Observing Simulations:

current limitations & future opportunities

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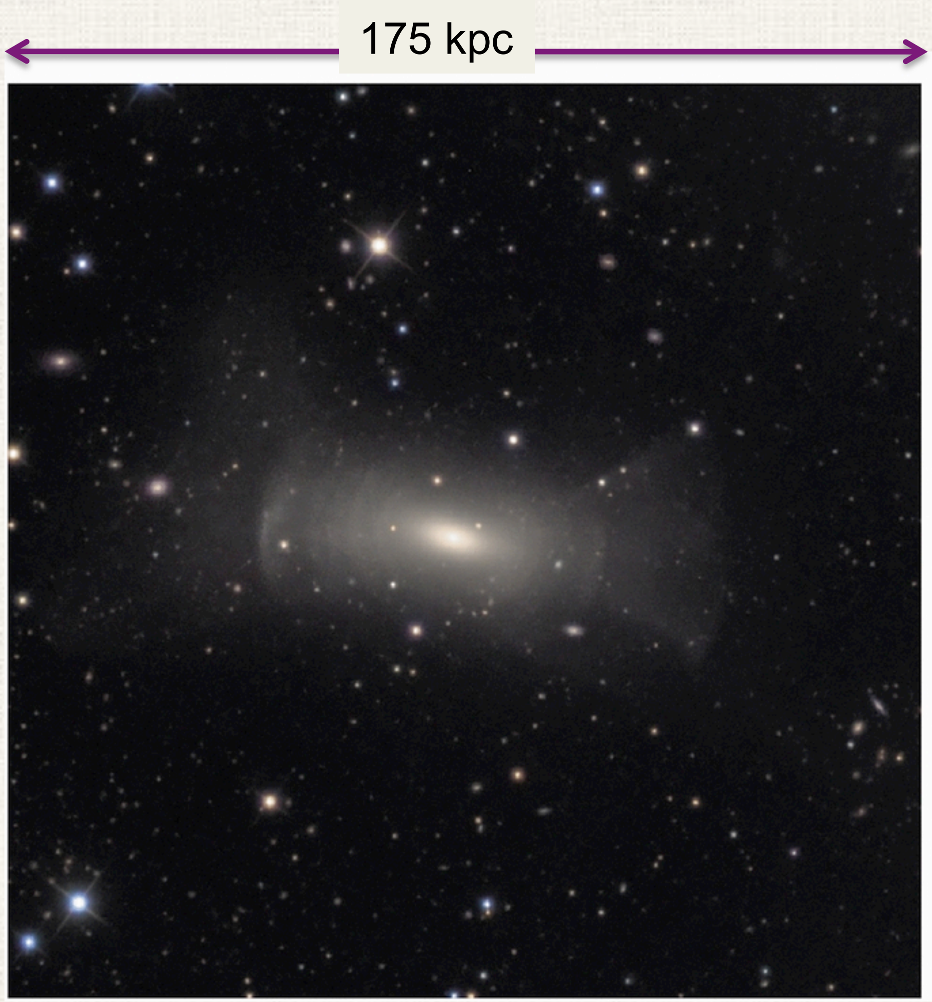
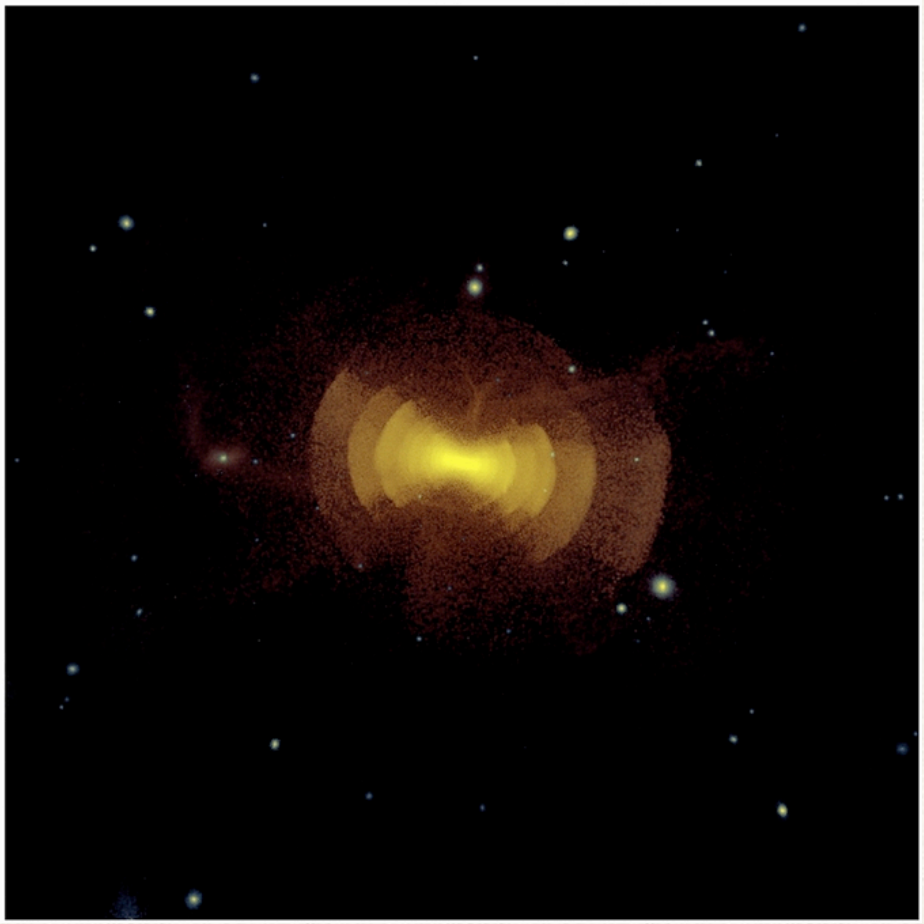
Simulations successfully reproduce observed galaxies

From Cooper + 2011, ApJ 743, L21

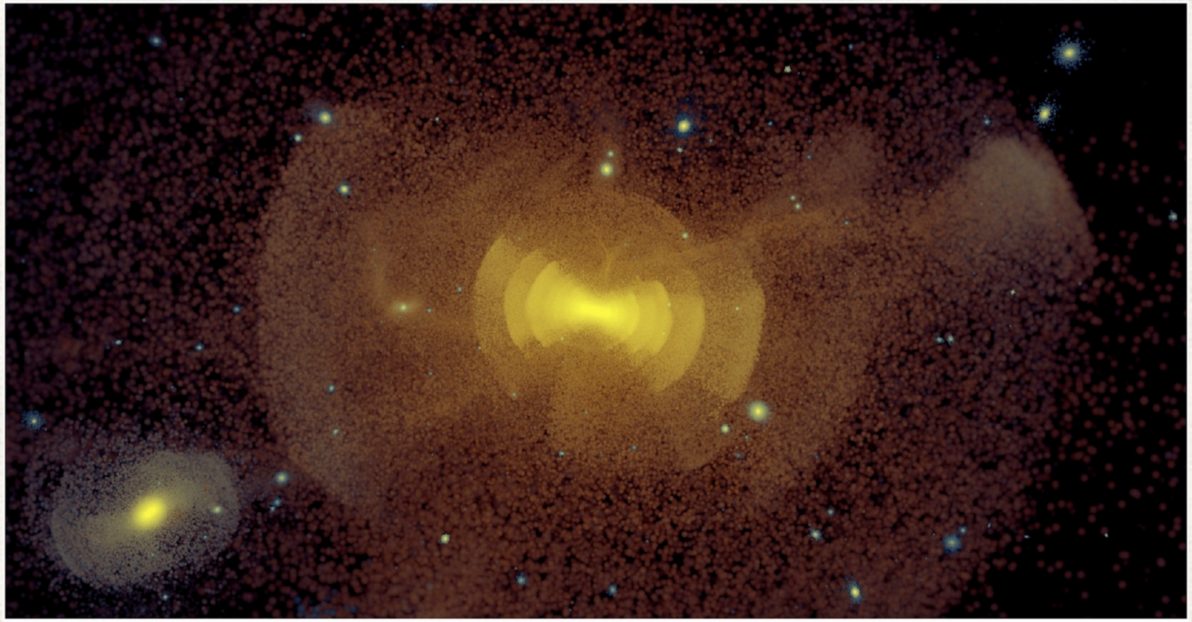
Image of NGC 7600

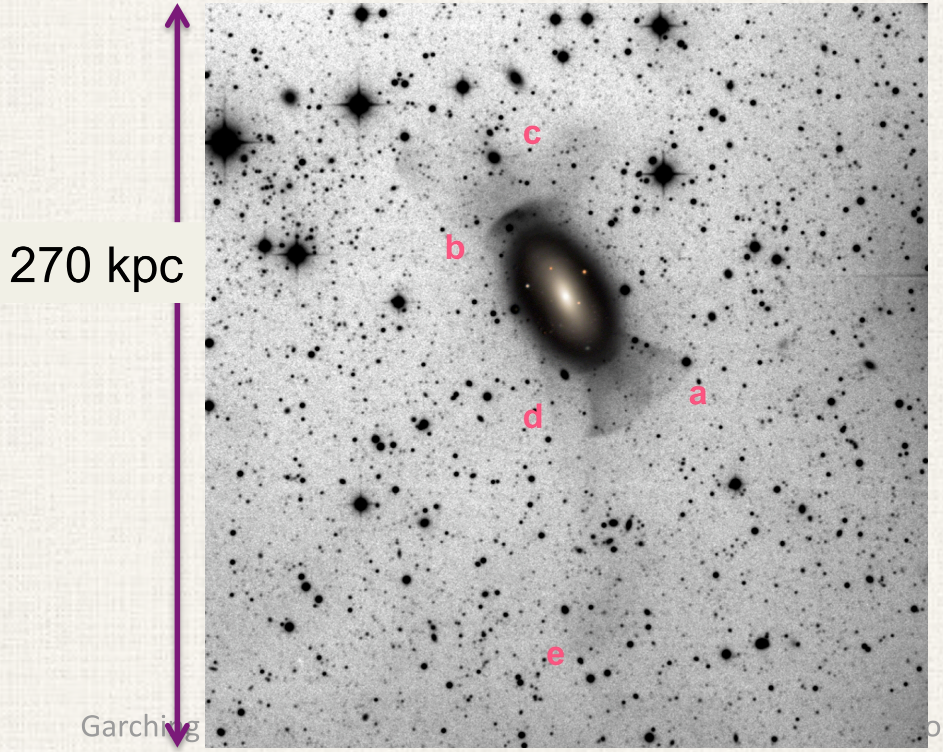


Aquarius Aq – F – 2 halo at z=0

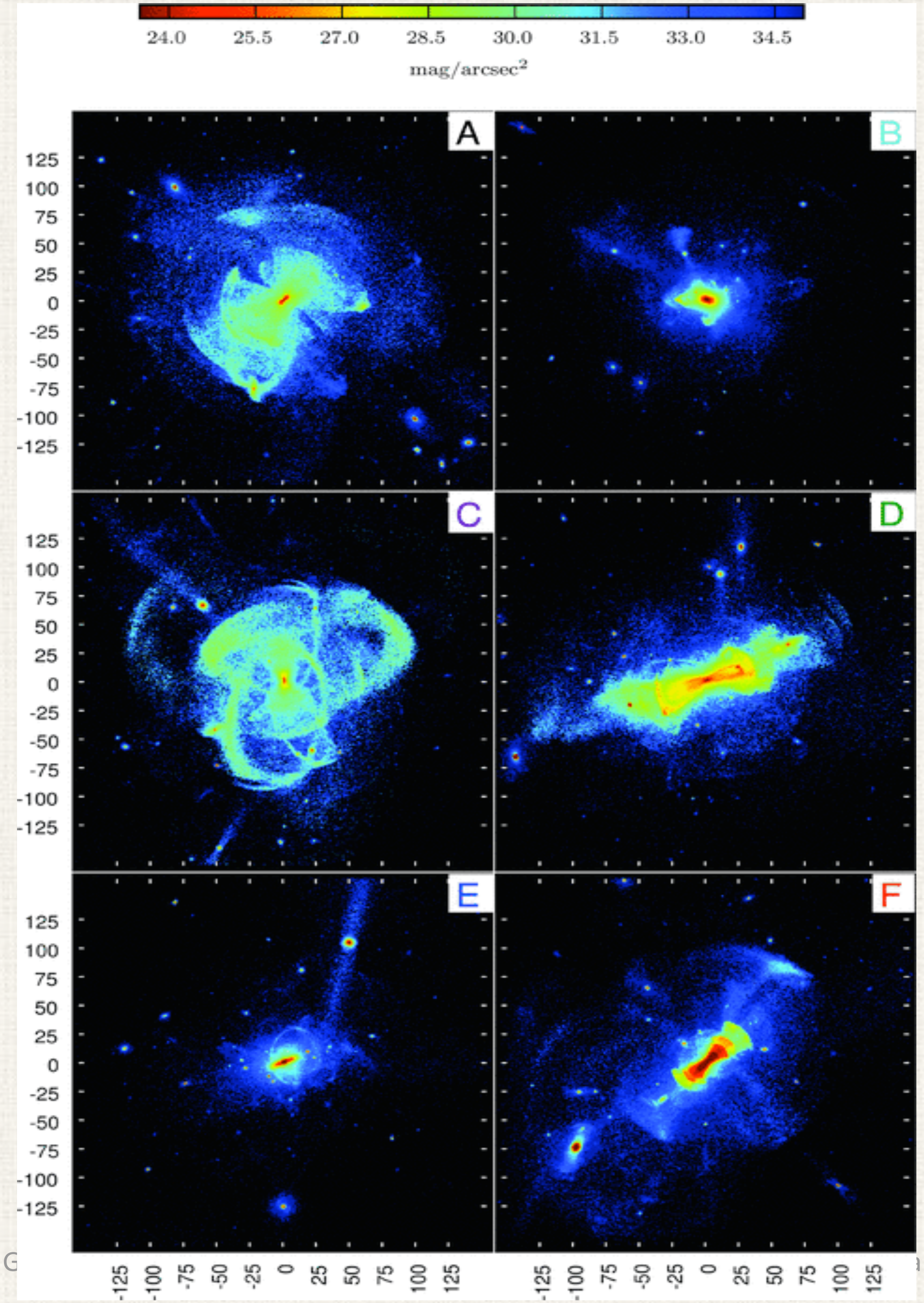


Stellar debris are spread over a very wide volume





Very deep image of NGC 7600 in Luminance filter (3500 < λ < 8500)
Total exposure of 11.33 hr



Six Aquarius haloes
From Cooper + 2010

A large variety of final shapes for the distribution of the accreted stars, related to the merging history of the halo

In the outer parts the stellar halo is extremely loose reaching 35 mag/arcsec^2

Even within a common cosmological context models predictions are different

Two major techniques : hybrid models versus full hydro simulations
+ details: different resolutions / volume size / halo size
Different prescriptions for baryonic physics
processes included / recipes to describe SF, feedback ..,

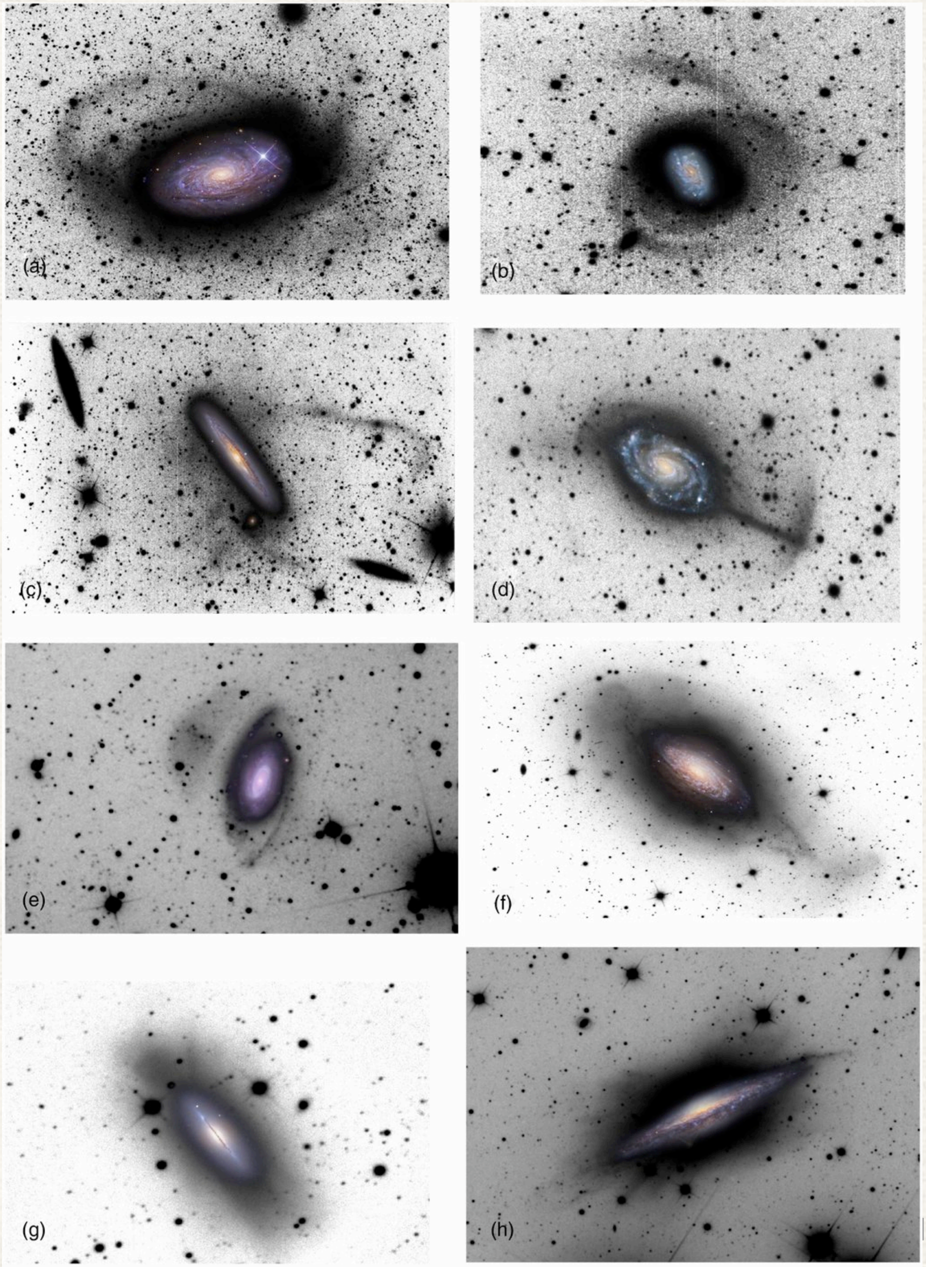
This is GOOD because it means that we can learn something from the comparison of models to the observations

How do we compare theoretical simulations to the observations?
What can se learn from this comparison?

among the various issues I consider here:

- Frequency and characteristics of substructures in galaxy halos
- Profile and 2D shape of the stellar mass distribution of galaxy halos
- Metallicity gradients in stellar halos

Question 1: demographics of substructures



Stellar halos are NOT smooth

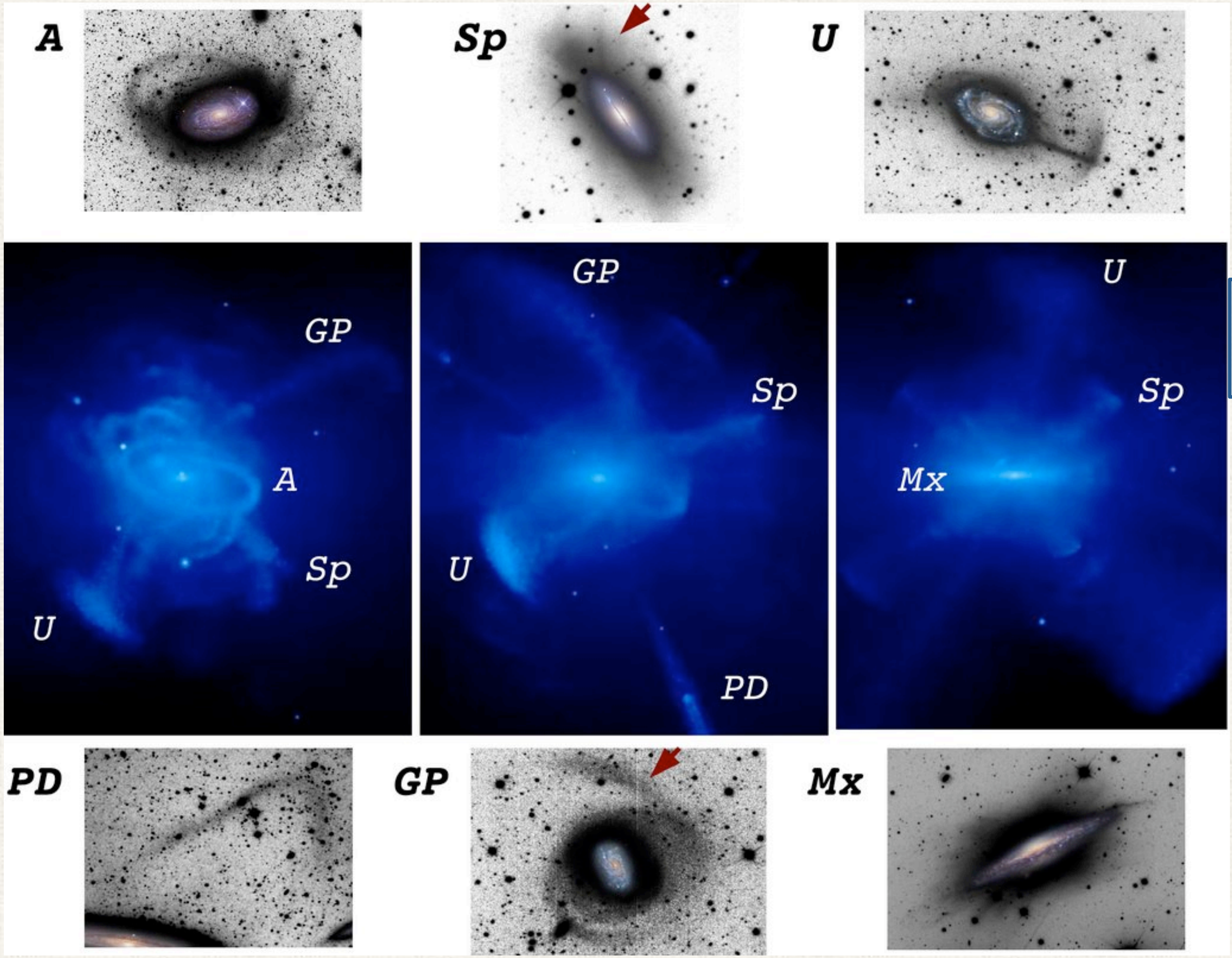
Martinez-Delgado + 2010 :
images with luminance filter
at small (< 0.5 m) telescopes
exposures between 6 and 18 hrs

A large variety of patterns

shapes likely related to the geometry of accretions

patterns need to be classified

A: great circle SP: spikes U: umbrella

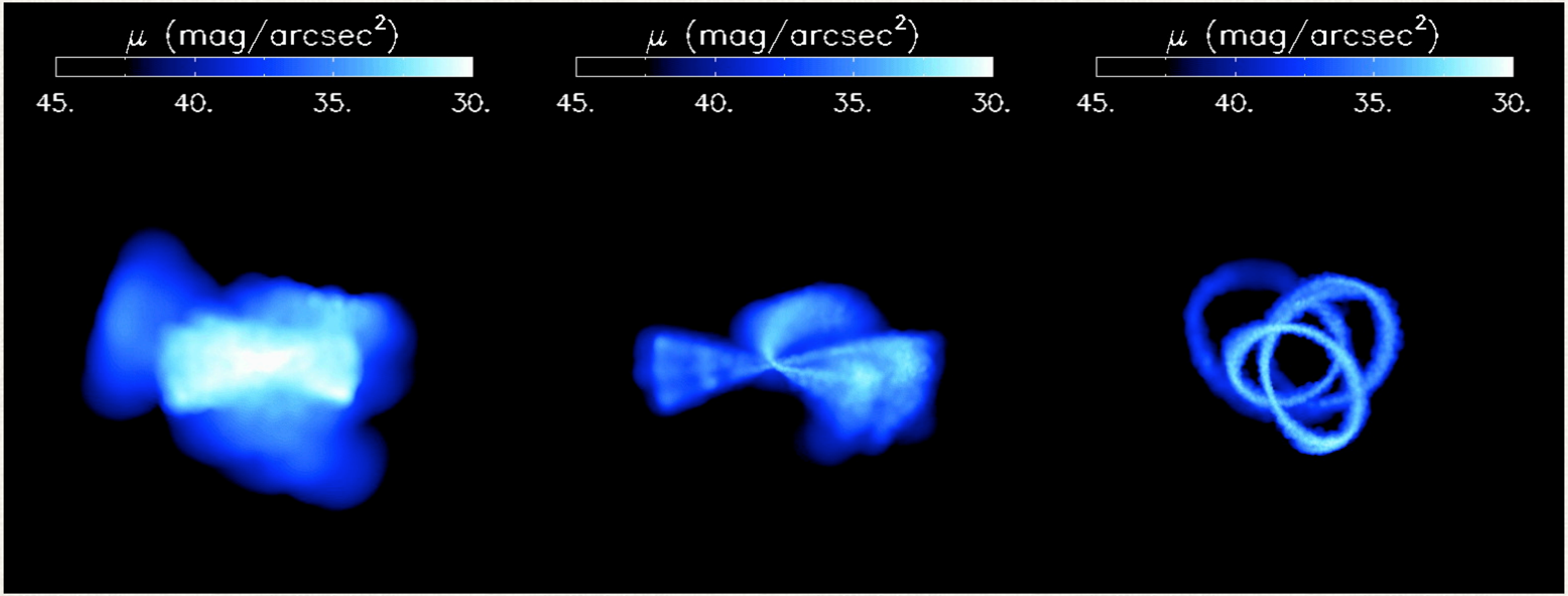


PD: partially disrupted GP: giant plumes Mx: mixed

Johnston+ 2008 models

Similar variety of shapes in dynamical models of halo formation from accreted and disrupted satellites

Johnston + 2008 models:
three major types of debris morphologies



Mixed

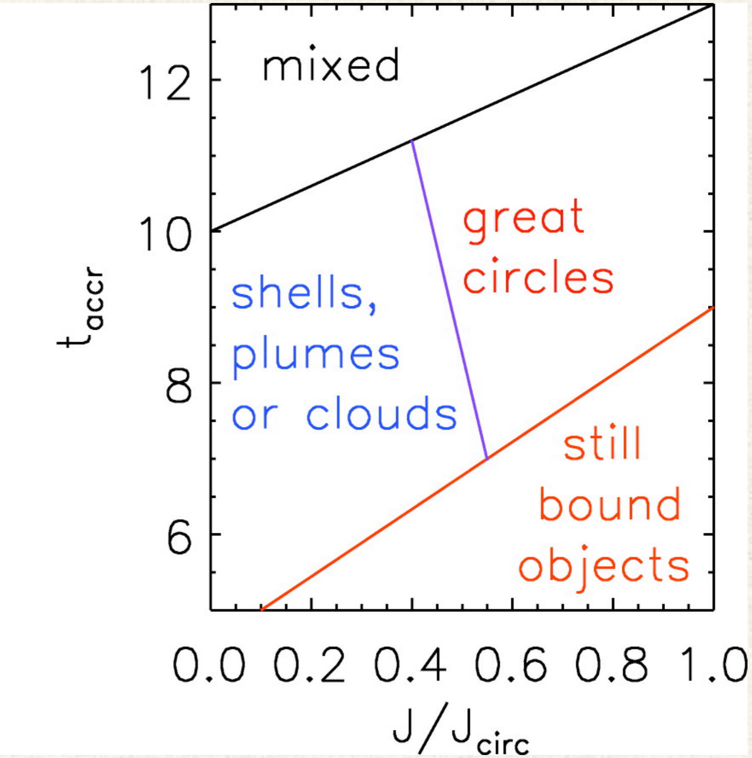
Shells, Plumes, clouds

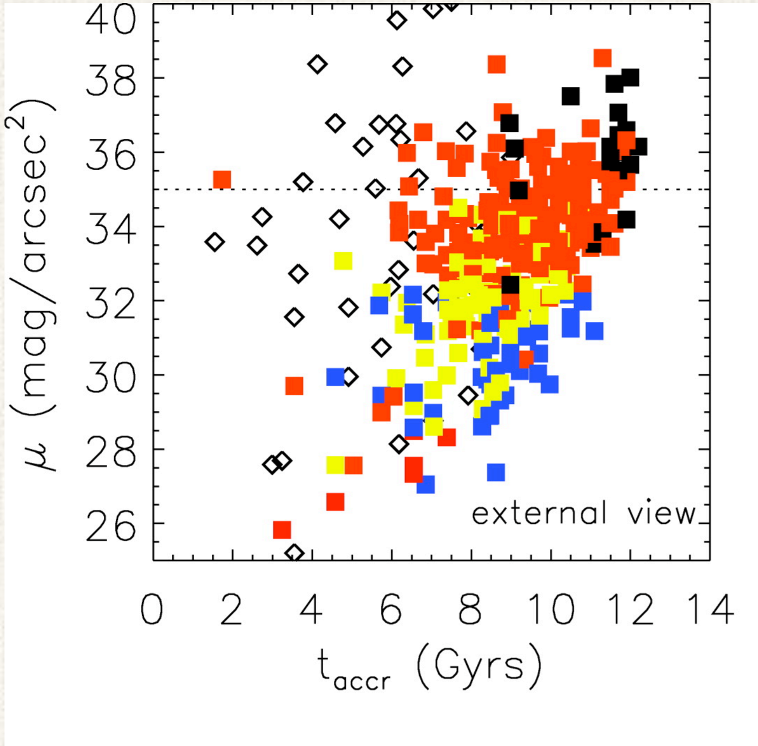
Great Circles

Different morphologies correspond to different characteristics of the accretion events

Mixed morphologies are obtained for ancient and radial mergers
Great Circles for satellite accretion on circular orbits
Shells/plumes are produced in relatively recent mergers

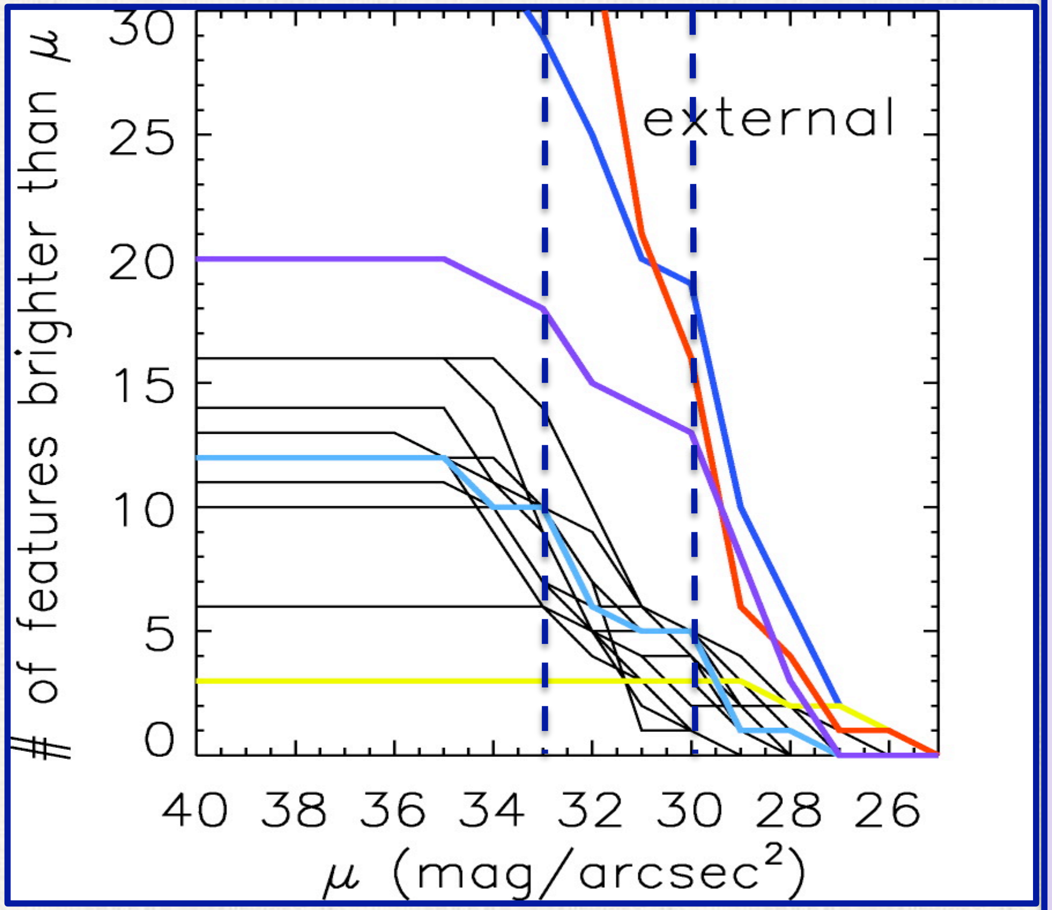
The older the accretion event the fainter its SB
More massive satellites (blue) provide brighter substructures





One can reconstruct the build up of the halo from the analysis of its substructures

SB distribution of features



Most features are fainter than SB = 30
Most features are brighter than SB = 33

Johnston + 2008 models:

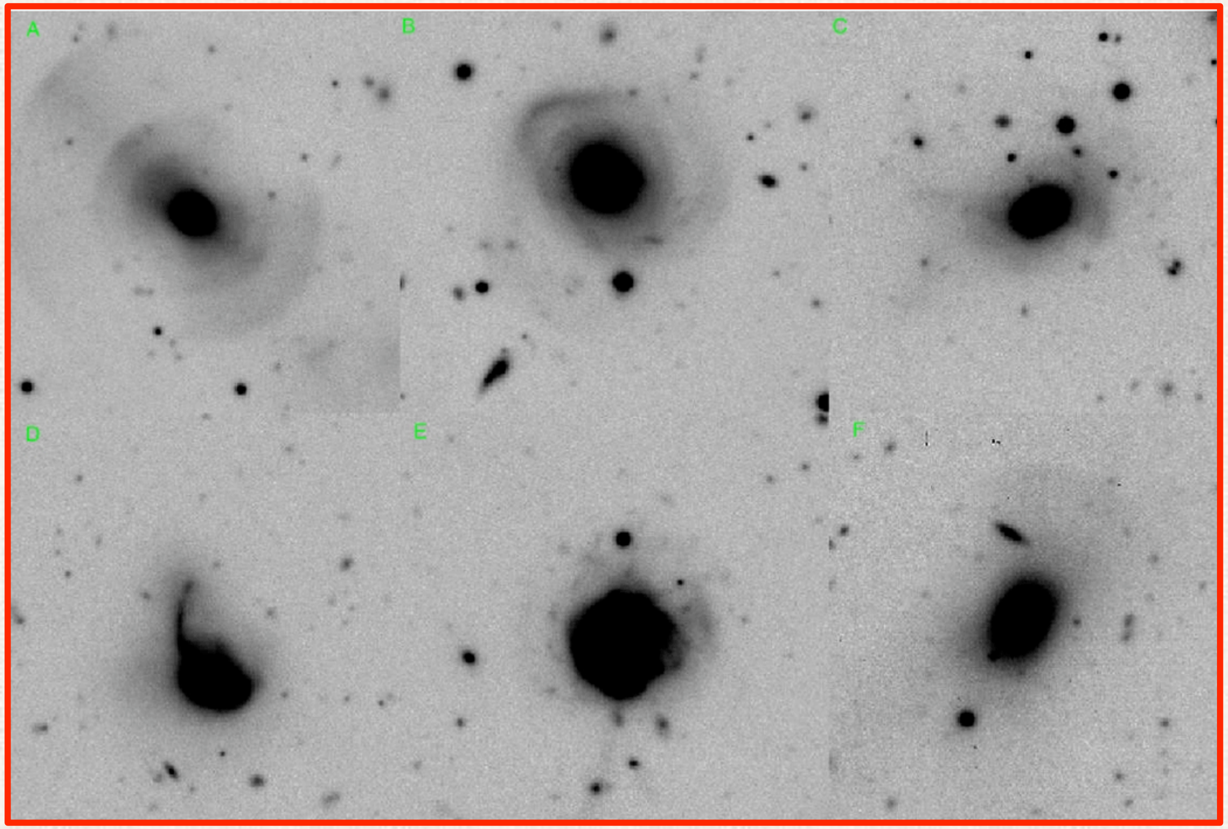
A MW type galaxy halo

- hosts ~ 2 features SB<30
  ~ 10 with SB < 33
- contains ~10 % of its mass in substructures
- hosts a similar share of great circles and shells
- great circles should be found at d ~ 20 – 50 Kpc, shells out to d ~ 100 kpc from the centers

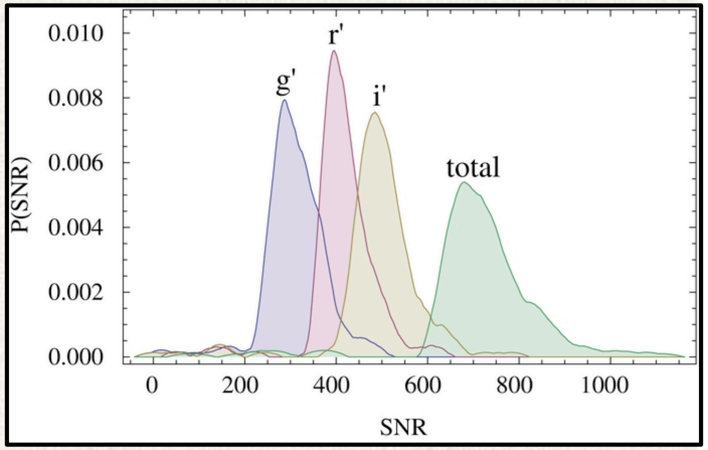
Atkinson, Abraham, Ferguson 2013:
Survey of faint tidal features in galaxies in $0.04 < z < 0.2$

Morphologies classified as:

Shells Streams Diffuse

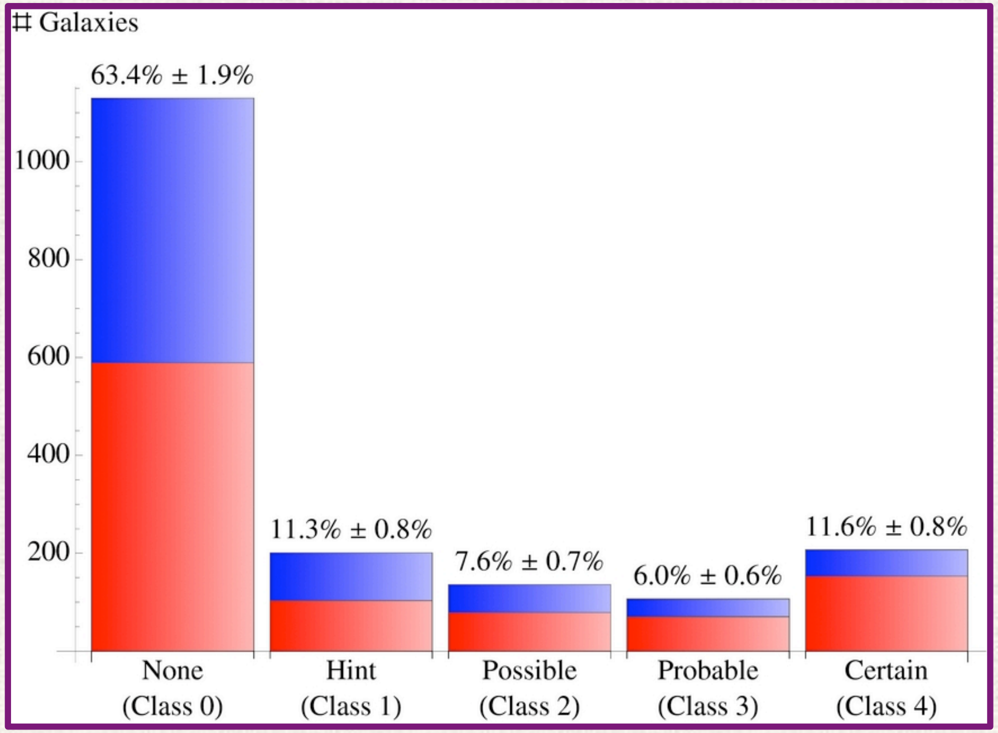


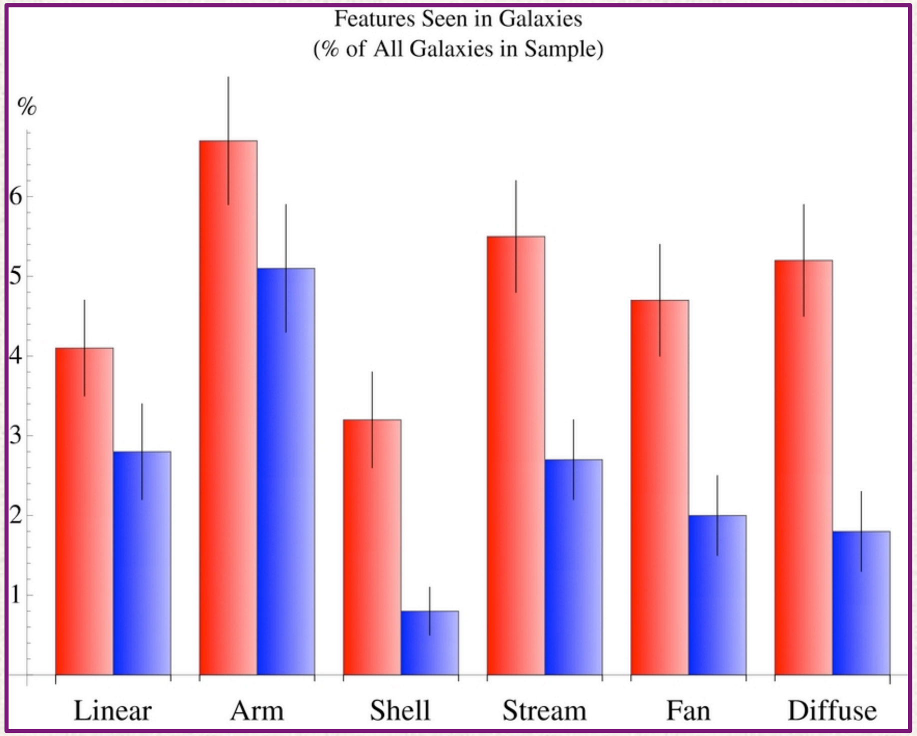
Arms Linear Fan



Detection at SB(g) <~ 27.7 signal enhanced by stacking g, r and i

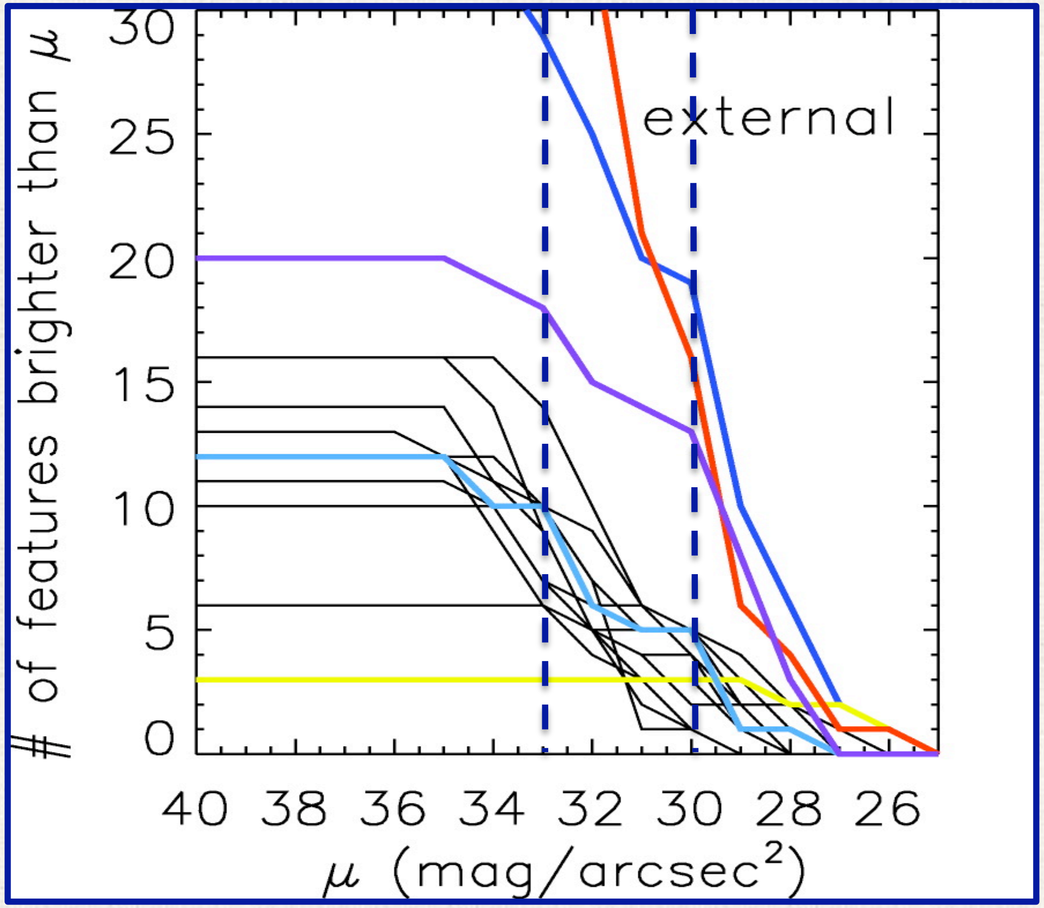
Statistics of the tidal features:
Only 20 % of the (~1800) galaxies show tidal disturbances
More frequently seen in red rather than blue galaxies
Arms is the most frequent shape





Other surveys yield not too different frequencies, but Van Dokkum + 2005, who finds a x 2 larger frequency (for red galaxies), and reaches fainter SB by about 0.8 mag

Johnston's models: at SB brighter than 29 very few tidal features are expected To compare predictions to observations we need to reach fainter than SB ~ 30 mag/arcsec^2



SKY surface brightness:
(@ Paranal)
B band : 22.2 mag/arcsec^2
V band : 21.6 mag/arcsec^2
I band : 19.4 mag/arcsec^2

Measurements below 0.5% (~ 6 mag) of the sky are extremely hard

The stellar halos at low surface brightness can be sampled with single star photometry

Relation between surface brightness and star's surface density

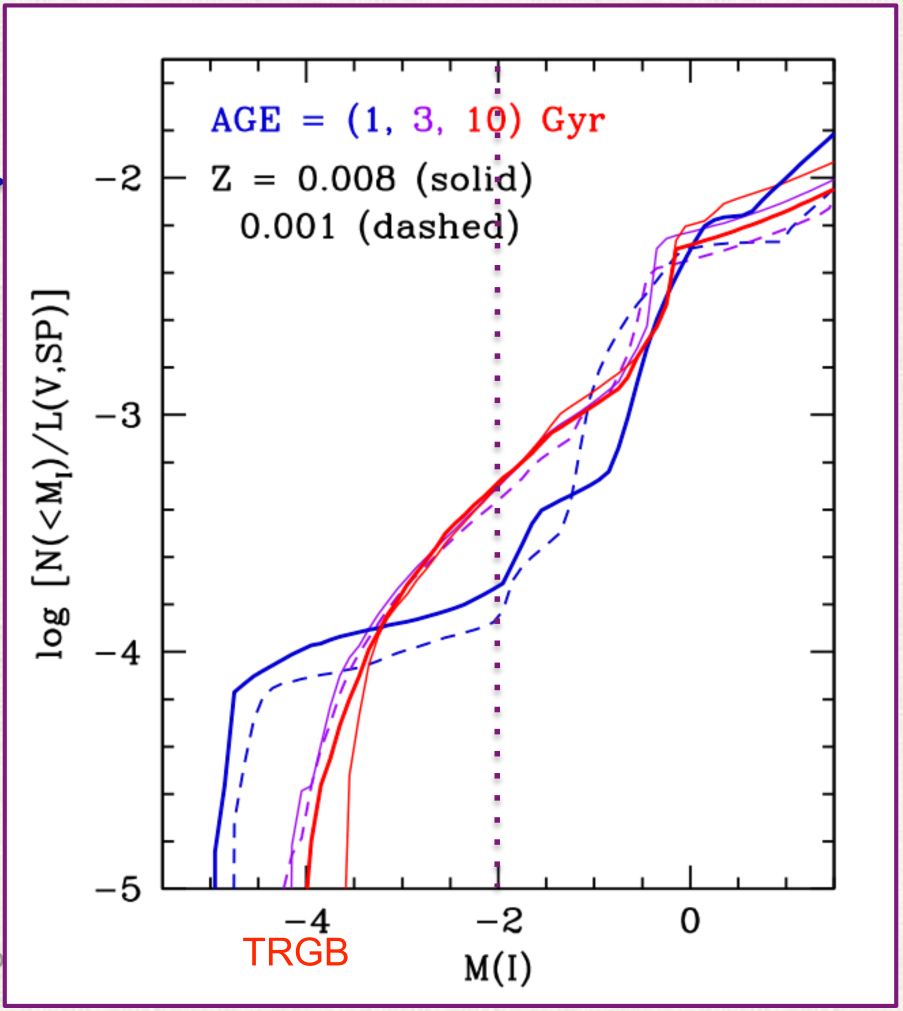
$$\mu = -2.5\log\frac{L}{A} + M_o + DM$$
$$= -2.5\log\frac{N_{<M}}{A} + 2.5\log\frac{N_{<M}}{L} + M_o + DM$$

$N_{<M}$ is the number of stars brighter than M

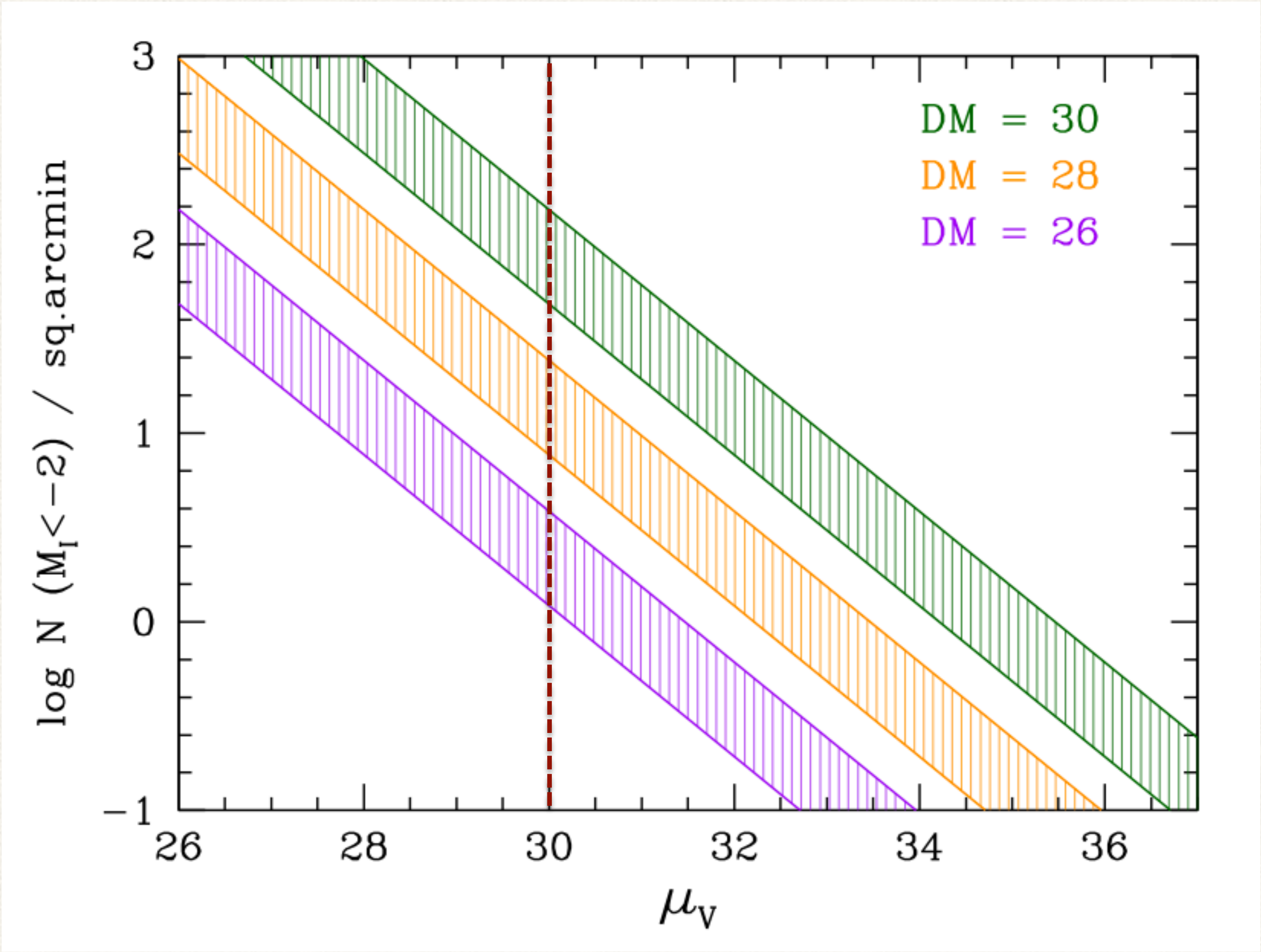
DM is the distance modulus

M_o is the magnitude of the sun

For 6 SSPs:
Number of stars brighter than M(I) normalized to the total V luminosity of the SSP as function of M(I)



There are ~ 2 10^{-4} (YOUNG)
5 10^{-4} (OLD)
stars brighter than M(I) = -2 per unit V-band luminosity of the parent stellar population



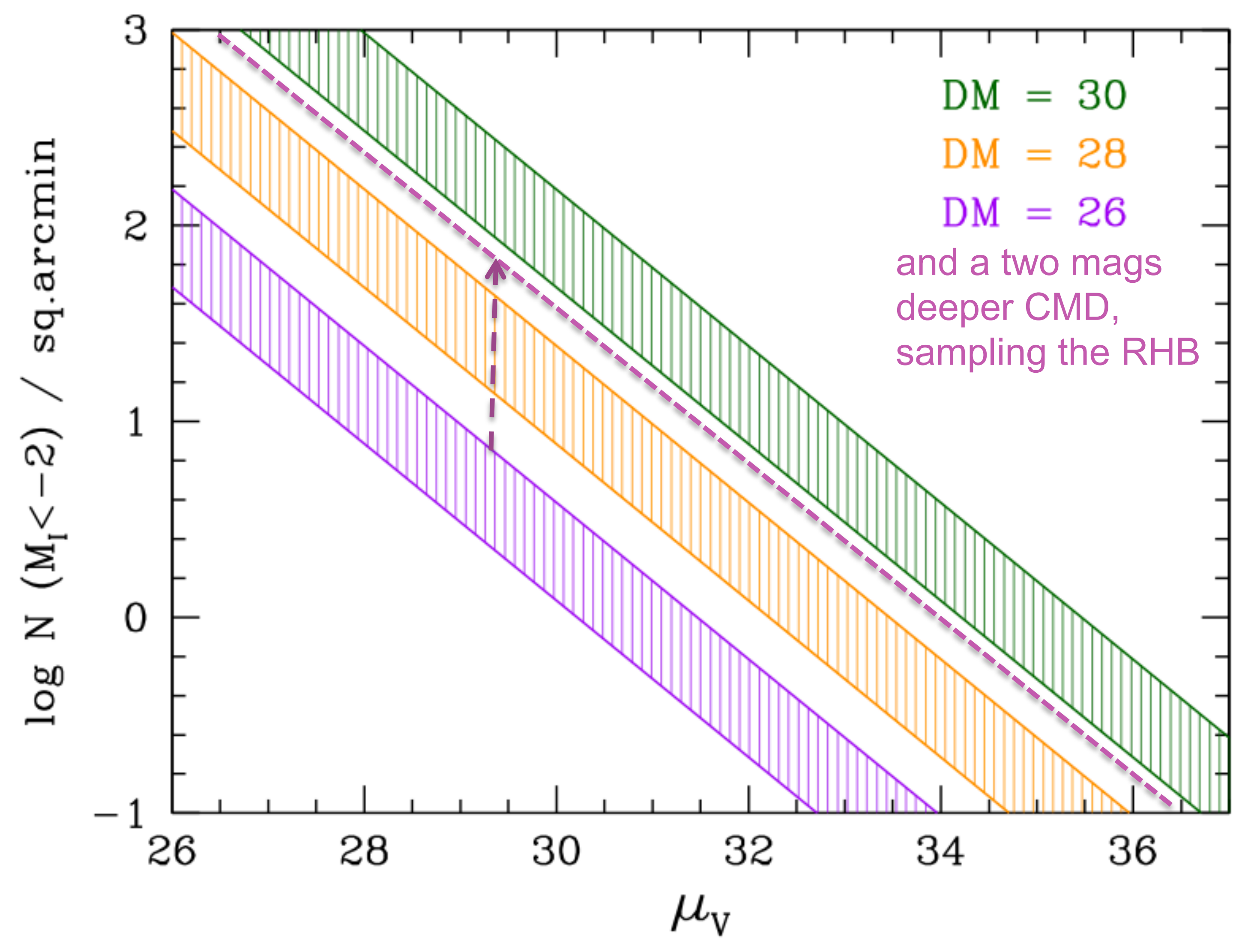
Using the upper 2 mag on the RGB, at the edge of the LG we need wide FoV to build up statistics at faint SB

Statistics improves at large distances but deeper photometry is needed to reach 2 magnitudes below the RGB Tip

Deeper photometry on nearby galaxies allows us to reach faint SB

There is a trade off between exposure times and FoV

But the same FoV maps a wider region at large distances



and a two mags deeper CMD, sampling the RHB

Foreground contamination

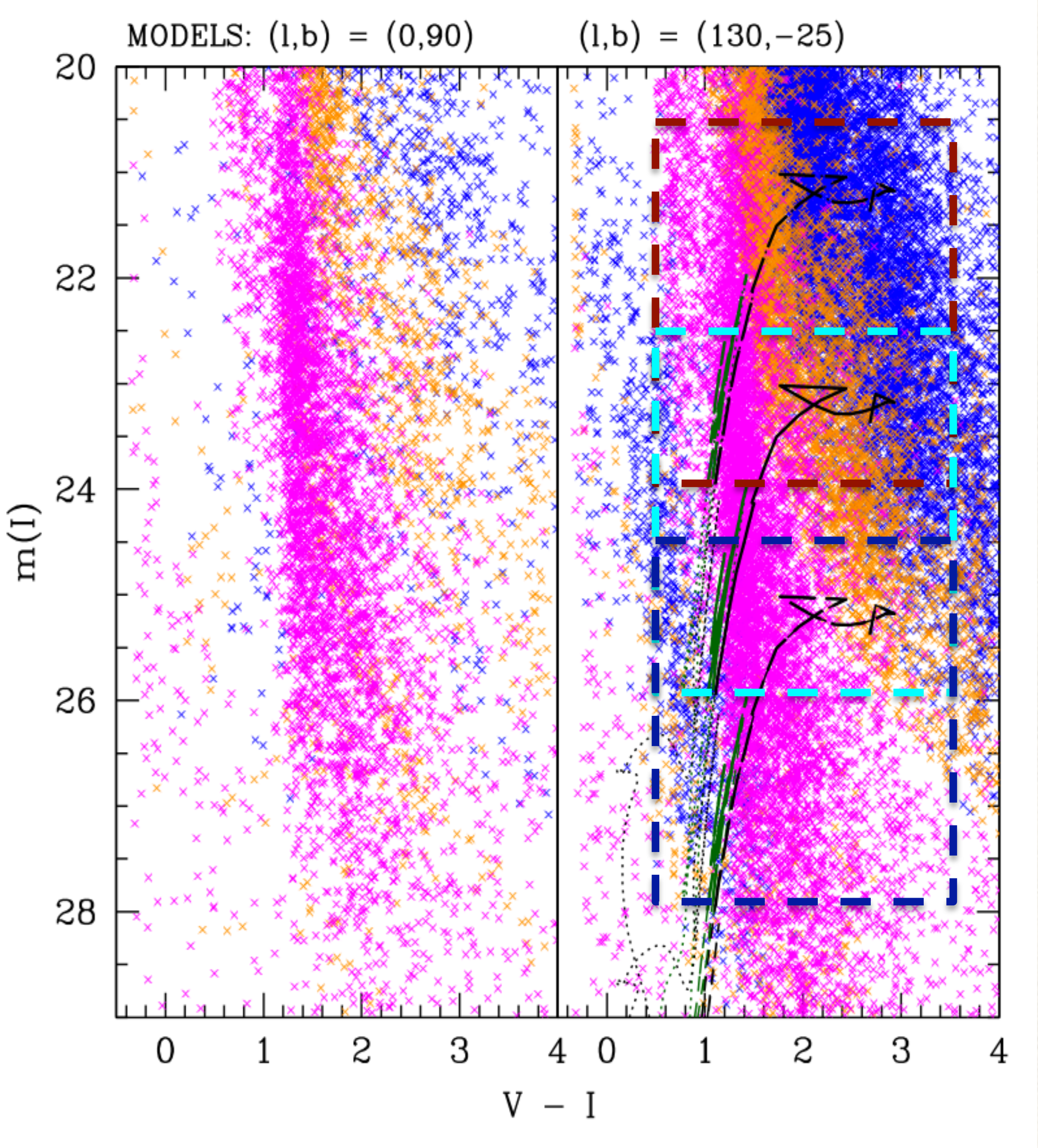
TRILEGAL simulations along two lines of sight.

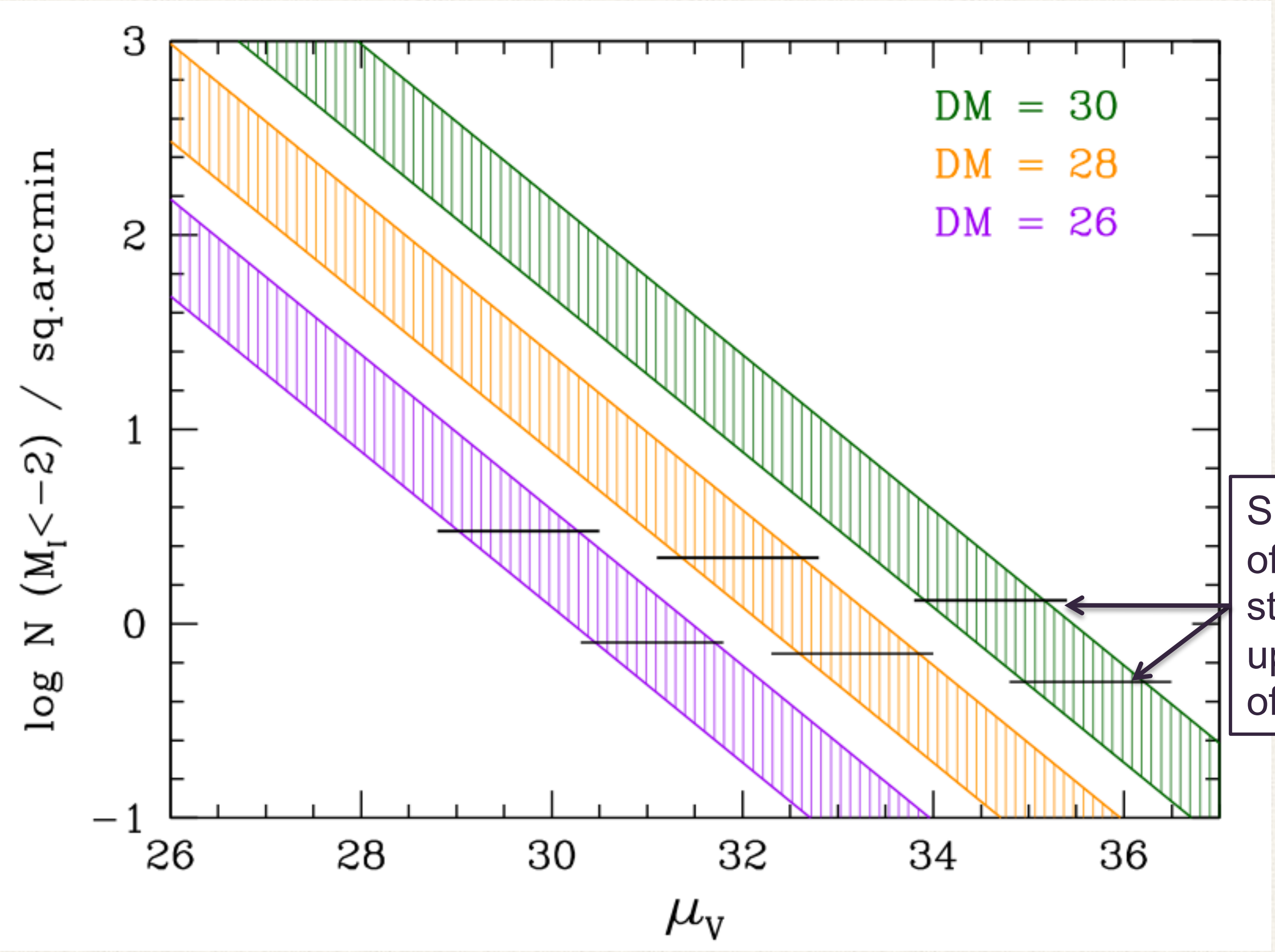
Contribution from stars of

- MW HALO
- MW THICK DISK
- MW THIN DISK

Isochrones with DM = 26, 28, 30 superimposed

In the relevant magnitude and color range we get a (variable) contribution from MW stars





Surface density of foreground stars in the upper 2 mag of the RGB

The foreground contamination has a much lower impact for galaxies at large distances at given SB

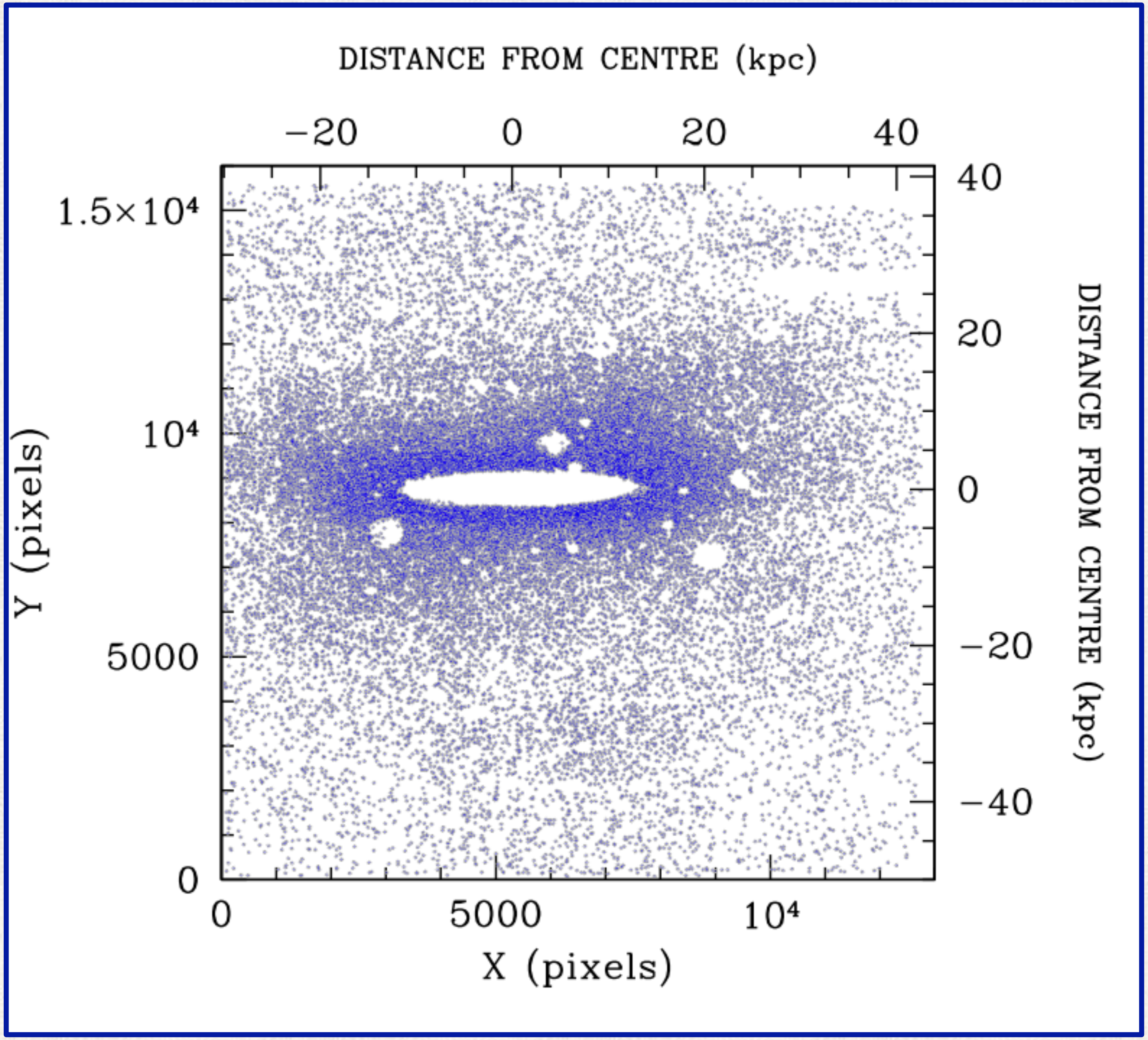
NGC 253: a Spiral (Sc), with a Luminosity $M_V \sim -21$
member of the Sculptor Group D~3.5 Mpc
hosts a central starburst and a galactic superwind
disk appears perturbed with a strong extraplanar component
and a shelf on the south side

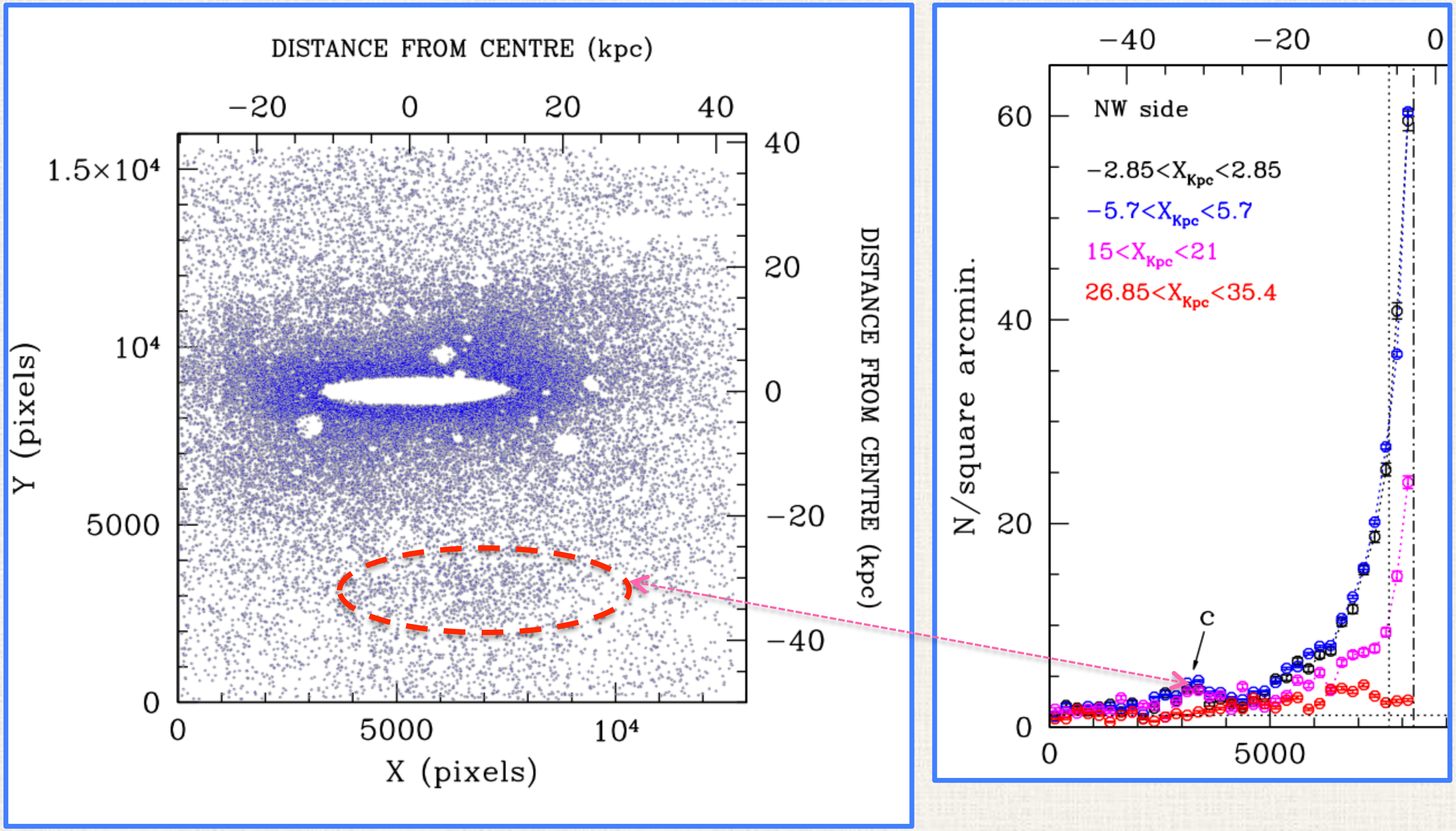
VISTA data:

Total exposure time
(~ x 3 on-target time)
22.1 hrs in J band (FWHM 0.9”)
9.6 hrs in Z band (FWHM 1.2”)
Processed with the VISTA Data Flow System at the Cambridge Astronomical Survey Unit
Limiting Magnitudes (S/N=3):
J = 24.5, Z = 23.5

Results in
Greggio, Rejkuba,Gonzales, Arnaboldi, Iodice, Irwin, Neeser, Emerson, 2014, AA 562, A73

Map of bona fide stellar members of NGC 253 on the J image





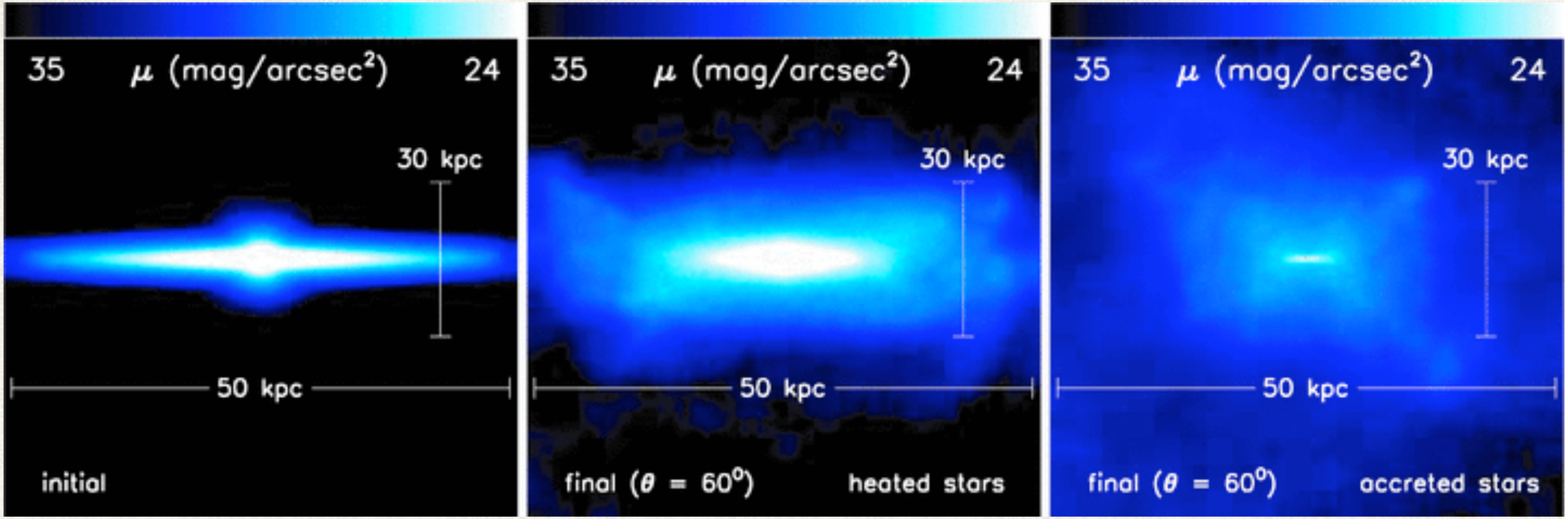
The overdensity consists of ~ 5 stars per arcmin^2 above the background counts

The data have J<~ 24, an old and metal poor SSP counts $N(M_J<-3.7)/L_J = 1.7\ 10^{-4}$

The detected substructure has $\mu_V \sim 30$ mag/arcsec^2

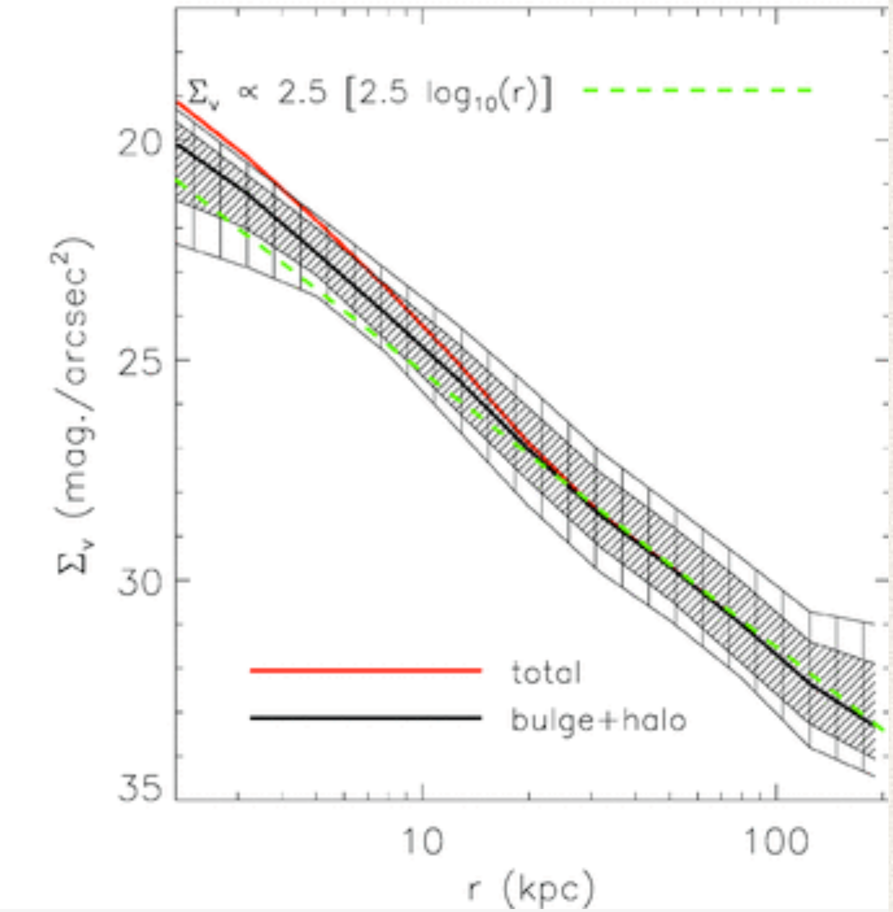
Question 2: profile and shape of the stellar halo
how extended is the in situ component?

Purcell, Bullock & Kazantzidis 2010:
effect of minor accretion events (1:10) on disc stars
the final state (5 Gyr after the event) shows disc stars scattered up to
~ 15 kpc from the plane – these are in situ stars, born in the disc of the accretor

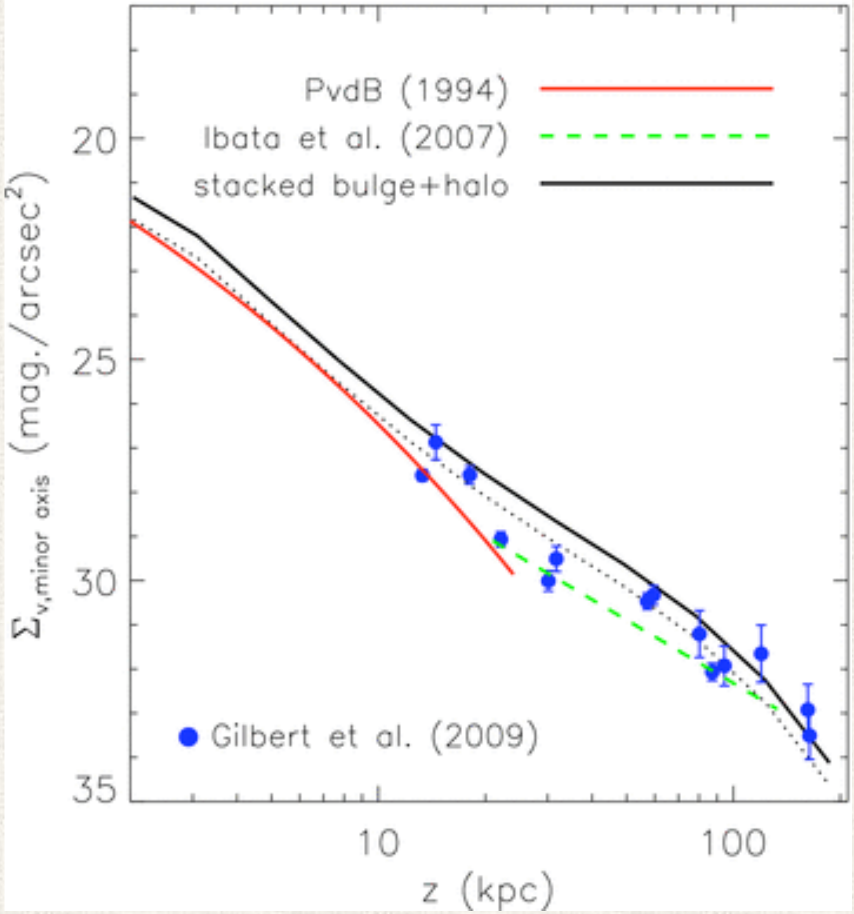


Font + 2011: GIMIC cosmological hydrodynamical simulations

The profile is not a single power law
There's a change of slope at r ~ 30 kpc, inside which the in situ component dominates
Wide range of slopes (hatched regions)

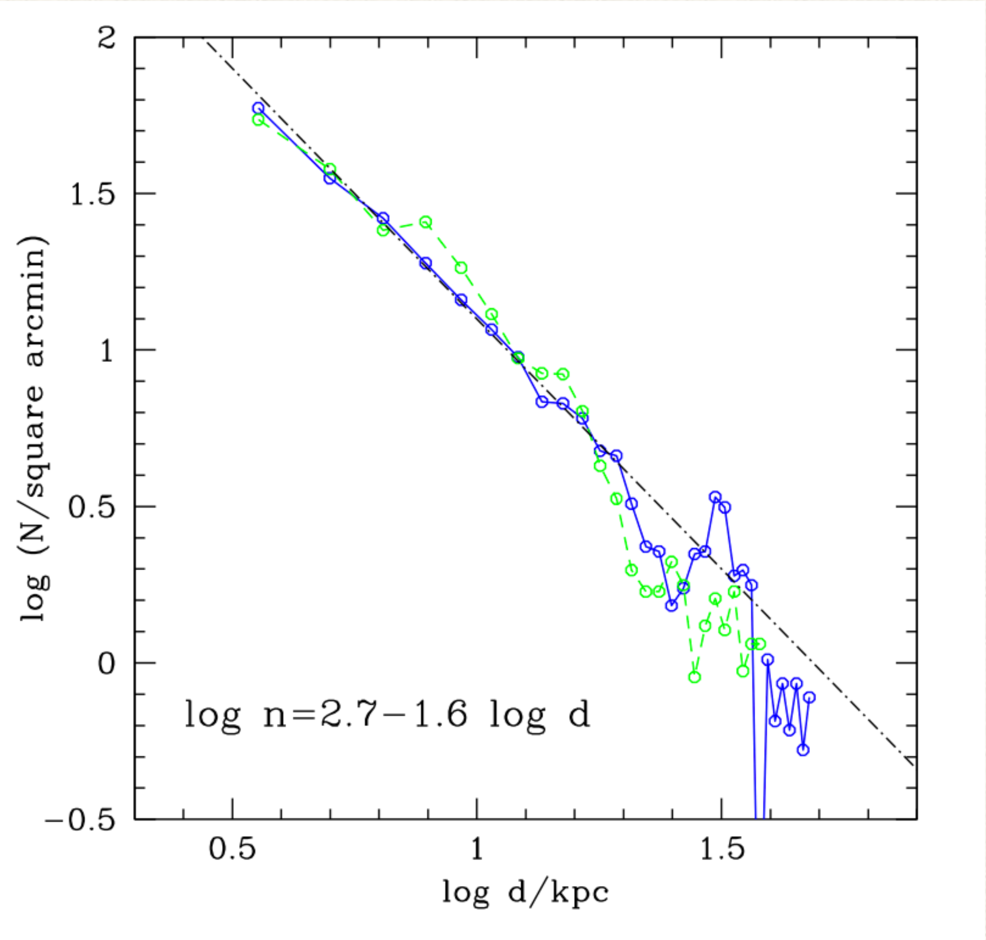


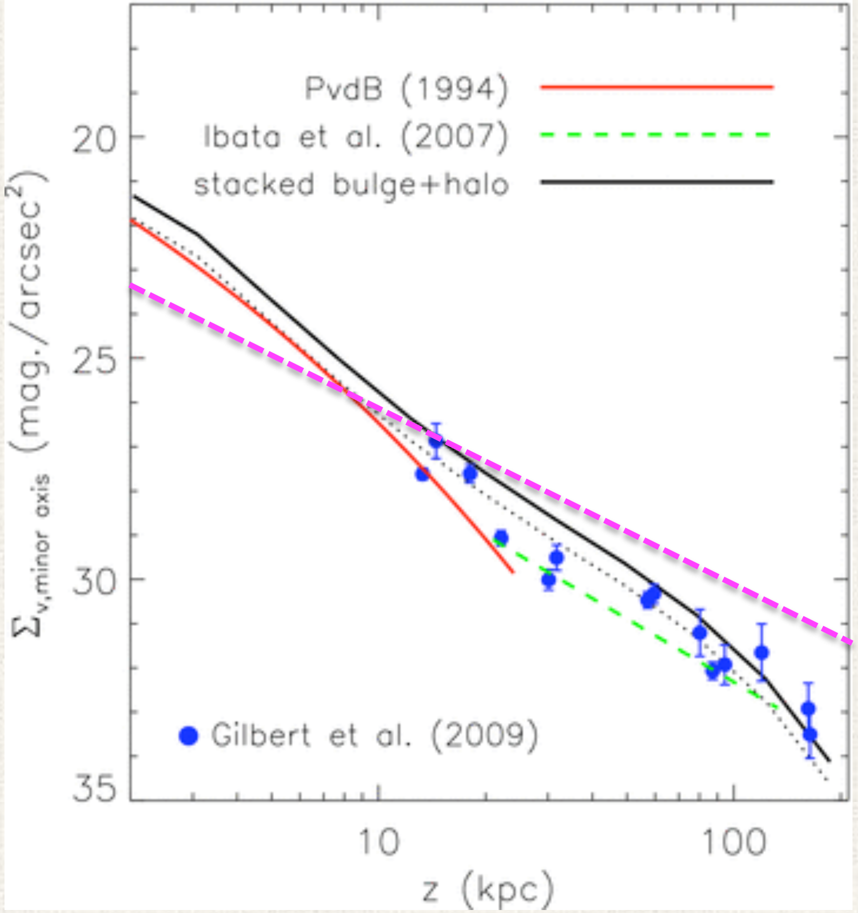
Azimutally averaged profiles
random orientations of simulated galaxies



Average of minor axis profiles
simulated galaxies all edge on oriented

NGC 253 stellar density profile along the minor axis

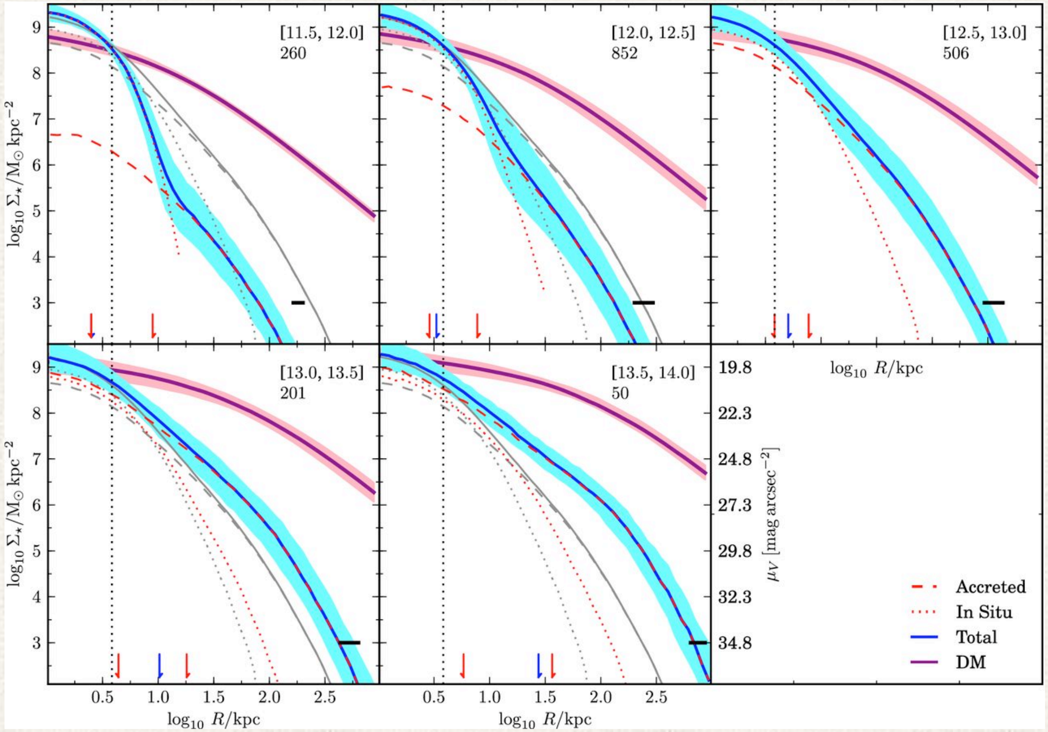




Is there a change of slope at about 20 kpc, as models predict? Maybe, but the overdensity complicates the profile

The slope measured for NGC 253 is quite flat, but the comparison is hampered by crowding in the inner parts.

Cooper + 2013: hybrid models with in situ component included



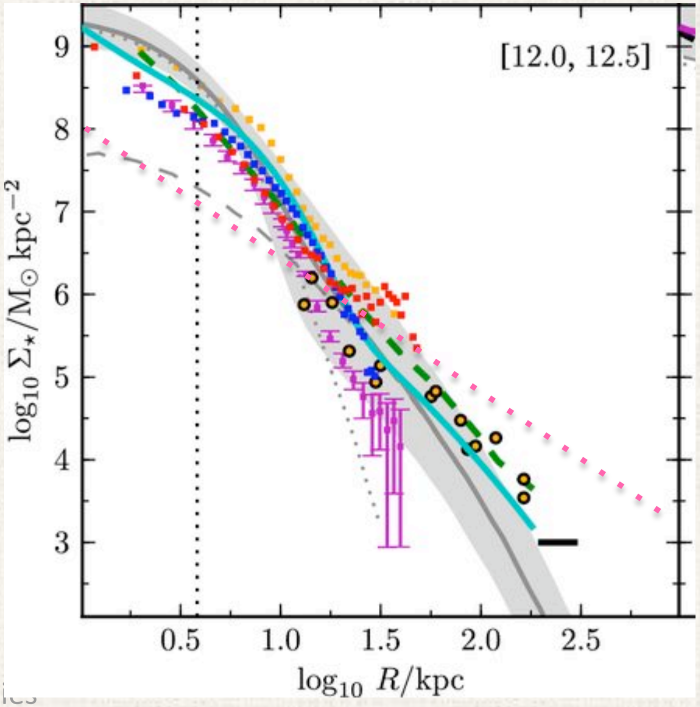
Also find a break in the profile at R ~ 20 kpc inside which the in situ component dominates

The effect depends on halo mass

GIMIC profile tends to be brighter in the outer parts

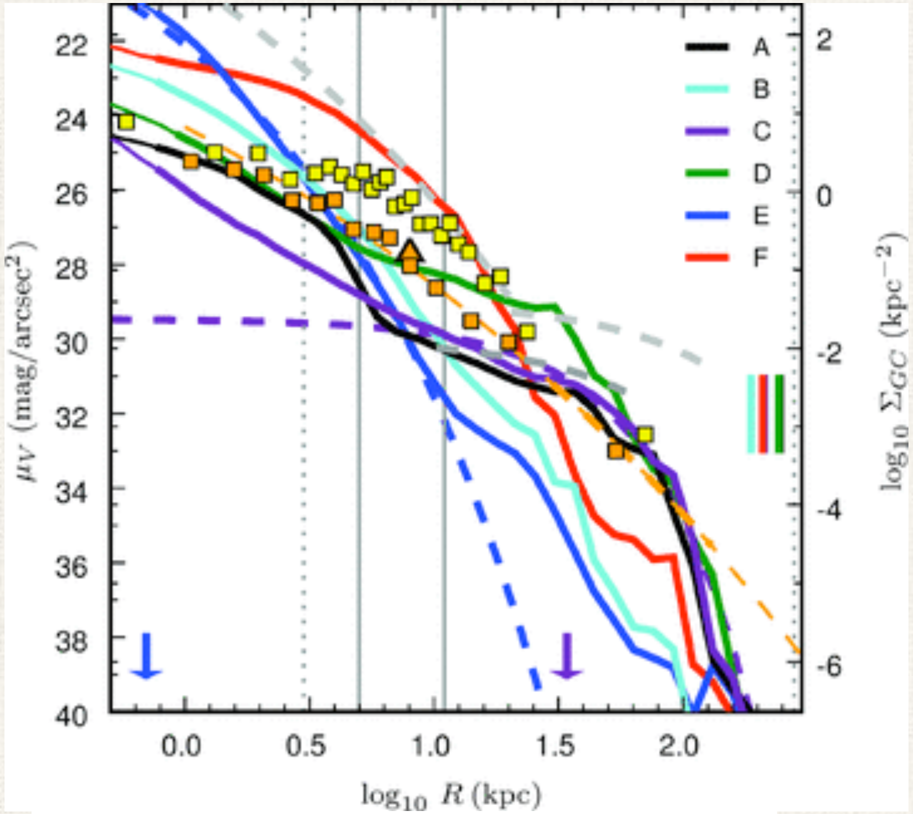
Dots are various data: seem compatible with the models, but still uncertain

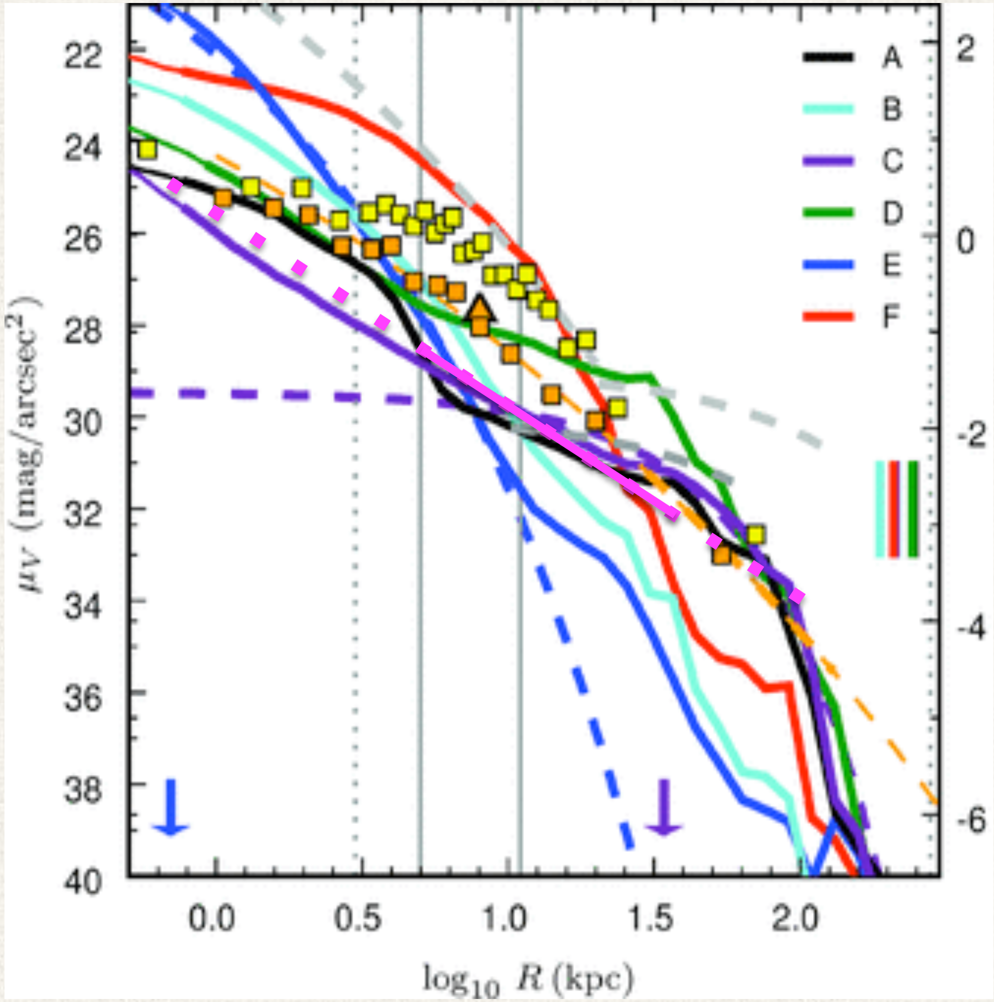
The slope of the average relation along the minor axis of NGC 253 is quite flat



From Cooper + 2010:
individual Aquarius halos show a large variety of SB profiles slopes

NGC 253 profile could be just one particular realization

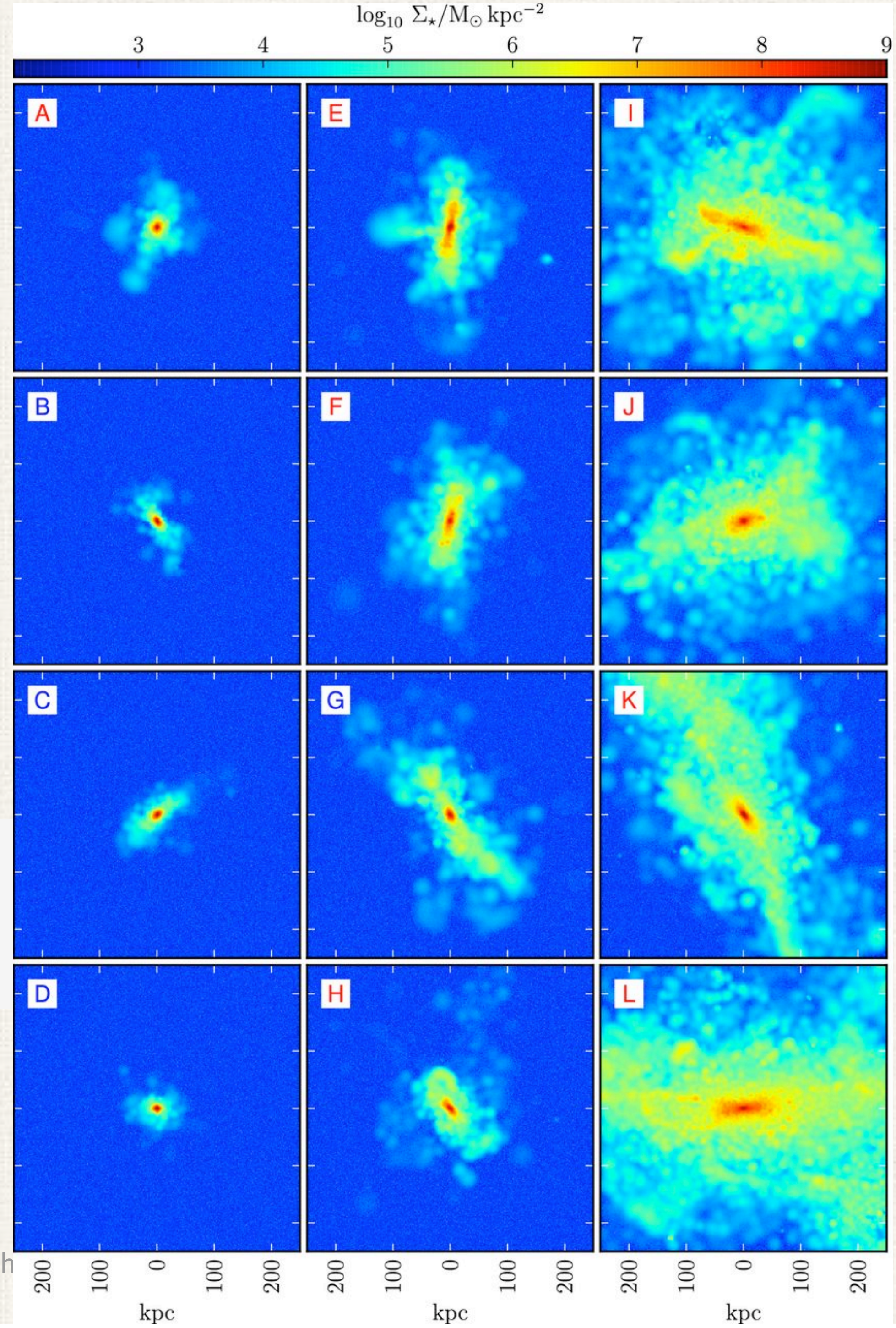




Dashed lines:
blue and purple Sersic fits to Aq-E and C
grey: M31 and M33 from Ibata+ 2007

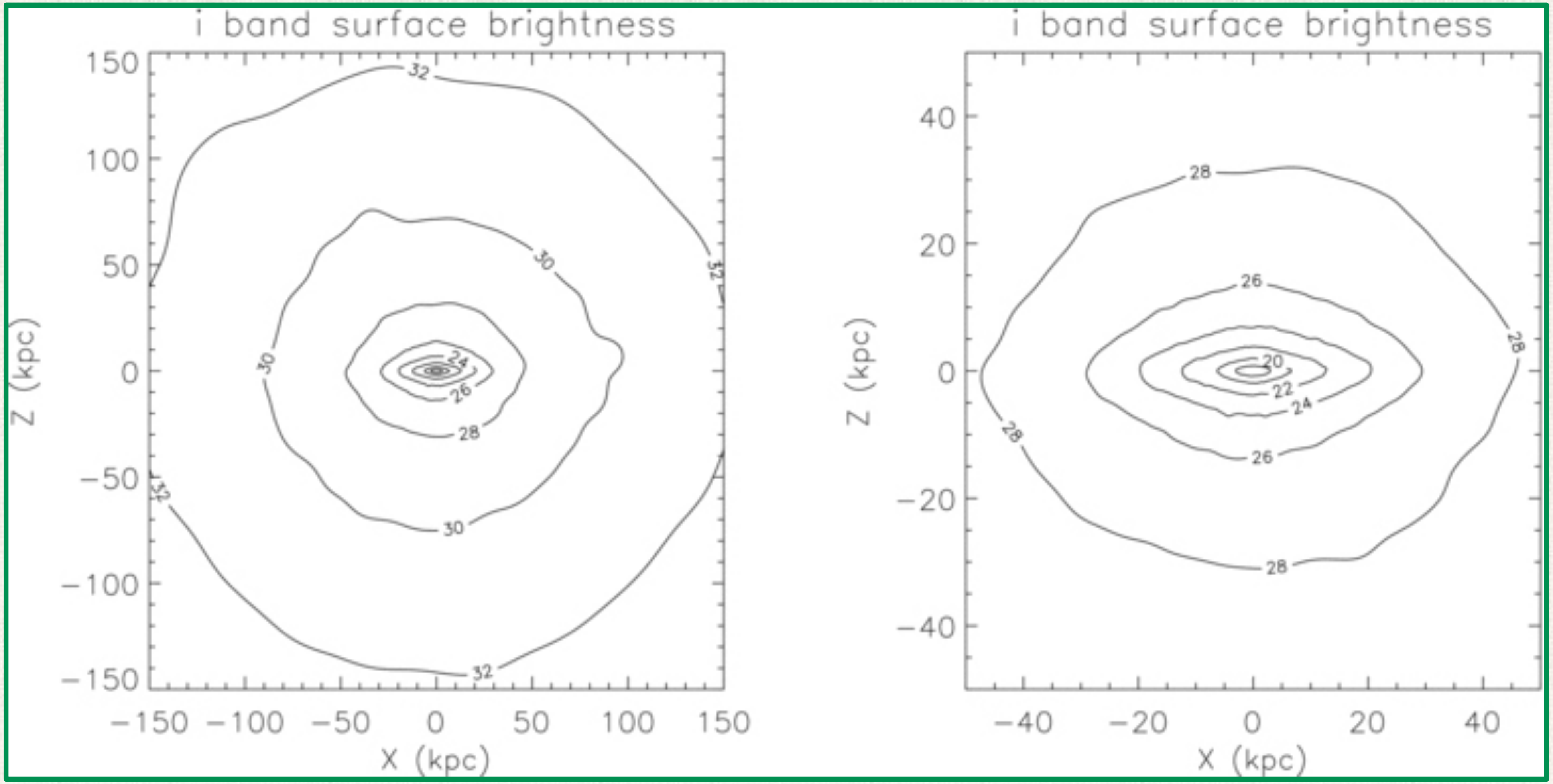
From Cooper + 2013:

Elongated shapes are typical for the stellar halos



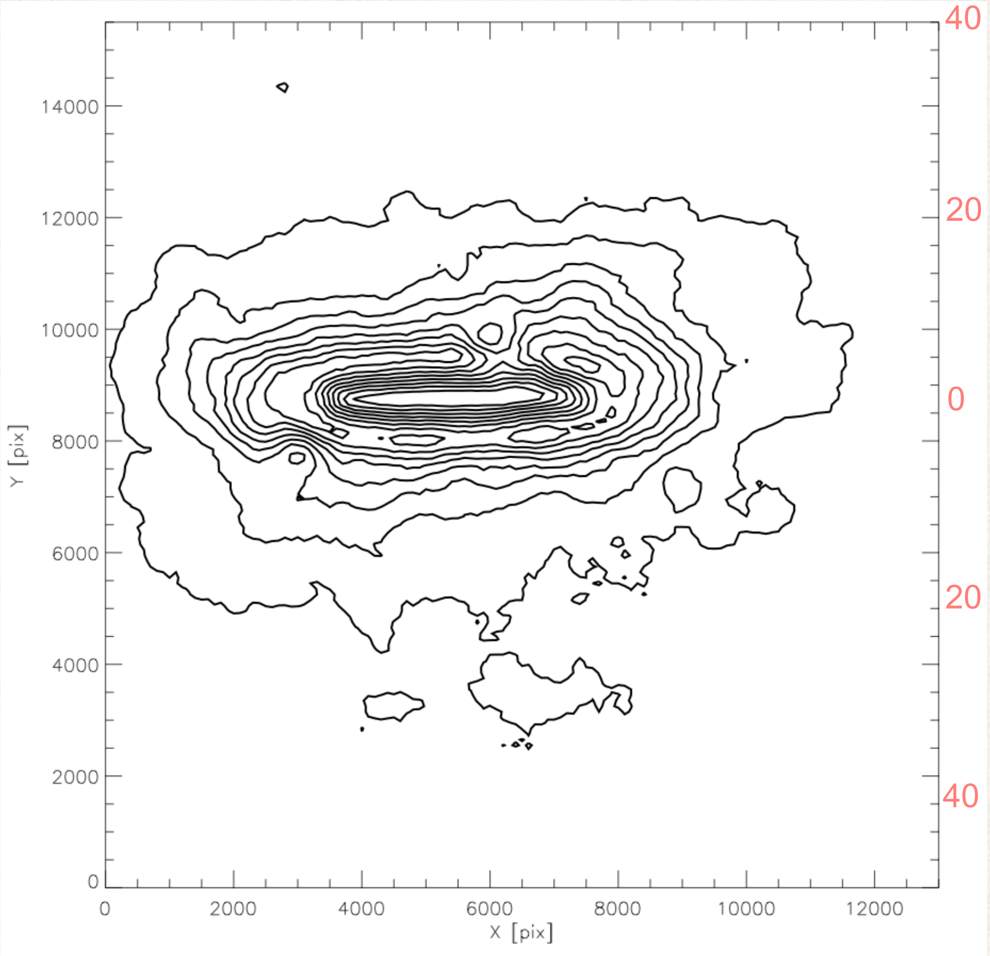
Left : MW like galaxies
Middle : massive isolated galaxies
Right: group/cluster central galaxies

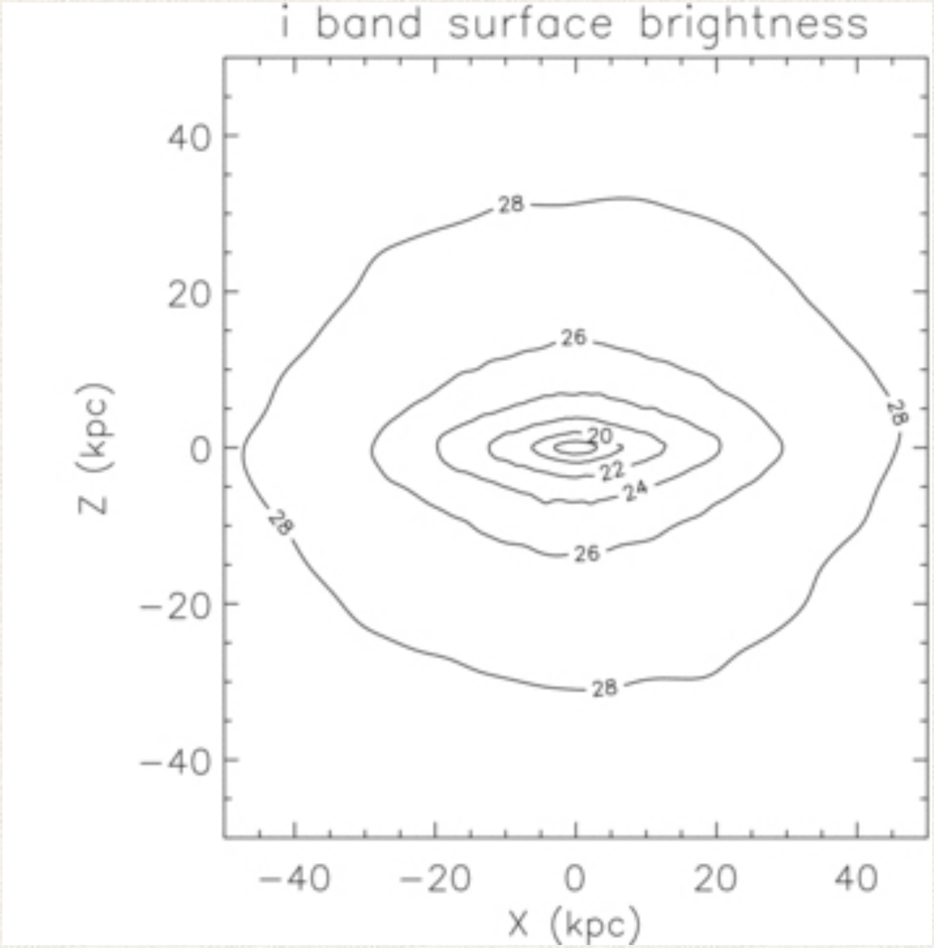
From McCarthy+ 2012:
Elongated inner shapes are also in GIMIC simulations, but the outer halos seem to become circular



The shape of the halo of NGC 253

The inner halo has an flattened shape (see also Bailin+ 2011)

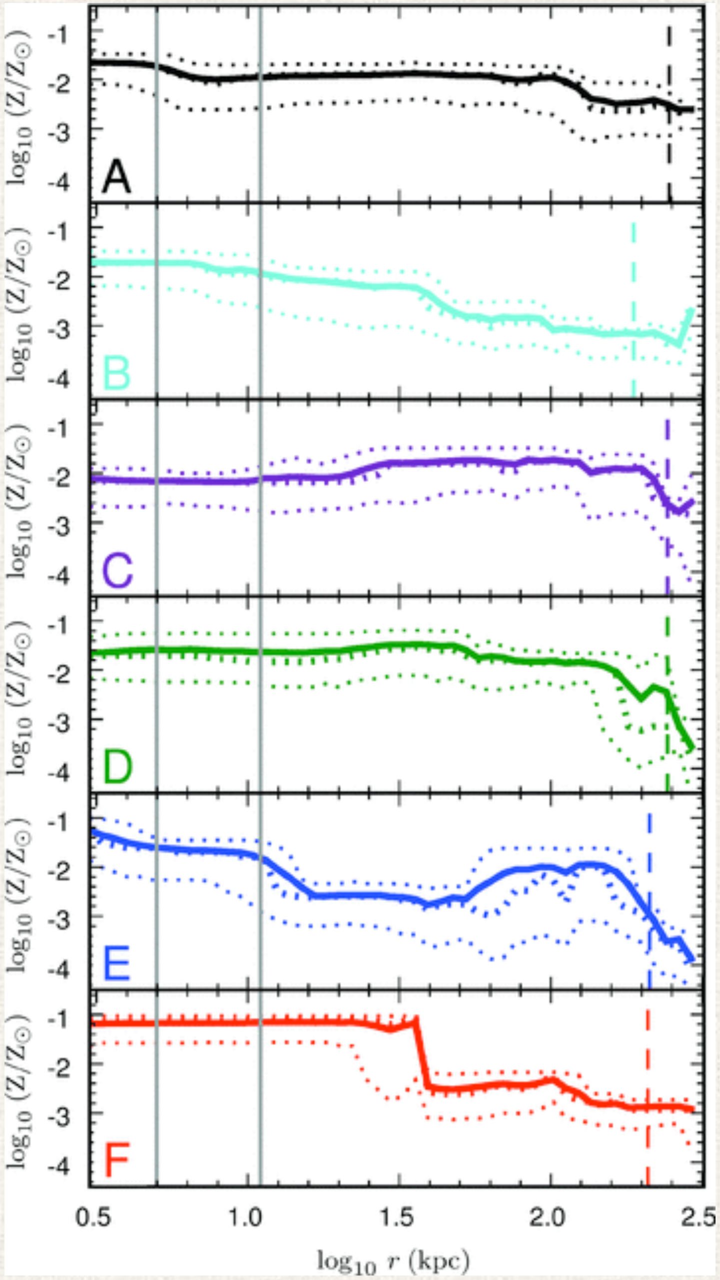




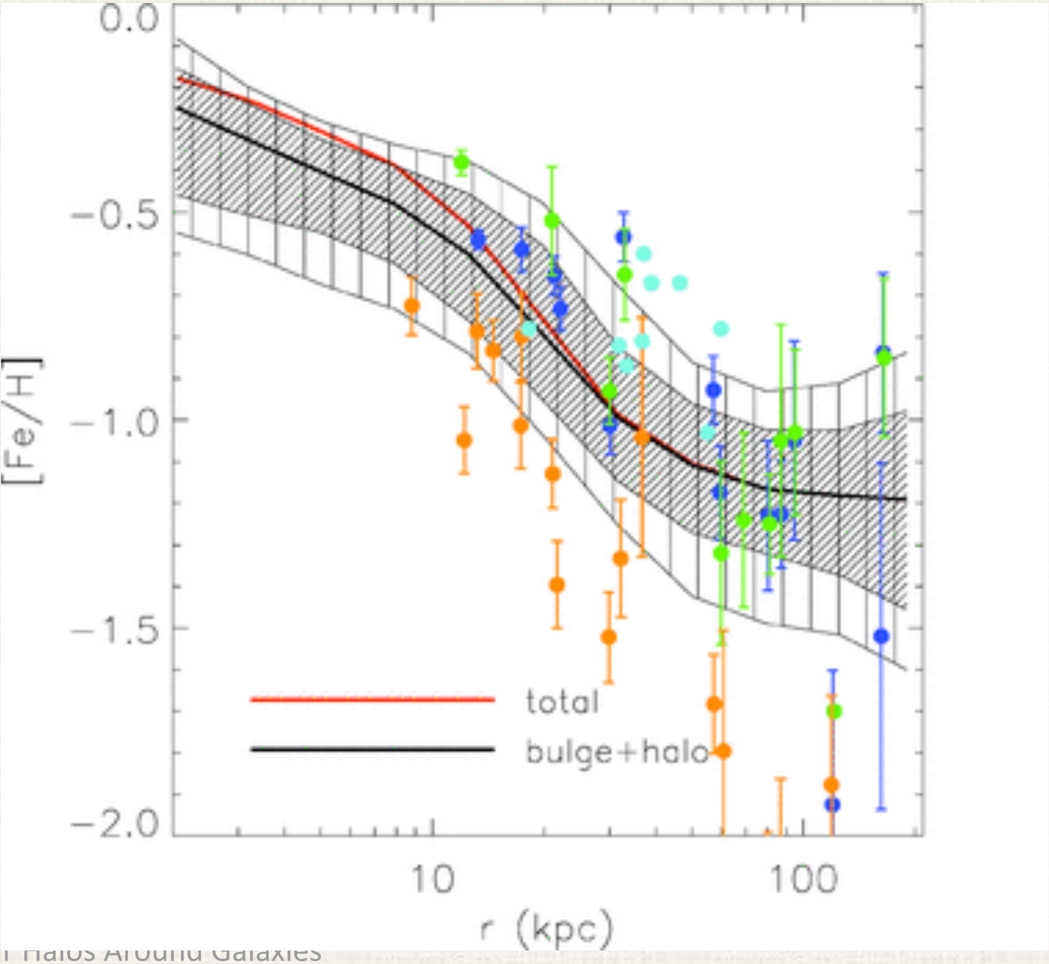
Counts averaged on
100x100 pix boxes

Question 3:
metallicity gradient of the stellar halo

Cooper + 2010: Aquarius halos
Hardly any systematic gradient if halos are built only with accreted satellites



Font + 2011: The in situ component is more metal rich than the accreted (low mass) satellites' stars, which populate the outer parts. The GIMIC simulations show a systematic metallicity gradient.



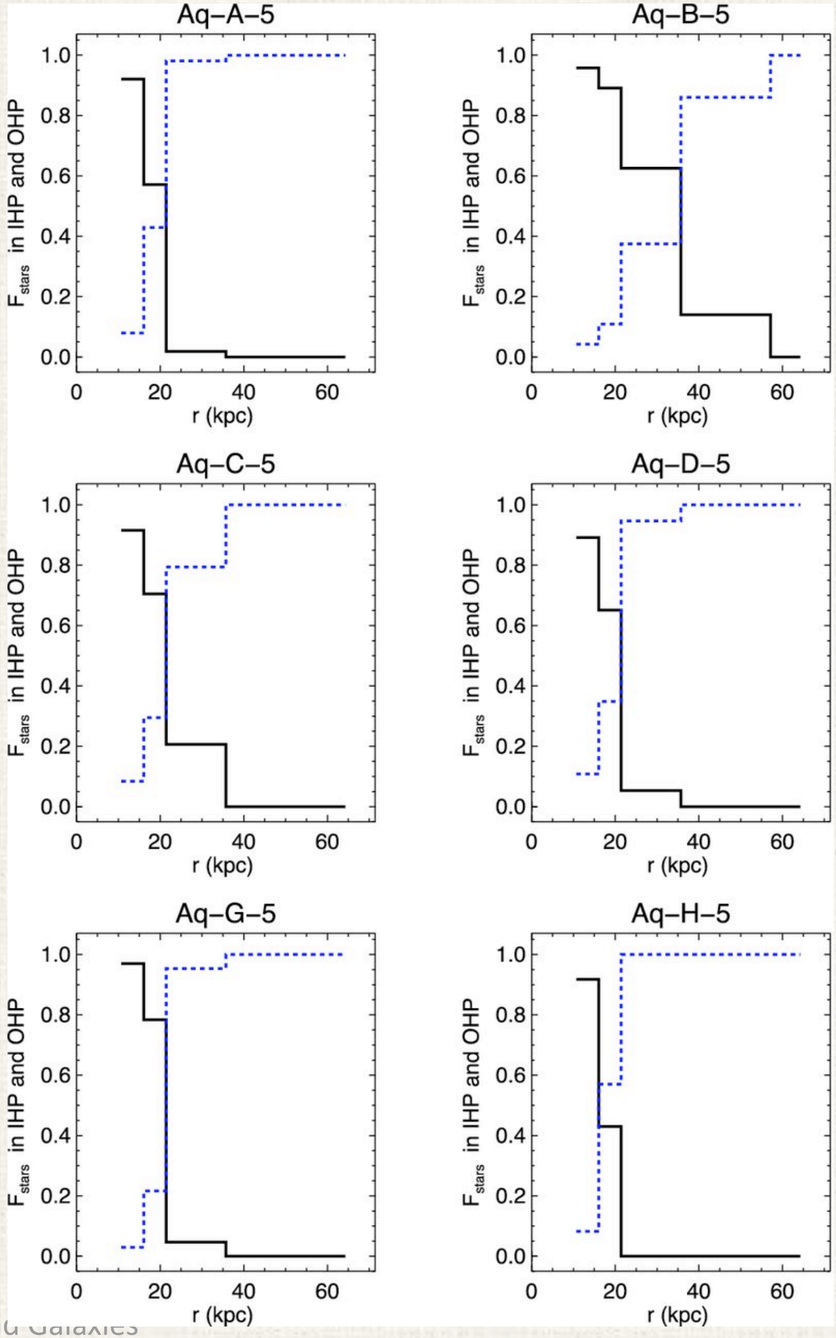
From Tissera+ 2013:
Detailed chemical properties of 6 Aquarius halos hosting MW like galaxies (re-simulated with SPH technique)

Stellar halo component is distinguished in
Inner halo Population (most gravitationally bound)
Outer halo Population (least gravitationally bound)

The IHP (solid) dominates the stellar component up to 20 Kpc, where the OHP becomes dominant

There is a sizable (~0.4) contribution of OHP in the inner regions (r<20 Kpc)

One expects wide Z distributions and different [α/Fe] ratios in the inner halos



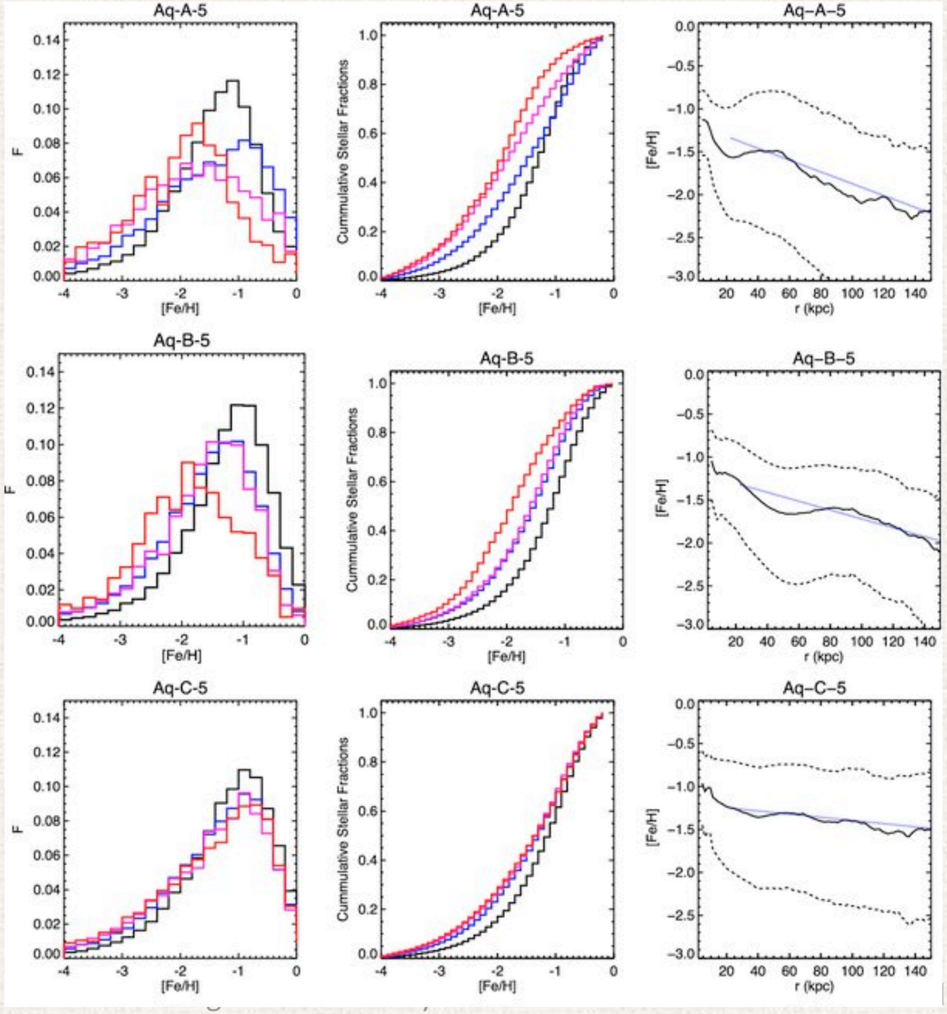
A metallicity profile originates because inner regions are populated with heated disk (+ endo-debris) stars, outer regions are populated with stars from accreted satellites.

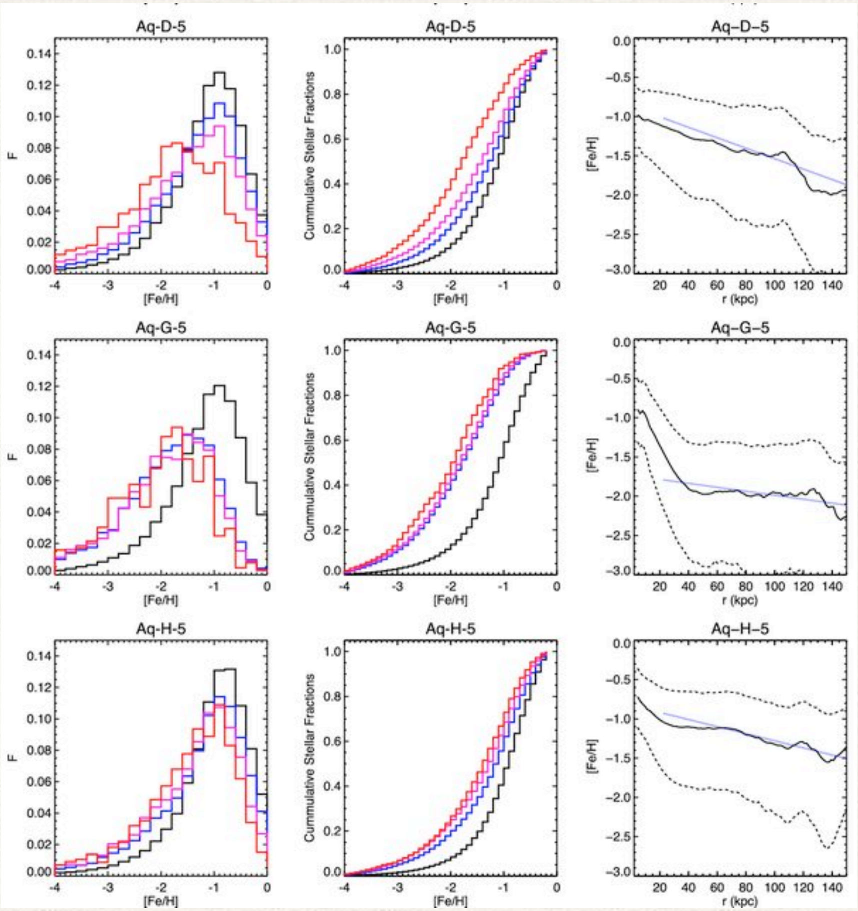
A gradient may be reinforced if massive satellites (more metal rich) are accreted, because they sink further in

The predicted metallicity distributions and gradients reflect the different assembly history of individual halos

(r < 20 20 <r< 40 60 < r < 80 80 <r<120) kpc

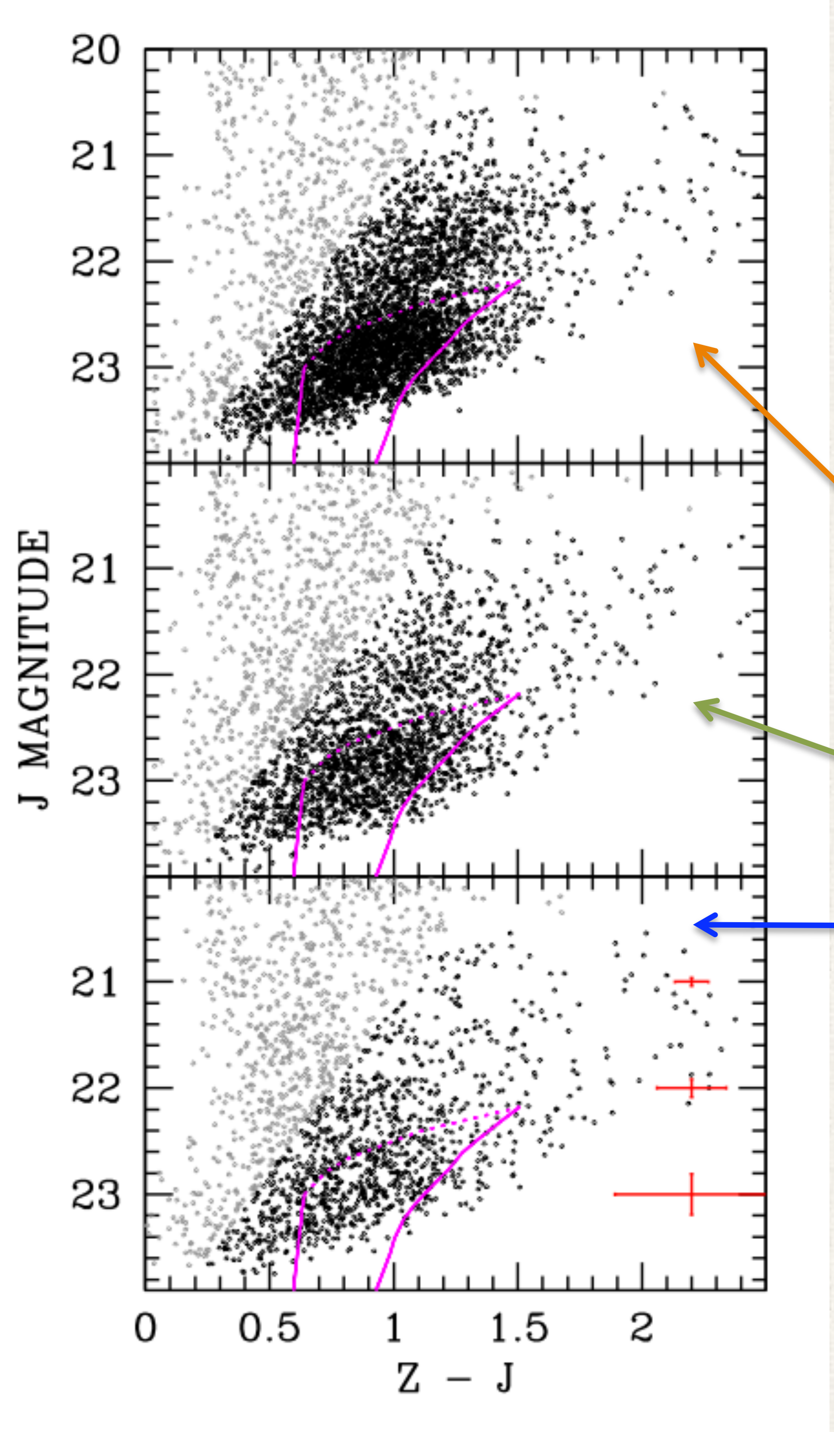
MDF Cumulative distrib. Median [Fe/H]

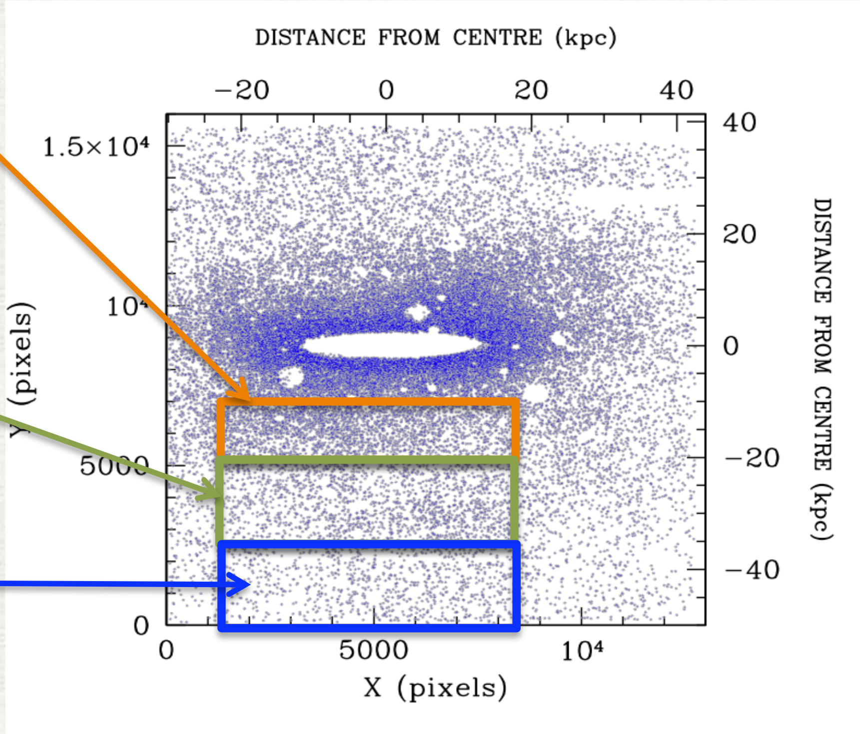




Wide distributions in all regions (and at all radii). Different individual realizations.

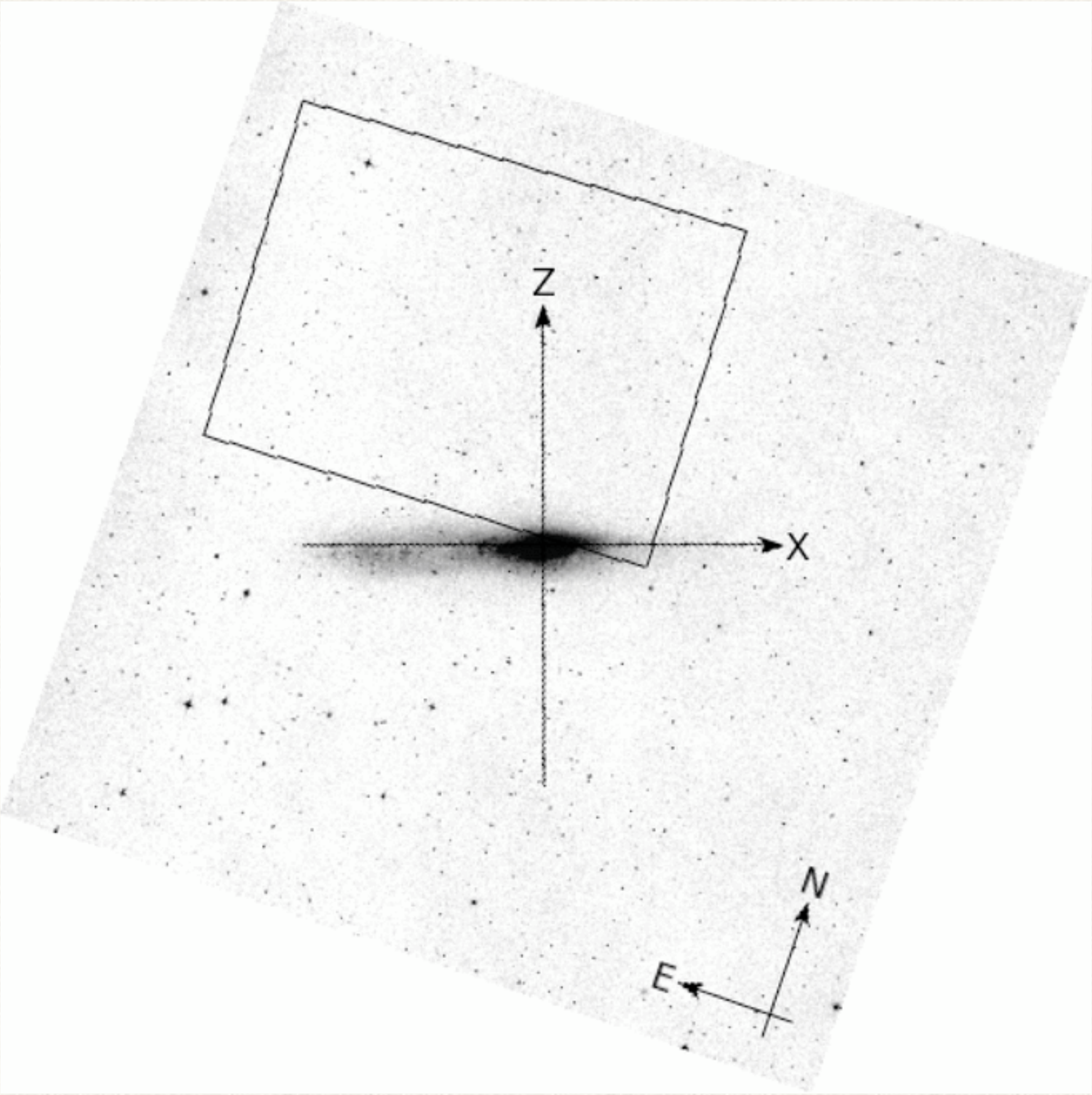
(Z,J) CMD of stars in selected regions of NGC 253 halo from VISTA data

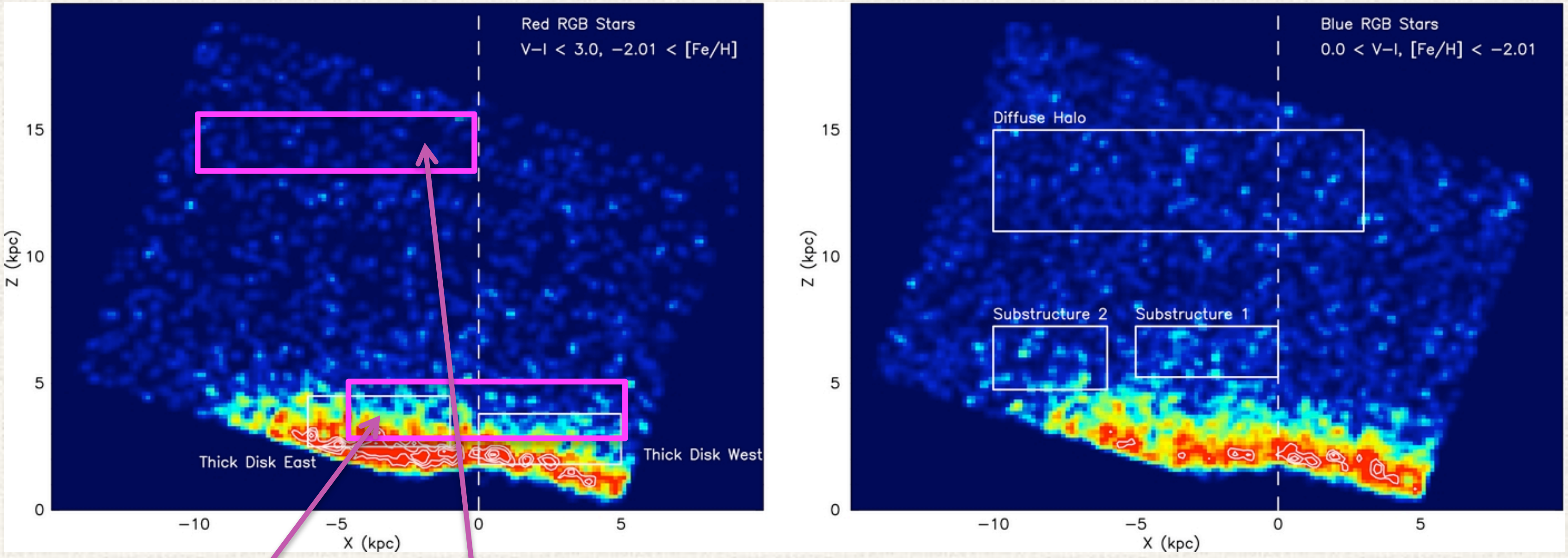


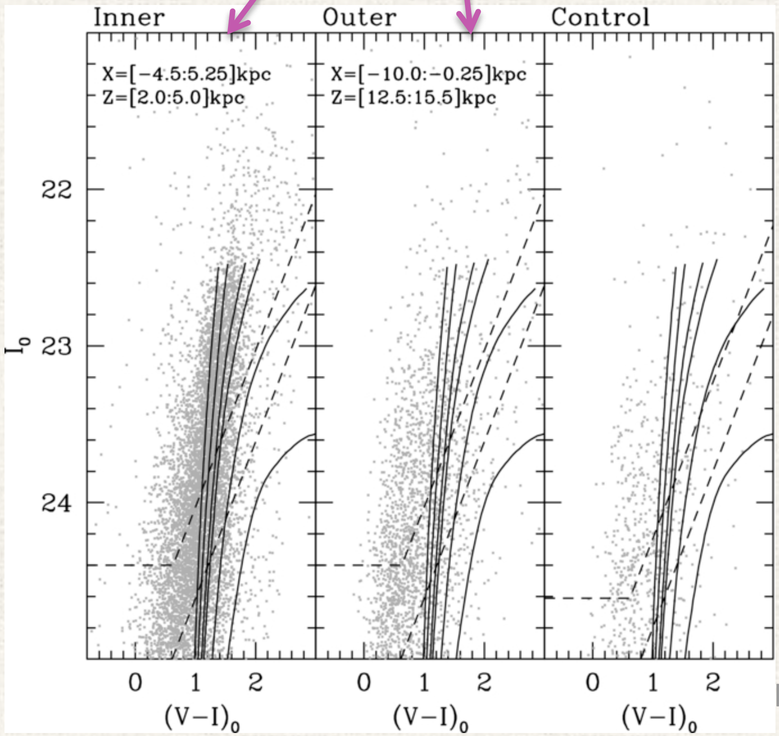


Magenta lines show theoretical RGBs for Z=0.0001 and 0.008
Photometric errors are too large to detect metallicity trends over the halo

Tanaka +, 2011:
Suprime-CAM @ Subaru
Observations of the
halo around NGC 55
an edge on spiral at
at ~ 2 Mpc

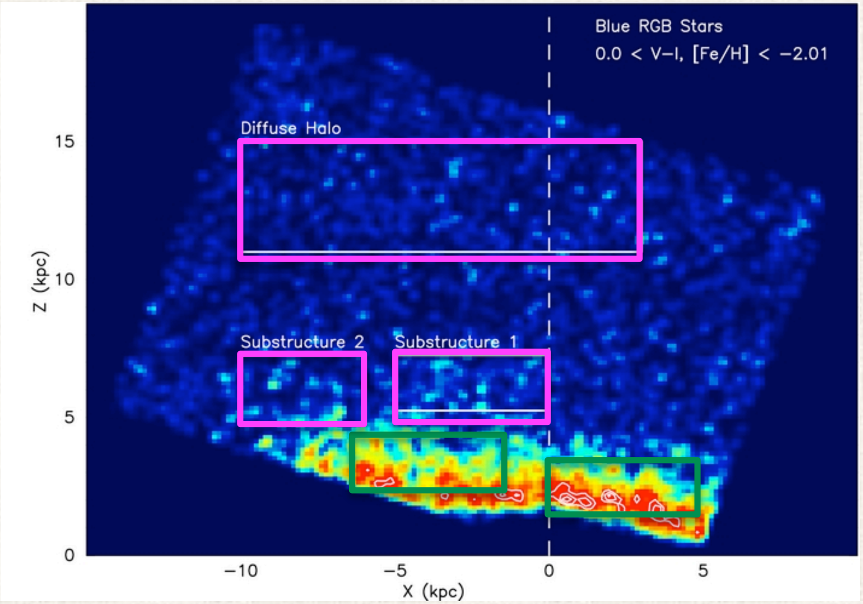


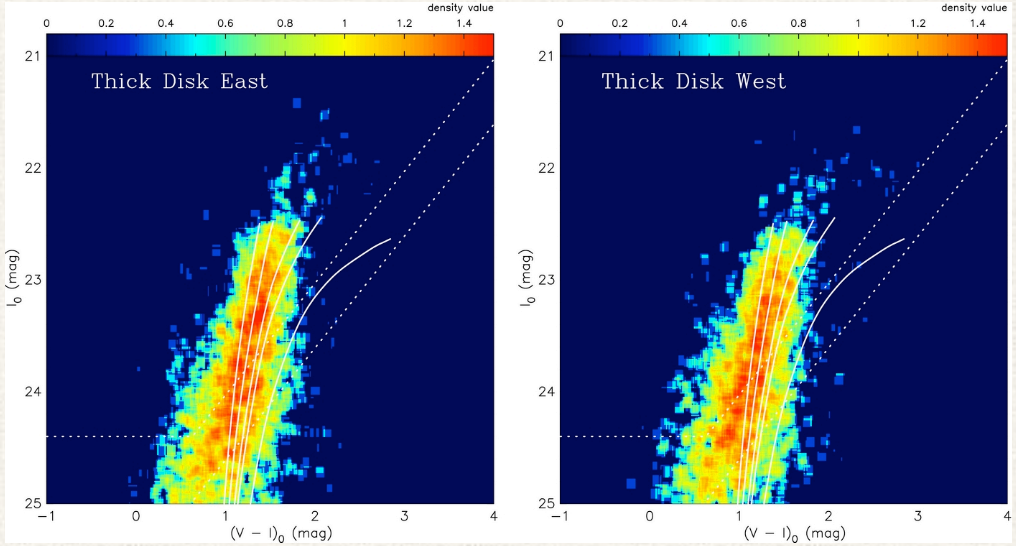


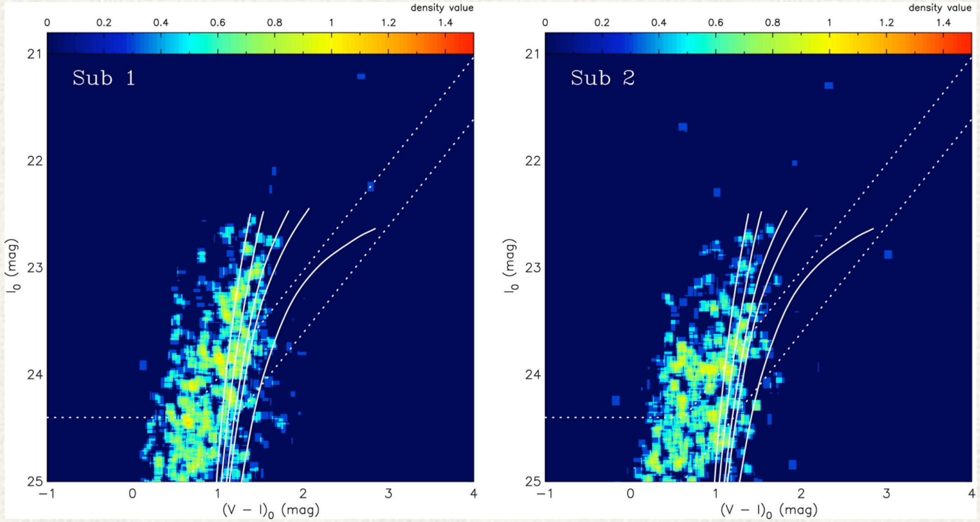


The control field is at the same b (= 76 °), but 3 degrees away from NGC 55

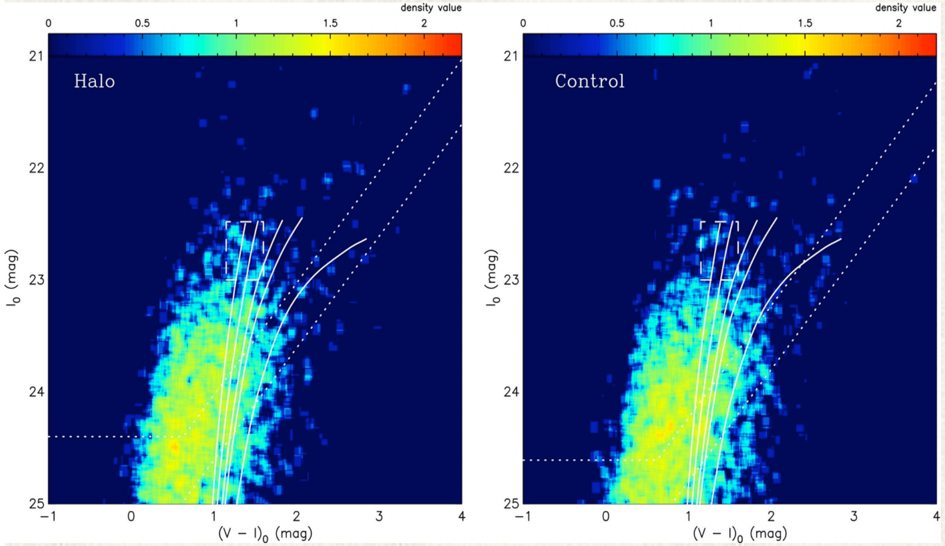
There is a clear trend in the surface density of the RGB stars, but not so clear trend of color distribution on the RGB







The substructures are more metal poor than the disk: distinct components



The metallicity distribution is wide in the various locations.
Accurate photometry is needed to refine the conclusions.

Summary

Models of galaxy formation in a cosmological context have reached a high degree of sophistication with detailed quantitative predictions to be compared to observations to learn more about the process of galaxy formation in the hierarchical universe

Some questions:

How does the number of substructures grow as we go to fainter surface brightness?

impacts on the understanding of the hierarchical build up of galaxy halos

Are the predicted trends between shapes of the substructures and their stellar populations properties confirmed?

impacts on the possibility of recovering the accretion history of individual galaxies

Is there a break in the profile of the stellar density distribution?

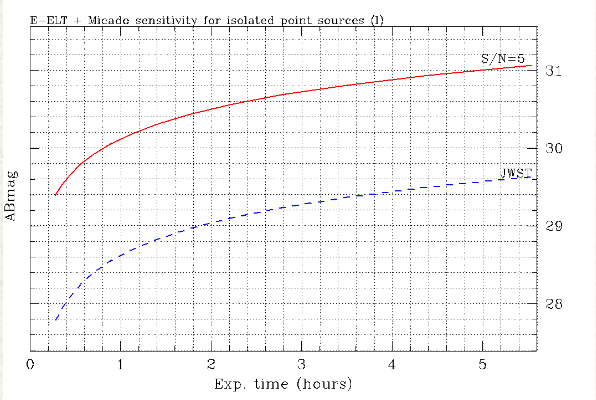
impacts on the proportion of in situ and accreted stars

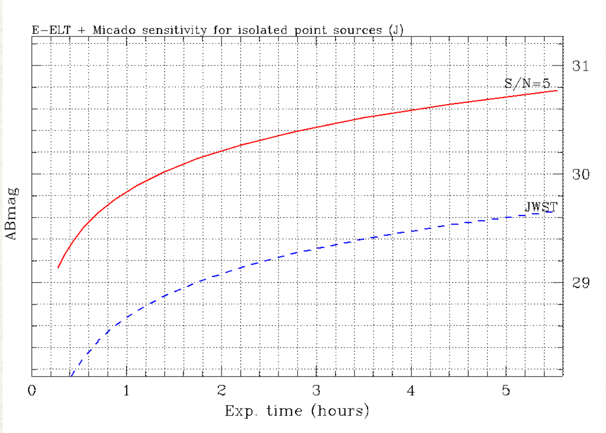
Which metallicity distributions and gradients characterize the stellar halos?

impacts on the descriptions of the halo build up

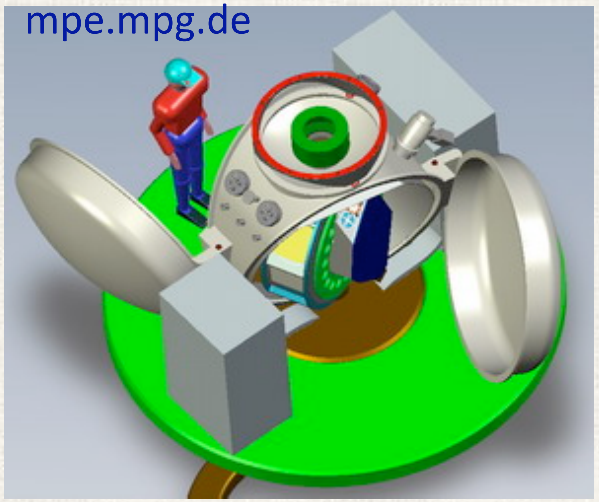
Limitations/Challenges:
Models: mass resolution / size of the simulated volumes/ gas physics
Data: depth and photometric quality, FoV, foreground (background)

Future Prospects



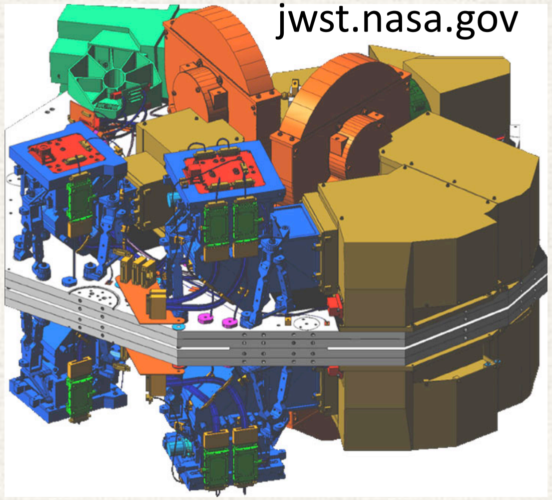


MICADO @ E-ELT


mpe.mpg.de

+ MAORY

NIRcam @ JWST


jwst.nasa.gov

FIELD OF VIEW	~ 53” x 53”	2 x (2.16’ x 2.16’)
PIXEL SCALE	~ 3 mas	~ 32 mas
MAGNITUDE LIMITS: (isolated, t_{exp}=3hrs, S/N=5) I – BAND (vegamag) J – BAND (vegamag)	30.3 29.5	28.9 28.4

Trace stellar halo properties using stars in bright evolutionary phases

Feature	M(I)	M(J)	Detected at S/N=5 up to DM	
RGB Tip	- 4	- 4.7	JWST	E-ELT
Bright RGB	< - 2	< - 2.7	~ 31	~ 32.2
Red HB	0	- 0.7	~ 29	~ 30.2
Blue HB	1.5	1.5	~ 27	~ 28

We will be able to trace :

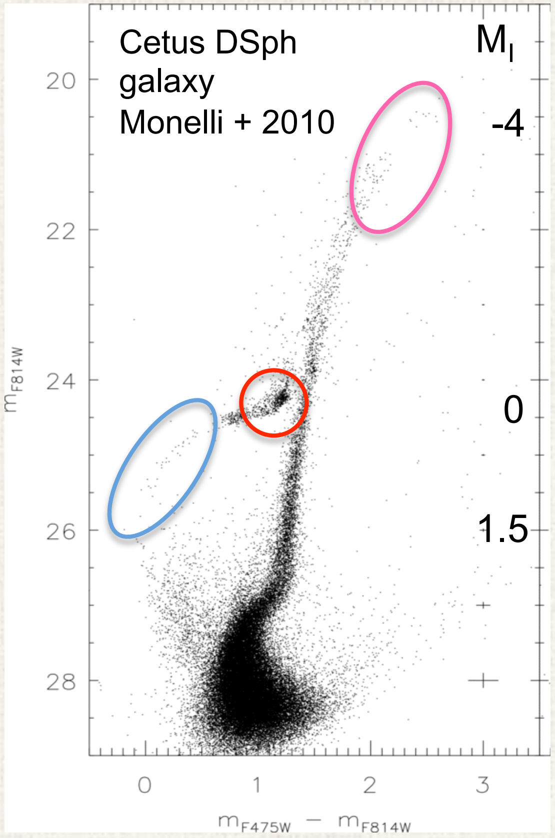
bright RGB stars up to 30 Mpc

red horizontal branch stars up to 11 Mpc

blue horizontal branch stars up to 4 Mpc

Two applications:

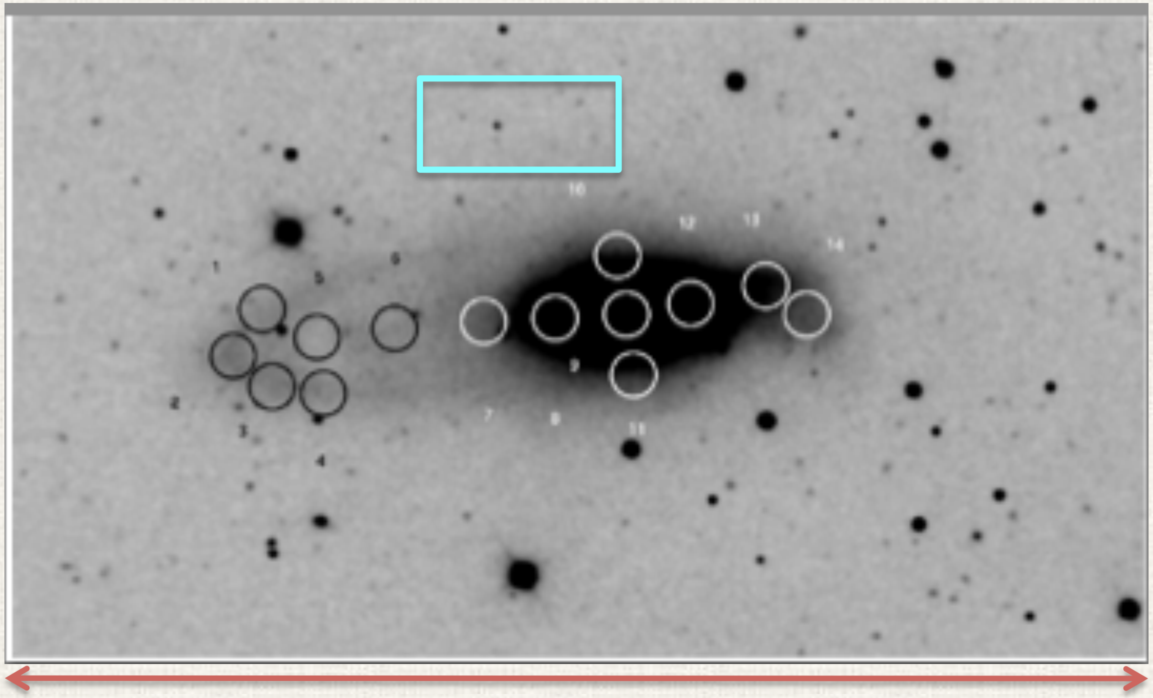
- Study of stellar population in the streams
- Sampling the very low SB regions of stellar halos



Stellar populations in tidal streams in galaxy halos

From Miskolczi, Bomans, Dettmar 2010:
SDSS image of NGC 7711

A large stream is clearly apparent
Typical SB in the stream is $\mu(V) \sim 24.5$ mag/arcsec^2

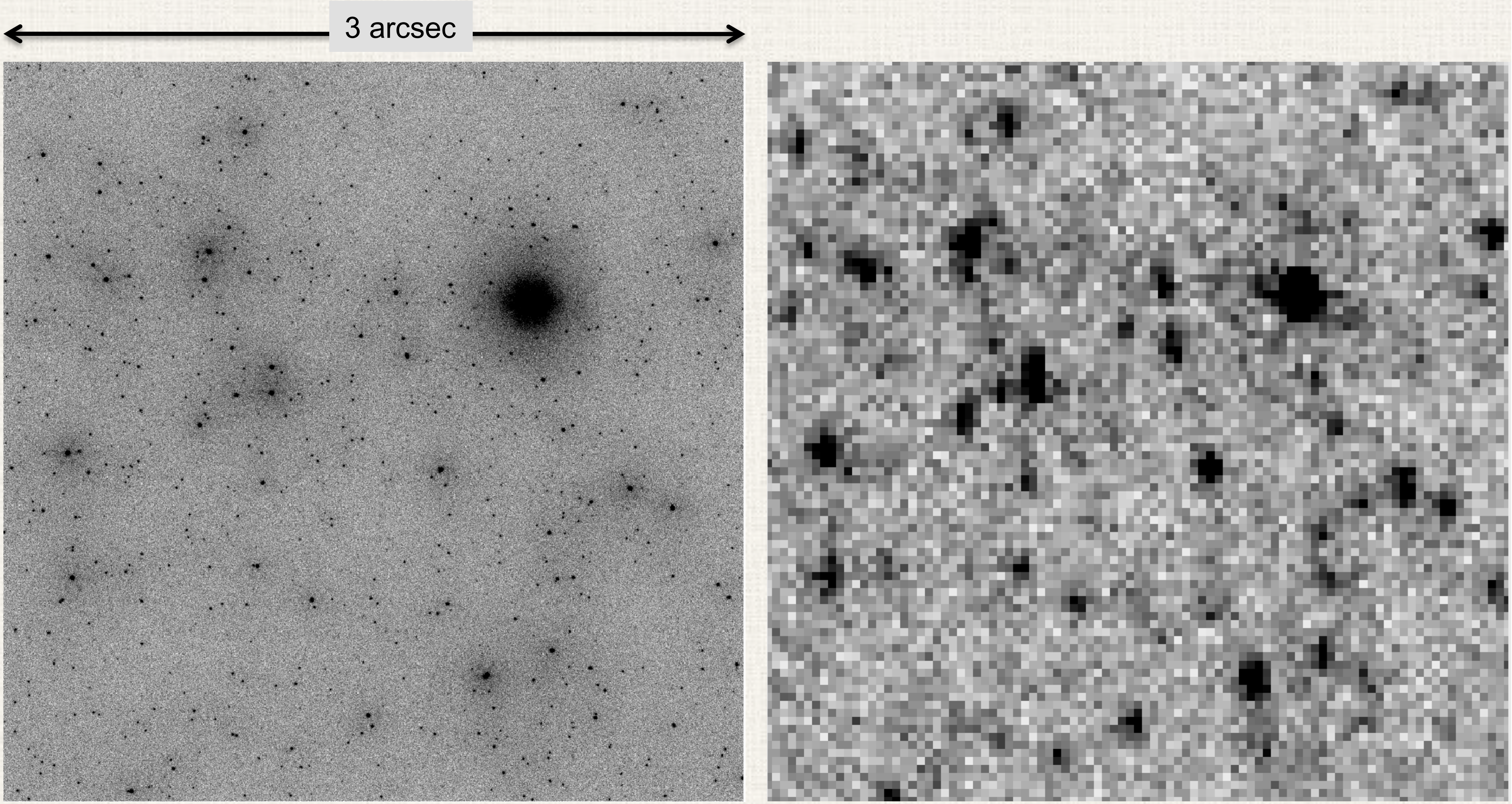

95 kpc

If the distance was of 8 Mpc one MICADO field would be ~ the size of one circle (maps ~ 2.3 kpc)

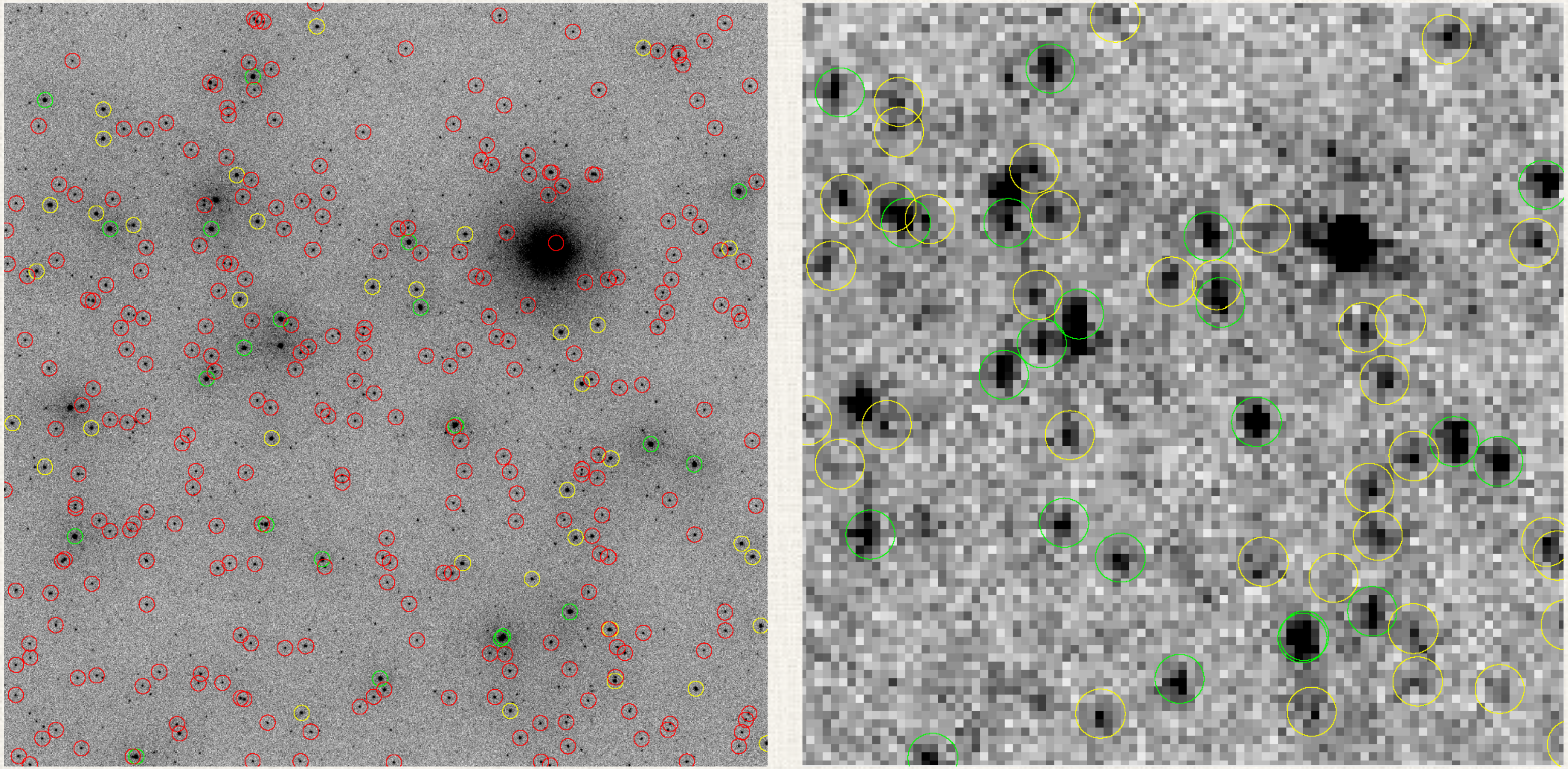
One NIRcam field would be ~ the cyan rectangle

AETC simulations of a stellar field at DM = 29.5 (8 Mpc) for a young stellar population.
Images are in the I band and assume 3 hrs exposure time.
The average surface brightness in the field is $\mu_V = 24.5$

The high resolution of E-ELT allows detection of faint stars close to bright objects



Thanks to Renato Falomo

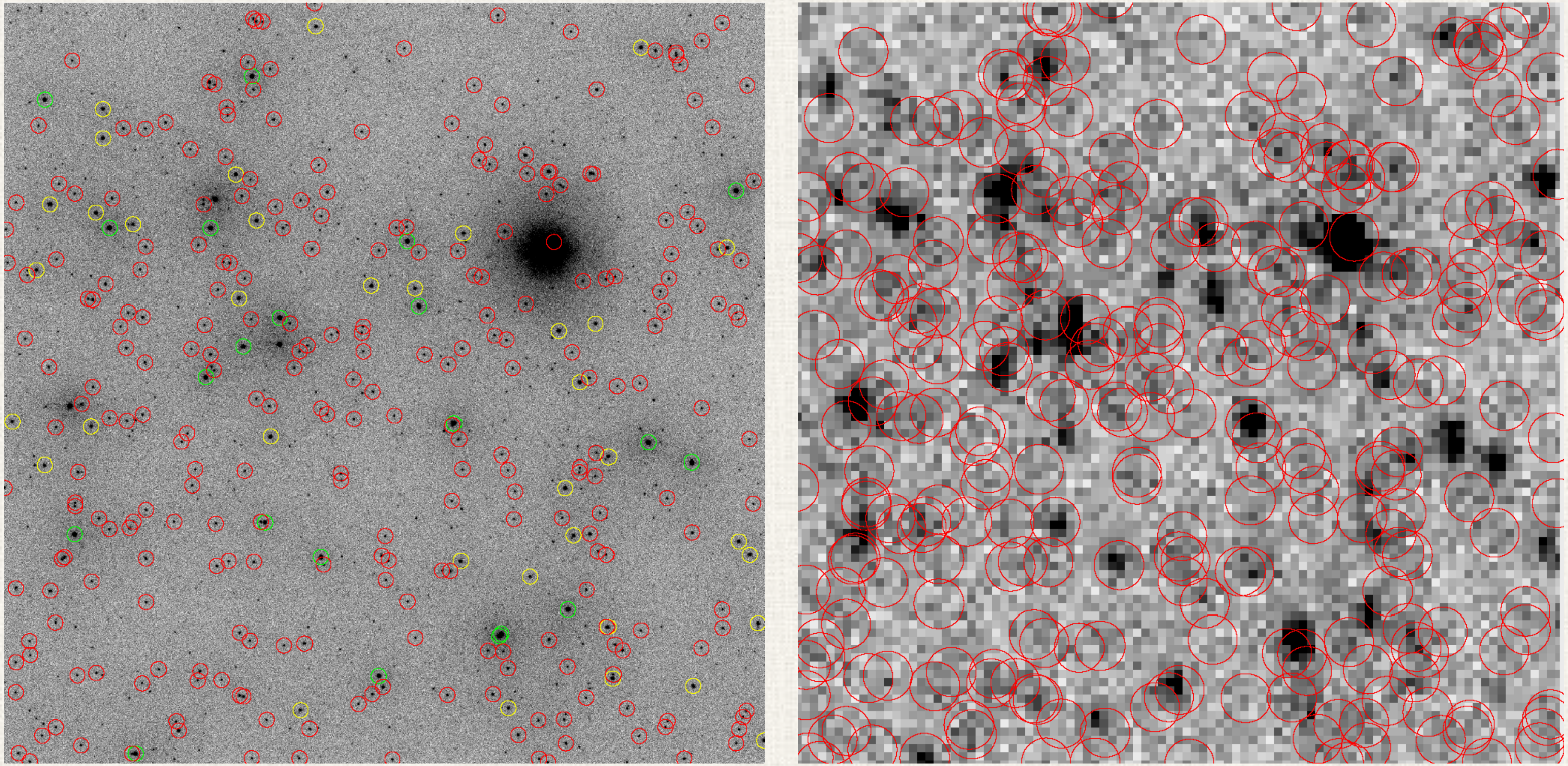


stars with 26.5 < I < 27.5

stars with 27.5 < I < 28.5

stars with 28.5 < I < 29.5

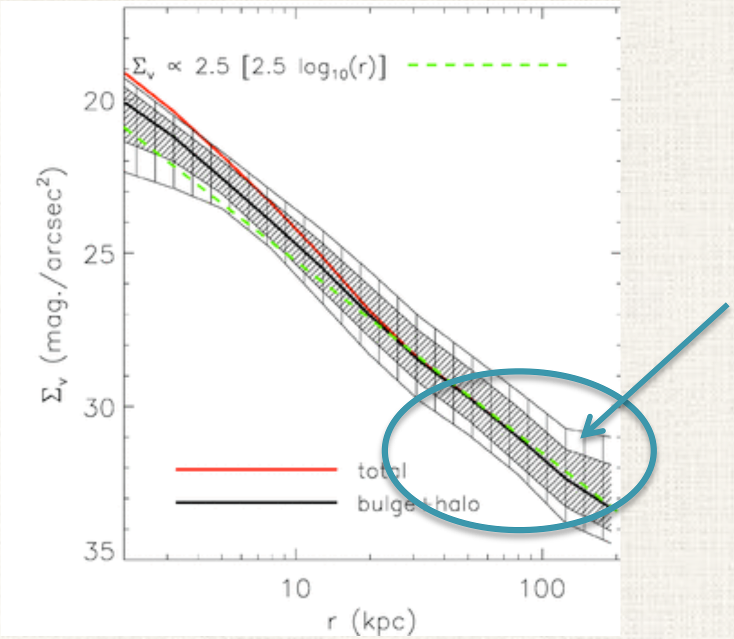
At DM = 29.5 the Red HB stars are found at I ~ 29.5. They are detected with MICADO, too faint for NIRcam.



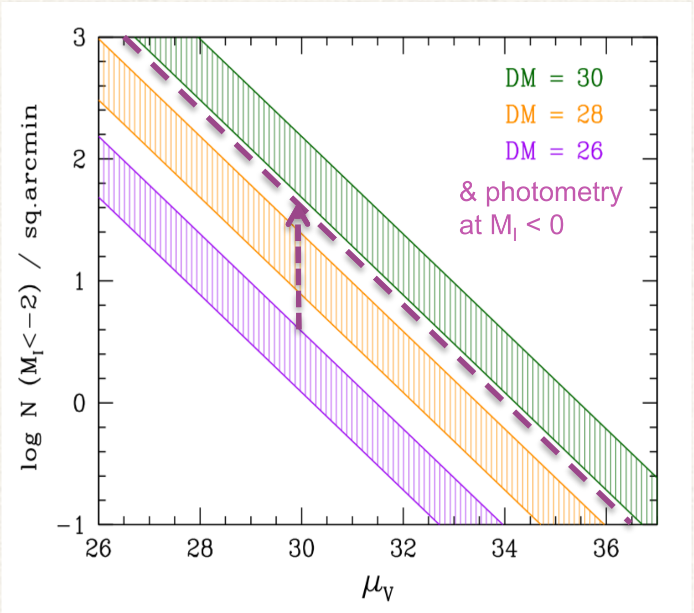
stars with 26.5 < I < 27.5
stars with 27.5 < I < 28.5
stars with 28.5 < I < 29.5

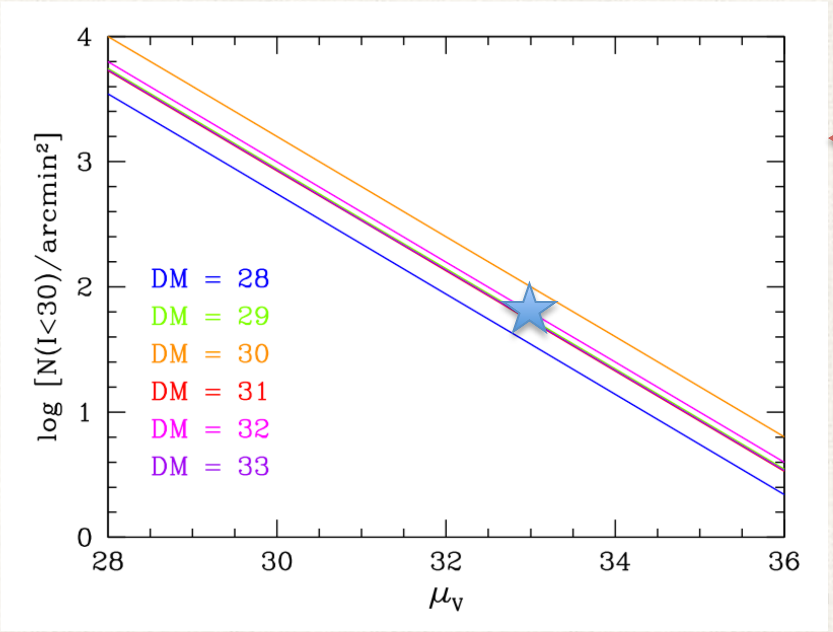
At DM = 29.5 the Red HB stars are found at M(I) ~ 29.5. They are detected with MICADO, too faint for NIRcam.

Mapping the outskirts of galaxy halos



To sample low SB regions (with a fixed FoV) either we survey a distant galaxy, or we go faint on a nearby one

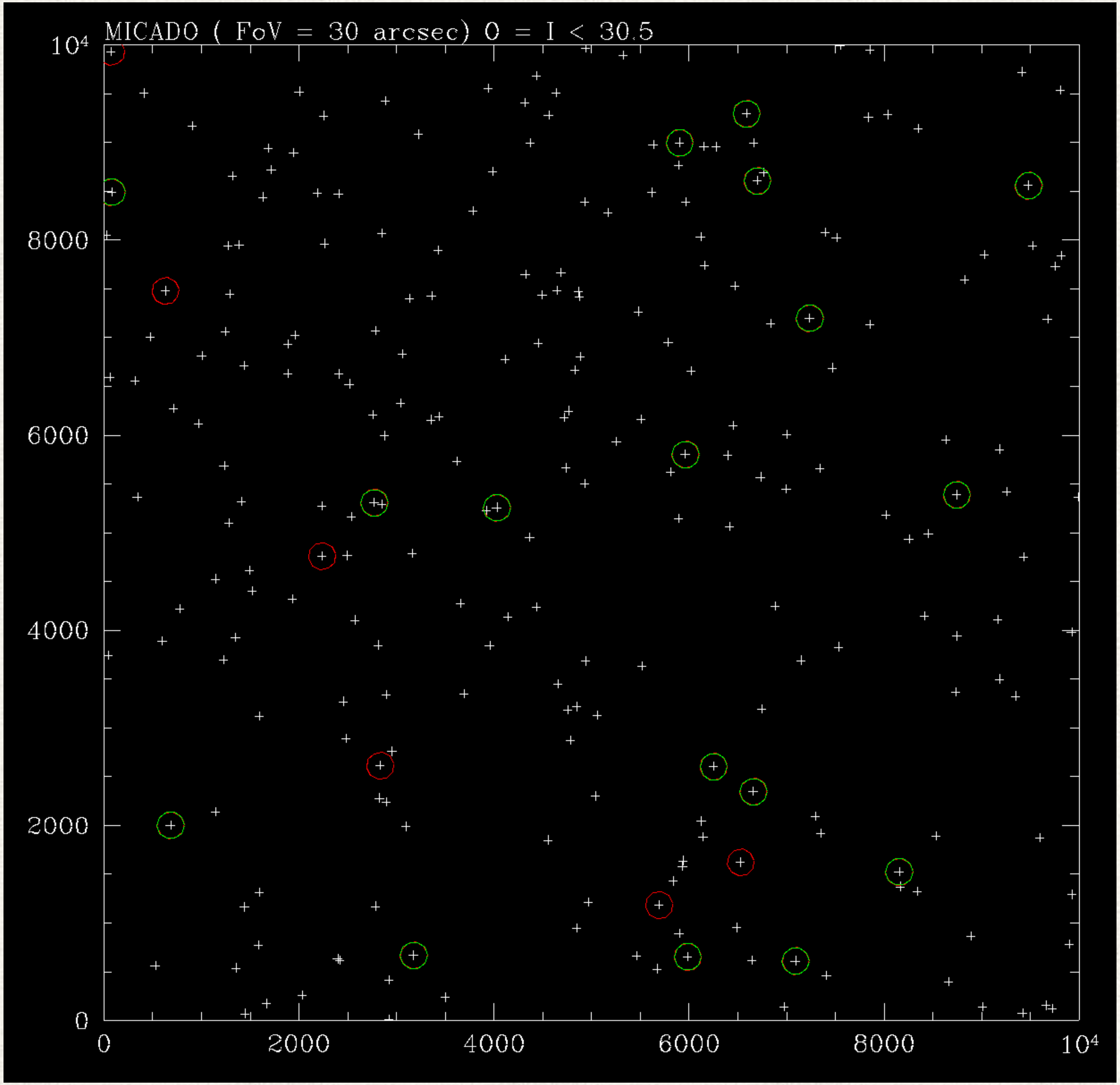




Relation between SB and surface density of stars brighter than a fixed APPARENT magnitude

As the galaxy moves farther
the FoV samples a wider physical area
(more stars)
the photometry samples a brighter portion of the LF
(less stars/square arcmin)
The two effects more or less compensate.

Still, at large distances, a given FoV samples wider physical regions

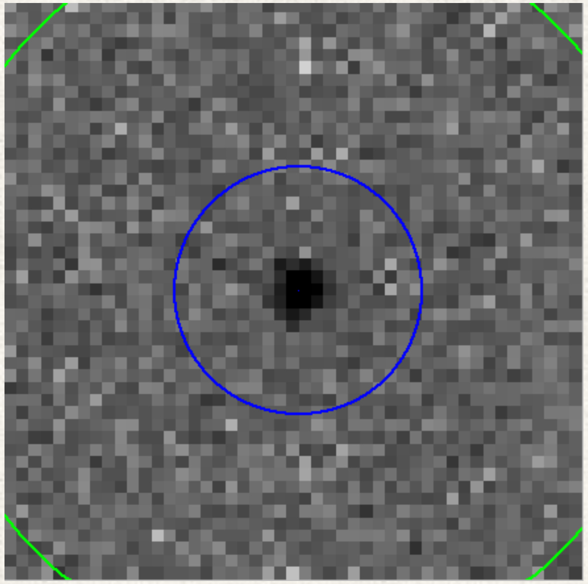


¼ MICADO field
μ_V = 33
D = 30 Mpc
DM= 32.4
t_{exp} = 3 hrs
I_{lim} = 30.4
M(I) < -2

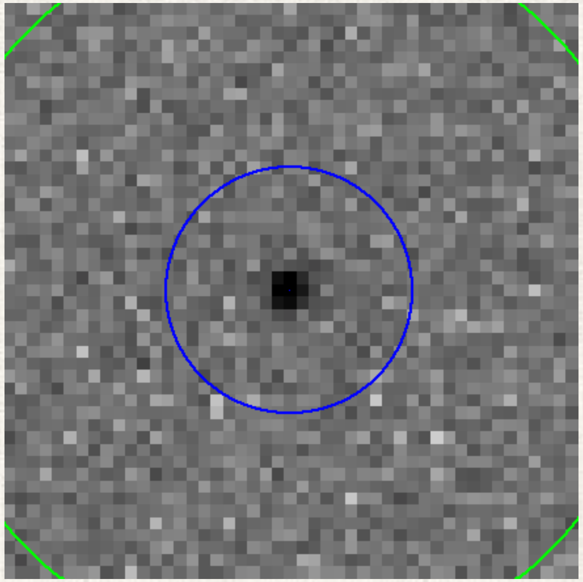
White crosses are all the simulated stars (m(I)<32) circles show those brighter than 30.5

Total light from stars fainter than I=32 is included as a pedestal with its Poisson noise

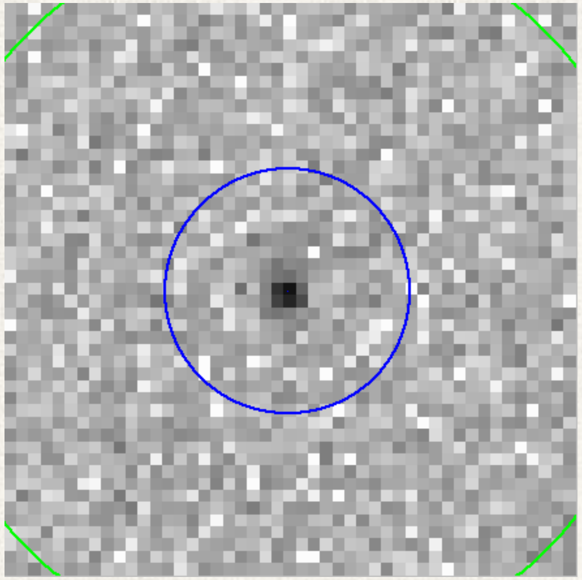
I=28.6

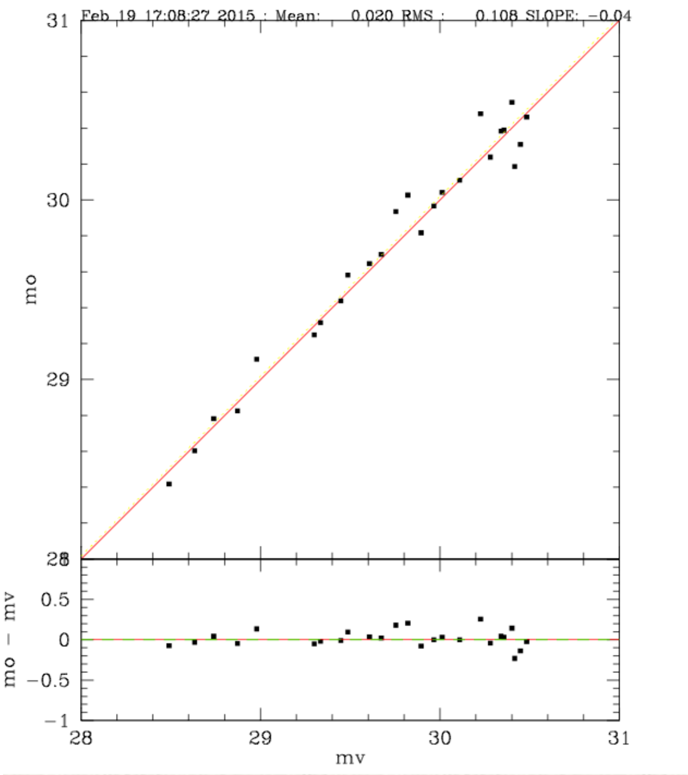


I=28.9



I=29.8

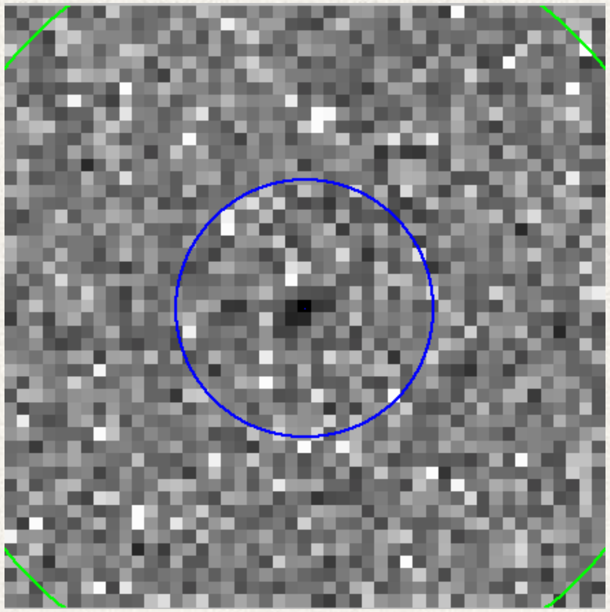




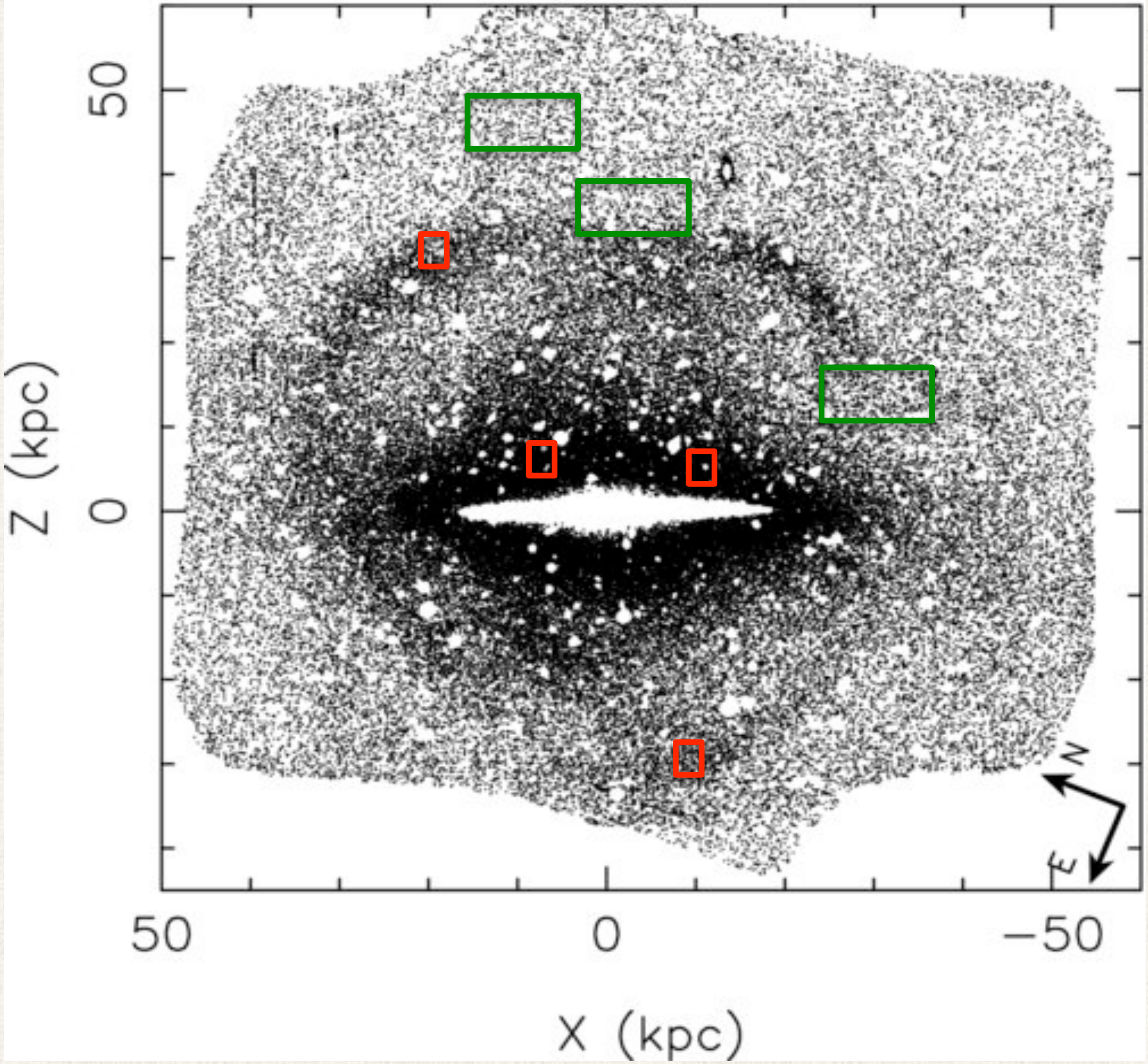
Photometry down to 2 mag below the tip is well feasible, but there are only ~ 80 such stars/arcmin^2 at these low SBs

Most of the frame is pitch black

I=30.5



Mouhcine, Ibata, Rejkuba, 2010 : Subaru image of NGC 891



At DM = 29.94

🟥 one MICADO field maps ~2.8 x 2.8 kpc^2 samples upper 4 mag on RGB + Red HB

🟩 one JWST field maps ~2 x (6 x 6) kpc^2 samples upper 3 mag on RGB

The combination will allow us to study efficiently the stellar populations in the substructures, and the mass and metallicity distribution of the stellar halo on large scales