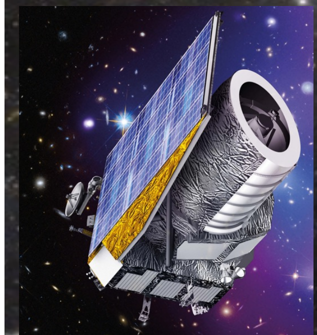
Galaxy Evolution with Euclid: The Local Universe View



Annette Ferguson
University of Edinburgh
w/ contributions from MWRSP SWG

Galaxy Assembly and Evolution Over Cosmic Time

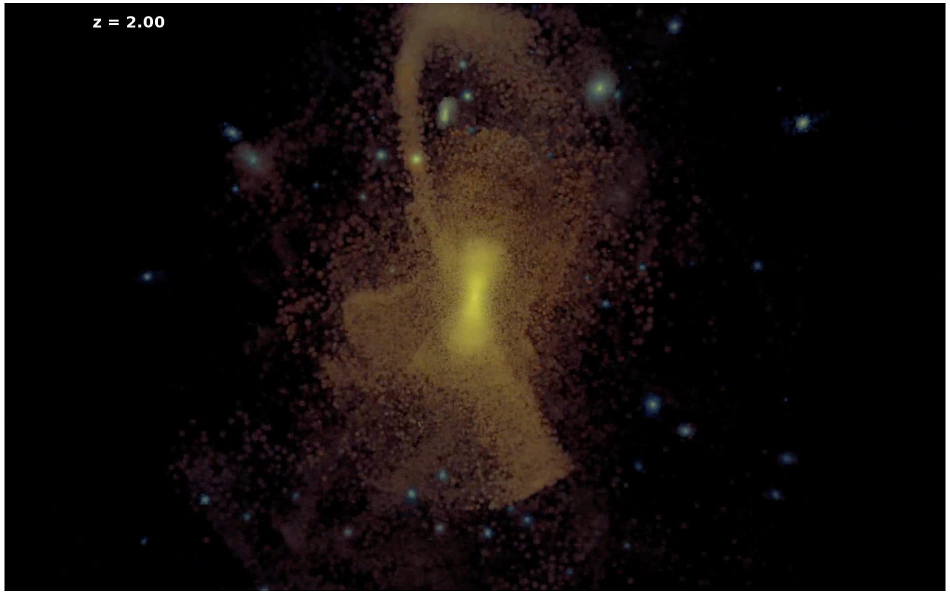
Goal is to build a coherent picture of how galaxies form and evolve from a few 100 Myr after the Big Bang through to the present-day.

- How did mass grow within individual galaxies/population of galaxies?
- What triggered and quenched star formation? How important was in situ star formation vs accretions/mergers?
- What is the shape of faint end of the galaxy luminosity function? What is the lower limit to galaxy formation?
- How representative are the Milky Way and M31 of other disc galaxies?
- Low and high redshift studies are complementary – do they provide a consistent picture?

Hierarchical Galaxy Formation

Galaxy growth in a ΛCDM universe is driven by mergers and accretions. Most vigorous activity expected during the first few billion years of evolution, with mostly small accretion events today.

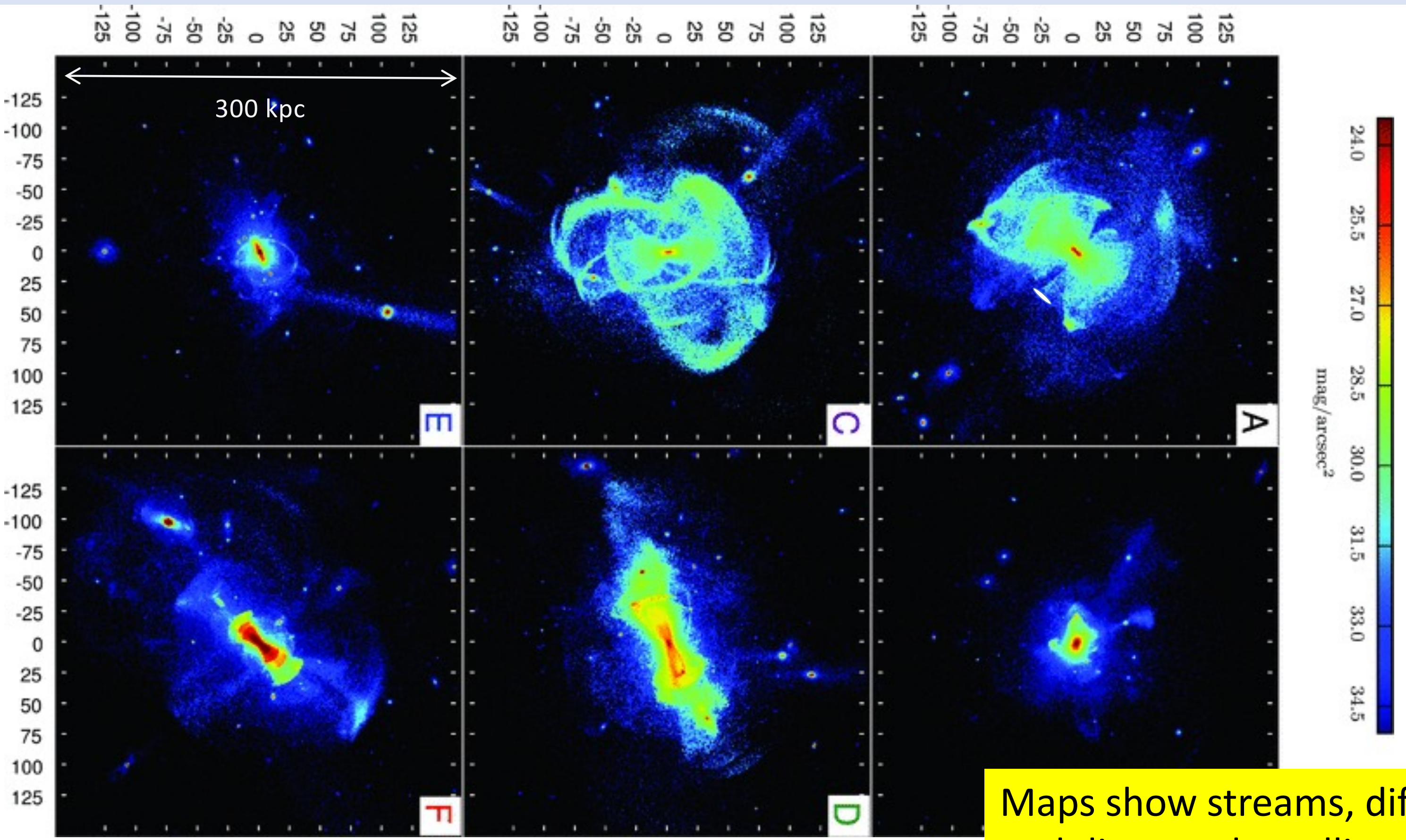
This hierarchical growth leaves copious signatures in galaxy outskirts that can persist for billions of years → tidal debris from decaying/destroyed satellites, huge stellar halos, globular star clusters.



Aquarius simulations
Credit: Andrew Cooper, John Helly, Shaun Cole, Carlos Frenk (University of Durham)

Galaxy Outskirts and Galactic Accretion Histories

Cooper et al. 2010, Aquarius simulations



μ_V in mag/sq. arscec

μ_V~27 → 1% dark sky

μ_V~29 → 0.1% dark sky

μ_V~32 → 0.01% dark sky

Maps show streams, diffuse halo light, and existing and disrupted satellites. A few hundred globular clusters will be present in each system too.

Galaxy Outskirts and Galactic Accretion Histories

Summary of General Trends for Stellar Halo Interpretation

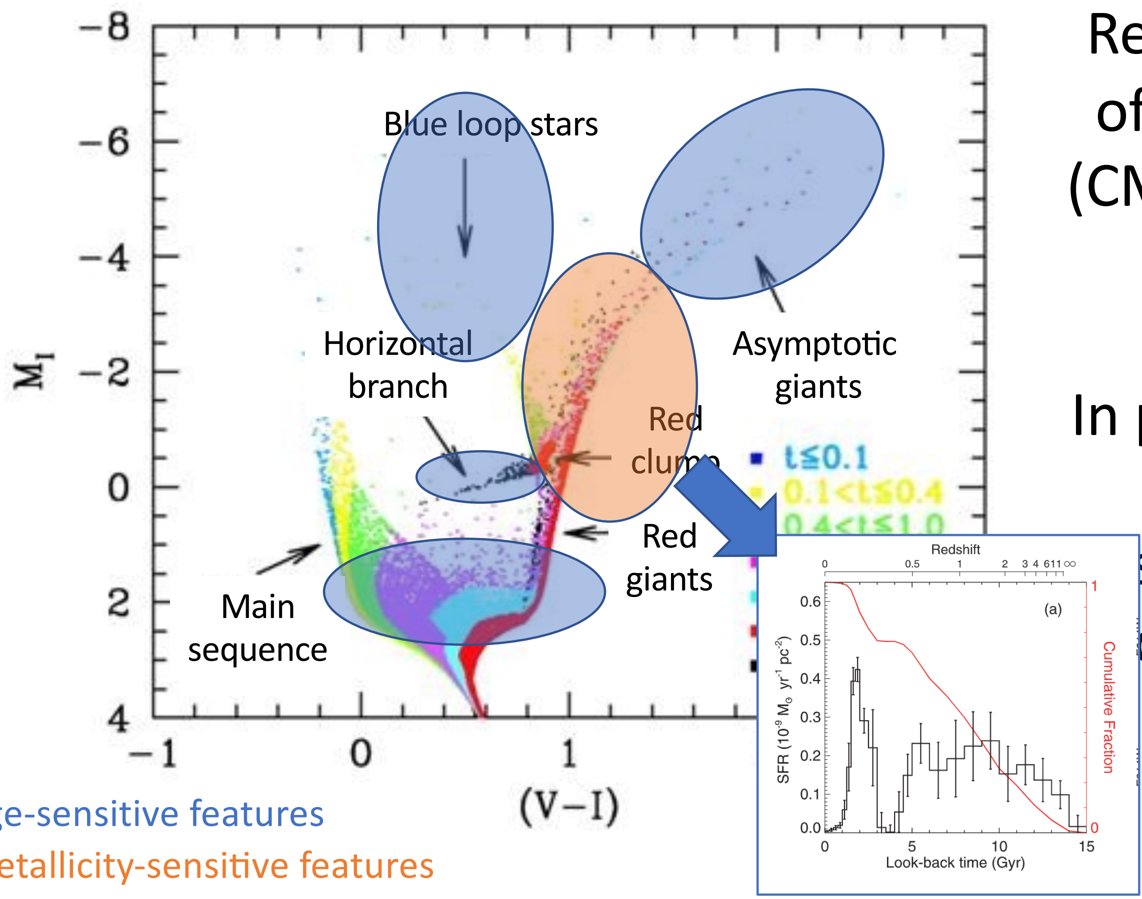
Observable Property	Interpretation	Implication
Fraction in substructure	Recent accretions	High fraction ⇒ many recent events Low fraction ⇒ few recent events
Scales in substructure	Luminosity function (and orbit type) of recent events	Large ⇒ high-luminosity events Small ⇒ low-luminosity events
Number of features	Number of recent events	Large ⇒ many events Small ⇒ few events
Morphology of substructure	Orbit distribution	Clouds/plumes/shells ⇒ radial orbits Great circles ⇒ circular orbit
[Fe/H]	Luminosity function	Metal-rich ⇒ high-luminosity events Metal-poor ⇒ low-luminosity events
[α/Fe]	Accretion epoch	α-rich ⇒ early accretion epoch α-poor ⇒ late accretion epoch

Caveat: Not all substructure is accreted!

Johnston et al. 2008; see also Hendel & Johnston 2015, Pillepich et al. 2014, Amorisco 2017 ++

Galaxy Archaeology with Resolved Stars

Aparicio & Gallart et al. 2005



Age-sensitive features

Metallicity-sensitive features

Resolved stars populate regions of a colour-magnitude diagram (CMD) according to their masses, ages and metallicities.

In populations older than ~1 Gyr, the red giant branch (RGB), symptotic giant branch (AGB) d red clump/horizontal branch are the dominant features.

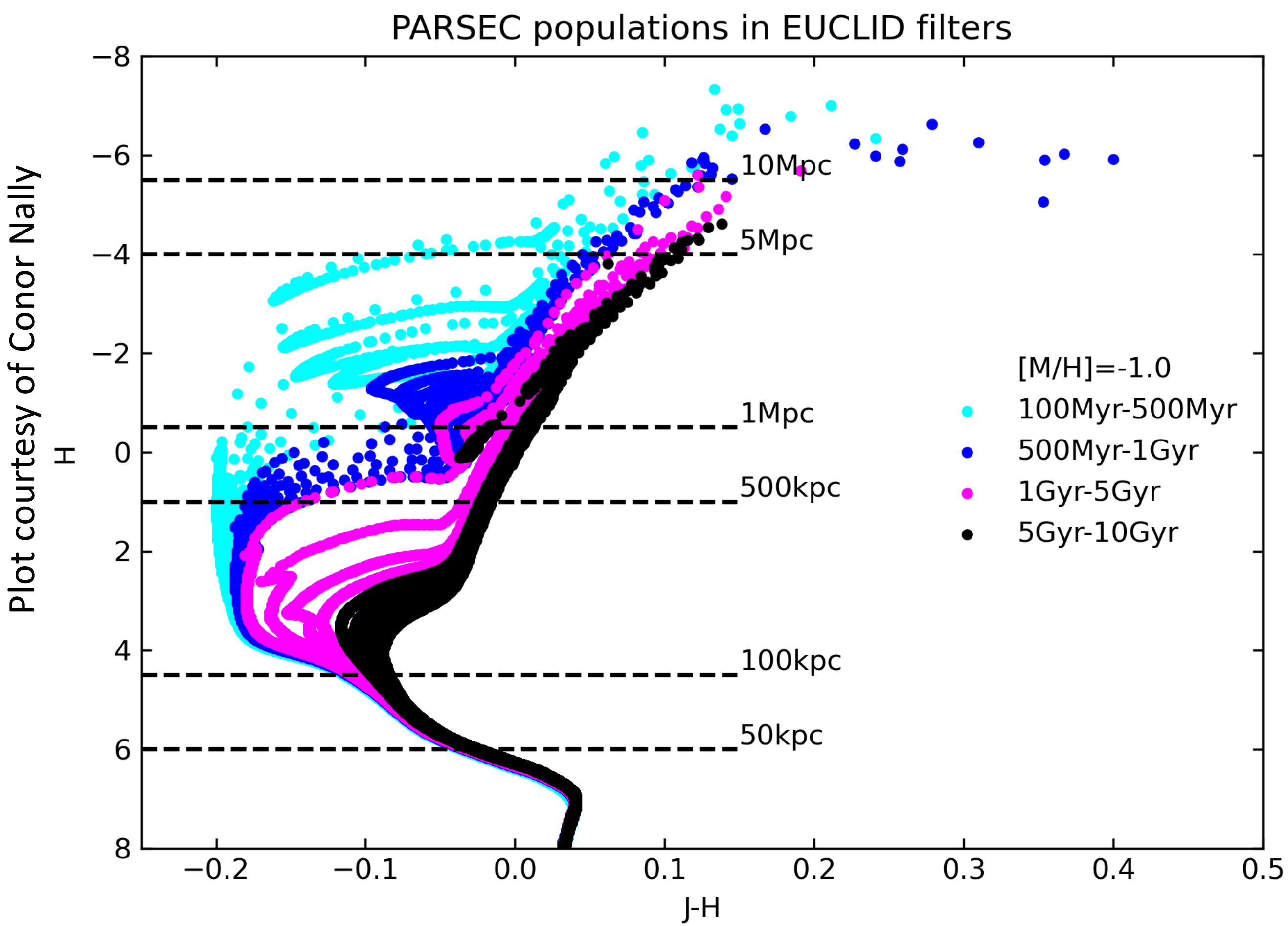
Galaxy Archaeology with Resolved Stars

- Sensitive to extremely low surface brightnesses, i.e. μ_V>30 mag per sq. arcsec:

10^6 TRGB */sq. deg $\Rightarrow \Sigma_V \approx 25$ mag/sq. arcsec
10^3 TRGB */sq. deg $\Rightarrow \Sigma_V \approx 32$ mag/sq. arcsec
10 TRGB */sq. deg $\Rightarrow \Sigma_V \approx 37$ mag/sq. arcsec

- Immune to flat-fielding, scattered light and cirrus which plague integrated light studies.
- Requires well-calibrated and deep photometry out to a sizeable fraction of a galaxy's virial radius (NB. 150 kpc is 1.7 degrees at 5 Mpc).
- Requires excellent and stable image quality to separate genuine stars and globular clusters from compact background galaxies (see Karina Voggel's talk).

Galaxy Archaeology with Euclid

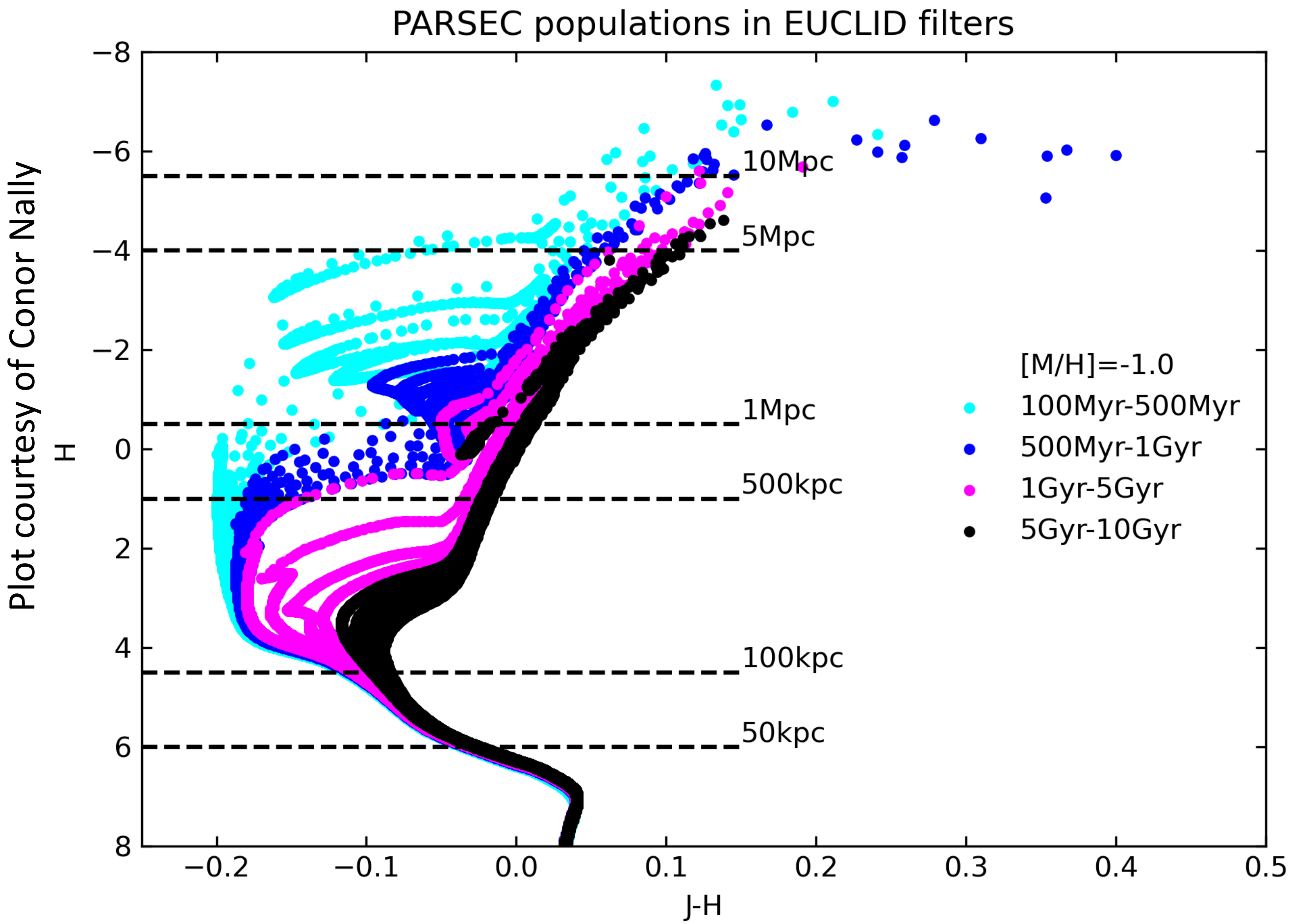


Example CMDs for stellar populations in the Euclid filters.

Lines correspond to Euclid 5 sigma depths of 24.5 AB.

Colour separation of populations will be even greater when Euclid and UNIONS/Rubin combined.

Galaxy Archaeology with Euclid



D < 10 Mpc, N_G~500

D < 5 Mpc, N_G ~250

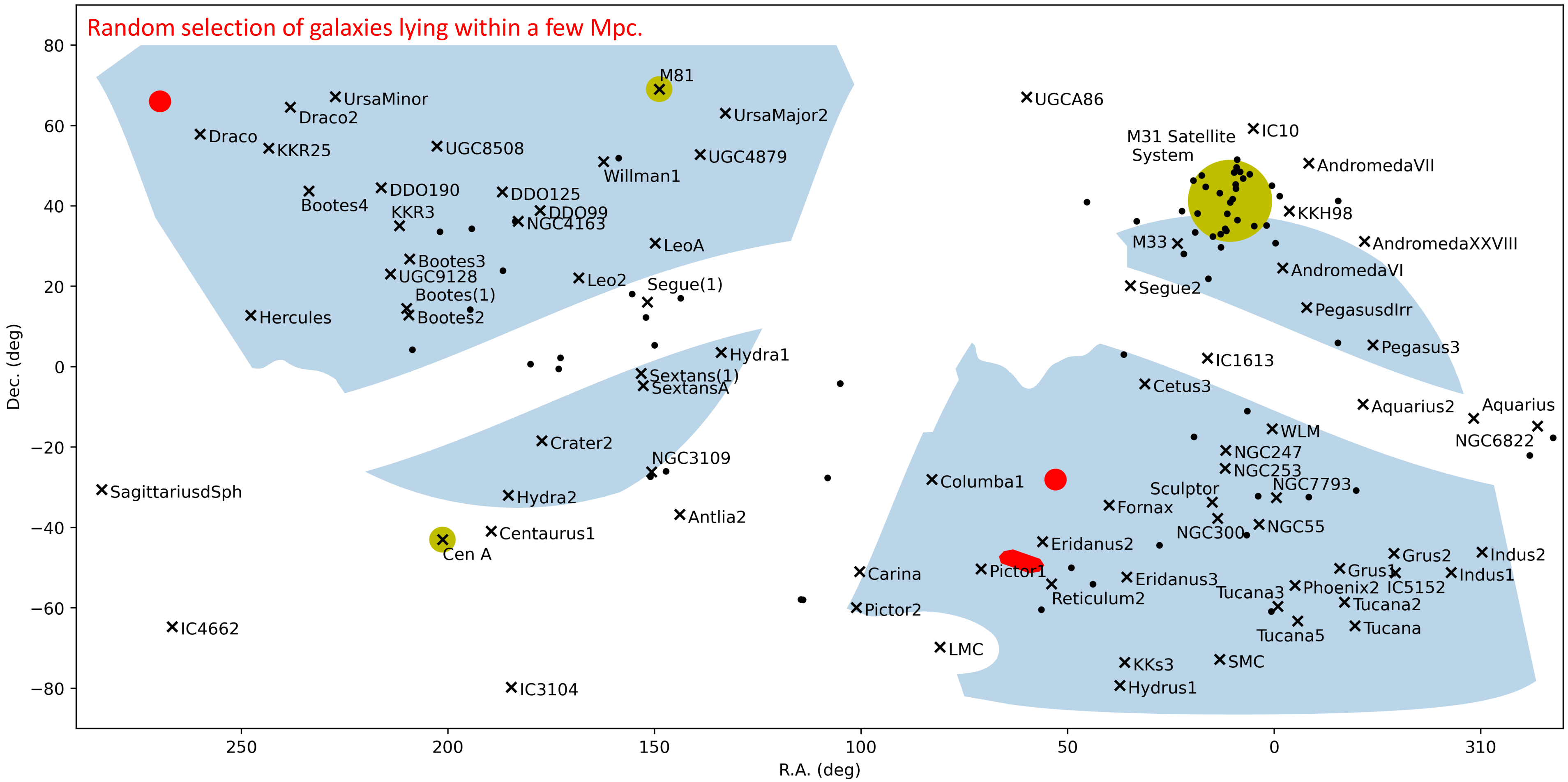
D < 1 Mpc, N_G ~80

D < 500 kpc, N_G ~40

D < 100 kpc, N_G ~25

Source: the Extragalactic Distance Database, http://edd.ifa.hawaii.edu
Tully et al. 2009

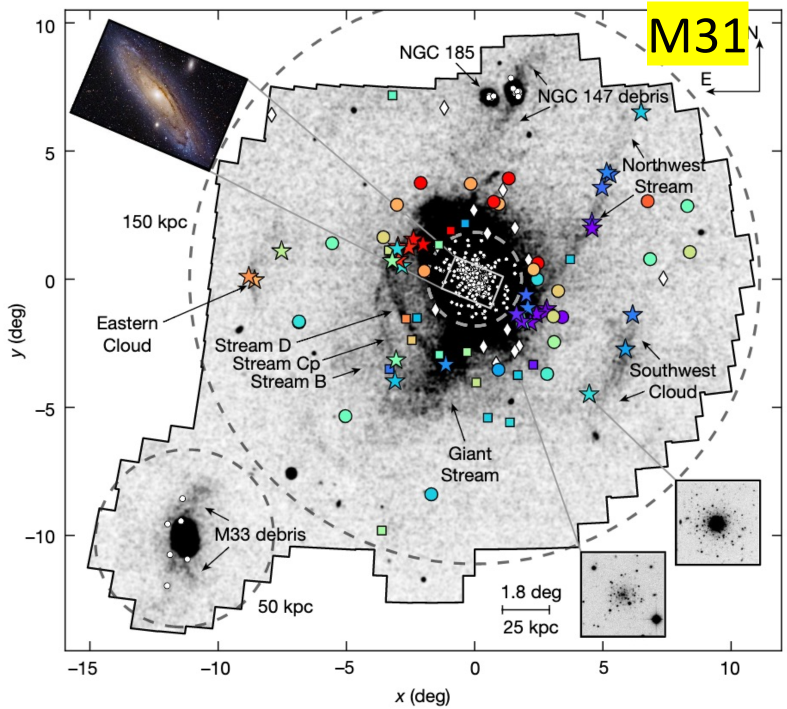
Galaxy Archaeology with Euclid



Plot courtesy of Pete Kuzma

Galactic Accretion Histories in the Local Group

Credit: ESA

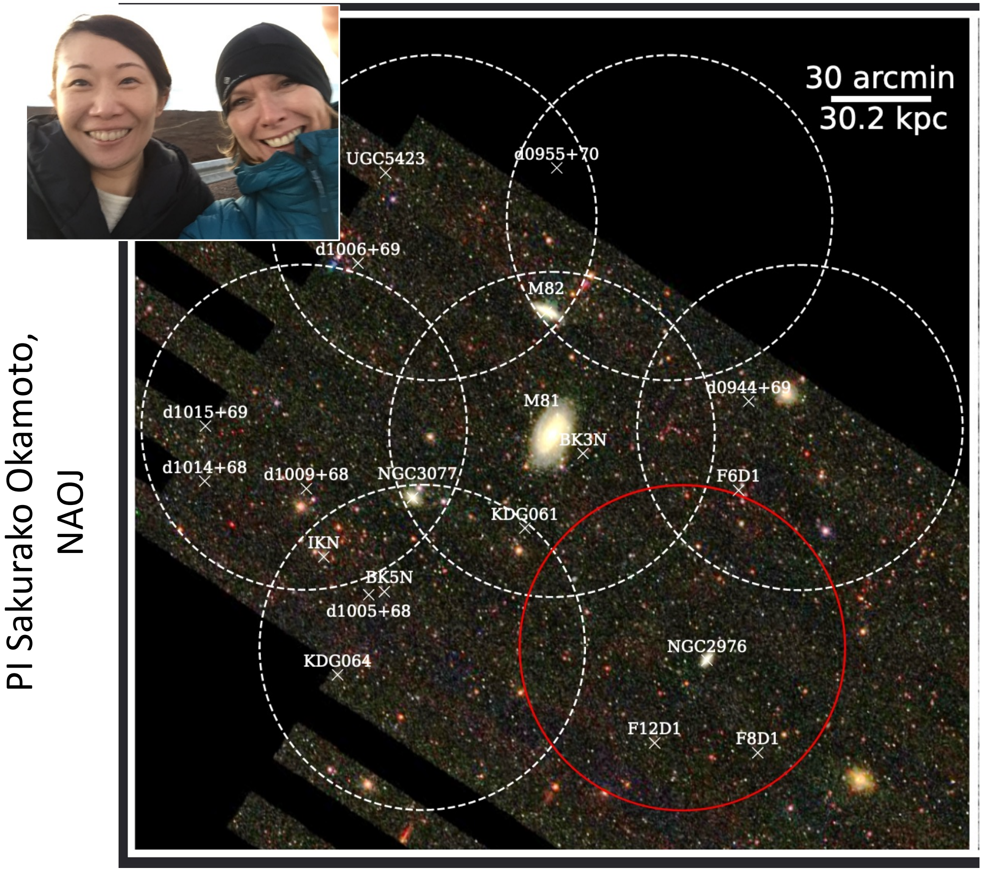


Mackey et al. Nature 2019

MW had a significant event ~10 Gyr ago when it merged with a similar-sized object but it has had a quiet history ever since.

M31 had a significant event ~2-3 Gyr ago when it experienced ~1:4-10 merger. May have had earlier significant events too.

A Preview of Euclid Local Volume Science



PI Sakurako Okamoto, NAOJ

~4 degrees = 240 kpc

Subaru/HSC M81 Group survey of individual red giant branch (RGB) stars over ~12 sq. deg (2015-2019).

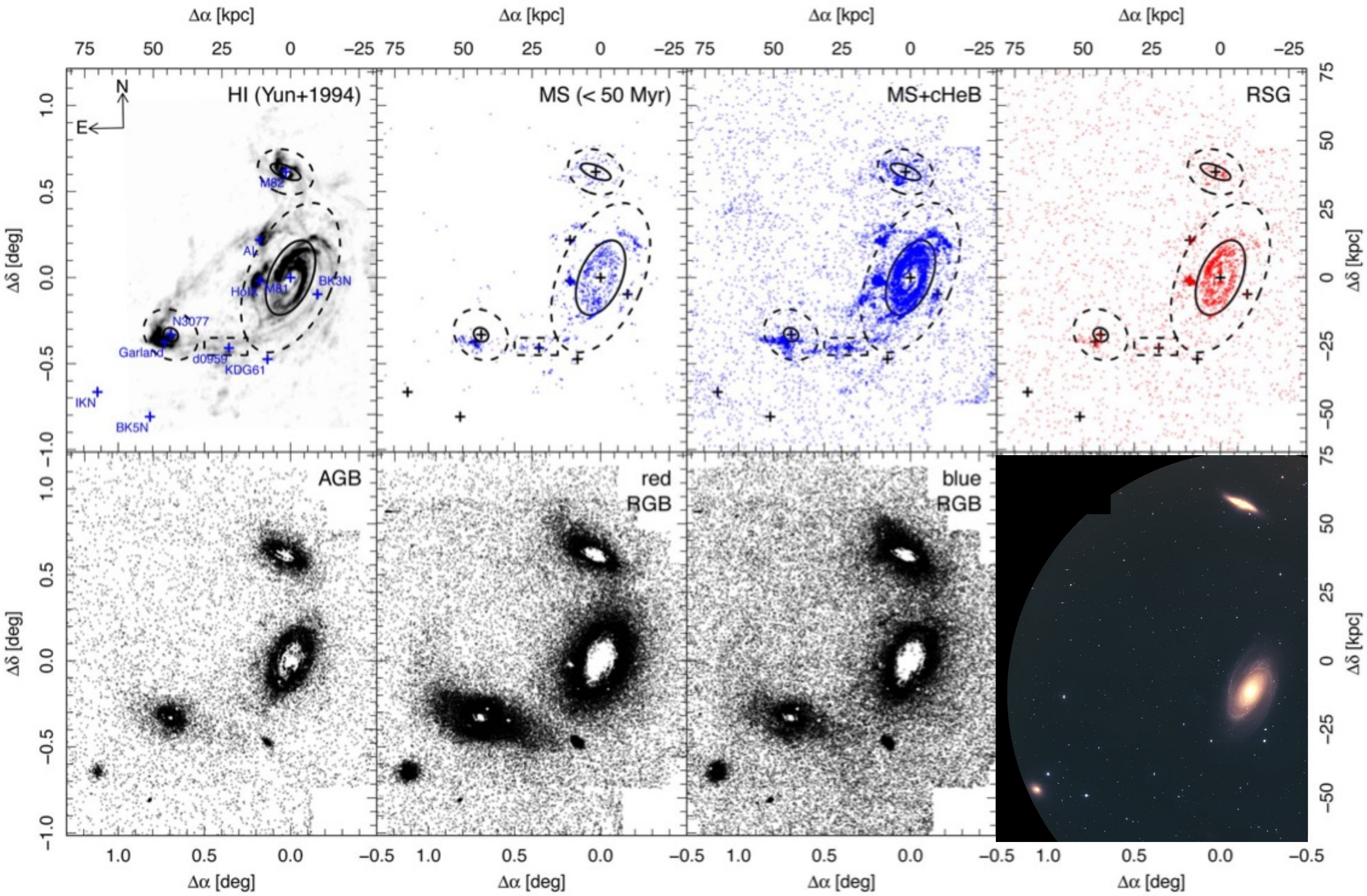
Reaches ~2 mag below tip of the RGB in M81. IQ ~0.6 – 1.0” [g~27.5, i~27].

Covers 4 prominent galaxies (M81,M82, N3077, N2976) and > 40 dwarfs/dwarf candidates (including tidal dwarfs).

(See Marina Rejkuba’s talk for view of Cen A Group)

A Preview of Euclid Local Volume Science

Okamoto, Arimoto, Ferguson et al 2015, 2019
See also Smercina et al 2020

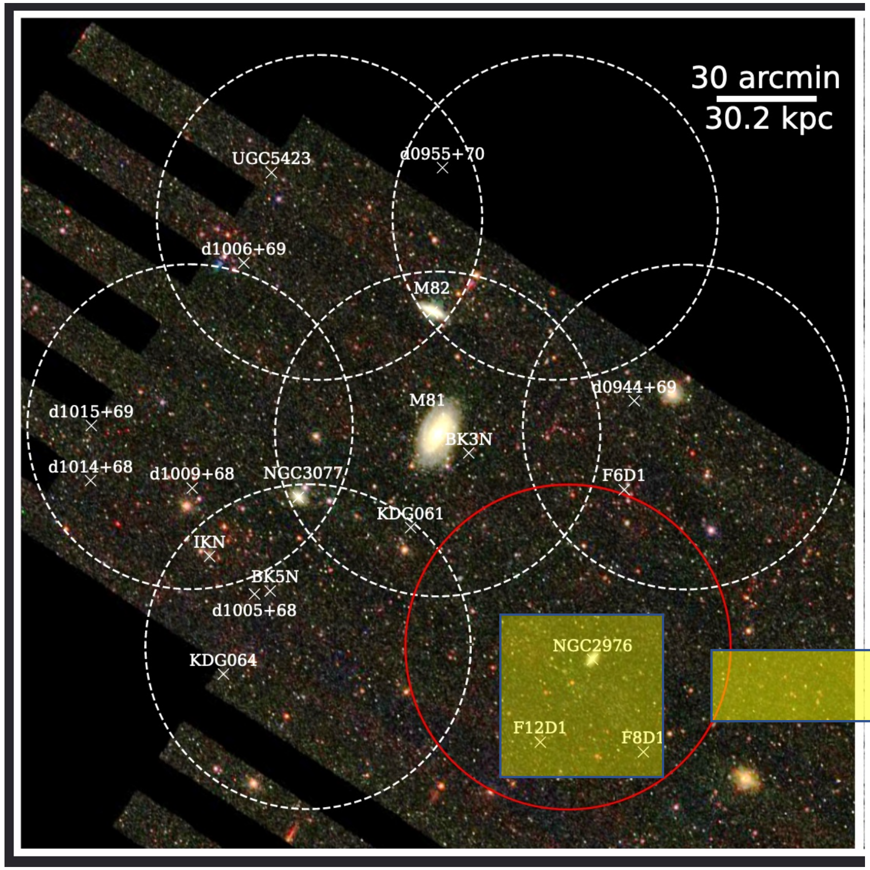


M81 unveiled to be tidally shredding its two nearest companions.

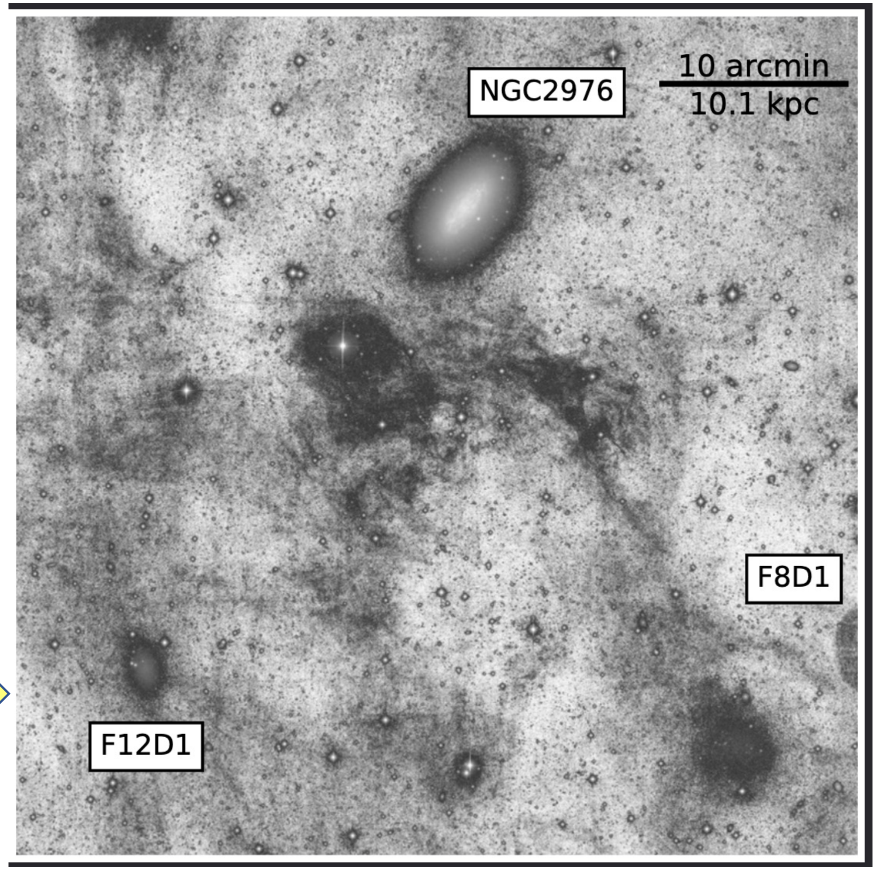
Is the Milky Way's largely quiescent history until now abnormal?

A Preview of Euclid Local Volume Science

PI Sakurako Okamoto

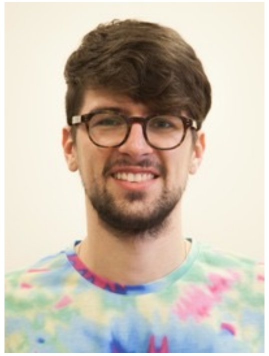


~4 degrees = 240 kpc

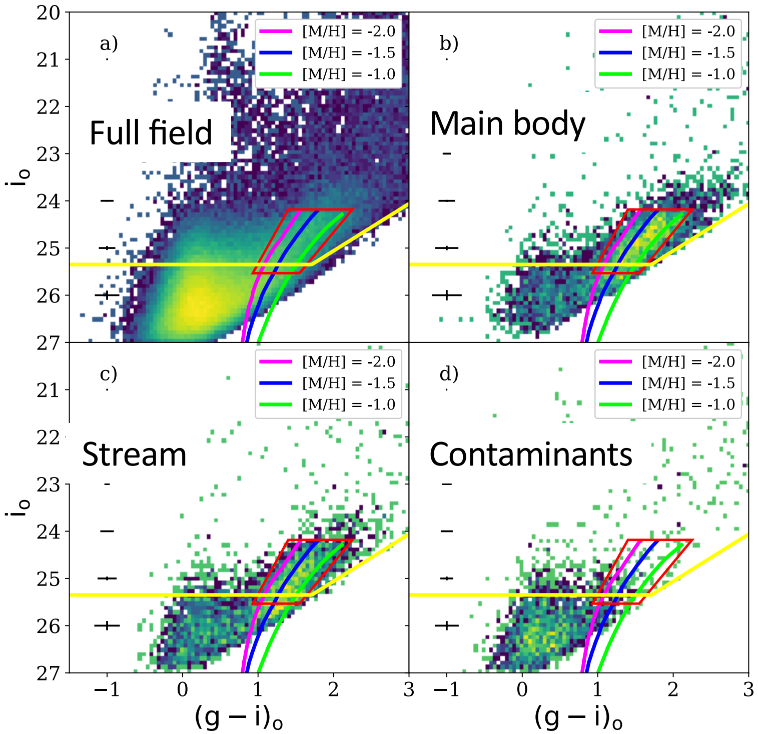


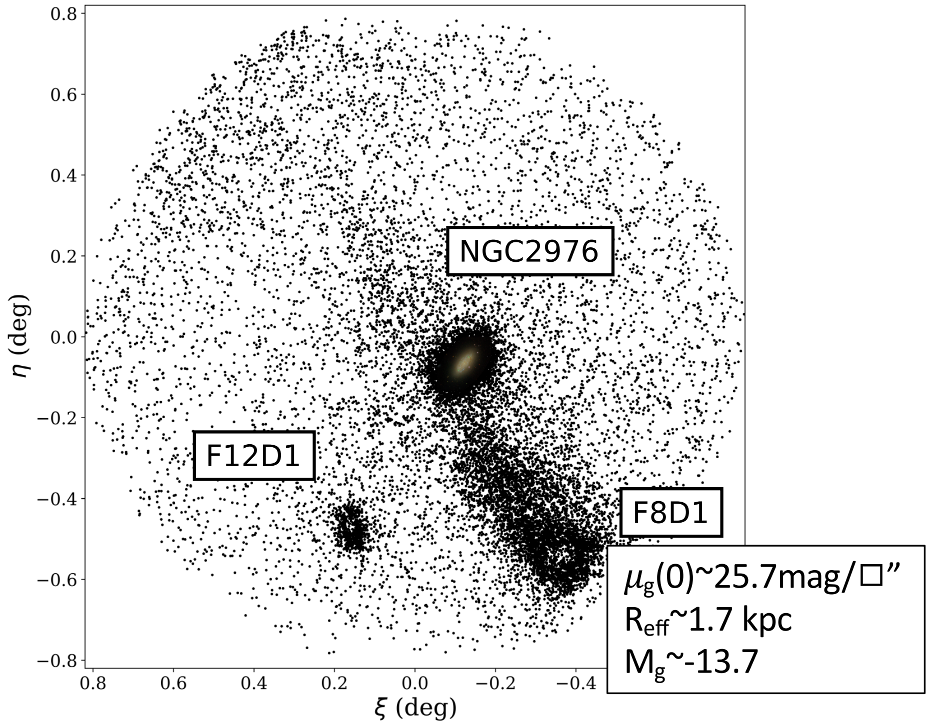
Deep CFHT/MegaCam i-band LSB- mode

A Preview of Euclid Local Volume Science



Žemaitis et al 2022
arXiv:2209.09713
MNRAS accepted

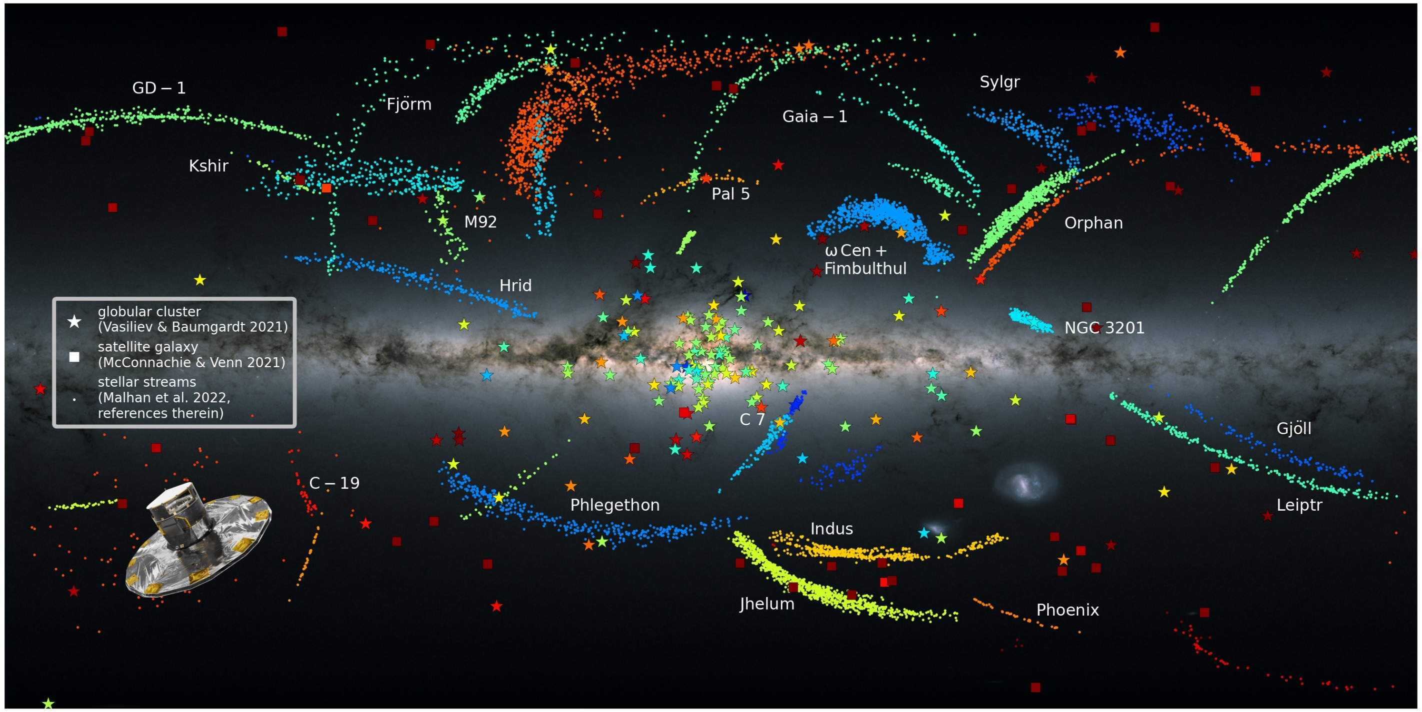




Huge (> 60 kpc in projection) stellar stream discovered emanating from the ultra-diffuse galaxy F8D1. Luminosity in visible stream is 7.2 x 10^6 $L_\odot$. If symmetric feature exists SW of galaxy, core stream contains 30 – 36% of F8D1's present-day luminosity.

Euclid and the Milky Way Halo

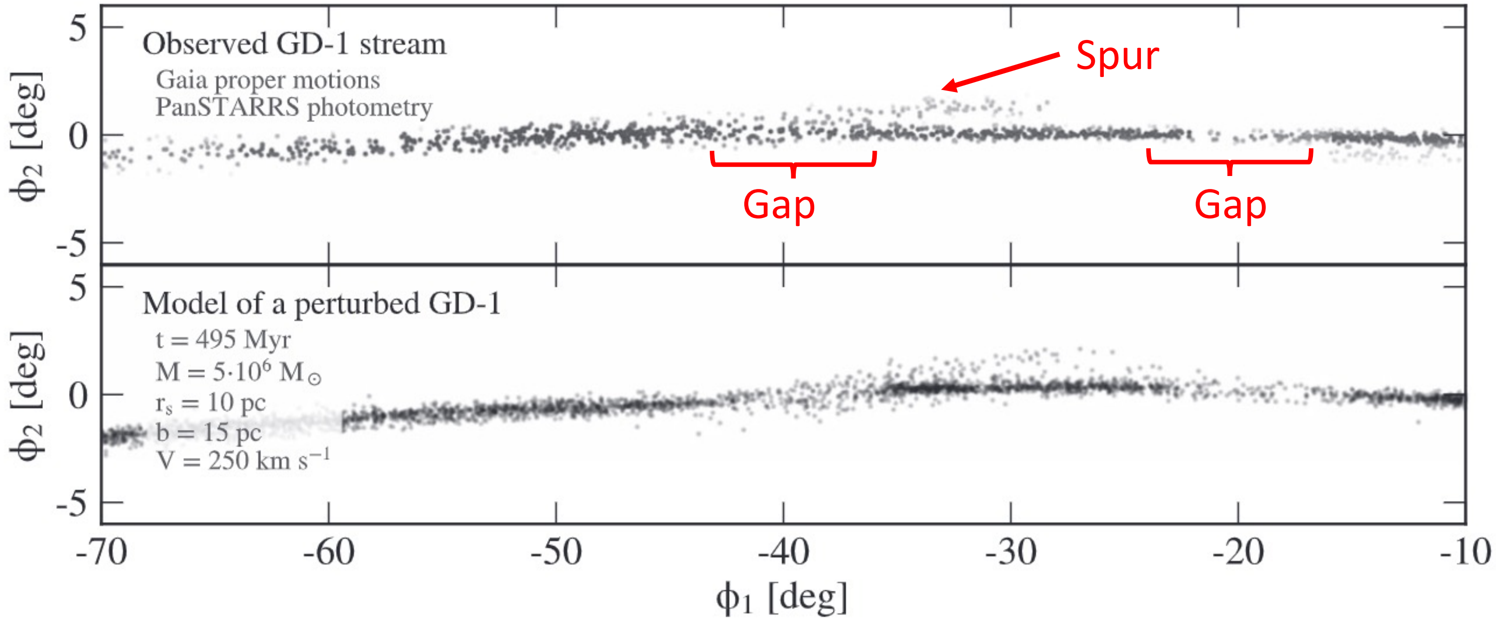
Malhan et al. 2022
STREAMFINDER



Many tens of stellar streams have been discovered in the inner (< 30 kpc) Milky Way halo thanks to SDSS, PS1, DES and Gaia. Euclid will provide precision CMDs for these streams and also allow searches to be extended to the outer halo.

Euclid and the Milky Way Halo

Bonaca et al. 2019;
see also Carlberg 2009-2020

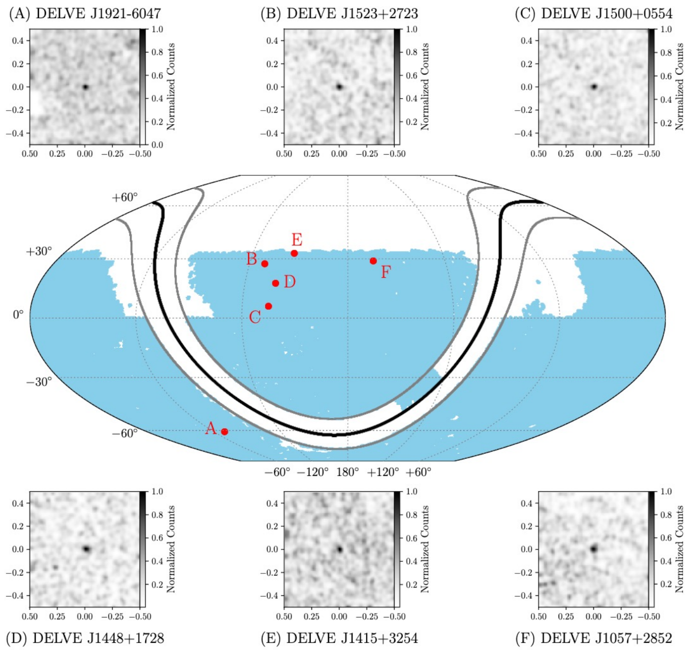


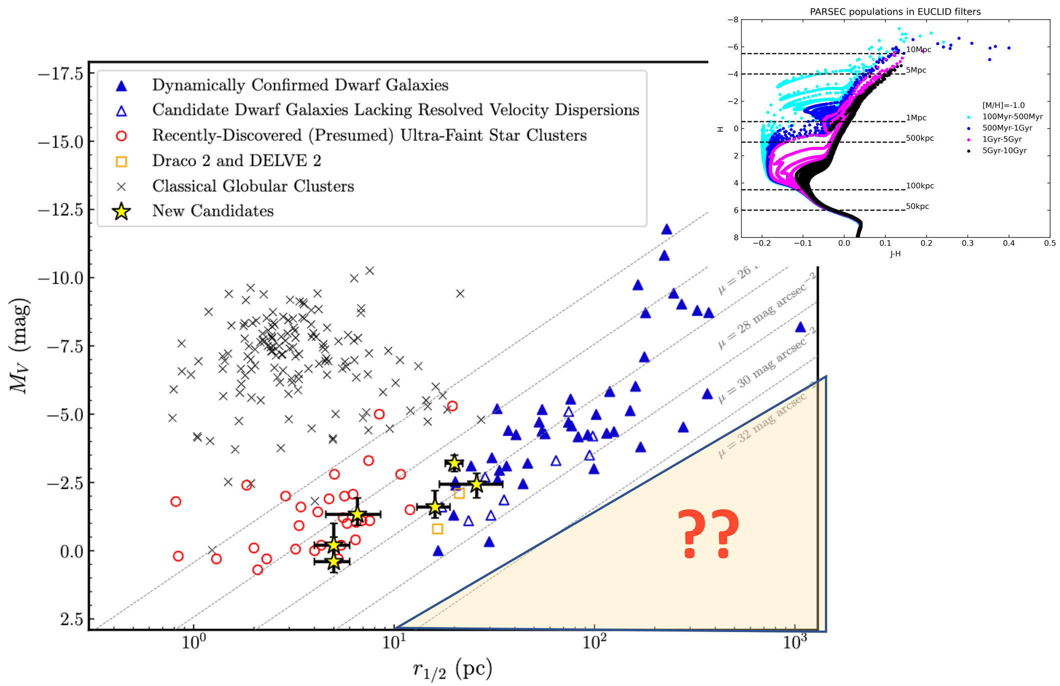
Gaps and spurs in thin streams in the Milky Way halo could be the result of encounters with dark matter subhalos. Euclid will allow exquisite characterization of the such features and improved constraints on the presence of subhalos.

Euclid and the Milky Way Halo

DELVE Survey
g~24
r~23.5
Z~22

Cerny et al. 2022, arXiv





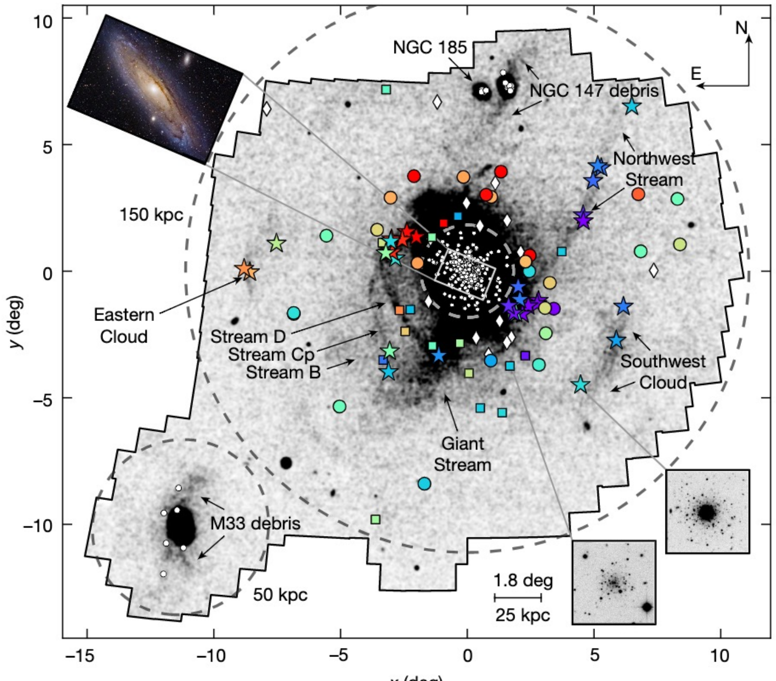
Many tens of low luminosity stellar systems have been discovered in the Milky Way halo thanks to SDSS, PS1, DES, Gaia and DELVE. Euclid will provide precision CMDs for these and also uncover many more, probing to even lower densities

Euclid Local Universe Synergies and Follow-up

- Deep optical photometry (ugriz) in combination with Euclid YJH hugely improves the characterization of resolved population ages and metallicities → must have access to same complementary datasets as core science (e.g. UNIONS) + require access to joint-photometry Euclid-Rubin DDPs
- Spectroscopic follow-up:
  - targeted WEAVE + MOONS programs and WEAVE, 4MOST and PFS surveys for diffuse stellar systems and GCs around external galaxies
  - MUSE and WEAVE IFUs for extragalactic partially-resolved systems.
- Deep high-resolution imagery:
  - HST and JWST observations (and eventually E-ELT MICADO) to construct CMDs several magnitudes below Euclid limit, mostly required for objects discovered at D > 1 Mpc.

Galaxy Evolution with Euclid: The Local Universe

- census of stellar halo properties (e.g. amount and types of substructures, streams, GC populations) in >1000 galaxies across a broad range of stellar mass and various (low density) environments: galactic accretion histories, tests MW typicality.
- searches for very low luminosity and/or low surface brightness systems out to virial radius of the MW: quantify the lower limit of galaxy formation, impact of reionization on the star formation histories and the nature of the star cluster-galaxy divide.
- use the fine structure of Milky Way thin stellar streams to constrain the nature of dark matter .



Many complementarities to other galaxy evolution science within the EC and to the core science goal of understanding dark matter!