Stellar Mass – an Infrared Perspective

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Outline

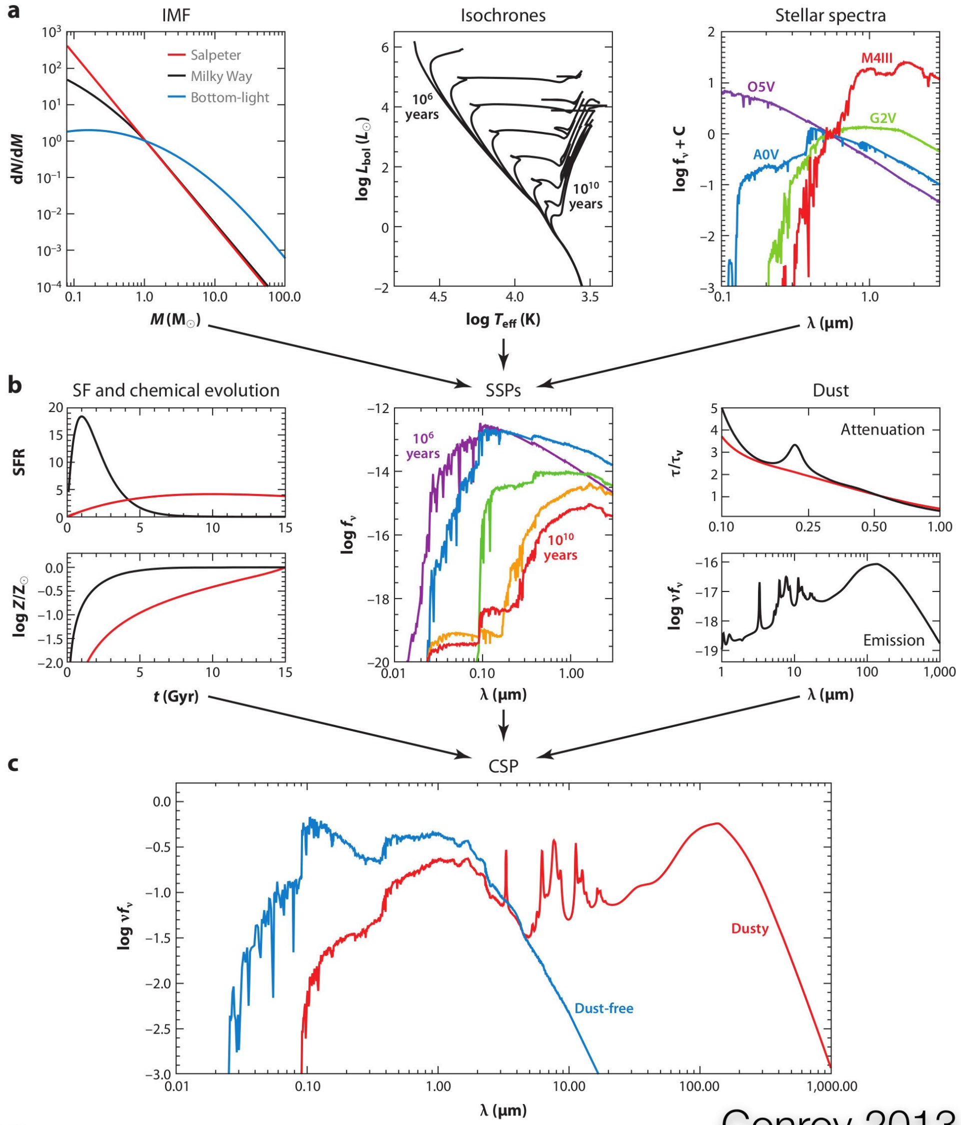
- How to determine stellar masses and minimize uncertainties
- Stellar masses from the infrared
- Separating dark and luminous matter

Stellar Population Synthesis: The Basics

- These days, stellar population models are (nearly) always evolutionary stellar population (EPS) models

- People use the concept of Single Stellar Populations (SSPs), of stars with all the same age and metallicity

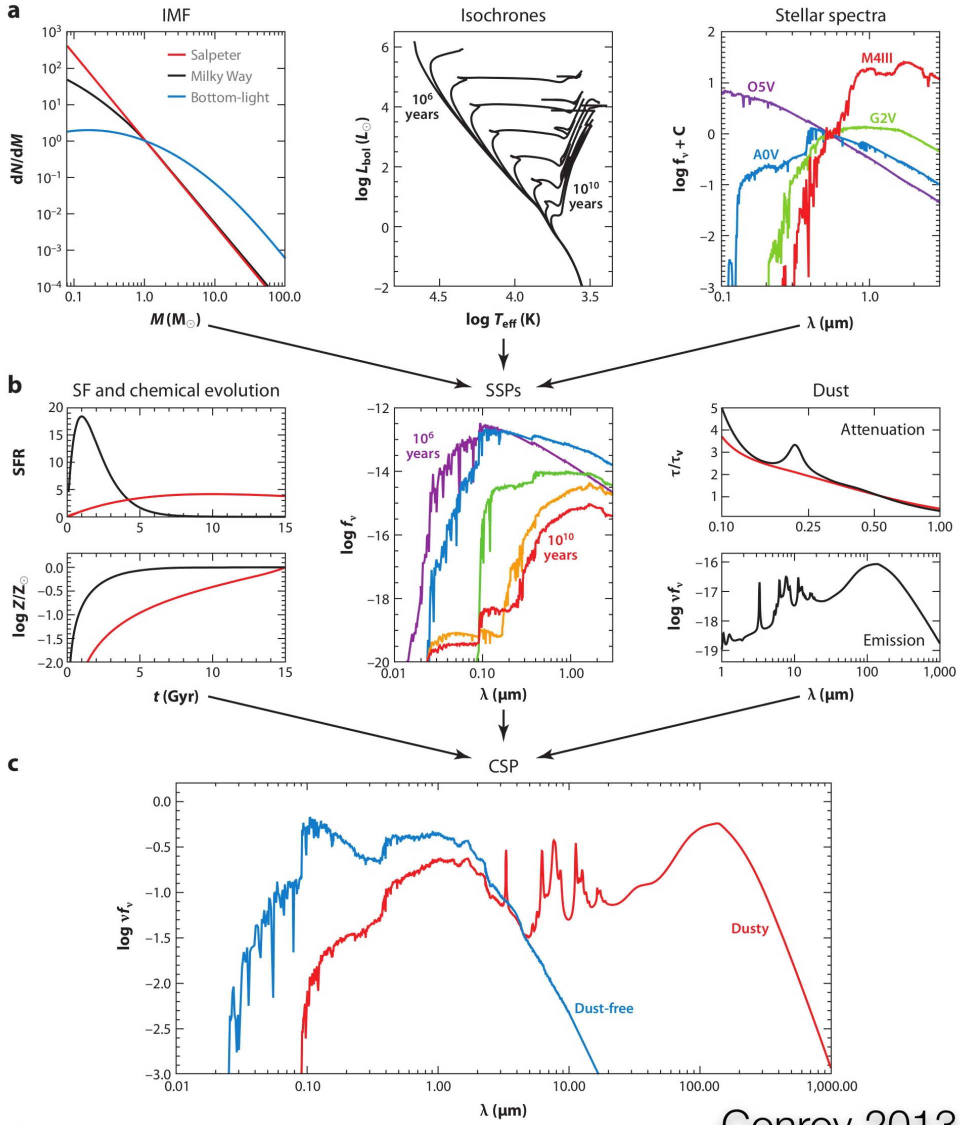
- SSPs can be combined to create CSPs (Composite stellar Populations)



Conroy 2013

Stellar Population Synthesis: The Basics

- An SSP is composed of 3 ingredients:
  - the stellar Initial Mass Function (IMF)
  - Stellar Isochrones
  - A stellar library covering the wavelengths of interest



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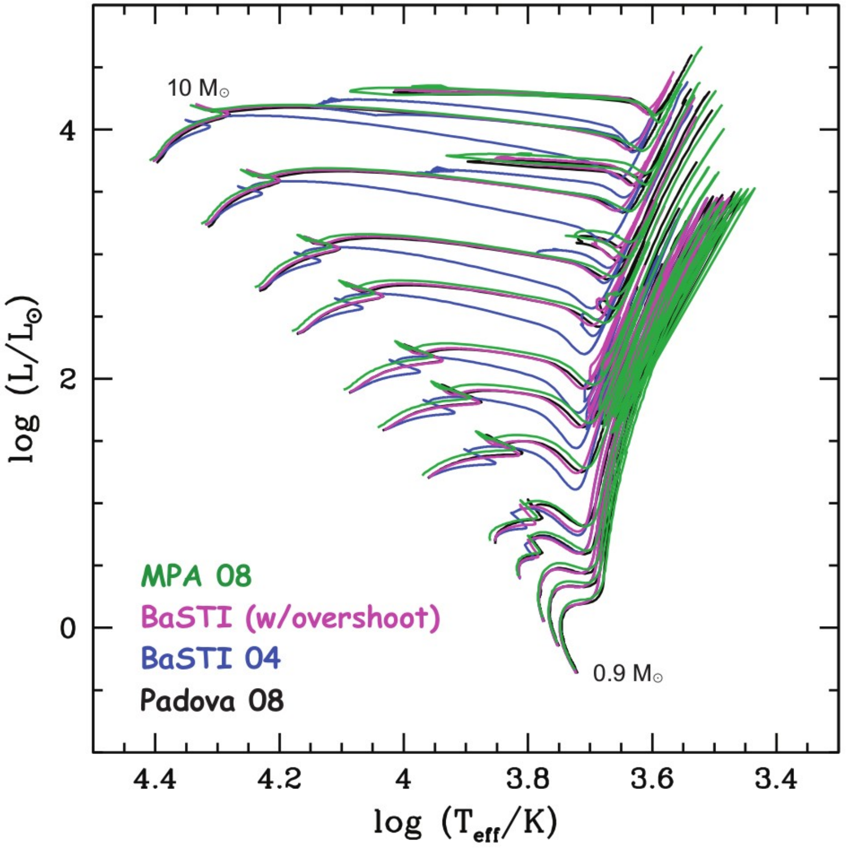
Isochrones

- Several different sets of isochrones available. little difference for low mass stars.

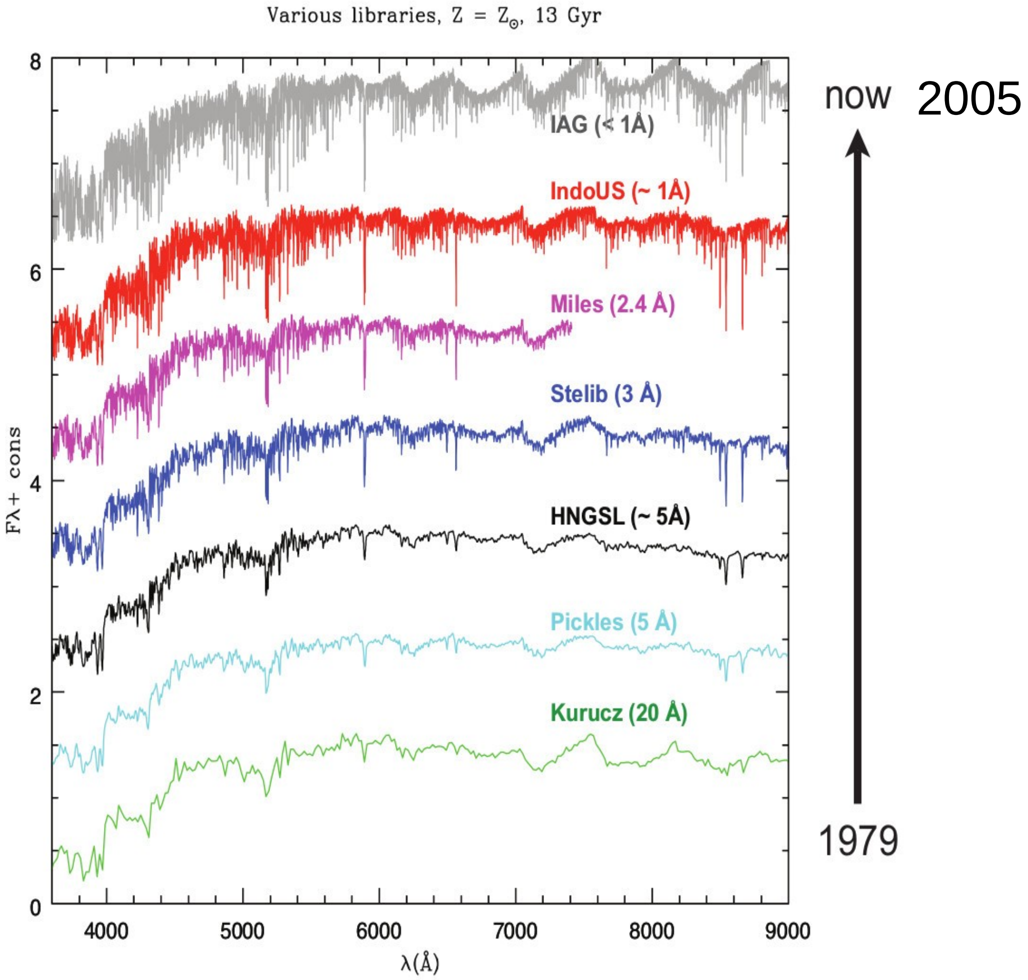
- … Except for late evolutionary phases: thermally pulsing Asymptotic Giant-Branch Stars (TP-AGB)



Stellar Libraries

A lot of choice:

- Parameter coverage (T_{eff}, log g, [Fe,H], …)
- Spectral resolution
- Spectral coverage
- Quality of (flux) calibration
- Observation vs. theory



IMF

What to choose?

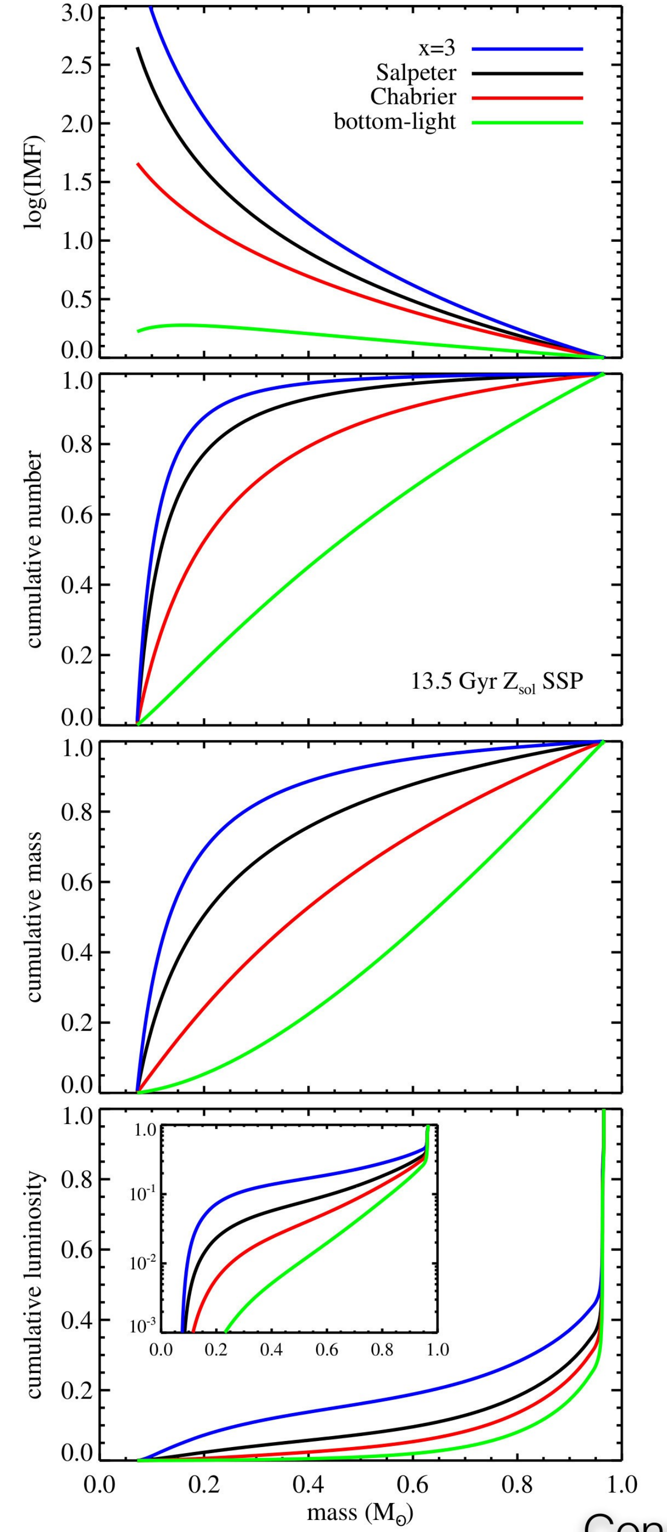
Milky Way: Chabrier or Kroupa

Other options:

- Salpeter (power law)
- bottom heavy
- bottom light

Problem: possibly big changes in mass for small changes in light (high M/L)

$$\varphi\left(m\right)dm \;\propto\; m^{\left(-\mu-1\right)}dm$$



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SSPs vs. CSPs

– If all stars formed in a single burst, at a single metallicity, stellar masses would be (relatively) rather easy to measure from direct fitting to spectra with reasonable S/N.

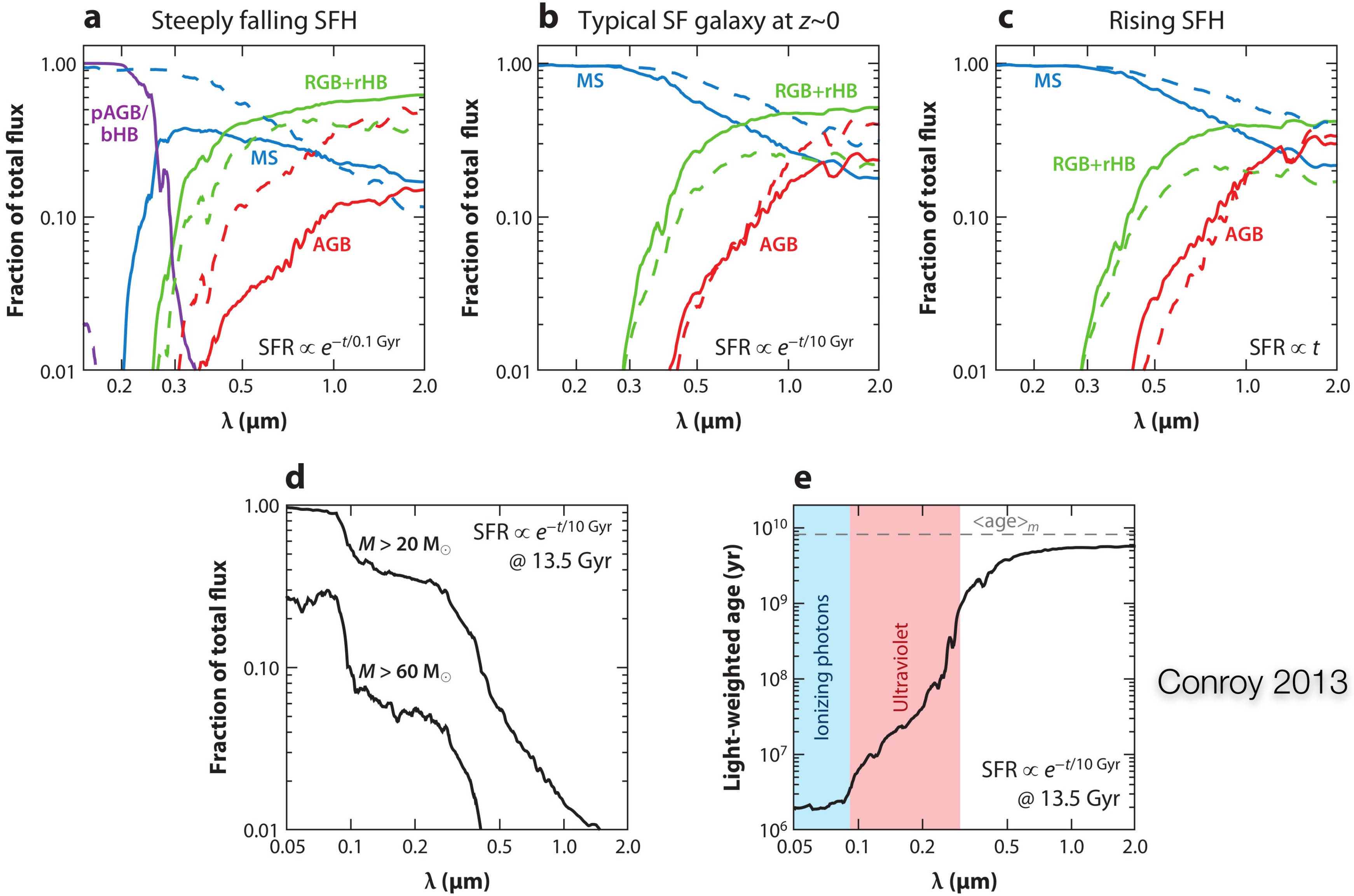
– This assumption, however, is unphysical, and in most cases not a good approximation either

– We therefore need to work with composite stellar populations (CSPs)

– We generally parametrize star formation histories (SFH) In a number of ways

– A favorite is the τ-model $SFR \propto e^{-\frac{t}{\tau}}$

Contributors to CSP light



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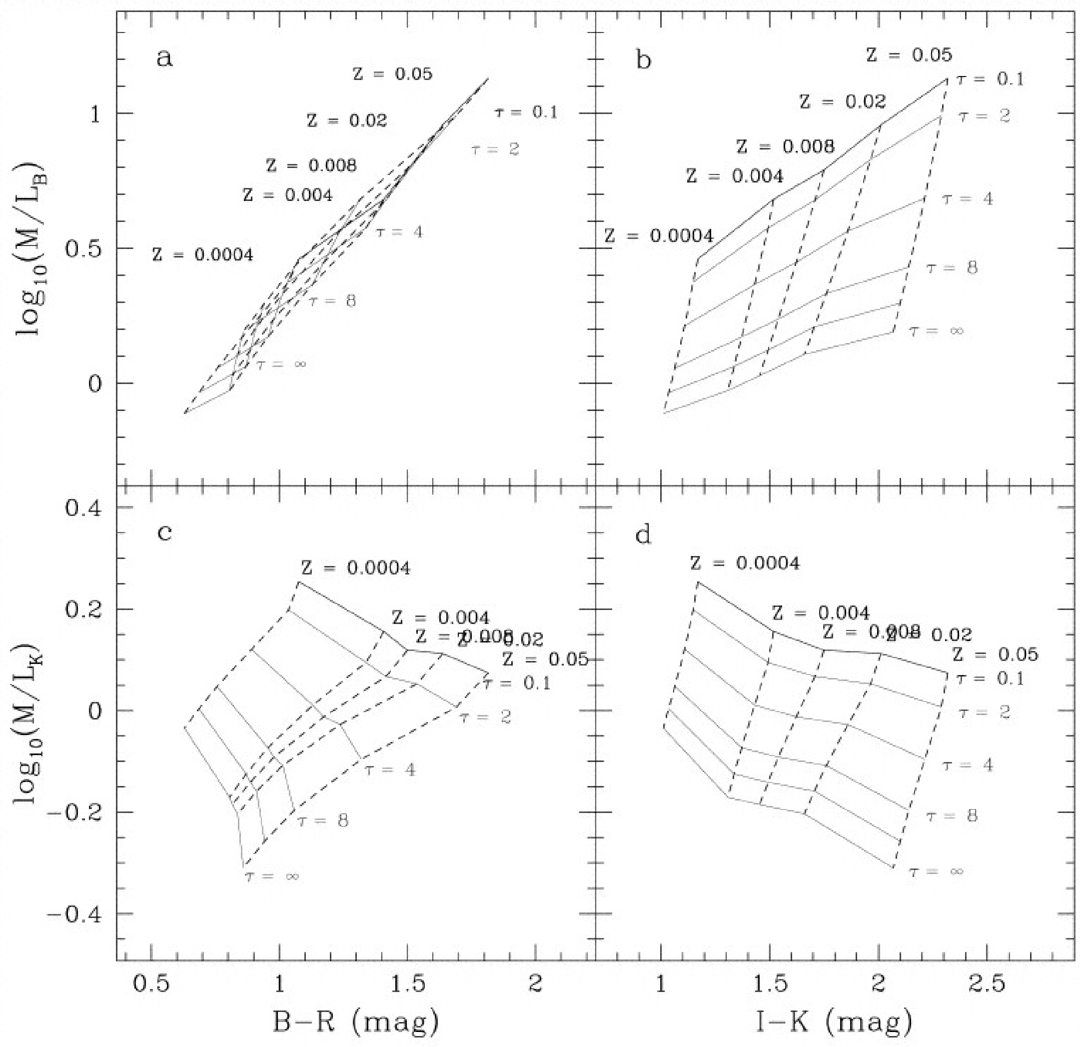
M/L ratios from Stellar Population Models

B



Age-Z grids

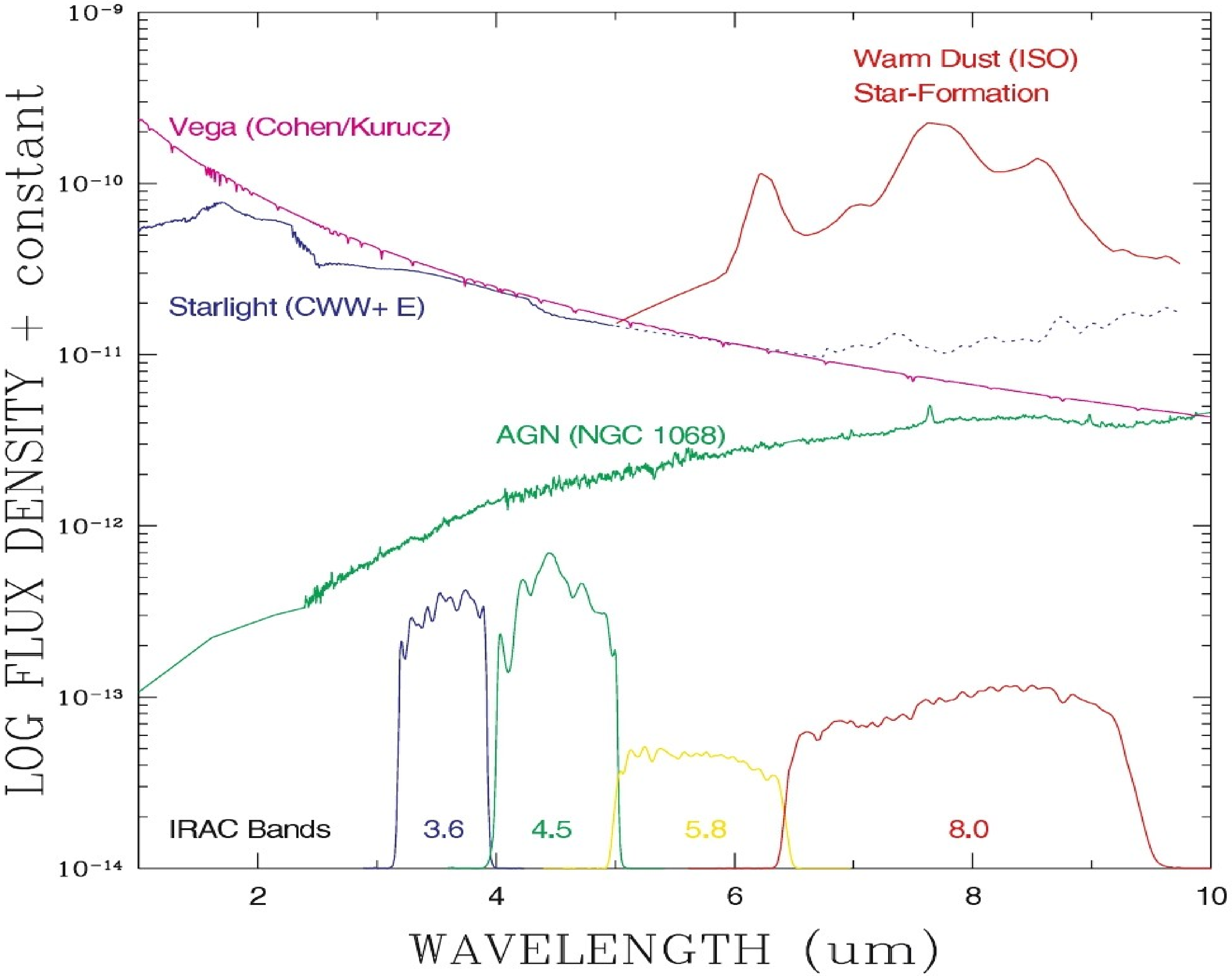
K

From Bell & de Jong (2001)

Bruzual & Charlot CSP-models with exponential SFH

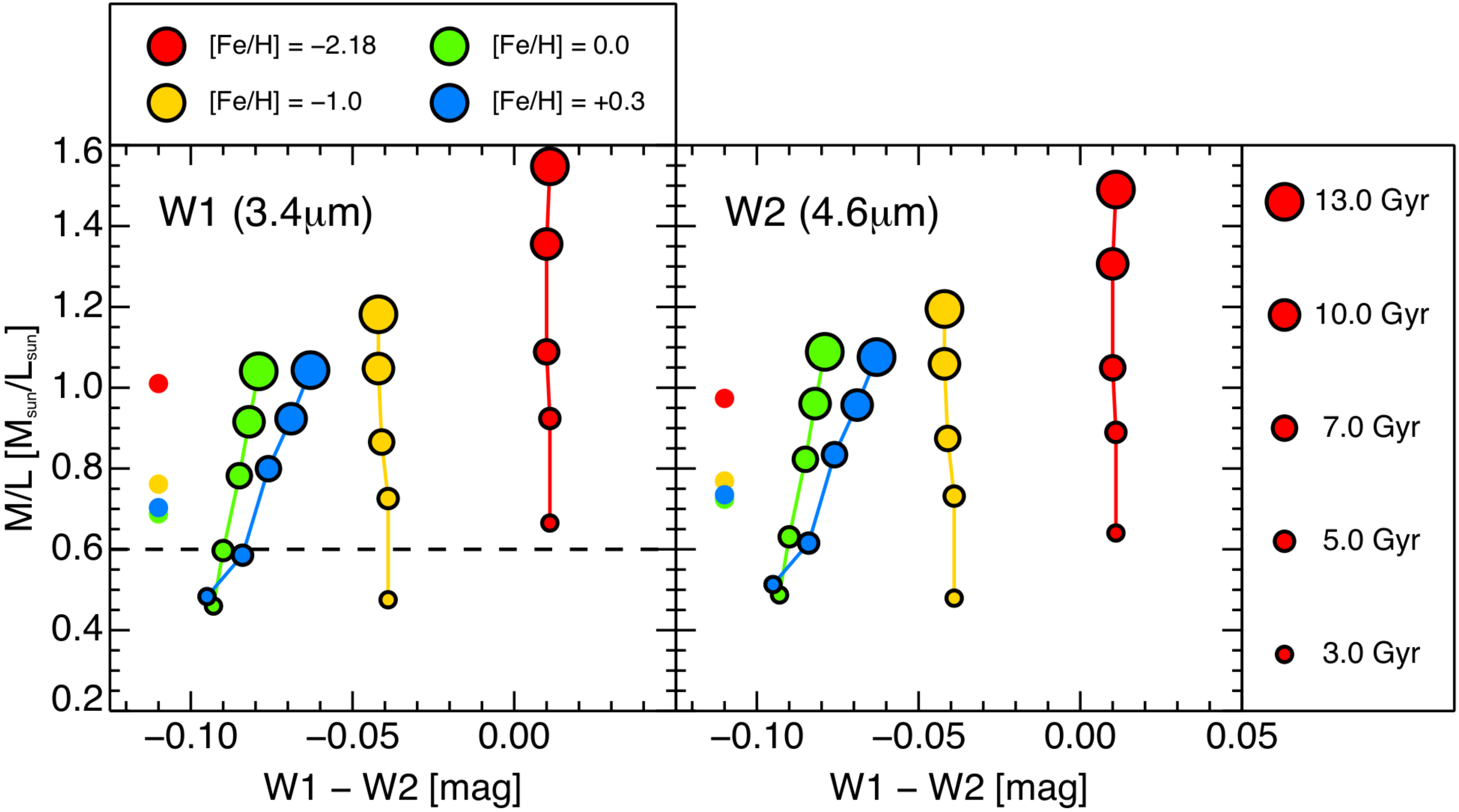
Advantages of the IR

- – M/L depends much less on age/metallicity than in the optical (especially the blue)
- – *'We measure the light from the stars that produce the mass'*
- – Effects of dust extinction are neglligible

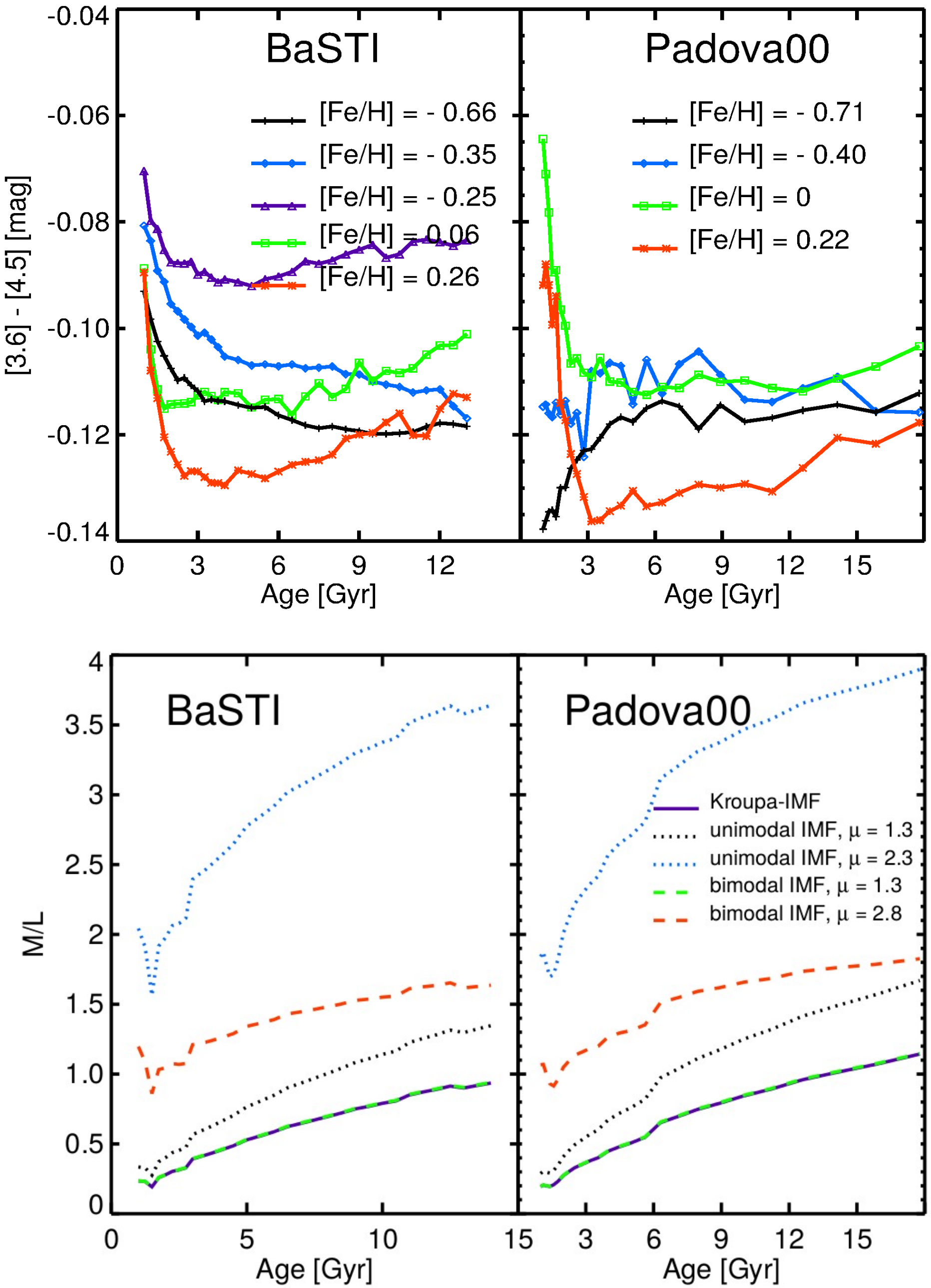


Dominated by stars

Norris et al. (2014): model colors for Wise passbands (SSP)



Other models: Rőck, Vazdekis & Peletier 2014

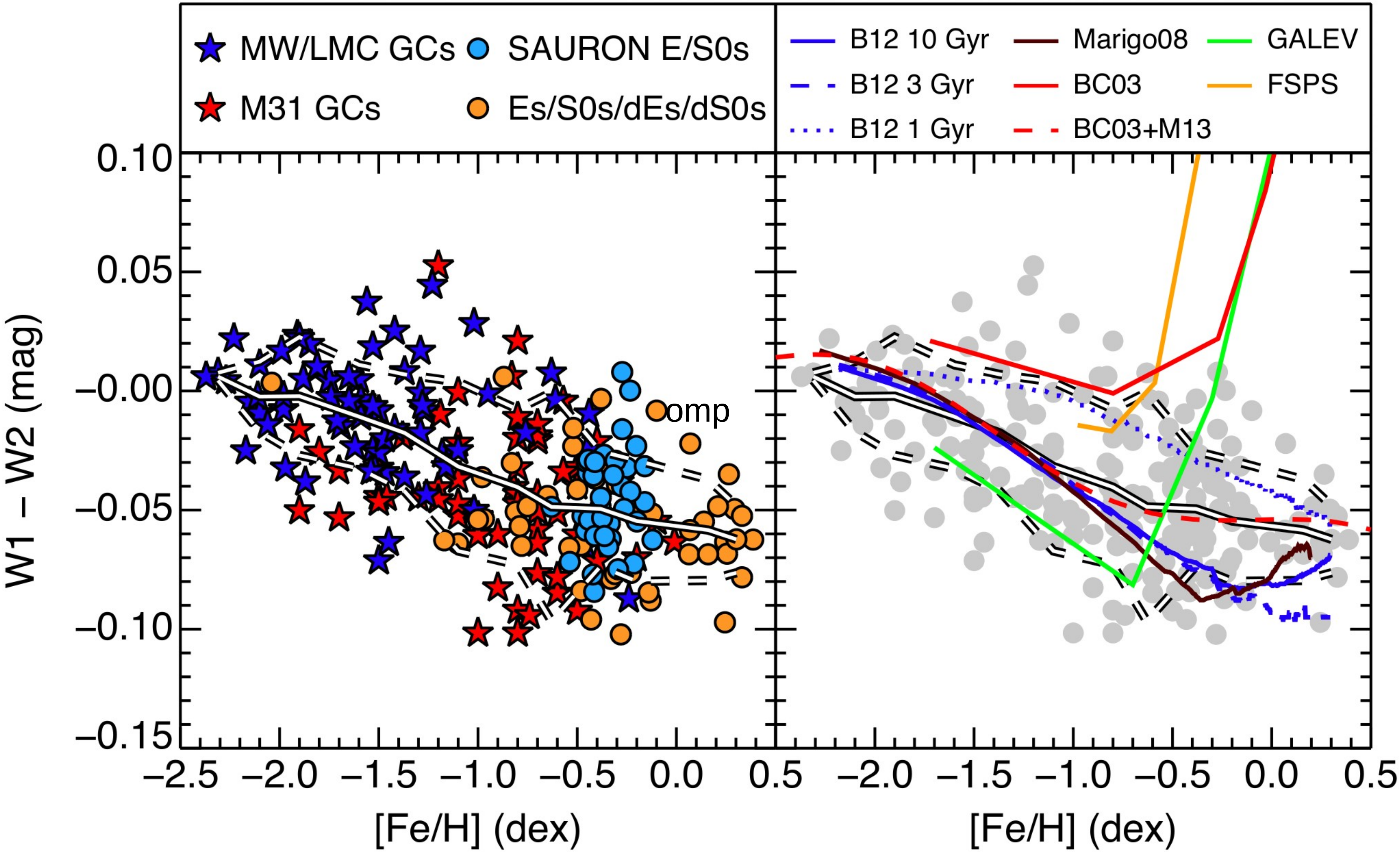


Based on Vazdekis (2010) prescription + IRTF library

$$\phi\left(m\right)dm \;\propto\; m^{\left(-\mu-1\right)}dm$$

Validating the models on observations of old stellar systems

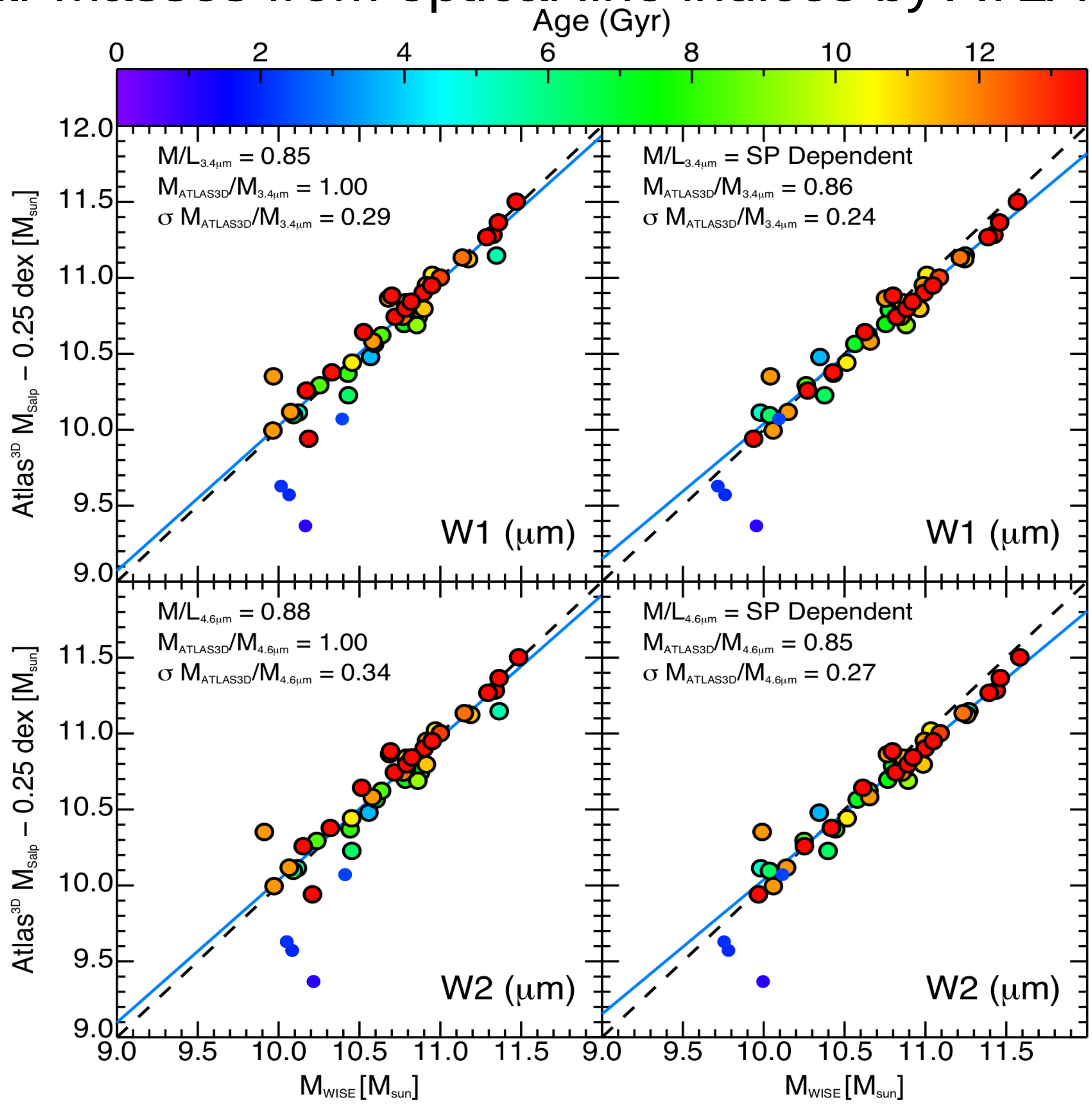
ʋComparison with Wise data of Gl. Cl. and Galaxies



Norris et al. (2014)

ATLAS3D early-type galaxies

Comparison of stellar masses from Wise (IR) fluxes
with stellar masses from optical line indices by ATLAS3D



The WISE W1 and W2 derived stellar masses for the SAURON survey (de Zeeuw et al. 2002) galaxies vs the stellar

Norris et al. (2014)

Determinations of the IMF

Determining masses of stellar systems

=

Stellar Mass

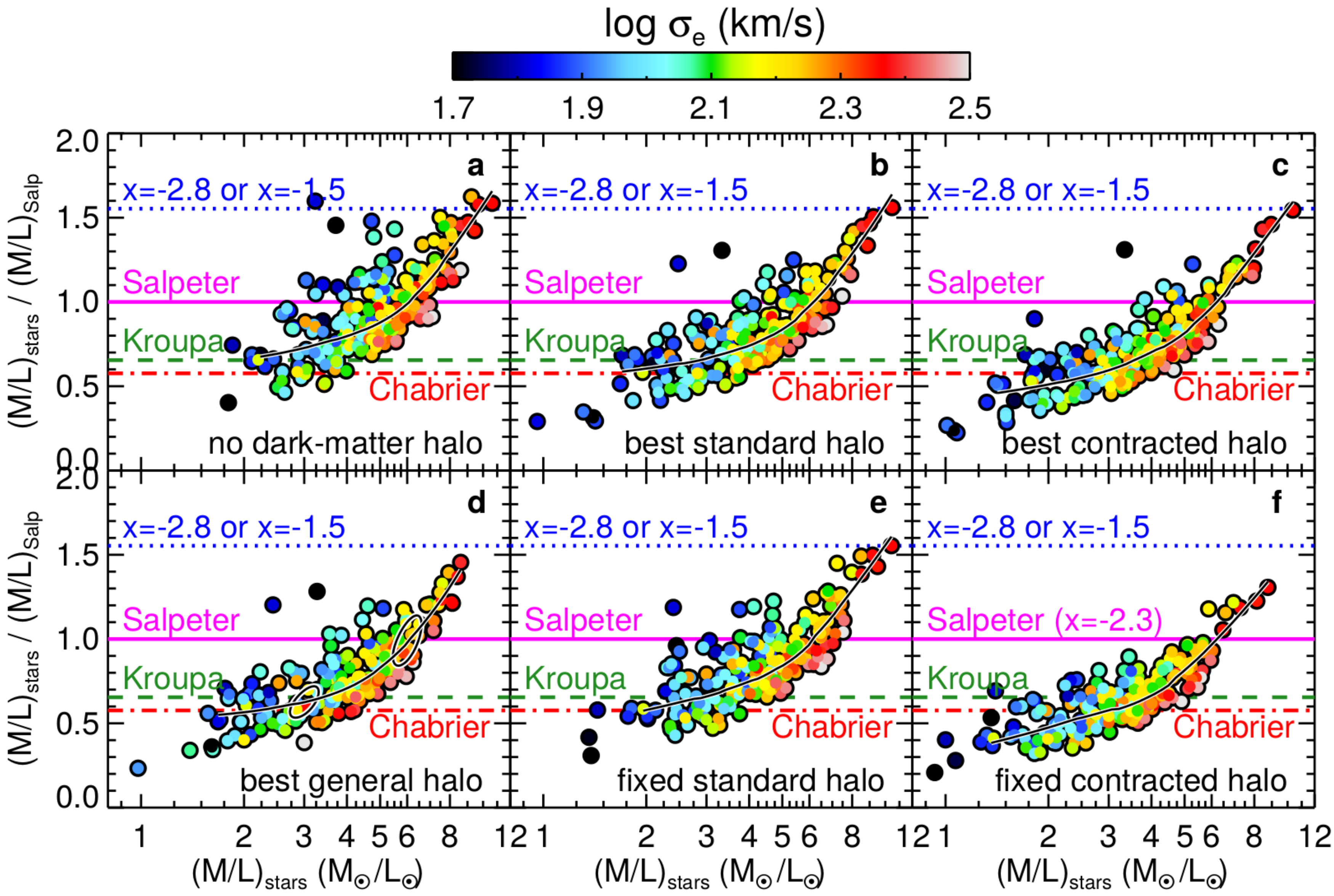
+

Dark Mass

So, by measuring the total mass, one can measure the dark matter, by calculating or assuming the IMF

For objects without dark matter, one can calculate the IMF slope by measuring the total mass.

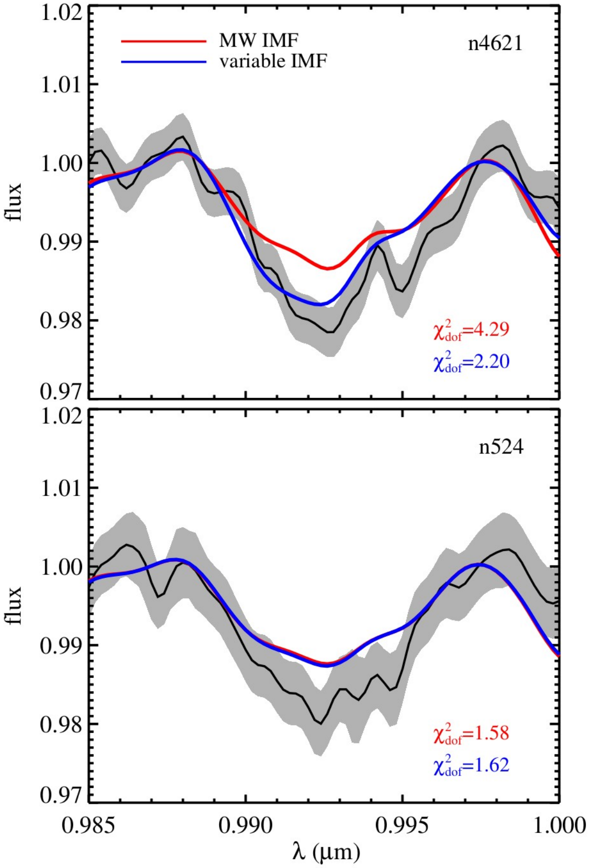
Cappellari et al. 2012 – Nearby giant early-type galaxies
Total mass from dynamical modelling

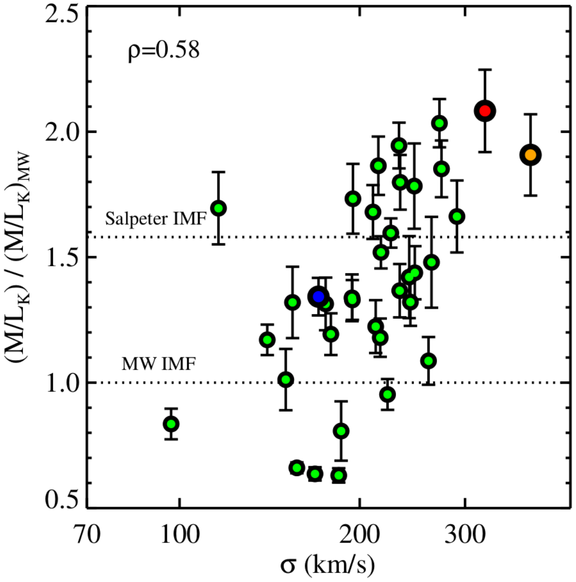


–-> IMF slope determined as function of galaxy mass

Direct IMF-slope determination

(Conroy & van Dokkum 2012)



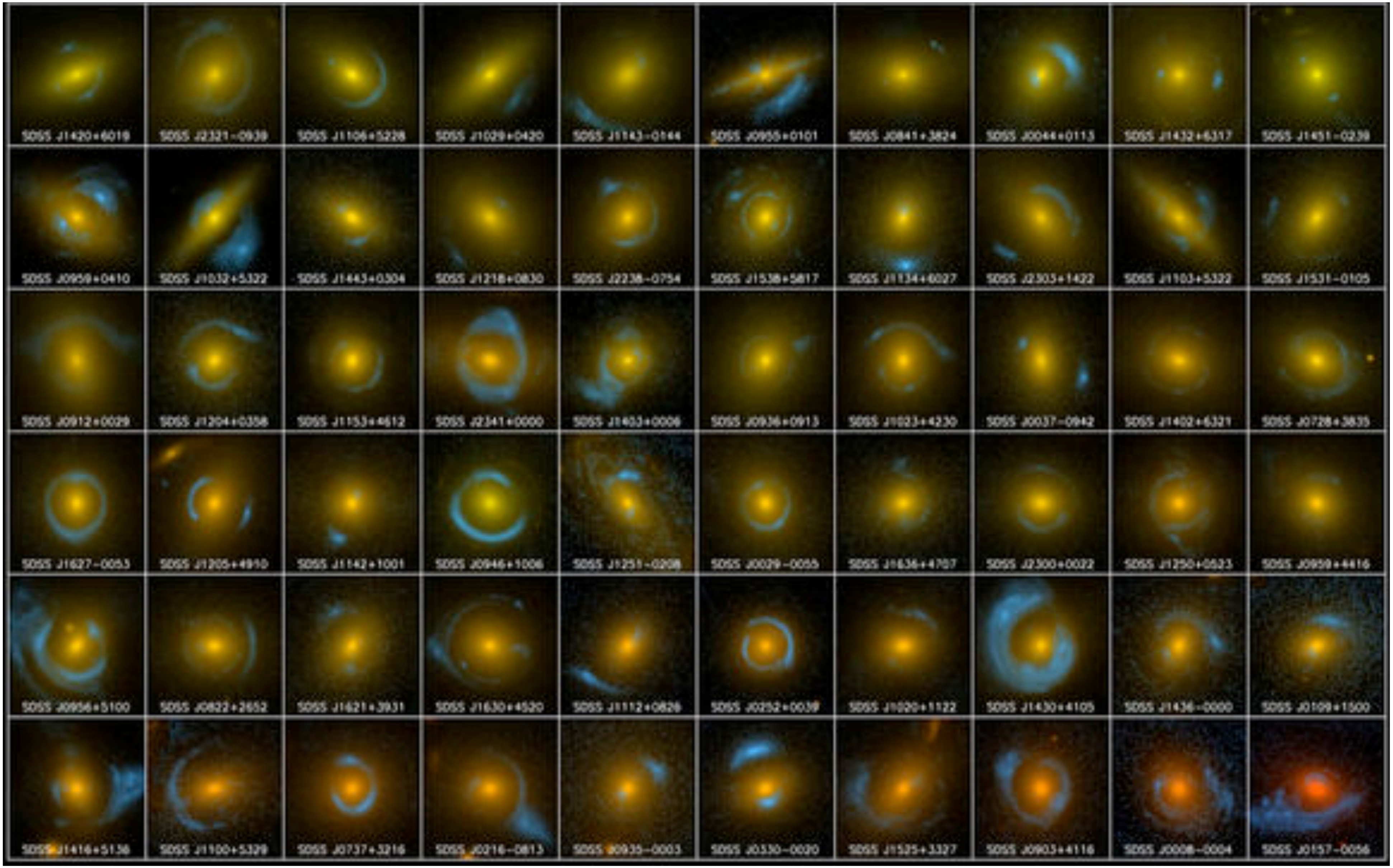


IMF-slope vs. mass

Use some specific dwarf-sensitive lines

Mass Determination through Gravitational Lensing

Lens Galaxies: Some ETG examples



SLACS

slide credit: Adam Bolton/SLACS

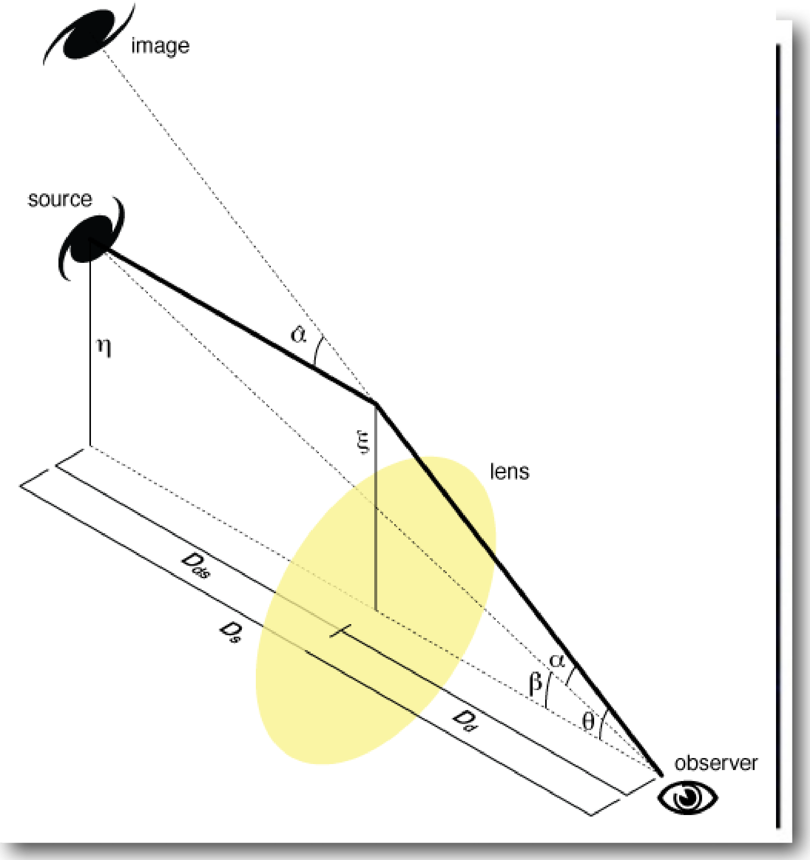
Total Mass of Galaxies (inside R_{Einst})

If the source is approximately on the optical axis, the images form a ring, called an "Einstein Ring"

Solving the lens equation for θ, assuming β=0, yields the Einstein Radius:

$$\theta_{\rm E} = \sqrt{\underbrace{\frac{D_{\rm ds}}{D_{\rm d} D_{\rm s}}}_{[\rm m^{-1}]} \underbrace{\frac{4GM(<\theta)}{c^2}}_{[\rm m]}}$$

Roughly speaking the angular ER is the square root of the angular Schwarzschild radius.



Typical numbers for galaxy masses are:

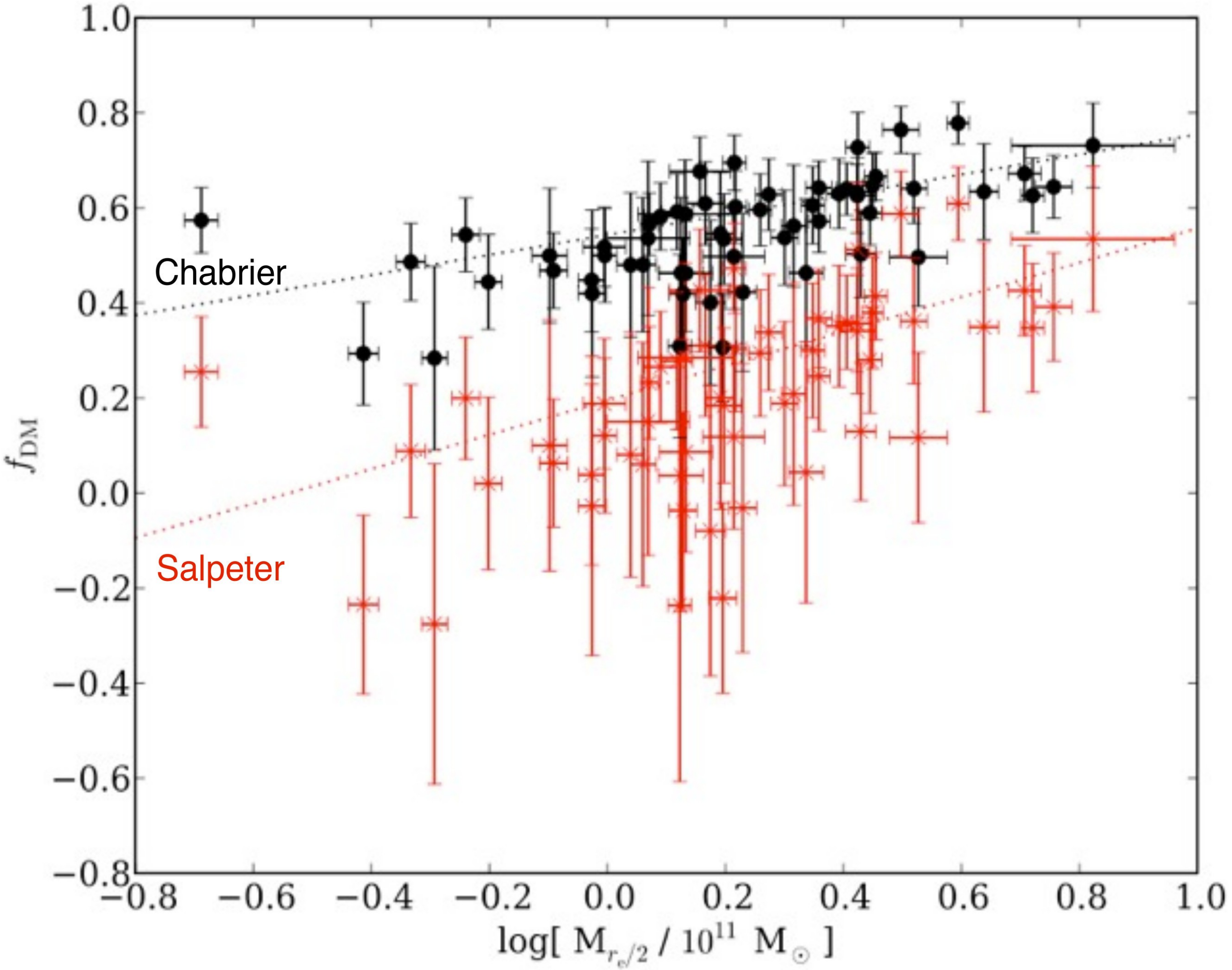
$$\theta_{\rm E} \approx \sqrt{\frac{M}{10^{11}\, M_\odot}} \sqrt{\frac{1 {\rm Gpc}}{D}}\ {\rm arcsec}$$

Measure this

Infer this

With $D \equiv \frac{D_{\rm d} D_{\rm s}}{D_{\rm ds}}$

Two Component Model: Stars plus Dark Matter



Subtracting the SPS stellar mass from the mass inside $R_{eff/2}$~R_{Einst}, suggests that the DM fraction in ETG increases with galaxy mass, assuming a fixed IMF.

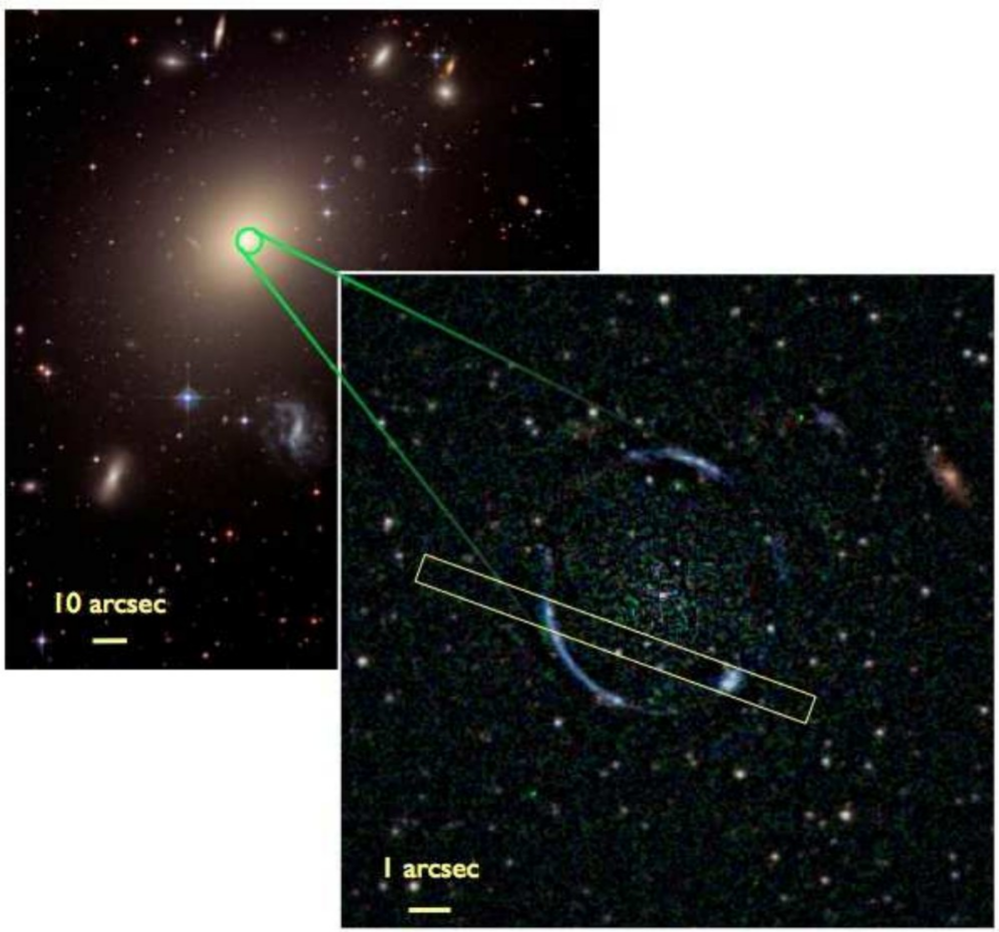
This has implications for feedback models in ΛCDM, increasing as galaxies get more massive.

Auger et al. 2010

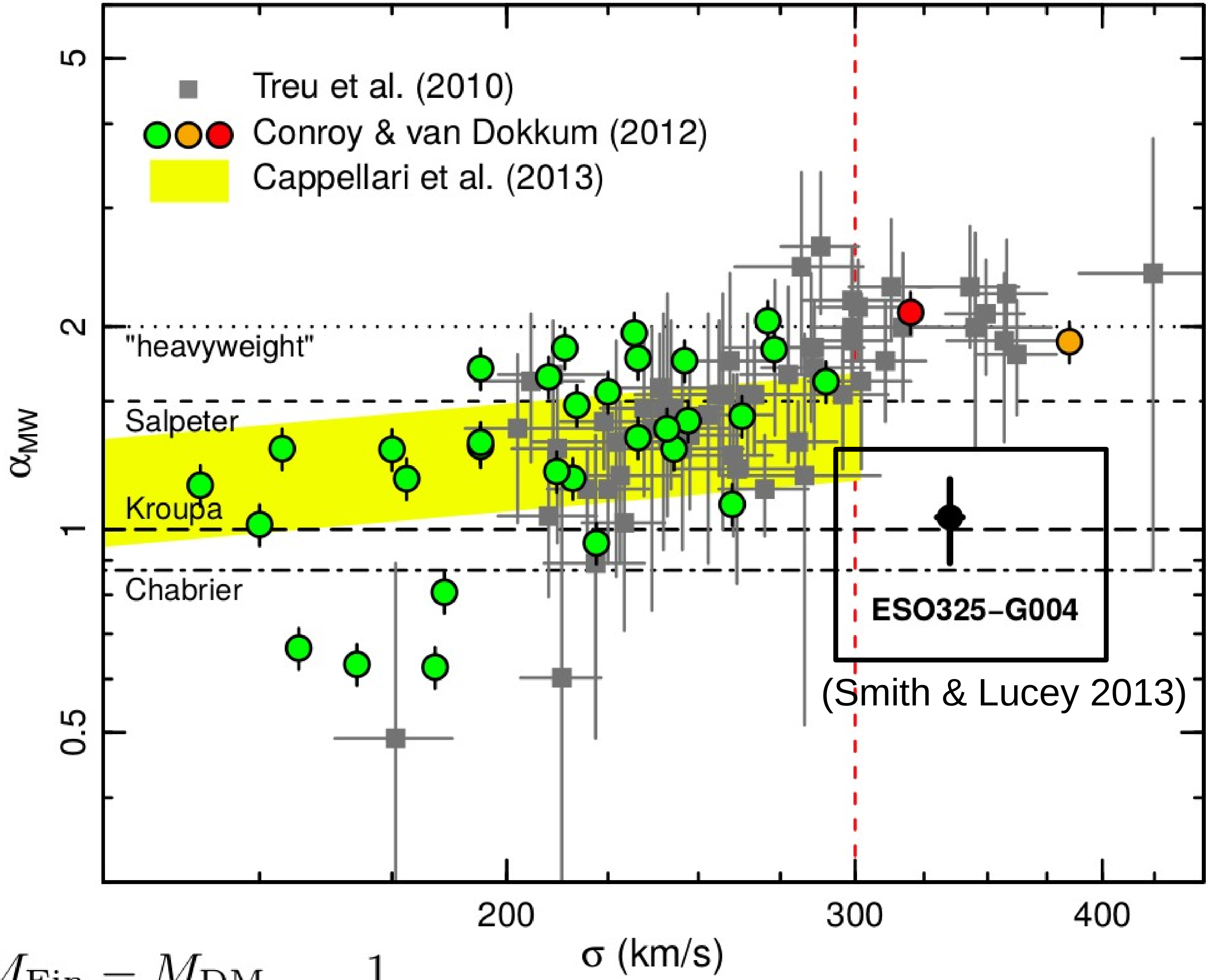
ESO 325-G004: a special case

(Smith & Lucey 2013)

After subtracting a smooth model of the galaxy at z=0.035, a system of lensed arcs is found at an Einstein radius of 2.85'', or $r_e/4$. At such a radius a galaxy contains very little dark matter, so that a direct measurement of the IMF-slope is possible.



Is the IMF truly variable in external galaxies?



(Smith & Lucey 2013)

$$\alpha_{\rm MW} = \frac{M_{\rm Ein} - M_{\rm DM}}{L_{\rm F814W}} \cdot \frac{1}{\Upsilon_{\rm MW}}$$

Conclusions

- Infrared fluxes and colours can be used to get excellent stellar masses. For determining the shape of the IMF absorption lines are needed.
- Lensing offers excellent possibilities to establish whether the IMF in external galaxies is variable.

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Pieter C. van der Kruit

Jacobus Cornelius Kapteyn

Born Investigator of the Heavens

Jacobus C. Kapteyn (1851–1922) was a Dutch astronomer who contributed heavily to major catalogs of star positions, such as the Cape Photographic Durchmusterung and the Harvard-Groningen Durchmusterung, and arranged extensive international collaboration through his Plan of Selected Areas. He contributed to the establishment of statistical astronomy and structure and dynamics of the Sidereal System. All aspects of Kapteyn's life are discussed, from his birth in Barneveld, the Netherlands, to his death in Amsterdam, and his entire resume of scientific achievements in between. Kapteyn had some conflicts with others in his field, especially after the world became divided on how to handle scientific contributions from Germany post-World War I. Both Kapteyn's struggles and achievements are written against the backdrop of both the historical context of the world at that time as well as the scientific one.

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