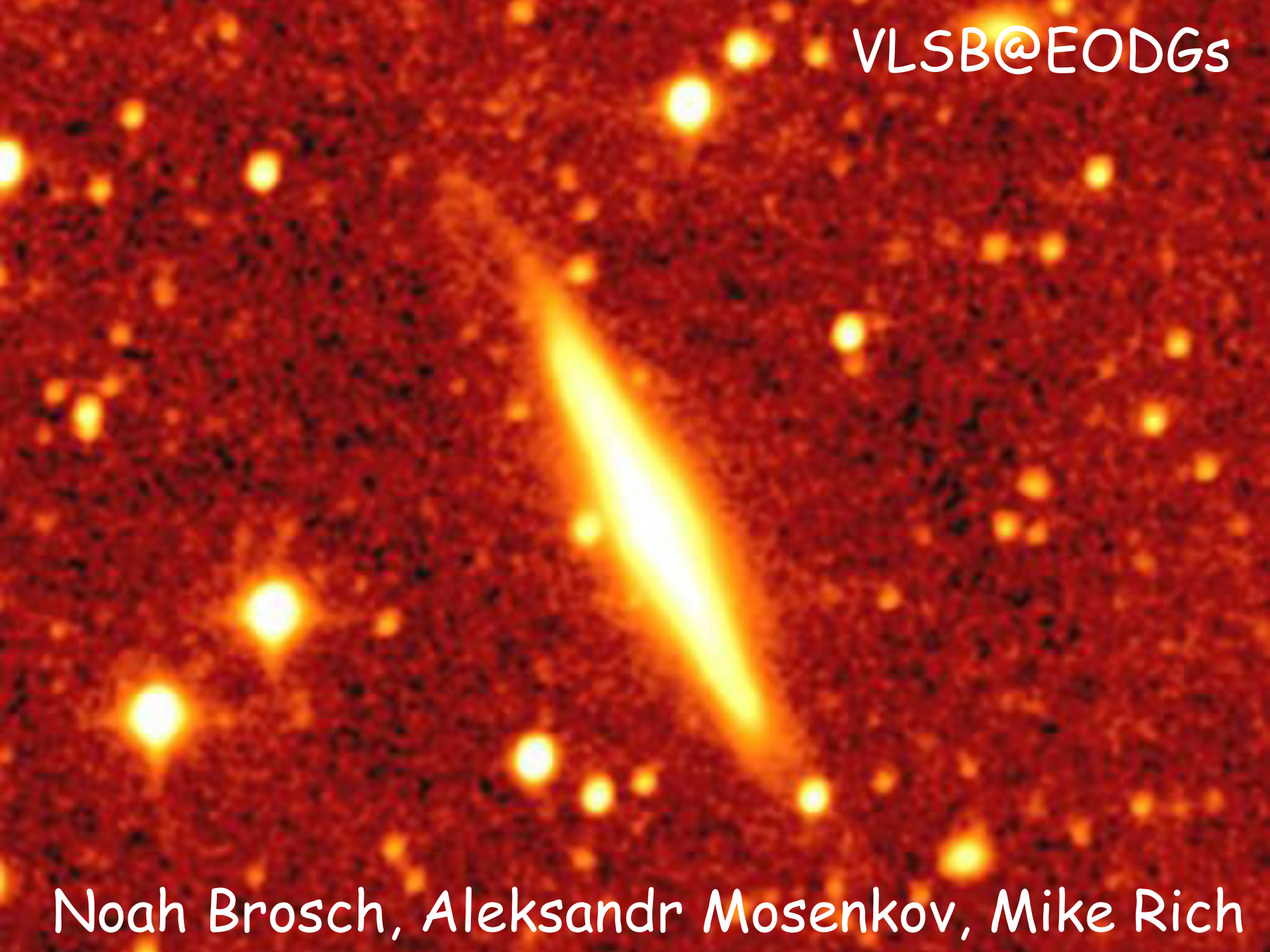
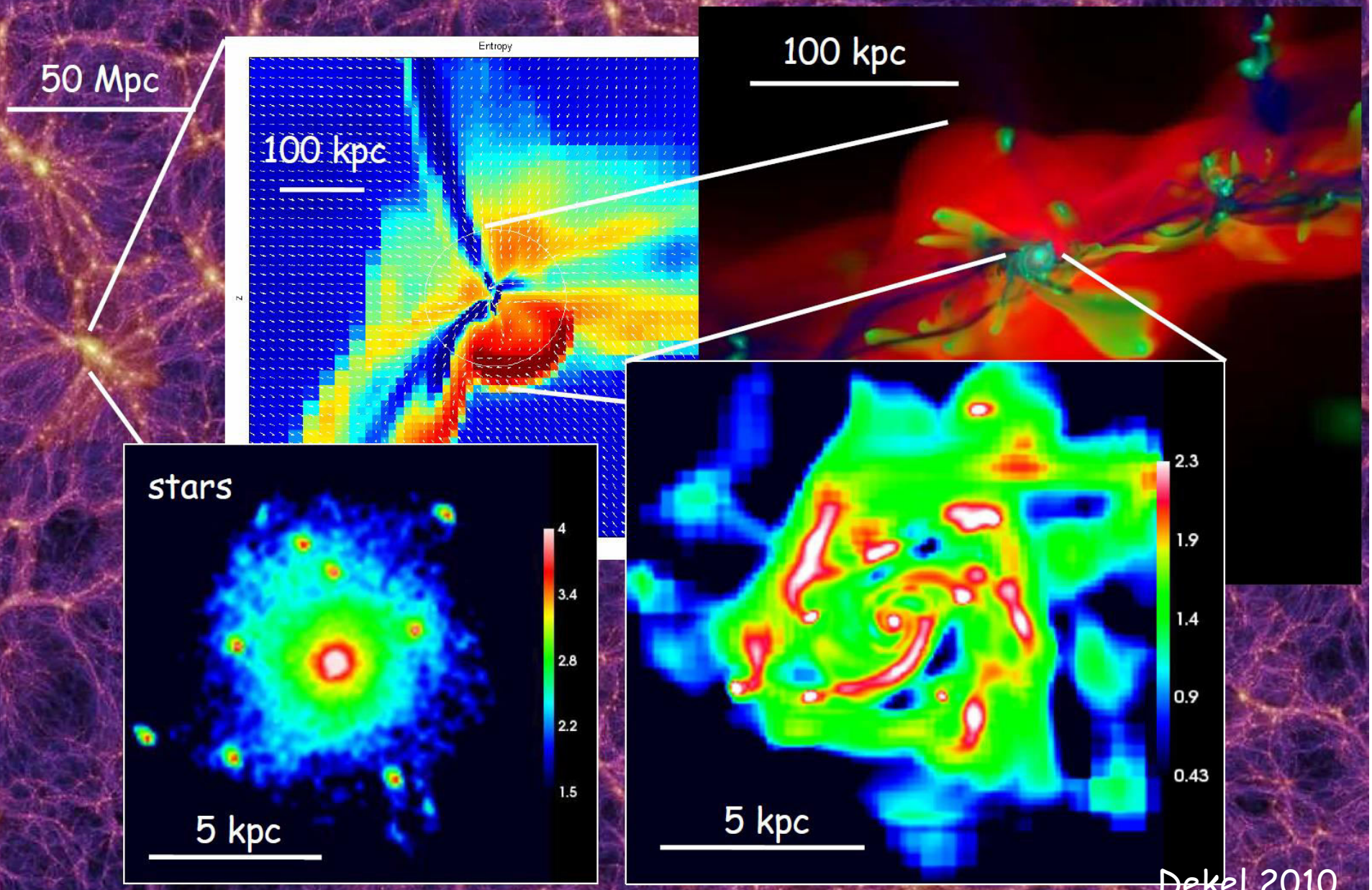

VLSB@EODGs
Noah Brosch, Aleksandr Mosenkov, Mike Rich

Outline:

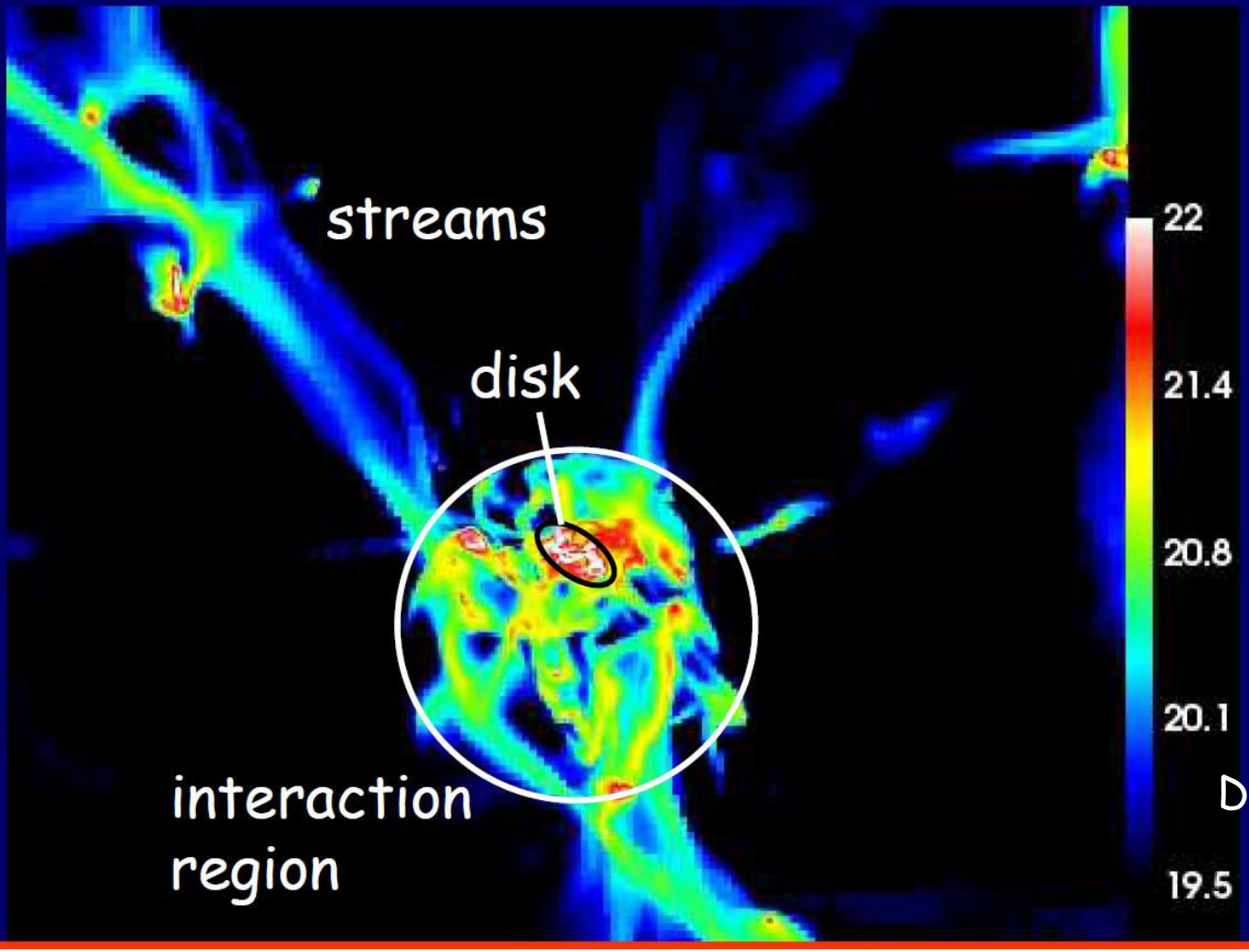
1. ΛCDM issues re galaxy formation and evolution, merging and galaxy build-up
2. The LSB Universe
3. Detecting LSB features
4. WiseObs observations & preliminary results

Cosmic Web, Cold Streams, Clumpy Disks & Spheroids



Dekel 2010

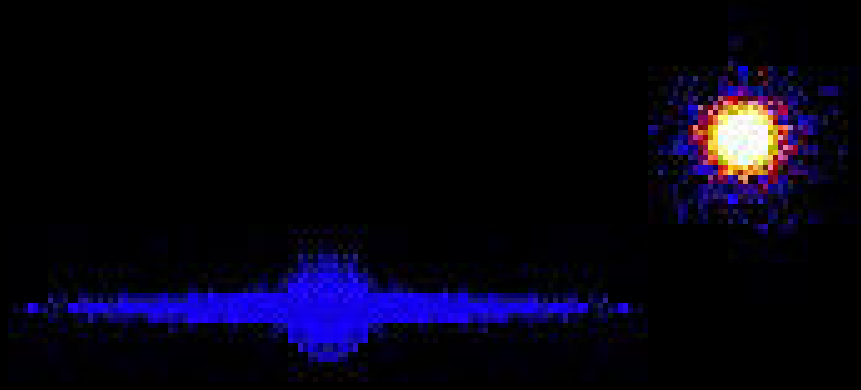
A Disk Fed by Cold Streams



Dekel 2010

Stream-disk interaction? Stream collisions? Stream instability – hydrodynamical? thermal? gravitational?

Kathryn Johnston movie of dwarf galaxy accretion & (LSB) stream formation

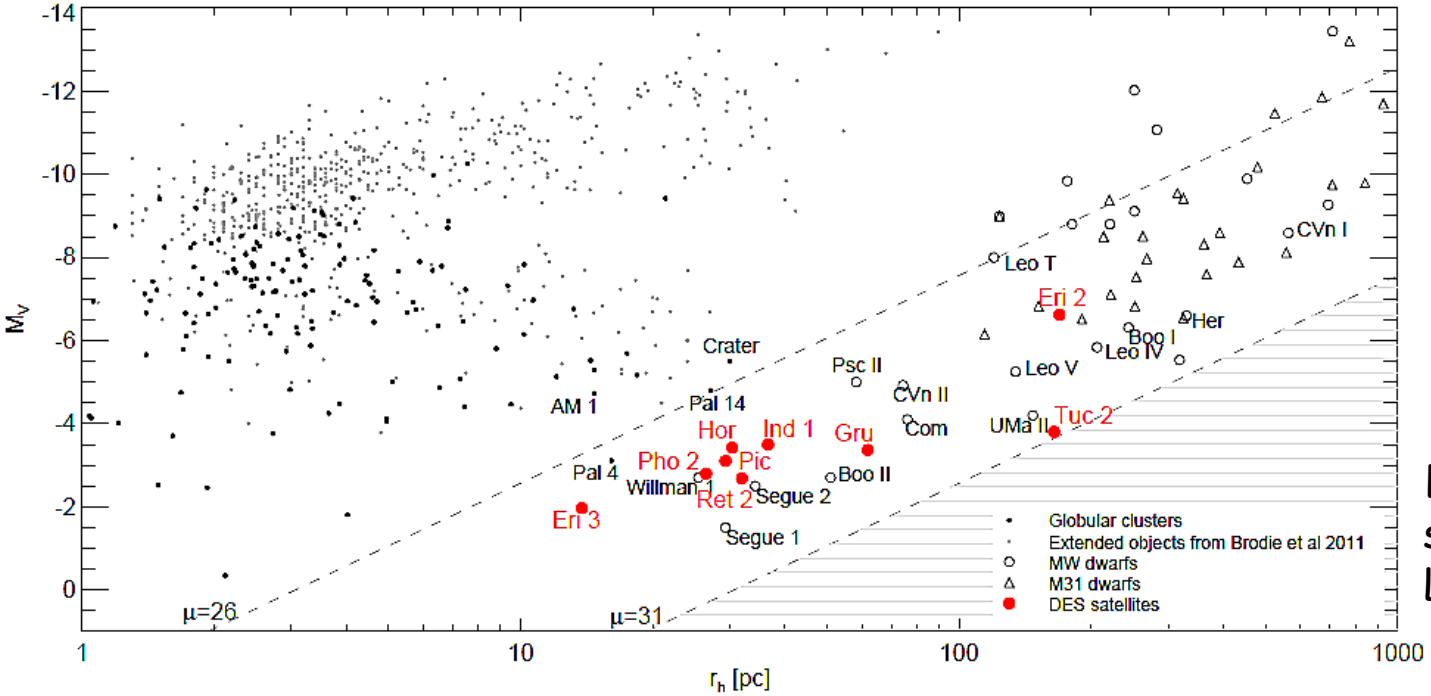


Over past ~40 years ~100x improvement in point source detection:

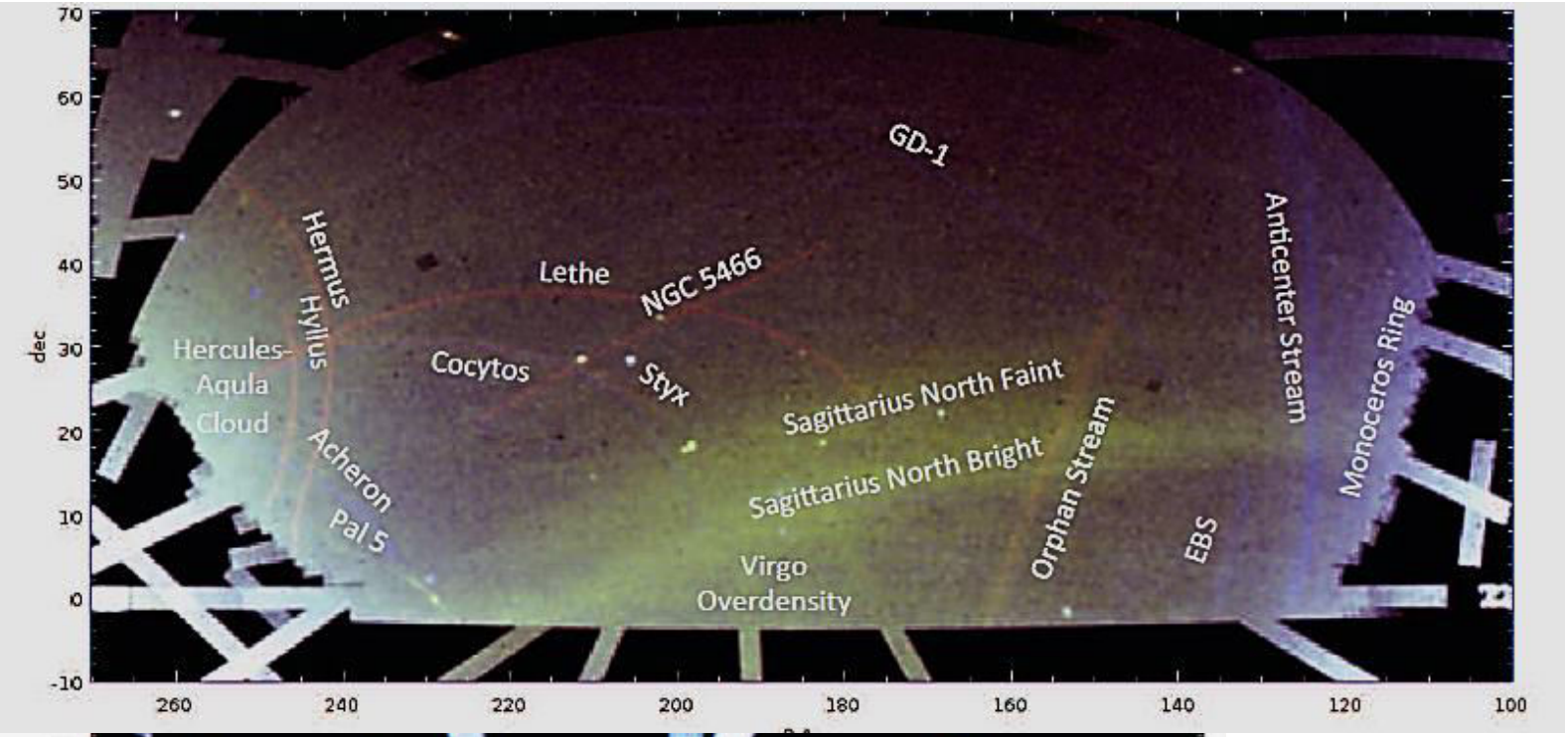
- Imaging mag 25 ➡ 30
- Spectroscopy mag 21 ➡ 26

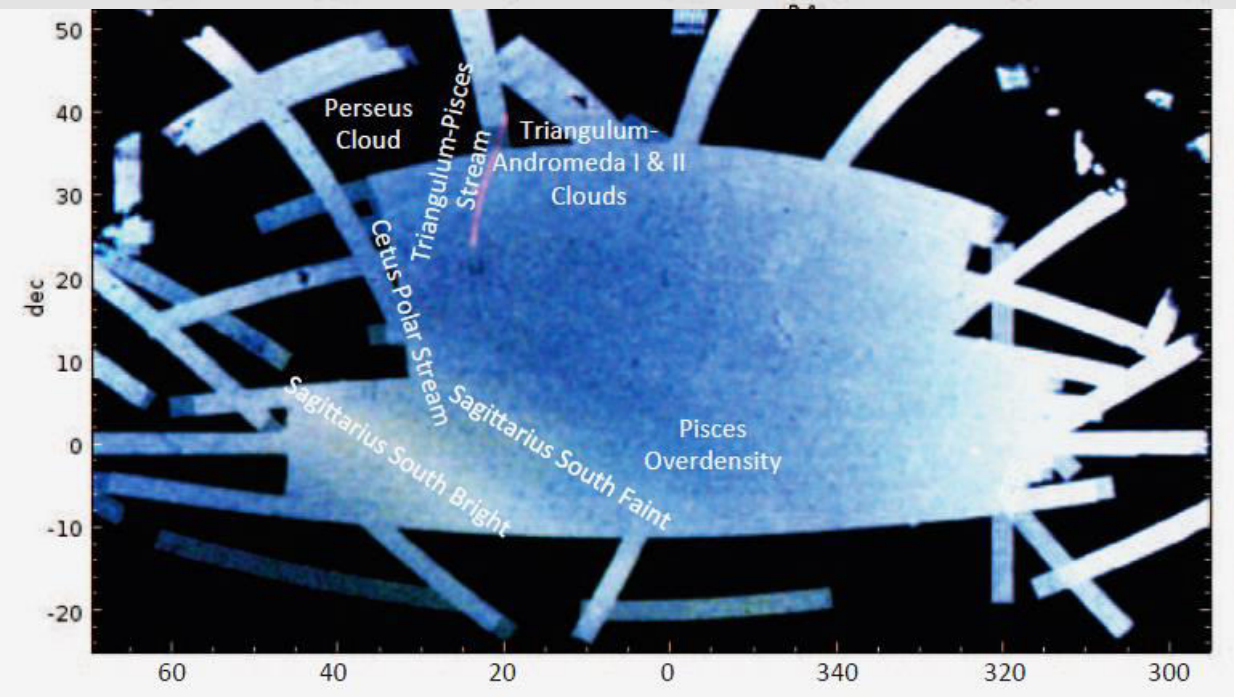
} Giant telescopes

However, the LSB sky remains ~unexplored: limits have not changed much in past 30+ years!



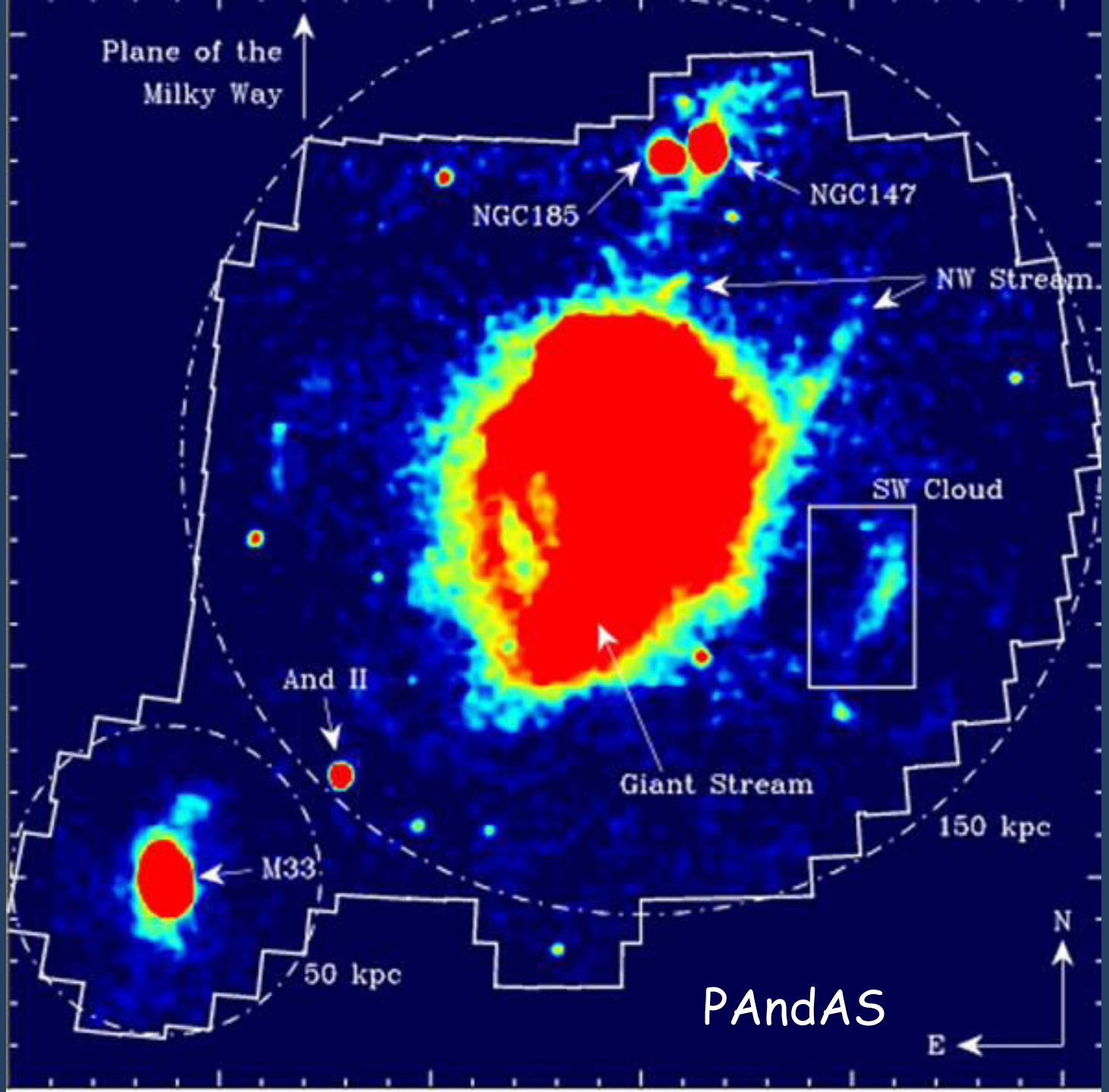
Koposov et al 2015 - satellites of MCs are LSB DGs





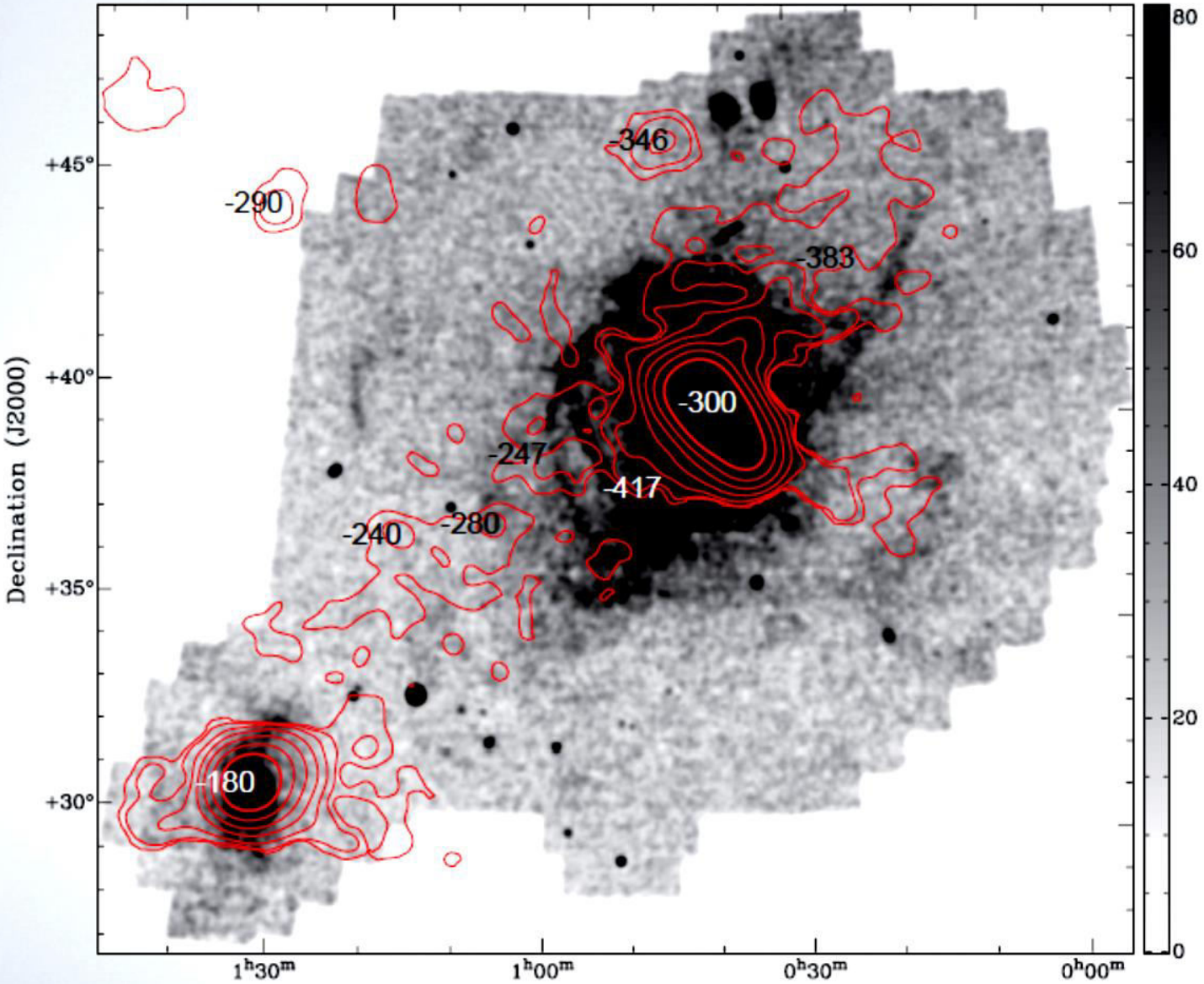
Stellar streams in the MW

Grillmair & Carlin 2016


Plane of the
Milky Way
NGC185
NGC147
NW Stream
SW Cloud
And II
Giant Stream
150 kpc
M33
50 kpc
N
E
PAndAS

Star/HI comparison

Lewis, Braun et al. (2012)

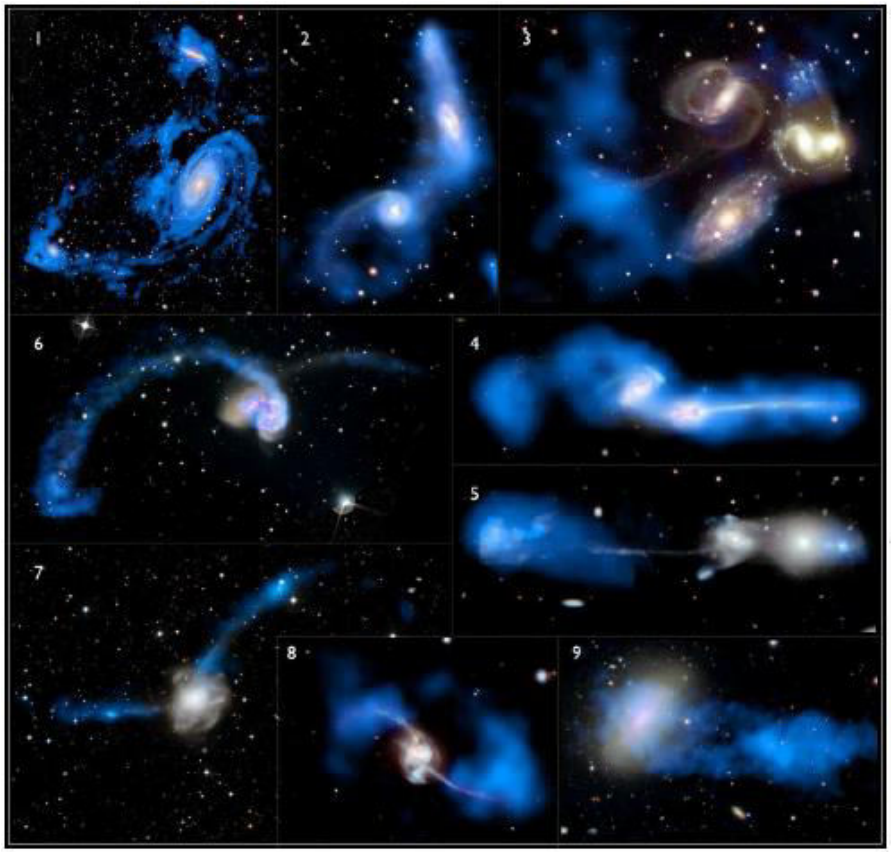


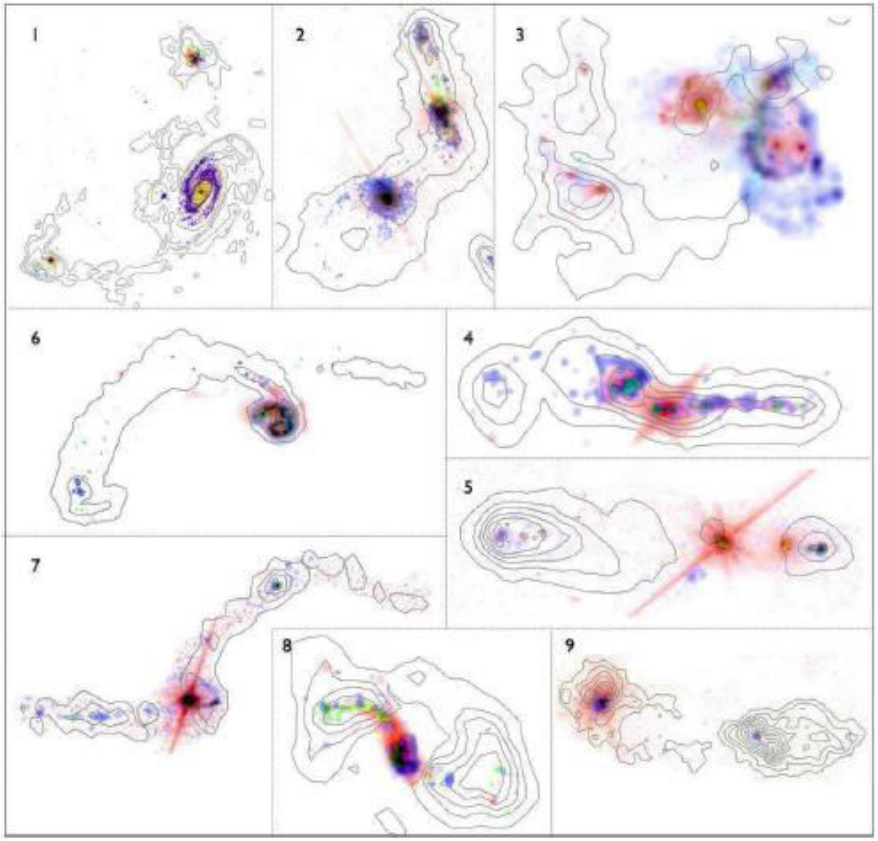
Metal-poor M31 RGBs

HI gas

Martin, 2013

Major mergers



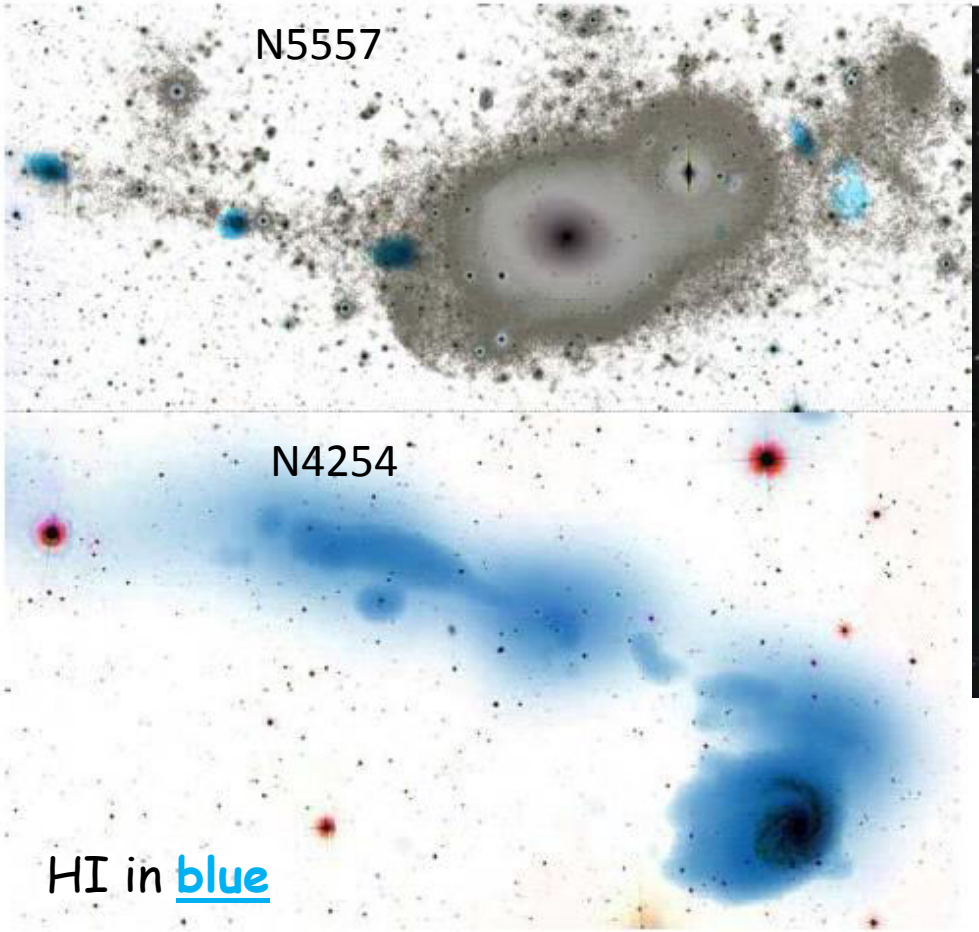


Merging galaxies: HI in blue

Star formation. HI contours, UV=blue, Ha=green, mid-IR=red

Duc & Renaud 2013

Gas-poor vs. gas-rich mergers

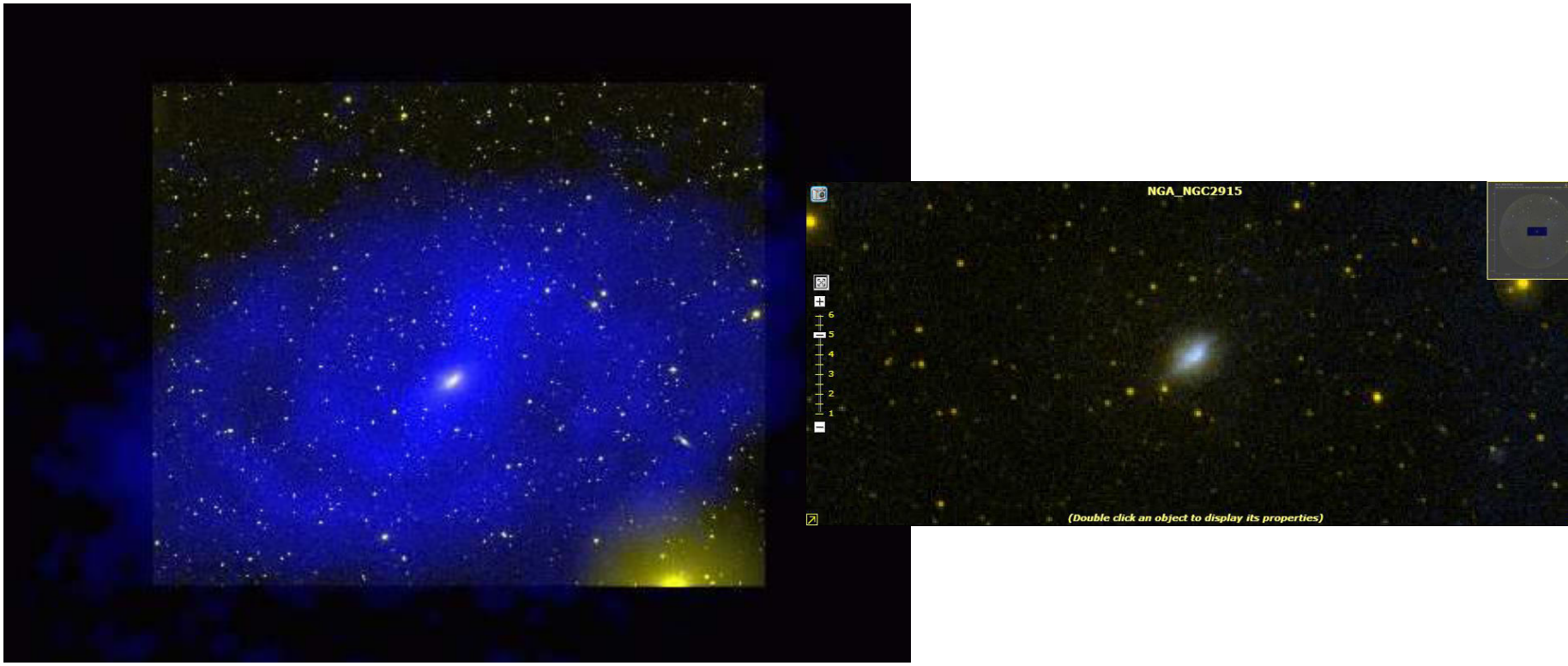


Stellar streams vs. gas streams

Stellar streams around N5907

Duc & Renaud 2013

Minor mergers & gas reservoirs

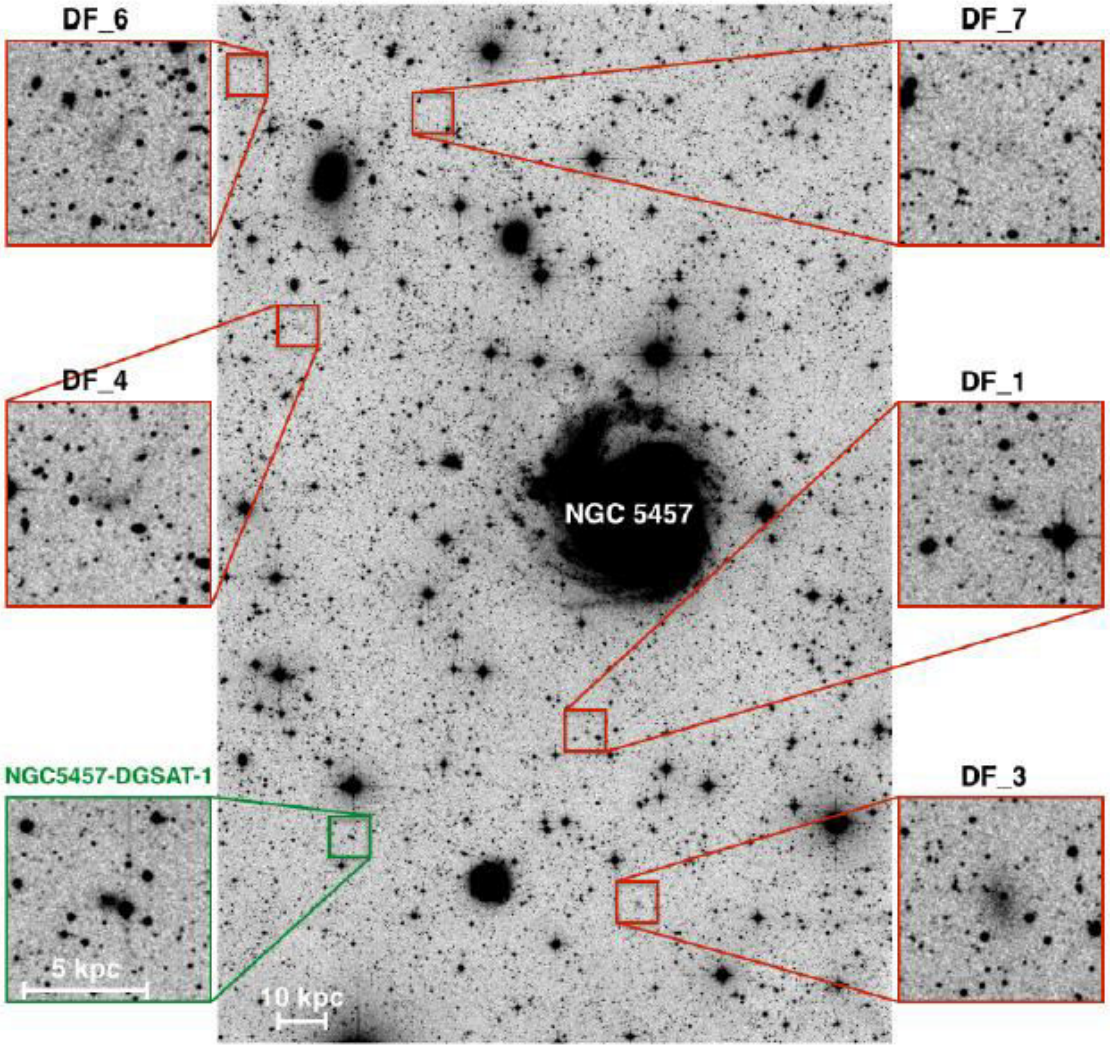


Composite optical (yellow) and HI (blue) image of the dwarf galaxy NGC2915 from Meurer et al. (1996), and GALEX (right image). "Accretion takes place both through the arrival and merging of gas-rich satellites and through gas infall from the intergalactic medium".

Search for LSB features

Sancisi et al. 2008

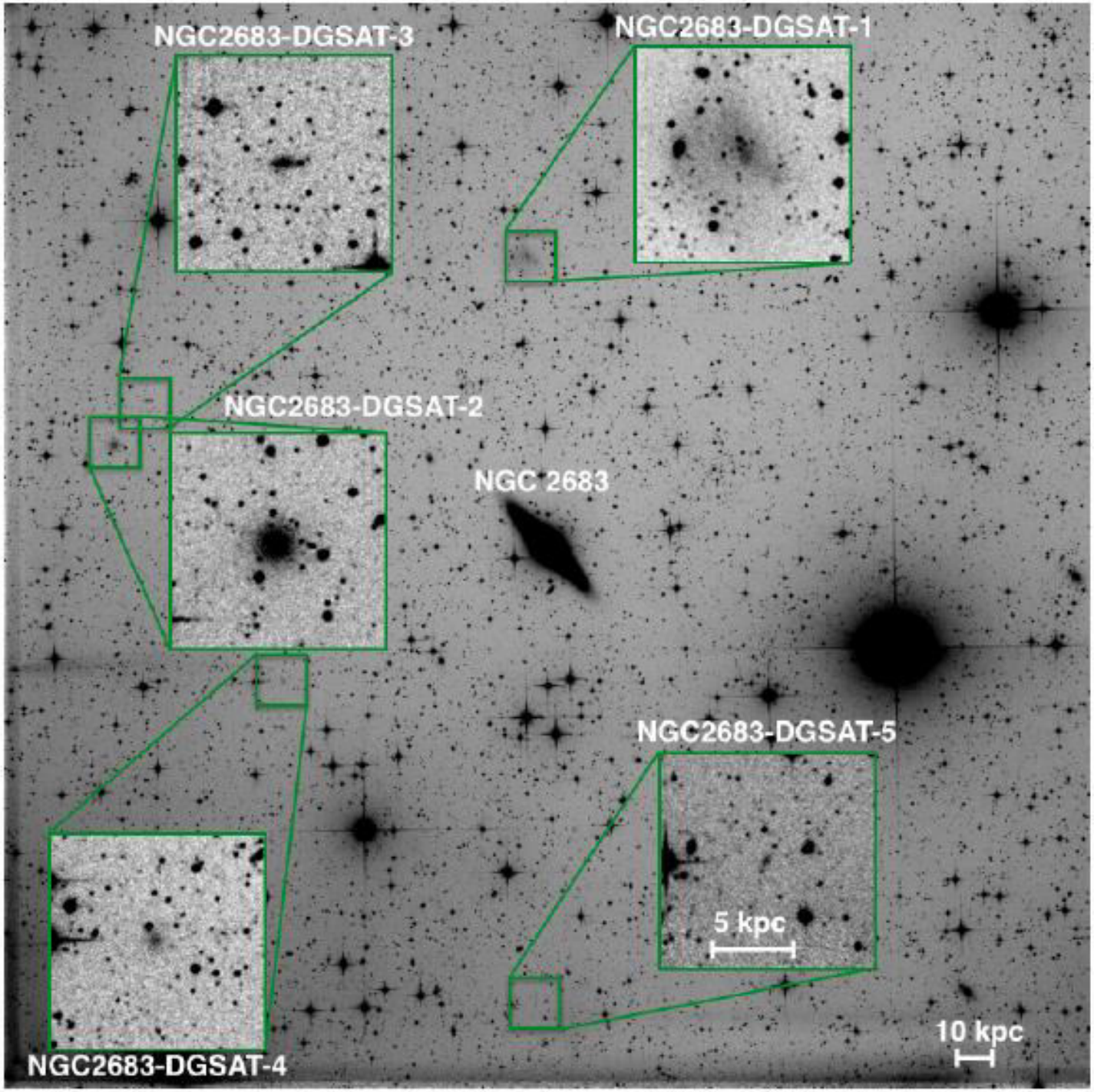
Target	Observatory	Location	Telescope	f/	Obs. Date	t_{exp} (s)	FOV (arcmin)	pixel scale (arcsec/pix)
NGC2683	ROSA(POLLUX)	Verclause, France	Newton 0.4-m	3.5	Feb-Mar 2015	24000	81'×81'	1.22
NGC3628	DGRO-Rancho Hidalgo	New Mexico, USA	RCOS 0.36-m	7.9	Dec 2011	36000	43'×43'	0.62
NGC4594	Riverdingo	Adelaide, Australia	RCOS 0.36-m	7.9	Apr 2009	25200	43'× 43'	0.62
NGC4631	Black Bird	New Mexico, USA	RCOS 0.5-m	8.1	May-Nov 2011	63000	31'× 31'	0.43
NGC5457	ROSA(POLLUX)	Verclause, France	Newton 0.4-m	3.5	Apr-May 2014	75600	81'×81'	1.22
NGC5457	Antares	Gossau, Switzerland	TEC140 APO	7.2	Feb - May 2012	87600	121'×80'	1.82
NGC7814	Rancho del Sol	California, USA	RCOS 0.5-m	8.3	Aug 2013	40800	29'×29'	0.43



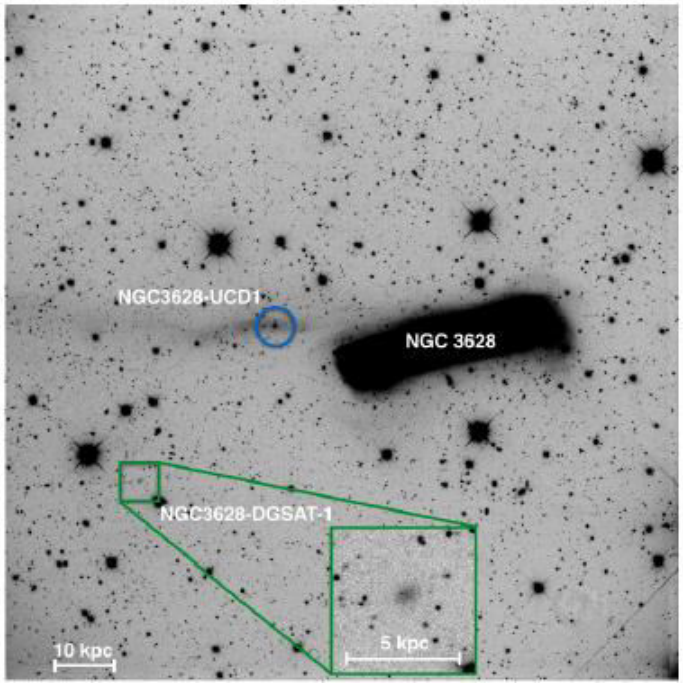
Small telescopes

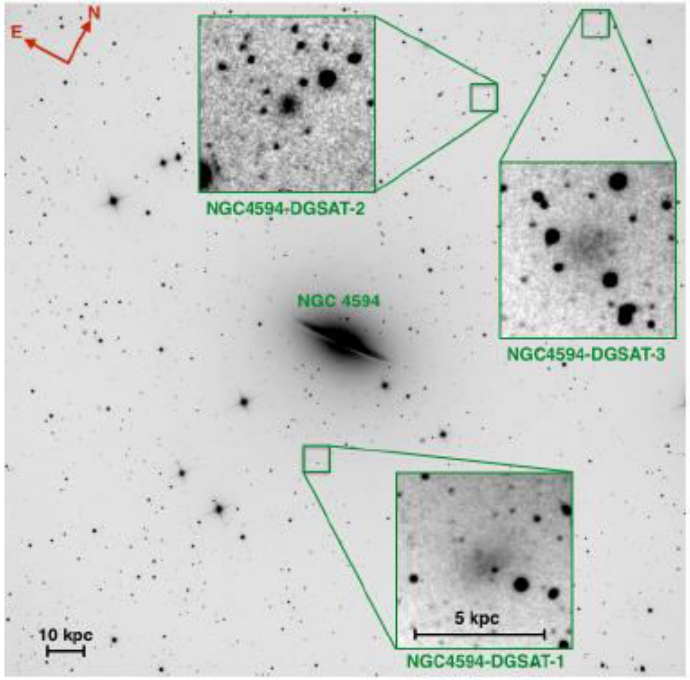
1. Use long exposures on small telescopes of amateur astronomers
2. Detect faint LSB "companions" in all the checked fields
3. **No distances**

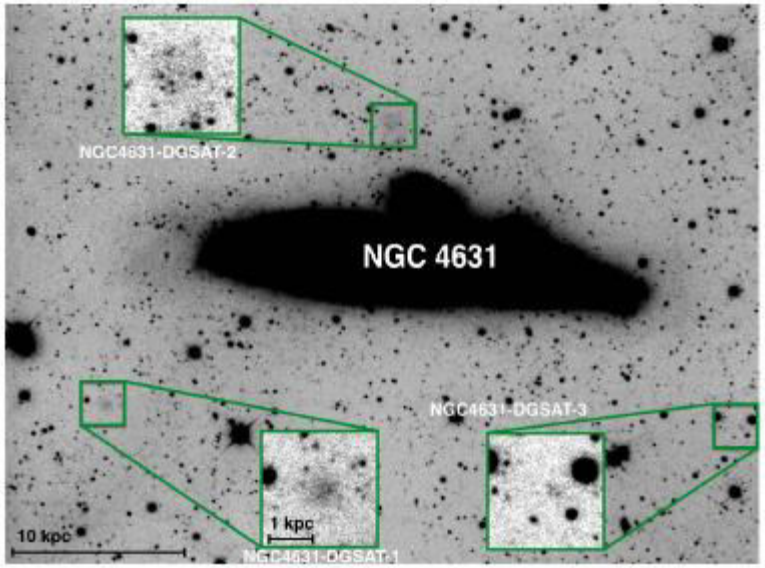
Javanmardi et al. 2015

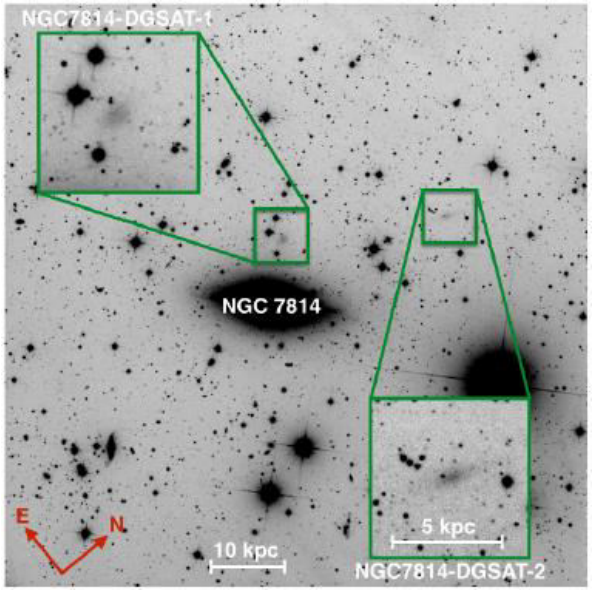


Javanmardi et al. 2015





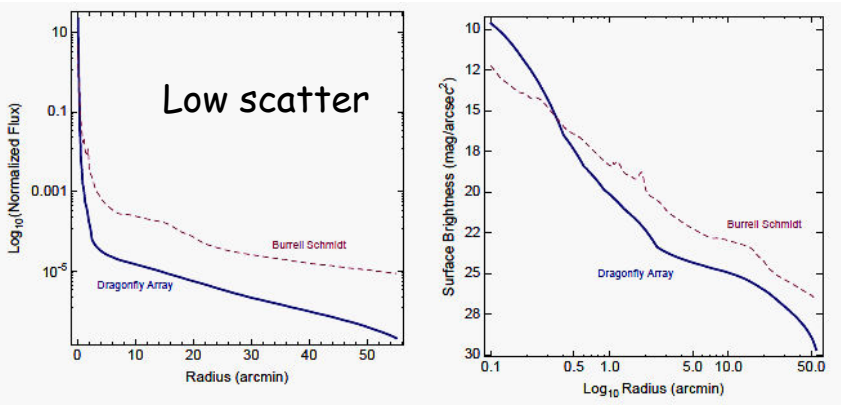




Javanmardi et al. 2015

DRAGONFLY:

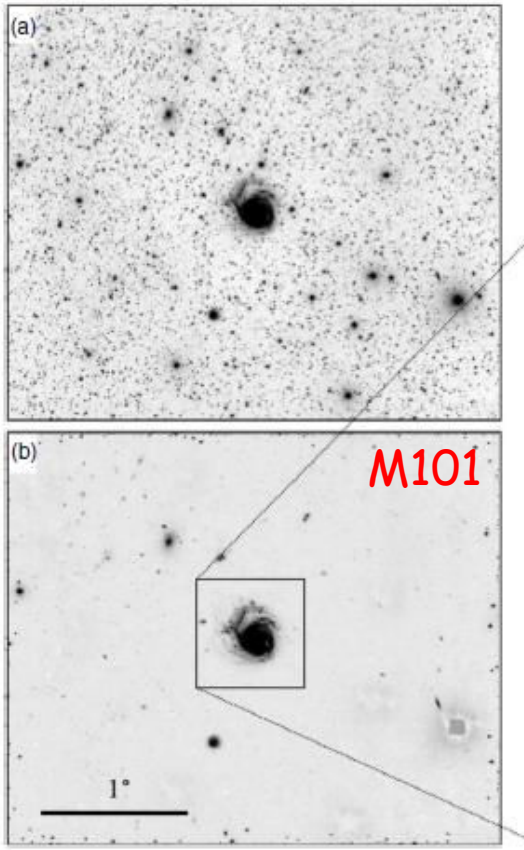
- Canon 400mm f=2.8 L IS II USM telephoto lenses coupled to eight science-grade commercial CCD cameras; uses **SDSS *g* & *r*** filters.
- Imaging capability equivalent to a 0.4m aperture f=0.9 refractor with a 2.6x1.9 square degrees field of view.
- Capable of imaging extended structures to surface brightness levels below B = 30 mag/arcsec^2 in 10h integrations
- Located in NM @2200m

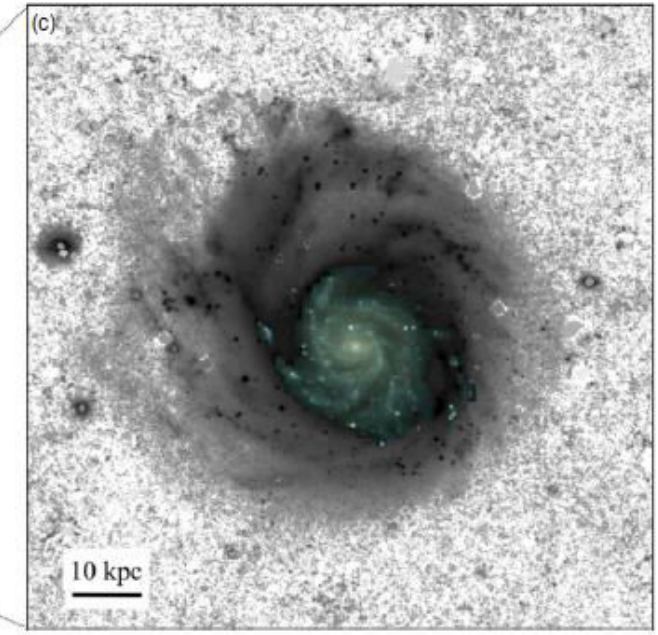


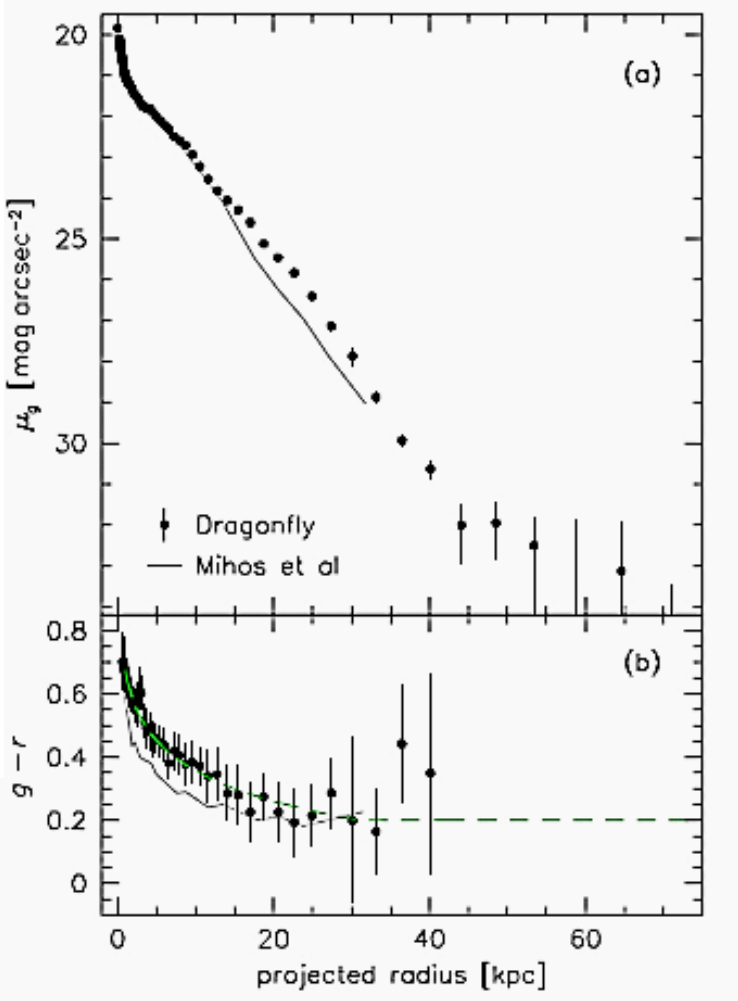
Abraham & v. Dokkum 2014

DRAGONFLY

some 1st results



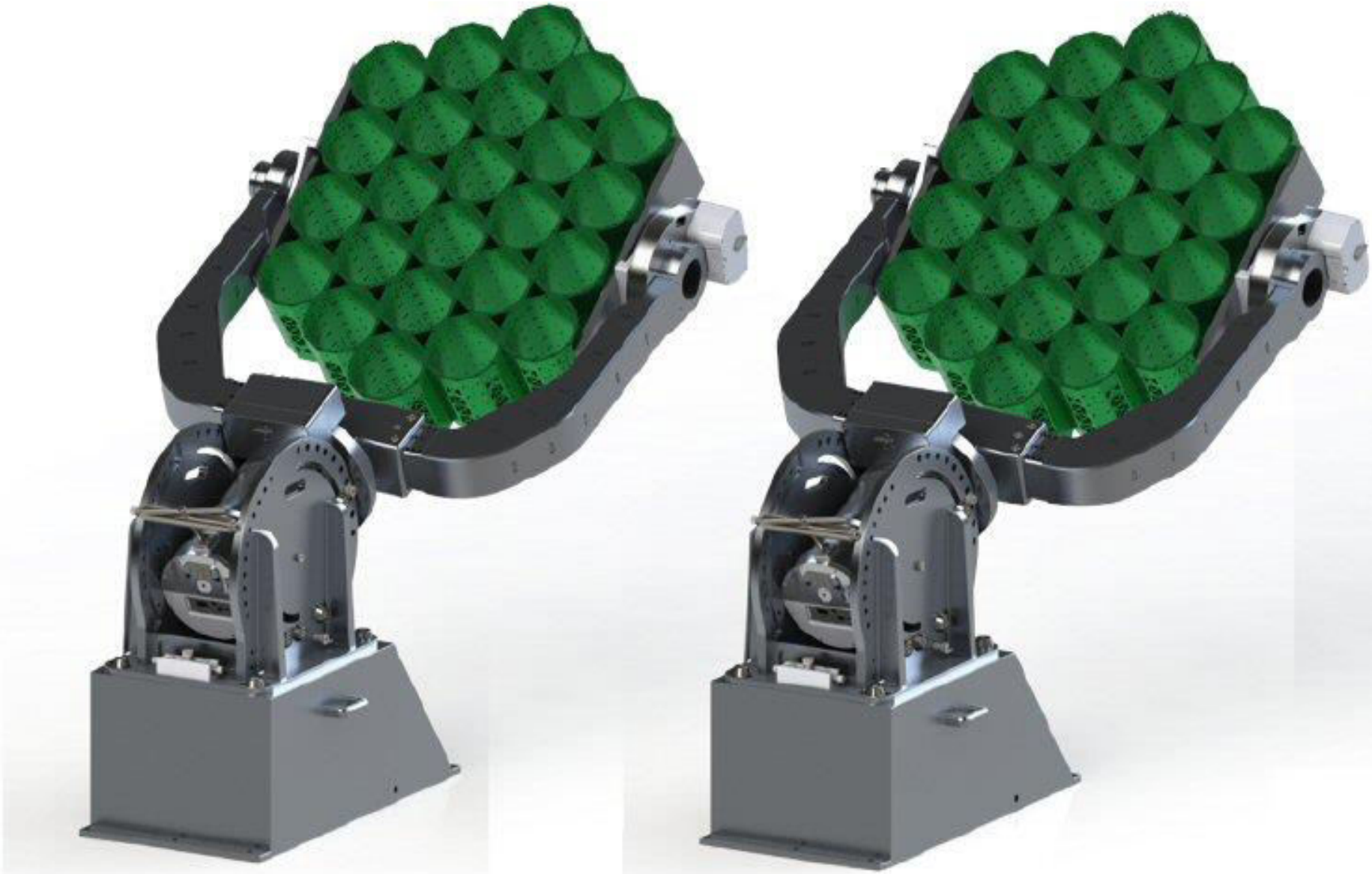




Total observing time=35 hours
LSB background due to MW cirrus

Targeting nearby luminous galaxies

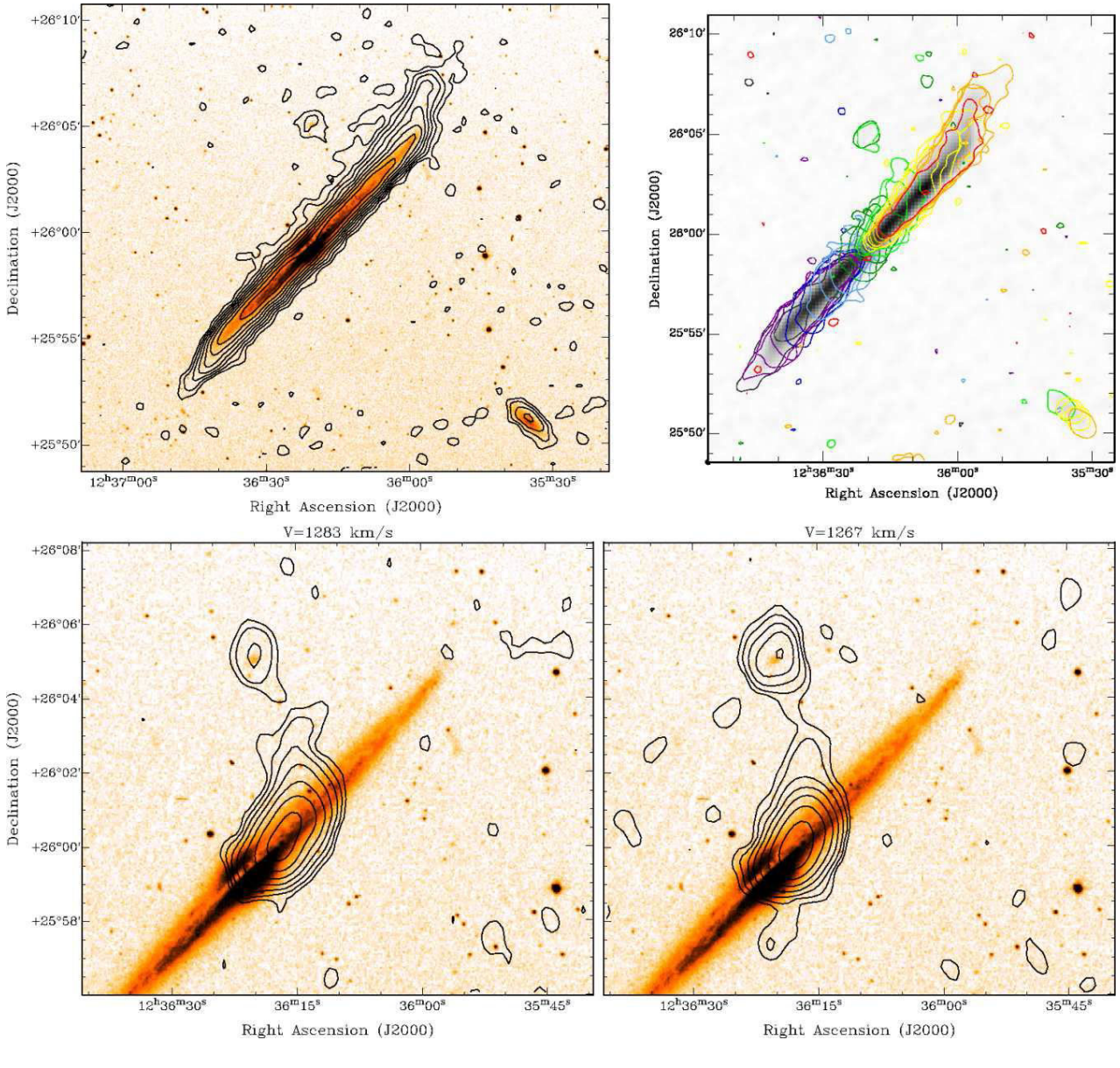
v. Dokkum et al. 2014



DRAGONFLY upgrade

50 lenses+CCD cameras;
equivalent to 1.0-m f/0.4

Minor mergers/interactions



Top left: HI map of NGC 4565 at a resolution of 30" superposed on the DSS image. Contours are 2, 4, 8, 16, 32 and 64 ×10^20 cm−2.

Top right: outer contours of the HI emission in individual channels (from blue to red) superposed on the total HI density map.

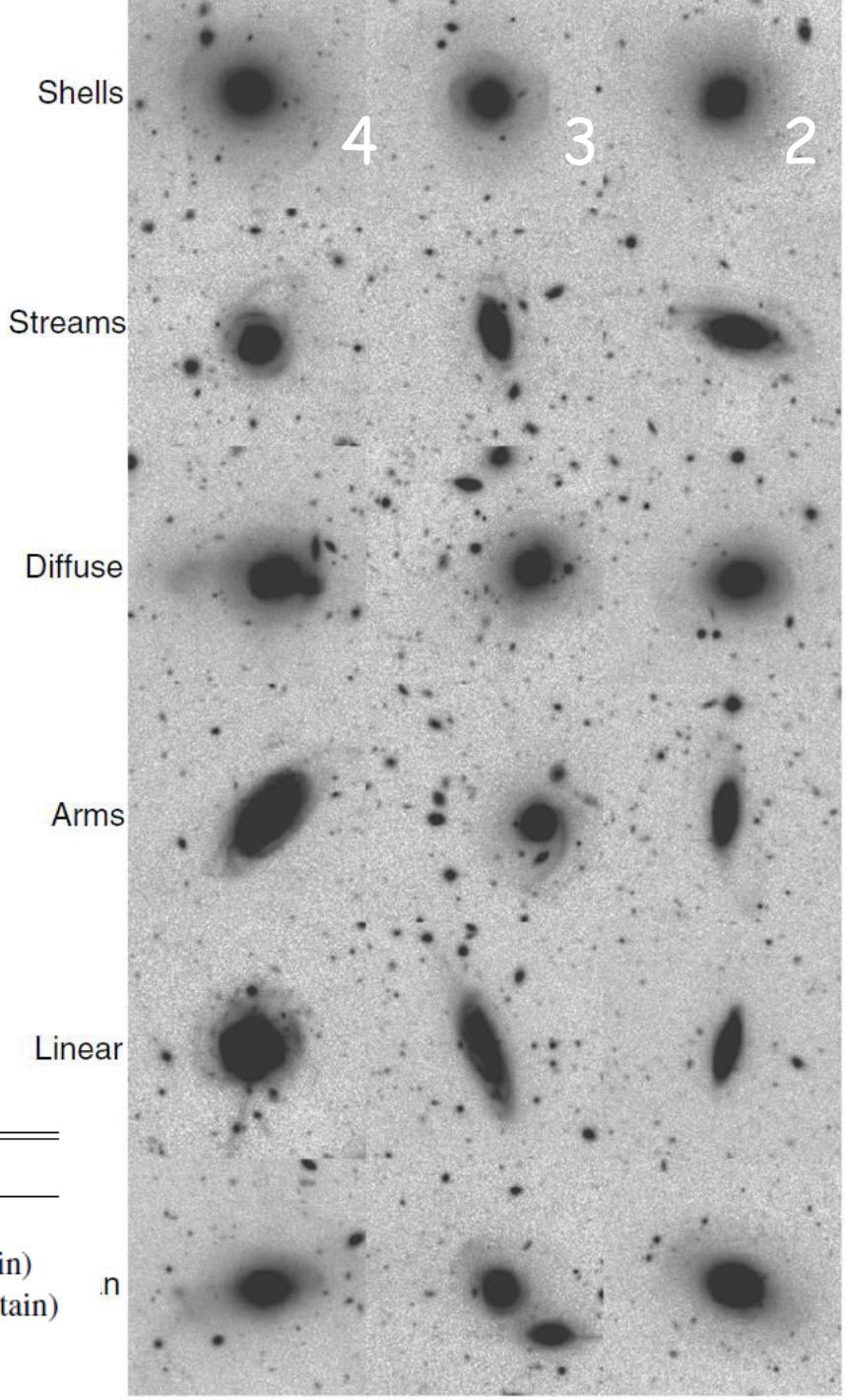
Bottom panels: HI channel maps at two representative velocities superposed on the DSS image of NGC 4565. They clearly show the interaction between NGC 4565 and its small companion.

Sancisi et al. 2008

Atkinson et al. (2013)

"tidal" feature classification from CFHT images of 1781 galaxies

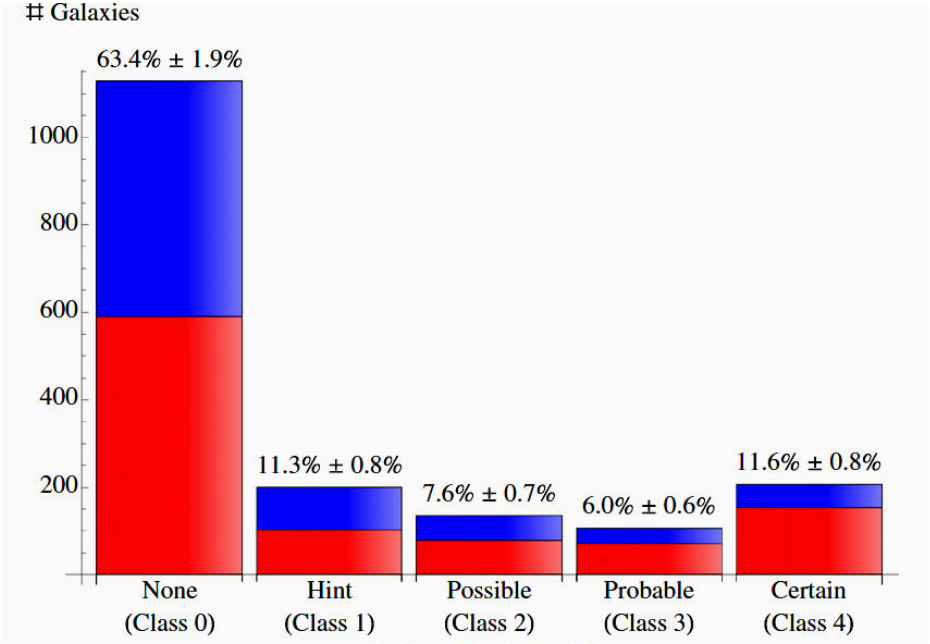
Examples of all six classifications of tidal features (top to bottom: shells, streams, miscellaneous diffuse structure, arms, linear features, and fans) in three different confidence bins with decreasing confidence from left to right (bins four, three, and two). Columns correspond to the confidences levels (defined in Table 2) that the tidal feature exists. Each individual thumbnail is ~56″ × 56″.

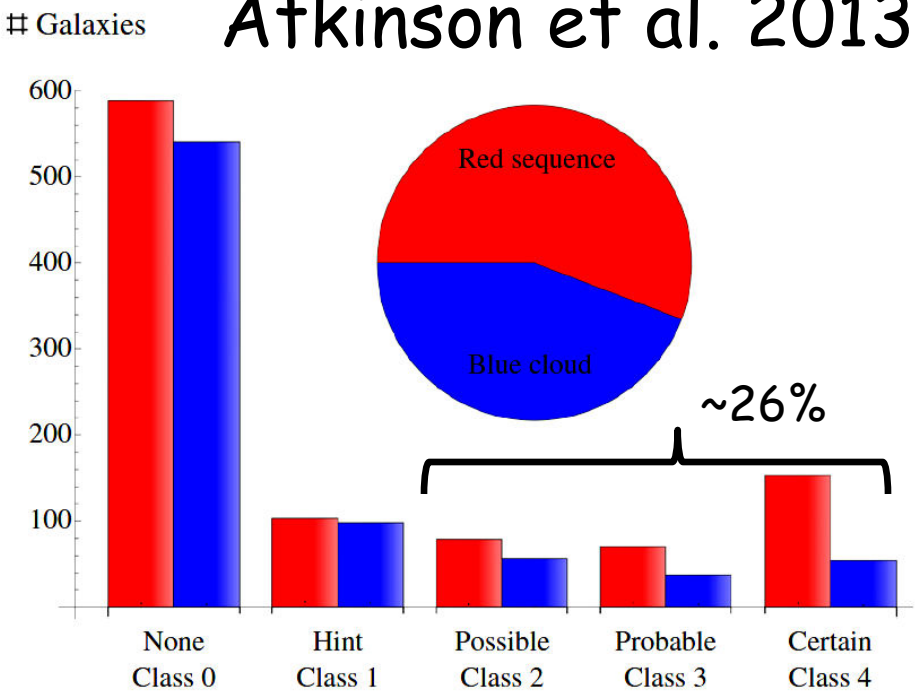


Detection Classes

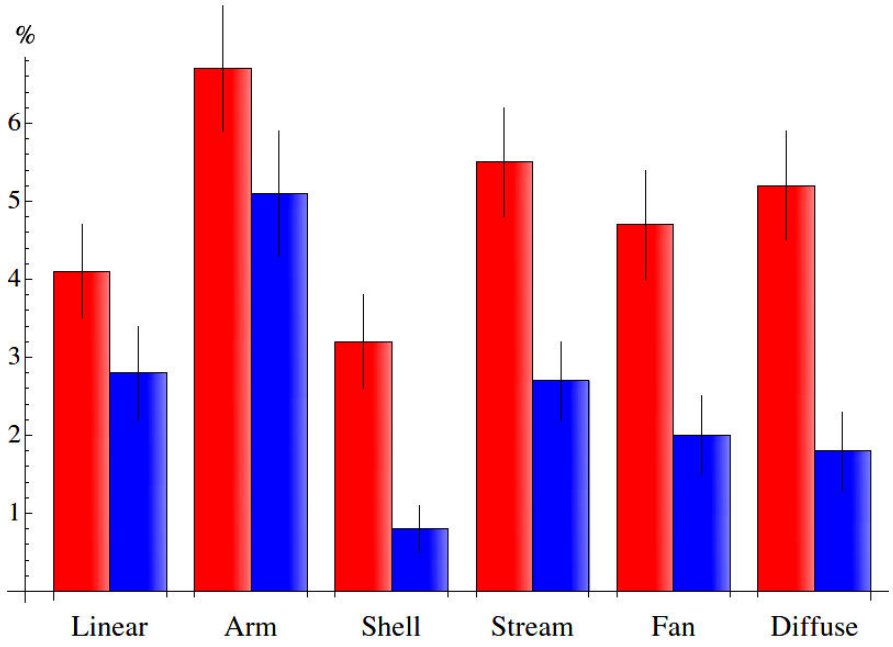
Confidence Level	Definition
4	Certain detection of a tidal feature
3	Probable detection of a tidal feature (over 75% certain)
2	Possible detection of a tidal feature (around 50% certain)
1	Hint of a potential tidal feature. Very uncertain
0	No evidence for tidal features seen

Atkinson et al. 2013

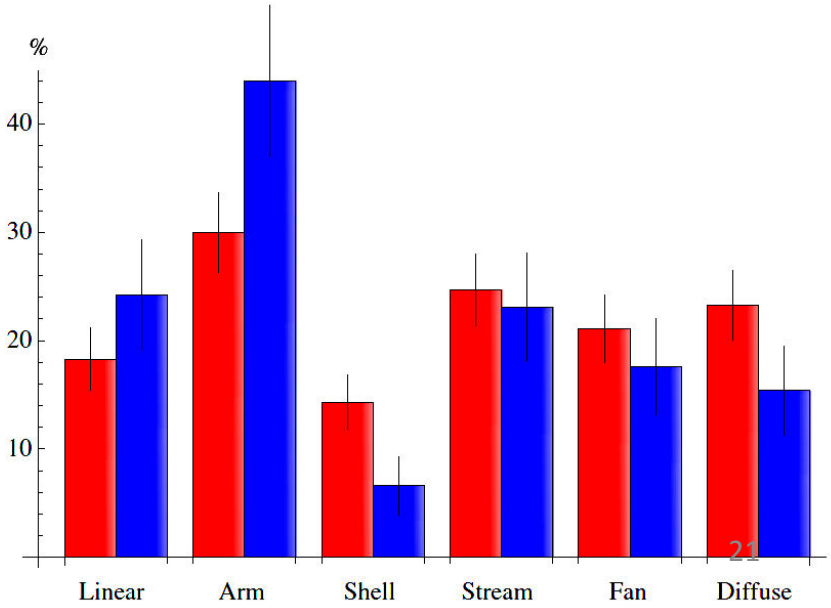




Features Seen in Galaxies
(% of All Galaxies in Sample)

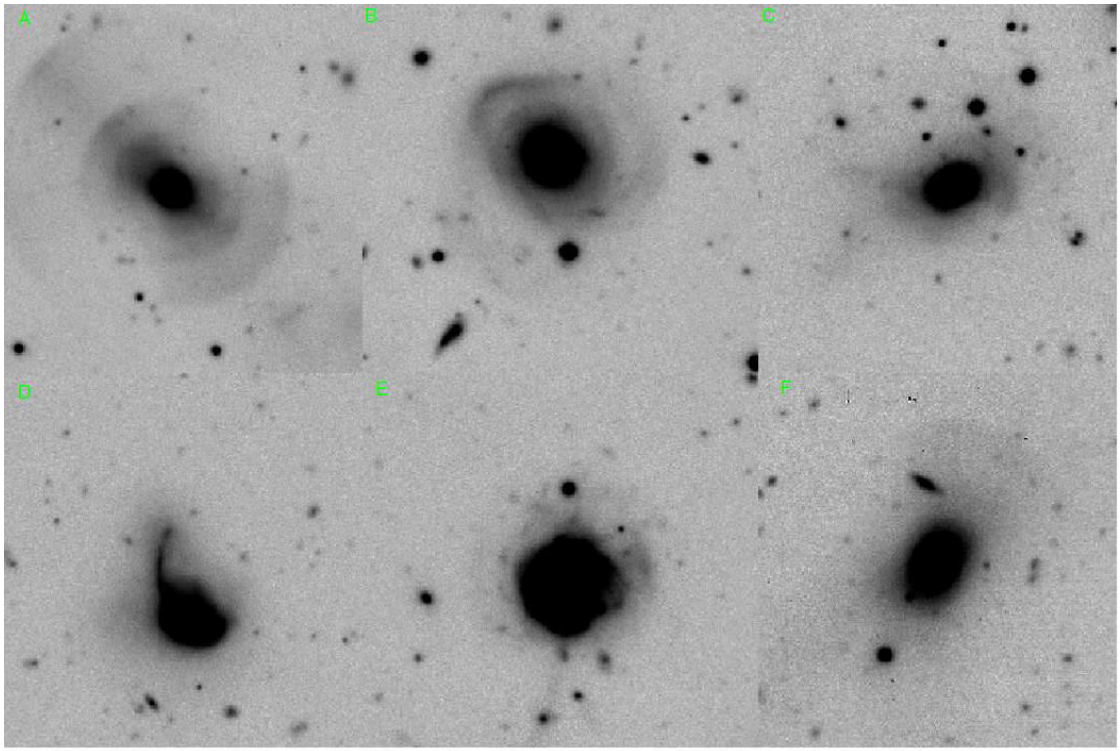


Features Seen in Galaxies
(% of Tidally Disturbed Sample)



Atkinson et al. (2013)

Examples of different categories of **tidal** disturbances used to classify objects in the paper. (a) Shells, (b) a stream (visible in the lower part of the image), (c) miscellaneous diffuse structure, (d) an arm, (e) a linear feature (visible at the bottom of the image), and (f) broad fans of diffuse light.



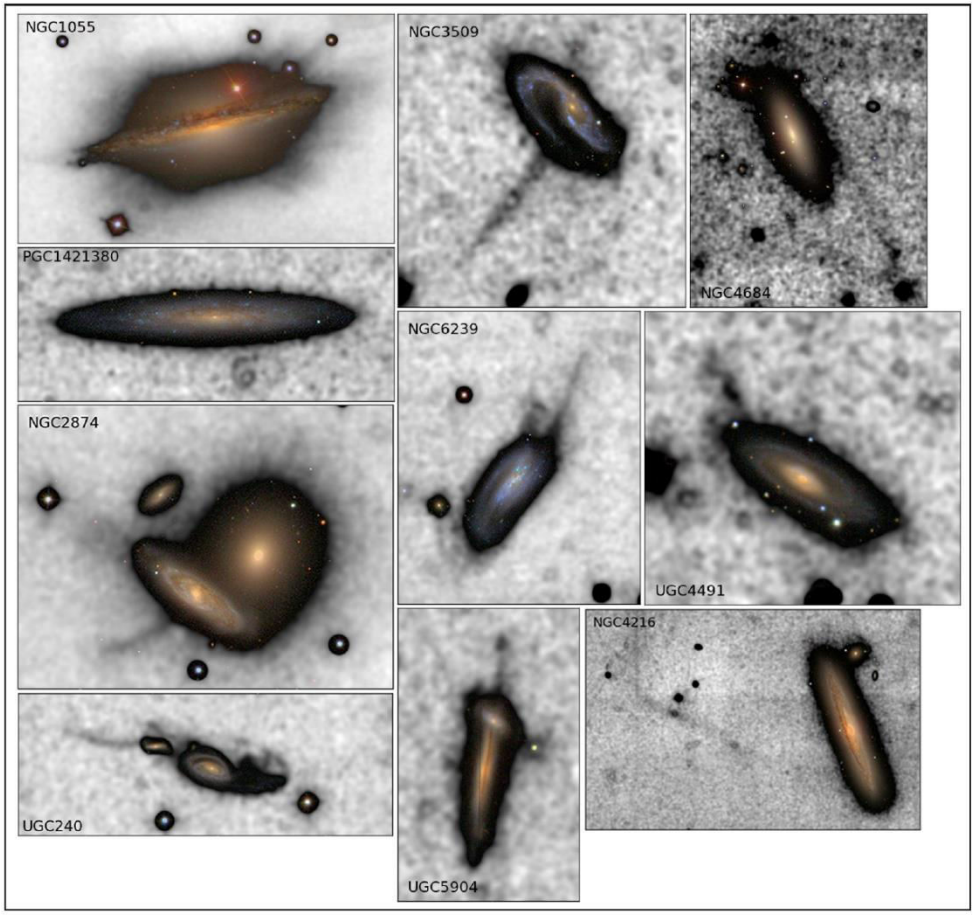
Summary of Tidal Feature Detections

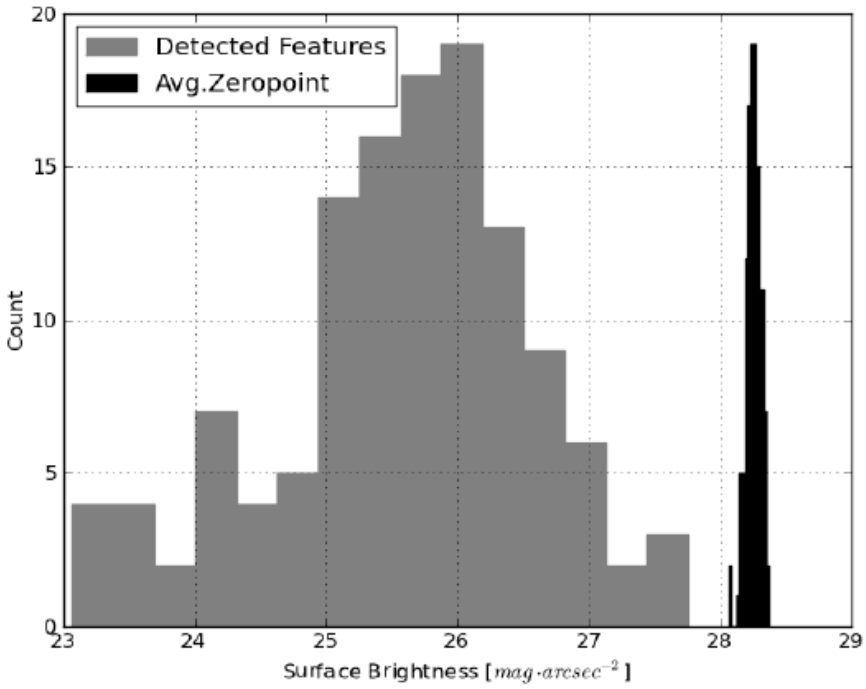
Confidence	Total Sample		Red Galaxies		Blue Galaxies	
	Number	%	Number	%	Number	%
4	207	11.6 ± 0.8	153	15.4 ± 1.2	54	6.9 ± 0.9
3	107	6.0 ± 0.6	70	7.0 ± 0.8	37	4.7 ± 0.8
2	136	7.6 ± 0.7	79	7.9 ± 0.9	57	7.2 ± 1.0
1	201	11.3 ± 0.8	103	10.4 ± 1.0	98	12.4 ± 1.3
0	1130	63.4 ± 1.9	589	59.3 ± 2.4	541	68.7 ± 3.0
Number of galaxies	1781		994		787	

~26%

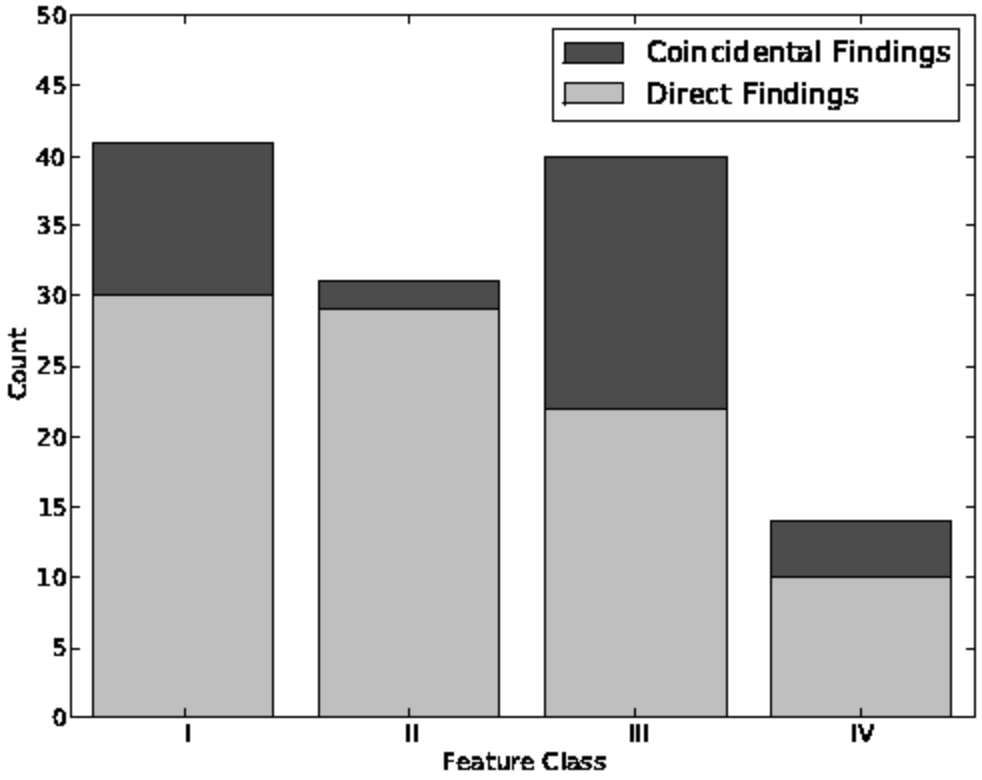
Tidal streams around 474 EODGs in SDSS DR7

- Inclination. Should be as close to edge-on as possible.
- Size. Galaxies should be at least two arcminutes in diameter.
- Morphology. Every galaxy type except elliptical galaxies





Miskolczi et al. 2011



41 galaxies in class I, 31 galaxies in class II, 40 galaxies in class III, and 14 galaxies in class IV,

Final results: 19% of galaxies show LSB features connected to the disk; 6% stream-like

I: Features which show clear streams which are not the result of major mergers or other large scale interactions.

II: Features which seem to be connected to some disc disturbance like warping.

III: Features which are possibly the result of (large) interacting galaxies and not between one large galaxy and its dwarf companion, where a minor merger origin cannot be certain.

IV: Unclassified. Those would be features which make it hard to estimate what they really are, e.g. when it looks like a stream, but could also be very well an extension of a spiral arm.

Miskolczi et al. 2011

Frequency of LSB features

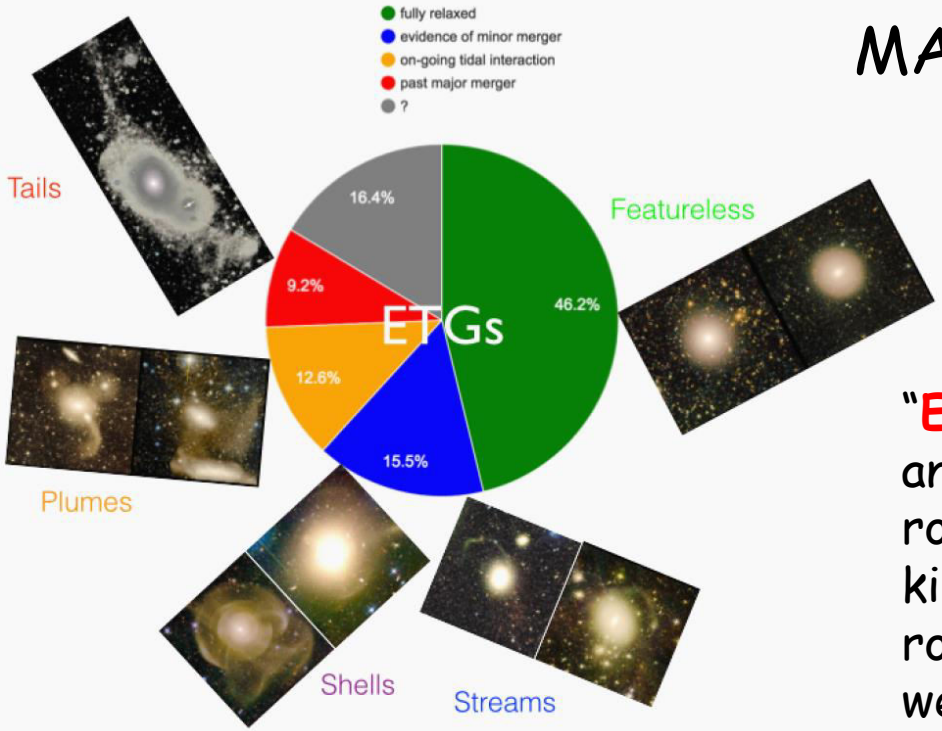
Atkinson et al. 2013

Table 1
Overview of Faint Substructure from Published Surveys

Investigation	N	Data Set	Selection	SB Limit (mag arcsec^{-2})	Summary %
This paper	1781	CFHTLS-Wide	$r' < 17$ $0.04 < z < 0.2$ $M'_r < -19.3$	$g'_{AB} \sim 27.7$ $(g'r'i')_{AB}$[a] ~ 27.3	Strong: 17.6% Weak: 25.2%
Adams et al. (2012)	3551	CFHT MENeaCS	Cluster ETGs $0.04 < z < 0.15$ $M'_r < -20$	$r'_{AB} \sim 26.5$	3%
Sheen et al. (2012)	273	CTIO Mosaic II	Cluster ETGs $z \lesssim 0.1$ $M'_r < -20$	$r'_{AB} \sim 30$	Total sample: 25% Bulge-dominated: 38%
Kim et al. (2012)	65	S^4G	ETGs	$[3.6\,\mu]_{AB} \sim 26.5$	17%
Miskolczi et al. (2011)	474	SDSS DR7	Edge-on disks $>2'$ diameter	$(g'r'i')_{AB}$[a] ~ 26[b]	Strong: 6% Weak: 19%
Nair & Abraham (2010)	14034	SDSS DR4	$g' < 16$; $0.01 < z < 0.1$	$g'_{AB} \sim 26.5$	7%
Bridge et al. (2010)	23854	CFHTLS-Deep	$i_{\rm vega} < 21.9$; $0.1 < z < 1.2$; $M_\star > 10^{9.5}\,M_\odot$	$g'_{\rm vega} < 29$[c]	4.3% ($z = 0.3$) 19% ($z = 1$)
Tal et al. (2009)	55	SMARTS (1 m)	Ellipticals $M_B < -20$ $15 < D_L < 50$ Mpc	$V_{\rm vega} \sim 27.7$	73%
van Dokkum (2005)	126	MUSYC + NOAO Deep-Wide	ETGs $R < 17$ $0.04 < z < 0.2$	$(BVR_{AB}$[a]$, BVI_{AB}$[a]$) \sim 28$	Total sample: 53% Bulge dominated: 71%
Schweizer & Seitzer (1988)	74	KPNO 0.9 m	E/S0	IIIaJ ~ 26.5	Strong: 16% Weak: >50%
Malin & Carter (1983)	327	UK Schmidt	E/S0	IIIaJ ~ 26.5	5.8% (shells only)
Malin & Carter (1983)	73	UK Schmidt	E/S0 (isolated)	IIIaJ ~ 26.5	16.5% (shells only)

Notes.
[a] Stacked.
[b] Detections decline after this surface brightness, but individual features were detected down to nearly 28 mag arcsec^{-2}.
[c] Cosmological dimming at the mid-redshift point of their sample ($z = 0.65$) is 2.2 mag arcsec^{-2}, considerably higher than any other entry (e.g., 0.4 mag arcsec^{-2} for of our sample's mid-redshift point of $z = 0.1$).

Preliminary results from the MATLAS deep imaging survey



MATLAS (*Mass Assembly of early-Type GaLAxies with their fine Structures*)

240 ETGs (targets)+120 incidental LTGs

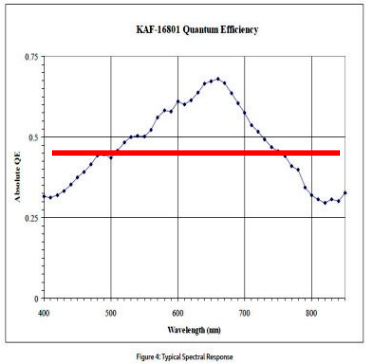
Tidally perturbed ~40%

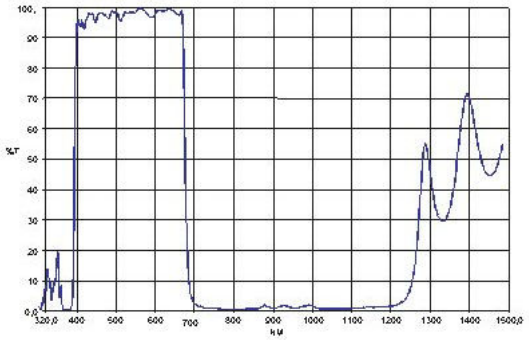
"**ETGs** with stellar masses above $10^{11} M_0$, and, in particular, among them the slow rotators, i.e. the galaxies with a stellar kinematics showing no indication of rotation, seem to have experienced recent wet major mergers with a frequency increased by a factor of 3. While a significant fraction of **LTGs** in our sample show evidence for on-going tidal interactions, only **few of them exhibit streams and tails indicative of a past strong minor/major merger activity**. Preliminary results further indicate a mild dependence of the fraction of tidally perturbed galaxies on the large scale environment."

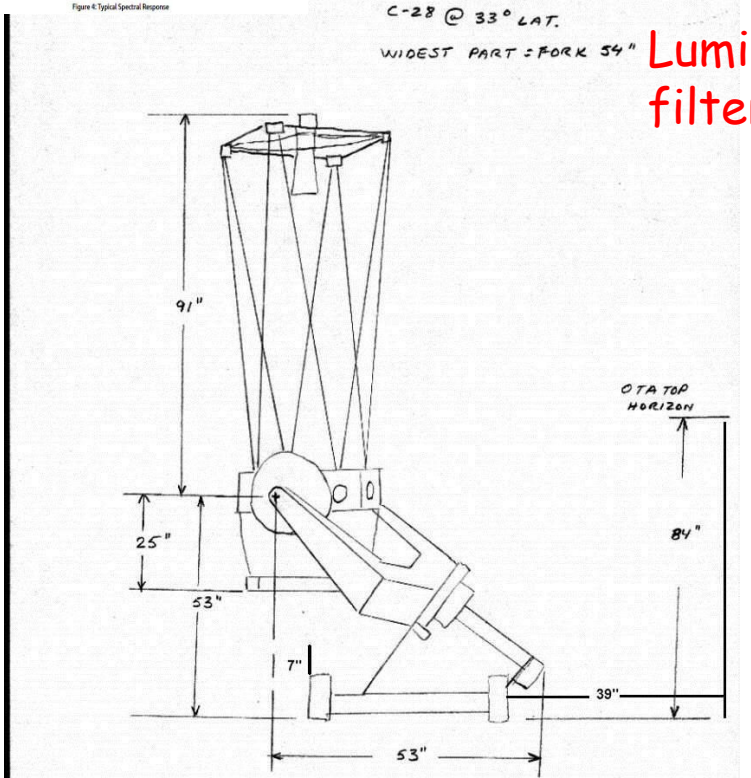
Duc (2016)

JBRT@WO

Robotic 0.72-m f/3.2 FOV=~1°@ 0".84/pix
FLI CCD 4Kx4K (Kodak 16801)





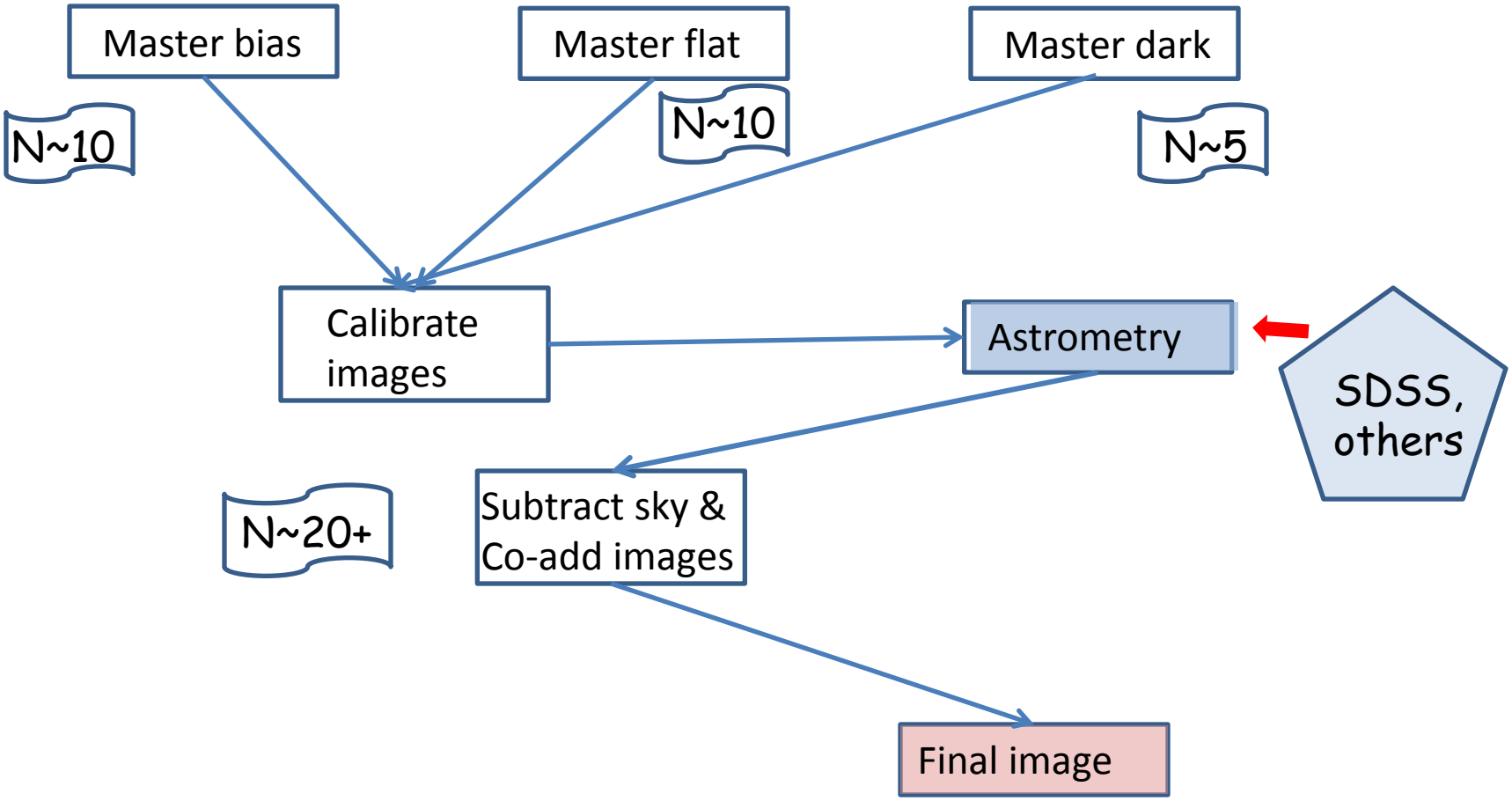


Luminance filter

Jay Baum Rich Telescope at Wise Observatory

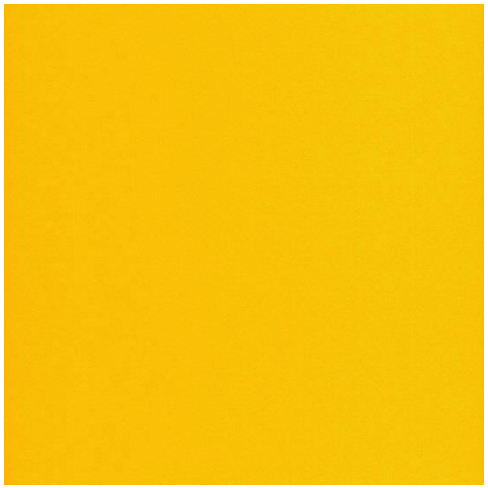
Deep imaging of edge-on disk galaxies

- With edge-on disks one can better see **accreting DGs** and **stellar streams**
- Galaxy-galaxy interactions cause:
  - Disk blow-up
  - Disk bends and morphological changes
  - **Peanut** and/or **boxy** bulges
- Project aims to deep-image ~170 disks with $2a>2'$ and $\delta>-30°$ with the JBRT: co-add 20 ⟹ 90 @300s images to go deeper that SDSS (e.g. Miskolczi et al. 2011)
- At most two galaxies/night ⟹ at least two years required for the entire sample
- Robotic observations
- Reduction pipeline with THELI

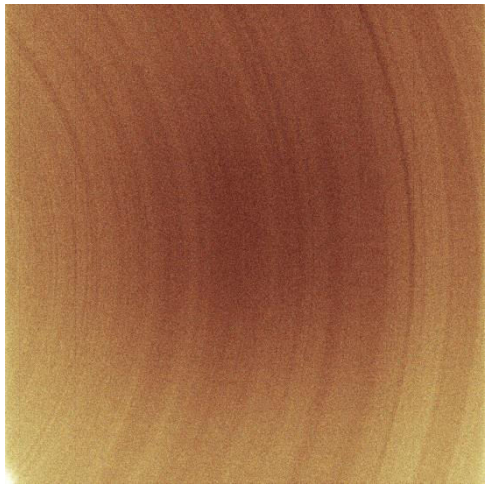


Pipeline reduction of JBRT images using THELIGUI

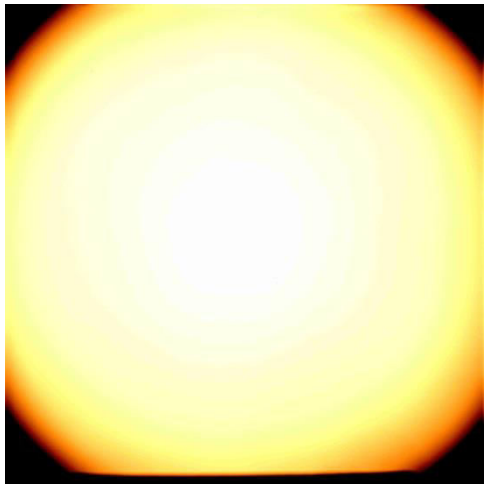
Bias

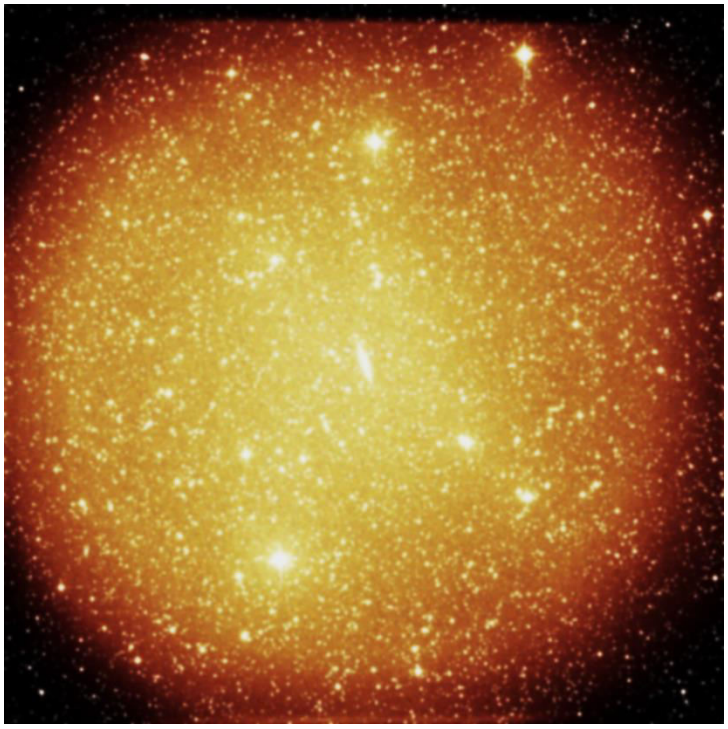


Dark

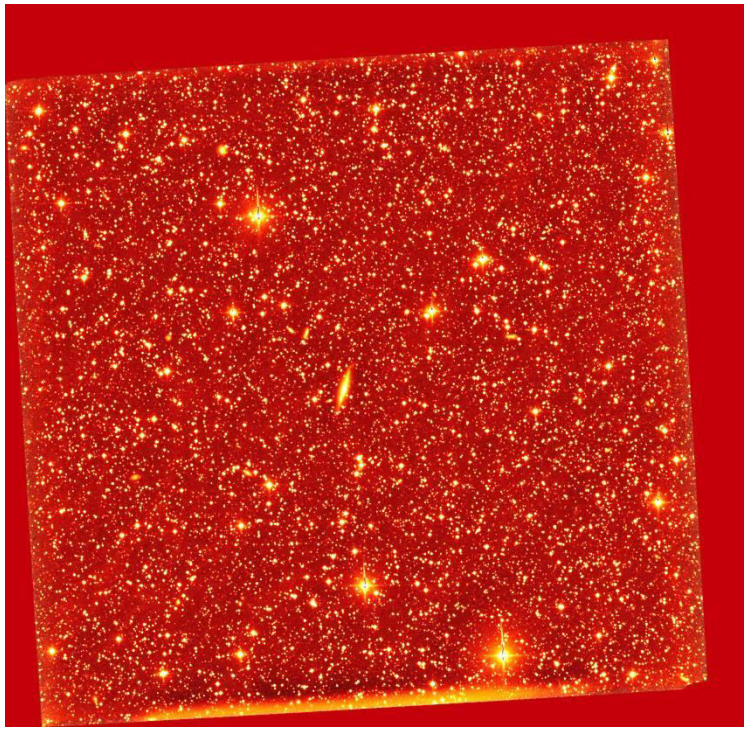


Flat



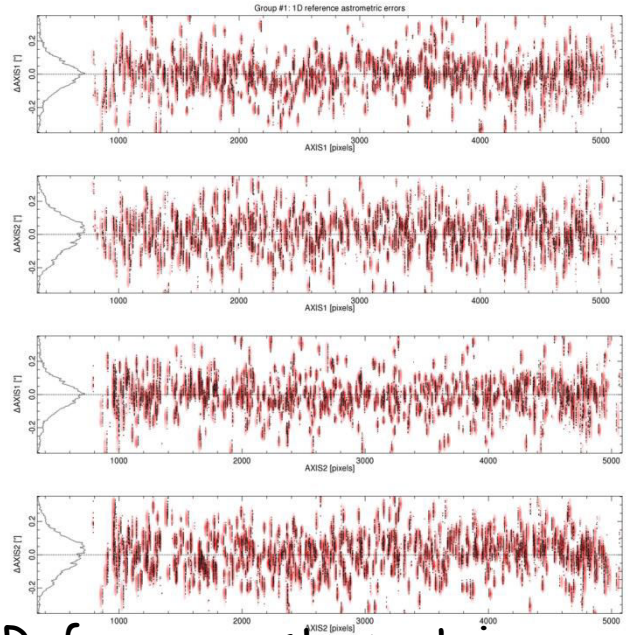


Single raw sky image

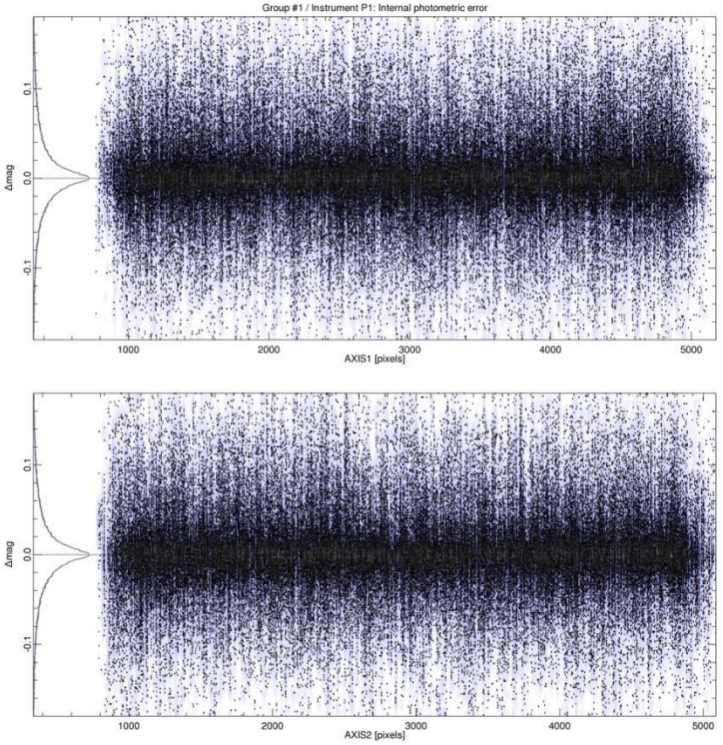


Final reduced & combined image

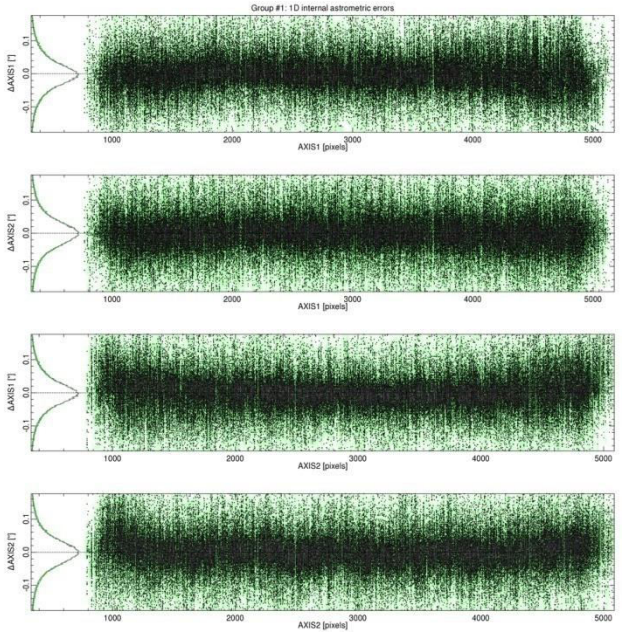
THELIGUI results



Reference astrometric errors

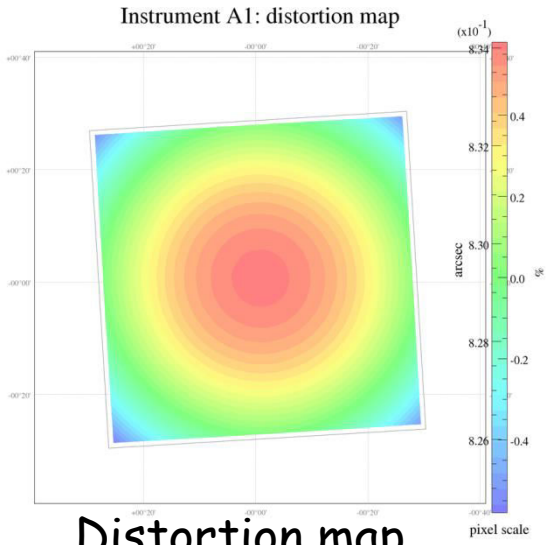


Internal photometric errors

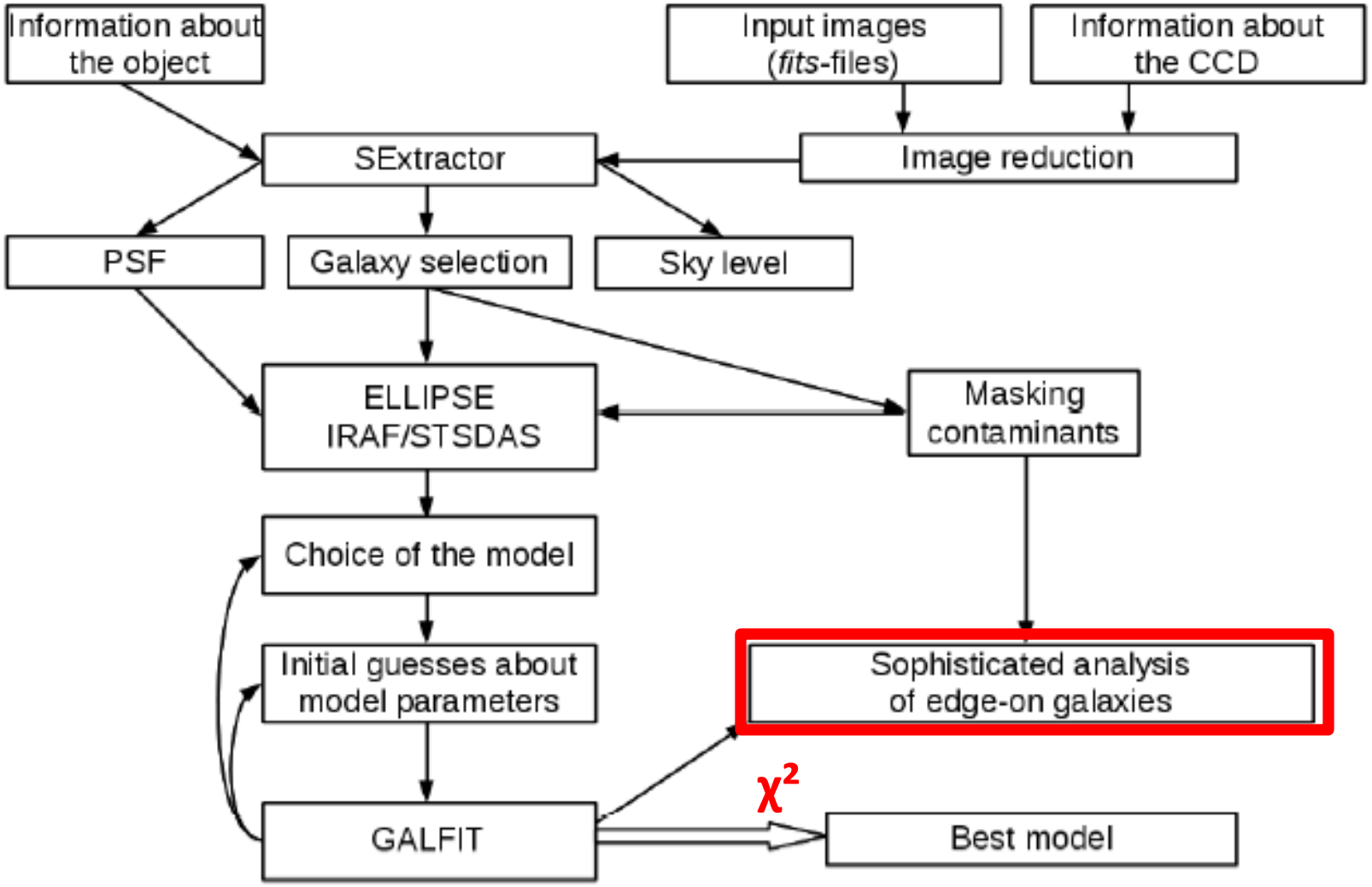


Internal astrometric errors

4° CCD rotation wrt (α, δ)



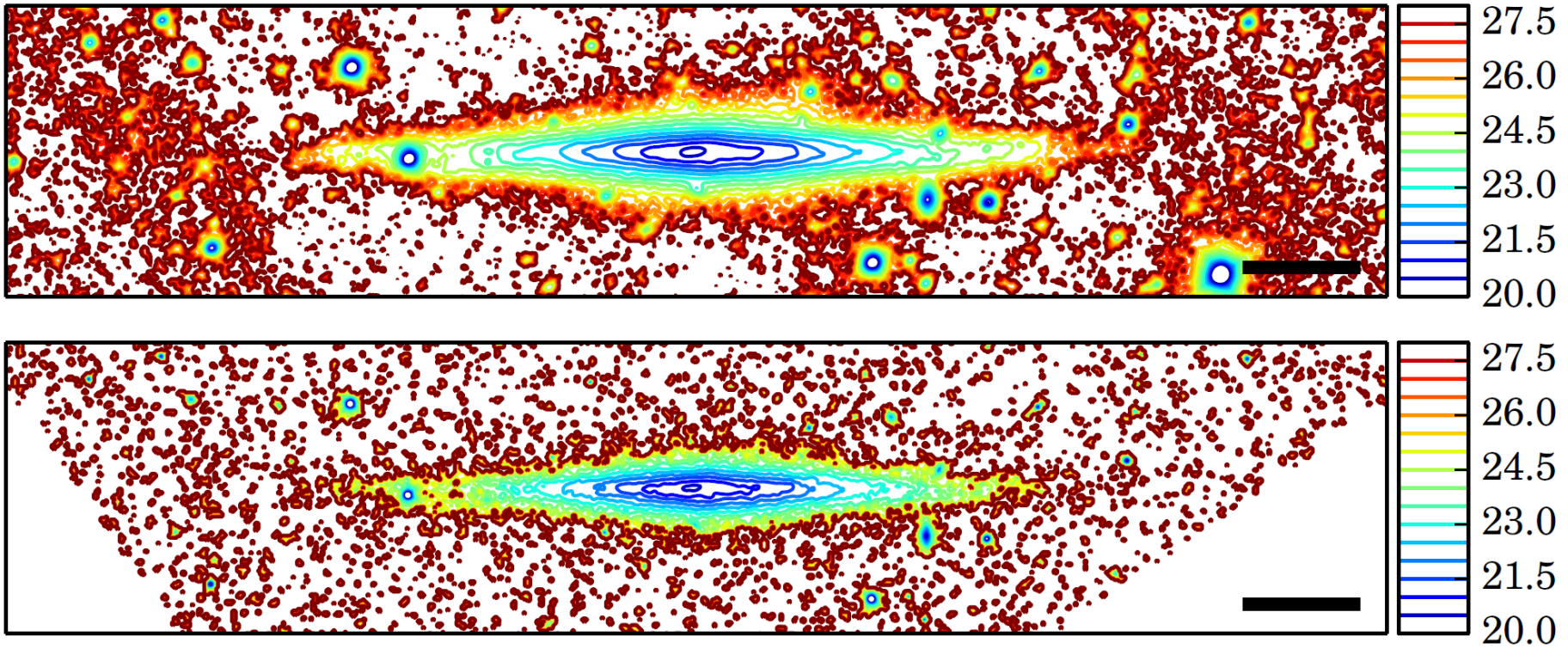
Distortion map



Pipeline reduction of final galaxy image using DECA

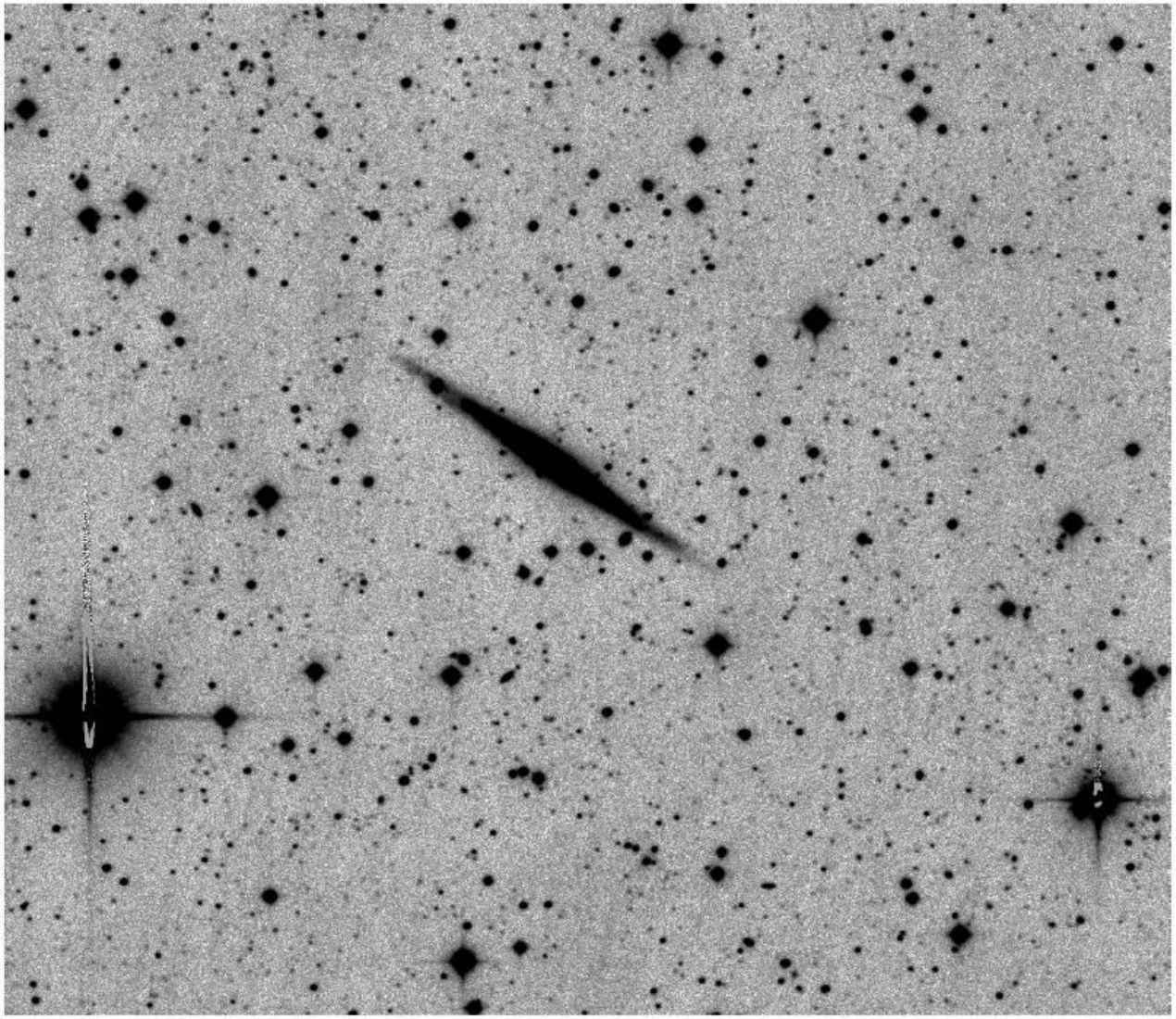
Mosenkov 2014

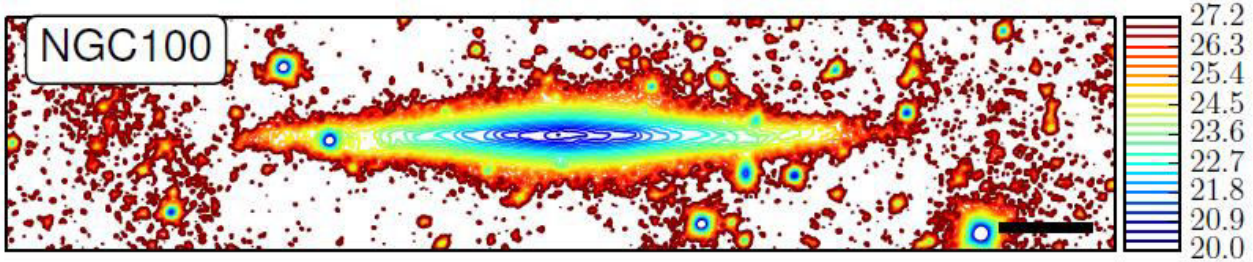
SDSS vs. JBRT

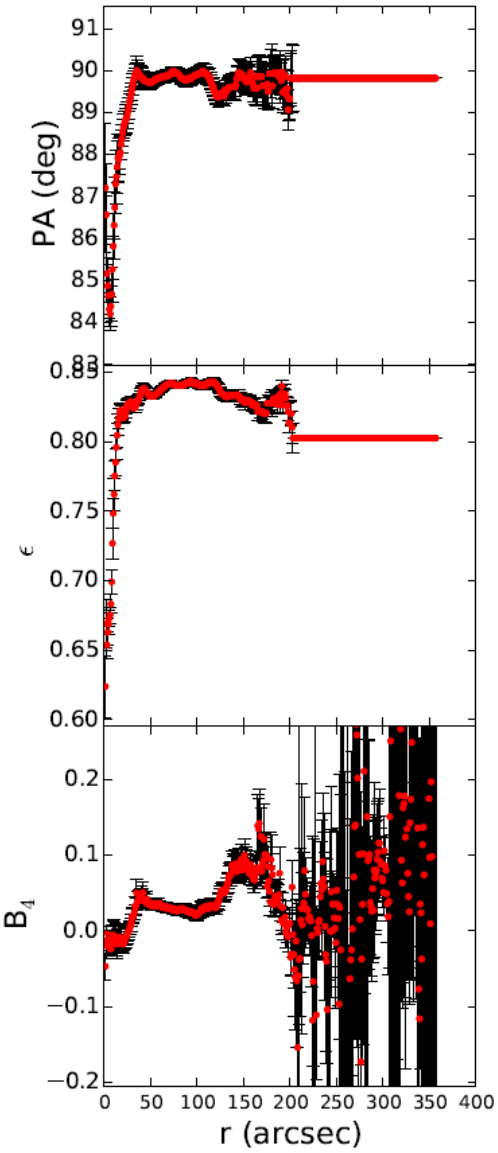


Comparison of two images for NGC 100: the deep image obtained at the WiseObs (top) and the SDSS image in the r-band rebinned to the first one. For the SDSS image all isophotes corresponding to the levels larger than 25.5 mag arcsec−2 are set to this level. The length of the bar in the bottom right corner is 1′.

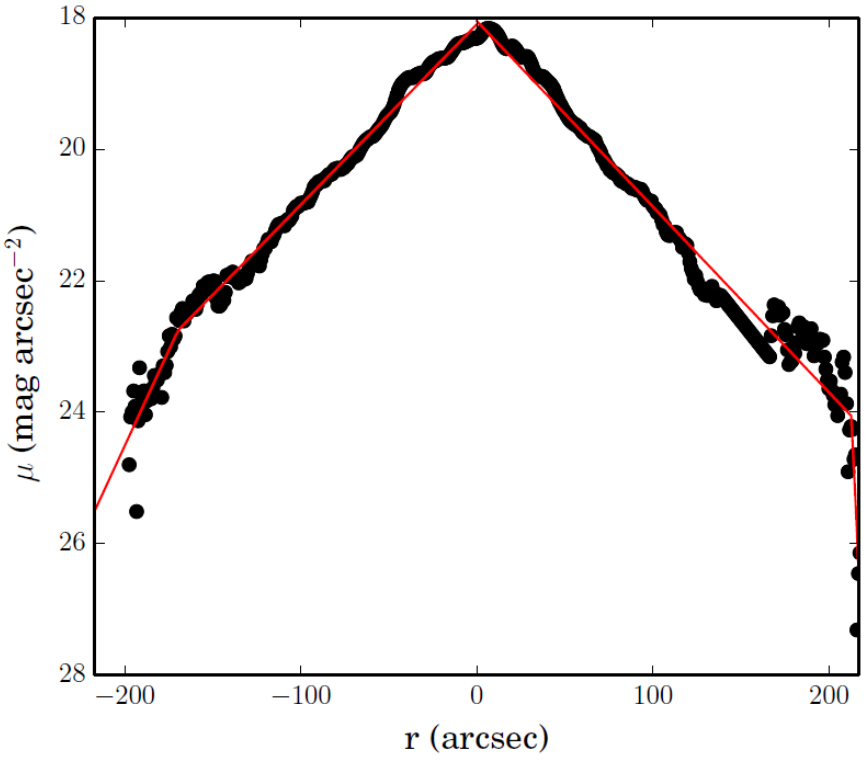
Simple disk

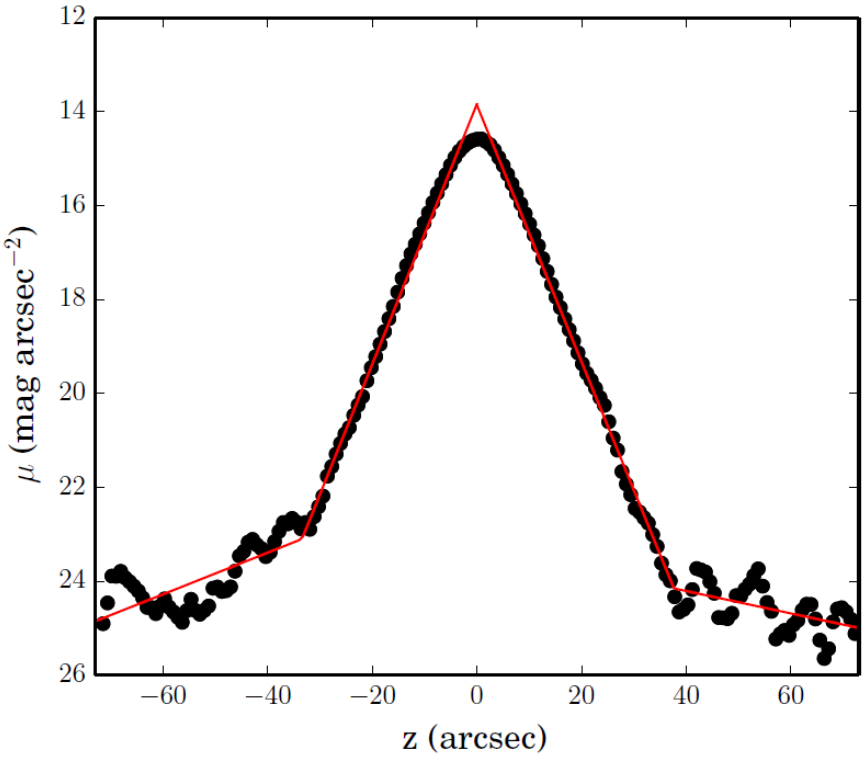



NGC100
27.2
26.3
25.4
24.5
23.6
22.7
21.8
20.9
20.0

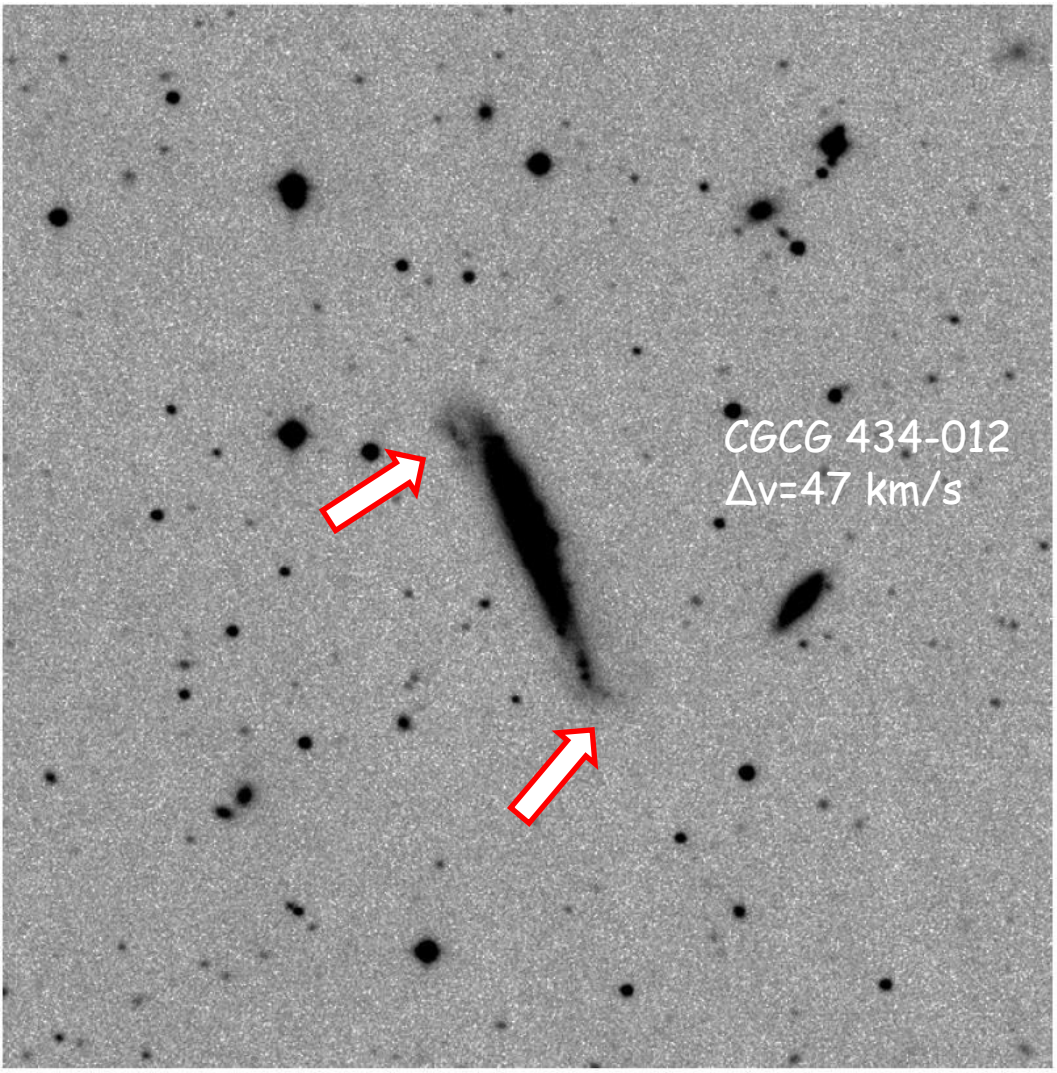

PA (deg)
91
90
89
88
87
86
85
84
ϵ
0.85
0.80
0.75
0.70
0.65
0.60
B4
0.2
0.1
0.0
−0.1
−0.2
0
50
100
150
200
250
300
350
400
r (arcsec)

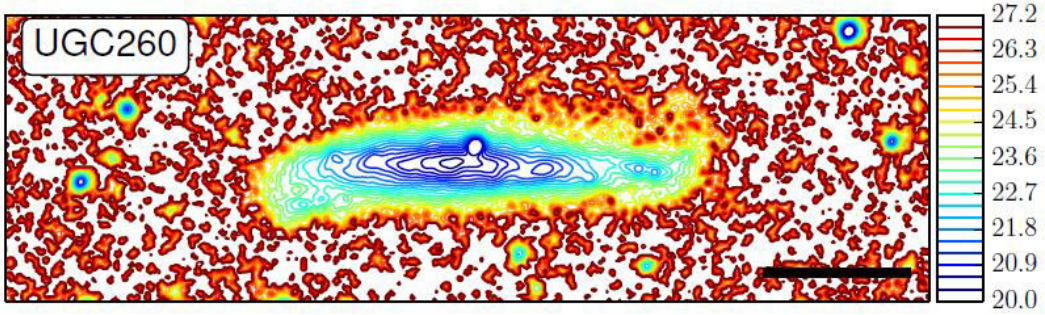
DECA fits for N100



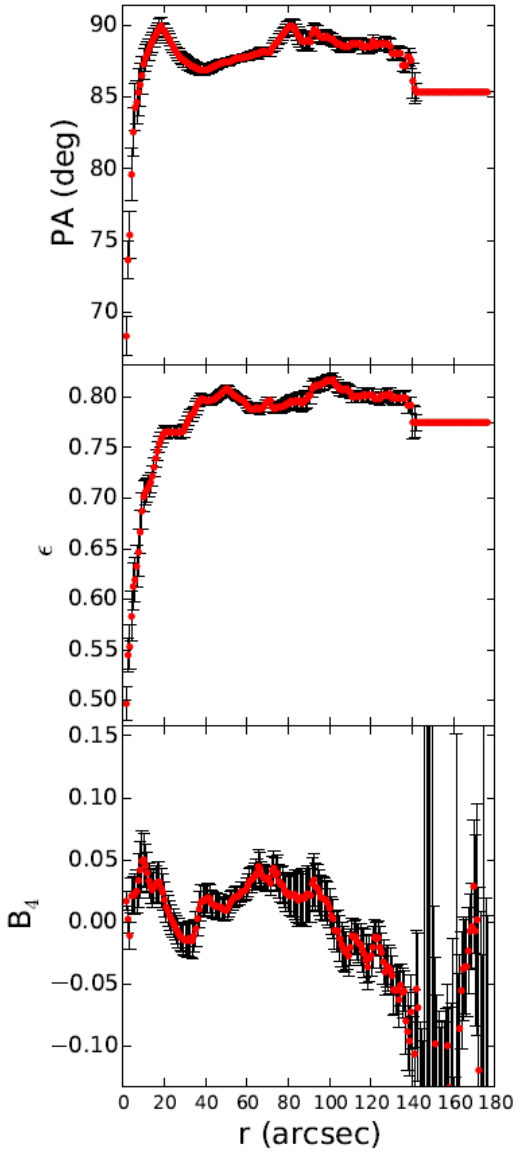


Cumulative horizontal (left) and vertical (right) profiles for NGC 100. Red lines represent the best-fit models of the piecewise linear functions





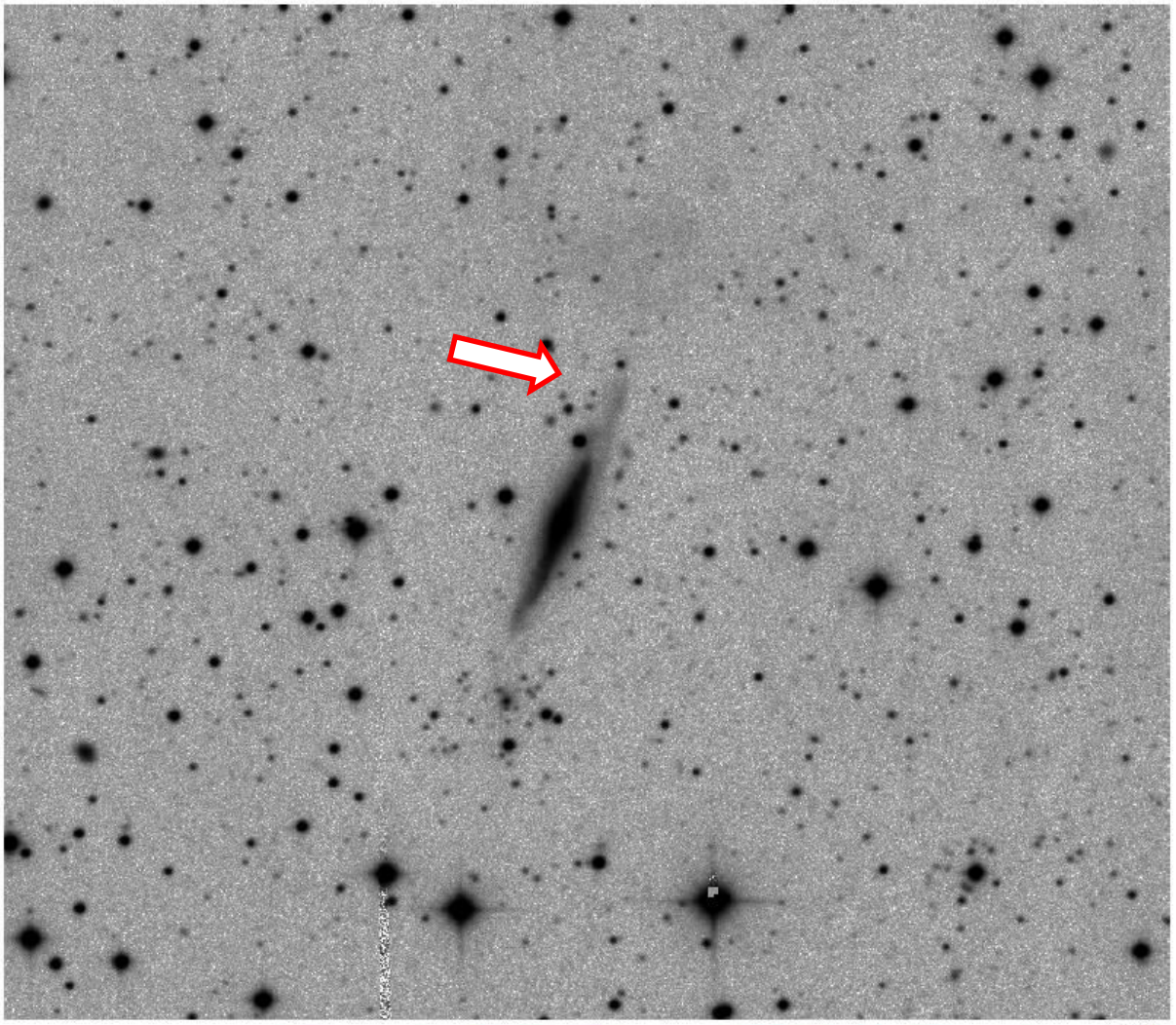
Distorted, with companion

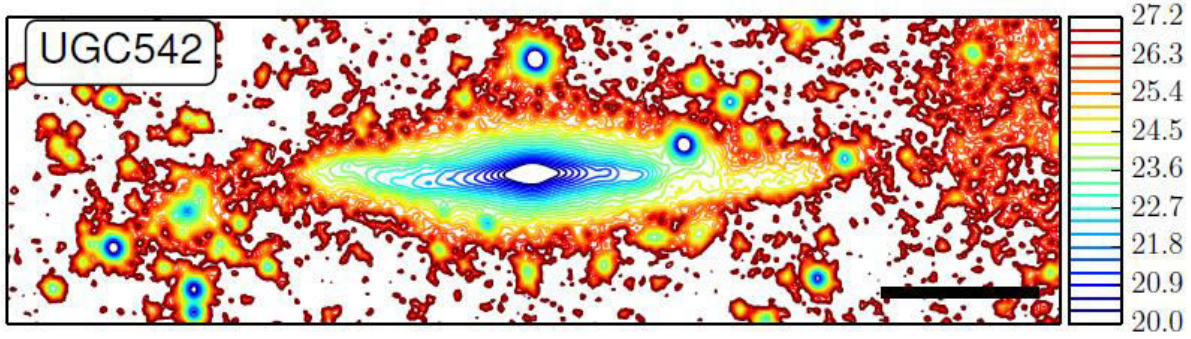


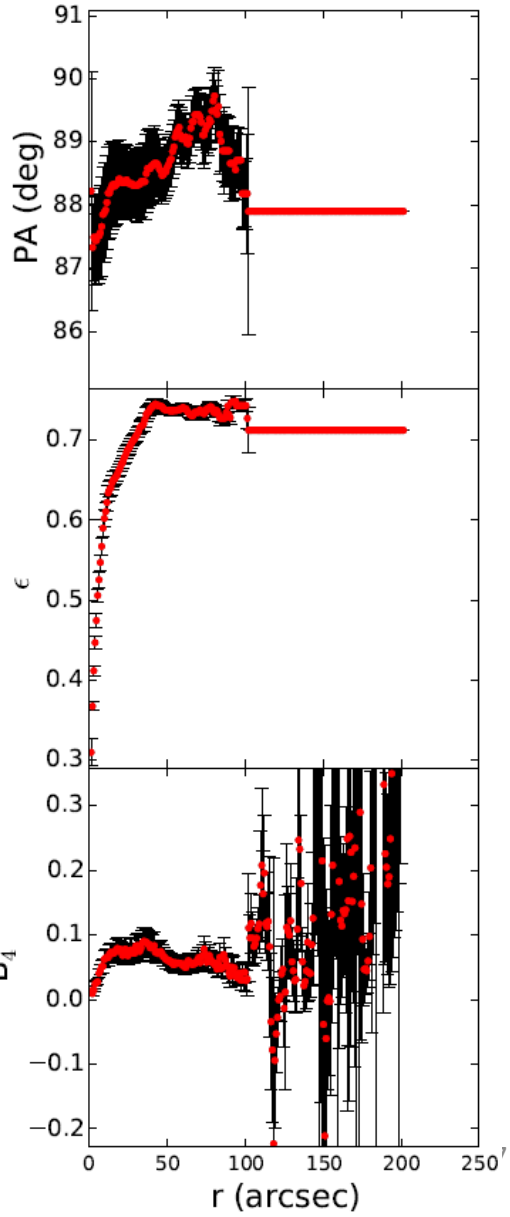
LSB feature

Lopsided disk

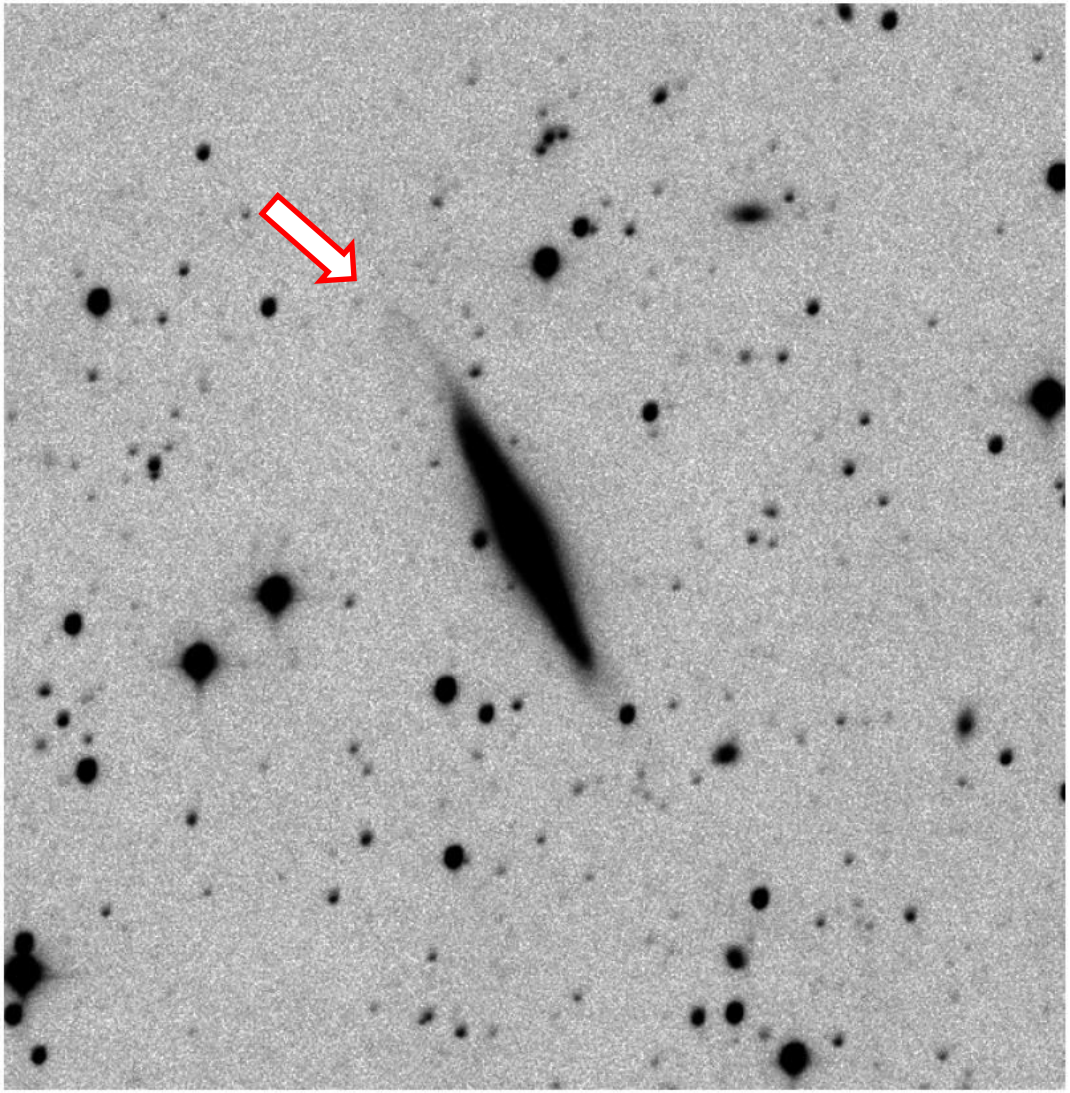
LSB feature

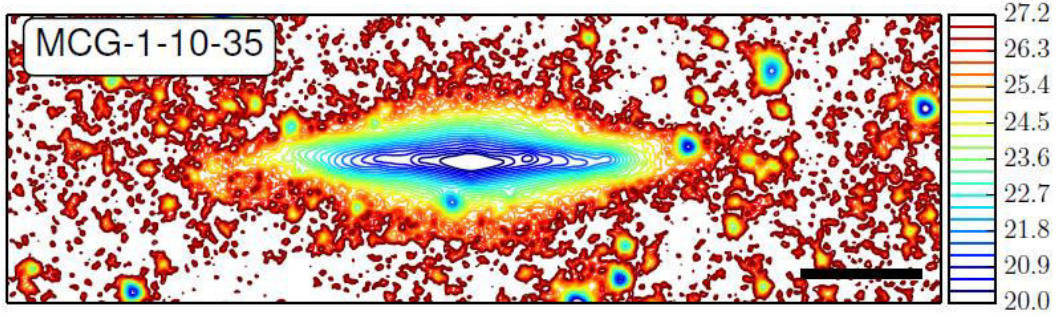


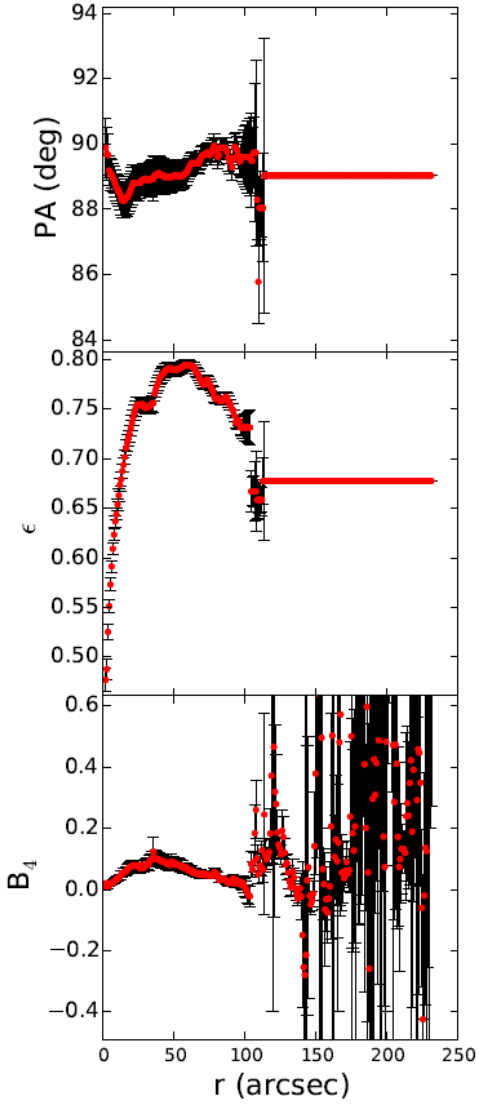




Lopsided disk







LSB feature

N5022

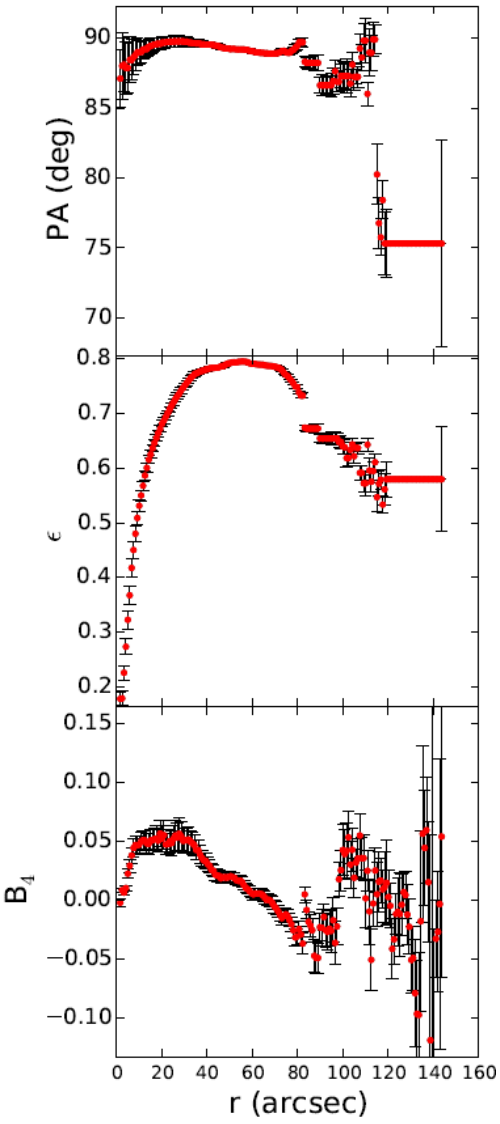
N5018

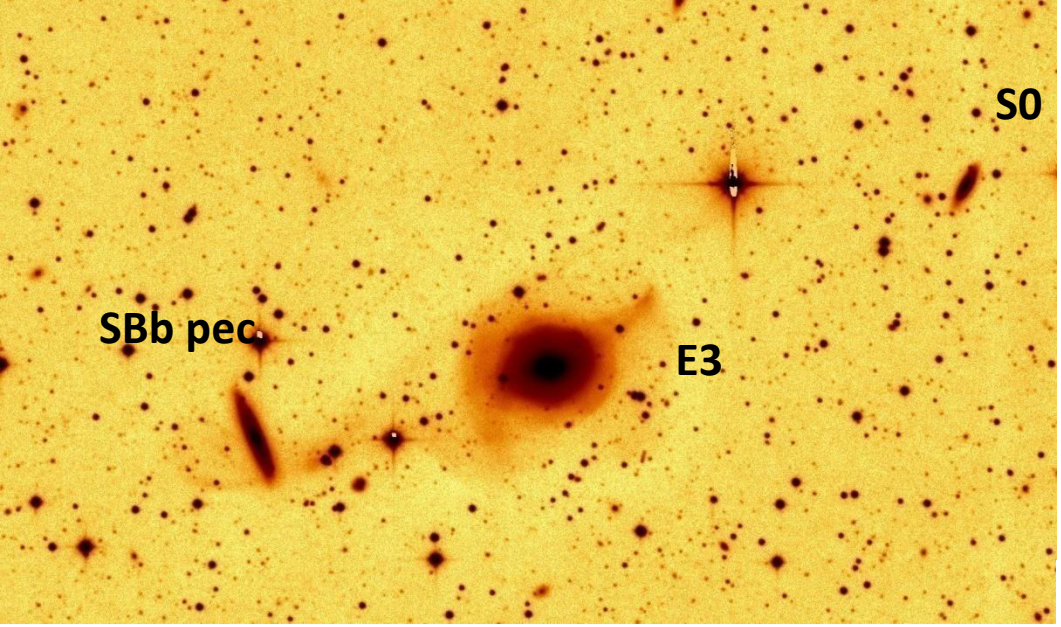
NGC5022

27.2
26.3
25.4
24.5
23.6
22.7
21.8
20.9
20.0

Interacting system

LSB feature





LSB surprises

N5022 (left) seems linked by an LSB filament to N5018 (center)

Conclusions

LSB feature

1. Observed 24 edge-on disks searching for LSB signs of minor mergers and interactions

2. Detected six genuine cases (25%); four already shown here. The other two are NGC 5777 and NGC 5907

3. Working to extend to full sample of ~170 objects


That's all Folks