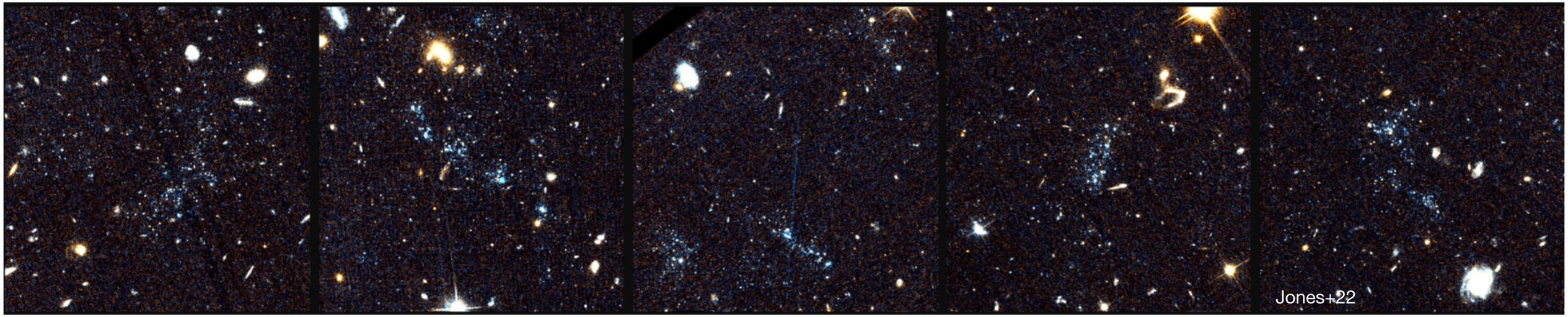
Low Mass Galaxies(?) and the Ultraviolet



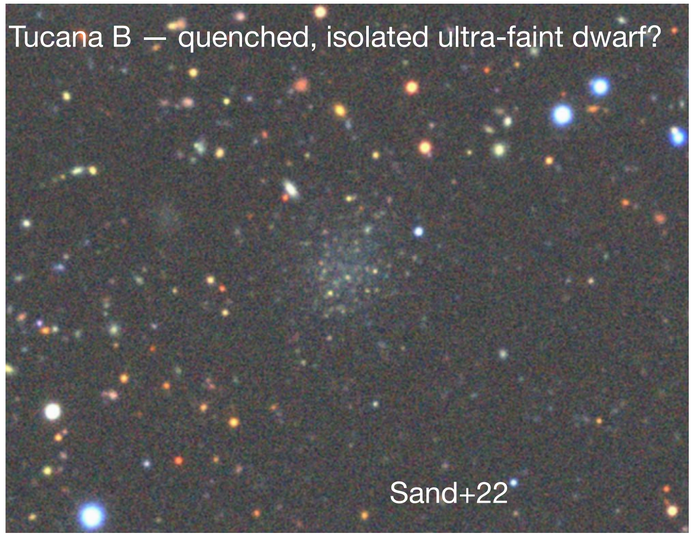
D. Sand (U of Arizona)
Michael Jones, D. Crnojevic, B. Mutlu-Pakdil, A. Karunakaran, K. Spekkens, P. Bennet
N. Mazziotti, S. Dey (undergrads at Arizona)
First UVEX Community Workshop; March 14, 2023

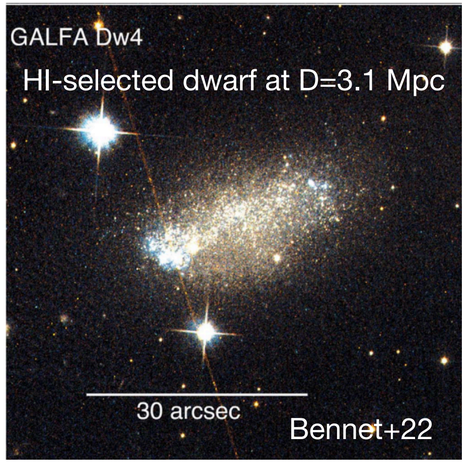
- The faintest dwarf galaxies are sensitive to dark matter and baryonic physics of star formation, SN feedback, tidal/ram pressure stripping, reionization. Finding and characterizing the faintest dwarfs in different environments tells us which of these effects matters most.

- HI-led search for isolated dwarf galaxies at the edge of the Local Group.

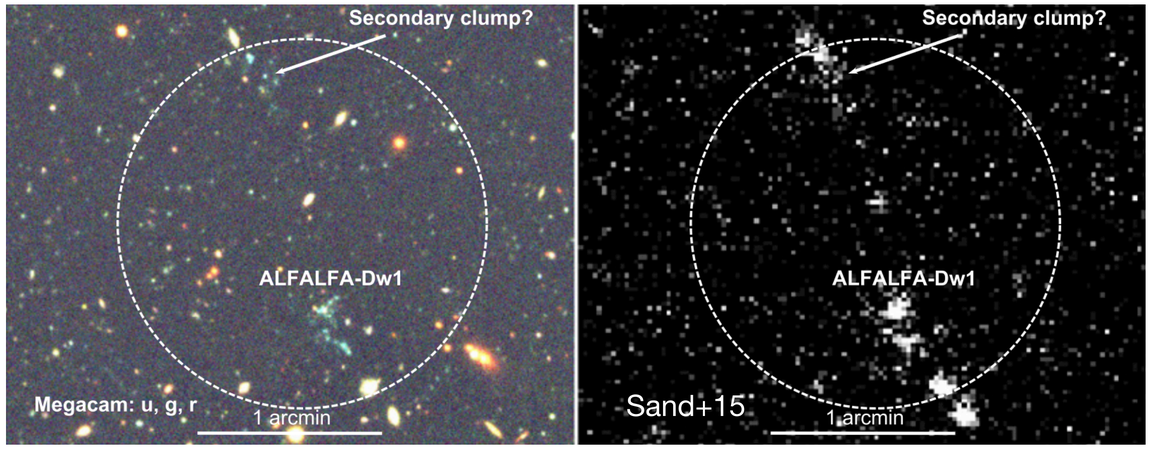
- New class of stellar system: isolated, strongly star forming, no old stars, high metallicity.

- New searches will find dwarfs at the edge of the Local Group, or in the field, that are quenched. Little to no UV emission: that's important too!





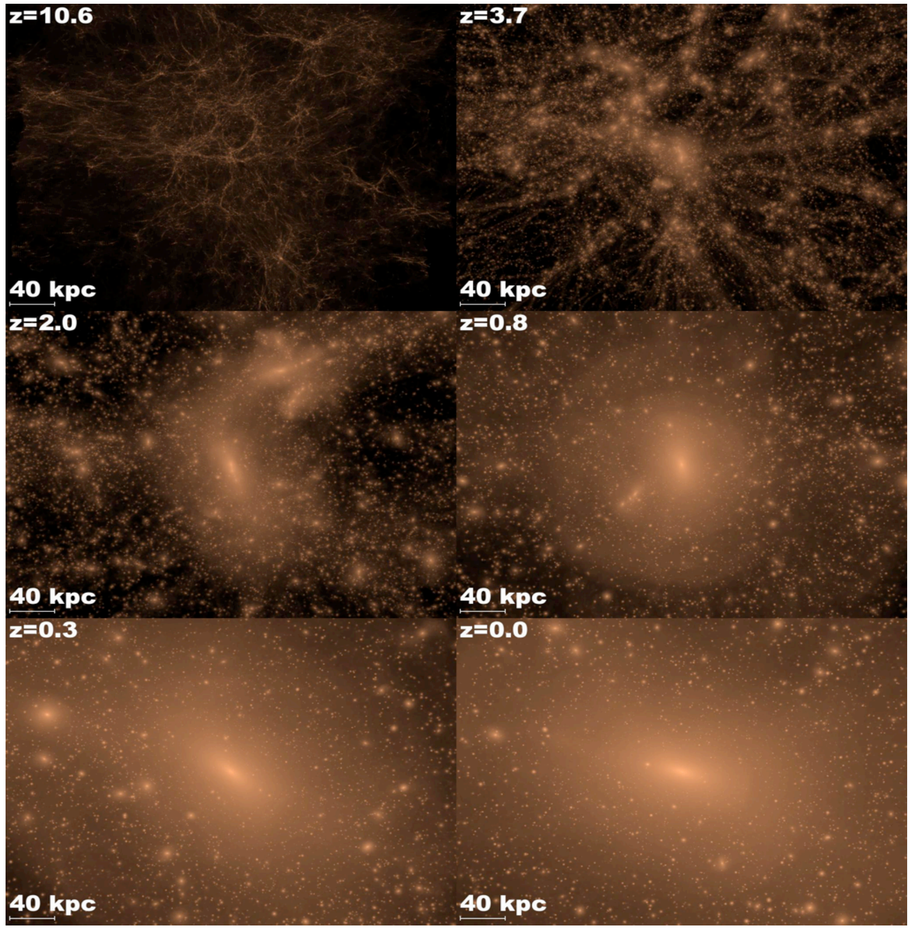
Isolated stellar system in the Virgo Cluster



Dwarf Galaxies — A window into dark matter on small scales

To go from the smooth beginning as seen in the cosmic microwave background to the complex structures seen today requires direct numerical simulation.

A ‘cold’ dark matter candidate (i.e. non-relativistic) can match the structure seen. There may be room for warm or self-interacting DM candidates

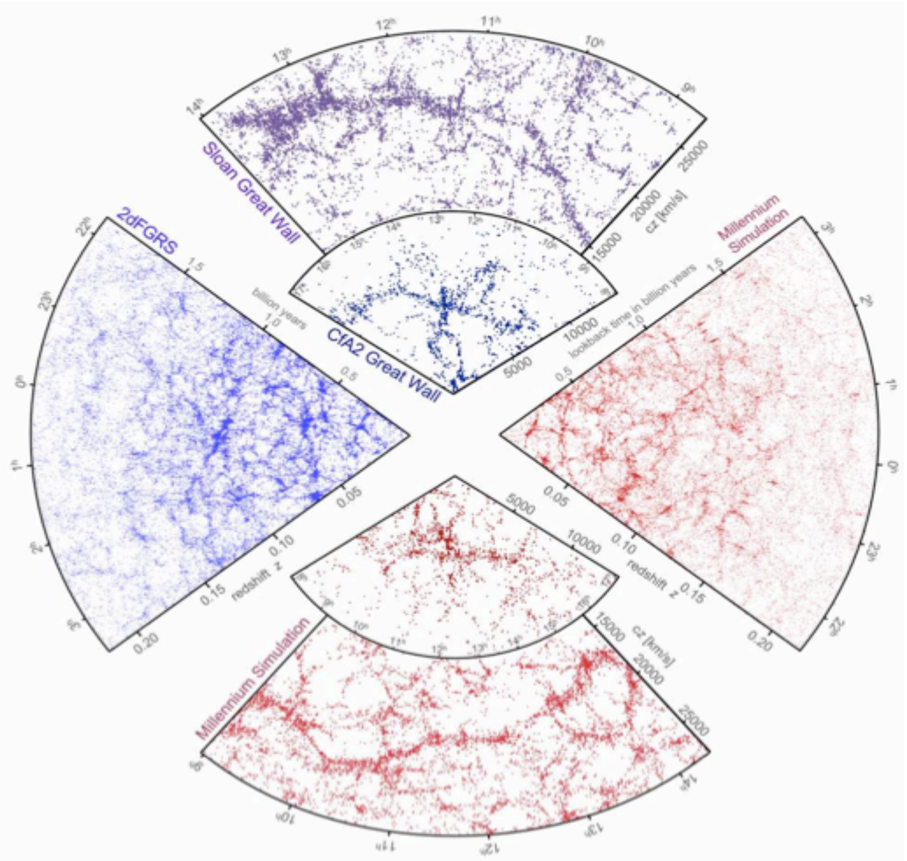


From the Via Lactea project page

The Cold Dark Matter Paradigm is Extremely Successful

Galaxy distribution from spectroscopic redshift surveys vs. mock catalogs from CDM simulations (see also CMB, Lyman alpha forest, etc).

But once you zoom in to the size of individual galaxies, there begin to be problems....

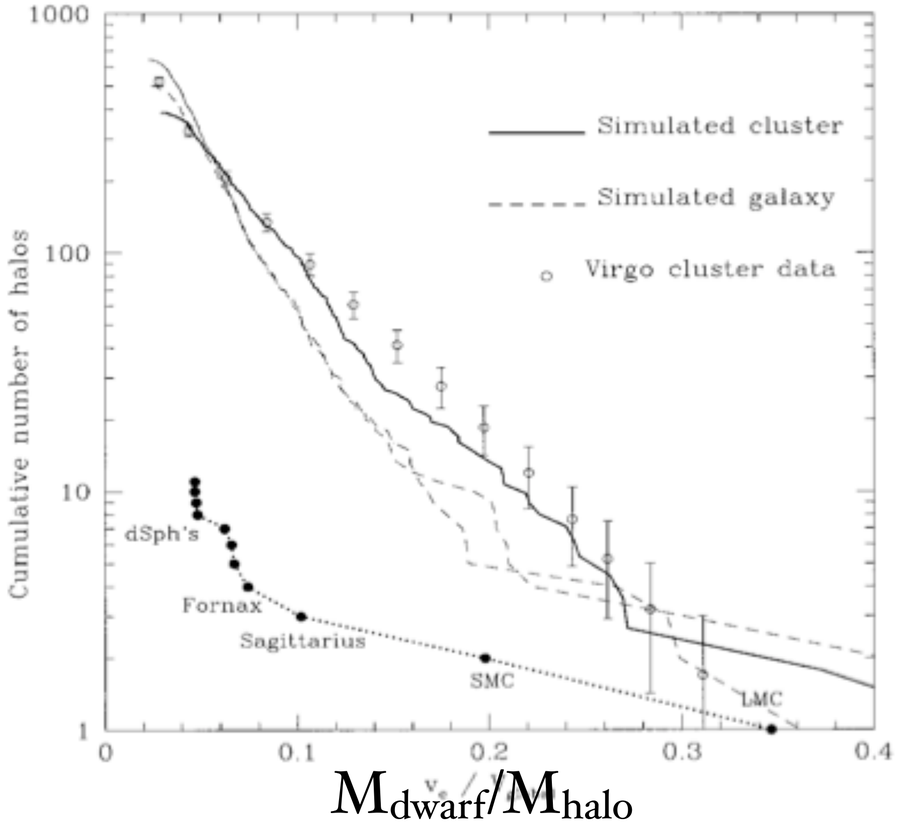


Springel et al. 2006

Cold Dark Matter Simulations — Number & Distribution of Subhalos

The ‘Missing Satellites’ Problem

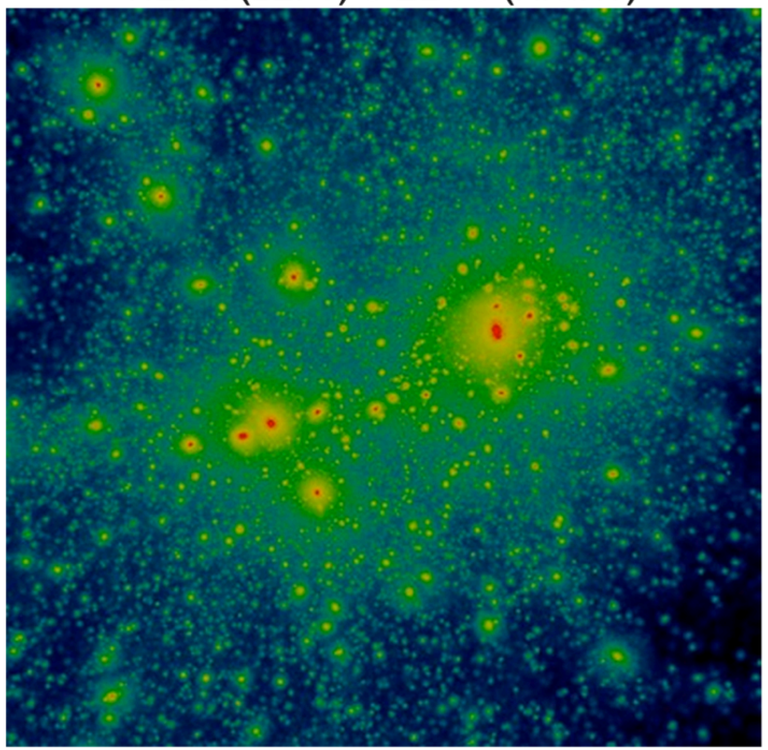
- As originally posed: Within the virial radius, the Milky Way should contain ~500 halos larger than Draco (M_V=-8.5; ~5x10^5 M_{sun})
- The galaxy cluster satellite function could reproduce numerical predictions, but not for a halo the size of the MW.
- Other ‘problems’ over the years: ‘too big to fail’, ‘core/cusp’, ‘planes of satellites’



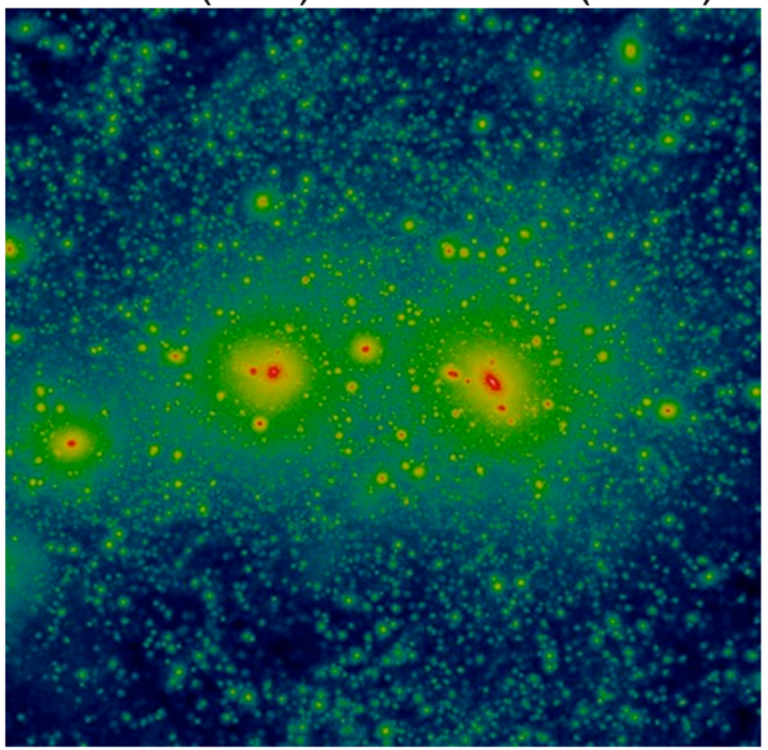
Moore et al. 1999; Clear lack of MW satellites, pre-SDSS

Cold Dark Matter Halos Have Lots and Lots of Subhalos
Does each subhalo correspond to a dwarf galaxy?

HERA (LEFT) & ZEUS (RIGHT)

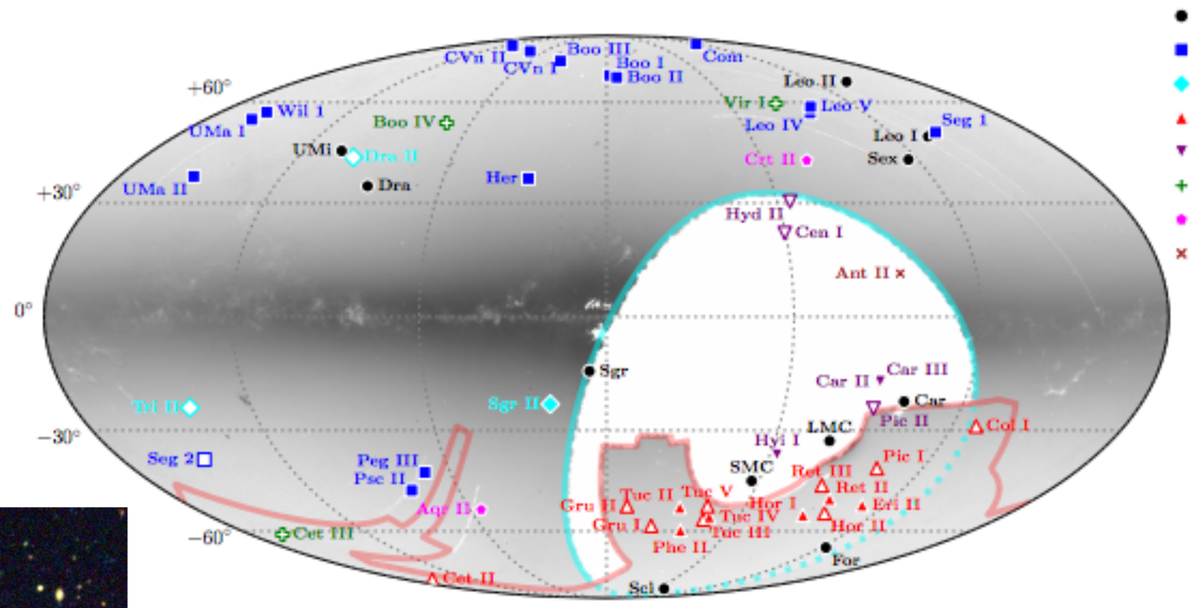


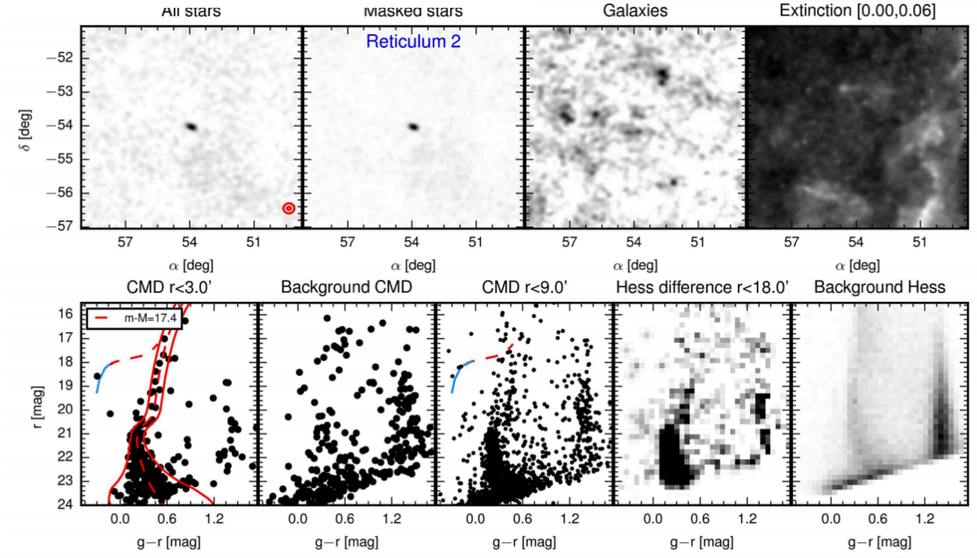
SCYLLA (LEFT) & CHARYBDIS (RIGHT)



- ELVIS simulations, meant to roughly correspond to the Local Group (Garrison-Kimmel+18)
- Does each subhalo correspond to a dwarf galaxy?

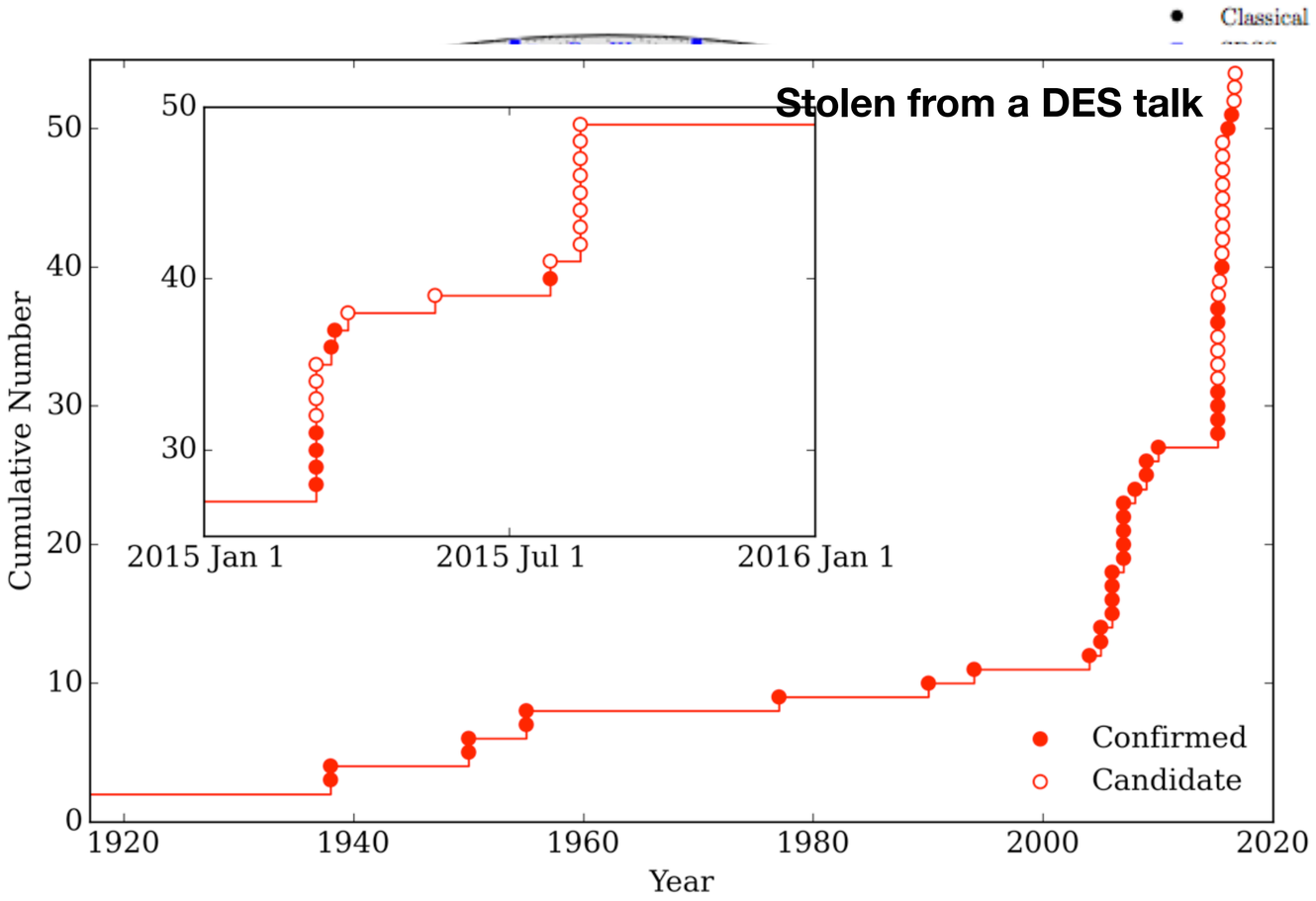
Dozens of New Milky Way and M31 Satellites

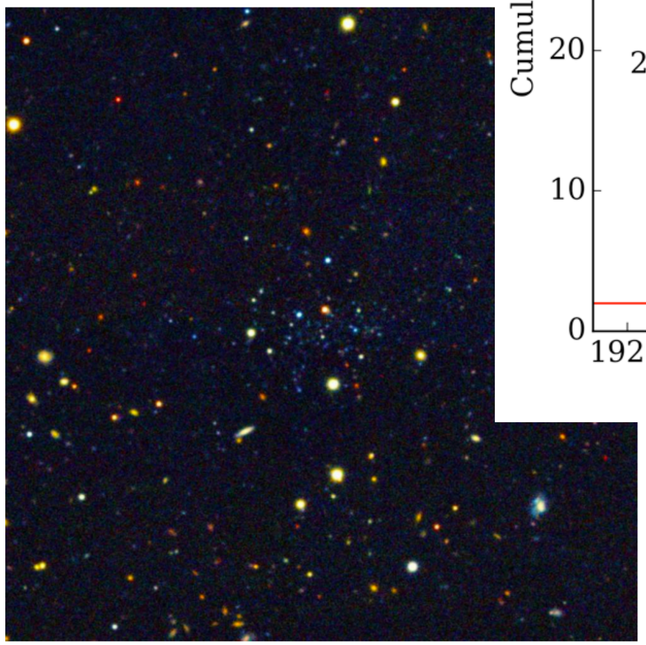




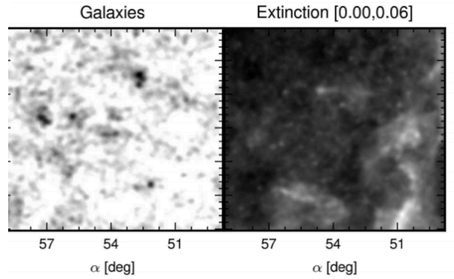
Most recently, Cerny+23

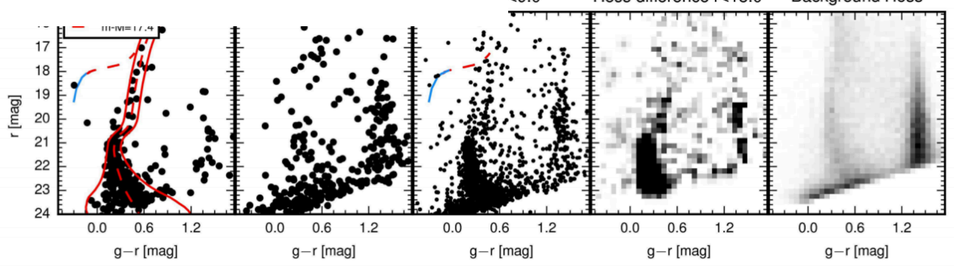
Dozens of New Milky Way and M31 Satellites



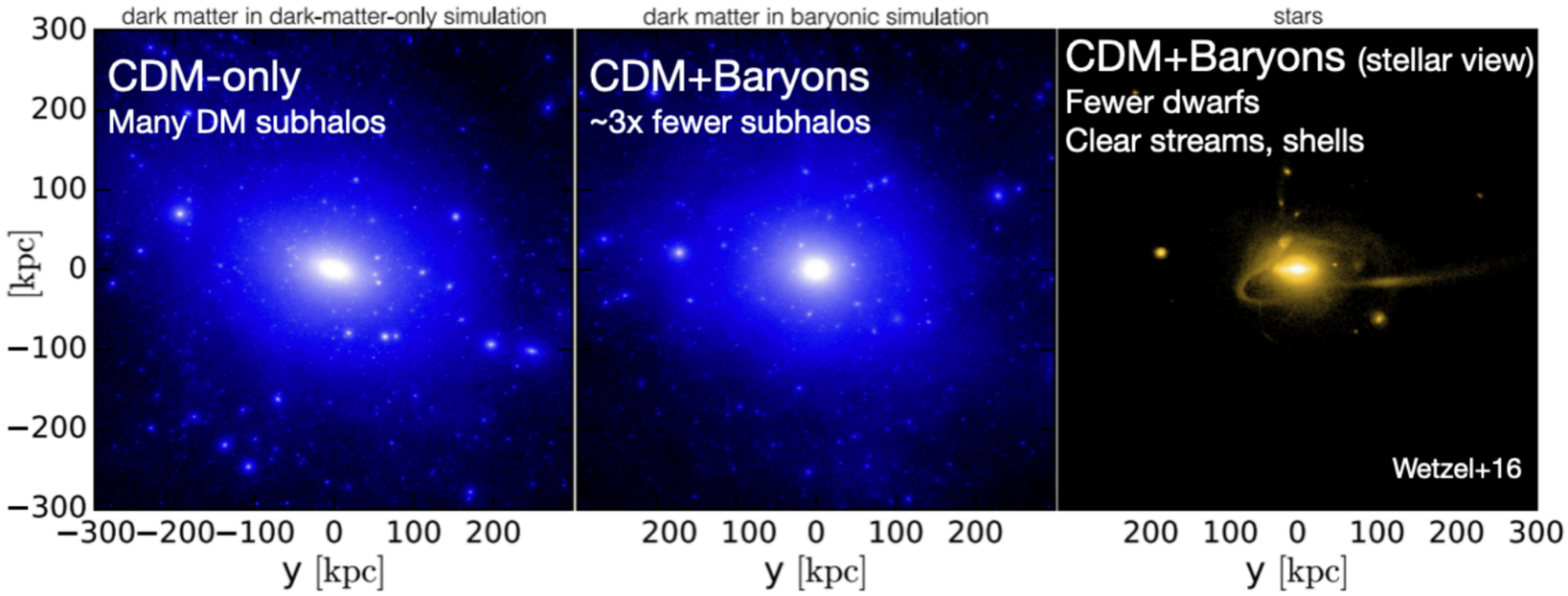


Most recently, Cerny+23





Cold Dark Matter Problems Could be ‘Fixed’ by Baryonic Processes

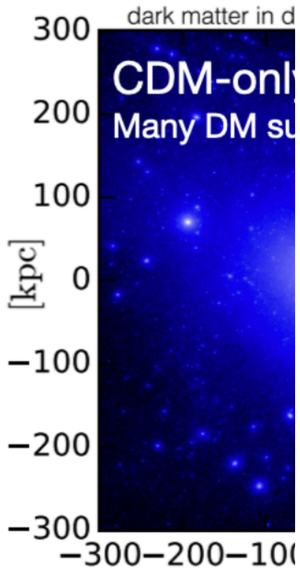


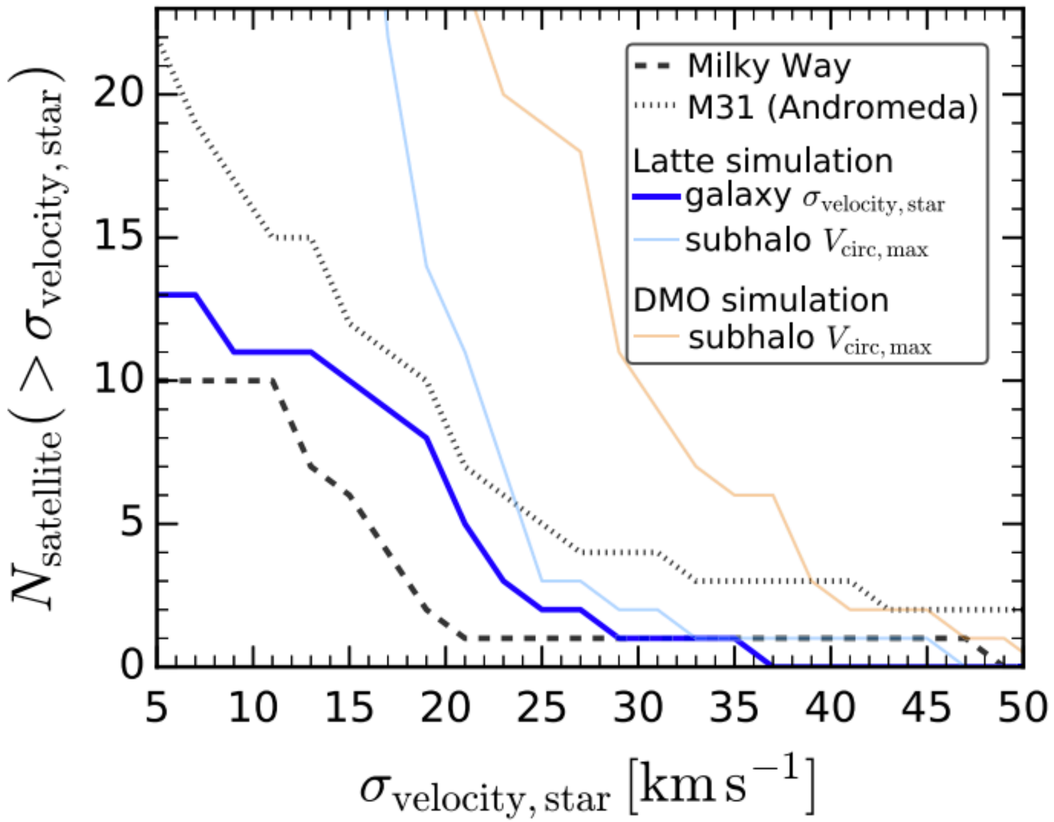
- Ultraviolet heating from reionization can keep gas from cooling in small halos, and so no/few stars form.

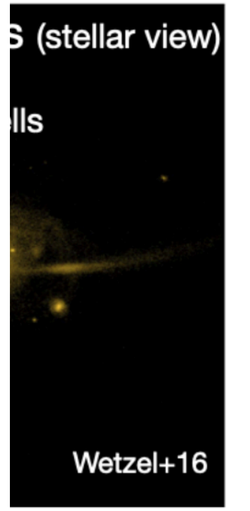
- SN feedback — a first generation of stars goes supernova, and drives out remaining gas in shallow potential well of low-mass DM halo.

- Tidal/ram pressure stripping of gas — may form fewer stars, or be disrupted.

Cold Dark Matter Problems Could be ‘Fixed’ by Baryonic Processes







- Ultraviolet heating from mall halos, and so no/few stars form.
- SN feedback — a first generation of stars goes supernova, and drives out remaining gas in shallow potential well of low-mass DM halo.
- Tidal/ram pressure stripping of gas — may form fewer stars, or be disrupted.

Where do we go from here?

The Local Group is nice, but…

- Are our baryonic solutions to the ‘missing satellites problem’ and other issues just tuned to the Local Group?
- Halo to halo scatter is expected. Can we observationally quantify this? What physically drives the scatter?
- Does parent galaxy morphology matter? Environment and accretion history, etc.
- Next step is to probe new systems beyond the Local Group. AND isolated dwarfs in the field, which have had few/no environmental influences.

Where do we go from here?

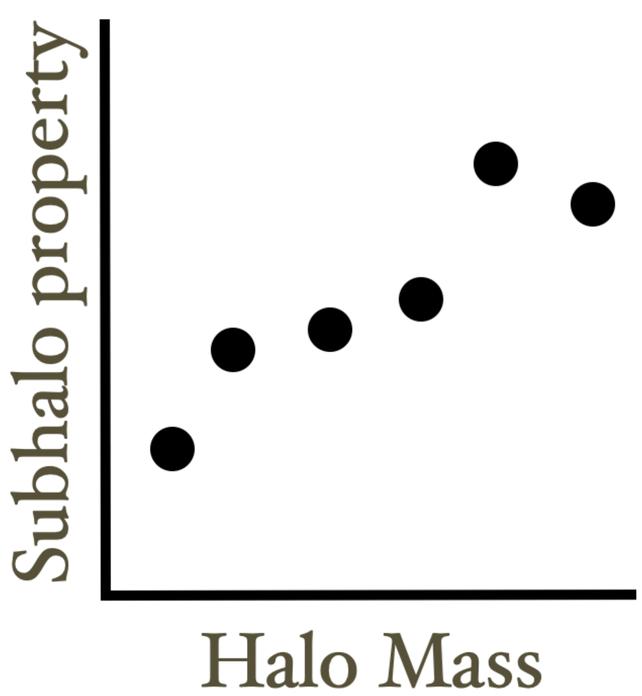
The Local Group is nice, but…

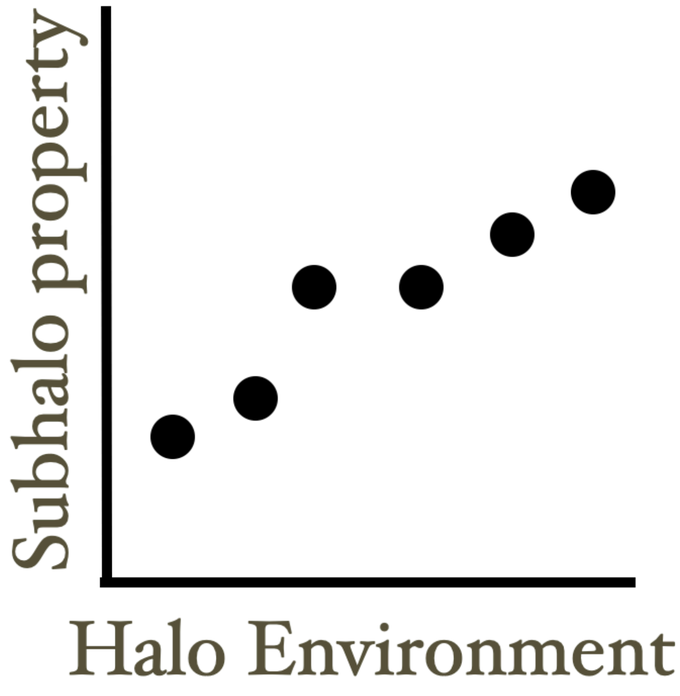
- Are our baryonic solutions to the ‘missing satellites problem’ and other issues just tuned to the Local Group?
- Halo to halo scatter is expected. Can we observationally quantify this? What physically drives the scatter?
- Does parent galaxy morphology matter? Environment and accretion history, etc. UV —> signal of star formation, environmental effects.
- Next step is to probe new systems beyond the Local Group. AND isolated dwarfs in the field, which have had few/no environmental influences. Isolated dwarfs should be star forming & UV-strong, unless quenched by reionization.

Where do we go from here?

The Local Group is nice, but…

What we want:



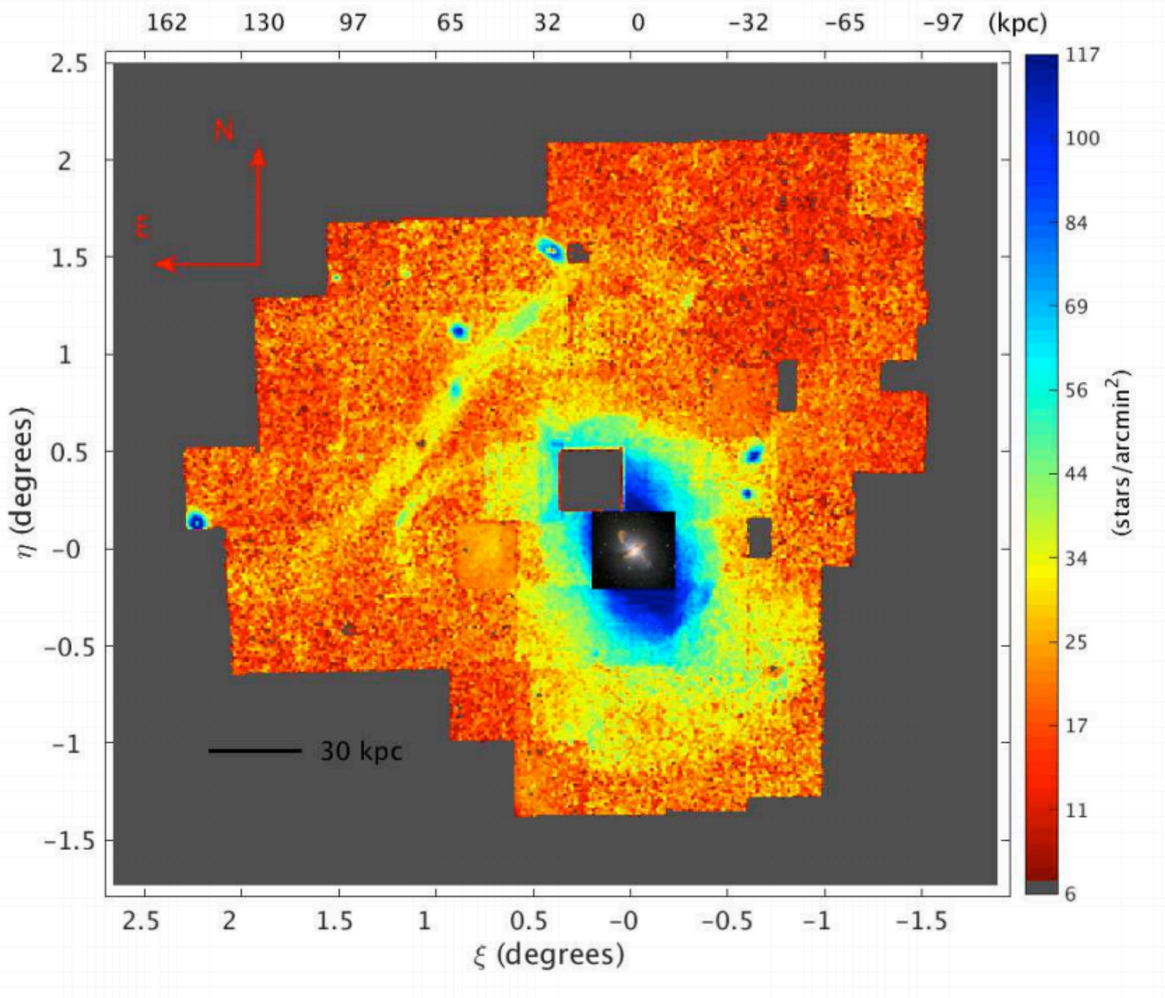


Subhalo property can be dwarf luminosity function, stream richness, you name it.

The Field of Streams of Centaurus A

- Clearly disrupting dwarf galaxies — detected not by low surface brightness measurements but in individual resolved stars
- 11 new satellites galaxies
- 122 new spectroscopically confirmed star clusters, some associated with streams, shells, & dwarf galaxies.

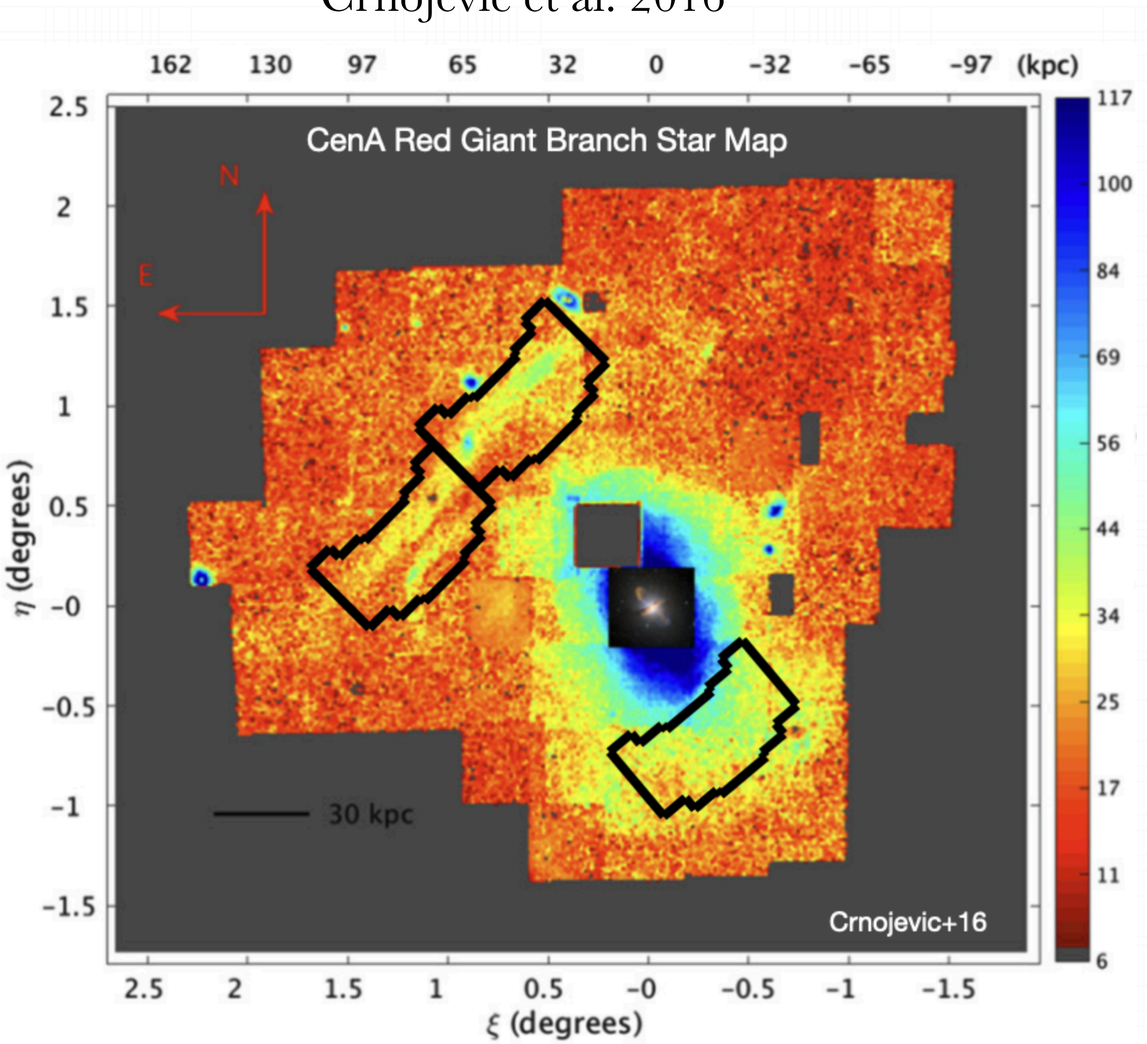
Crnojevic et al. 2016



The Field of Streams of Centaurus A

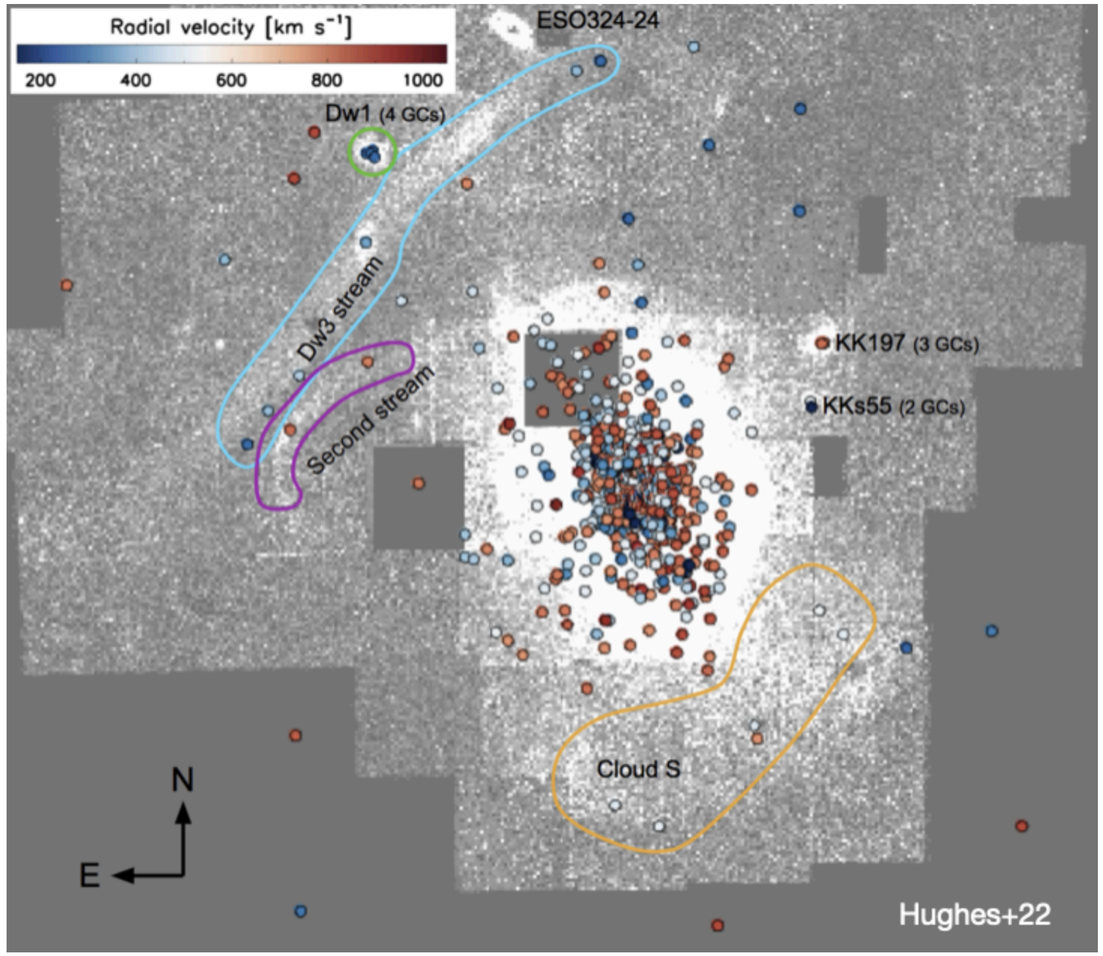
- Clearly disrupting dwarf galaxies — detected not by low surface brightness measurements but in individual resolved stars
- 11 new satellites galaxies
- 122 new spectroscopically confirmed star clusters, some associated with streams, shells, & dwarf galaxies.

Crnojevic et al. 2016



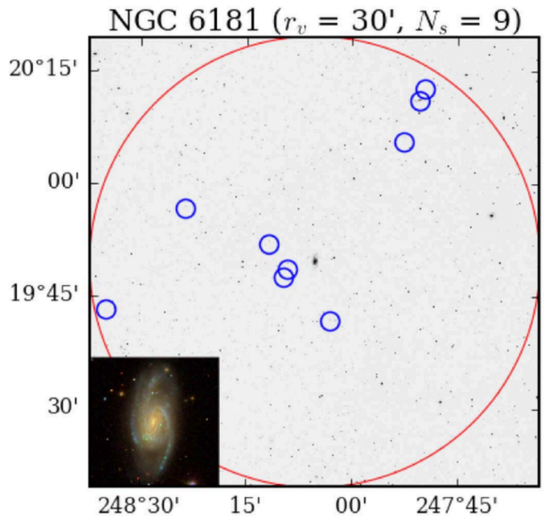
The Field of Streams of Centaurus A

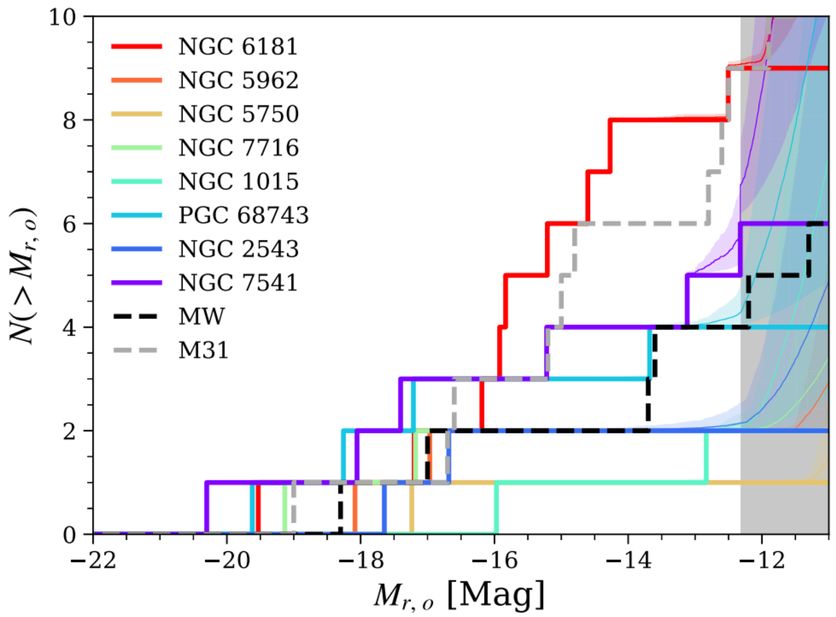
- Clearly disrupting dwarf galaxies — detected not by low surface brightness measurements but in individual resolved stars
- 11 new satellites galaxies
- 122 new spectroscopically confirmed star clusters, some associated with streams, shells, & dwarf galaxies.



Searches for satellites around Milky Way-like Galaxies

- Searches Around Galactic Analogs (SAGA). Geha+17; Mao+21
- Ultimately ~100 MW-like galaxies at D=25-40 Mpc
- Spectroscopic ‘search’, down to Leo I-like satelites M_r=-12.3 mag.
- 36 MW-analogs, 127 satellites today.

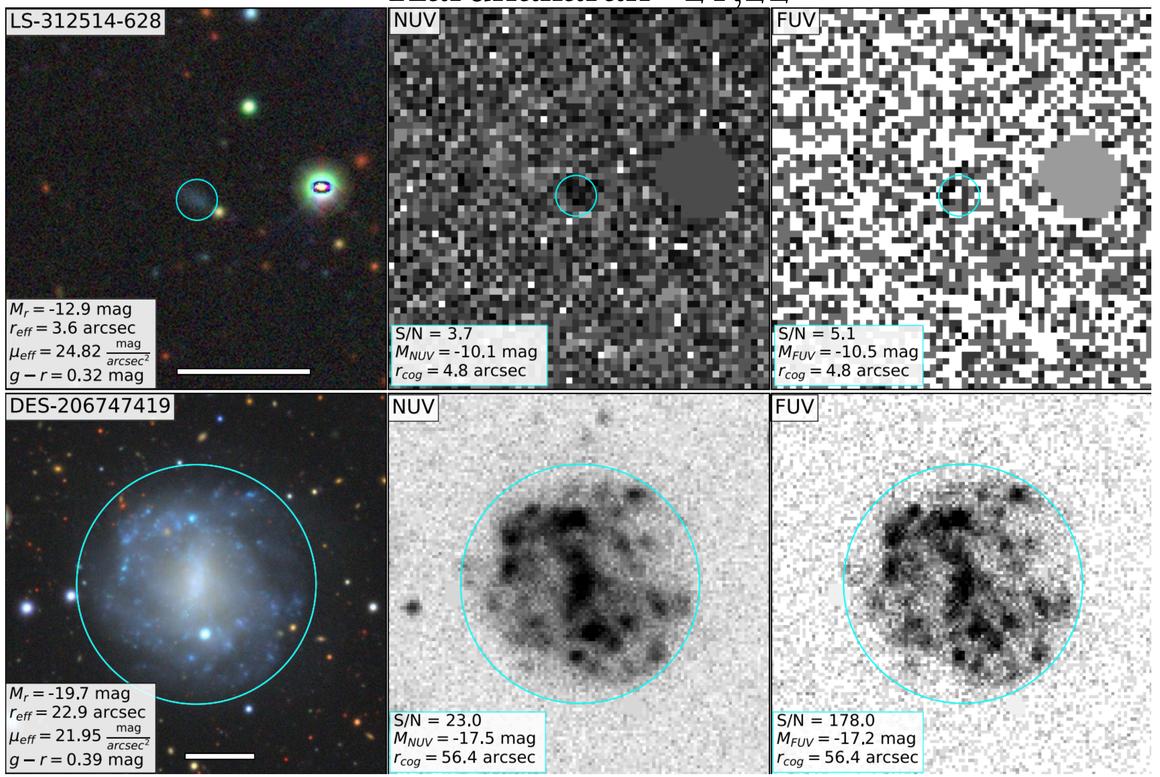




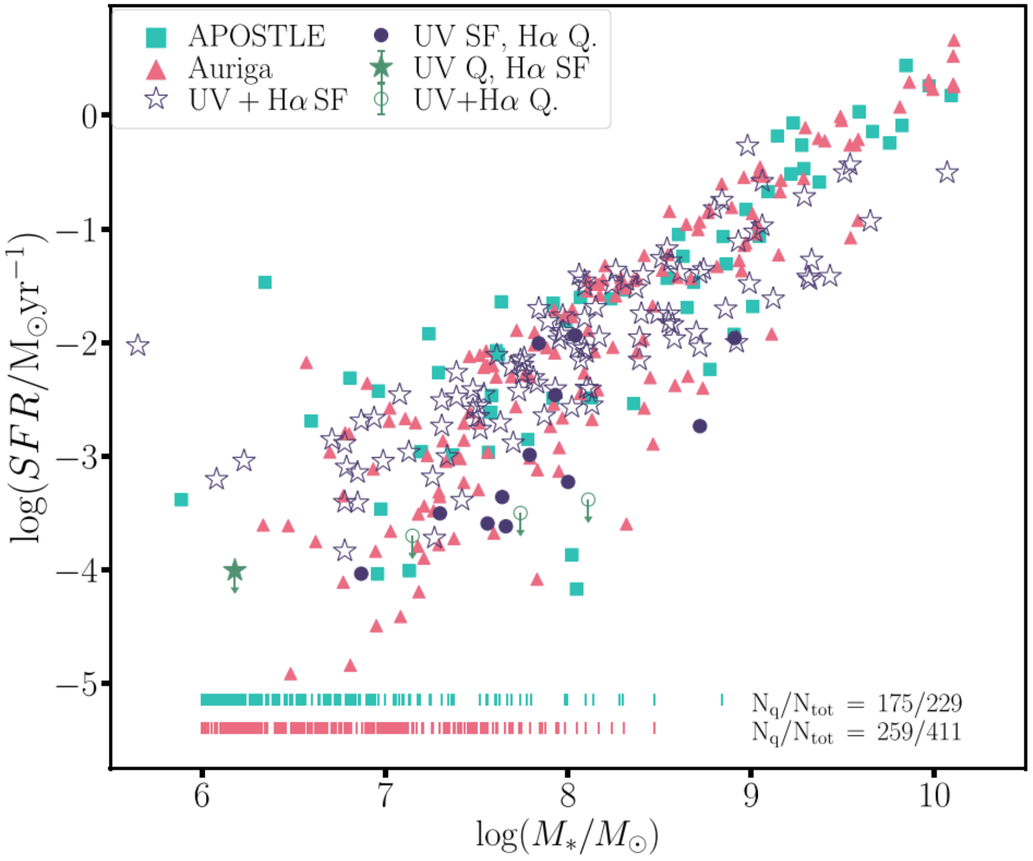
UV observations of MW-like satellites: Star formation and quenching

- GALEX UV constraints on the SAGA satellites.
- Compared directly to MW simulations: APOSTLE & Auriga.
- Quenched fraction in some tension between SAGA and simulations.
- Similar results seen in local samples of satellite galaxies (Carlsten+21).

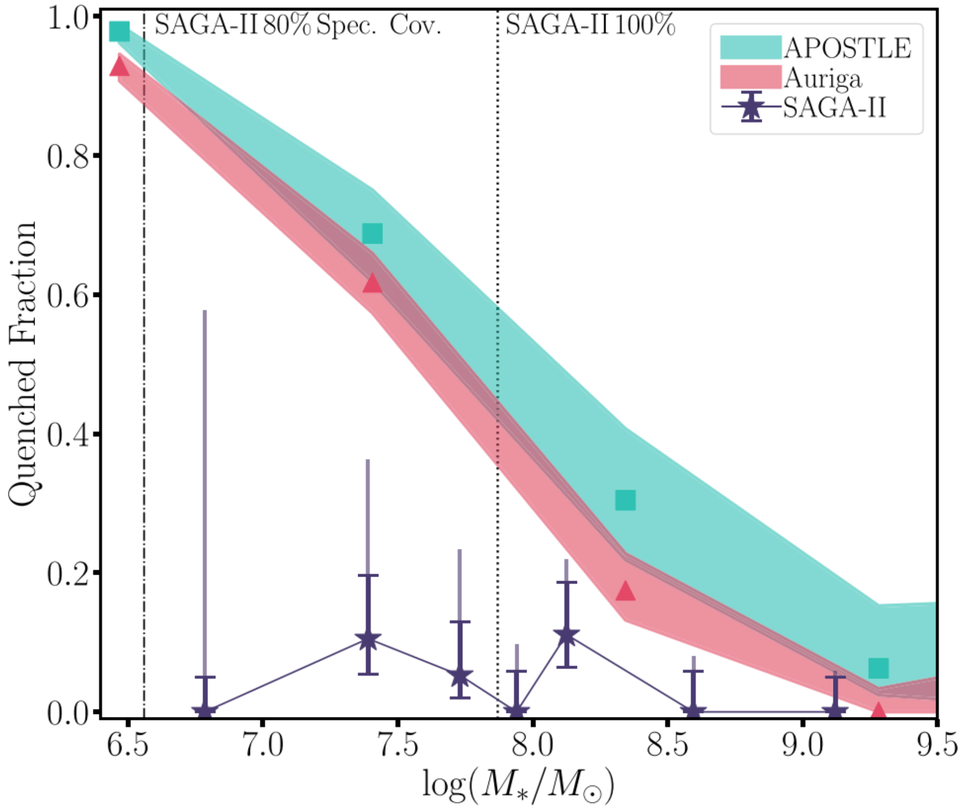
Karunakaran+21,22



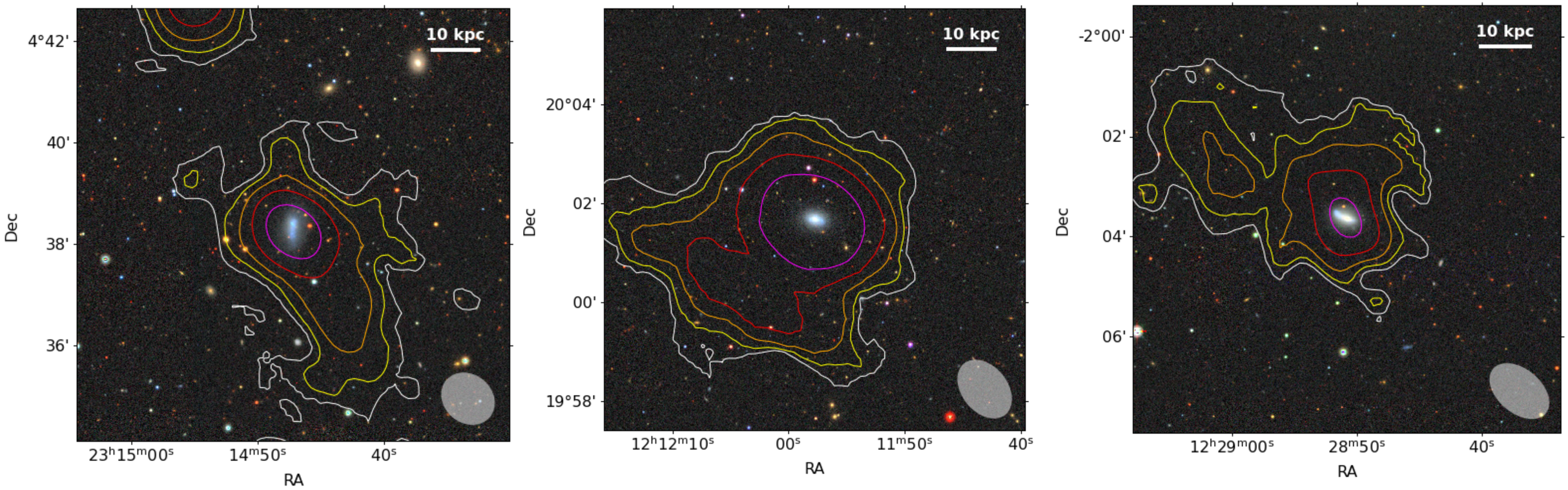
UV observations of MW-like satellites: Star formation and quenching



Karunakaran+21,22

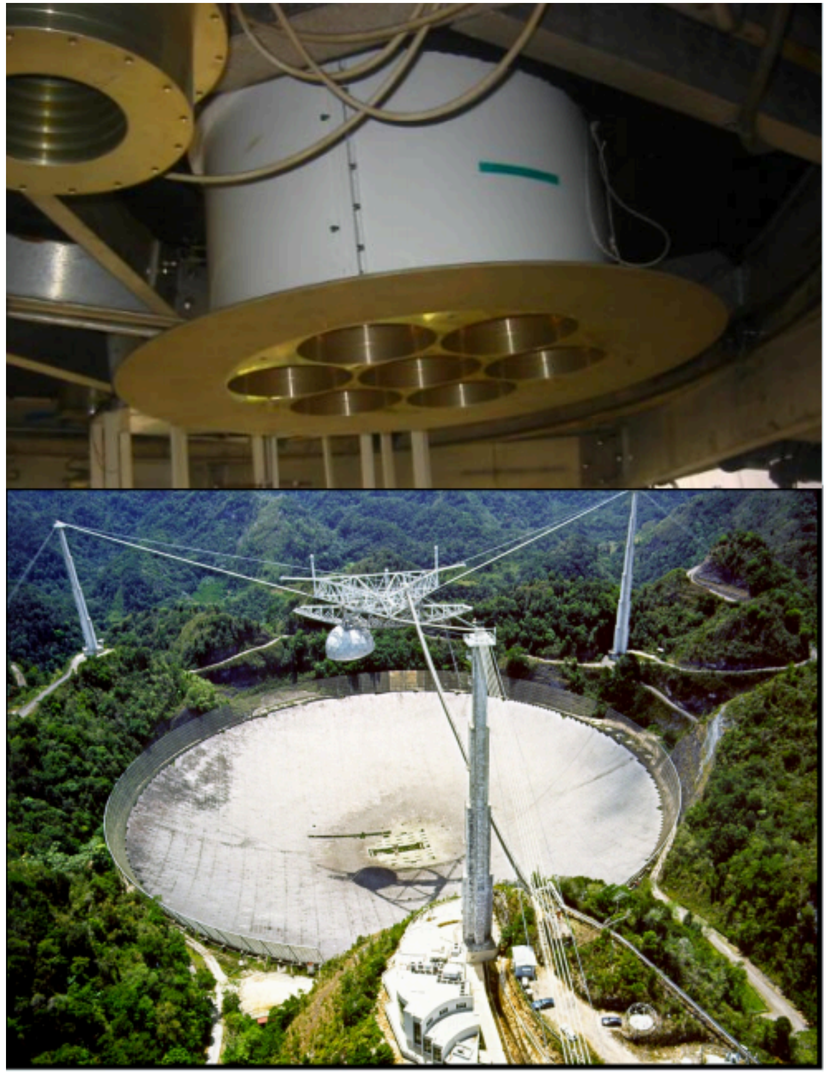


Next Step: Understand Quenching in MW-like Satellite Systems



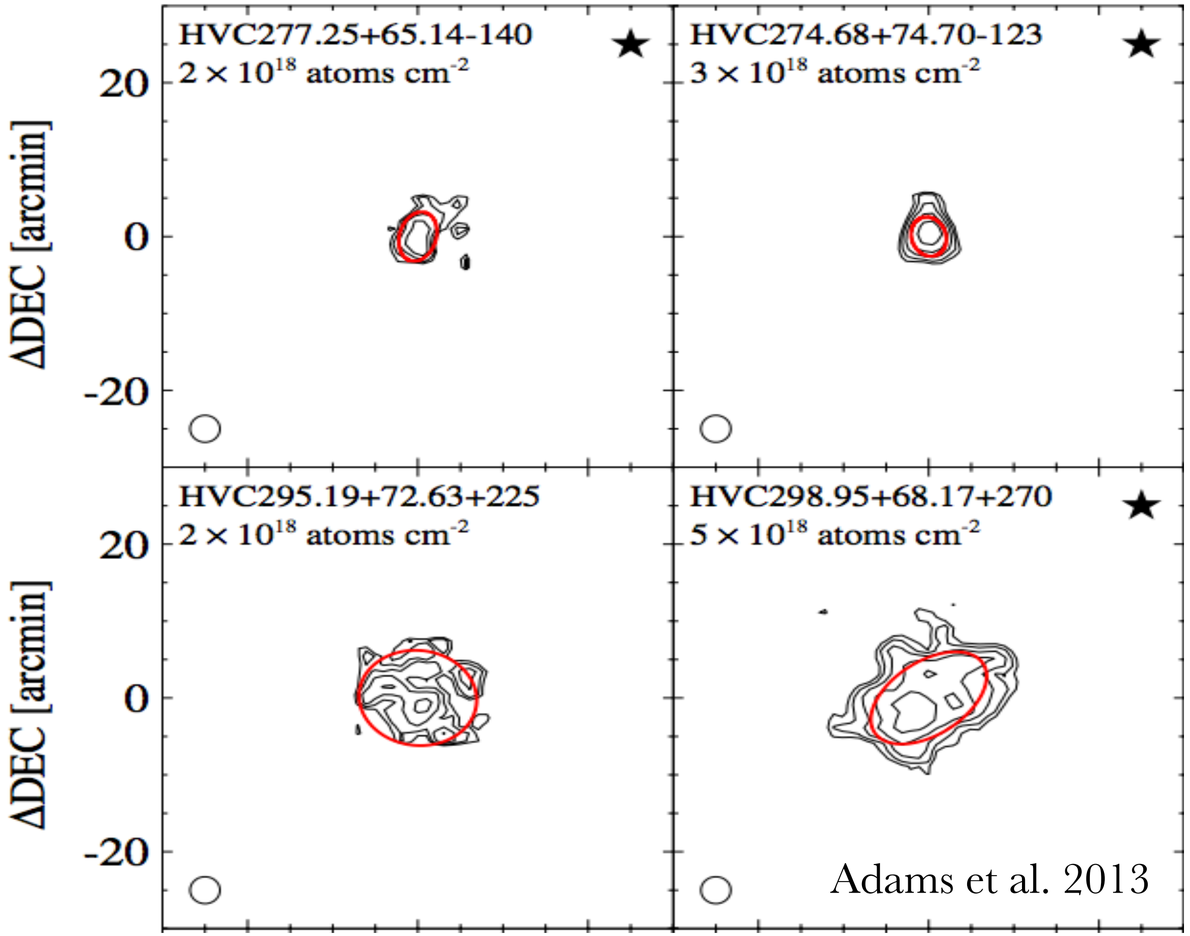
Field Dwarfs: Search for dwarf galaxies associated with HI Gas?
Modern Blind HI Surveys

- Arecibo Legacy Fast ALFA Survey (ALFALFA) and the Galactic Arecibo L-band Feed Array HI (GALFA-HI).
- ~7000 sq degrees
- ~10 km/s resolution; 3.5’ beam
- 10^5 M_{sun} of HI out to 1 Mpc
- More surveys in progress now. May be usefully paired with UVEX? APERTIF, MeerKAT MIGHTEE, ASKAP WALLABY, FAST



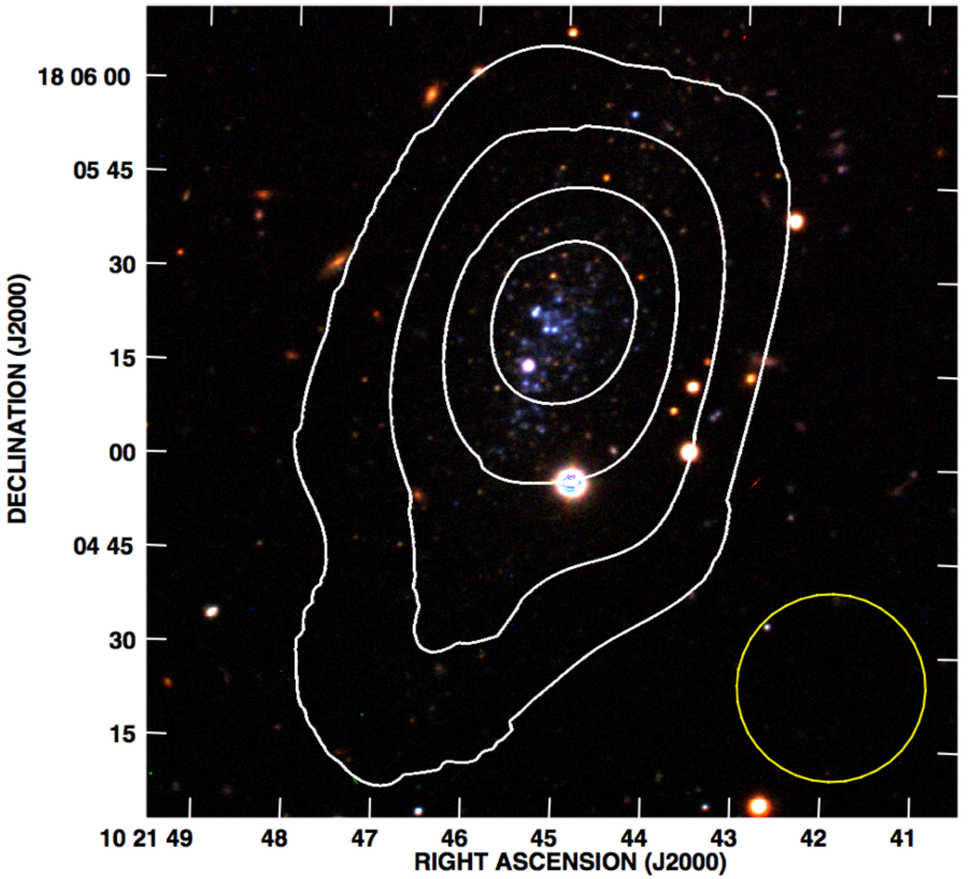
Ultra Compact High Velocity Clouds (UCHVCs)

- ALFALFA and GALFA-HI have both put out 'UCHVC' catalogs as possible nearby, star forming (or dark) galaxies. ~80 targets total. (Adams et al. 2013, Saul et al. 2012)
- Median size of ~10'
- High velocity $|V_{LSR}| > 90$ km/s
- There *should* be more than 10+ ultra-faint dwarf galaxies at the edge of the Local Group in ALFALFA (Tollerud & Peak 2018)



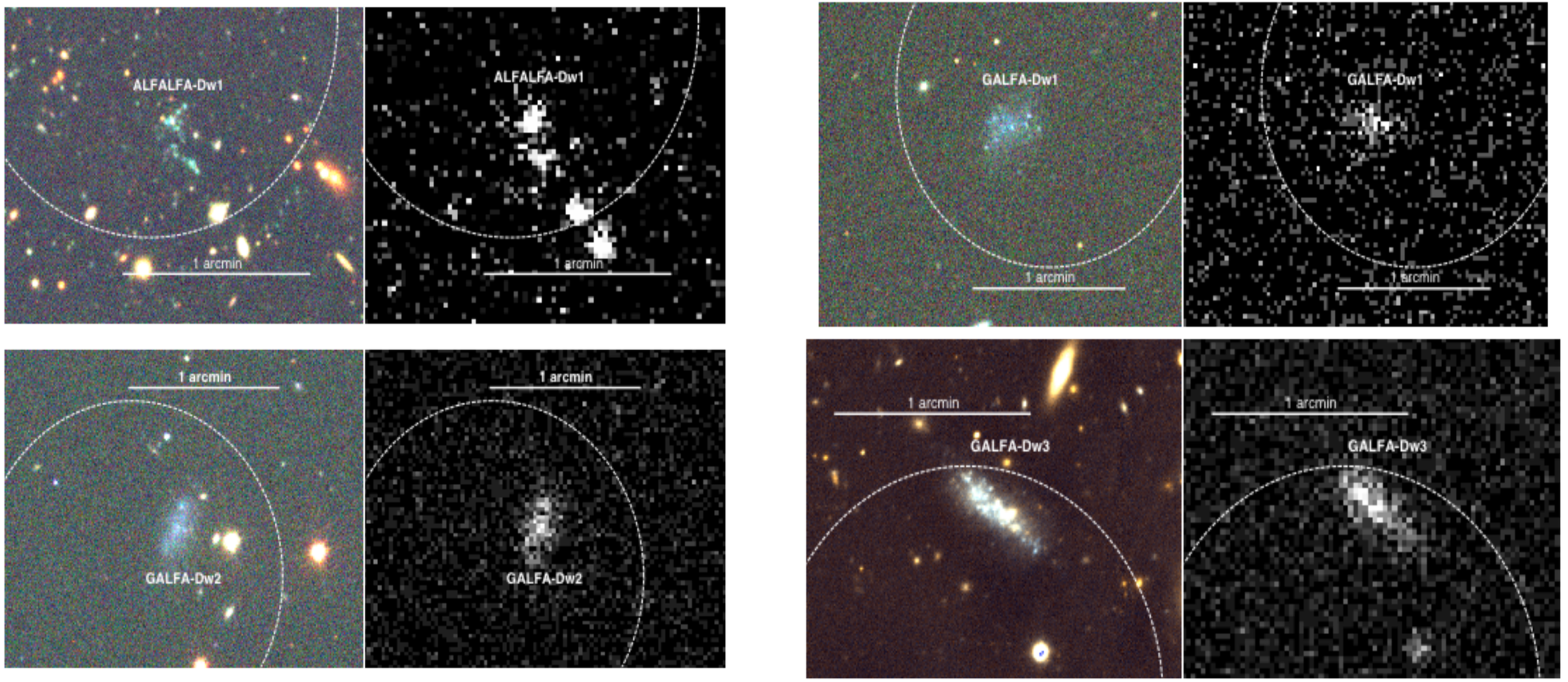
Leo P -- The Poster Child of a HI-selected Metal Poor, Faint Dwarf

- D~1.7 Mpc
- M_{HI}~9.5x10^5 M_{sun}
- M_{HI}/M_{star}~2.6
- M_V=-9.5
- extremely metal poor (I am sure this will be talked about more in this session)
- If there were dozens of Leo P's at the edge of the Local Group, it would be a major focus of UVEX!



Giovanelli et al. 2013; Rhode et al. 2013; McQuinn et al. 2015a,b

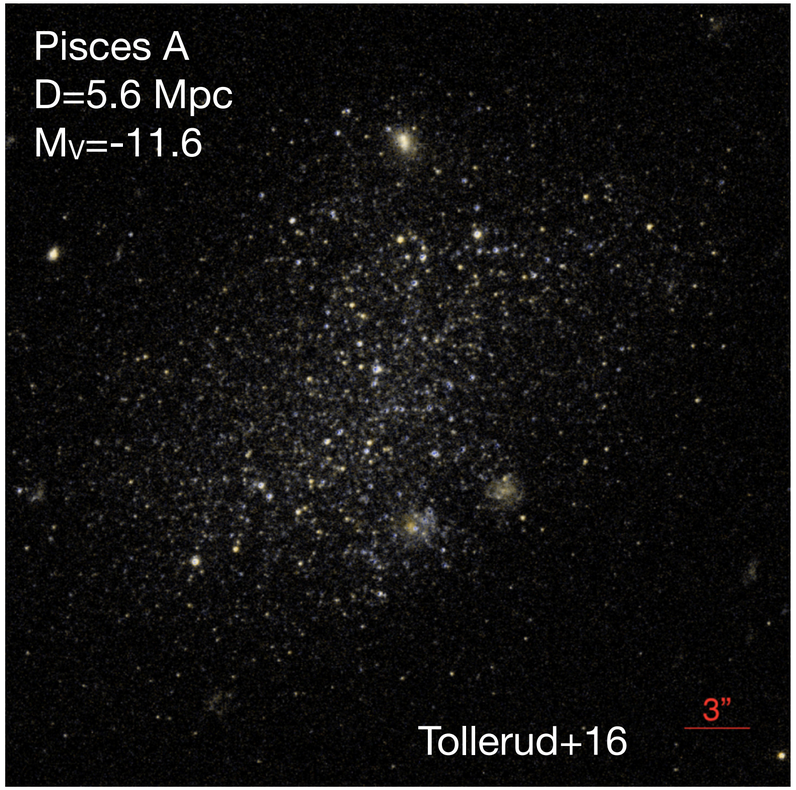
A Systematic Search for Dwarf Counterparts to UCHVCs

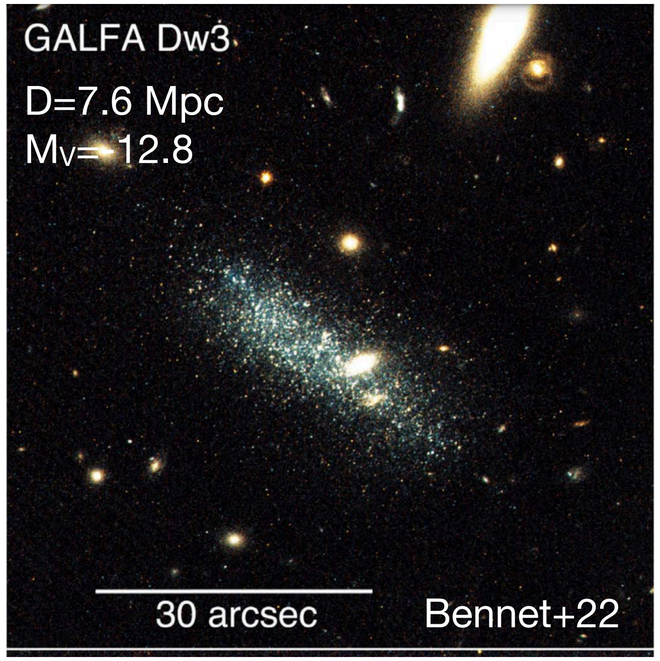


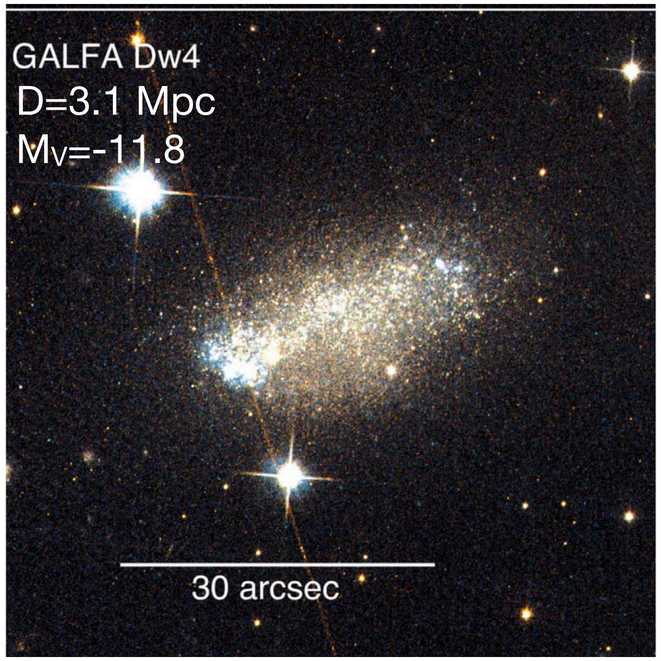
Optical (Left) and GALEX UV (Right) Observations

Sand+15; Tollerud+15; Bellazzini+15

Nearly all are Bona Fide Faint, Isolated Dwarfs In the Local Volume

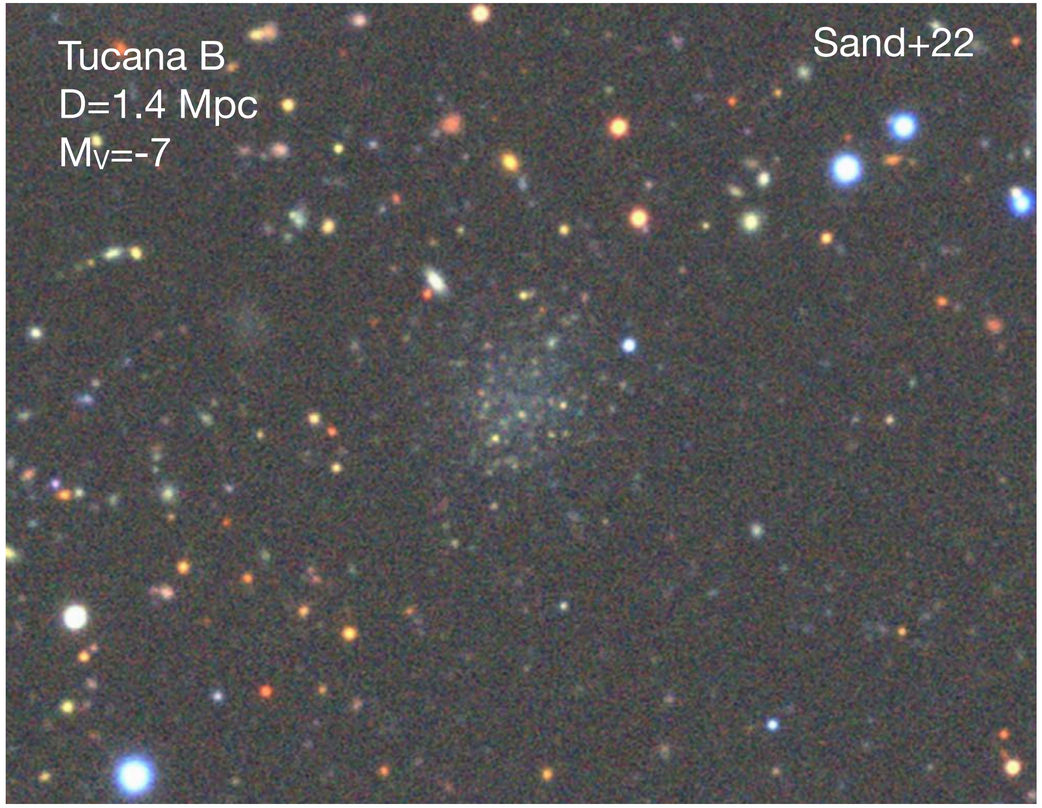






But Not the Ultra-Faint Dwarfs At the Edge of the Group we were Looking For

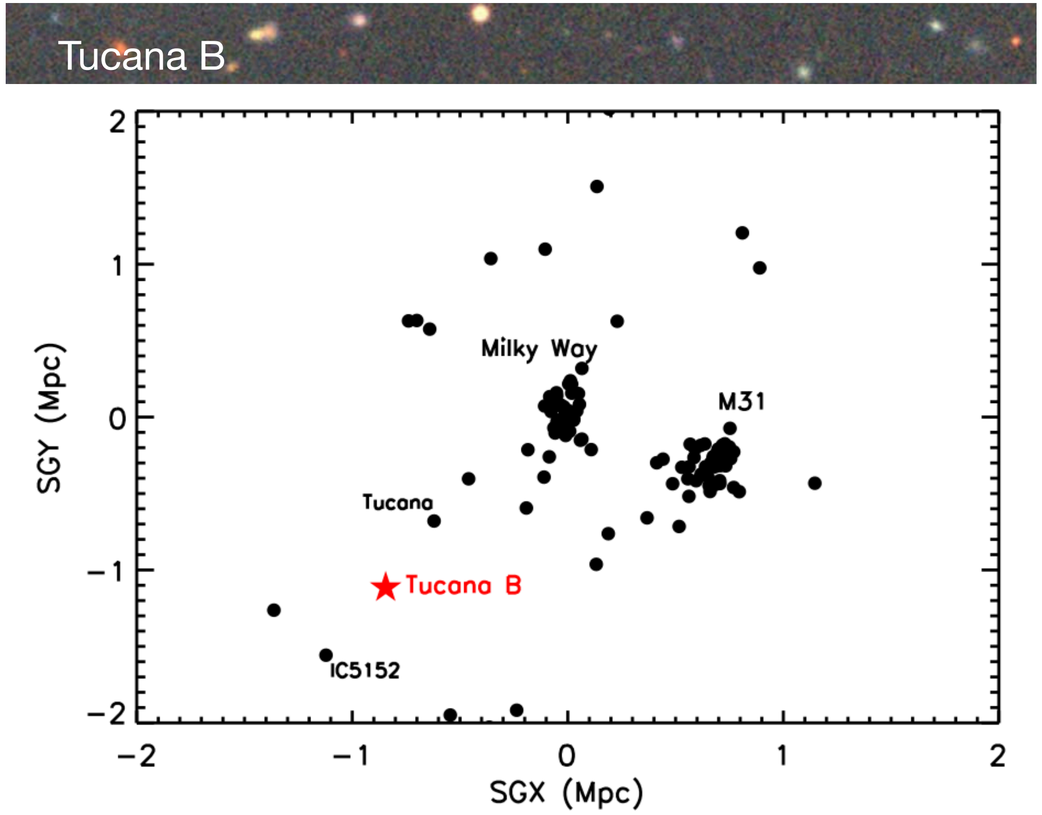
What is missing? Quenched Ultra-faint dwarfs at the edge of the Local Group?



Weak to no UV emission for this class of objects:
This is important too!

- No sign of young stars or HI gas
- Could be a ‘backsplash’ galaxy, but is quite distant for such objects (Buck+19)
- Quenched by reionization? Clean because this object has likely never interacted with a larger galaxy (no ram pressure/tidal stripping).
- Need JWST imaging down to the oldest MSTO to really confirm this.
- Other candidate objects coming in…

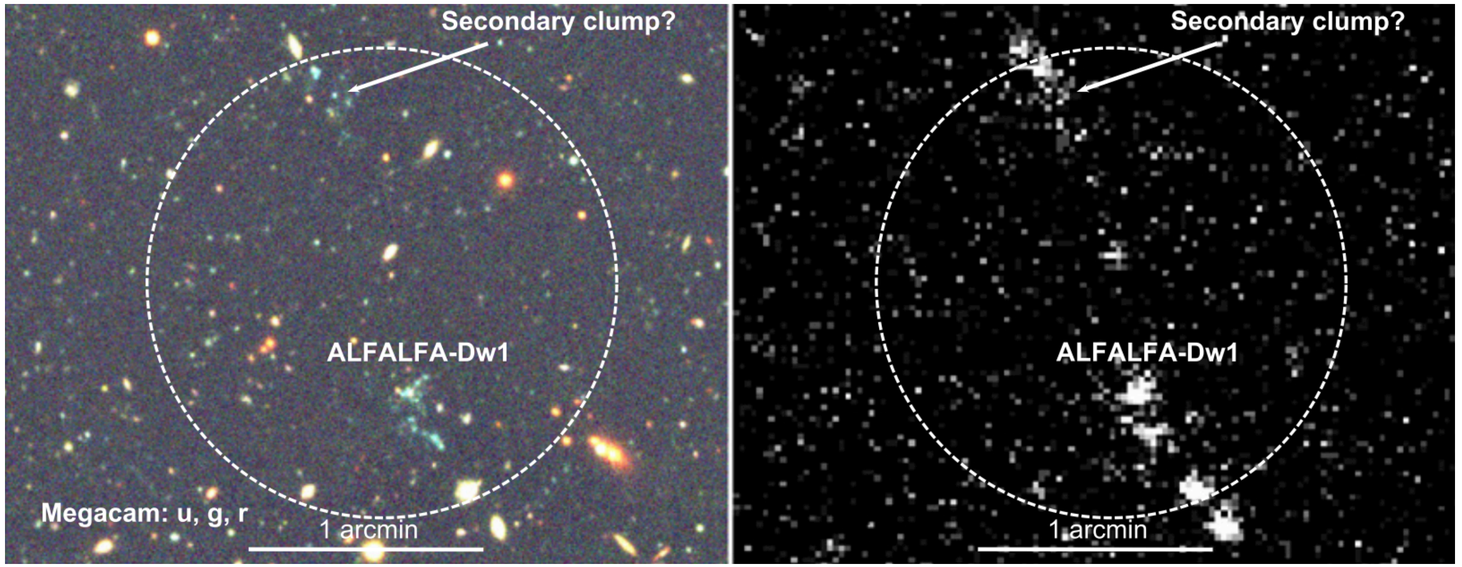
What is missing? Quenched Ultra-faint dwarfs at the edge of the Local Group?



Weak to no UV emission for this class of objects:
This is important too!

- No sign of young stars or HI gas
- Could be a ‘backsplash’ galaxy, but is quite distant for such objects (Buck+19)
- Quenched by reionization? Clean because this object has likely never interacted with a larger galaxy (no ram pressure/tidal stripping).
- Need JWST imaging down to the oldest MSTO to really confirm this.
- Other candidate objects coming in…

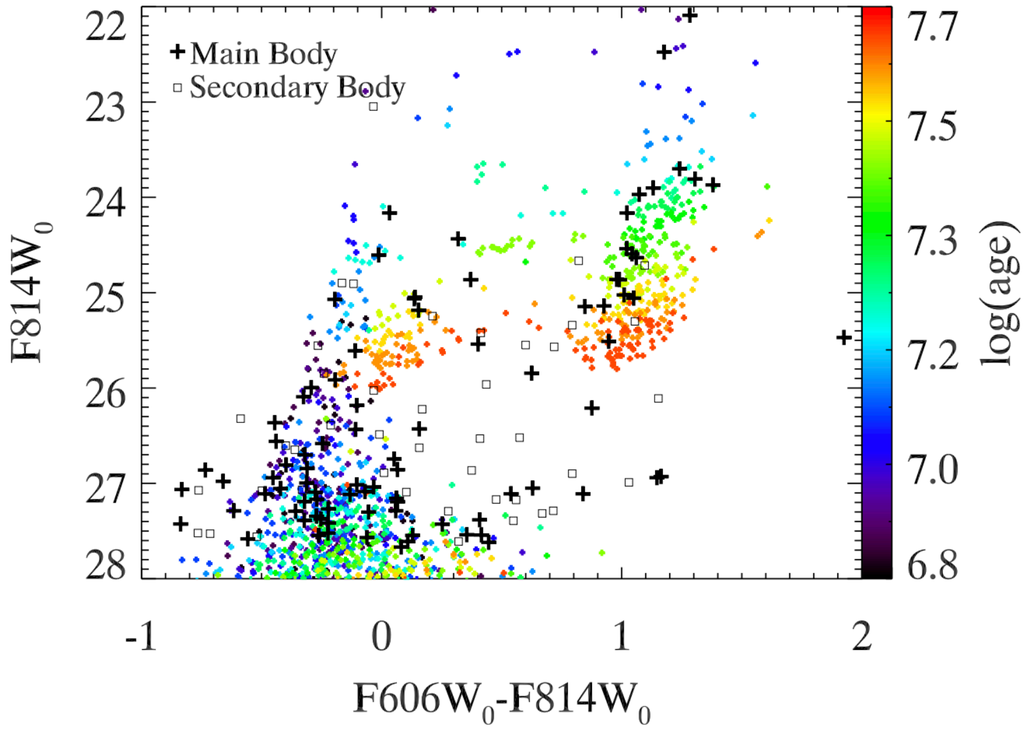
One object was not like the others



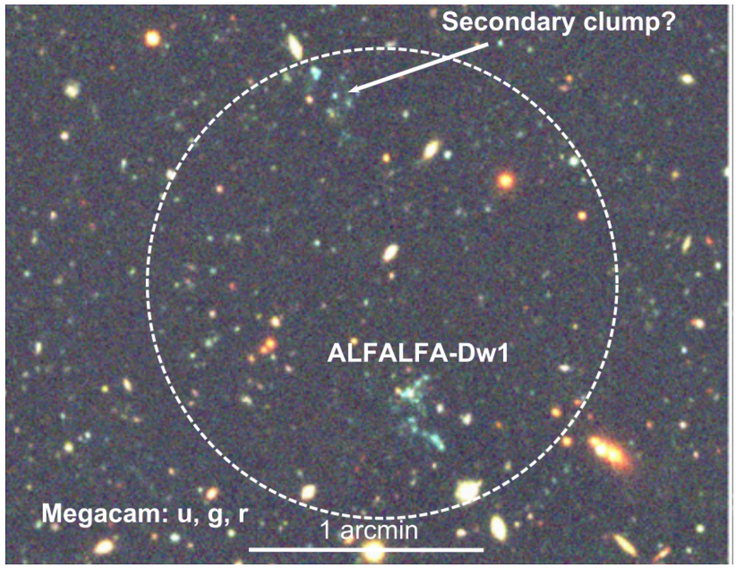
Sand+15

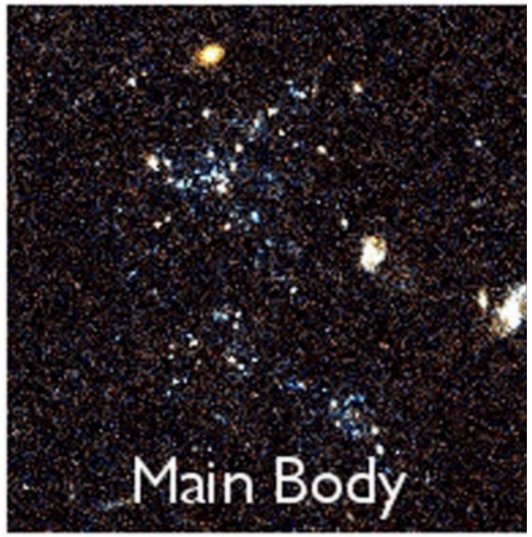
- One gas cloud did have some stars, but it wasn't near the Milky Way at all.
- ~18 Mpc in the Virgo galaxy cluster
- Strange, disjoint morphology. Detailed gas observations also indicated clumpy morphology.
- Needed a closer look…

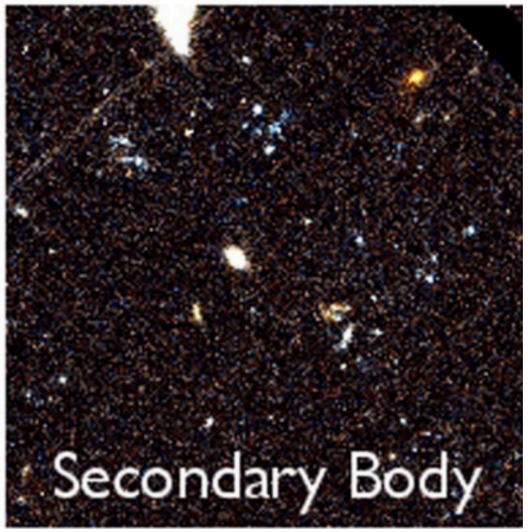
One object was not like the others — HST follow-up



Sand+17



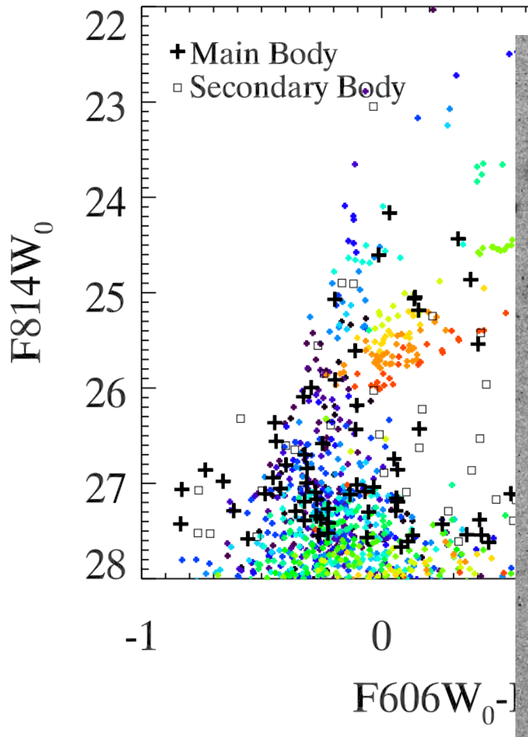


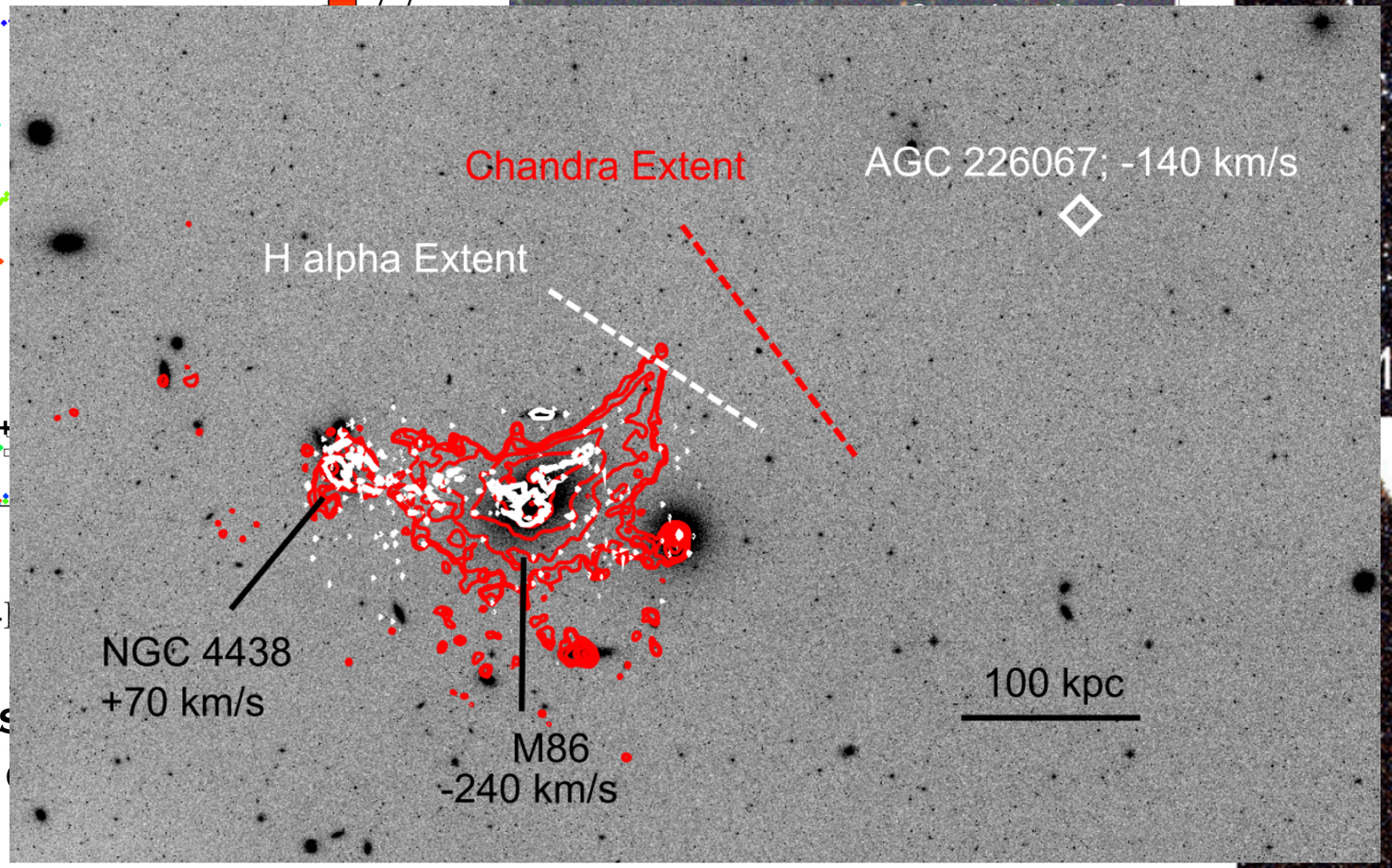


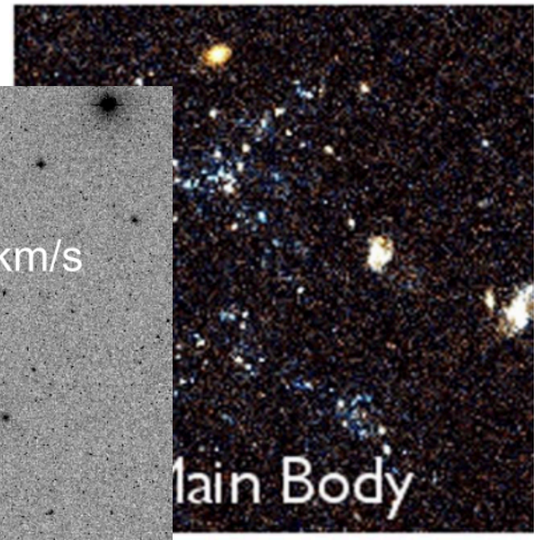
No old stars at all, pure young population
In the Virgo Cluster, but no nearby cluster galaxies
Where did this come from?

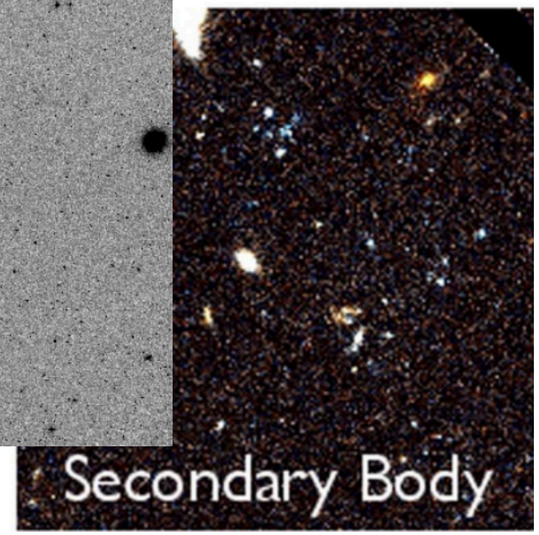
One object was not like the others — HST follow-up

Sand+17





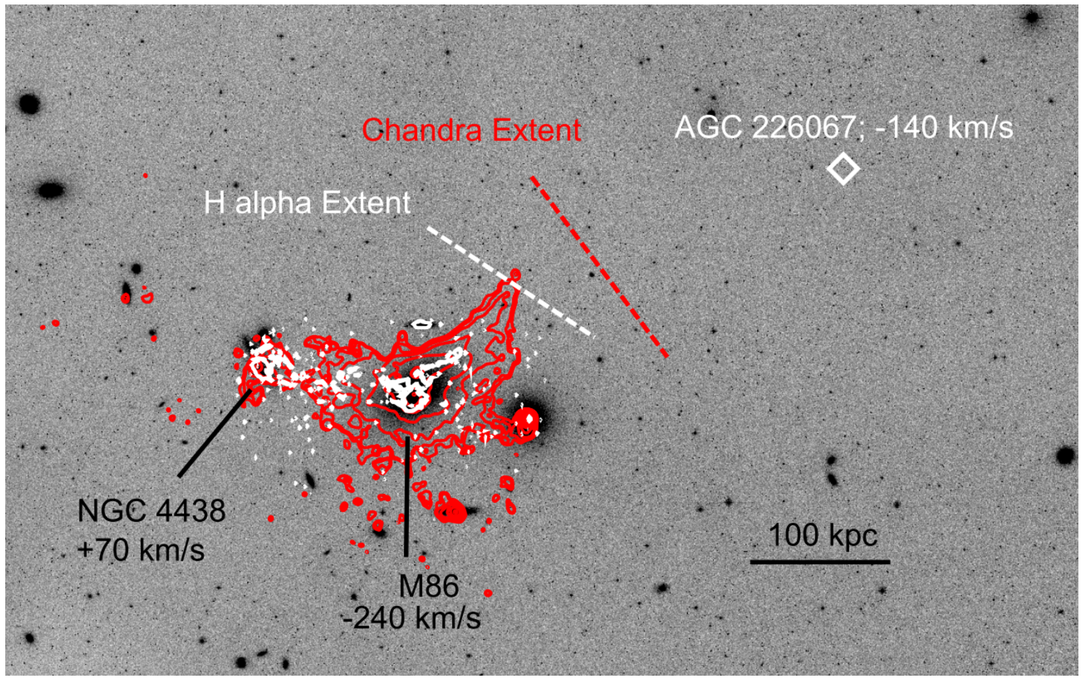




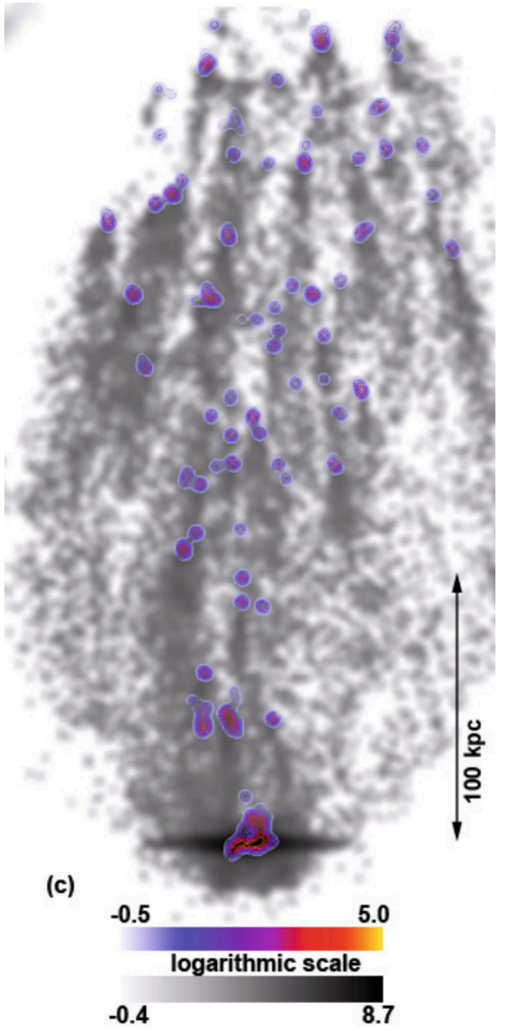
No old s

In the Virgo

What is this? New star formation associated with Ram Pressure, but very far fromthe stripped galaxy

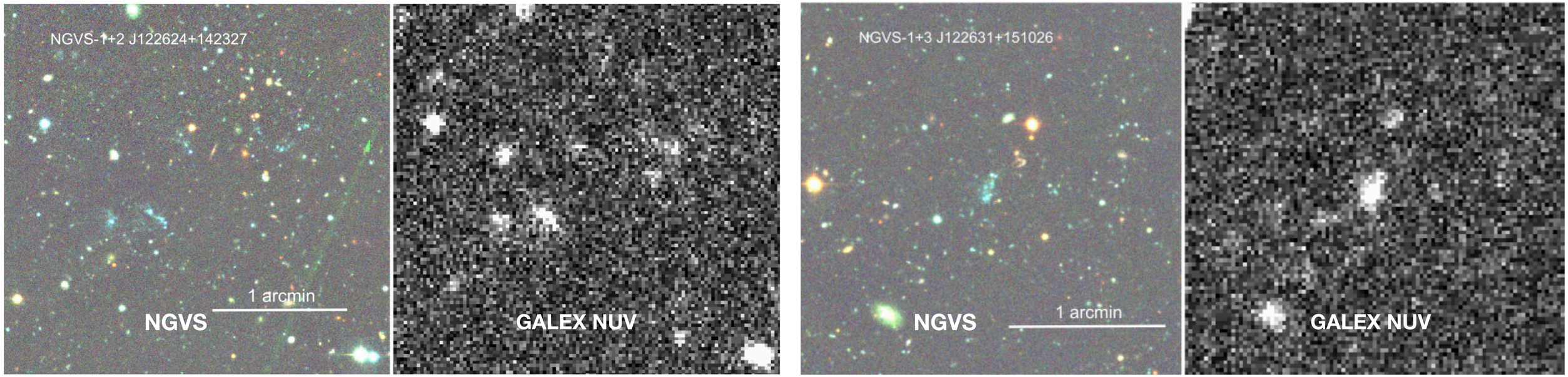


Kapferer+09



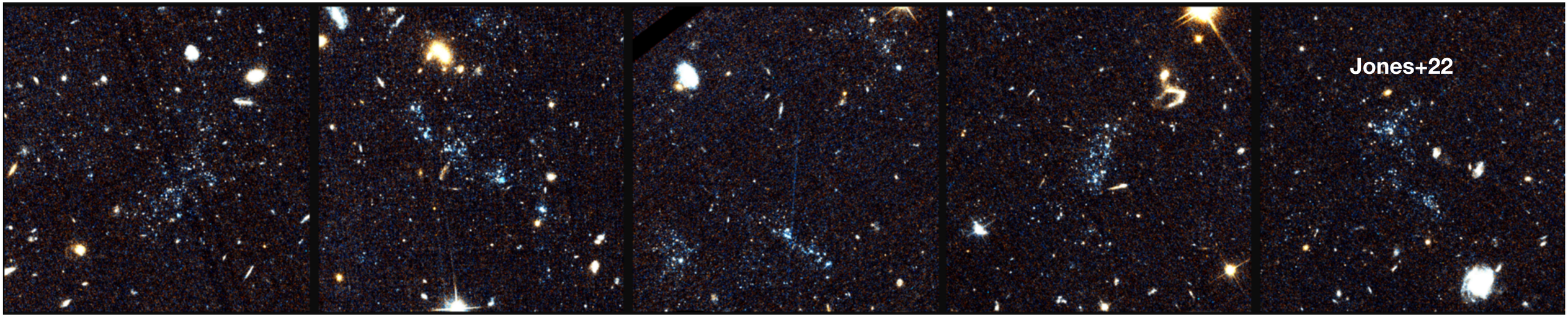
- Tidal Dwarf Galaxy? These are typically ejected at <400 km/s. Would take ~billions of years to become isolated.
- Ram pressure stripping can occur at >1000 km/s. More natural time scale.

More Examples in the Virgo Cluster
Citizen Science and By-Eye Searching
NGVS+GALEX



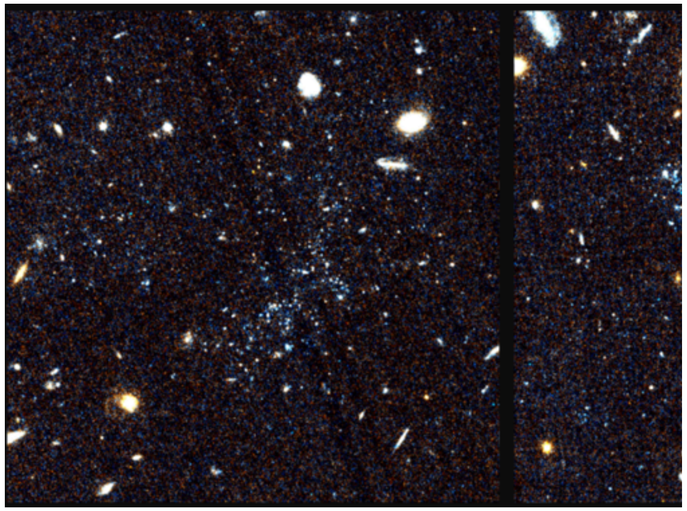
- Must be very isolated, clumpy morphology, no clear underlying old stellar population.

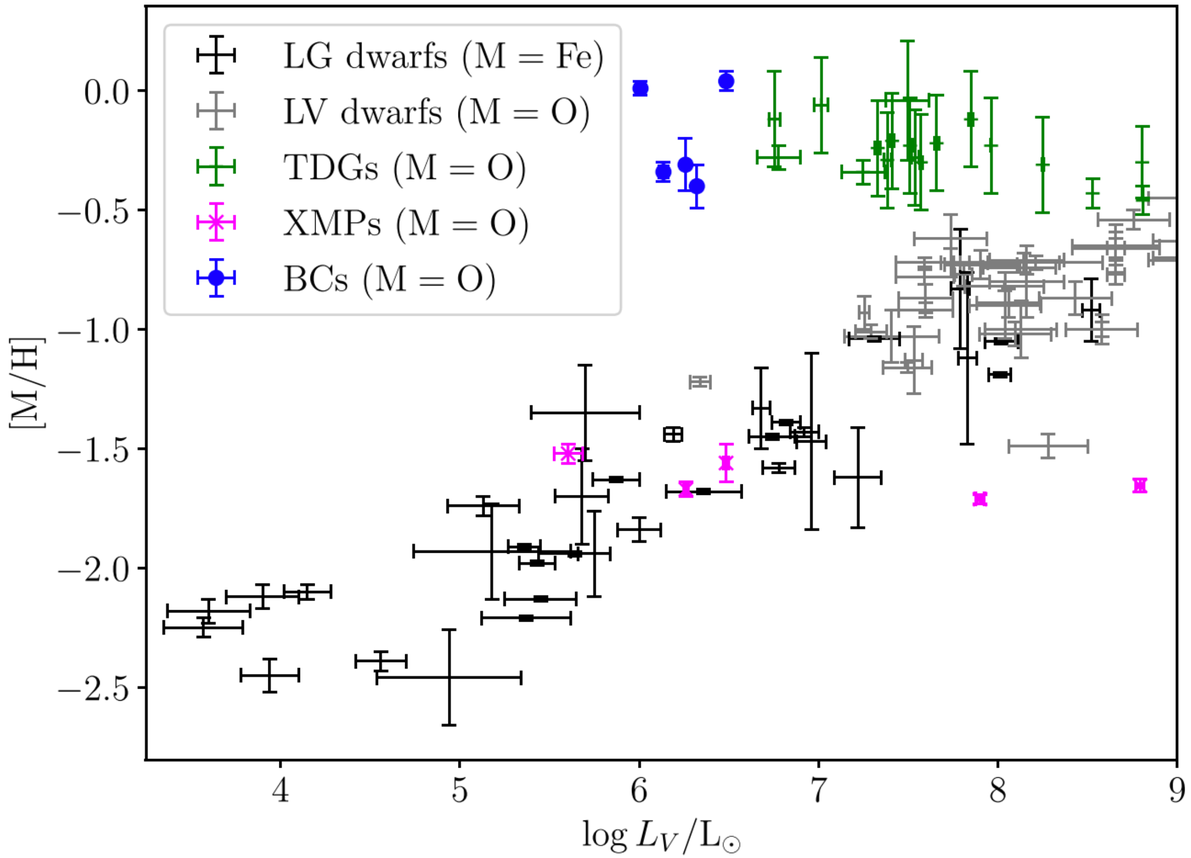
HST + MUSE IFU Follow-up



- All have similar properties; 10-100 Myr stellar population — no old stellar population to be seen.
- No clear progenitor for the stripped gas in any instance, although there are candidates.
- IFU measurements of the full sample show each comprises multiple HII regions.
- Metallicity elevated well above that expected at these luminosities based on the L-Z relation. Points to pre-enriched gas — stripped origin.
- Velocity dispersions consistent with 0 km/s — likely no DM halo.

HST + MUSE IFU Follow-up





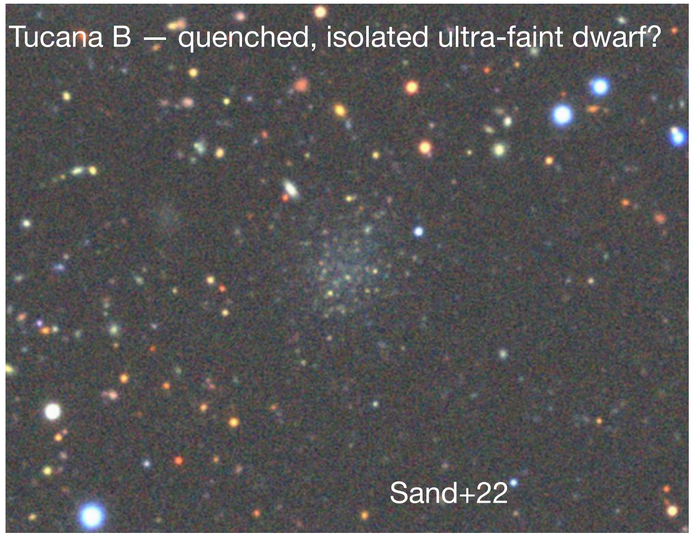
- All have similar properties; 10) be seen.
- No clear progenitor for the str .
- IFU measurements of the full
- Metallicity elevated well above that expected at these luminosities based on the L-Z relation. Points to pre-enriched gas — stripped origin.
- Velocity dispersions consistent with 0 km/s — likely no DM halo.

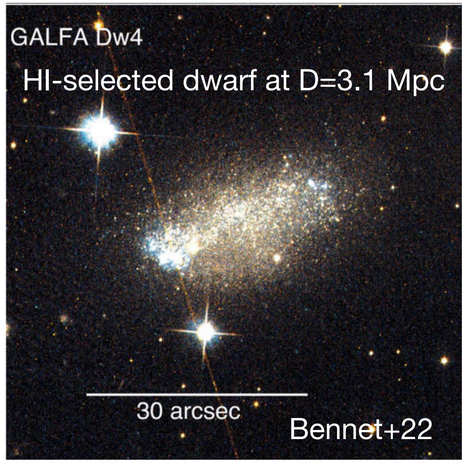
- The faintest dwarf galaxies are sensitive to dark matter and baryonic physics of star formation, SN feedback, tidal/ram pressure stripping, reionization. Finding and characterizing the faintest dwarfs in different environments tells us which of these effects matters most.

- HI-led search for isolated dwarf galaxies at the edge of the Local Group.

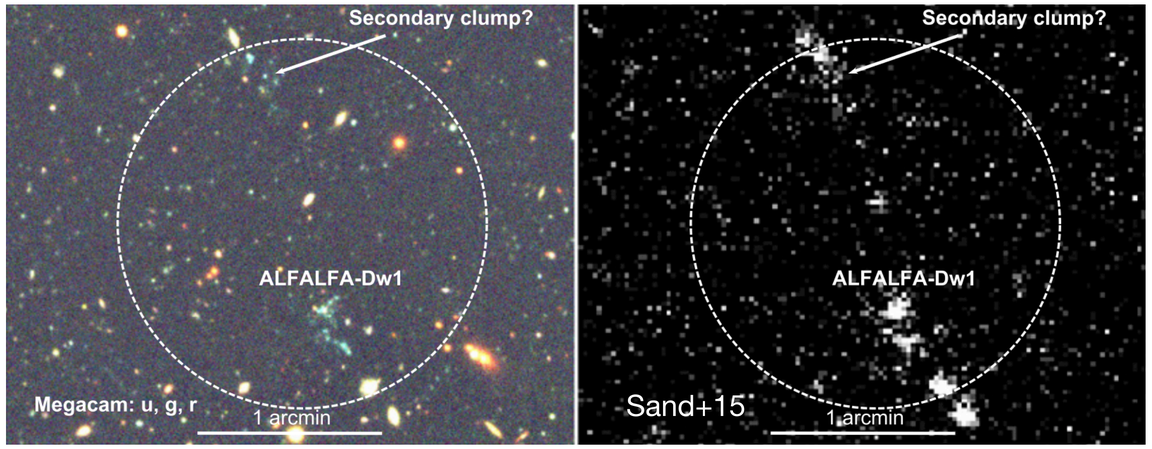
- New class of stellar system: isolated, strongly star forming, no old stars, high metallicity.

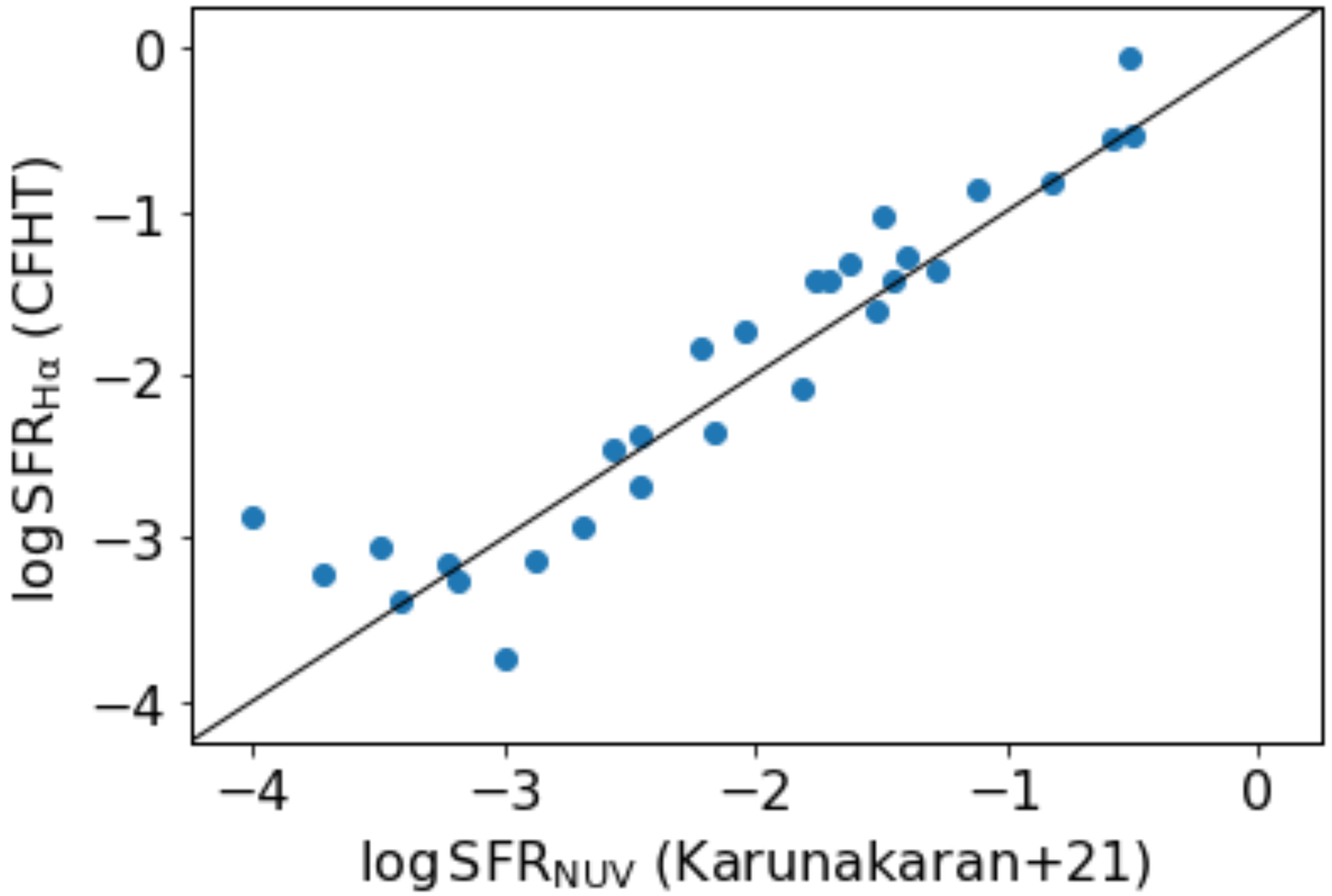
- New searches will find dwarfs at the edge of the Local Group, or in the field, that are quenched. Little to no UV emission: that's important too!



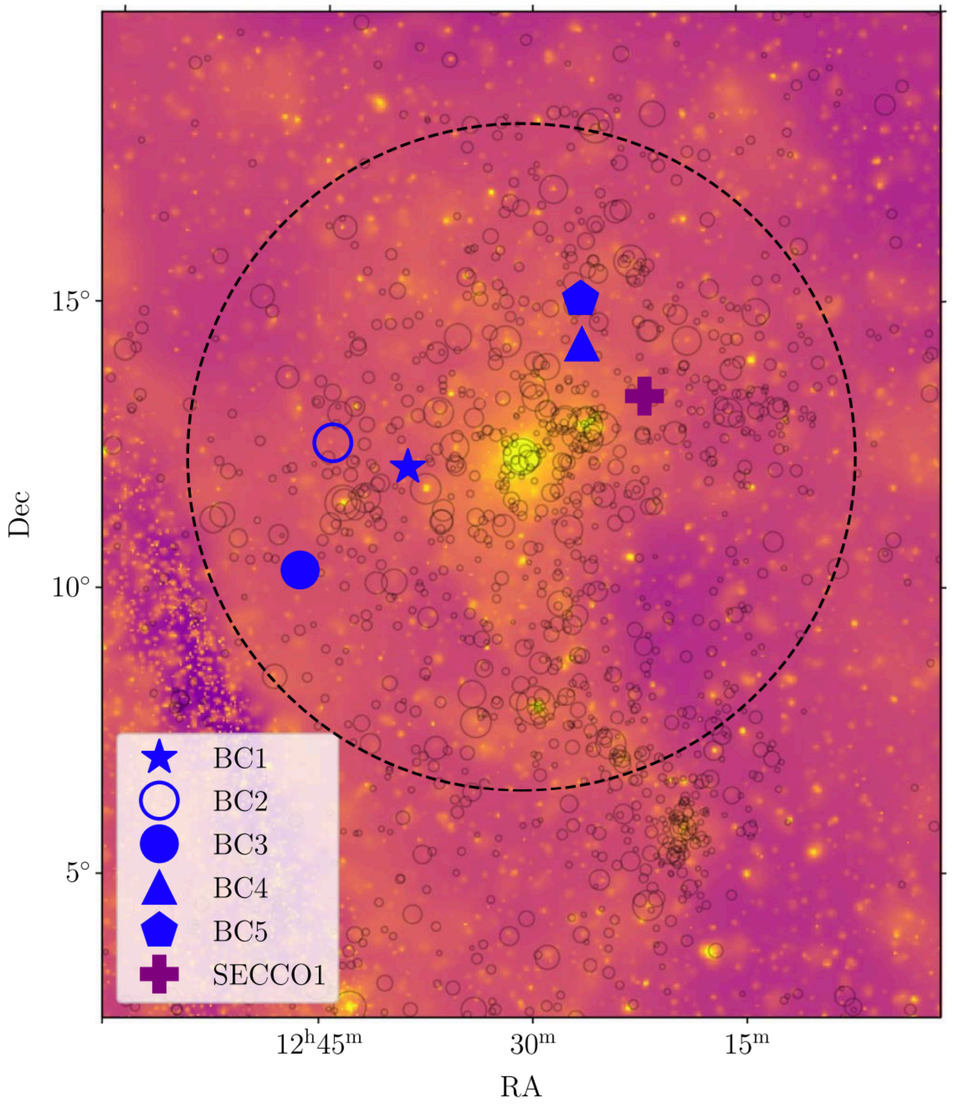


Isolated stellar system in the Virgo Cluster



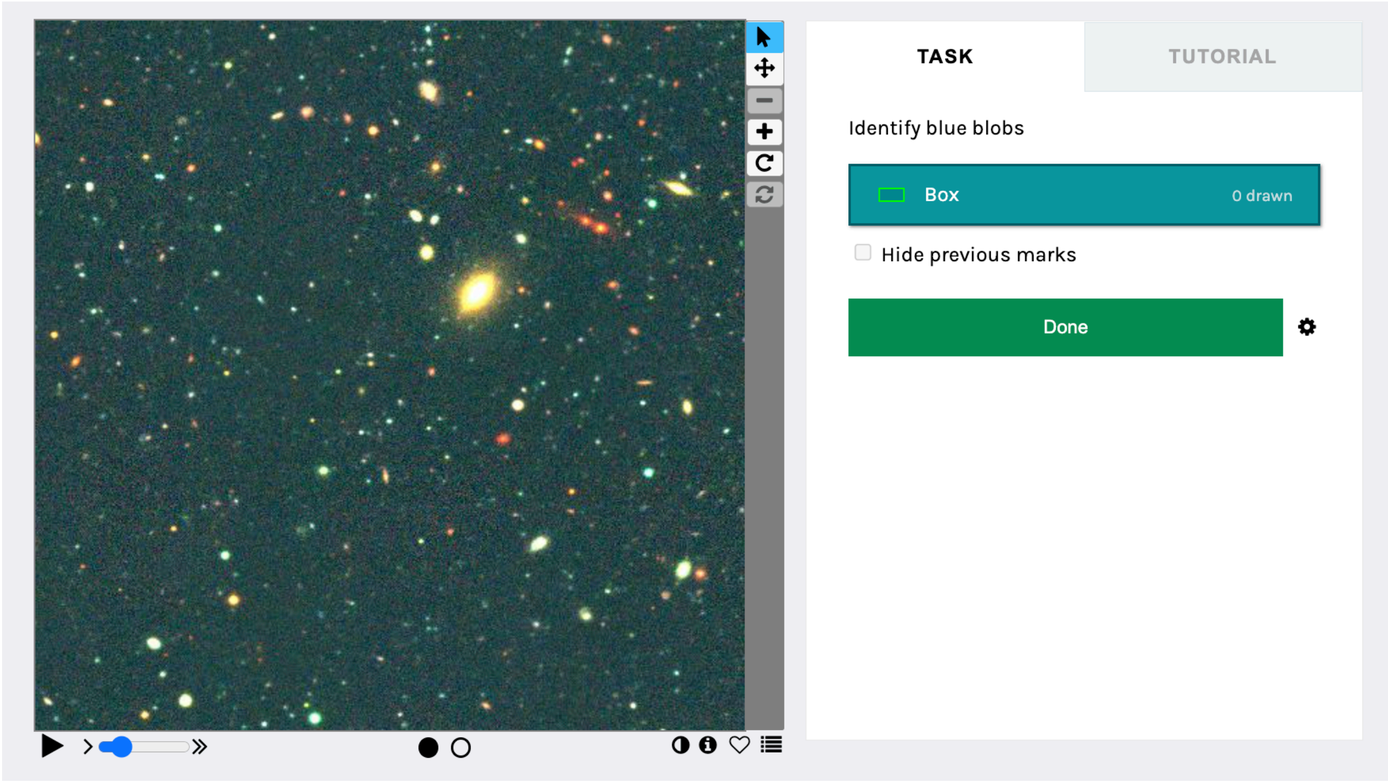

0
−1
−2
−3
−4
log SFR$_{H\alpha}$ (CFHT)
−4
−3
−2
−1
0
log SFR$_{NUV}$ (Karunakaran+21)

Where are the blue blobs?



What's Next?

- Finding more examples of 'blue blobs' is somewhat difficult — they do not lend themselves to standard detection or machine learning techniques.
- Using the 'citizen science' platform Zooniverse to identify new examples via crowdsourcing!

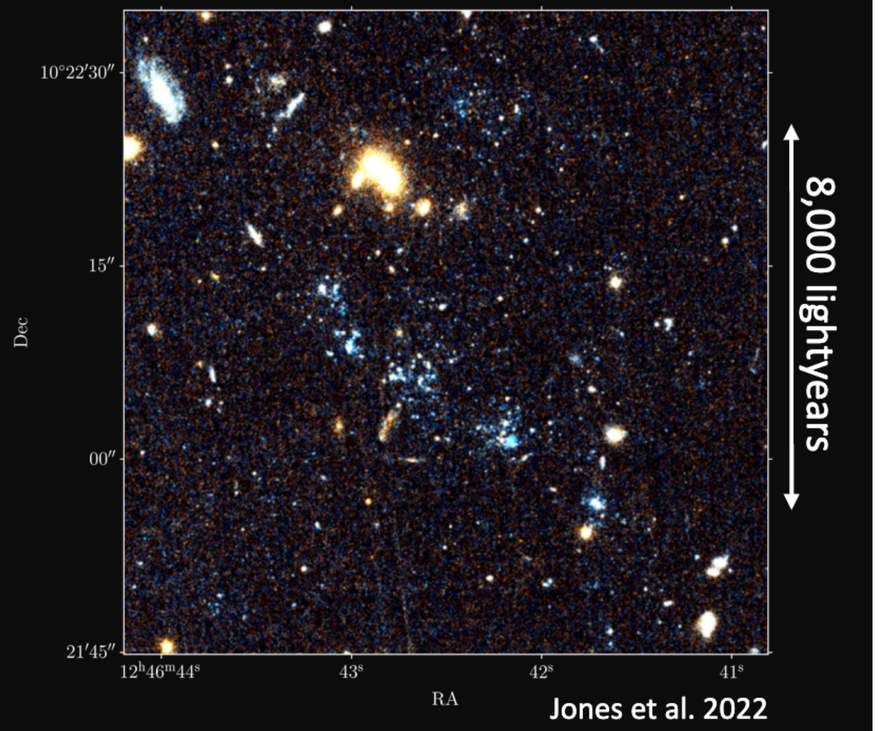


ZOONIVERSE

Tiny oases in a desert

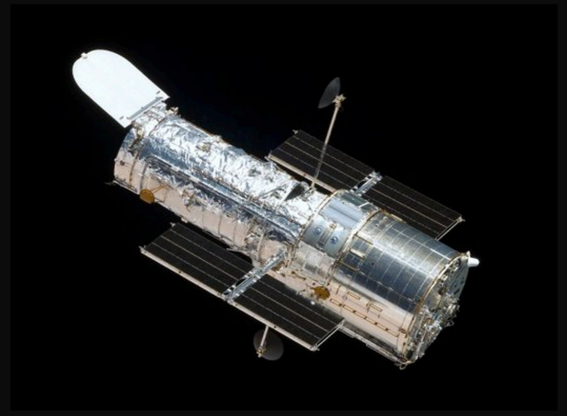
- We have identified 5 irregular, blue, and isolated stellar systems in the Virgo cluster.
- All are dominated by young, blue stars.
- Around a million times less massive than our galaxy.
- They are isolated, at least 200,000 lightyears from any possible parent galaxy.

Hubble Space Telescope image of one blue blob in the Virgo cluster



Jones et al. 2022

How to find out more about blue blobs?



Hubble Space Telescope
(Low Earth orbit)

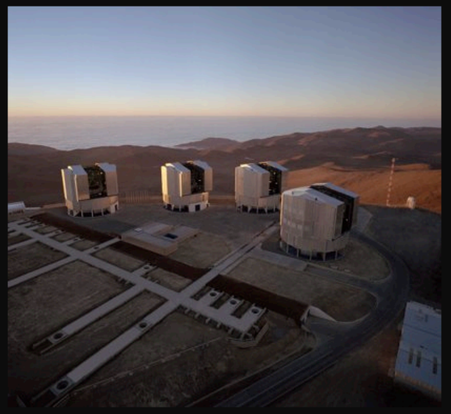
Best possible resolution (before JWST).

Ideal for studying the stars in blue blobs.

Very Large Array
(New Mexico)

Sensitive to radio emission from neutral hydrogen gas.

Can detect gas before it is turned into stars.



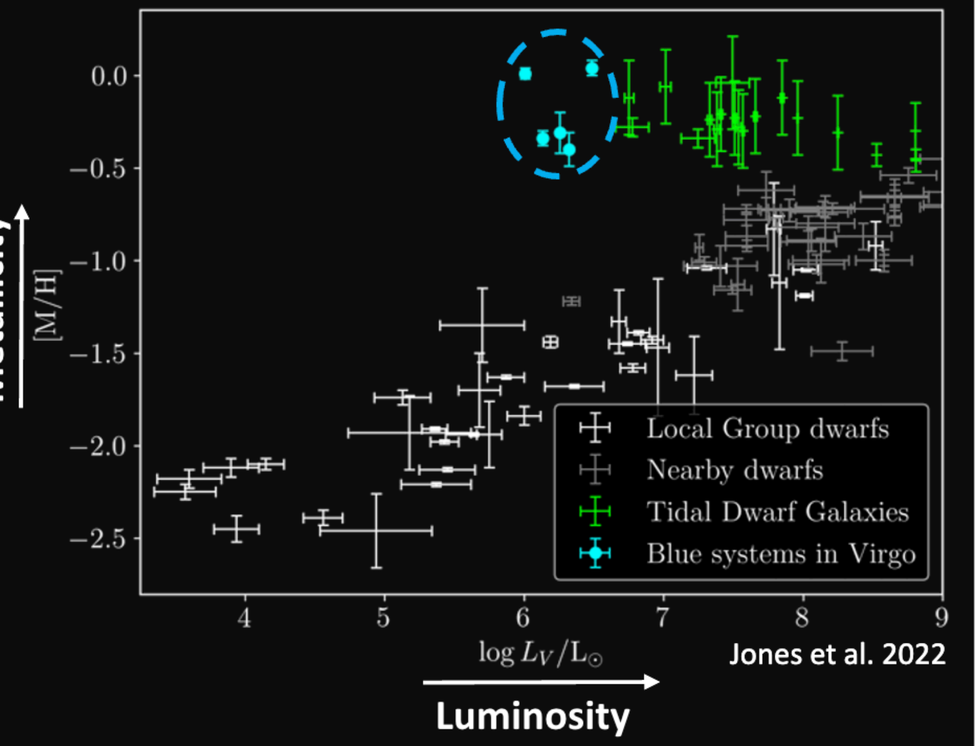
Very Large Telescope
(Chile)

Can map emission lines from star-forming regions.

Measure the chemical composition of blue blobs.

Formed from pre-enriched gas

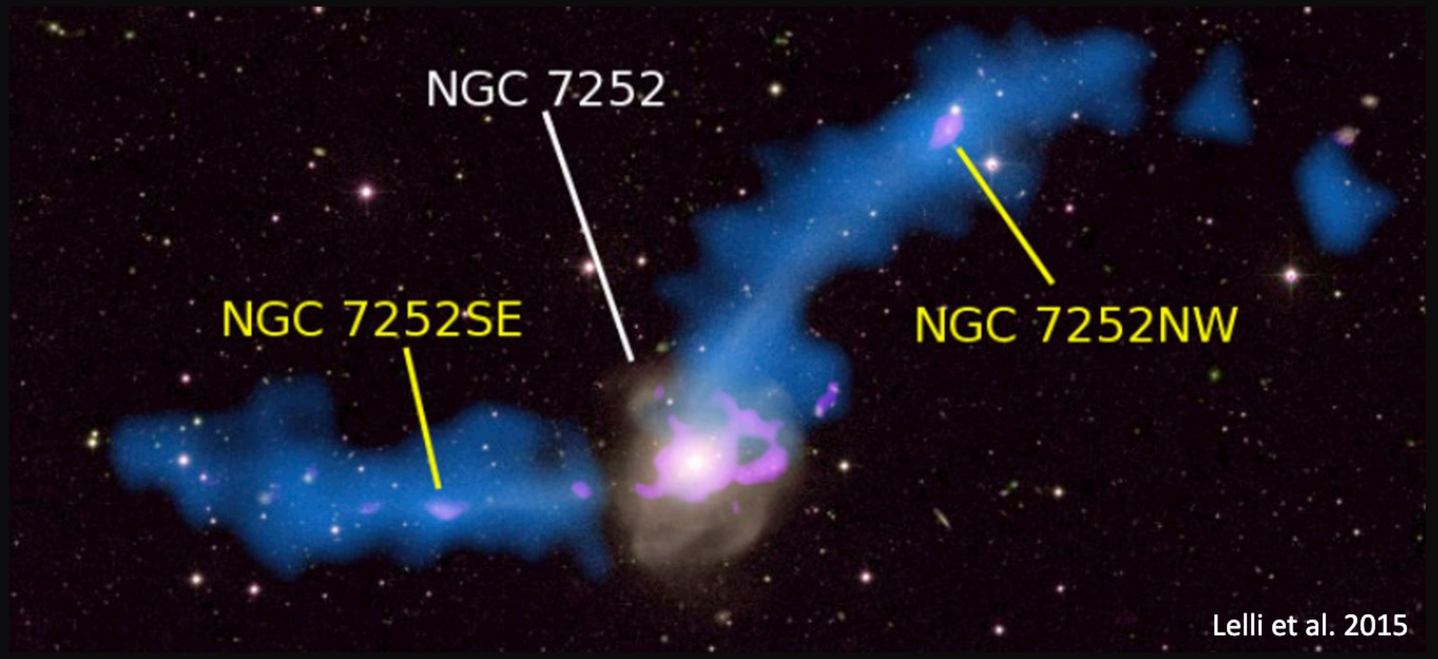
- Generally bigger galaxies are richer in heavy elements, that is they are of higher "metallicity."
- Blue blobs do not follow this trend.
- This is a telltale sign that they formed from gas stripped from a large galaxy.



Tidal stripping

- Tidal stripping can occur when 2 (or more) galaxies past close by each other and interact gravitationally.
- Gas clouds can collapse to form "tidal dwarfs".

Tidal dwarf galaxies forming in gas-rich tidal tails



Ram pressure stripping

- Ram pressure stripping occurs when a gas-rich galaxy falls into a galaxy cluster, colliding with the intra-cluster medium.
- Gas is forced from the galaxy and stars can form in the wake.

Ram pressure forcing out gas from a galaxy.

Boselli et al. 2021

Ram pressure stripping

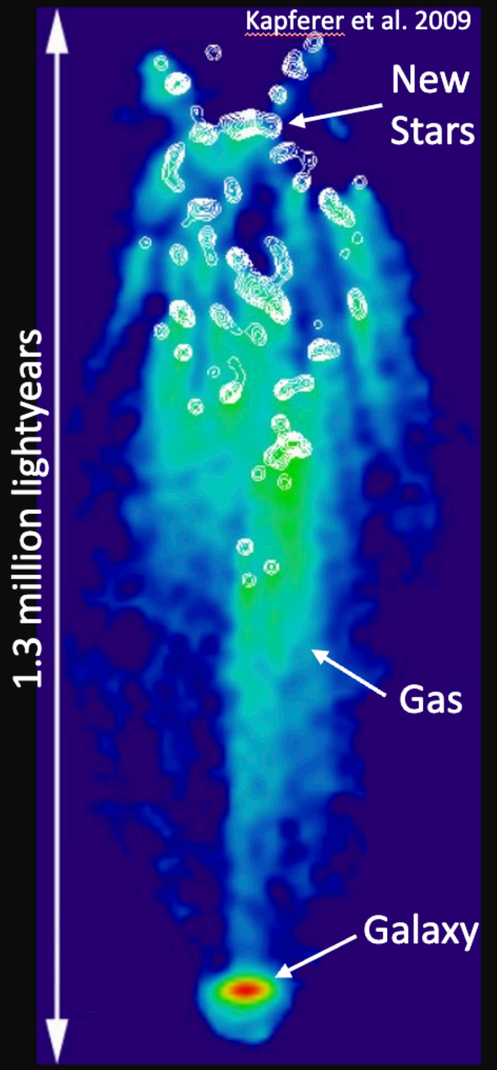
- Ram pressure stripping occurs when a gas-rich galaxy falls into a galaxy cluster, colliding with the intra-cluster medium.
- Gas is forced from the galaxy and stars can form in the wake.

R galaxy.

Boselli et al. 2021

How did they become so isolated?

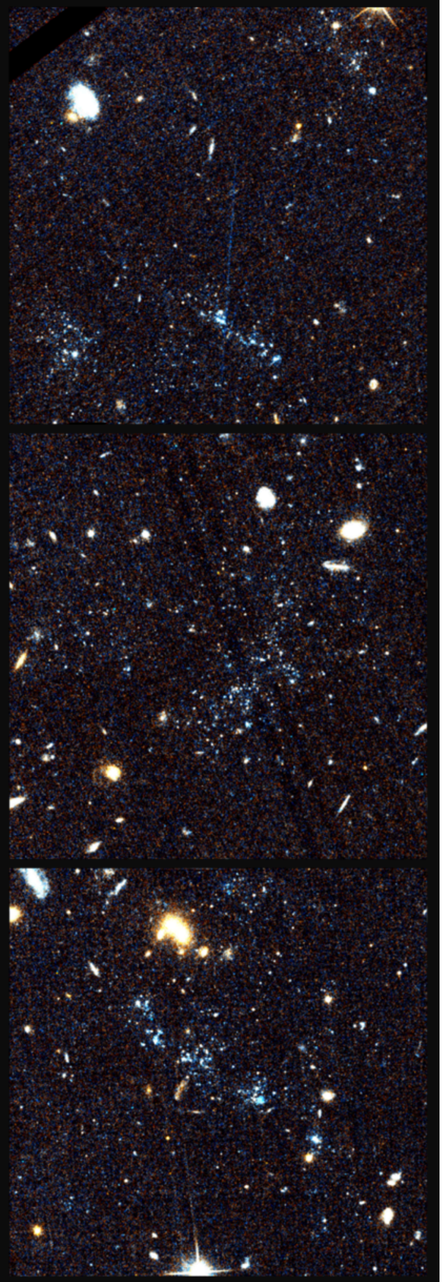
- Tidal dwarf galaxies are typically ejected at <400 km/s.
- They would take billions of years to become isolated.
- Ram pressure stripping can occur at >1000 km/s.
- Isolation is more naturally explained in the ram pressure stripping scenario.



Simulation of ram pressured stripped gas and new stars.

A new class of stellar system

- "Blue blobs" reside in a galaxy cluster, but are isolated and made up of young stars, making them unlike any other known stellar systems.
- Their high metallicities indicate that they formed from stripped gas.
- Formation via ram pressure stripping is the mechanism that most naturally explains their properties, in particular their isolation.



What's Next?

- Move to new environments. The Fornax Cluster.
- JWST observations will allow for a much deeper study of the stars in blue blobs
- Continued study of a larger sample with HST to probe the range or properties of the population.
- Multi-wavelength data is essential.