Stellar Populations - Lecture I

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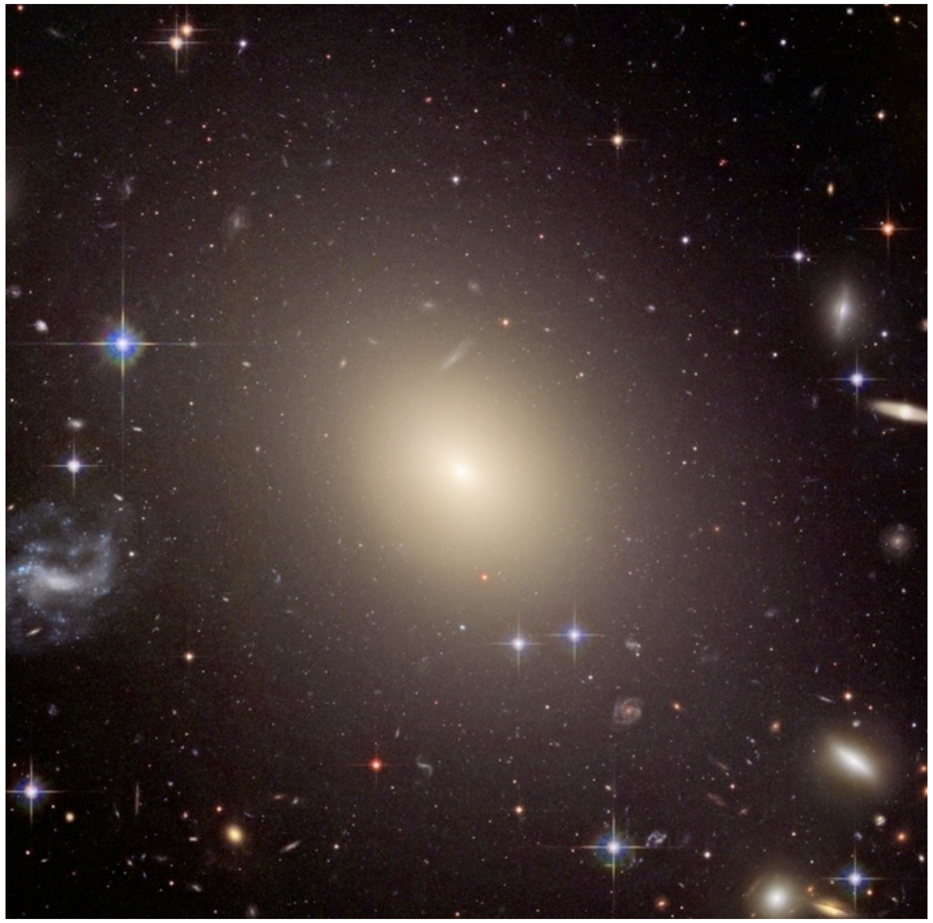
http://astro.dur.ac.uk/~rjsmith/stellarpops.html



Course outline

1. Introduction

- Phases of stellar evolution
- Simple Stellar Populations

2. Resolved Stellar Populations

- Cluster CMDs
- SSP fitting: age, metallicity, IMF
- Complex populations: SFH, MDF
- Exotica

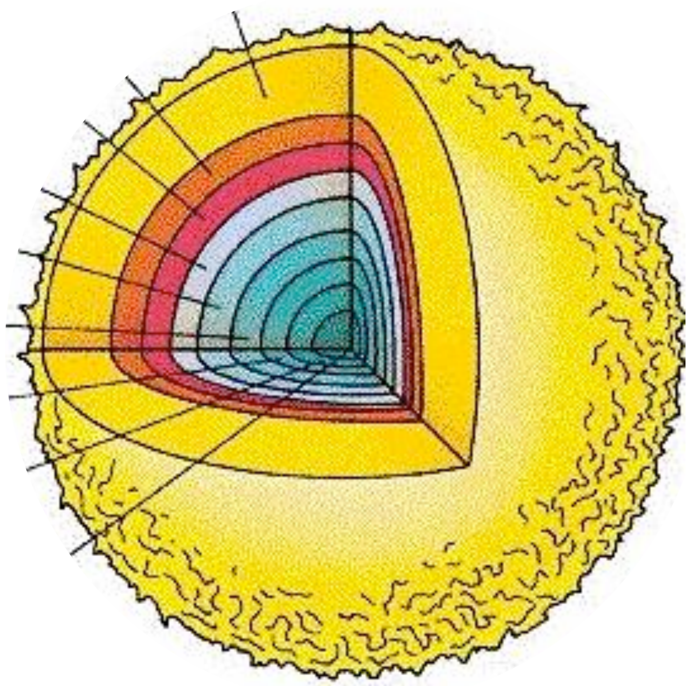
3. Population synthesis

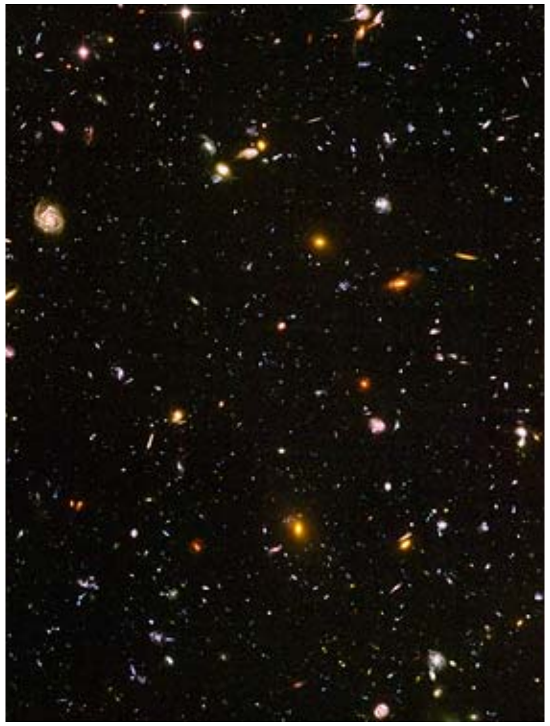
- Inputs
  - Isochrones & extensions
  - Bolometric corrections
  - Stellar libraries
- Colours
  - Optical age-metallicity degeneracy
  - Beyond the optical
- Spectral synthesis

4. Applications

- Star-formation histories
- Stellar masses & photometric redshifts
- Chemical evolution.

What is “stellar populations”?





* Interface between “stellar astrophysics” and “properties of galaxies” (and star clusters).

* Properties of stellar systems (galaxies/clusters) arising from regularity in their stellar content.

* Point of connection between “theory” (galaxy formation models) and “observation”.

Aim of these lectures

* Appreciation of the underpinnings of modern stellar population models: methods and ingredients. (What's in the box?)

* Awareness of the limitations of the models.

* Some illustration of applications to learning about galaxies.

Not aimed at experts... but at students in "neighbouring" research fields.

Stellar evolution reminder

HERTZSPRUNG-RUSSELL DIAGRAM

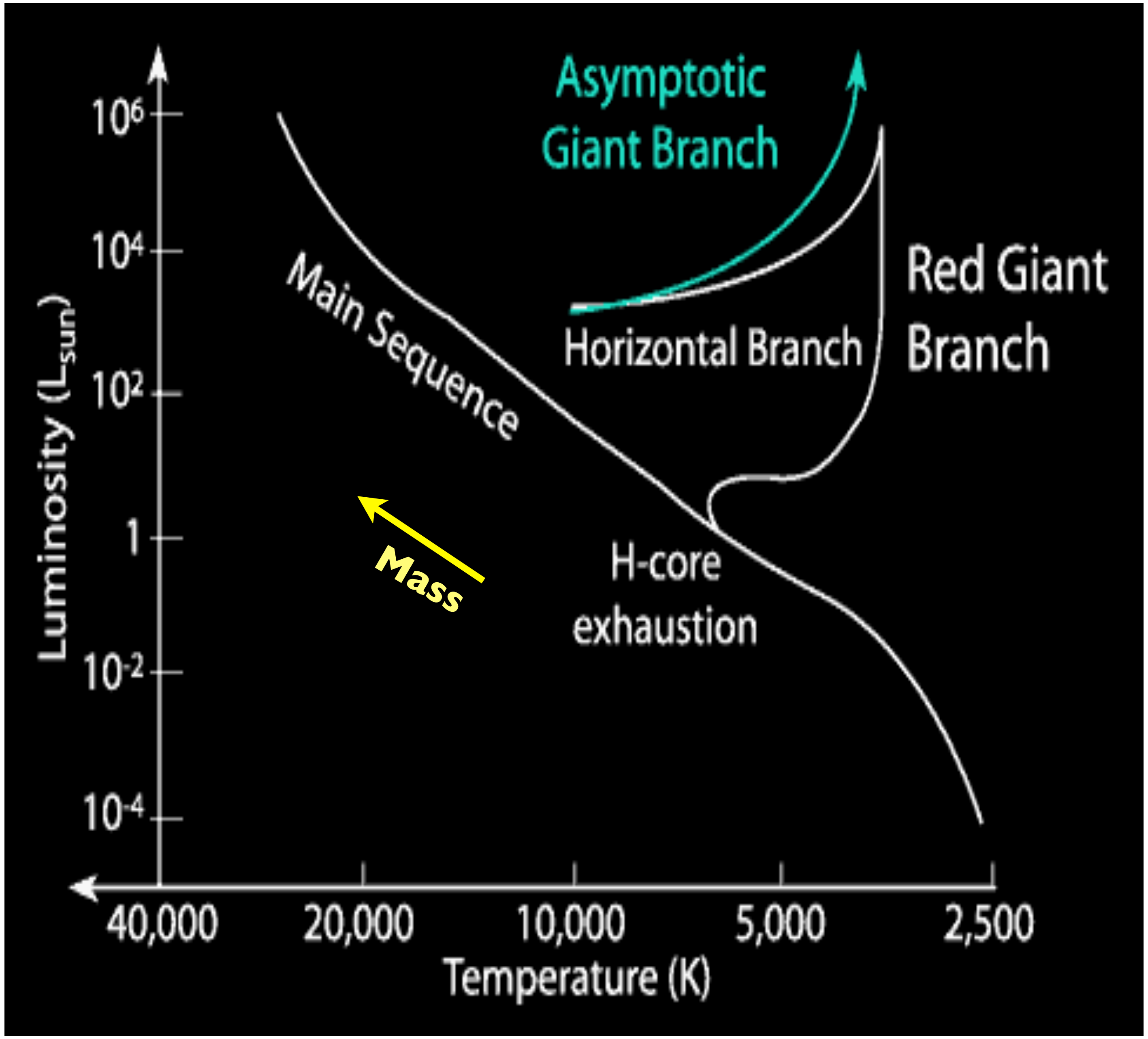
Plots luminosity of stars, versus their temperature.

Stars populate distinct regions of this plane, corresponding to particular evolutionary phases.

Terminology:

HRD is “theory” plane: temperature vs bolometric luminosity.

CMD (colour-magnitude diagram) is its empirical analogue.



Stellar evolution reminder

MAIN SEQUENCE (MS)

Core hydrogen burning phase. Longest phase of evolution.

TURN-OFF

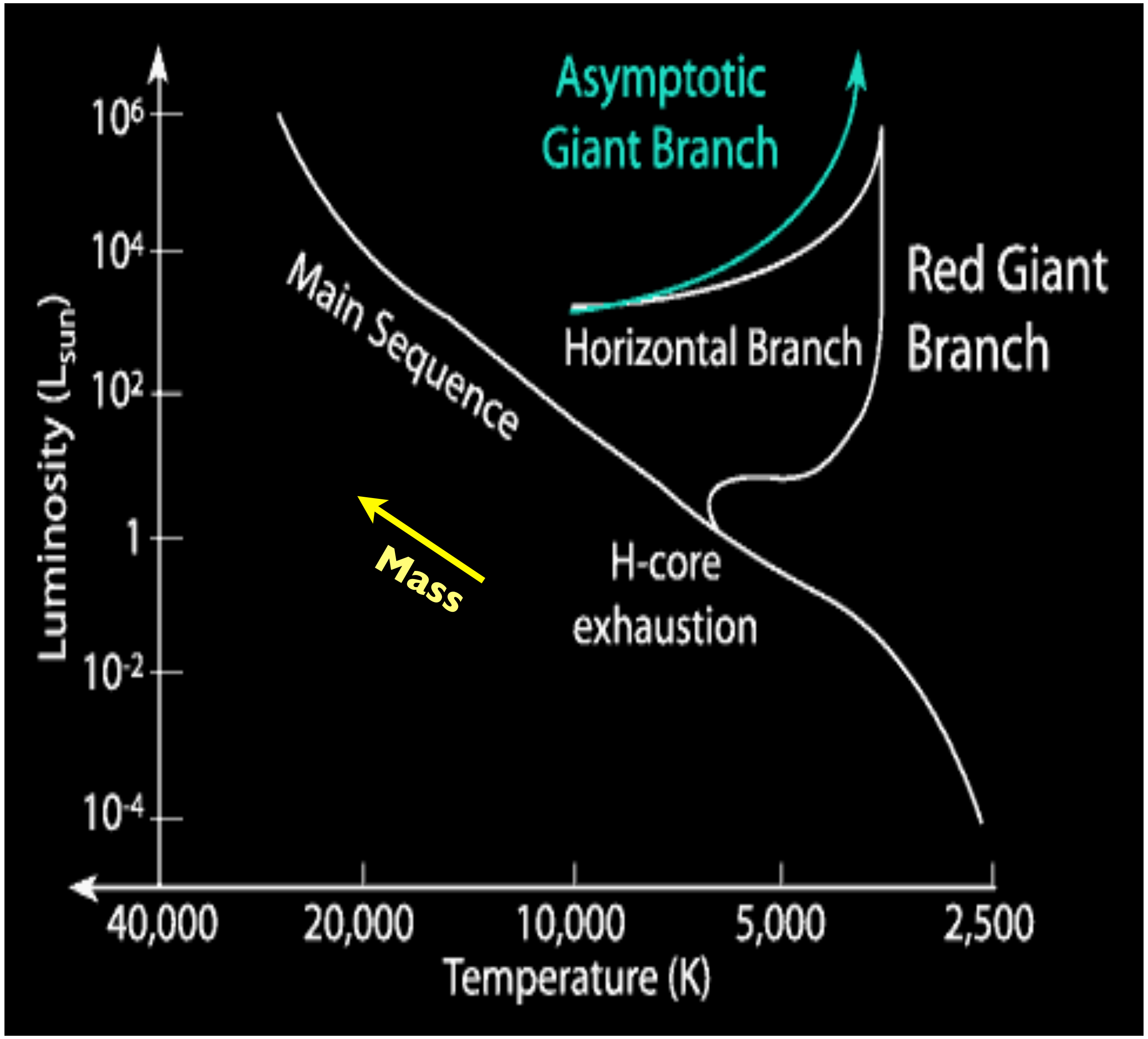
Hydrogen exhausted in core, start of "interesting" evolution.

RED-GIANT BRANCH (RGB)

Hydrogen burning in shell around inert helium core. Growth of He core.

RGB TIP

End of RGB phase: core massive and hot enough to ignite He-burning (the "helium flash")



Stellar evolution reminder

HORIZONTAL BRANCH (HB)

Core He burning. Details depend on metallicity and on mass-loss in the RGB phase.

ASYMPTOTIC GIANT BRANCH (AGB)

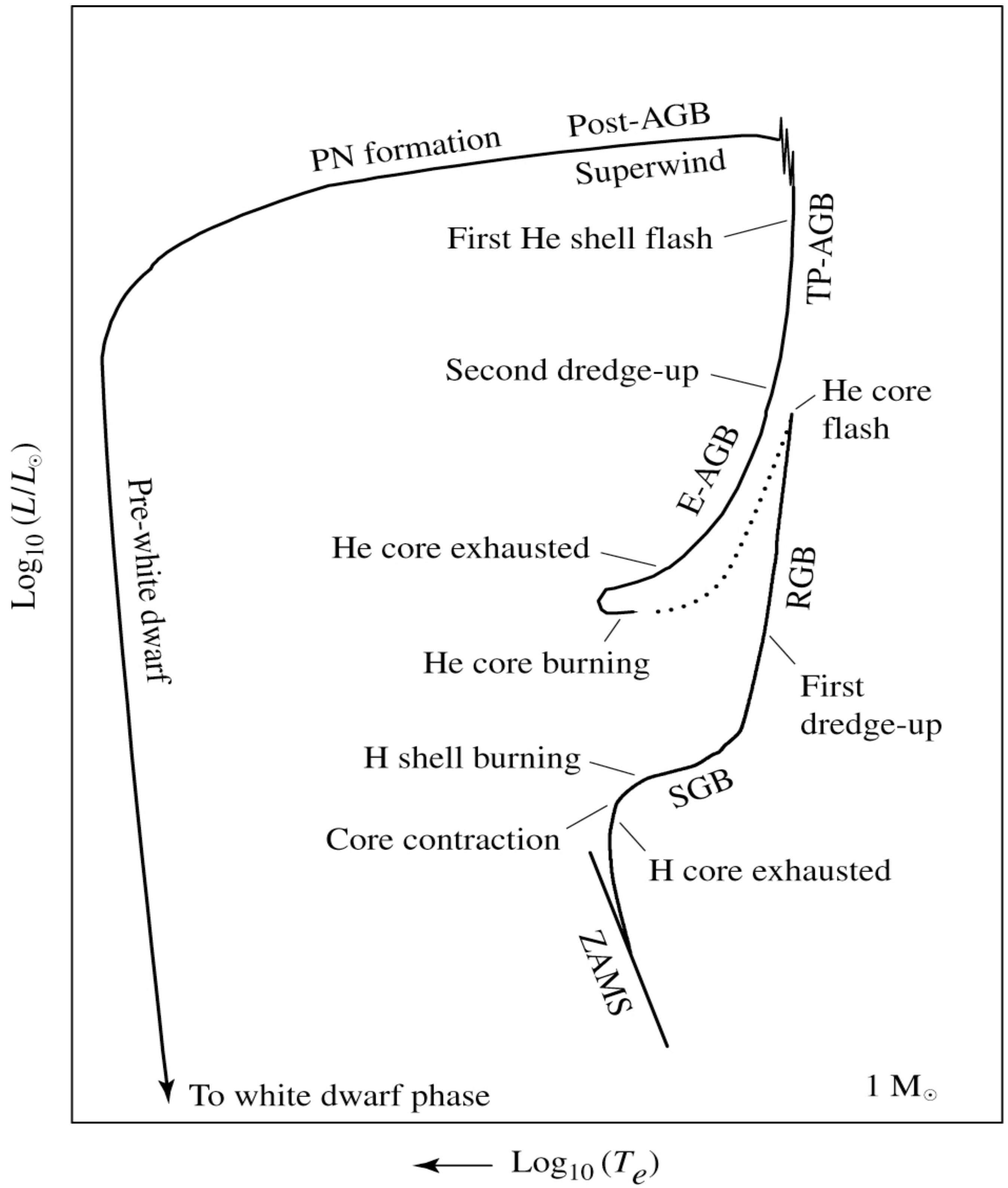
He burning in shell around inert C/O core. Complicated mass-dependent evolution from here on.

WHITE DWARF SEQUENCE (WD)

Low-mass stars eject envelope and leave inert C/O core which cools as a WD.

SUPERNOVAE

Massive stars explode as SNe.



Stellar evolution reminder

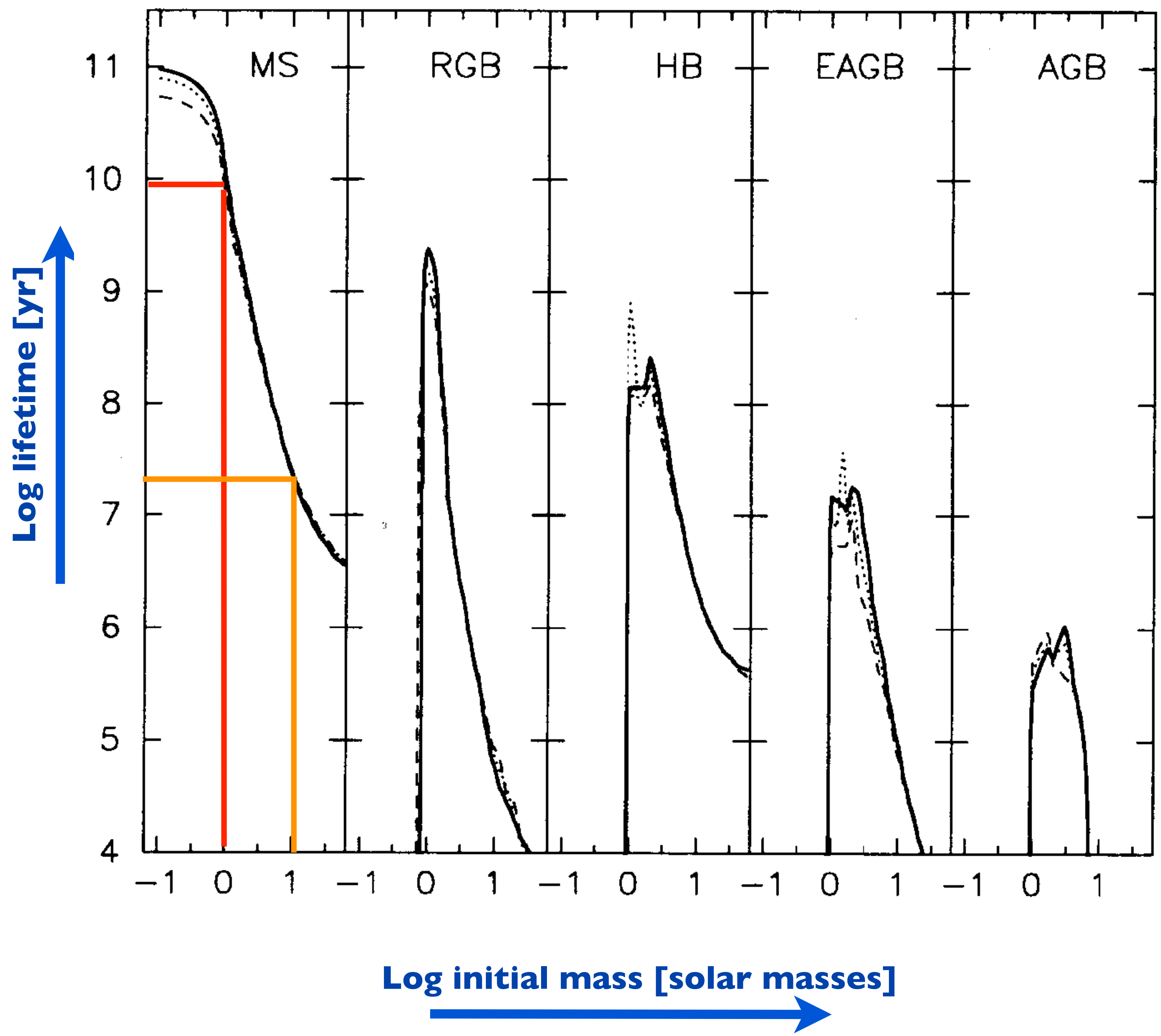
MASS-DEPENDENT LIFETIMES

Lifetime in each evolutionary phase depends sensitively on initial mass.

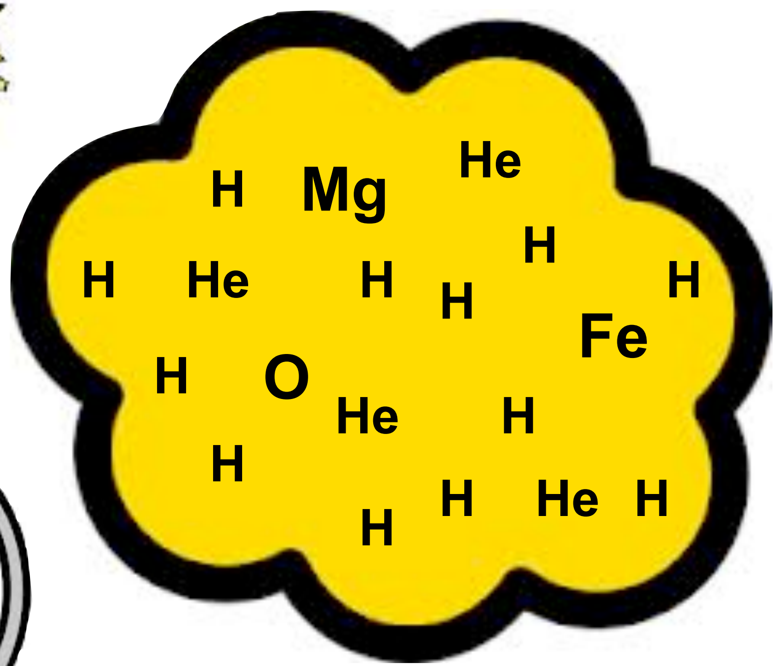
MS lifetime is $\sim 10^{10}\,(M/M_{sun})^{-2.5}$ yrs: so 10 Gyr at 1 solar mass, but only ~20 Myr for 10 Msun.

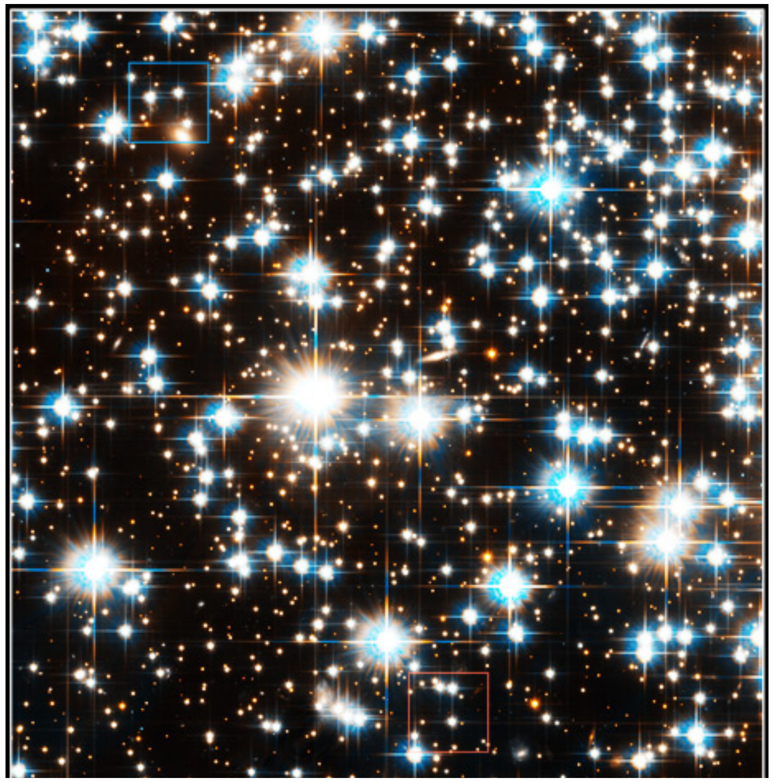
Subsequent phases shorter-lived.

Below ~ 0.9 Msun, the MS lifetime is longer than age of Universe!



The simple stellar population: SSP





Convert a **homogeneous** package of gas **instantaneously** into stars.

Can initially describe resulting population by its chemical composition - loosely **metallicity** (inherited from the the gas) and **initial mass function** (distribution of stellar masses).

Track subsequent evolution with time since formation, i.e. **age**.

Tracks and isochrones

Outputs of stellar modelling / inputs to galaxy modelling

Tracks:

Describe evolution of a single star with time.

Tables of stellar parameters (luminosity, temperature, surface gravity; core temperature, core composition, current mass, etc etc).

Isochones:

Join parameters for stars of different masses at the same time.

Isochrone tables: same content as tracks, but rearranged!

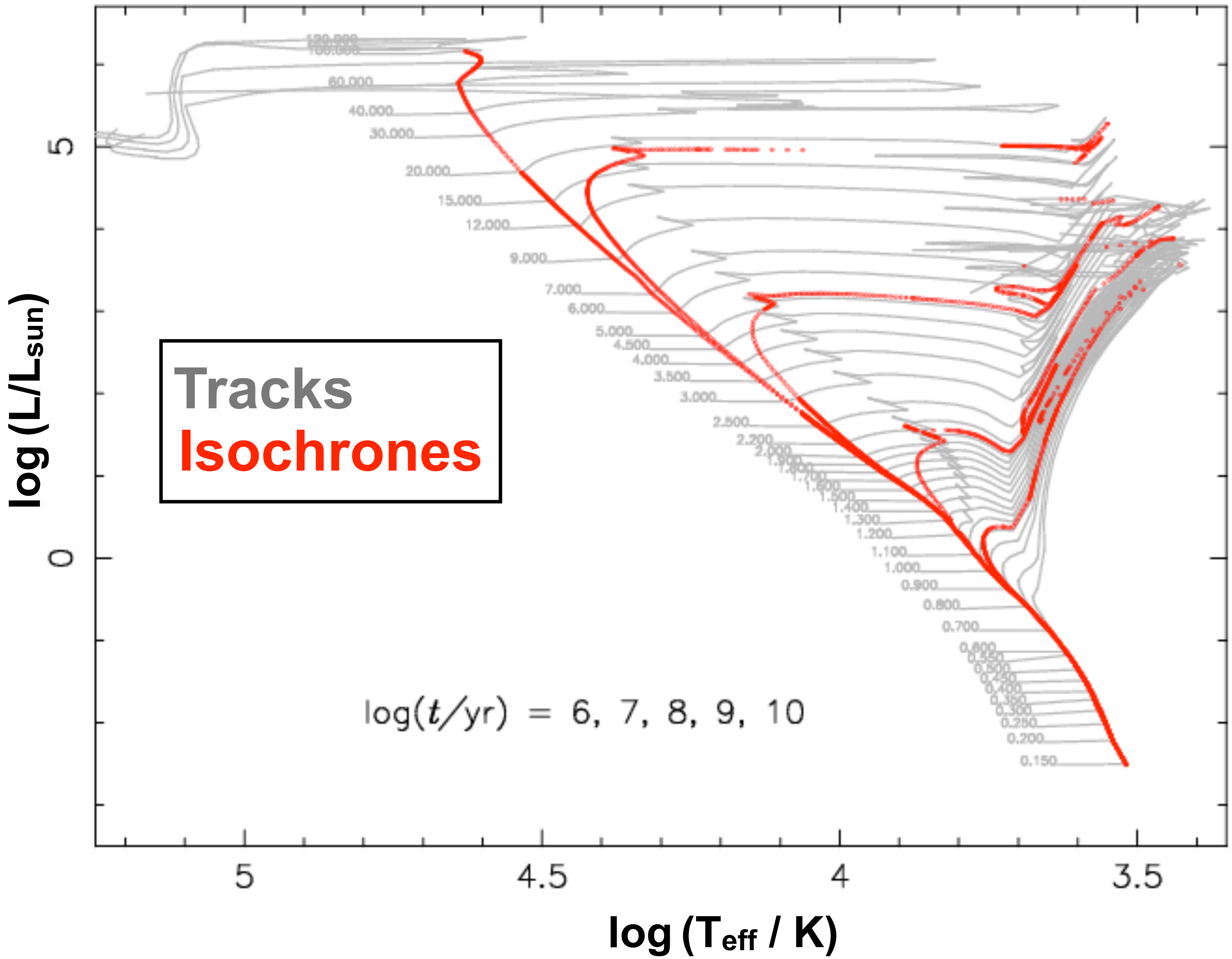
For a true SSP, after time T, all stars sit on the age=T isochrone.

Common sources:

"Padova" : Bressan et al. 2012 - http://stev.oapd.inaf.it

"BaSTI" : Cordier et al. 2007 - http://albione.oa-teramo.inaf.it

Tracks and isochrones

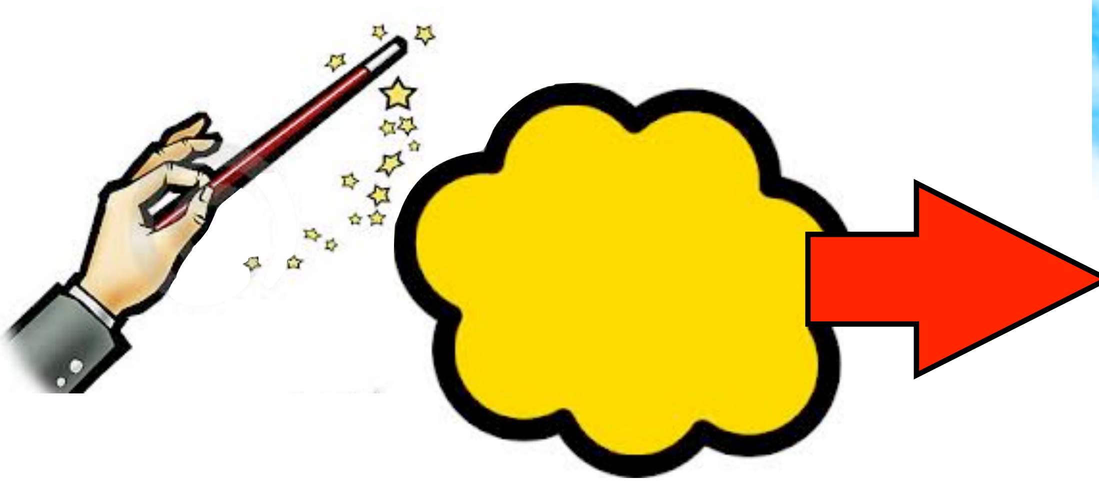


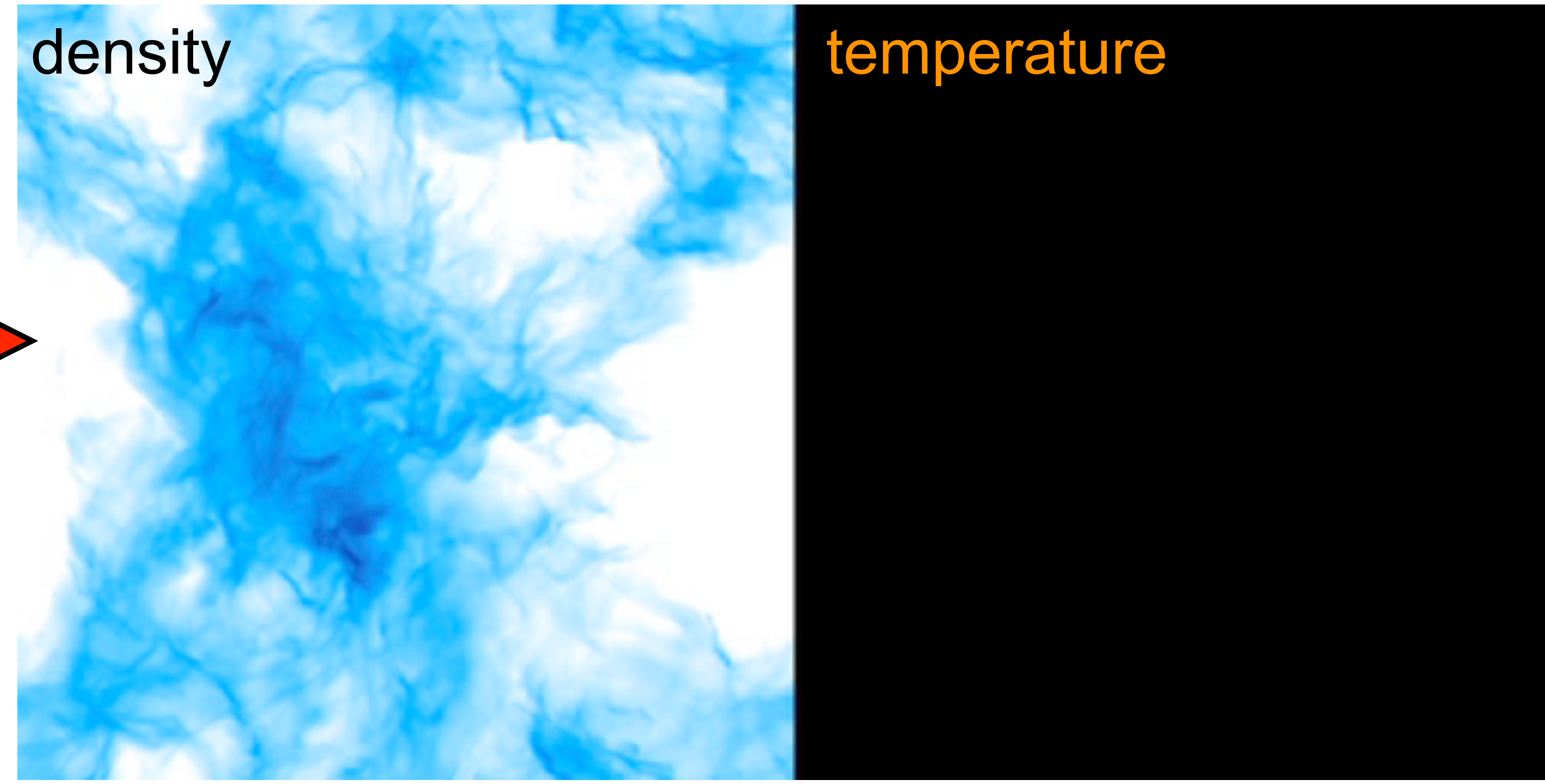
NB: still in “theory plane” of temperature and total (bolometric) luminosity.

Need additional information to transform to magnitude & colours measured in particular bandpasses.

Zhang et al. 2012

Initial mass function





Krumholz et al. 2012

How is the gas distributed among stars of different masses?

To predict from first principles, need to understand fragmentation of gas clouds and accretion onto pre-stellar cores during star-formation.

Complex physics: turbulence, self-gravity, magnetic fields, radiation feedback...

Initial mass function

How many stars formed per unit mass?

Determines number of stars expected at each point along isochrone.

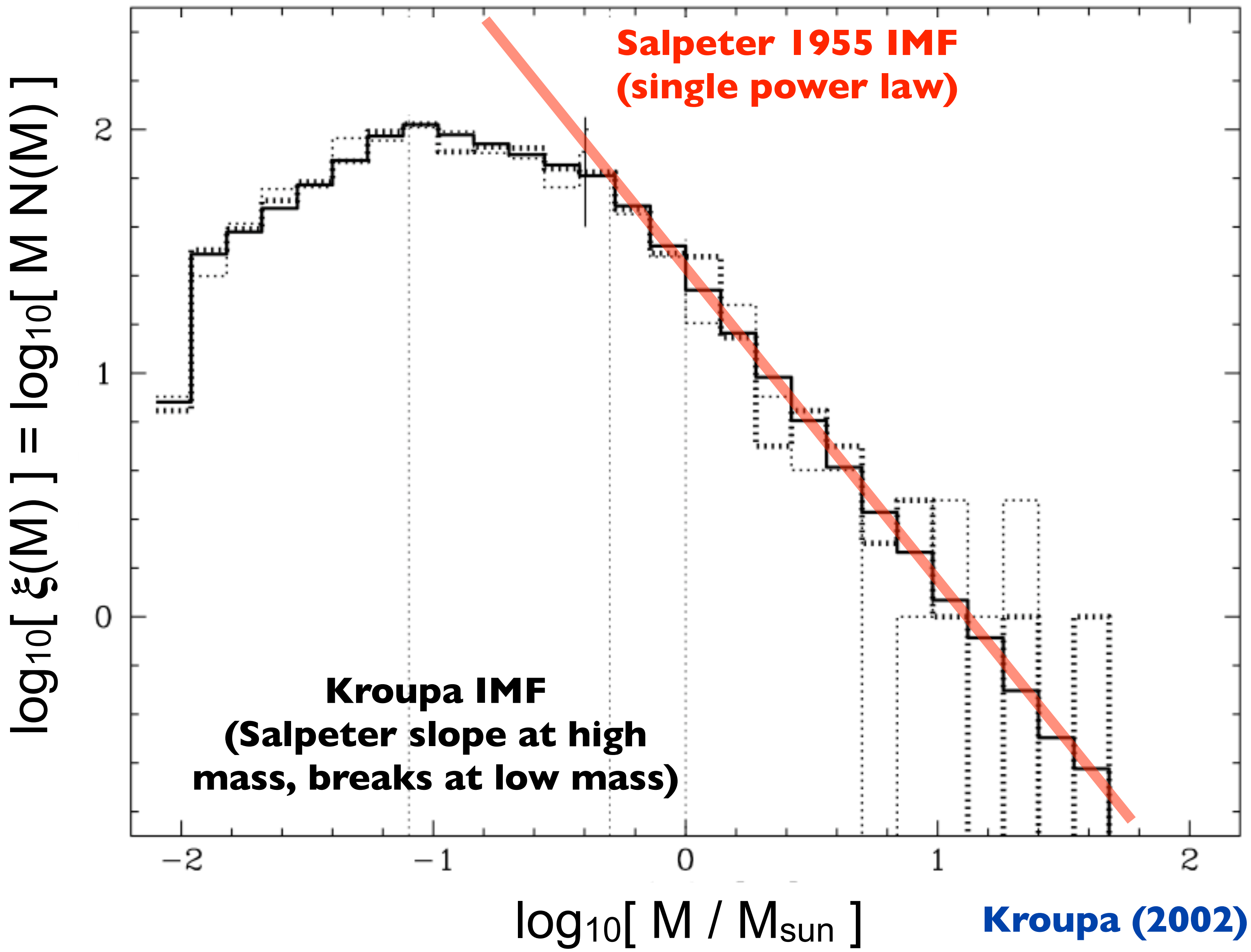
Constrained from detailed observations of star-forming regions in the MW.

In MW, high-mass power-law

$N(M)\,dM \sim M^{-2.35}\,dM$

(Salpeter 1955), but breaks to ~lognormal at $M<0.5M_{sun}$ (Kroupa 2001, Chabrier 2003)

Is the IMF universal? (Bastian et al. 2010)



Kroupa (2002)

[Note there are two conventions in use: $N(M) \sim M^{-2.35}$ and $\xi(M) = M\,N(M) \sim M^{-1.35}$ both refer to the "Salpeter" slope!]

MW-like IMF generally assumed for wide range of environments beyond MW!

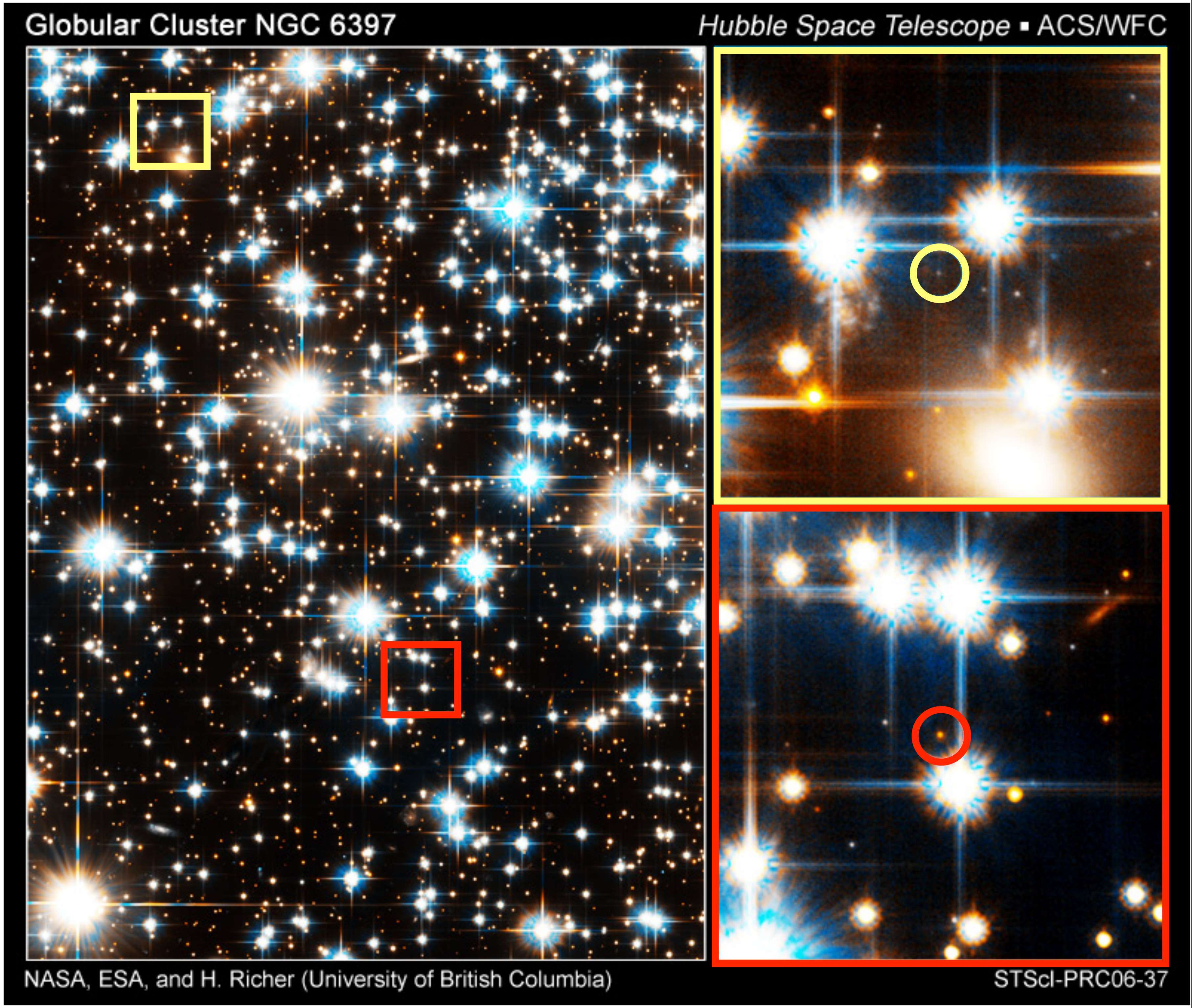
Resolved stellar populations

In MW, and in very nearby galaxies, we can resolve and measure fluxes for individual stars.

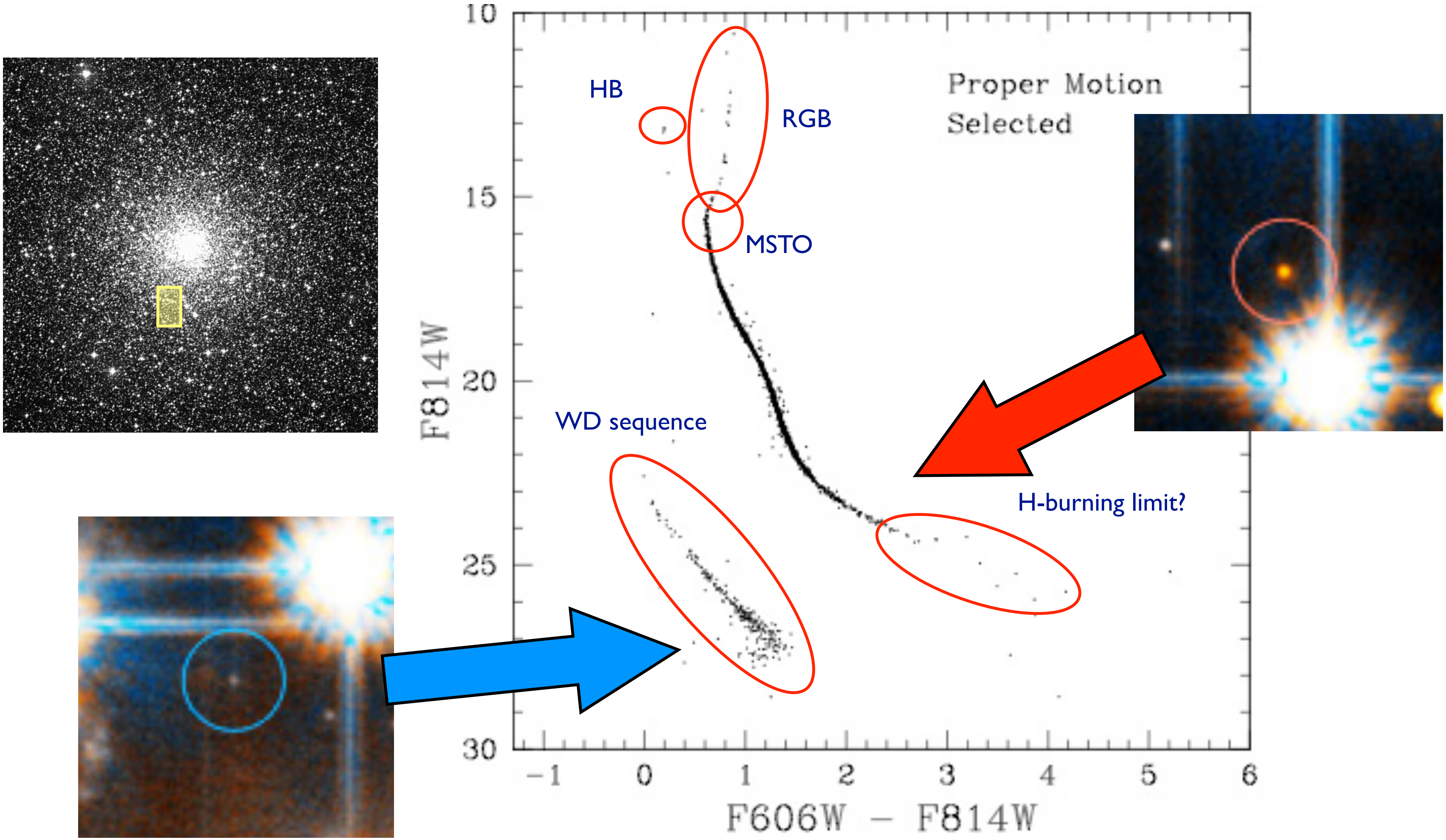
Often working in crowded fields, and over large dynamic range.

Need specialised “psf-fitting” methods to extract star fluxes, accounting for instrument point-spread function, and its variation over the field.

Construct colour magnitude diagrams and fit theoretical isochrones.



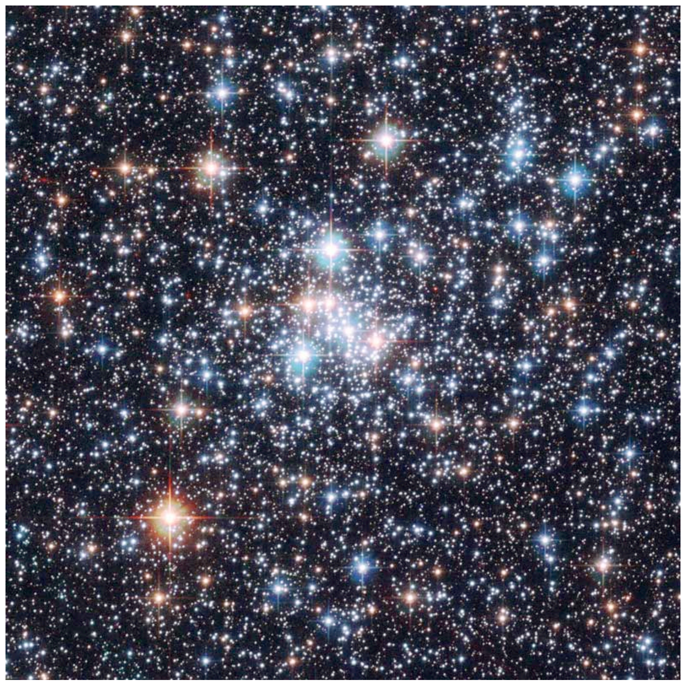
Resolved stellar populations

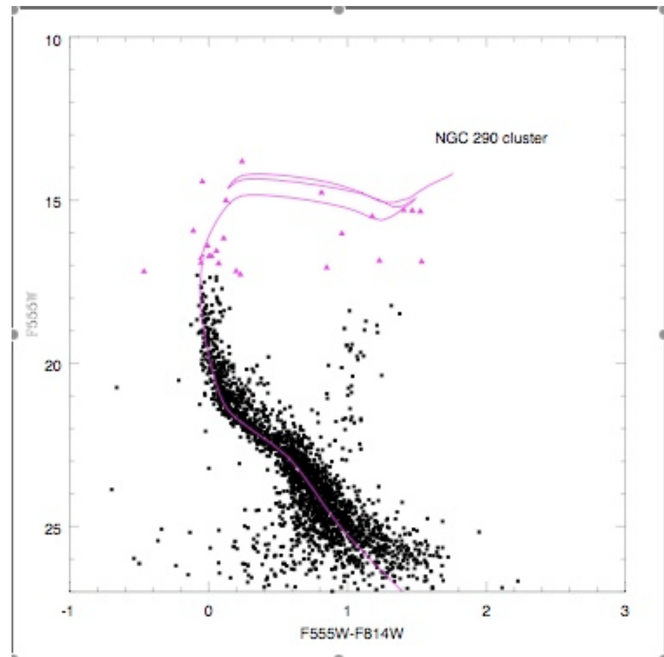


NGC 6397 (Richer et al. 2007)

MW star clusters

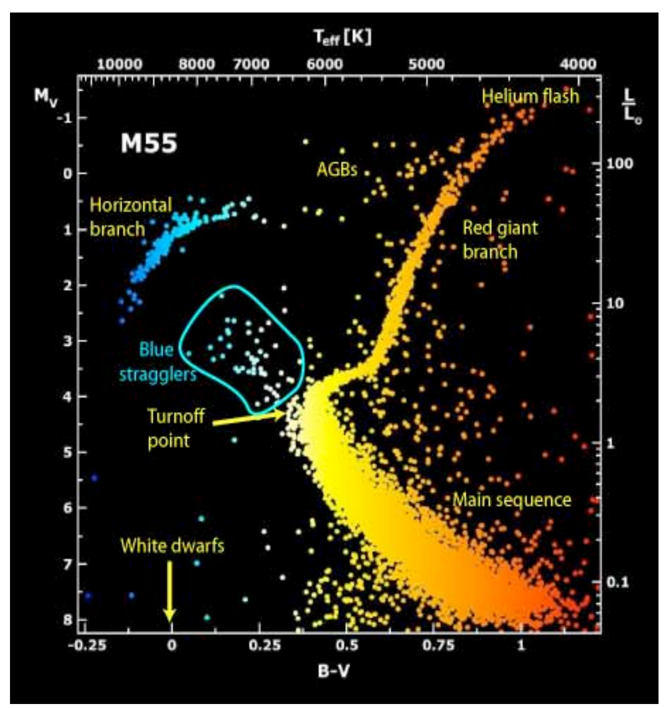
Approximate realization of SSPs.





OPEN CLUSTERS

MS dominant, few RGB or other evolved stars. Only few 100s or 1000s of stars.



GLOBULAR CLUSTERS

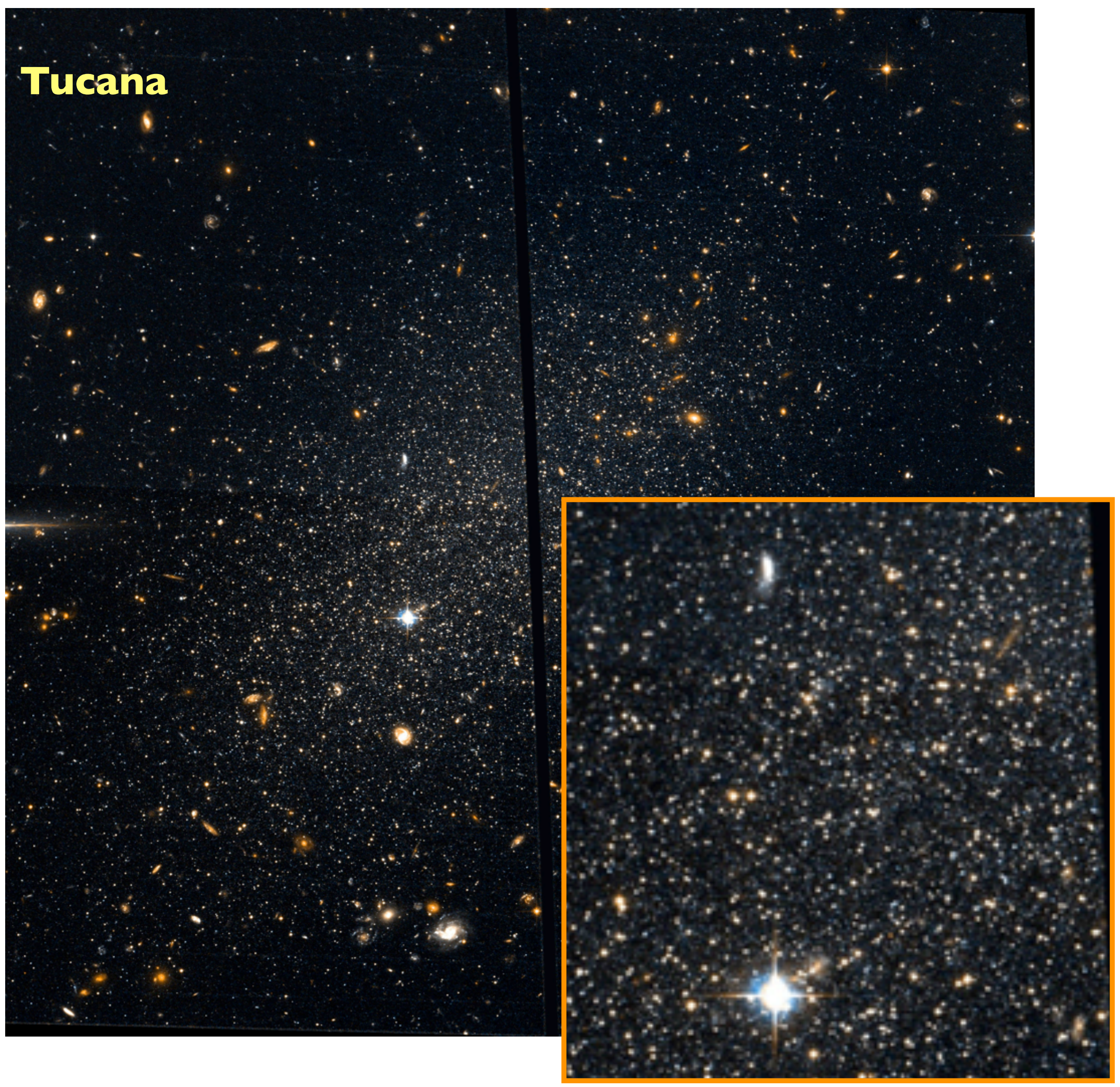
De-populated upper MS. Strong RGB and HB.

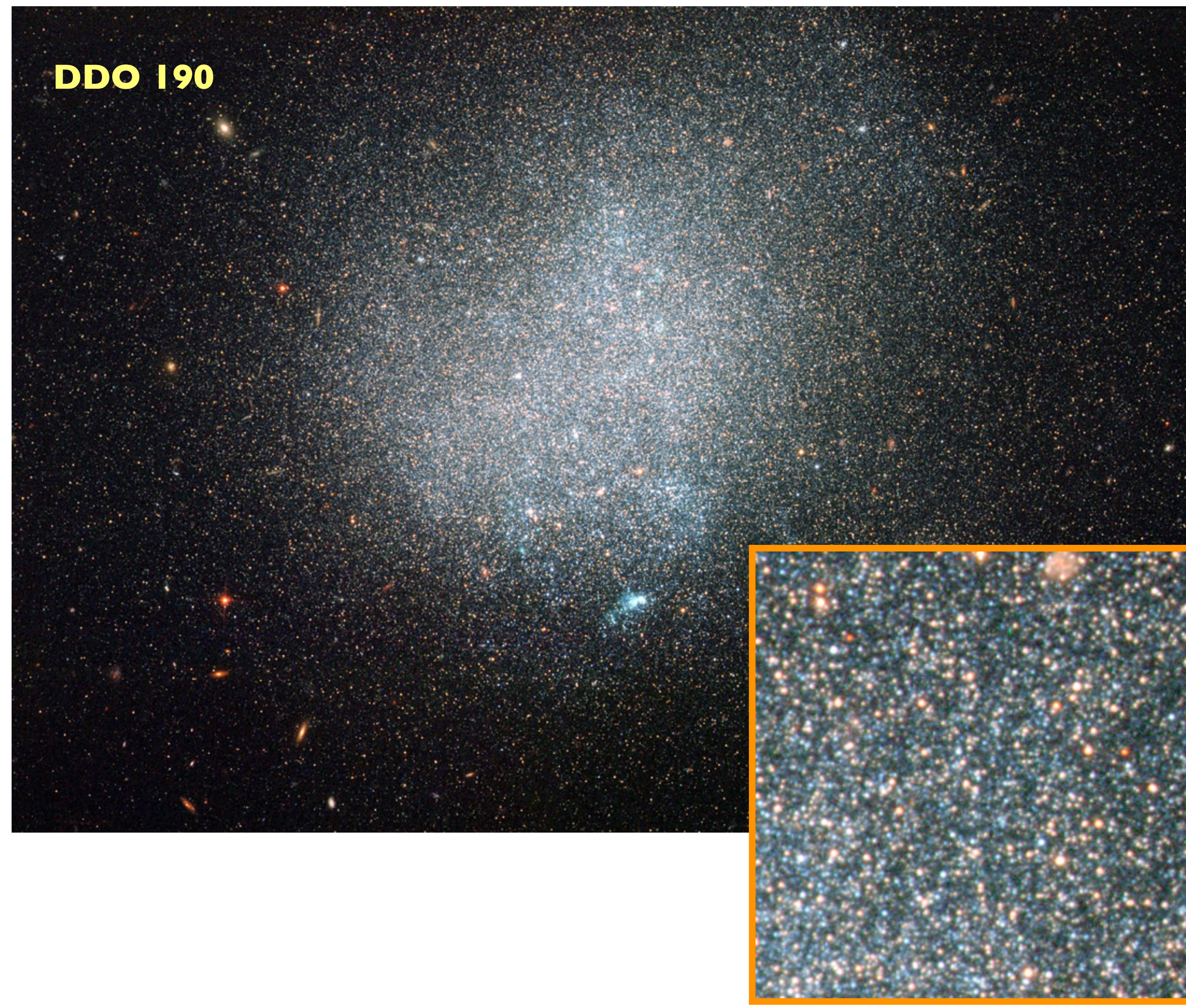
1,000s to 100,000s of stars.

Resolved galaxies

Local group and other nearby galaxies.

Usually more complex populations (multiple bursts, extended SF history).





Theoretical isochrones vs data

The classic tool for "resolved stellar populations".

First need to predict observable quantities, i.e. band luminosities and colours.

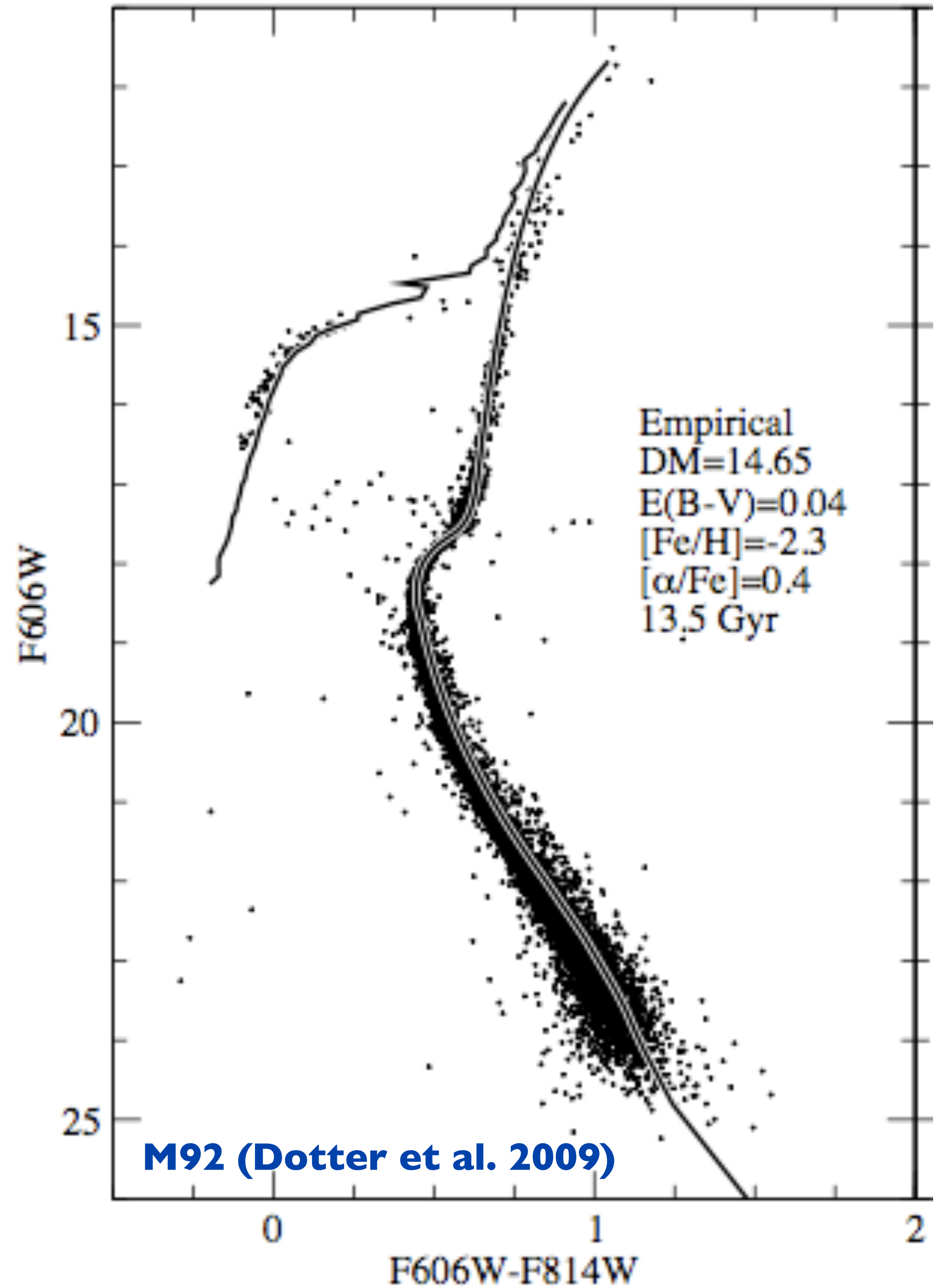
COLOUR TRANSFORMATIONS

Need to translate physical parameters (T_{eff}, log g, L_{bol}) to observed colours (e.g. B-V, J-K), based on theoretical stellar atmospheres (or empirical libraries).

ISOCHRONE FITTING

For deep CMDs, there is enough information to decouple many parameters: age, metallicity, distance, reddening etc.

For shallower data, some of these quantities will be poorly constrained (e.g. age unless MSTO is reached).



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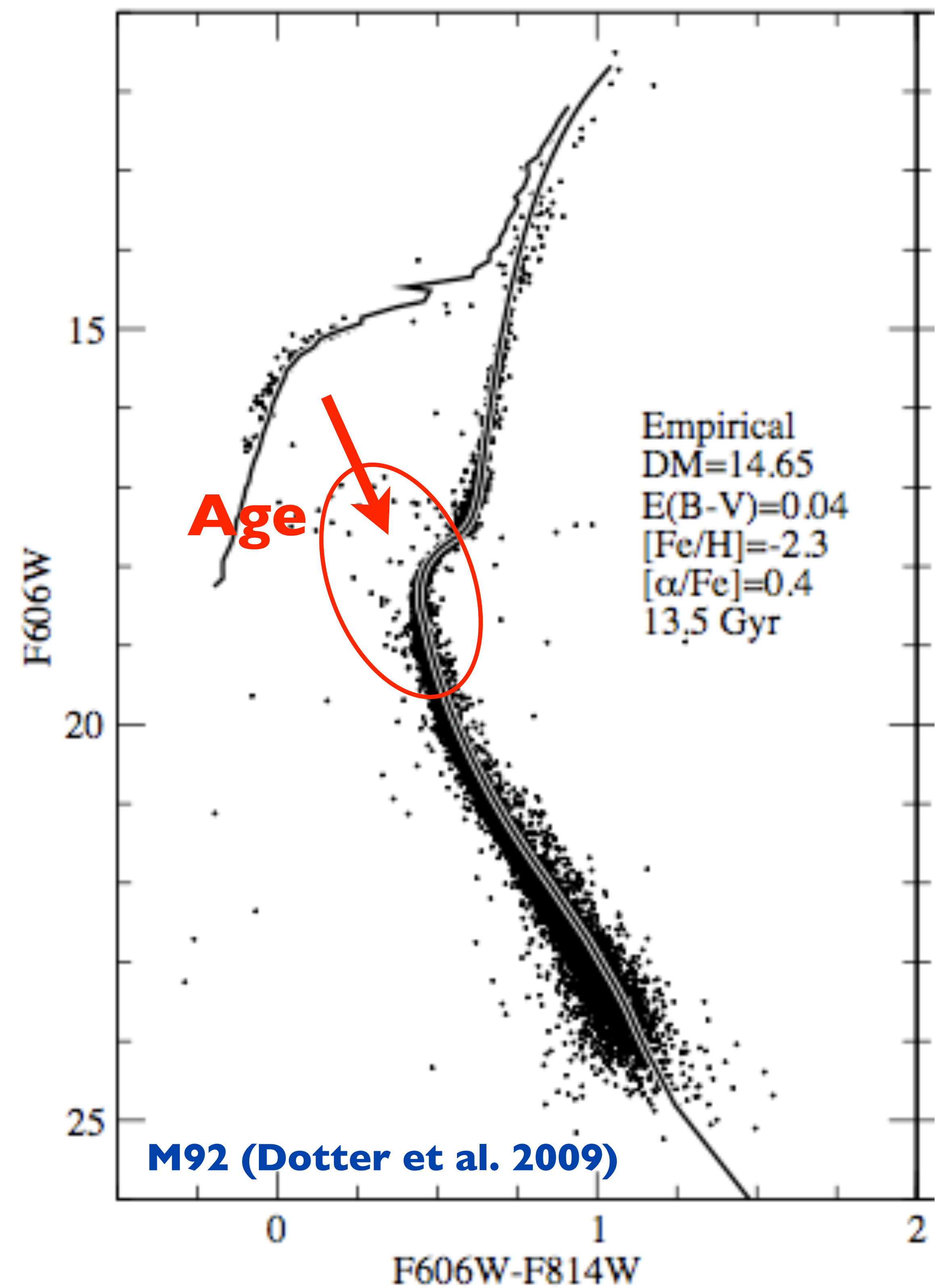

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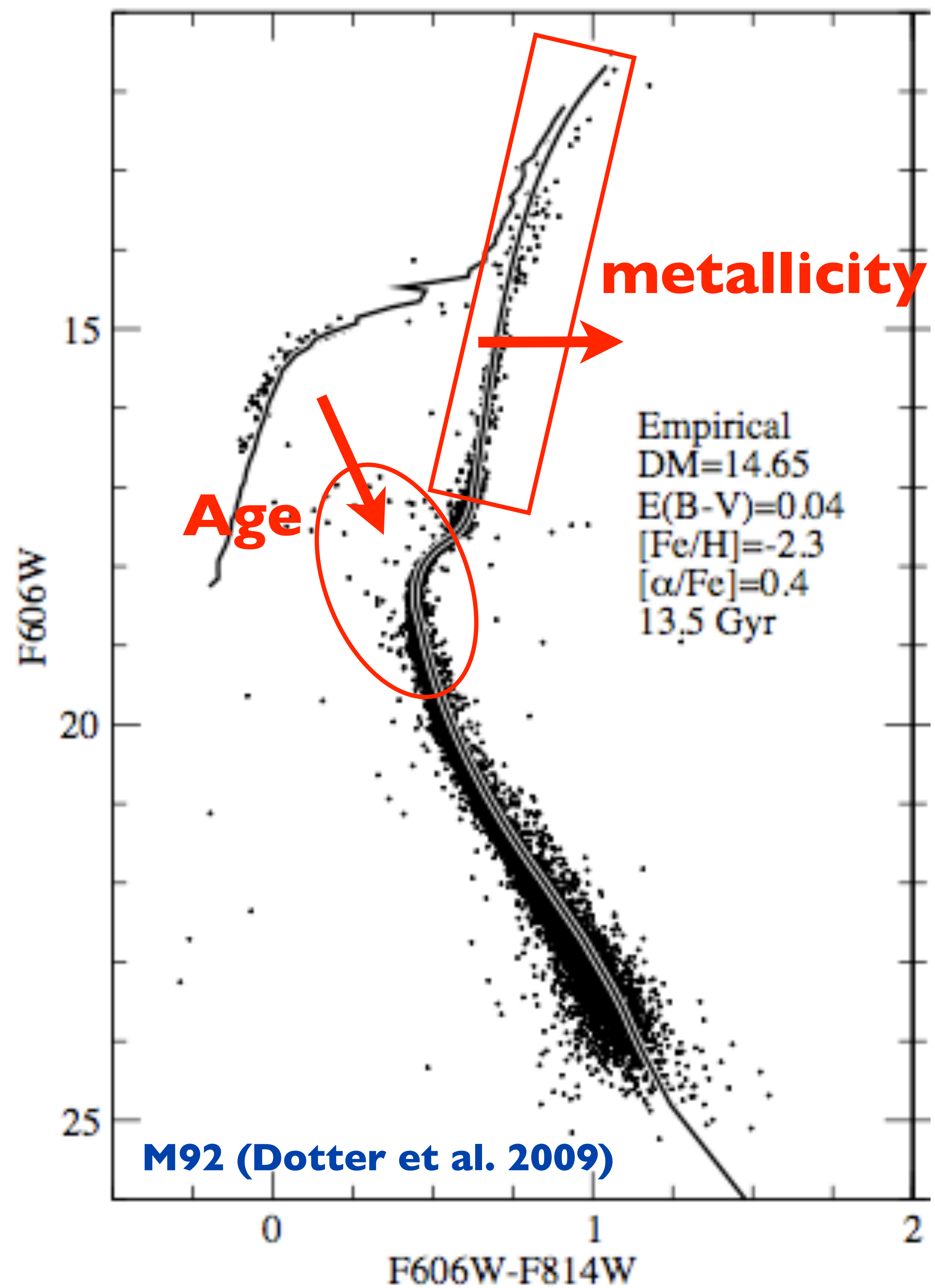

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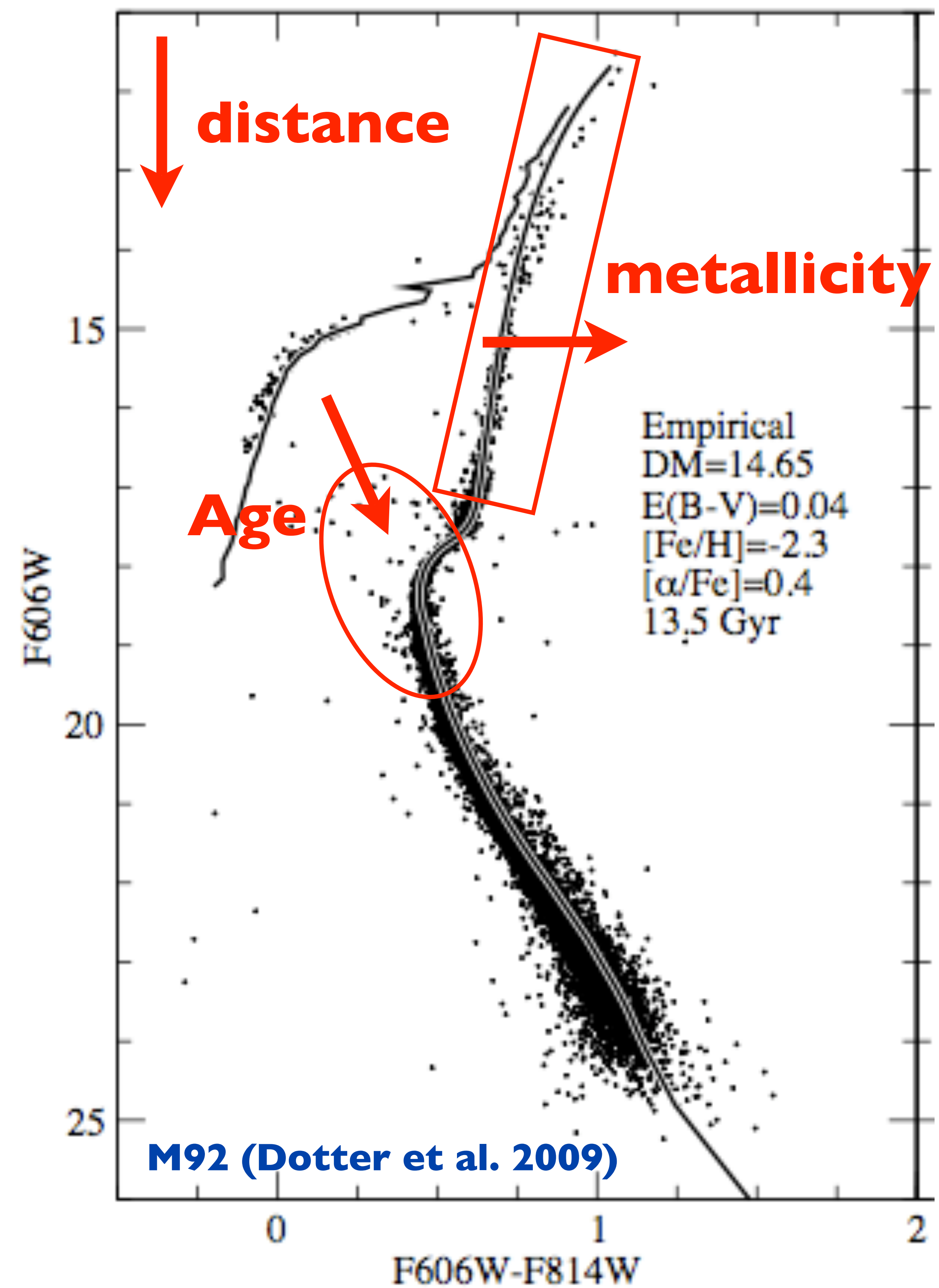

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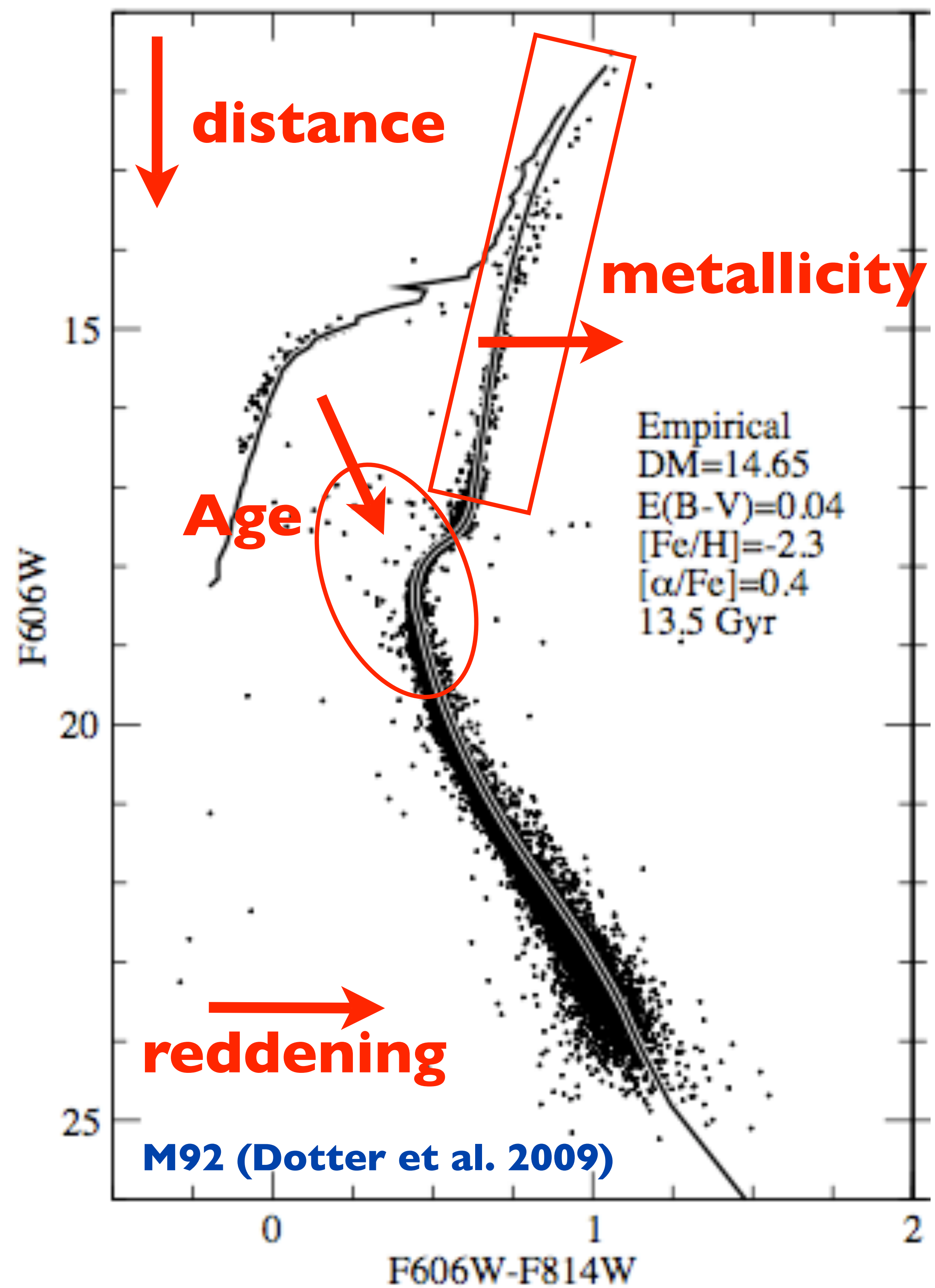
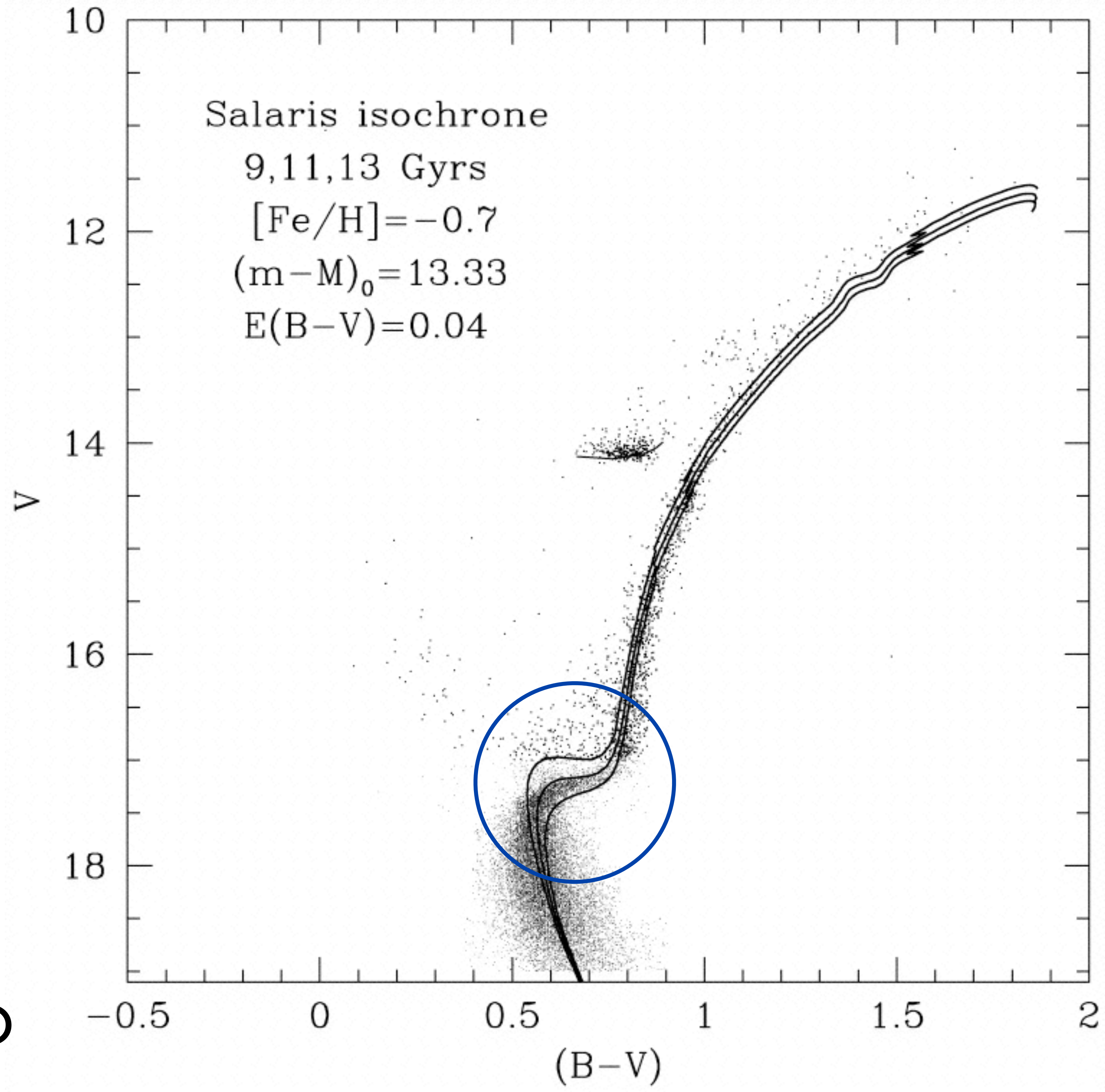


Age from main-sequence turn-off

Schiavon et al. (2002) fit to globular cluster 47 Tuc



Stellar evolution as a clock

MS lifetime versus mass relation: luminosity (and colour) of stars at TO depends on time since formation.

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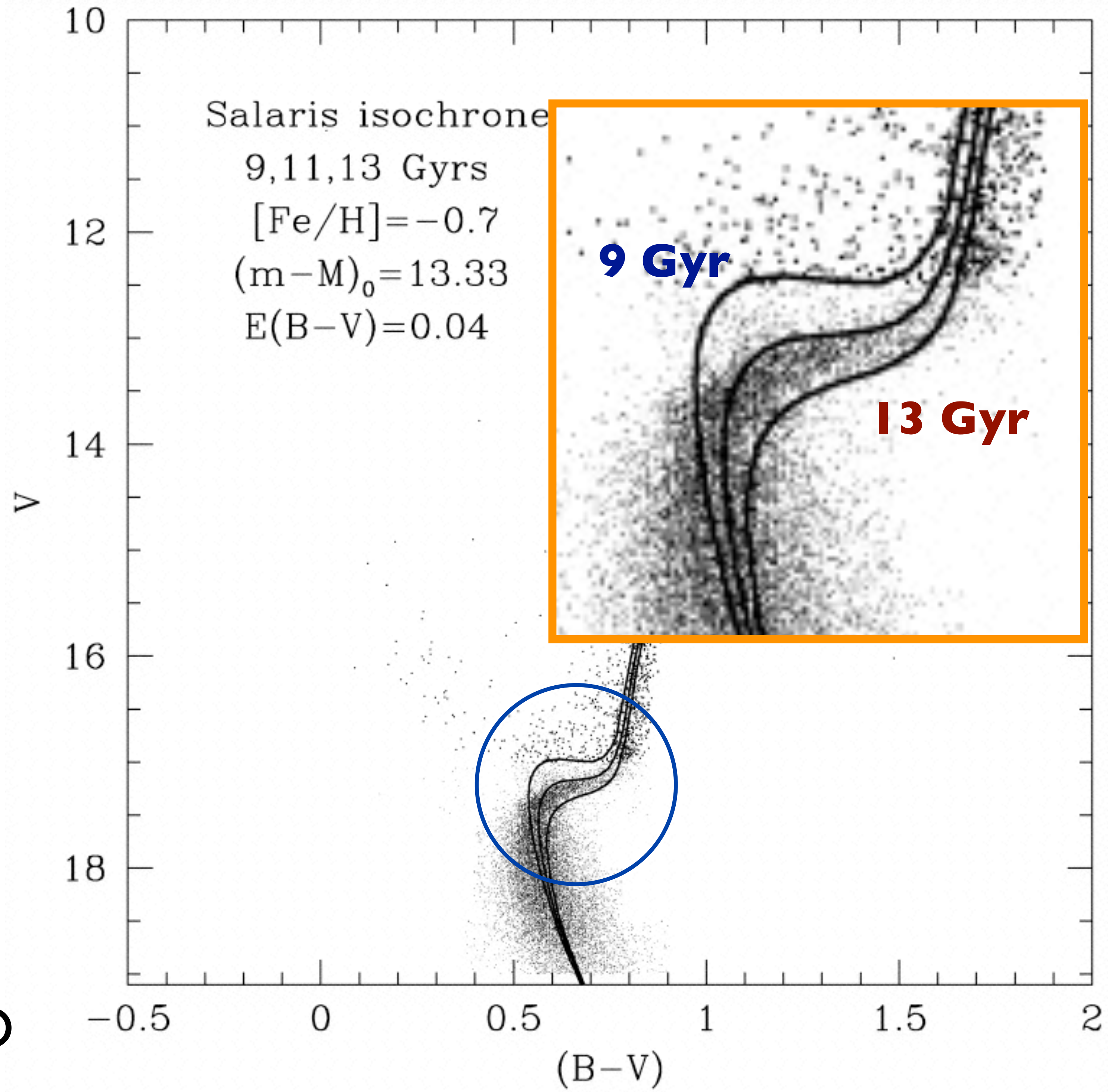


Stellar evolution as a clock

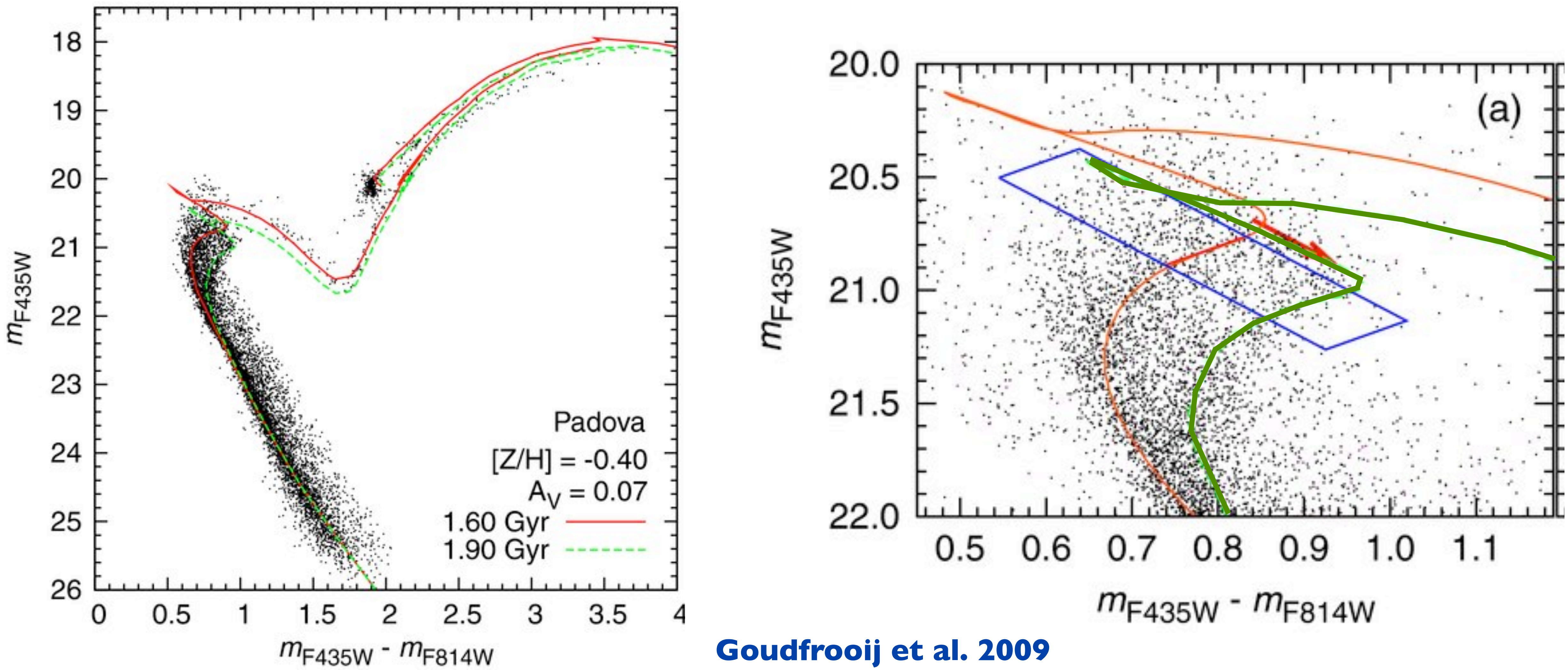
MS lifetime versus mass relation: luminosity (and colour) of stars at TO depends on time since formation.

More complicated CMDs

MULTIPLE AGES

In general, stellar systems may have extended formation histories.

E.g. extended / multiple MSTO in NGC 2209 (intermediate-age cluster in LMC)



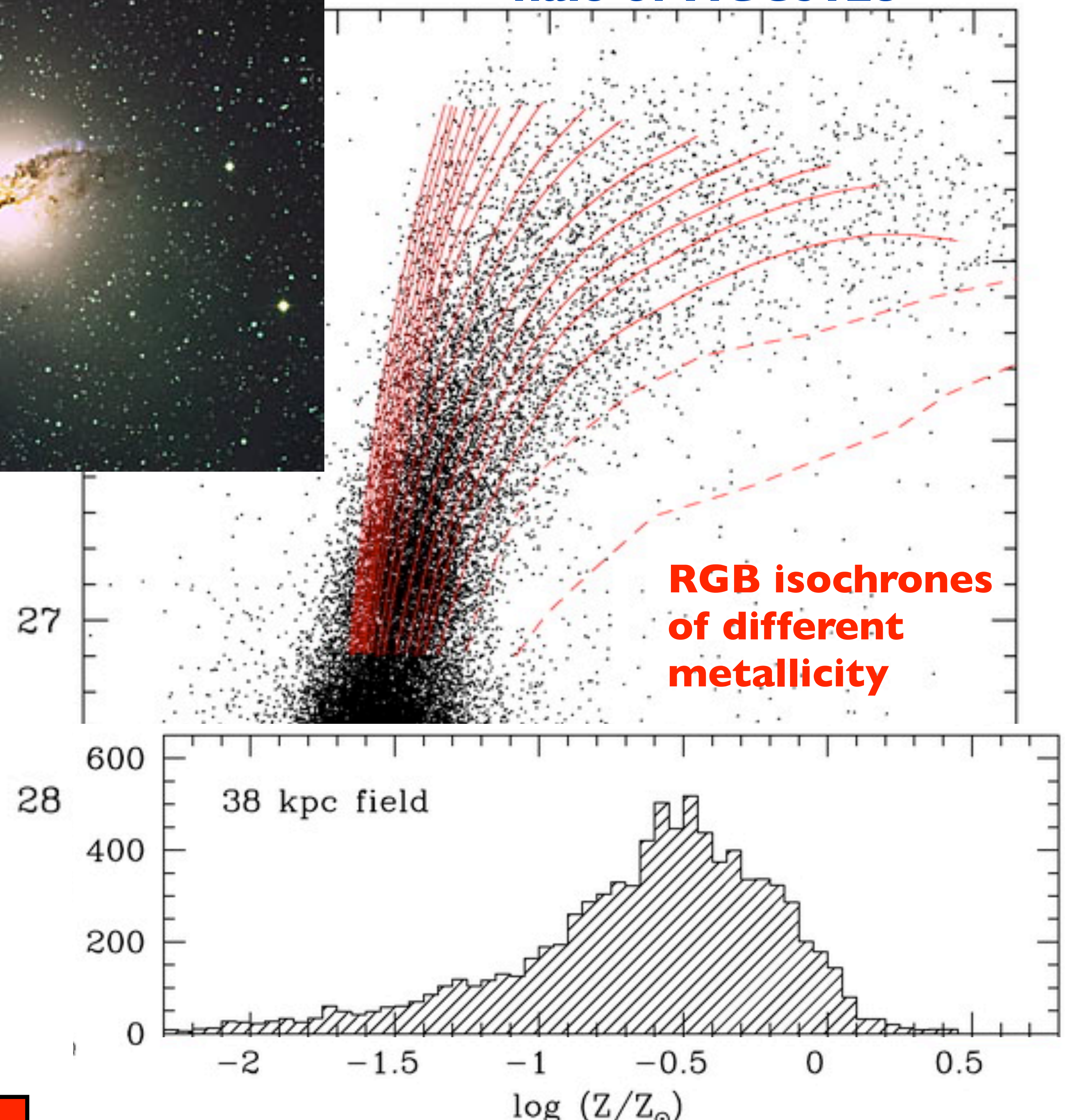
Goudfrooij et al. 2009

Metallicity spreads

MULTIPLE METALLICITIES

In general there might be a mix of different metallicities (especially in galaxies).

Rejkuba et al. red giants in halo of NGC5128



Chemical composition of ISM varies with time (e.g. enrichment from supernovae).

RGB colour depends on metallicity, so the RGB is broadened by any metallicity spread.

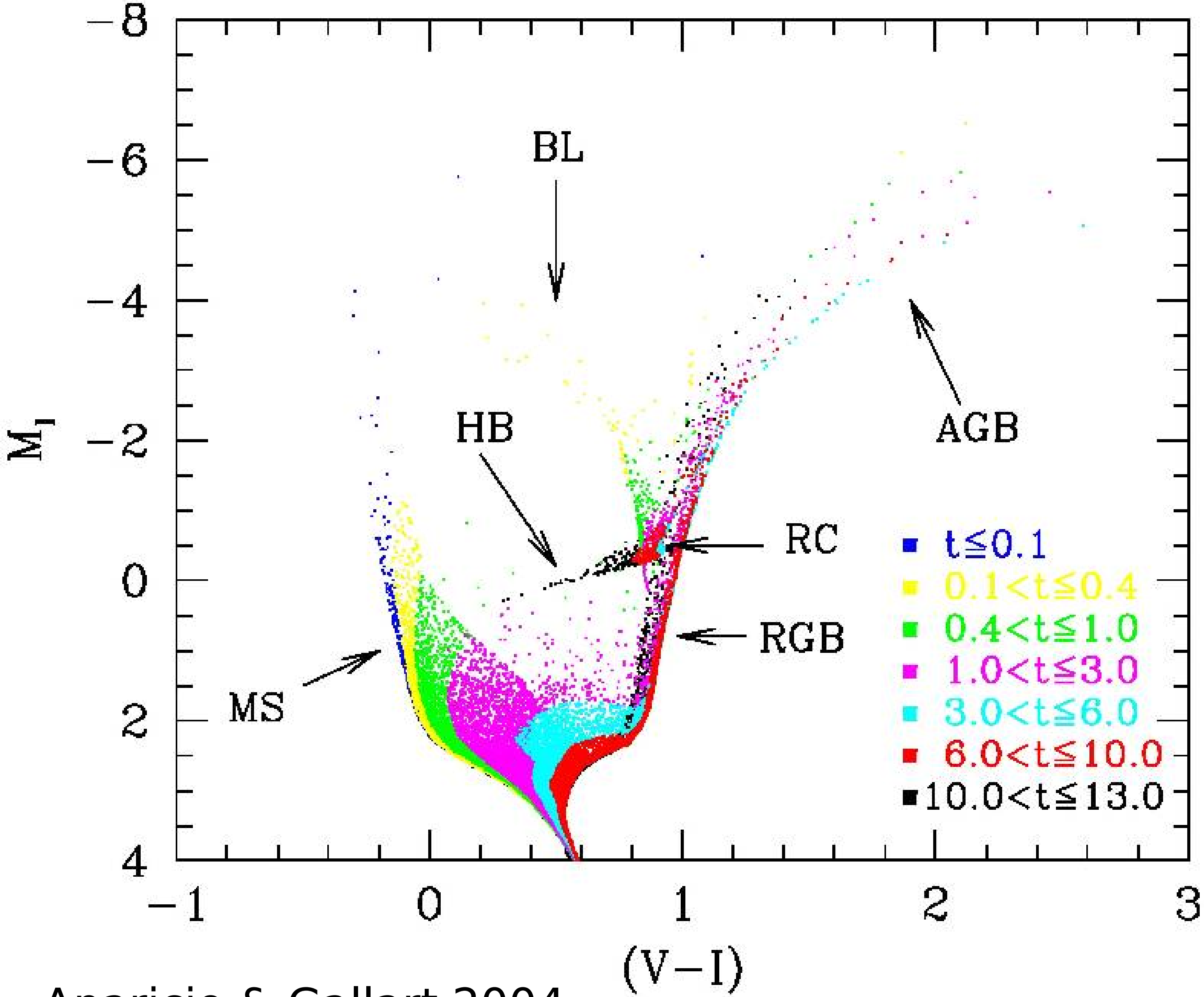
Age & metallicity histories

General methods for fitting multiple populations in resolved populations.

Recover stellar mass formed in a range of age bins.

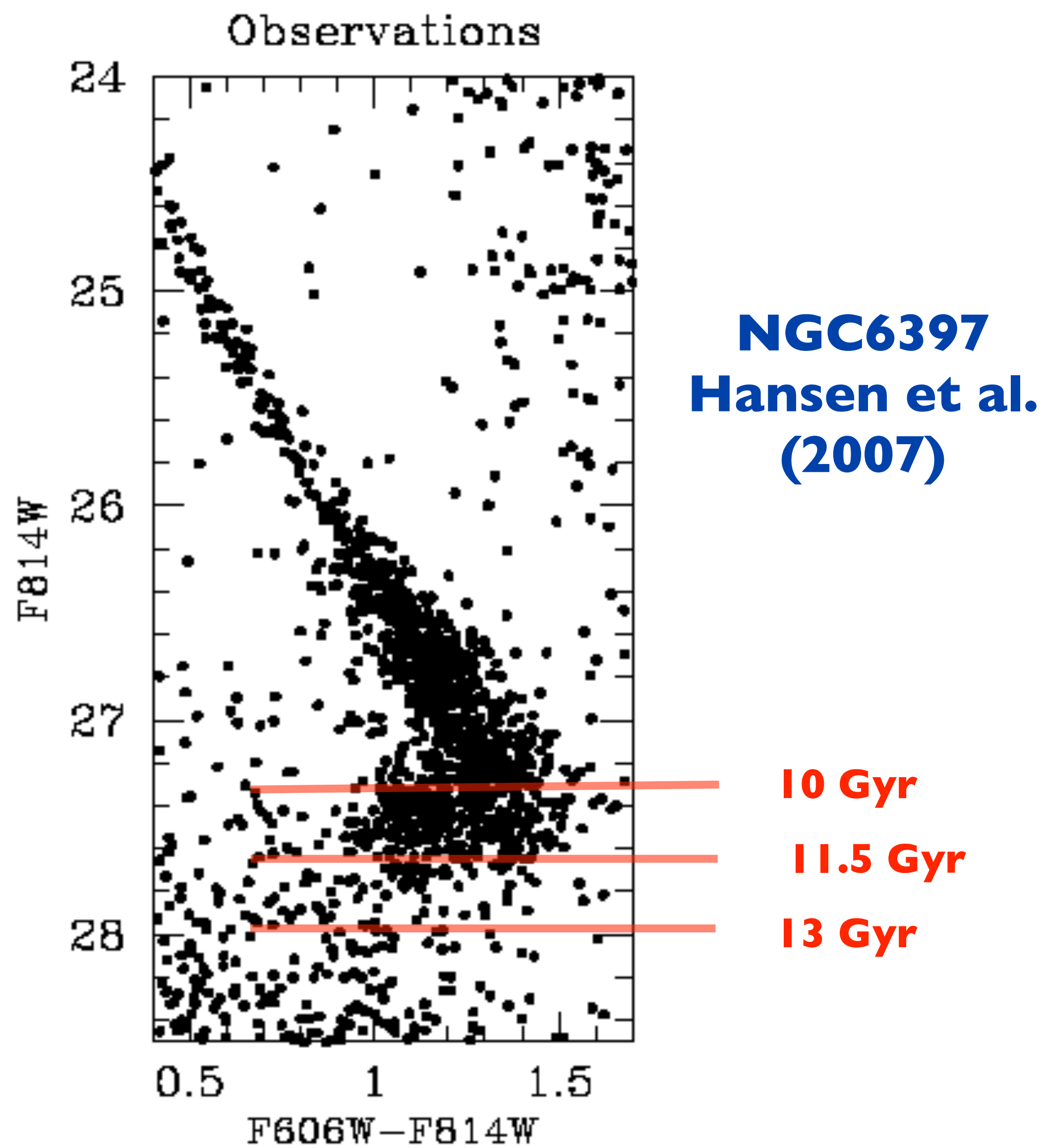
Can also fit the metallicity in each age bin.

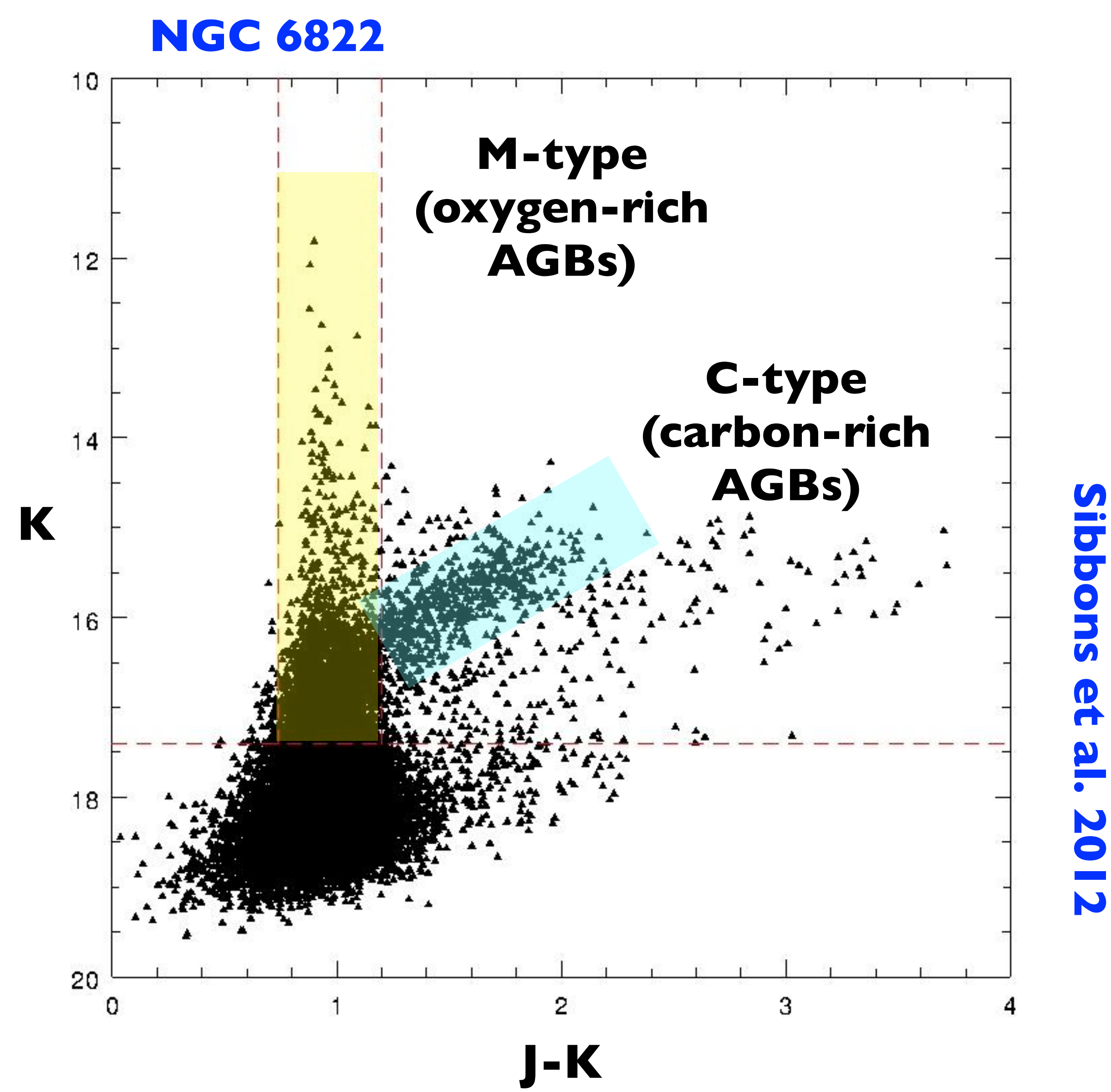
More ambitiously, can aim to recover fraction of stars formed on a grid of age *and* metallicity.



Aparicio & Gallart 2004

Some other age / metallicity tracers

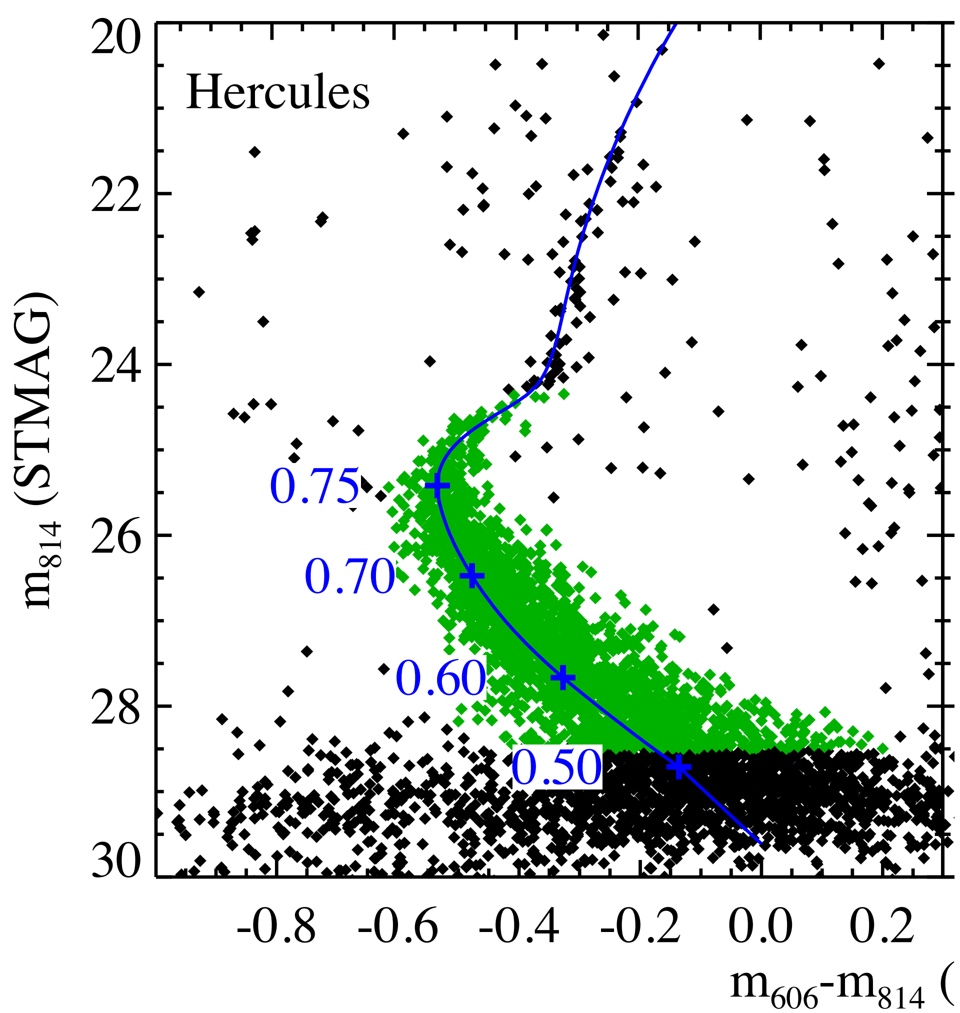




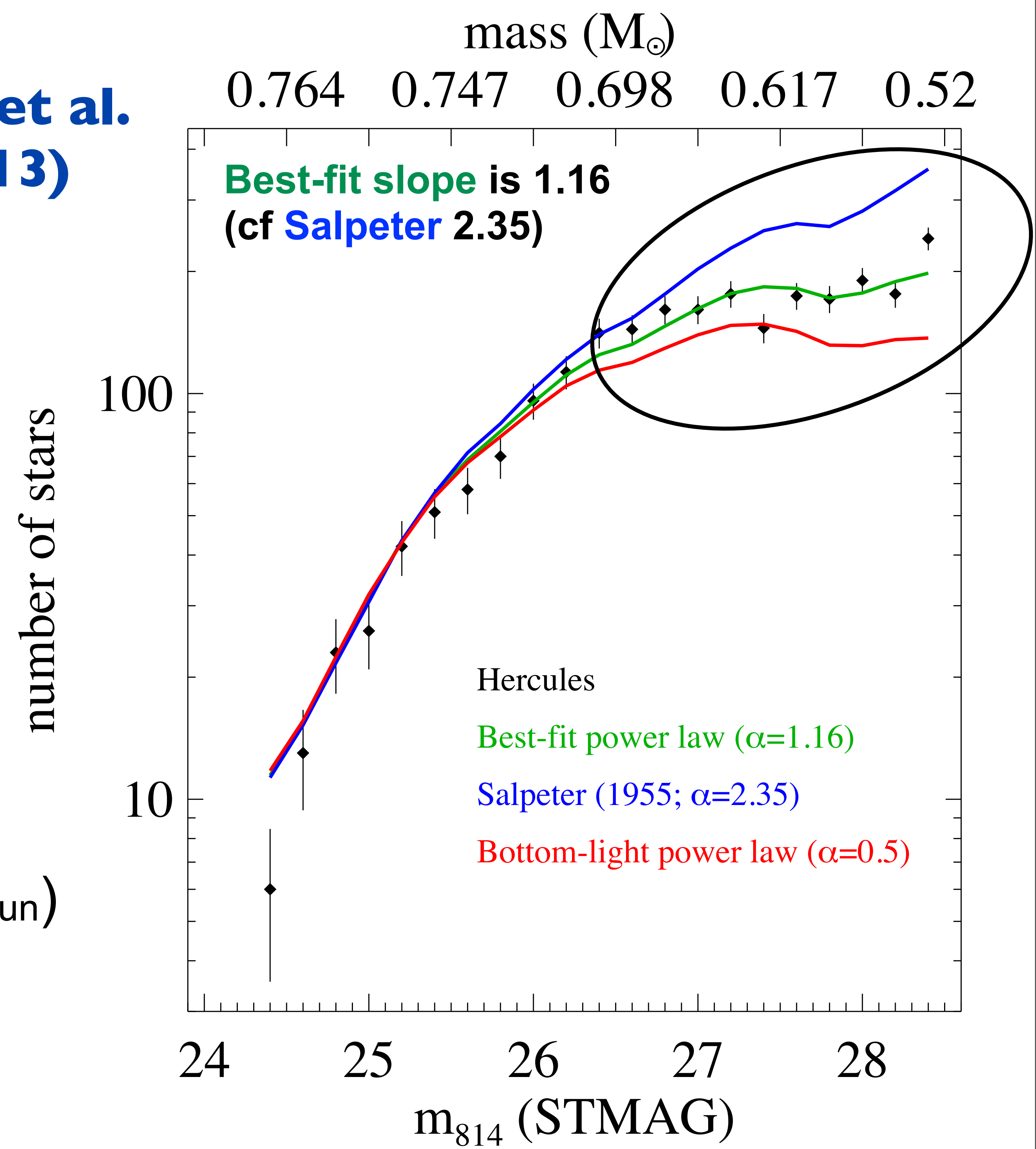
Oldest white-dwarfs are fainter and cooler in older populations.

Carbon stars (where C dredged to surface in late AGB, affecting IR colours) are more common at low metallicity, so C/M ratio is a metallicity indicator using only very luminous stars.

Initial Mass Function



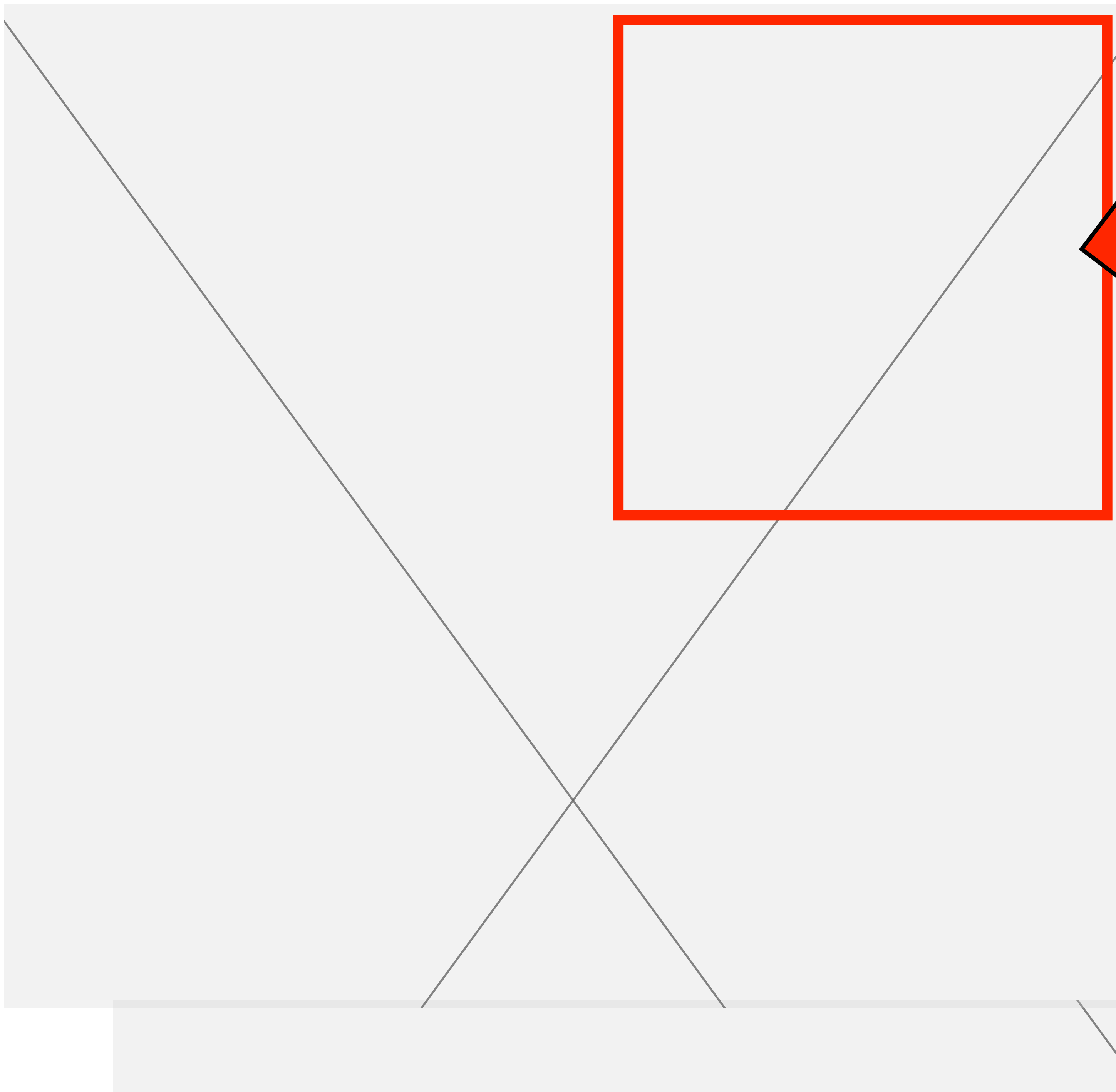
Geha et al. (2013)

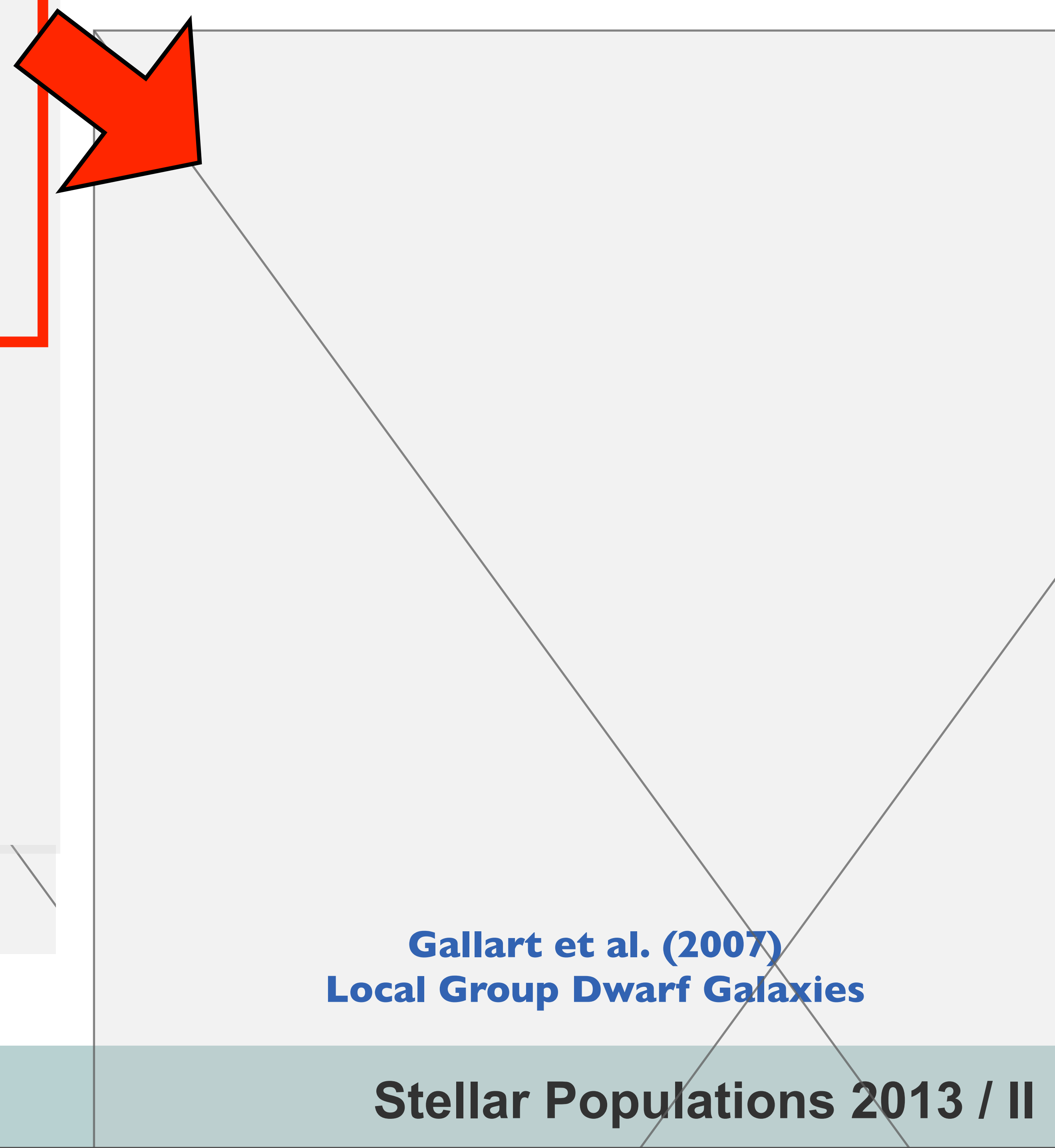


Direct constraints on low-mass (~0.5 M_{sun}) end of the IMF.

Requires very faint photometry so possible only in nearby LG dwarfs.

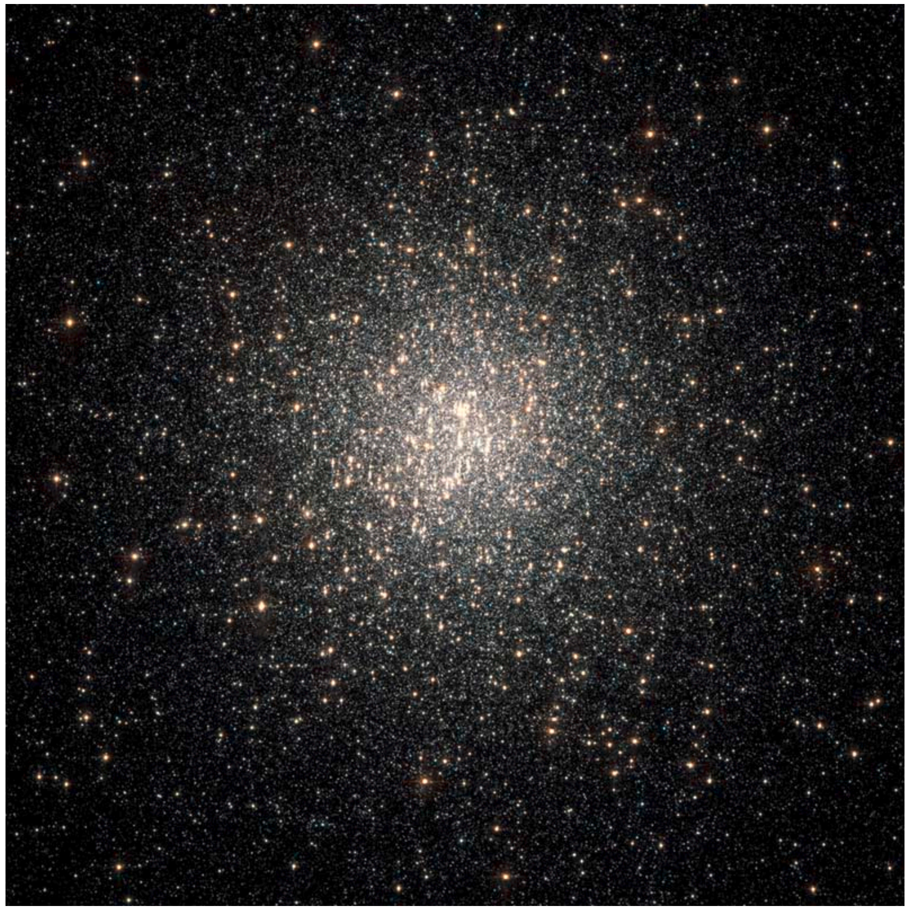
Age & metallicity histories

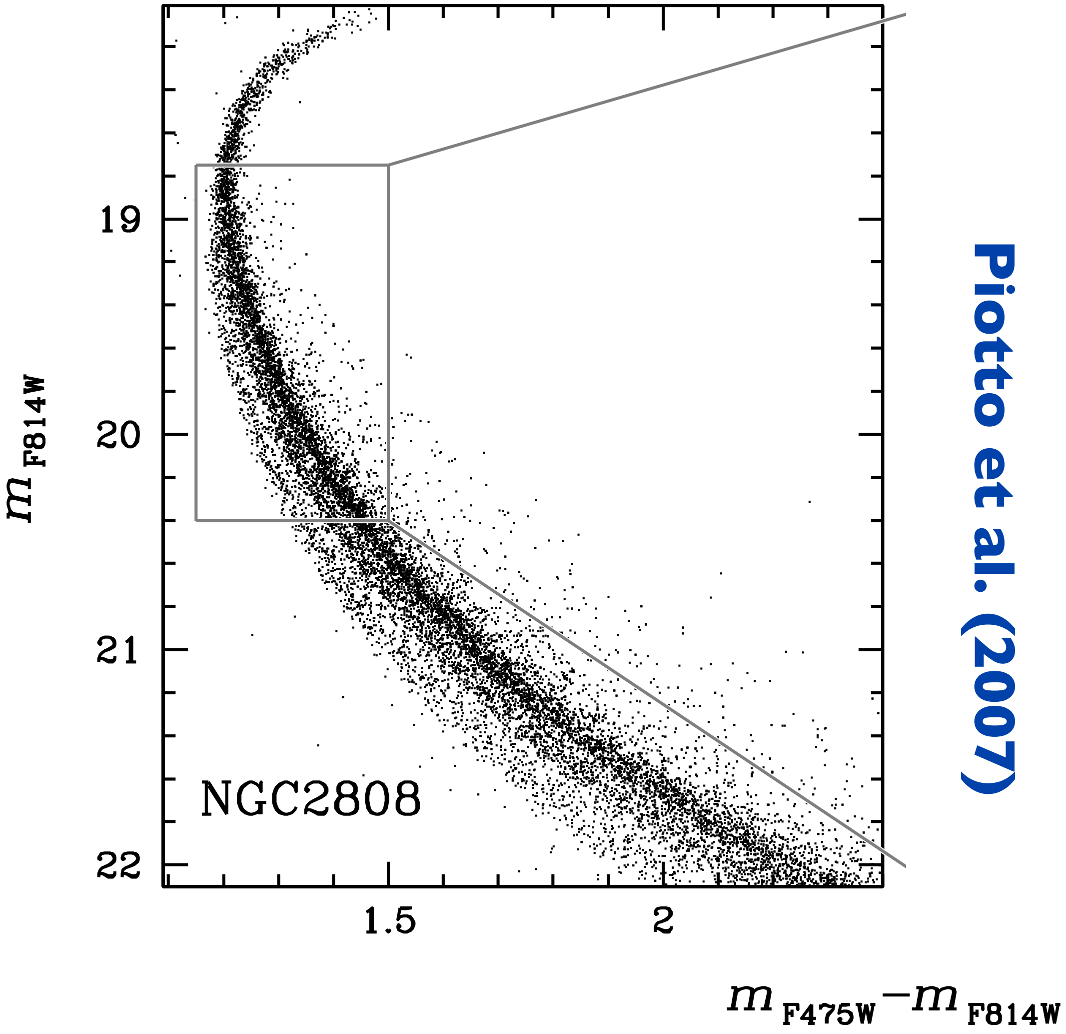




Gallart et al. (2007)
Local Group Dwarf Galaxies

CMD exotica: multiple Main-Seq in GCs





Piotto et al. (2007)

Many globular clusters (especially more massive ones) now show evidence for multiple populations. (Not such good SSP approximations after all!)

Surprisingly, the red MS is more metal rich than blue MS.

Colour shift interpreted as evidence for increased He abundance in 2nd-generation stars.

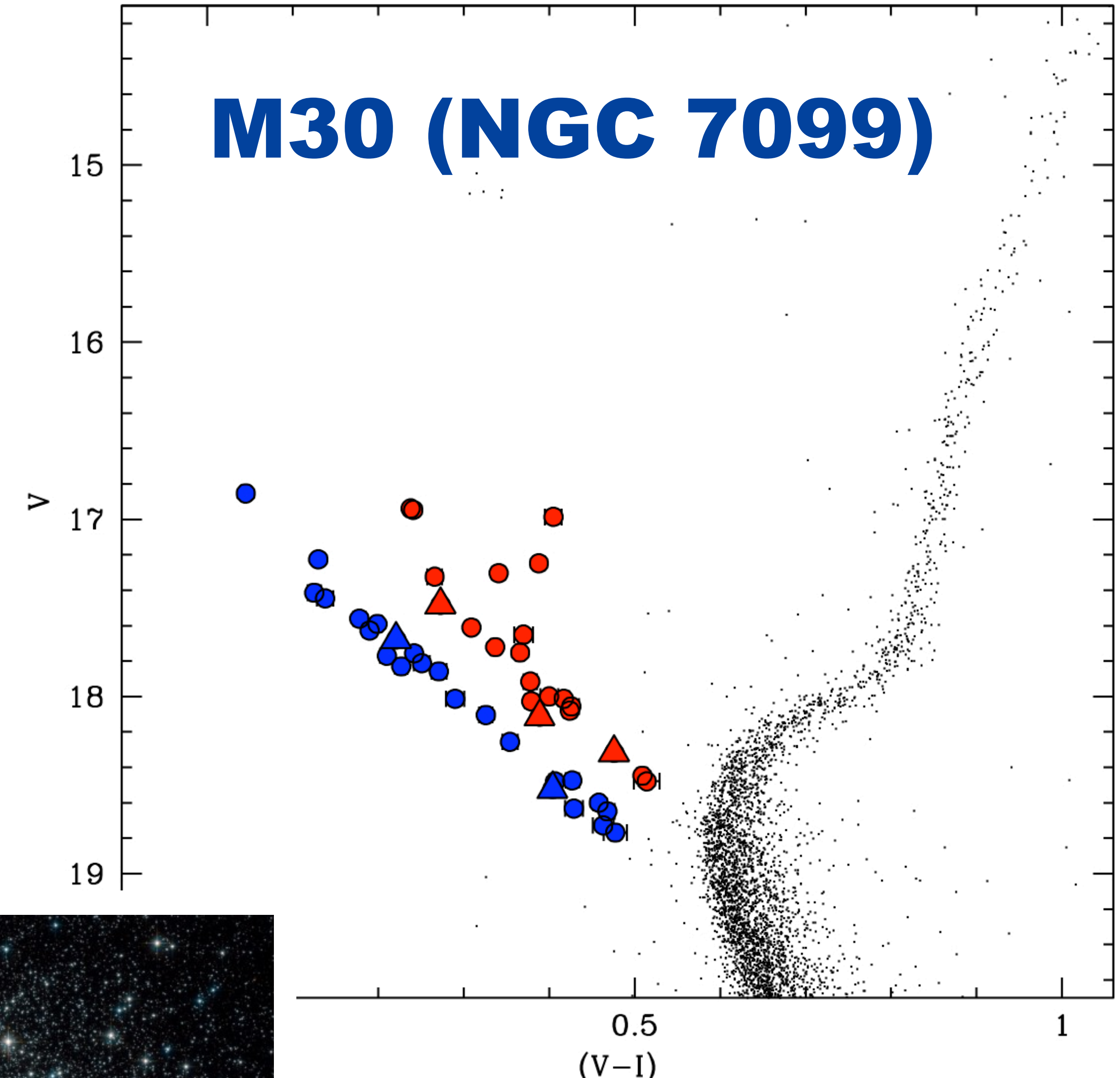
CMD exotica: blue stragglers

Why haven't these stars evolved off the main sequence like others of similar mass?

Not thought to be young, but rather "delayed" evolution.

Most likely due to stellar collisions or mass transfer in binary stars: "stellar re-fuelling".

We don't know how to predict from first principles the <u>number</u> of BS stars formed in a population.



Ferraro (2009)

Two sequences of BS matching **collisional** and **mass-transfer** models.

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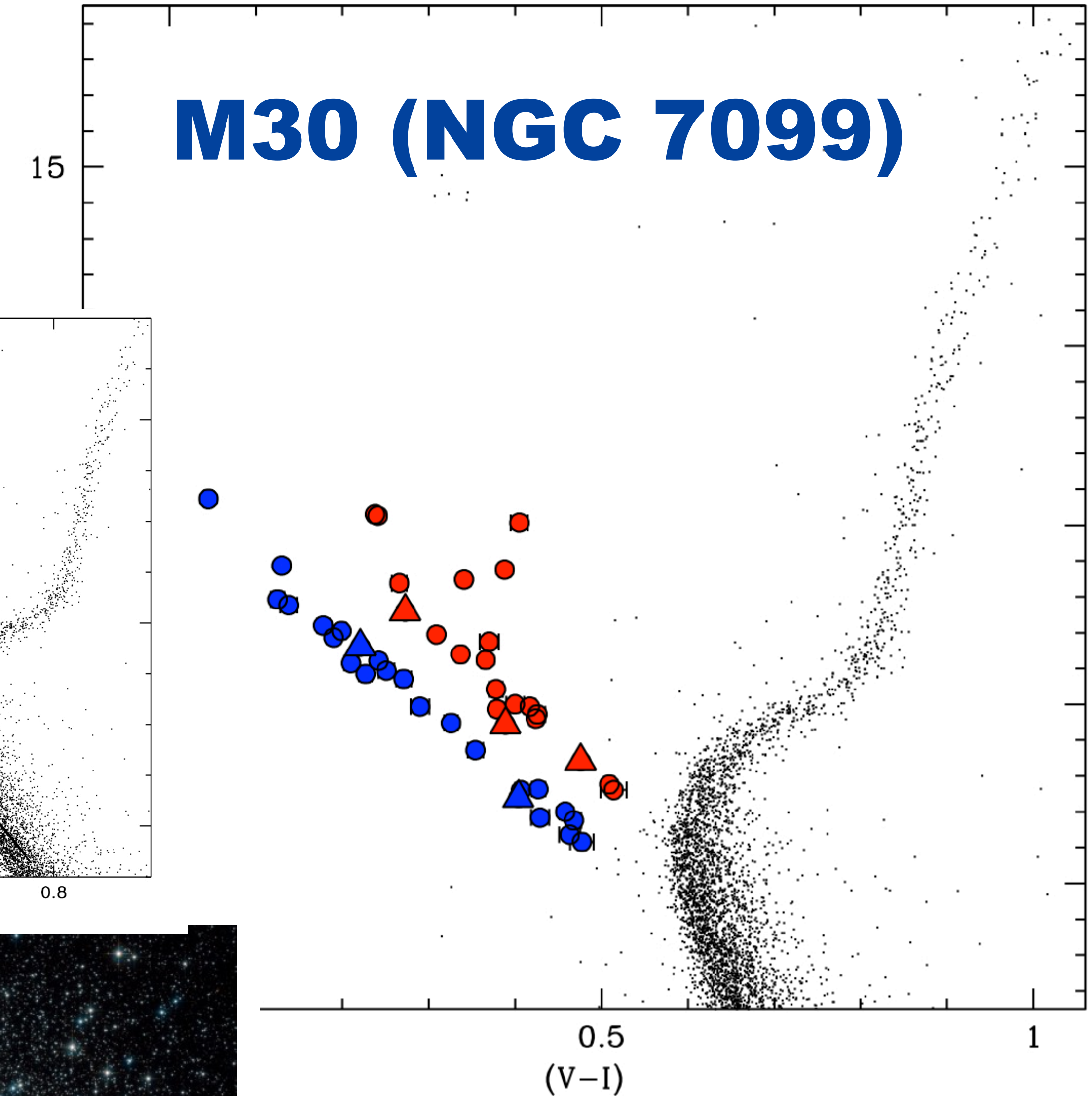

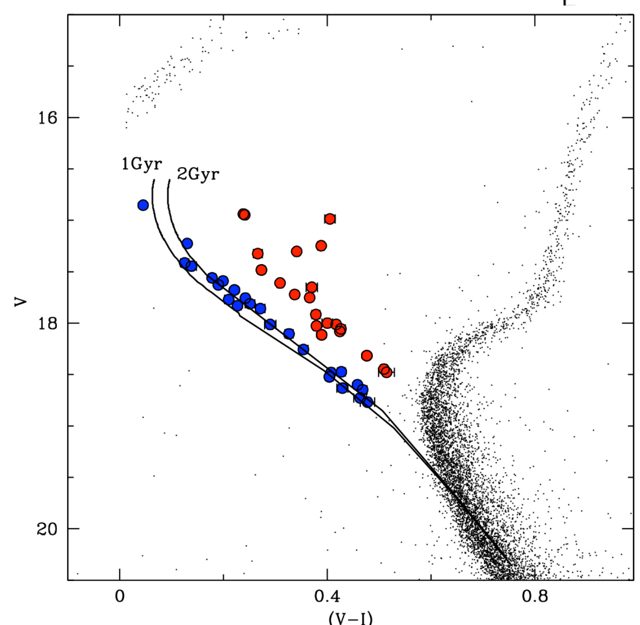

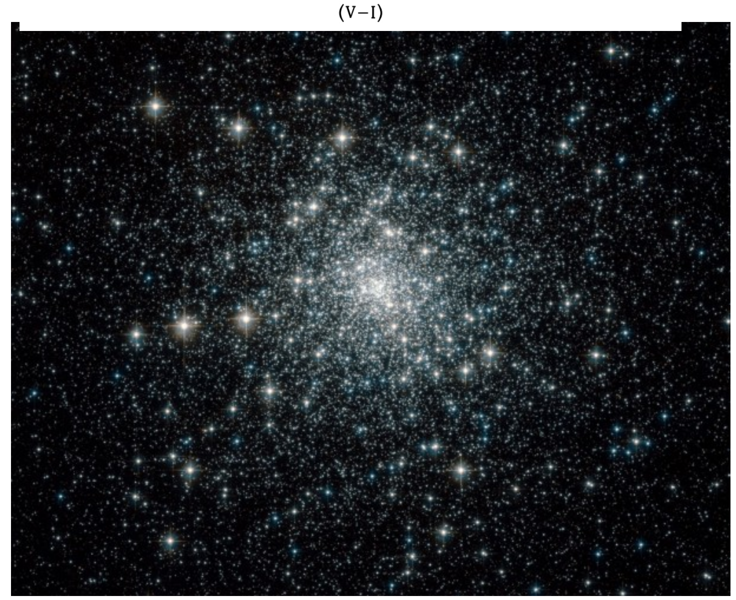

Ferraro (2009)

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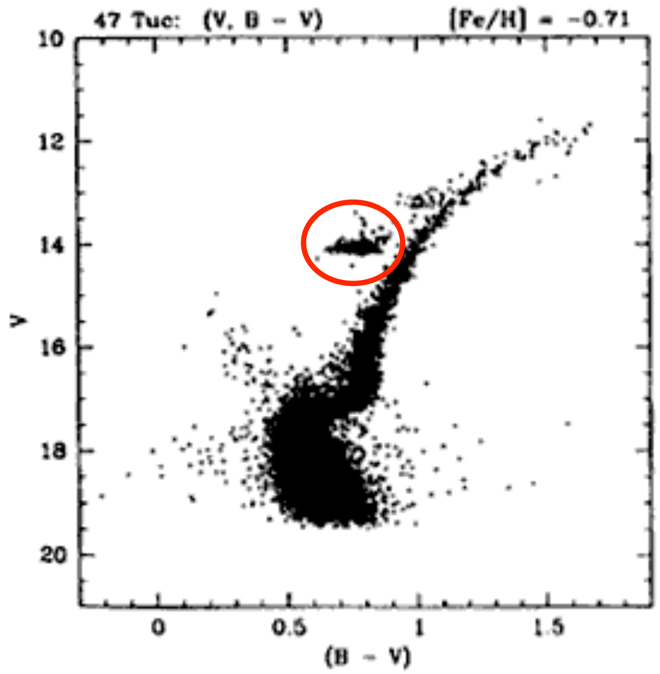
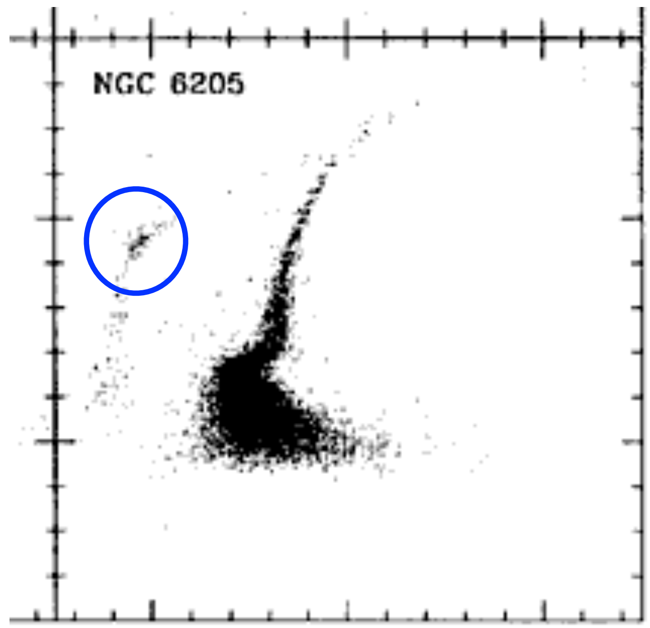
CMD exotica: horizontal branch



Classic High-Fe/H "Red Clump"



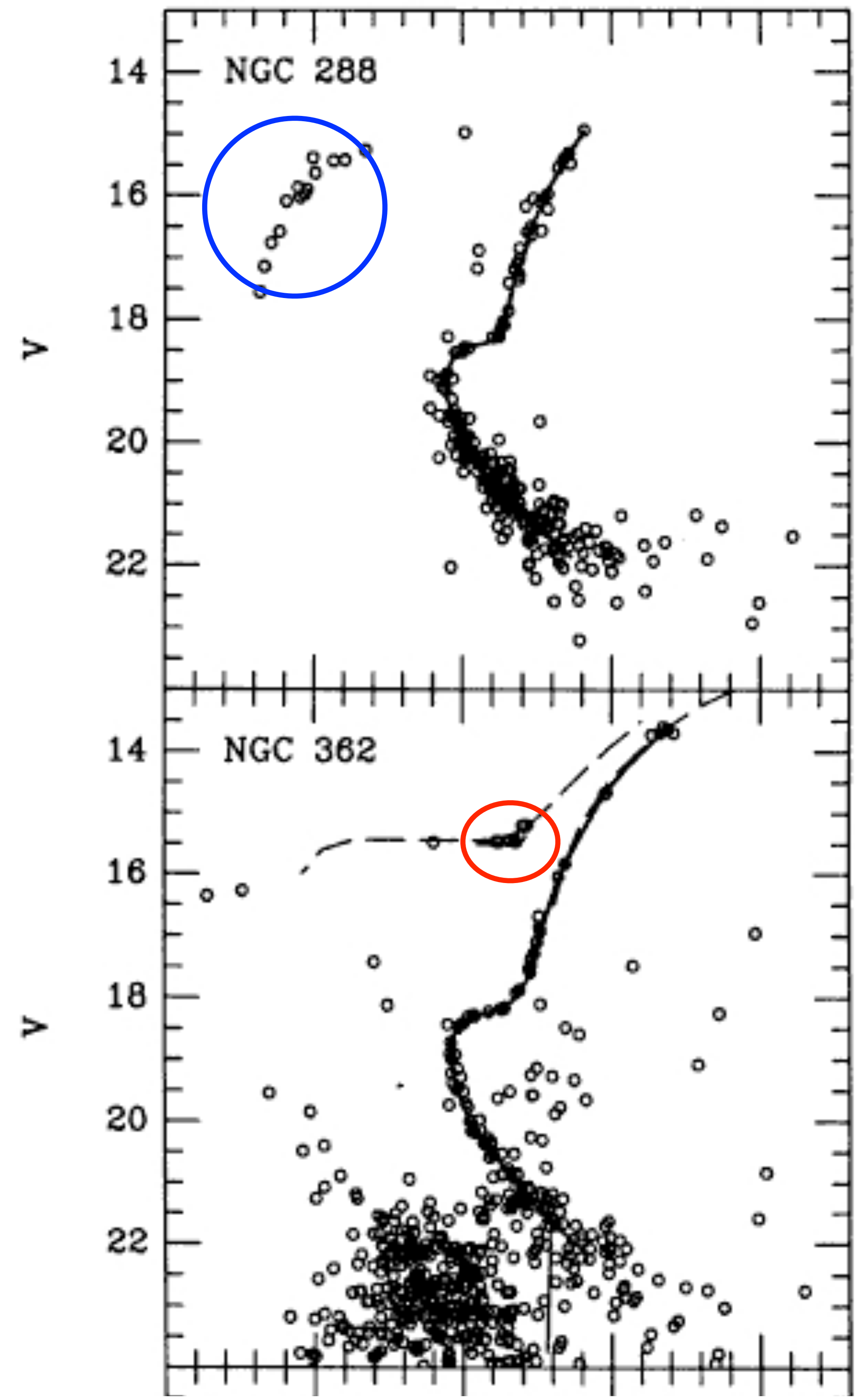
Classic Low-Fe/H Blue HB

HORIZONTAL BRANCH MORPHOLOGY

Temperature of HB stars depends on how much mass was lost on the RGB. Difficult to model.

The temperature distribution on the HB in globular clusters depends on mostly on their metallicity.

But some differences not attributable to metallicity: what is the "second parameter" that determines HB form at given Fe/H?



Famous "2nd parameter" pair with same Fe/H but very different HB

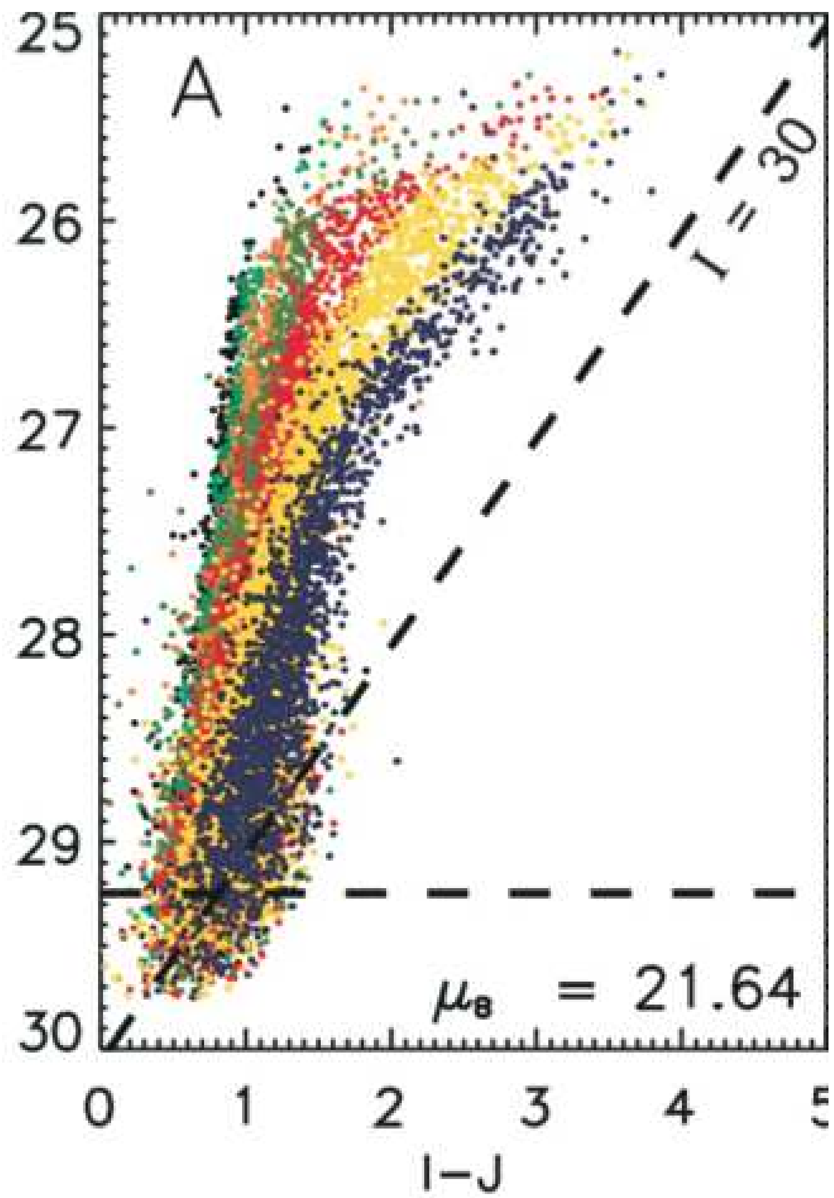
Practical limitations

Difficulties for resolved photometry in more distant galaxies:

* Faintness (limited information if MSTO not reached)

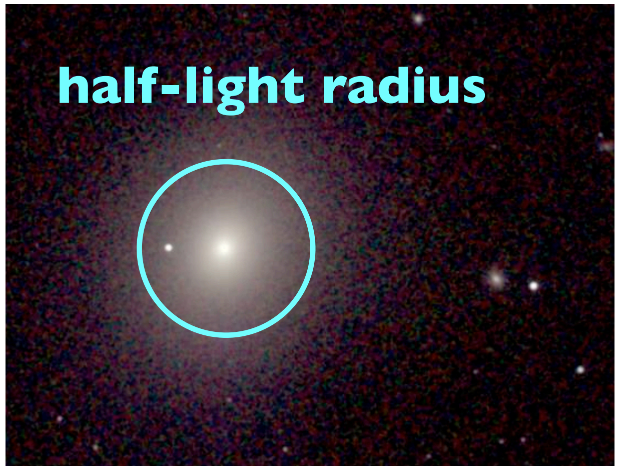
* Crowding (forces observations into outer halo - unrepresentative?)

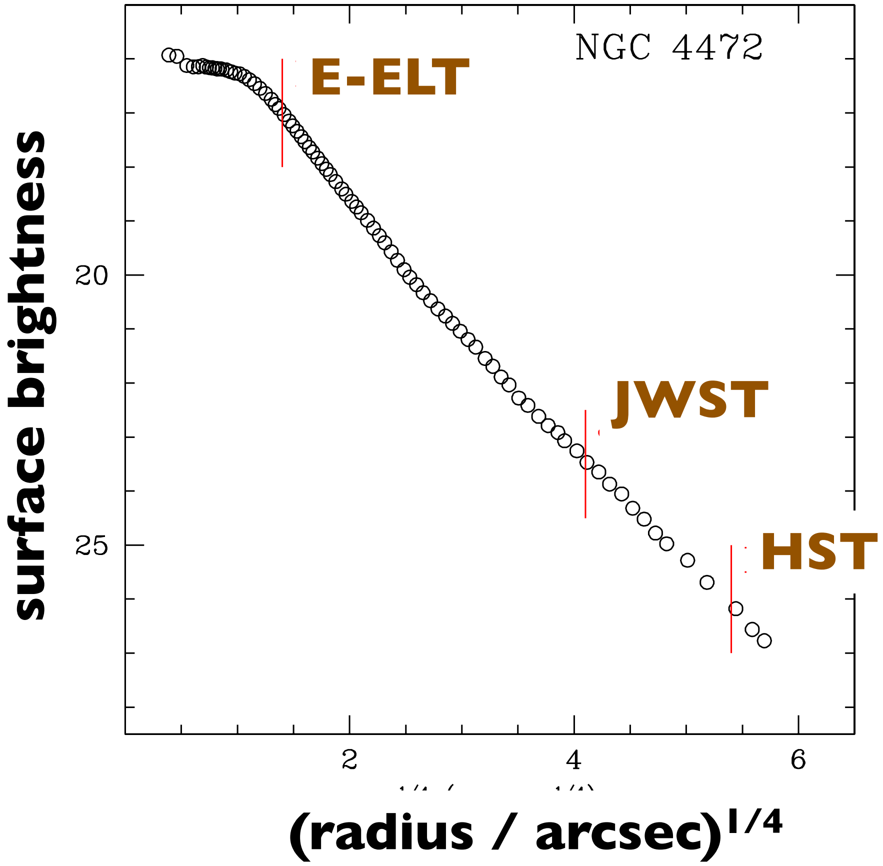
Improving on this situation a major low-z science goal for 30m-class telescopes and JWST.



Simulated RGB for Virgo ellipticals at $R_{eff}/2$ with E-ELT

(Schreiber et al. 2013)





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Difficulties for resolved photometry in more distant galaxies:

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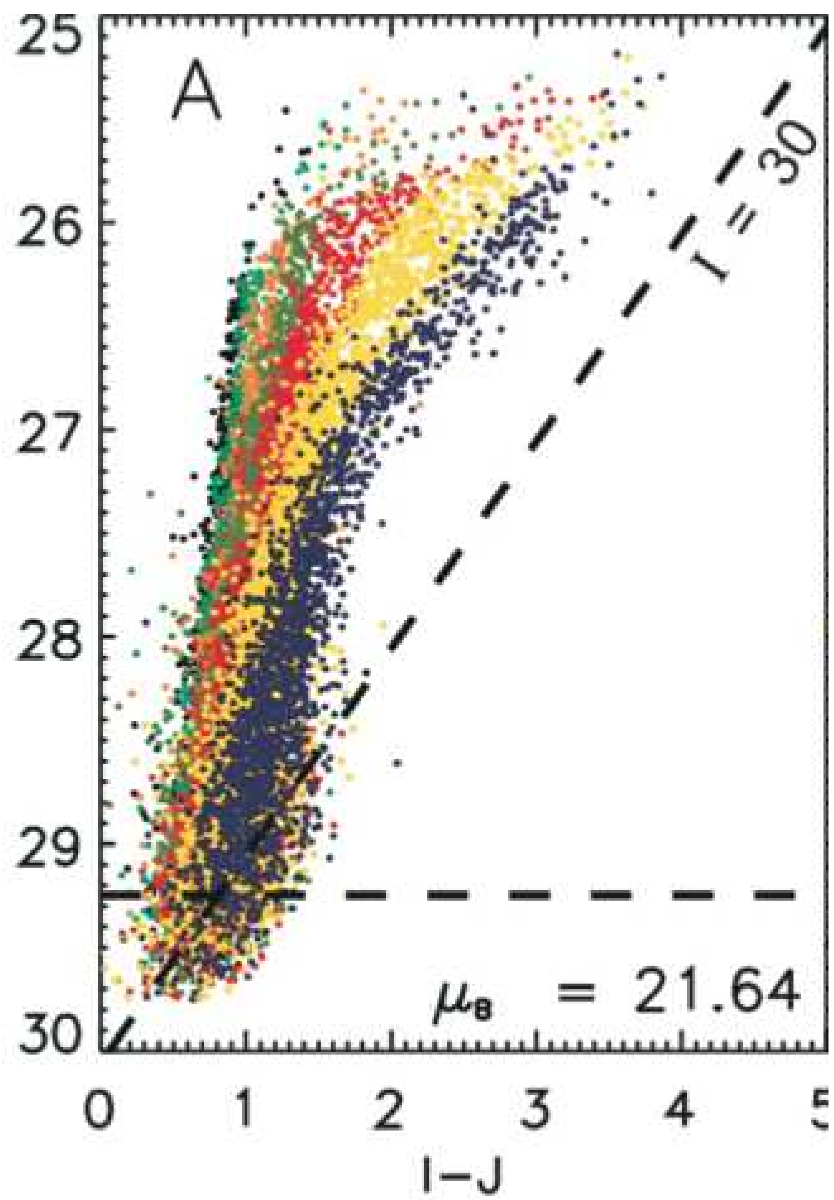

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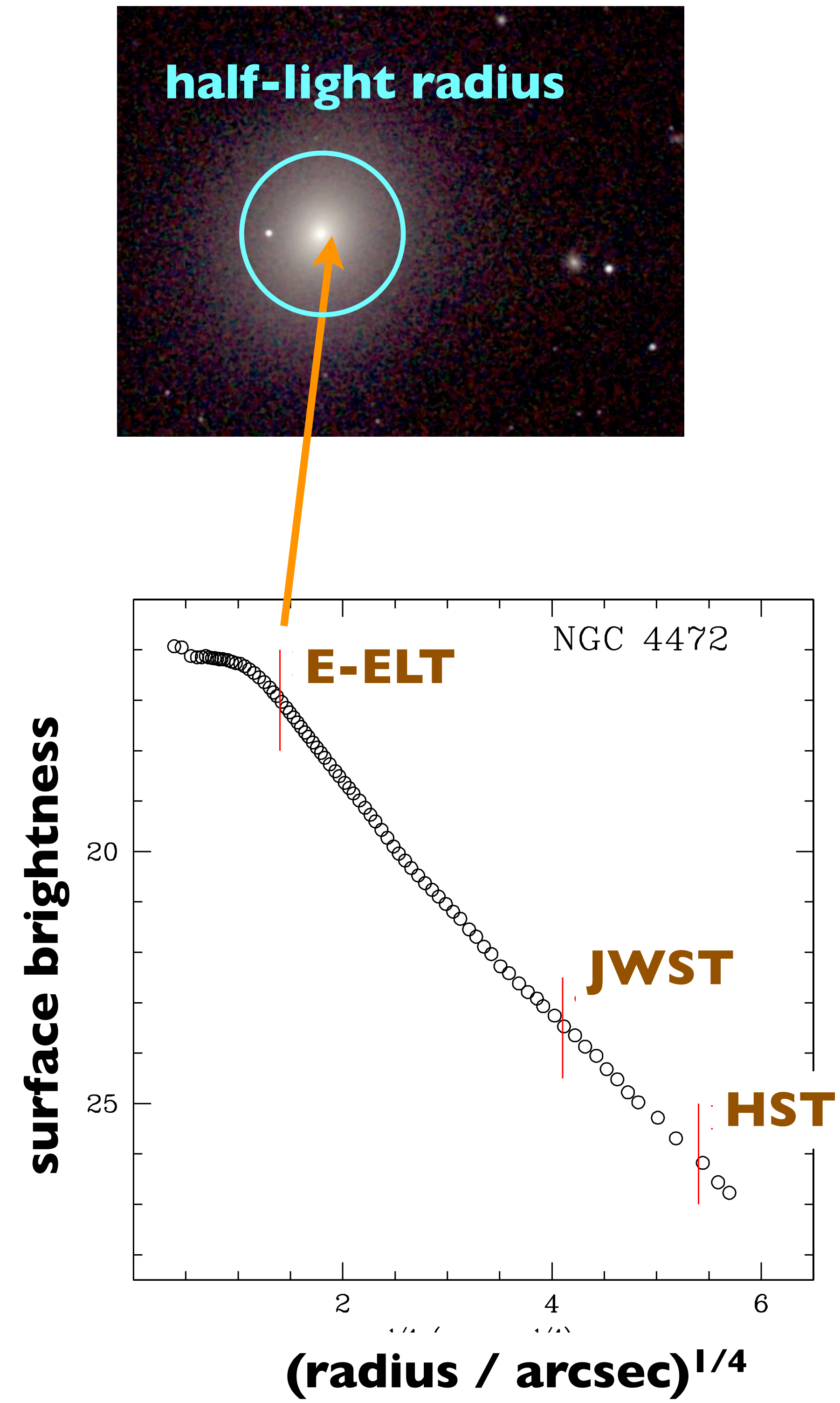

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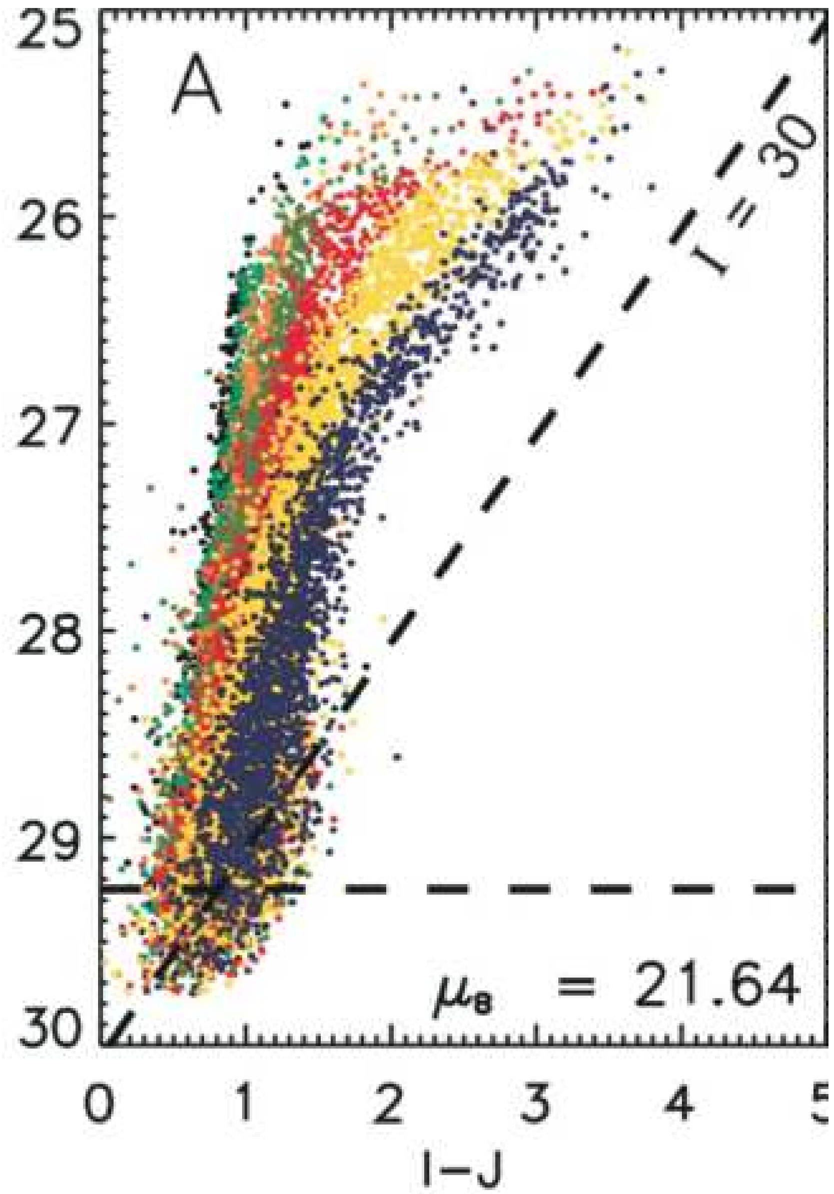

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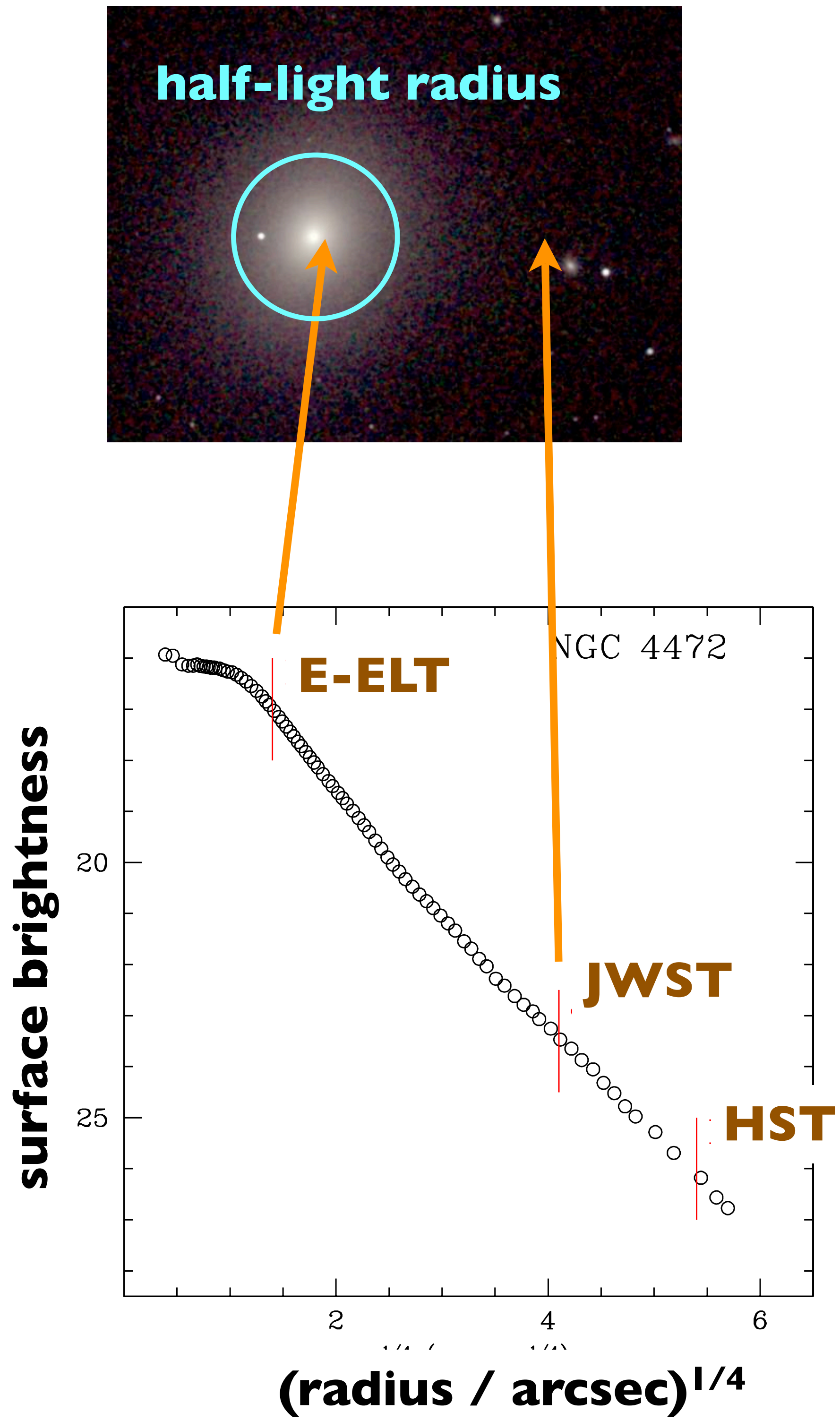

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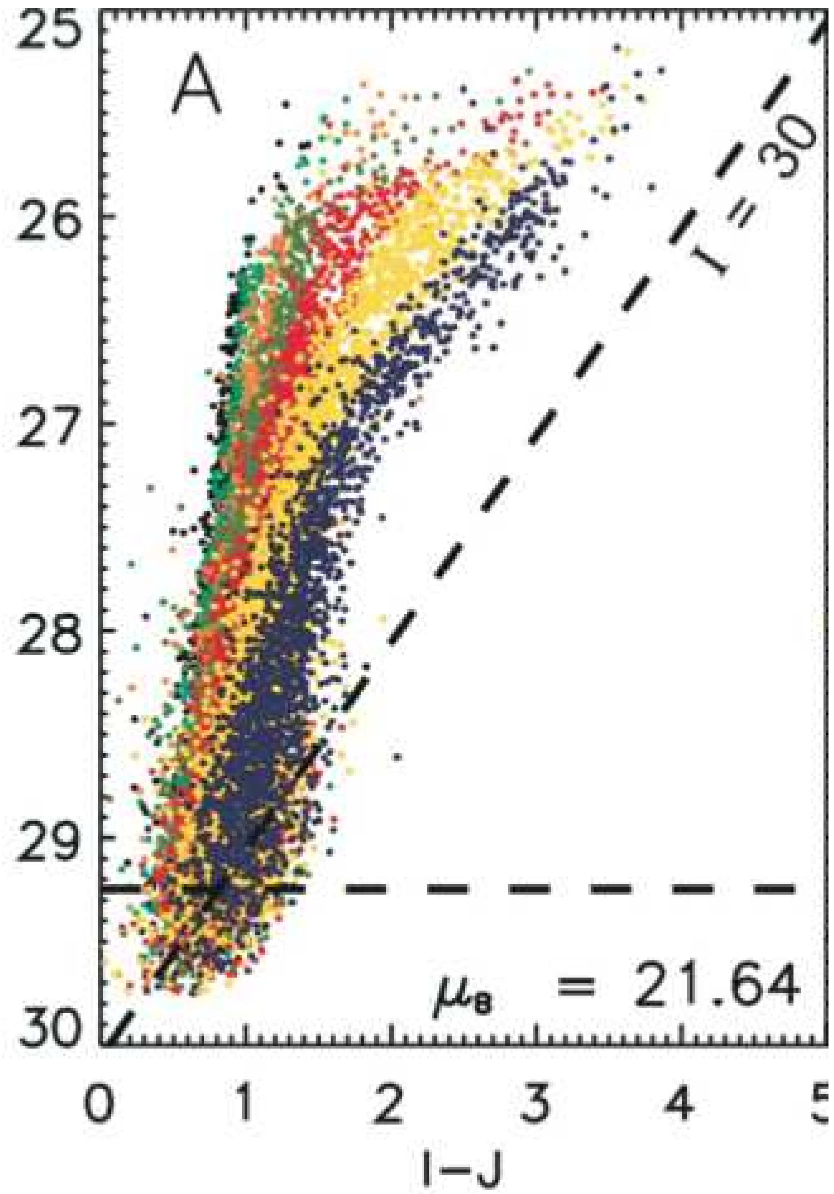

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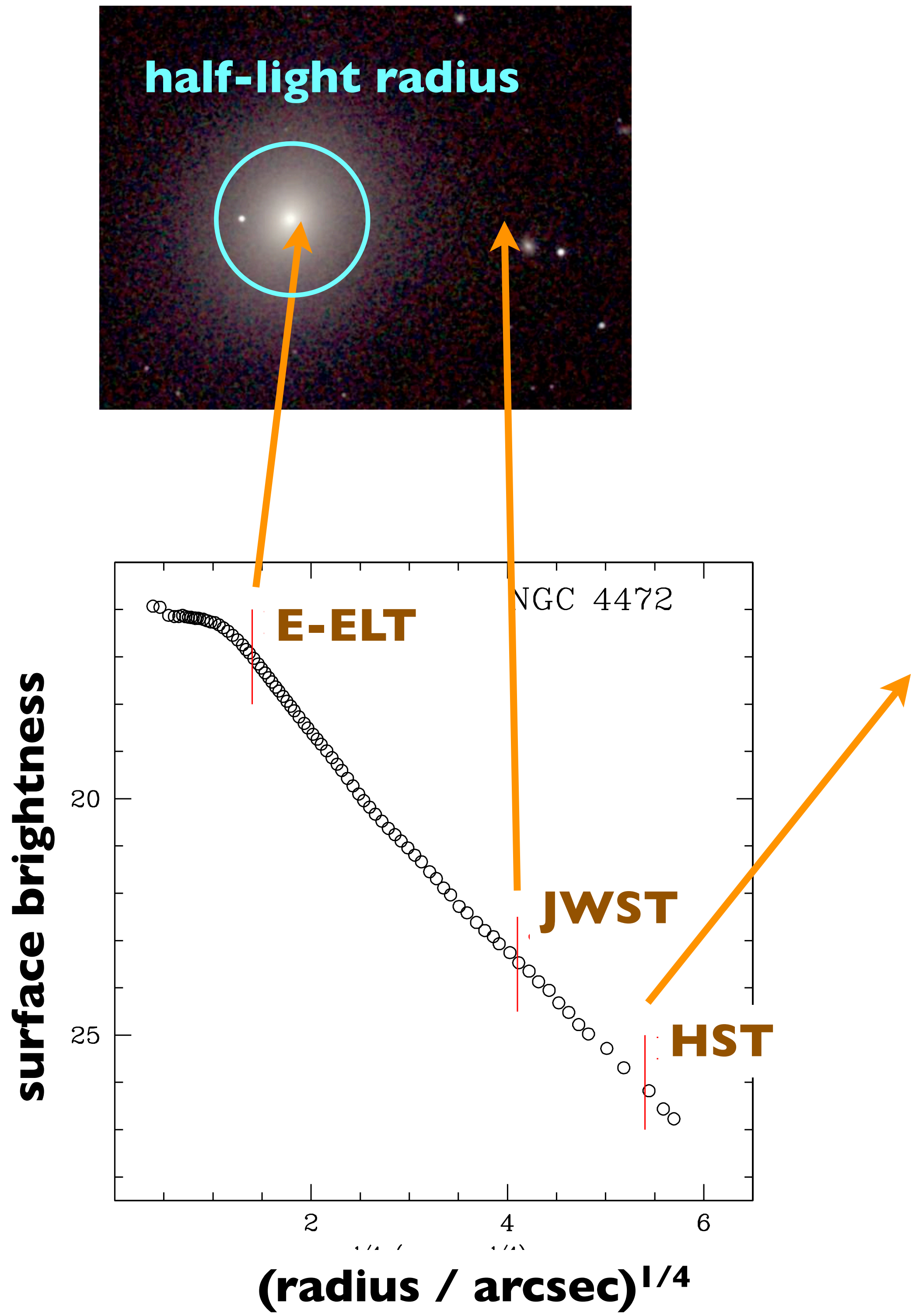

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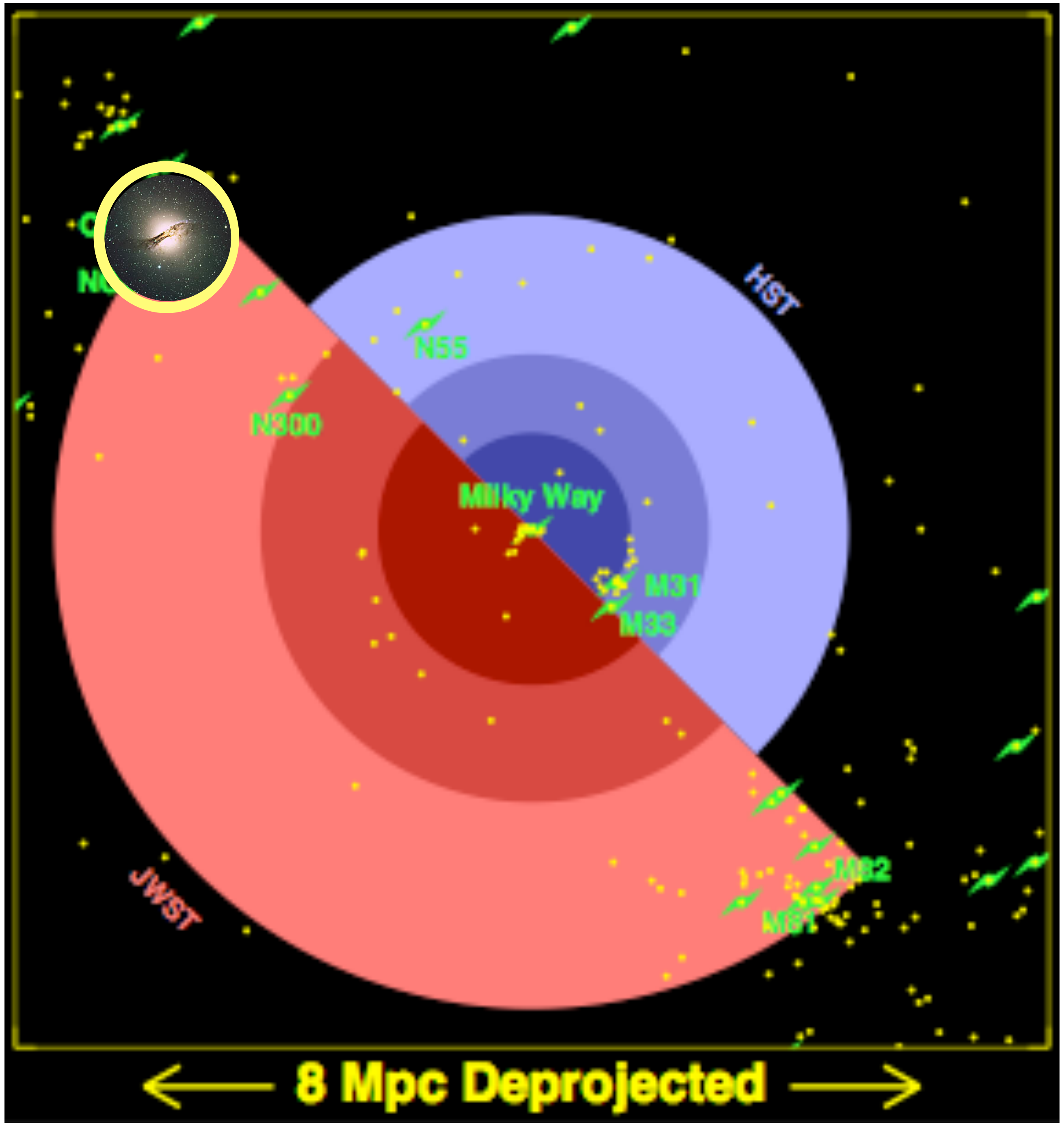

Galaxies with 12-Gyr MSTO accessible to HST/JWST in 10, 100, 1000 hours. (Brown et al. 2008)

Resolved stellar pops : summary

Review of stellar evolution.

Population model inputs: isochrones and initial mass function.

Observed cluster colour magnitude diagrams.

Isochrone fitting methods: ages, metallicities.

(We can learn a lot from this kind of data, if we can get it.)

More complicated cases & exotica.

(Maybe more common than we would like to think.)

Practical limitations.

(Resolved studies cannot fairly sample the population of galaxies.)

To go beyond the resolved populations in and near the LG, we need to understand how to learn from **unresolved** stellar pops.