

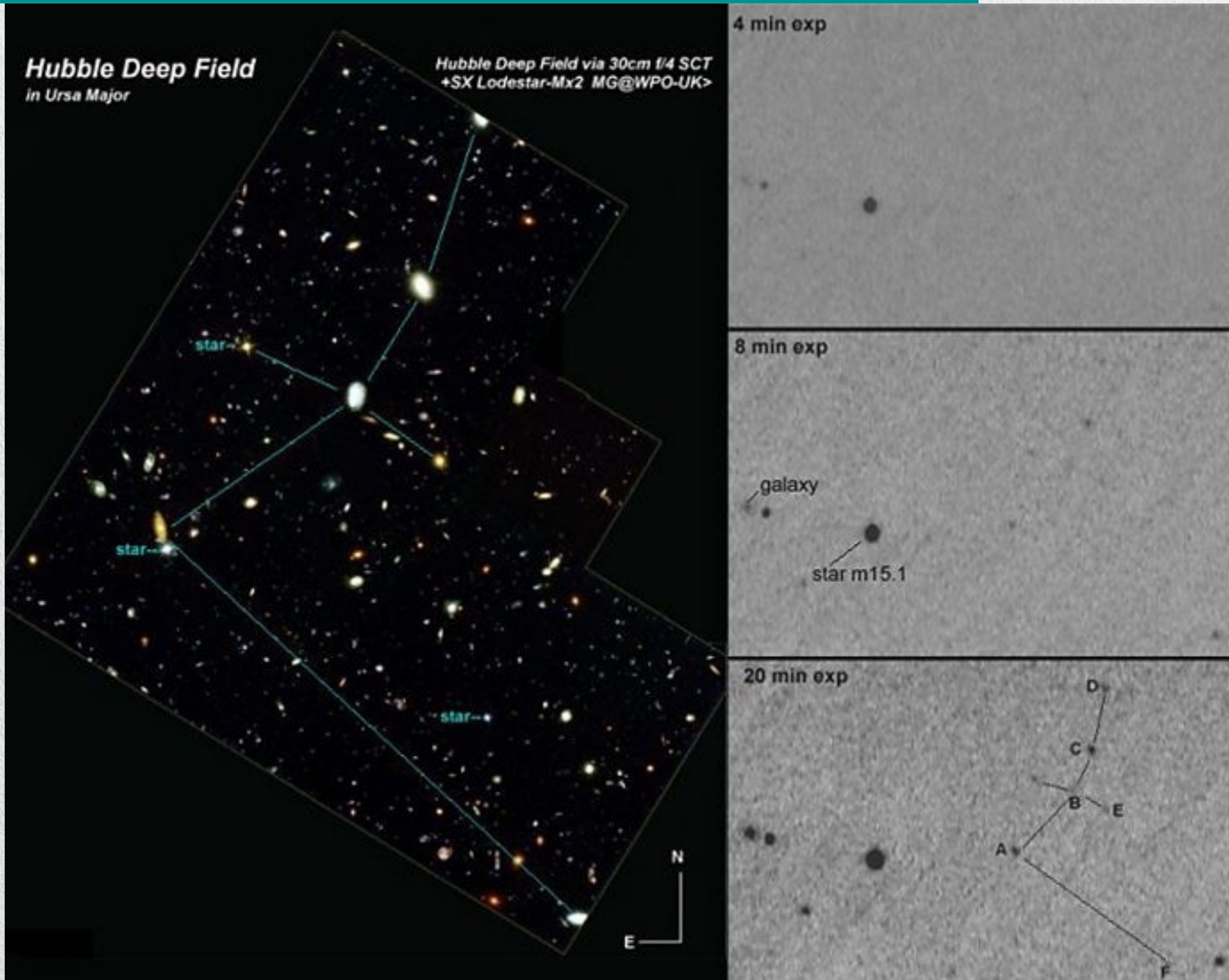
The **intracluster light**: the missing piece in the galaxy cluster evolution puzzle

Mireia Montes
UNSW Sydney

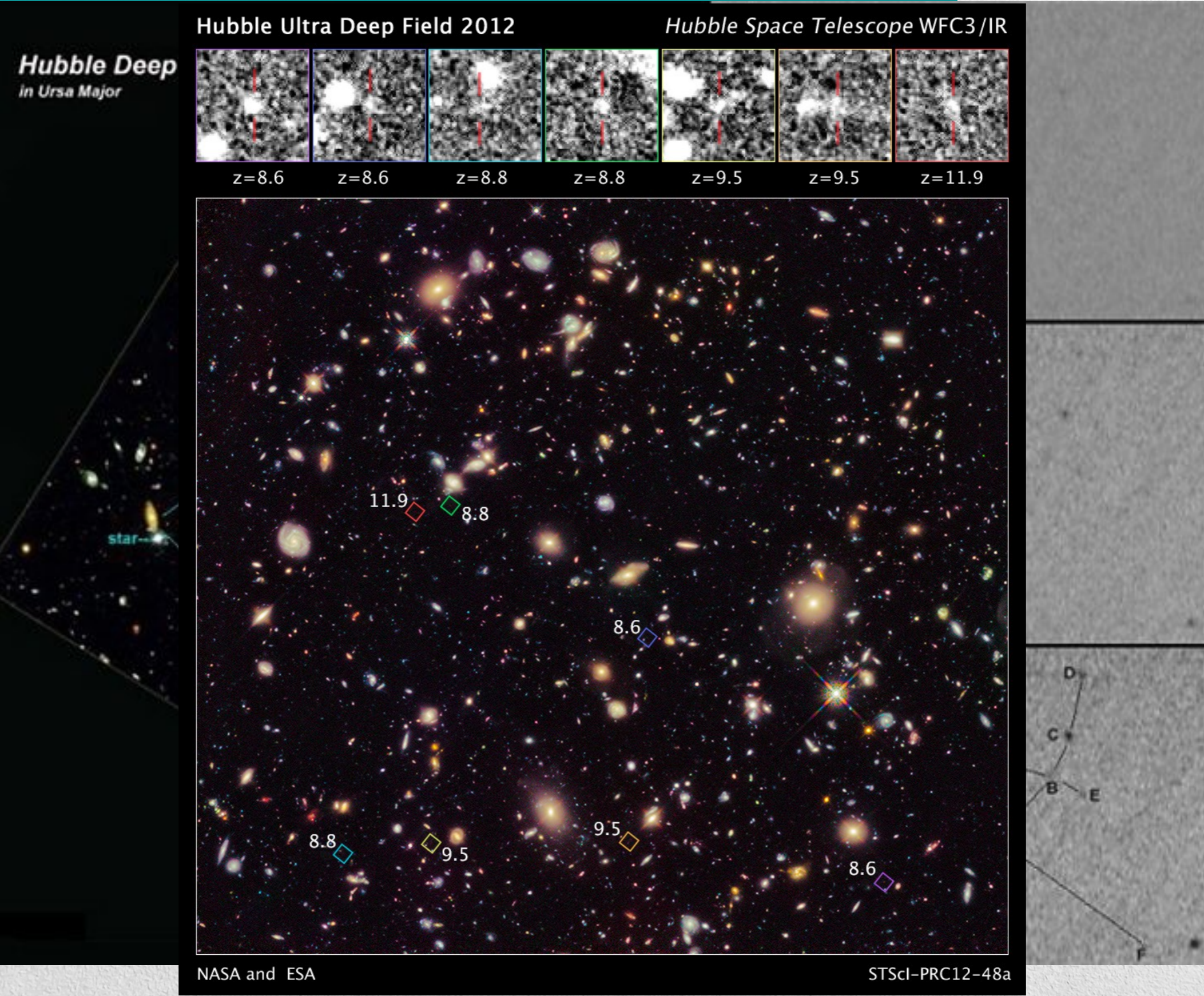
 @mireiamontesq



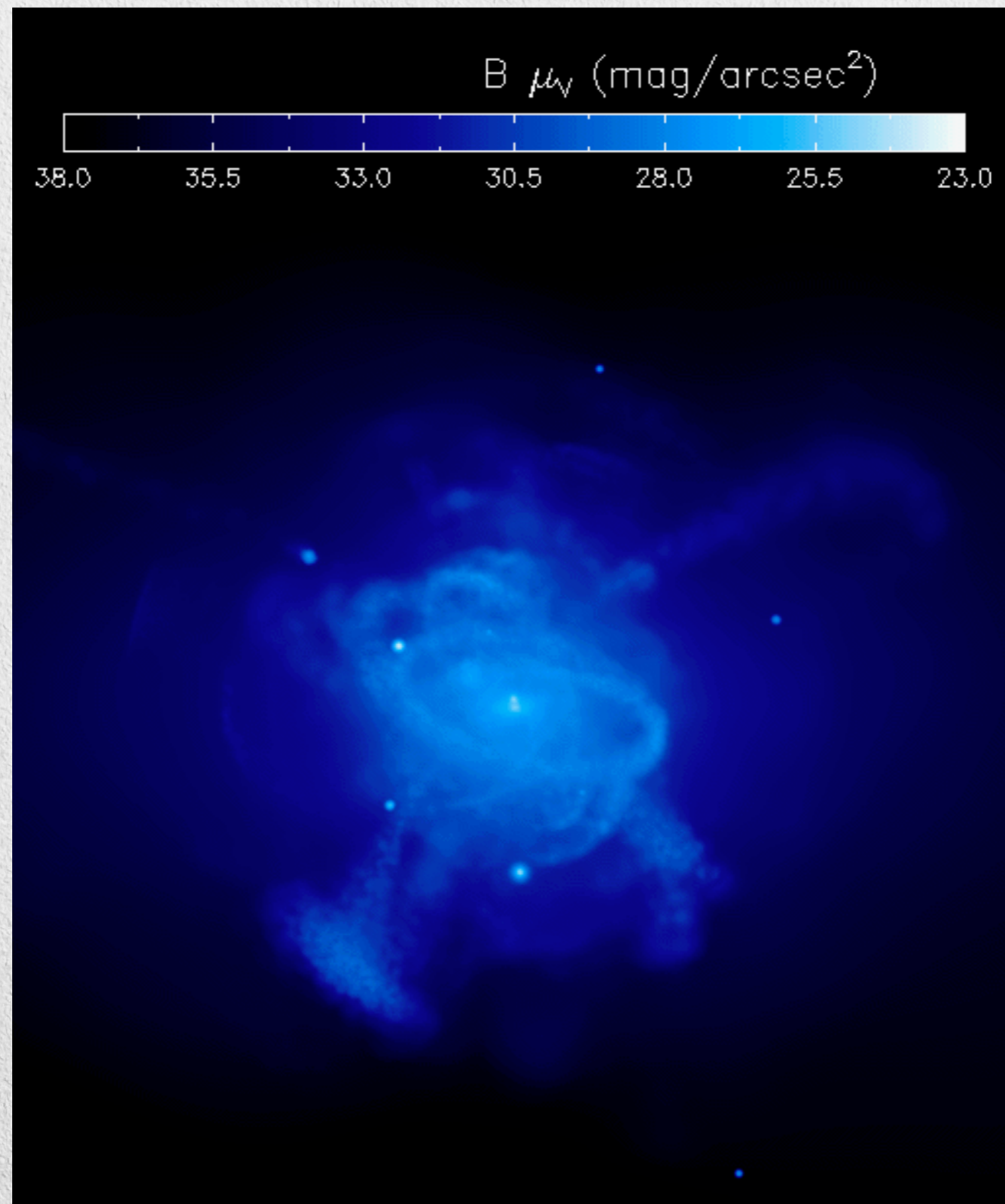
The hidden Universe



The hidden Universe

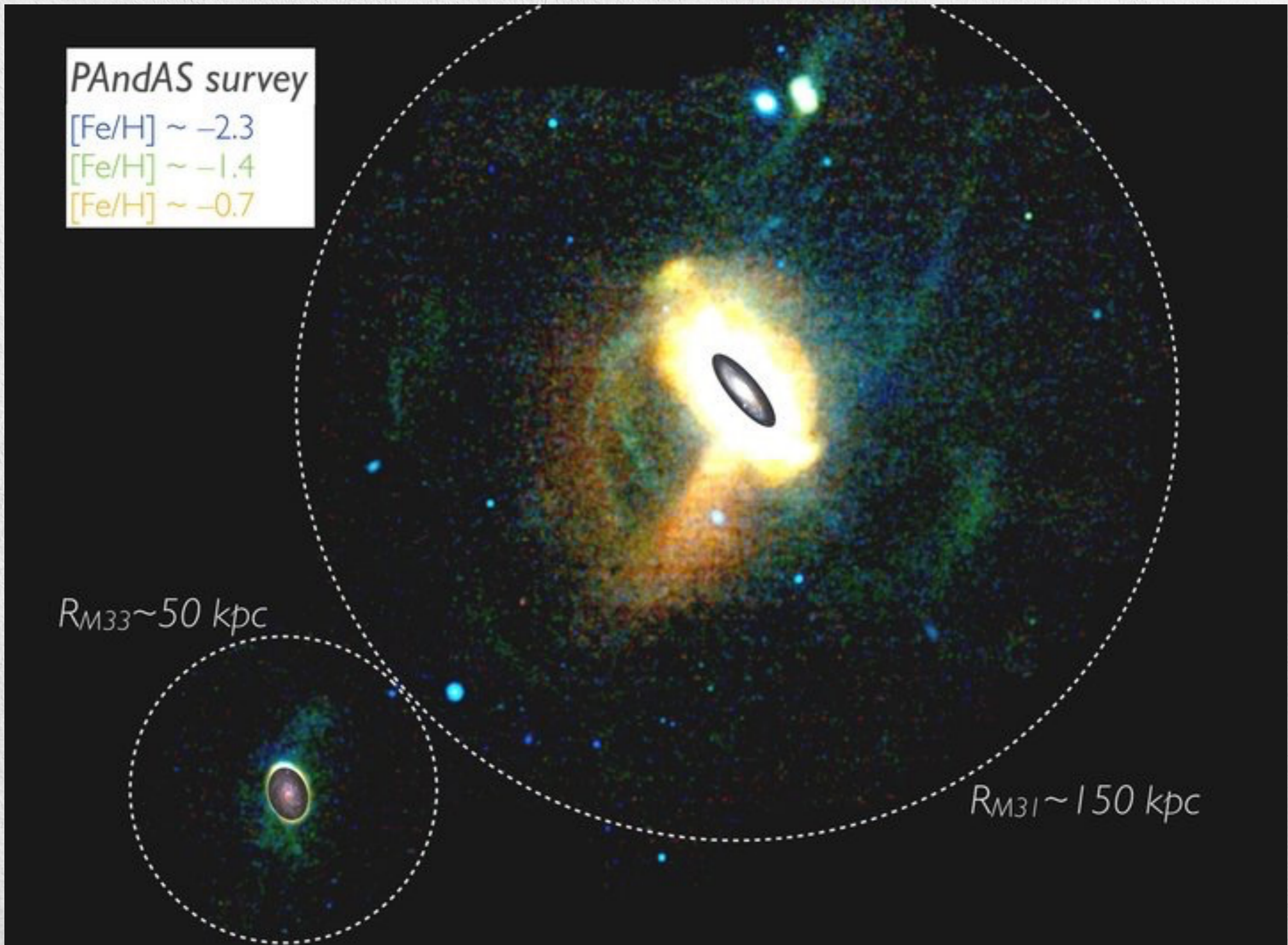


The low surface brightness Universe

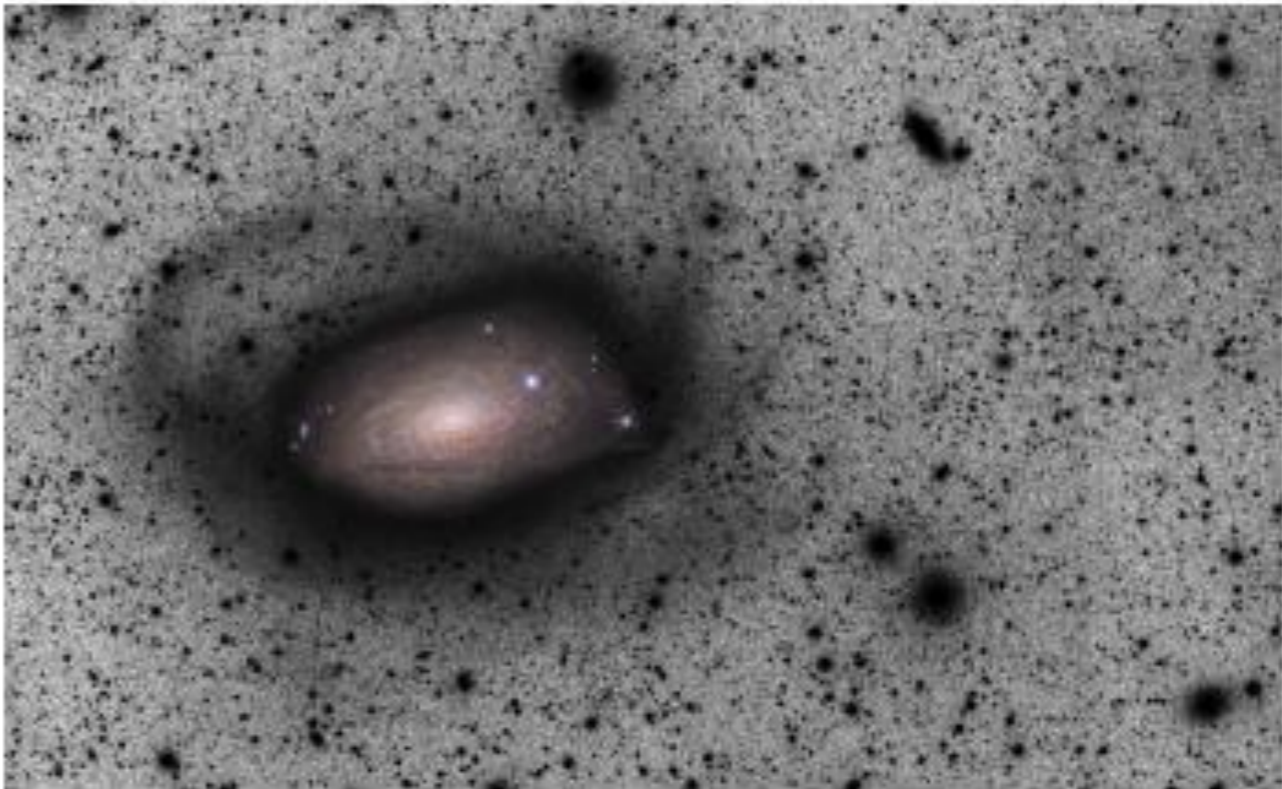
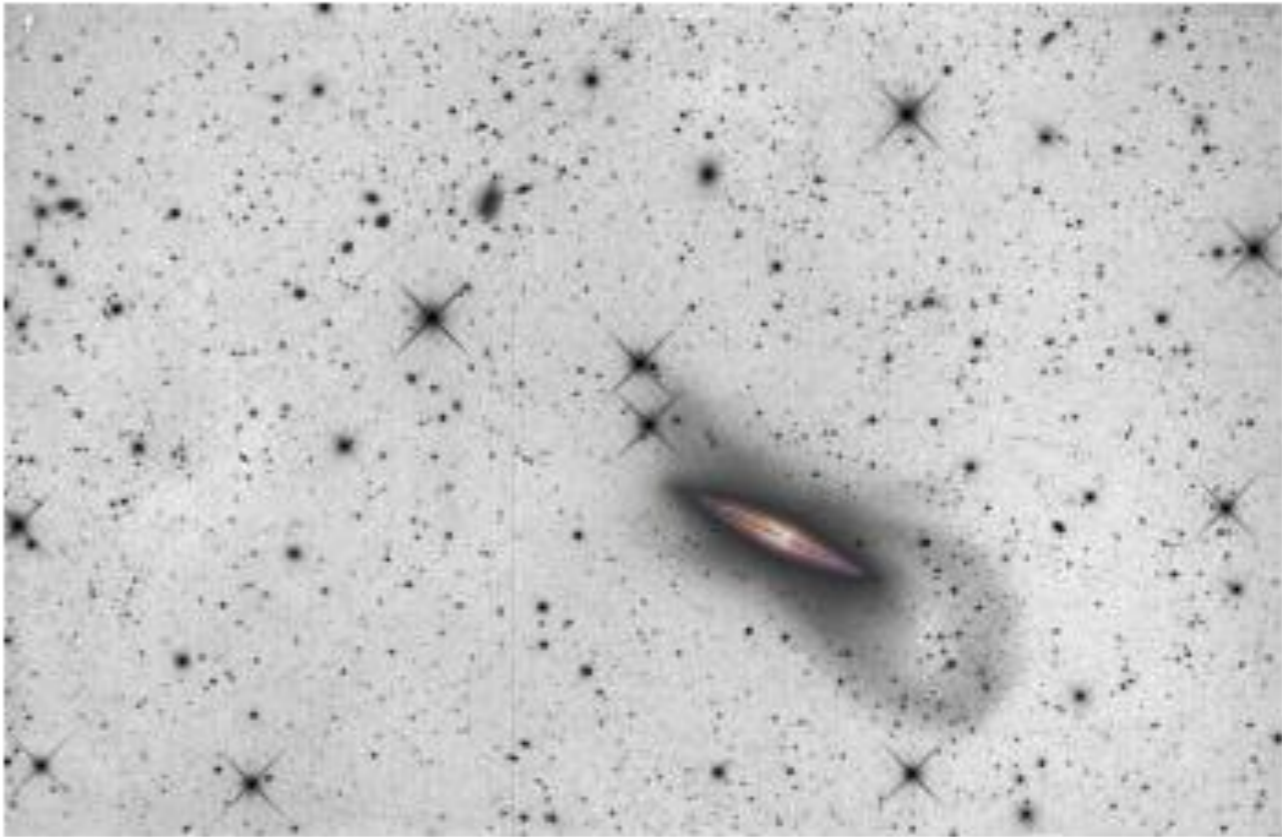
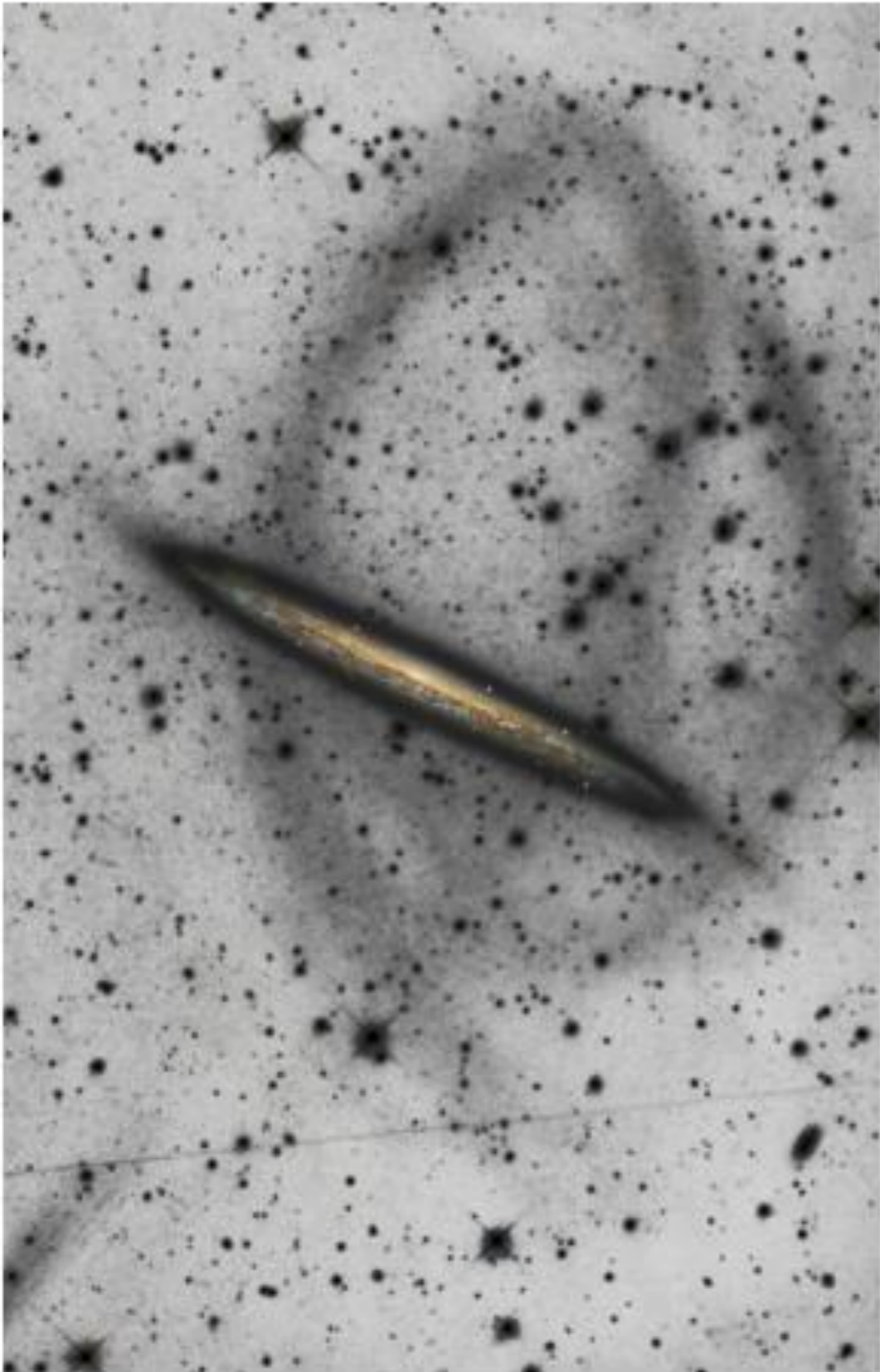


Bullock & Johnston 2005

The low surface brightness Universe



The low surface brightness Universe



The low surface brightness Universe

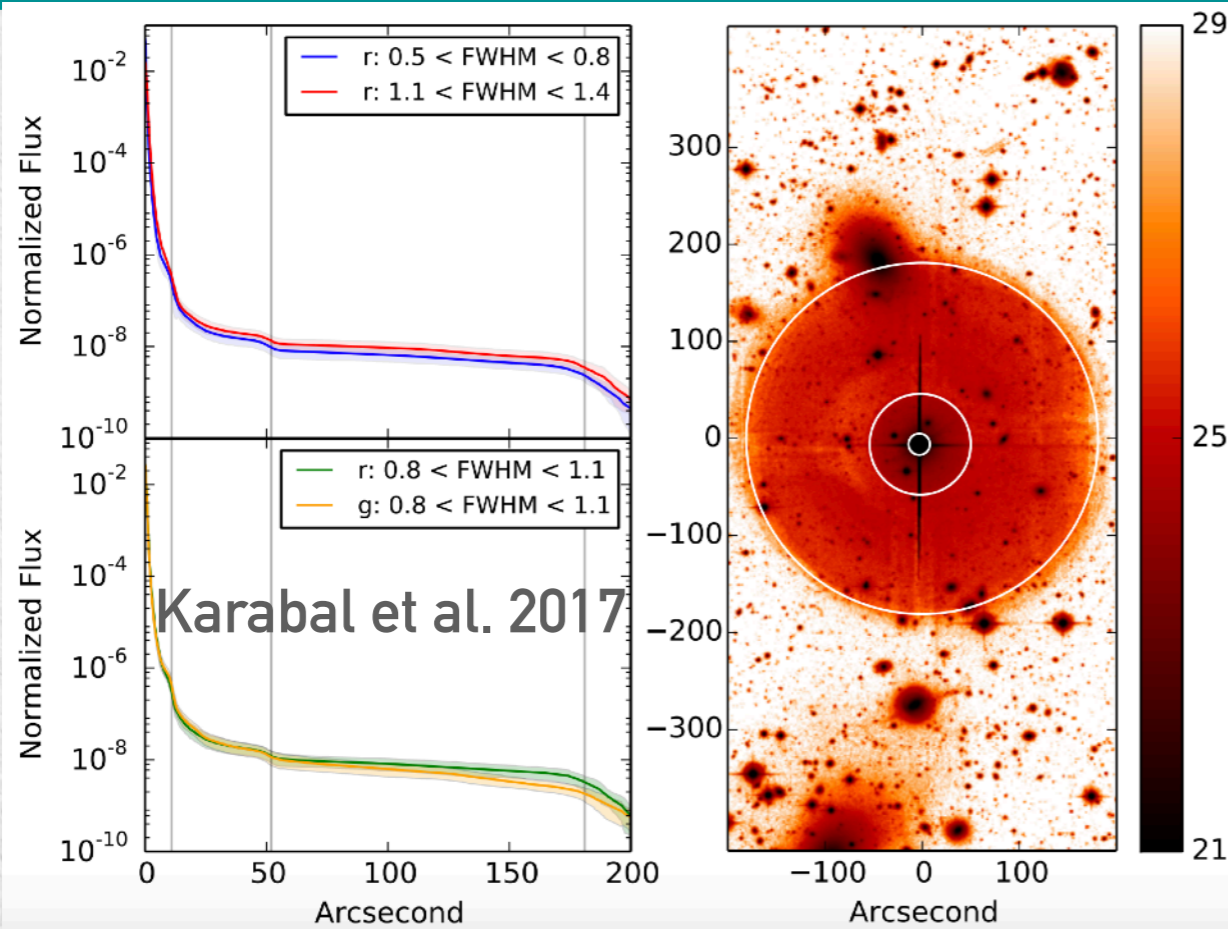
$$\mu_v > 27 \text{ mag/arcsec}^2$$

- Buildup of structure
 - Galaxy halos Trujillo & Bakos 2013, Merritt et al. 2016, Buitrago et al. 2017, Huang et al. 2018
 - ICL MM & Trujillo 2014, 2018
- Missing baryons?
 - ICL Gonzalez et al. 2007, 2013
- Missing satellites?
 - LSB satellites? Crjonovic et al. 2016, Bennet et al. 2017
- Dark Matter ?
 - Ultra diffuse galaxies van Dokkum et al. 2015, Román & Trujillo 2017a,b
- Other phenomena, e.g. :
 - Astrospheres of dying stars Sahai & Mack-Crane 2014

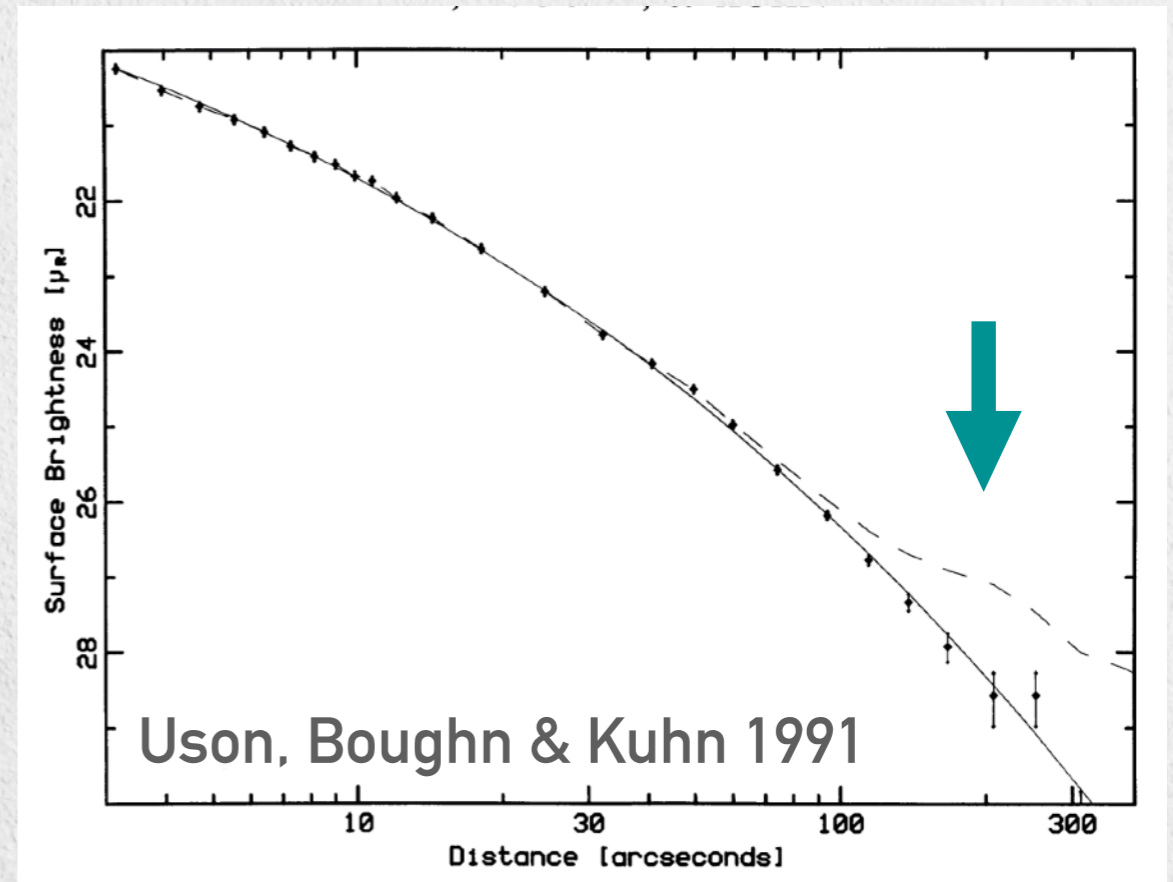
Observing LSB

Observing LSB

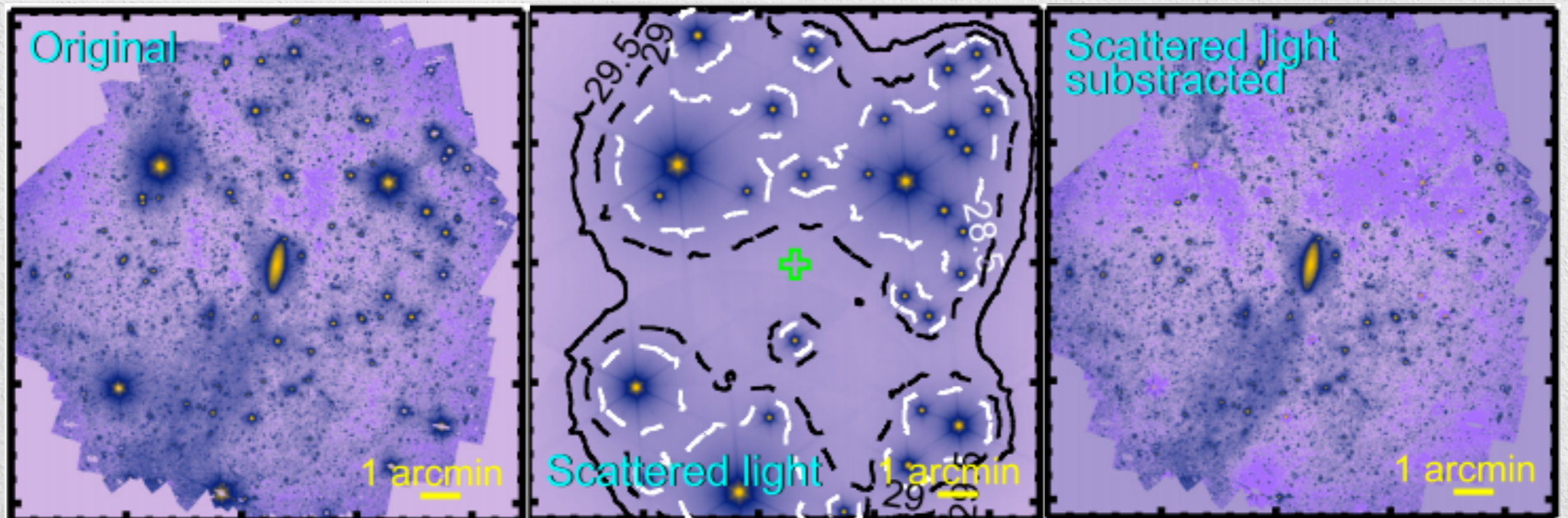
Scattered light



Karabal et al. 2017

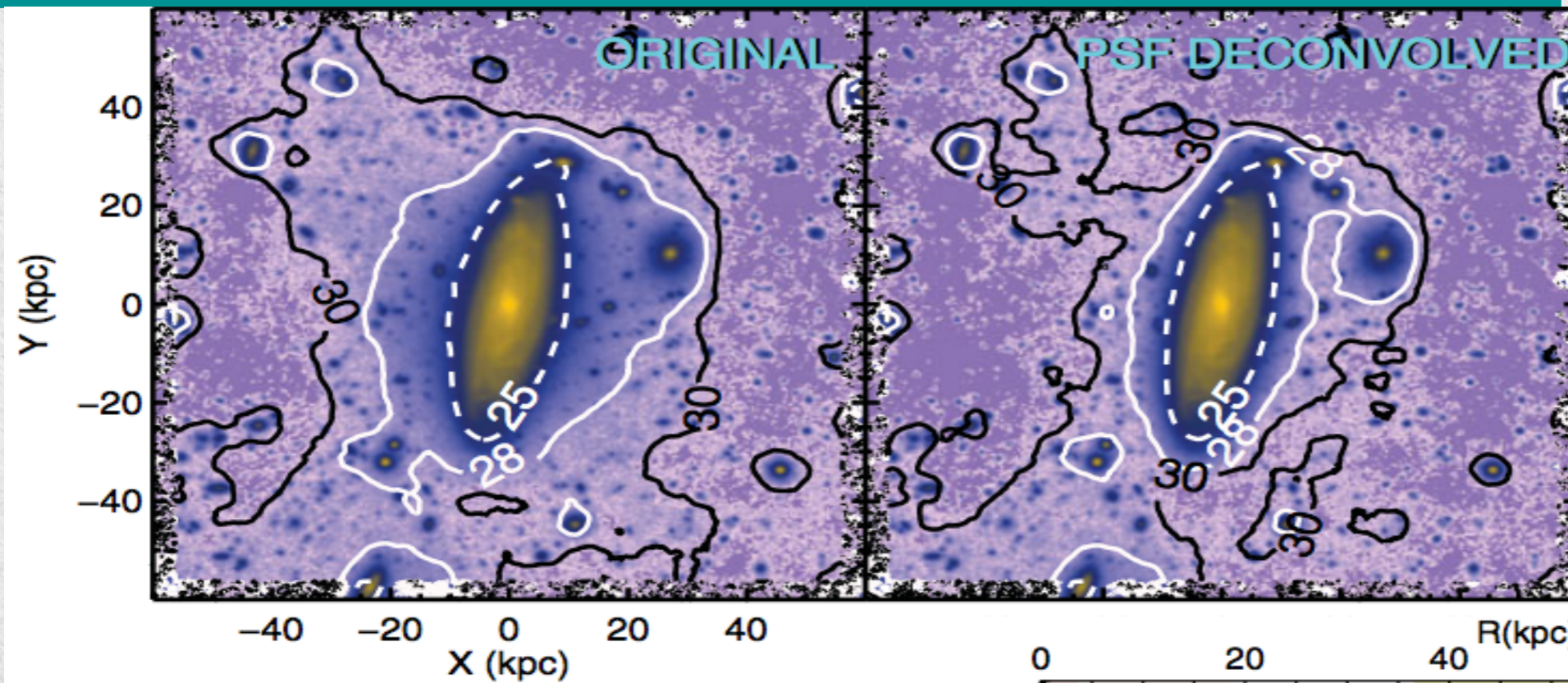


Uson, Boughn & Kuhn 1991



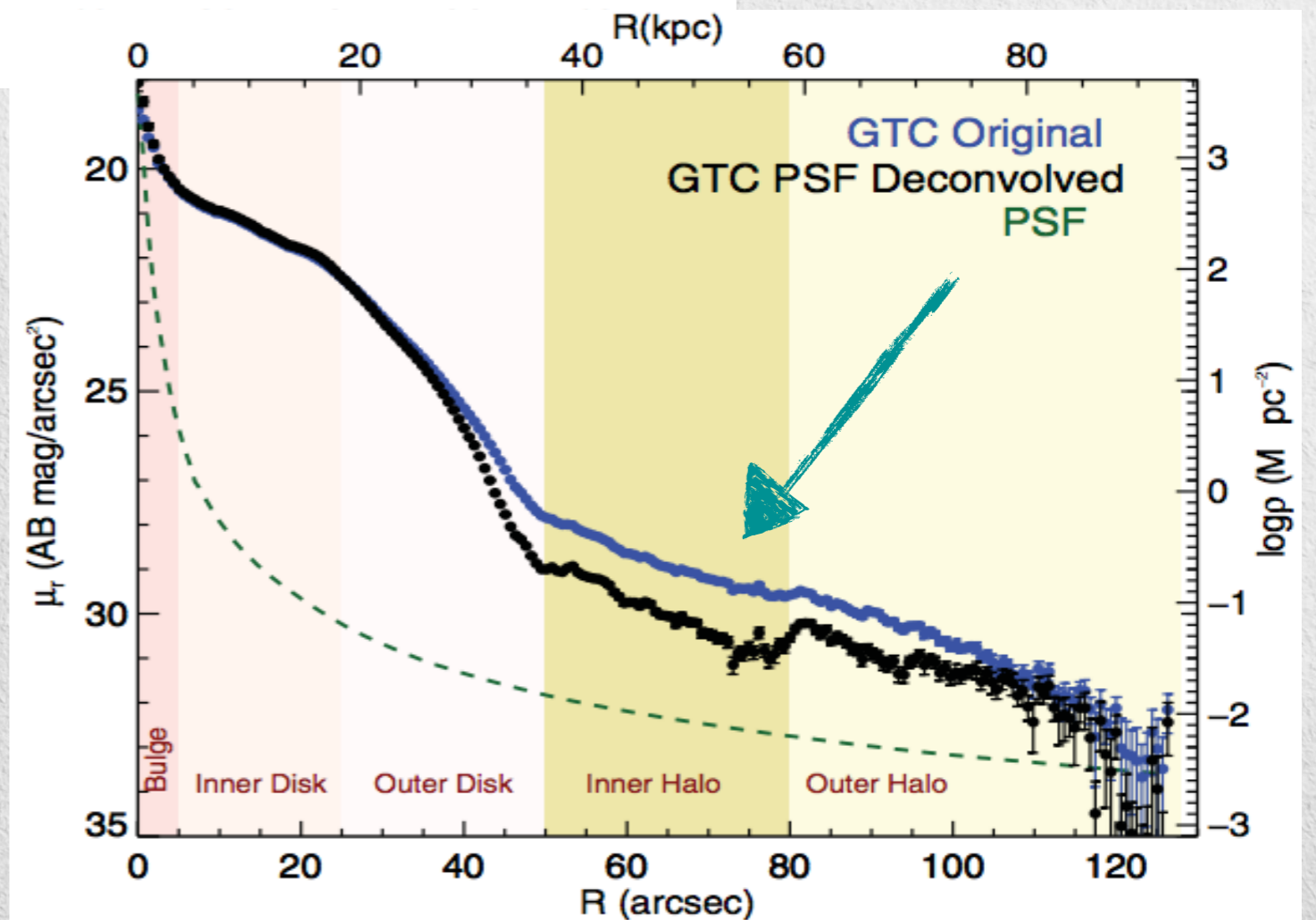
Trujillo & Fliri 2016

PSF effect



Trujillo & Fliri 2016

Mimic stellar halo

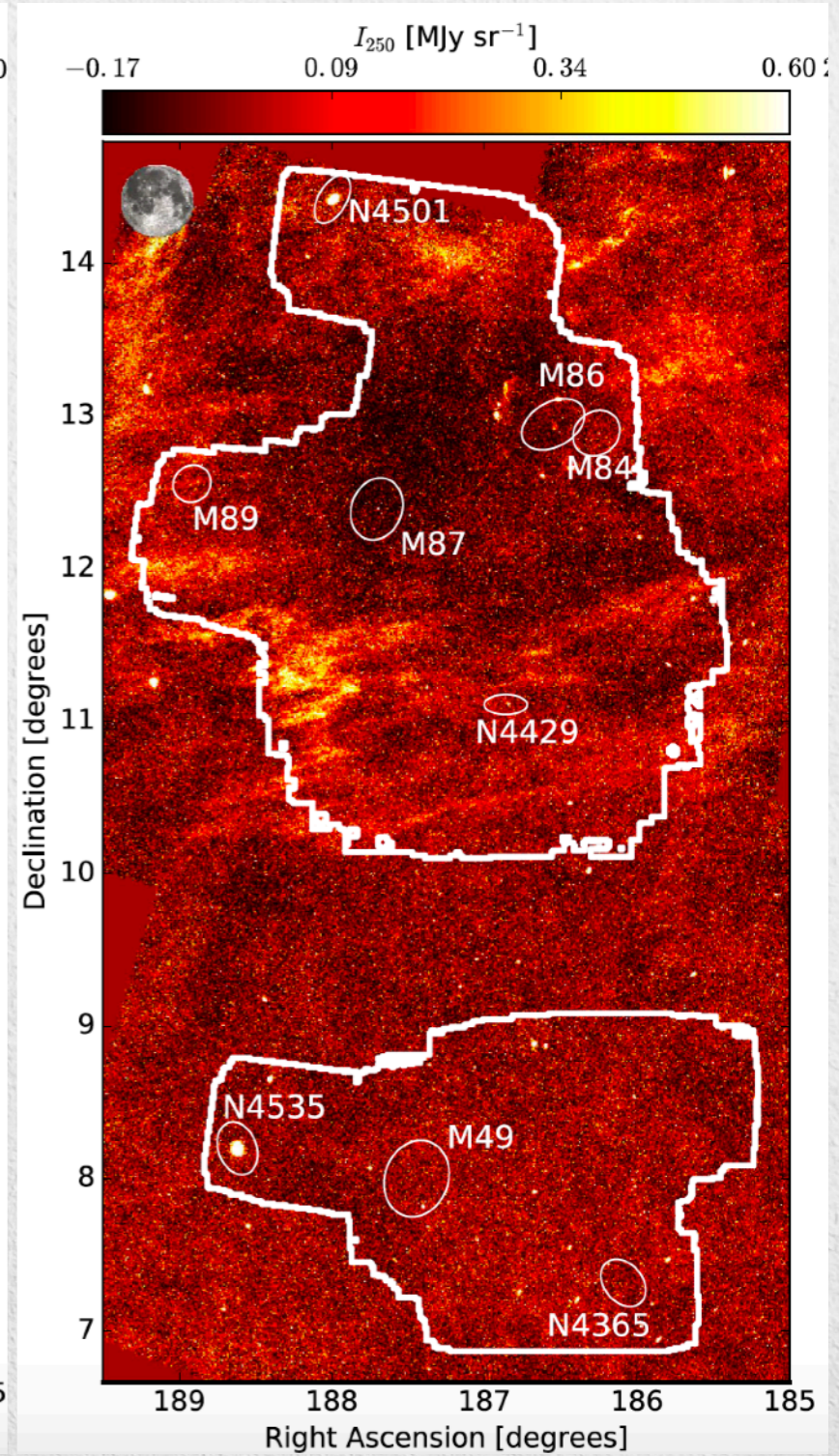
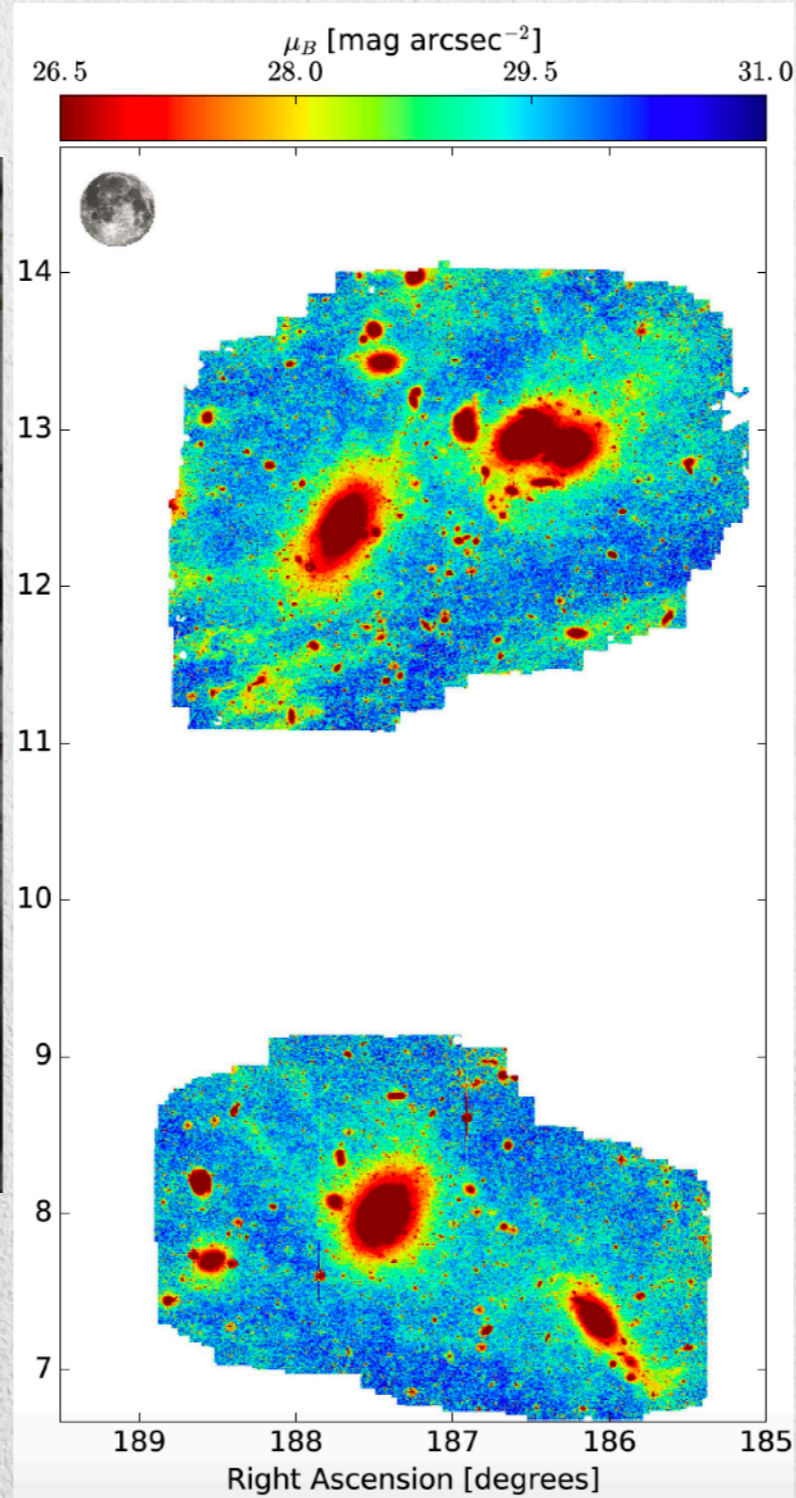


Affects more smaller systems

Galactic Cirri

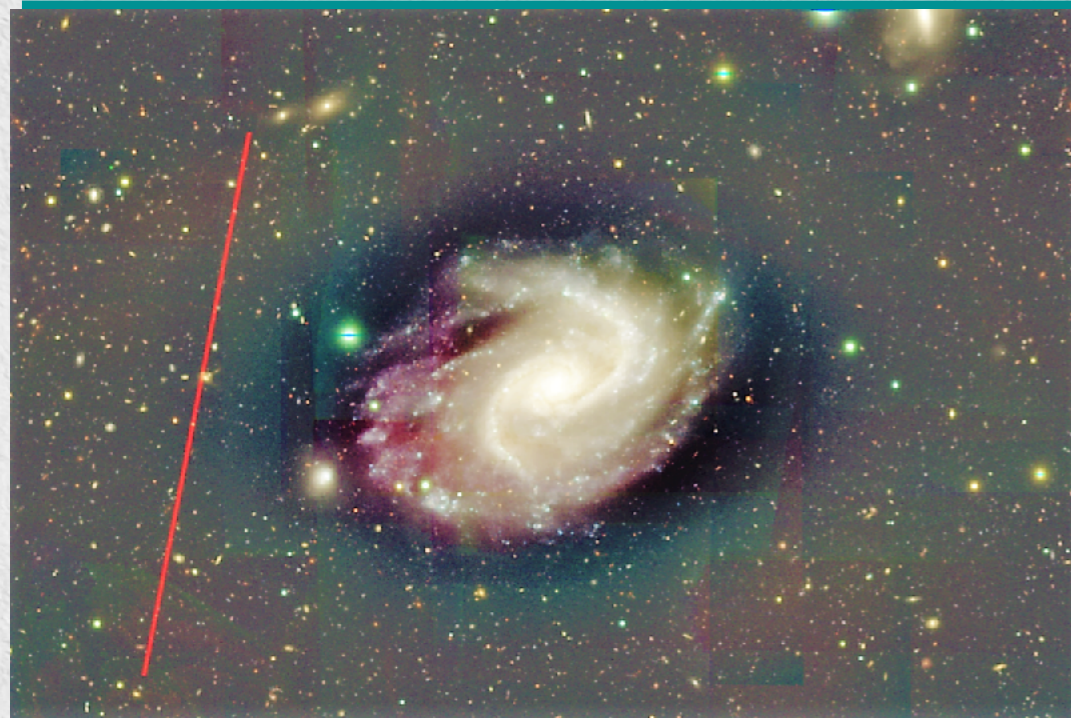


Duc et al. 2015



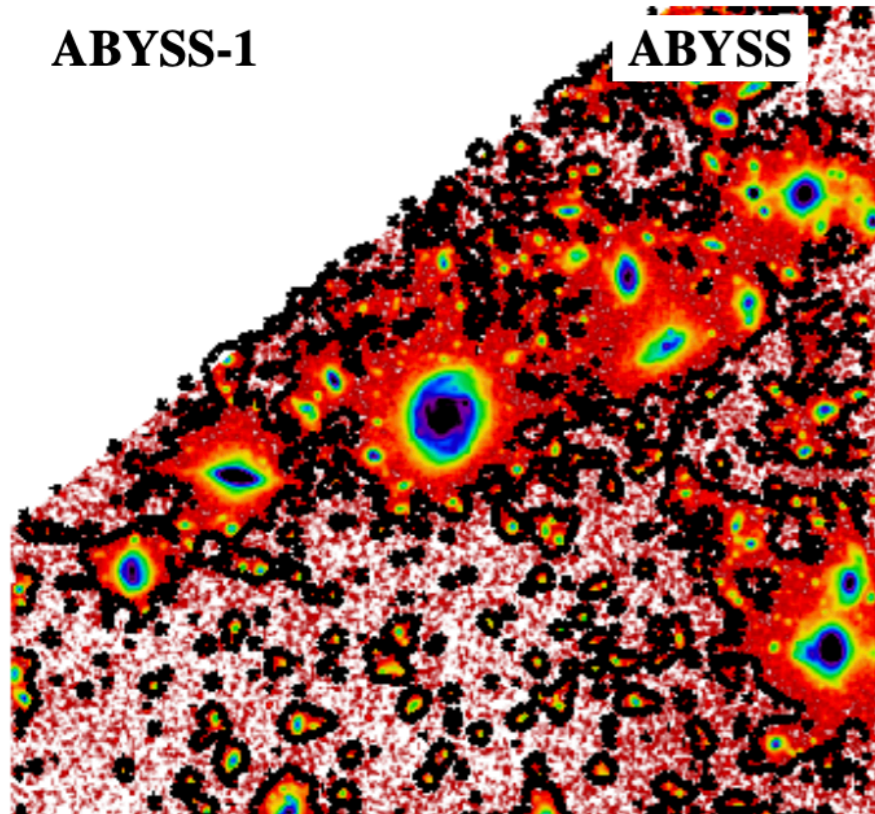
Mihos et al. 2017

Sky subtraction

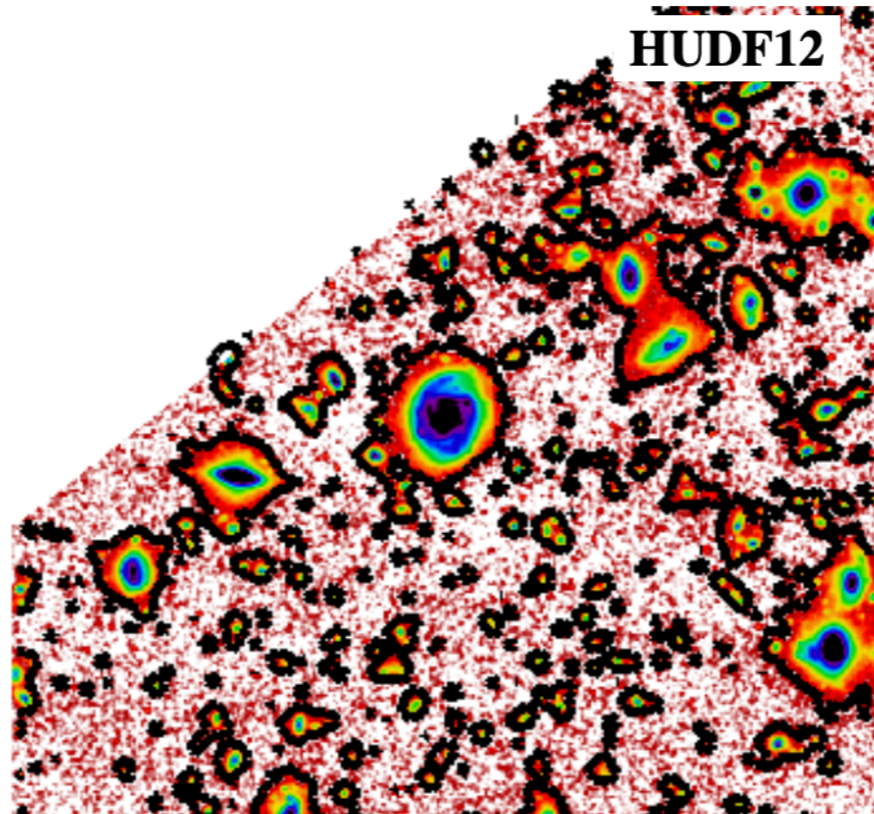


Aihara et al. 2018

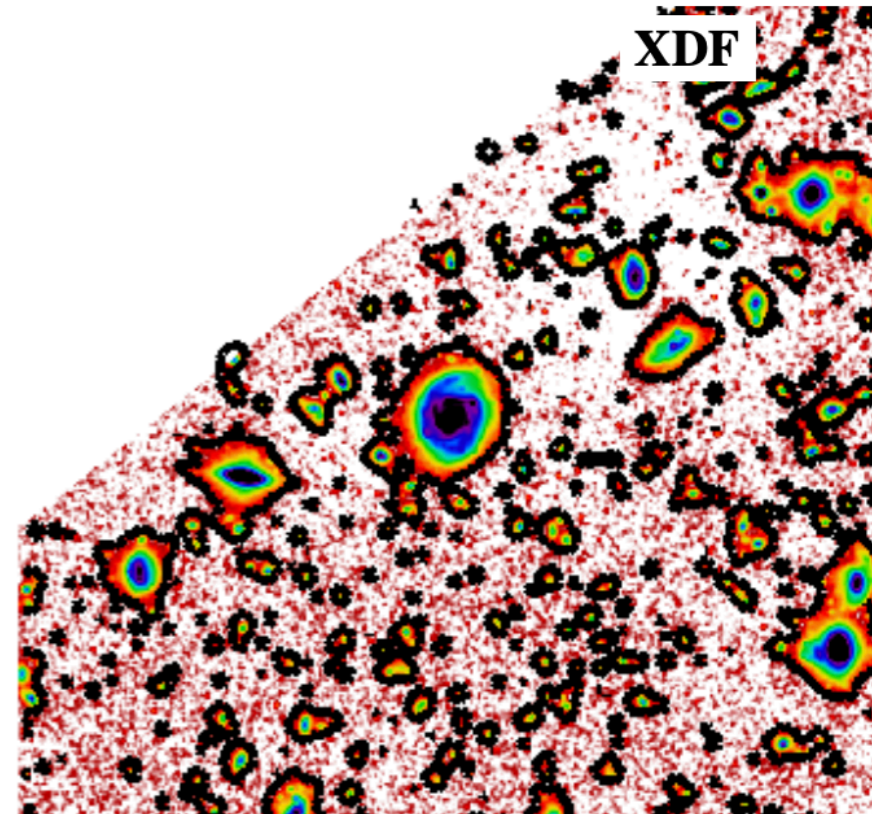
ABYSS-1



ABYSS



HUDEF12



XDF

Borlaff et al. 2019

The ICL

The ICL

The beginning



Diffuse light proposed by Zwicky 1937

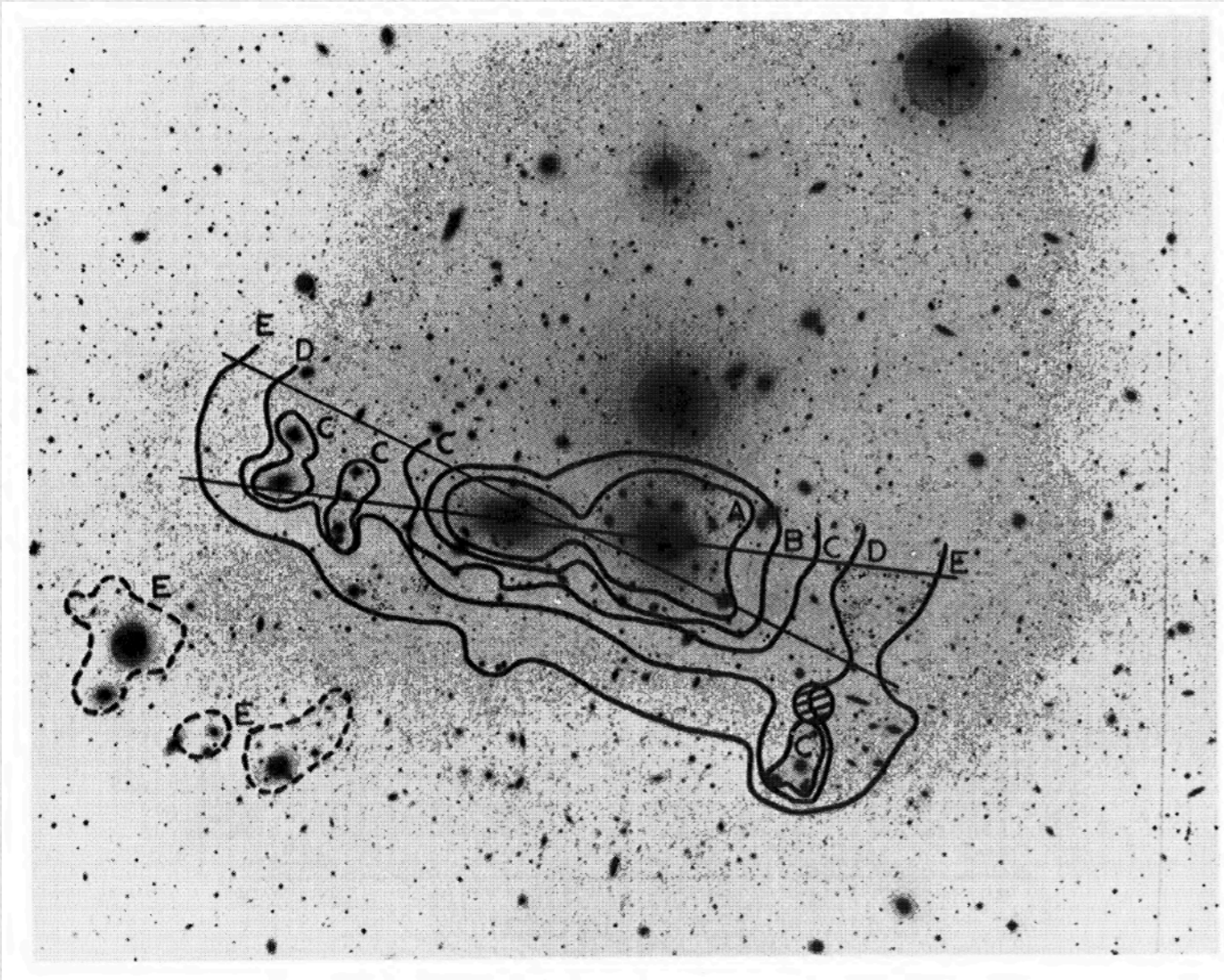
field nebulae. In the second place, we should expect a considerable number of stars, as well as matter in dispersed form from disrupted nebulae, to be scattered through the internebular spaces within clusters. Sufficiently large amounts of internebular matter in clusters

and first observed by Zwicky 1951 in Coma

One of the most interesting discoveries made in the course of this investigation is the observation of an extended mass of luminous intergalactic matter of very low surface brightness. The objects which constitute this matter must be considered as the faintest individual members of the cluster. They indicate that the

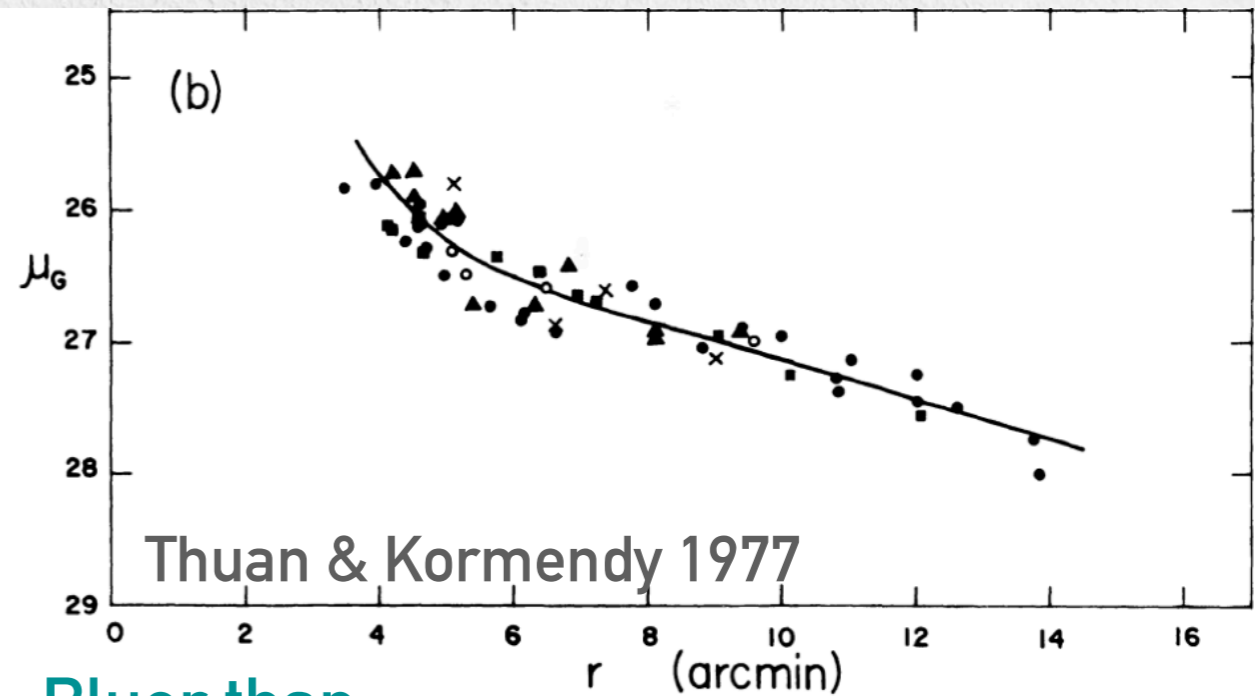
The beginning

Trying to solve the “missing” mass problem in clusters of galaxies (Zwicky 1933)

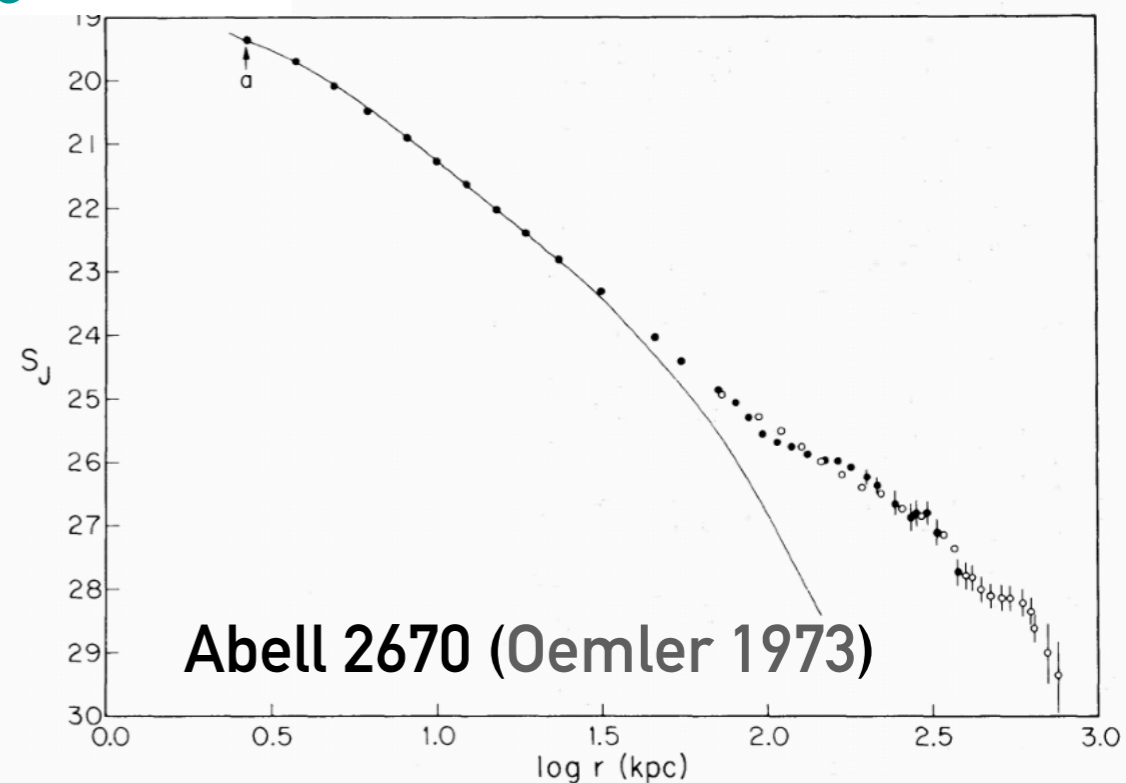


De Vaucouleurs 1960; Arp & Bertola 1969; de Vaucouleurs & de Vaucouleurs 1970; Welch & Sastry 1971; Melnick et al. 1977

ICL is 1% of the night sky or fainter!

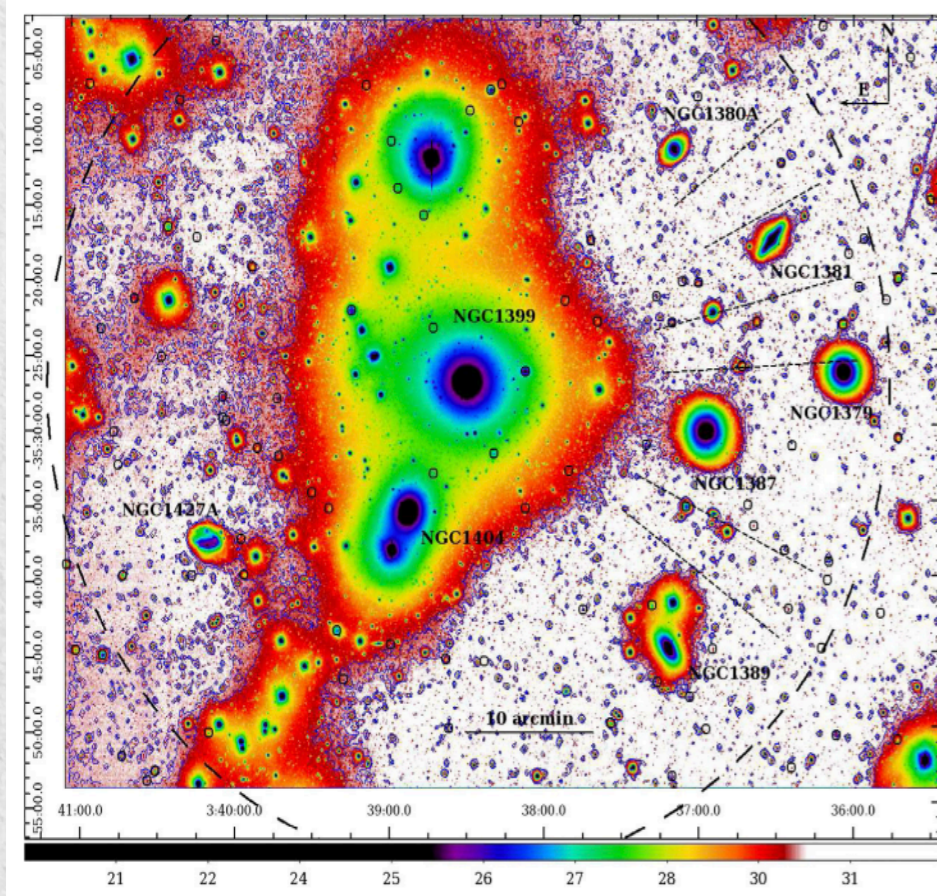


Bluer than
the galaxies!

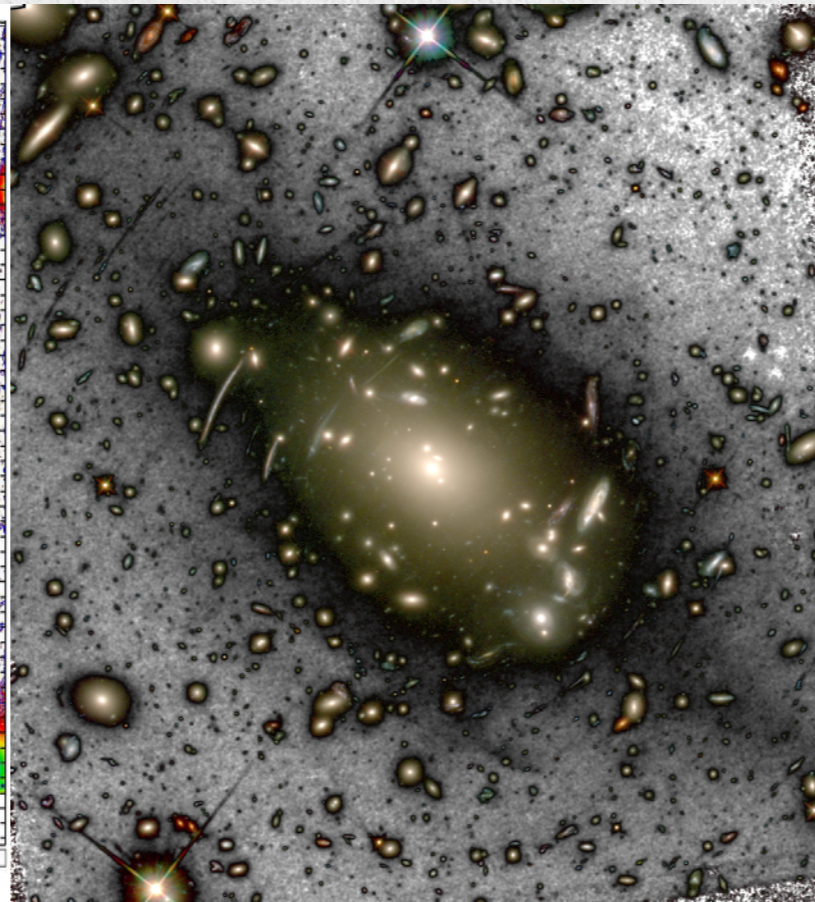


Today

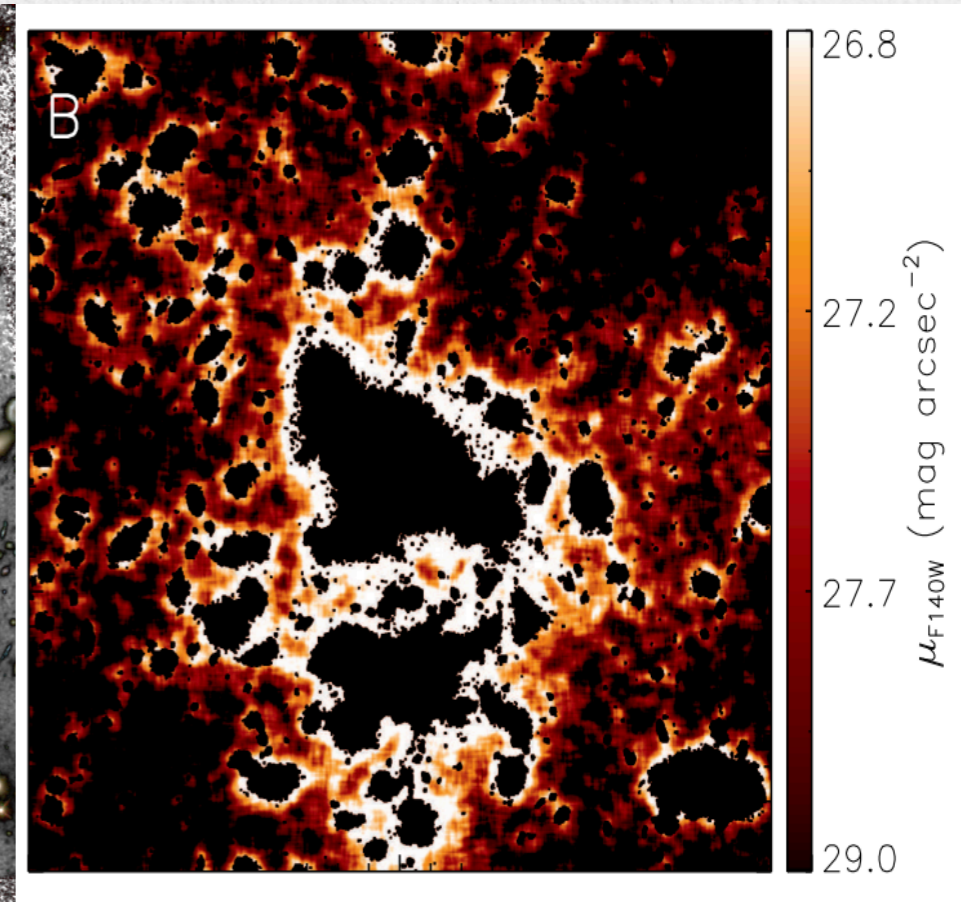
Deeper and farther



Low-z ($z \sim 0$)
Iodice et al. 2017



Intermediate-z ($z \sim 0.4$)
MM & Trujillo 2019

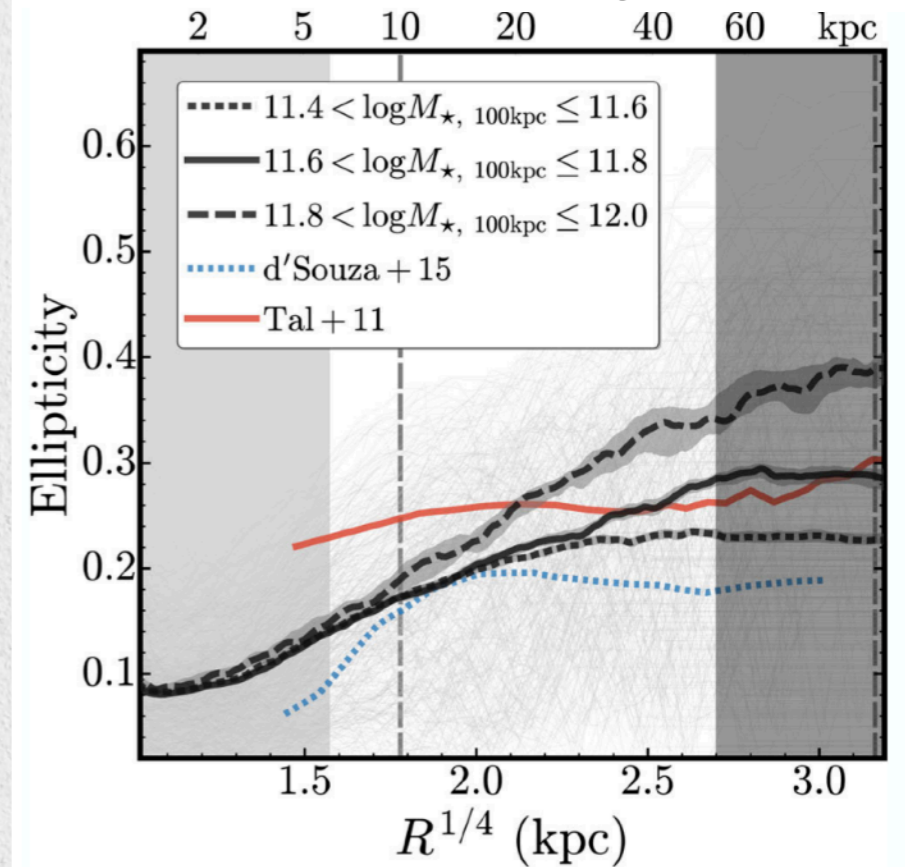
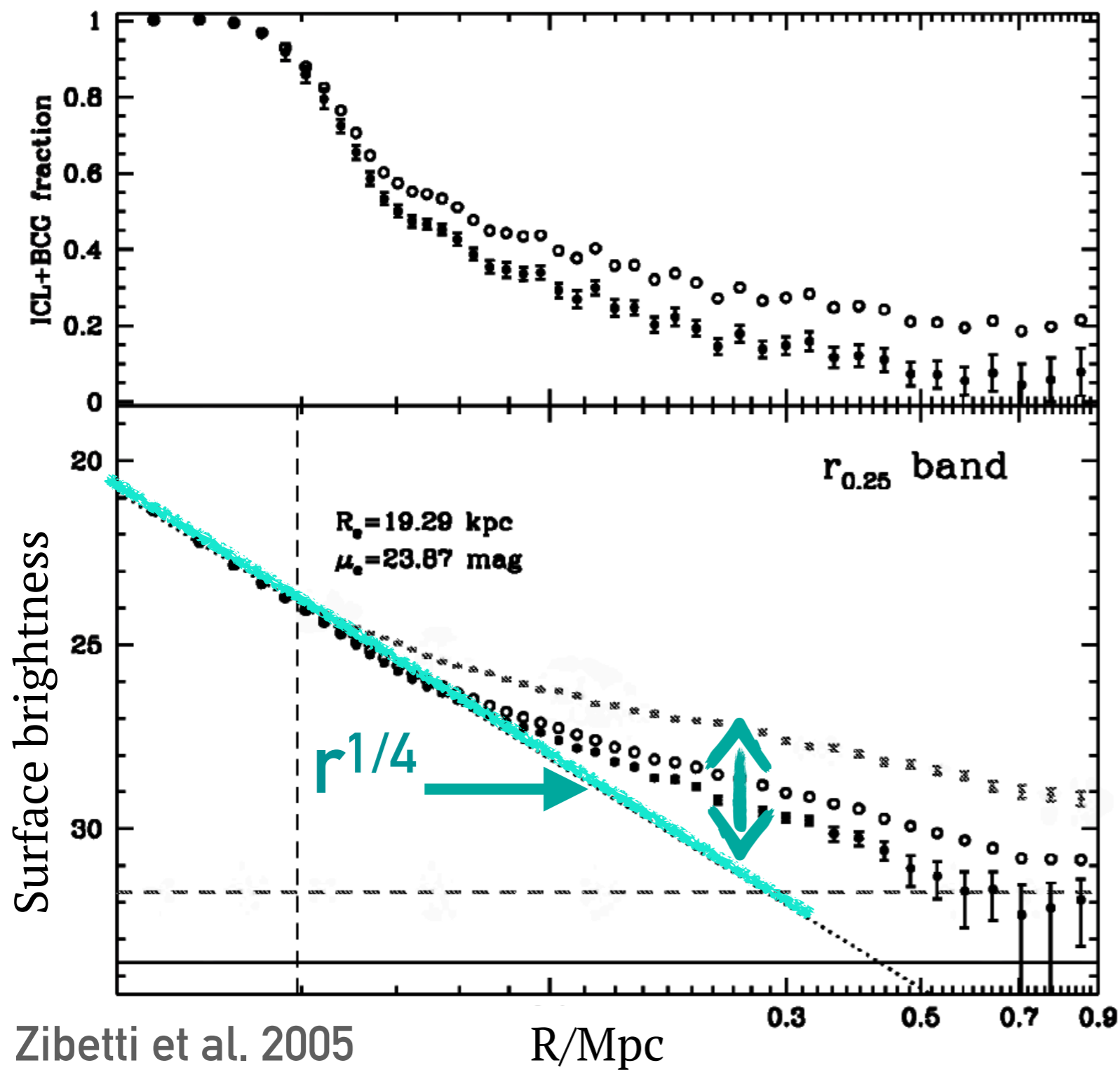


$z \sim 1.24$
Ko & Jee 2018

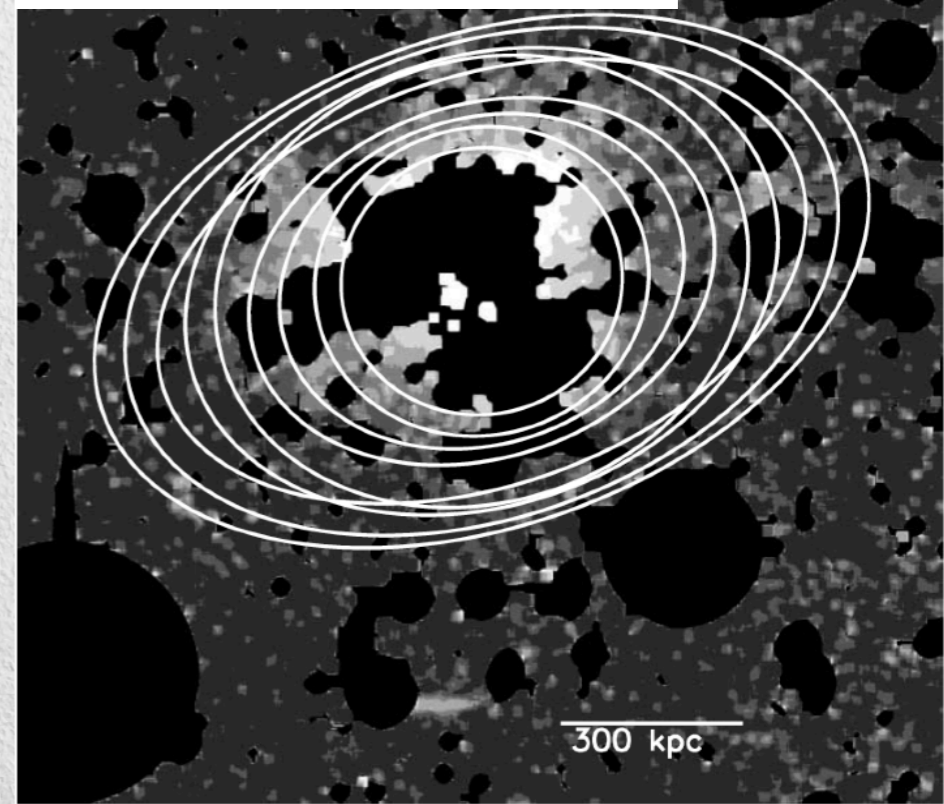
Rudick et al. 2010; Toledo et al. 2011; Gonzalez et al. 2013; Giallongo et al. 2014; Presotto et al. 2014; MM & Trujillo 2014, 2018, 2019; Watkins et al. 2014, 2015; DeMaio et al. 2015, 2018; Edwards et al. 2016; Mihos et al. 2017; Morishita et al. 2017; Jiménez-Teja et al. 2016, 2018, 2019; Iodice et al. 2016, 2017; Zhang et al. 2018

What exactly is the ICL?

Huang et al. 2018



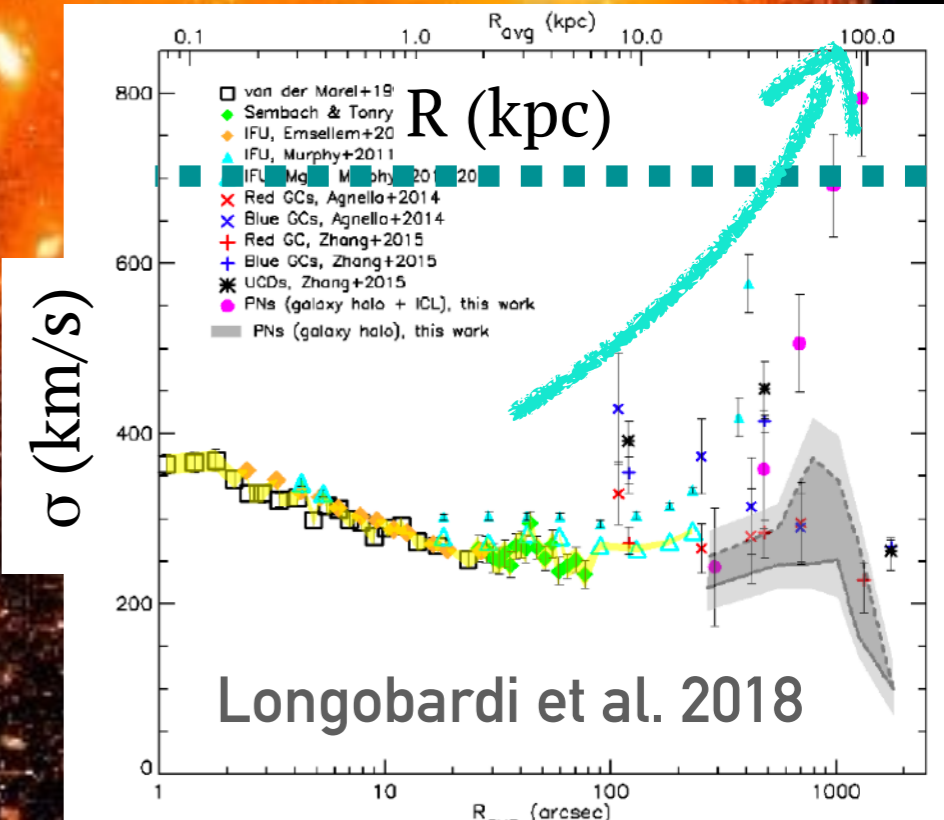
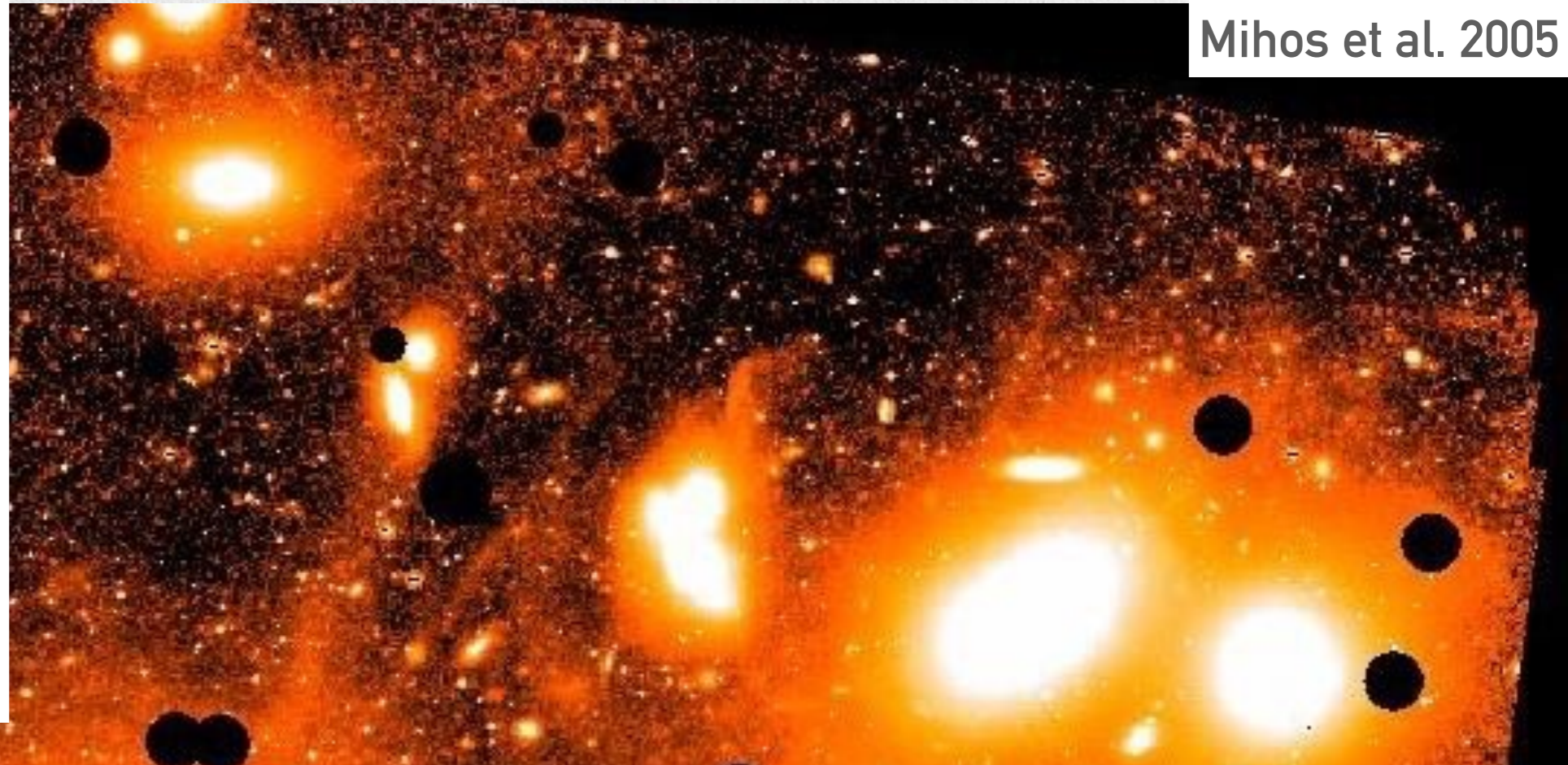
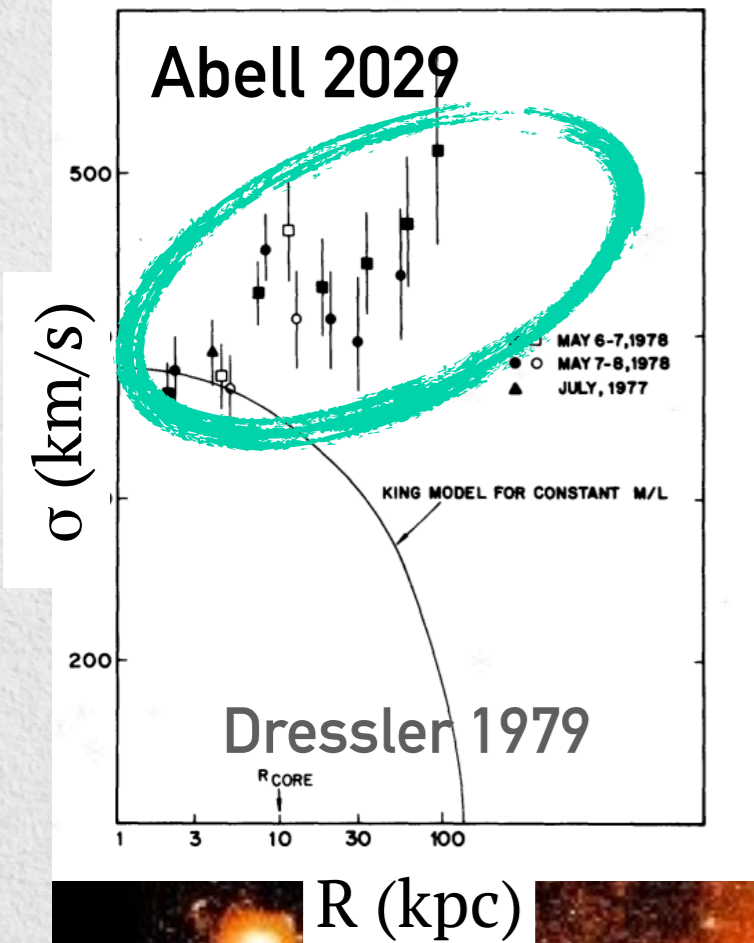
Krick & Bernstein 2007



Distinct stellar component !!!

What exactly is the ICL?

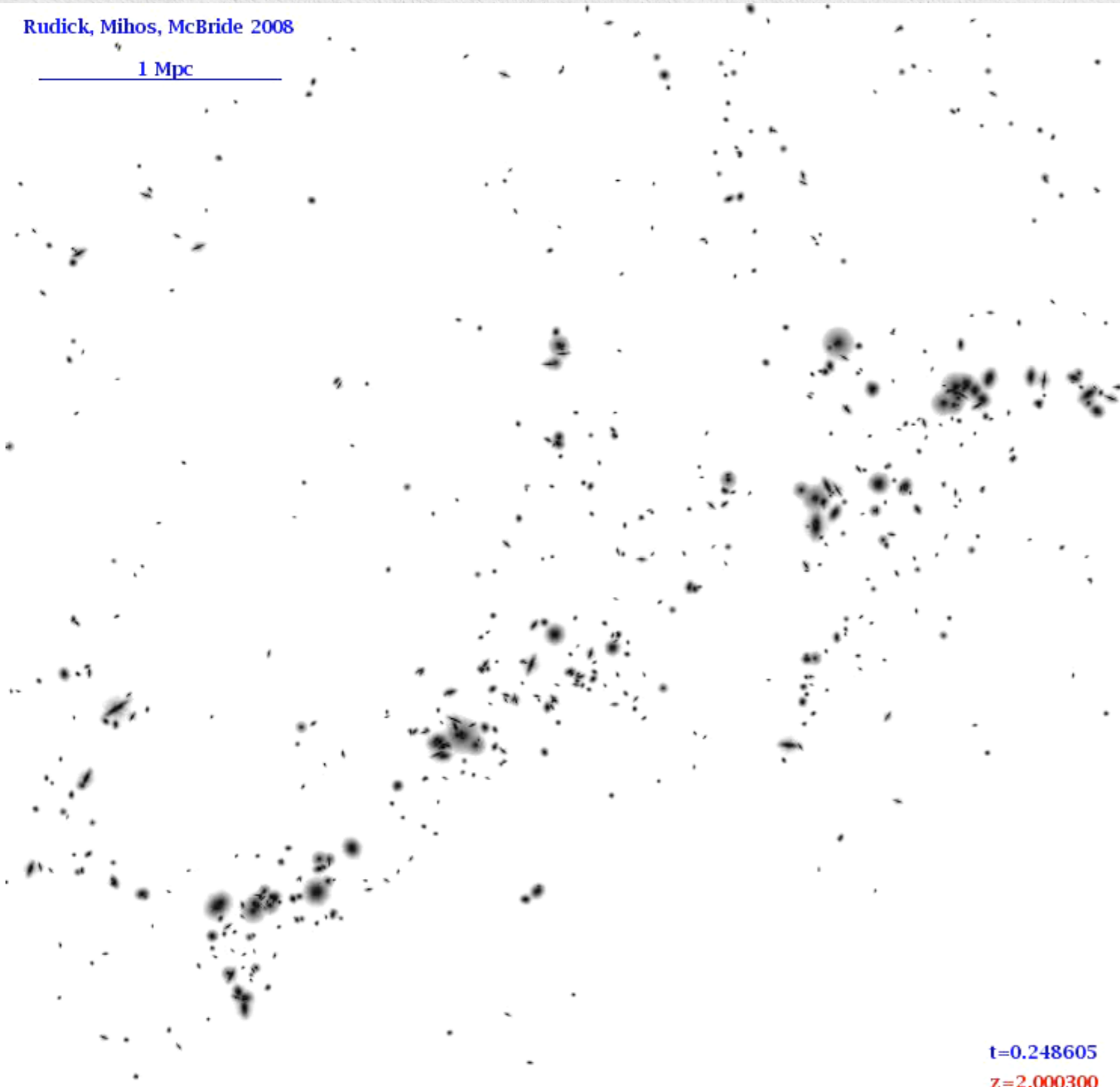
Mihos et al. 2005



Why study the ICL?

Rudick, Mihos, McBride 2008

1 Mpc



$t=0.248605$

$z=2.000300$

Encodes merger histories
of cluster of galaxies

Why study the ICL?

Rudick, Mihos, McBride 2008

1 Mpc



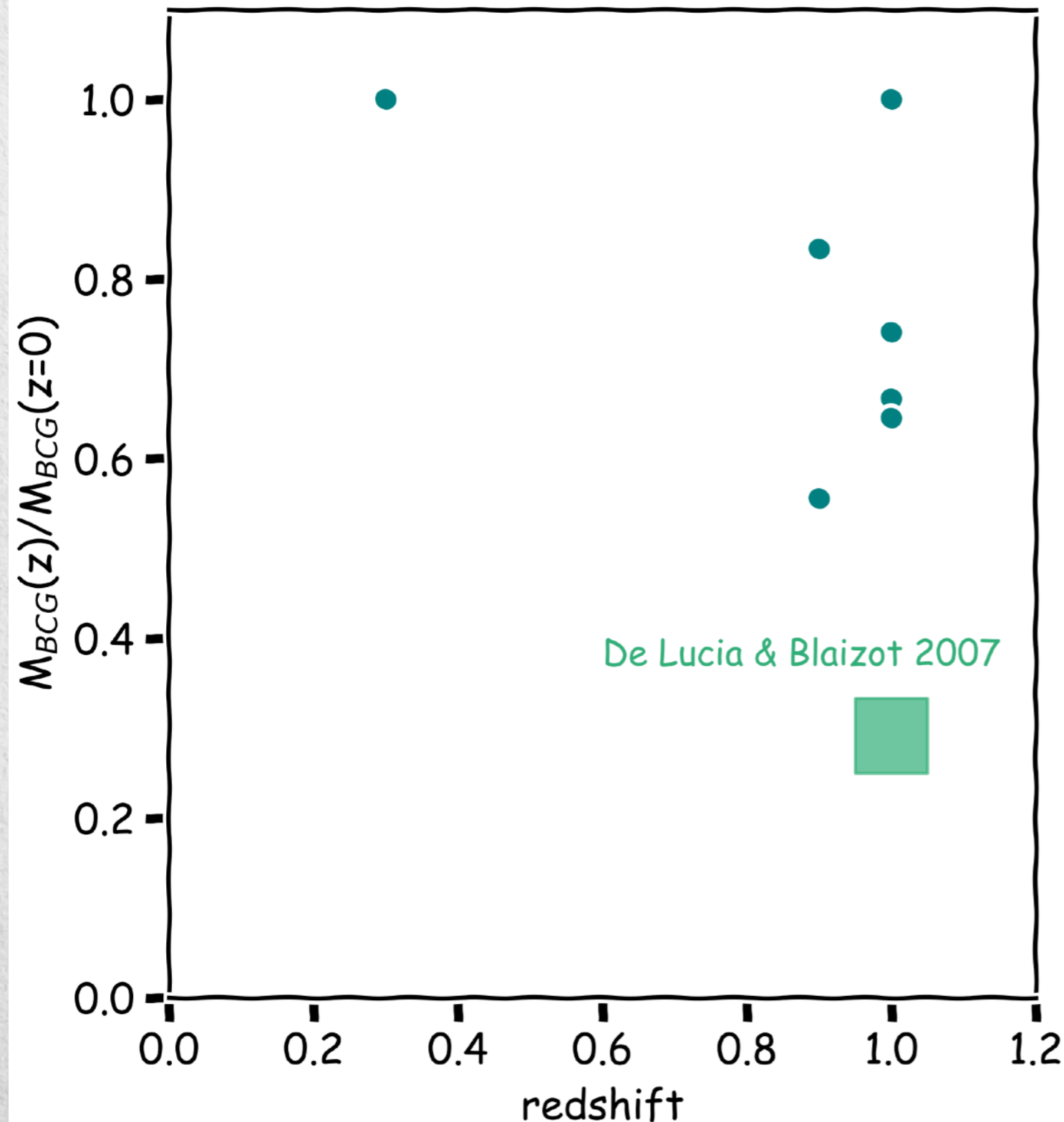
t=0.248605

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Encodes merger histories
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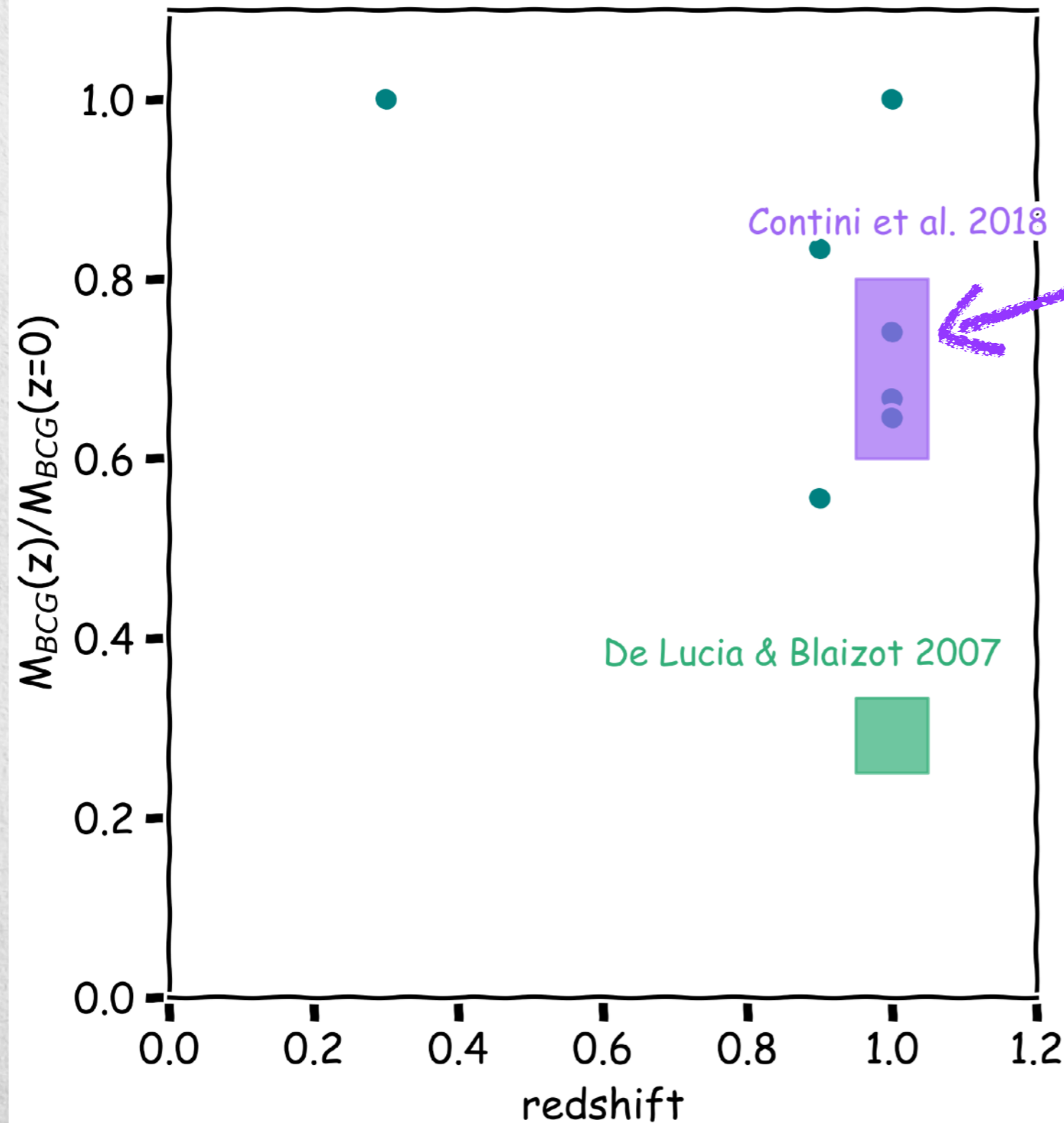
Why study the ICL? Buildup of the BCG

Whiley et al. 2008; Collins et al. 2009; Stott et al. 2010; Lidman et al. 2012; Lin et al. 2013; Oliva-Altamirano et al 2014; Burke et al. 2015; Zhang et al, 2016



Why study the ICL? Buildup of the BCG

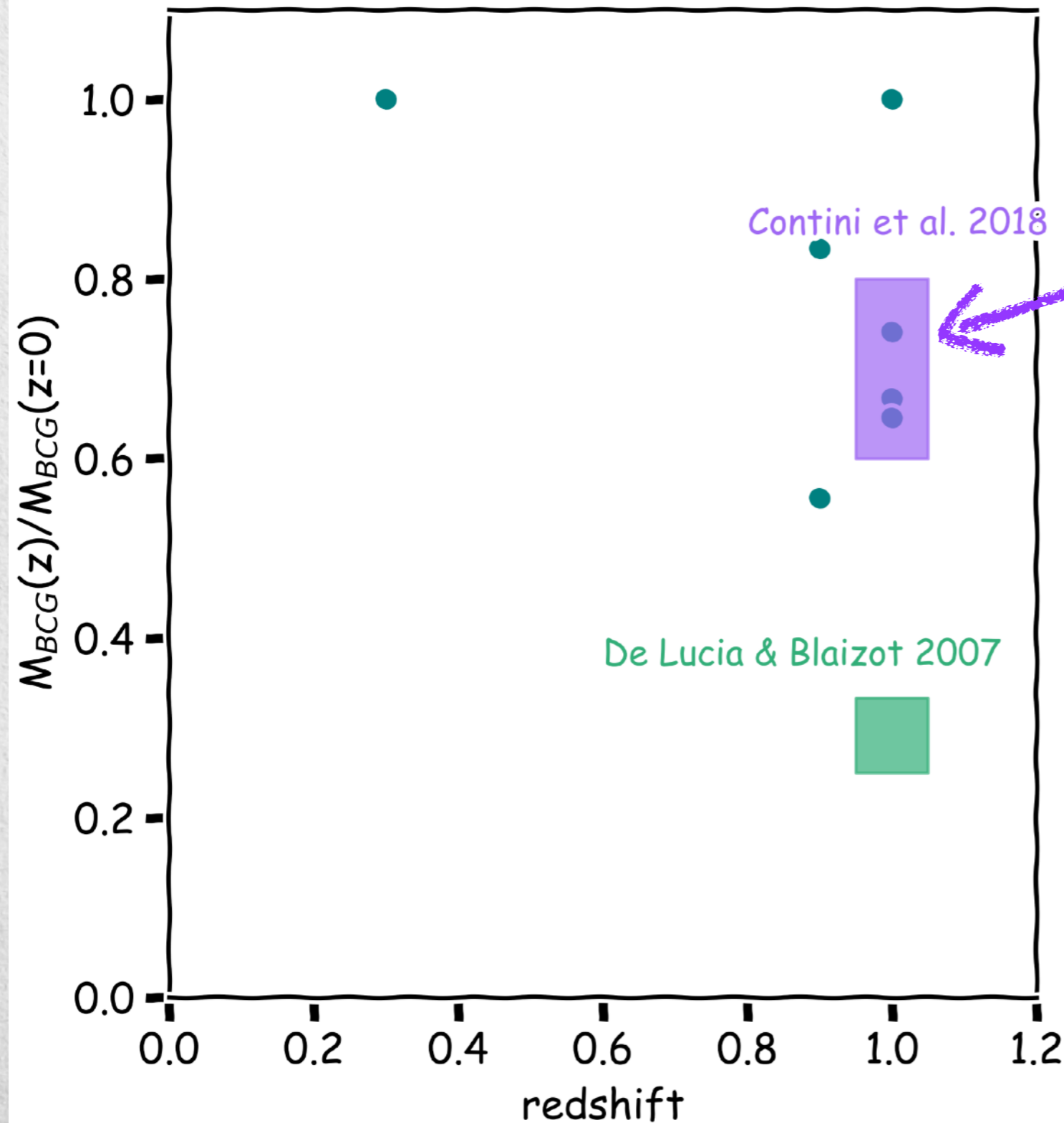
Whiley et al. 2008; Collins et al. 2009; Stott et al. 2010; Lidman et al. 2012; Lin et al. 2013; Oliva-Altamirano et al 2014; Burke et al. 2015; Zhang et al, 2016



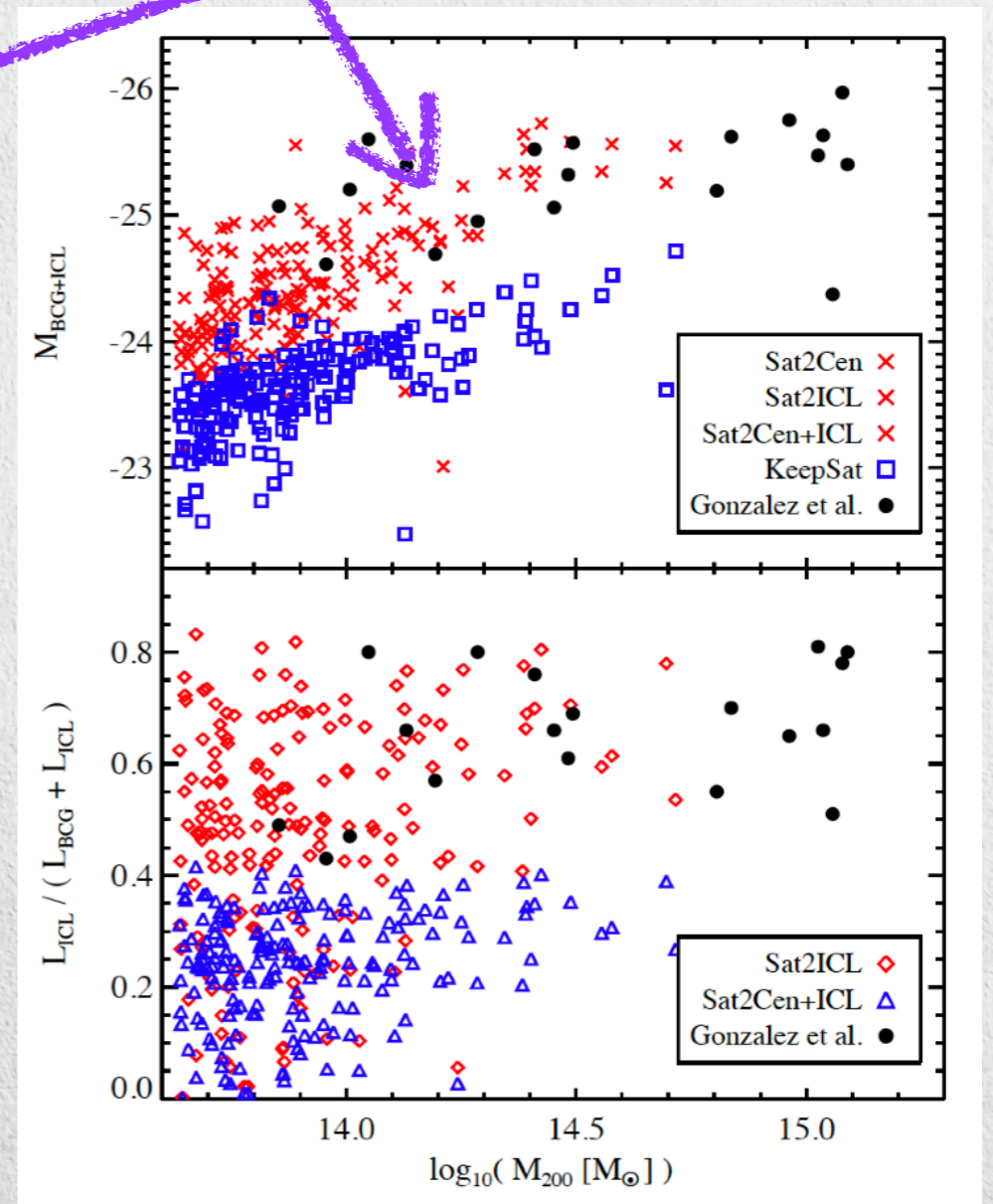
If formation of ICL

Why study the ICL? Buildup of the BCG

Whiley et al. 2008; Collins et al. 2009; Stott et al. 2010; Lidman et al. 2012; Lin et al. 2013; Oliva-Altamirano et al 2014; Burke et al. 2015; Zhang et al, 2016



If formation of ICL



Conroy et al. 2007

Origin

e.g. Conroy et al. 2007
Murante et al. 2007



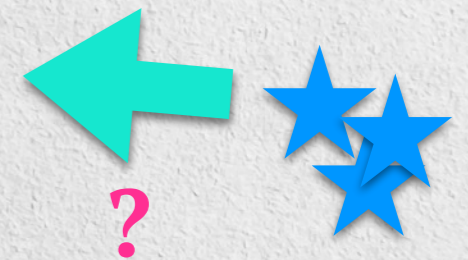
e.g. Rudick et al. 2009
Contini et al. 2014, 2019



e.g. Mihos 2004
Rudick et al. 2006



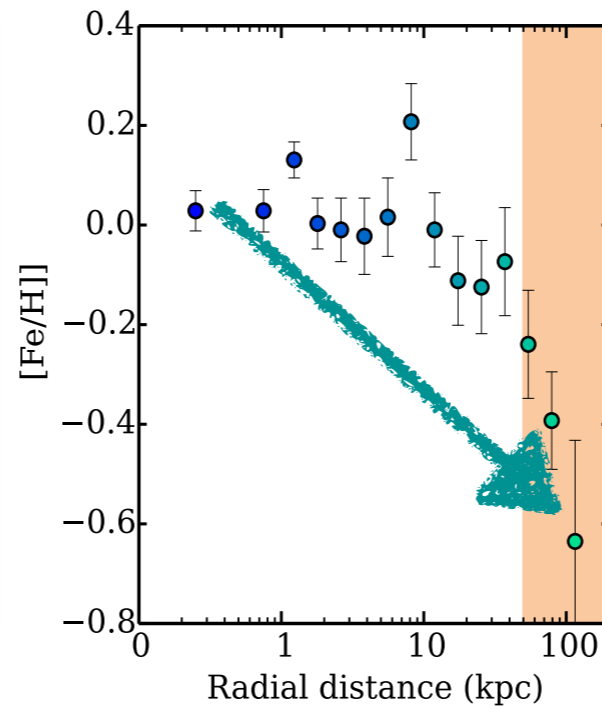
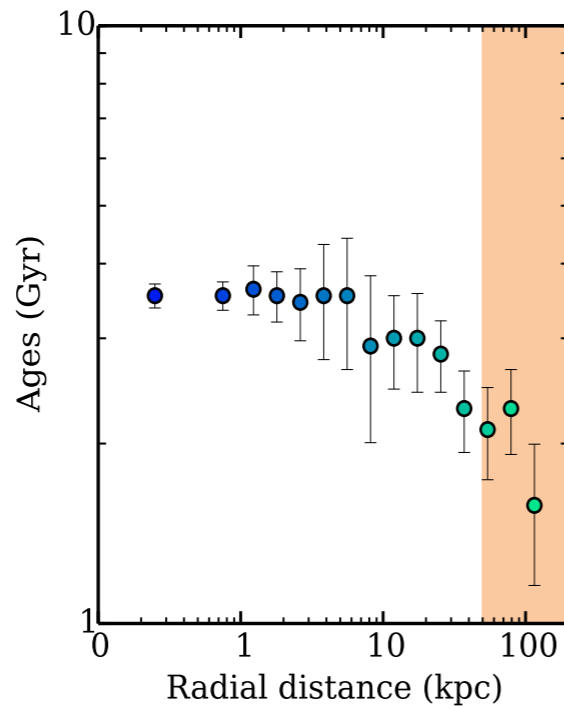
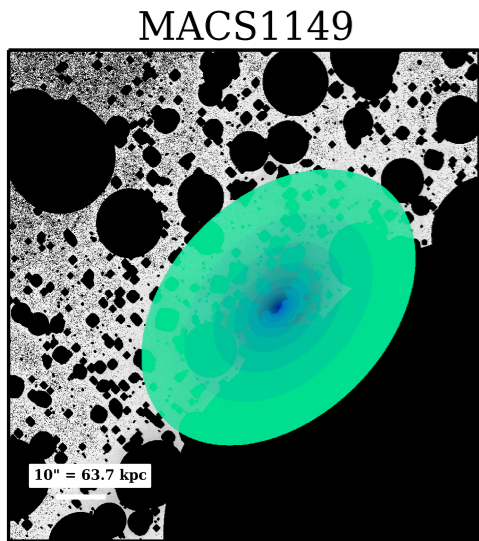
e.g. Purcell et al. 2007



Puchwein et al. 2010

Stellar properties

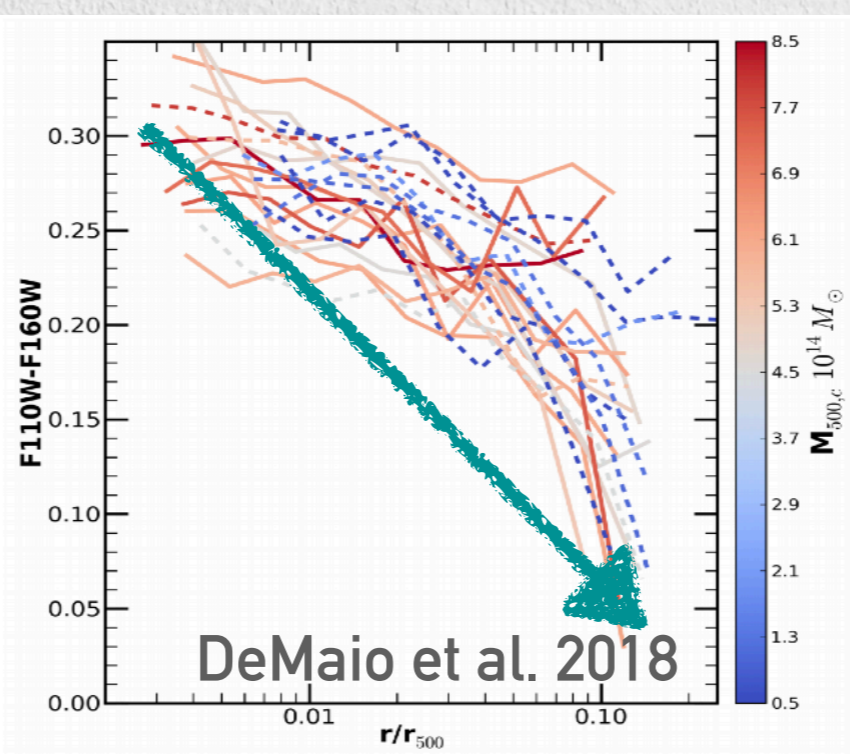
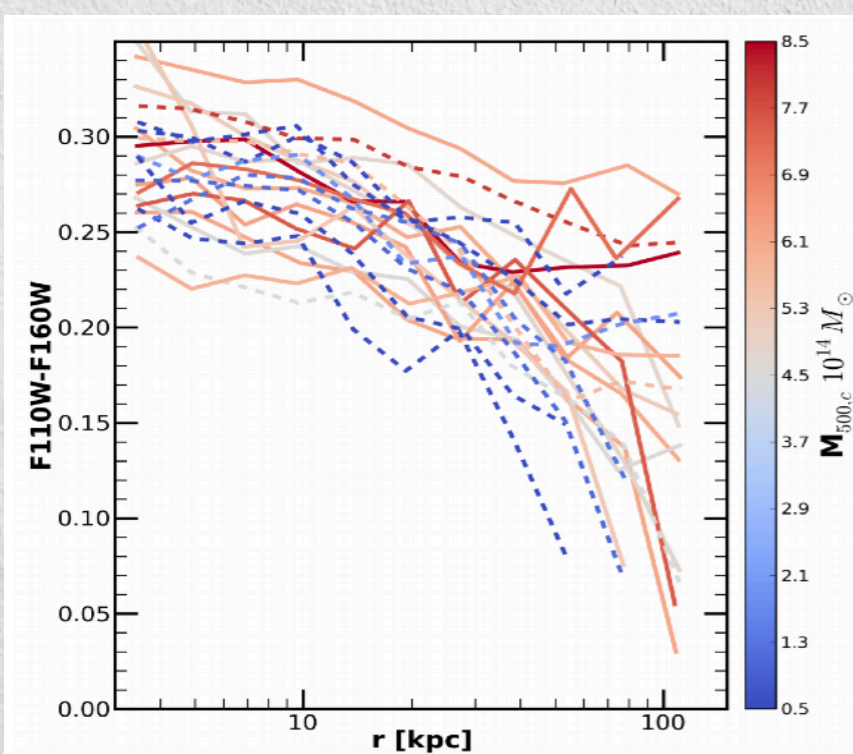
Gradients in color and metallicity



Also MM & Trujillo 2014

MM & Trujillo 2018

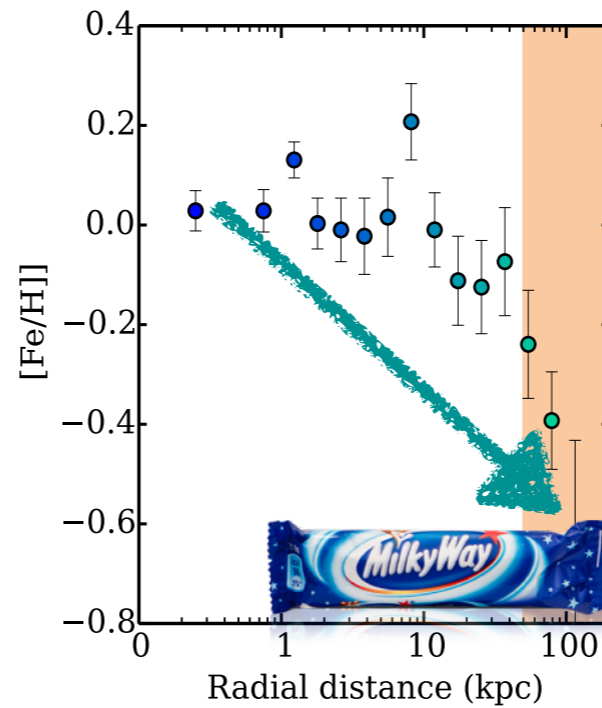
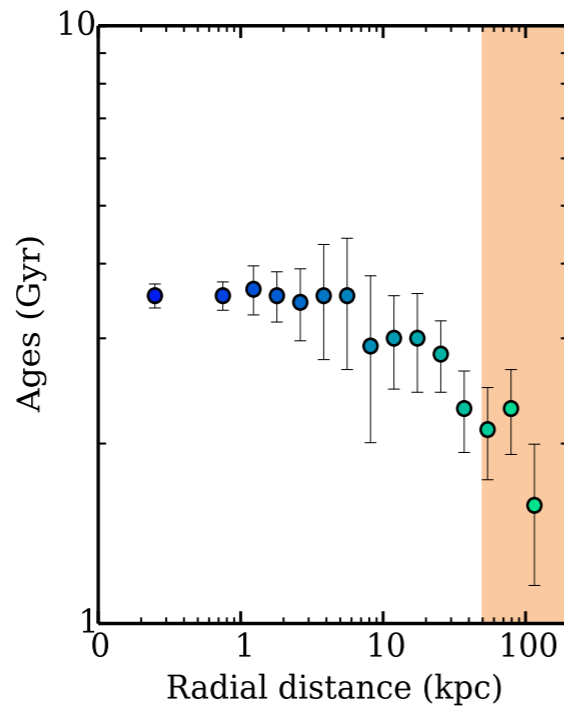
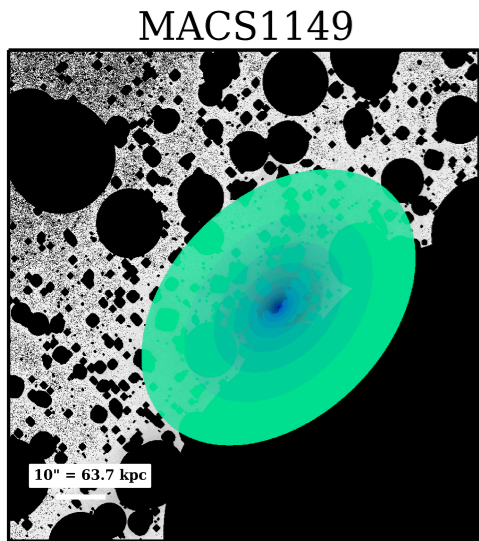
DeMaio et al. 2018



Also see Iodice et al. 2017, Mihos et al. 2017 for nearby clusters

Stellar properties

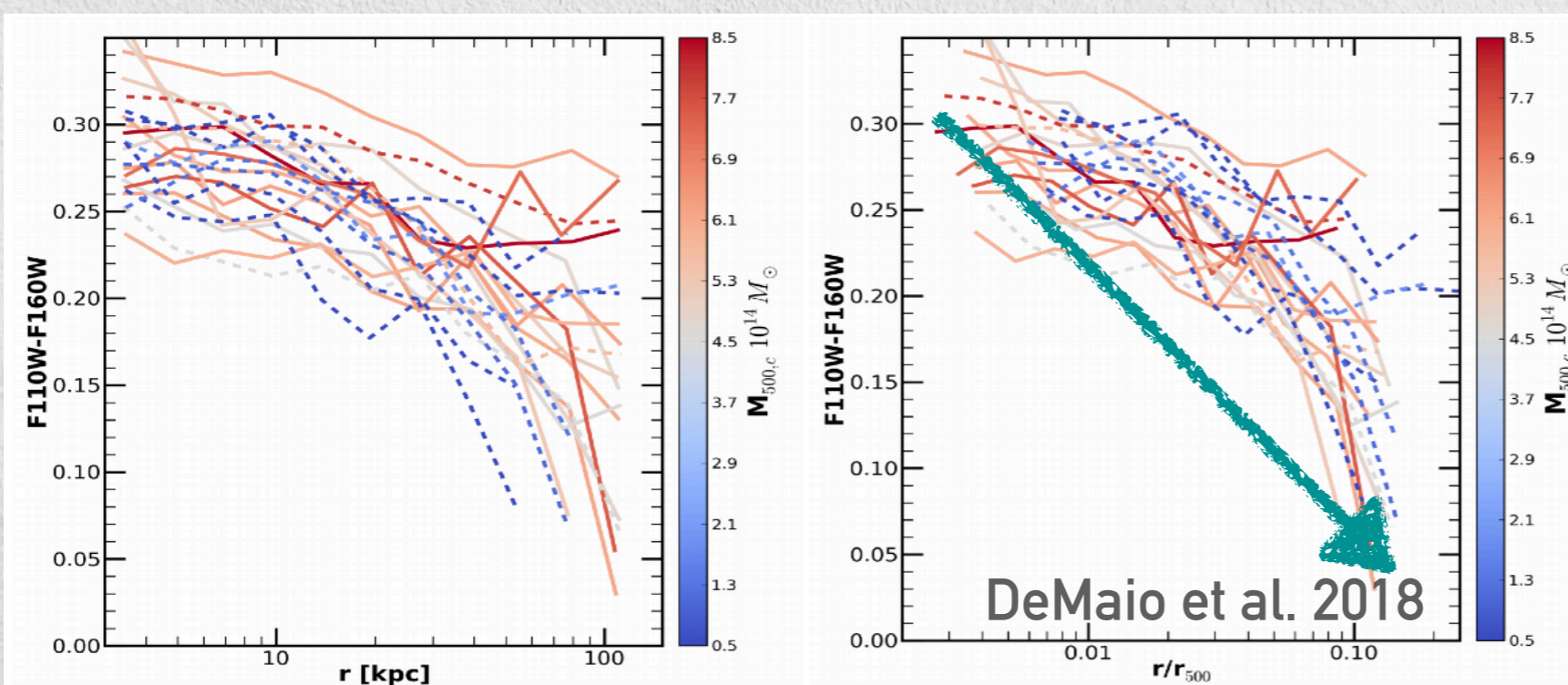
Gradients in color and metallicity



Also MM & Trujillo 2014

MM & Trujillo 2018

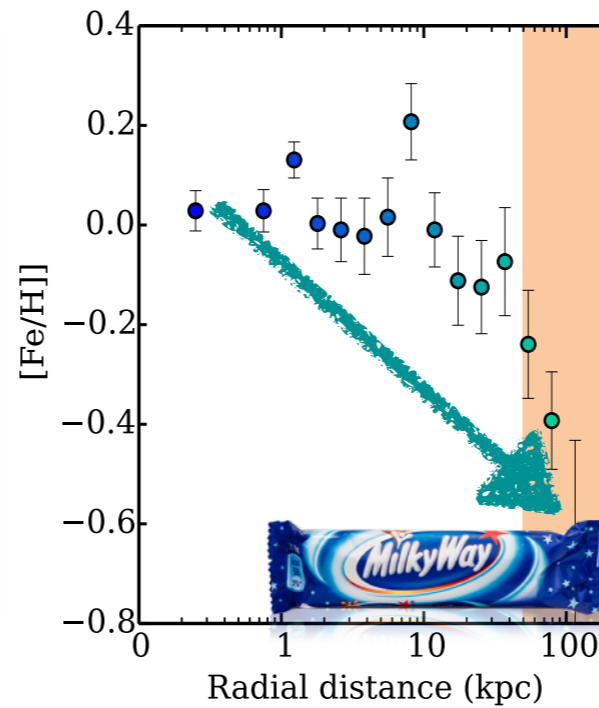
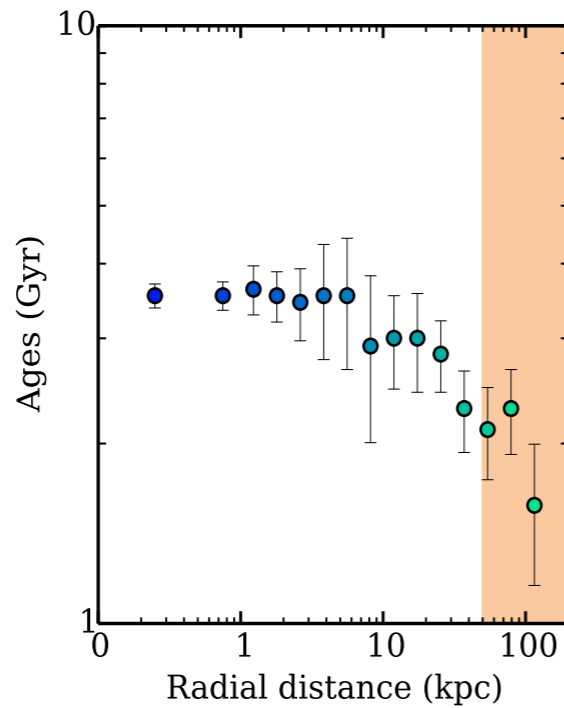
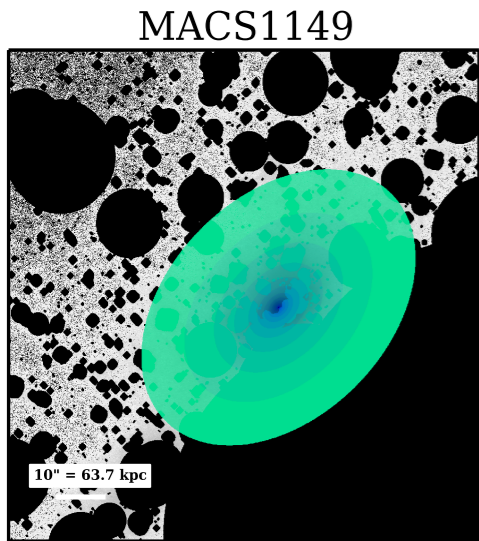
DeMaio et al. 2018



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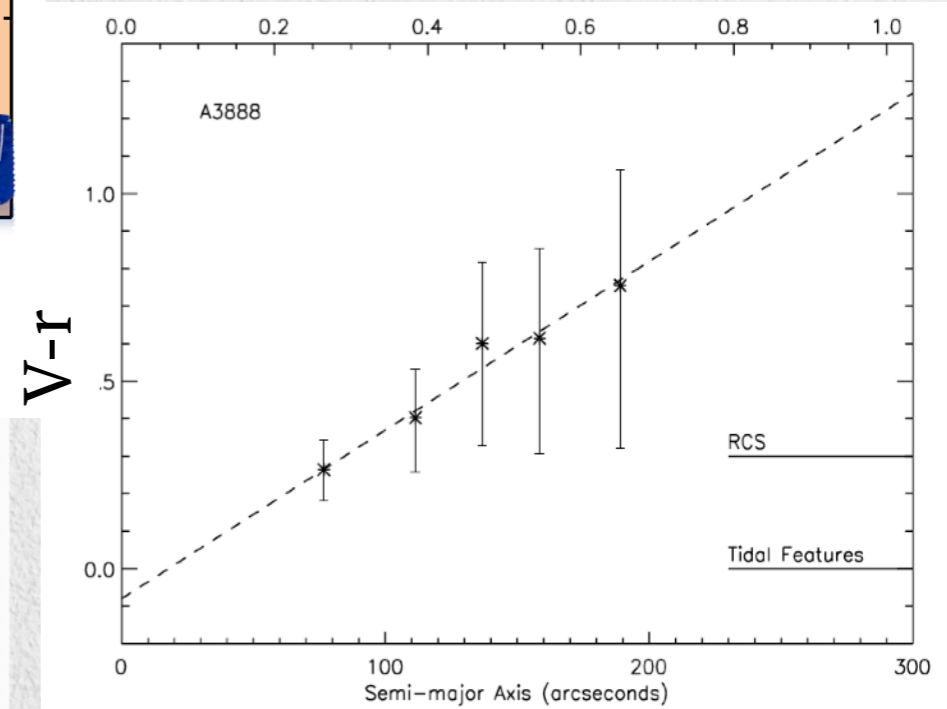
Stellar properties

Gradients in color and metallicity

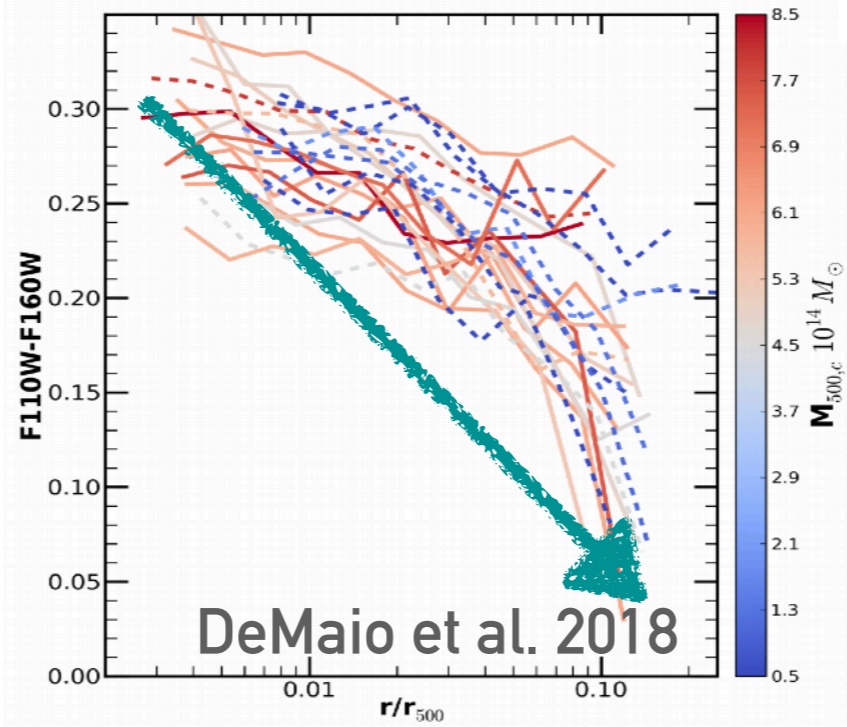
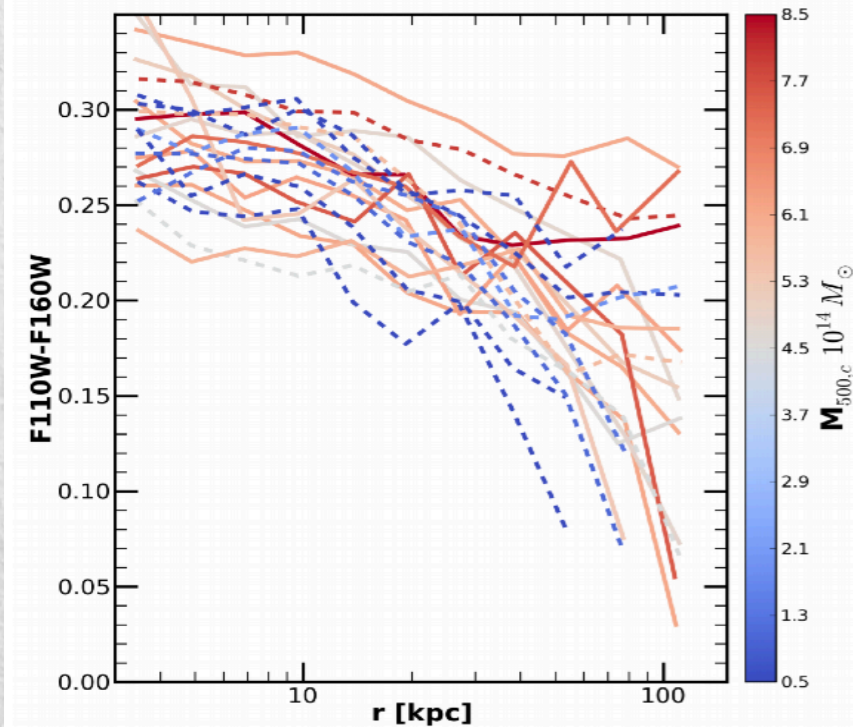


Also MM & Trujillo 2014

MM & Trujillo 2018



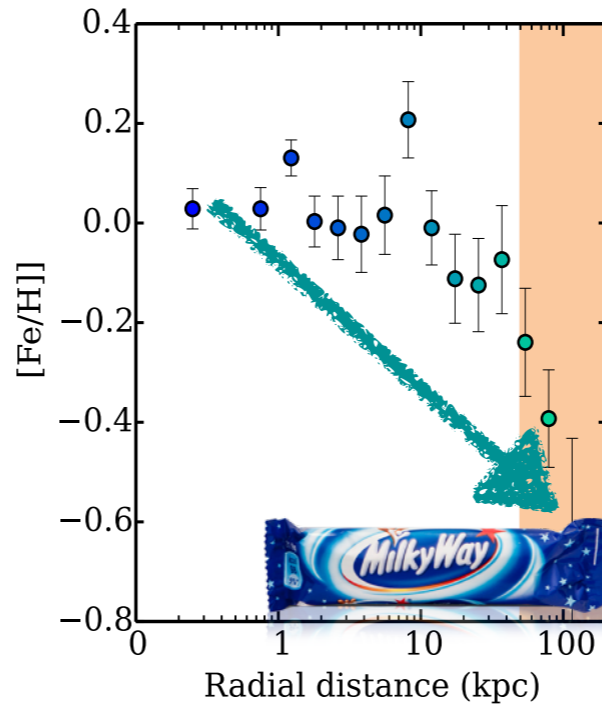
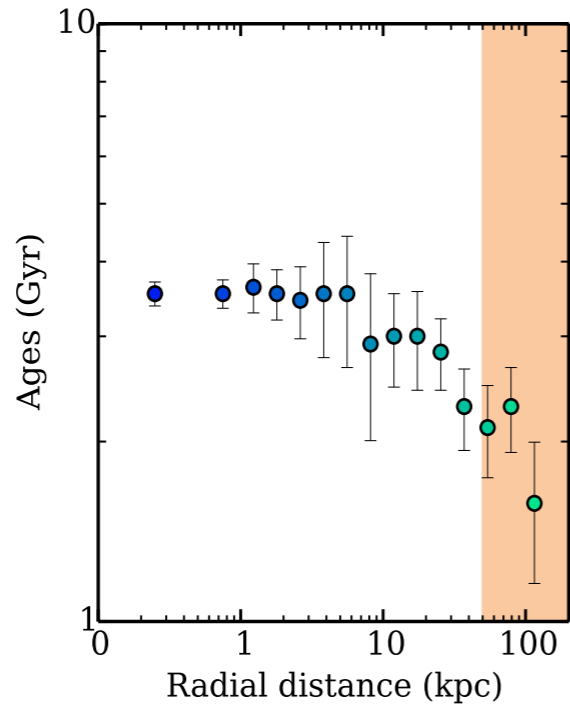
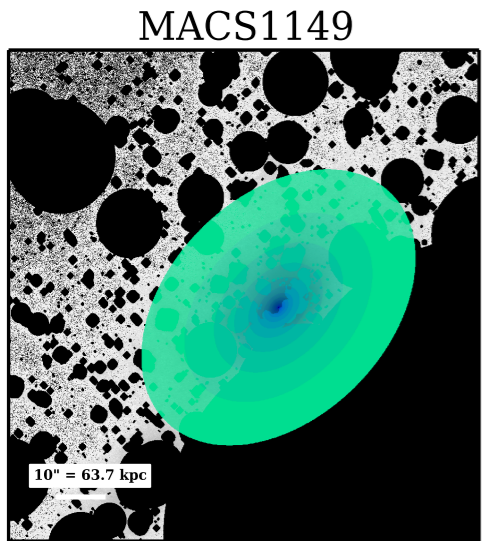
Krick & Bernstein 2007



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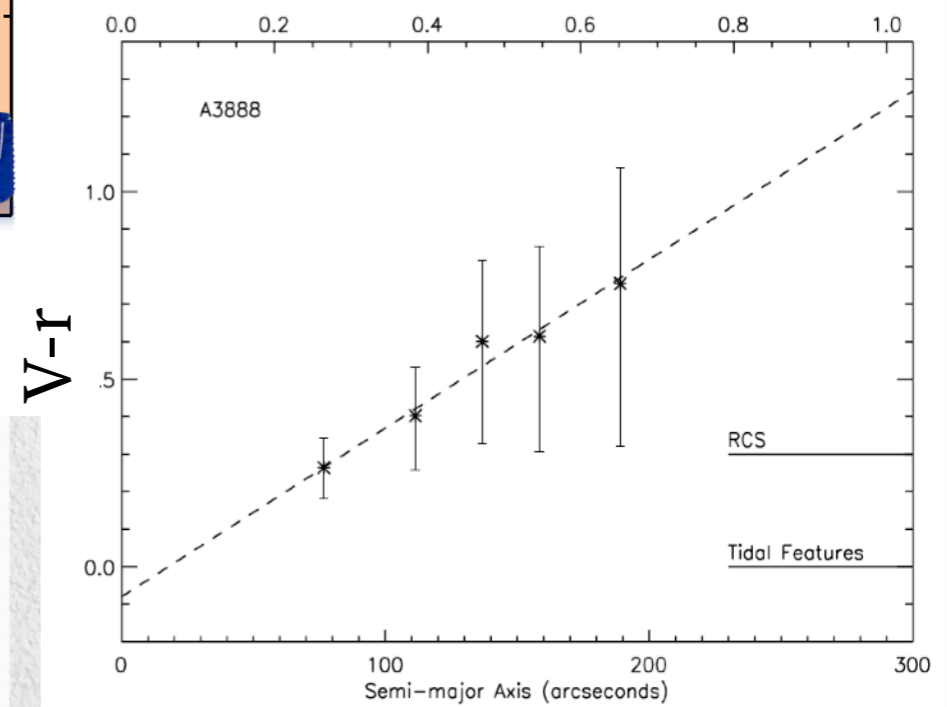
Stellar properties

Gradients in color and metallicity



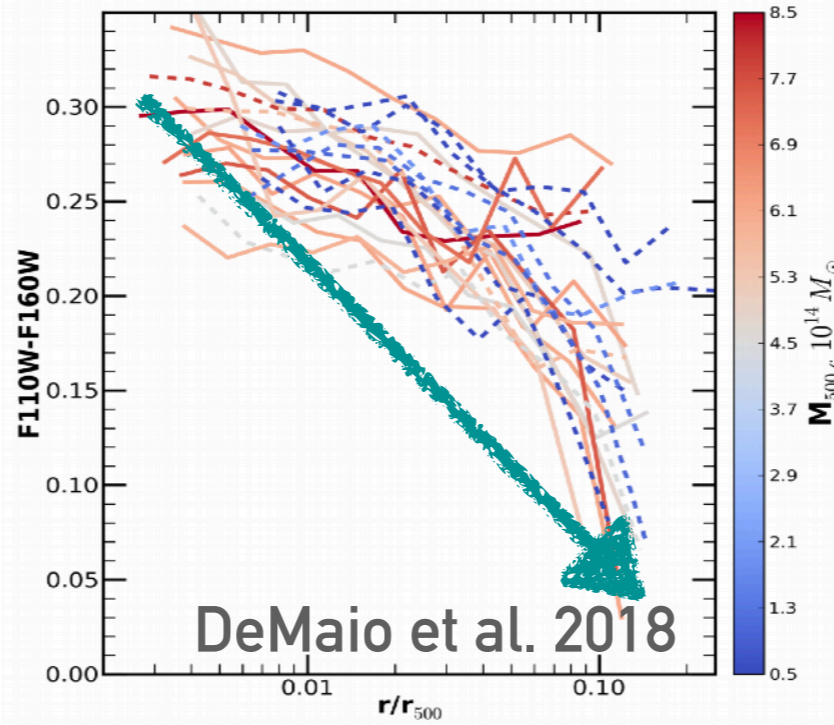
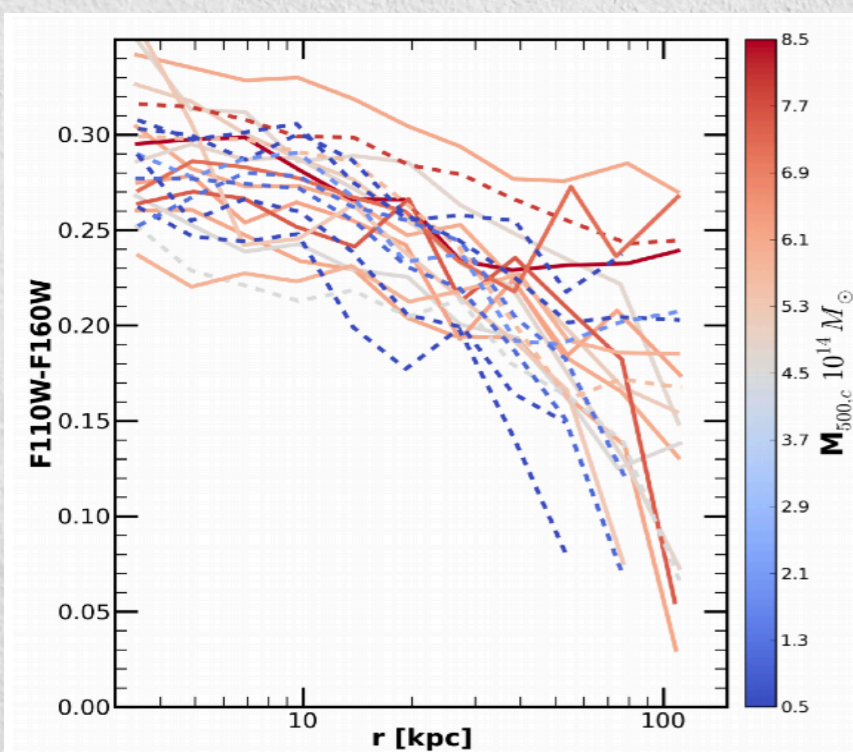
MM & Trujillo 2018

Also MM & Trujillo 2014



Krick & Bernstein 2007

20-30%, $t < 10 \text{ Gyr}$, $[M/H] > -0.5$
 70-80% $t > 10 \text{ Gyr}$, $[M/H] \sim -1.3$
 (Williams et al. 2007)

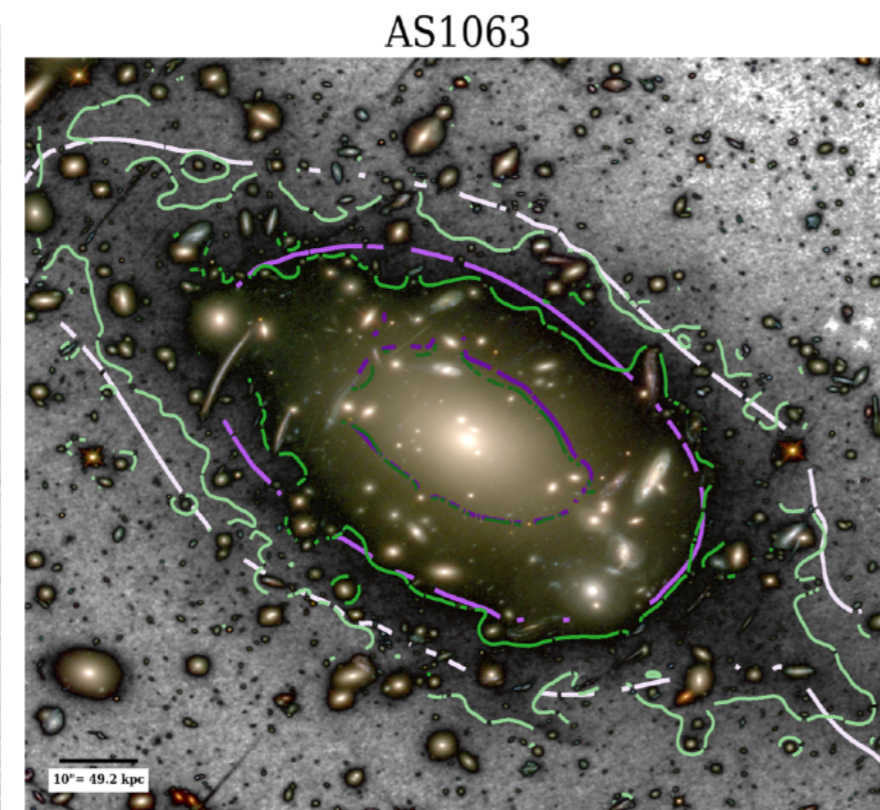
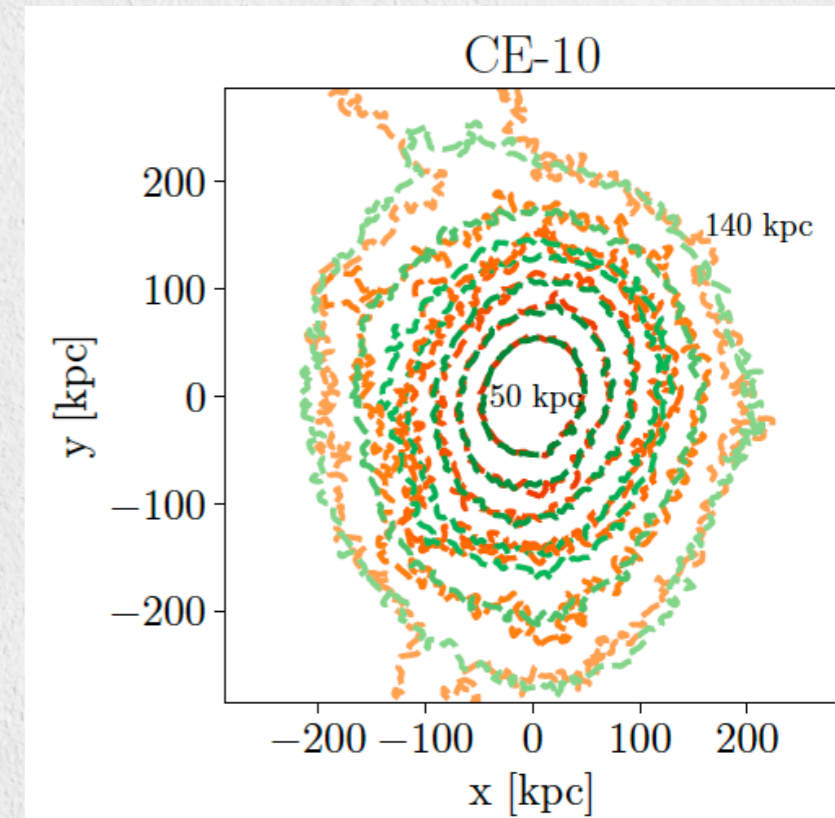
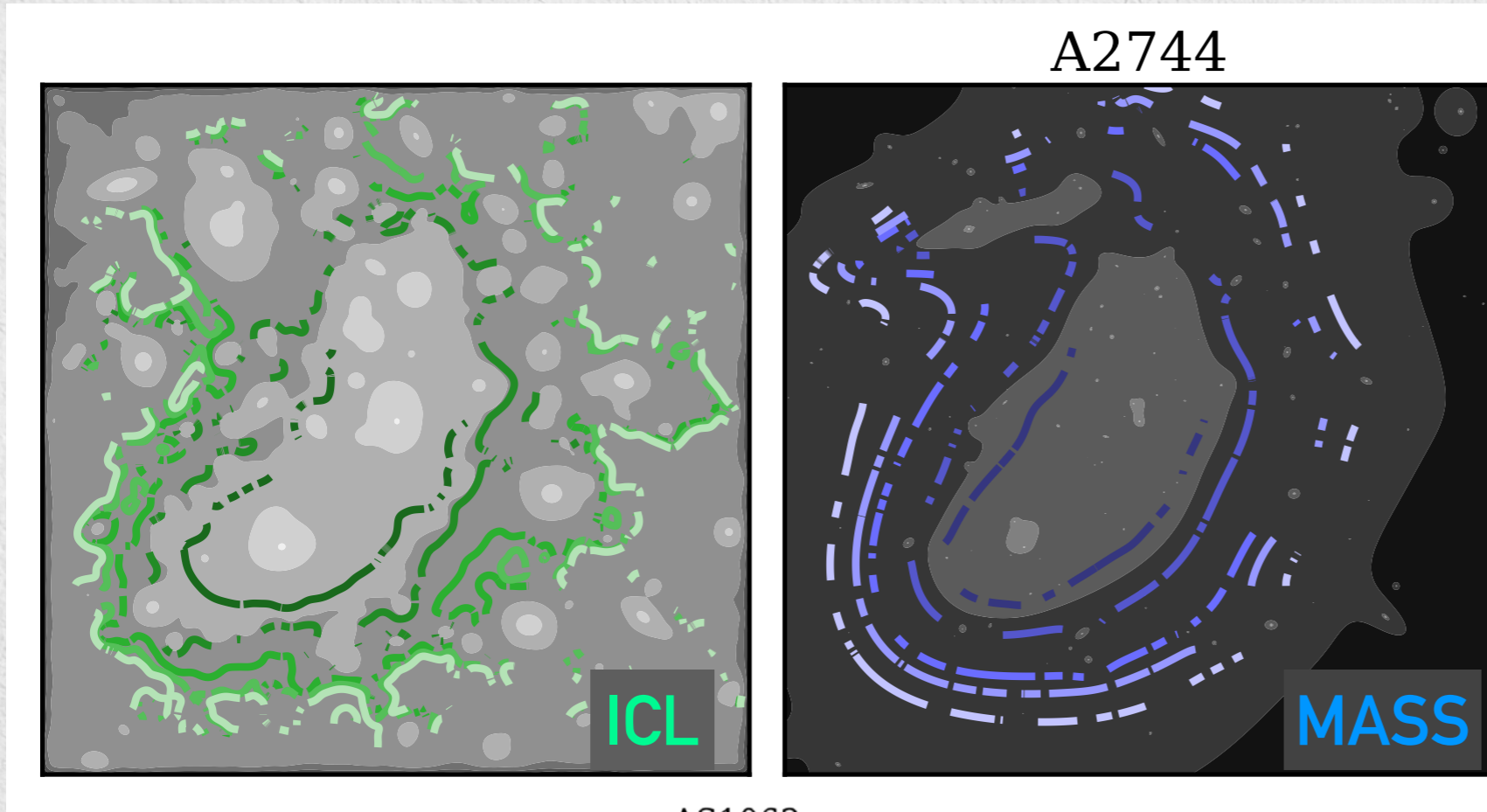


DeMaio et al. 2018

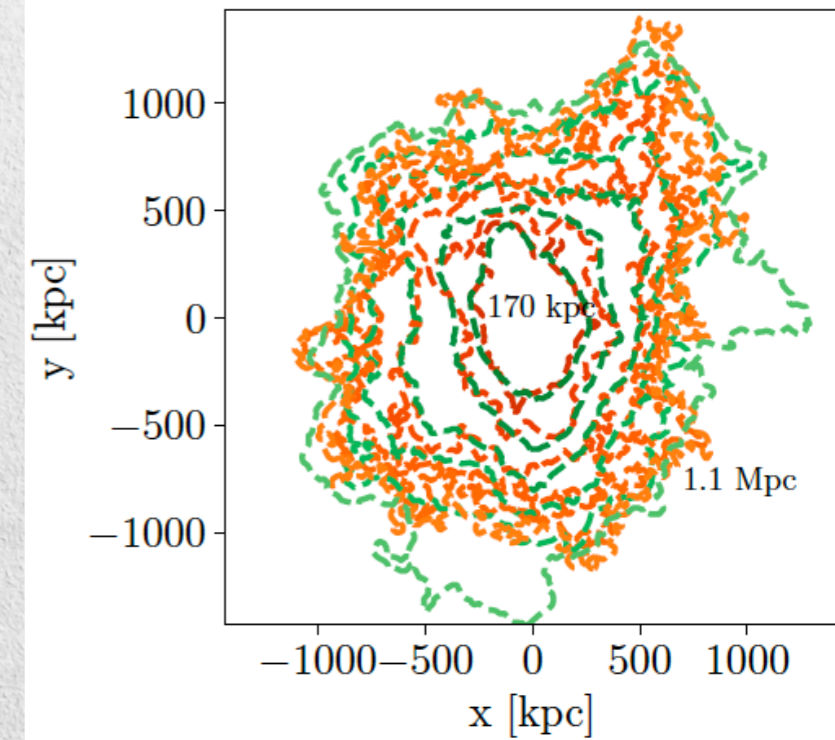
Also see Iodice et al. 2017, Mihos et al. 2017 for nearby clusters

Tracer of the dark matter halo

Alonso-Asensio et al. 2020

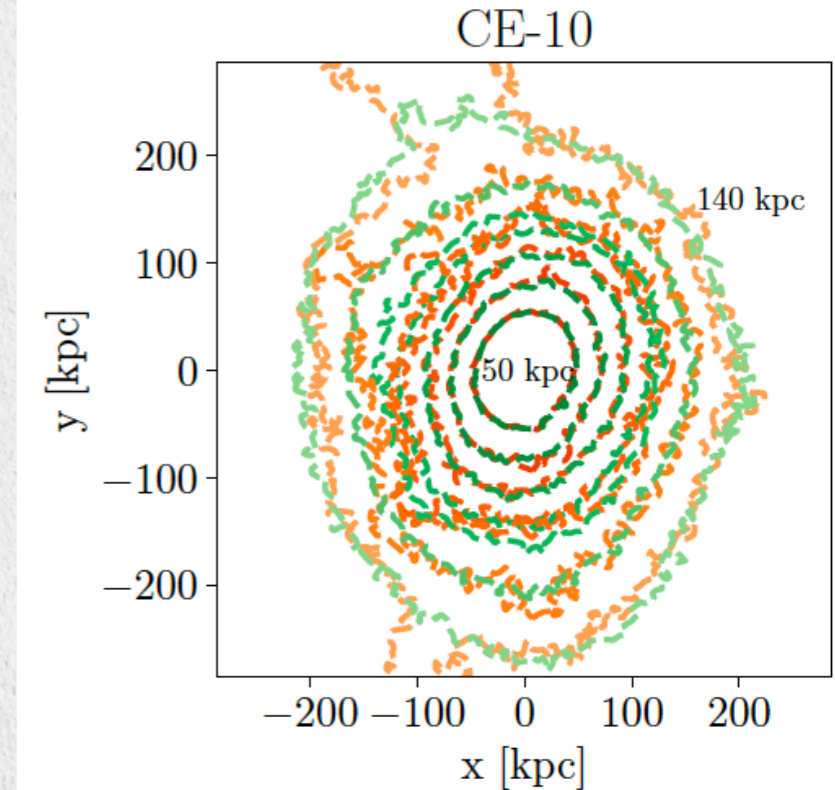
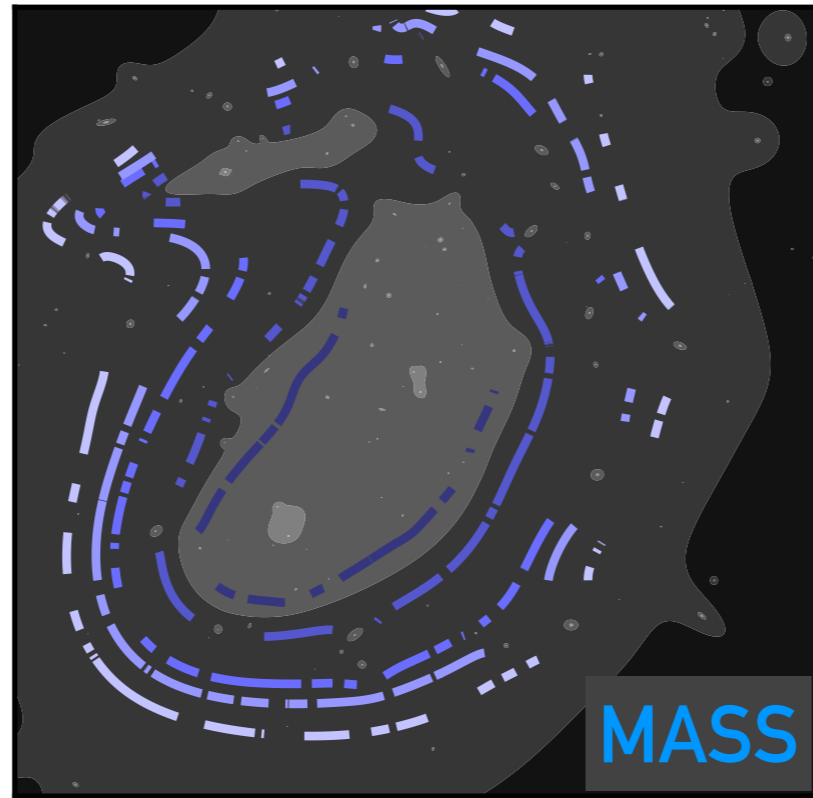
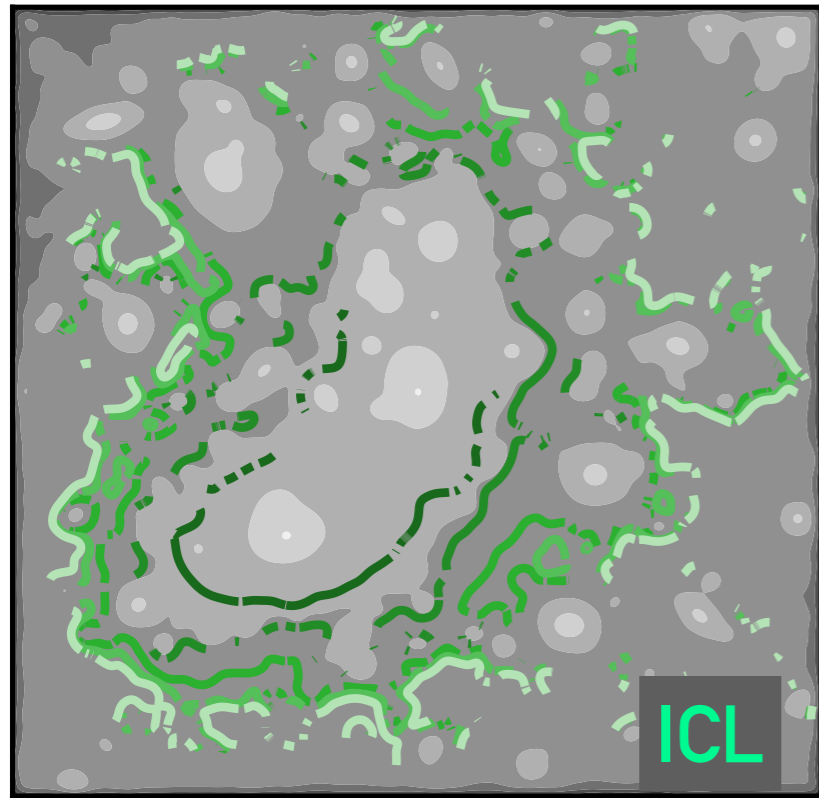


MM & Trujillo 2019

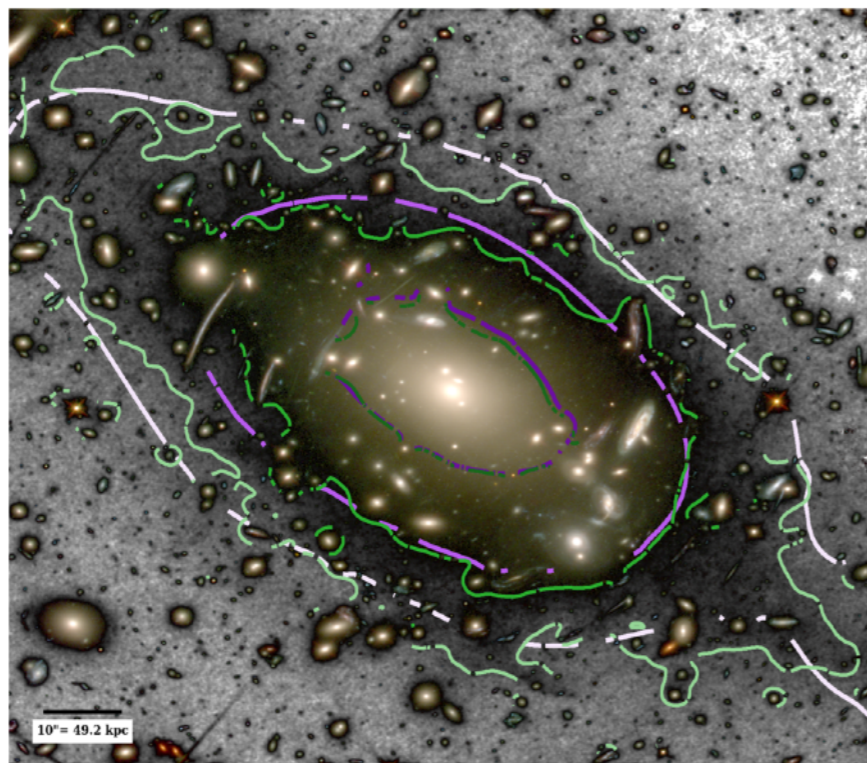


Tracer of the dark matter halo

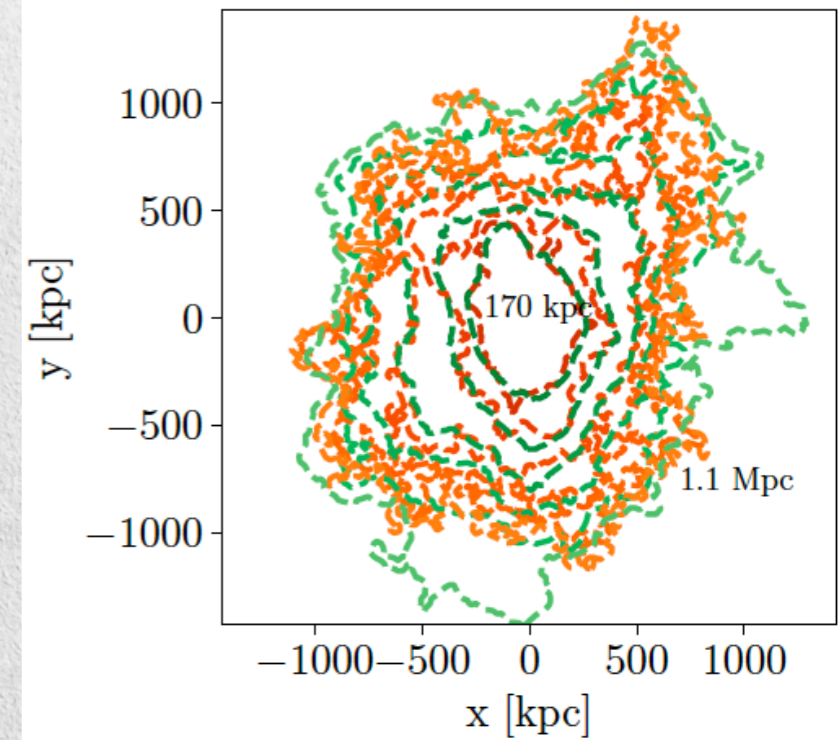
Alonso-Asensio et al. 2020



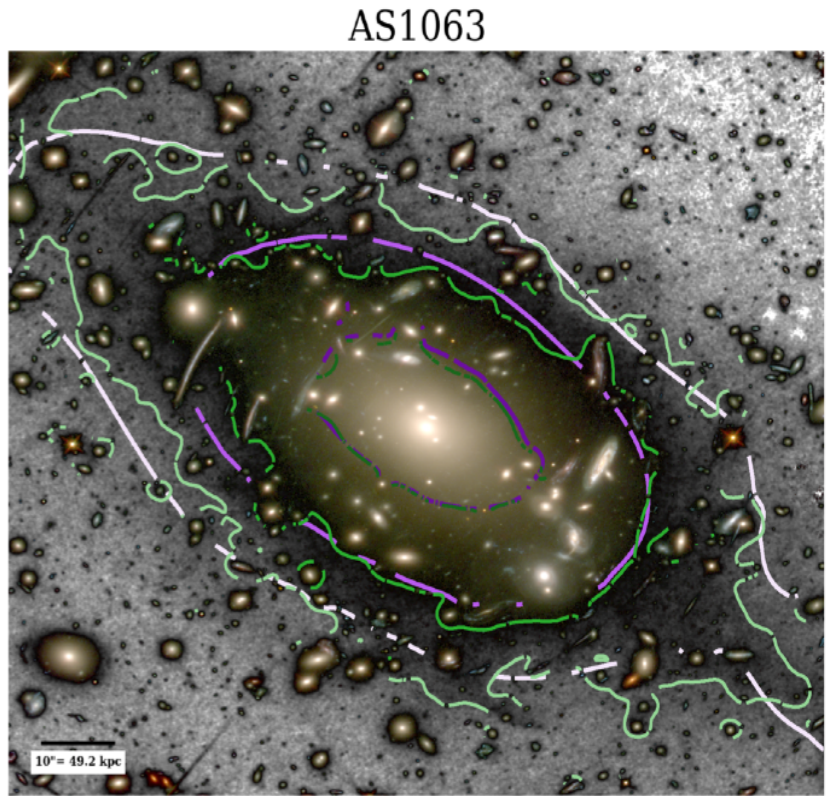
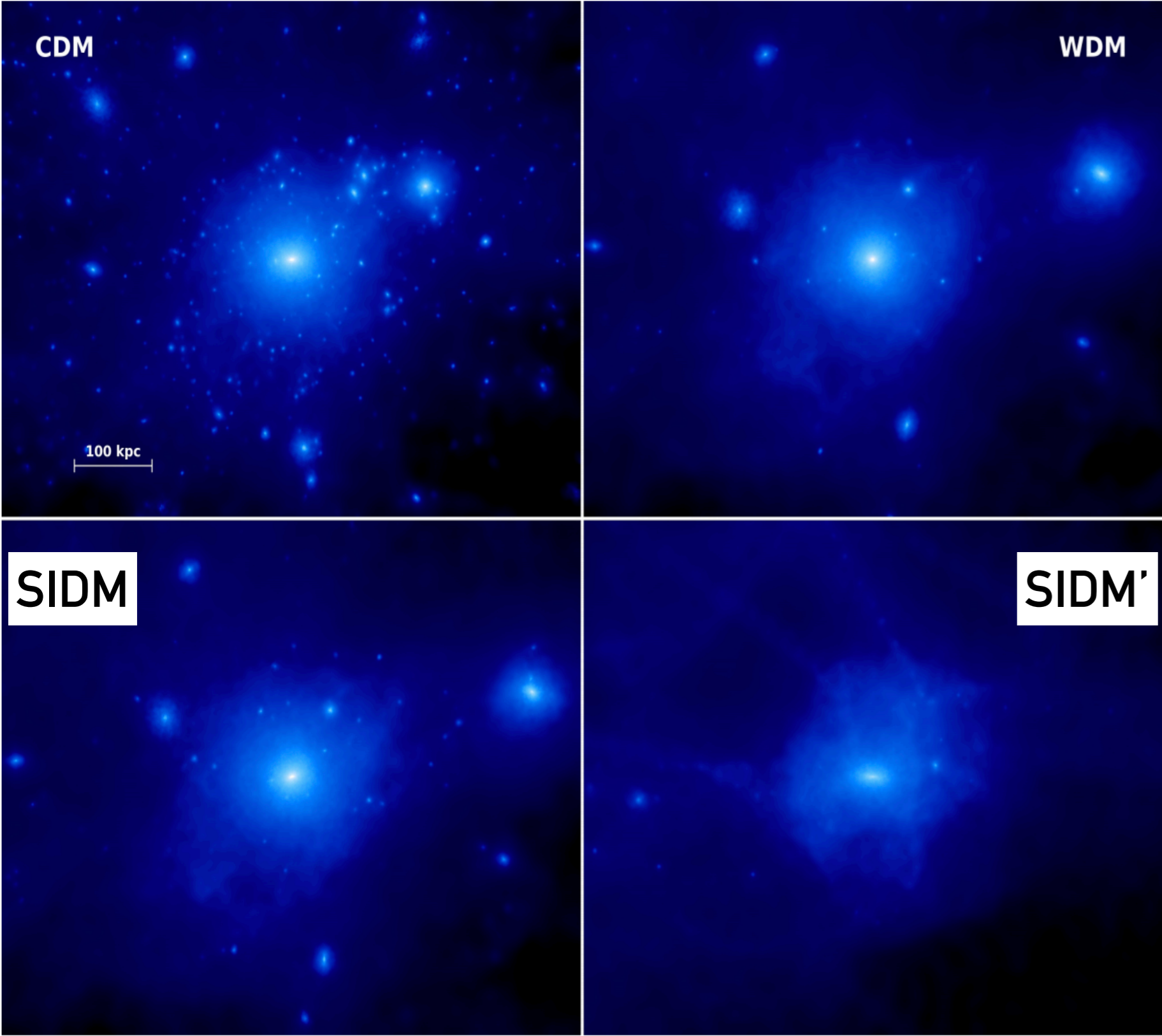
AS1063



MM & Trujillo 2019

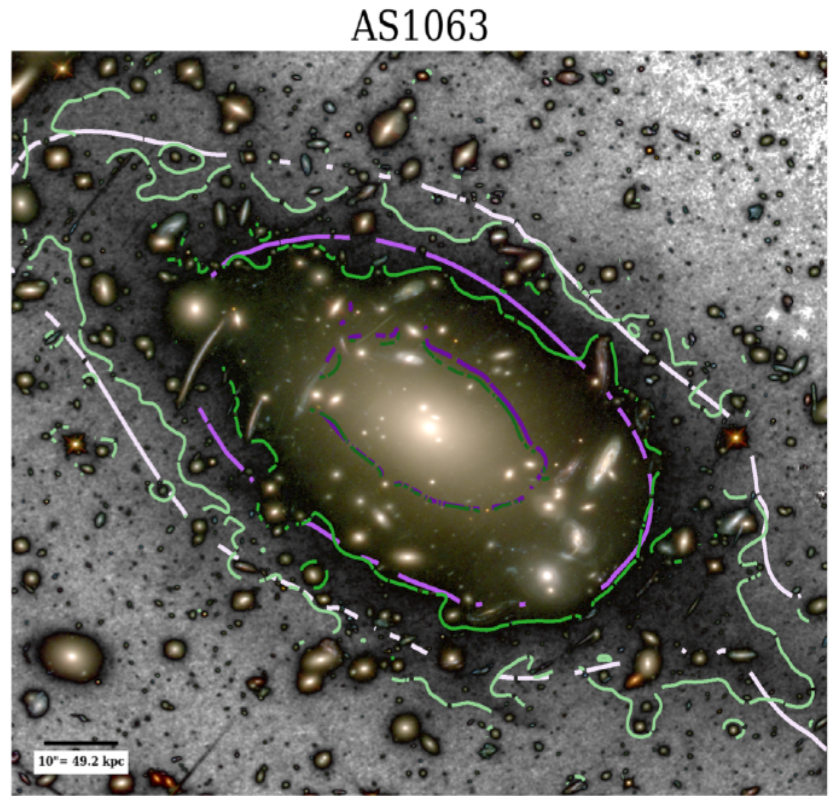
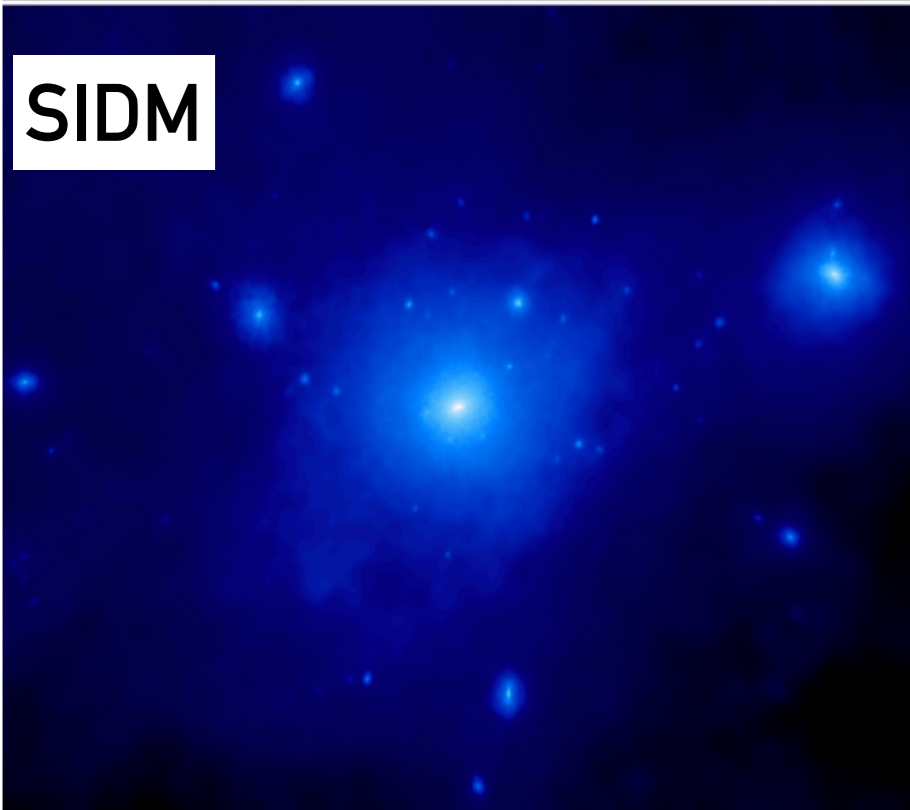
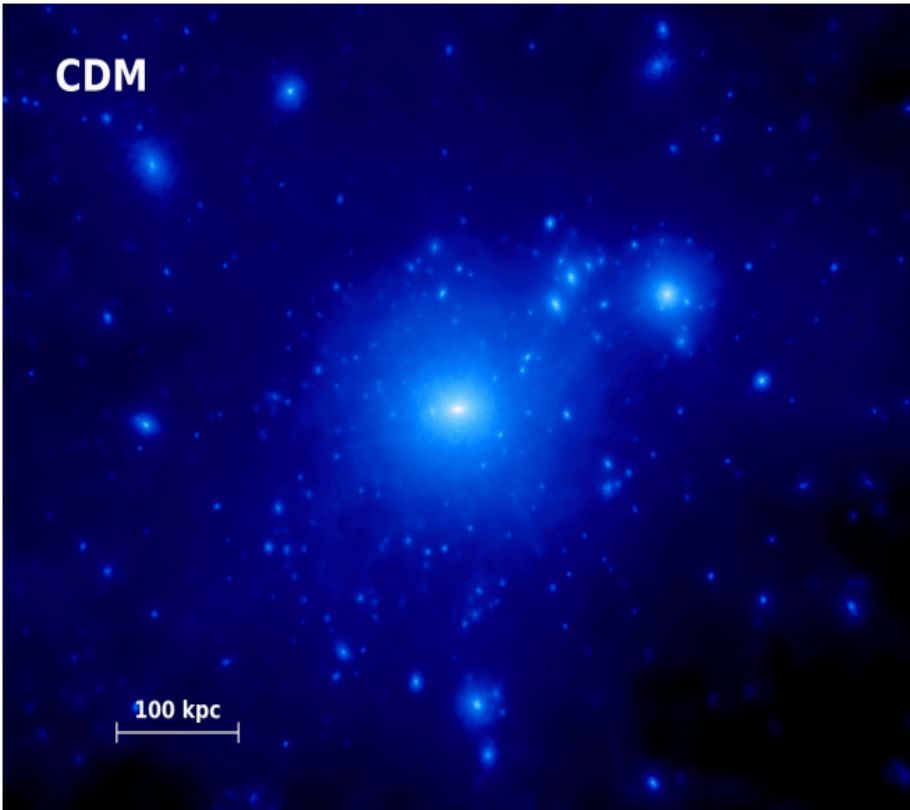


Tracer of the DM halo



MM & Trujillo 2019

Tracer of the DM halo



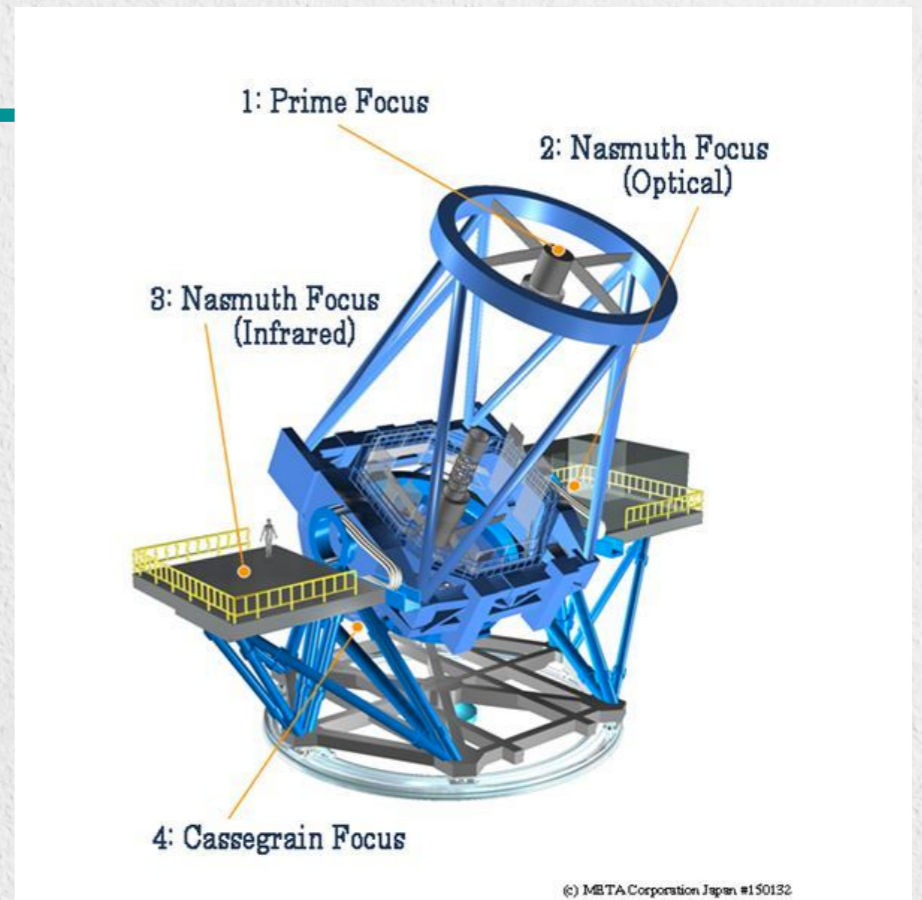
MM & Trujillo 2019

Discern the nature of dark matter?

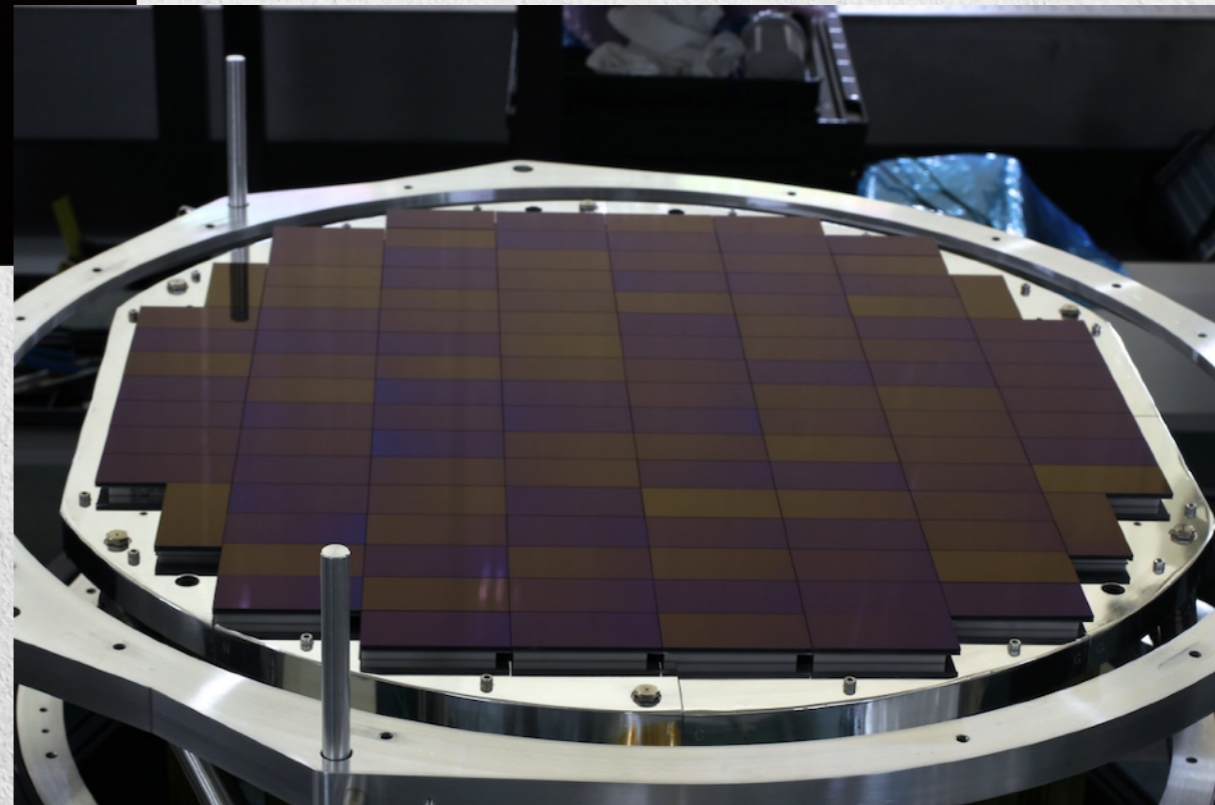
Unveiling the ICL

Unveiling the ICL

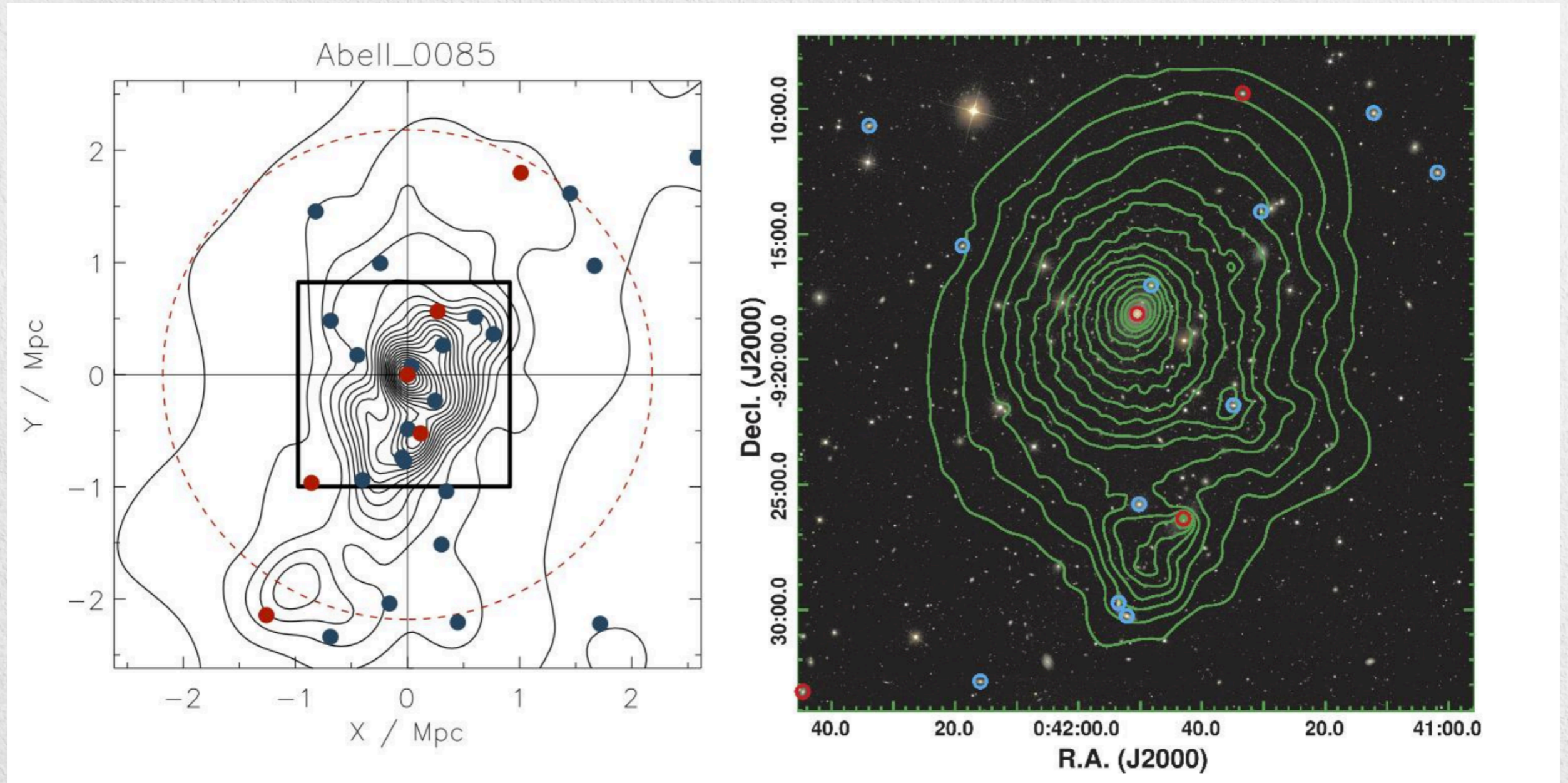
Hyper Suprime-Cam



1.5 deg diameter



Abell 85



$$R_{\text{vir}} = 2.42 \text{ Mpc} \\ = 0.63^\circ$$

Owers et al. 2017

“Homemade” data reduction

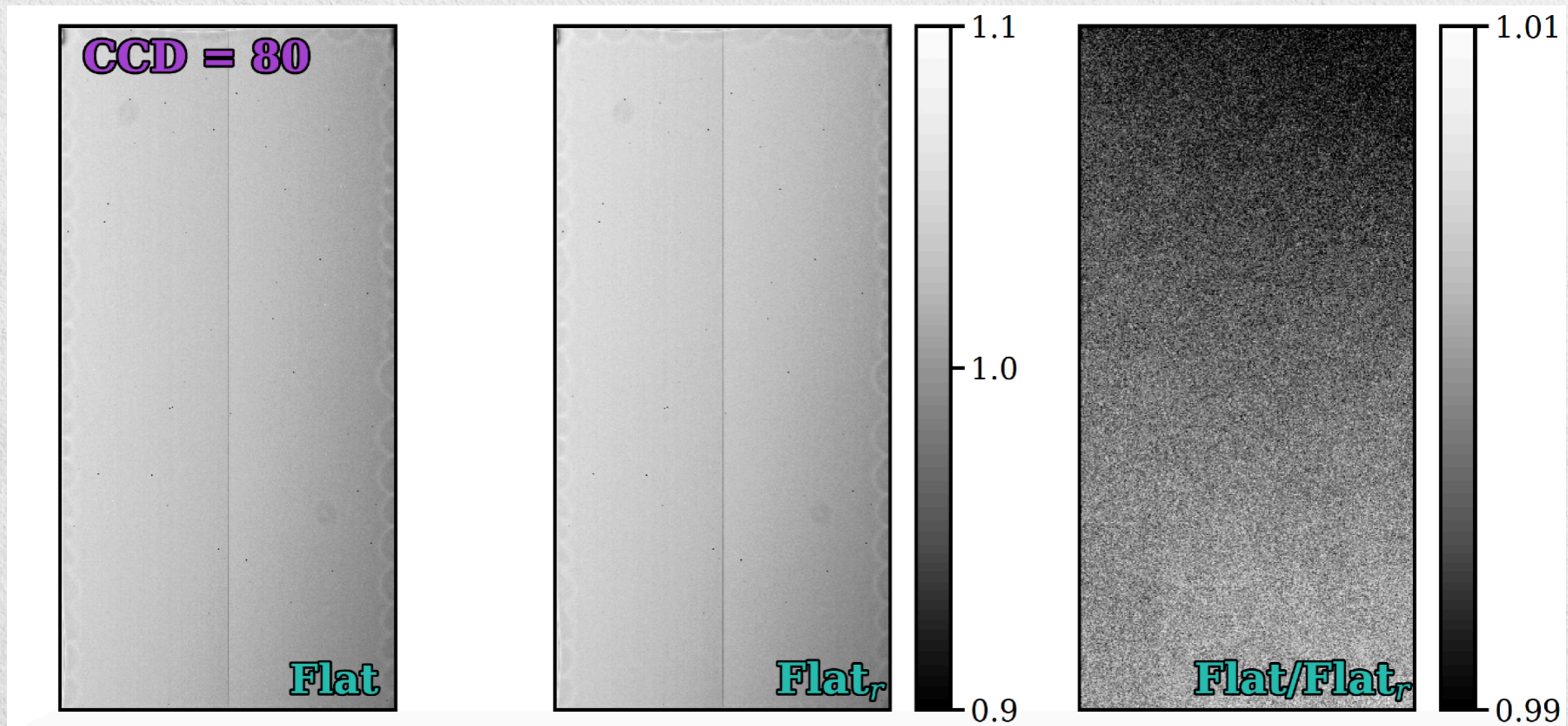
★ CCD processing (Bias/ Darks)

“Homemade” data reduction

- ★ CCD processing (Bias/ Darks)
- ★ Flat-field correction

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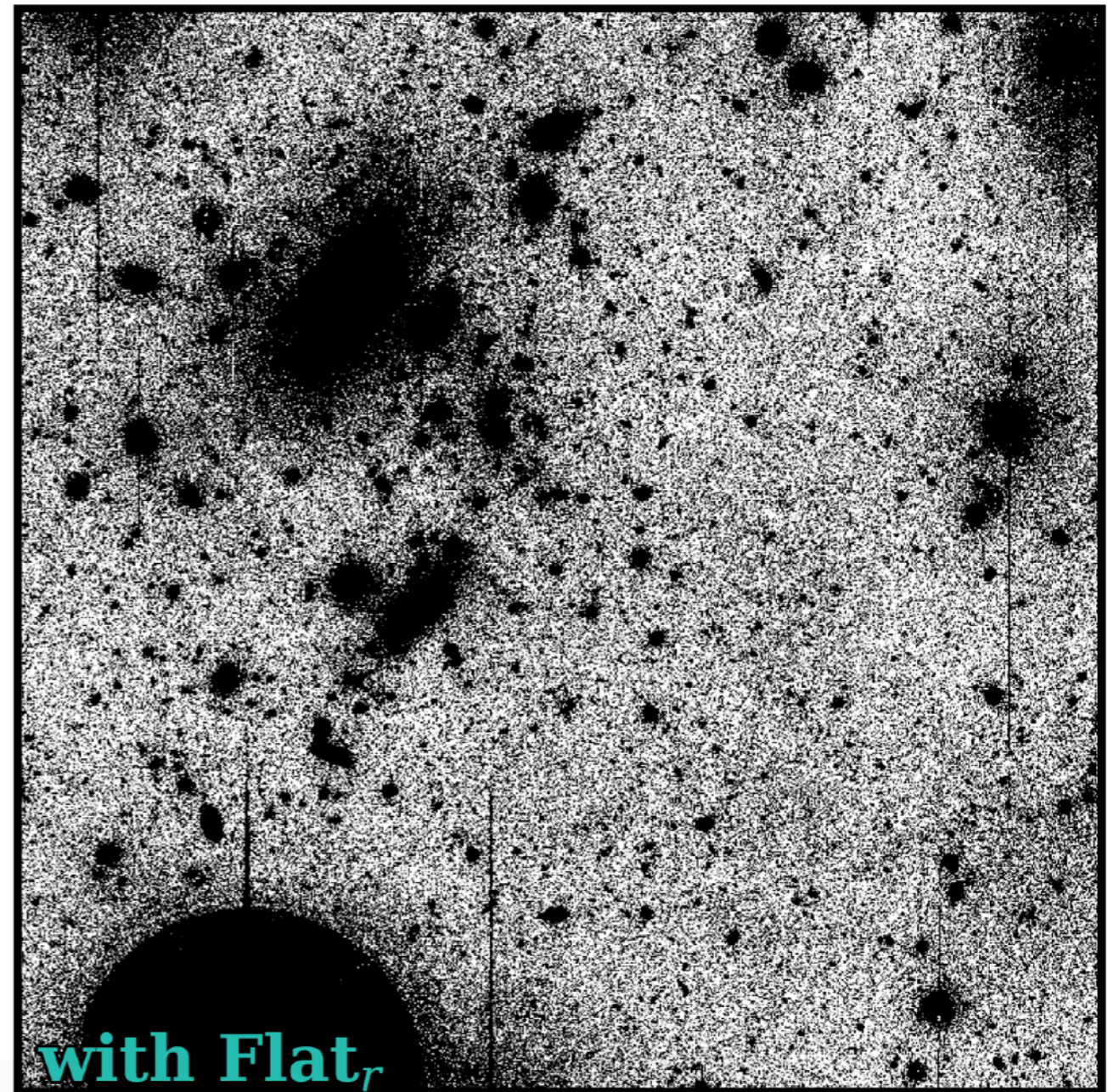
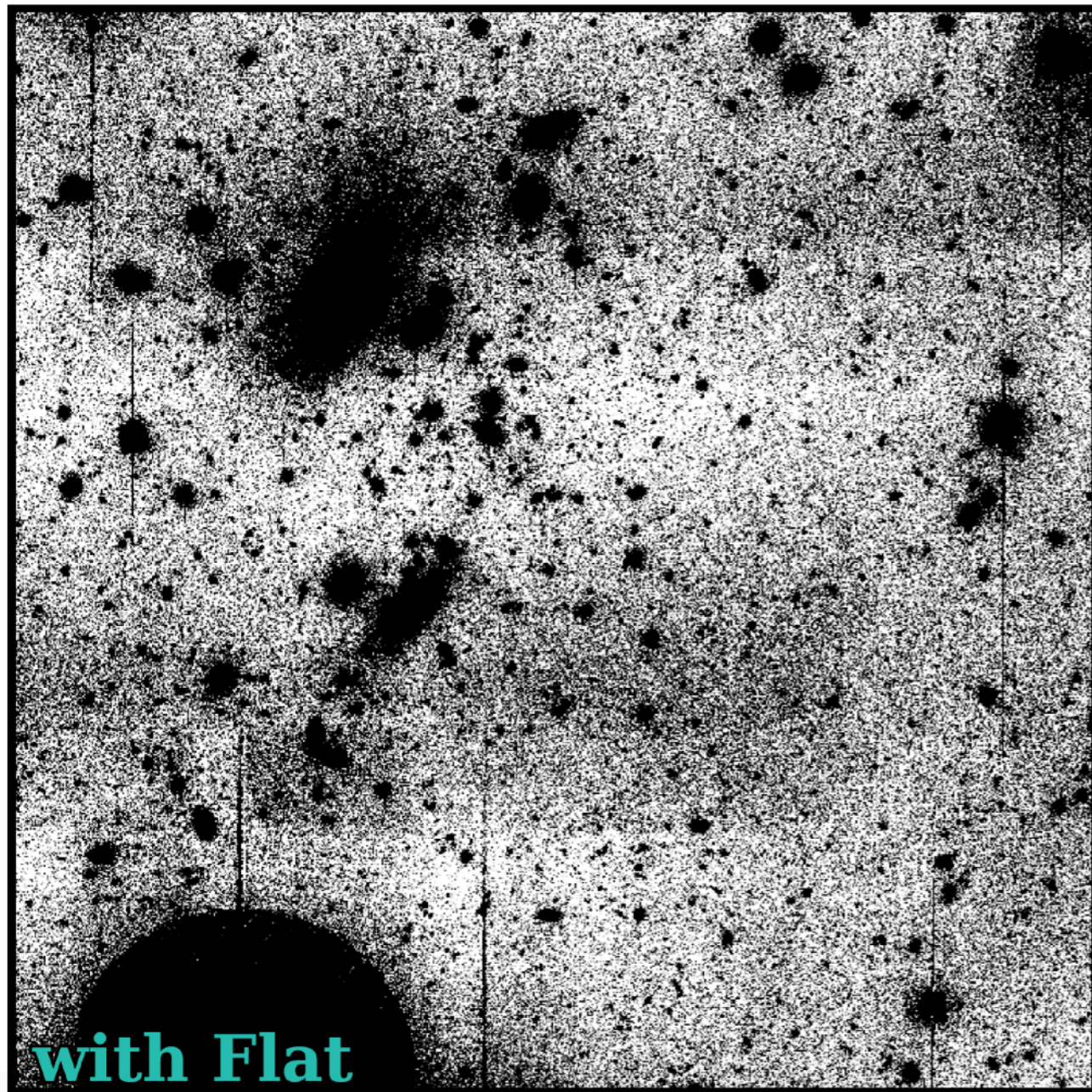
$\langle \text{INR-STR} \rangle = -5$

$\langle \text{INR-STR} \rangle = 114$

Images: $\langle \text{INR-STR} \rangle = 124$

Gradient of 1% across the CCD

“Homemade” data reduction



Abell 85: MM, Brough, Owers & Santucci, 2020, submitted

i-band

“Homemade” data reduction

- ★ CCD processing (Bias/ Darks)
- ★ Flat-field correction
- ★ Frame assembly
- ★ Sky subtraction Plane + constant

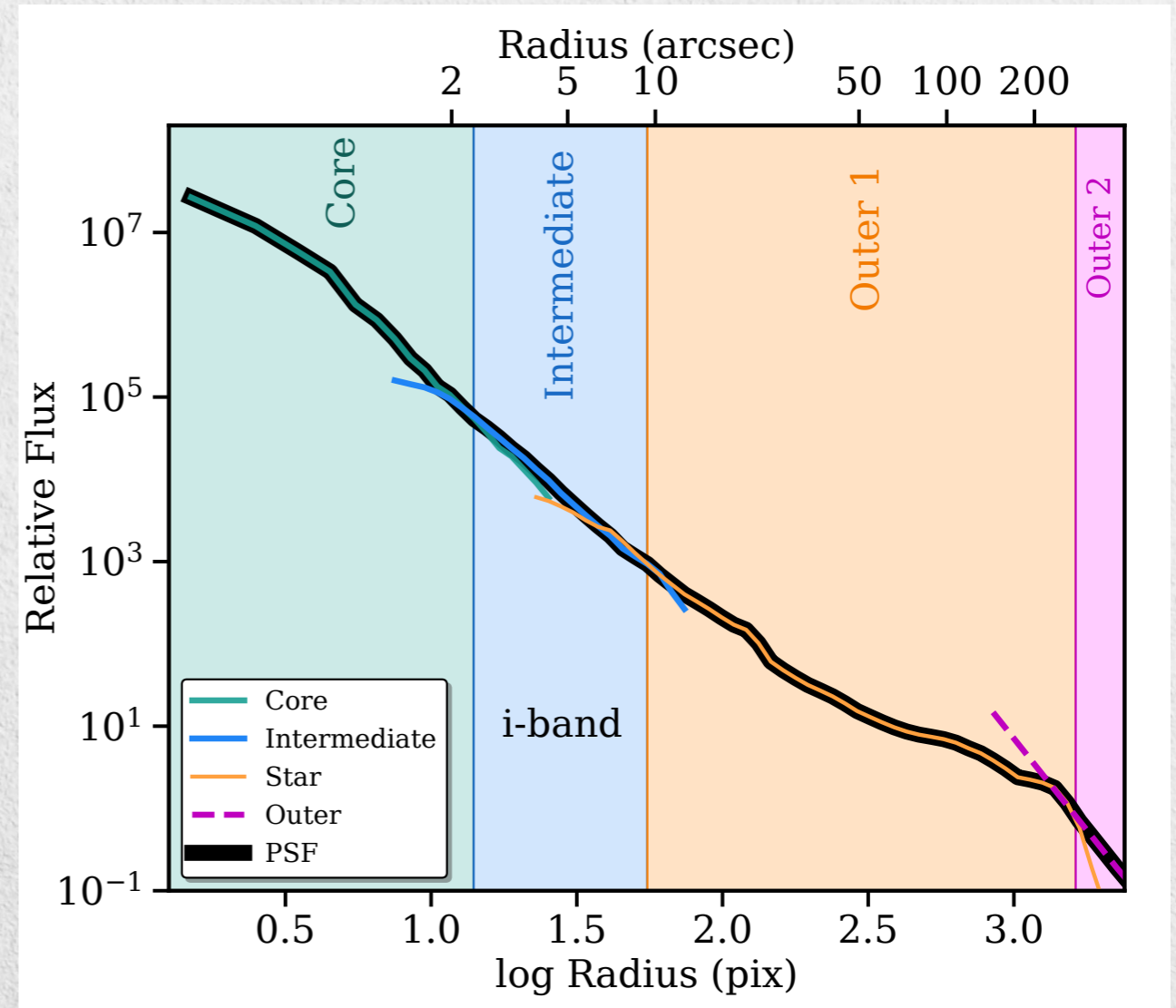
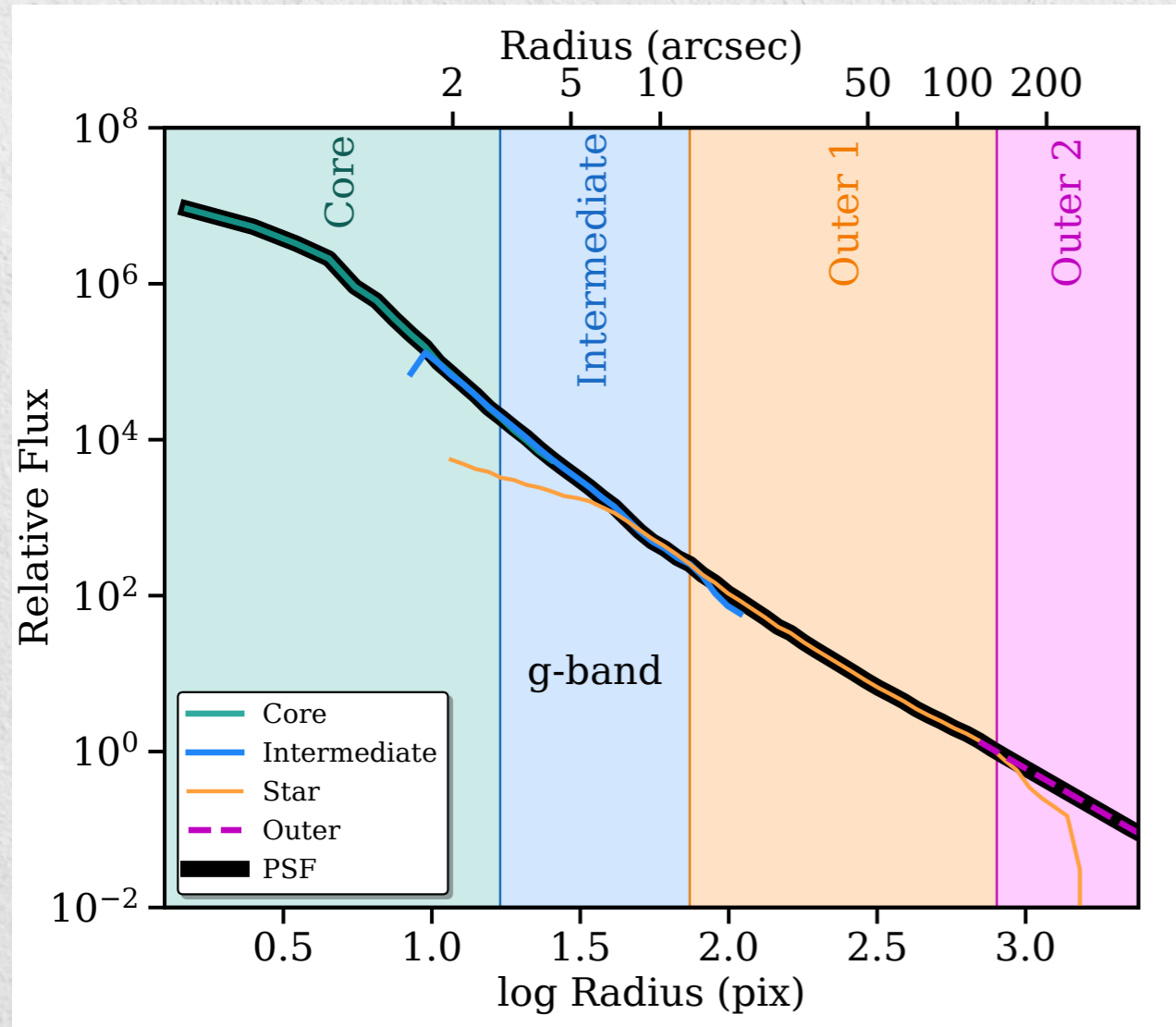
“Homemade” data reduction

- ★ CCD processing (Bias/ Darks)
- ★ Flat-field correction
- ★ Frame assembly
- ★ Sky subtraction
- ★ Final co-addition

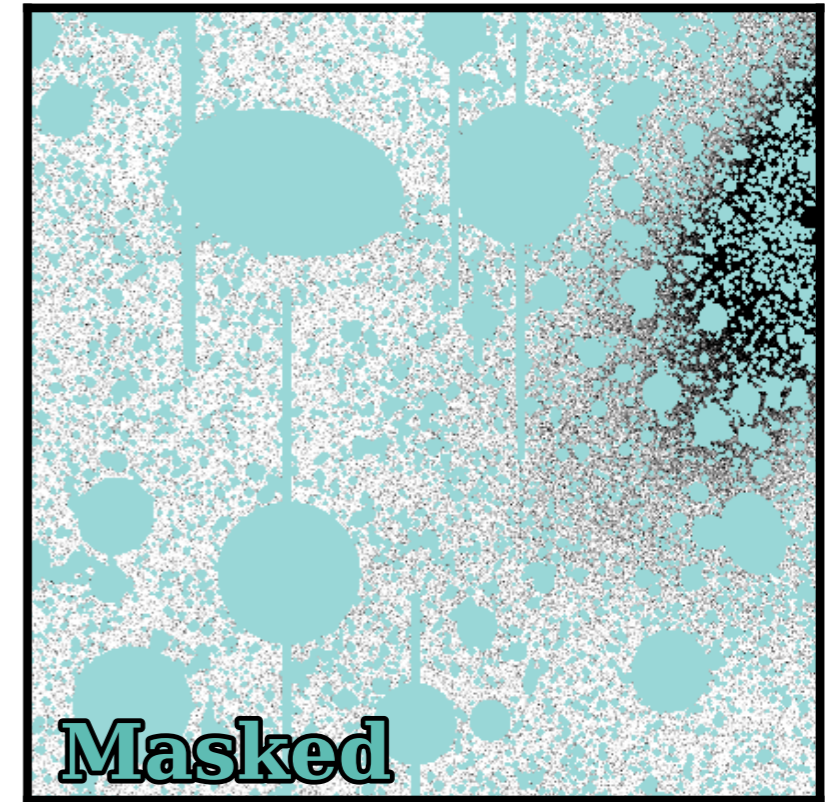
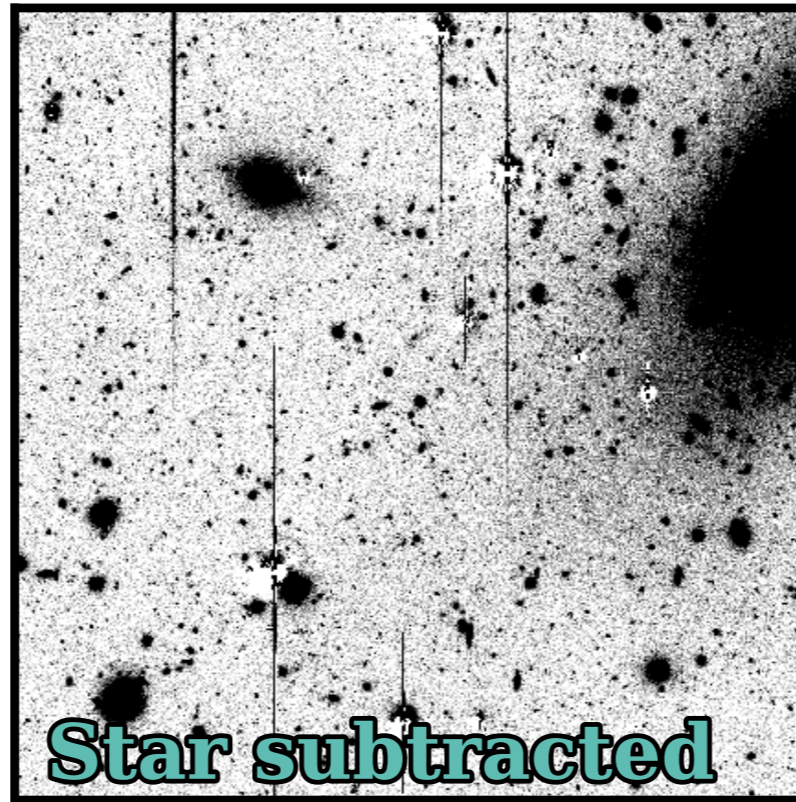
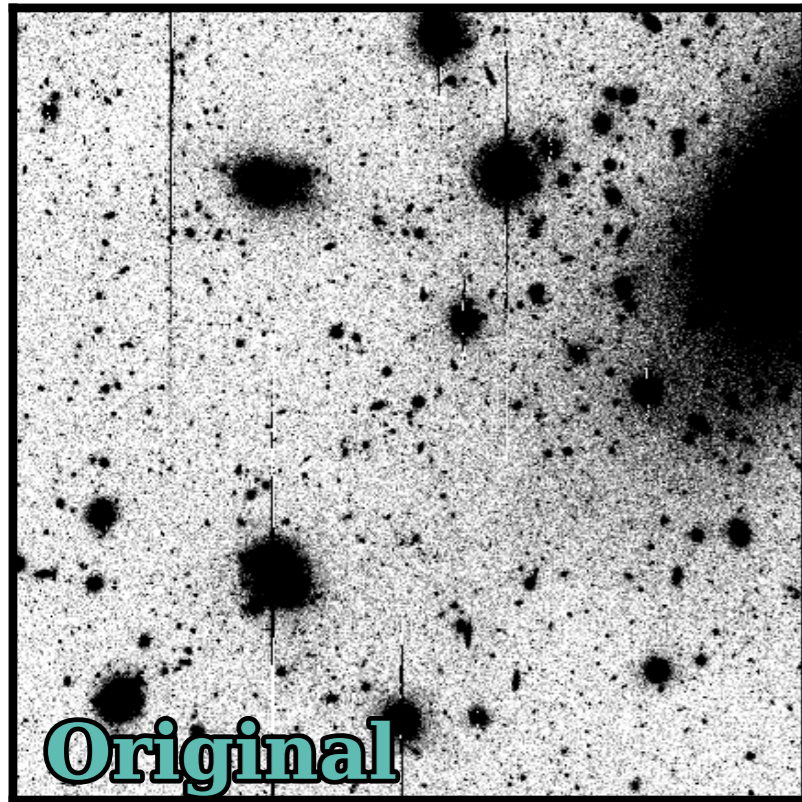
- 🌐 Star subtraction and masking

Star subtraction

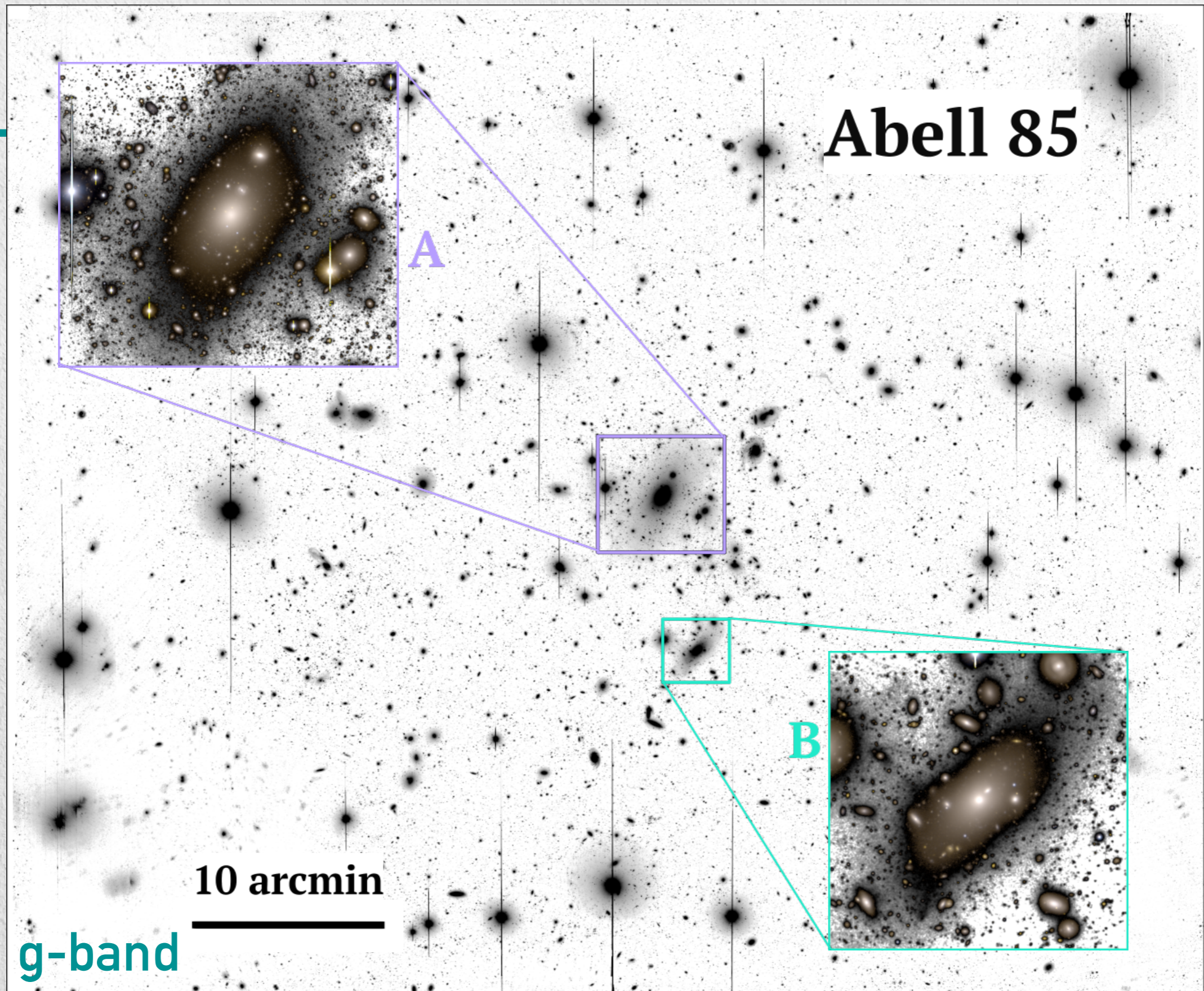
2-D PSF models



Star subtraction & masking



i-band

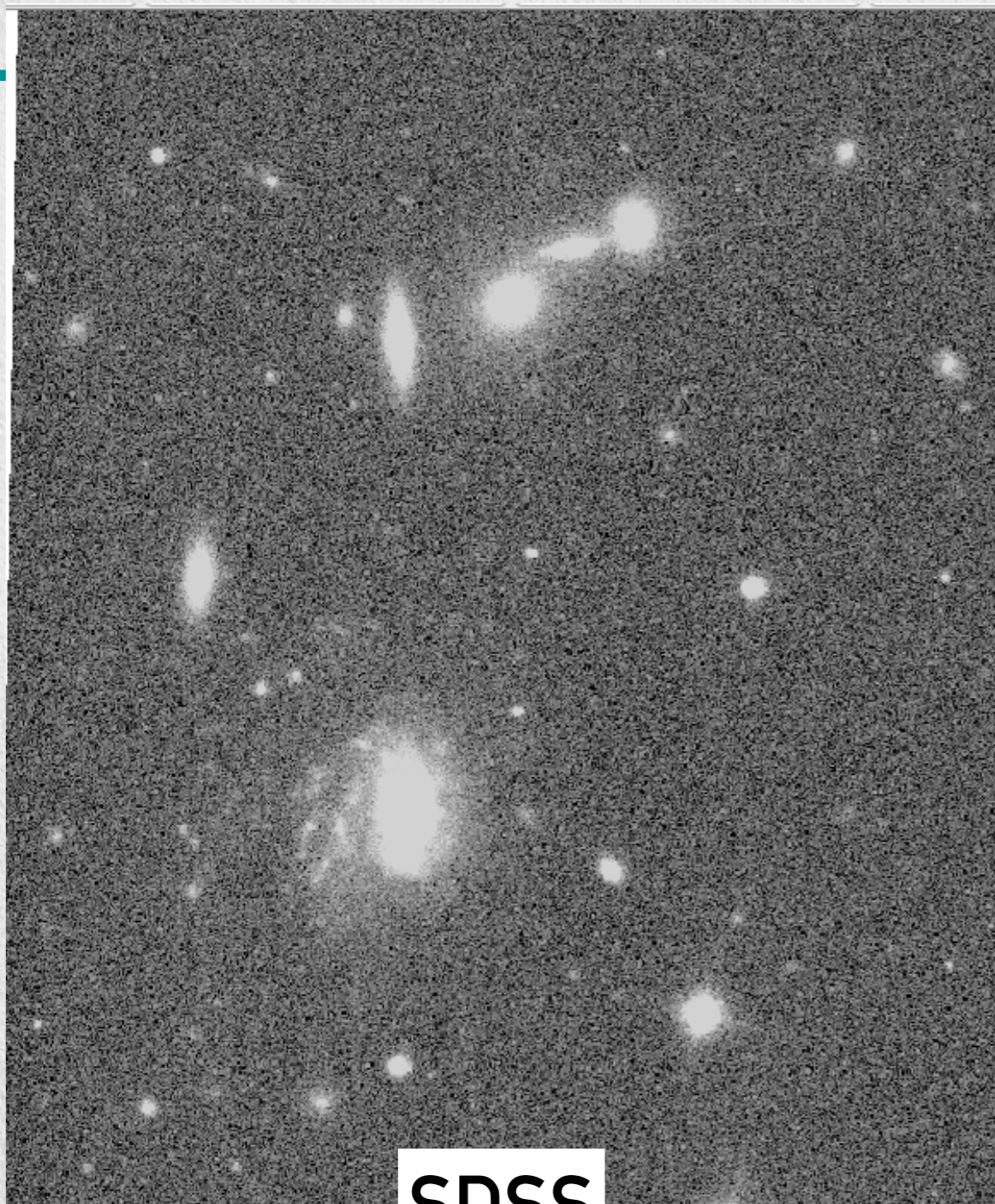


$g_{\text{lim}} = 30.8 \text{ mag/arcsec}^2 (10'' \times 10'', 3\sigma)$

52' x 52'

$i_{\text{lim}} = 29.6 \text{ mag/arcsec}^2$

MM et al. 2020, submitted



SDSS

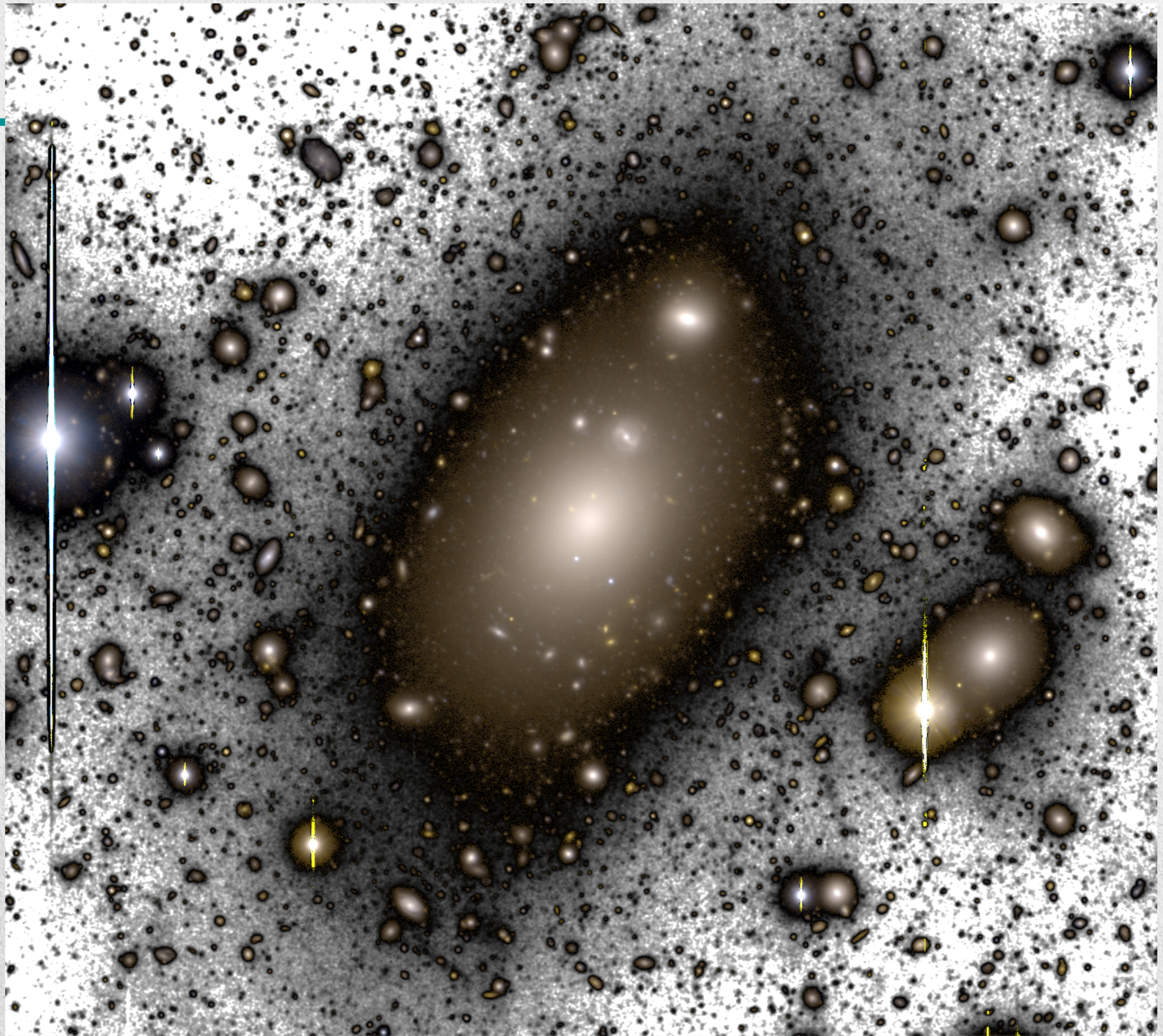
53.9 s

g-band



HSC

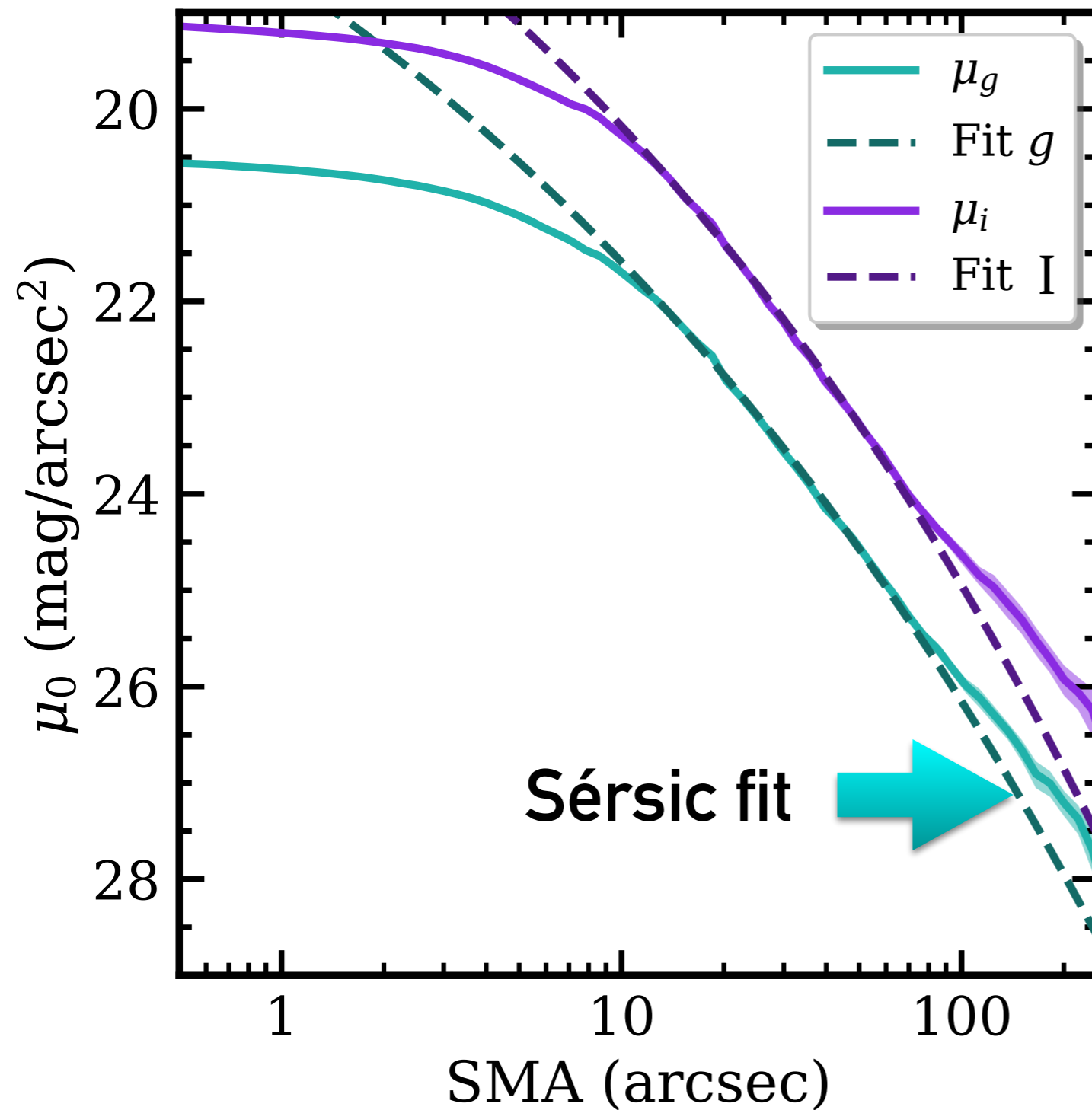
9 x 200 s = 30 min



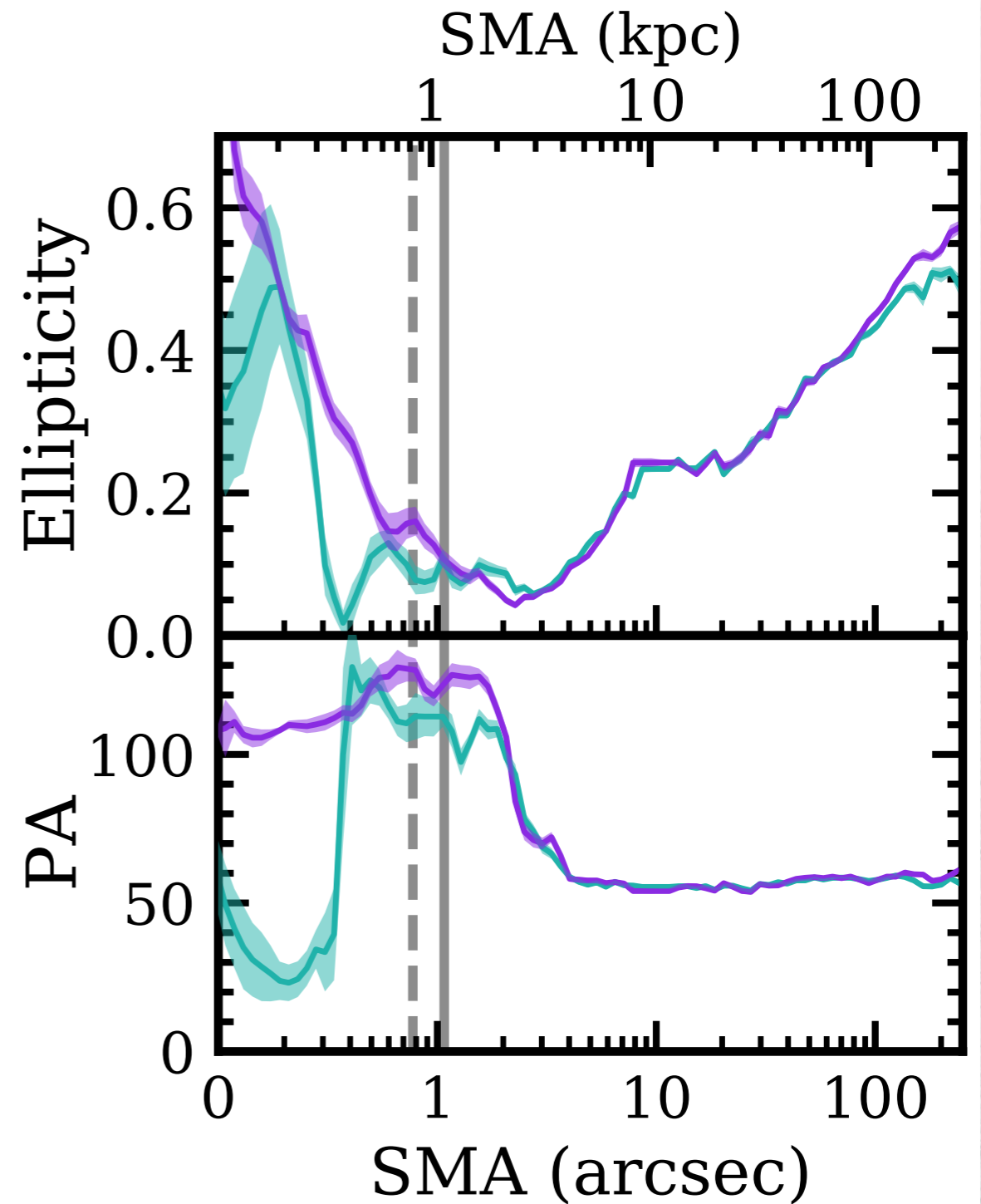
780" x 700"

MM et al. 2020, submitted

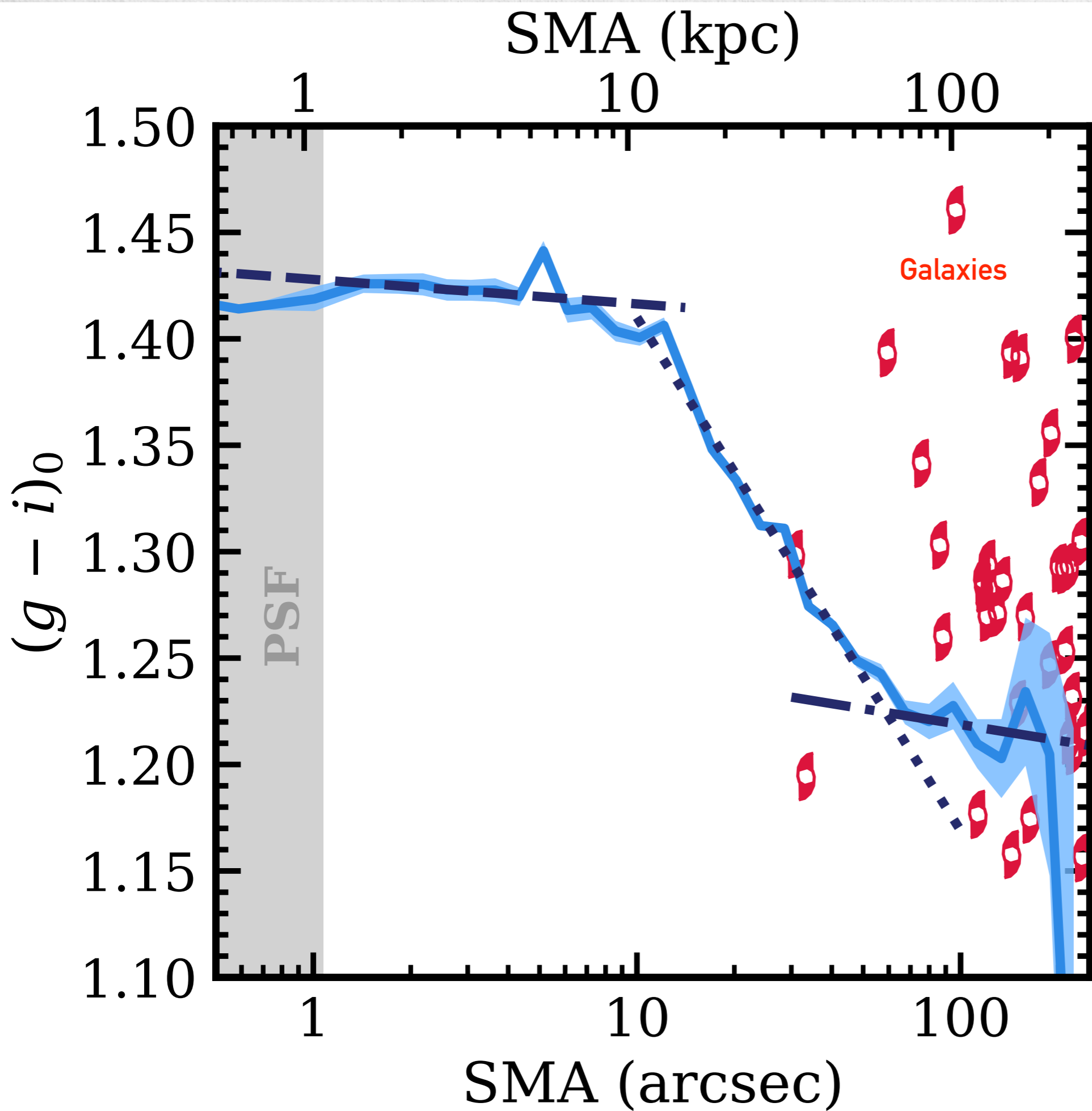
Stellar populations of Abell 85



g-band



i-band




And only in
30 mins!!



g-i ~ 1.23
M* ~ 10¹⁰ M_⊙

Also
MM & Trujillo 2014, 2018

Conclusions

- ICL is **ubiquitous** in clusters of galaxies. Formed by stars following the potential of the cluster.
- The ICL encodes the history of hierarchical assembly of the cluster. And makes simulations agree with the observed BCG mass evolution.
- Luminous tracer of dark matter. 
- It forms via tidal stripping of massive satellites.

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LSB observers be like...

Thanks!

