Deep imaging of low surface brightness structures near galaxies

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**Central Astronomical Observatory of the RAS, Russia*

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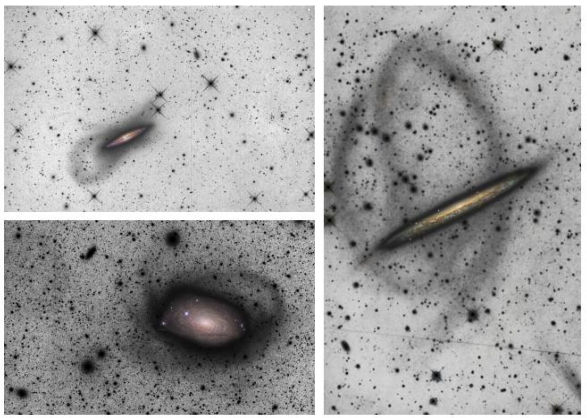
Current state



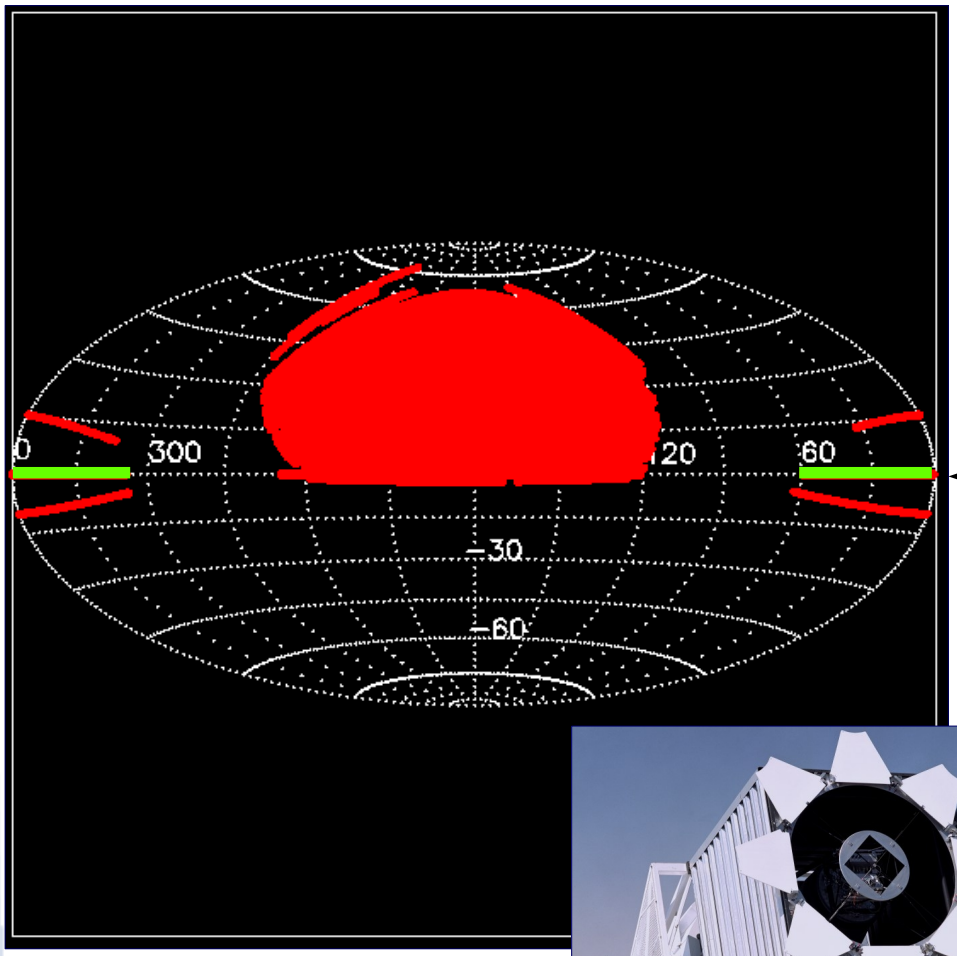
- Modest-sized robotic telescopes (0.16-0.5m). t_{exp}=6-11h. Depth 28.5 mag/arcsec^2 (MartÍnez-Delgado).

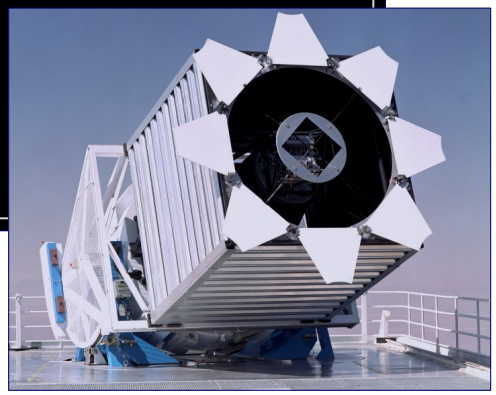
- **Dragonfly** (Abraham & van Dokkum). Two clusters of 24 telephoto (Canon 400) lenses. Equivalent to a 99 cm diameter refractor, with a focal length of 40 cm. Specially-coated optical glass that reduces scattered light. 2 × 3 deg field of view an angular resolution of 2.85 arcsec/pixel.

- **MegaCam** (Pierre-Alain Duc), a major instrument at the **CFHT** observatory (Canada-France-Hawaii Telescope), 3.6m.

- **GTC** (Gran Telescopio de Canarias), 10.4m (Trujillo).

Current state





Stripe82 SDSS area

-50°≤RA≤+60°

-1.25°≤DEC°≤+1.25°

275 square degrees

Repeated ~80 times

~1h total exposure

Depth 28.5 mag/arcsec^2

u,g,r,i,z

Fliri & Trujillo (2016)

Our interests in this

- ΛCDM models predict an increasing amount of substructures (stellar streams, shells, filaments) within the stellar haloes of galaxies when lowering the surface brightness threshold to values below 28-30 mag arcsec^{-2}.
- The properties of the galaxy envelope (halo) as a mix of debris from the host and the merger galaxy.
- Low-surface brightness and ultra-diffuse galaxies.

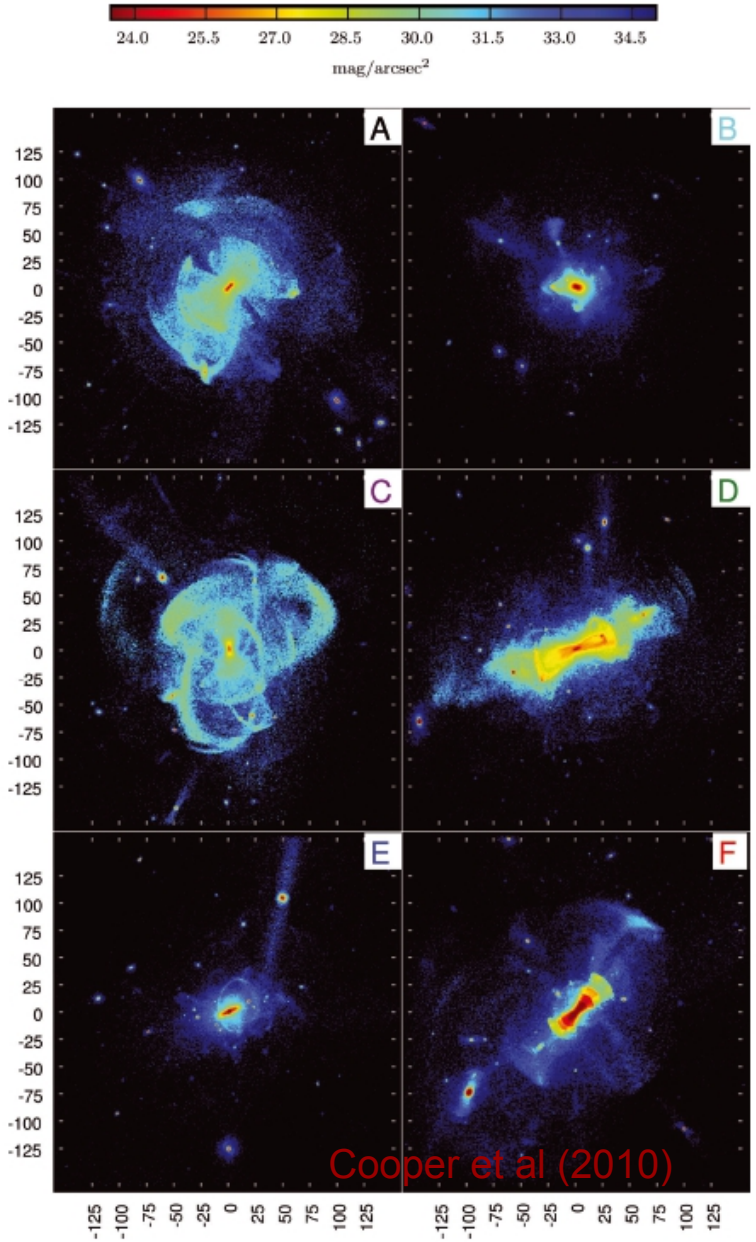
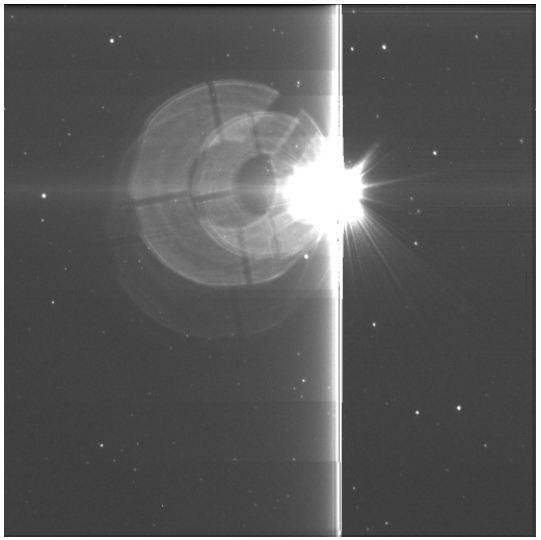


Figure 6. *V*-band surface brightness of our model haloes (and surviving satellites), to a limiting depth of 35 mag arcsec^{-2}. The axis scales are in kiloparse
Only stars formed in satellites are present in our particle model; there is no contribution to these maps from a central galactic disc or bulge formed in situ (s
Section 3.3).

The aims of this study

- Study extended galaxy stellar halos, stellar streams and tails, heated disc material, and possibly complex non-spherical shapes of galaxy bulges, which can be produced by minor merger events.
- Search for candidates to LSB and ultra diffuse galaxies.

Some technical challenges

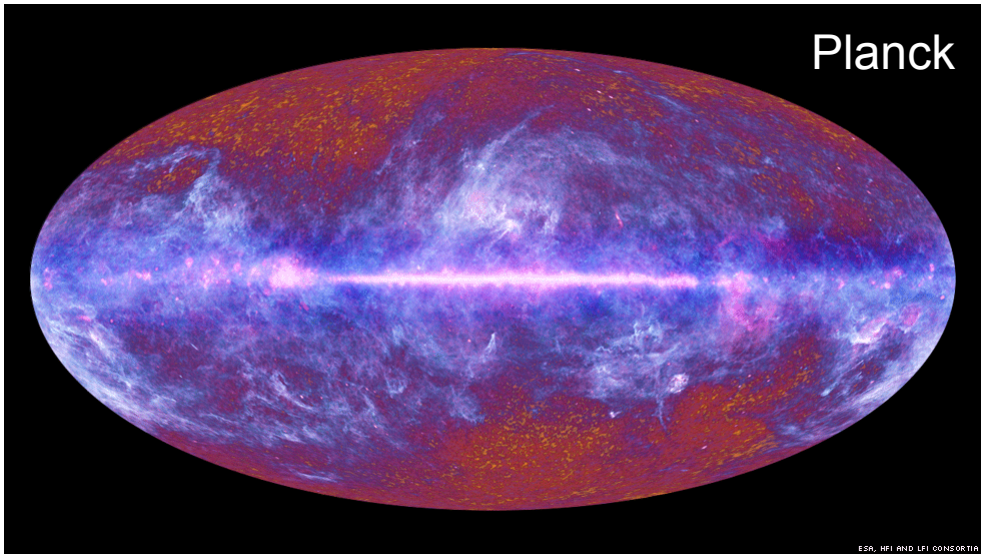


Problem	Potential solution
Sky brightness: μ_V~22 mag/arcsec^2 Over- or undersubtraction of the sky, systematic background fluctuations	- Integrate long enough $\mathrm{SB} \propto \left(\frac{D}{2f}\right)^2 \times t_{exp}$
Internal reflections: μ_V >26 mag/arcsec2	- Telescopes with simple optics - Clever observing strategy
Scattered light: μ_V~29.5 mag/arcsec^2	- Exquisite characterization of the Point Spread Function. Deconvolution I. Trujillo's talk

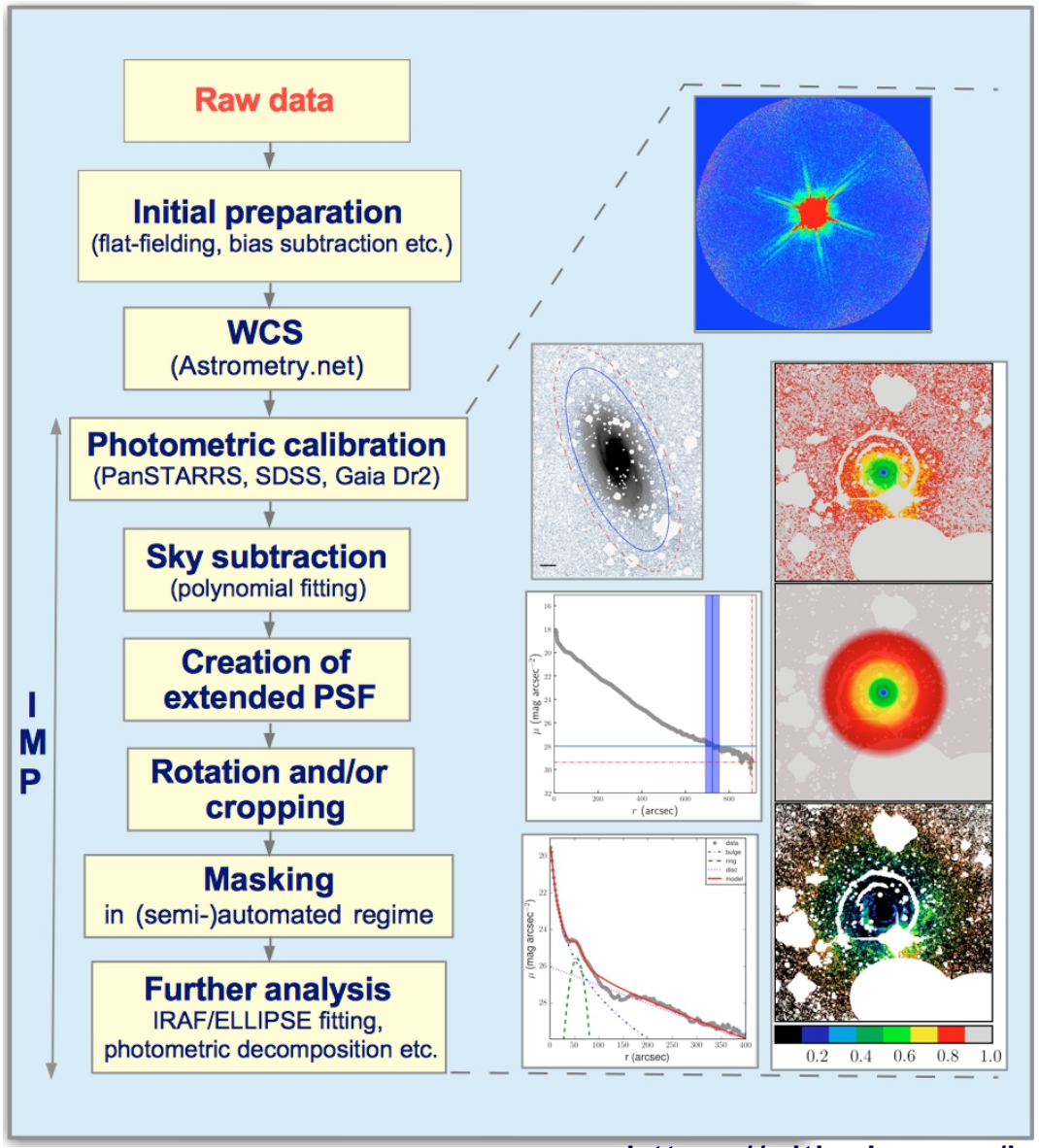
Some other challenges

Galactic Cirrus!

Only few spots in the sky are free of dust features if observed very deep



My pipeline for image reduction

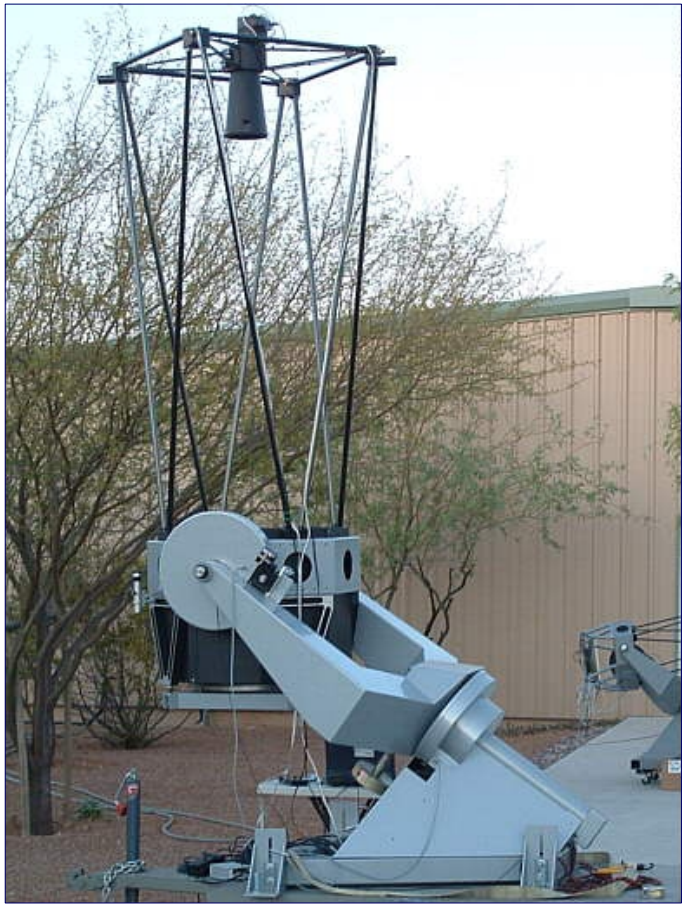


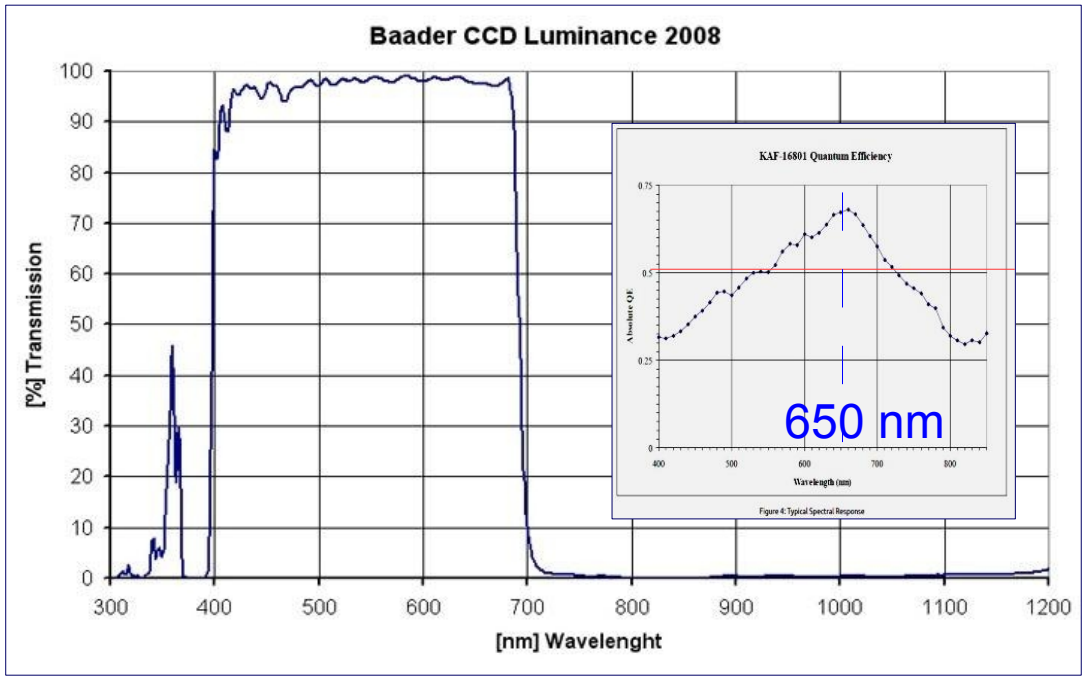
https://github.com/latrop
https://bitbucket.org/spiral_galaxies/iman/src/master

The Centurion 28-inch (UCLA) and the Wise Observatory (Tel Aviv)

70-cm f/3.2 Hyperbolic primary, doublet corrector lens
4kx4k FLI CCD
Wide-R filter (250 nm, 95% transmission, ~rectangular profile)
Co-adding 10s of (dithered) 300s images

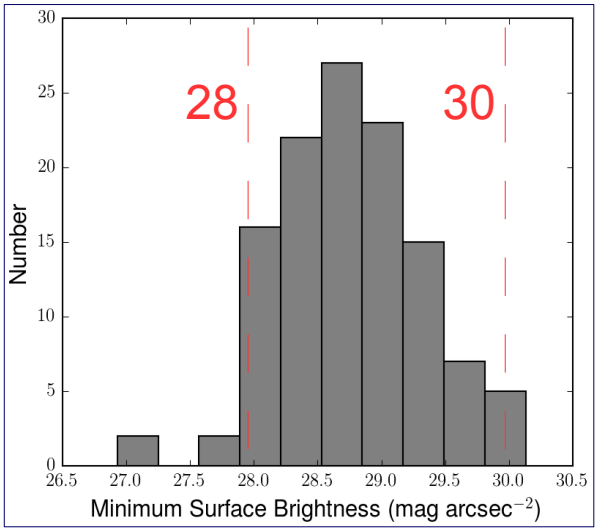
Rich et al. (2019), Brosch et al. (2015, 2019)

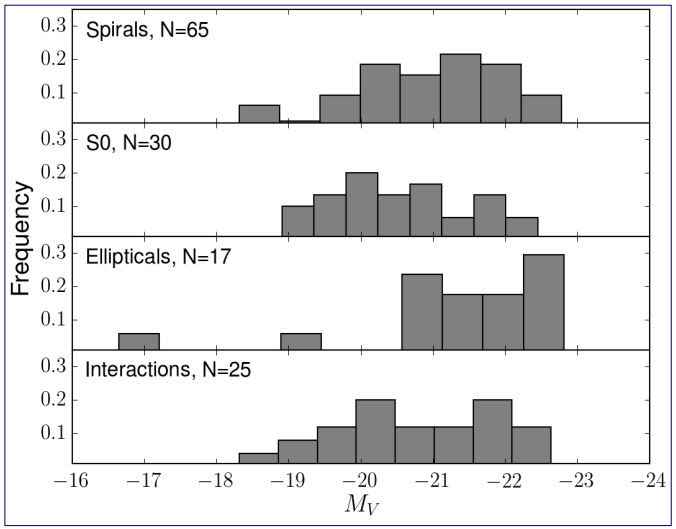




The Halos and Environments of Nearby Galaxies (HERON) Project

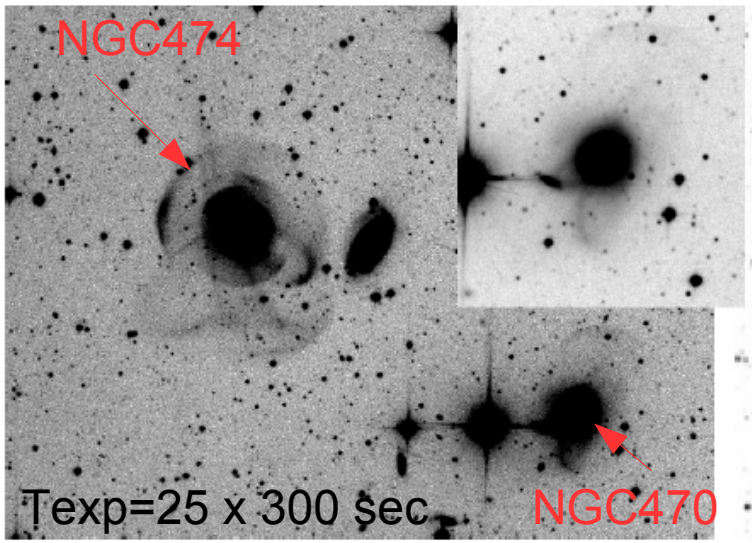
- ~ 150 galaxies observed down to SB~28-30 mag arcsec^{-2}.
- The sample includes nearby dwarf galaxies, spiral and lenticular galaxies, and more distant giant ellipticals.



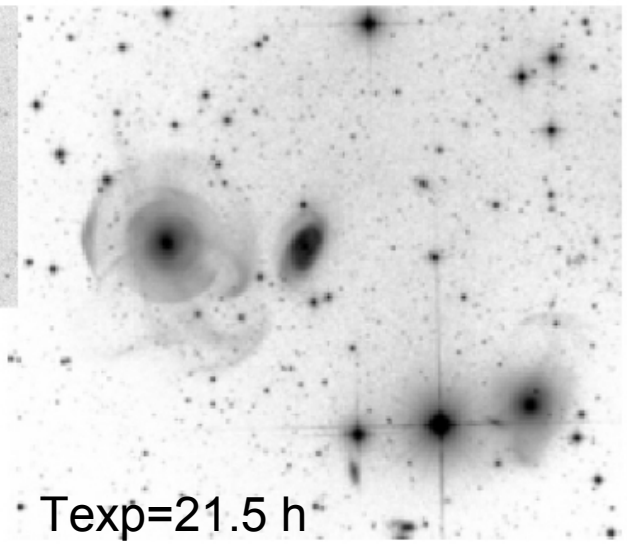


The HERON: comparison with other studies

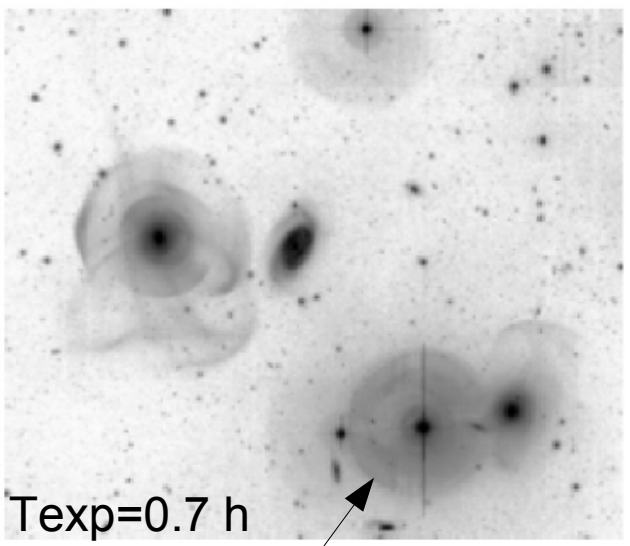
HERON



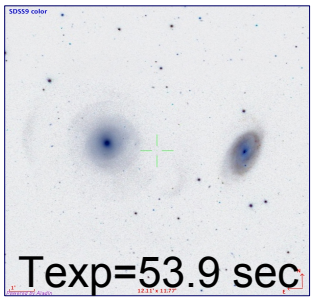
The Irida Observatory 12”astrograph



CFHT



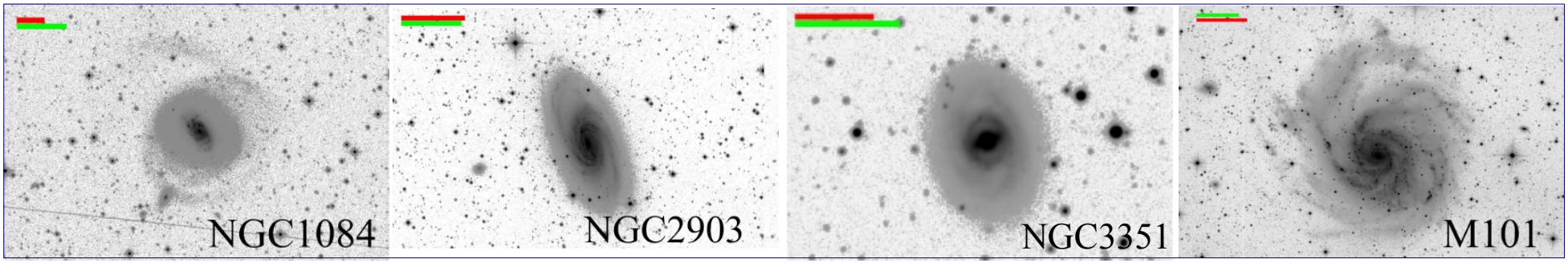
SDSS

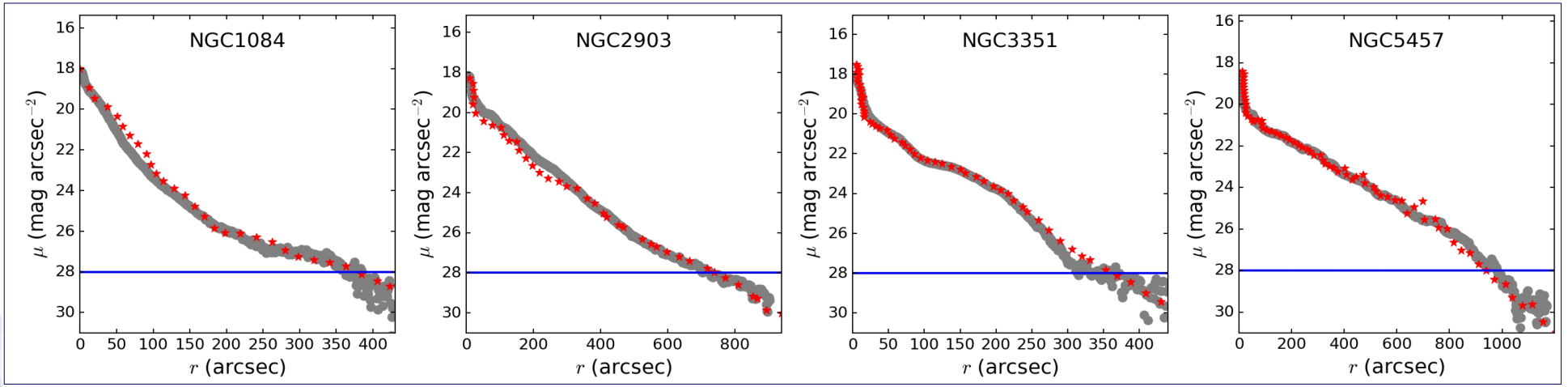


Duc et al. (2016)

Internal reflections of brights stars

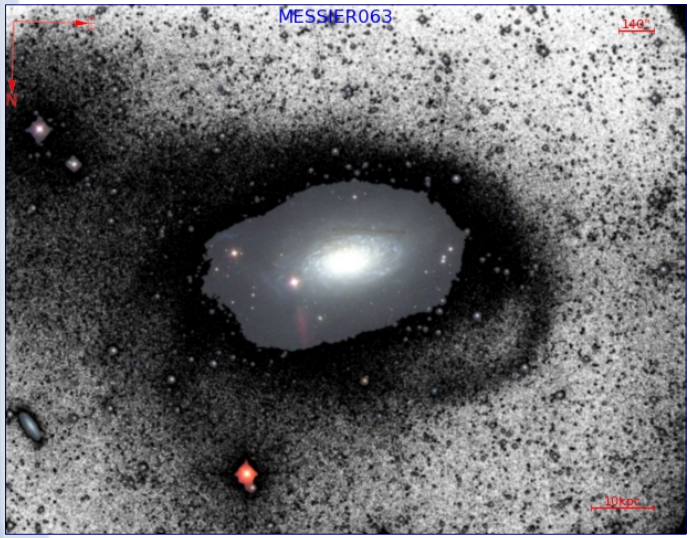
The HERON: comparison with other studies

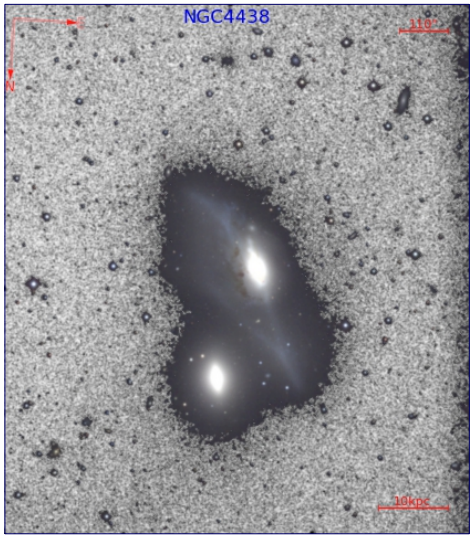


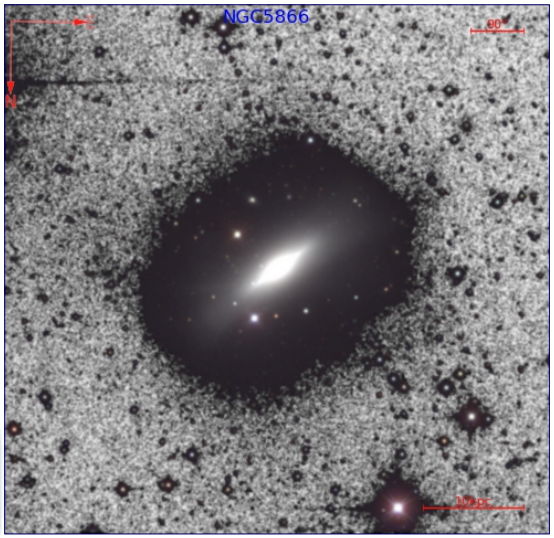


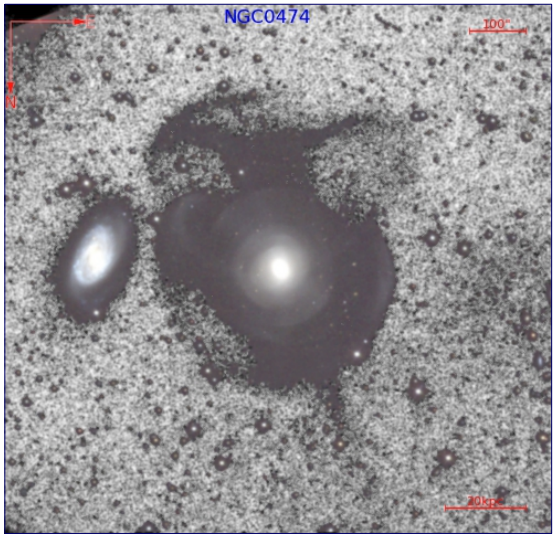
★ Merritt et al. (2016)

The HERON: observations

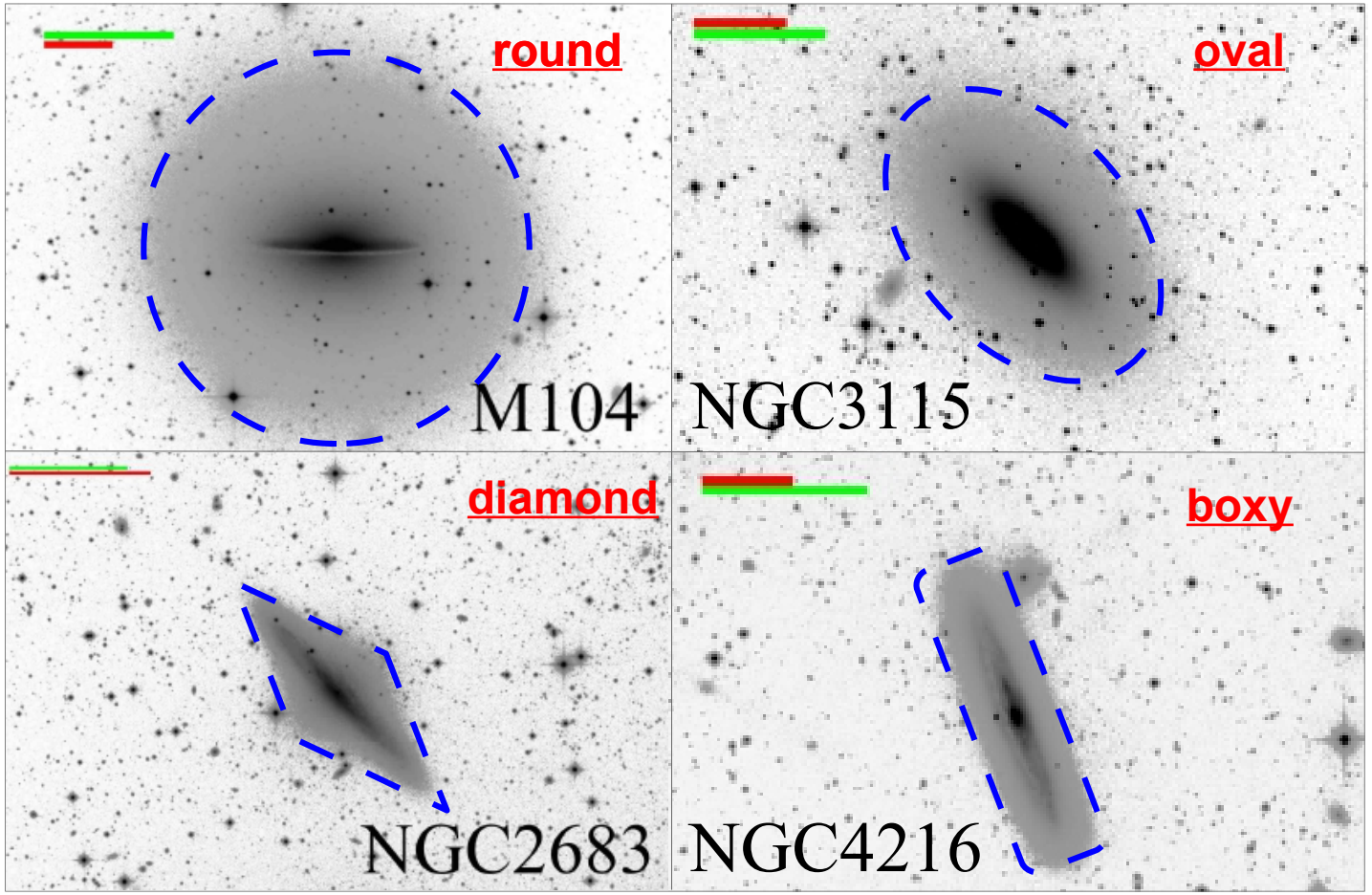








Envelope shapes

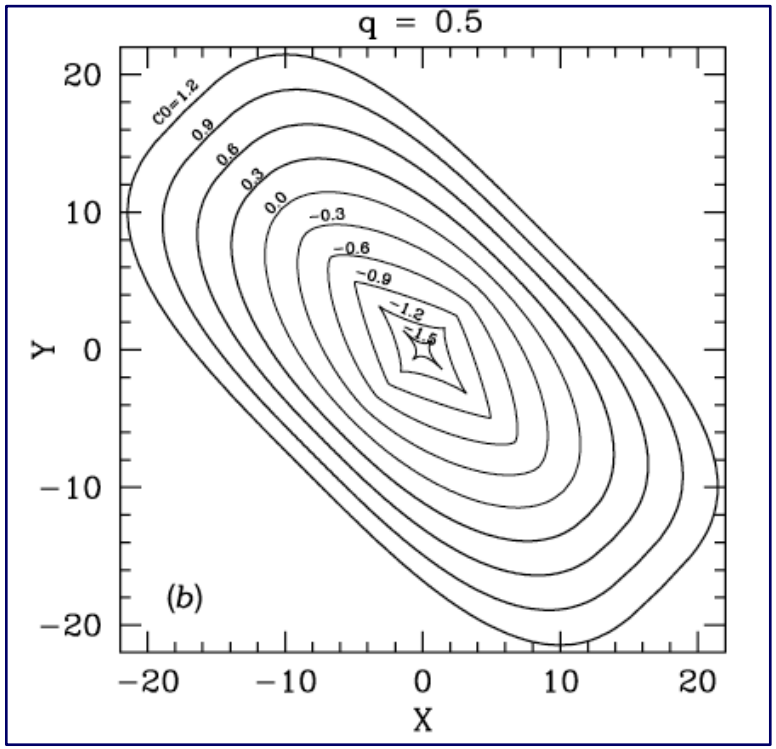


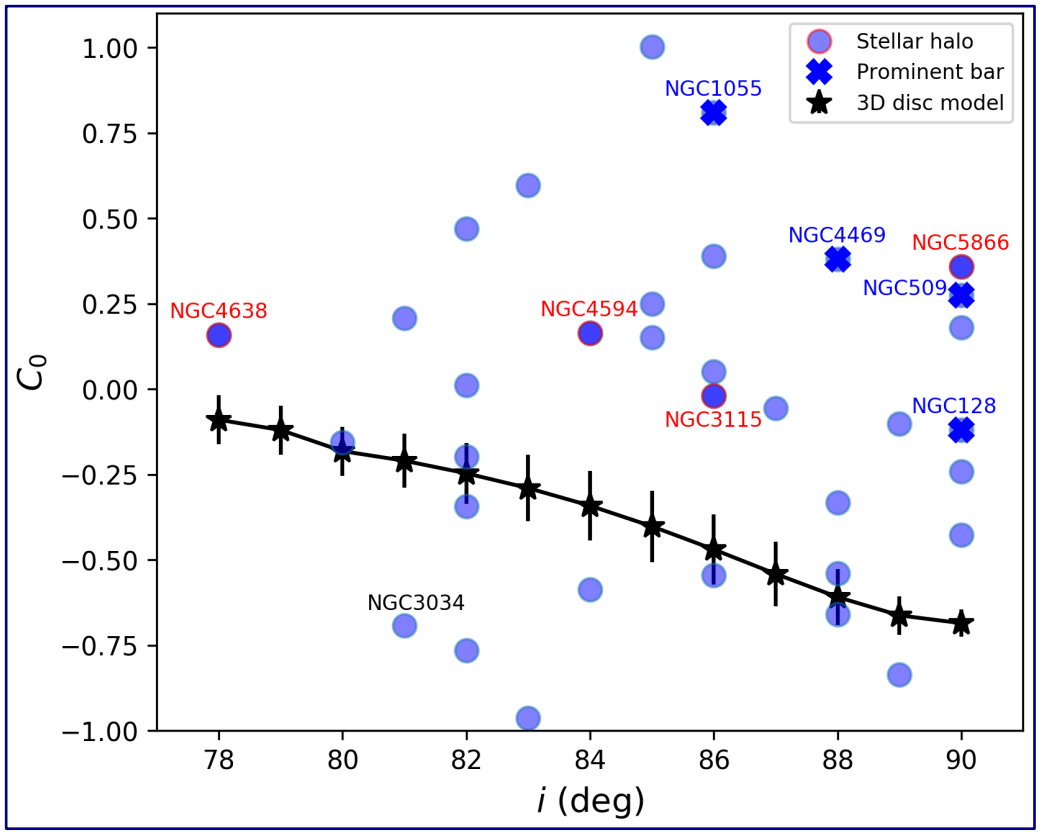
Edge-on galaxies in our sample

Generalized ellipse:

$$r(x, y) = \left(|x - x_0|^{C_0+2} + \left| \frac{y - y_0}{q} \right|^{C_0+2} \right)^{\frac{1}{C_0+2}}$$

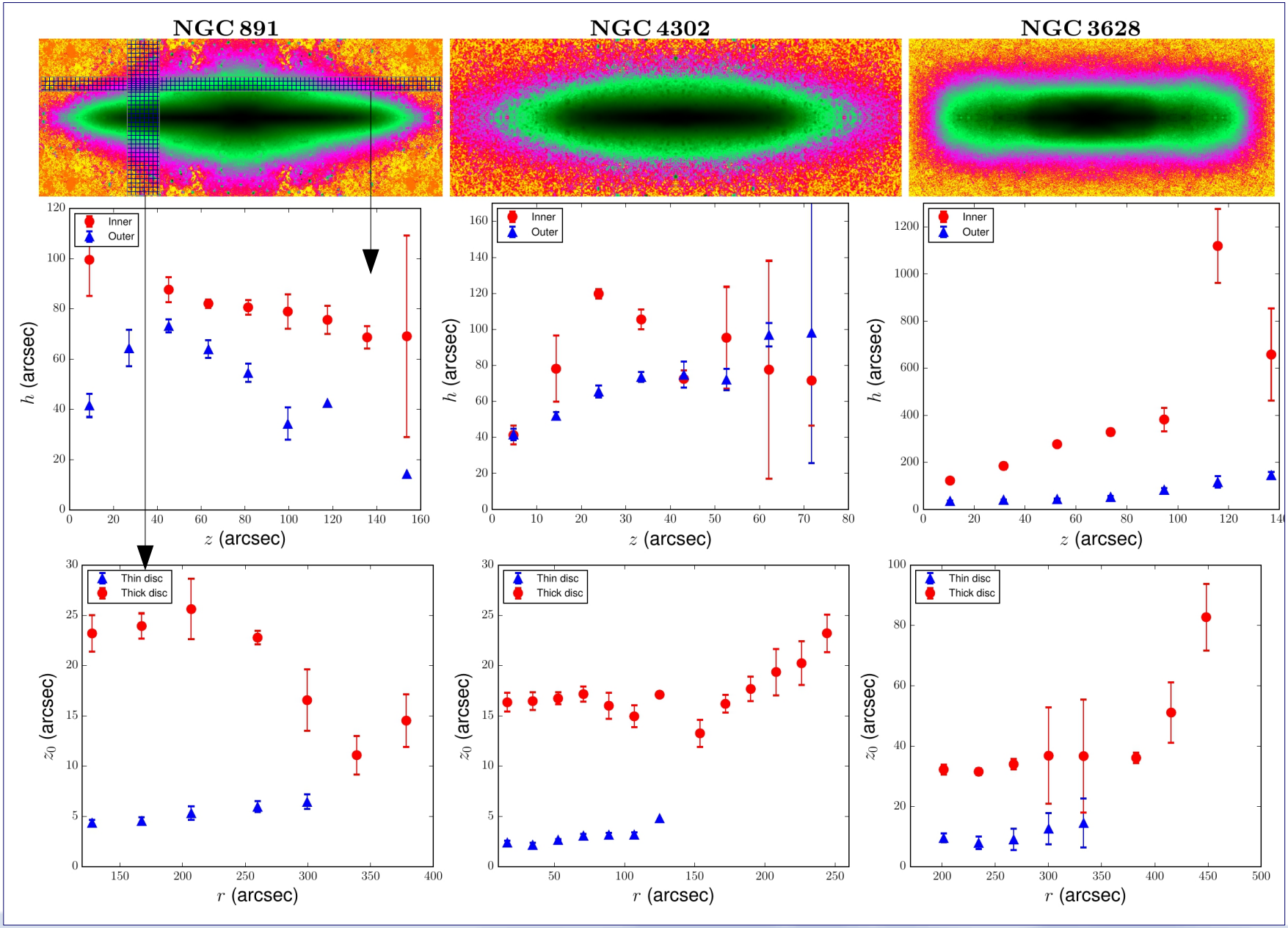
C_0 is the diskyness/boxyness parameter





We fitted a Sersic law with the free C_0 parameter to the outer part of the galaxy (SB>24 mag arcsec^{-2}), convolved with an extended PSF. C_0 is mostly larger than it follows from our 3D exp-disc modeling.

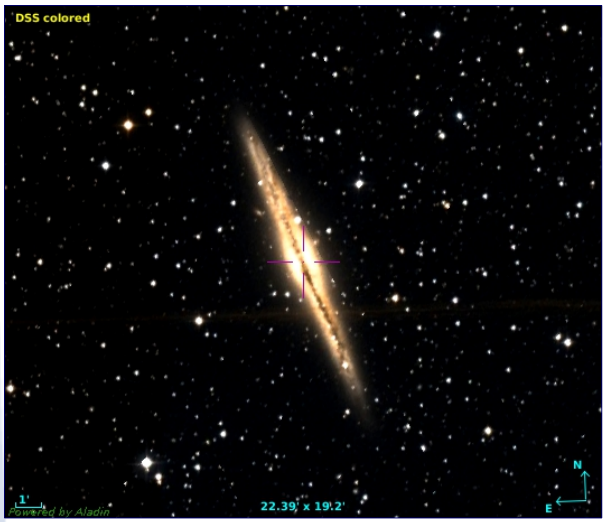
The three shapes of envelopes:



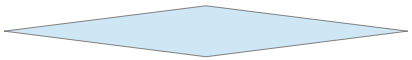
S4G (3.6μm)

Possible explanation

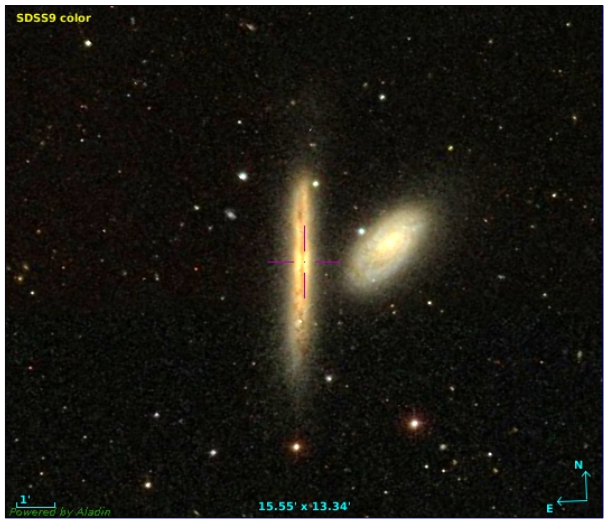
NGC 891



No past or ongoing merging

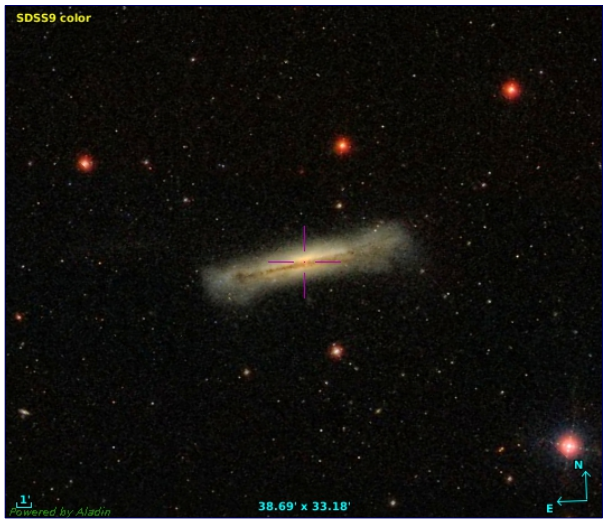


NGC 4302



Ongoing merging

NGC 3628

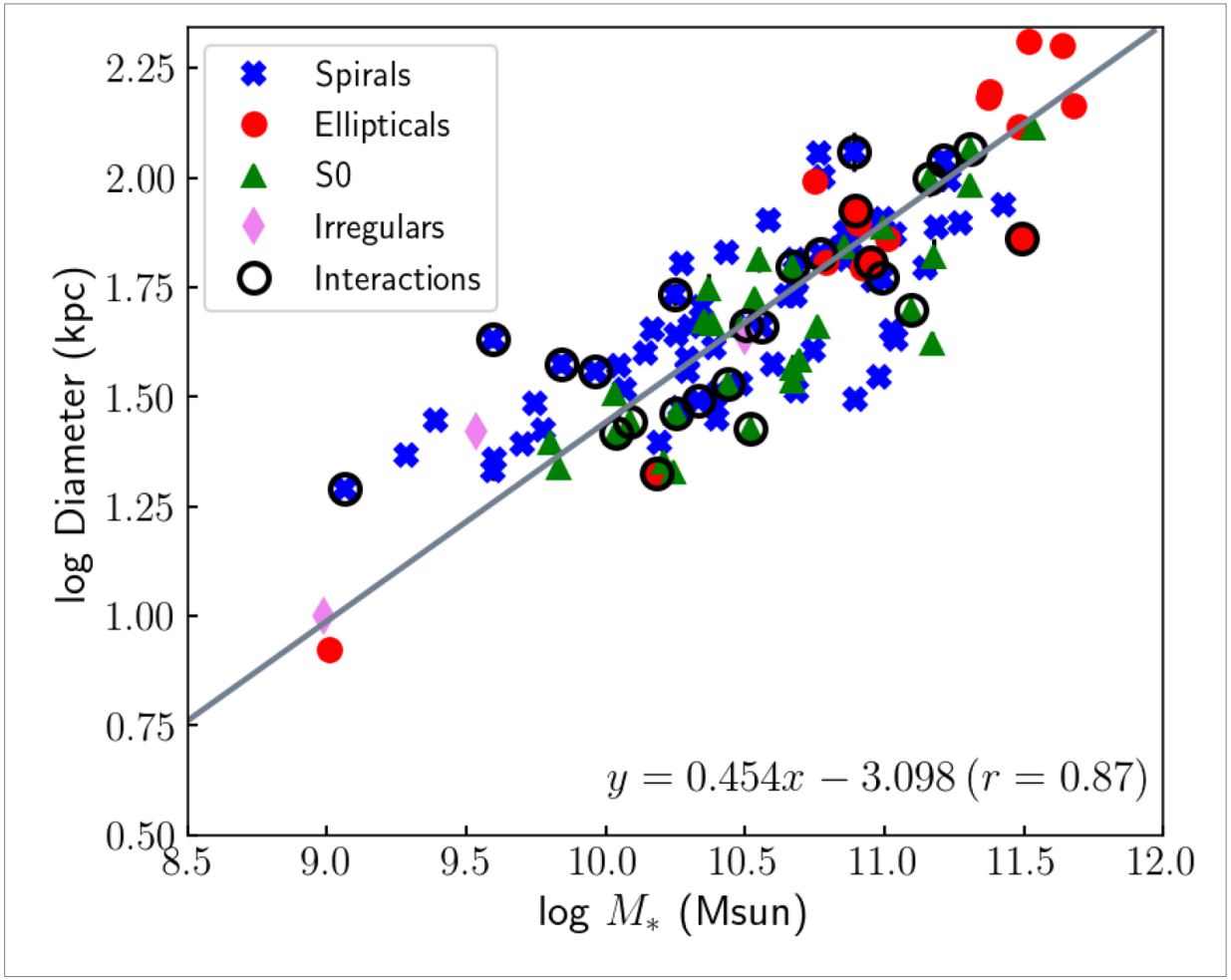


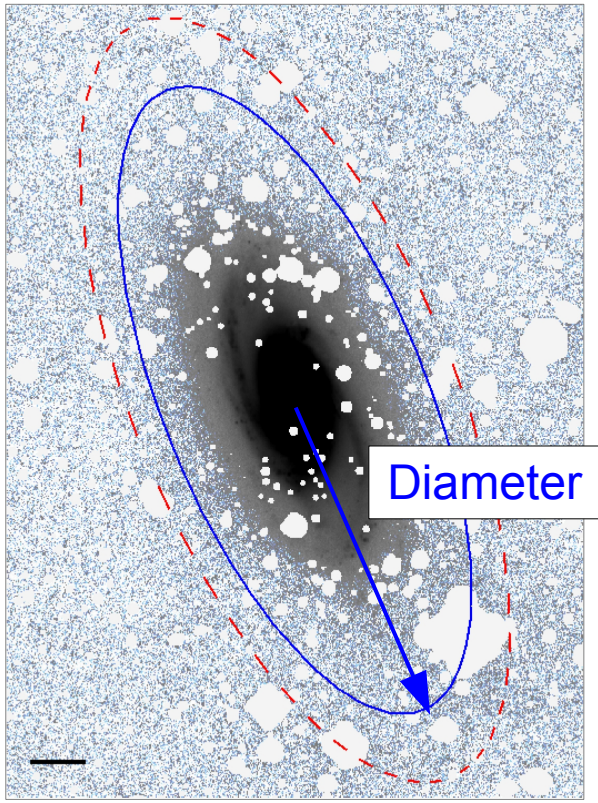
Recent merging

4 mechanisms for creating a thick disc:

1. Secularly by thin disc stars heated by overdensities (GMCs, spirals) and by stars moved outwards from their original orbits by radial migrations.
2. By the heating of the thin disc by satellites and the tidal stripping of them.
3. Formed fast and already thick at high redshift in an highly unstable disc.
4. Formed originally thick at high redshift by the merger of gas-rich protogalactic fragments. The thin disc formed afterwards within it.

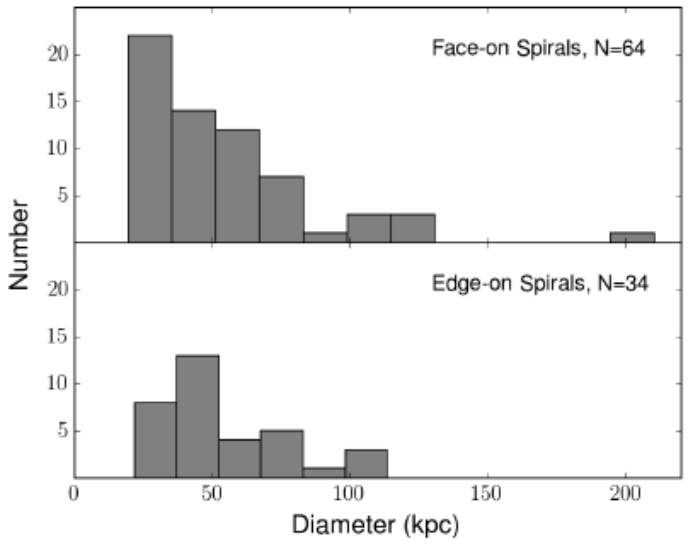
Envelope diameter Vs Mass



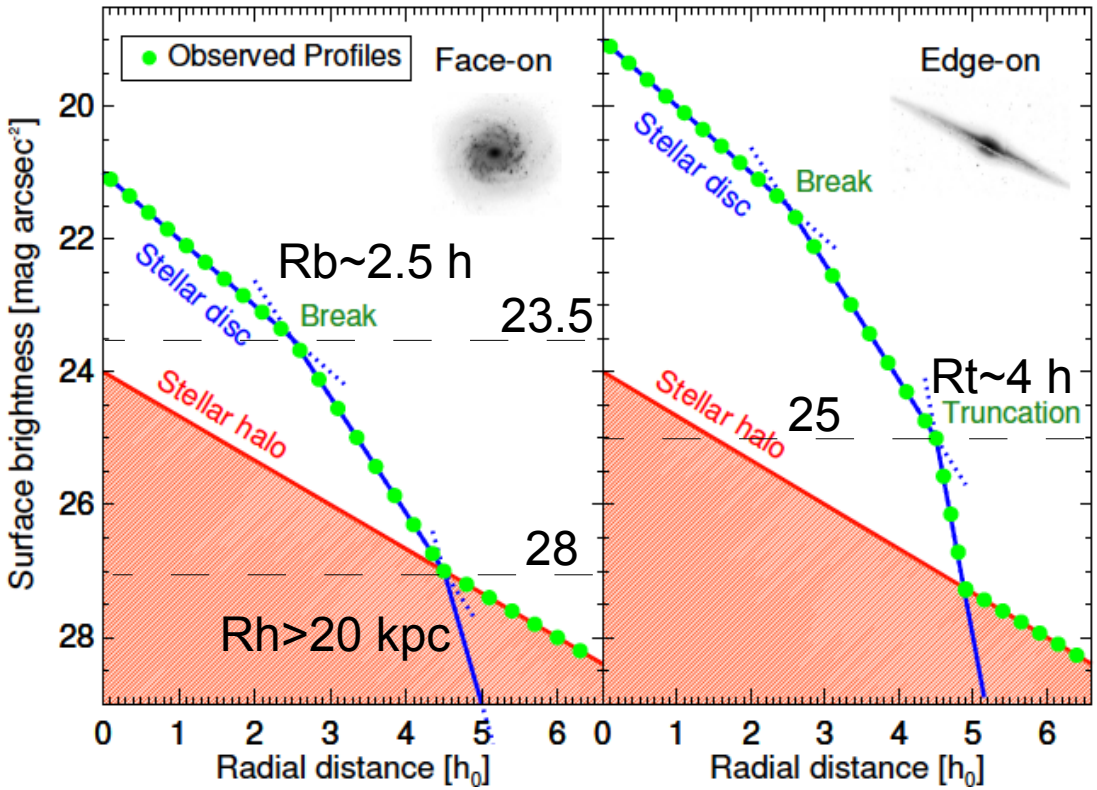


Diameter = D28 at
SB=28 mag arcsec^{-2}

Diameter of face-ons Vs edge-ons

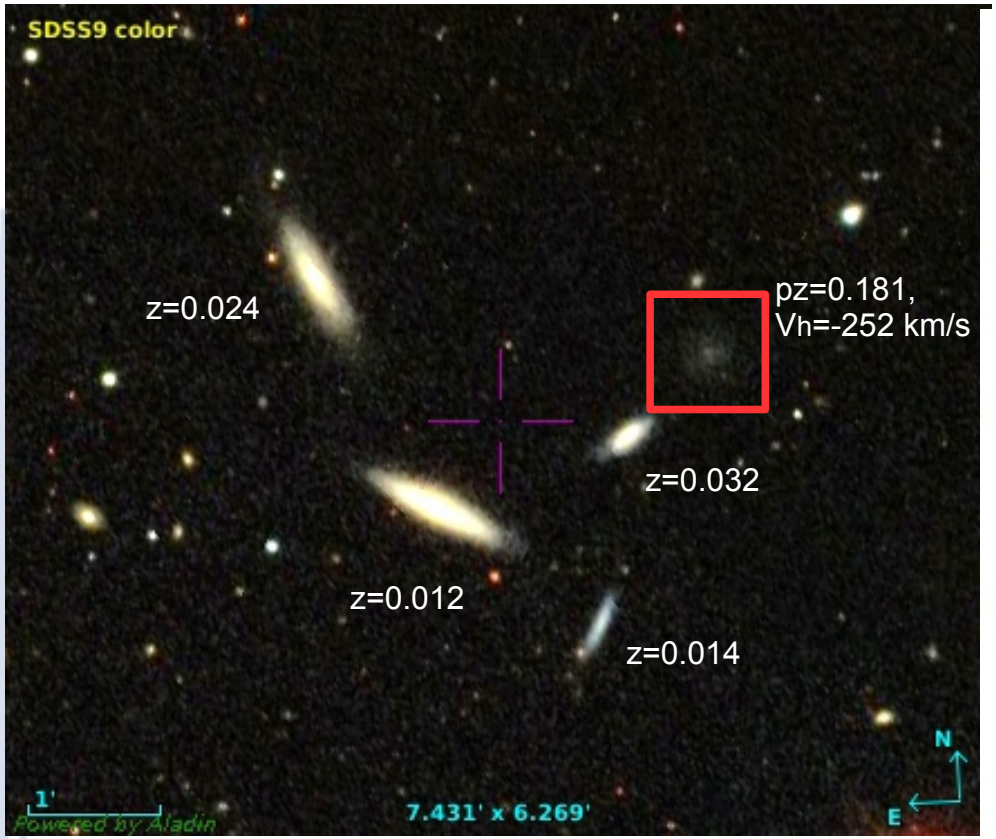


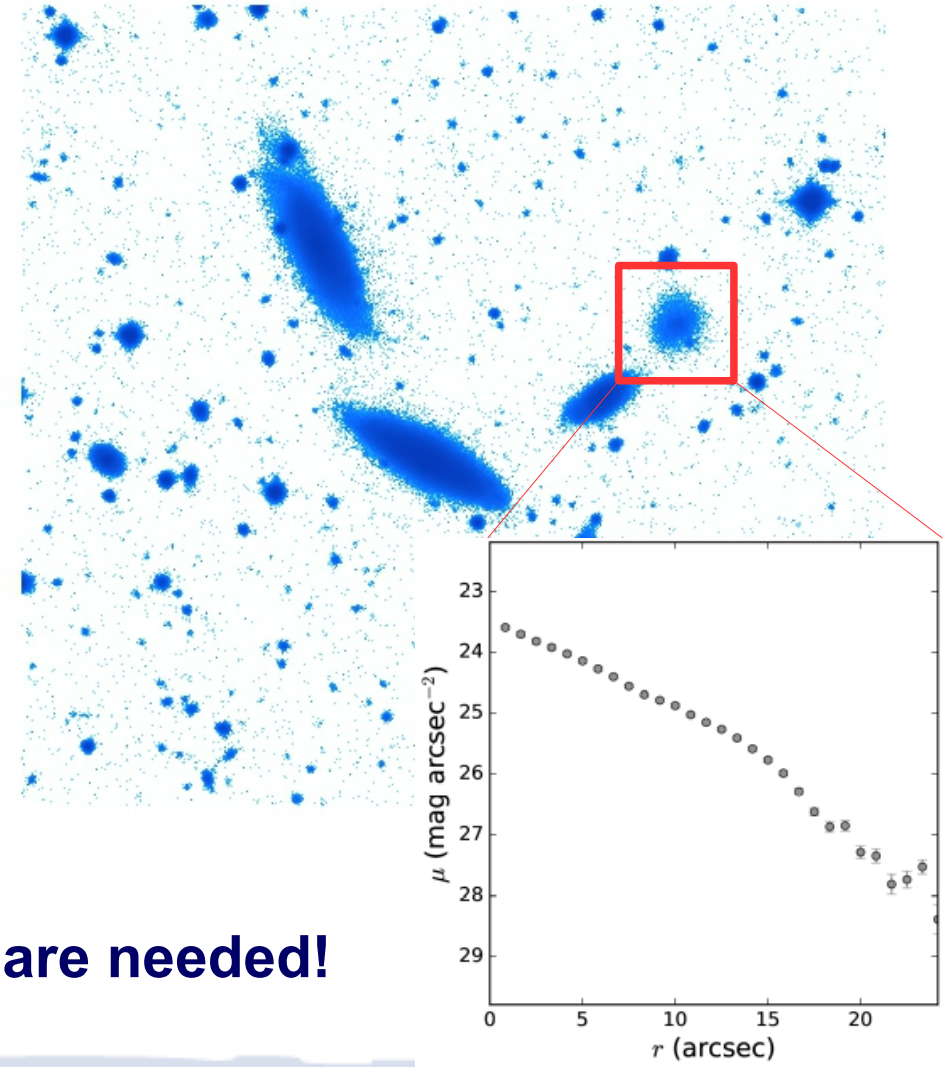
- Both samples have similar distributions by Mv0.
- The similar distributions by Diameter point to the fact that we reach the inner part of the stellar halo.



Martin-Navarro et al. (2014)

Search for LSB and dwarf galaxies





Spectroscopic observations are needed!

Ghost detections

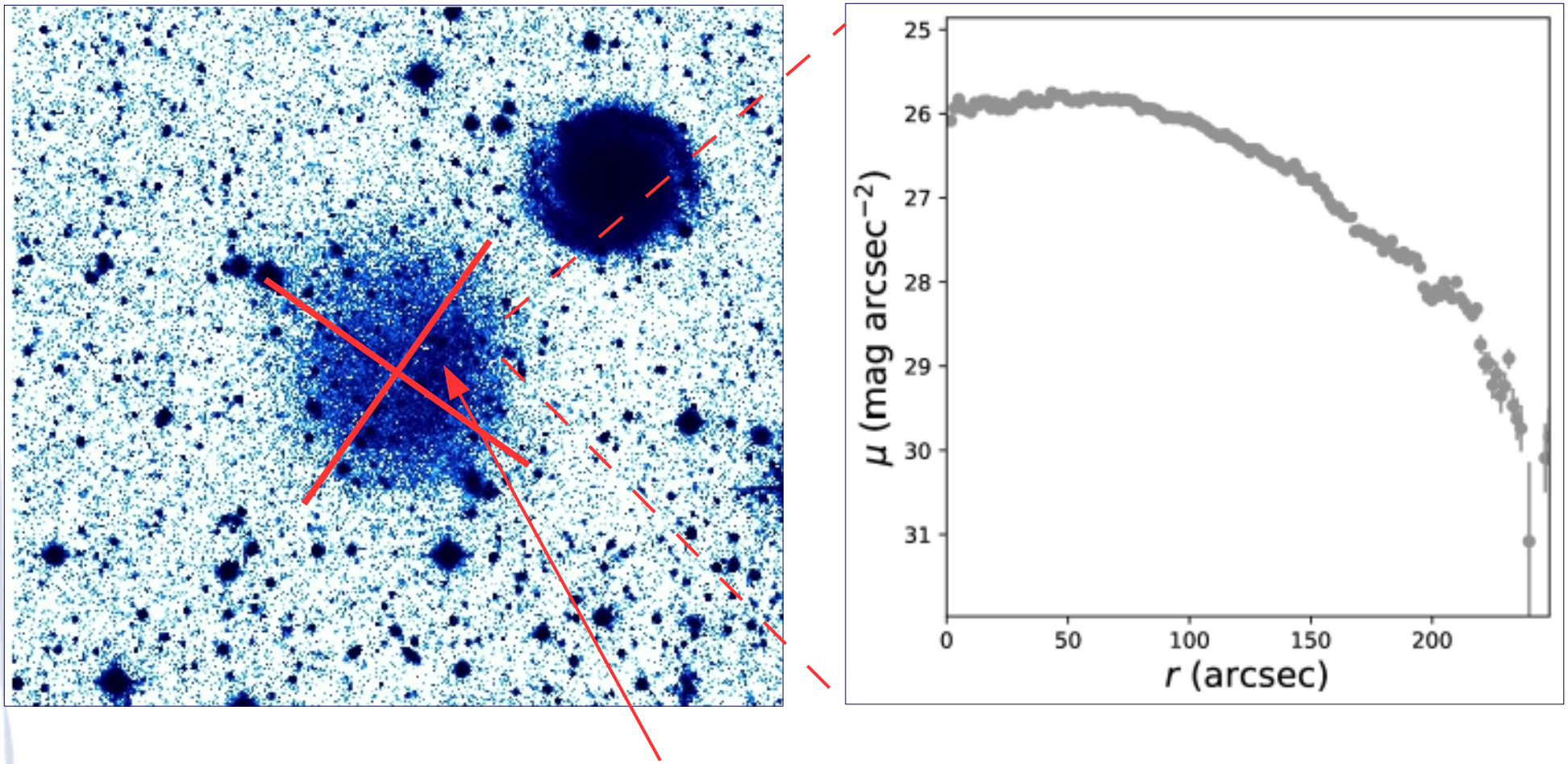


Image artifact!

Our total observational material

- ~100 deg^2 for The Halos and Environments of Nearby Galaxies (HERON) Survey sample,
- ~150 deg^2 for the sample of edge-on galaxies (123 galaxies) and 40 Hickson Compact Groups.

  In total, ~ sky coverage of the SDSS Stripe 82.
- Will become available soon!

Conclusions

- Low surface brightness universe (>28 mag/arcsec^2) is a unique area of parameter space in astronomical surveys, that is almost completely unexplored.

- Our ongoing projects will provide the astronomical community with a treasure trove of observational material. These will enable fundamental tests of local stellar mass distribution, galaxy and cluster formation scenarios, and dark matter.

Thank you for your attention!

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