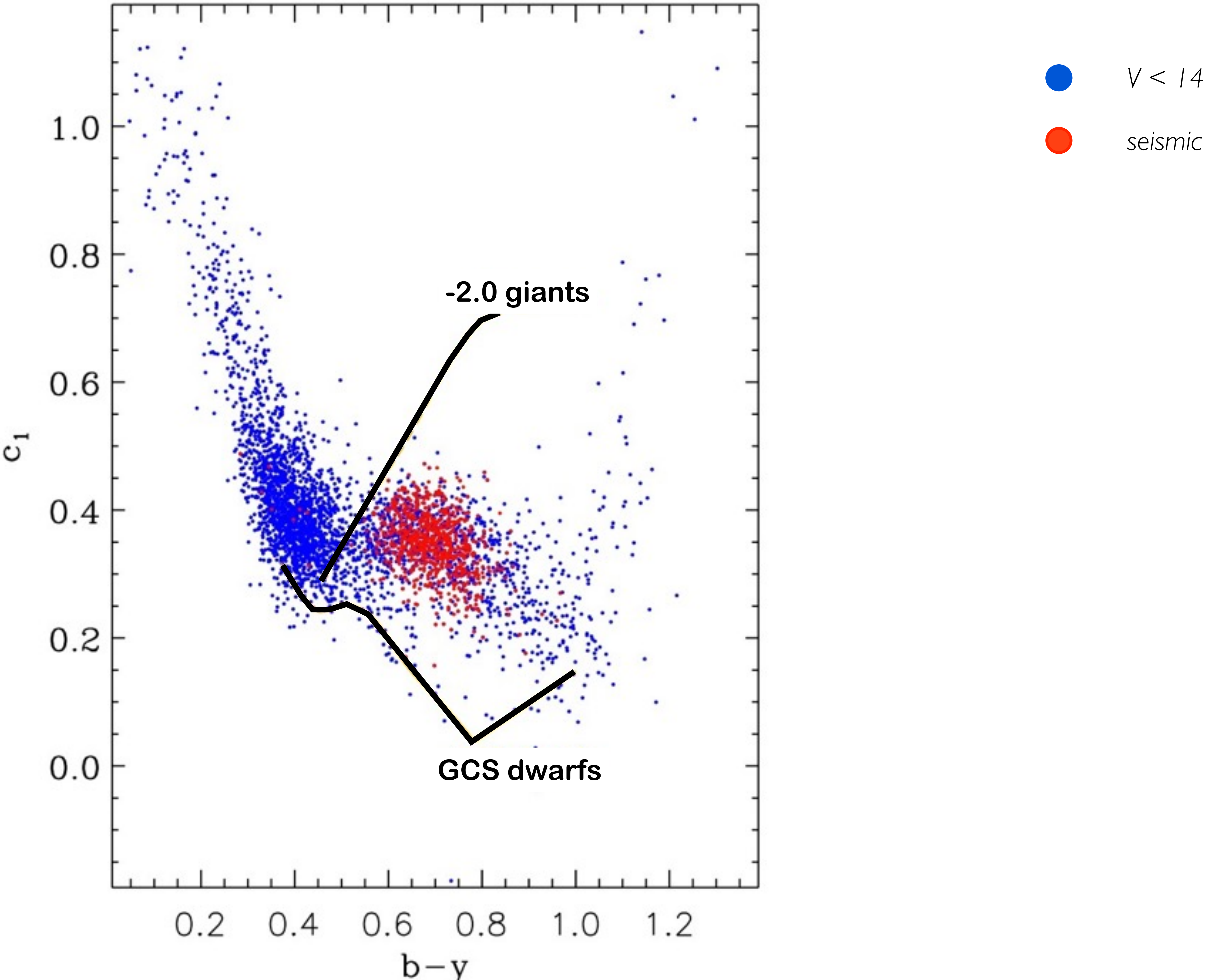


V < 14

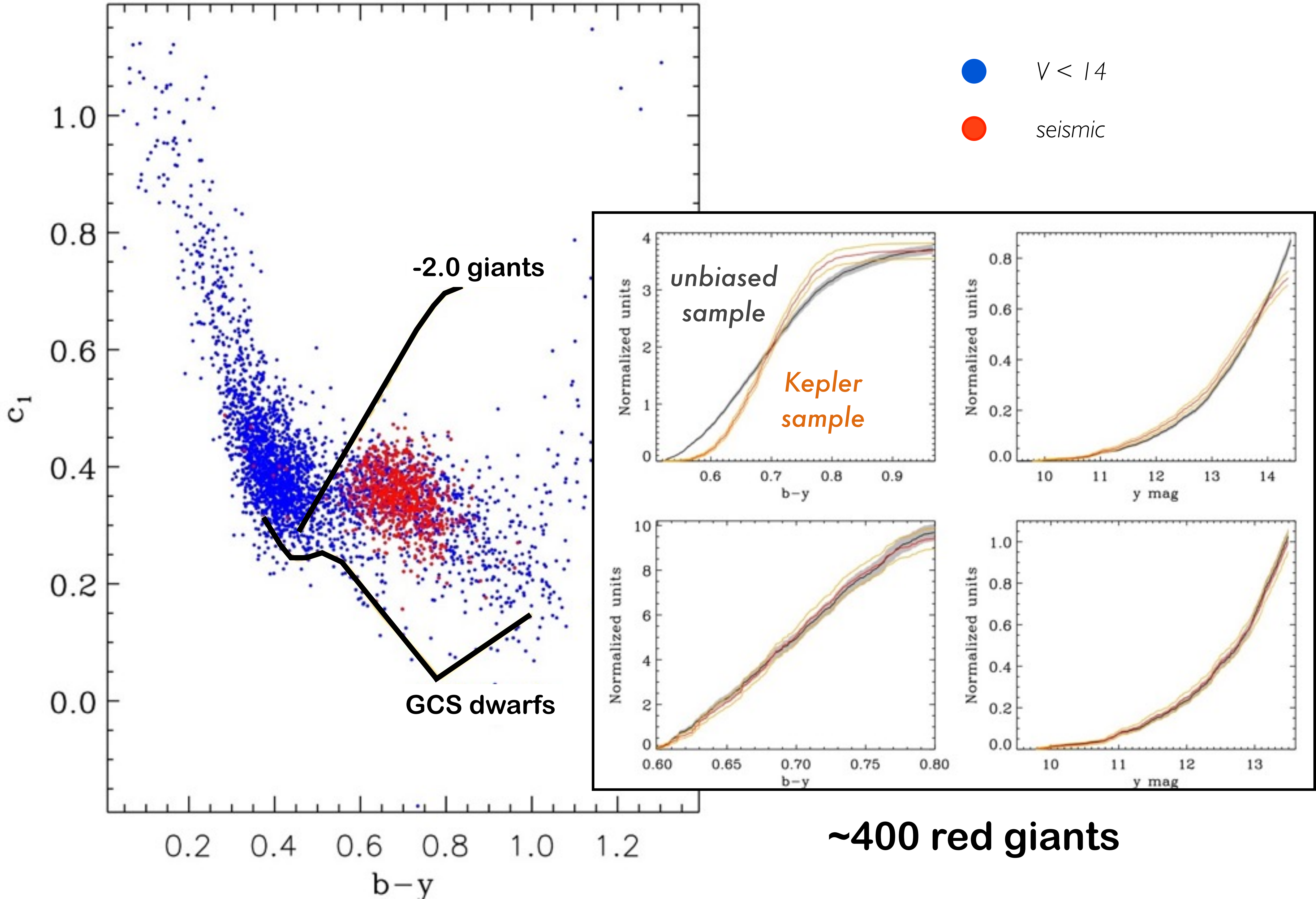
Benchmarking



Benchmarking



Benchmarking



~400 red giants

Conclusions

- In the spirit of this program, not not sure I should give conclusions!
- Pedantic photometric details do matter for precision photometric parameters (reddening!)
- The same constraints available for the Solar Neighbourhood (ages from GCS) soon to other part of the Galaxy
- Synergy with asteroseismology has just started
- The best is yet to come!