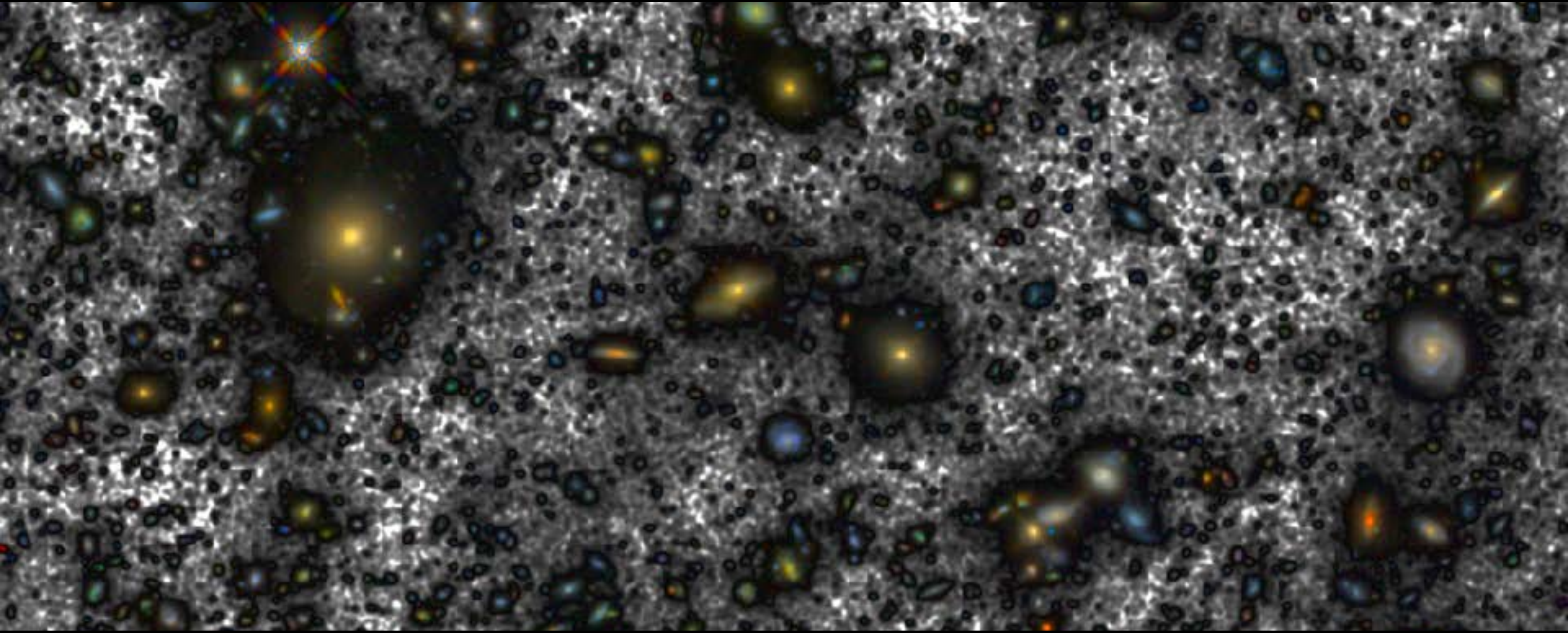
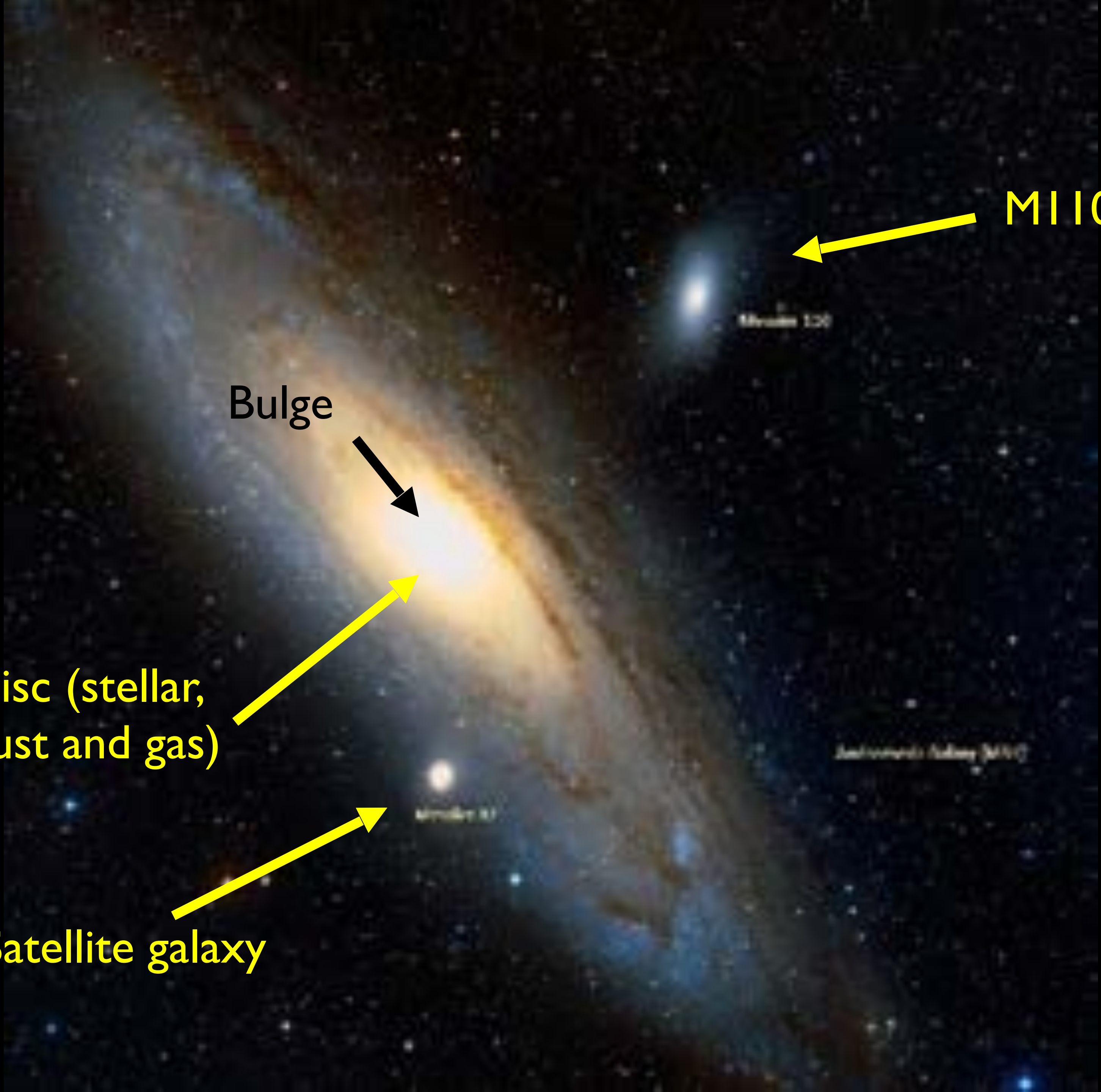
The ultra-low surface brightness Universe with HST and future space telescopes

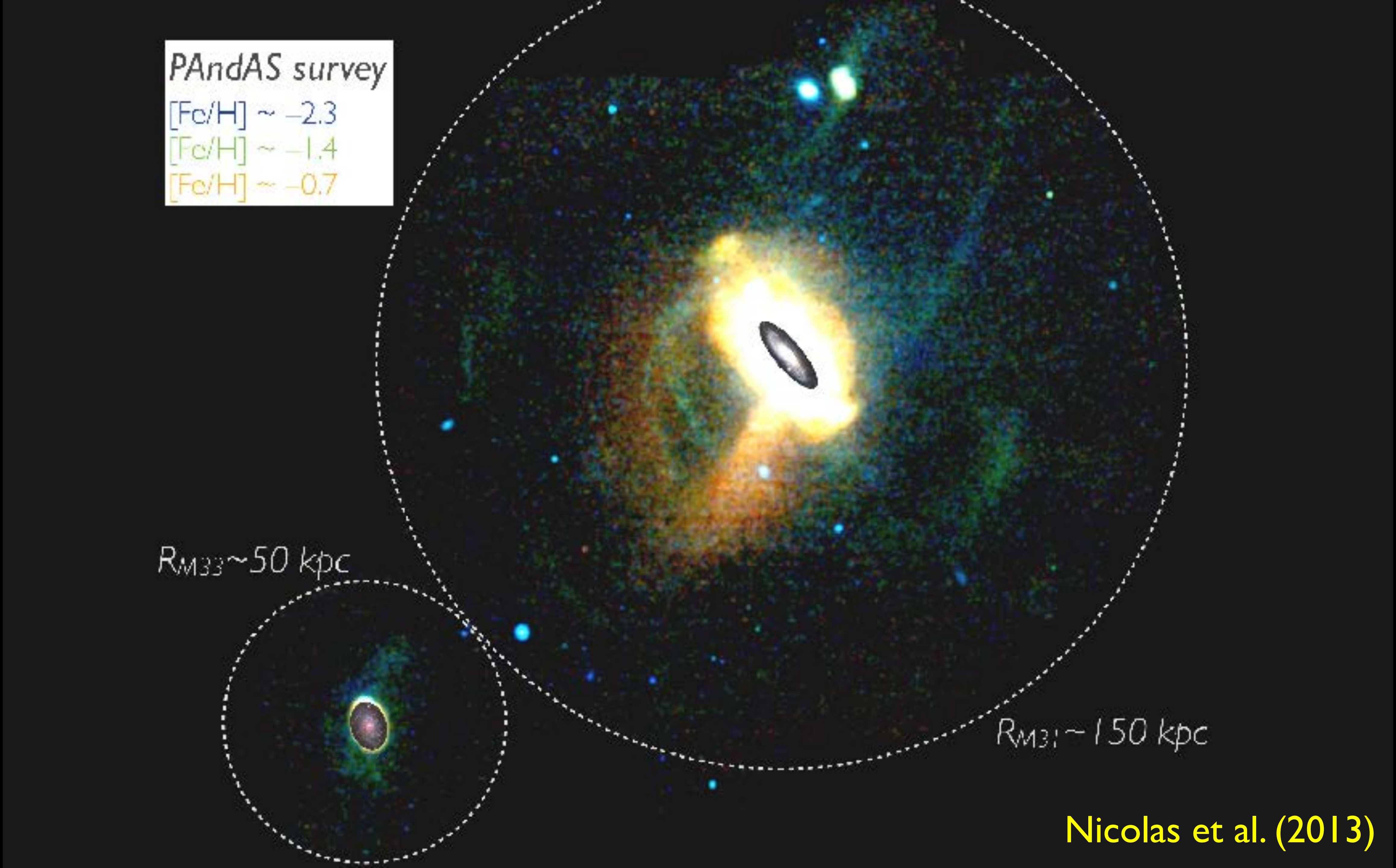


Alejandro S. Borlaff

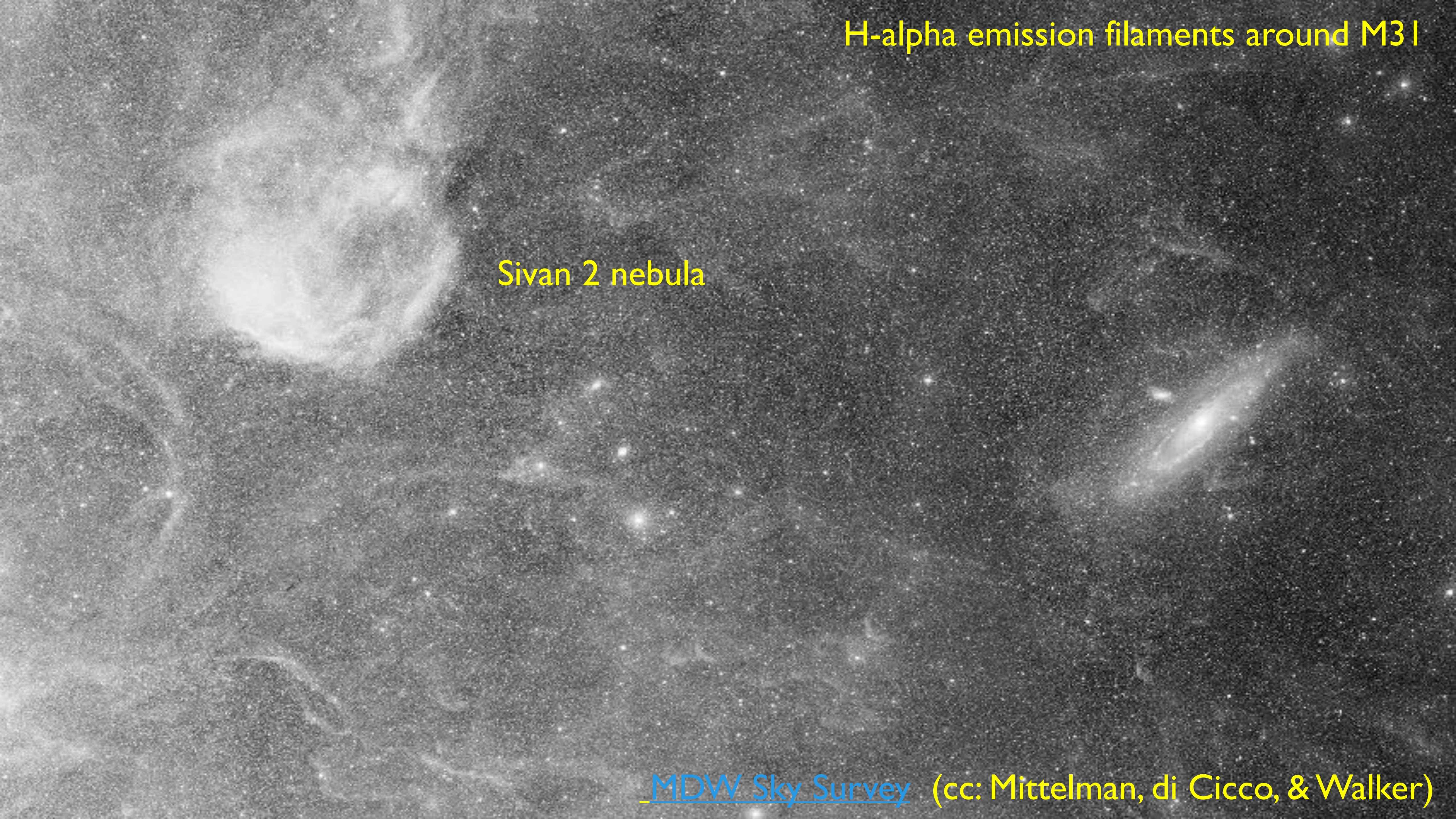
ESAC Seminar – 31 Jan 2019

M31 – Andromeda



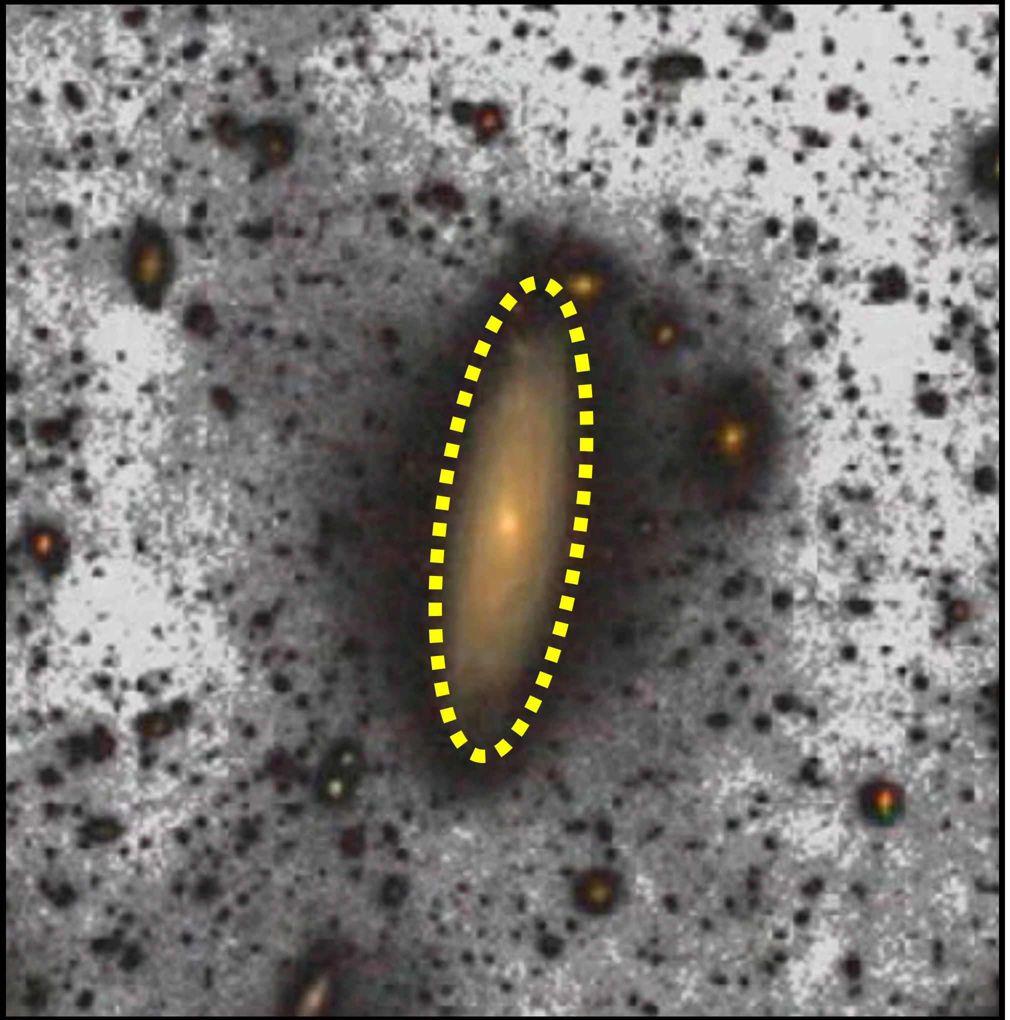


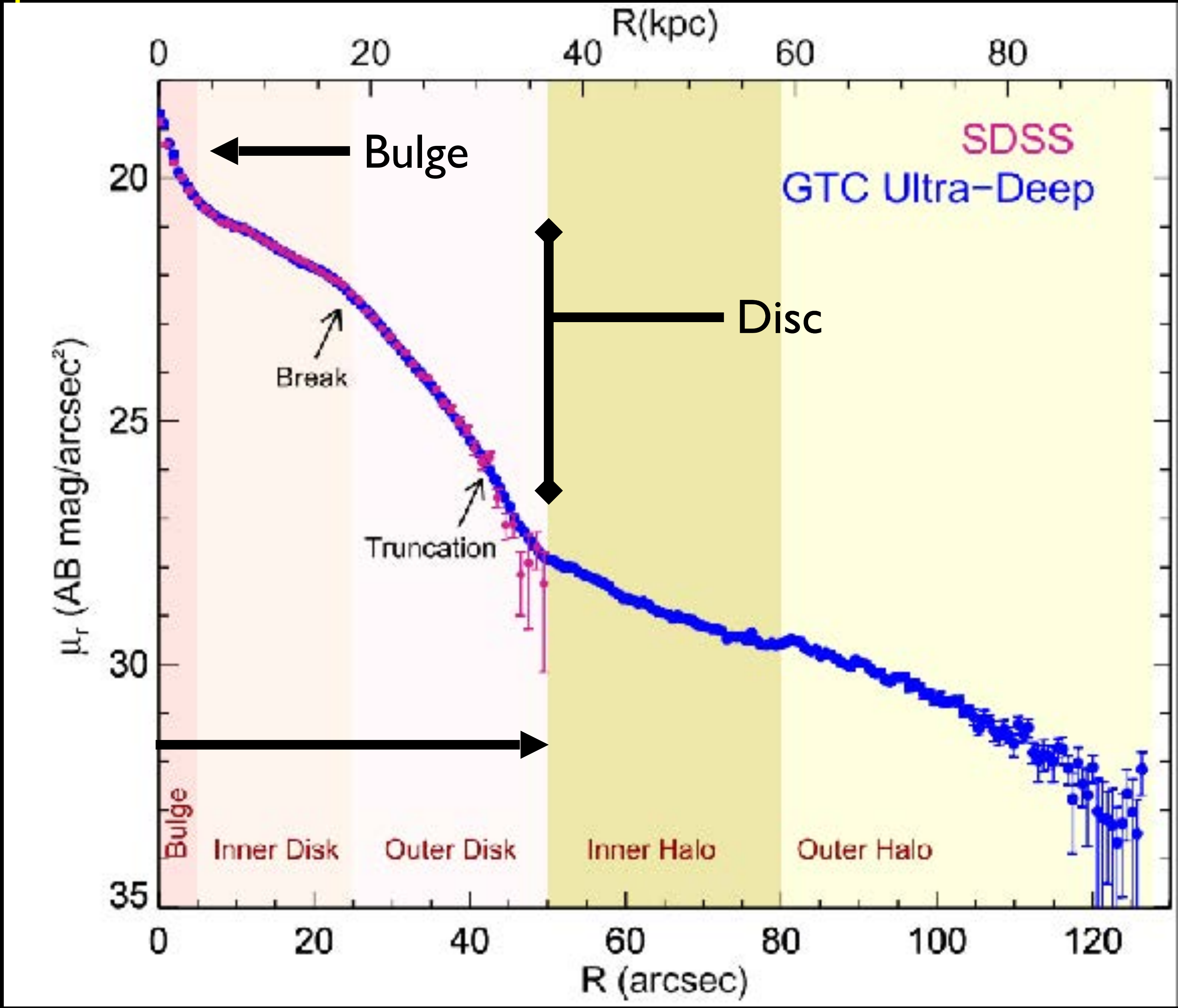
Nicolas et al. (2013)


H-alpha emission filaments around M31
Sivan 2 nebula
MDW Sky Survey (cc: Mittelman, di Cicco, & Walker)

Galaxy structure – Surface brightness profiles

Trujillo & Fliri (2016)
Ultra-deep imaging of UGC00180





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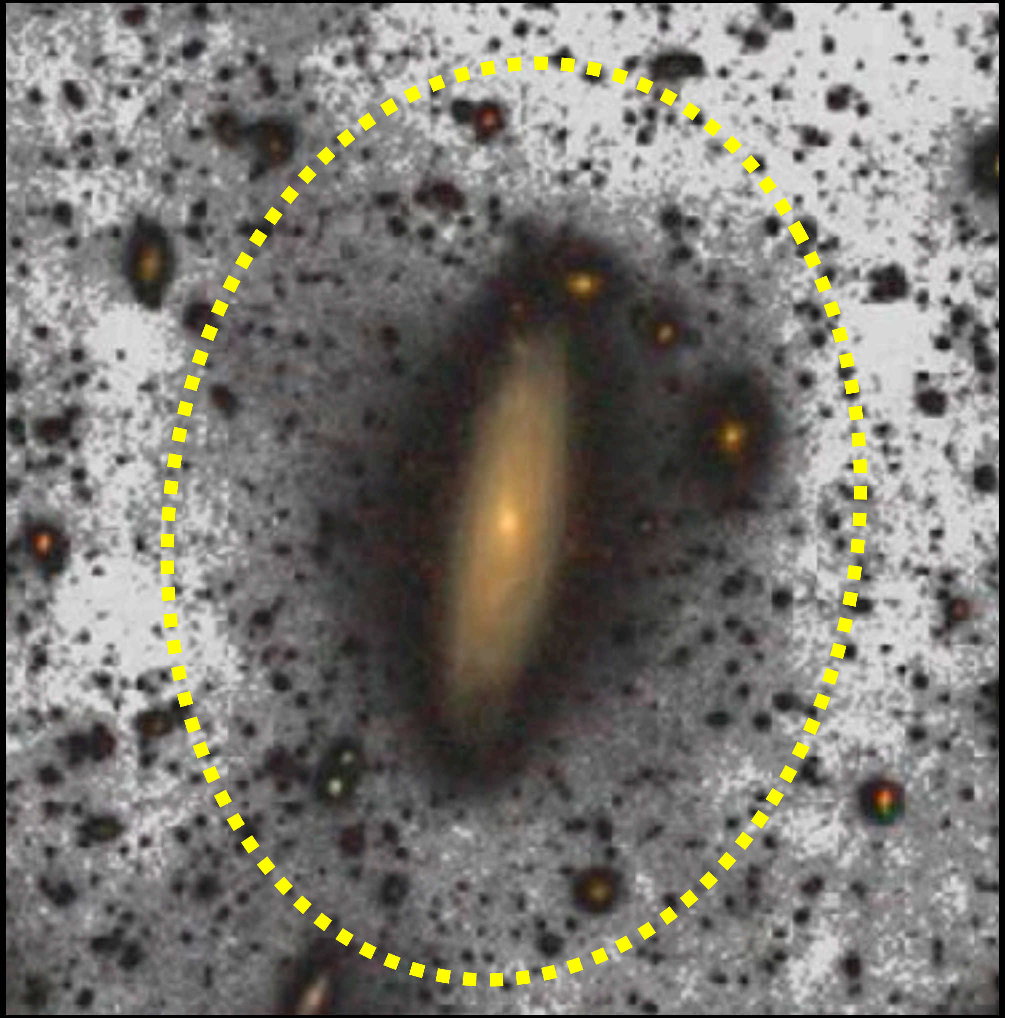
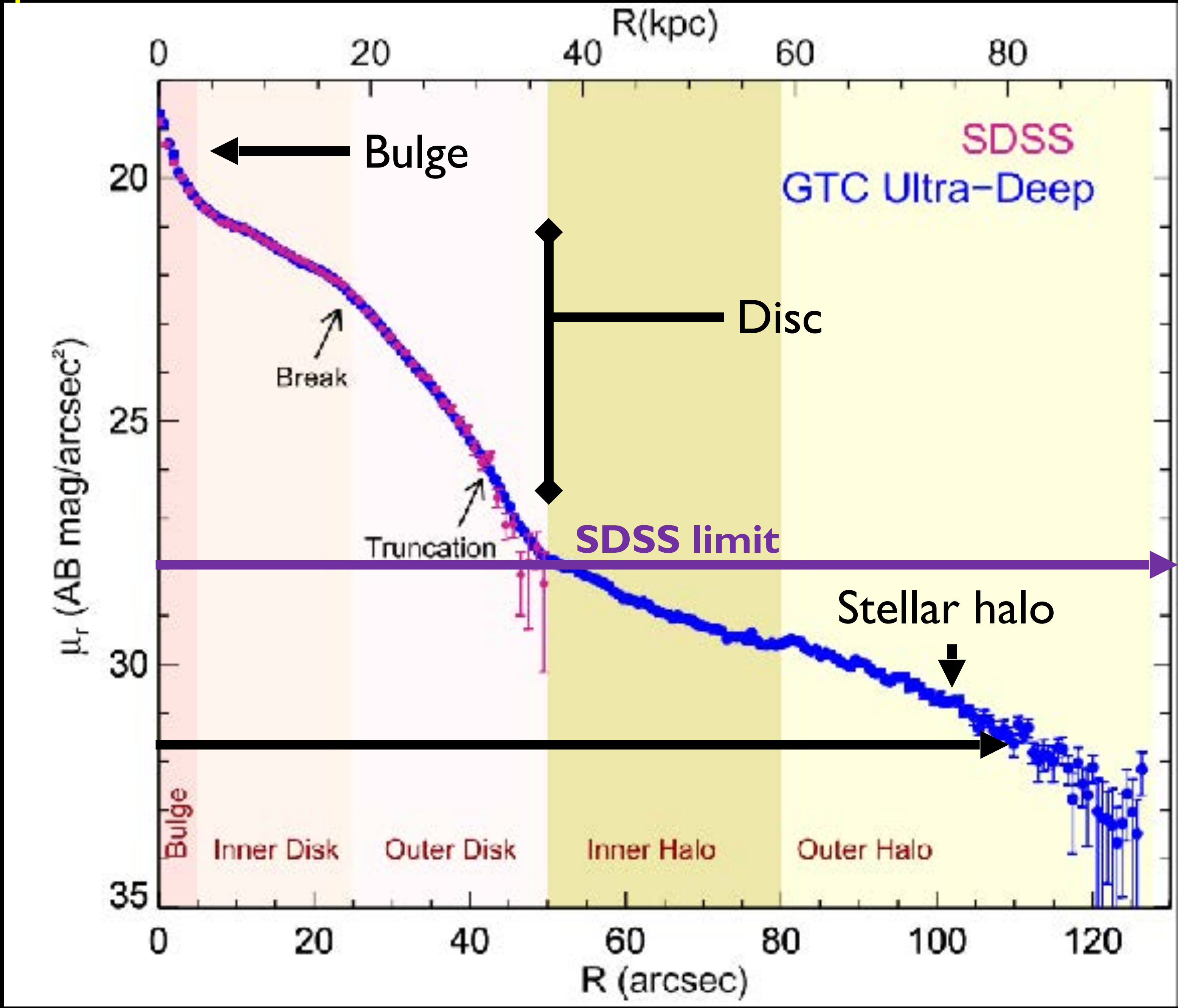
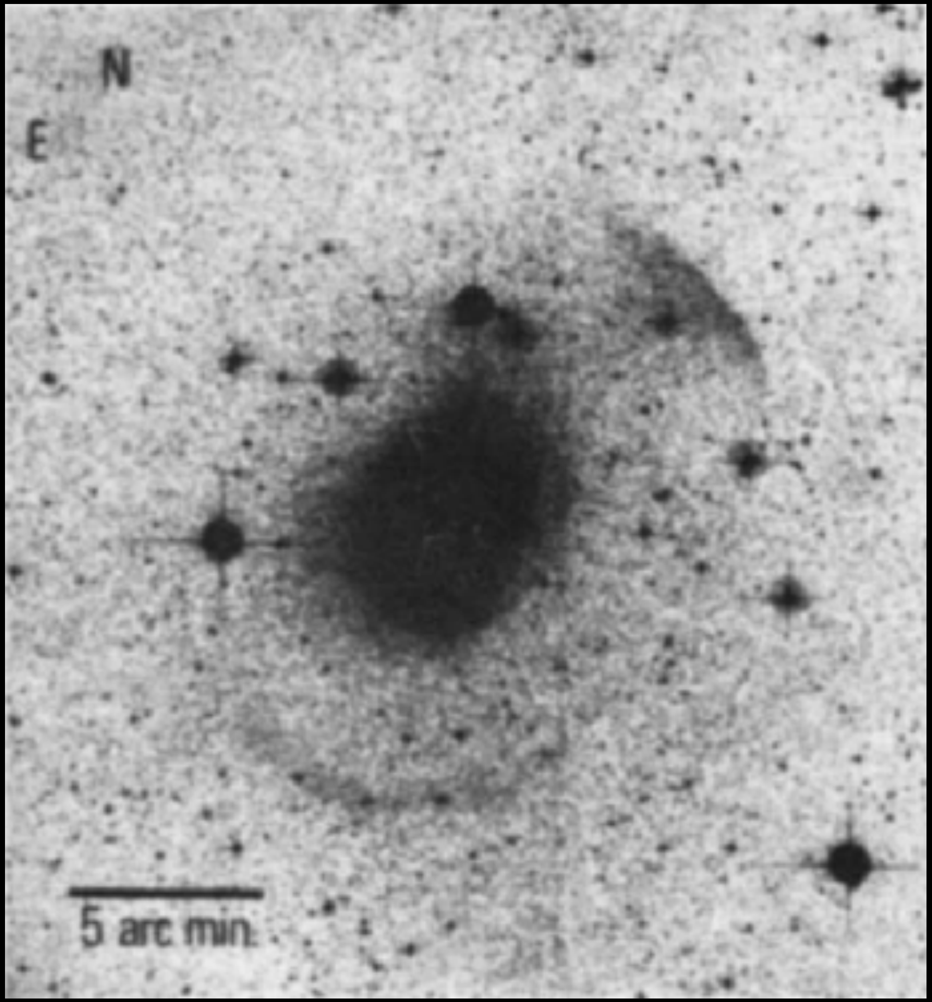




Malin & Carter (1980) – Detection of shells on NGC1344



Three hypothesis:

1) Explosive event that displaced stars to the outskirts
2) Powerful shockwave that propagated star formation to the outskirts
3) Remnants from an ancient merger (discarded!)
   Reason: The central regions of NGC1344 did not appear to be disturbed.

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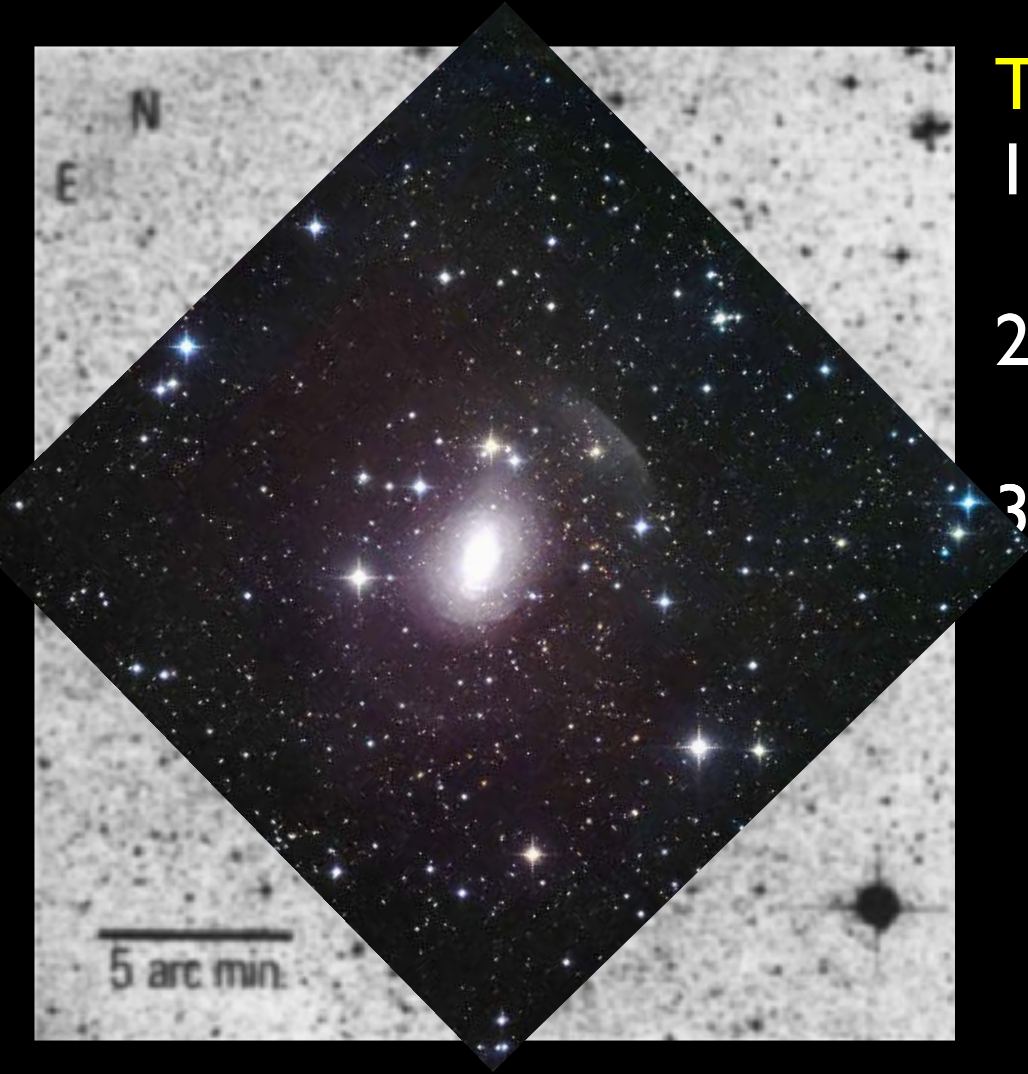

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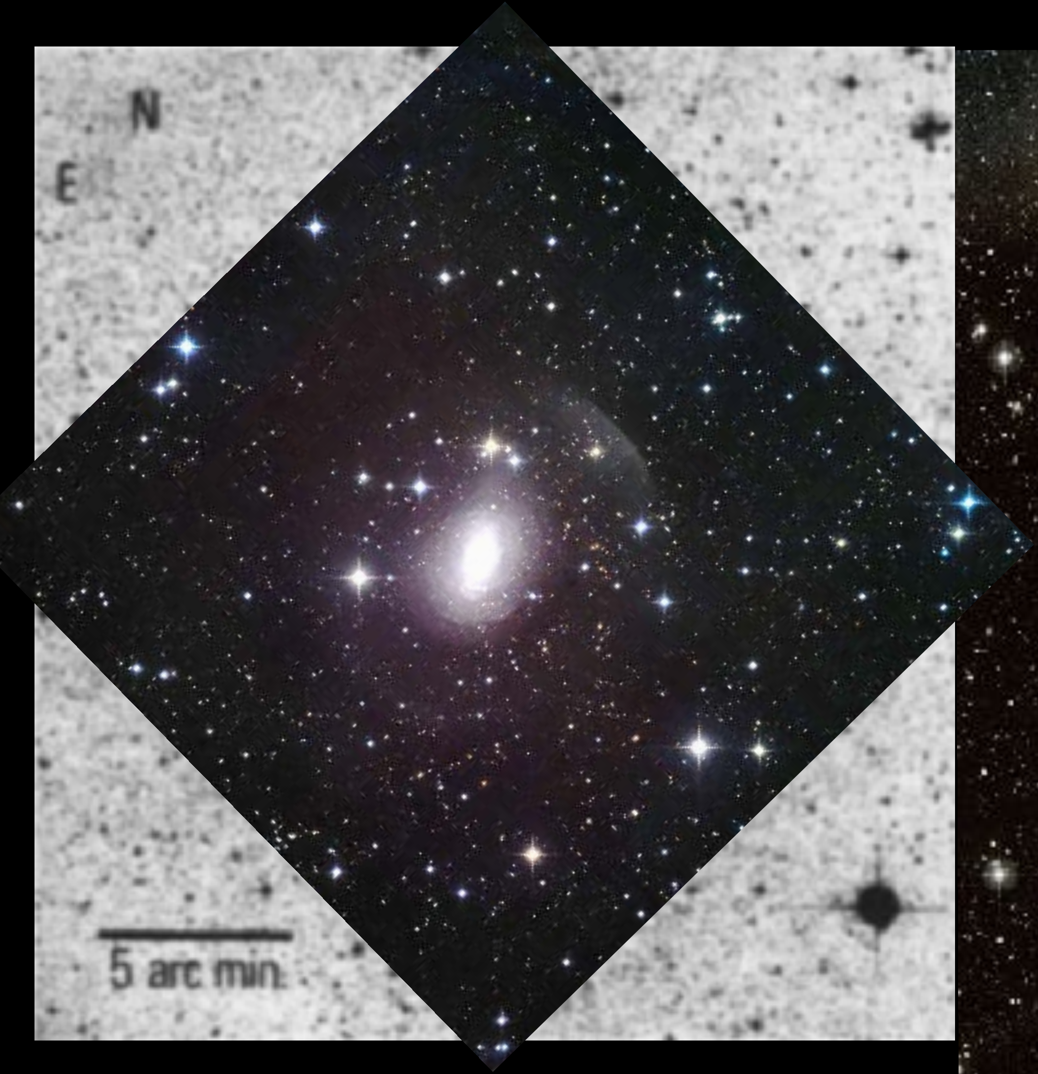
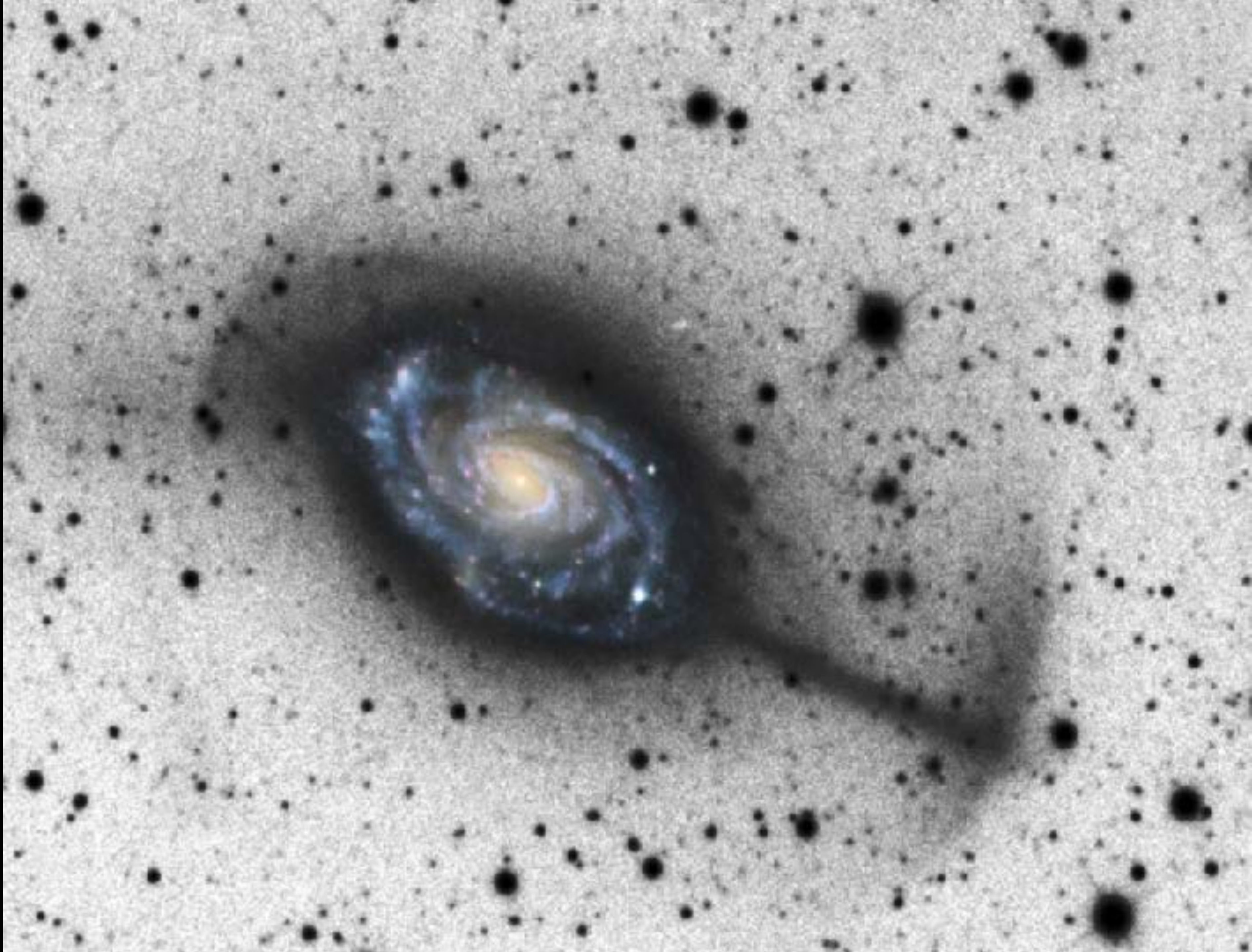


NGC4651
Martinez-Delgado et al. (2010)

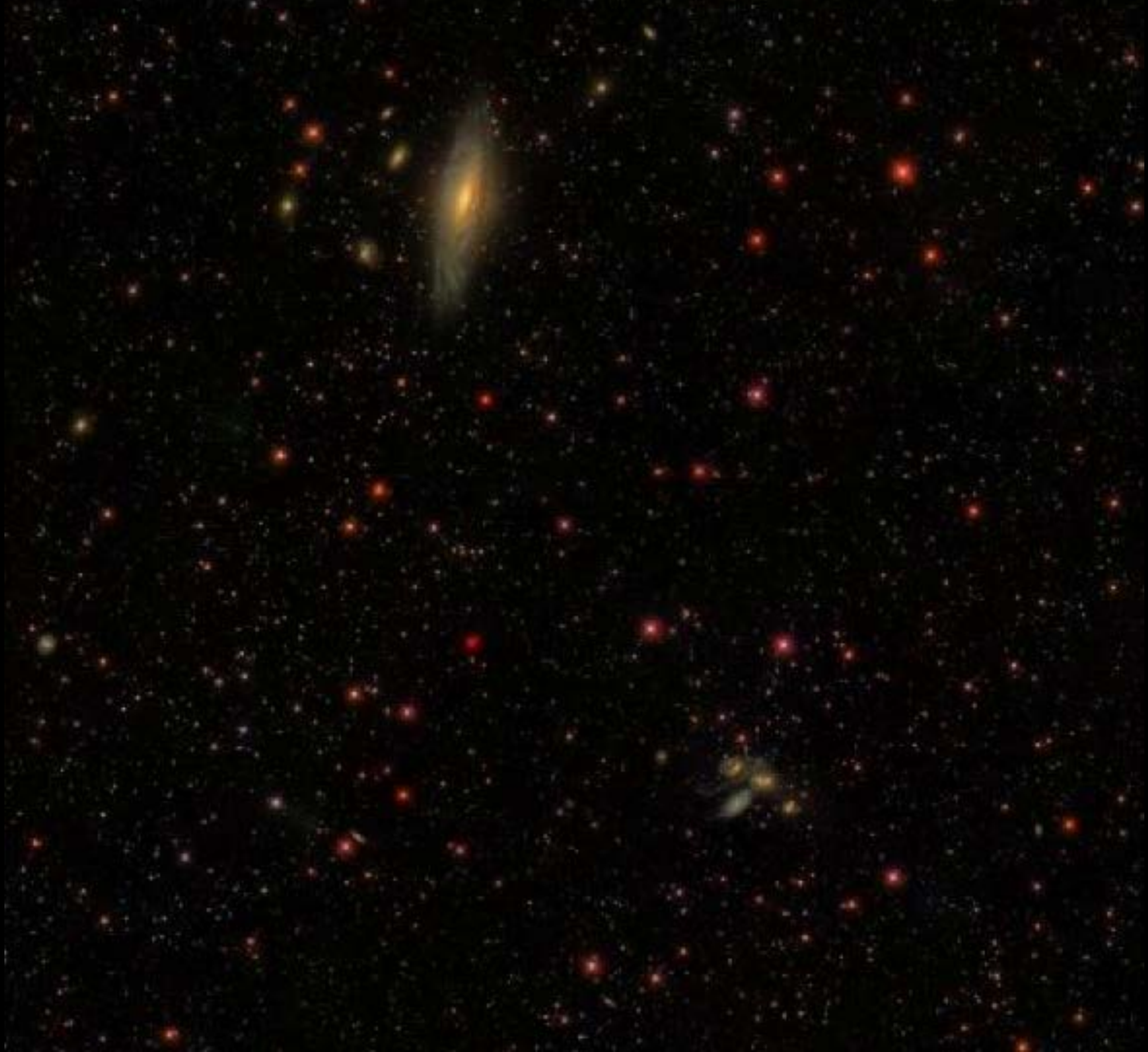
Simulations:
50% of galaxies would show at least a tidal structure at μlim ~ 30 mag arcsec^{-2} (Bullock & Johnston 2005; Johnston et al. 2008).



Stephan's Quintet and NGC7331 Deer Lick Group

(SDSS)

Surface brightness magnitude limit (g-band) 26.5 mag arcsec^{-2}



Stephan's Quintet and NGC7331 Deer Lick Group

(CFHT)

Duc, Cuillandre & Renaud (2018)

Surface brightness magnitude limit (u, g, r bands) 29.0, 28.6, and 27.6 mag arcsec^{-2}

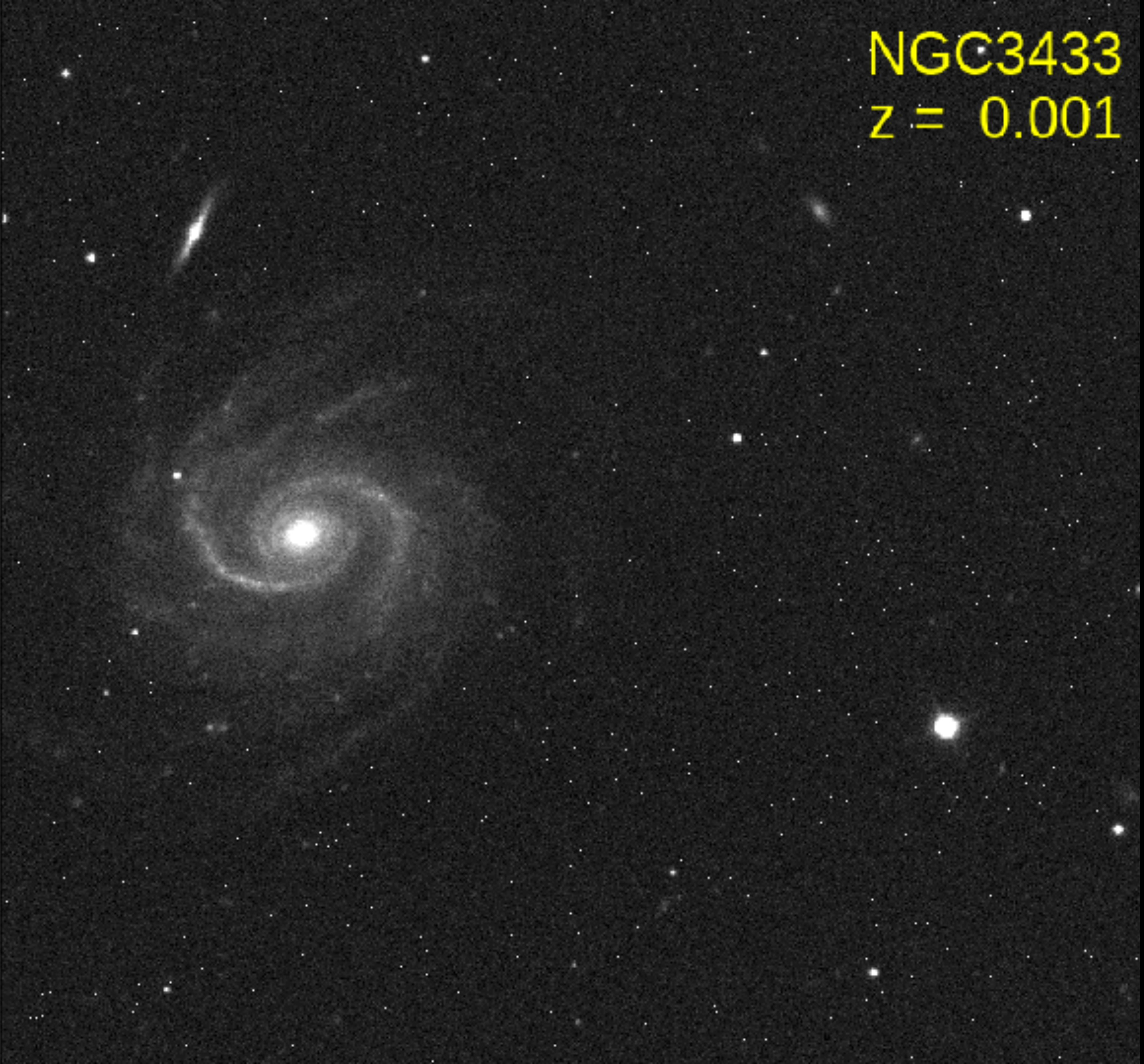
Three main reasons to study the low Surface brightness Universe

1) Dim structures in the near Universe

   Dust filaments, ultra diffuse galaxies, tidal tails, stellar halos

2) Not-so-dim structures at high-z: Cosmological dimming

   Evolution of galactic discs and stellar haloes

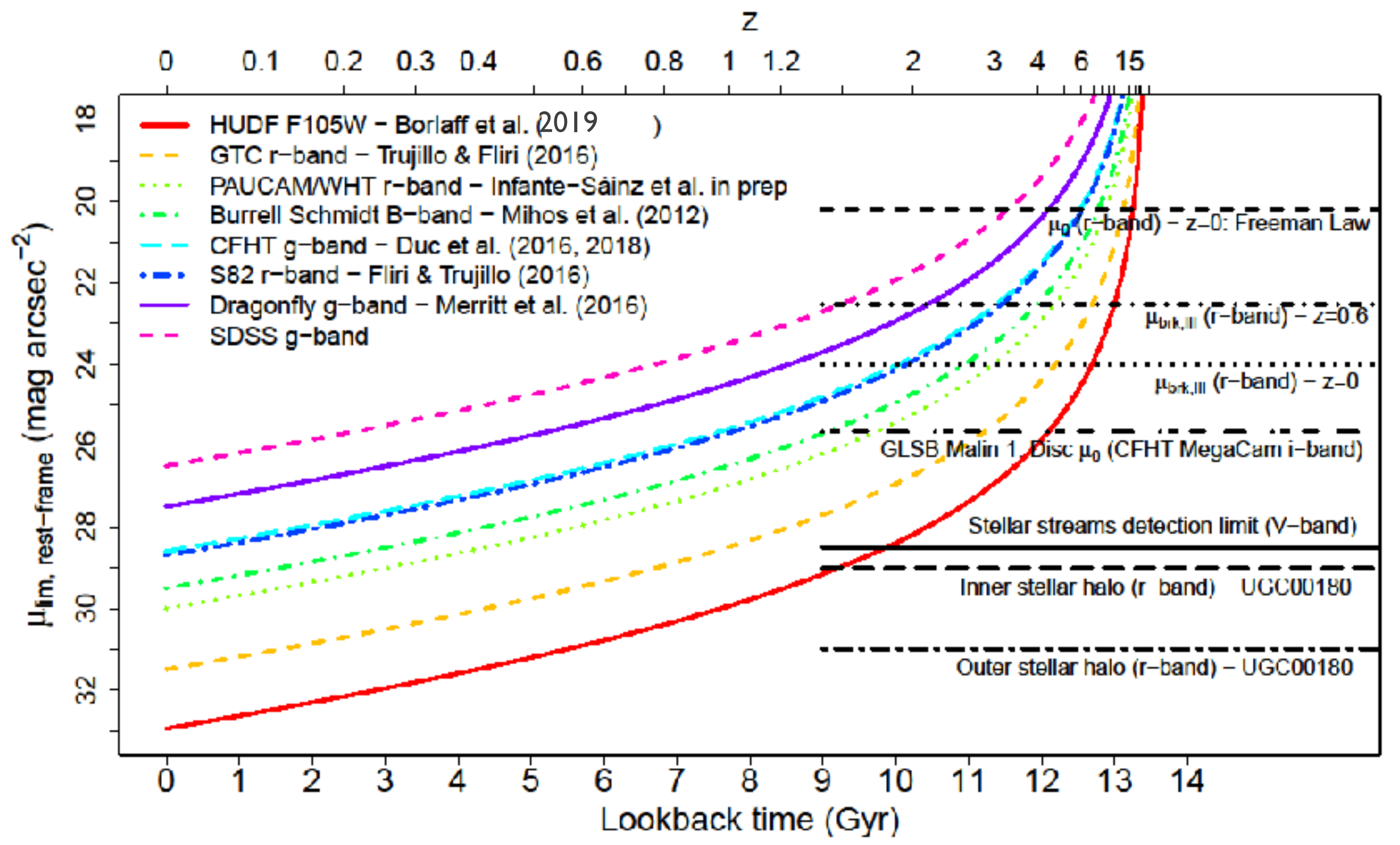


Cosmological dimming greatly reduces the observed flux with increasing redshift:

At z=0.6, (6.3 Gyr ago) we need to reduce the noise by a factor ~ 6 – 7 in intensity.
This is 2 magnitudes deeper to detect the same structure!

Ho
We
Ob

1)
2)
3)
4)



z
0 0.1 0.2 0.3 0.4 0.6 0.8 1 1.2 2 3 4 6 15
HUDF F105W − Borlaff et al. (2019)
GTC r−band − Trujillo & Fliri (2016)
PAUCAM/WHT r−band − Infante−Sáinz et al. in prep
Burrell Schmidt B−band − Mihos et al. (2012)
CFHT g−band − Duc et al. (2016, 2018)
S82 r−band − Fliri & Trujillo (2016)
Dragonfly g−band − Merritt et al. (2016)
SDSS g−band
μ0 (r−band) − z=0: Freeman Law
μbrk,III (r−band) − z=0.6
μbrk,III (r−band) − z=0
GLSB Malin 1, Disc μ0 (CFHT MegaCam i−band)
Stellar streams detection limit (V−band)
Inner stellar halo (r−band) − UGC00180
Outer stellar halo (r−band) − UGC00180
μlim, rest−frame (mag arcsec−2)
18 20 22 24 26 28 30 32
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14
Lookback time (Gyr)

Three main reasons to study the low Surface brightness Universe

1) Dim structures in the near Universe

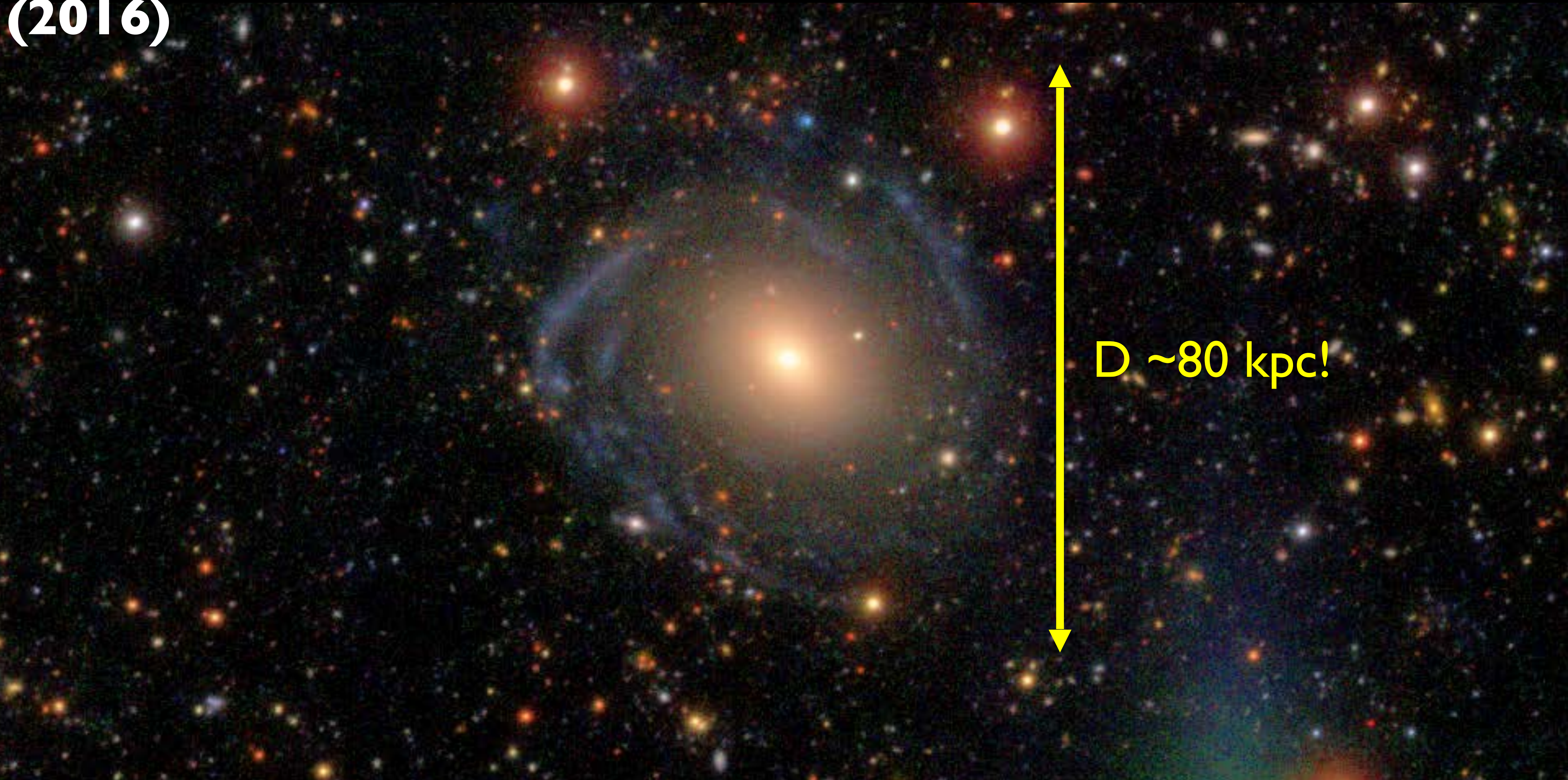
   Dust filaments, ultra diffuse galaxies, tidal tails, stellar halos

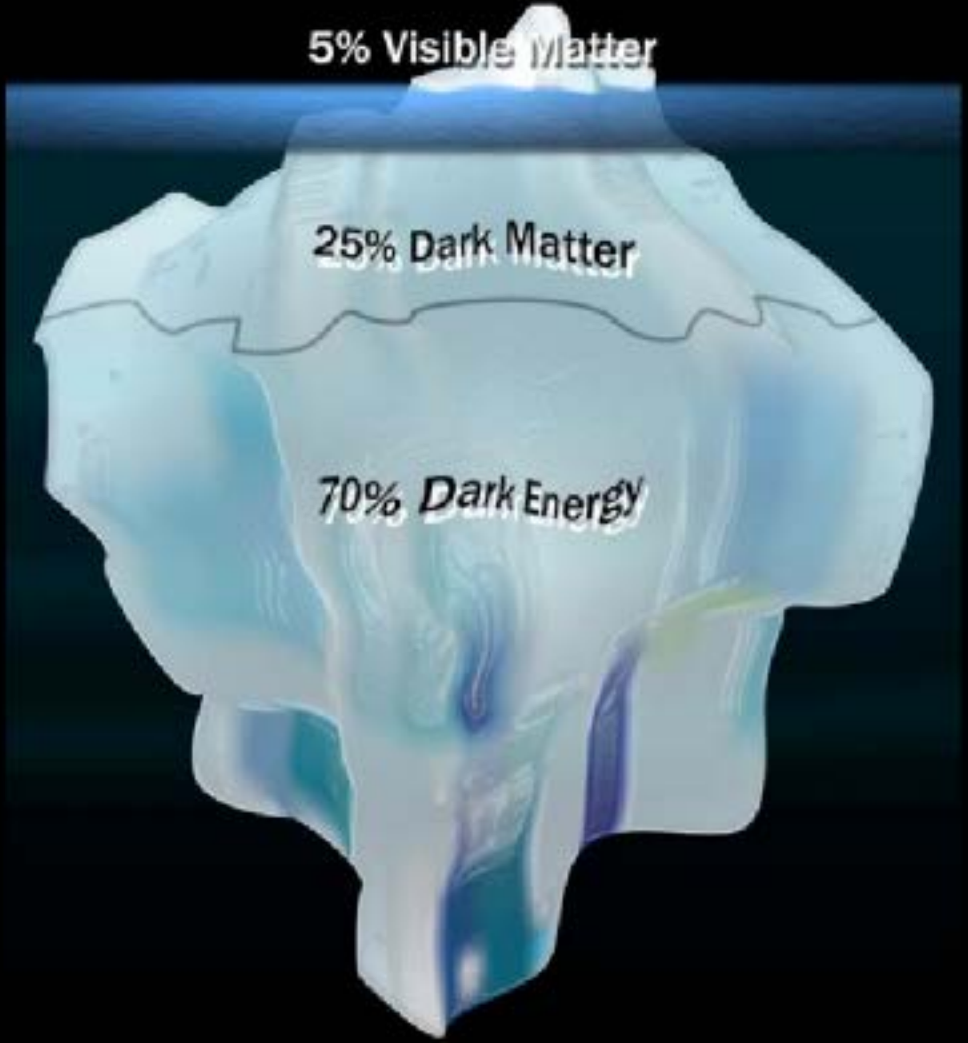
2) Not-so-dim structures at high-z: Cosmological dimming

   Formation of galactic discs and stellar haloes

3) "Because it is there": New classes of objects & structures

UGC1382: A Giant Low Surface Brightness Galaxy - Lea et al (2016)

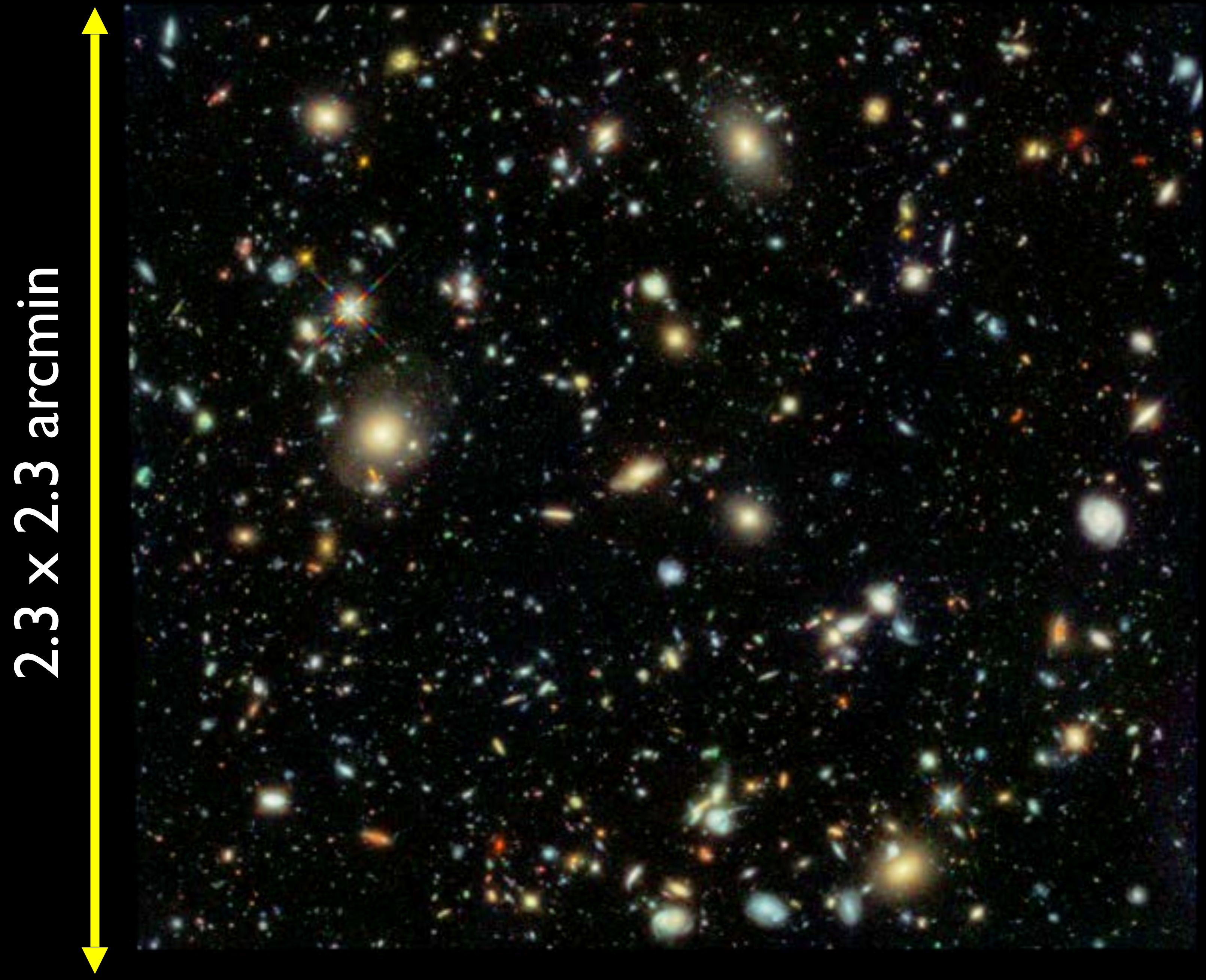




[...] galaxies are like icebergs and what is seen above the sky background may be no reliable measure of what lies underneath.

M. Disney (1976)

How galactic discs evolve with time? The Hubble Ultra Deep Field



The deepest image of the Universe ever done

F105W HST WFC3/IR

μ_{lim} = 33 mag arcsec^{-2}

(3σ in 10x10 arcsec^2 boxes)

Multi-wavelength ancillary data. (VLA, ALMA, MUSE, Spitzer, HST/ACS, HST/UVIS Chandra, XMM-Newton...)

Main objective:

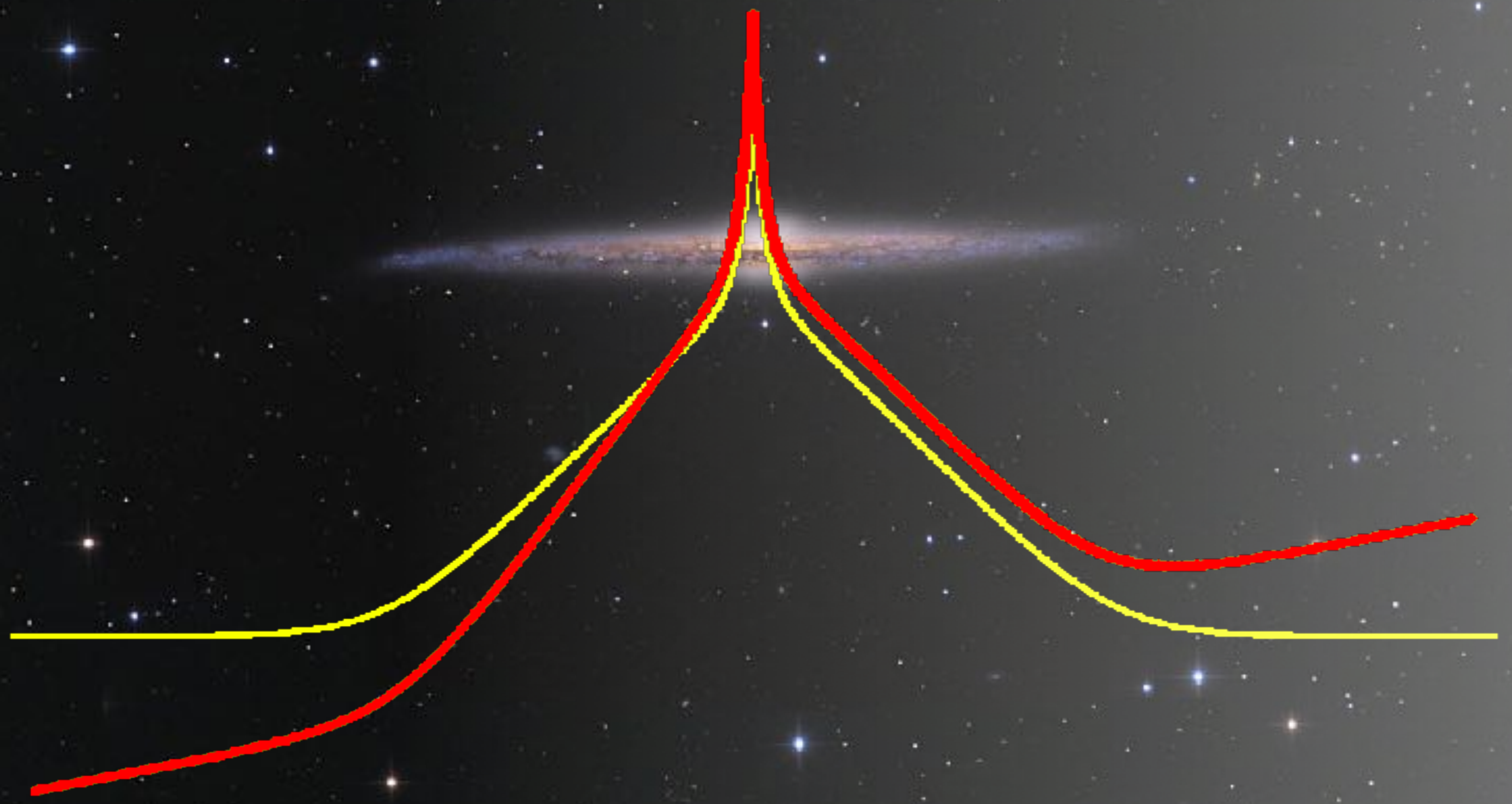
Detect galaxies at *z ~ 8 - 10.*

HUDF12 – Koekemoer+ 2012

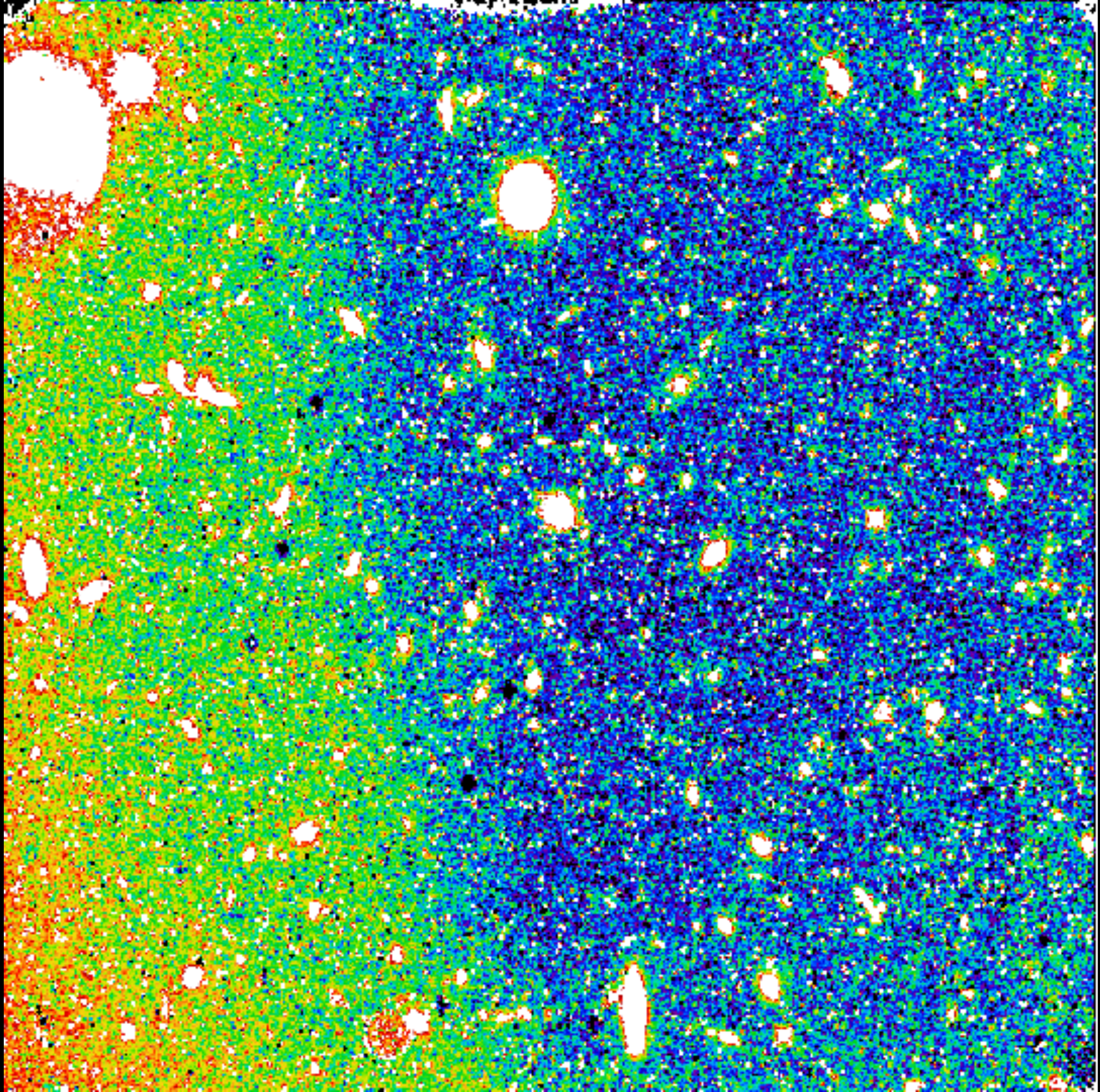
XDF - Illingworth+2013

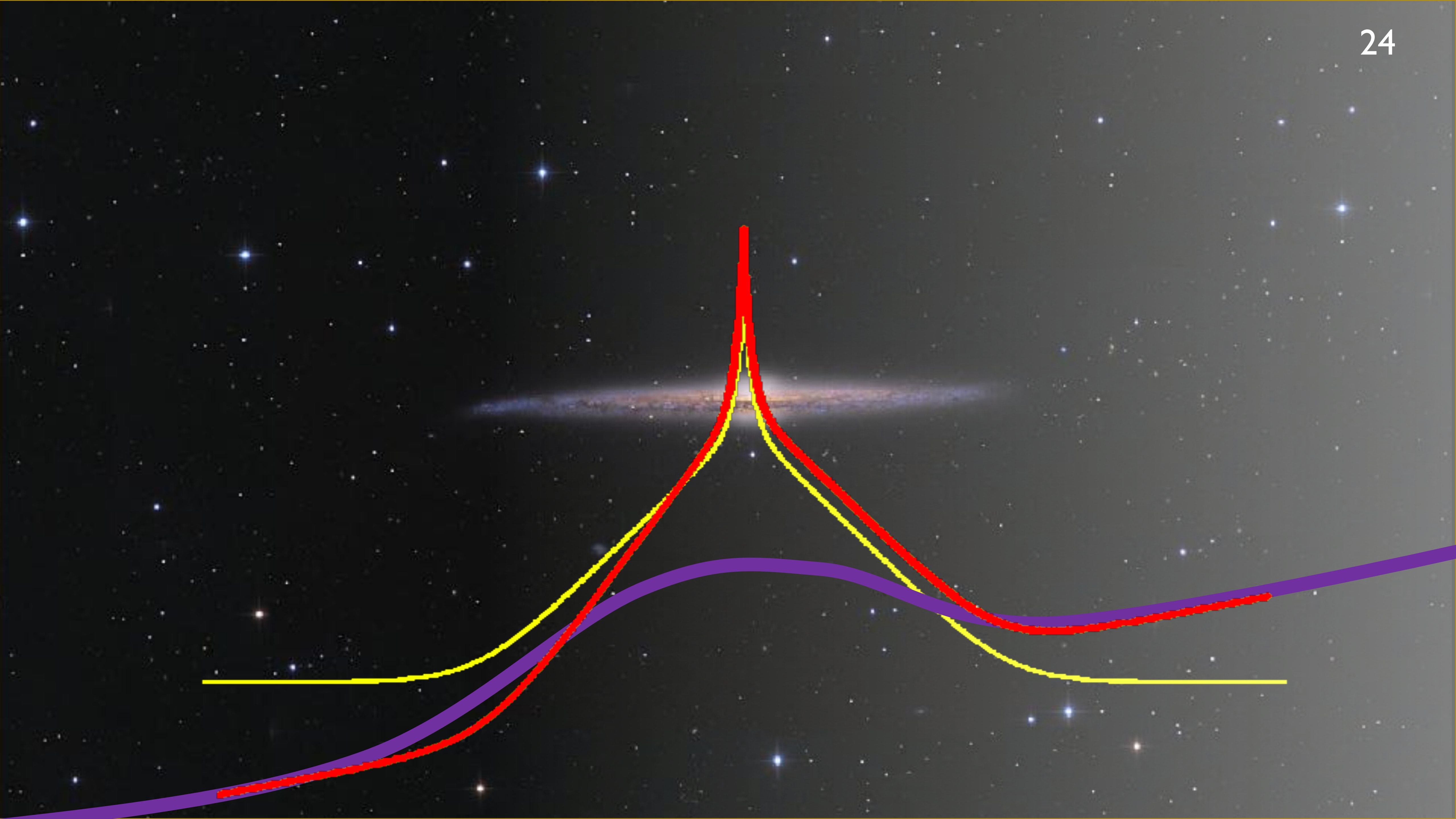
Real surface brightness profile

Observed surface brightness profile
(with gradient contamination)

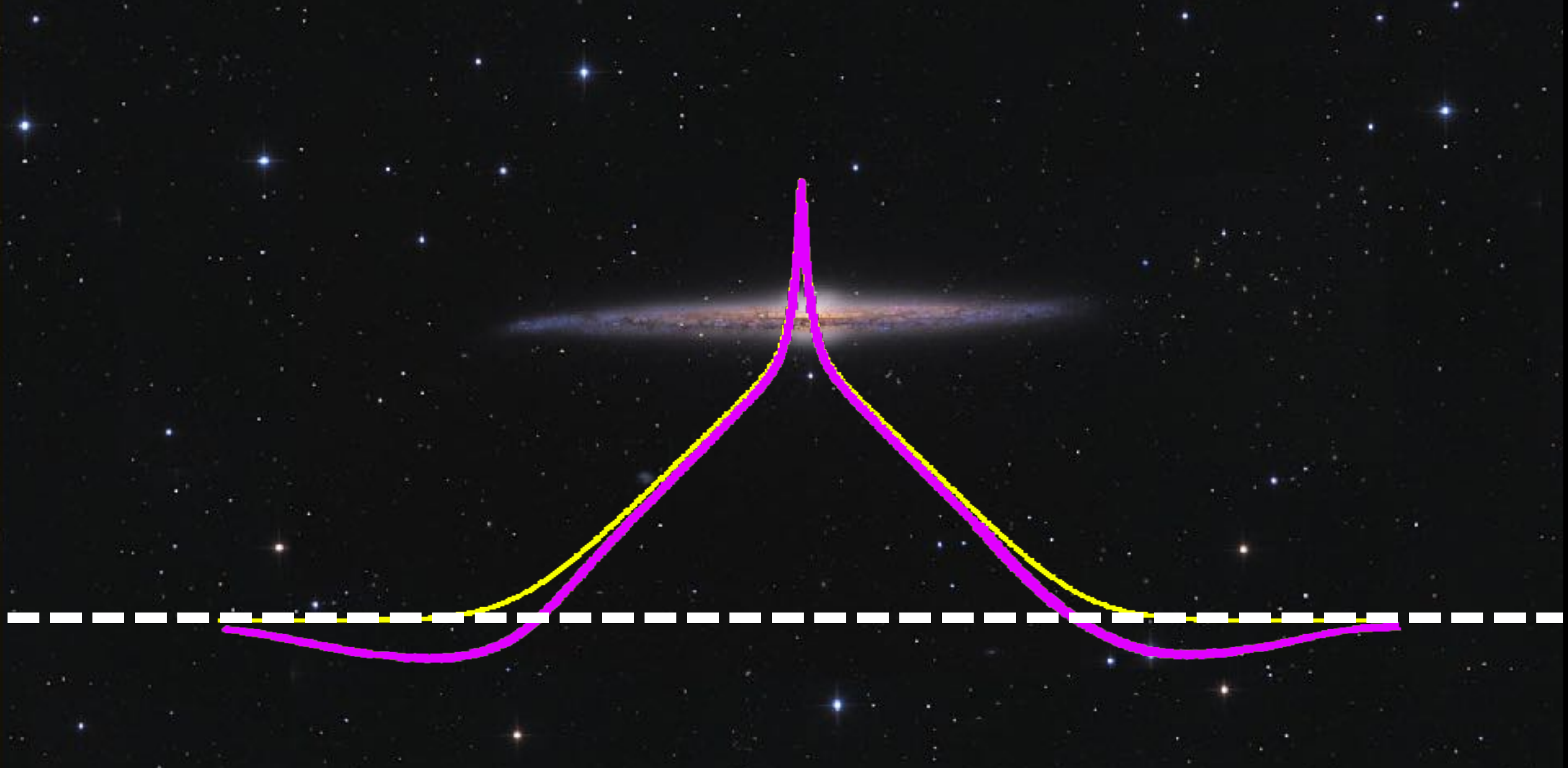



SEBASTIANSZ





Sky noise limit ------

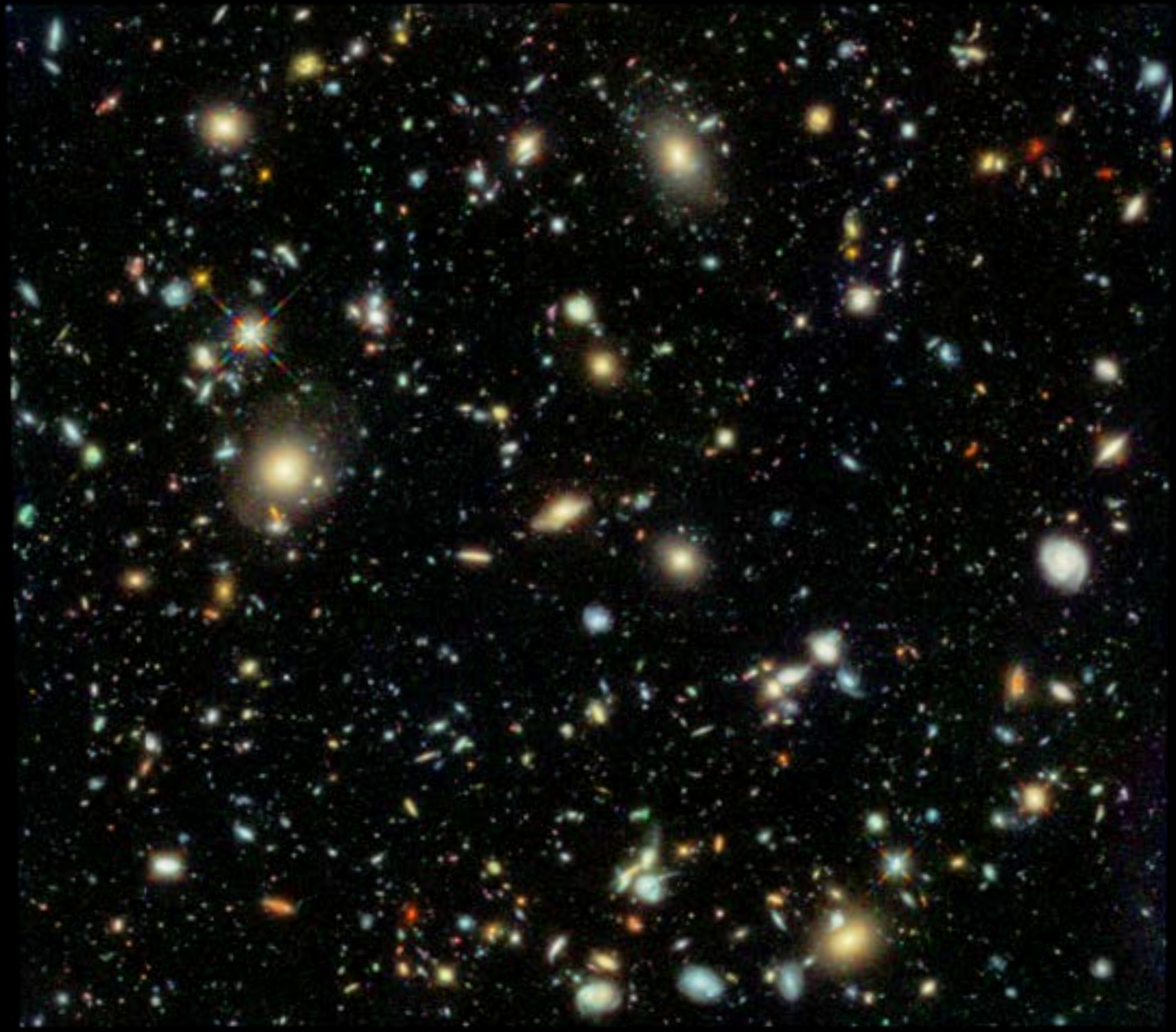


Sky oversubtraction is a common issue in most surveys

Hyper Suprime-Cam Subaru Strategic Program Data Release 1
Aihara et al. (2018)

The Hubble Ultra Deep Field - XDF (2014)

2.3 x 2.3 arcmin



Dithering pattern:
1) < 0.05 arcsec
2) ~ 1-3 arcsec

Most images were taken with the same position angle.
Sub-optimal observing strategy for low-surface brightness structures

1) Cosmetic defects
2) Systematic gradients
3) Flat field residuals

Solution: Removal of residual gradients by 2D fitting and subtraction.

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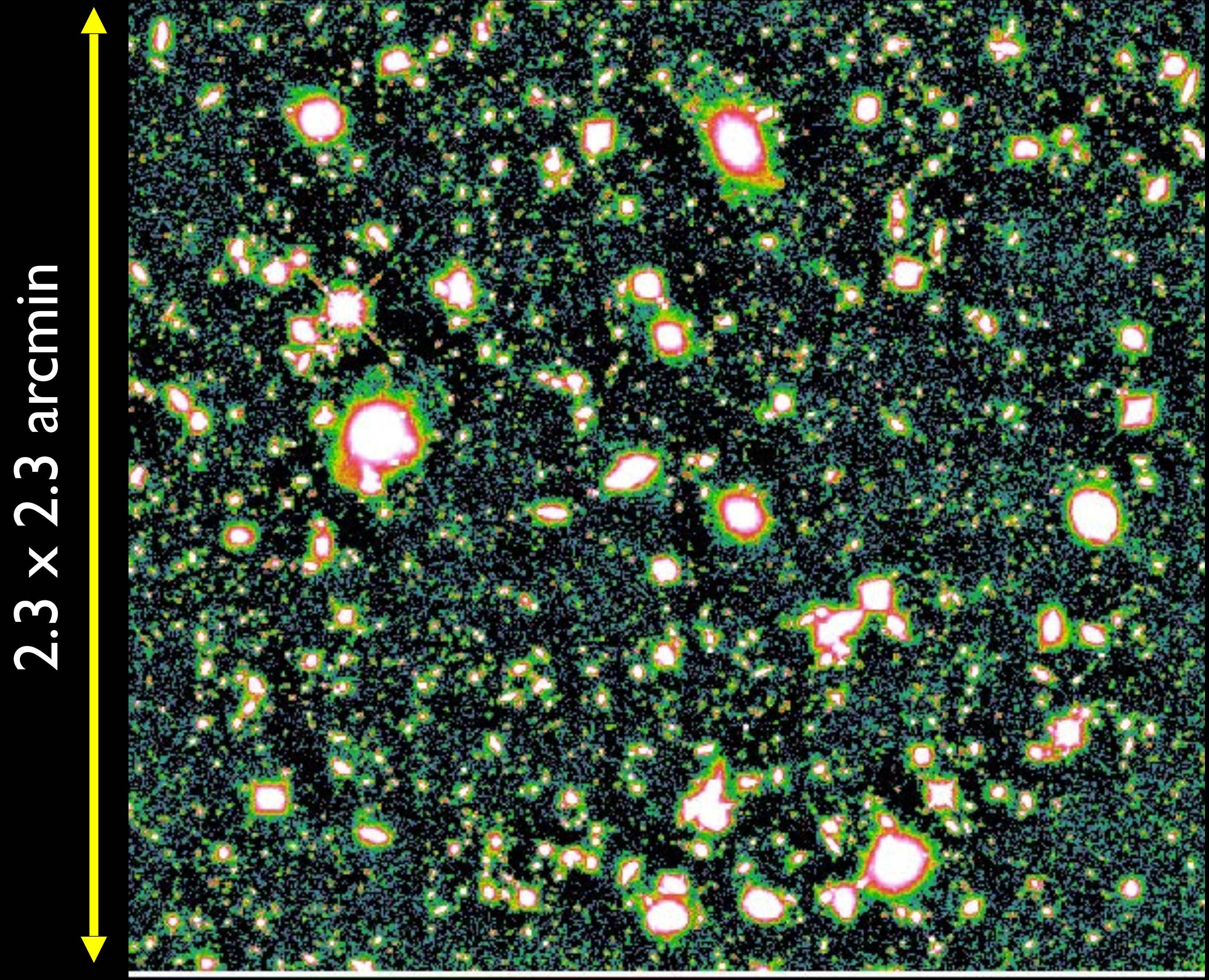

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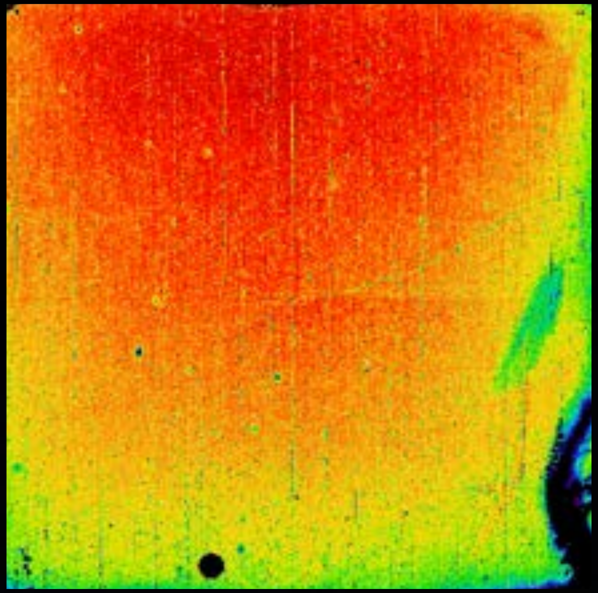
Looking for the missing light of the HUDF

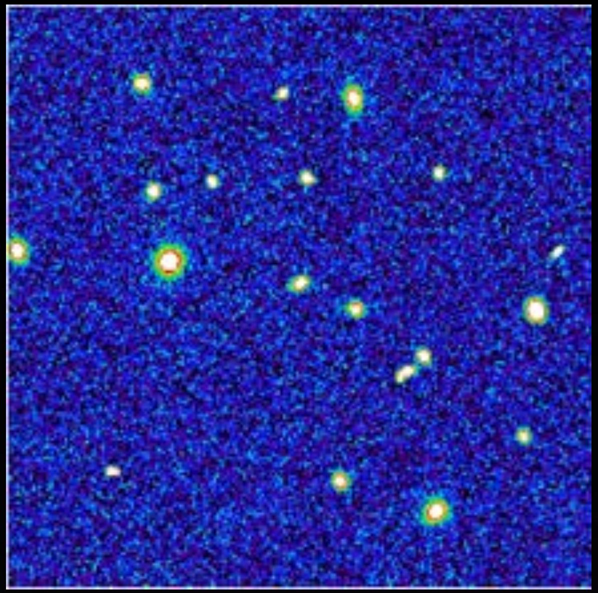
Fact: There was no current reduction available for WFC3/HUDF data dedicated to the low-surface brightness features of the largest objects.

How can we improve the reduction? Key points:

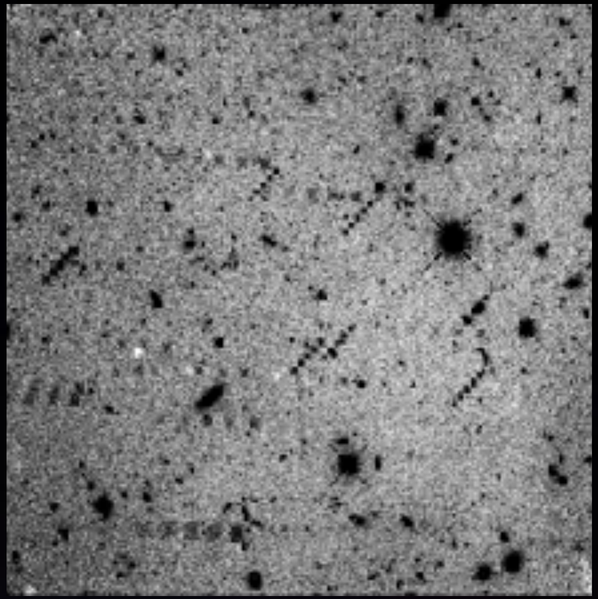
1) Flat fielding



2) Sky correction



3) Persistence



STS-125 (14/04/2009)

Astronaut Andrew Festel on EVA while installing WFC3 on the Hubble Space Telescope

In-flight calibration of HST – Sky flat-fielding

The flat fields of HST/WFC3 are a combination of several solutions:

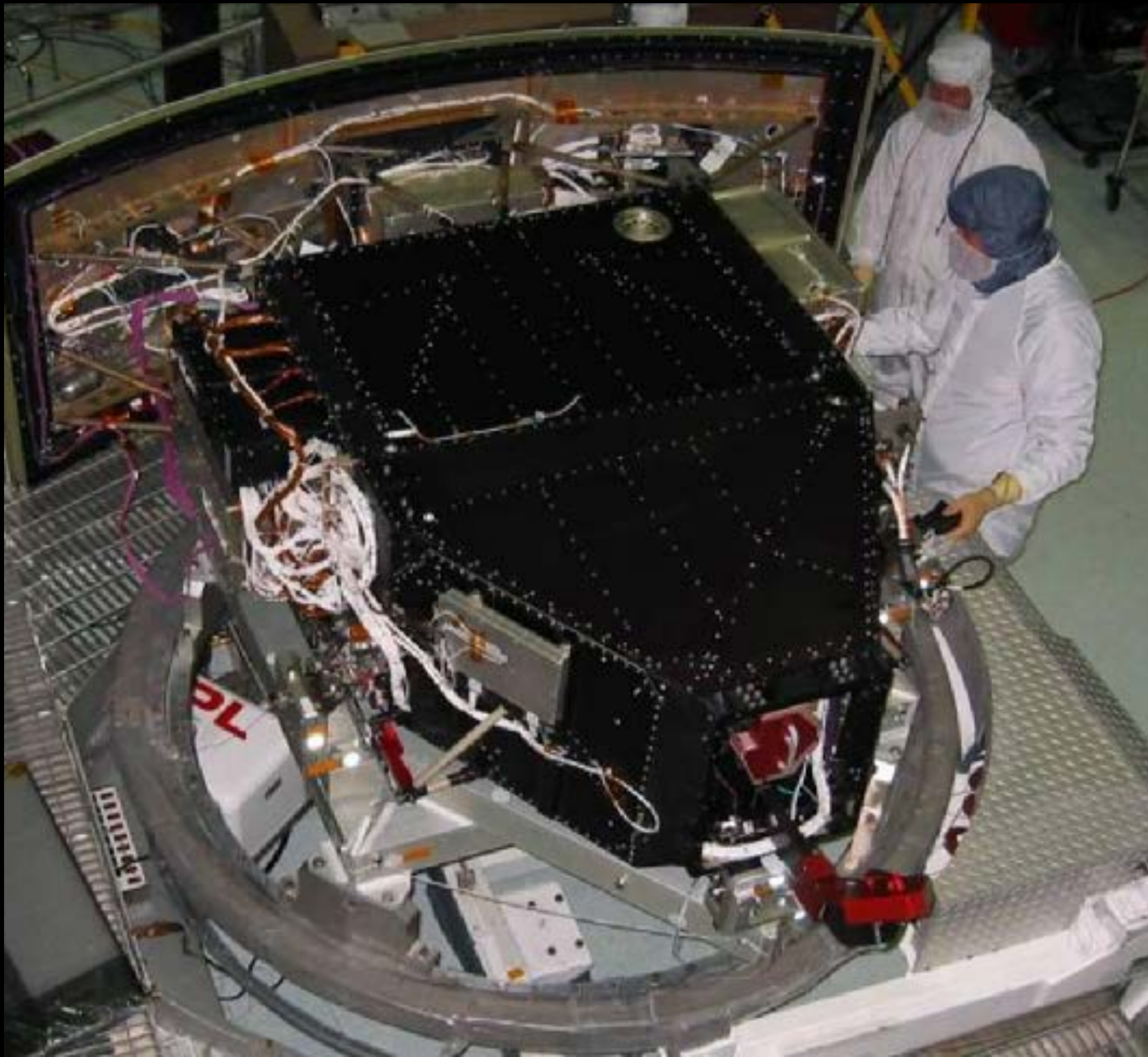
1) Ground-flat fields (LP flats) calculated before launch in a simulator (CASTLE) +

2) Second order correction calculated as a combination of images from *all* filters (delta sky flats Pirzkal et al 2011).

Main problems:

1) Second order correction

2) No variation (grey flats)



Flat fielding – Why time dependent?

Vacuum – (10^-11 atm): Outgassing of molecules + deposit

Atmospheric aerosol particles: Responsible for the appearance of the WFC3/IR blobs

O - Atomic oxygen: Produced by UV radiation. Cause degradation of internal and external surfaces. (Neutral particles in space also cause drag forces and altitude loss)

UV radiation: Damages polymers and darkens materials

Ionizing radiation: Cosmic rays (GC or solar), solar proton events and radiation belts

WFC3/IR Snowballs: Transient emission in WFC3/IR images – Area = 40 pixels^2 . Possibly caused by alpha decay of Th232 or U238 present in orbit at ~1ppm.

Plasma (Charged ions + free electrons): Cause parasitic negative charge of surfaces.

Flat fielding – Why time dependent?

Space is a hard place to live: Micrometeoroids & space debris (Kearsley et al. 2017)

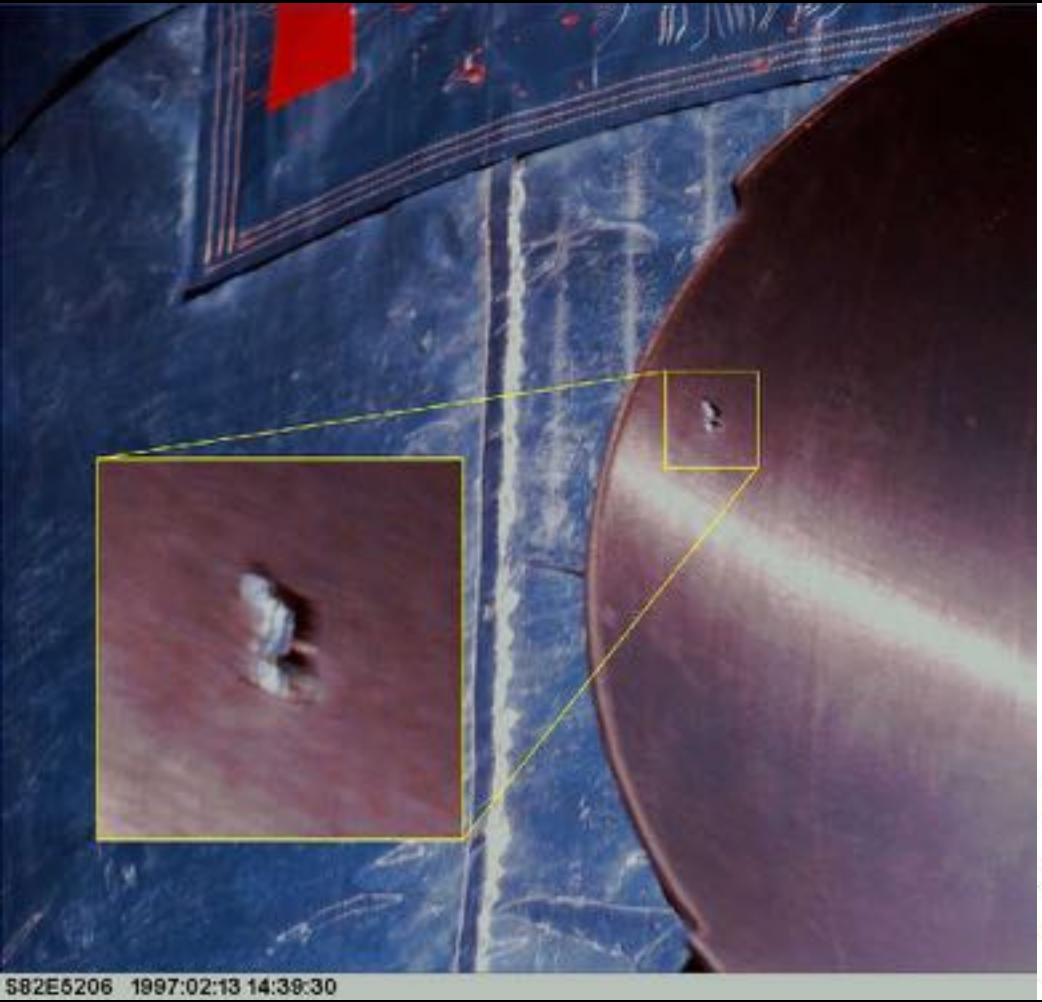


Fig. 1. The WFPC2 radiator shield wrapped in Llumalloy sheeting at the Johnson Space Center (NASA-JSC), locations of the large craters indicated by arrows.

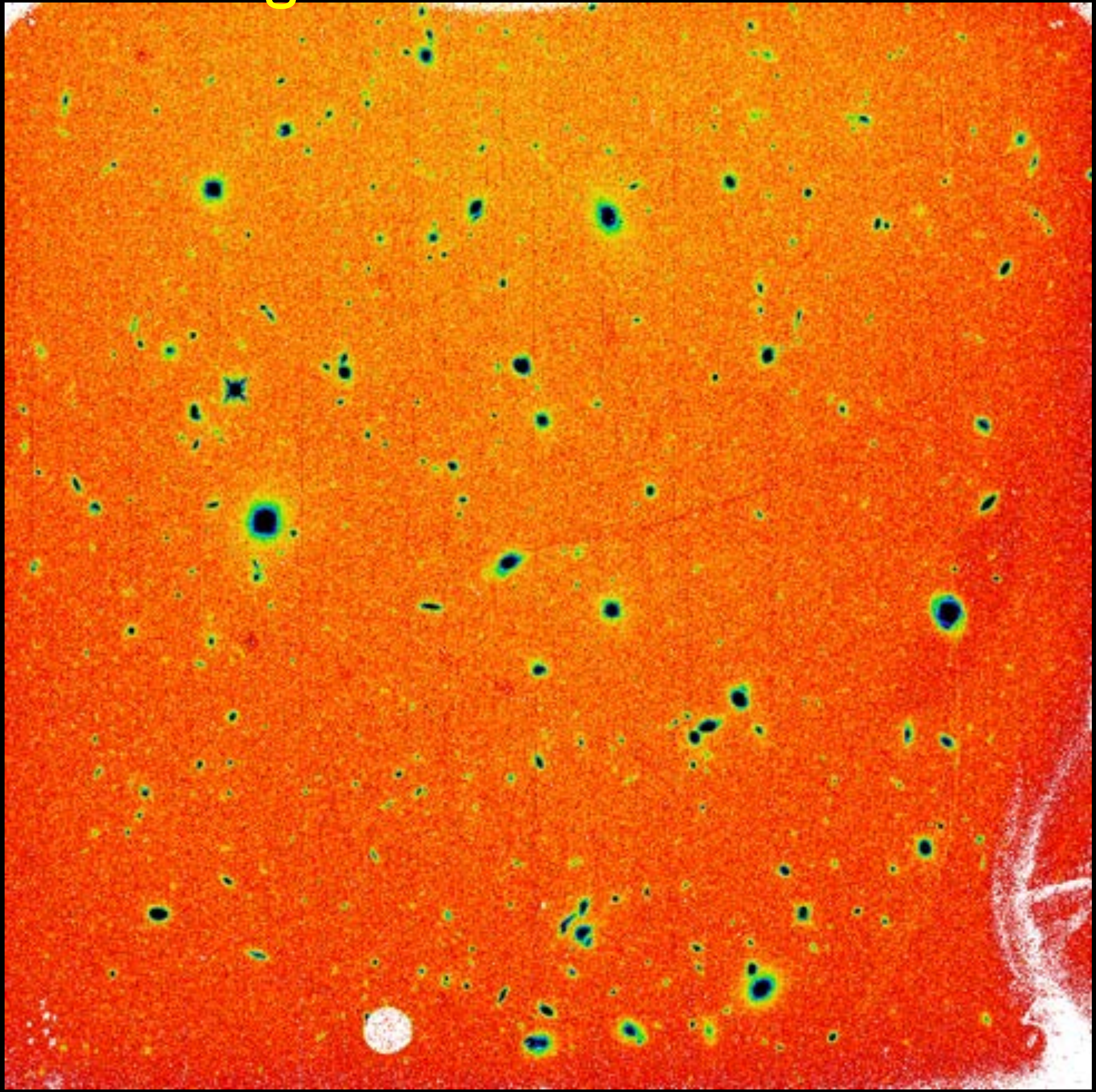
In-flight calibration of HST – Sky flat-fielding

Our approach:

1) Identify valid sky-flat images (GOODS-N, GOODS-S, AEGIS, COSMOS, ...)

2) Visual classification of images for sky-flat (+2000 images per filter) and masking of sources (GNU/Noisechisel).

3) Normalization + combination via robust statistics (bootstrapping + MonteCarlo simulations).
Hard computational effort.



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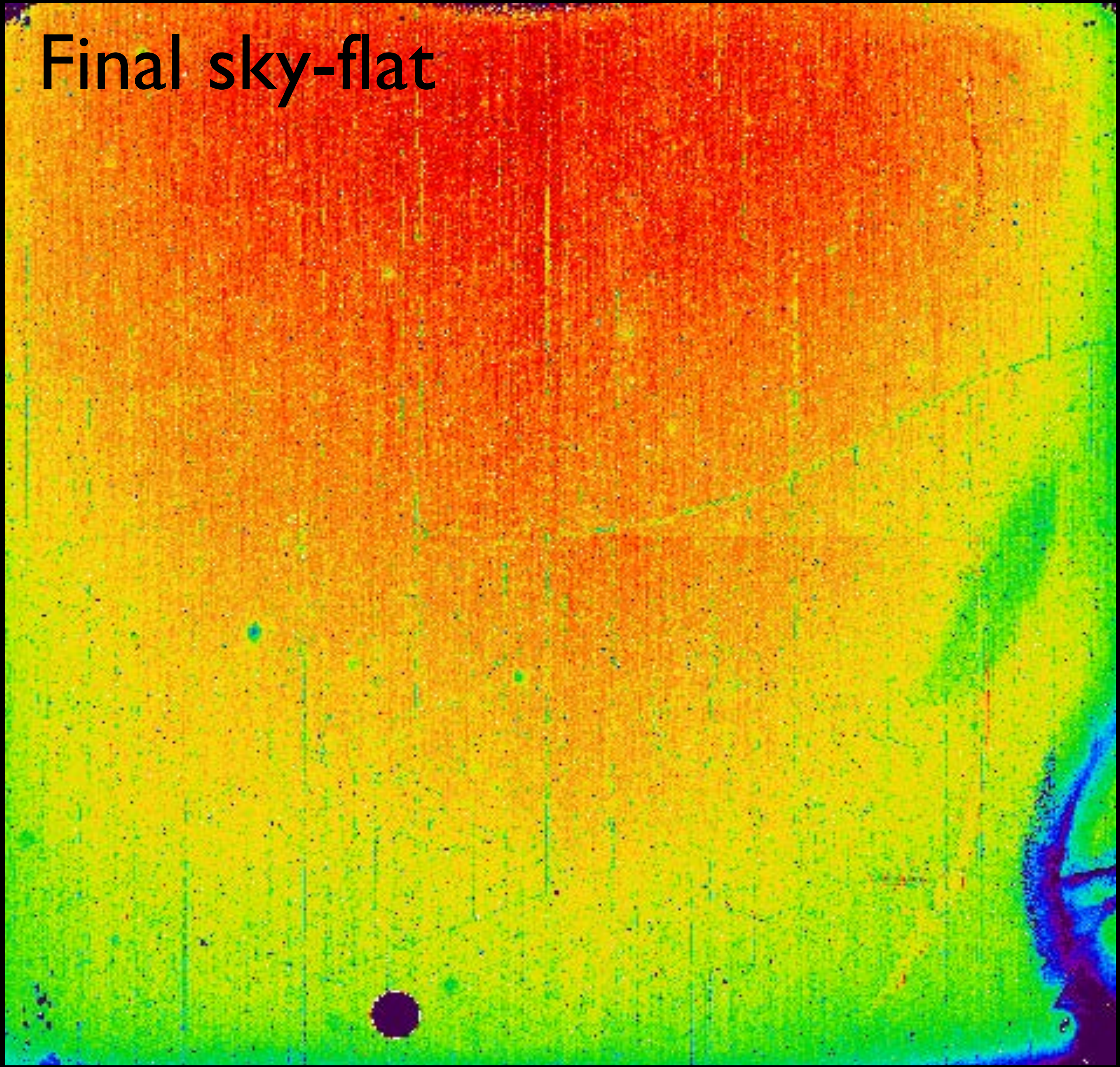
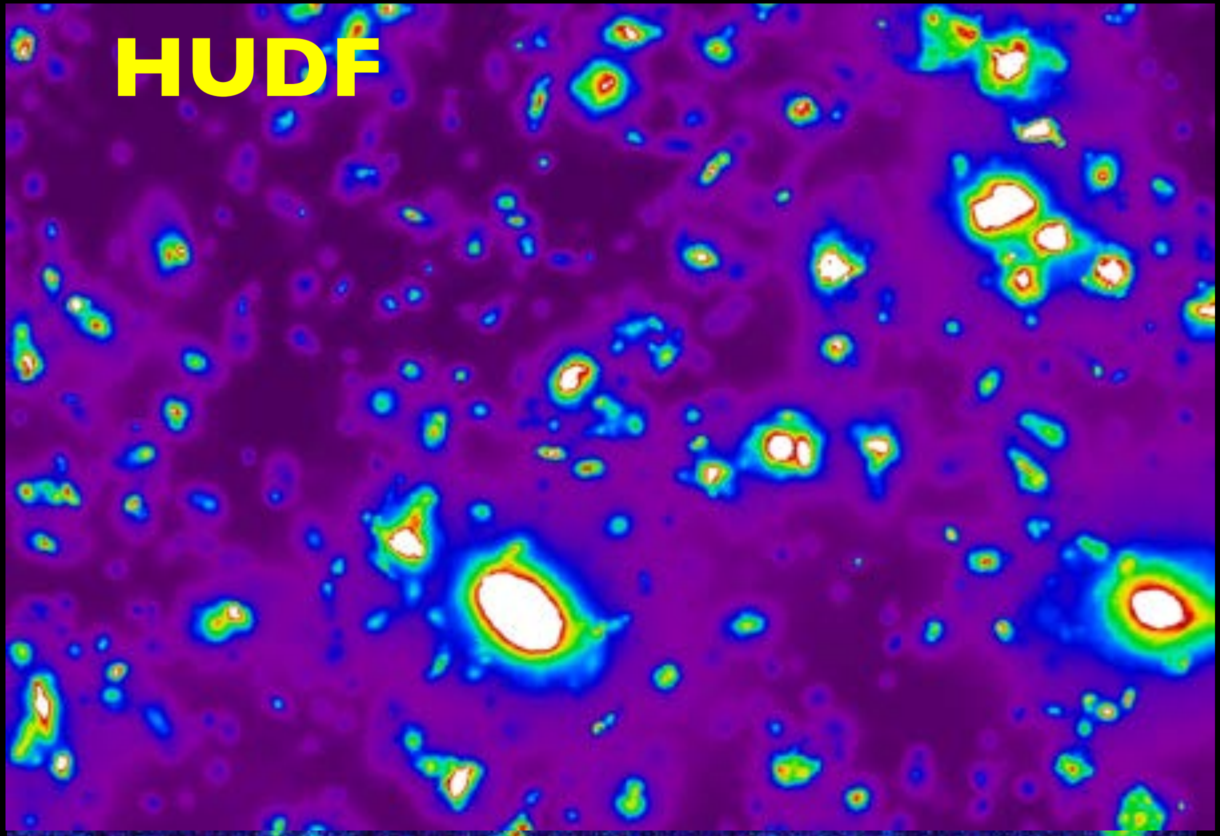


Sky substraction

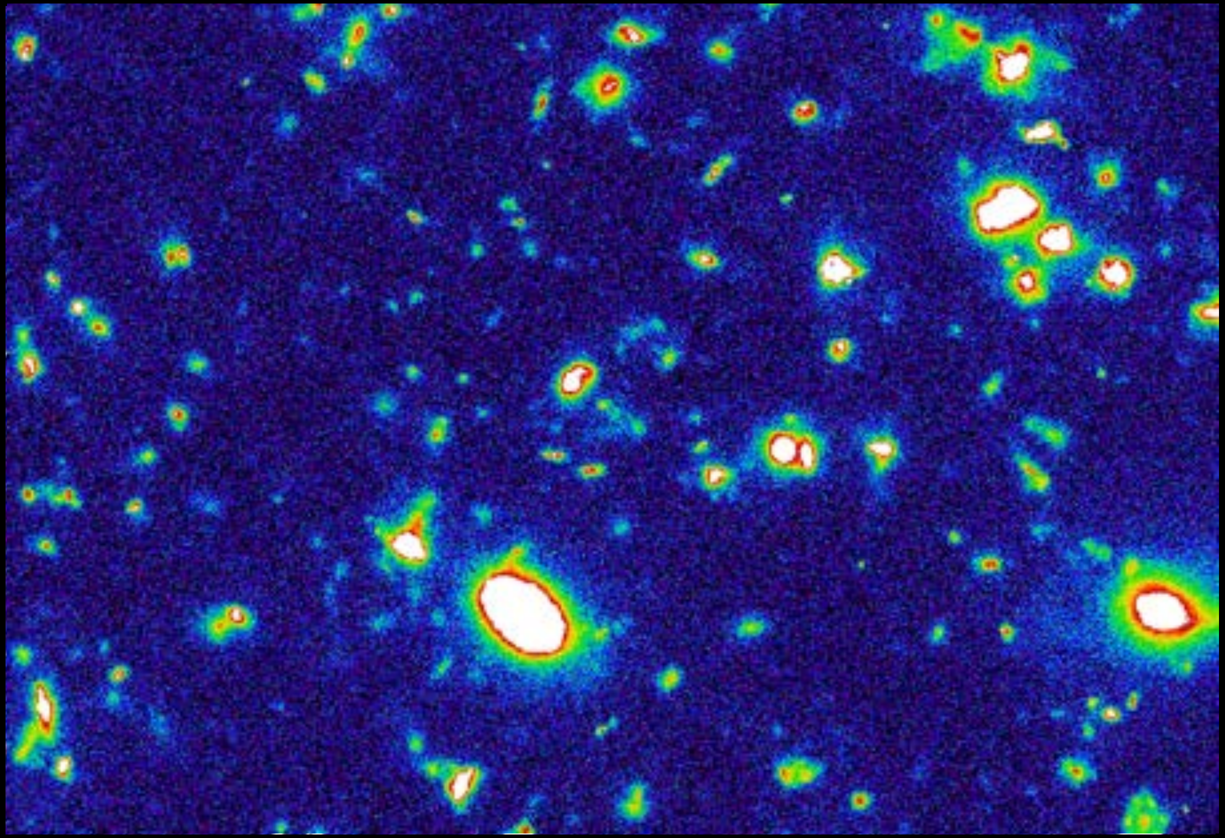
Sigma clipping methods fail dealing with low-surface brightness biases (extended haloes, MW dust). We need robust sky-measures

Test: Benchmark of different masking methods using simulated observations

Illustris simulation



Noised simulation



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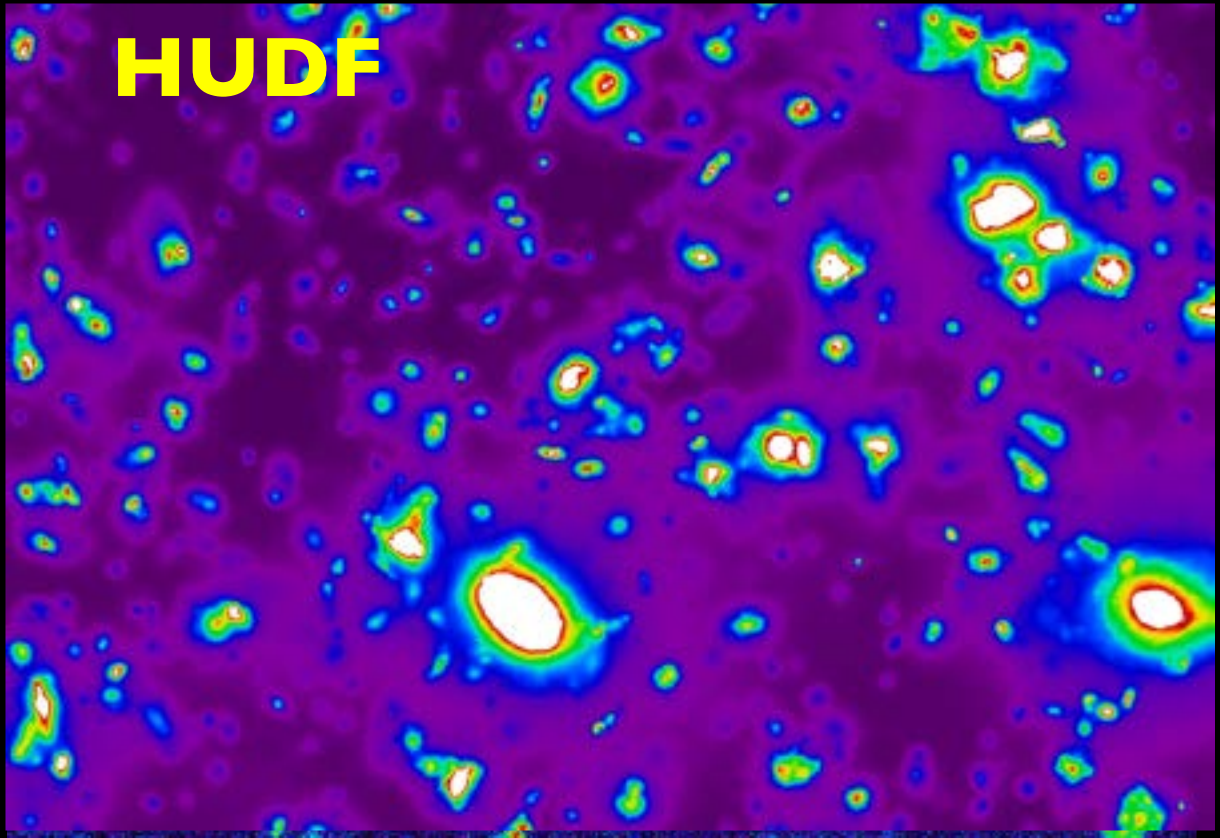
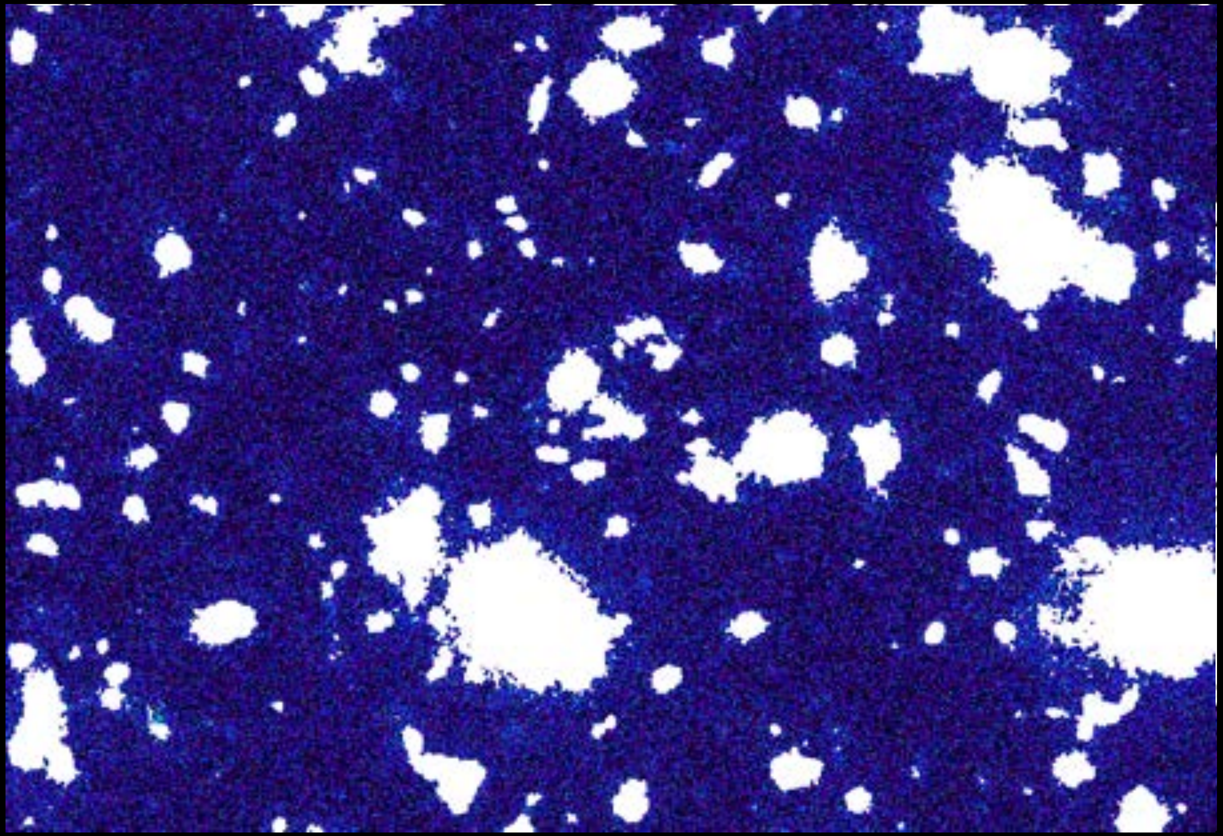


SExtractor mask



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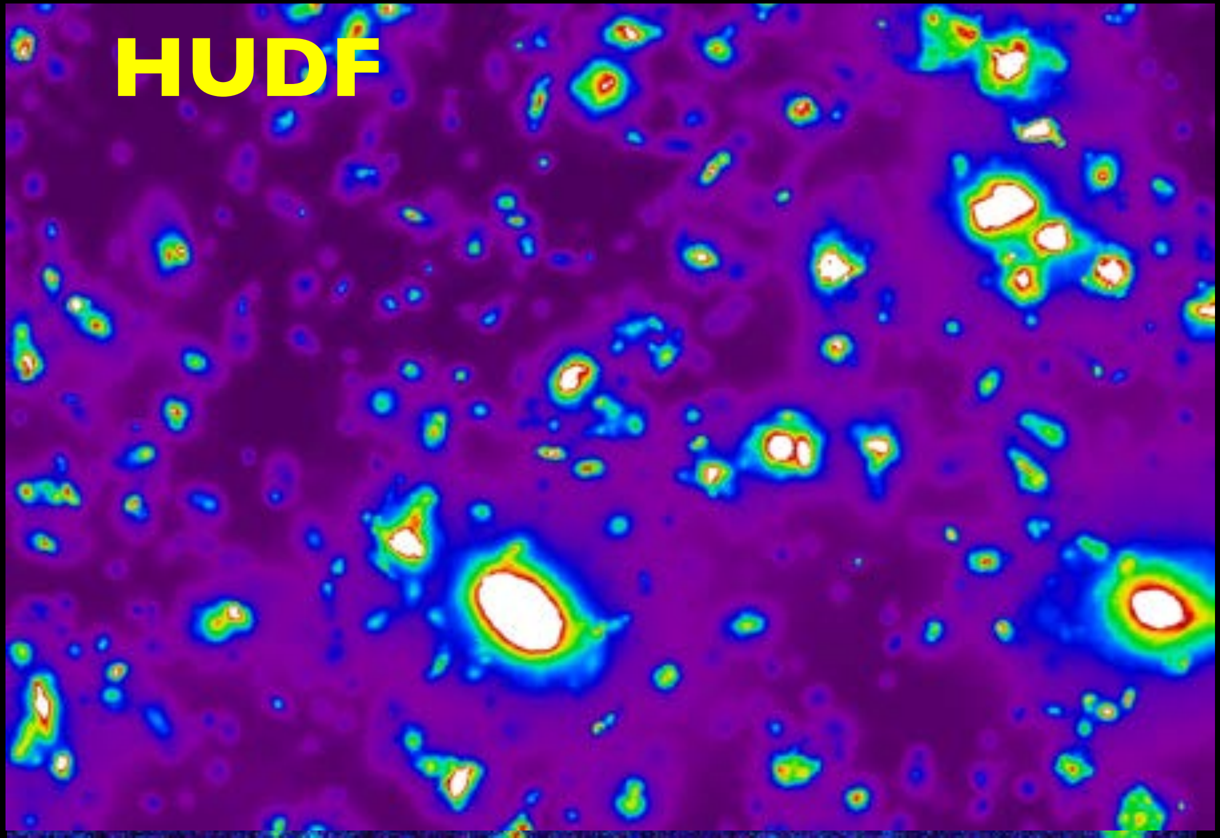
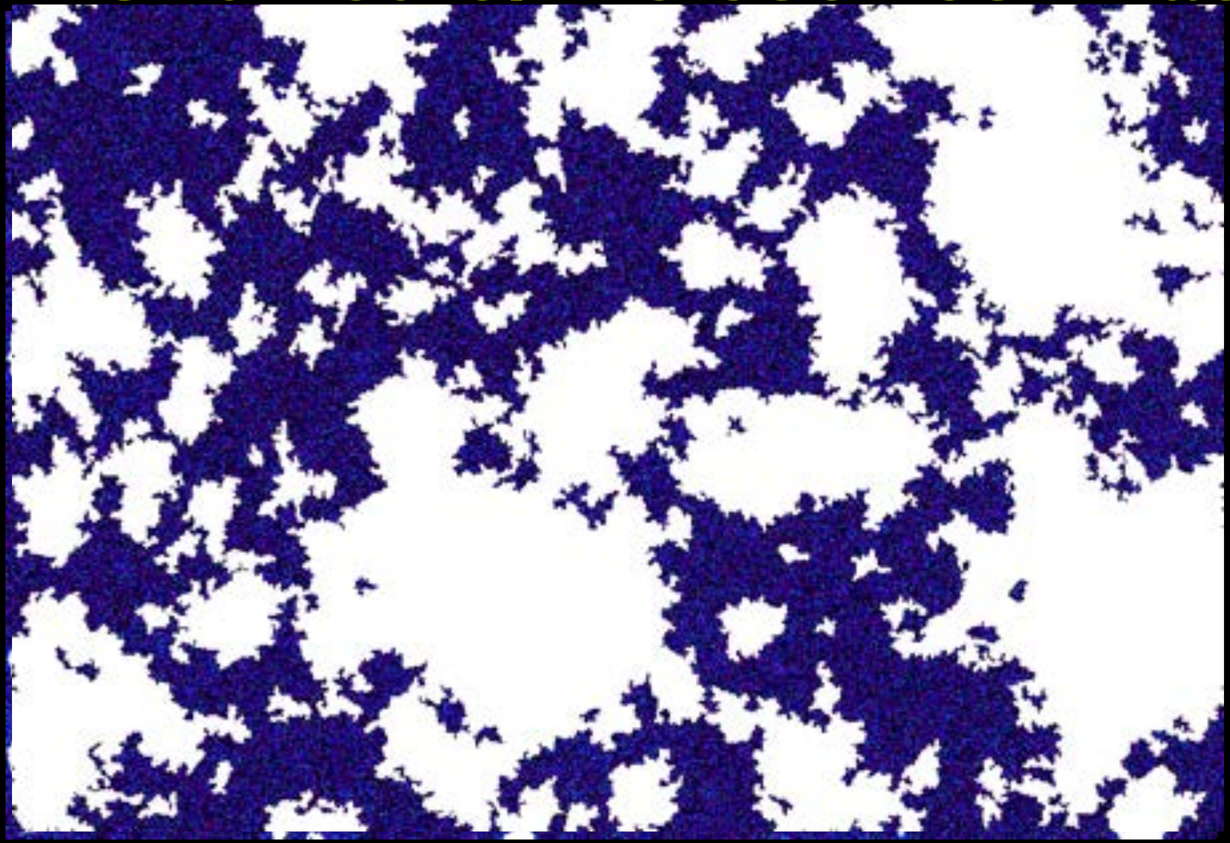


GnuAstro/Noisechisel mas



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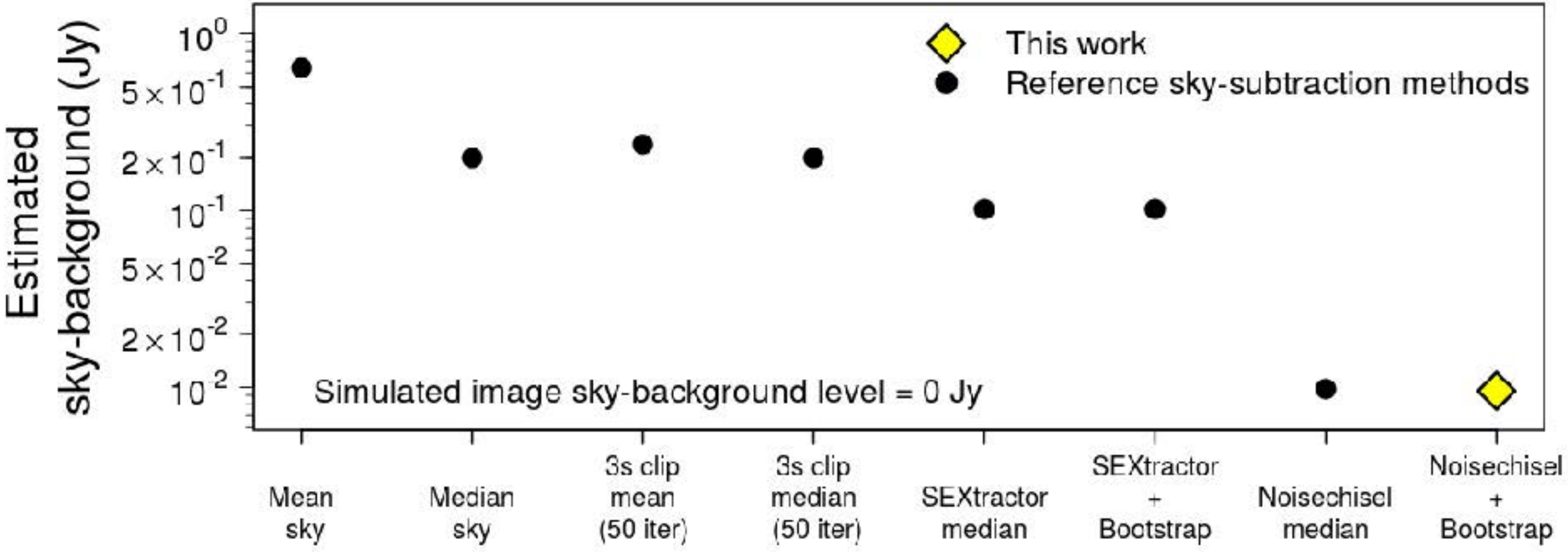
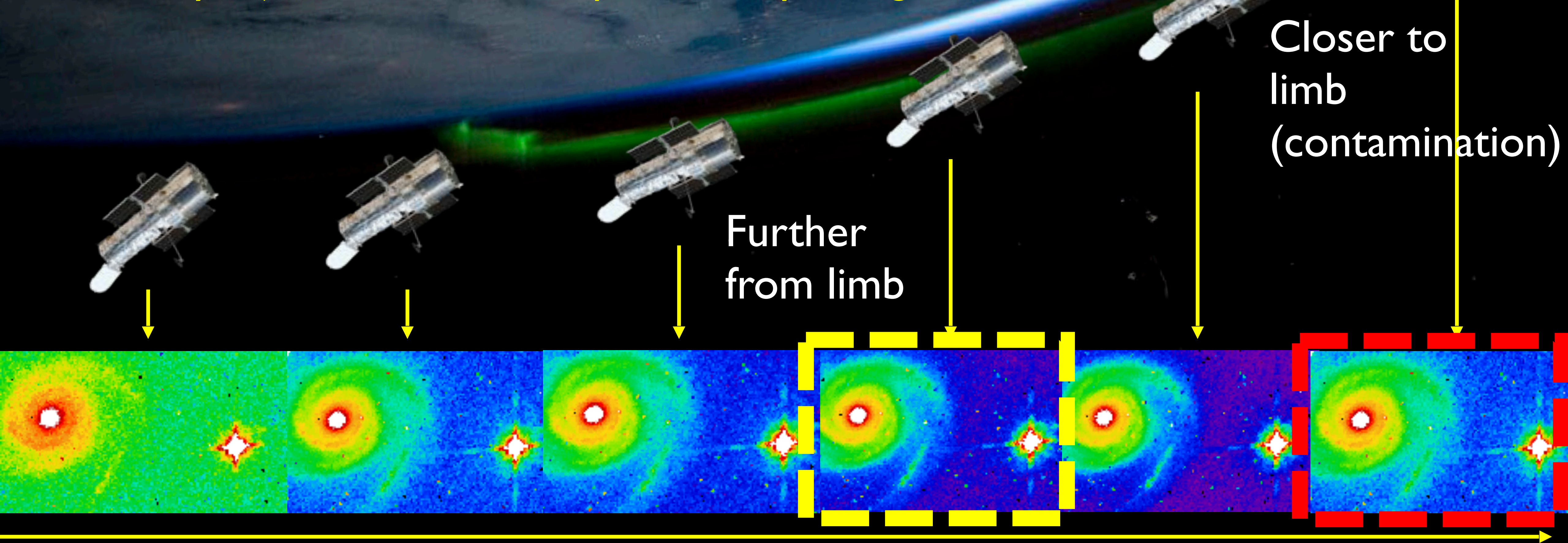


Time dependent sky background

MULTIACCUM: WFC3 default mode of observation.
Multiple non-destructive readouts of each single exposure.
Cosmic ray rejection and time dependent sky background.



Exposure time (single *flt.fits* after calibration)

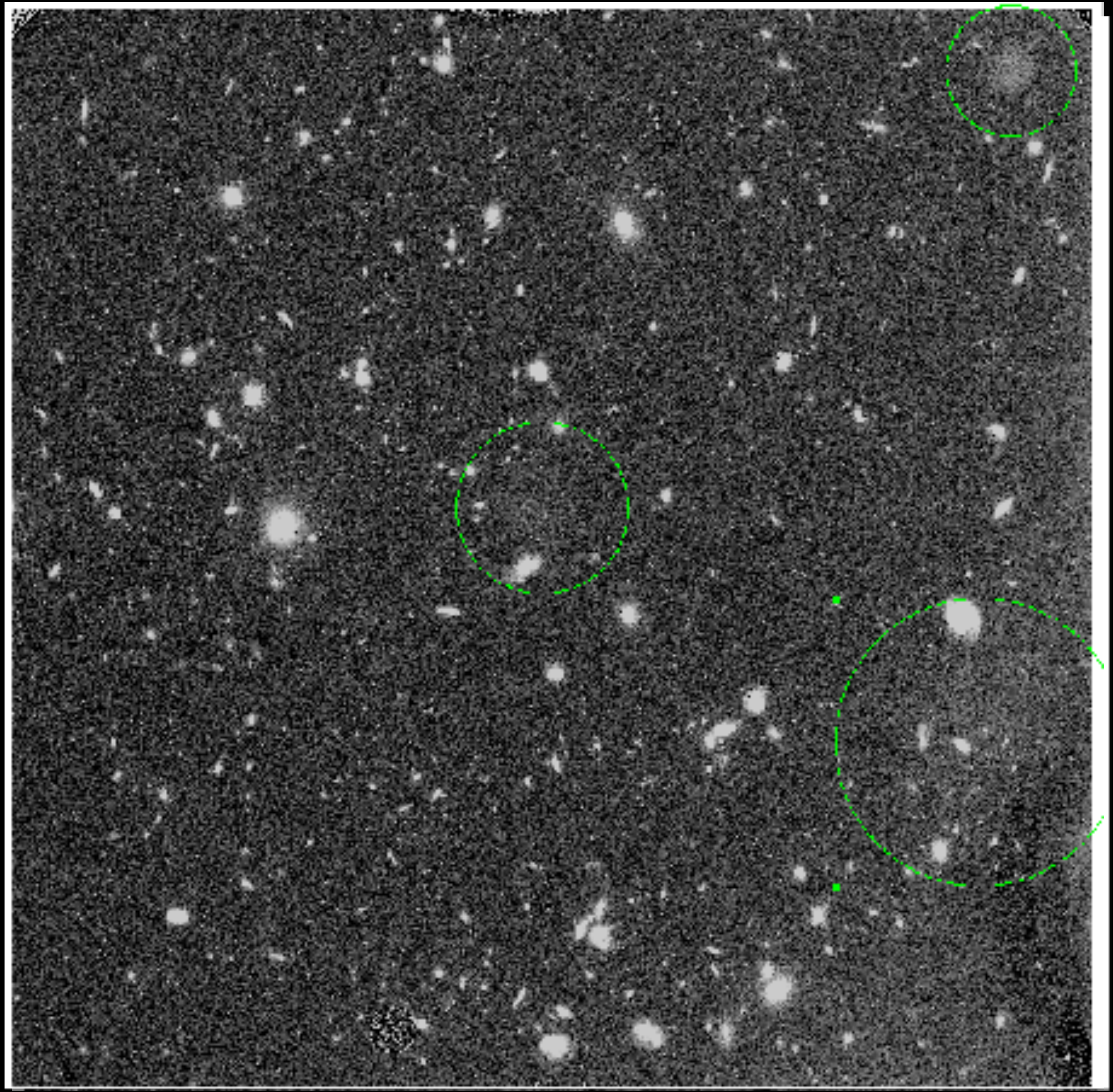
Persistence

Temporary increase in dark current after illumination. *Afterglow*

Typical from IR detectors
Can last hours or several days
Depends on:
- Time since the exposure
- Saturation level
- Time the charge sat on the detector
- Time since last exposure
- CCD type […]

Problem: HUDF/F160W is strongly affected by persistence.

Currently for HST: Model with only one image from the last 16 hours.



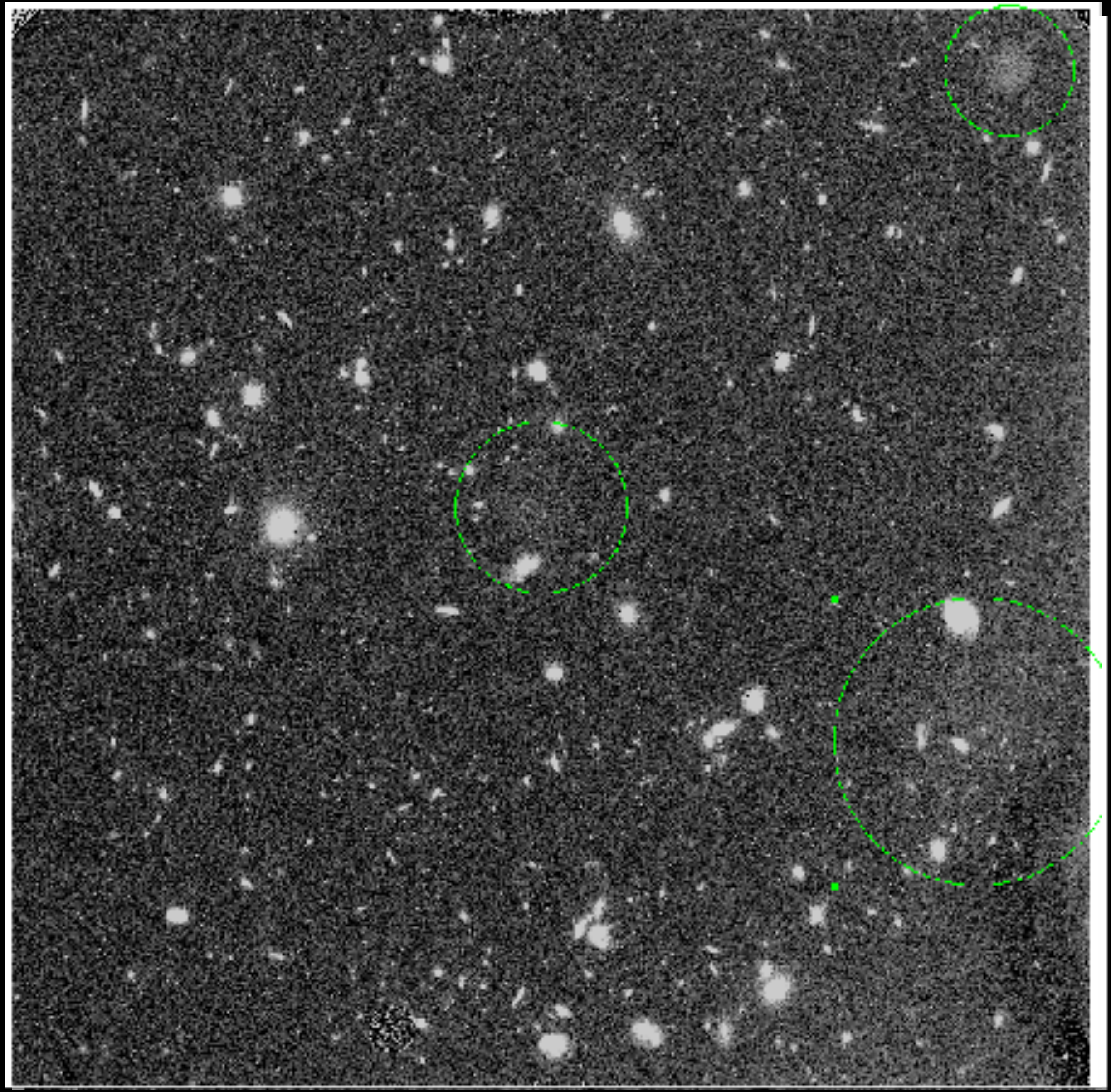
Persistence

Temporary increase in dark current after illumination. *Afterglow*

Problem 1: HUDF exposures are strongly affected by persistence.

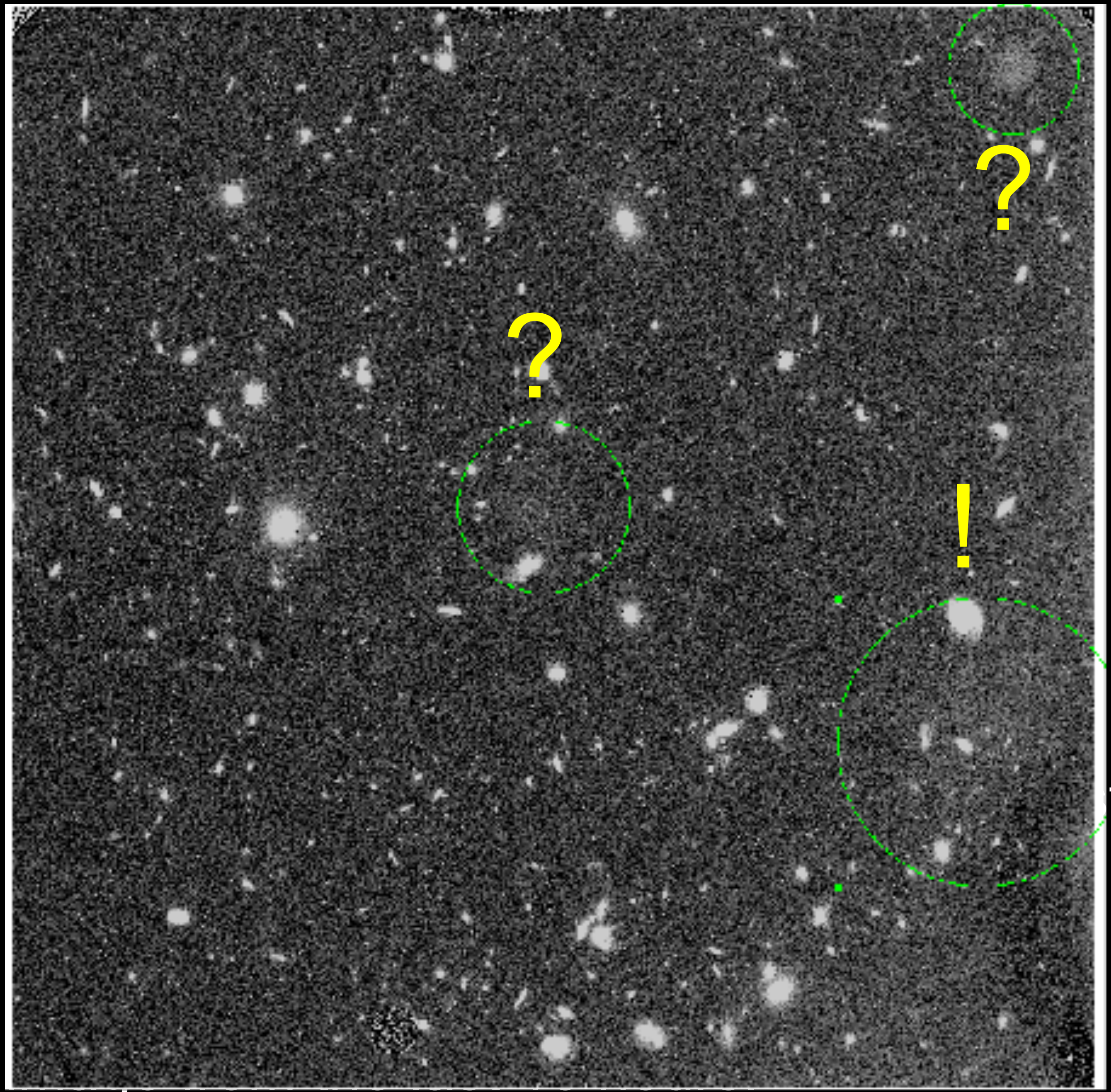
Problem 2: Each image is affected by ALL exposures taken in the previous ~96h.

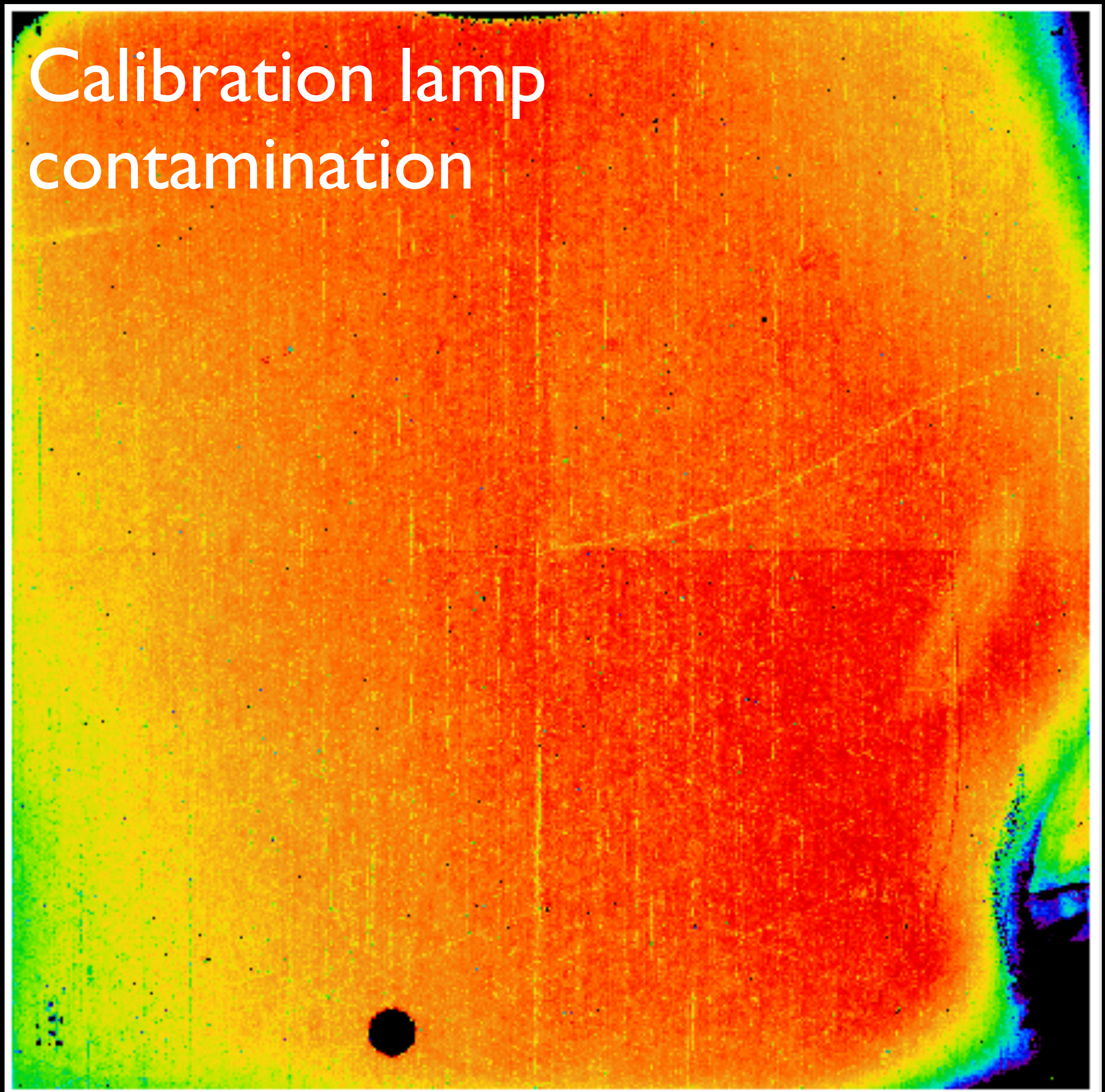
One example:
Combined contamination of one F105W exposure of the HUDF.



Persistence

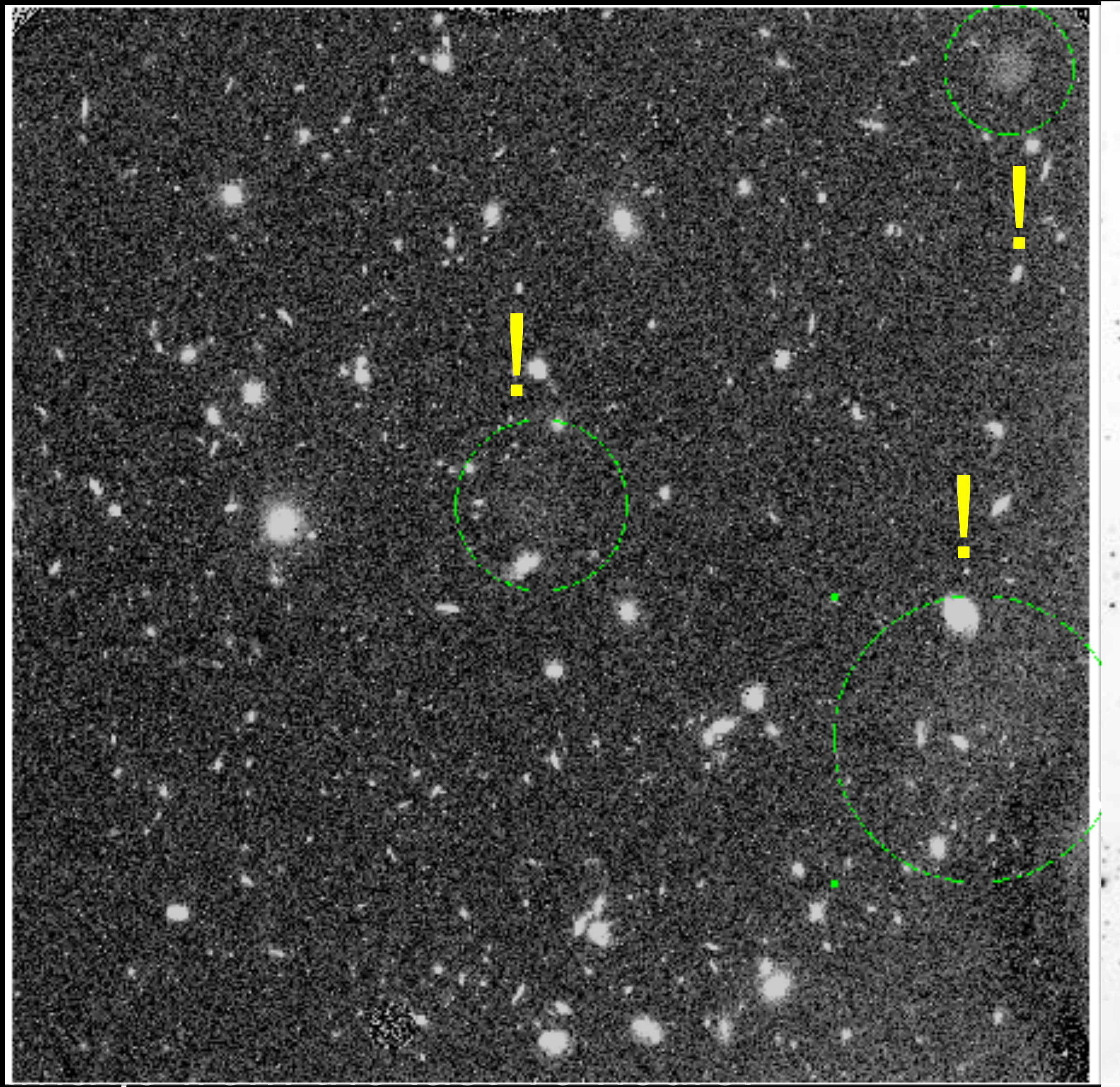
8 hours before the observations (included in persistence calculations)

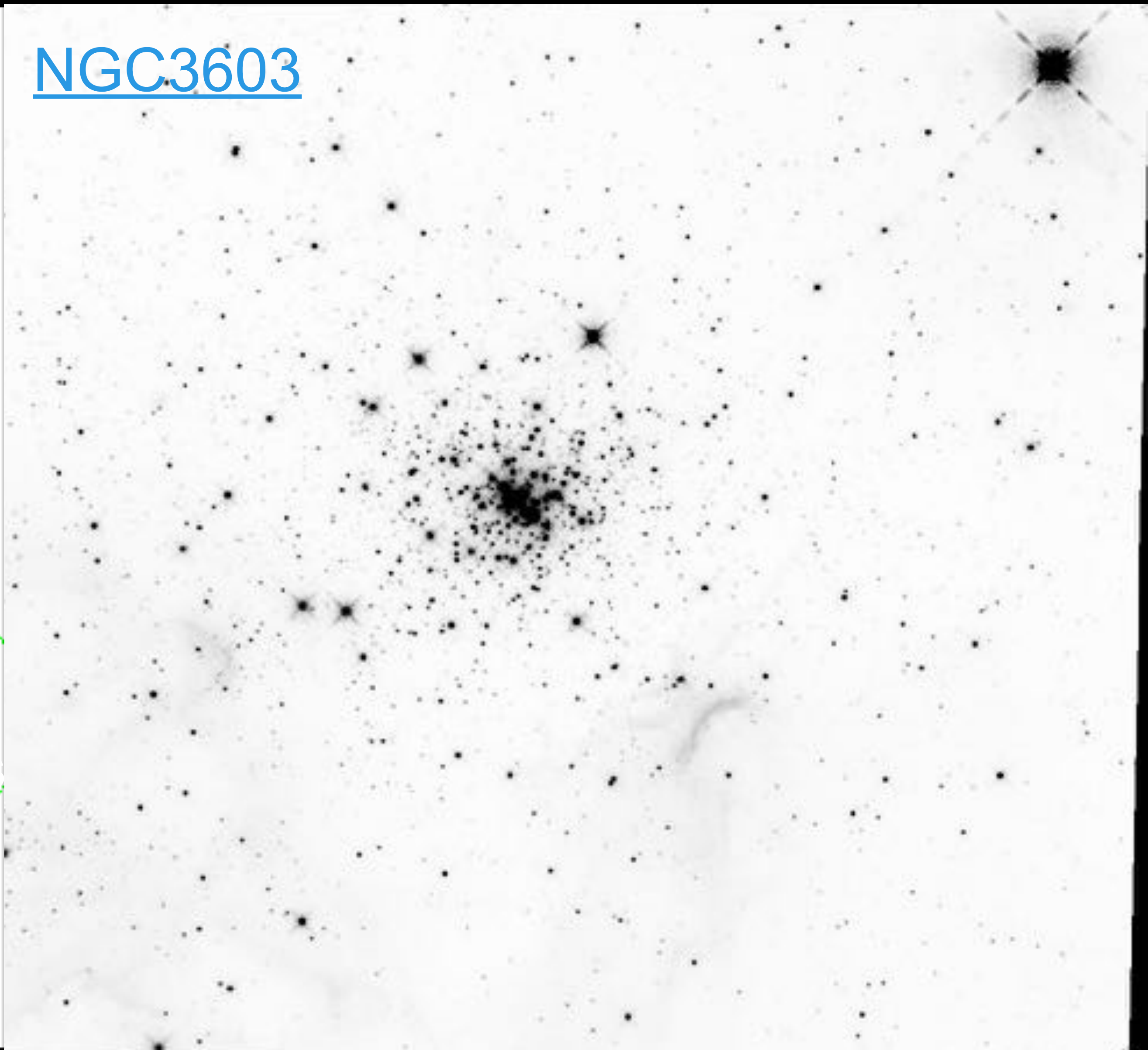




Persistence

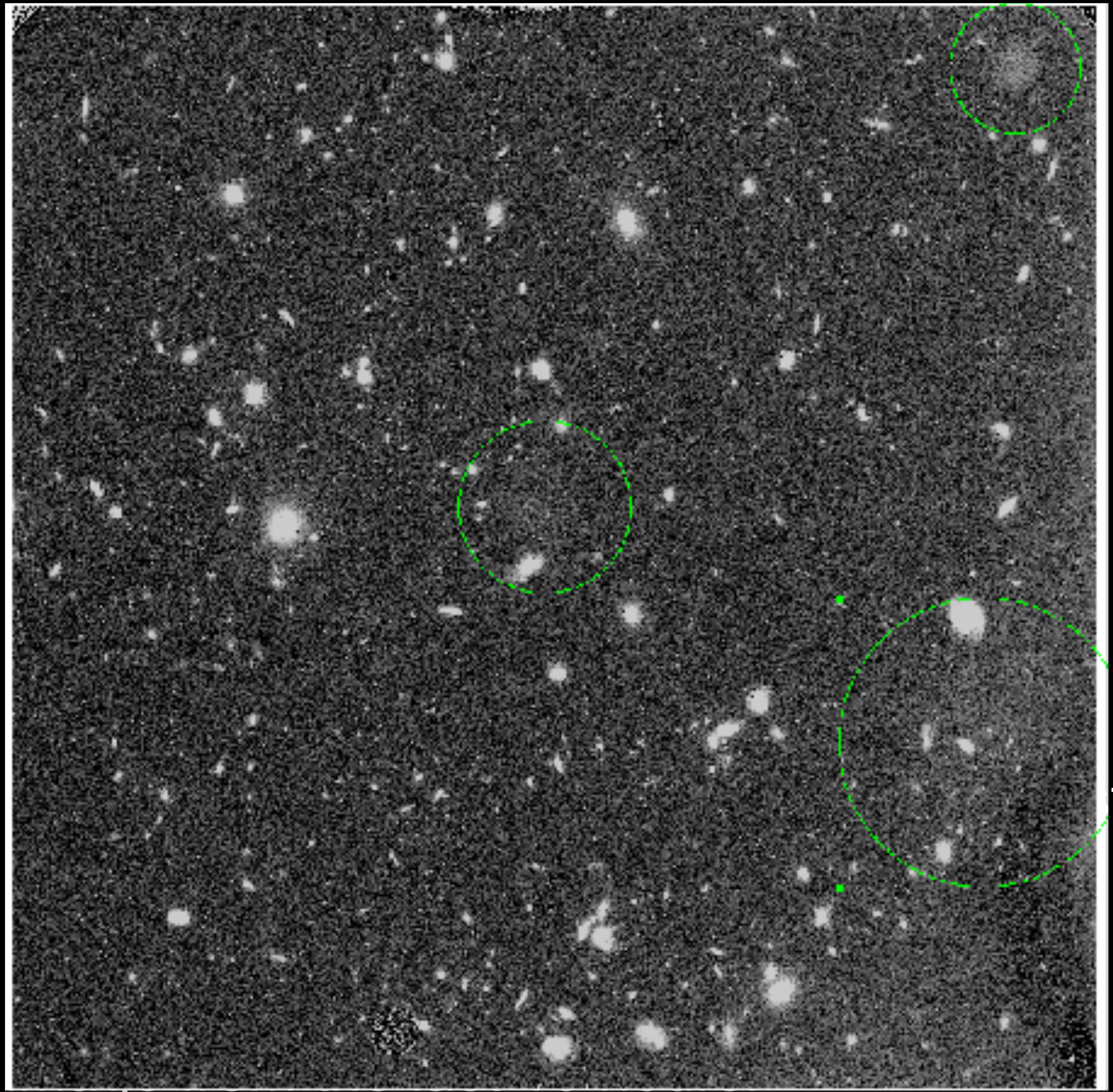
20 hours before the observations: (NOT included in persistence calculations)

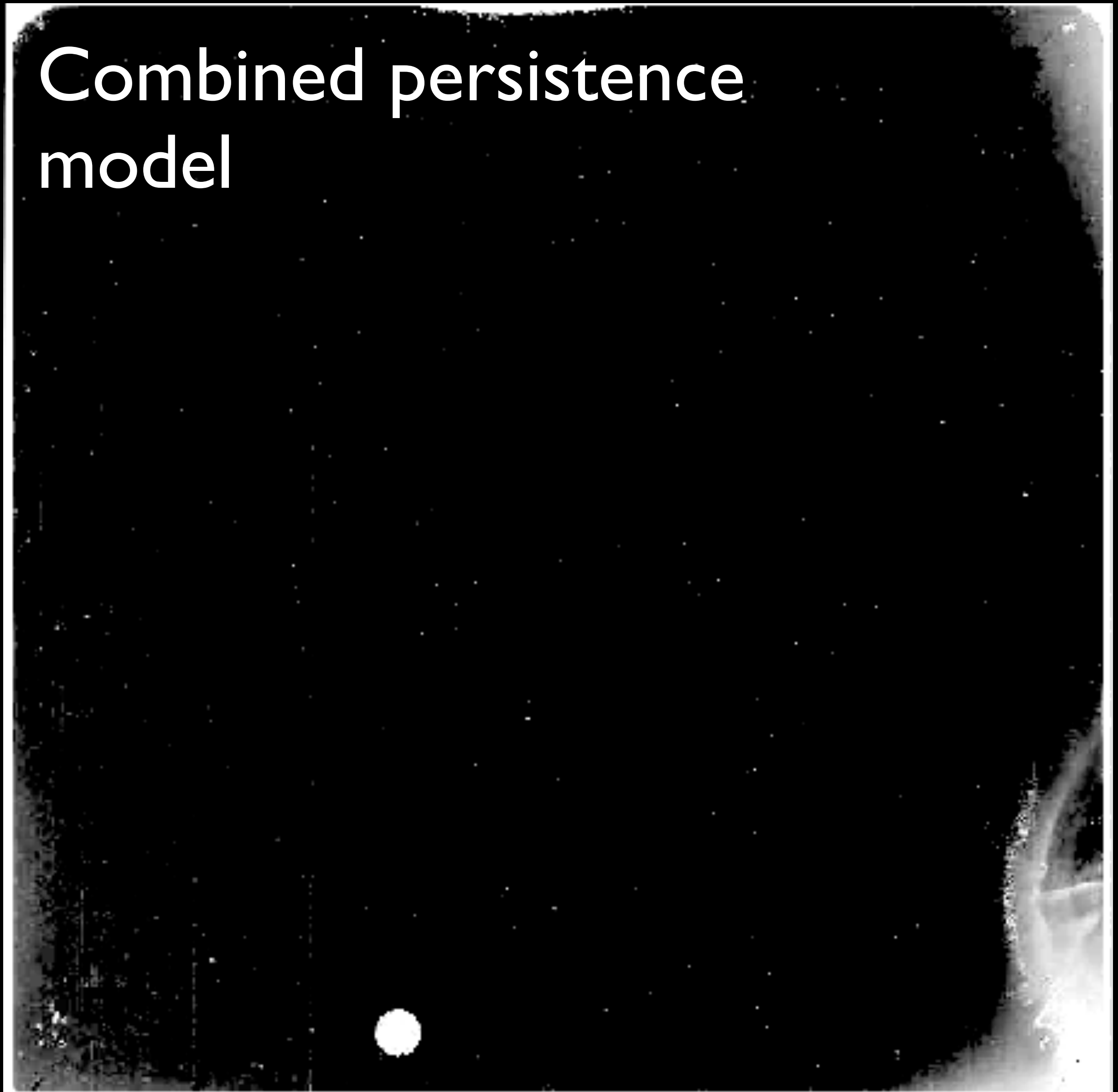




Persistence – which pixels can I trust?

Solution: Increase the lookback time to create better persistence models.

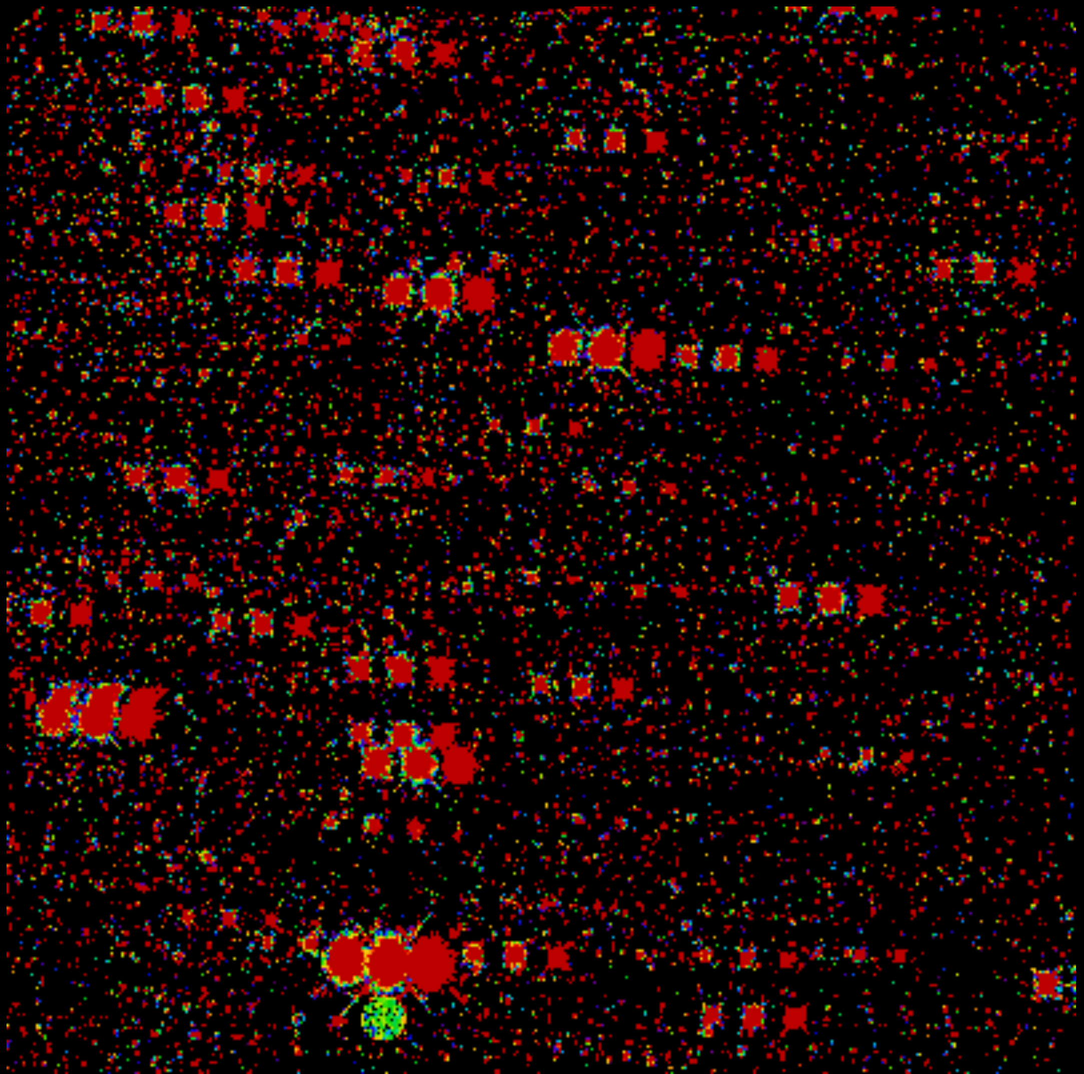




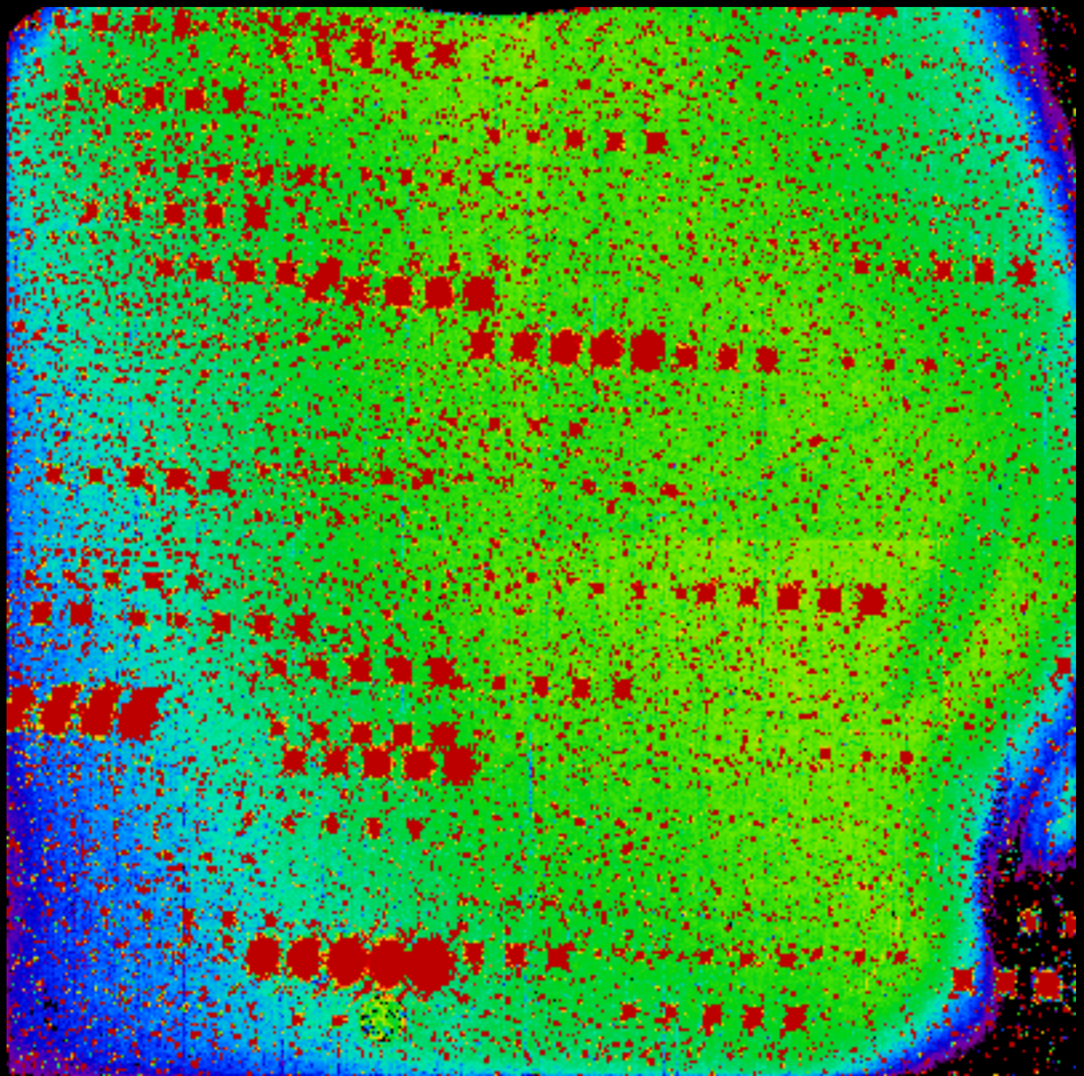
Persistence

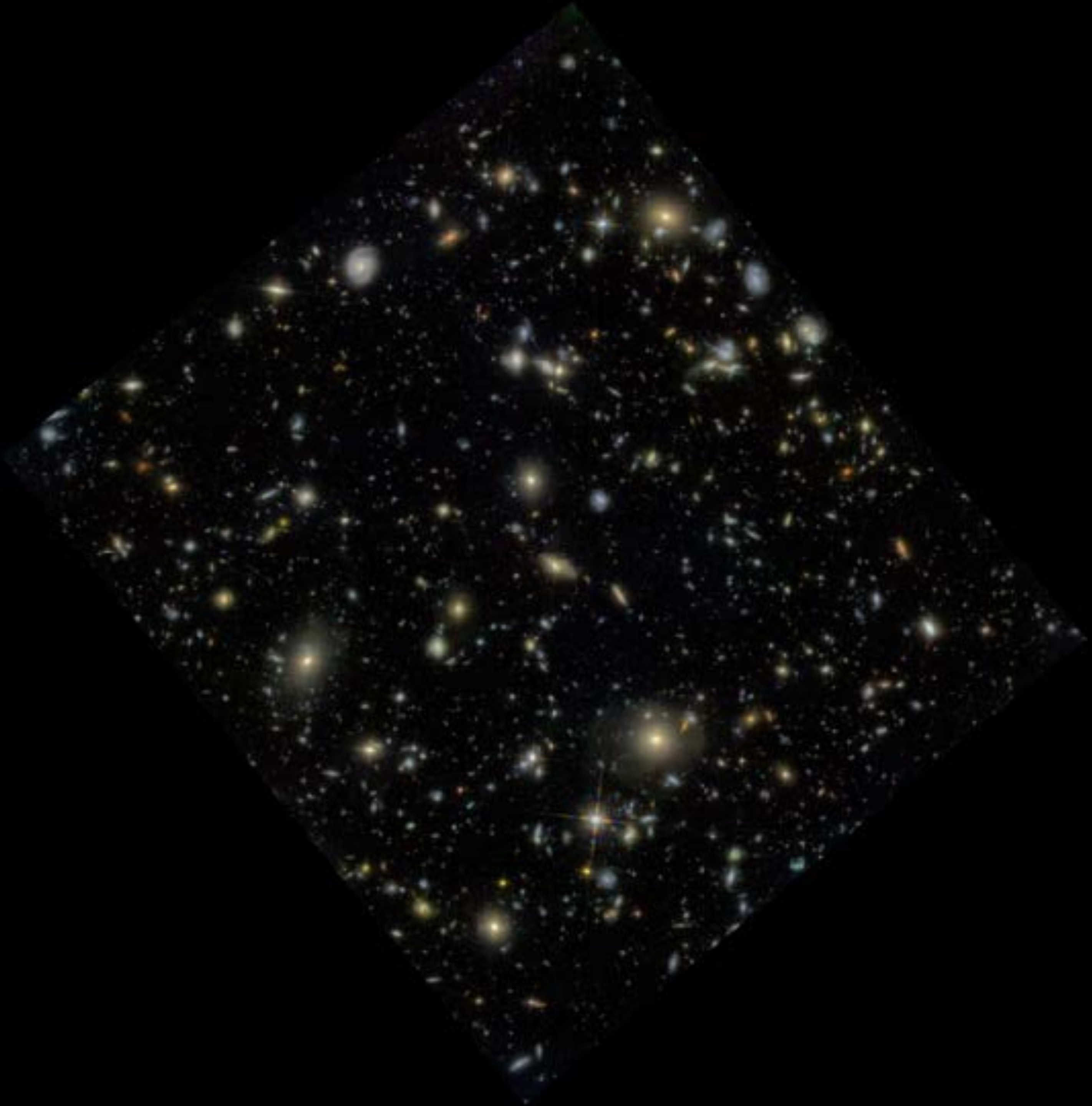
Temporary increase in dark current after illumination. *Afterglow*

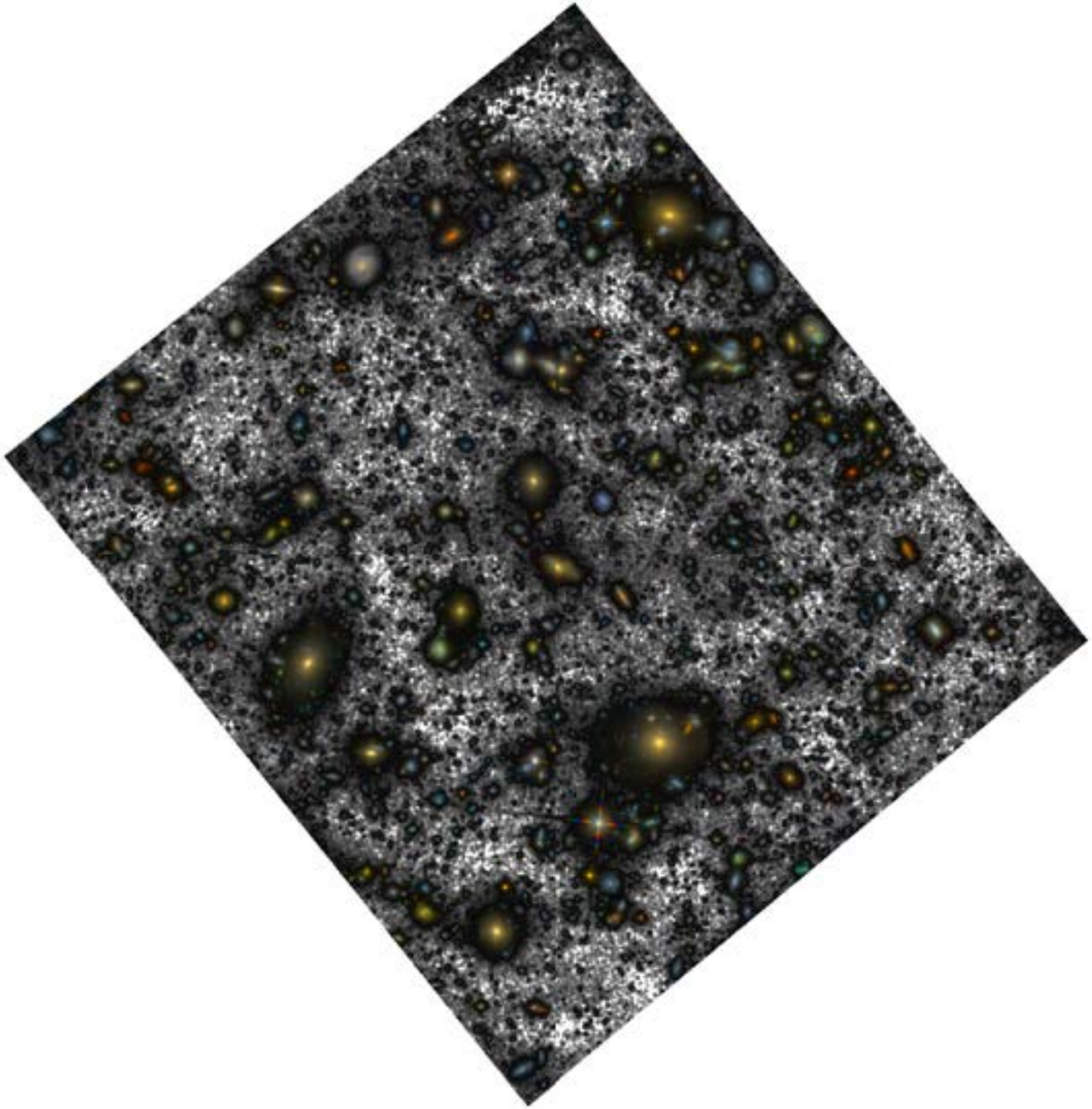
Official HST persistence models



Improved HST persistence models



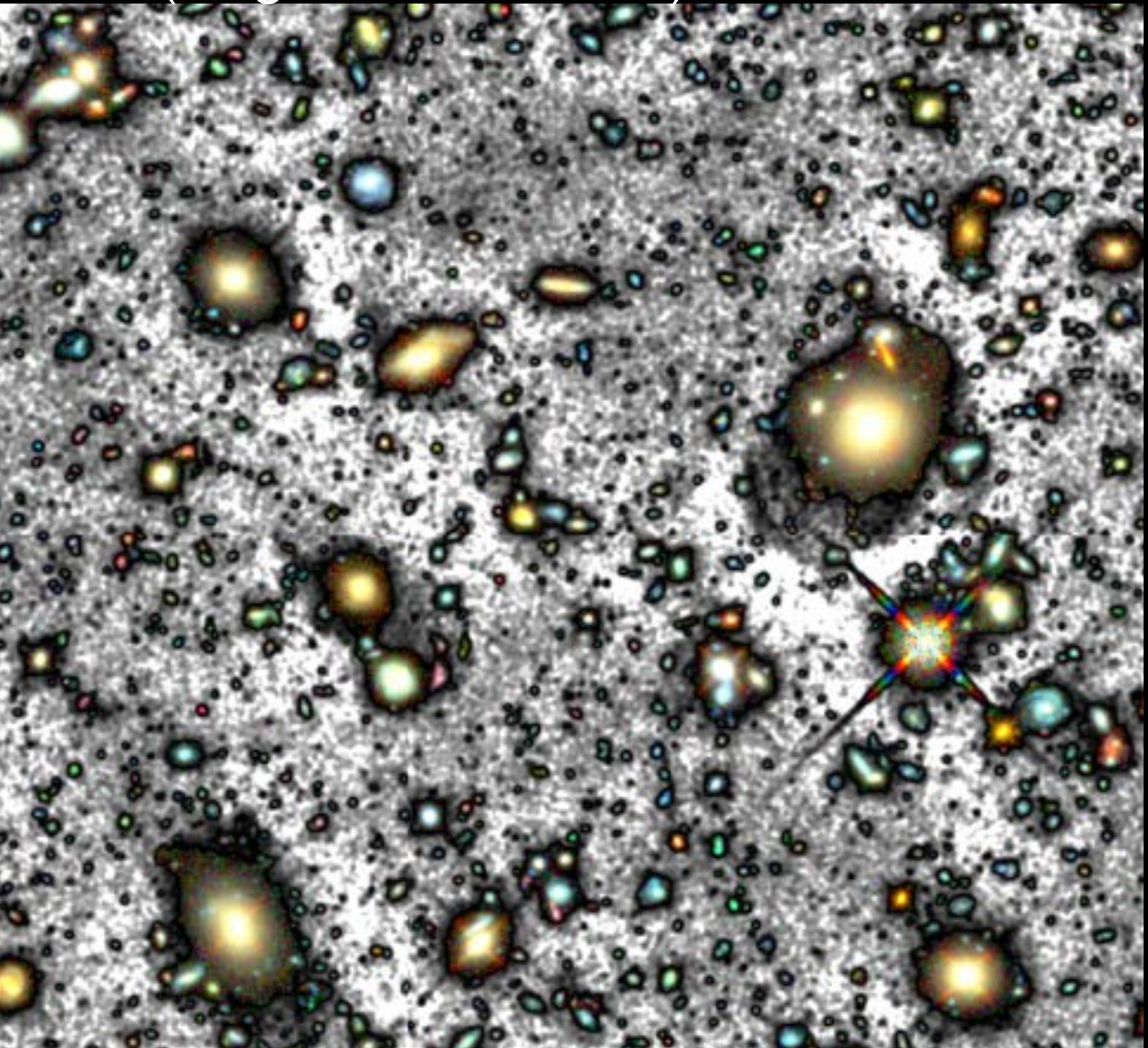




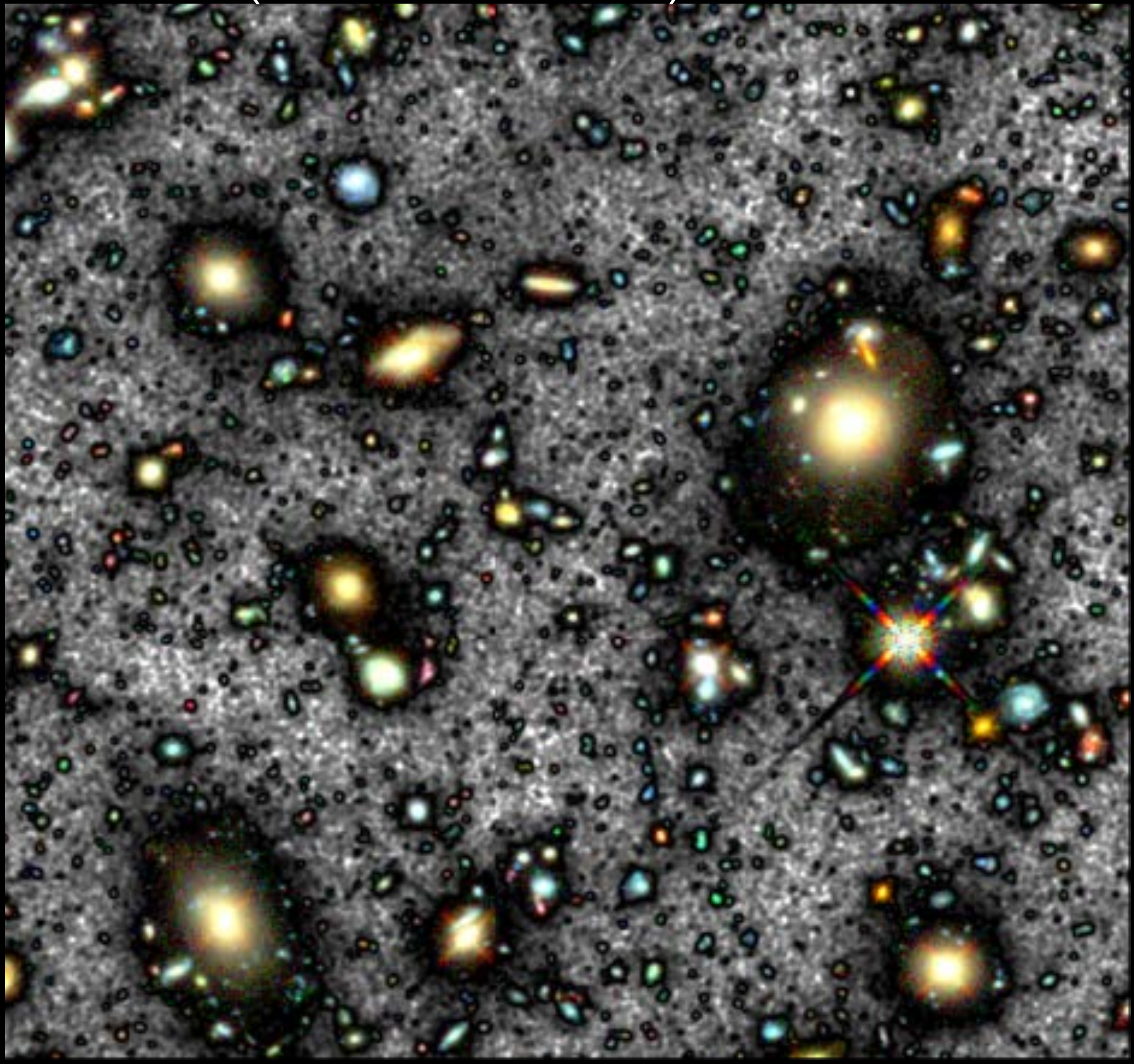
Results

Our mosaics successfully recover the outskirts of the extended galaxies in the HUDF

XDF (Illingworth et al. 2013)

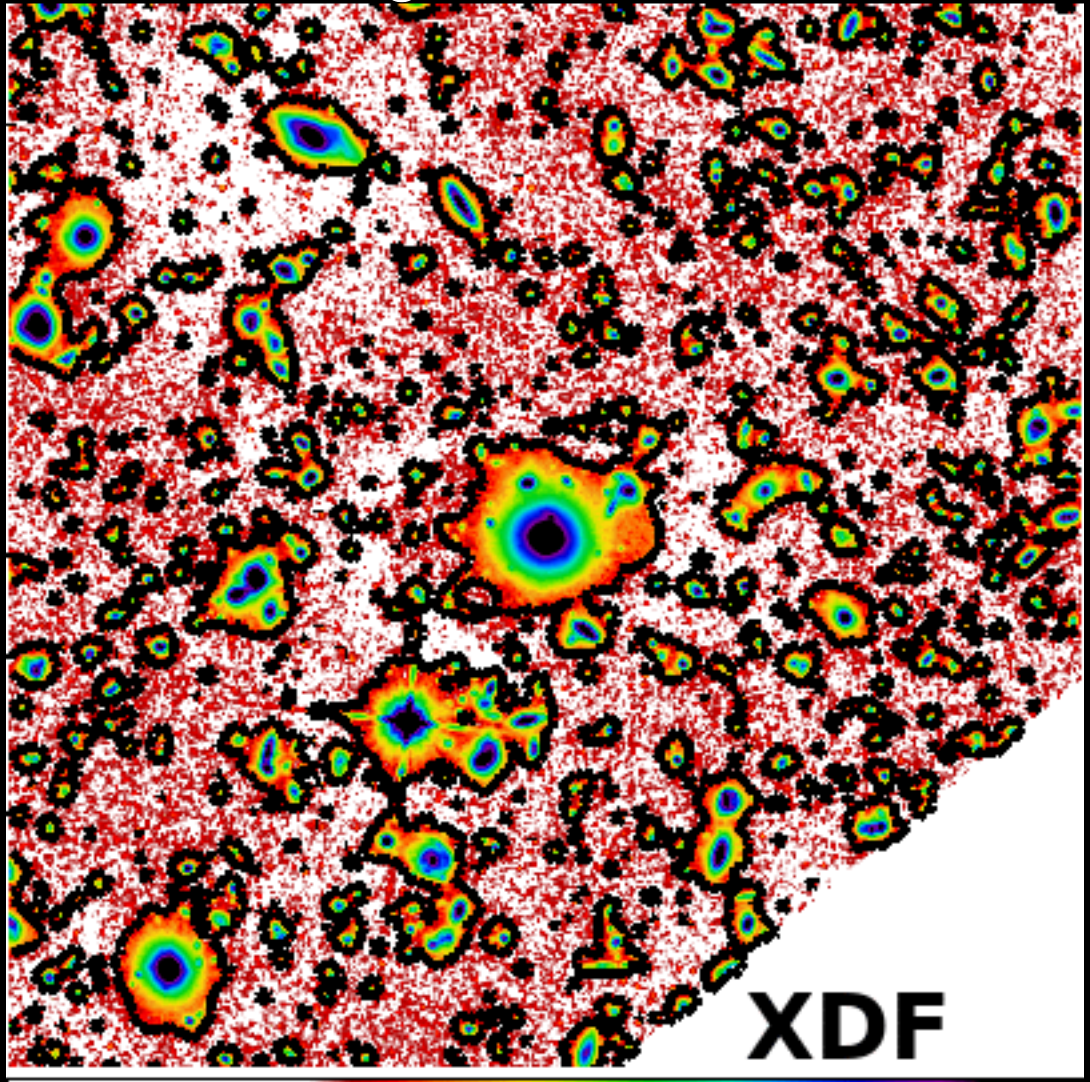


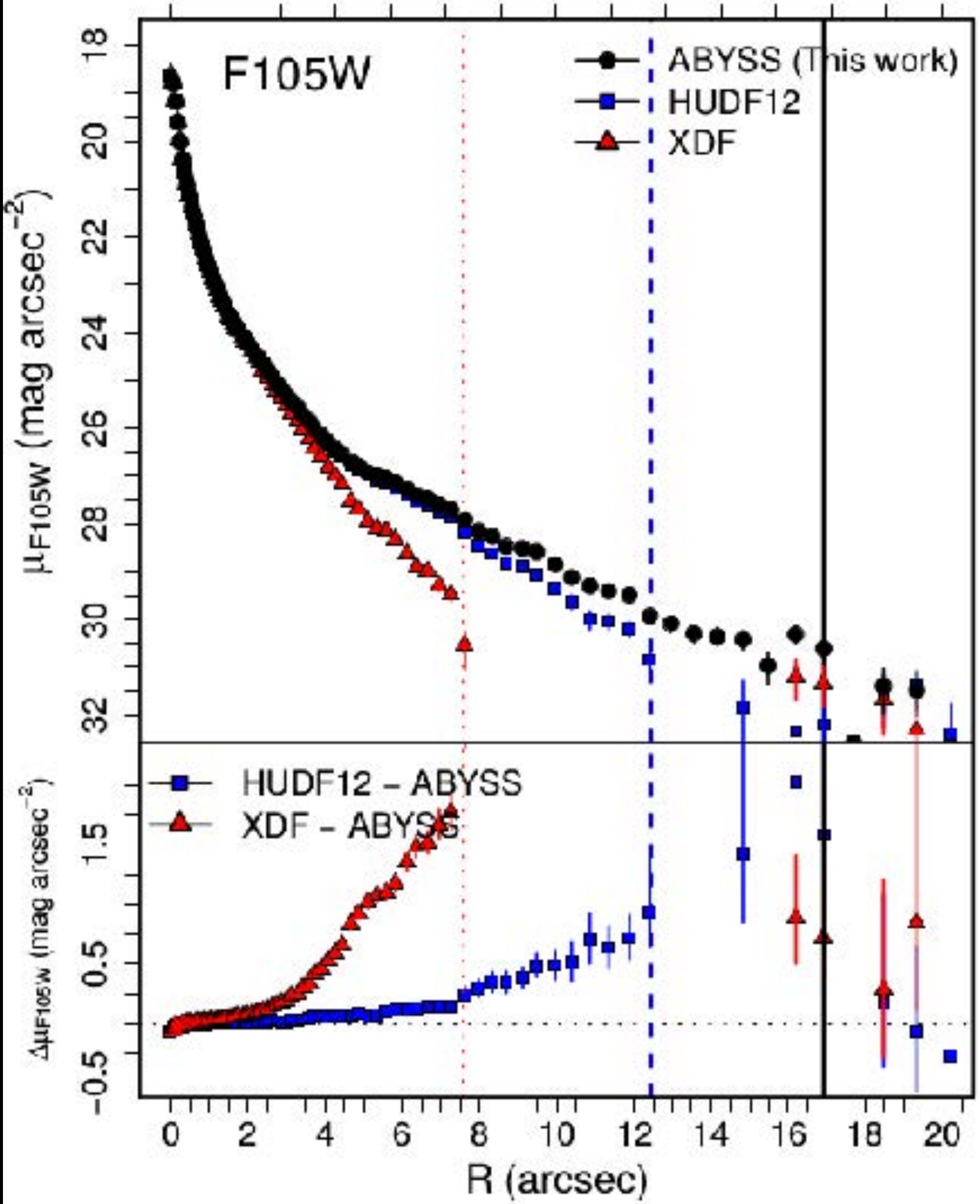
ABYSS (Borlaff et al. 2019)



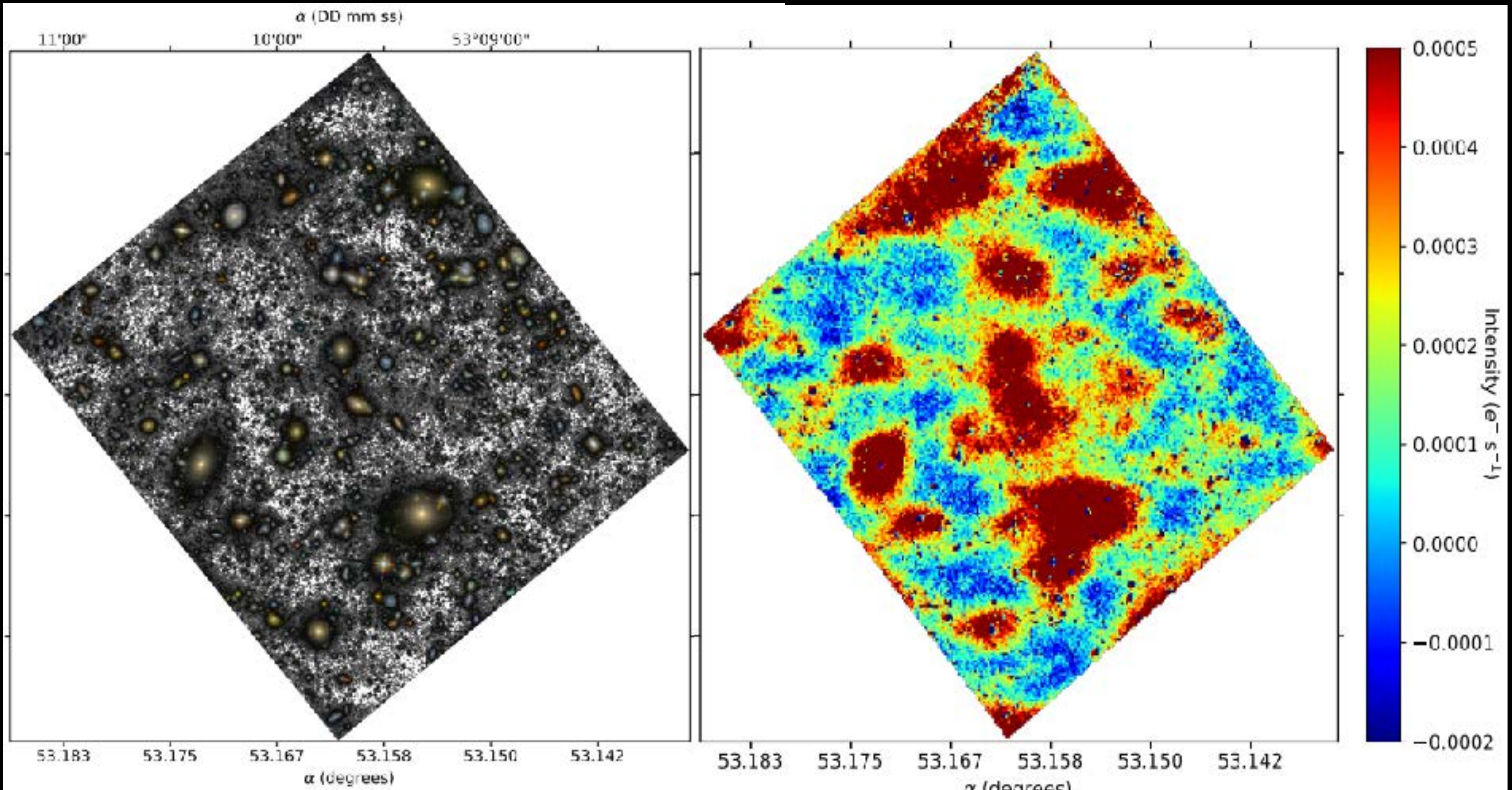
Results

The new mosaics (ABYSS) recover up to ~1.5 mag arcsec^{-2} in the outskirts of the largest galaxies, increasing their size



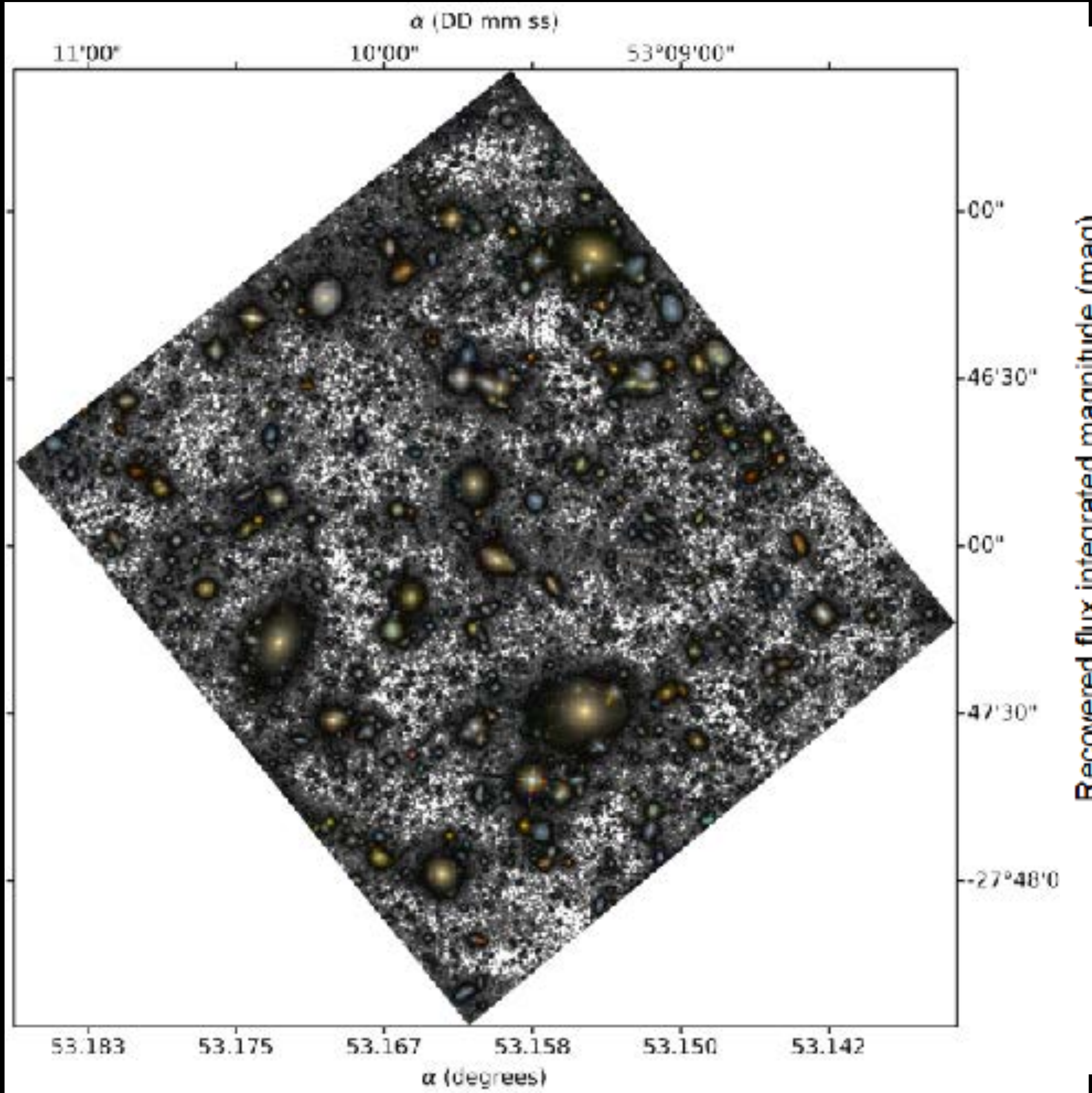


Results

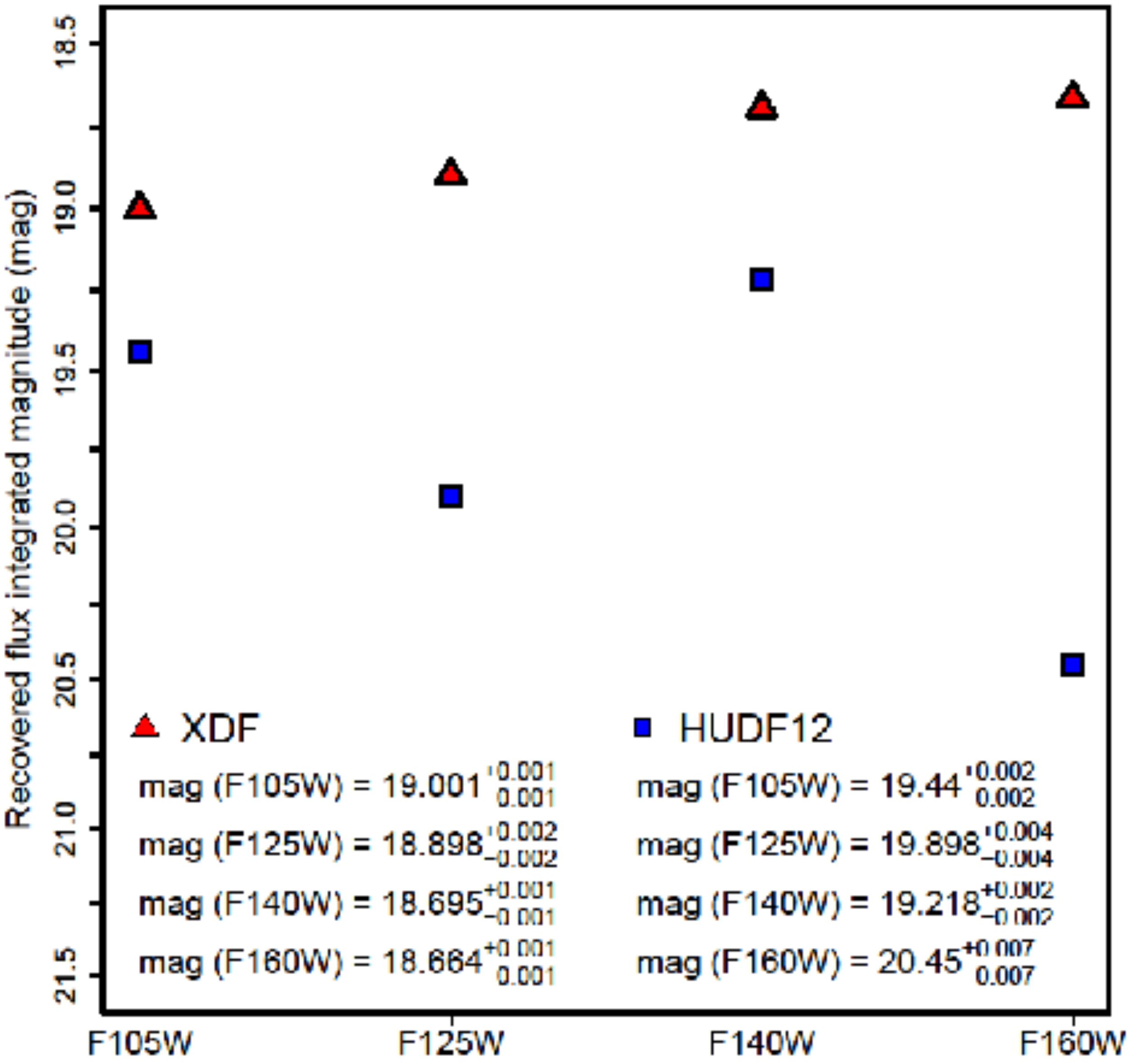


α (DD mm ss)
11'00"
10'00"
53°09'00"
53.183
53.175
53.167
53.158
53.150
53.142
α (degrees)
0.0005
0.0004
0.0003
0.0002
0.0001
0.0000
−0.0001
−0.0002
Intensity (e⁻ s⁻¹)

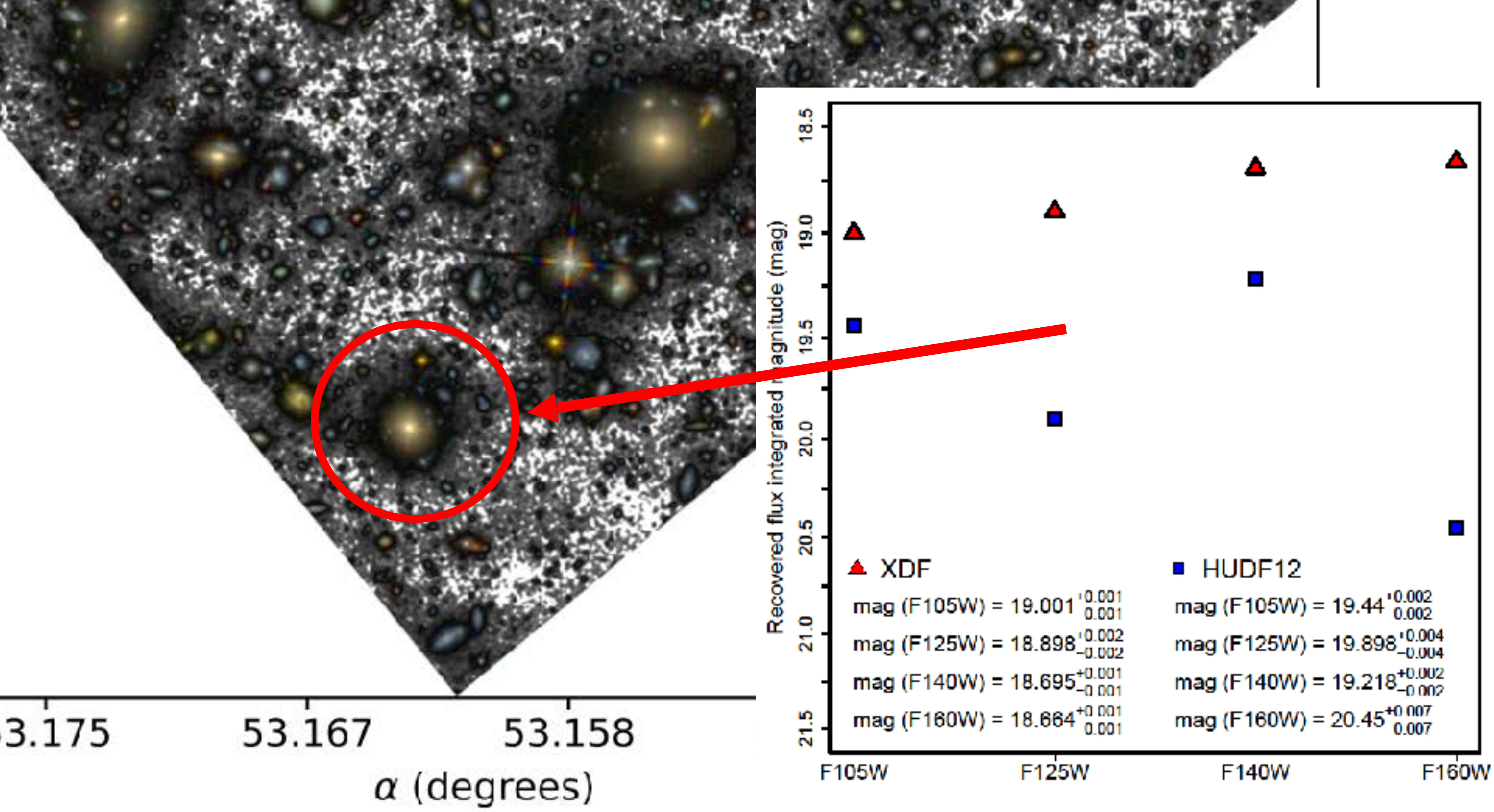
Results



α (DD mm ss)
11'00"
10'00"
53°09'00"
00"
46'30"
00"
47'30"
-27°48'0
53.183
53.175
53.167
53.158
53.150
53.142
α (degrees)



Recovered flux integrated magnitude (mag)
18.5
19.0
19.5
20.0
20.5
21.0
21.5
XDF
HUDF12
mag (F105W) = $19.001^{+0.001}_{0.001}$
mag (F125W) = $18.898^{+0.002}_{-0.002}$
mag (F140W) = $18.695^{+0.001}_{-0.001}$
mag (F160W) = $18.664^{+0.001}_{0.001}$
mag (F105W) = $19.44^{+0.002}_{0.002}$
mag (F125W) = $19.898^{+0.004}_{-0.004}$
mag (F140W) = $19.218^{+0.002}_{-0.002}$
mag (F160W) = $20.45^{+0.007}_{0.007}$
F105W
F125W
F140W
F160W



53.175
53.167
53.158
α (degrees)
Recovered flux integrated magnitude (mag)
18.5
19.0
19.5
20.0
20.5
21.0
21.5
XDF
HUDF12
mag (F105W) = 19.001 +0.001 0.001
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mag (F125W) = 19.898 +0.004 −0.004
mag (F140W) = 19.218 +0.002 −0.002
mag (F160W) = 20.45 +0.007 0.007
F105W
F125W
F140W
F160W

Conclusions

Borlaff et al. (2019)

1) We have created a new set of flat-fields dedicated to the WFC3/IR HUDF

2) Improved sky-background subtraction: GnuAstro/NoiseChisel

3) New persistence models: from 16h to 96h before each exposure

Results

Taking into account systematic errors, the ABYSS HUDF is now the deepest version of the Hubble Ultra Deep Field

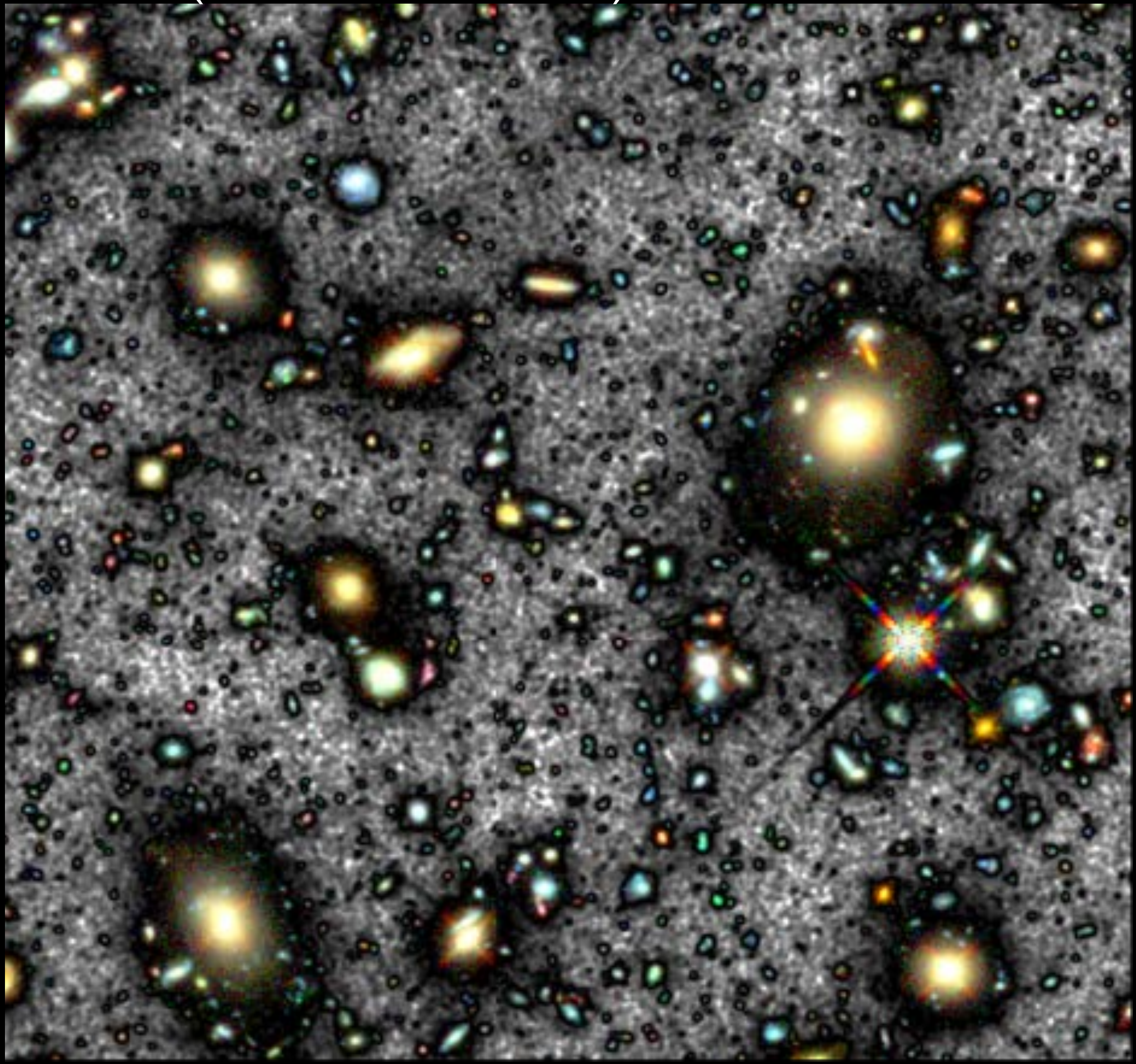
These methods are applicable directly to EUCLID, JWST and beyond

Paper published (23/01/19):
A&A: bit.ly/2FXerSg
ArXiV: arxiv.org/abs/1810.00002

Images publicly available at:
www.iac.es/proyecto/abyss

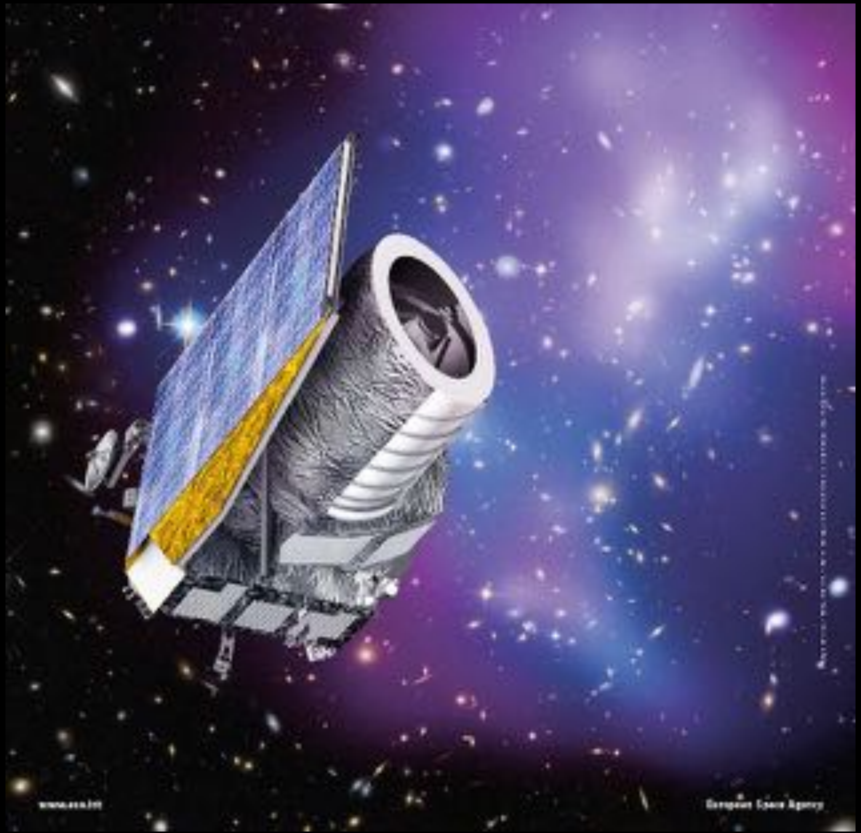
Contact: asborlaff@gmail.com

ABYSS (Borlaff et al. 2019)



Future missions – How is the ideal LSB telescope?

1) Wider: Large FOV and wide survey area to avoid sky over-subtraction
2) Redder: Higher z require infrared observations – NIR detectors
3) Sharper: We need increasingly angular resolution – Space-based
4) Deeper: SDSS is at the very edge of the LSB Universe



1)FOV = 0.53 deg^2
Wide Survey=15.000 deg^2, Deep Survey=40 deg^2

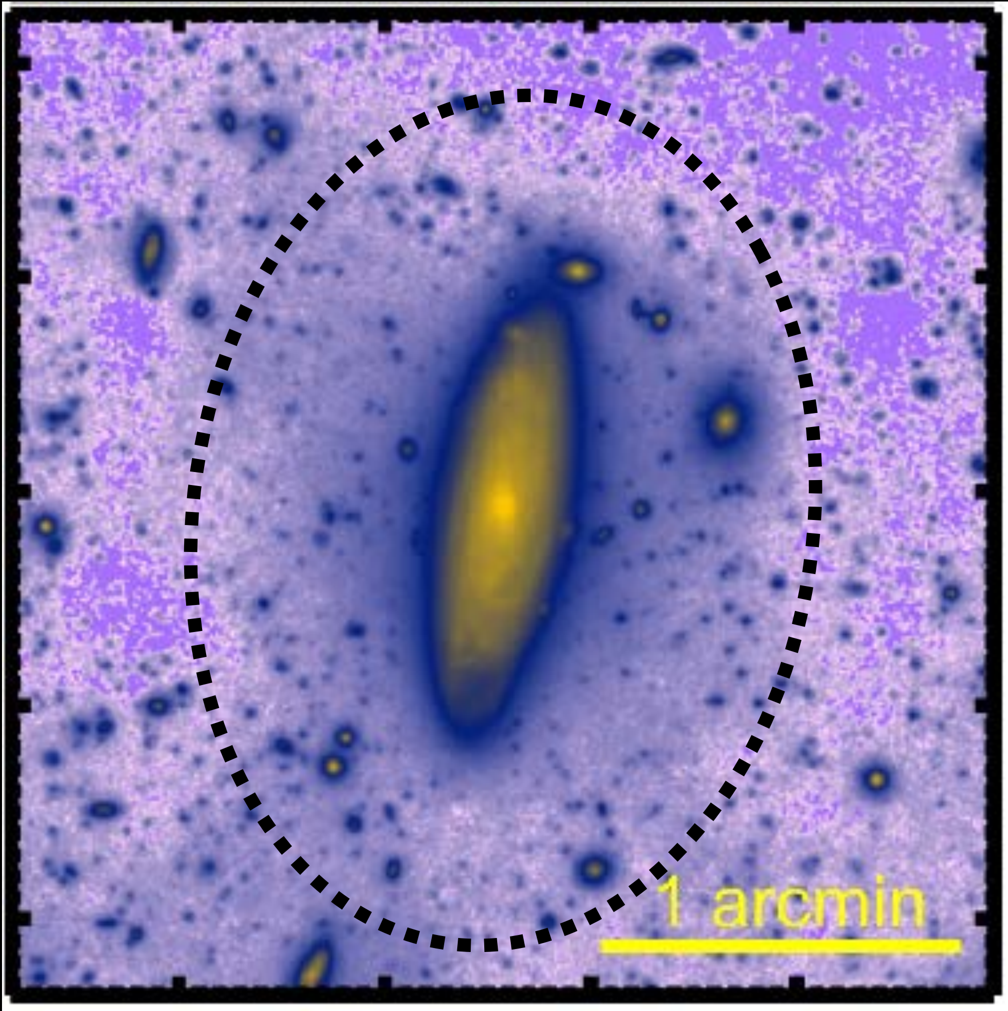
2) VIS (R+I+Z) and NISP (Y, J and H)

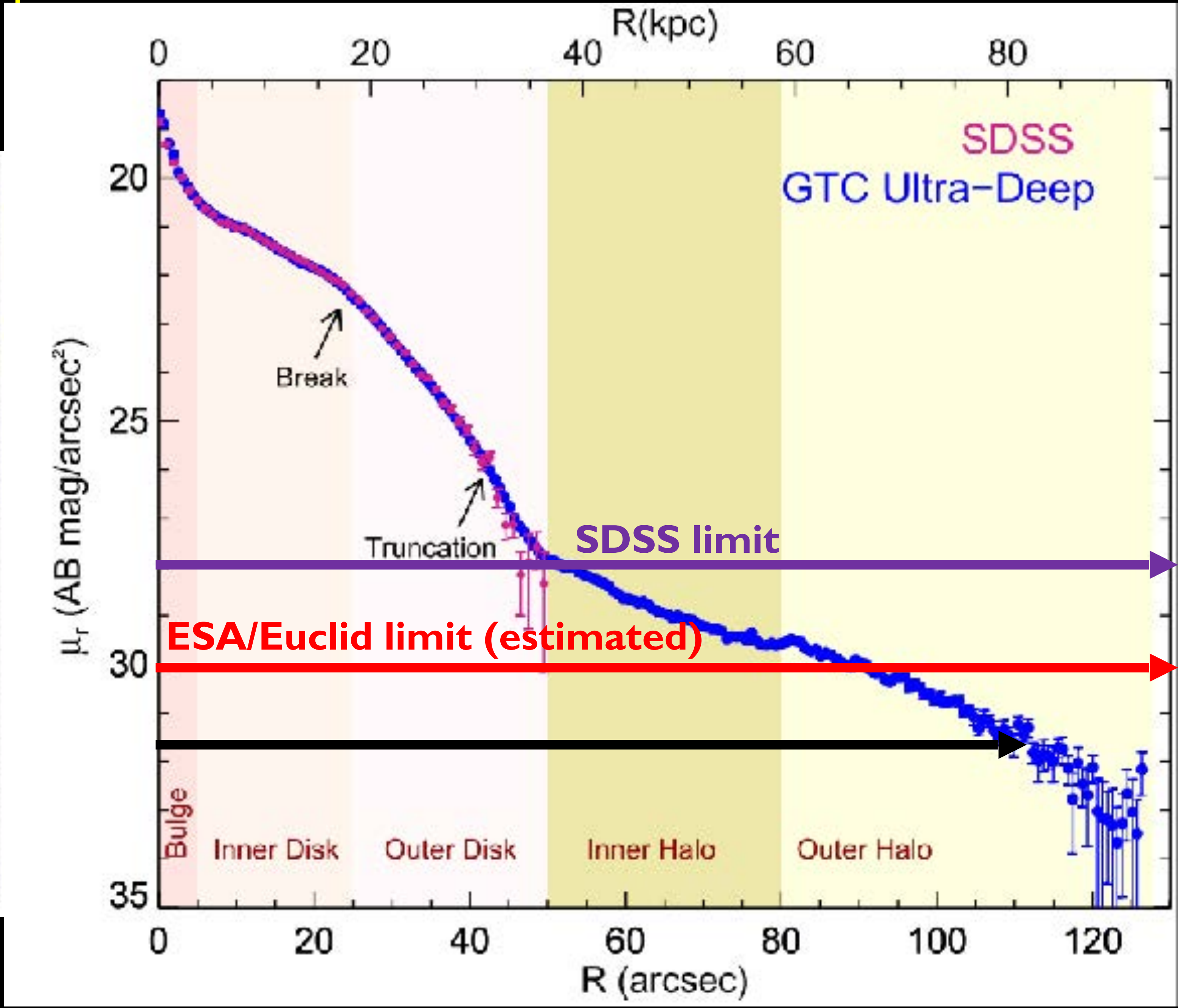
3)FWHM $_{VIS}$ = 0.2", FWHM$_{NISP}$ = 0.3"

4) ~ 2 magnitudes deeper than SDSS

Galaxy structure – Surface brightness profiles

Trujillo & Fliri (2016)
Ultra-deep imaging of UGC00180





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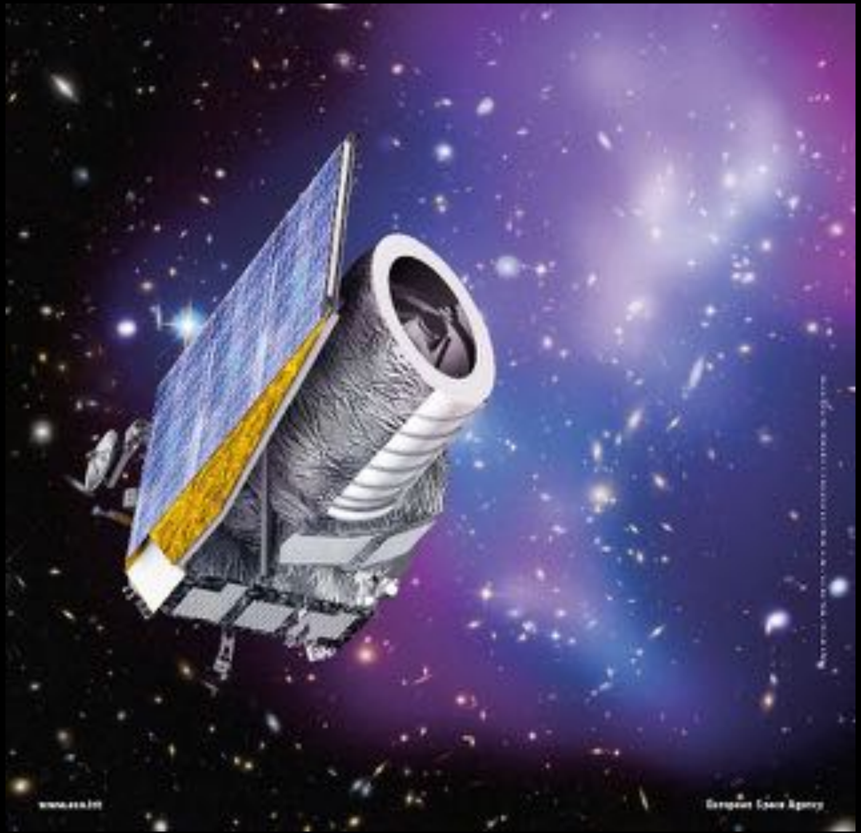

Project proposed for CNES Fellowships
(Pierre-Alain Duc / ObAS)

Low surface brightness pipeline for ESA/Euclid:

- In-flight calibration (sky flat-fields pipeline)
- HST + Simulated data until launch in 2022