

# Building Dwarf Galaxies from Bottom Up: Evidence of Dwarf-Dwarf Mergers in the Nearby Universe

Francesca Annibali

INAF - Astrophysics and Space Science Observatory of Bologna (OAS)

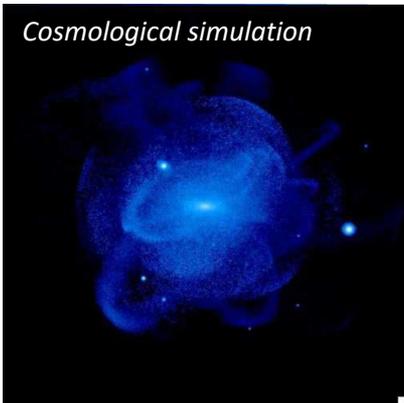
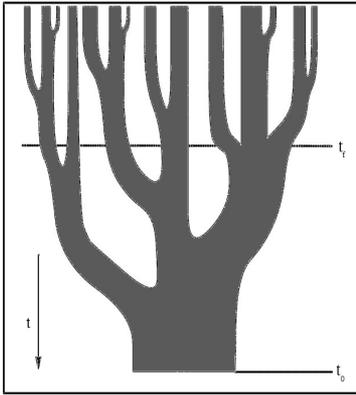
**M. Bellazzini** (INAF-OAS), **A. Aloisi** (STScI), **G. Beccari** (ESO), J.M. Cannon (Macalester), **M. Cignoni** (UniPi), **L. Ciotti** (UniBo), **M. Correnti** (INAF-OAR), **F. Cusano** (INAF-OAS), **F. Ficara** (INAF-OACN, UNISA), **L. Hunt** (INAF-OAA), M. Marinelli (STScI), **C. Nipoti** (UniBo), **D. Paris** (INAF-OAR), **R. Pascale** (INAF-OAS), **D. Perez-Millan** (INAF-OAS), S. Roychowdhury (Munich Univ. Obs.), **E. Sacchi** (Leibniz-Inst., Potsdam), L. Schisgal (Macalester), T. Sohn (STScI), **M. Tosi** (INAF-OAS)

*INAF - OAAb, March 12, 2026*



# $\Lambda$ CDM and hierarchical structure formation

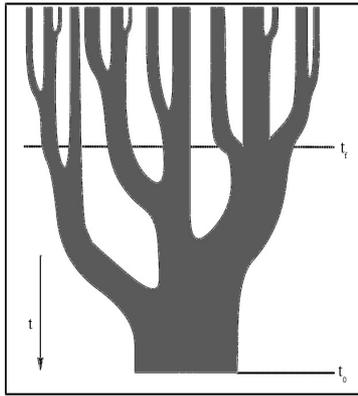
*Lacey & Cole (1993)*



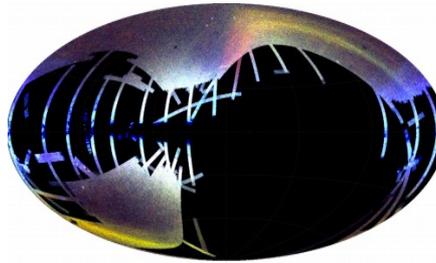
Bullock & Johnston 2005

# $\Lambda$ CDM and hierarchical structure formation

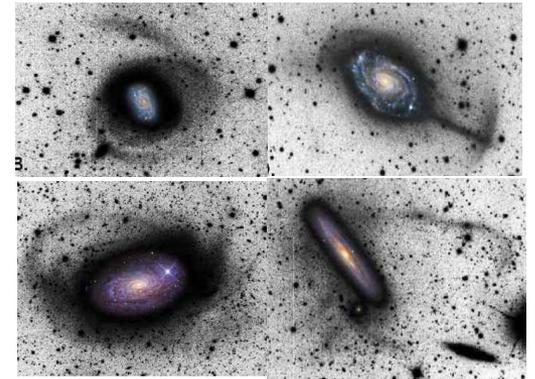
Lacey & Cole (1993)



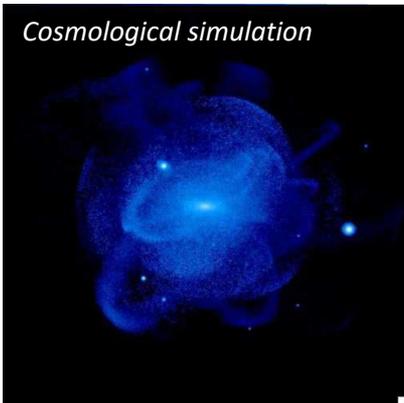
Milky Way  
(Belokurov + 06)



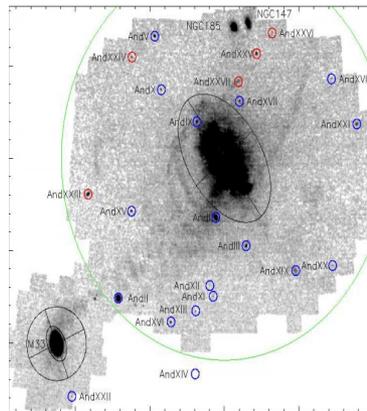
Spiral galaxies (Martinez-Delgado + 2010)



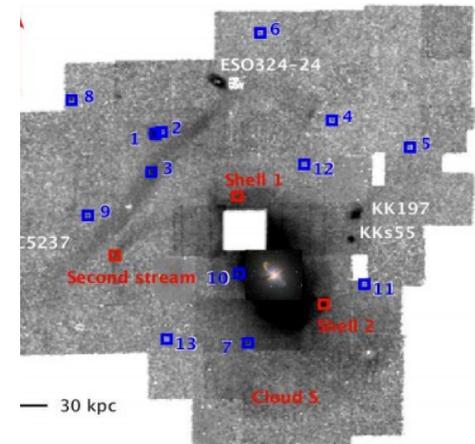
Cosmological simulation



Bullock & Johnston 2005



M31 spiral  
(Ibata+2001; Richardson + 11)

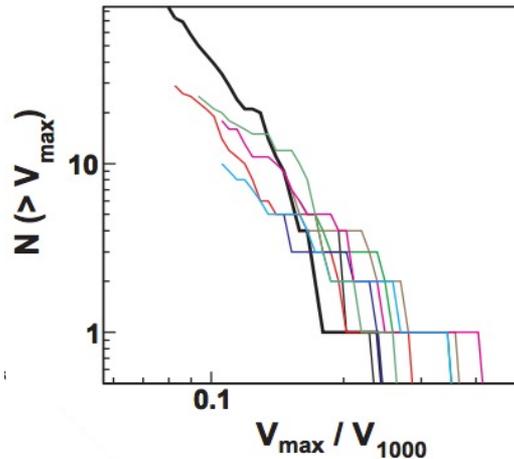


CenA elliptical  
(Crnojevic' + 16)

# Mergers at the dwarf galaxy scales

DM halos and sub-halos have the  
same relative abundance of  
substructures

(Diemand + 2008, Nature 454, 735)

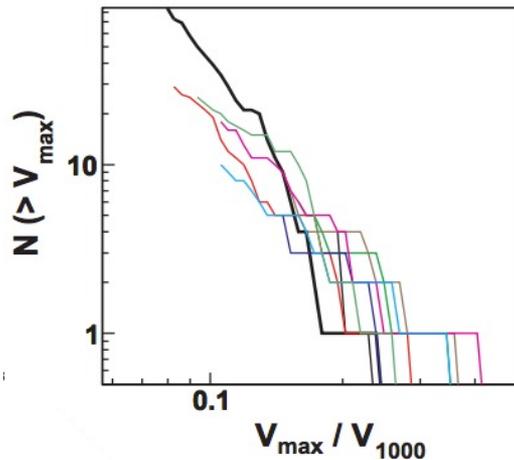


Hence in principle **satellites of dwarf galaxies** should exist as well as the signature of **interaction with them!**

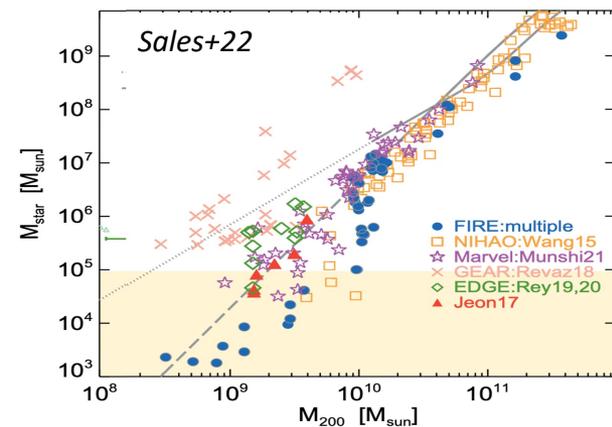
# Mergers at the dwarf galaxy scales

DM halos and sub-halos have the same relative abundance of substructures

(Diemand + 2008, Nature 454, 735)



The situation is complex when considering baryons!

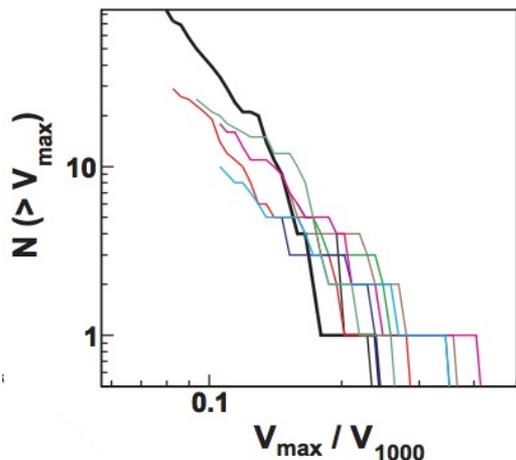


- **SM-HM relation**  
(large scatter at low M)
- **Halo occupation fraction**  
(steep and uncertain at low M)
- **Threshold for starless DM halos**  
( $10^{7.5} - 10^{9.3} M_{\odot}$  range at  $z=0$  in the literature)

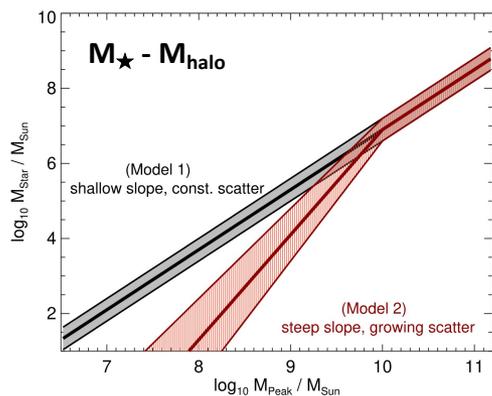
# Mergers at the dwarf galaxy scales

DM halos and sub-halos have the same relative abundance of substructures

(Diemand + 2008, Nature 454, 735)

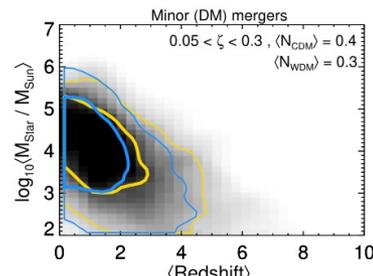
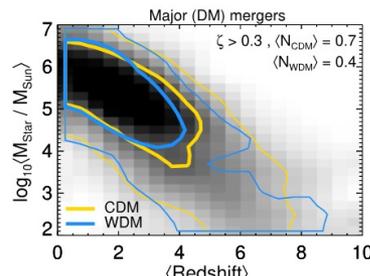
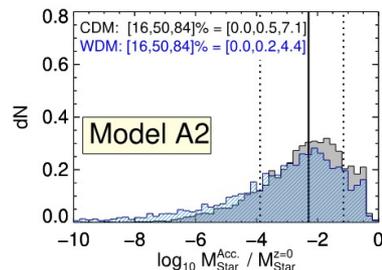
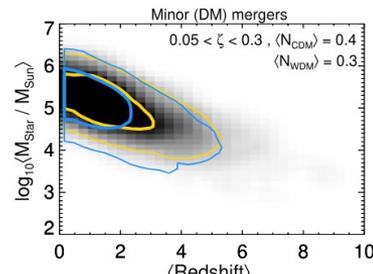
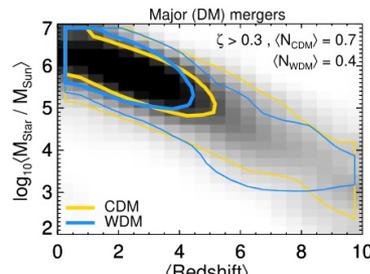
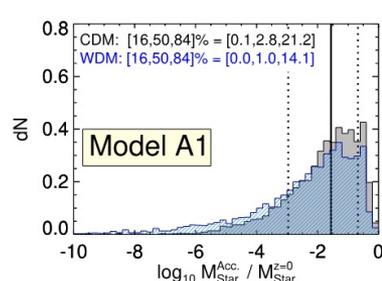


The situation is complex when considering baryons!

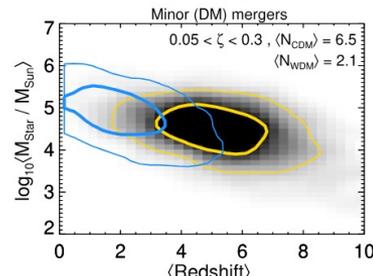
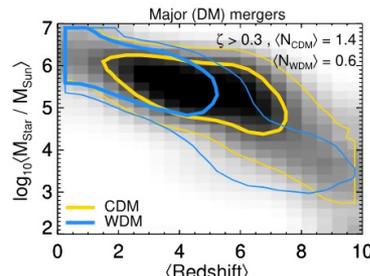
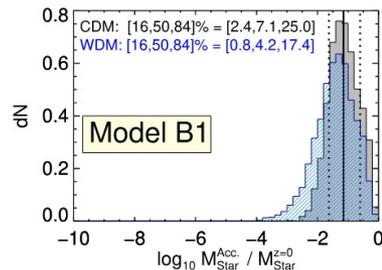
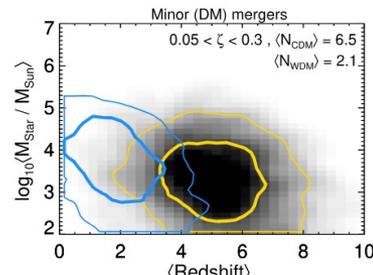
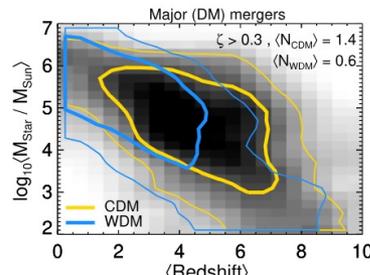
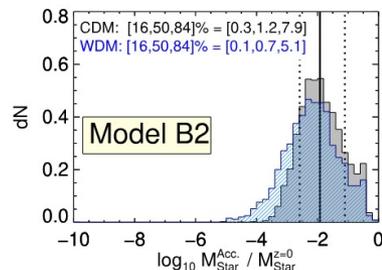


- $10^{10} M_{\odot}$  DM halo
- Accreted stars as function of  $M_{\star} - M_{\text{halo}}$  relation and galaxy occupation (Deason+22)

High mass threshold for SF ( $10^{9.3} M_{\odot}$ )

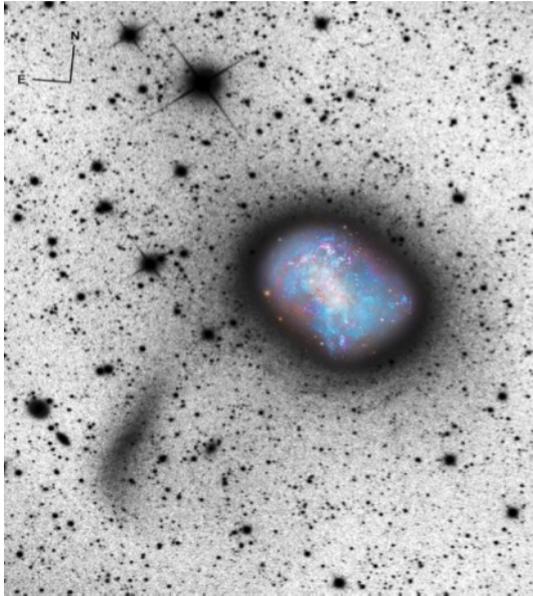


Low mass threshold for SF ( $10^{7.5} M_{\odot}$ )

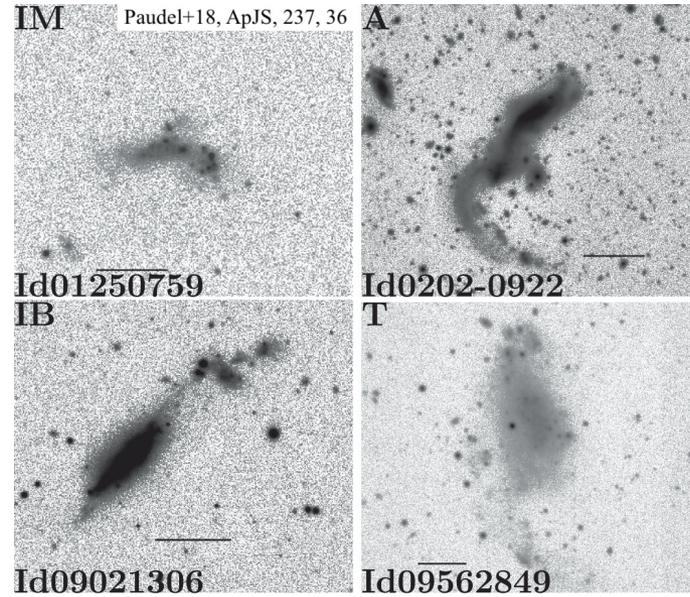


# Mergers at the dwarf galaxy scales: observations are challenging!

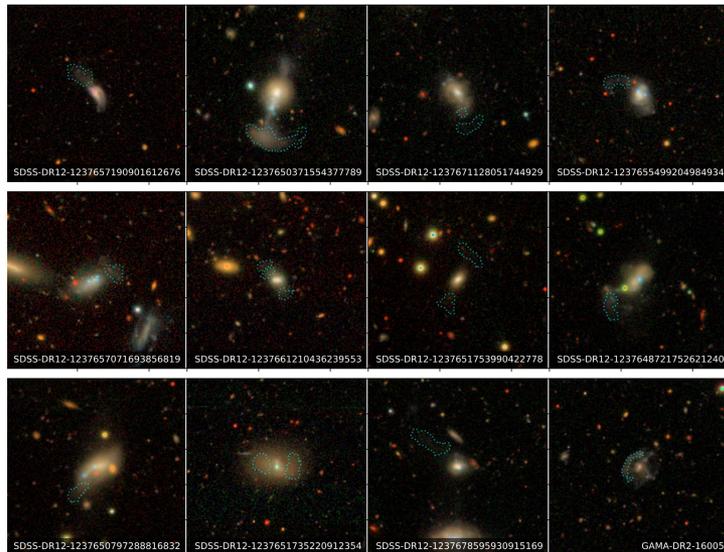
NGC 4449 (Martinez-Delgado + 12; Rich + 12)



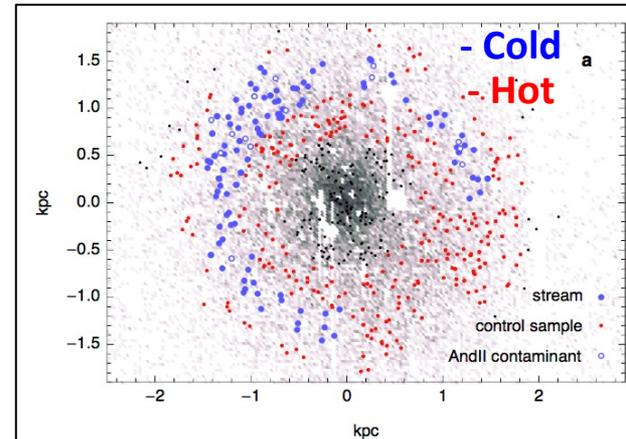
Paudel + 2018



Kado-Fong + 2019

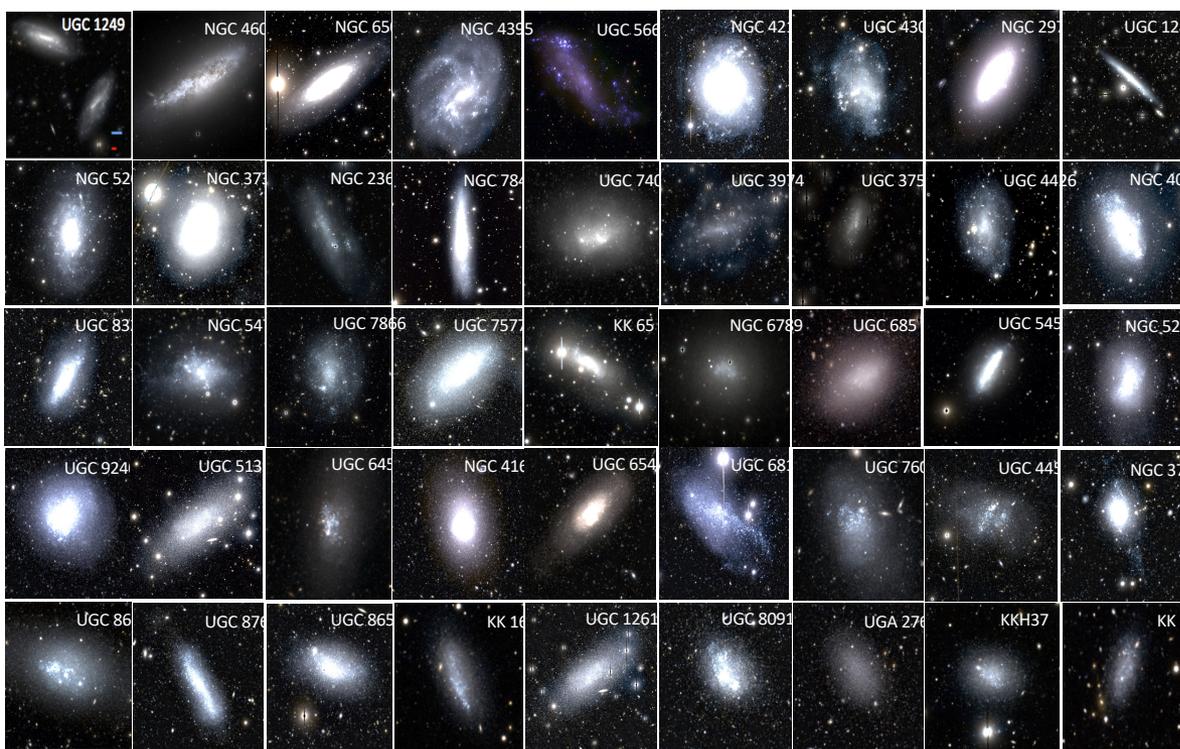


“kinematical stream” in AndII, with  
 $10^7 M_{\star}$  (Amorisco +14)



# The Smallest Scale of Hierarchy Survey (SSH)

- ✓ Characterizing the occurrence of accretion/merging events in dwarf galaxies
- ✓ Understanding the connection between merging and star formation



## THE SSH SURVEY:

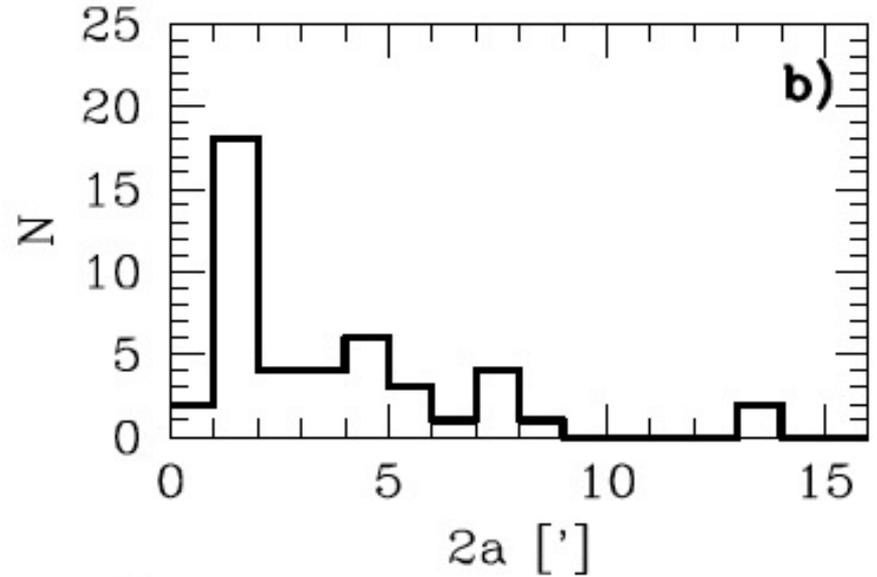
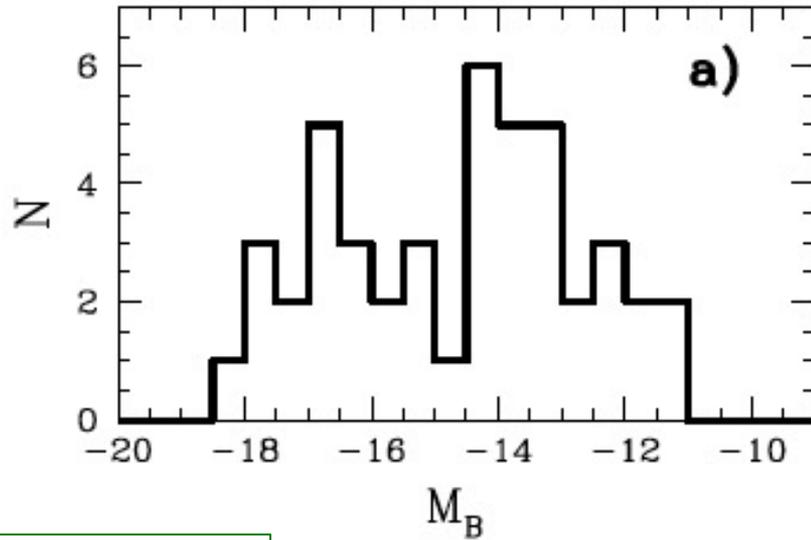
- Deep Large Binocular Telescope  $g, r$  images of **45 nearby** ( $D < 11$  Mpc) **late-type dwarfs**
- Having **HST imaging** in the central part
- Magnitudes  $-11 < M_B < -19$
- Range of environment, but typically low density

[Annibali + 20; Annibali + 22; Sacchi + 24; Pascale + 24]

## OTHER SURVEYS OF RESOLVED STAR DWARFS:

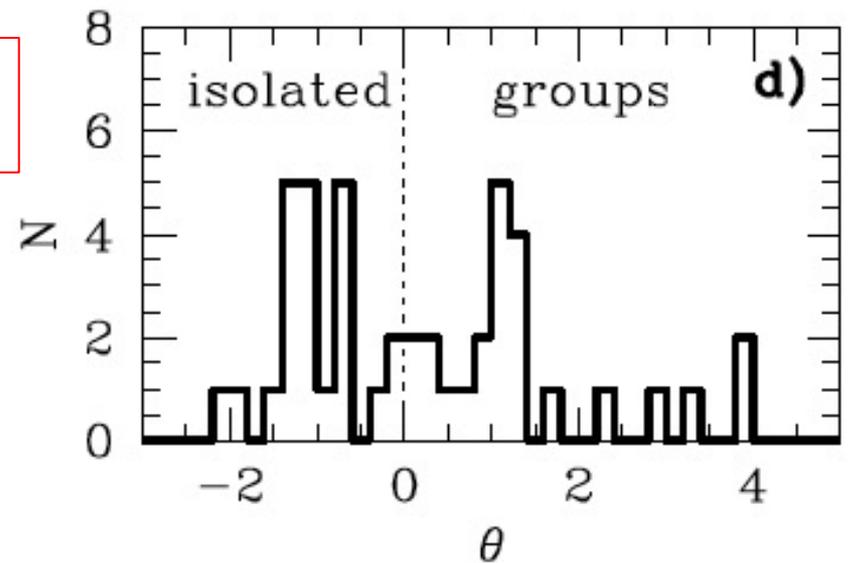
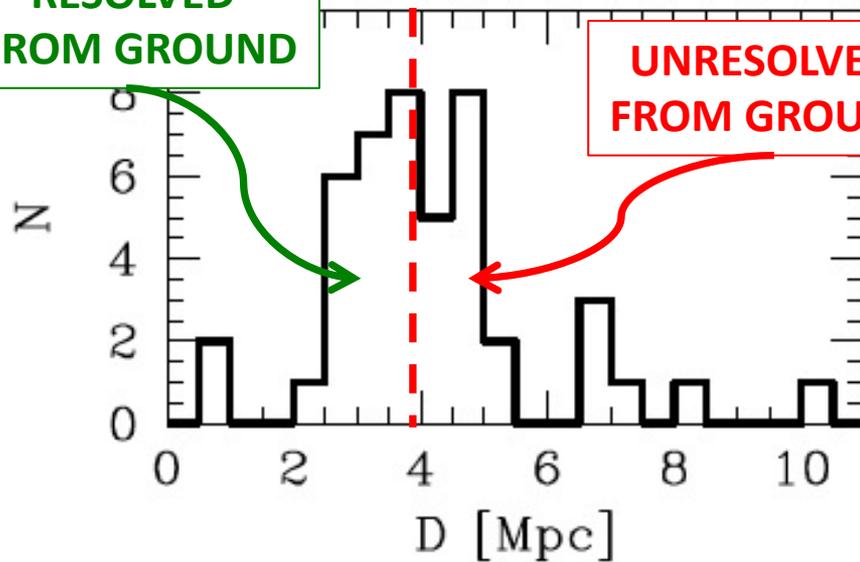
- **SOLO** (Higgs + 2021) : isolated, local dwarf galaxies
- **MADCASH** (Carlin + 2016), focusing on Magellanic type galaxies

# SSH: The Smallest Scale of Hierarchy Survey

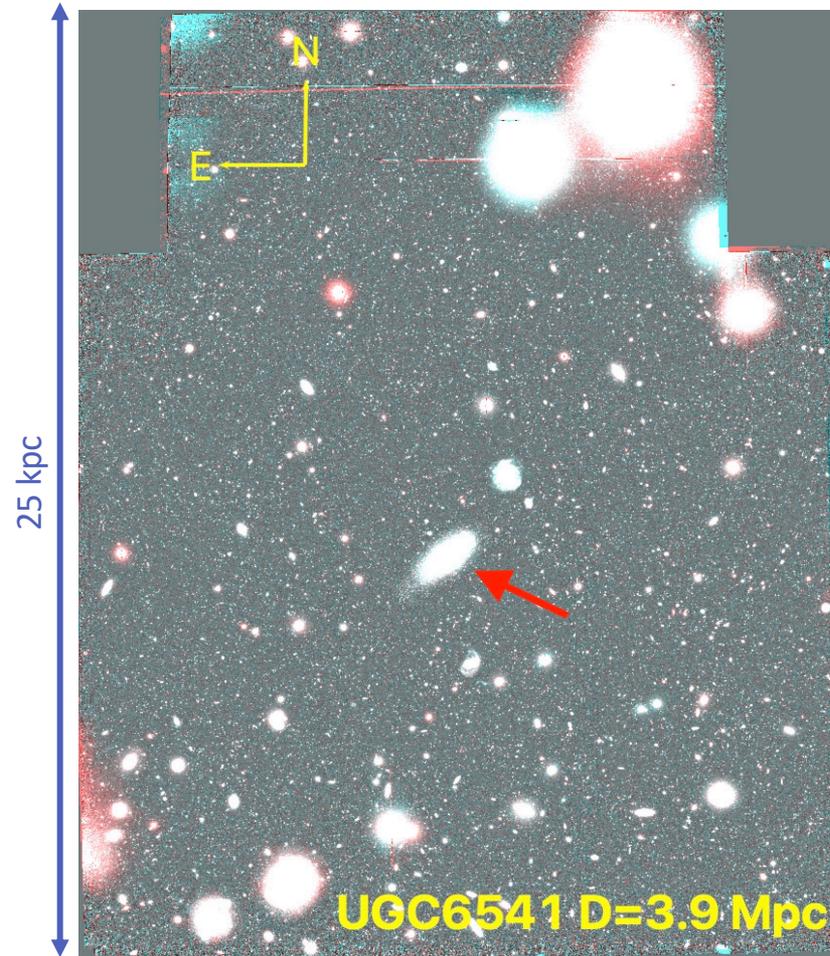


RESOLVED  
FROM GROUND

UNRESOLVED  
FROM GROUND

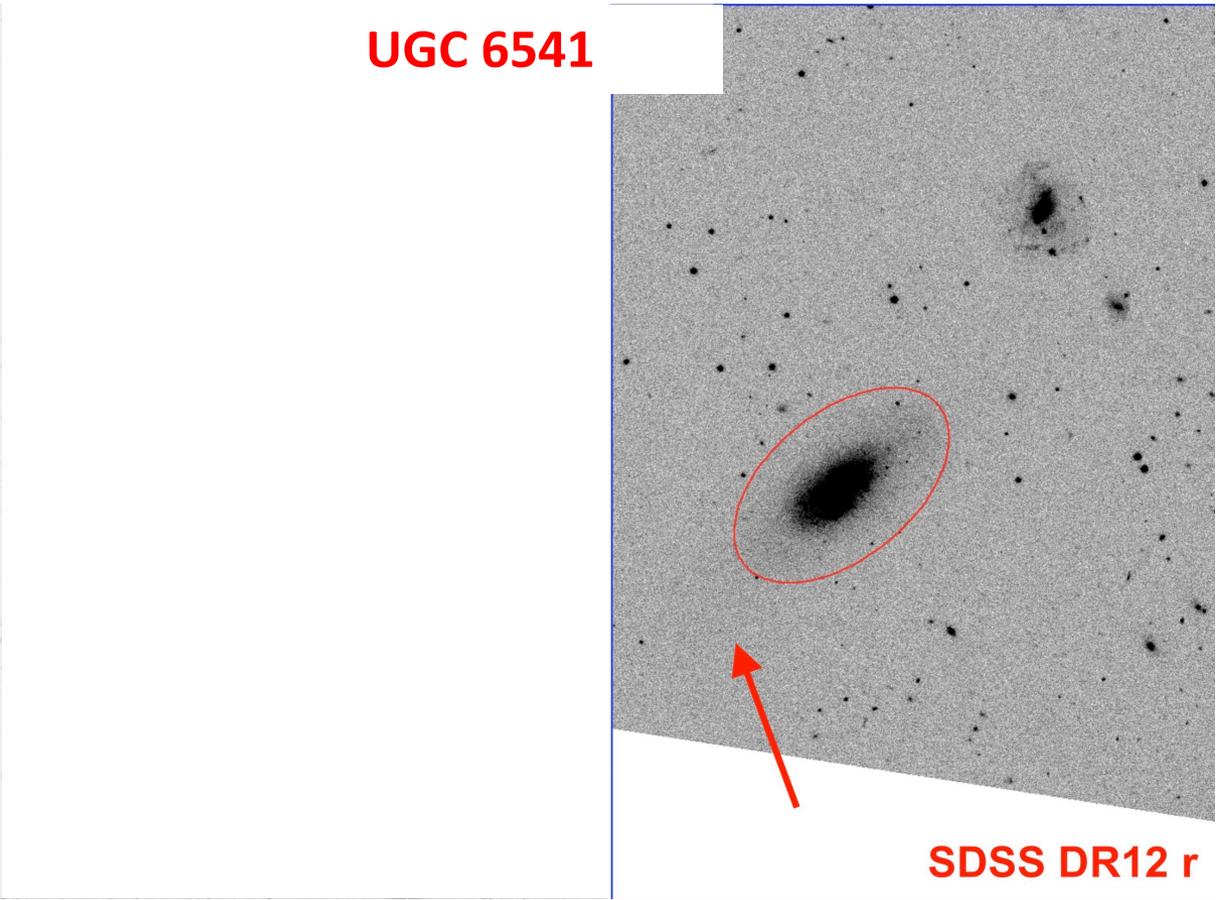


# Deep, wide field $g,r$ imaging with LBC@LBT

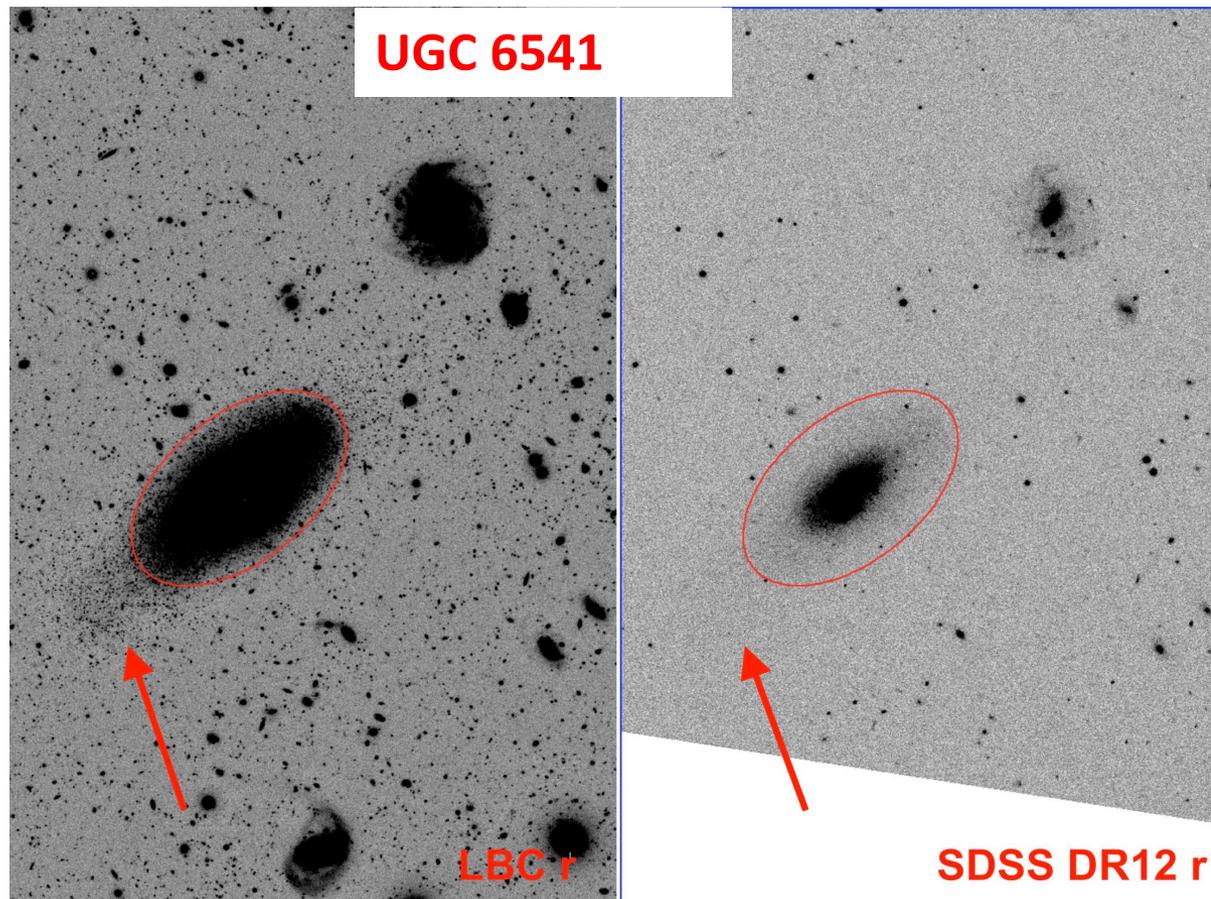


- FoV  $\sim 23' \times 23'$
- Sub-arcsec seeing
- Tracing stellar structures down to  $\mu_r \sim 30.5 \text{ mag/arcsec}^2$

# Deep, wide field $g,r$ imaging with LBC@LBT

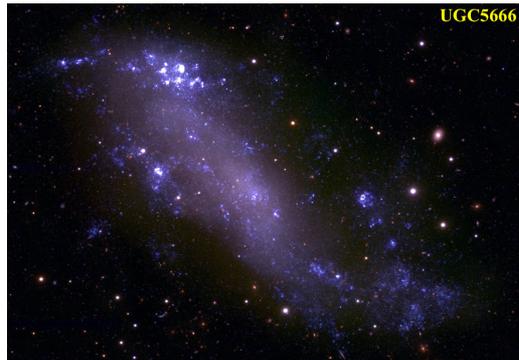
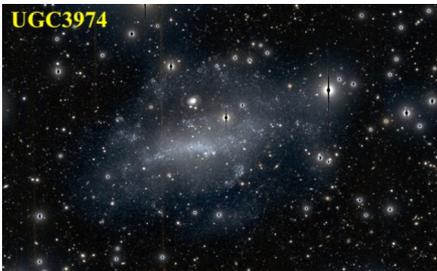


# Deep, wide field $g,r$ imaging with LBC@LBT



# Recognizing tidal disturbances

Star Formation may occur in very asymmetric configurations in dwarfs **mimicking** disturbance

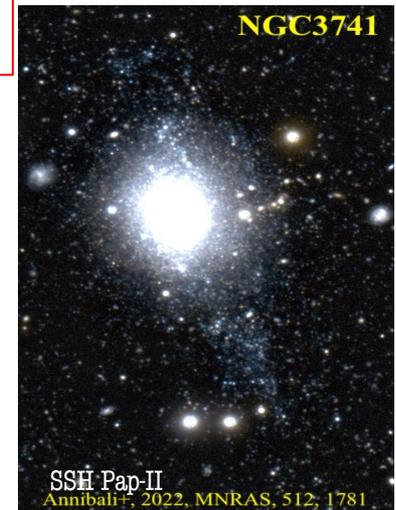
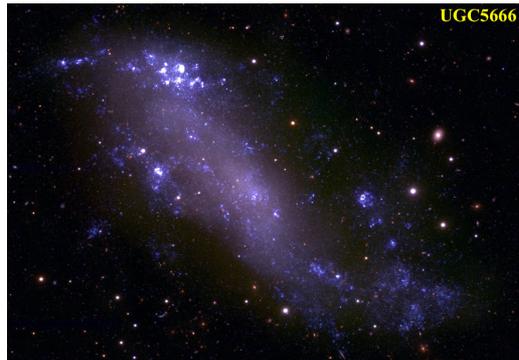
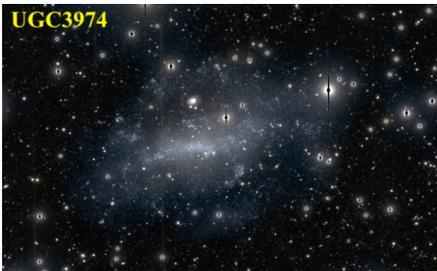


# Recognizing tidal disturbances

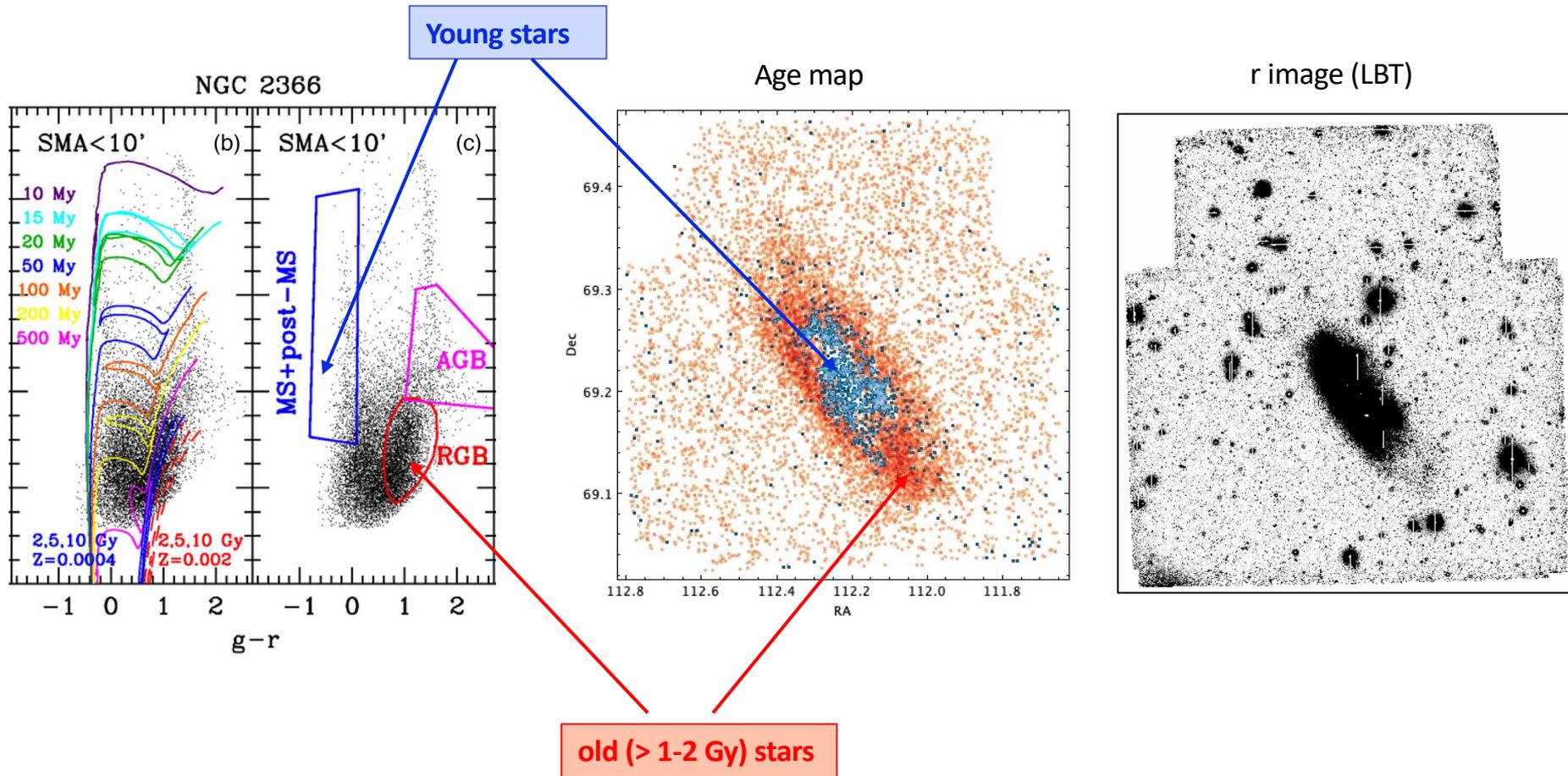
Star Formation may occur in very asymmetric configurations in dwarfs **mimicking** disturbance



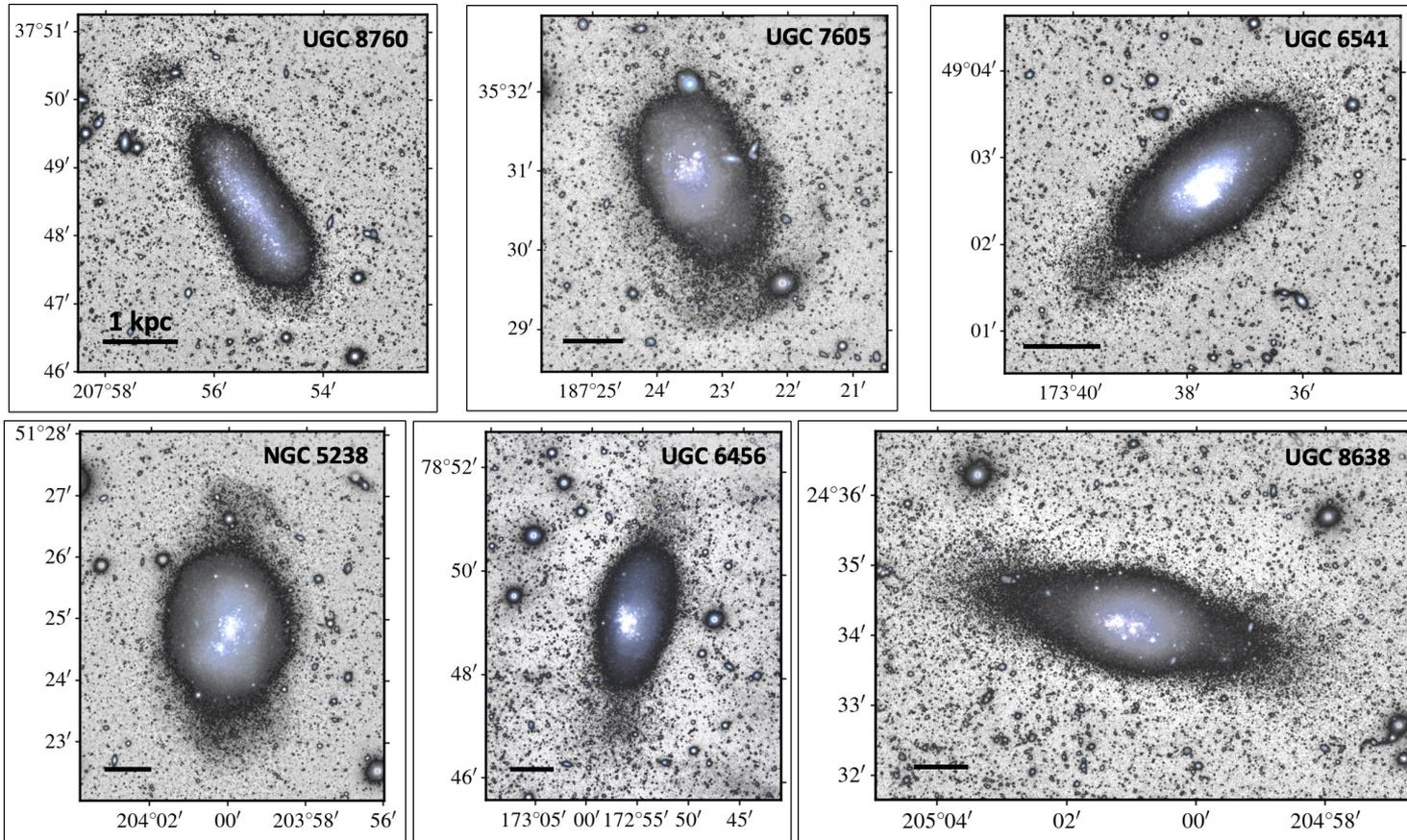
For this reason we consider only features dominated by old stars (RGB; age  $\gtrsim 2$  Gyr) that must trace genuine perturbations of the gravitational potential



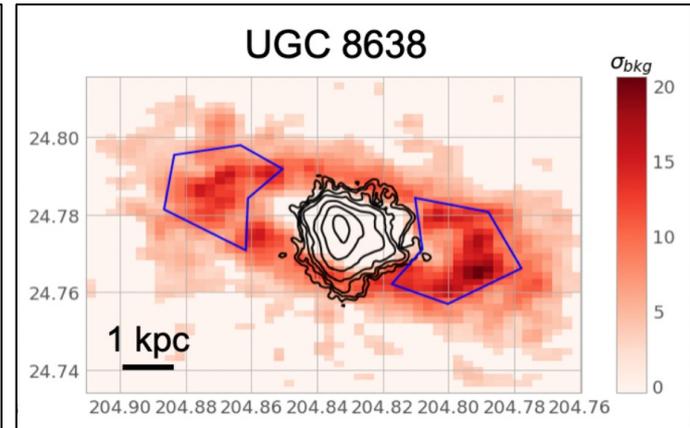
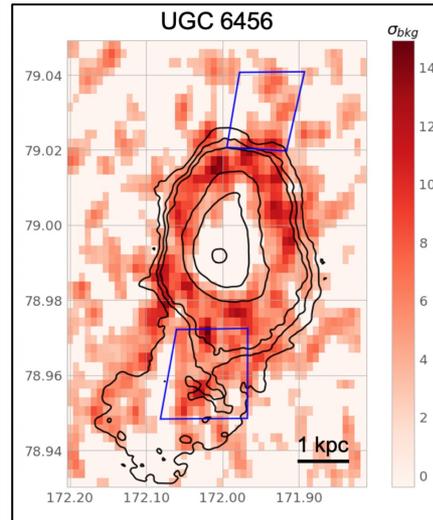
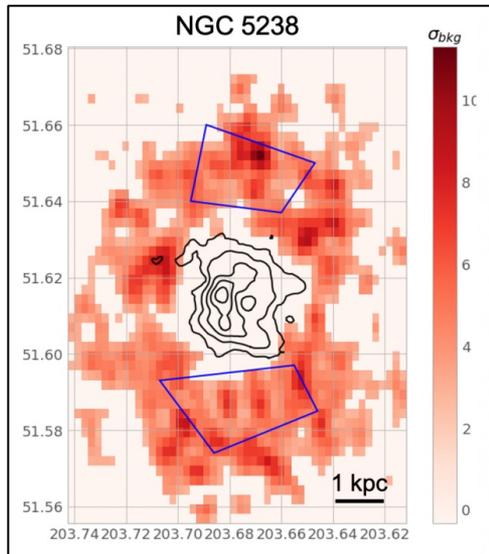
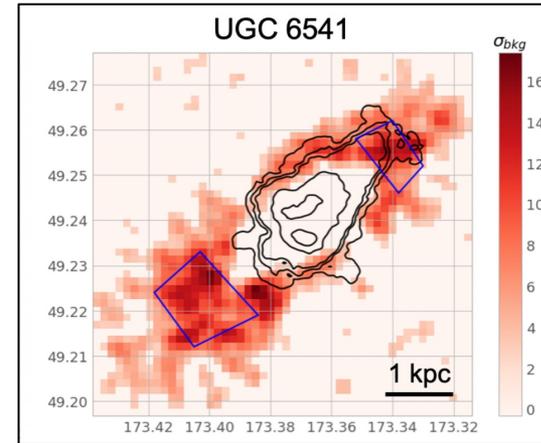
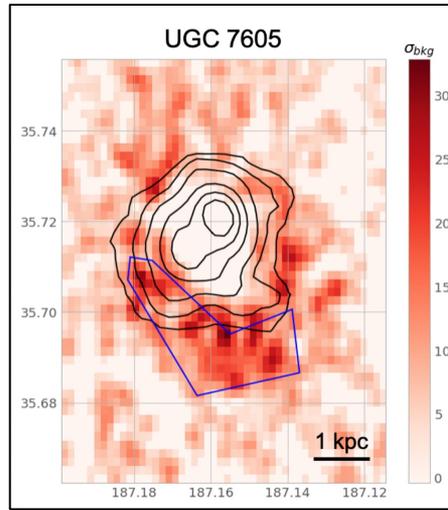
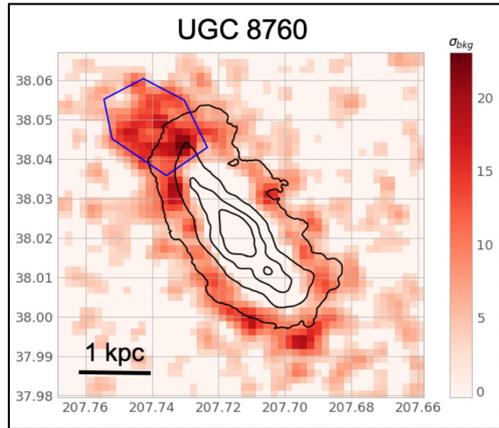
# Color-magnitude diagrams allow to trace the morphology of old vs young stars!



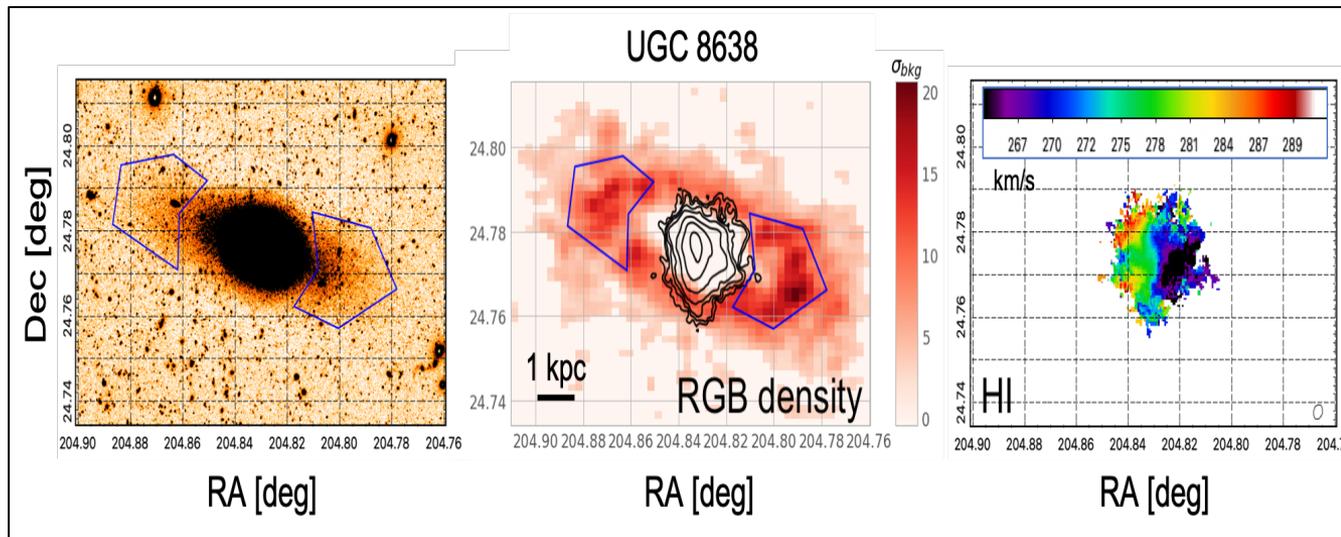
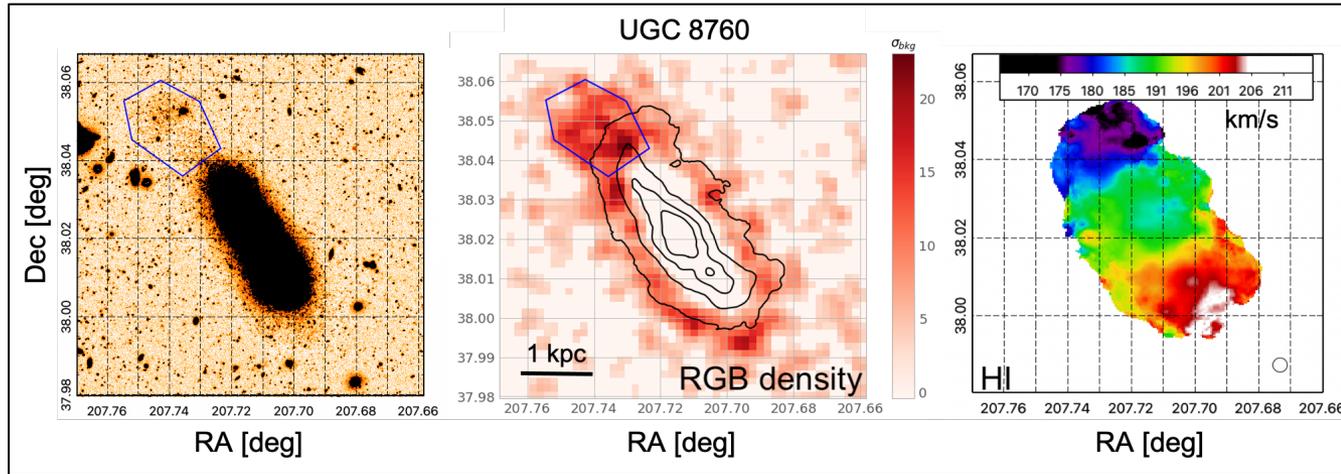
# Six cases of clear disturbances in SSH...



... that are also traced by old (RGB) stars



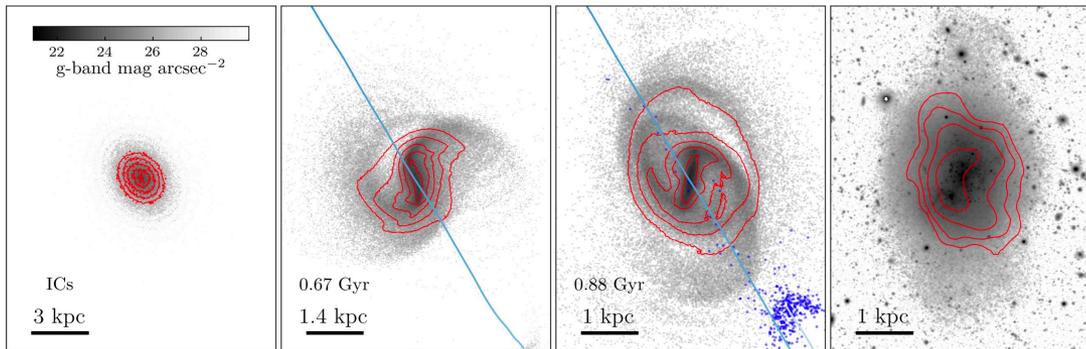
... also HI is quite disturbed



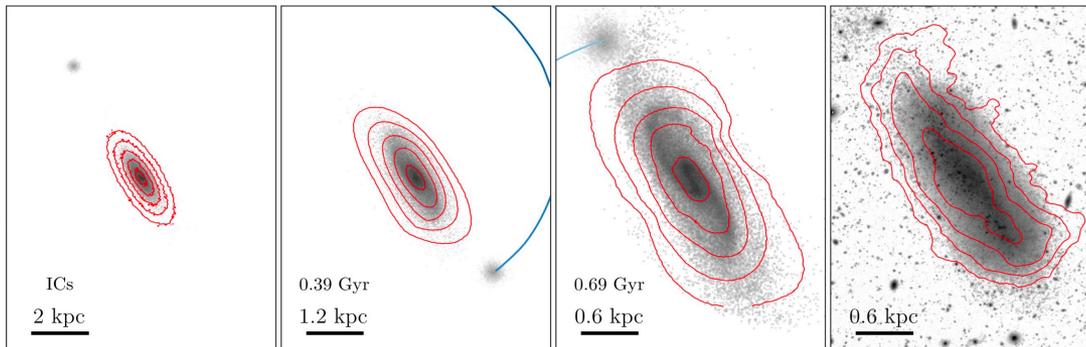
# N body+hydrodynamical simulations

Pascale et al. 24

NGC 5238  
 $M_{\star} \sim 10^8 M_{\odot}$



UGC 8760  
 $M_{\star} = 2 \times 10^7 M_{\odot}$

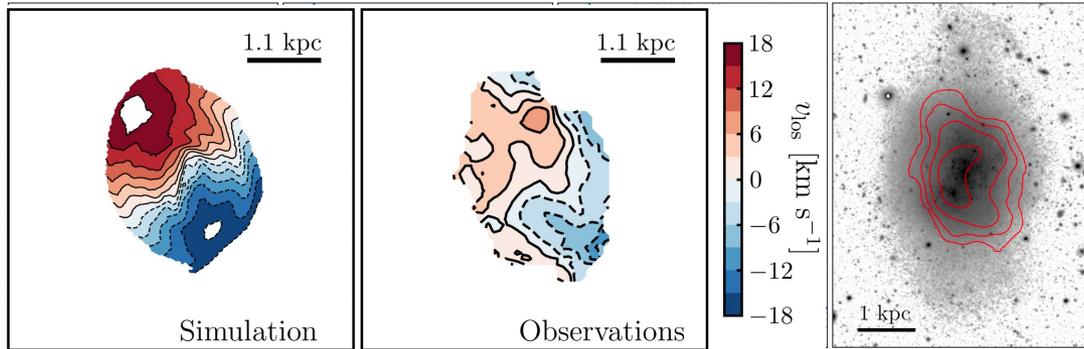


- Simulations of a dwarf interacting with a smaller satellite (AREPO code)
- Able to reproduce the **distribution of stars** and HI (+ HI kinematics)
- For both NGC 5238 and UGC 8760, the satellite **has 50 times lower stellar mass** than the host
- Merger mass ratio 1:10

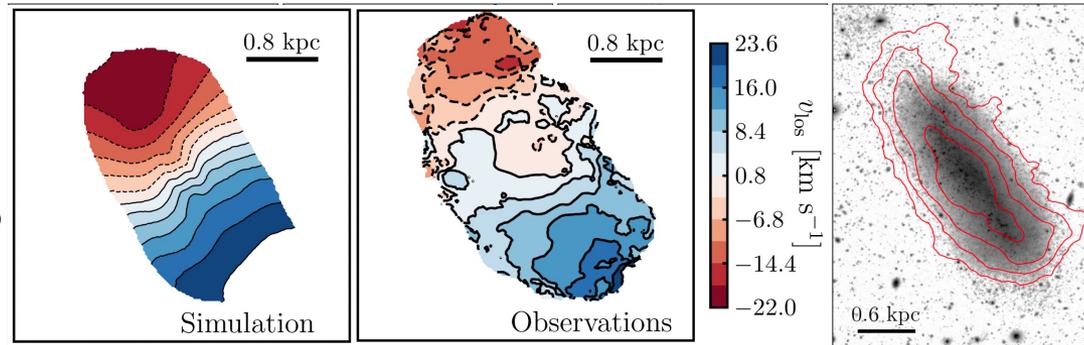
# N body+hydrodynamical simulations

Pascale et al. 24

NGC 5238  
 $M_{\star} \sim 10^8 M_{\odot}$



UGC 8760  
 $M_{\star} = 2 \times 10^7 M_{\odot}$



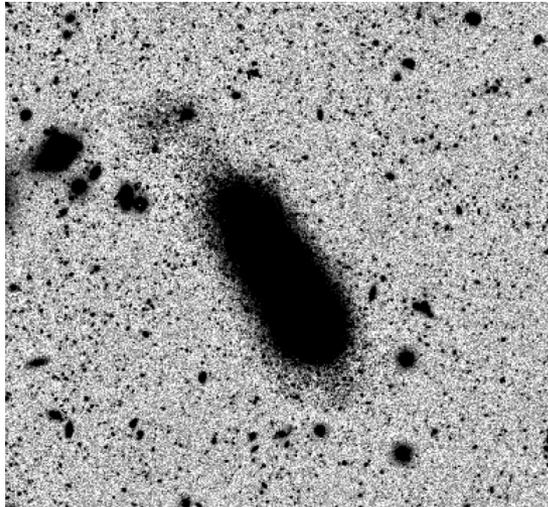
- Simulations of a dwarf interacting with a smaller satellite (AREPO code)
- Able to reproduce the distribution of stars and **HI (+ HI kinematics)**
- For both NGC 5238 and UGC 8760, the satellite **has 50 times lower stellar mass** than the host
- Merger mass ratio 1:10

# Quantifying RGB star asymmetries

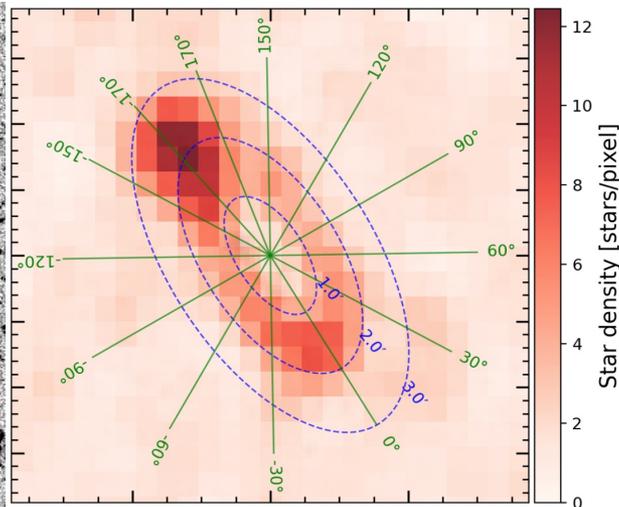


David Perez-Millan

UGC 8760 – LBT *r*



UGC 8760 – RGB stars

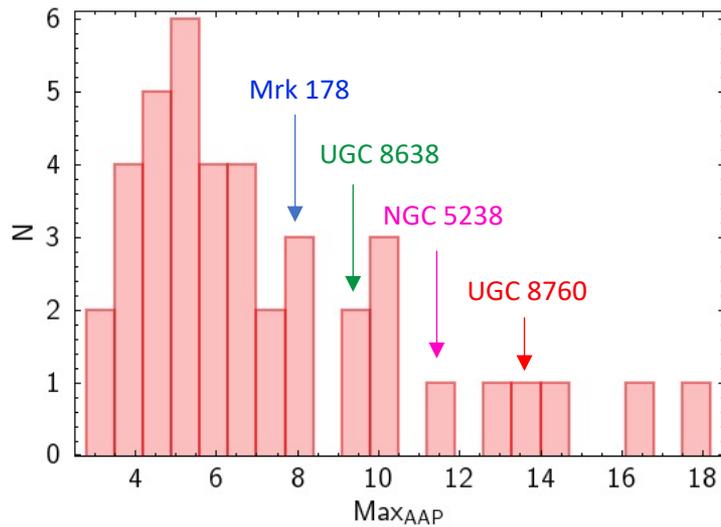


Azimuthal Asymmetry Parameter:

$$AAP = \frac{\sqrt{\sigma_{obs}^2 - \sigma_U^2}}{\sigma_U}$$

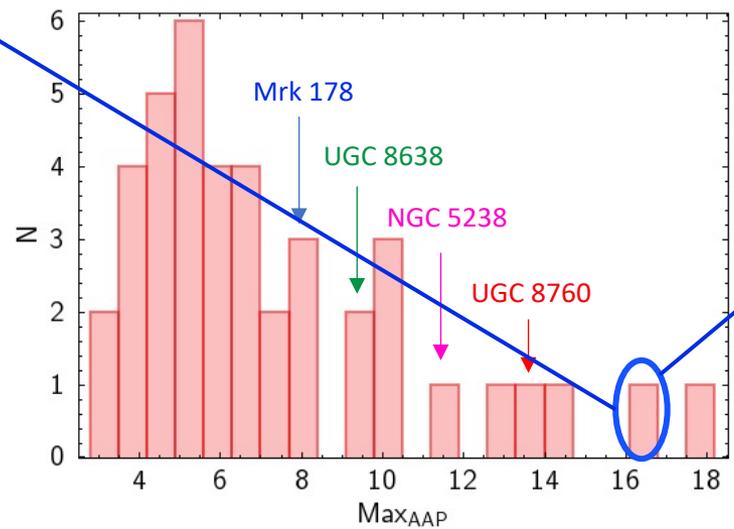
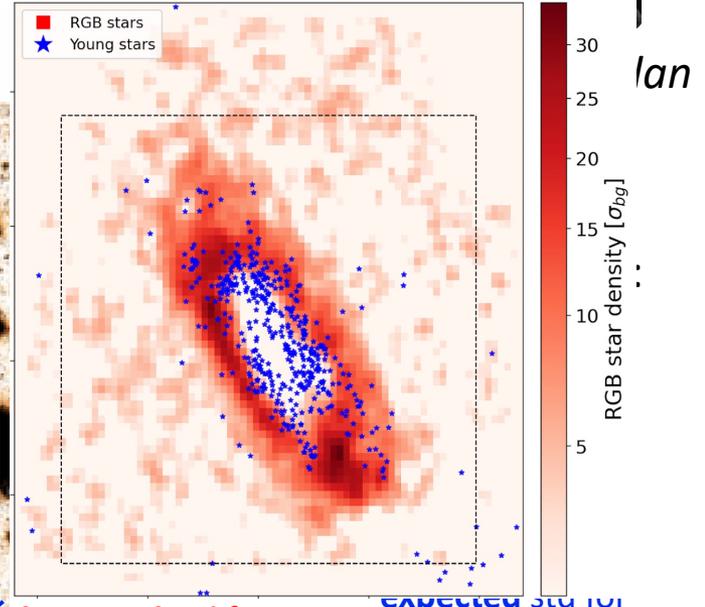
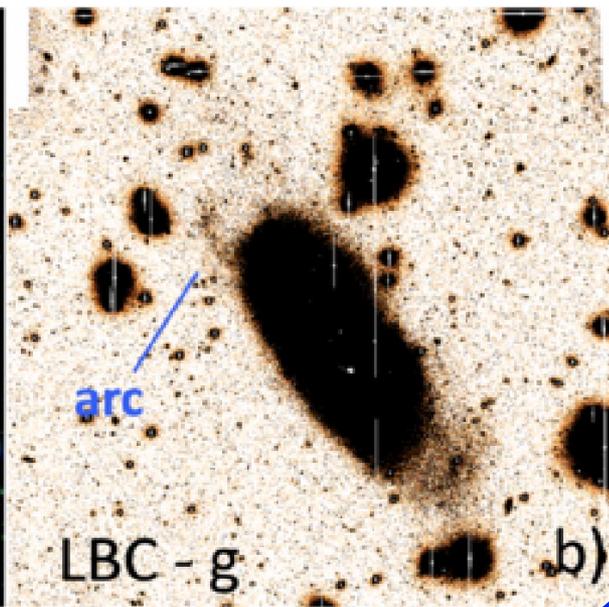
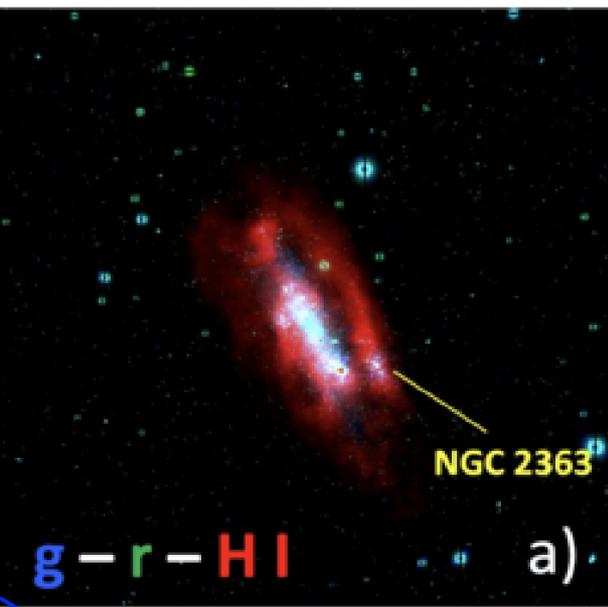
observed std for RGB density

expected std for uniform RGB distribution (Poisson noise)



# Quantifying RGB star asymmetries

## NGC 2366

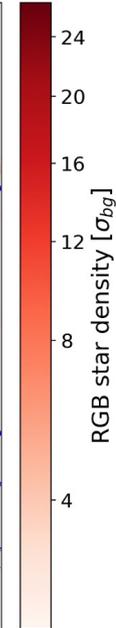
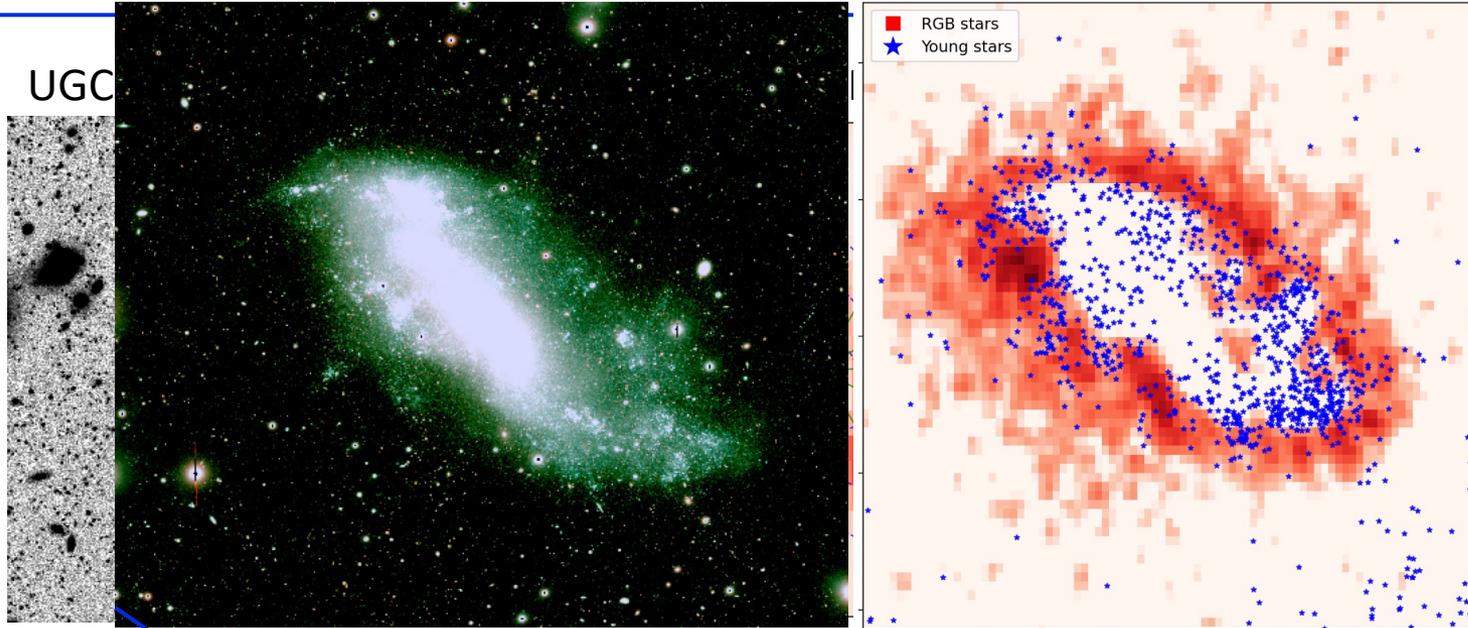


# Quantifying RGB star asymmetries

## UGC 5666



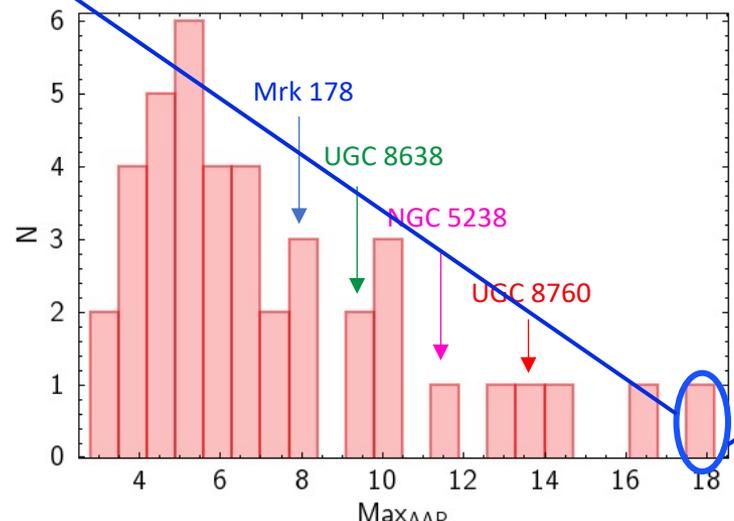
David Perez-Millan



Parameter:

$$\sigma_U^2$$

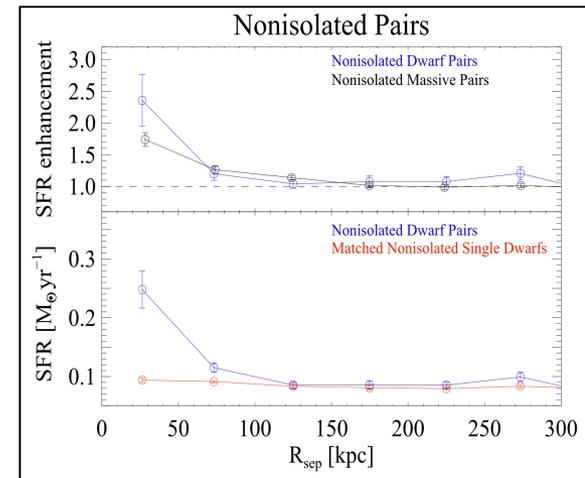
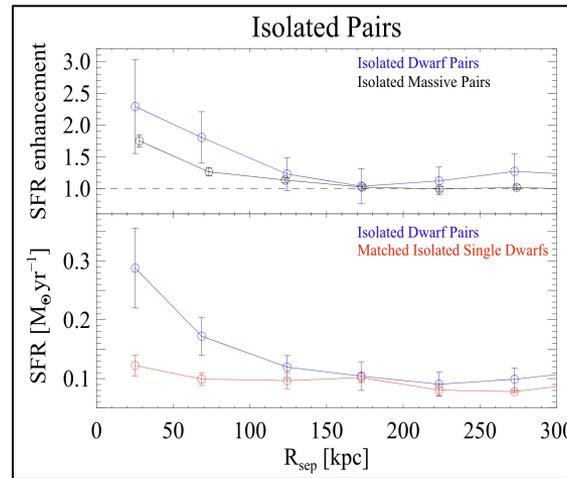
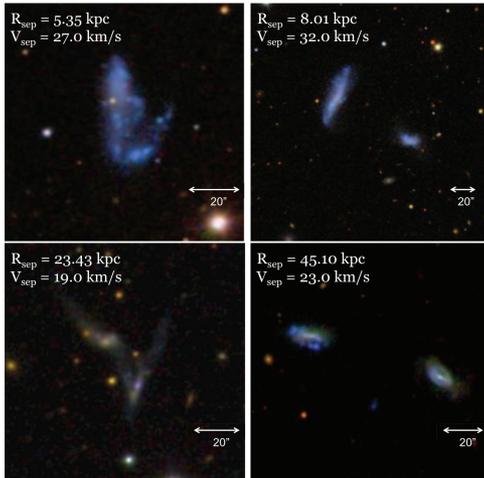
Expected std for uniform RGB distribution (Poisson noise)



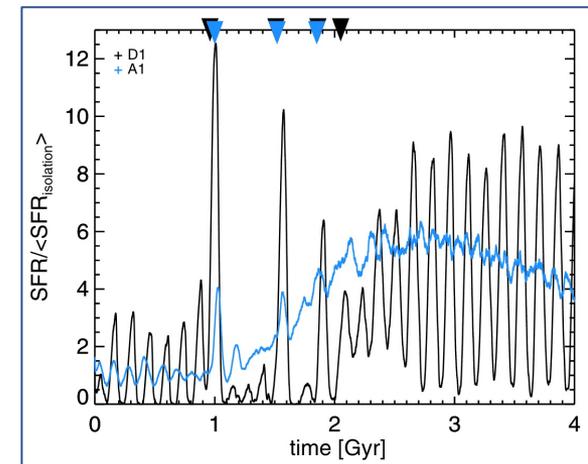
observed standard deviation  
RGB density

# Mergers and SF in dwarf galaxies

- ✓ Star formation enhanced in paired dwarfs compared to single ones (Stierwalt +2015, see also Lelli + 2014)



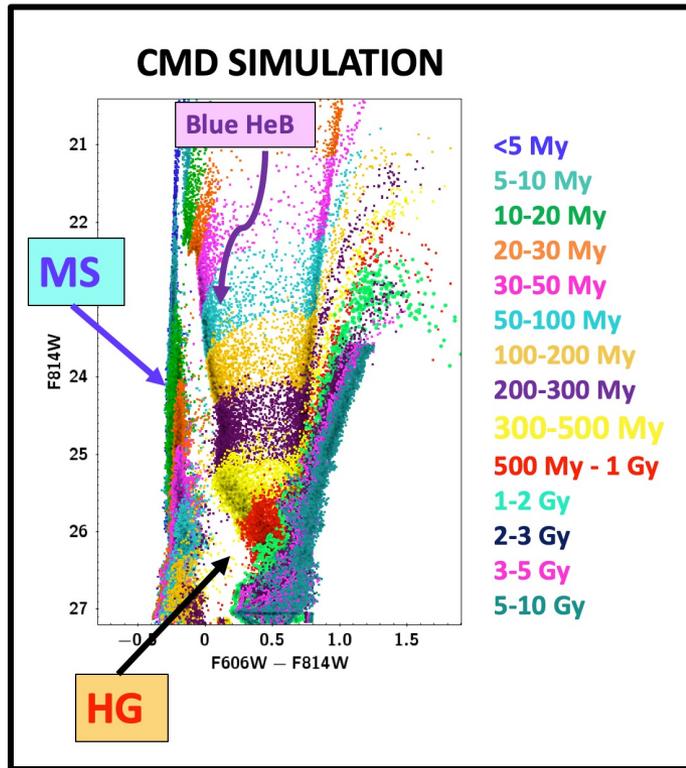
- ✓ Dwarf-dwarf mergers can trigger **central starburst** and form massive central **cores** dominated by **young stars** → BCDs (see simulations by Bekki 2008; A. Cloet-Osselaer+ 2014; Bekki 2015)



- ✓ Starburst triggered at pericenter passages (Starkenburger+2016)

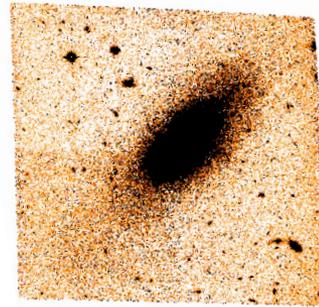
# The relation between SF and merging events in dwarfs

32 orbits in HST cycle 30 (PI Annibali)

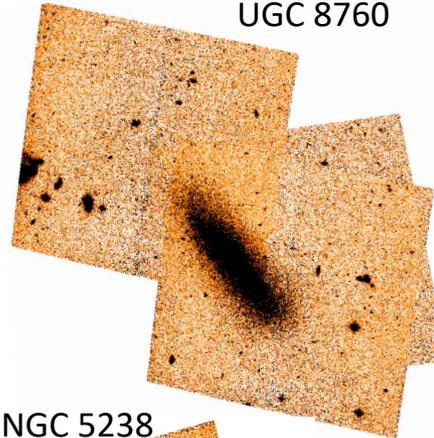


From hydro-dynamical simulations, the interaction has occurred within the **last ~1 Gyr** → our CMDs can reveal SF bursts at those epochs !

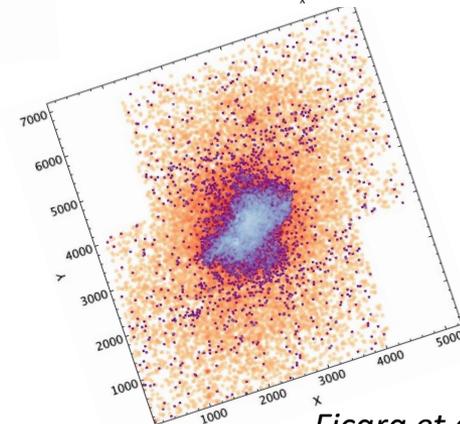
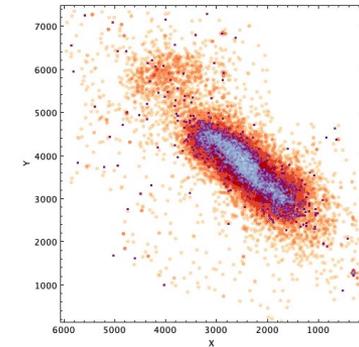
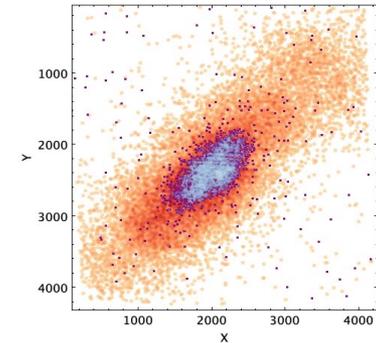
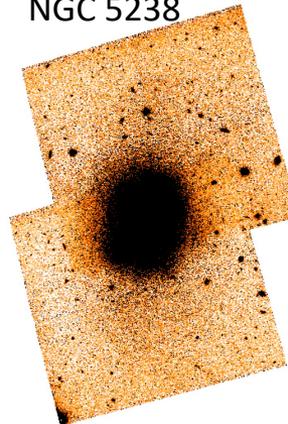
Mrk 178



UGC 8760



NGC 5238

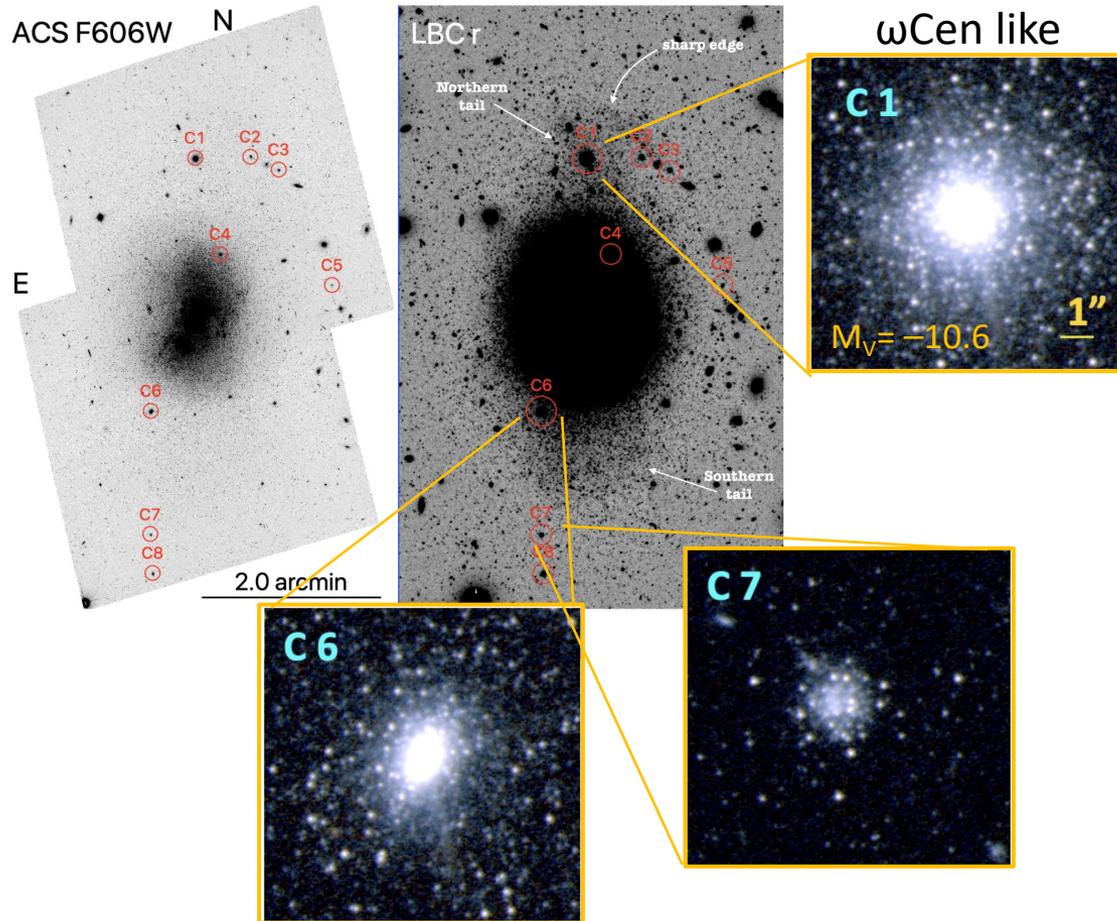


Young

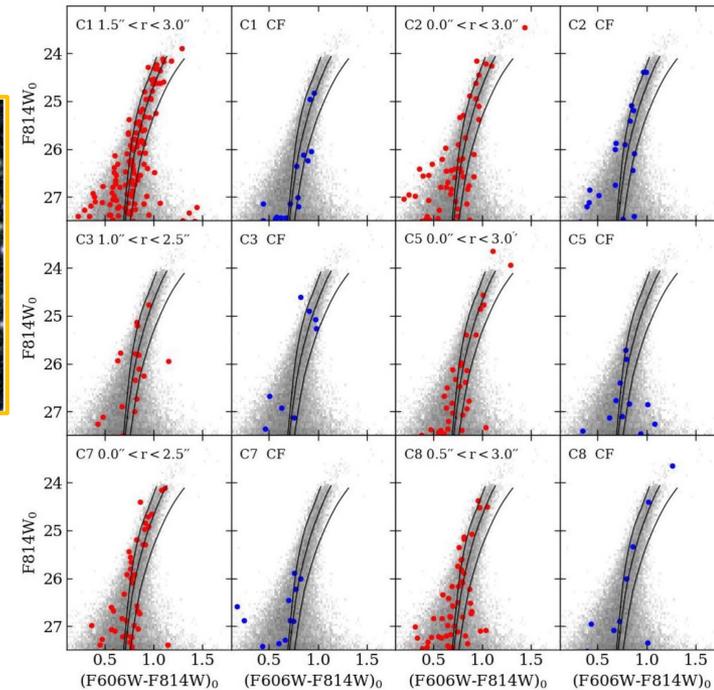
Old

# Old massive star clusters in tails of NGC 5238

- ✓ GCs associated with NGC 5238 **tidal tails**, similar to the case of MW (Bellazzini+ 2020) and M31 (Mackey + 19)
- ✓ **C1** like  $\omega$ Cen in the MW, thought to be the nuclear remnant of a disrupted satellite

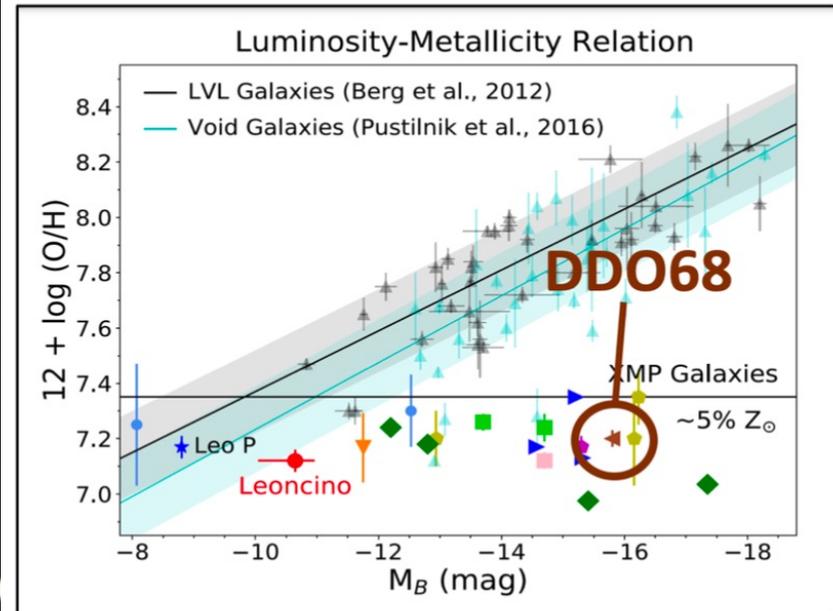


Bellazzini et al 2024



# DDO68: a multiple-merging dwarf in a void

- ✓ DDO68 is a BCD at  $D \sim 13$  Mpc, in the Lynx-Cancer void
- ✓ Extremely metal poor (5% solar)
- ✓ Strong outlier in the mass – Z relation
- ✓ Disturbed morphology

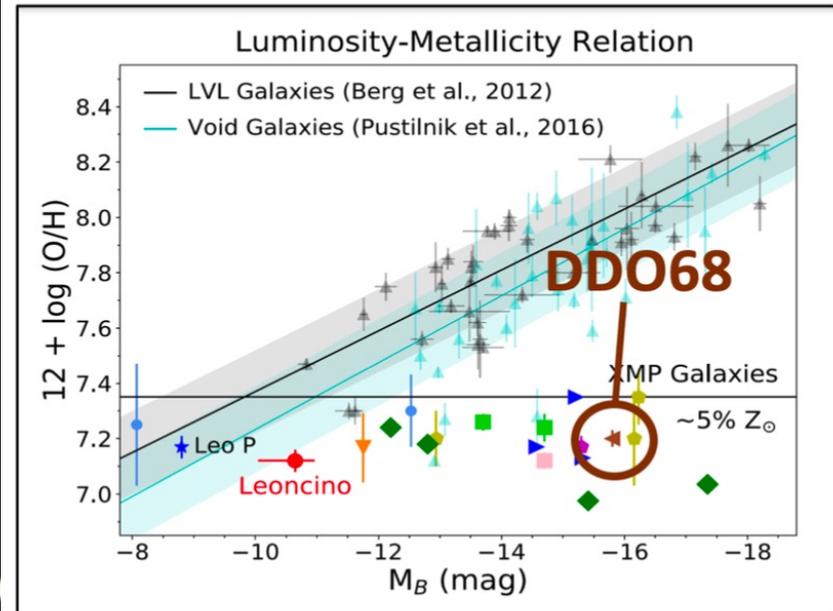
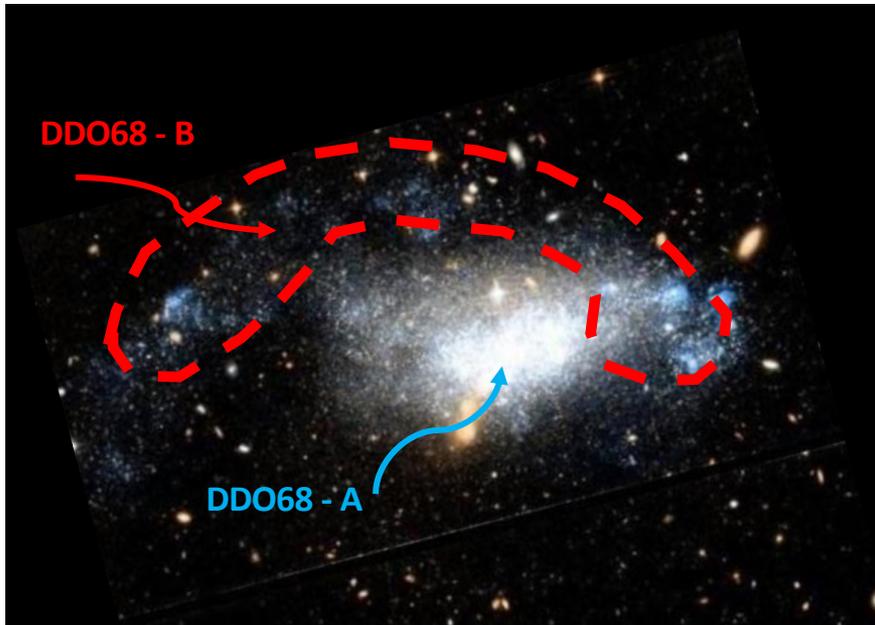


# DDO68: a multiple-merging dwarf in a void

- ✓ DDO68 is a BCD at  $D \sim 13$  Mpc, in the Lynx-Cancer void
- ✓ Extremely metal poor (5% solar)
- ✓ Strong outlier in the mass – Z relation
- ✓ Disturbed morphology



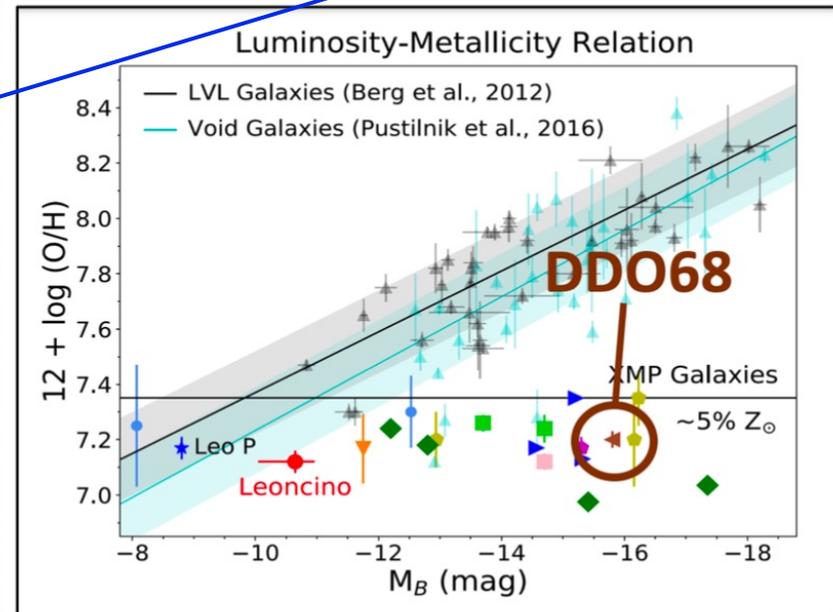
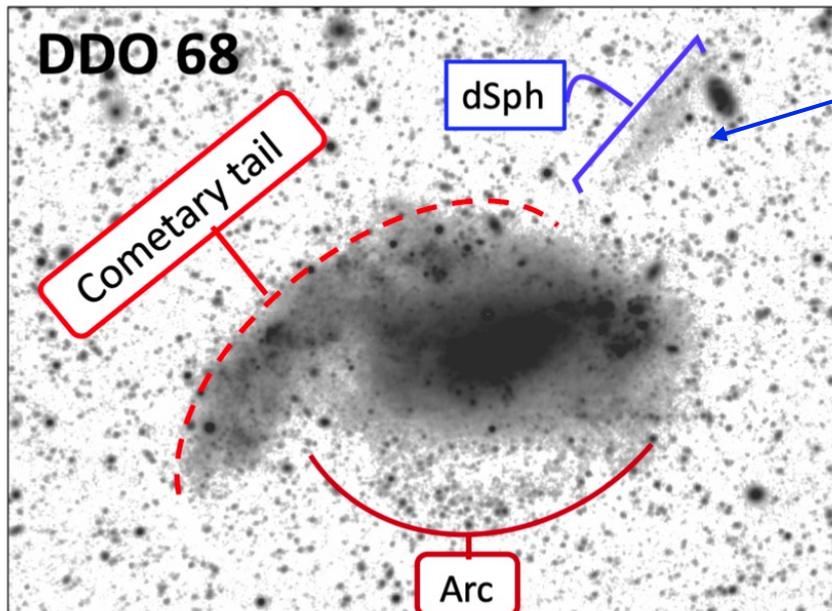
SUGGESTED TO HAVE  
UNDERGONE  
INTERACTION/MERGING



# DDO68: a multiple-merging dwarf in a void

- ✓ DDO68 is a BCD at  $D \sim 13$  Mpc, in the Lynx-Cancer void
- ✓ Extremely metal poor (5% solar)
- ✓ Strong outlier in the mass – Z relation
- ✓ Disturbed morphology

3<sup>rd</sup> component with LBT (Annibali+16)

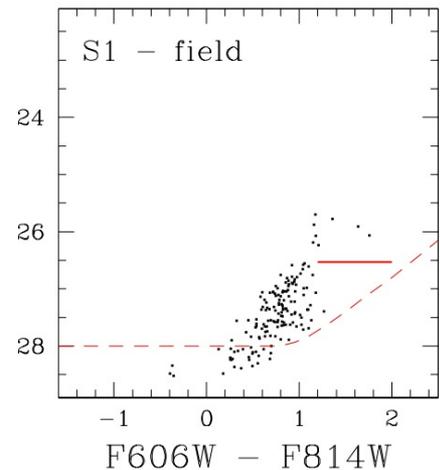
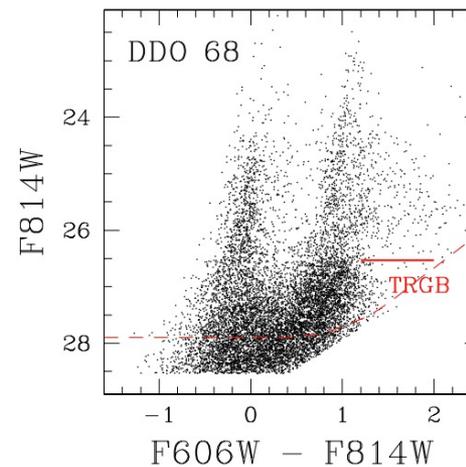
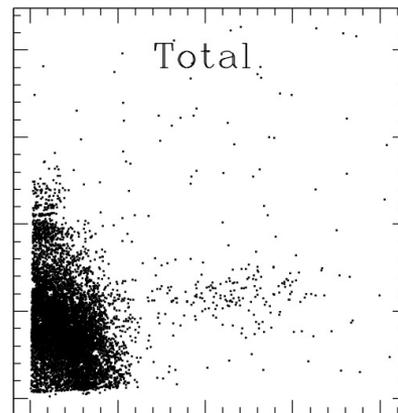
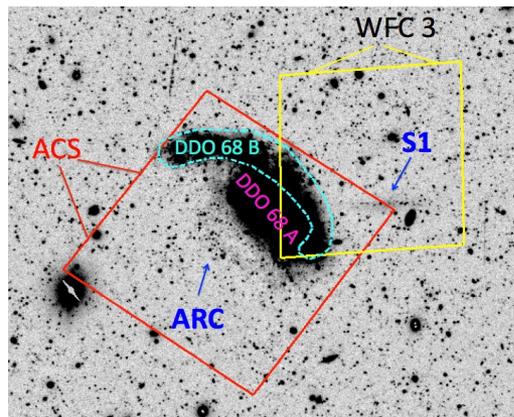


# DDO68: a multiple-merging dwarf in a void

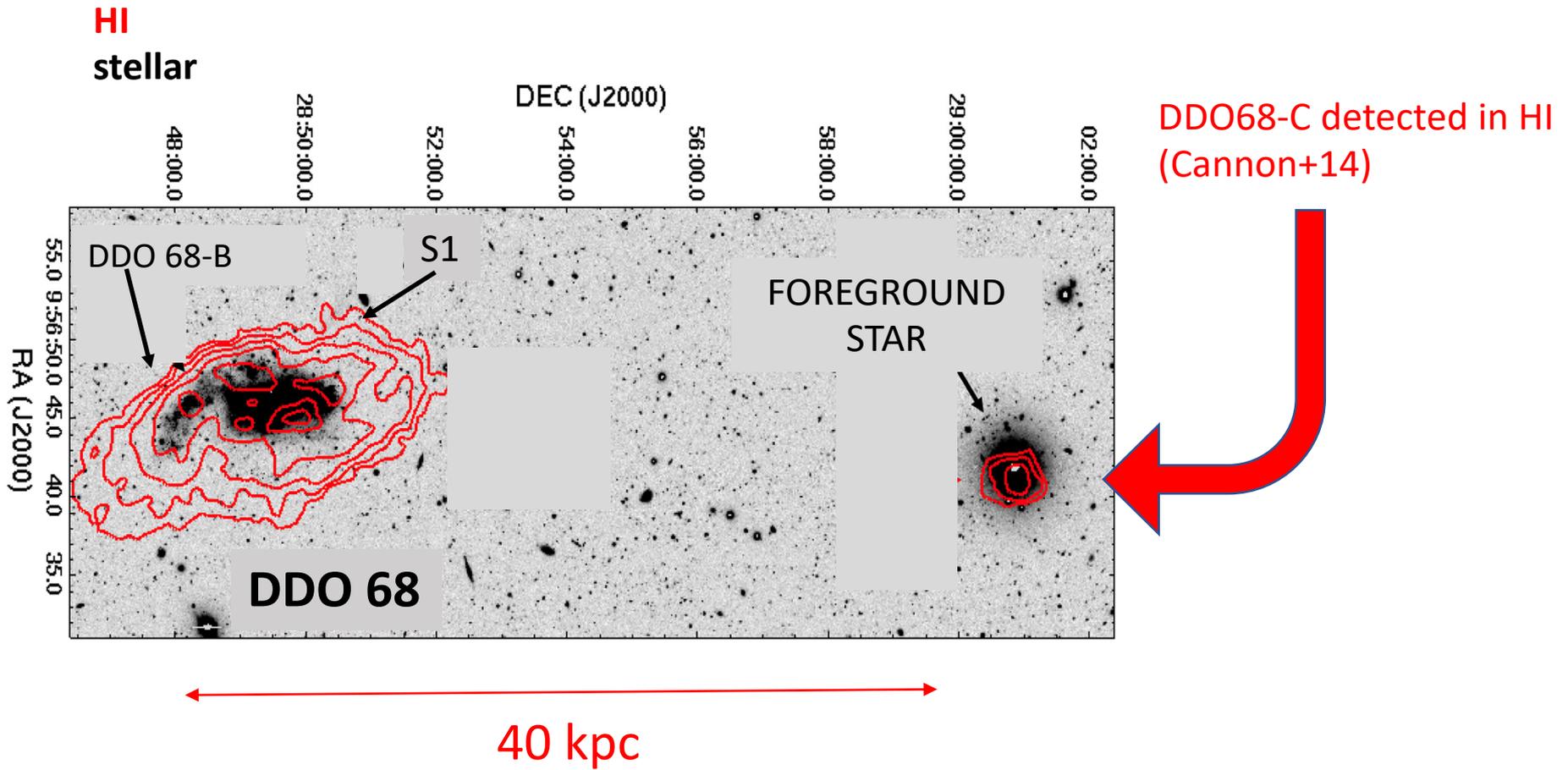
- ✓ DDO68 is a BCD at  $D \sim 13$  Mpc, in the Lynx-Cancer void
- ✓ Extremely metal poor (5% solar)
- ✓ Strong outlier in the mass – Z relation
- ✓ Disturbed morphology
- ✓ 3<sup>rd</sup> component S1 confirmed through HST data (RGB tip)

**RGB TIP INDICATES SAME DISTANCE**

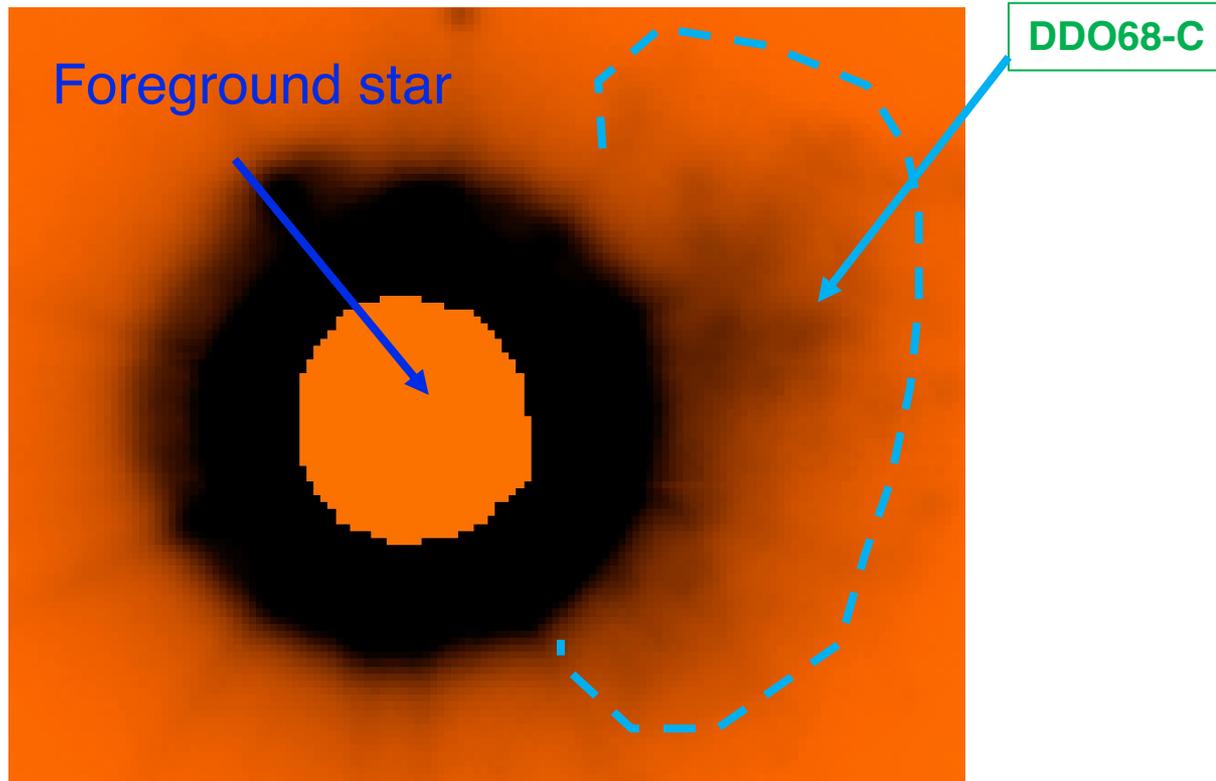
Annibali + 19



# DDO68-C: a 3rd satellite of DDO68?

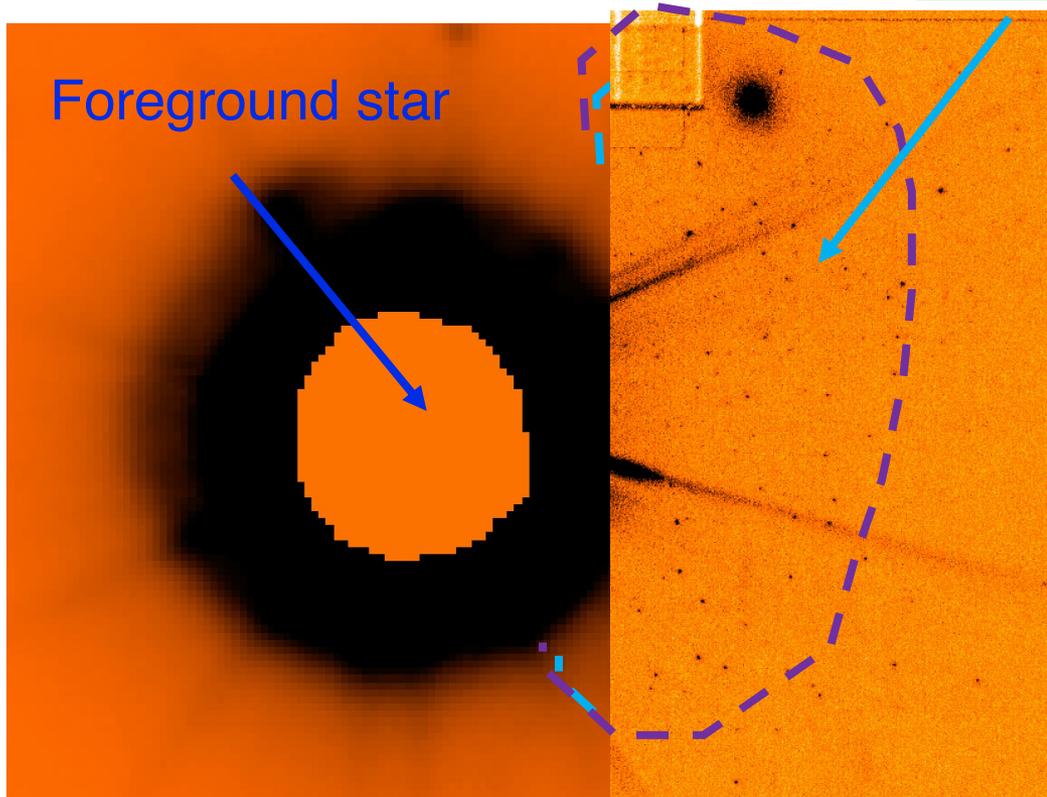


# DDO68-C: a 3rd satellite of DDO668?

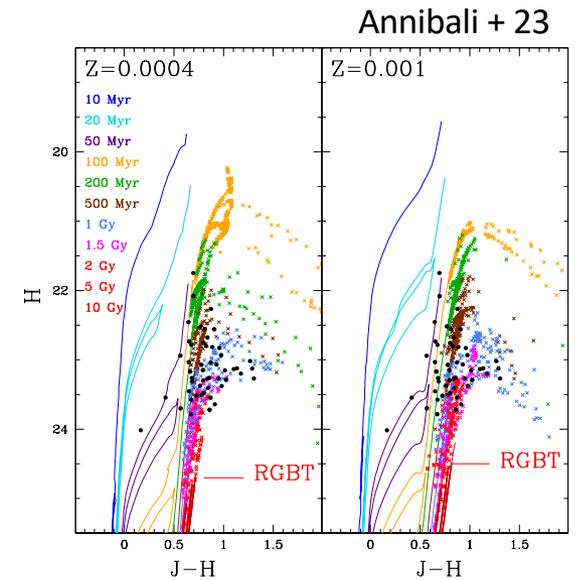


# DDO68-C: a 3rd satellite of DDO68?

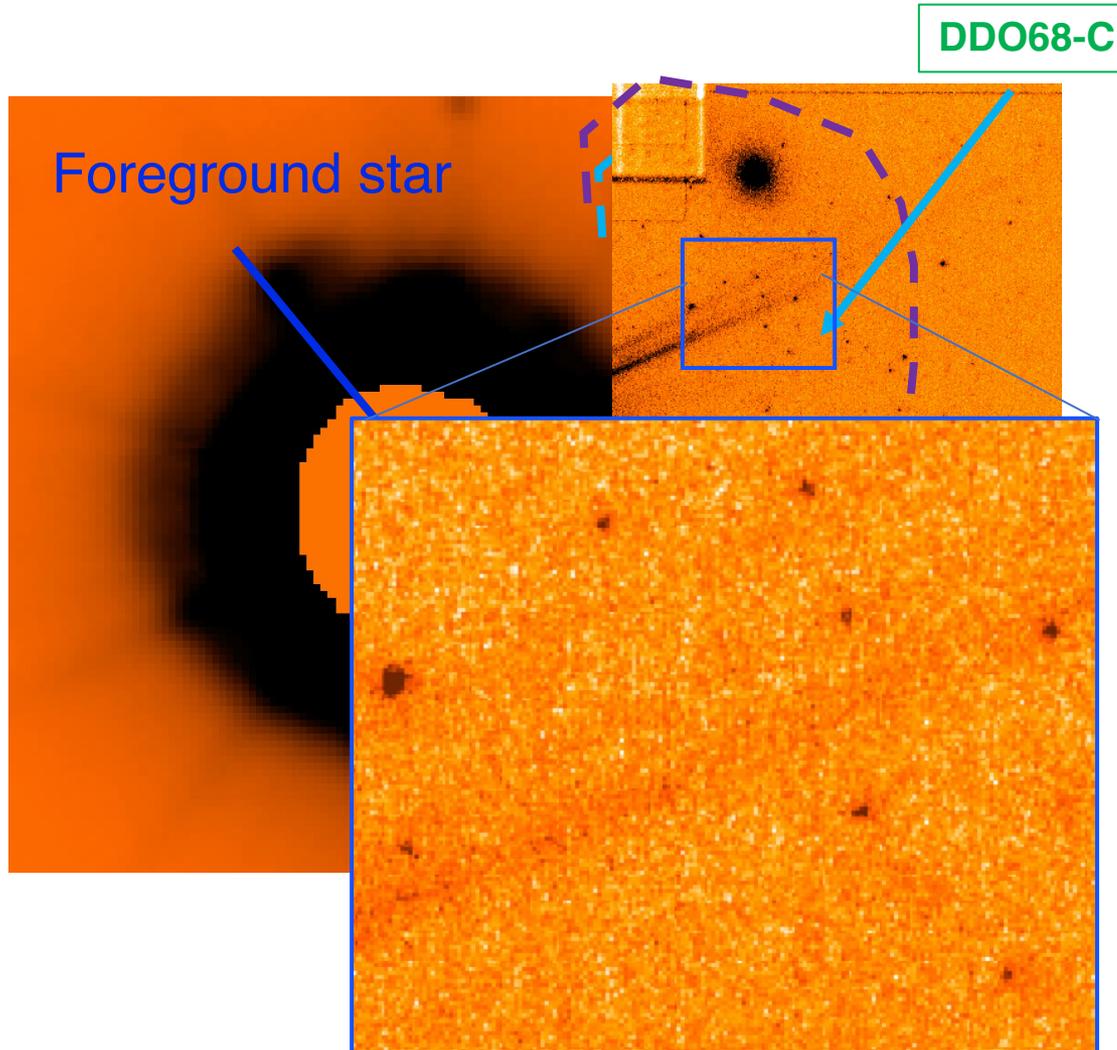
DDO68-C



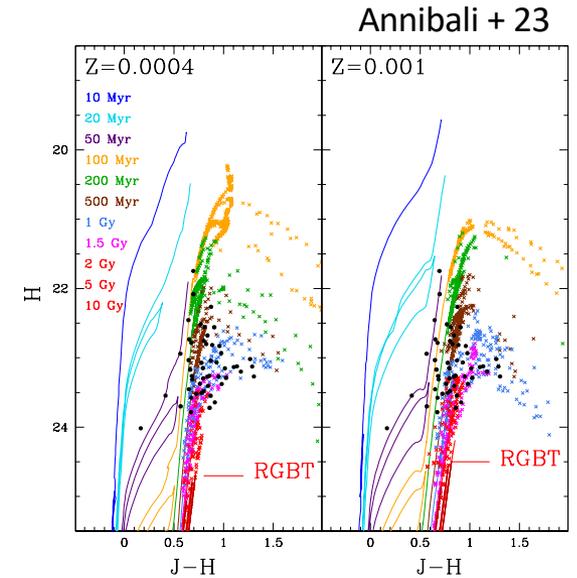
- ✓ Adaptive optics with LUCI@ LBT resolves individual stars in DDO68-C
- ✓ CMD consistent with bright AGB and red core He burning stars at 13 Mpc



# DDO68-C: a 3rd satellite of DDO68?

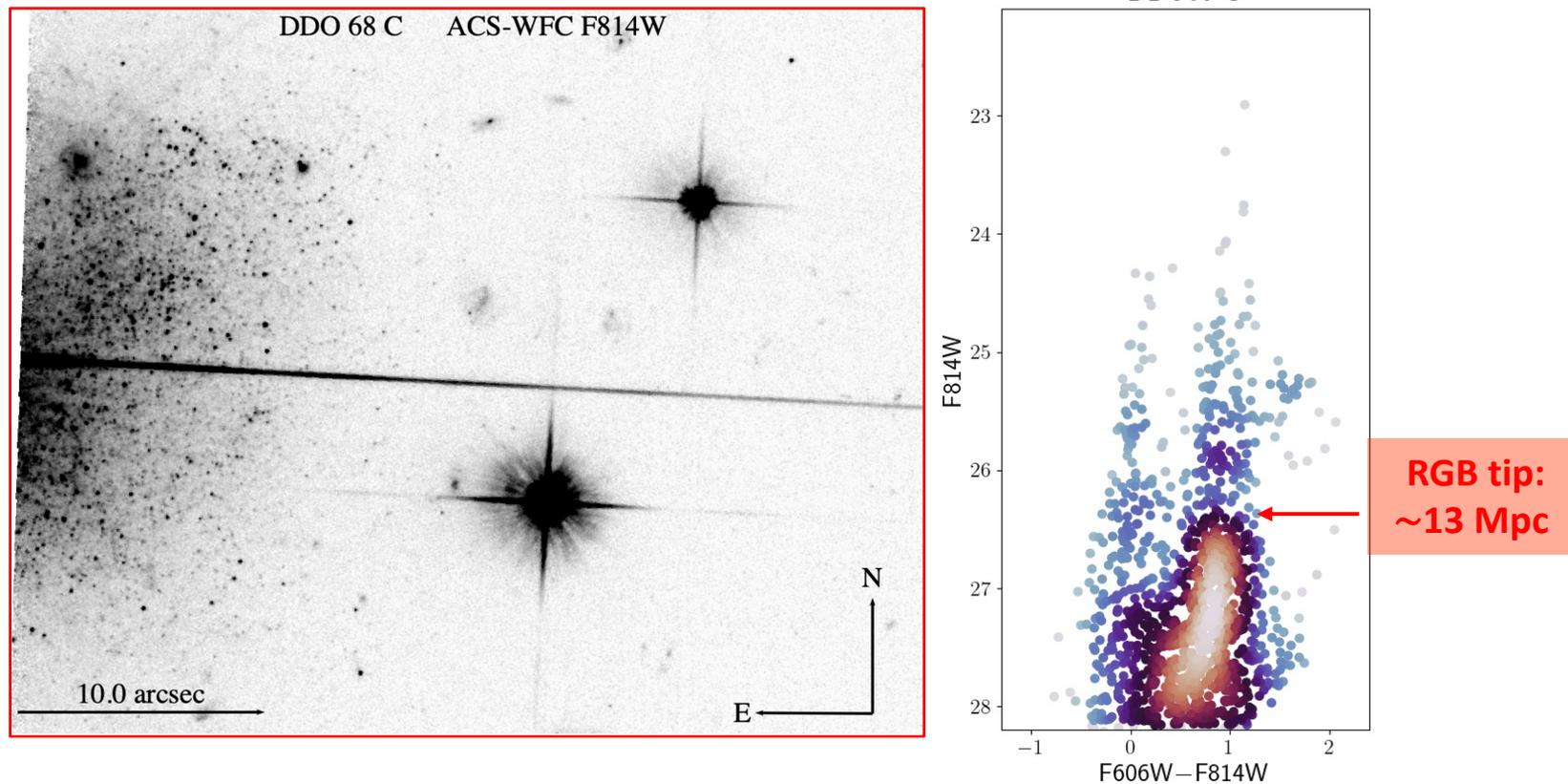


- ✓ Adaptive optics with LUCI@ LBT resolves individual stars in DDO68-C
- ✓ CMD consistent with bright AGB and red core He burning stars at 13 Mpc



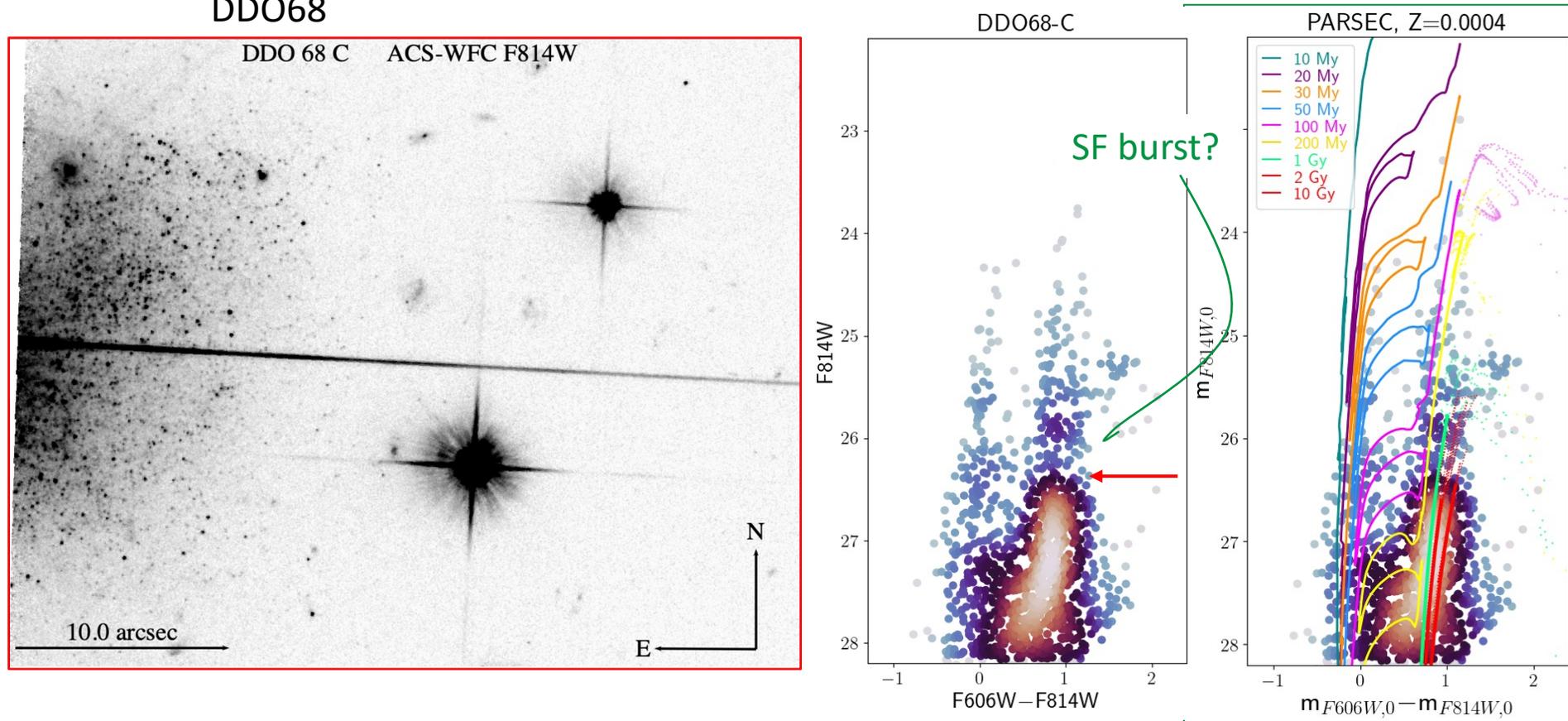
# DDO68-C: a 3rd satellite of DDO68?

- ✓ New HST images
- ✓ RGB tip: same  $\sim 13$  Mpc distance as DDO68
- ✓ Stellar mass  $\sim 10^7$  Msun, i.e. 10 times lower than DDO68



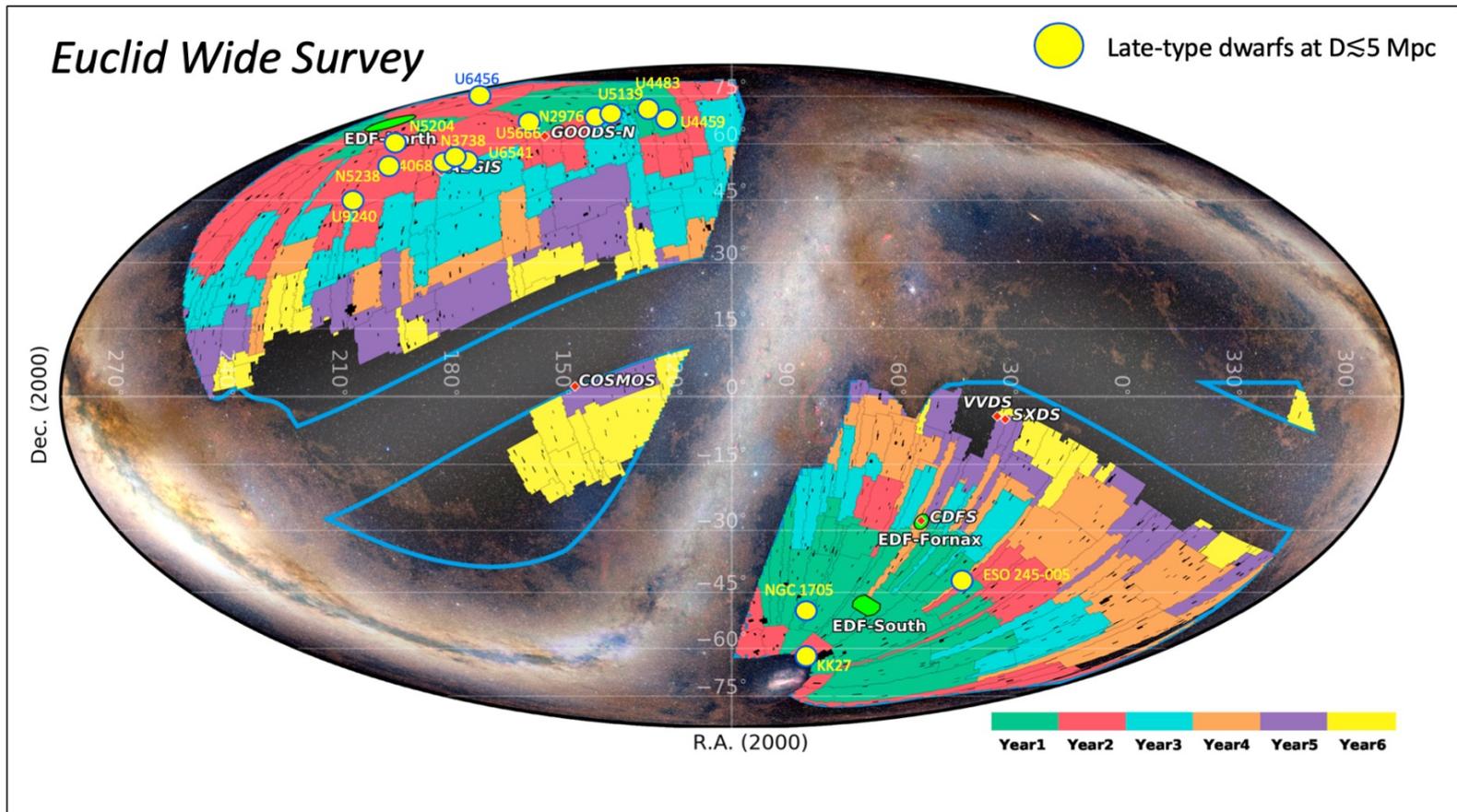
# DDO68-C: a 3rd satellite of DDO68?

- ✓ New HST images
- ✓ RGB tip: same  $\sim 13$  Mpc distance as DDO68
- ✓ Stellar mass  $\sim 10^7$  Msun, i.e. 10 times lower than DDO68



# Euclid view on dwarf galaxy assembly

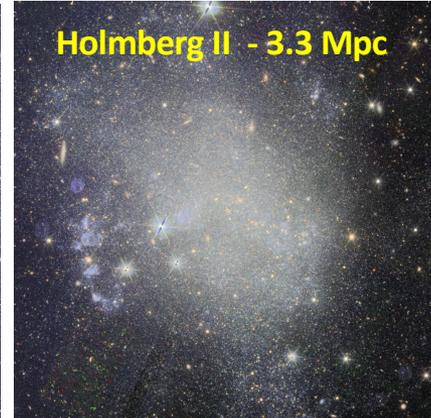
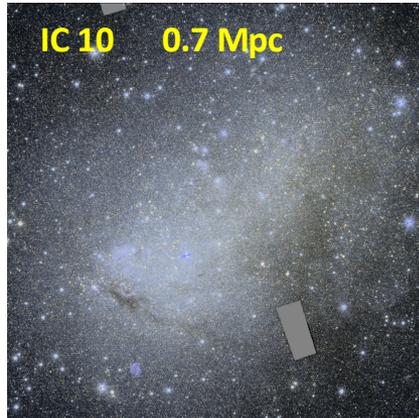
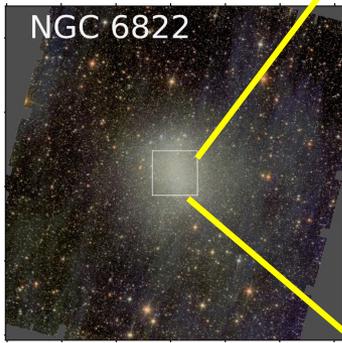
- ✓ ESA Euclid mission launched on July 2023, successfully commissioned and currently taking data
- ✓ Besides main focus on dark energy and dark matter content of the Universe, Euclid will also allow for key legacy science
- ✓ High spatial resolution ( $\lesssim 0.15''$  in I) and large field of view (0.67 square degrees) ideal to study low surface brightness, extended tidal remnants of the Lambda CDM assembly



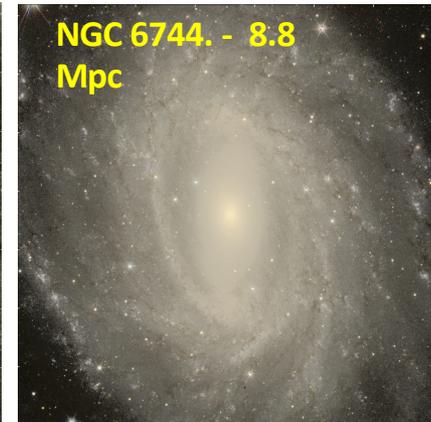
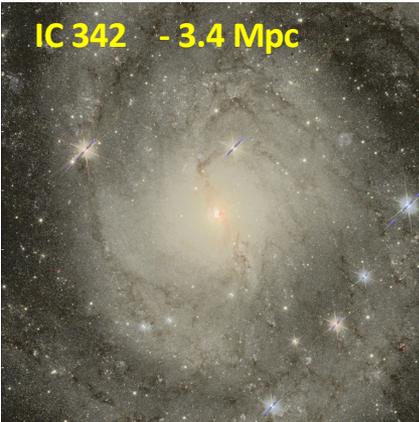
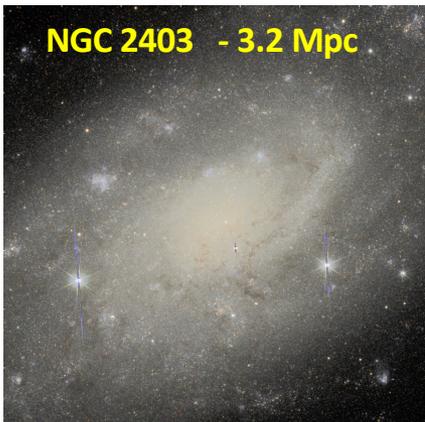
# Euclid ERO Nearby Galaxy Showcase Program

Observed from Aug to Nov 2023 (PI L. Hunt)

Hunt et al. (2024)



3 dwarfs



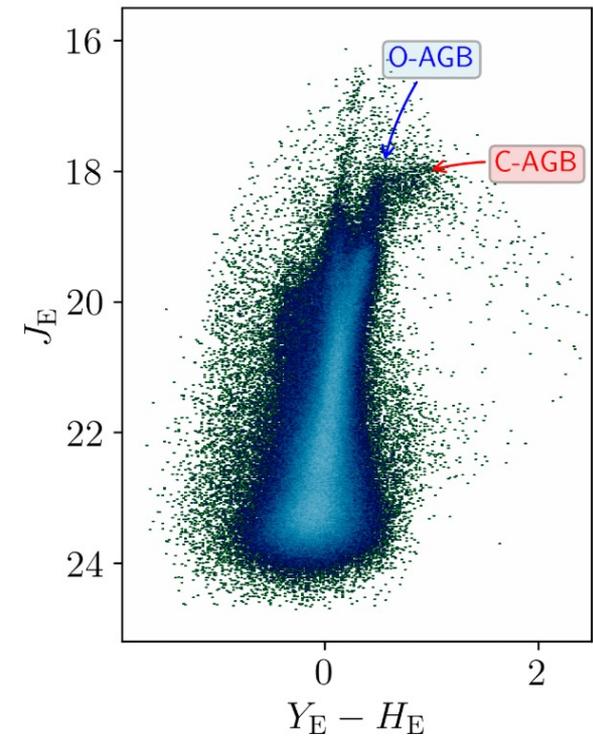
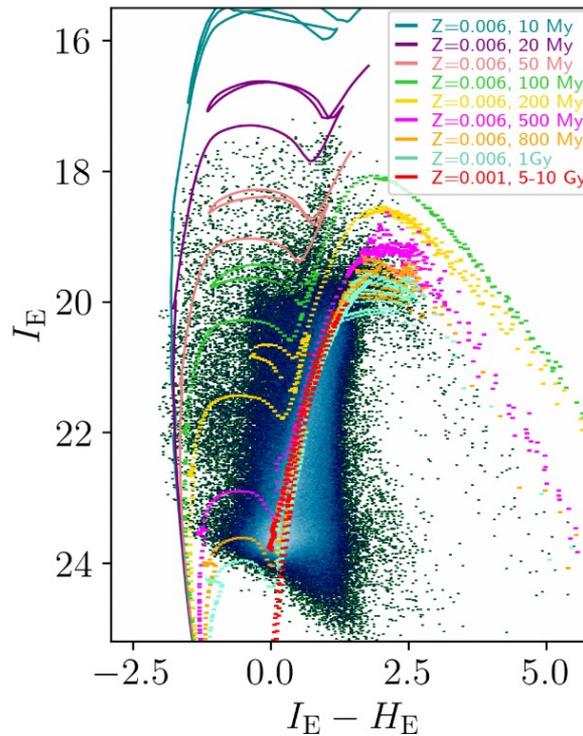
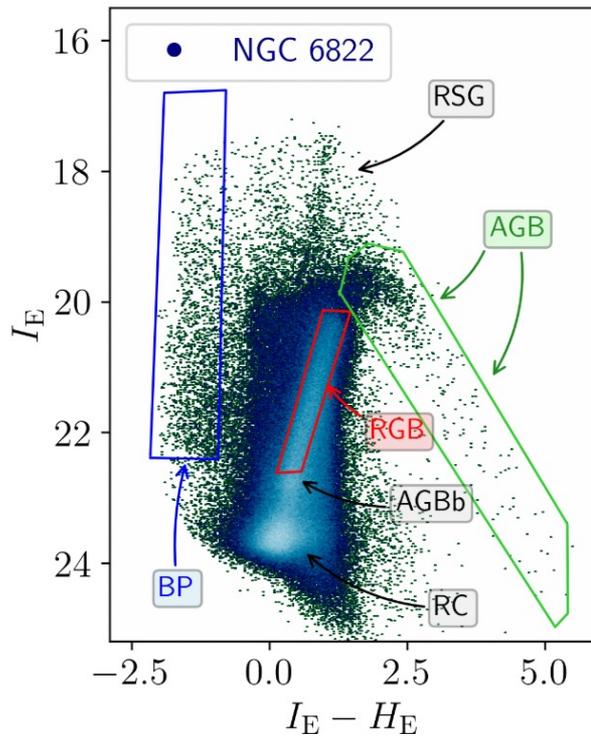
3 spirals

- Selected from WISE Extended Source Catalog
- Angular size < Euclid FoV (to fit in 1 ROS)
- Ancillary data (e.g. HI)

# Euclid color-magnitude diagrams of nearby galaxies

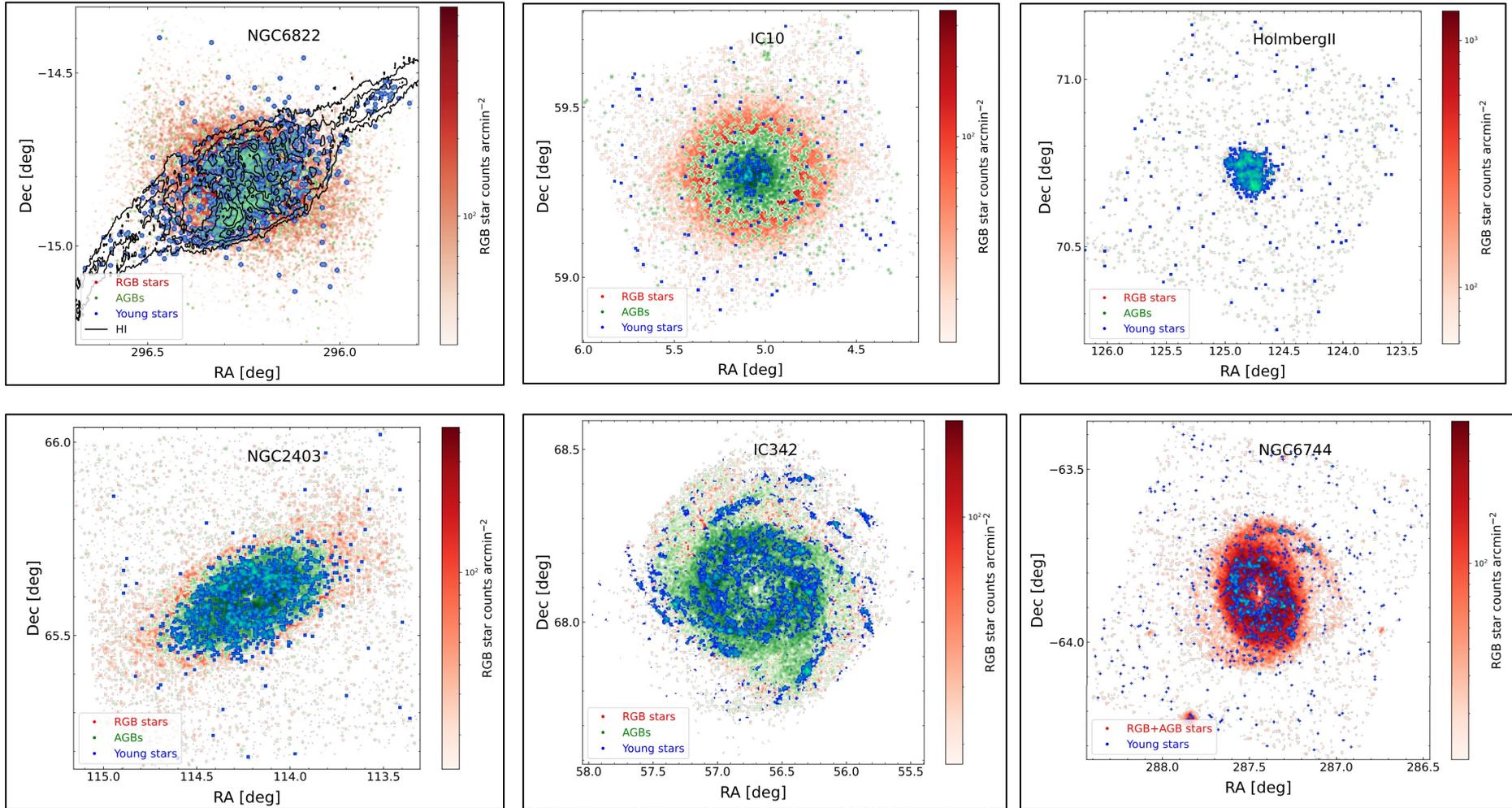
- ✓ High resolution ( $\lesssim 0.15''$  in I) allows to infer **deep CMDs** of individual stars in nearby galaxies
- ✓ Large FoV ( $\sim 0.7$  deg) allows to study stellar population distribution **out to large radii**

Hunt et al. (2024)



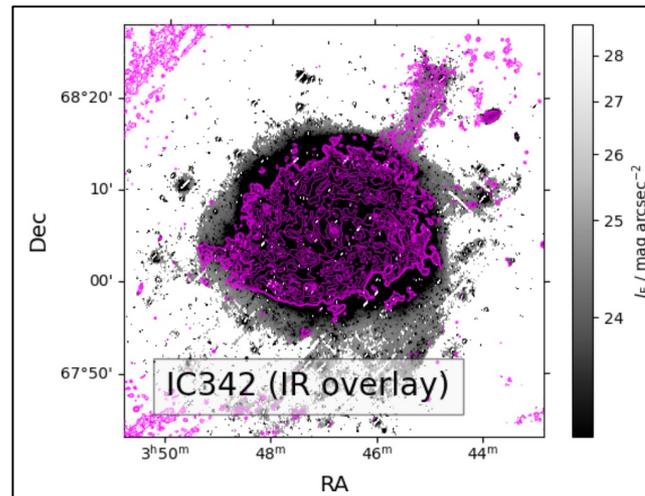
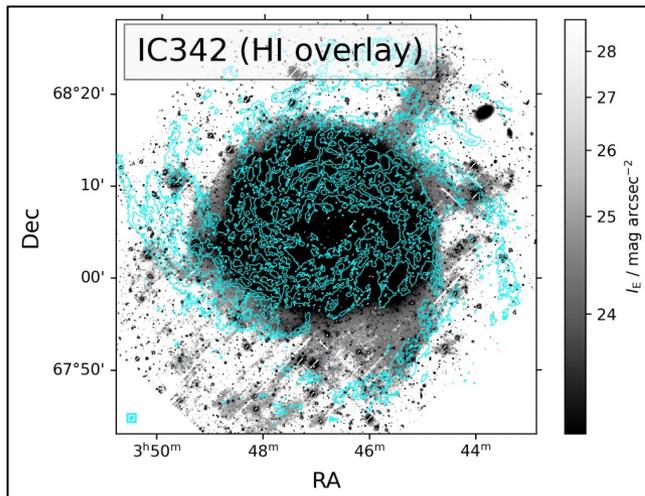
# Stellar population maps with star counts

Hunt et al. (2024)



# A warning for interpreting IL features..

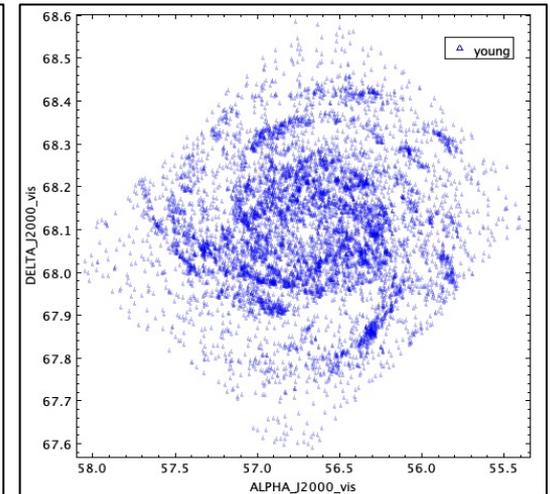
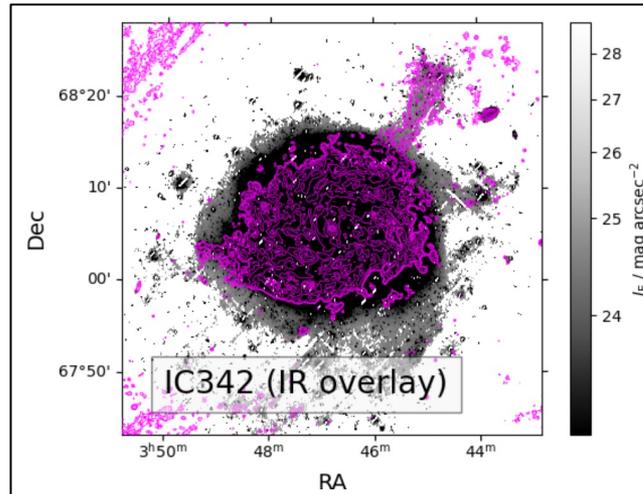
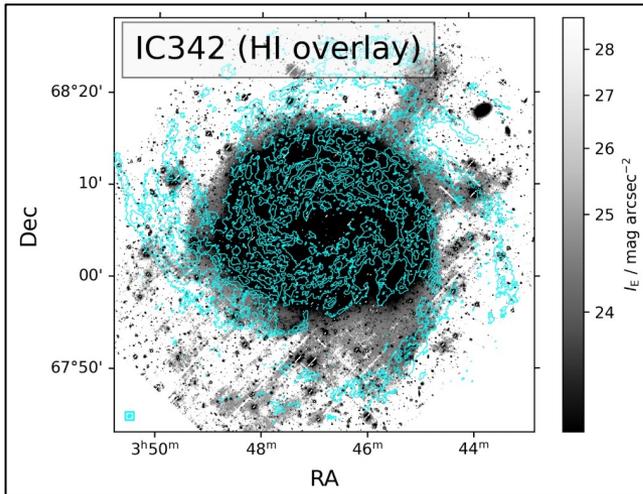
*Hunt et al. (2024)*



# A warning for interpreting IL features..

Hunt et al. (2024)

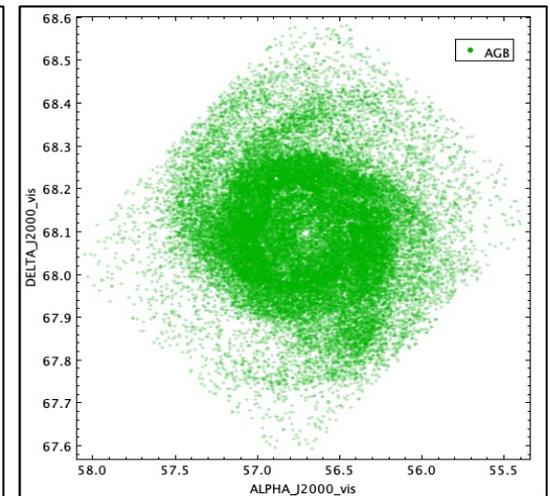
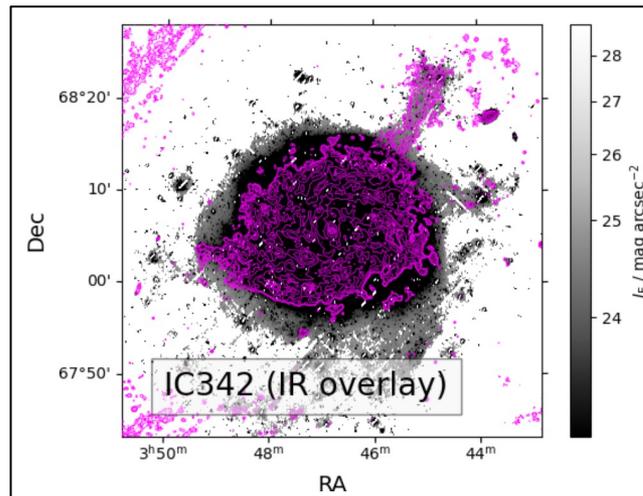
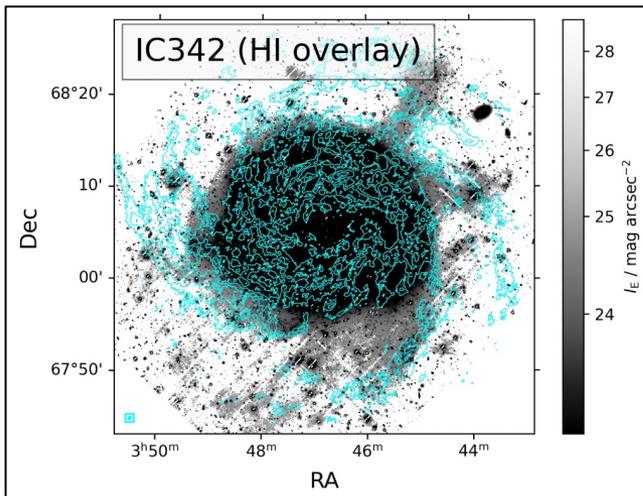
Young  
( $\lesssim 100$  Myr)



# A warning for interpreting IL features..

Hunt et al. (2024)

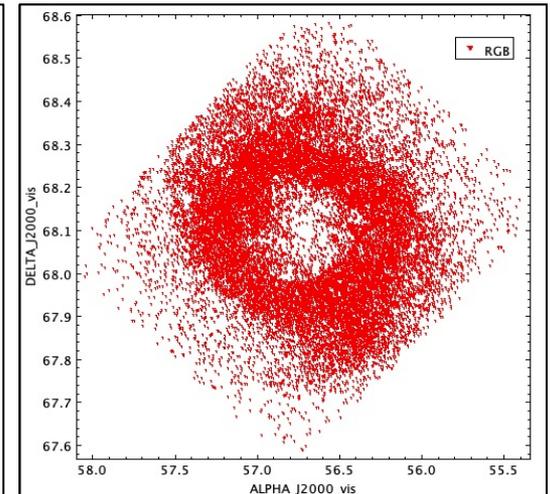
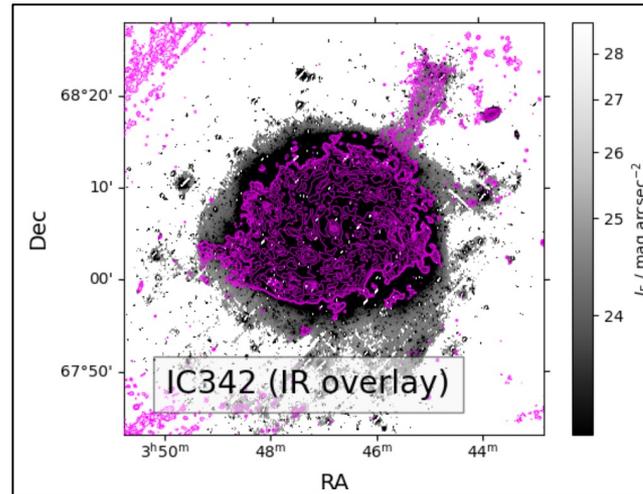
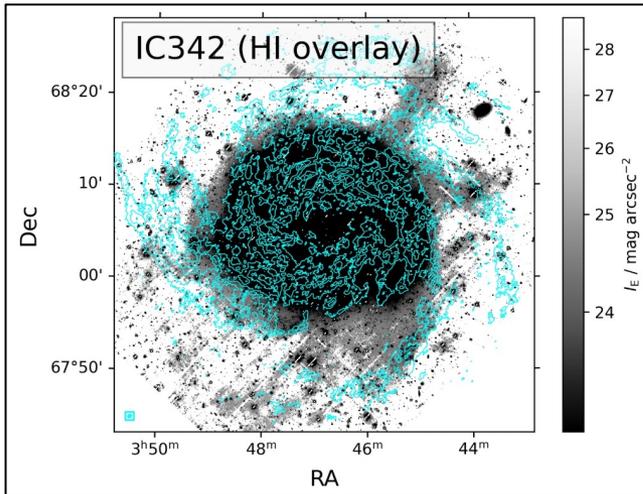
Intermediate  
(~0.1 – 2 Gyr)



# A warning for interpreting IL features..

Hunt et al. (2024)

Old  
( $\geq 2$  Gyr)

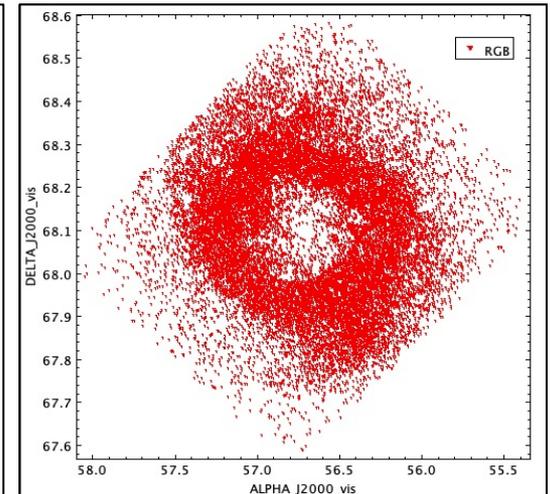
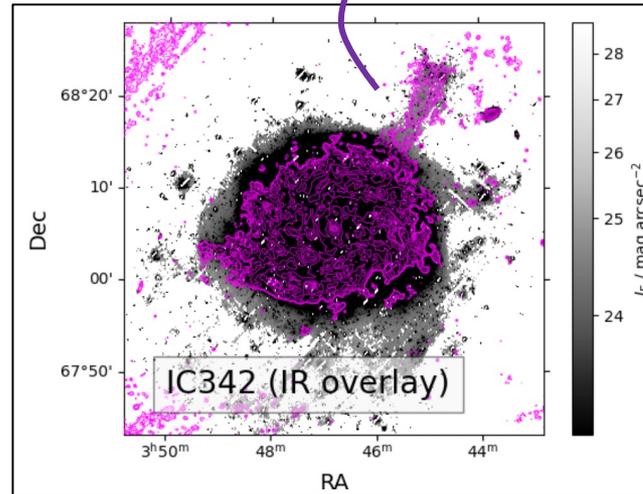
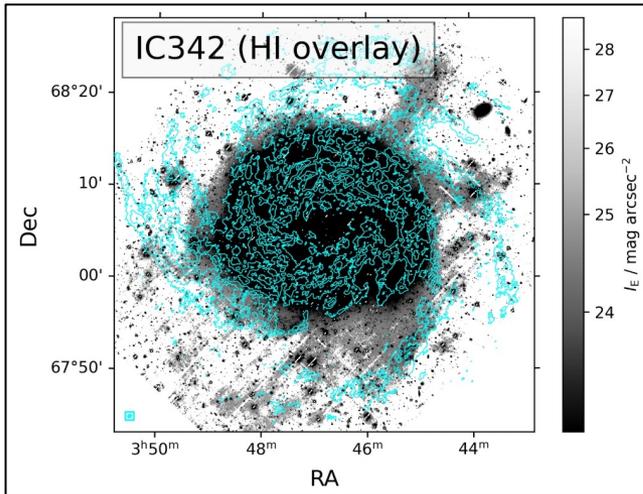


# A warning for interpreting IL features..

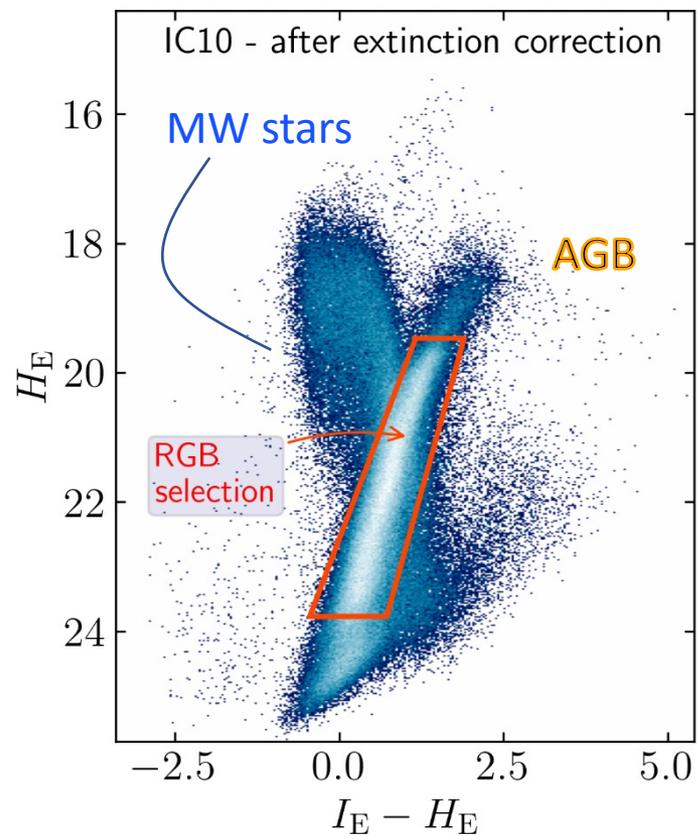
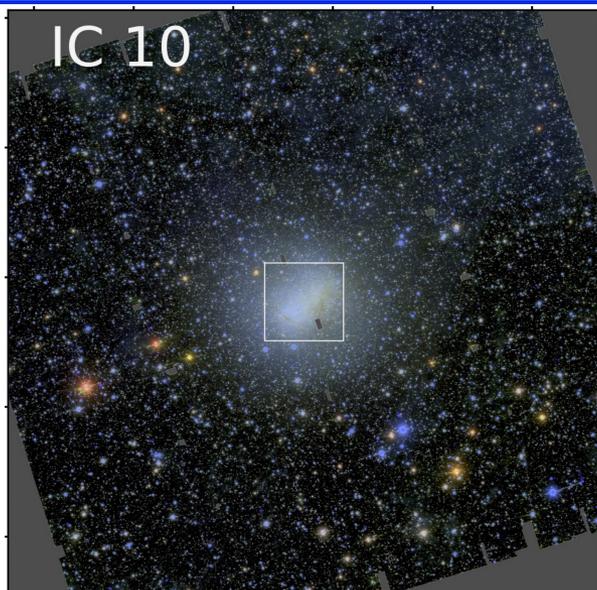
Hunt et al. (2024)

No spur in HI or stars  
→ Galactic cirrus!

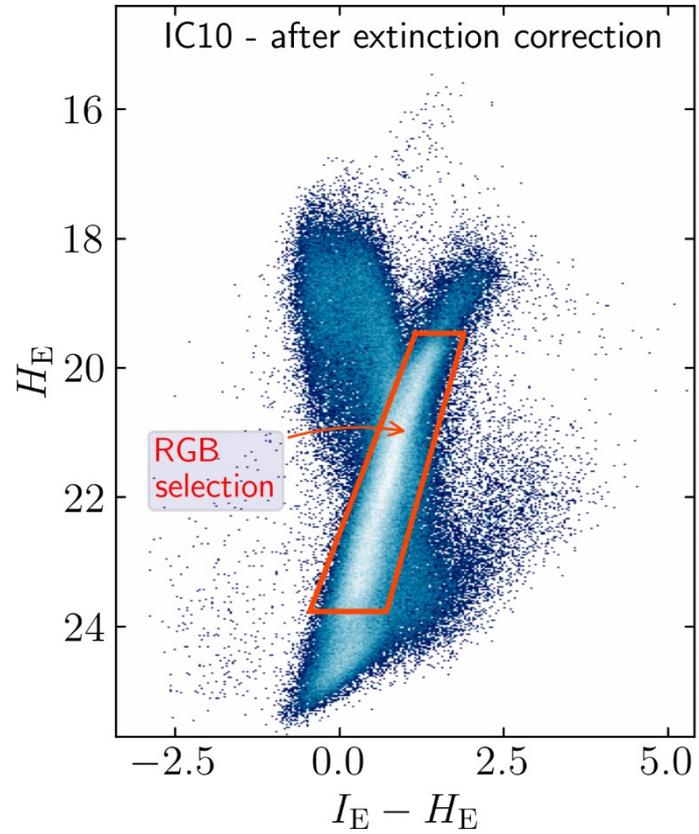
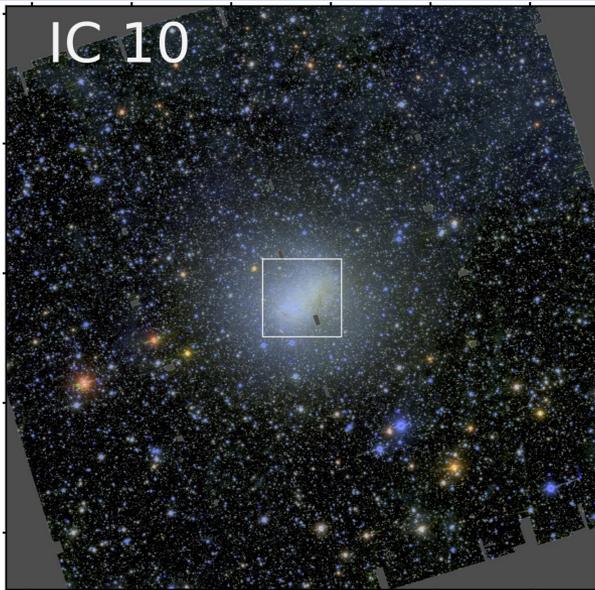
Old  
( $\geq 2$  Gyr)



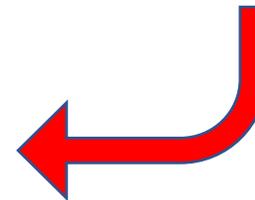
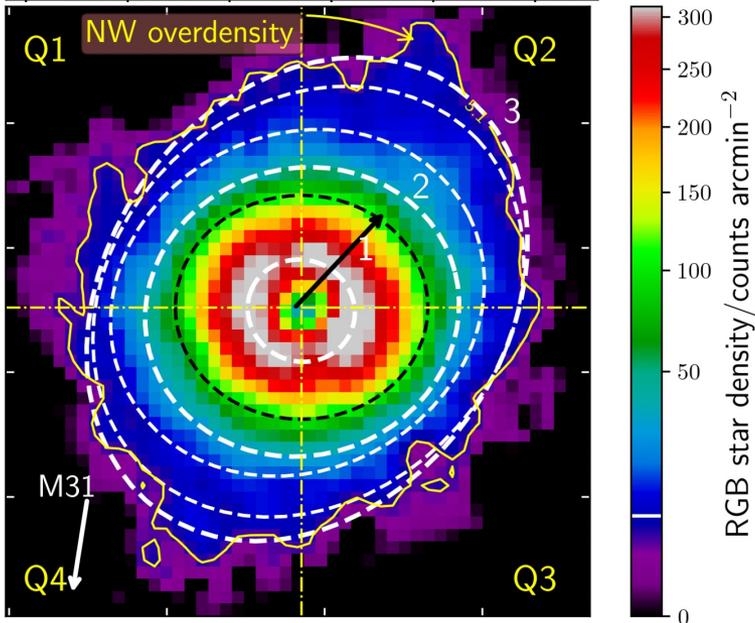
# The extended stellar component of IC10



# Euclid ERO Nearby Galaxy Showcase Program

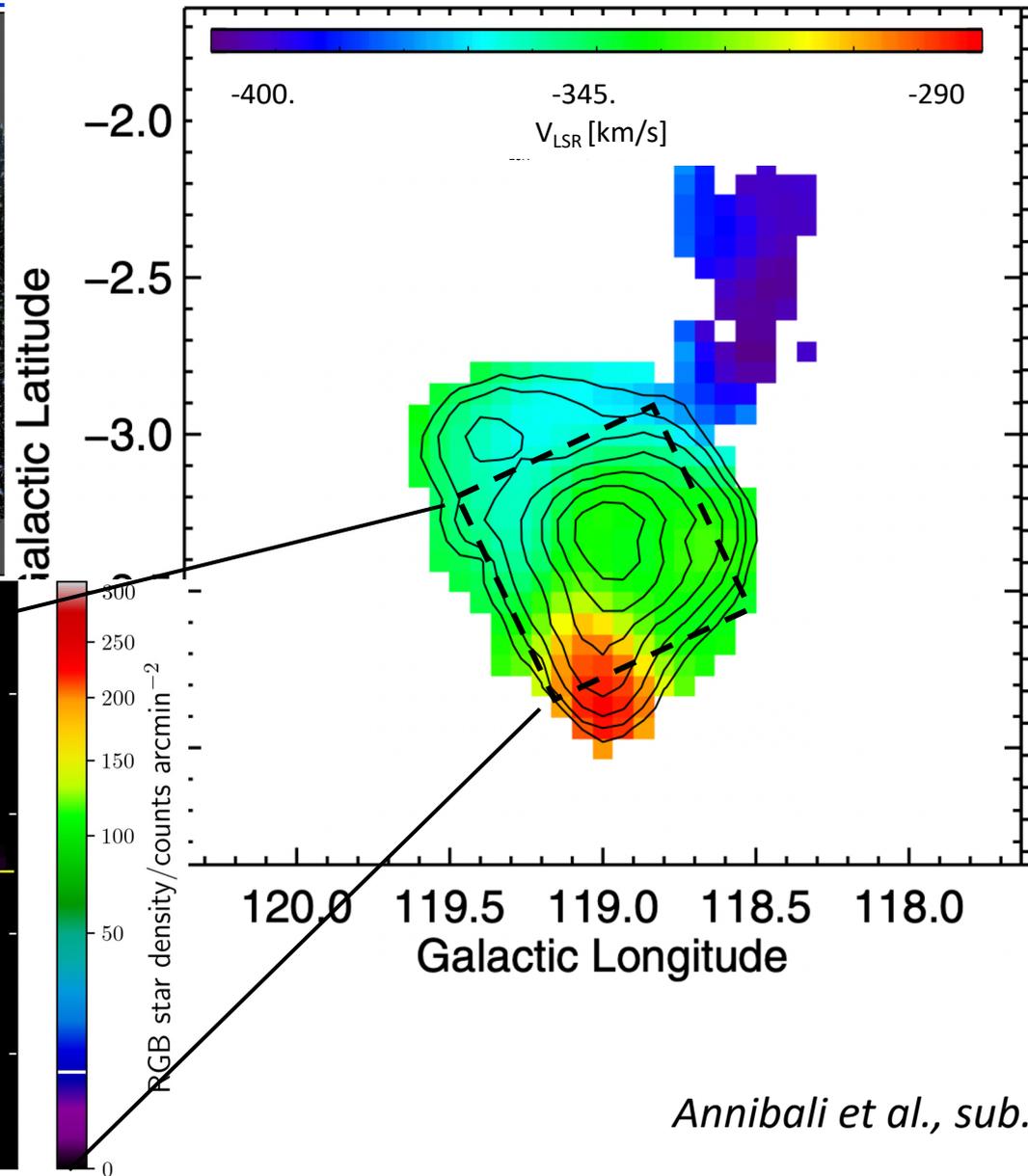
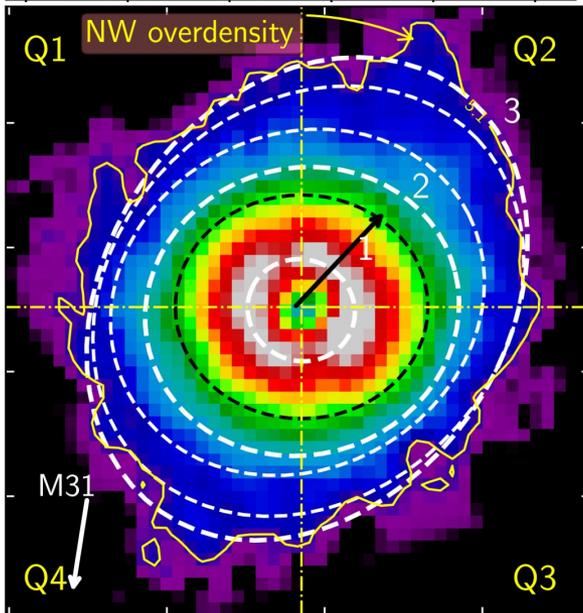
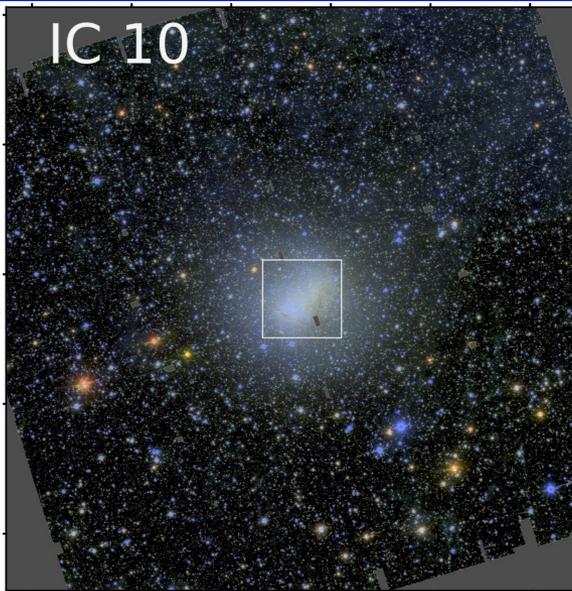


**Spatial distribution of RGB stars**



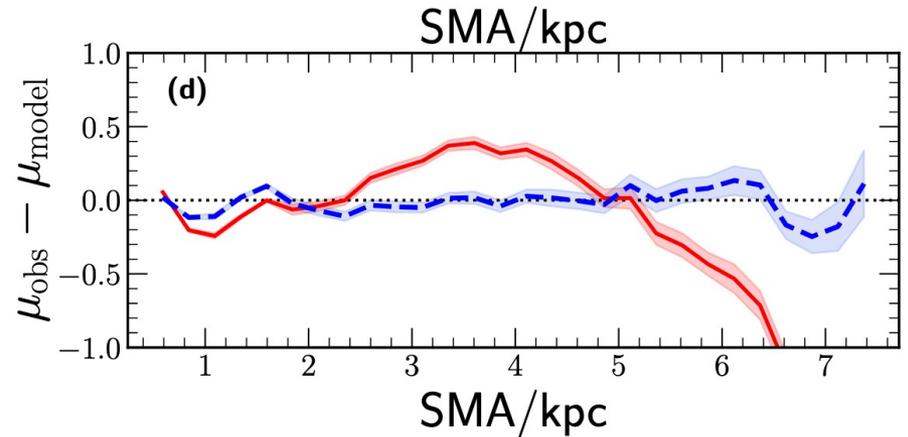
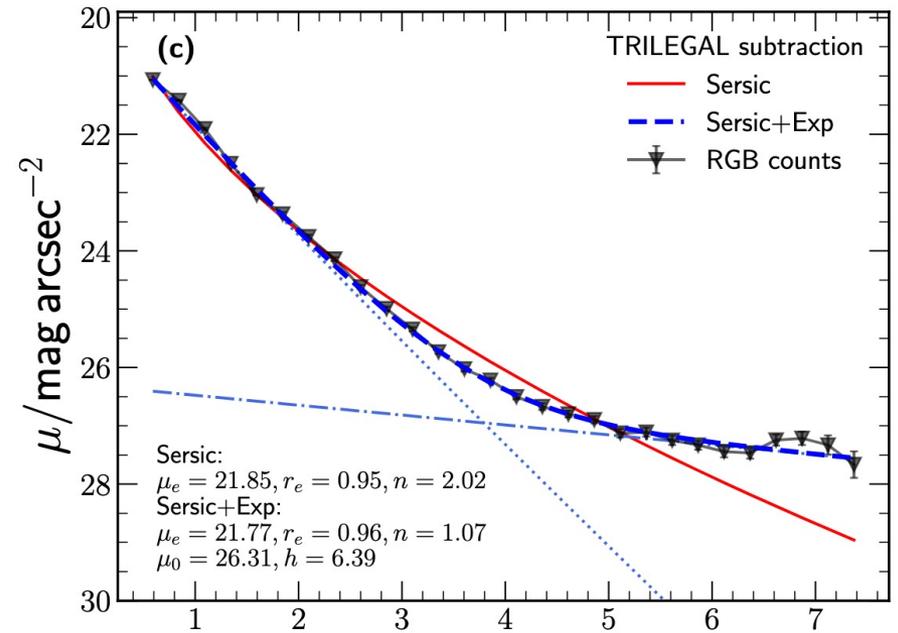
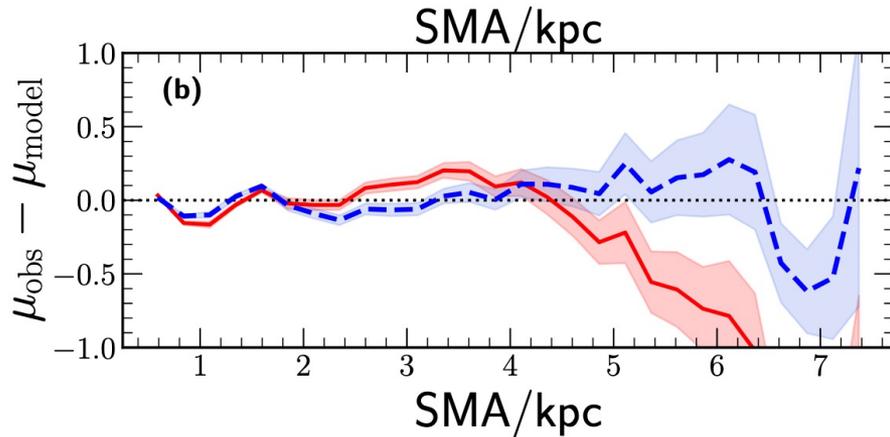
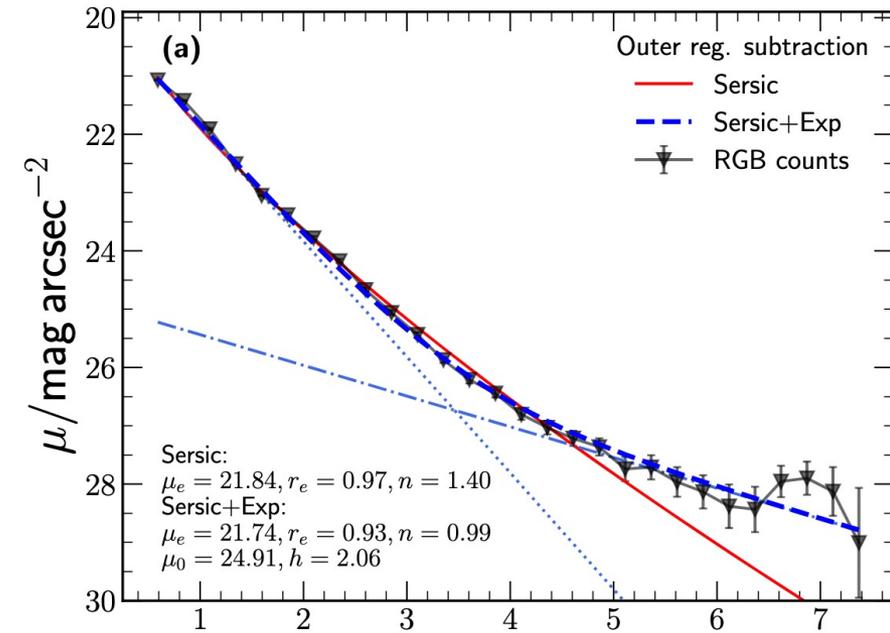
# The extended stellar component of IC10

Interaction with dwarf satellite

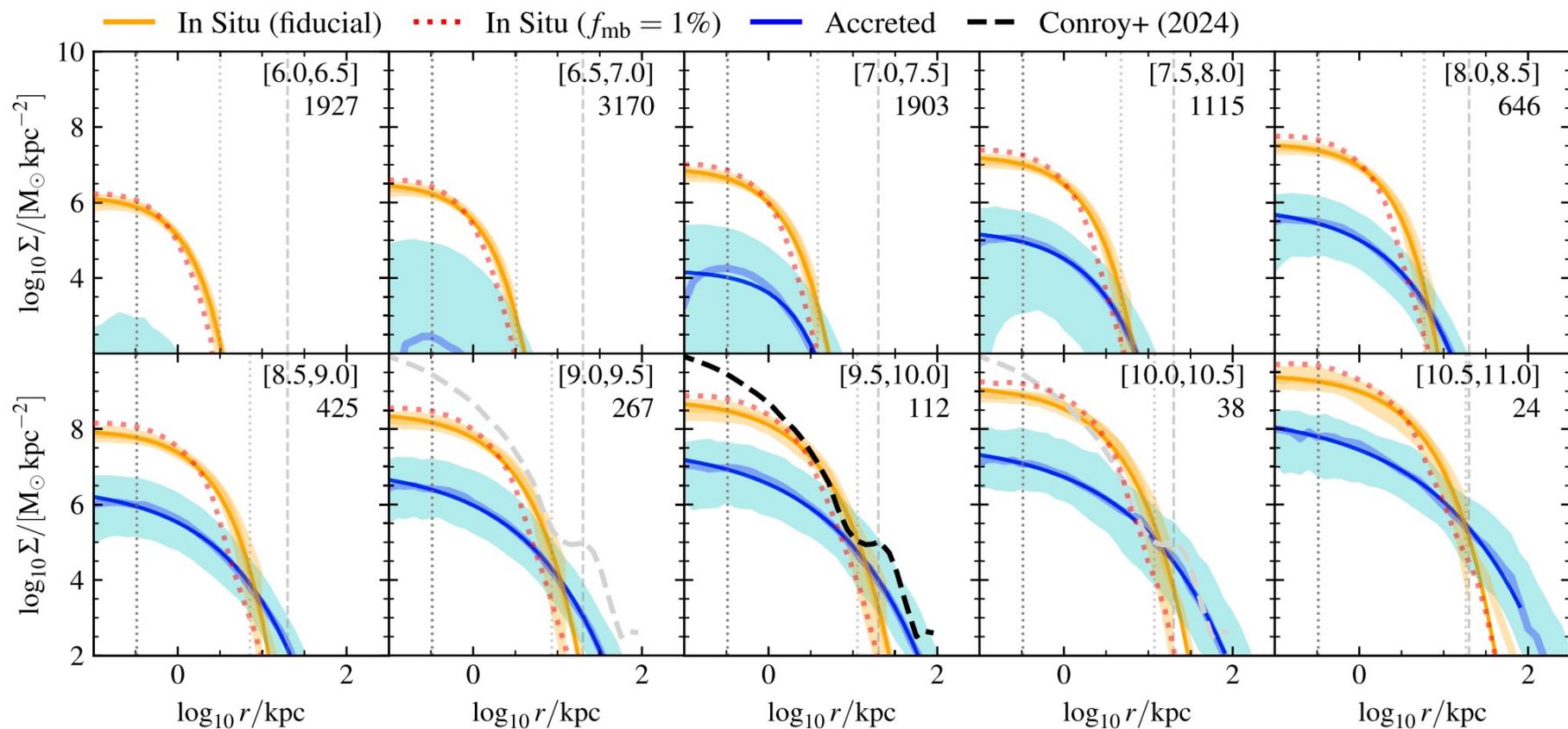


# The extended stellar component of IC10

Old star profile requires two components



# Simulation predictions - *in situ* versus *ex-situ* mass

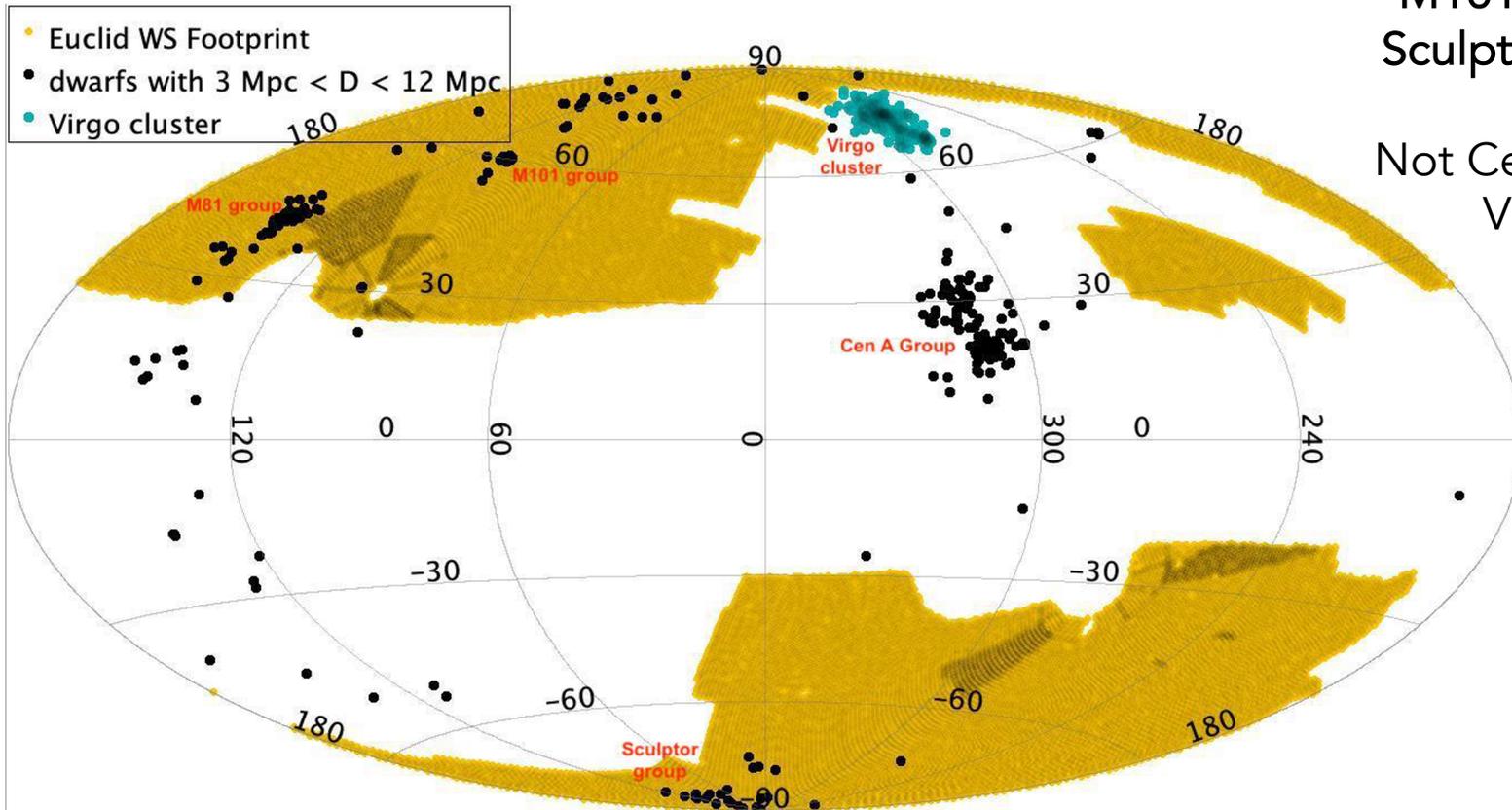






# Future perspectives

Euclid Wide Survey will image **outskirts** of many nearby systems



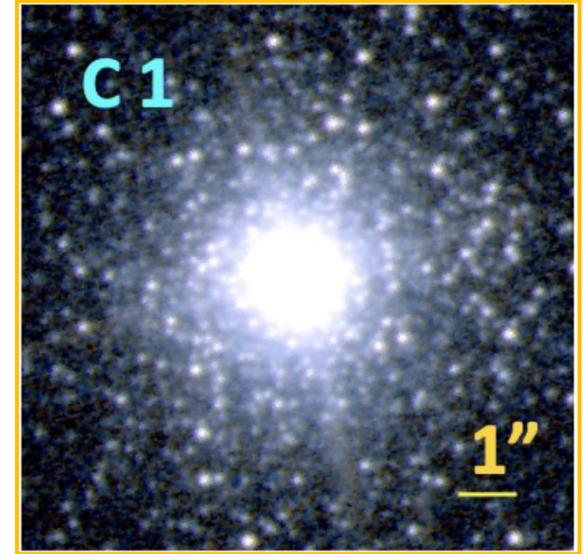
M81 group,  
M101 Group,  
Sculptor group

Not Cen A, Not  
Virgo

# Future perspectives

Follow-up of compact remnants of merged systems (e.g., C1 in NGC 5238)

Need  
High Sensitivity + Spatial Resolution

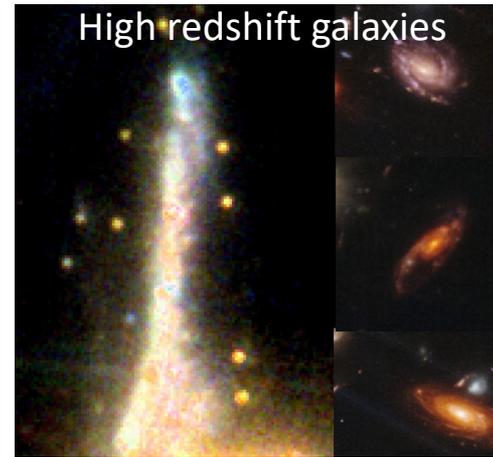
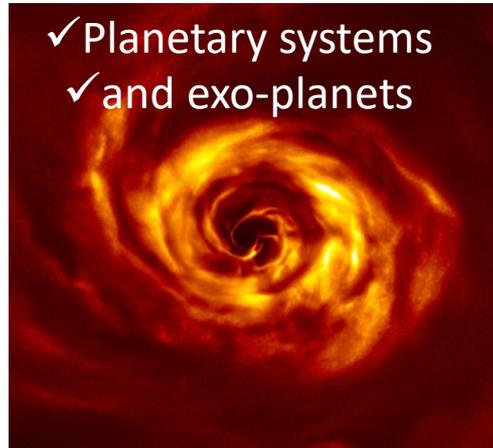
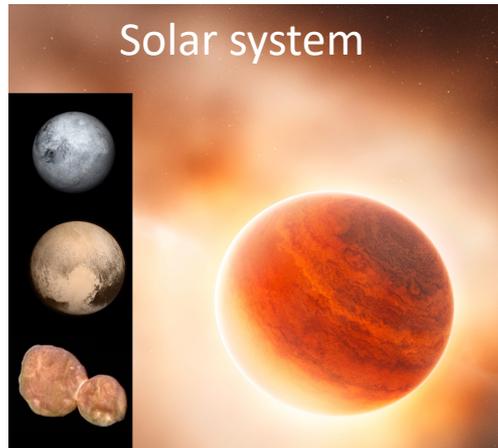


ELT

- ❖ **MORFEO** (PI Ciliegi) is the AO instrument for the ELT, with major involvement of INAF. It will provide MCAO correction to MICADO/HARMONI
- ❖ **MICADO** (PI Davies): diffraction limited imaging in I,Y,J,H,K + NB filters + longslit (same sensitivity as JWST, 7 times better resolution)
- ❖ **HARMONI** (PI Dunlop): high resolution IFU



# MORFEO Science Team working on a large variety of science cases



Revision of Fiorentino+17 white book to account for:

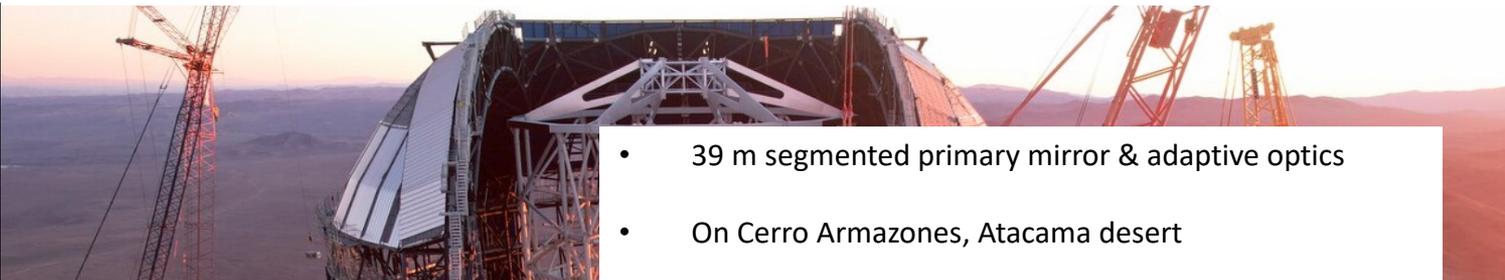
- ❖ Revised MORFEO performances
- ❖ New discoveries (e.g., JWST)
- ❖ **Contact us** if interested in contributing to the new WB

# Additional Slides

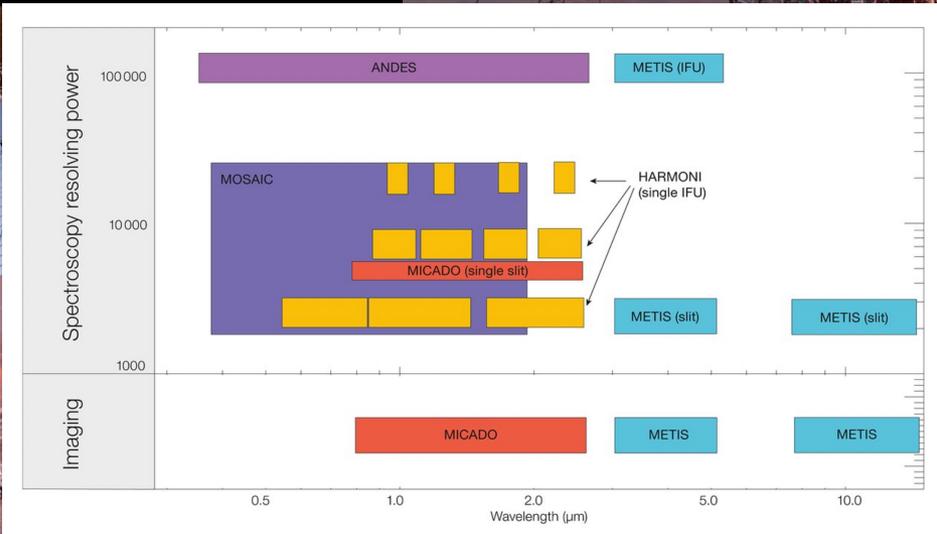
---



# Extremely Large Telescope (ELT): the largest optical/IR telescope in the world



- 39 m segmented primary mirror & adaptive optics
- On Cerro Armazones, Atacama desert
- First science light in 2030
- 1<sup>st</sup> generation instruments:  
MICADO, METIS, MORFEO, HARMONI
- 2<sup>nd</sup> generation instruments:  
ANDES, MOSAIC, PCS



ELT in January 2025



# MICADO: Multi-AO Imaging Camera for Deep Observations

(PI R. Davies)

- First light instrument for the ELT
- Will operate in stand-alone mode (SCAO) until MORFEO will arrive at ELT a couple years later
- Key capabilities:

- ❖ 0.8-2.4 $\mu\text{m}$  with 27 broad/narrow filters
- ❖ 1.5 & 4mas pixels for 19" & 51" FoV at 6-12mas
- ❖ Similar sensitivity to JWST, and 6 $\times$  better resolution

- ❖ 10-50 $\mu\text{as}$  precision anywhere in the field
- ❖ 10 $\mu\text{as}/\text{yr}$  = 5km/s at 100 kpc after only a few years

- ❖ focal & pupil plane coronagraphs
- ❖ angular differential imaging
- ❖ small inner working angle

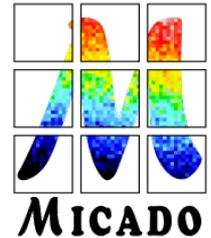
- ❖ for compact sources
- ❖ fixed configuration for 0.83-1.57 $\mu\text{m}$  & 1.50-2.46 $\mu\text{m}$
- ❖ R  $\sim$  20000 for point sources (R  $\sim$  10000 across slit)

IMAGING

ASTROMETRIC  
IMAGING

HIGH CONTRAST  
IMAGING

SPECTROSCOPY

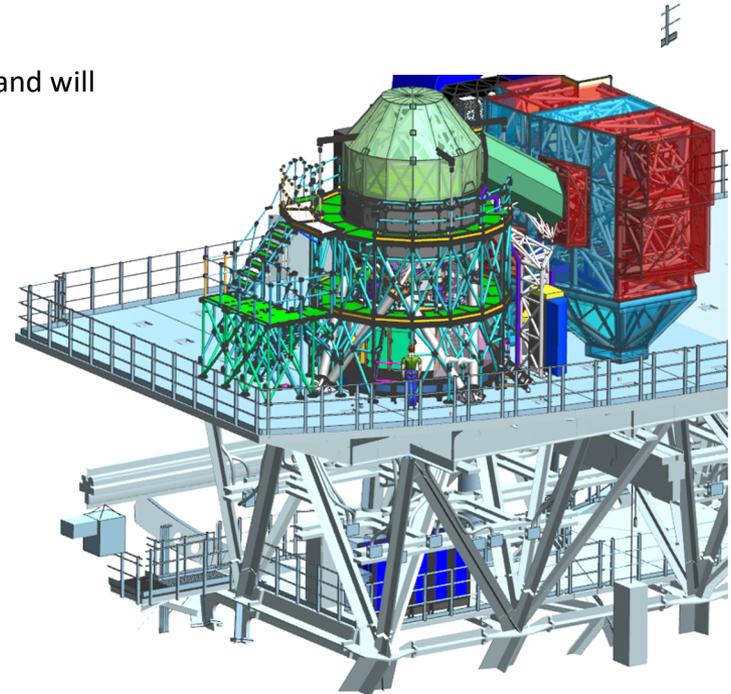


# MORFEO: Multiconjugate adaptive Optics Relay For ELT Observations (PI P. Ciliegi, INAF)

- MORFEO is the AO instrument for the ELT (serving MICADO and HARMONI) and will provide MCAO correction
- First Technical light end of 2031, commissioning in 2031-2032
- One of the largest projects with INAF leadership:
  - ❖ INAF: leader institute, 85% of FTE
  - ❖ CNRS, France : LGS WFS module
  - ❖ University of Galway, Ireland : Test Unit
  - ❖ NRC, Canada : Real Time Computer
  - ❖ Three Japanese Institutes (NAOJ, University of Kyoto, University of Osaka): two Optical elements

## GTO (105 NIGHTS IN TOTAL)

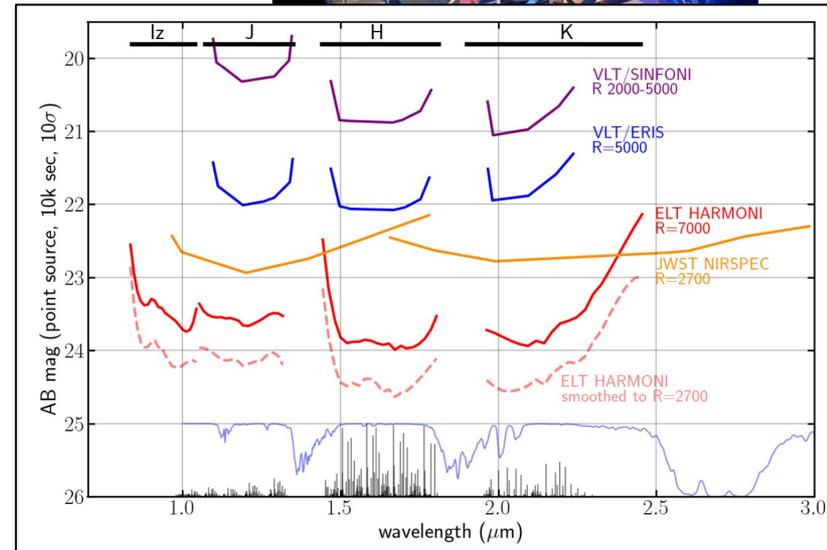
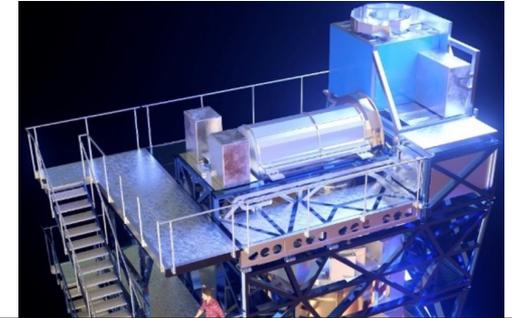
INAF	80.3
CNRS	9.2
UoG	2.5
NRC	6.0
JPI	7.0



# HARMONI: High Angular Resolution Monolithic Optical and NIR Integral field spectrograph (PI J. Dunlop, Univ of Edinburgh, UK)

- HARMONI recently rescoped (MORFEO will provide AO correction)

Simplified HARMONI	
Spatial pixel scale	6x6 mas    25x25 mas
FoV	1.2"x 0.9"    3.8" x 5.1"
Wavelength range	0.8 – 2.4 $\mu\text{m}$
Spectral resolution	R=7000 (Iz, J, H, K) R=3000 (Iz+J, H+K)
SCAO	4x4 mas sampling
MCAO	



- Courtesy Mark Swinbank (HARMONI PS)

# AO with MORFEO at ELT

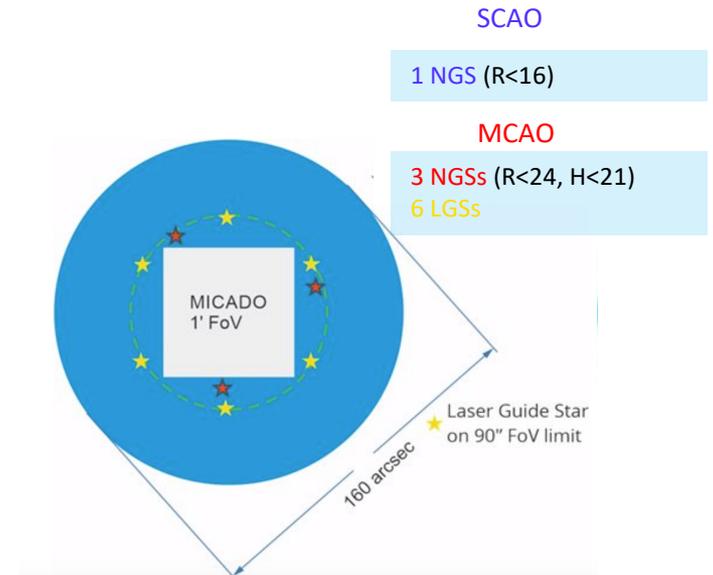
- ✓ MORFEO will provide spatially uniform multi-conjugate adaptive optics (MCAO) correction to MICADO over a large field of view ( $\sim 1$  arcmin<sup>2</sup>)
- ✓ MORFEO will also support SCAO over a smaller  $\sim 10''$  field of view



- ✓ Uniform Strehl Ratio and FWHM over a large field of view
- ✓ Large sky coverage



Possibility to address a large variety of science cases based on astrophysical relevance rather than on feasibility criteria

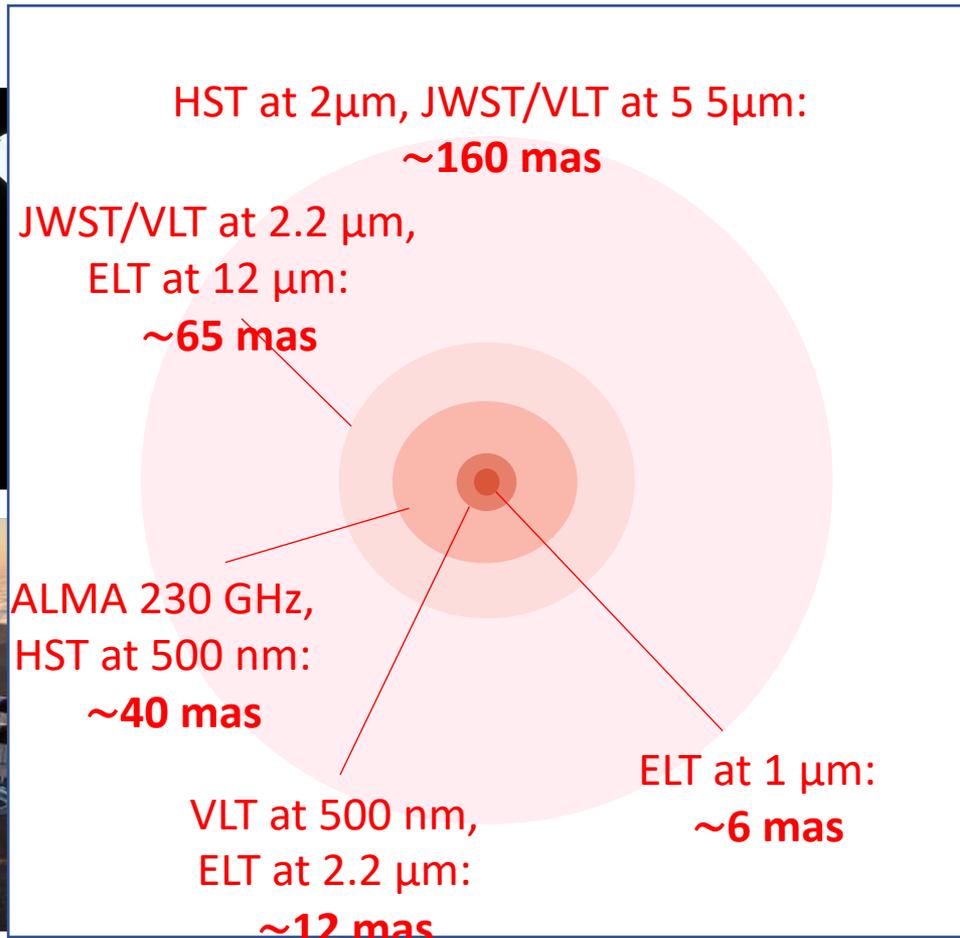


# MORFEO+MICADO: resolution in context



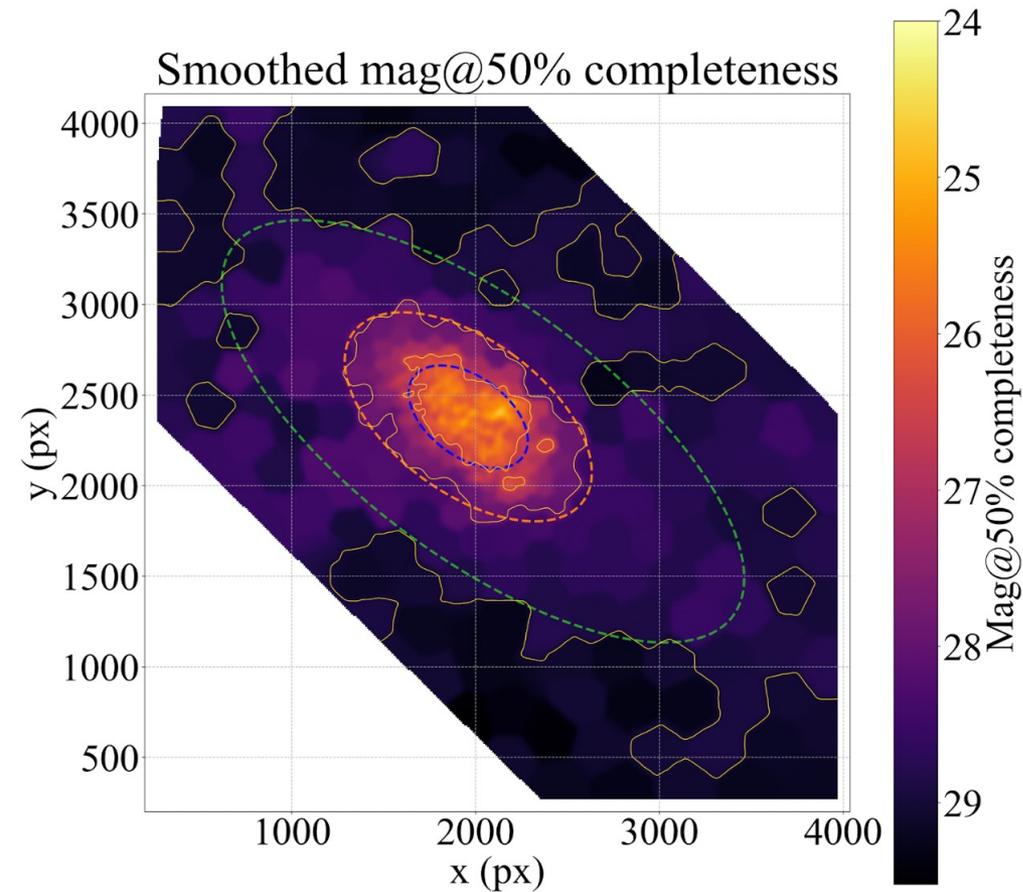
10 mas at:

Galactic Center	8 kpc	0.4 mpc
Cen A	4 Mpc	0.2 pc
Virgo Cluster	18 Mpc	1 pc
Cosmic Noon	$z \sim 2$	80 pc



# The relation between SF and merging events in dwarfs

Mrk 178



# DDO68-C: a 3rd satellite of DDO68?

- ✓ Low surface brightness ( $N_H \lesssim 5 \cdot 10^{18} \text{ cm}^{-2}$ ) HI bridge connecting DDO68 and DDO68-C (Cannon et al 2014)

