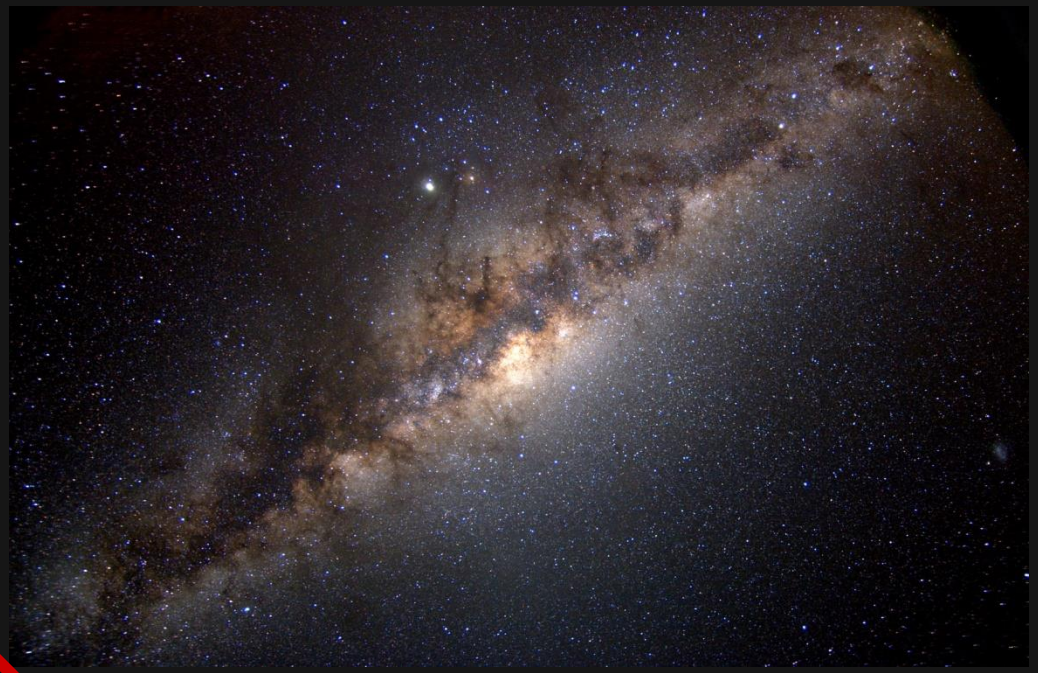
Galaxy formation research projects for astrophotographers

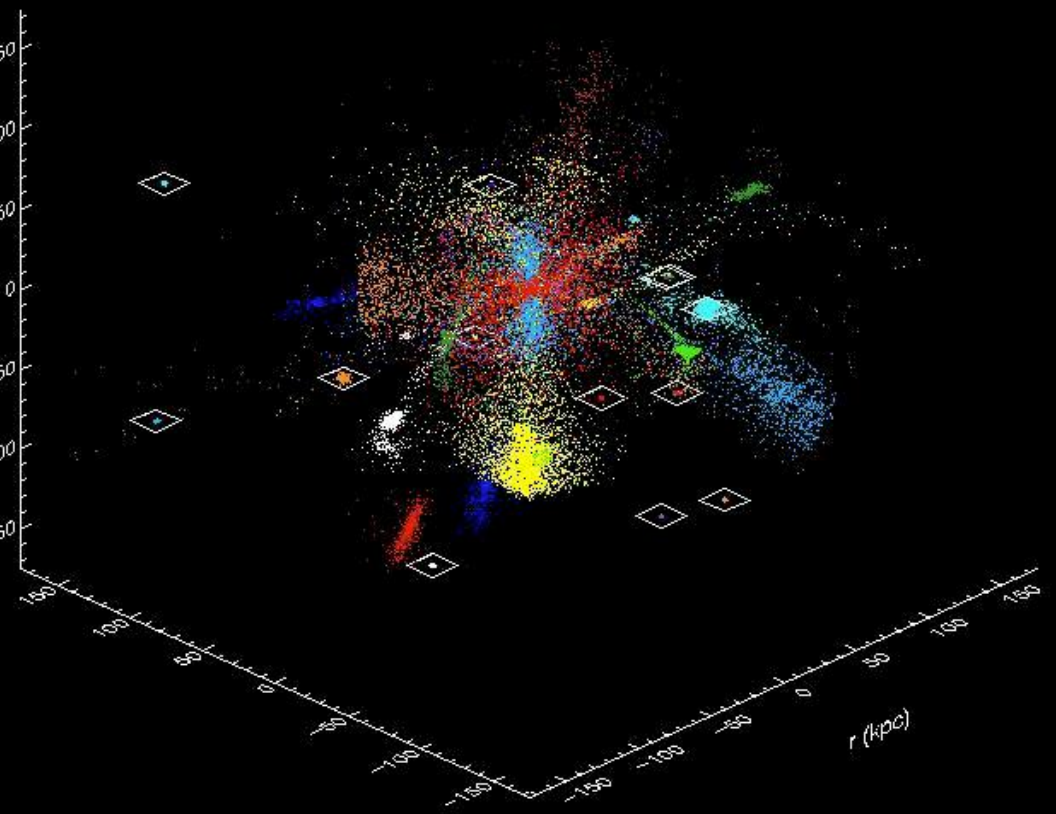
David Martinez Delgado
ARI, Univ. Heidelberg



NGC 891 (BBO)

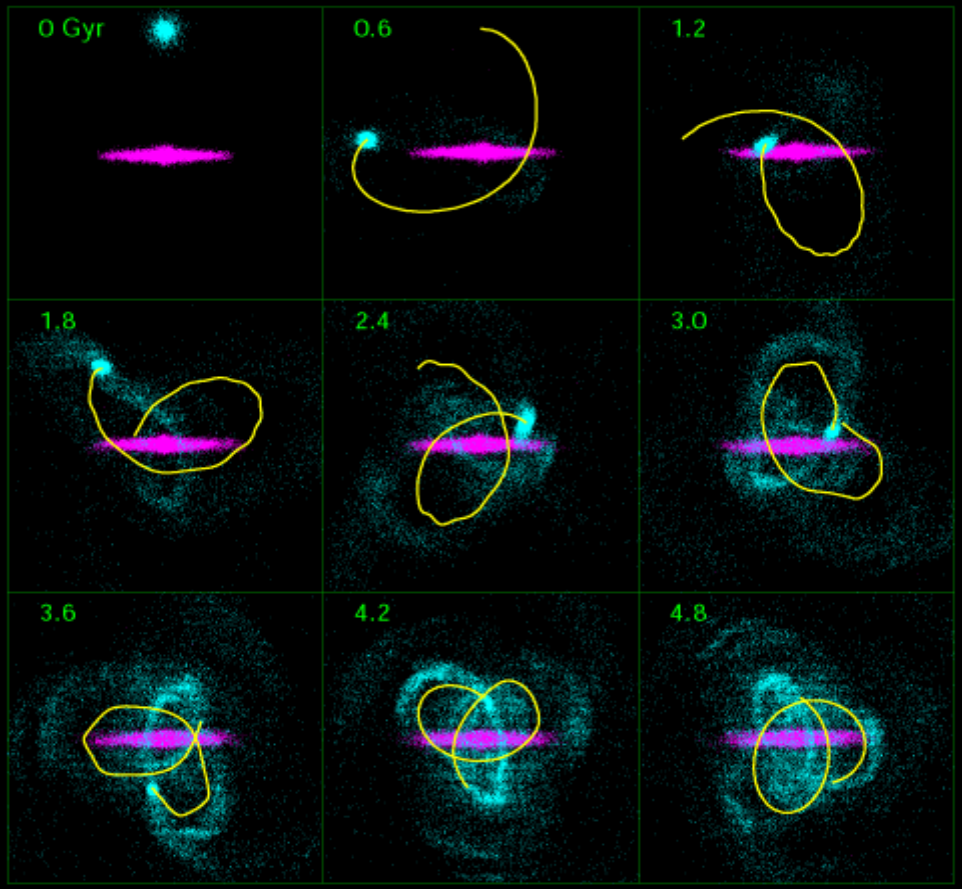
Jay Gabany

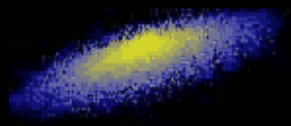
GALACTIC ARCHAEOLOGY



The fossils from the accretion of hundreds of dwarf galaxies should be still detectable in halos of nearby spiral galaxias nowadays.

The ghost of a dwarf galaxy: stellar tidal streams

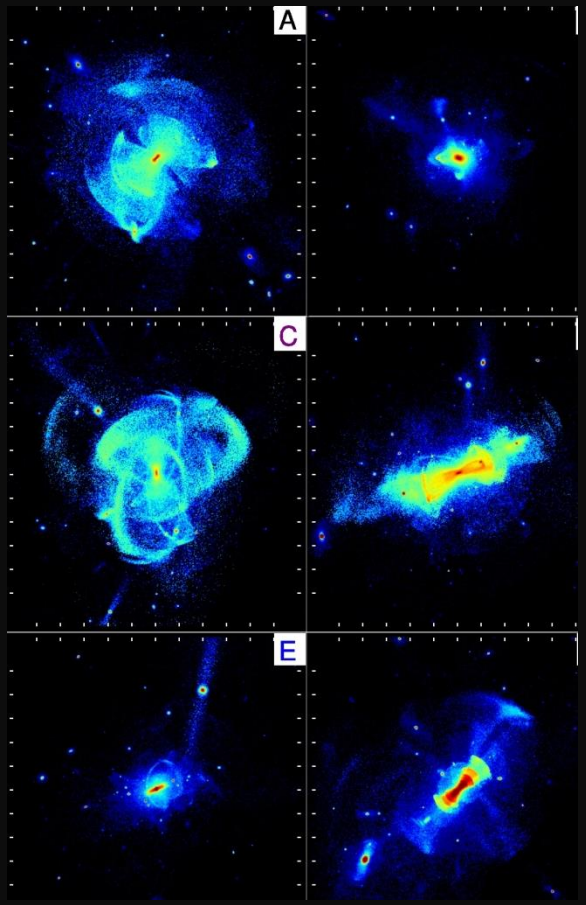




The tidal destruction of a single satellite in the halo of a spiral galaxy is enough to produce a giant and complex debris in a few Gyrs

Forbes et al. 2003

A Field Guide for Tidal Stream Hunting



Cooper et al. 2010: 6 models (Aquarius simulation)

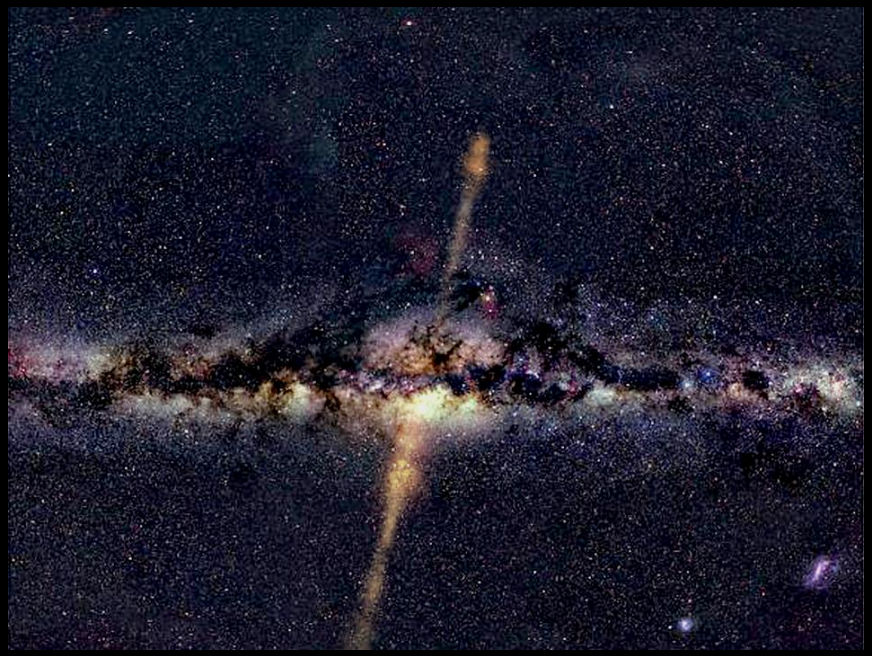
- Streams are really faint stuff: few brighter than 28 mag/arcsec^2; typical SB~ 30 mag/arcsec^2

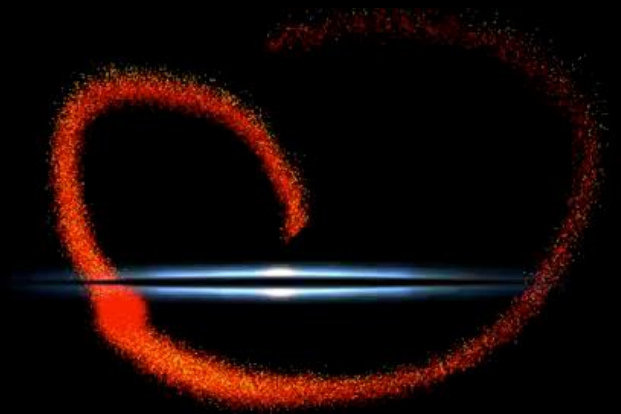
- All MW-like galaxies should show tidal debris in their outskirts if you go deep enough

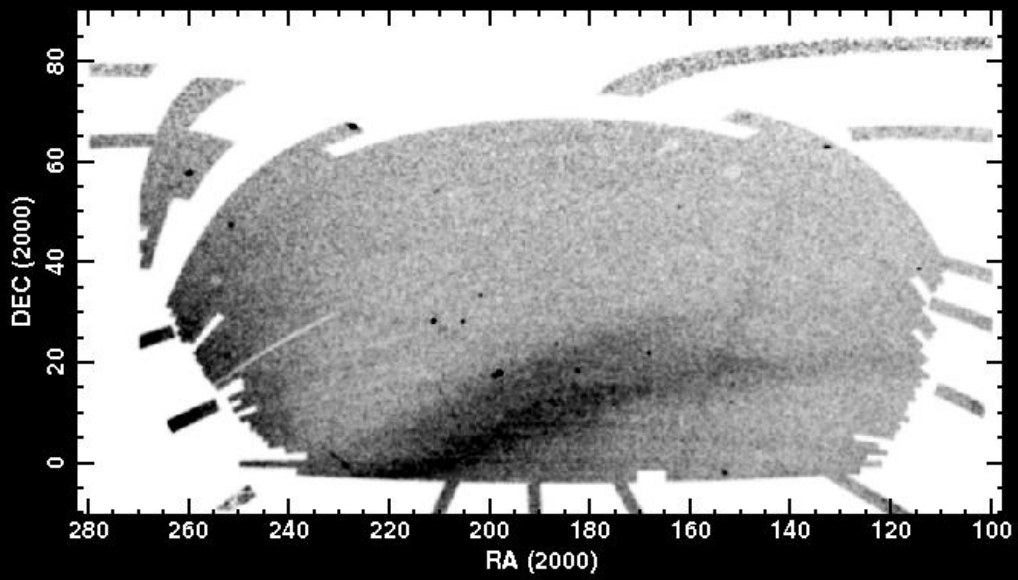
- A large variety of merging histories: streams of different morphology types are expected if you look at large number of spiral galaxies.

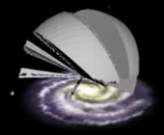
STREAMS ARE OUT THERE

THE SAGITTARIUS STELLAR STREAM









IT CROSSES THE FULL SKY!!

althought includes only the 15% of the mass of the progenitor

The Stellar Tidal Stream Survey

- **OBJECTIVE: OBSERVATIONAL CONTRAINTS ON THE RATE AND CONSEQUENCES OF MINOR MERGERS IN SPIRAL GALAXIES OF THE LOCAL VOLUME**

- **Deep probes of spiral galaxies halos: detecting relics of hierarchical galaxy formation (stellar tidal debris).**

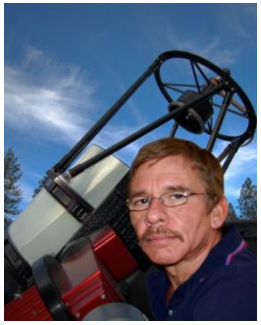
- **Target galaxies are spiral Milky Way analogues in the Local Volume: i) comparison with available CDM models of stellar halos; ii) to explore if the Milky Way merging history is typical by comparing with nearby galaxies.**

Pilot survey (2007-2009) finished; Systematic survey started in Spring 2010 (PI. Martinez-Delgado)

STELLAR TIDAL STREAM SURVEY

PI. Martinez-Delgado

OBSERVER TEAM



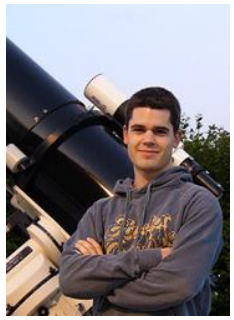
J. Gabany
BBO, USA

K. Crawford
RdS, USA

K. Teuwen
ROSA, French

J. Schedler
CHART32 Chile

A. Block
Mt. Lemmon, USA



F. Neyer
Switzerland

M. Hanson
DGRO,USA

N-BODY MODELS

Elena D´Onghia (Winsconsin) **Nicola Amorisco (DARK Institute)**

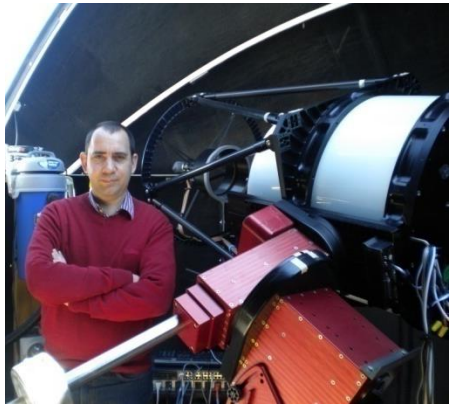
FOLLOW-UP COLLABORATIONS:

R.Beaton (OCIW), A. Romanowski (Santa Cruz), D. Zarisky (Arizona), E. K. Grebel (ARI), Z. Jennigs(Santa Cruz), G. Morales (ARI), T. Chonis (Texas), M. Hilker (ESO), J. Fliri (IAC), S.R. Majewski (Virginia)

ΛCDM MODELS

A. Cooper , C. Frenk , R. Kennedi, S. Shaun (Durham, UK)

Observational Strategy

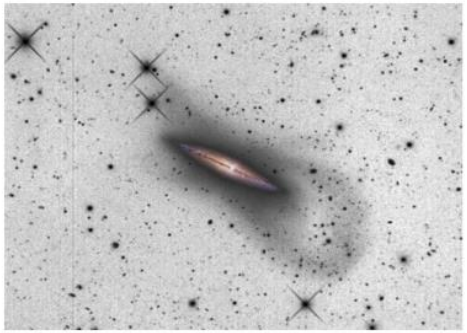


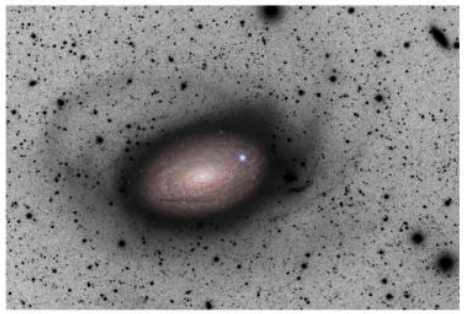
A amateur robotic small telescope network

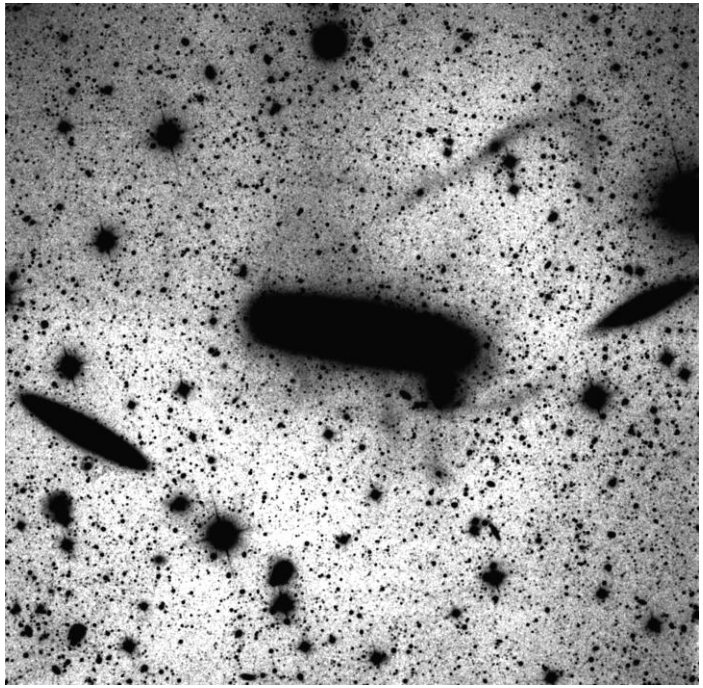
Luminance (g+r) filter + 7-12 hours exposure time

Calibration with r-band SDSS archive images

Color information only for the brightest streams (assumed (g-r)~0.45 for the rest)





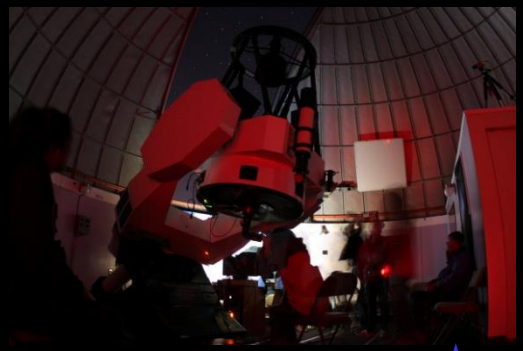


SB limit ~ 29 mag/arcsec^2 r-band (2.5-3 magn. deeper than SDSS)

The STTS robotic amateur telescope network

RdS 0.5-m ★

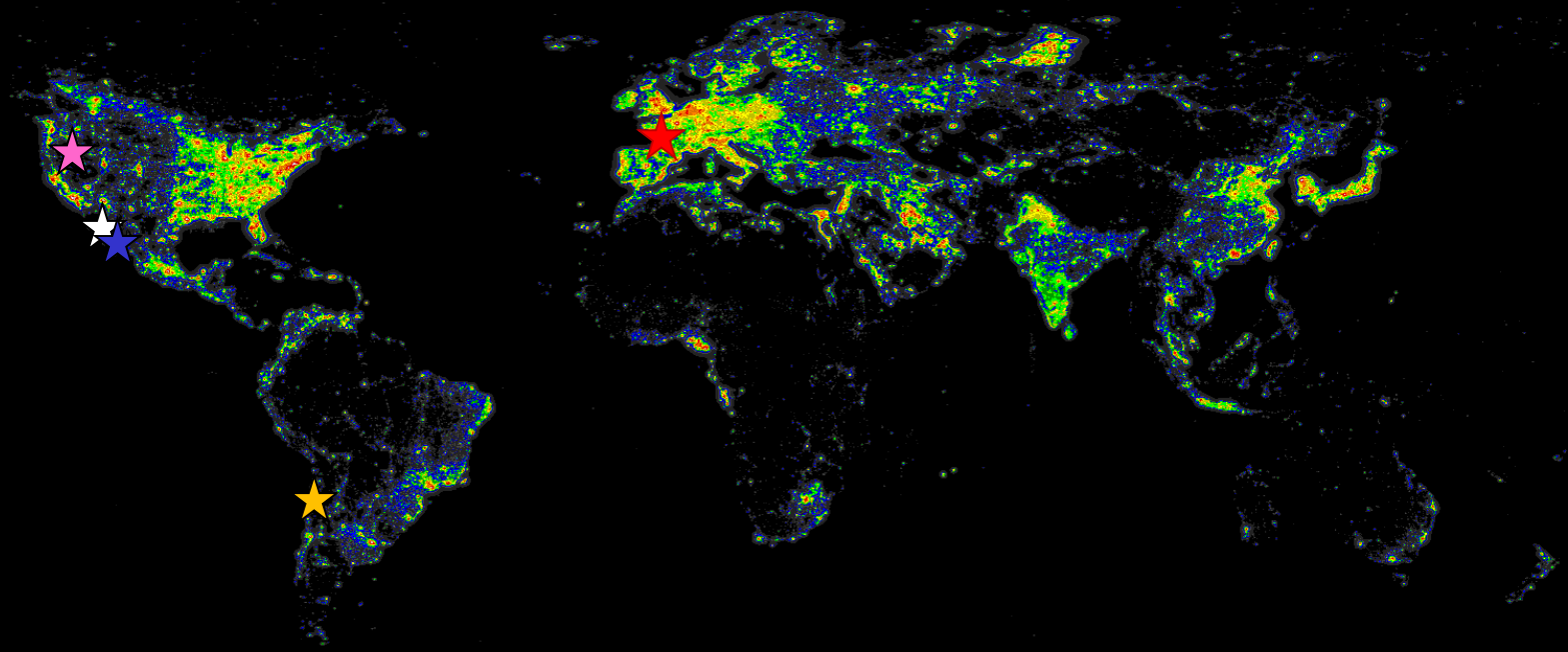
BBO-II 0.5-m ★



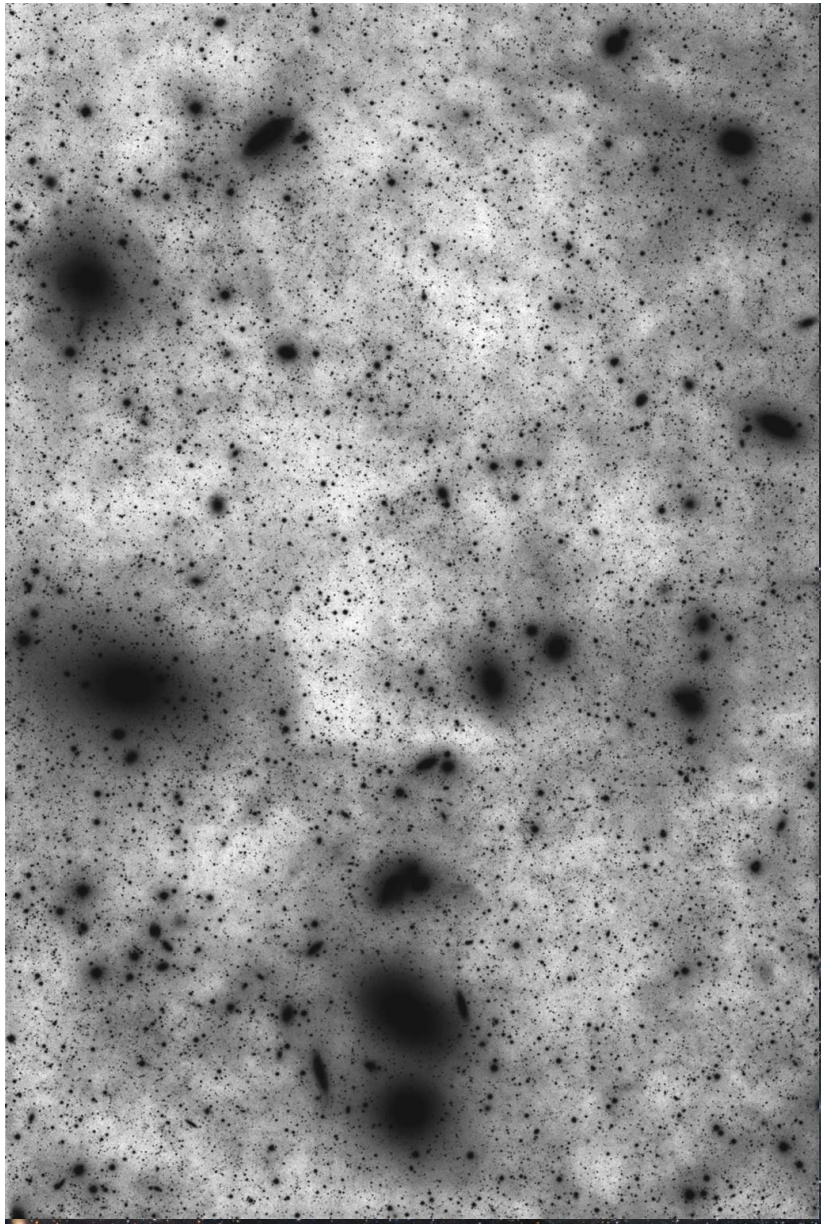
Mt. Lemmon 0.8-m ★

CHART32 0.8-m ★

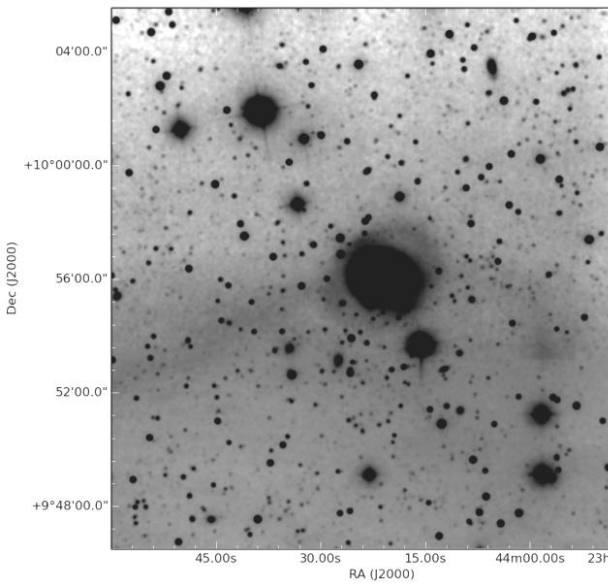
ROSA 0.3-m ★

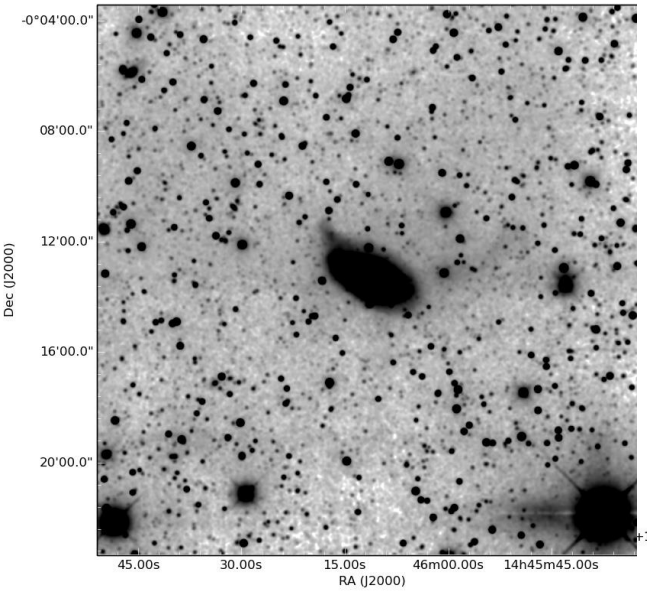


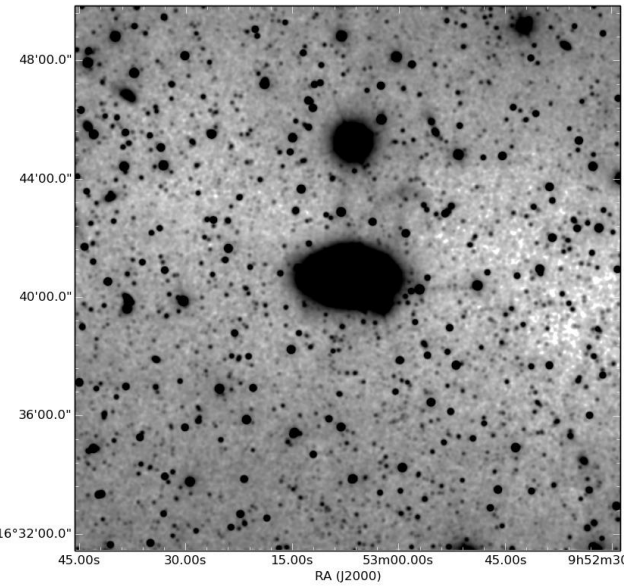
Virgo cluster ED-10cm 36 hours



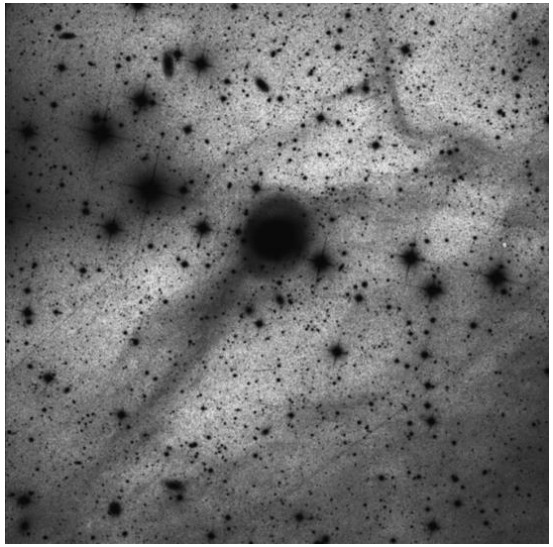
SDSS g+r+i

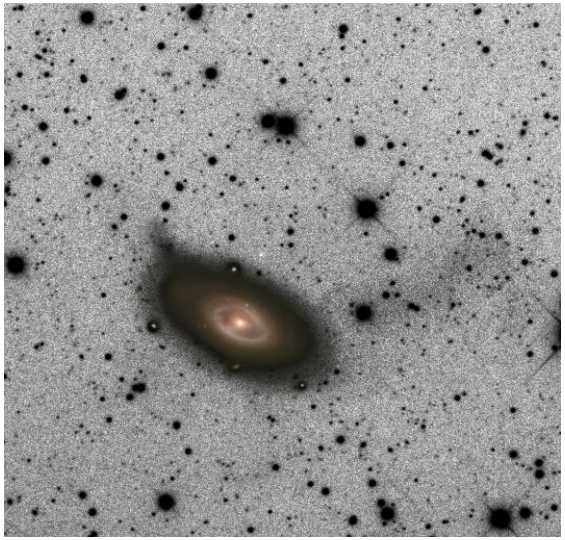


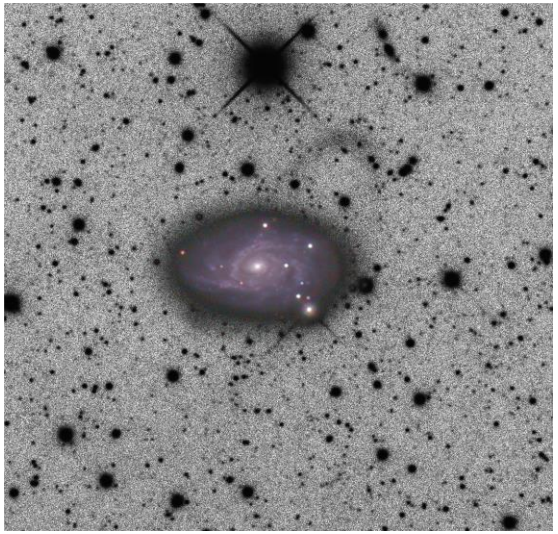


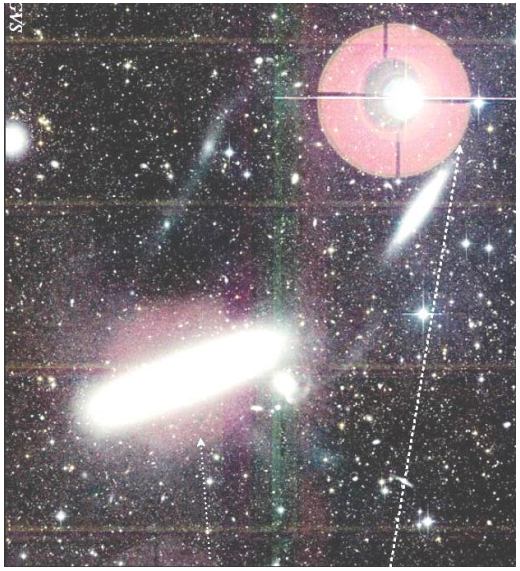


STSS L-filter









ATLAS 3D early type galaxies

CFHT 3.5m OmegaCam (Duc et al. 2015)

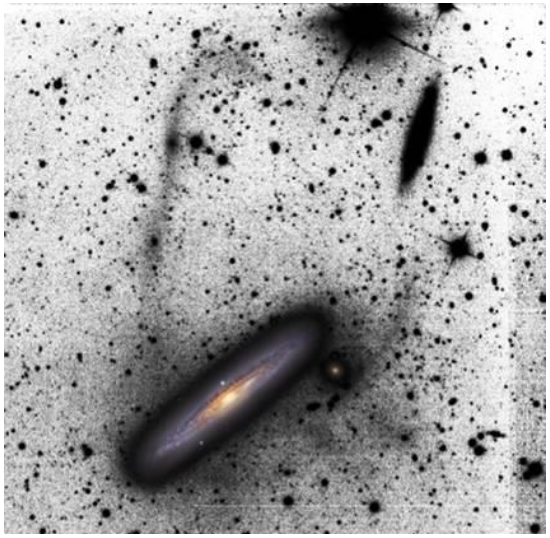
SB~29.5 mag/arcsec^2

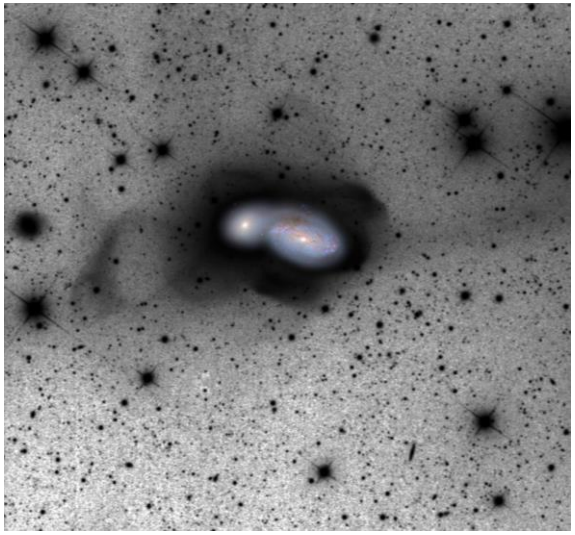
Sub-arcsec seeing

Broadband gri photometry

Bright stars, scattered light

Artificial “halos” in galaxies





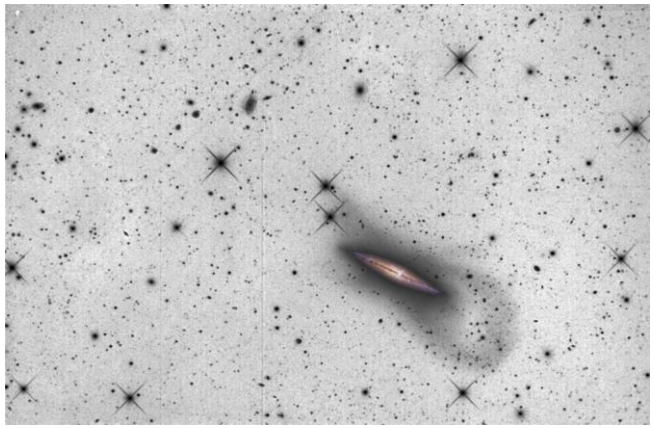
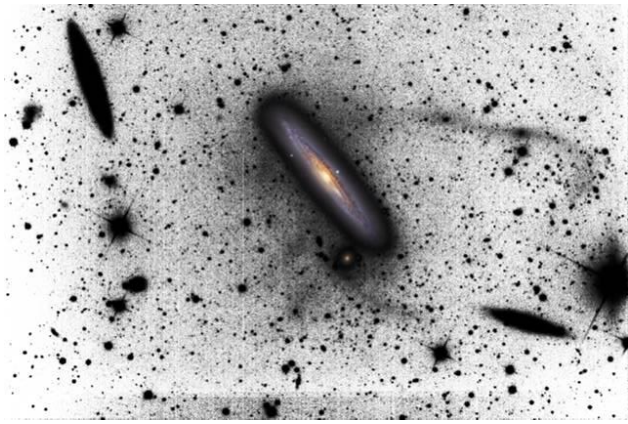
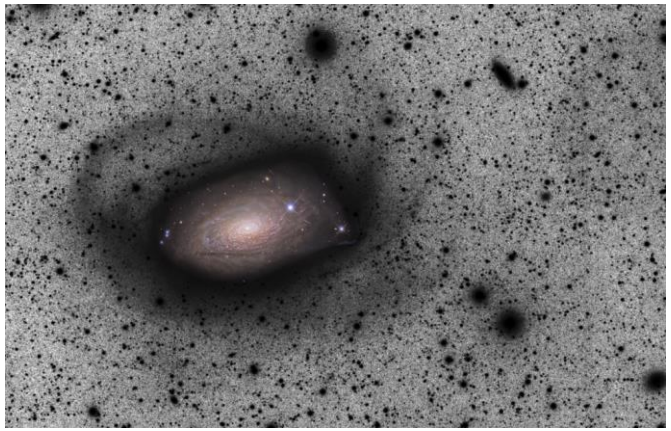
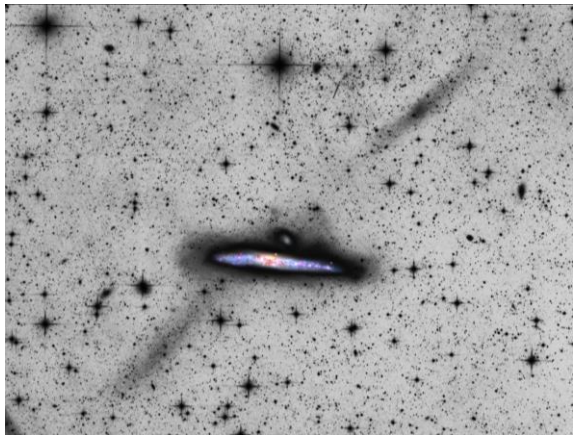
RC 0.5-m reflectors

SB~29.5 mag/arcsec^2

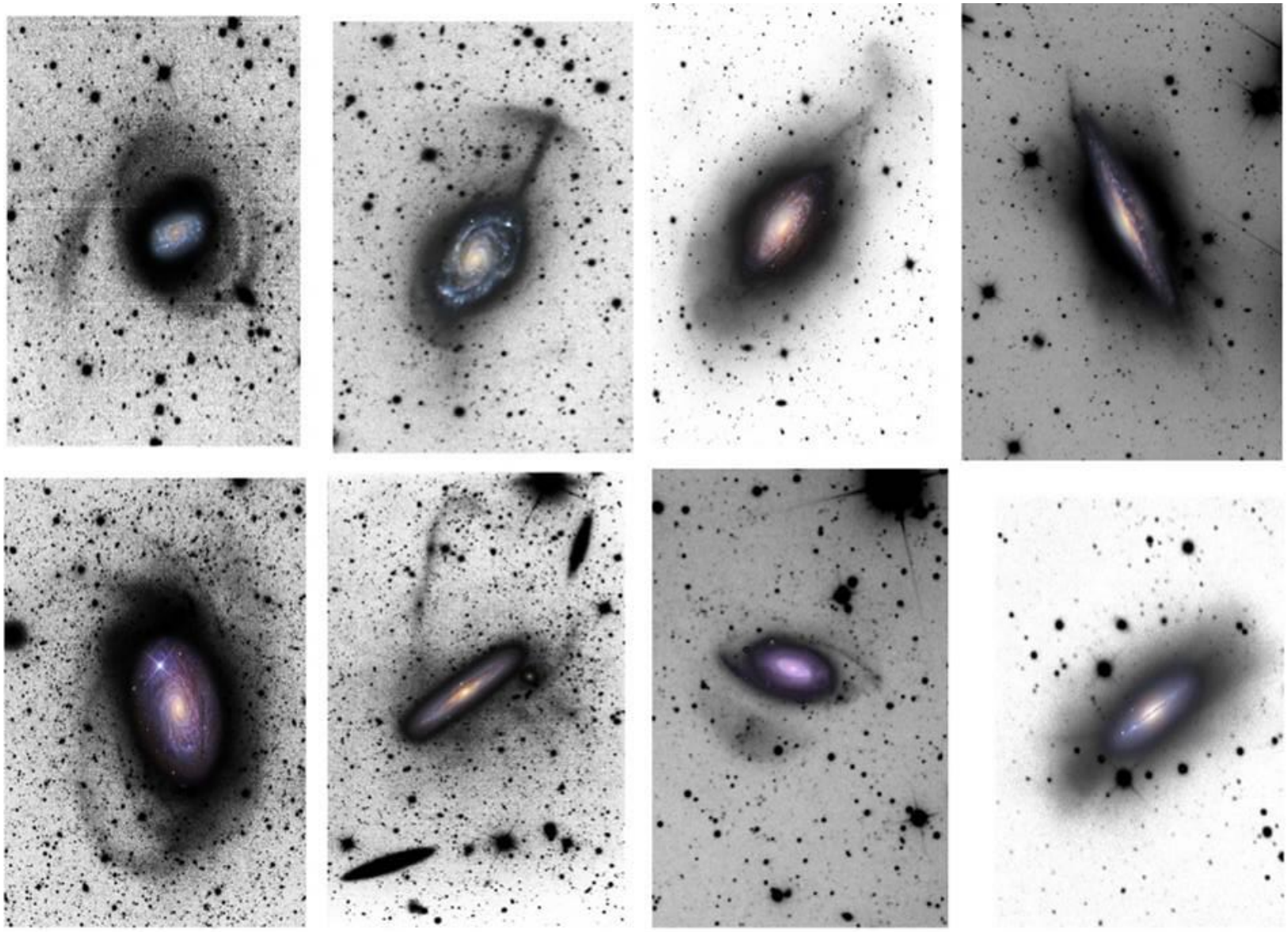
Mediocre seeing (1.5”)

L-filter photometry

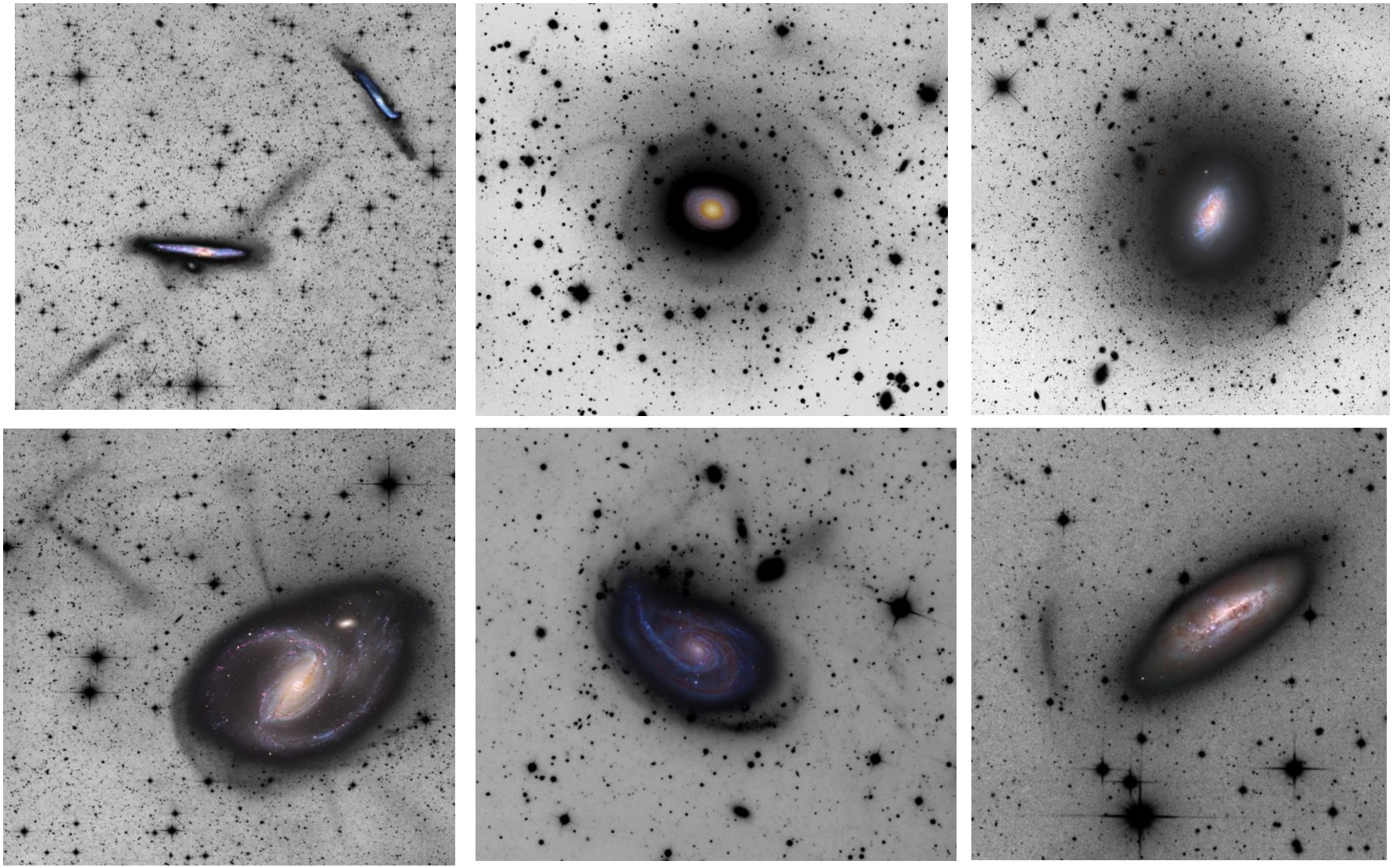
No bright stars, less reflections problems

Martinez-Delgado et al. 2008, 2010

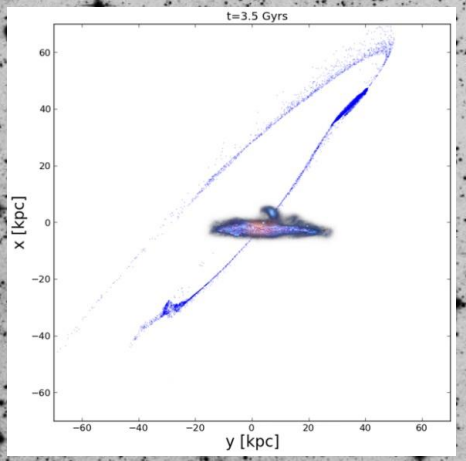


Martinez-Delgado et al. 2010

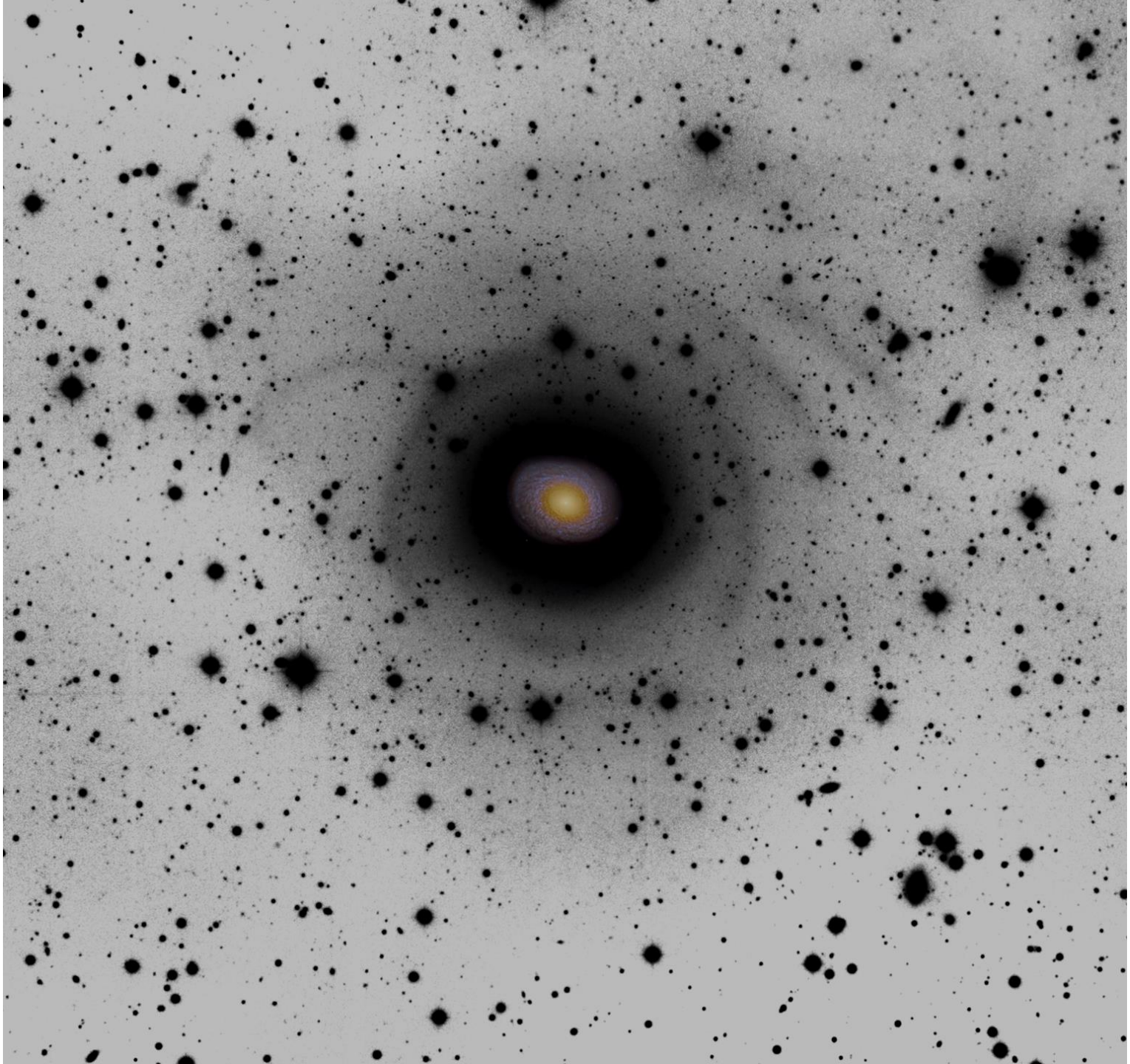


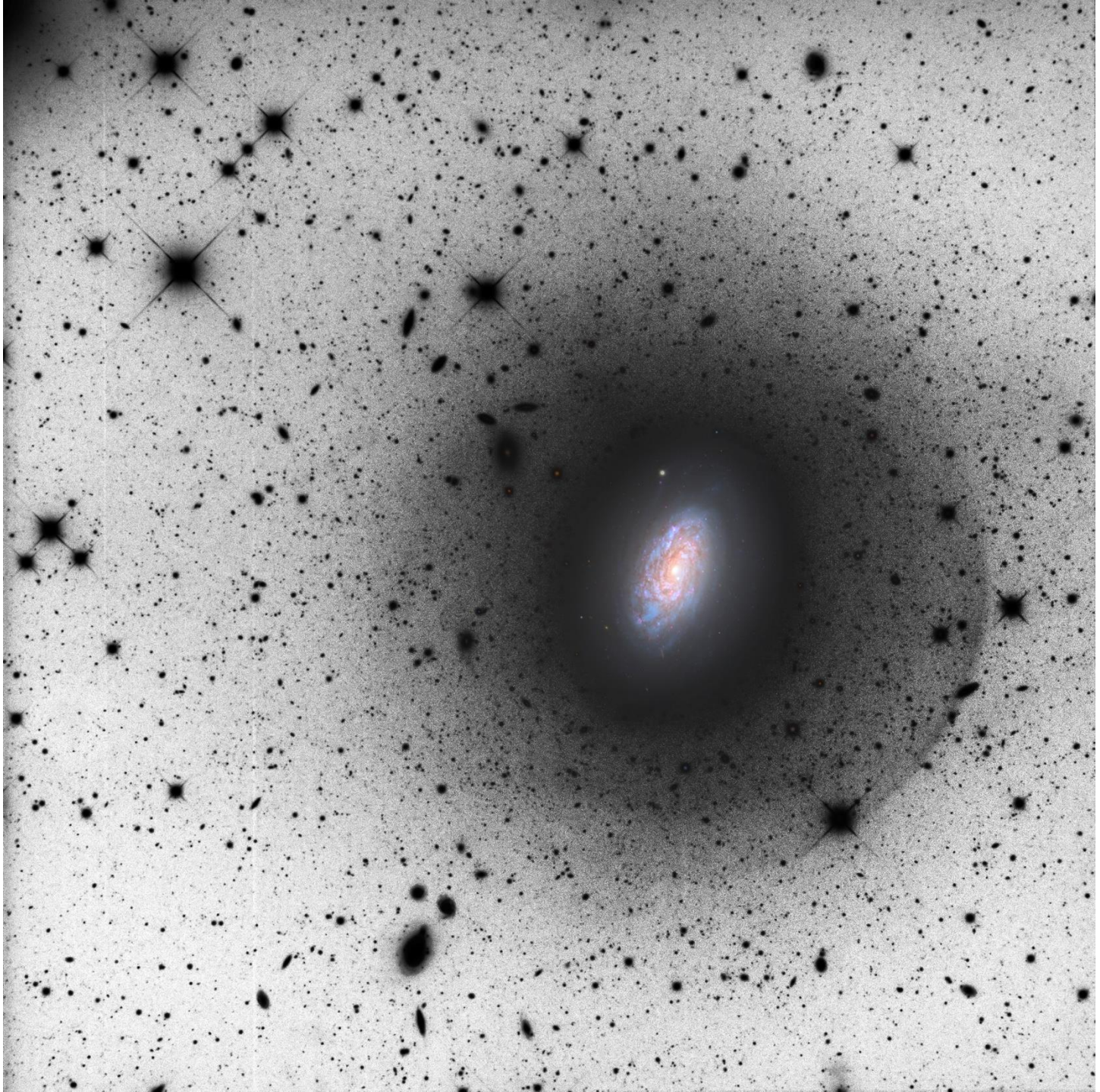
Martinez-Delgado et al. 2015

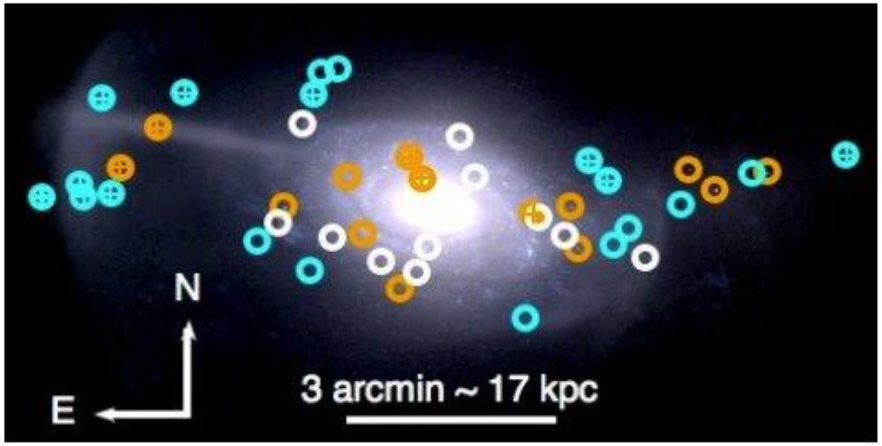
NGC 4631: Tidal streams around the Whale galaxy

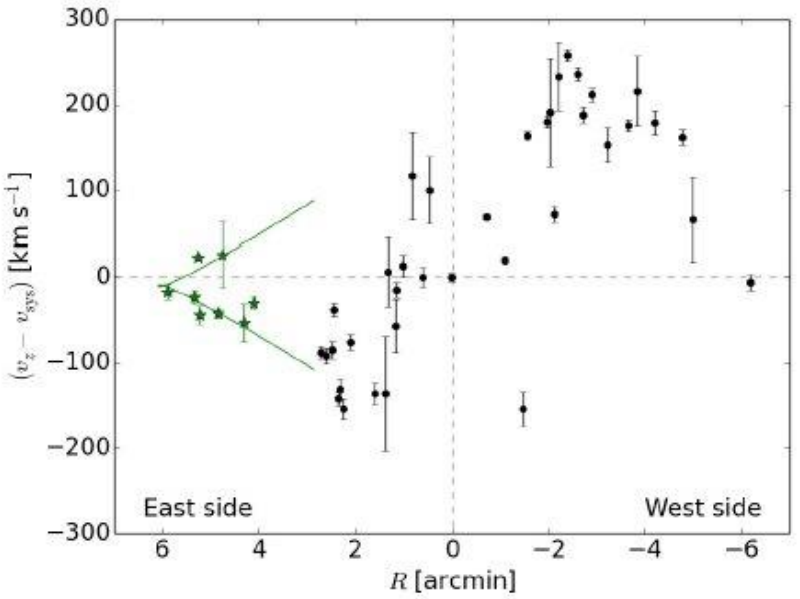


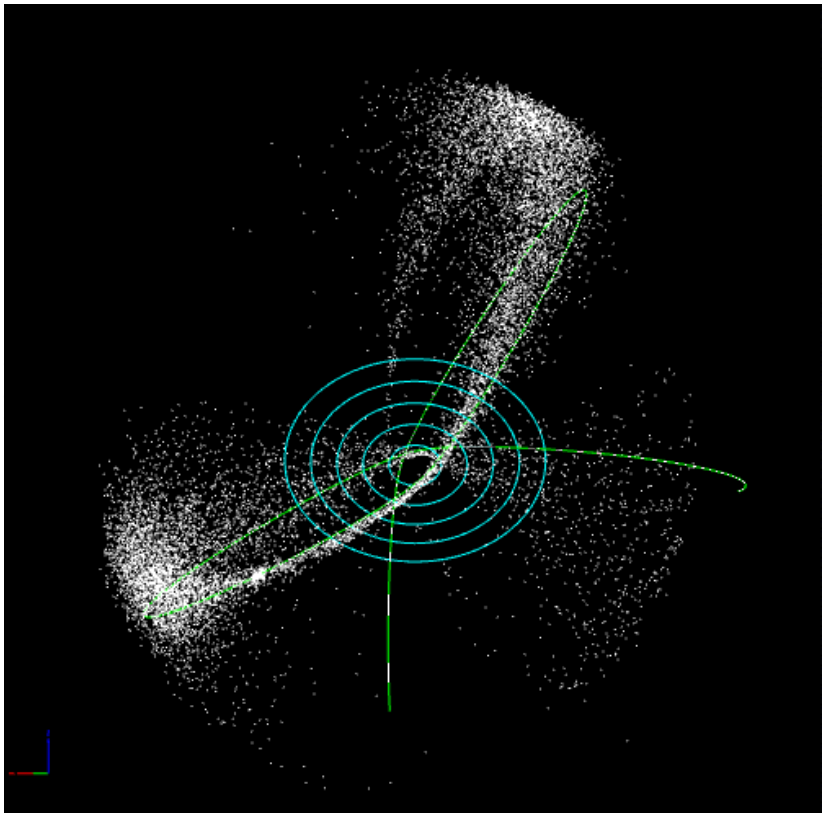
Martinez-Delgado et al. 2015

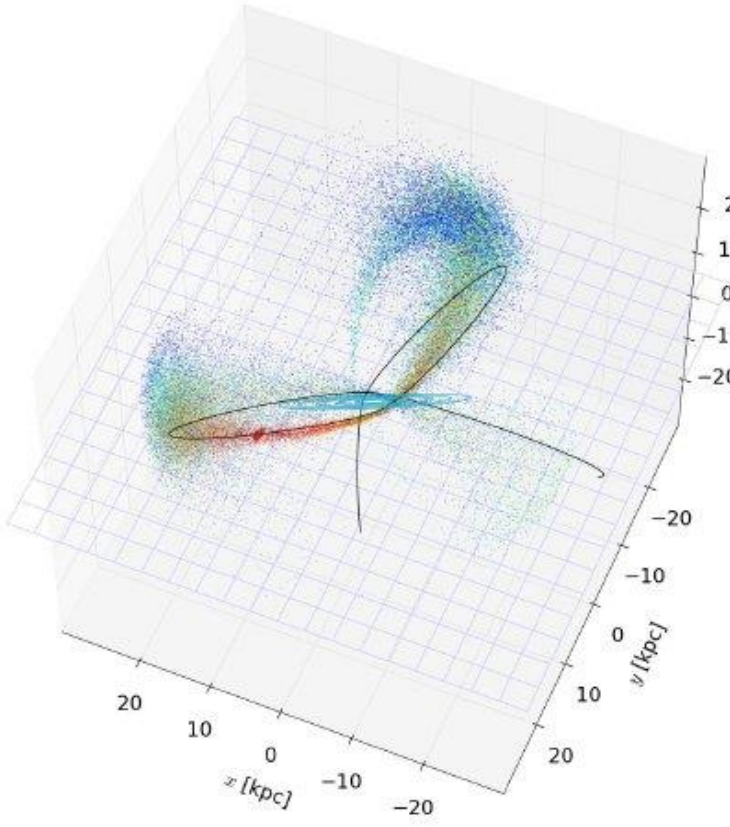




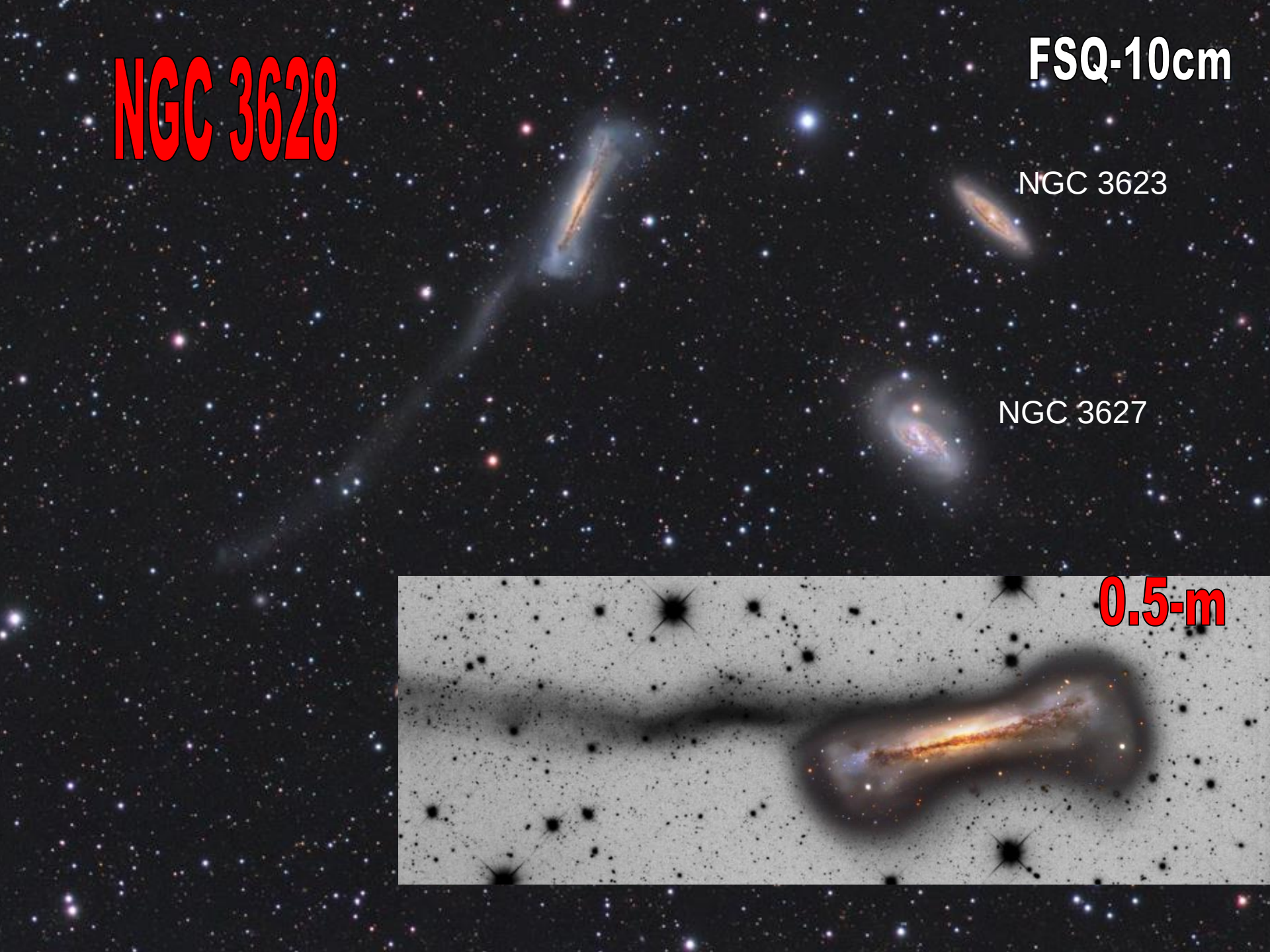








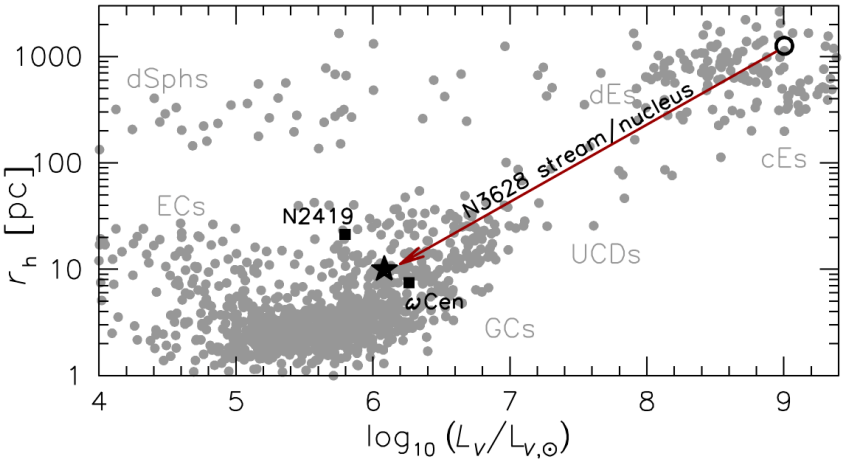
Foster et al. 2014


NGC 3628
FSQ-10cm
NGC 3623
NGC 3627
0.5-m

Subaru

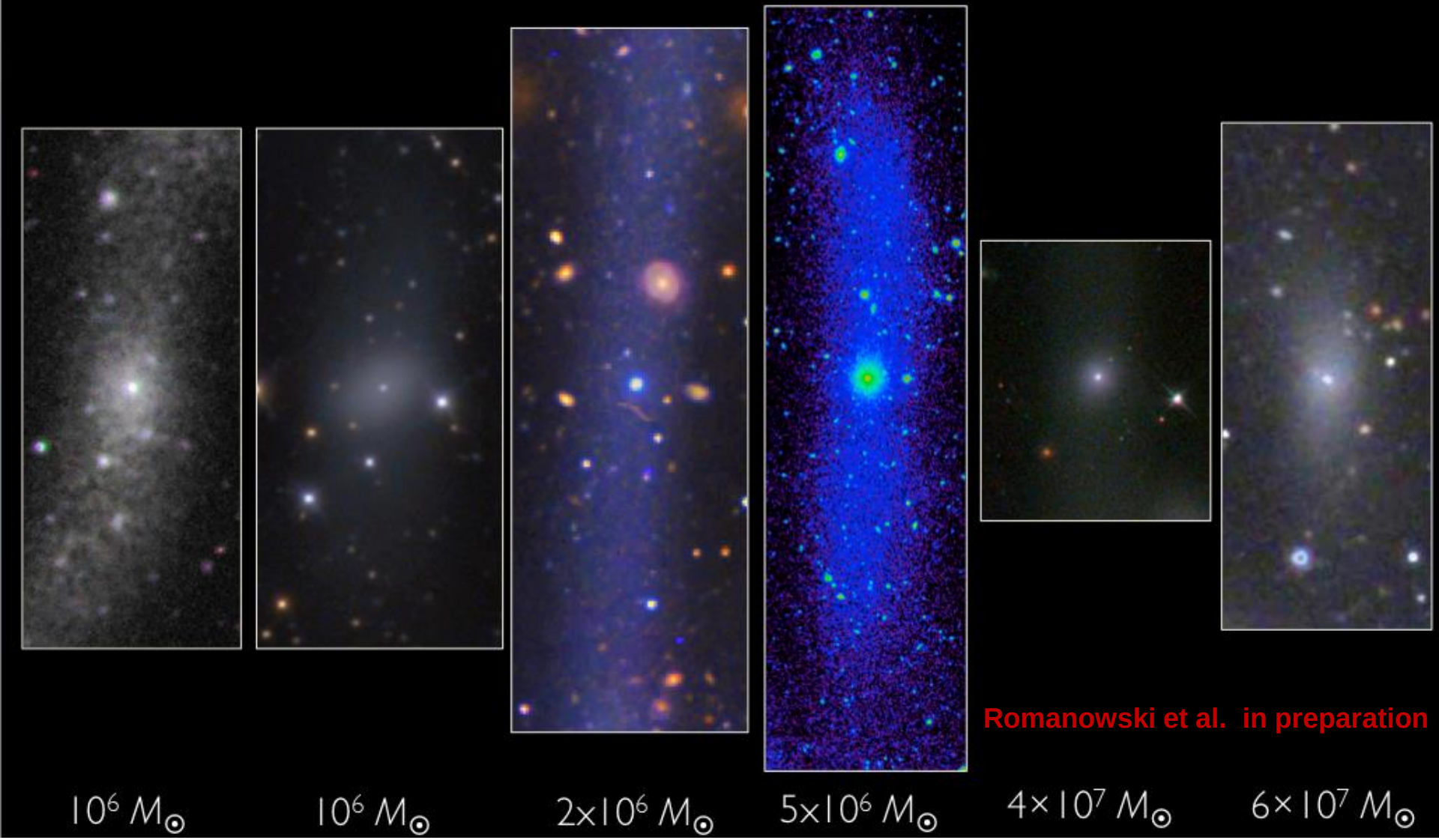
An old, metal poor, compact Omega Cen-like star cluster embedded in the tidal stream.

Evidence that at least some of the R_h ~10 pc cluster population could be accreted by tidal stripping of larger dwarf galaxies



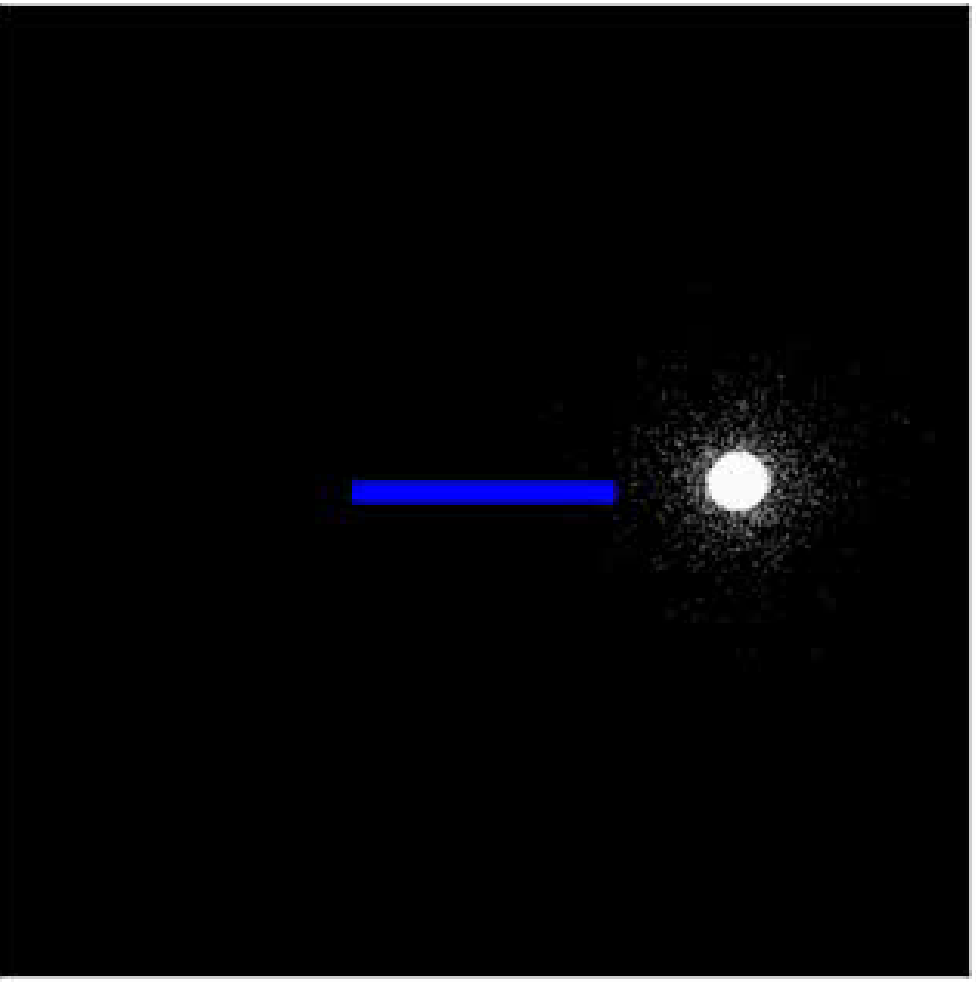
Jennigs et al. 2015

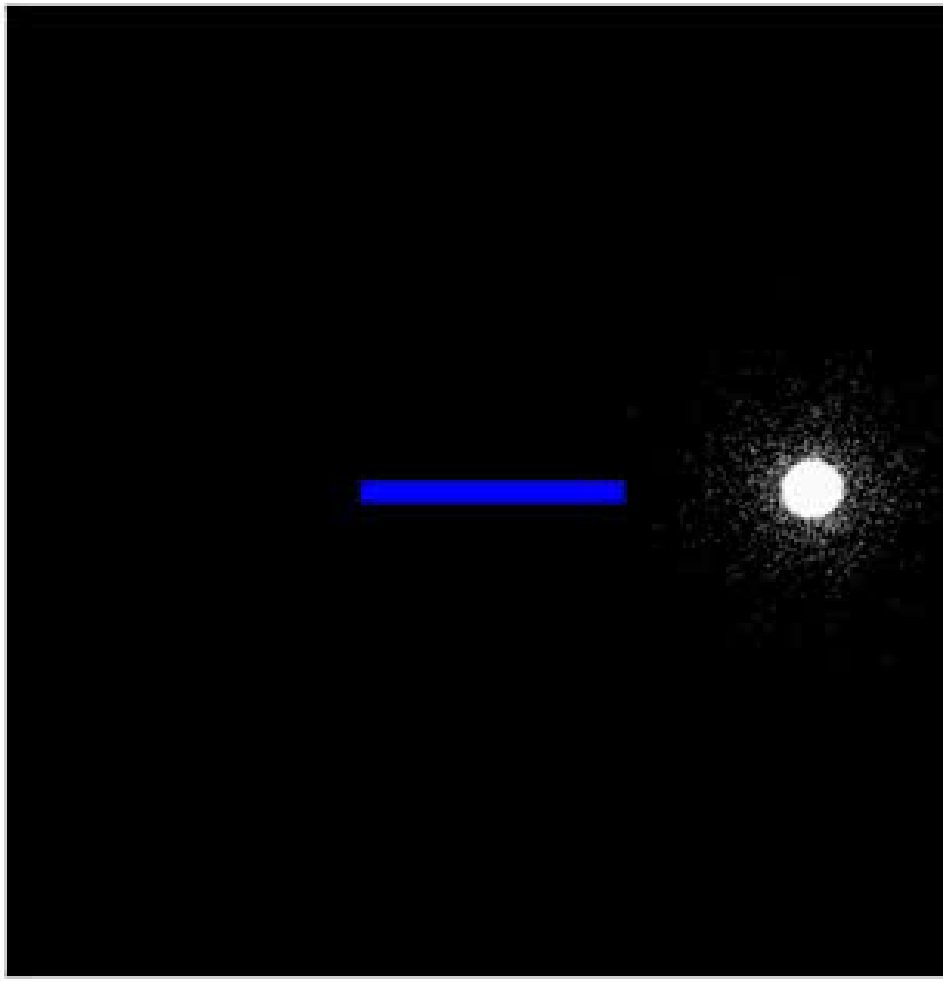
GCs and UCDs in formation

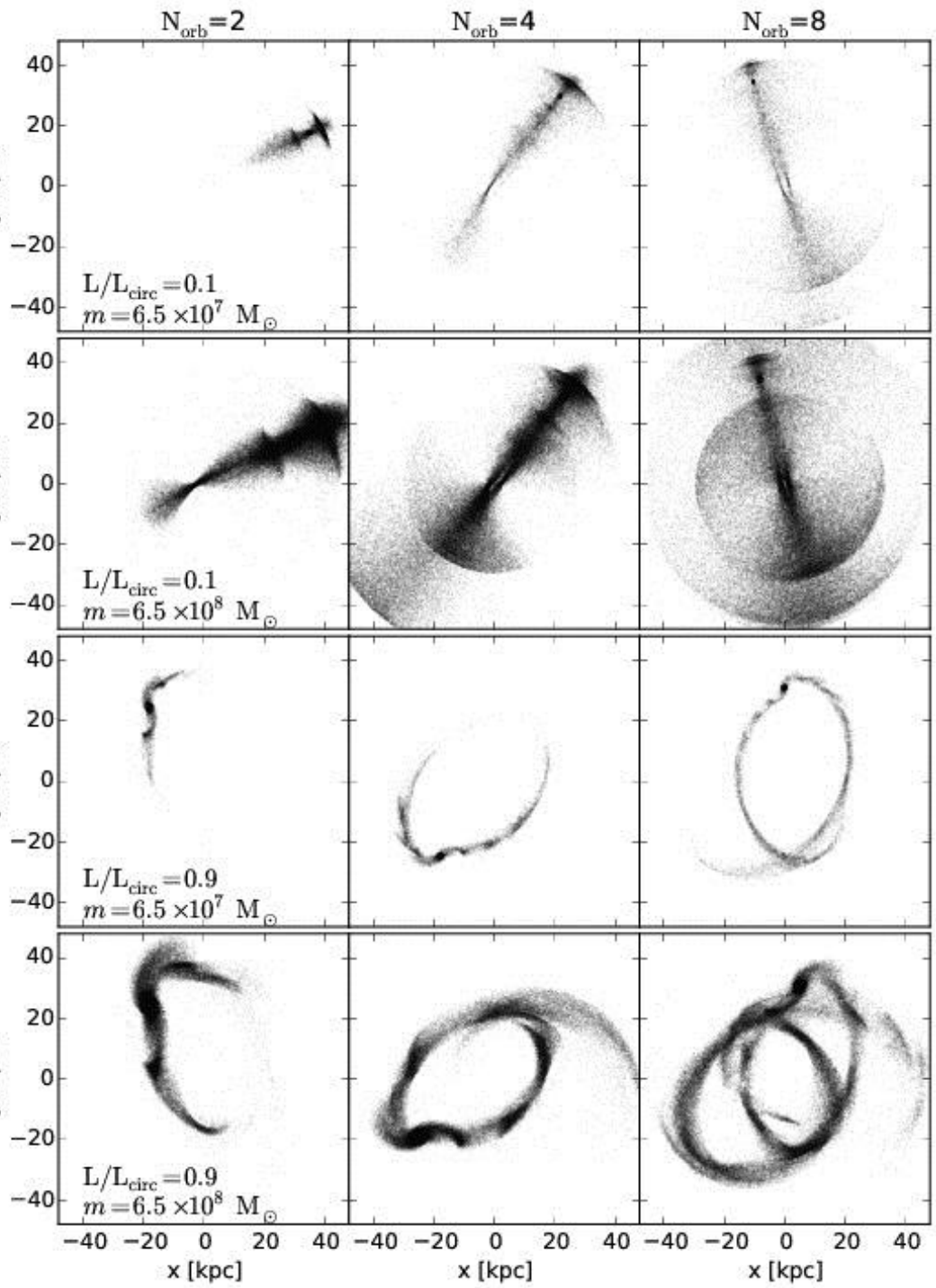


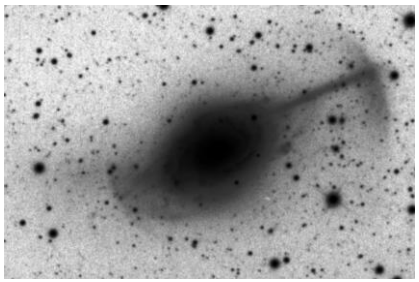
Romanowski et al. in preparation

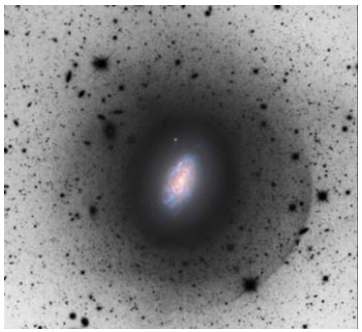
$10^6\ M_\odot$ $10^6\ M_\odot$ $2\times10^6\ M_\odot$ $5\times10^6\ M_\odot$ $4\times10^7\ M_\odot$ $6\times10^7\ M_\odot$

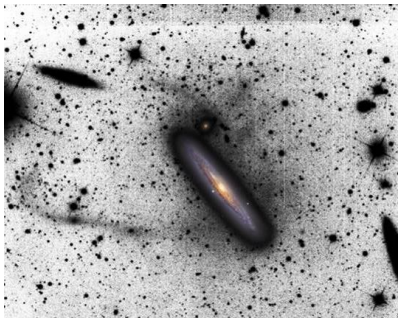


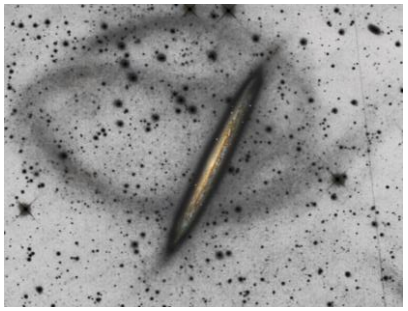




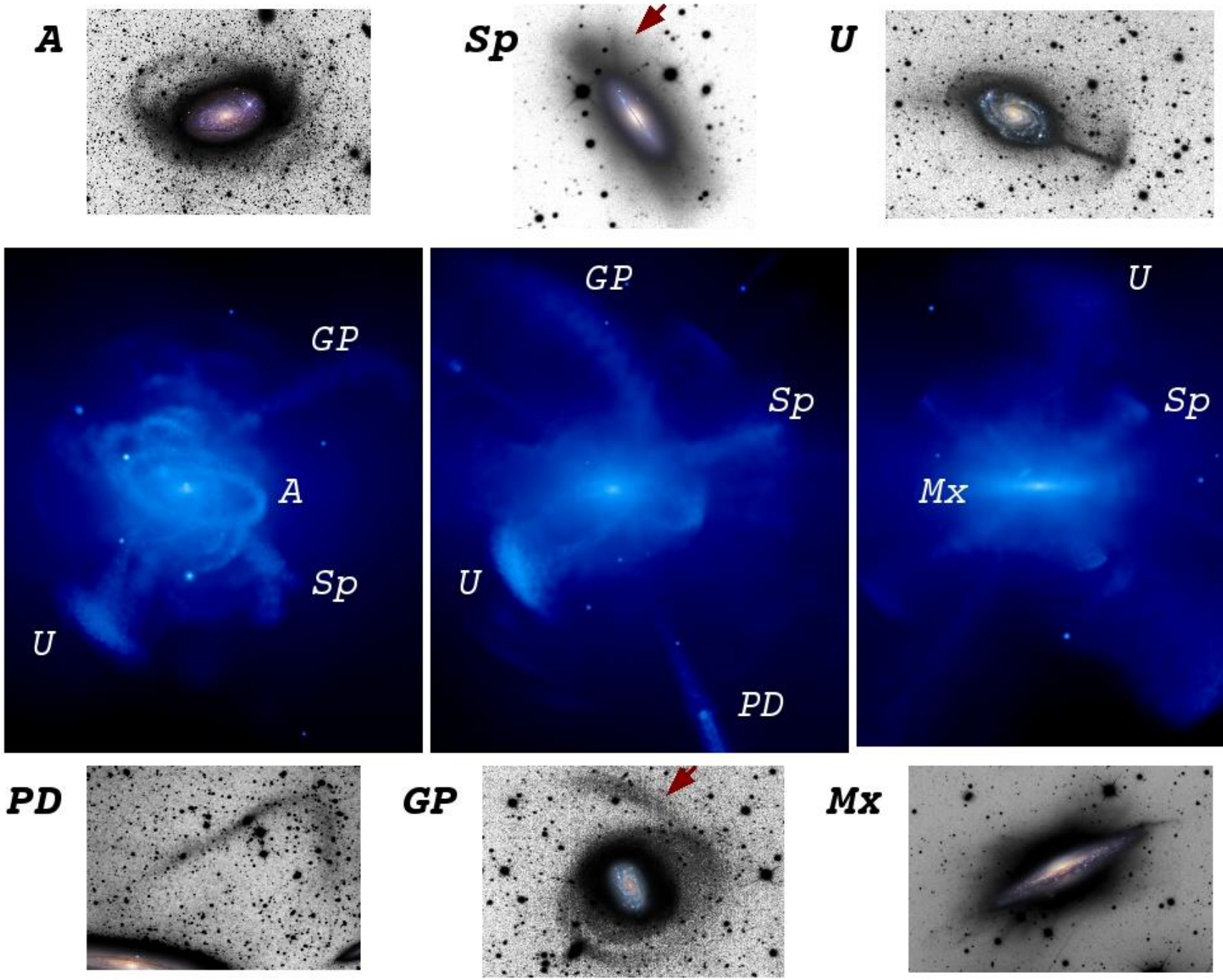






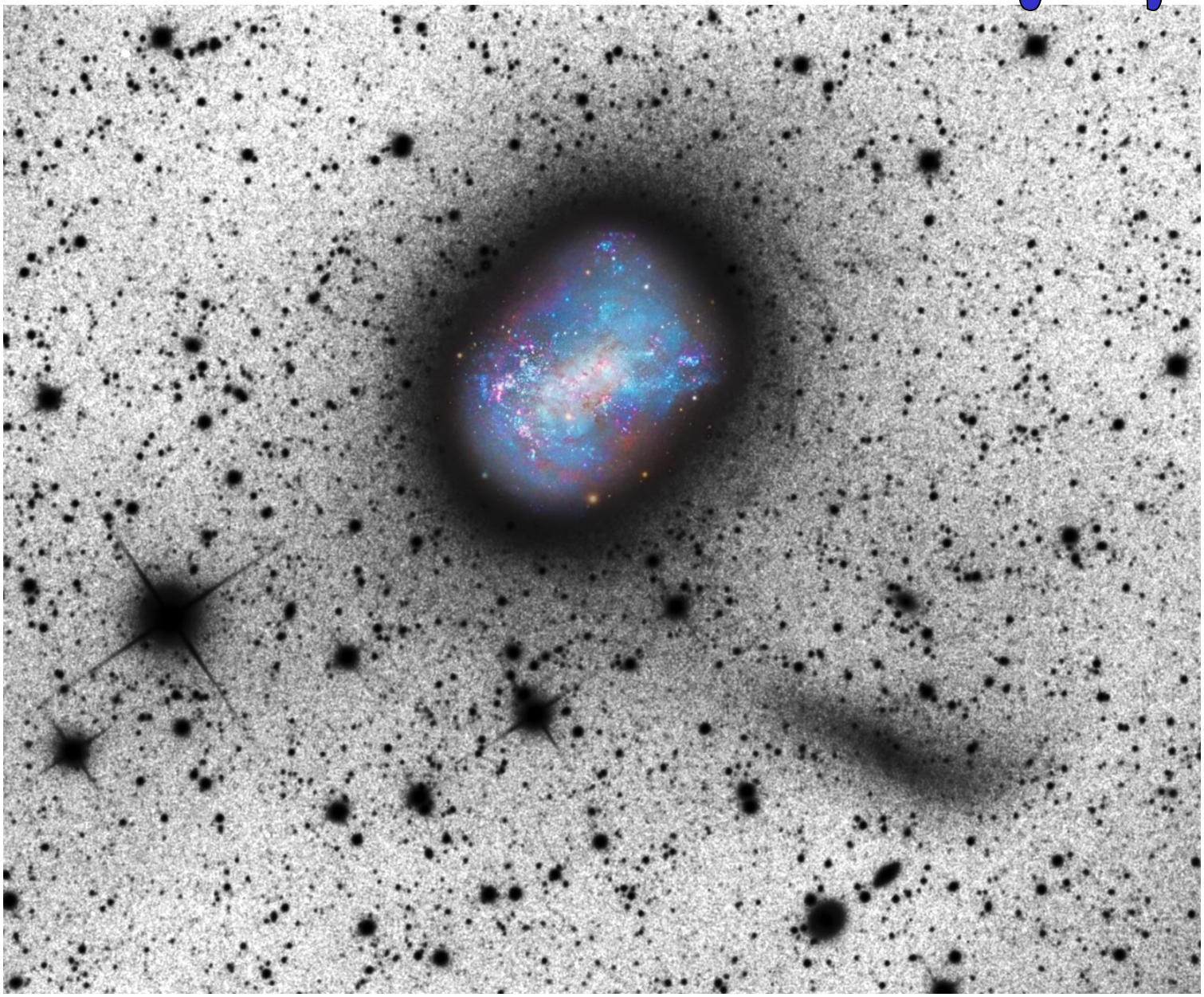


Hendel & Johnson 2015

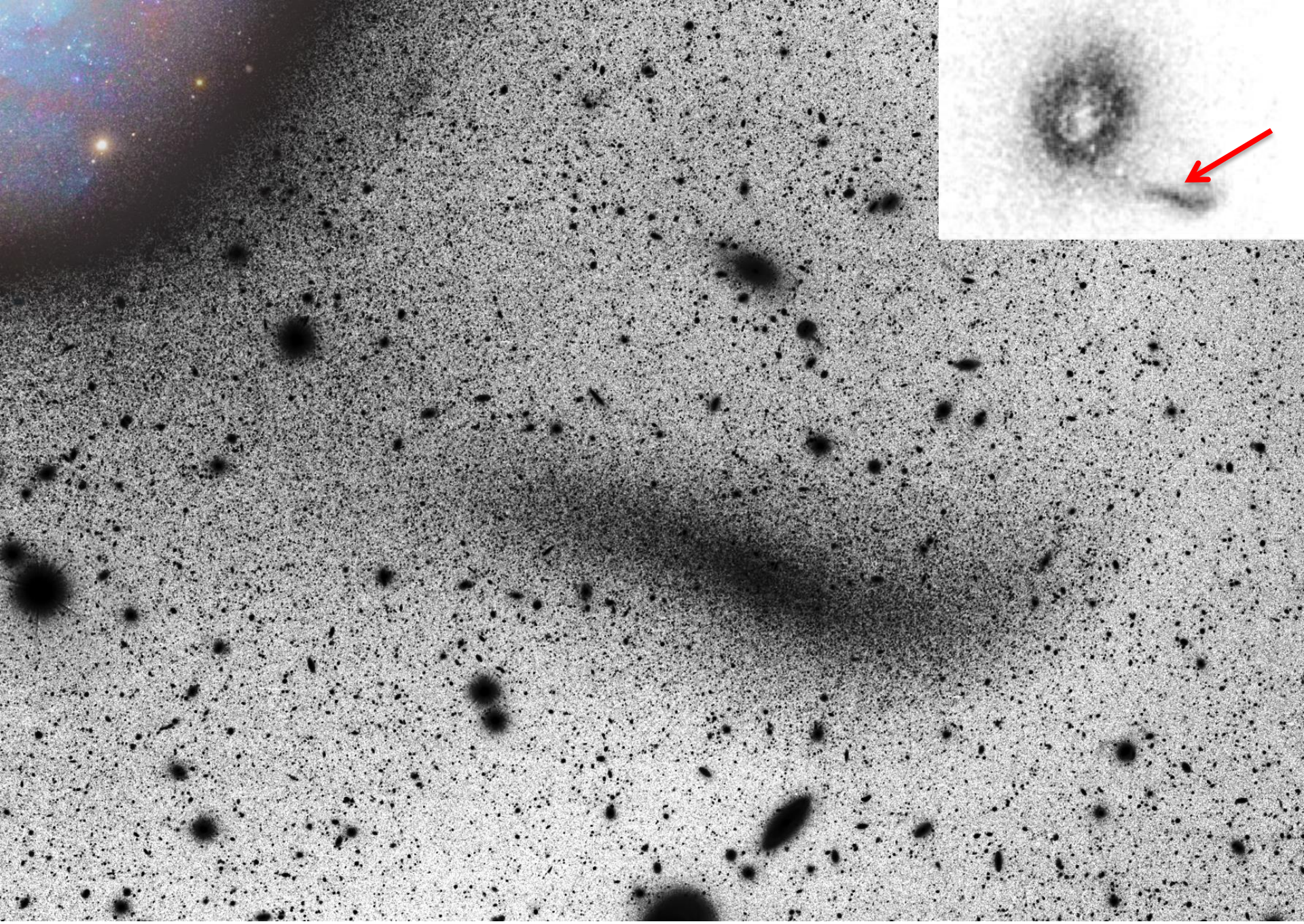


Martinez-Delgado et al. 2010

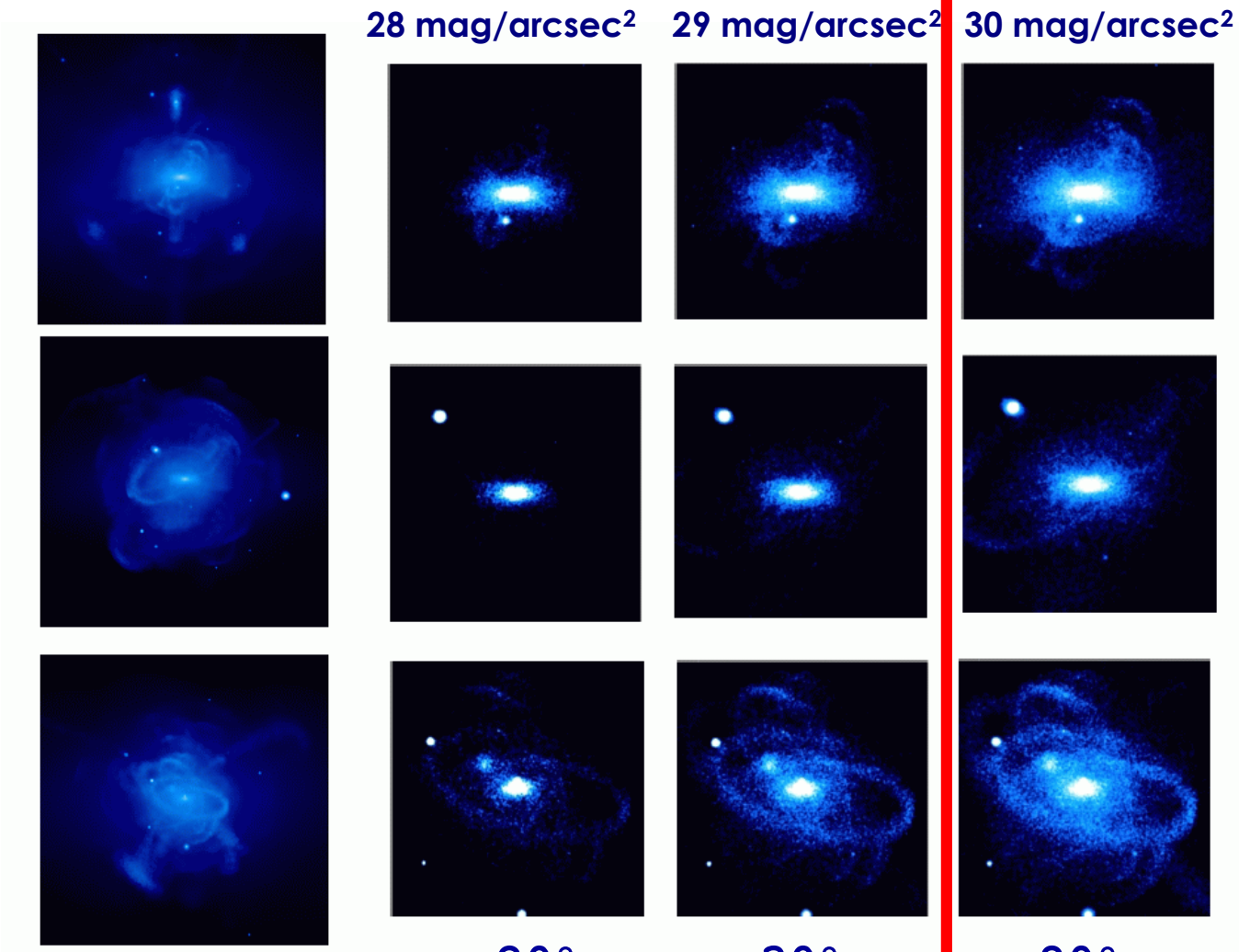
NGC 4449: A stellar stream around a dwarf galaxy



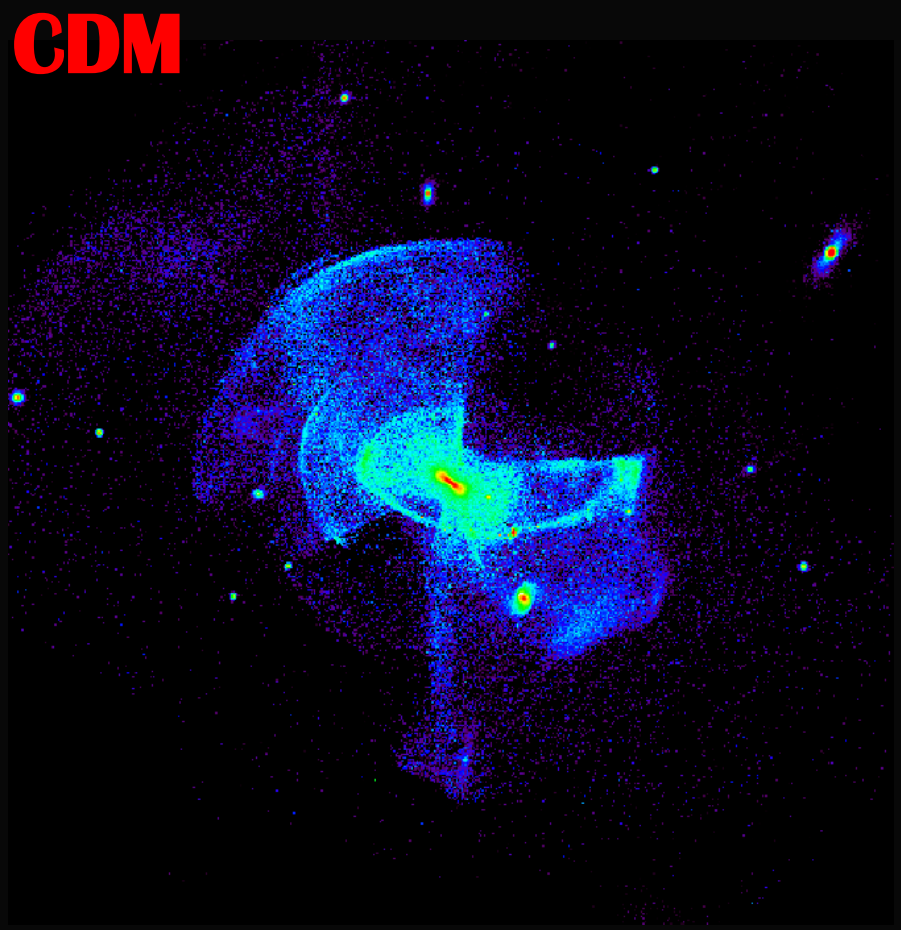
Martinez-Delgado et al. 2012

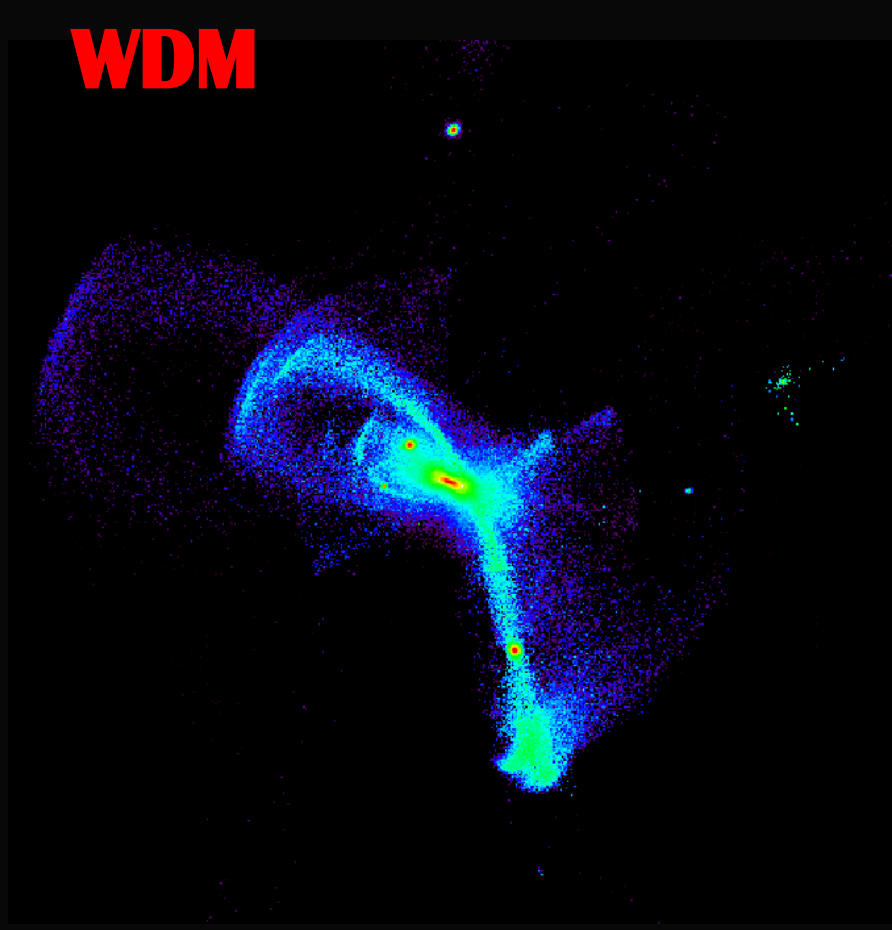


Martinez-Delgado et al. 2012



Our SB limit only allow to detect the brightest stream in each stellar halo (if any)



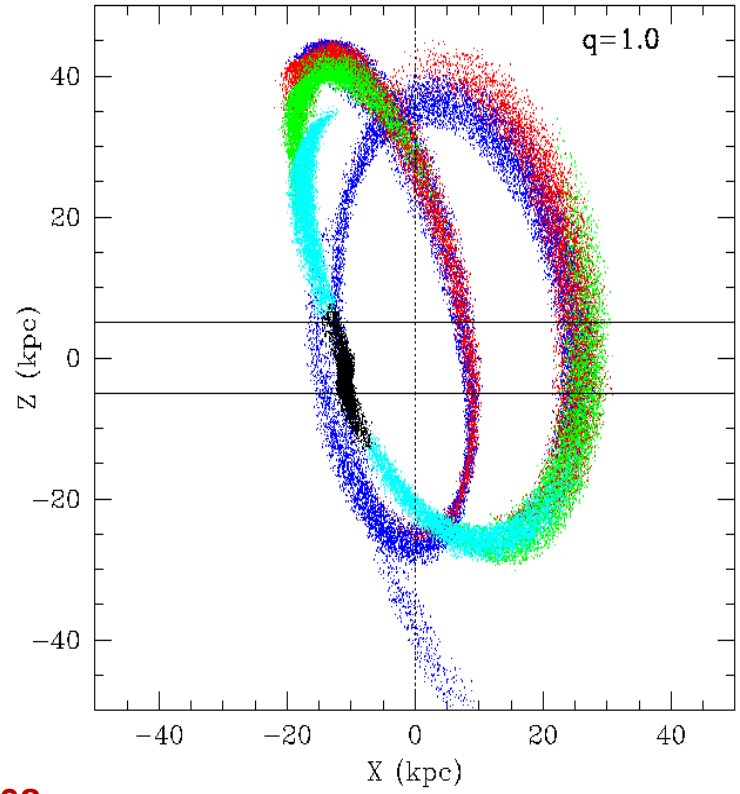


Models by Rachel Kennedi et al. (Durham)

SB(r-band) $_{lim}$= 35 magn/arcsec^2

N-body models of external stellar streams

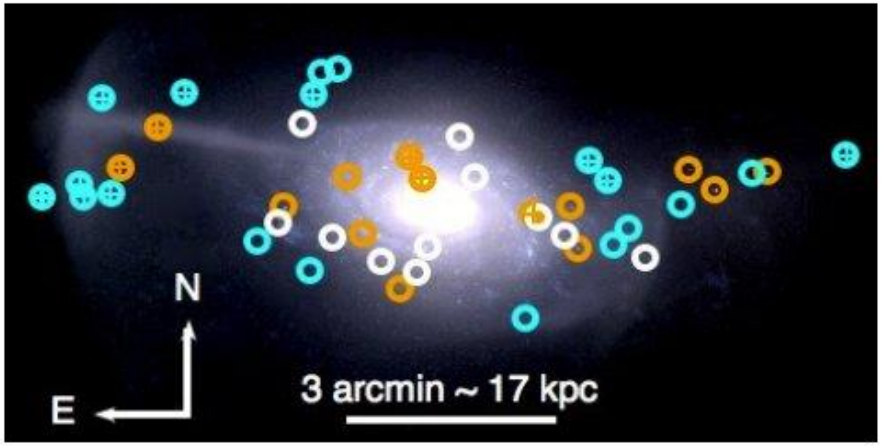
N-body model comparison provides information on:

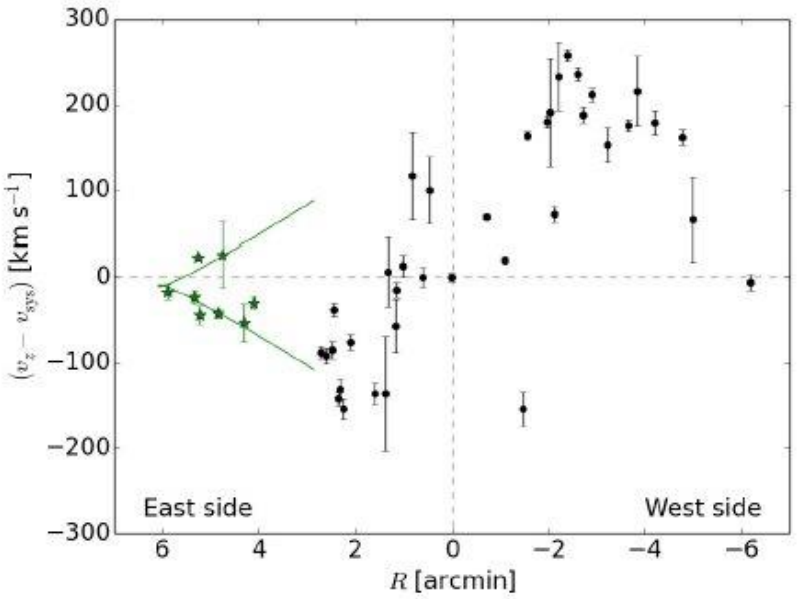


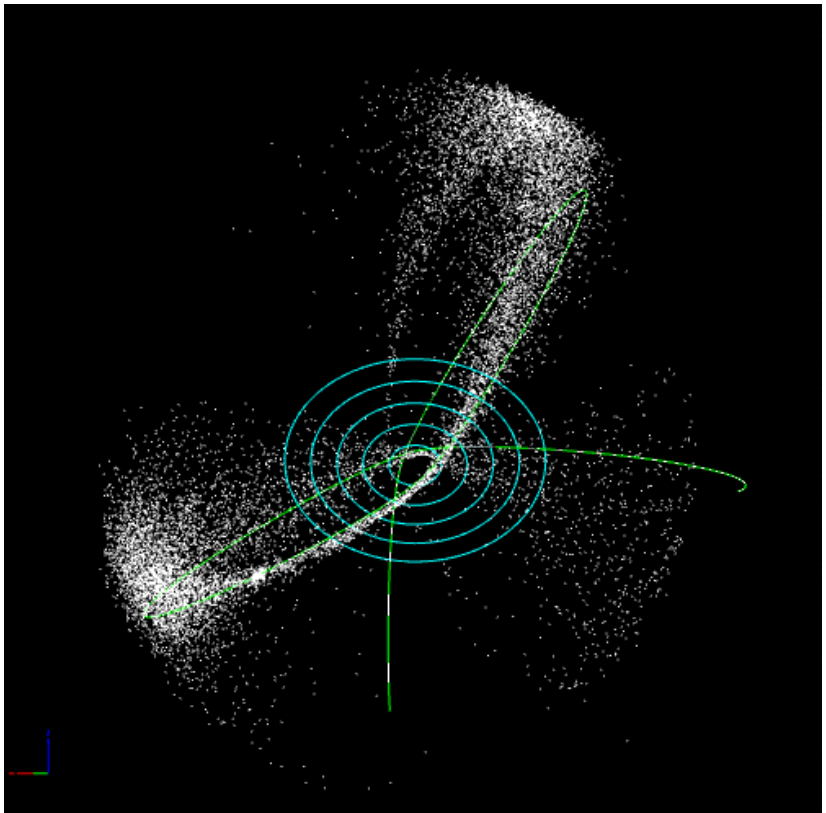
Martinez-Delgado et al. 2008

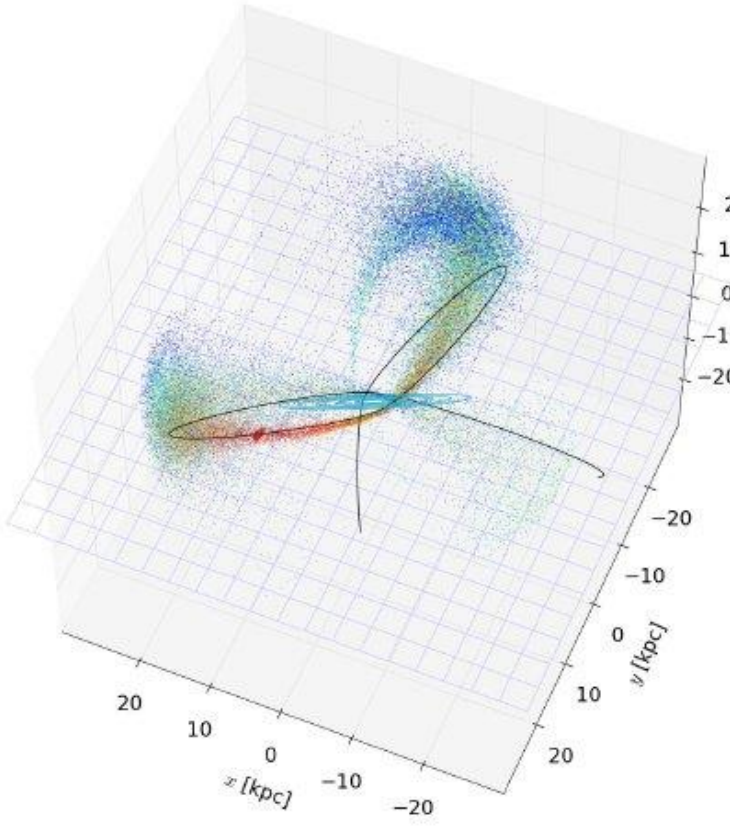
- **Possible initial orbit, morphology and t_{acc}**
- **Initial mass and 3D structure**
- **Nature and position of the progenitor**
- **Mass loss and wraps of different unbound debris (SP gradients)**
- **Single or multiple merger events**

Kinematic information of LSB stream pieces (26-27 magn/arcsec^2) is hard to obtain even in 8-m class telescopes: only sky-projected path of the stream available.



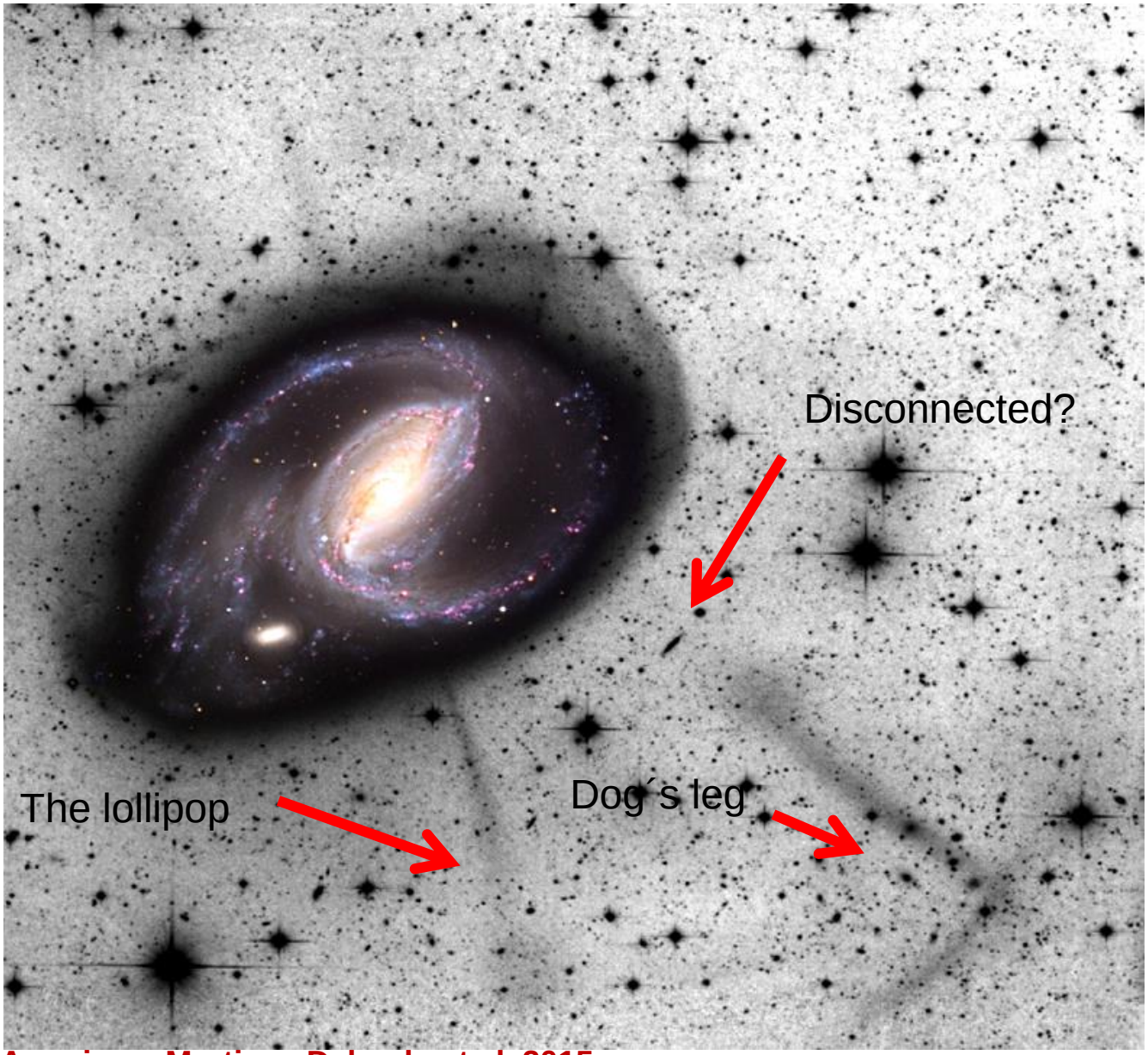






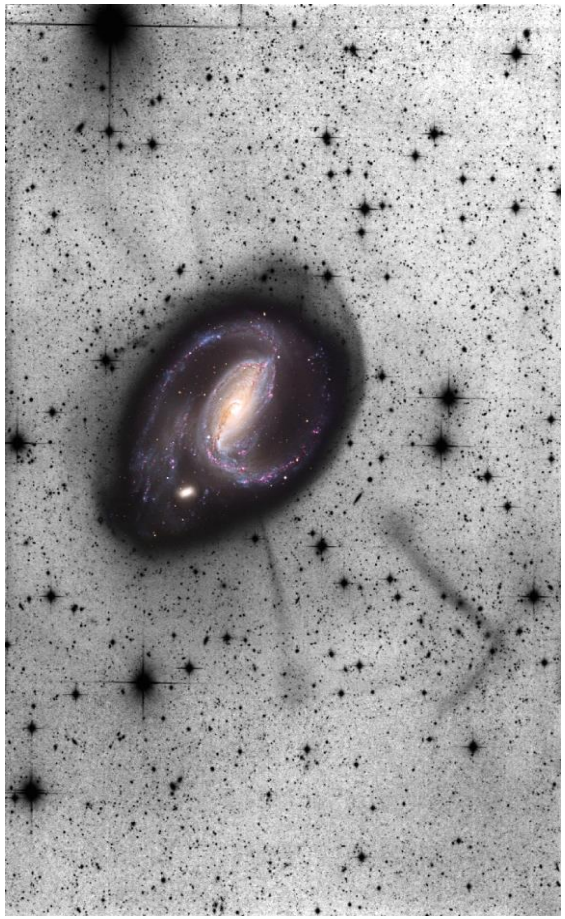
Foster et al. 2014

Revisiting a 70´s classic: the "jets" of NGC 1097

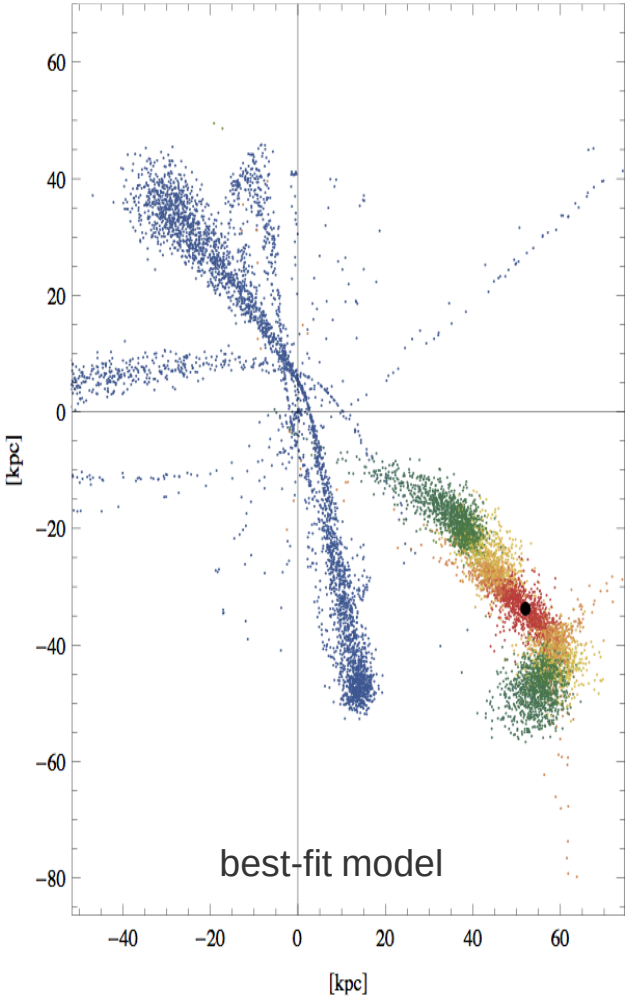


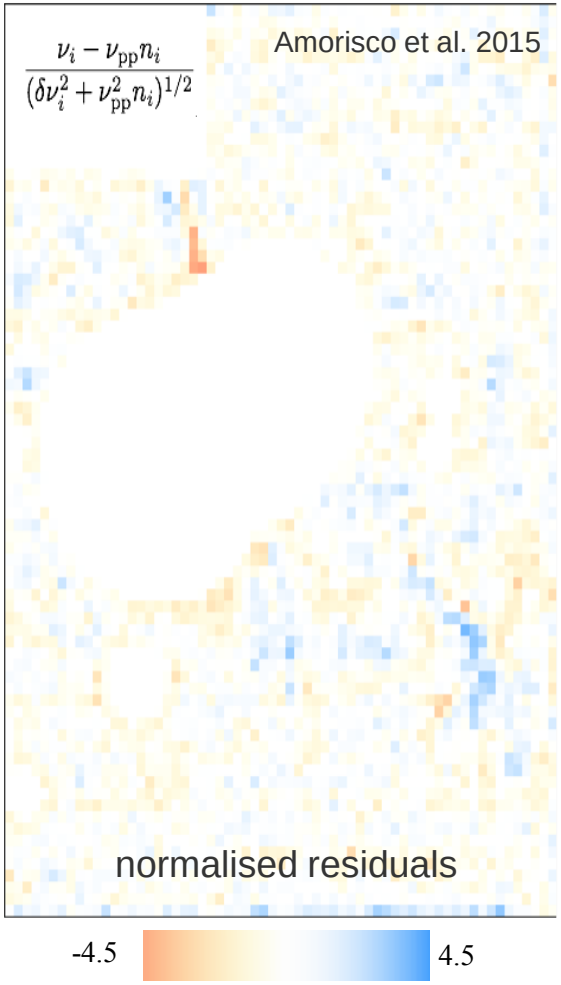
Amorisco, Martinez-Delgado et al. 2015

A quantitative model of the ‘dog-leg’ stream



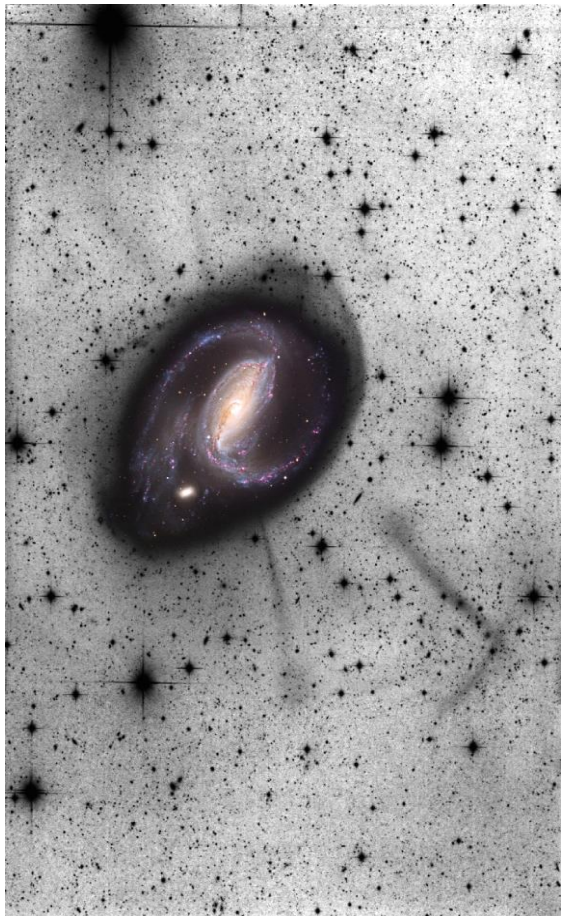
NGC1097



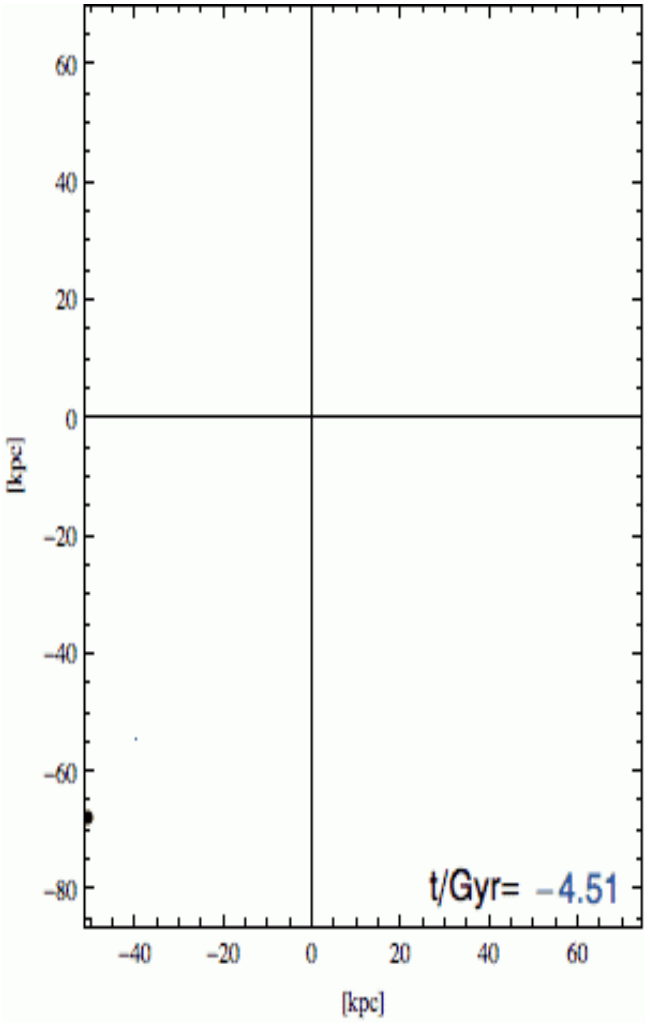


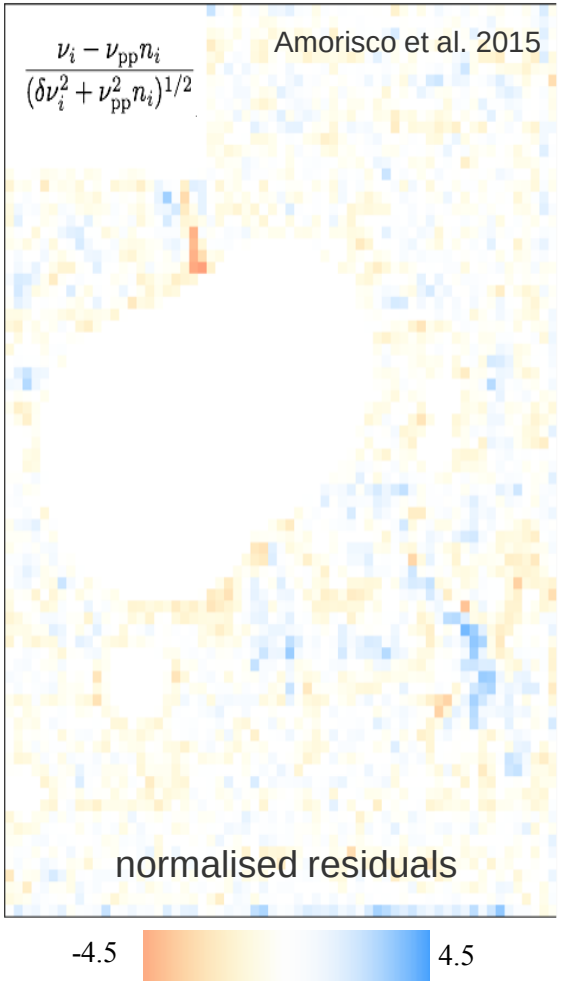
from maximum-likelihood fit to the surface brightness of the stream alone

A quantitative model of the ‘dog-leg’ stream



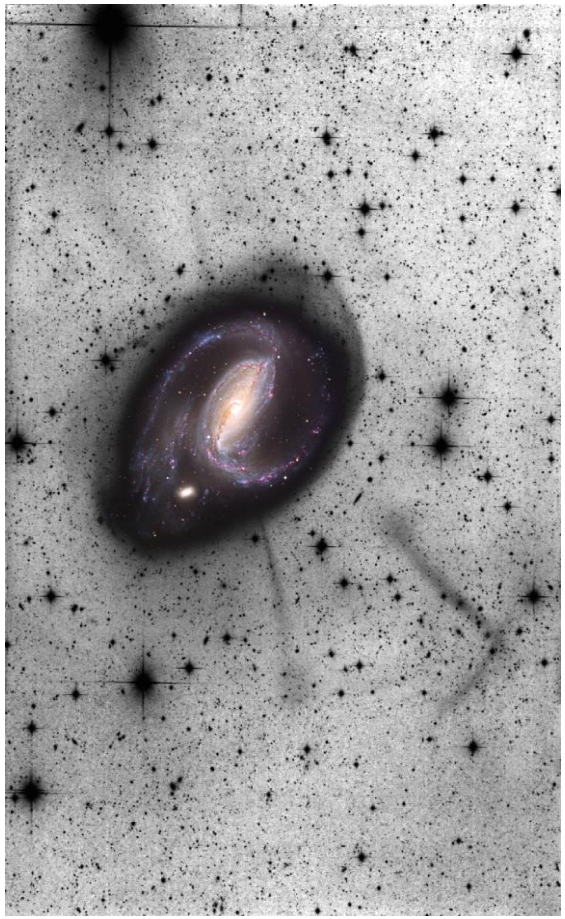
NGC1097



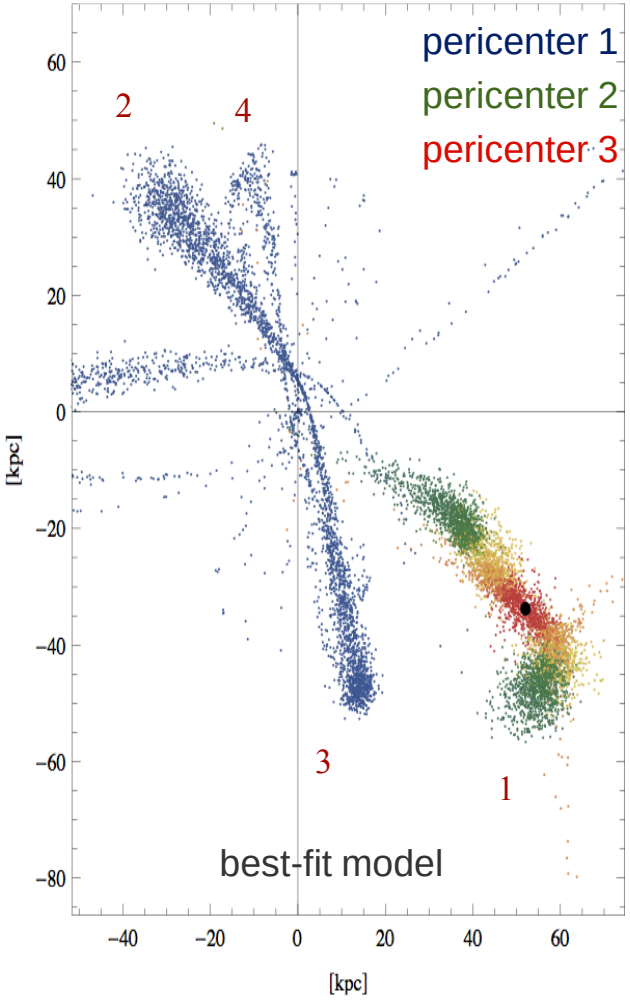


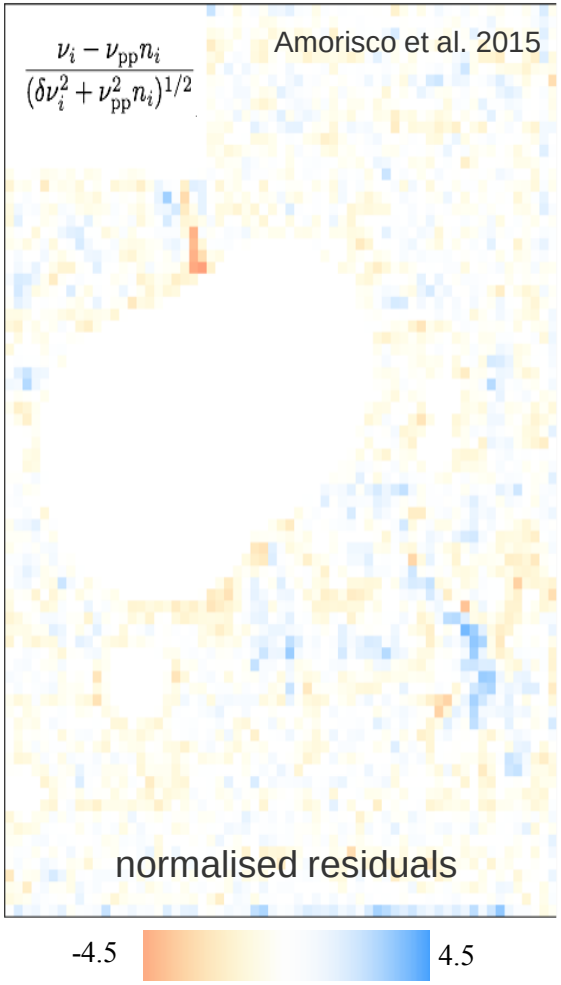
- infall = - 5.4 ± 0.6 Gyr
- 3 pericentric passages

A quantitative model of the ‘dog-leg’ stream



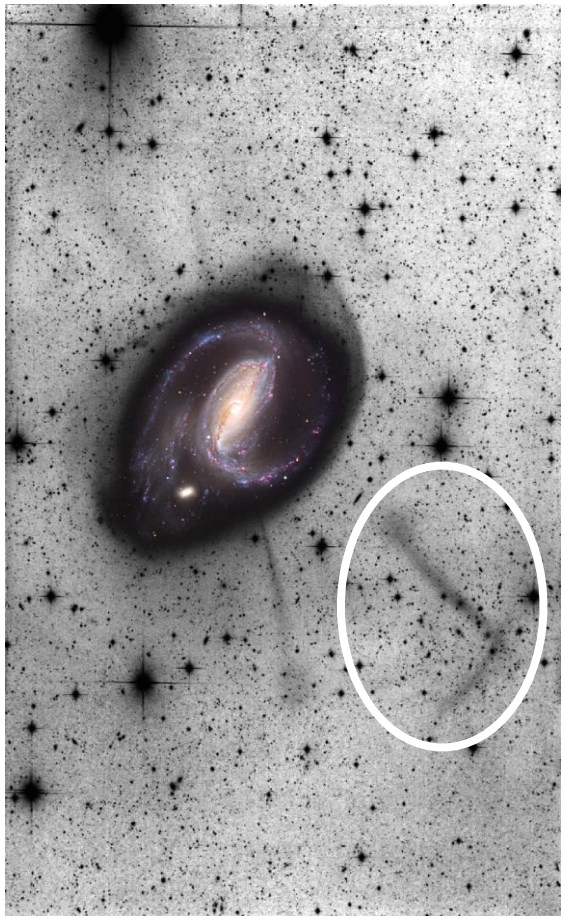
NGC1097



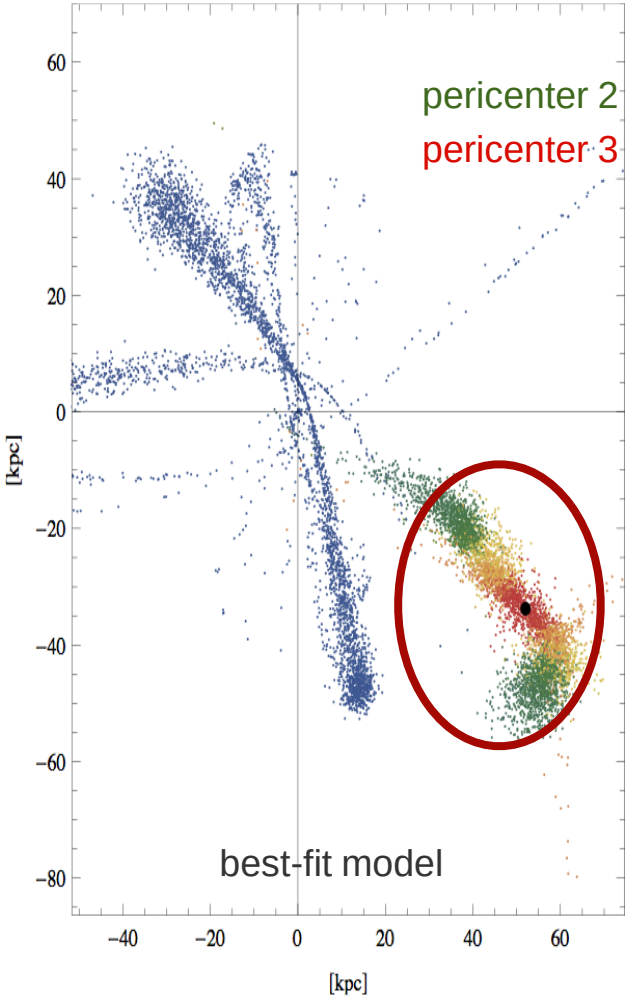


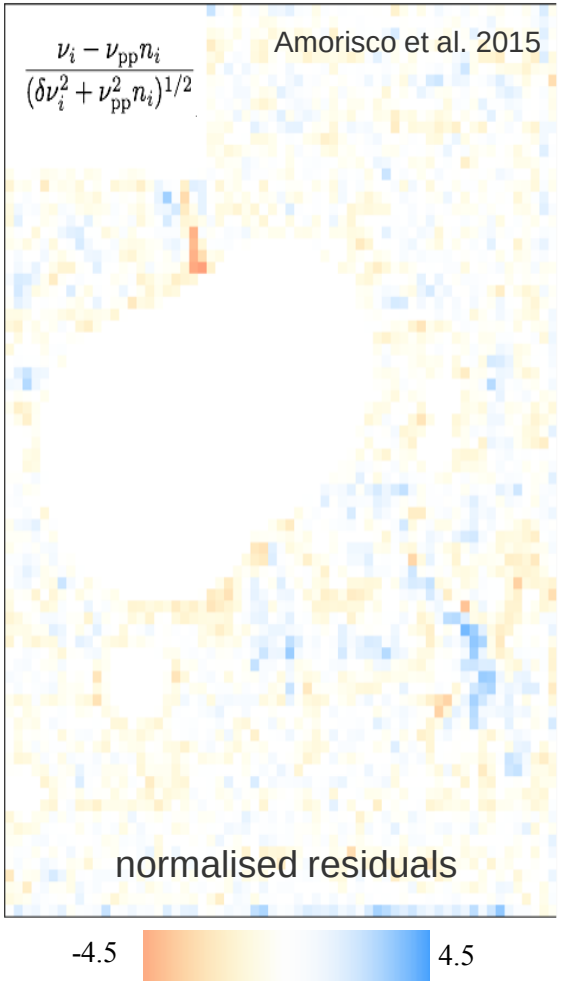
- 4-plumed X-shape

A quantitative model of the ‘dog-leg’ stream



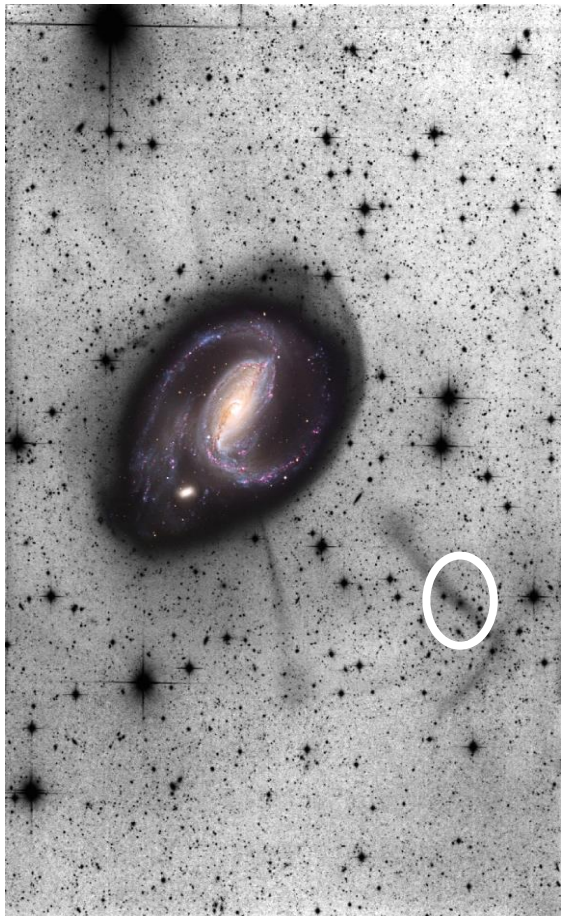
NGC1097



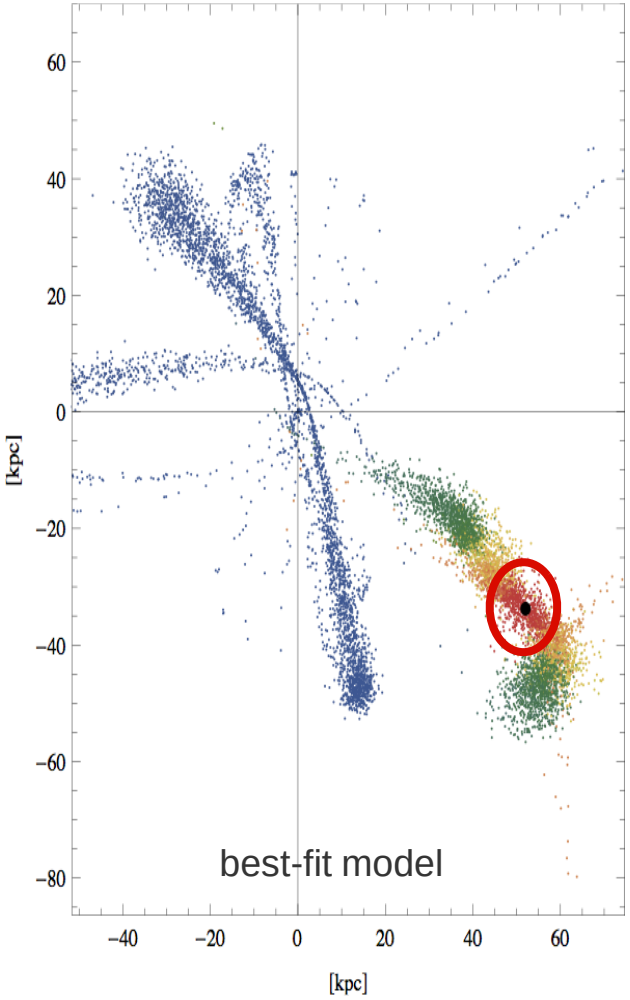


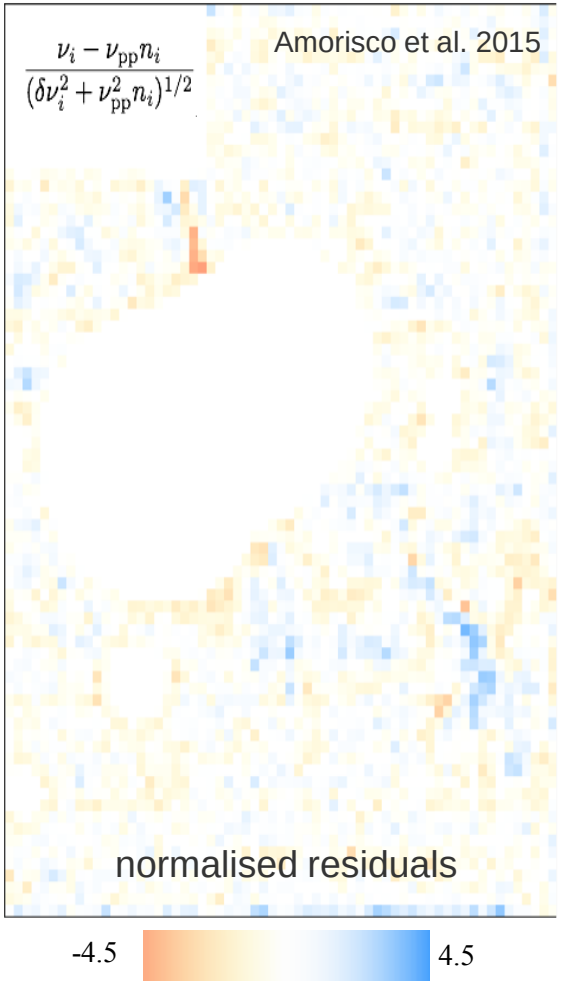
- 4-plumed X-shape
- ‘dog-leg’ morphology

A quantitative model of the ‘dog-leg’ stream



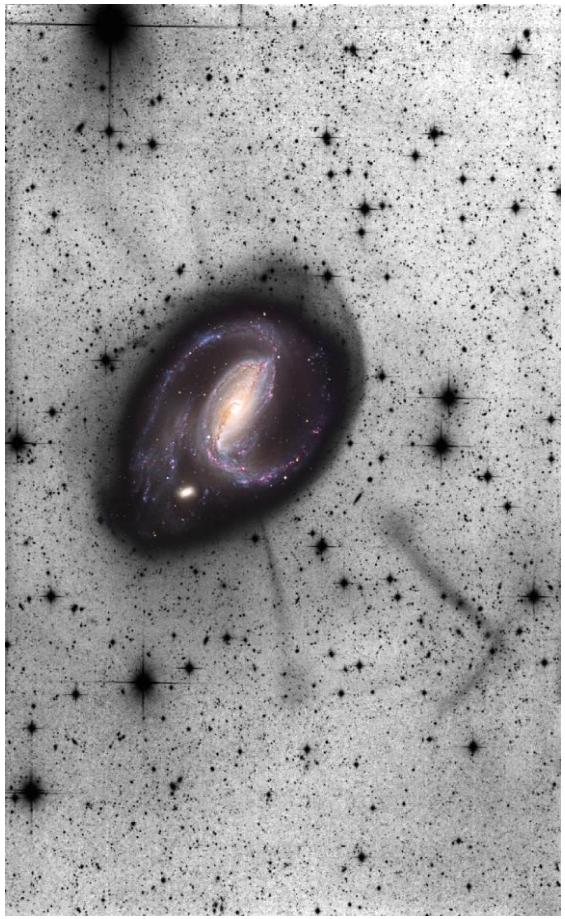
NGC1097



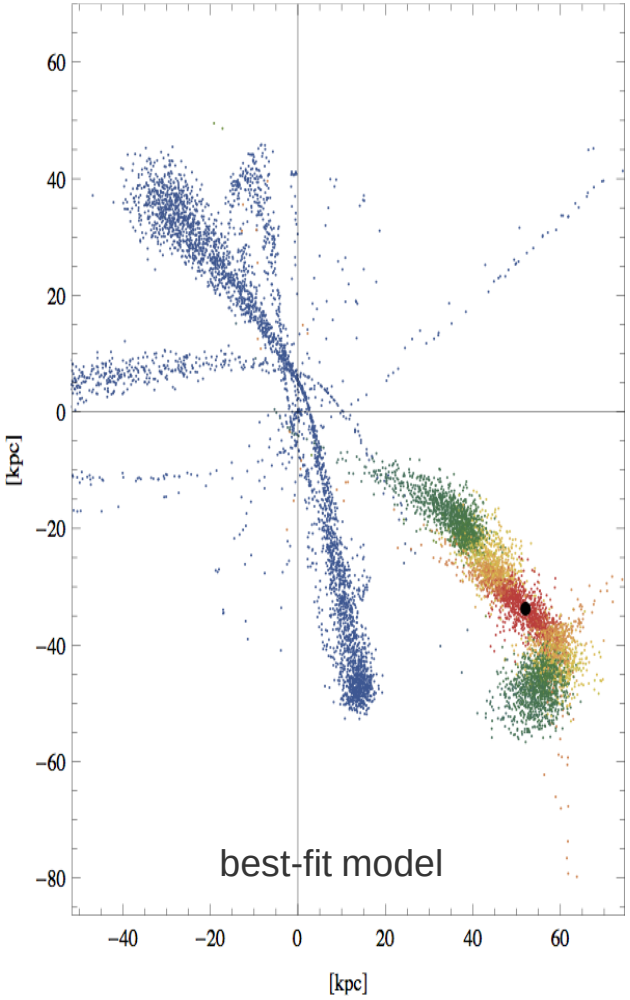


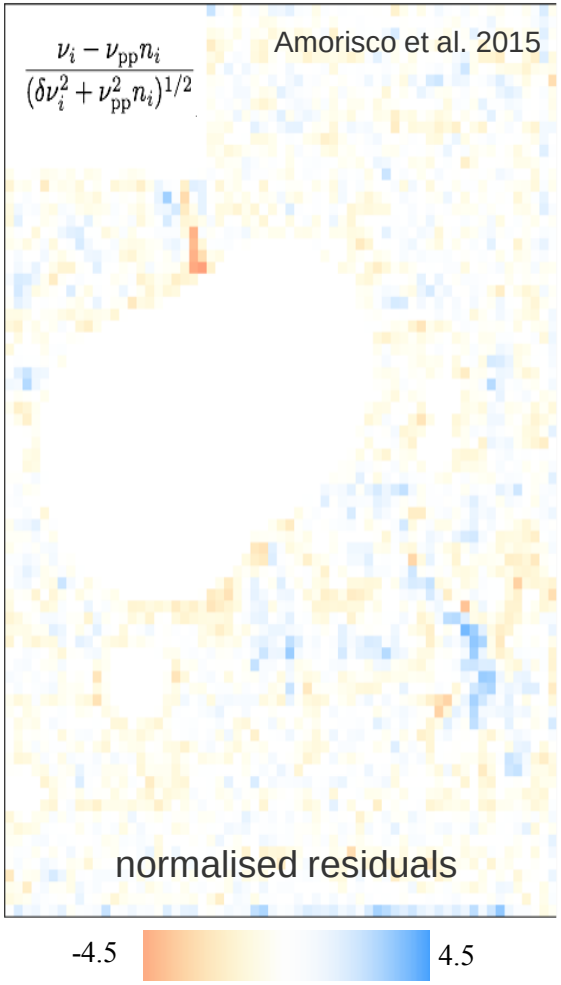
- remnant’s projected position
- 4-plumed X-shape
- ‘dog-leg’ morphology

A quantitative model of the ‘dog-leg’ stream



NGC1097



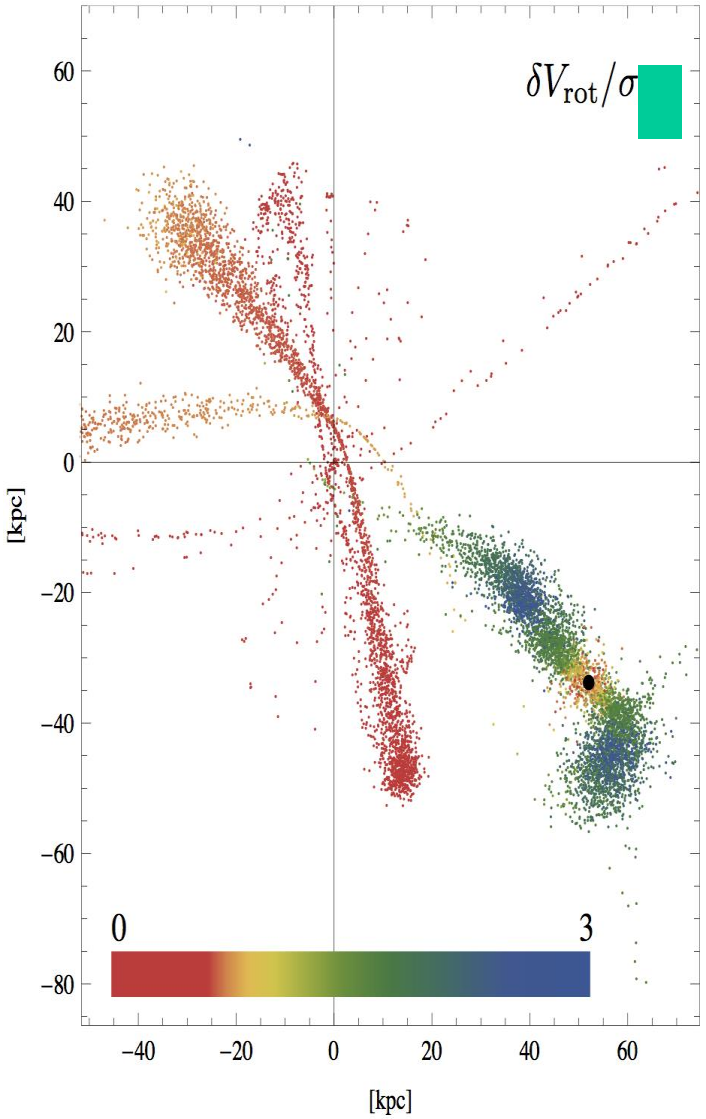


⇒ correctly predicts the remnant’s LOS-velocity

- model: -51 ± 16 km/s
- observed: -30 ± 30 km/s

Galianni et al. 2010

The ‘dog-leg’: signature of internal rotation



long sharp 90° turn requires ordered escape velocities

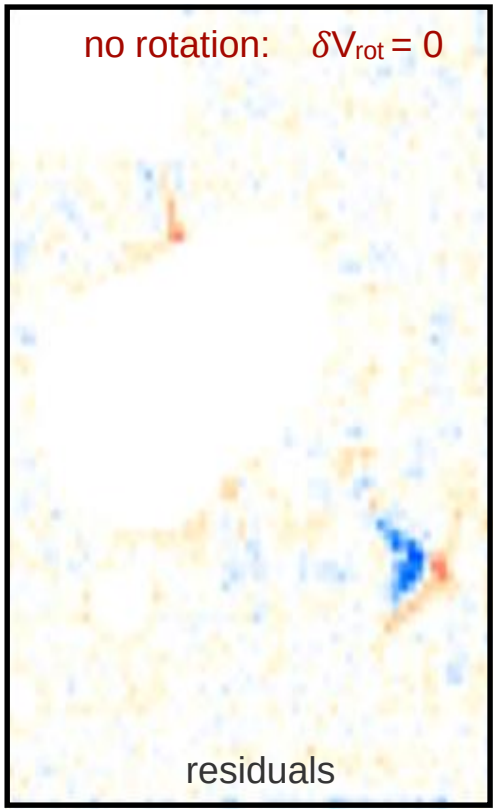
suggesting the progenitor was rotating

- random vel. at escape: σ
- if internal angular momentum in progenitor

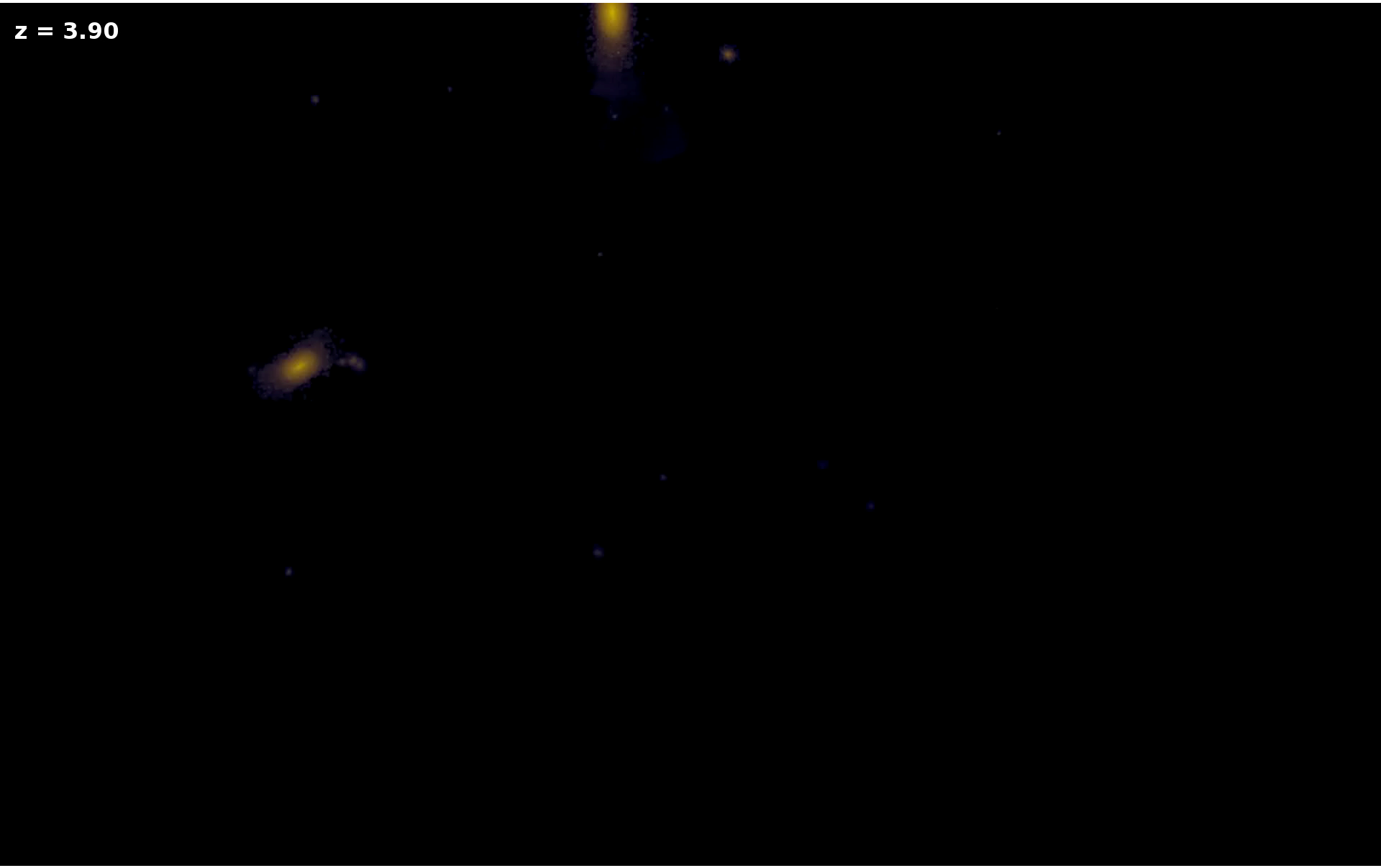
⇓

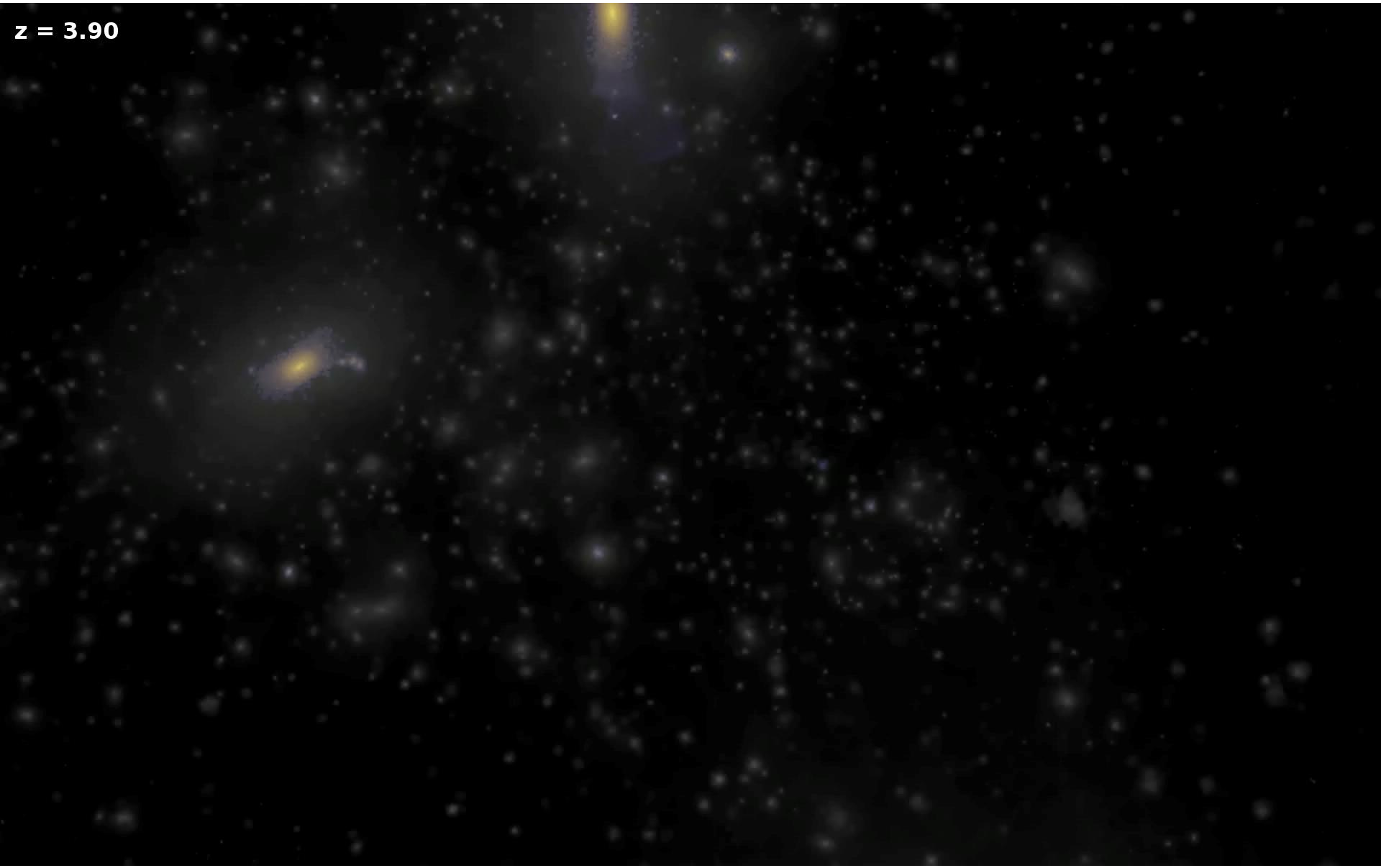
ordered vel. at escape

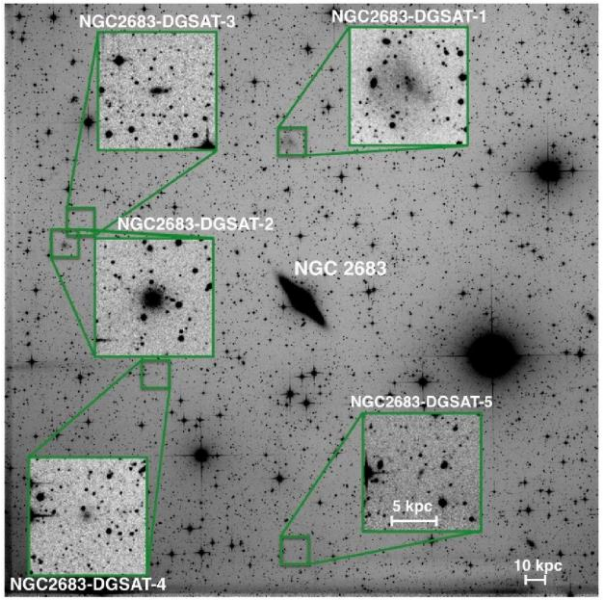
$\delta V_{\rm rot} \approx 10$ to 15 km/s

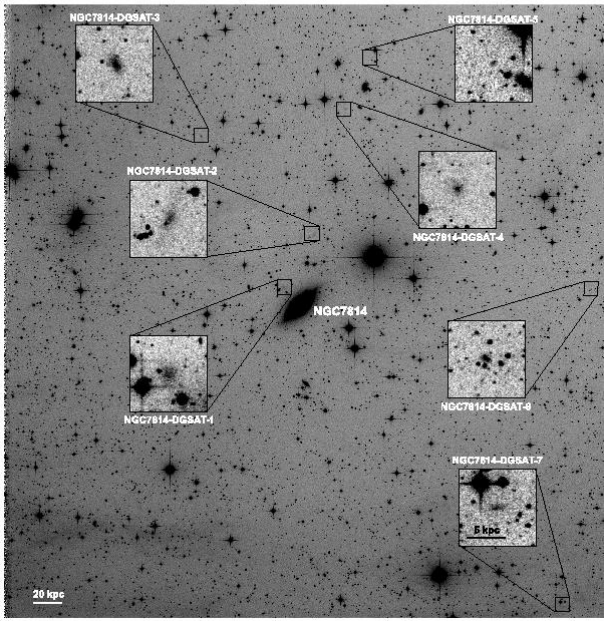


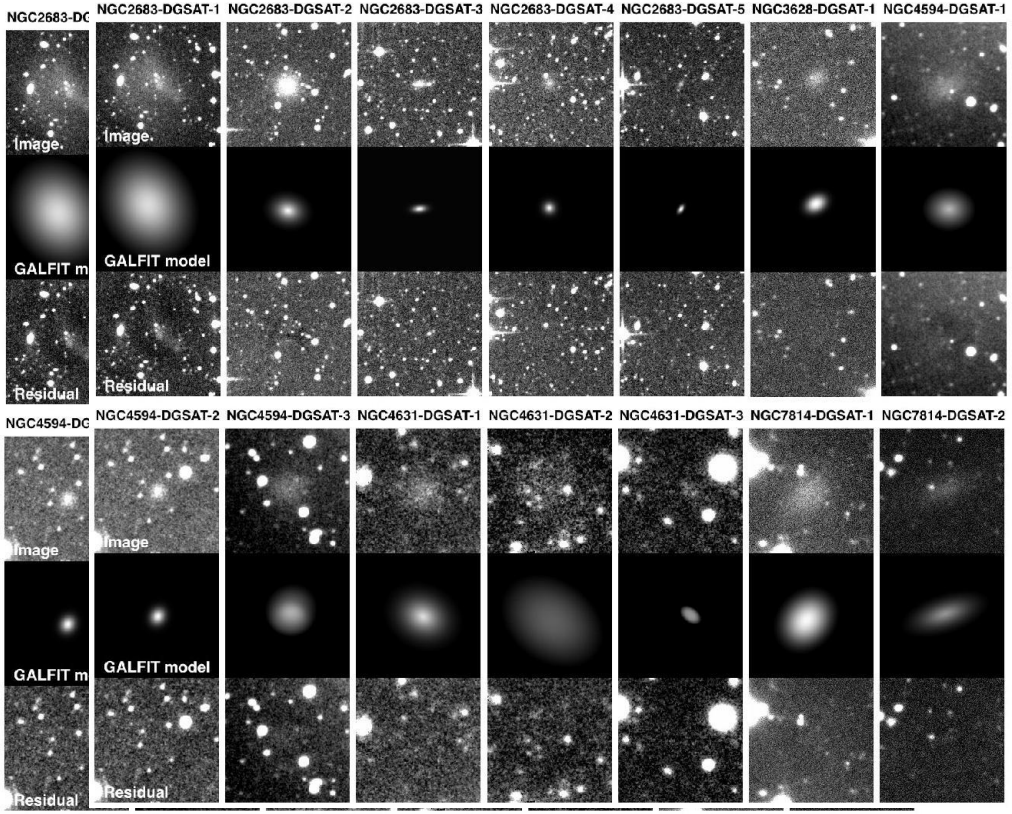
D. Looking for the “missing satellites” in nearby spiral galaxies

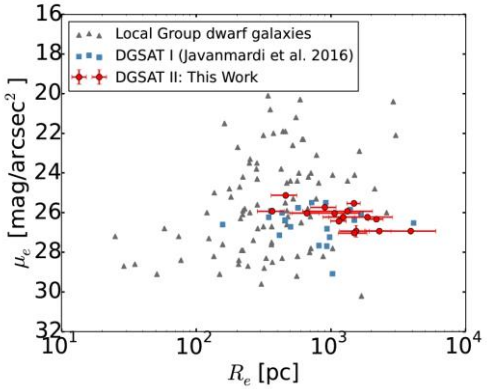

z = 3.90

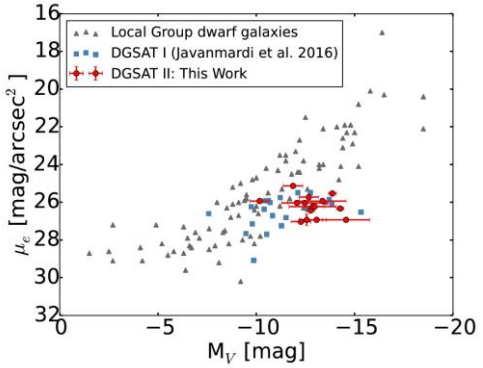

z = 3.90





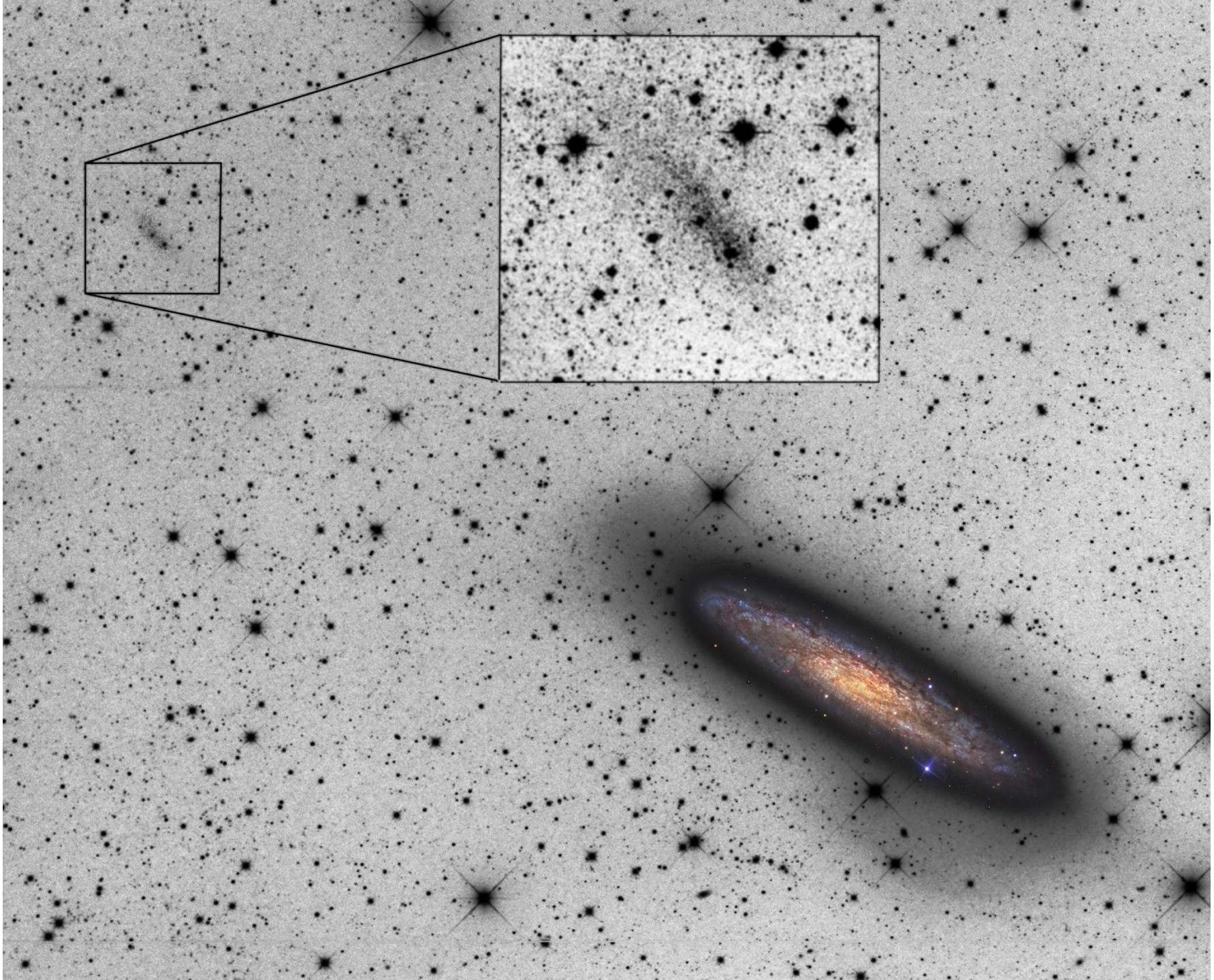






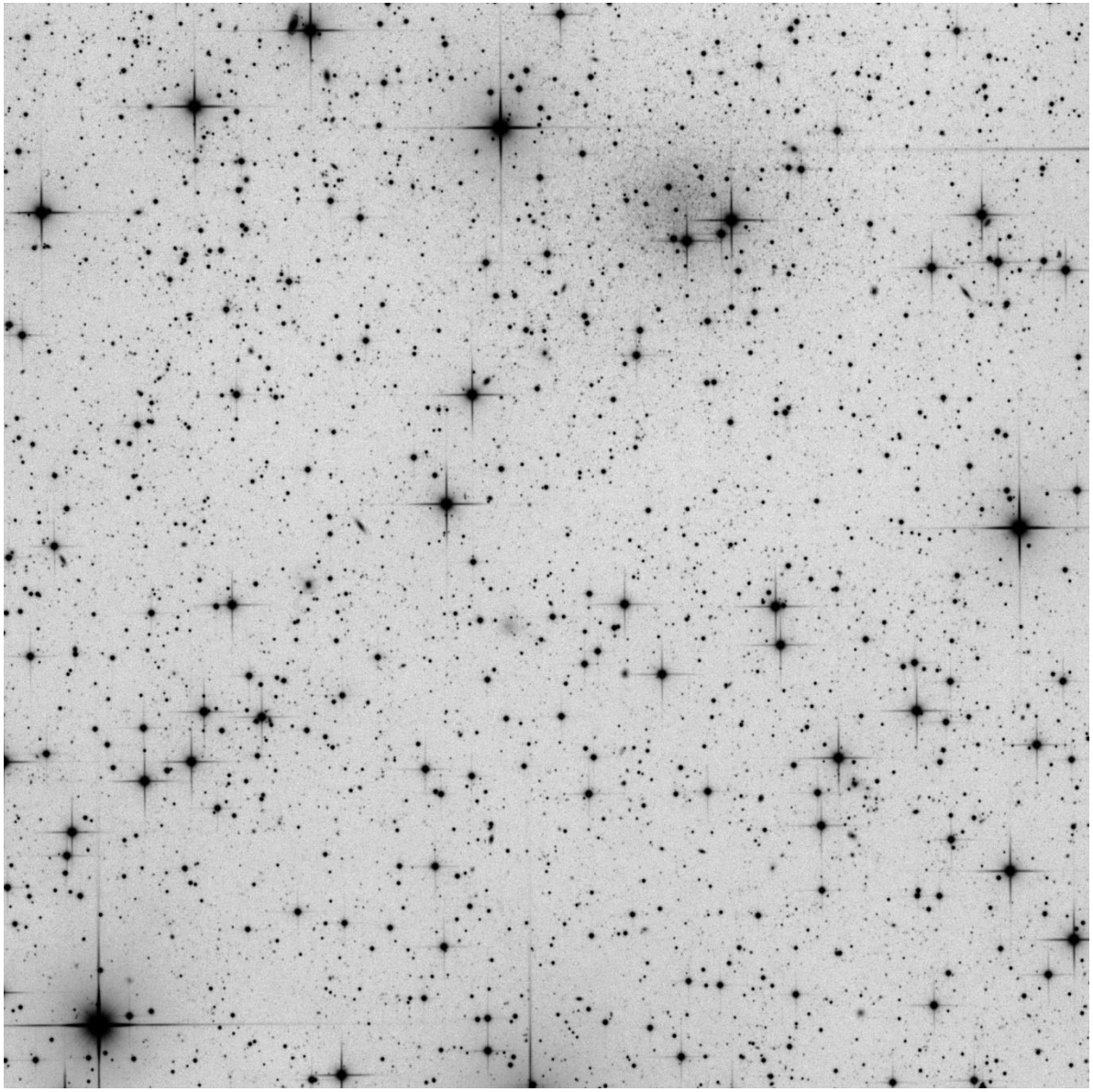
The Dwarf Galaxy Survey with Amateur Telescopes (DGSAT)

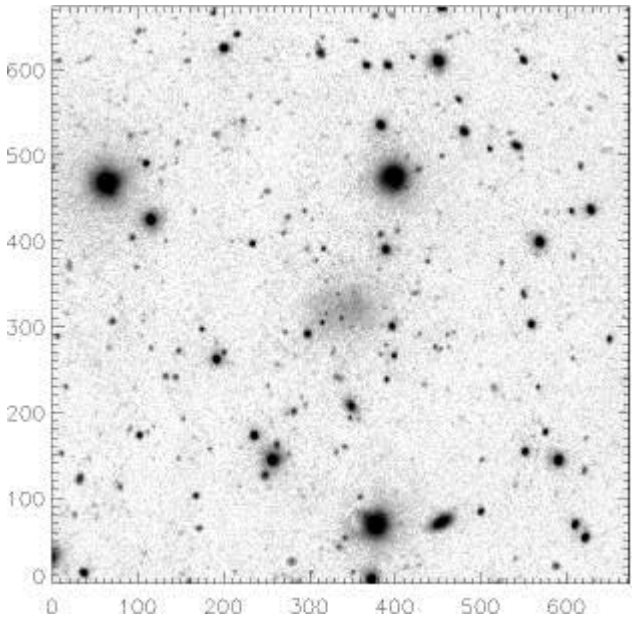
Javanmardi,. Martinez-Delgado et al. 2016 (images by Karel Teuwen (ROSA team)

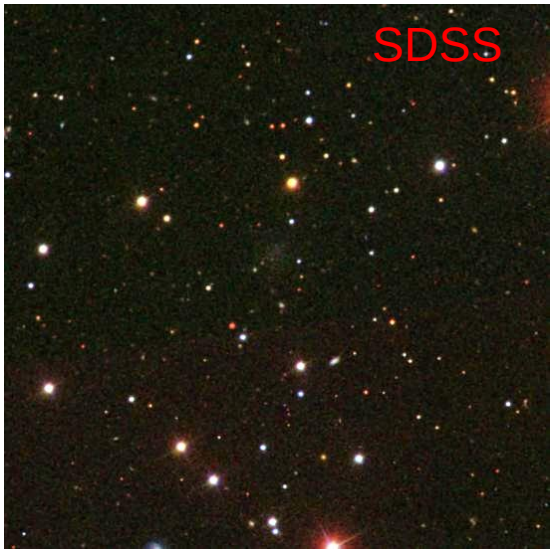


C. The misterious Ultra-Diffuse Galaxies (UDGs)

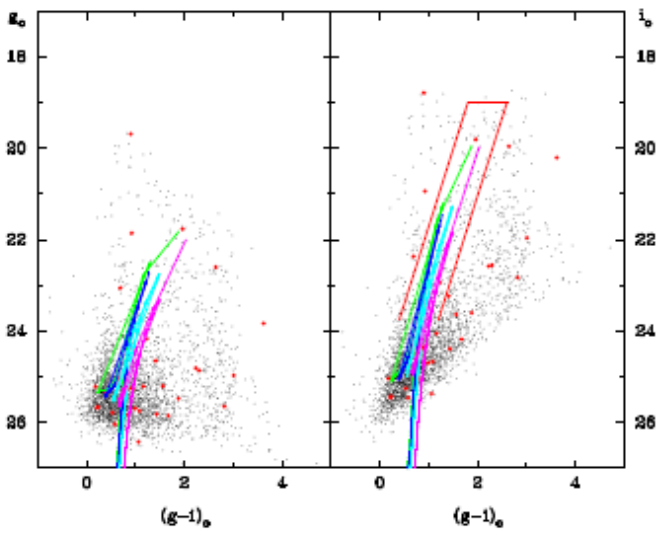

Candidate 1

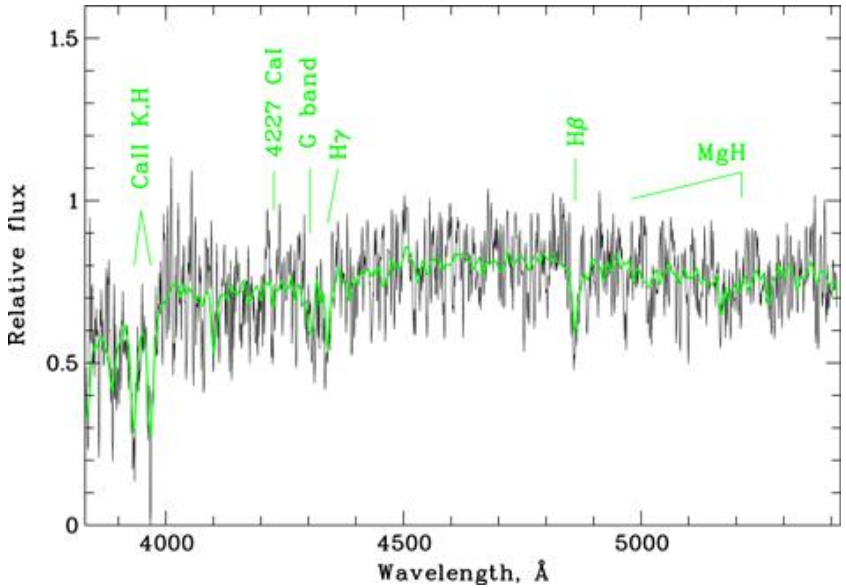






Martinez-Delgado et al. 2013

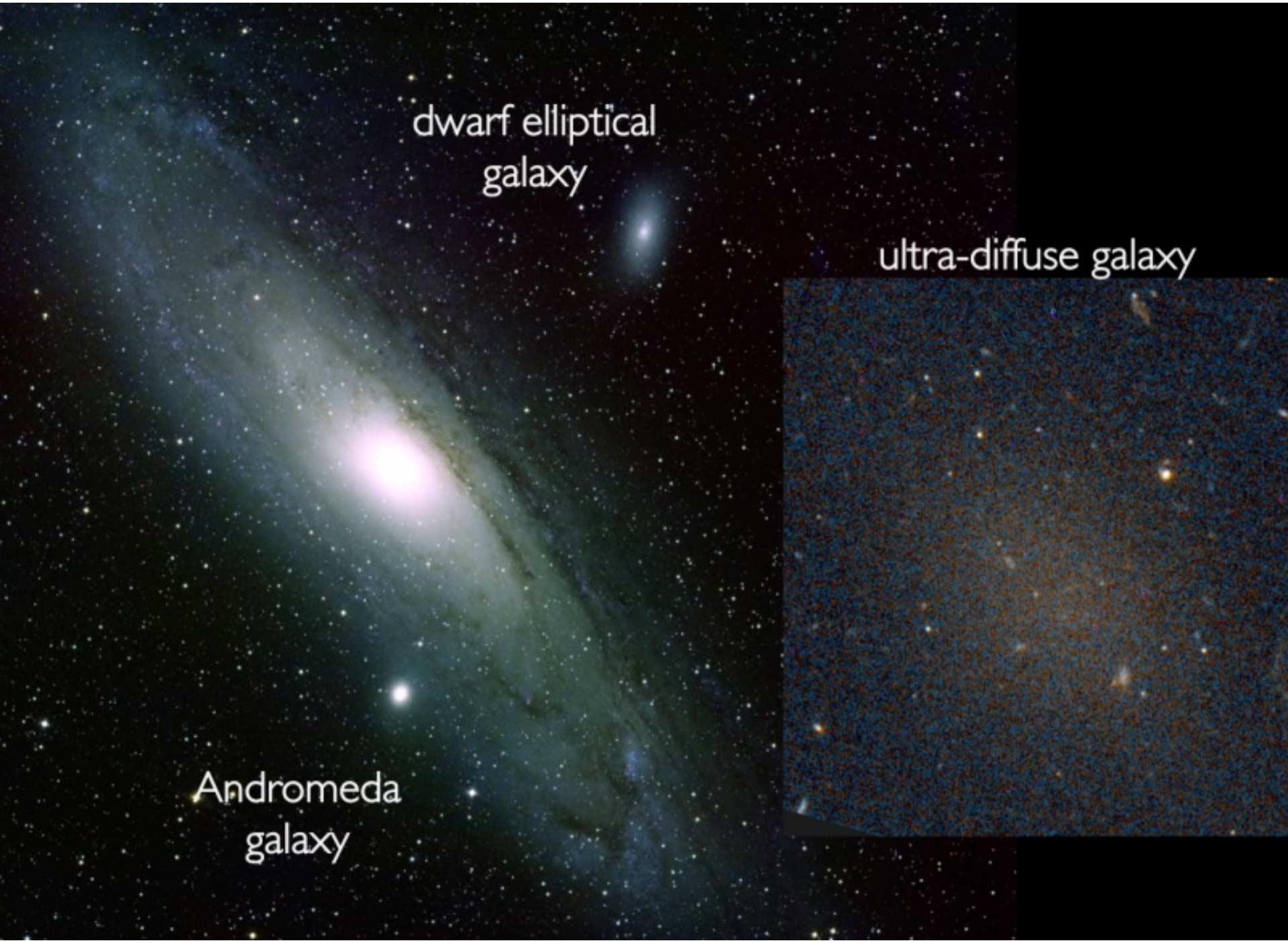


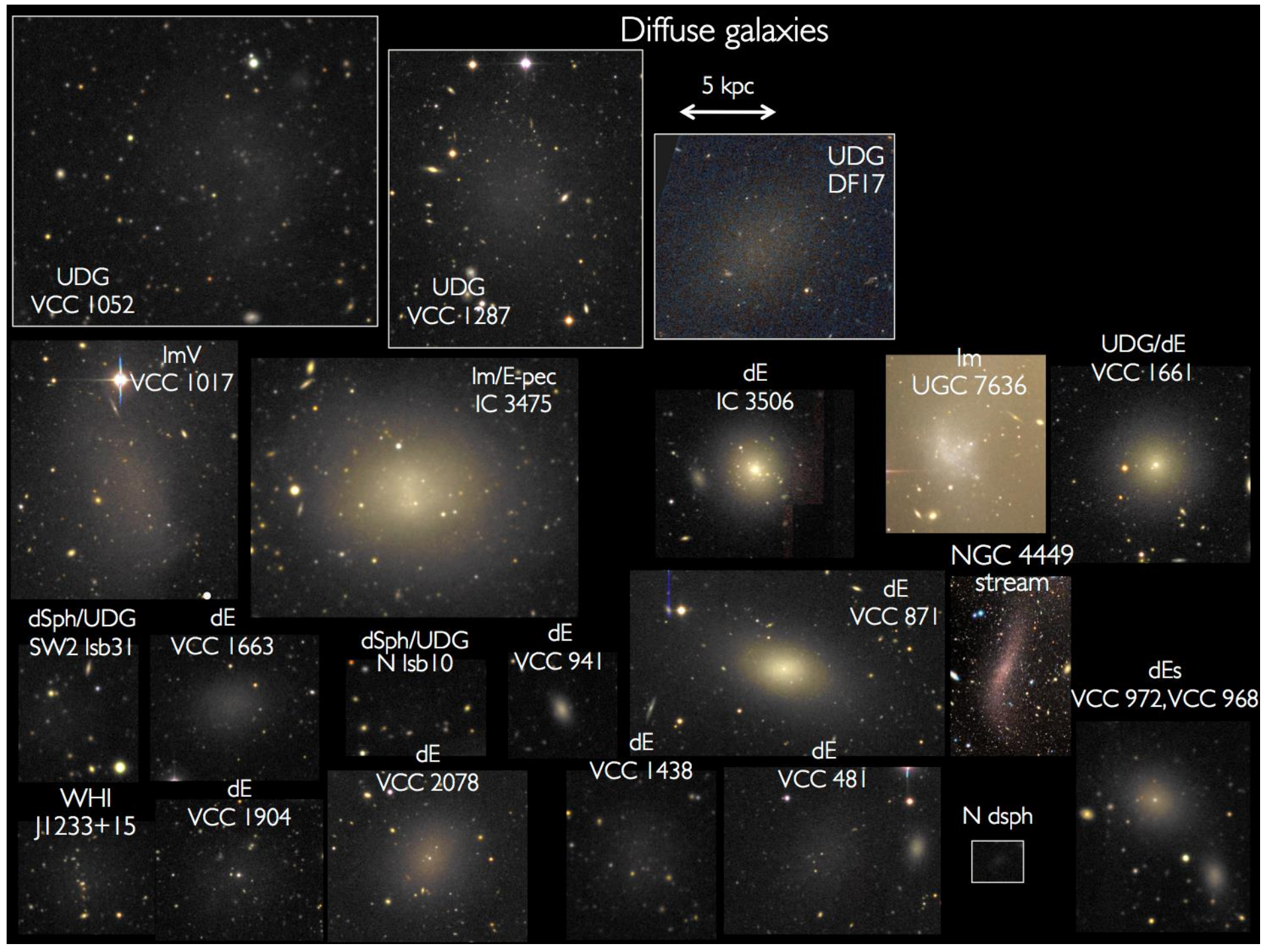


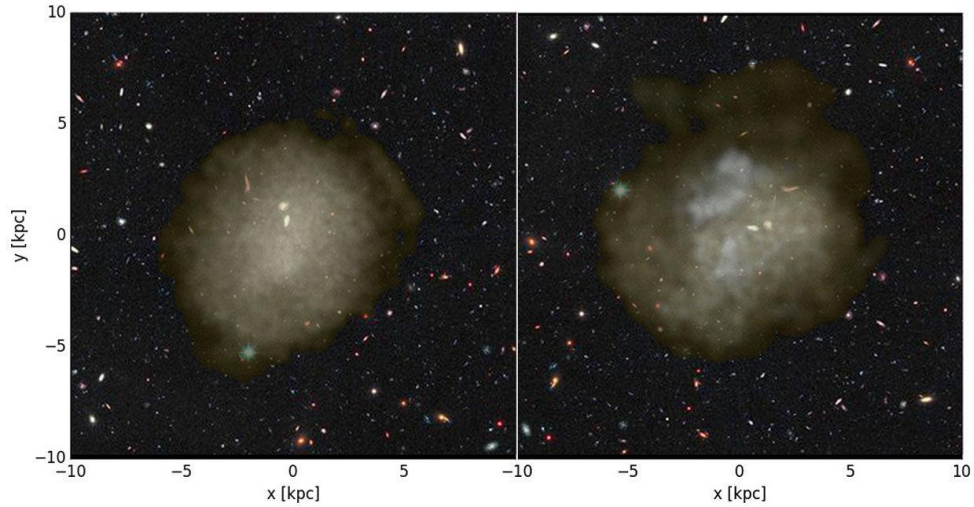
- The candidate is visible in archive SDSS and **Subaru data as unresolved object** with apparent g-band magnitude g≈ 18.5 and R_half≈ 12.8".

- μ(g-band)≈ 25.5, smooth structure and ausence of emission lines of typical of a **dwarf spheroidal**. No visible en deep Hα images with 6-meter telescope.

- **Distance estimated** from 6-m telescope spectra: 75 Mpc!!! **Size: 12 kpc!**

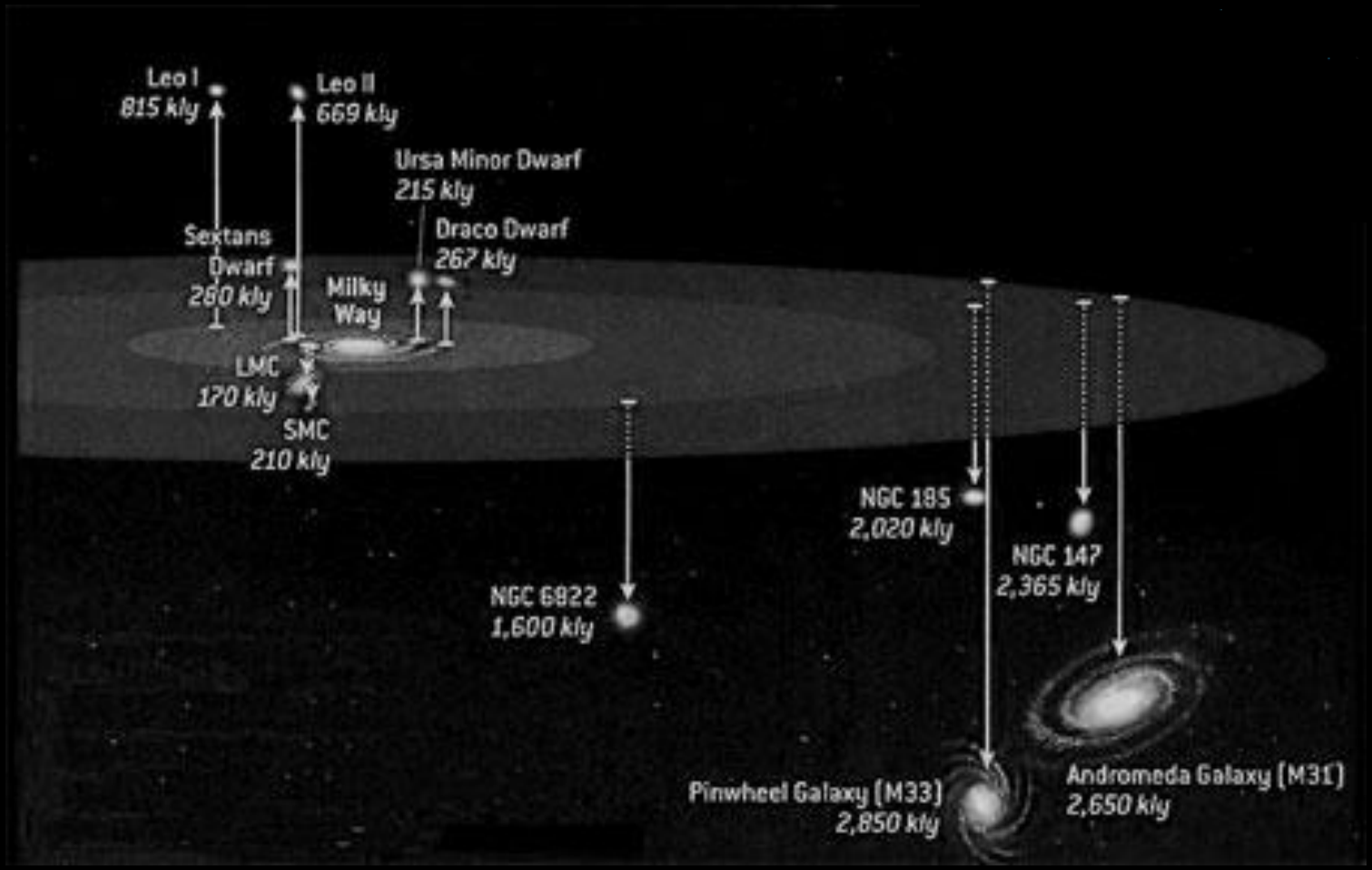

dwarf elliptical
galaxy
ultra-diffuse galaxy
Andromeda
galaxy

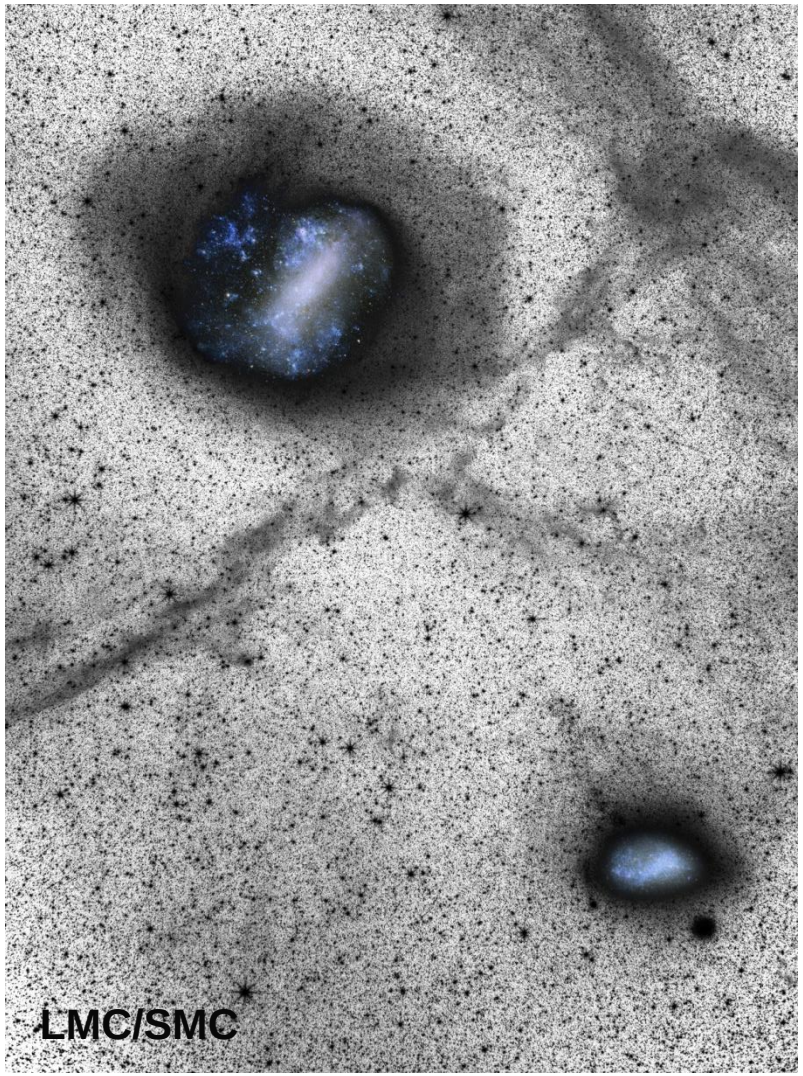

Diffuse galaxies
5 kpc
UDG
VCC 1052
UDG
VCC 1287
UDG
DF17
ImV
VCC 1017
Im/E-pec
IC 3475
dE
IC 3506
Im
UGC 7636
UDG/dE
VCC 1661
NGC 4449
stream
dE
VCC 871
dSph/UDG
SW2 Isb31
dE
VCC 1663
dSph/UDG
N Isb10
dE
VCC 941
dEs
VCC 972,VCC 968
dE
VCC 2078
dE
VCC 1438
dE
VCC 481
WHI
J1233+15
dE
VCC 1904
N dsph


y [kpc]
x [kpc]
x [kpc]


DGSAT I HST

C. Stellar streams and over-densities in the outskirts of Milky Way dwarf satellites

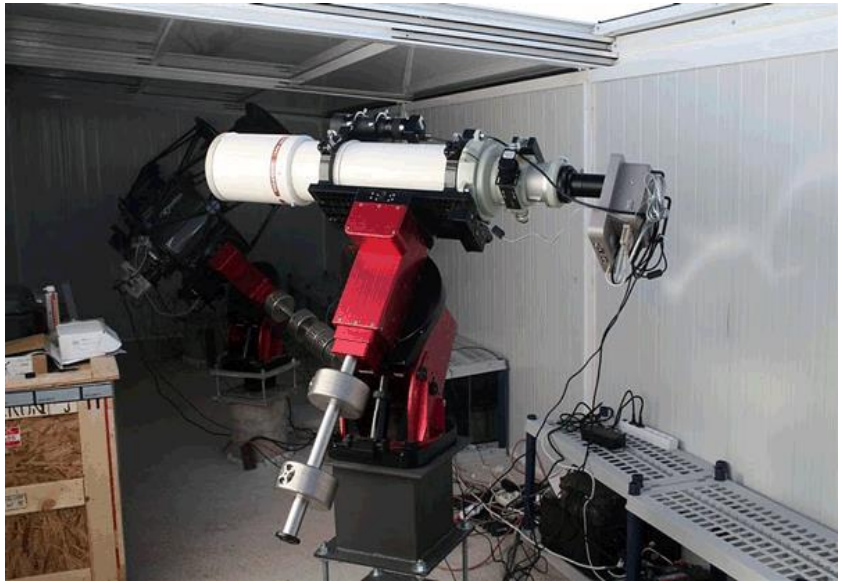

Leo I
815 kly
Leo II
669 kly
Ursa Minor Dwarf
215 kly
Draco Dwarf
267 kly
Sextans
Dwarf
260 kly
Milky
Way
LMC
170 kly
SMC
210 kly
NGC 6822
1,600 kly
NGC 185
2,020 kly
NGC 147
2,365 kly
Pinwheel Galaxy (M33)
2,850 kly
Andromeda Galaxy (M31)
2,650 kly



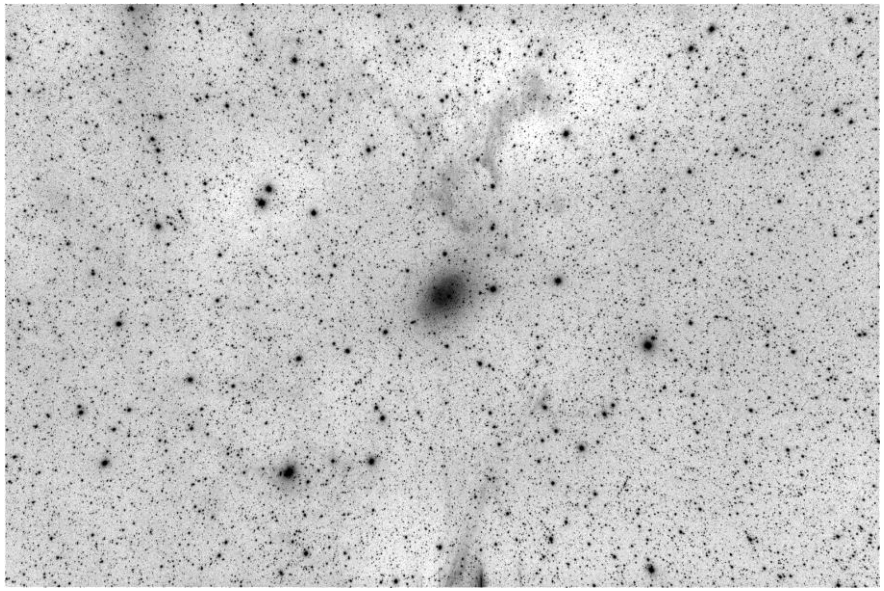
Y. Beletsky

- **Canon 50**

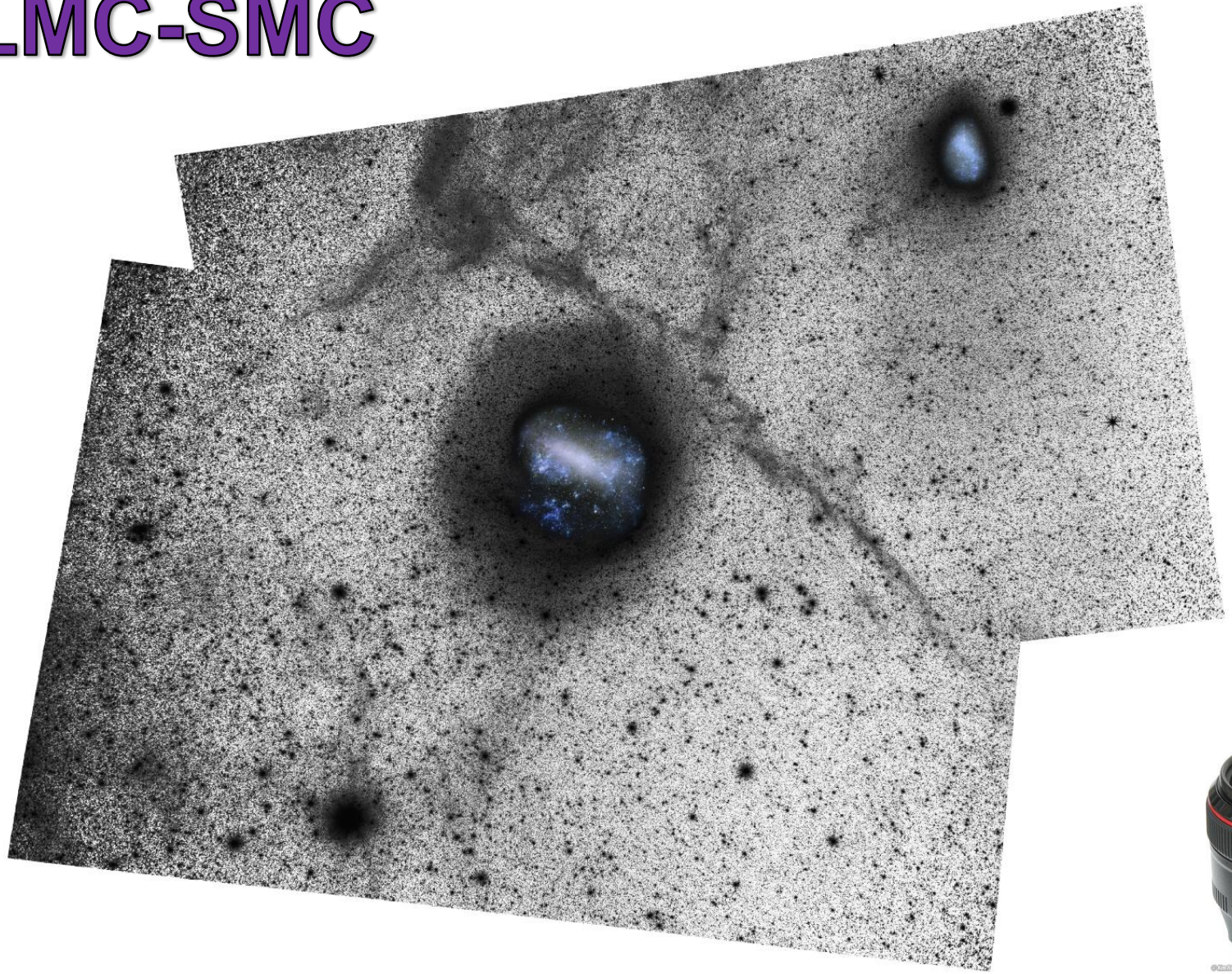
FSQ- 106, 10 cm, f/5 (1.7”/pix)



- **Canon 200 f/2.8 (9.3”/pix)**



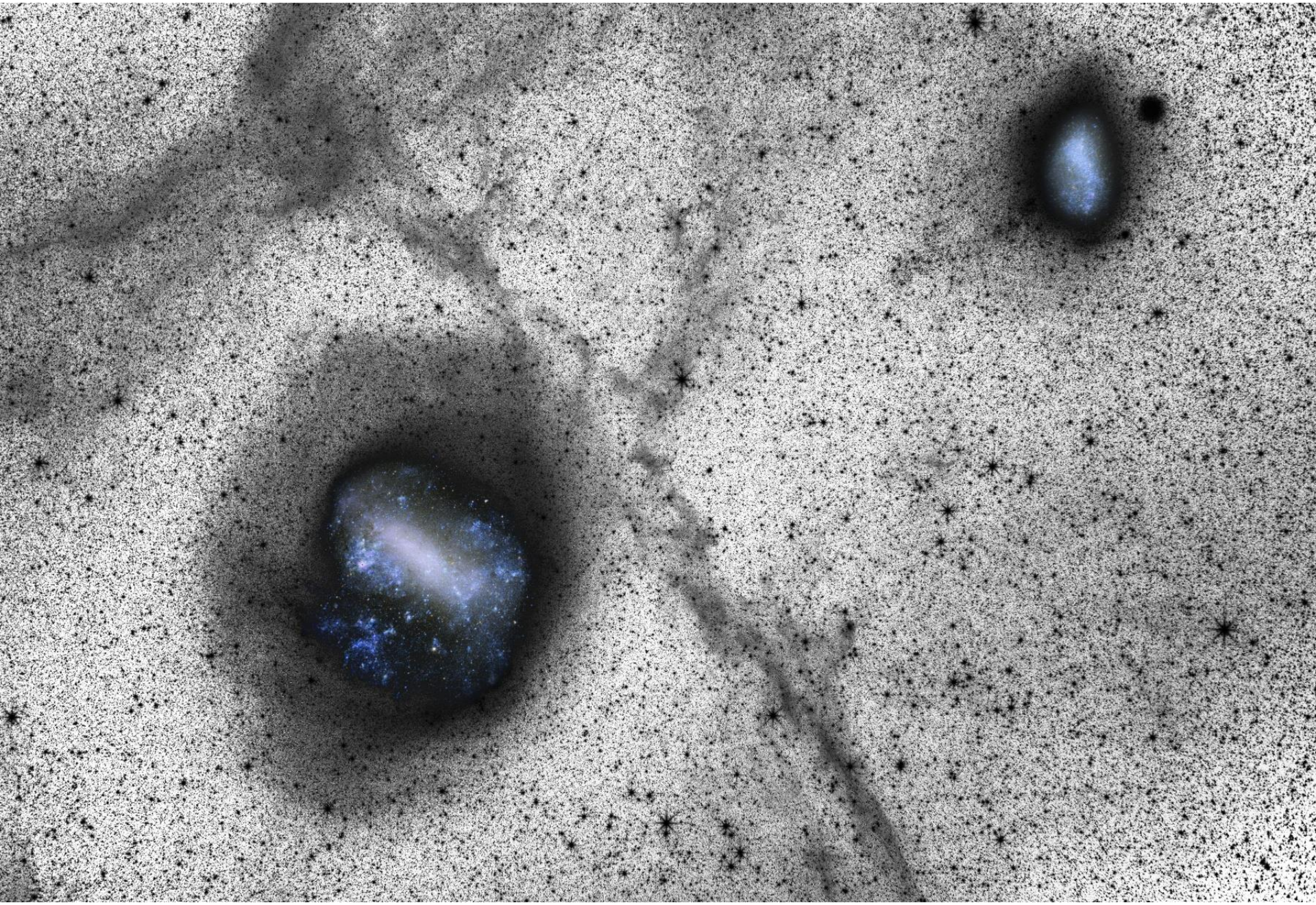
LMC-SMC



39º x 27º 9.3 “/pixel

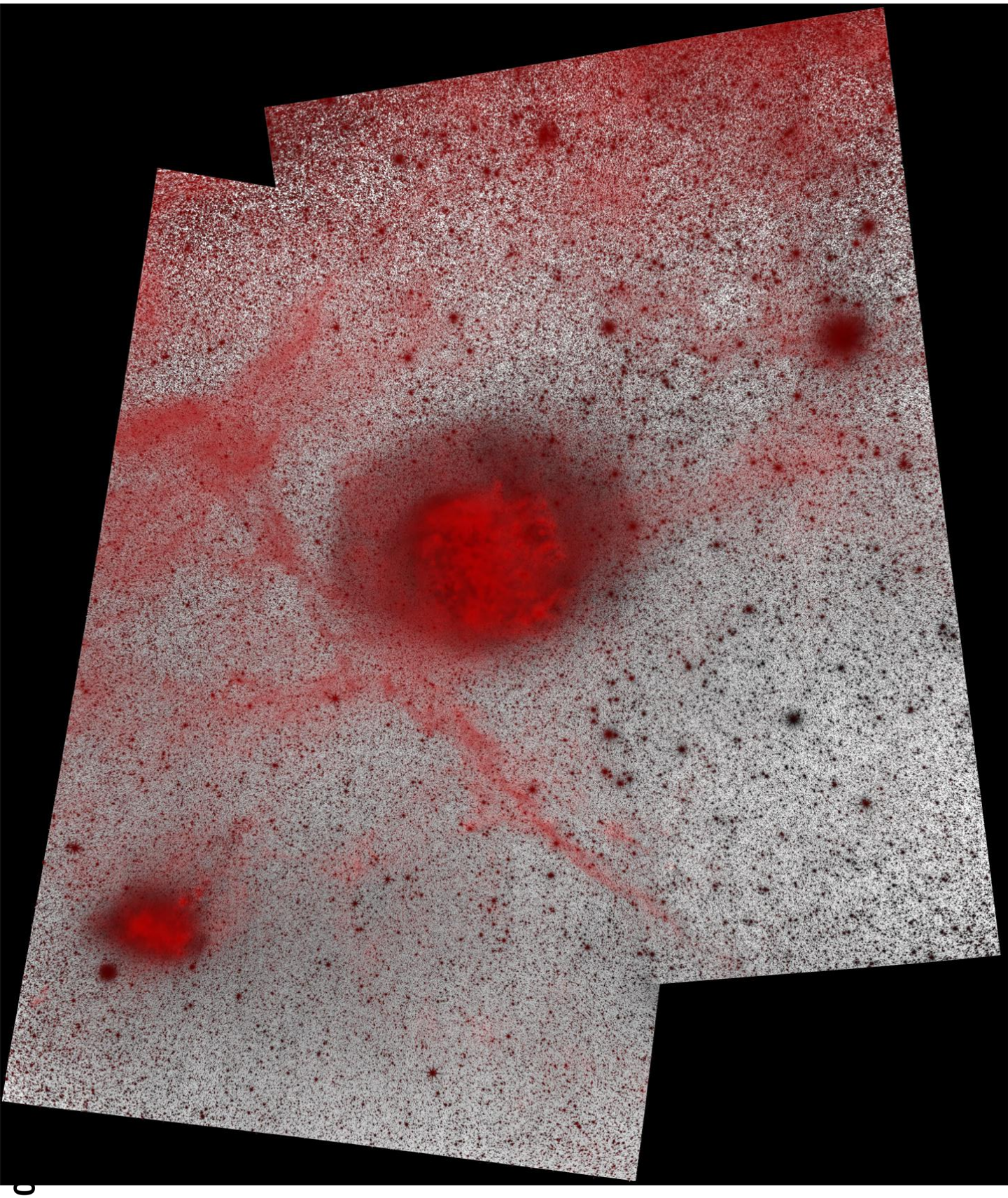
Besla, Martinez-Delgado et al. 2016 ApJ; image by Yuri Beletsky

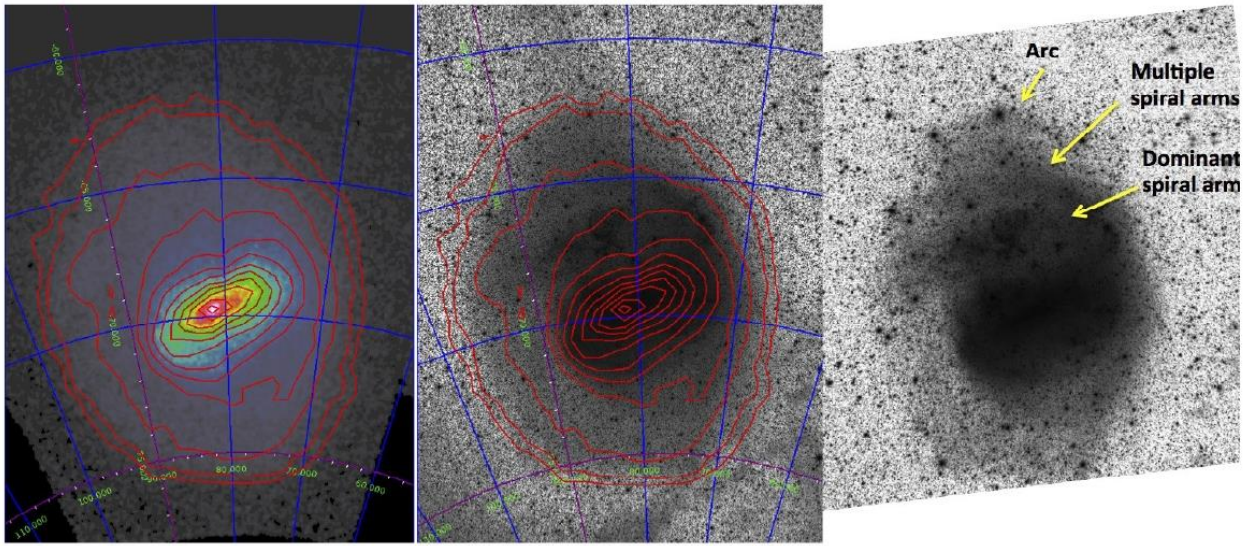
- **Canon 50**

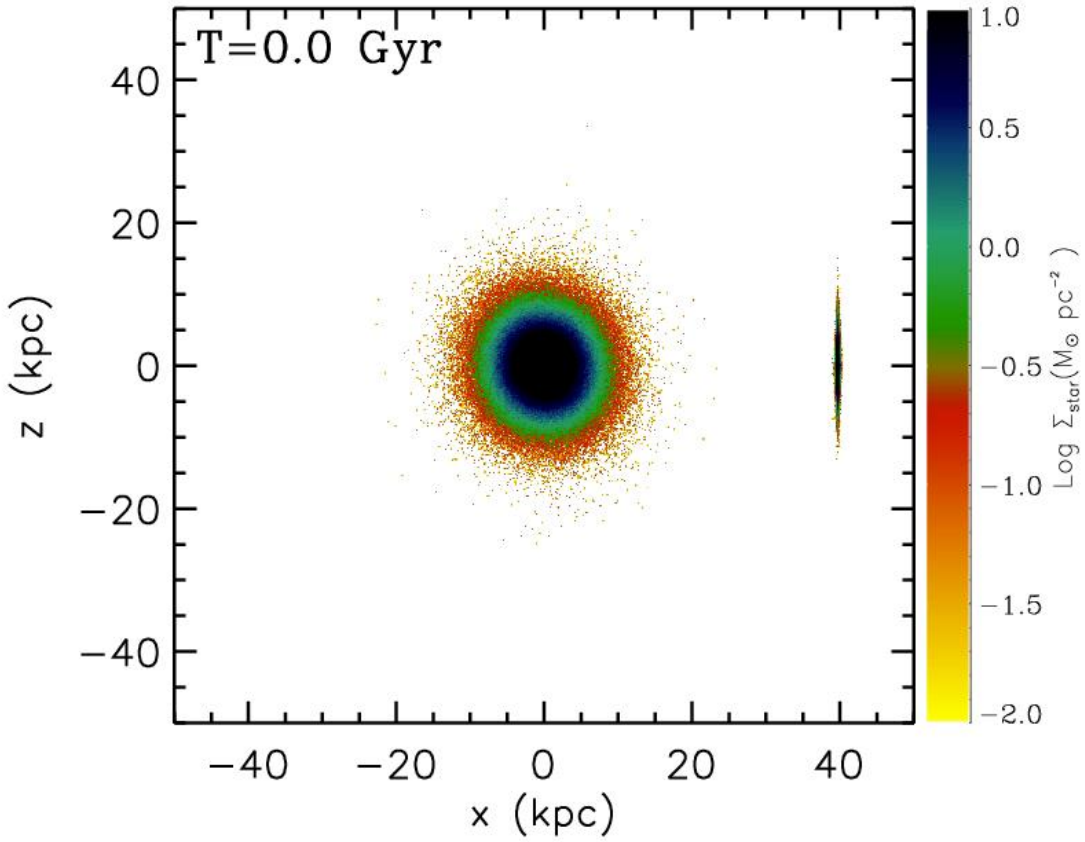


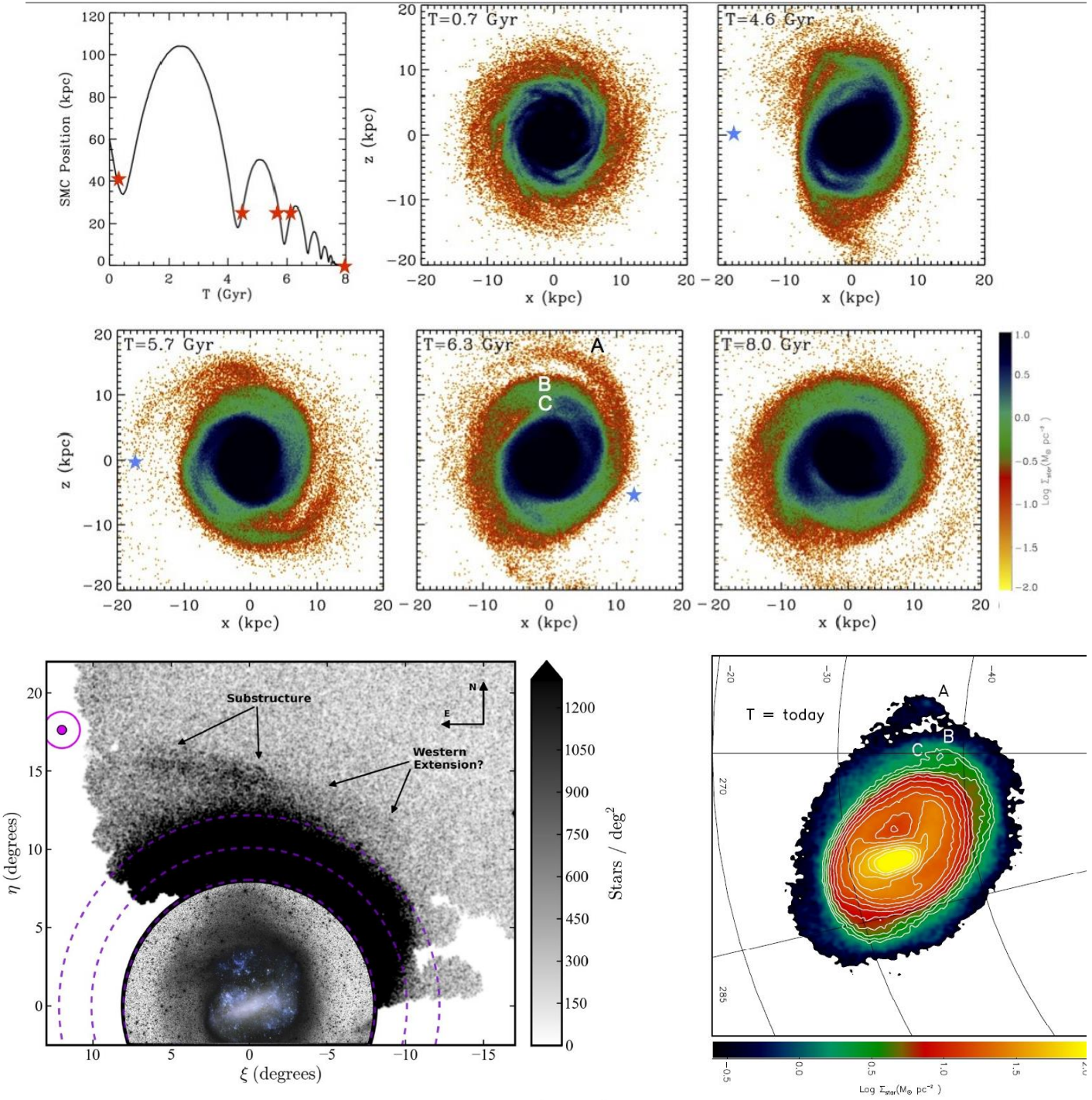
- **Canon 50**

Besla, Martinez-Delgado et al. 2016 ; processing by Fabian Neyer




Arc
Multiple
spiral arms
Dominant
spiral arm

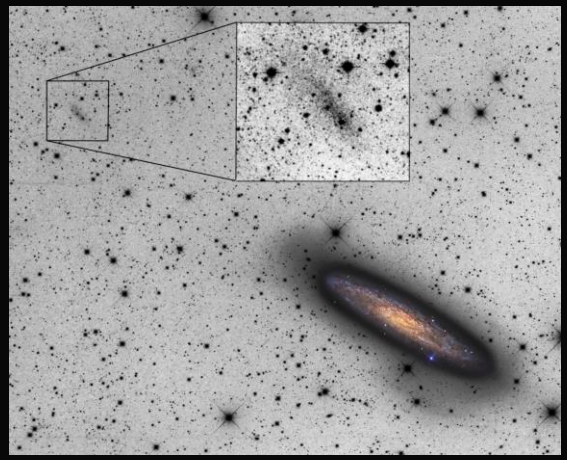

T=0.0 Gyr
40
20
0
−20
−40
z (kpc)
−40
−20
0
20
40
x (kpc)
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
Log Σstar(M⊙ pc−2)


SMC Position (kpc)
T (Gyr)
T=0.7 Gyr
T=4.6 Gyr
T=5.7 Gyr
T=6.3 Gyr
T=8.0 Gyr
A
B
C
z (kpc)
x (kpc)
Log Σstar(M⊙ pc−2)
Substructure
Western Extension?
N
E
η (degrees)
ξ (degrees)
Stars / deg2
T = today

Research Projects for Astrophotographers

The Stellar Tidal Stream Survey

Dwarf Satellite Survey for Amateur Telescope (DGSAT)



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