Probing the mass assembly of massive galaxies with ultra-deep imaging

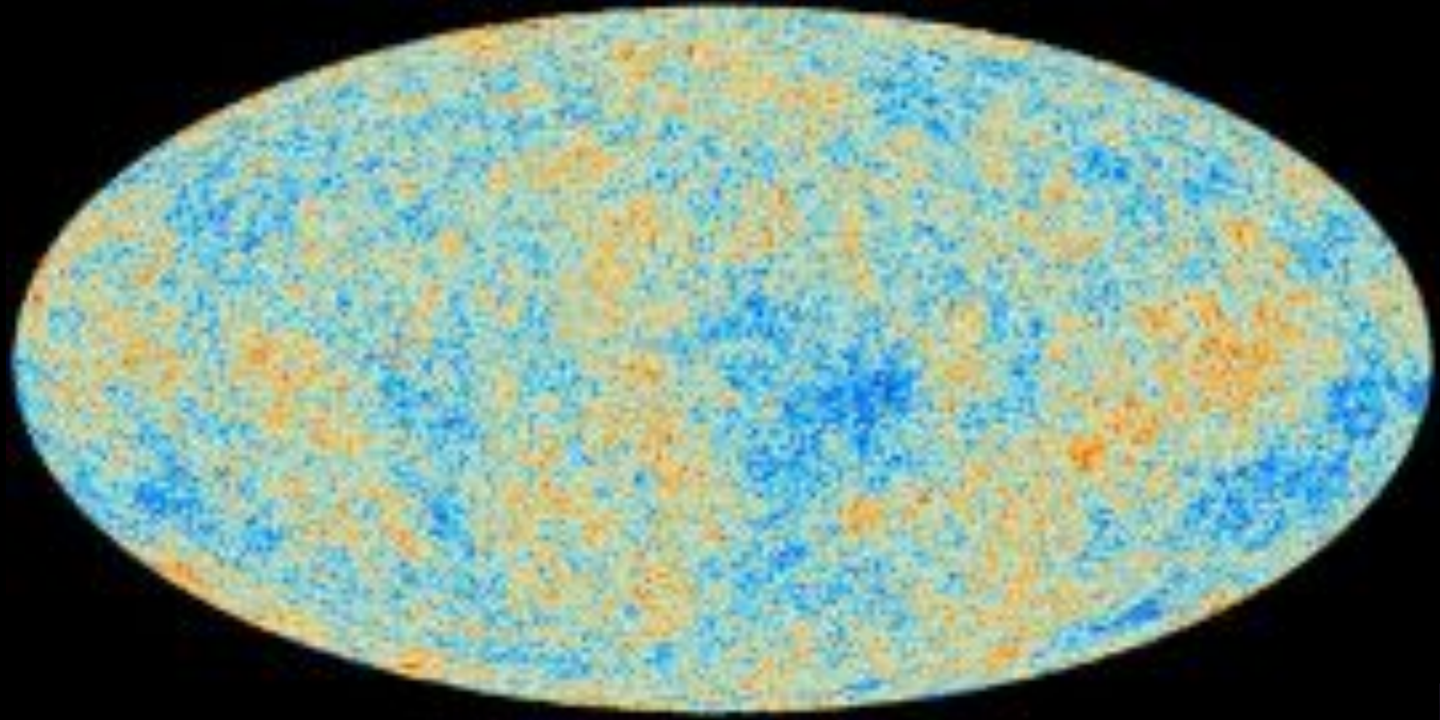
Student's session

Pierre-Alain Duc

Laboratoire AIM, CEA-Saclay/CNRS-INSU/Université Paris Diderot

Places of special interest for me

Fine structures and mass assembly: predictions from simulations



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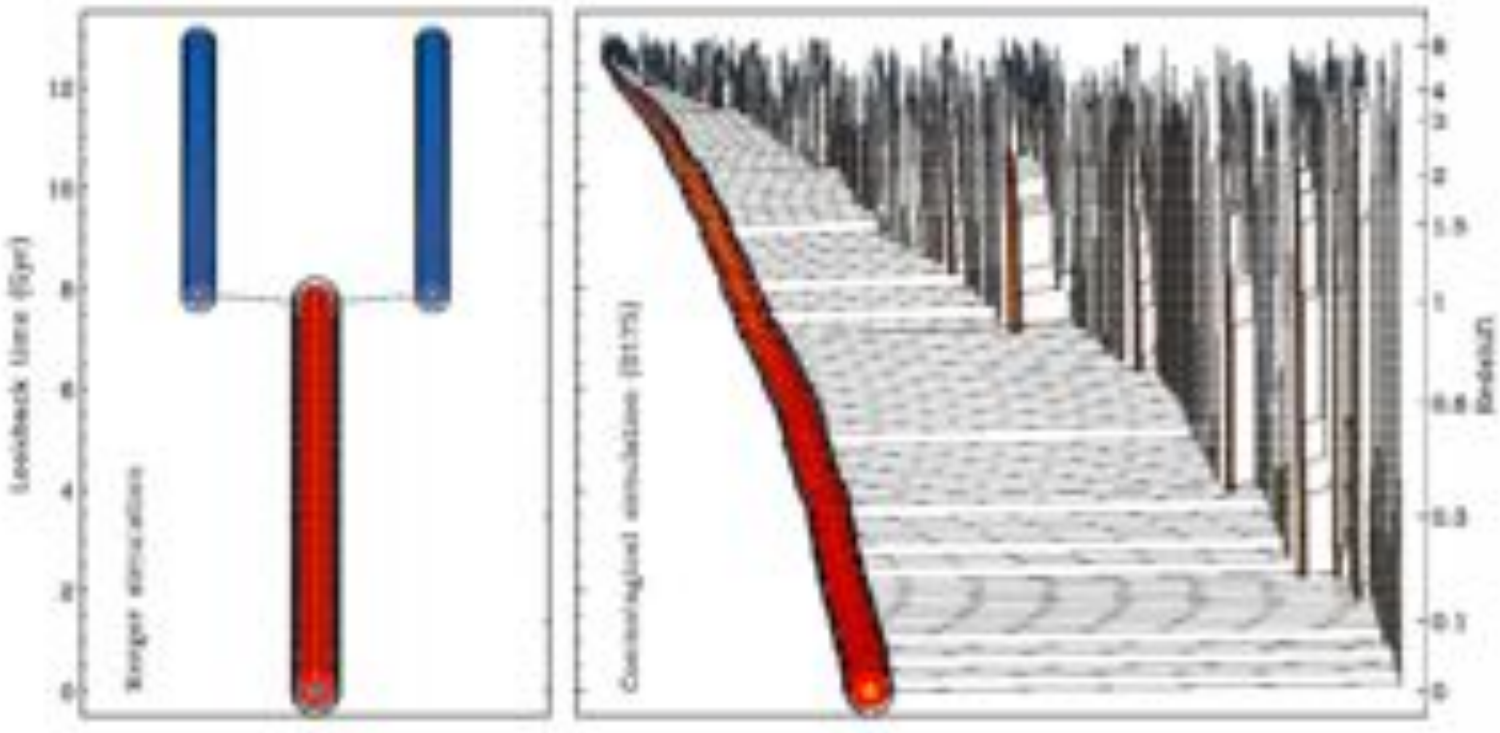
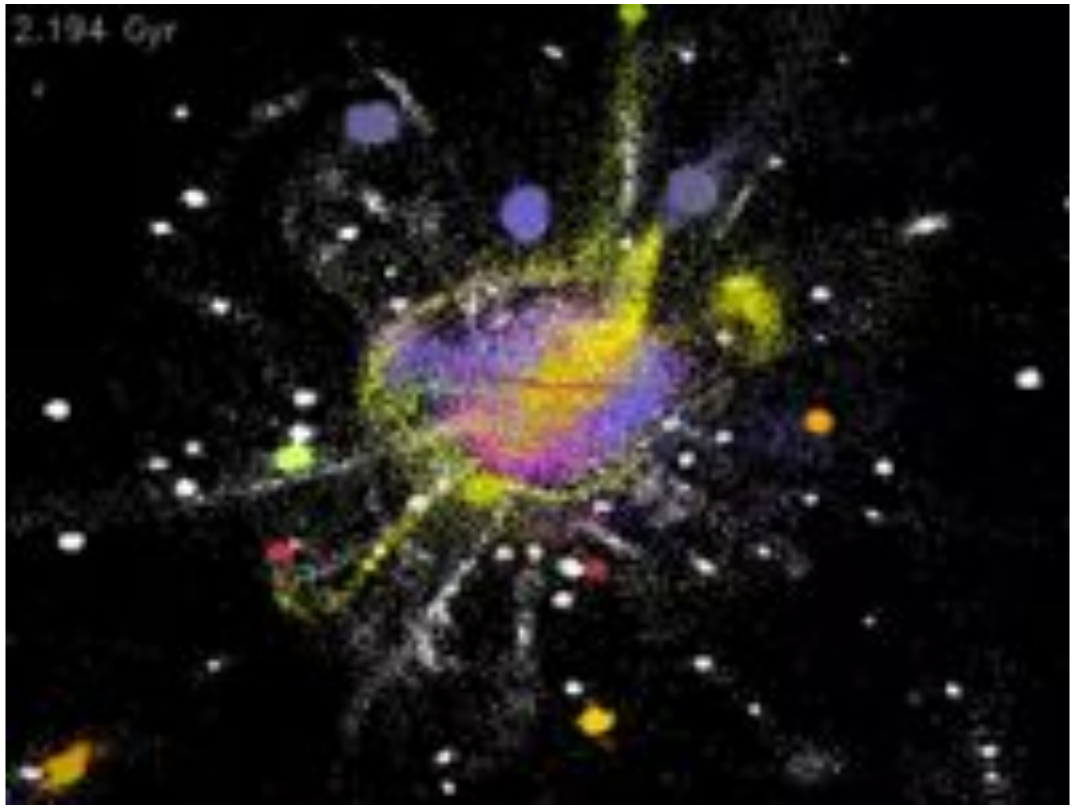
From here …

… to here



- A fundamental role given to mergers

Naab et al., 2013



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- An active debate on the role of
- major vs minor mergers
- gas rich vs gas poor mergers vs cold gas accretion
- on their relative importance as a function of morphological class, environment, redshift

- This talk: fine structures, as probed by deep imaging, can tell something about this

Renaud, Bournaud & Duc, 2014

✓ Major mergers between (gas-rich) spirals

➡ Produce gas-rich long, stellar tidal tailS, with structures within them

Bournaud, Duc & Emsellem, 2008

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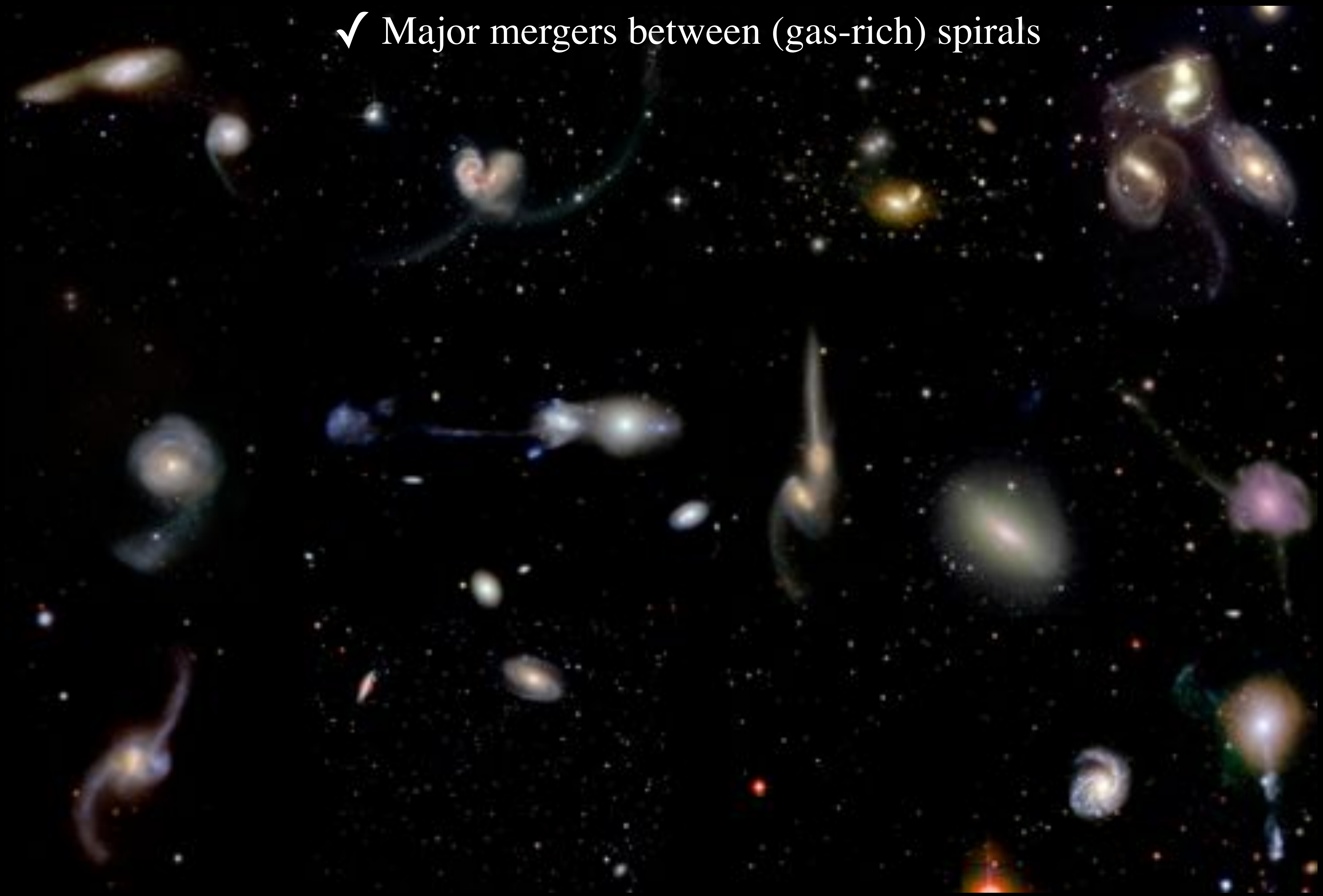

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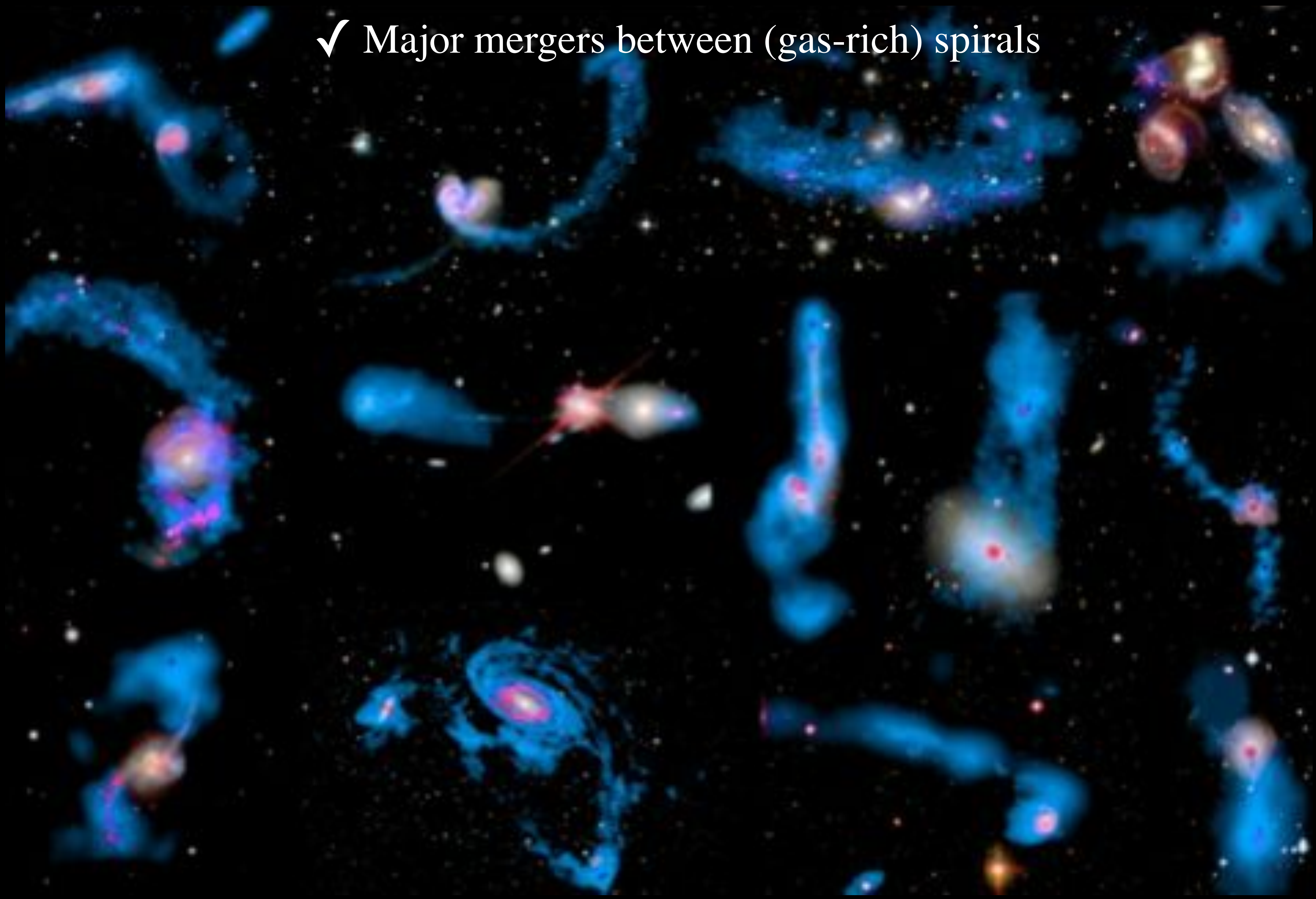


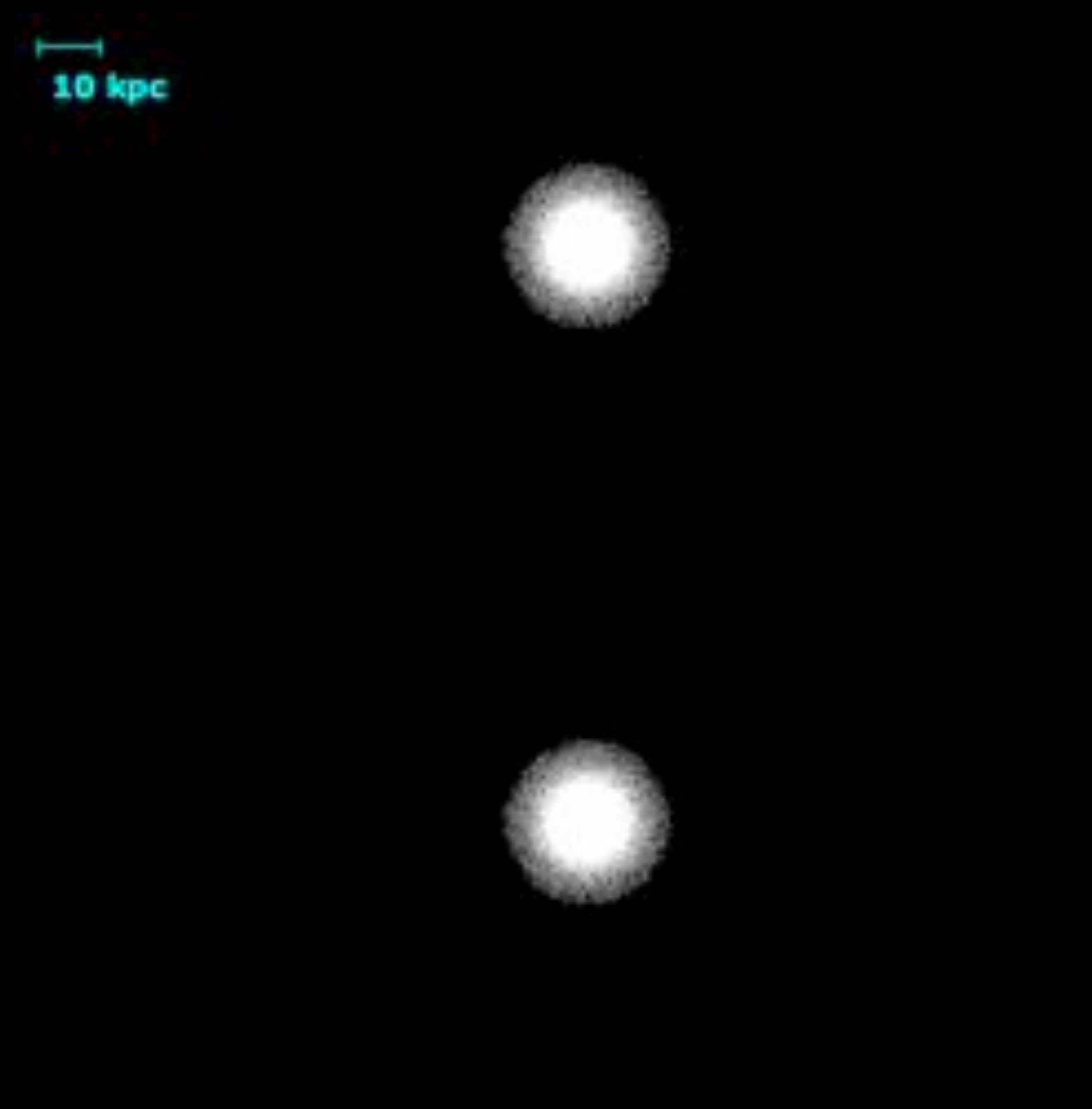
✓ Major mergers between (gas-poor) early-type galaxies

➡ Do not produce any narrow tidal tails but distorted halos....

➡ The identification of a prominent narrow *tidal tails* with a mixture of young/old stellar populations reveal a gas-rich major merger

GalMer

Di Matteo et al.



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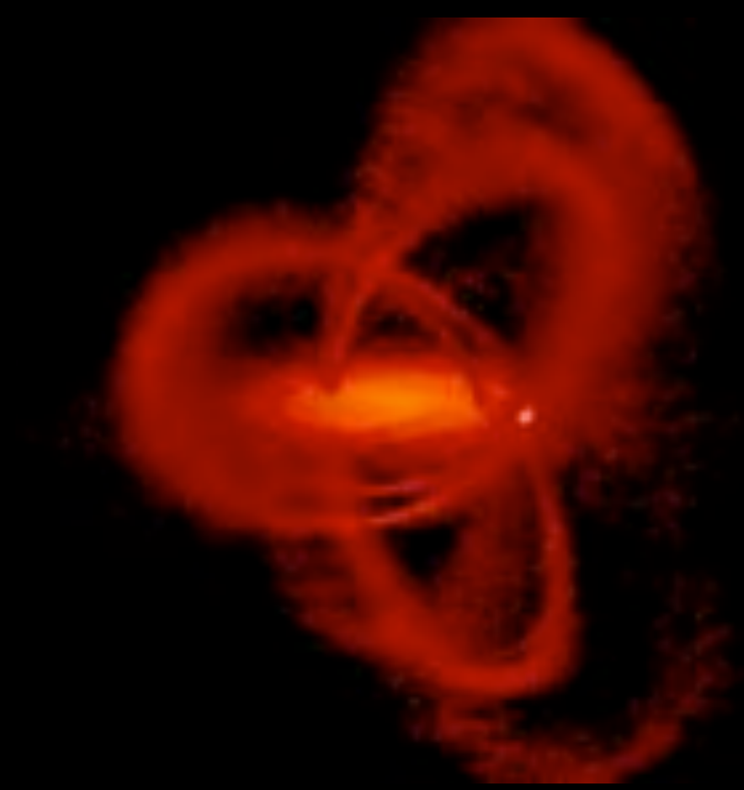
Fine structures and mass assembly: predictions from simulations

✓ Major mergers between (gas-poor) early-type galaxies

✓ Minor mergers involving (gas-poor) dwarf satellites

➡ Produce gas-poor, narrow, tidal tails wrapping along their host



➡ The presence of narrow stellar *streams* with a possibly a massive condensation within it (the progenitor) favors minor mergers

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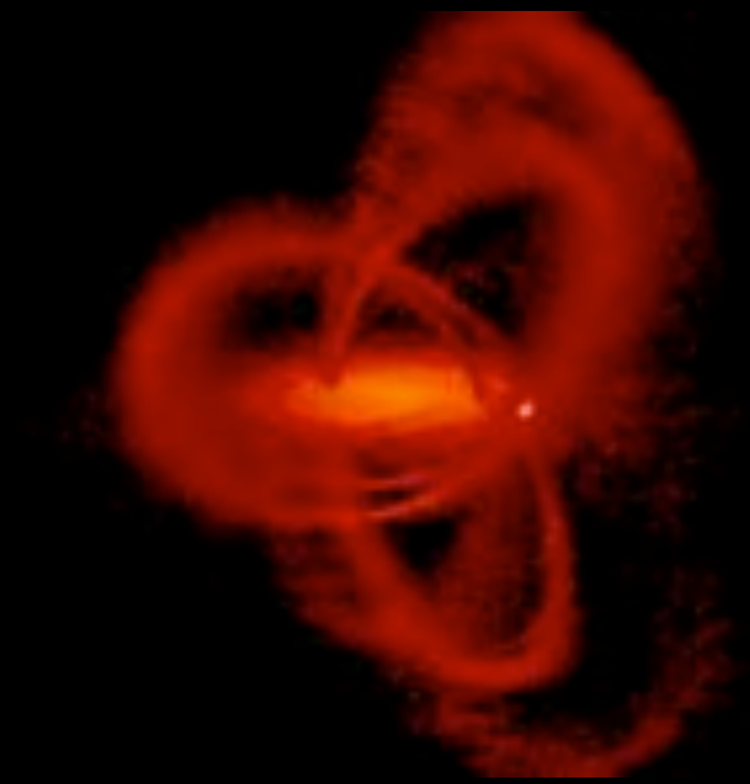

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© Martin et al.

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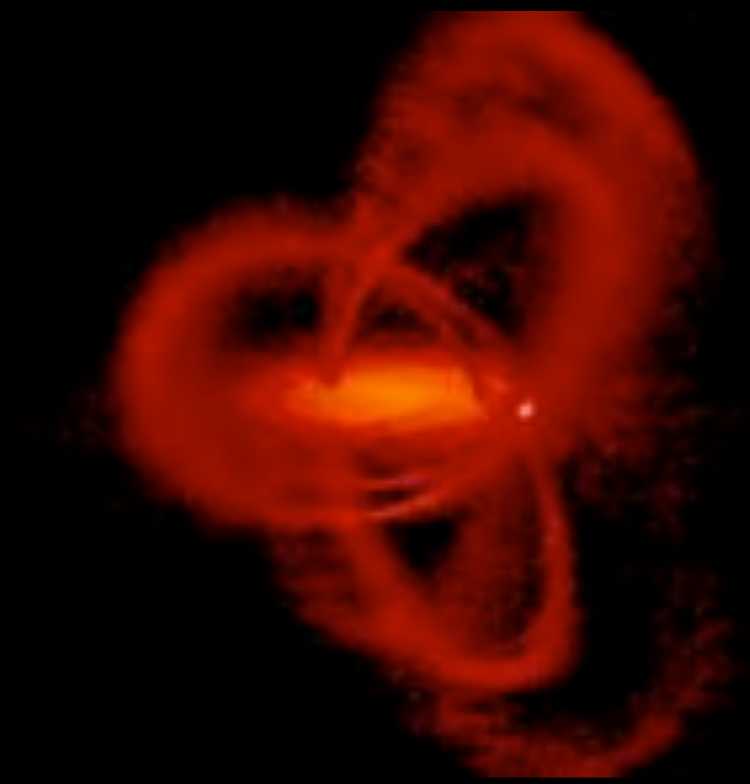

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© Martin et al.

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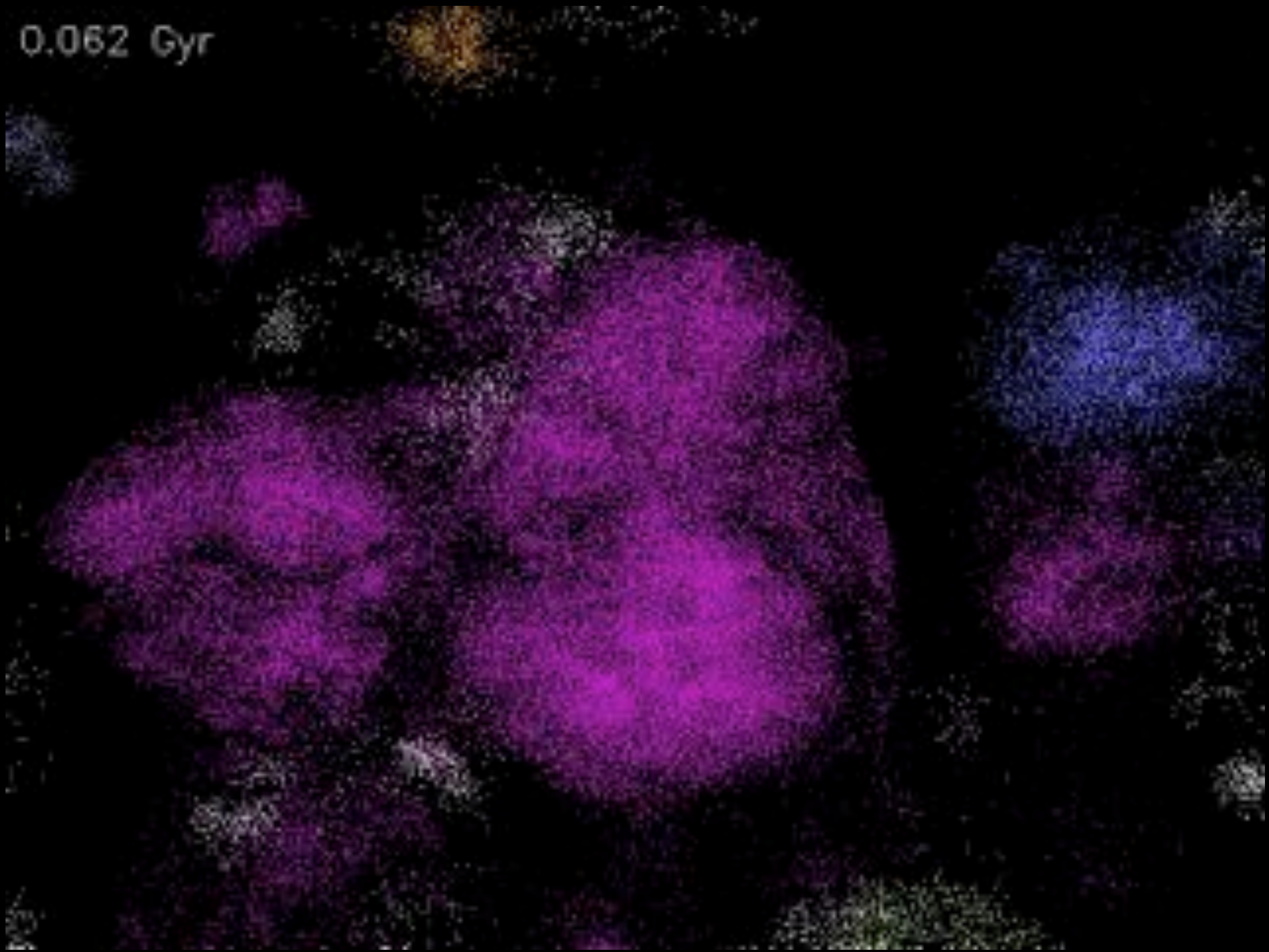
Martinez-Delgado et al., 2010



✓ In the hierarchical cosmological context: series of cold accretion, major and minor merger events. Importance varying with time and environment

➡ each event generate its own fine structures, which may be destroyed by the following event

➡ The mass assembly of galaxies may be reconstructed from their fine structures if their survival time is known

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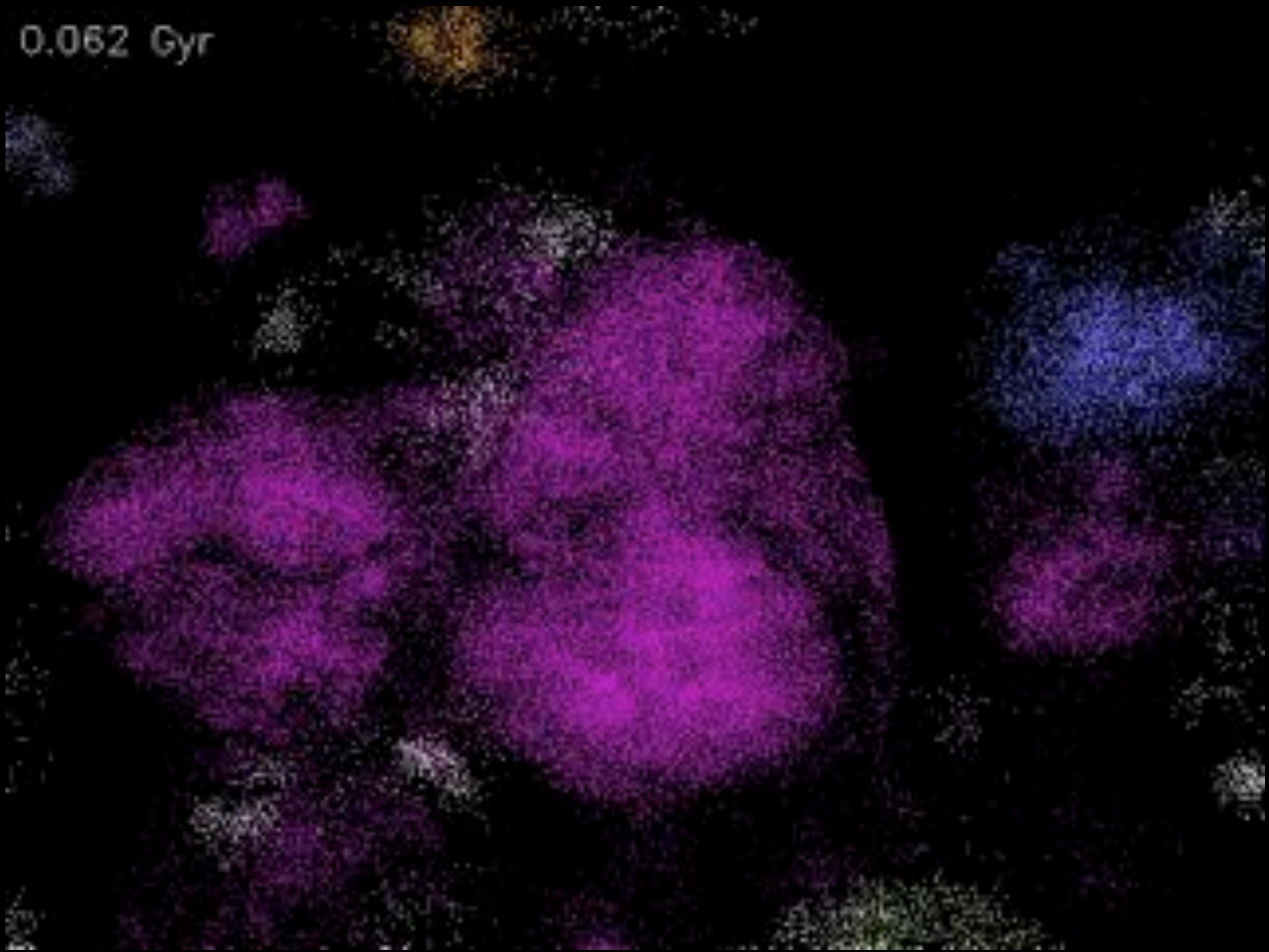

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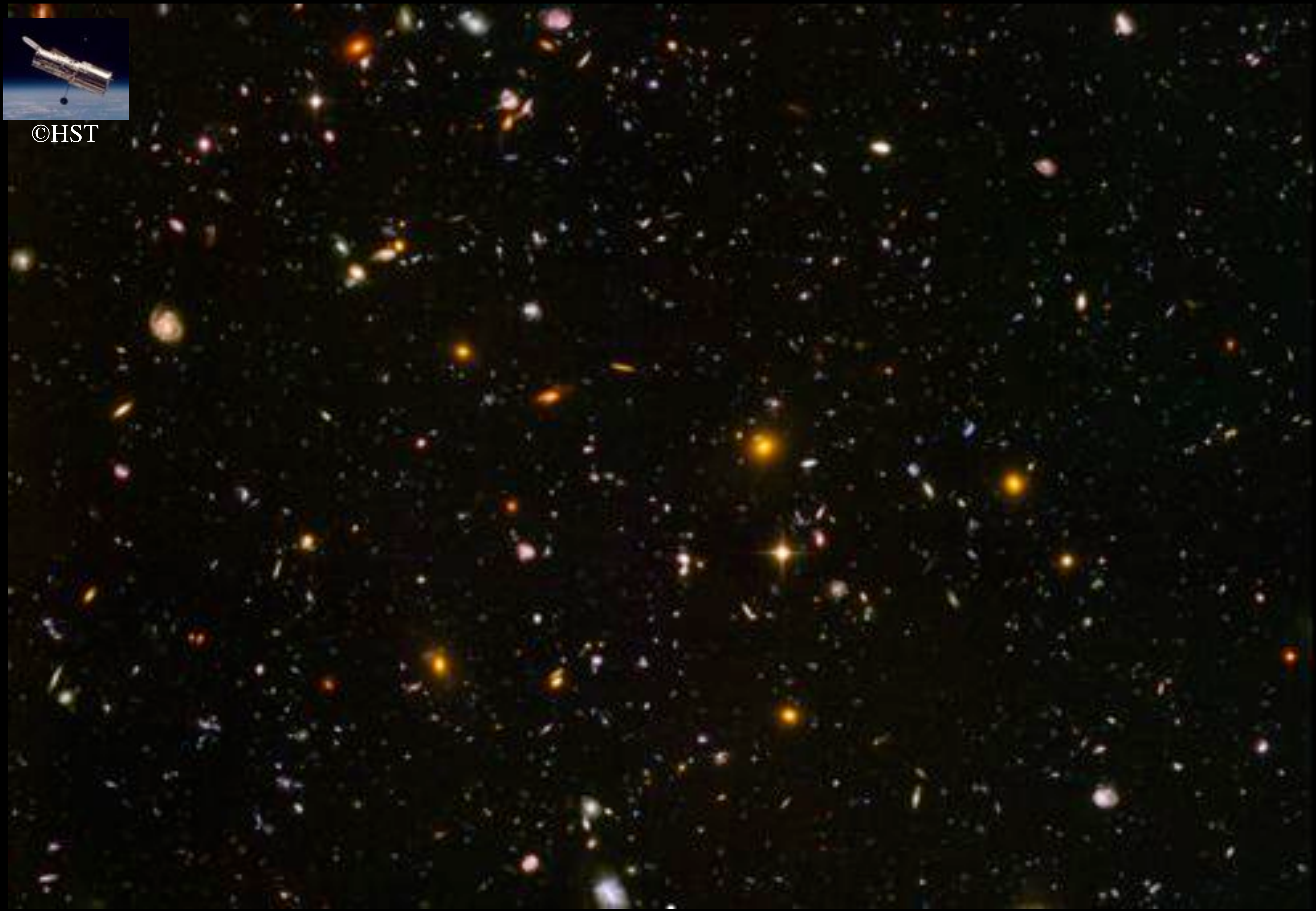
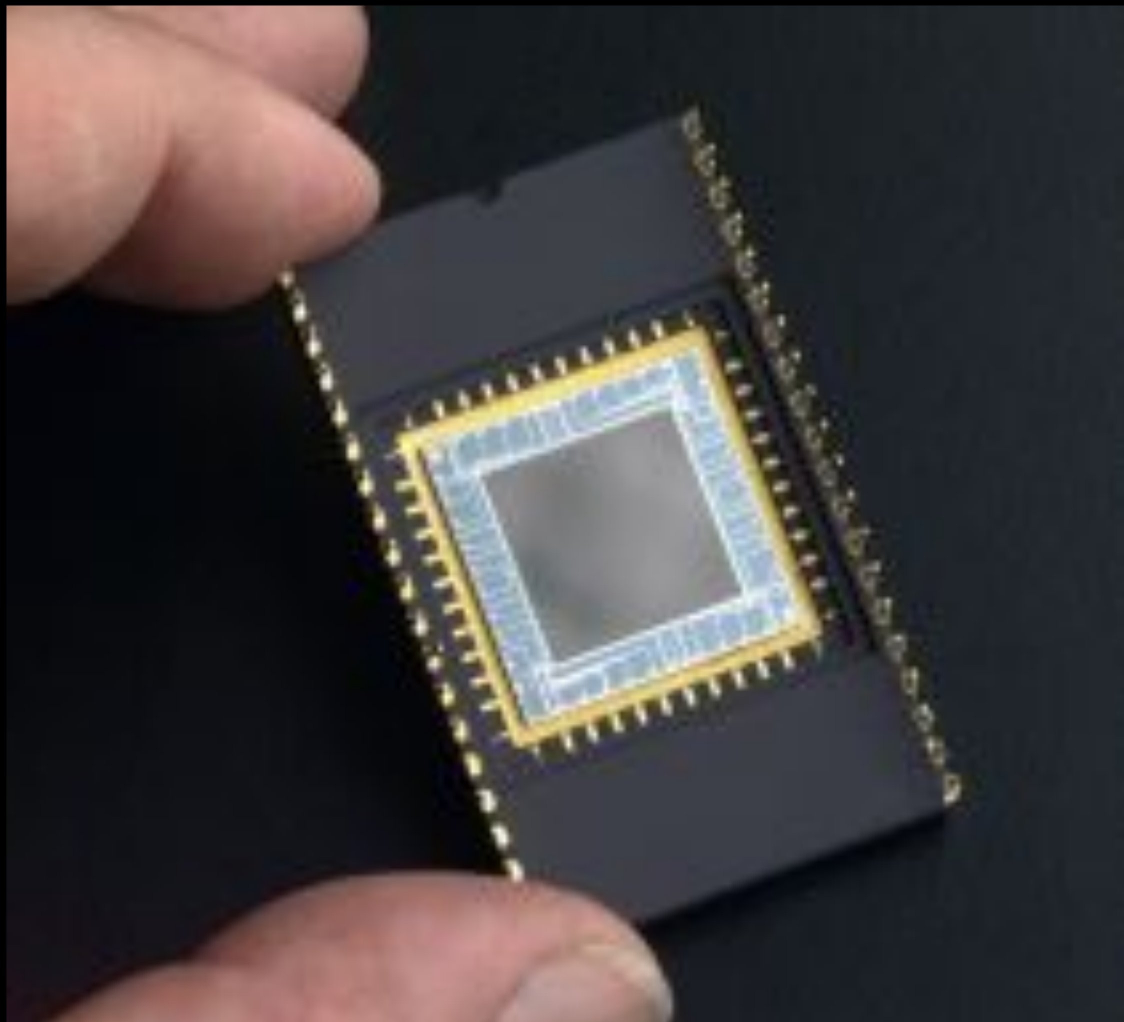
Deep optical imaging à la HST?



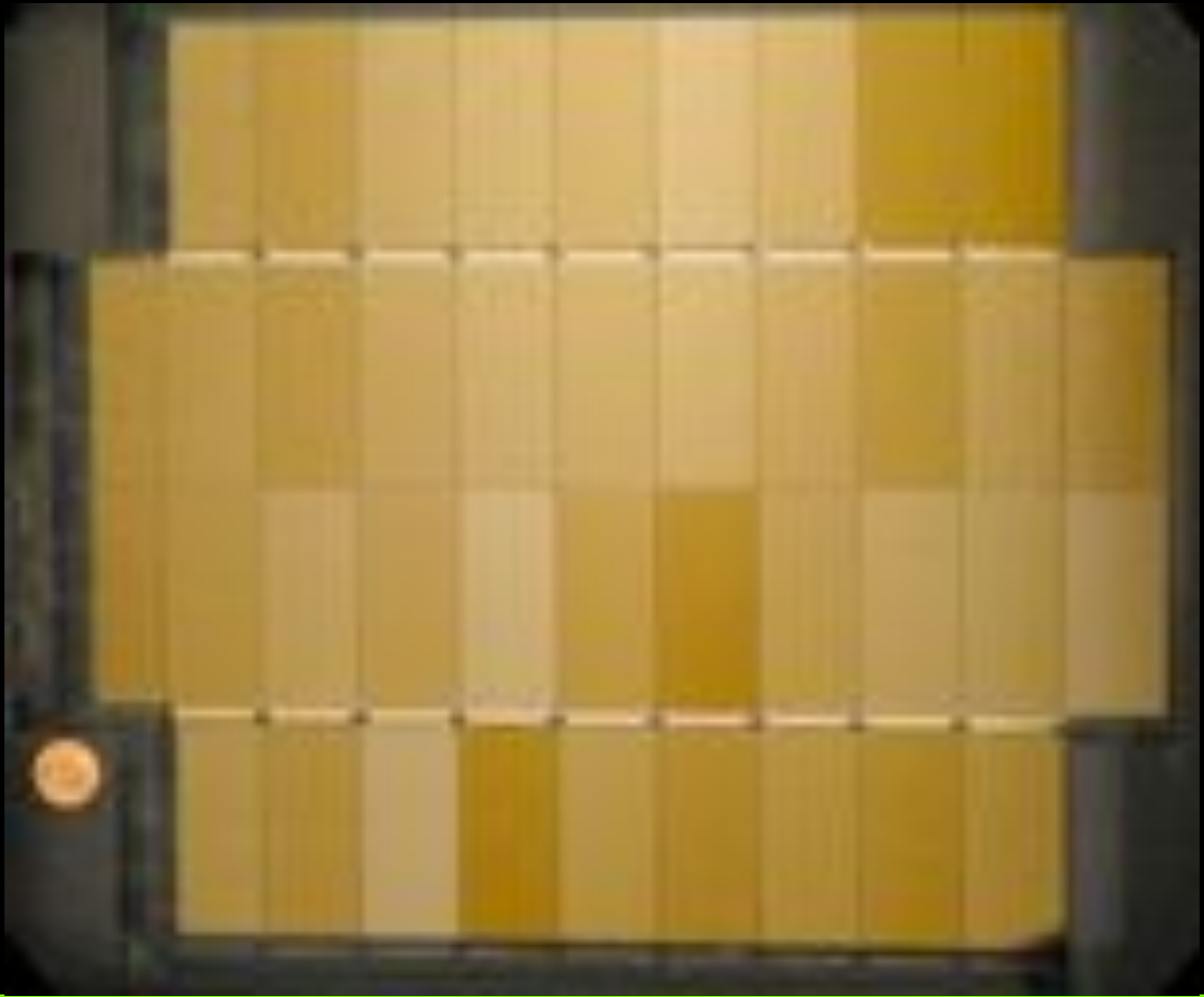


CCDs

- Detecting the extended faint diffuse light has become a challenge with the advent of CCDs

Photographic plate

• With the advent of mosaic of CCDs, the field of view has increased again.



• Coupling with specific observing techniques and data reduction procedures, this diffuse extended light can be recovered

Issues of deep imaging with current detectors

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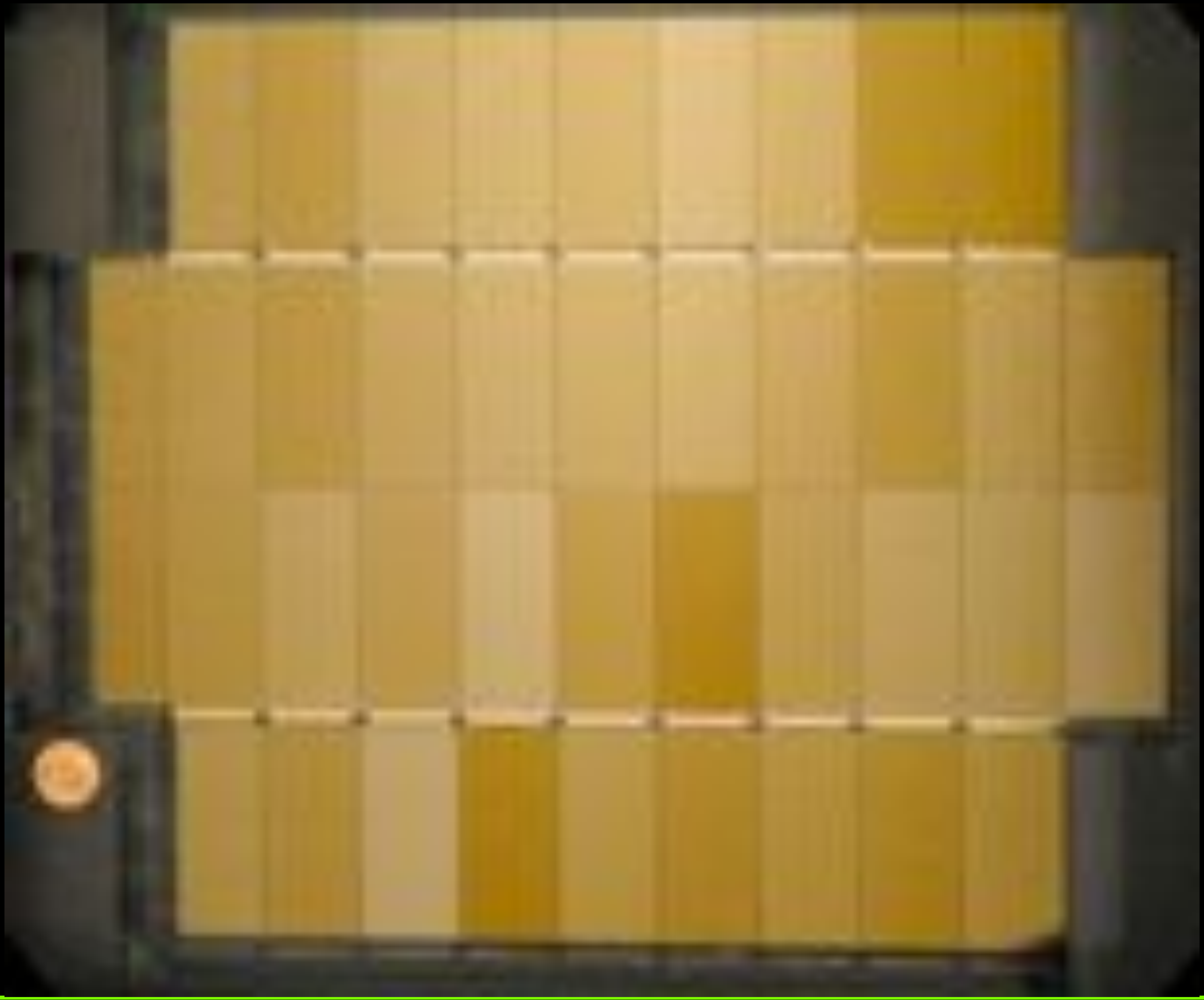

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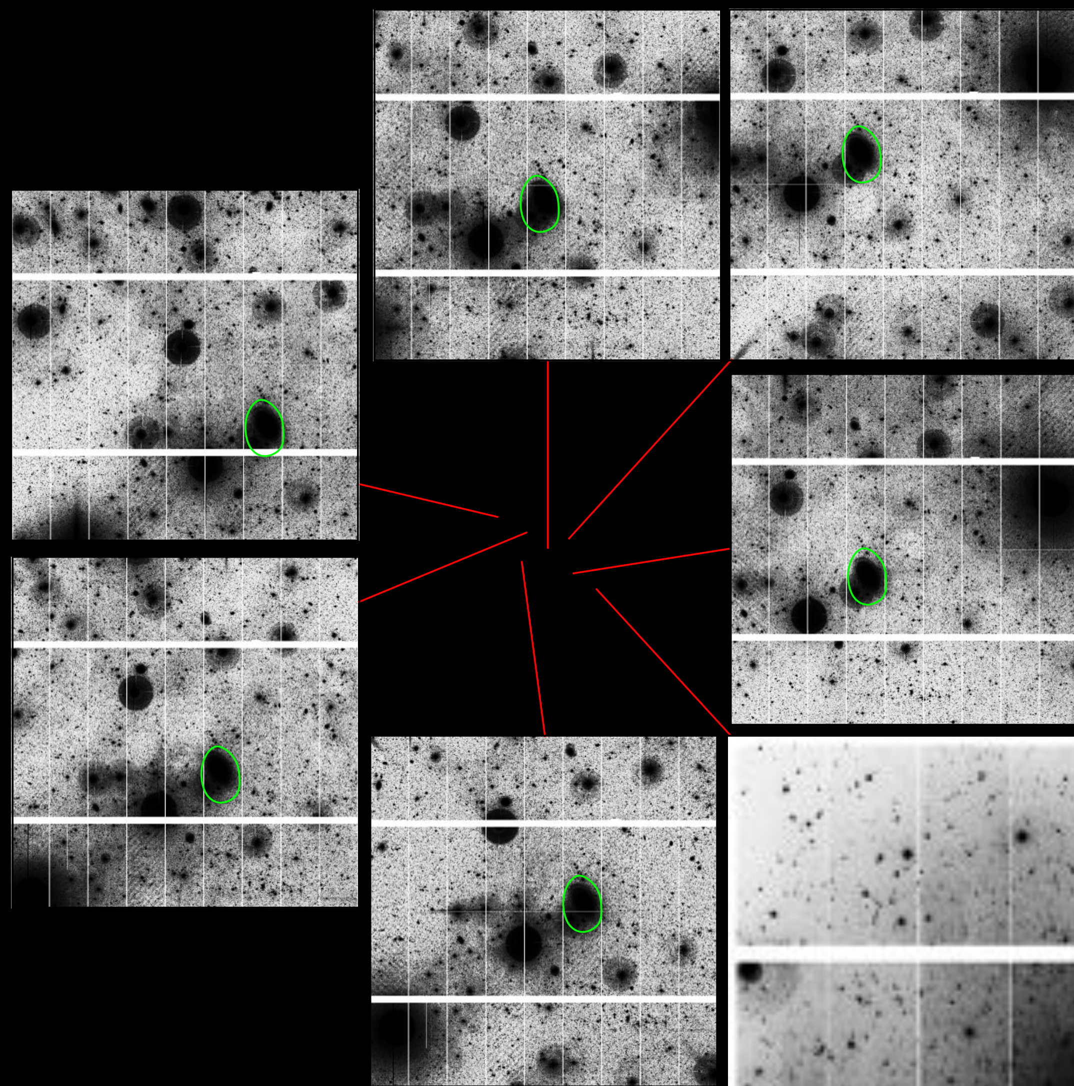
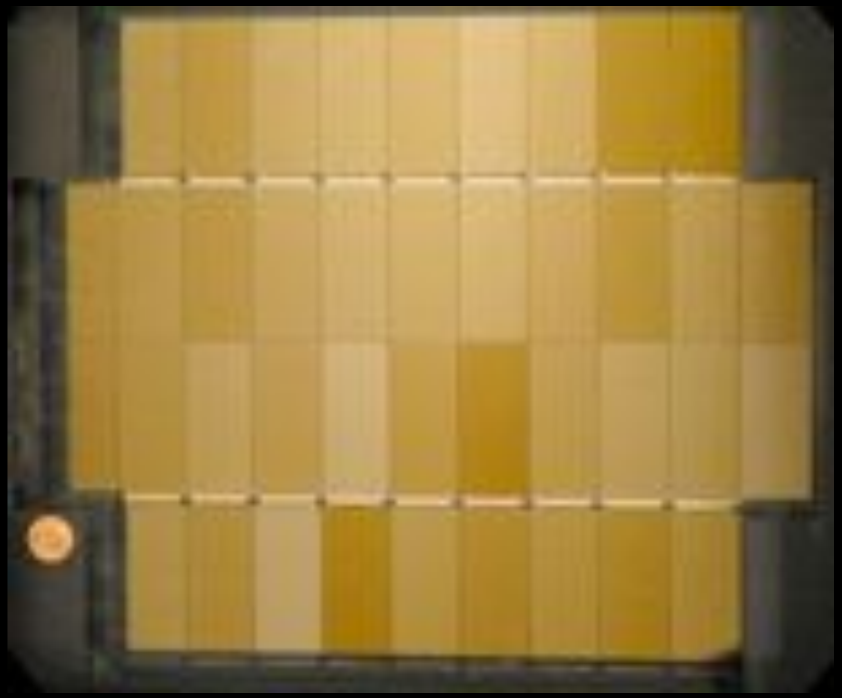
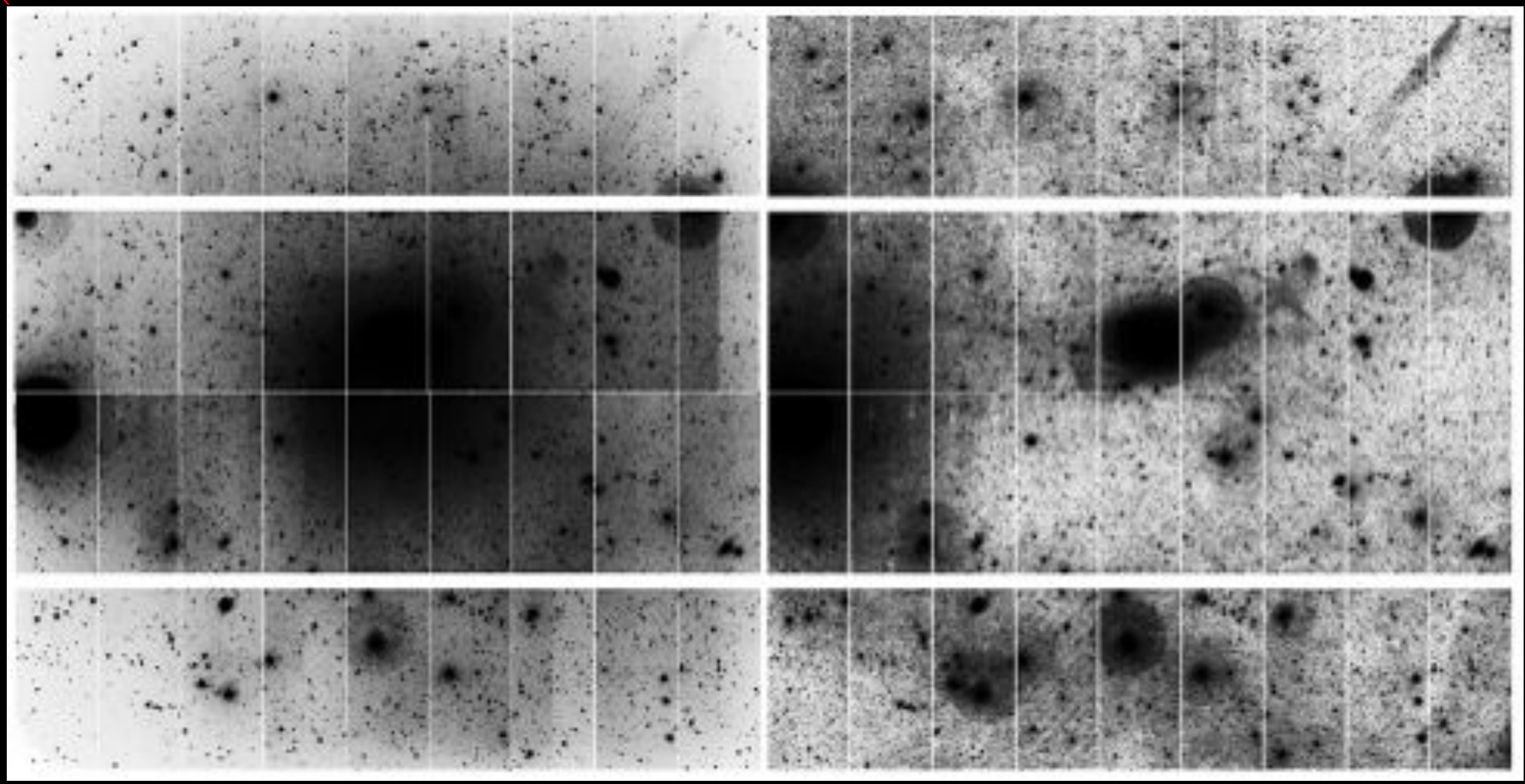






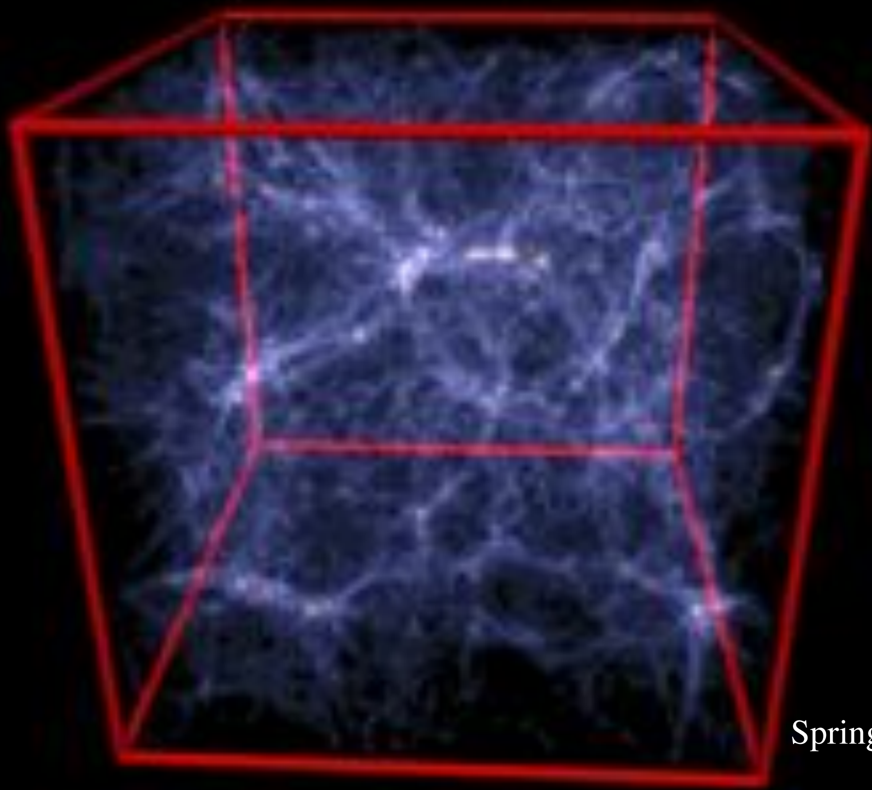
- Technique inherited from infrared astronomy

Probing the mass assembly of massive galaxies with ultra-deep imaging

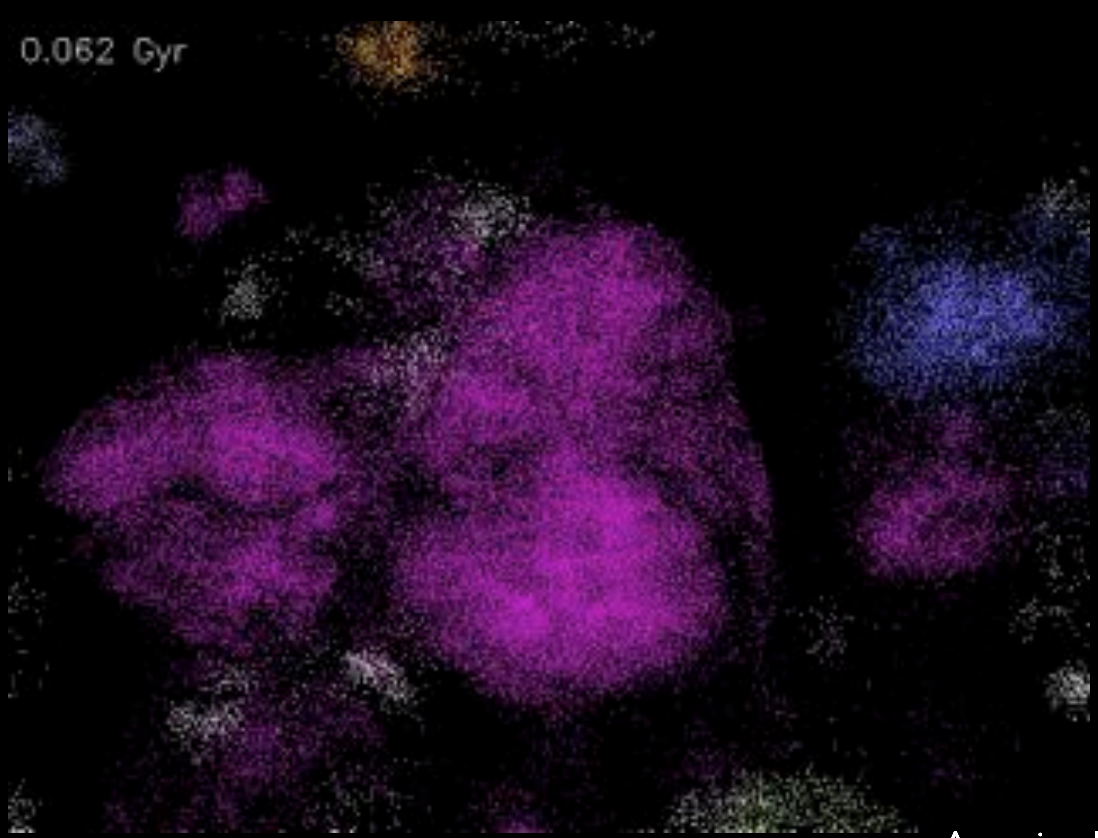
Pierre-Alain Duc

Motivations: predictions from models

Merger based

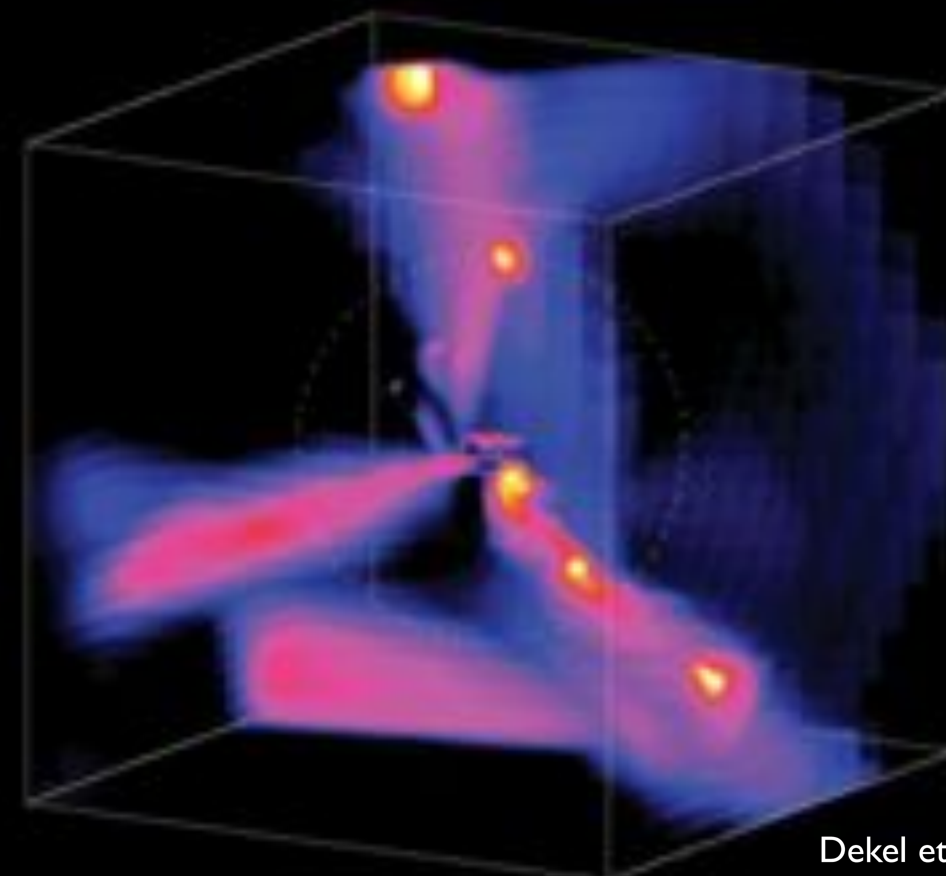


Springel et al, 2013

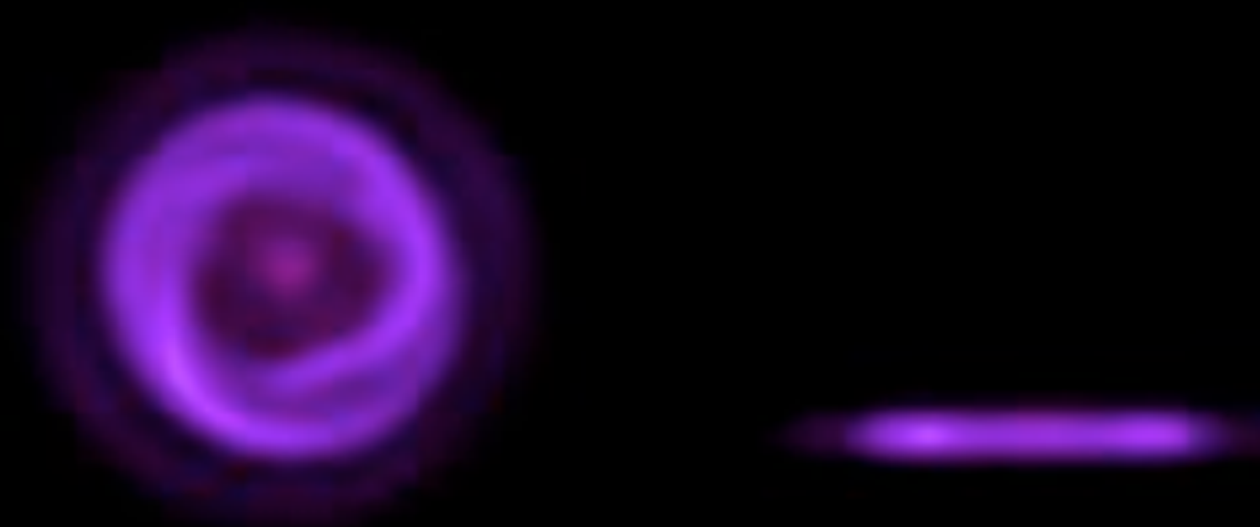


Aquarius, Helmi et al.

Accretion based



Dekel et al.



Bournaud et al.

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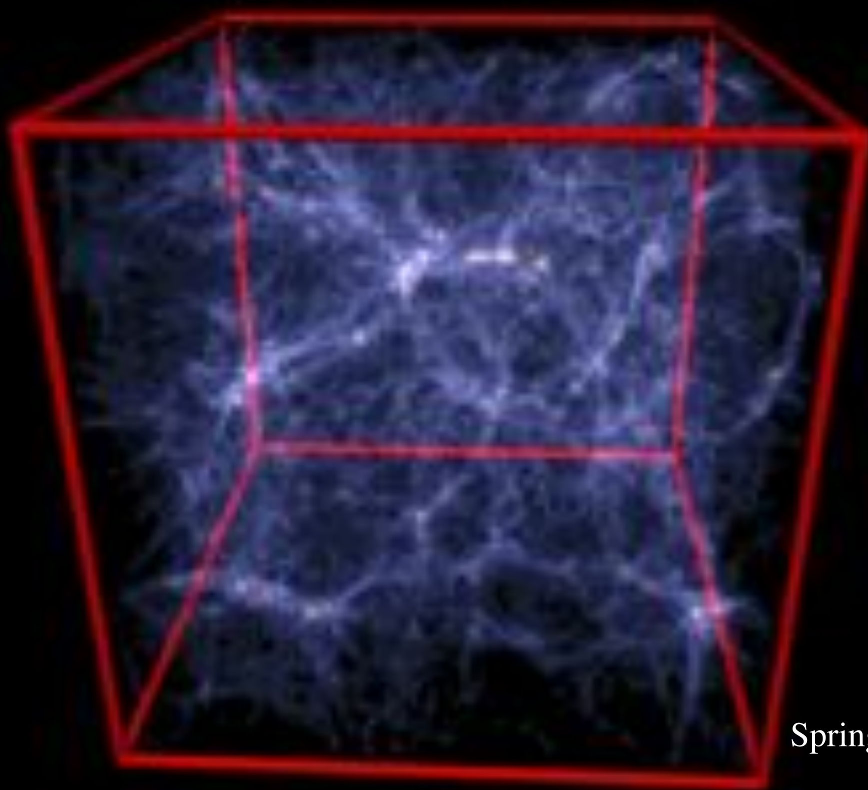
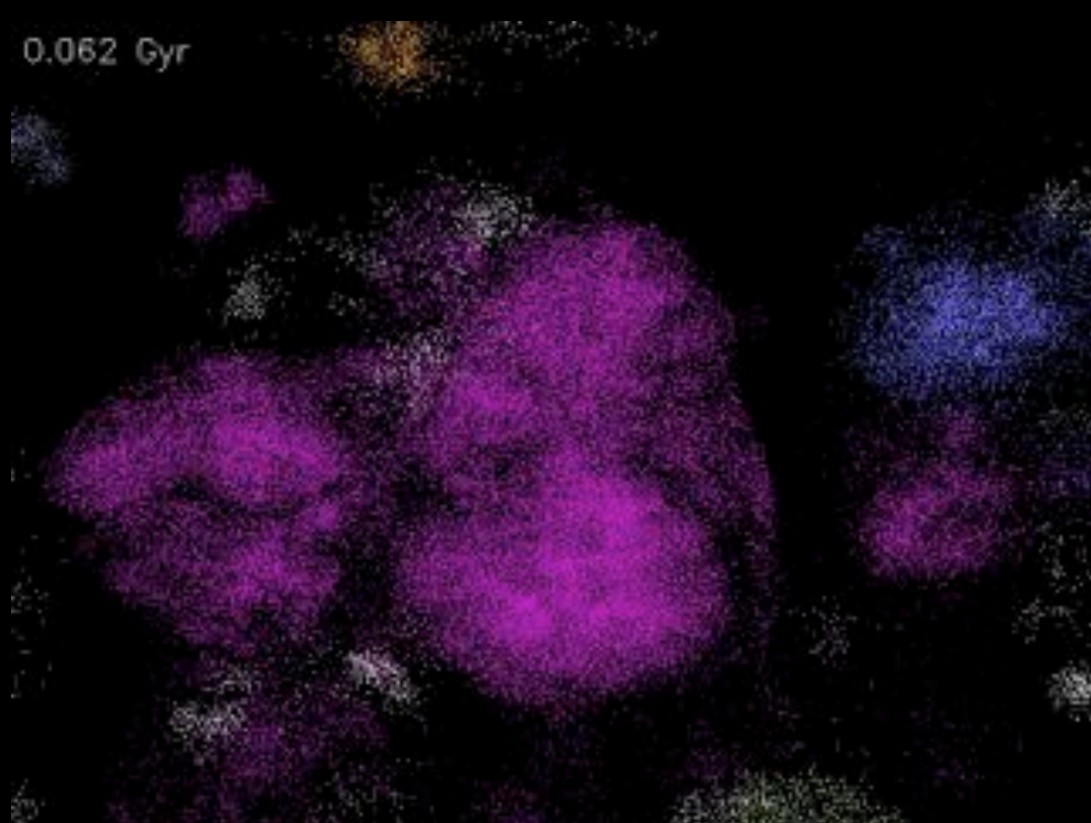


Springel et al, 2013



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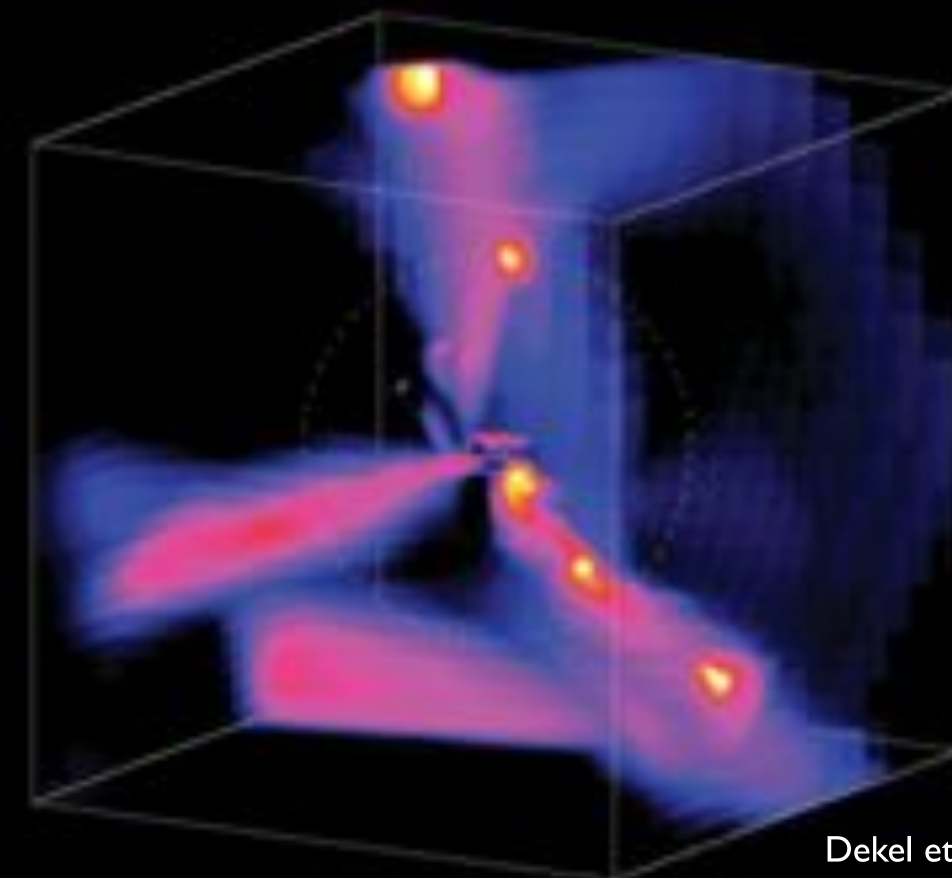

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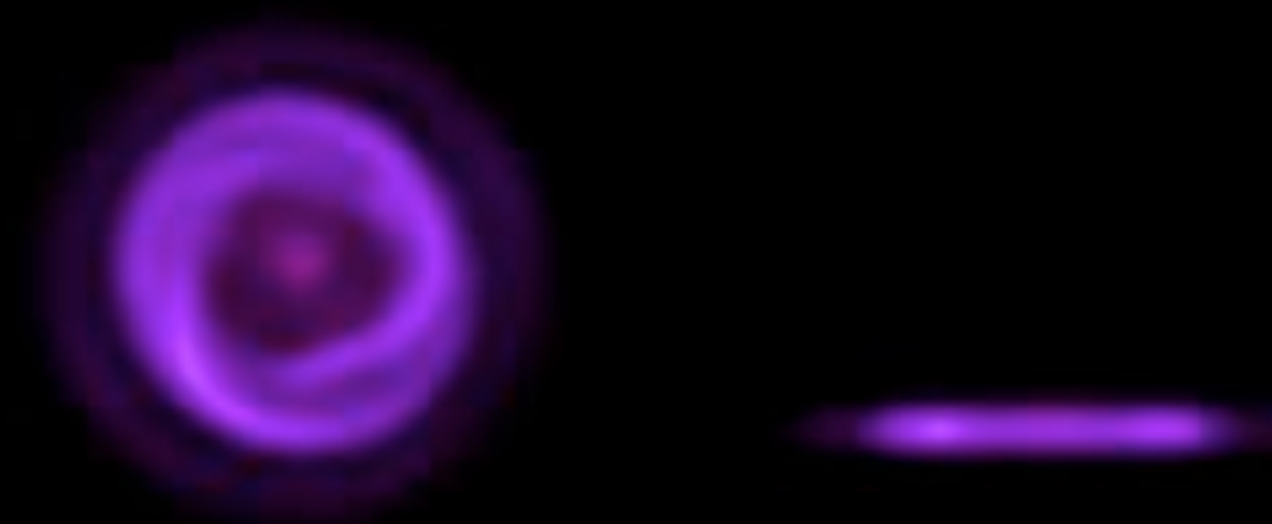

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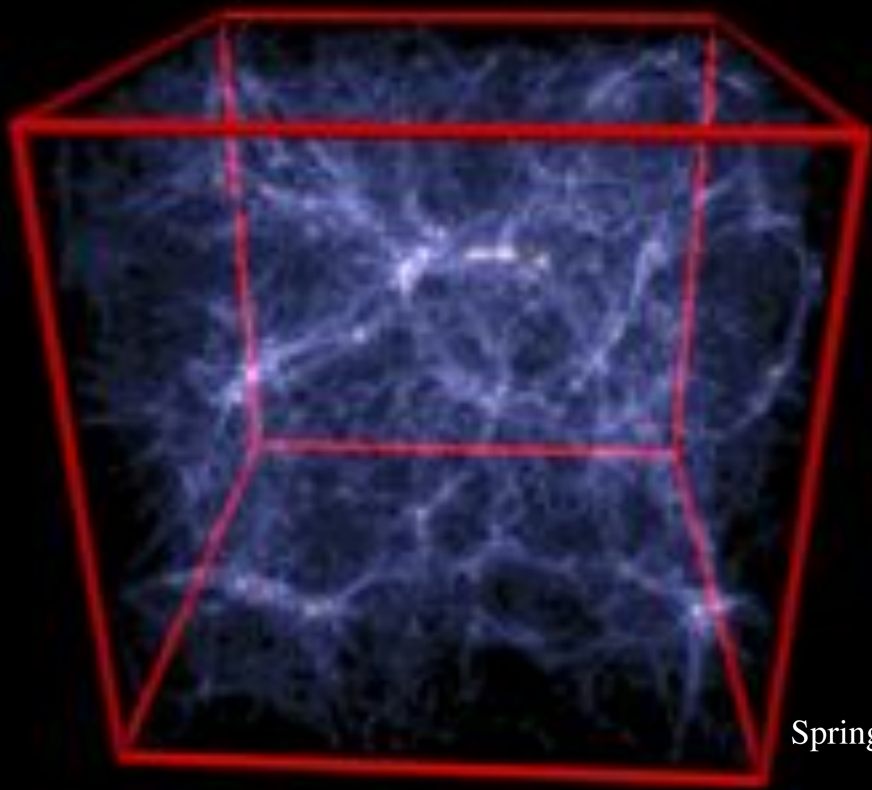
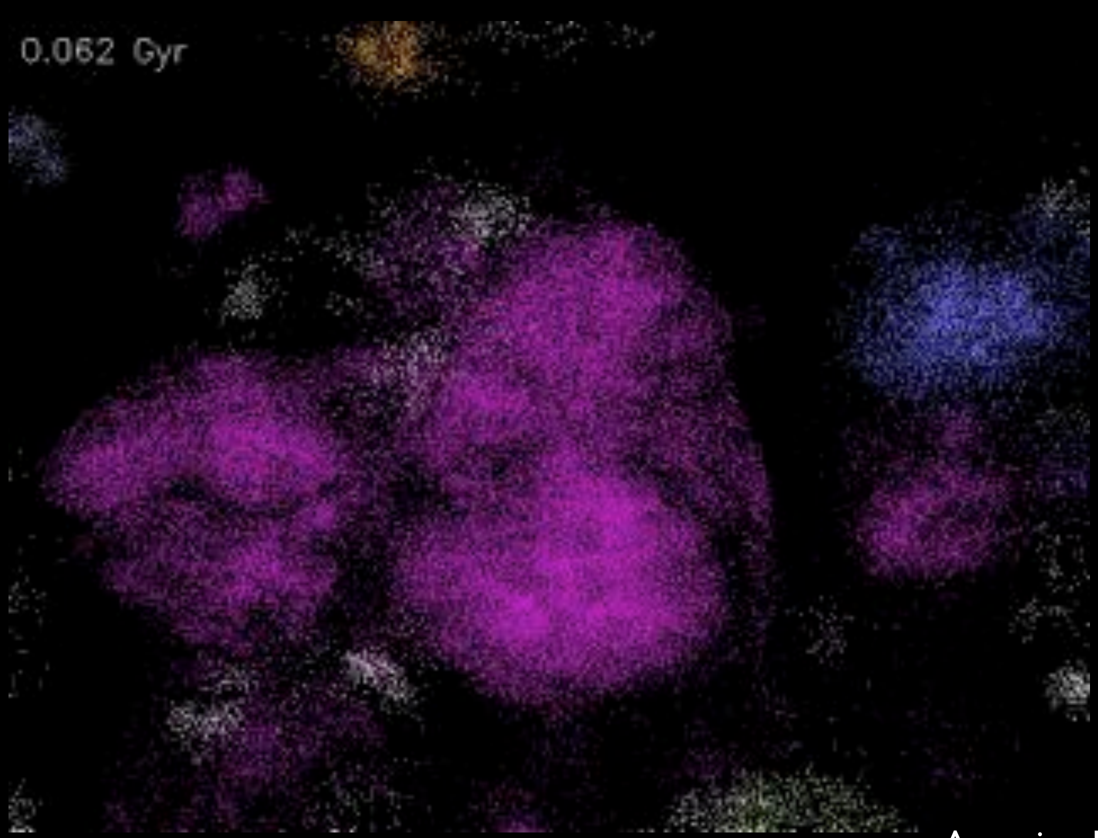


Springel et al, 2013



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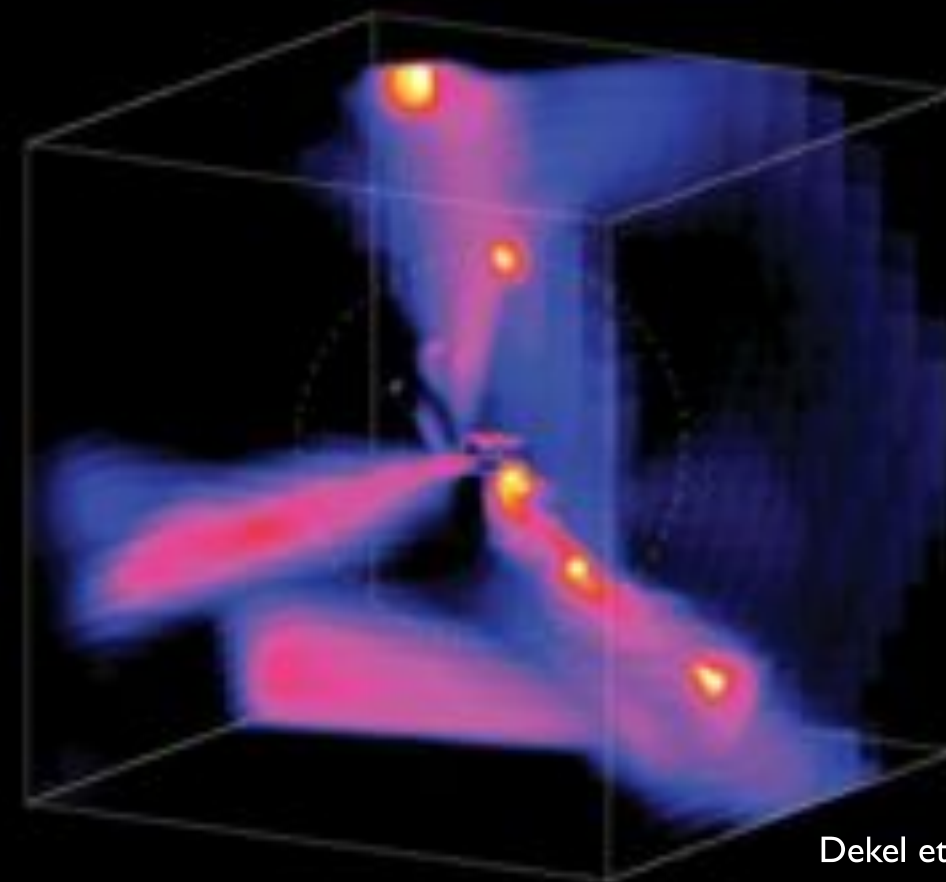

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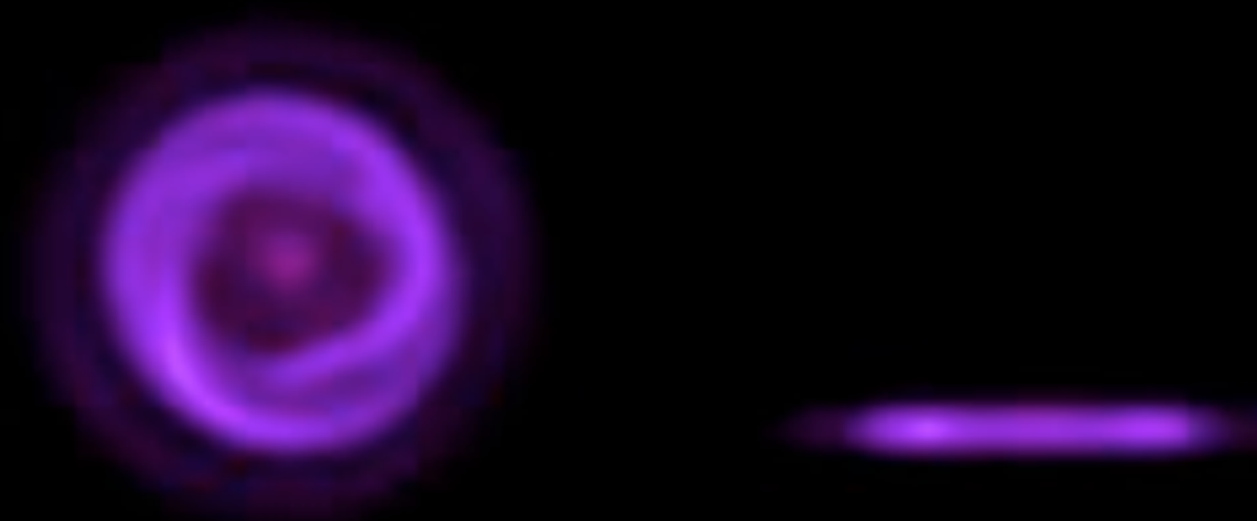

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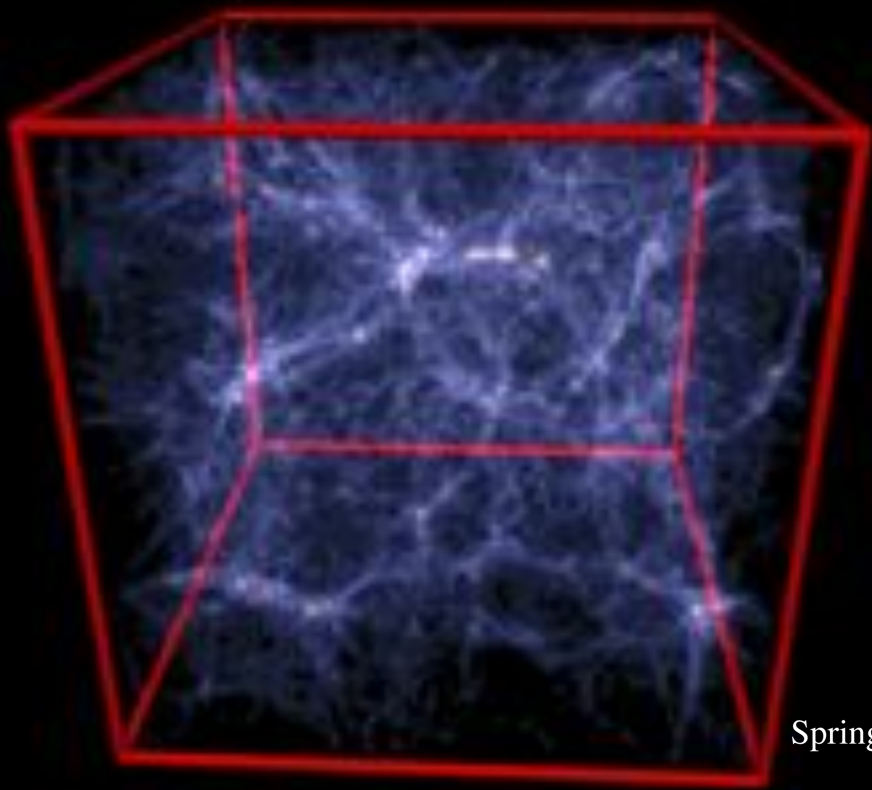

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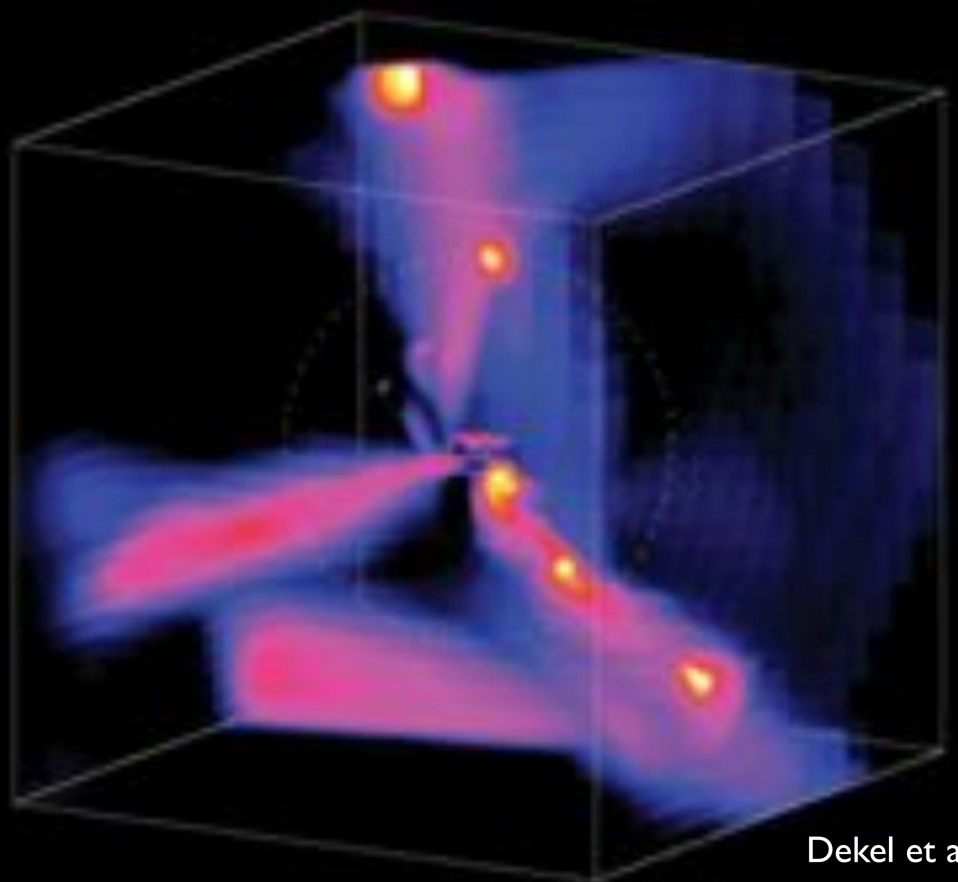
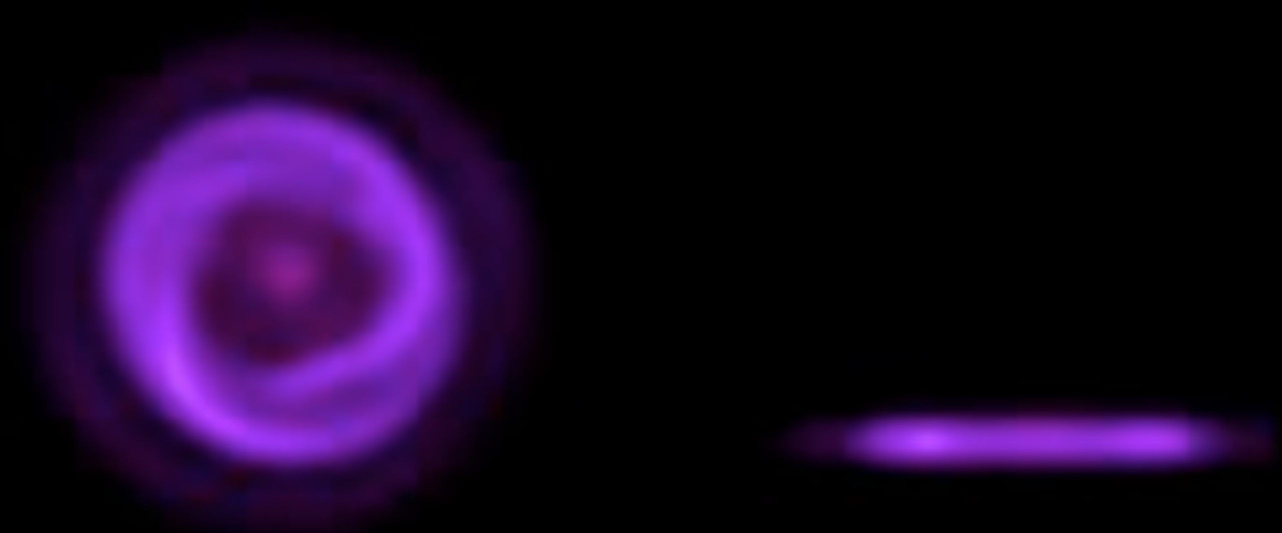
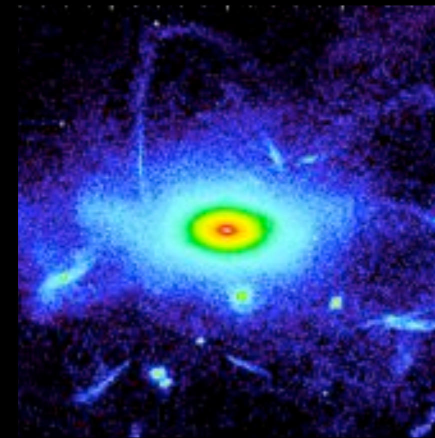


Dekel et al.



Bournaud et al.

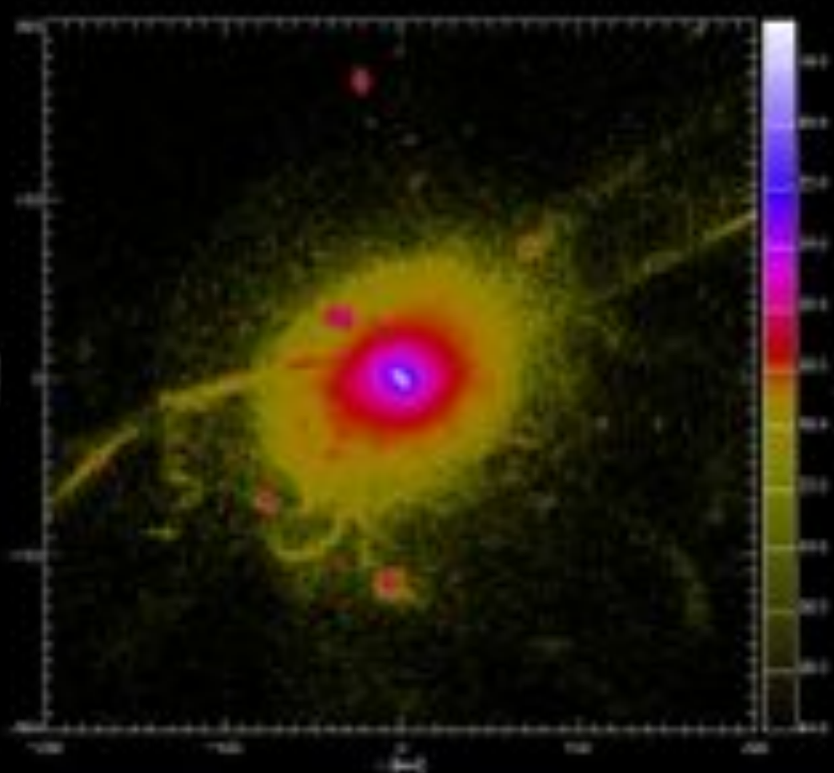
Surface brightness limitations



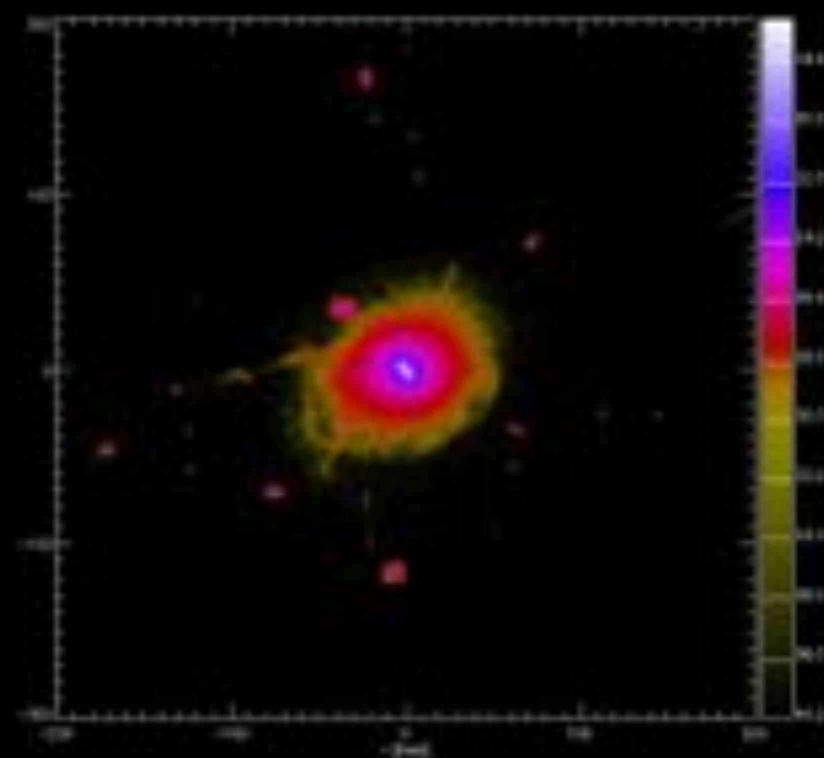
✓ At unlimited sensitivity

• *Simulated surface brightness maps*

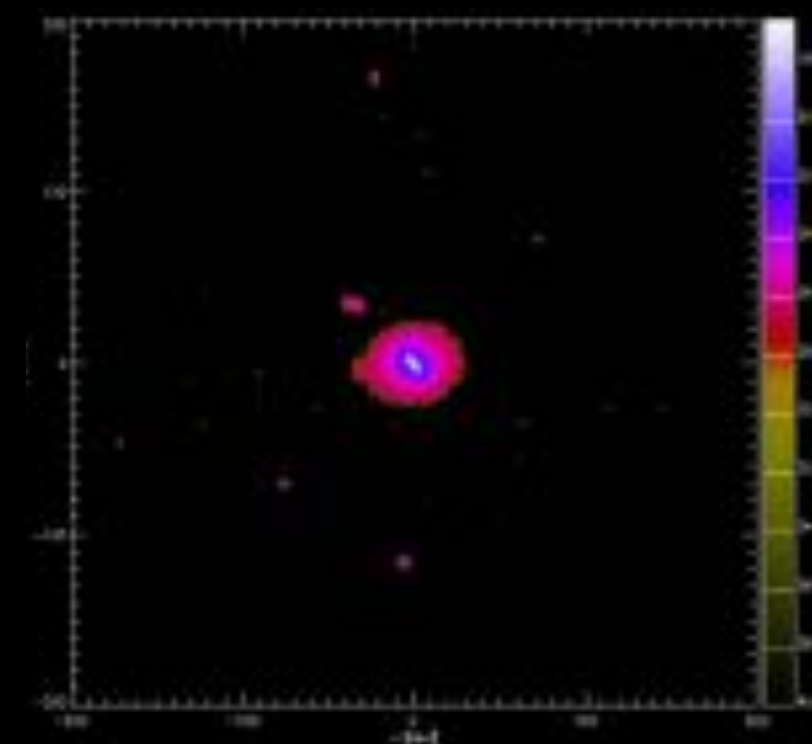
Michel-Dansac et al, 2013



✓ At 32 mag/arcsec^2



✓ Cutting at 29 mag/arcsec^2



✓ Cutting at 27 mag/arcsec^2

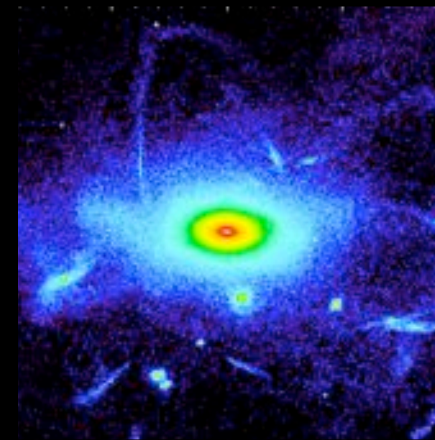
• Surface brightness maps which are reached from star counts (e.g. PAndAS)
For Local Group galaxies

• Surface brightness limit of on-going ultra-deep surveys probing the integrated diffuse light of nearby galaxies

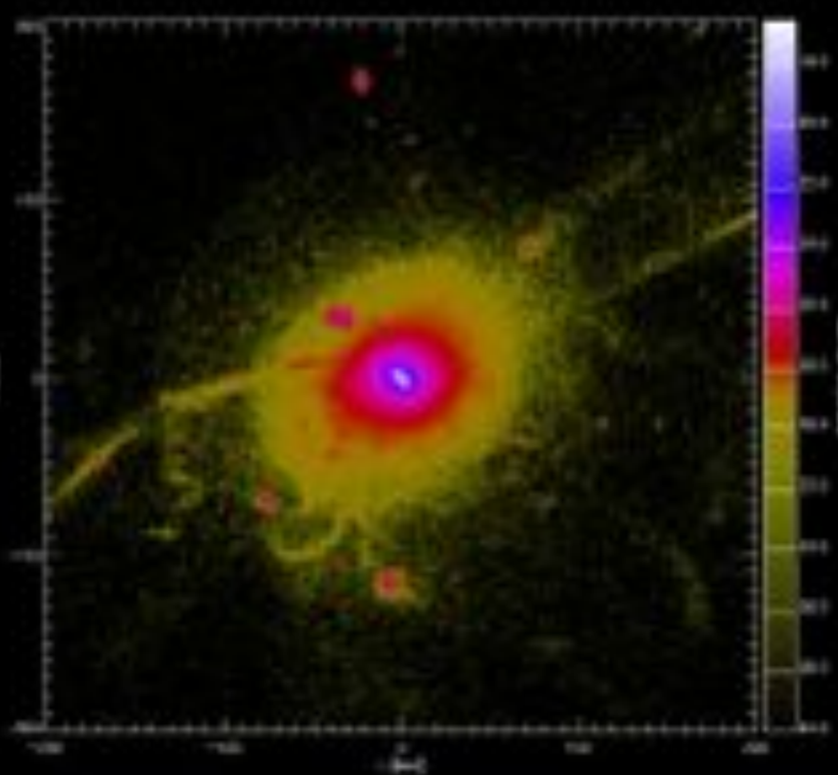
• Surface brightness limit of traditional images of nearby galaxies (SDSS, CFHTLS)

Surface brightness limitations

- *Simulated surface brightness maps*



Michel-Dansac et al, 2013



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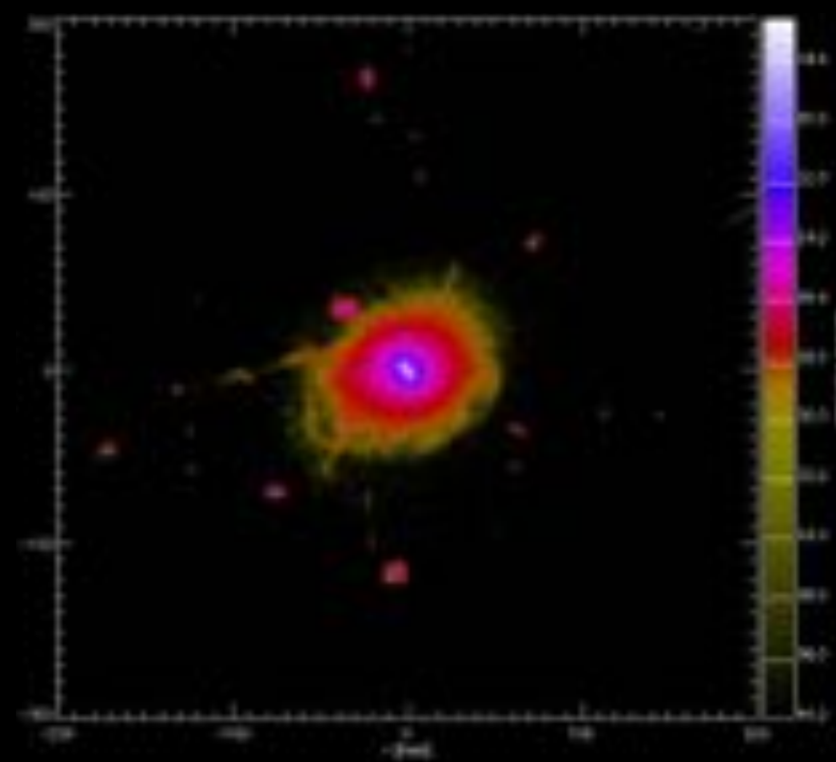

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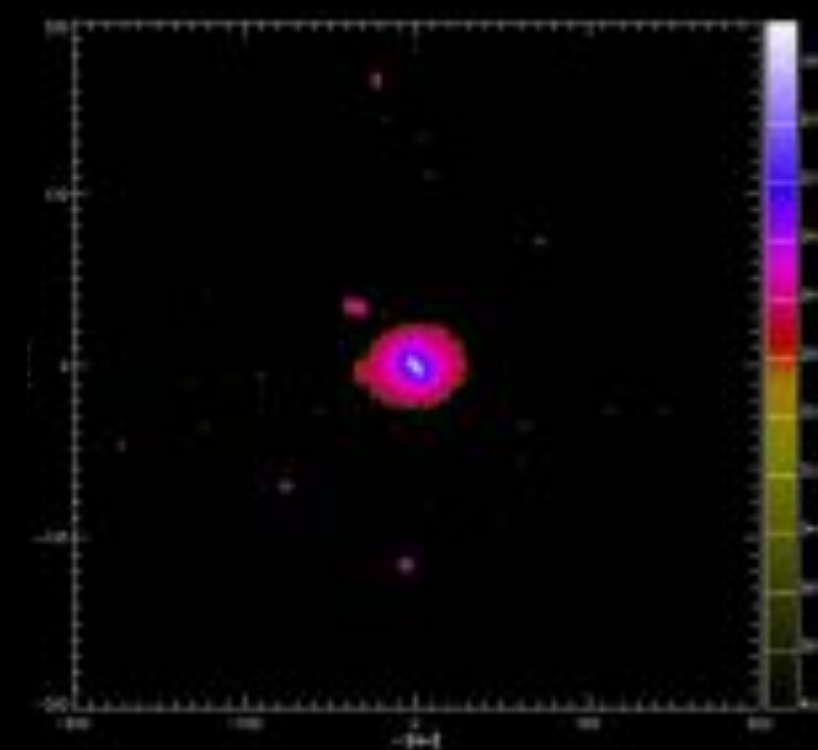

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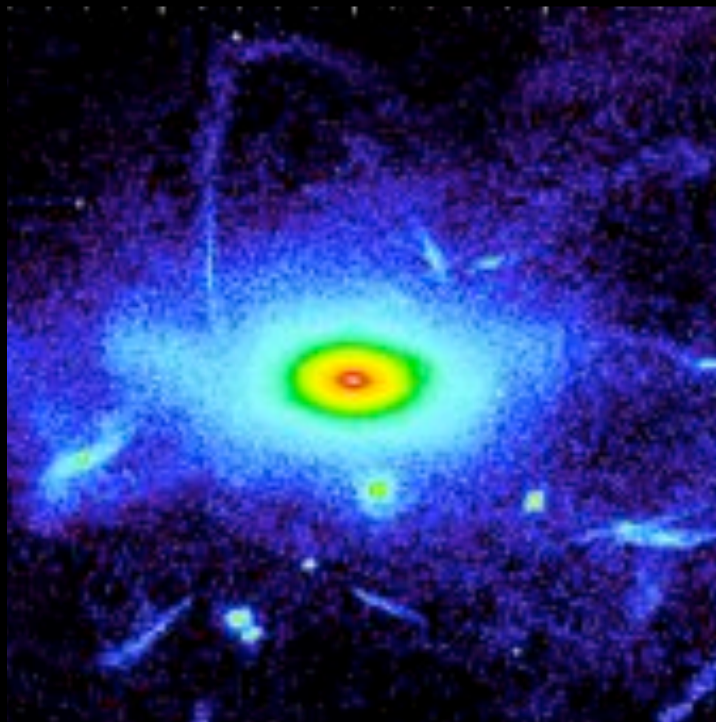
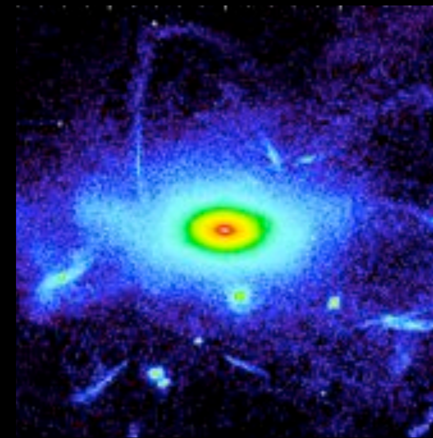


- *Andromeda as seen by PAndAS*

McConnarchie et al, 2011

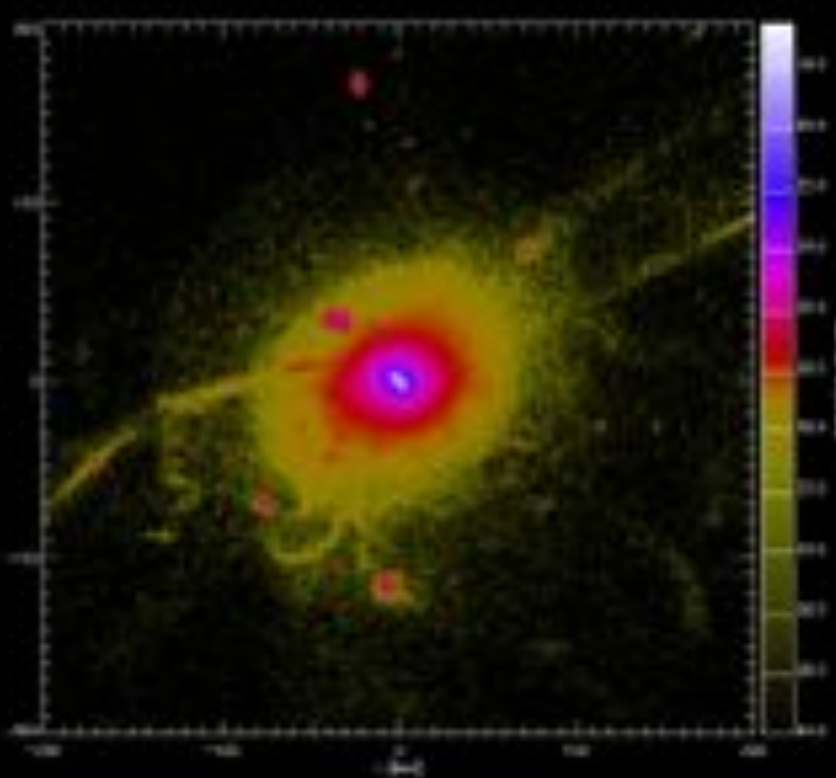
- Should all evolved/massive galaxies ressemble M31 at 32 mag.arcsec^{-2}?

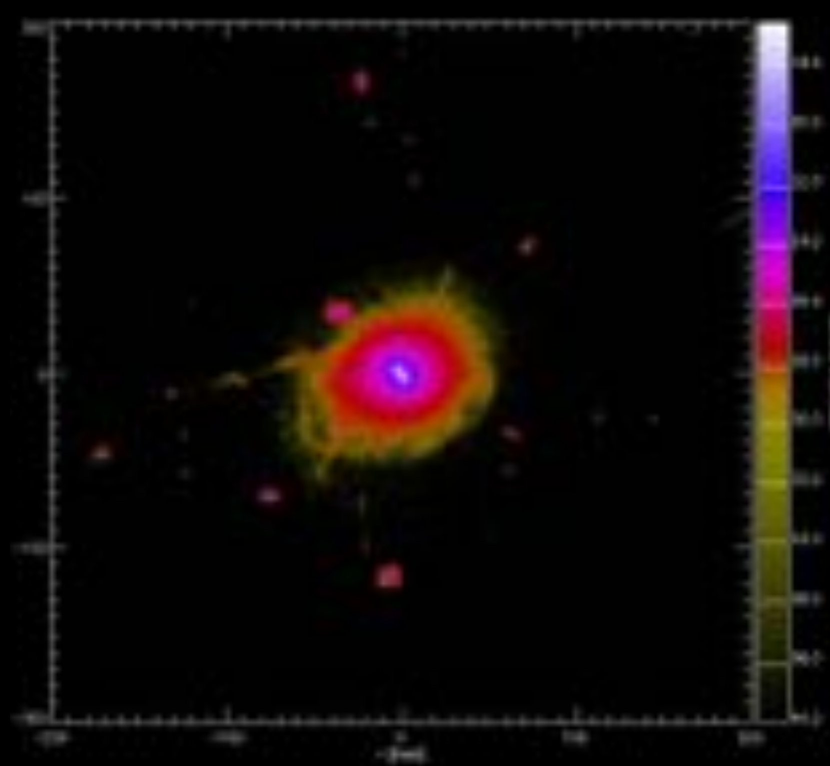
Surface brightness limitations

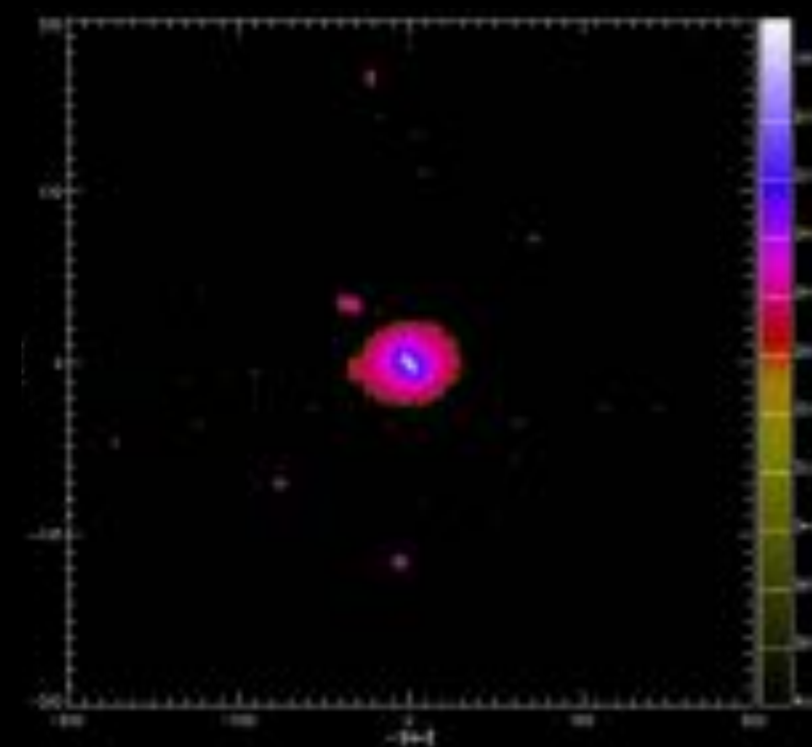


- *Simulated surface brightness maps*

Michel-Dansac et al, 2013







✓ At 32 mag/arcsec²

✓ Cutting at 29 mag/arcsec²

✓ Cutting at 27 mag/arcsec²

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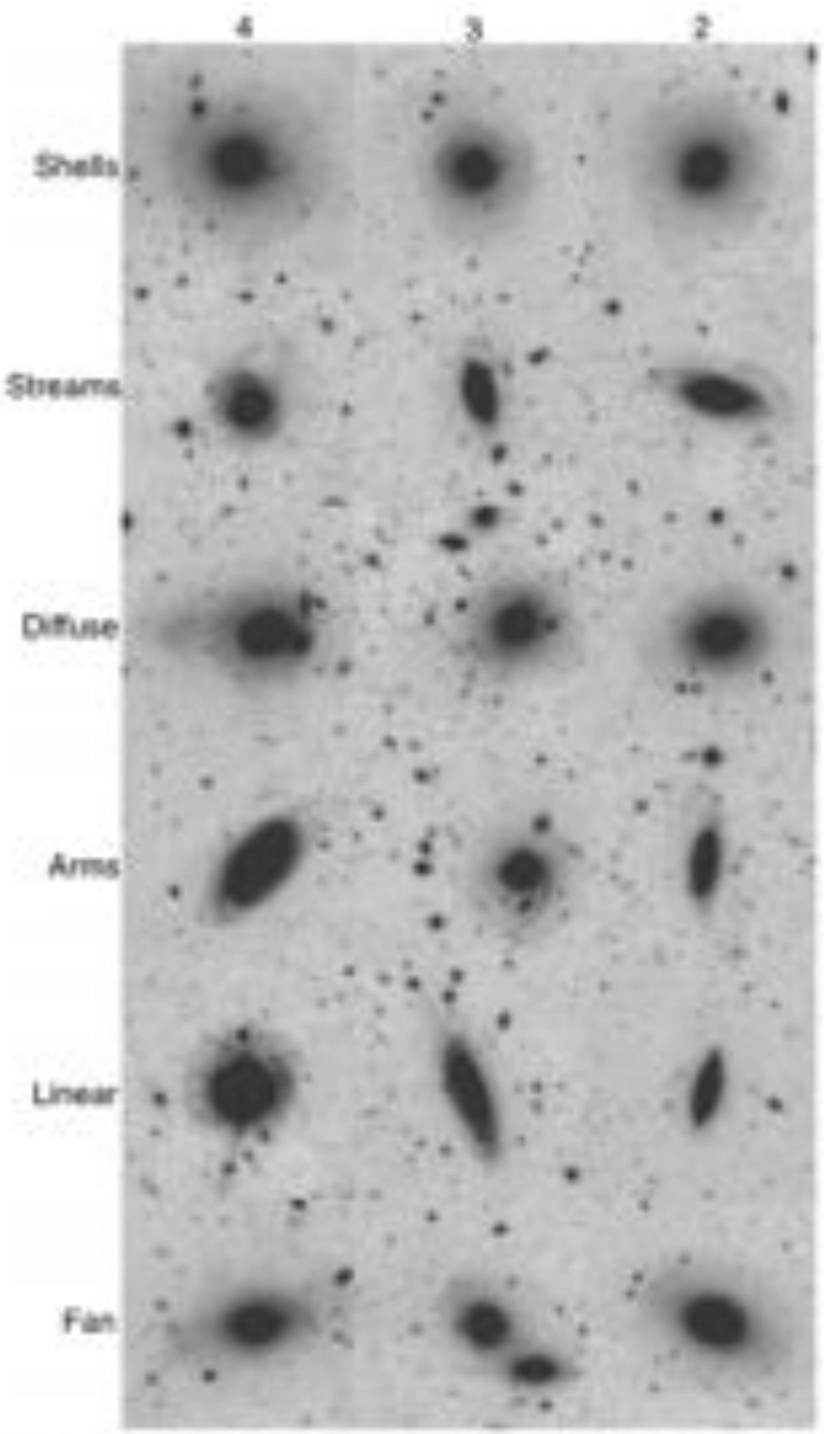
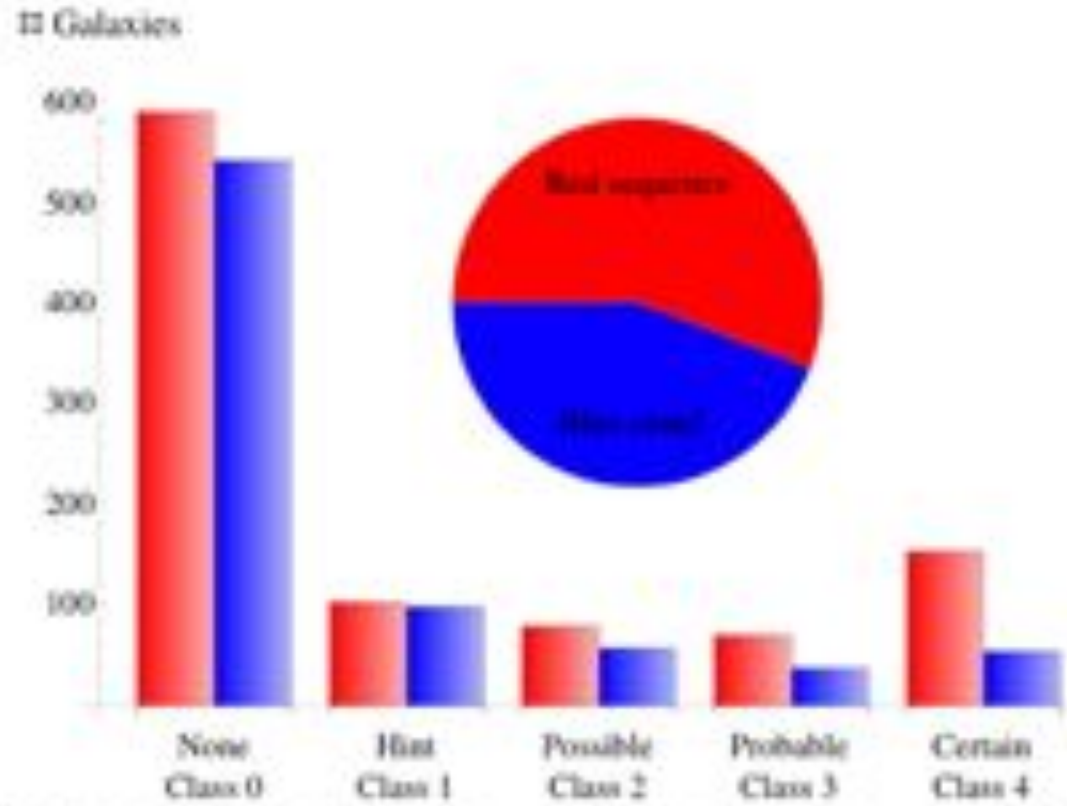
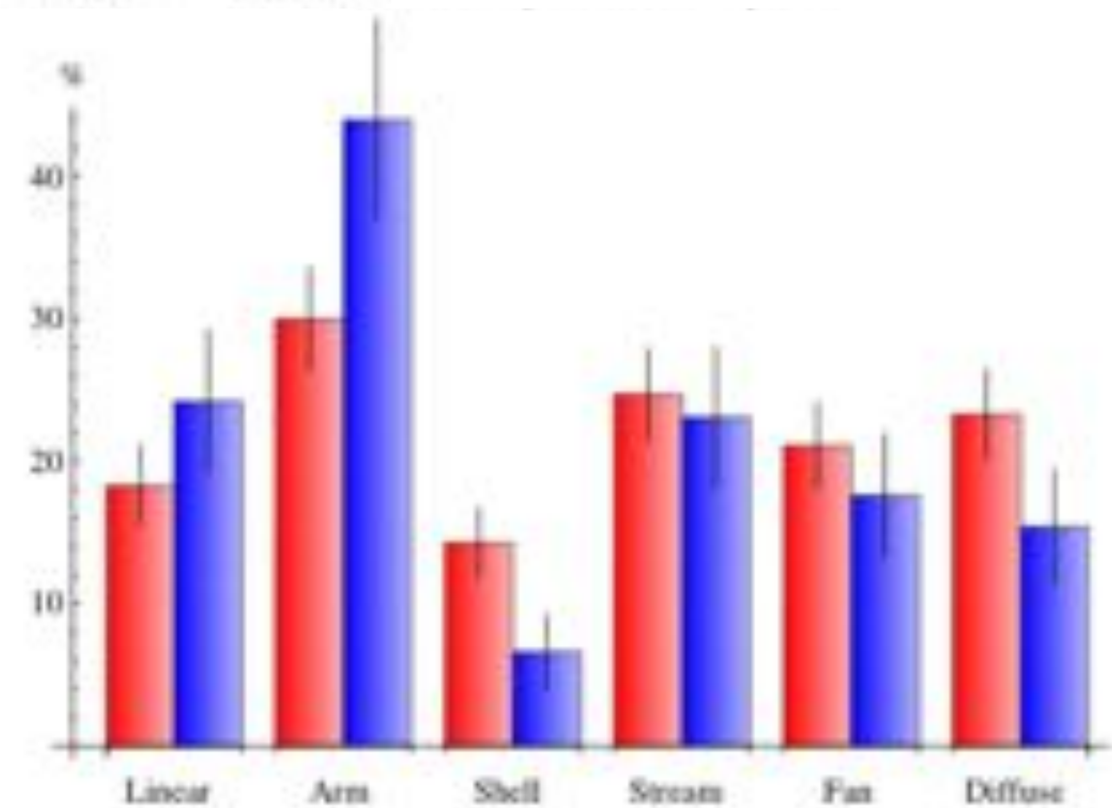
Surface brightness limitations

CFHTLS



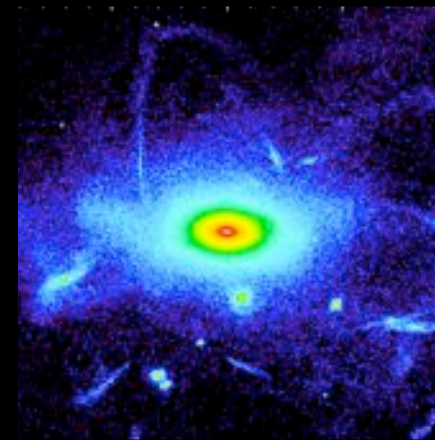
Atkinson et al., 2013





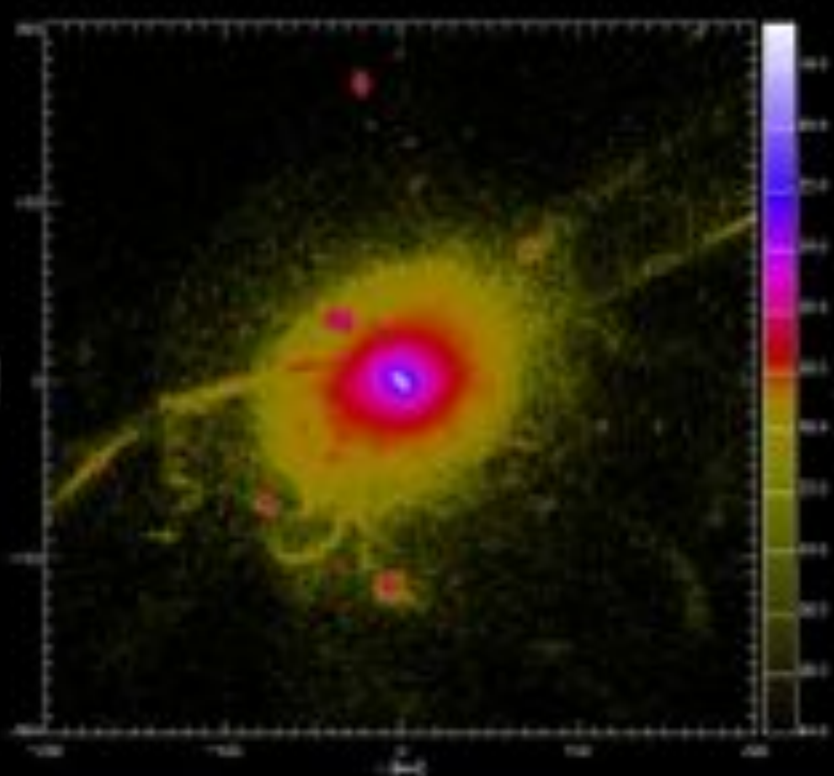
- 12% galaxies with Mr<-19.3 show tidal features

Surface brightness limitations



• *Simulated surface brightness maps*

Michel-Dansac et al, 2013



✓ At 32 mag/arcsec^2

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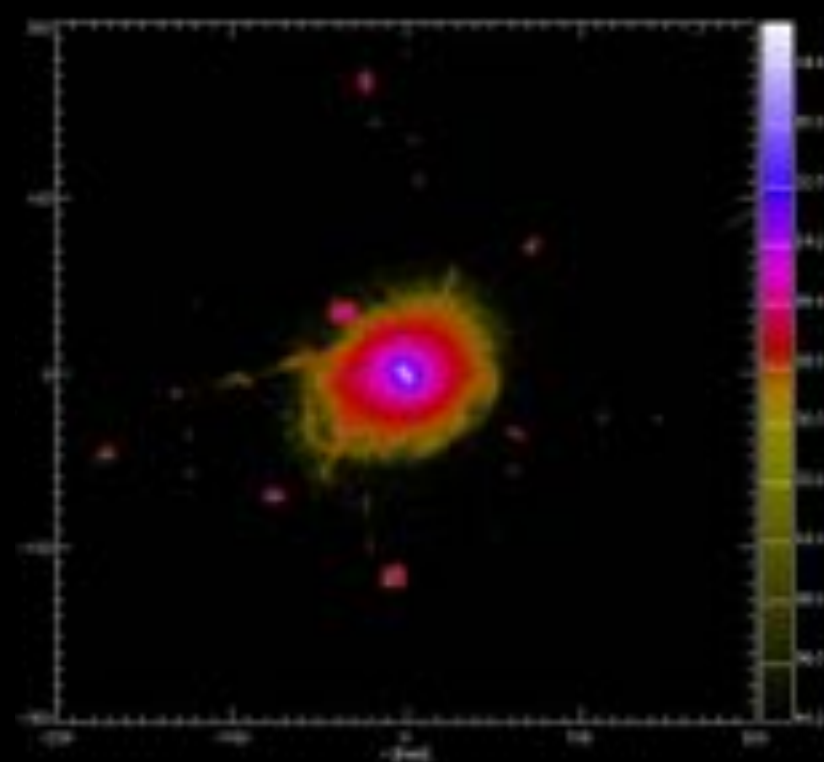
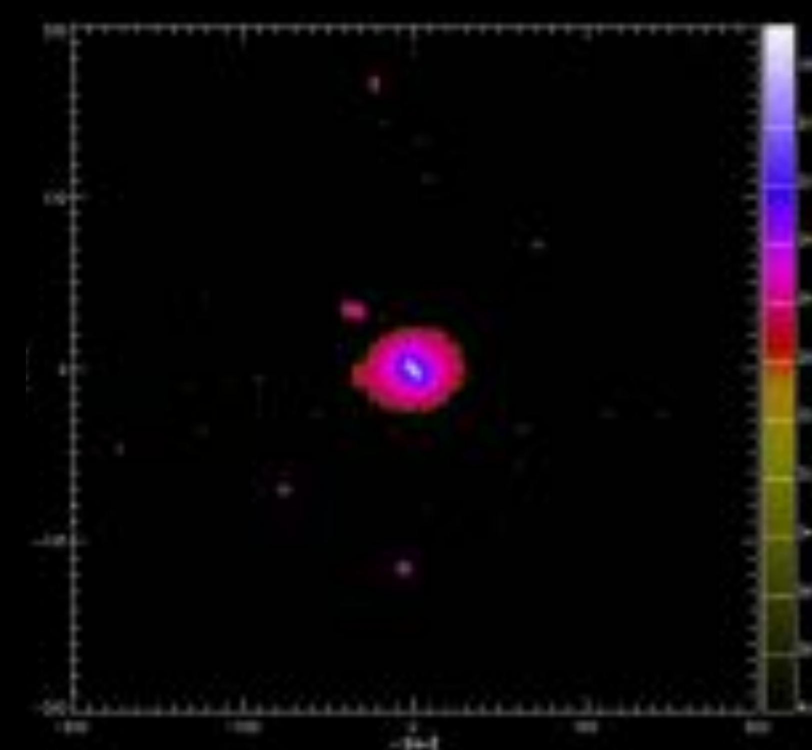
For Local Group galaxies



✓ Cutting at 29 mag/arcsec^2

• Surface brightness limit of on-going *ultra-deep surveys* probing the integrated diffuse light of nearby galaxies



✓ Cutting at 27 mag/arcsec^2

• Surface brightness limit of traditional images of nearby galaxies (SDSS)

Extreme deep imaging with MegaCam on the CFHT

A volume-limited sample of 260 massive Early Type Galaxies with D < 42 Mpc (Atlas^{3D}), $M_K < -21.5$

Ferrarese et al, 2011

Cappellari et al, 2011

Duc et al, 2013

- Observed with the large field of view camera MegaCam (multiband:u,g,r,i) on the CFHT, as part of NGVS for the Virgo ETGs, and MATLAS for the other ones; integration time of 30-45 min

Extreme deep imaging with MegaCam on the CFHT

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bonus: 100 spirals in the same field as ETGs

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Extreme deep imaging with MegaCam on the CFHT

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Ferrarese et al, 2011

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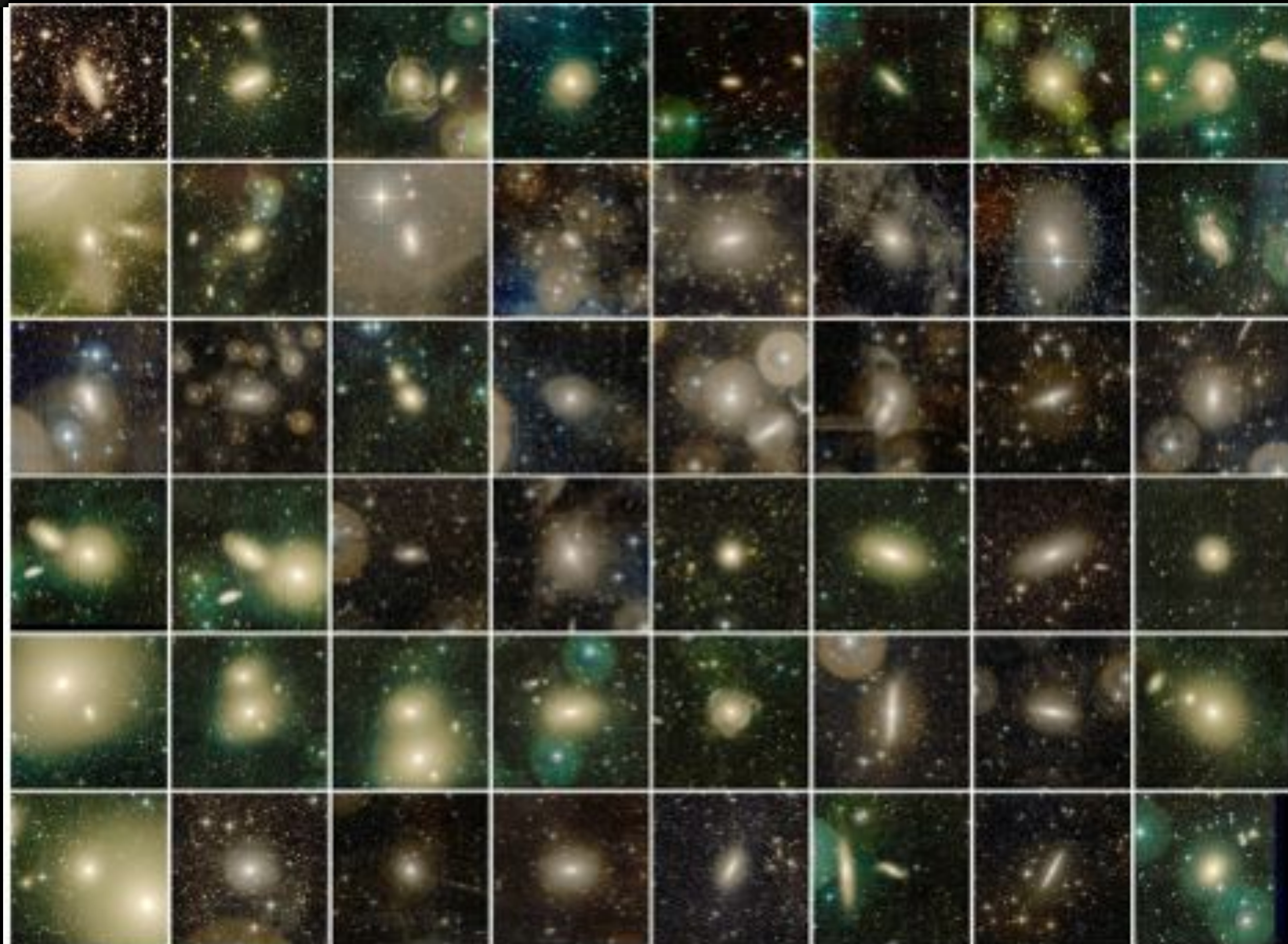
Duc et al, 2013

- With specific observing strategy (large offsets, sky subtraction) and data reduction technique (Elixir-LSB) to optimize the detection of low surface brightness features

SDSS images of the Atlas^{3D} ETGs

MegaCam images of the Atlas^{3D} ETGs

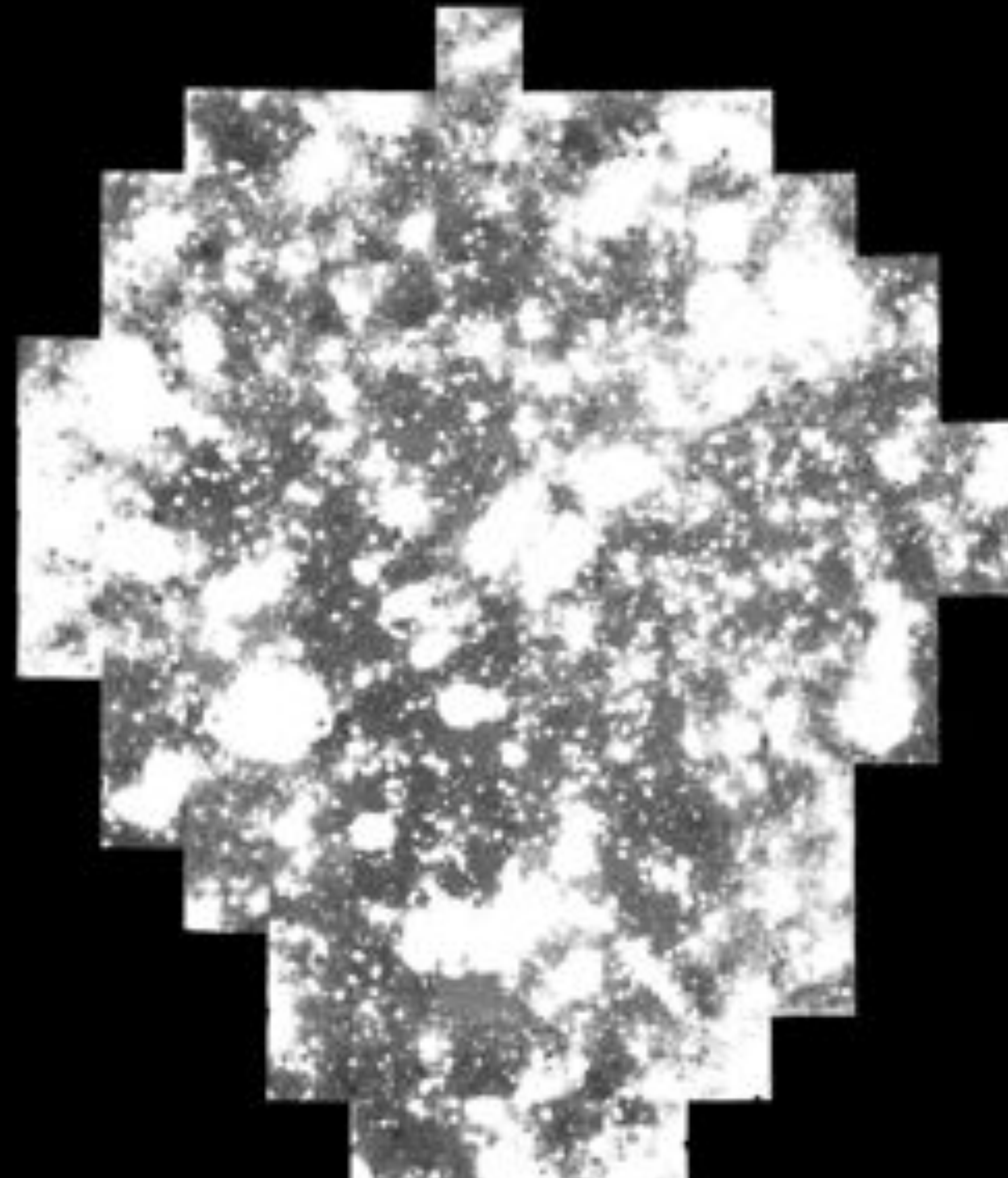


The Virgo cluster as seen by

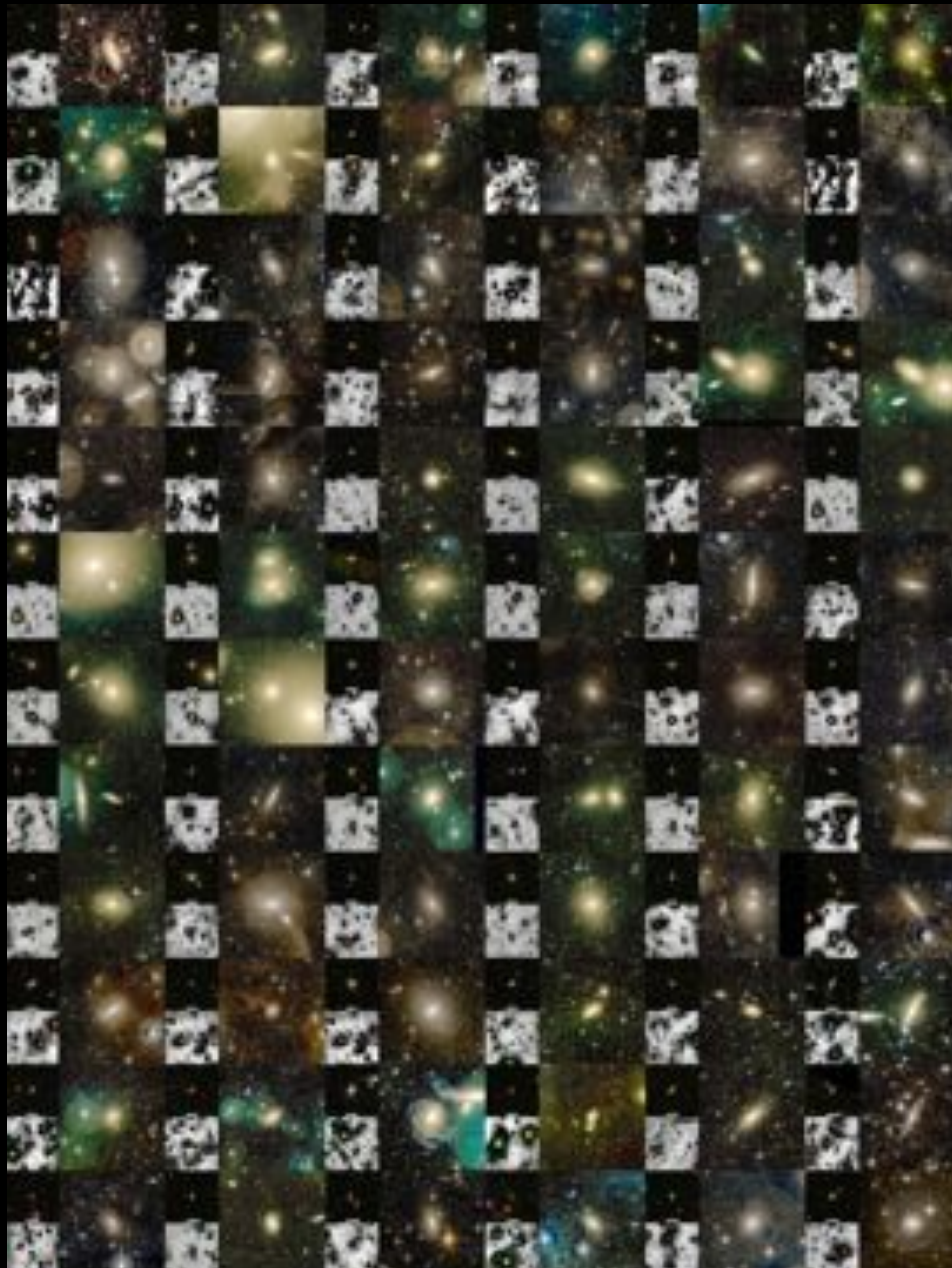
the SDSS

The Virgo cluster as seen by

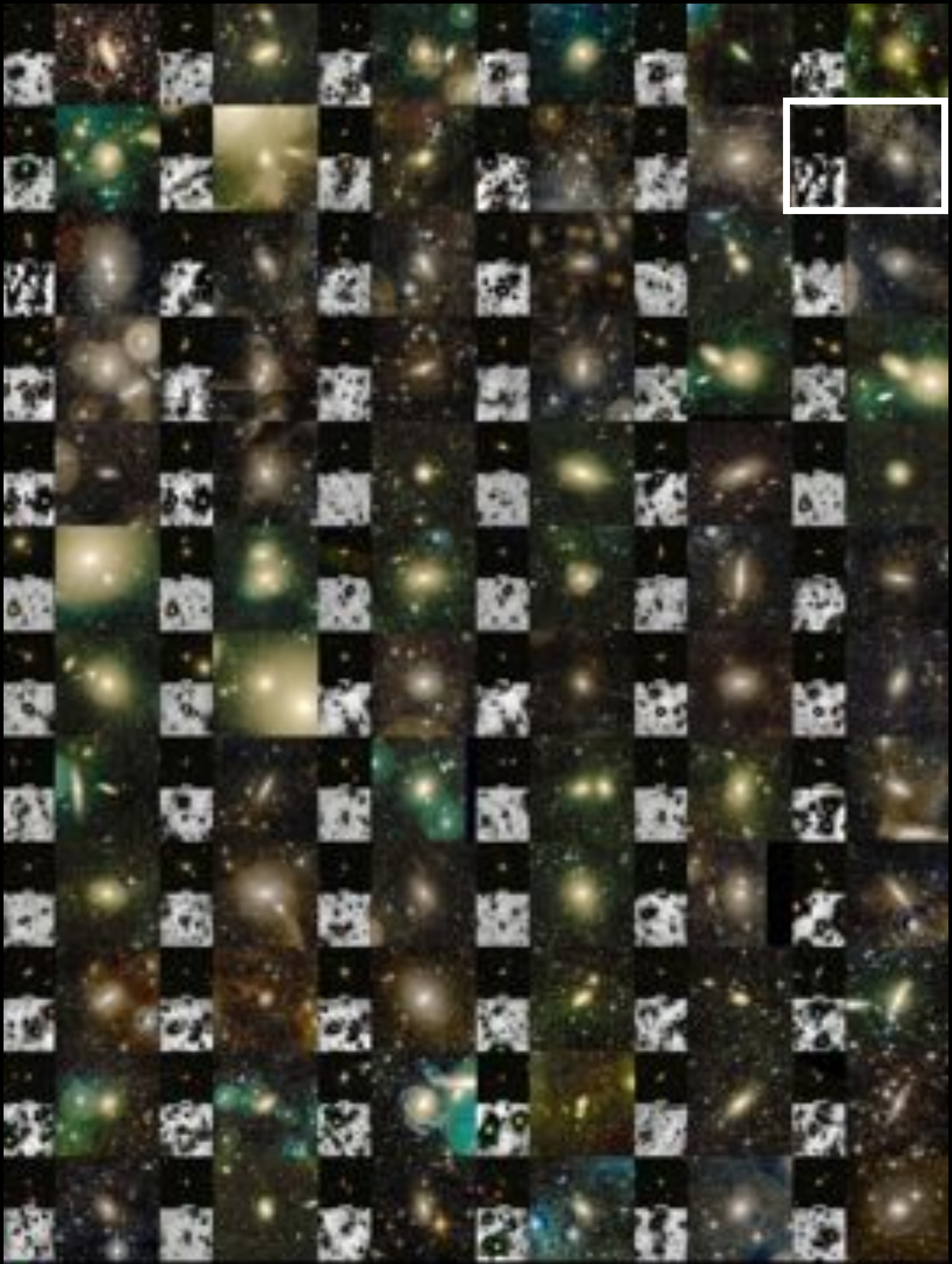
the SDSS



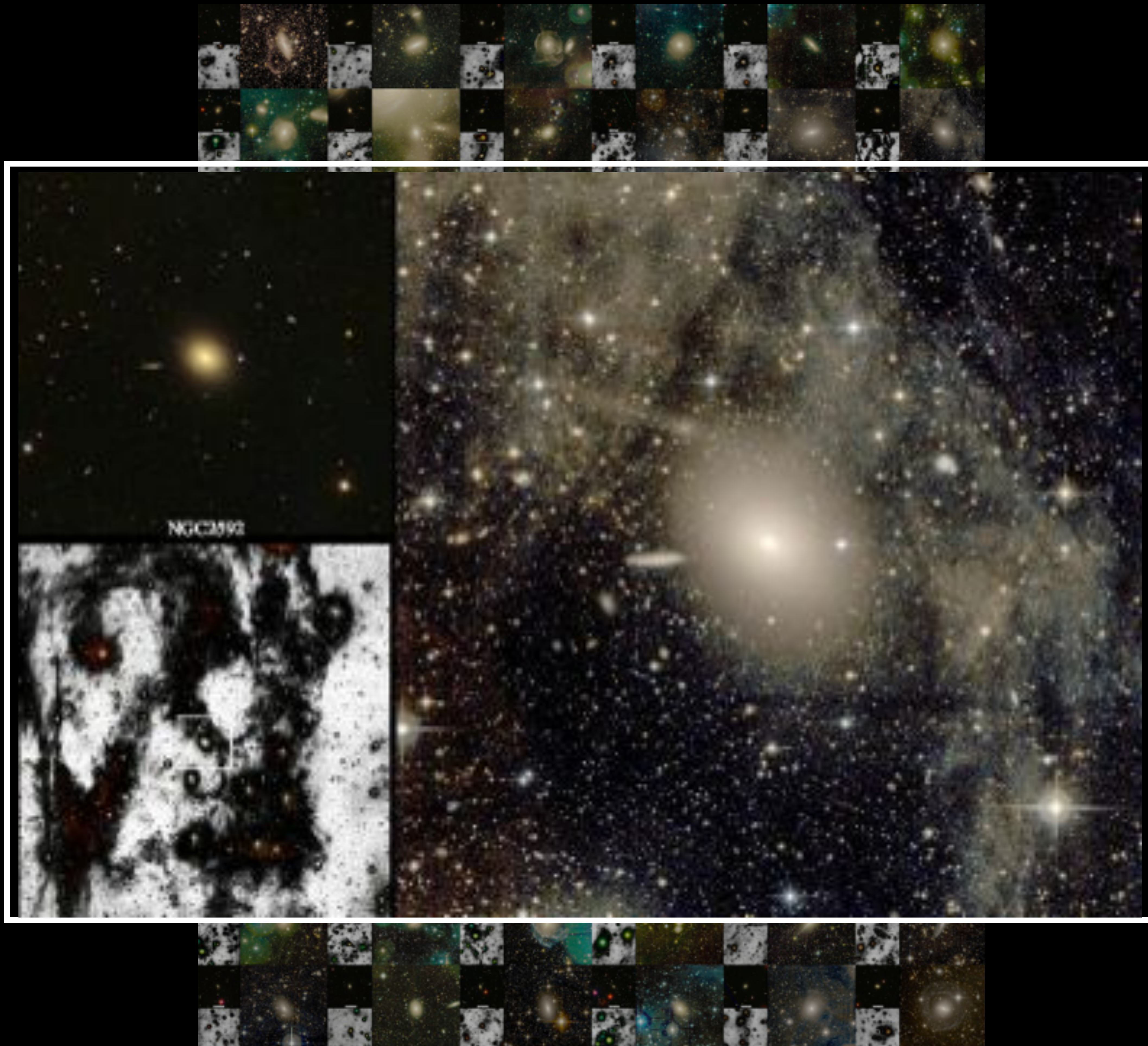
the NGVS



Early–type galaxies as seen by ultra–deep imaging

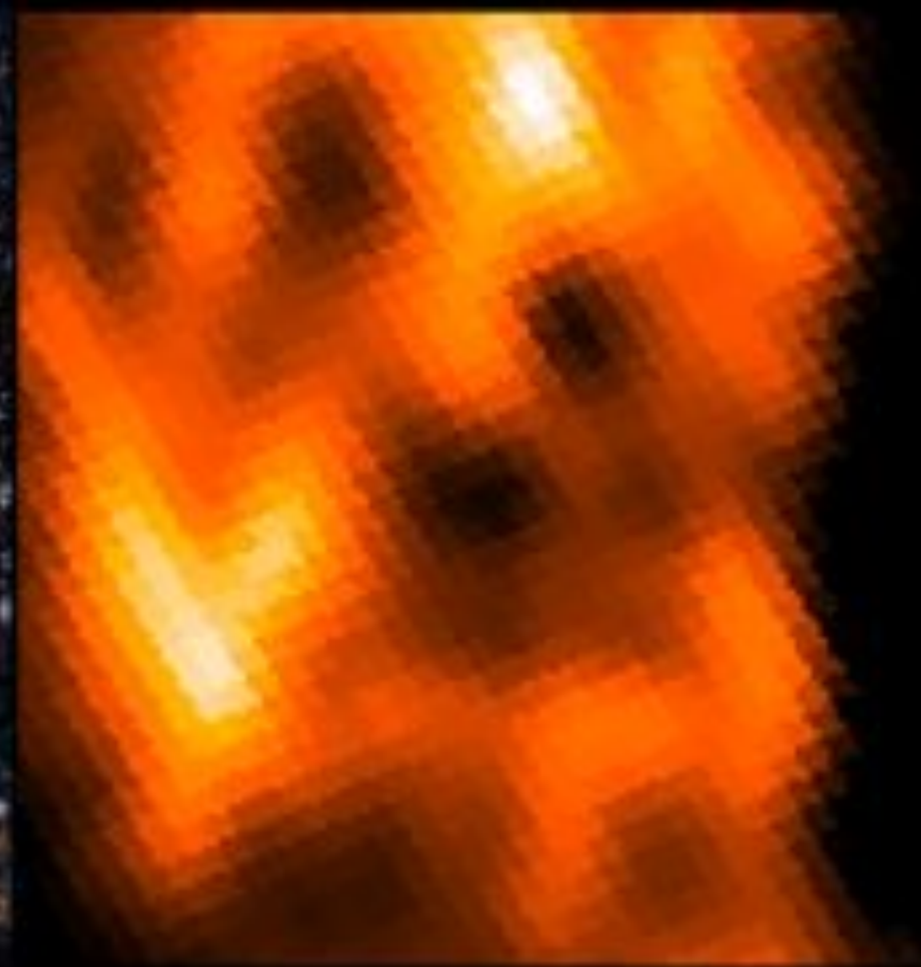


Early–type galaxies as seen by ultra–deep imaging



Early–type galaxies as seen by ultra–deep imaging

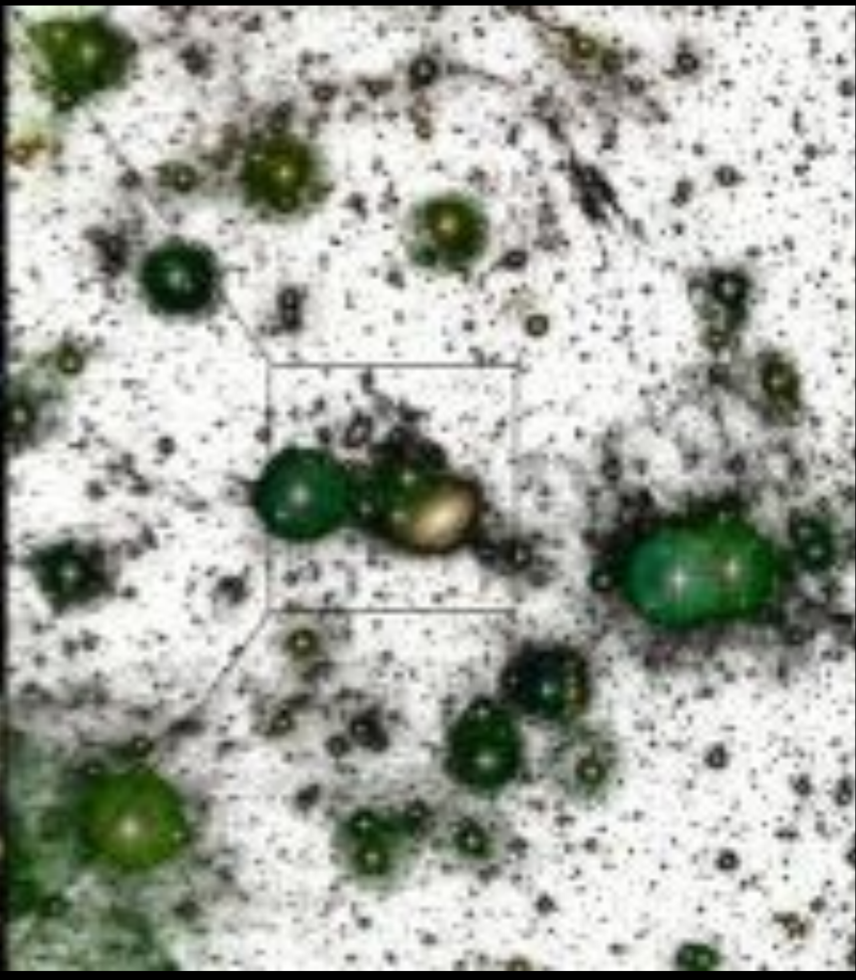
The bad!

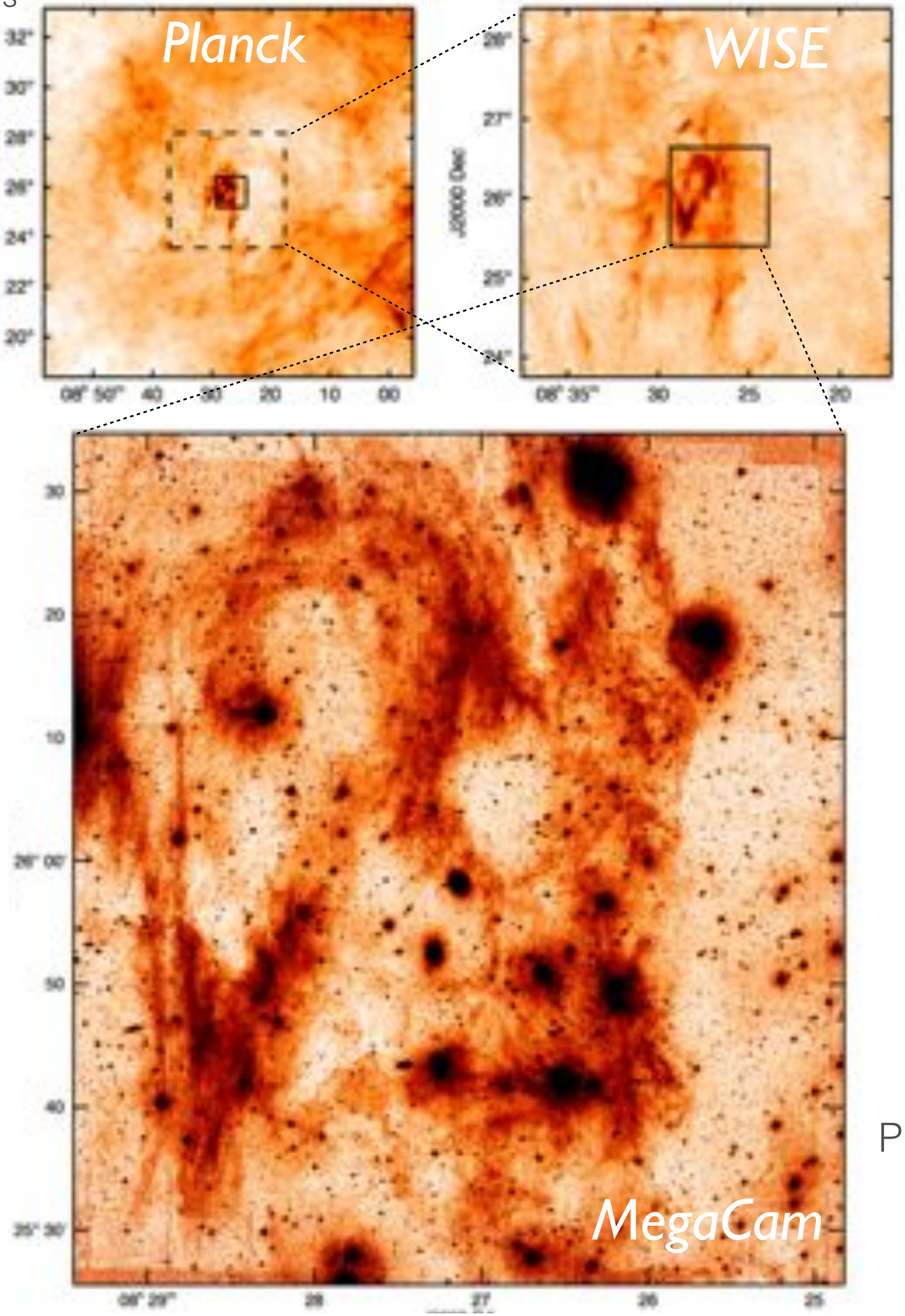


Cirrus emission
identified at other
wavelength (FIR, UV)

Mimic stellar streams

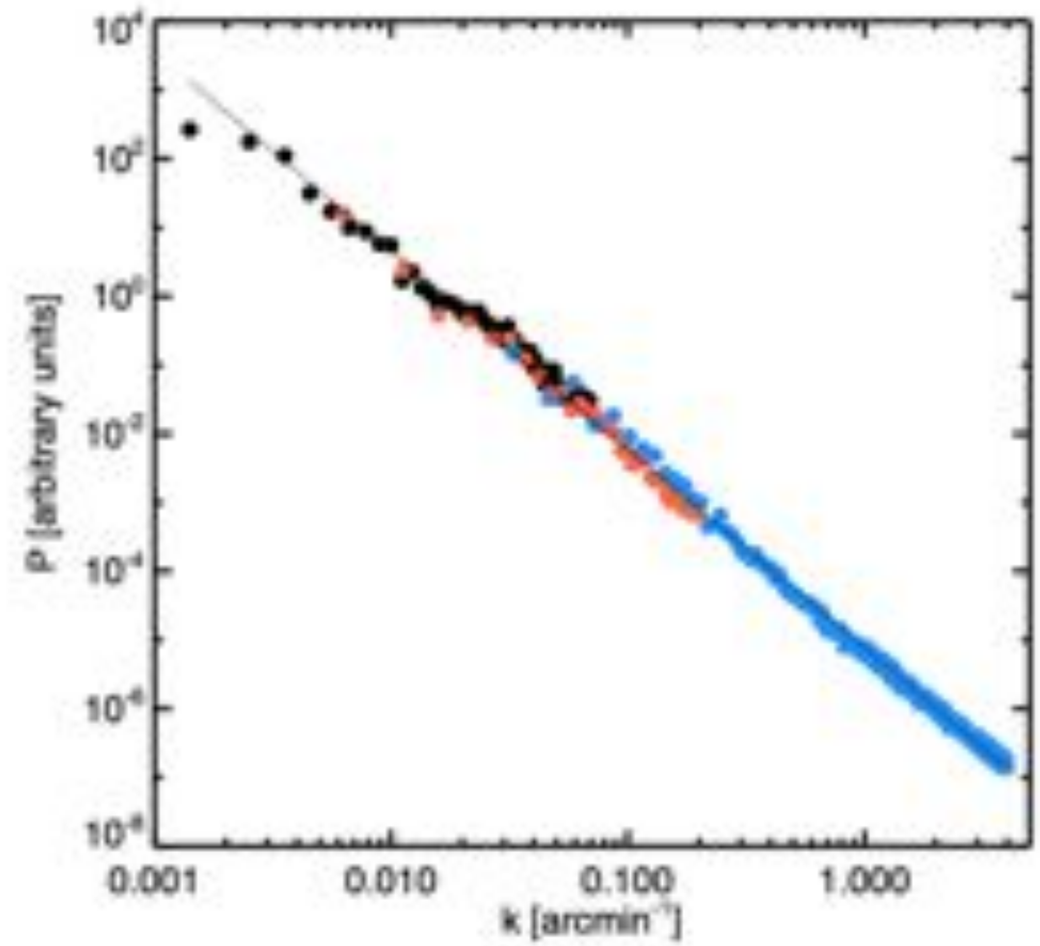
Can be masked, but not
subtracted…





Galactic cirrus

- a gain of x500 in resolution in the optical



Miville-Deschenes & Duc., 2016

Probing the turbulence cascade in the diffuse ISM at the smallest scales (0.01 pc)

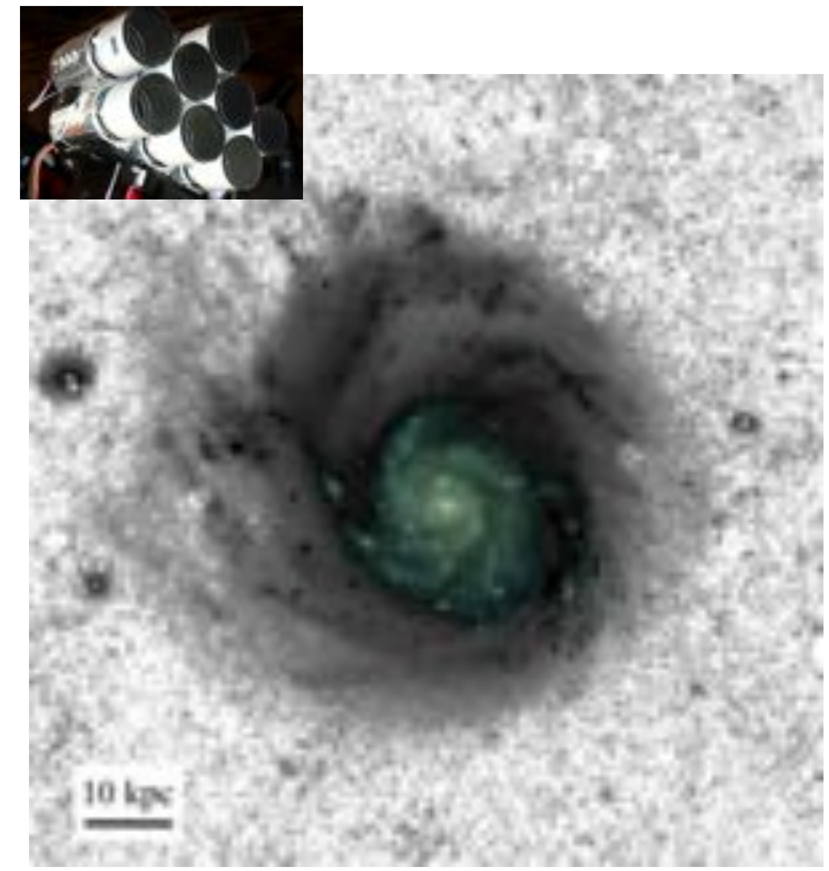
The bad!

The reflection halos

@ CFHT/NGVS   Paudel et al., 2013
@ 29 mag.arcsec^{-2}

@ Irida observatory (Bulgary)
@ 28? mag.arcsec^{-2}

- The competition does better, including amateur astronomers…



@ with Dragonfly
@ 32?? mag.arcsec^{-2}

@ CFHT,-

@ blackbird (USA)

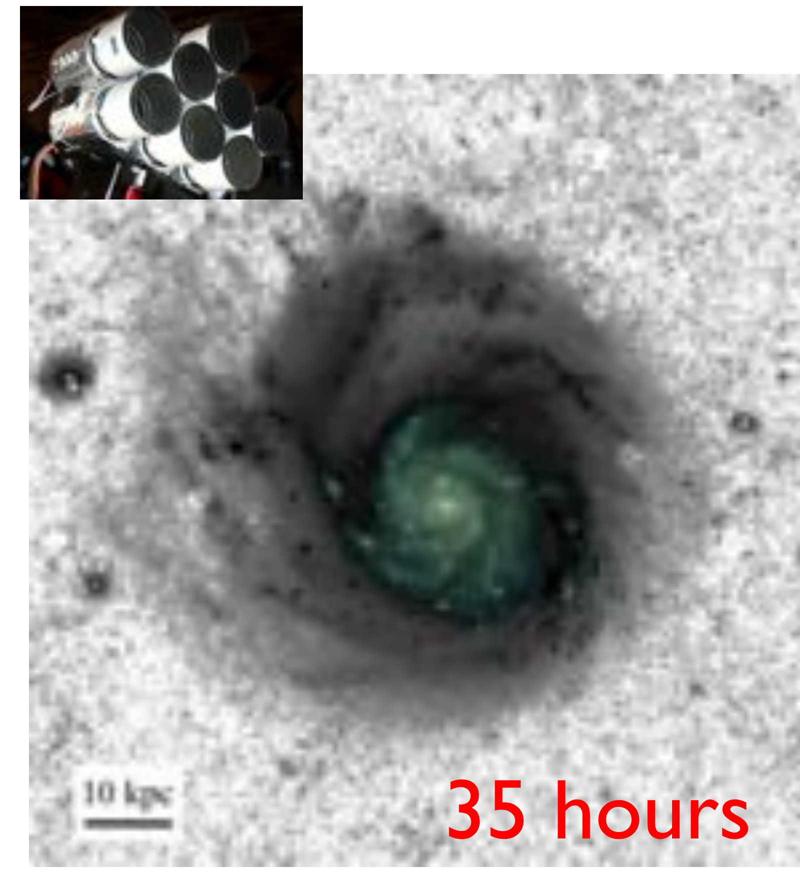
- Dealing with extended reflection halos of stars … and galaxies is tricky

The reflection halos

@ CFHT/NGVS Paudel et al., 2013
@ 29 mag.arcsec^{-2}

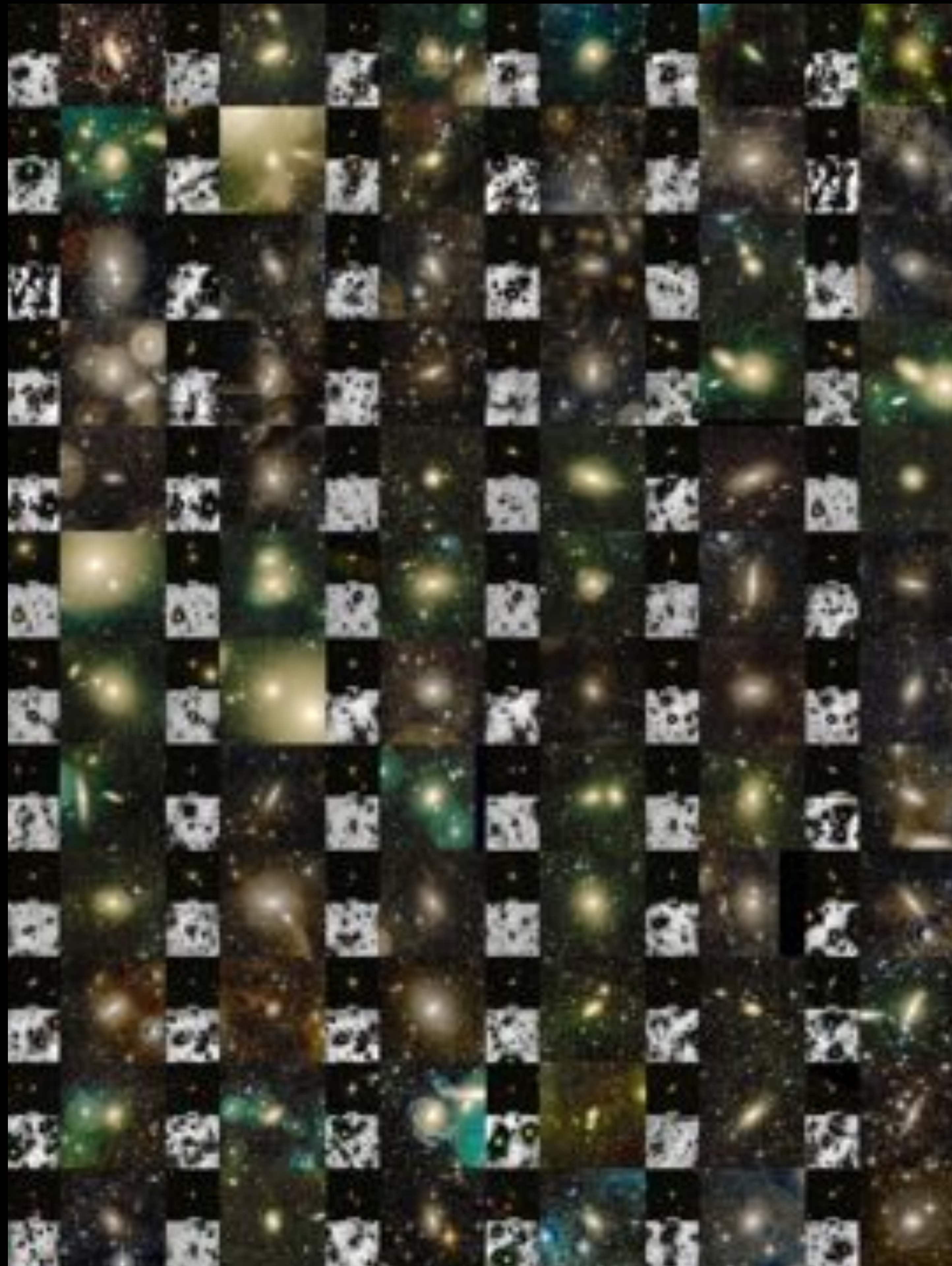
@ Irida observatory (Bulgary)
@ 28? mag.arcsec^{-2}

- The competition does better, including amateur astronomers…

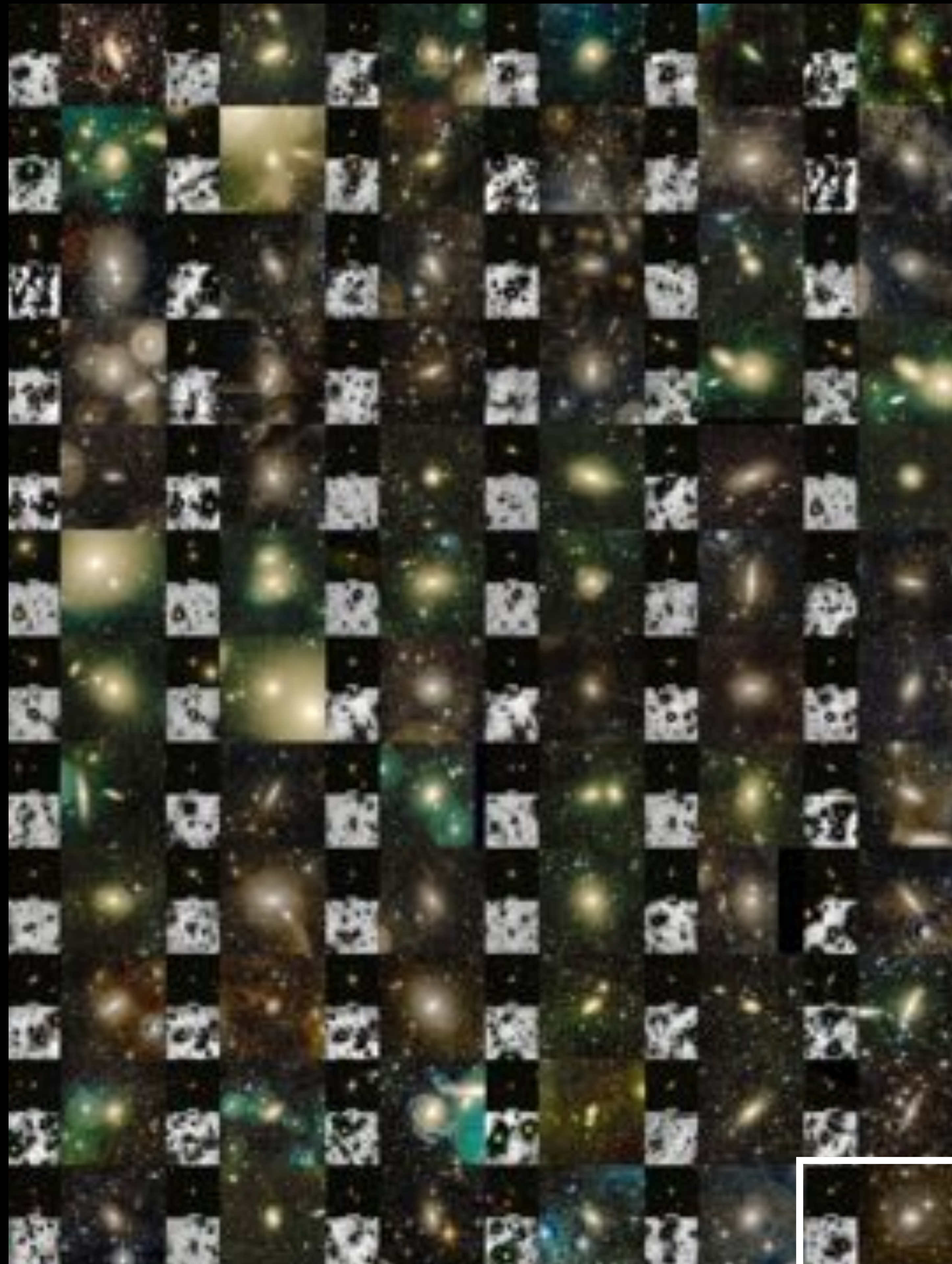


@ with Dragonfly: van Dokkum et al.
@ 32?? mag.arcsec^{-2}

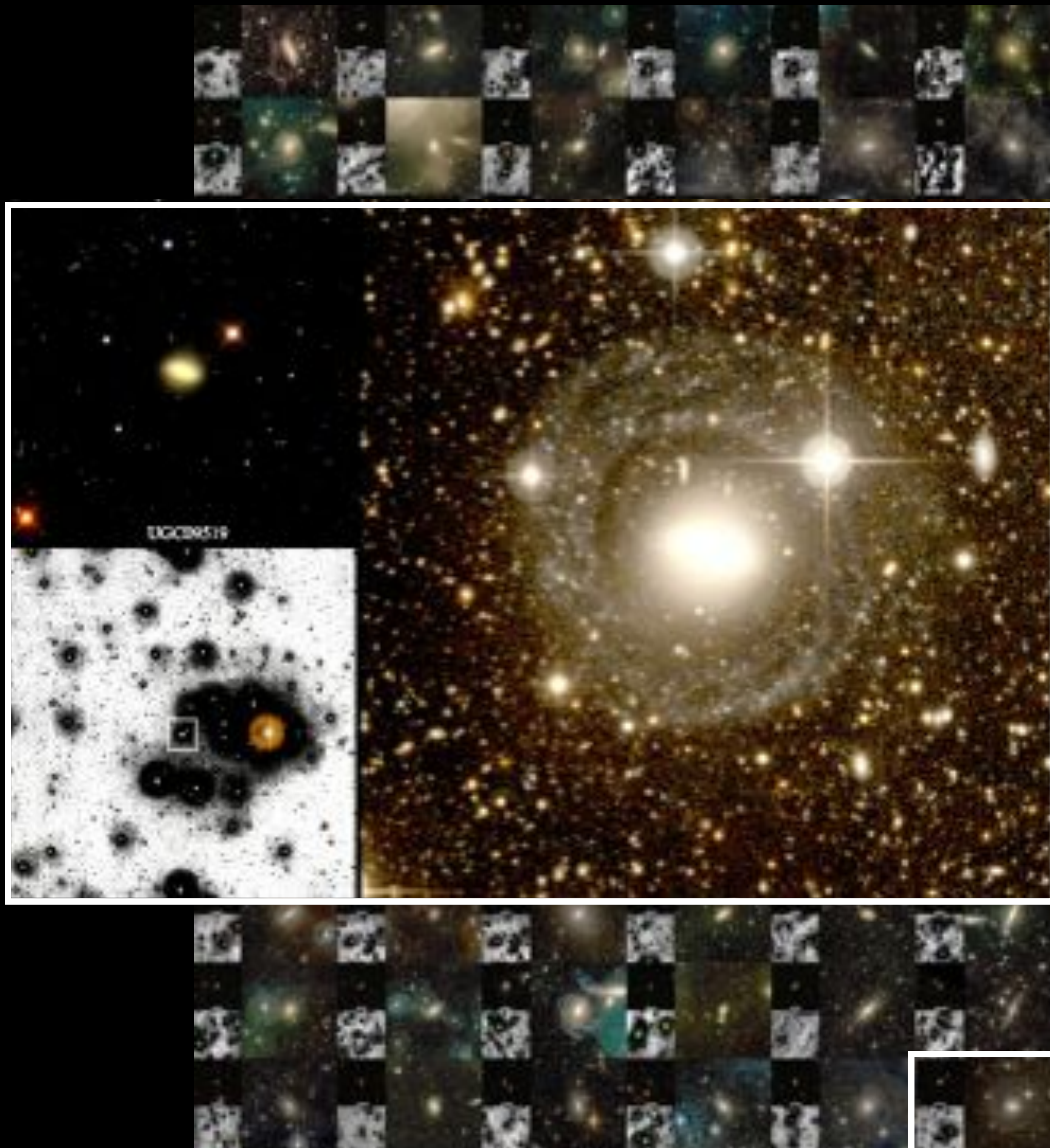
… with much larger exposure times



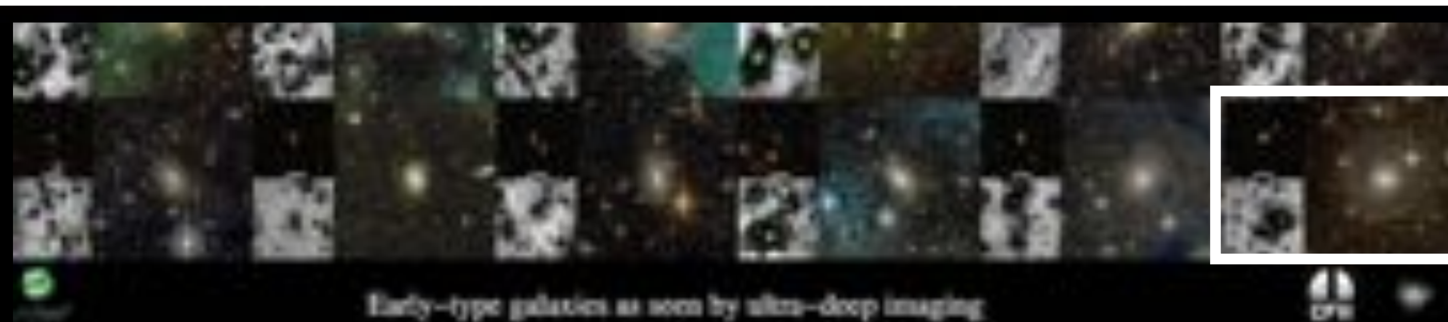
Early−type galaxies as seen by ultra−deep imaging



Early–type galaxies as seen by ultra–deep imaging



Early–type galaxies as seen by ultra–deep imaging



➡ Also prominent in UV / Galex, associated with extended HI disks

The Hubble diagram as seen with SDSS-like observations

©SDSS

©NGVS/Atlas3D/MATLAS

The Hubble diagram as seen with MegaCam

spirals with
a red halo

ETGs with star-
forming disks

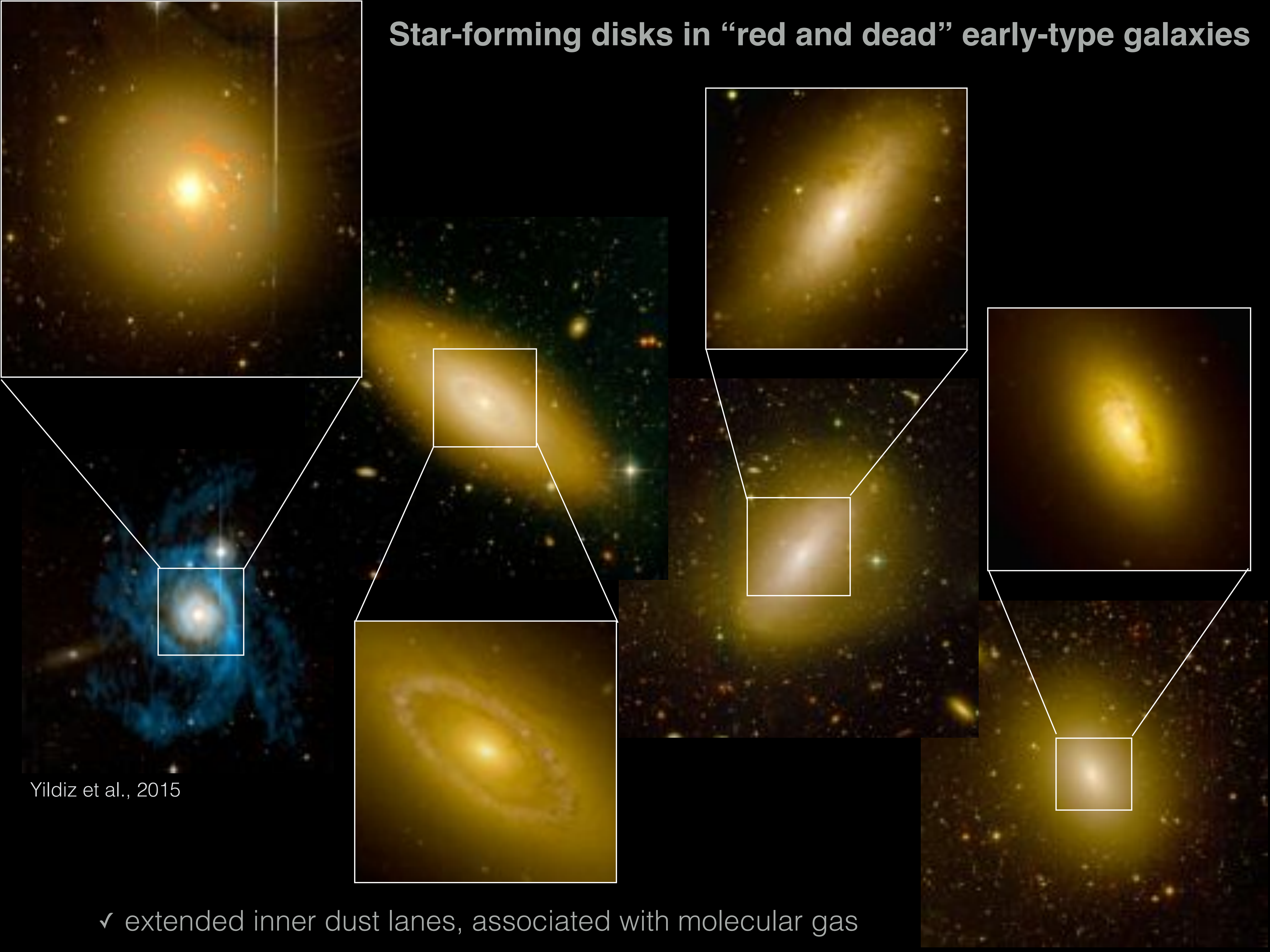
The Hubble diagram as seen with MegaCam

spirals with a red halo

ETGs with star-forming disks

A classification just based on apparent morphology may be misleading

Star-forming disks in “red and dead” early-type galaxies



Yildiz et al., 2015

✓ extended inner dust lanes, associated with molecular gas

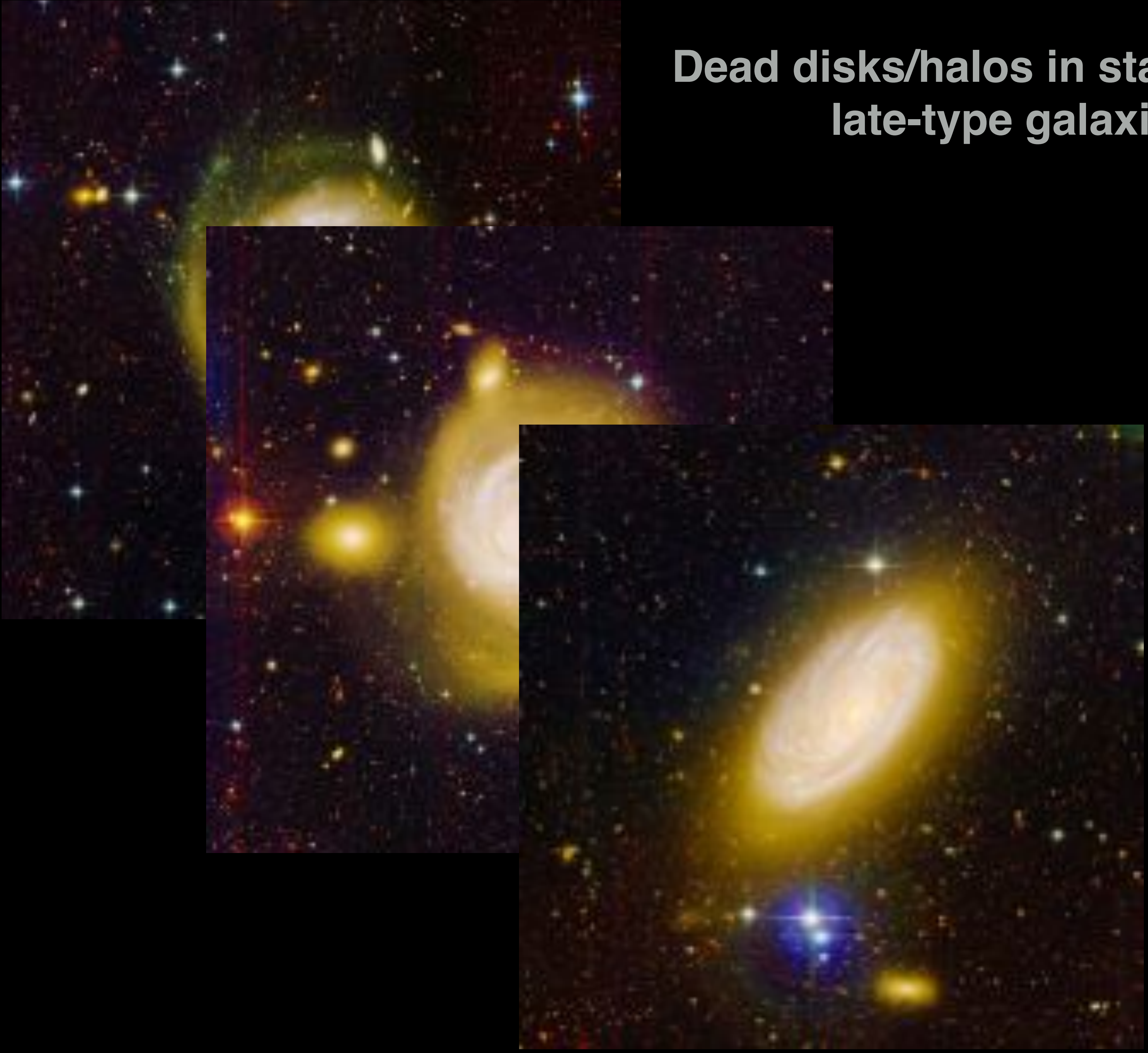
Dead disks/halos in star-forming late-type galaxies

✓ Virgo Cluster: sequence of LTGs with increasing halo size … or decreasing star-forming disk

Dead disks/halos in star-forming late-type galaxies

✓ Virgo Cluster: sequence of LTGs with increasing halo size … or decreasing star-forming disk

Dead disks/halos in star-forming late-type galaxies



- ✓ Virgo Cluster: sequence of LTGs with increasing halo size … or decreasing star-forming disk

Dead disks/halos in star-forming late-type galaxies

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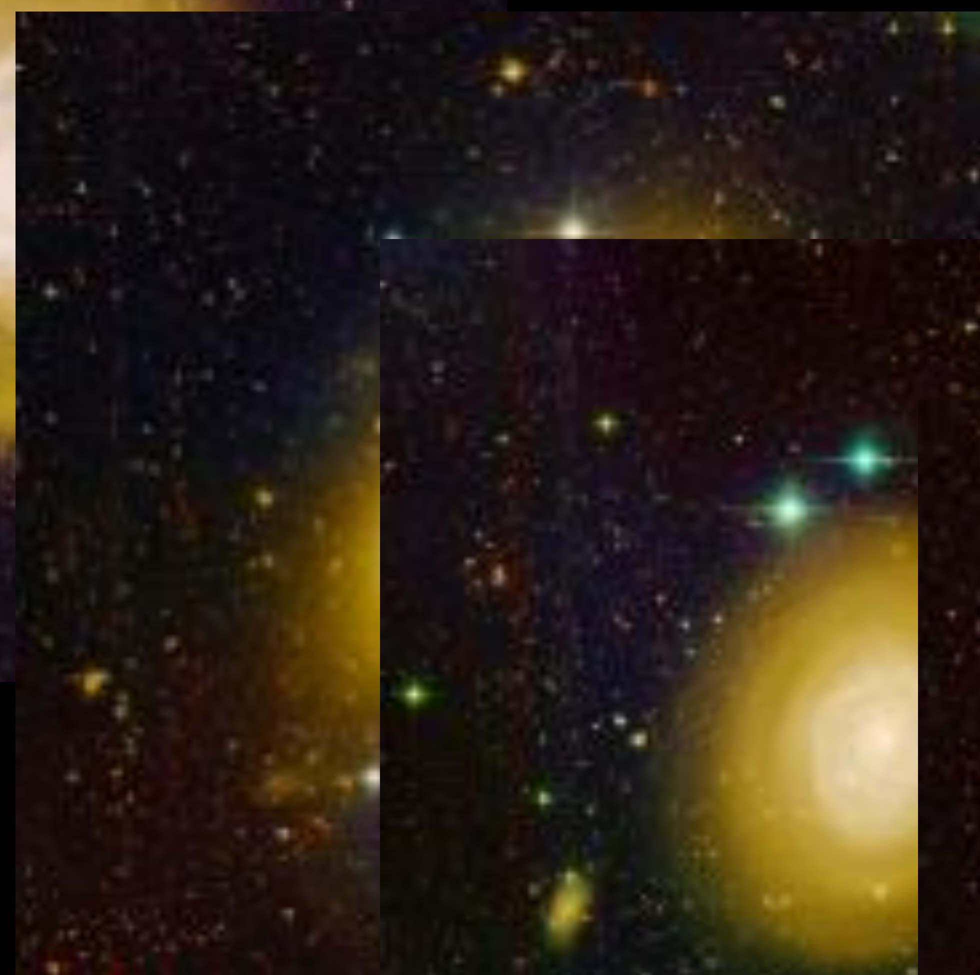
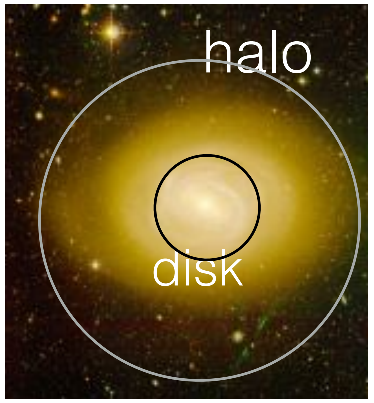


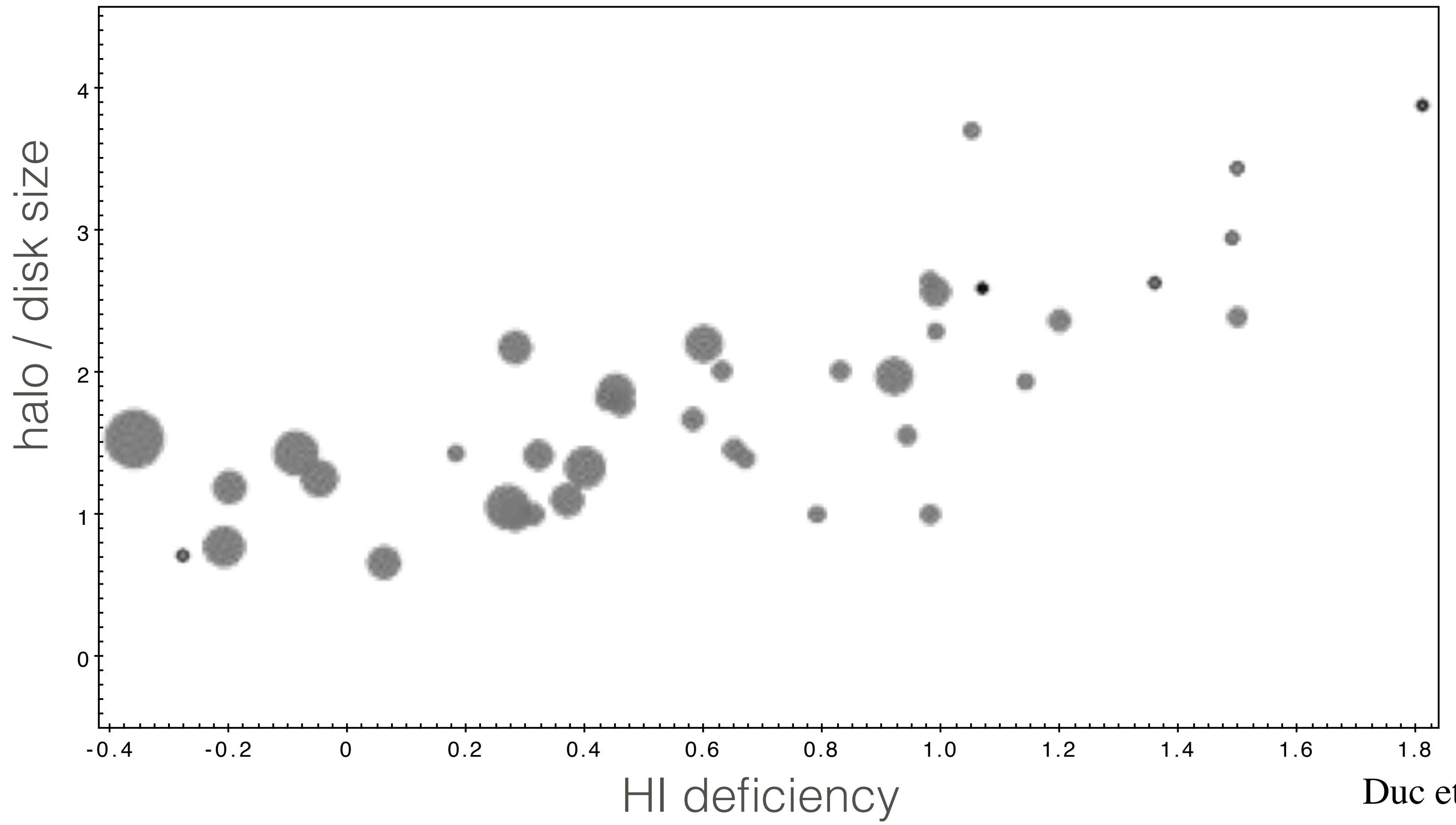
- ✓ Virgo Cluster: sequence of LTGs with increasing halo size … or decreasing star-forming disk

Dead disks/halos in star-forming late-type galaxies

✓ Virgo Cluster: sequence of LTGs with increasing halo size … or decreasing star-forming disk

Generating the old stellar « halo »

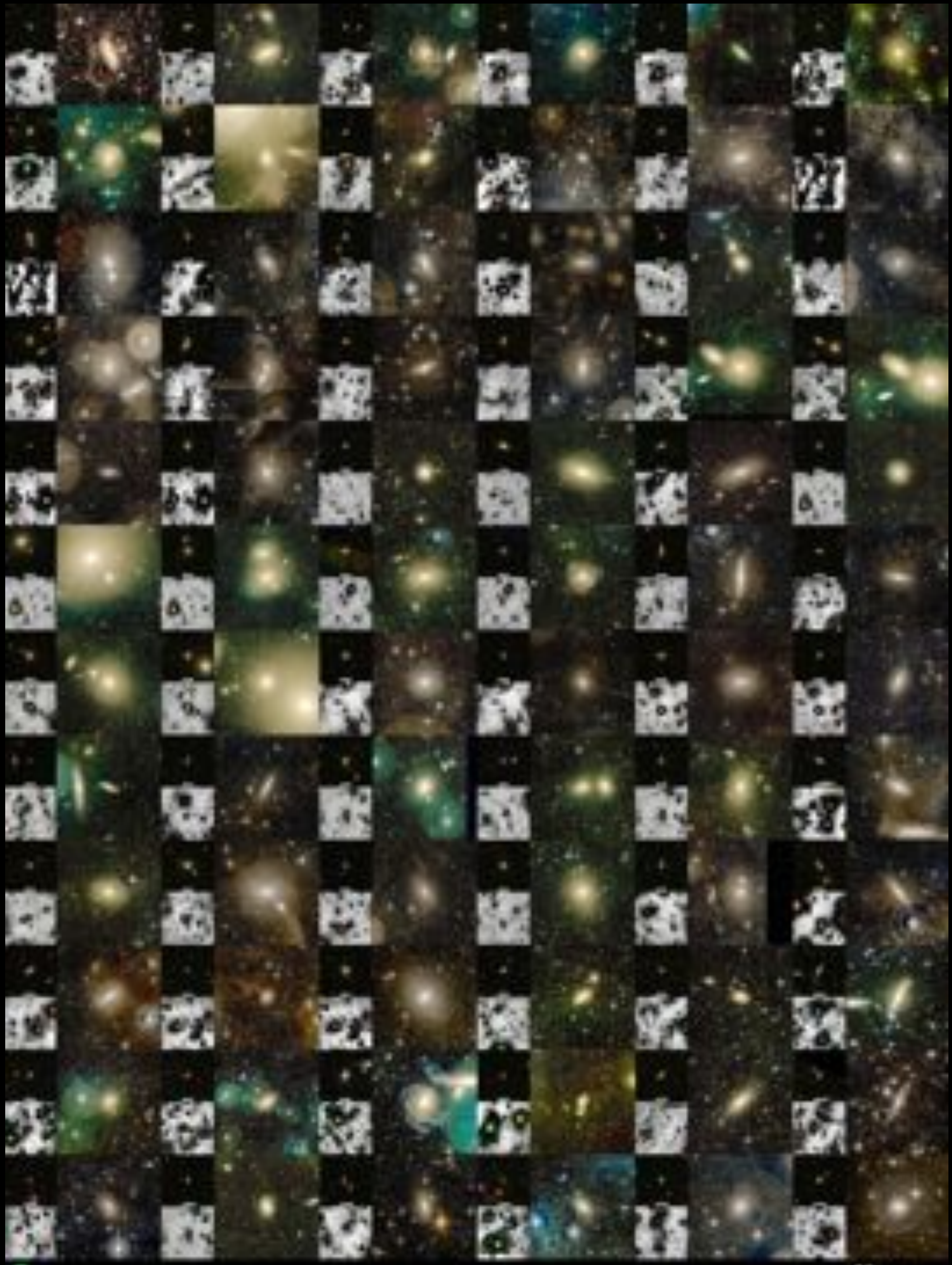




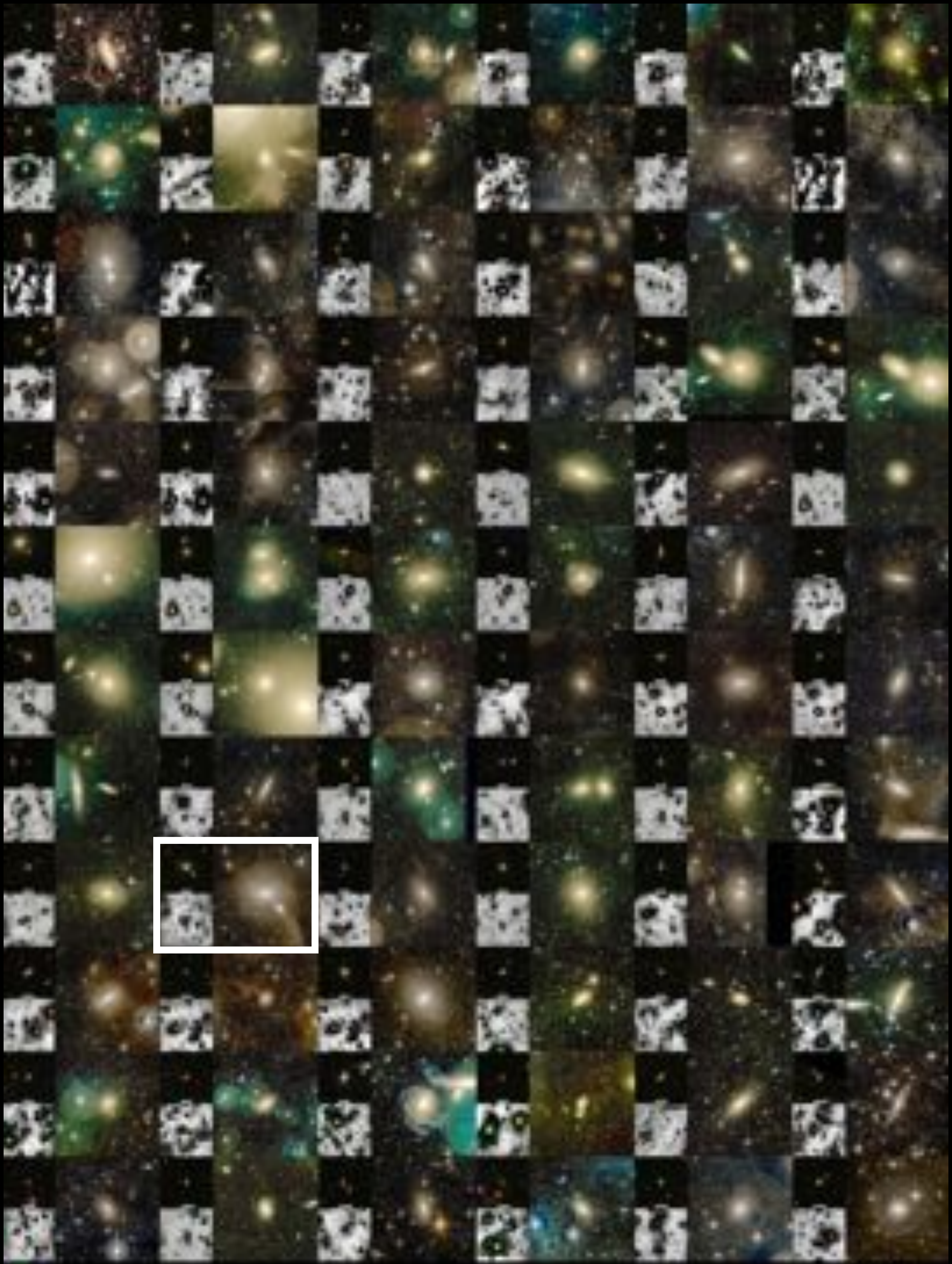
Duc et al., in prep

- ✓ Star formation truncation linked with the HI deficiency induced by ram pressure

HI (VIVA: Chung et al) on deep optical images



Early–type galaxies as seen by ultra–deep imaging



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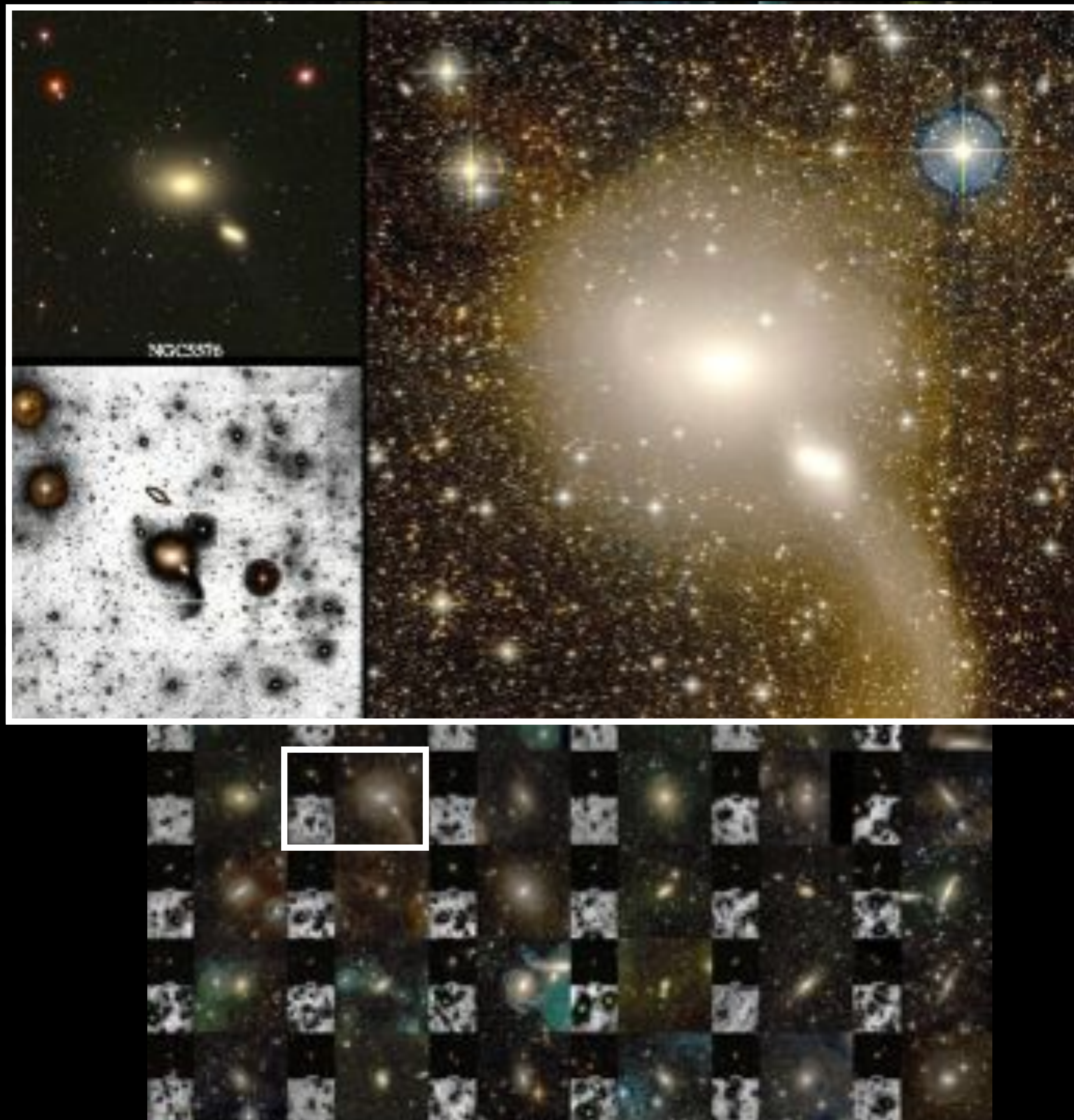
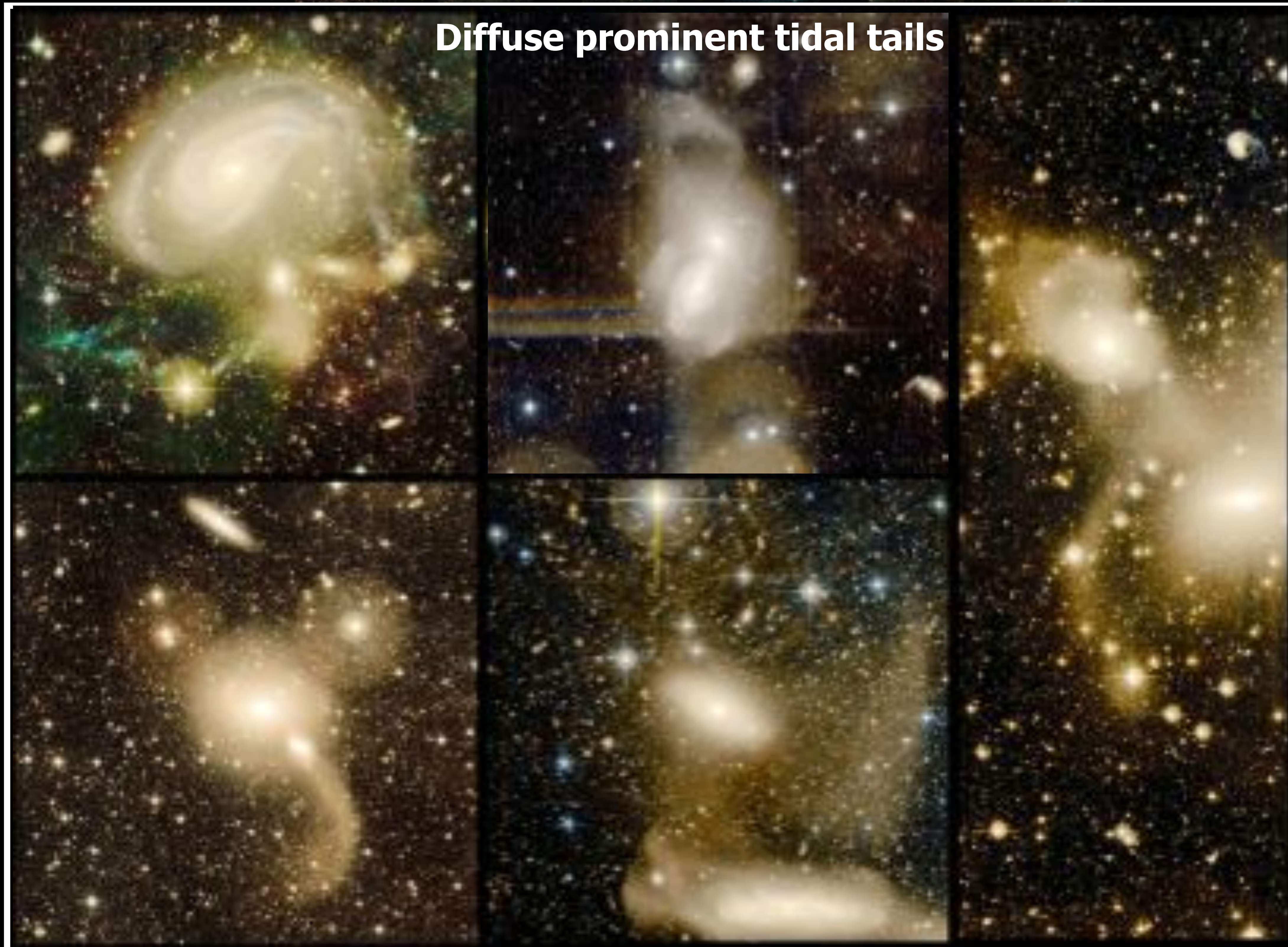


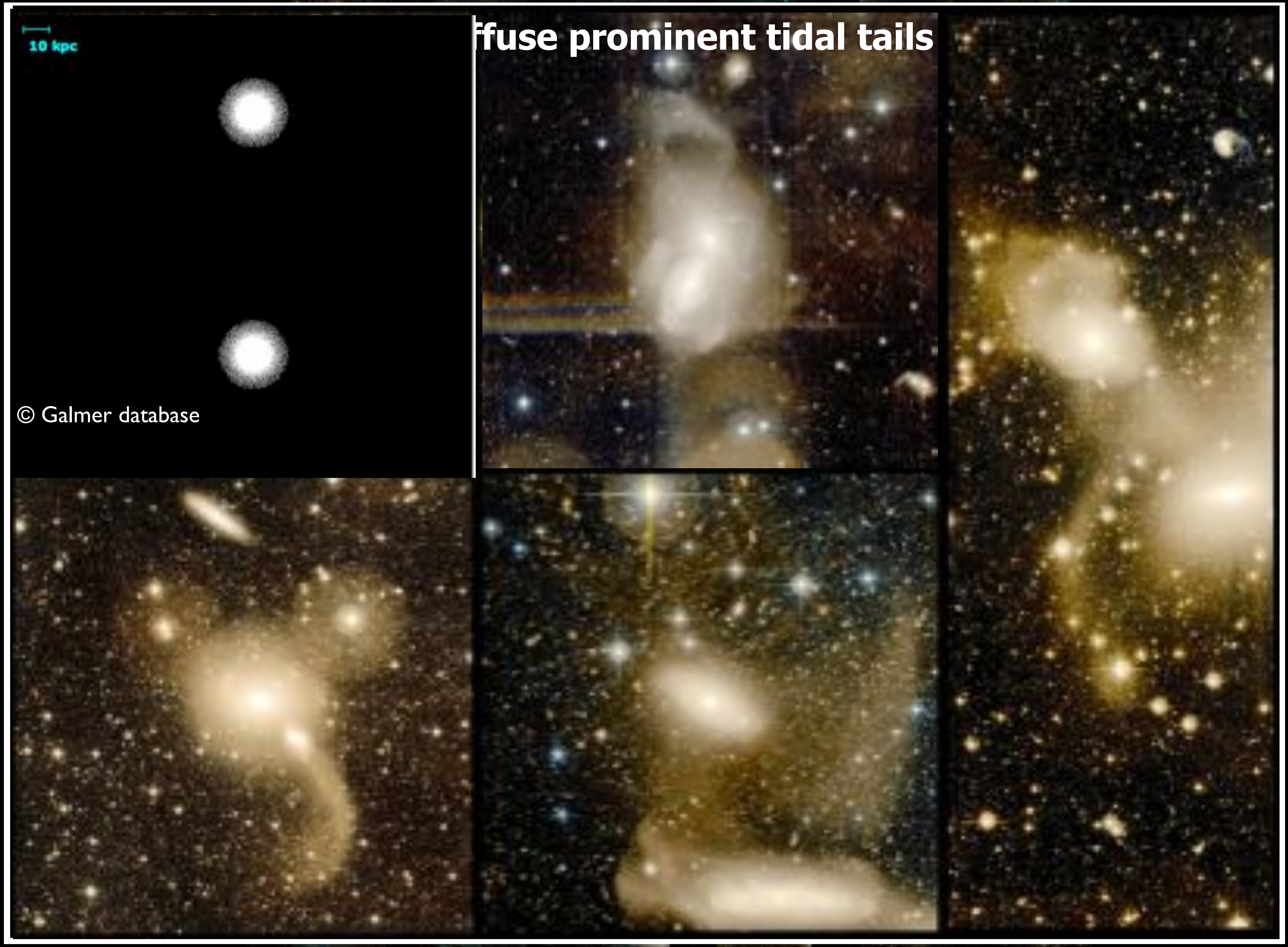
Early–type galaxies as seen by ultra–deep imaging

Diffuse prominent tidal tails



… disclosing on-going tidal interactions with massive companions

Early–type galaxies as seen by ultra–deep imaging



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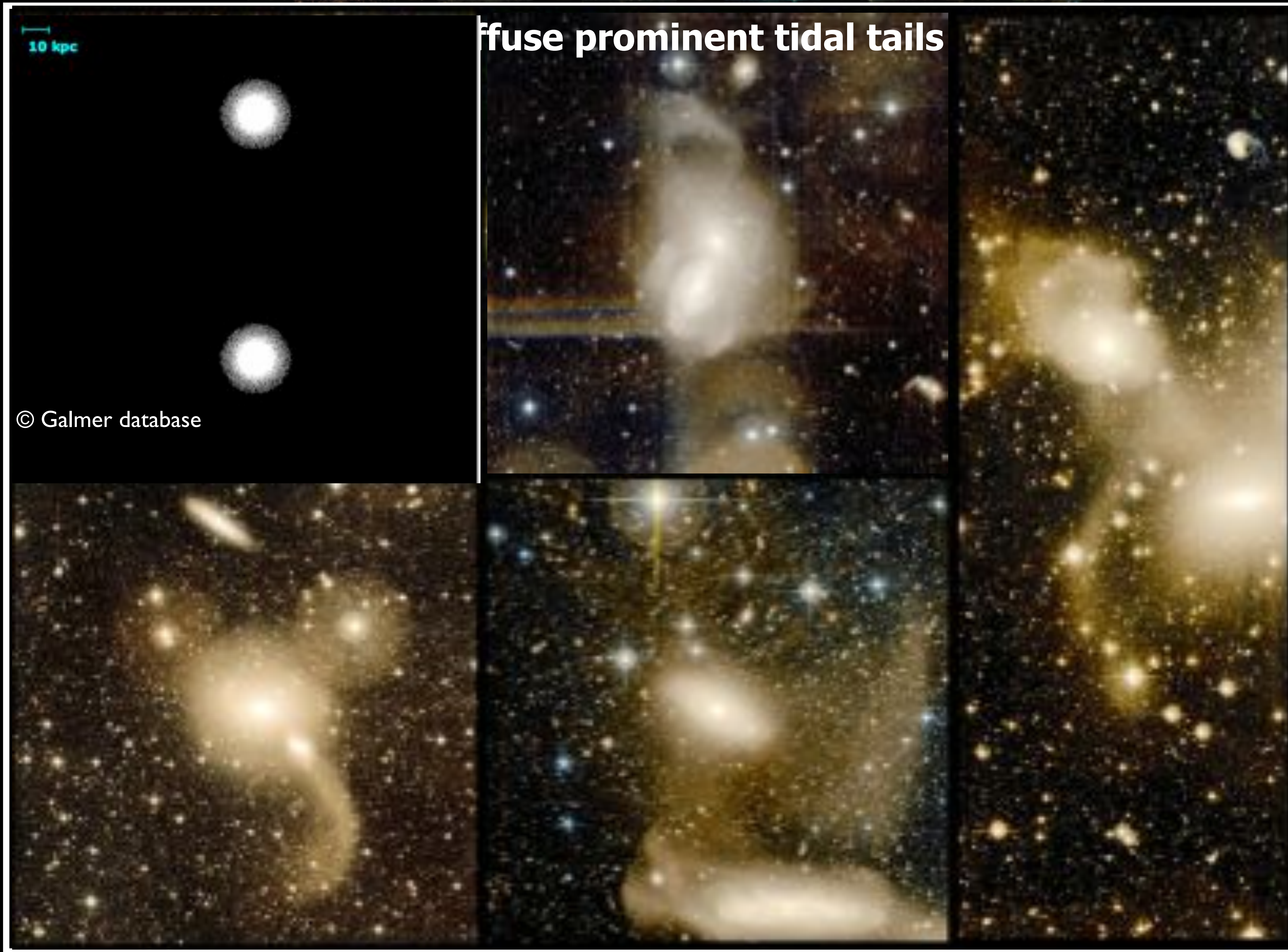

… disclosing on-going tidal interactions with massive companions

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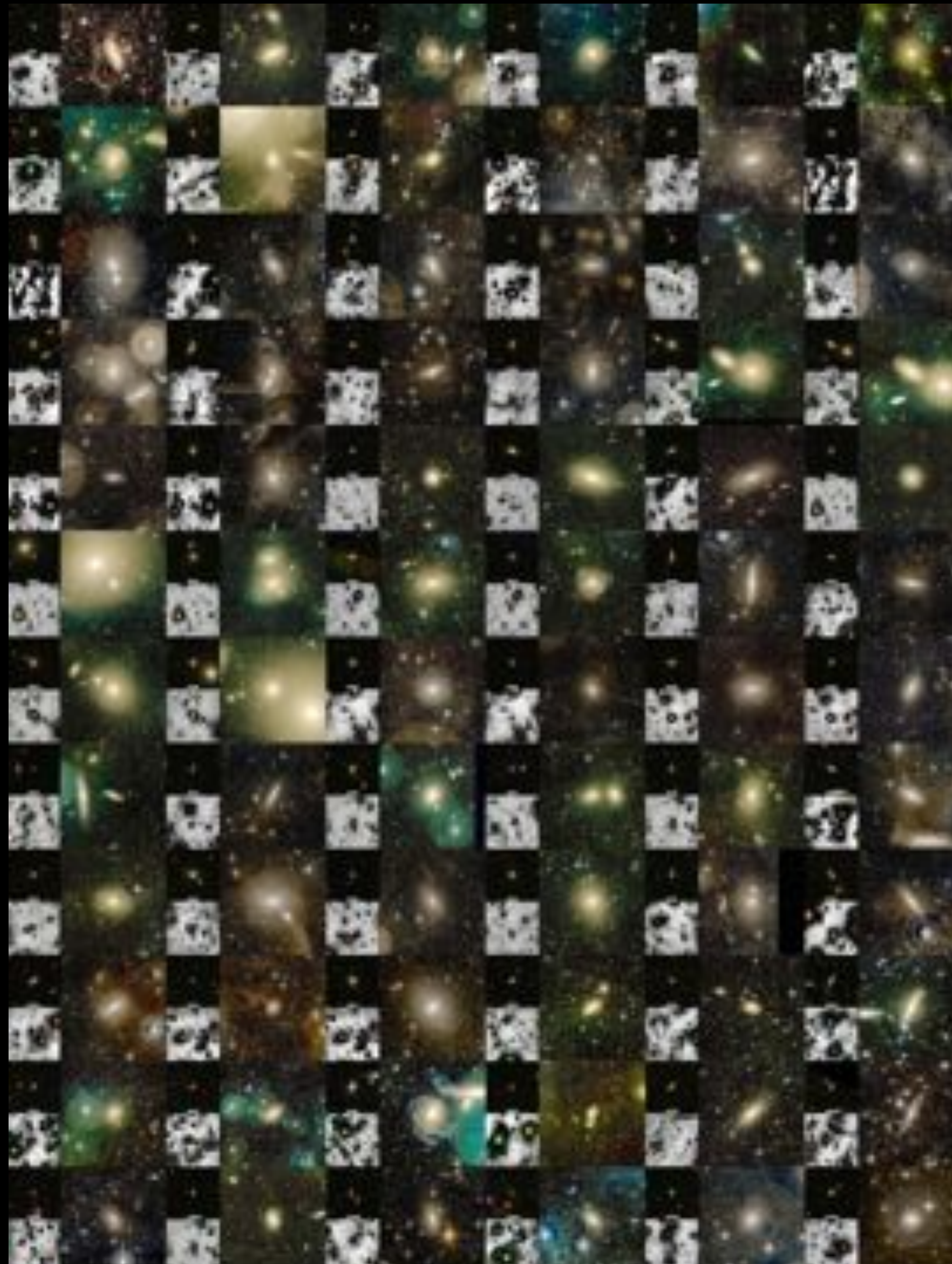
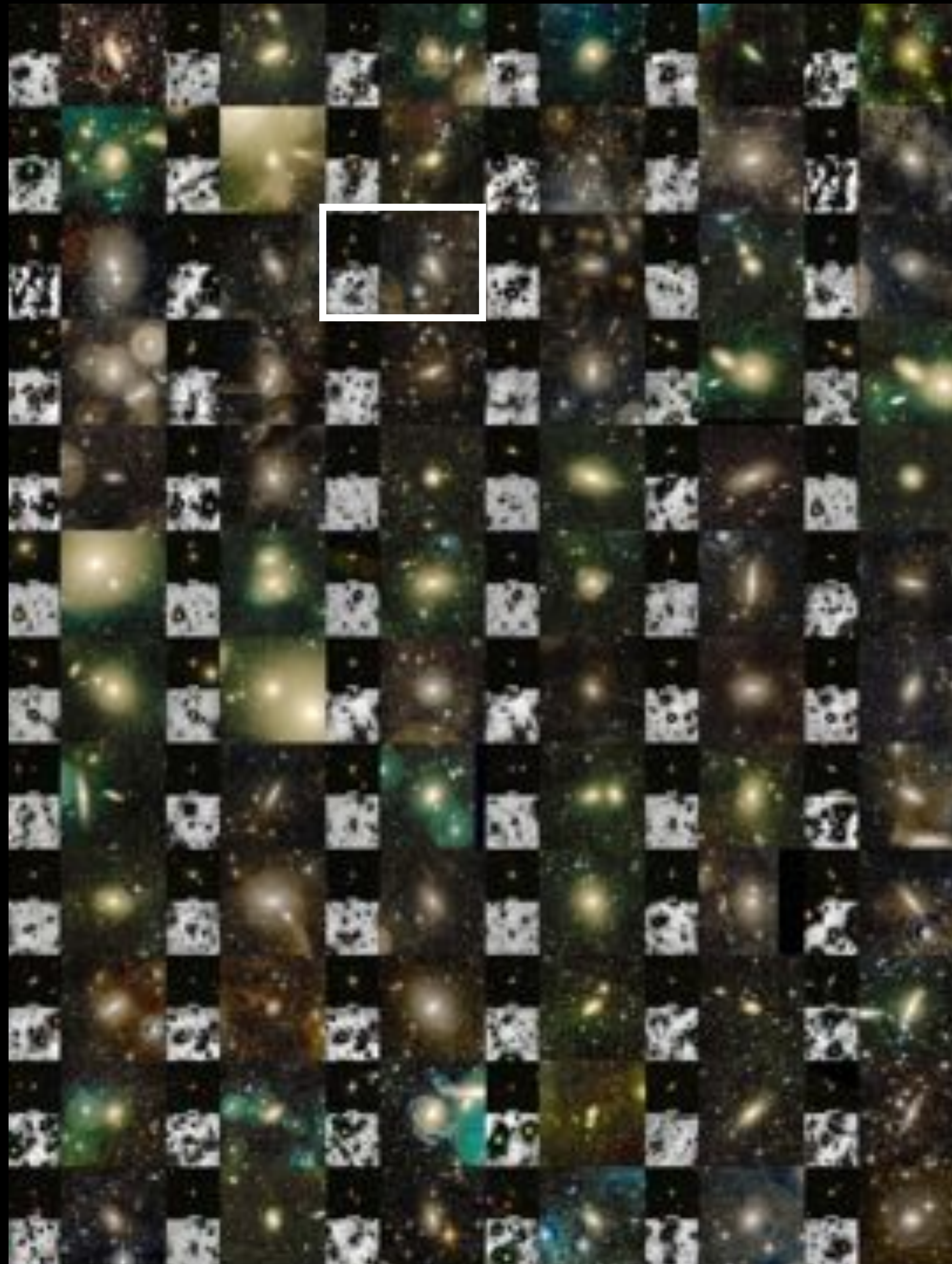


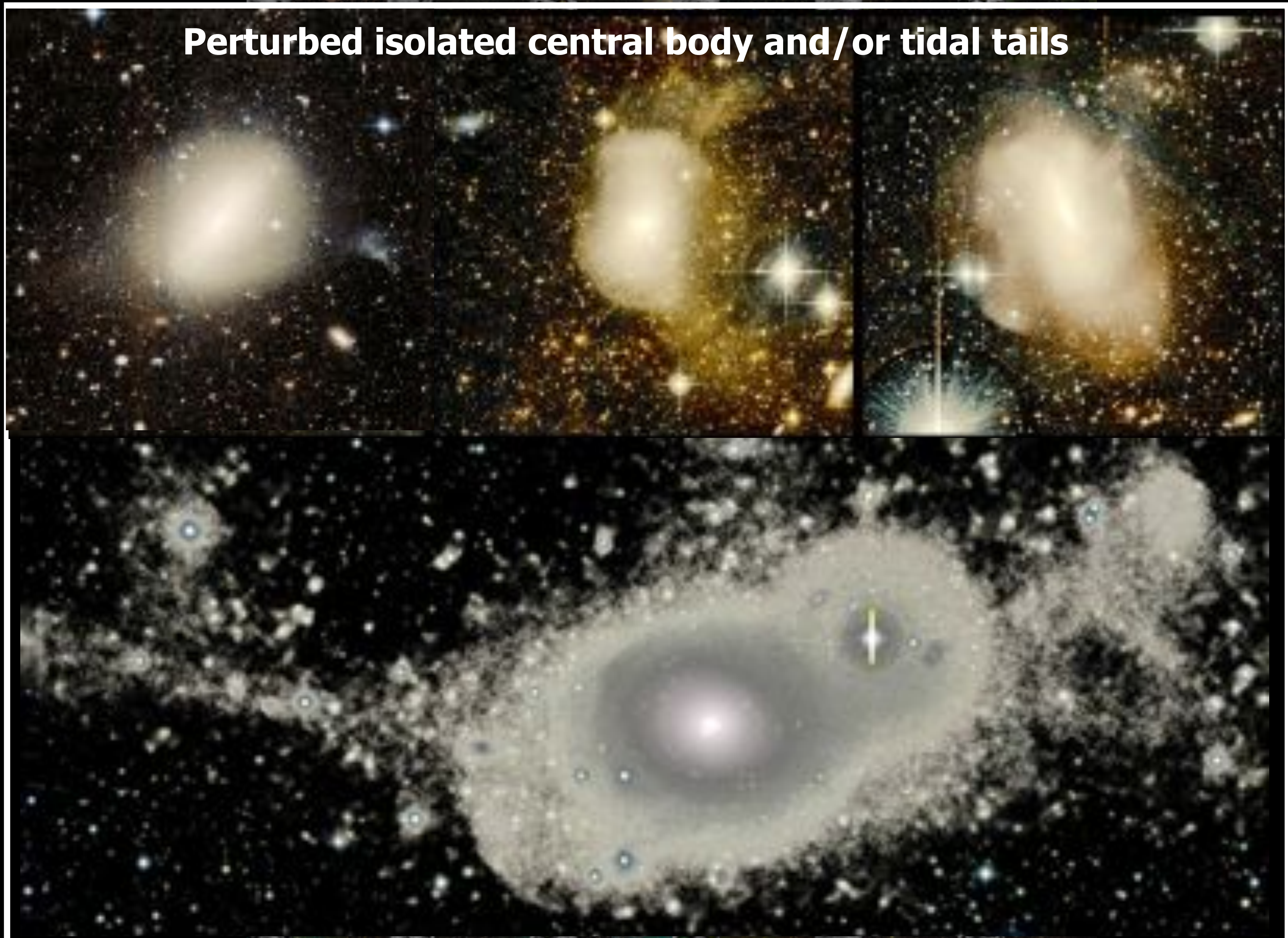
Early–type galaxies as seen by ultra–deep imaging



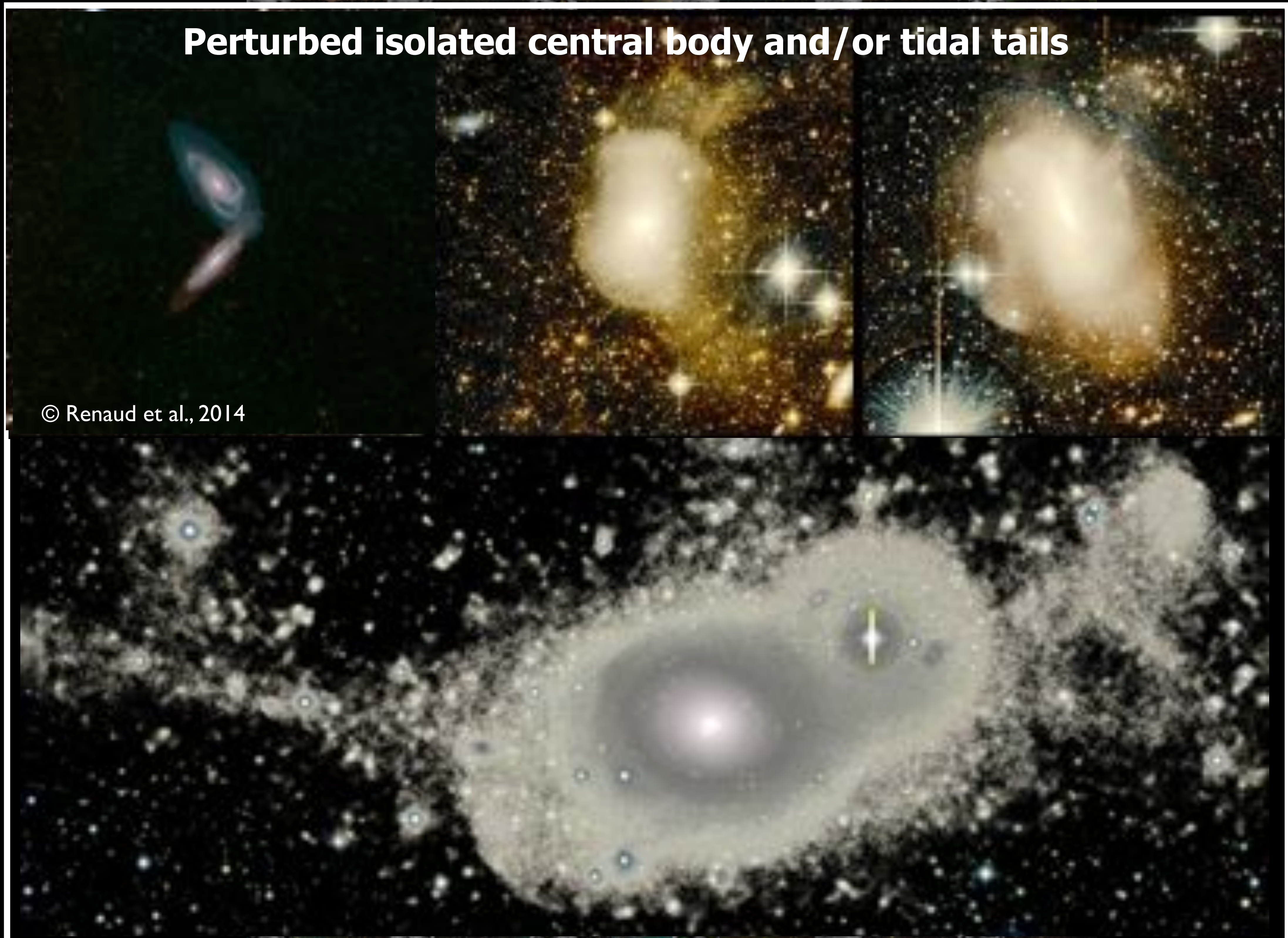
Early–type galaxies as seen by ultra–deep imaging

Early–type galaxies as seen by ultra–deep imaging

Perturbed isolated central body and/or tidal tails



… revealing past gas-rich major merger



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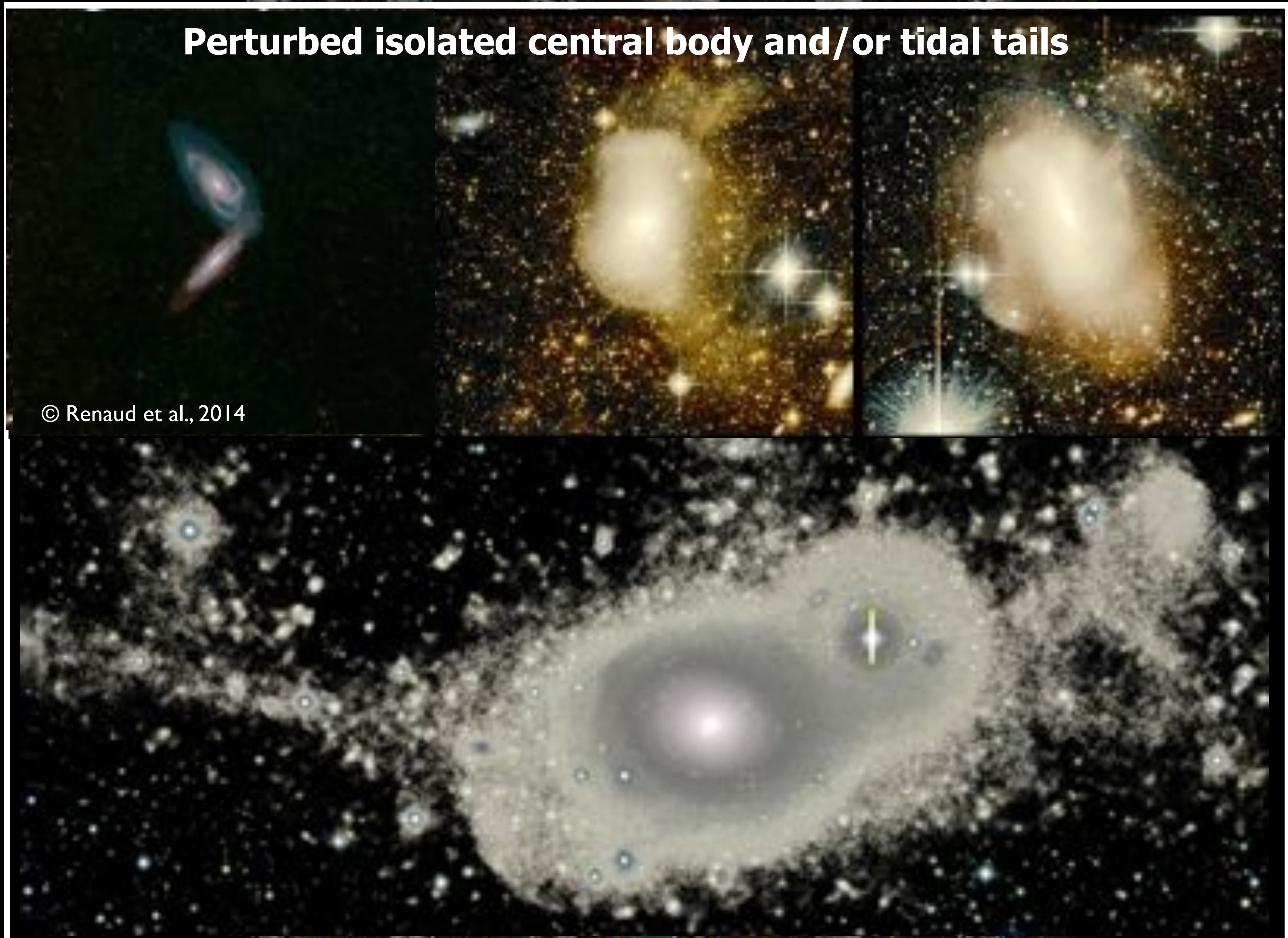
➡ Typical life time of tails of 1-2 Gyr



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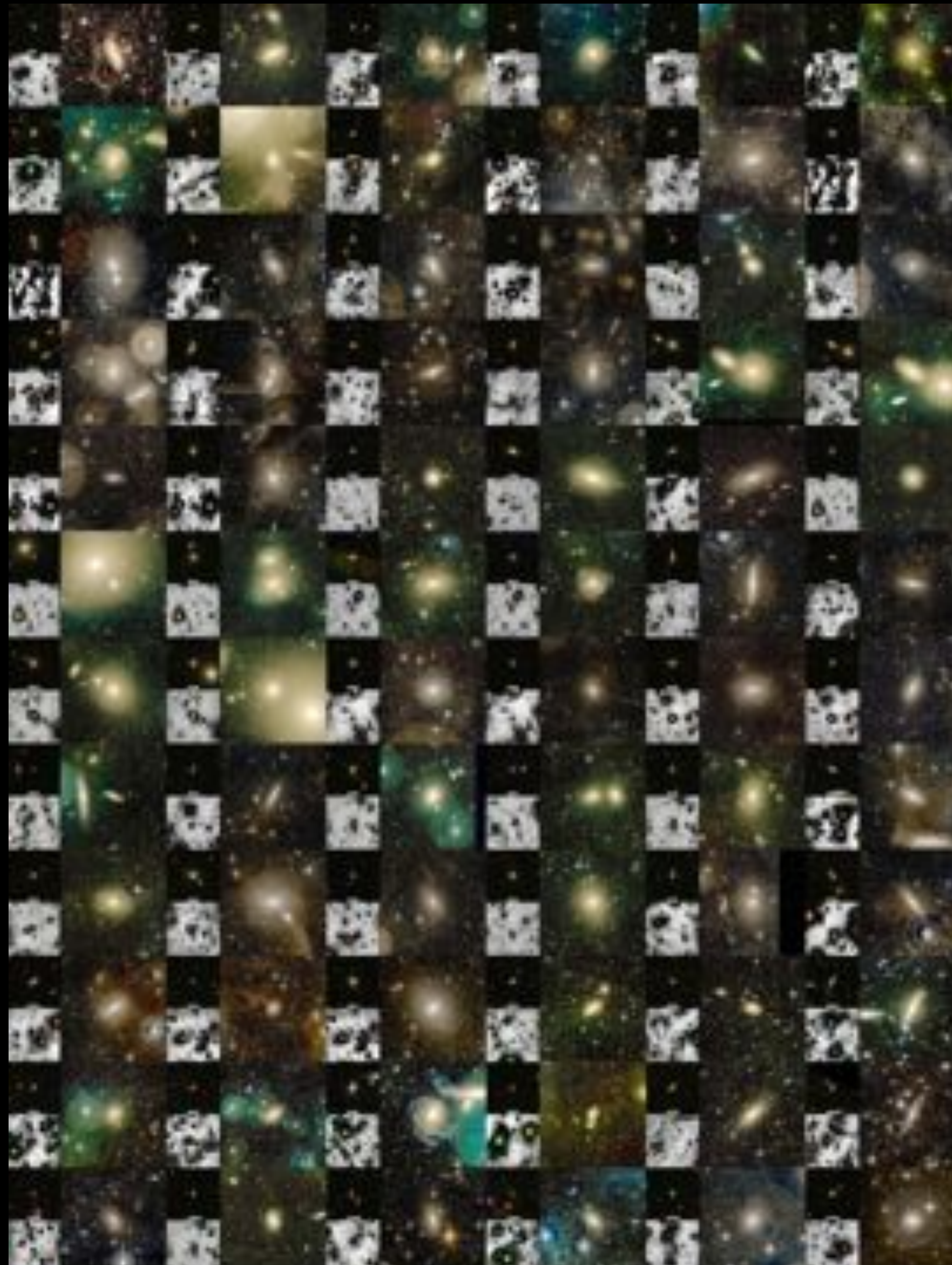
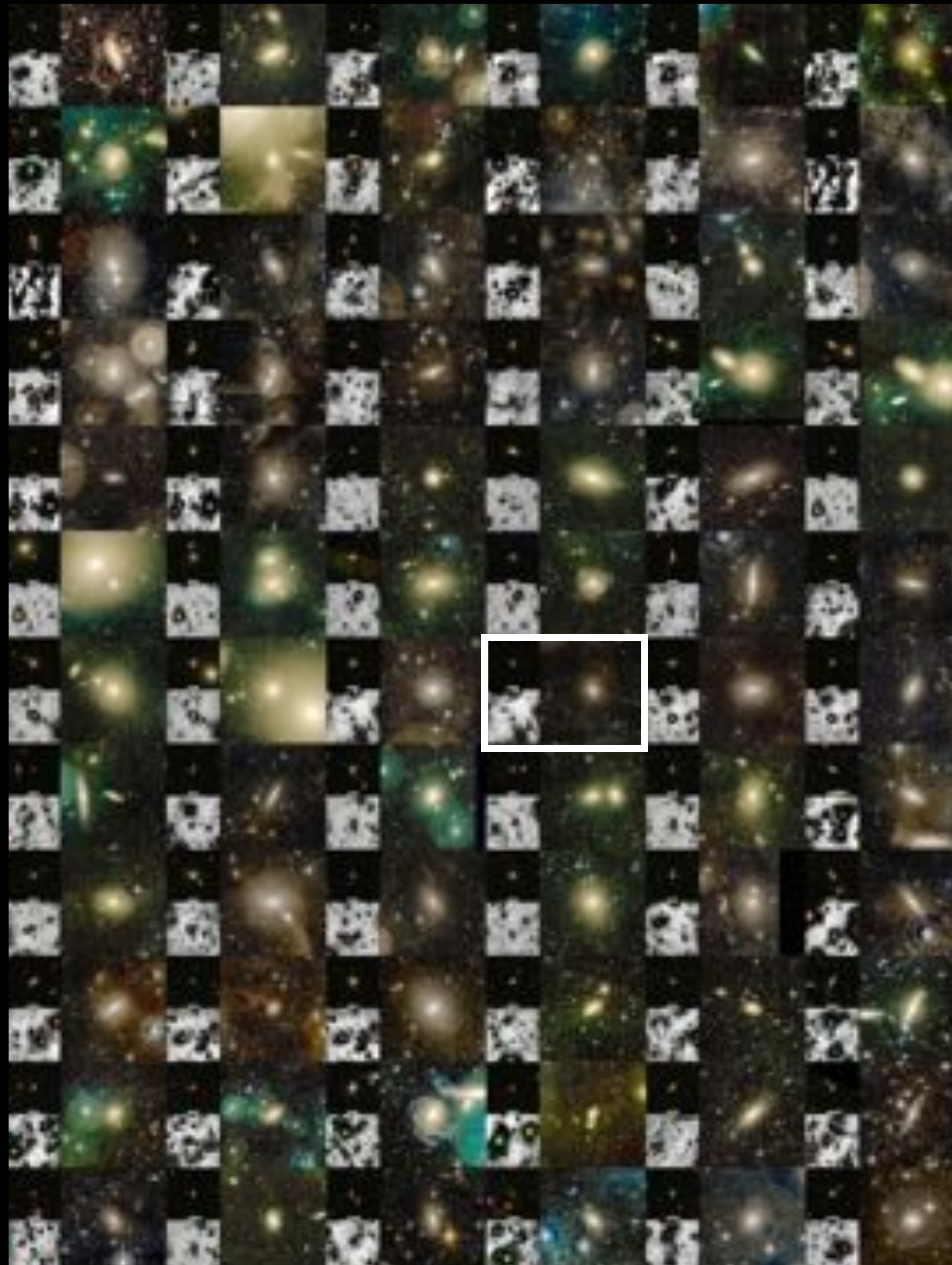
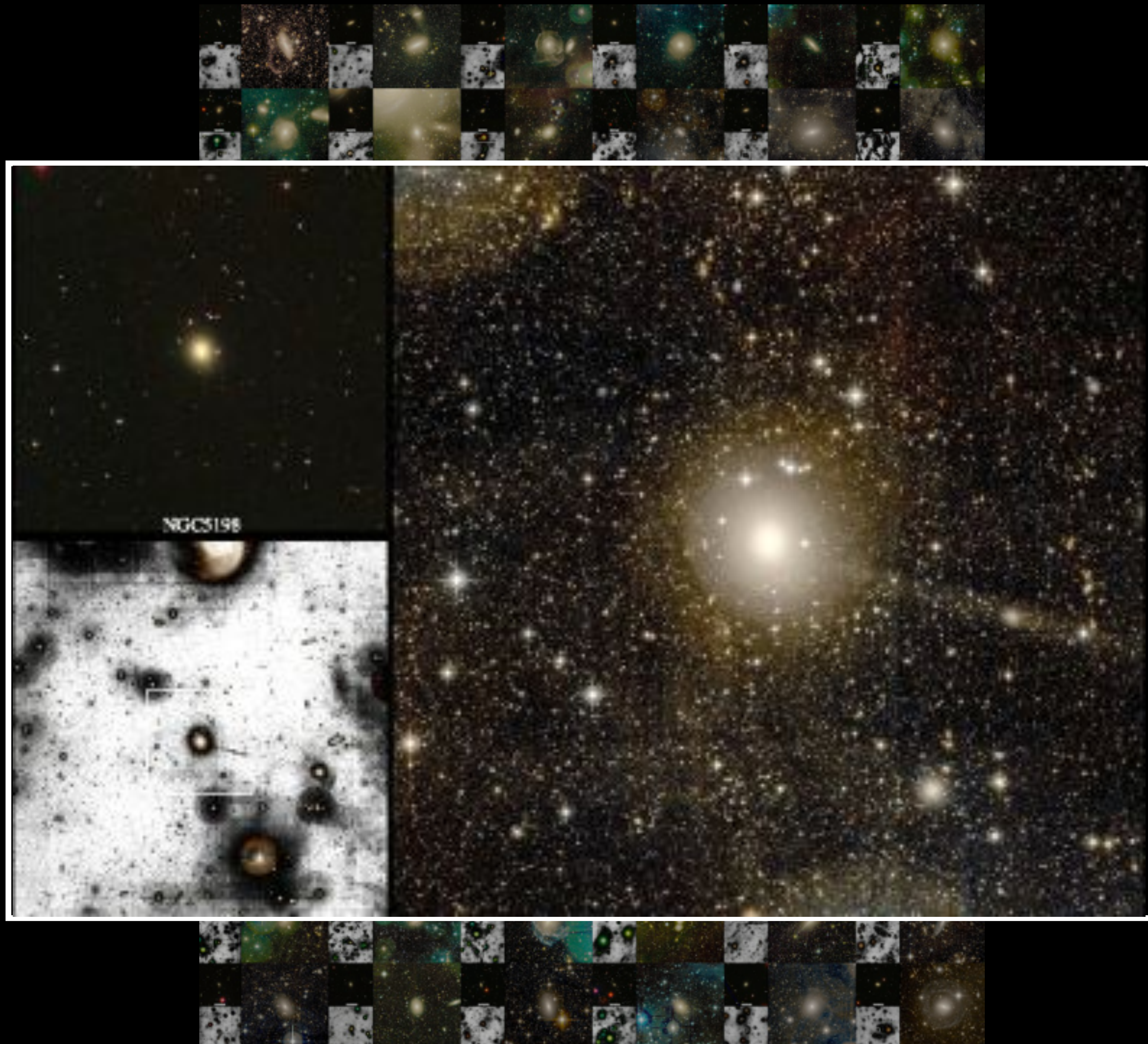


Early–type galaxies as seen by ultra–deep imaging



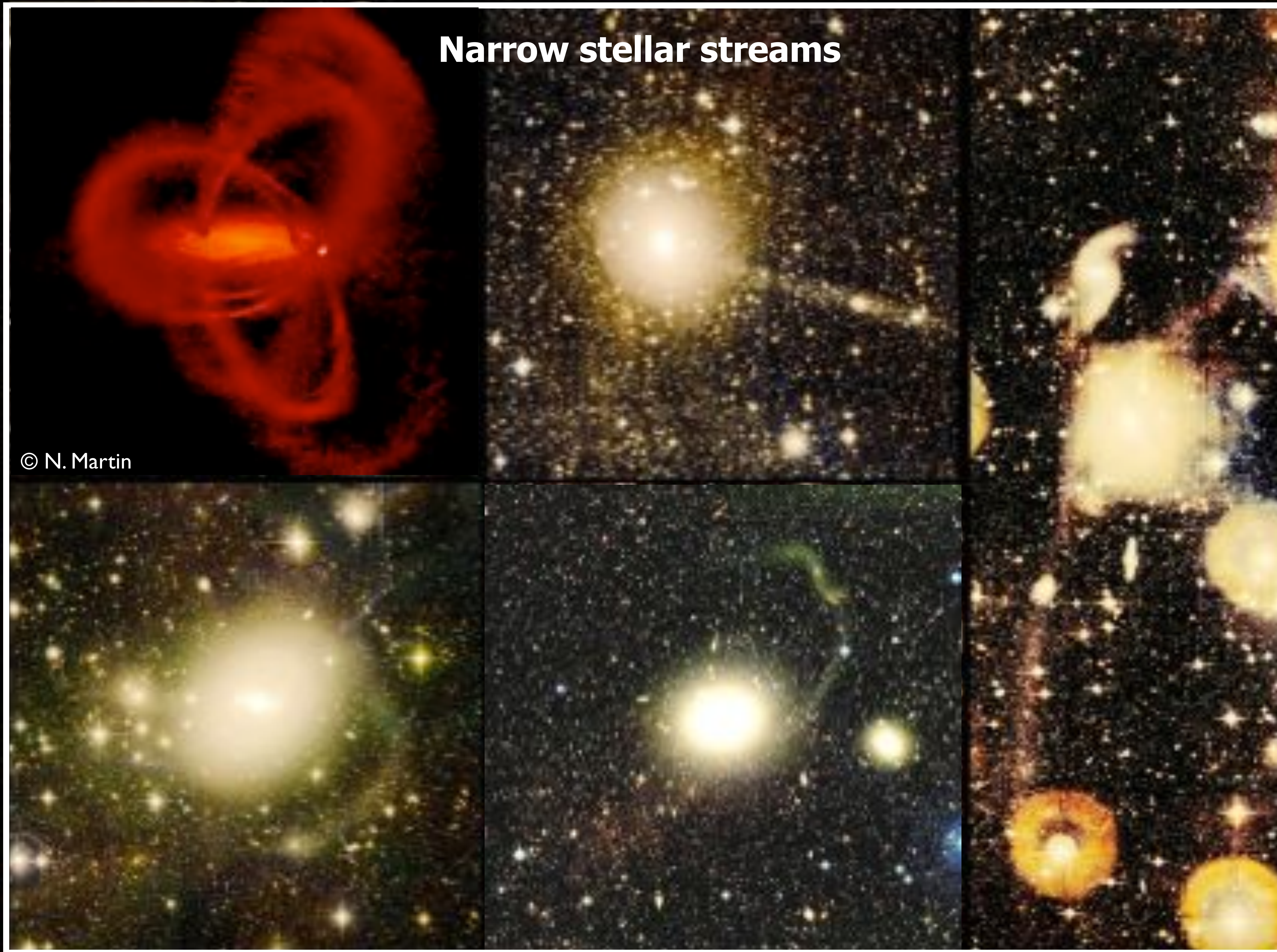
Early–type galaxies as seen by ultra–deep imaging



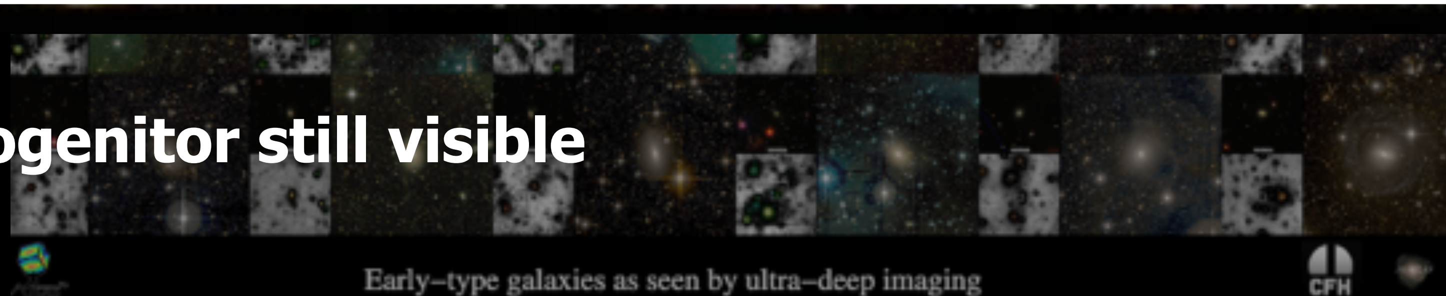
Early–type galaxies as seen by ultra–deep imaging

… revealing on going / past gas-poor minor mergers

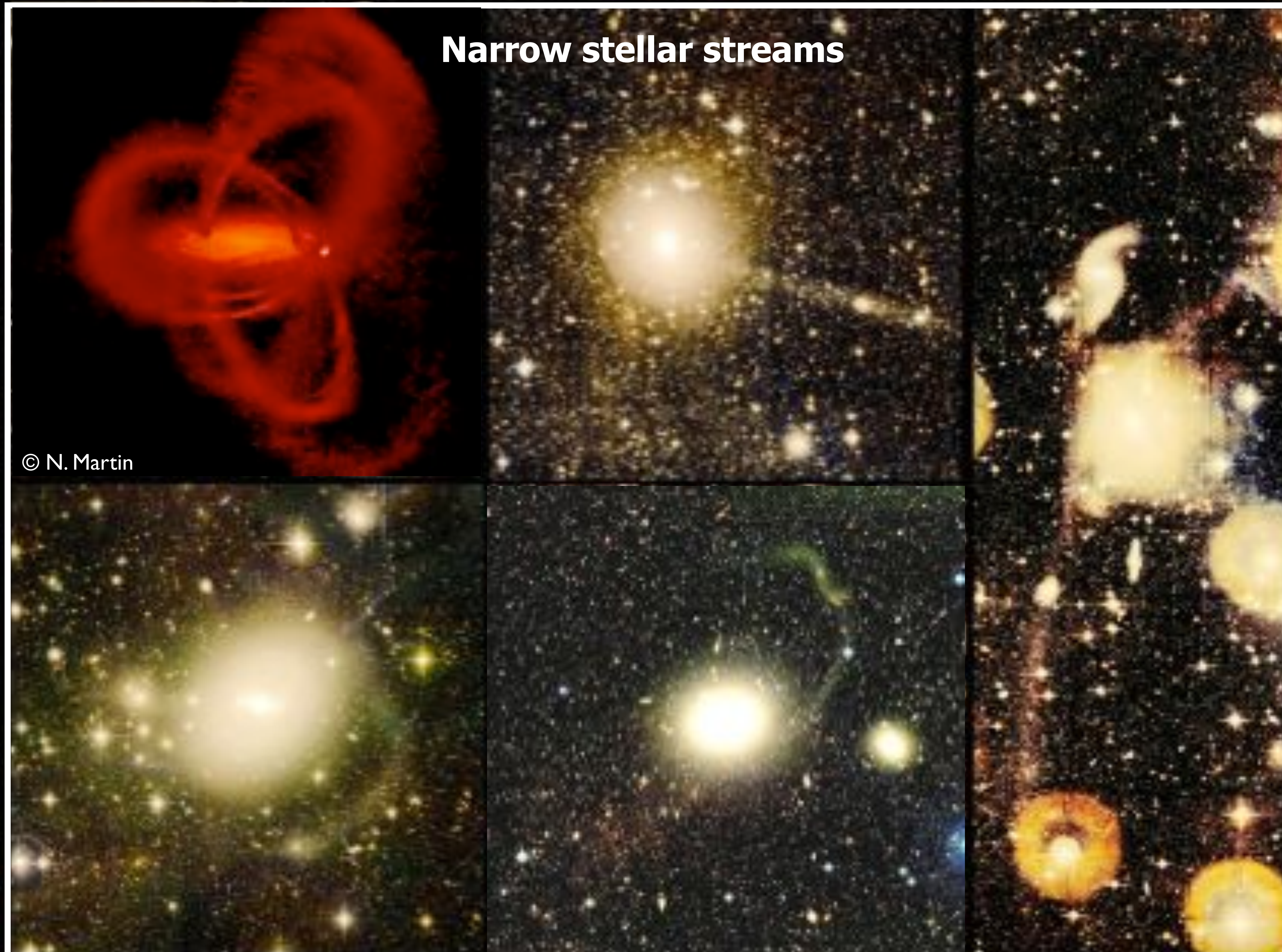
Narrow stellar streams



Disrupted progenitor still visible

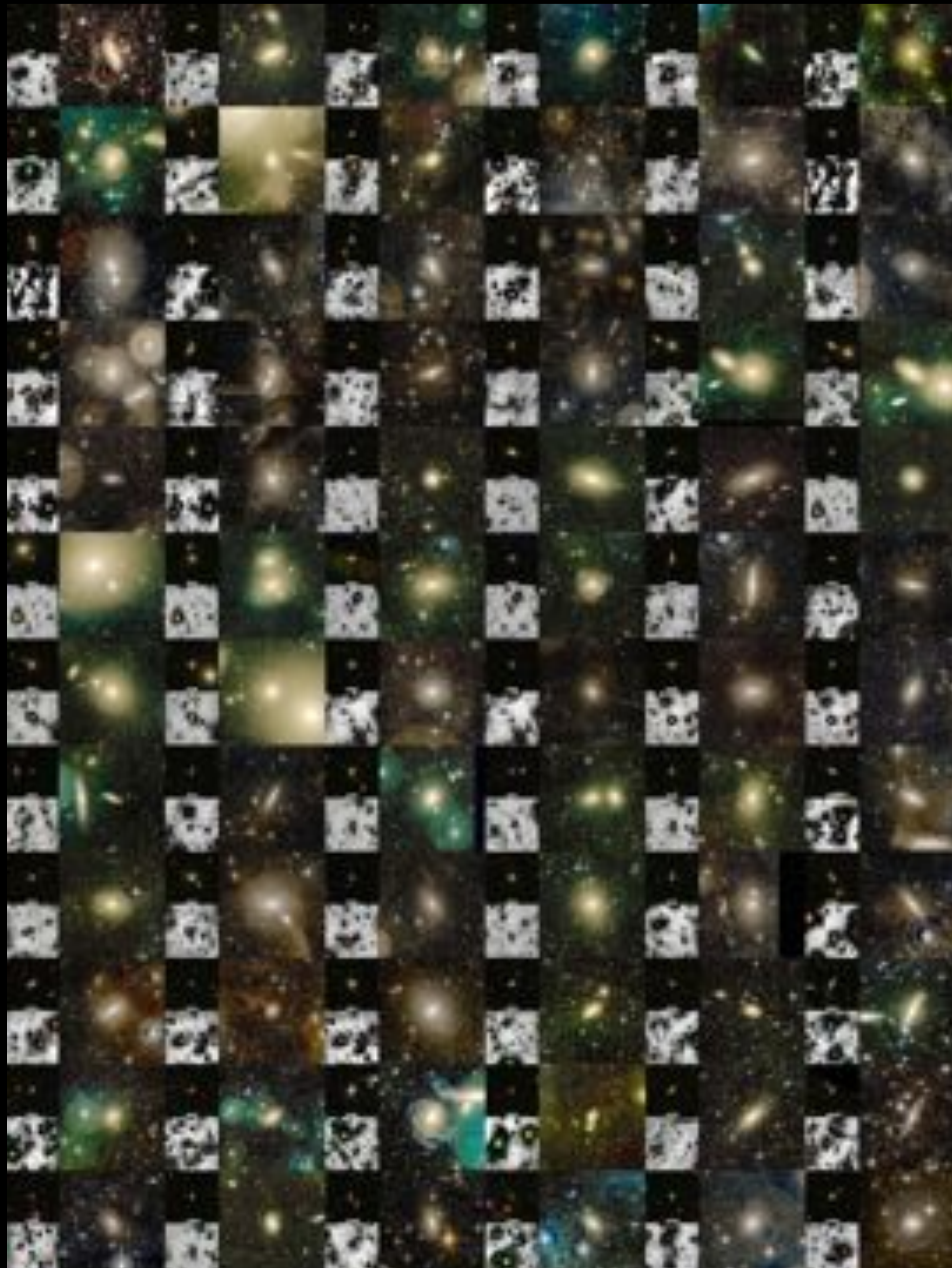


➡ Typical life time of streams of 2-3 Gyr

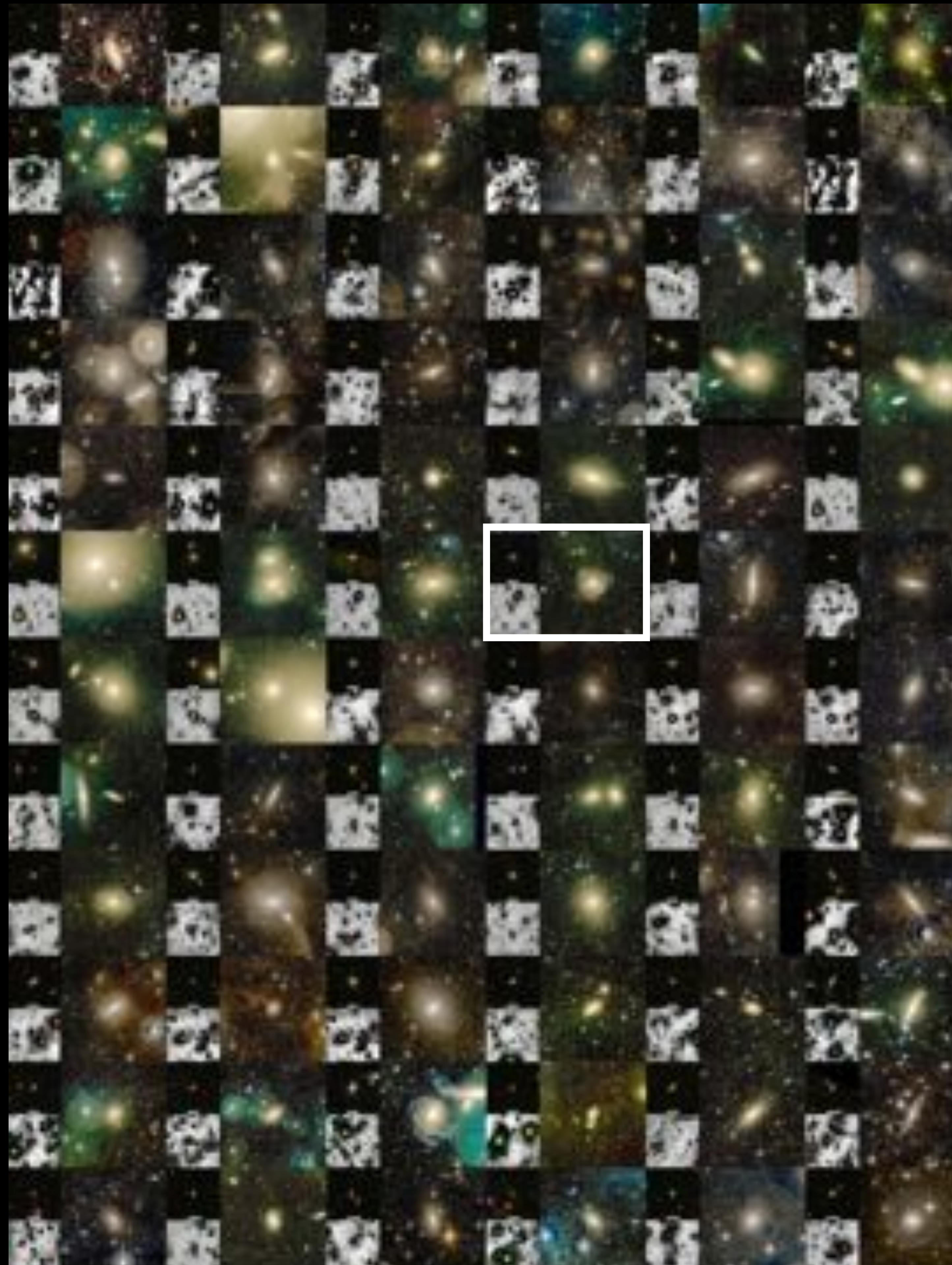


Disrupted progenitor still visible

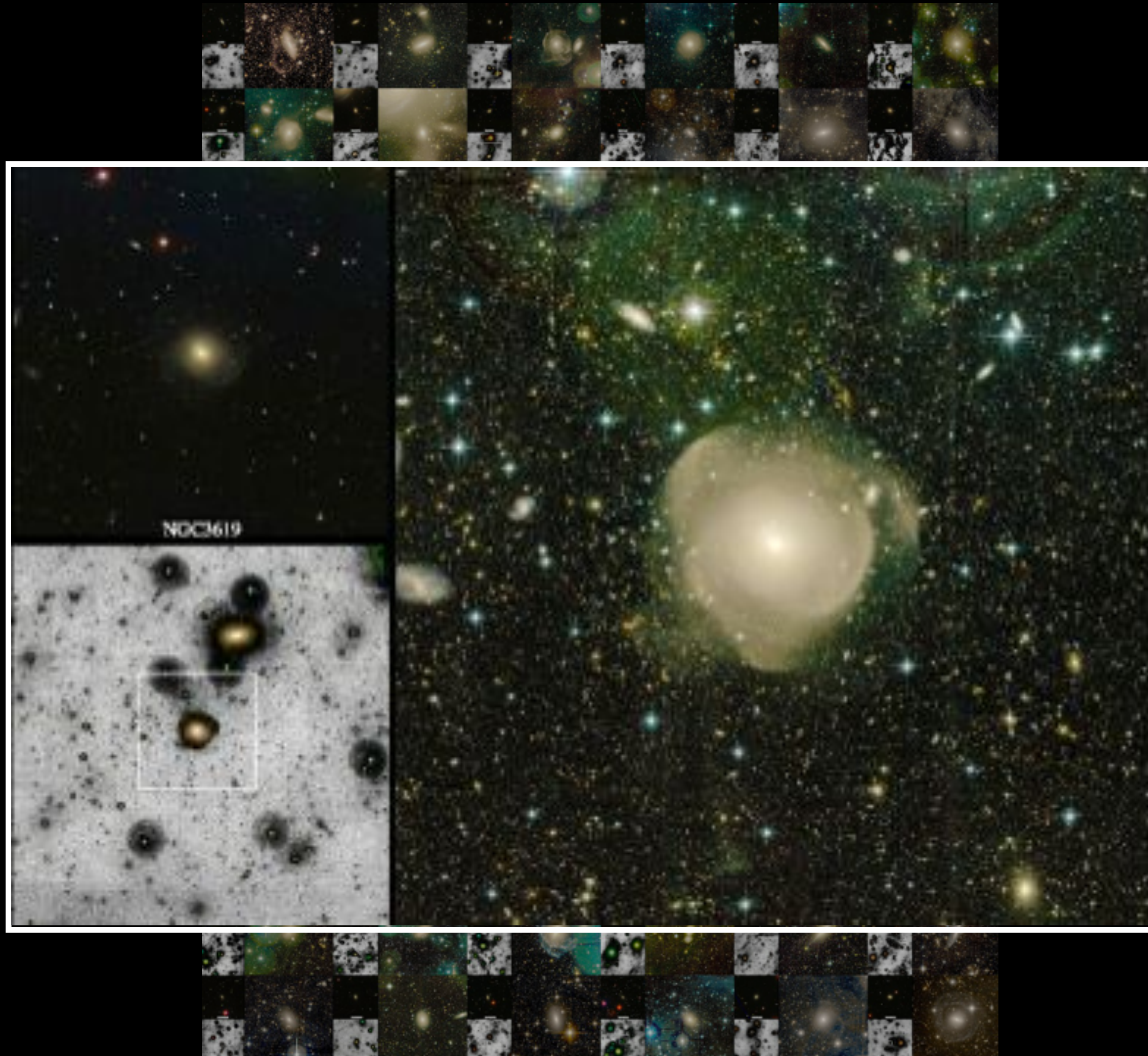
➡ Typical life time of streams of 2-3 Gyr



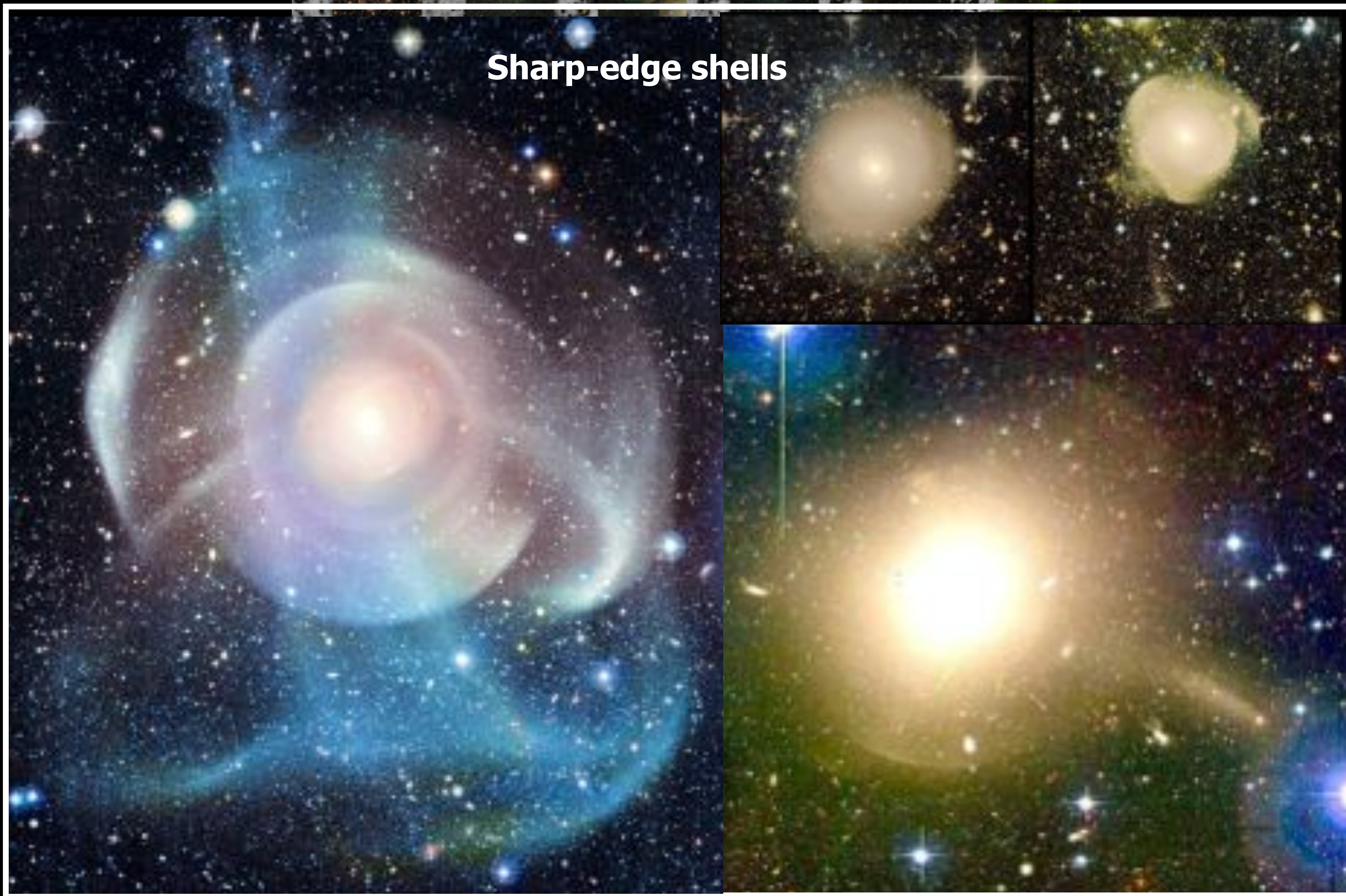
Early–type galaxies as seen by ultra–deep imaging



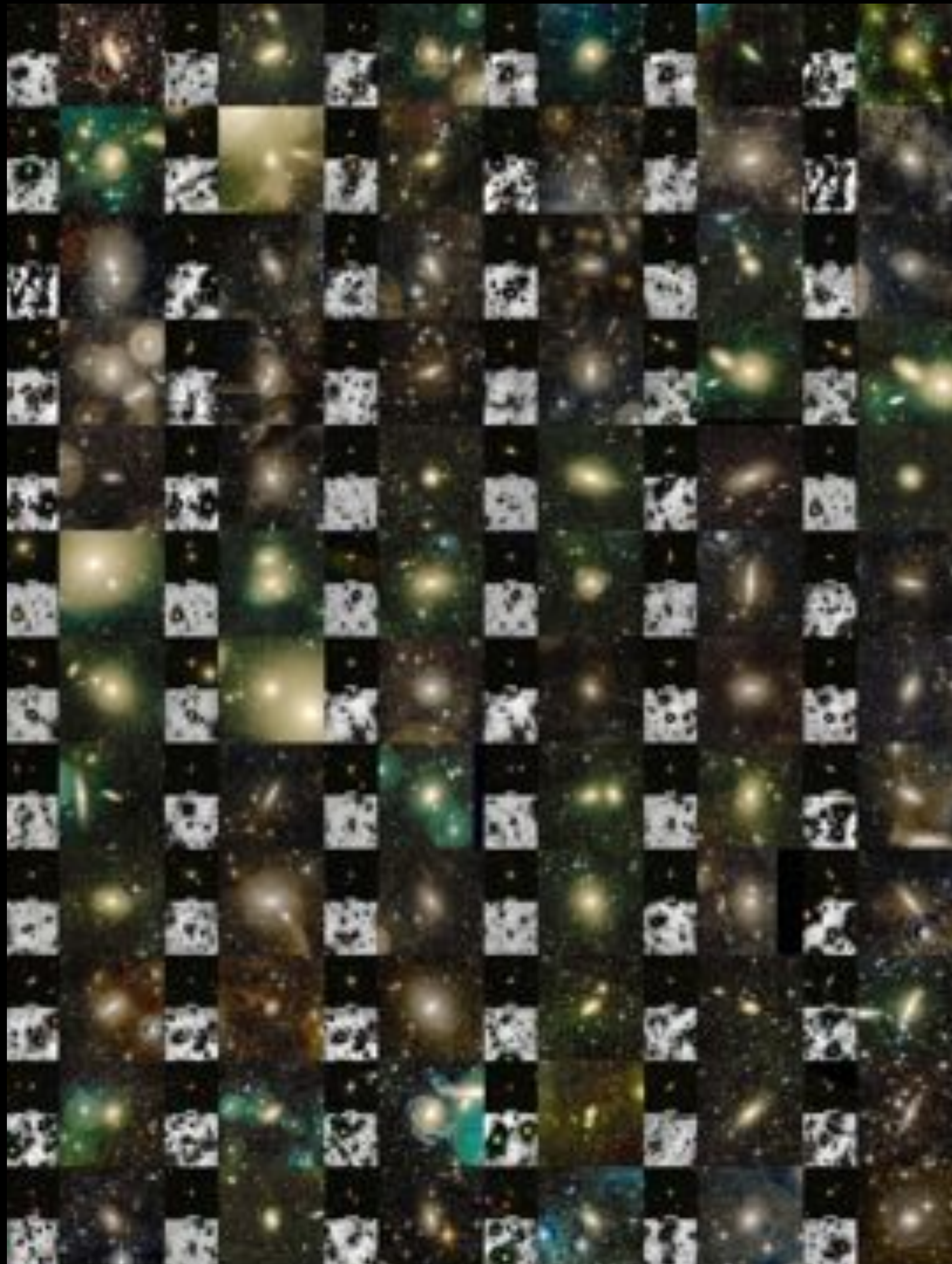
Early–type galaxies as seen by ultra–deep imaging



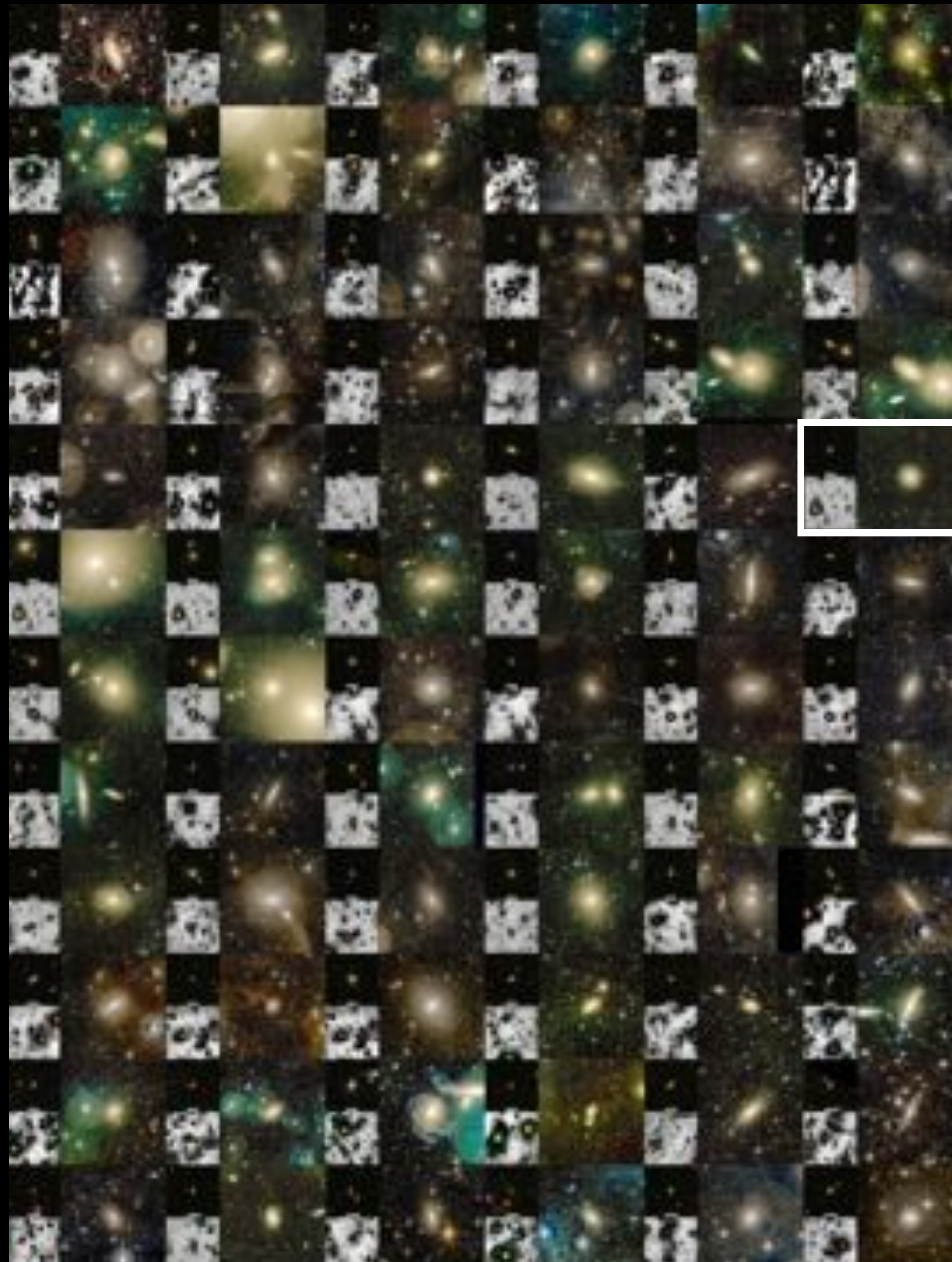
Early–type galaxies as seen by ultra–deep imaging



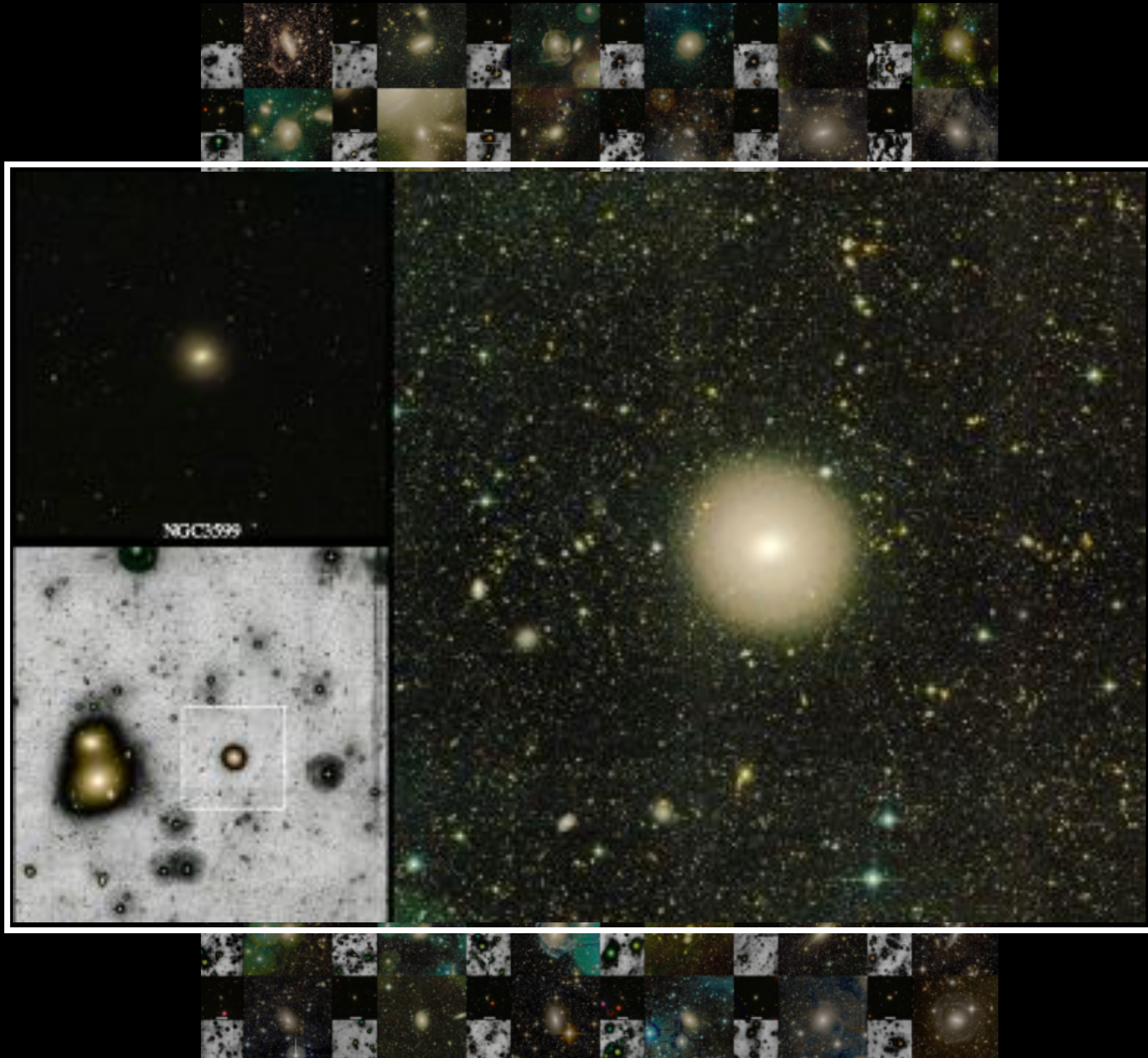
… revealing past intermediate mass mergers



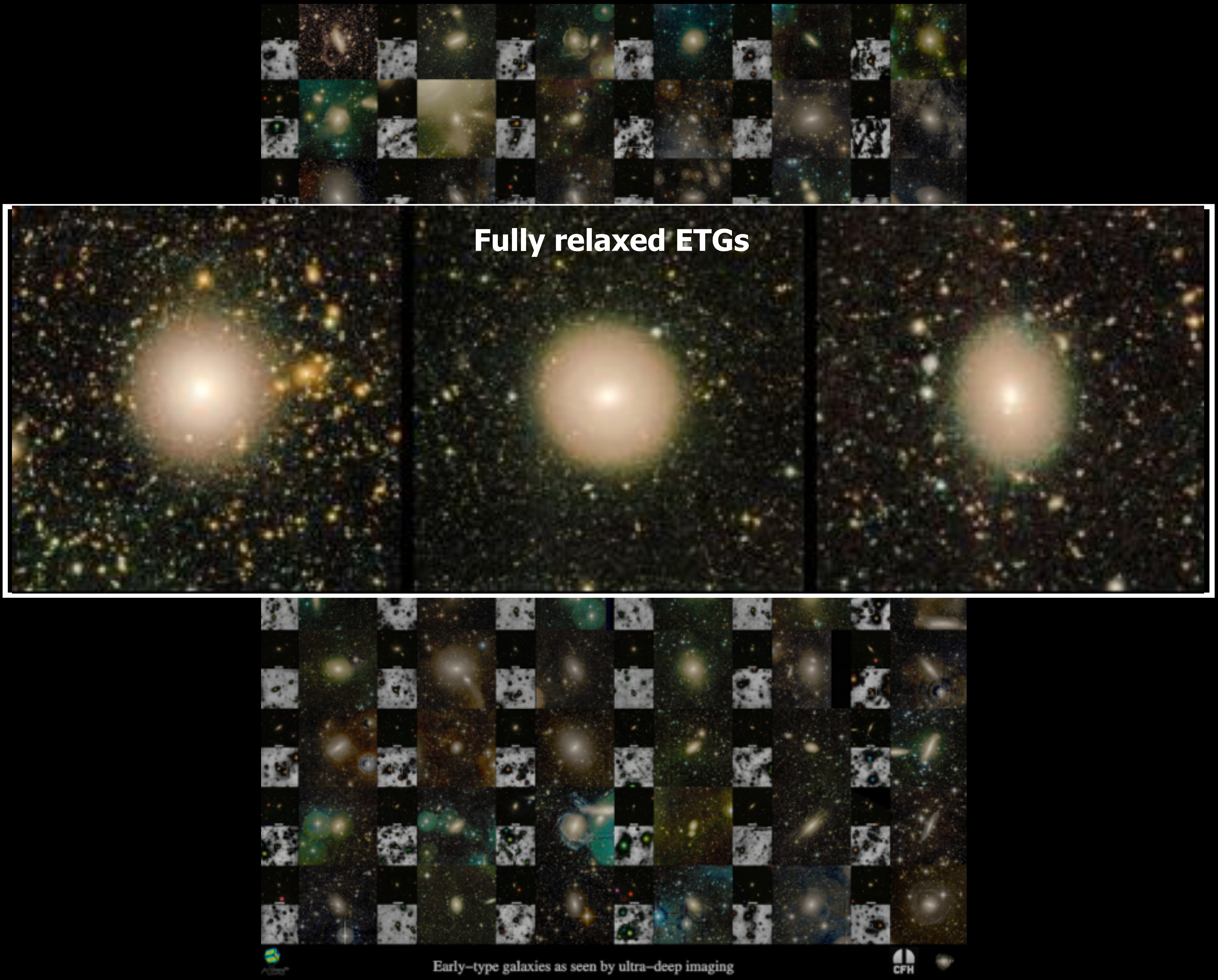
Early–type galaxies as seen by ultra–deep imaging



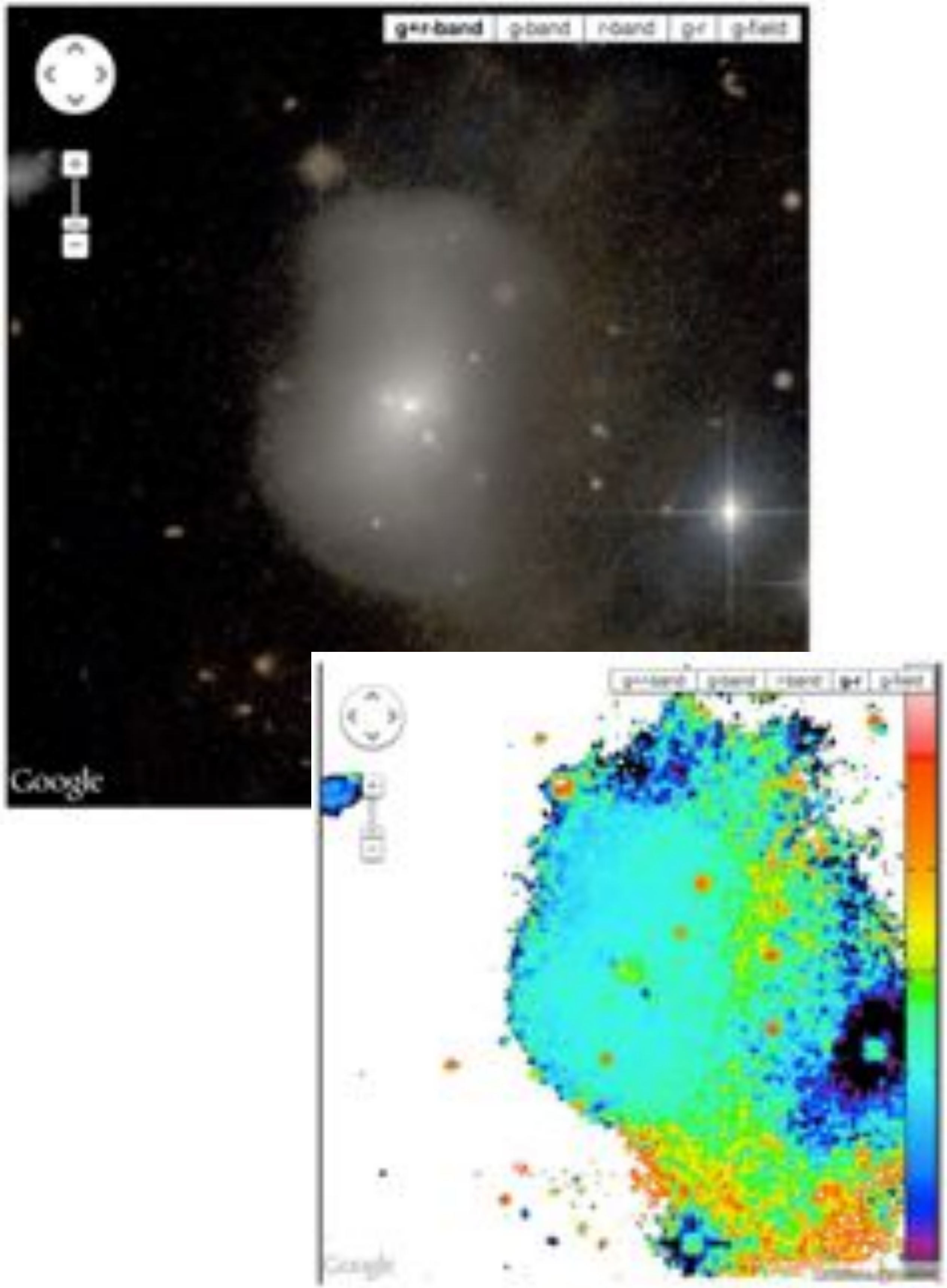
Early–type galaxies as seen by ultra–deep imaging

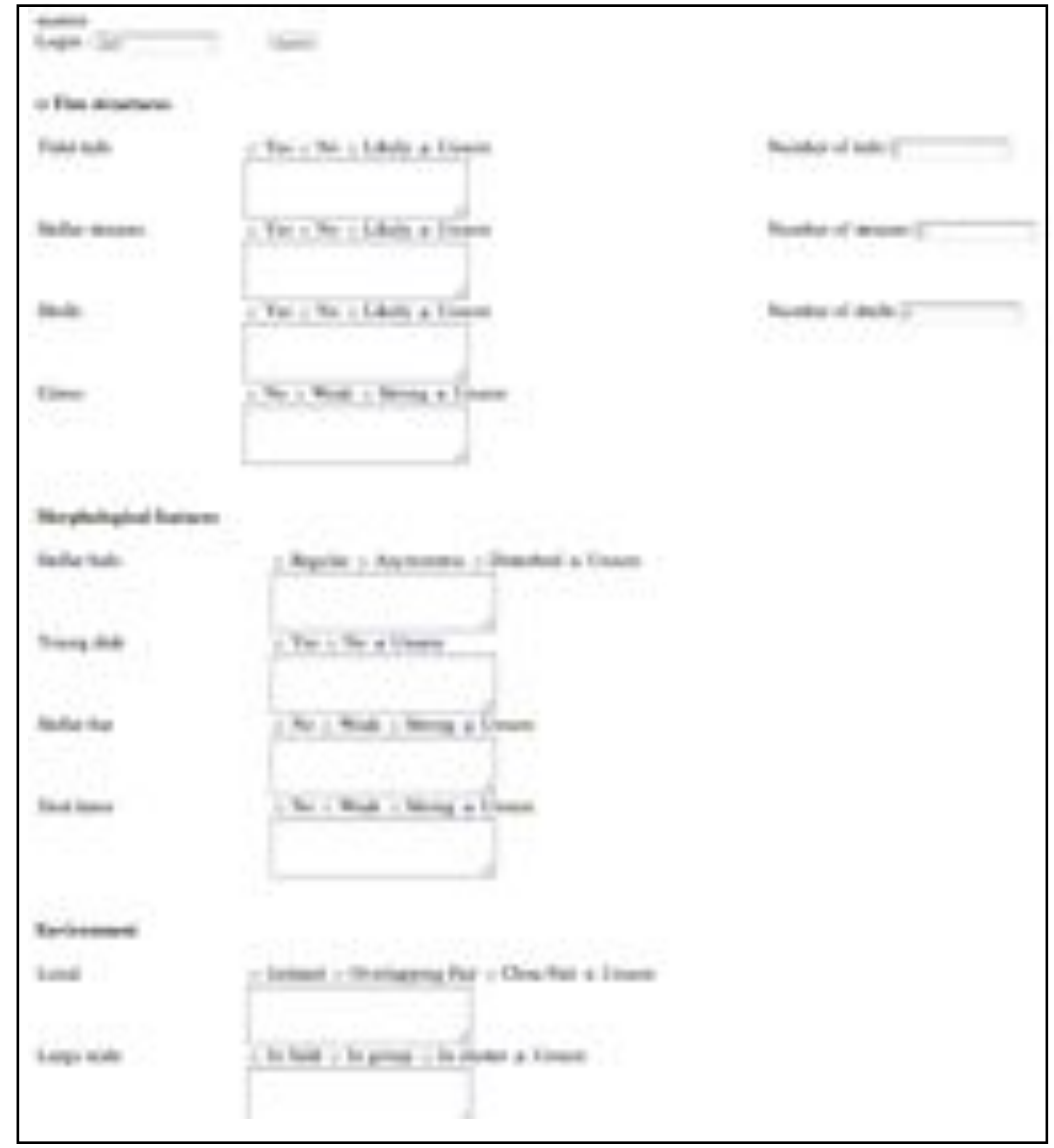


Early–type galaxies as seen by ultra–deep imaging


Fully relaxed ETGs
Early–type galaxies as seen by ultra–deep imaging
CFH

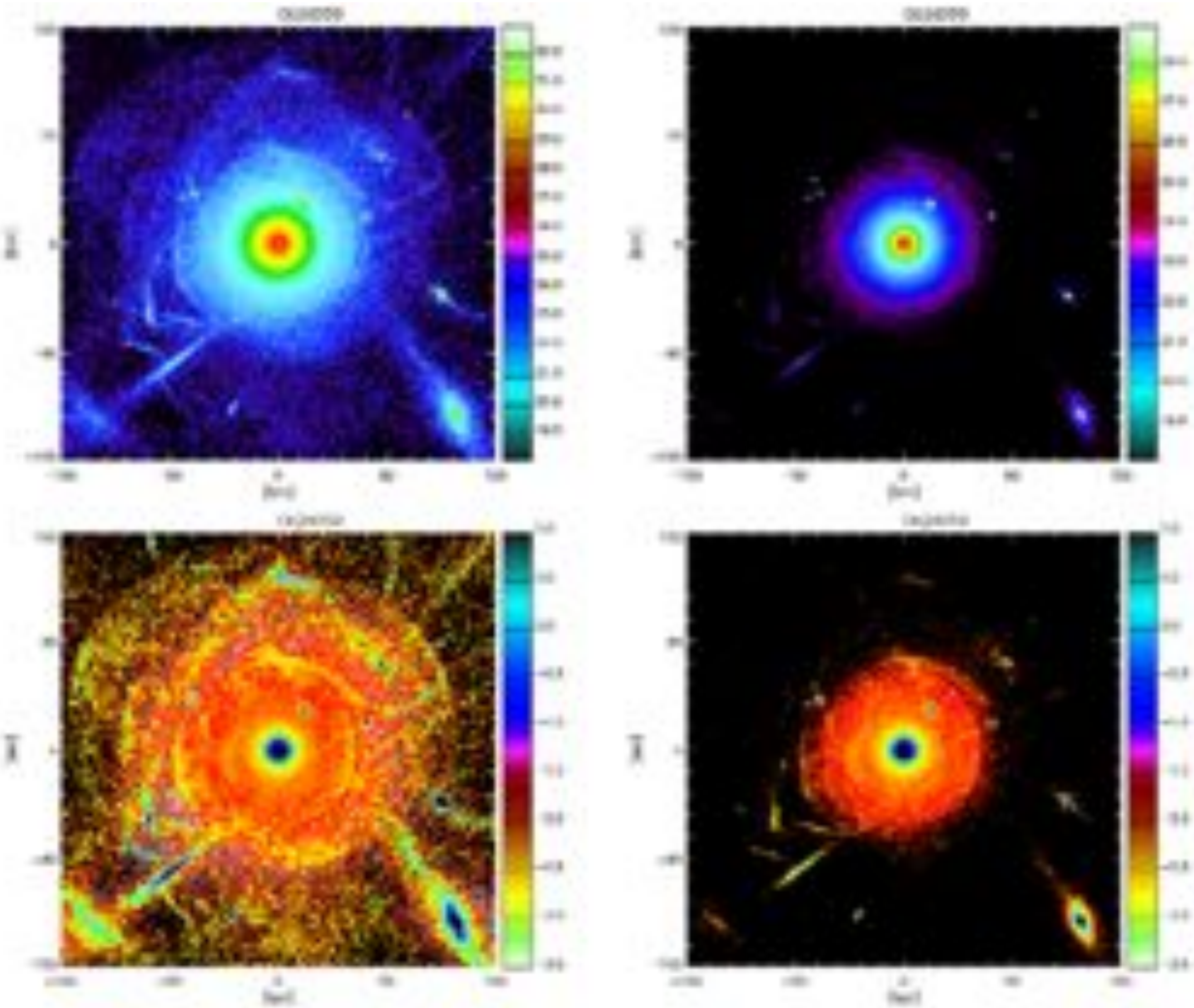
Fine structure identification on deep images

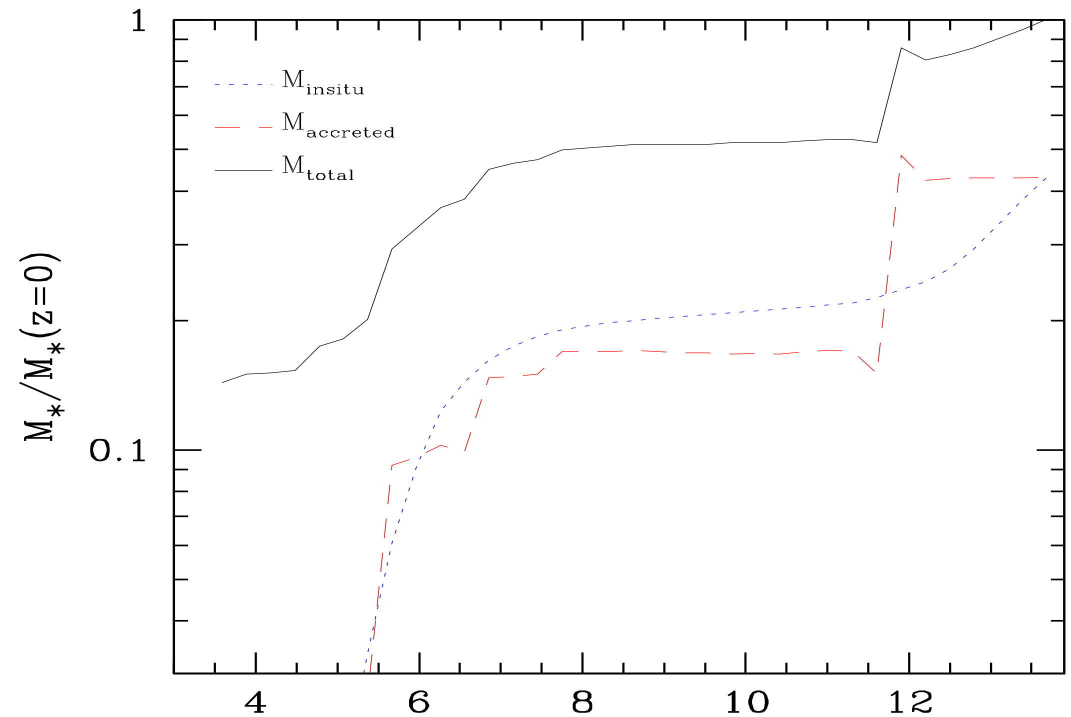




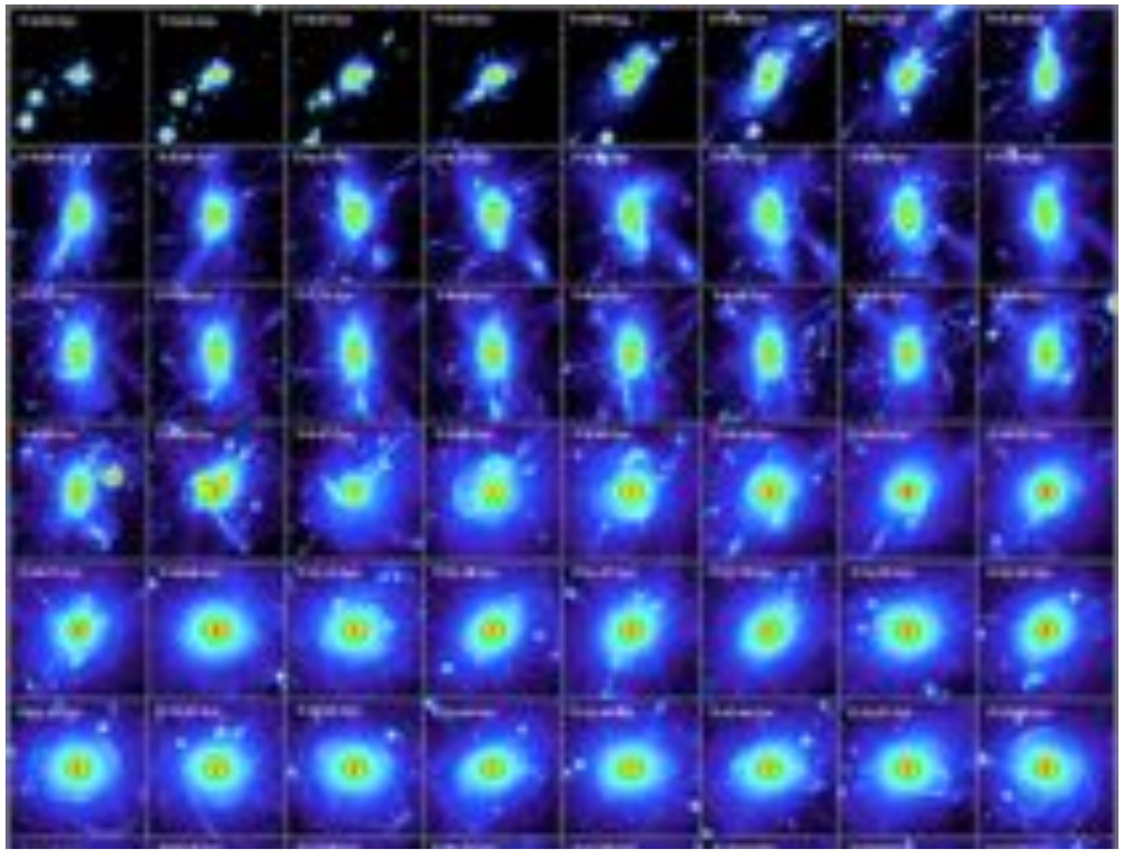
- Made by eye
- Based on multi band / color images and residual maps
- Poll filled with a web interface
- Around 5 classifiers per galaxy

Fine structure identification on simulations



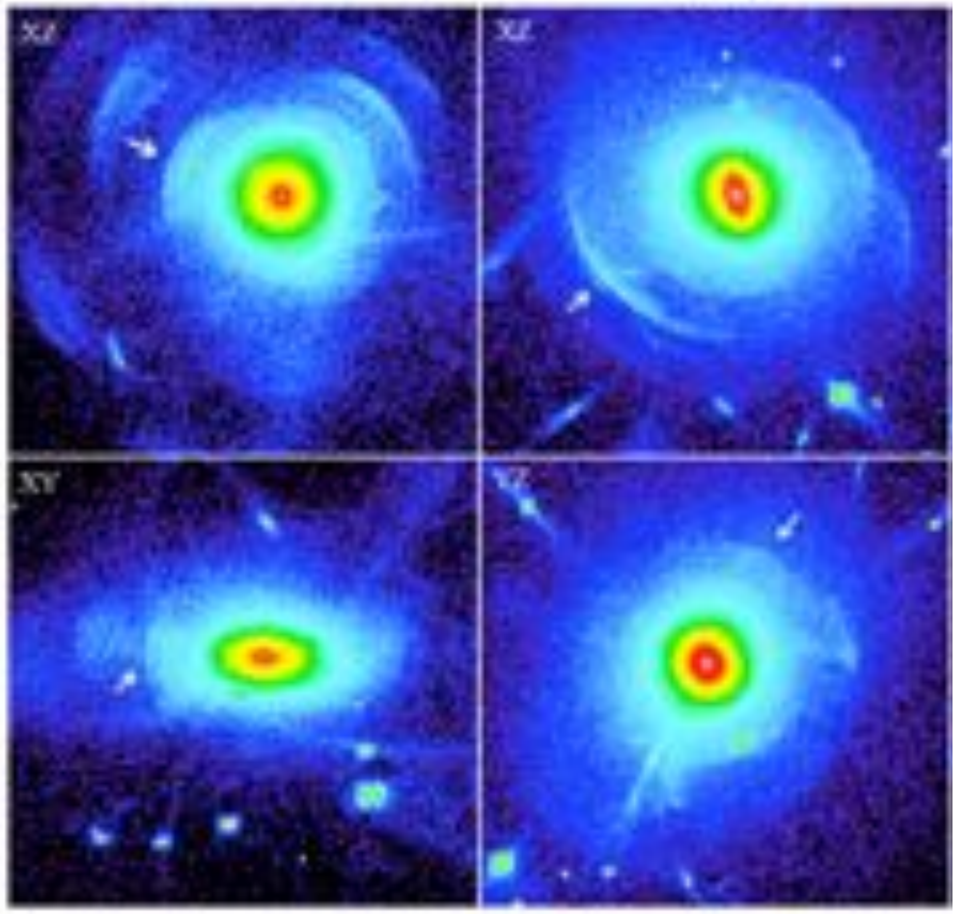


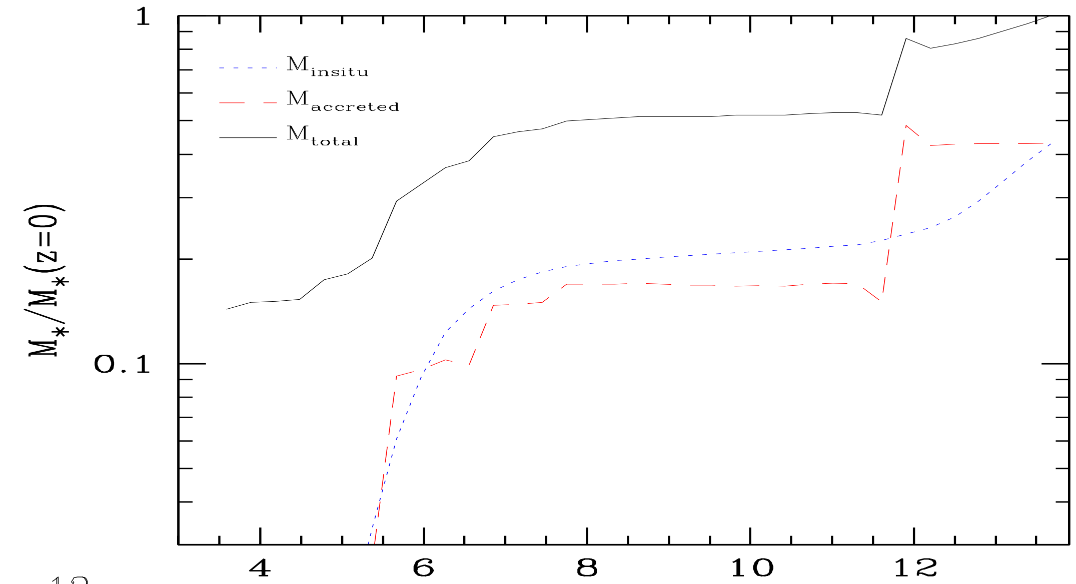
Martig et al., 2009



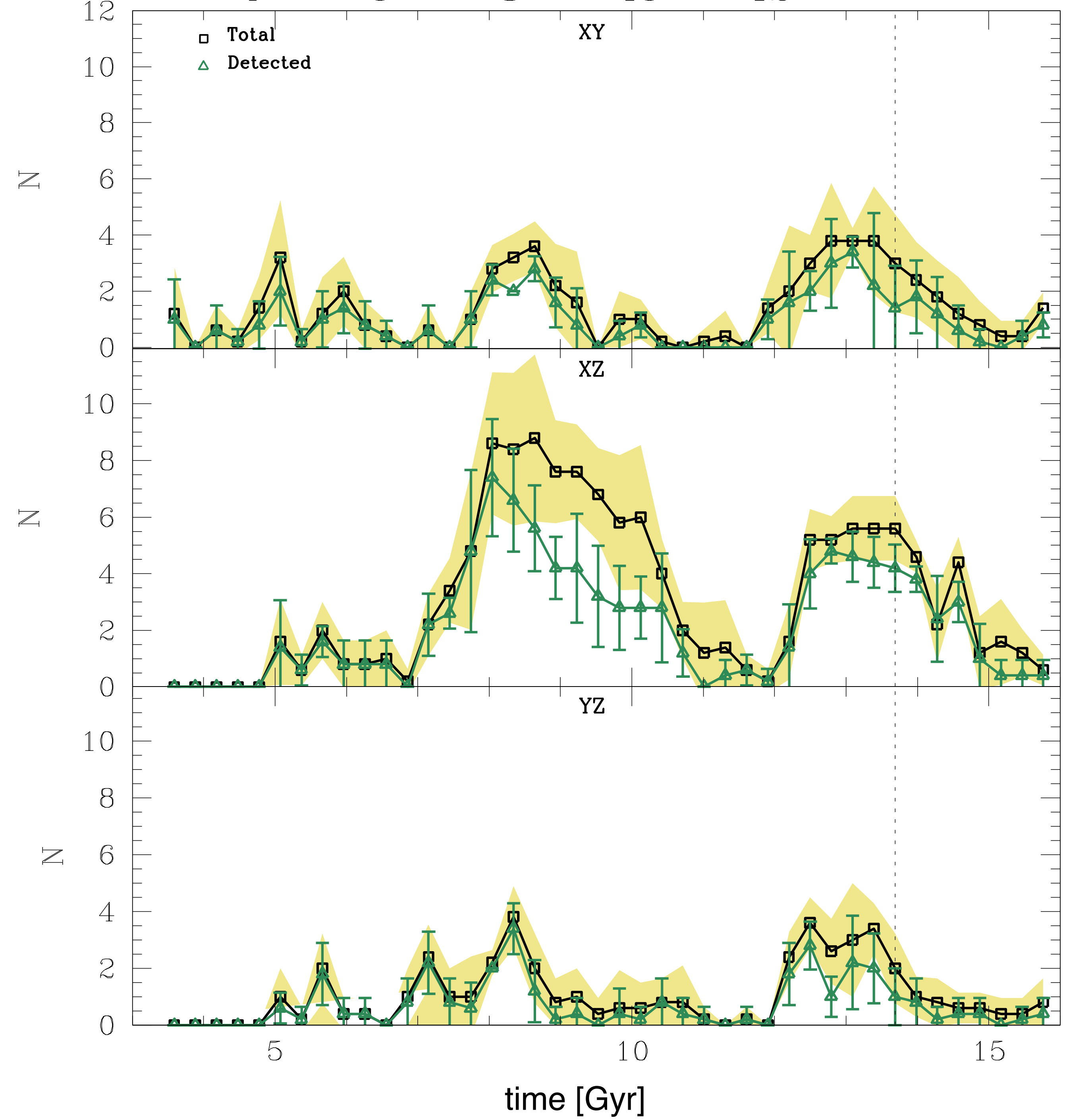
- Based on a re-simulation made in cosmological context, with « realistic » merger history
- Fine structures identified by eye, based on their shape, color, brightness
- Snapshots previously shuffled, mixing 3 different orientations
- Exercice made by 5 classifiers

✓Shells



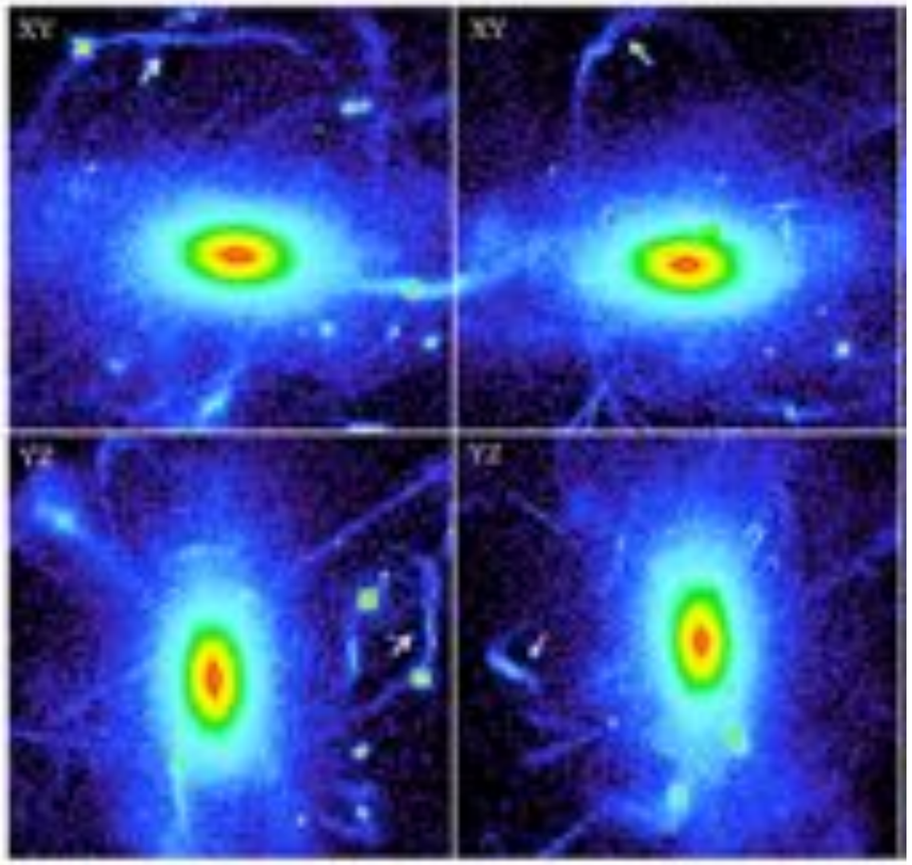


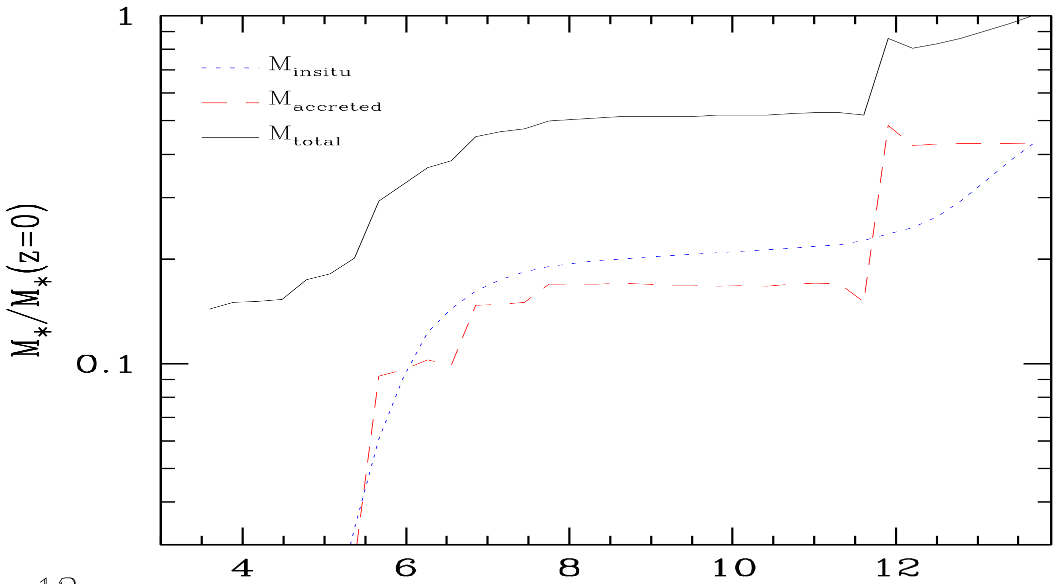
Mancillas et al., 2016

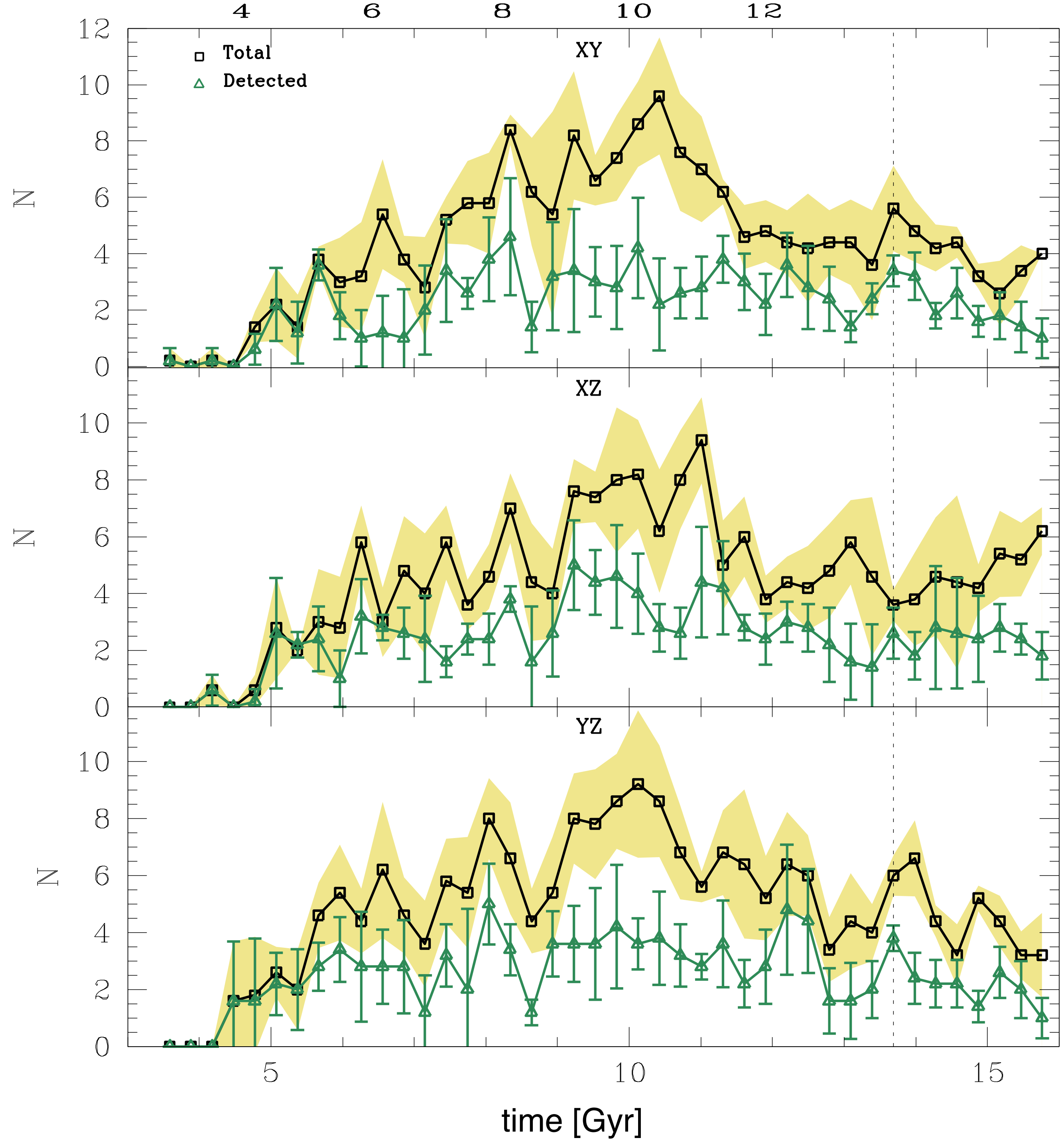


- Trace minor and major mergers
- Long lived (3-4 Gyr)
- Detection depends strongly on the *orientation*, but weakly on the *surface brightness limit*

✓ Streams

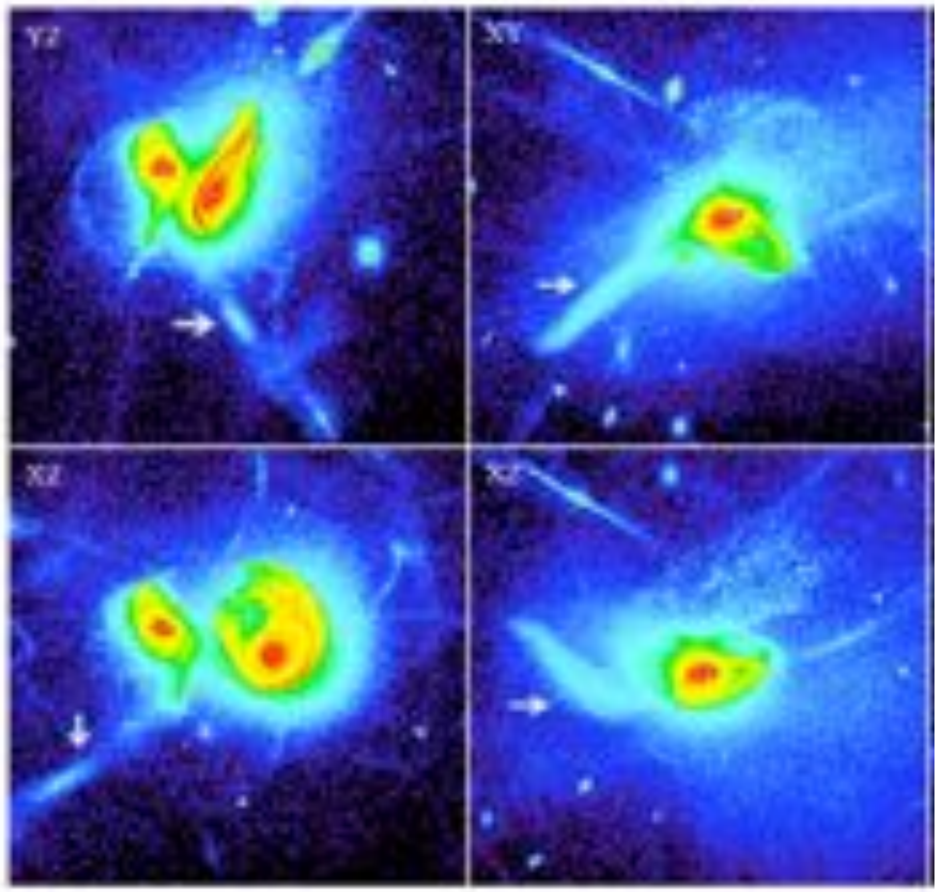




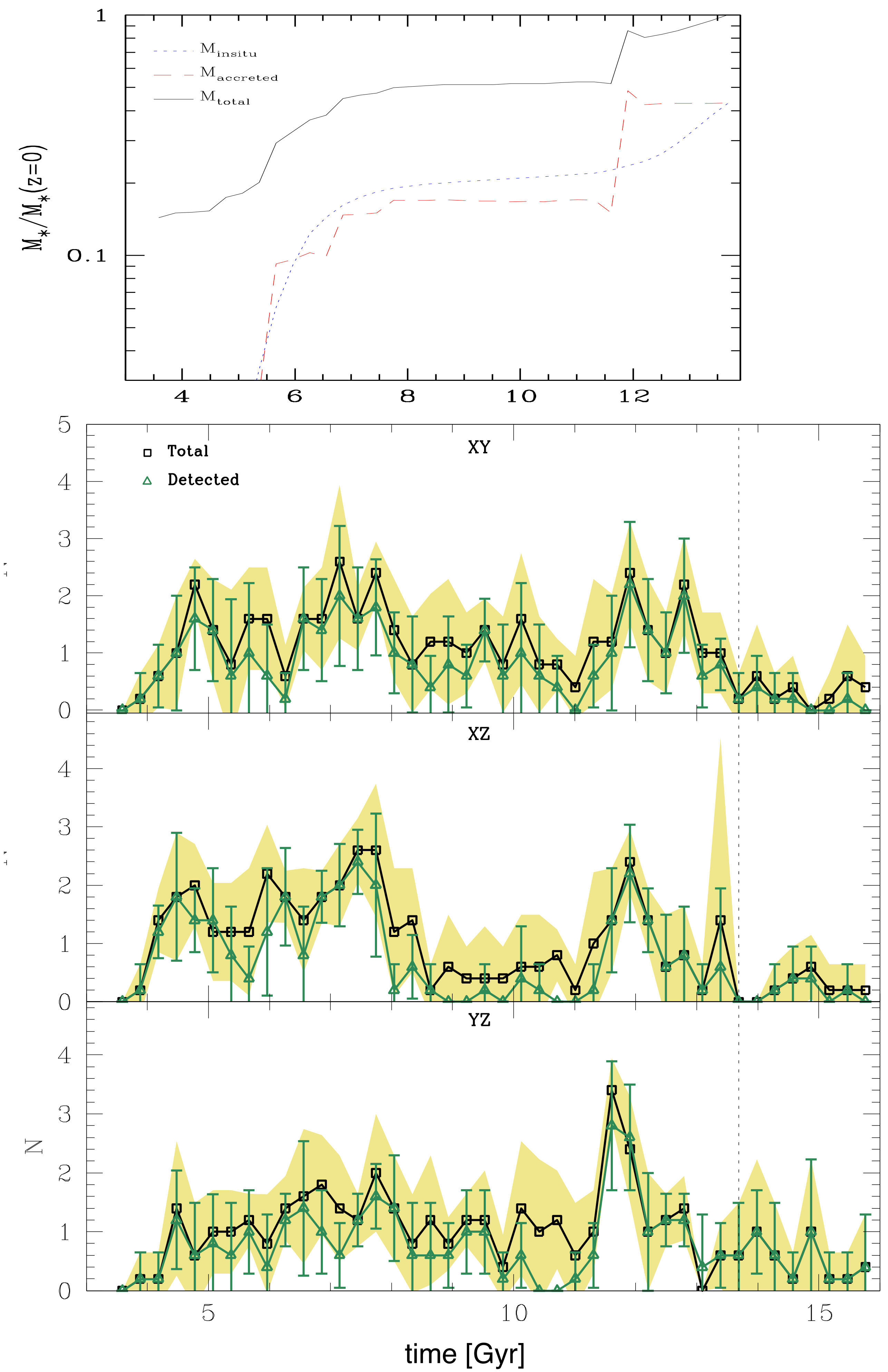


- Trace minor mergers
- Rather long lived (2-3 Gyr)
- Detection depends weakly on the *orientation*, but strongly on the *surface brightness limit*

✓ Tails



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



✓Morphology

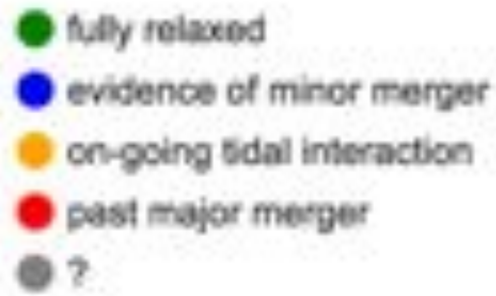
N=238 (almost complete, volume limited)

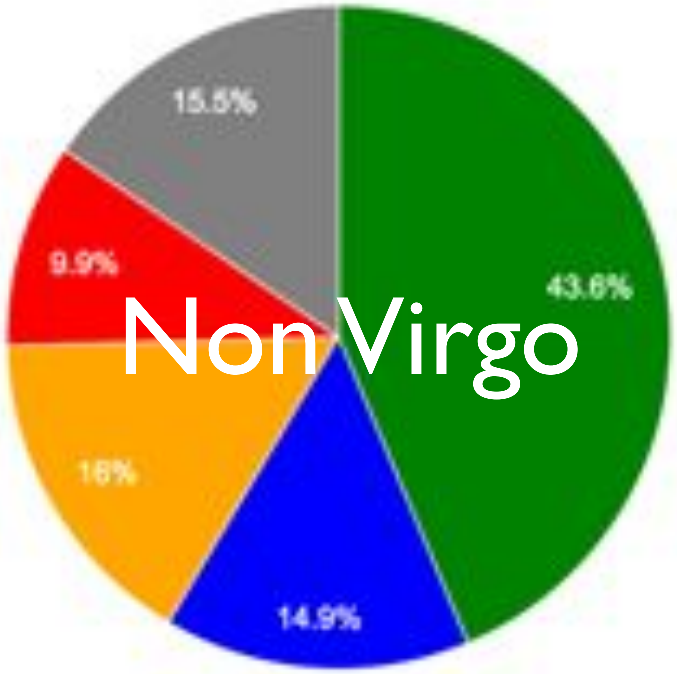
N=116 (incomplete, biased towards ETG rich groups)

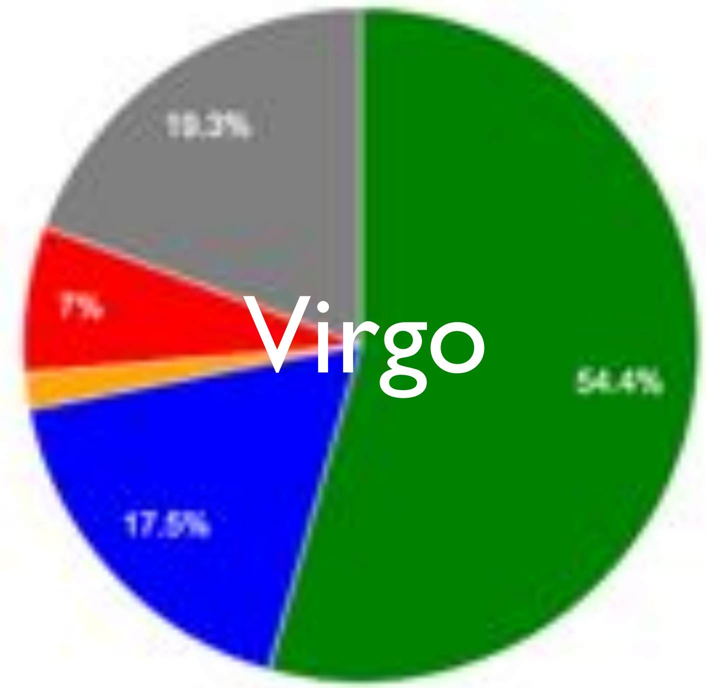
- At least 40% of all ETGs in our sample show signs of tidal perturbations, to be compared to about 15% in previous shallower surveys.

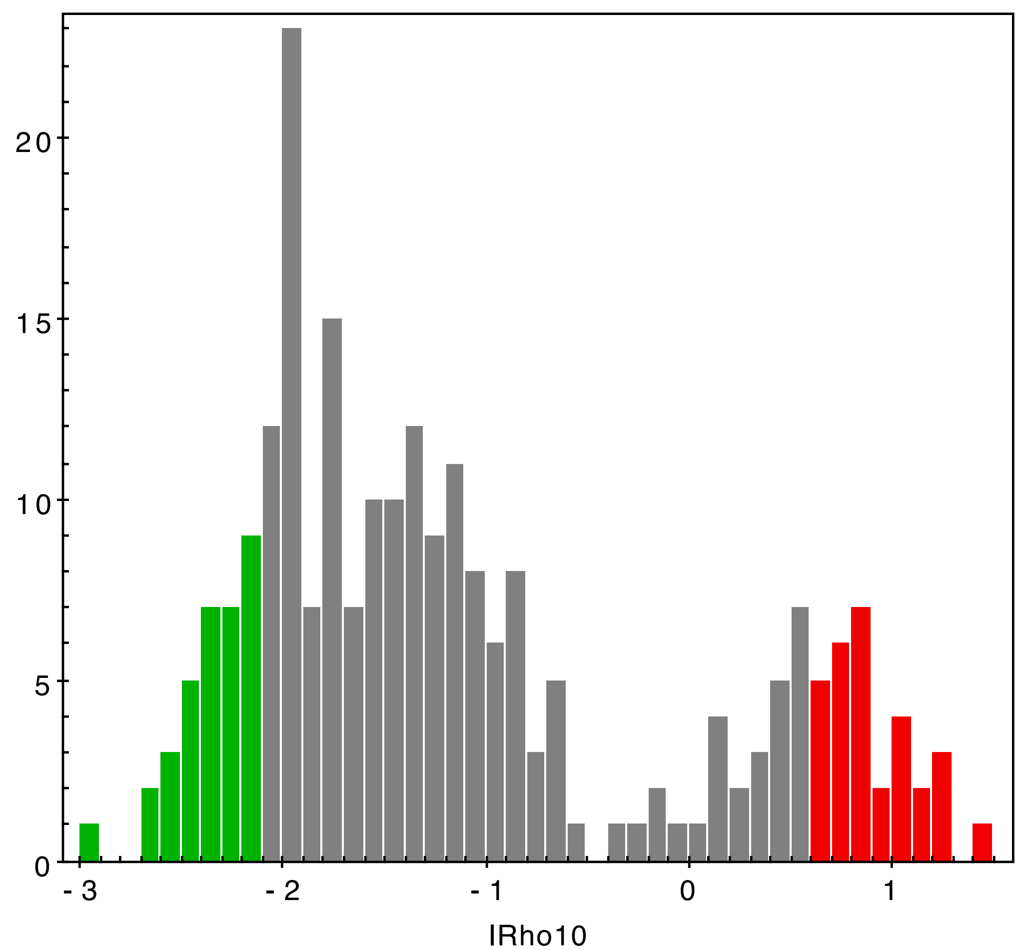
- Equivalent fraction of tidally perturbed LTGs, with expectedly a larger fraction of on-going tidally interacting systems and tiny fraction of major mergers.

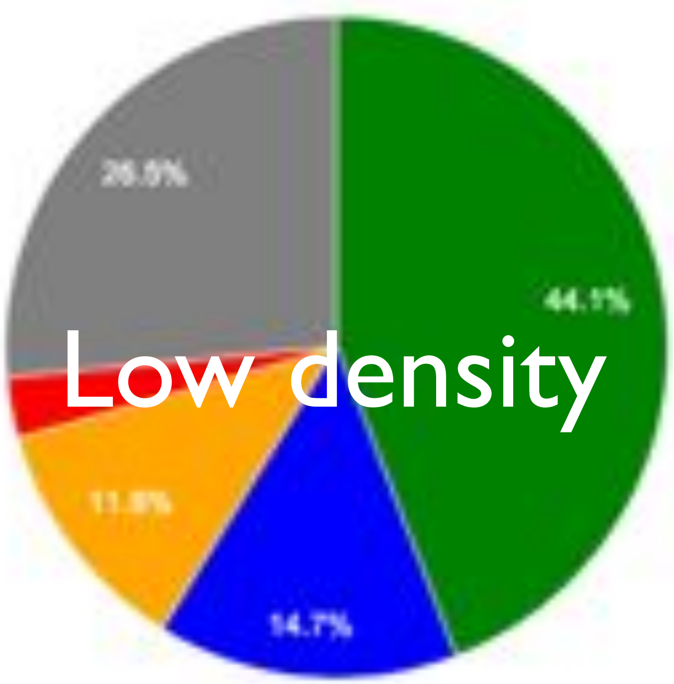
✓ Environment

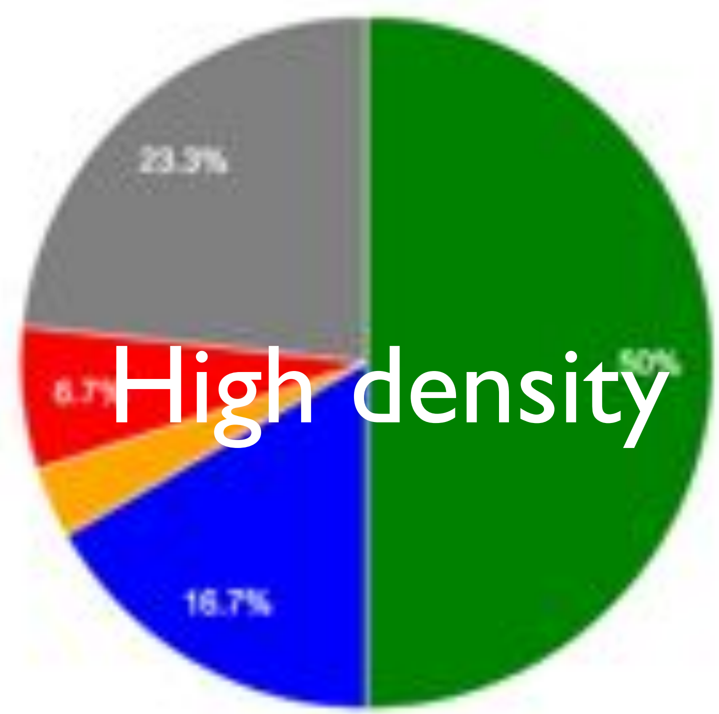






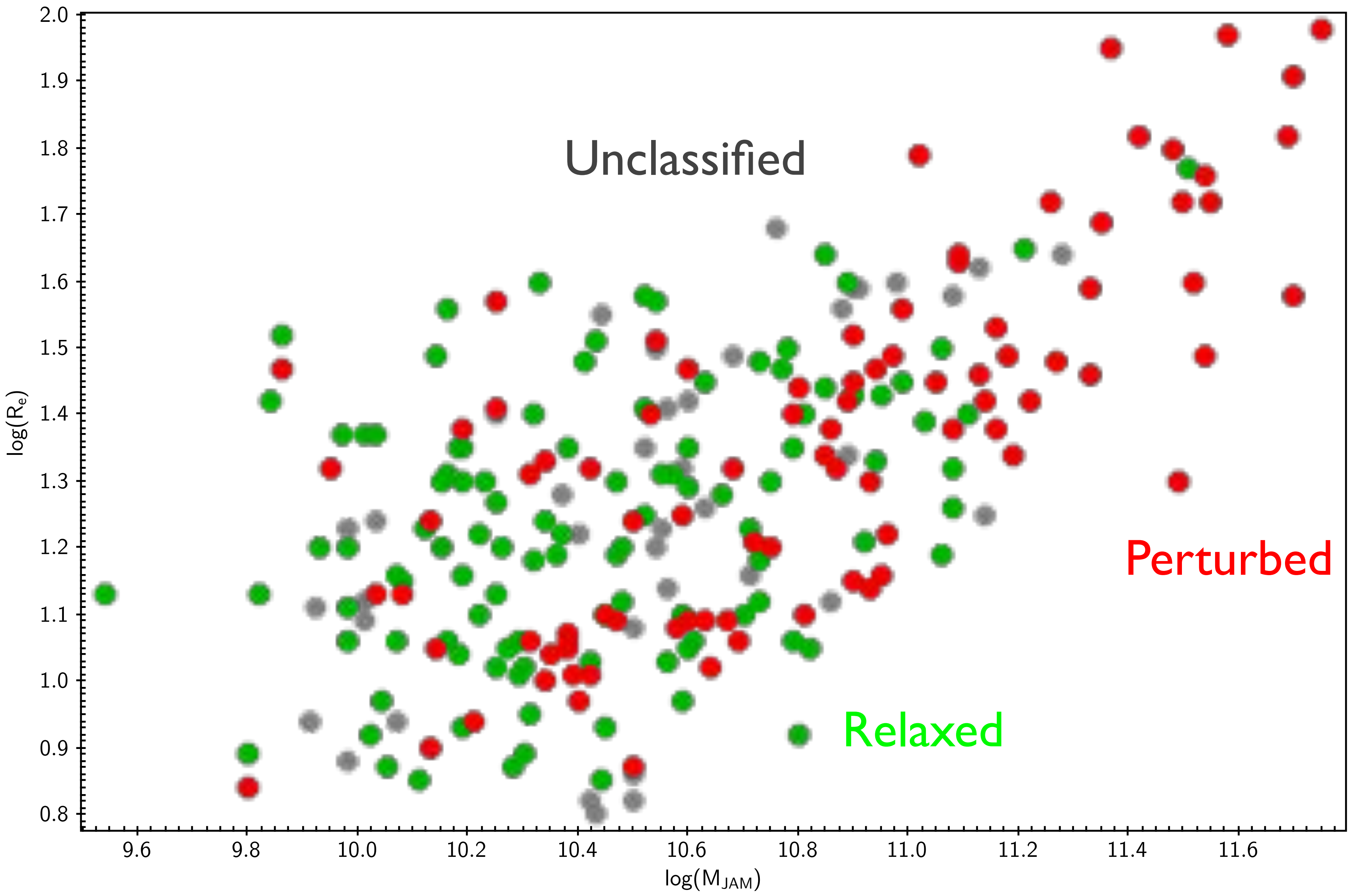






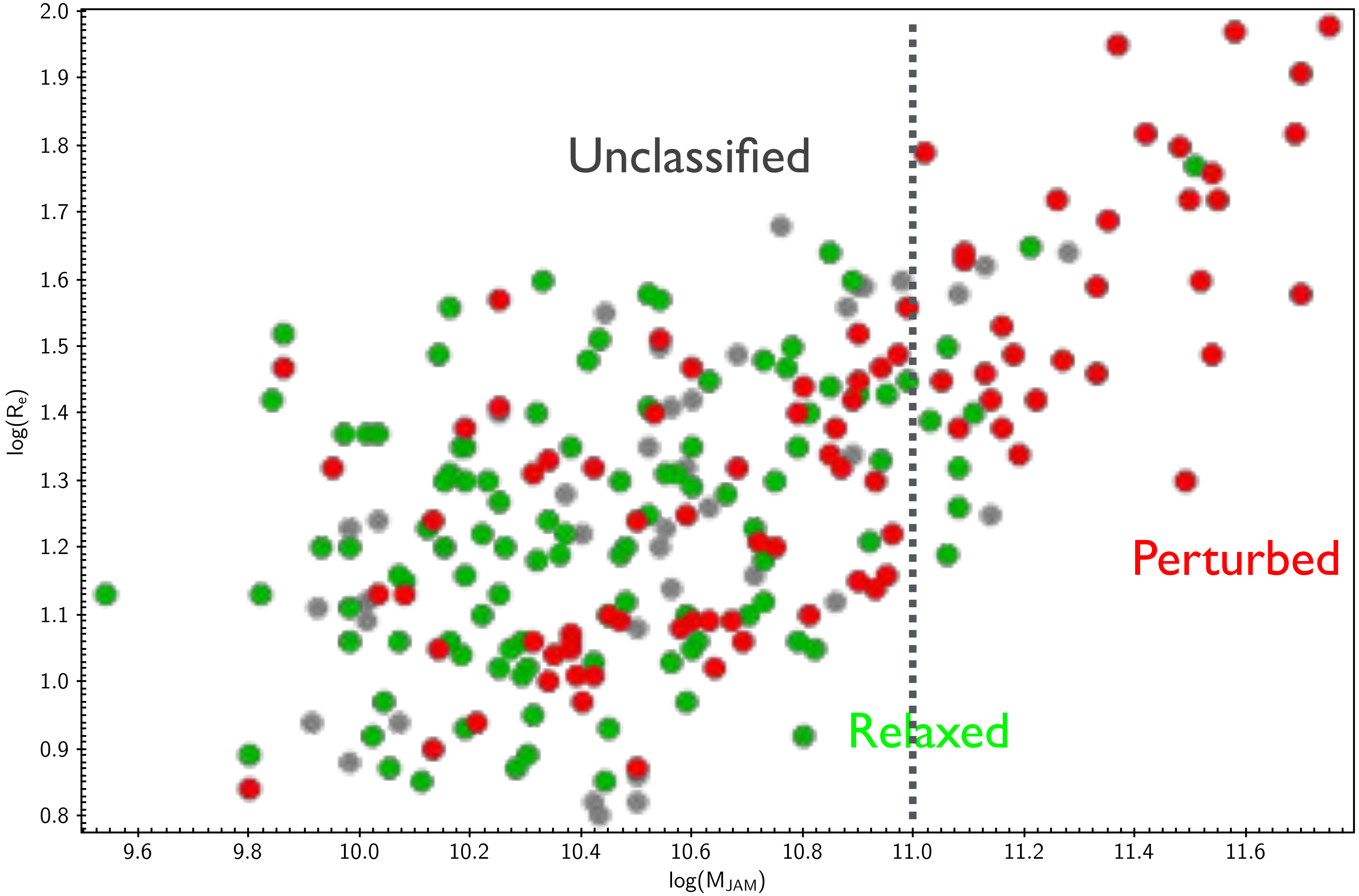
- No strong effect of the large scale and local environment. The evaporation of tidal features due to the environment is limited.

✓ Mass and Size



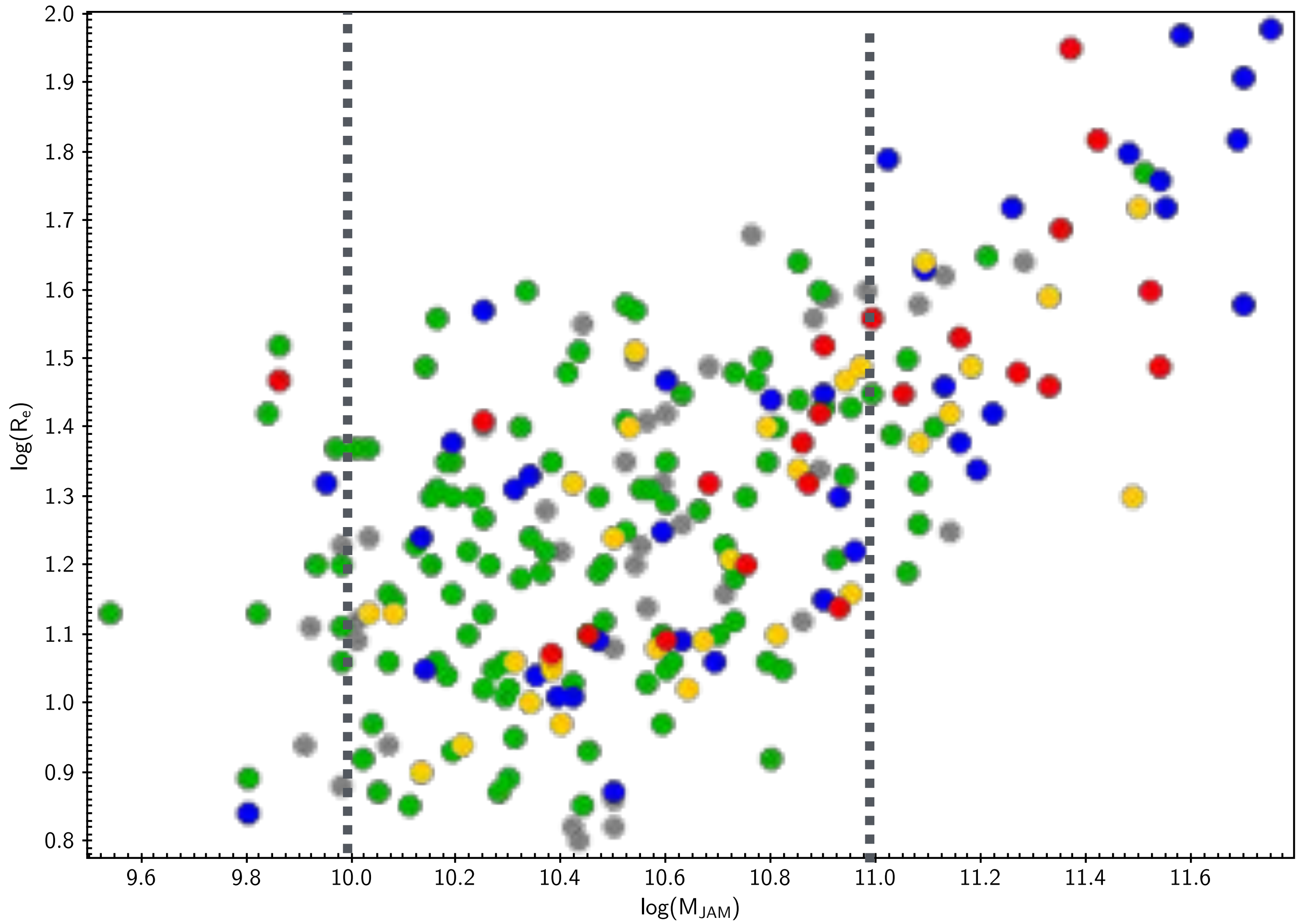
- High mass galaxies more perturbed

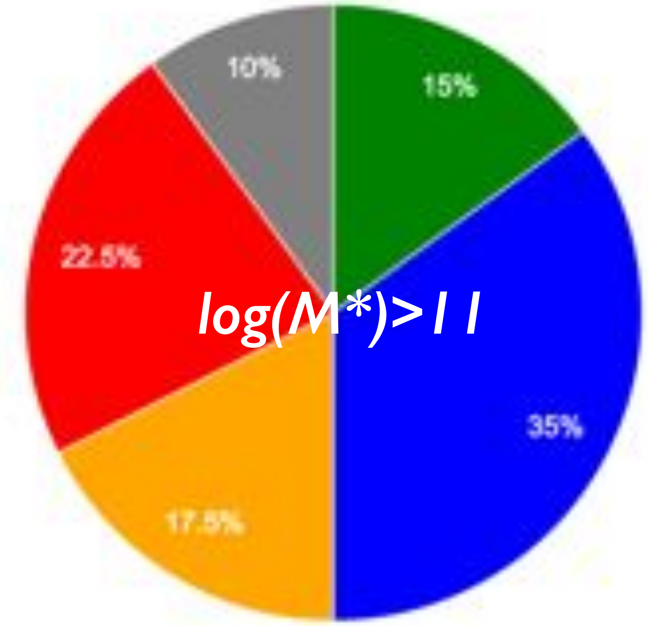
✓ Mass and Size

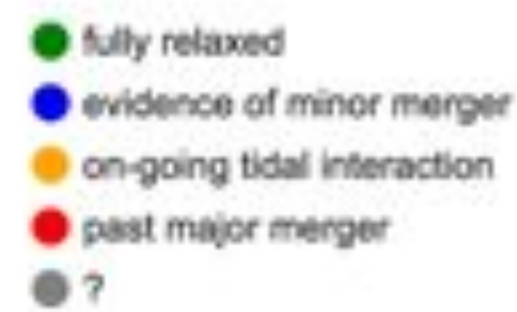


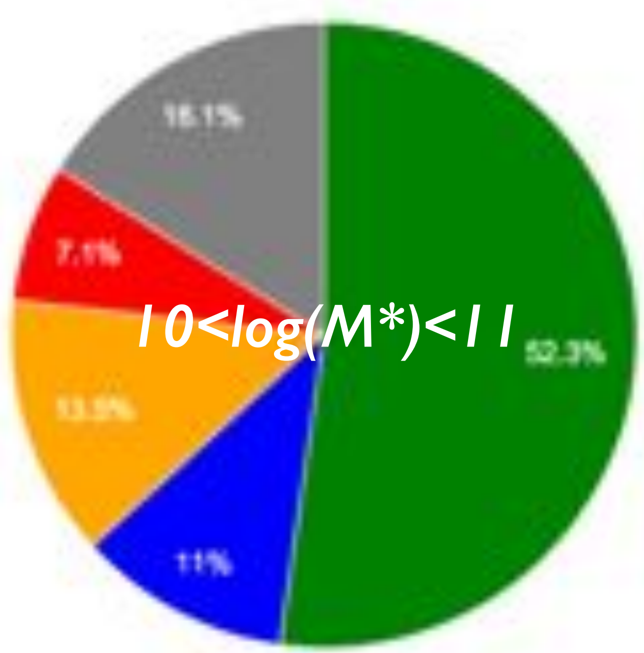
- High mass galaxies more perturbed

✓ Mass and Size



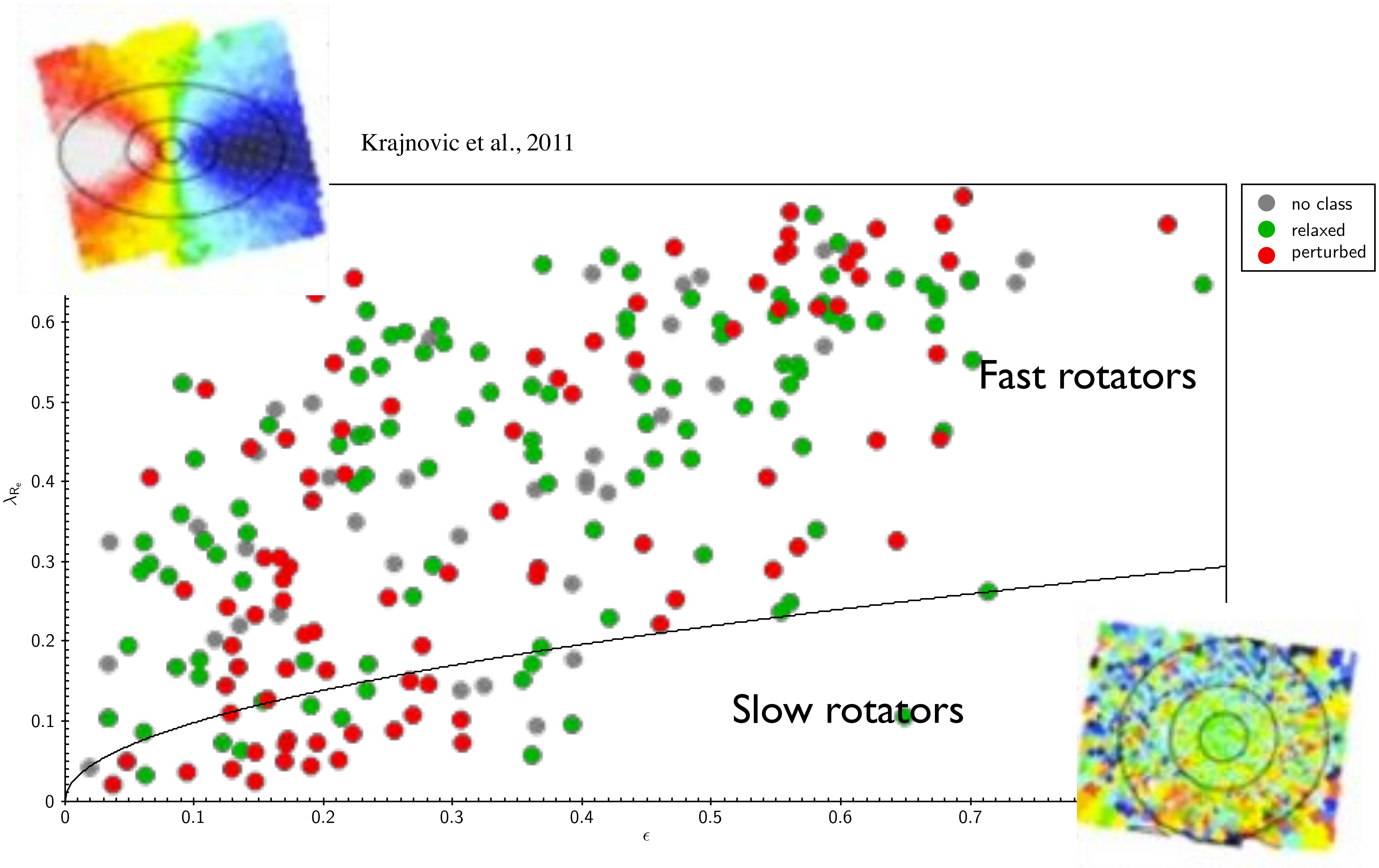






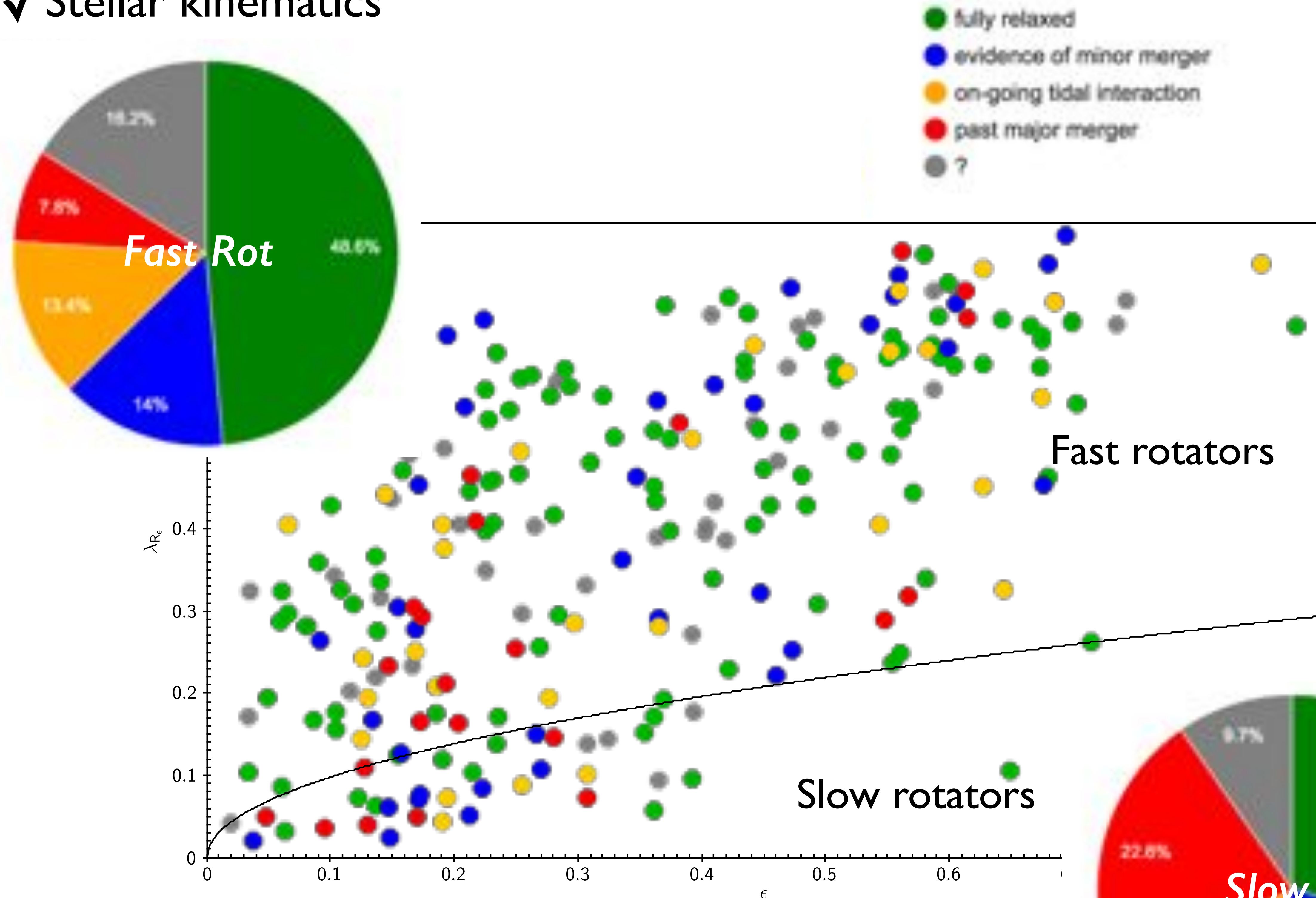
- Above 10^{11} M_o, the fraction of galaxies with evidence of minor and major merger is multiplied by 3

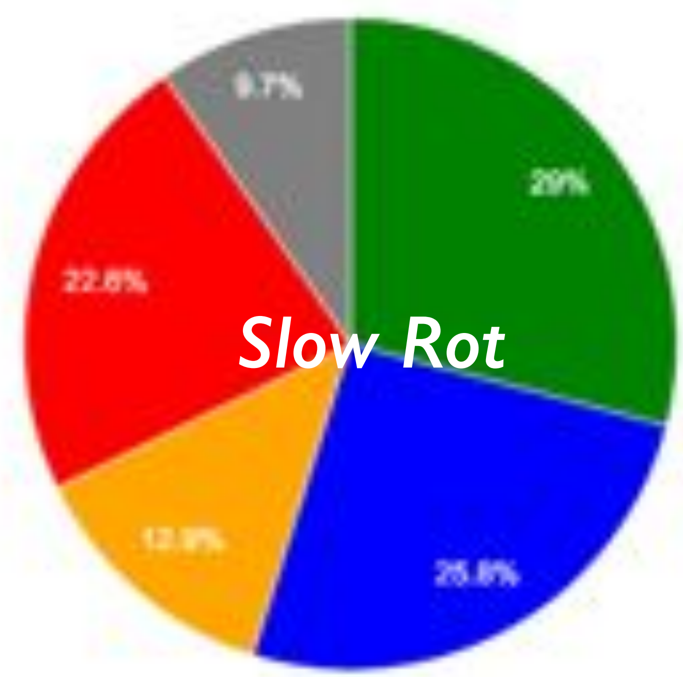
✓Stellar kinematics



- Slow rotators more perturbed than fast rotators

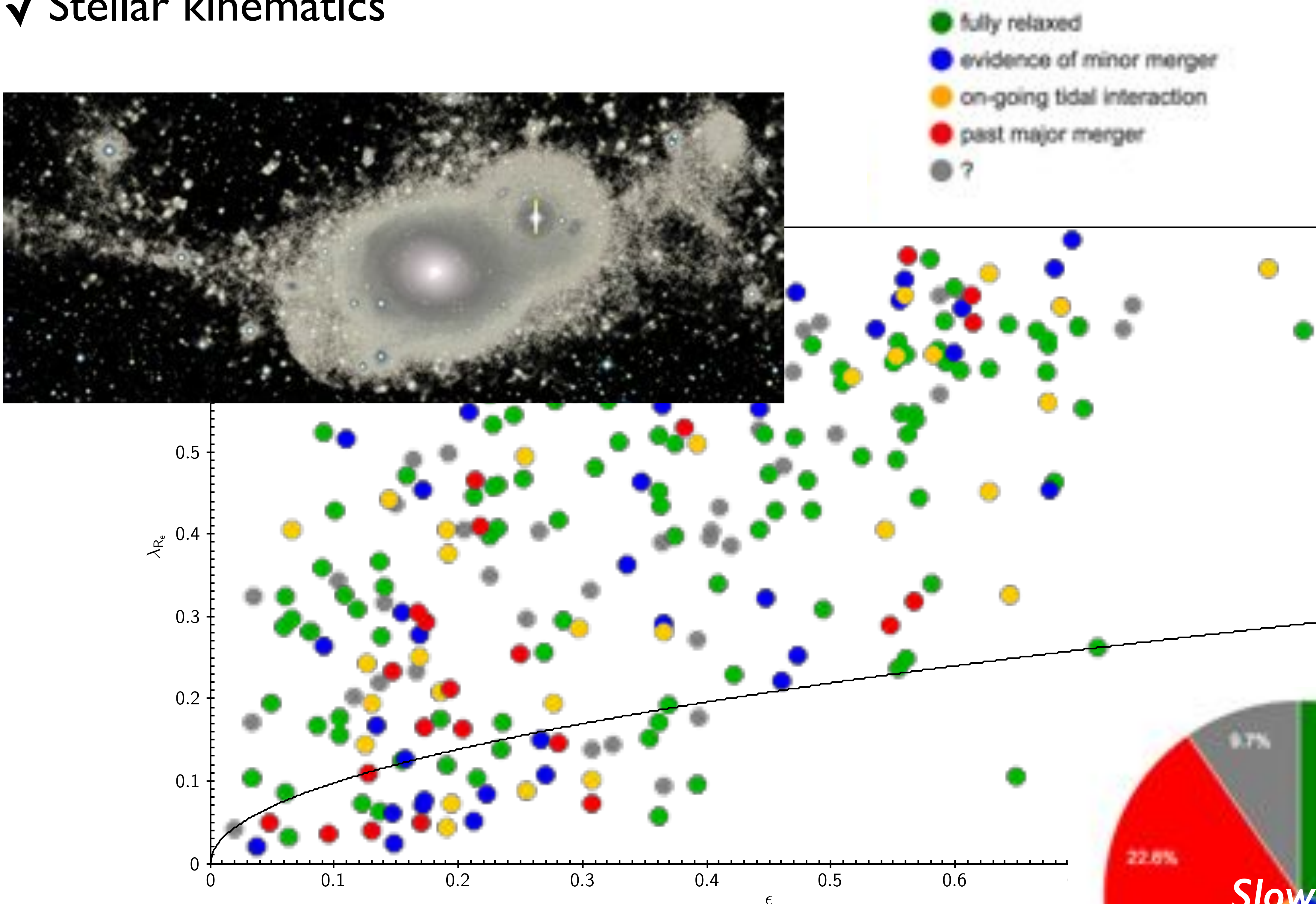
✓Stellar kinematics

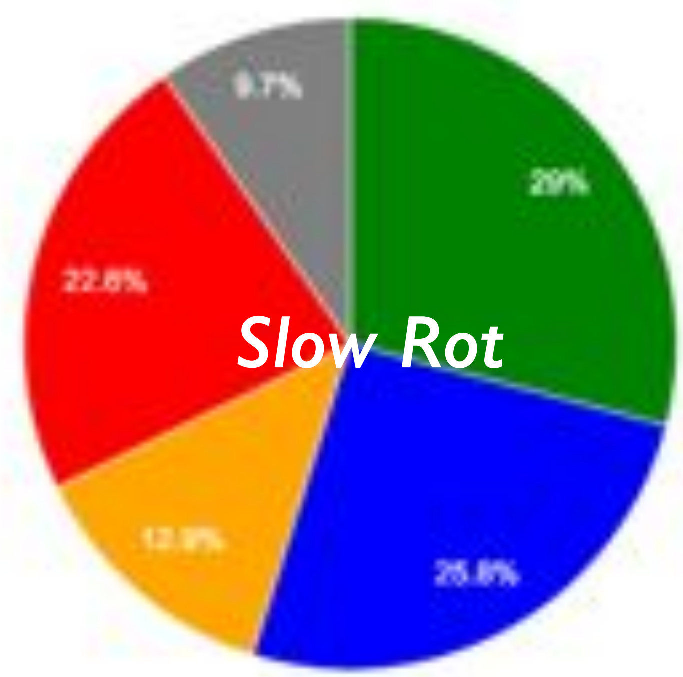




- A significant fraction of old major mergers among the slow rotators

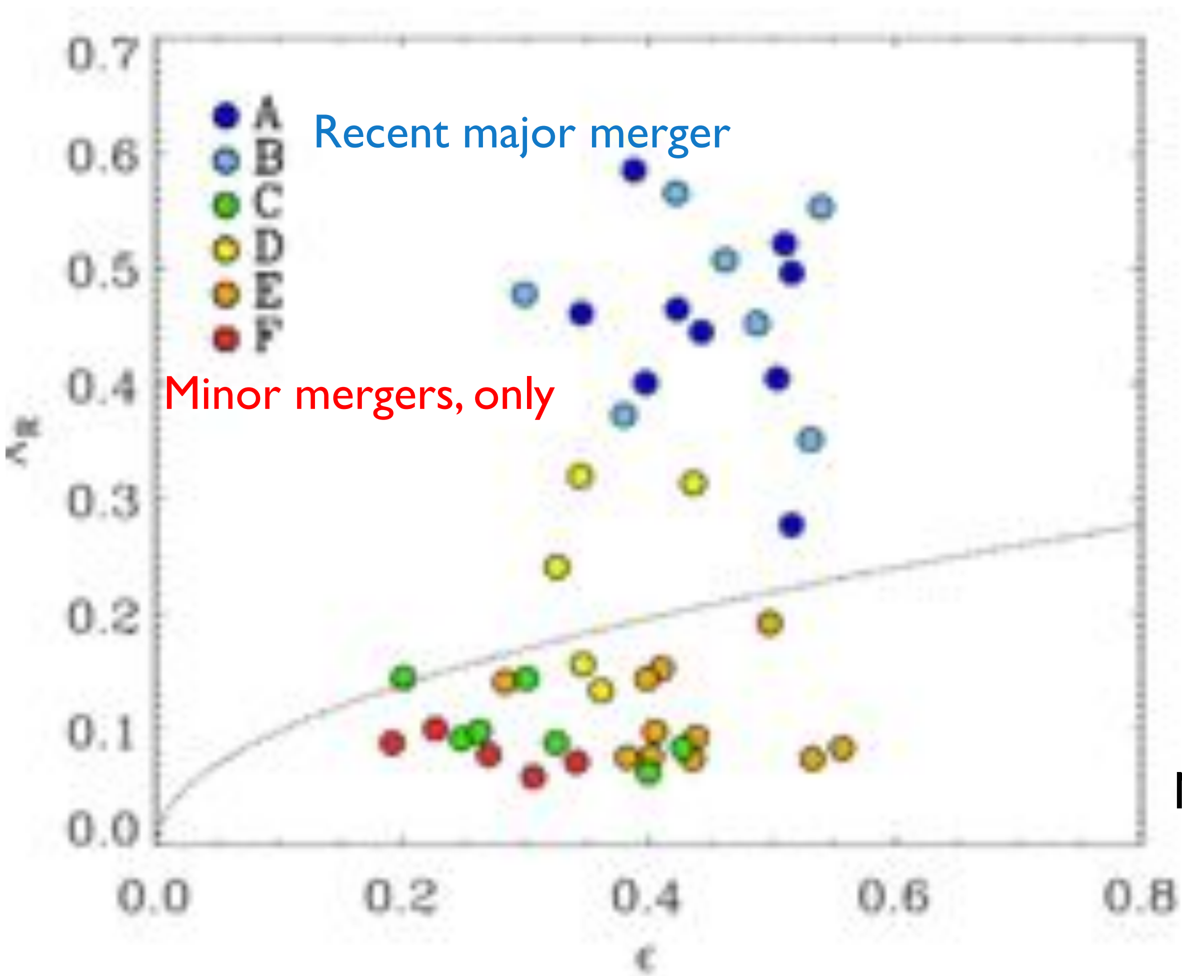
✓Stellar kinematics



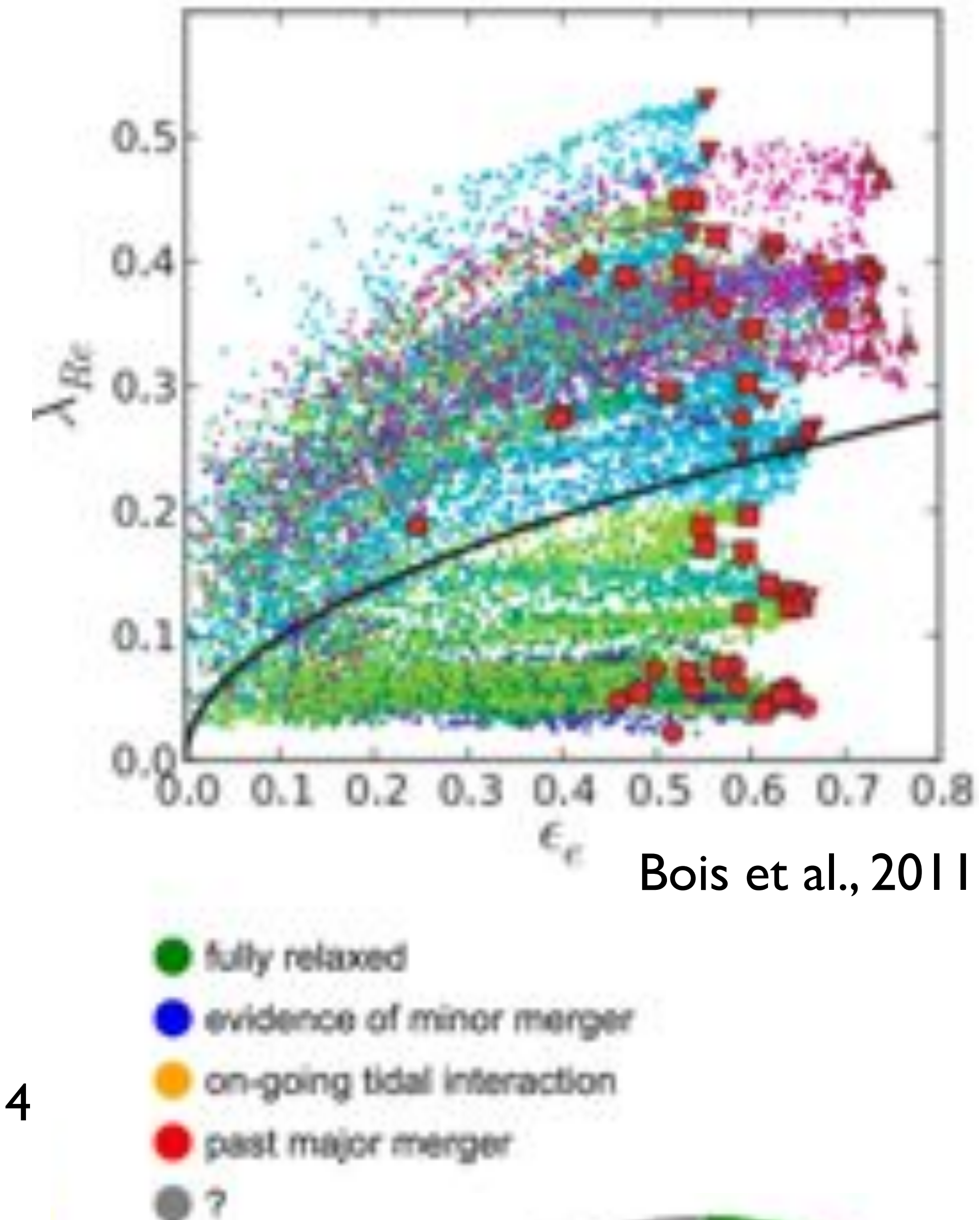


- A significant fraction of old major mergers among the slow rotators

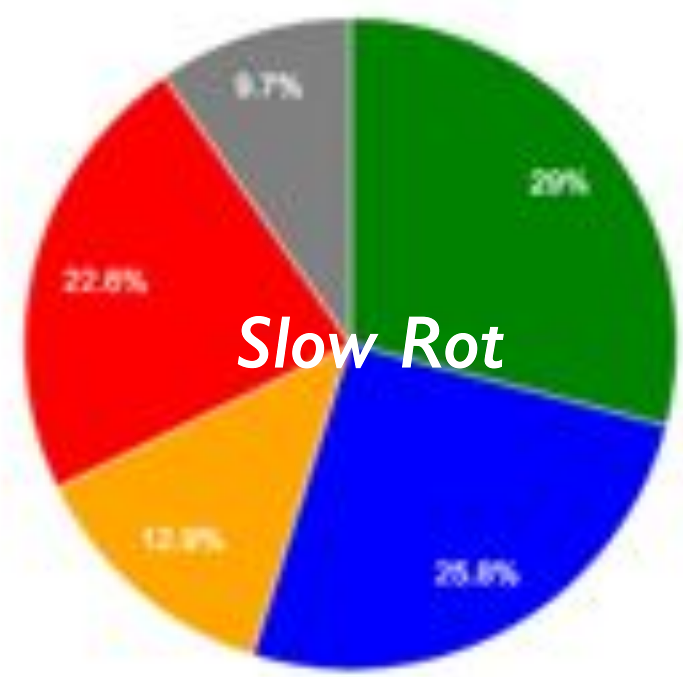
✓Mass assembly of slow rotators



Naab et al., 2014



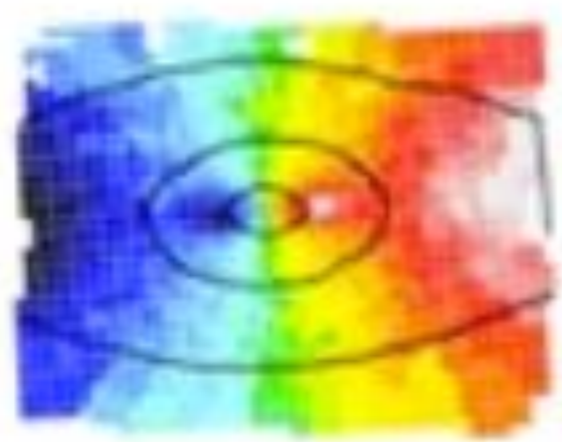
Bois et al., 2011



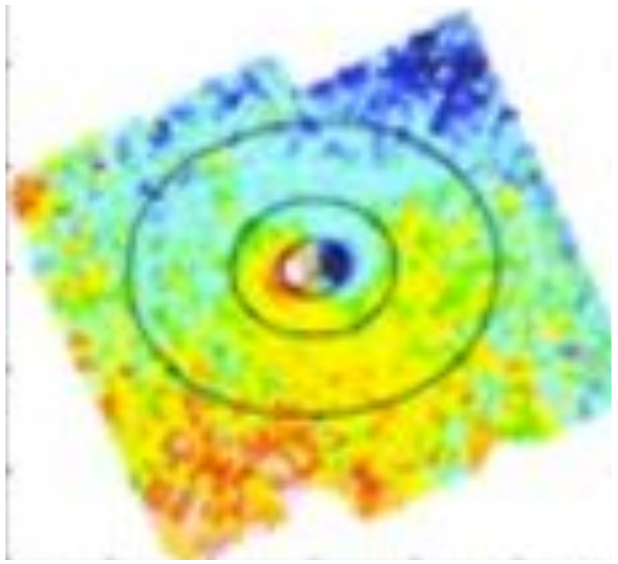
- Slow rotators may be formed in idealized simulations of binary major mergers, under specific circumstances

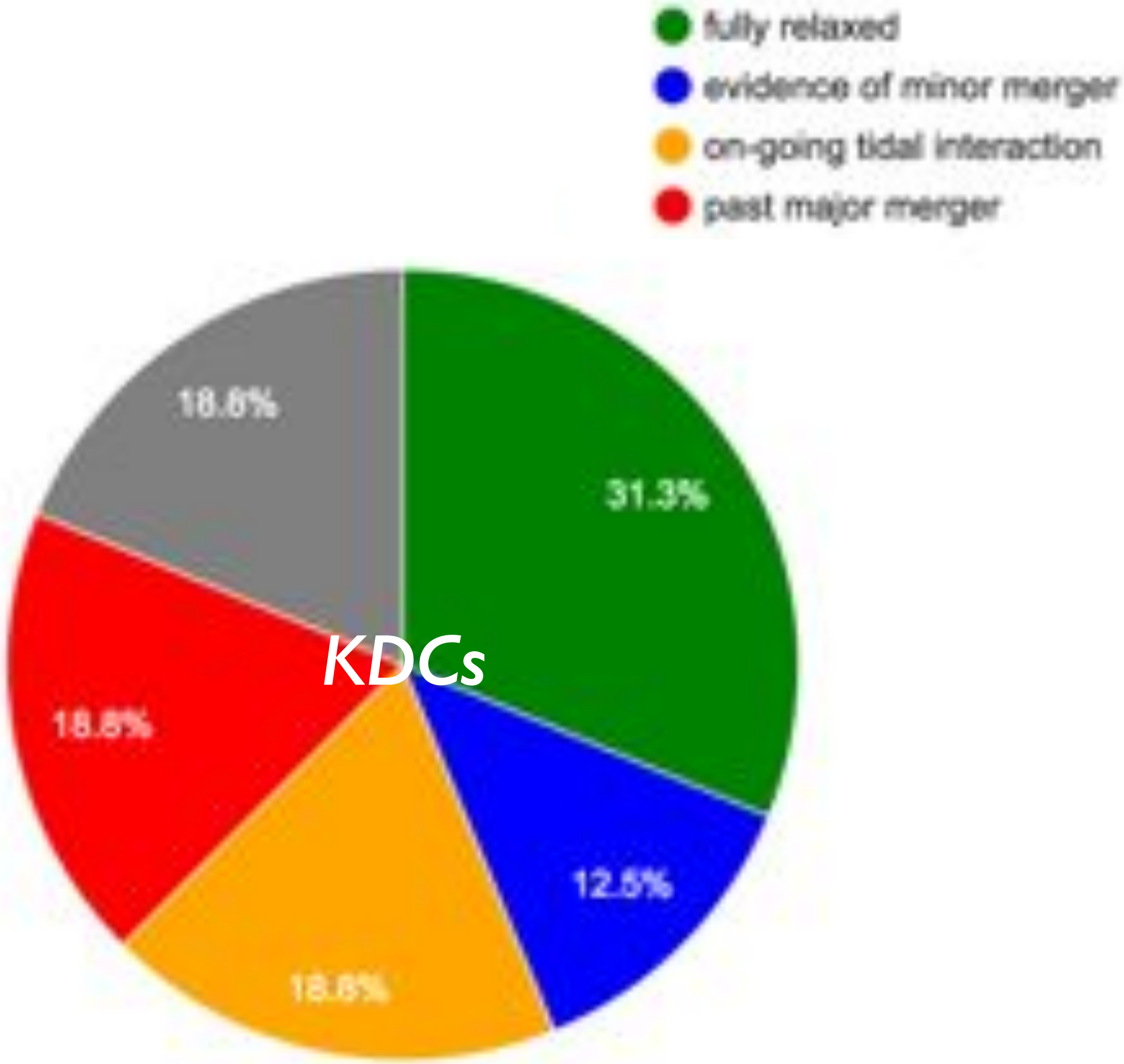
- The fraction of major mergers among the slow rotators is stronger than expected from cosmological (re)simulations

✓Origin of KDCs

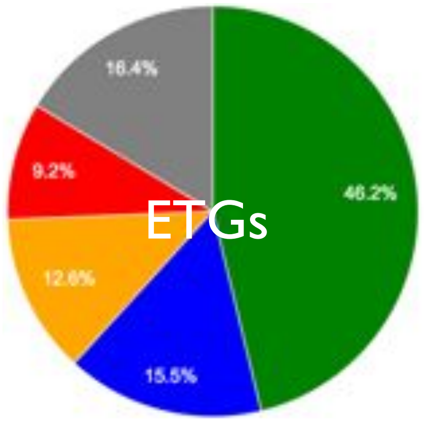


Krajnovic et al., 2011

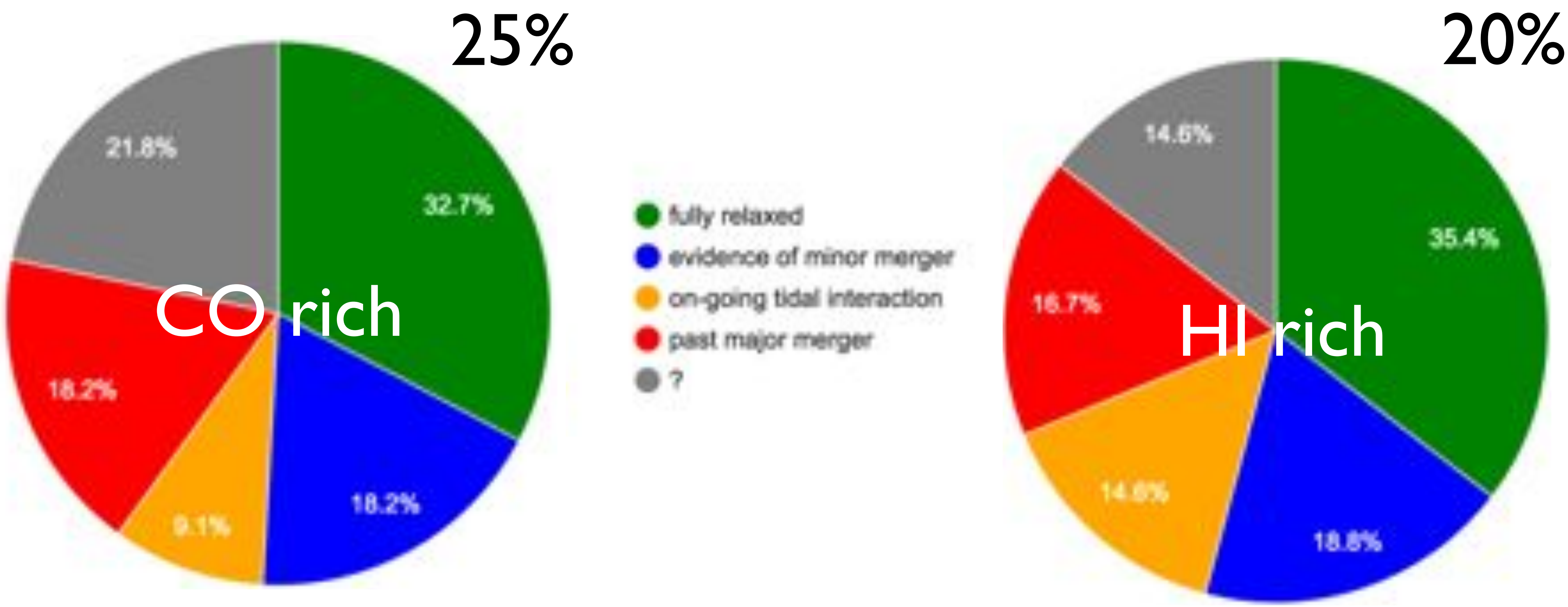




• ETGs with kinematically decoupled cores show more evidence of past recent major mergers

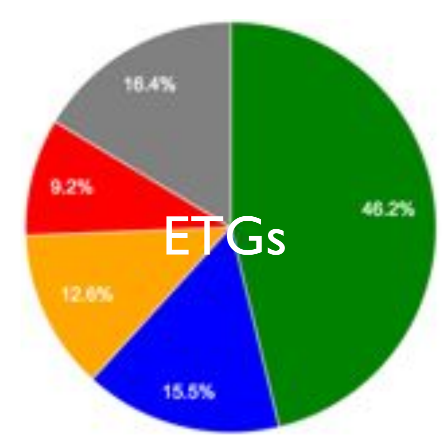


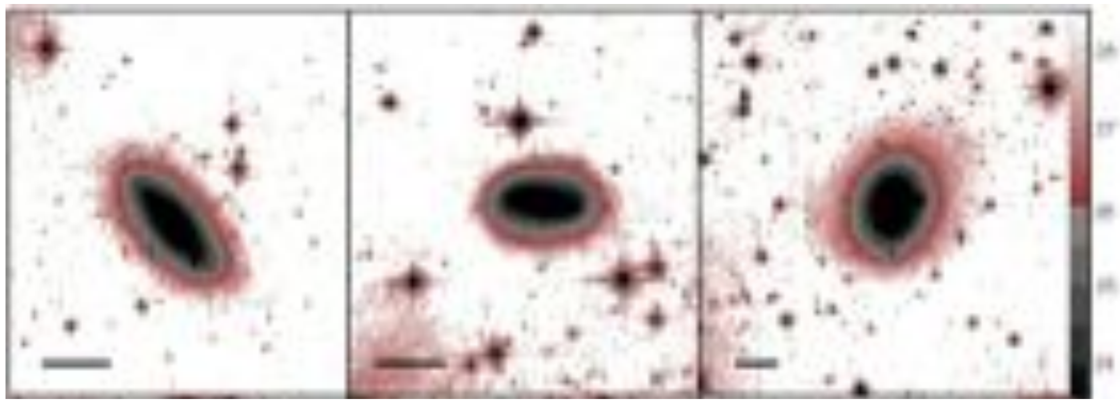
✓ Gas content



- Galaxies with unsettled HI (irregular morphology) or CO not kinematically aligned with stars more tidally perturbed

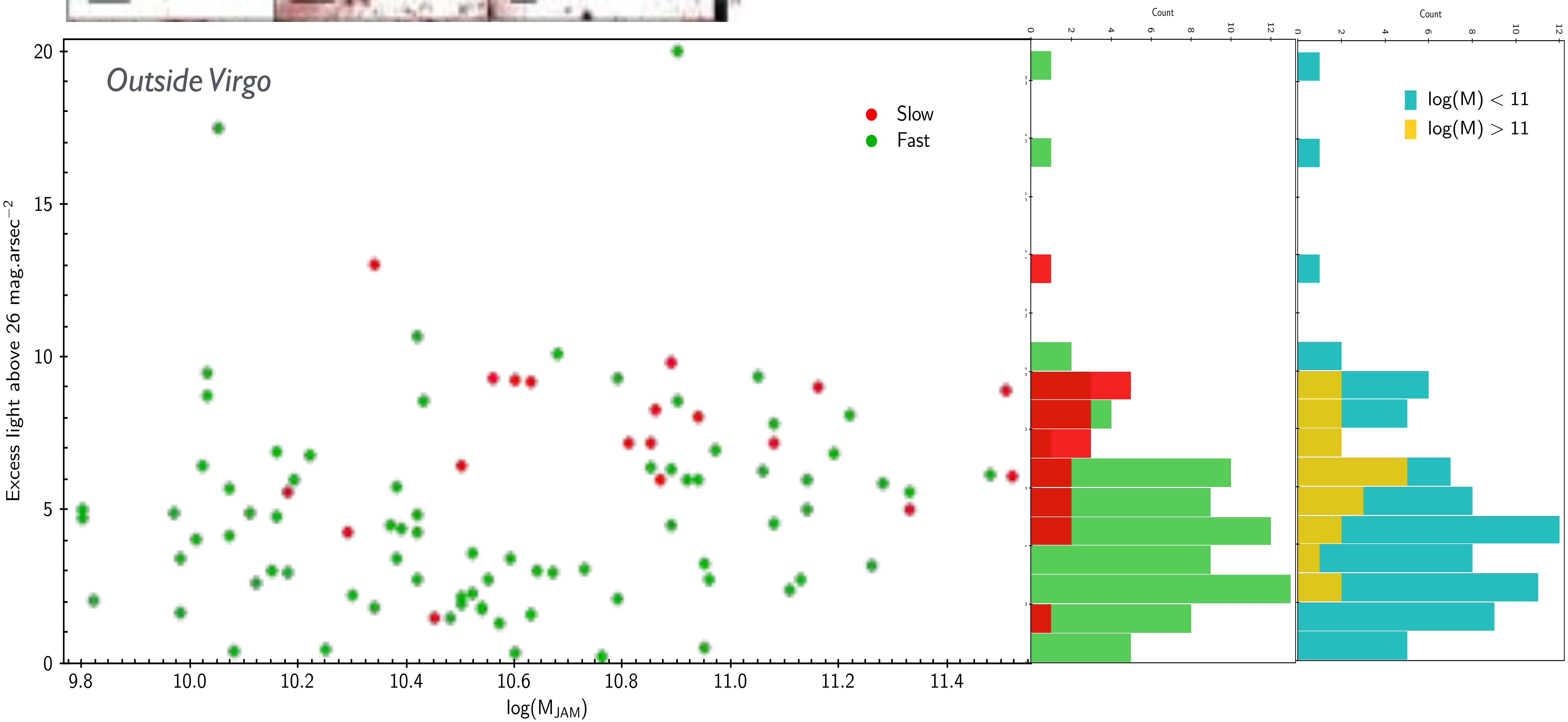
‣ An external origin for this gas





Clues from the outer halo

✓ Light excess

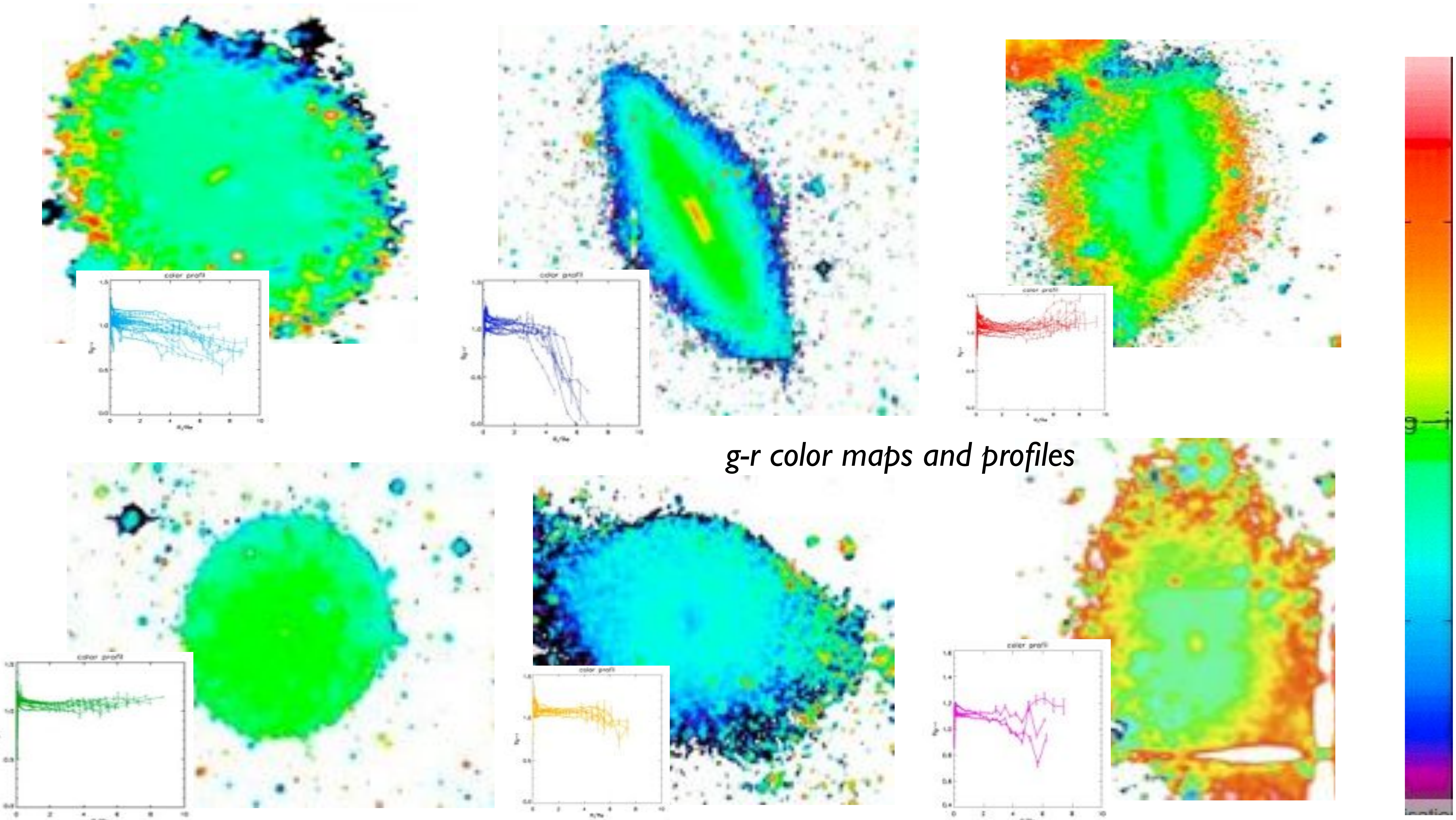


- Light excess - percent of total light above 26 mag.arcsec^{-2} - remains small (5%), but is correlated with mass, and for a given mass with kinematical status.

- Slow rotators have both a fine structure and halo excess

Clues from the outer halo

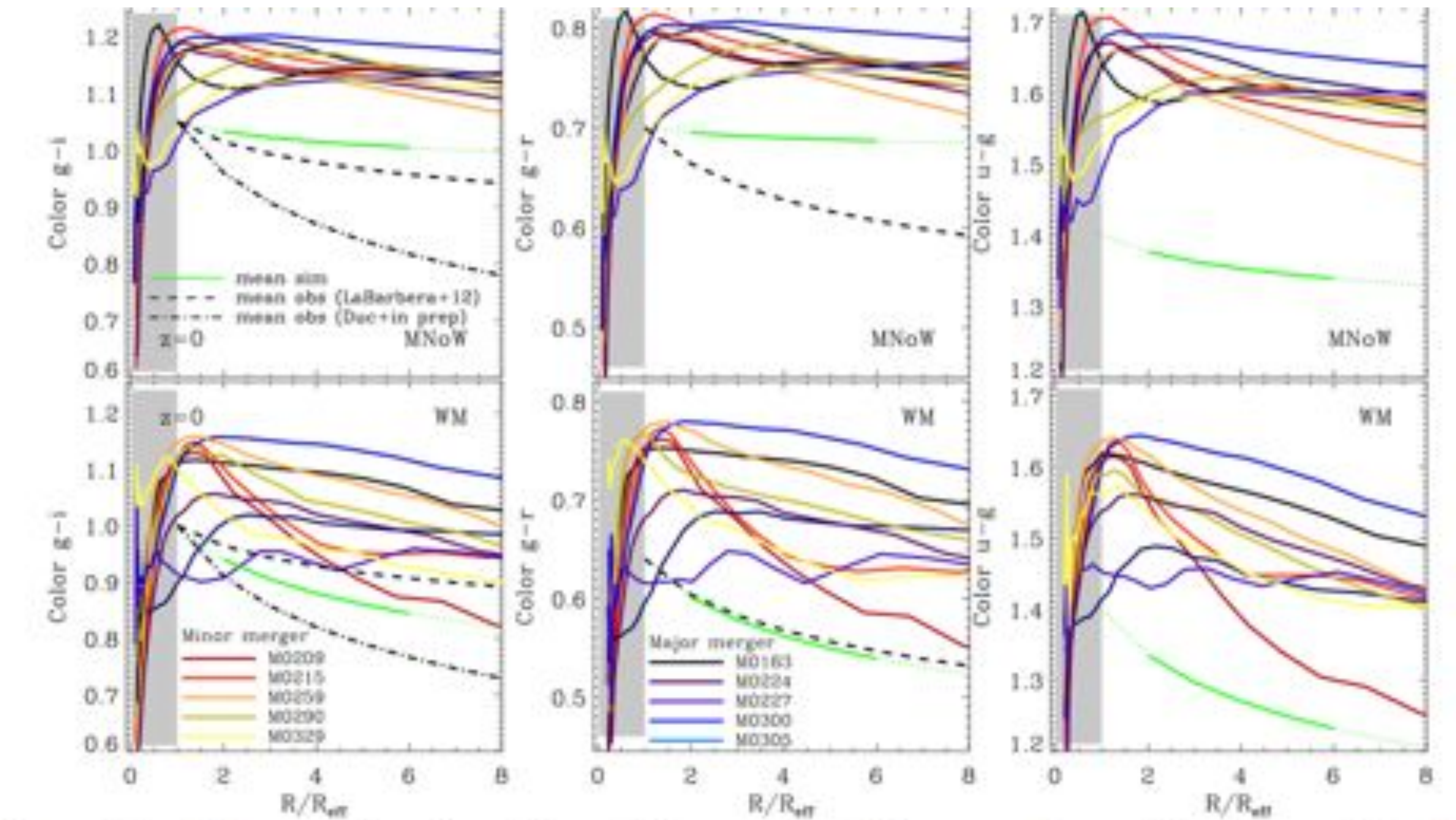
✓Color gradients



• A variety of color profiles (Age, Z), reflecting different merger histories

Color profiles at large Re

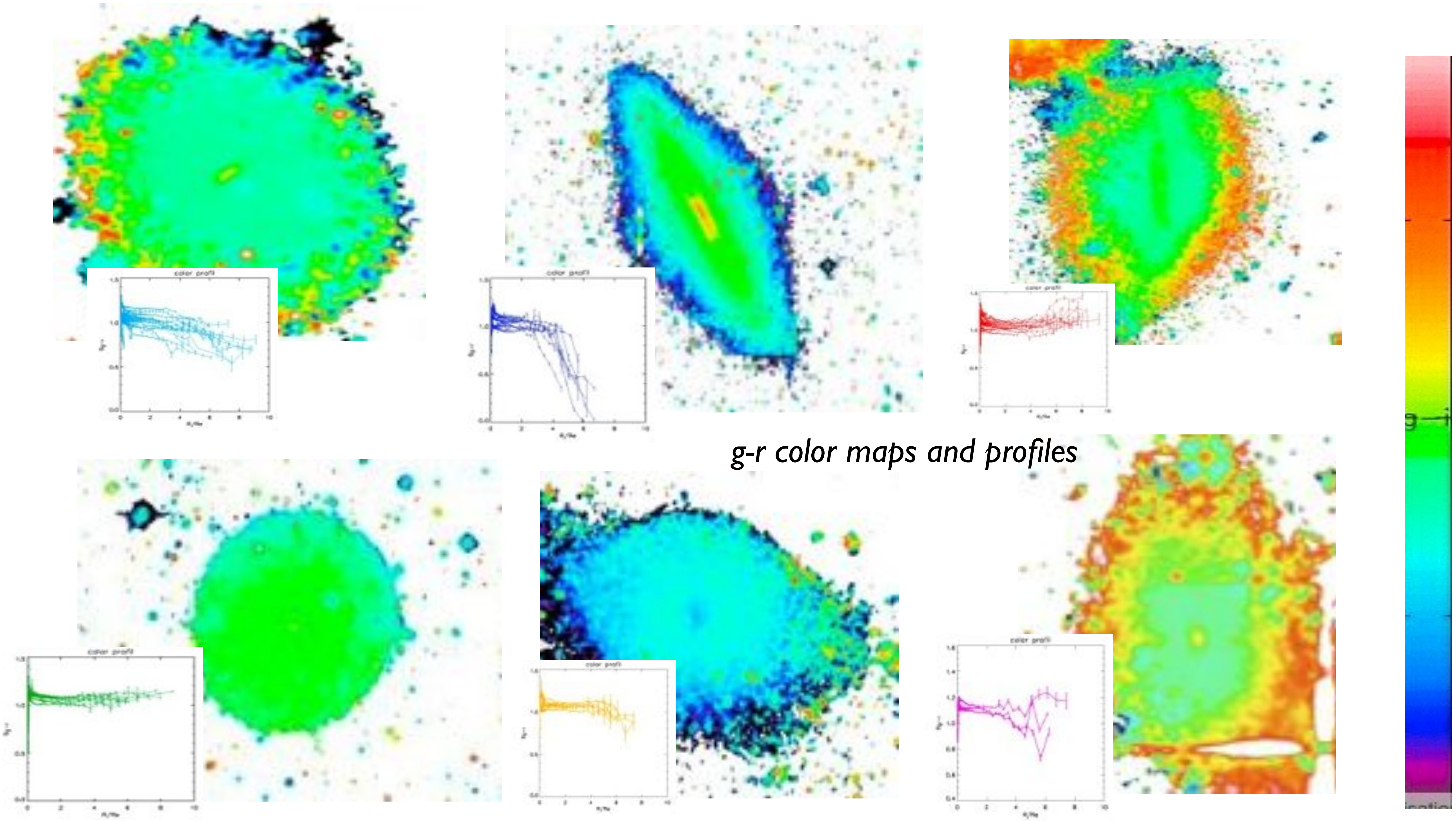
✓ Predicted from cosmological re-simulations



Hirschmann, Naab et al., 2015

Clues from the outer halo

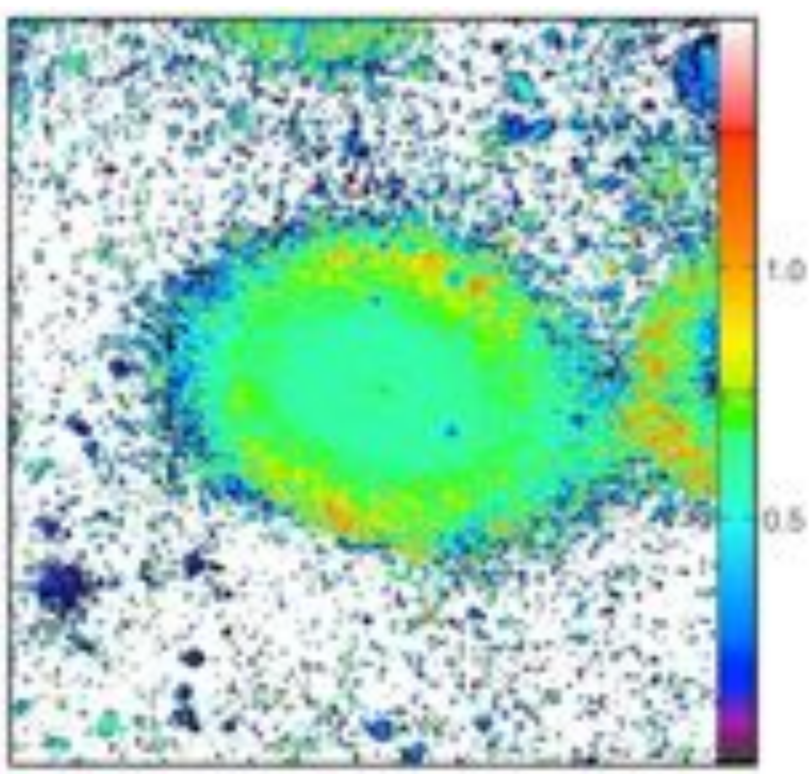
✓Color gradients



• A variety of color profiles in fact also reflecting instumental effects!

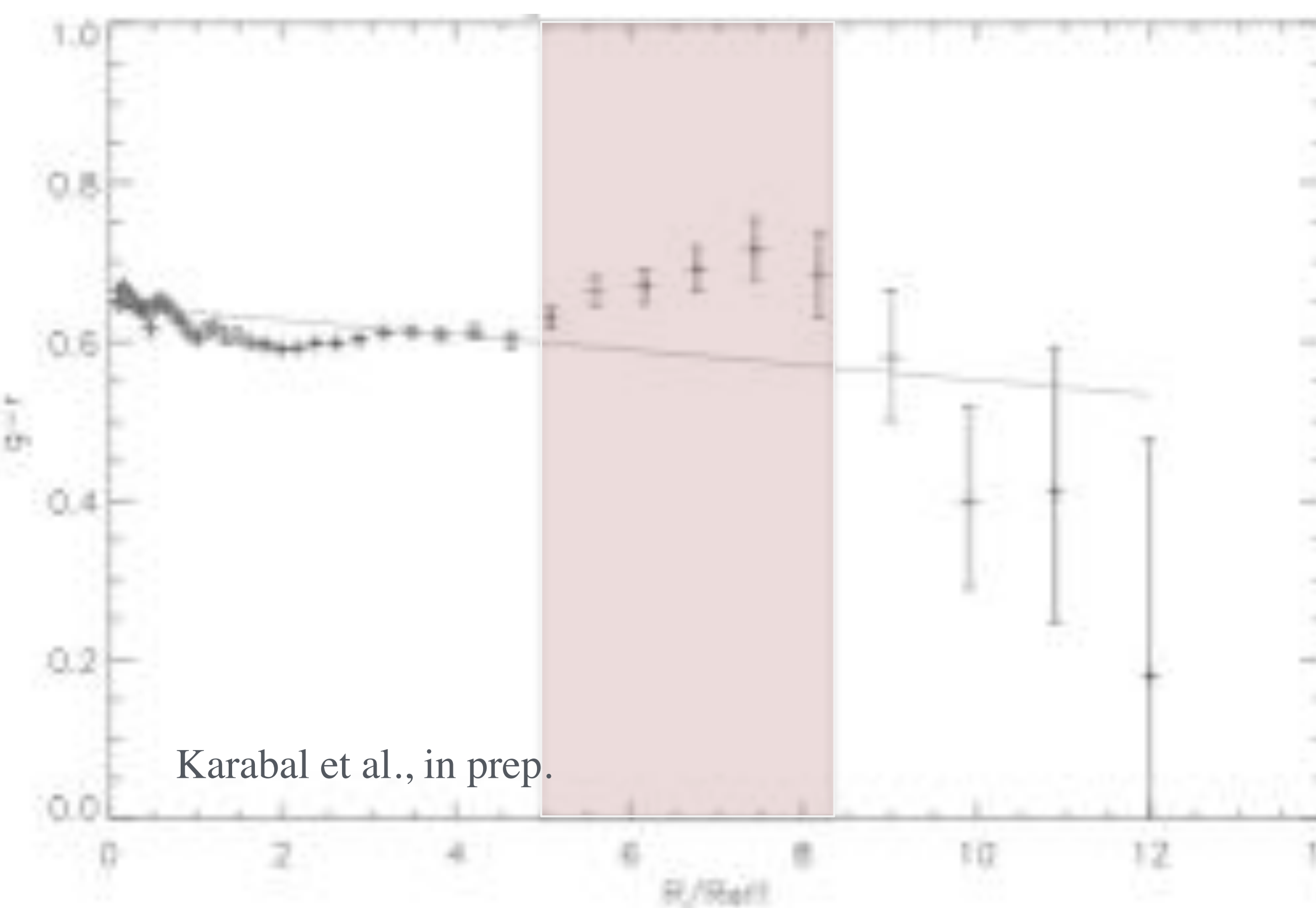
Issues with deep imaging: scattered light from galaxies

✓ similar shapes but more diffuse: mimic galaxy halos



✓ shows up as a red ring on color maps, and reddening on color profiles

✓ directly visible in the r band around small or edge-on galaxies with bright compact nucleus



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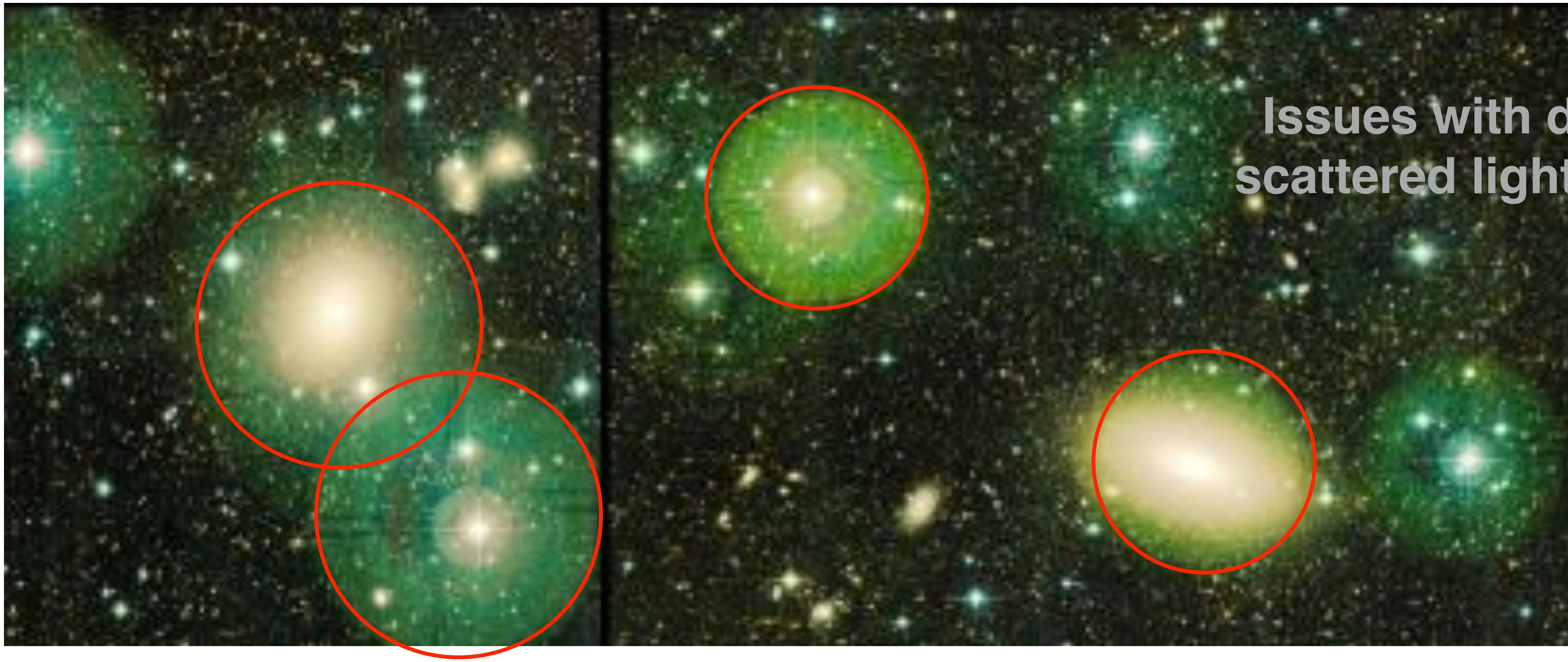

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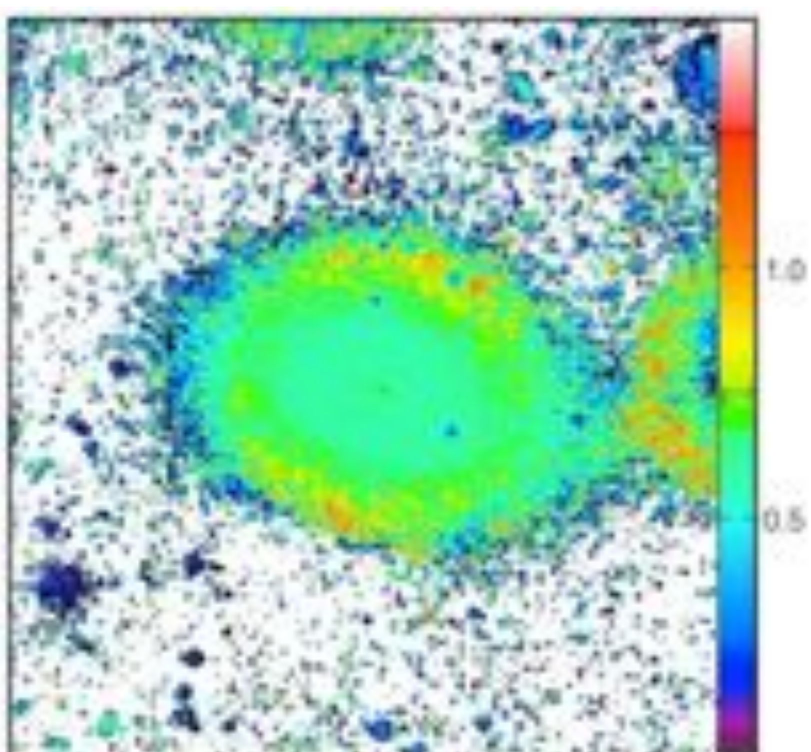

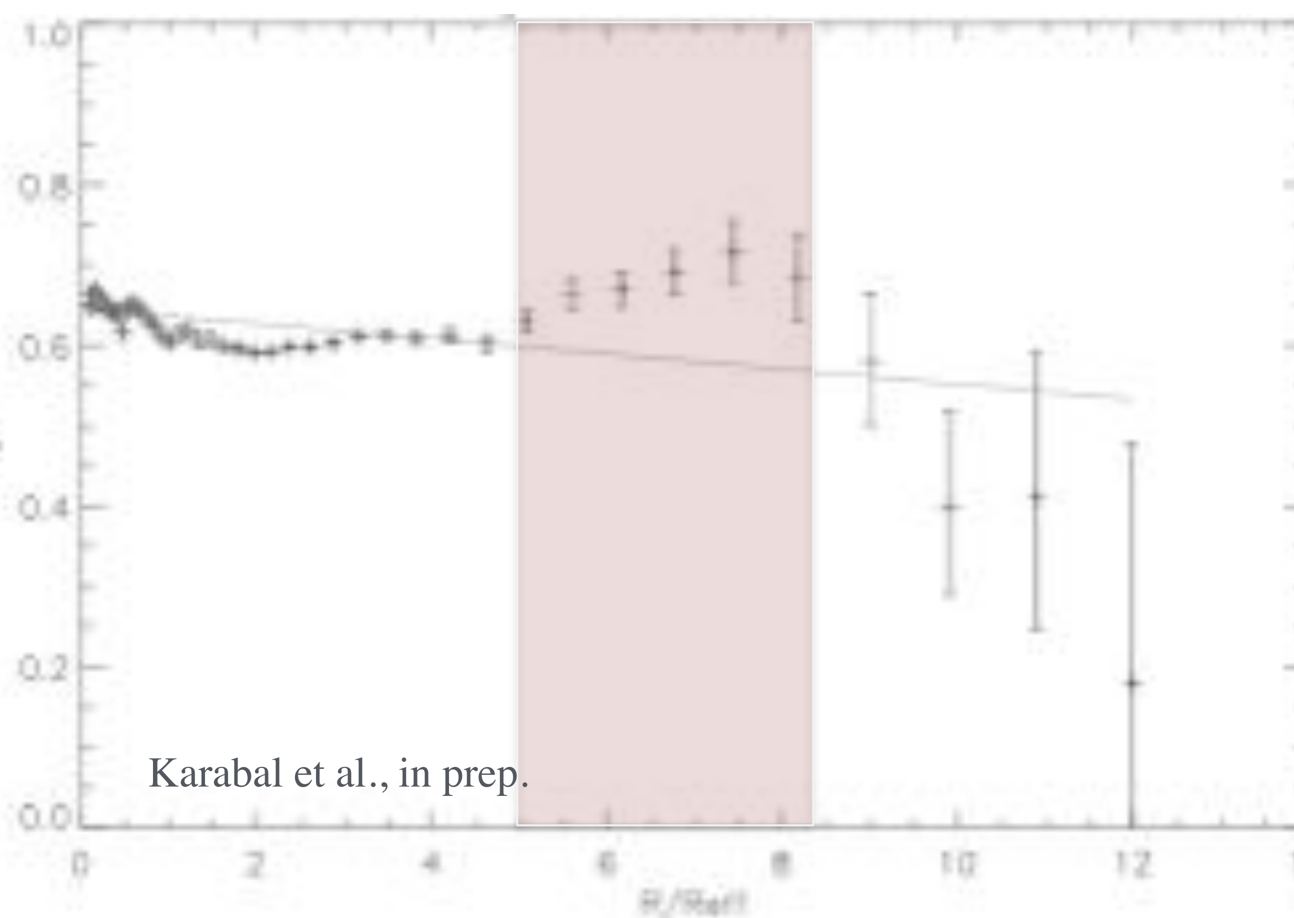

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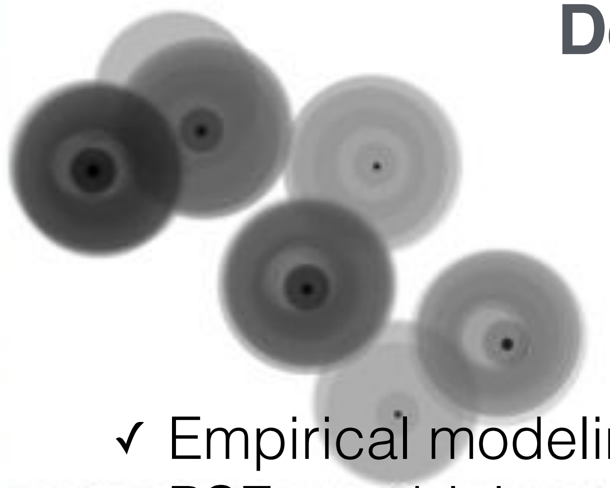
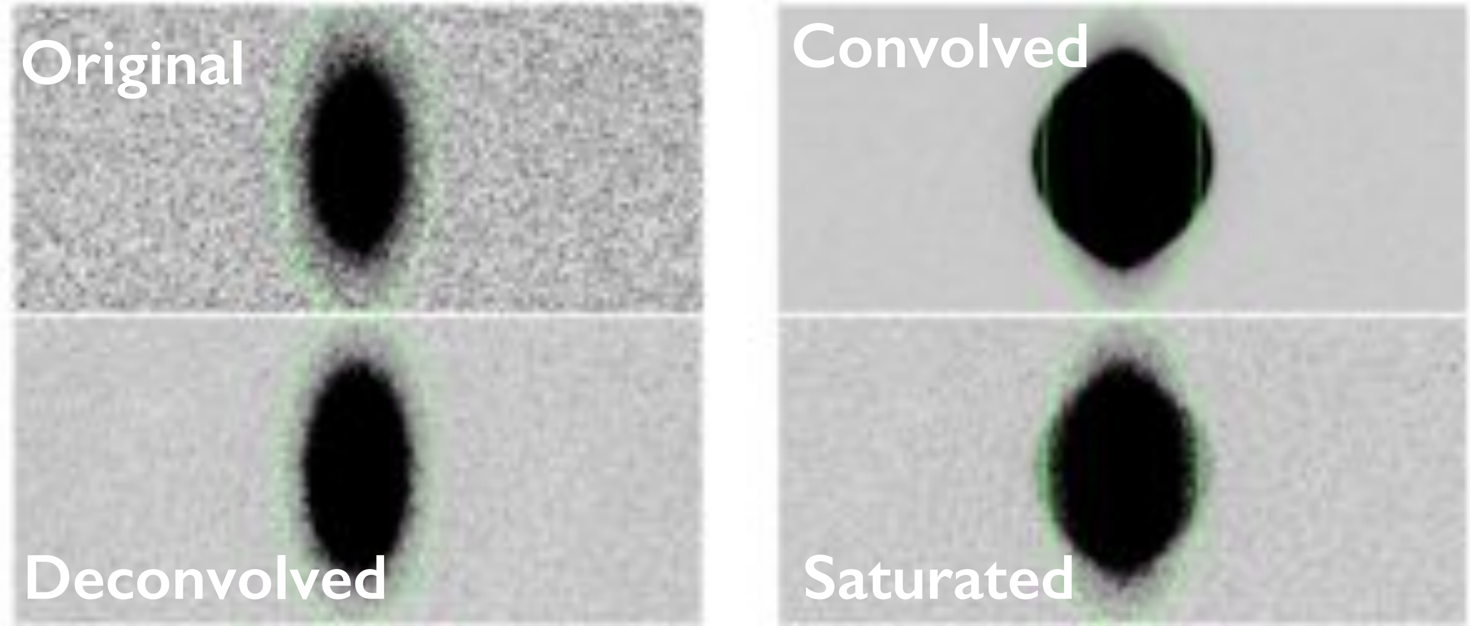
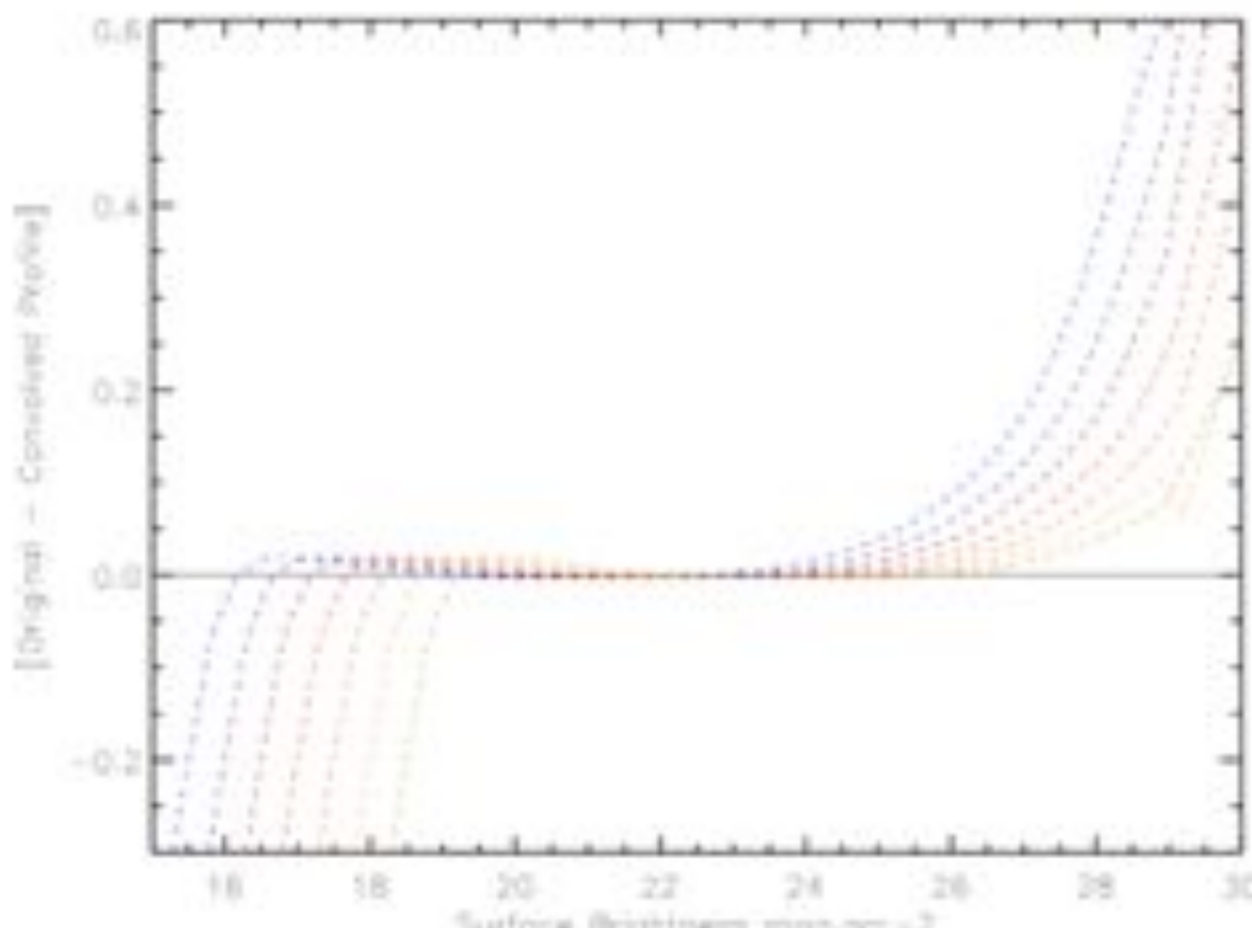
Deconvolution techniques and tests

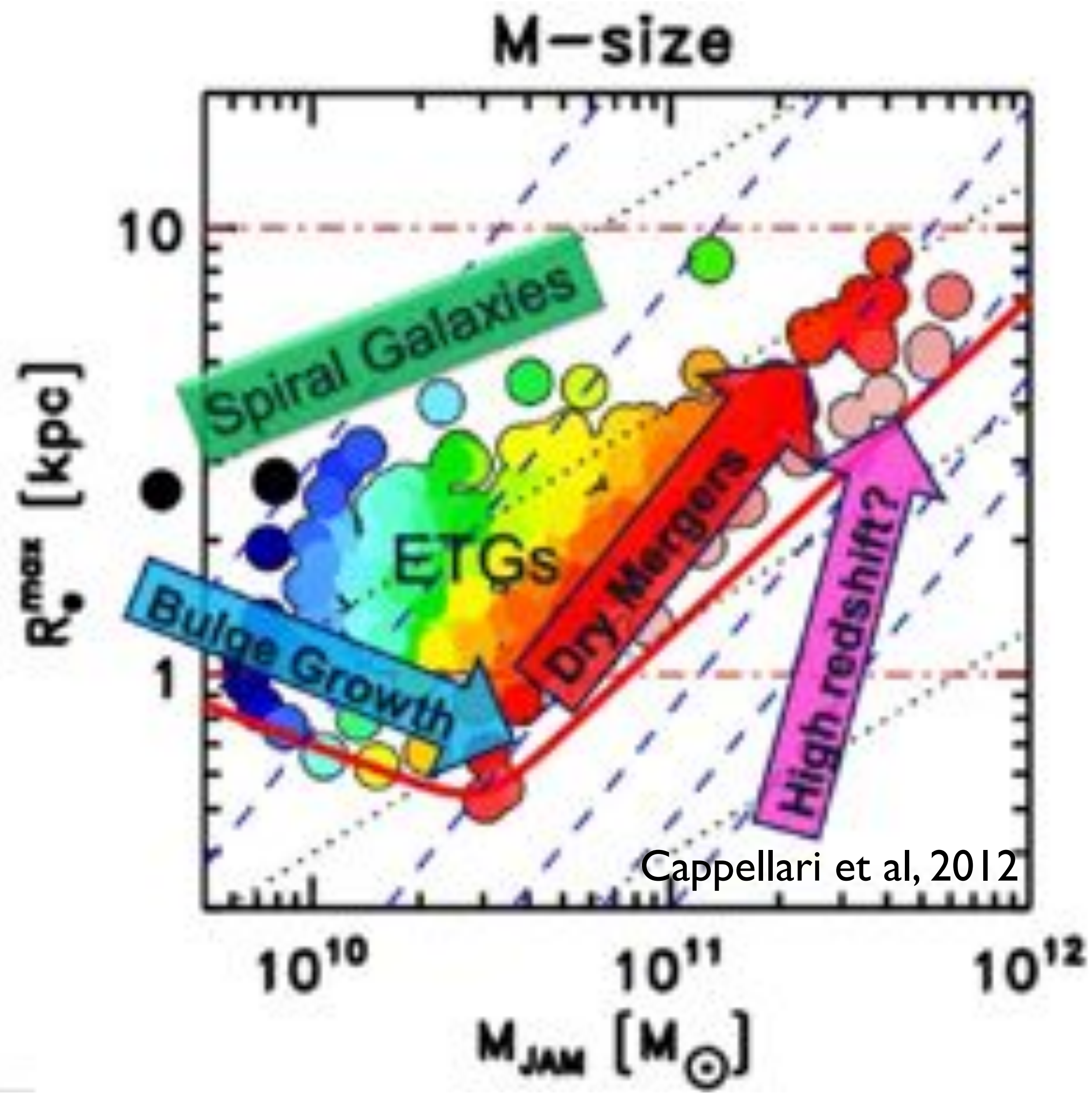




- ✓ Empirical modeling of the PSF, combining seeing-dependent inner PSF (from PSFex) and manual modeling of the complex extended wings
- ✓ Physical modeling of the PSF under progress
- ✓ Convolution/deconvolution technique tested with simulated images
- ✓ Effects strongly depend on the central surface brightness, saturation
- ✓ PSF are different in each band, creating artificial color gradients



The mass assembly of galaxies: a unified story?



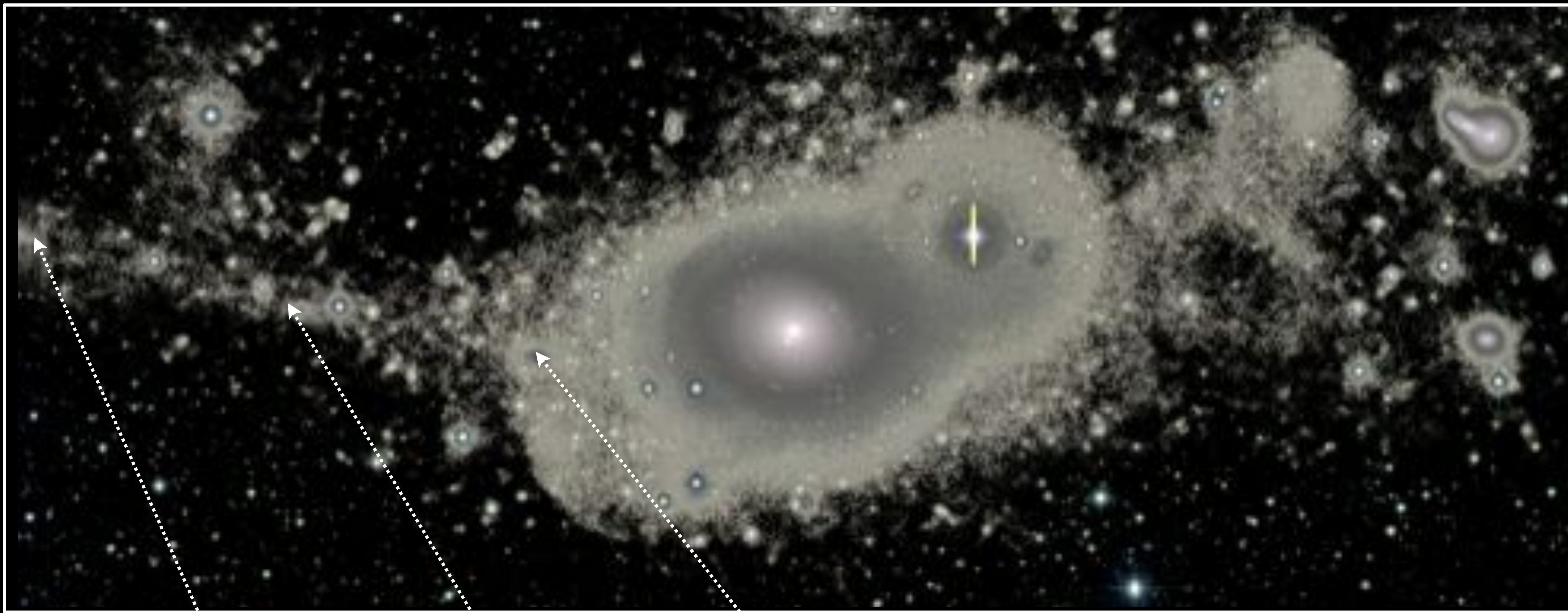
Conventional view: a two phase process for the assembly of ETGs:

- dissipative process at high redshift, making the bulge seed
- gradual growth through minor mergers

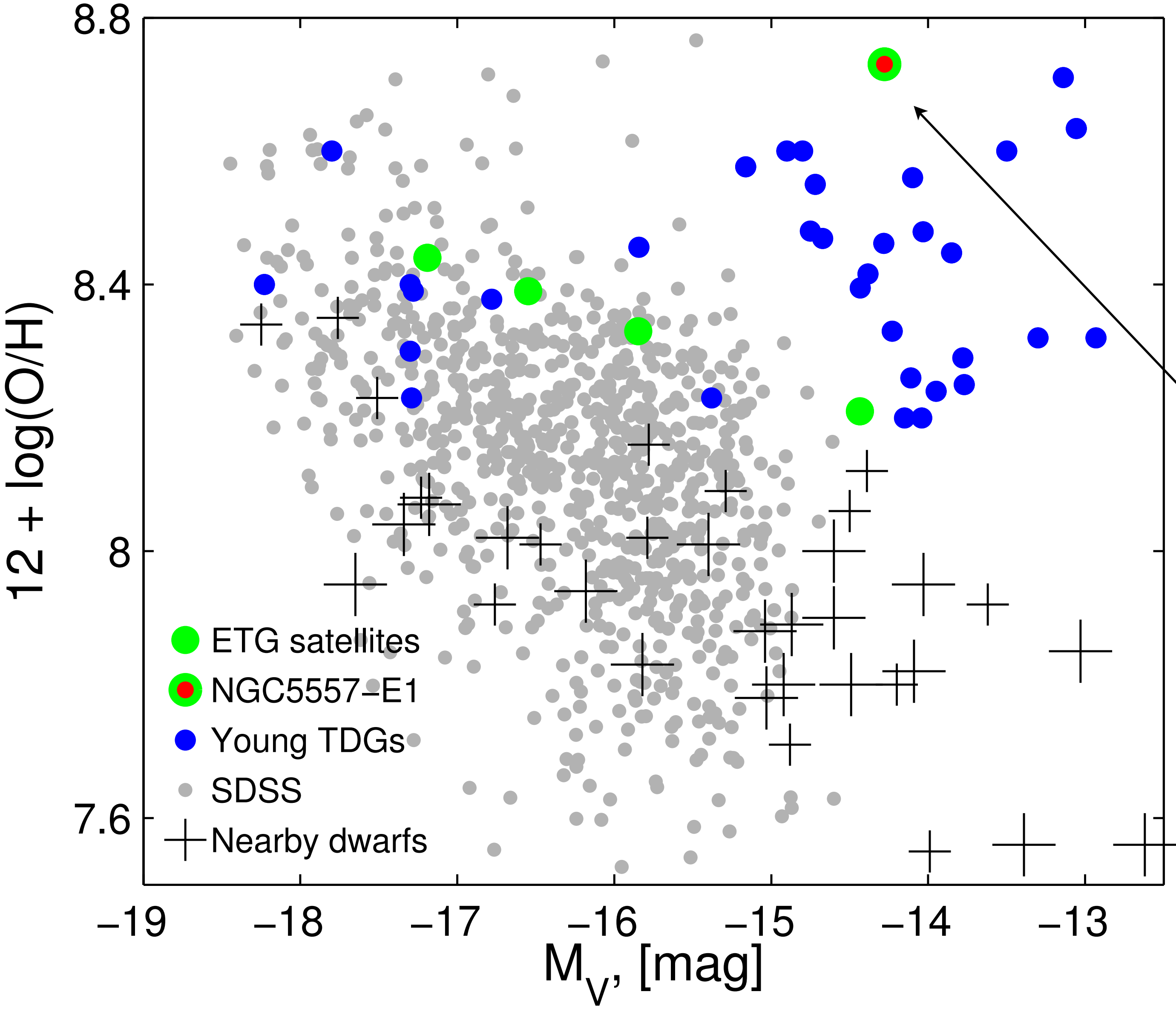
MATLAS preliminary results

- ✓ Outer outer properties (fine structures) correlates well with other tracers of past merger events (extended halo, KDCs, gas)
- ✓ Massive galaxies ($M_* > 10^{11}$ $M_\odot$), and specifically among them, slow rotators, show strong evidence of a strong recent (<4 Gyr) merging activity. They grow at z<0.5 not only through minor mergers.
- ✓ Mass assembly of low mass fast rotators and massive slow rotators significantly different, justifying a classification based on mass/kinematics rather than on apparent morphology
- ✓ No « fundamental » differences between ETGs and LTGs

Other science goals: Birth and death of satellite dwarf galaxies



- Three gas-rich tidal dwarf galaxies aligned along a tidal tail from a major merger



- A paternity test, positive for at least one galaxy, with an estimated age of 4 Gyr

- The oldest confirmed TDG so far identified

Other science goals: Birth and **death** of satellite dwarf galaxies

- Several gas-poor satellites « sharing » the same narrow tidal tail around a spiral in the Virgo Cluster

NGVS-NGC4216

Paudel et al., 2013

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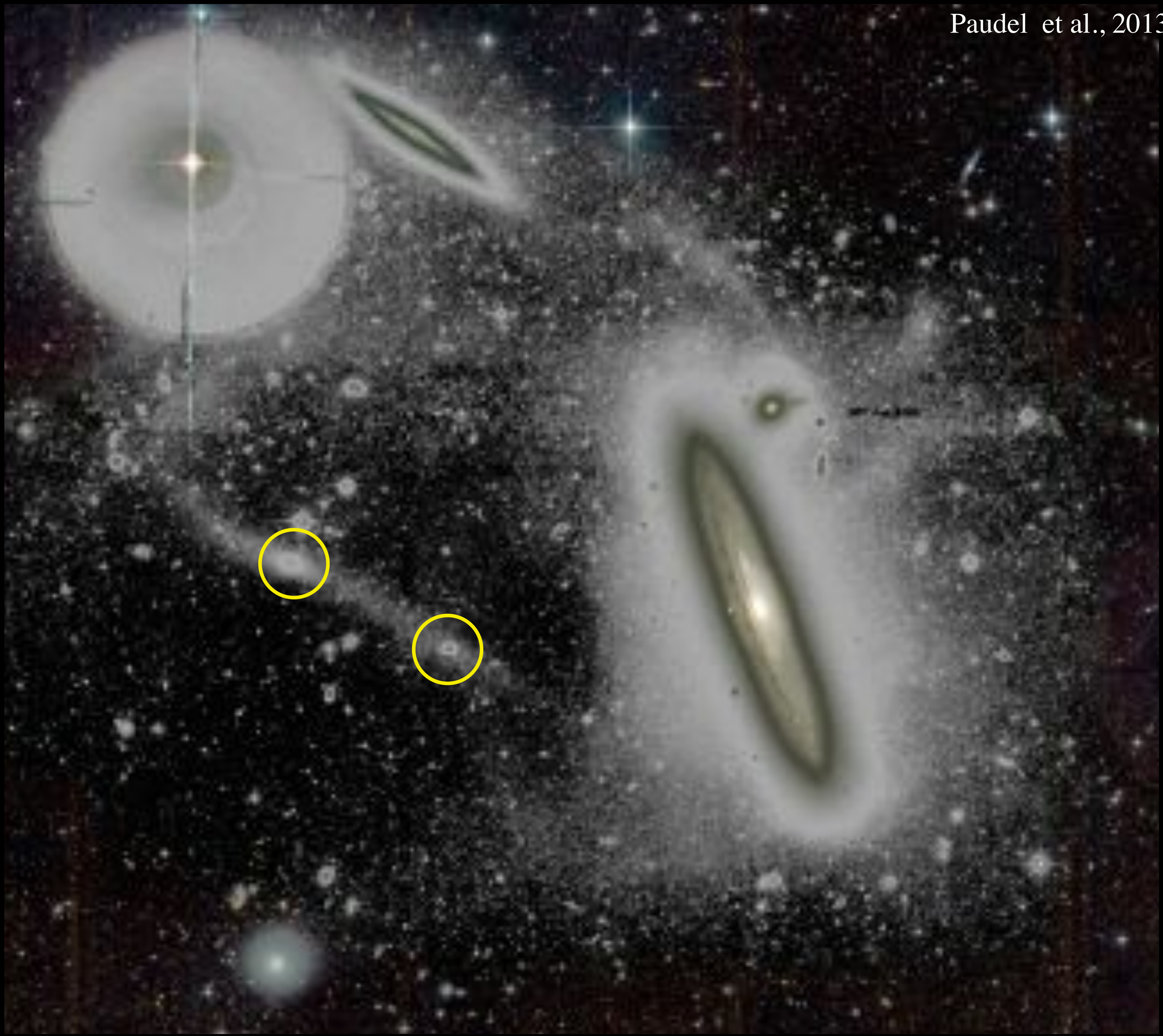

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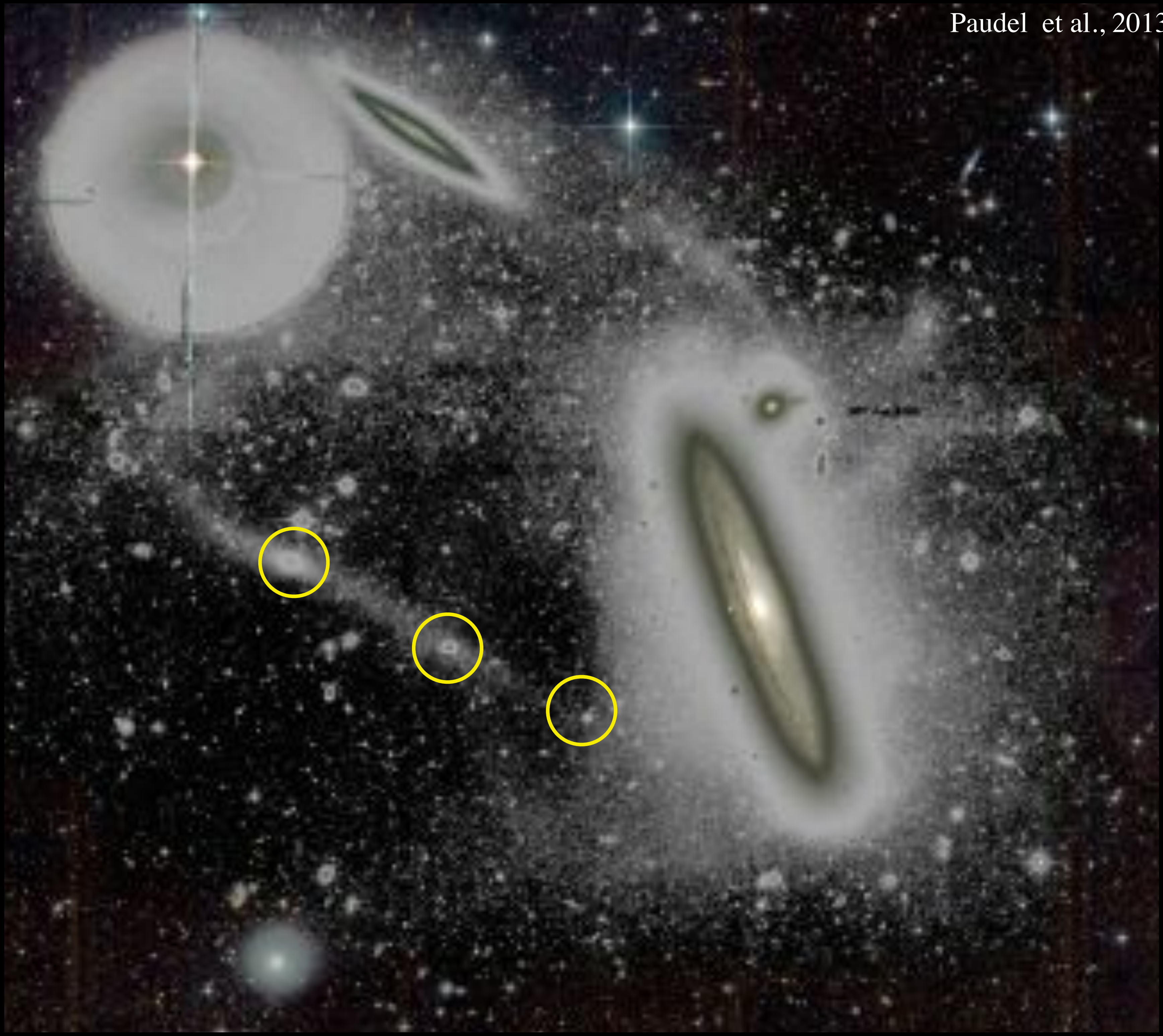
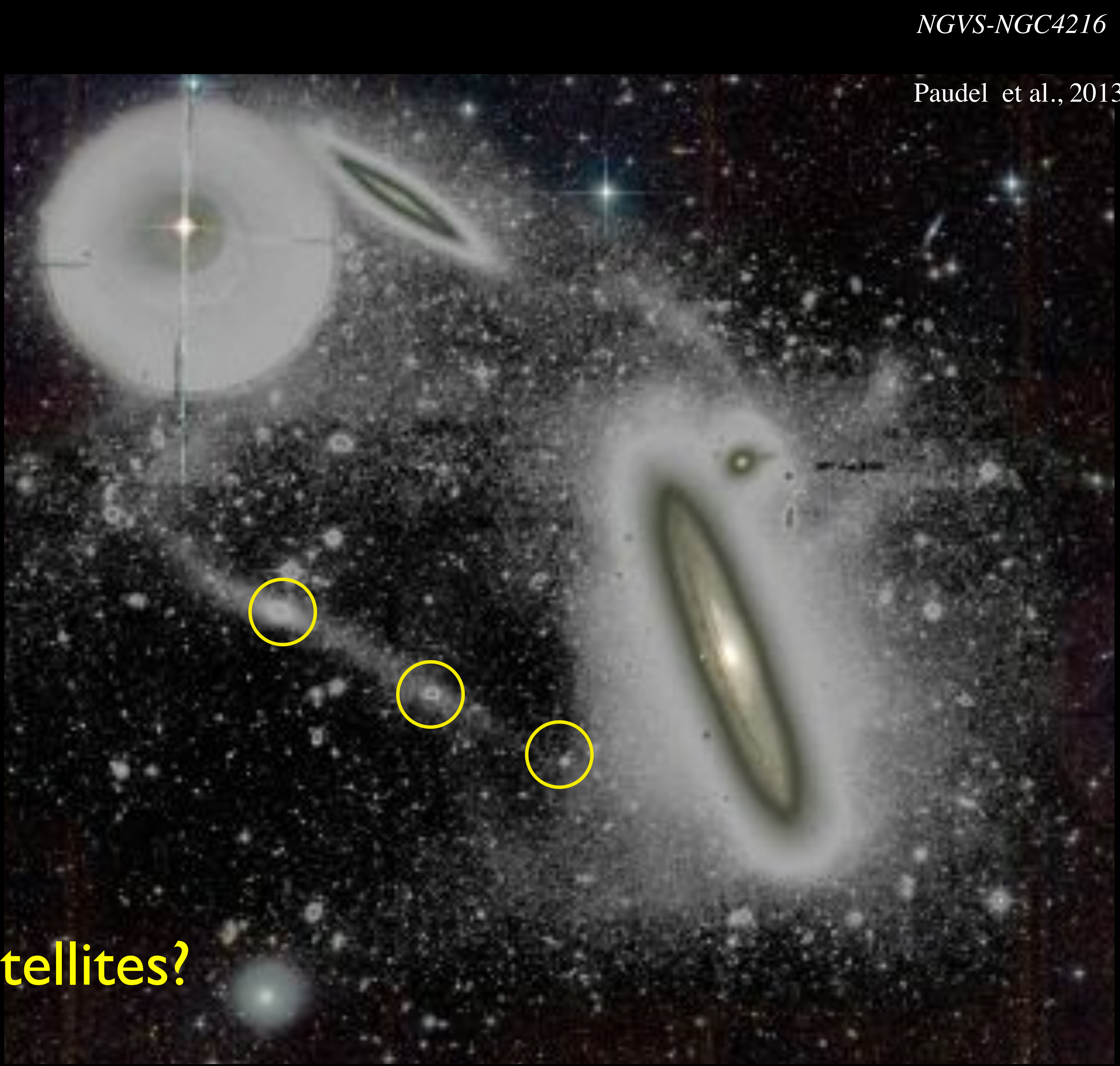


Paudel et al., 2013



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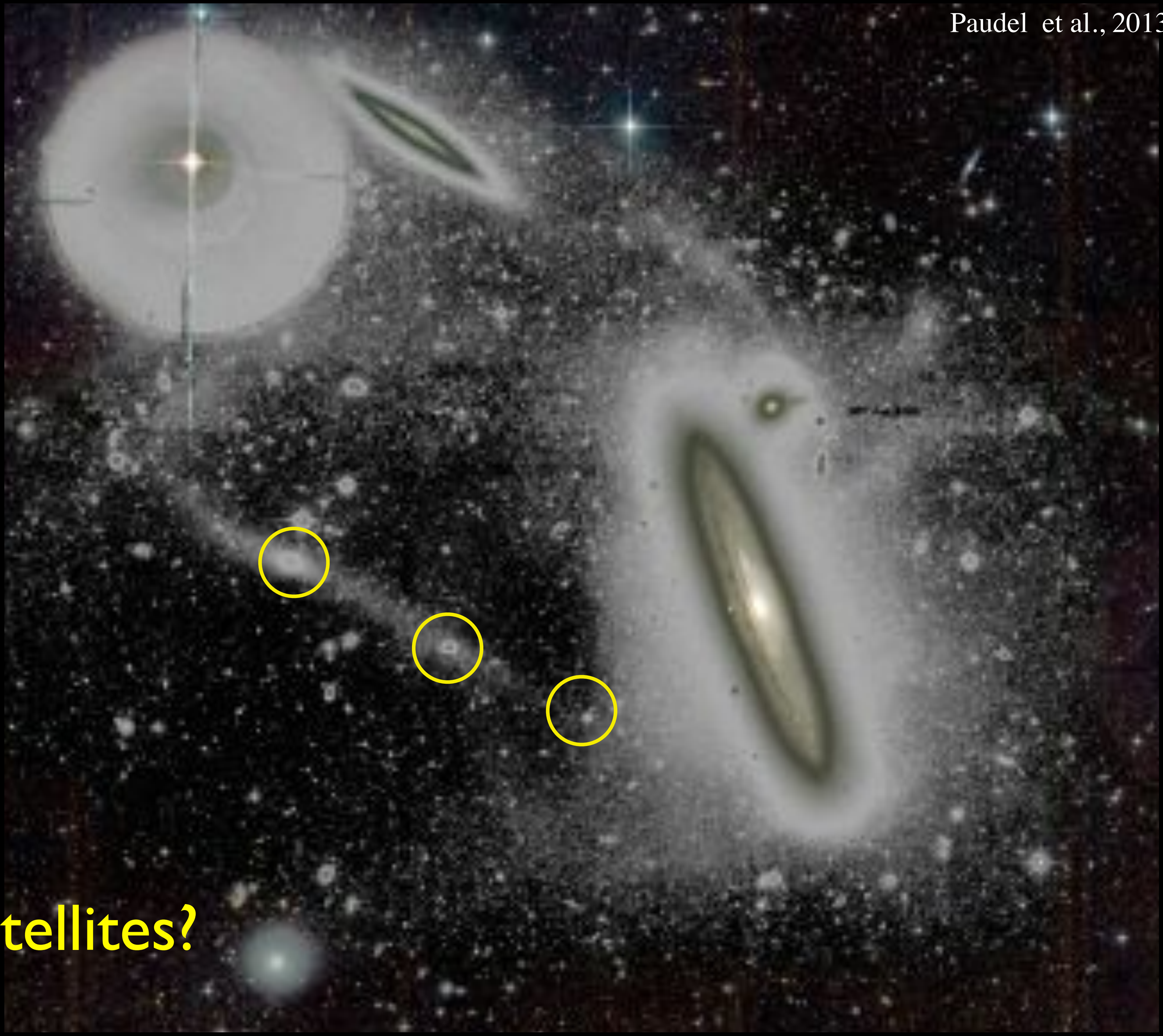
Creating Disk of Satellites?

Other science goals: Birth and **death** of satellite dwarf galaxies

NGVS-NGC4216

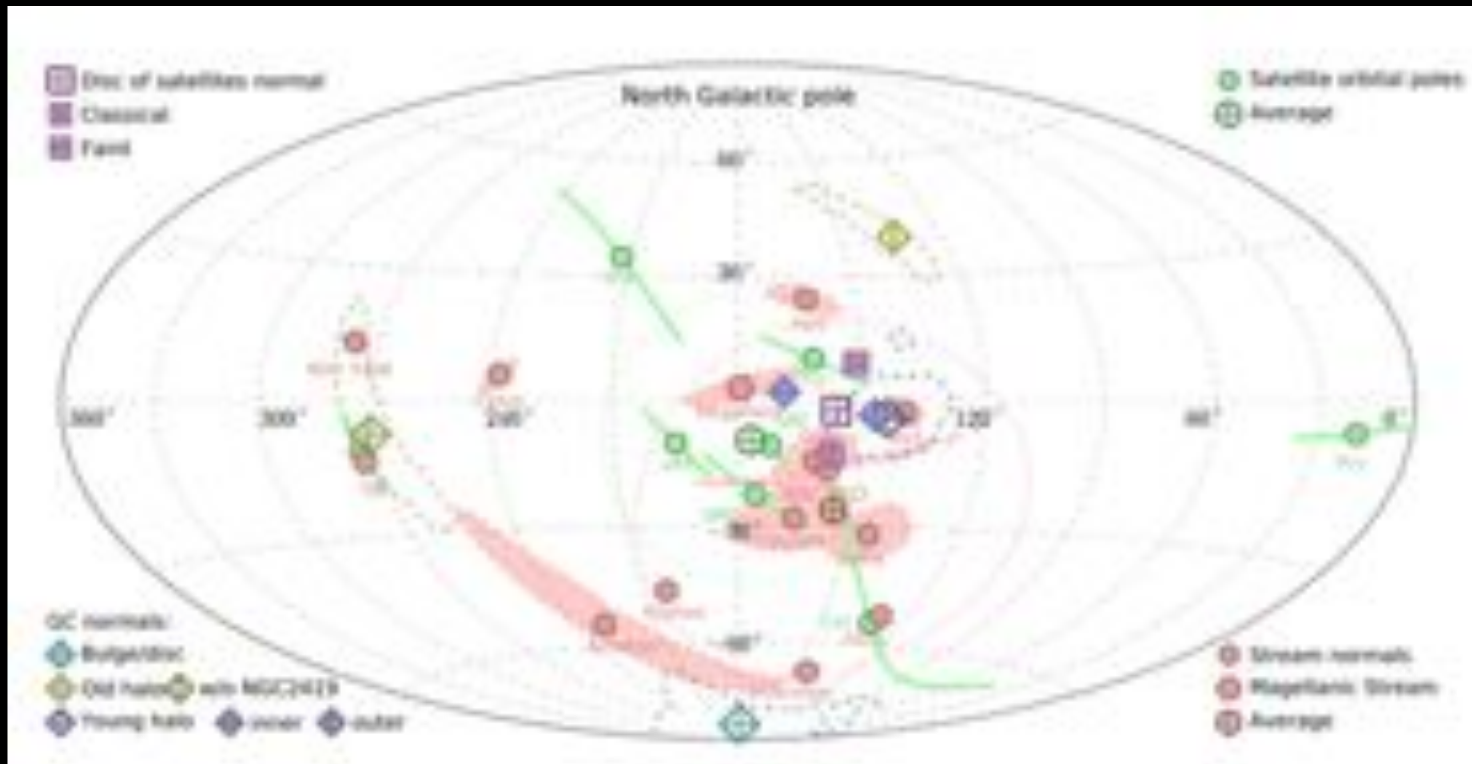
Paudel et al., 2013



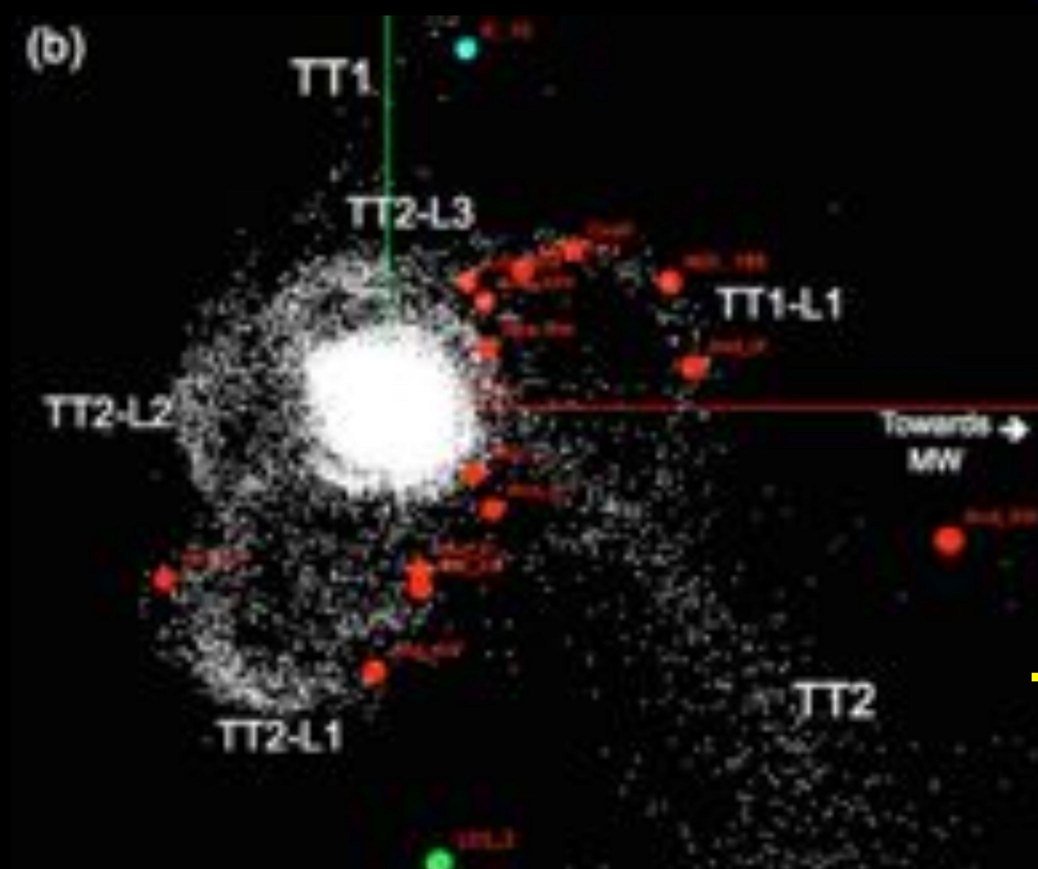
- Several gas-poor satellites « sharing » the same narrow tidal tail around a spiral in the Virgo Cluster

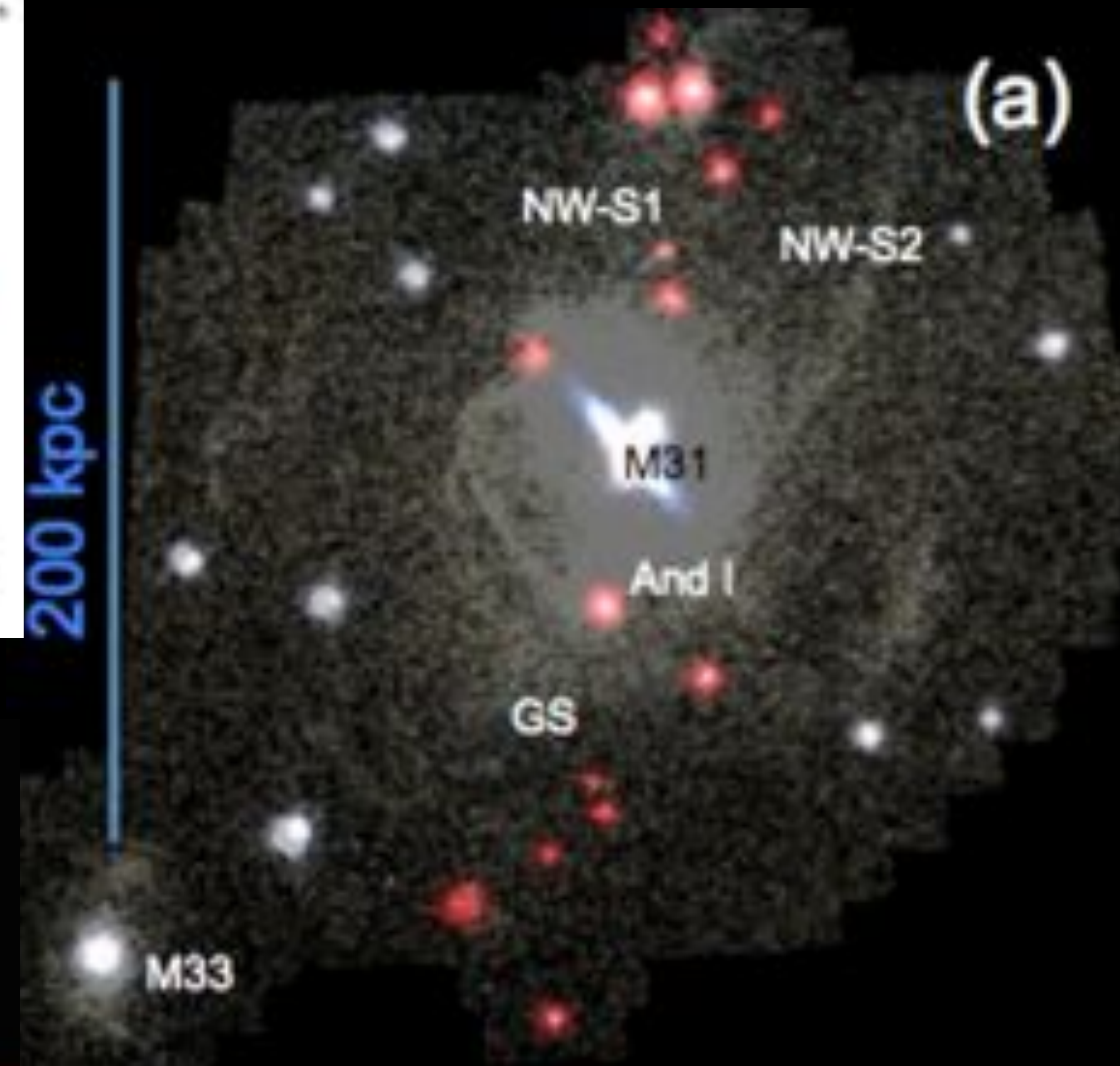
- Unlikely to be TDGs

Creating Disk of Satellites?



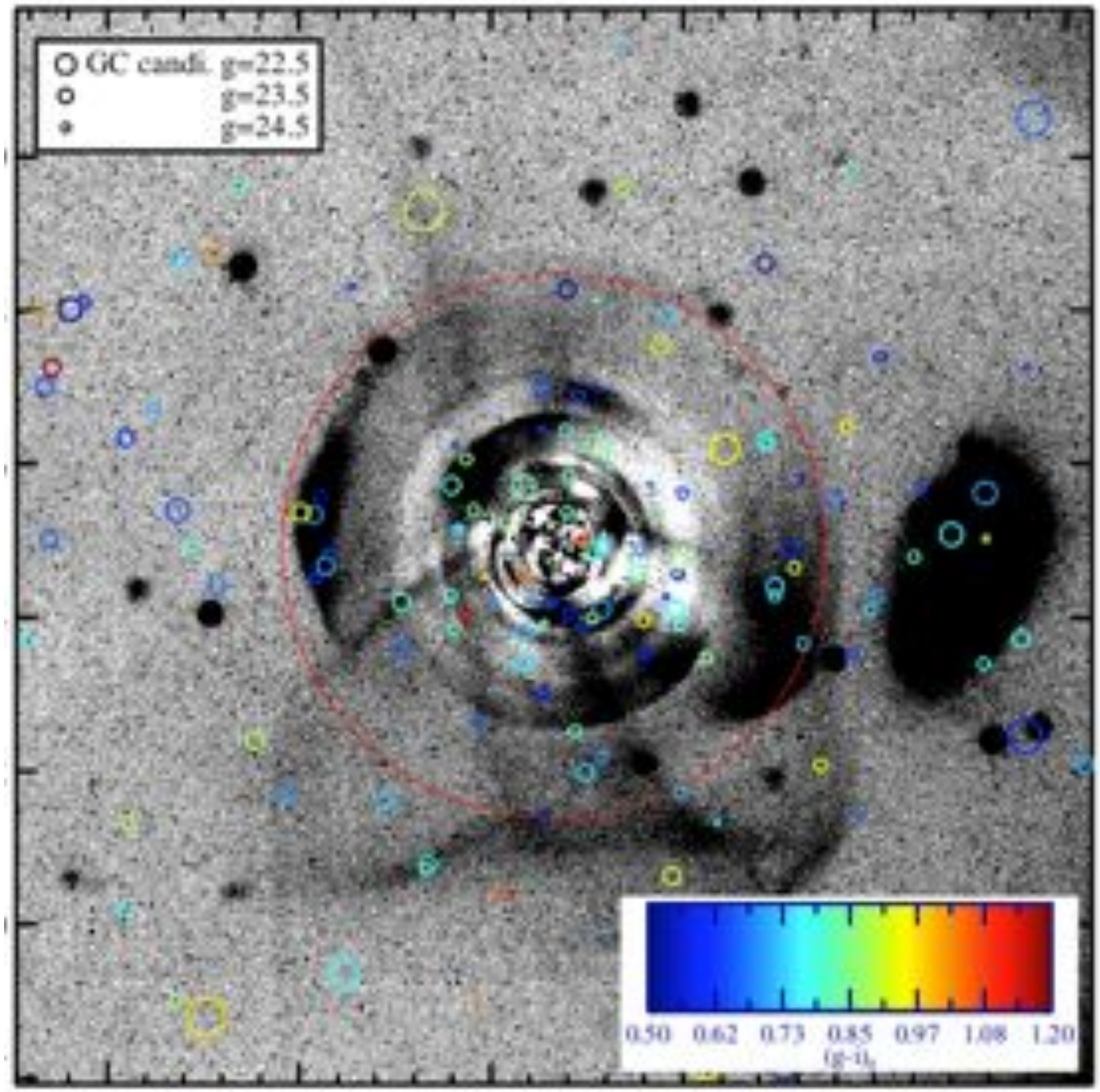
Pawlowski et al., 2014





Hammer et al., 2013

Tidal or cosmological origin?



Lim et al 2016, in prep

- Association of GC clusters with collisional debris?

- Fine structures give hints on the recent mass assembly of galaxies, but have usually a very low surface brightness

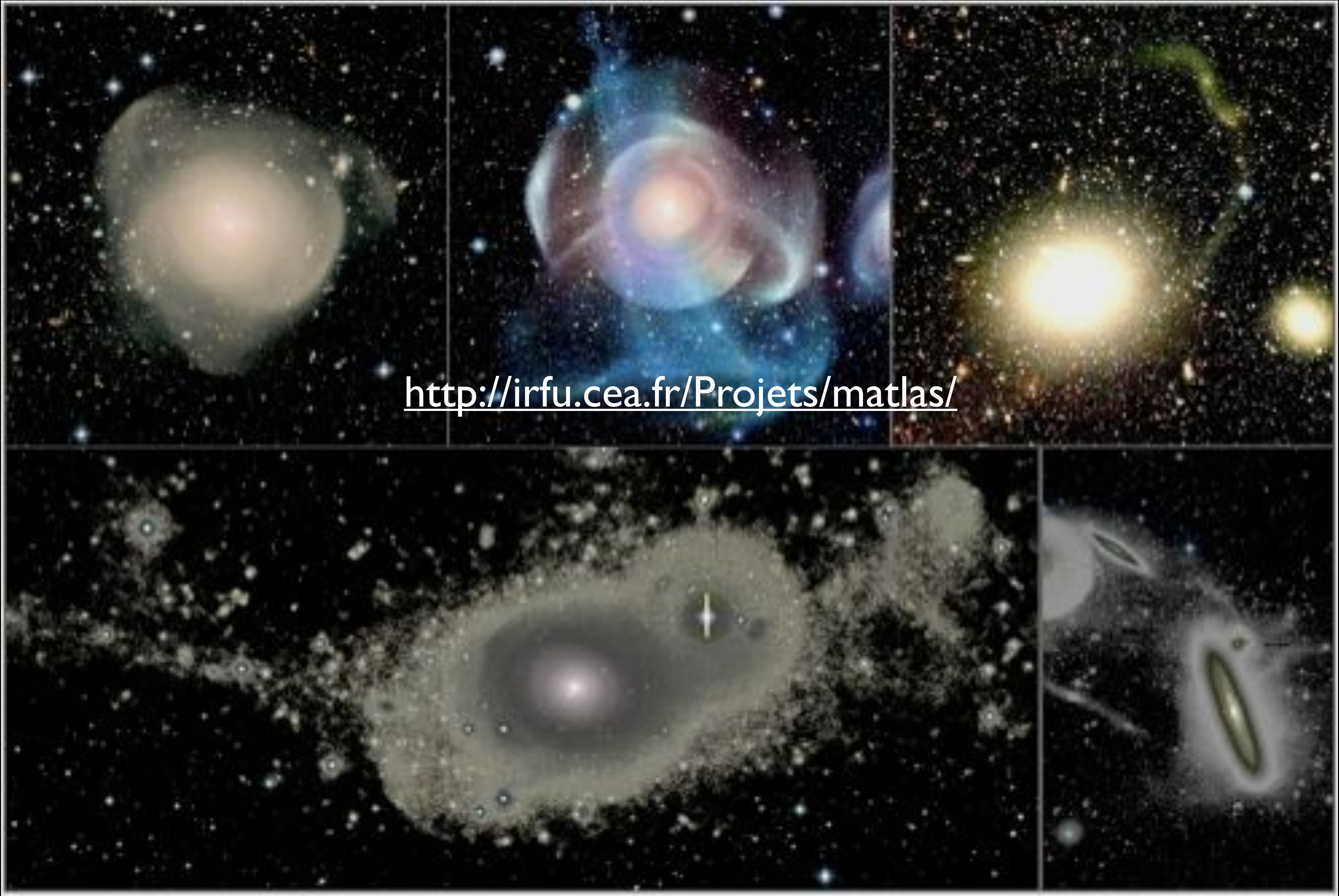
- Deep imaging programs ‘(NGVS, MATLAS) at CFHT with optimized observing and data reduction techniques reach a high surface brightness limit (29 mag.arcsec^{-2}) allow us to detect a variety of fine structures.

- New structures found changing our vision of (some) massive galaxies: blue spirals structures around ETGs (and red halos around spirals), tails, streams and shells telling about past mergers. Variations with galaxy property (mass, kinematics)

- A number of technical challenges (ghost halos affecting the color of galaxies), and new opportunities: the study of the ISM at high spatial resolutop,

- Other science goals: origin and destruction of ETG satellites, Globular Clusters

Conclusions



http://irfu.cea.fr/Projets/matlas/

Merci with love!