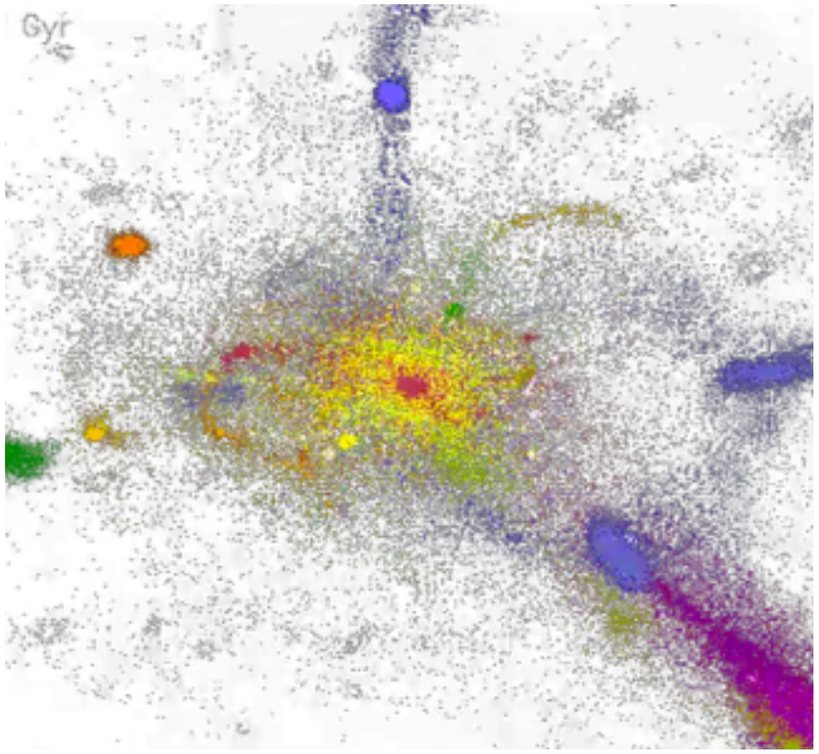
The faint stellar « halos » from deep optical imaging

Pierre-Alain Duc

Motivations: models

Checking the mass assembly of galaxies and predictions from numerical simulations

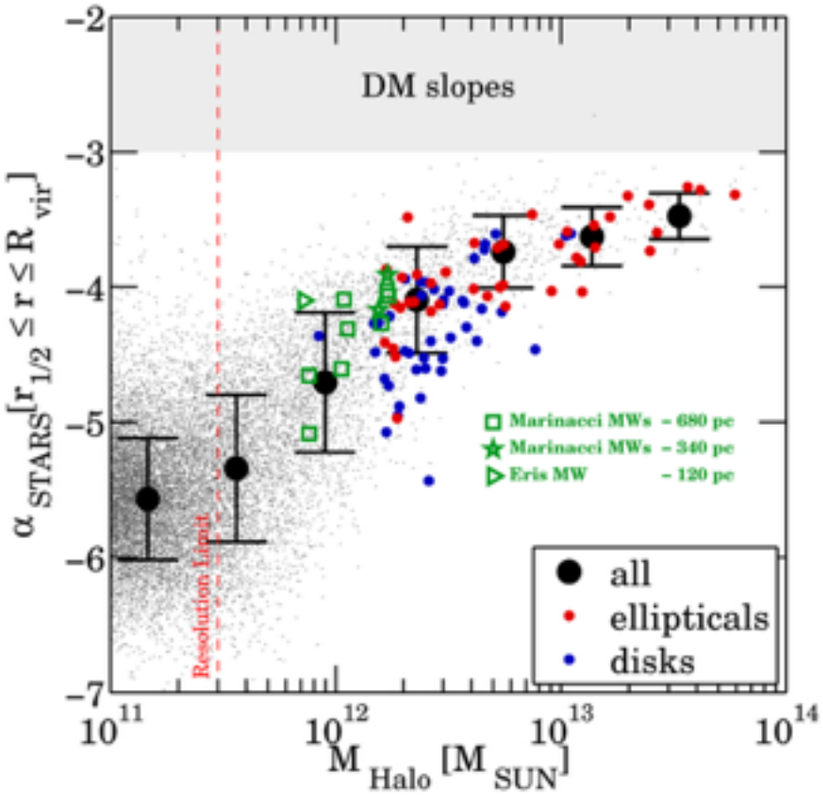


© Aquarius, A. Helmi et al.

See Guinevere, Nicolas's talk

- ✓ Galaxies surrounded by relics of past mergers: streams evolving into diffuse halos

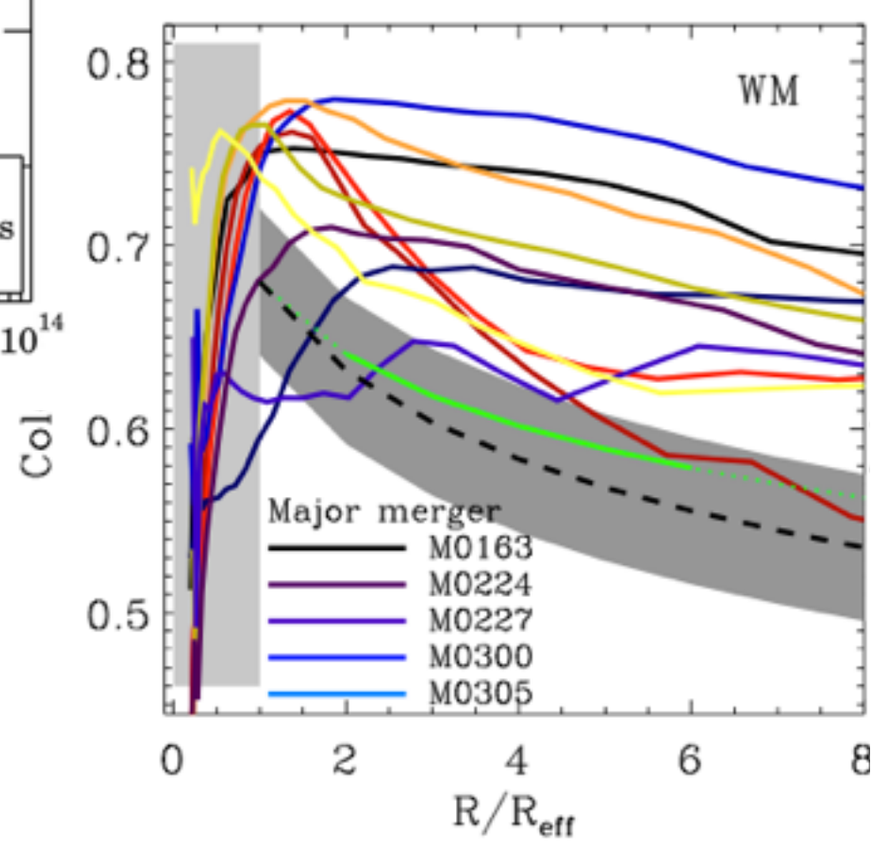
- ✓ Slope of stellar profile depends on mass and morphological type



© Illustris, A. Pillepich et al. 2014

See Annalisa's talk

- ✓ Color profiles (Z,age) depends on merging history



Hirschmann et al. 2015

Motivations: models

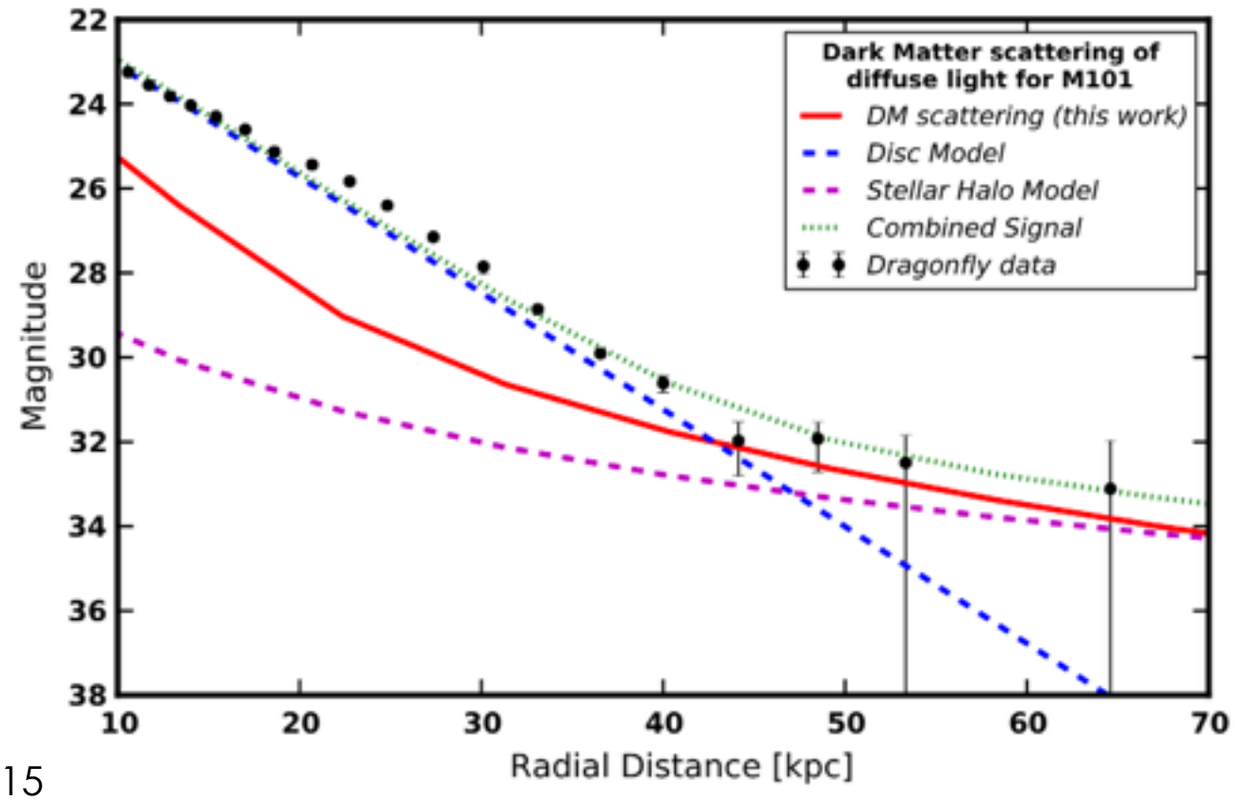
Checking the dark matter profile of galaxies

© Martin, Ibata et al.

- ✓ The shape of the streams orbiting their host probes the shape of the DM halo

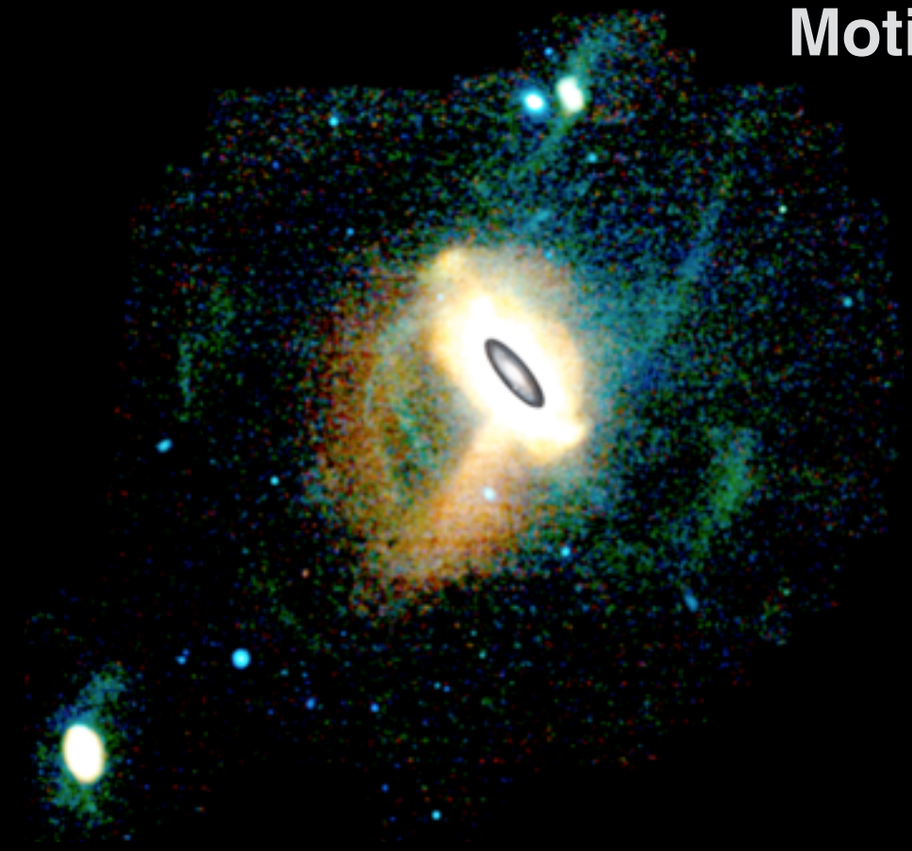
See Wyn's talk

- ✓ DM halos directly observed with scattered light



Davis & Silk 2015

Motivations: observations



McConnarchie et al, 2011

See Rodrigo and Karoline's talk

- ✓ Galaxy archeology with star counts: M31 as seen by PAndAs: *outside the Local Group?*

Martinez-Delgado et al., 2010

- ✓ « Amateur » type images reveal LSB streams from diffuse light: *how frequent?*

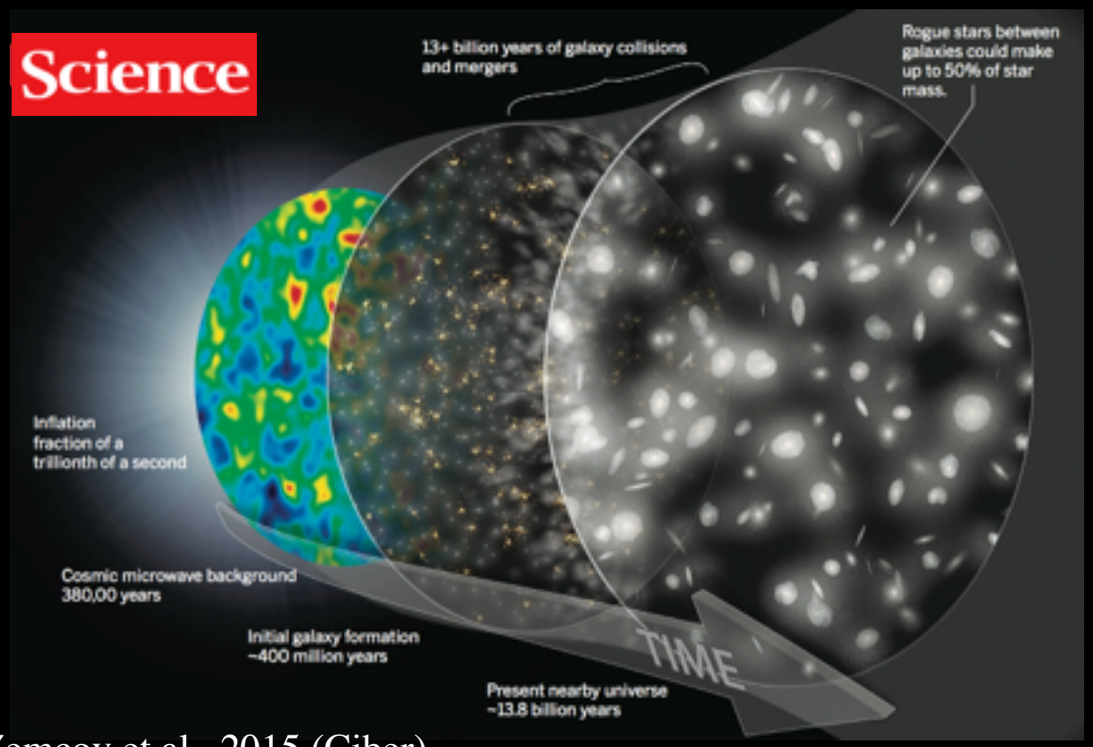
See David's talk

- ✓ Near-infrared background light anisotropy determined by the Ciber experiment: half of the stars outside « galaxies »

- ✓ Not consistent with deep surveys of the intra-cluster light

Montes & Trujillo, 2014: >6% contribution

See Ignacio's talk

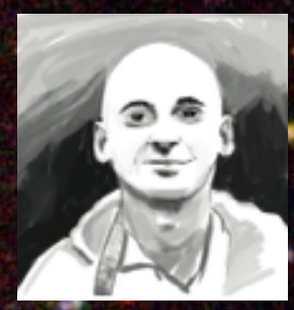


Zemcov et al., 2015 (Ciber)

Atlas^{3D} team

The faint stellar halos from ground based imaging

Jean-Charles Cuillandre



Emin Karabal

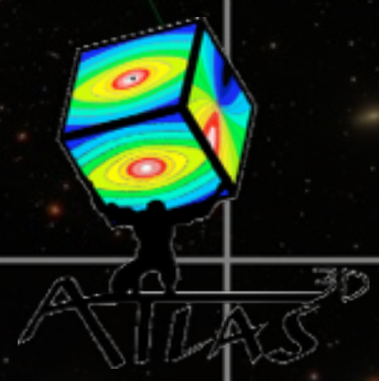
NGVS team

Pierre-Alain Duc

Deep imaging of massive nearby galaxies with MegaCam on the CFHT

- Volume-limited sample of 260 massive ETGs with D < 42 Mpc (Altas^{3D})

- Comparison sample of 120 massive LTGs from Altas^{3D} parent sample



Cappellari et al, 2011

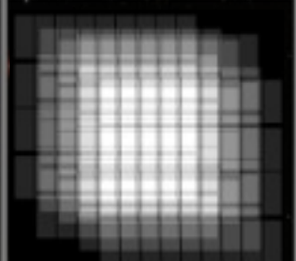
- Observed with the large field of view camera MegaCam (multiband:u,g,r,i) on the CFHT, as initially Atlas3D regular programs, followed by a Large CFHT Program (MATLAS, ->2015), and complemented for Virgo galaxies with the NGVS

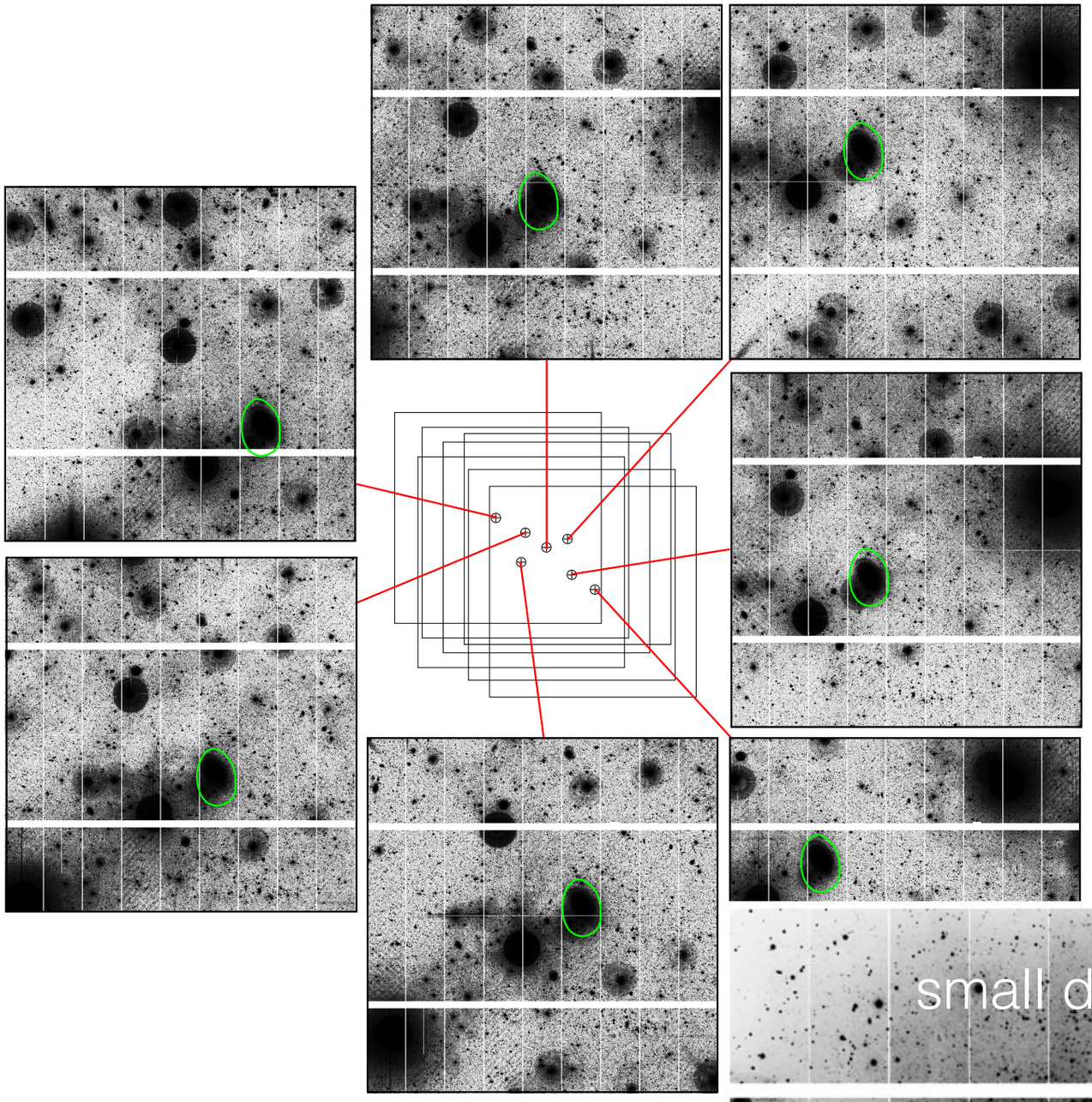
MATLAS

Duc et al, 2015

NGVS

Ferrarese et al, 2011



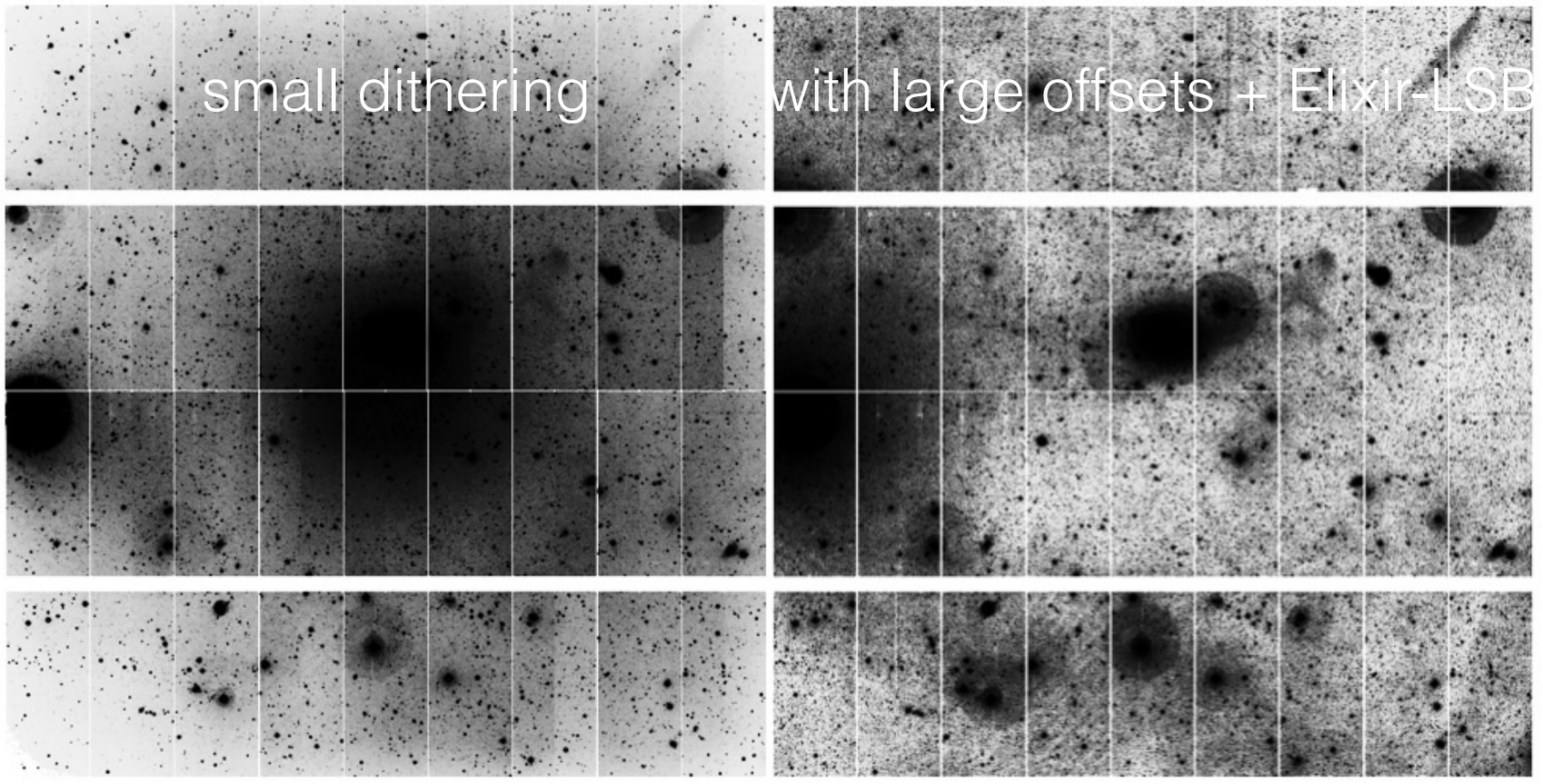


A dedicated imaging strategy and data-reduction technique

- ✓ optimized for the detection of extended low surface brightness features
- ✓ resulting in a gain of several mag with respect to regular techniques

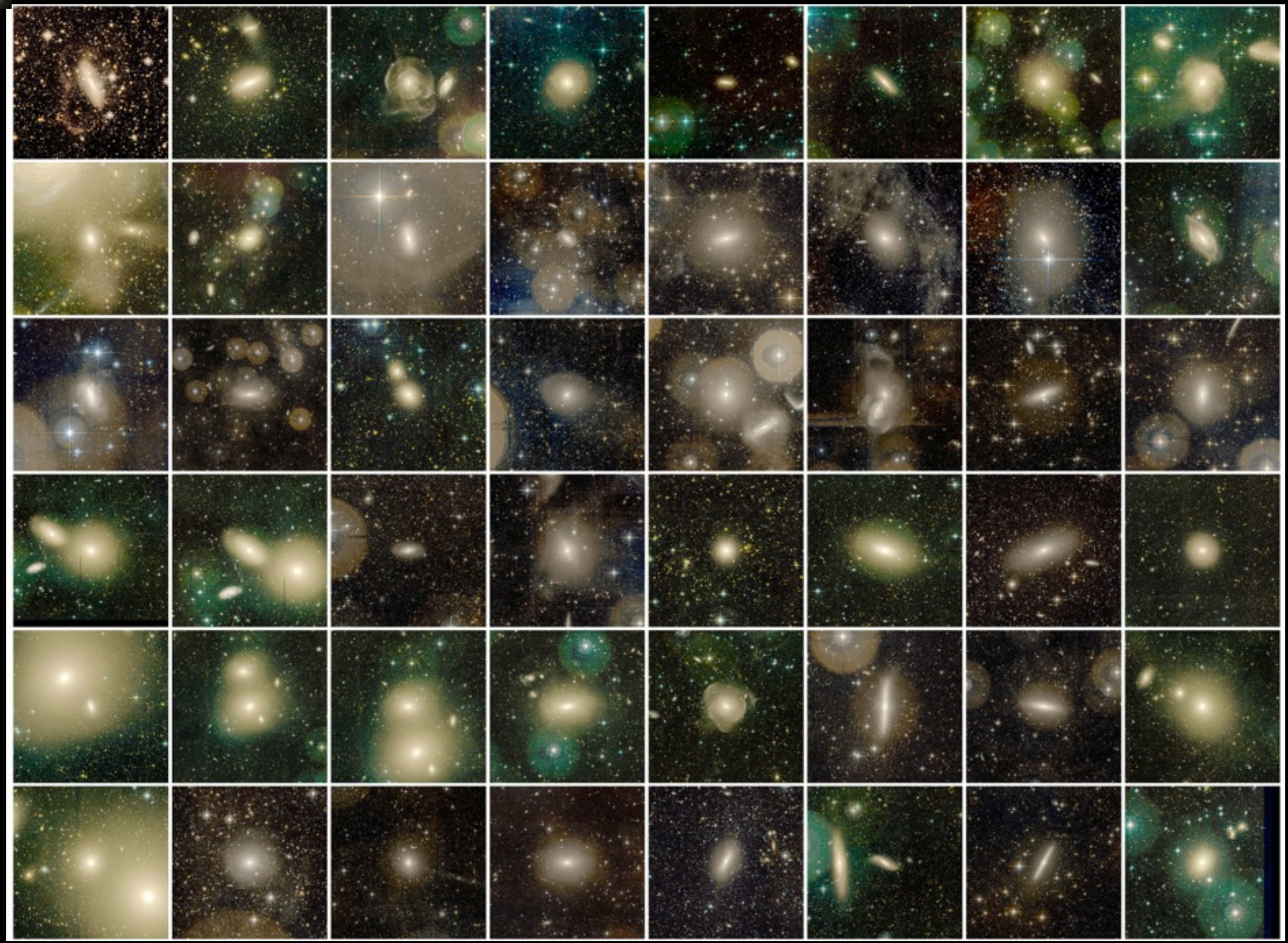
Duc et al., 2015

- ✓ limiting magnitude of about 28.5-29 mag.arcsec^{-2} (g) over **scales of 10”**



SDSS images of the Atlas^{3D} ETGs

MegaCam images of the Atlas^{3D} ETGs



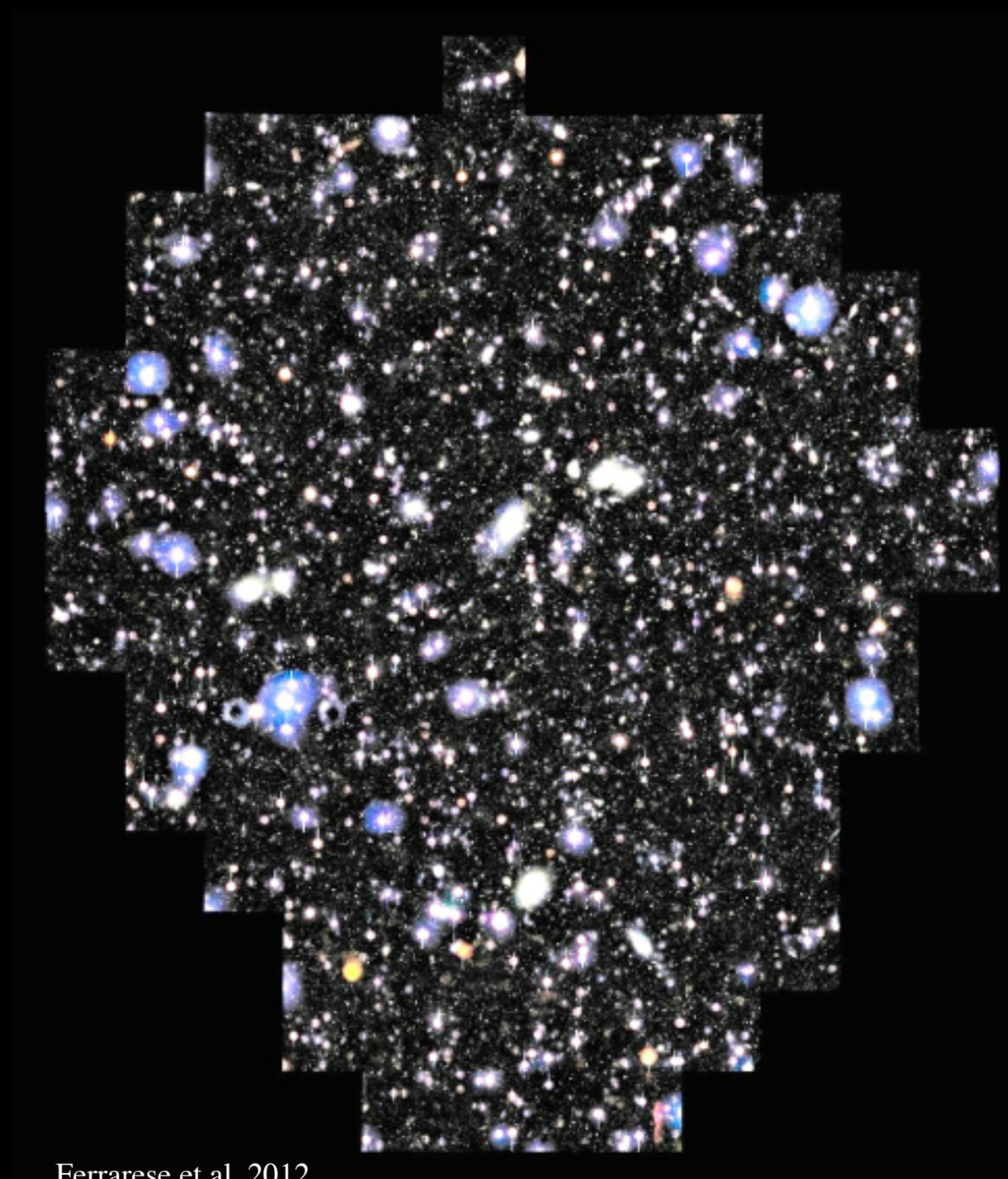
SDSS images of the Atlas^{3D} ETGs

The Virgo cluster as seen by

the SDSS

The Virgo cluster as seen by

the SDSS



the NGVS

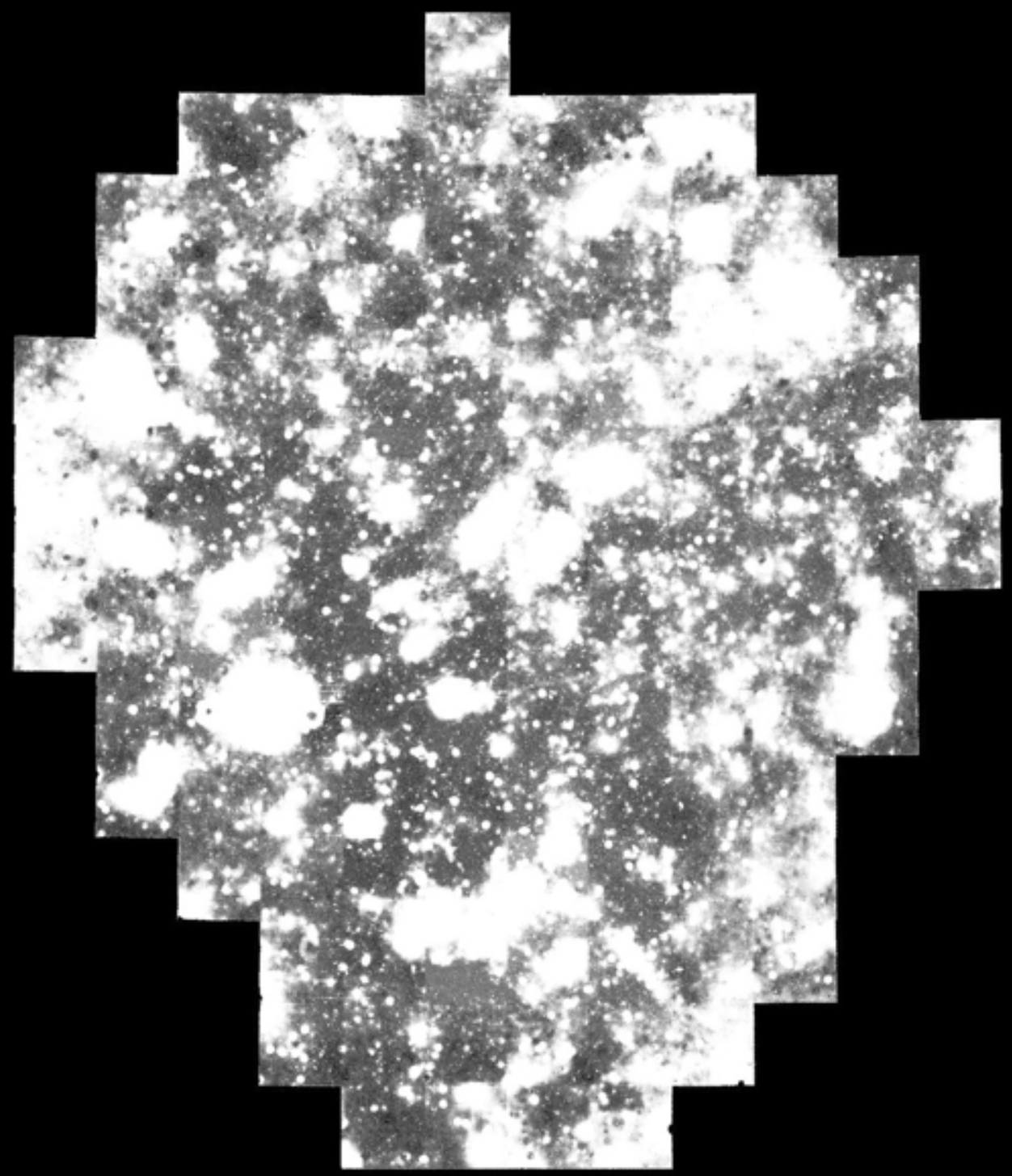
Ferrarese et al, 2012

104 square degrees in u,g,i and z

The Virgo cluster as seen by

the SDSS

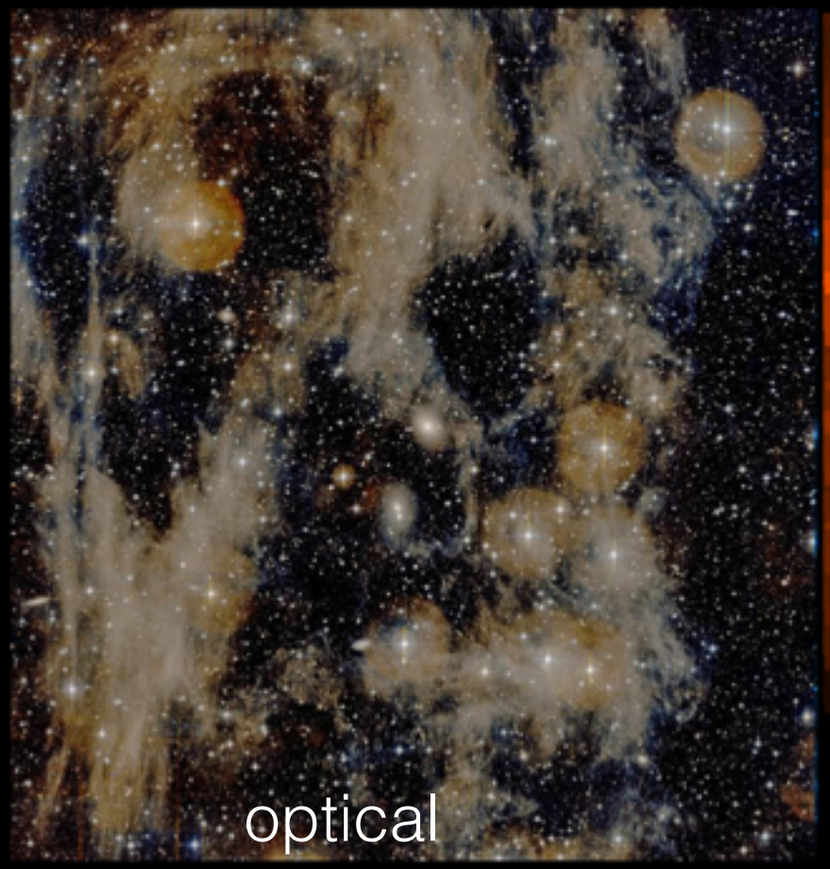
A dark sky

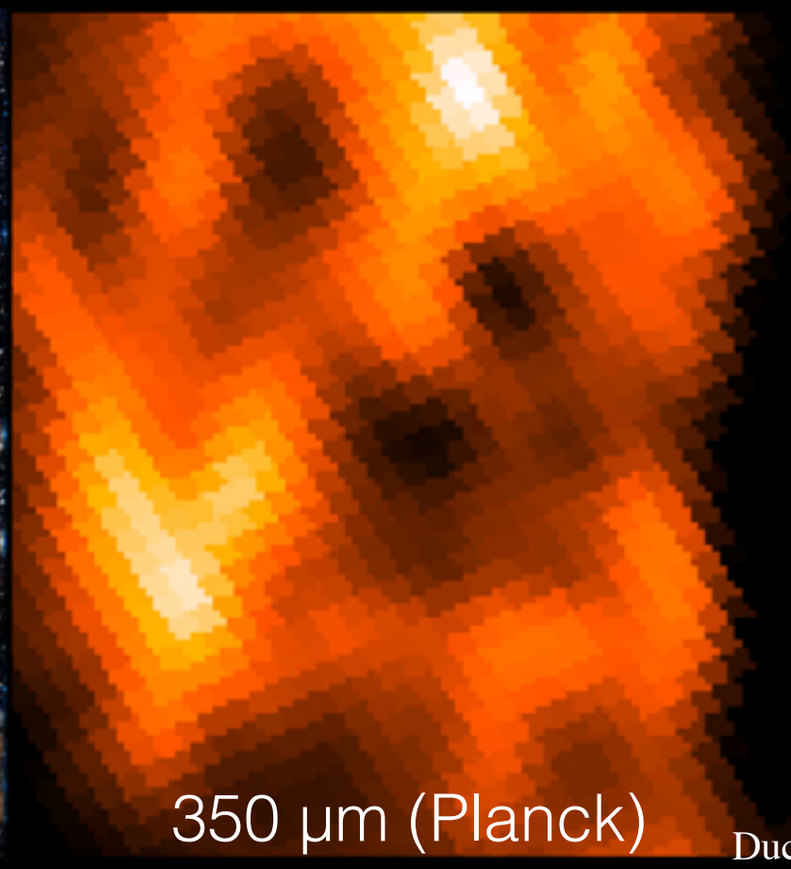


the NGVS

A white sky

Issues with deep imaging: Galactic cirrus



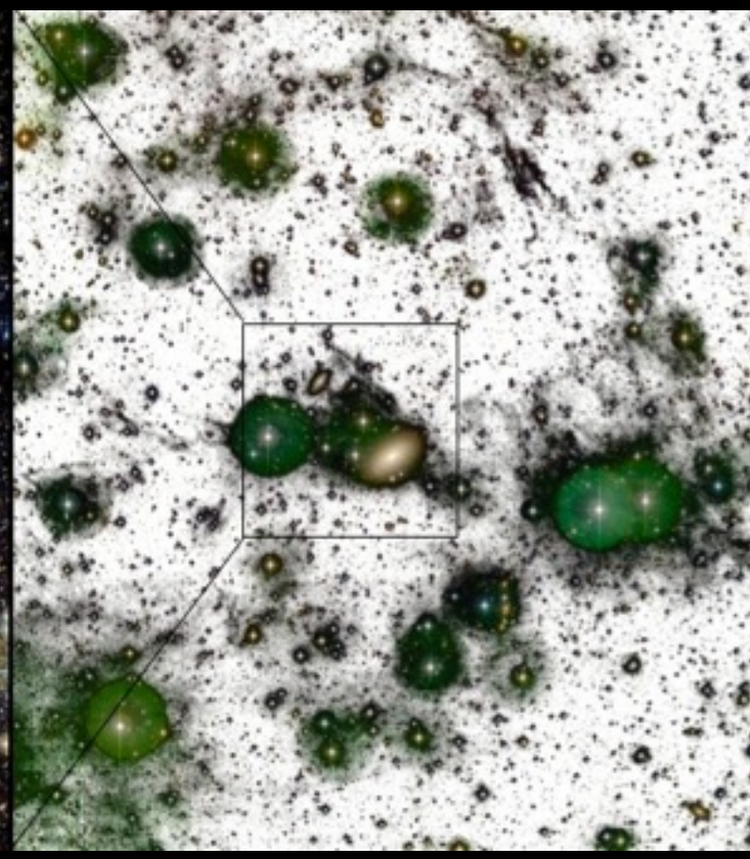


Duc et al., 2015

- ✓ Extended, with a filamentary structure and colors resembling stellar streams

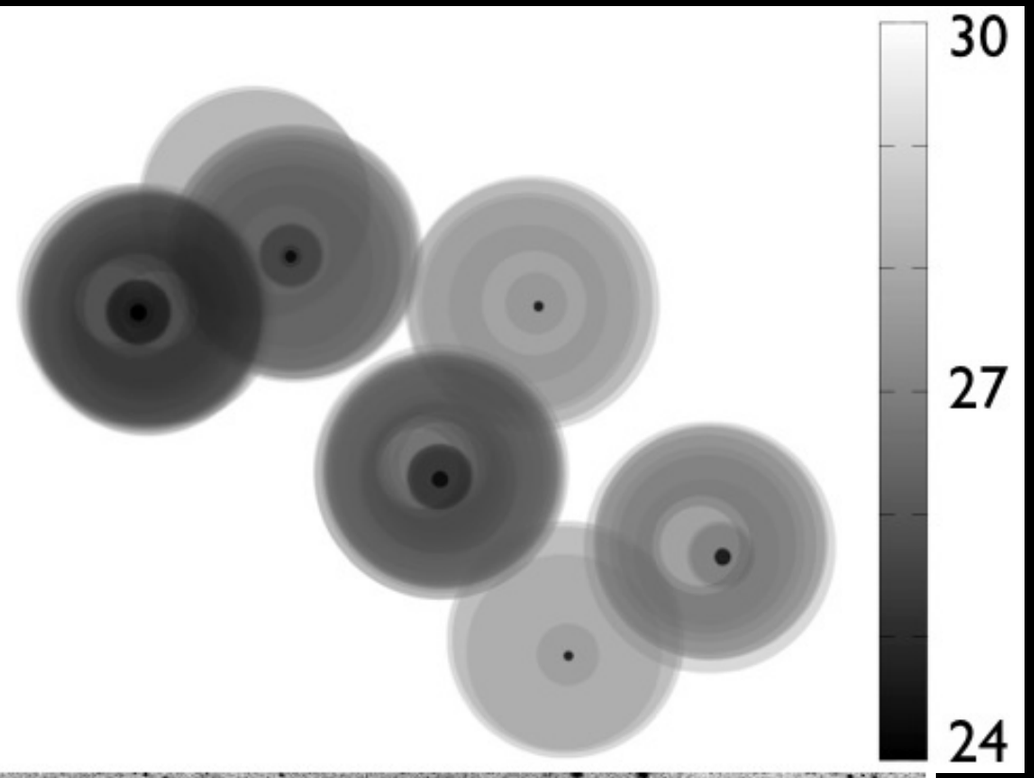
- ✓ Can be identified at other wavelength (far UV, far IR), masked, but not subtracted…

- ✓ Allows us to study the distribution of dust clouds at unprecedented spatial resolution

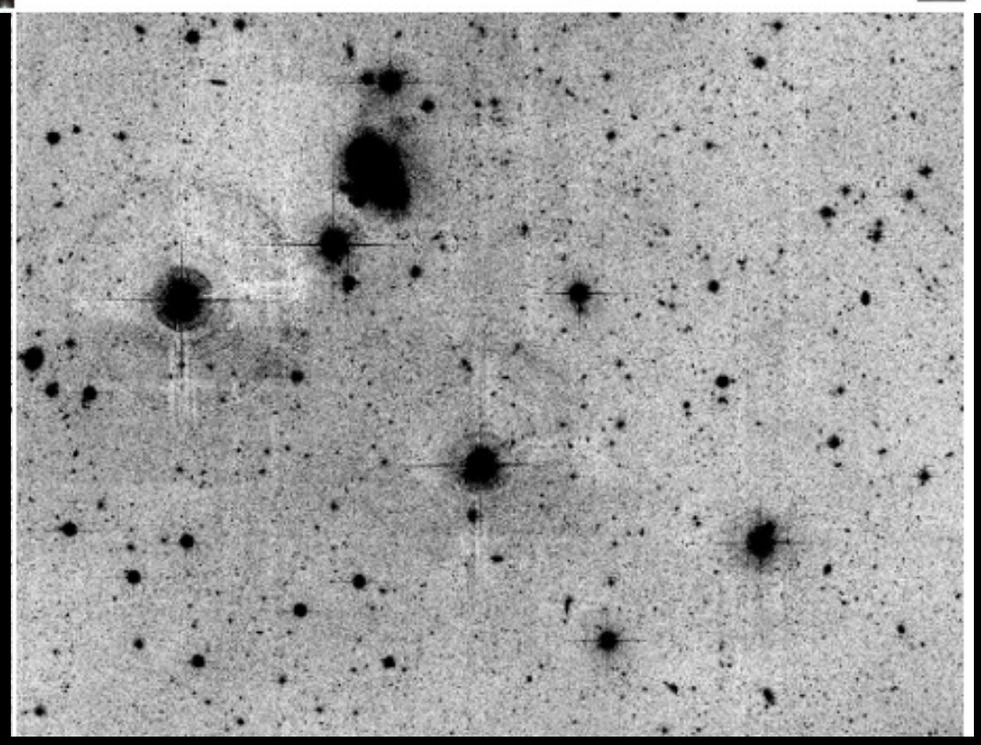


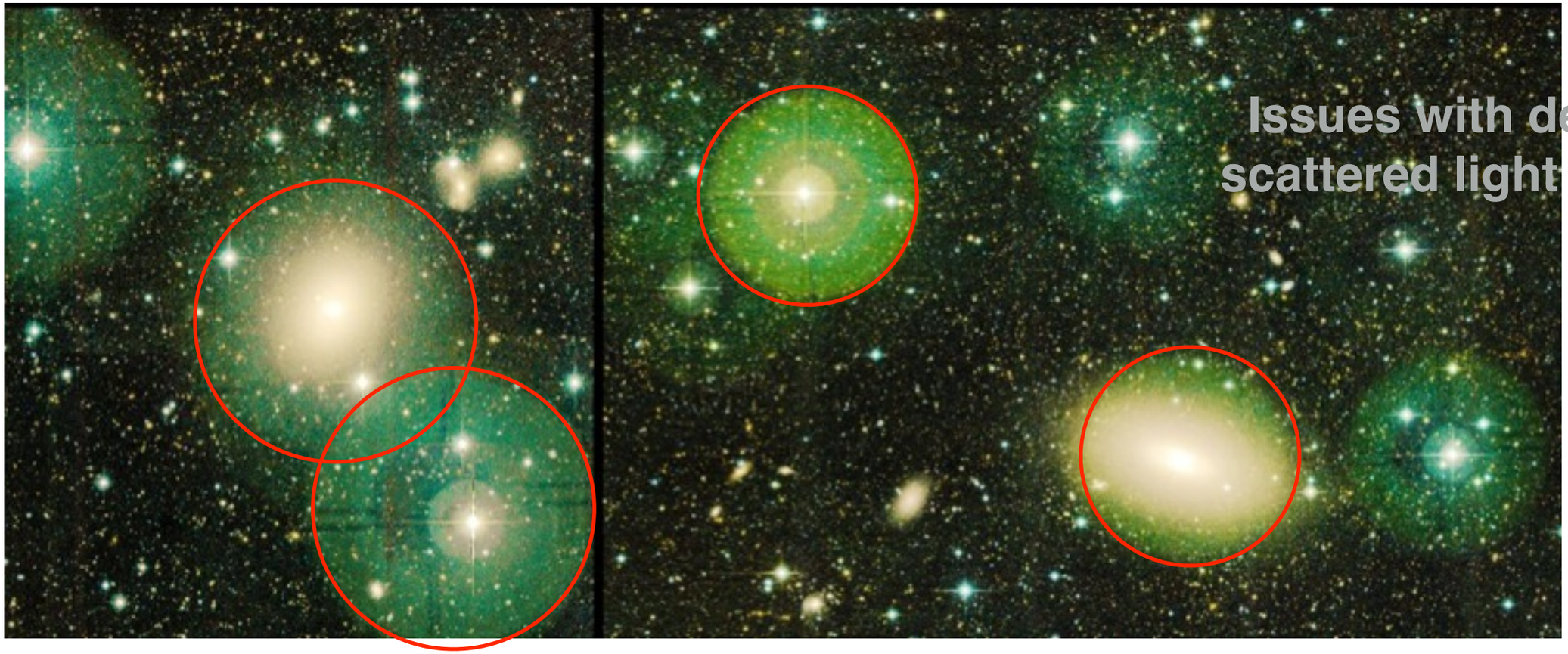
Issues with deep imaging: scattered light from stars

✓ wings of the PSF plus extended arcmin size halos due to multiple internal reflections in the camera



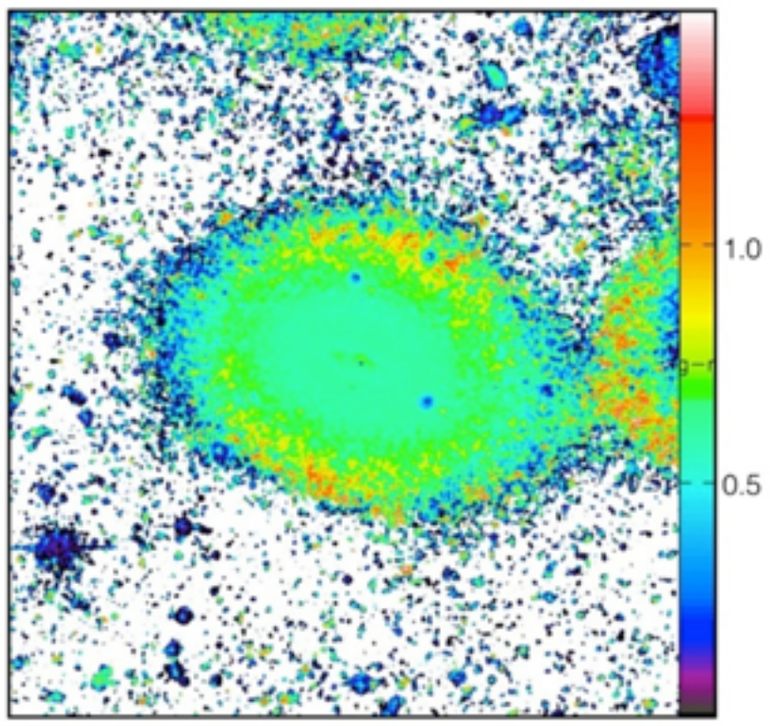
- ✓ contaminate the morphology/ colors of close-by galaxies
- ✓ halos globally similar, in details depend on position on the image
- ✓ modeled by hand and subtracted from the images





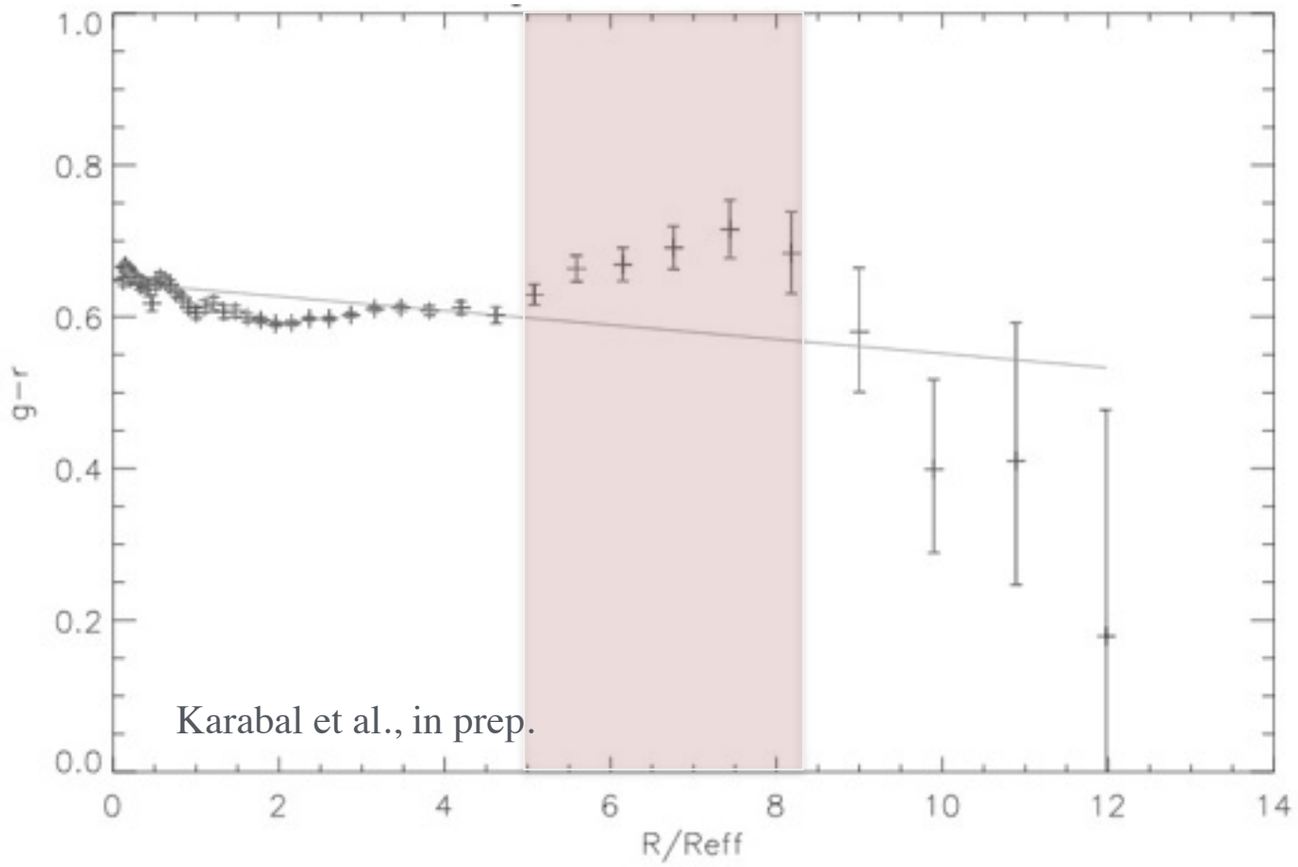
Issues with deep imaging: scattered light from galaxies

✓ similar shapes but more diffuse: mimic galaxy halos

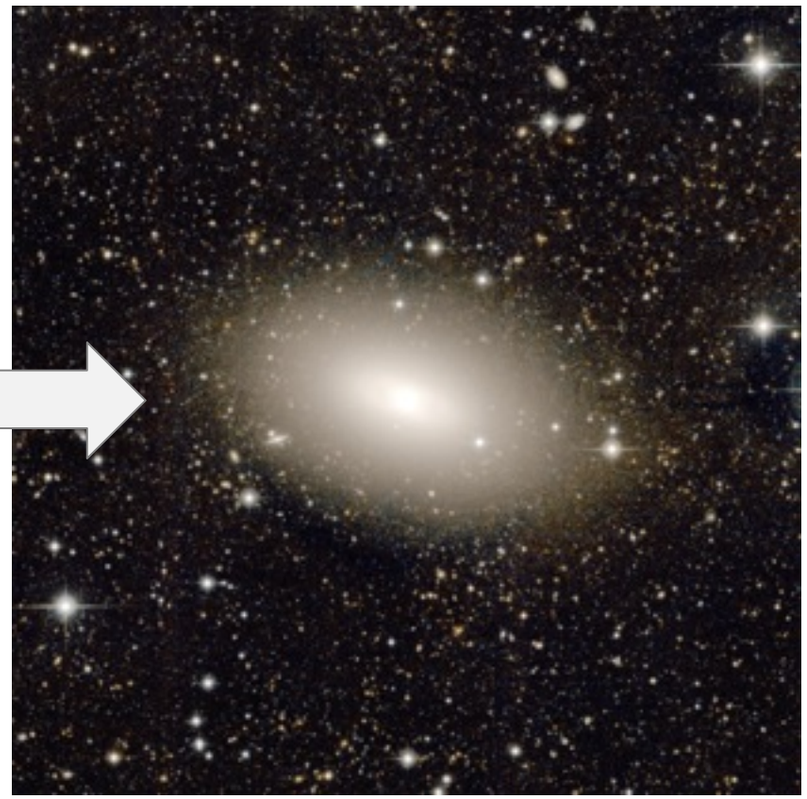


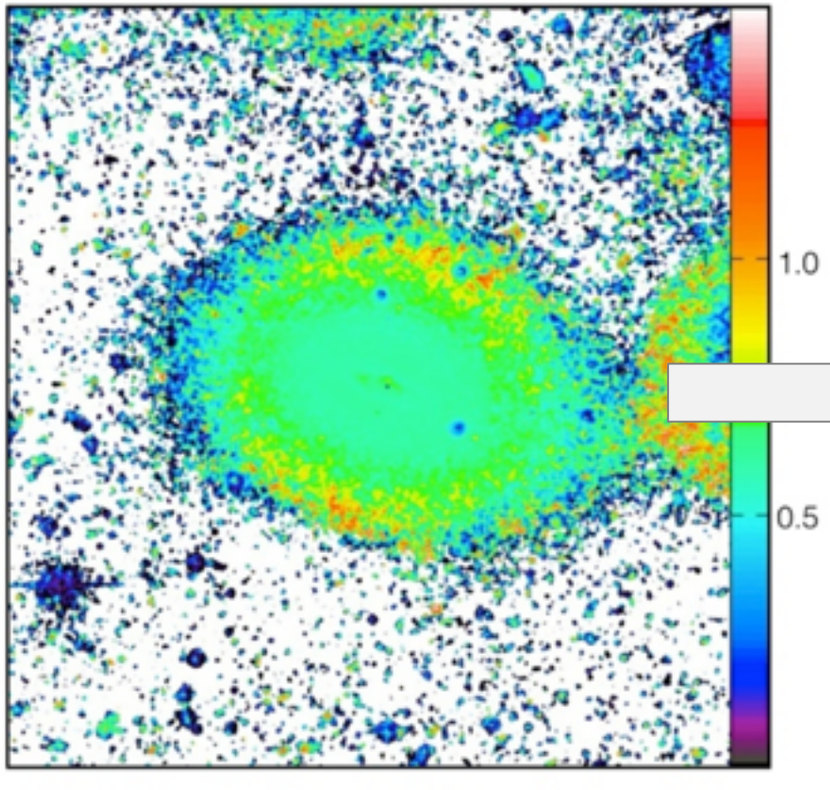
✓ shows us as a red ring on color maps, and reddening on color profiles

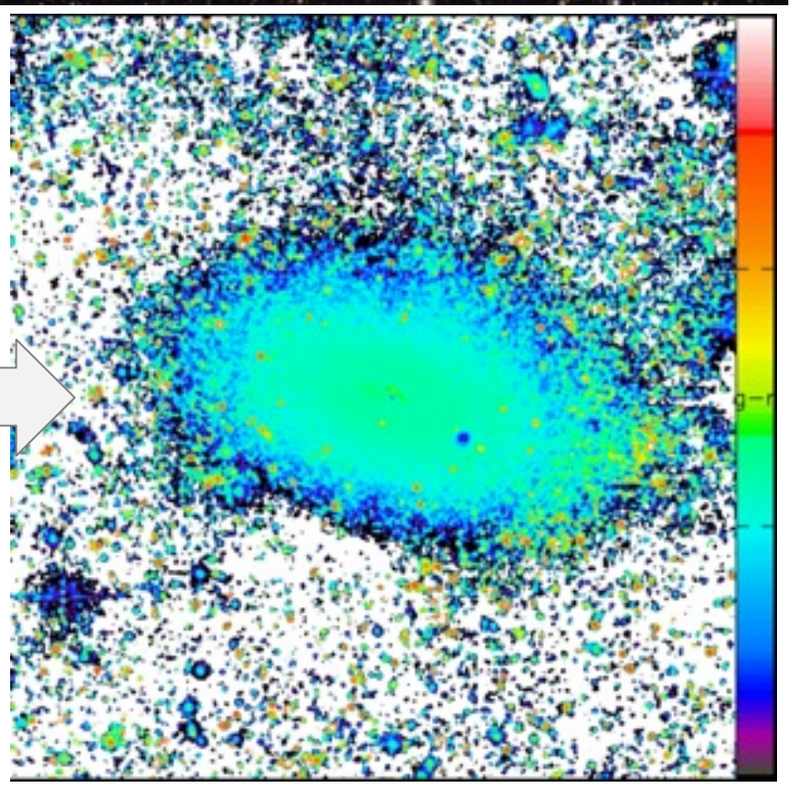
✓ directly visible in the r band around small or edge-on galaxies with bright compact nucleus



Issues with deep imaging: scattered light from galaxies

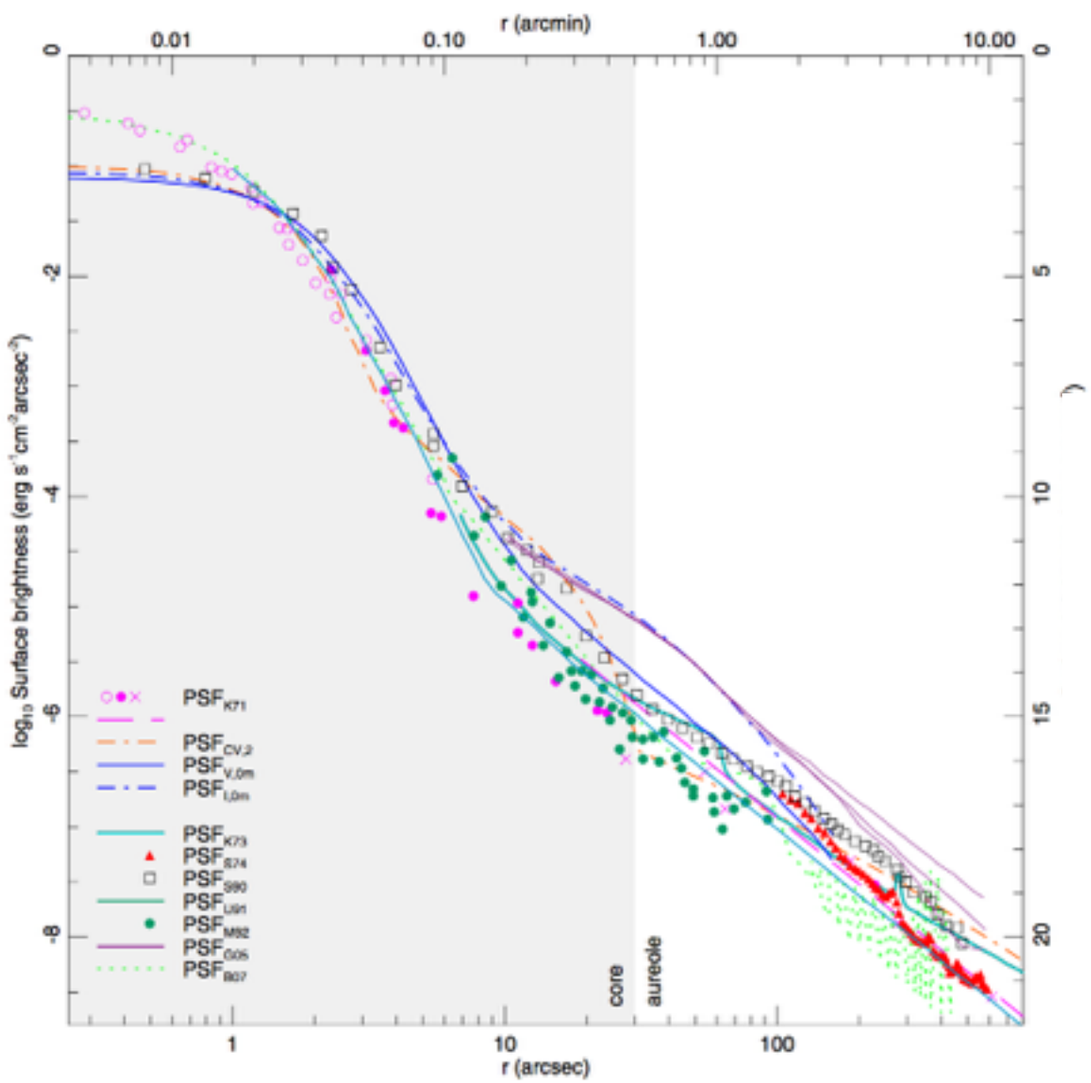






- ✓ On going efforts to estimate the contamination level as a function of galaxy size, inclination, compactness
- ✓ Attempts to directly subtract it for galaxies for which the halo is directly visible
- ✓ A serious issue for all the other galaxies

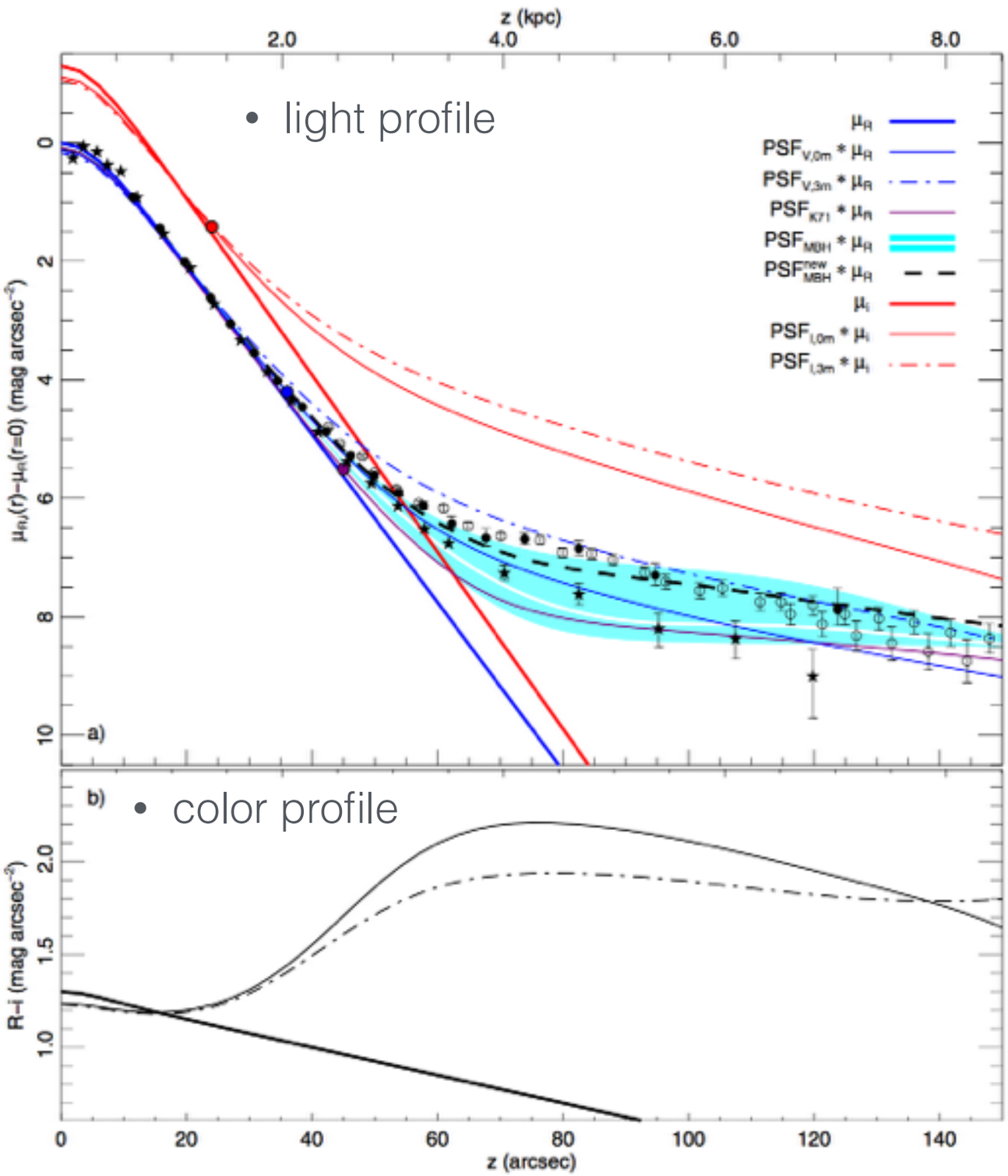
Issues with deep imaging: scattered light from galaxies



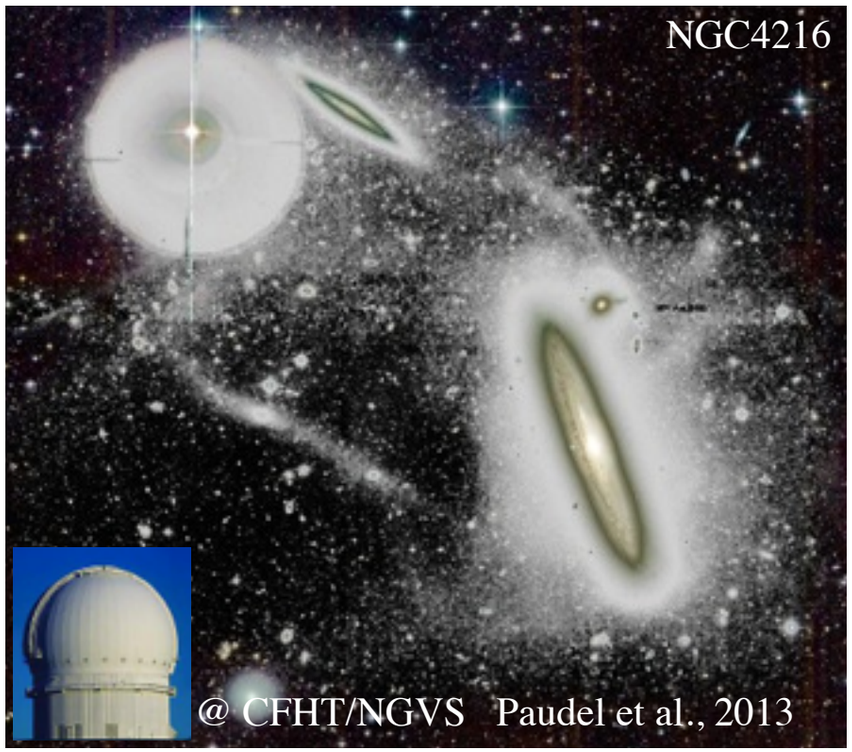
Sandin et al., 2014

- ✓ Convolution with PSF models can help to determine the contamination level
- ✓ Low effect on early-type galaxies, strong for inclined spirals

See Christer's poster



Issues with deep imaging: scattered light from galaxies



@ 29 mag.arcsec^{-2}

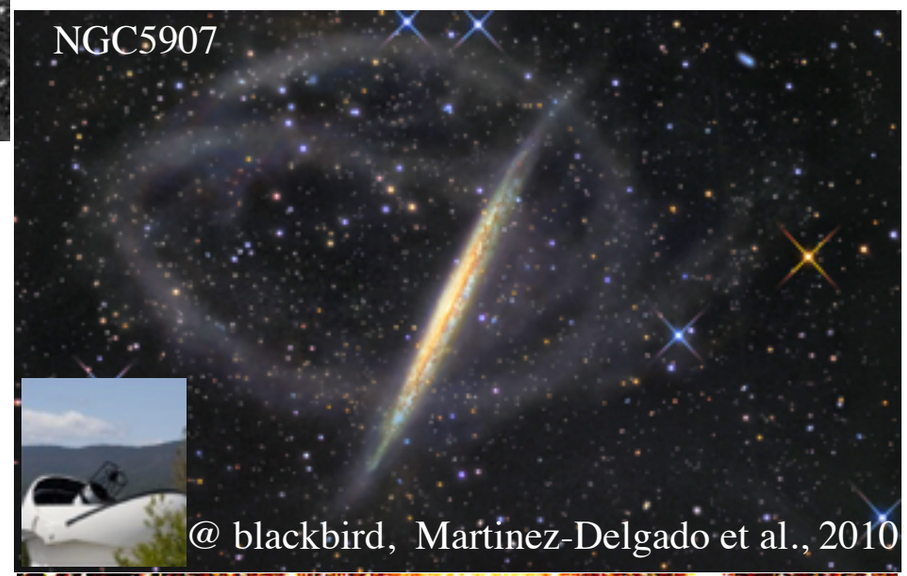
@ 28? mag.arcsec^{-2}

The competition does better….

Stellar halos minimized with

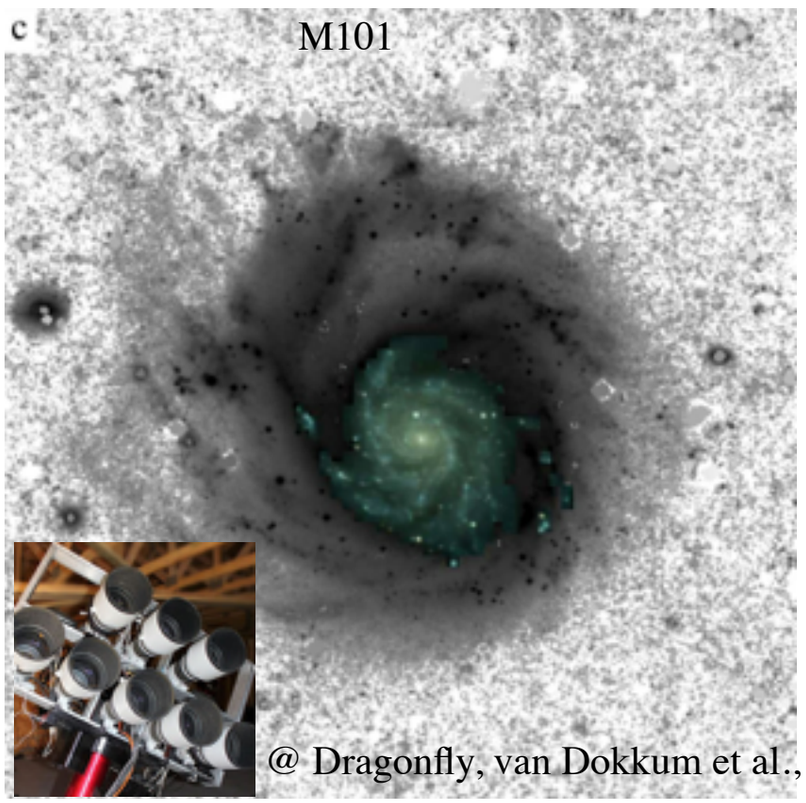
- ✓ with amateur telescopes and cameras with simple optics

See David's talk

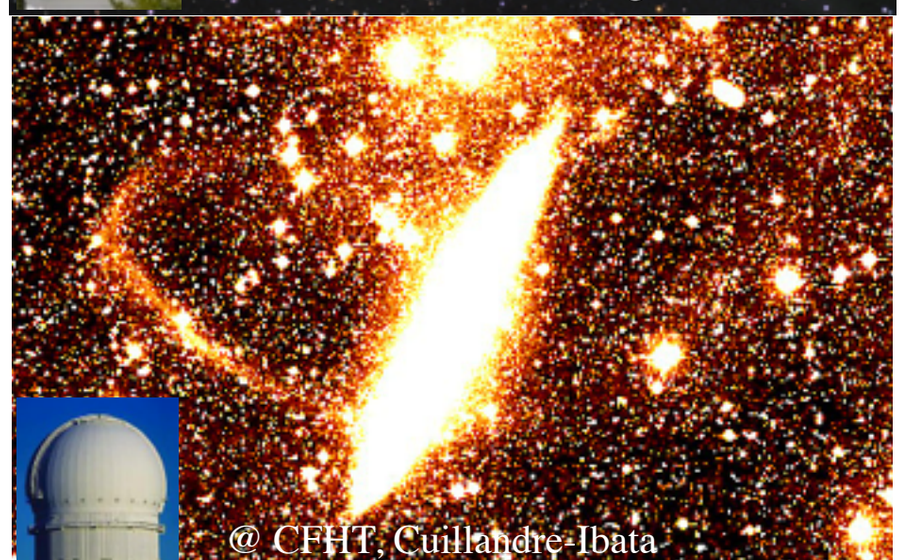


- ✓ with dedicated cameras, coated optics, that minimize the stellar halos

See Chris's talk



@ 32? mag.arcsec^{-2}



Issues with deep imaging: scattered light from galaxies

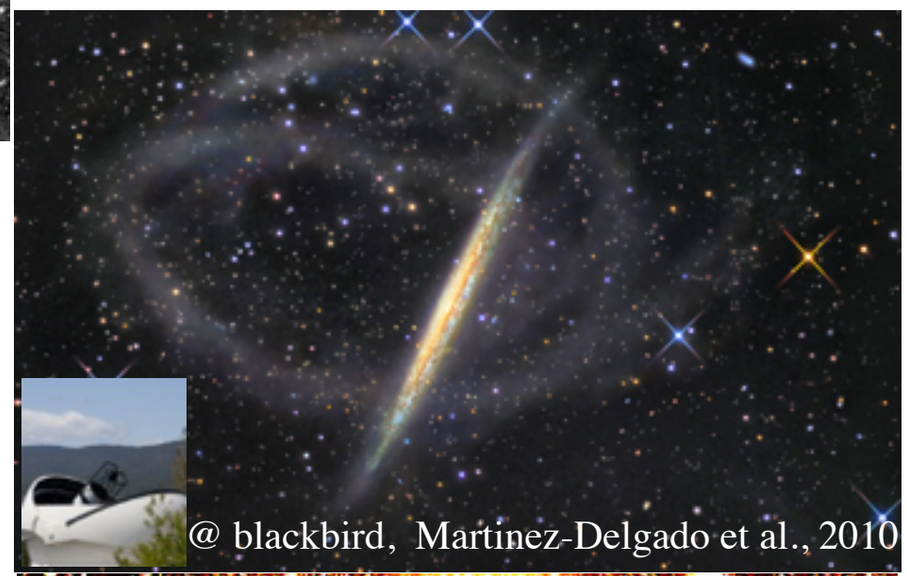
@ 29 mag.arcsec^{-2}

@ 28? mag.arcsec^{-2}

The competition does better….

but with long exposure times still preventing large surveys

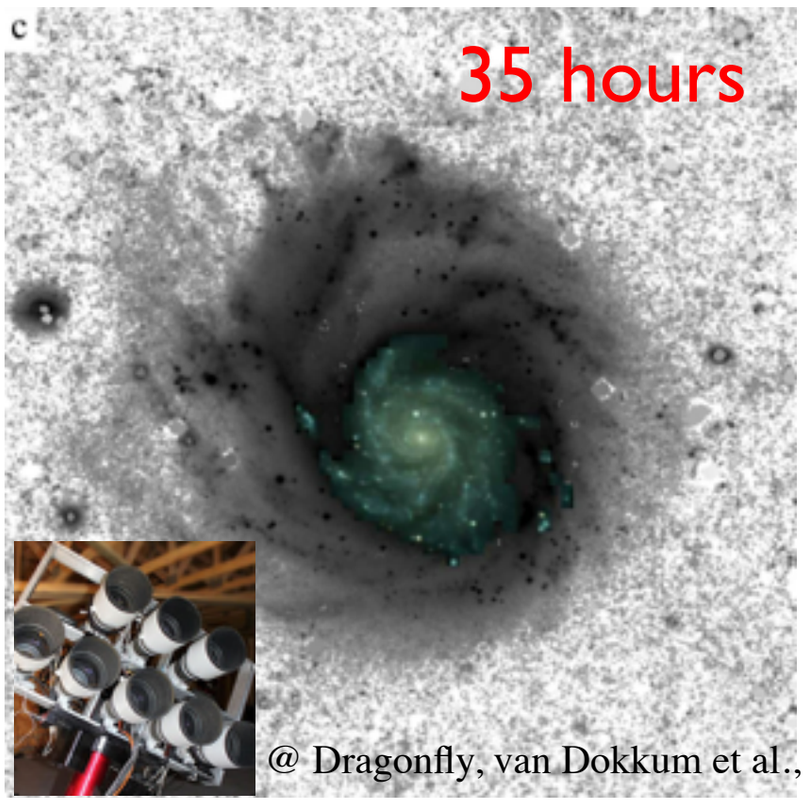
✓ with amateur telescopes and cameras with simple optics

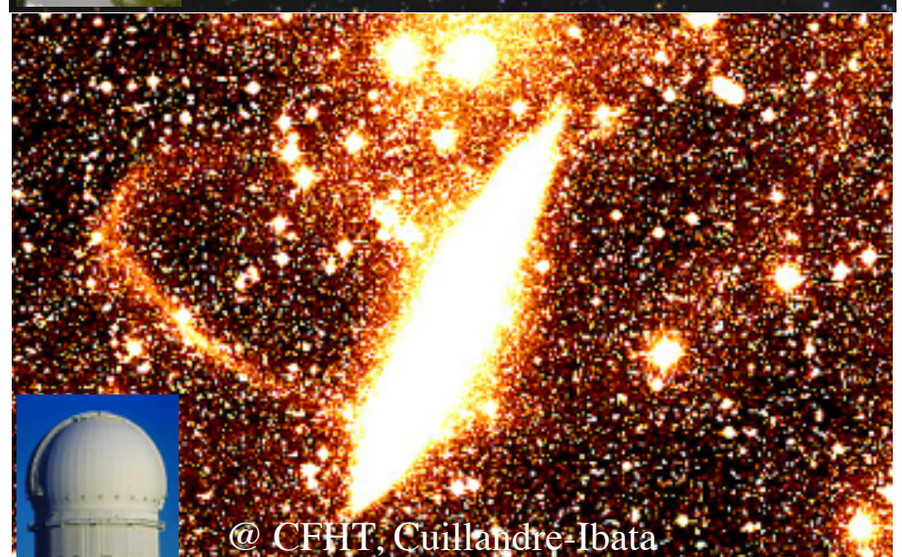


✓ with dedicated cameras, coated optics that minimize the stellar halos

… and uncertainties on the photometry, achieved surface brightness, and bad IQ

@ 32? mag.arcsec^{-2}





Issues with deep imaging: scattered light from galaxies

The competition does better….
but with long exposure times still preventing large surveys

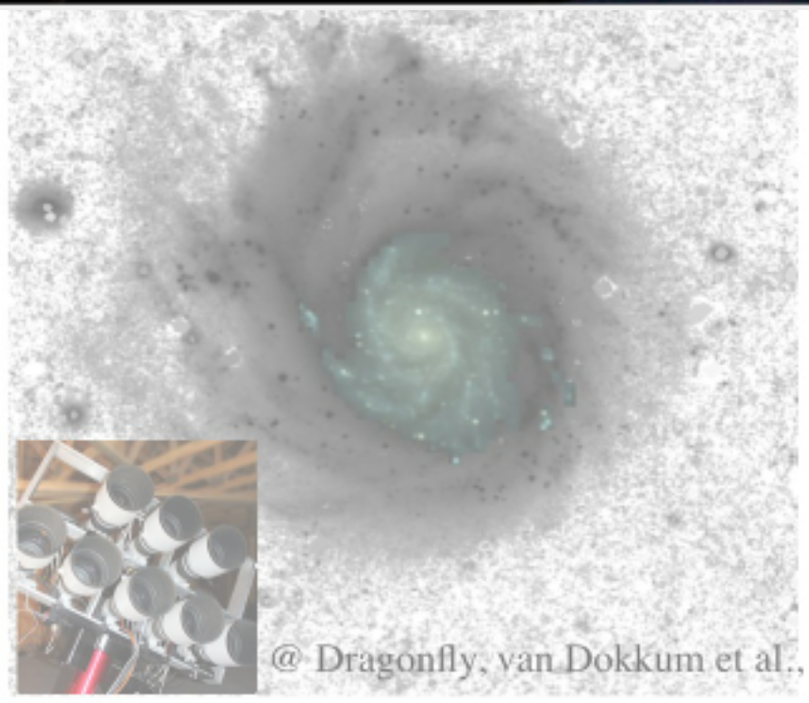
✓ with amateur telescopes and cameras with simple optics

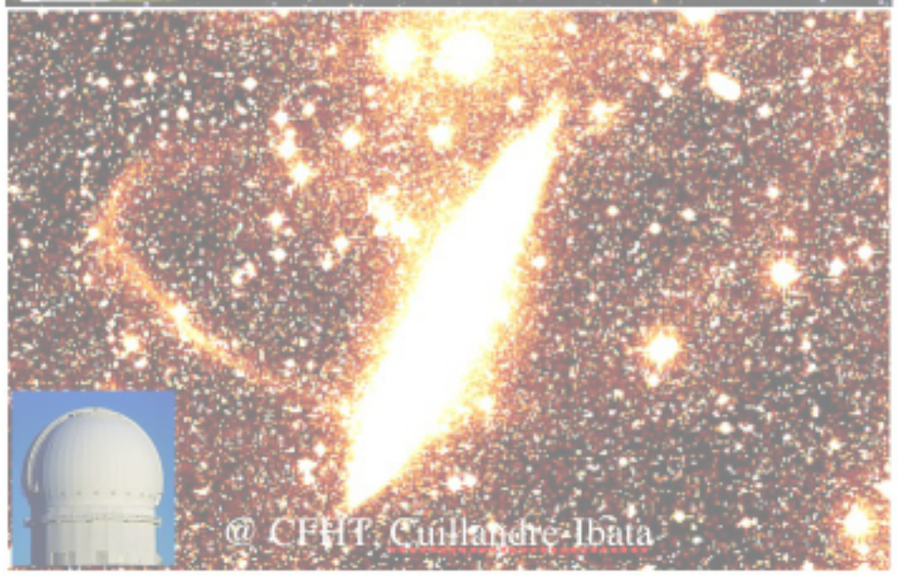
See talks at SP 16

✓ with dedicated cameras, coated optics that minimize the stellar halos

… and uncertainties on the photometry, achieved surface brightness, and bad IQ

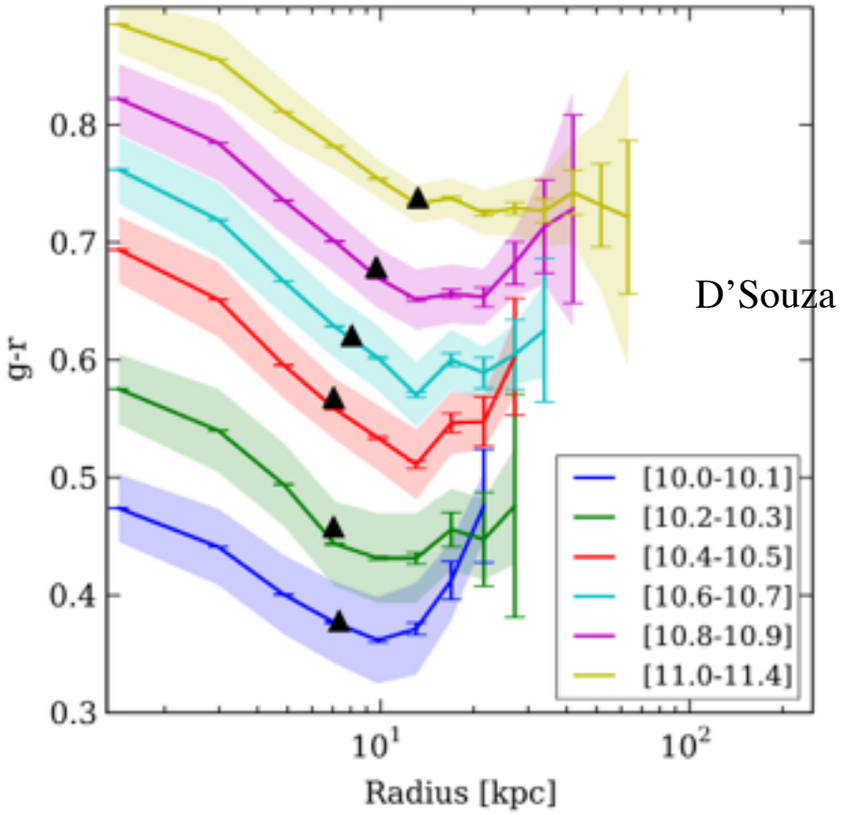
@ 32? mag.arcsec^{-2}





Issues with deep imaging: scattered light from galaxies

The competition does not necessarily better….

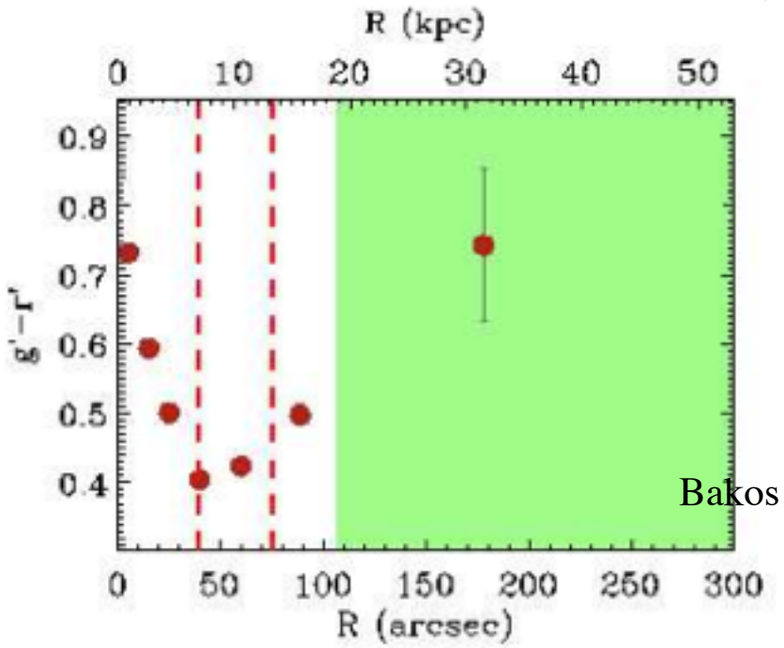


D'Souza et al., 2014

✓ with SDSS stacked images

See Richard's talk

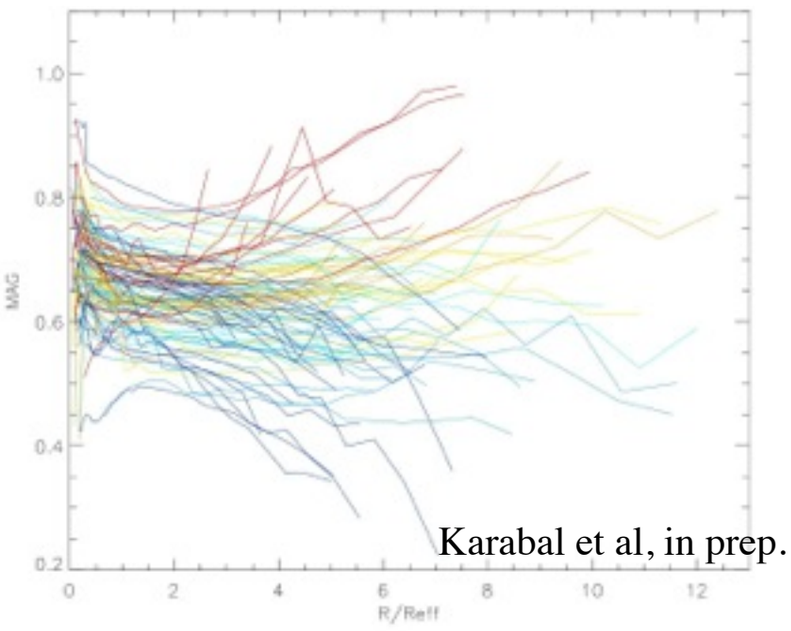
✓ with SDSS Stripe 82 deep survey



Bakos & Trujillo, 2012

See Kelvin's talk

✓ with MATLAS/NGVS individual studies of about 400 massive galaxies

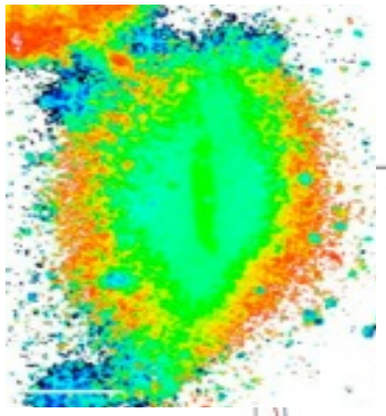


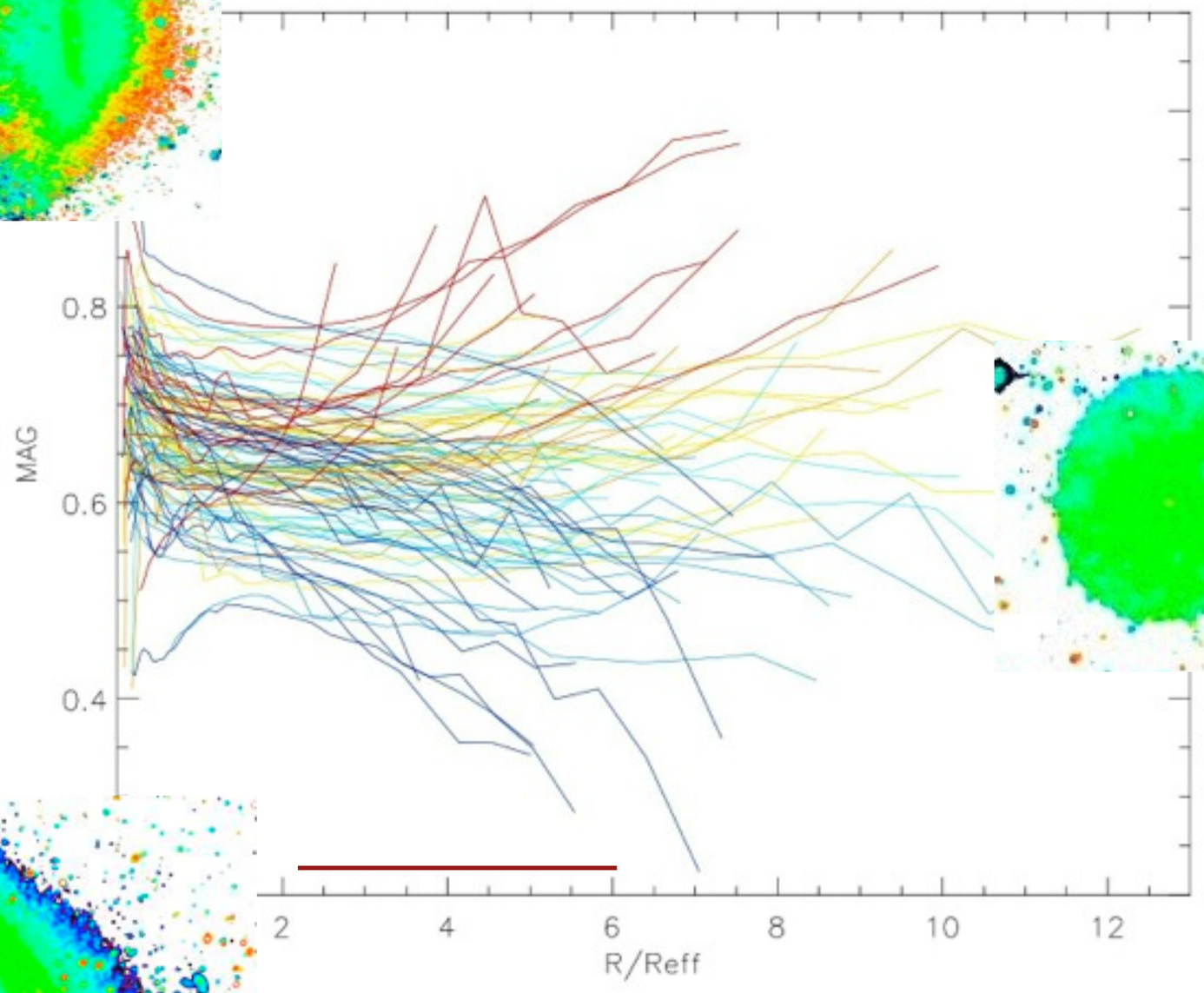
Karabal et al, in prep.

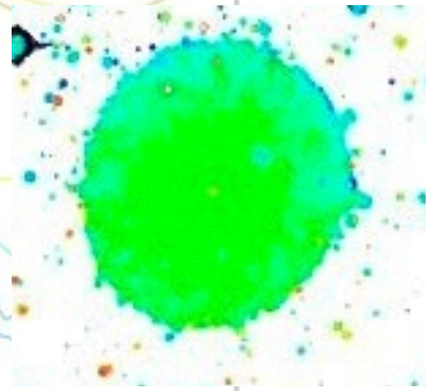
✓ are reddish halos confirmed in galaxies with resolved stellar populations / spectroscopic measurements?

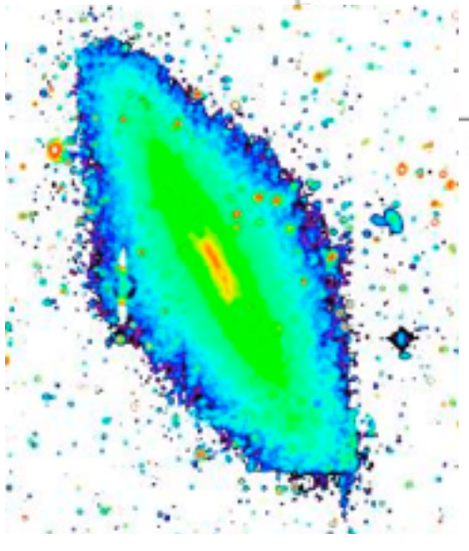
See Roelof, Antonella, Marina / Nicholas & Nicolas's talk

Color profiles with deep imaging



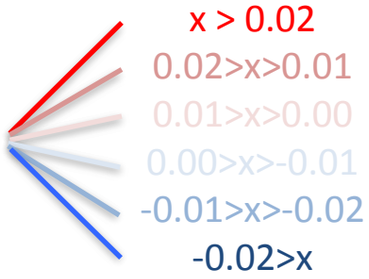


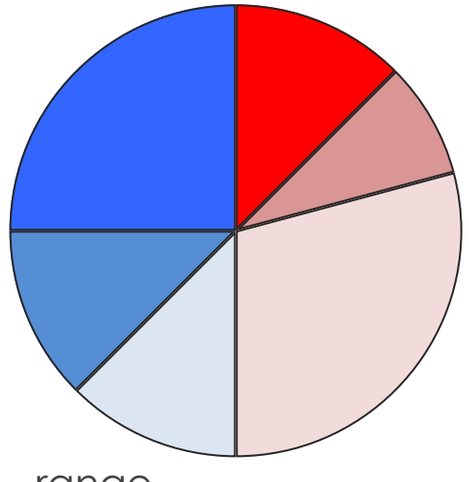




- a variety of color profiles

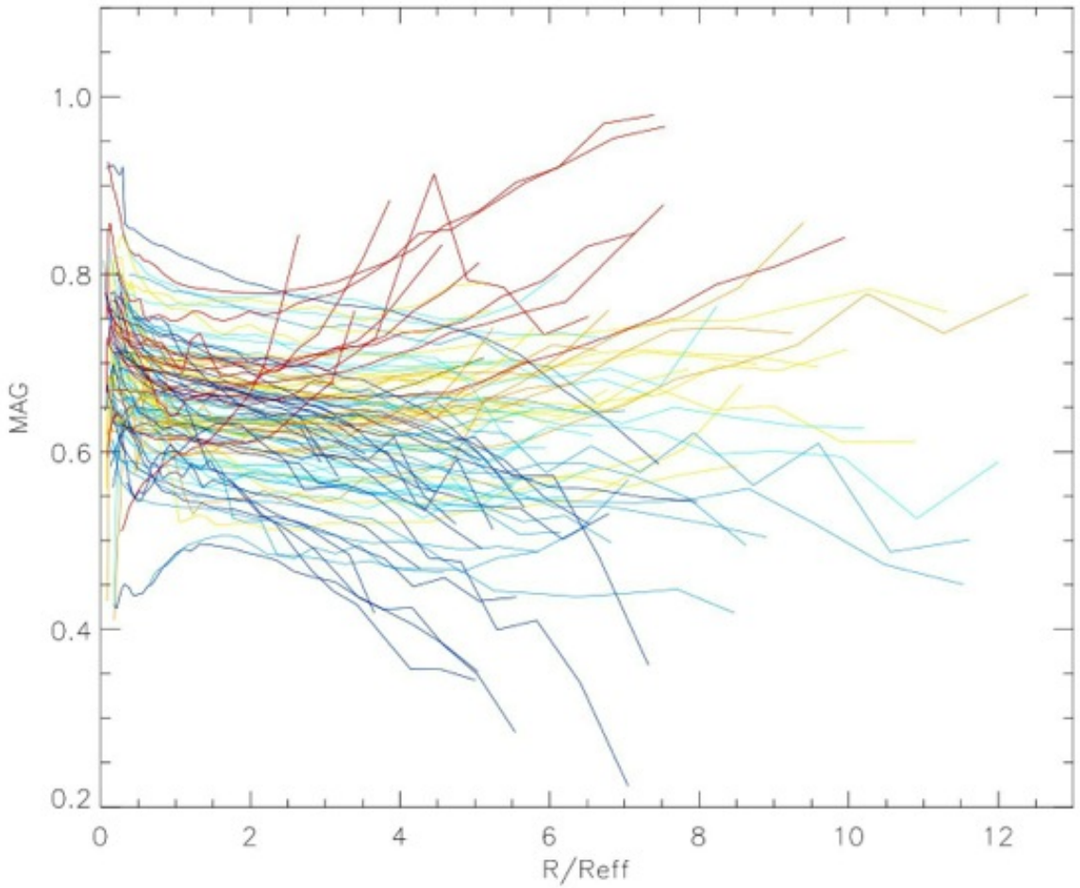
- statistics on color gradients



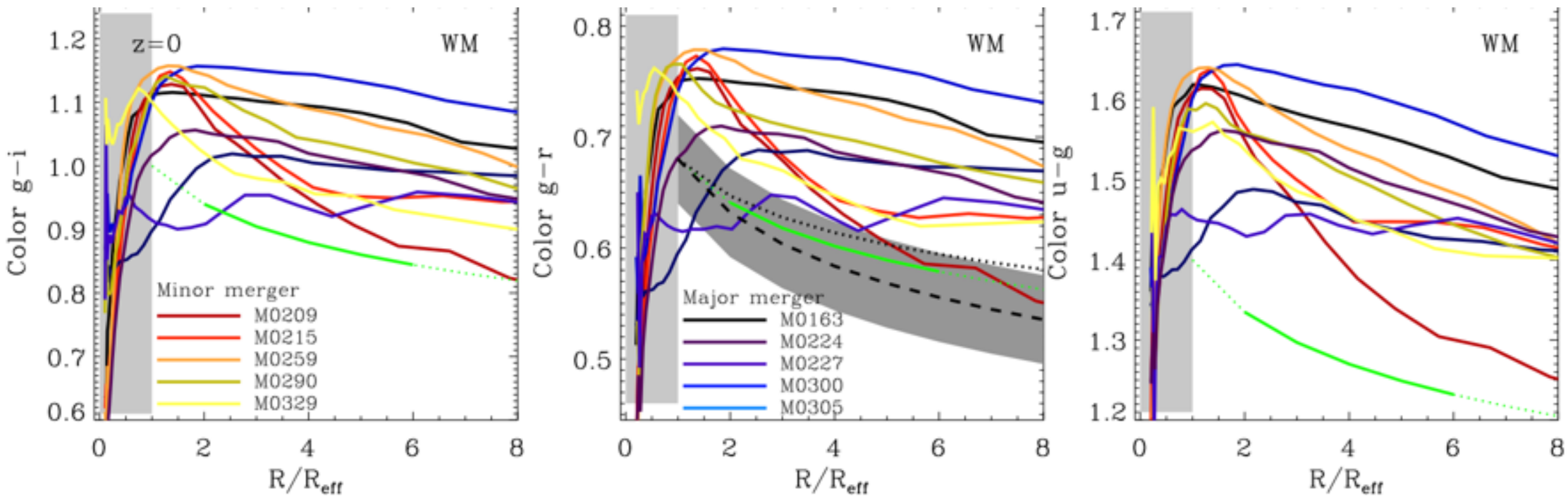


2-6 R_{eff} range

Color profiles with deep imaging: comparison with simulations

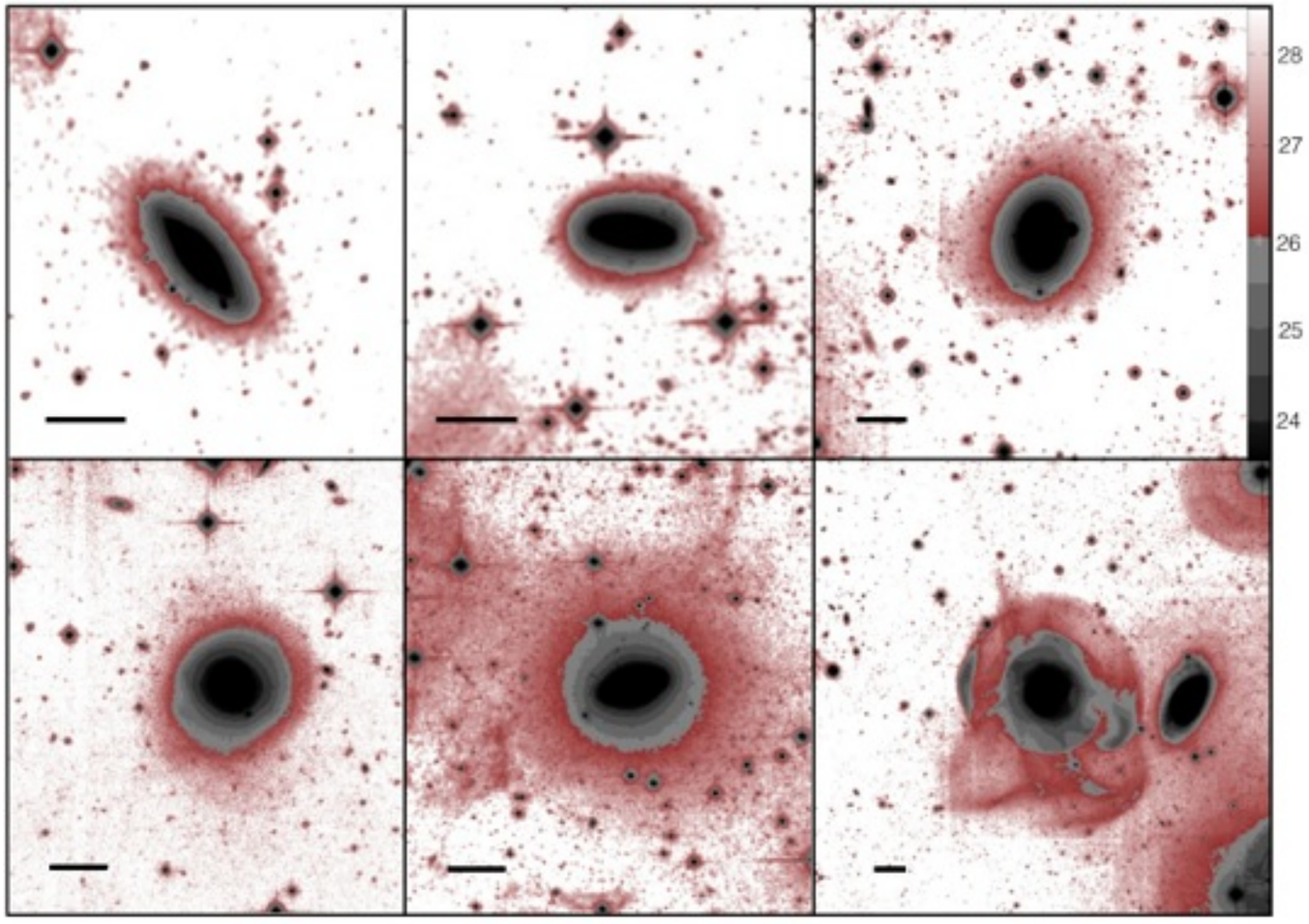


- ✓ on average: observed profiles flatter than predicted
- ✓ interpretation awaiting correction for PSF effects

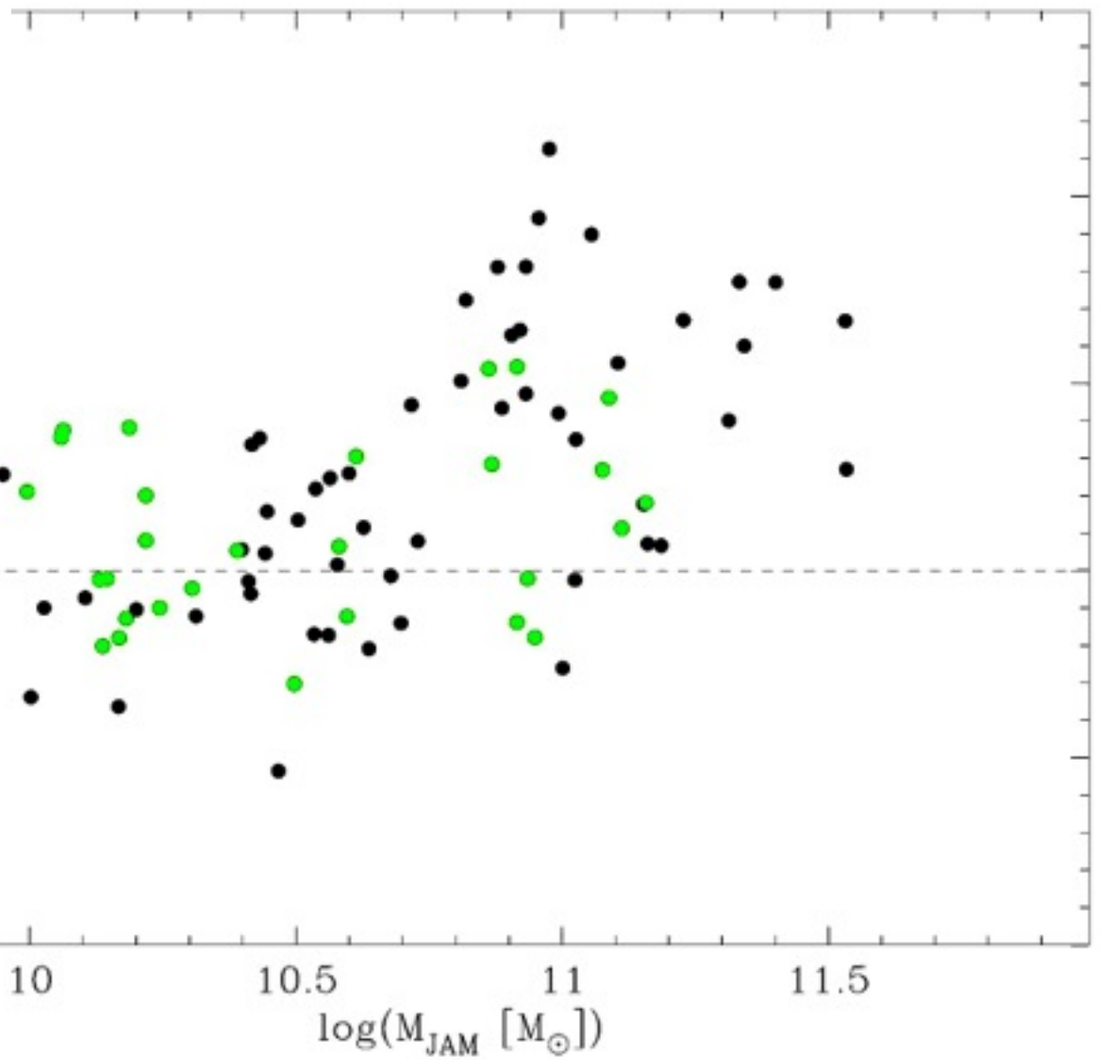


Hirschmann et al. 2015

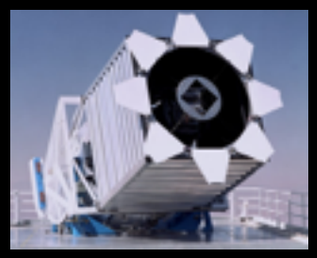
Deep imaging and the fundamental scaling relations of ETGs



- ✓ The stellar mass in the galaxies « halo » (beyond isophote of 26 mag arcsec^{-2}) is small: 6 percent on average
- ✓ However systematic changes with mass, galaxy type



- ✓ Effective radius changed by a factor of up to 1.6 for galaxies more massive than 10^{11} Mo
- ✓ uncertainties in Re contribute to the scatter of the size-mass relation



©SDSS

Revising morphological classification with deep imaging

blue star-forming spirals

red and dead ETGs

- ✓ The Hubble diagram as seen with SDSS-like observations

©NGVS/Atlas3D/MATLAS

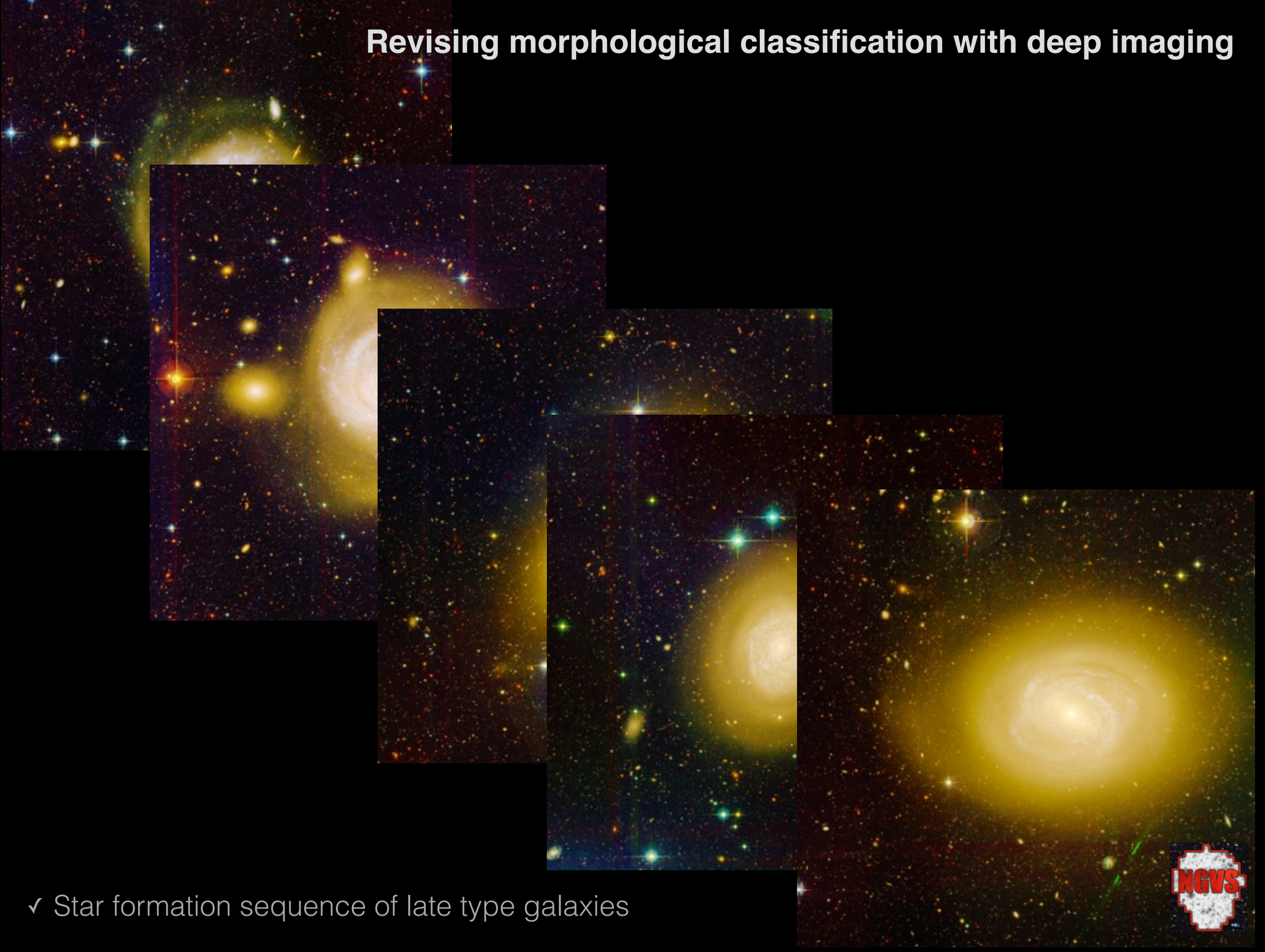
Revising morphological classification with deep imaging

spirals within a red halo

ETGs with star-forming disks

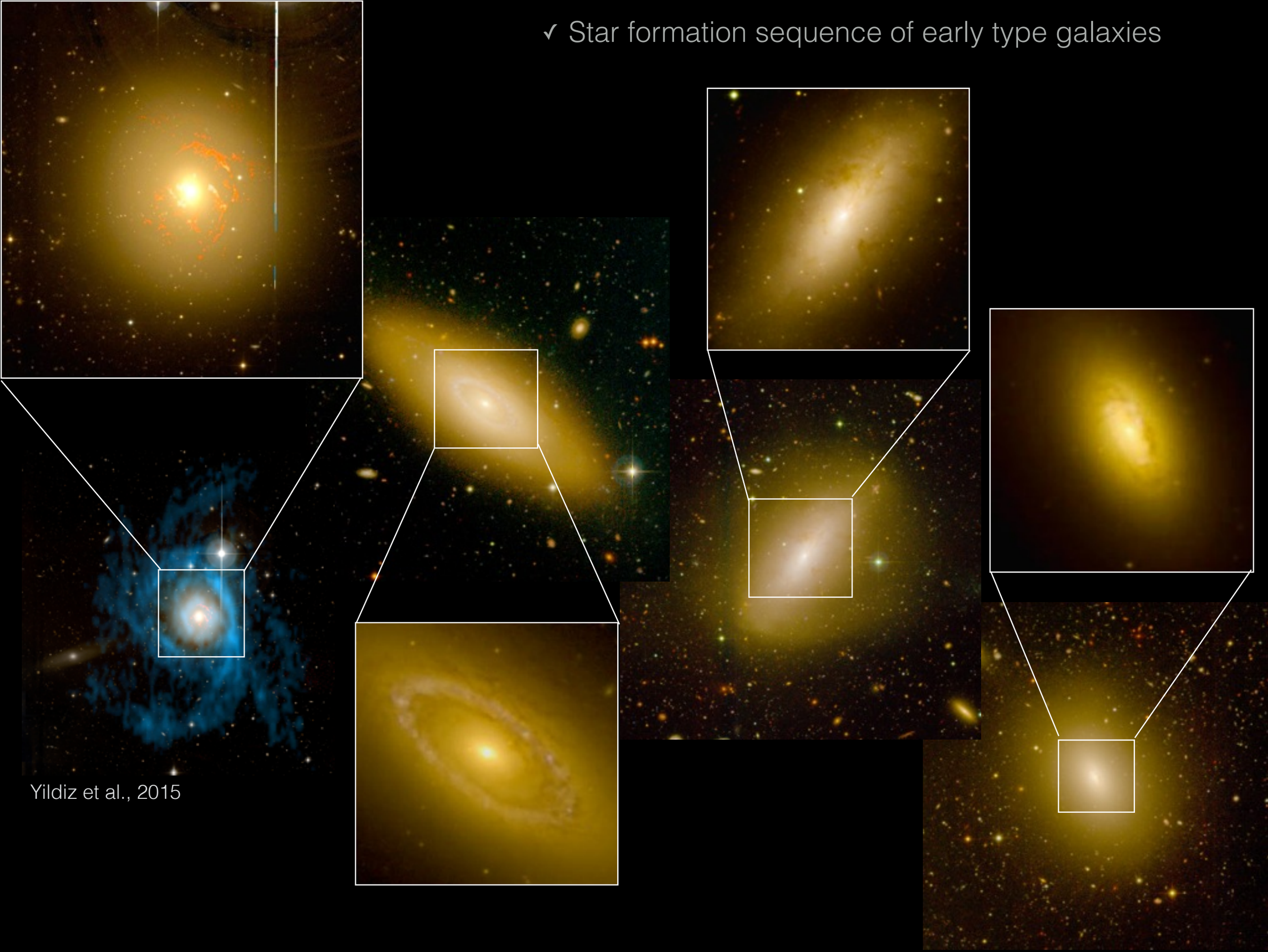
- ✓ The Hubble diagram as seen with MegaCam observations

Revising morphological classification with deep imaging

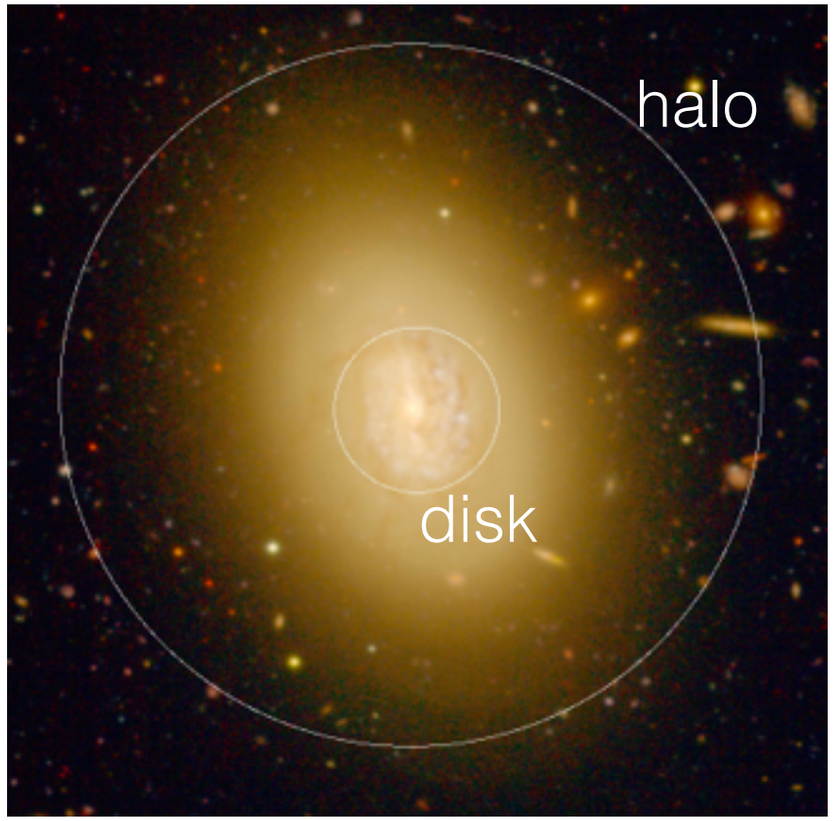


✓ Star formation sequence of late type galaxies

✓ Star formation sequence of early type galaxies



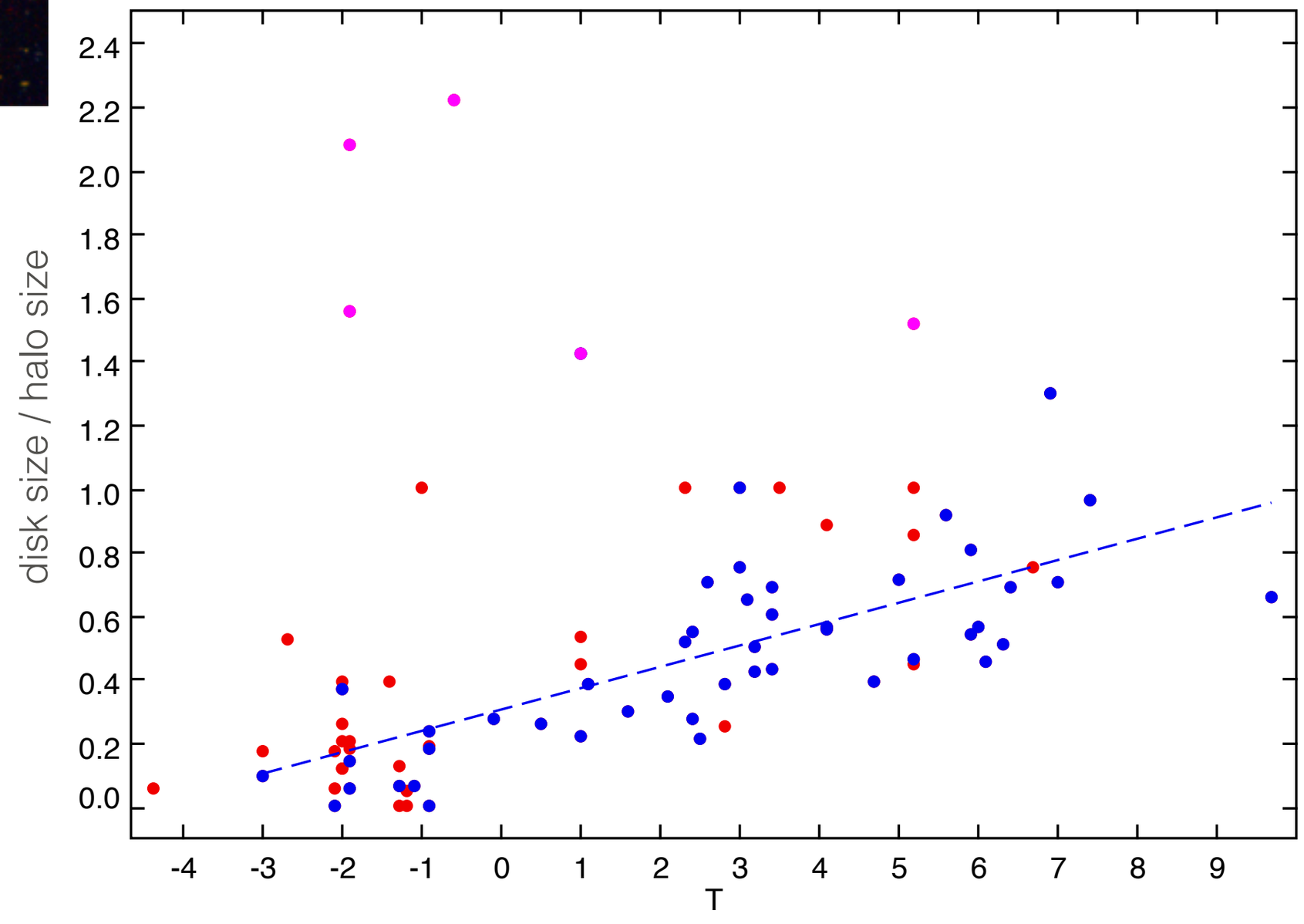
Yildiz et al., 2015



Star formation and galaxy type

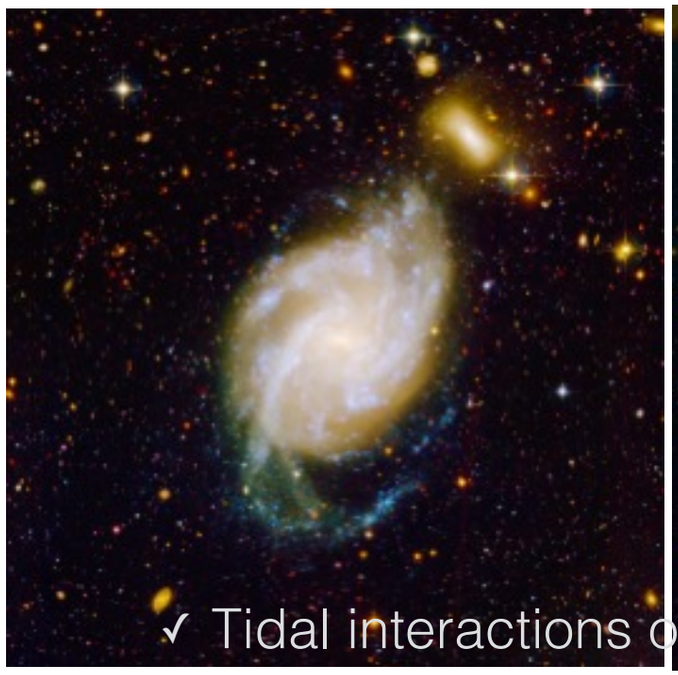
- ✓ Extent of star-forming regions parametrized with the ratio between the young disk and outer halo made of old stars

- ✓ A strong correlation: ETGs may have SF regions, but their extent is much smaller than in LTGs



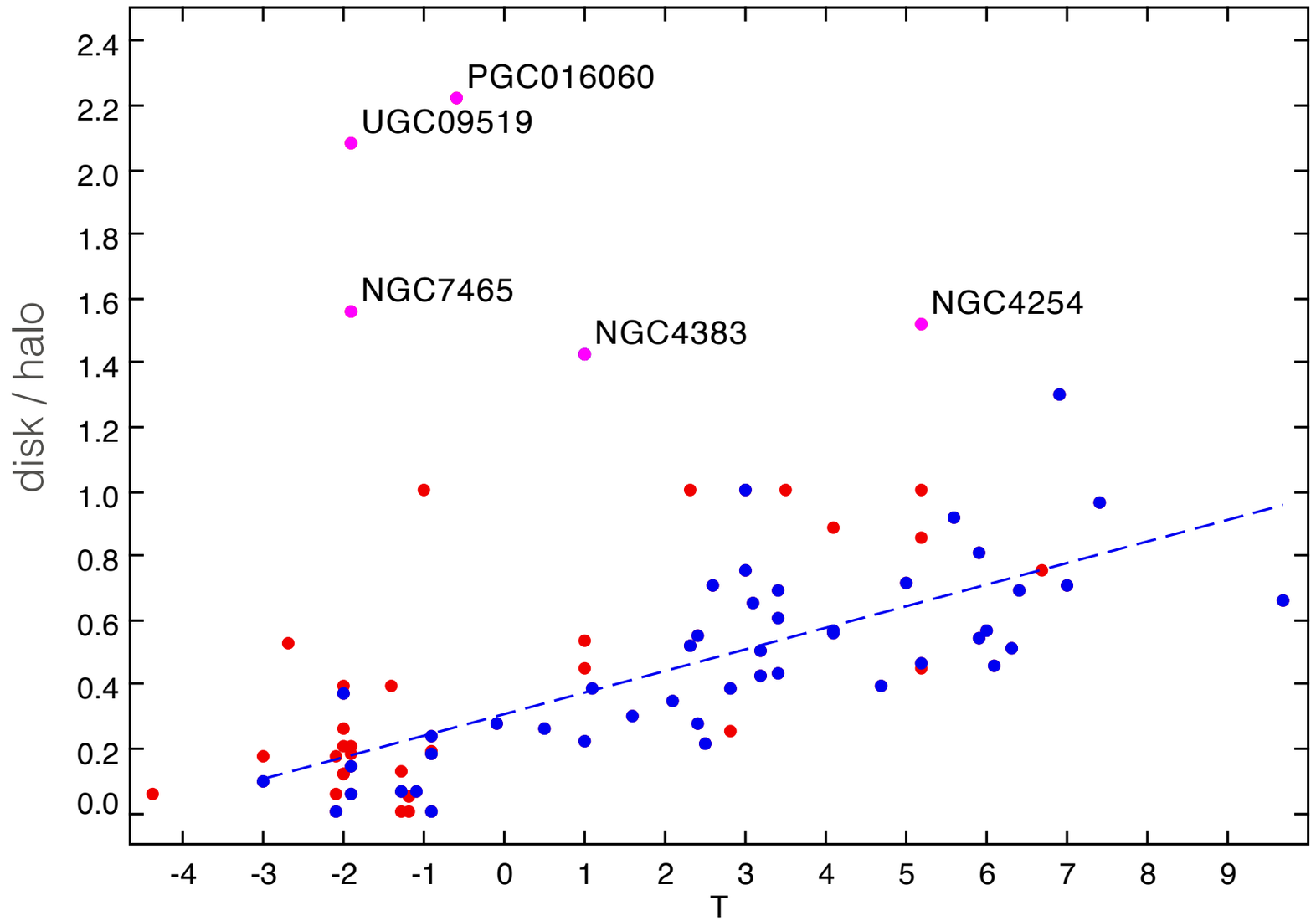
Star formation and galaxy type

- ✓ Deviant galaxies with external star-formation



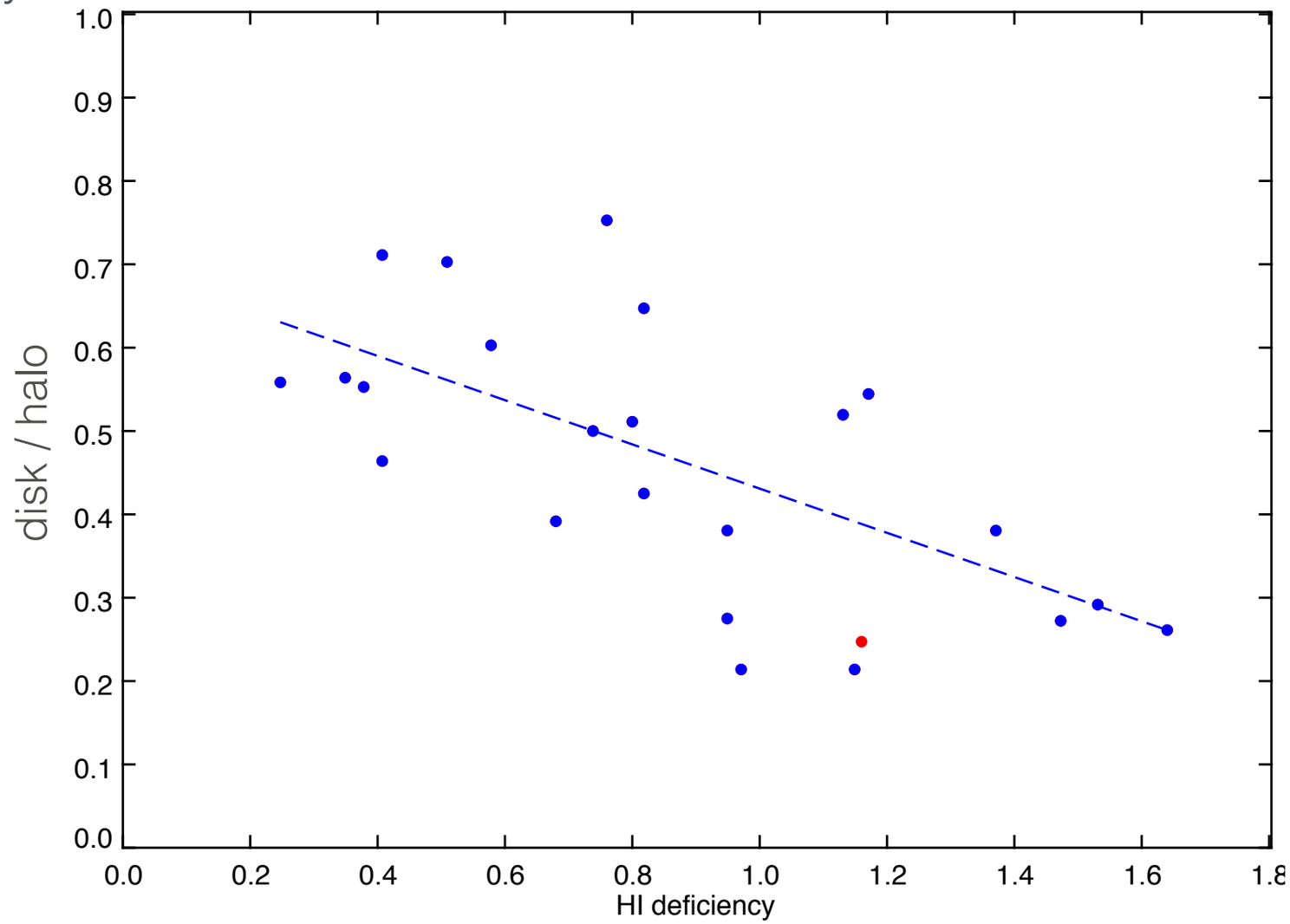
✓ Tidal interactions or ram pressure stripping?

✓ External accretion?

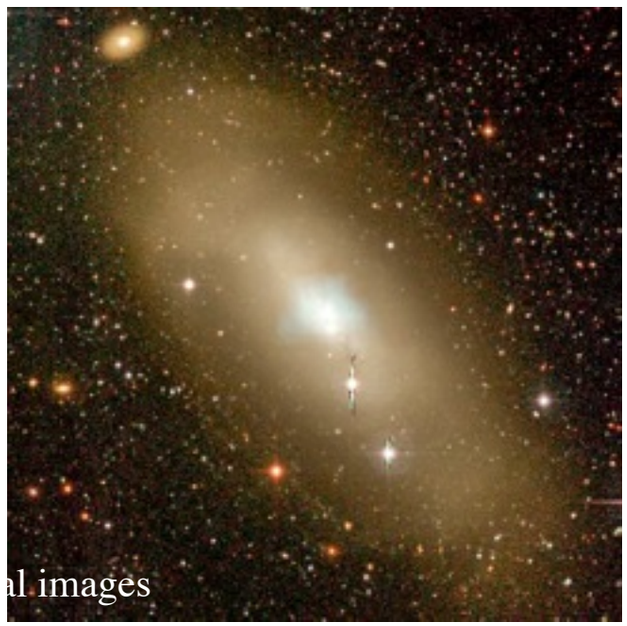


Generating the old stellar « halo » ?

- ✓ Star formation truncation linked with the HI deficiency



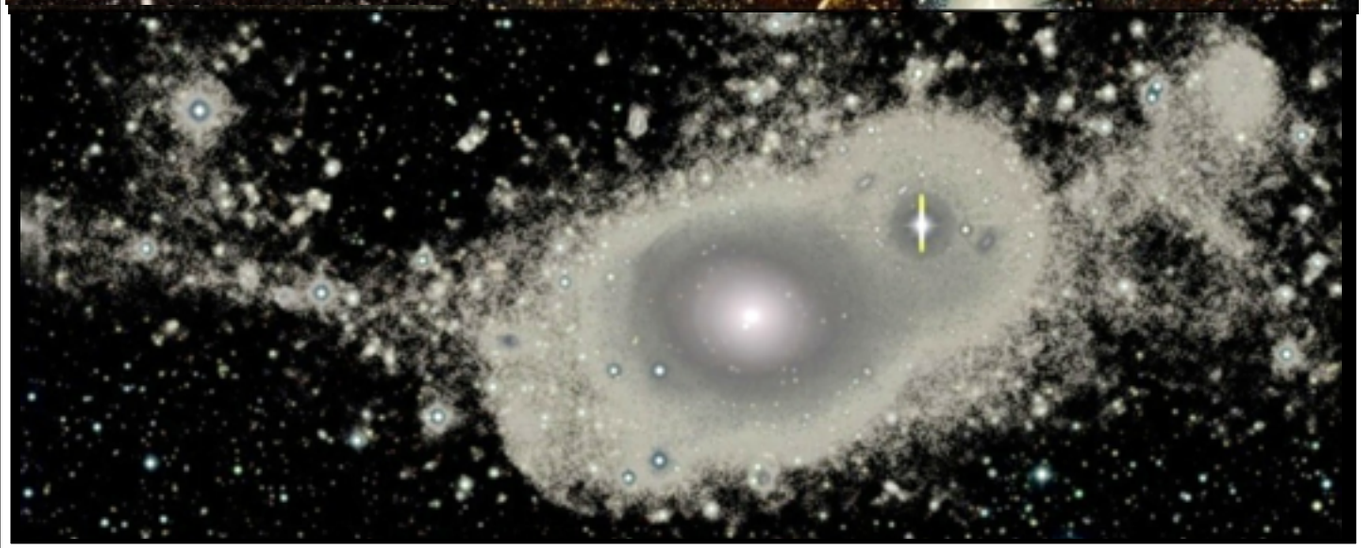
at the origin of the outer stellar halo of spirals (at least in dense environments)?



Deep imaging and the detection of fine structures

- ✓ Diffuse prominent tidal tails …
  … revealing on going / past gas-poor minor mergers

- ✓ Typical life time of tails of 1-2 Gyr



- ✓ Perturbed isolated central body and/or tidal tails … revealing past gas-rich major merger

Deep imaging and the detection of fine structures

✓ Narrow stellar streams … … revealing on going / past gas-poor minor mergers

✓ Typical survival time of >4 Gyr

✓ Sharp-edge shells…… revealing past intermediate mass mergers

Classification scheme

- ✓ Made with eye and with on-line poll tools (à la galaxy zoo)

Galaxy	Class
NGC0448	I+s
NGC0474	M+s+r+ph
NGC0502	M+t?+r?+ah-wc-h
NGC0509	R-pc
NGC0516	R-pc
NGC0524	U-pc-h
NGC0525	R-pc-h
NGC0661	U+ah-pc

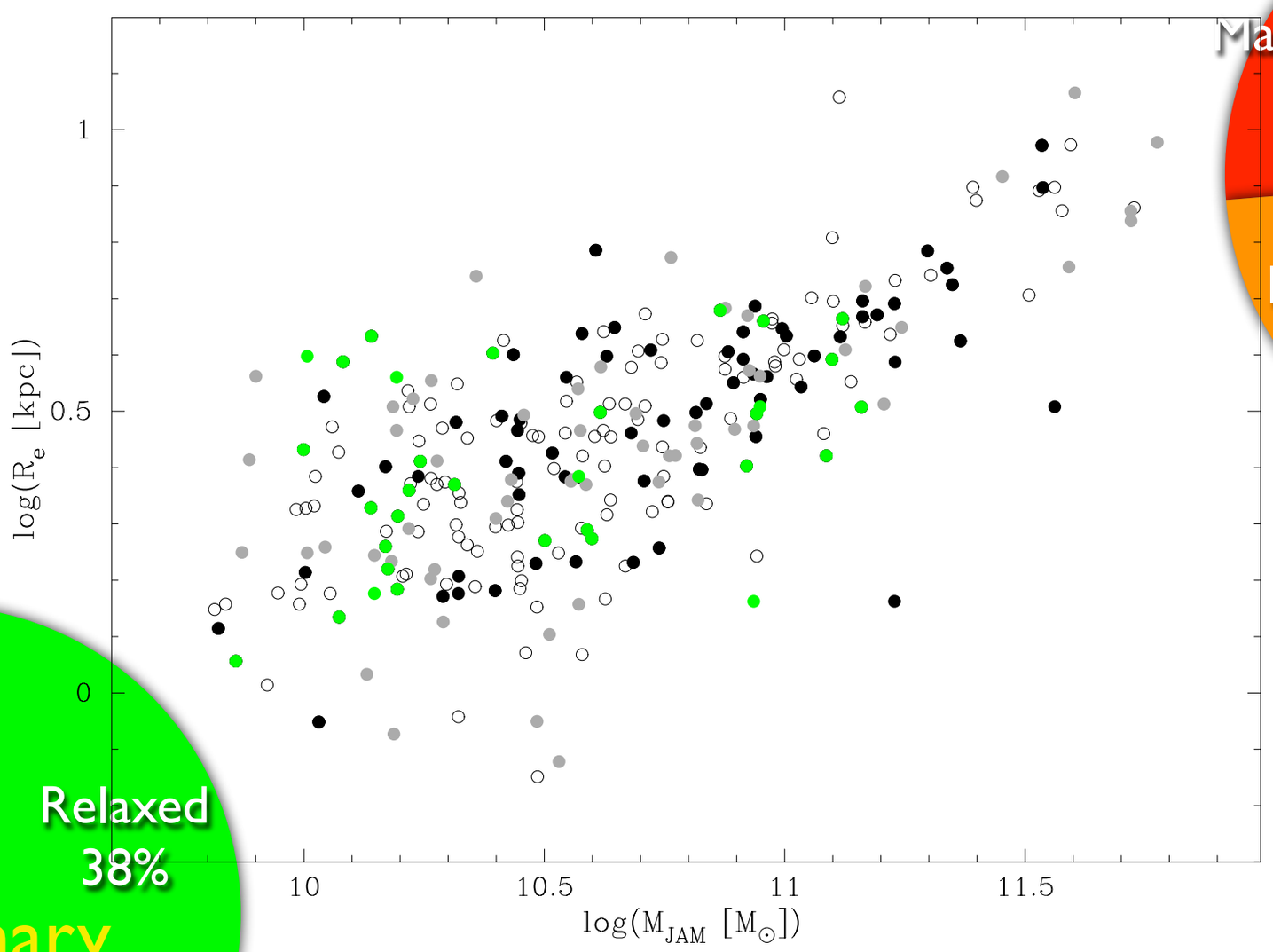
Code	Type	Description
R	Fully relaxed	Regular halo; no fine structure
C	Minor merger	Regular halo; streams or shells from an accreted low-mass companion
M	Major merger	Strongly perturbed halo; dust lanes; tidal tails; no massive companion
I	Interacting	Perturbed halo; prominent tails due to a tidal interaction with a massive companion
U	Undetermined	Too close to a bright halo or Galactic cirrus to assign a type

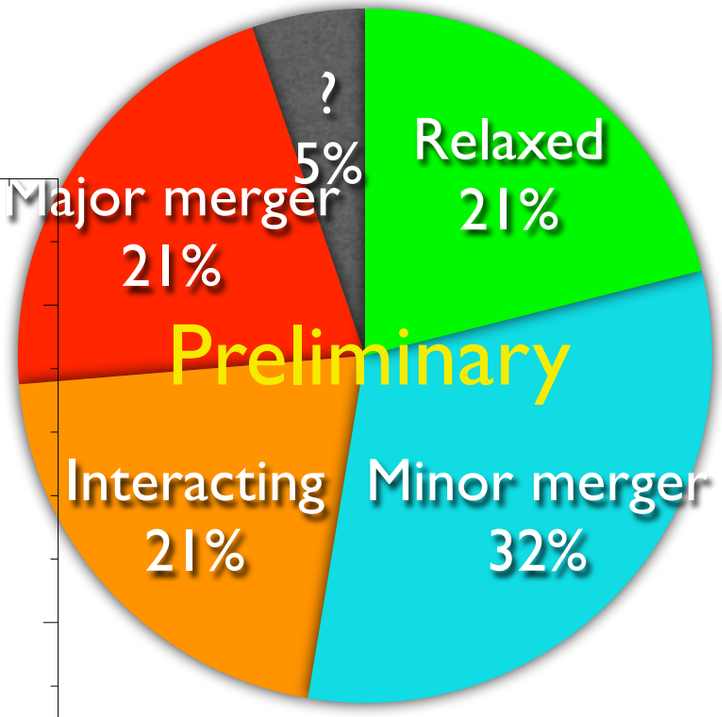
Code	Features / contaminants
+s	stream
+r	shells / ripples
+t	tail
+d	external star-forming disc / ring
+ah	asymmetric halo
+ph	perturbed halo
+wl	weak central dust lanes
+pl	prominent dust lanes
-h	galaxy embedded in the halo of a nearby star or galaxy
-wc	weak Galactic cirrus in the field
-pc	prominent Galactic cirrus
?	presence of a given feature is uncertain

Duc et al., 2015

Correlating fine structure index with:

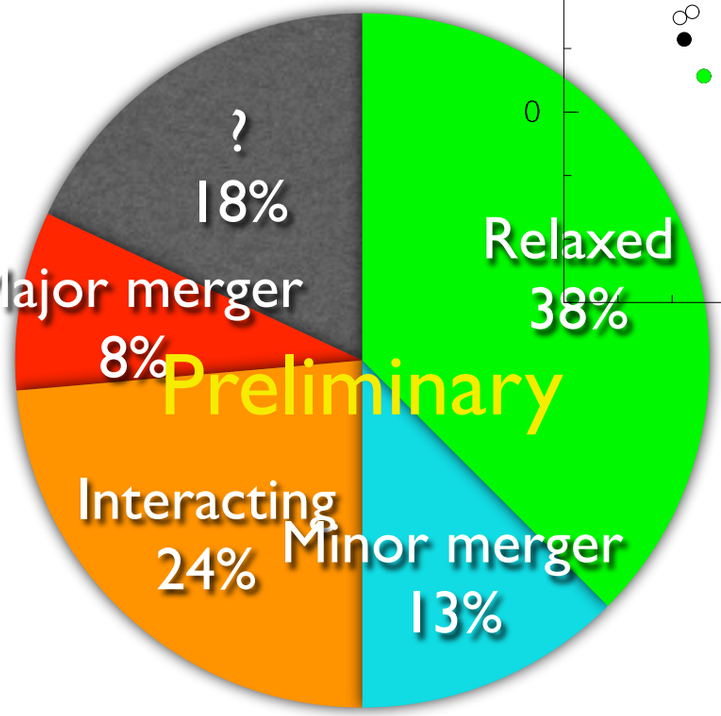
✓ Mass and Size





log(M)>11*

Outside Virgo!

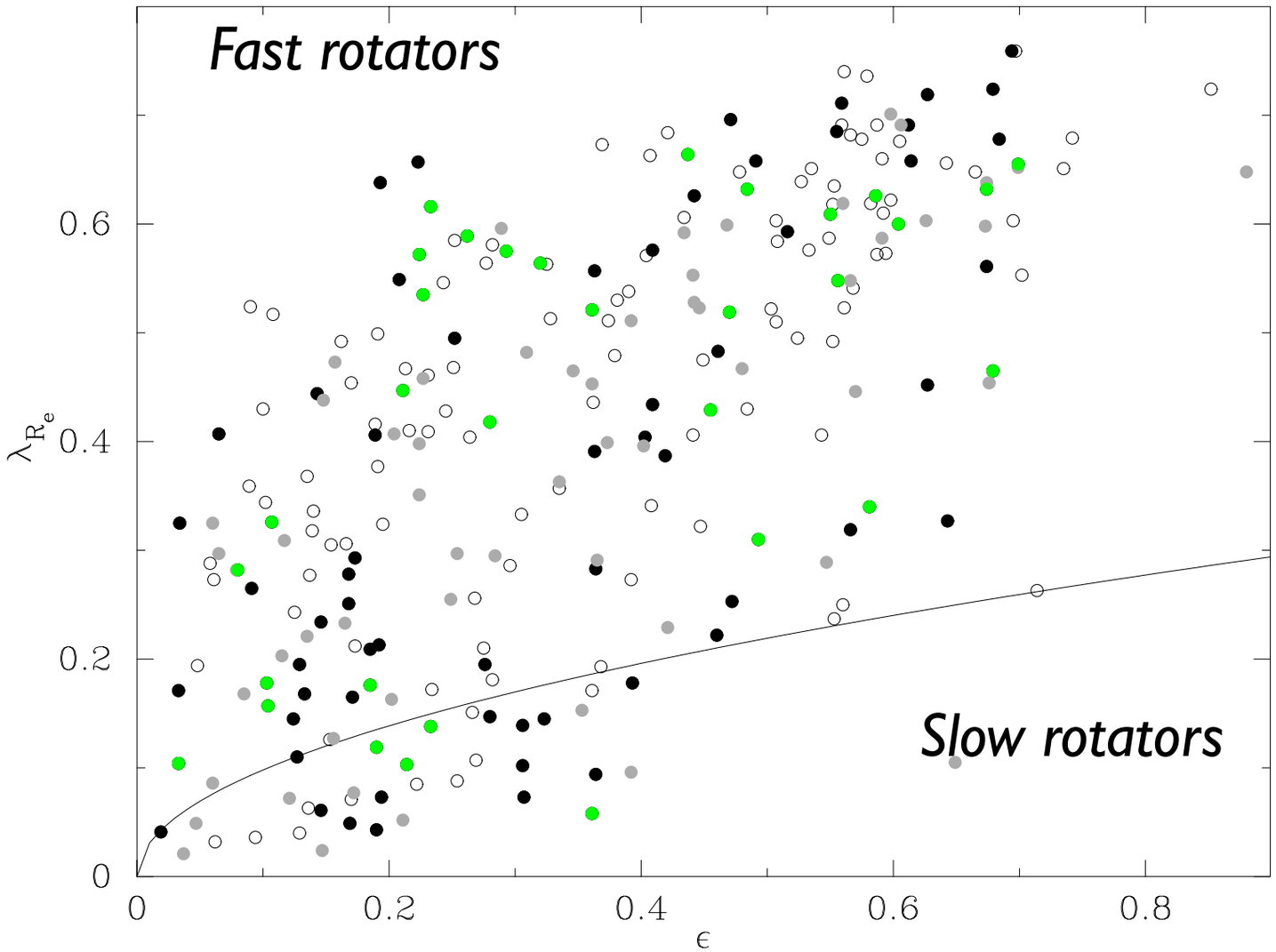


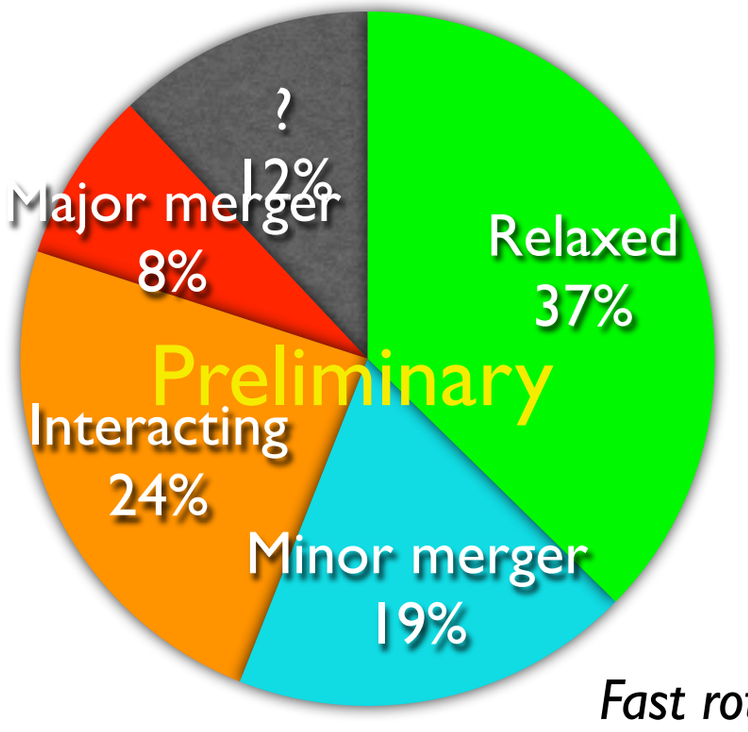
log(M)<11*

- Low mass galaxies more relaxed

Correlating fine structure index with:

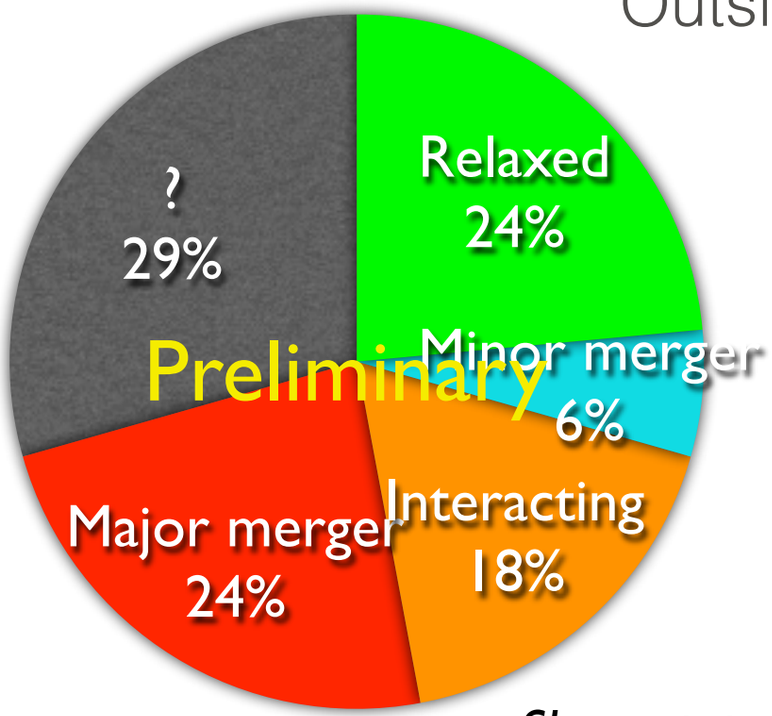
✓ Stellar kinematics





Fast rotators

Outside Virgo!



Slow rotators

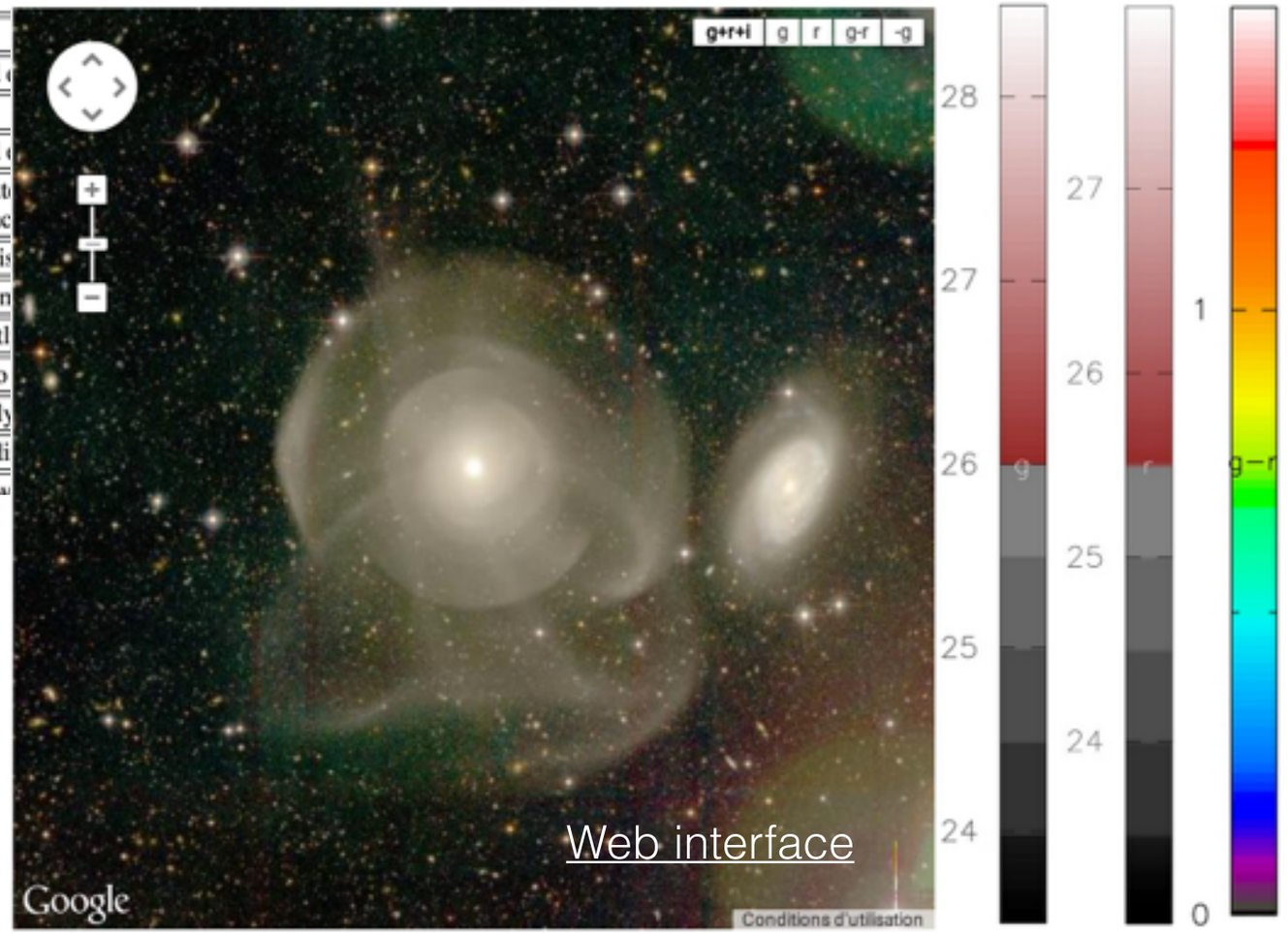
- Fast rotating ETGs more relaxed than slow rotating ones

http://matlas.in2p3.fr/

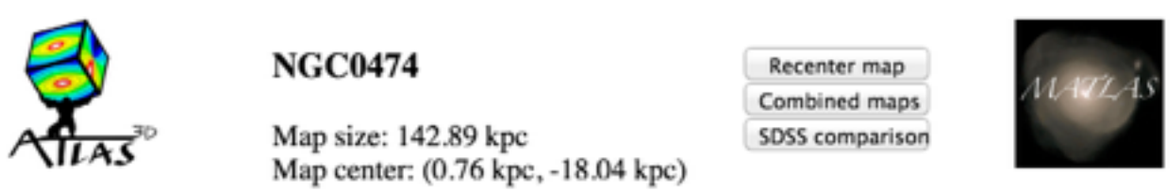
Early-type galaxies as seen with deep optical images

The 92 ETGs galaxies in this list are presented in Atlas3D Paper XXIX, Duc et al., 2014, MNRAS in press. See tables 2 and 3 for explanations on the morphological class adopted here. Clicking on the galaxy name gives access to the jpeg true color images, surface brightness and color maps, residual images after galaxy model subtraction. Images may be explored with a navigation tool. A pdf version of the image catalog is available here.

Galaxy	Class	Comments
NGC0448	I+s	The ETG is in a tidal interaction with a disturbed companion.
NGC0474	M+s+r+ph	The ETG is surrounded by multiple concentric shells and hosts several radial streams. Its outer halo reaches the disk of the unperturbed companion spiral galaxy, NGC 0470.
NGC0502	M+t?+r?+ah-wc-h	The stellar halo of the ETG is asymmetric, possibly due to the presence of a diffuse tidal tail and/or a shell.
NGC0509	R-pc	
NGC0516	R-pc	
NGC0524	U-pc-h	The ETG is surrounded by galactic cirrus and
NGC0525	R-pc-h	
NGC0661	U+ah-pc	The ETG is surrounded by galactic cirrus and
NGC0680	I+t+s+r+ph+wl-wc	The ETG is tidally disturbed, showing two ext going interaction or a past major merger is unc
NGC0770	I+t-pc	The ETG lies within a prominent tidal tail. It is
NGC0936	C+s+wl	A stellar stream hosting a tidally disrupted con
NGC1023	U+ah-h	The stellar halo of the ETG seems to be slightl
NGC1121	U-h	The ETG totally lies within the reflection halo
NGC1222	M+t+r?+ph+pl	The ETG exhibits multiple signs of a relatively
NGC1248	R-pc-h	The ETG does not show any evident sign of di
NGC1266	C+s?+wl-pc	The ETG has several low mass companions, w



- ✓ Data (jpg maps) publicly available online for 92 galaxies



Conclusions

- ✓ Tremendous progress in deep imaging techniques, coupled with numerical simulations

Conclusions

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Conclusions

- ✓ Frontiers between early and late type galaxies blurred

Conclusions

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Conclusions

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Conclusions

An elliptical or a spiral?

- ✓ Frontiers between early and late type galaxies blurred

Conclusions

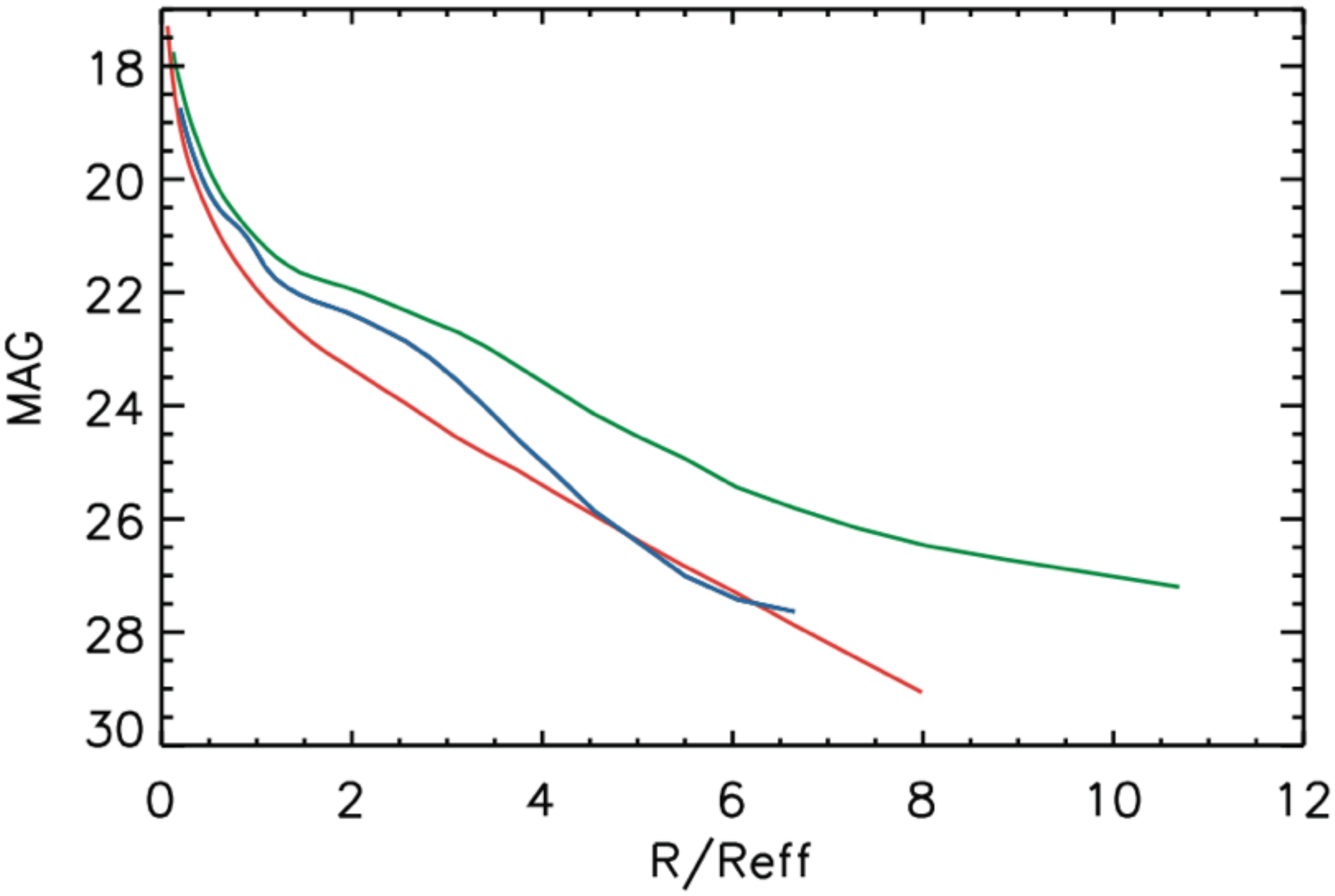
✓ Dealing with the ghost halos is tricky

Conclusions

✓ Dealing with the galactic cirrus is a nightmare

Conclusions

✓ thanks with Love


MAG
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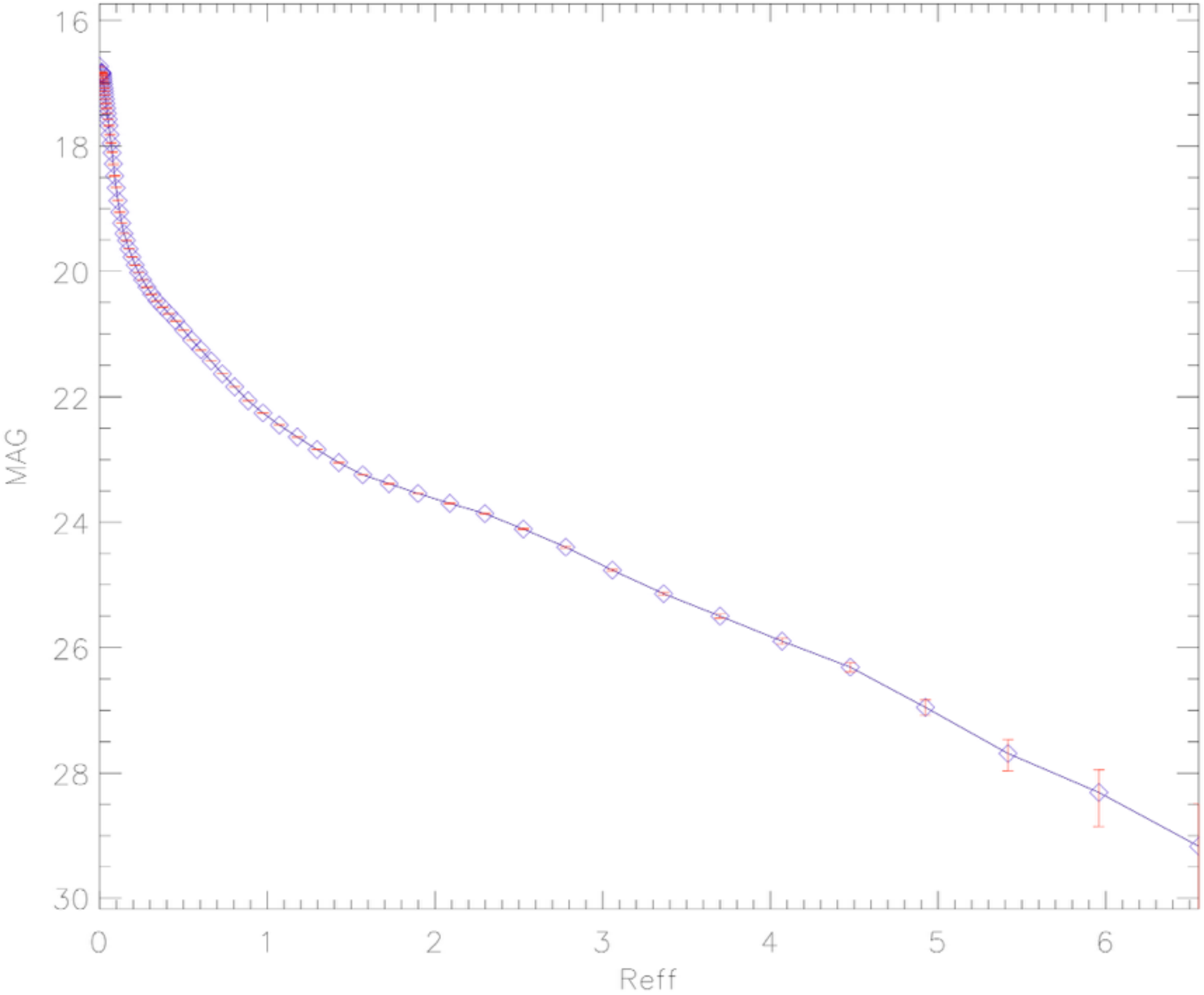
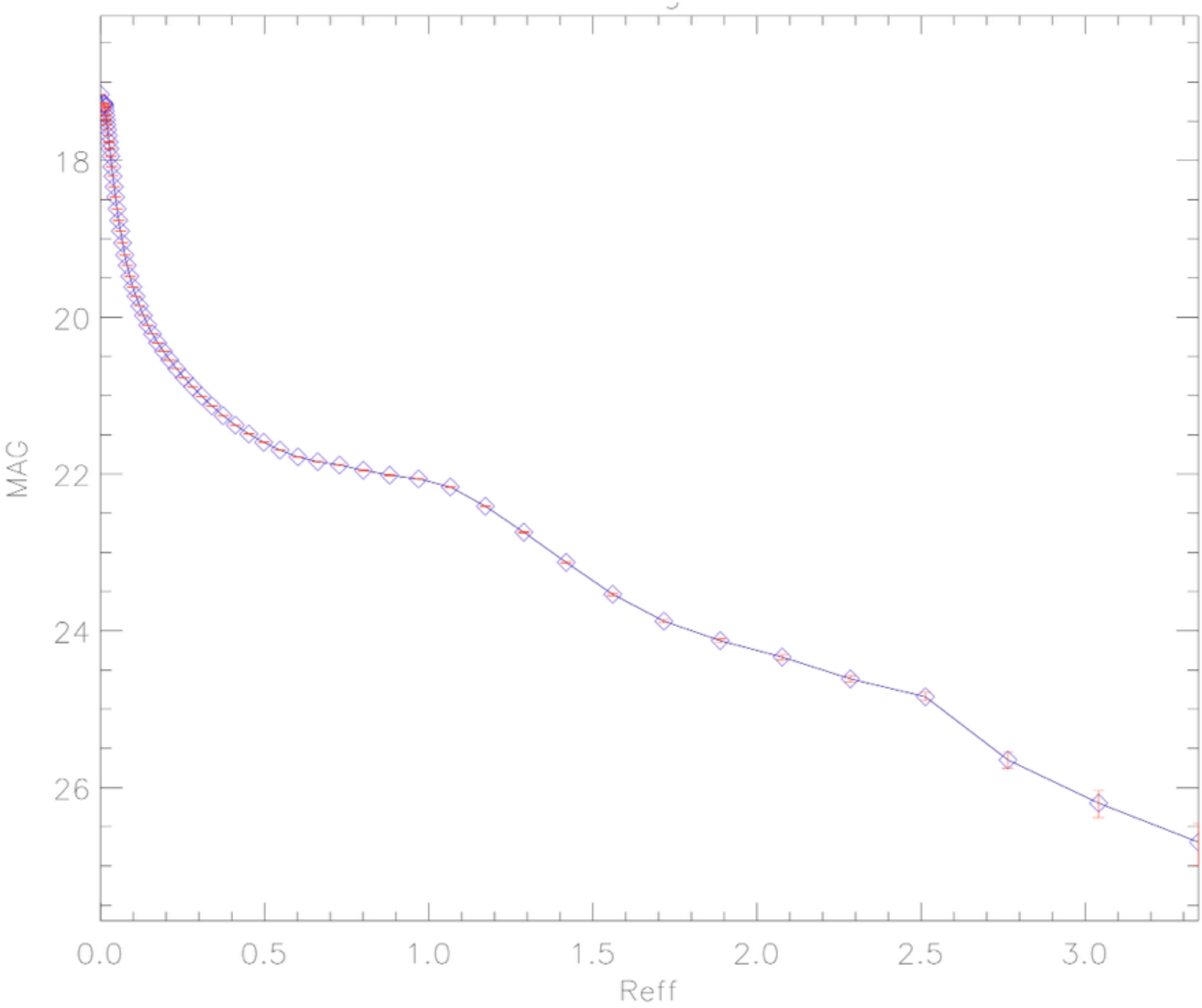
20
22
24
26
28
30
0
2
4
6
8
10
12
R/Reff


16
18
20
22
24
26
28
30
MAG
0
1
2
3
4
5
6
Reff


MAG
18
20
22
24
26
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Reff