Class 13: The IMF: Observations

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Mark Krumholz

Outline

- General considerations: resolved vs. unresolved, field vs. cluster
- Resolved populations
  - The IMF in the field
  - The IMF in star clusters
  - The most massive clusters
- Unresolved populations
  - Hα-based methods for star-forming galaxies
  - Spectral feature methods for passive galaxies
  - M/L methods for passive galaxies

General considerations

- Massive stars have very short lifetimes. Implications:
  - Can only study massive part of the IMF in young regions
  - Can be hard to study the low-mass part of the IMF in these regions —worse statistics, and usually not on the main sequence yet
  - As a result, studies of low-mass and high-mass parts of the IMF often done separately, in different regions and with different methods

- Individual stars are only resolvable out to ~M31 distances. Within this distance, star-forming environment properties cover the range:
  - Metallicity $Z/Z_\odot$ ~ 0.2 (SMC) to 2 (MW centre)
  - Gas surface density (at kpc scales) ~ 0.1 (SMC) to 300 (MW centre) $M_\odot$ pc^{-2}
  - Relatively large dwarfs (SMC) through medium spirals (MW, M31)
  - NO mergers, starbursts, ULIRGs, wimpy dwarfs, very metal poor systems — these can ONLY be studied using unresolved stellar populations

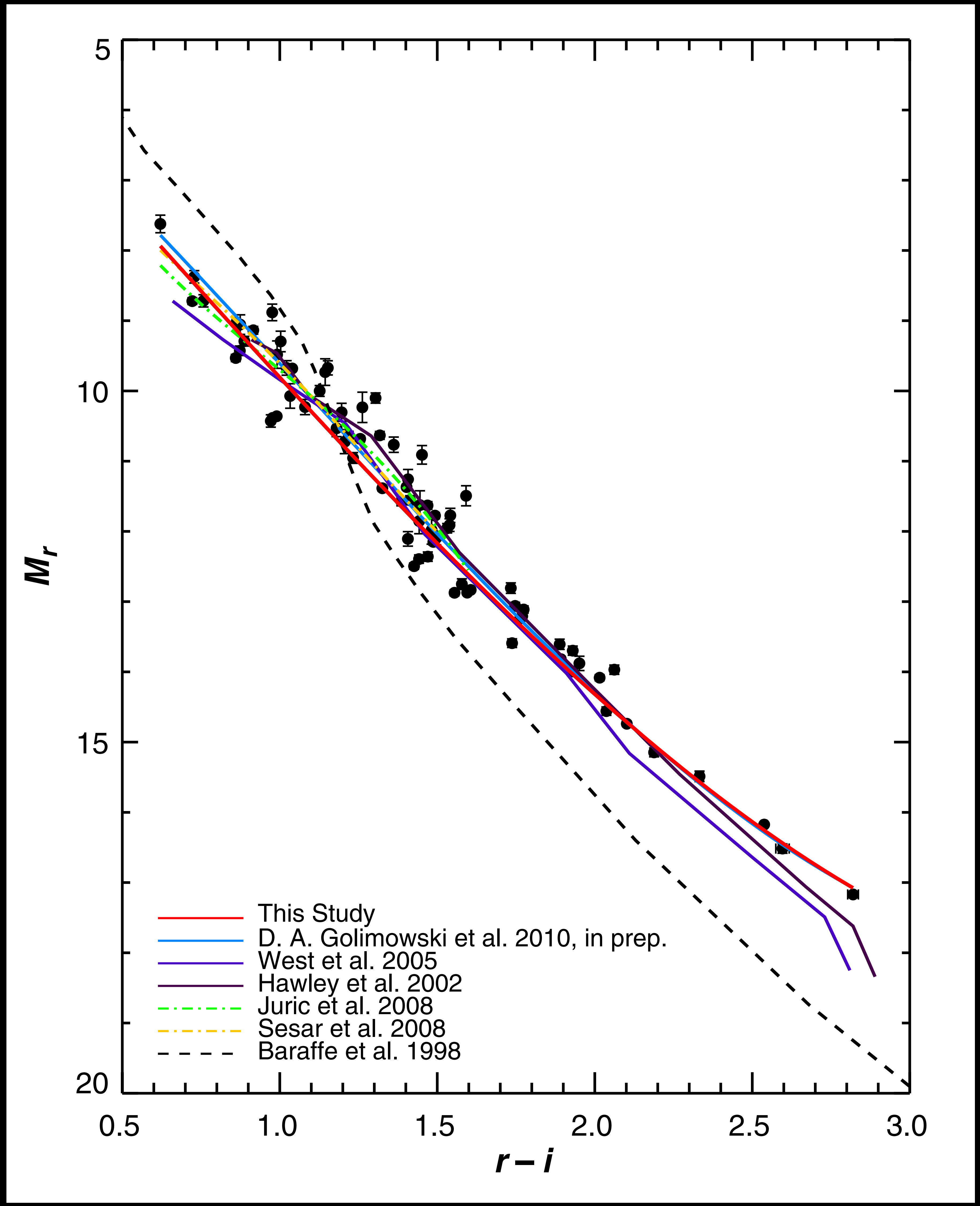
The IMF in the Galactic Field

- For stars with mass low enough that lifetime $\gtrsim$ 10 Gyr age of the Galaxy (mass $\lesssim 1\ M_\odot$), best statistics come from using whole galactic field — samples of $>10^6$ possible
- Spectroscopy of large samples is expensive, particularly for dim targets, so biggest samples are photometric only
- Basic steps in a field IMF measurement
  - Measure apparent luminosity function (LF) and colour distribution
  - Use distance estimates / colours to convert to intrinsic LF
  - Correct for biases (extinction, Malmquist, metallicity)
  - Correct for unresolved binaries
  - Convert corrected LF to mass distribution

LFs and distances

Sources and methods

- Apparent LFs are relatively easy to obtain from large sky surveys (e.g. SDSS)
- Distances are bigger challenge:
  - Pre-*Gaia*, parallax distances only available for bright, nearby stars → studies used CMD for sample with parallax distances to convert colour to absolute magnitude for all other stars
  - Post-*Gaia*, parallax sample ~10^5, can get distances directly (though still smaller sample than colour-based studies)



Colour-magnitude diagram for stars with parallax distances (c. 2010 data) — Bochanski+ 2010

Bias mitigation

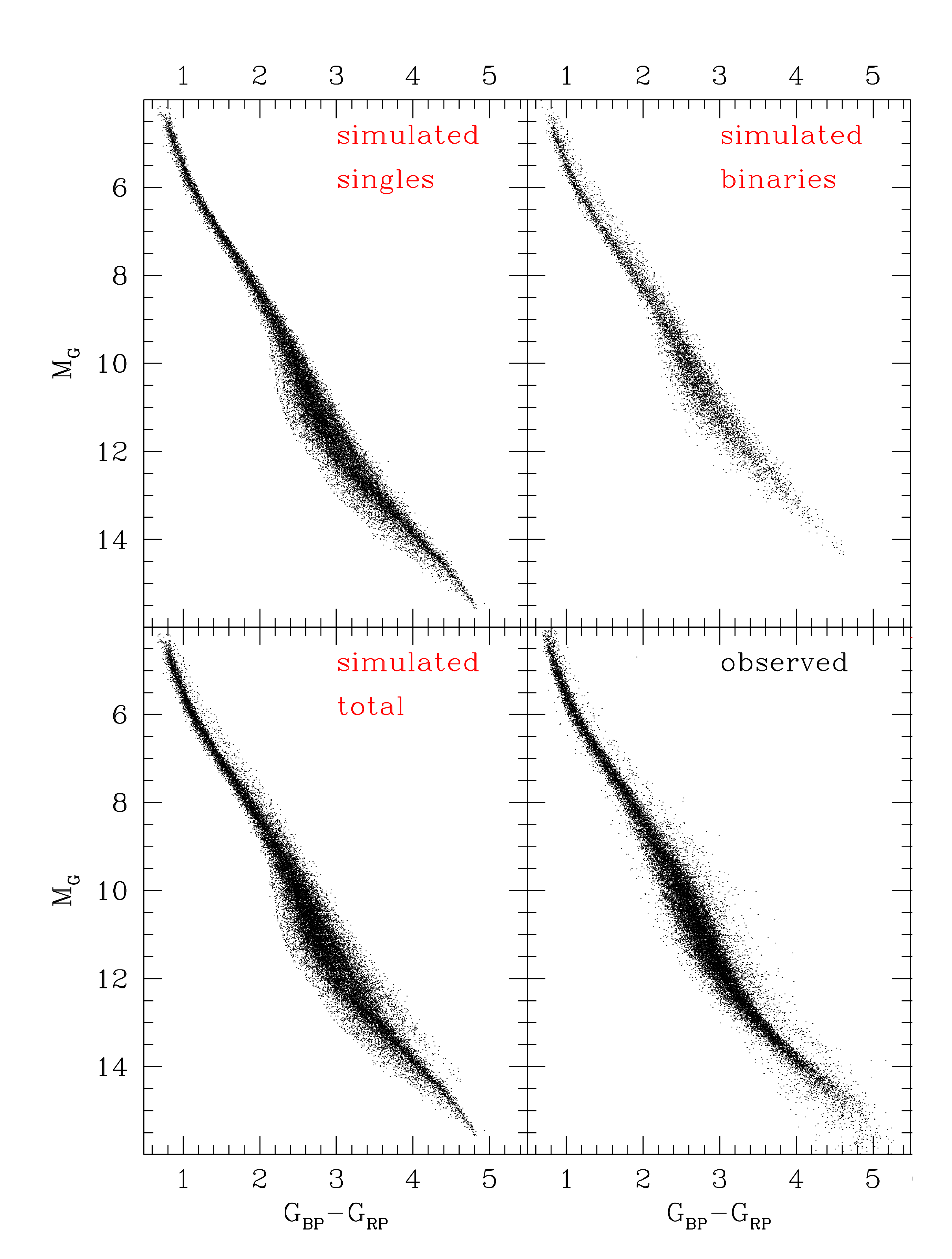
For both photometric and parallax studies

- Extinction bias: distant objects are both reddened and dimmed, so stars assigned artificially low luminosities → mass is underestimated
- Malmquist bias: near magnitude limit of sample, errors are asymmetric: stars more likely to be kept if error is positive (makes star look brighter) than negative (makes star look dimmer) → mass on average overestimated
- Metallicity bias (for photometric method): empirical CMD used to assign luminosities is based on nearby stars, which have higher mean metallicity than full sample (since metal-poor stars more common at large scale height) → metal-poor stars are bluer, so magnitude assigned is to bright, mass is overestimated

Binarity correction

The biggest bias of all

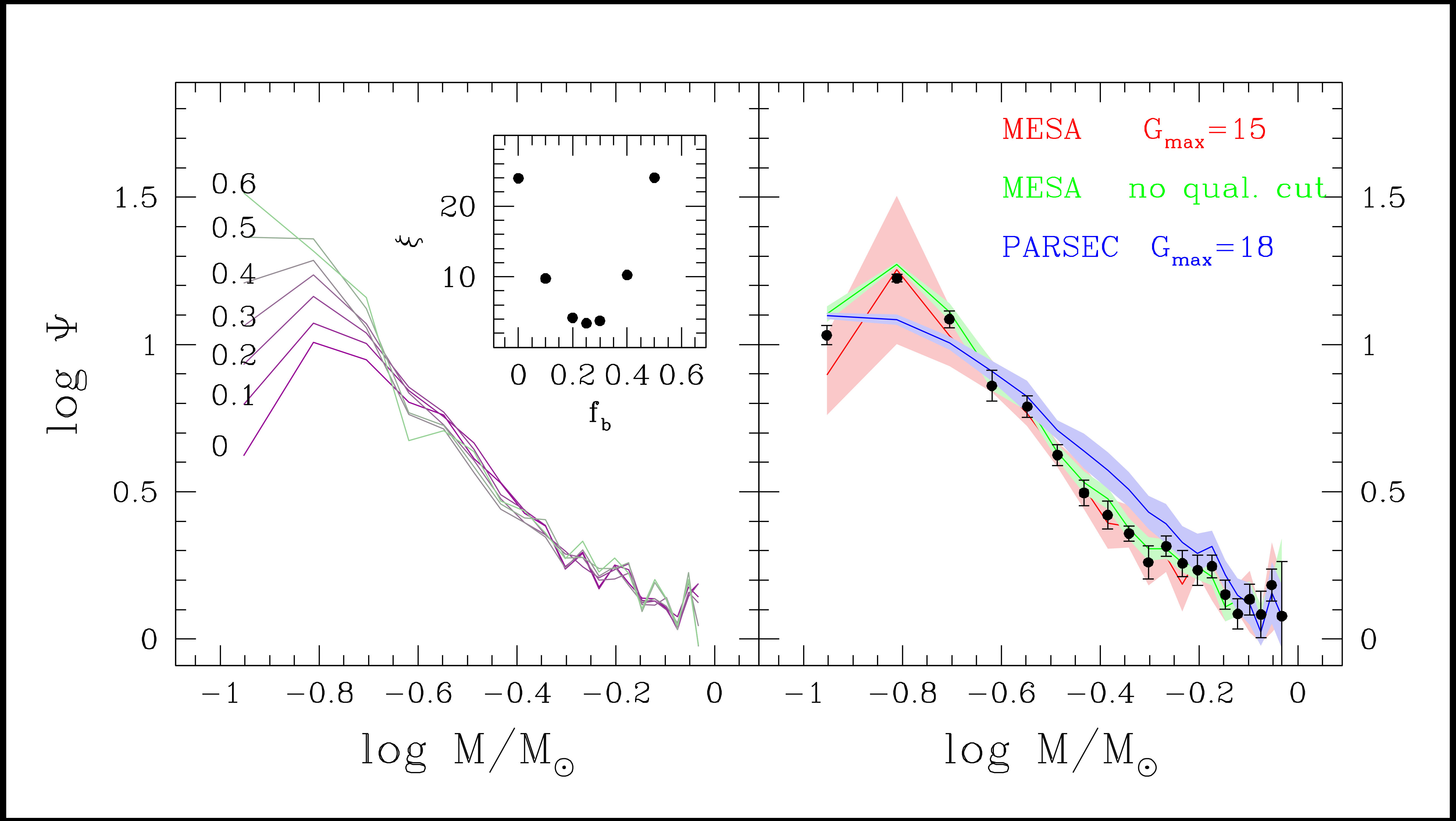
- Some fraction of stars are unresolved binaries
- Complex effects; depends on mass ratio q:
  - If $q \lesssim 0.3$, primary much brighter, secondary not seen at all → properties of primary recovered correctly, but secondary missed
  - If $q \approx 1$, colour unaffected, but true luminosity = 2 × value of single star → error in distance or mass, depending on how luminosity is used
- Must be modelled based on *a priori* knowledge of binary fraction, mass ratio distribution



Simulated CMD including the effects of binaries, being matched to observed CMD from *Gaia* (Sollima 2019)

From luminosity to mass functions

- Convert corrected LF to mass function using empirical or theoretical mass-magnitude relation (MMR)
- Empirical MMRs come from binary star dynamical mass measurements; also subject to metallicity bias
- Theoretical MMRs uncertain, particularly for low-mass stars at red colours, where molecular opacities in stellar atmospheres are complex



Mass functions derived using different assumed unresolved binary fractions (left)
three different theoretical MMRs (right) — Sollima 2019

IMFs in young clusters

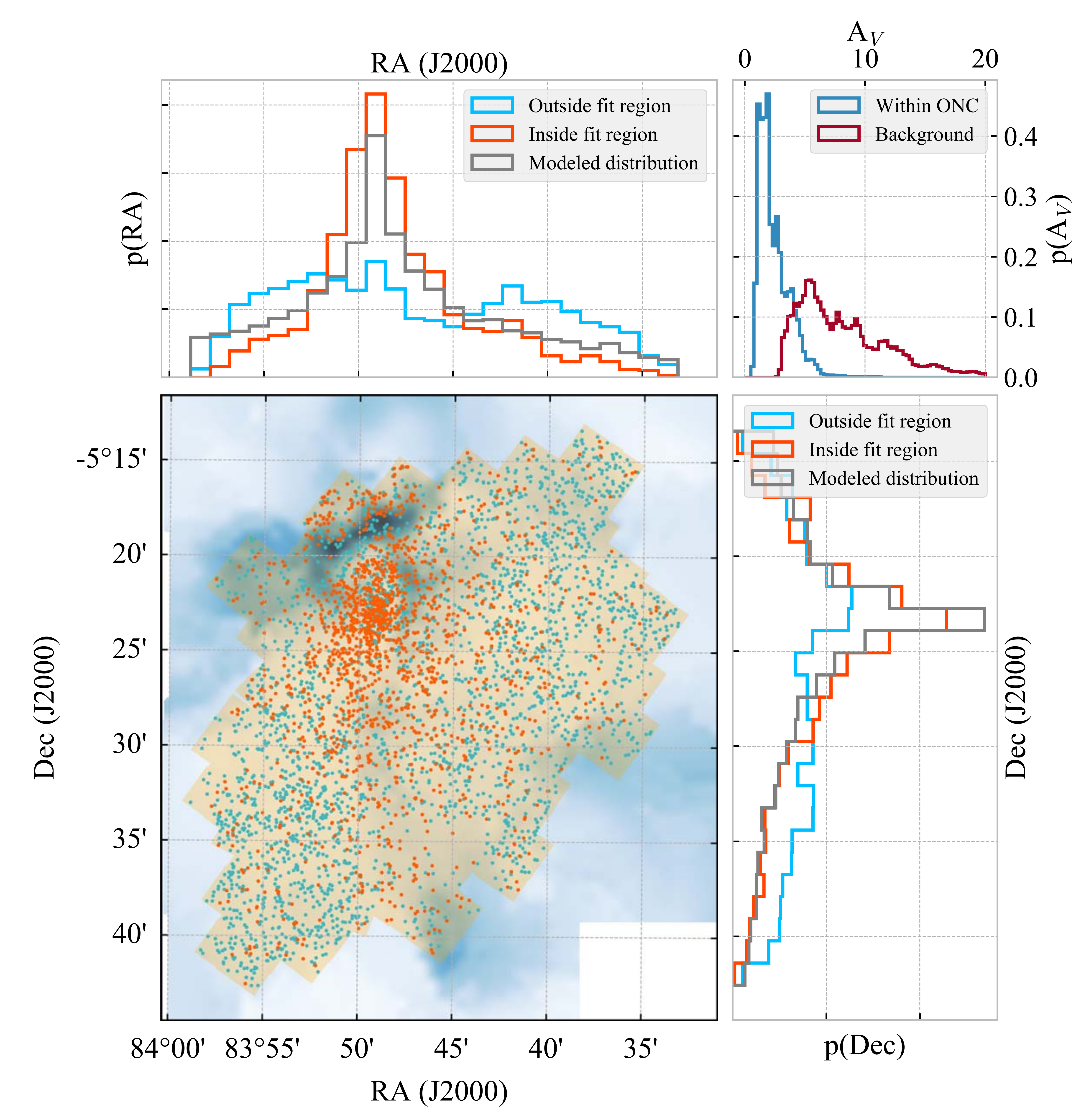
General considerations

- Advantages:
  - Only way to probe IMF of stars ≳ few $M_\odot$
  - Near-uniform metallicity, distance, foreground dust → greatly reduced bias
  - Low-mass stars / brown dwarfs brighter when young, can go to lower mass
- Disadvantages:
  - Much worse statistics (~10^3 - 10^4 stars instead of ~10^5 - 10^6)
  - Low-mass stars will be pre-main sequence → much more uncertain MMR
  - Need to separate cluster members from foreground / background objects
  - Differential extinction due to dust within the cluster
  - Dynamical ejections / mass segregation may be a concern

Example: the ONC

Best Galactic case

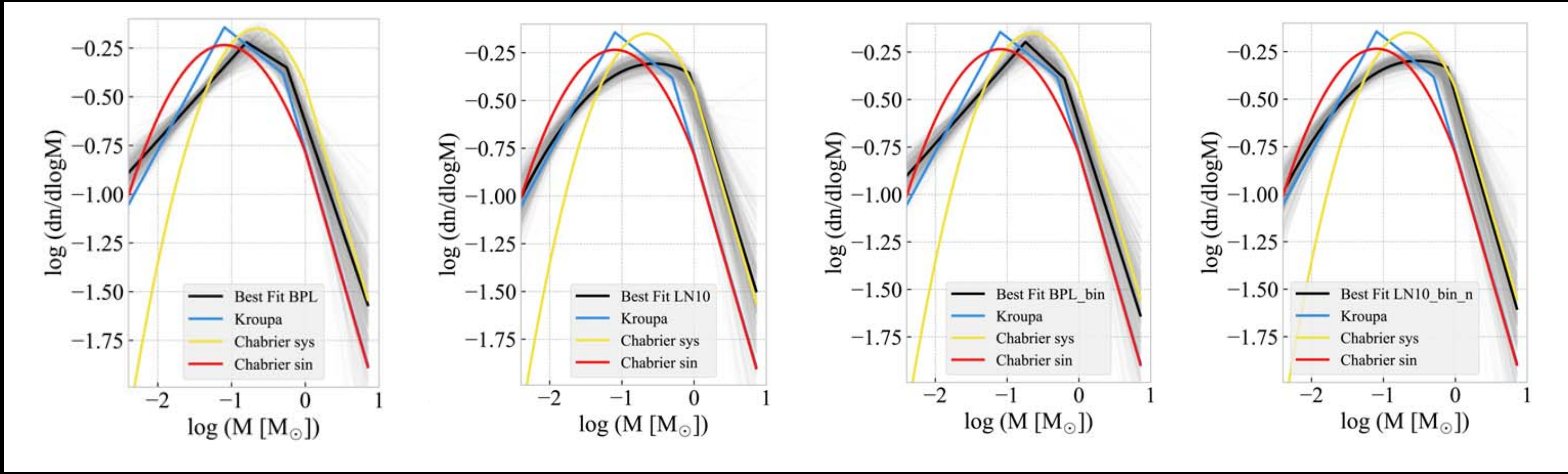
- LF in Orion Nebula Cluster (ONC) measured using HST down into the brown dwarf / planet regime
- d = 400 pc from parallax, extinction well-mapped
- Can separate background based on colours
- Age distribution roughly known — reduces MMR uncertainty



Blue dots = background objects, orange = ONC stars; background shading = dust extinction map; Gennaro & Roberto 2020

ONC results

- ONC IMF roughly roughly consistent, with errors, with measured field IMF
- Exact details depend on assumed age distribution, binary corrections
- Clearly detected turnover of ~few × 0.1 $M_\odot$

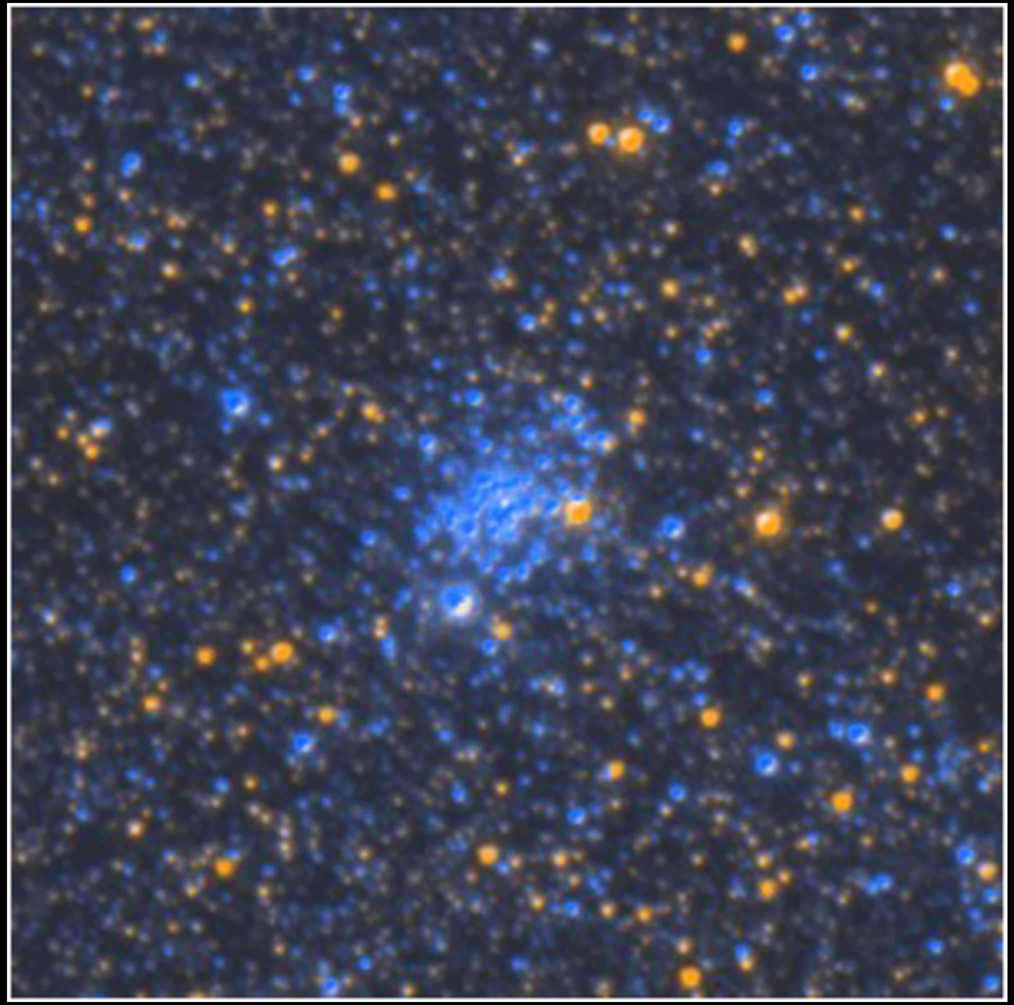


ONC IMFs for different assumed star formation histories and different functional forms — Gennaro & Robberto 2020

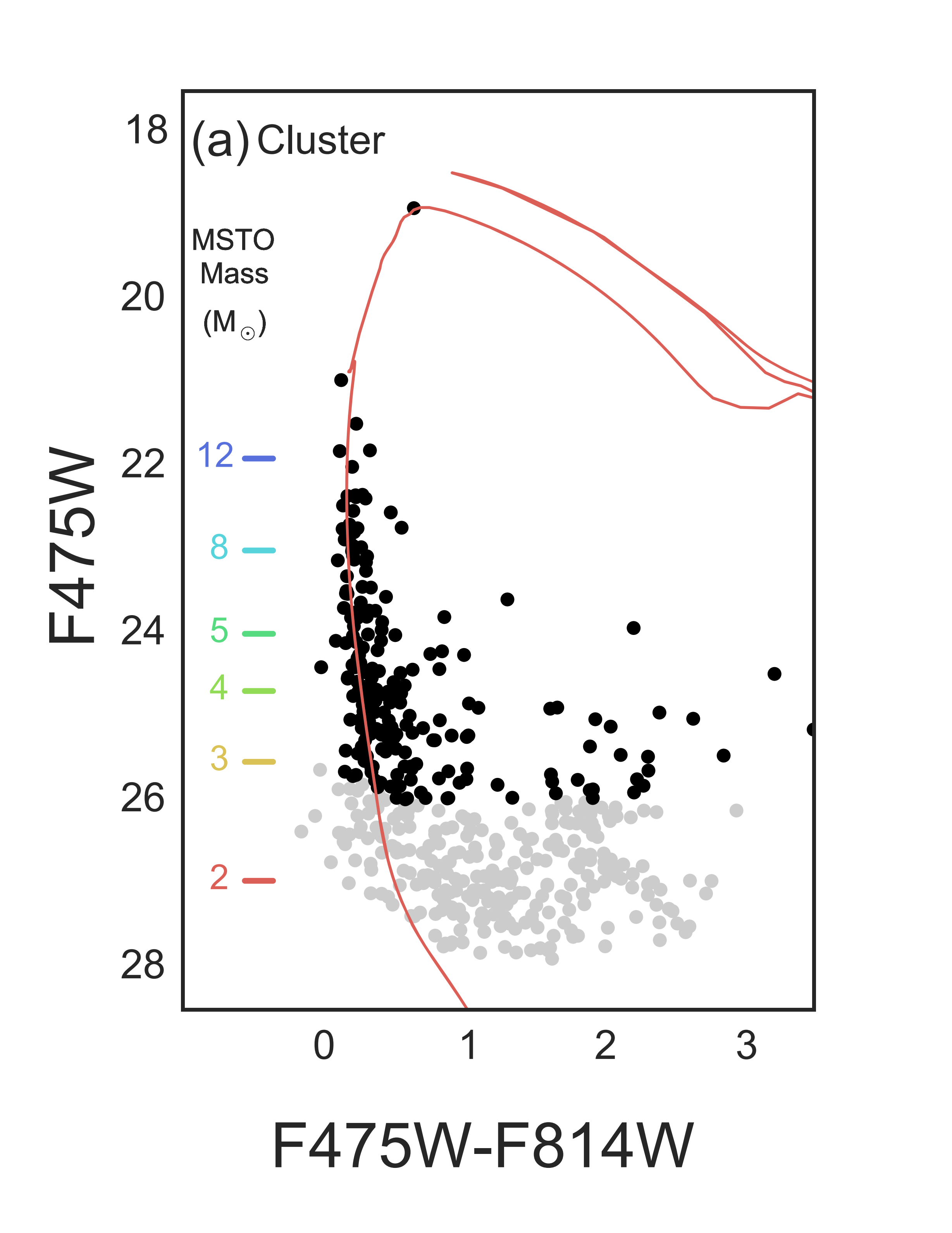
Example: M31 / PHAT

Best extragalactic case

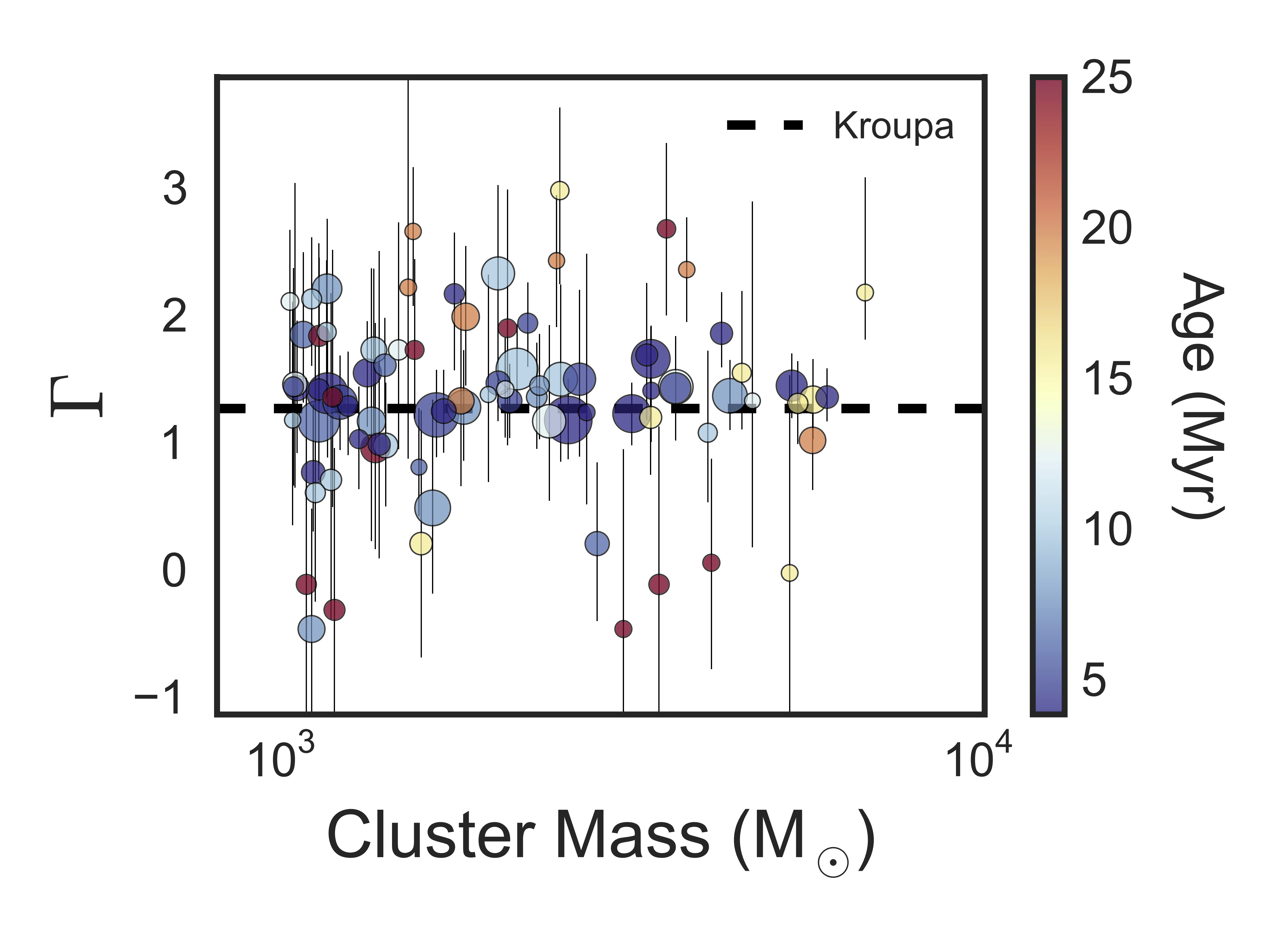
- In M31 using HST, can see individual stars down to ~2 - 3 $M_\odot$ in ~100 clusters 5 - 25 Myr old — probably best measurement of high mass IMF in resolved stars
- High mass slope in individual clusters has big uncertainties due to small number of stars, but large number of clusters provide strong constraint on IMF in galaxy as a whole
- No distance uncertainty, minimal extinction uncertainty



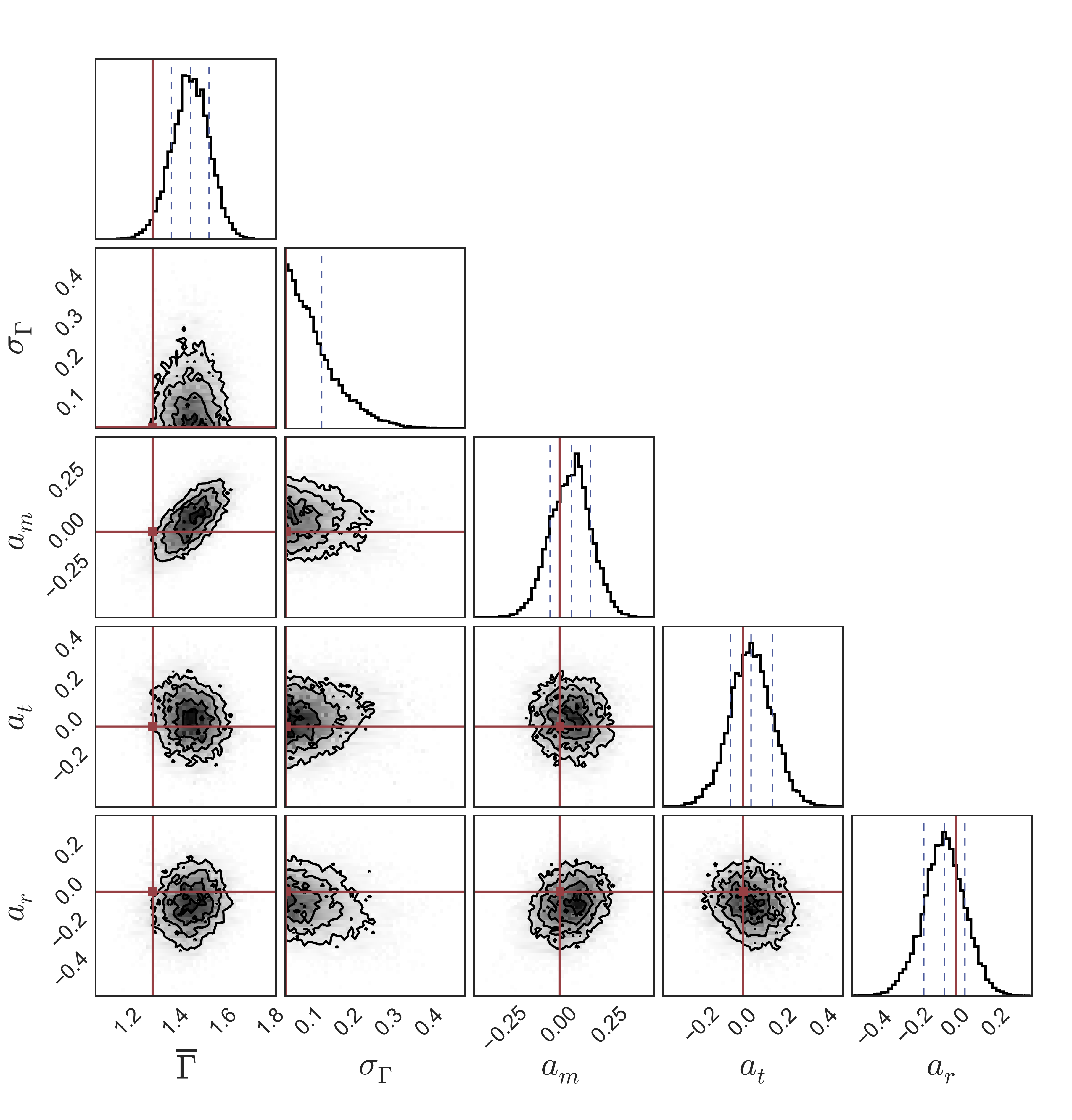
Weisz+ 2015



PHAT result



High mass slopes Γ of individual clusters



Posterior PDF for mean high mass slope in galaxy Γ, cluster-to-cluster scatter in high mass slope σ_Γ, and scaling of slope with cluster mass, age, radius (a_m, a_t, a_r)

Summary of resolved observations

For most local star-forming environments

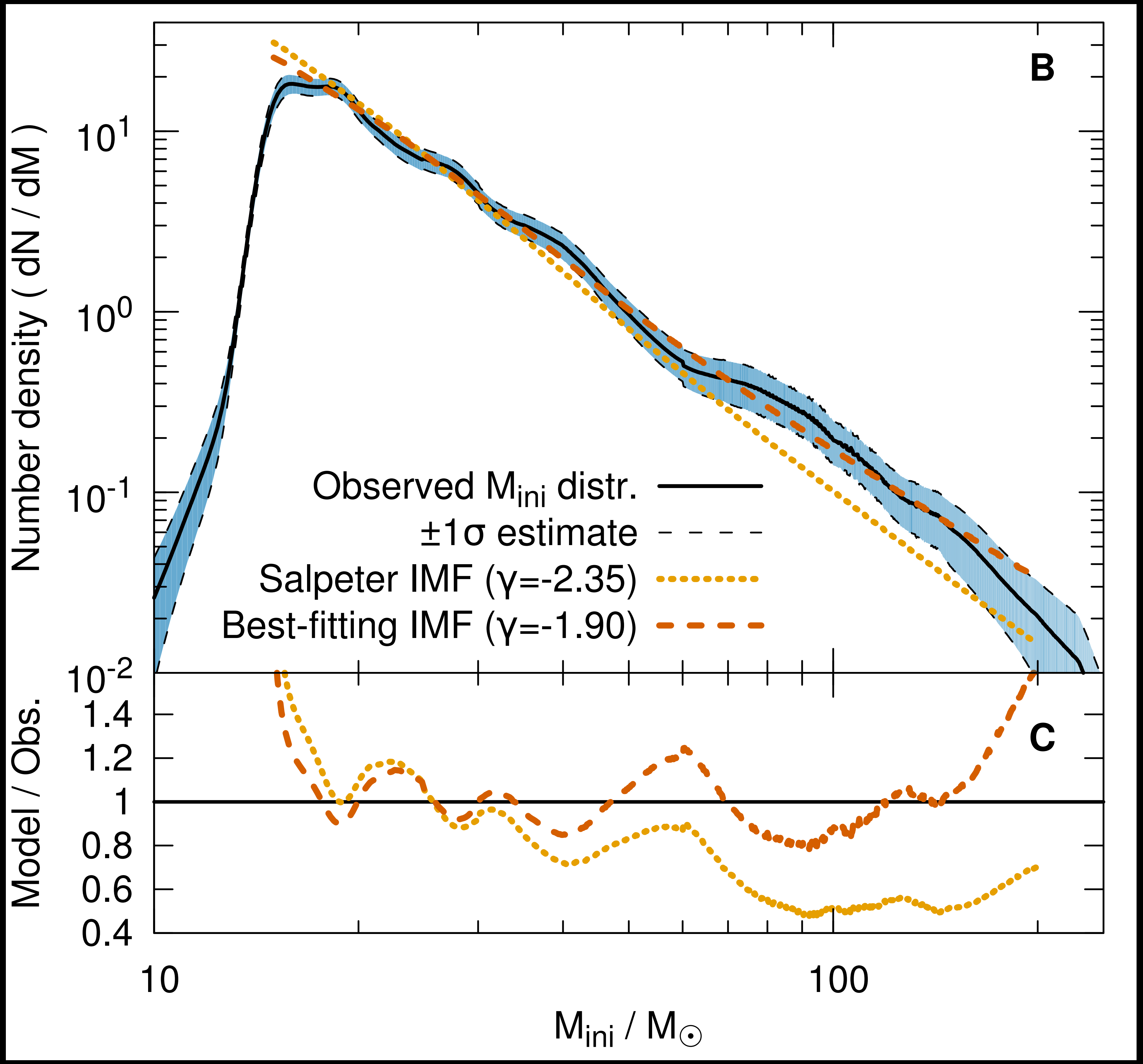
- Low-mass IMF in clusters similar to that inferred for the field — flattens to peak at ~ few × 0.1 $M_{\odot}$
- High mass IMF shows little scatter between clusters — slope similar to Salpeter value (dn / dm ~ $m^{-2.3}$) with perhaps ~0.1 dex variation
- No evidence for systematic variation in either peak or slope with environment (cluster mass or age, field vs. cluster) within the disc of the MW or M31
- Best evidence for a “universal” IMF

The most massive clusters

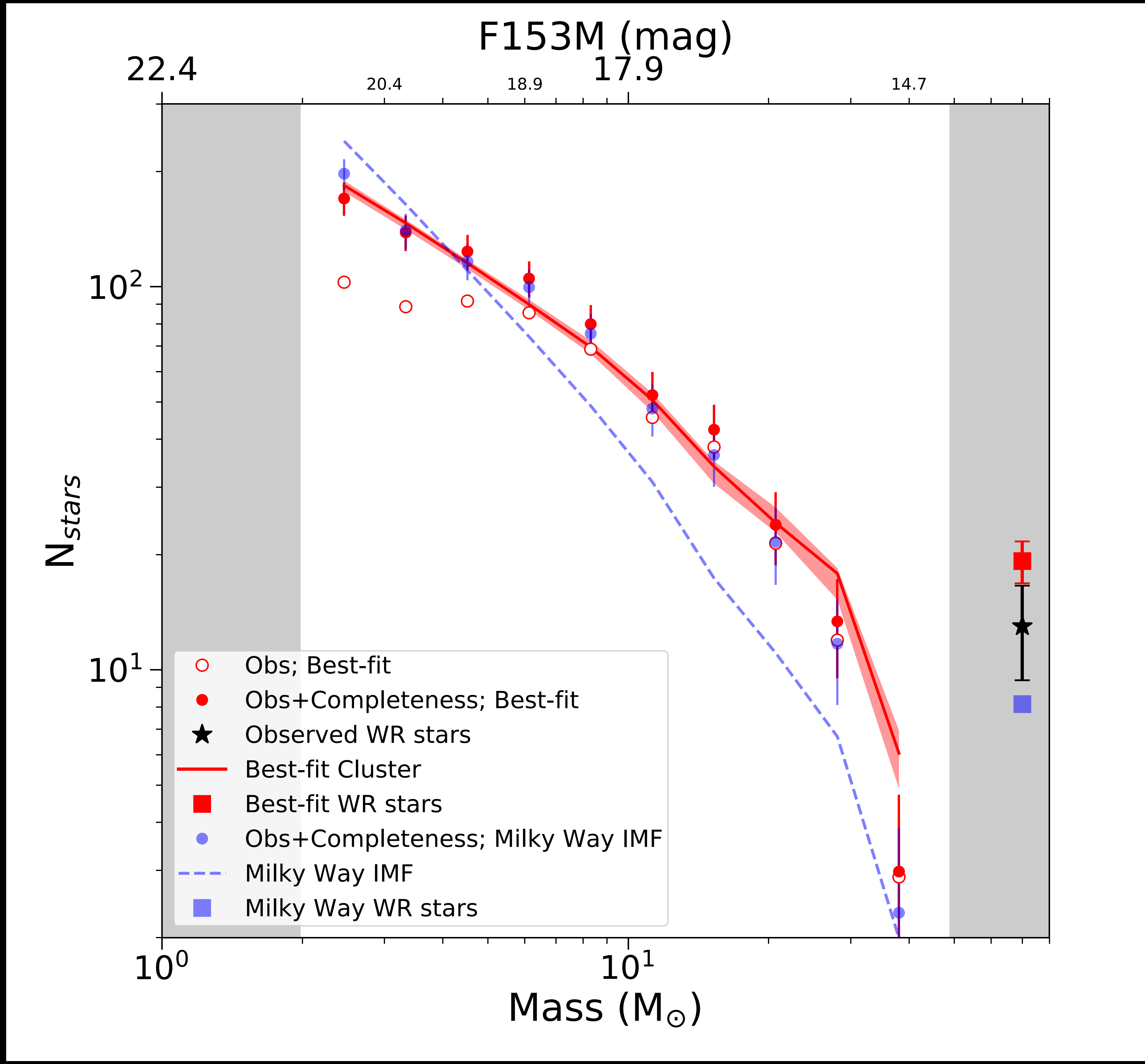
Pushing toward a broader range of environment

- Most extreme environments available for resolved star IMFs are massive clusters near Galactic Centre in Milky Way (Arches, Quintuplet, Wd 1) and 30 Doradus cluster in LMC
- Characteristics: cluster mass > 10^5 $M_\odot$, density > 10^5 stars pc^{-3}
- Can only see relatively massive stars due to confusion
- Despite caveats: tentative evidence for slightly shallower slope

IMFs in Arches and 30 Doradus



Schneider+ 2018



Hosek+ 2018

Class exercise: what are some potential problems / biases that could potentially produce a shallower IMF measurement? That is, what should we be worried about before we trust these measurements?

Unresolved stellar populations

General considerations

- IMF measurements for unresolved populations use spectral synthesis:

$$L_\nu = \int_0^\infty \dot{M}_*(t) \int_0^\infty \frac{dn}{dm} L_\nu(m,t)\, dm\, dt$$

- General problem is degeneracy between IMF and SF history — output light depends on both, so need a way to disentangle to constrain IMF
- Basic approaches:
  - Choose ν where $L_\nu \to 0$ at small *t*, so we can assume constant SFR
  - Use some proxy to calibrate out dependence on SF history
  - Choose systems where SFR has been 0 for a long time (~10 Gyr), so range of stellar ages *t* is small

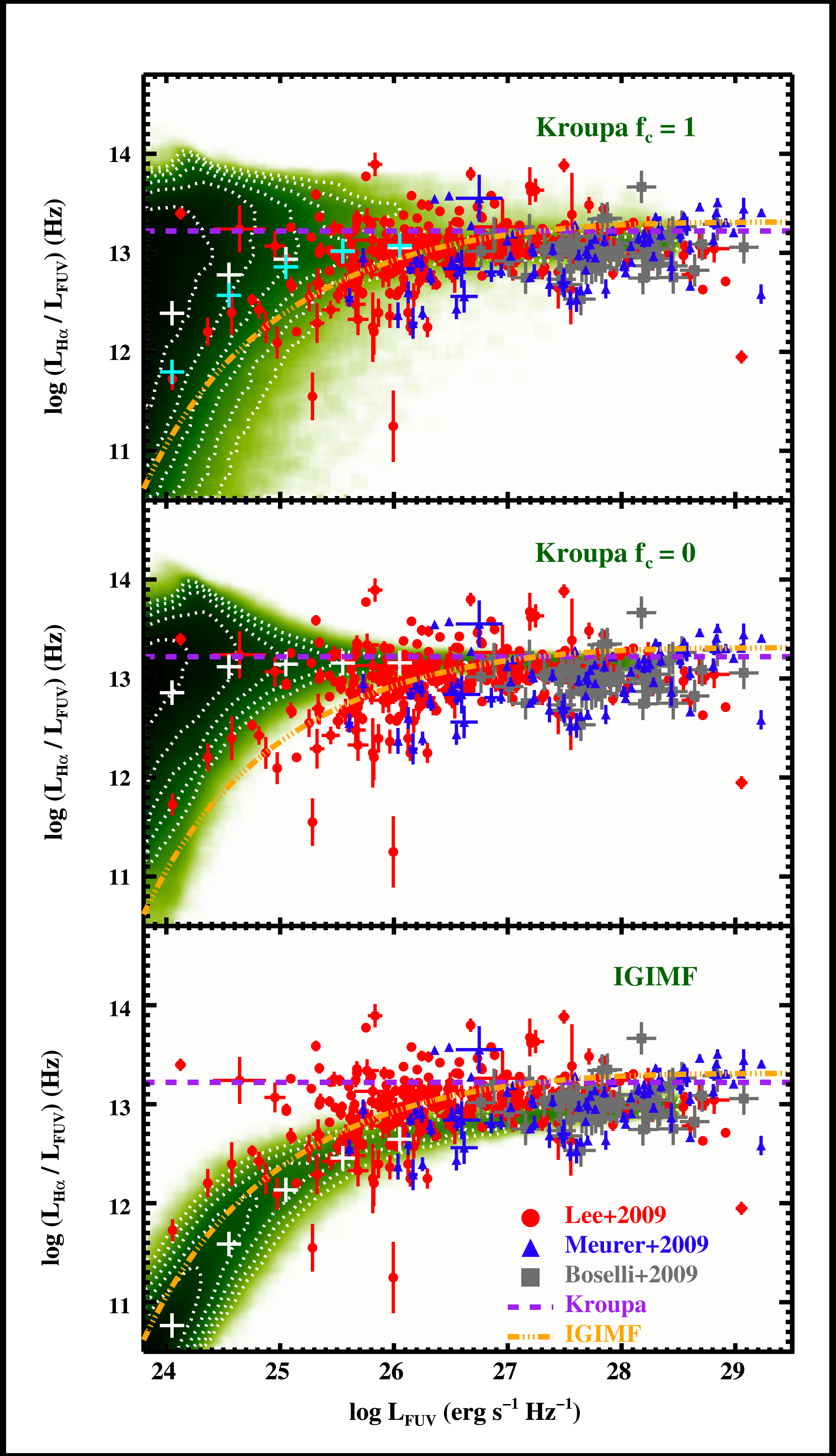
Hα-based methods

Basic idea

- Hα comes from recombination, and thus ultimately from ionising photons
- Ionising photons are predominantly produced by the most massive stars in the IMF — for a Chabrier IMF at zero age, half of ionising photons come from stars > 50 - 60 $M_\odot$
- Ratio of ionising photons to tracers of lower mass stars is sensitive to the IMF
- Timescale of Hα emission is short — ~5 Myr
- Main challenge is the tracer to which to compare Hα, since tracers of lower mass star usually integrate over longer timescale

Hα-FUV ratio method

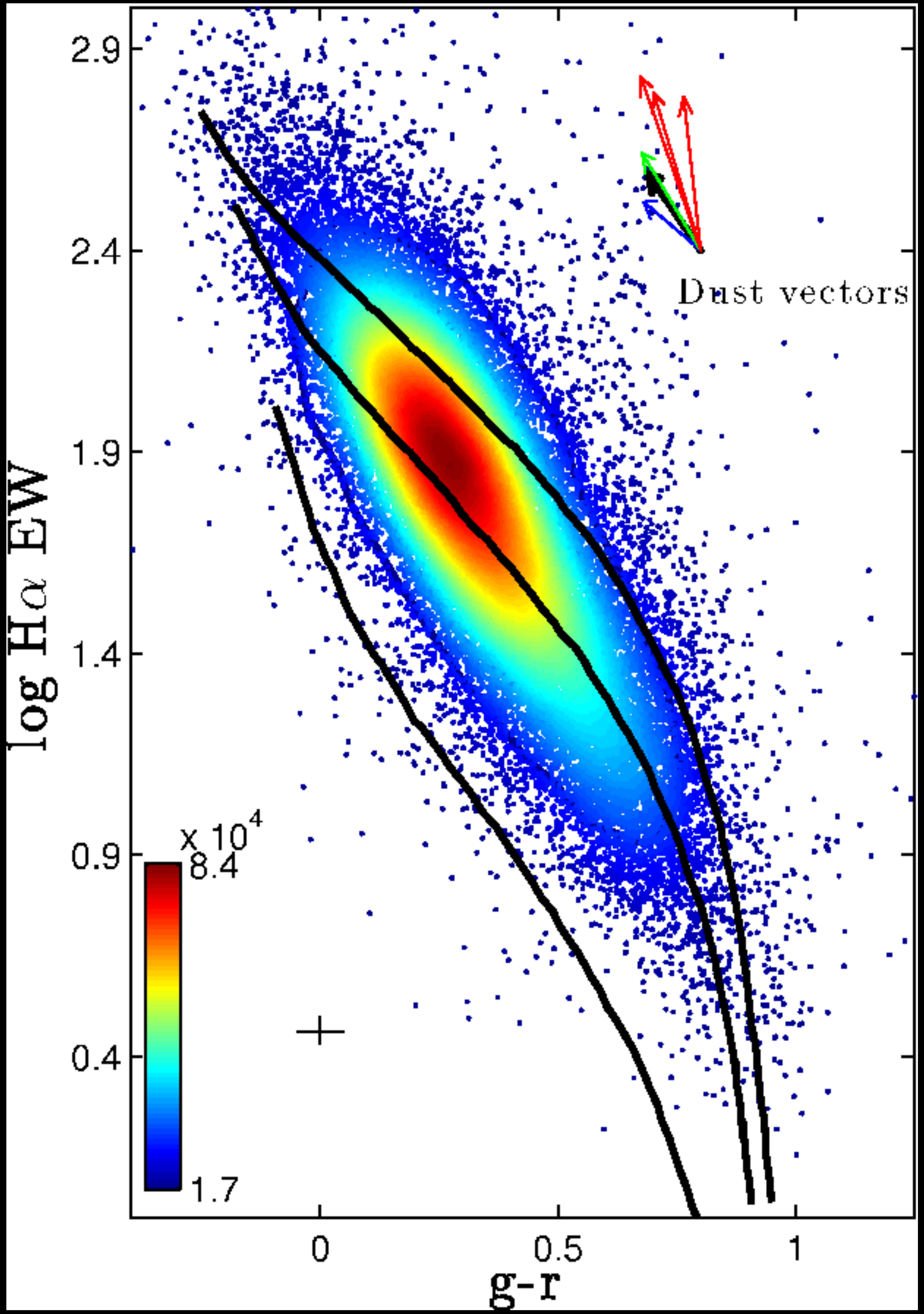
- FUV comes mainly from ~10-20 M☉ stars, so timescale is ~30 Myr — probably safe to assume constant SFR in most galaxies
- Hα / FUV therefore a proxy for ratio of > 60 M☉ stars to ~10-20 M☉ stars → IMF slope
- Hα / FUV ~ constant in spirals, but falls in dwarfs with SFR ≲ 0.1 M☉ / yr: IMF variation?
- No! At low SFR, Hα is highly stochastic due to rarity of massive stars and clustering of stars in time, so spectral synthesis needs to account for this. When it does, normal IMF fits data!



Fumagalli+ 2011

Hα-colour method

- FUV only accessible from space; from ground, can use colour as a proxy for SF history
- Hα equivalent width versus colour depends on slope of IMF *or* location of low-mass turnover — position on track depends on age of stellar population
- Published claims suggest shallower IMF or higher turnover mass for higher SFR; however, major uncertainties not yet checked:
  - Stochasticity
  - Ionising photon escape
  - Dust absorption of ionising photons



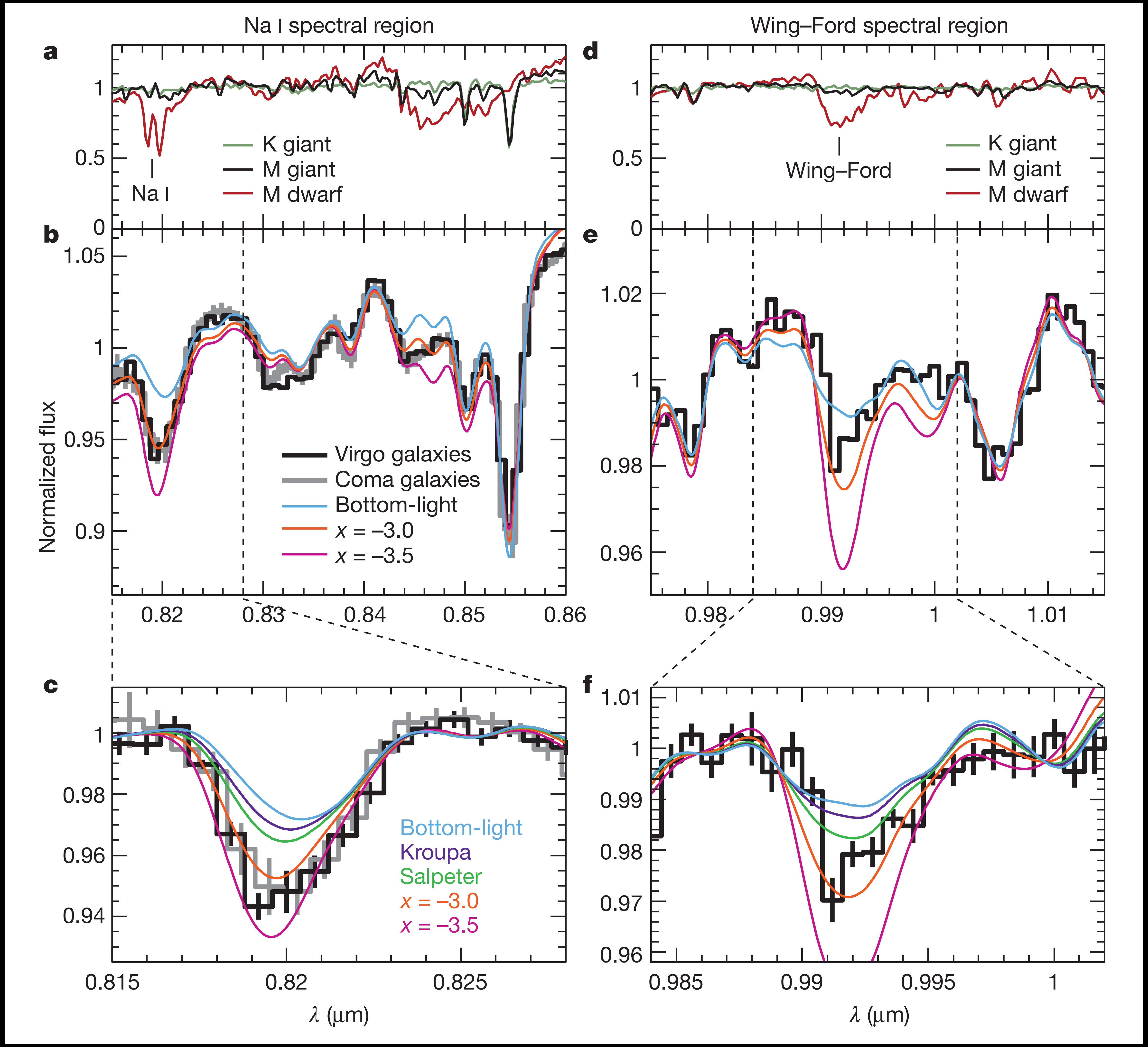
Gunawardhana+ 2011

Spectral feature methods
General considerations

- Stochasticity, and SF history in general, is a problem for star-forming galaxies
- To avoid this, can look at massive elliptical galaxies instead — these have little gas, and mostly stopped forming stars very early ($z > 2$)
- Since stars are all old, can only study low-mass part of IMF
- Light output dominated by giant stars that have left the main sequence; subject major uncertainties in spectral synthesis
- Basic idea: use gravity-sensitive features to separate dwarfs from giants, focus on dwarfs, look for IMF-sensitive features in them

M vs. K dwarfs

- Na I, Fe-H, Ca II, TiO_2 features separate dwarfs and giants
- Features appear in M dwarfs (~0.1 $M_\odot$) but not K dwarfs (~0.3 - 0.5 $M_\odot$), so depth of feature in integrated spectrum measures position of IMF peak / slope in region of peak
- Observations favour IMF peak at lower masses / steeper slope in ellipticals with higher velocity dispersion
- Caveat: spectral features calibrated from MW sample, but abundances in MW do not match ellipticals



van Dokkum & Conroy 2010

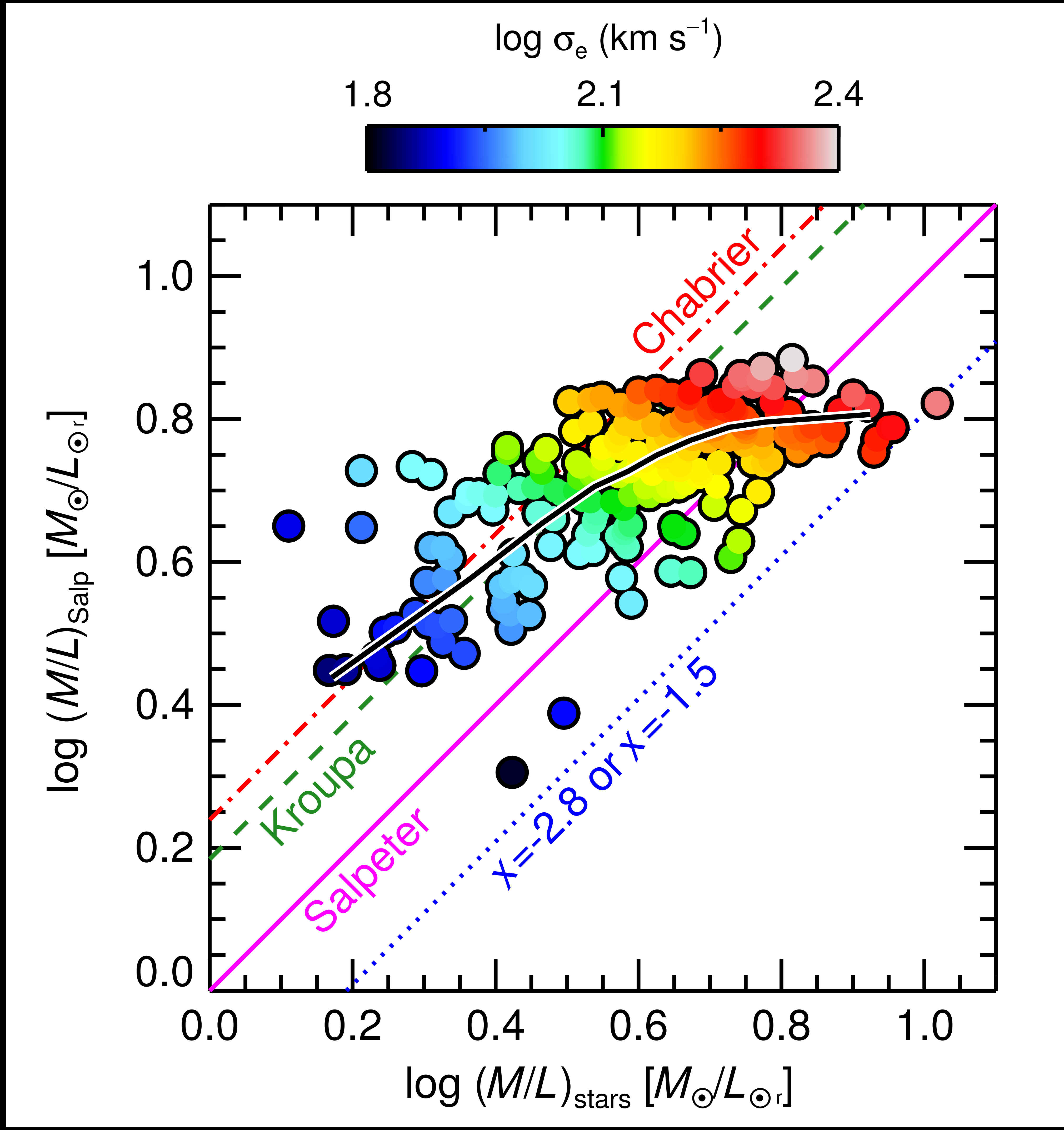
M/L methods

General idea

- Measure ratio of mass to luminosity in some broad band, compare to predicted value for a given IMF
- Luminosity is easy to measure; M/L in a broad band for a given IMF is easy to predict, much fewer uncertainties than spectral features
- Hard part is measuring mass. Two basic approaches:
  - Jeans (orbit) modelling
  - Gravitational lensing
- Target centres of ellipticals, where mass is dominated by stars, to avoid uncertainties on dark matter

IMF from M/L

- Results from lensing + Jeans analysis both suggest higher M/L in ellipticals with higher velocity dispersion
- Broadly consistent with spectral result, since higher M/L → lower IMF turnover mass
- However, poor agreement on a galaxy-by-galaxy basis — two methods sensitive to somewhat different radii in galaxy
- Effect is fairly small: factor of ~2 in M/L



Cappellari+ 2013

Final notes

- There is some tension between the elliptical results and the massive cluster / high-SFR results:
  - Stars we see in ellipticals today formed at very high SFR, probably formed massive clusters — so if these environments lead to an IMF with more massive stars, why do ellipticals seem to have fewer massive stars?
- In general, history of the field suggests that claims of IMF variation should be treated with extensive skepticism: number of abandoned / retracted claims ≫ number of still-viable claims
- Editorial viewpoint: I consider the elliptical work much more credible than the star-forming galaxy work, with the cluster work in between

Exercise: consider two stellar populations, one with IMF slope –2.3 from 0.1 - 1 $M_\odot$, one with slope –1.3 from 0.1 - 0.5 $M_\odot$ and –2.3 from 0.5 - 1 $M_\odot$. By what factor do their M/L ratios differ (approximately)?