Challenges in Stellar Population Studies

Jarle Brinchmann (Leiden Observatory)

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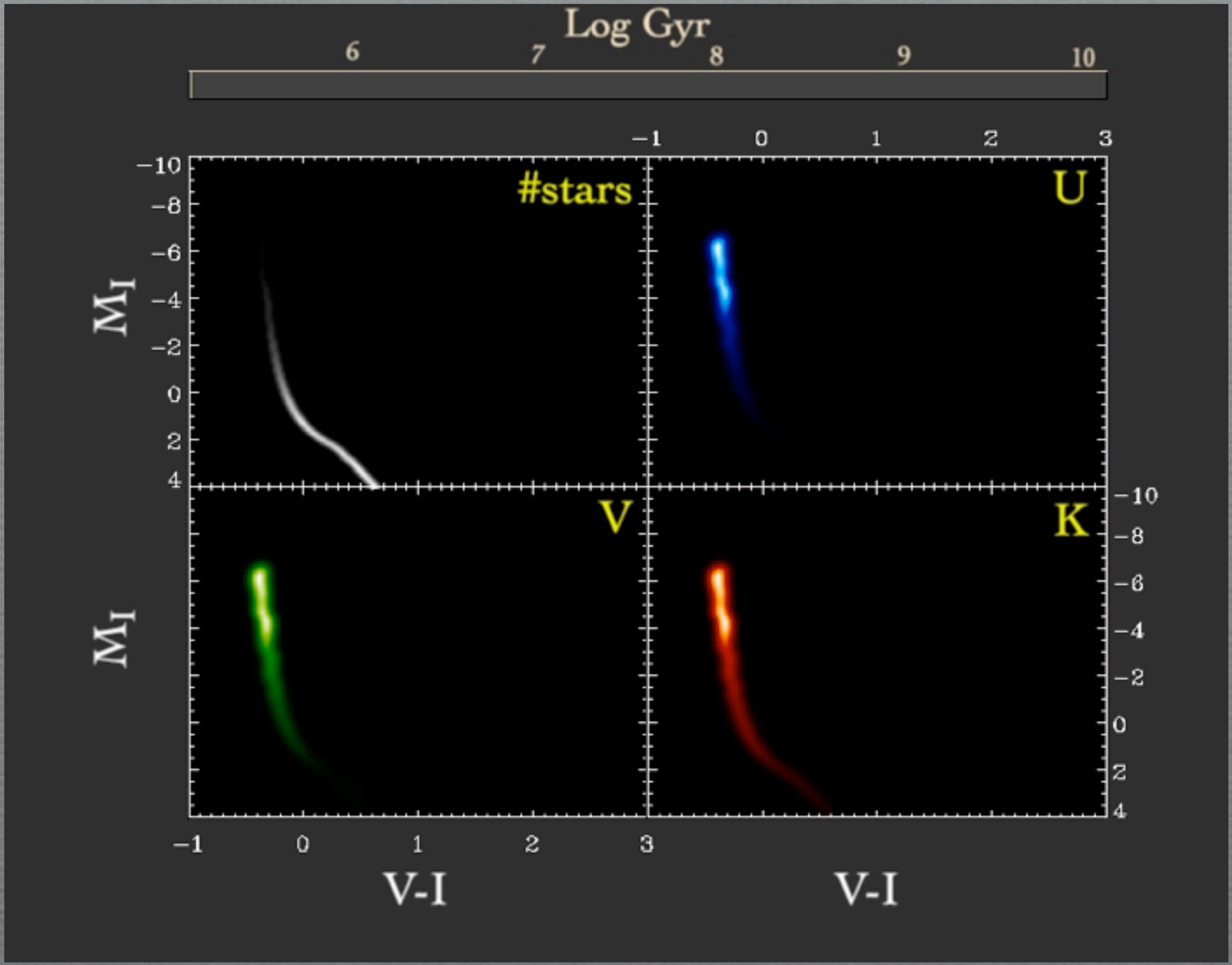
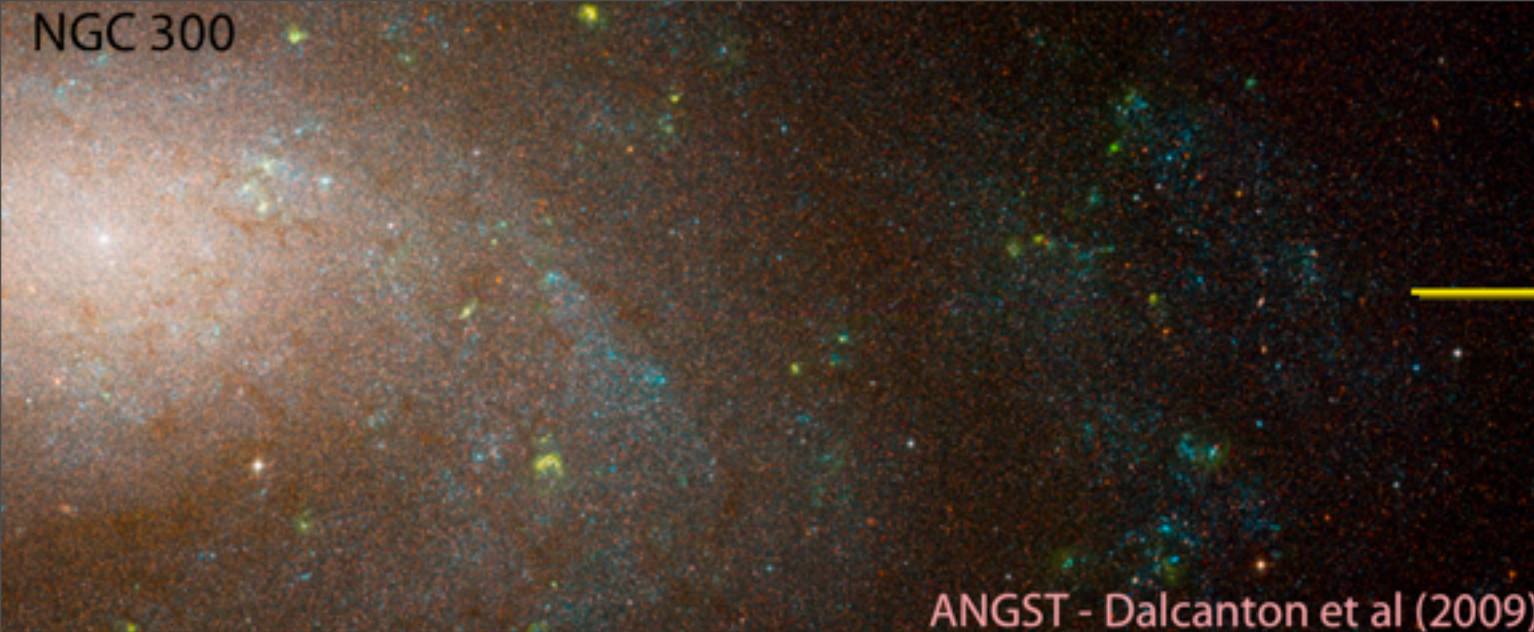
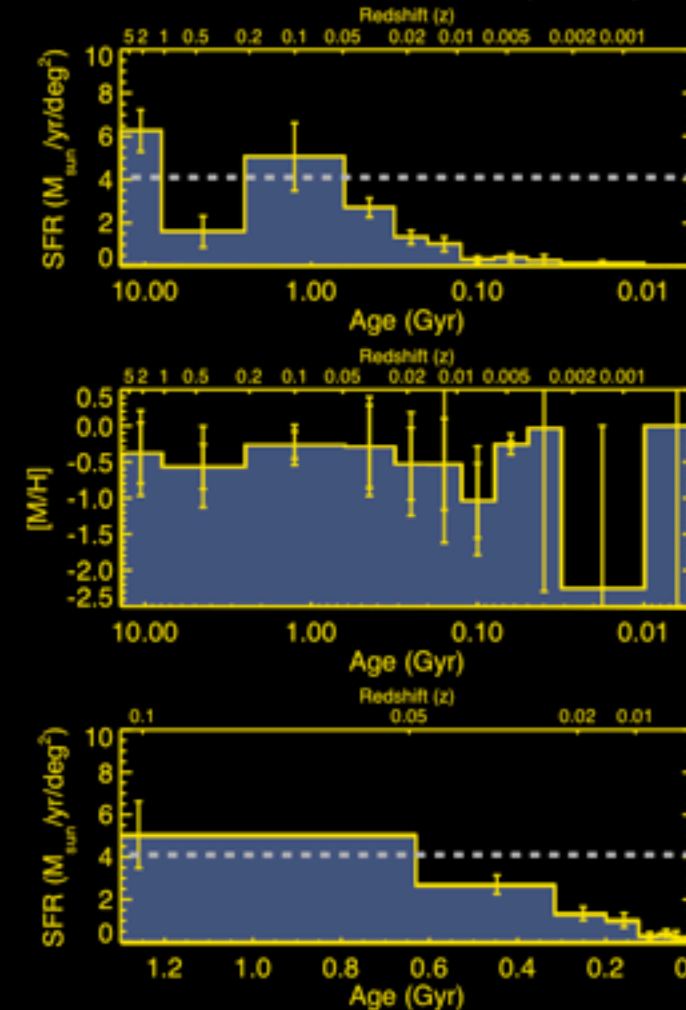




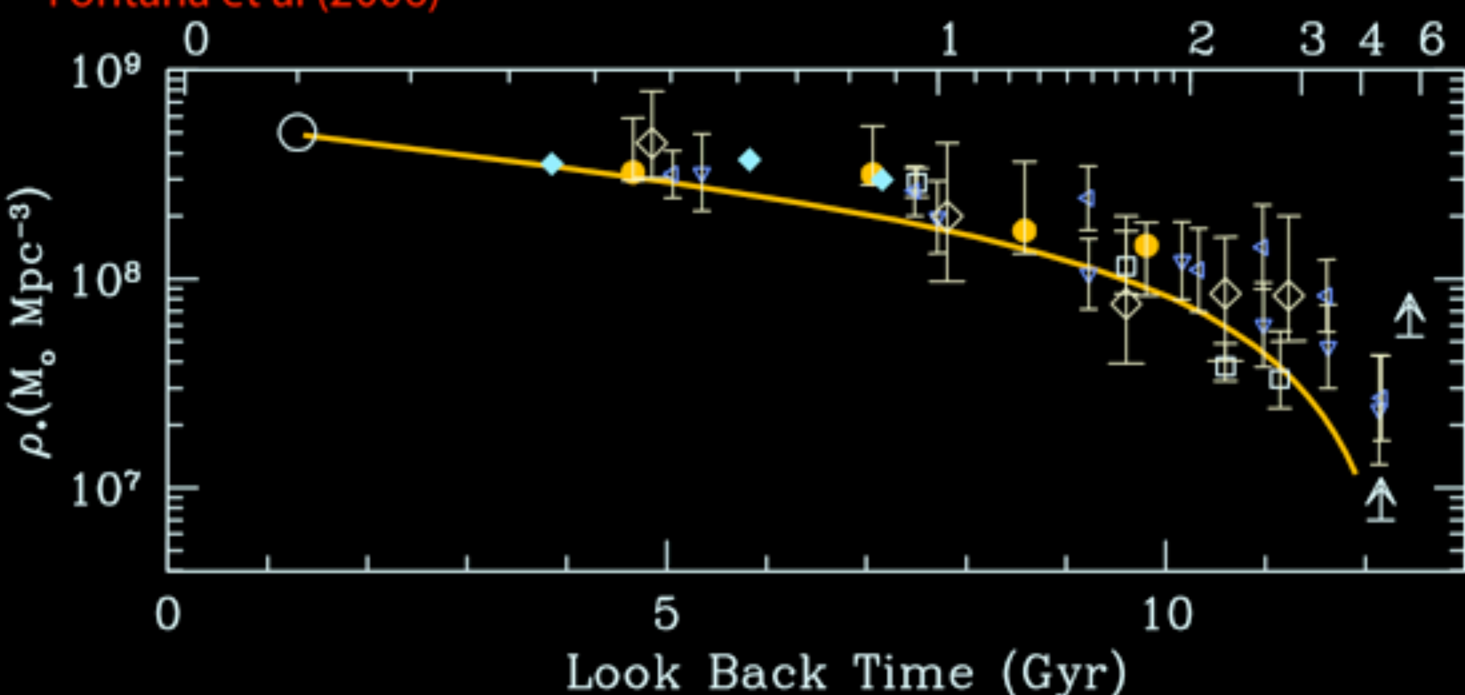
ANGST - Dalcanton et al (2009)

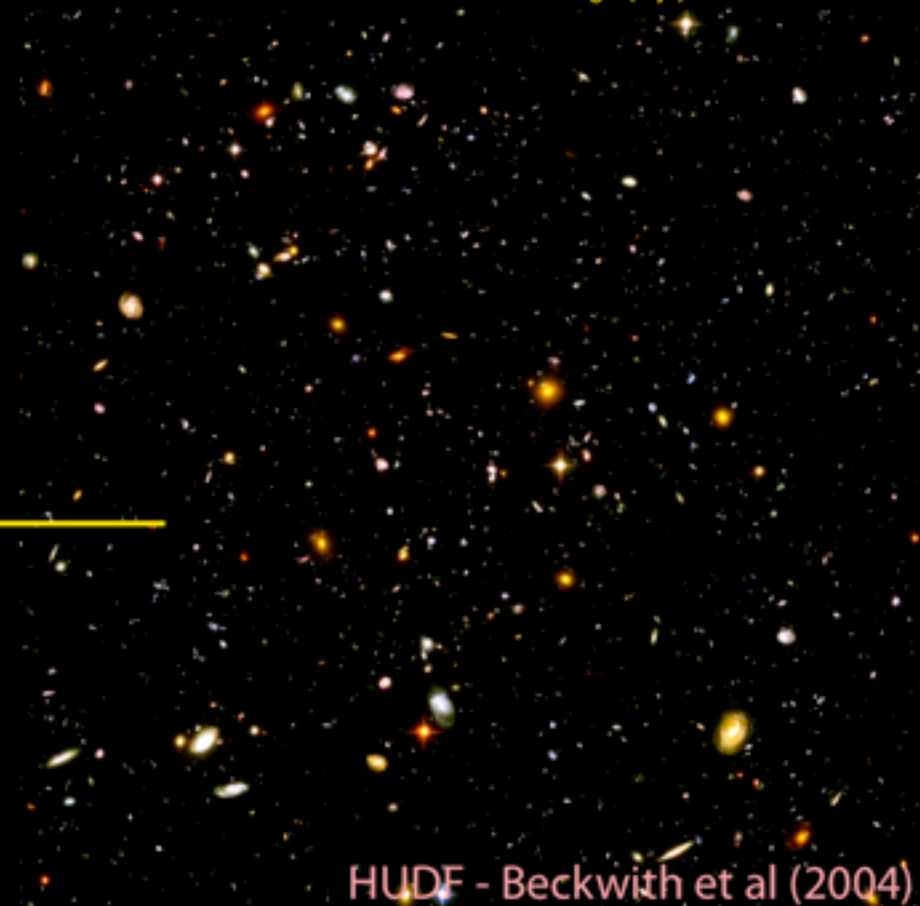
ANGST - Williams et al (2009)



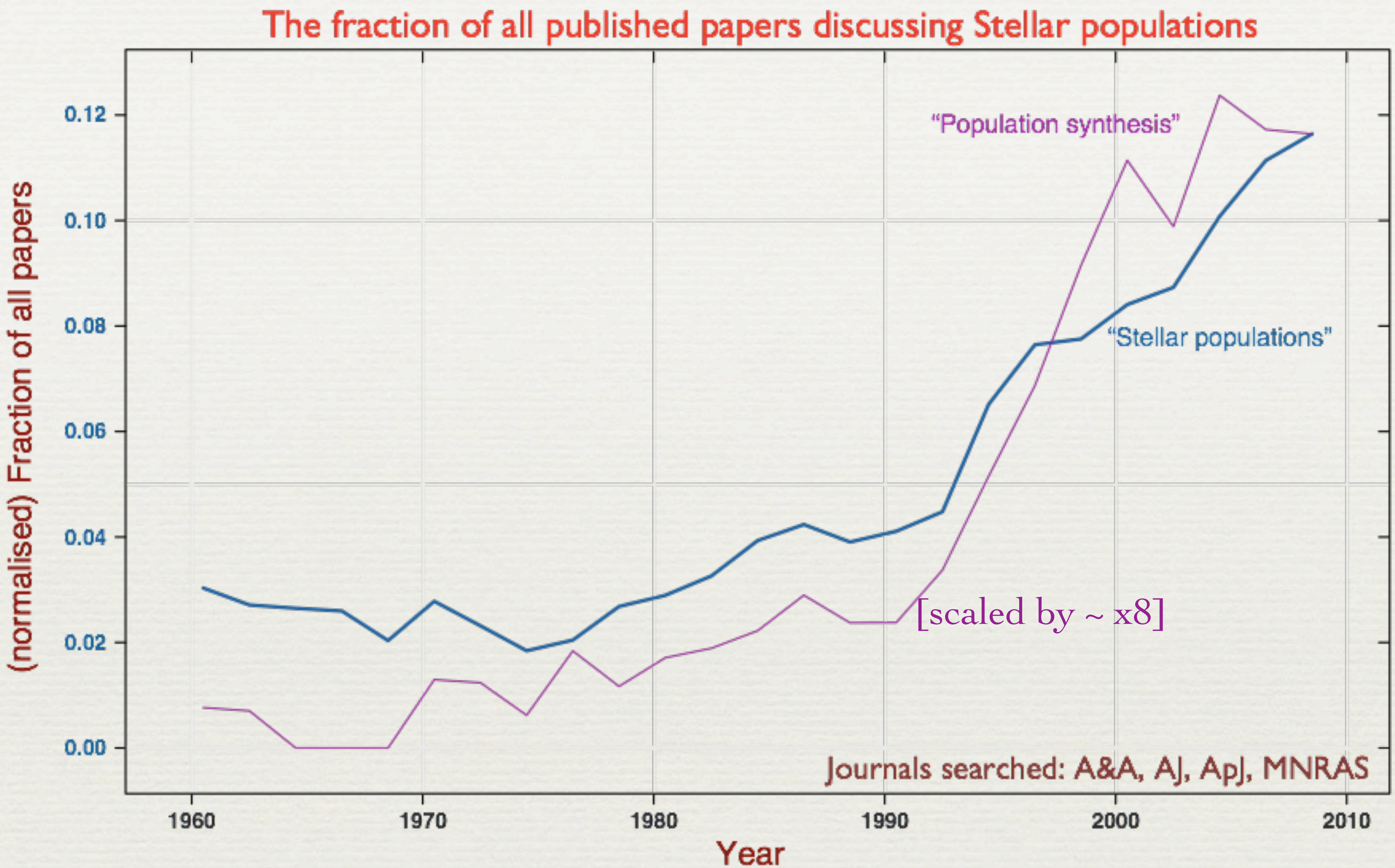
Why do we need stellar population modelling?

Fontana et al (2006)



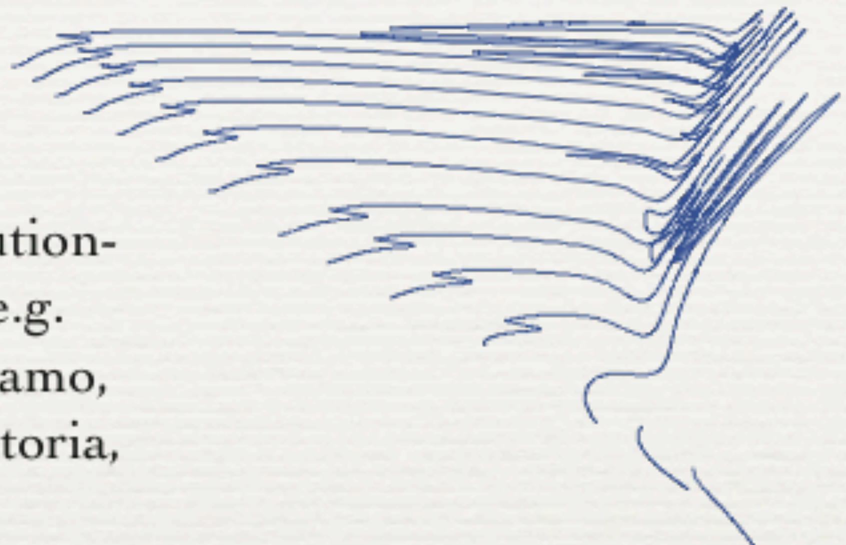


HUDF - Beckwith et al (2004)



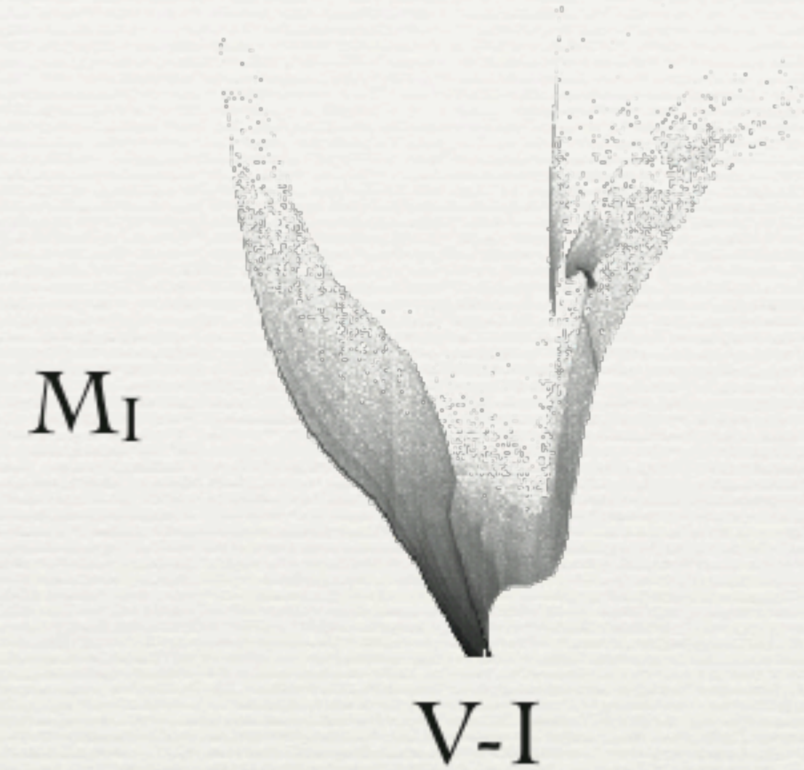
Today around **12%** of all papers published mention stellar populations in their abstract (half of these deal with modelling). Around ~**1.5%** mention population synthesis but this fraction has risen quickly. By 2080 all papers will deal with stellar populations!

Population synthesis

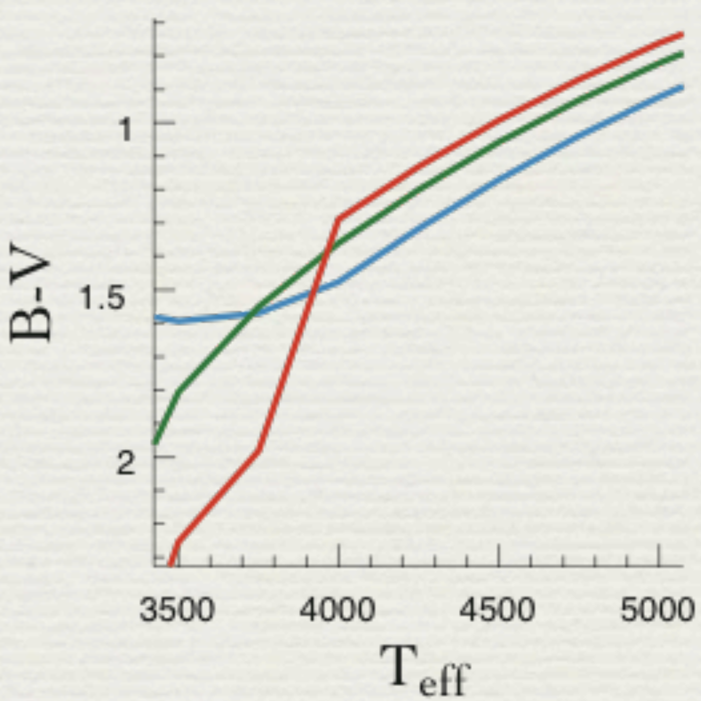


Stellar evolutionary tracks (e.g. Padova, Teramo, Geneva, Victoria, Yale)

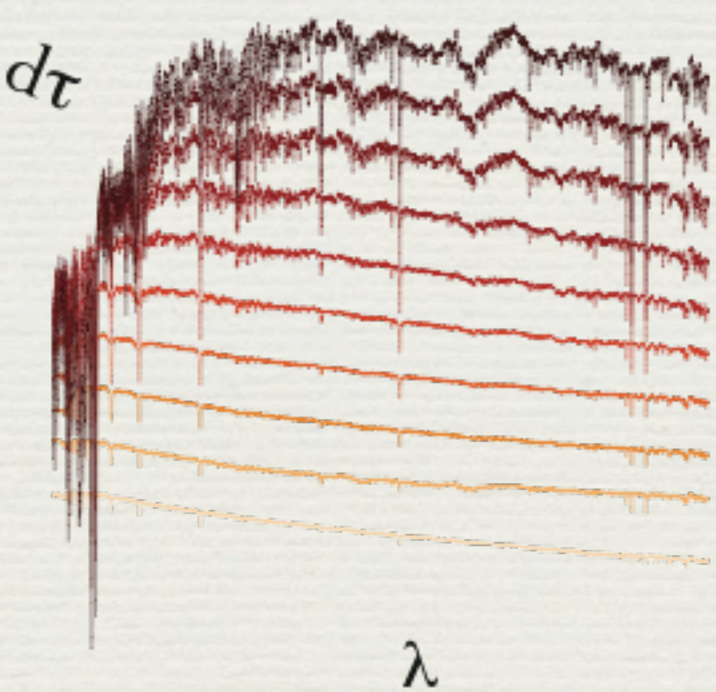
Monte-Carlo



Translation from HR diagram to observational features. E.g. BaSeL, Pickles, Stelib, MILES, IndoUS, ELODIE

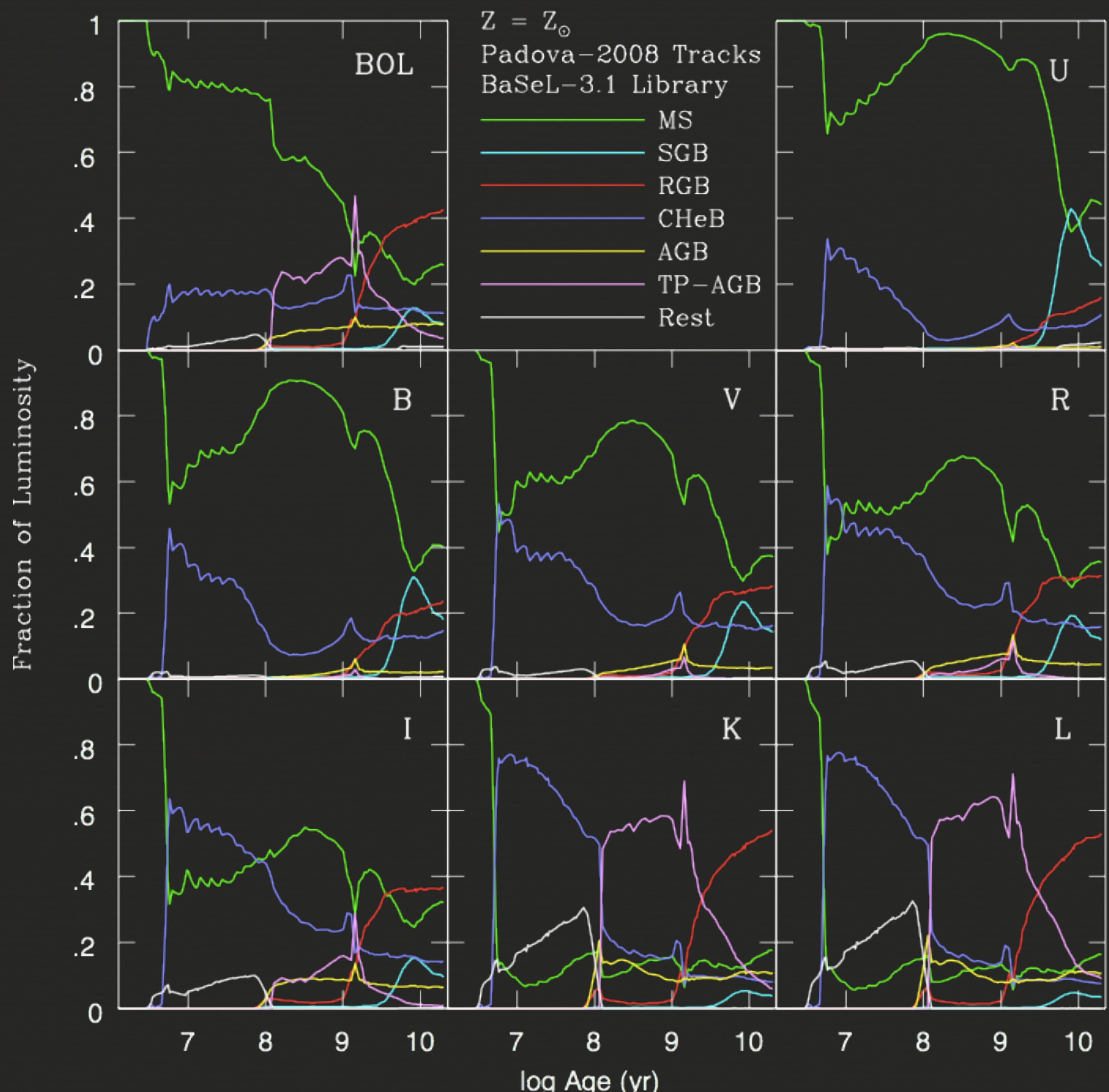


$$\int SFR(t-\tau)\, F(\lambda, \tau)\, d\tau$$



Comparison techniques

Figure courtesy G. Bruzual - the relative contribution to the flux of a single stellar population



Exponentially declining SFH with time-constant 6 Gyr, solar metallicity, Starburst 99, Padova 1994 tracks

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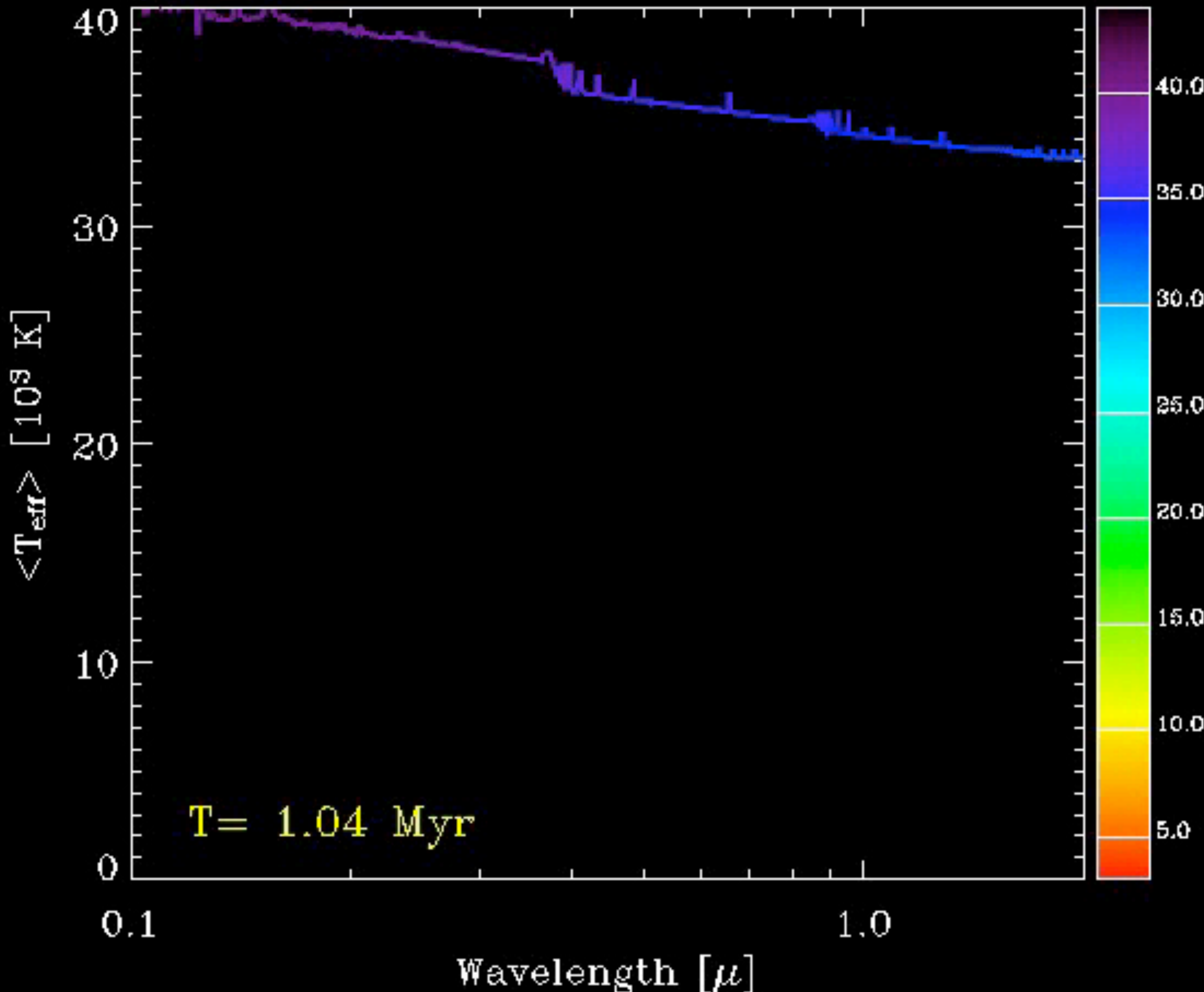
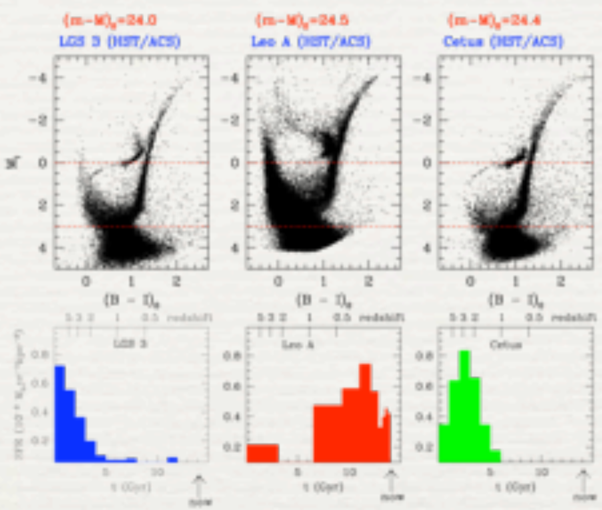


Some highlights



The SFH of nearby galaxies can be inferred from the distribution of stars in CMDs.

Beautiful example of the power of stars & also potentially excellent for testing stellar models.

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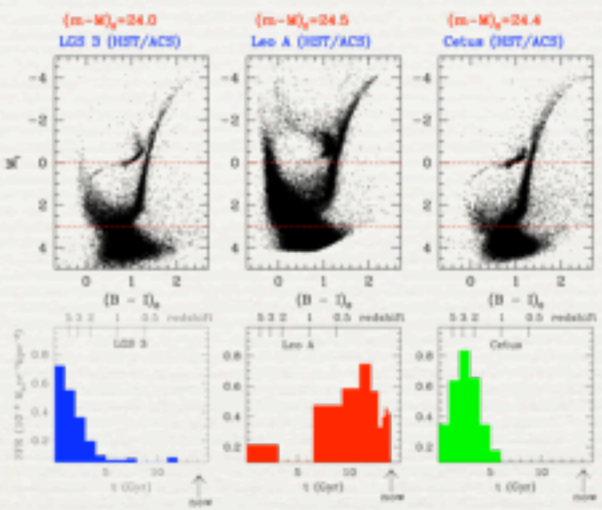

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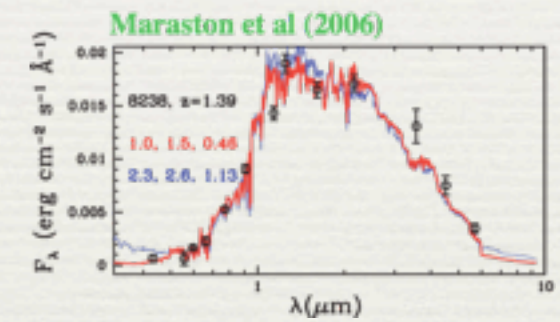
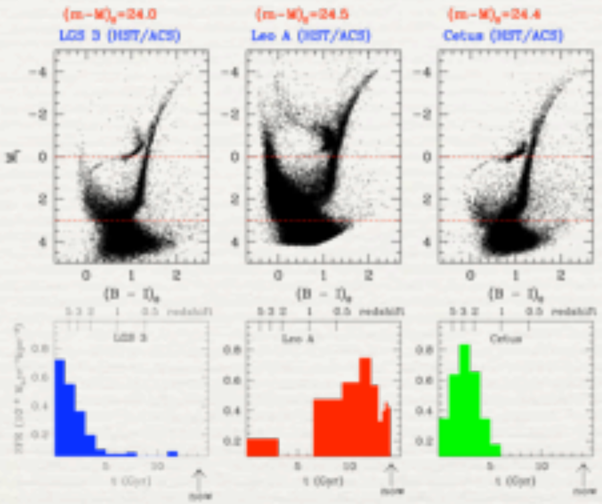


data ➙ models ➙ physical parameters

In particular, the stellar mass of a galaxy.

Some highlights



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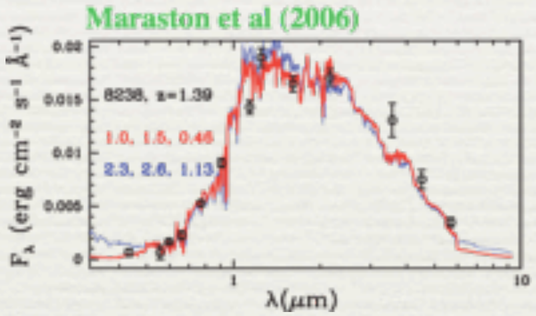

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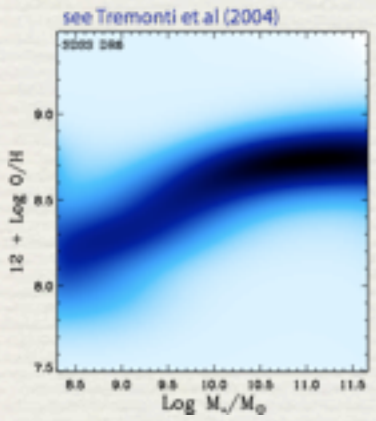
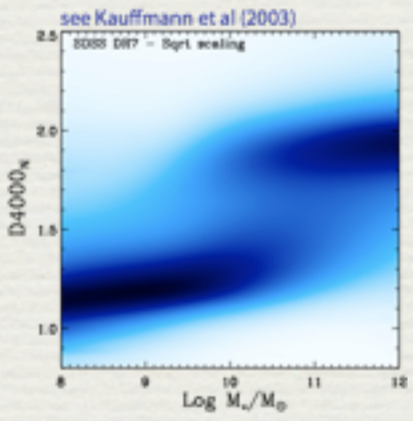
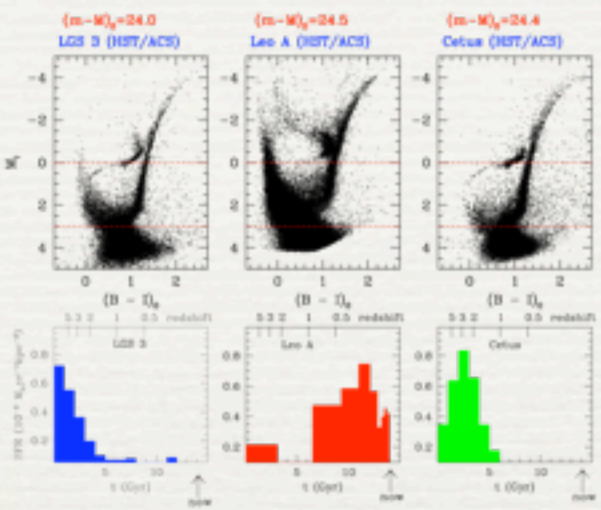




This has led to stellar mass having become the most important independent variable in galaxy evolution studies. And it has also allowed us to reconstruct the history of **stellar mass assembly** in the Universe.

Some highlights



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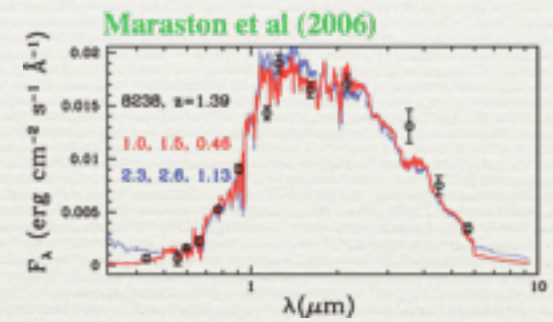

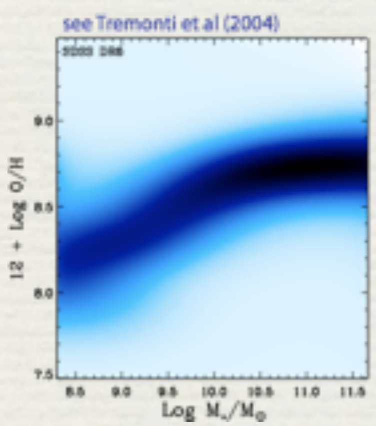

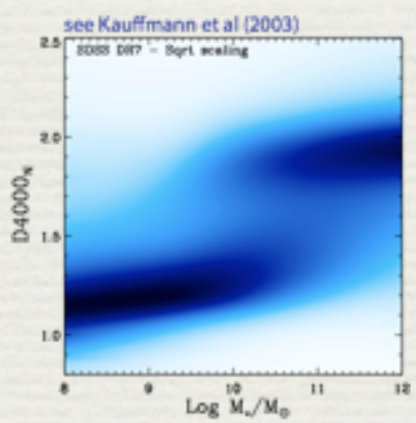

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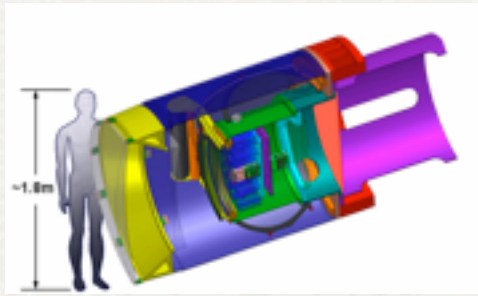
- Nature of massive galaxies (e.g. Lick indices).
- Fits of the full galaxy spectrum allowing the reconstruction of SFHs of large galaxy samples.
- Constrain stellar evolution through observations of galaxies.

The future - not only ELTs...

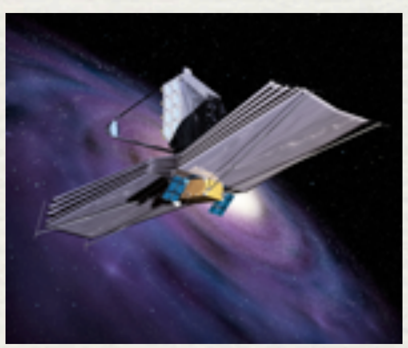
Surveys (e.g. VISTA, LSST, LAMOST, SDSS-III, GAIA):



Large samples, multi-wavelength surveys. Random uncertainties will be pushed significantly down. Mostly enlarging existing studies (SDSS, 2MASS, 2dF/6dFGRS, UKIDSS, RAVE etc. etc.)

Requires good control of systematic uncertainties.
Will open for systematic studies in the **time-domain**.

James Webb Space Telescope (JWST):



It will transform the way we look at the extra-galactic sky. **NIR** & **MIR** will become much more important overall than now.

Will require good stellar populations models over a wide range in wavelength & in time.

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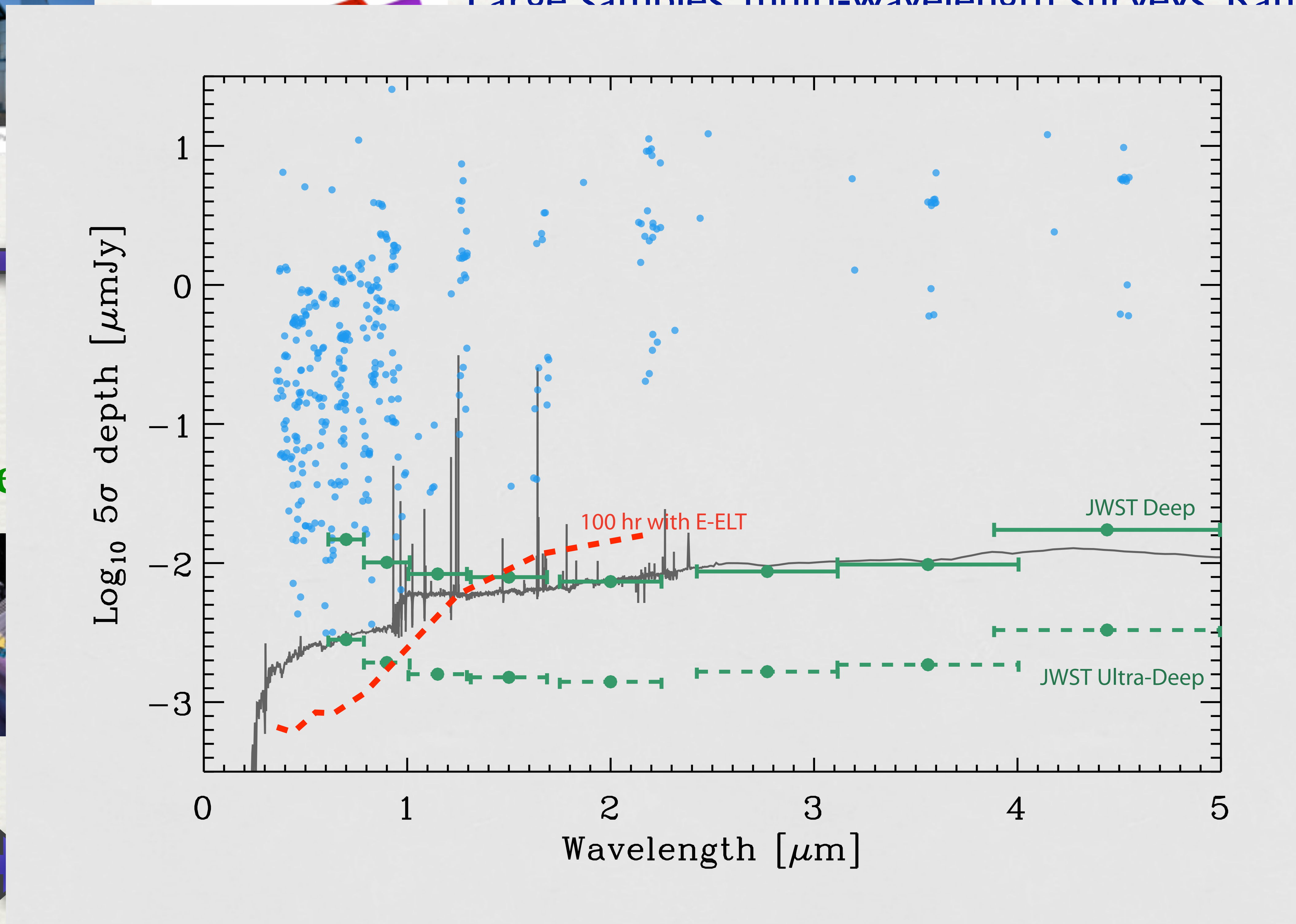
IDSS, RAVE

nain.

Jame



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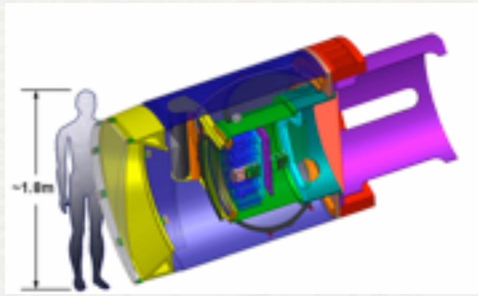

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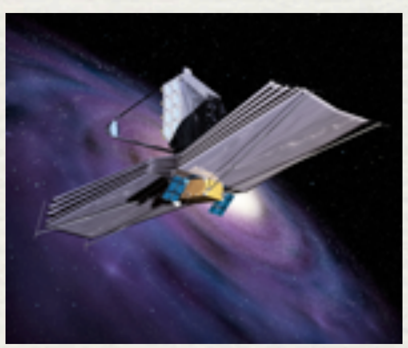

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Will require good stellar populations models over a wide range in wavelength & in time.

Extremely Large Telescopes

- Large collecting area ➙ faint/distant sources, high spectral resolution.
  - Any wavelength, will be comparable/better than JWST at λ < 1 μm. Seeing limited in optical (e.g. MOBIE/WFOS on TMT, OPTIMOS on E-ELT, GMACS on GMT) or **AO** assisted in the **near-IR** (e.g. NIRMOS/GMTNIRS on GMT, IRIS/NIRES on TMT, HARMONI/SIMPLE for E-ELT)
  - Distant galaxies (rest-UV/optical), nearby stellar populations (optical for faint, near-IR for distant/confused).
- Large diameter ➙ very high spatial resolution
  - Mainly applicable for near-/mid-IR (e.g. EAGLE/MICADOR/METIS for E-ELT, IRIS/IRMOS/WIRC for TMT, GMTIFS/HRCam/MIISE on GMT)
  - Resolved stellar populations, distant galaxies, galaxy evolution & assembly.

- Very faint objects in the optical-MIR (imaging & spectroscopy)
  - Can we determine galaxy properties accurately?
  - Are models good enough to exploit rest-frame NIR data fully?
  - Are model spectra of good enough quality for comparisons?
- Very high spatial resolution in the NIR (imaging & spectroscopy), much improved resolution in the MIR & optical.
  - Resolved stellar populations - systematic uncertainties?
  - Surface brightness fluctuations - what can we learn about rare stellar evolutionary stages?
- Very large samples over wide areas of sky (optical, NIR)
  - Galaxy properties/NIR data - can we exploit the data fully?
- Time-variability studies on an entirely new scale.
  - Should we seek to exploit this further in modelling of stellar populations? Are models good enough?

Challenges (opportunities)

Model uncertainties - how do you quantify them?

The Near-IR - are the models good enough? (stellar masses)

Can we make use of high quality data? Non-solar abundance ratios

The IMF - the elephant in the room

Do we understand the properties of the first stars?

The rest-UV - a window to massive stars

Binaries - crucial or avoidable?

Sources of *Modelling* Uncertainty

- Observational uncertainties in the empirical data (e.g. spectra) included in the models.
- Uncertainties in atomic data.
- Mismatch between observed stars and theoretical tracks (e.g. metallicity, age, T_{eff}, log g). E.g. for TP-AGB stars.
- Numerical uncertainties in the model calculation (e.g. interpolation artefacts, numerical precision).
- Treatment of uncertain/untractable phases of stellar evolution (e.g. HB stars, post-AGBs; binaries) - how do we deal with stochastic processes?

First attempt to integrate this into a pop. synth. code: Conroy et al (2009)

Sources of *Modelling* Uncertainty

- Observational uncertainties in the empirical data (e.g. spectra) included in the models.

These uncertainties must be understood for high S/N data. This is a major challenge for the next generation of models. An alternative is to use observations to construct an *empirical* uncertainty estimate.

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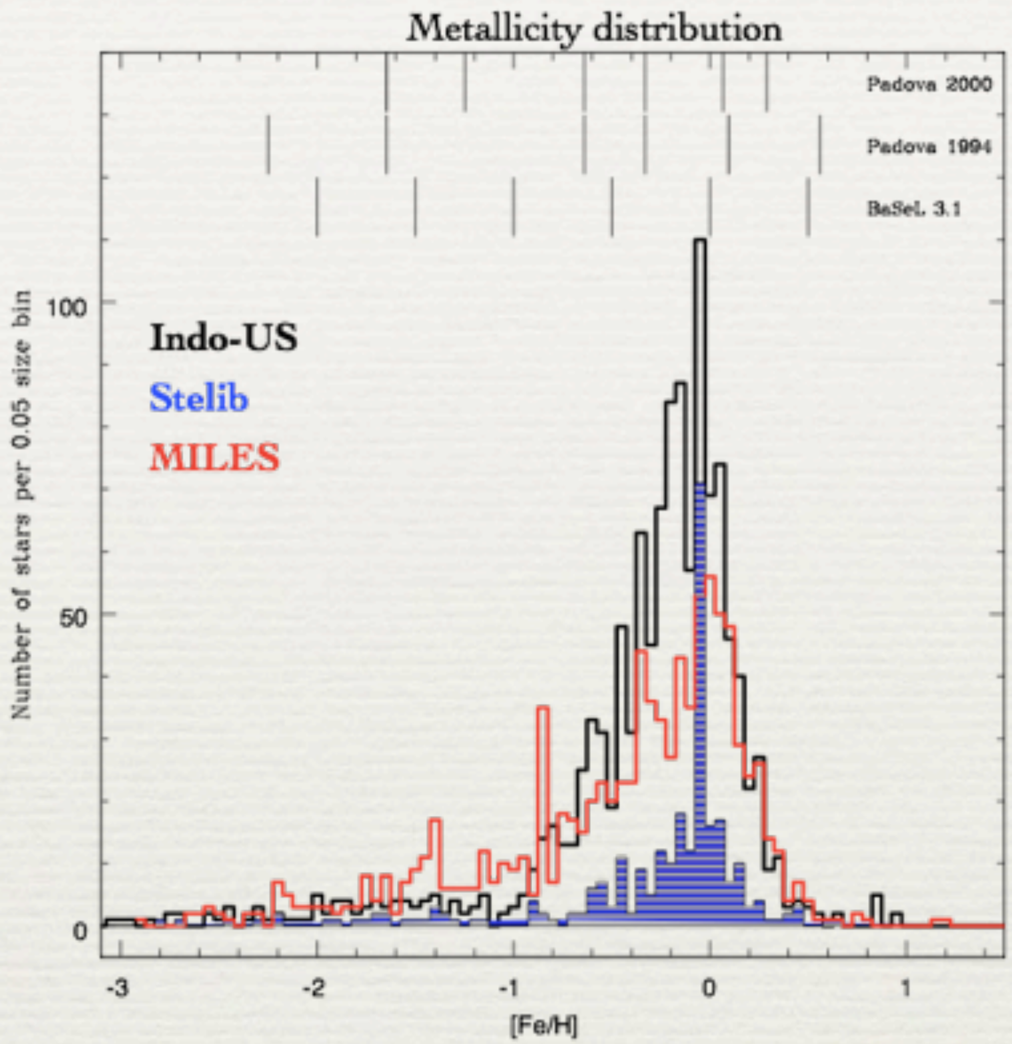
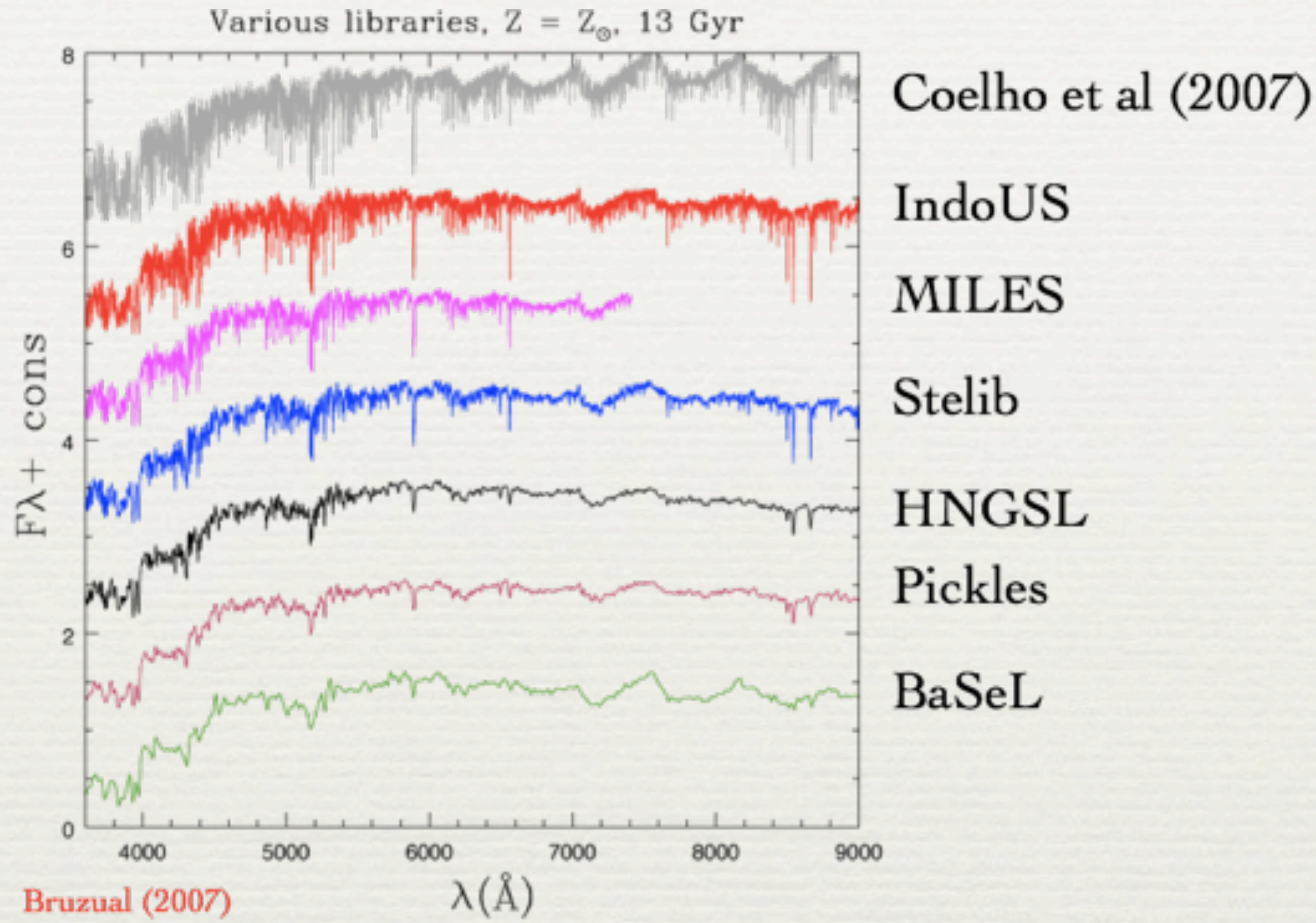
Spectral resolution & sampling of the HR diagram





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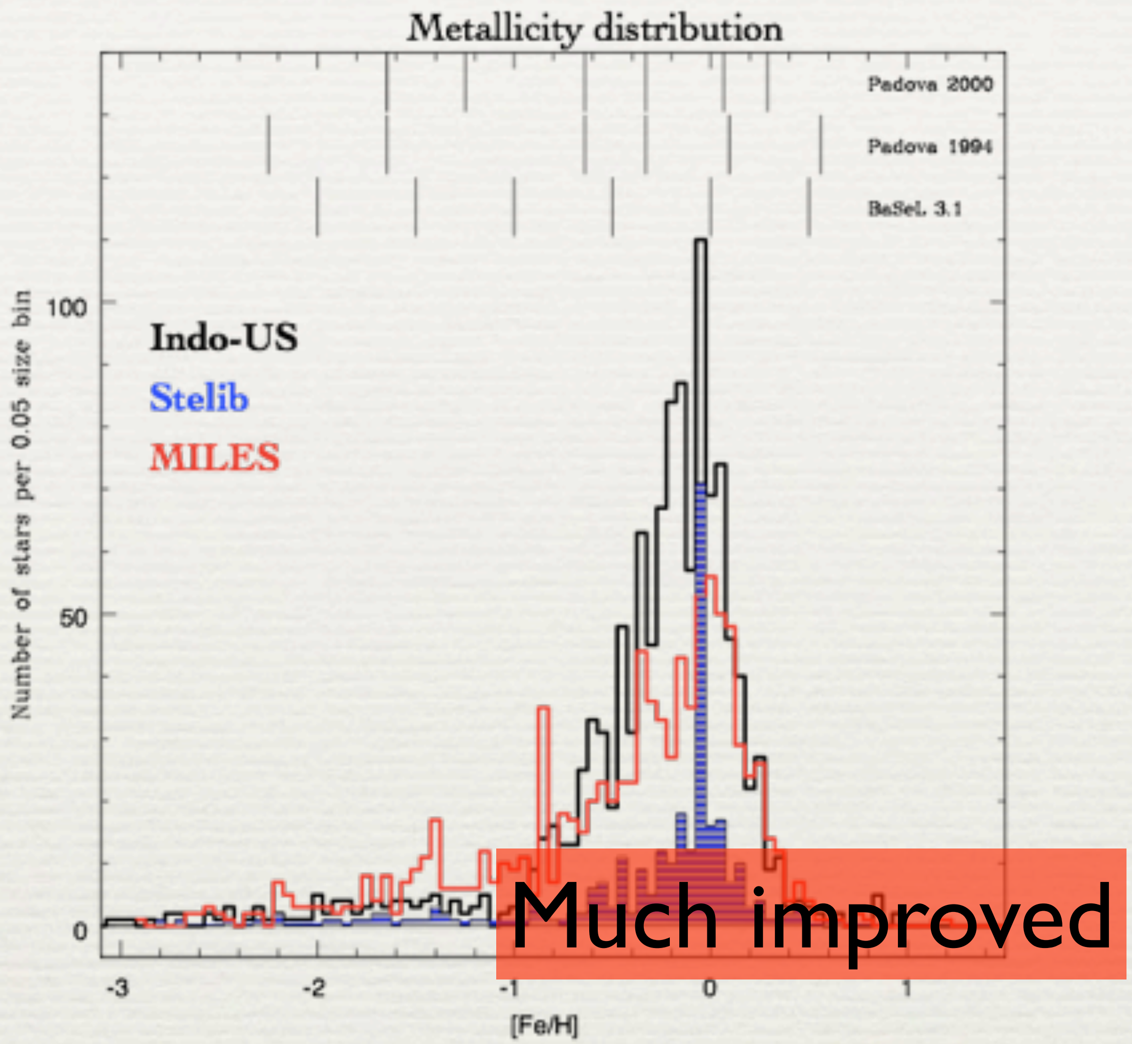

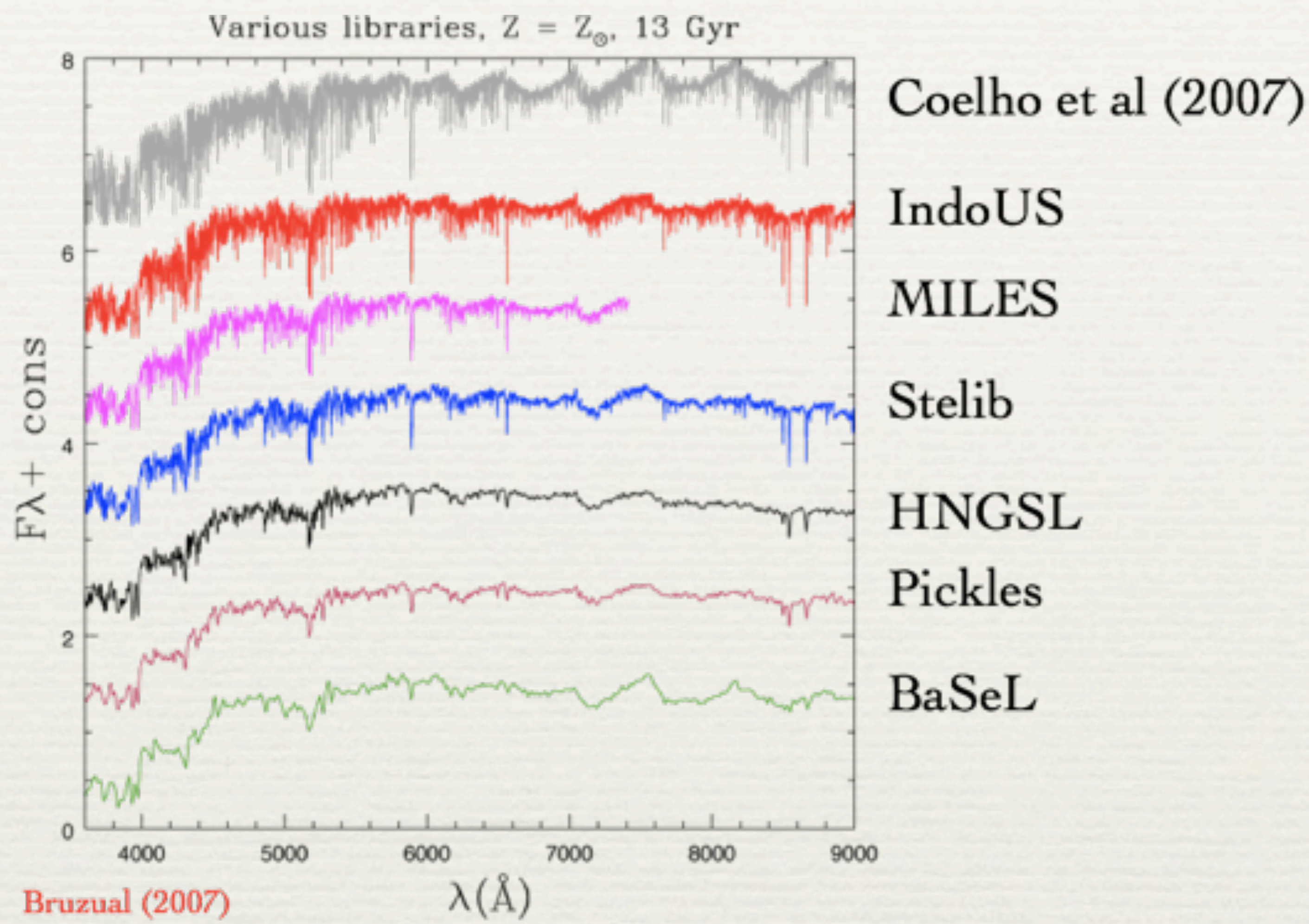

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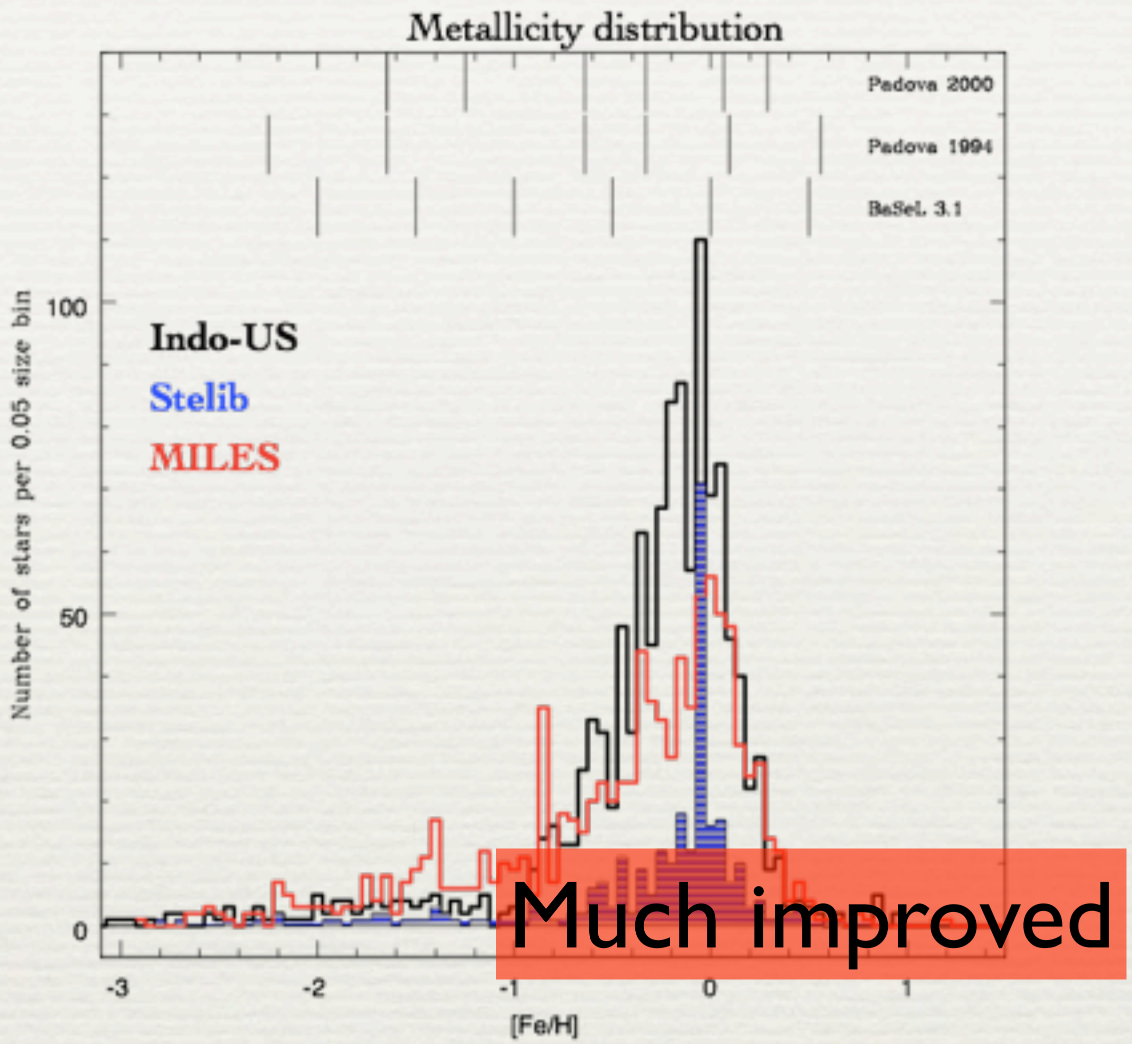
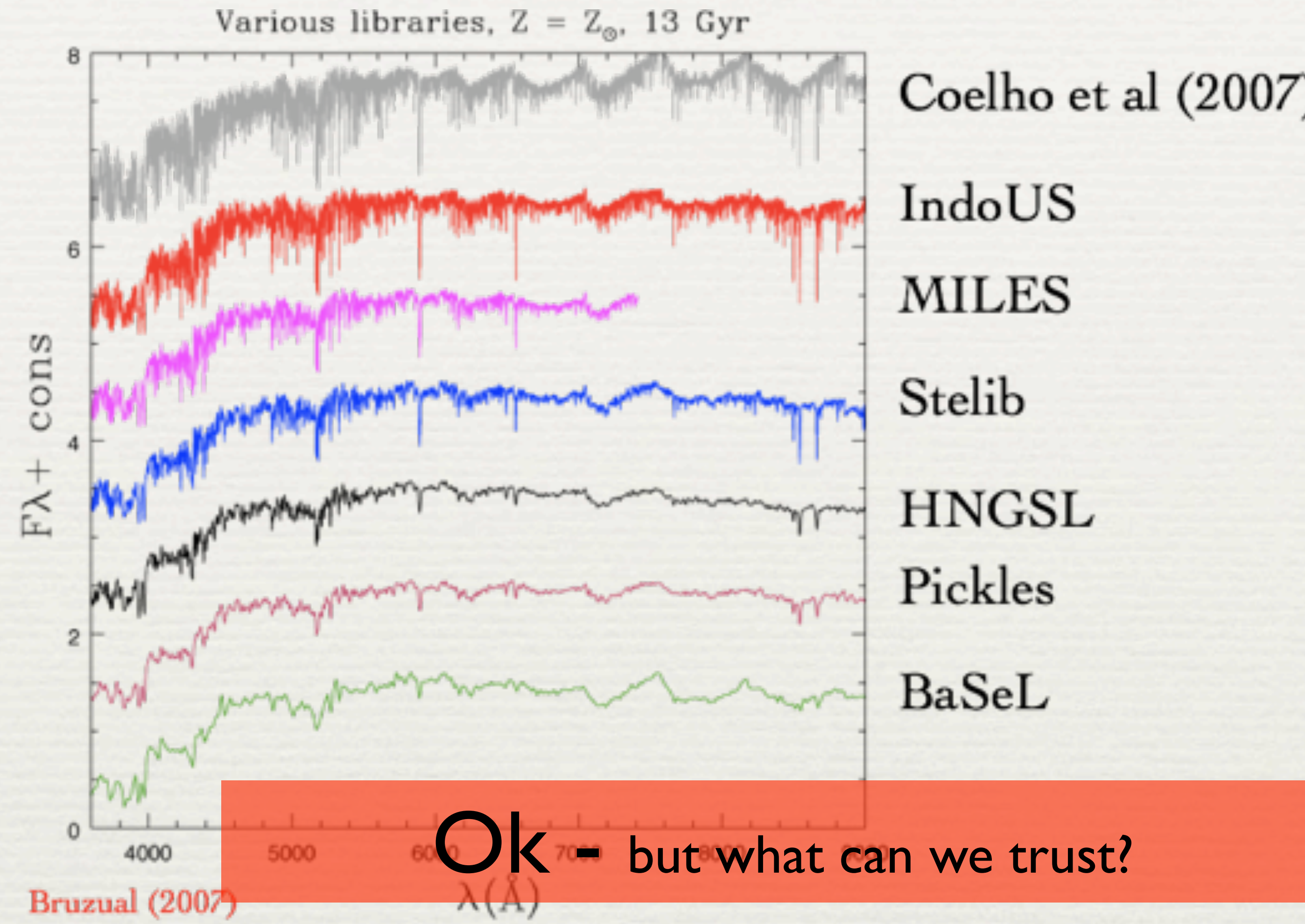


Much improved



Ok - but what can we trust?

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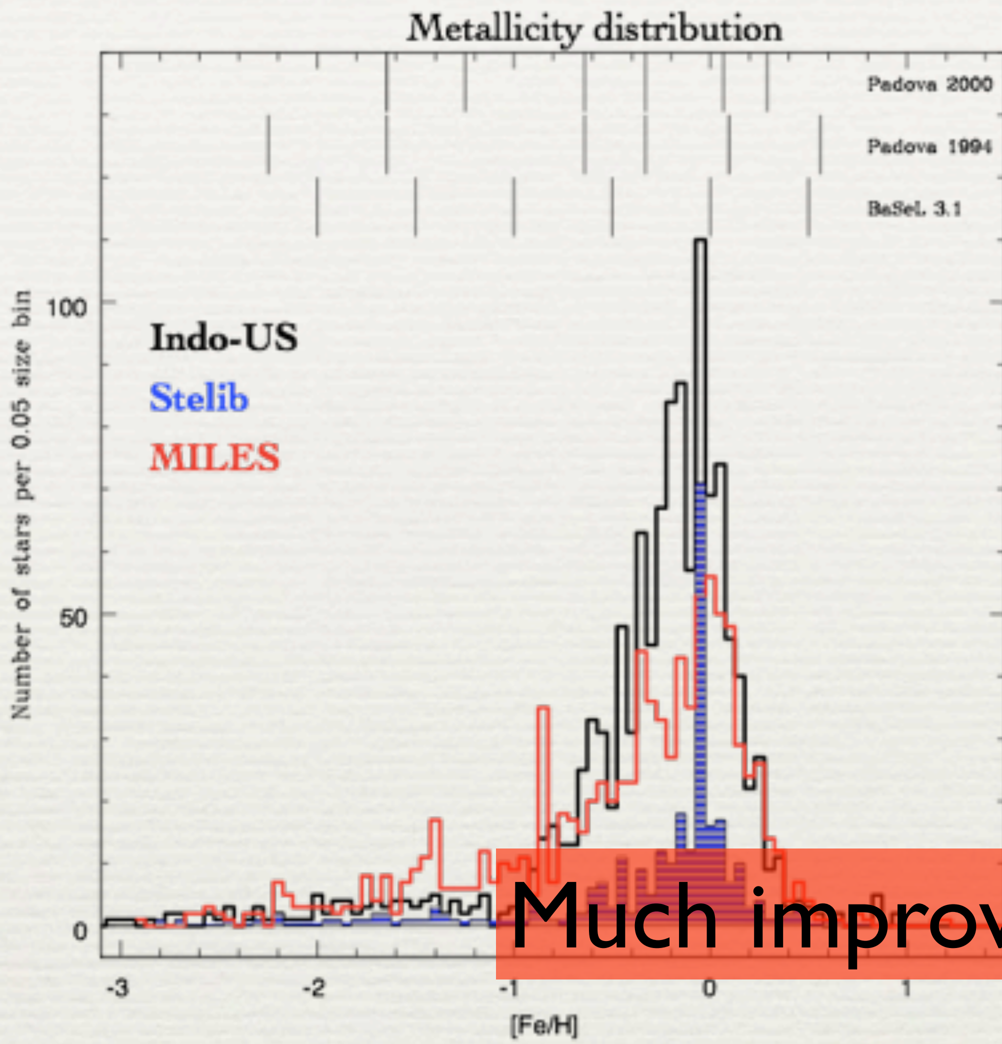

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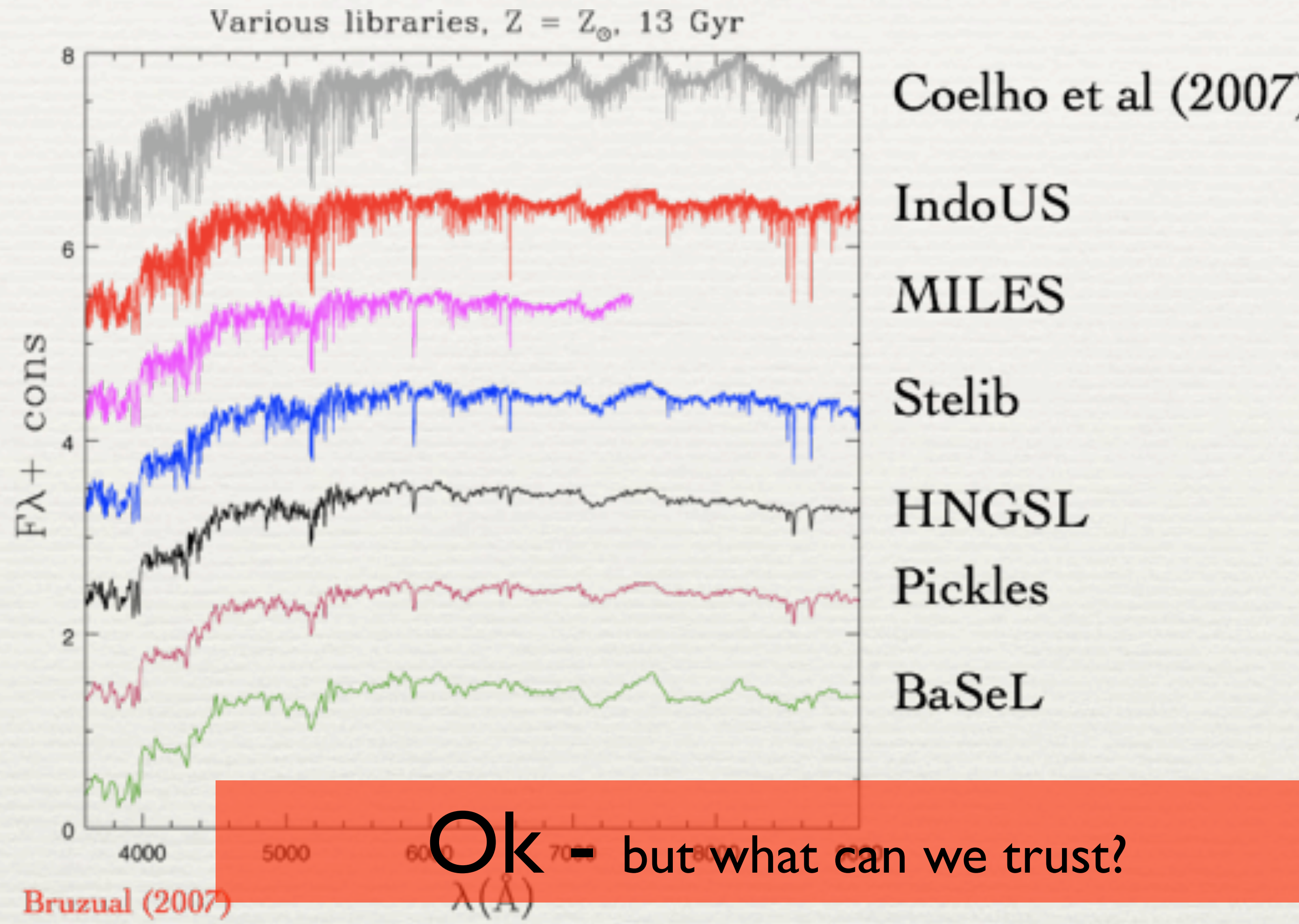

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Observational libraries: Need lots of telescope time, how do you estimate stellar parameters, dust reddening.

Theoretical libraries: Physical parameters (opacity etc), Non-LTE effects, geometry, treatment of mass-loss/hydrodynamics

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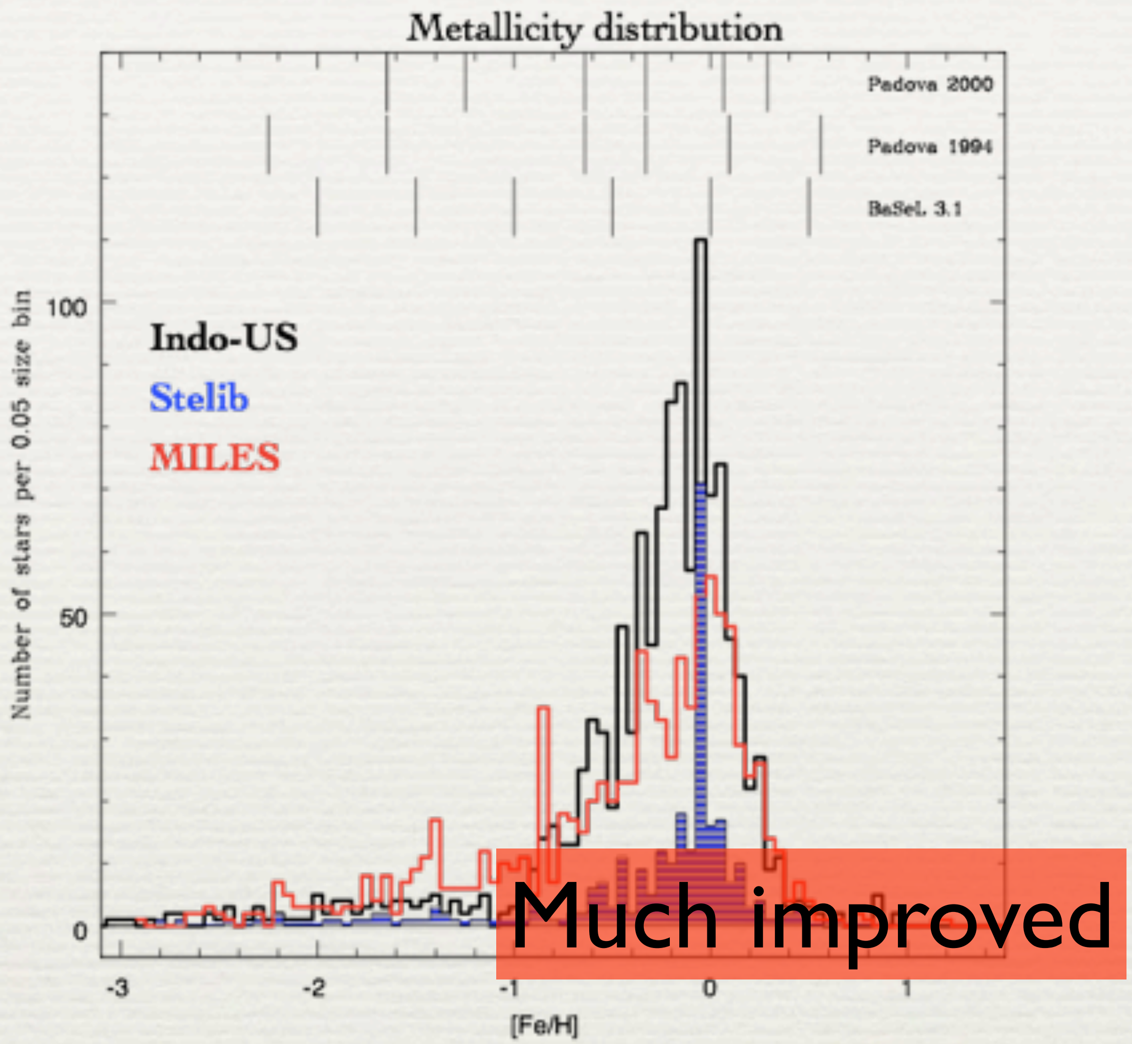

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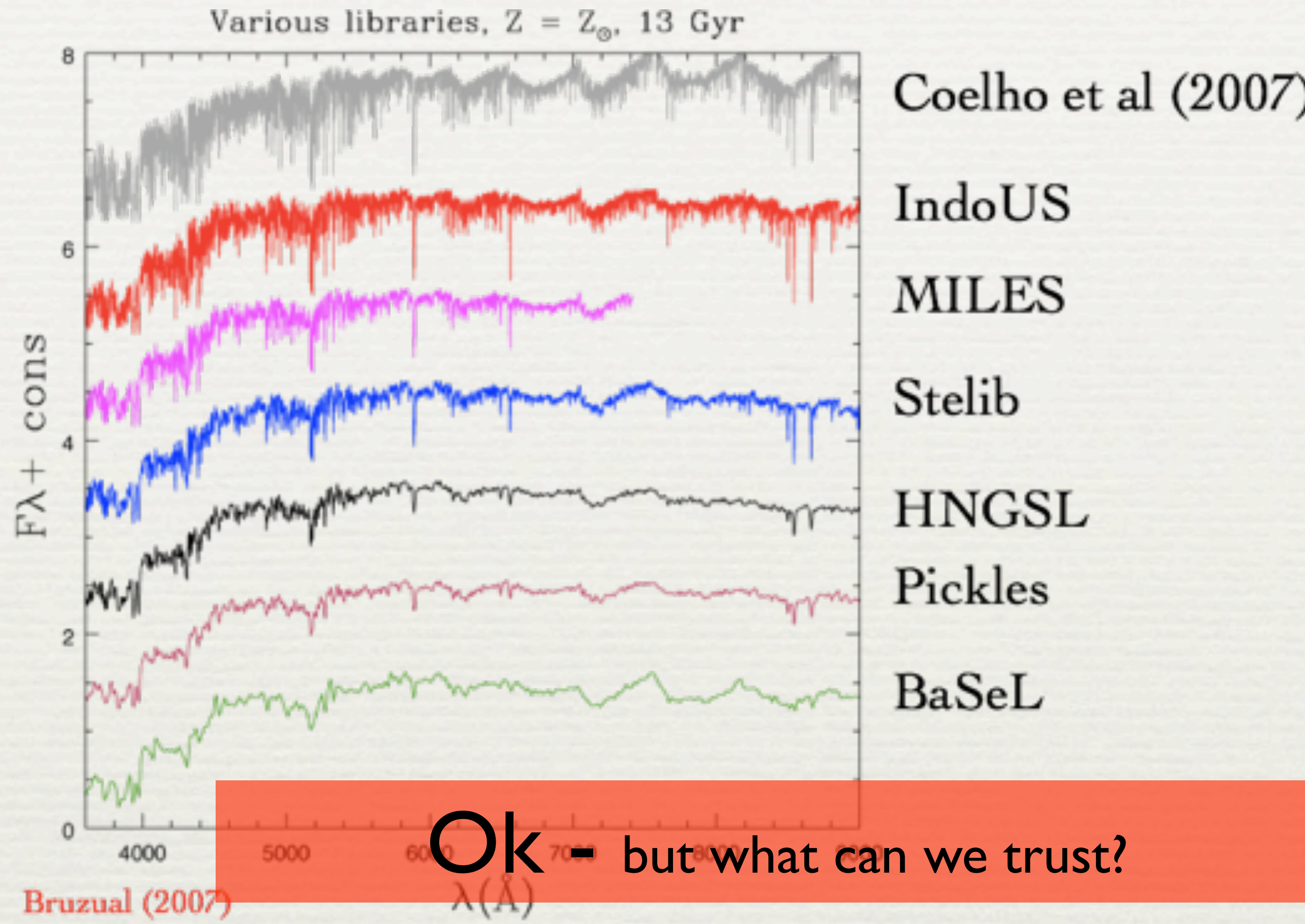

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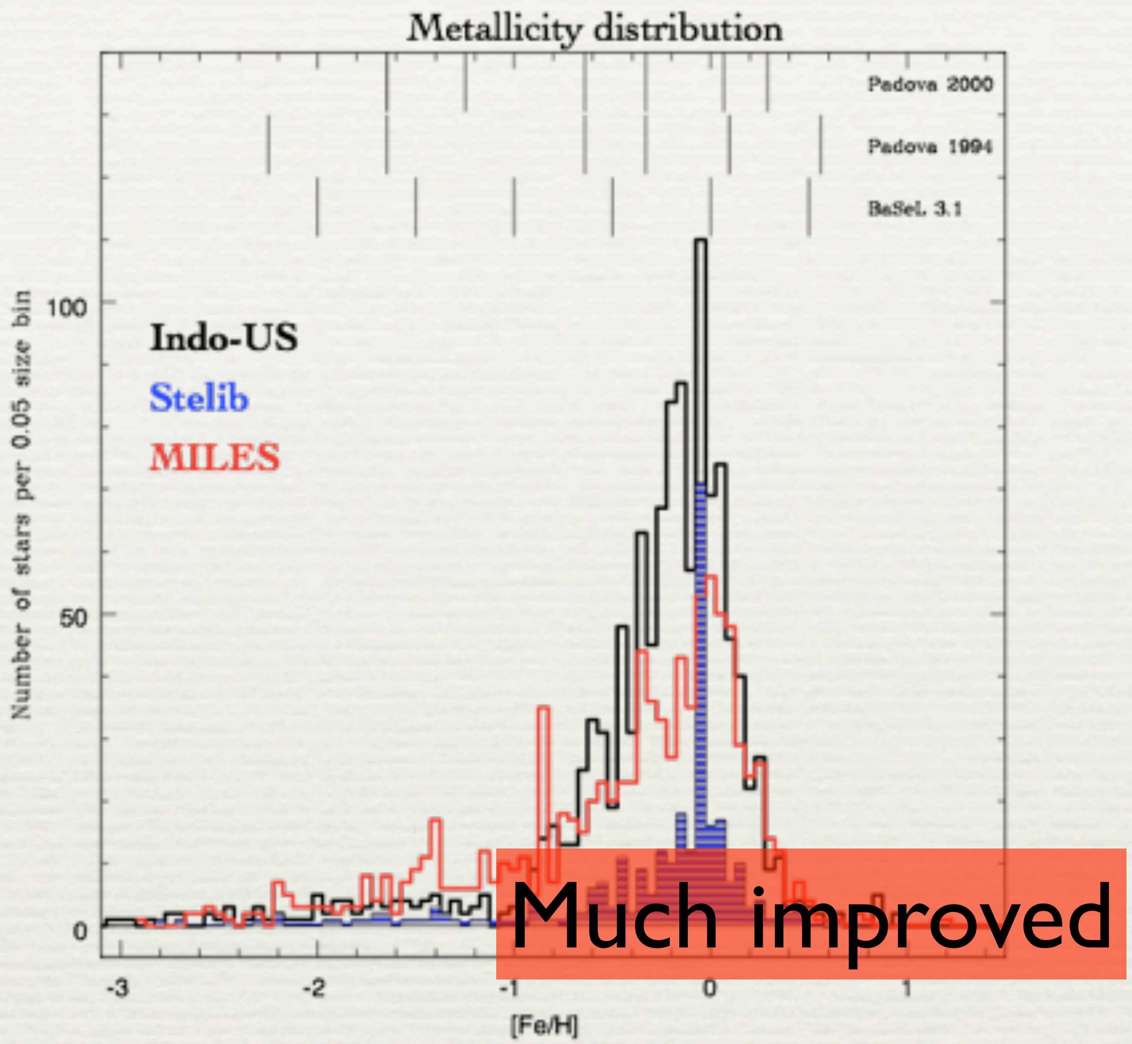

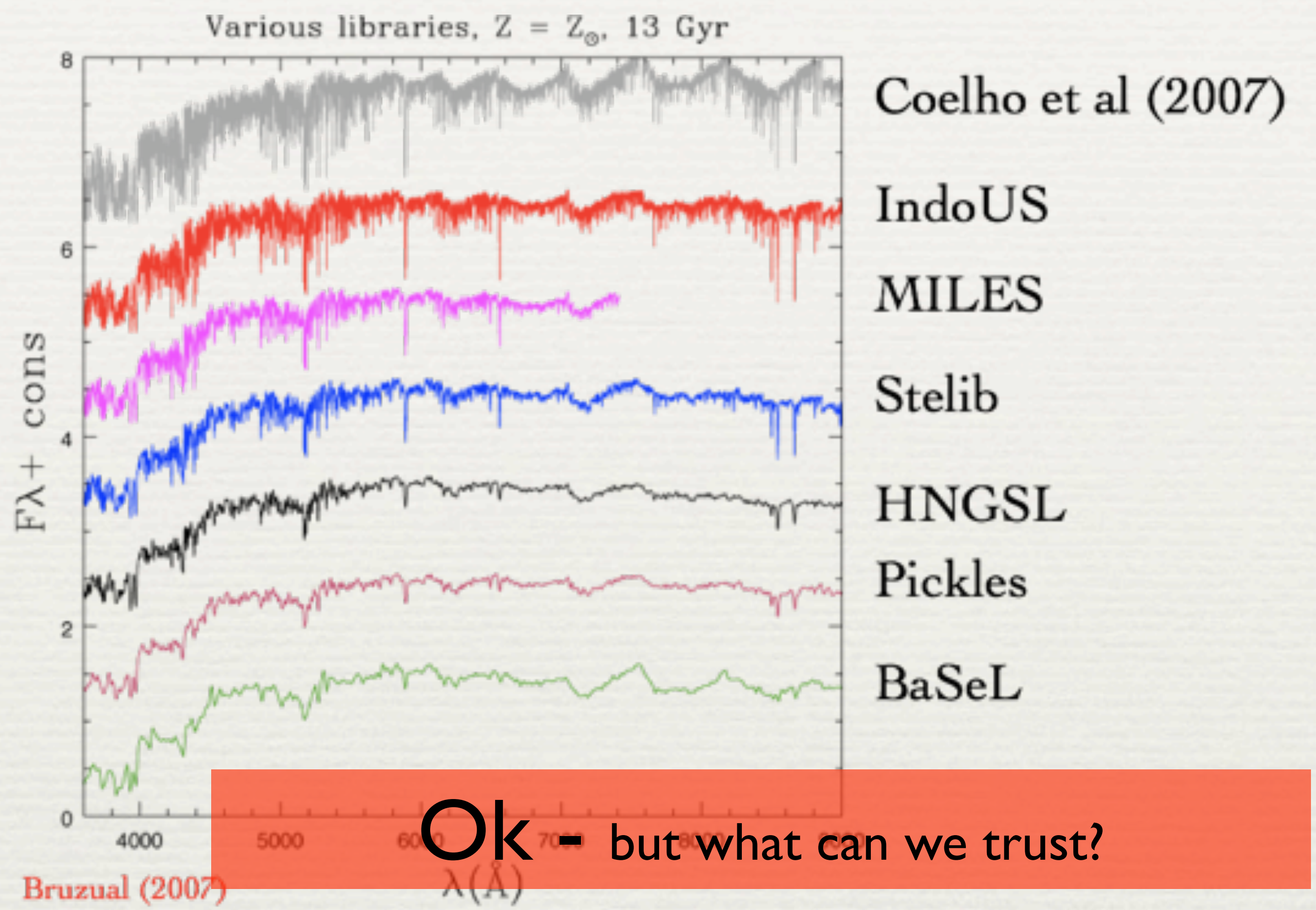

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Well suited for hot stars(?)

The near-IR - are the models good enough?

JWST - The major gain will be in the observed MIR. Thus many galaxies will be probed in the 2-4μm region. Are the models good enough to make use of these data?

ELTs - High quality adaptive optics will probably predominantly work in the NIR. Are the models ready for this>

YES?

Blanton & Roweis (2007) show that one can predict the NIR magnitudes of nearby galaxies using their optical properties.

Carter et al (2009) show that a wide range of different population synthesis codes show good agreement in the estimates of age & metallicity for nearby E/S0s

NO!

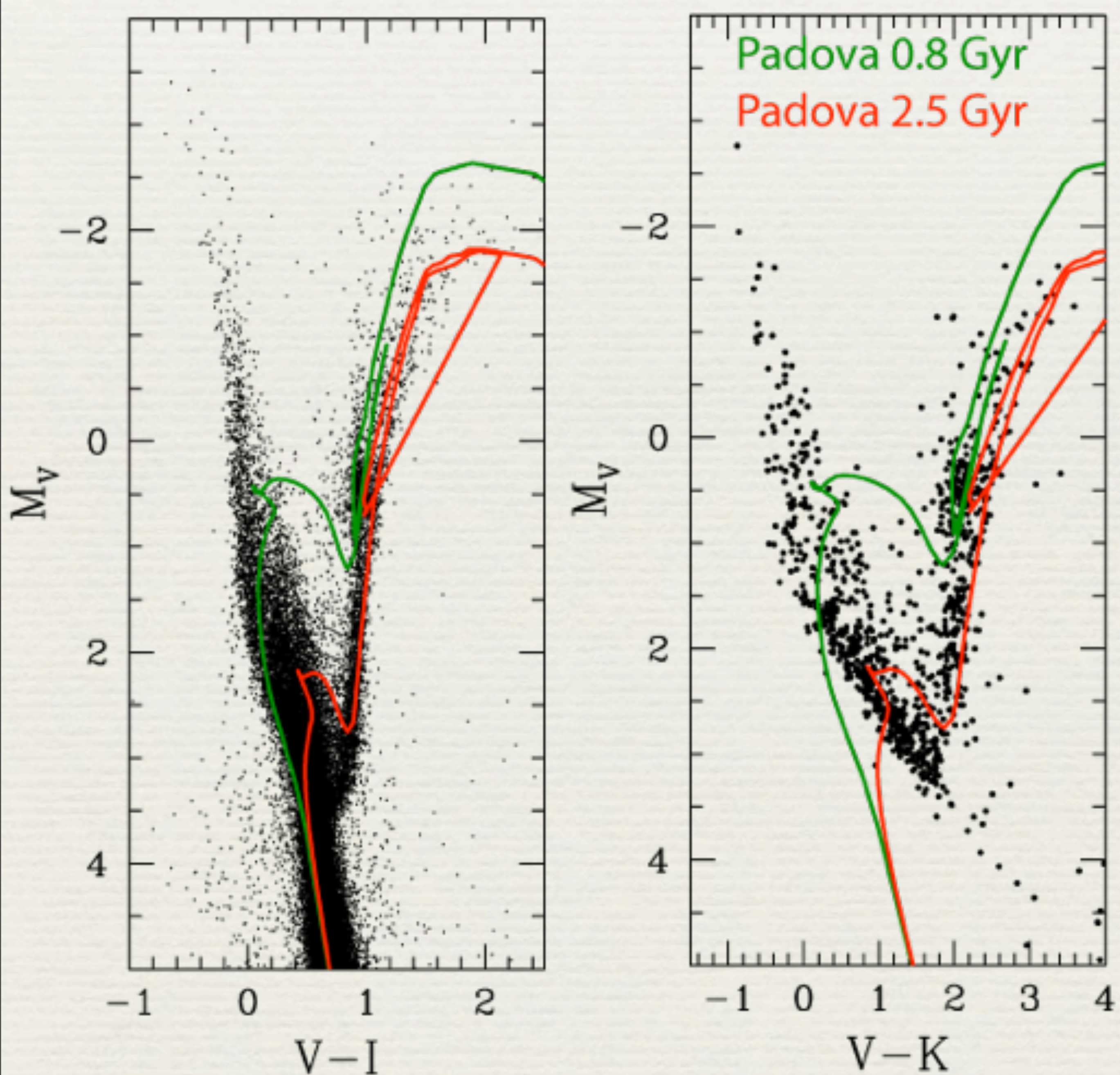
Fits using different population synthesis models by various authors, e.g. Muzzin et al (2009), find systematic differences in the physical parameters estimated with different models.

Integrated photometry is not terribly well reproduced by models yet.

Resolved populations in the NIR - essential for the E-ELT!

Tests have been made in the Milky Way & LMC. Reasonable agreement between models & data.

Fiorentino et al - NGC 1928 with MAD



E(B-V) = 0.07
Z = 0.008
Distance modulus = 18.5

This is a good example of what will be a routine task for ELTs in the future. This needs more testing & for a broader range of stellar evolutionary stages.

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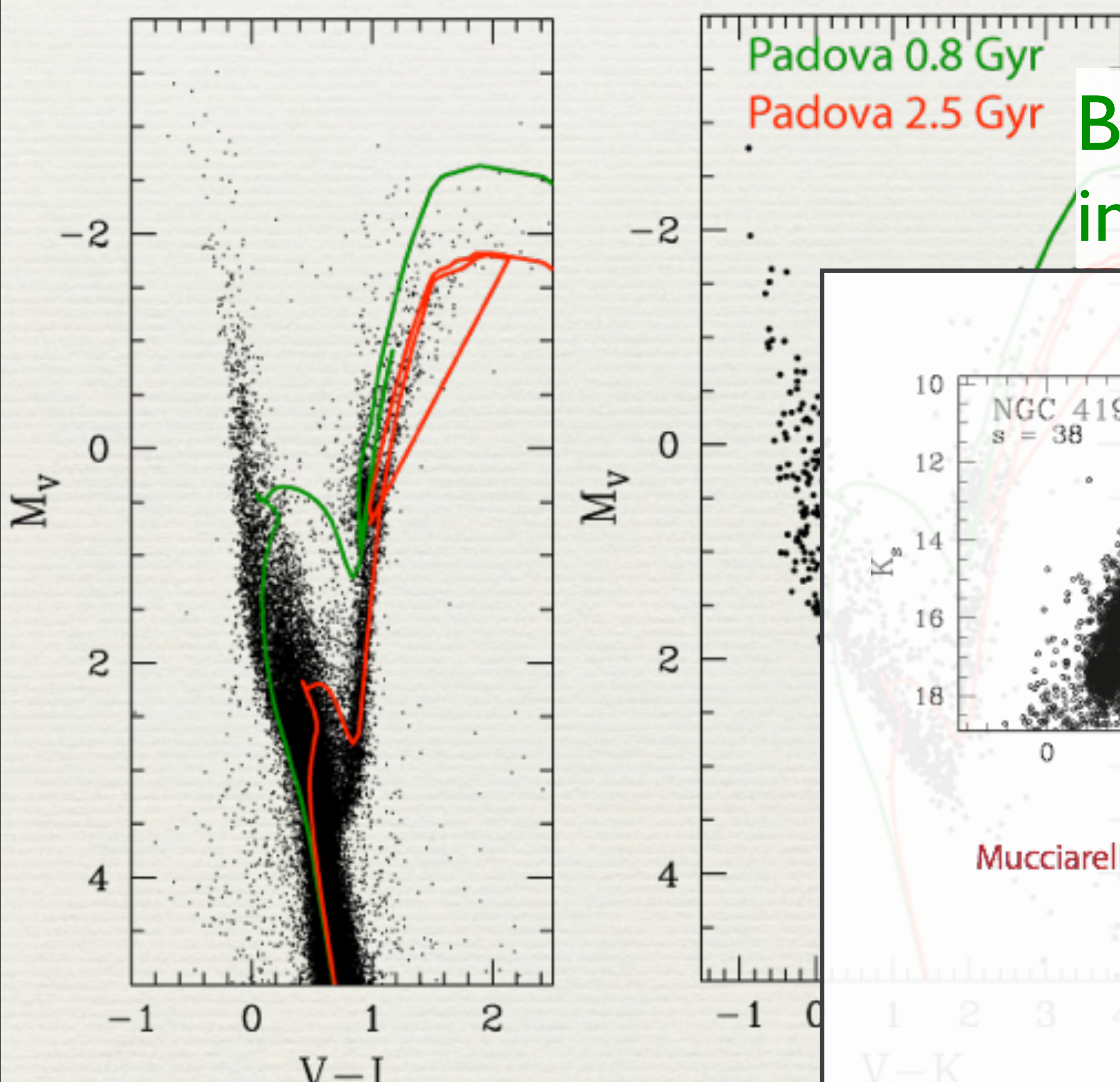

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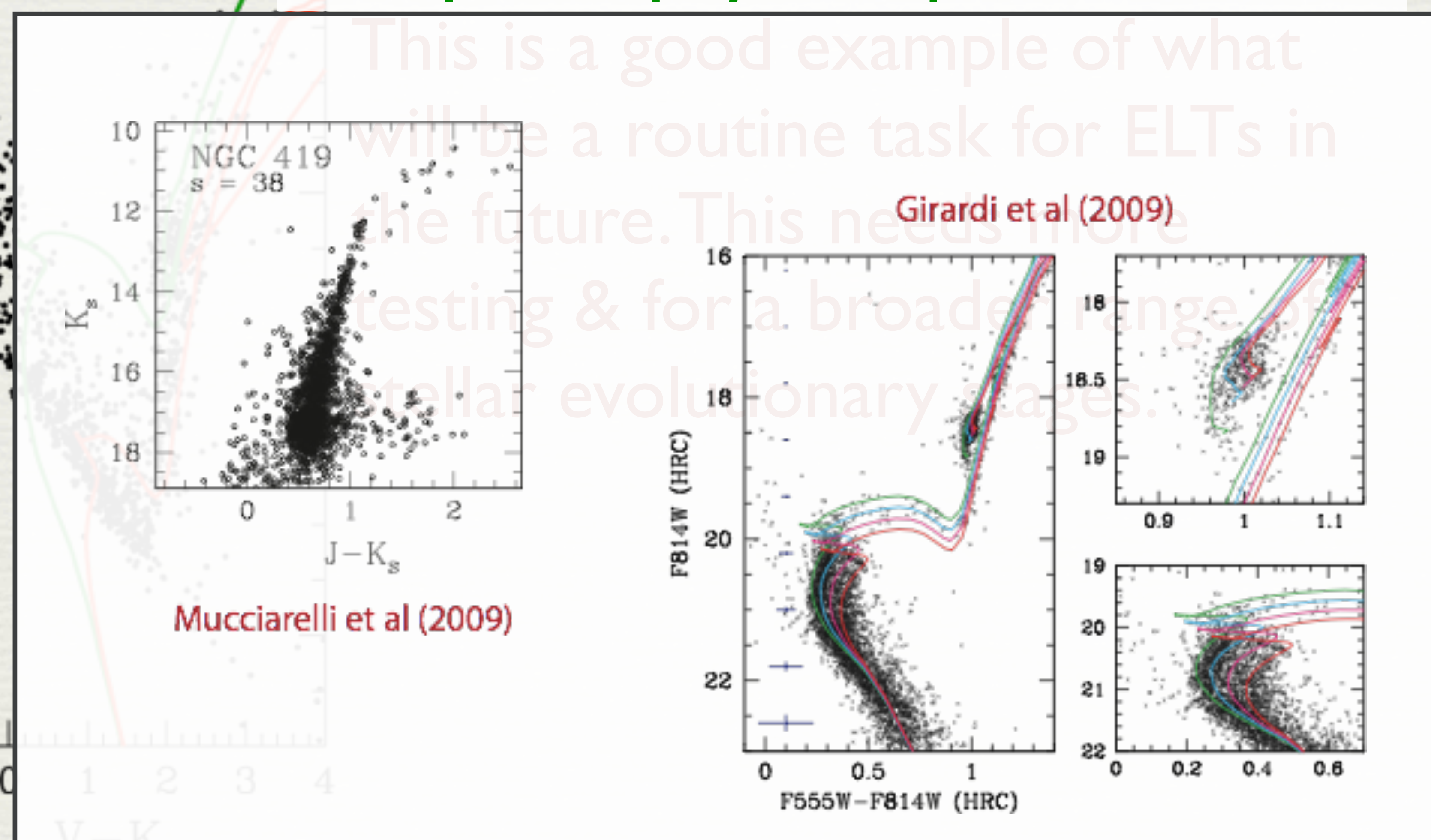
But the observations are limited in depth & physical parameters:



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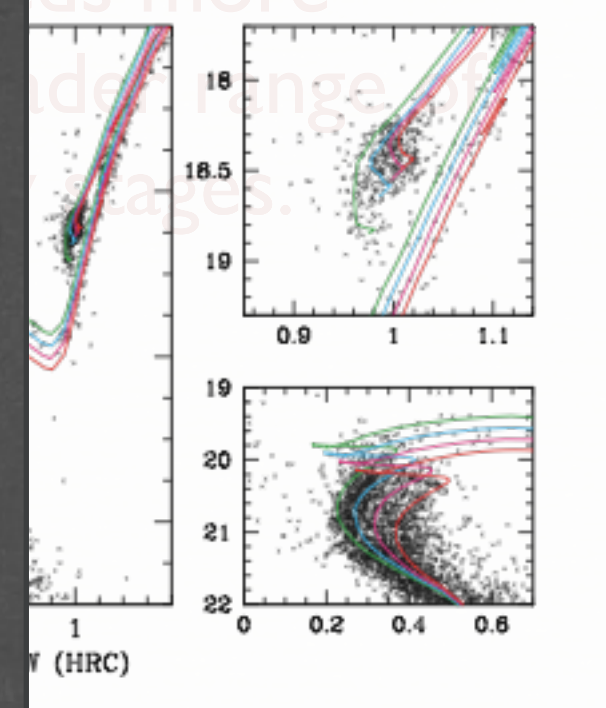
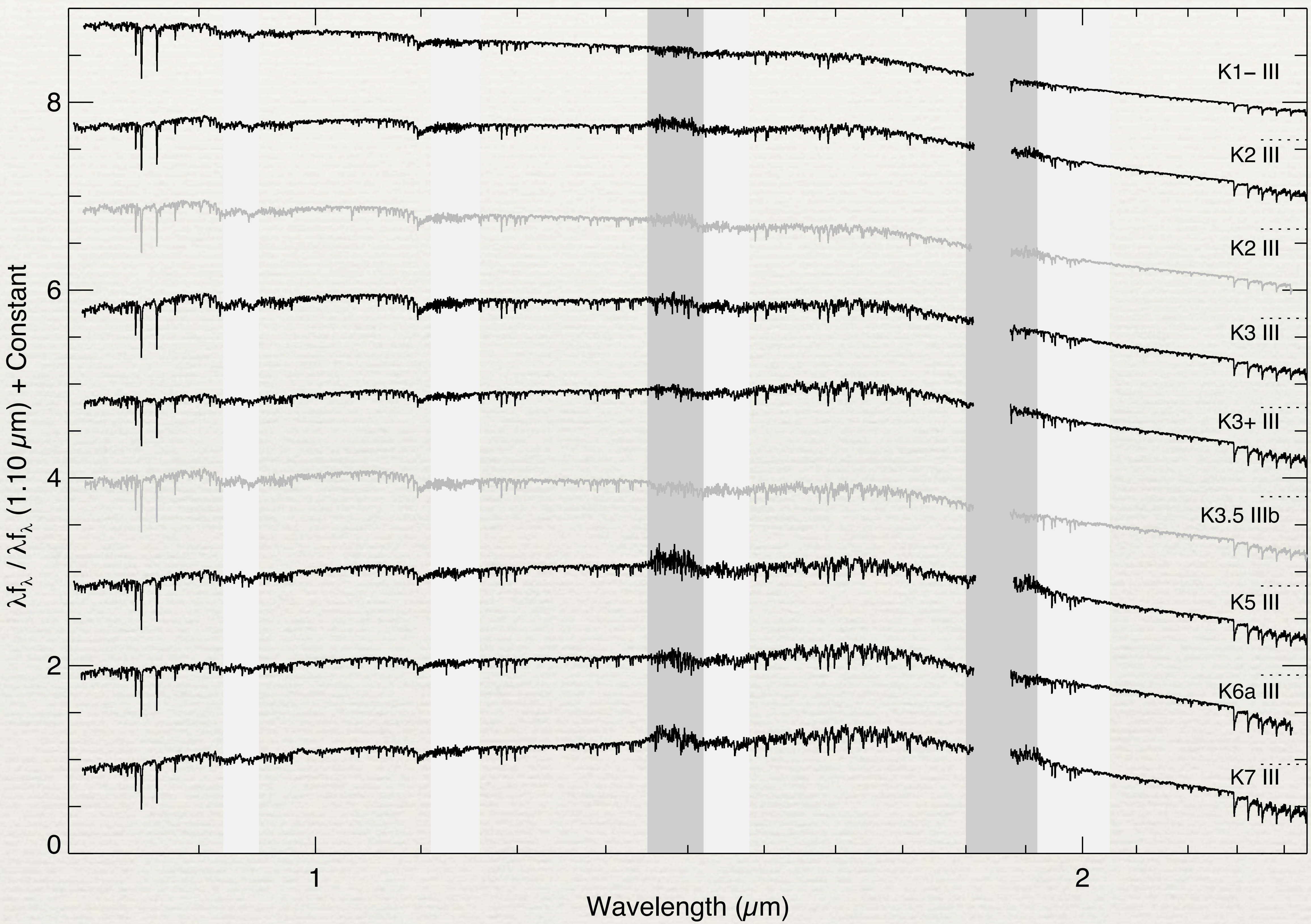


An (important) aside:

The optical or optical-NIR CMD is more informative than the NIR-NIR CMD - can the science goals be achieved without AO in the optical (HST resolution not good enough?). Spectroscopy (APOGEE help?)

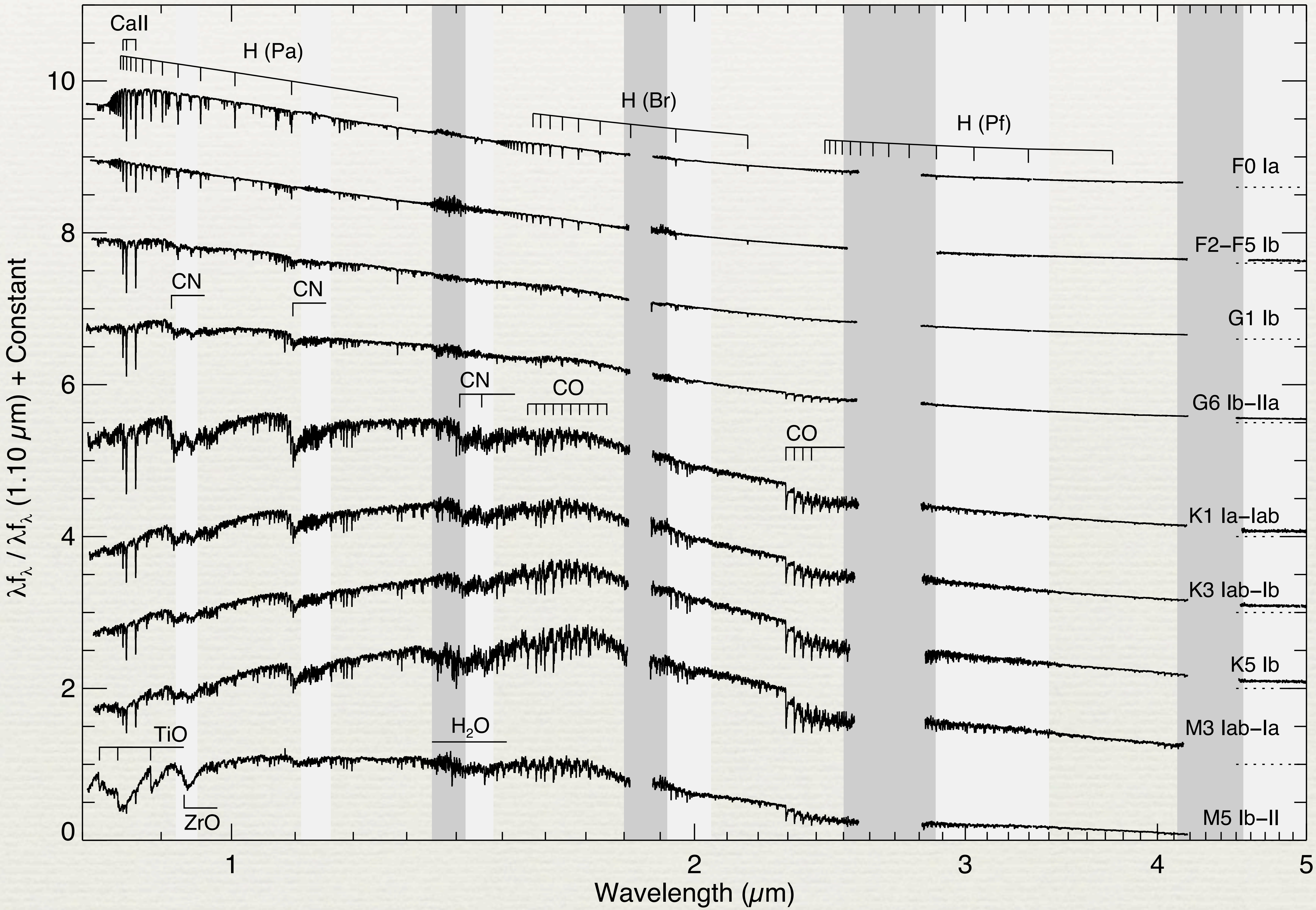
Spectroscopy

Rayner, Cushing & Vacca (2009) - IRTF spectral library. K-giants



Spectroscopy

Rayner, Cushing & Vacca (2009) - IRTF spectral library (supergiants)



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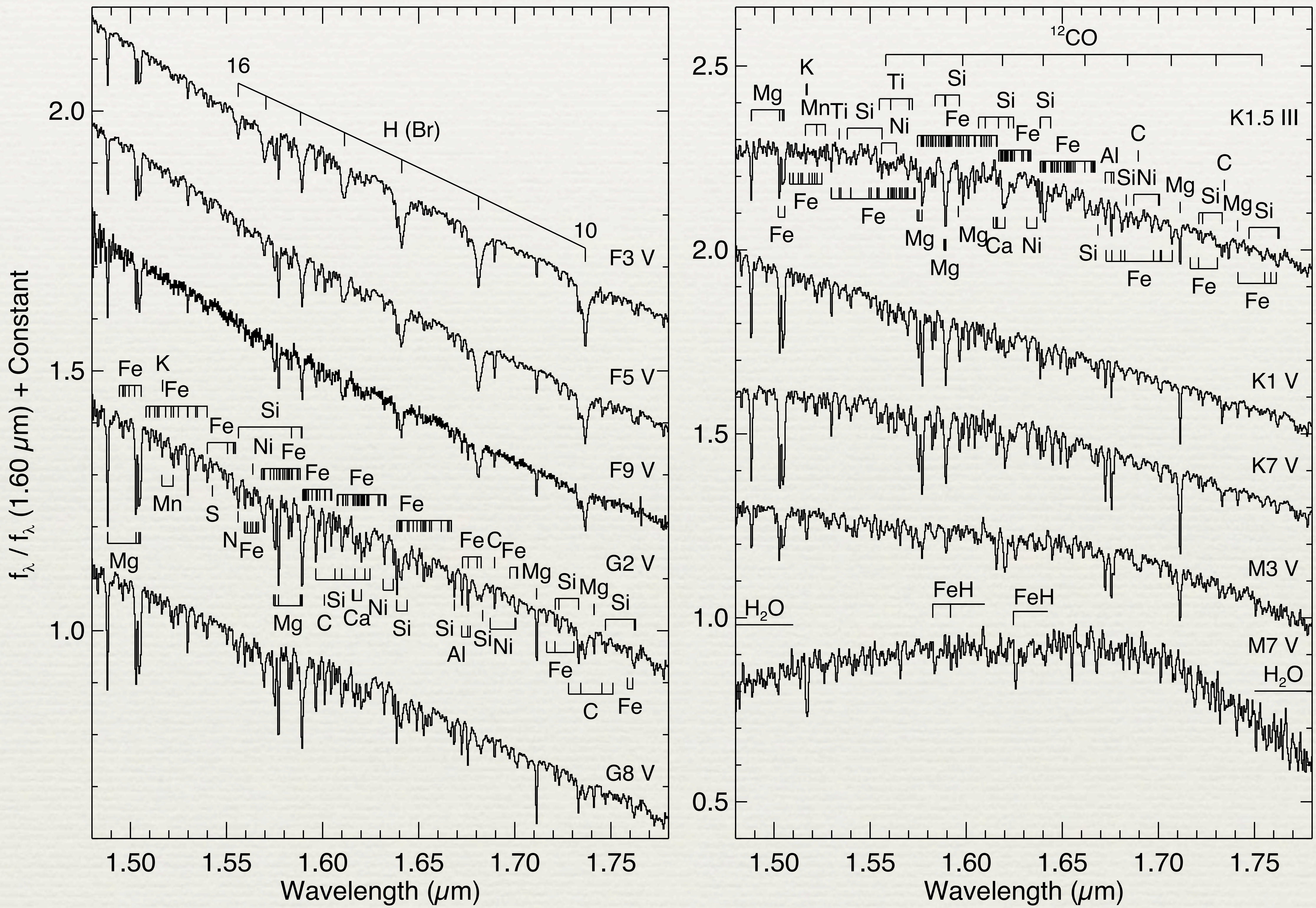
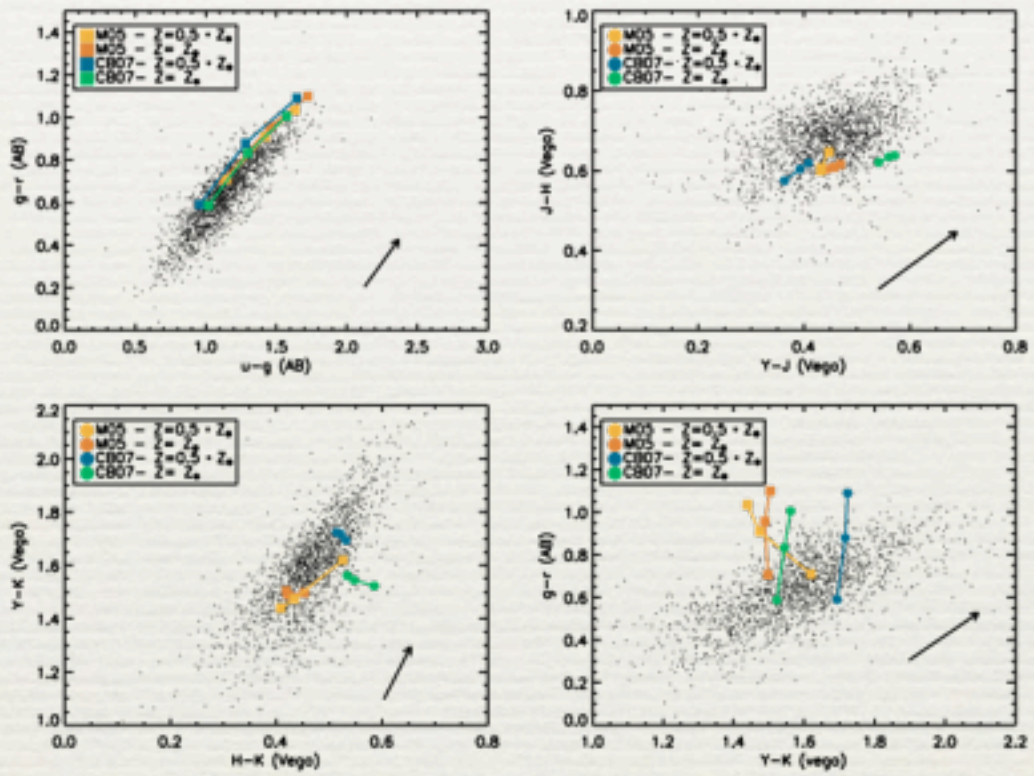
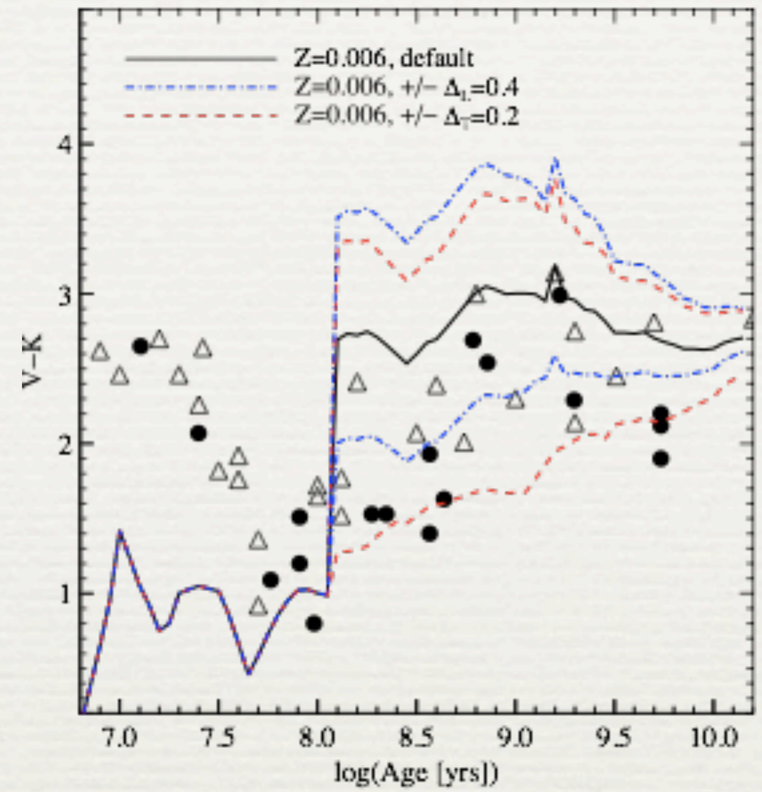


Certainly a lot of information!

Integrated broad-band properties

Example: Eminian et al (2008) - SDSS star-forming galaxies with UKIDSS photometry. Optical shows good agreement between codes. Near-IR less good: J-H too blue, H-K/Y-K less good.





Conroy et al (2009) point out that the V-K colour in observed clusters in the LMC is not well reproduced at early ages (observational issues?).

Key to much of this *might* be TP-AGB stars. Major advances have been made recently (e.g. Marigo et al 2008 & refs) but the fact is that we need more a) empirical SEDs and b) larger samples of TP-AGBs over a wide range in metallicity (LMC, SMC might not be appropriate).

Surface brightness fluctuations in the NIR might be very helpful here! (e.g. Raimondo 2009; Lee et al 2009) since they depend on L^2.

Stellar mass estimates

At low redshift stellar masses are probably fairly ok (possibly because they do not use NIR data extensively)

Typical uncertainties are probably ~0.3 dex
e.g. Conroy et al (2009)

But systematic uncertainties between algorithms can be ~0.2 dex
c.f. Pozzetti et al (2008)

Different models agree to within 0.15 dex with small shift.
e.g. Tojeiro et al (2009)

At higher redshift the situation is not so clear (at least when rest-NIR is included due to TP-AGB stars):

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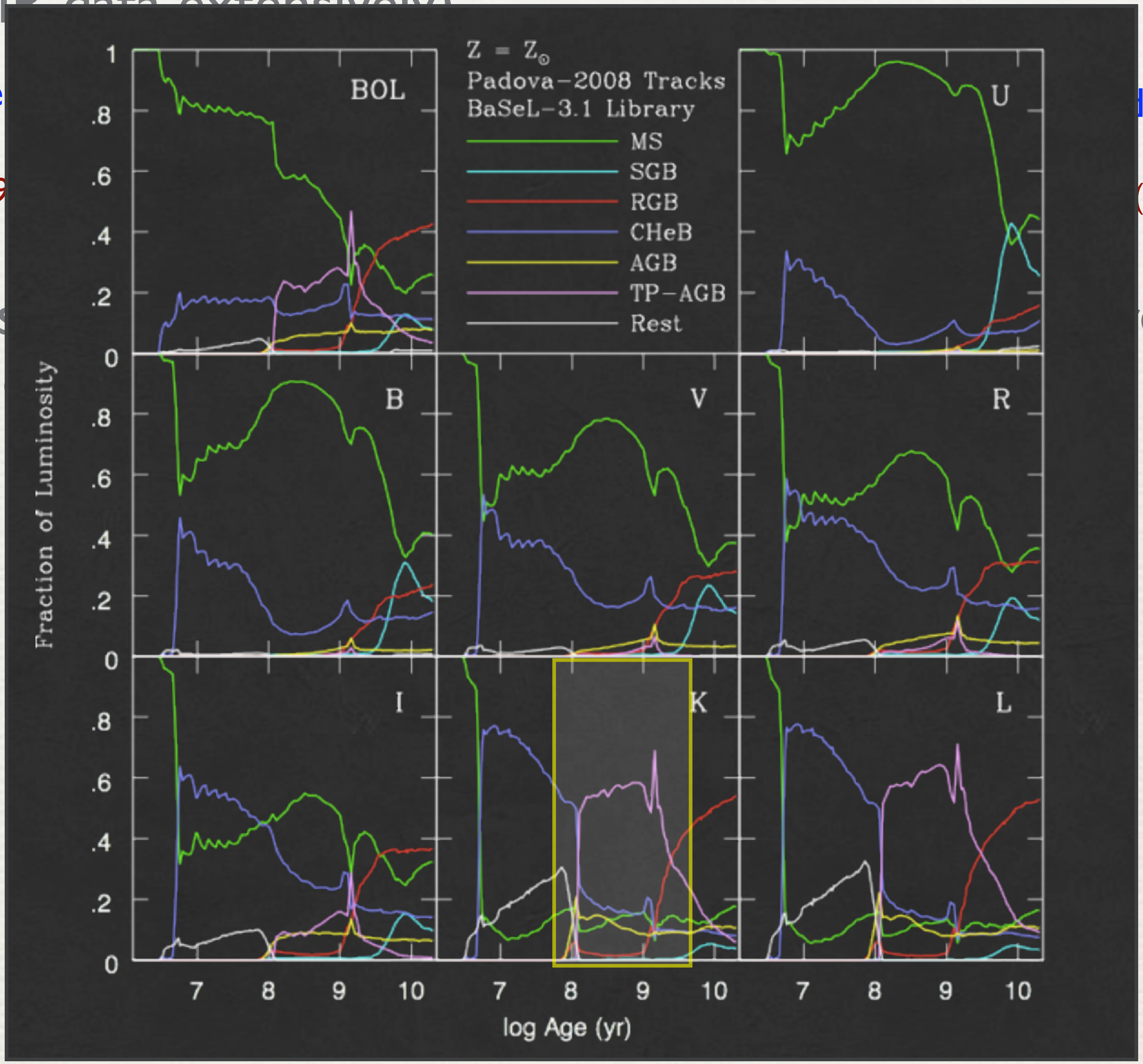

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Maraston et al (2006): Emphasised the importance of TP-AGB stars for mass measurements at z~2-3 because the typical age of a galaxy is ~1-3 Gyr where TP-AGB stars might dominate the light. Showed discrepancy between BC03 & M05 - still no complete convergence on this issue (c.f. Bruzual 2007).

e.g. Muzzin et al (2009) showed that the differences between different population synthesis codes (M05, BC03, CB08) is the largest systematic uncertainty out of the parameters they explored (limited exploration of SFH)

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Stellar masses at $z>1$ are not yet robustly estimated and model differences must be better understood - are relative masses ok?

Might be good do more comparisons to dynamical masses:

e.g. van der Wel et al (2006) for early-type galaxies: Adding rest-frame NIR to model fits leads to inconsistent solution at $z=0$ and $z\sim1$. Their conclusion: Might be better to stick with optical data only.

Non-solar abundance ratios

Models for full spectrum prediction often assume solar abundance ratios, but many galaxies do show clear signs of deviations from a solar abundance pattern in detail.

With the ELTs it will be easy to reach very high S/N - can we use it?

Since SNe Ia explode delayed relative to Type II (the "effective" delay is ~1 Gyr in the MW - Matteucci & Recchi 2001), thus systems that formed most of their stars before then will be Fe deficient.

Note: This means that galaxy spectra at z≳4 **are likely to be Fe deficient** (or α-enhanced).

Not a big deal for broad-band colours. The typical offsets in the most sensitive regions of the optical spectrum may reach ~few %. But it does matter for spectral features.

Remember: **This does provide useful information!**

Status

Isochrones & atmospheres:

Isochrones available, sparse sampling. Theoretical atmosphere libraries exist, but lacking in empirical libraries.

e.g. Cassisi et al (2004); Weiss et al (2007); Pietriferni et al (2006); Coelho et al (2005); Munari et al (2005); Dotter et al (2007) - see Martins & Coelho (2007).

Modified Lick indices:

Calculate the response of indices to changes in abundance around a particular isochrone & apply to existing models - requires the use of fitting functions

e.g. Trager et al (2000); Thomas et al (2003); Tantalo et al (2007)

Complete spectra:

Calculate stellar tracks and stellar atmospheres for different α/Fe.

e.g. Coelho et al (2007); Percival et al (2009)

Major progress has been made over the last decade and well suited for some regions in parameter space but we are not yet at a stage where high-resolution spectra are spot on, although they can be used already (c.f. Walcher et al 2009), index models are in better shape.

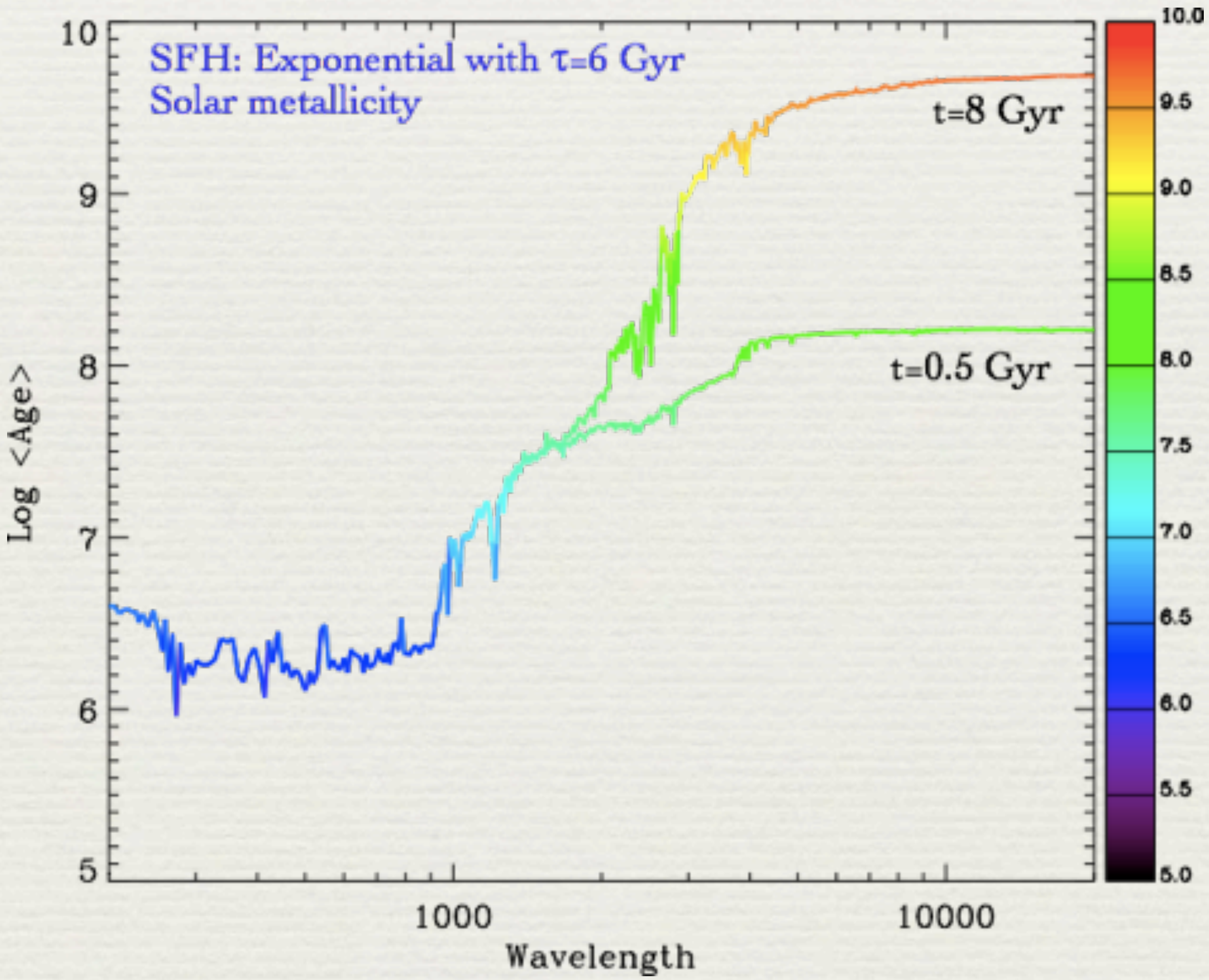
However: Should we just vary the α-element abundance? Probably not!

See for instance the NSSPM project (Lee, Worthey & collaborators)

The rest-UV - massive stars

Can we predict the key features of the rest-UV spectrum?

This is essential for making optimal use of the steadily growing sample of rest-UV spectra of z~2-3 galaxies.



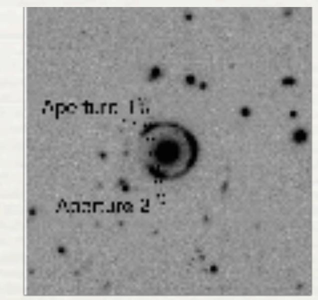
Lensed Lyman-break galaxies is essential here because the gain from lensing (20-30) is comparable to that of going from 8-10m to 30-40m. Thus they are excellent testing grounds.

The rest-UV - massive stars

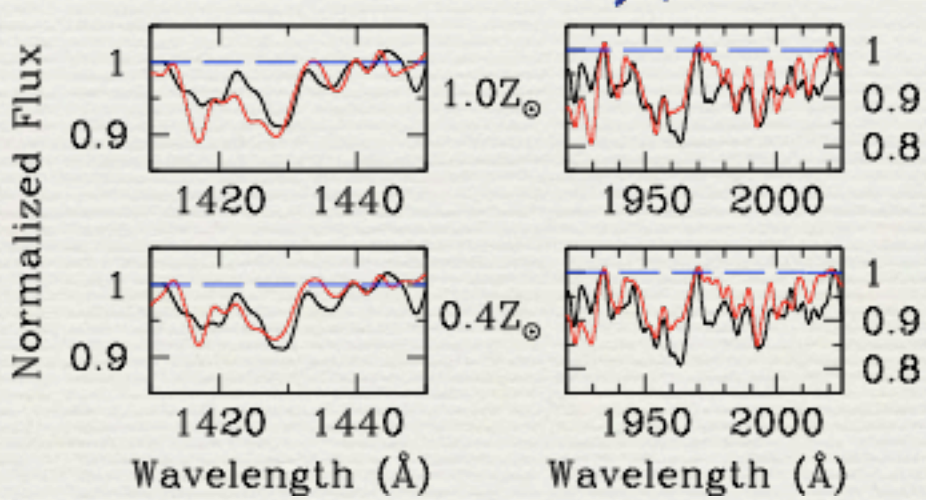
Can we predict the key features of the rest-UV spectrum?

Lensed Lyman-break galaxies (e.g. cB58, Cosmic Horseshoe, 8 o'clock arc) are amplified by factors of ~20-30, similar to the gain from 8-10m to 30-40m:

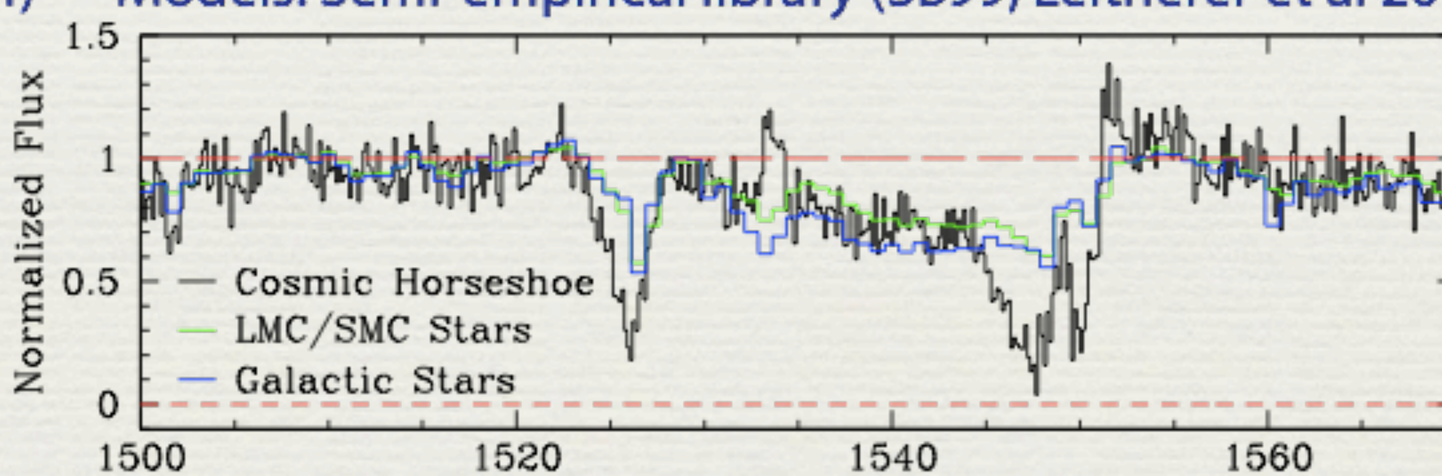
The Cosmic Horseshoe (Quider et al 2009)
z=2.379



Models: Theoretical library (Rix et al 2004)



Models: Semi-empirical library (SB99, Leitherer et al 2001)



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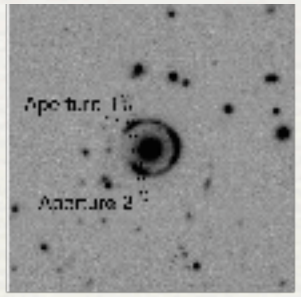

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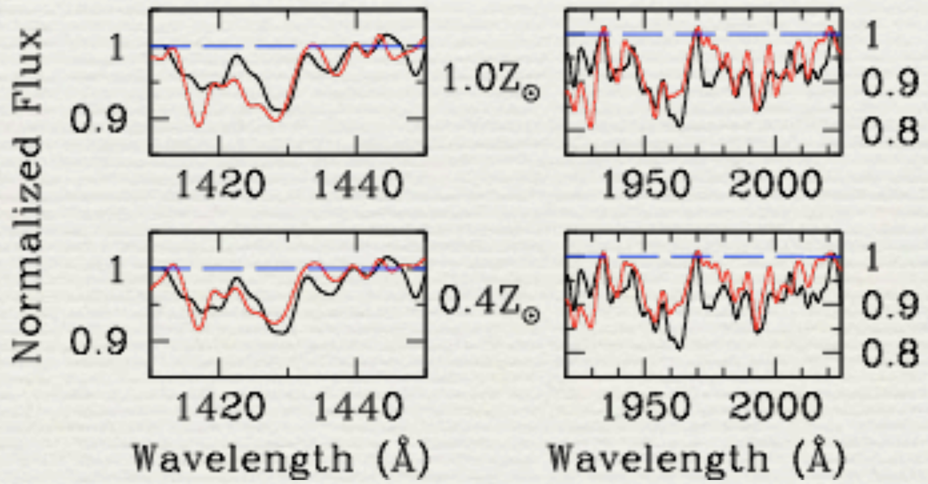

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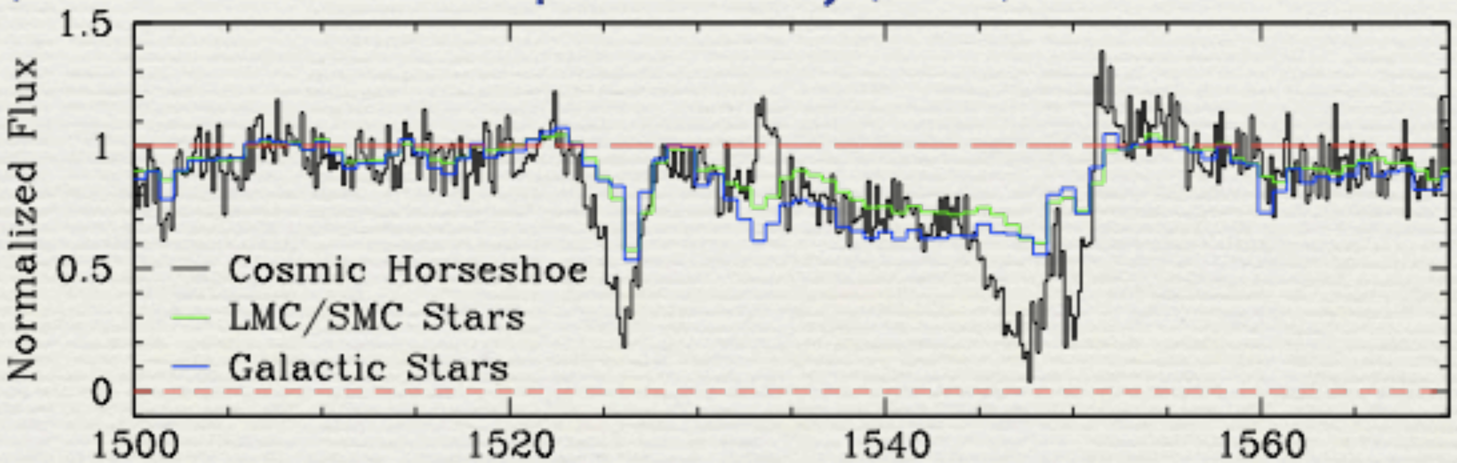
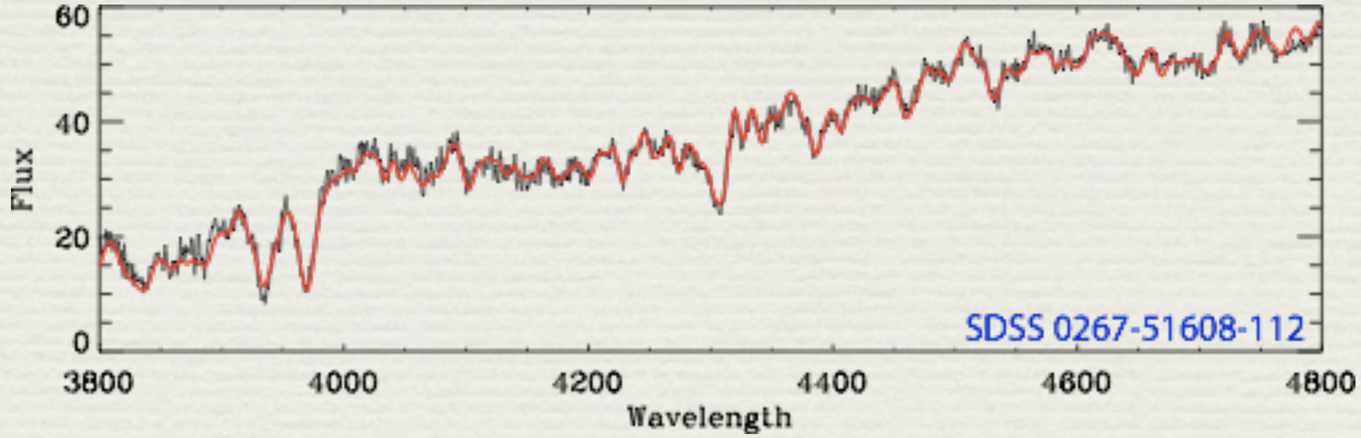


This can be contrasted with the quality of fit in the rest-frame optical with current models (here Charlot & Bruzual 2009).



The rest-UV/massive stars

Can we predict the key features of the rest-UV spectrum?

Current theoretical models are not fully successful, but rapidly improving - quite possibly the way to go (avoid e.g. reddening), but need more work (**mass-loss**). Empirical libraries are probably essential to guide.

Do we understand the ionizing (far-UV) spectrum of massive stars?

Crucial for emission line modelling, ISM energetics.

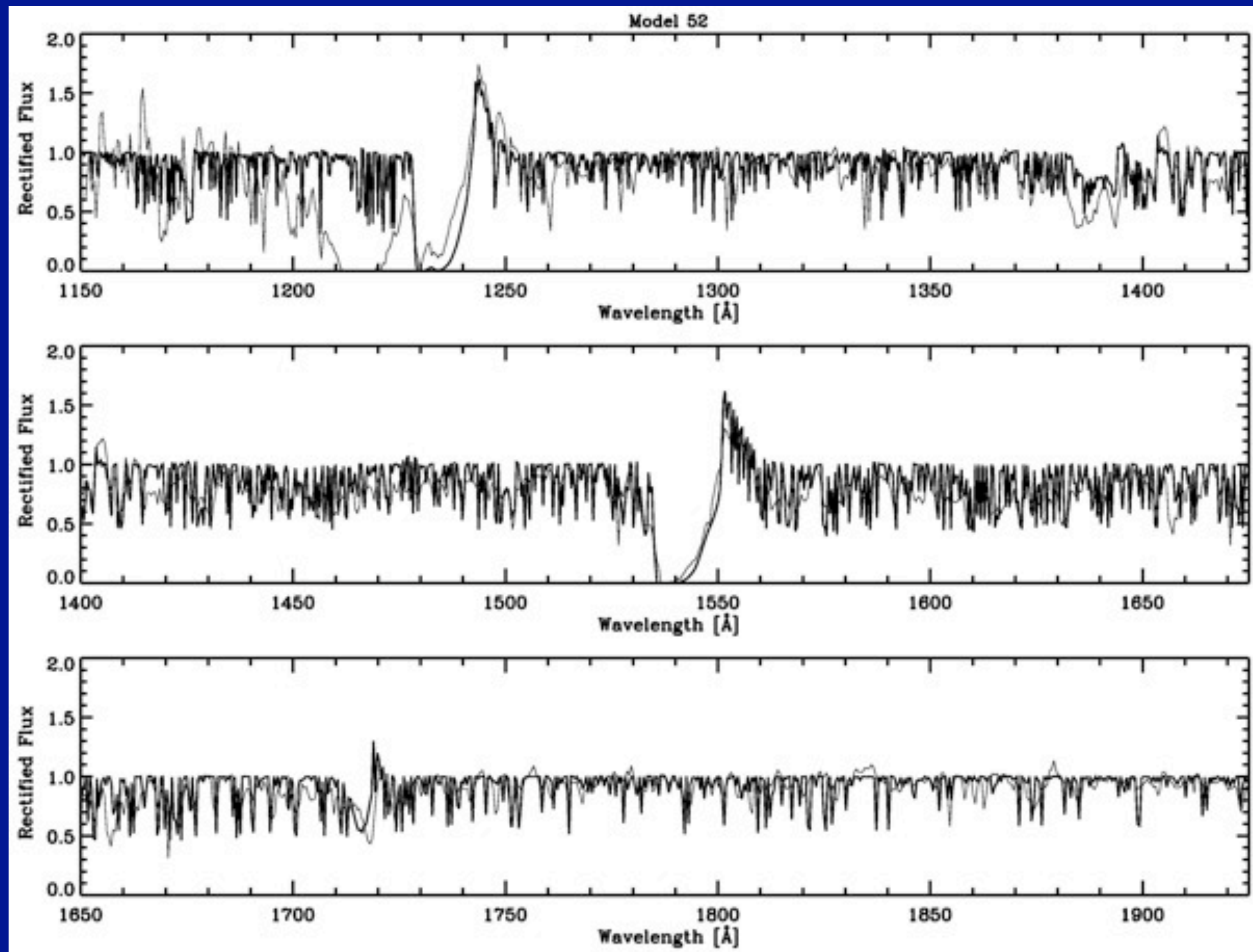
Rotation/binaries - *when* do you have to include it?

Important for ionising spectrum, certain features (e.g. Wolf-Rayet), resolved populations (e.g. Vazquez et al 2007; Maeder & Meynet et al; Heger et al; Han et al; Eldridge et al).

Why is the very near-UV sometimes badly fit? (e.g. Walcher et al 2008)

The rest-UV/massive stars

From C. Leitherer's presentation at the IAU



Purely theoretical library (here O7.5 III star compared to IUE)

Can we ... **ectrum?**

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Crucial

Rotation

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Why is t ... **Walcher et al 2008)**

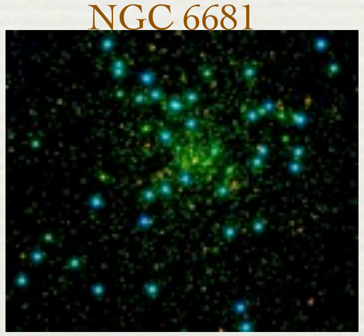
Binaries - are they essential?

We know they are there! But they add extra degrees of freedom to models.

It is therefore important to understand **when** and in what **wavelength range** their effect is important.

Binary models have been successful at explaining the properties of field sdB stars & the EHB stars in globular clusters (e.g. Han 2008). Possibly also blue stragglers?

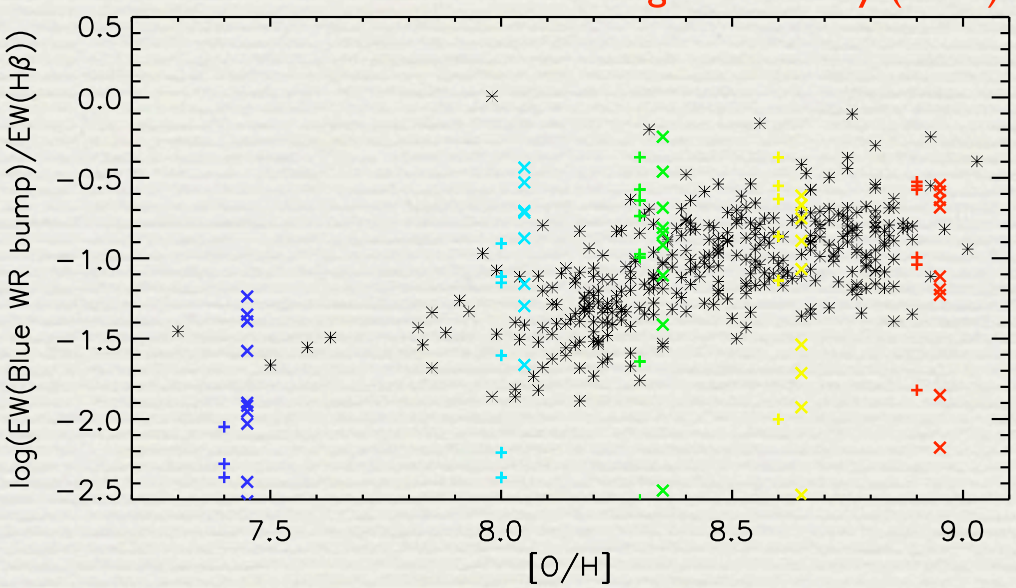
NGC 6681



(Brown et al 2001)
FUV, NUV +opt

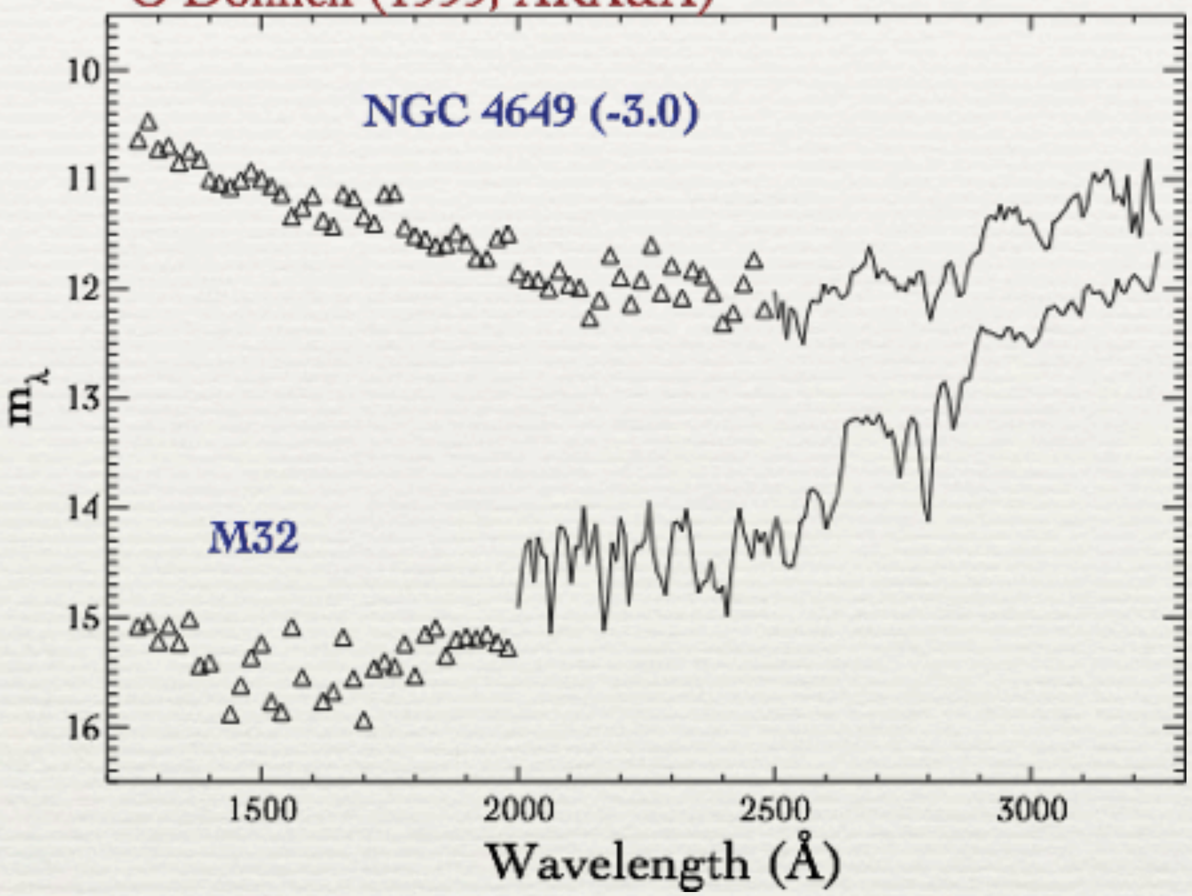
They also provide an interesting channel for the production of Wolf-Rayet stars which are very useful probes of massive star evolution (c.f. Crowther 2007)

Eldridge & Stanway (2009)

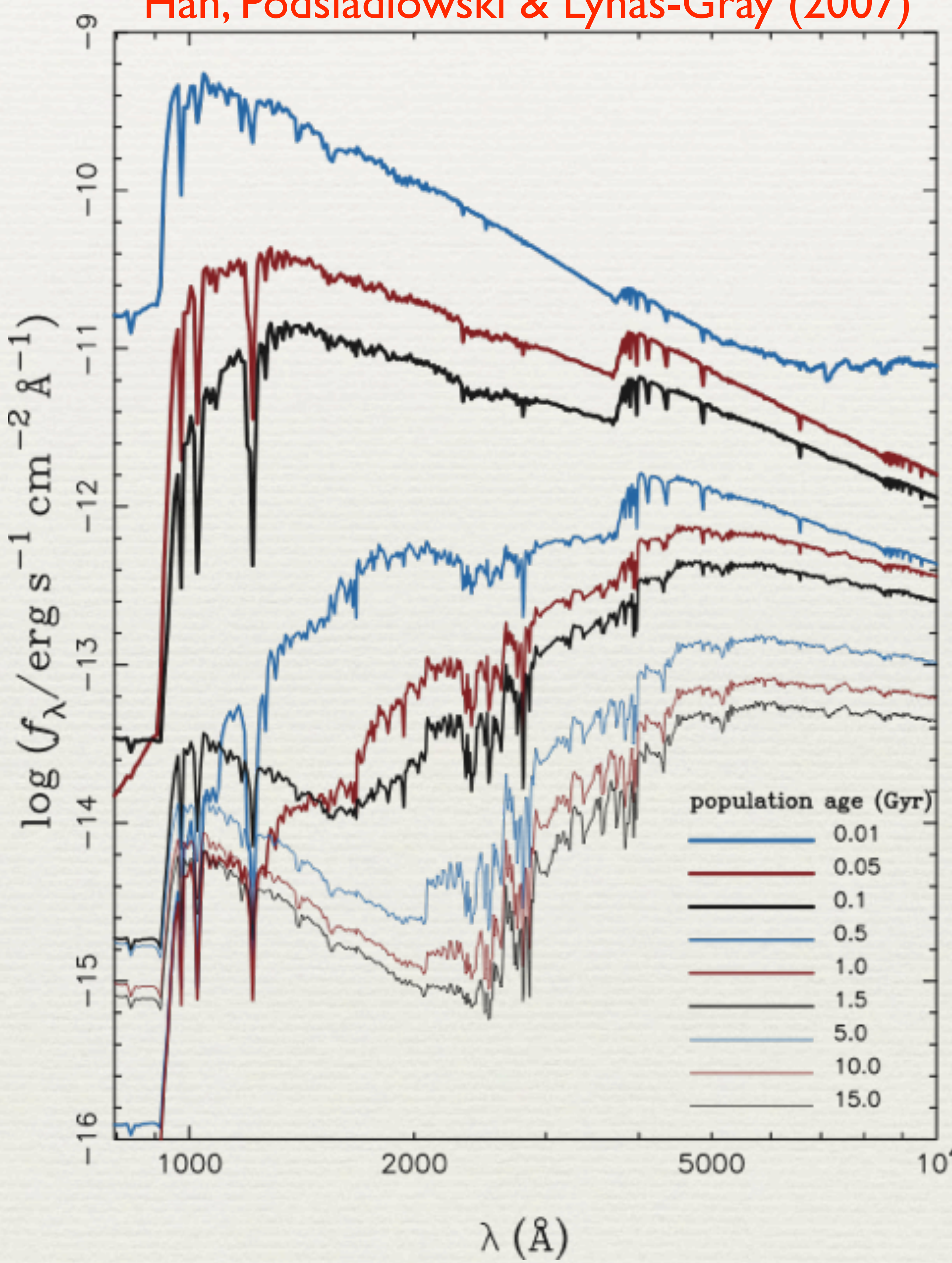


Binaries & the near-UV

O'Donnell (1999, ARA&A)



Han, Podsiadlowski & Lynas-Gray (2007)



Binaries offer an appealing way to explain the UV upturn in elliptical galaxies.
But is this affected by stochasticity?
What about age effects? [c.f. GCs EHBs are rarely binaries, sdBs are often]

A pre-summary

Far- to near-UV

Massive stars - model atmospheres, mass-loss, rotation, binarity.
Lower mass stars - (Extreme) Horizontal branch stars - origin, mass-loss, binarity, metallicity dependence.

Optical

Most stars: Non-solar abundance ratios, isochrones, emitted spectrum, abundance patterns.
Massive stars: Ionizing continuum, Wolf-Rayet features, binarity, rotation.

Near-IR

Intermediate-mass: TP-AGB evolution, atmospheres [stellar parameters]
Wide-range of mass: Evolution on the giant branch, identification and understanding of NIR spectral features.
More testing & calibration is required!

Summarising the challenges

- The near-IR predictions of stellar population models must be better tested/ improved & empirical libraries (e.g. Mármol-Queraltó et al 2008 for CO 2.3μm)
  - This involves resolved stellar populations, NIR spectroscopy, integrated populations and surface brightness fluctuation studies.
- We need improvements in the rest-frame UV model predictions.
  - Empirical spectral libraries, stellar wind models, indirect testing of the far UV using emission lines, improved theoretical libraries & careful testing of them!
- Uncertainties in models should be better propagated/quantified.
- We need better full-spectrum models for non-solar abundance ratios.
- Is it necessary to include binaries in population synthesis models or can their influence be captured in a few parameters?
- How do we best deal with rare/hard to model stellar phases in the models to learn about them through galaxy observations? (e.g. Blue stragglers, EHBs, TP-AGBs, post-AGBs).
- Resolved & integrated modeling should join forces more often!
- Stellar population models must continue to take a broader view (dust, partially resolved models, multi-wavelengths data (X-ray to radio))
- *The rest: IMF, dark matter annihilation, consistency of mass assembly & SFR history etc. etc.*