GALAXY HALOS AND OTHER DIFFUSE LIGHT

JOHANNA HARTKE – LA SILLA SUMMER SCHOOL 2020

WITH THANKS TO CAMILA NAVARRETE AND THE PN.S CONSORTIUM

WHAT IS A HALO?

Cambridge Dictionary:

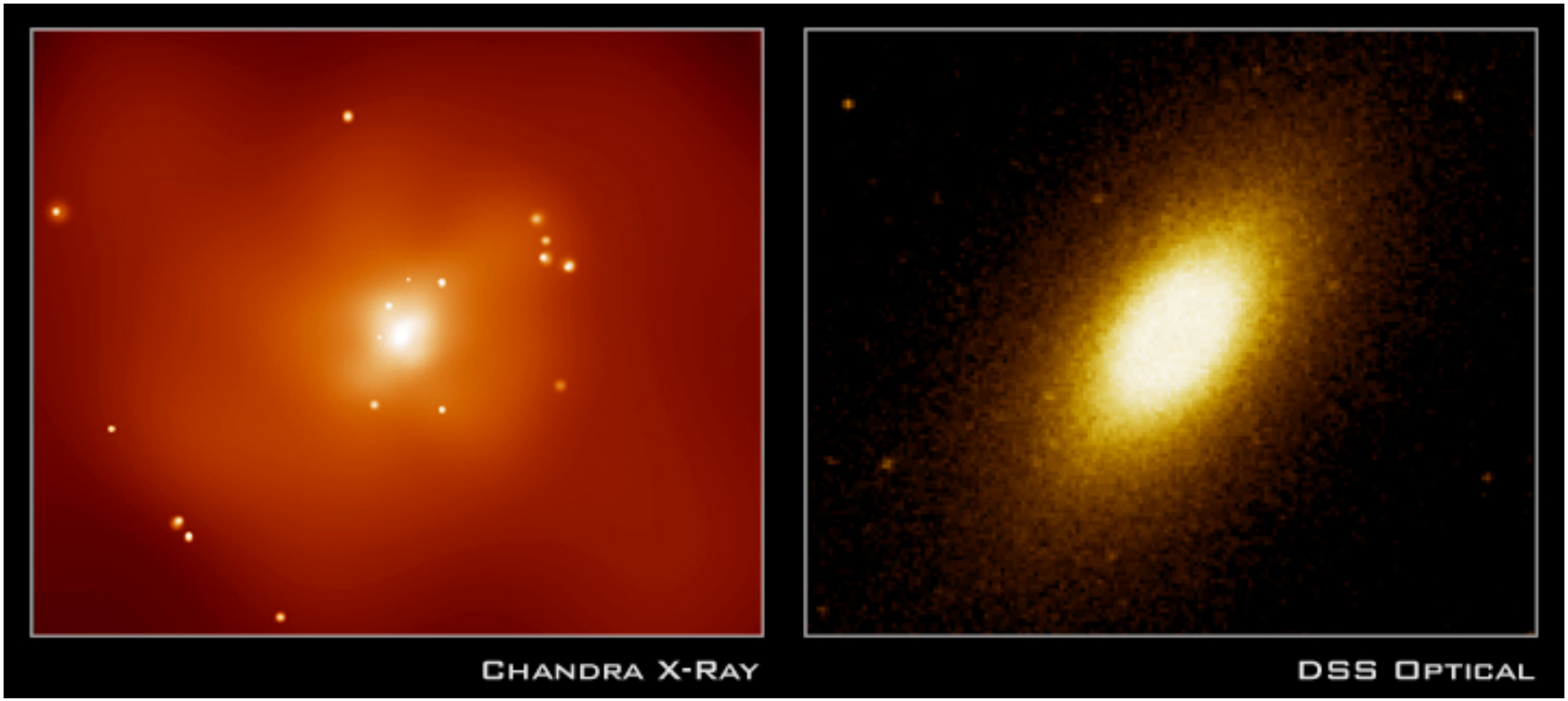
- a ring of light around the head of a holy person in a religious drawing or painting
- a bright circle of light around something

WHAT IS A HALO?

Astronomer's Dictionary:

- ~~a ring of light around the head of a holy person in a religious drawing or painting~~
- faint ellipsoid : around a galaxy

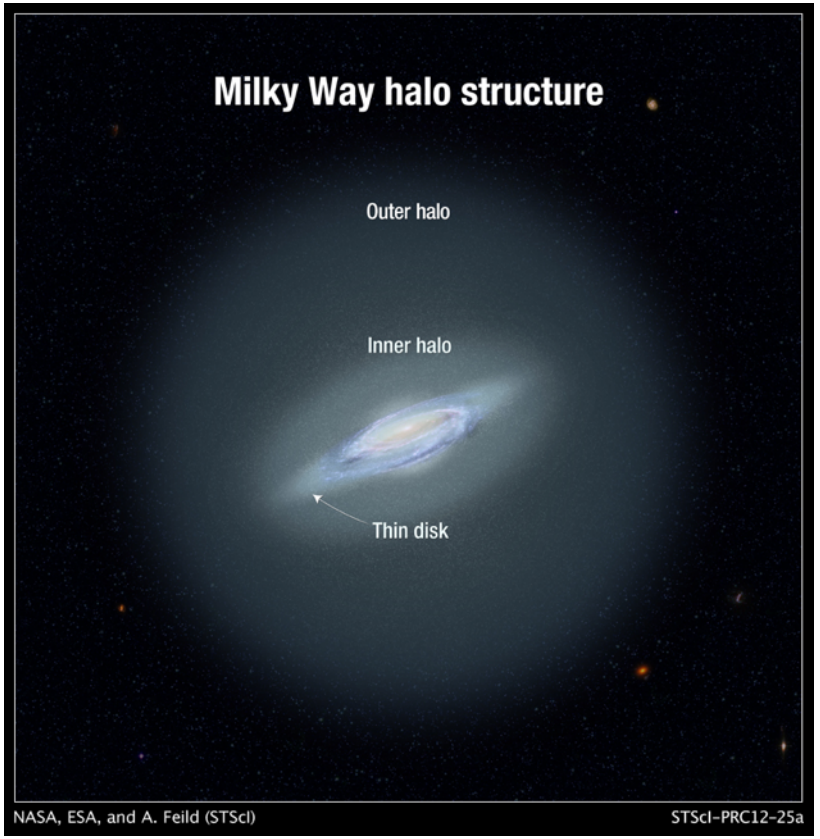
FLAVOURS OF HALOS



Credit: X-ray: NASA/CXC/UCI/D.Buote et al., Optical: DSS U.K.Schmidt Image/STScI

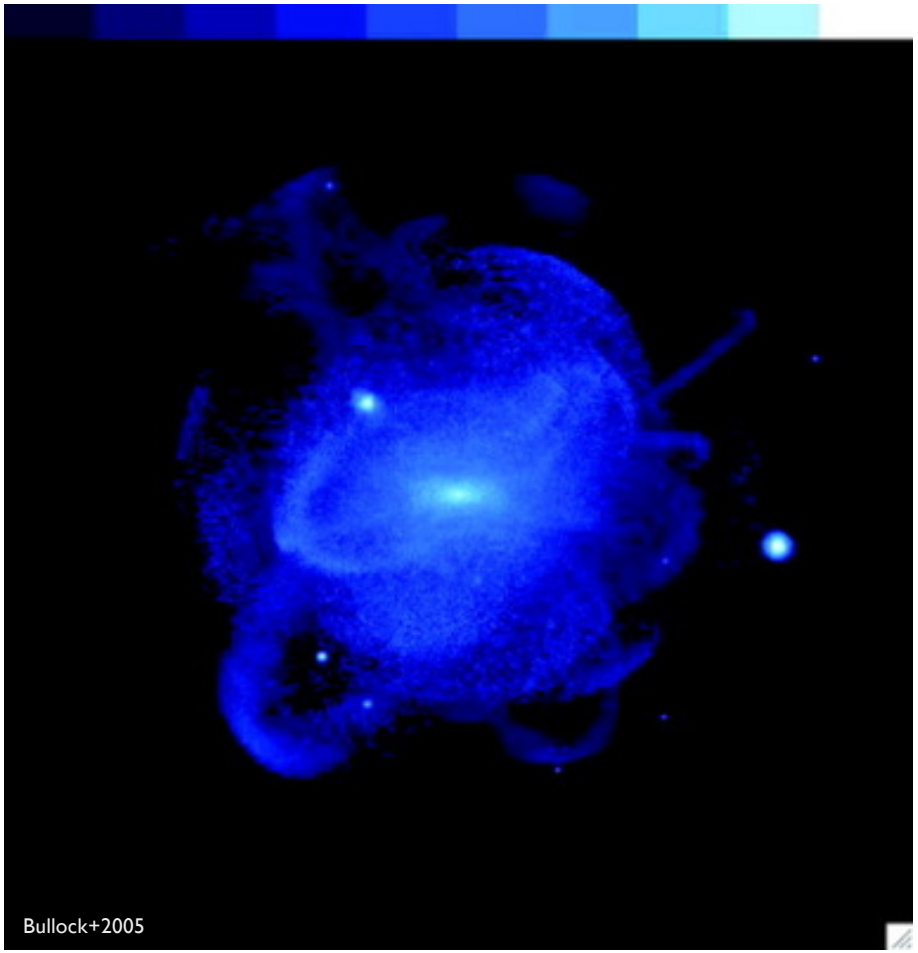
WHAT IS A STELLAR HALO?

- Stars at large distances
- Stars at low surface brightness
- Accreted stars
- Stars not on circular orbits
- …



WHY DO WE CARE?

- Galaxy evolution is a two-phase process
  1. In-situ star formation
  2. Growth through mergers and accretion
- Accretion events → long-lasting signatures in the galaxies' halos
- Low-density structures
- Numerical simulations: majority of the stars in the halo have been accreted
- Probe late stages of galaxy evolution, accretion events and their timescales



Bullock+2005

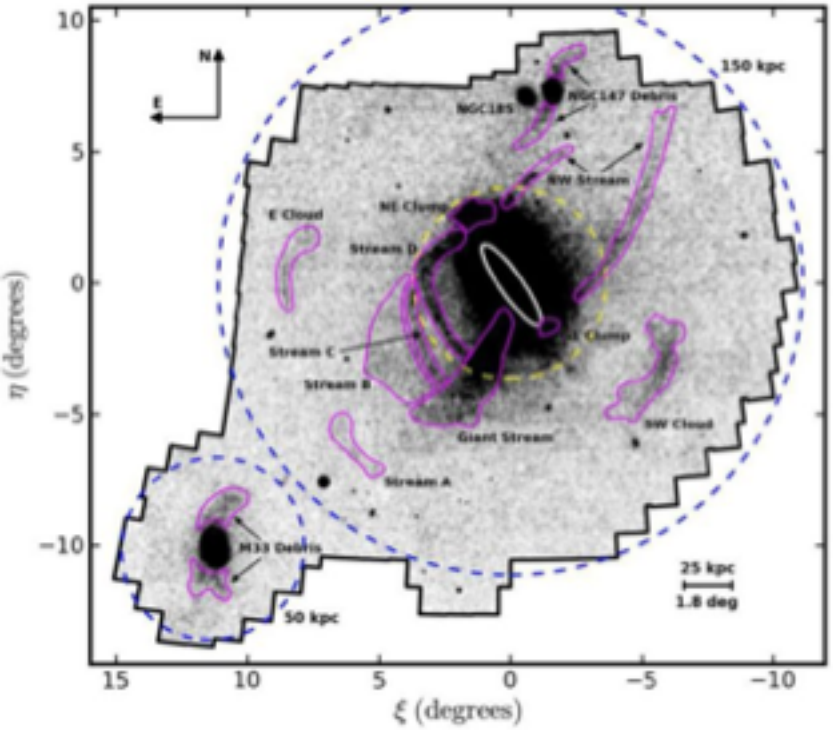
STELLAR HALOS IN OUR BACKYARD:

THE MILKY WAY AND ITS CLOSEST NEIGHBOURS

COURTESY OF CAMILA NAVARRETE

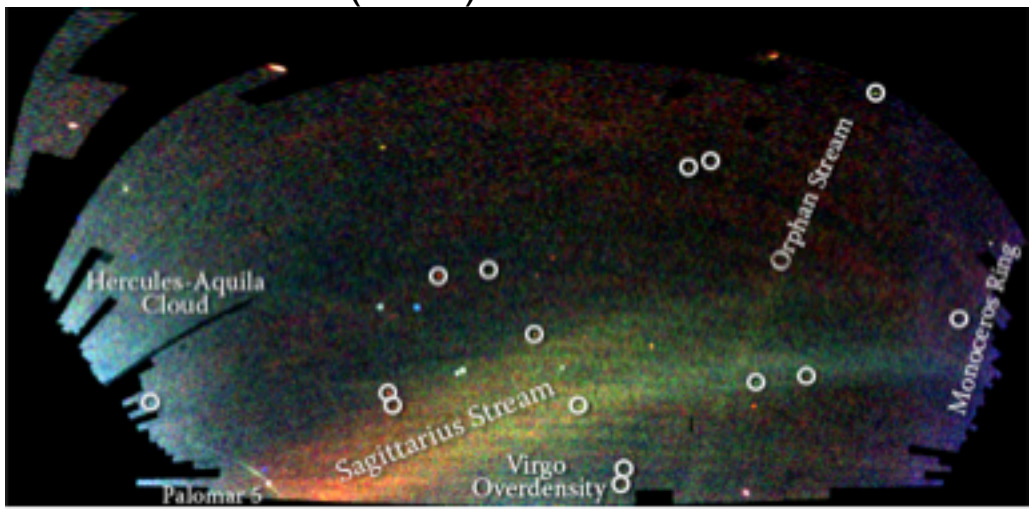
Courtesy of Camila Navarrete

Hierarchical assembly at all scales



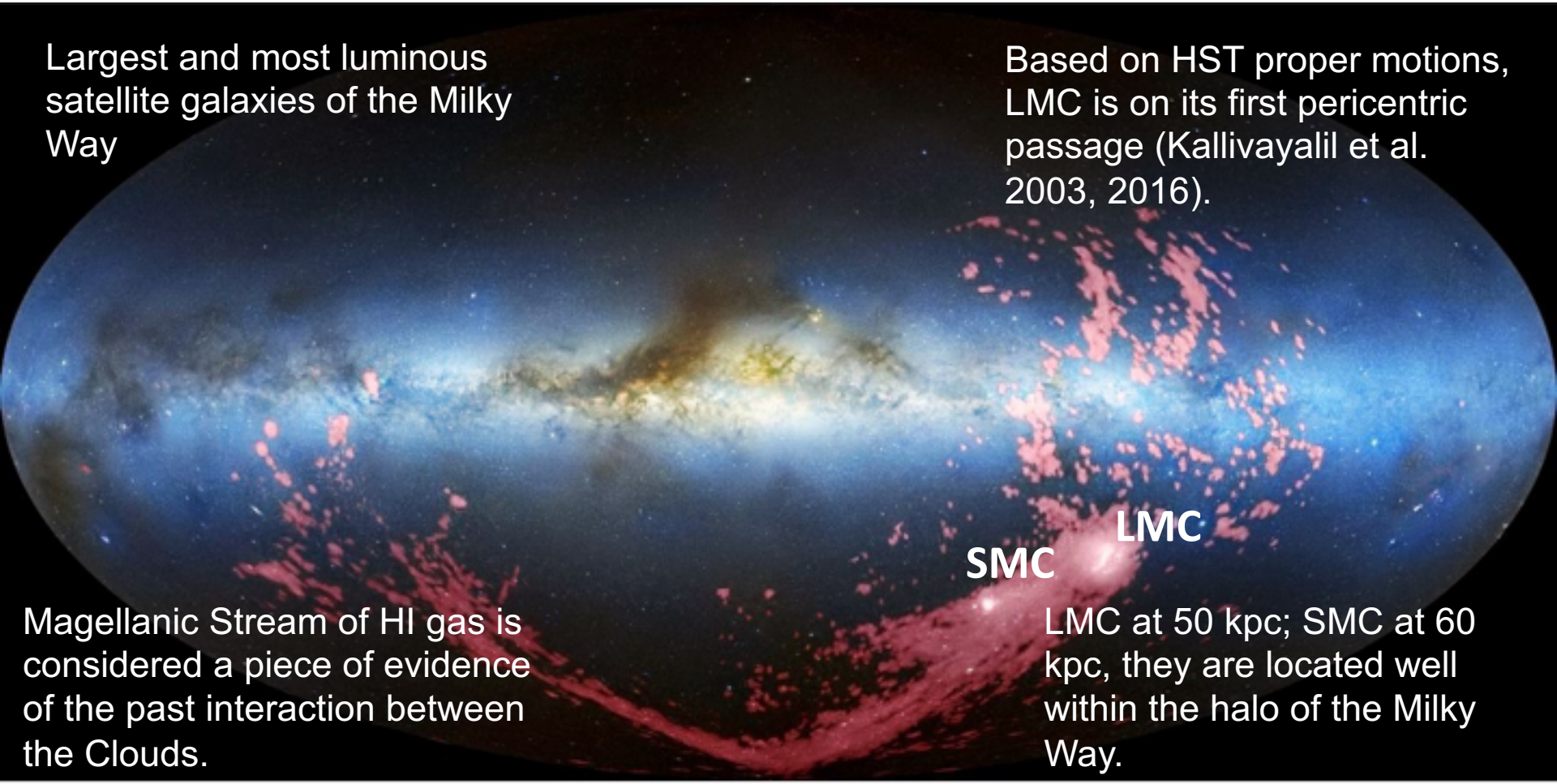
Andromeda ($M \sim 1.5 \times 10^{12}\ M_\odot$)
Ferguson et al. (2016)

Field of streams in the Milky Way ($M \sim 8.0 \times 10^{11}\ M_\odot$)
Belokurov et al. (2006)



Courtesy of Camila Navarrete

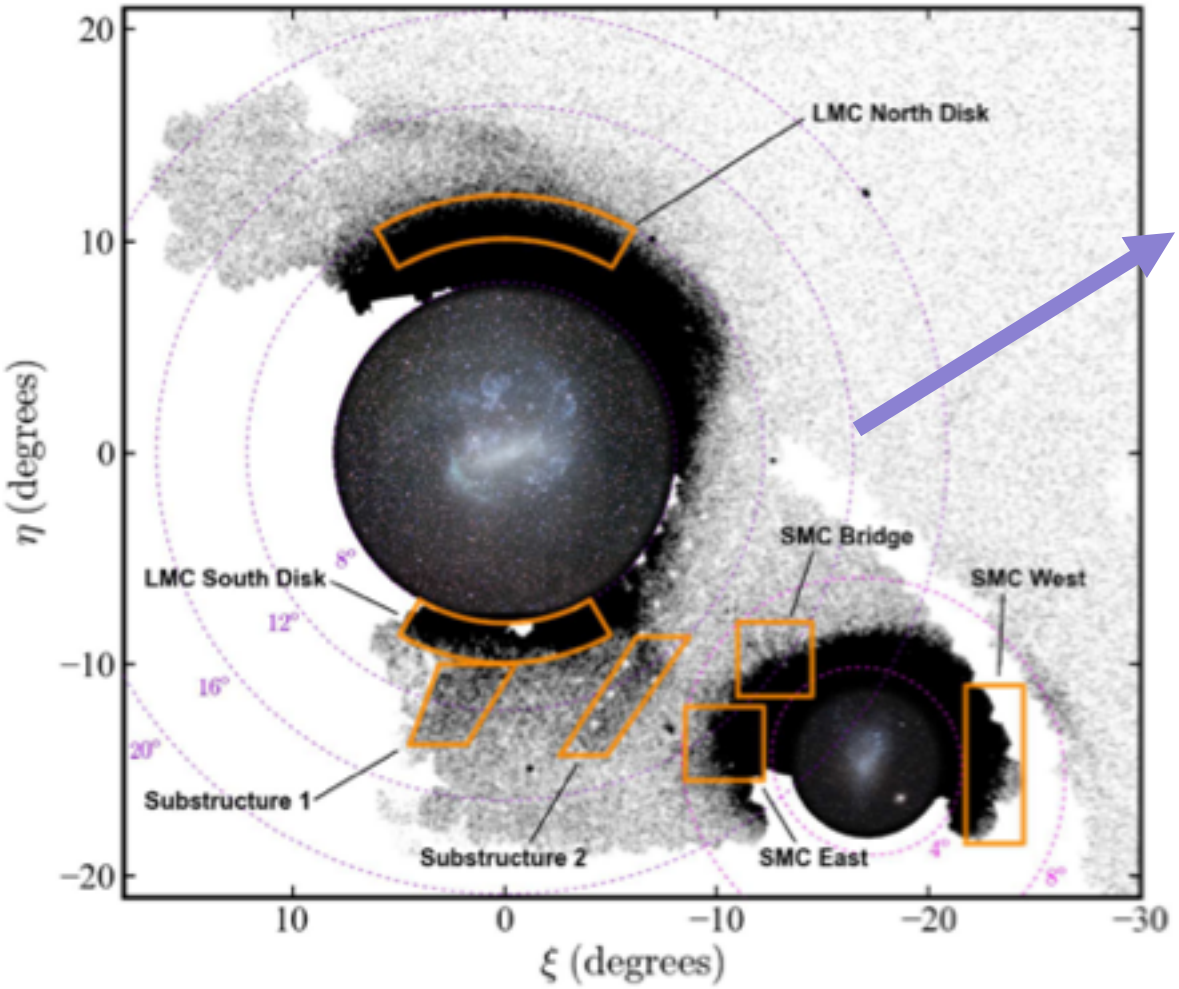
The Magellanic Clouds



Nidever et al. (2010)

Courtesy of Camila Navarrete

LMC OUTER STELLAR POPULATIONS



LMC halo?

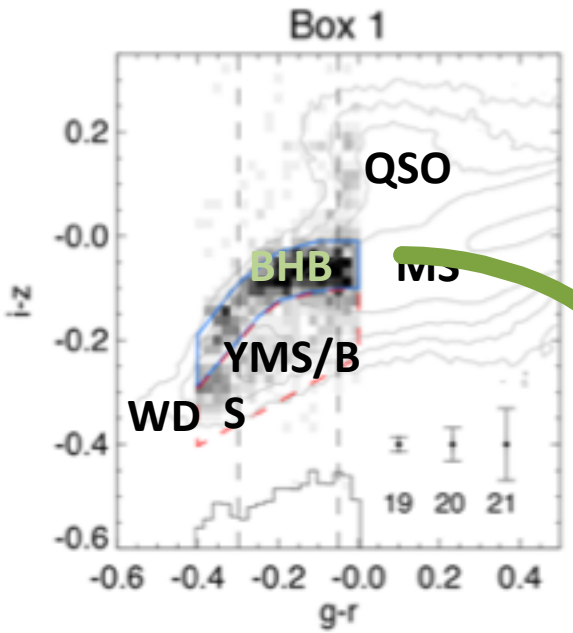
Magellanic stellar streams?

SMC stripped stars?

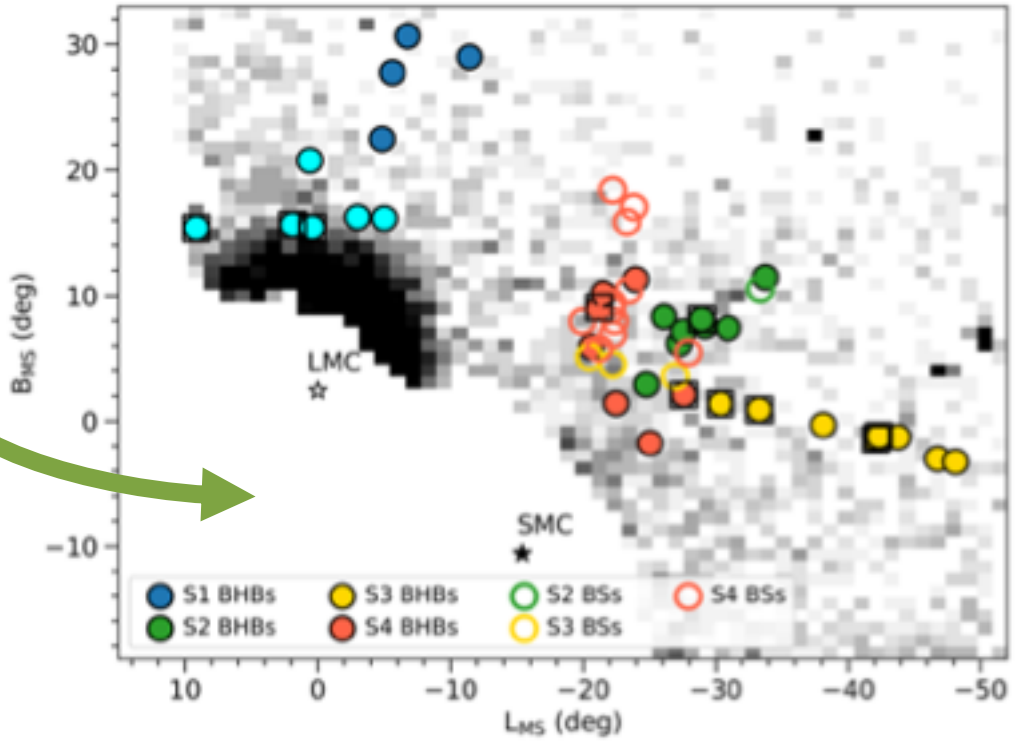
Mackey et al. (2018)

Courtesy of Camila Navarrete

Using Blue Horizontal Branch Stars to trace streams around the Magellanic Clouds



Belokurov & Koposov (2016)

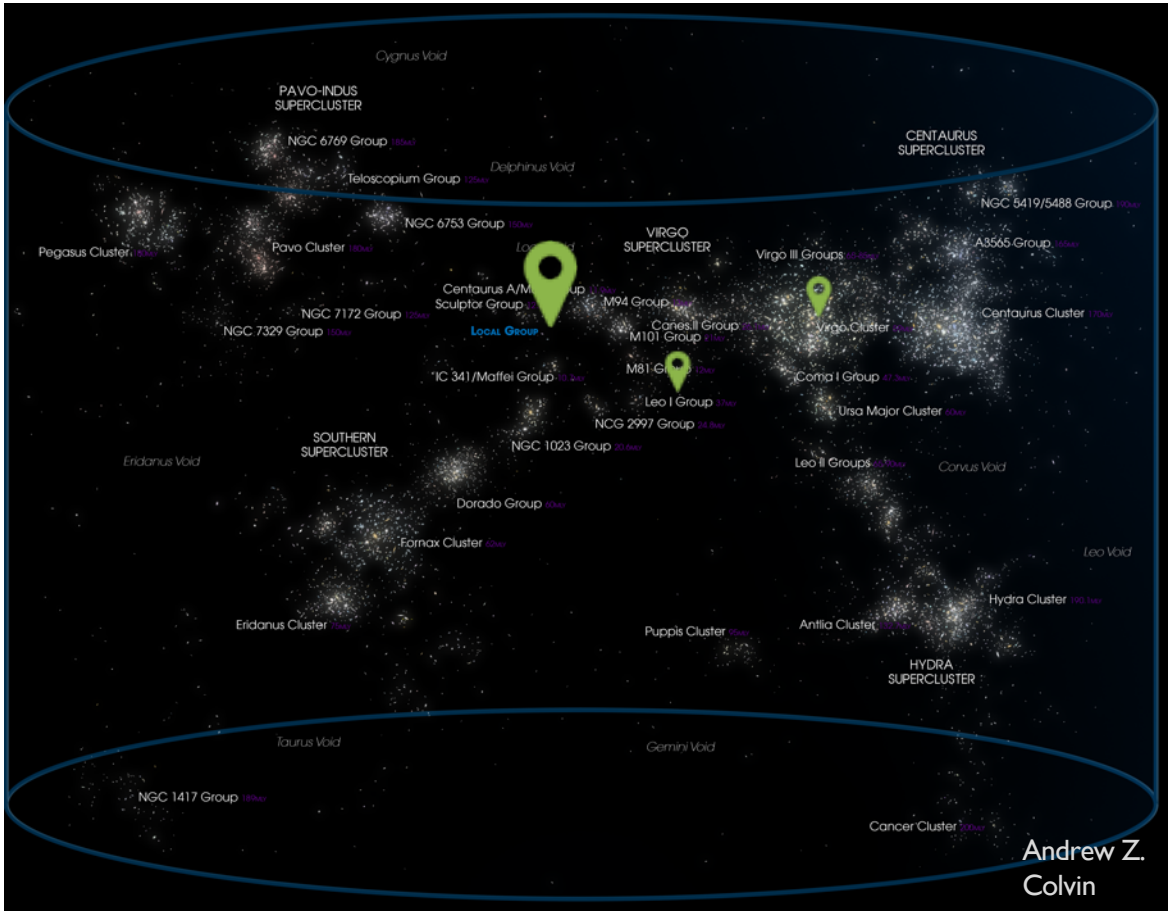


Navarrete et al. (2019)

STELLAR HALOS IN THE LOCAL UNIVERSE:

THE CASE OF M49 IN THE VIRGO CLUSTER

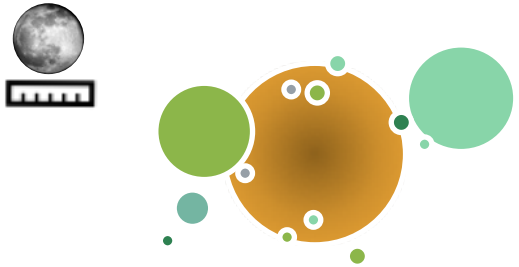
GALAXY GROUPS AND CLUSTERS: WHERE GALAXY-GALAXY INTERACTIONS ARE FREQUENT



THE ISSUE

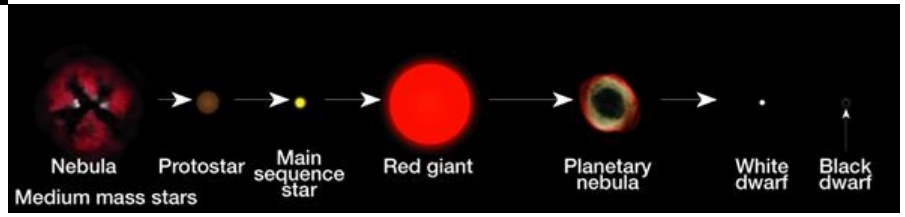
- Galaxies in groups and clusters are distant (> 10 Mpc – 100 Mpc)
- They are too distant to use individual RGB stars as spectroscopic tracers

- Their halos are extended (> 100 kpc) and still big on the sky
- IFU spectroscopy not feasible:
  - would need 900 pointings (1 hour each) with MUSE to map halo of big early-type galaxies in Virgo



USING PLANETARY NEBULAE (PNE) AS TRACERS IN GALAXIES

- Dying asymptotic giant branch stars
- Expanding, ionized gas shell



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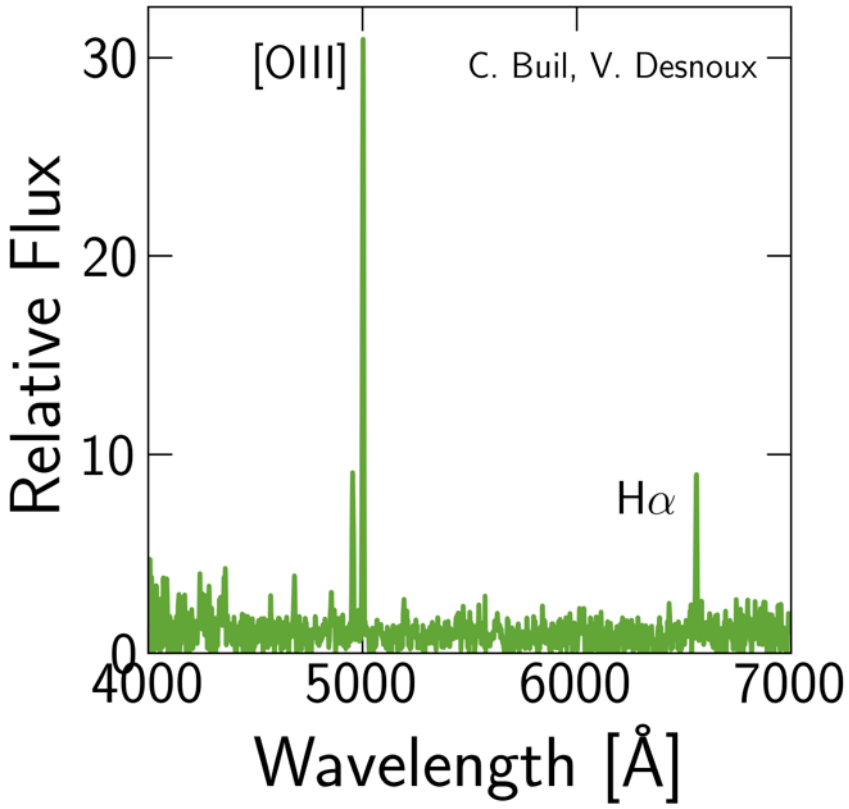
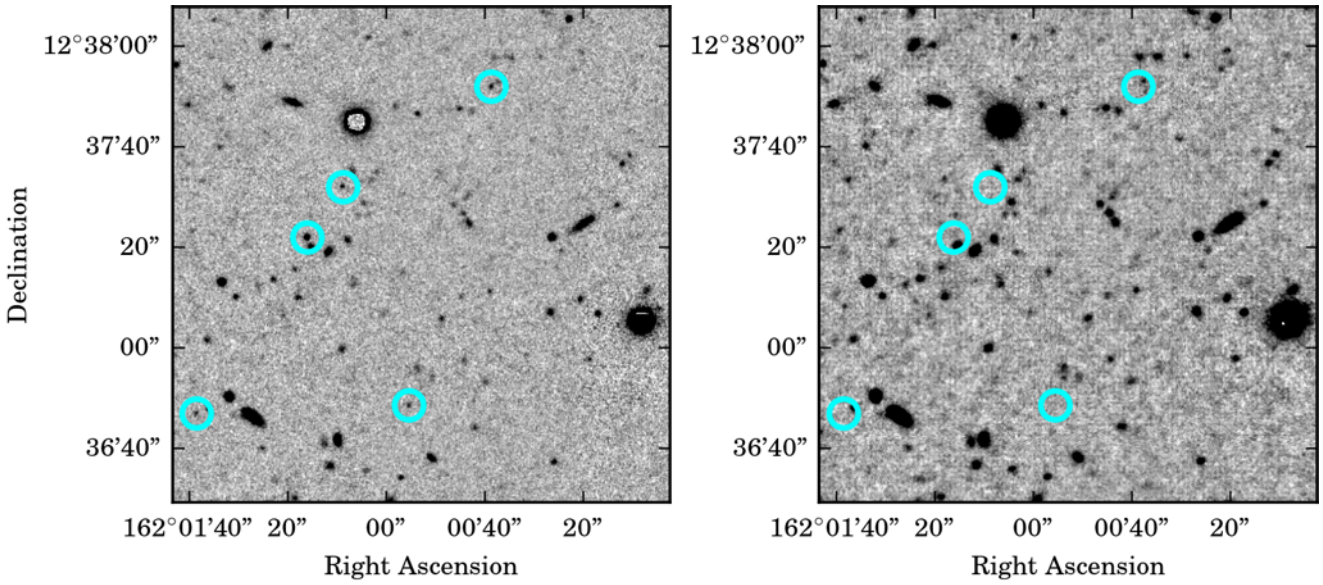


- The [OIII] line emission at 5007Å is the strongest emission from a PN
  - Identification
  - Radial velocities

PNE IDENTIFICATION: ON-OFF TECHNIQUE

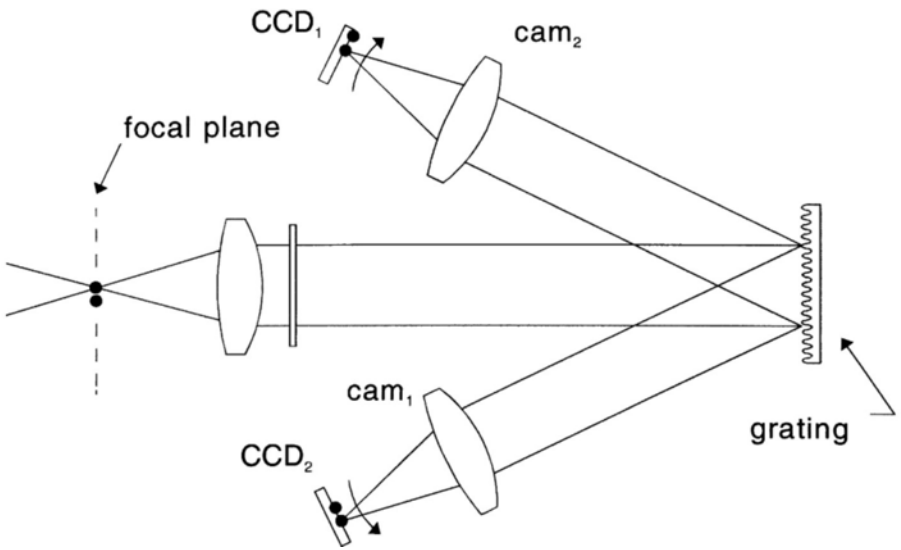
[OIII] narrow-band filter

broad-band *V* filter



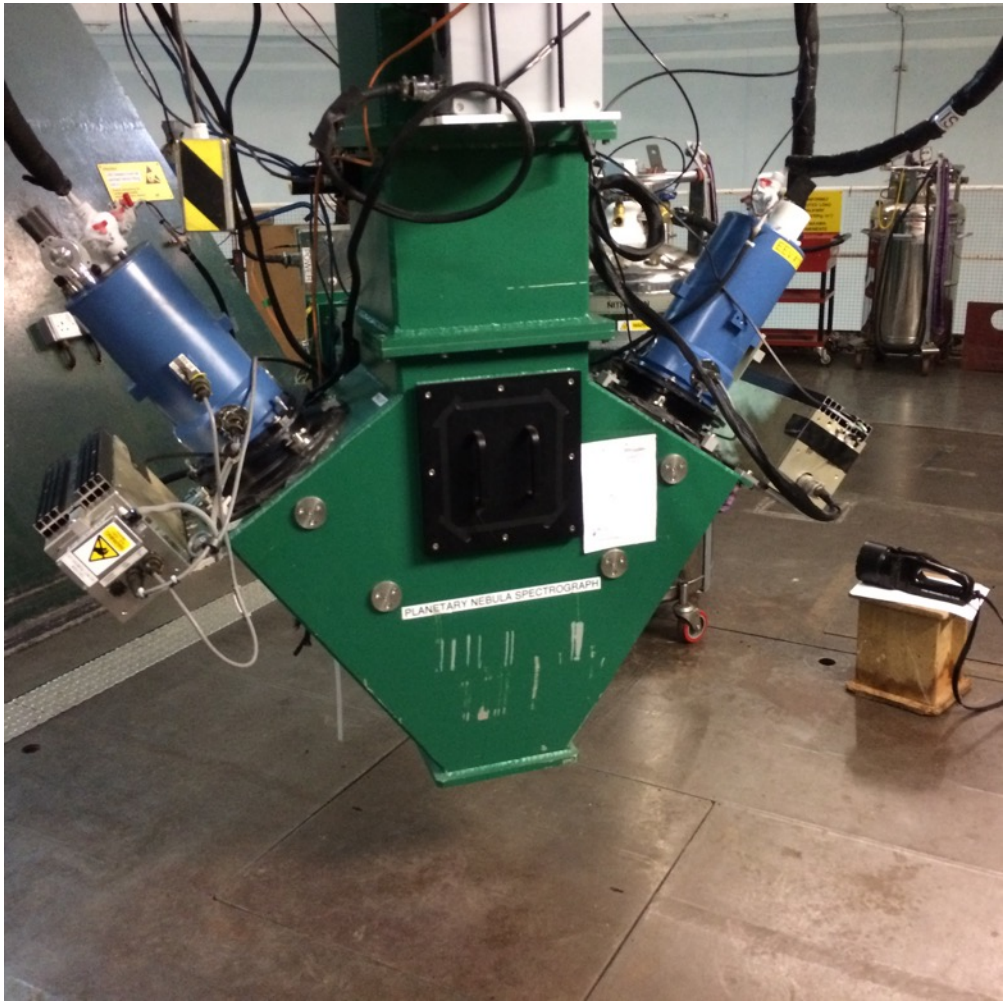
Hartke (2018)

PNE IDENTIFICATION
COUNTER-DISPERSED IMAGING

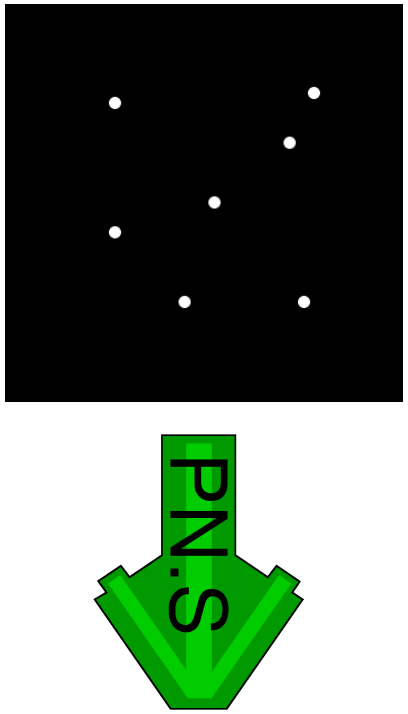


Douglas & Taylor, 1999


4.2m
William-
Herschel
Telescope


PLANETARY NEBULA SPECTROGRAPH

COUNTER-DISPERSED IMAGING



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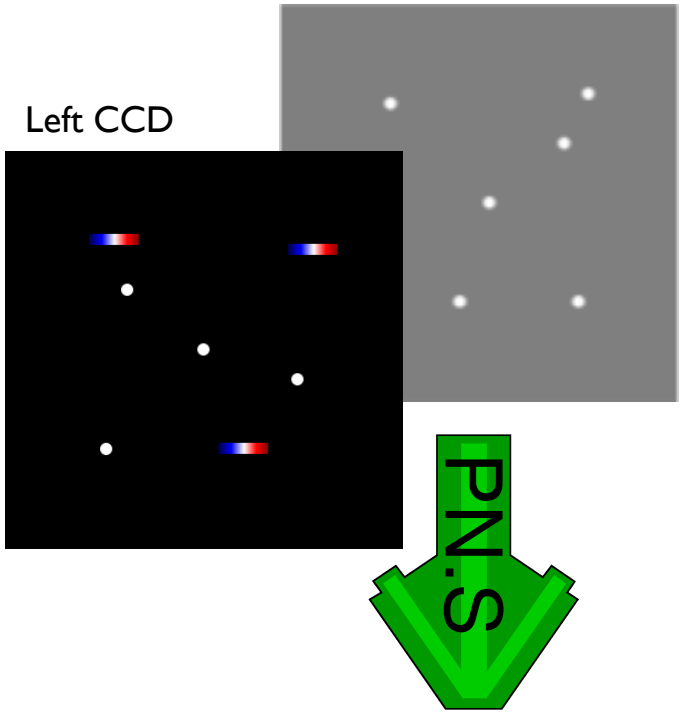

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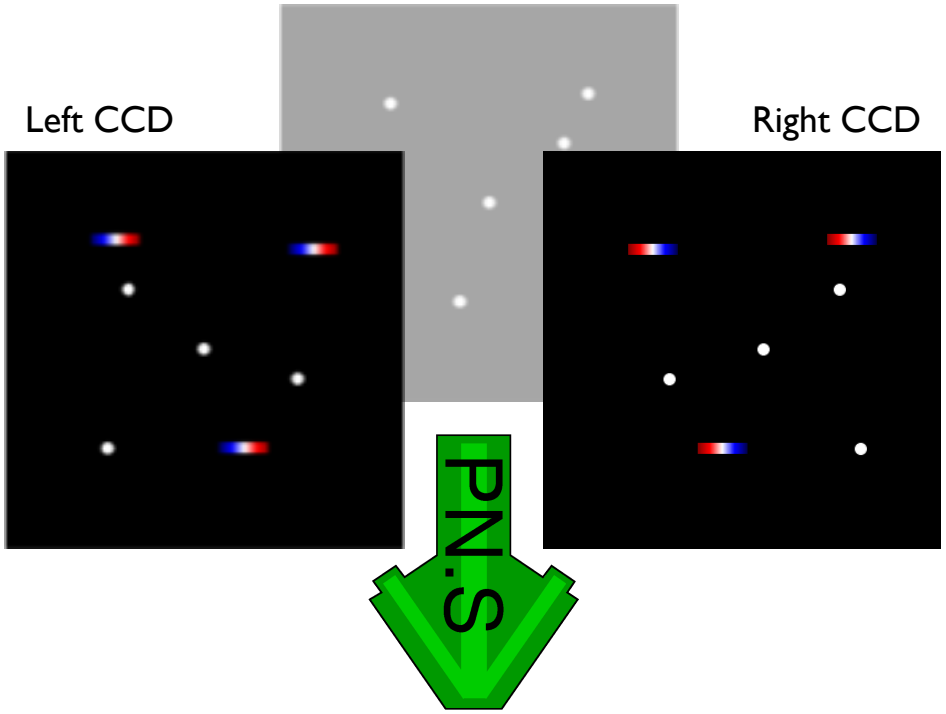

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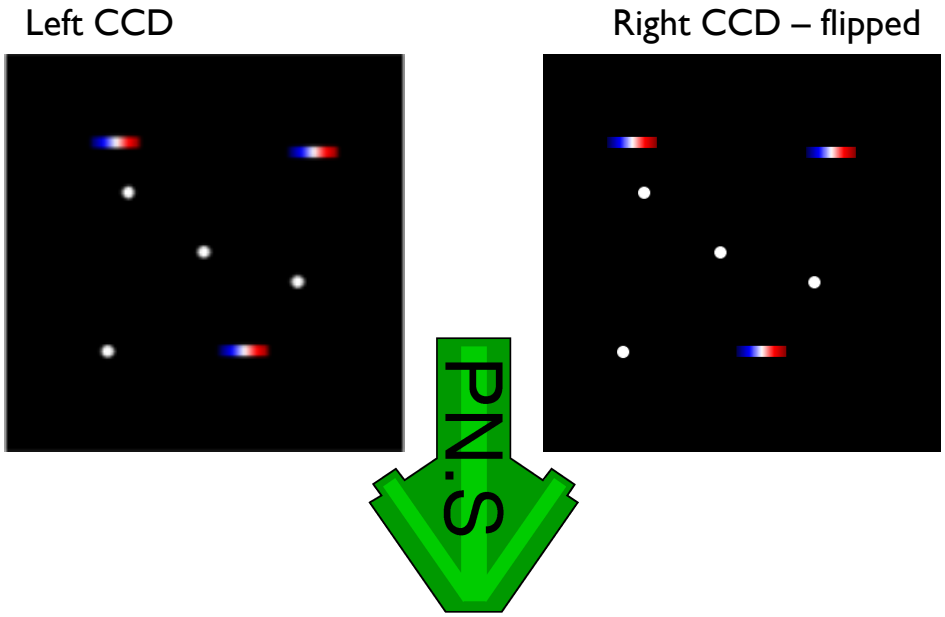

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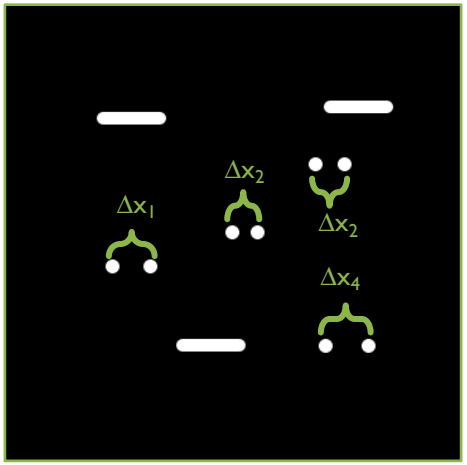
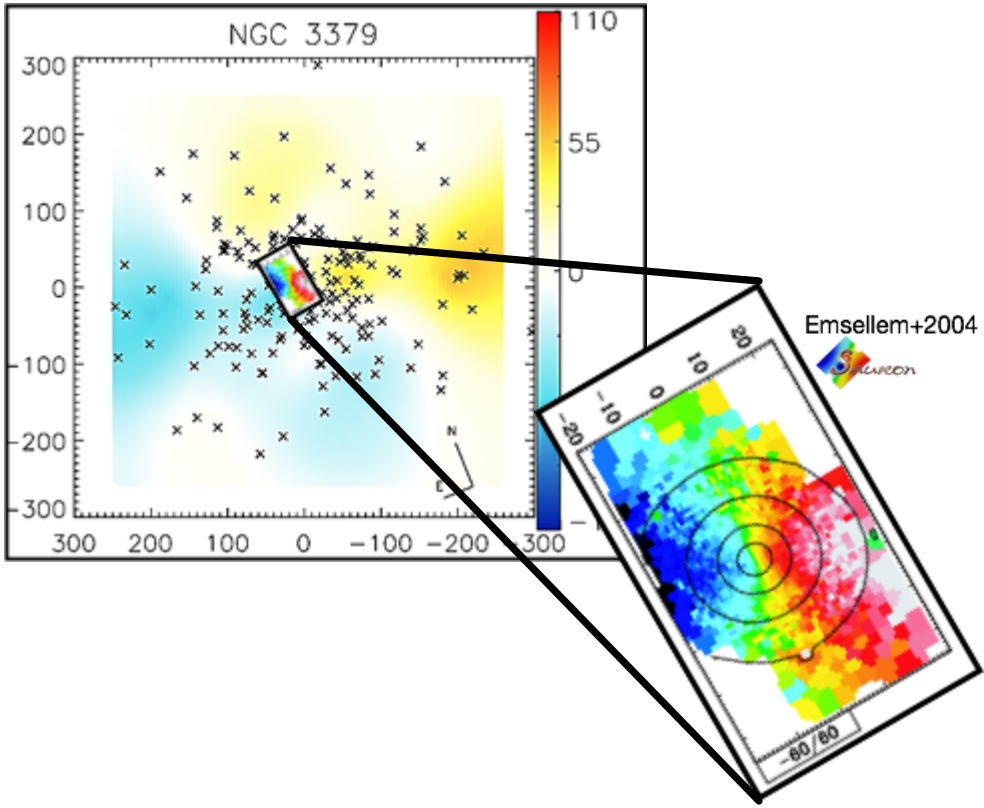


The distance Δx between the PNe on the two images is linearly related with their line-of-sight velocity.

THE EXTENDED PN.S EARLY-TYPE GALAXY SURVEY (EPN.S)

Pulsoni+2018, A&A 618, 94
PI: Arnaboldi

- 2-phase formation scenario of early-type galaxies
- Probe transition from central regions to galaxy halos
- Survey of 33 nearby early-type galaxies
- Radial extent between 3 and 13 effective radii



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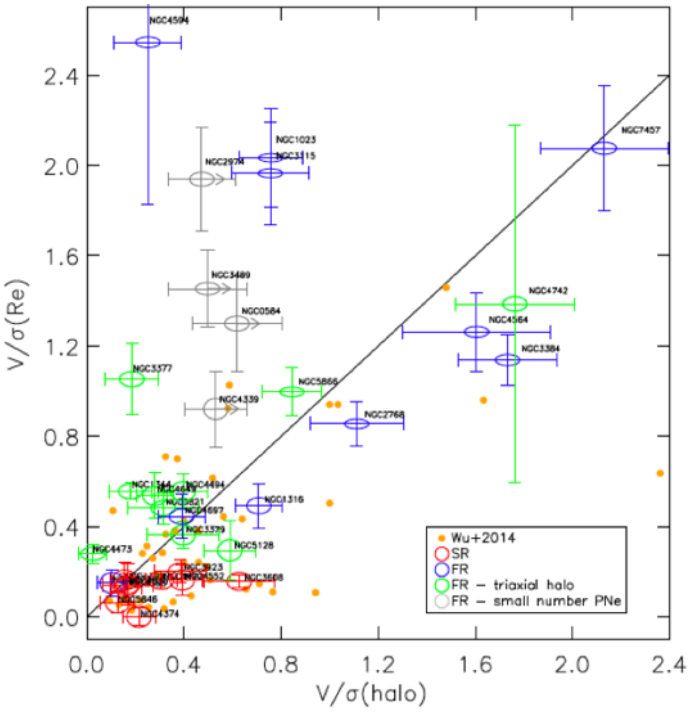

ETG halos have more diverse kinematic properties than their central regions:

Slow Rotators: onset of rotation in the halo

Fast Rotators:

- 70% with slowly rotating outer spheroid
- 30% rapidly rotating at large radii (extended disk component or rapidly rotating outer spheroid)
- 40% ePN.S fast rotators with evidence of triaxial halo, consistent with presence of photometric twists

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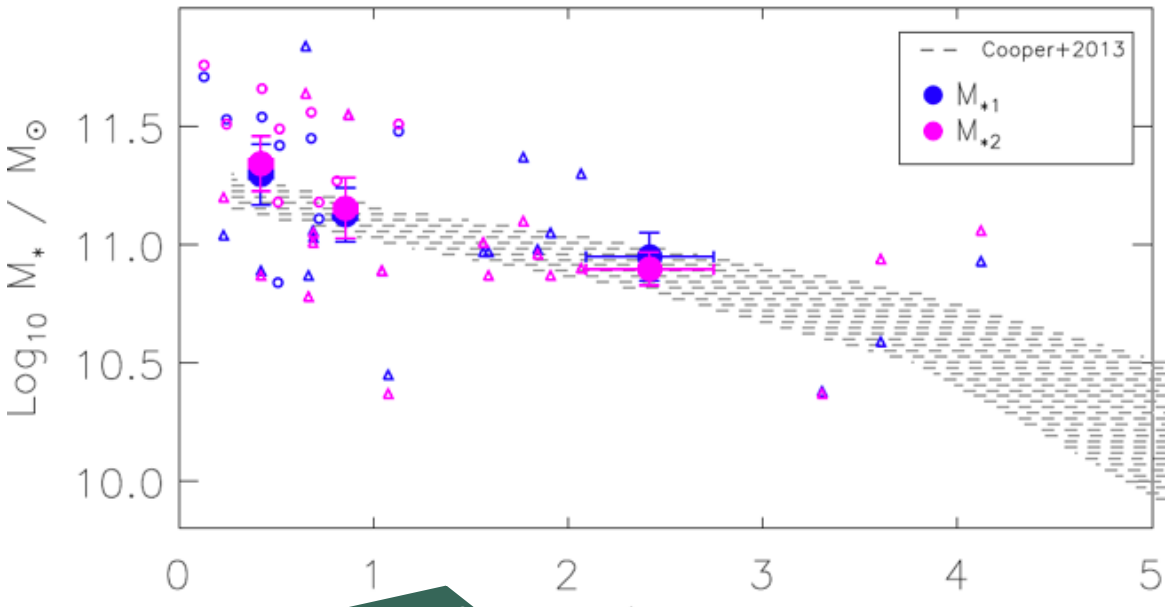

kinematics change from central regions to the halos

THE EXTENDED PN.S EARLY-TYPE GALAXY SURVEY (EPN.S)

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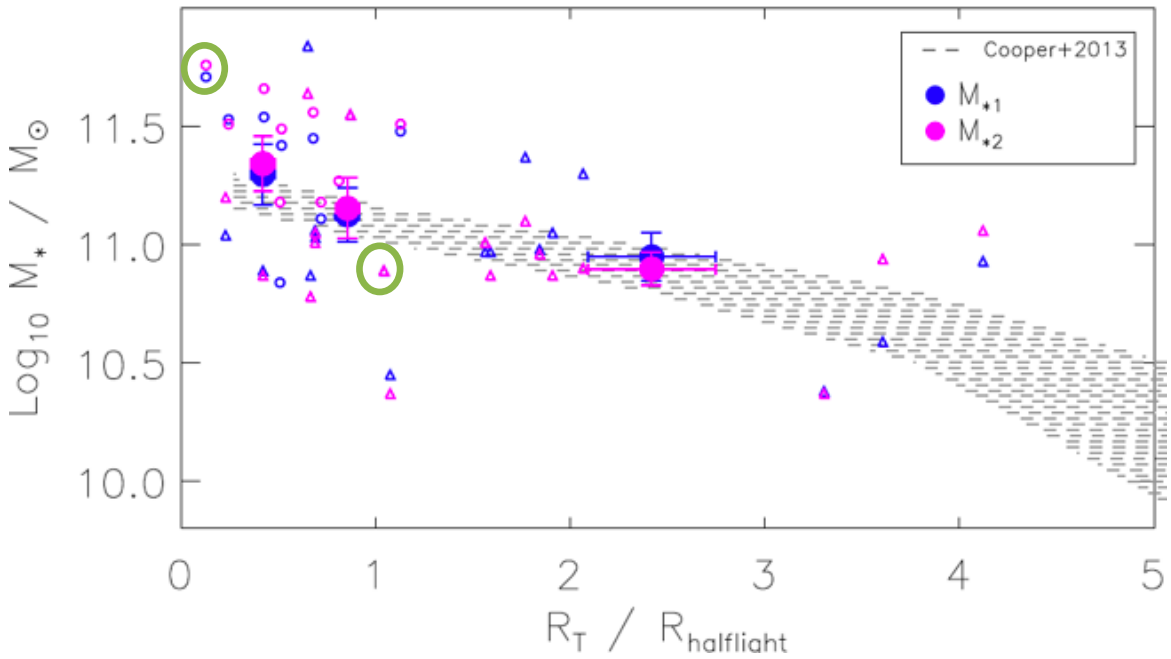
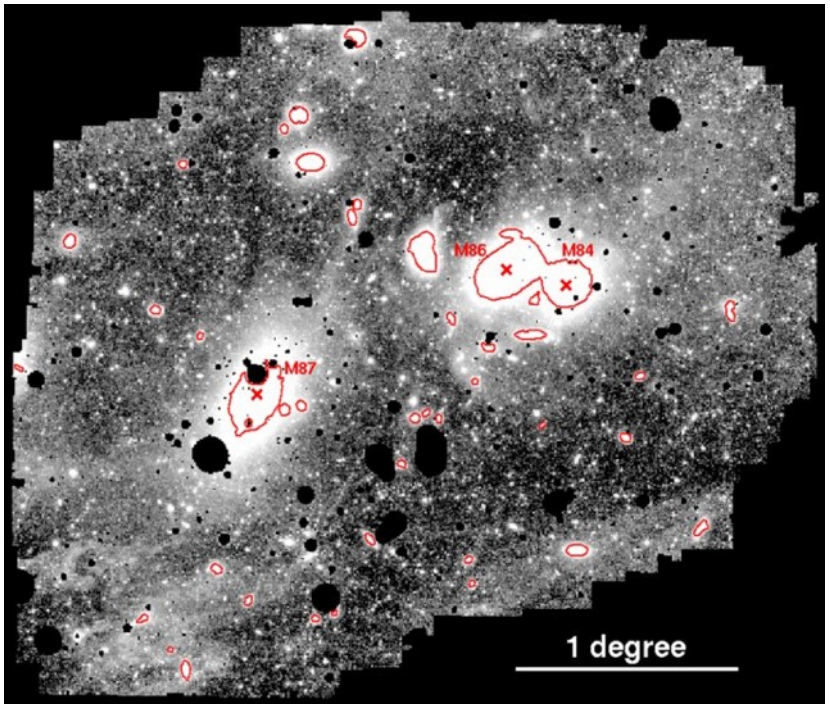


- Detailed study of two early-type galaxies in group and cluster environments:
  - M49 (NGC 4472)
  - M105 (NGC 3379)

M49 IN THE VIRGO CLUSTER

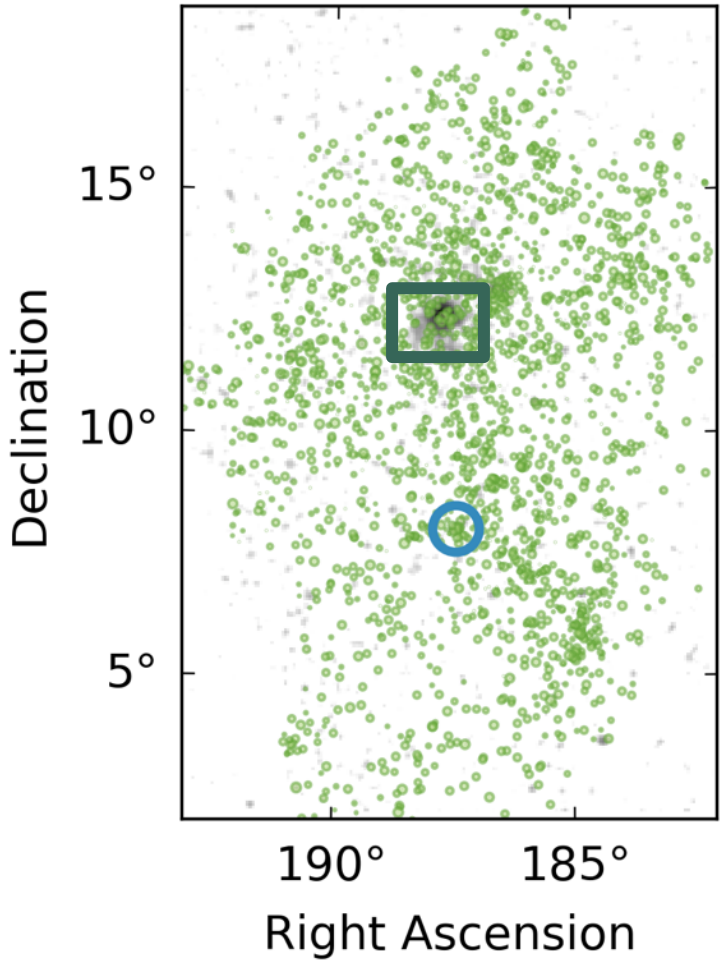
DIFFUSE LIGHT BEYOND STELLAR HALOS

- In larger-scale structure (clusters and groups) more complex situation: Intracluster and Intragroup light
  - Diffuse starlight that fills the space between galaxies in clusters/groups
  - Tidal debris from merging galaxies



Data from BSDVS

CLUSTER ENVIRONMENTS ARE DYNAMICALLY RICH

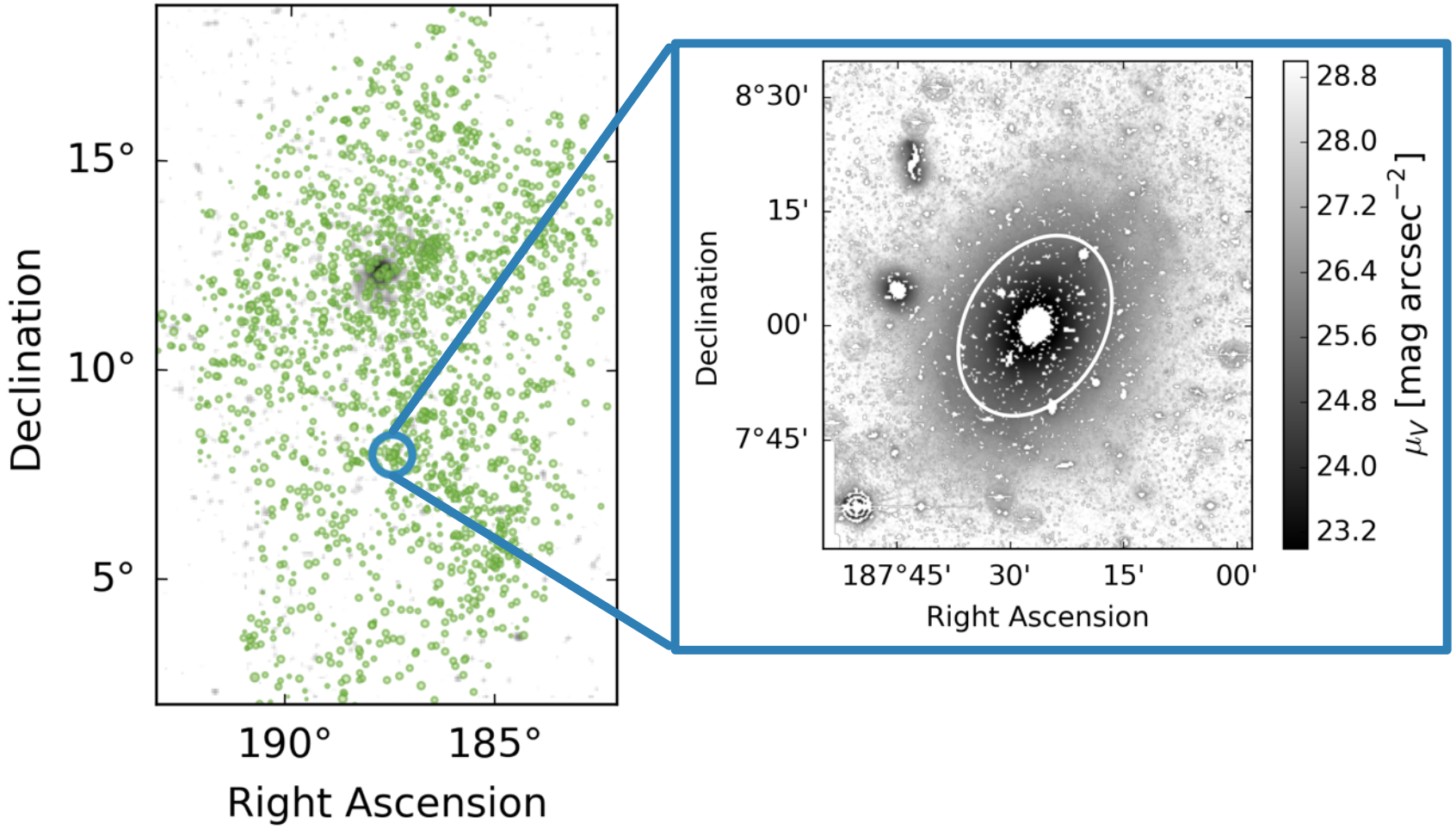


Virgo Cluster

- nearest cluster to the Local Group
- at 16.5 Mpc distance
- 1300+ member galaxies
- 3 subclusters

Data from VCC, RASS, BSDVS

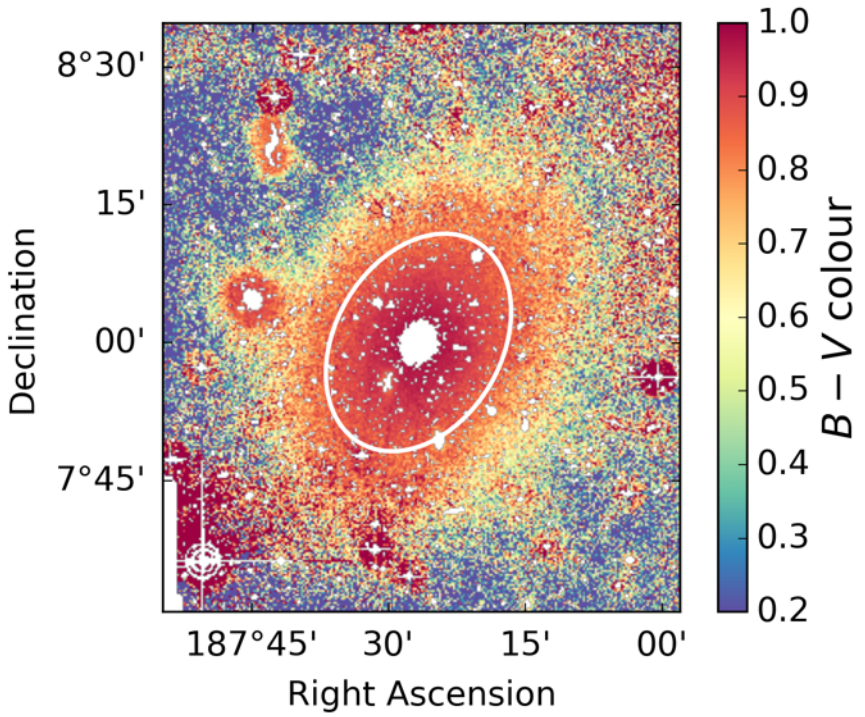
M49 AT THE HEART OF VIRGO'S SUBCLUSTER B



Data from VCC, RASS, BSDVS

M49 AND ITS BLUE ENVIRONMENT

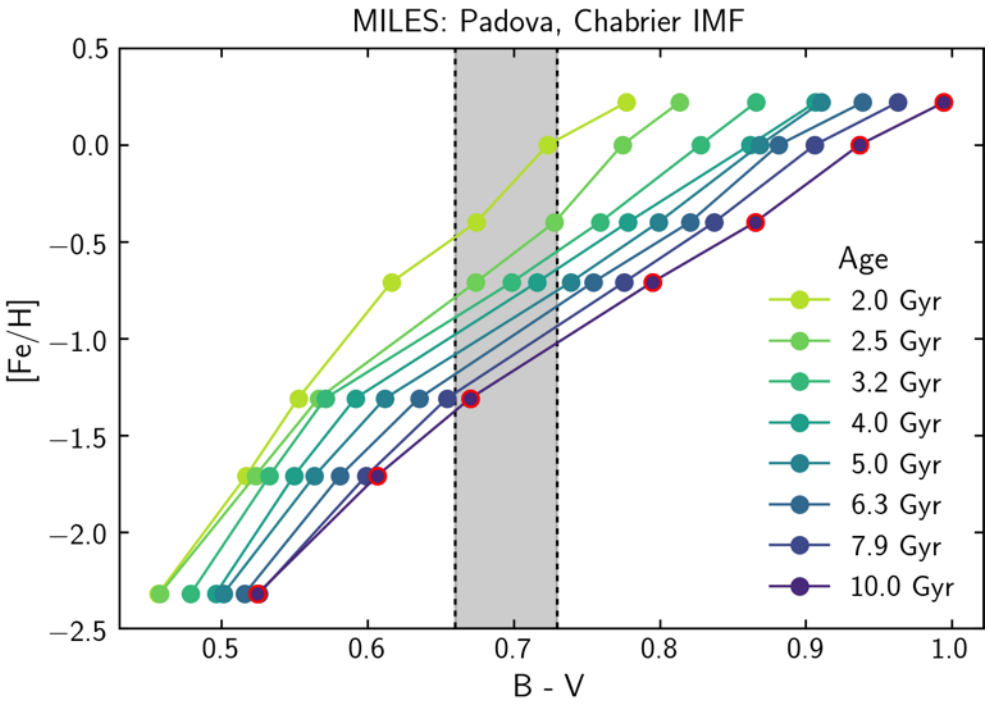
- Brightest elliptical galaxy in the Virgo cluster (subcluster B)
- Very extended stellar halo
- Signatures of past accretion: layered system
- Ongoing satellite accretion
- Blue color gradient towards the outer halo: B - V < 0.6 (Mihos+2013, 2017)
- **What are the progenitors that have built this envelope?**



Data from BSDVS

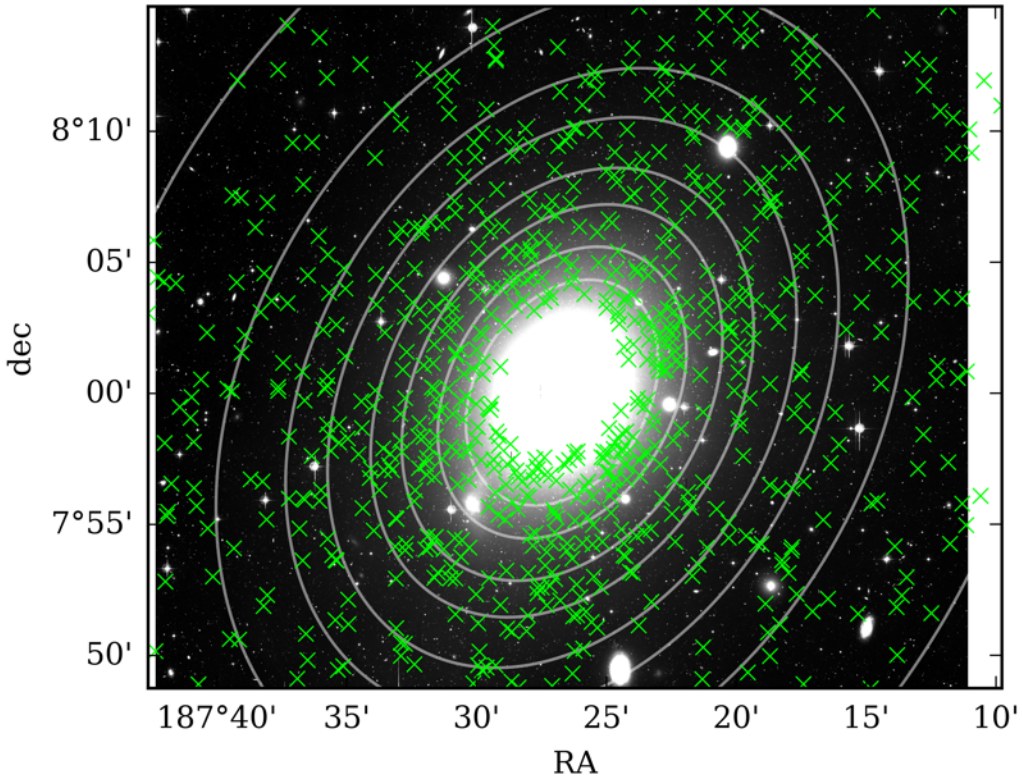
WHAT ARE THE PROGENITORS OF THE OUTER BLUE HALO?

- Age-metallicity degeneracy:
  - Age < 2 Gyr: recent merger with massive star-forming galaxy
    - BUT: recent merger should be visible in photometry
  - Metallicity [Fe/H] < -1:
    - Mass-metallicity relation (Tremonti et al., 2004) → $M_* = 10^9\ M_\odot$
    - Merger-mass ratio 10^{-3}
    - BUT: cosmological simulations predict mass-merger ratios of 1:5
  - Need to assess dynamics of the halo



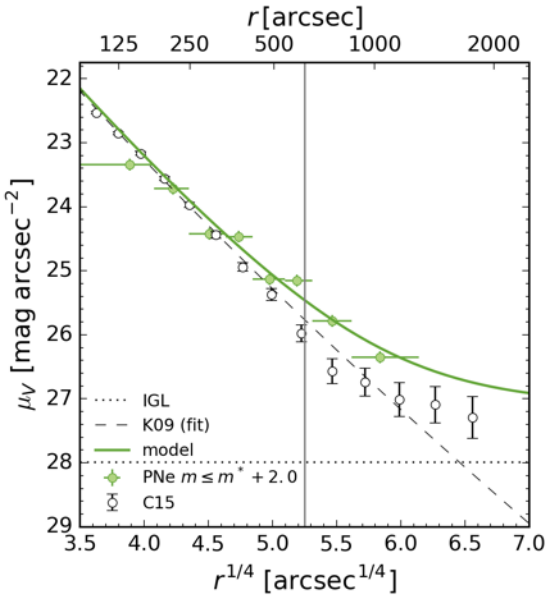
THE PN-SAMPLE IN M49

Hartke+2017, *A&A*, 603:A104



TRACING STELLAR LIGHT WITH THE PN NUMBER DENSITY

Hartke+2017, *A&A*, 603:A104

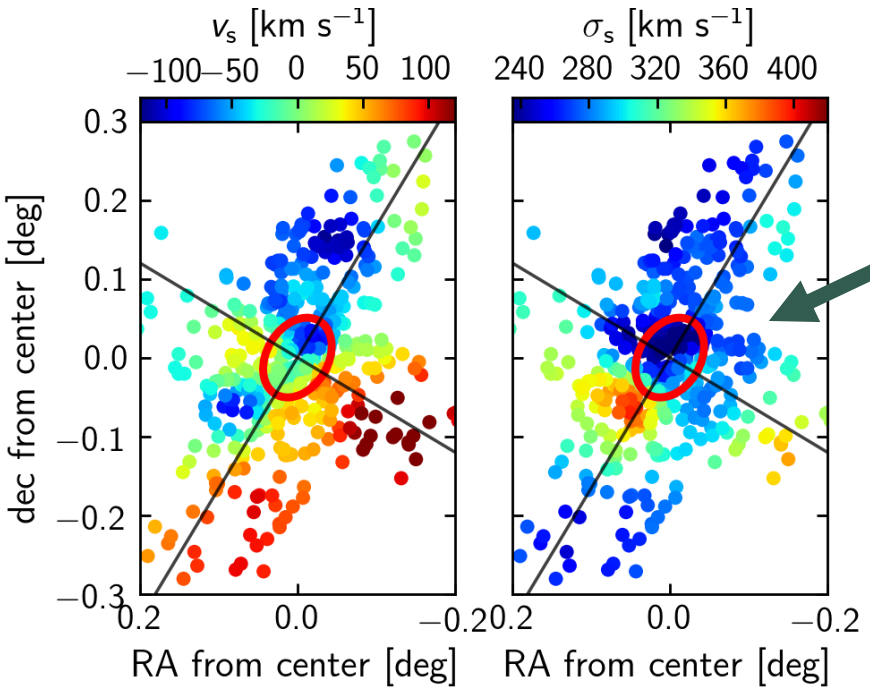


- Kormendy+2009: main galaxy follows Sérsic profile
- Capaccioli+2015: flattening in outer halo
- PN number density follows stellar light, but flatten earlier
- Two component model:
  - Sérsic
  - Flat, constant SB component

3x higher PN-yield in outer halo → different parent stellar population

M49'S KINEMATICS

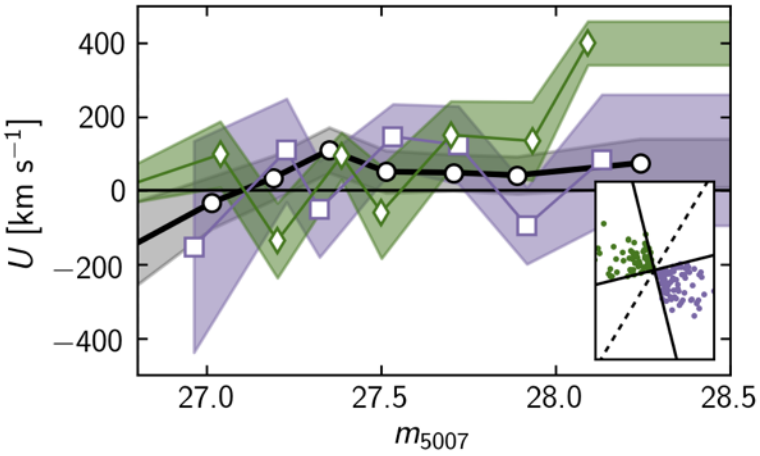
Hartke+2018, *A&A*, 616:A123

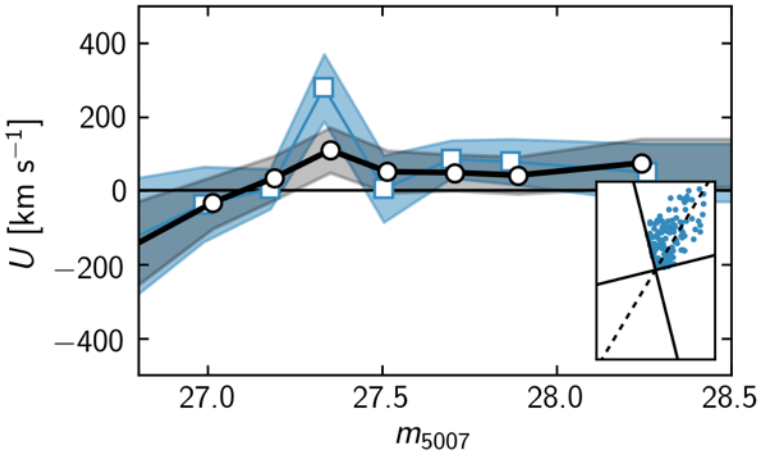


This is pretty messy for a big early-type galaxy!

Hartke+2018, *A&A*, 616:A123

HOW ADDITIONAL PHOTOMETRY CAN HELP US





Hartke+2018, *A&A*, 616:A123

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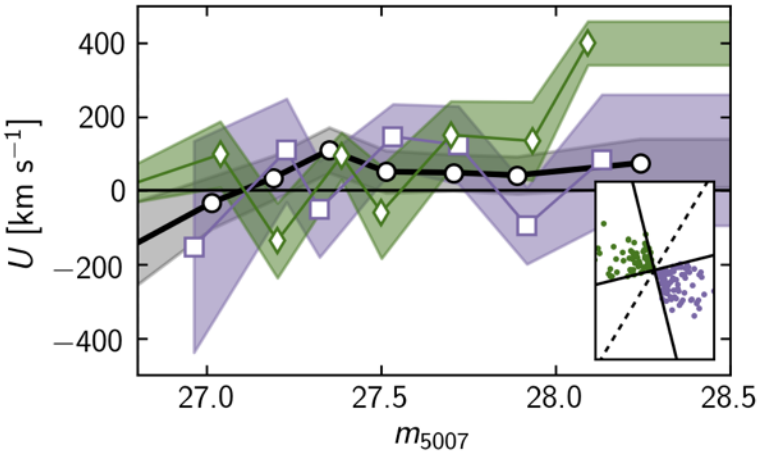
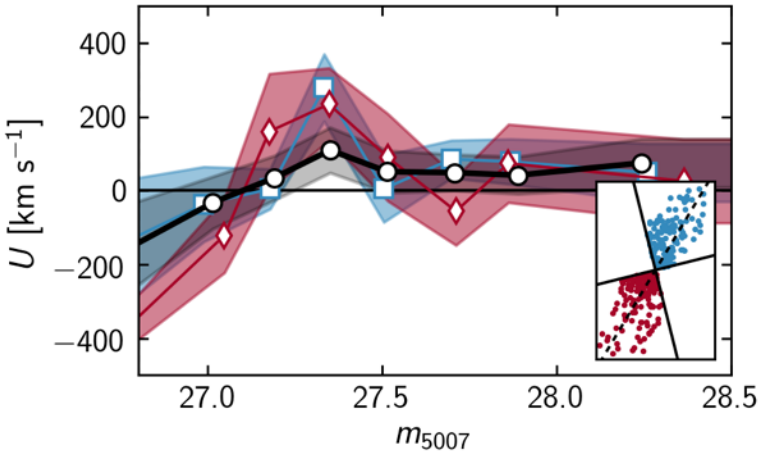
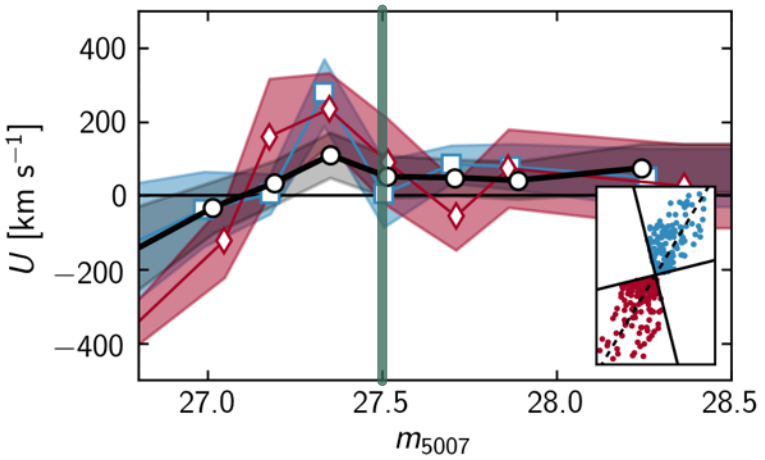




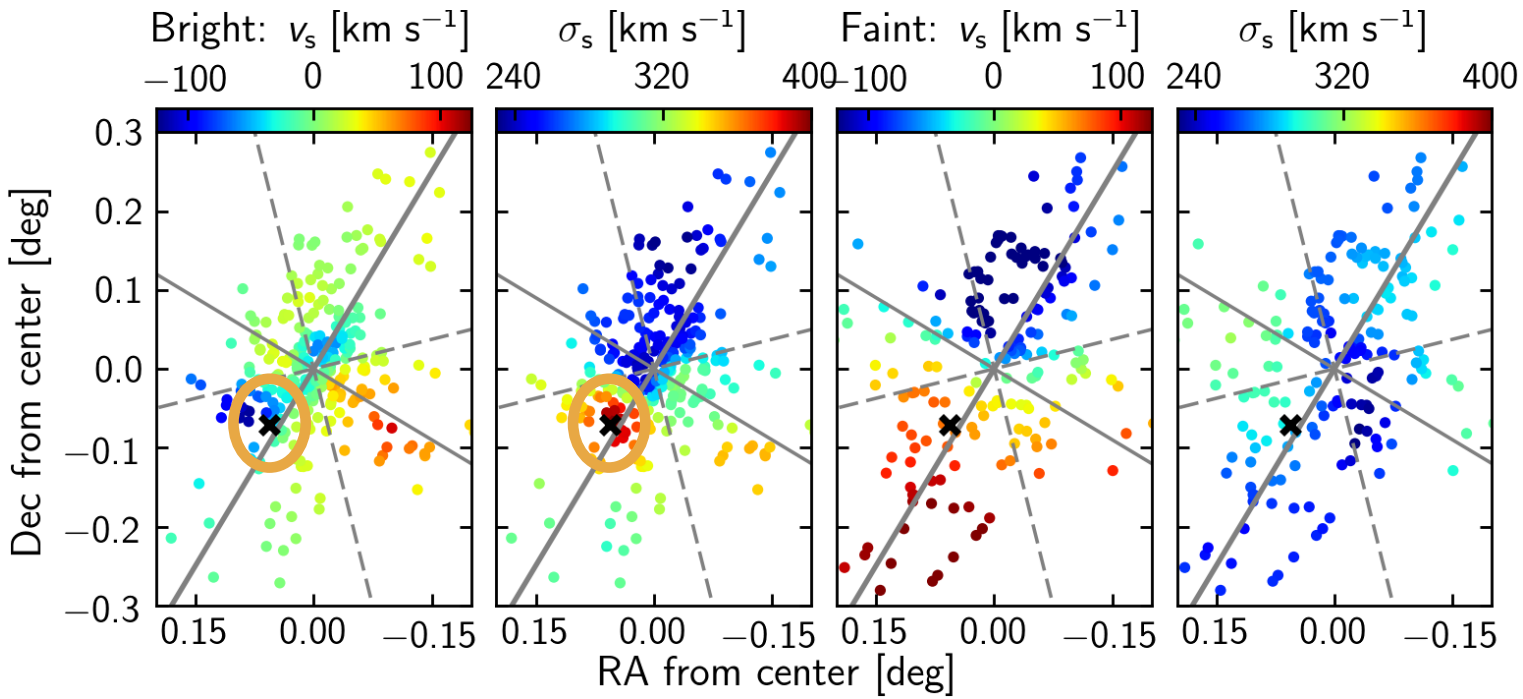
HOW ADDITIONAL PHOTOMETRY CAN HELP US

- Excess of **bright** planetary nebulae that co-rotate
- Divide the sample in bright and faint components

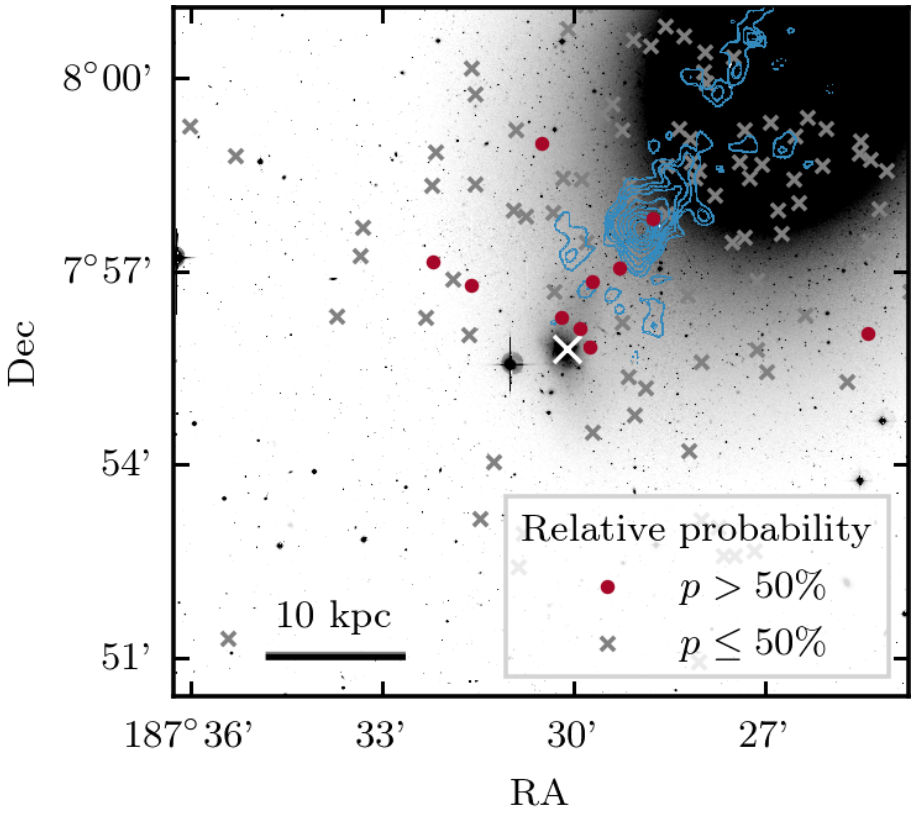


Hartke+2018, *A&A*, 616:A123

MULTIPLE PN POPULATIONS



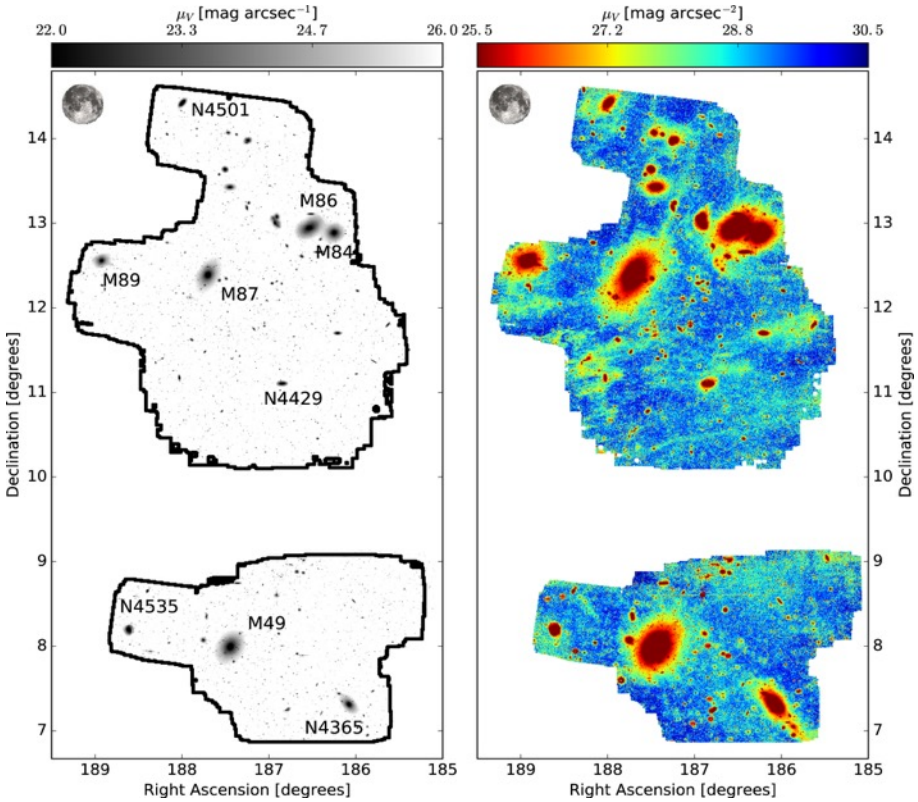
ACCRETION OF VCC 1249



Hartke+2018, *A&A*, 616:A123

EXTENDED HALO OR INTRAGROUP LIGHT?

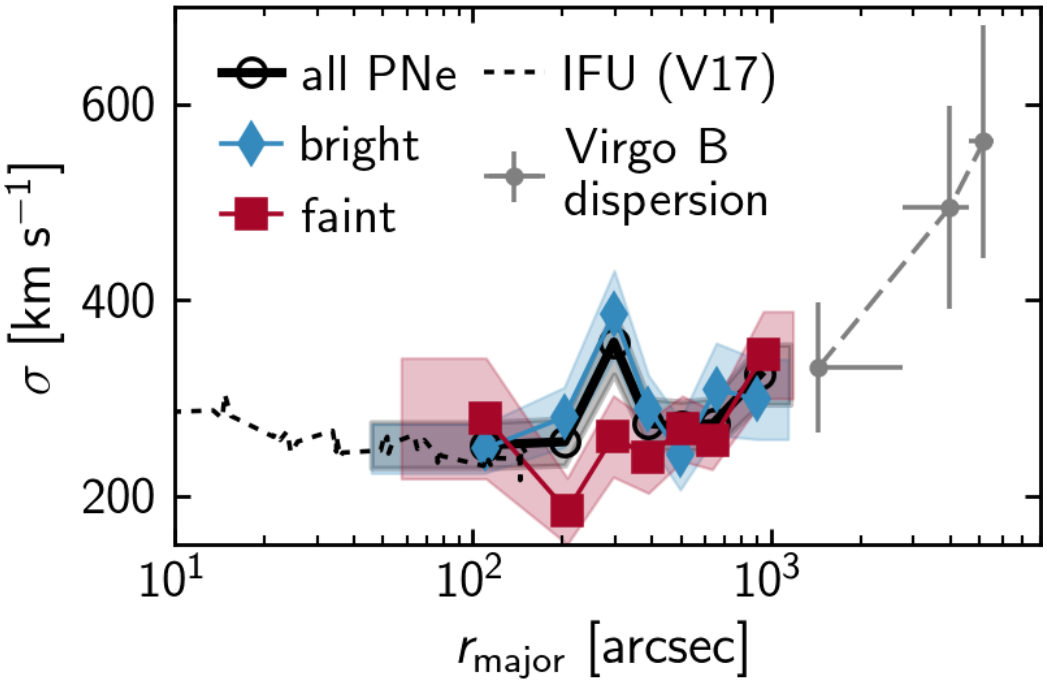
- Remember:
- M49 is in the centre of the Virgo Subcluster B
- In larger-scale structure (clusters and groups) more complex situation: Intracluster and Intragroup light
  - Diffuse starlight that fills the space between galaxies in clusters/groups
  - Tidal debris from merging galaxies



Mihos+2017

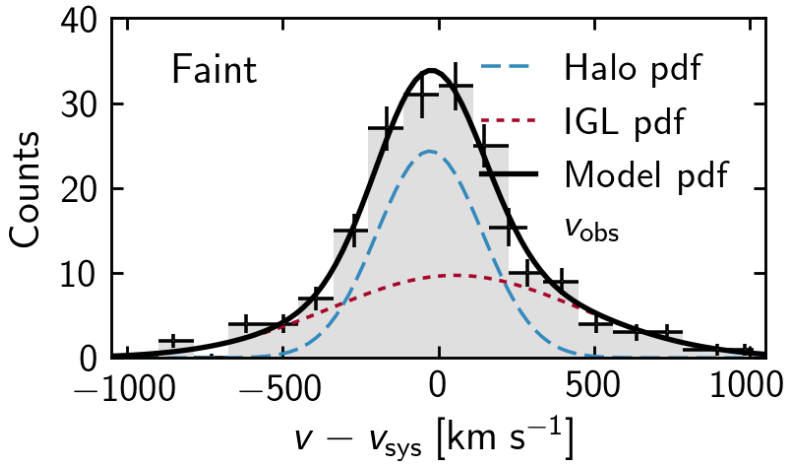
INTRA-GROUP LIGHT

Hartke+2018, *A&A*, 616:A123



Hartke+2018, *A&A*, 616:A123

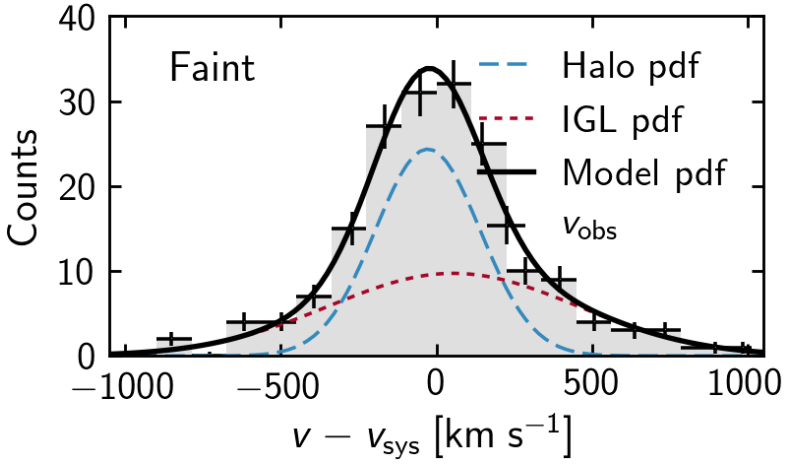
KINEMATIC PROPERTIES OF THE IGL

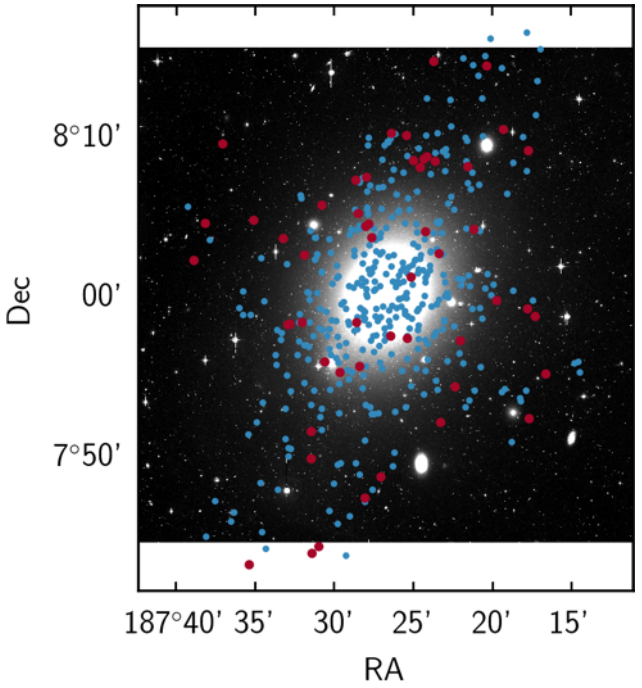


- Bin-free double-Gaussian model
  - Halo: σ = 170 km/s
  - IGL: σ = 400 km/s

Hartke+2018, *A&A*, 616:A123

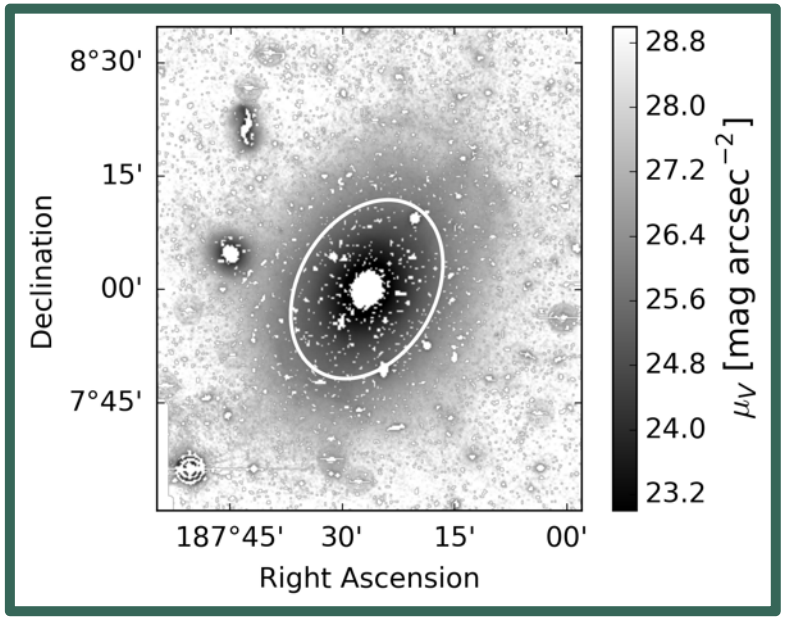
SPATIAL DISTRIBUTION OF THE IGL



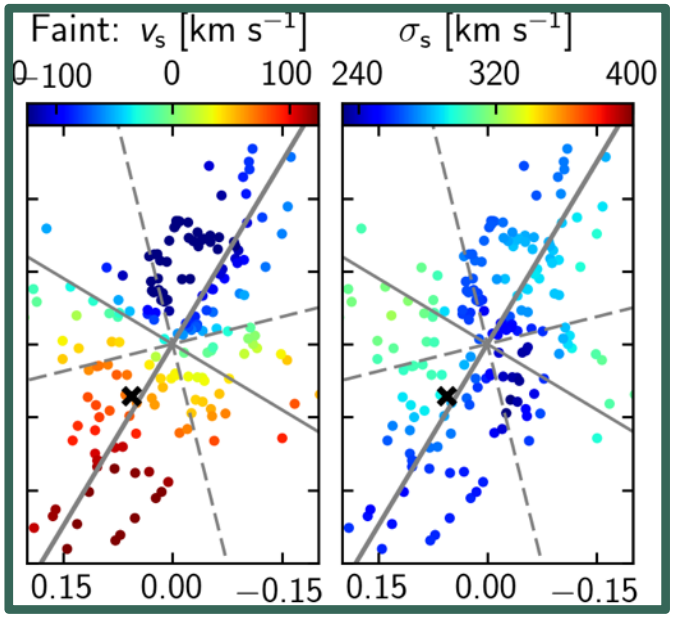


Hartke+2018, *A&A*, 616:A123

PROPERTIES OF HALO & IGL AROUND M49



+

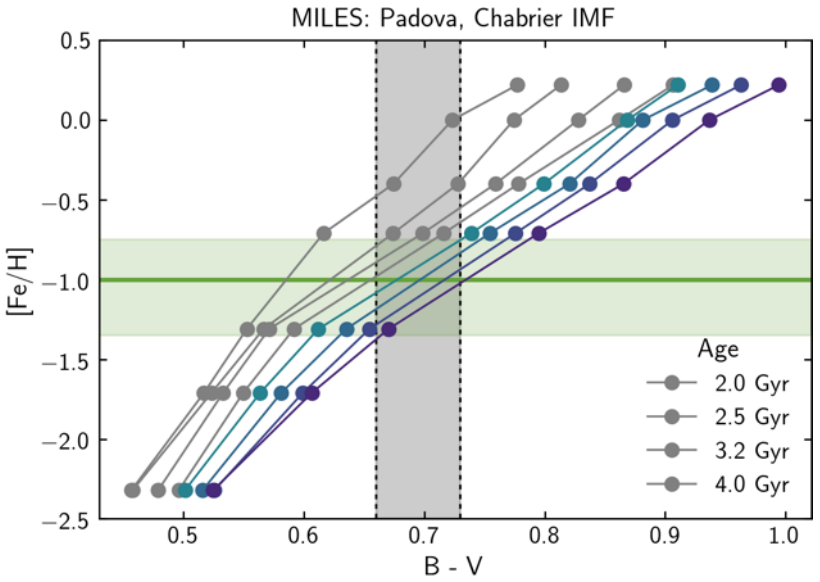


- Photometry: smooth halo
- Kinematics: Featureless velocity field

Hartke+2018, *A&A*, 616:A123

PROPERTIES OF THE IGL AROUND M49

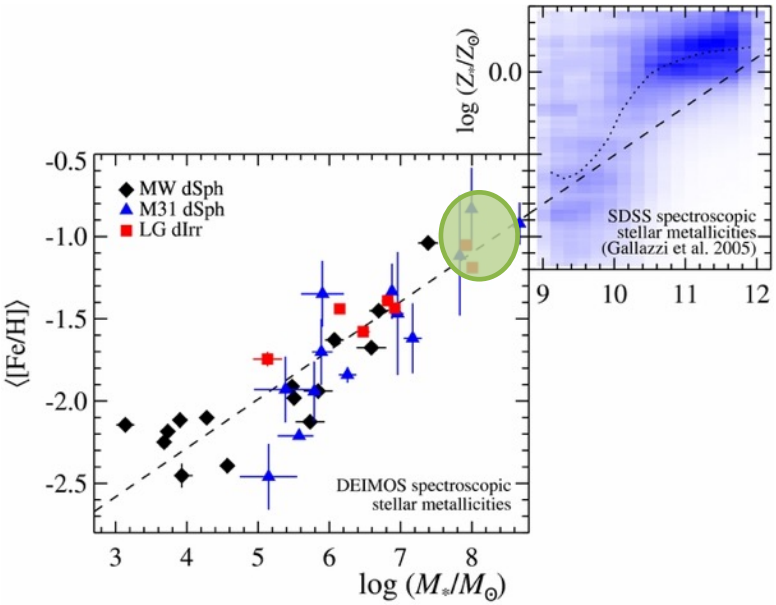
- Photometry: smooth halo + Kinematics: Featureless velocity field
  - Dynamical age older than orbital precession time (5 Gyr)
- We infer from SSP models (Falcón-Barroso+11)
  - [Fe/H] < -1. ± 0.3



Hartke+2018, *A&A*, 616:A123

PROPERTIES OF THE IGL AROUND M49

- Photometry: smooth halo + Kinematics: Featureless velocity field
  - Dynamical age older than orbital precession time (5 Gyr)
- We infer from SSP models (Falcón-Barroso+11)
  - [Fe/H] < -1. ± 0.3
- Mass-metallicity relation (Kirby+13):
  - $M_* < 10^8\ M_\odot$
  - Merger-mass ratio to M49: 10^{-4}



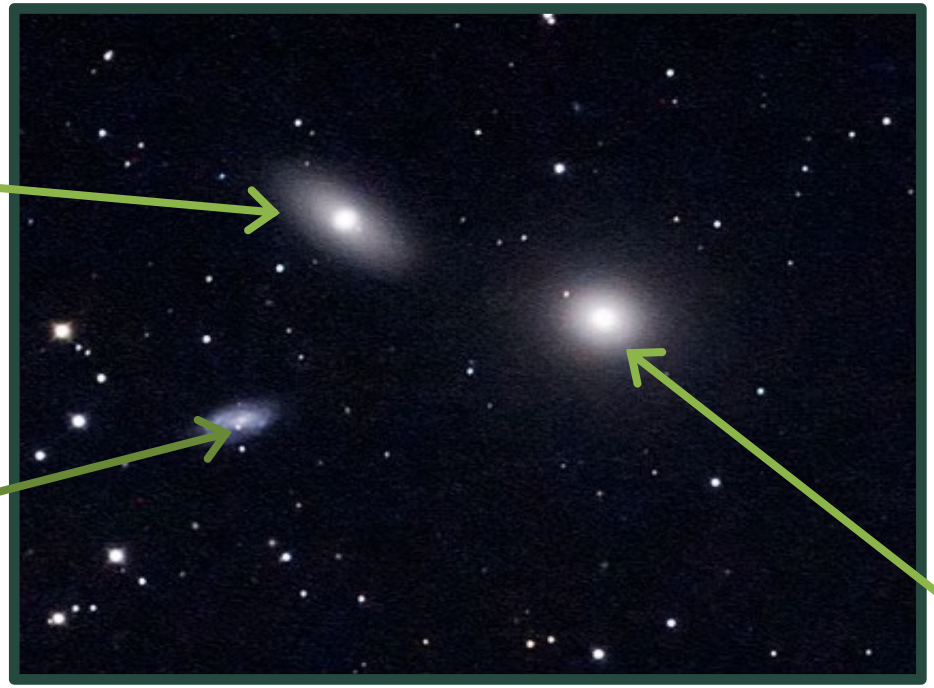
M49: TAKE-HOME MESSAGES

- PNe are good probes to trace the extended kinematics of early-type galaxies
- Adding magnitude information to the kinematics is vital to identify different stellar populations:
  - Infall of dwarf irregular galaxy VCC 1249
  - Halo of M49
  - Intra-group light that reaches the velocity dispersion of the Virgo Subcluster B
- Progenitors that have formed the IGL:
  - Many low-mass galaxies that were accreted before $z < 0.5$
  - Potential effects on simulation feedback?

M105 IN THE LEO I GROUP

A METAL-POOR HALO EMERGES

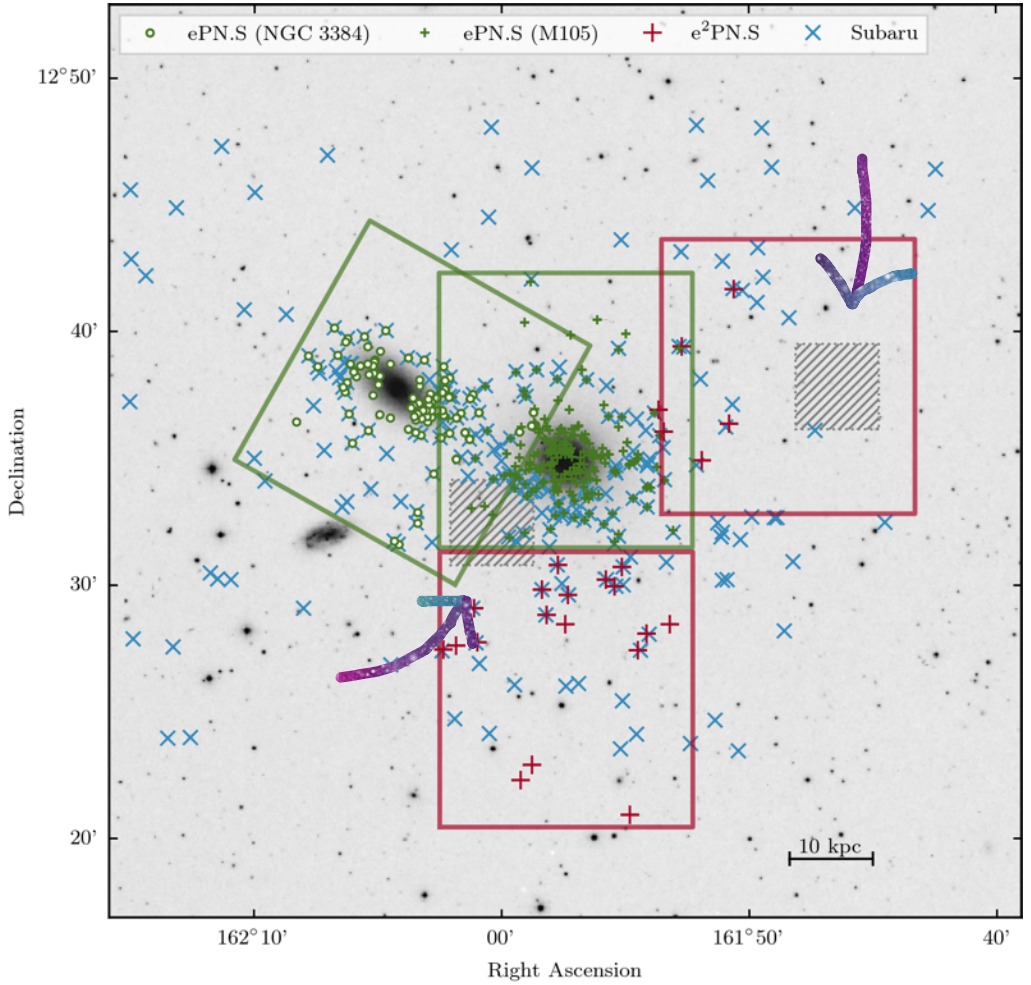
The Leo I Group



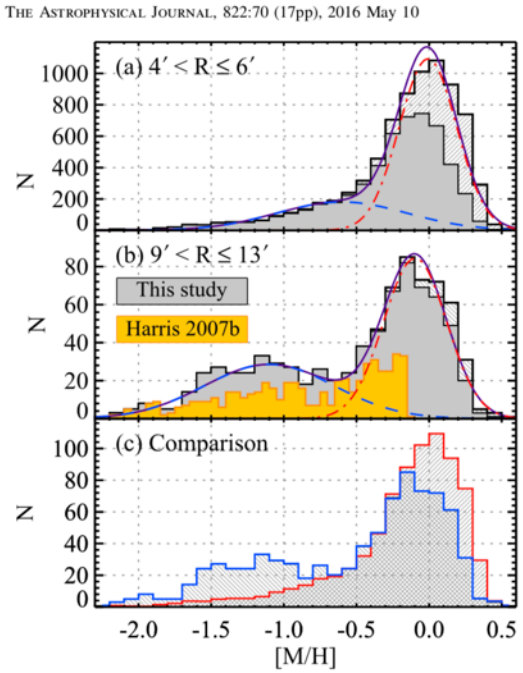
PNE IN THE LEO I GROUP

- Disentangle contributions from M105 and NGC 3384
- Accurately map velocity dispersion profile of M105 out to large radii

Photometry from HST → resolved stellar populations

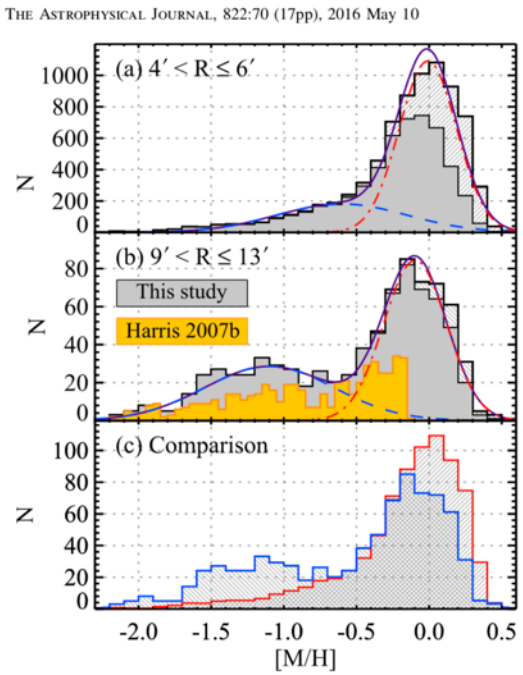


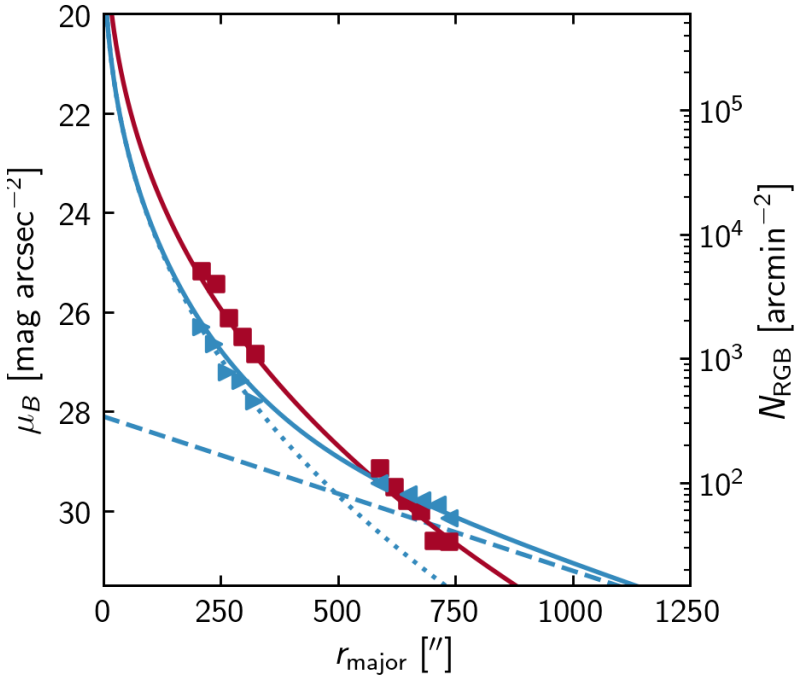
M105: A METAL-POOR HALO EMERGES



- HST photometry of the outer halo of M105:
  - Spatially resolved red-giant branch (RGB) stars
  - Emergence of metal-poor halo (Harris et al., 2007)
  - Lee & Jang (2016) compared metallicity distribution functions in the outer and inner halo

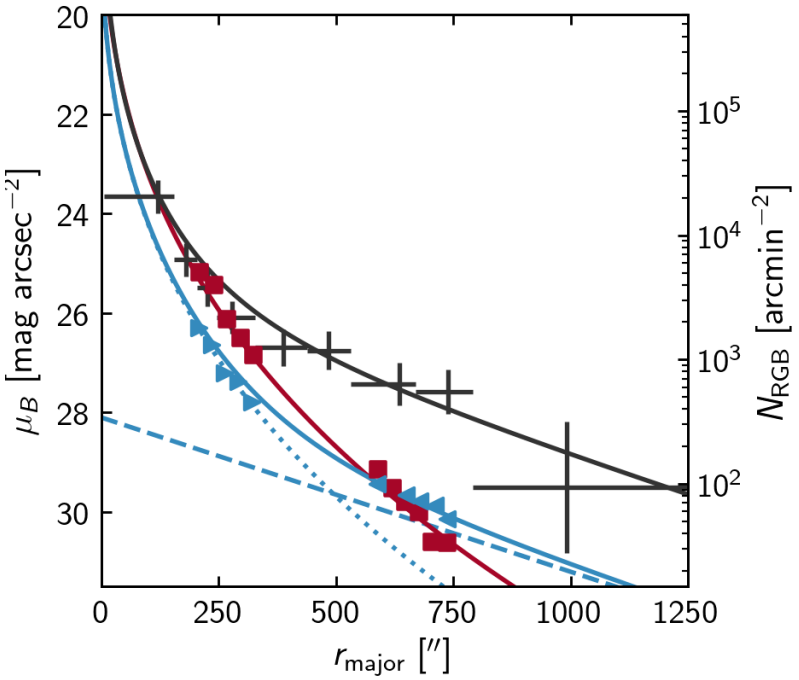
M105: A METAL-POOR HALO EMERGES





M105: A METAL-POOR HALO EMERGES

- What about the PNe?
- PN number density follows stellar light, but flattens earlier
- Two component model:
  - Sérsic (intermediate & metal-rich population)
  - Exponential (metal-poor population)



SUMMARY

- The concept of galaxies being built from composite single stellar populations (SSPs) has been widely accepted. It has now become evident that the same holds on the level of PN populations.
- PNe are excellent tracers of the diffuse halo and IGL and can facilitate the detection of the IGL even down to magnitude levels where the current state-of-the-art broad-band photometric surveys cannot reach.
- We have observed the kinematic transition from the halo of brightest cluster galaxy (BCG) to the IGL based on the velocities of individual stars for the first time.
- The combination of PNe and resolved RGB stars revealed a direct link between a high PN-yield and a low metallicity of the parent stellar population.