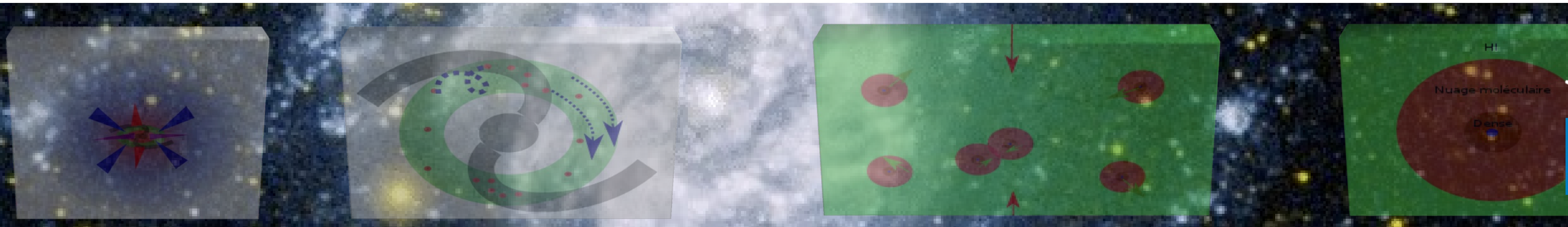
Physics of galaxies: some basis

I: Galactic (Chemical) Evolution; introduction, examples, abundance measurements, definitions, IMF, SFR, returned fraction.

II: Star Formation Laws; threshold, resolution effects, star formation laws, state of the art of observations, gas measurements.

III: Outskirts of galaxies: truncations, anti-truncations, XUV disks, HI, CGM, shells, ...

Samuel Boissier,
Laboratoire d'Astrophysique de Marseille
Galaxies, Etoiles et Cosmologie group



OUTSKIRTS OF GALAXIES

DAGAL

Formation and Evolution of Galaxy Outskirts

IAUS321. Toledo, Spain 14-18 March 2016

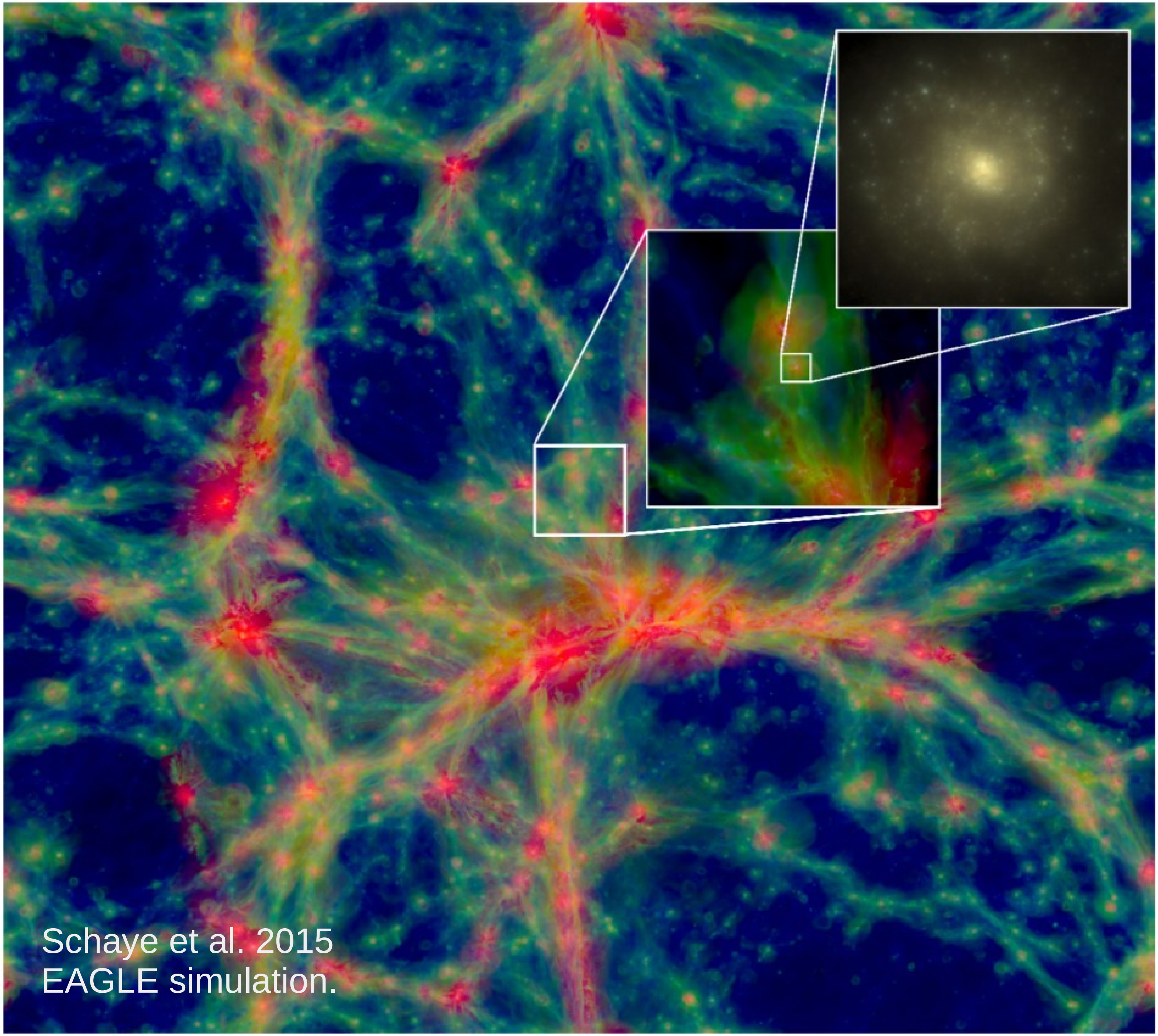
GOBIERNO DE ESPAÑA
MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD

Borrowing from the « outskirts of galaxies » 2016 symposium in Toledo

Special thanks to
Annette Ferguson,
Bob Abraham,
Pierre-Alain Duc

OUTSKIRTS OF GALAXIES

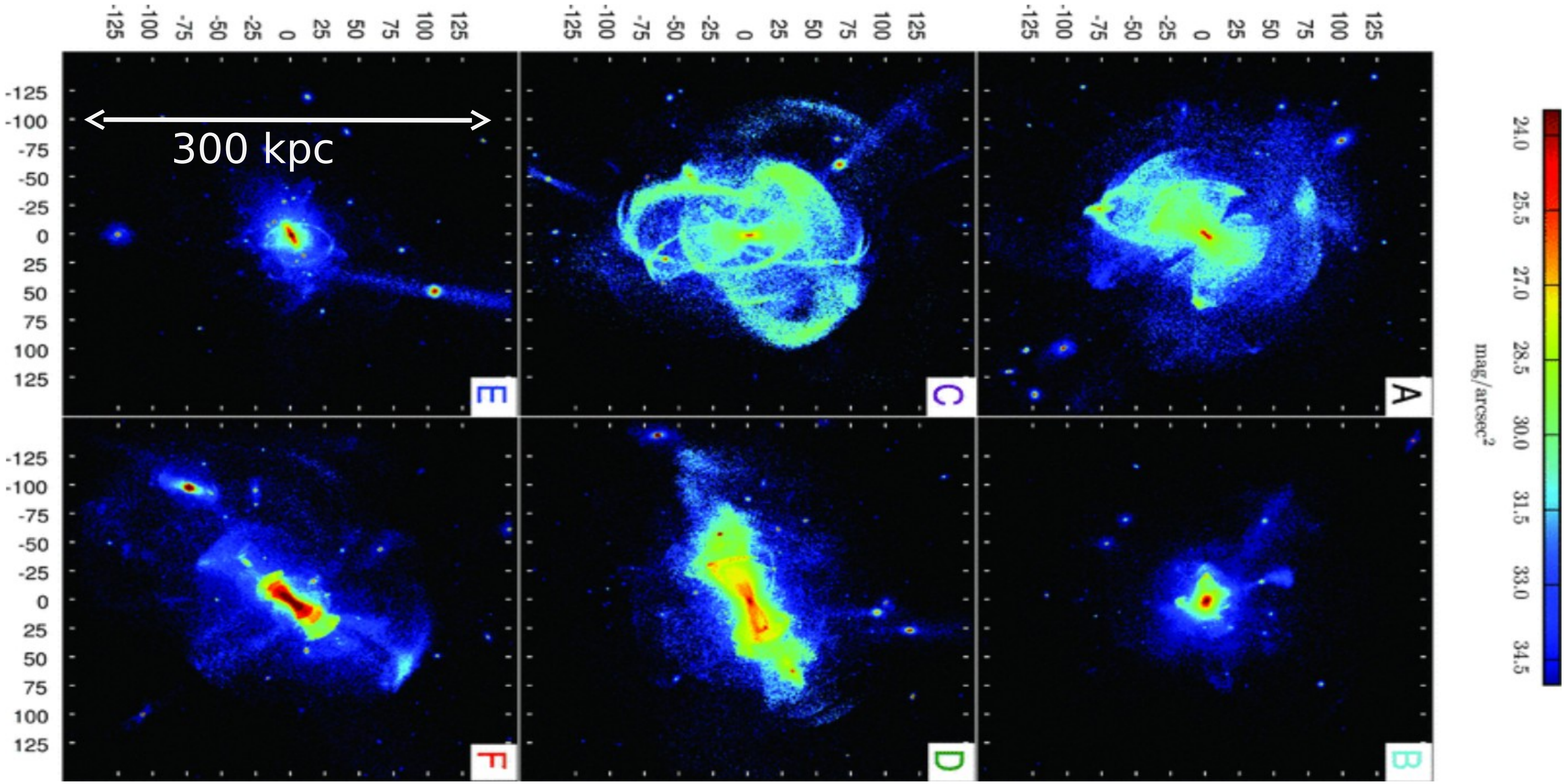
a) What outskirts tell us about galaxy evolution



Schaye et al. 2015
EAGLE simulation.

Figure 1. A $100 \times 100 \times 20$ cMpc slice through the Ref-L100N1504 simulation at $z = 0$. The intensity shows the gas density while the colour encodes the gas temperature using different colour channels for gas with $T < 10^{4.5}$ K (blue), $10^{4.5}$ K $< T < 10^{5.5}$ K (green), and $T > 10^{5.5}$ K (red). The insets show regions of 10 cMpc and 60 ckpc on a side and zoom into an individual galaxy with a stellar mass of $3 \times 10^{10}\,\mathrm{M}_{\odot}$. The 60 ckpc image shows the stellar light based on monochromatic *u*-, *g*- and *r*-band SDSS filter means and accounting for dust extinction. It was created using the radiative transfer code SKIRT (Baes et al. 2011).

Cooper et al. 2010,
Aquarius simulations



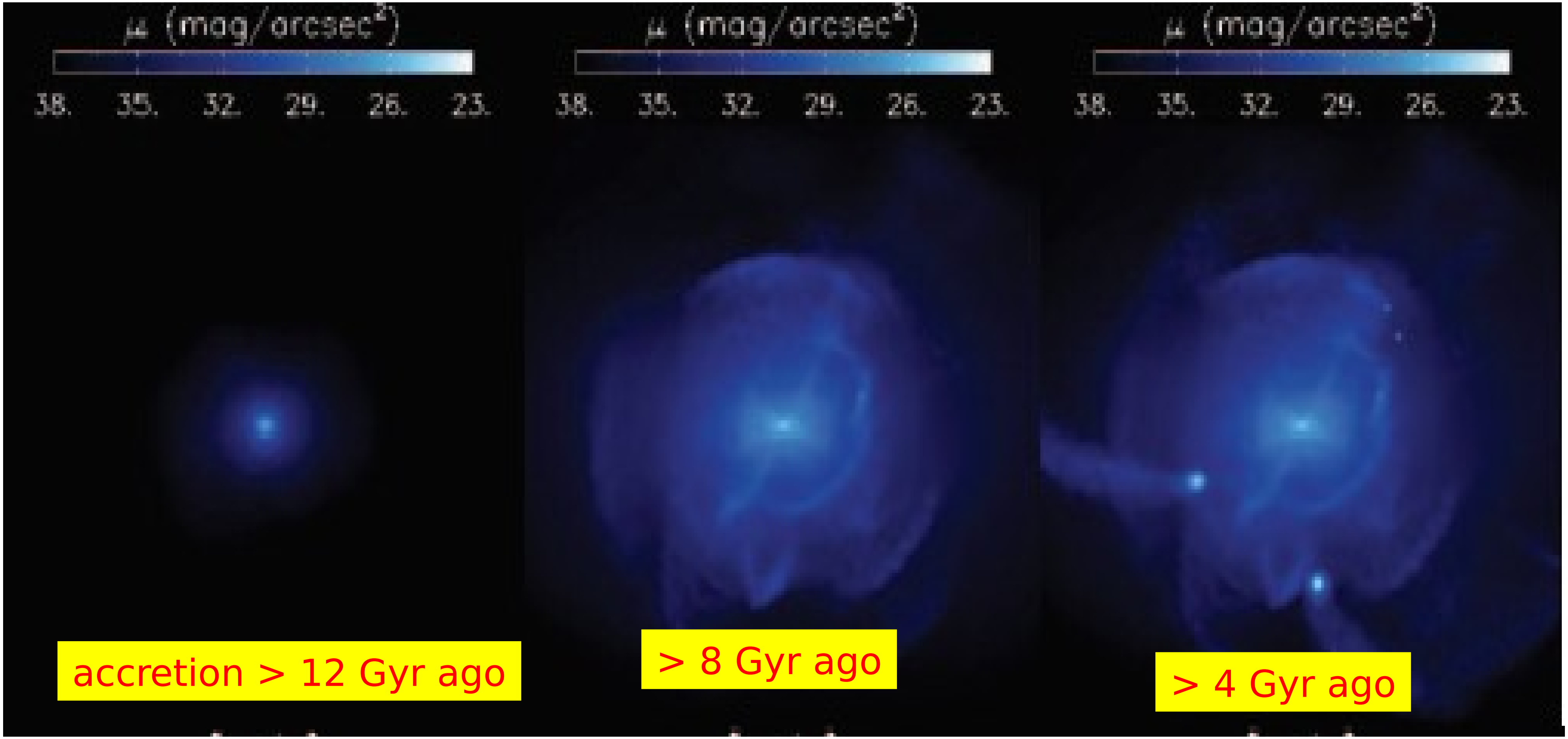
1% sky

0.1% sky

0.01% sky

Expect lots of faint substructure in galaxy outskirts, the amount and morphology of which reflect precise details of the host galaxy's accretion history.

Bullock & Johnston 2005,
Johnston et al. 2008

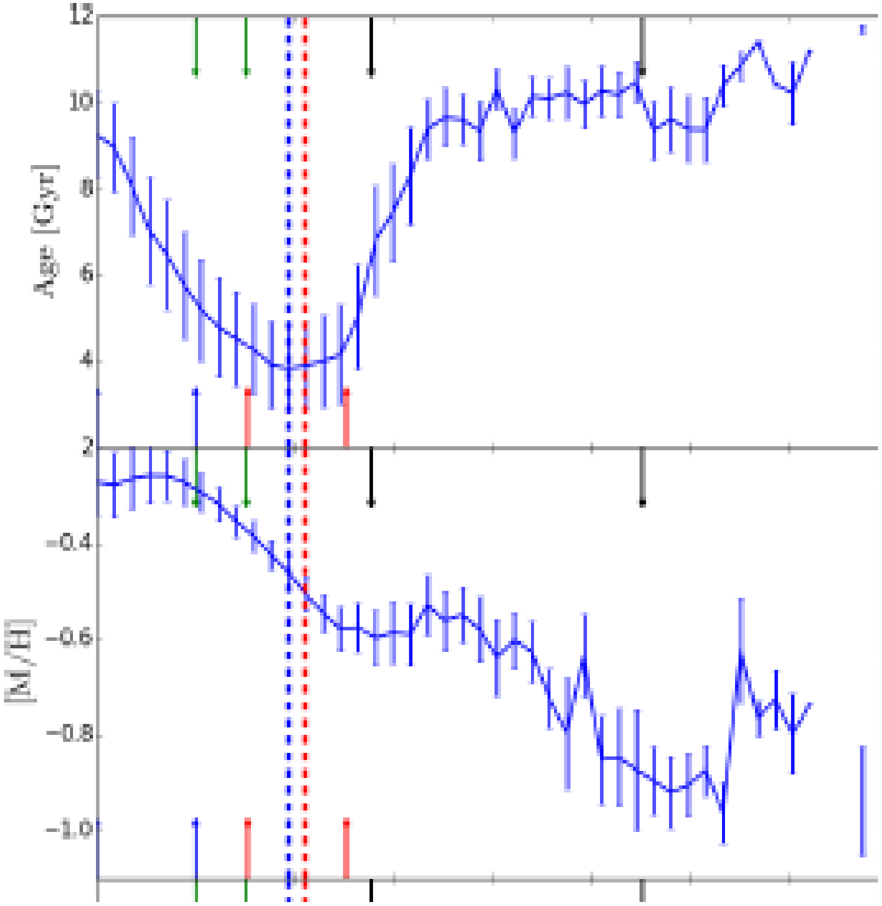


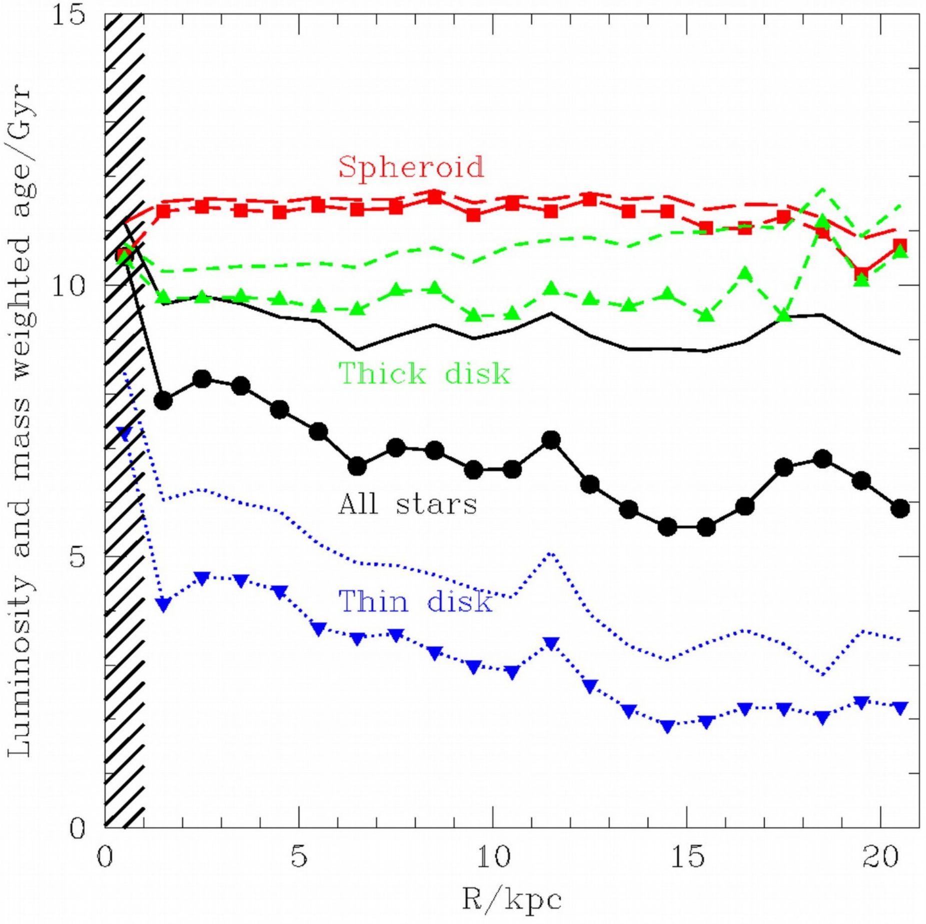
Dynamical timescales long hence little mixing – brightest features come from the most recent events. Observing the amount of substructure in galaxy outskirts can test whether ΛCDM accretion histories are realistic.

Galaxy Outskirts Tell Us About Disc Assembly

But exact predictions depend crucially on the baryonic physics invoked in simulations – direct constraints come from measuring the age and metallicity distributions of stars in discs and how they changes with radius.

Ruiz-Lara et al. 2016





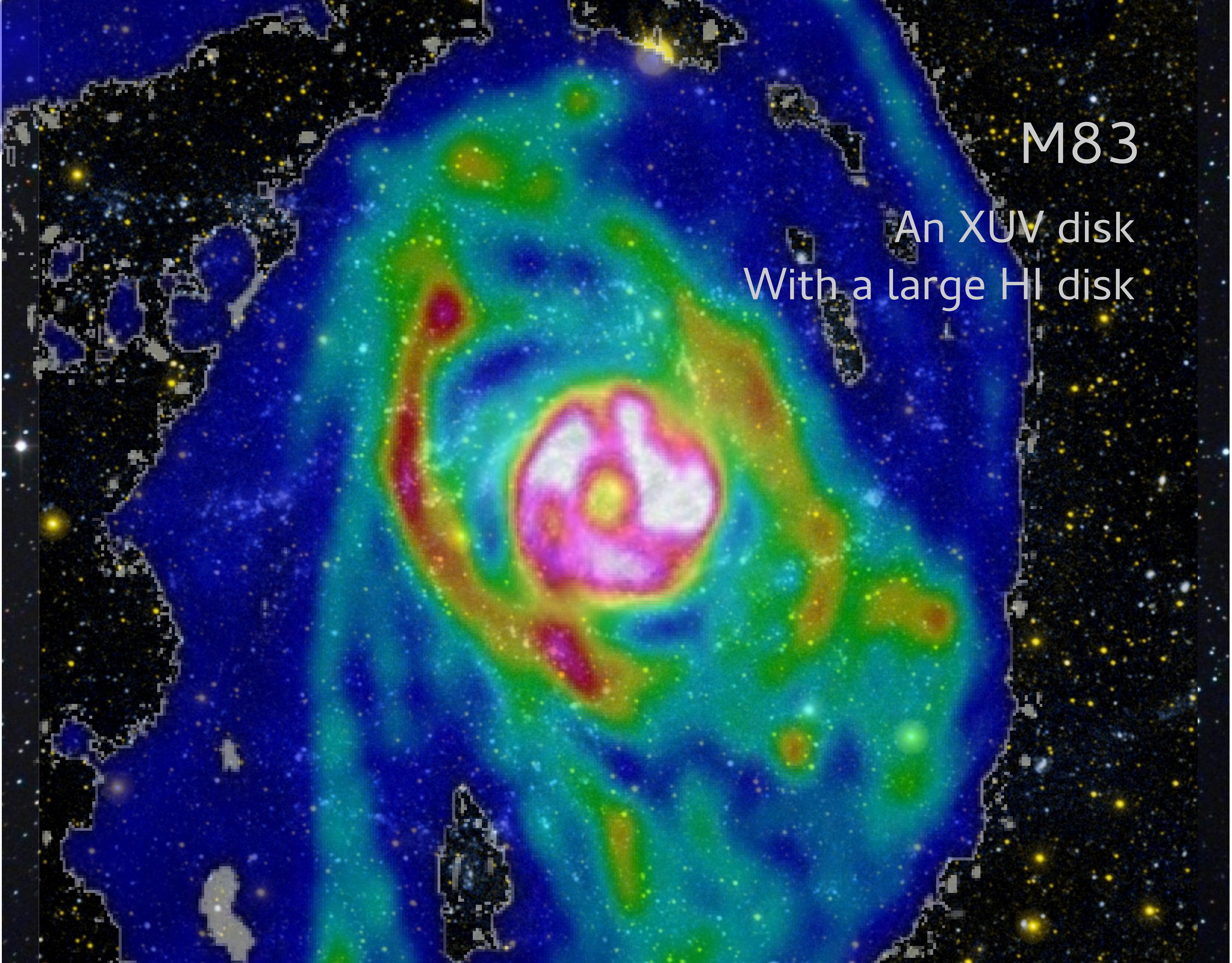
Abadi et al 2003

> formation, accretion, radial flows, interactions...

M83

M83

An XUV disk



M83

An XUV disk

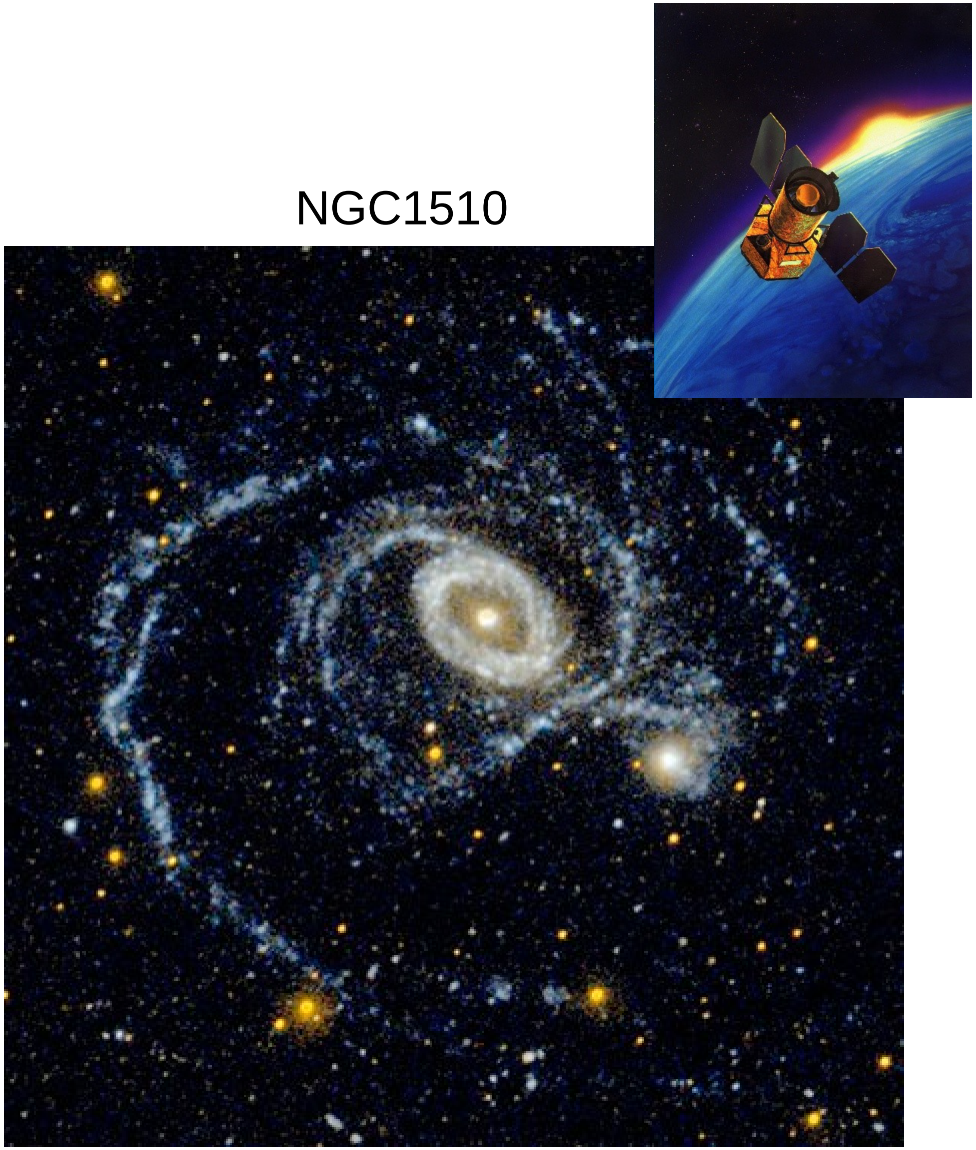
With a large HI disk

eXtended Ultra Violet galaxies

NGC4625

GALEX

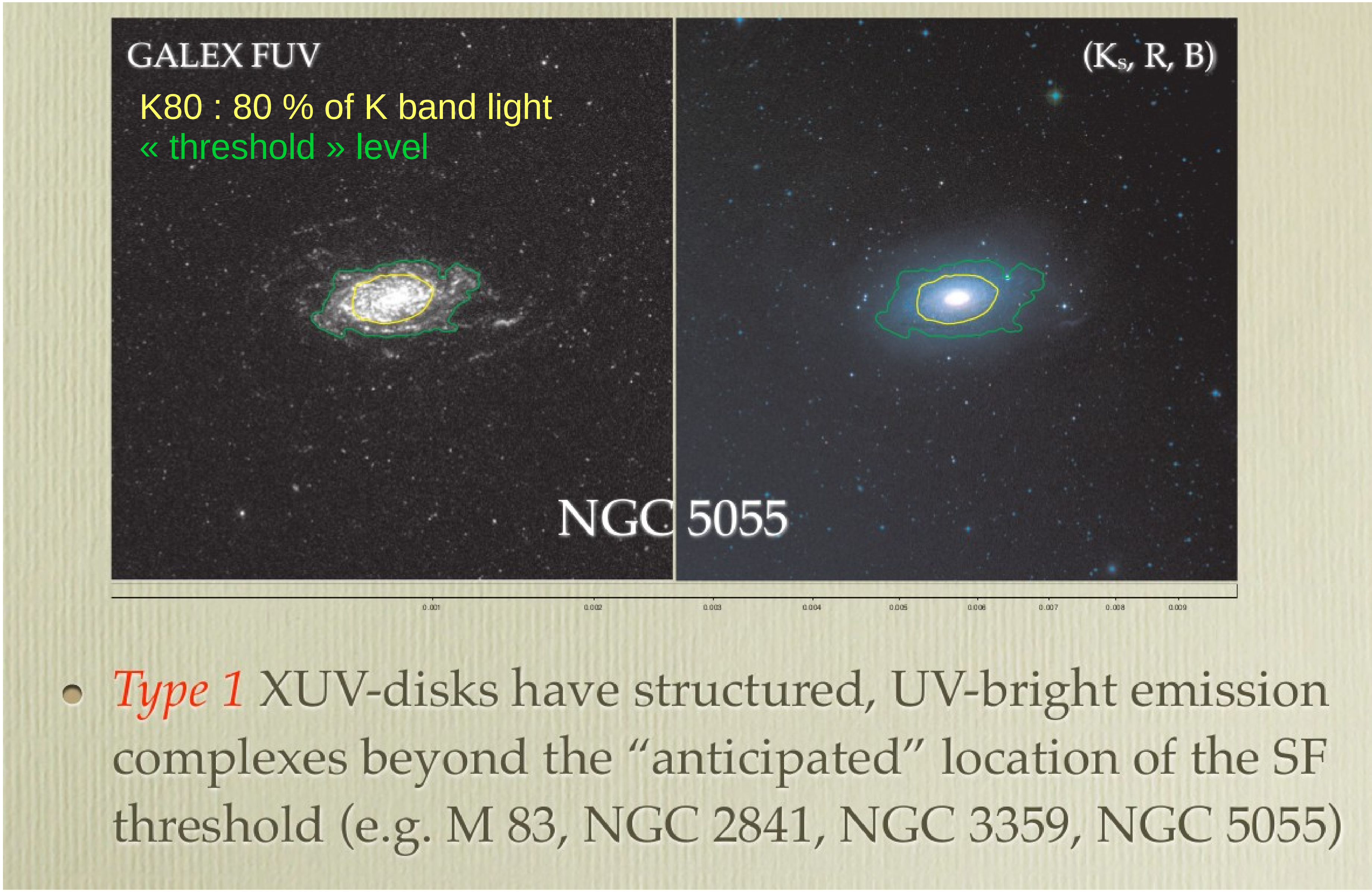
NGC1510



Discovery :

- Gil de Paz et al. 2005 (NGC4625),
- Thilker et al. 2005 (M83)

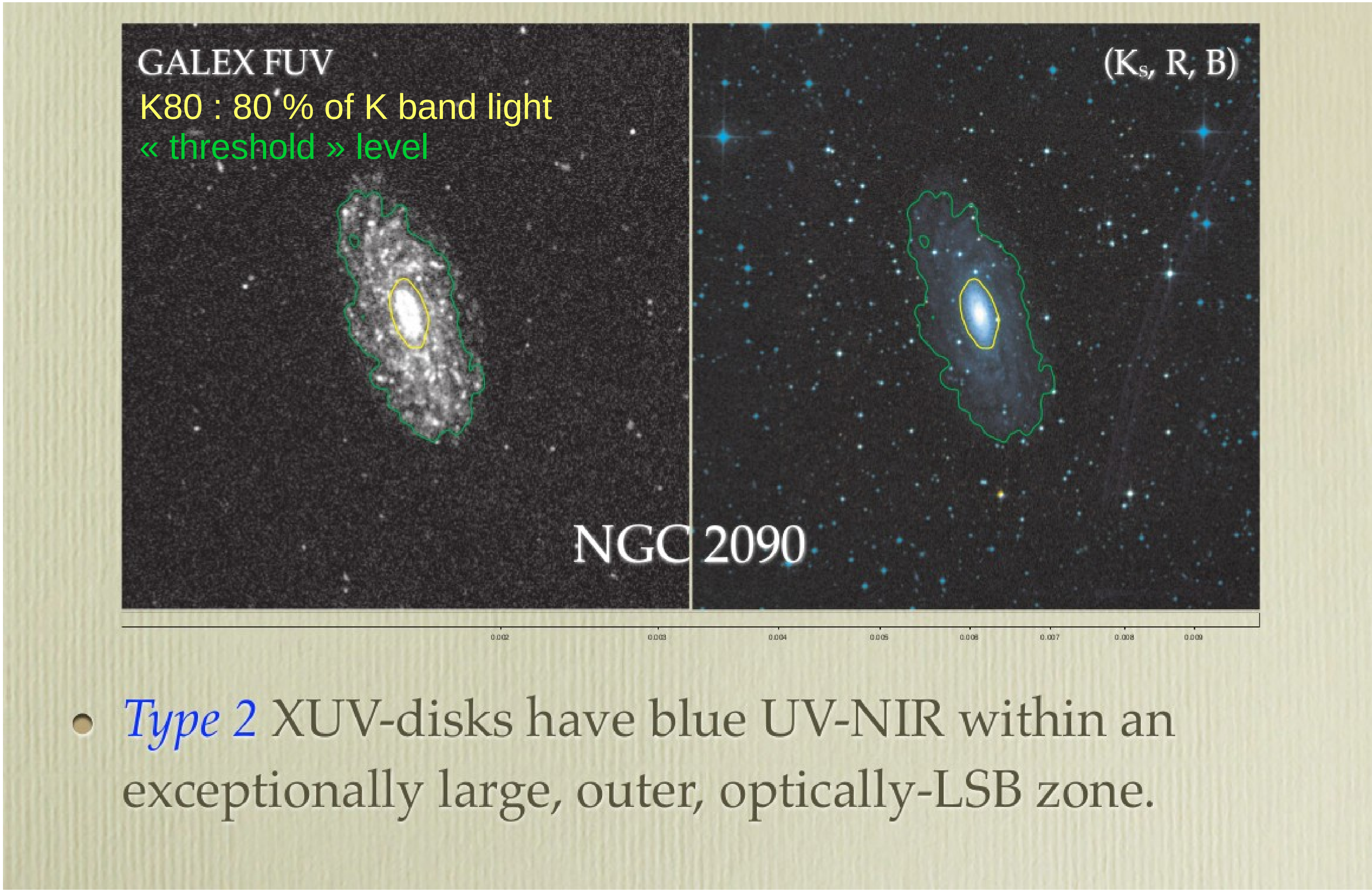
eXtended Ultra Violet galaxies



- *Type 1* XUV-disks have structured, UV-bright emission complexes beyond the “anticipated” location of the SF threshold (e.g. M 83, NGC 2841, NGC 3359, NGC 5055)

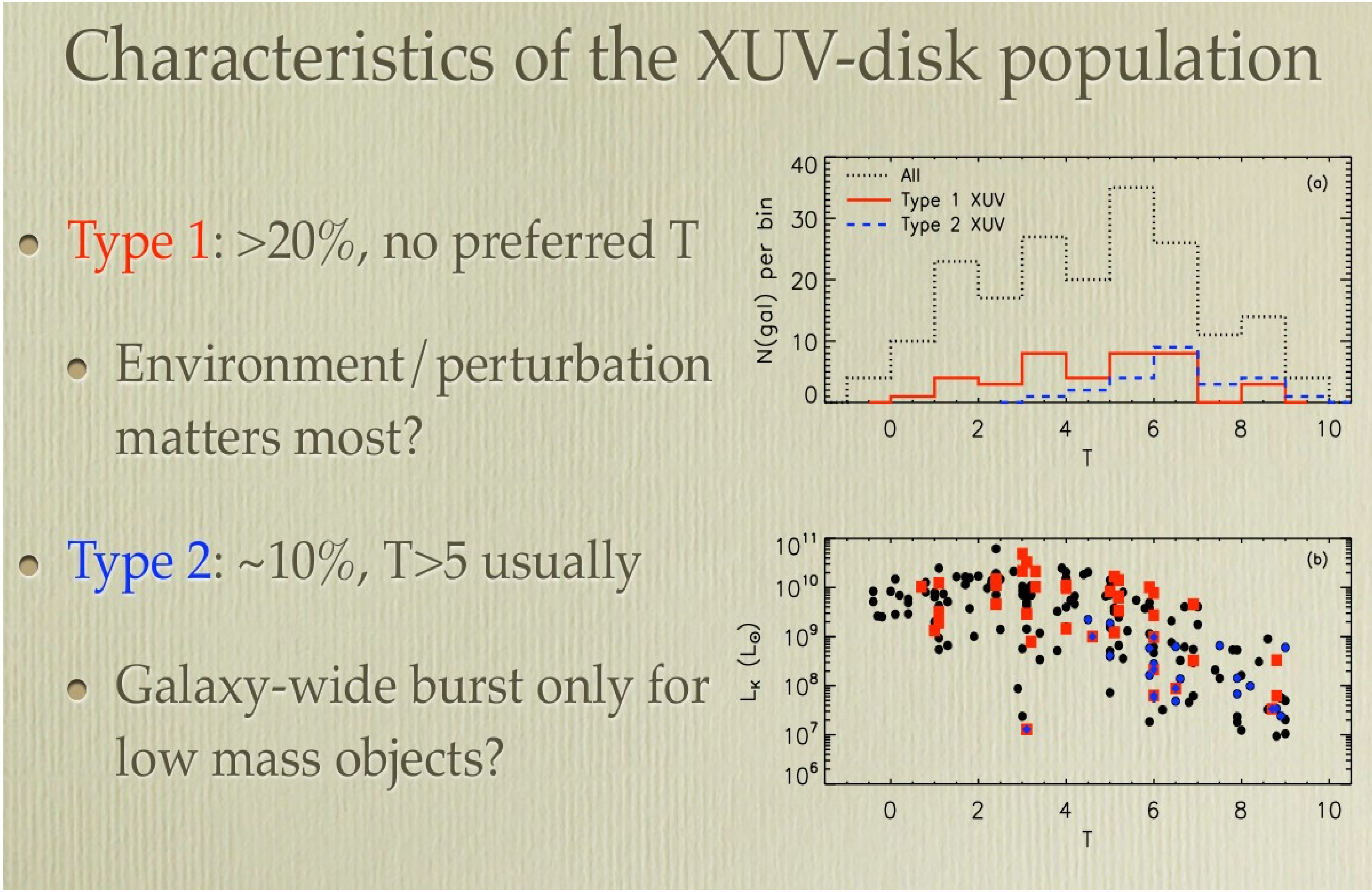
Statistical Study : Thilker et al. 2007

eXtended Ultra Violet galaxies



- *Type 2* XUV-disks have blue UV-NIR within an exceptionally large, outer, optically-LSB zone.

Statistical Study : Thilker et al. 2007

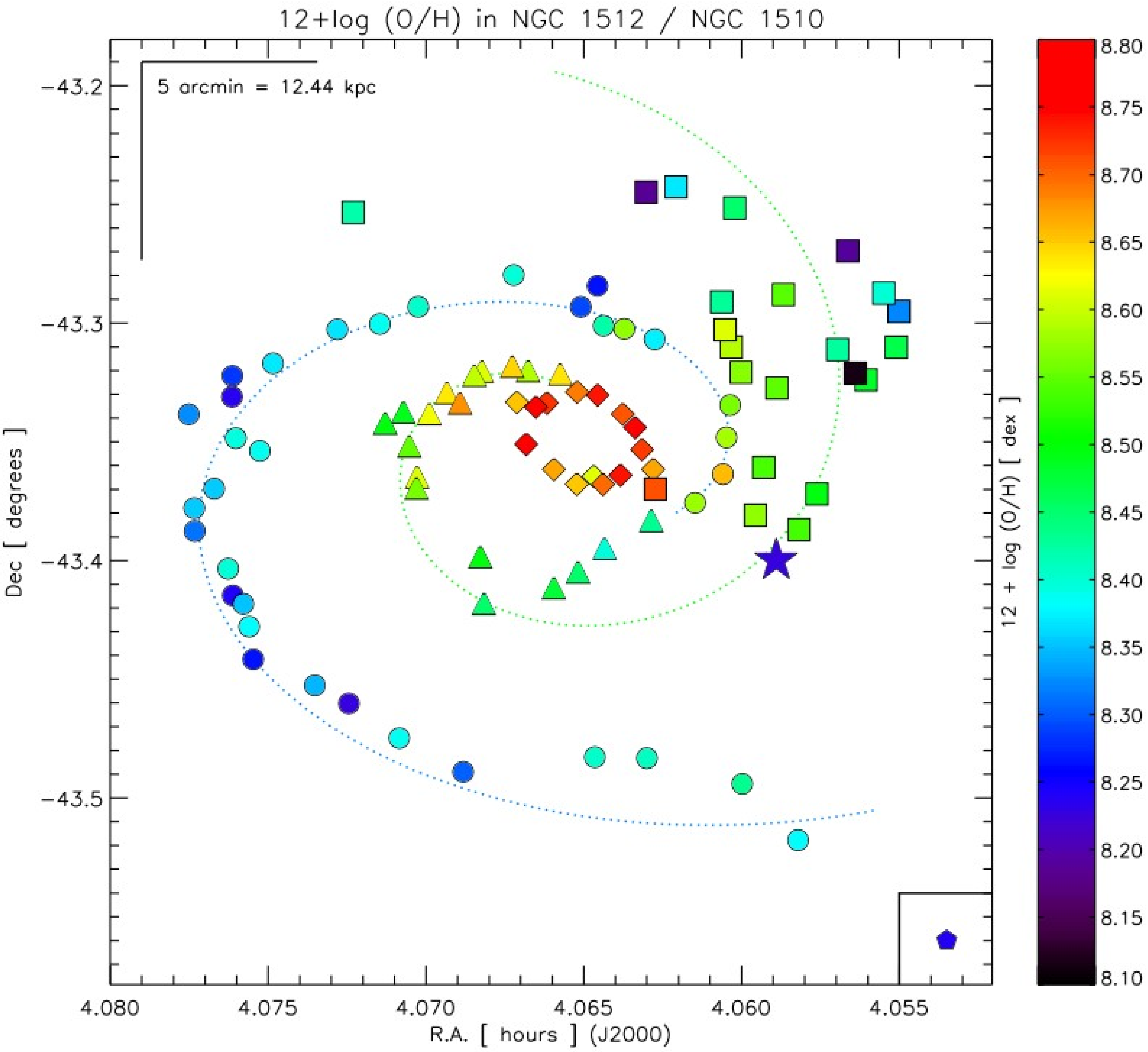


Characteristics of the XUV-disk population

- Type 1: >20%, no preferred T
  - Environment/perturbation matters most?
- Type 2: ~10%, T>5 usually
  - Galaxy-wide burst only for low mass objects?

Statistical Study : Thilker et al. 2007

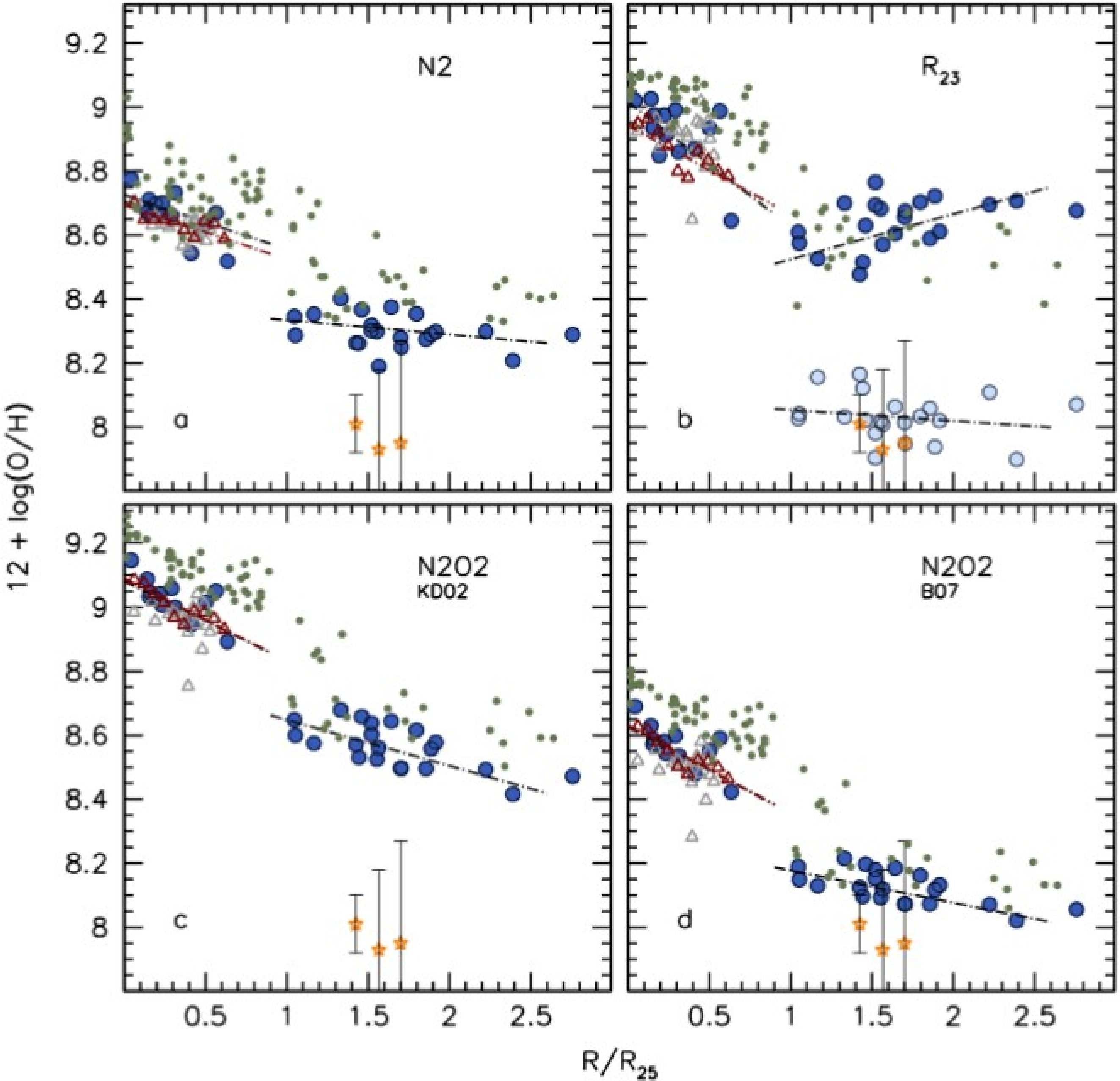
Abundance gradient in NGC1512



Accretion and desctruction of gas rich dwarfs ?

Lopez-sanchez et al. (2015)

Abundance gradient in NGC4625

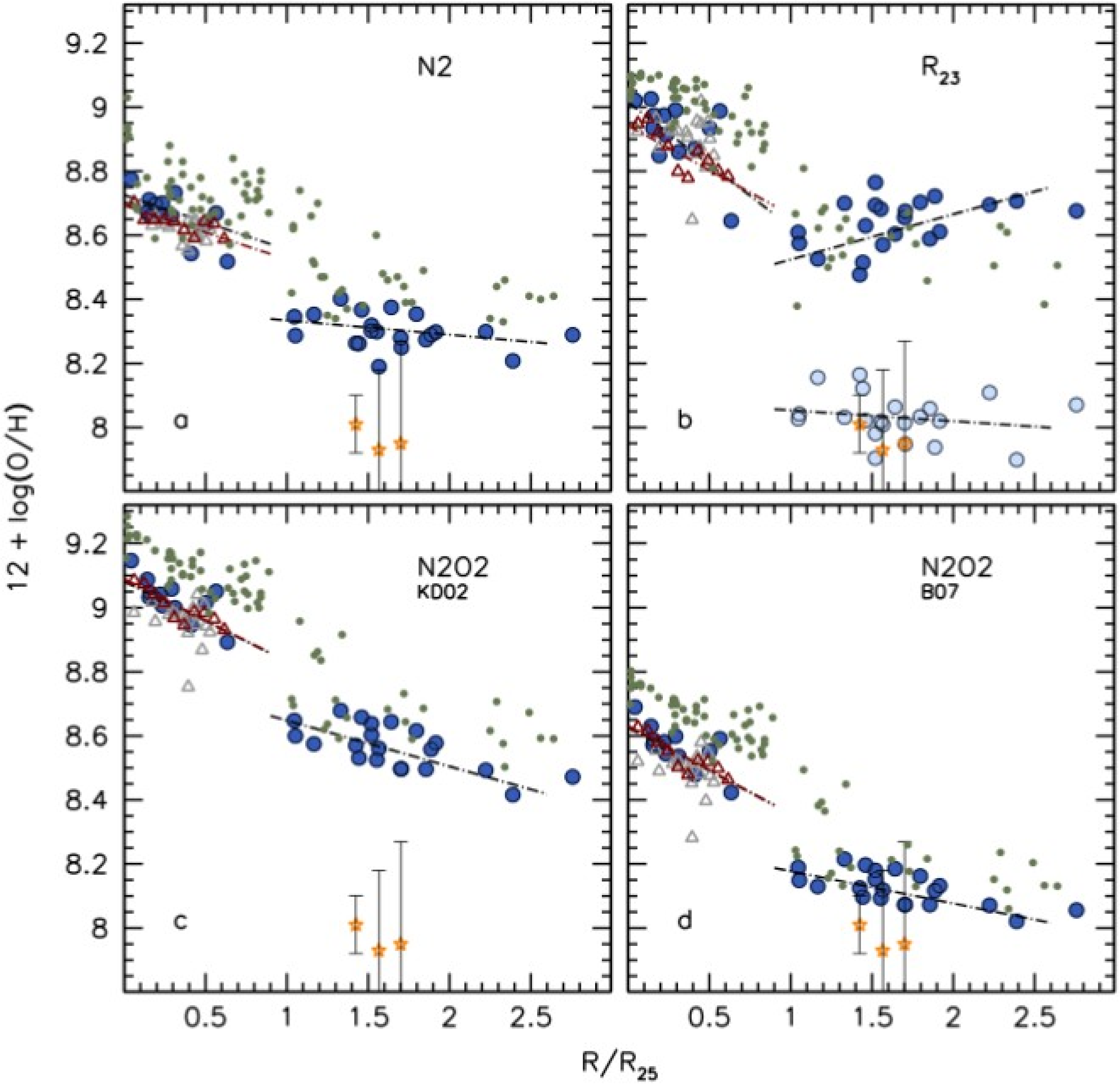


Goddard et al. (2010)

These outer regions have lower metallicity than inner regions, they provide a « primordial » environment in which we can study star formation, and galactic physics at low metallicity.

See also
Patterson et al. (2012) for M81
Gil de Paz et al. (2007) for M83, NGC4625

Abundance gradient in NGC4625



Goddard et al. (2010)

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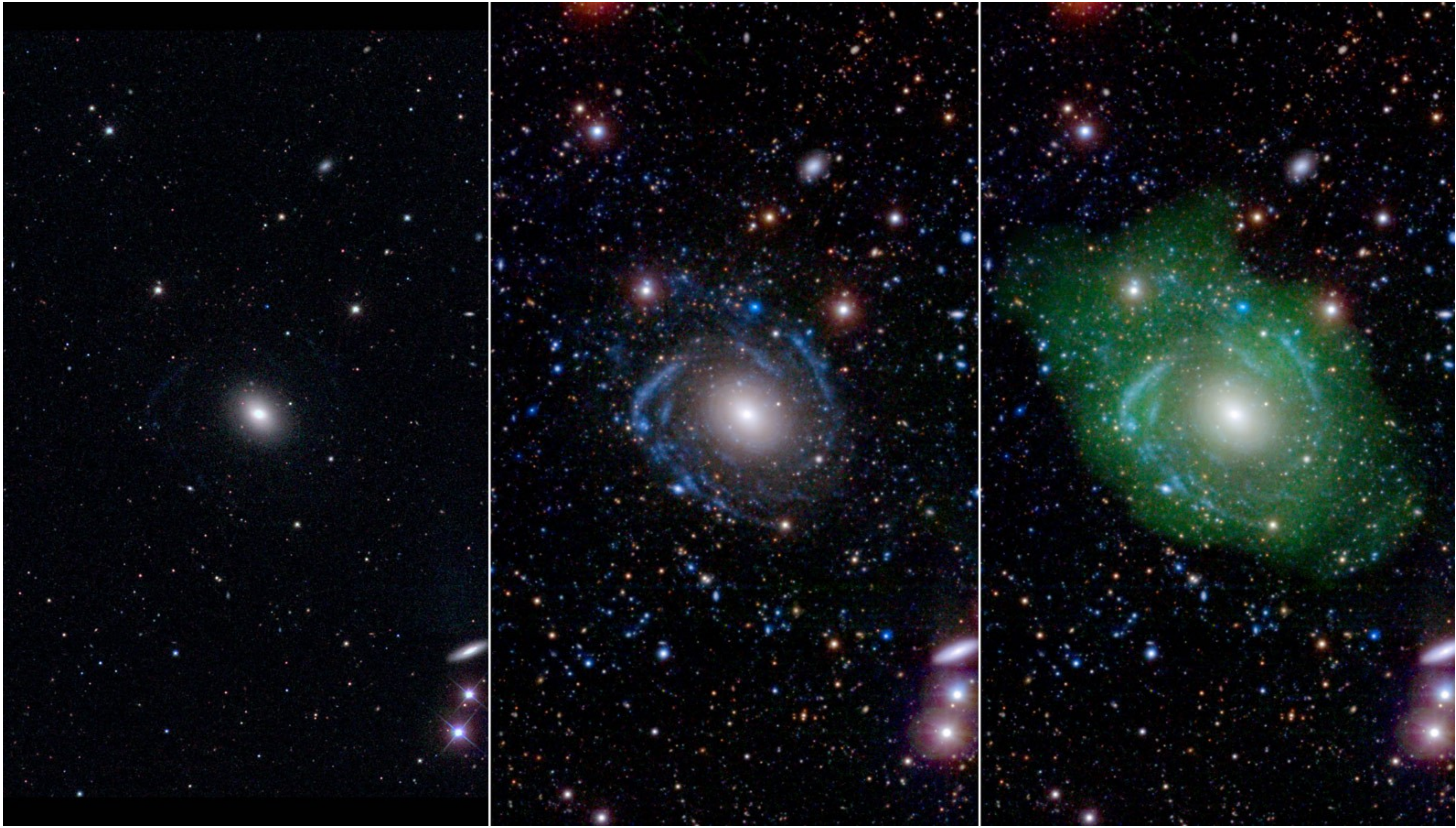
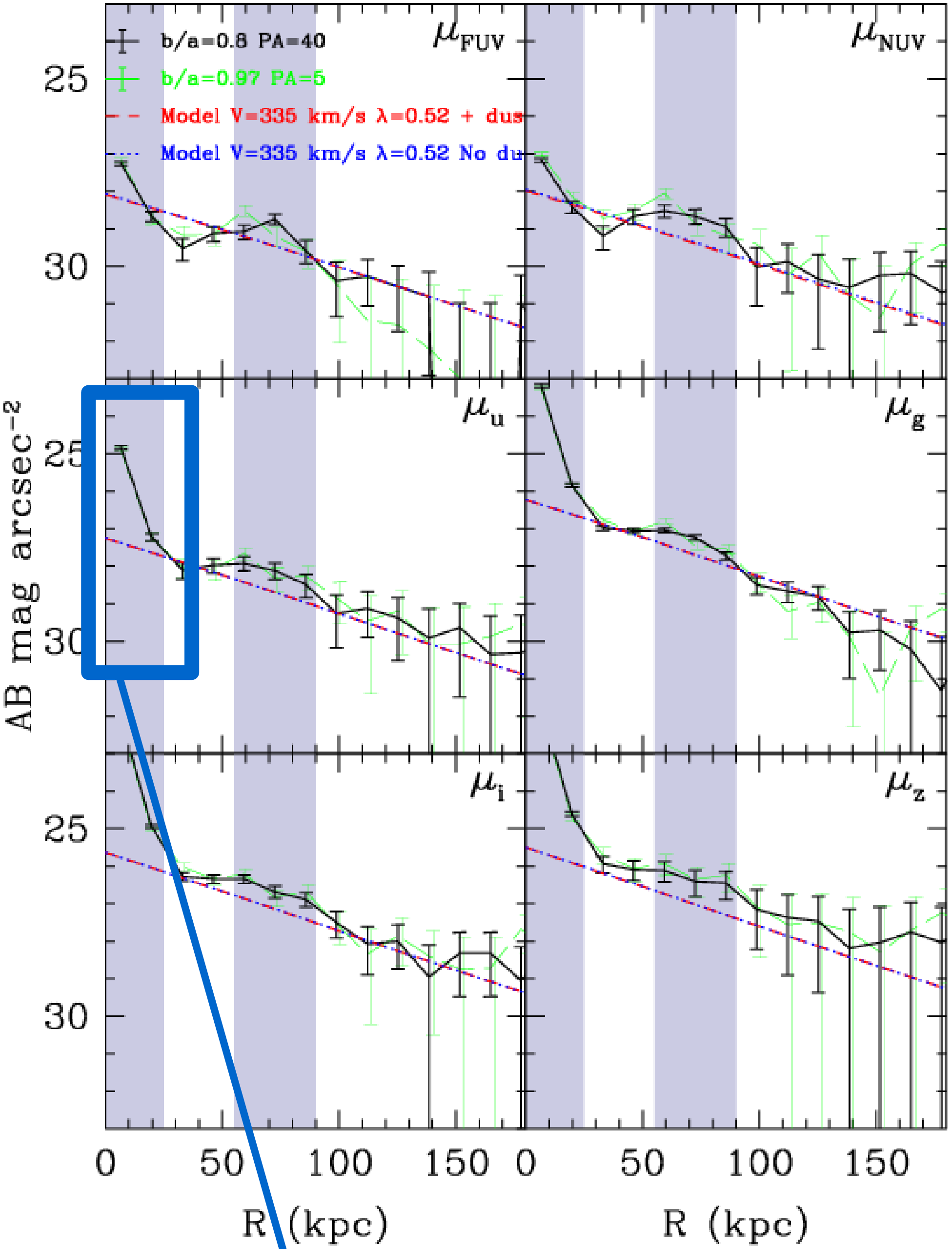
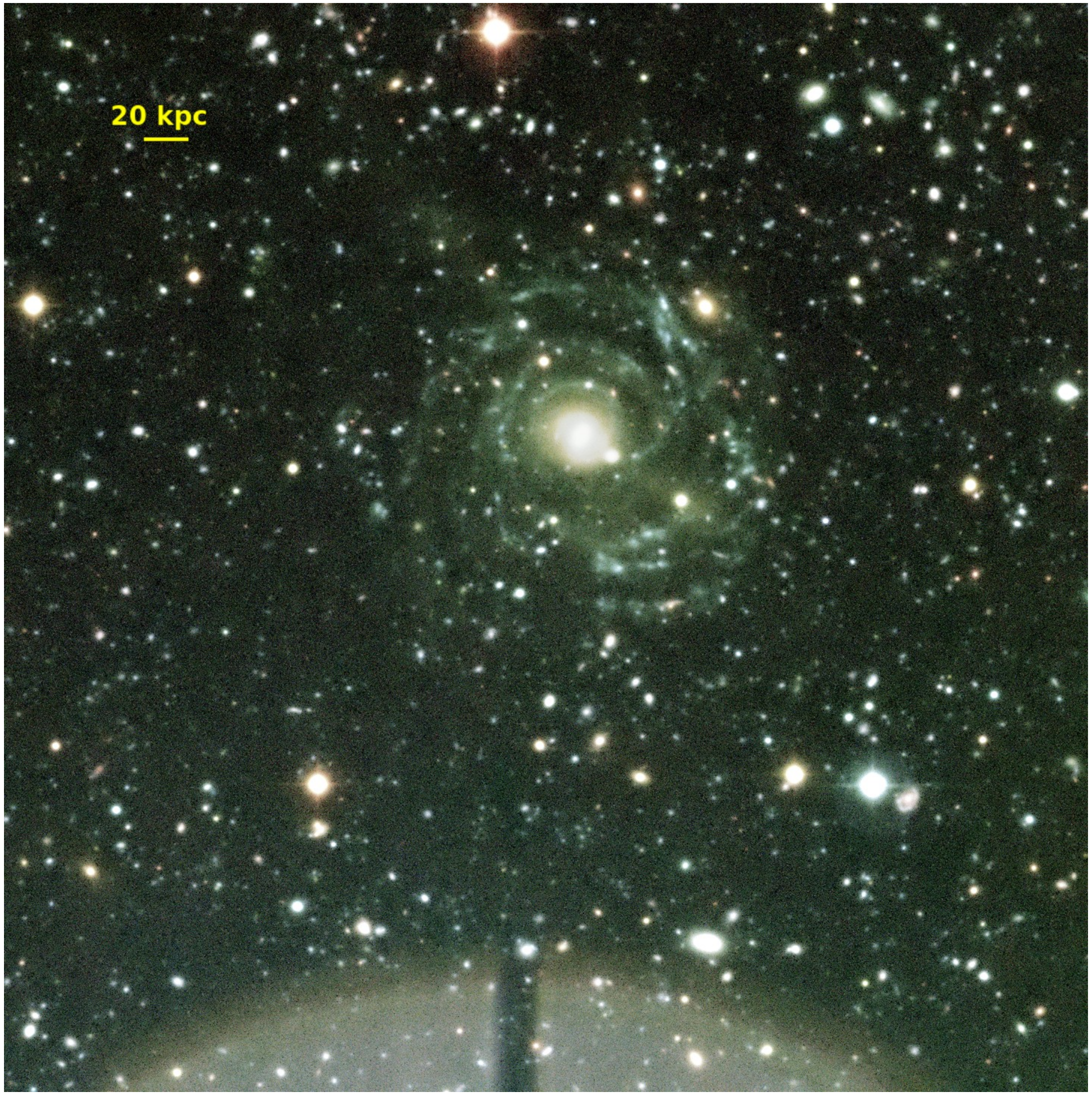
UGC 1382
Hagen et al. 2016





Malin 1

Boissier et al., 2016, submitted
Galaz et al. 2015

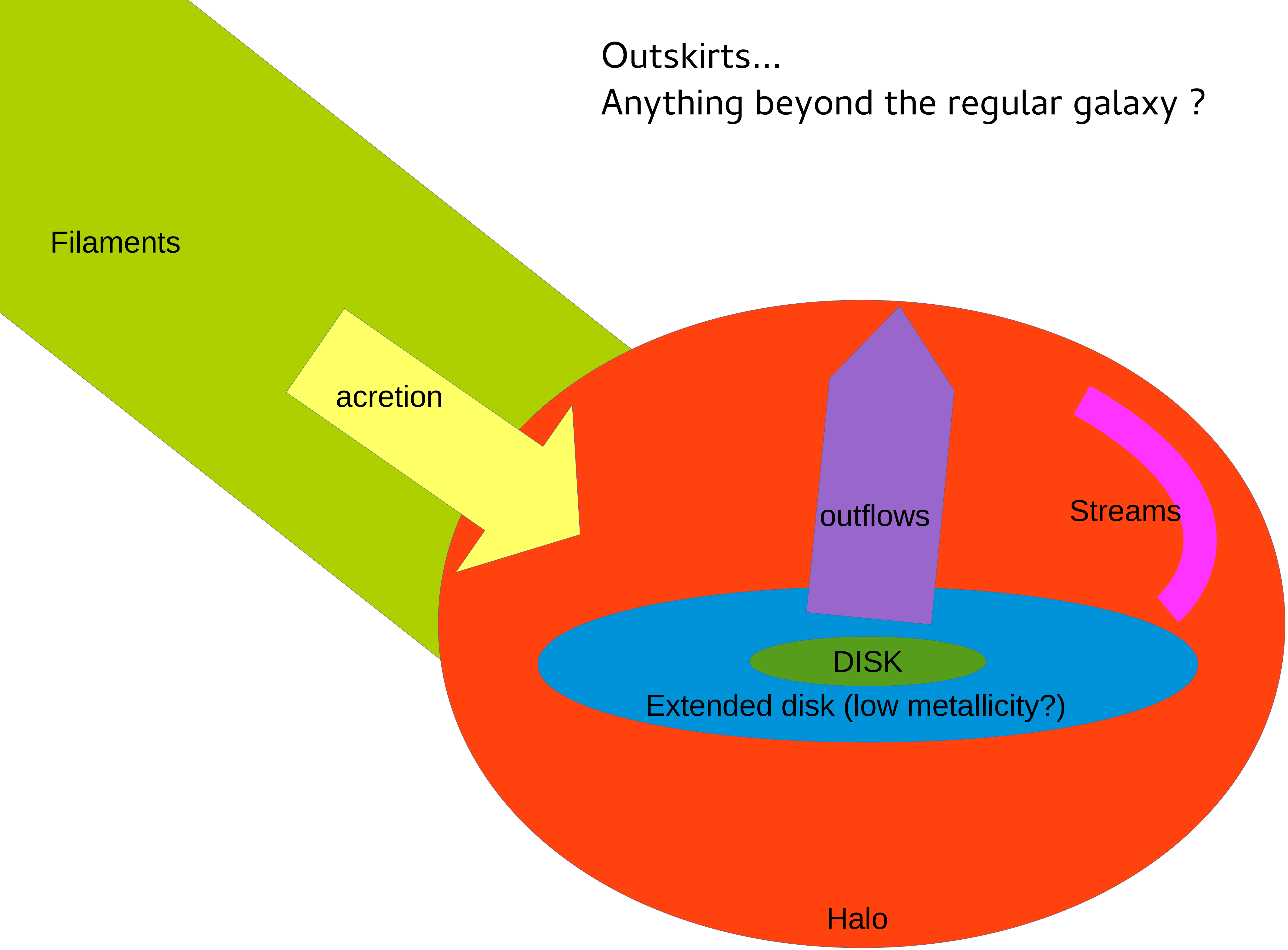


Barth et al. 2007 :
The central part = bar+bulge+disk

Low Surface Brightness disks,
XUV galaxies :
« outskirts » of regular disks ?

Outskirts...

Anything beyond the regular galaxy ?



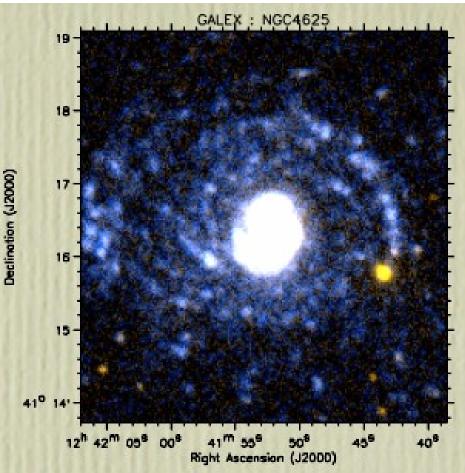
OUTSKIRTS OF GALAXIES

a) What outskirts tell us about galaxy evolution

b) How to observe outskirts of galaxies

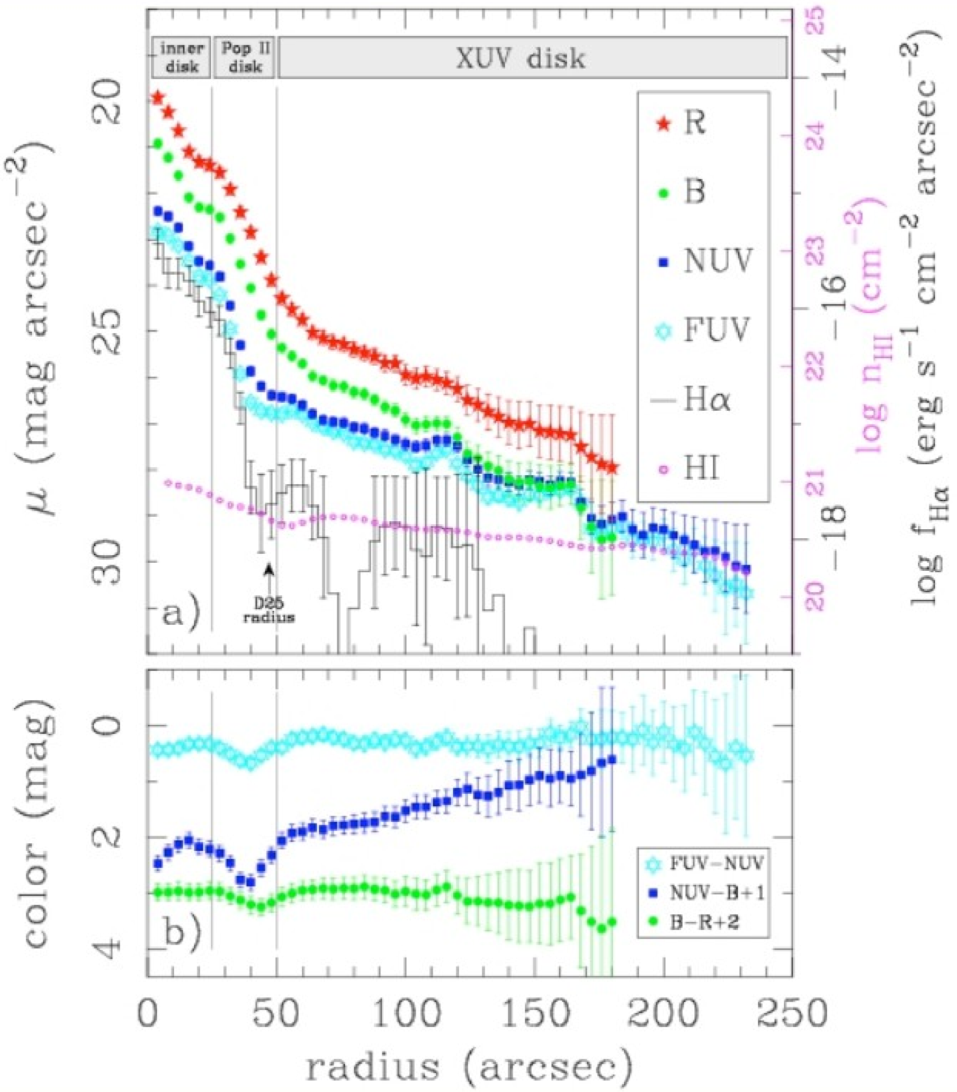
- deep photometry
- resolved stars
- absorption systems

eXtended Ultra Violet galaxies



Color profiles in NGC 4625

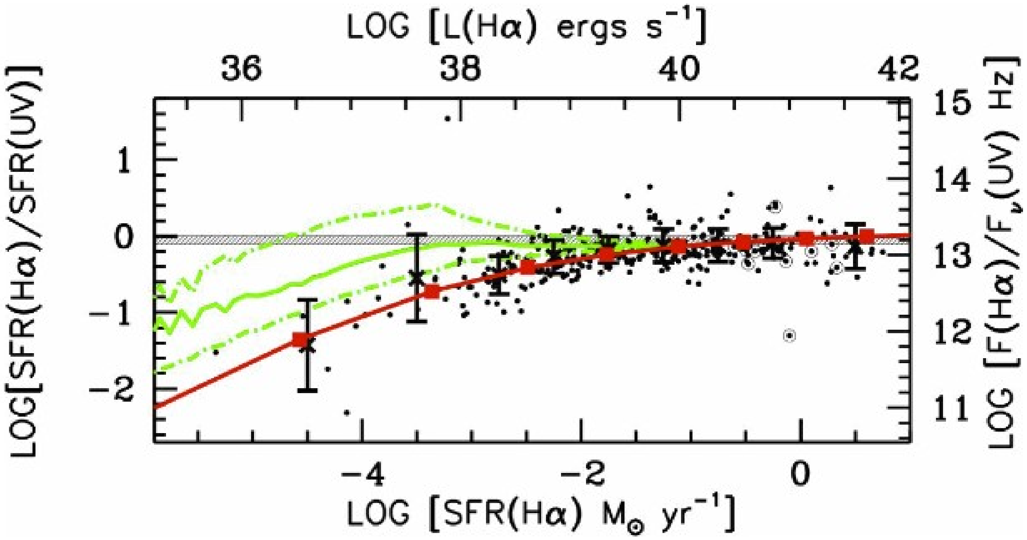
- (NUV-B) gets progressively bluer in XUV-disk outside D_{25}
- SFH changing within XUV disk



Gil de Paz et al. (2005)

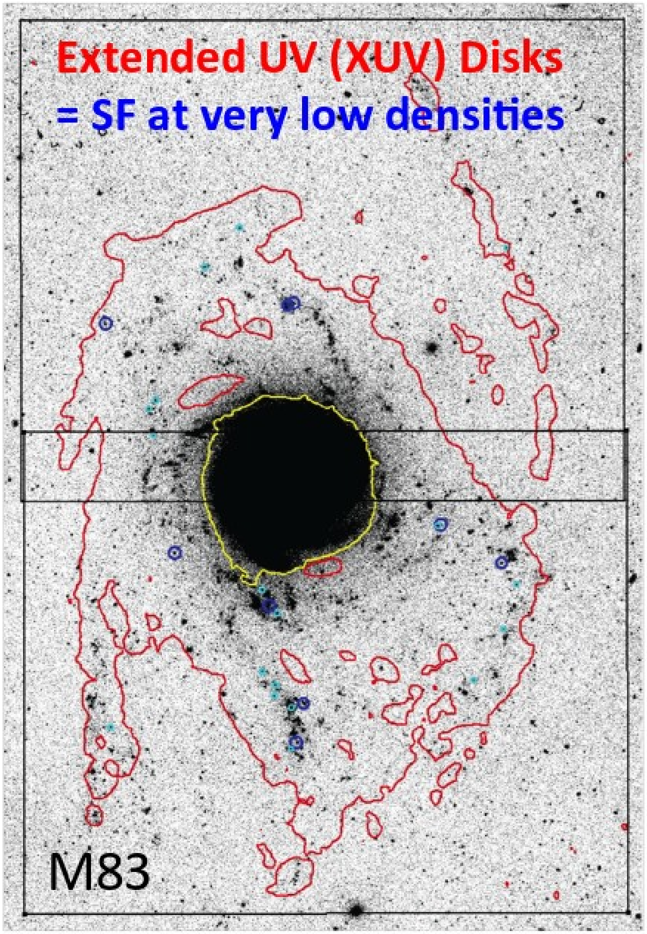
Deep photometry

Suggestion of variable IMF to explain Ha/UV ratios



(Lee et al. 2009, Meurer et al. 2009, Hoversten & Glazebrook 2008)

Koda et al.



Deep Hα (+BVR) Imaging Survey of XUV Disks with Suprime-Cam + u-band imaging with CFHT + GALEX (Koda and collaborators) : analysing stellar clusters of few 1000 Msun to test IMF variations in XUV disks.

First results : universal IMF in XUV disks

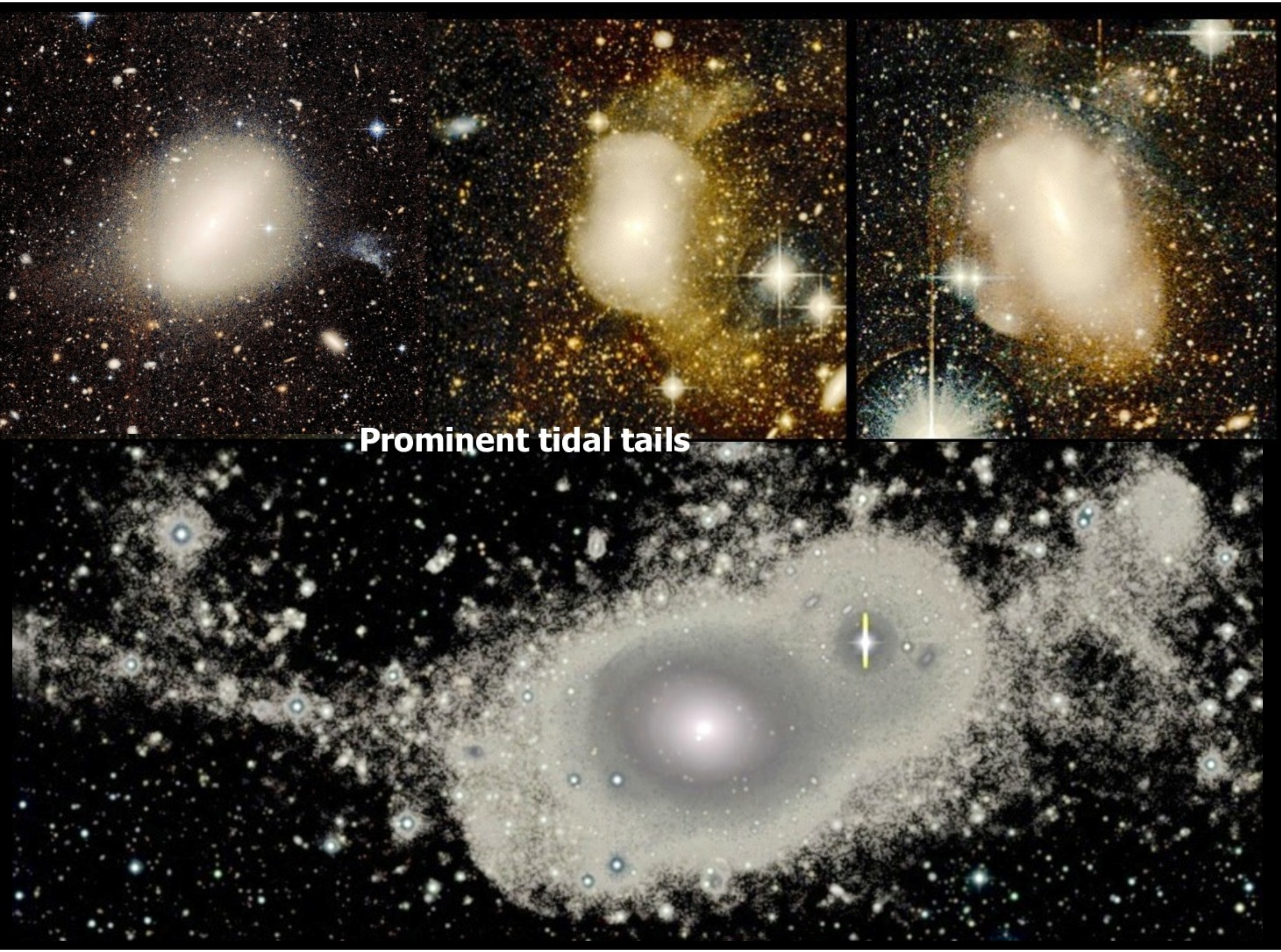
Deep photometry

Slides courtesy of PA Duc

Duc et al., 2015

MEGACAM, images deep fields

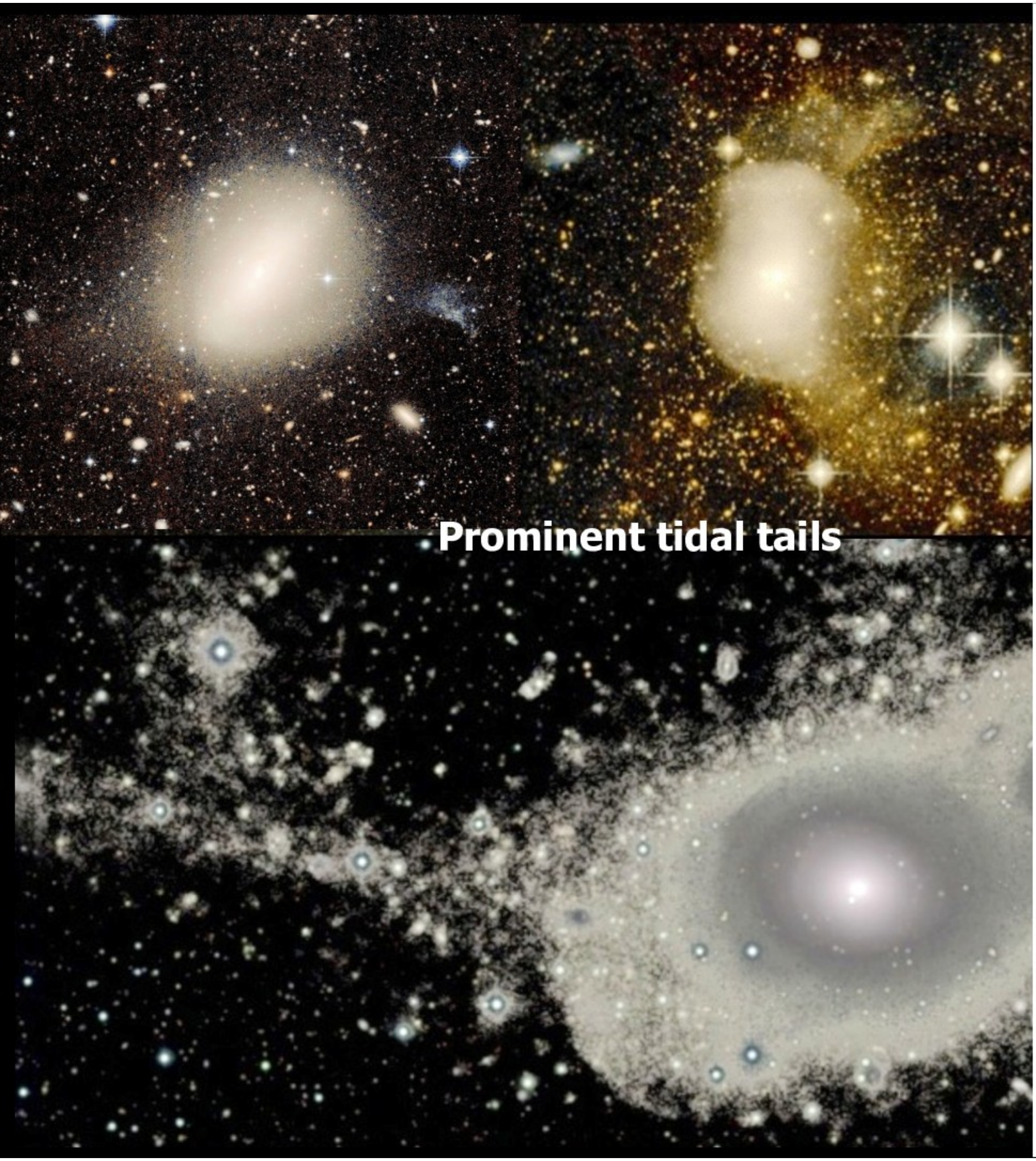
Deep photometry

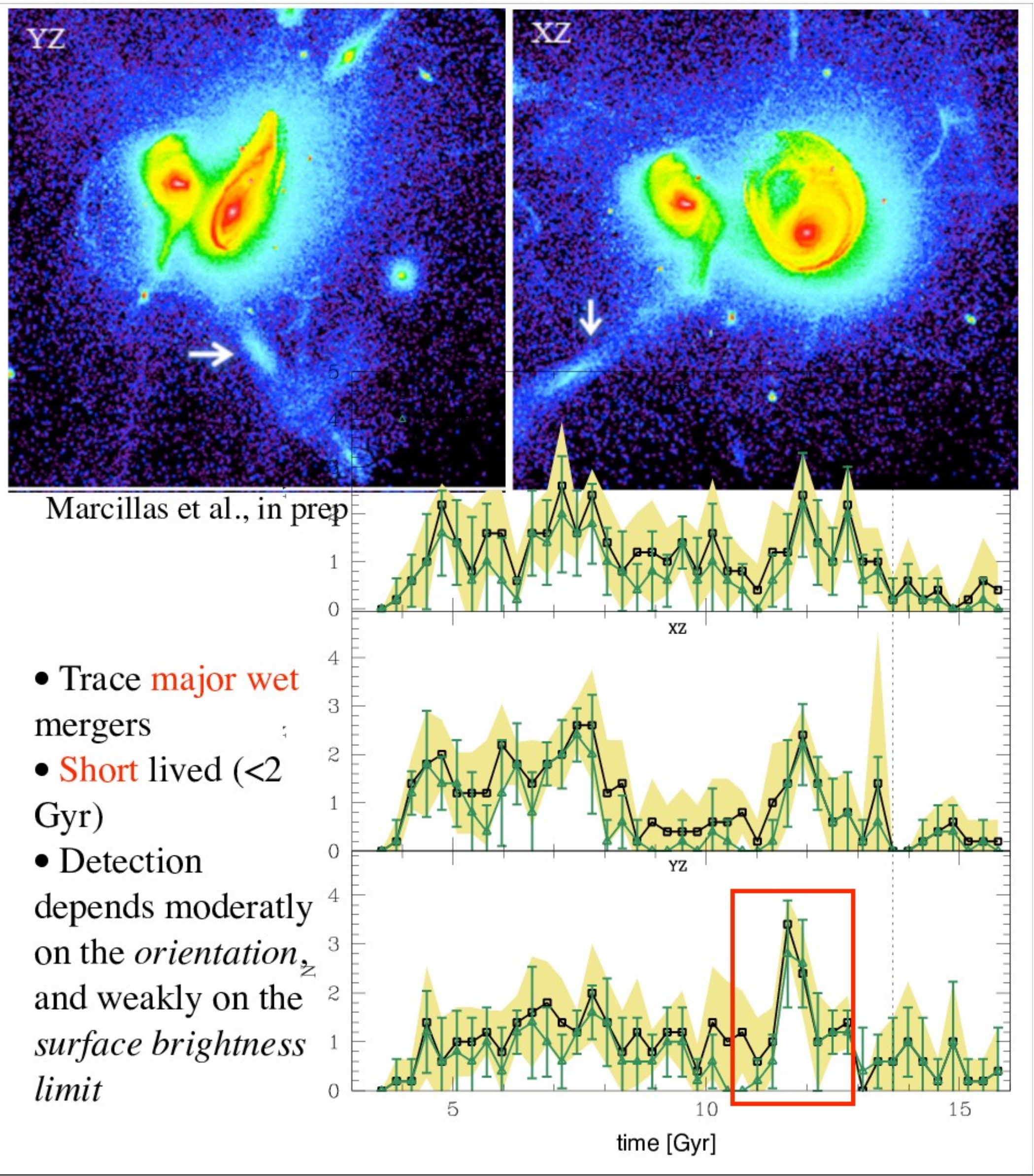


Duc et al., 2015

MEGACAM, images deep fields

Deep photometry





Marcillas et al., in prep

- Trace major wet mergers
- Short lived (<2 Gyr)
- Detection depends moderatly on the *orientation*, and weakly on the *surface brightness limit*

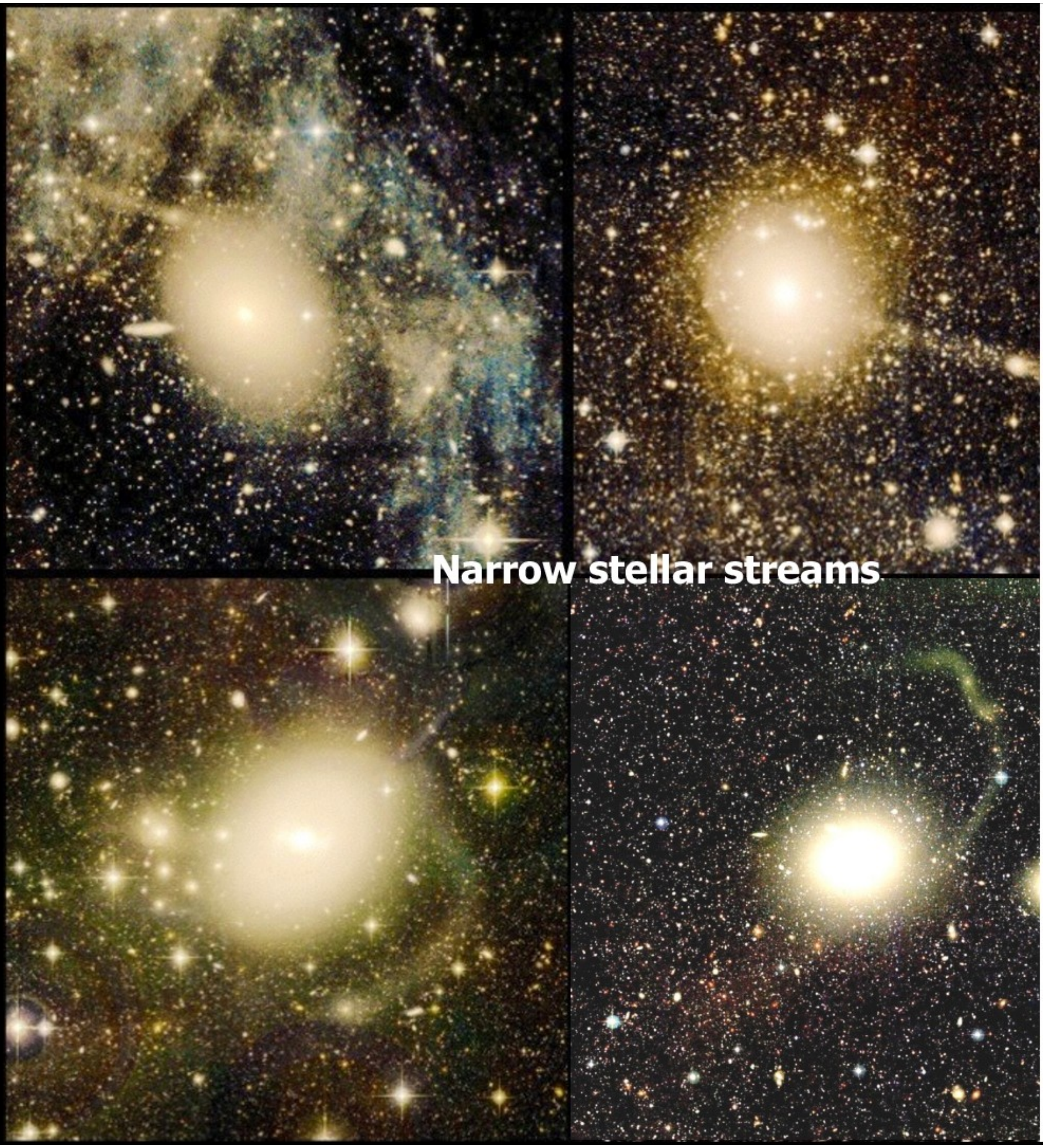
Simulations help to estimate the duration / detectability of such features

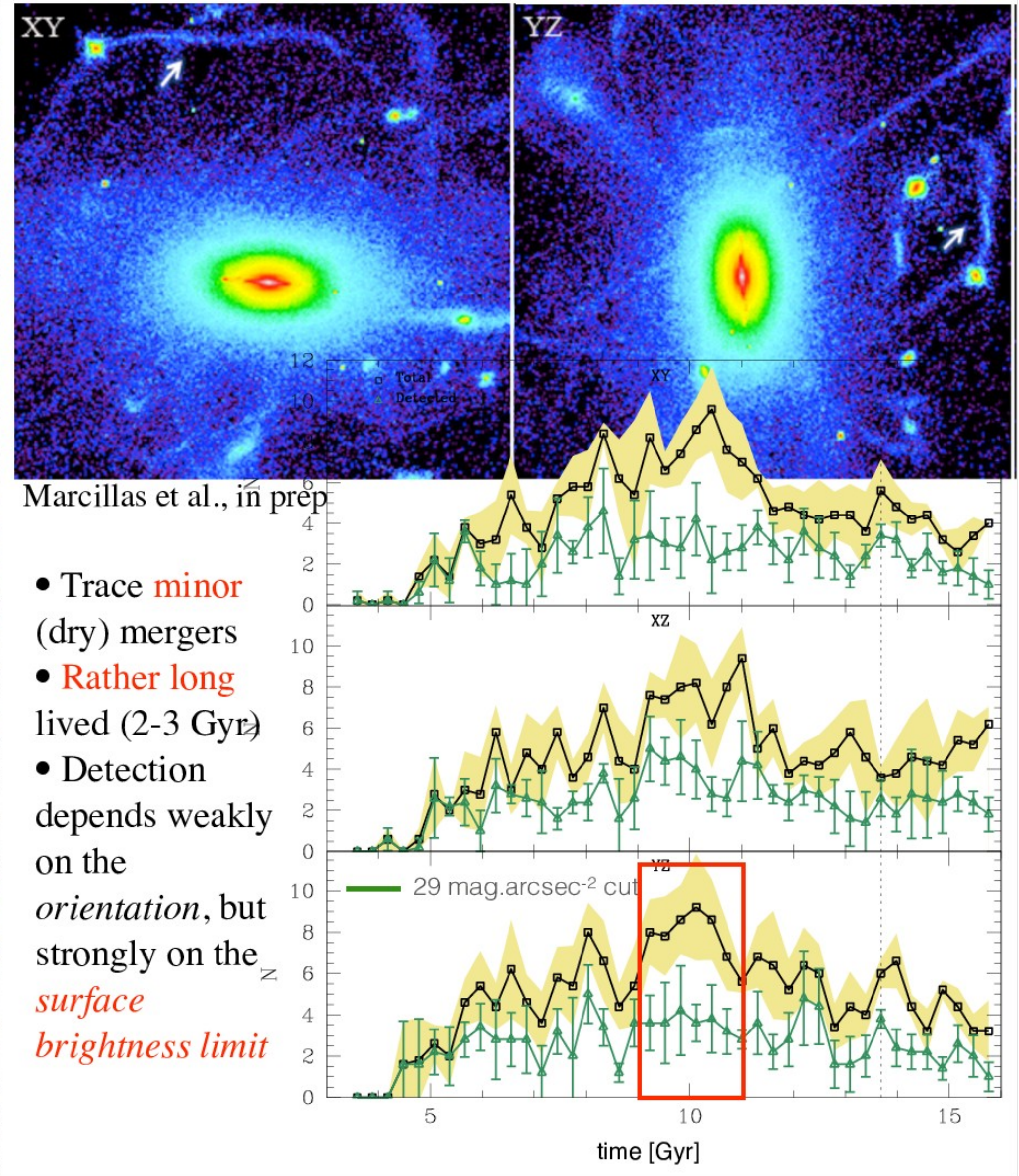
Deep photometry

Narrow stellar streams

Duc et al., 2015

Deep photometry



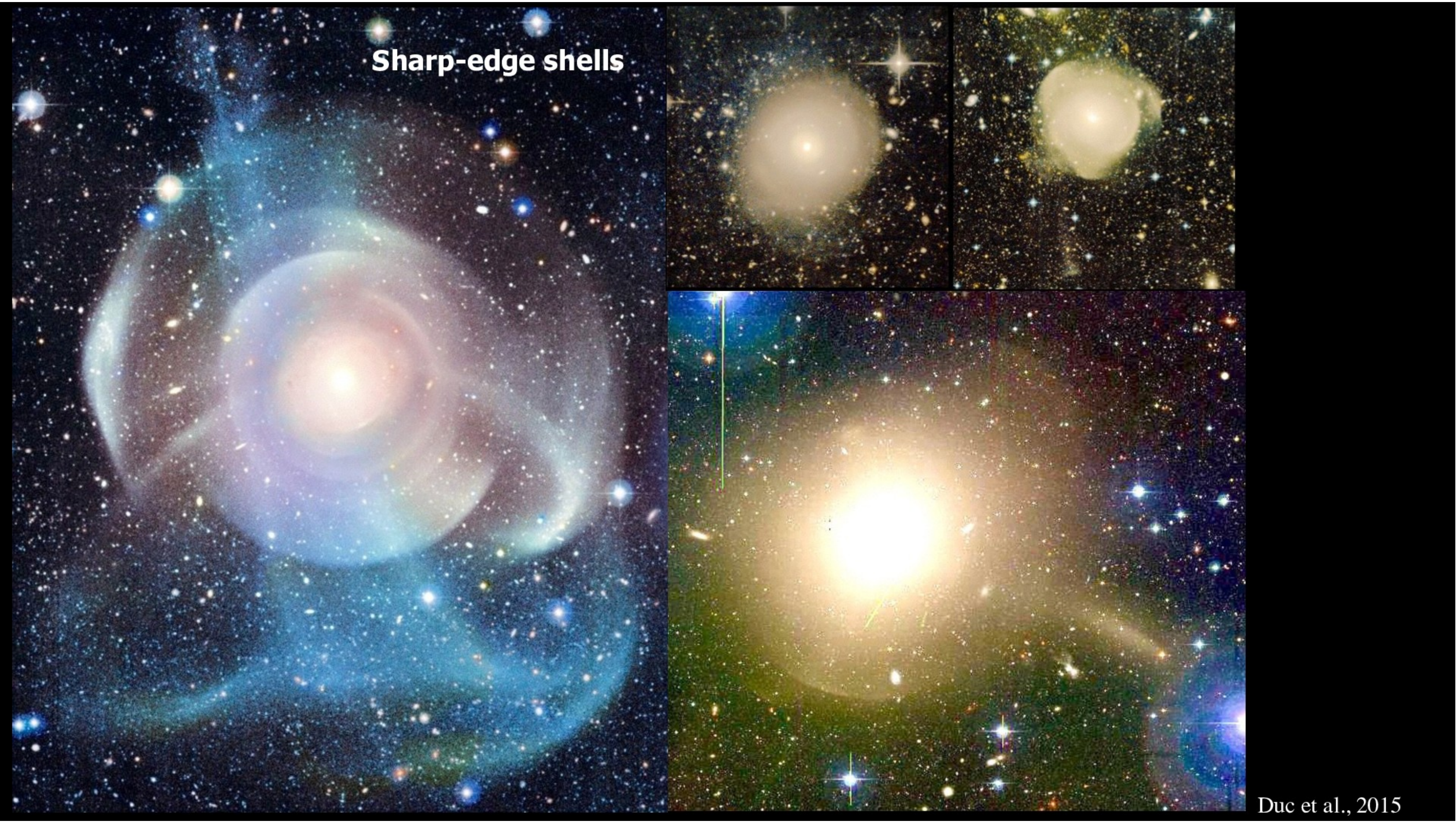


Marcillas et al., in prep

- Trace minor (dry) mergers
- Rather long lived (2-3 Gyr)
- Detection depends weakly on the *orientation*, but strongly on the *surface brightness limit*

MEGACAM, images deep fields

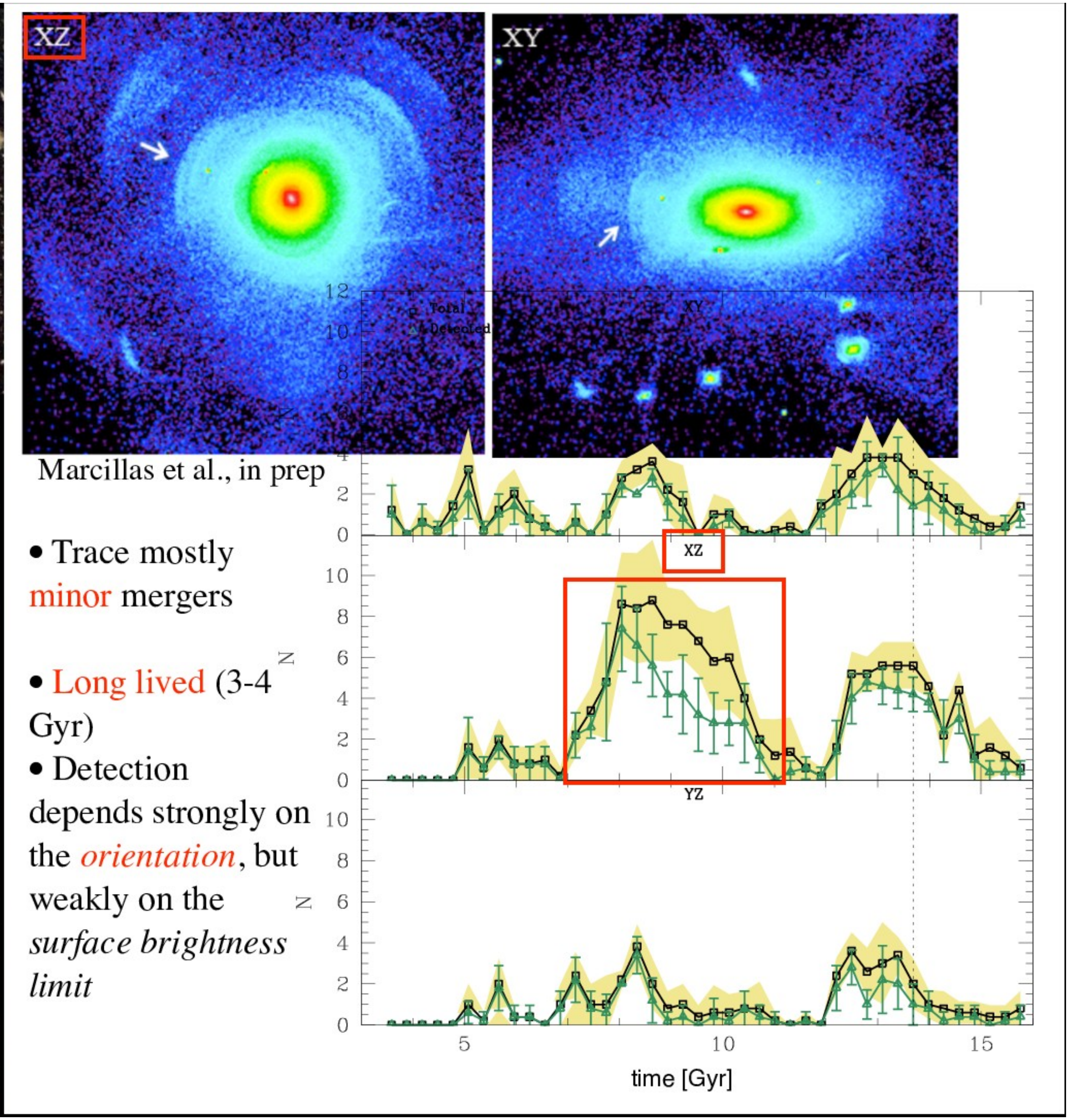
Deep photometry



Duc et al., 2015

MEGACAM, images deep fields

Deep photometry

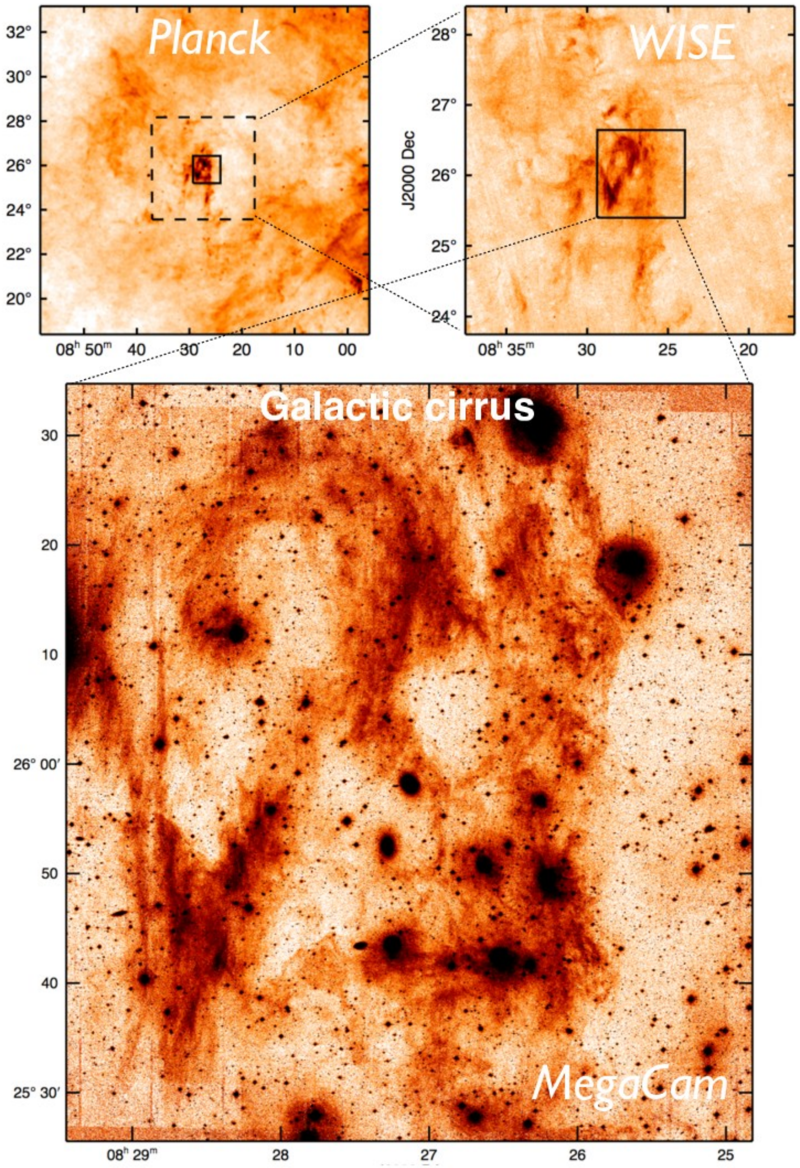


Marcillas et al., in prep

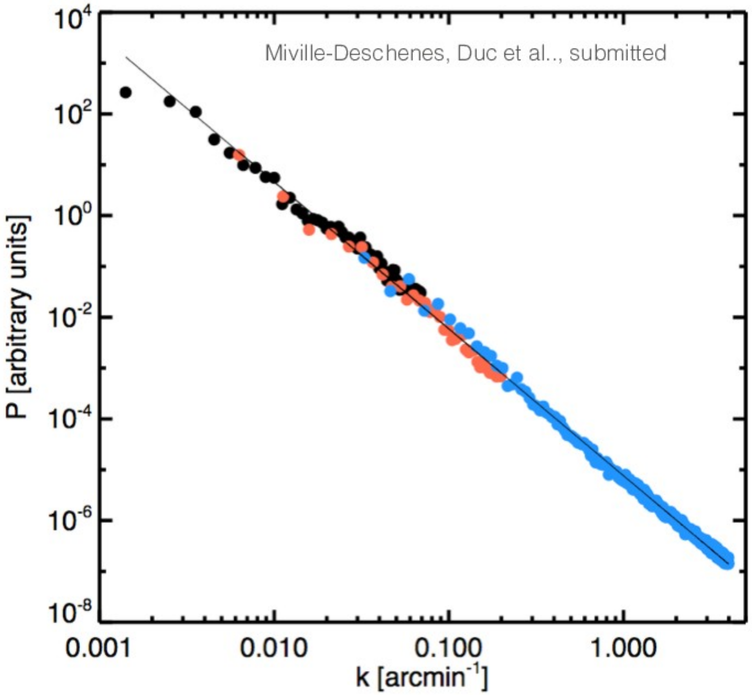
- Trace mostly minor mergers
- Long lived (3-4 Gyr)
- Detection depends strongly on the *orientation*, but weakly on the *surface brightness limit*

MEGACAM, images deep fields

Deep photometry



Deep uv/optical observations : we see The galactic cirrus (everywhere and on all scales!)

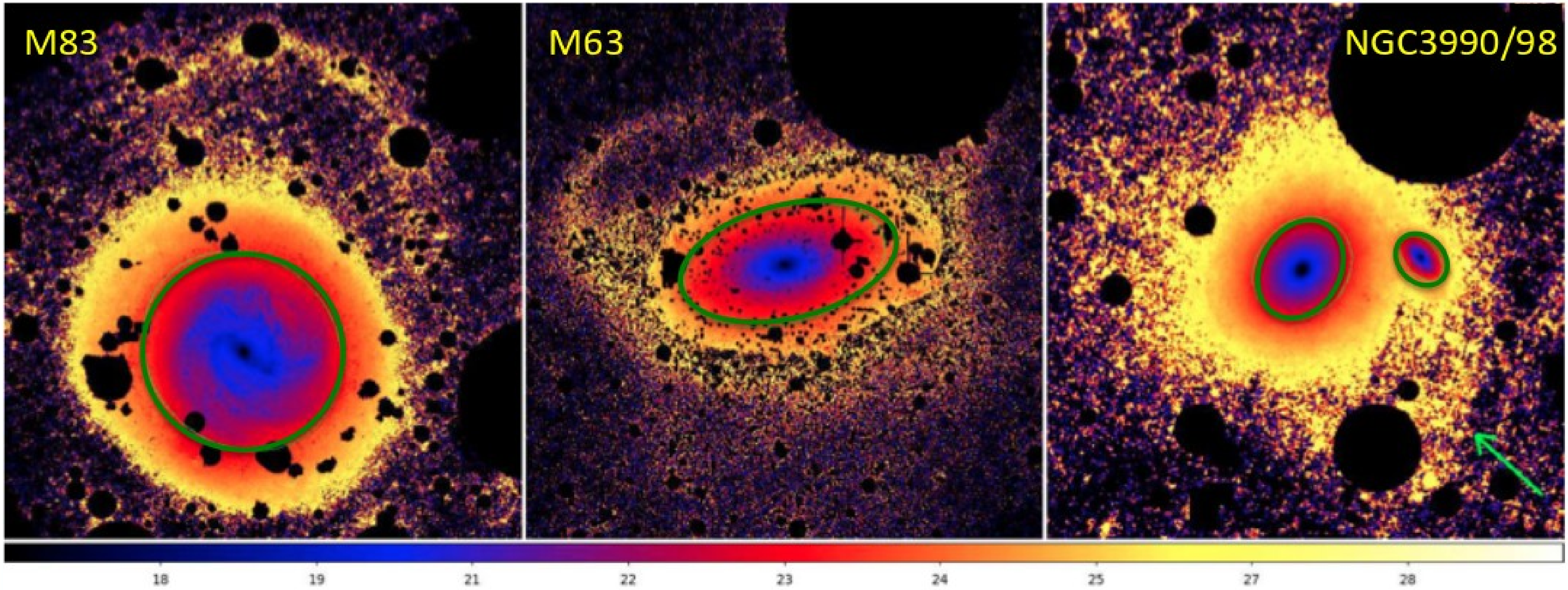


Probing the turbulence cascade in the diffuse ISM at the smallest scales (0.01 pc): no evidence for a break of the power spectrum!

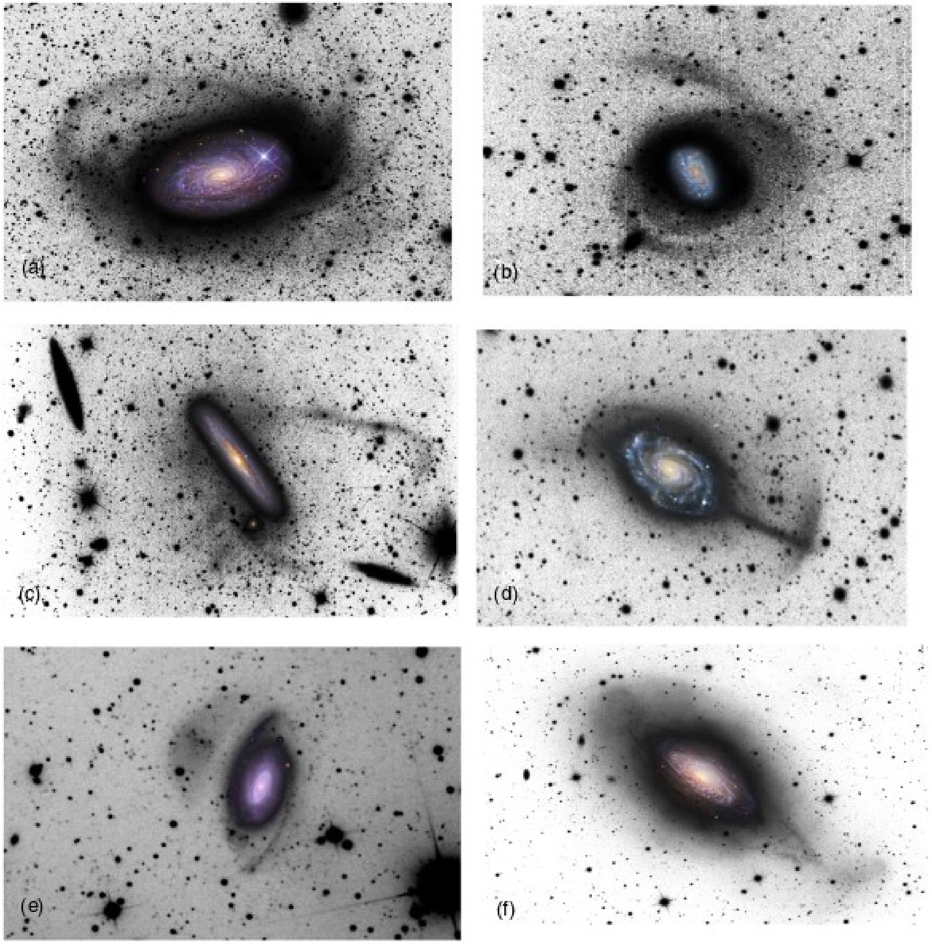
Van Zee e tal.
Deep survey
with Spitzer

EDGES Results

- Full EDGES survey includes 92 normal galaxies
- We detect extended stellar distributions and stellar streams in many of these fields



Deep photometry

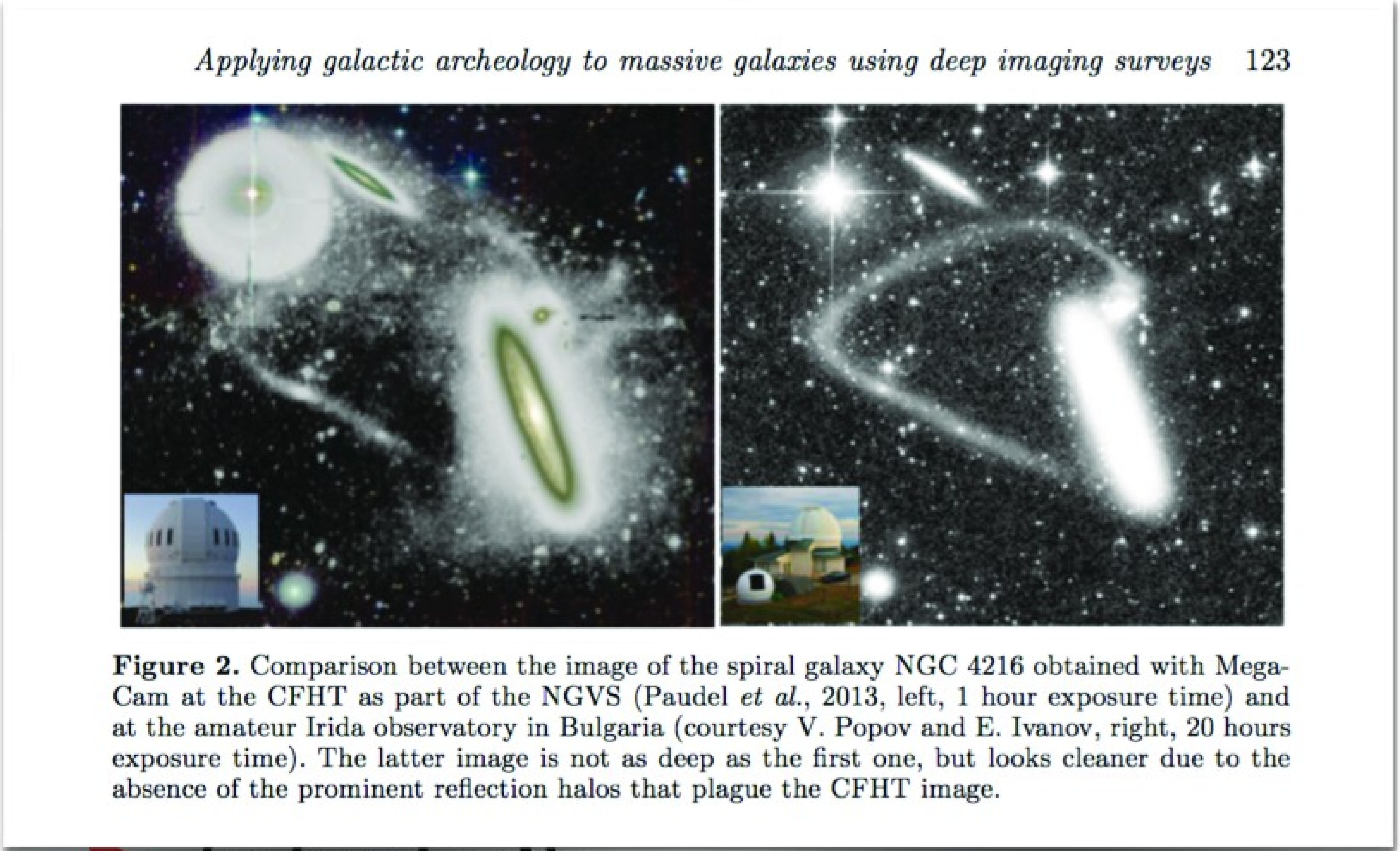


Martinez-Delgado et al. (2010)

Modest aperture telescope can catch the brightest of the structures (large FOV, less haloes)

To fix it in hardware, the telescope doesn't have to be big

This the relevant equation for computing signal in extended

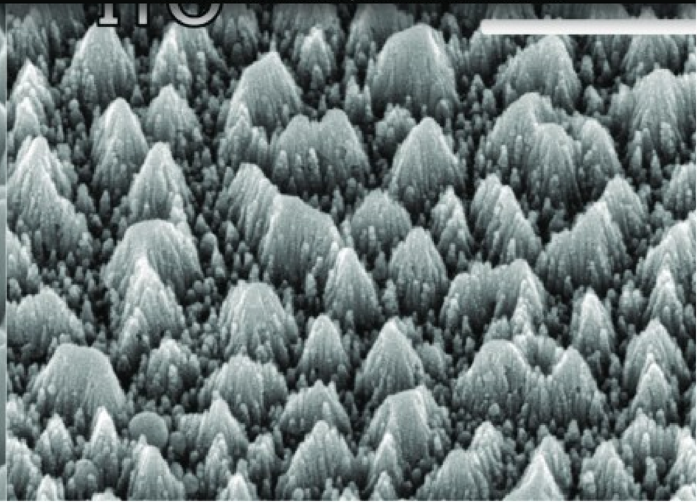


Applying galactic archeology to massive galaxies using deep imaging surveys 123

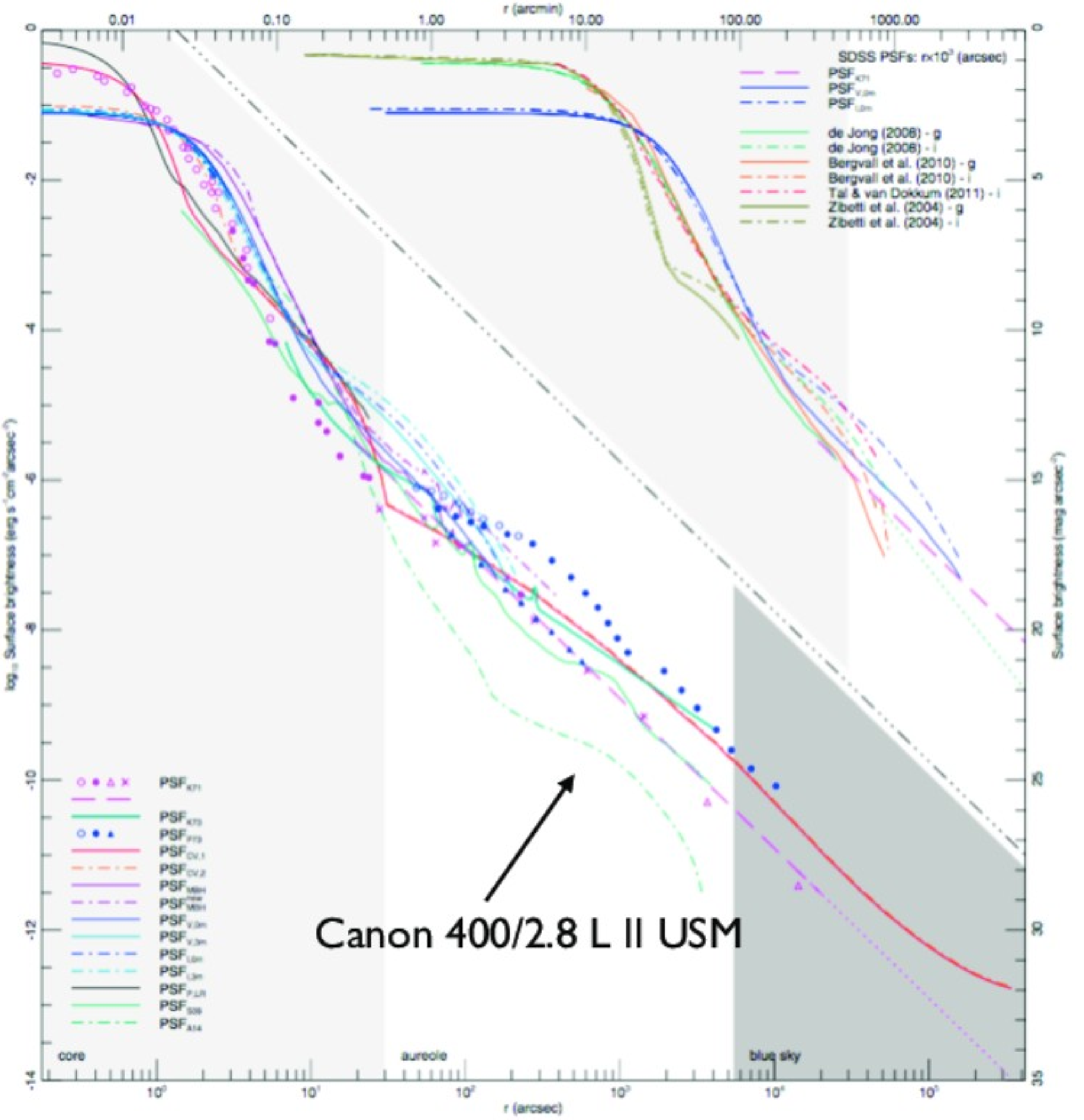
Figure 2. Comparison between the image of the spiral galaxy NGC 4216 obtained with MegaCam at the CFHT as part of the NGVS (Paudel *et al.*, 2013, left, 1 hour exposure time) and at the amateur Irida observatory in Bulgaria (courtesy V. Popov and E. Ivanov, right, 20 hours exposure time). The latter image is not as deep as the first one, but looks cleaner due to the absence of the prominent reflection halos that plague the CFHT image.

f = focal ratio
E = throughput of instrument
a = pixel area

CANON 7D + EF 400MM F/2.8L II USM - ALEX CANON



C. Sandin: The influence of diffuse scattered light. I.



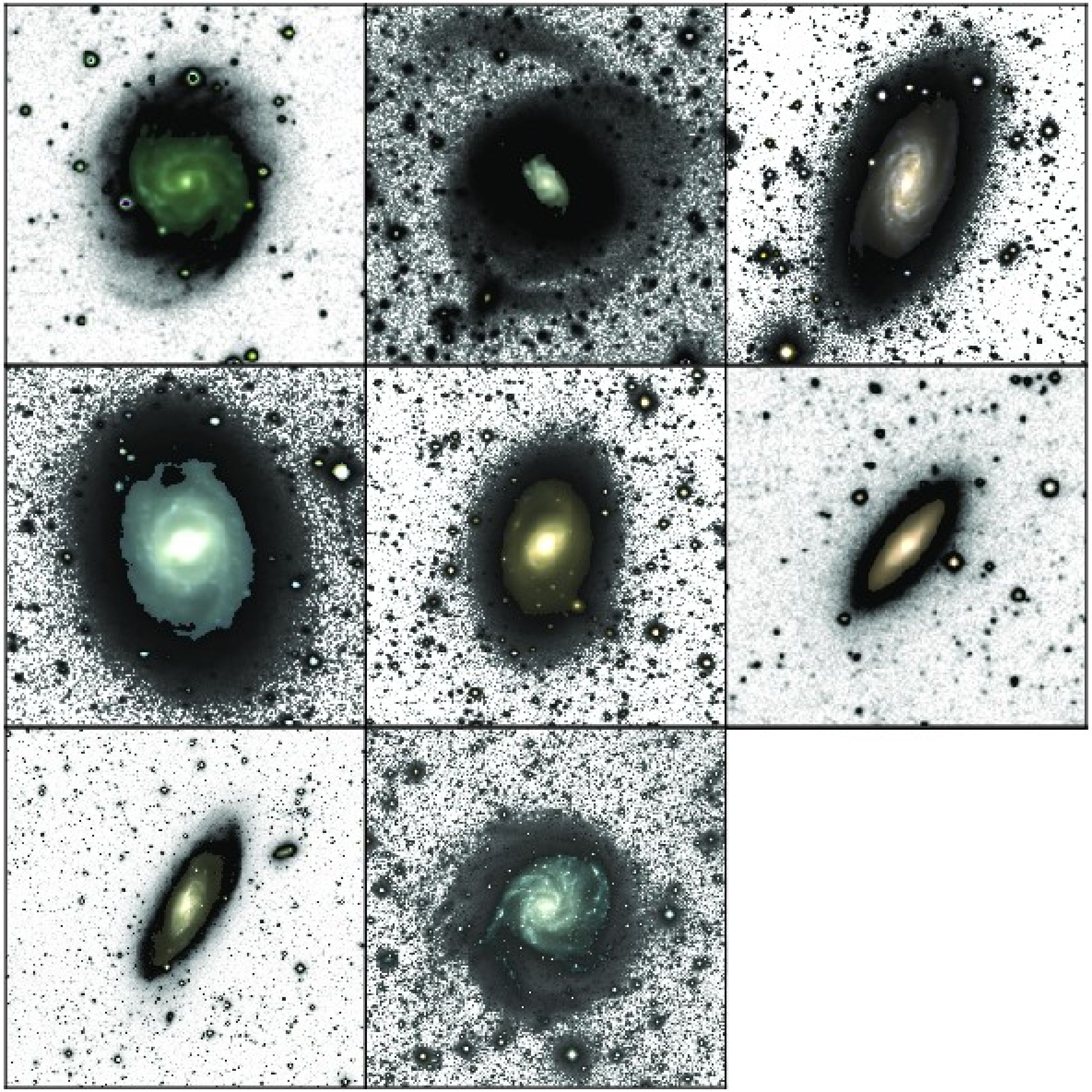
Canon 400/2.8 L II USM

Fig. 1. PSF surface-brightness profiles versus the radius r for a 0 mag point source. Individual PSFs are drawn with coloured lines and symbols as indicated in the figure, see also Table 1. PSFs of stacked SDSS images are shown in the upper part of the figure, as a function of $10^3 \times r$; $PSF_{V,0m}$, $PSF_{i,0m}$, and the outer regions of PSF_{K71} are shown in both parts as references. Extrapolated PSFs are shown with dotted lines. The light (medium) grey region indicates the PSF core (blue sky) and the white region the aureole, as defined for $PSF_{CV,1}$ and $PSF_{CV,2}$ (CV83).

Dragonfly

A. Merritt

Spiral sample (so far)

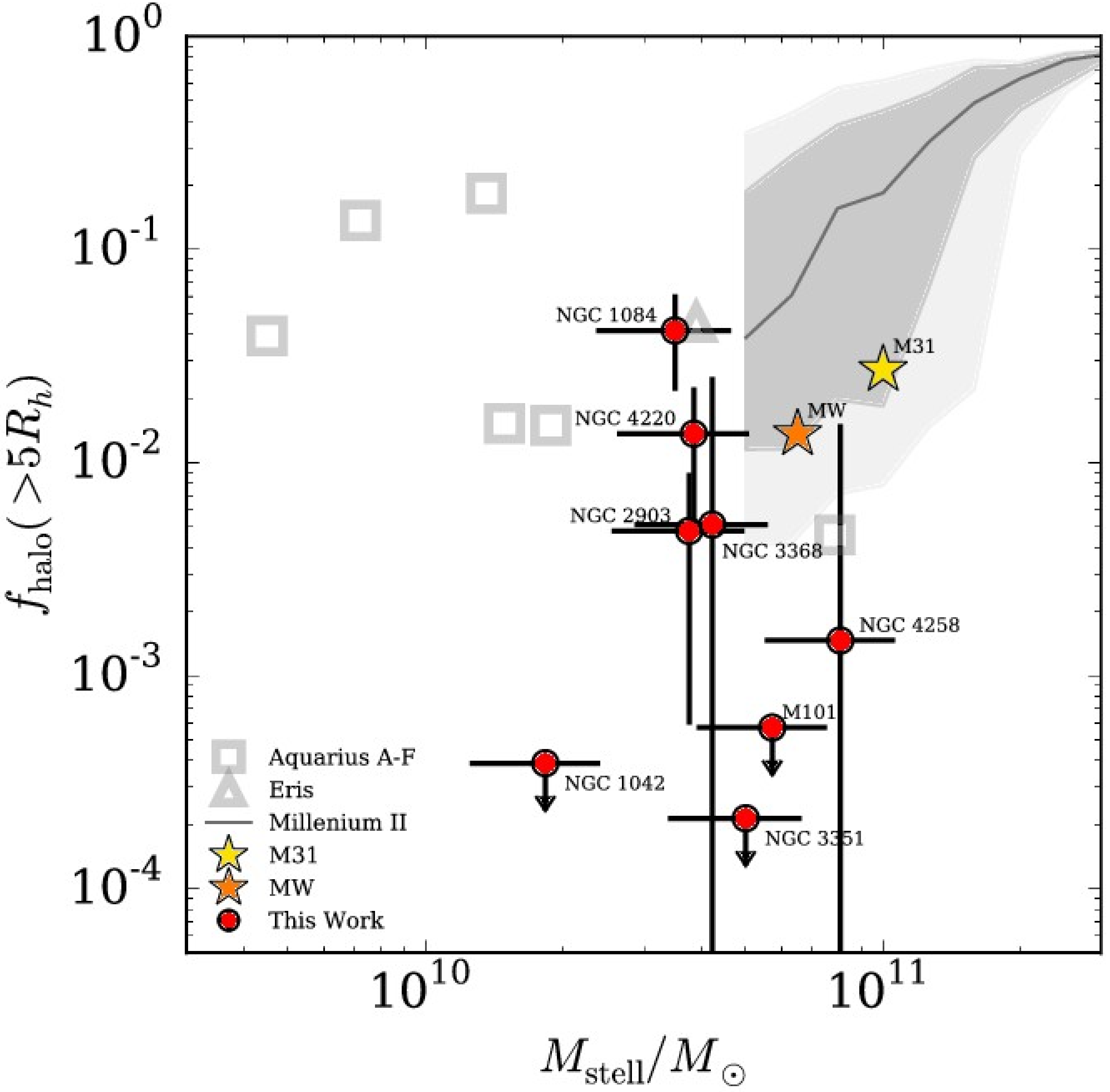


Bright ($M_B < -19.5$) spirals in Dragonfly fields

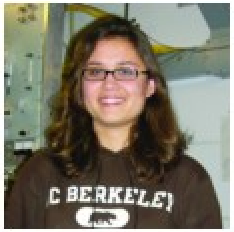
selected based on low cirrus in the fields.

no selections based on previously known stellar halos

Huge variation in halo fraction at similar stellar mass



Dragonfly work



A. Merritt

Deep photometry Summary

- Allow to detect structures, but we need to aim at very faint S.B.
- Challenges
  - Flat fielding to 0.01 %
  - Galactic cirrus
  - Scattering : ray-trace or model can help to remove some, but it is diffult, or use instruments avoiding it in the first place.

OUTSKIRTS OF GALAXIES

a) What outskirts tell us about galaxy evolution

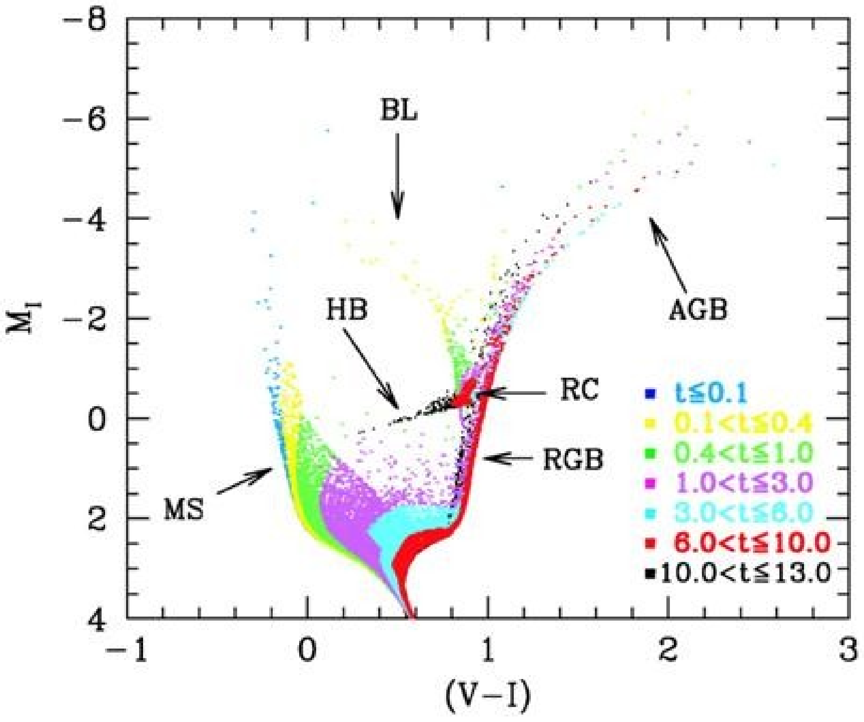
b) How to observe outskirts of galaxies

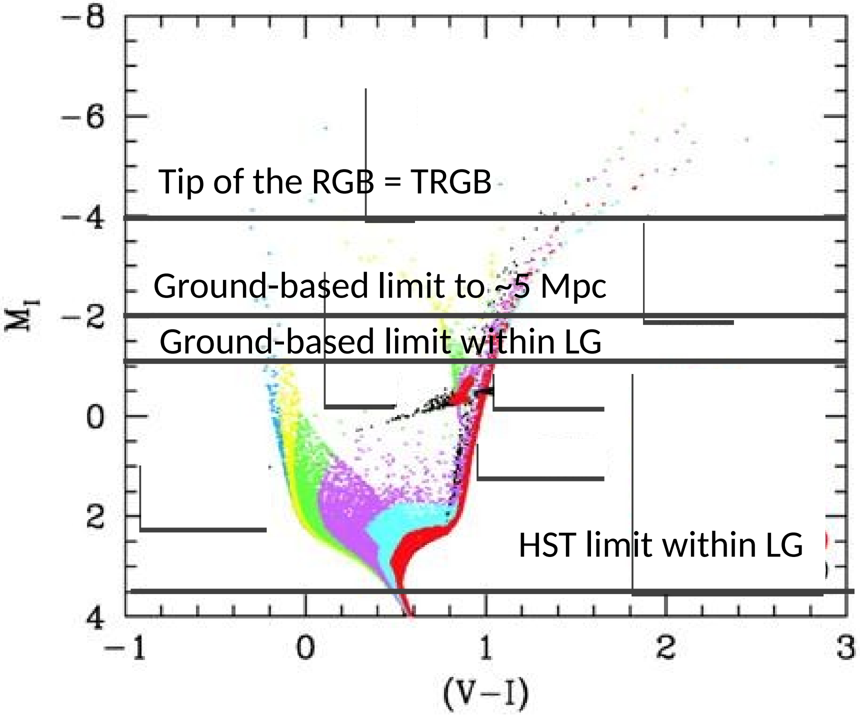
– deep photometry

– resolved stars

– absorption systems

Resolved stars





CMDs from Aparicio & Gallart 2004

- Possible to reach very low surface brightness (fainter than 30 mag arcsec-2)
- Avoid problems of flat-fielding, scattered light, cirrus
- Also bring metallicity/age/star formation history constraints

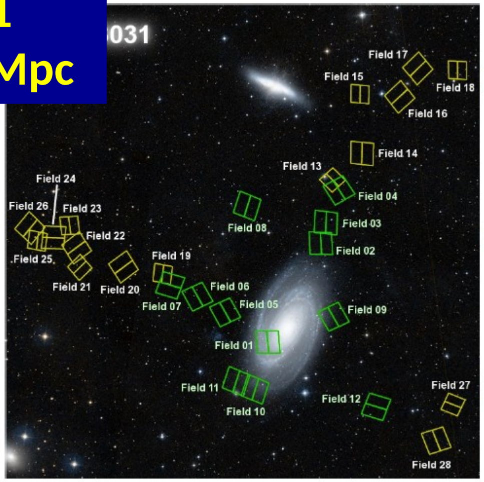
Challenges for Resolved Stars

- Tip of the RGB @1.5 Mpc is m_I=21.9, @3.5 Mpc is 23.7 and @5 Mpc is 24.5
  Require detections to *at least* 1.5-2 mag below the TRGB (and ideally deeper) with good S/N to be interesting……

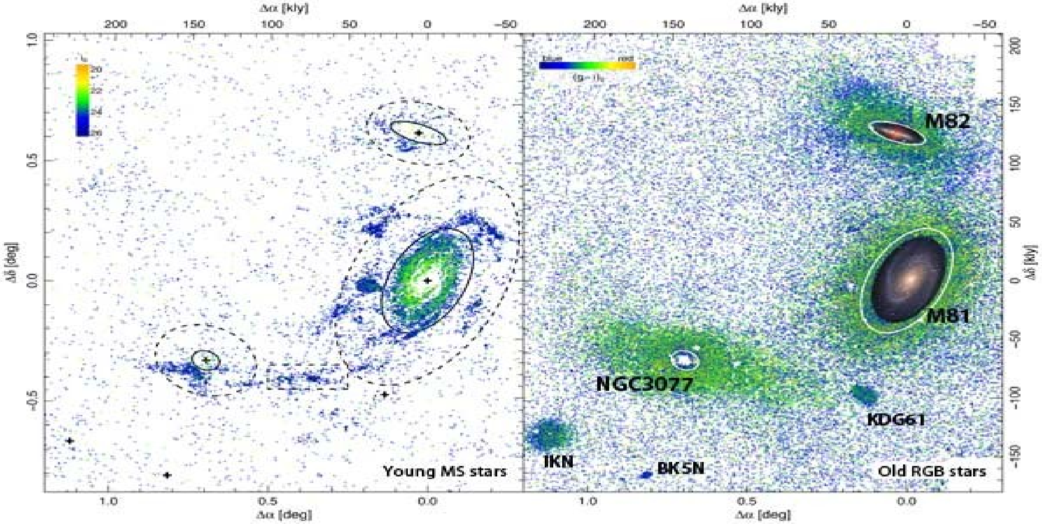
Local Group work can be done with 4m class telescopes; beyond the Local Group requires 8m class or HST. Current volume limit from ground ~5 Mpc…

- Nearby galaxies are large on sky, and galaxy outskirts are complex…..
  Small FOV studies can be difficult to interpret while contiguous mapping surveys are observationally expensive and challenging…

M81
@ 3.6 Mpc



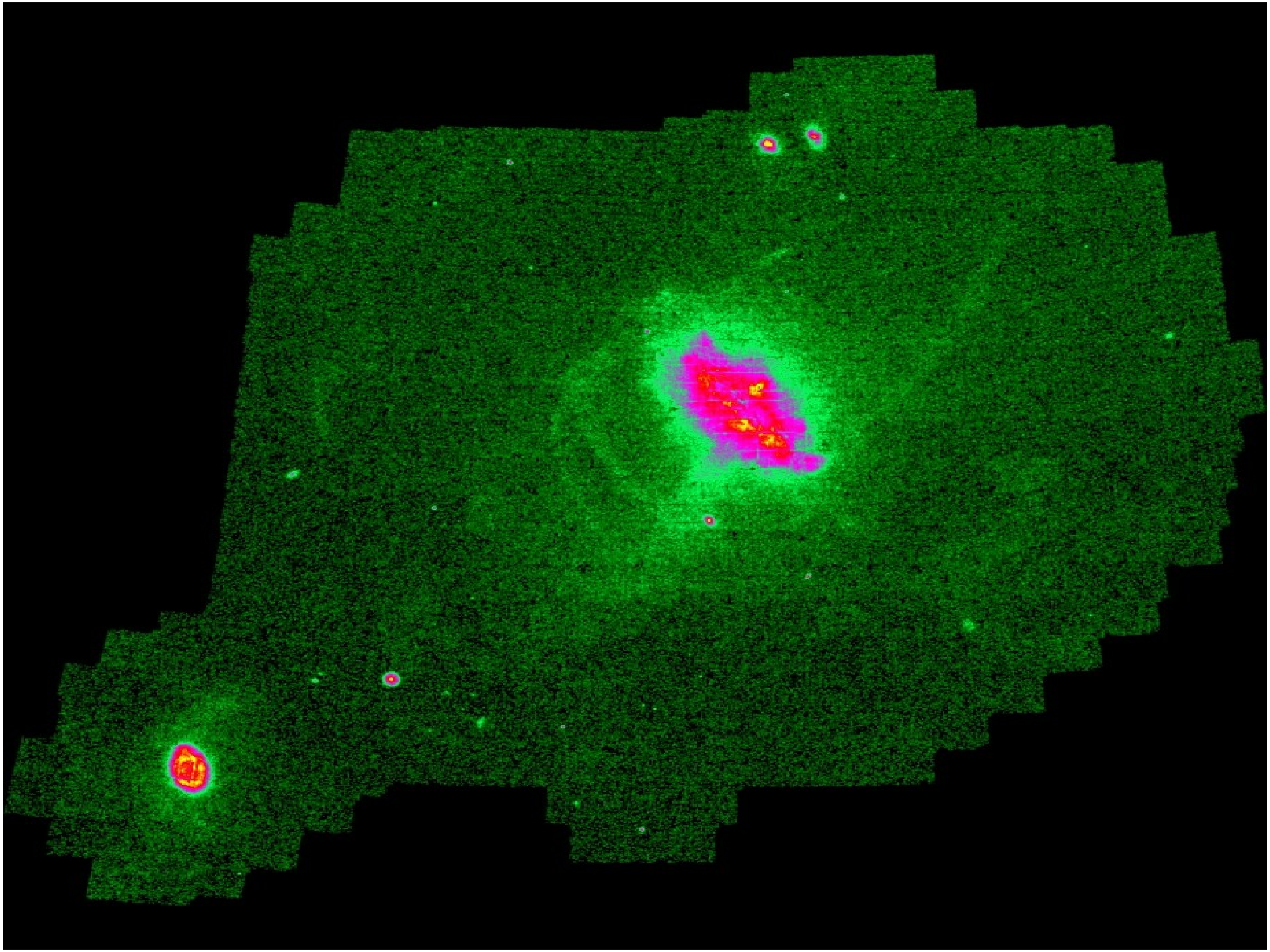
Monachesi et al. 2016



Okamoto et al. 2015

- Good image quality needed to distinguish backgroudn galaxies/stars

The Pan-Andromeda Archaeological Survey - PAndAS

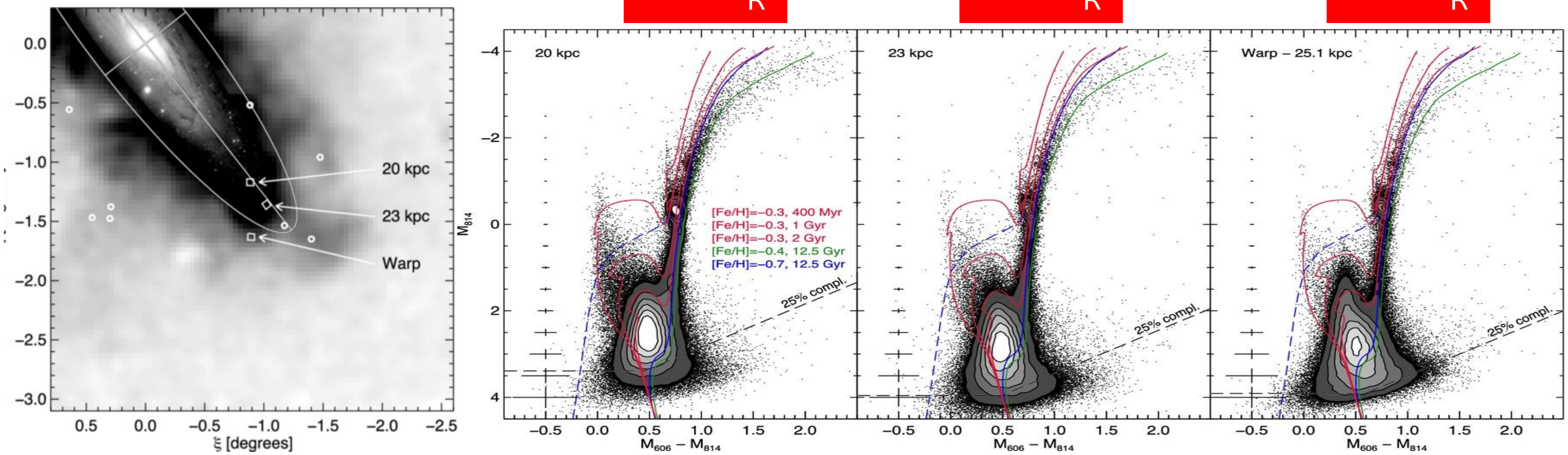


faintest features have peak SBs of Σ_V ~30-32 mag/❑
~0.05-0.01% of the dark night sky

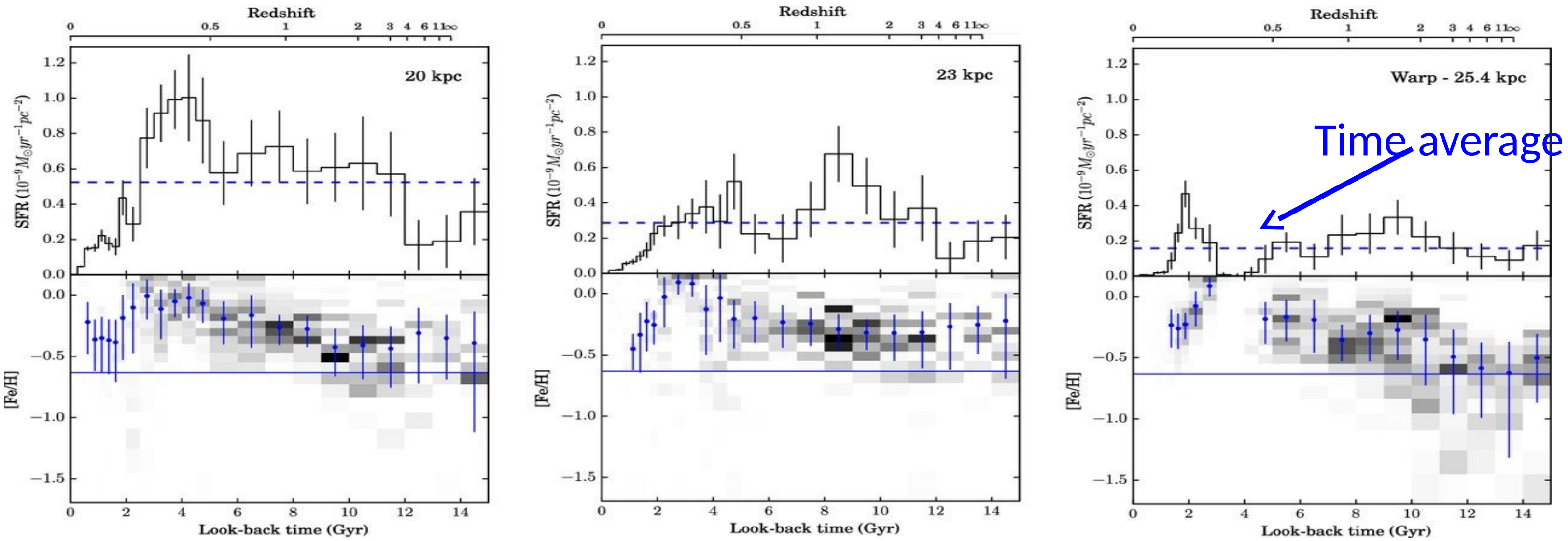
McConnachie (PI) et al 2009, 2010, Ibata et al. 2014

Bernard et al 2015

3.8α_R 4.3α_R 4.7α_R



Deep HST photometry obtained at 3 locations along M31's SW major axis, reaching to the oldest Main Sequence Turn-Offs.



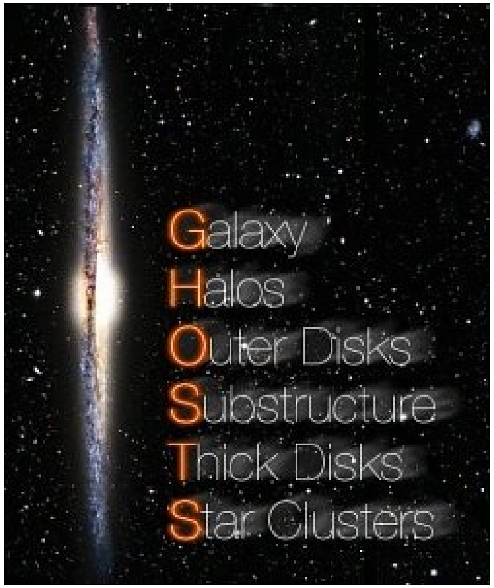
Time average

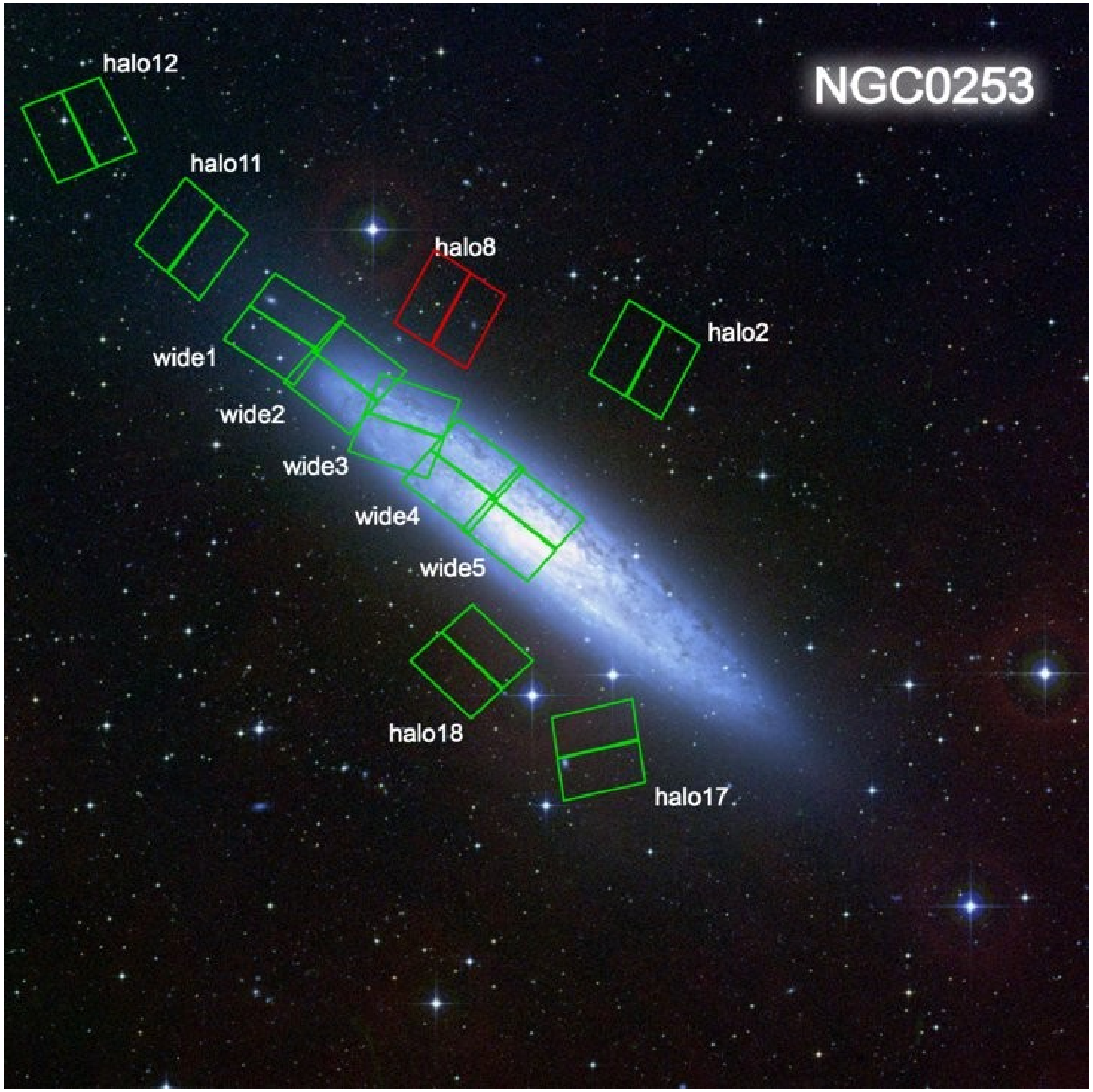
In all fields, star formation began early on and occurred more or less continuously across the history of the disc

M31 was already a large disc at high redshift!

Galaxy Halos, Outer disks, Substructure, Thick disks and Star clusters project.

Roelof de Jong (PI)





HST Analysis of extraplanar stellar population in nearby galaxies

Lessons learned from resolved stellar populations :

- Powerful but limited to nearby universe
- Extent of galaxies R > 50-200 kpc (implications cross-section, metal absorption systems, hostless Sns
- Complex. Low S.B. envellope common, nature not clear
- In M31 : outer regions in place early on

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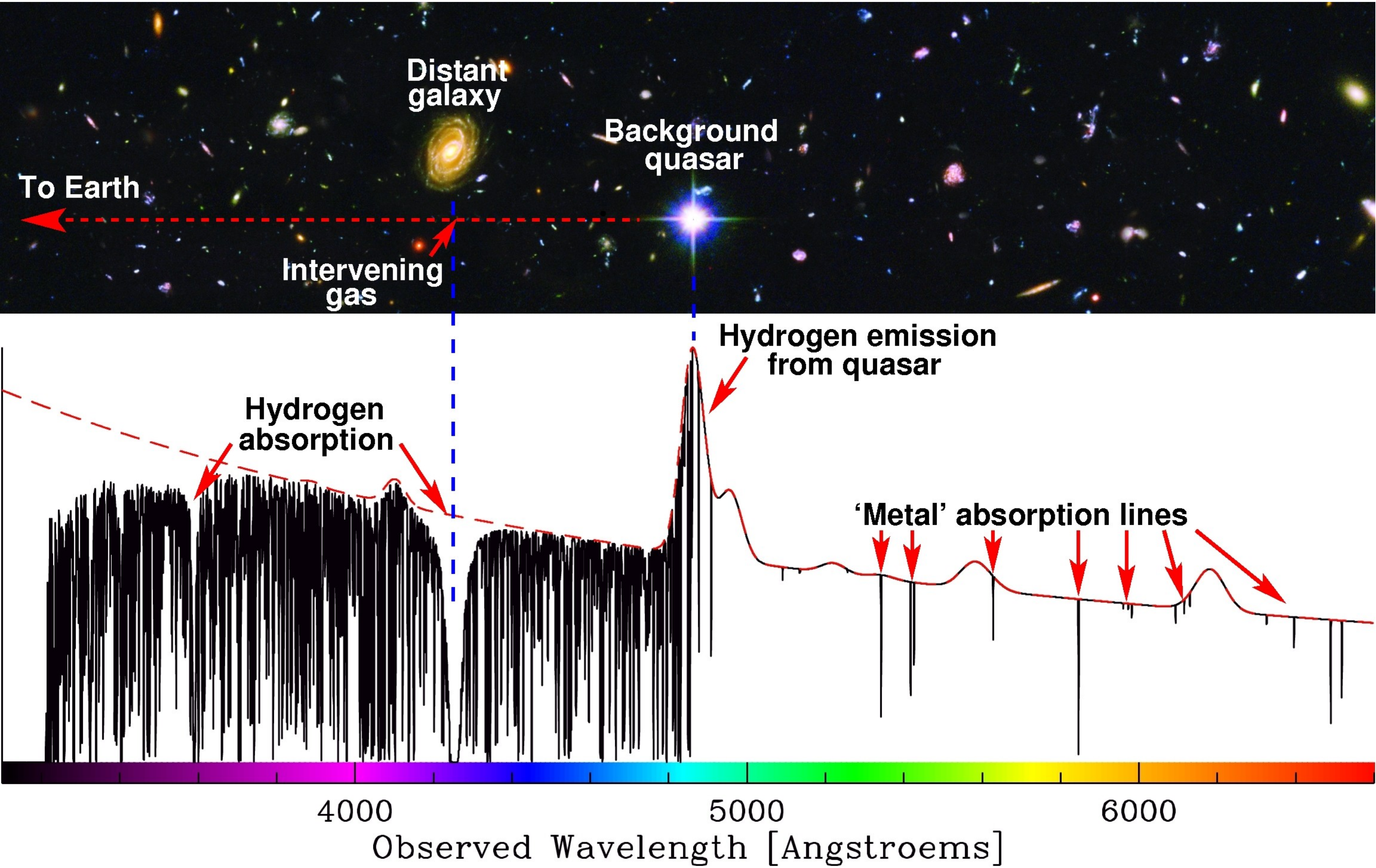
a) What outskirts tell us about galaxy evolution

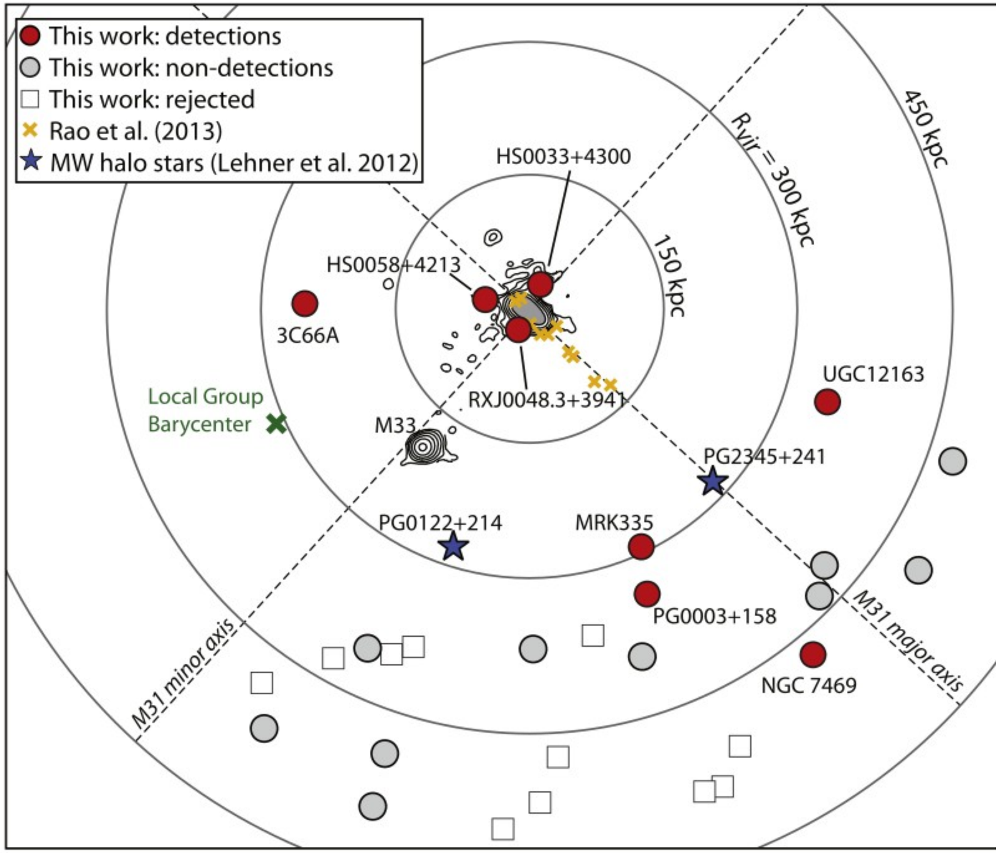
b) How to observe outskirts of galaxies

- deep photometry
- resolved stars
- absorption systems

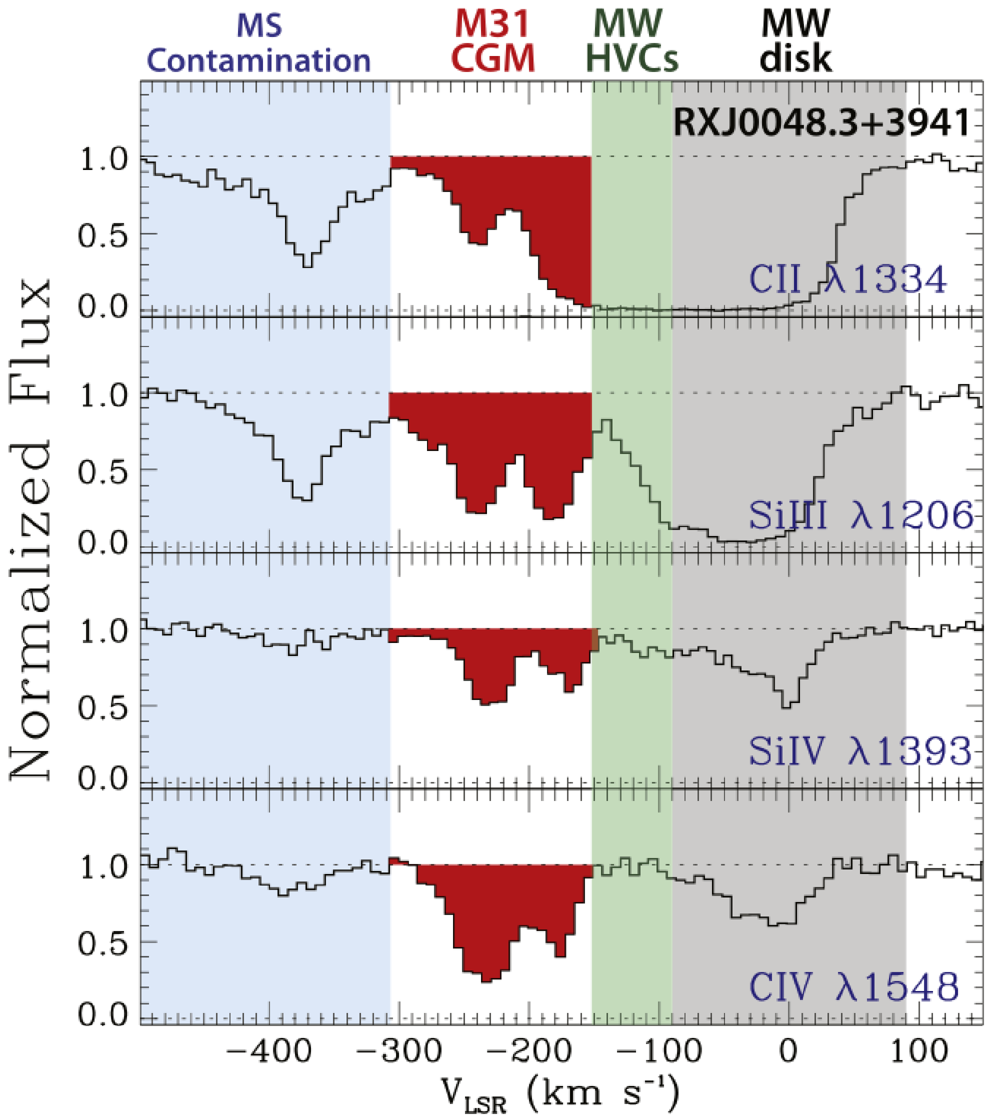
The general idea…



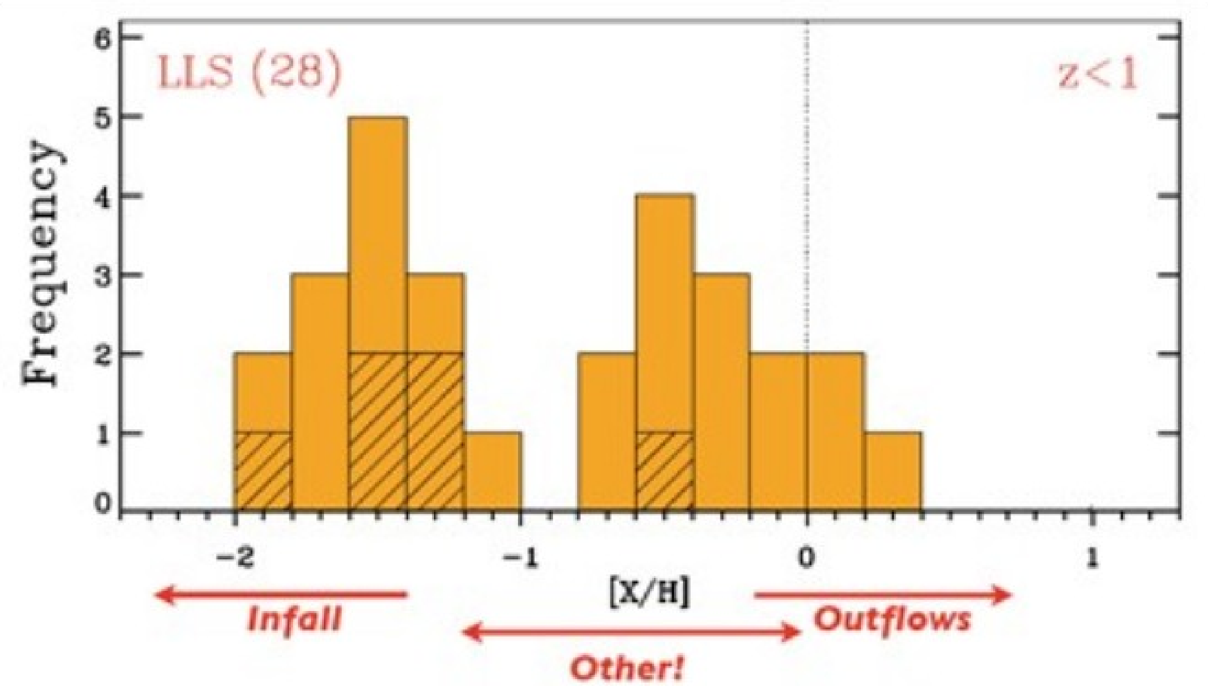
Example : around M31



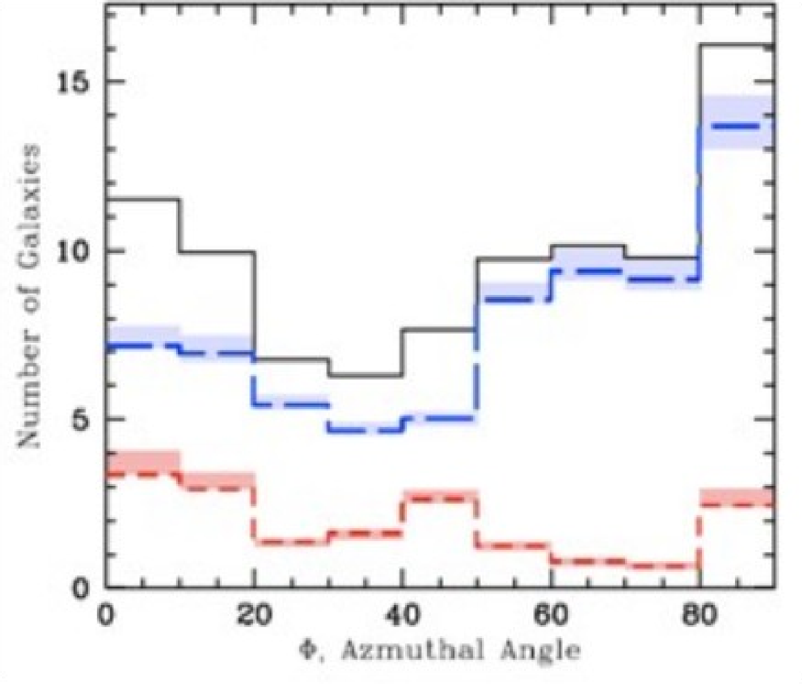
Lehner et al. (2015)



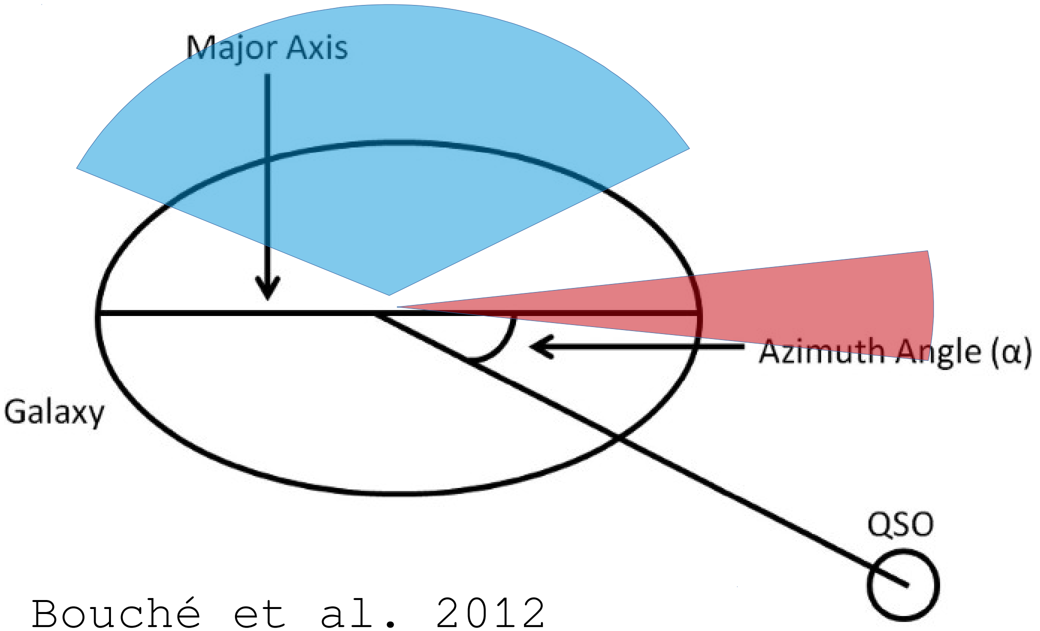
Absorbers to probe infall and outflows



Lehner et al. 2013



Kacprzak et al 2012



Bouché et al. 2012

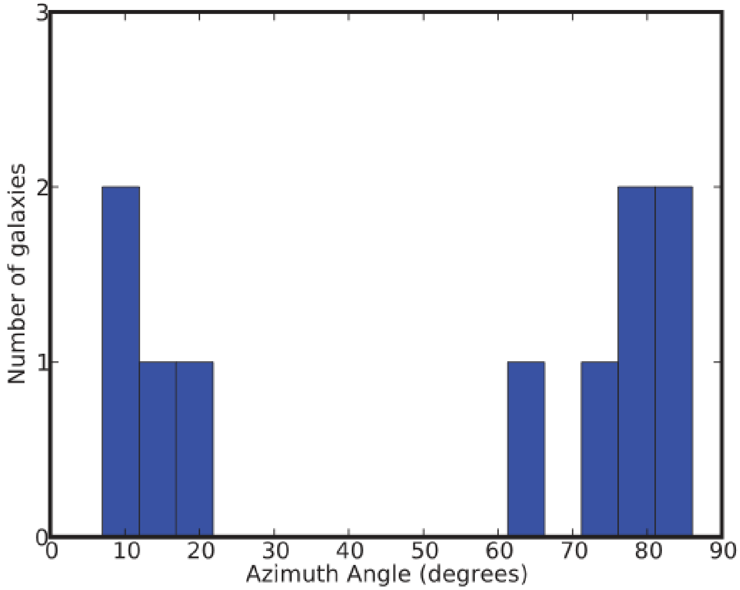


Figure 2. The bimodal distribution of the azimuth angle $|\alpha|$ for our sample

OUTSKIRTS OF GALAXIES

a) What outskirts tell us about galaxy evolution

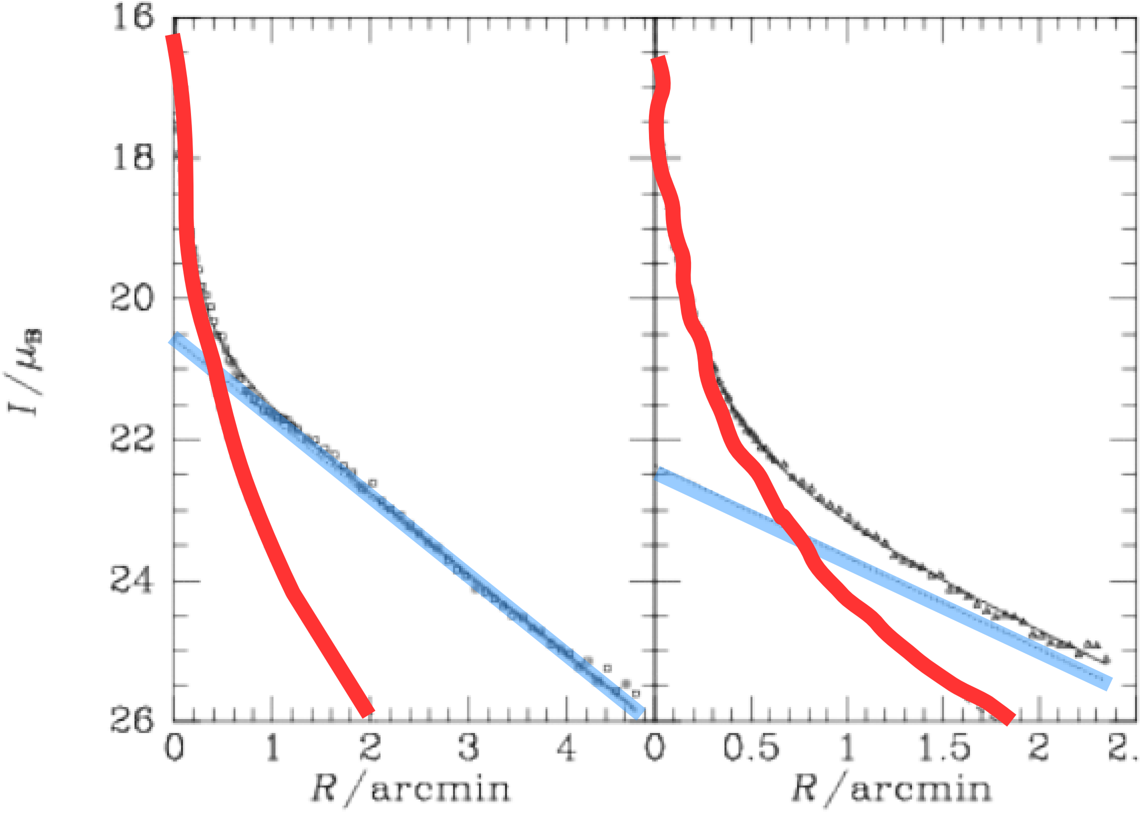
b) How to observe outskirts of galaxies

- deep photometry
- resolved stars
- absorption systems

c) Radial Profiles

Radial profiles

- Textbook profiles de Vaucouleur or exponential



Binney & Merrifield, Galactic Astron

De Vaucouleurs law

$$I(R) = I_e e^{-7.67[(R/R_e)^{1/4}-1]}$$

Spheroids

Exponential profile

$$I(R) = I_o \exp(-R/R_d)$$

Disks

Freeman law : mu_0 ~21.65 mag

Radial profiles

Empirically devised by Sersic (1963) as a good fitting fn

$$I(r) = I_0 \exp(-\left(\frac{r}{\alpha}\right)^{1/n})$$

$I(r)$ = intensity at radius r

I_0 = central intensity (intensity at centre)

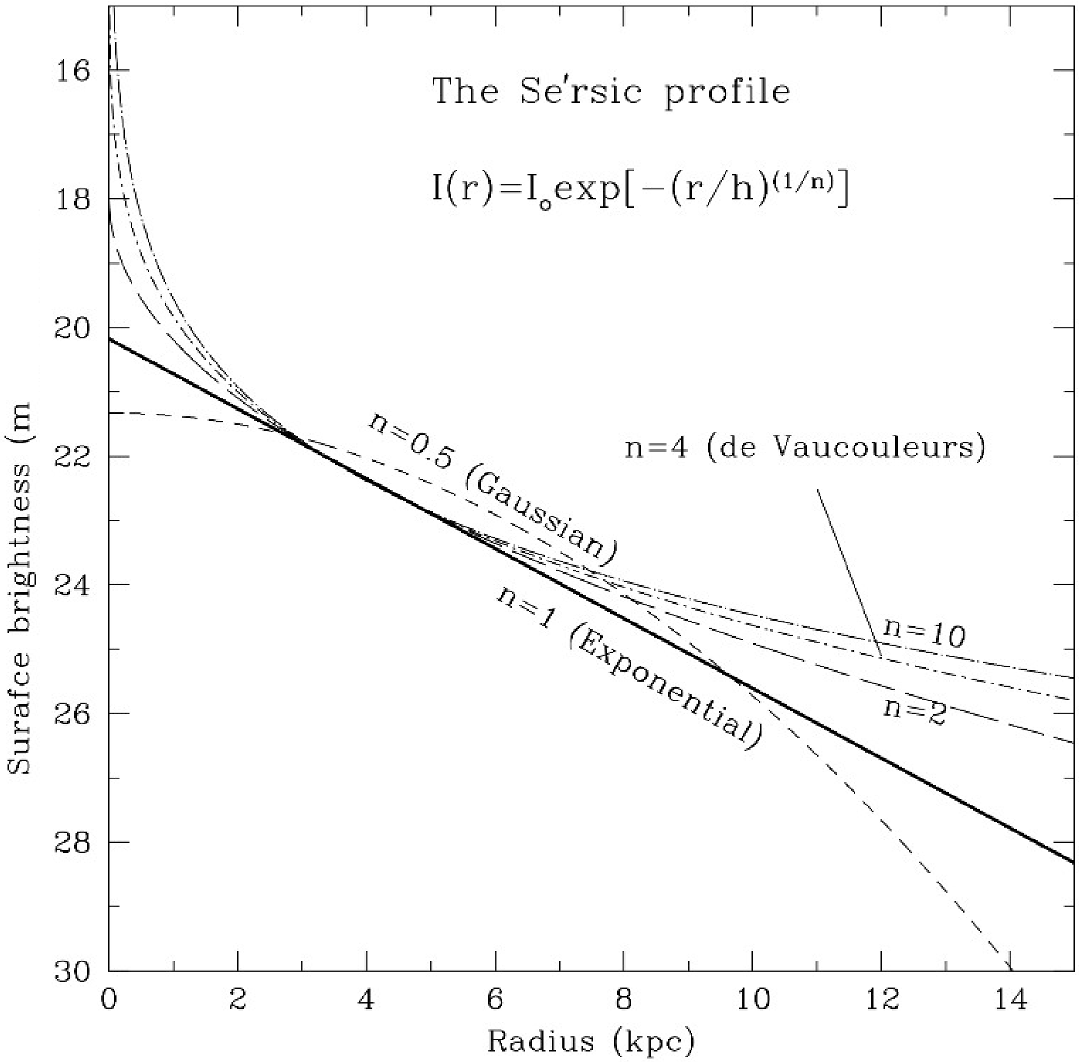
α = scalelength (radius at which intensity drops by e^{-1})

n = Sersic index (shape parameter)

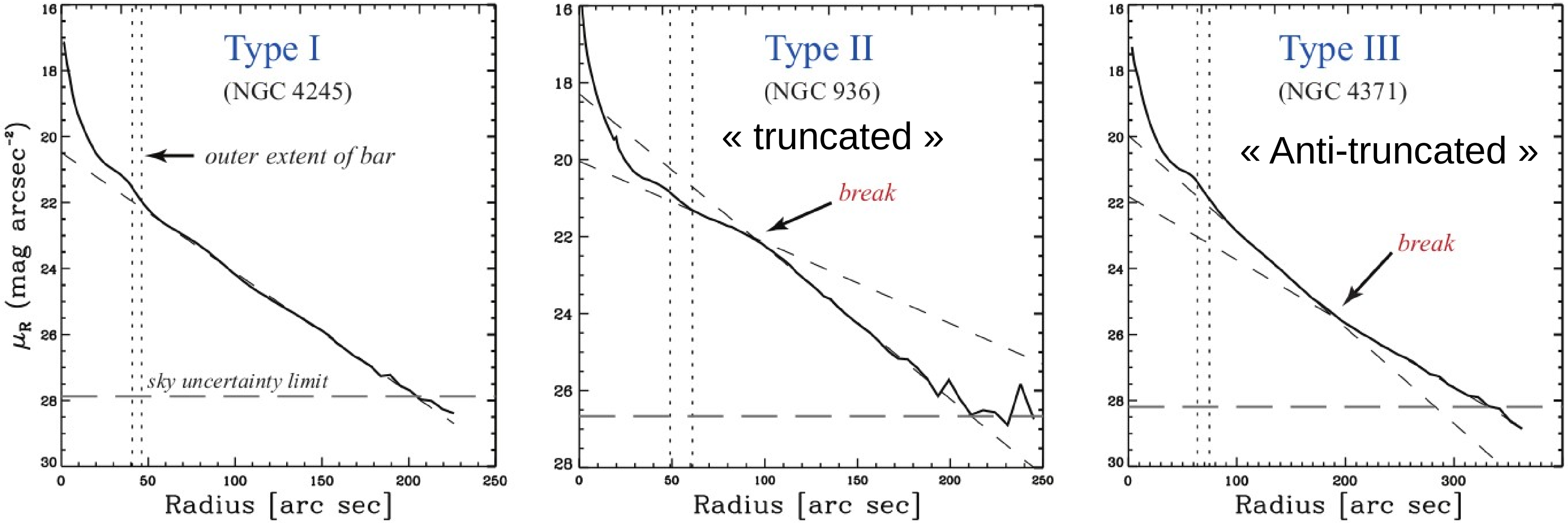
Can be used to describe most structures, e.g.,

Elliptical: $1.5 < n < 20$ Bulge: $1.5 < n < 10$
Pseudo-bulge: $1 < n < 2$ Bar: n~0.5
Disc: n~1

Total light profile = sum of components.



Modern view : extended disks

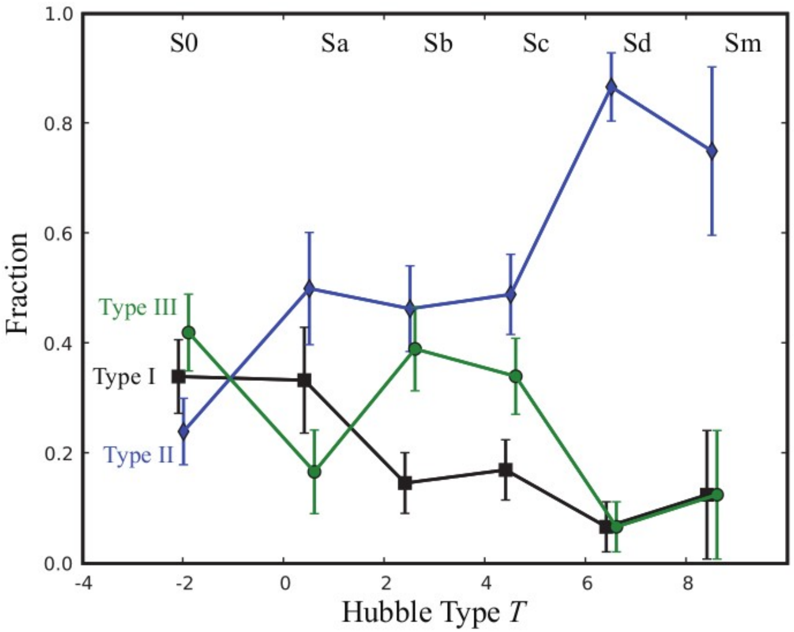


« truncated »

« Anti-truncated »

- Most galaxies are not type I !
- Fraction of type II large in late-type disks

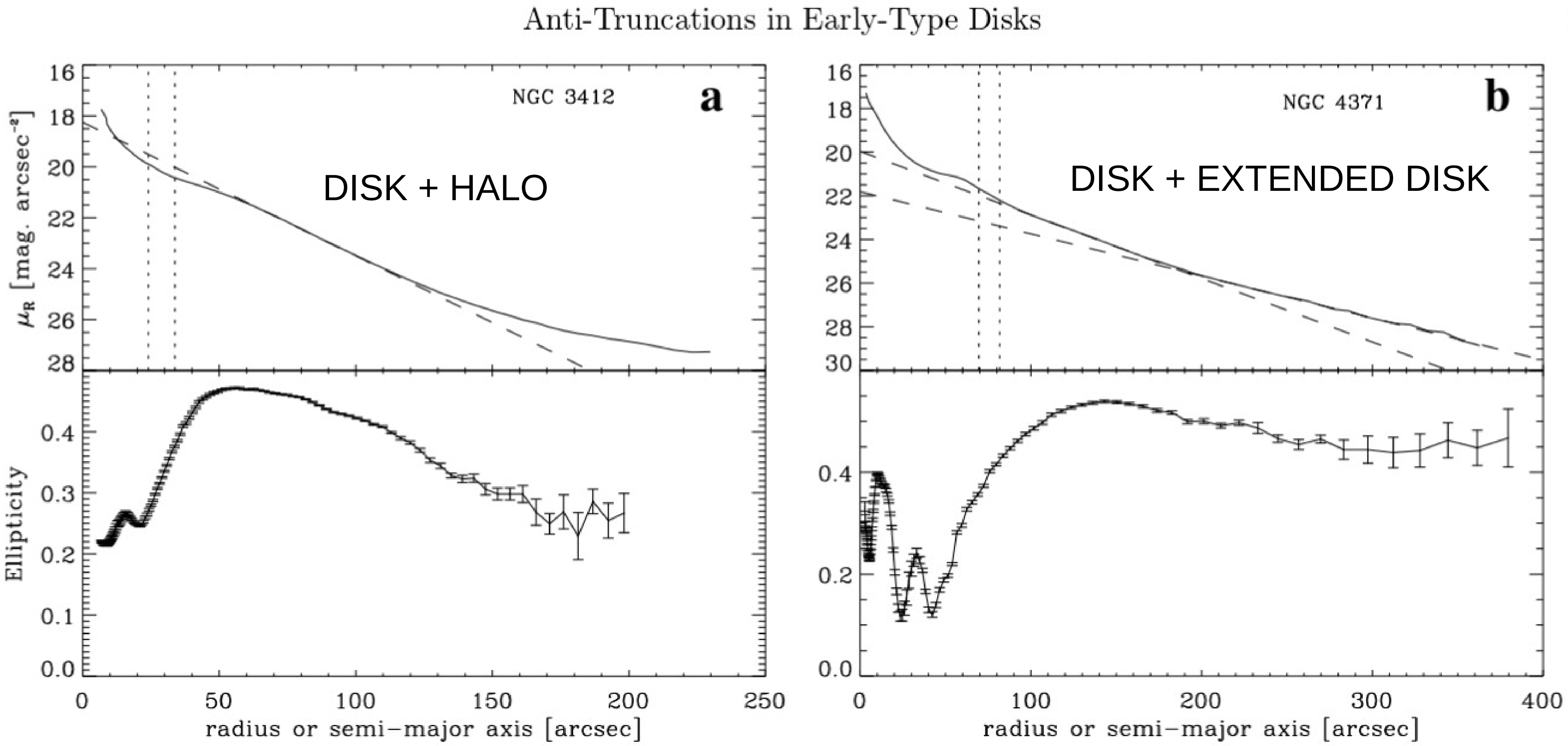
```
- Pohlen & Trujillo 2006
- Erwin et al. 2008
```



Also observed at high z

- Perez 2004
- Trujillo & Pohen 2005
- Azzollini et al. 2008

Erwin et al. 2005



DISK + HALO

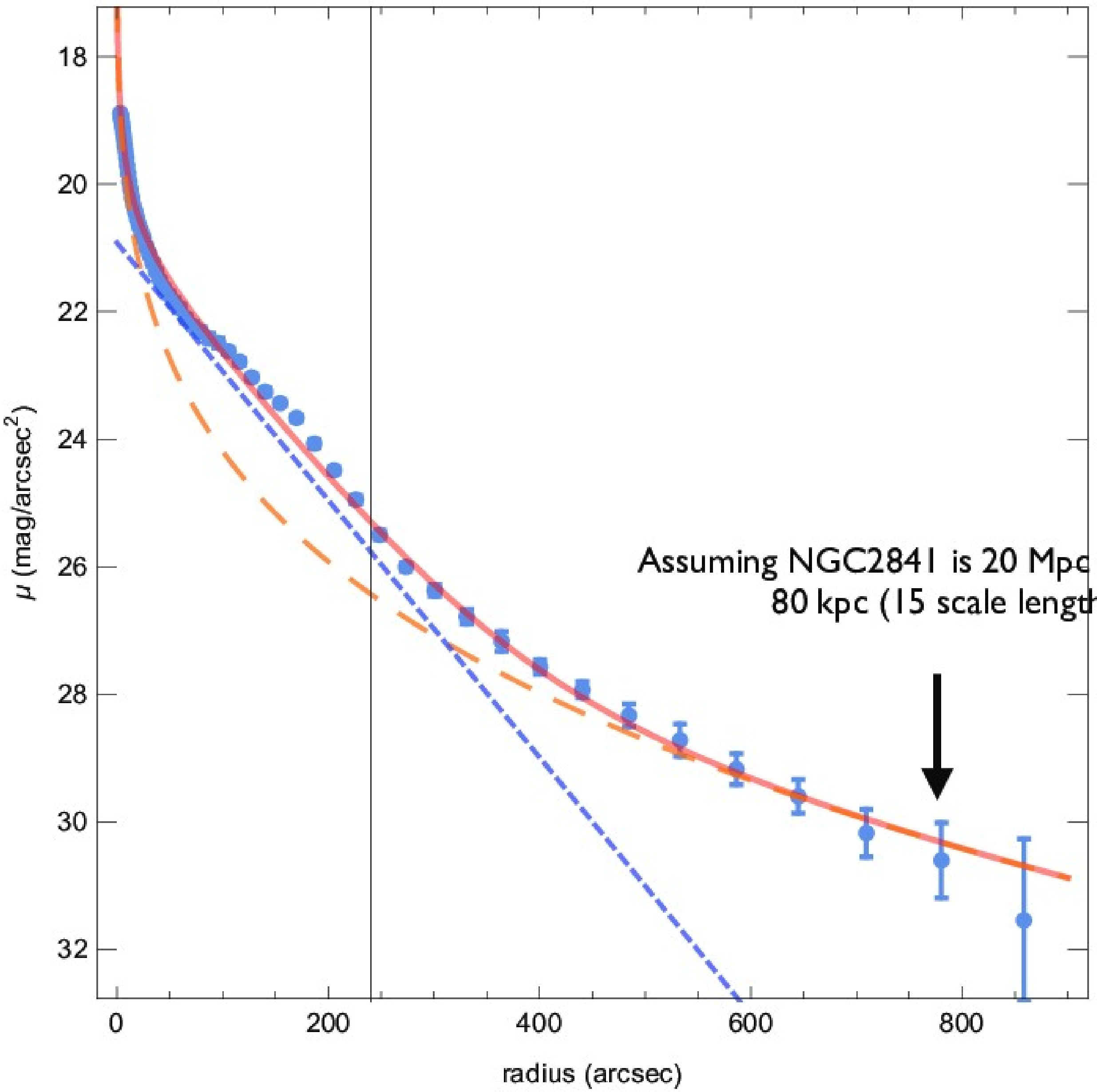
DISK + EXTENDED DISK

Smooth transitions
Rounder isophotes at large radius

Sharper transitions
Fit as a double exponential.
Same ellipticity at large radius

NGC 2841 surface brightness profile

With Dragonfly

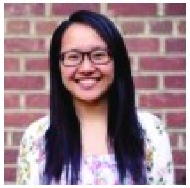


Assuming NGC2841 is 20 Mpc away, this is
80 kpc (15 scale lengths)

In this fit,
The « bulge » fits
the very outer points !

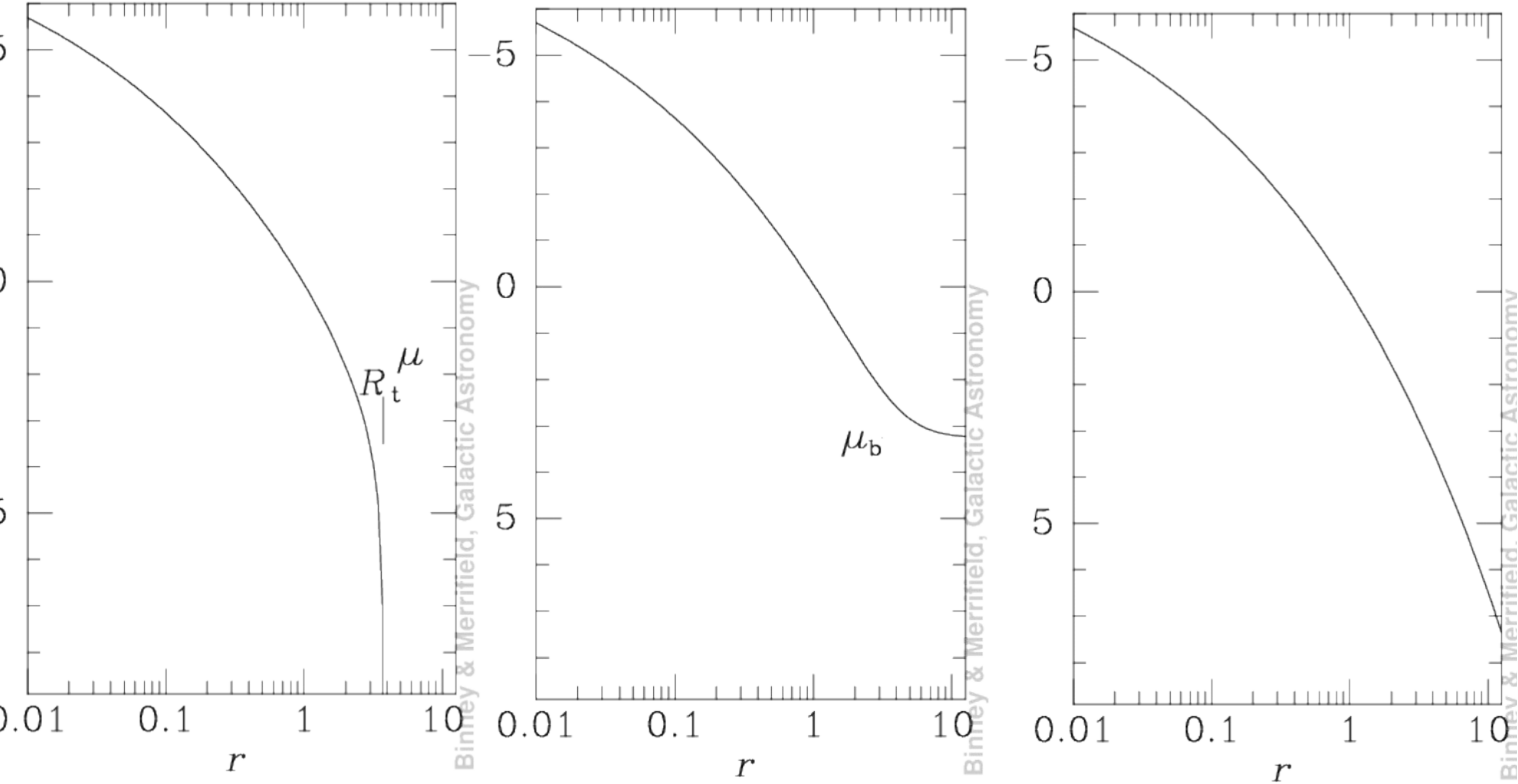
=>in fact associated to
The HI exetended disk

Stars ? Dust scattering ?
(Bland Hawthorn et al ; 2005)
Scattering from DM
(Davis & Silk 2015)
Scatering from hot gas ?
(Yamazaki & Loeb 2016)



J. Zhang

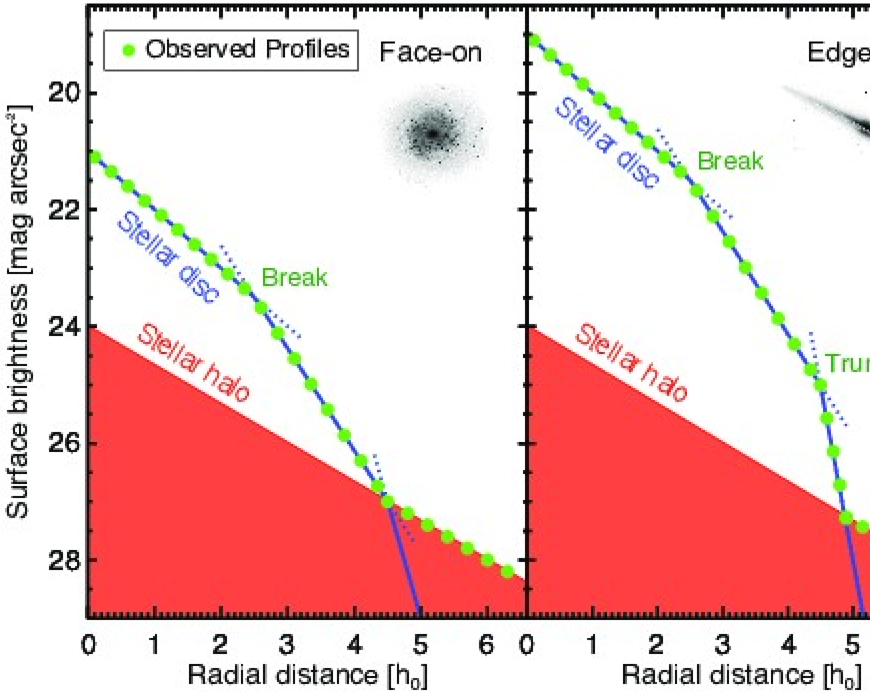
Radial profiles : sky substraction importance

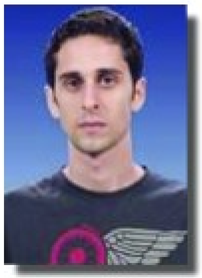


Binney & Merrifield book

Radial profiles : importance of the PSF

The measurement is simple *in principle*:





Martin-Navarro
2014

PSF tails and galaxy halo light 1525

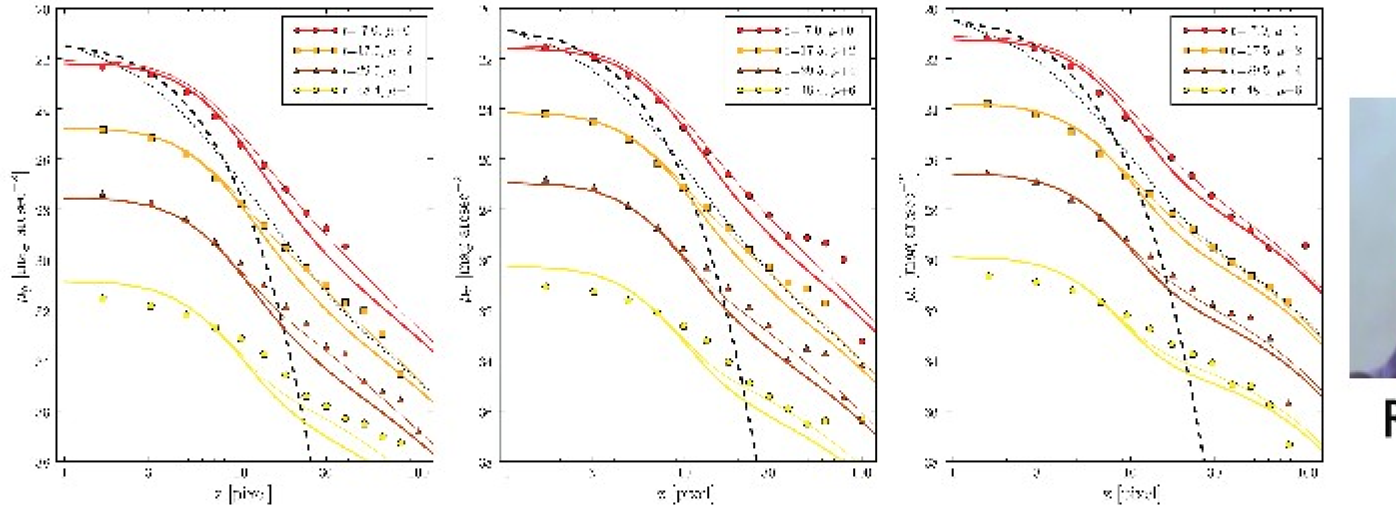


Figure 3. Light profiles parallel to the minor axis at four distances from the galaxy centre for the *g* band (left-hand side), *r* band (middle) and *i* band (right-hand

This is a surprisingly hard measurement and I'm a bit skeptical…

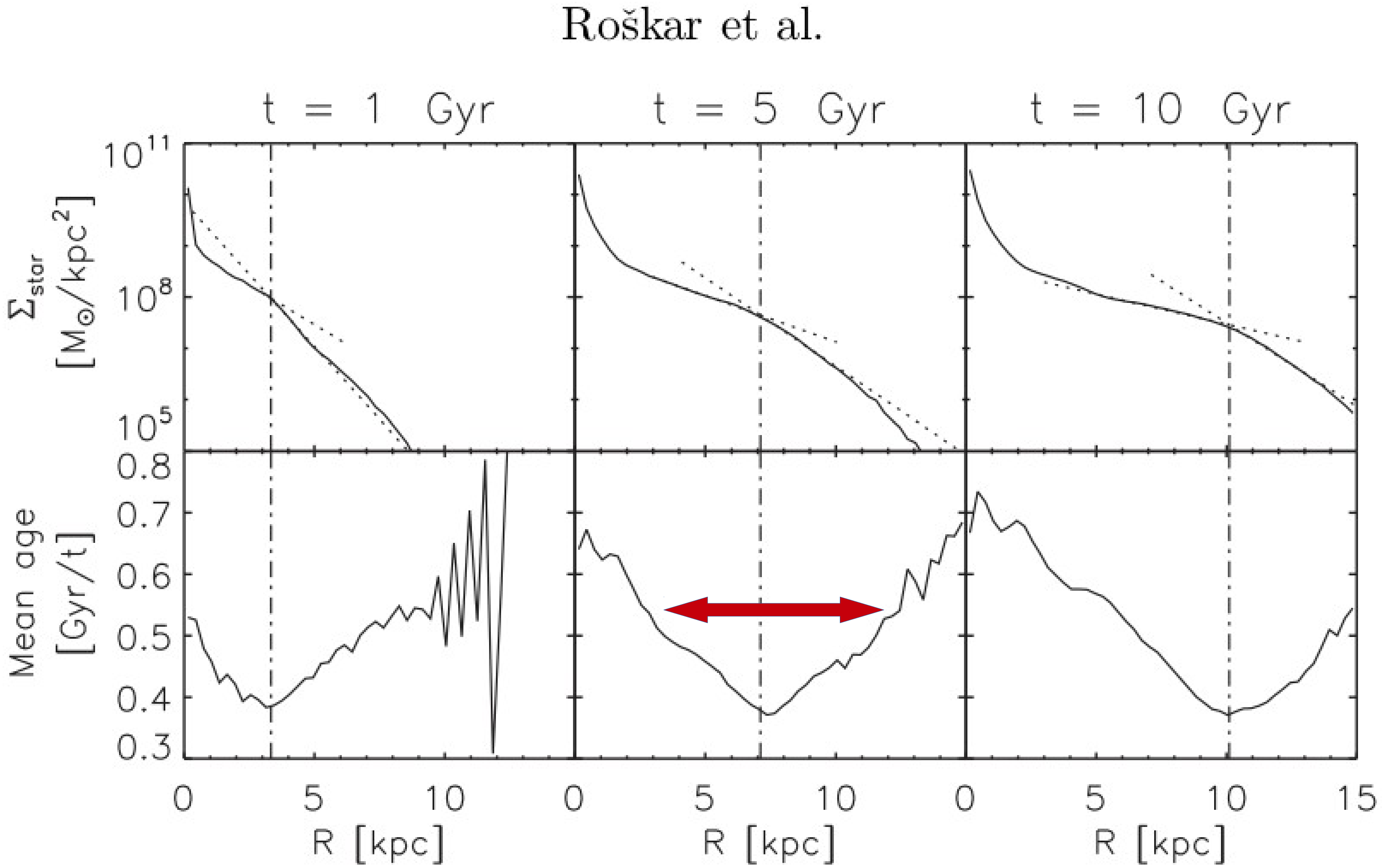
R. de Jong
2008

Possible origins

- Type II down-bending :
  - Ram-pressure stripping (Boselli et al. 2006)
  - Star formation threshold (Kennicutt 1989)
  - Bar-induced dynamical evolution (Minchev Famay, 2010)
  - Overlap of spiral and bar resonances (Minchev et al. 2011)
  - Resonant interaction by spiral arms (roskar 2008)
  - Corotation resonance of transient spirals (Sellwood & Binney 2002)
  - Satellites (Quillen et al. 2009)

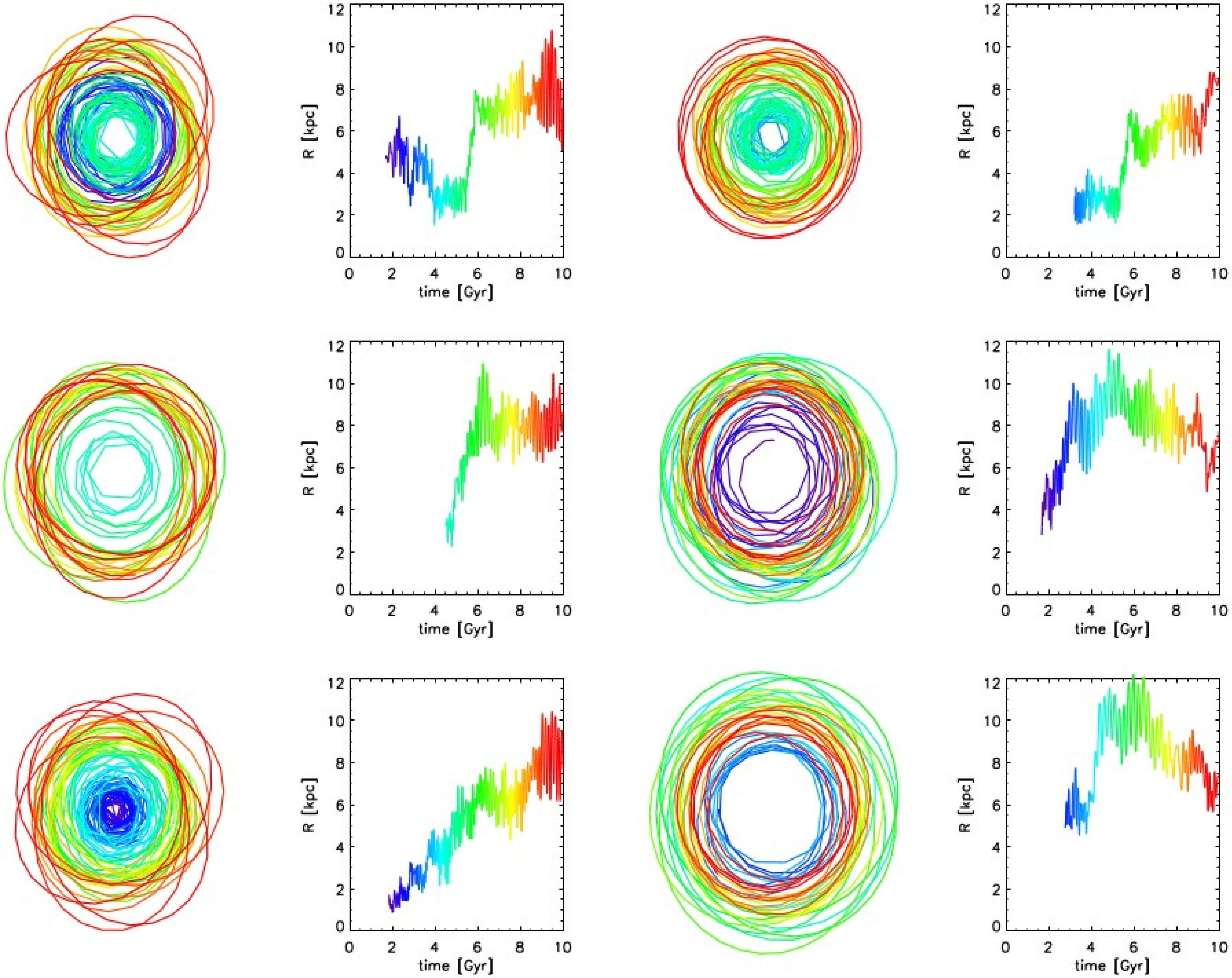
Possible origins

- Type III anti-truncated:
  - New accretion event ? Warps and XUV disks could be due to misaligned cold accretion at low redshift (Roskar et al. 2010).
  - Mergers (Athanassoula et al. 2016)
  - Interactions (LSB disks in e.g. Mapelli et al. 2007)
  - Bar (Head et al. 2015, Herpich et al. 2015)
  - Stellar haloes oushining the disk at large radii (Maltby et al. 2015 : few galaxies explained like this)



N-body + SPH simulations :

- implement star formation with a break
- recuring transient spirals => scattering of stars


R [kpc]
0
2
4
6
8
10
12
time [Gyr]
0
2
4
6
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10
R [kpc]
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2
4
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8
10
12
time [Gyr]
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2
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R [kpc]
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time [Gyr]
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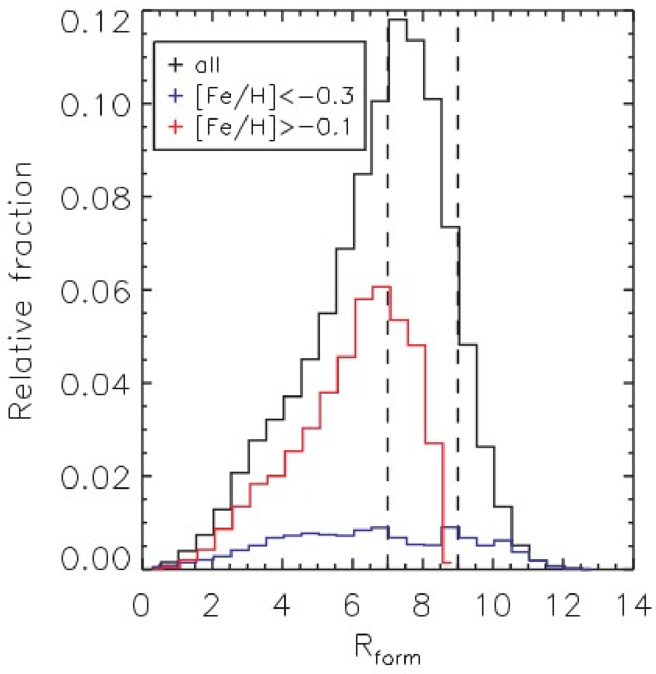
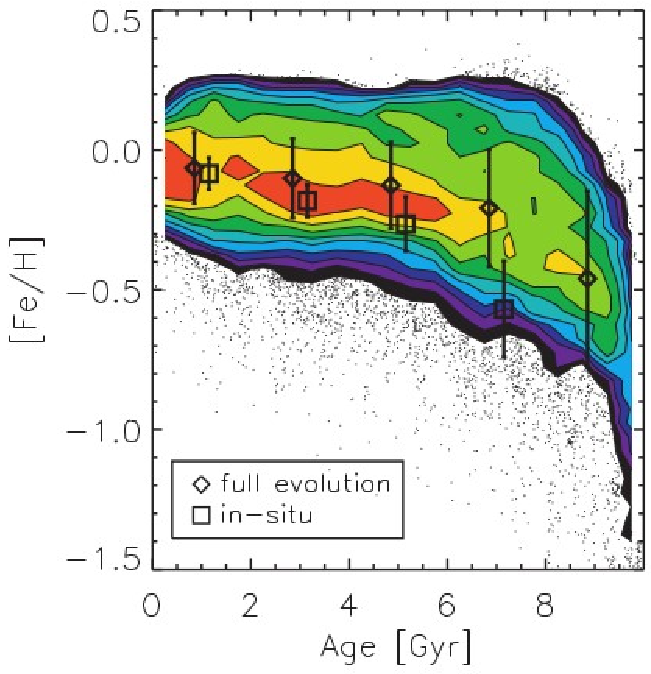
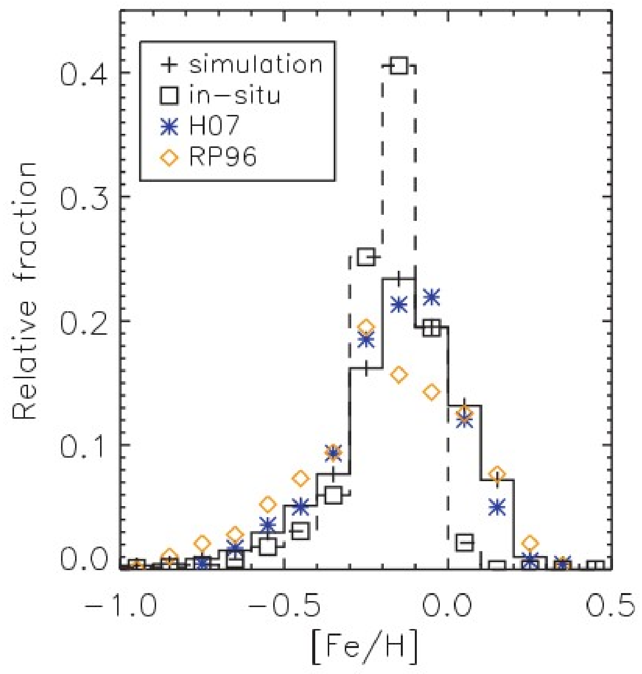
Consequences for chemical evolution

- May solve g-dwarf problem in Solar neighborhood
- May better explain a flat age-metallicity relationship
- May explain dispersion
- May explain thick disk ?



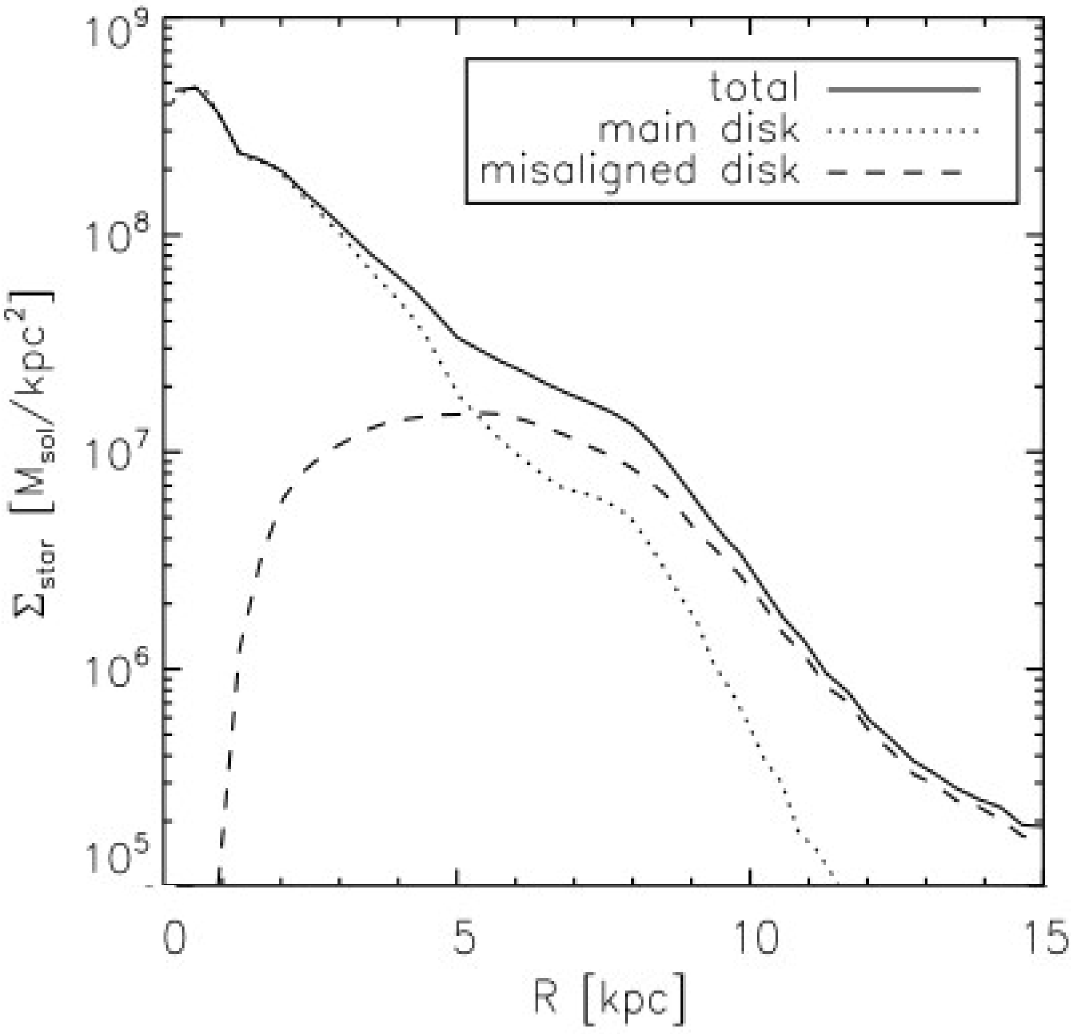




See also Kubryk, Prantzos, Athanassoula 2013

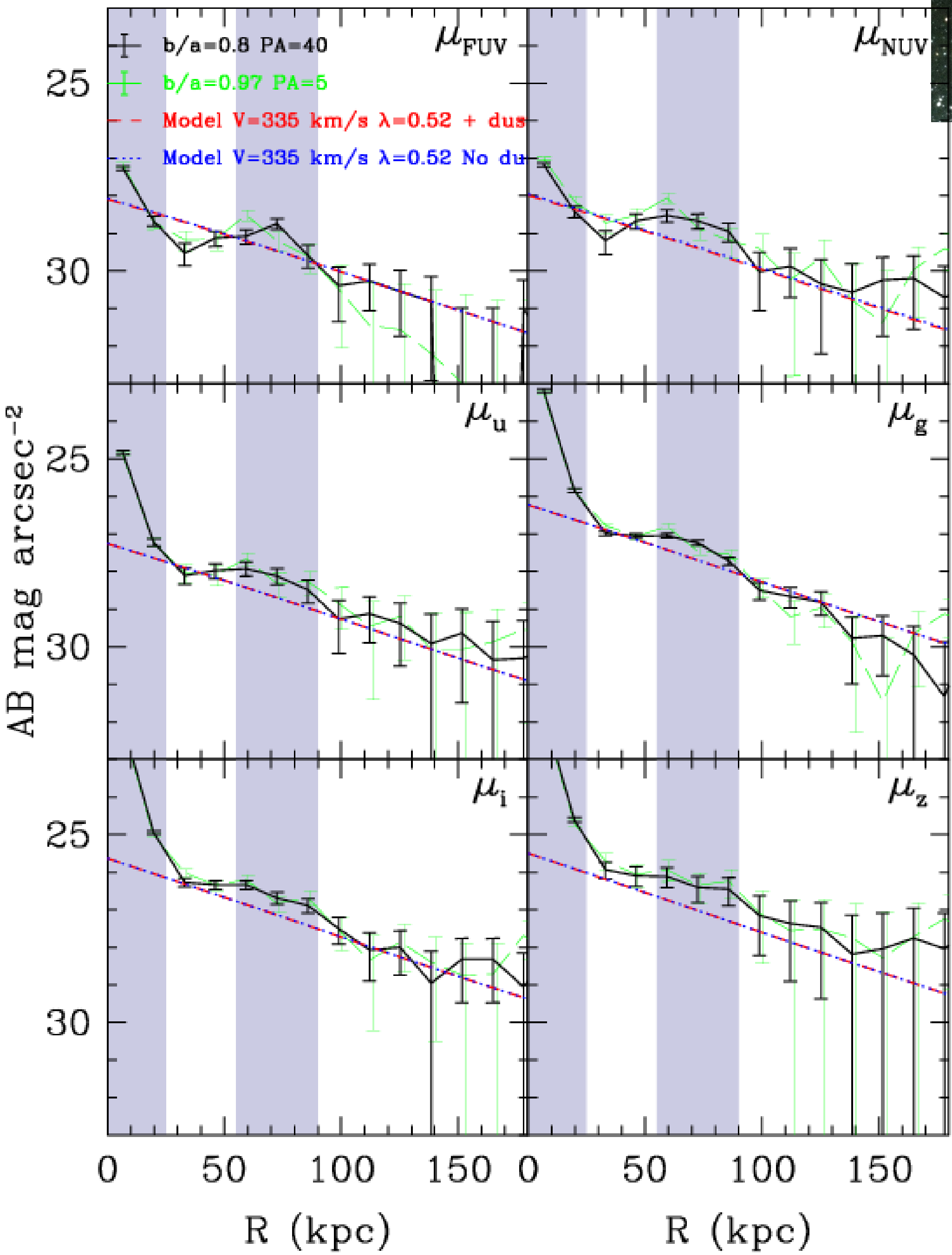
Roskar et al. 2010

Misaligned accretion : main disk + misaligned disk



Malin 1

Boissier et al., 2016, submitted



The extended disk profiles and colors are consistent with a « normal » disk with a very large angular momentum.

Accretion of a second disk, independent of the central one ?

Athanassoula et al. 2016

Formation of a disk after a wet merger

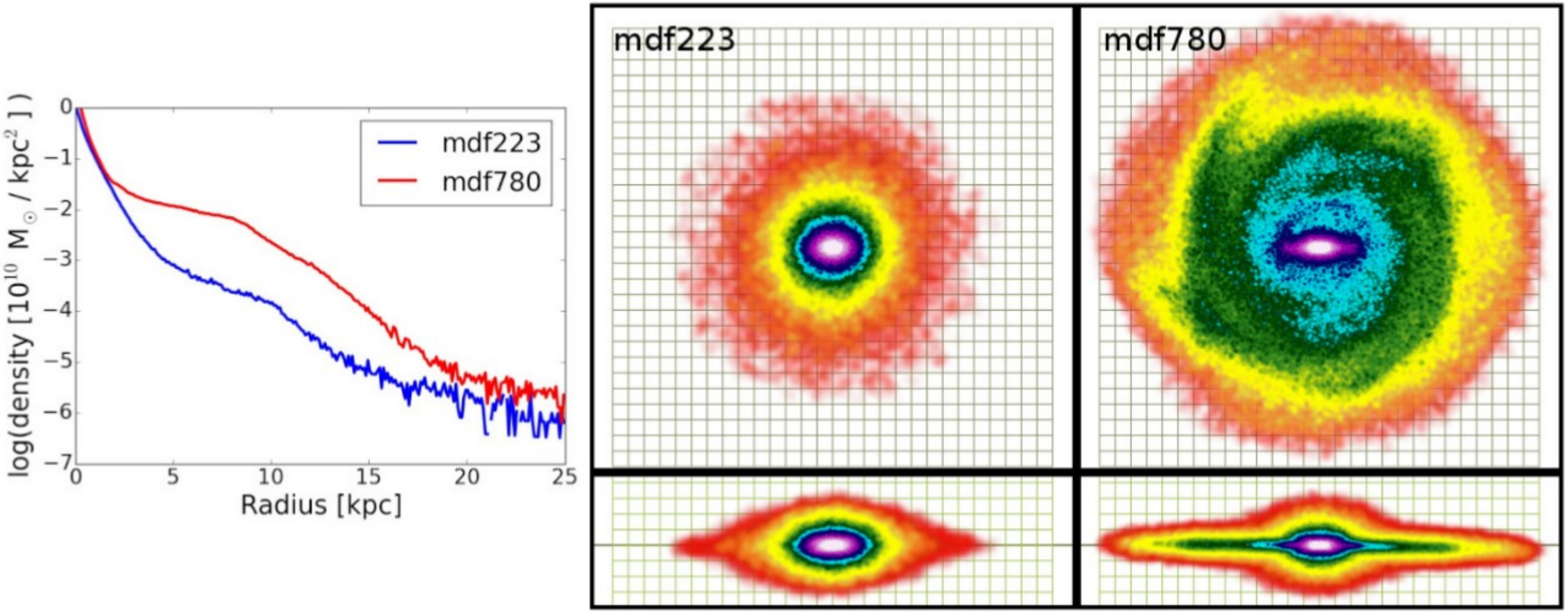
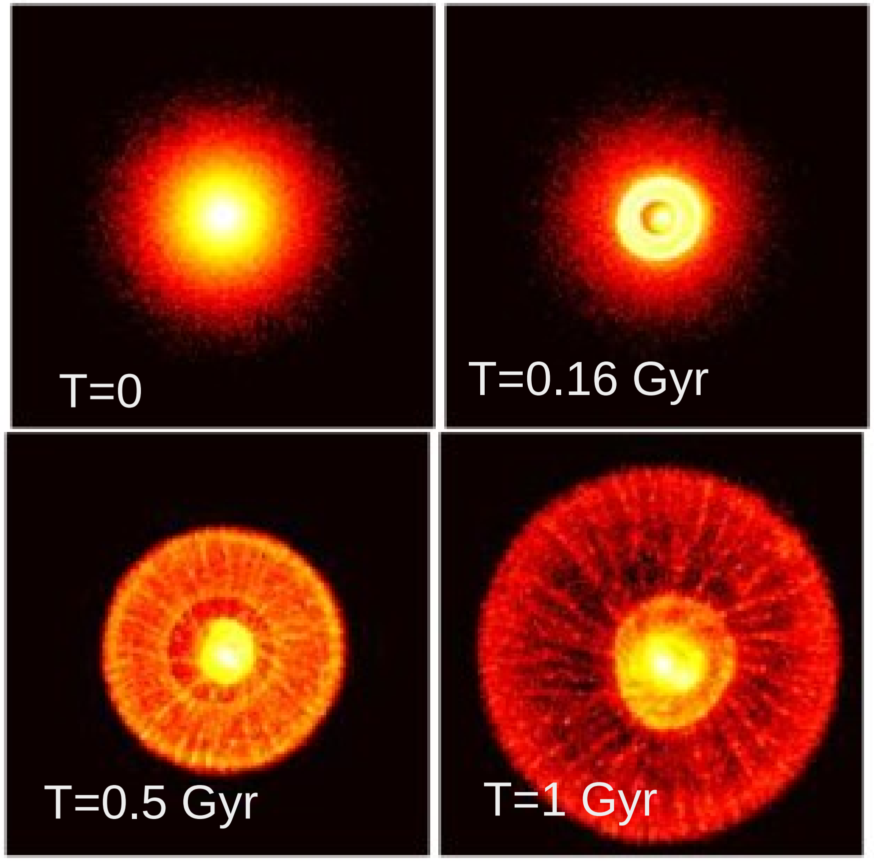
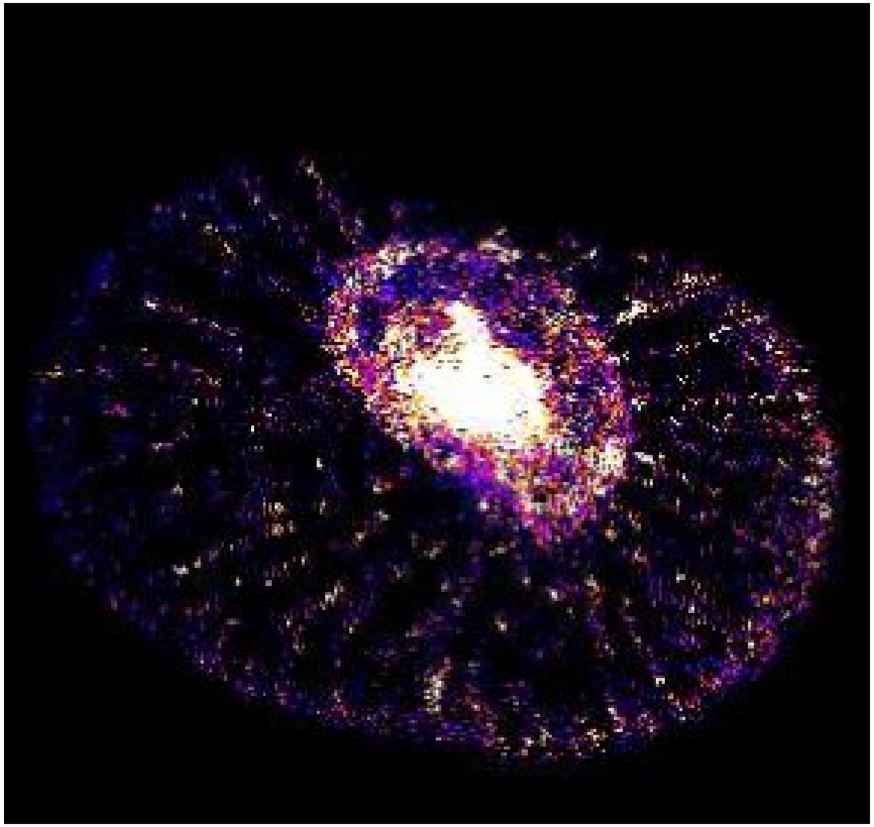


Figure 8. Comparison of two simulations, one with (mdf780) and the other without (mdf223) a hot gaseous halo, both at time t=10 Gyr. Left: The radial projected stellar surface density profiles. Middle: Face-on (upper) and edge-on (lower subpanels) views for mdf223. Right: Same for mdf780. Note the big difference in the disk extent and in its mass relative to the classical bulge component.

Mapelli et al. (2008) : formation and evolution of ring galaxies during head-on collisions

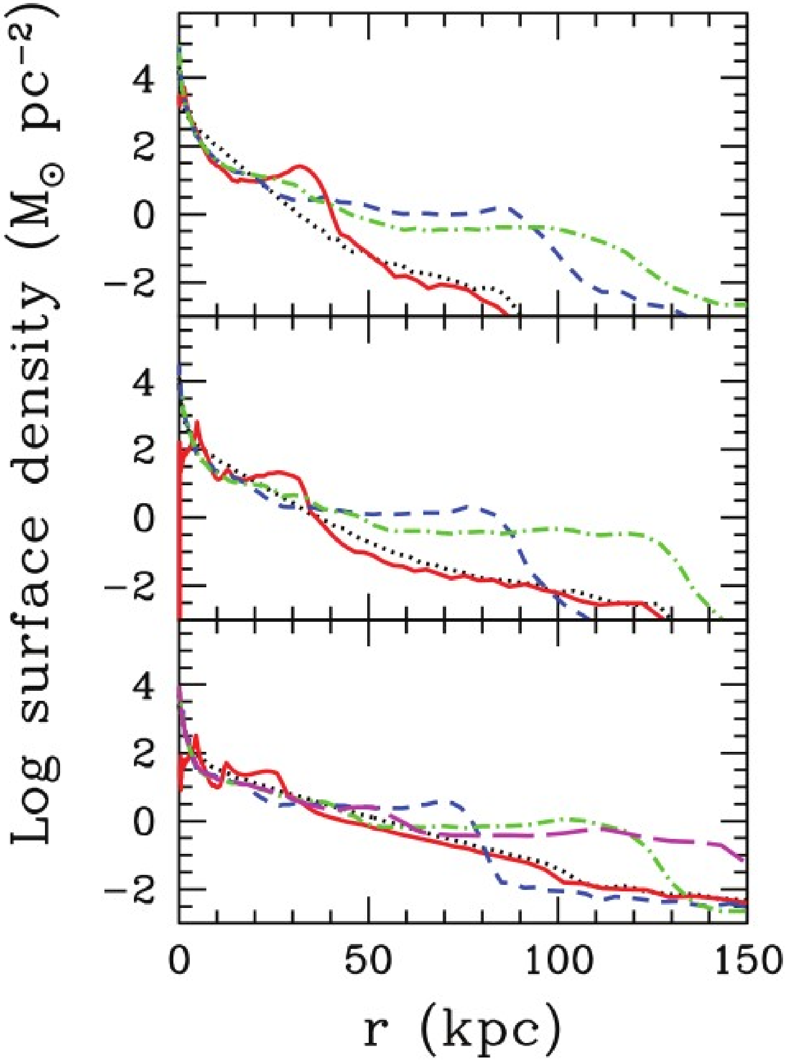


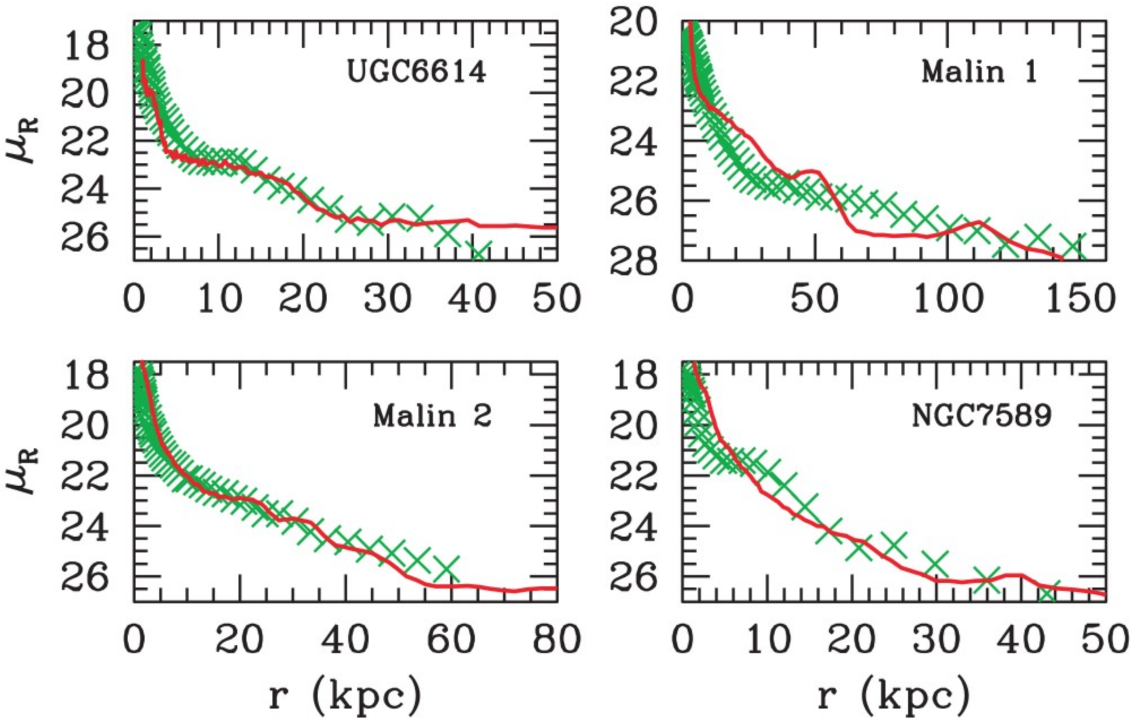
Simulation of the evolution



Prediction for Malin-1 like galaxy

Mapelli et al. (2008) : formation and evolution of ring galaxies during head-on collisions





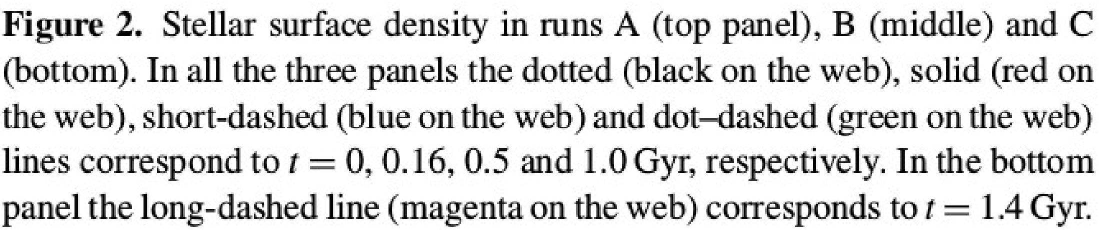
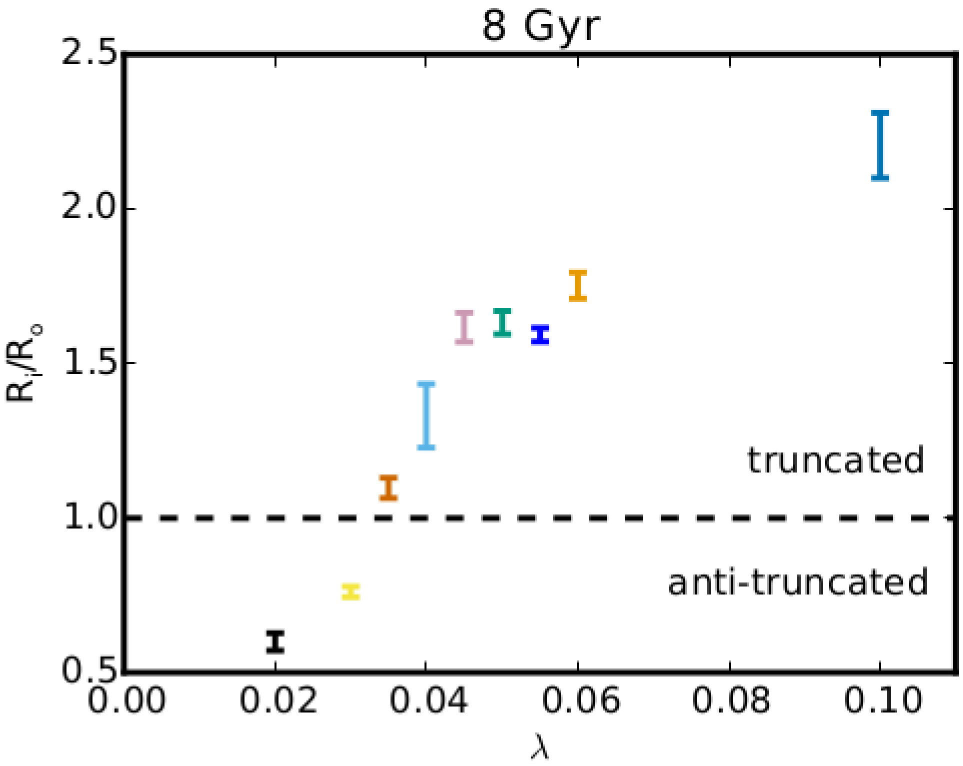


Figure 2. Stellar surface density in runs A (top panel), B (middle) and C (bottom). In all the three panels the dotted (black on the web), solid (red on the web), short-dashed (blue on the web) and dot–dashed (green on the web) lines correspond to $t = 0$, 0.16, 0.5 and 1.0 Gyr, respectively. In the bottom panel the long-dashed line (magenta on the web) corresponds to $t = 1.4$ Gyr.

Anti-truncated disks with the Bar...



Herpich et al. (2015) simulations suggest :

- the spin parameter of the halo decide the shape of the profile

- orbital resonance put stars on eccentric orbits that form an extended disk with high radial dispersion and low rotation.


20 kpc