The low-mass IMF: a review and an illustration of future prospects with *JWST* (*and Roman !*)

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Motivation

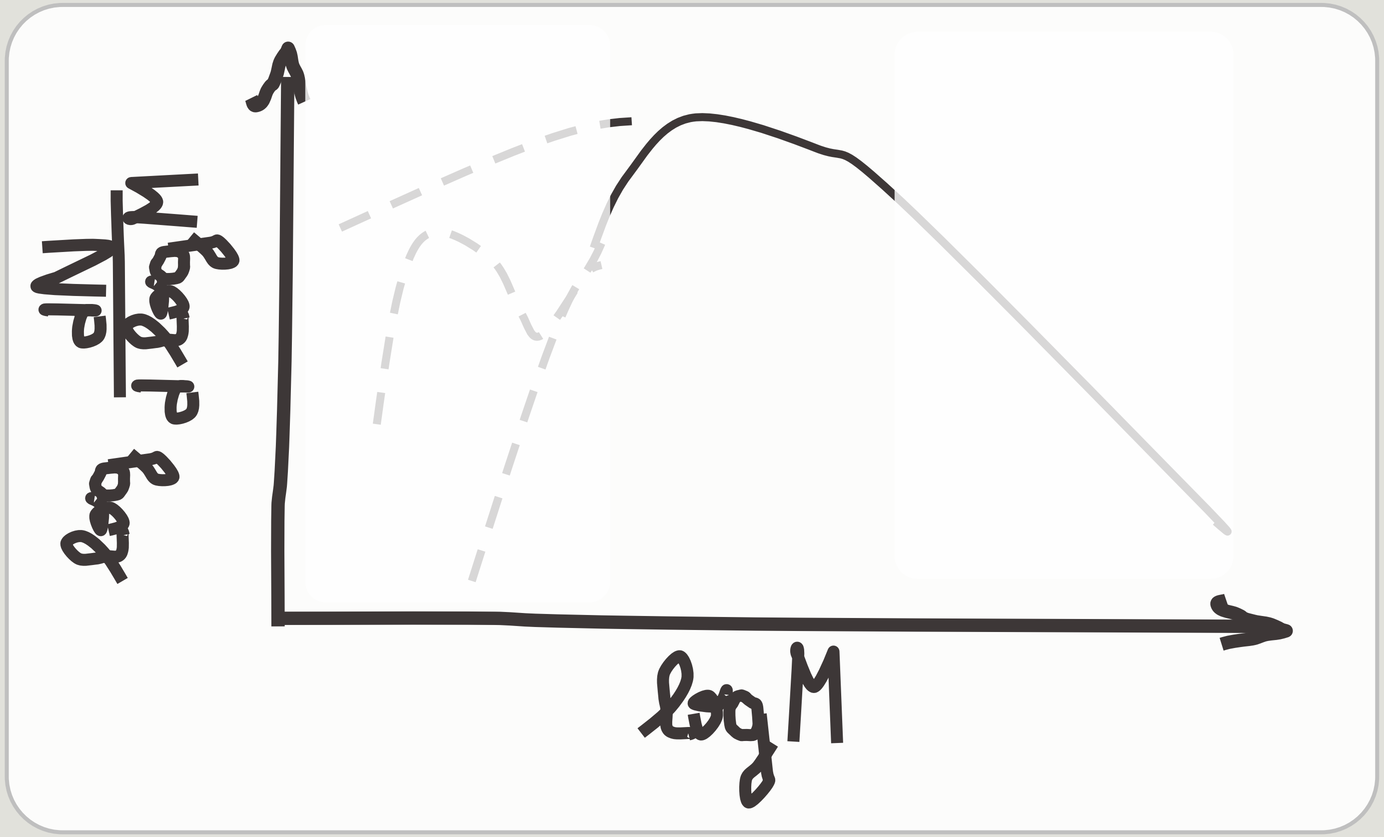
The Initial Mass Function (IMF) is a fundamental outcome of the process of star formation

It can be measured (directly or indirectly), thus provides a very important test for theories of star formation

It is an "ingredient" for many, diverse astronomical studies:

- Counting habitable planets
- Supernovae / mergers / feedback
- Cycle of metals
- Galaxy evolution

THE LOW-MASS STELLAR REGIME

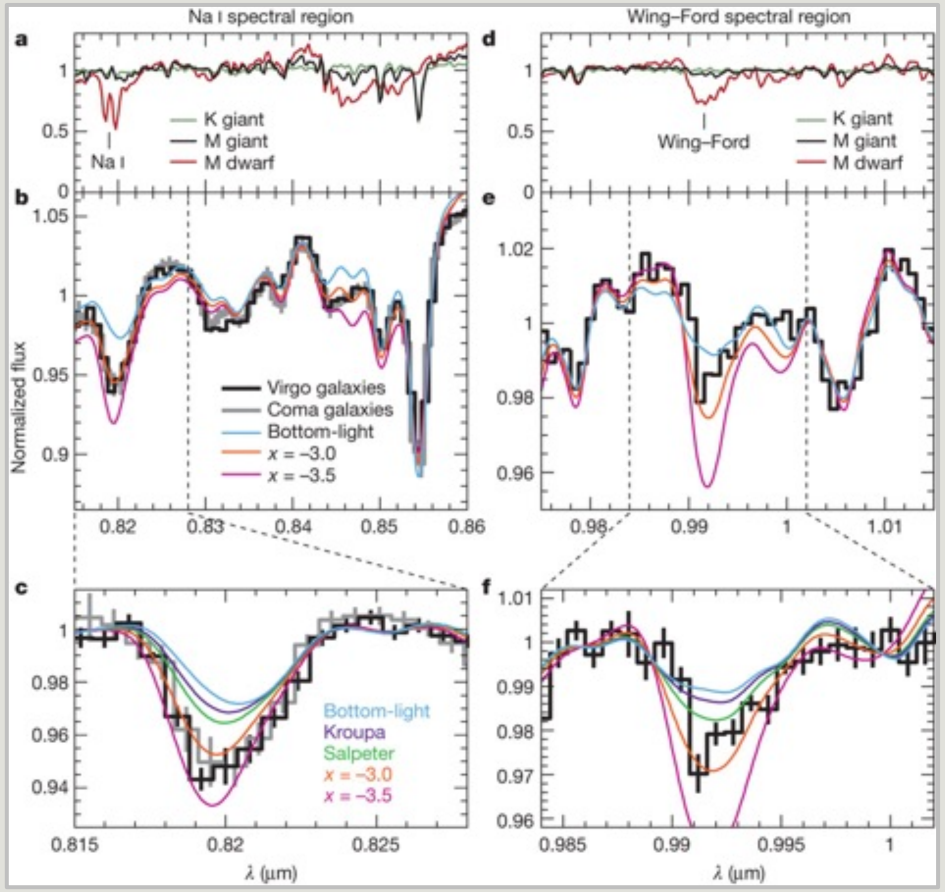


- Peak / characteristic mass / break mass (broken power law model)
- This is the region where most of the stellar mass is
- This region can be probed directly in Milky Way satellites

OBSERVATIONAL EVIDENCE

- **Universality in our Galaxy (disk, clusters, Bulge) and "in general"**
  - 2010 Review by Bastian, Covey, Meyer

- **Evidence of variations in Giant Ellipticals**
  - Integrated light + dynamics (Cappellari et al., 2012)
  - Spectra, e.g. Wing-Ford, NaI dwarf-sensitive features (van Dokkum, Conroy, several papers)
  - Caveats of methodology (Smith, 2020; Maraston et al. 2020)



Expected Variations of the Low-Mass IMF

Possible mechanisms to explain the presence of a peak at low stellar masses vs. the scale-free power law at high mass and the variations observed in giant ellipticals (Krumholz, 2014):

- **Thermal support**, $M_{peak} \sim \rho^{-1/2}\, T^{3/2}$ Larsson (1992), Bate & Bonnel (2005):
  - Not clear how to define the boundaries for computing the mean ρ, T
  - Huge variations observed even within the same molecular cloud

- **Turbulent support**, $M_{peak} \sim M_J / (v_T/c_s)$
  - If one thinks of turbulence as a cascade down from galactic scales: $M_{peak} \sim c_s^4 / \Sigma$ (Hopkins, 2013)
  - c_s and Σ increase with star formation intensity → fine-tuning to explain IMF in ellipticals

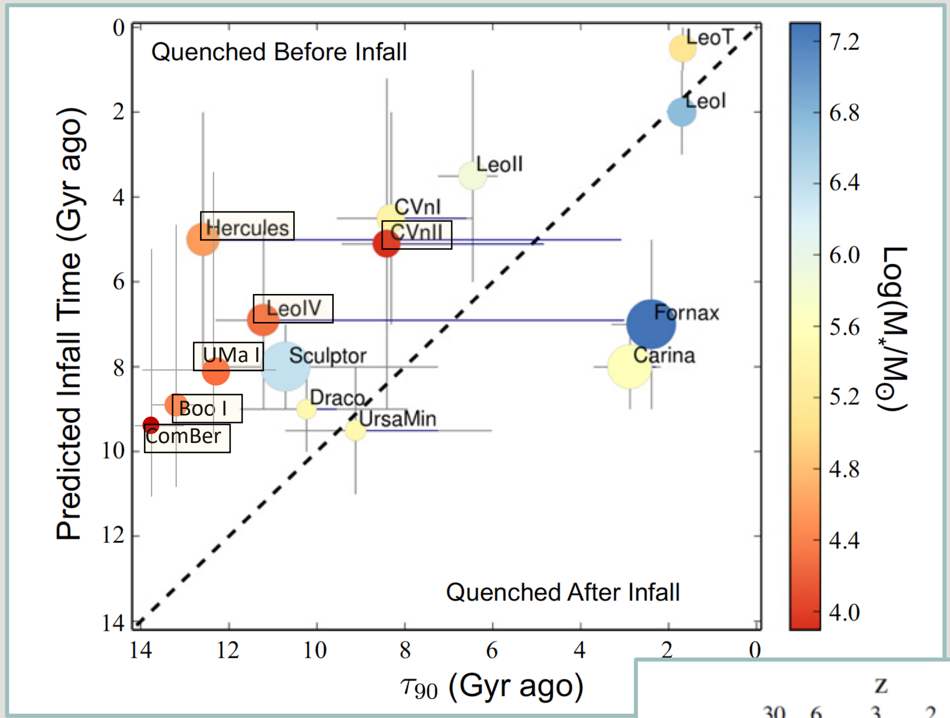
- **Protostellar radiative feedback** (self-regulated, local M_J)
  - Very weak dependence on cloud conditions $\rho^{-1/9}$ (Bate, 2009), $P^{-1/18}$ (Krumholz, 2011)
  - Weak dependence on metallicity (through dust opacity), M_{peak} decreases as Z increases

Exploring Environmental IMF Variations With Resolved Stellar Populations

The Case of Ultra Faint Dwarf (UFD) Galaxies

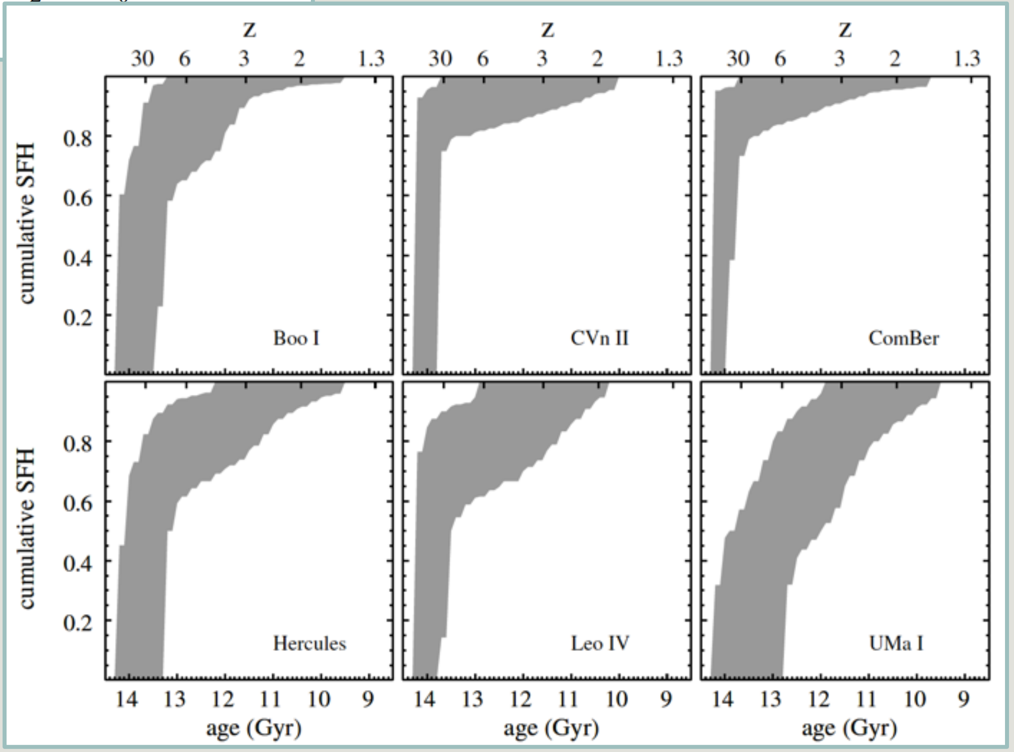
THE IMF IN ULTRA FAINT DWARF GALAXIES

- UFDs contain a fossil record of the star-formation process in the high-z Universe.
- UFDs are very-low metallicity systems: -4.0 < [Fe/H] < -1.5
- UFDs are Dark Matter dominated, collisionless systems with extremely long relaxation times: no mass segregation and no mass-dependent evaporation



The UFDs in our sample formed all their stars before their first infall towards the Milky Way

Adapted from Weisz et al. (2015) using data from Rocha et al. (2012) and Brown et al. (2014)



The UFDs in our sample formed most/all of their stars by the epoch or reionization.

Adapted from Brown et al. (2014)

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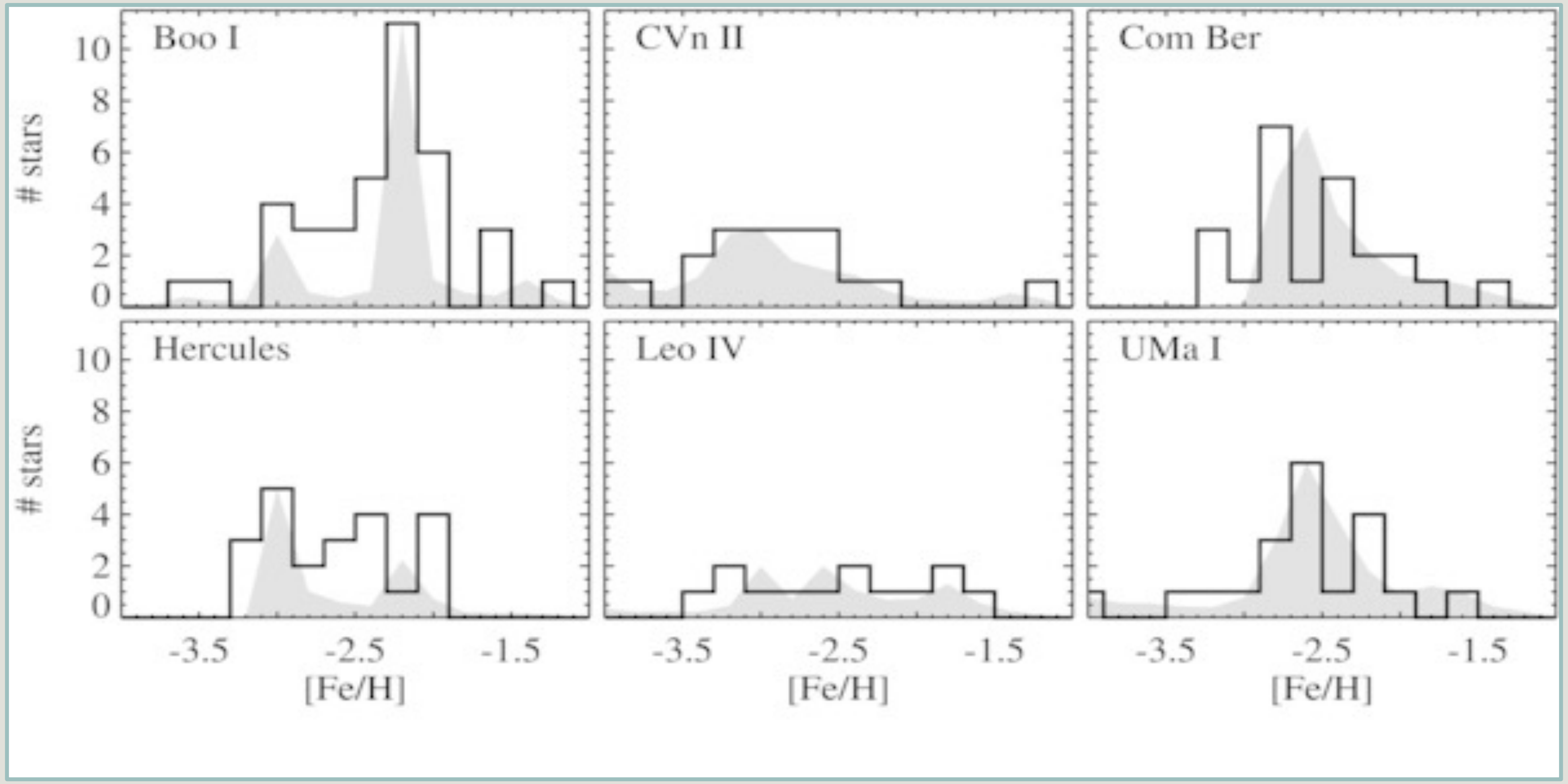

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$$t_{\rm rel}\,[{\rm Gyr}] \sim \frac{1.1}{N}\left(\frac{v}{\rm km\ s^{-1}}\right)^3\left(\frac{m}{M_\odot}\right)^{-2}\left(\frac{R}{\rm pc}\right)^3$$

Like GCs → Mass

100x GCs → M/L_V

0.01x GCs → M_V

10x GCs → $r_{\rm Plummer}$

Galaxy	Mass ($M_\odot$)	M/L_V ($M_\odot/L_\odot$)	M_V	$r_{\rm Plummer}$ (pc)
Ursa Major II[a]	$(4.9 \pm 2.2) \times 10^6$	1722 ± 1226	-3.8 ± 0.6	127 ± 21
Leo T	$(8.2 \pm 3.6) \times 10^6$	138 ± 71	-7.1 ± 0.3	170 ± 15
Ursa Major I	$(1.5 \pm 0.4) \times 10^7$	1024 ± 636	-5.6 ± 0.6	308 ± 32
Leo IV	$(1.4 \pm 1.5) \times 10^6$	151 ± 177	-5.1 ± 0.6	152 ± 17
Coma Berenices	$(1.2 \pm 0.4) \times 10^6$	448 ± 297	-3.7 ± 0.6	64 ± 7
Canes Venatici II	$(2.4 \pm 1.1) \times 10^6$	336 ± 240	-4.8 ± 0.6	132 ± 16
Canes Venatici I	$(2.7 \pm 0.4) \times 10^7$	221 ± 108	-7.9 ± 0.5	554 ± 63
Hercules	$(7.1 \pm 2.6) \times 10^6$	332 ± 221	-6.0 ± 0.6	321 ± 36

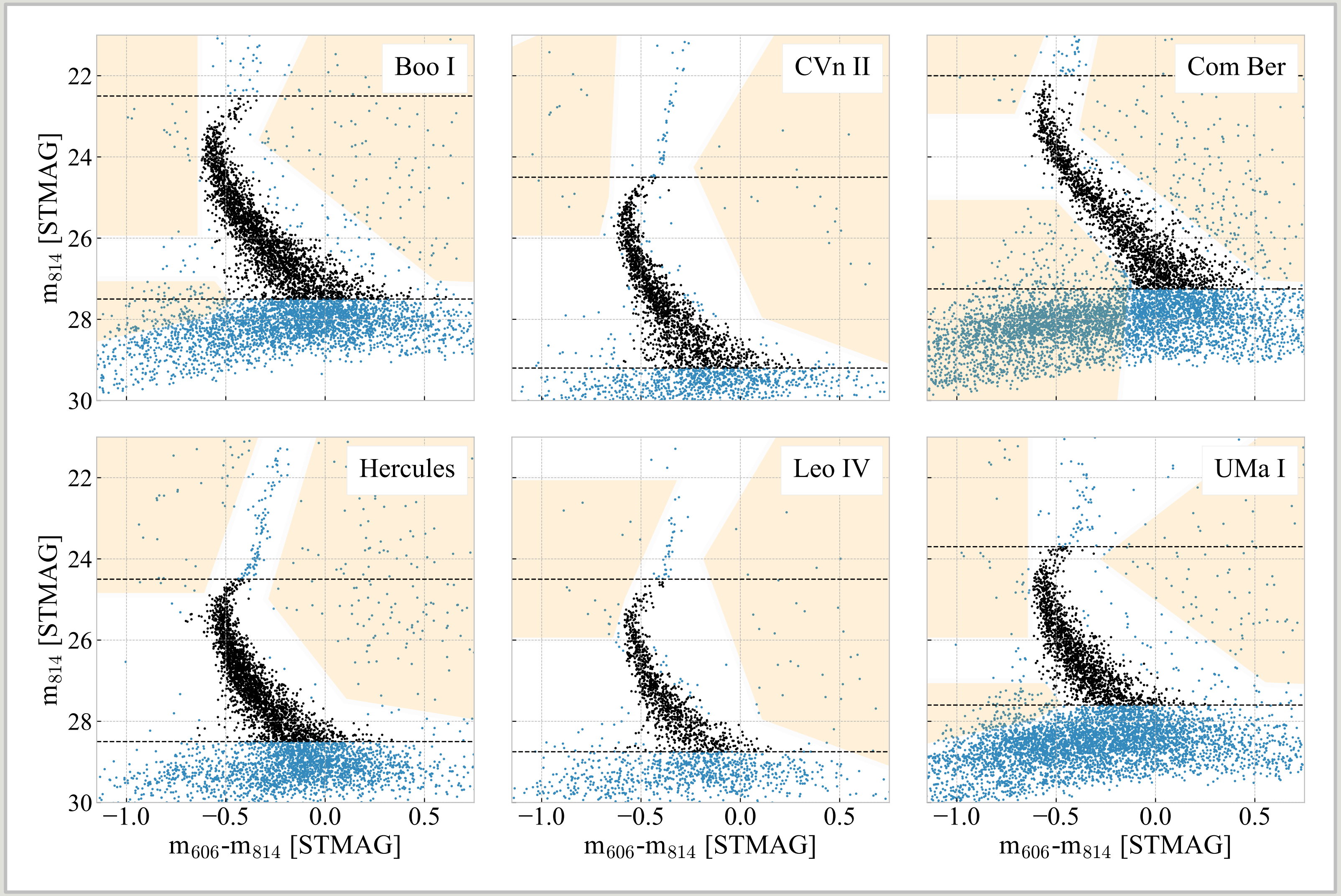
Adapted from Simon & Geha (2007)

The IMF in UFDs

The State of the Art Using HST

Optical *HST* ACS/WFC CMDs

- Original data from Brown et al. (2014)
- The data in the orange regions and those plotted in blue are excluded from the fit
- Typical limiting mass of the order of 0.4-0.5 M_{sun}



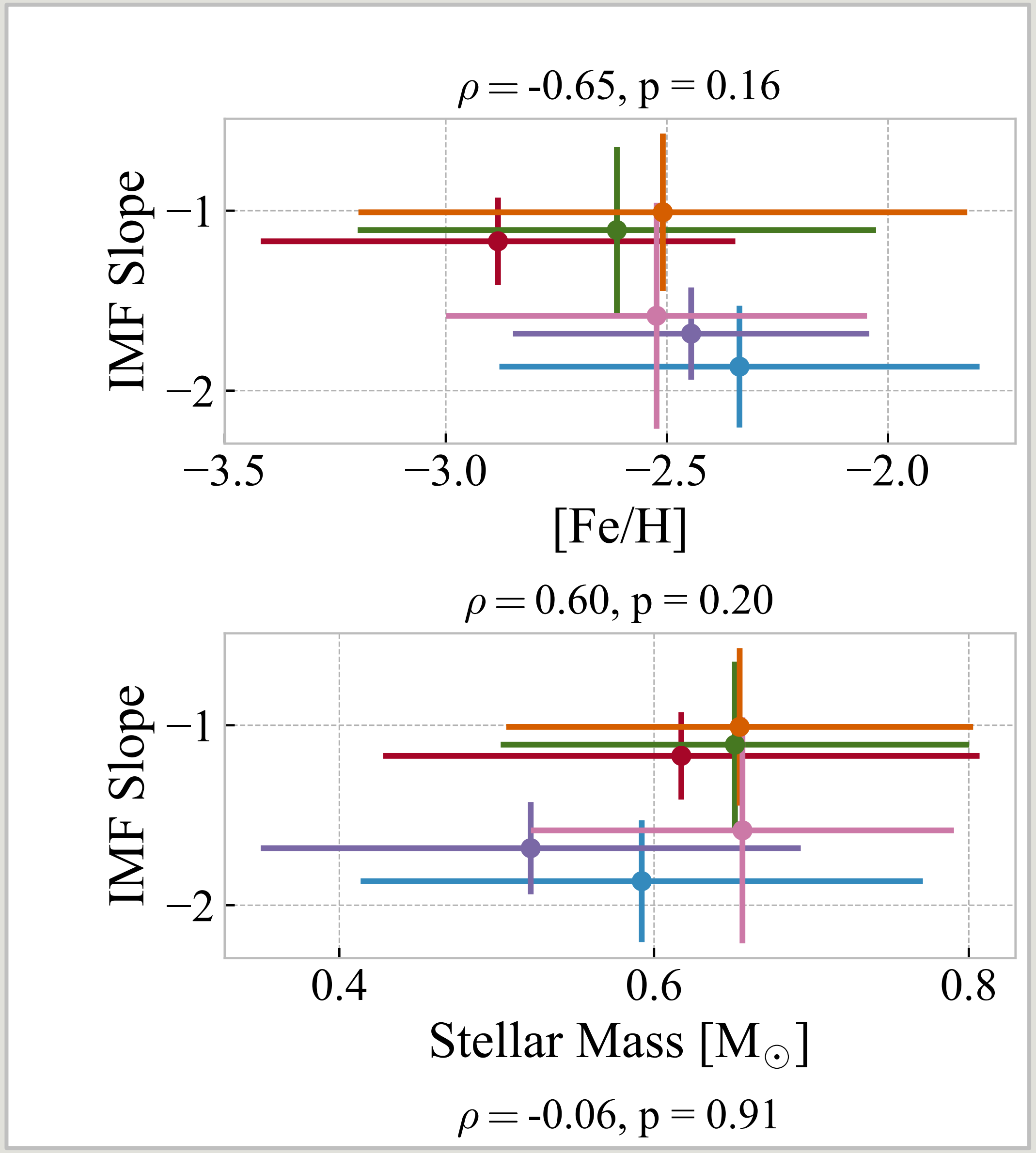
Adapted from Gennaro et al. (2018a)

Main Results

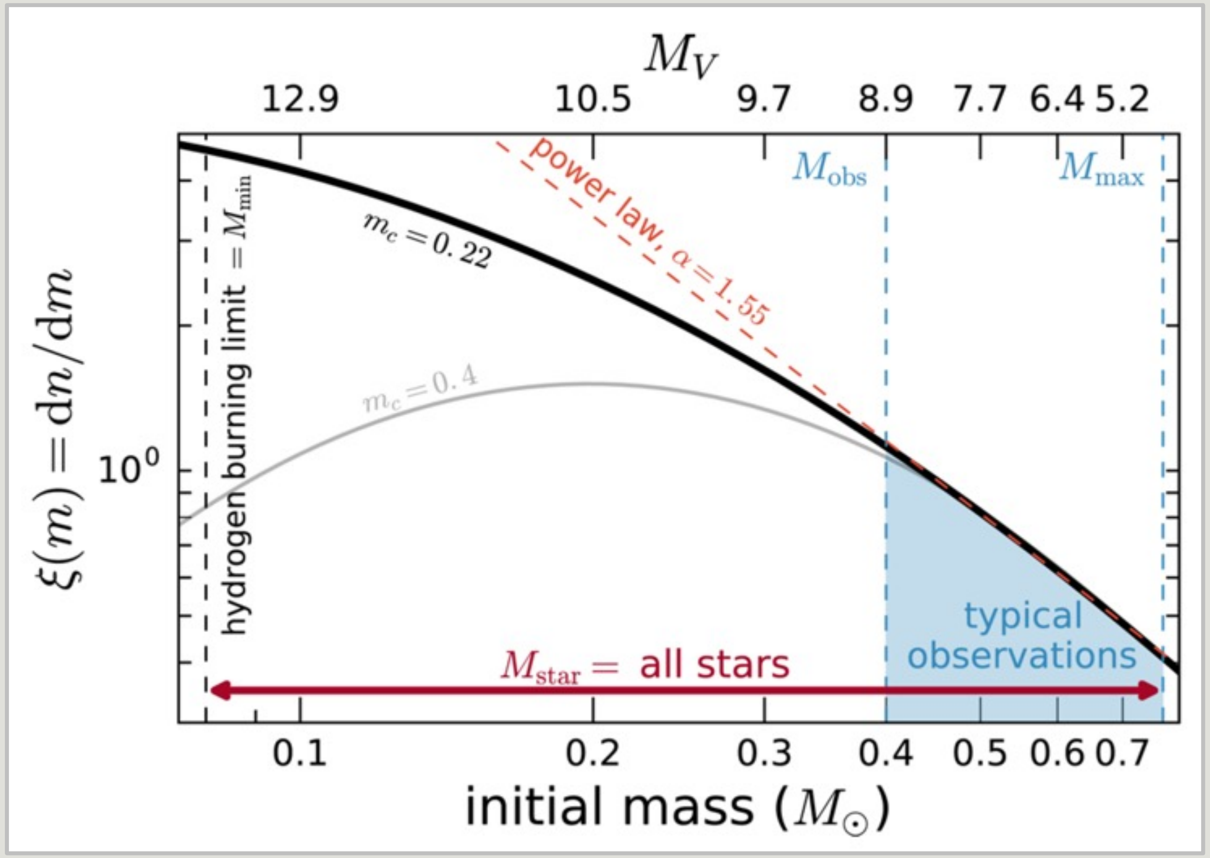
- The SPL best fit values are significantly flatter than a Salpeter IMF

- There is large variance within the sample

- There are interesting (but low significance) correlations between slope and mass/metallicty



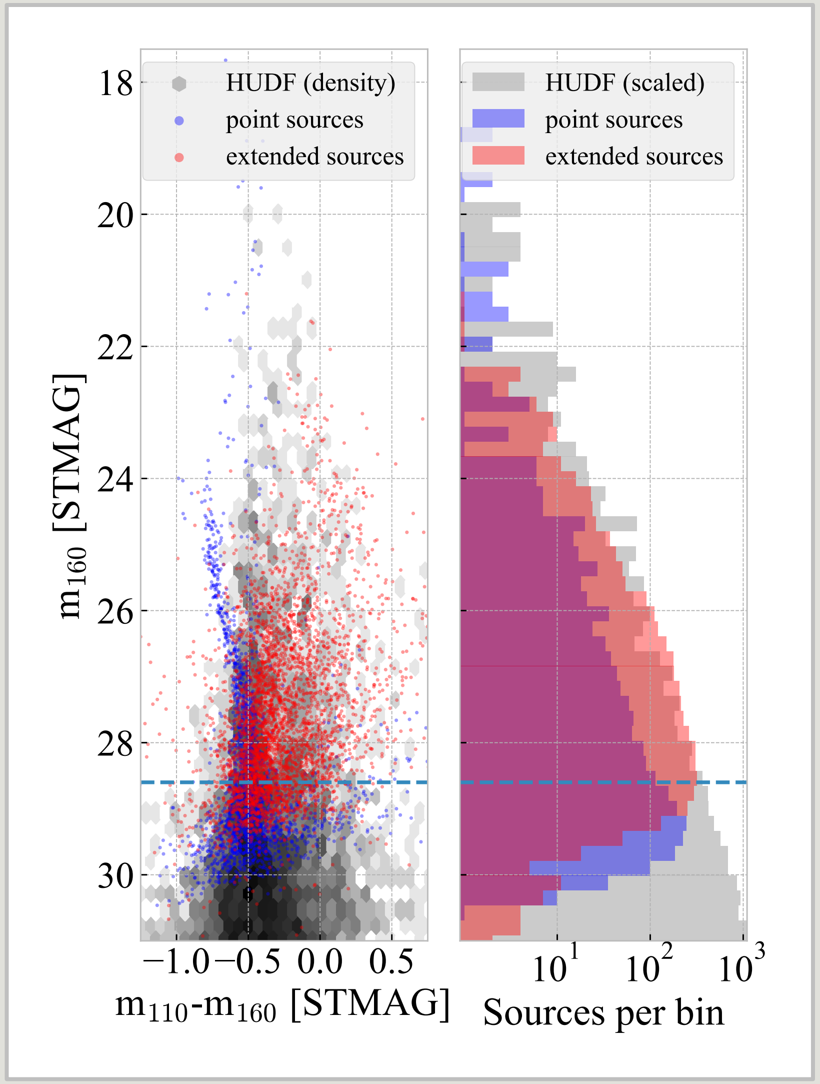
Possible statistical biases



Adapted from El-Badry et al. (2017)

- We know that in the Milky Way the SPL model breaks
- Our results for a log-normal model are more consistent with the Milky way (although the variance within the sample is still there)
- The (m_c,σ) covariance makes it possible to get different m_c when fitting only a limited mass range

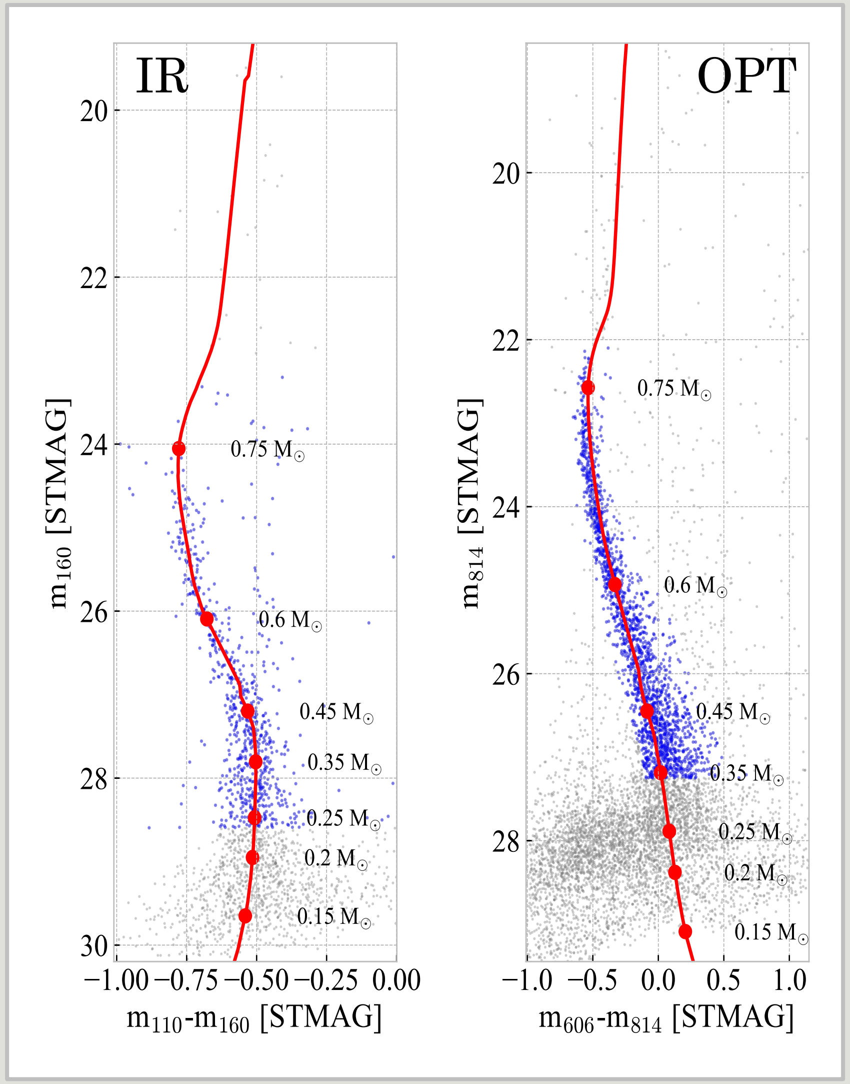
Deeper Data with WFC3/IR in Coma Berenices



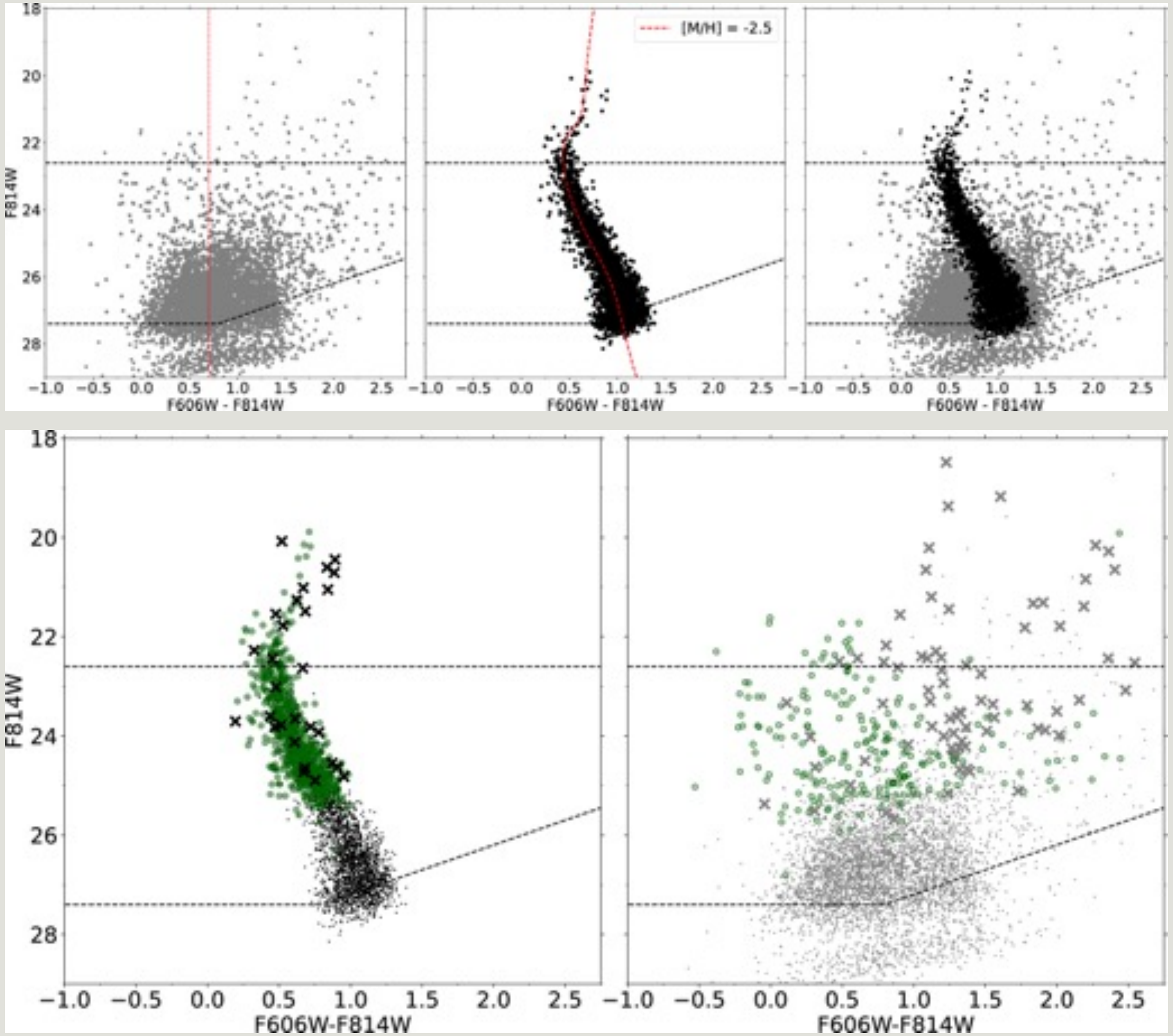
WFC3/IR data reach ~0.15 M_{sun} for the UFD Com Ber

Background contaminants limit the sample purity to ~0.23 M_{sun}

Even with these data, a Milky Way IMF cannot be ruled out with high significance



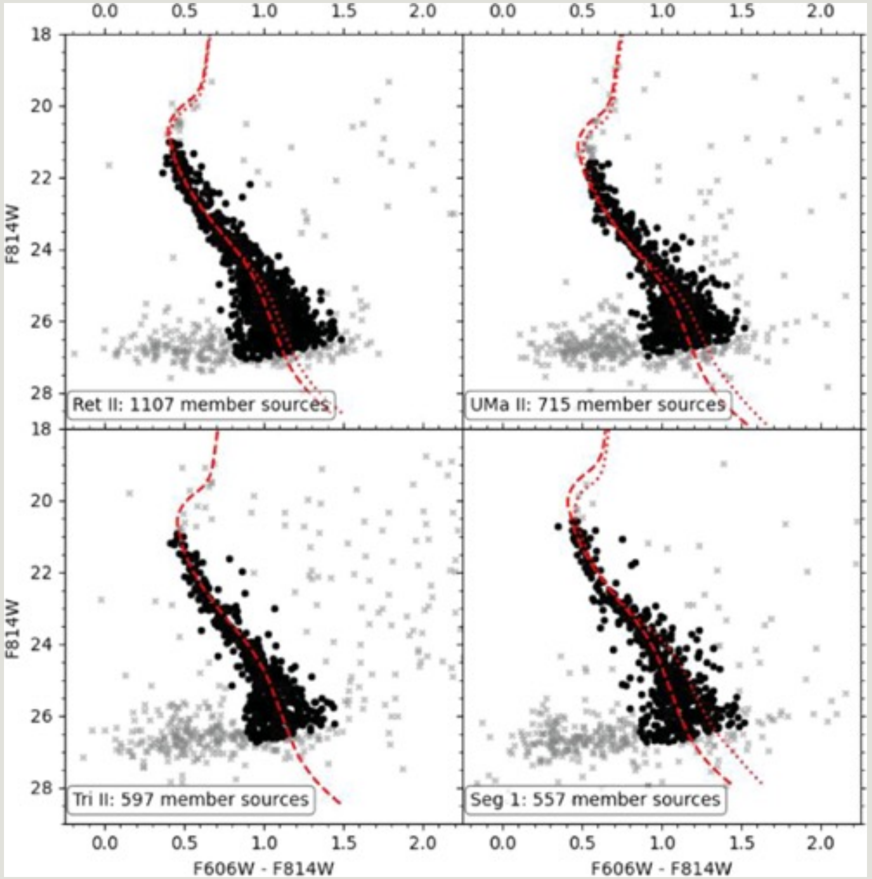
DEEPER ACS DATA



Broadly consistent with Milky Way IMF

Caveats:

- Depth
- Contamination
- Total Number of stars



Filion et al. (2022)

Filion et al. (2024)

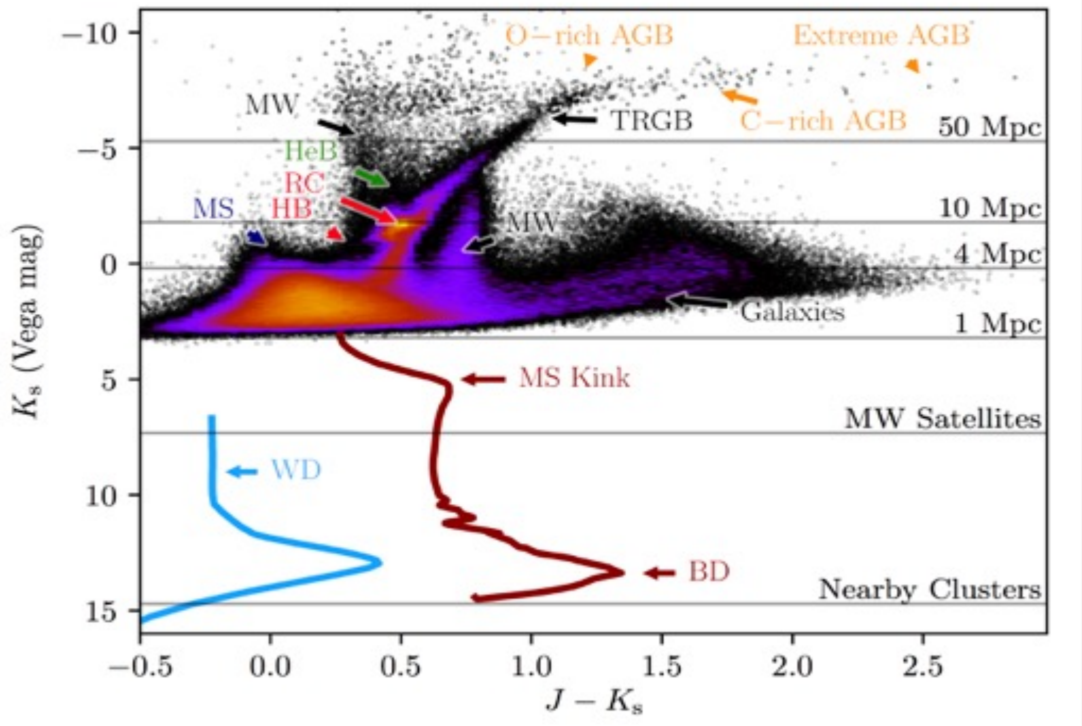
Moving Forward in Resolved Low-Mass IMF studies

WITH THE JAMES WEBB SPACE TELESCOPE

JWST Enables Resolved Stars Science:

- at larger distances
- to fainter luminosities
- at higher extinctions
- in higher crowding regions

Near-IR CMD of the LMC (Cioni+ 2011)



Milky Way:
MS "kink" for all GCs

300 kpc:
low-mass stellar IMF

1-2 Mpc:
Proper Motions

3-4 Mpc:
Ancient Star Formation Histories

5 Mpc:
10-100 pc scale extinction maps

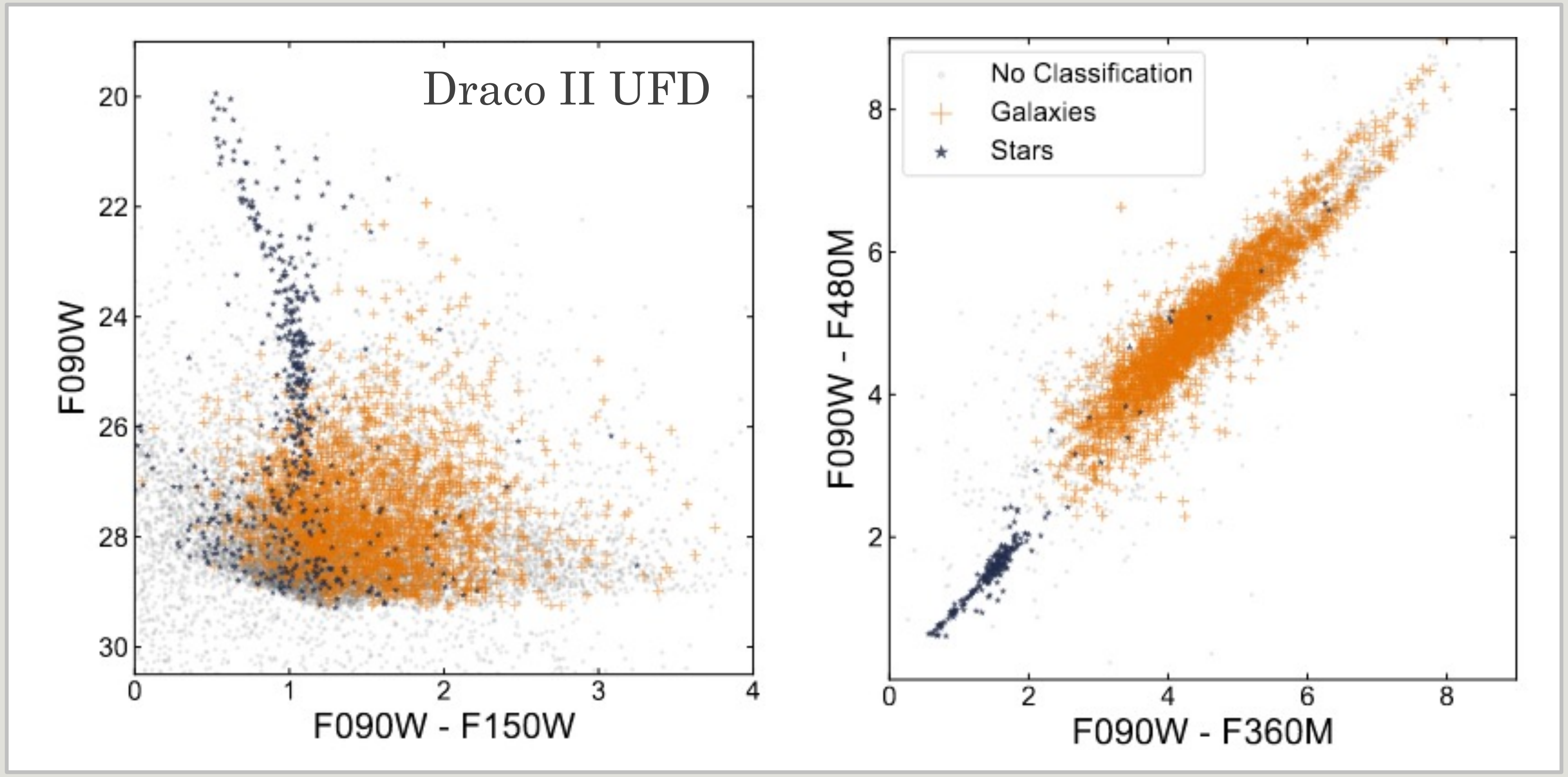
5-10s of Mpc:
Evolved Stars, (TRGB, HB, RR Lyrae)

Distance

And more:
variable stars, stellar evolution, star clusters, embedded SF, …

JWST OFFERS FURTHER ADVANTAGES IN TERMS OF CONTAMINATION

Background galaxies are much redder than stars when using the NIRCam SW-LW channel color baseline



Adapted from Warfield et al. (2023)

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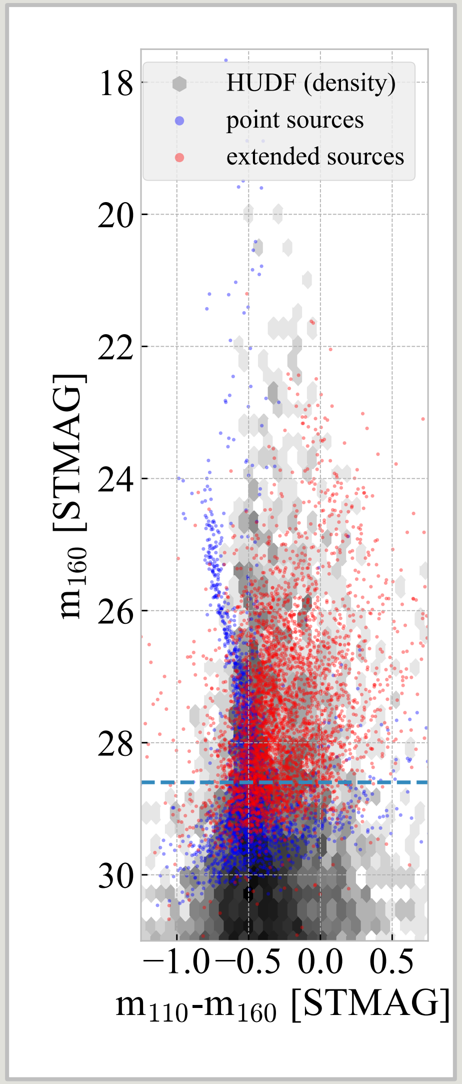
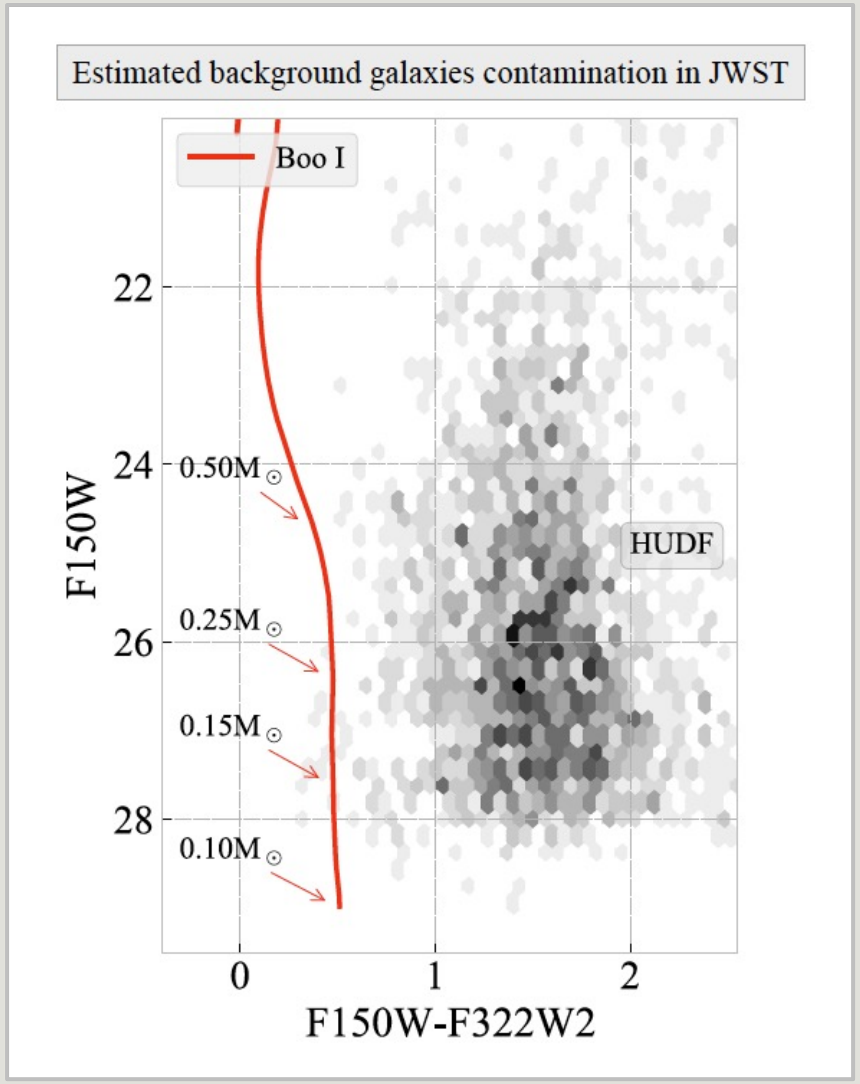
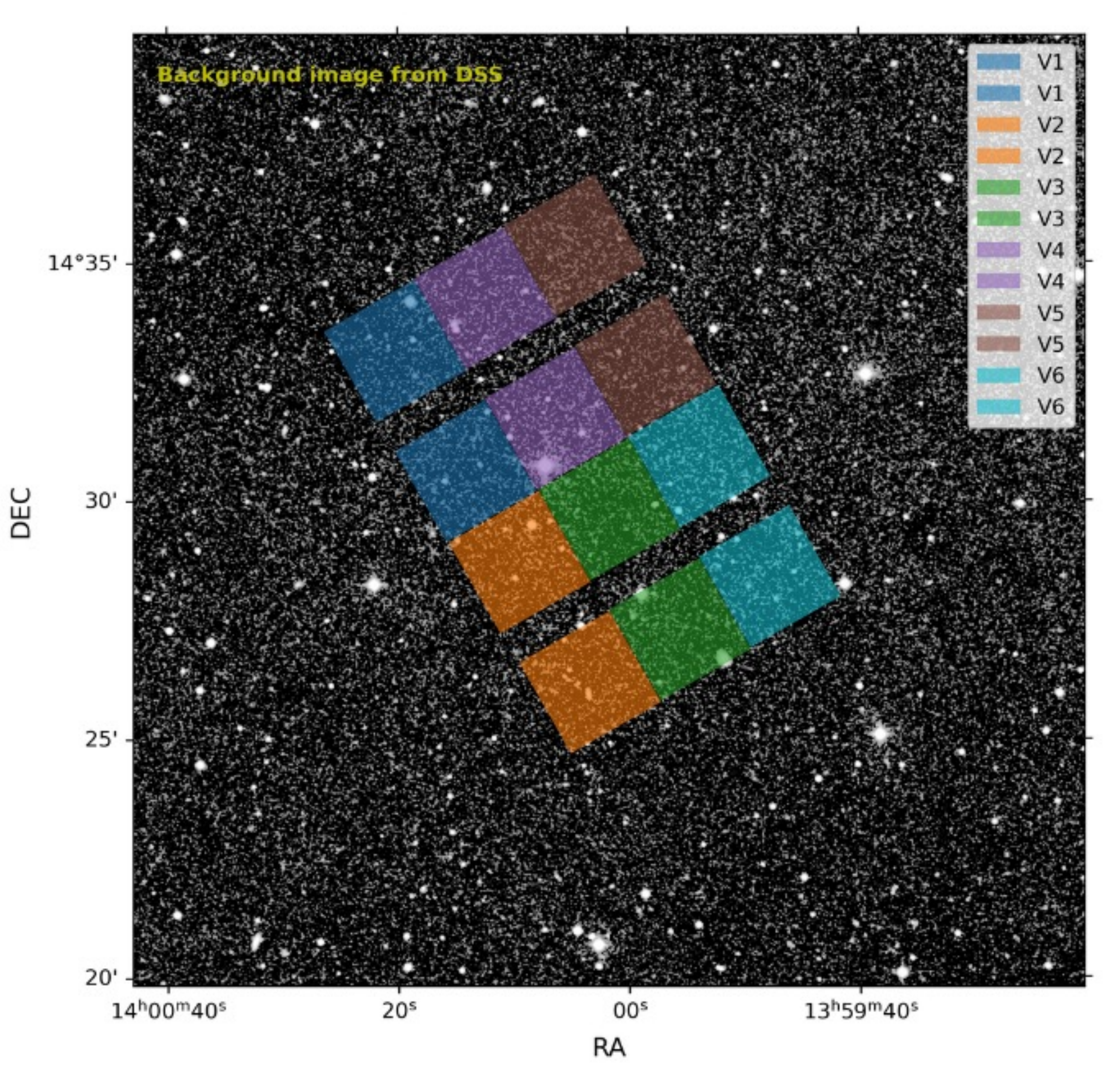




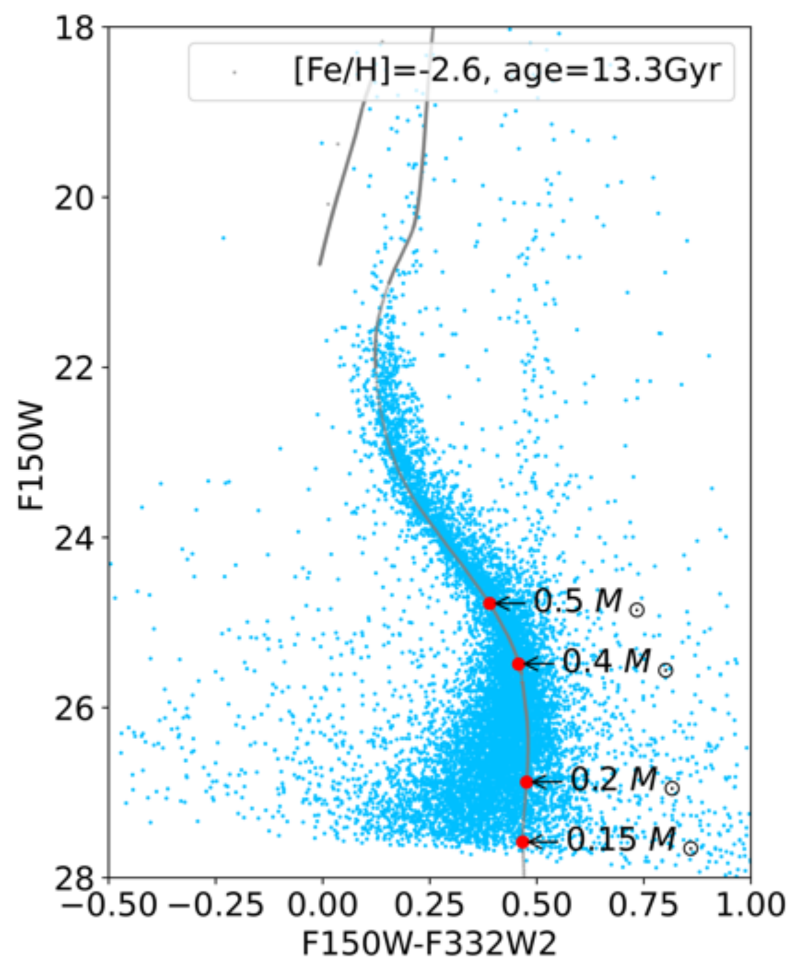
JWST PID 3849

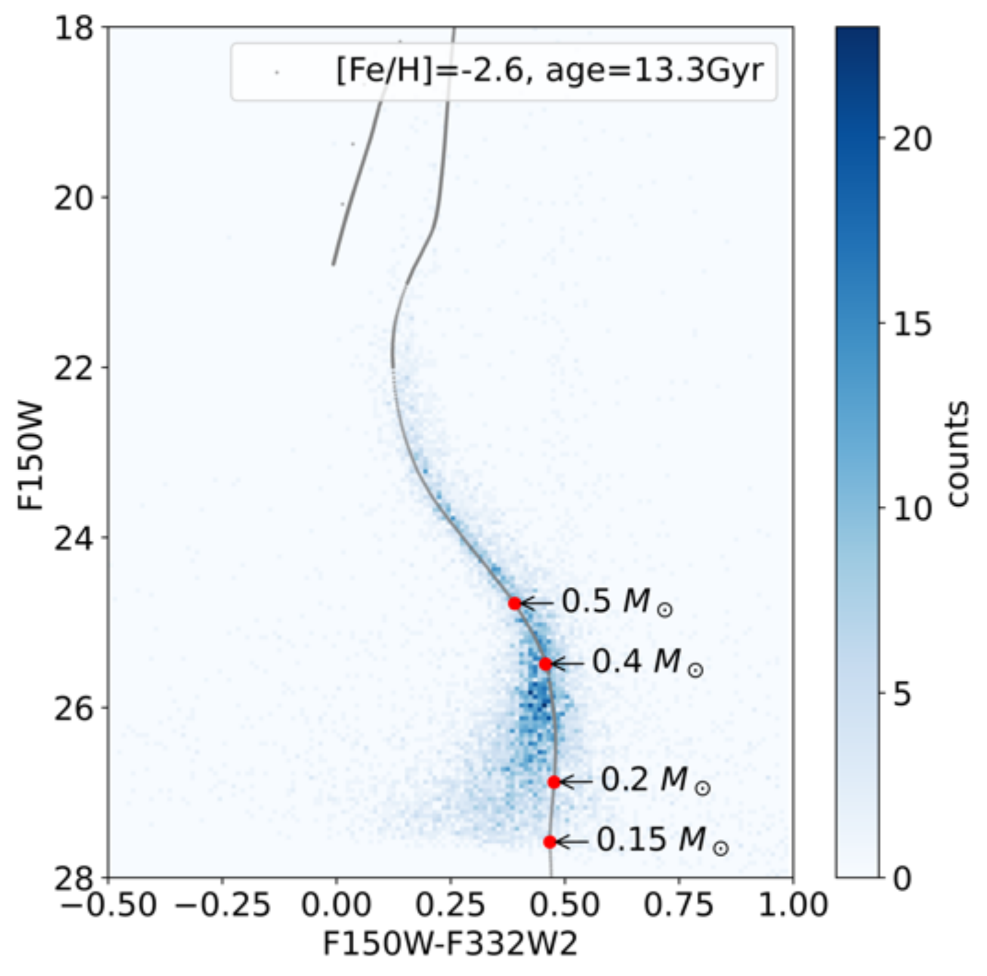
A Pristine IMF Probe of the Star-Forming Conditions in the Early Universe

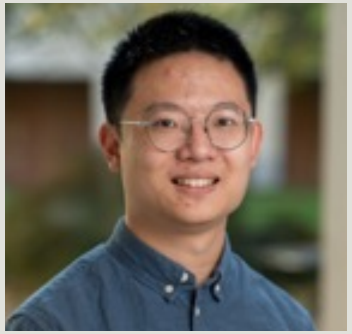


- Targets Boötes I with 6 non-overlapping tiles
- 10 detectors x 20 dithers x 6 visits =1200 files
- ~1000s per dither ~= 5.5 hours per tile
- Goal: reach 0.15 M_{sun} and observe 10,000 stars

Preliminary NIRCam CMD of Boötes I







Keyi Ding (UMD)

SUMMARY

Using HST:

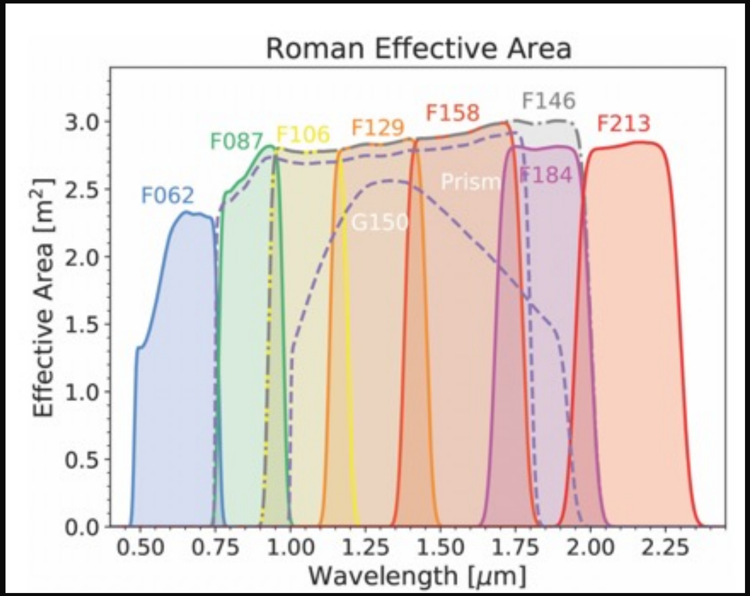
- We measure differences in the IMF w.r.t the Milky Way, however the significance is limited
- We measure interesting trends of the IMF bottom-lightness vs. metallicity
  - Such trends are qualitatively an extension of the trends observed for Giant ellipticals
- There is however:
  - Concern for possible systematics due to probing a limited range in mass
  - Some large variance within the sample, which may be related to observational biases, but may also be real

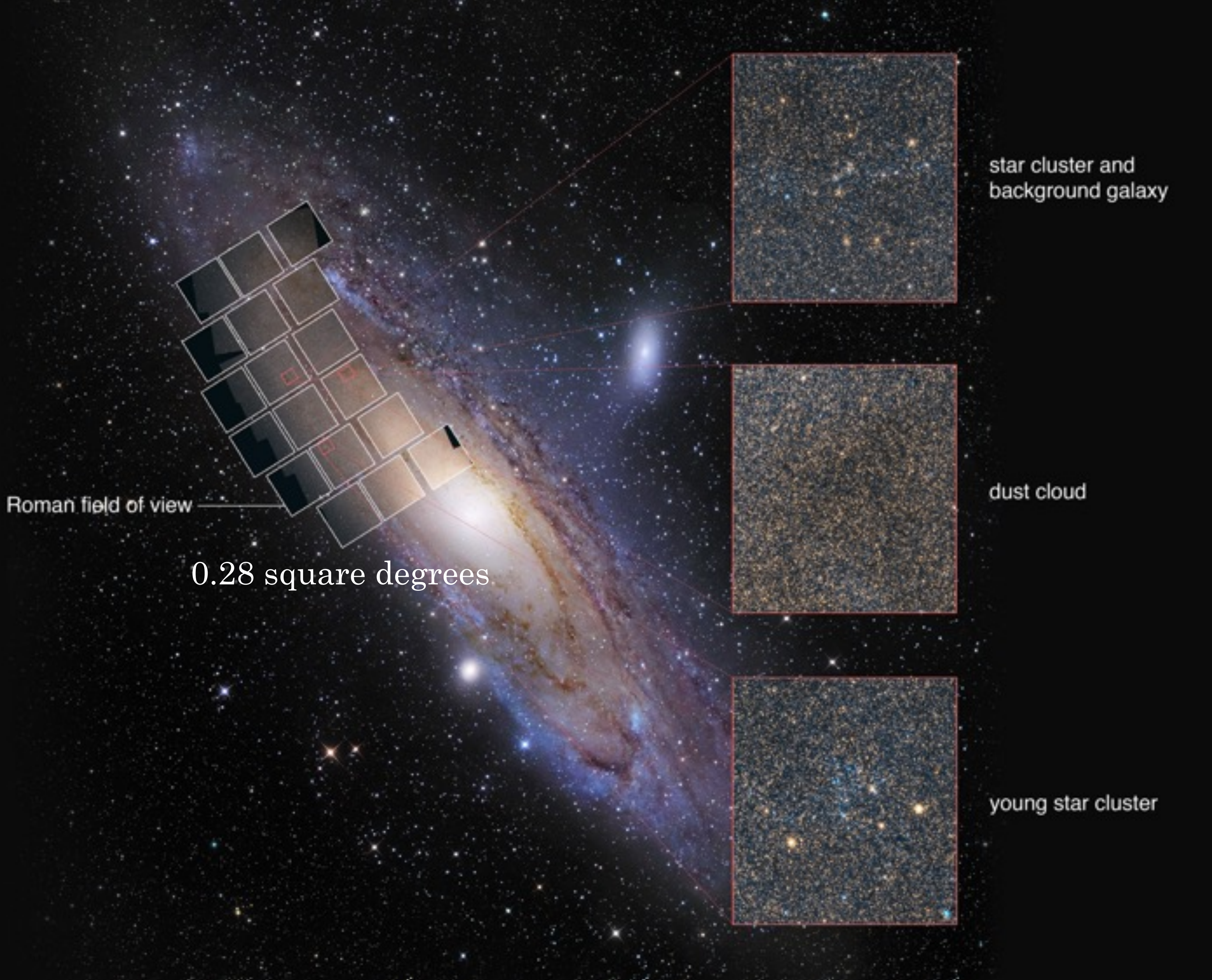
JWST has the potential to shed light on possible IMF variations in the Local Group:

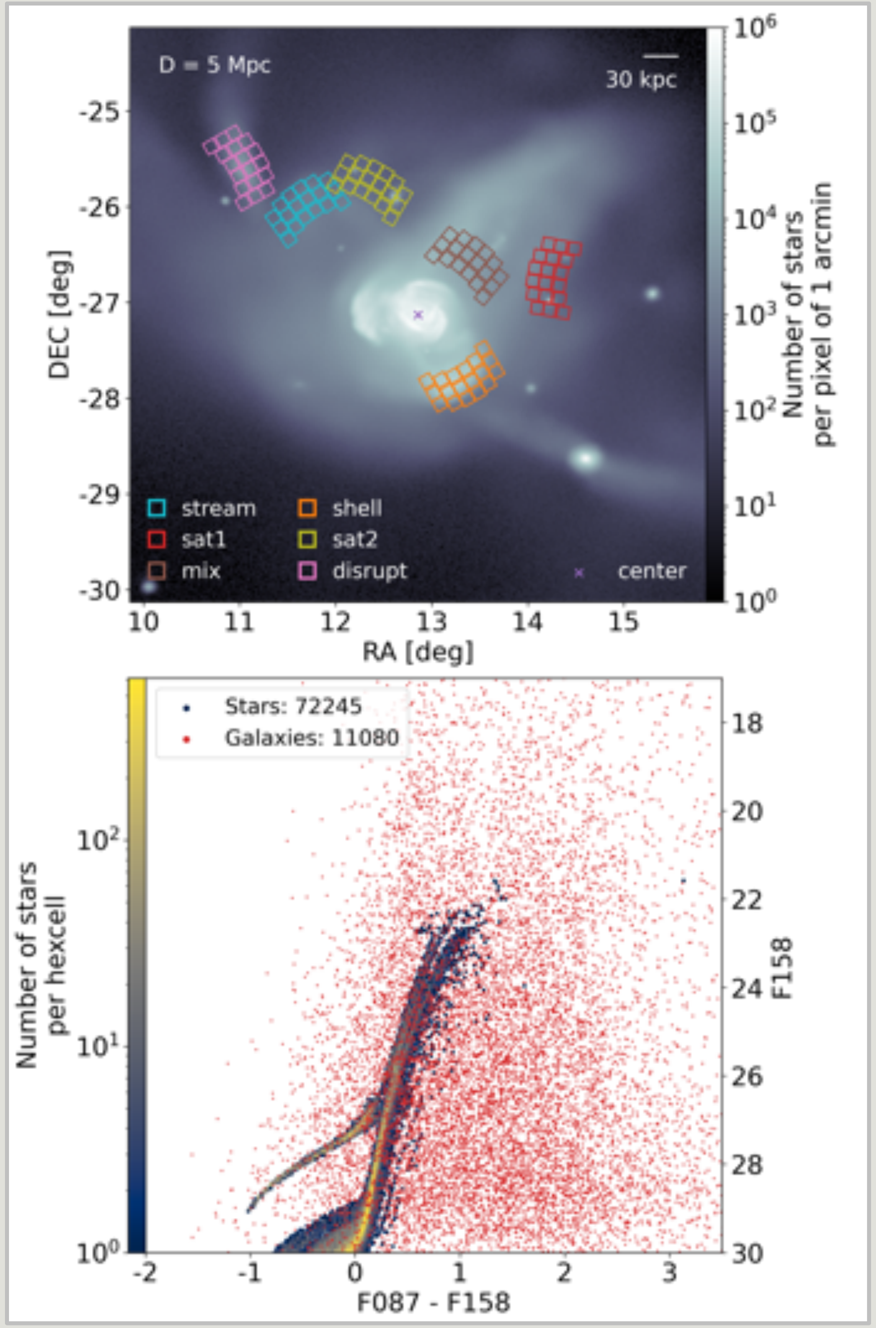
- unprecedented sensitivity and angular resolution, contamination severely reduced thanks to wider color baseline
- Boötes I NIRCam data will improve our understanding of the outcome of star-formation in high redshift, low-metallicity

A Giant Leap In Resolved Stellar Populations Studies

WITH THE NANCY GRACE ROMAN SPACE TELESCOPE


Roman Effective Area
Effective Area [m^2]
Wavelength [μm]
F062
F087
F106
F129
F158
F146
F213
F184
Prism
G150
0.0
0.5
1.0
1.5
2.0
2.5
3.0
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.25


Roman field of view
0.28 square degrees
star cluster and background galaxy
dust cloud
young star cluster



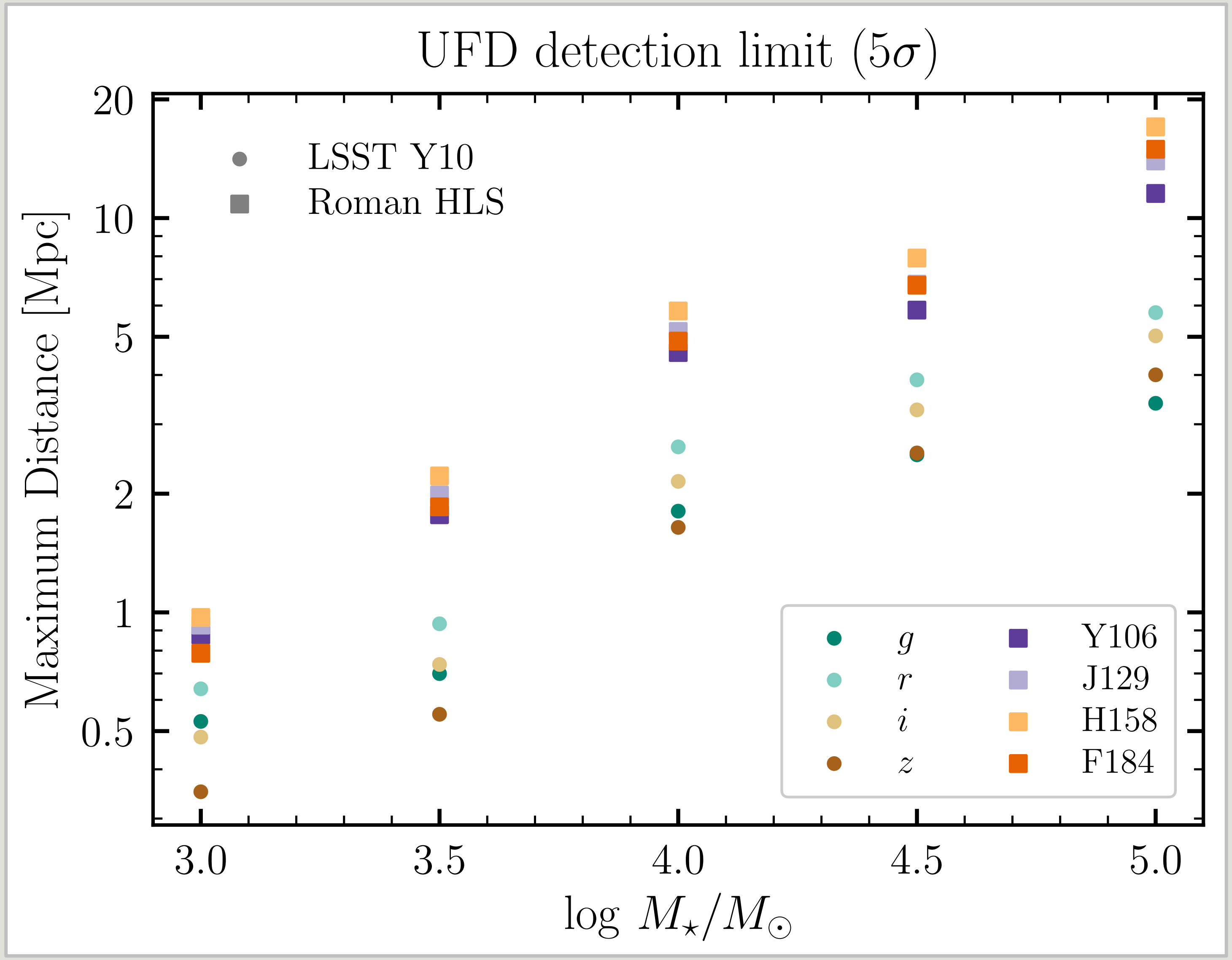


Figure credit: Jiaxuan Li (Princeton)

(Adapted) Figure credit: Adrien Thob, Robyn Sanderson, UPenn