Ultra-Diffuse Galaxy Dragonfly 44

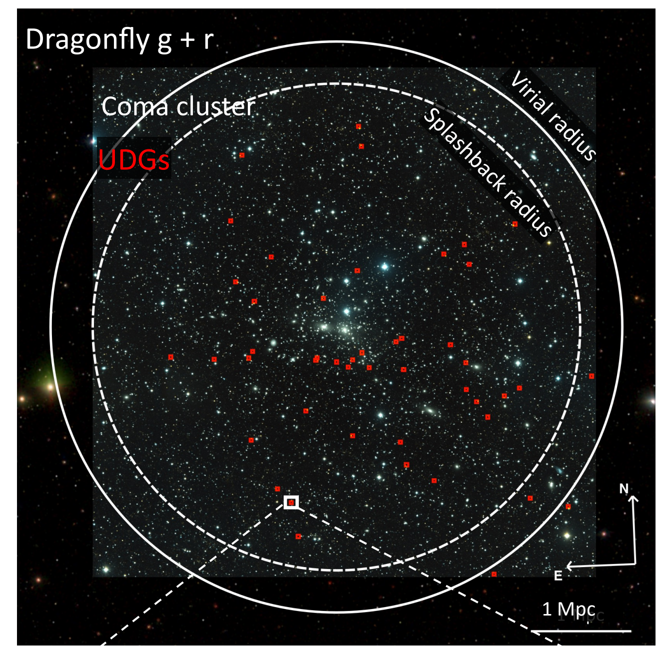
Still at Odds with Conventional Galaxy Evolution

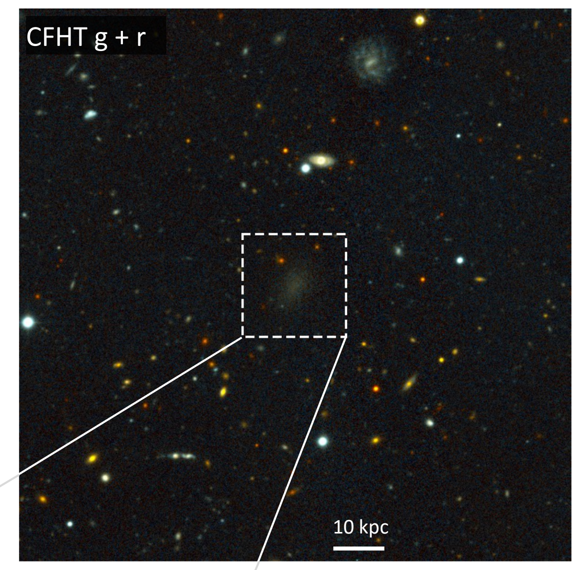
Simultaneously Modeling Photometry and Spectroscopy to Measure DF44's Star Formation History

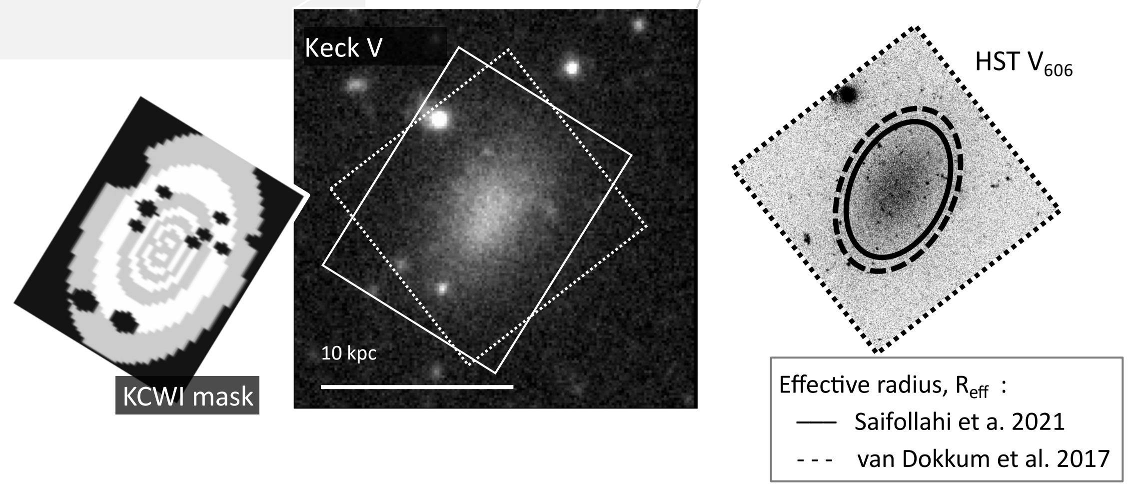
Kristi Webb,[1,2] Alexa Villaume,[1,2] Seppo Laine,[3] Aaron J. Romanowsky,[4,5] Michael Balogh,[1,2]
Pieter van Dokkum,[6] Duncan A. Forbes,[7] Jean Brodie,[8] Christopher Martin,[9] Matt Matuszewski[9]

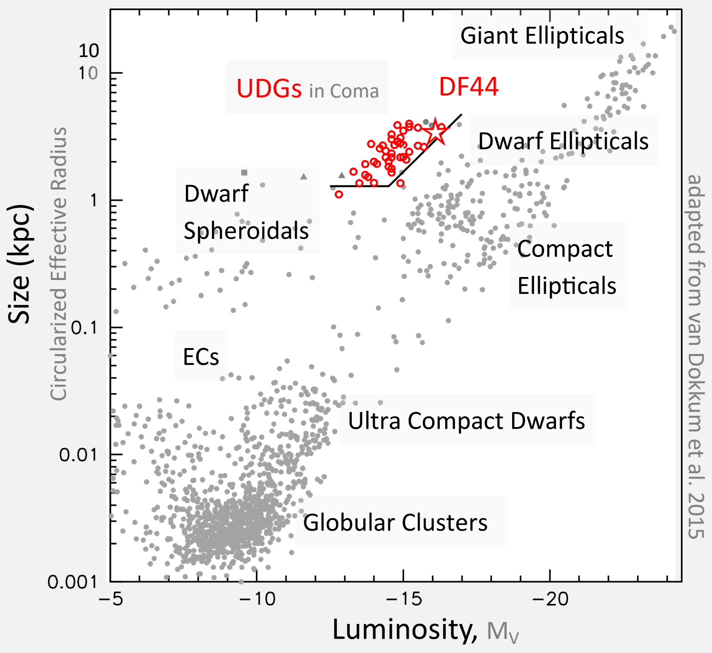
Abstract: The Ultra-Diffuse Galaxy (UDG) Dragonfly 44 (DF44) has a curious set of properties which are inconsistent with theoretical models of UDG formation. This challenges conventional theories for galaxy evolution, implying that current models models are missing the true diversity of galaxy formation and evolution. We summarize the observational properties of DF44, including our work determining its star formation history (SFH).

Right column: A non-comprehensive summary of photometric and spectroscopic observations of DF44.









UDGs have sizes like giant galaxies, but luminosities like dwarf galaxies.

Left: Sizes and magnitudes of quiescent objects from the literature. Black lines denote the selection criteria for UDGs: $R_{eff} \geq 1.5$ kpc and $\mu_0(g) \geq 24$ mag arcsec^{-2}.

What makes UDGs different? Are they large dwarf galaxies? Or "failed" giant galaxies?

Theoretical models attempt to explain UDGs as enlarged dwarfs, invoking only conventional galaxy evolution, and environmental-quenching. UDGs and dwarf galaxies should therefore have similar properties. Observations of UDGs have shown that the population is diverse, and that there are several discrepancies with the predicted properties from simulations.

The alternative "failed galaxy" scenario suggests that UDGs would have been massive galaxies had their evolution not been interrupted. This idea was initially proposed to explain why some UDGs have abundant globular cluster (GC) populations, implying over-massive DM halos (by conventional scaling relations). While UDG halo masses are controversial, it remains a compelling scenario in that it correctly predicts the stellar population properties, sizes, and ages of some UDGs.

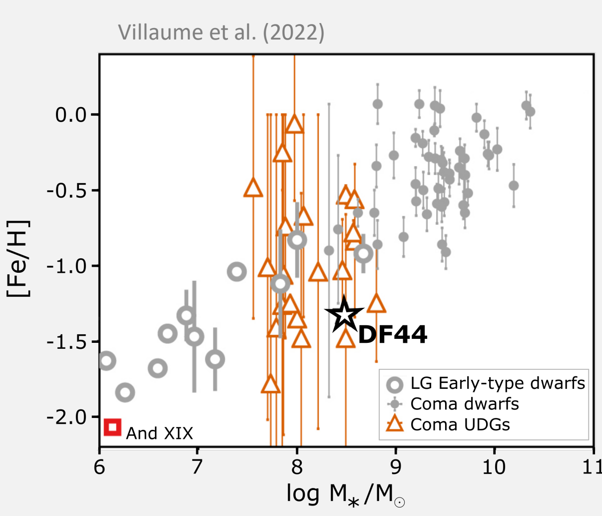
Dragonfly 44 – observed properties suggest this UDG is not an enlarged dwarf.

DF44 is one of the **largest UDGs** in Coma, beyond the predictions of most models.

Found in the outskirts of the Coma cluster, DF44's kinematics and dynamics suggest that it is on first infall into this cluster (< 2 Gyr ago), and hence has **not been environmentally processed.** Moreover, it appears to be a part of a cold group, and has no tidal distortion features.

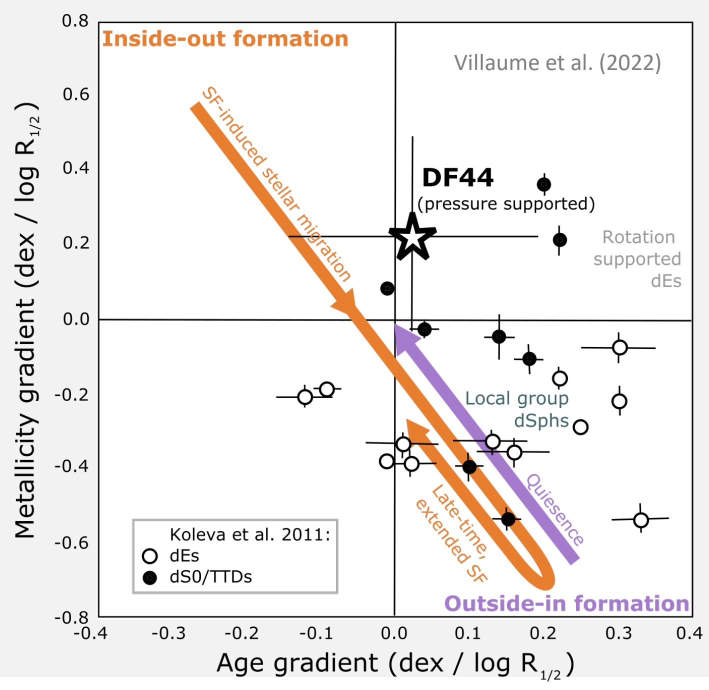
DF44's **stellar populations are old and quiescent**, and hence it quenched prior to infall into Coma. This is in contrast to nearly all theoretical models, which require post-infall environmental quenching.

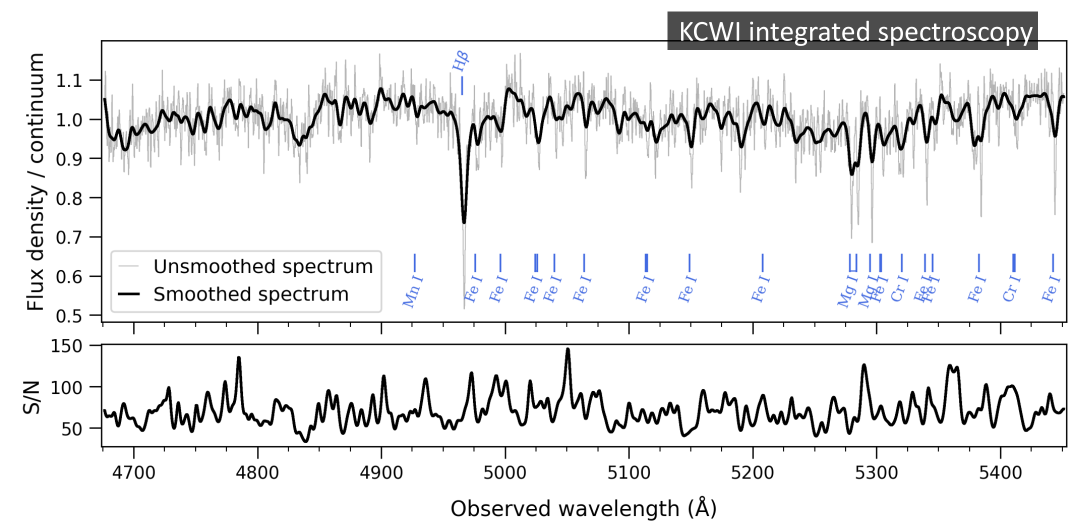
High-resolution and high-S/N Keck CWI observations showed that the **stellar population properties and gradients of DF44 are dissimilar to canonical dwarf galaxies**.

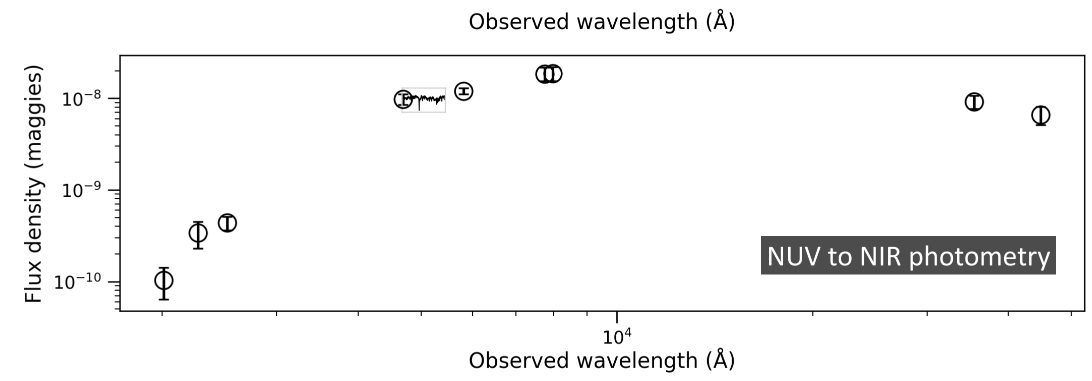


Left: DF44 falls below the mass-metallicity relation of canonical dwarfs (by ~2.3σ). This suggests that DF44 had a very short star formation (SF) timescale.

Right: DF44's stellar population gradients are inconsistent with both observations of dwarfs, and predictions from simulations of canonical dwarfs.





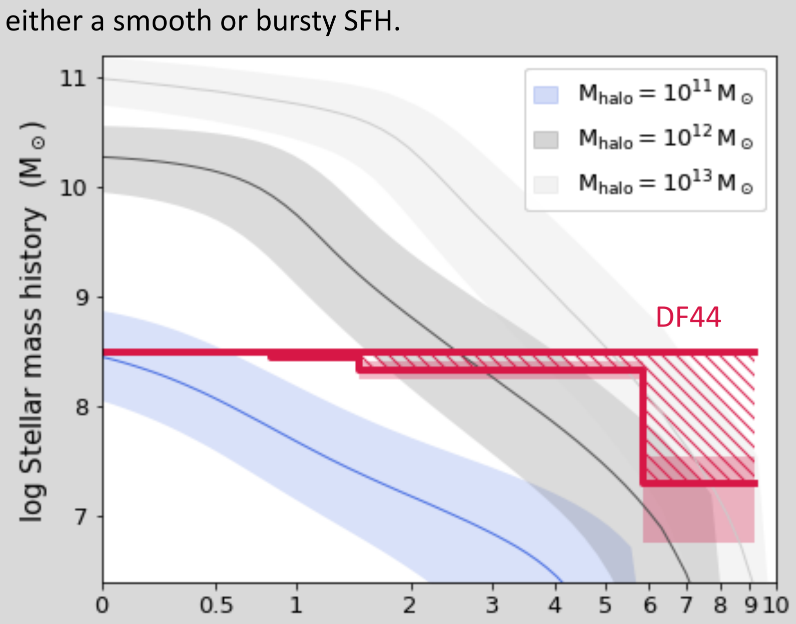


DF44 formed very early and quenched rapidly – again at odds with theoretical models.

DF44's stellar population gradients suggest that it quenched early and catastrophically, but timescales are needed to compare with theoretical simulations.

We simultaneously fit the photometry and spectroscopy to a physical model, with a flexible 'nonparametric' star formation history. The fitting is preformed in a fully Bayesian framework with the inference code Prospector (Leja et al. 2017b, Johnson et al. 2019, 2021b).

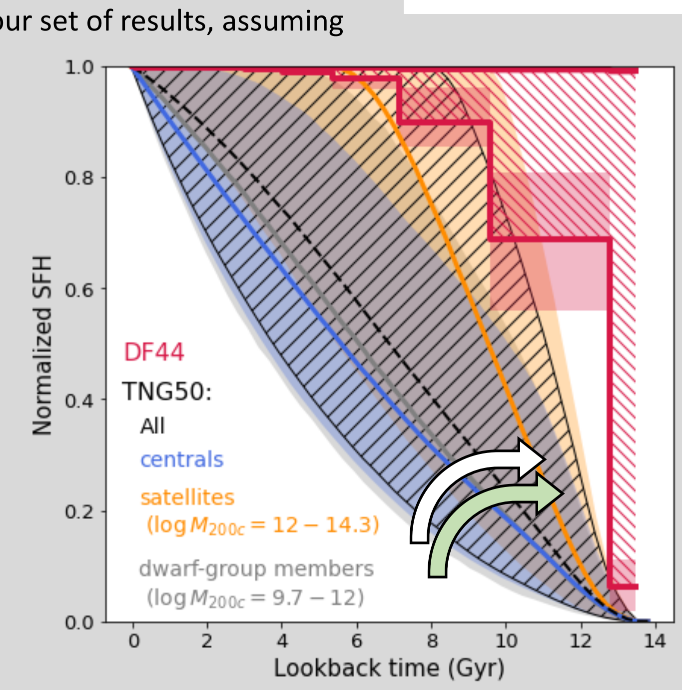
Measuring the ages/SFHs of old stellar populations is challenging in several ways – we therefore present the range of results for different assumptions about the mass assembly history. Hatched red lines indicate the range in parameter space between our set of results, assuming either a smooth or bursty SFH.



Left: Comparing DF44's stellar mass history against predictions for ***average*** **galaxies in halos of different mass**.

Models from the Universe Machine (Behroozi et al. 2019).

DF44's forms the bulk of its mass during an epoch where galaxies in dwarf-scale haloes significantly different from those in more massive haloes.



Left: Comparing DF44's SFH with predictions for the stellar mass assembly of **dwarf galaxies in different environments.**

Models from TNG50 (Joshi et al. 2021).

DF44's SFH resembles that of the satellite dwarfs which have early infall times and large stellar-to-halo mass ratios. Yet DF44 appears to have only recently accreted into Coma.

Higher $\log(M_*/M_{halo})$
Earlier infall

Proposed UDG formation scenario

Observable	Failed L* galaxy	Failed dwarf galaxy	Enlarged dwarf: Tidal interaction	Enlarged dwarf: Stellar feedback	Enlarged dwarf: High-spin	Enlarged dwarf: Early mergers
Large size	✓	✗	✓	✗		?
Recent infall into Coma	✓		✗	✗	✓	?
Abundant GC population (?)	✓		✗	✗	?	?
Stellar pop. gradients	✓		✗	✗	✗	?
Formed early, quenched rapidly	✓		✓		✗	?

DF44 is the product of unique galaxy evolutionary processes, not described by current theoretical models of UDG formation

Left: The implications of DF44's properties for proposed UDG formation models. The majority of "enlarged dwarf" scenarios cannot simultaneously explain DF44's properties.

The early-major merger model (Wright et al. 2021) remains intriguing in that quenching is not necessarily linked to environment, however more predictions are needed to test whether objects like DF44 can be described by this model.

DF44 stands out among Coma UDGs in size and SFH, but it's one of a number of "outliers".

UDGs are a diverse population, likely with distinct formation pathways.
Theoretical models of galaxy evolutions need to be revised to explain these exotic galaxies.

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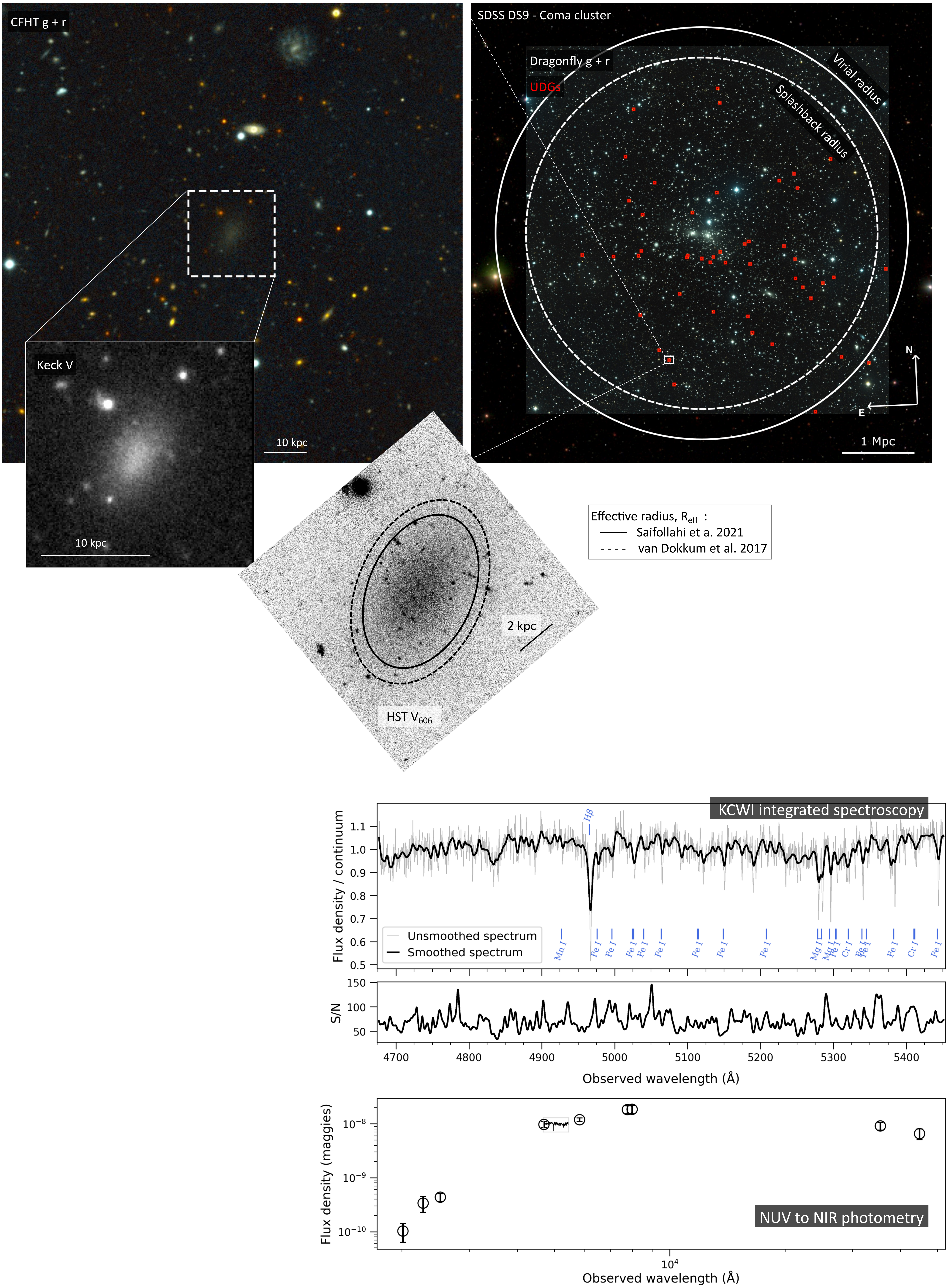
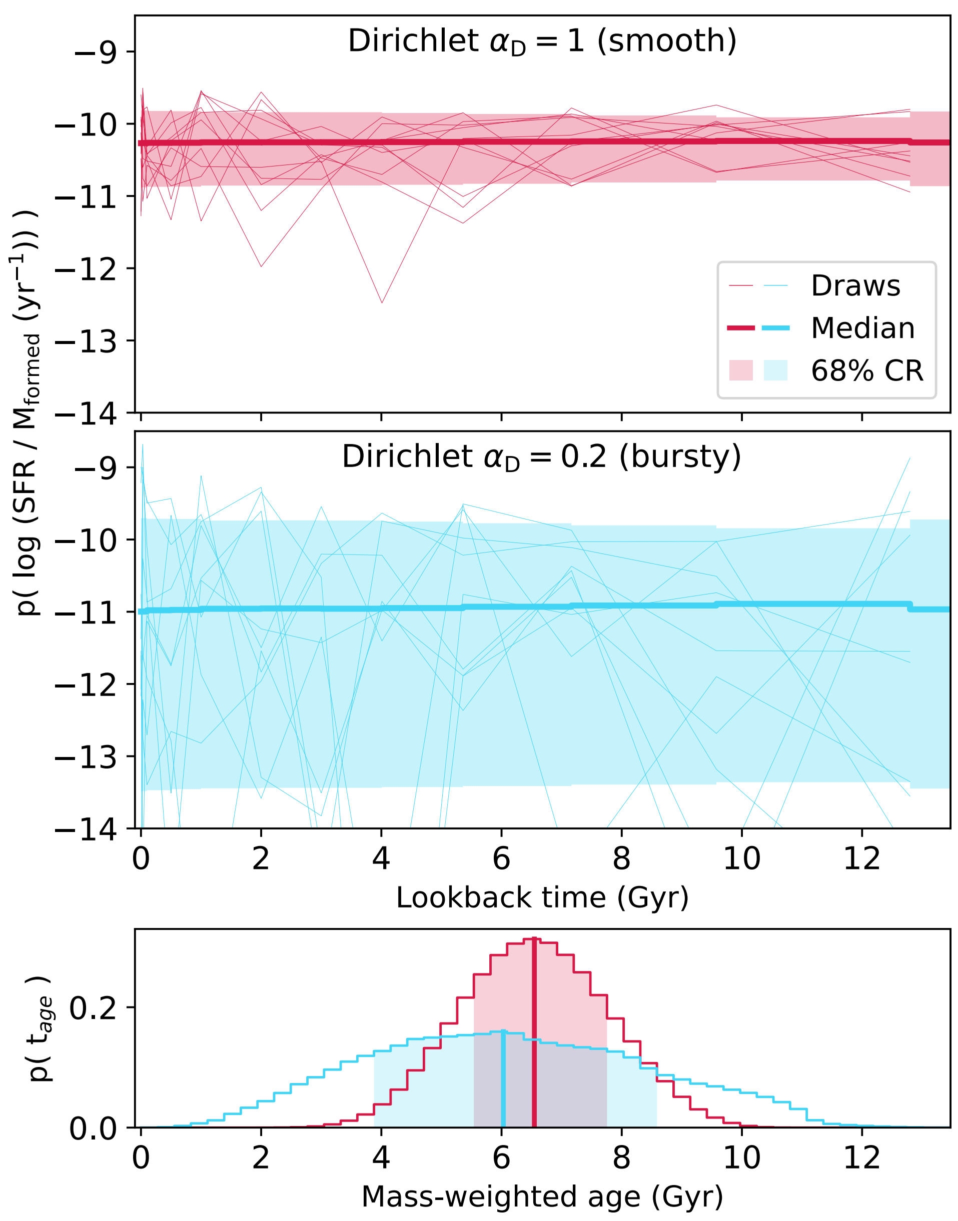
Affiliations: 1) Waterloo Centre for Astrophysics, 2) University of Waterloo, 3) IPAC, 4) San José State University, 5) UC Santa Cruz, 6) Yale, 7) Swinburne University, 8) Cahill Center for Astrophysics

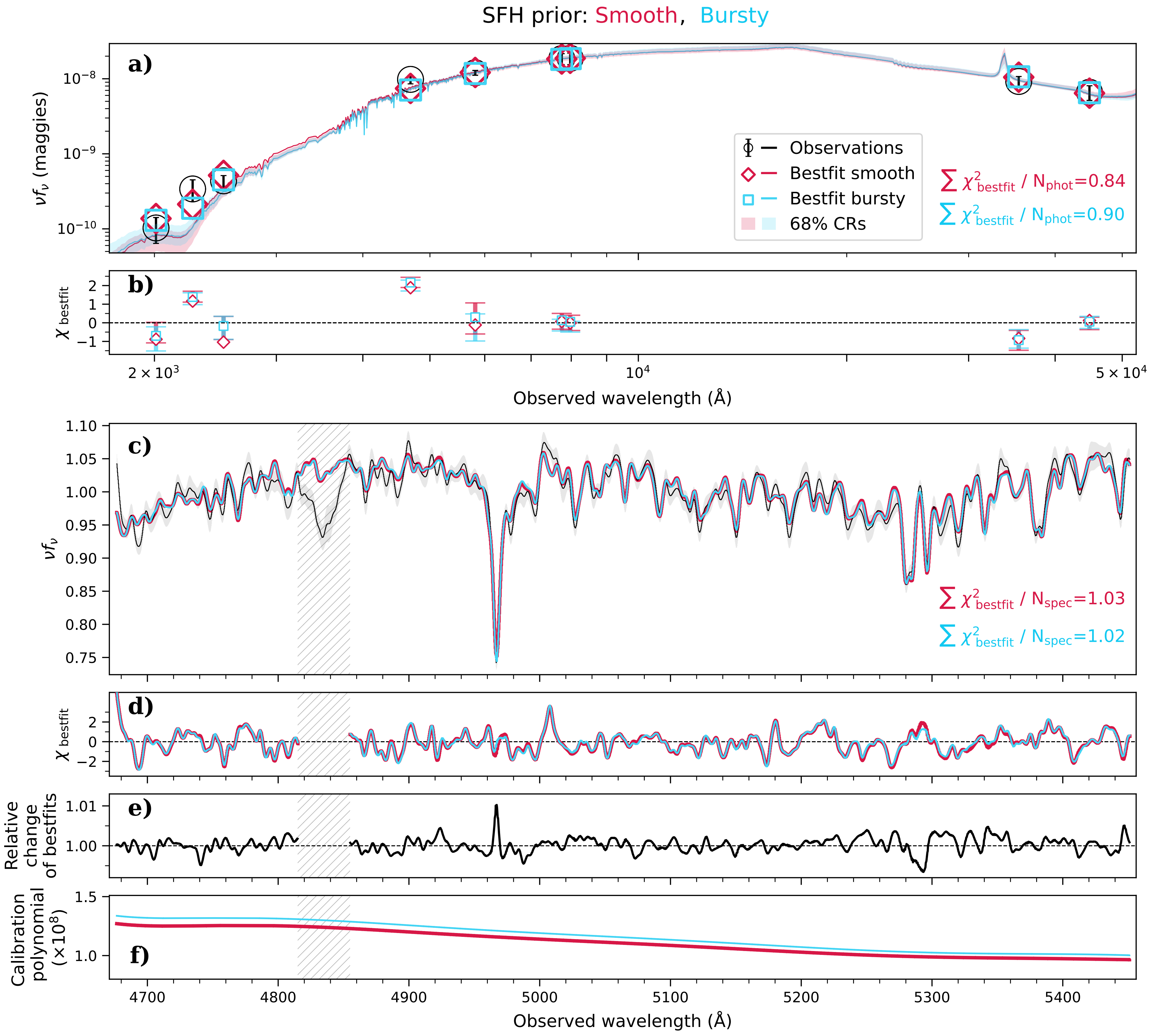


CFHT g + r
10 kpc
Keck V
10 kpc
SDSS DS9 - Coma cluster
Dragonfly g + r
UDGs
Virial radius
Splashback radius
N
E
1 Mpc
Effective radius, R$_{eff}$:
Saifollahi et a. 2021
van Dokkum et al. 2017
2 kpc
HST V$_{606}$
KCWI integrated spectroscopy
Hβ
Unsmoothed spectrum
Smoothed spectrum
Flux density / continuum
S/N
Observed wavelength (Å)
NUV to NIR photometry
Flux density (maggies)
Observed wavelength (Å)

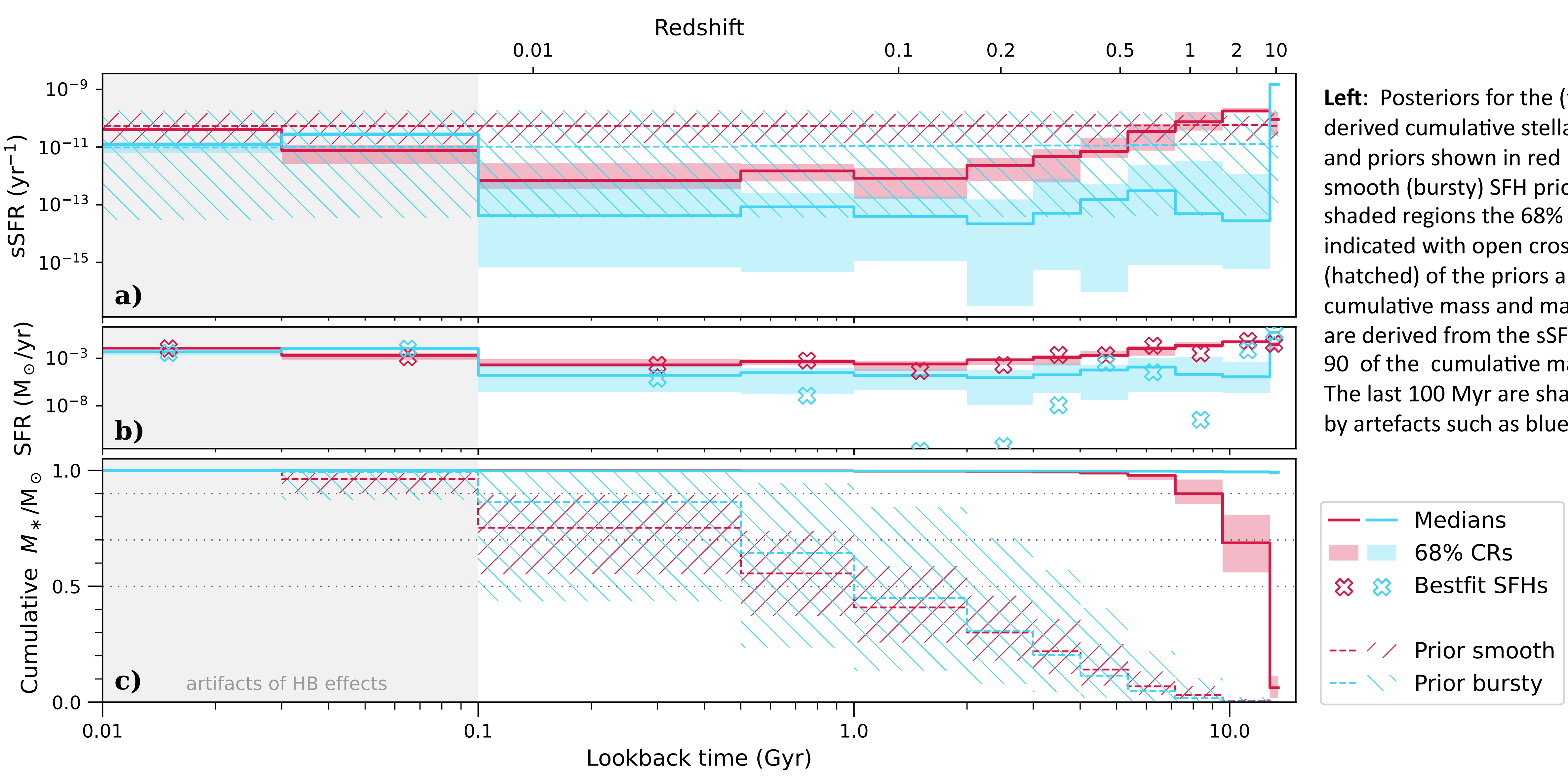
Measuring the ages/SFHs of old stellar populations is challenging in several ways – <u>we therefore present the range of results for different assumptions about the mass assembly history</u>.



Above: Comparison of SFH priors between specific SFR (SFR per unit mass; first and second panels) and corresponding mass-weighted age (third panel). The sSFR is shown as a function of lookback time for ten random draws (thin lines) from the Dirichlet SFH priors with α_D=1 (smooth; red) and α_D=0.2 (bursty; blue). The medians and 68% credible regions (CRs) of the prior are indicated with thick lines and shaded regions, respectively. The implicit mass-weighted age priors are shown in the lower panel, with vertical lines indicating the median, and shaded regions indicating the 68% CRs.



Above: Summary of the fitting results for DF44. The observed data (black) is compared to the bestfit models (red, smooth SFH prior; blue, bursty SFH prior) and the 68% CR of 500 randomly drawn models from the posteriors (red/blue shaded). From the top: i) the observed (circles) and bestfit (diamonds and squares) photometric points, where the χ^2/N_{data} of the bestfit SED is listed and ii) shows χ ([data-model]/σ) of the bestfit points.
iii) The observed (uncertainties shown in grey) spectrum and bestfit spectra (multiplied by the spectrophotometric calibration polynomial). The light grey region indicates the spectral region masked throughout the fitting process. iv) The χ of the bestfit spectra as a function of wavelength, v) the relative change of the bestfit models, and vi) the spectrophotometric calibration polynomials.



Left: Posteriors for the (from the top) i) sSFR, ii) derived SFR, and iii) derived cumulative stellar mass for the fits shown above. The results and priors shown in red (blue) colours correspond to the fit with a smooth (bursty) SFH prior. Solid lines indicate the median, and the shaded regions the 68% CR. The SFHs of the bestfit models are indicated with open crosses. The median (dashed line) and 68% CRs (hatched) of the priors are shown for reference. Note that the cumulative mass and mass-weighted age priors are implicit, as they are derived from the sSFR prior. Dotted lines are drawn at 50, 70, and 90 of the cumulative mass for reference.
The last 100 Myr are shaded grey to indicate that the SFH is affected by artefacts such as blue horizontal branch stars.

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[1] *Waterloo Centre for Astrophysics, University of Waterloo, Waterloo, Ontario, N2L3G1, Canada*
[2] *Department of Physics and Astronomy, University of Waterloo, Waterloo, Ontario N2L 3G1, Canada*
[3] *IPAC, Mail Code 314-6, Caltech, 1200 E. California Blvd., Pasadena, CA 91125, USA*
[4] *Department of Physics & Astronomy, San José State University, One Washington Square, San Jose, CA 95192, USA*
[5] *Department of Astronomy and Astrophysics, University of California Santa Cruz, 1156 High Street, Santa Cruz, CA 95064, CA, USA*
[6] *Astronomy Department, Yale University, 52 Hillhouse Avenue, New Haven, CT 06511, USA*
[7] *Centre for Astrophysics & Supercomputing, Swinburne University, Hawthorn VIC 3112, Australia*
[8] *Cahill Center for Astrophysics, California Institute of Technology, 1216 East California Boulevard, Mail Code 278-17, Pasadena, CA 91125, USA*

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ABSTRACT

We study the star formation history (SFH) of the ultra-diffuse galaxy (UDG) Dragonfly 44 (DF44) based on the simultaneous fit to near-ultraviolet to near-infrared photometry and high signal-to-noise optical spectroscopy. In fitting the observations we adopt an advanced physical model with a flexible SFH, and we discuss the results in the context of the degeneracies between stellar population parameters. Through reconstructing the mass-assembly history with a prior for a smooth SFH (akin to methods in the literature) we find that DF44 formed 90 per cent of its stellar mass by $z \sim 0.9$ (~ 7.2 Gyr ago). In comparison, using a prior that prefers short star formation time-scales (as informed by previous studies of DF44's stellar populations) suggests that DF44 formed as early as $z \sim 8$ (~ 12.9 Gyr ago). Regardless of whether DF44 is old or very old, the SFHs imply early star formation and rapid quenching. This result, together with DF44's large size and evidence that it is on its first infall into the Coma cluster, challenges UDG formation scenarios from simulations that treat all UDGs as contiguous with the canonical dwarf population. While our results cannot confirm any particular formation scenario, we can conclude from this that DF44 experienced a rare quenching event.

Key words: galaxies: evolution – galaxies: dwarfs