A JWST Project on 47 Tucanae. Overview, Photometry, and Early Spectroscopic Results of M Dwarfs and Observations of Brown Dwarfs

Marino A. F. et al. 2024
ApJ 965, 189

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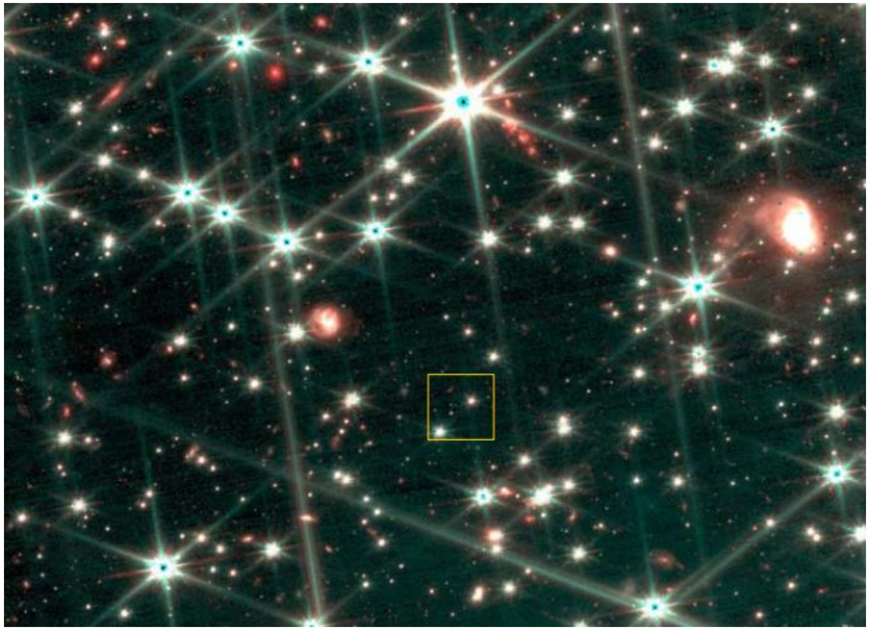
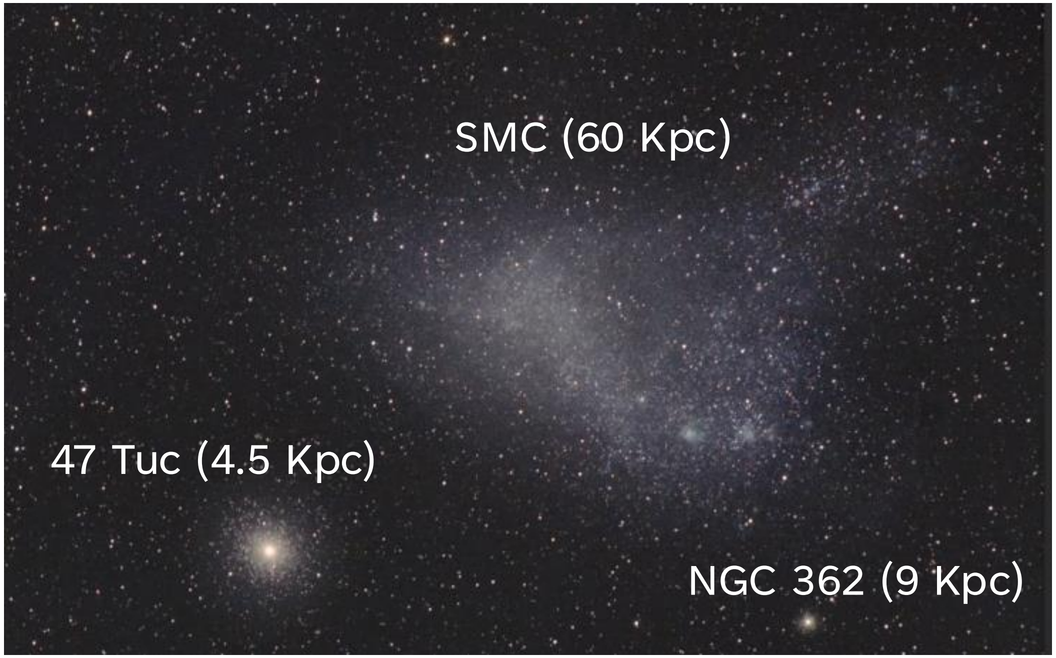
Group Meeting 2024.11.11

What do the faintest stars populating a Globular cluster hide?





47 Tucanae (NGC 104) is the second brightest and largest globular clusters in the sky (mag ~ 4.0, apparent diameter ~ 5.6 arcmin). It lies at low declinations (-72°) and stands out against the Small Magellanic Cloud.

47 Tuc is about 13 Gyr old and its metallicity is ~ -0.72 dex (Harris et al. 2010)

The deepest CMD of a Globular cluster ever shown so far

– A number of substructures are visible in the faintest portion of the Main Sequence: gaps, changes of slope, color spread

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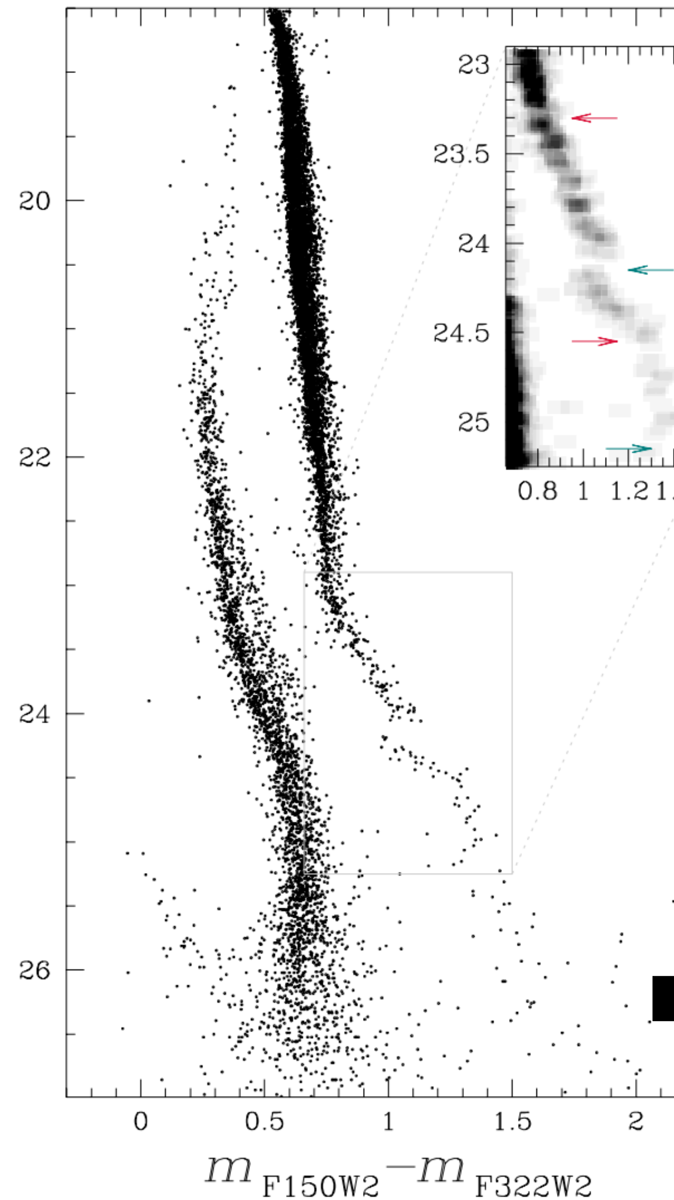
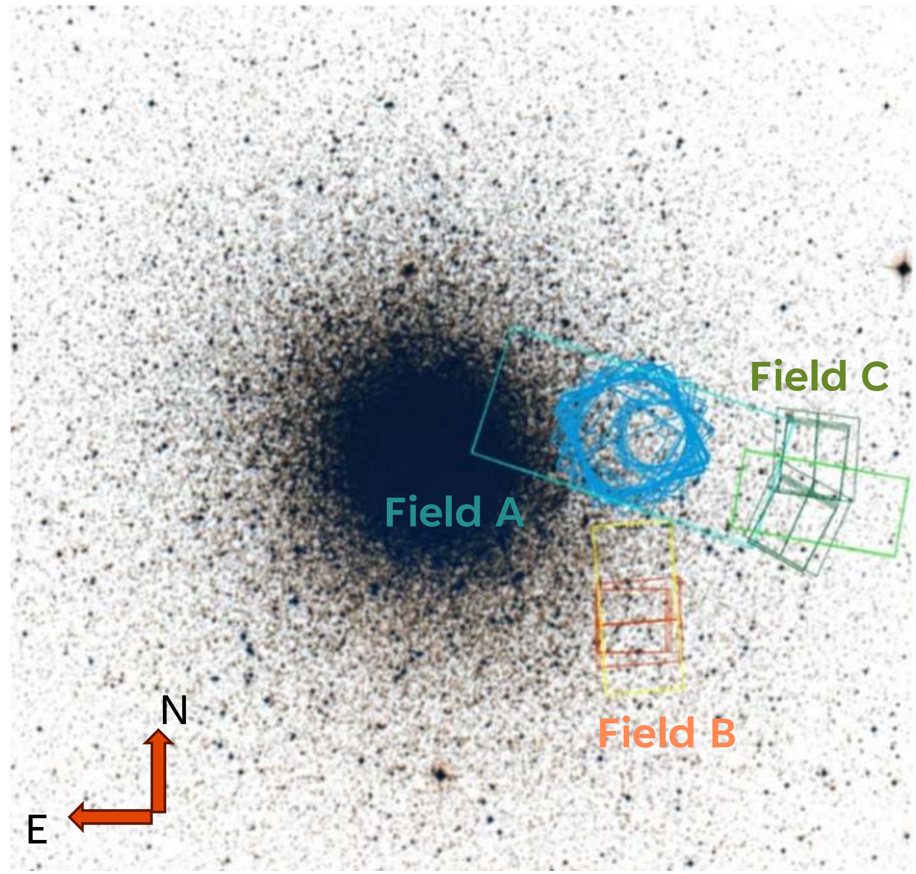
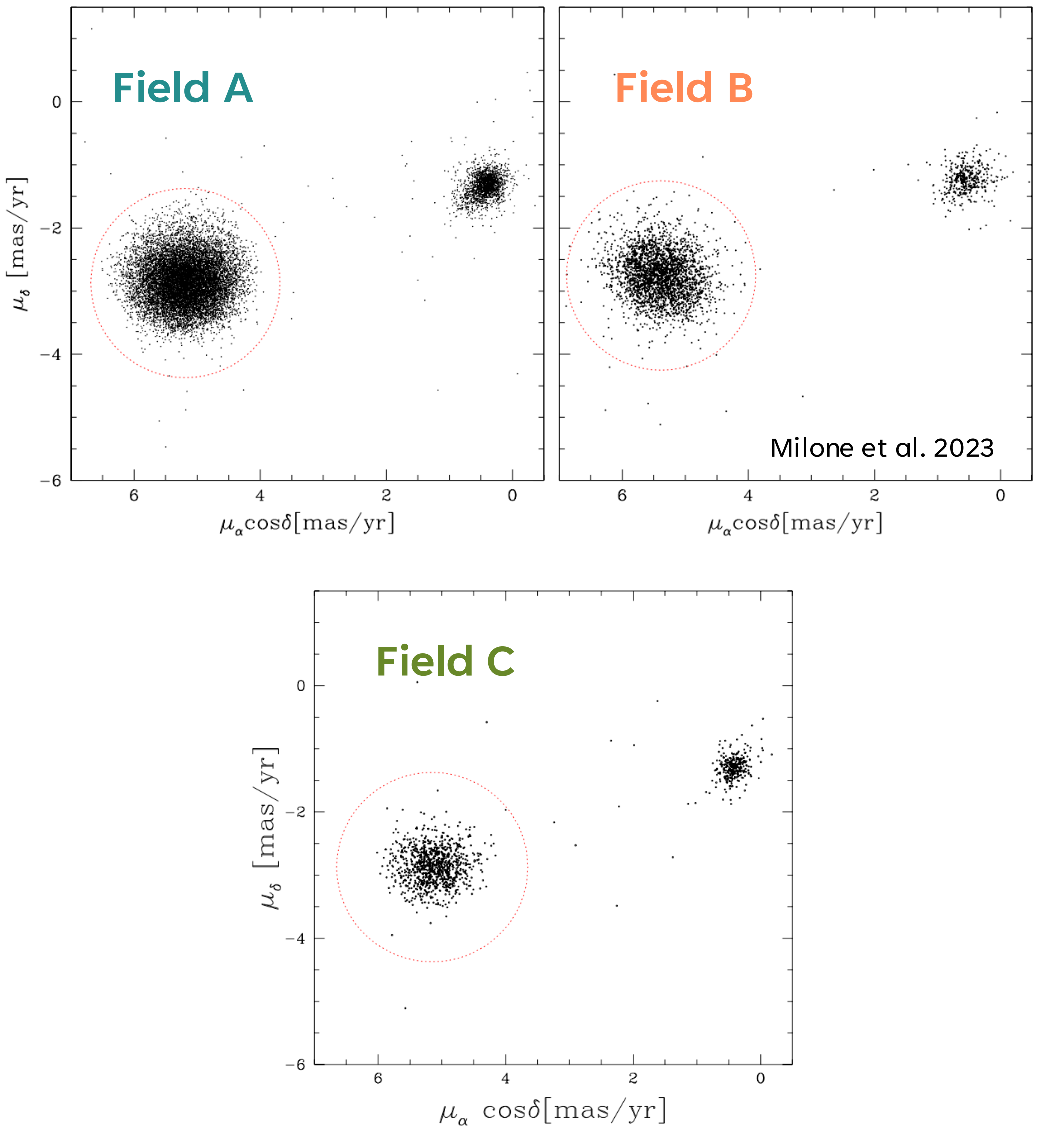


The observations taken with different instruments (ACS and WFC3 (IR channel) onboard HST and NIRCAM onboard JWST) cover several fields located Westward and South-Westward from the cluster center

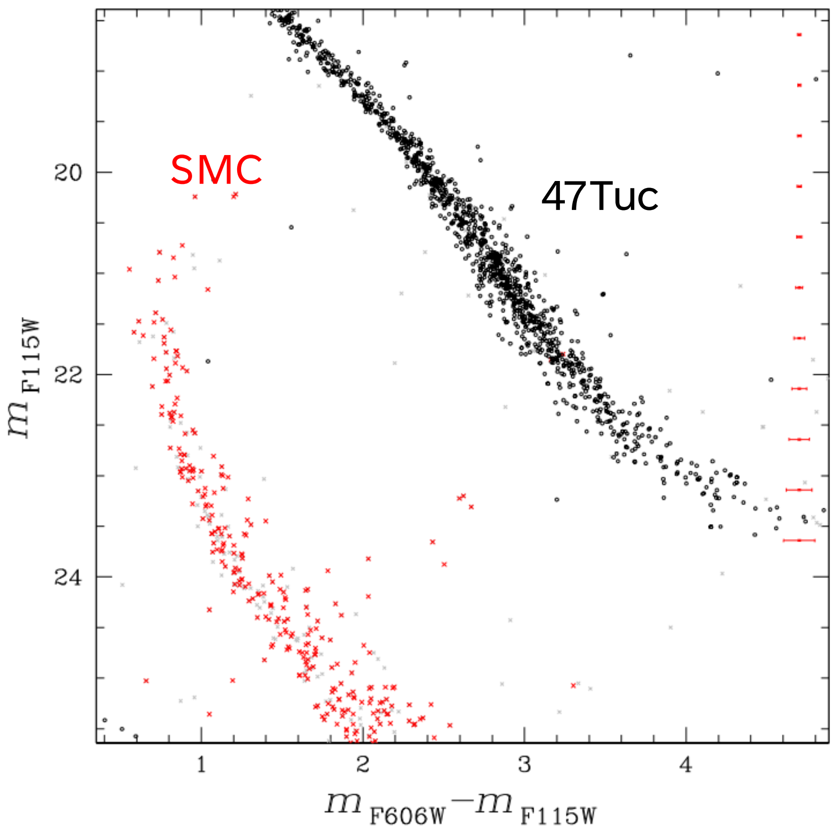


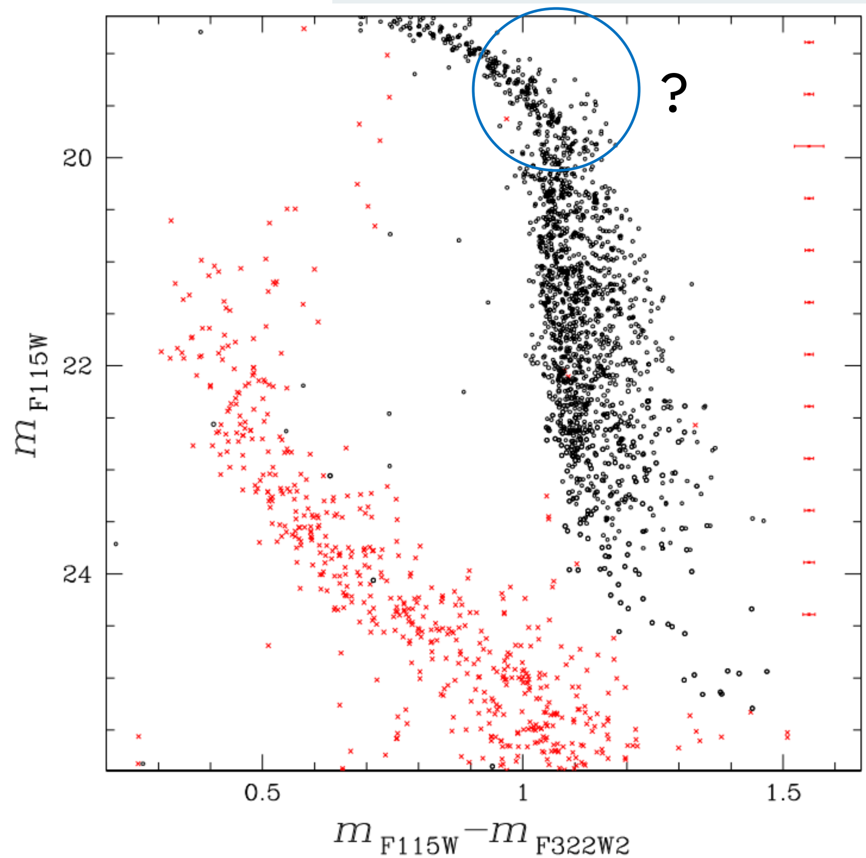
Temporal baseline ~ 13 years



Multi-epoch images allow to calculate the internal proper motions in GC stars

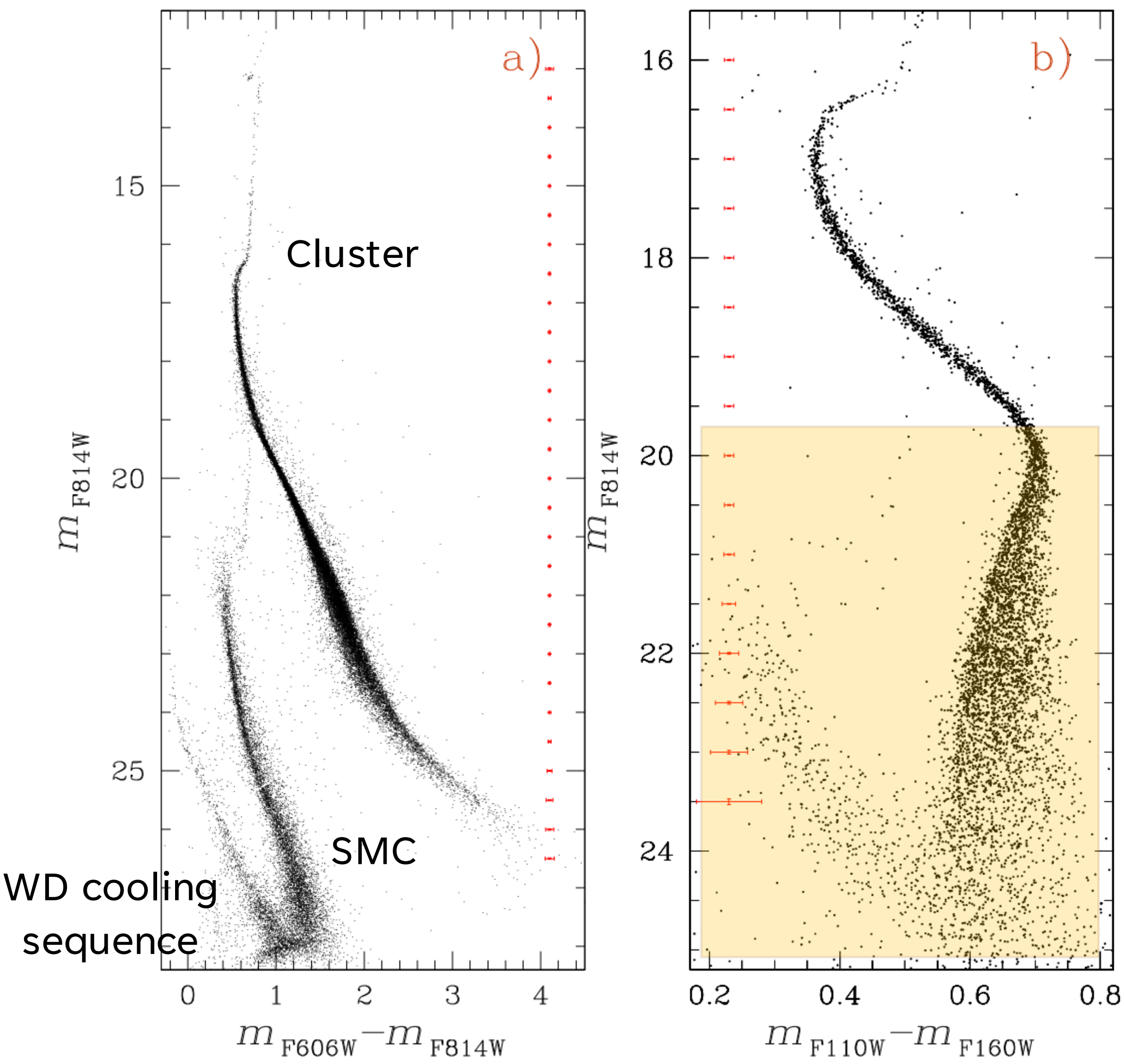
Proper motion field-cluster membership





Milone et al. 2023

MNRAS 522, 2429



In IR bands the main sequence shows a "knee" Stars with masses of , than the order of 0.5 $M_{\odot}$ (M dwarfs) appear bluer than MS stars at higher masses

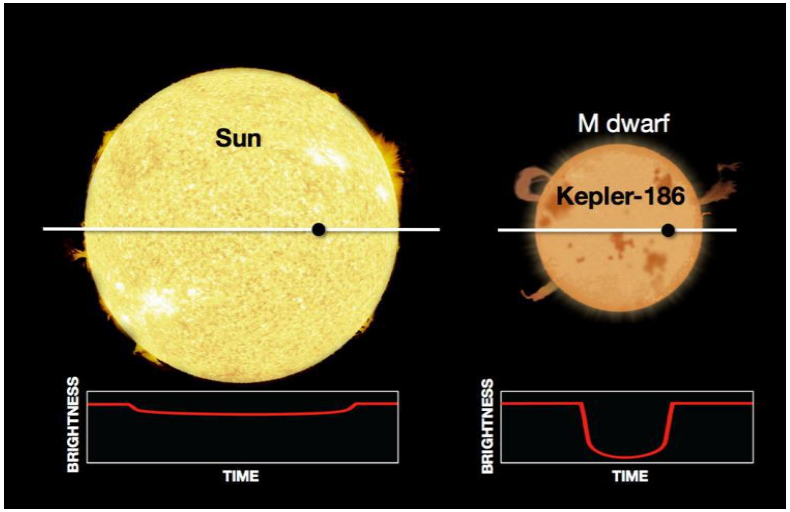
Why studying M dwarfs

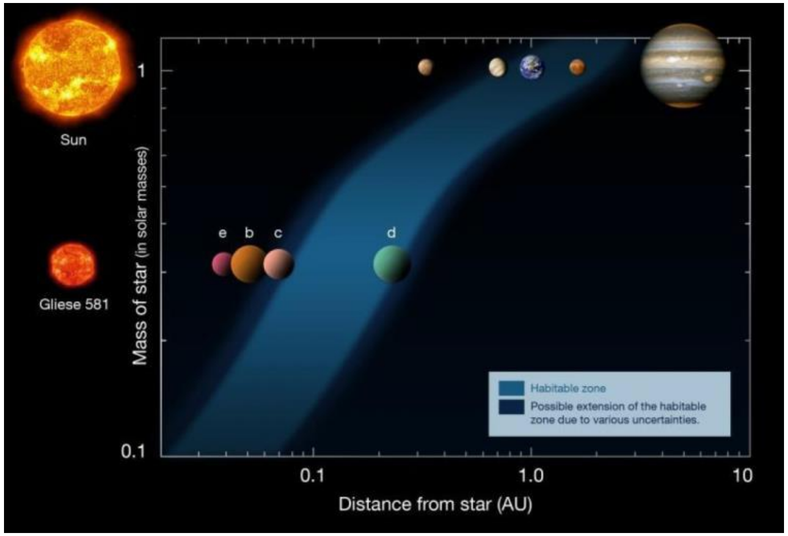
M dwarfs represent ~70% of all stars in the Galaxy (0.5 $M_{\odot}$ < Mass < ~0.08 $M_{\odot}$ = hydrogen-burning limit) Small planets are easier to detect orbiting small stars via radial velocity and transits, as well as with spectroscopic techniques

Habitable zones are closer to these stars than those of Sun-like stars

Their extremely long lifetimes allow for biological development and evolution of life on orbiting planets

... but these objects represent a challenge for stellar evolution





Why studying M dwarfs

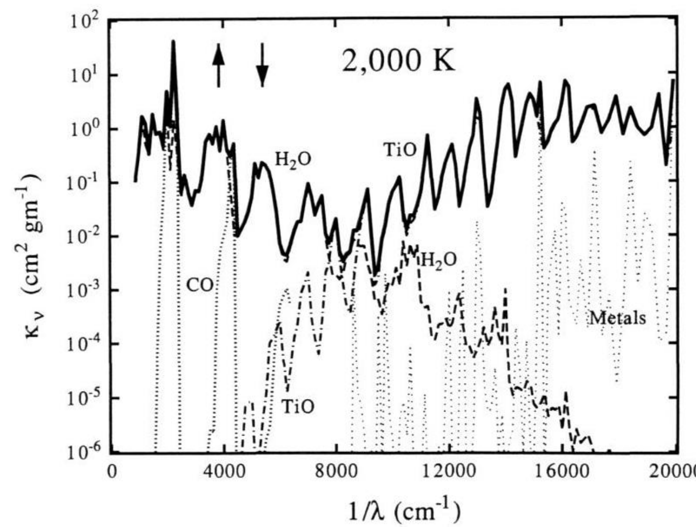
$M/M_\odot$	T_c (K)	ρ_c (gr·cm^{-3})	T_{phot} (K)	ρ_{phot} (gr·cm^{-3})
1.0	$\sim 1.6 \cdot 10^7$	~100	~6000	$\sim 10^{-7}$
0.6	$\sim 10^7$	~150	~4000	$\sim 10^{-6}$
0.1	$\sim 5 \cdot 10^6$	~500	~2800	$\sim 10^{-5}$

Many M-dwarfs are fully convective and extremely dense and cold

Difficult to predict evolution of their thermal properties & atmospheric opacity

In their envelopes & atmospheres almost all H is present as H_2, carbon as CO, while oxygen contributes to form molecules of TiO, VO and H_2O

An exclusive opacity source for M-dwarfs is the H_2 **CIA (Collisionally-Induced Absorption)**



CIA + molecular spectral features

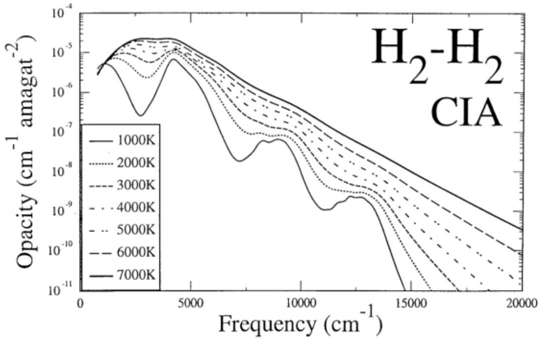


Fig. 1. CIA opacities of H_2–H_2 at temperatures between 1000 and 7000 K.

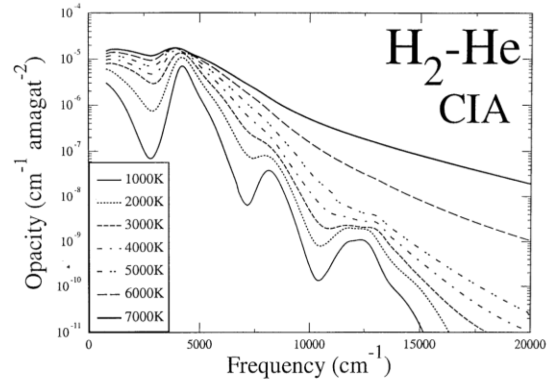


Fig. 2. CIA opacities of H_2–He at temperatures between 1000 and 7000 K.

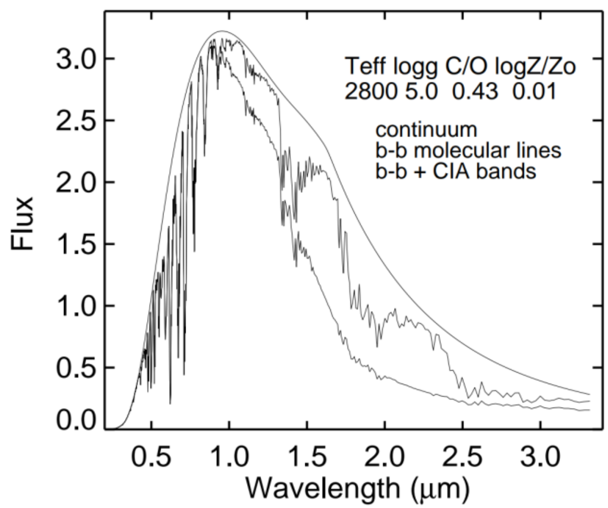
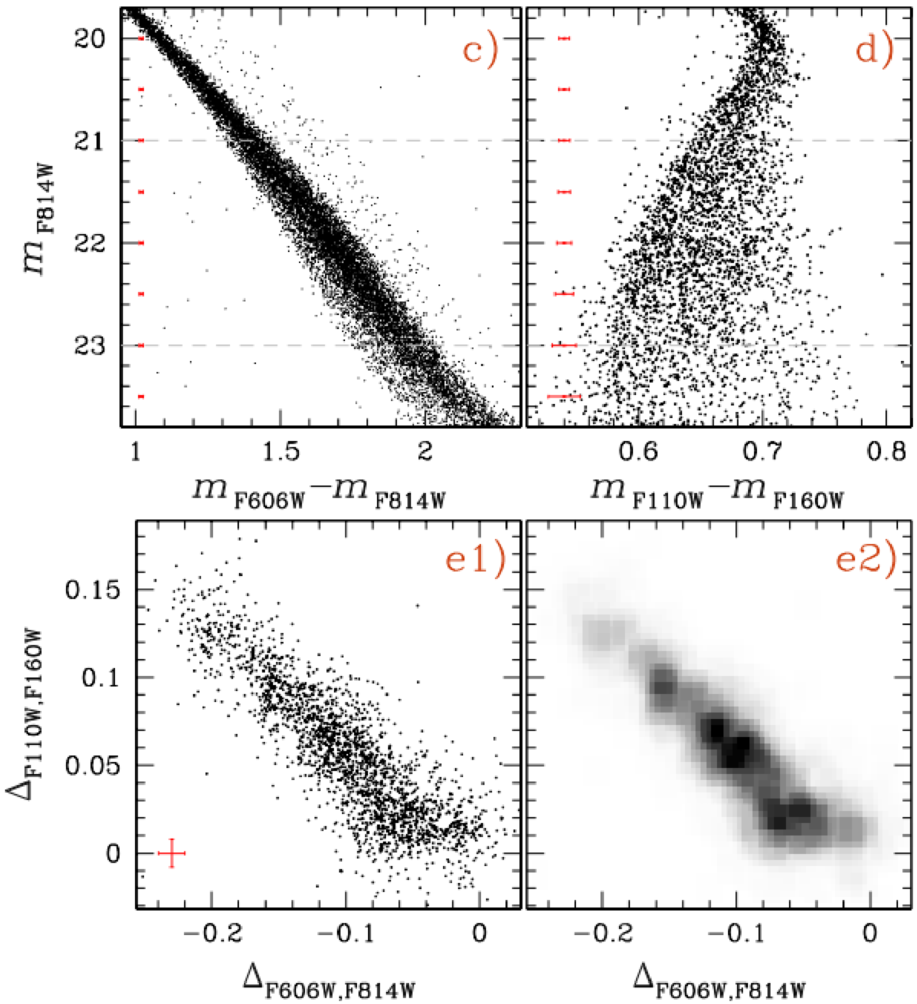


Fig. 4. The contributions of various opacity sources to the spectrum of a stellar model with $T_{\rm eff}$ = 2800 K, log(g) = 5.0, and $Z = 10^{-2} Z_\odot$ – a typical main sequence member of a globular cluster. The model computation includes opacities of continuum sources, molecular lines, and CIA. The spectra are computed based on the continuum alone (upper, convolving curve), continuum + molecular (b–b) lines, and continuum + molecular lines + CIA. Only the latter is consistent with the underlying model atmosphere, but the difference between the three spectra illustrates the relative contribution of the three sources of opacity.

The combination of opacity by metallic compounds and CIA makes impossible to define a true continuum in M-dwarf stars

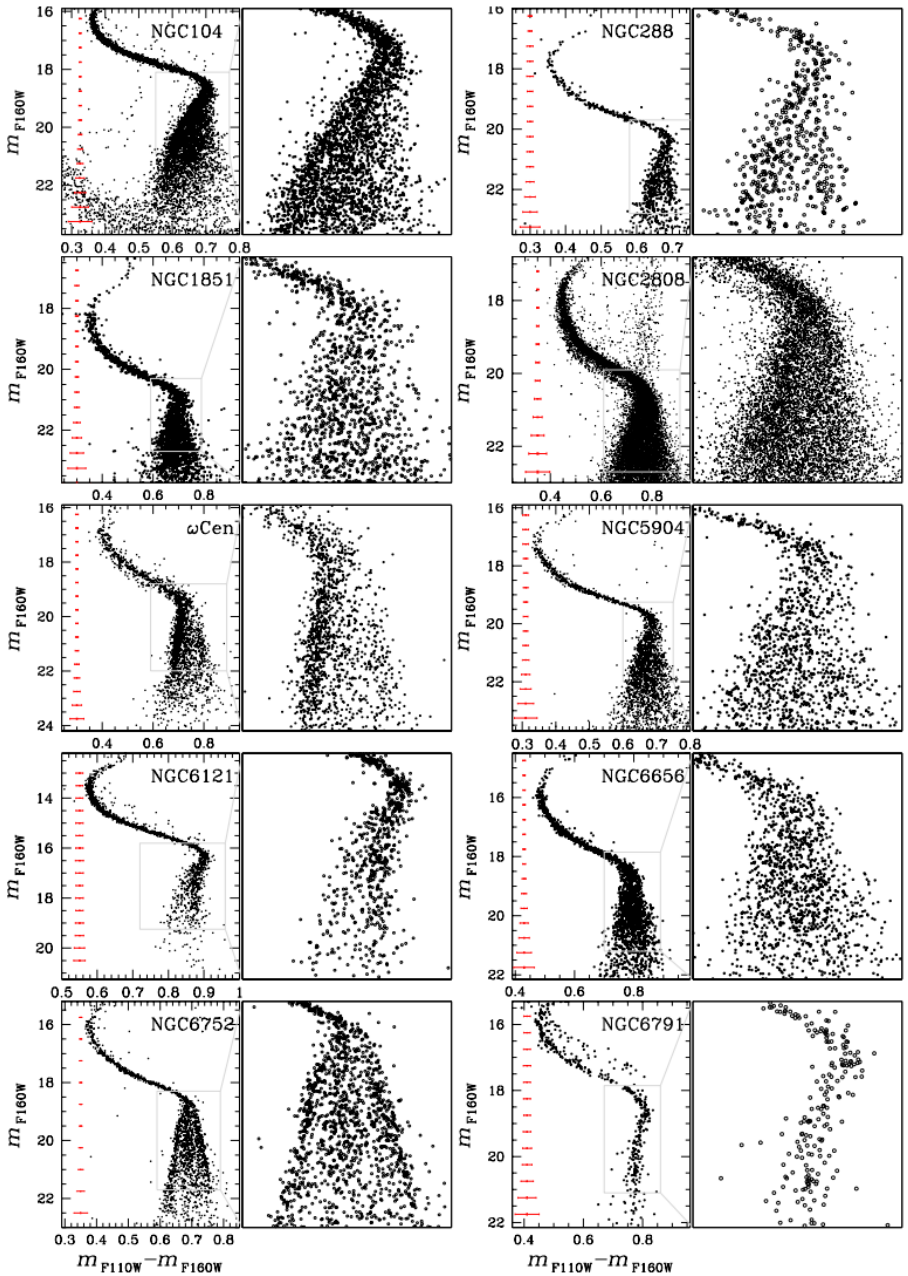
Borysow et al. 1997

Below the Main Sequence Knee



Combination of two distinct colors shows that stars are grouped into distinct regions.

Milone et al. 2023



Color spread among M-dwarfs is a common feature observed in other GCs

Dondoglio et al. 2022

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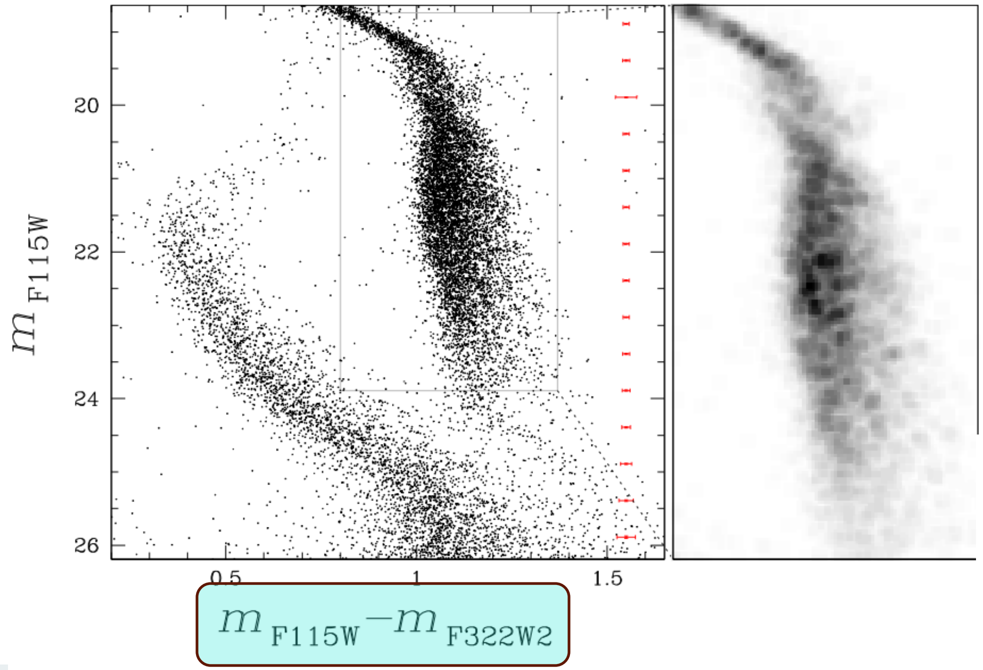
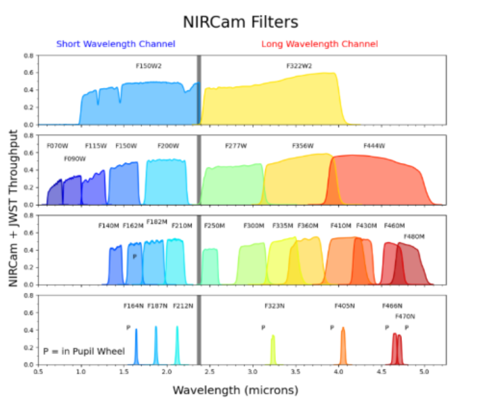
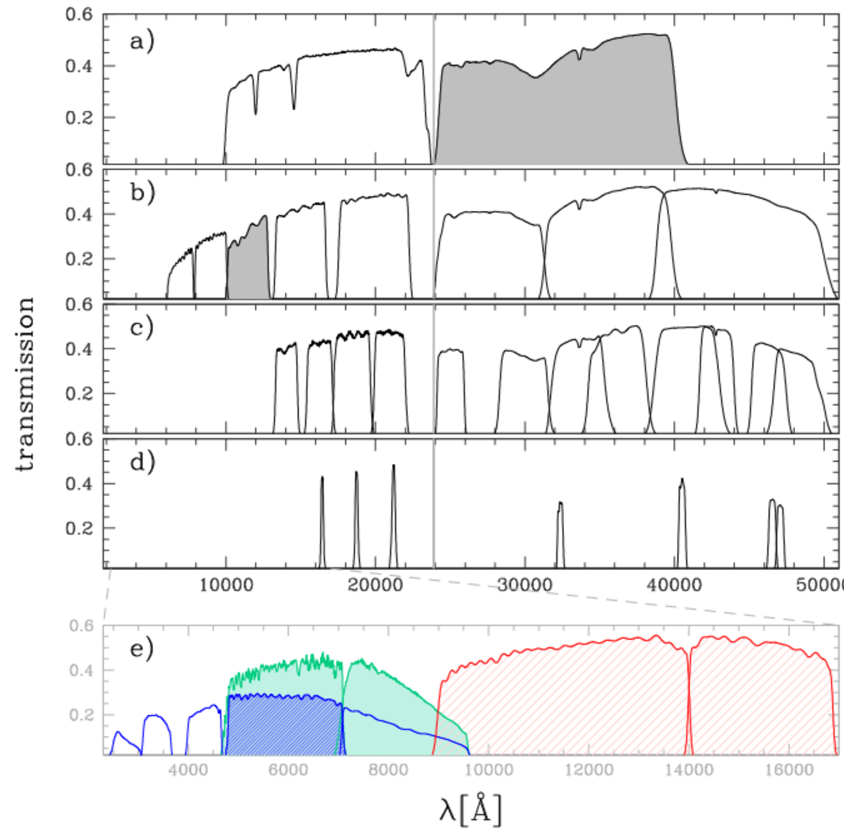
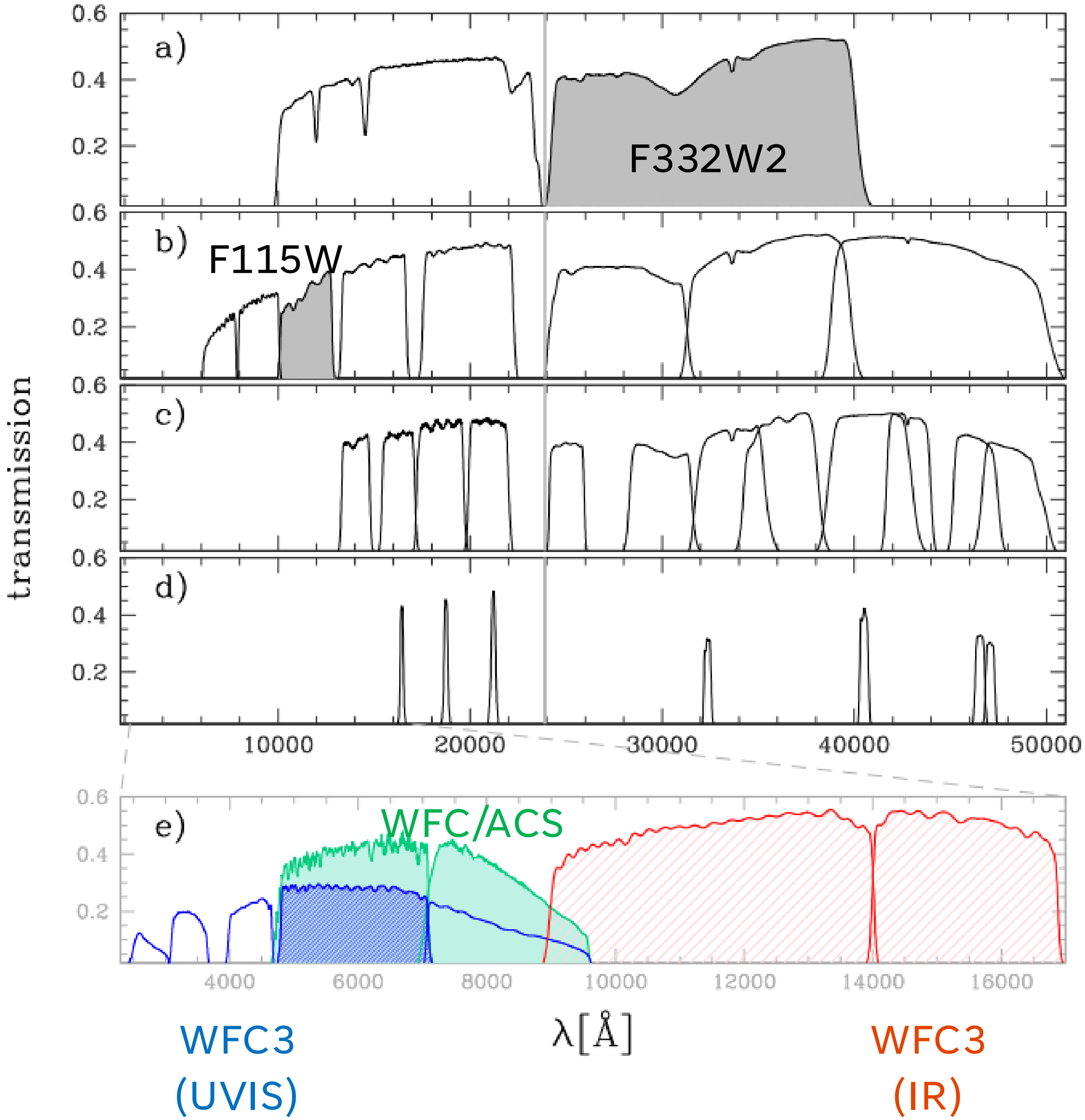






NIRCam + JWST filter throughputs



Milone et al. 2023

Synthetic spectral analysis

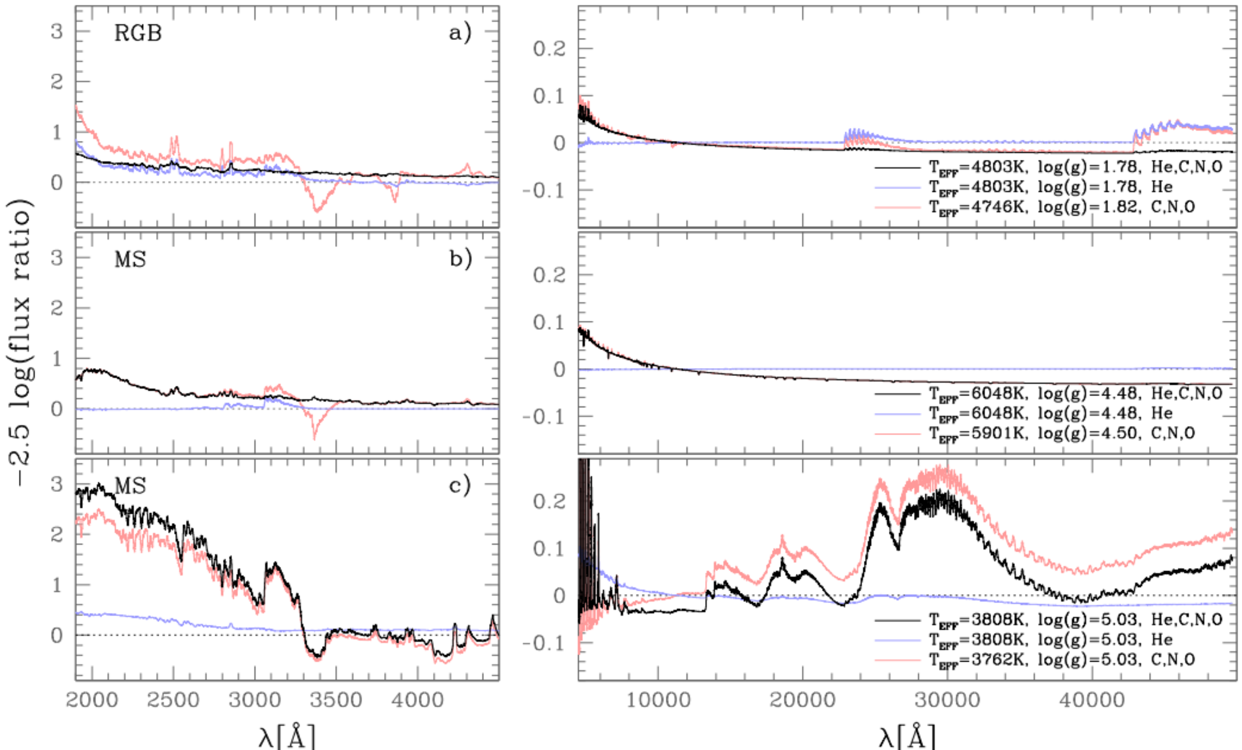


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Figure 9. The black lines compare the fluxes of simulated spectra for stars with the same *F*115*W* magnitude but 1P-like and 2P-like stellar compositions, with 2P stars being enhanced in helium and nitrogen, and depleted in carbon and oxygen with respect to the 1P. Panel a refers to RGB stars, whereas panels b and c are focused on a bright K-dwarf and M-dwarf, respectively. The pink lines refer to stars with the same He content abundances as 1P stars but different abundances of C, N, and O, while the azure lines are derived from spectra with the same C, N, and O content as 1P stars but enhanced helium content. The left and right panels refer to the wavelength intervals with $\lambda < 4500$ Å and $\lambda > 4500$ Å, respectively. See the text for details.

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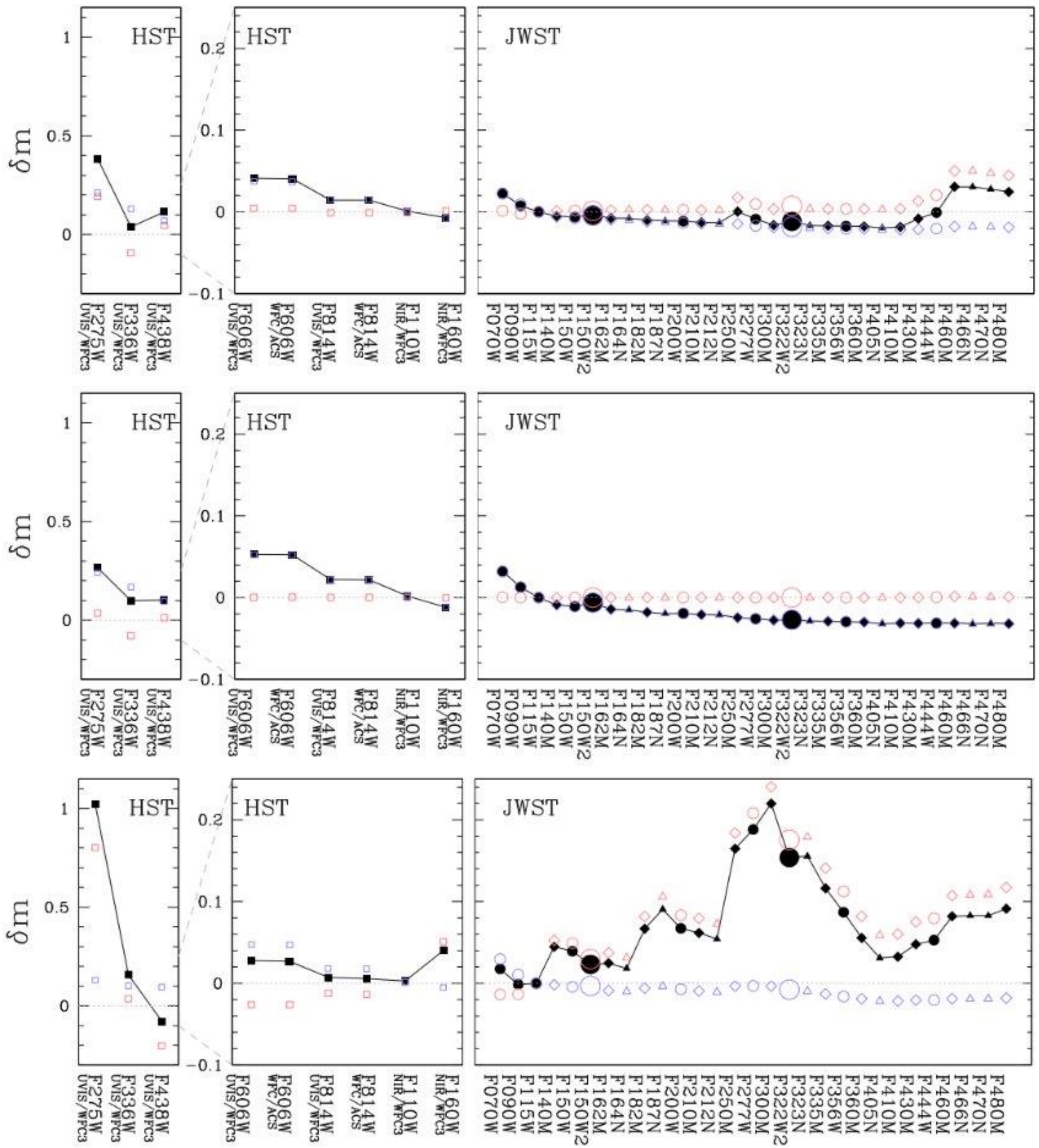

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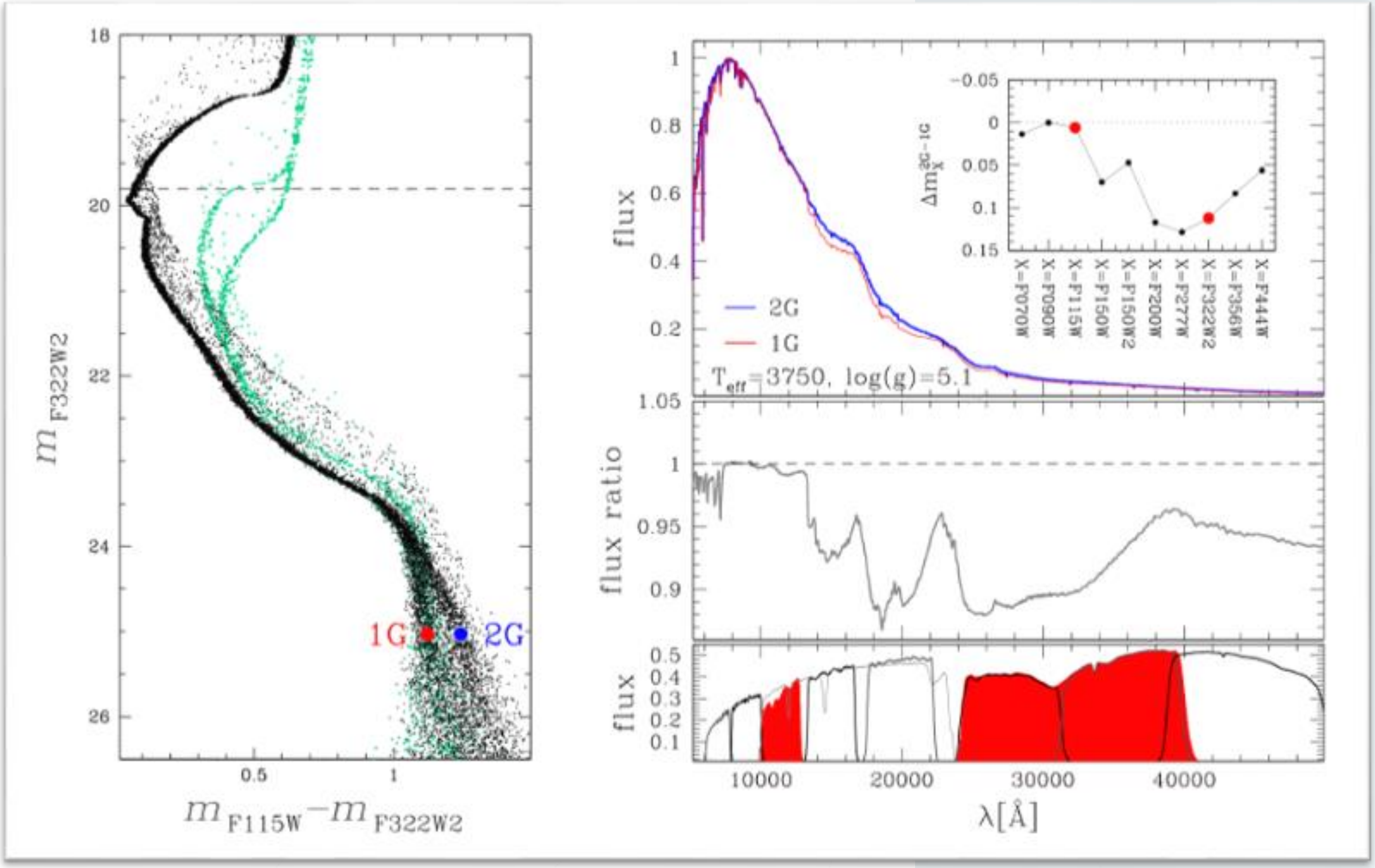
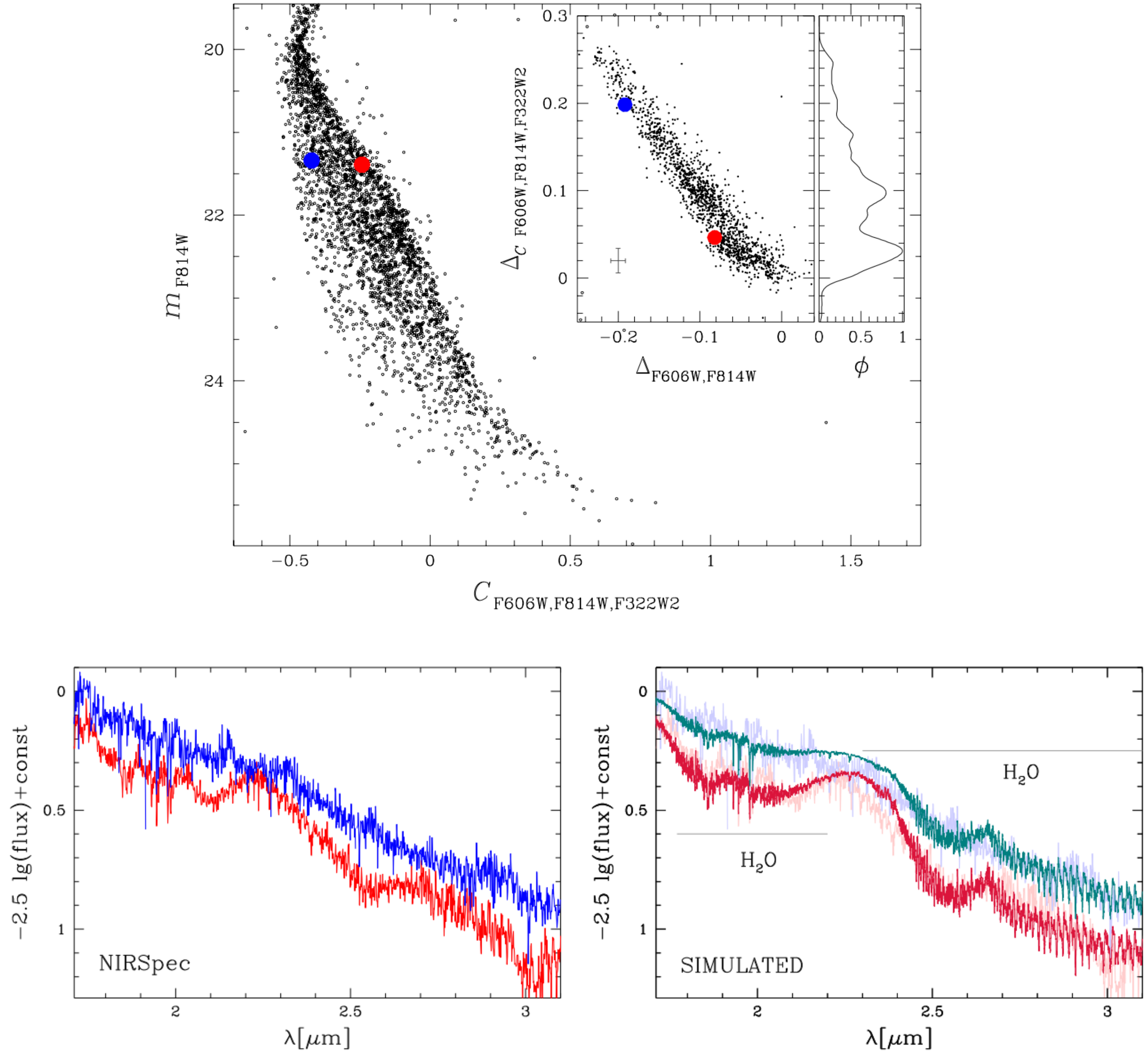
Best band combination to study Multiple Stellar Populations among M-dwarf stars





m_{F814W}
$C_{F606W,F814W,F322W2}$
$\Delta_{C\ F606W,F814W,F322W2}$
$\Delta_{F606W,F814W}$
ϕ
$-2.5\ lg(flux)+const$
$\lambda[\mu m]$
NIRSpec
SIMULATED
H_2O
H_2O

Table 2
Average [O/Fe] Abundances, Associated Error, and rms of the Inferred for the Four Stellar Populations Selected on the M Dwarf Chromosome Map

	[O/Fe]	±	rms	#
1P	+0.30	0.04	0.13	10
2Pa	+0.18	0.03	0.09	11
2Pb	+0.04	0.09	0.09	2
2Pc	−0.08	0.06	0.13	5

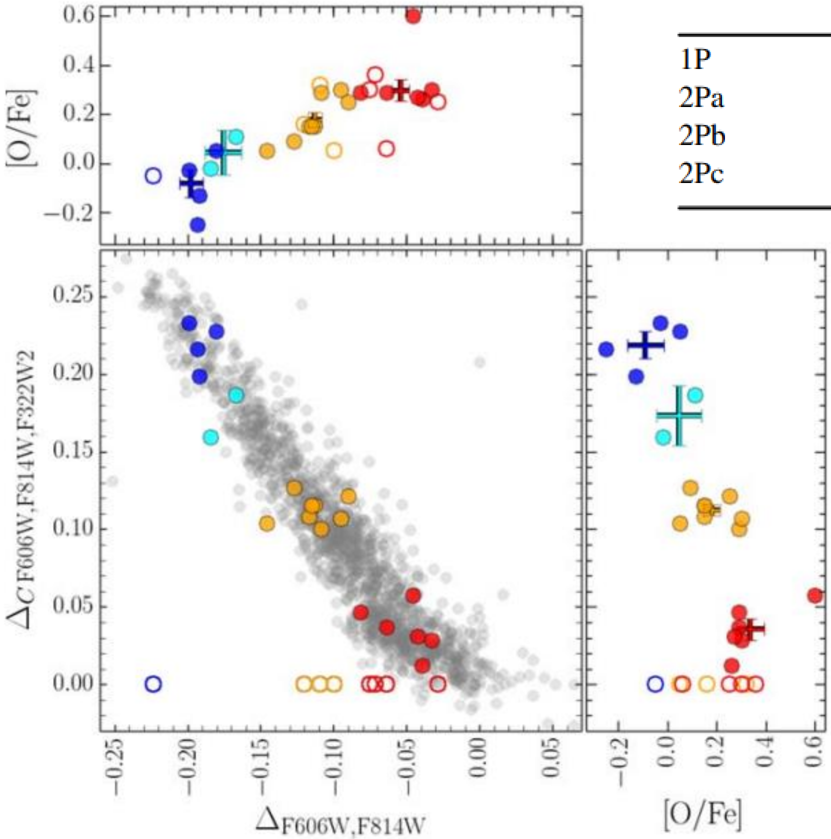


Figure 4. ChM diagram of M dwarfs in 47 Tucanae from JWST-HST photometry (gray dots). Spectroscopic targets observed with NIRSpec at JWST are represented with filled colored circles. Targets with no available m_{F322W2} from NIRCam at JWST are plotted with $\Delta_{C\ F606W,F814W,F322W2} = 0.00$ as empty circles. Different colors have been used for stars associated with different stellar populations on the ChM, specifically: first population (1P) stars are colored in red, second population ones have been colored in orange (2Pa), cyan (2Pb), and blue (2Pe). The [O/Fe] abundance vs. the $\Delta_{F606W,F814W}$ and $\Delta_{C\ F606W,F814W,F322W2}$ values are shown in the upper and right panels, respectively. For each population, we plot the average values and the associated error.

Marino et al. 2024b

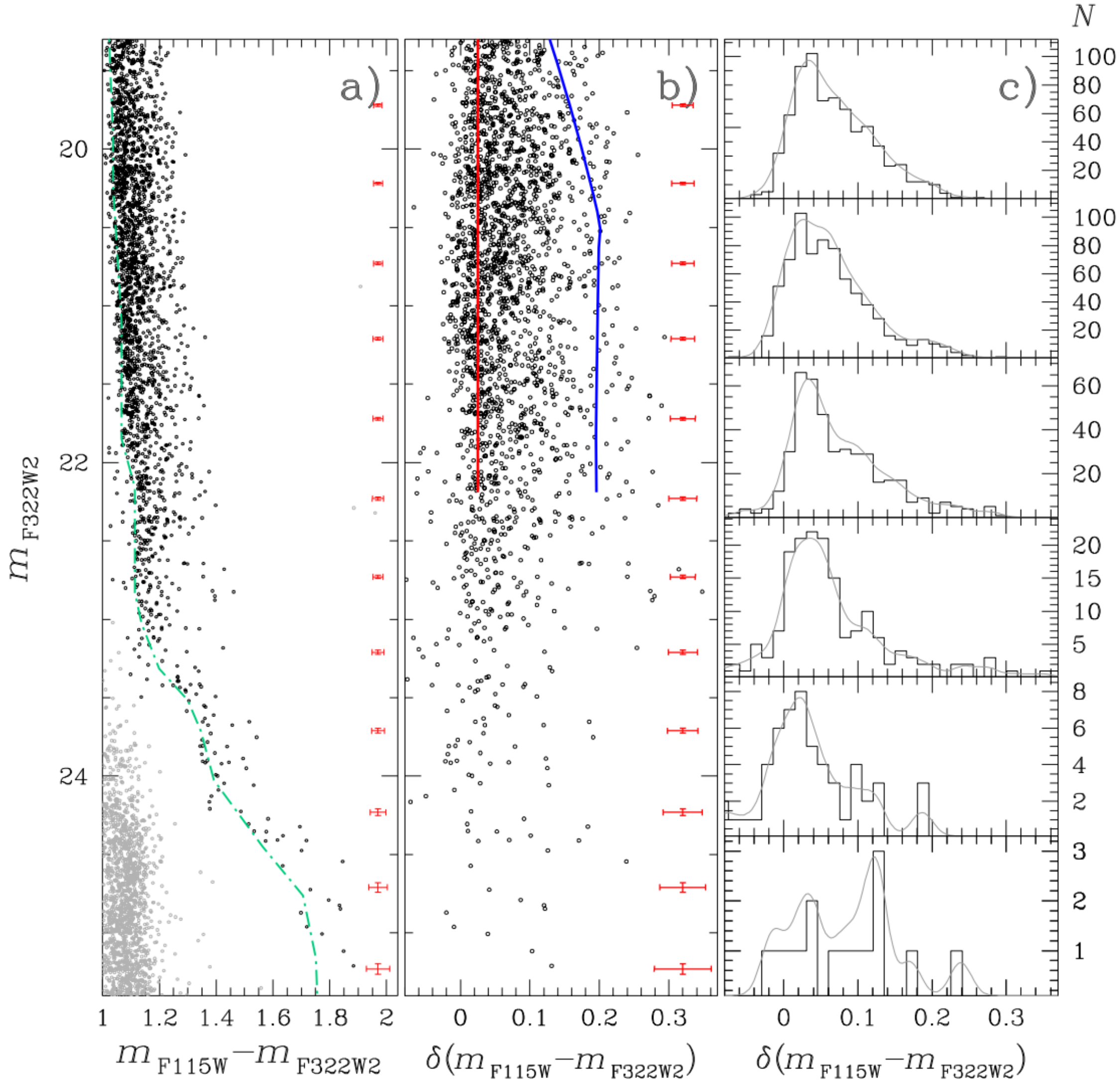
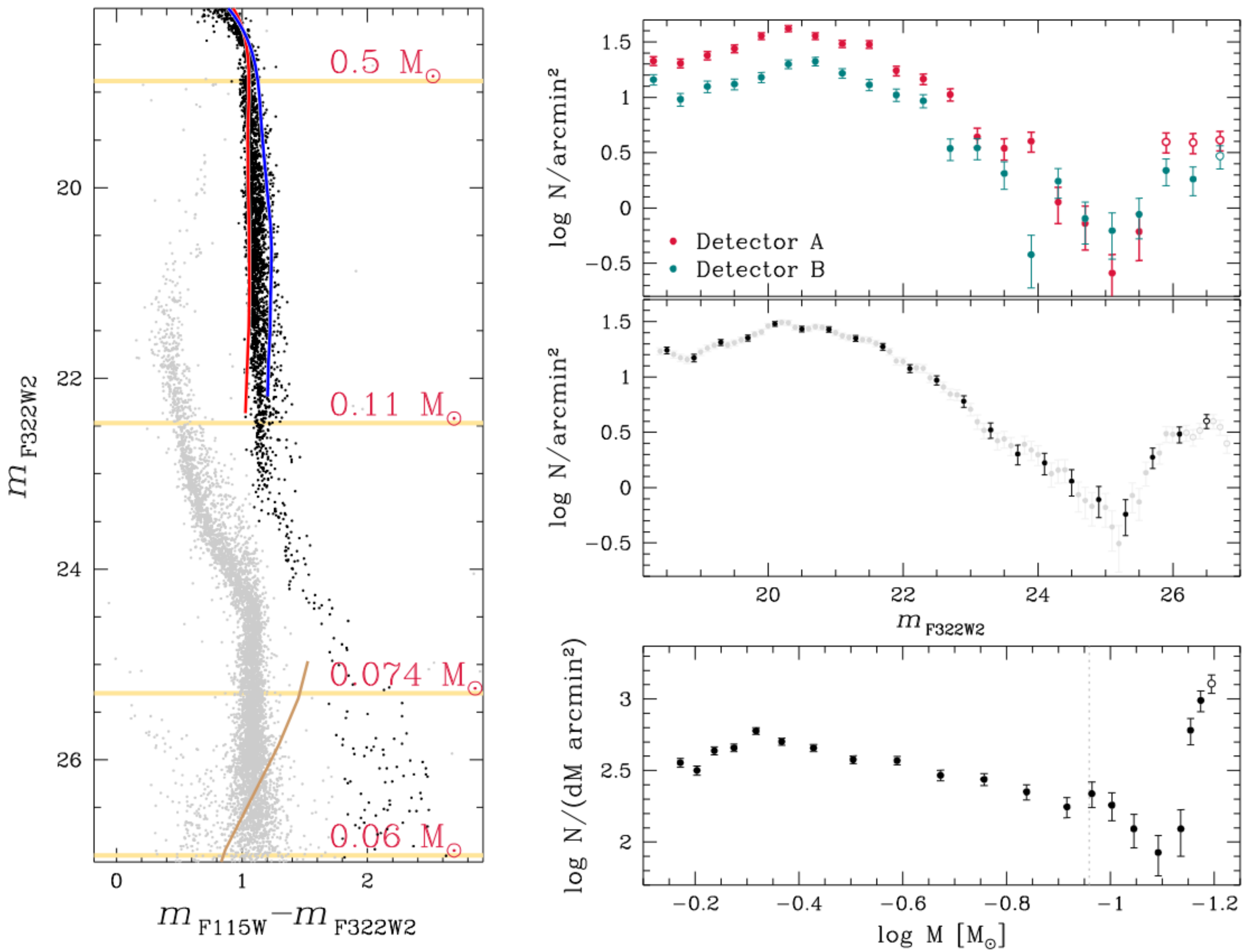


Figure 7. Reproduction of the $m_{\rm F322W2}$ vs. $m_{\rm F115W} - m_{\rm F322W2}$ CMD of Figure 4 zoomed in around the bottom of the MS of 47 Tucanae (panel (a)). The aqua line is the blue boundary of the MS and is used to derive the $m_{\rm F322W2}$ vs. $\delta(m_{\rm F115W} - m_{\rm F322W2})$ verticalized diagram shown in panel (b). The red and blue lines are the best-fit isochrones for MS stars with [O/Fe] = 0.4 and [O/Fe] = −0.1 dex, respectively (Dotter et al. 2008; Milone et al. 2023a). Panel (c) illustrates the δ $(m_{\rm F115W} - m_{\rm F322W2})$ histogram distributions for stars in six F322W2 magnitude intervals and the corresponding kernel-density distributions.

What is the nature of the gaps along the lowest MS?



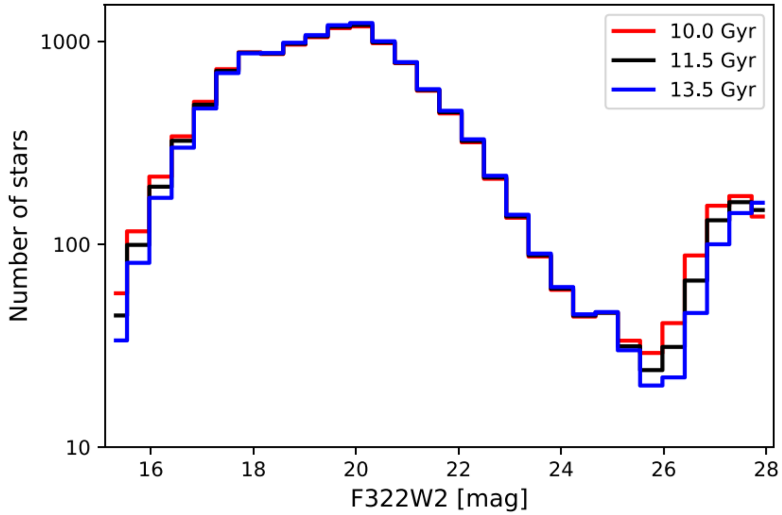


Figure 9. Predicted magnitude distribution of stars and brown dwarfs in 47 Tucanae at three different ages. The bright and faint peaks represent the main sequence and the brown dwarfs of the cluster, respectively, with a clear stellar/substellar gap in between. The distribution is normalized to the number of stars in the data set (Section 3). An animated version of this figure is available in the digital version of the publication. The animation lasts 6 s and includes 30 frames. The animation shows the evolution of the magnitude function from 0.1 to 13.5 Gyr. Initially, the magnitude function only has one peak around $m \sim 20$ corresponding to the main sequence of the cluster. The stellar/substellar gap forms at $m \sim 23.5$ around 0.5 Gyr. Over time, it gradually deepens, widens, and shifts to fainter magnitudes.

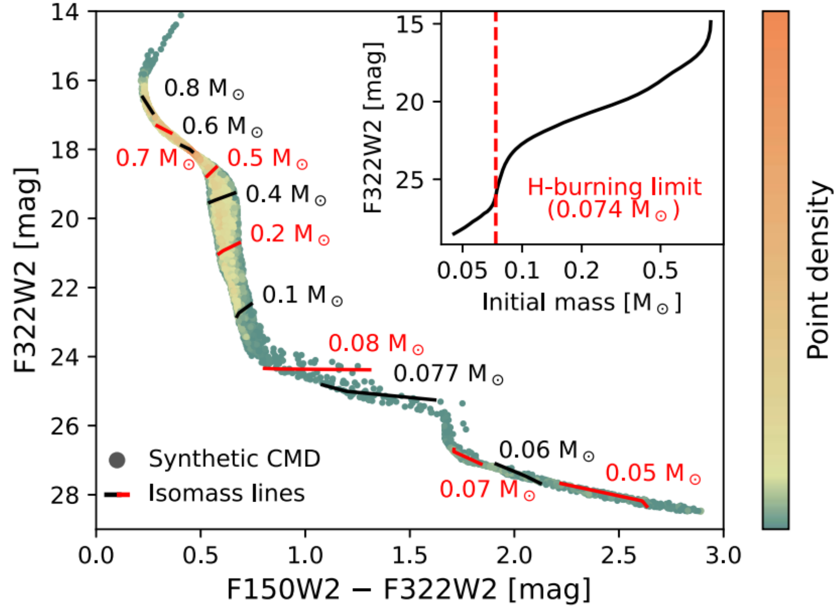


Figure 10. Predicted CMD of 47 Tucanae from the subgiant branch to the substellar sequence. Isomass lines are shown for selected masses. The color scatter in the figure is derived from the inferred distribution of [O/Fe] near the end of the main sequence. The inset in the upper right corner shows the mass–magnitude relationship for the ridgeline isochrone with the HBL highlighted.

Gerasimov et al. 2024