

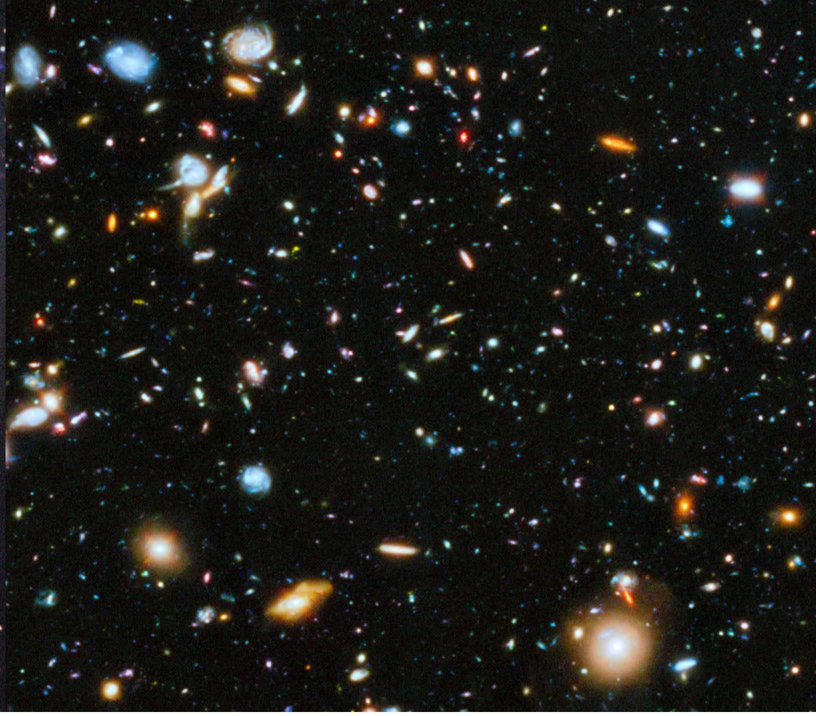

Measuring the Stellar Initial Mass Function

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IMF measurement approaches

- **Stellar:** Directly measuring star counts and luminosity functions, calculating mass function from mass-luminosity relations, accounting for stellar evolution and dynamical evolution.
- **Galaxy:** Stellar population synthesis (SPS) models compared to observed metrics, such as the Kennicutt method (Kennicutt 1983, ApJ, 272, 54), the Buat method (Buat et al., 1987, A&A, 185, 33), the "dwarf-to-giant" ratio method, and mass-to-light ratio methods.
- **Cosmic:** Requiring self-consistency between luminosity and mass densities of galaxy populations.
- **Chemical abundances:** Yields from SNe enrich subsequent stellar generations, and abundance measurements in stars can be used to infer the historical IMF. This can be a probe of each of the above, but is perhaps most relevant to a Galaxy IMF.

The IMF vs astrophysics

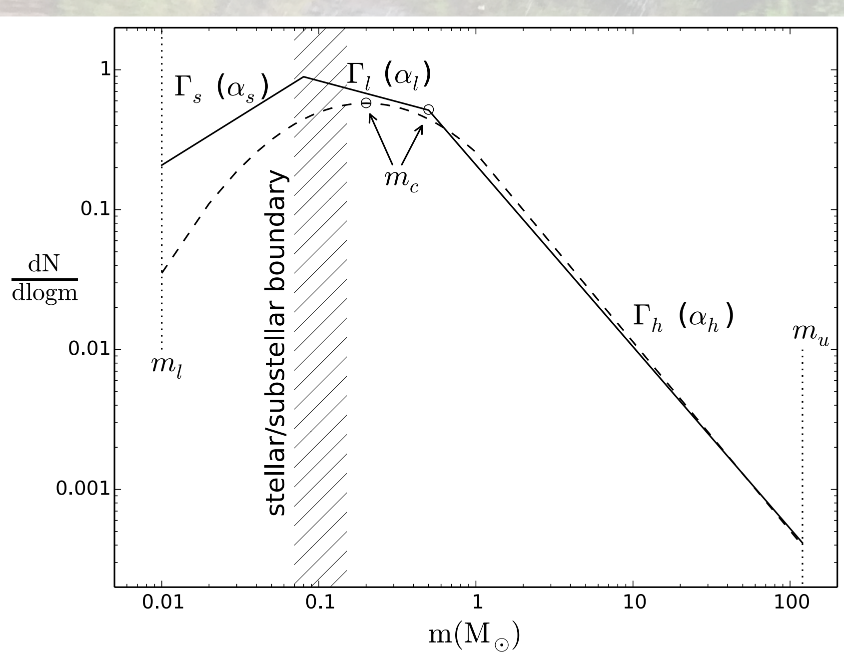
- I focus here on the IMF as measured (or rather, inferred) by various observational approaches.
- There is a difference between whether the ***IMF*** is universal, and whether there is a universal ***physical process*** that produces an IMF. This distinction is important.
- A universal IMF may be produced by a universal physical process, but ***a universal physical process doesn't necessarily lead to a universal IMF*** (e.g., Narayanan & Davé 2012, MNRAS, 423, 3601; Hopkins 2013, MNRAS, 433, 170).
- There continues to be an important question, not addressed here, around the underlying physical processes driving star formation, and whether or not they may be different at different epochs or in different environments.

Conventions and terminology can be ambiguous

$$\frac{dN}{dm} \propto \left(\frac{m}{M_\odot}\right)^{\alpha}$$

$$\frac{dN}{d\log m} \propto \left(\frac{m}{M_\odot}\right)^{\Gamma}$$

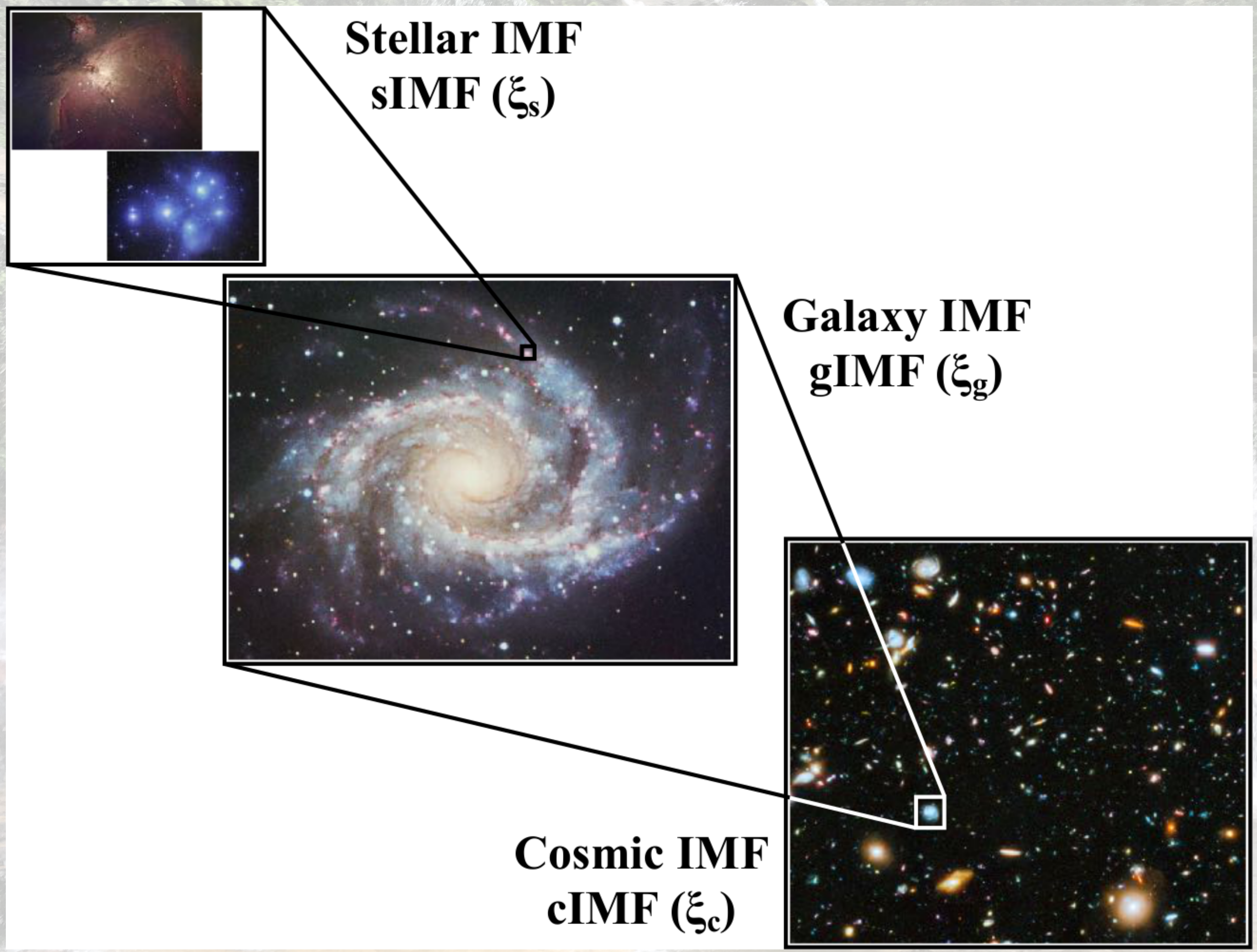
$$\Gamma = \alpha + 1$$



- Whether or not the negative sign is included in the exponent, so the Salpeter slope is given either as α =−2.35 or α =2.35.
- Using alternative symbols (x or γ instead of α for example). Also, using the same symbol to mean different things.
- Whether or not the mass limits are specified.
- Shape descriptions: flat/steep, upturn/downturn, turnover.
- Variation descriptions: top heavy, bottom heavy, bottom light, heavyweight, dwarf-rich.

Hopkins 2018, PASA, 35, 39

A consistent approach



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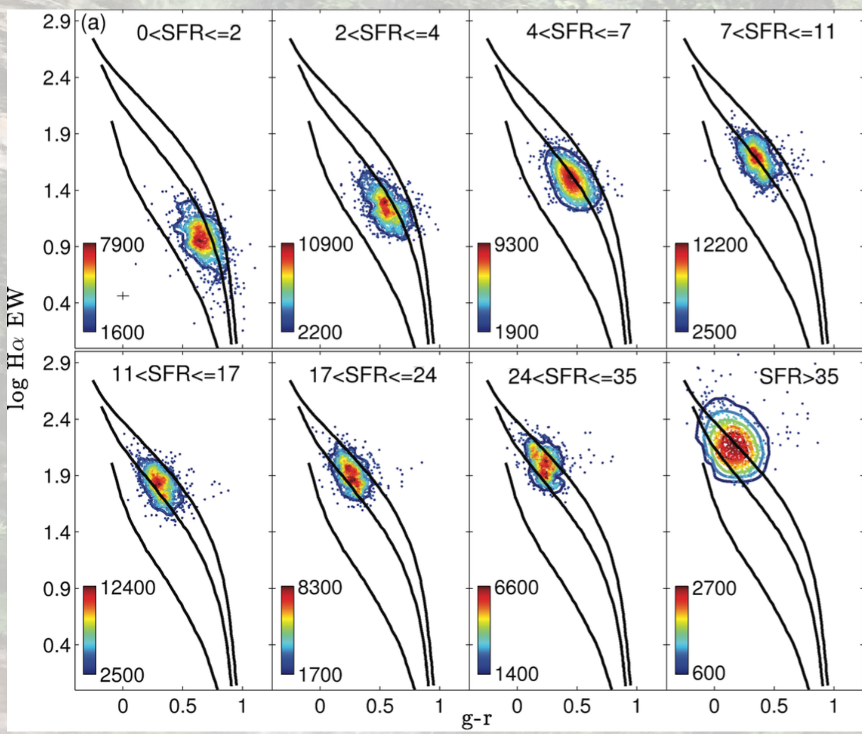
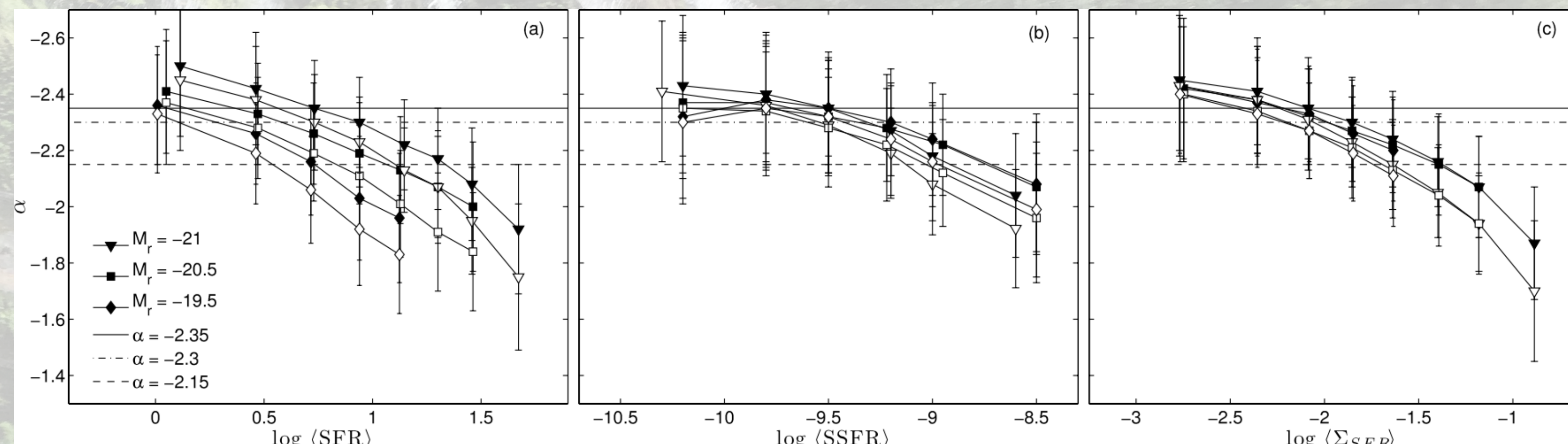
IMF of galaxies: Star forming galaxies

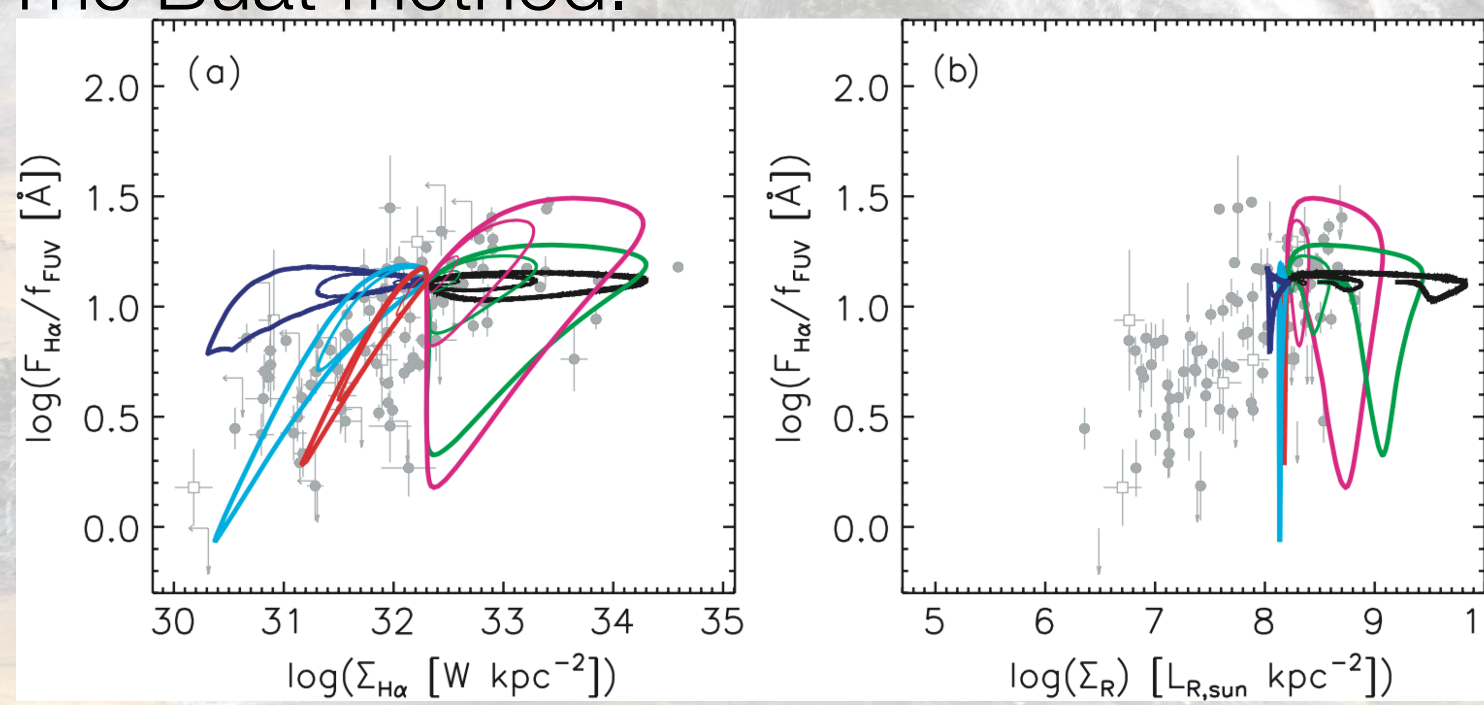
The Kennicutt method.





Gunawardhana et al., 2011, MNRAS, 415, 1647

The Buat method.



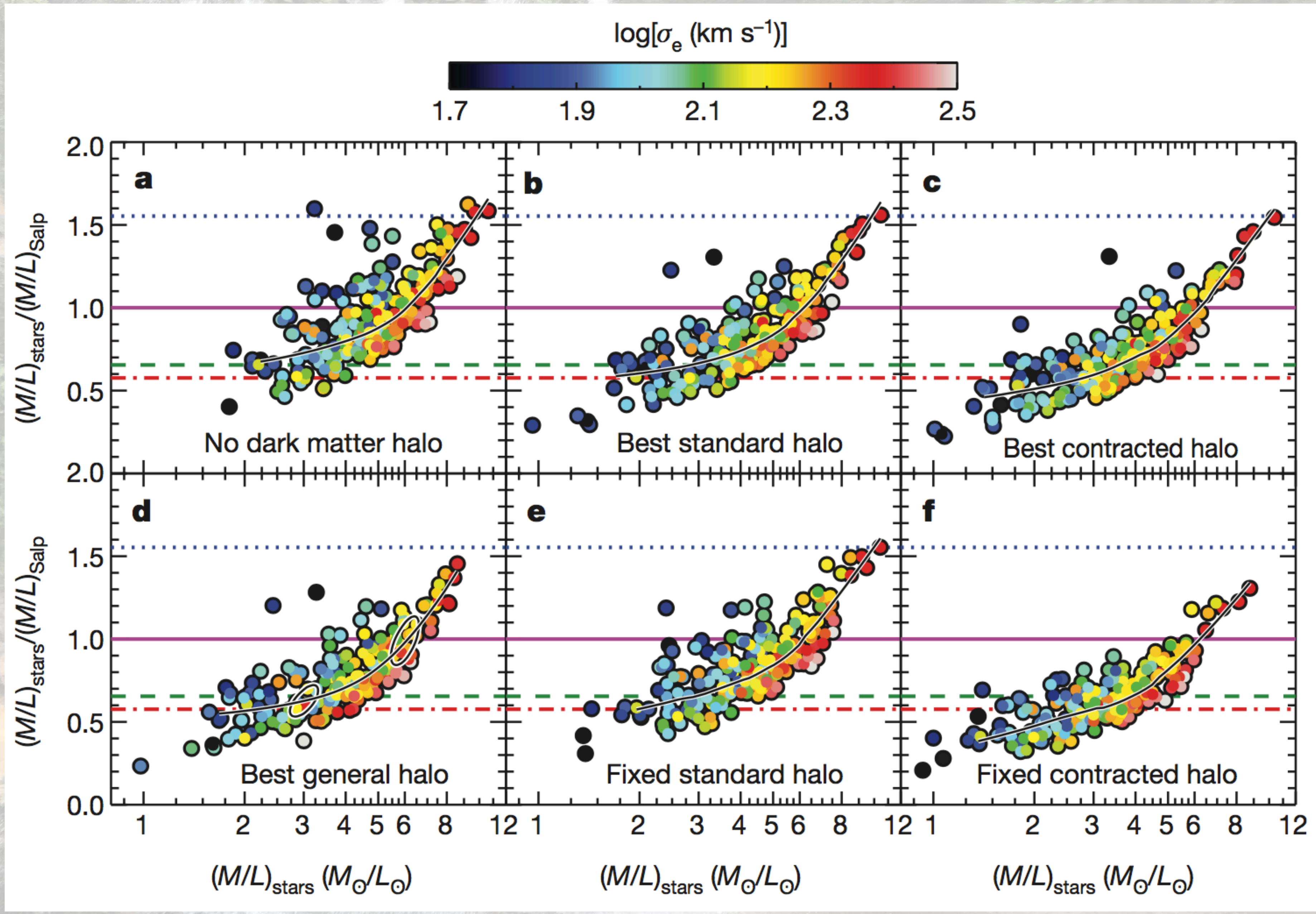
Meurer et al., 2009, ApJ, 695, 765

Star forming galaxies have more positive (flatter) high-mass IMF slopes (a relative excess of high-mass stars)

IMF of galaxies: Passive galaxies

Kinematic methods:

ATLAS3D

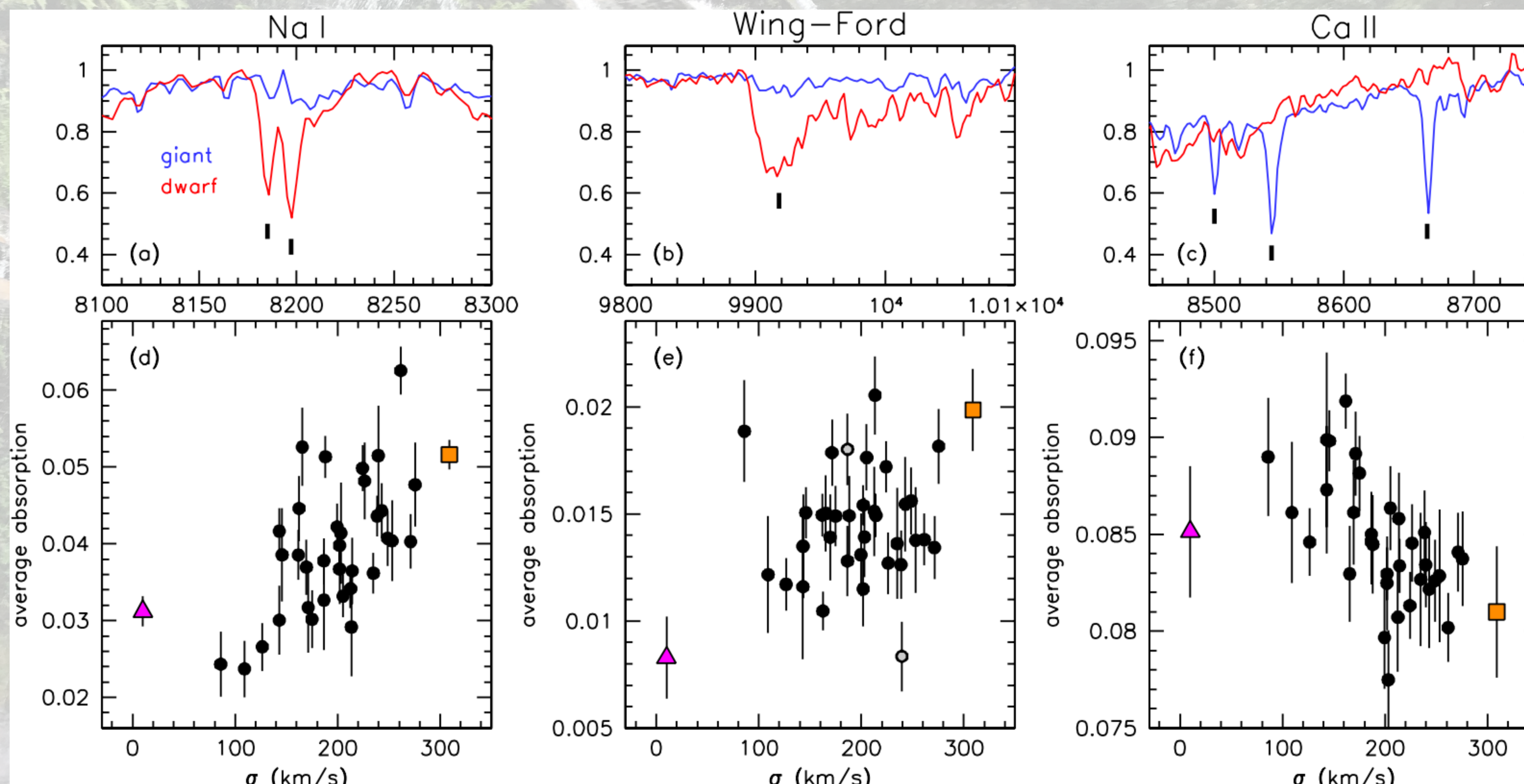


Cappellari et al., 2012, Nature, 484, 485

Passive galaxies have more negative (steeper) low-mass IMF slopes (a relative excess of low-mass stars)

IMF of galaxies: Passive galaxies

Dwarf-to-giant ratio method:

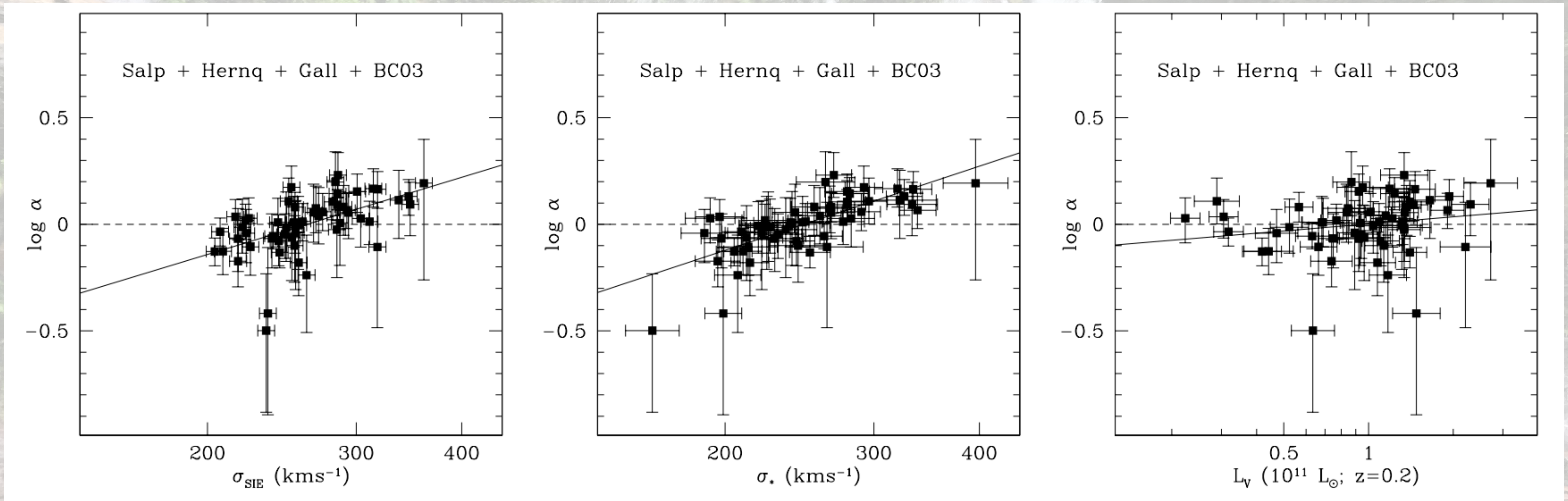


van Dokkum & Conroy, 2012, ApJ, 760, 70

Passive galaxies have more negative (steeper) low-mass IMF slopes (a relative excess of low-mass stars)

IMF of galaxies: Passive galaxies

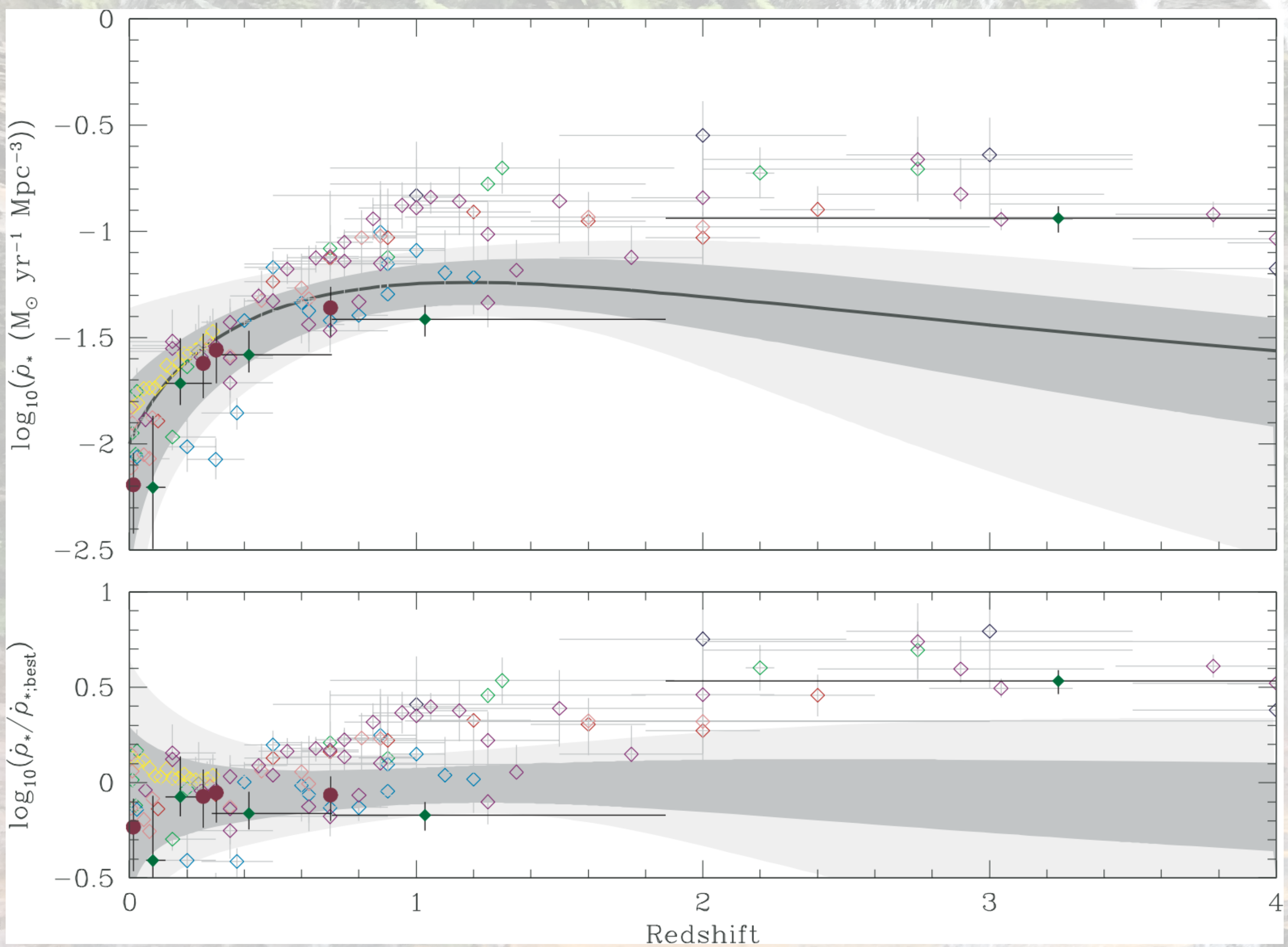
M/L methods:



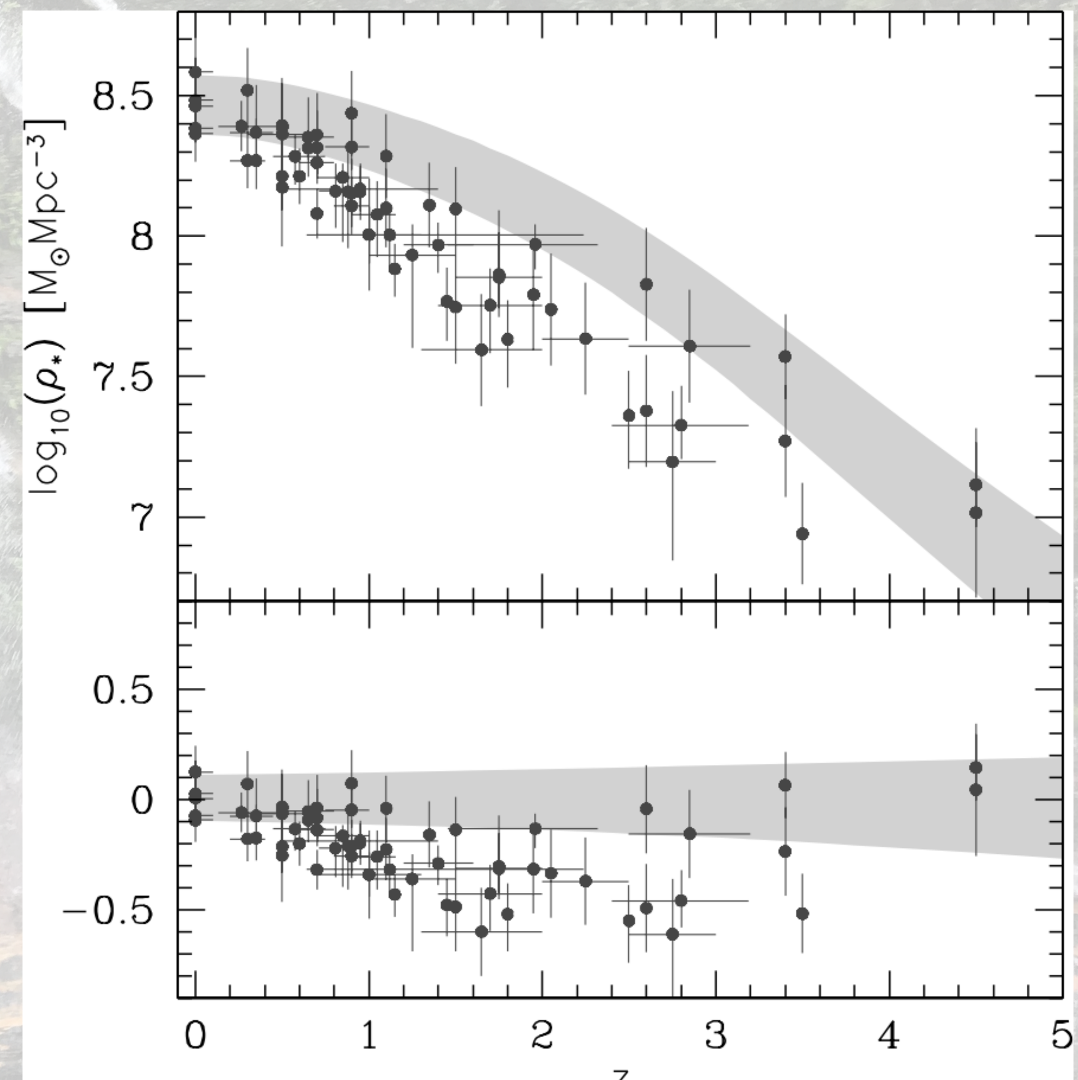
Treu et al., 2010, ApJ, 709, 1195

Passive galaxies have more negative (steeper) low-mass IMF slopes (a relative excess of low-mass stars)

IMF from cosmic census measurements



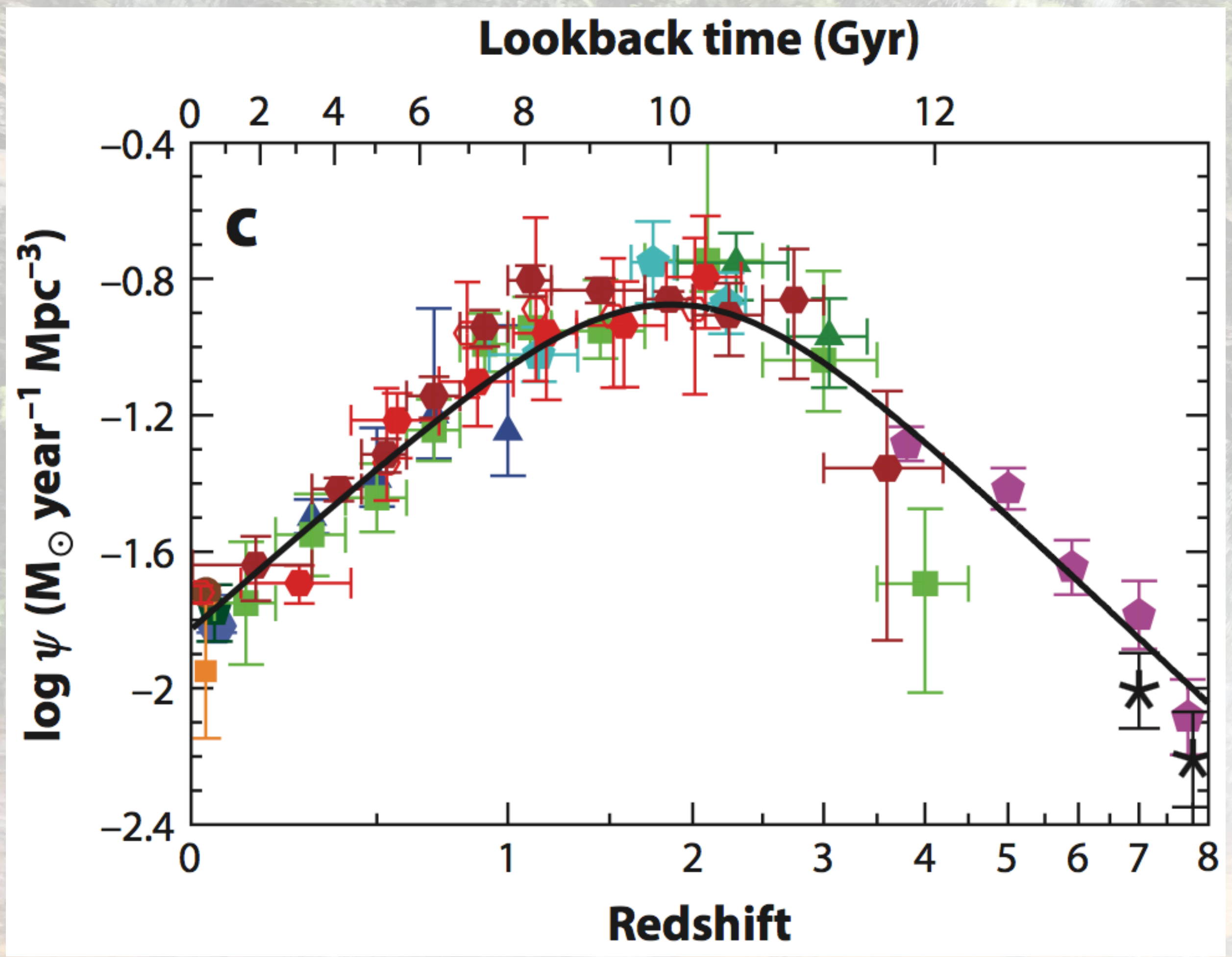
Wilkins et al 2008, MNRAS, 385, 687

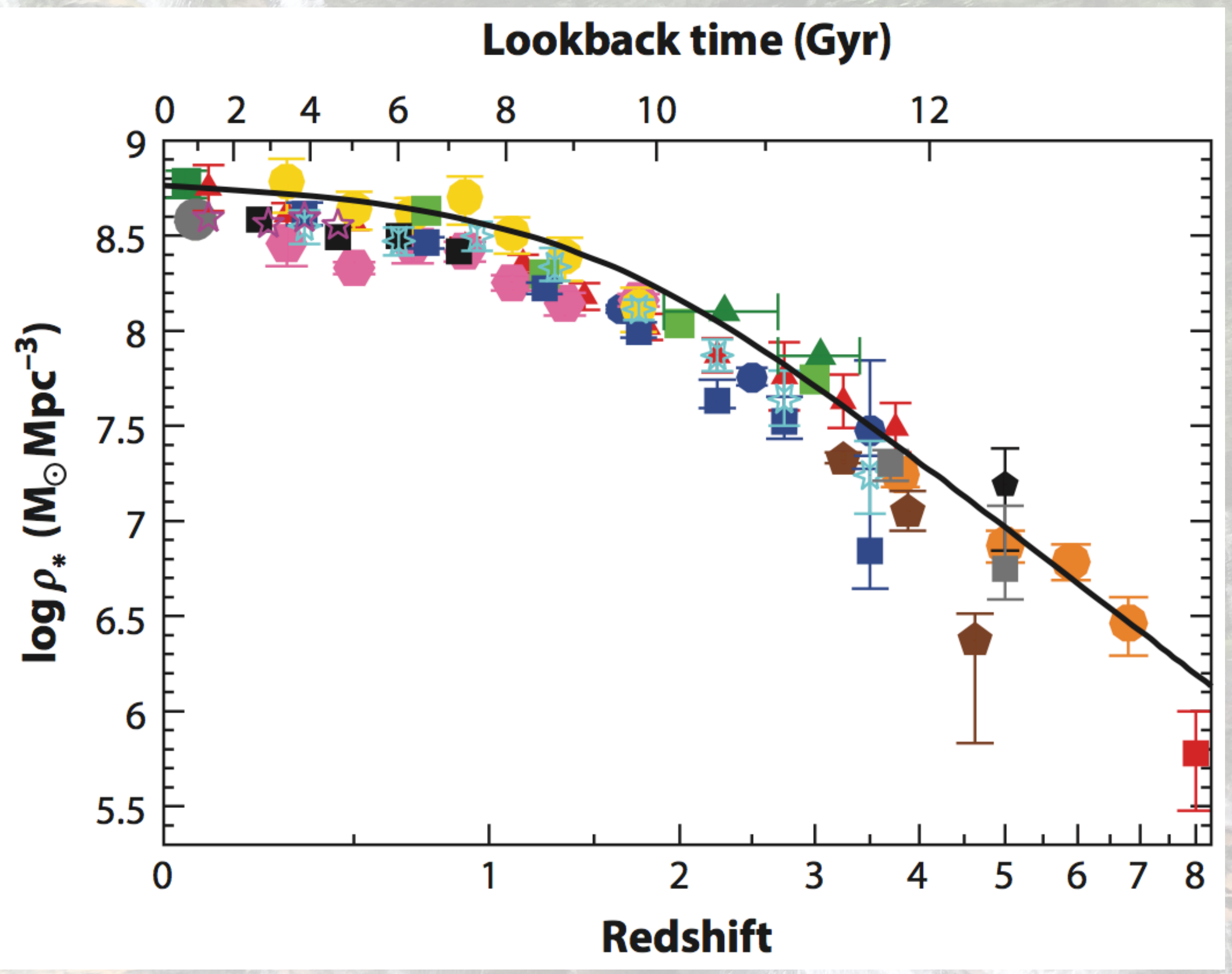


Wilkins et al 2008, MNRAS, 391, 363

- Even the $\alpha_h=-2.15$ (“top-heavy”) Baldry & Glazebrook IMF does not completely resolve the discrepancies.
- This implies a **need for an evolution in the IMF** high-mass slope.

IMF from cosmic census measurements

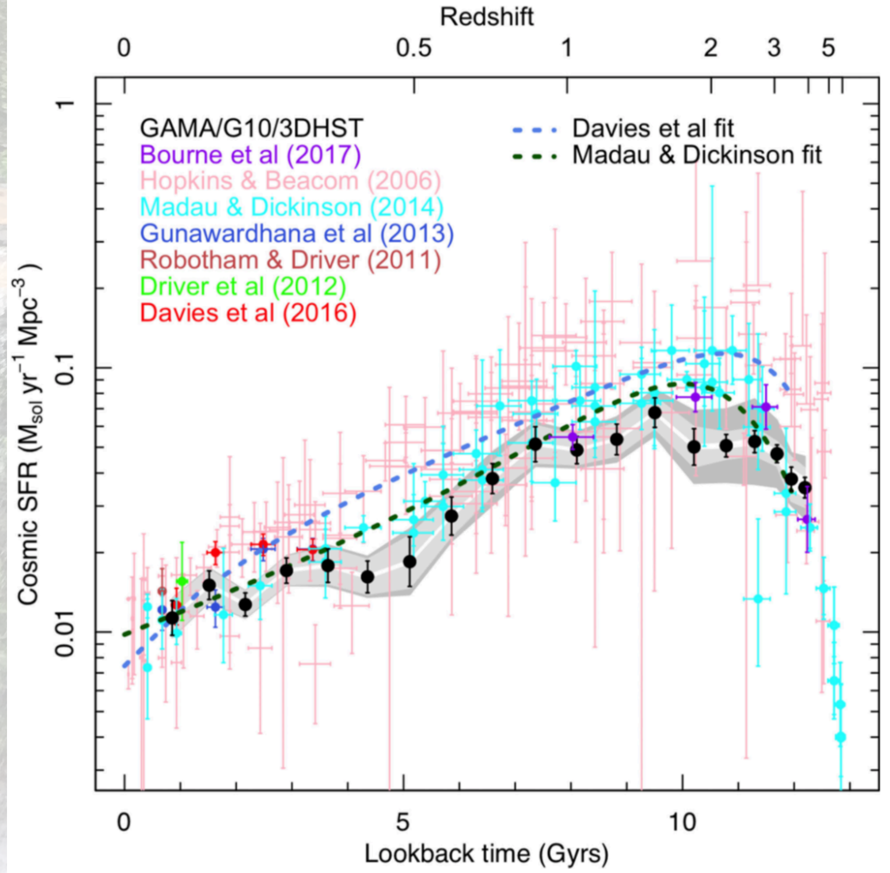


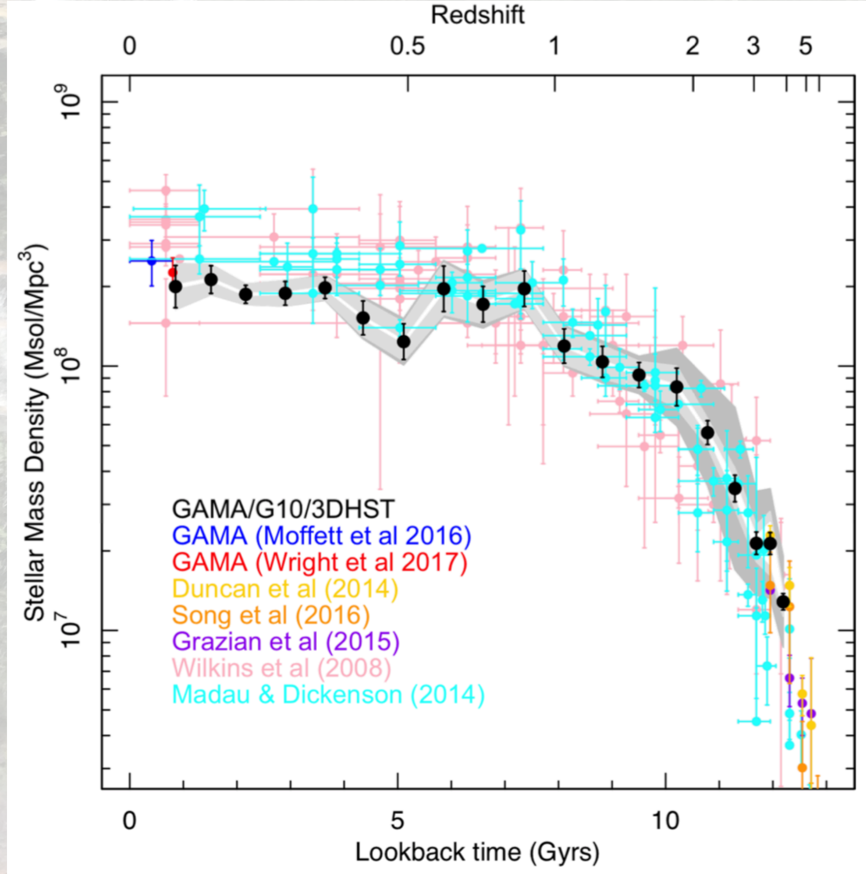


Madau & Dickinson 2014, ARA&A, 52, 415

- Uses a Salpeter IMF ($0.1 < m/M_\odot < 100$), and claims that typical MW IMFs reduce the residual discrepancy from 0.2 to 0.1 dex in the SFH/SMD constraint.
- But omits some z~1-2 SFH measurements that are higher, and more recent SFH measurements at high-z may also be higher.

IMF from cosmic census measurements





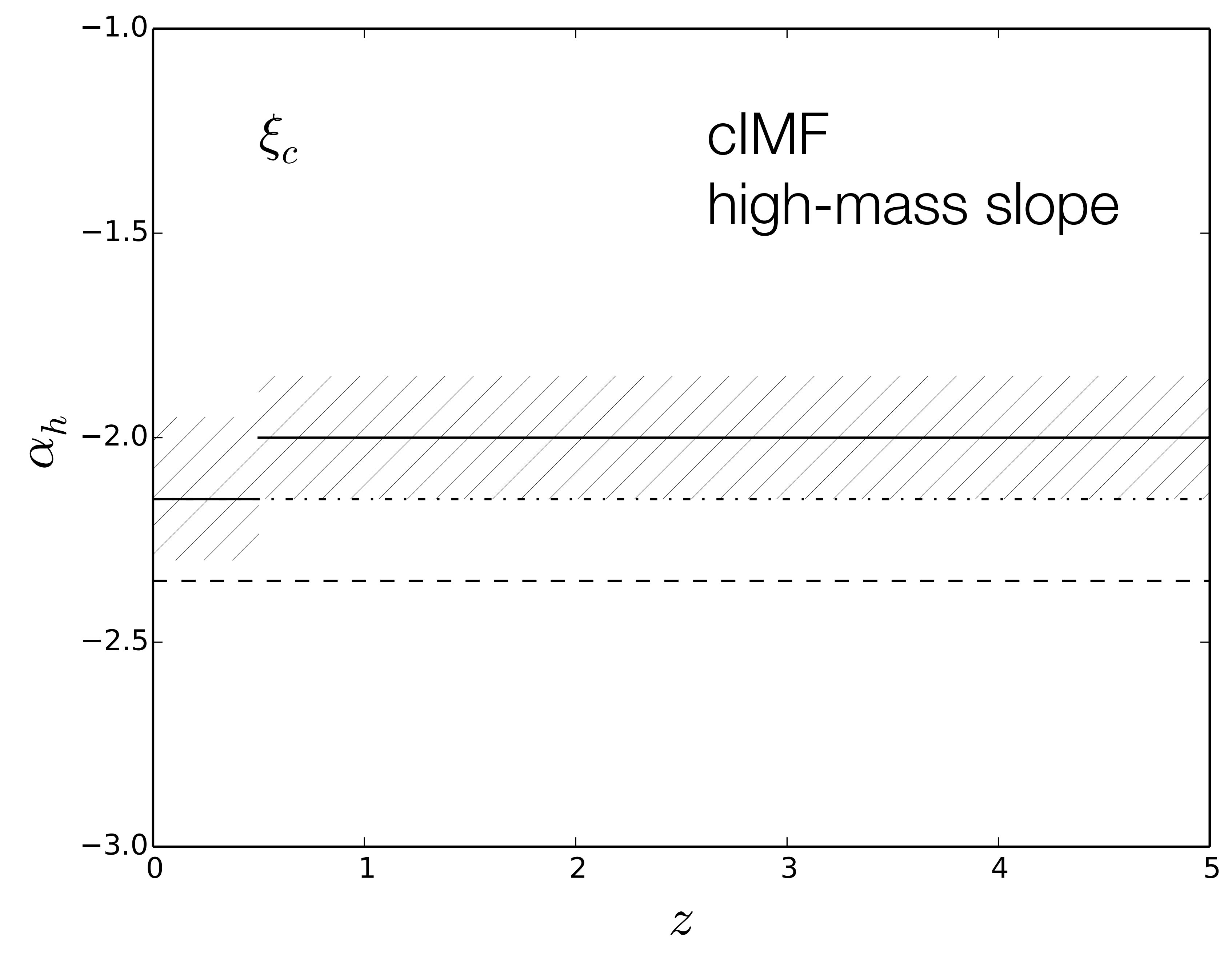
Driver et al., 2018, MNRAS, 475, 2891

- Uses a Chabrier IMF (0.1<m/M$_\odot$<100), and MAGPHYS fitting to almost 600,000 galaxies from GAMA, G10-COSMOS, and 3D-HST.
- Now appears marginally underestimated at low-z, although they note a likely cosmic variance explanation for the dip seen at z~0.5.
- Chruślińska et al (2020, A&A, 636, A10) apply the IGIMF approach, and find ***the total SFRD is decreased with respect to the universal IMF case at all but very low redshifts***; the difference increases towards high redshifts and remains within a factor of approximately two.

So where does that leave us?

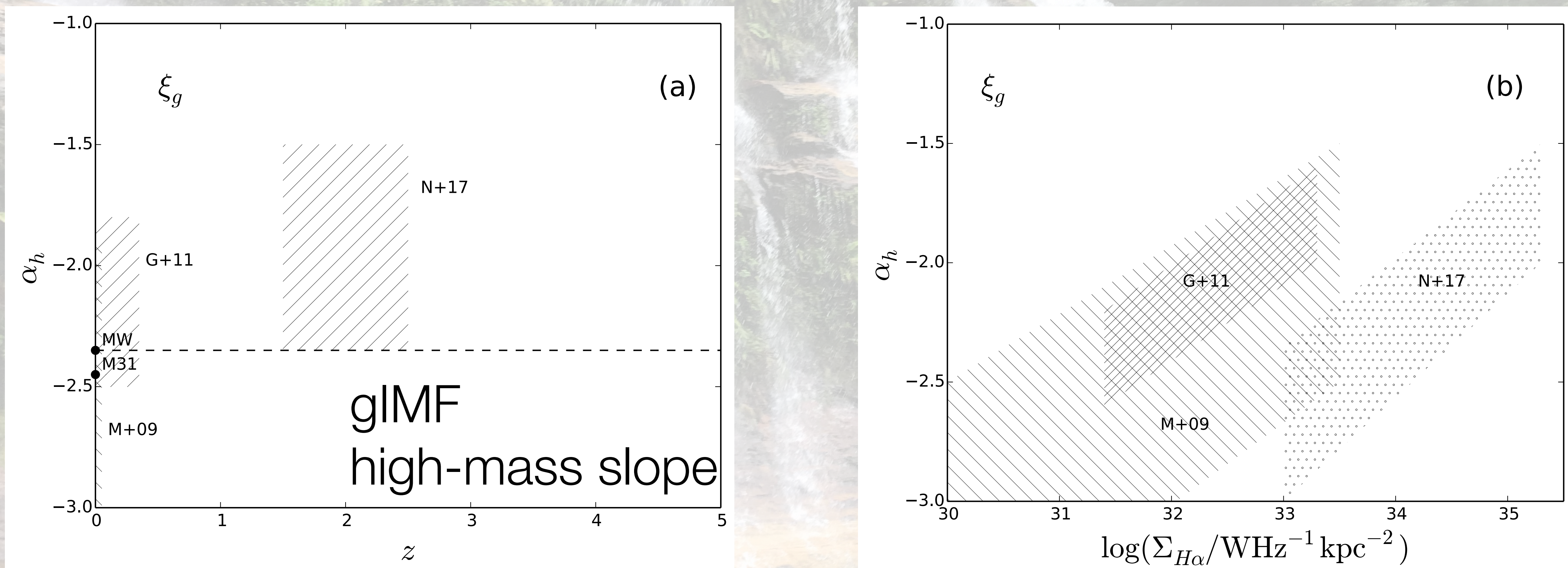
- The sIMF seems to show some degree of variation between galaxies (M31, M83, LMC, SMC) and in extreme star forming regions.
- The gIMF appears dramatically different between star forming and passive galaxies, although the methods are different and have not been tested self-consistently.
- The cIMF shows hints of evidence for evolution.
- This suggests that recasting the question as “How much does the sIMF/gIMF/cIMF vary?” rather than “Does the IMF vary?” is a necessary step forward.
- The challenge is in ensuring well-defined physical quantities, and well-posed questions. “Is the IMF universal?” is not well posed, since “IMF” is not well-defined. Differentiating the sIMF, gIMF, cIMF is an important step toward resolving this issue.
- Techniques such as Kroupa’s IGIMF approach can be applied in this framework to link the sIMF, gIMF, cIMF through an underlying model.

New IMF diagnostic diagrams



Hopkins 2018, PASA, 35, 39

New IMF diagnostic diagrams



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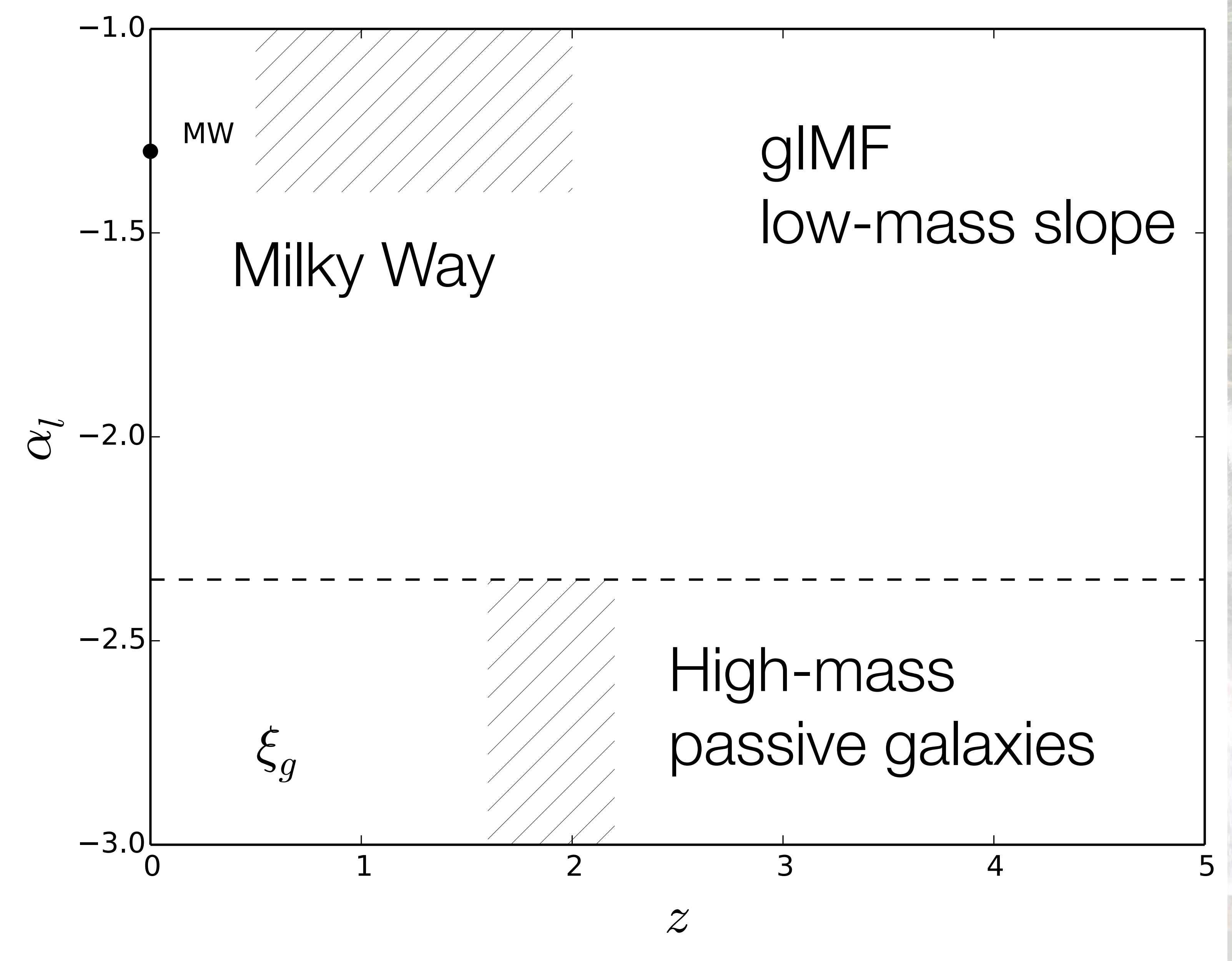
New IMF diagnostic diagrams



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Summary

- The puzzle of the stellar initial mass function is real. It is a complex challenge and has triggered a substantial and growing amount of research in the past decade.
- Existing work has established a broad range of observational constraints, observational and theoretical tools and physical insights, but still leaves us with many apparent inconsistencies.
- We need the conversation to move on from "Is the IMF universal?" to "How much does the sIMF/gIMF/cIMF vary?" and to rigorously quantify random and systematic uncertainties to address this.
- There is scope for SPS/SED modelling tools to be refined and extended in order to self-consistently test and compare different IMF metrics, and perhaps identify new ones.
- It is important to explore models, such as the IGIMF, to explain observed differences between measured IMFs, but the observations need to be well defined (sIMF? gIMF? cIMF?), unambiguously presented (mass ranges? IMF parameterisation?), and with robustly estimated uncertainties, to ensure any models are not misled.

So, IMF: universal or not?

- **If universality is assumed, it can never be demonstrated.**
- Set aside for the moment that the question is poorly posed. Assuming the "IMF" is universal ironically rules out the capability to identify that it is, only that it is not (by observations that unambiguously falsify the assumption).
- A "universal" assumption or mindset (preconception) means that any discrepancies with data will tend to be dismissed as observational error, astrophysical systematics that are hard to correct for, unreliable data, or other special pleading. This merely leads to reinforcing the preconception rather than any new insight.
- If there are IMF variations, they can only be measured with tools and techniques established with variations in mind, and implemented in a self-consistent fashion.
- If there are no variations, the same tools can be used to place ever tighter constraints, that now provide quantitative evidence, around a putative "universal" IMF. ***Therefore moving to the default assumption that the IMF may vary is the most productive way to make progress.***