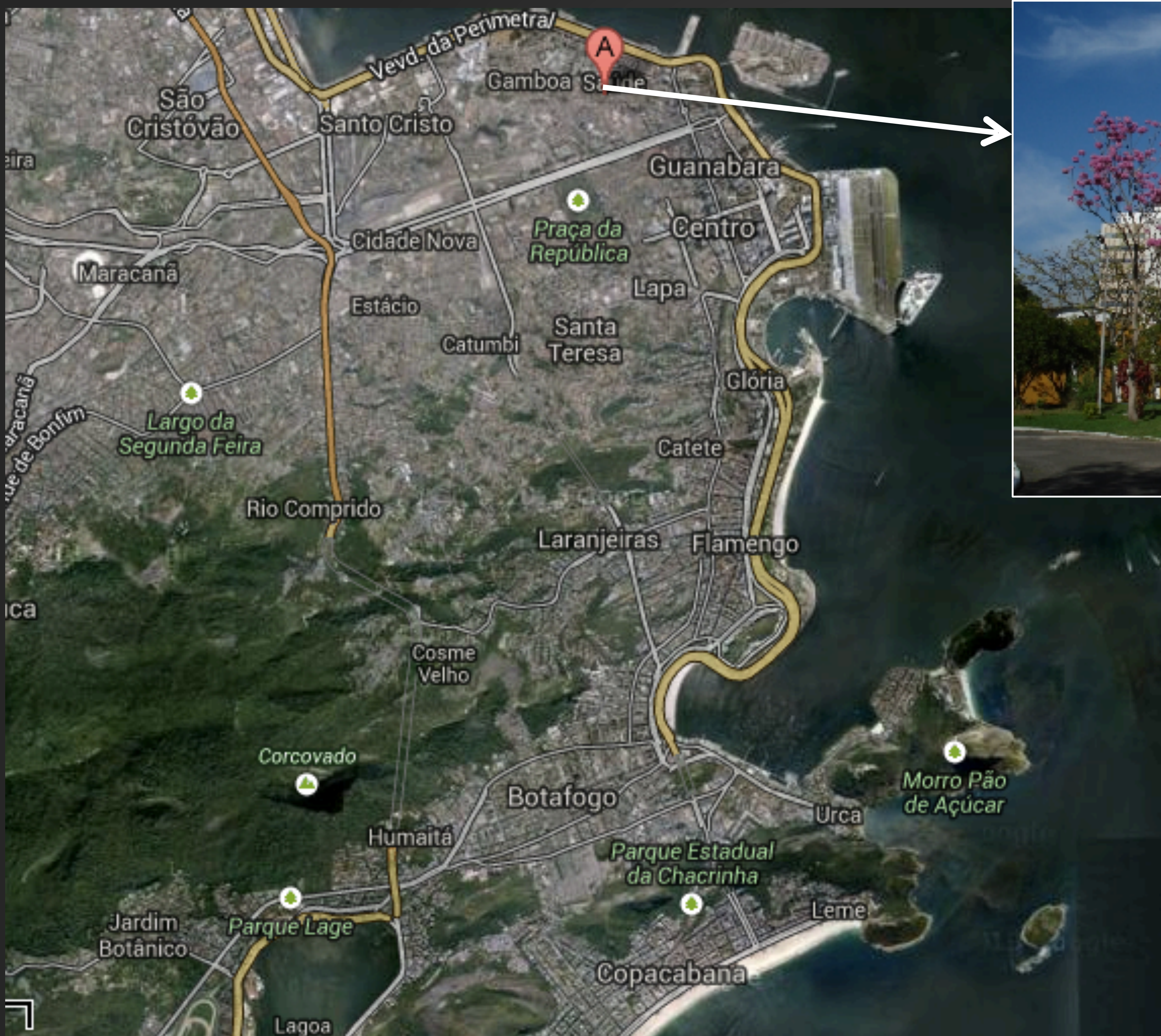
Galaxy Formation and Dark Matter

Thiago S. Gonçalves
Karín Menéndez-Delmestre
Observatório do Valongo
Universidade Federal do Rio de Janeiro

Valongo Observatory

Astronomy Department of the Federal University of Rio de Janeiro



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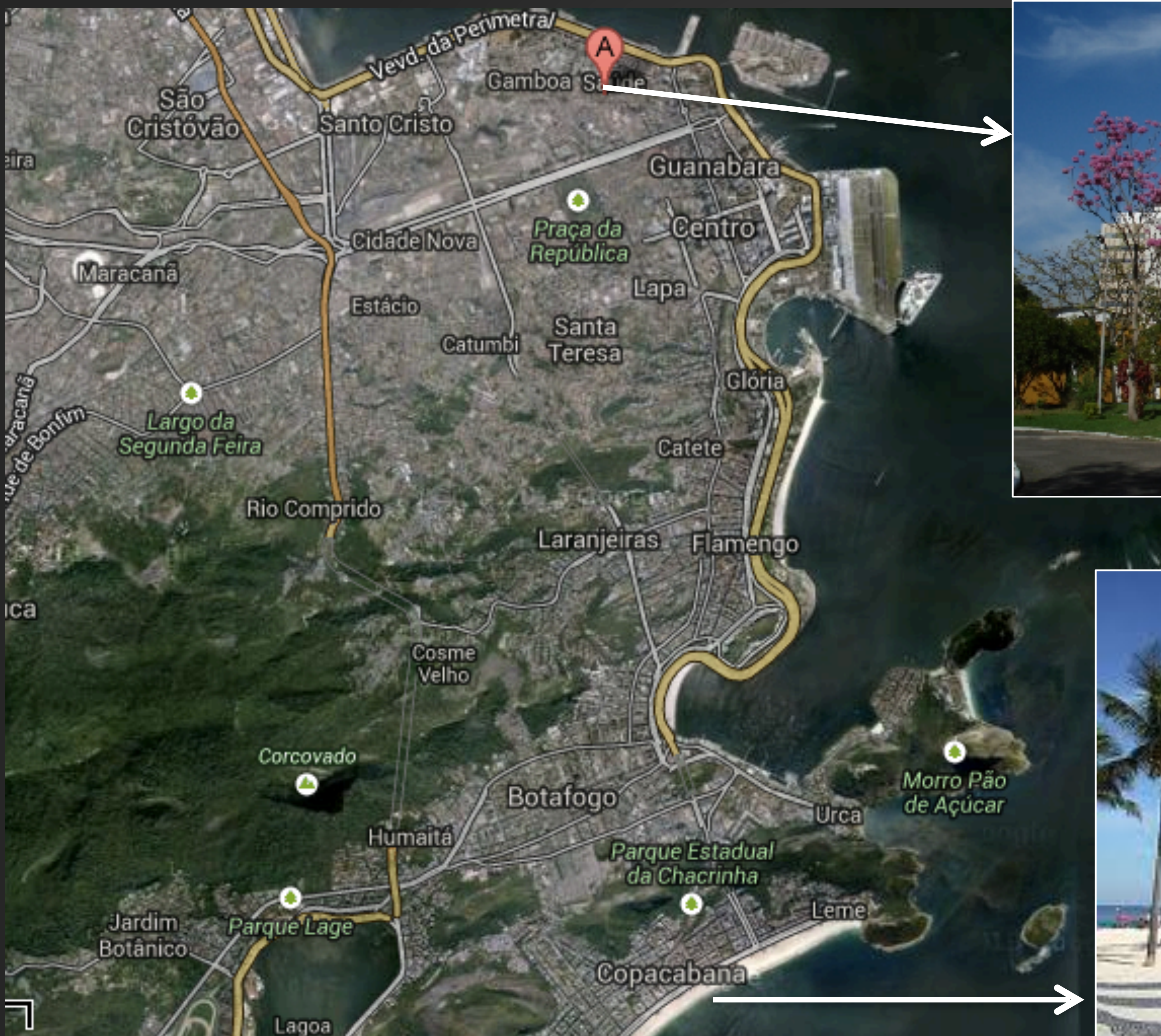

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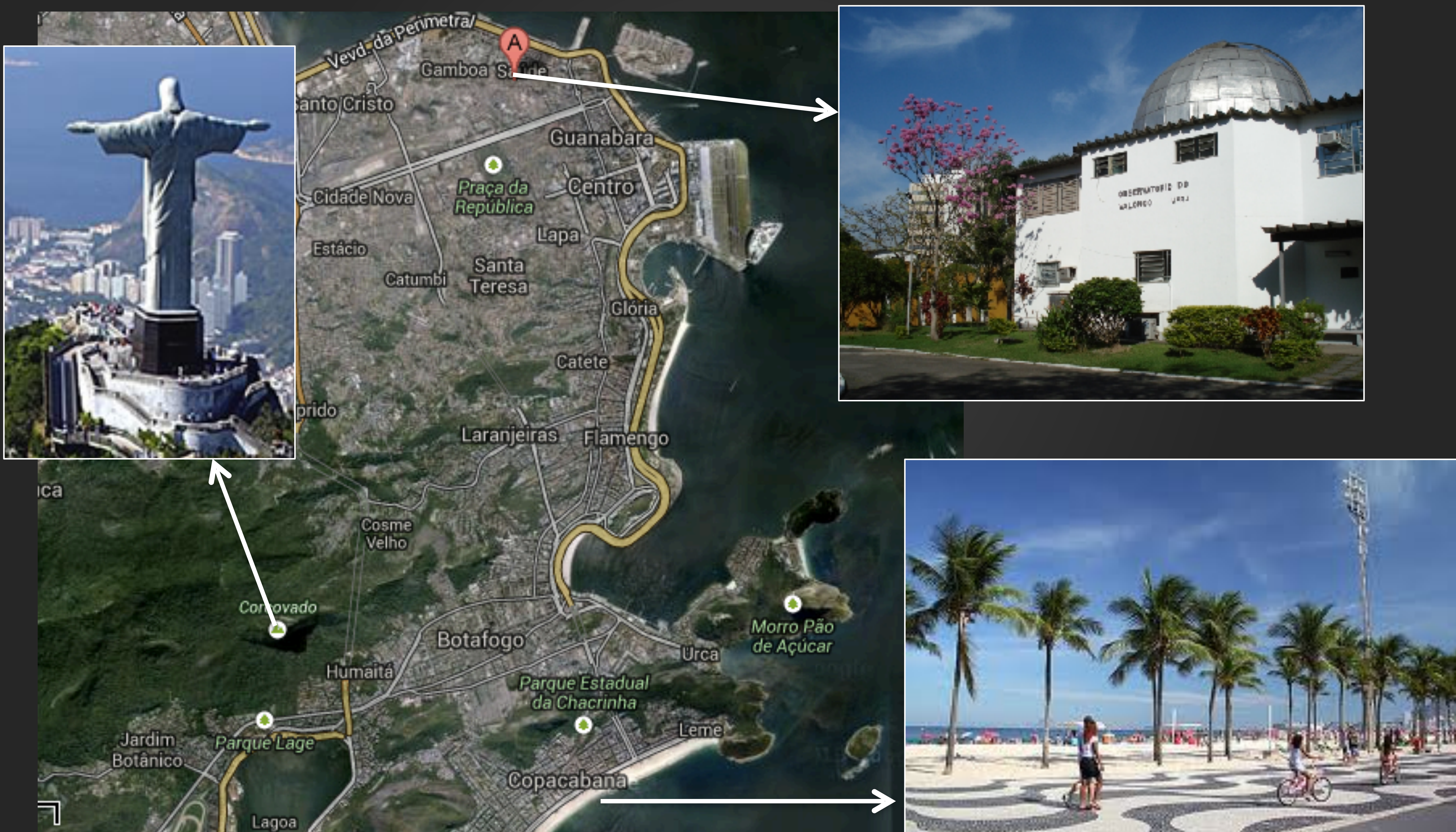


Valongo Observatory

Astronomy Department of the Federal University of Rio de Janeiro

- 60 years forming undergraduate Astronomy students
  - the only one in Brazil until very recently
- >10 years of Master Program, ~5 years of PhD program
- Demographics:
  - 14 professors
  - ~5 postdocs
  - 12 master students
  - 10 PhD students
  - 20 new undergrads/semester

Astronomy in Brazil

80 institutes in total
(based on the Brazilian Astronomical Society 2011 census)

- UFRN +3

- UESC +1

- LNA
- UFMG +5

- Valongo/UFRJ
- National Observatory +9
- CBPF

- IAG/U. São Paulo +17
- INPE

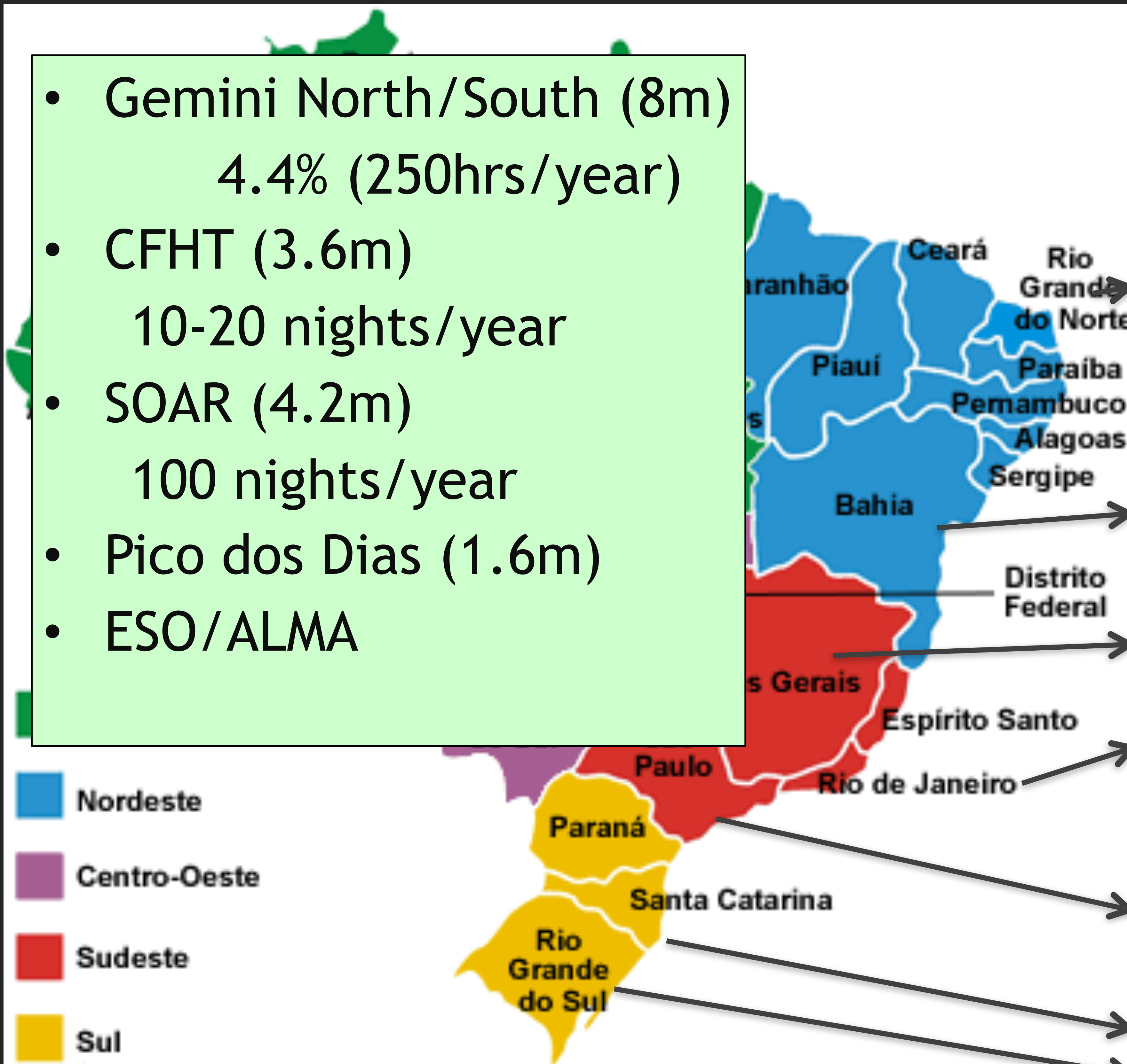
- UFSC +3

- UFRGS +7

+22 other institutes, including SOAR!

Astronomy in Brazil

- Gemini North/South (8m)
  4.4% (250hrs/year)
- CFHT (3.6m)
  10-20 nights/year
- SOAR (4.2m)
  100 nights/year
- Pico dos Dias (1.6m)
- ESO/ALMA



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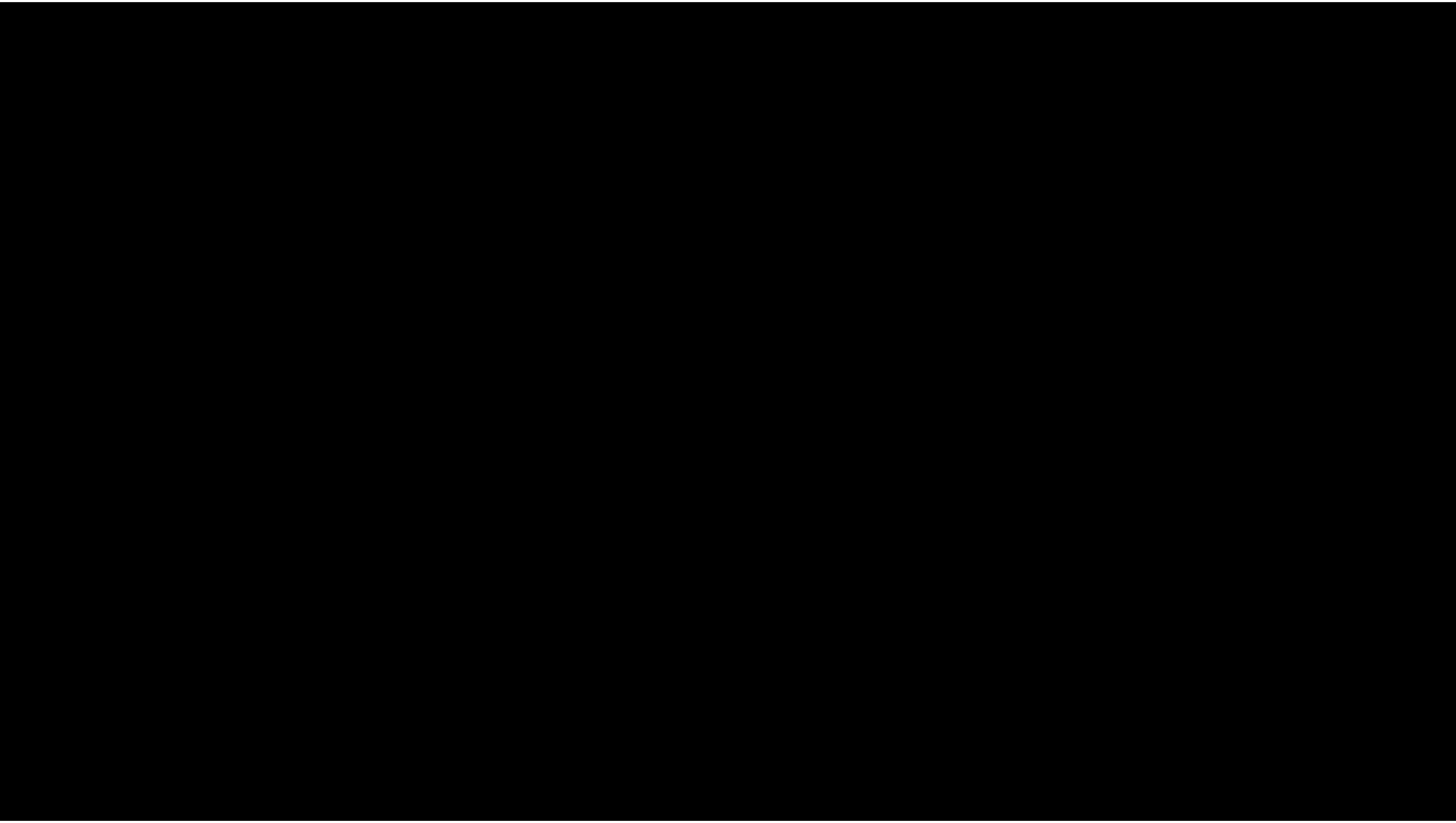
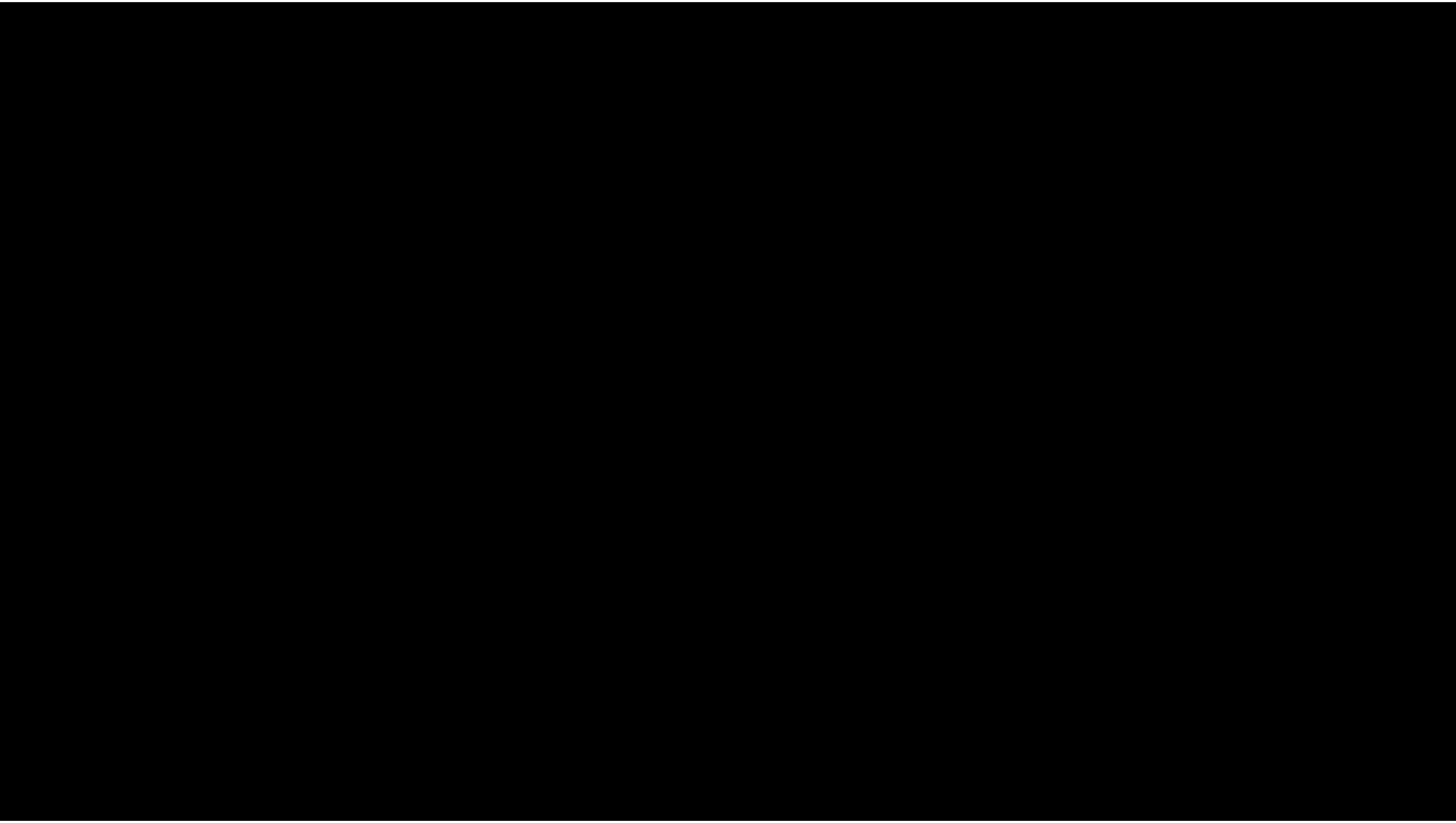
Galaxy formation:

The classical view

Galaxy formation: The classical view

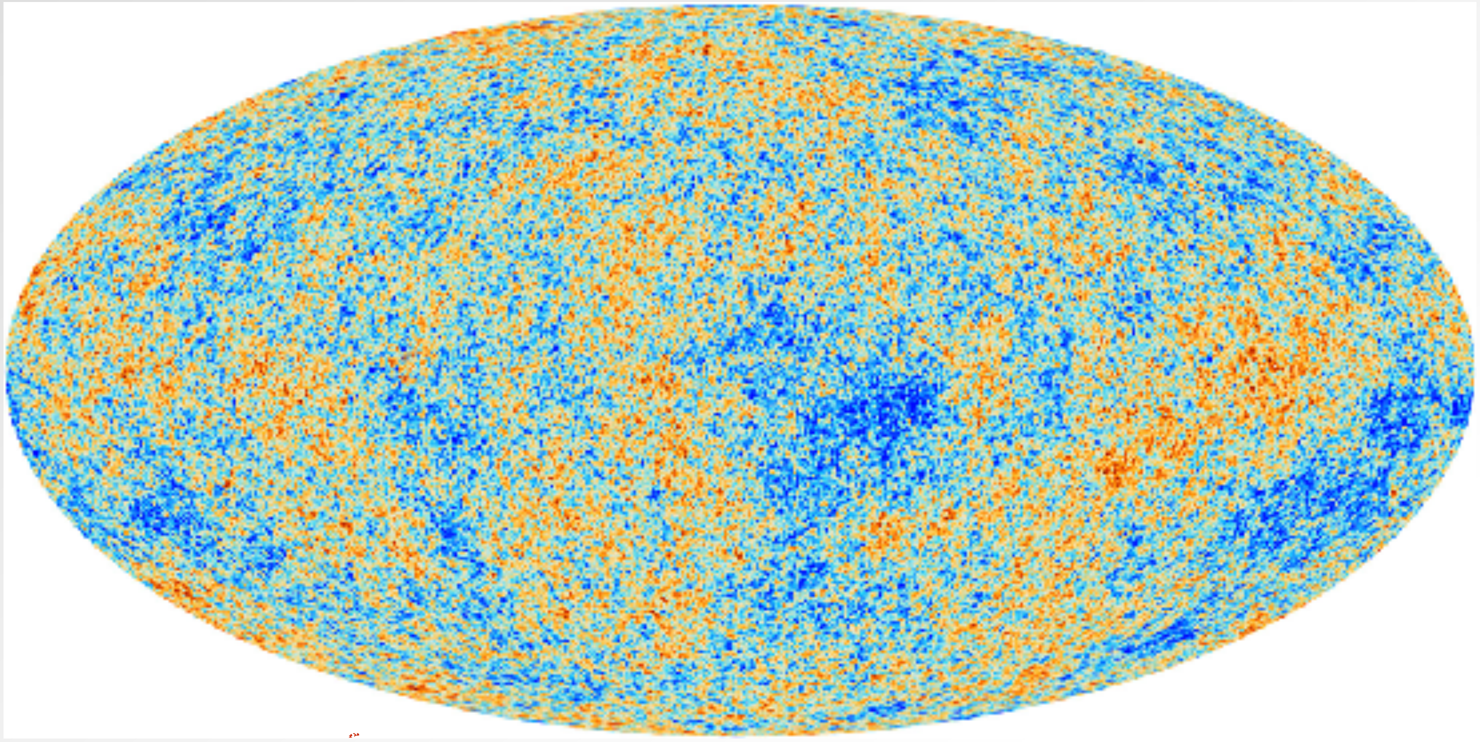


Galaxy formation: The classical view

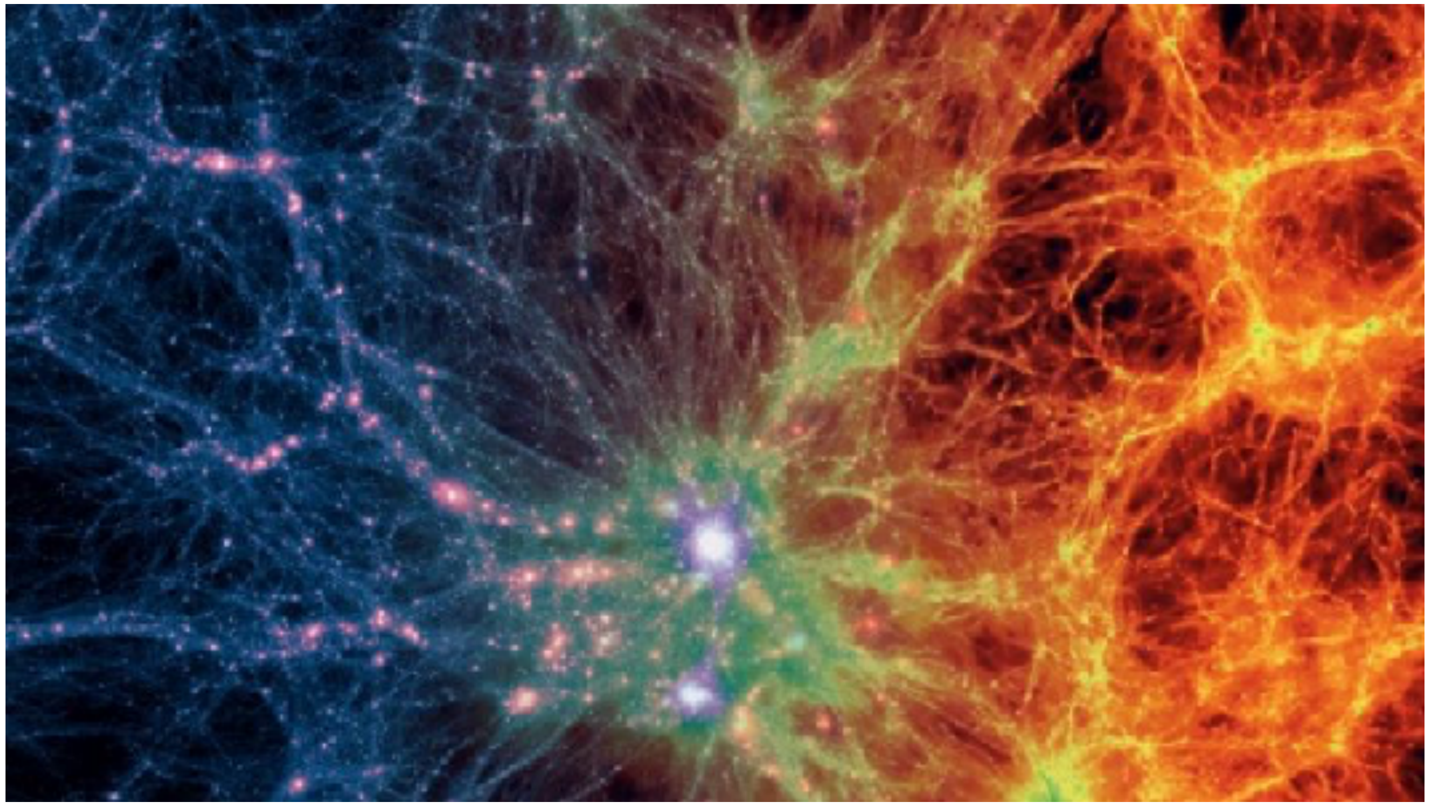


Galaxy formation: The classical view

Planck collaboration



Formation of the large-scale structure



Illustris

Galaxy formation: The classical view

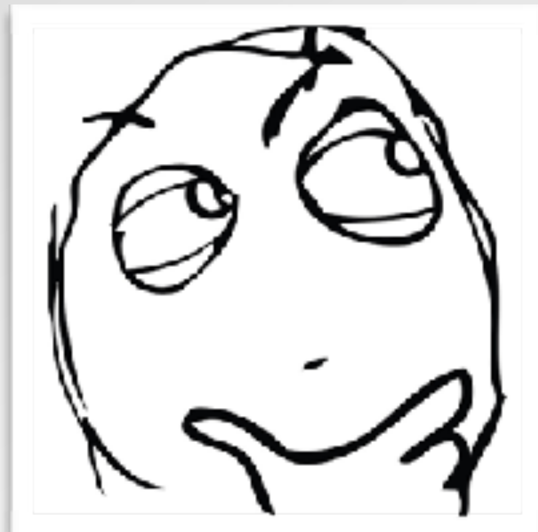
HST

The interstellar medium (ISM): gas and stars

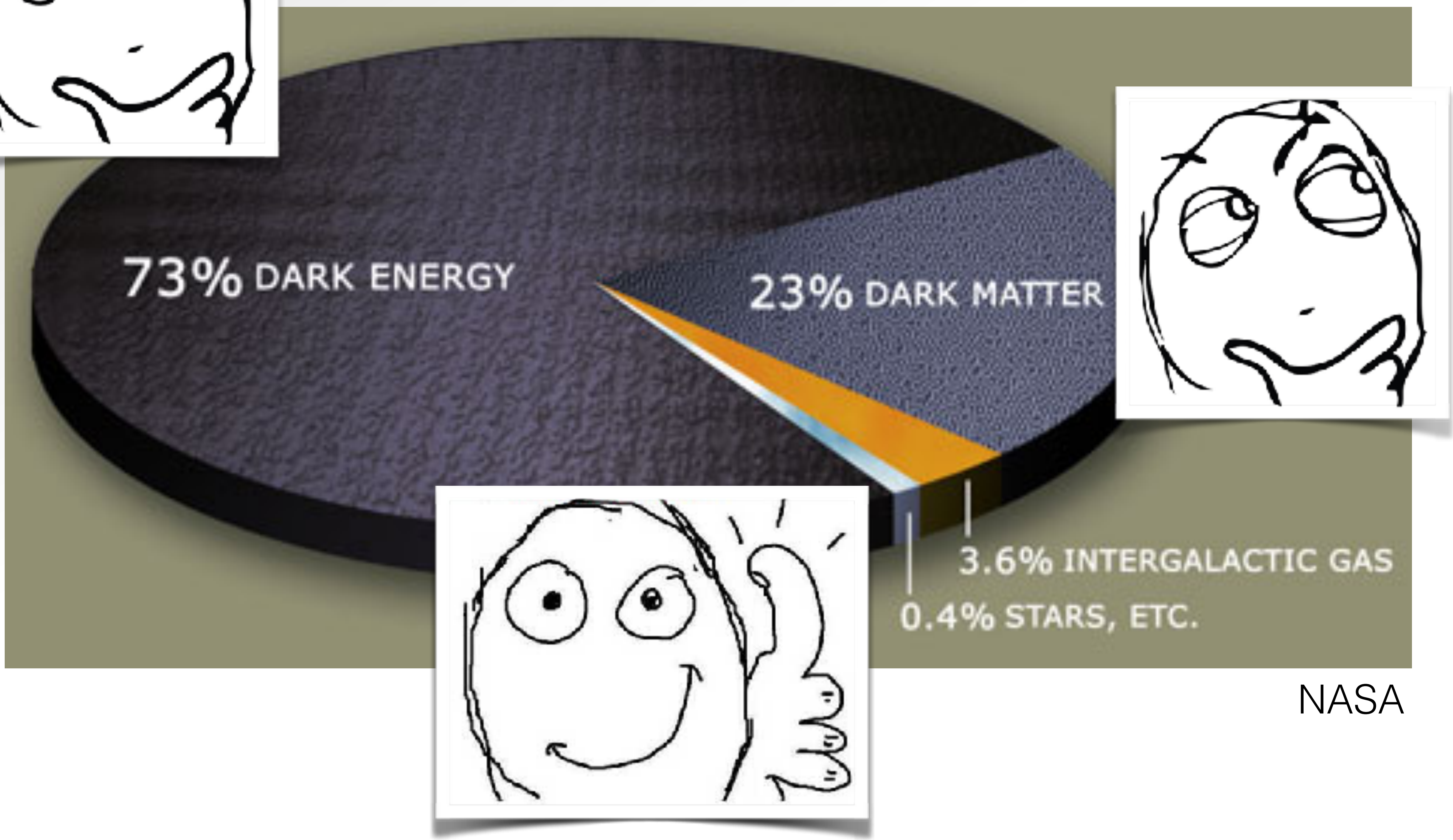
Non-linear processes: mechanical & radiative feedback, turbulence, magnetic fields

Gastrophysics

Galaxy formation: The classical view



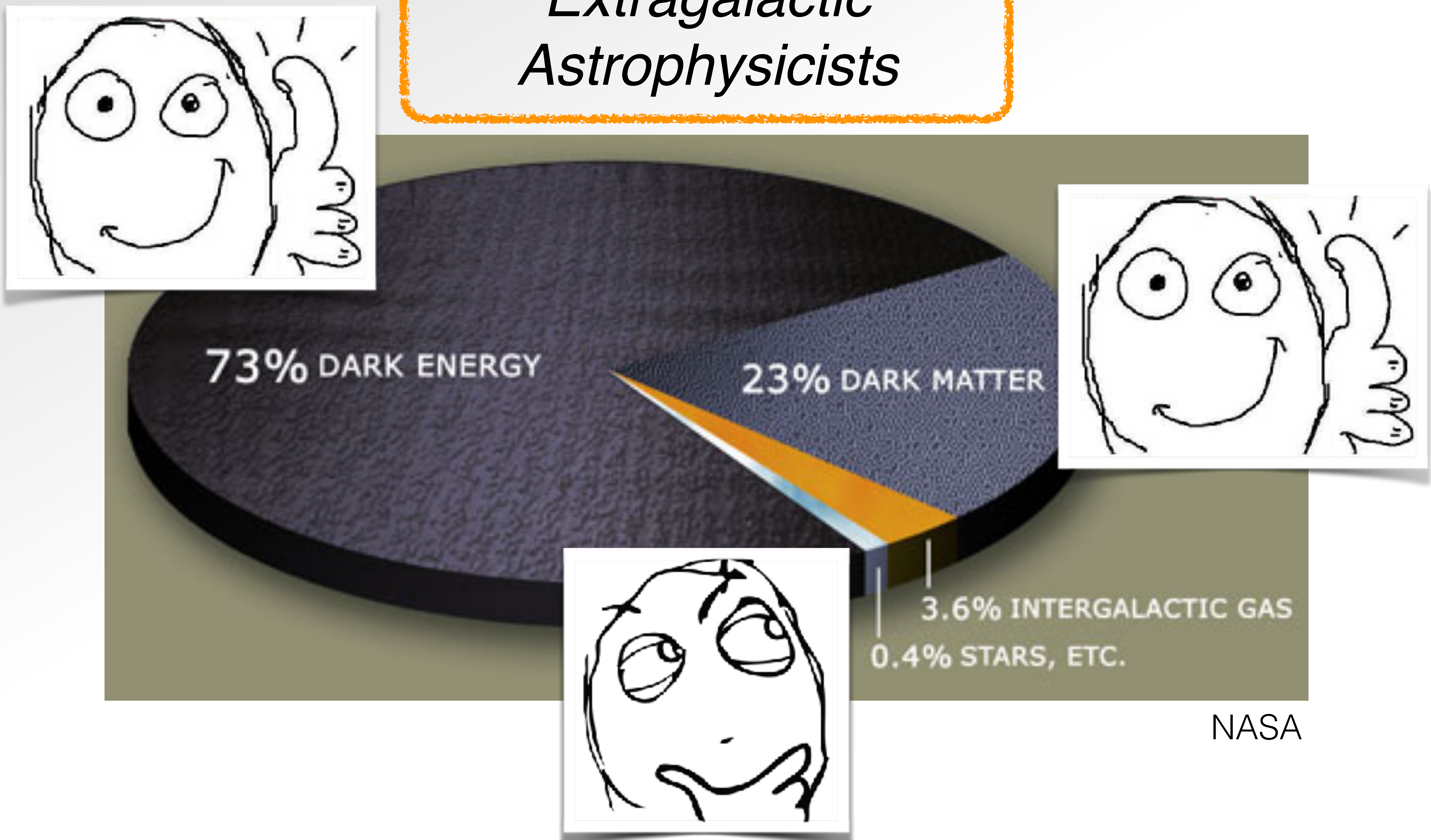
Cosmologists



NASA

Galaxy formation: The classical view

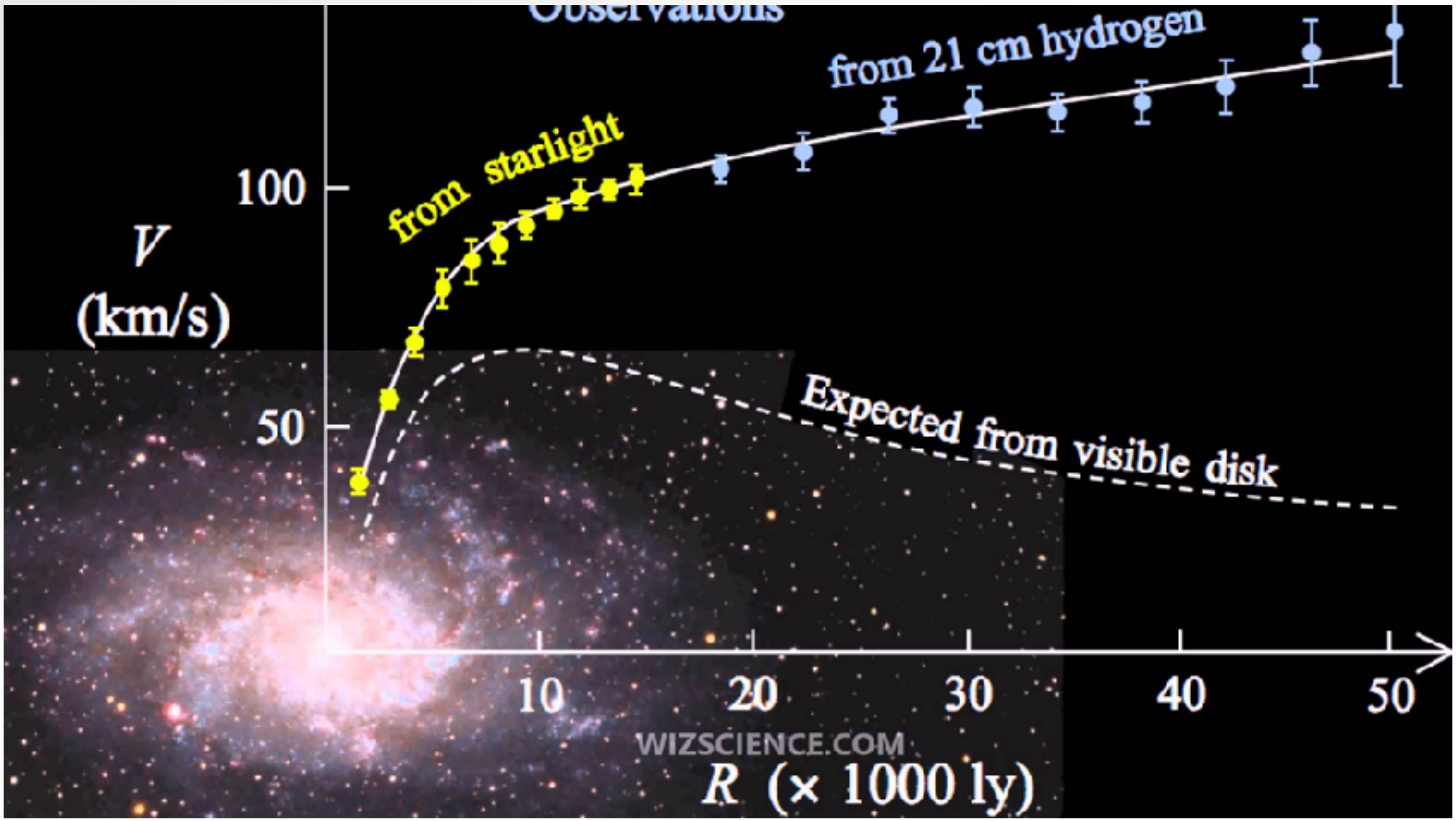
Extragalactic Astrophysicists



NASA

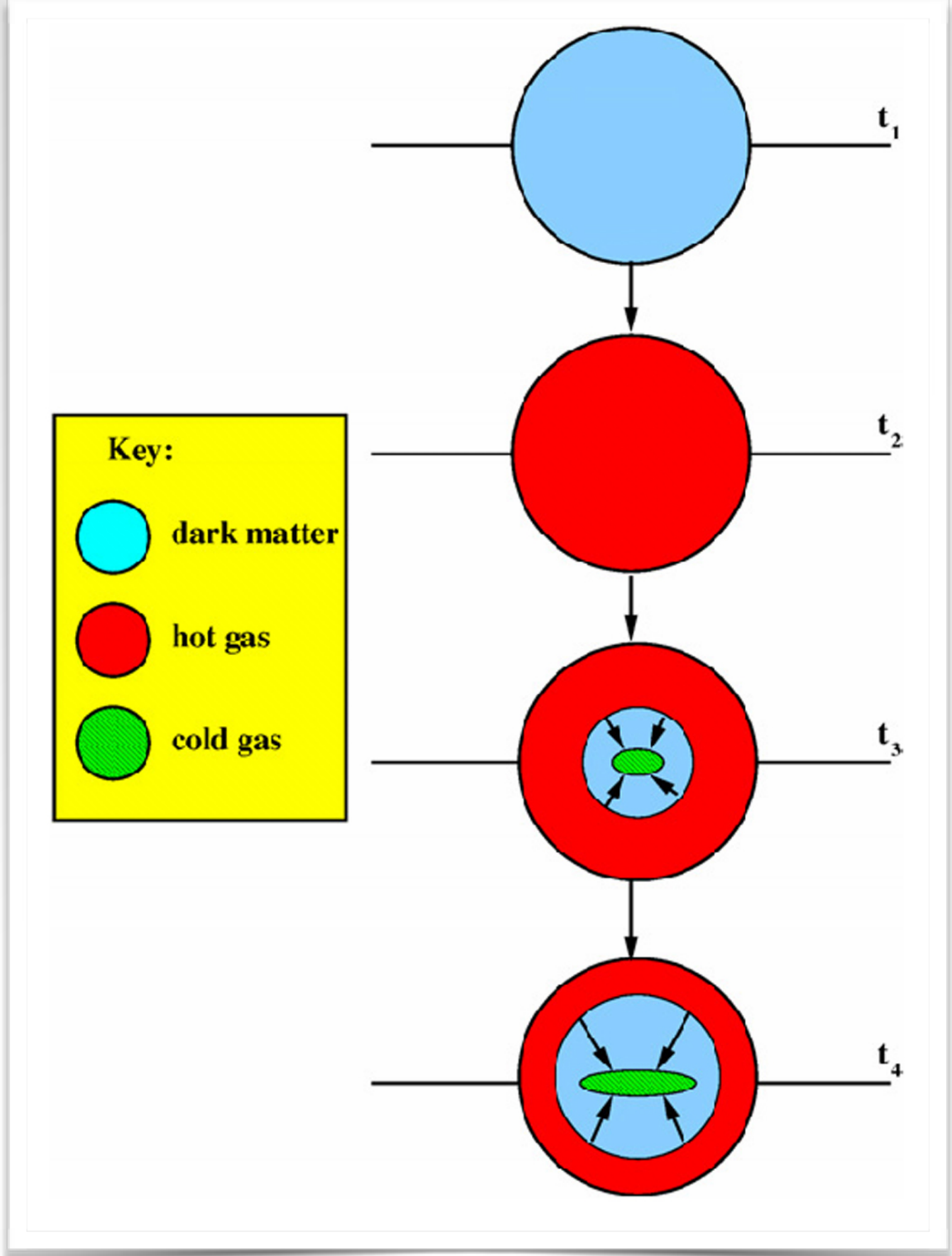
Galaxy formation: The classical view

But dark matter is a fundamental ingredient



Galaxy formation: The classical view

Baugh (2006)

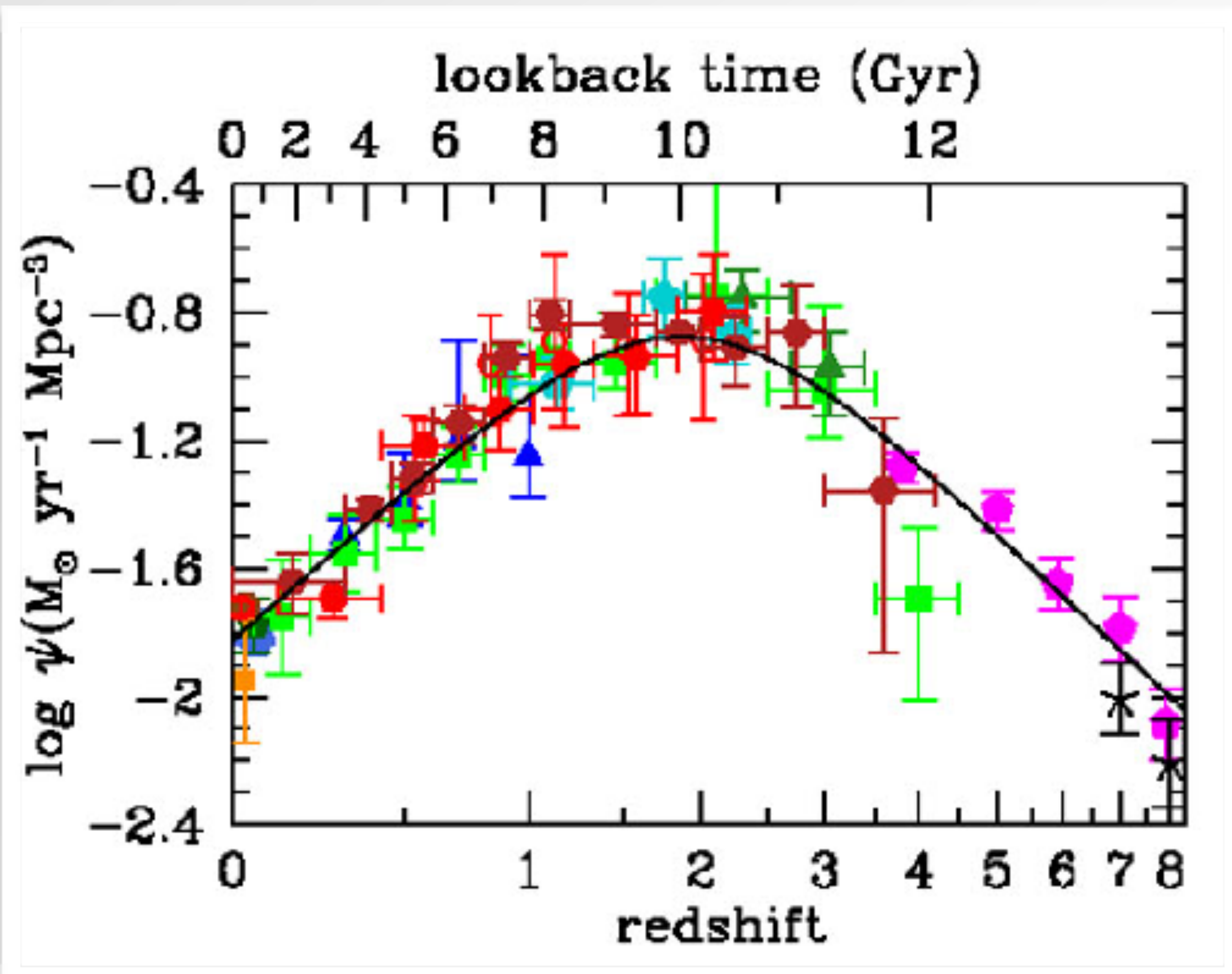


Classical view: gas collapse and disk formation

High redshift:

A different paradigm

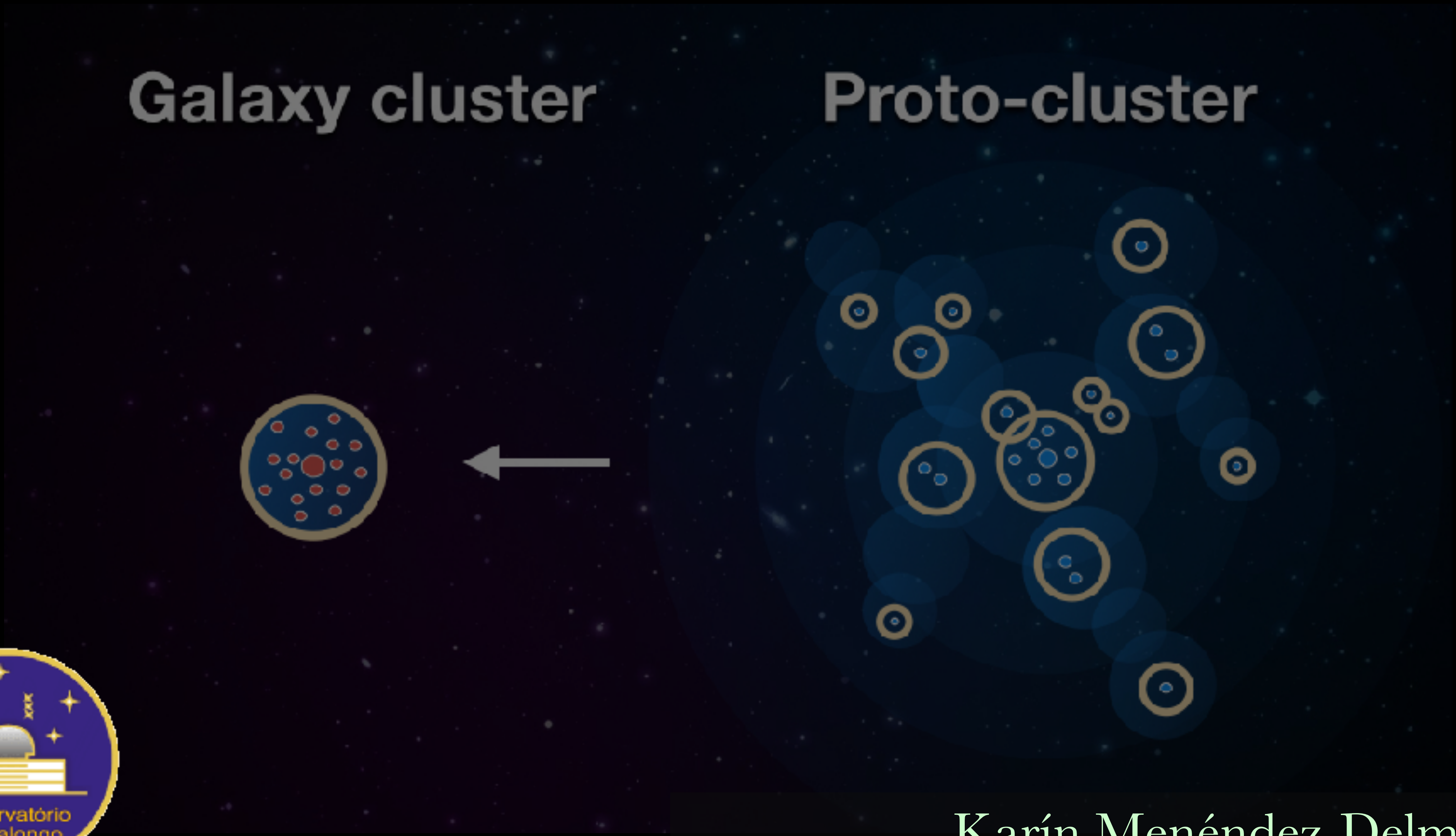
High-redshift: a different paradigm



Madau & Dickinson 14

The universe was forming stars more rapidly in the past

Protoclusters and the Establishment of the Galaxy-Environment Relation



Toy model (Yi-Kuan Chiang, U. Texas)

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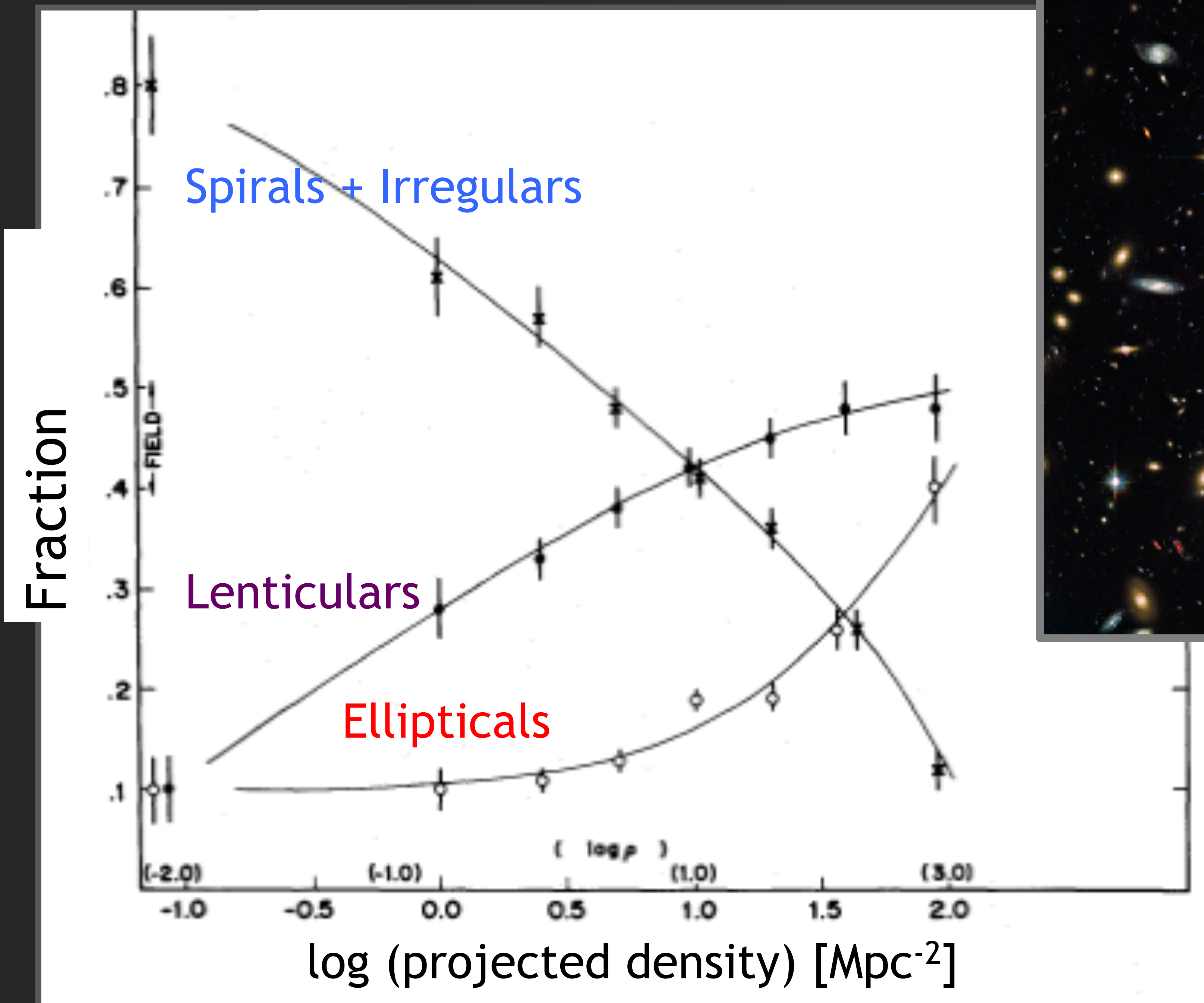
Galaxy properties are connected to the environment

- Morphological segregation



Dressler+80

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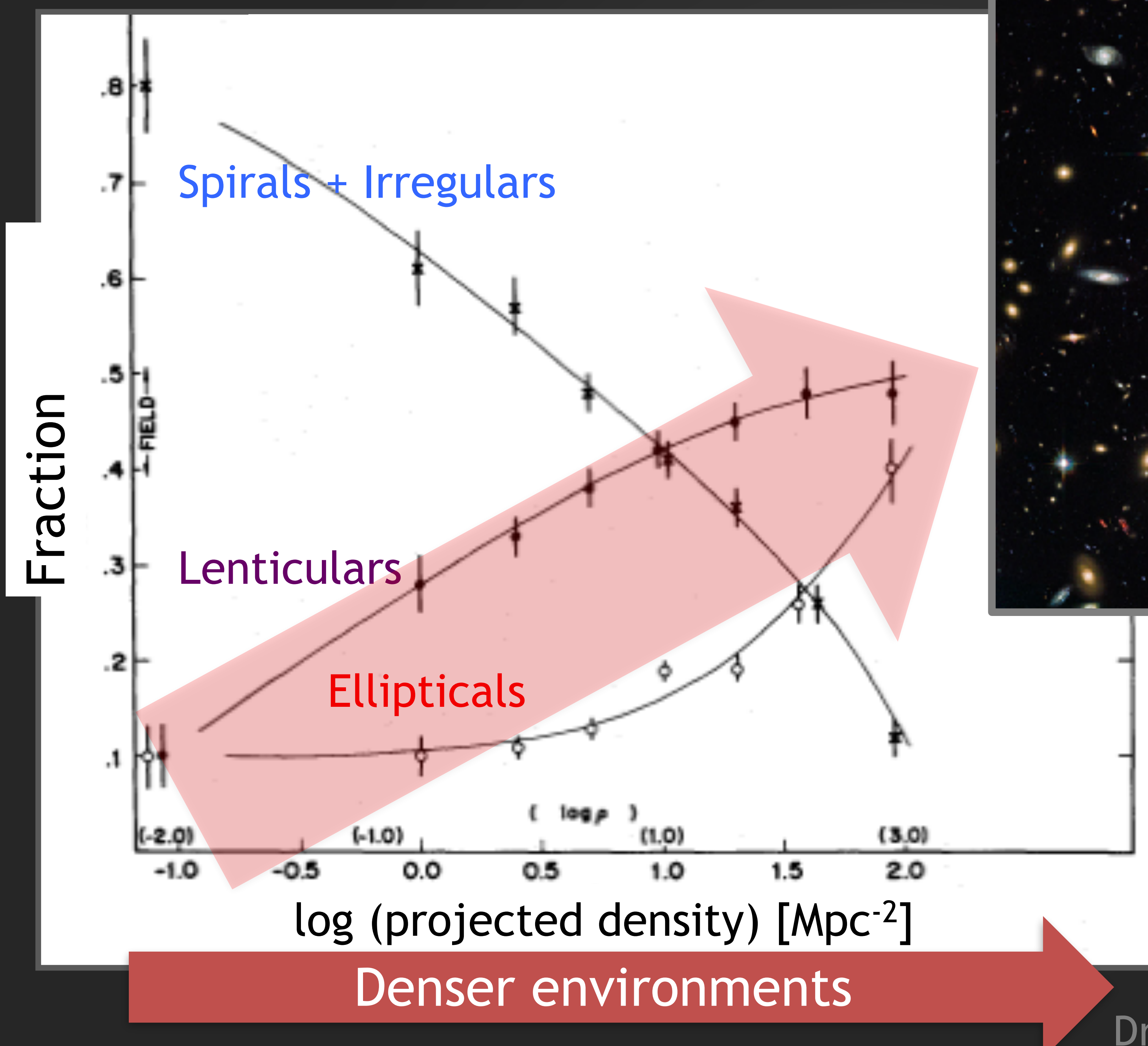

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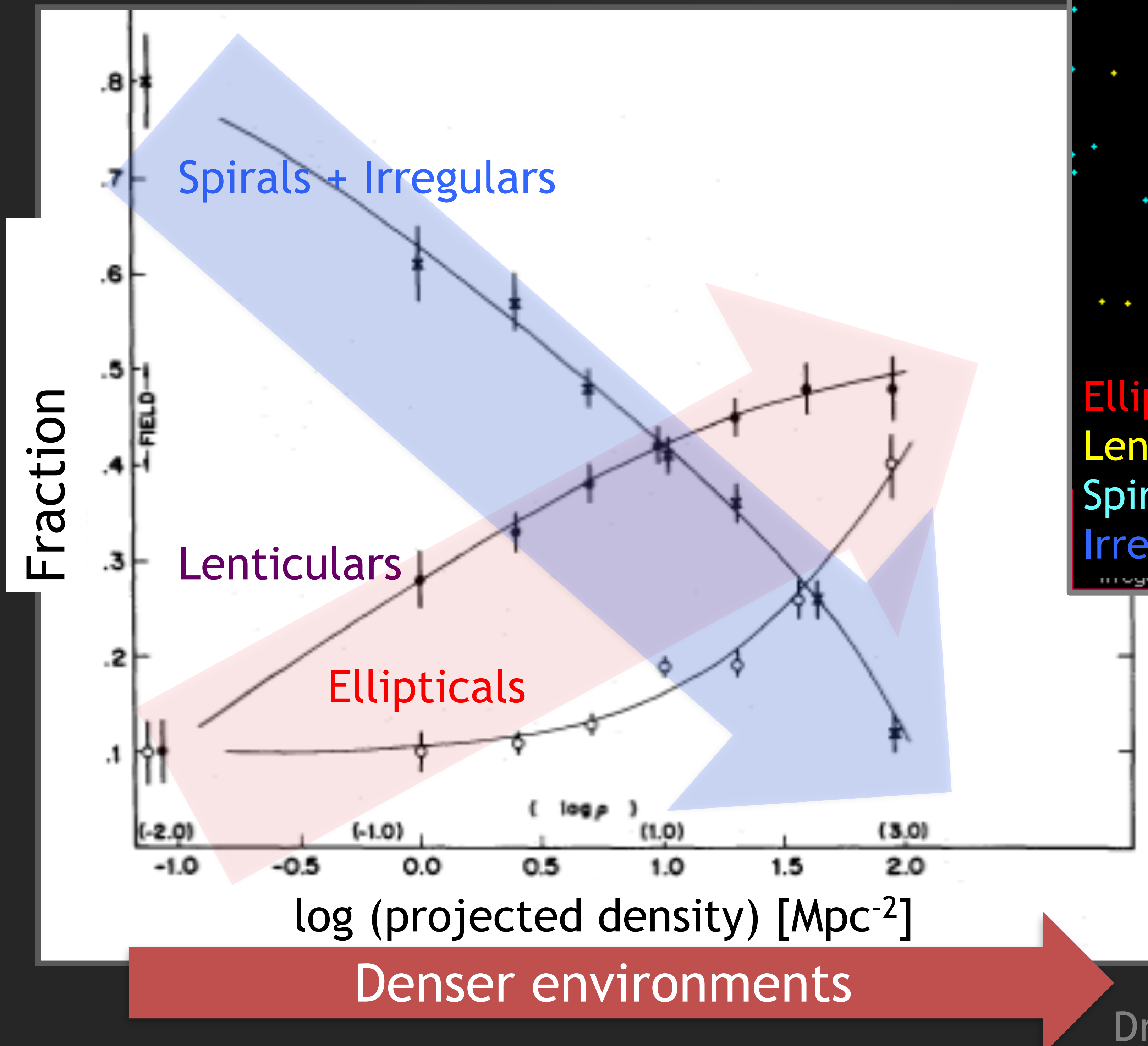

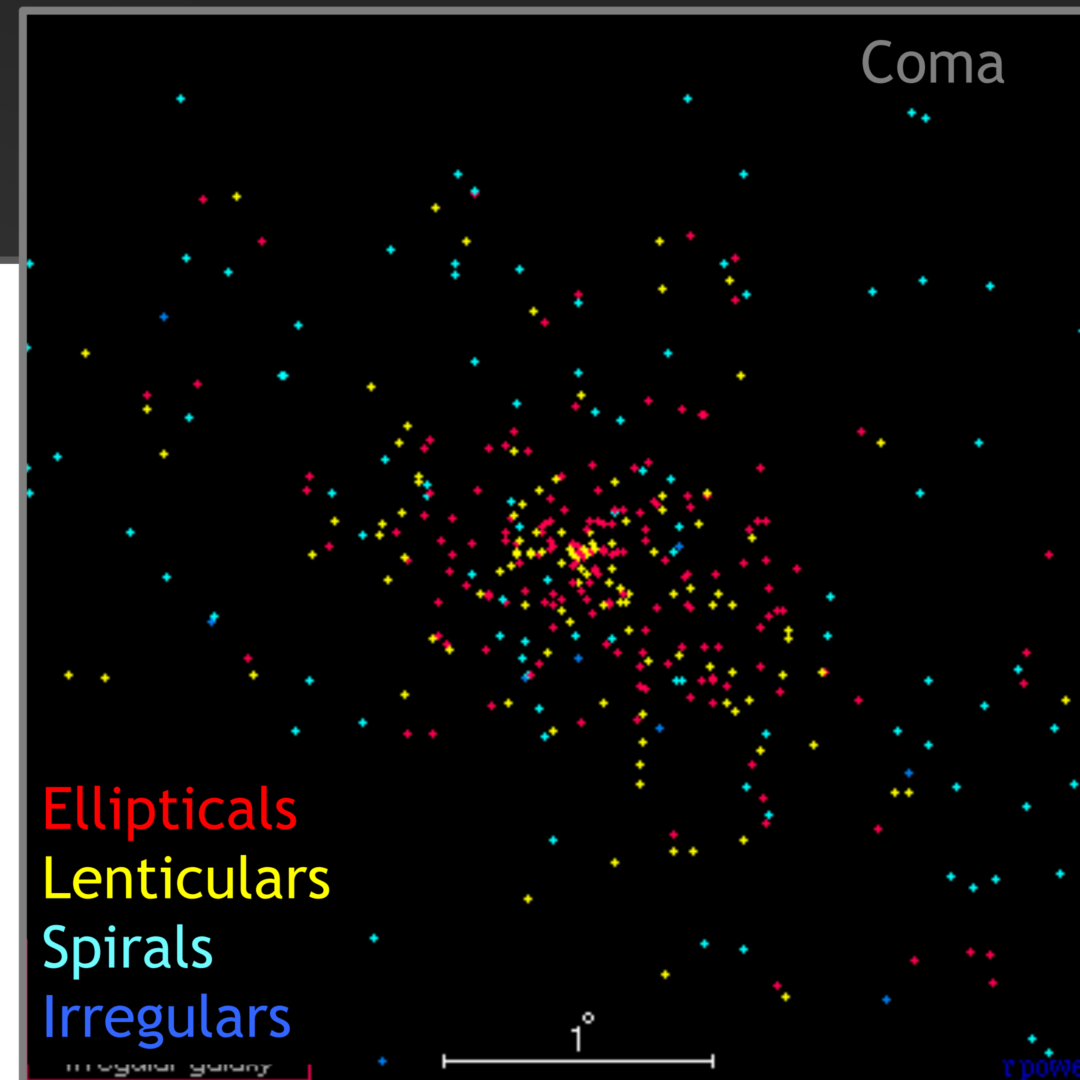

Fraction of spirals (star-forming galaxies) decreases with increasing galaxy number density

Dressler+80

What's the origin of the galaxy-environment relation? Nature or Nurture? (that is the question…)

Nature?

- The environment establishes different initial conditions for different galaxies
- Galaxies are intrinsically different from the beginning
- The formation of ellipticals occurs at high-z in the densest regions

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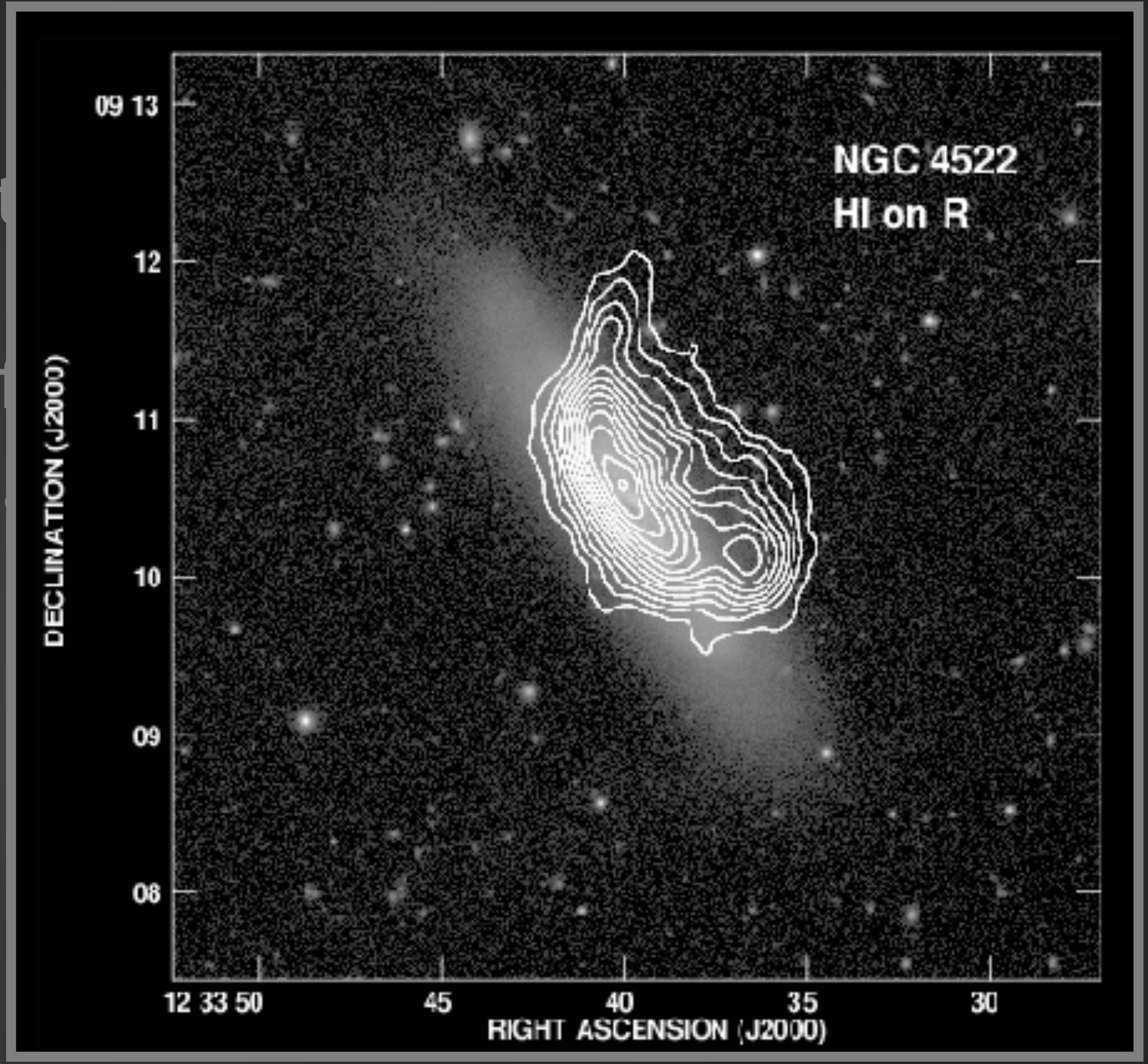

Kenney et al. 2003

Nurture?

- Galaxies follow different evolutionary paths, depending on their local environment.
- Dense environments transform actively star-formging galaxies into more quiescent galaxies via interactions and removal of gas

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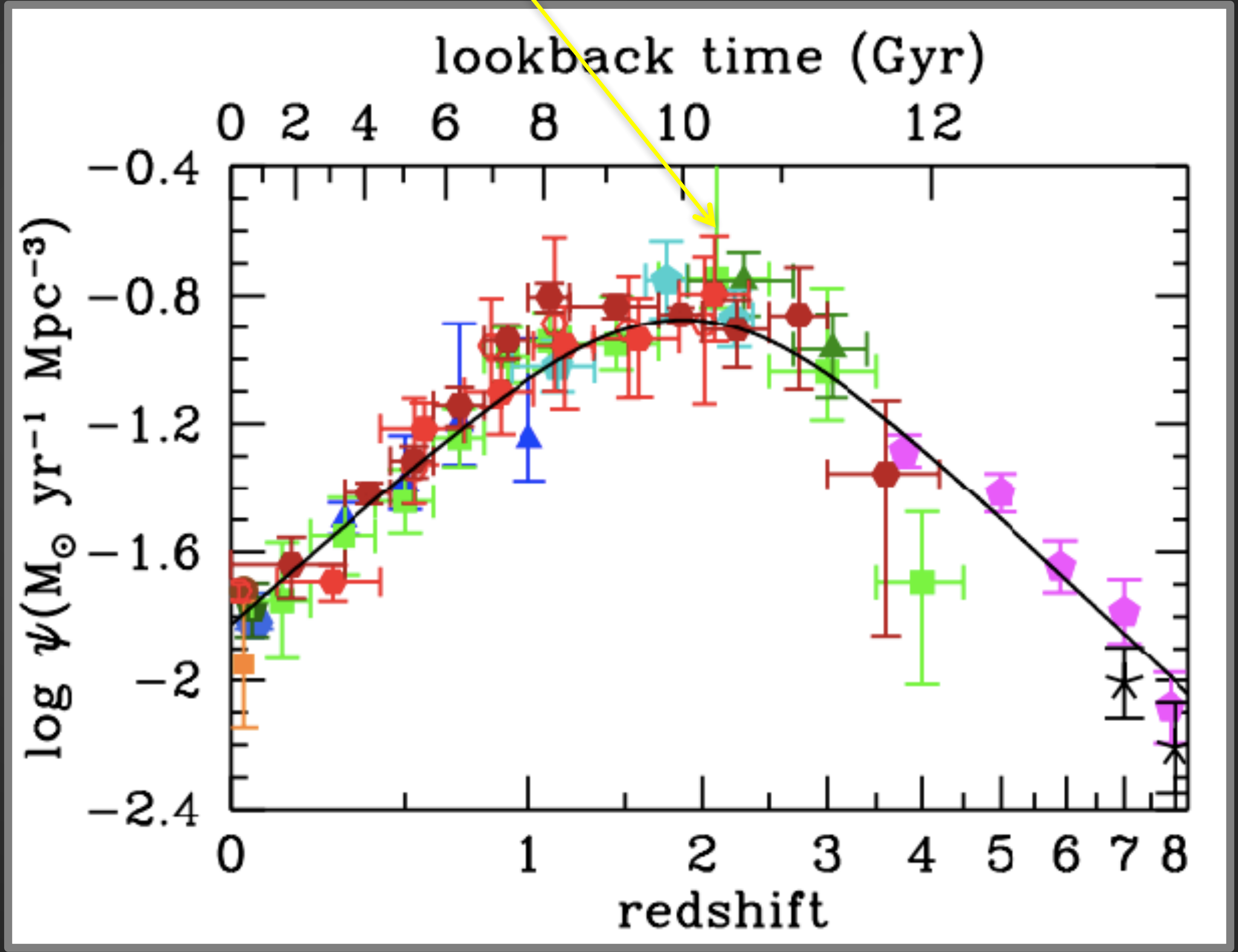
BOTH?

- There are isolated galaxies with low star formation rates

  à the environment is not the only determinant!

What's the origin of the galaxy-environment relation?

- Need to look back at the peak epoch of galaxy formation, where initial conditions likely set the stage for the establishment of the galaxy-environment relation.



Outstanding challenges remain to identify and characterize overdense regions in the distant universe.

Madau & Dickinson 2014

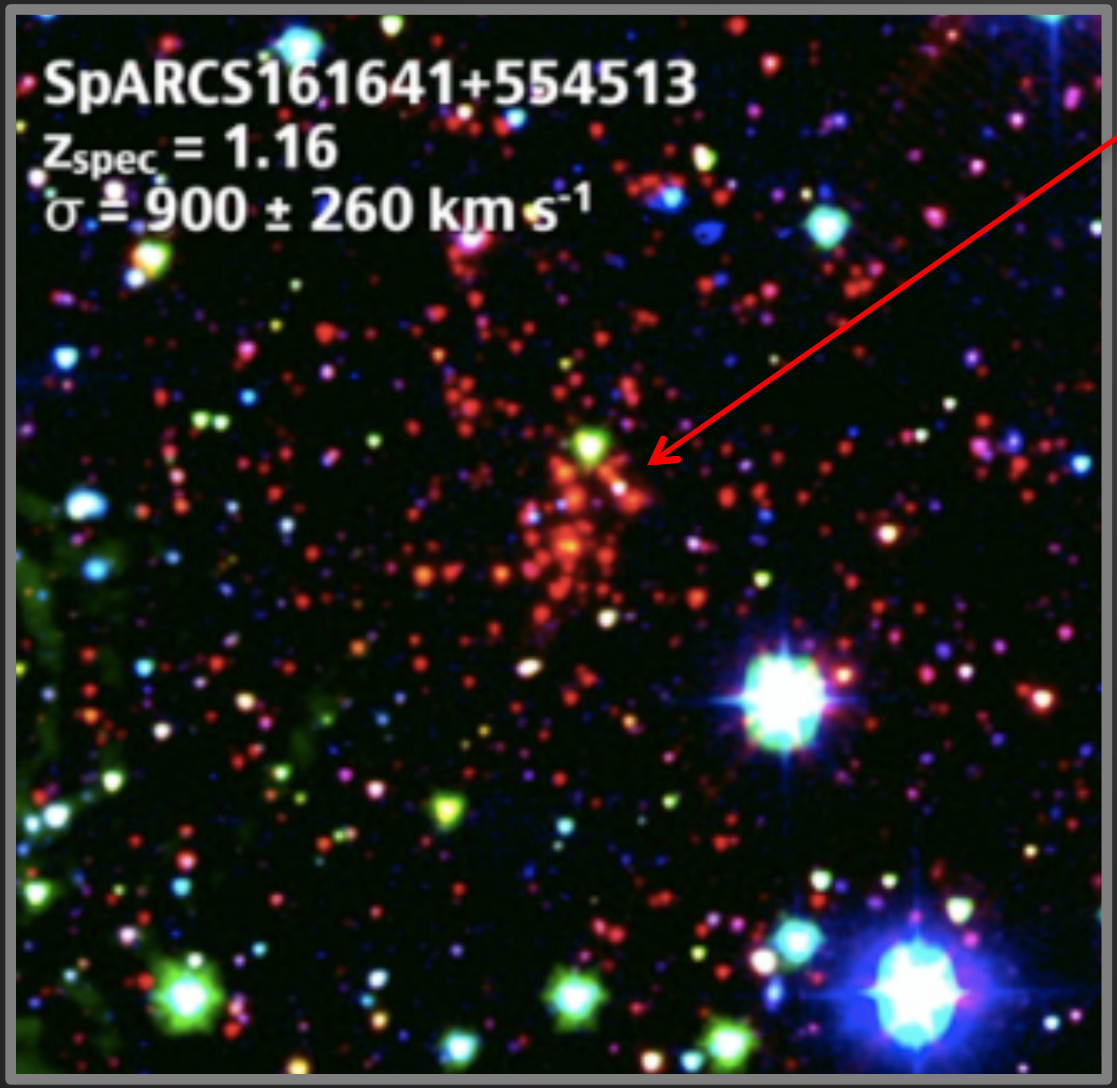
How to identify galaxy-overdense regions?

At low redshift:

① Galaxies

– Optical/near-IR/mid-IR: look for the red sequence in already-established clusters

(Gladders & Yee 2000)



SpARCS collaboration

How to identify galaxy-overdense regions?

<u>At low redshift:</u>

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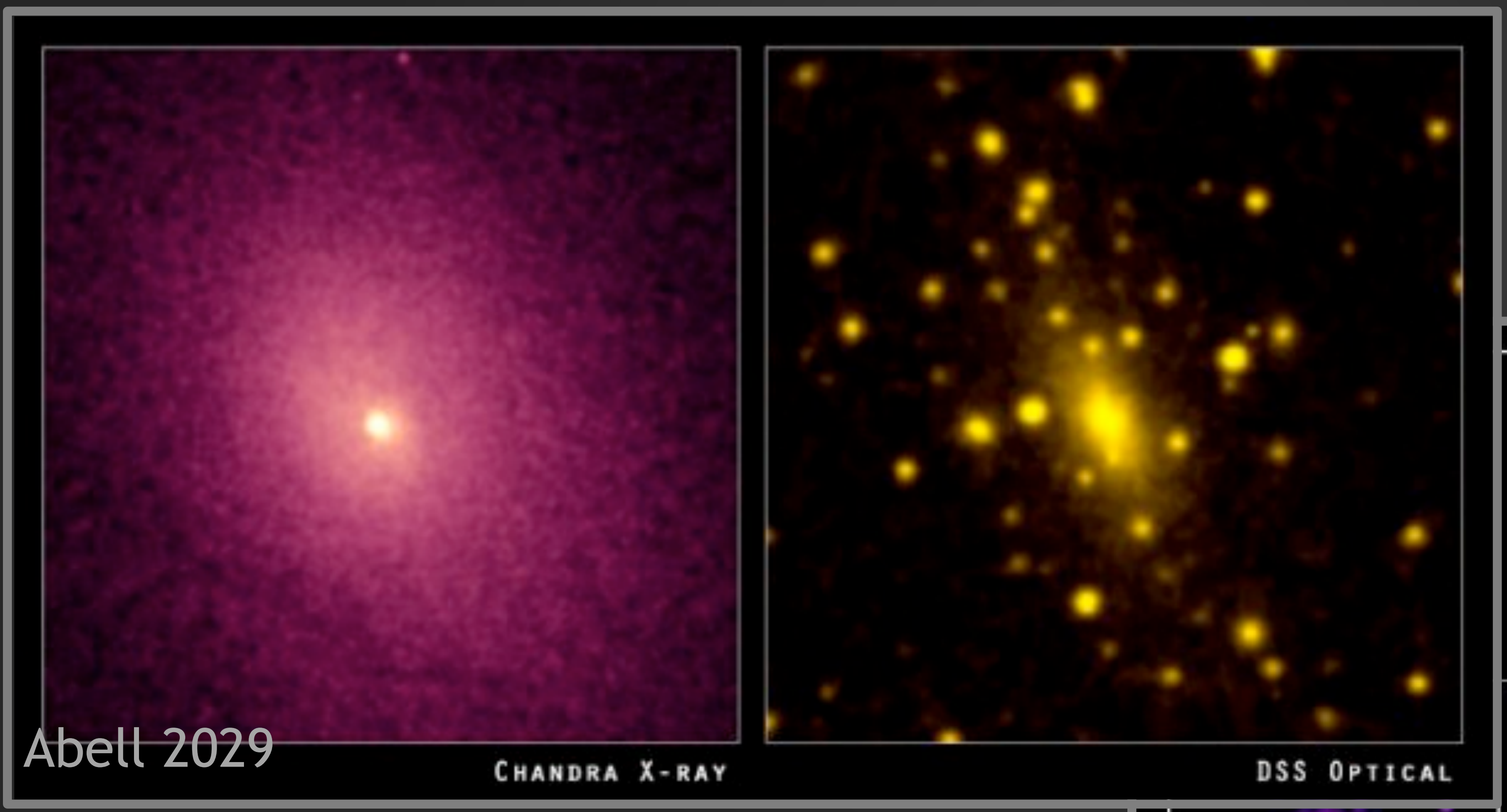
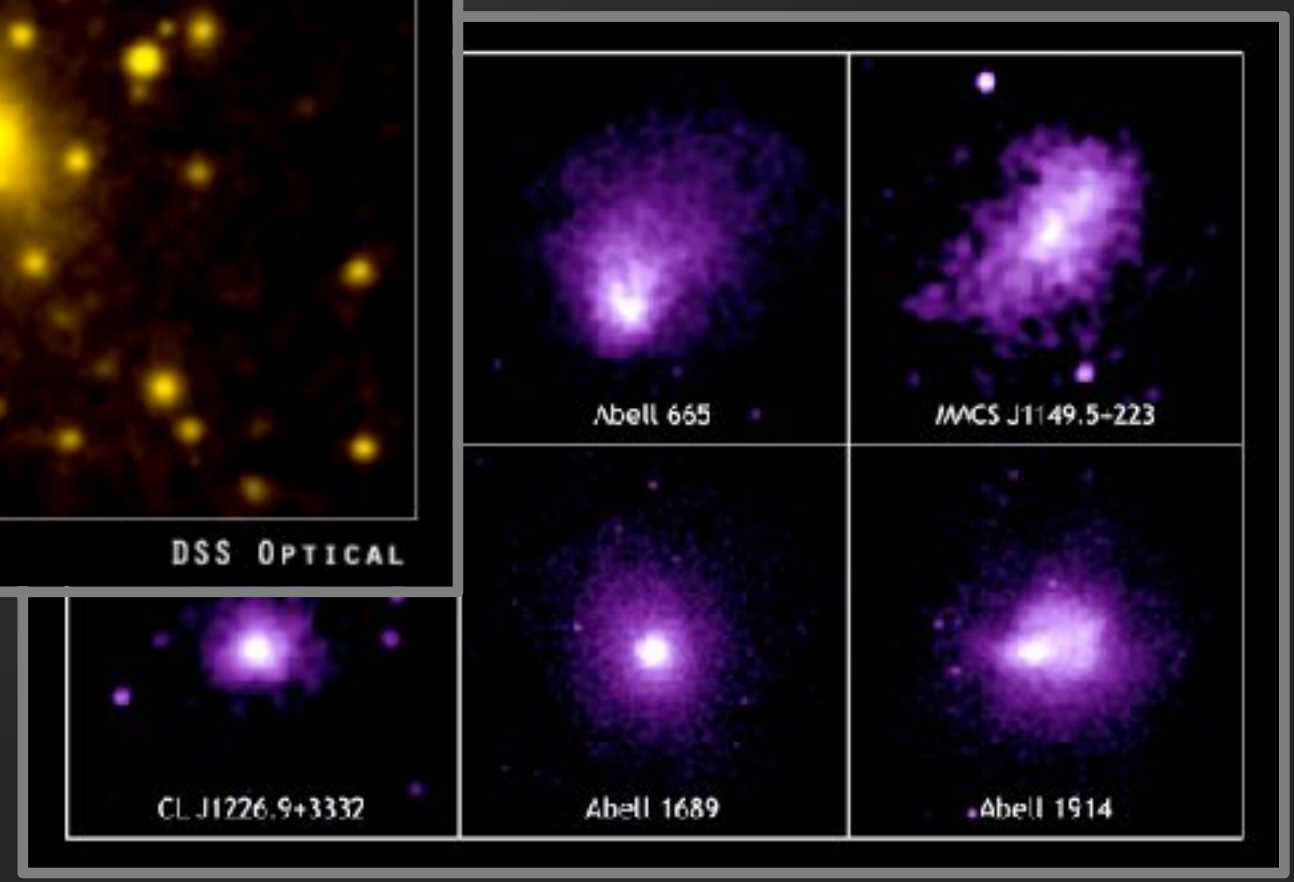
② Gas

– X-ray: trace the hot intracluster gas (e.g., Chandra, XMM)





Chandra images
Credit: NASA/CXC/MSFC/M.Bonamente et al.

How to identify galaxy-overdense regions?

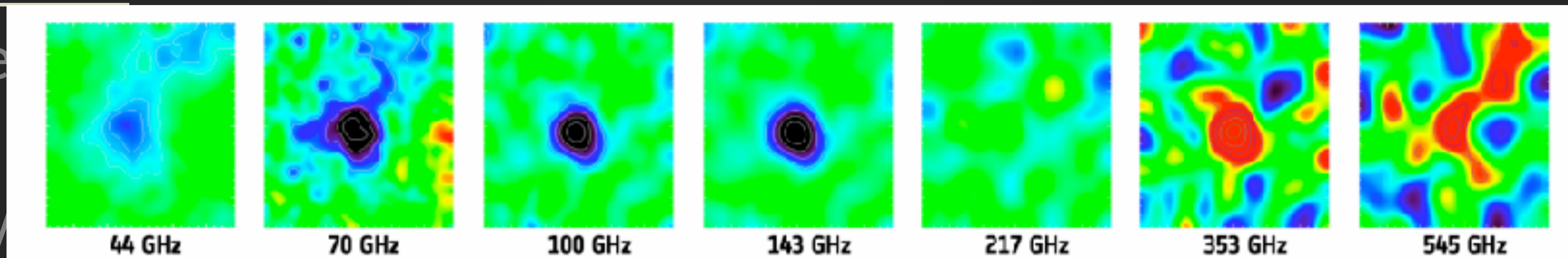
At low redshift:

Abell 2319 Planck/ESA

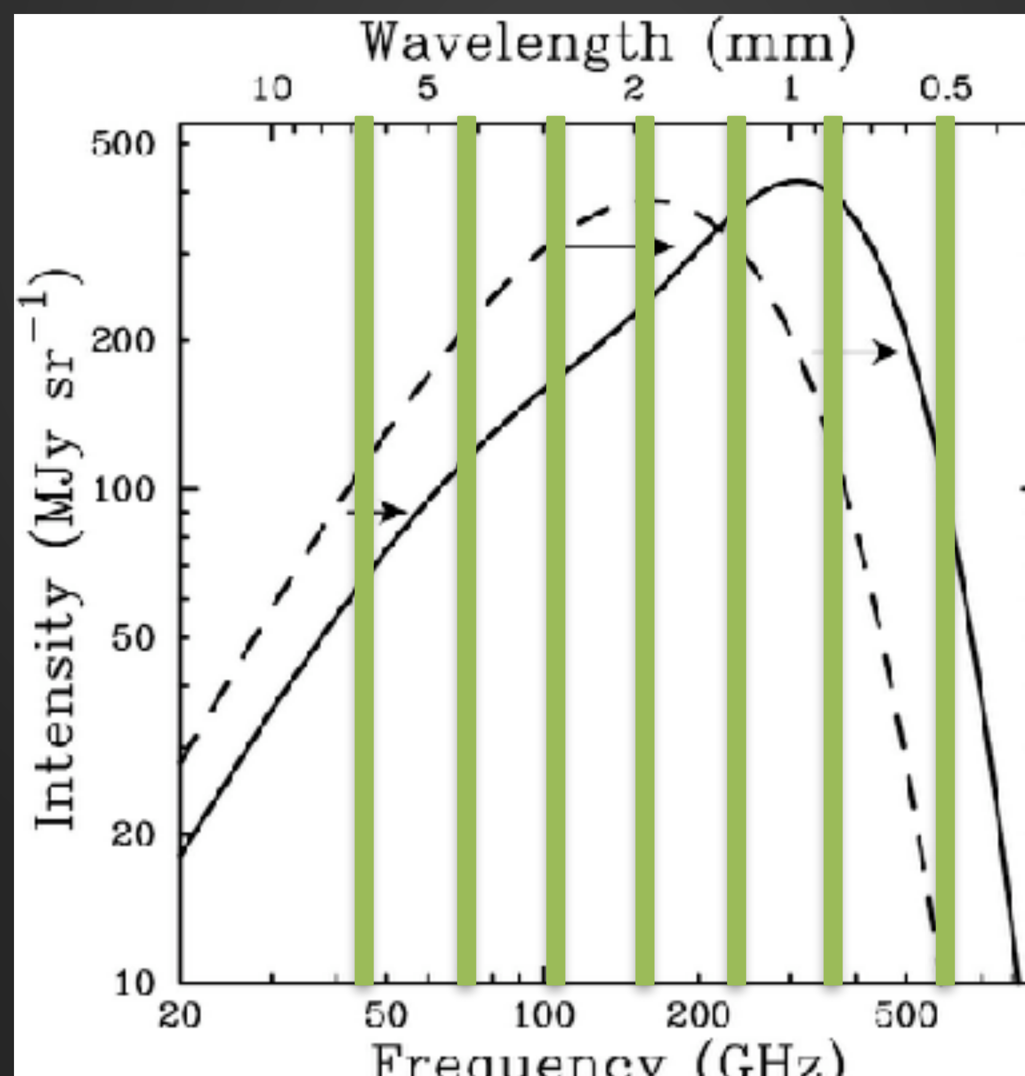
① Galaxie

② Gas

– X-ray



– Sunyaev-Zeldovich effect using CMB experiments (SPT, ACT, Planck)



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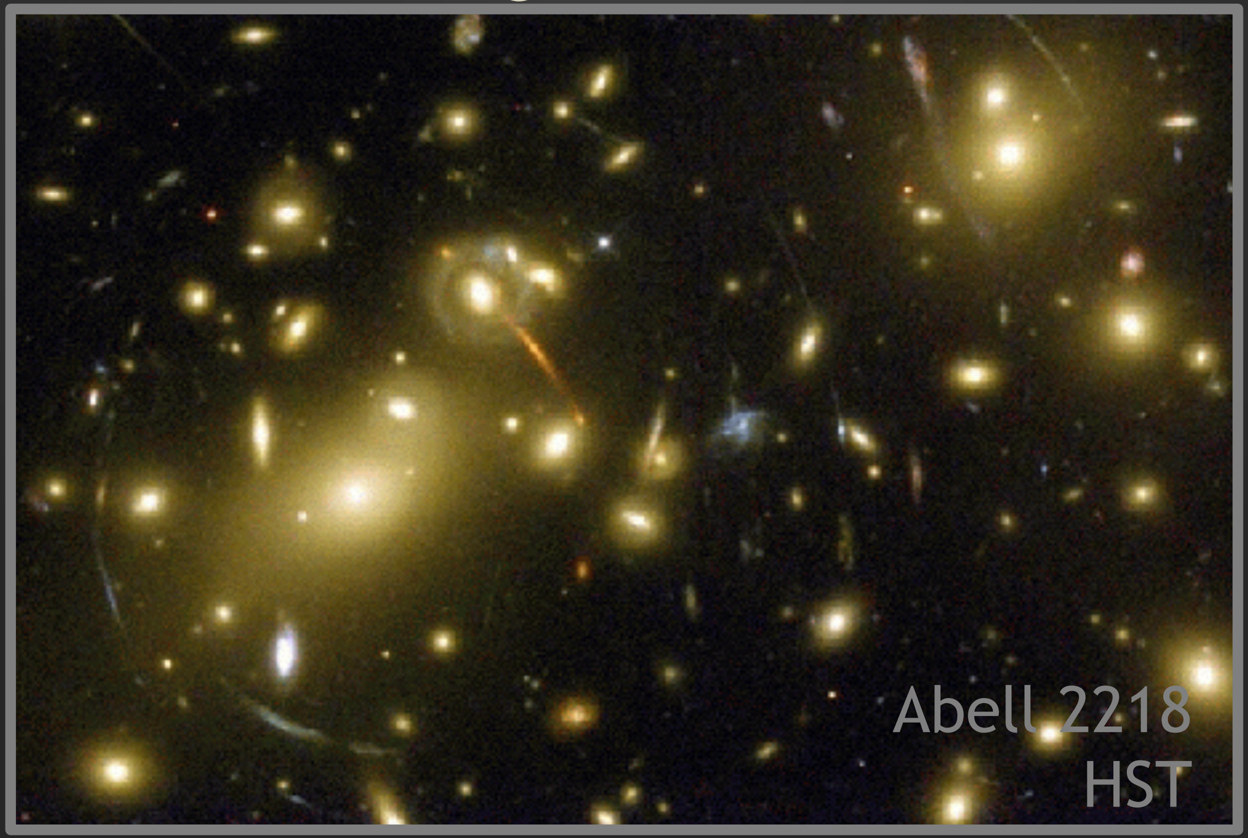
③ Gravitational lensing

- Currently expensive, but, e.g., ESA's Euclid mission, ~2020



NASA/ESA

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No perfect approach... out to z~1-2

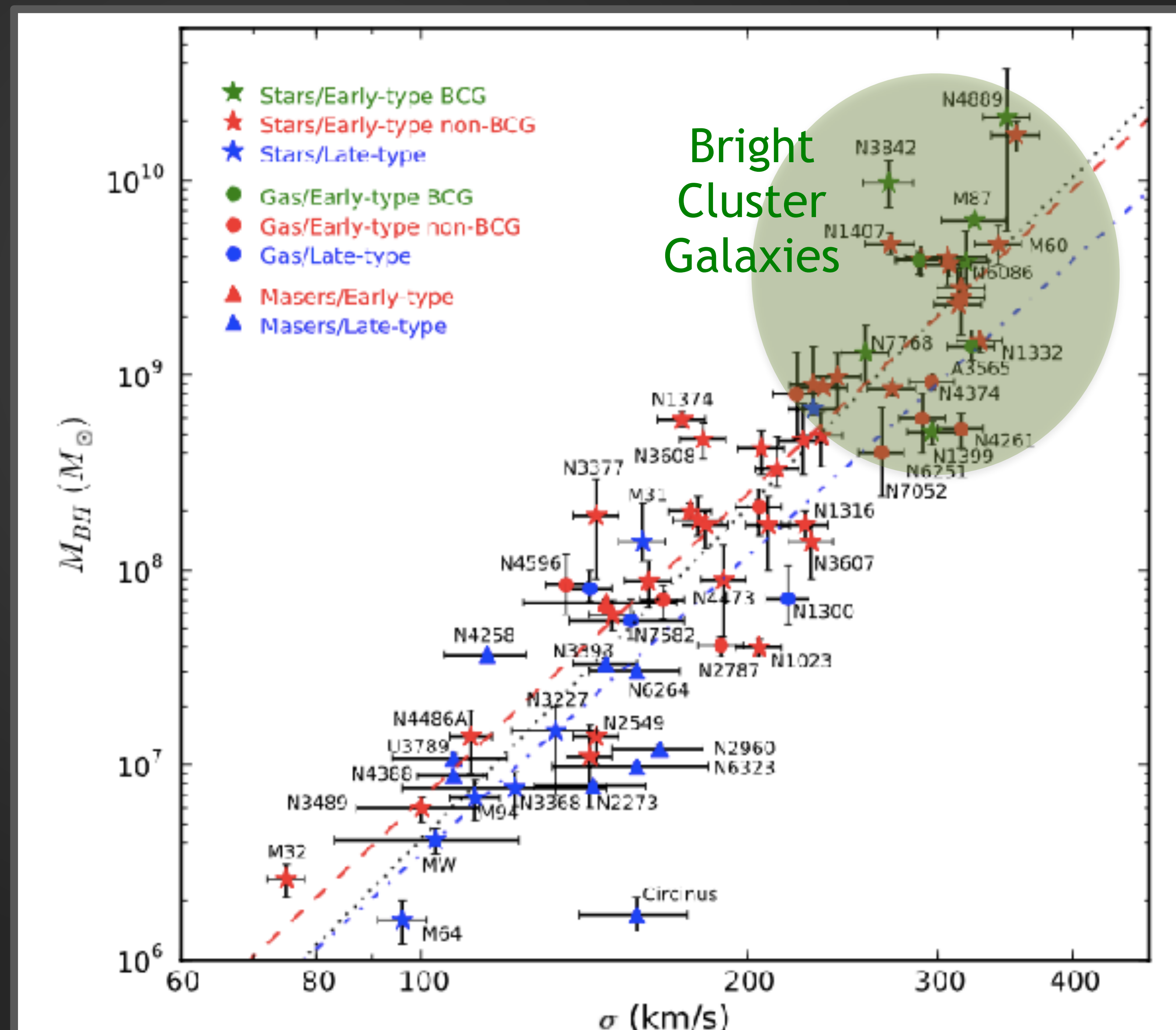
(though extending further with follow-up of SZ-detections)

By the nature of these techniques, (most of) of these clusters are already "formed"

Protocluster tracers at higher redshifts

- Radio galaxies and quasars have been used to map the large scale structure at z ~ 2-5 (e.g., Venemans+02, Kurk+04, Overzier+05)

Largest black holes (and biggest galaxies) at high redshift, so likely progenitors of BCGs!



McConnel & Ma 2013

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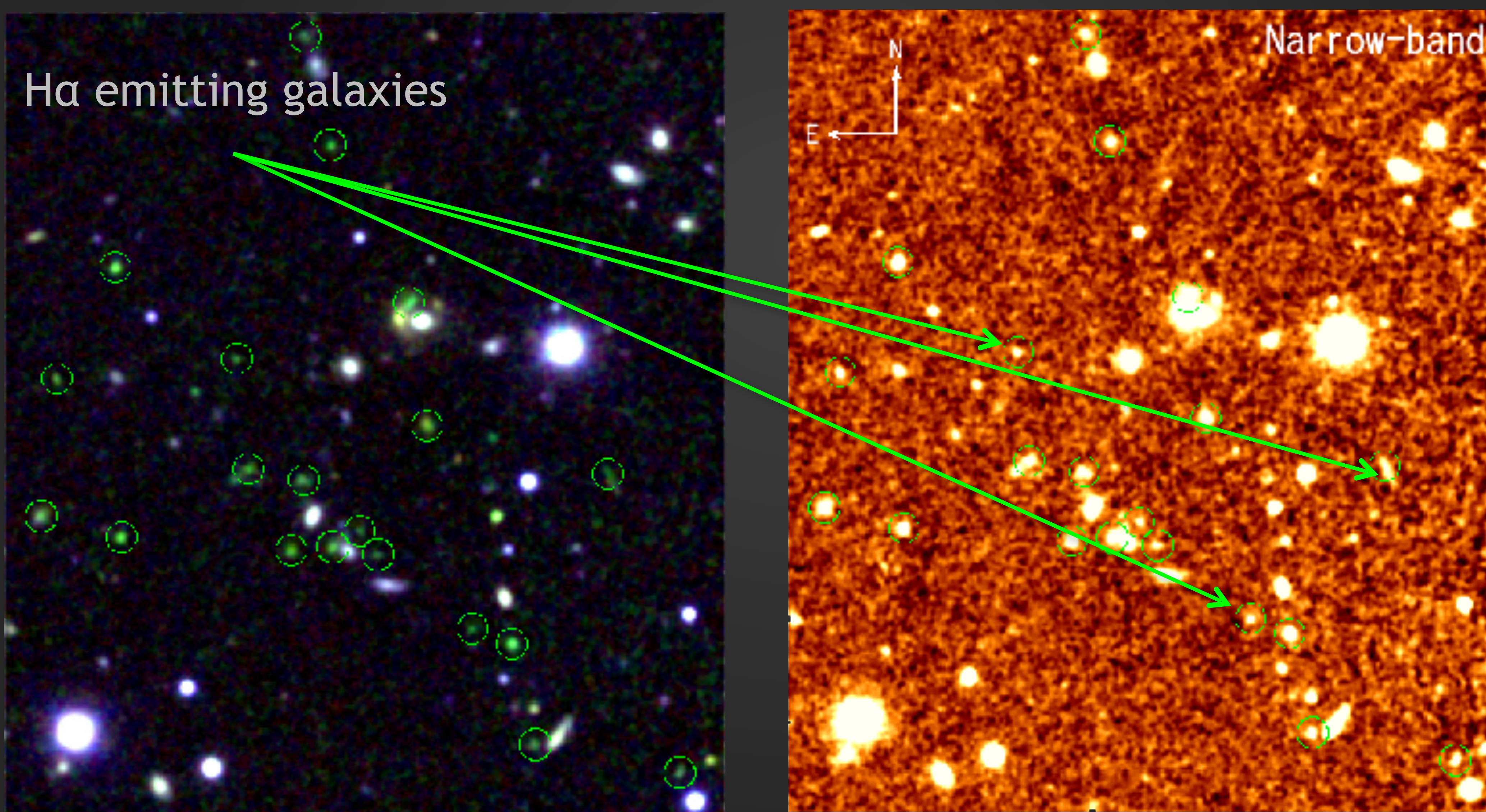

Protocluster at z~2.2 around radio galaxies with Subaru Telescope (Shimakawa+14)

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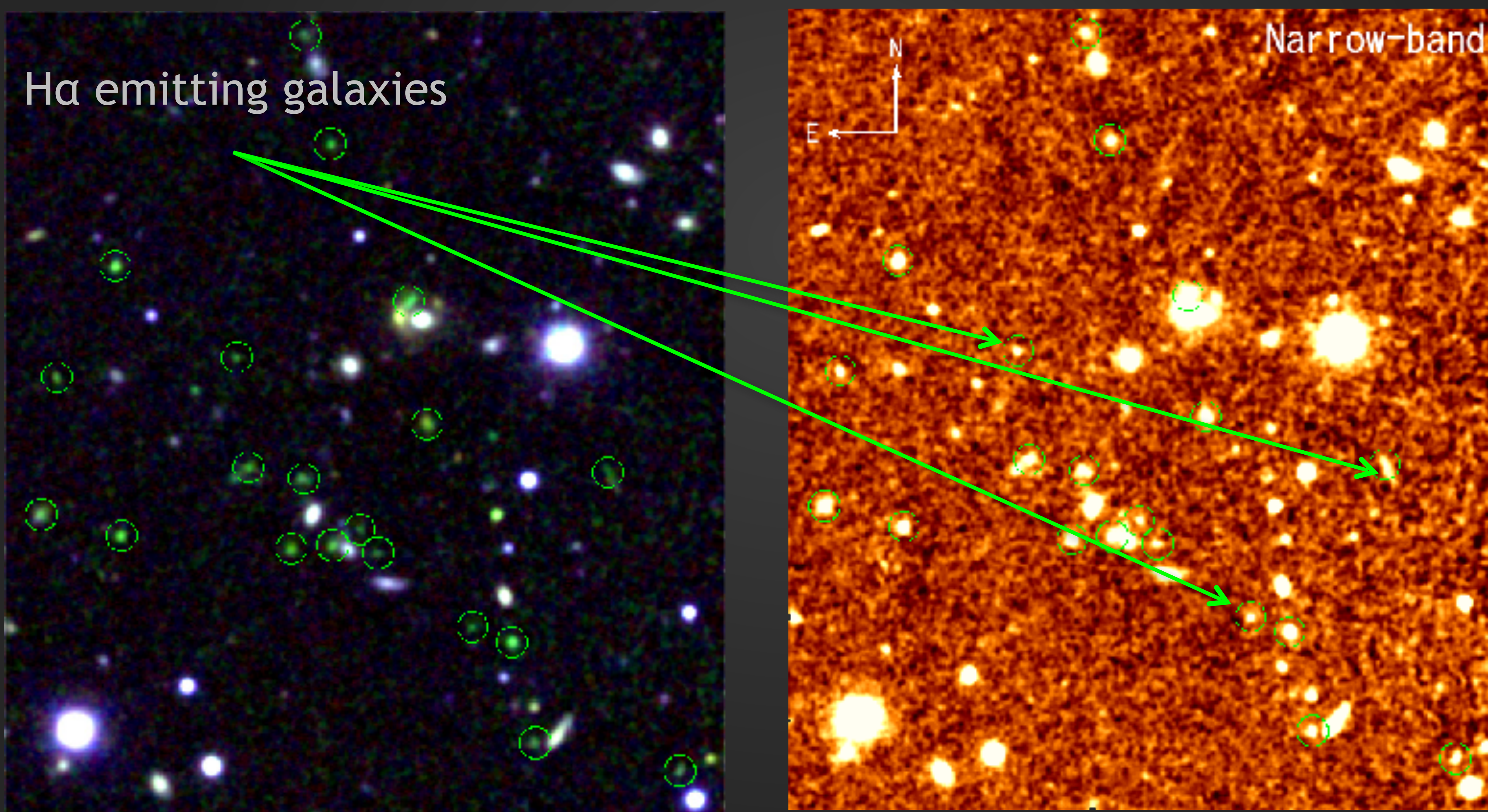

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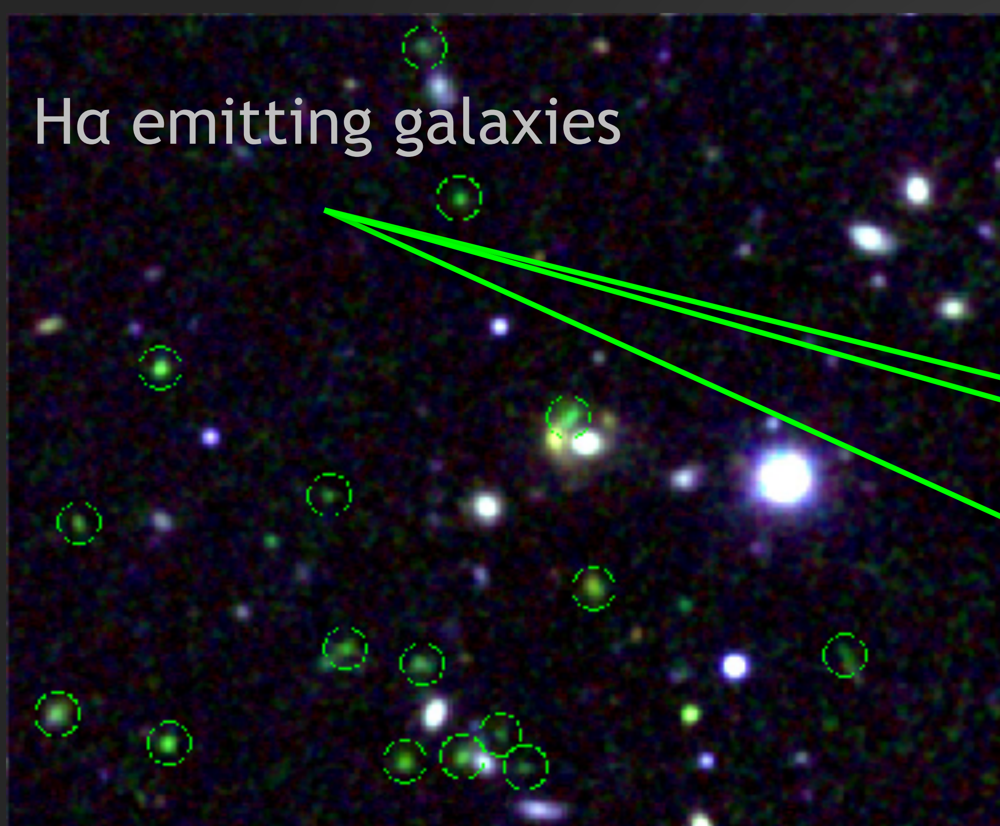

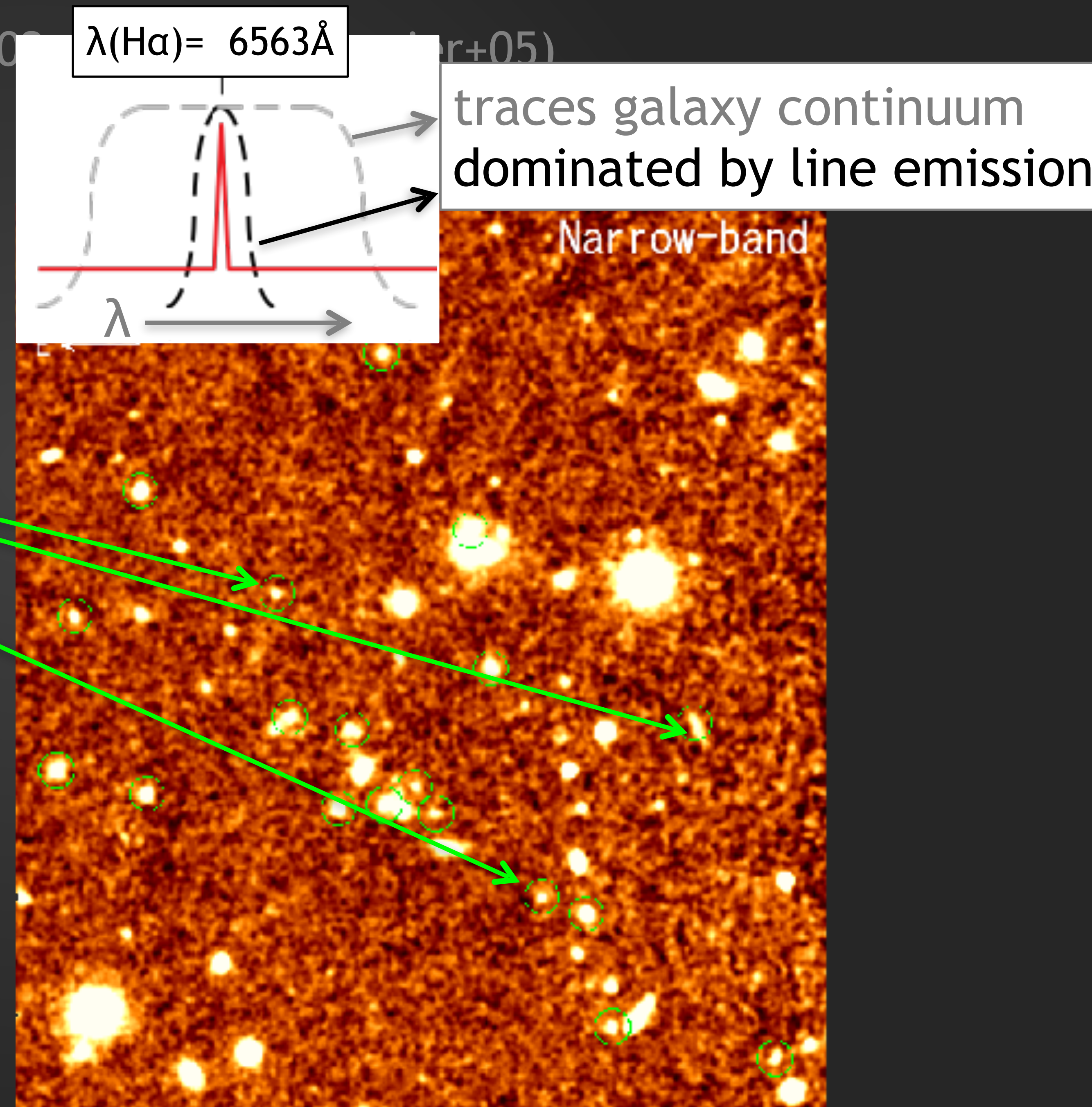

Approach:
Look for "more normal" galaxies in the vicinity of these tracers

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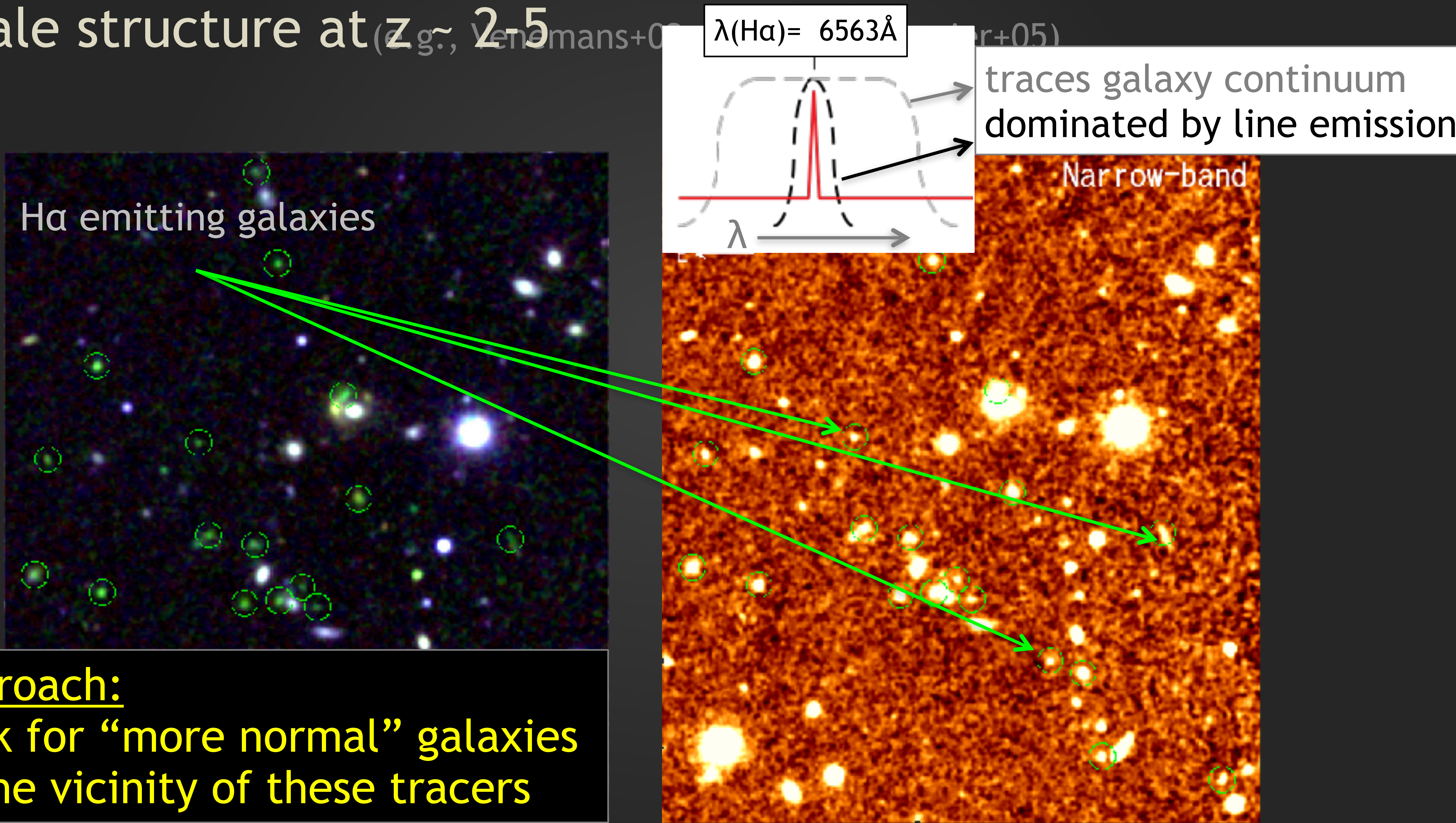

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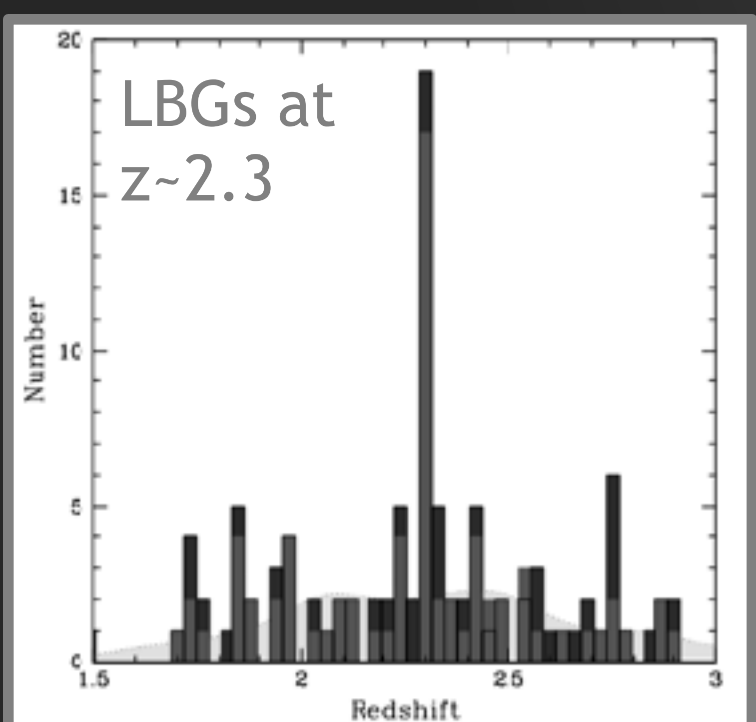
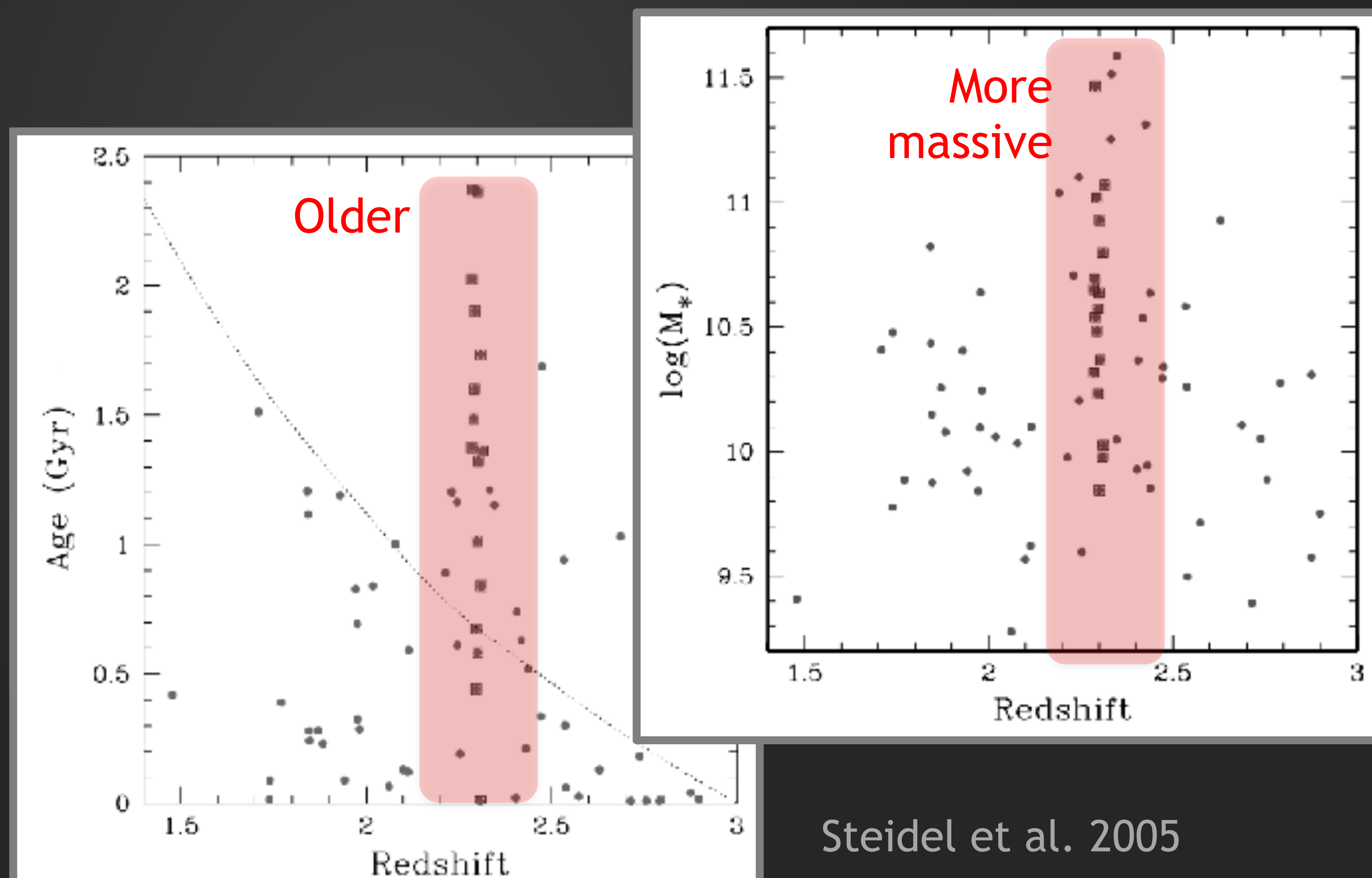
- Protocluster galaxies are already more evolved than those in the field → accelerated formation in dense regions

Already evidence for enhanced evolution





Steidel et al. 2005

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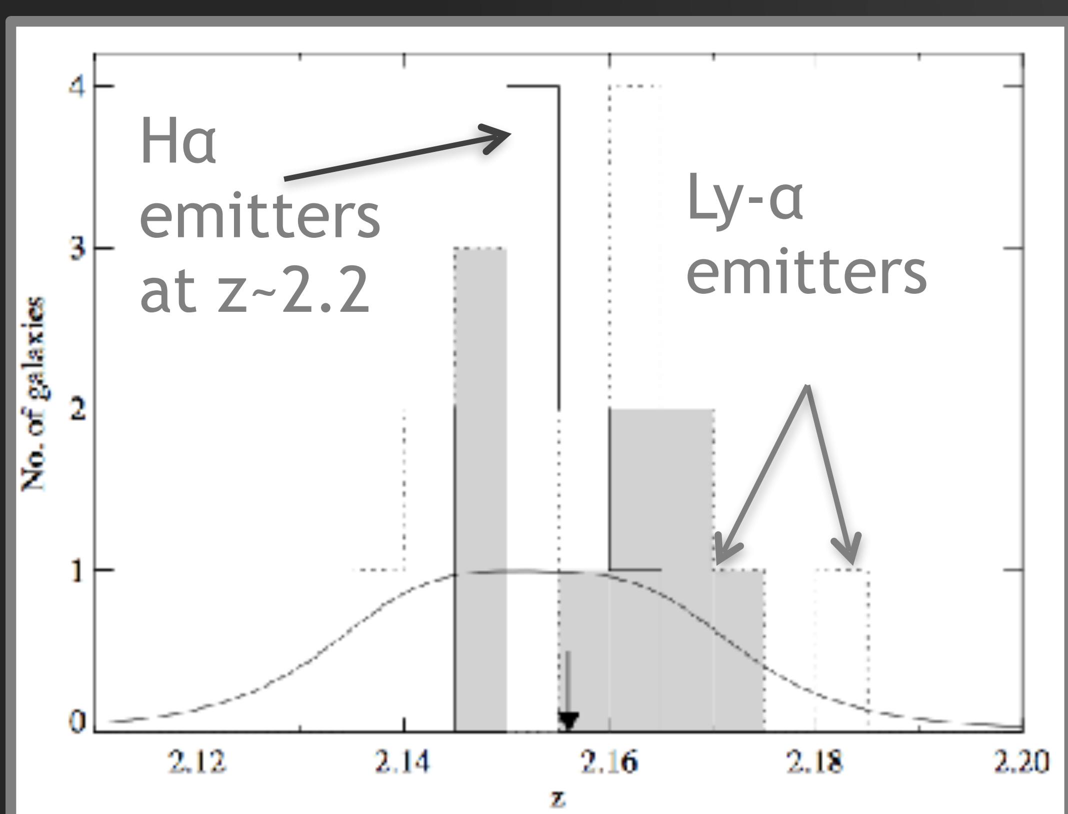
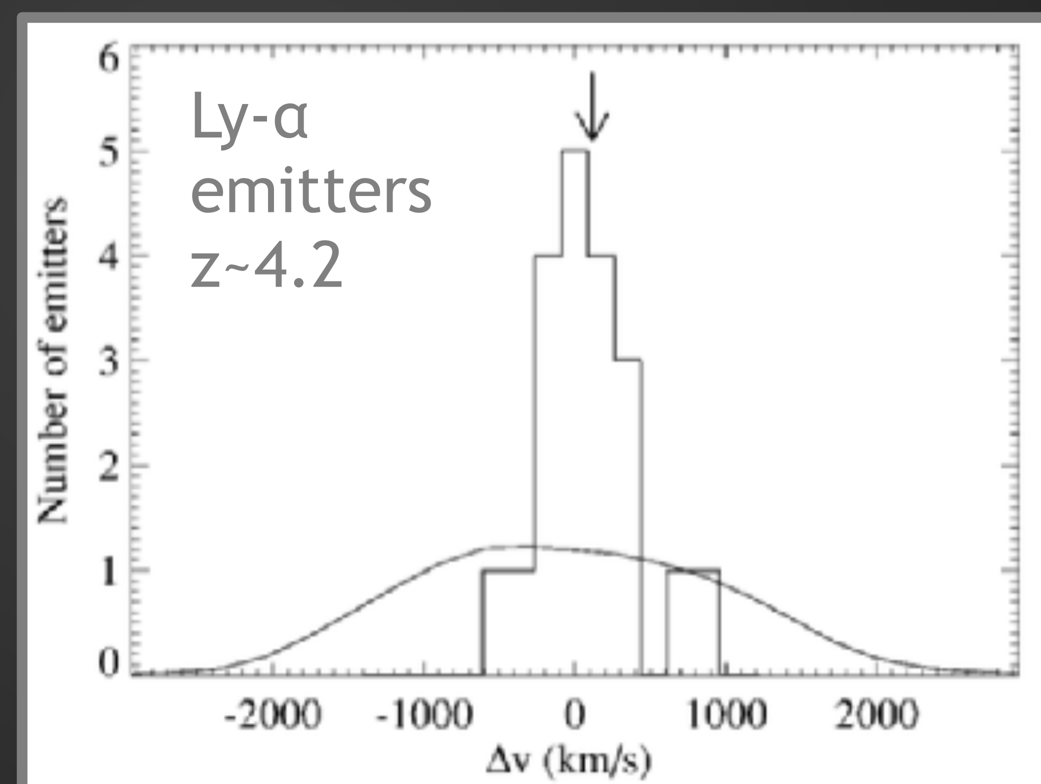
Quite successful approach



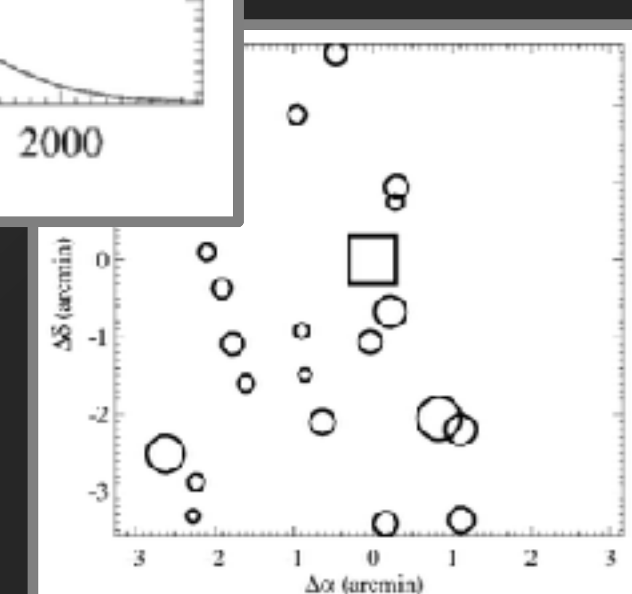
Around radio galaxy PKS 1138-262

Kurk+04



Around radio galaxy TN J1338-1942

Venemans+02



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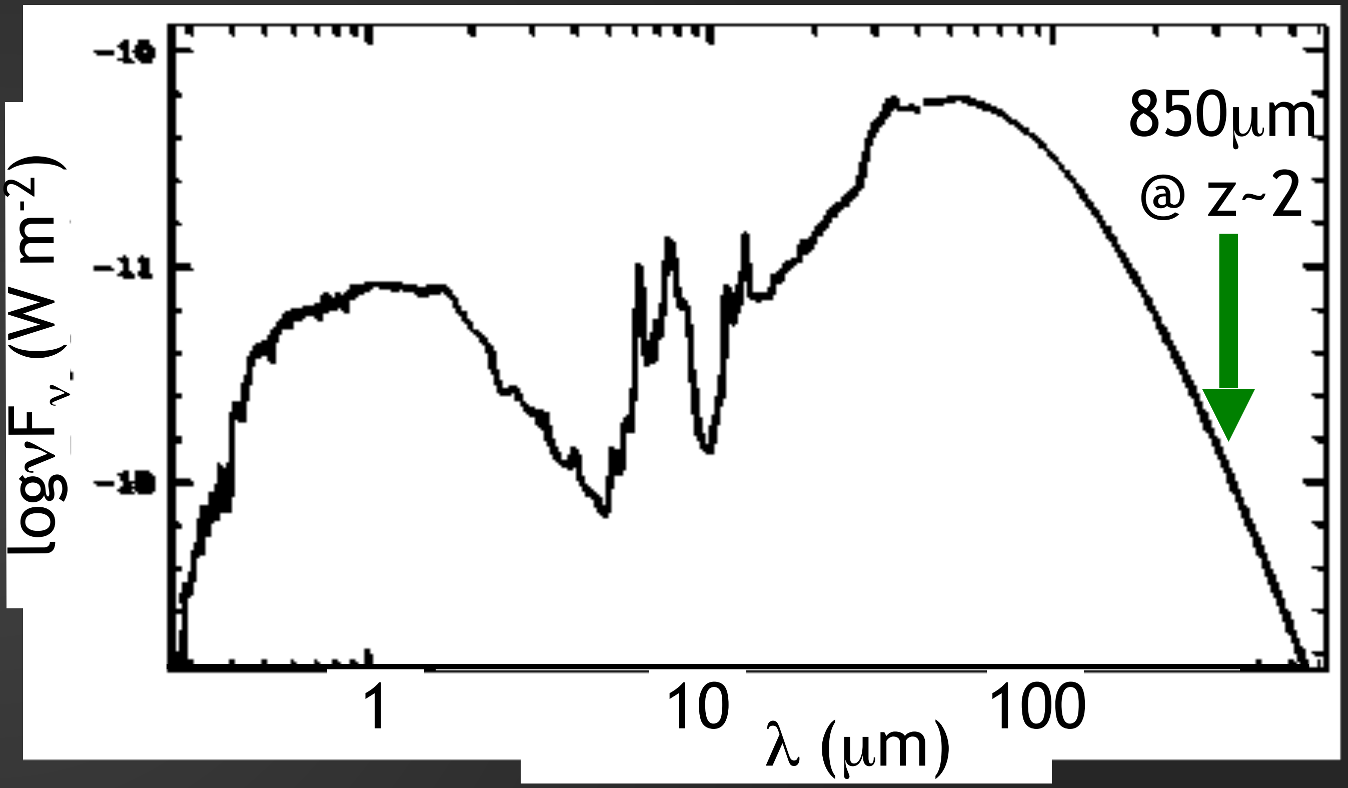
HOWEVER:

1. These tracers represent a short stage in the life of a galaxy (~ 10^7 years)
2. Radio fluxes drop with redshift
   – strong observational bias towards more evolved structures

Many additional forming clusters… We need more abundant (somewhat less extreme) tracers!

High-Redshift Ultra-luminous Galaxies – untapped tracers of large-scale structure

- More abundant than QSOs by a factor of ~5-10 (Chapman+03+05, Coppin+06)
  - Submillimeter-selected ULIRGs



Kennicutt+03

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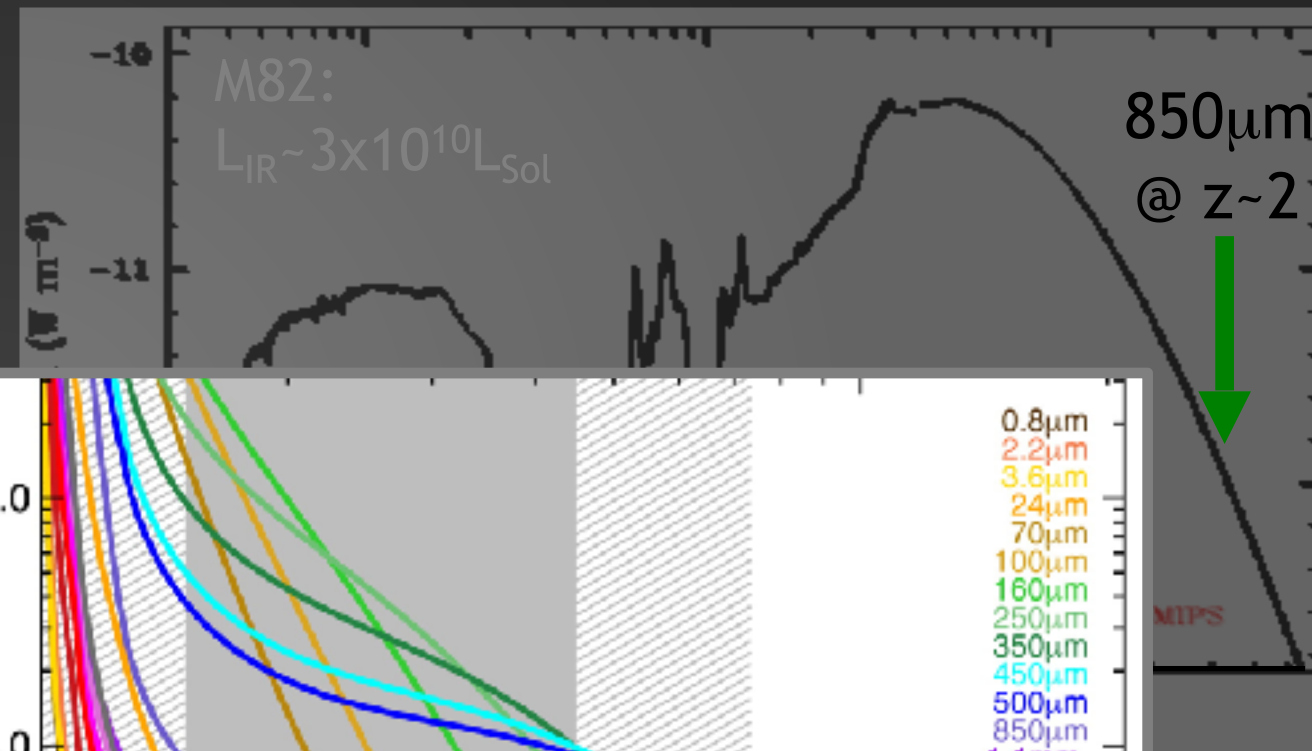
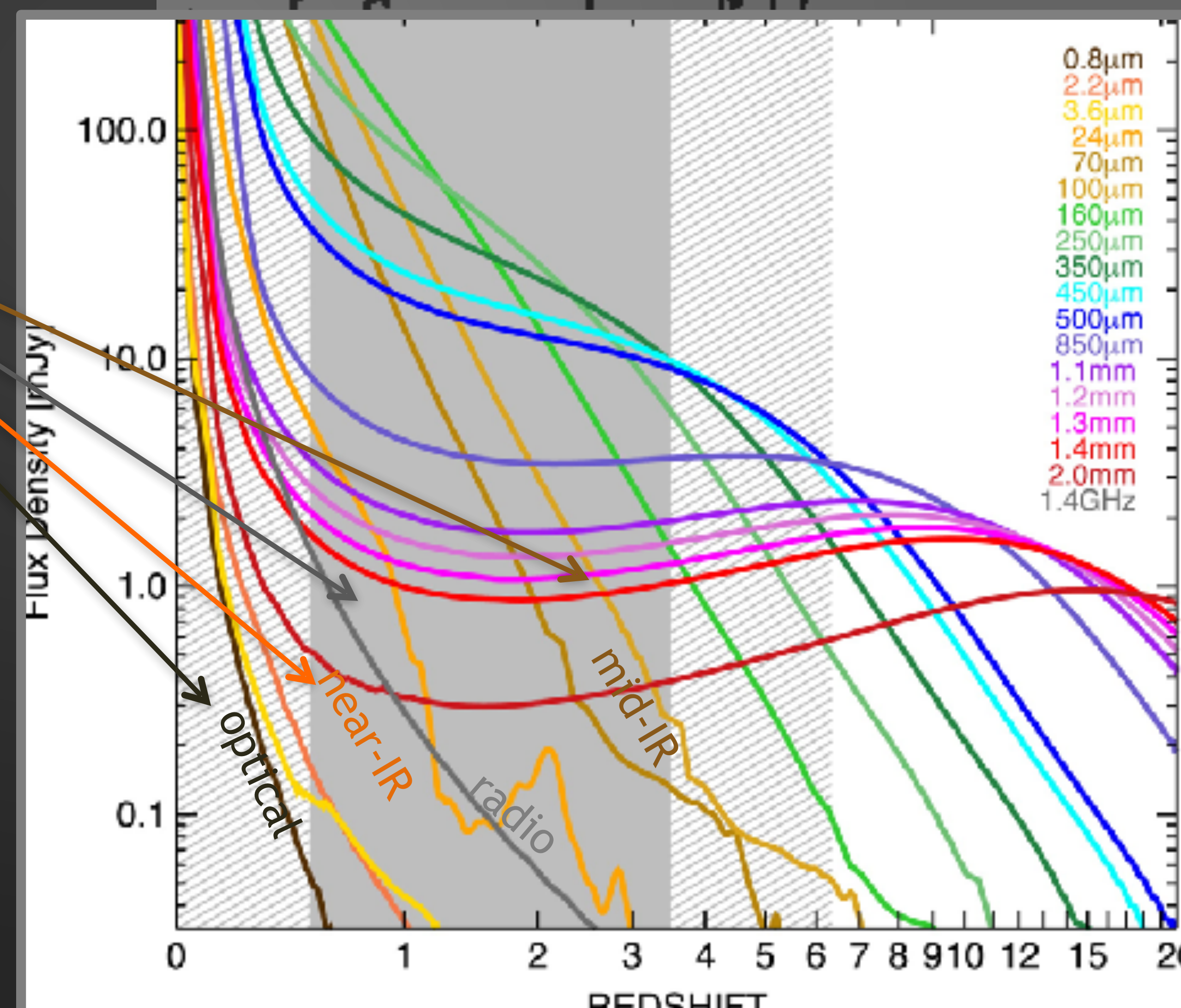


Why is the submm selection so special?

- "Normally", the further a galaxy is, the fainter it appears



Casey+14

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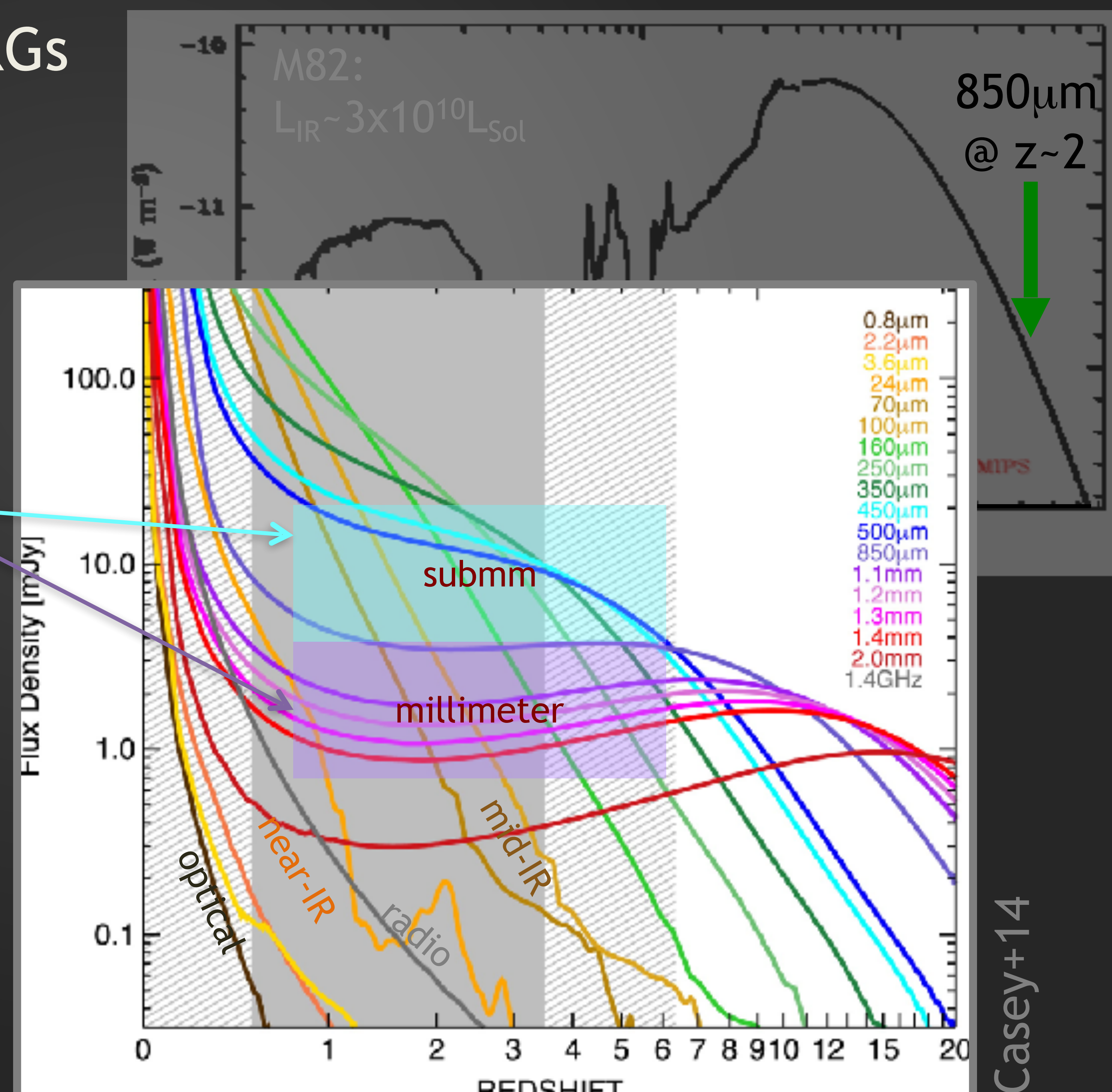
- (negative) K-correction in the submm/mm beats the odds!
  - As we search for galaxies further and further away, the submm/mm flux stays approximately the same!

SMGs are just as submm-bright at z~1 as they are at z~5 → key to inspect the very distant universe!



Submm Galaxies: Signposts of Protoclusters

(an on-going investigation…)

Co-Is: Peter Capak (Caltech, EUA), Andrew Blain (Leicester, UK), Kartik Sheth (NRAO, EUA), Thiago S. Gonçalves (Valongo/UFRJ), Claudia Scarlata (U. Minnesota, EUA), Aldée Charbonnier (Valongo/UFRJ), Harry Teplitz (Caltech, EUA), Paulo A. Lopes (Valongo/UFRJ)

Keck LRIS

Palomar LFC

Magellan IMACS

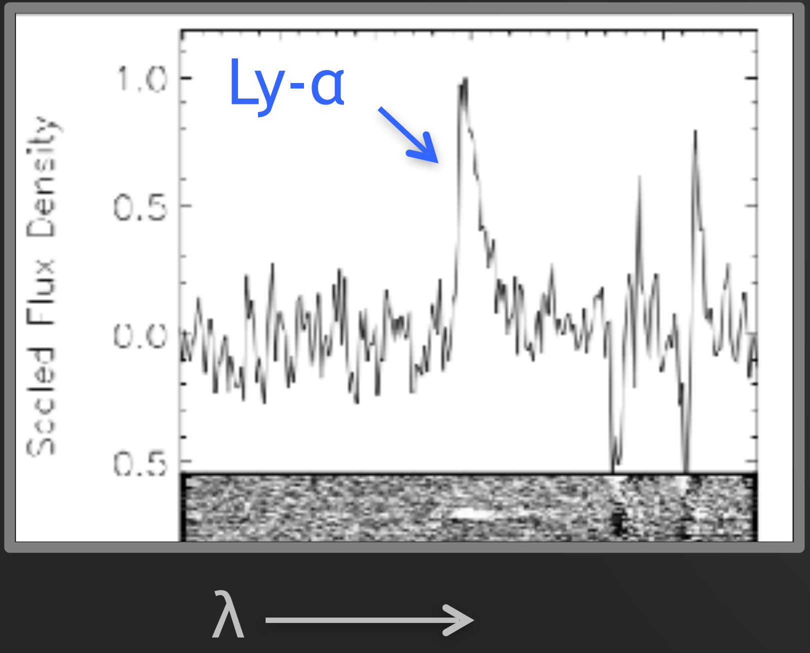
Submm Galaxies: Signposts of Protoclusters

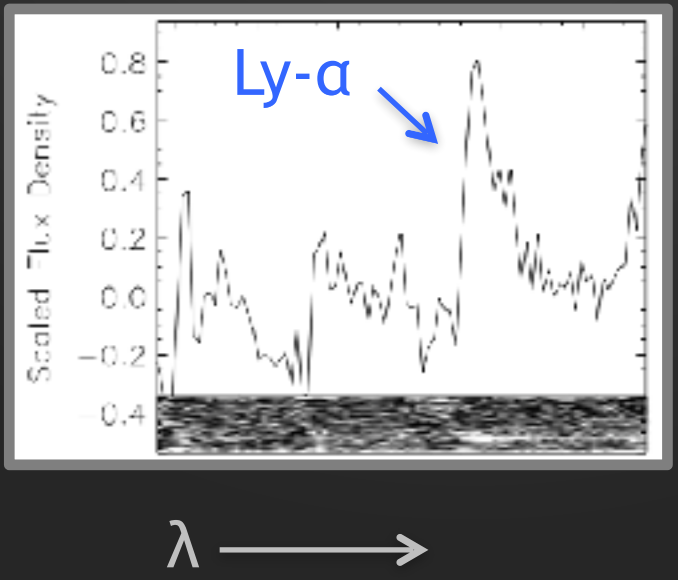
(an on-going investigation…)

- We target candidate overdensities at z~1-5
  - > 4 Gyr during which a protocluster slowly approaches virialization

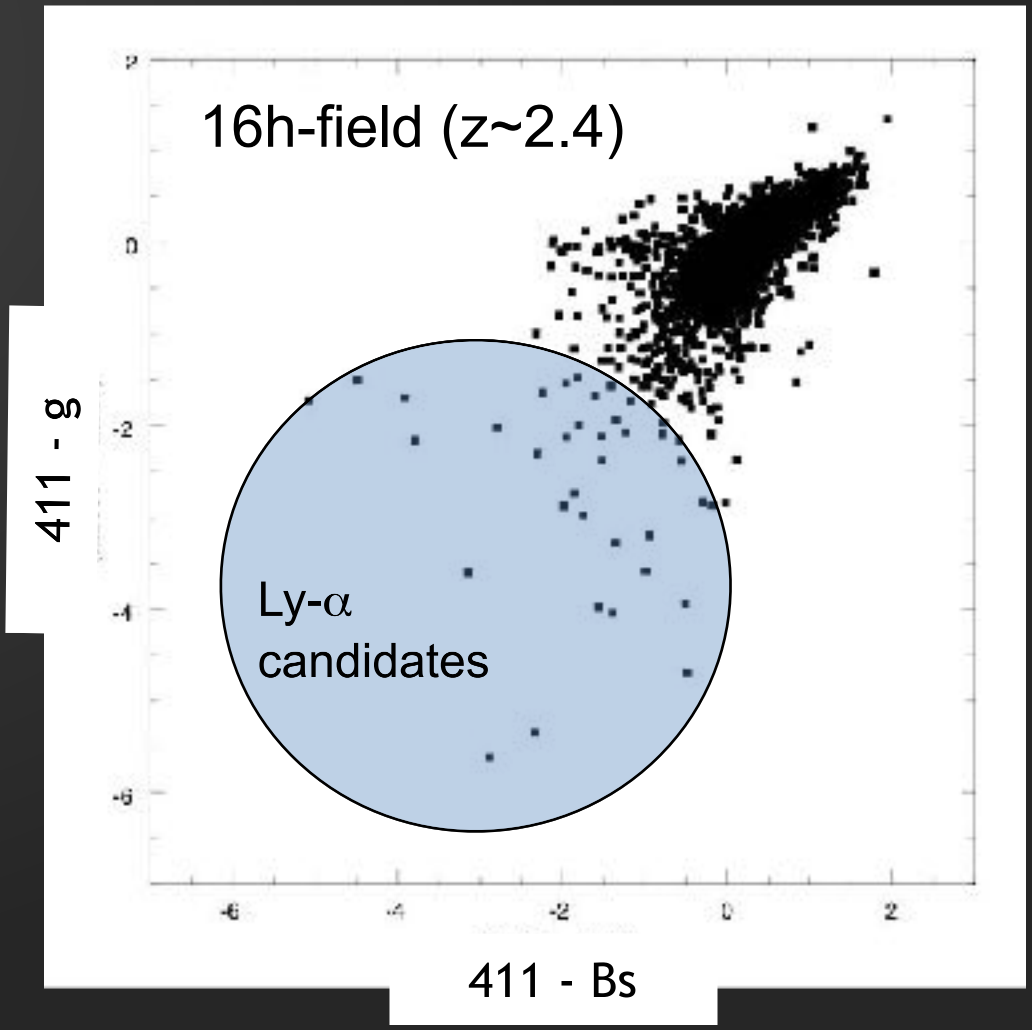
Steps

① Identification of overdensity members





Narrow-band selection of Lyα emitters



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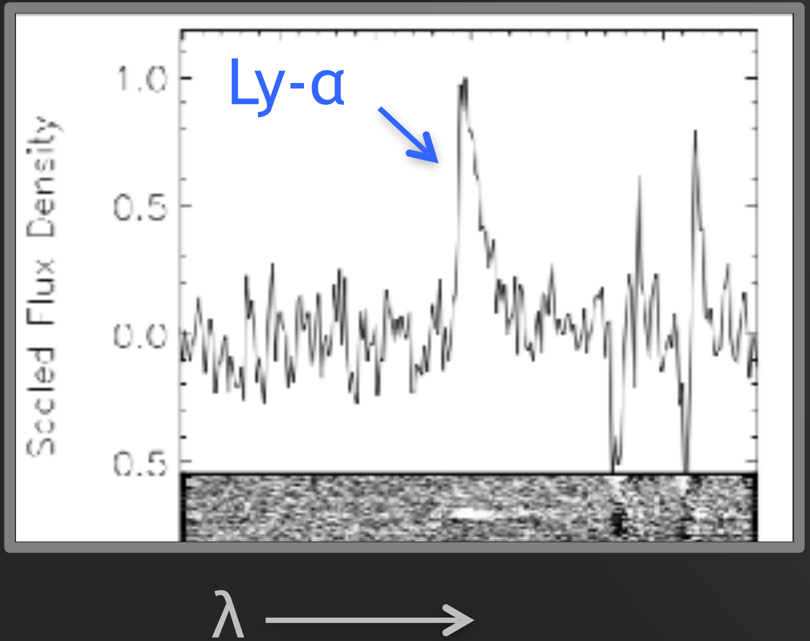

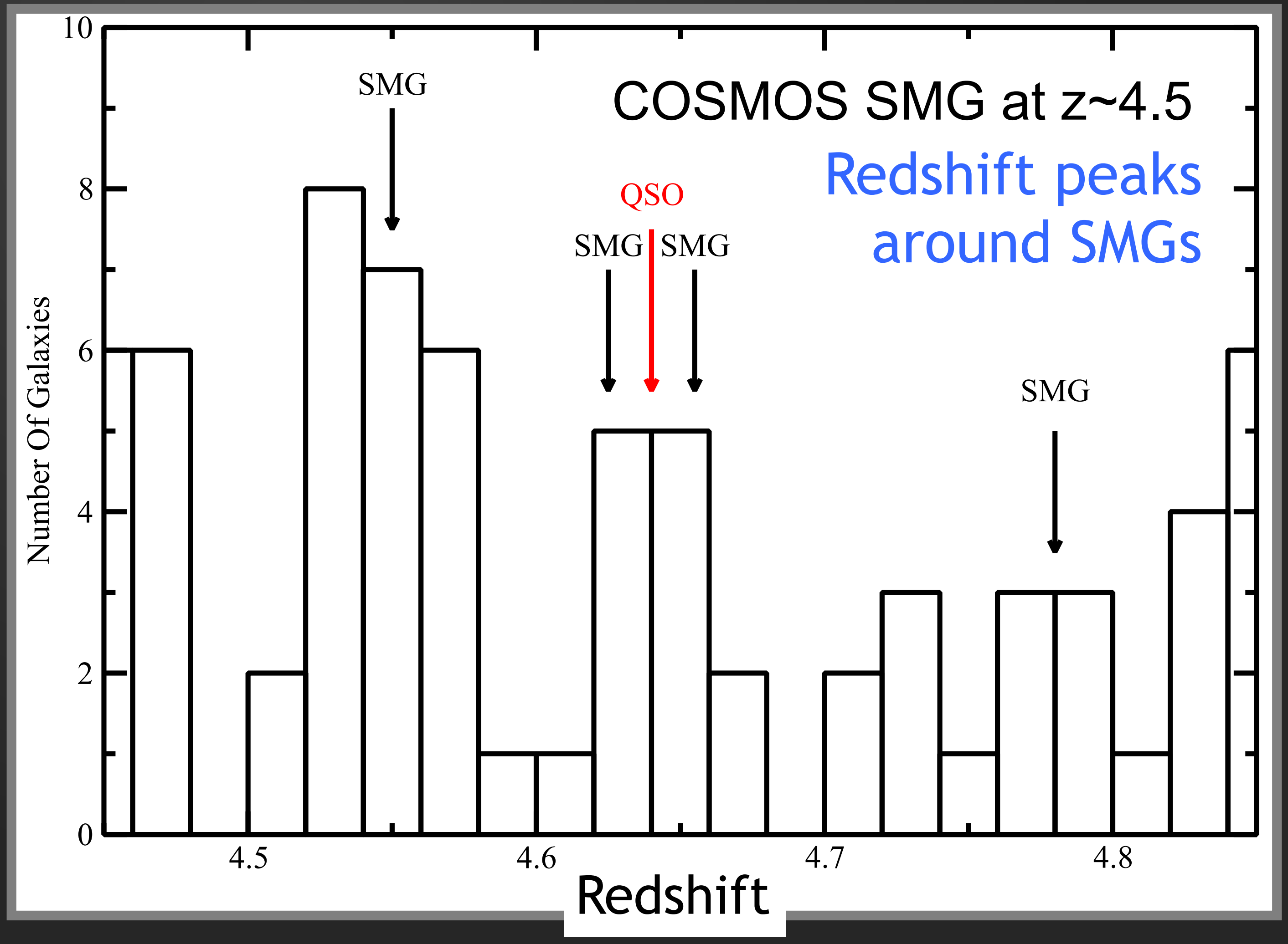

Submm Galaxies: Signposts of Protoclusters

(an on-going investigation…)

- We target candidate overdensities at z~1-5
  - > 4 Gyr during which a protocluster slowly approaches virialization

Steps

① Identification of overdensity members

② Characterization of overall significance of the overdensity

– use studies of Lyα emitters in the field (i.e, outside of overdensity) at similar redshifts as a control comparison

(e.g., Large Lyman Alpha Survey; Rhoads et al. 2000)

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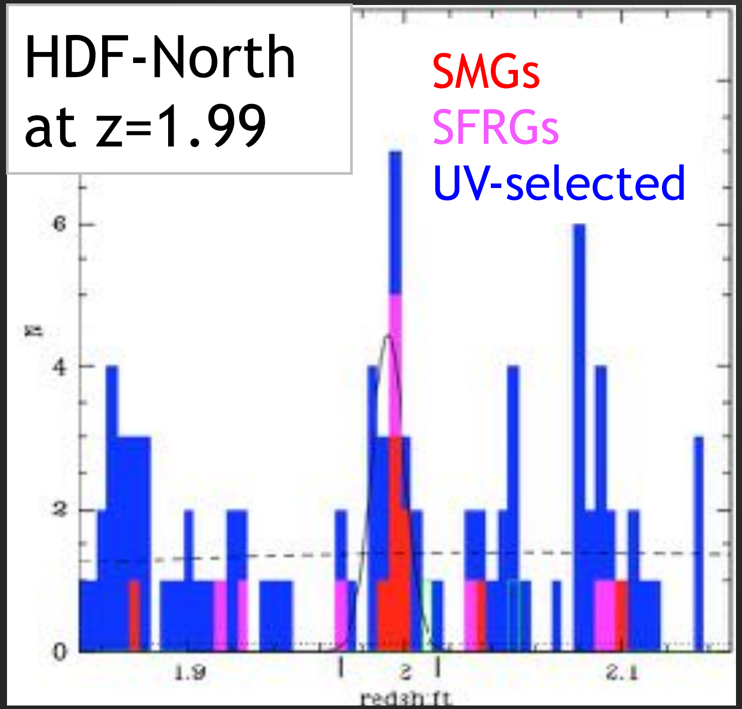

Chapman+09

Tracers of halos with more modest masses, caught in an active period

→ SMGs appear to trace a wider range of environments!

Submm Galaxies: Signposts of Protoclusters
(an on-going investigation…)

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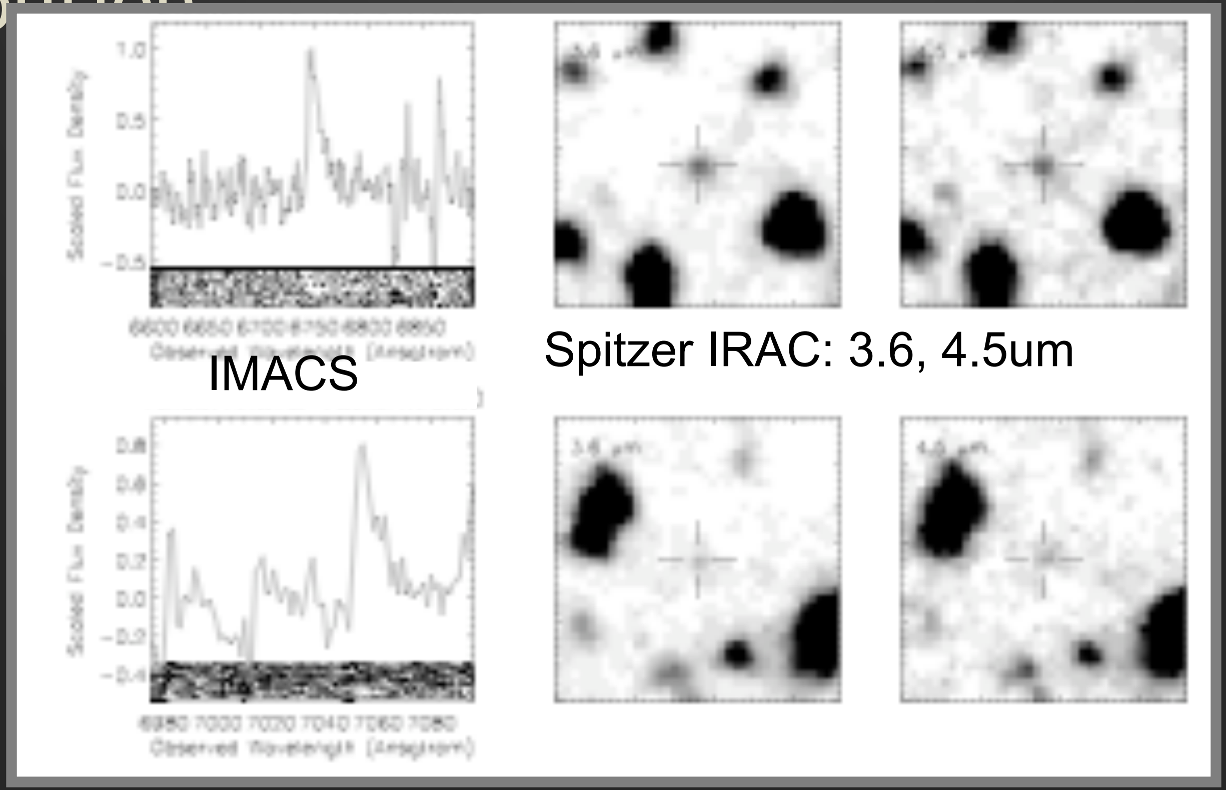
③ Follow-up study of overdensity members to extract individual/ stacked galaxy properties (e.g., mass, activity), probing for trends in the spatial distribution



Submm Galaxies: Signposts of Protoclusters

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- We target candidate overdensities at z~1-5

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Steps

① Identification of overdensity members

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③ Follow-up study of overdensity members to extract individual/ stacked galaxy properties (e.g., mass, activity), probing for trends in the spatial distribution

④ Assessment of distribution in galaxy properties according to protocluster maturity (e.g., overdensity mass, gaussianity of the relative velocity of overdensity members)

Take Away Points

- Most massive structures formed over a wide redshift range
  - They are forming their stars/galaxies at $z>2$
  - Need to probe higher redshifts to trace the origin (and evolution) of the galaxy-environment relation

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→ SMGs may be tracers of a wider range of environments beyond the progenitors of todays very rich clusters

Take Away Points

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  → SMGs may be tracers of a wider range of environments beyond the progenitors of todays very rich clusters
- With our program we aim to probe for changes in the distribution of galaxy properties and explore the way galaxy and local environment relate to each other within the broader picture of a cosmologically-evolving overdensity.

The Nebular Gas in star-forming galaxies at high redshift

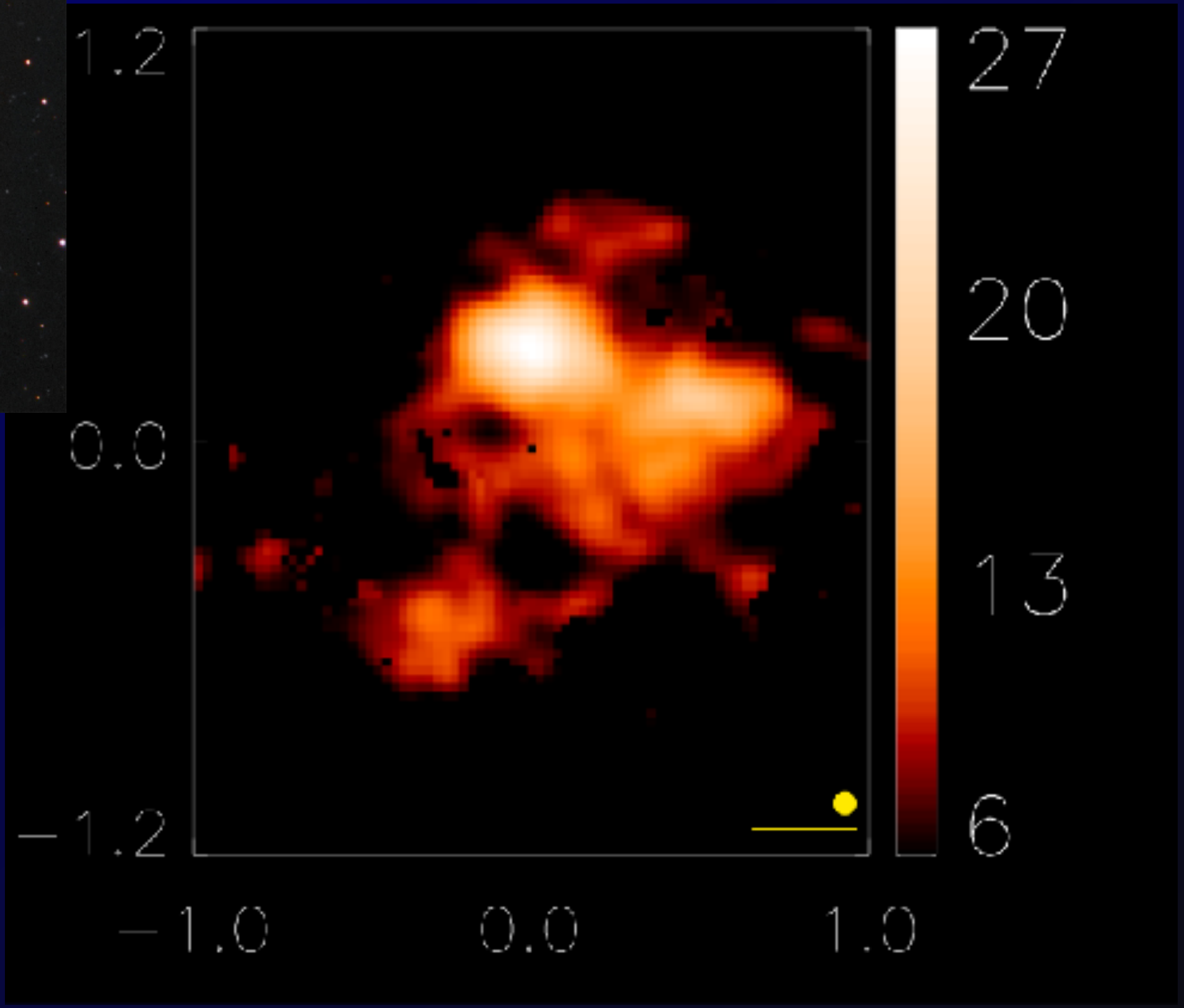
Star formation in galaxies

Star formation in galaxies

Local universe

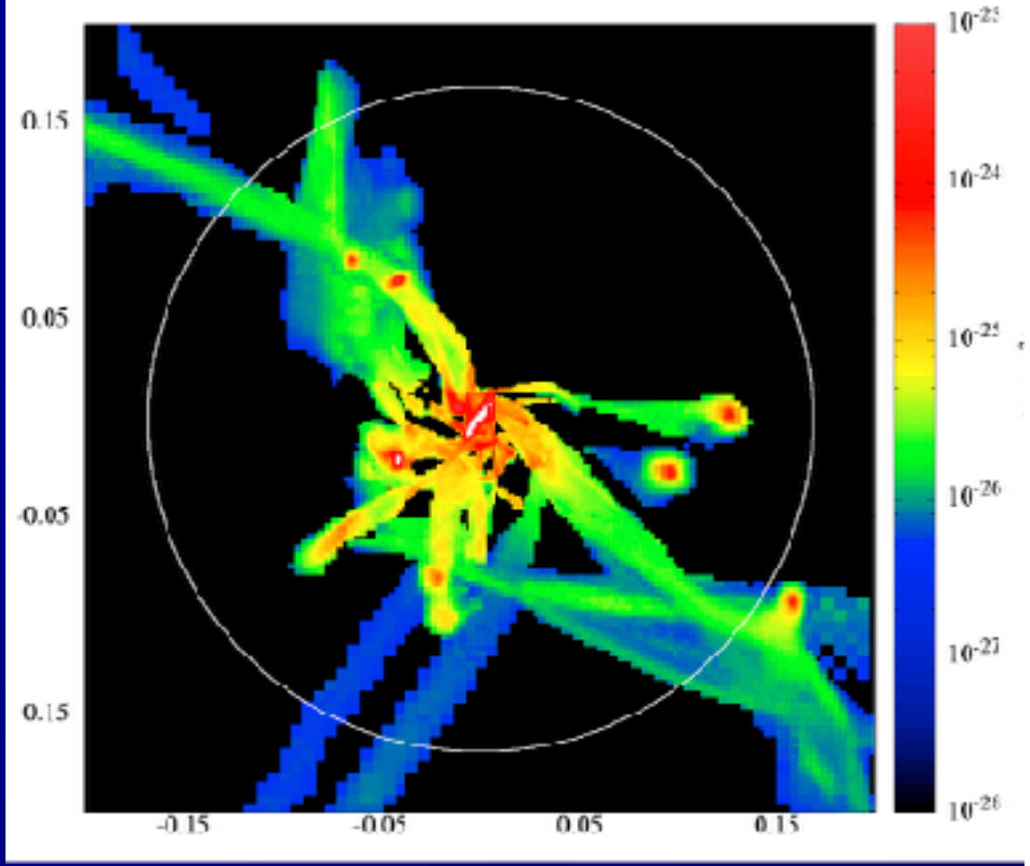
Star formation in galaxies

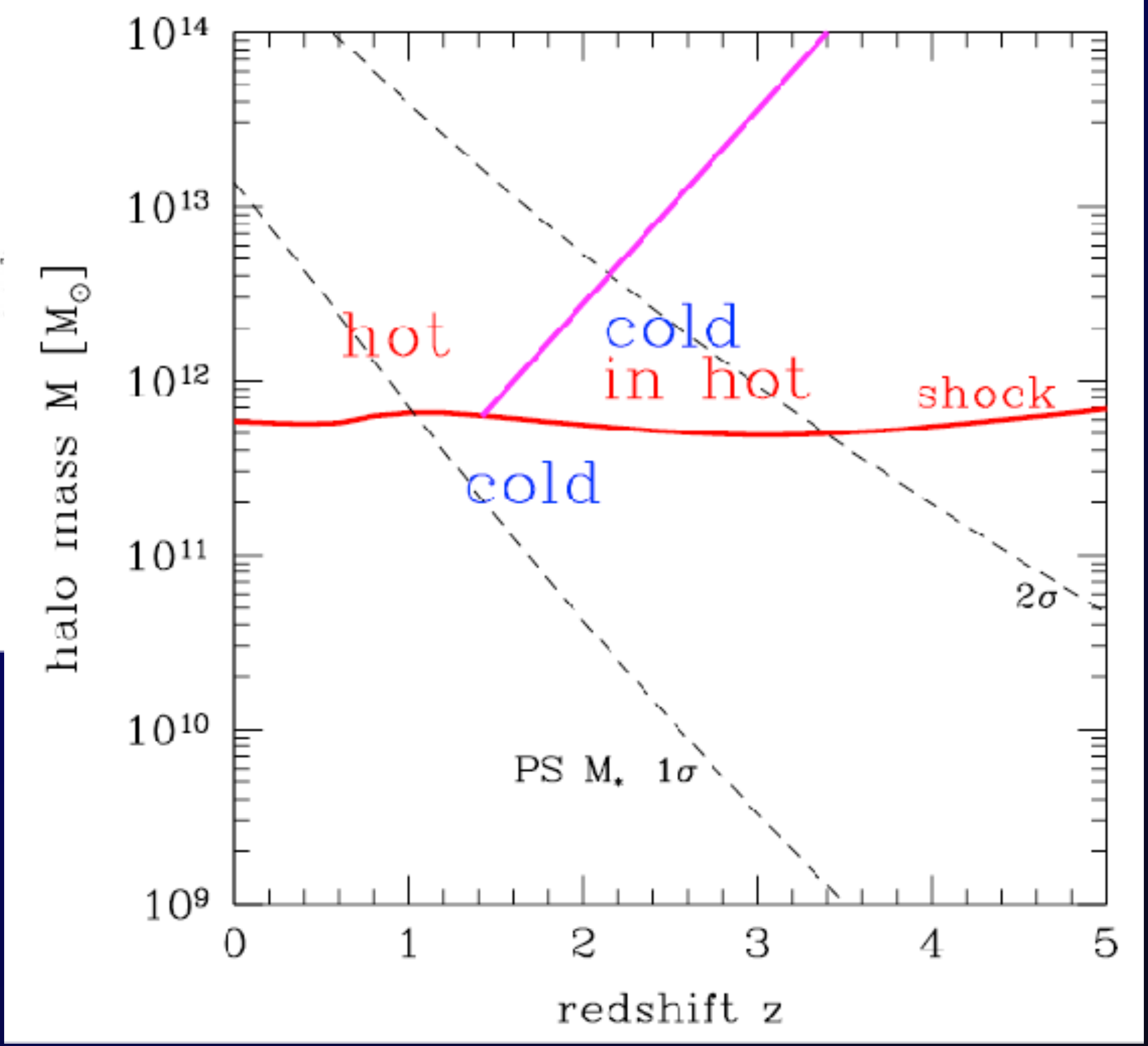
Local universe



High redshift

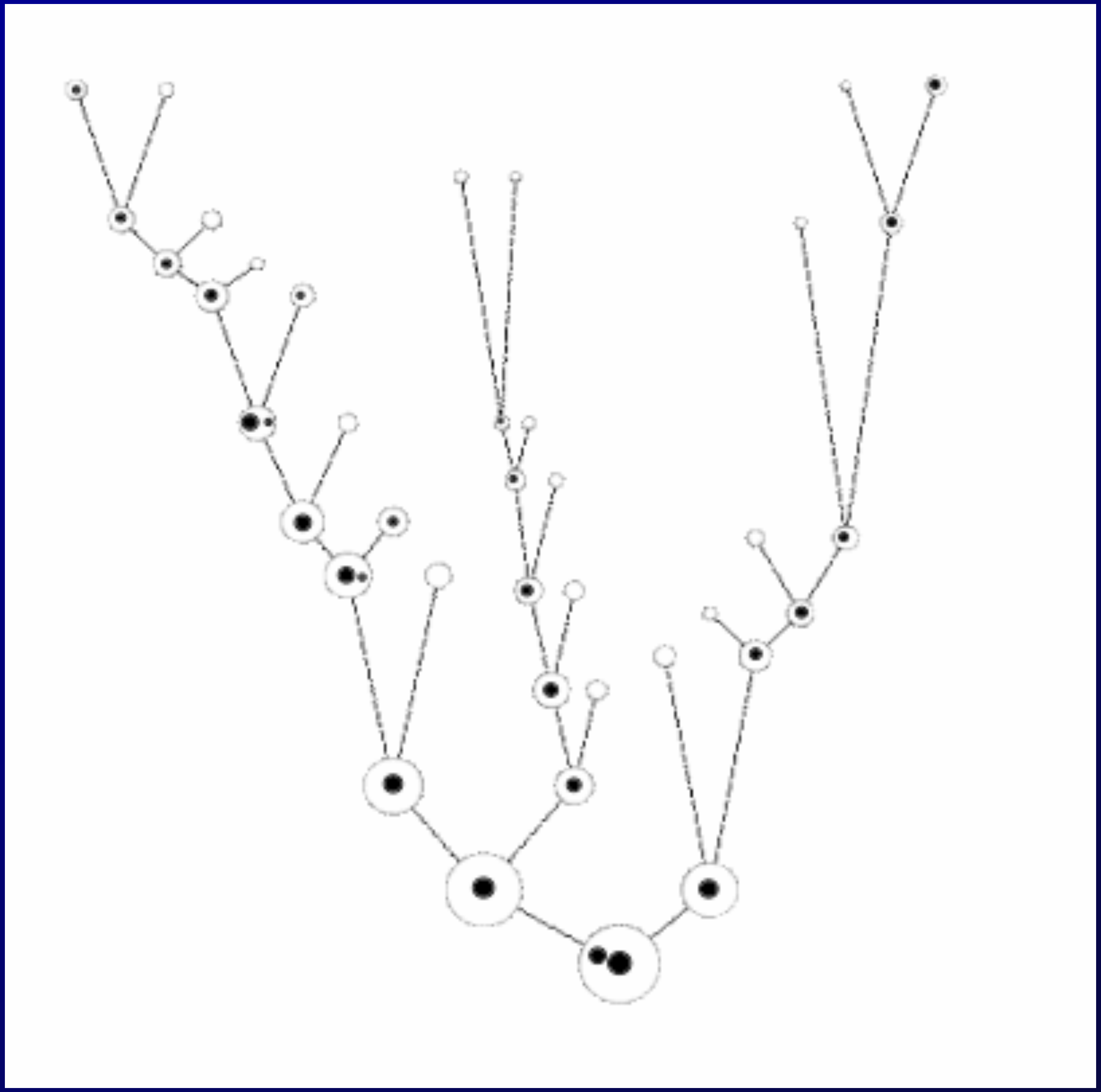
Cold flows





Dekel & Birnboim 2006

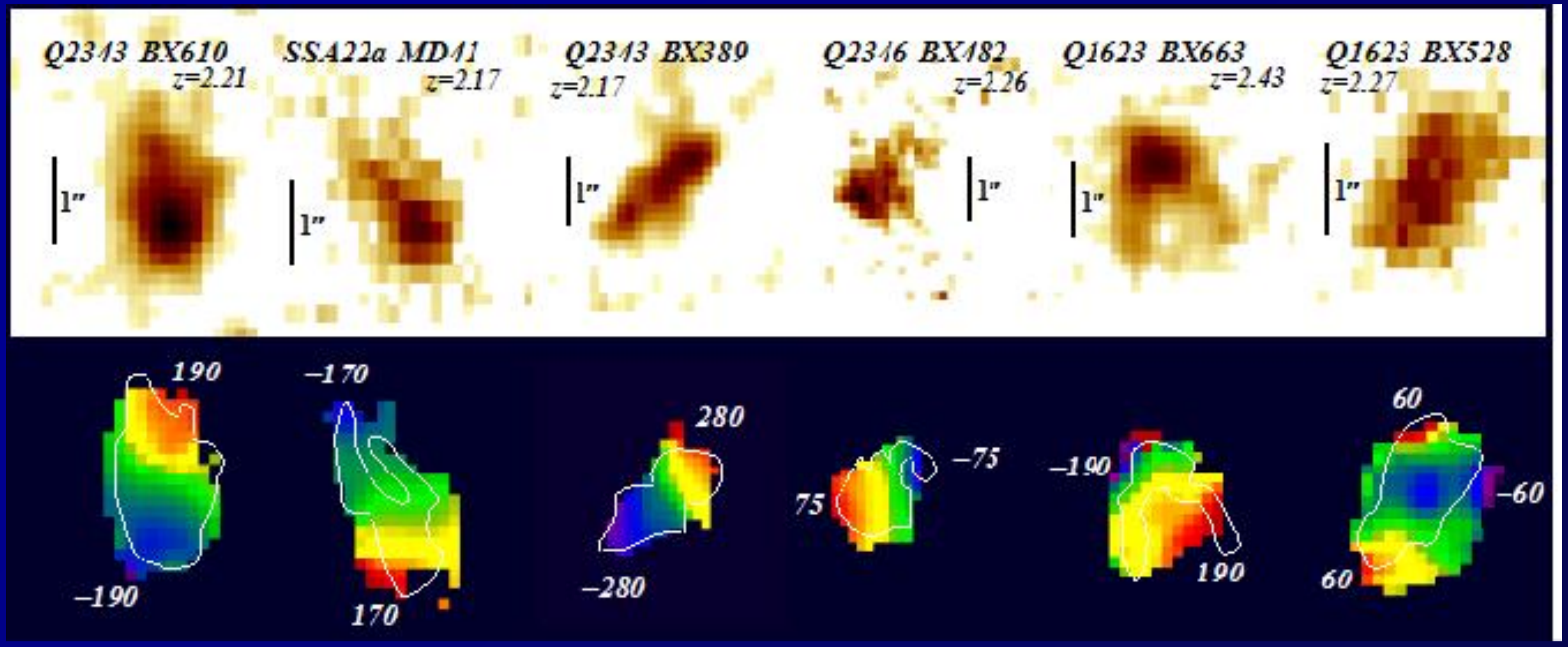
Interactions and mergers?



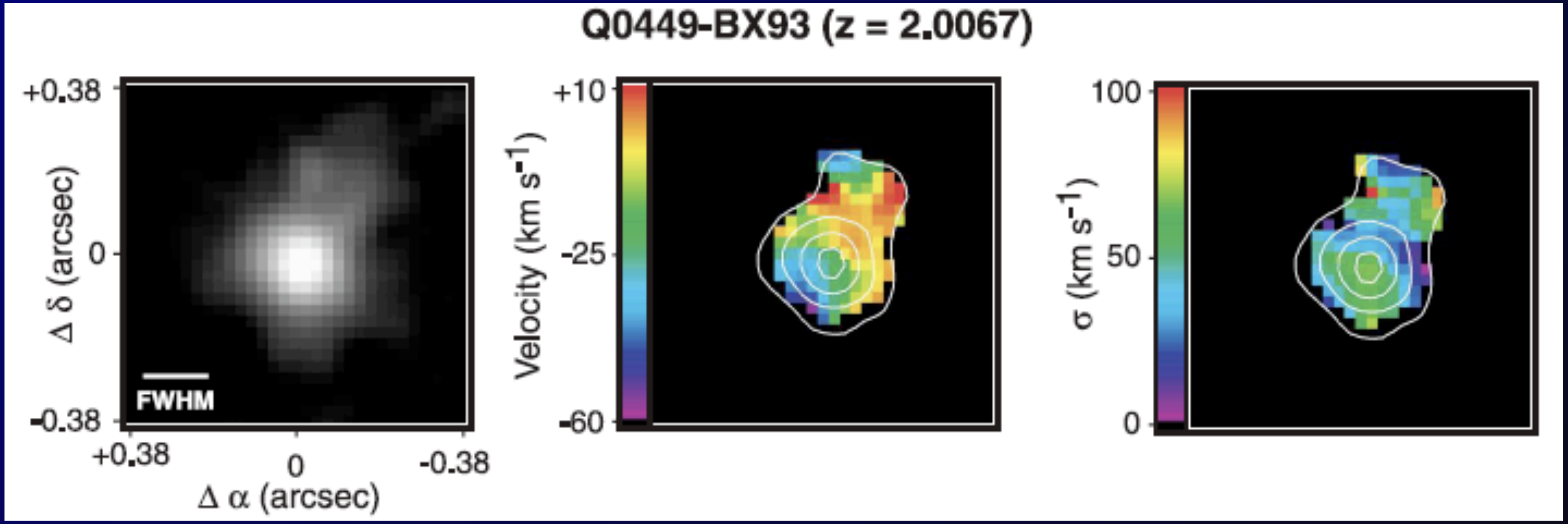
Marta Volonteri, UMich

HST

IFU studies at z~2

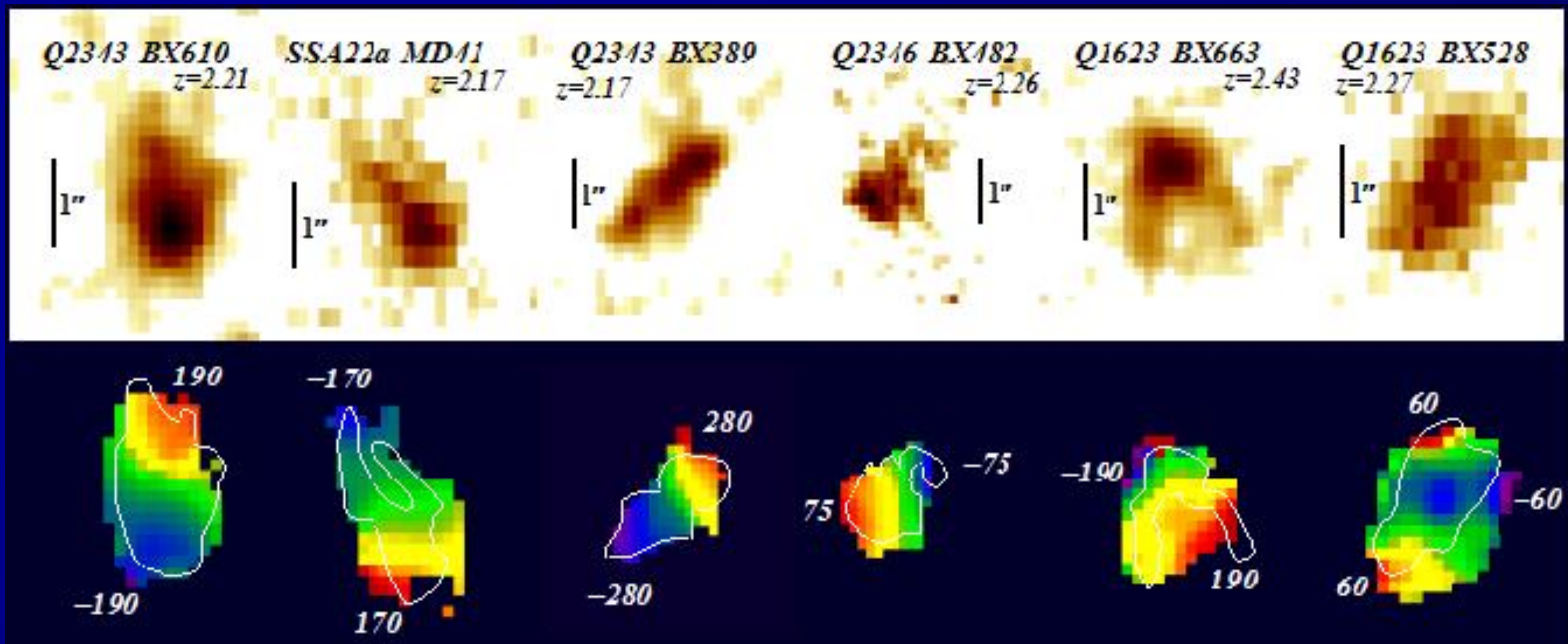


Förster-Schreiber+09

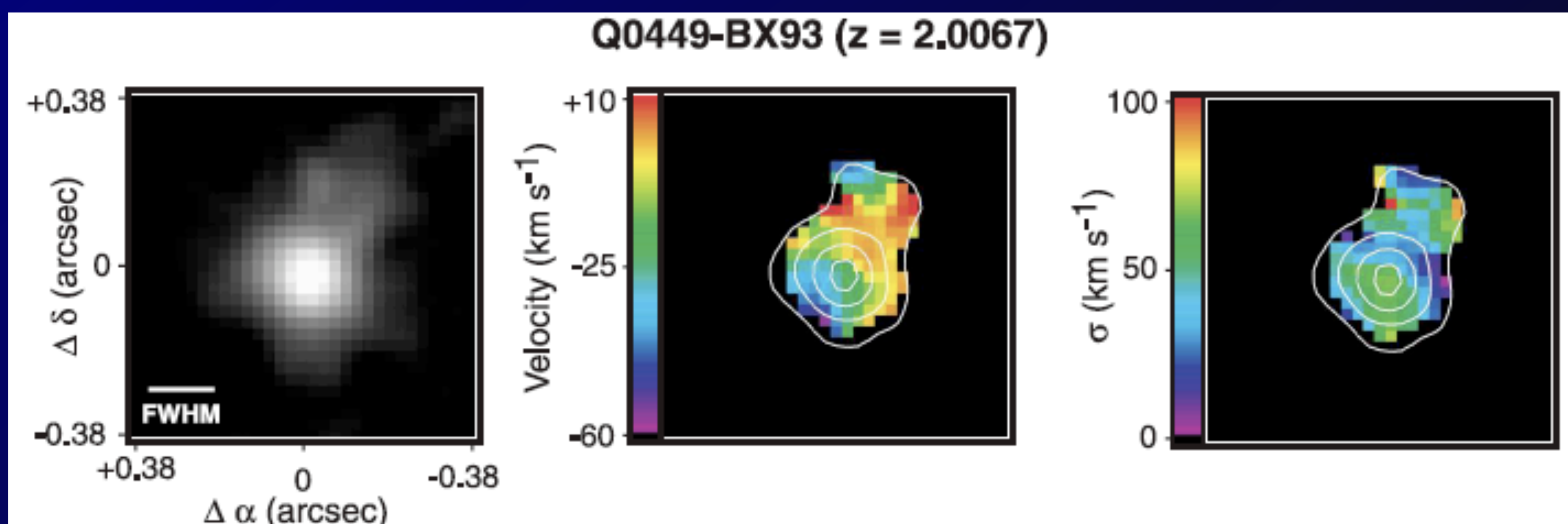


Law+09

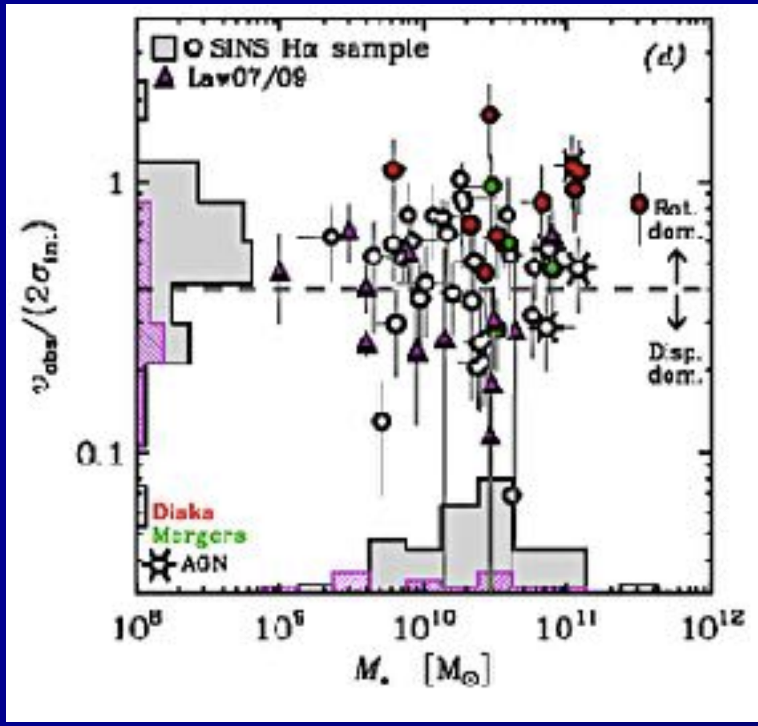
IFU studies at z~2



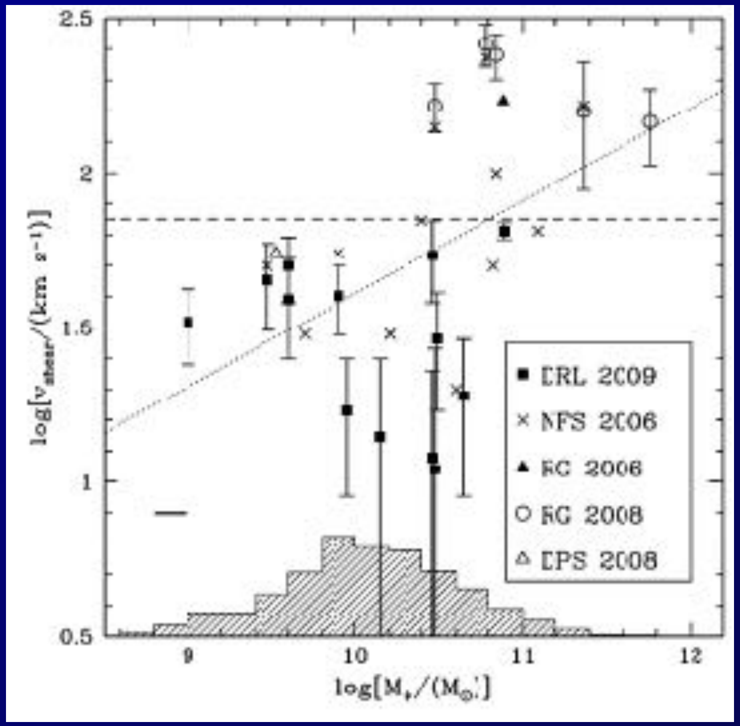
Förster-Schreiber+09

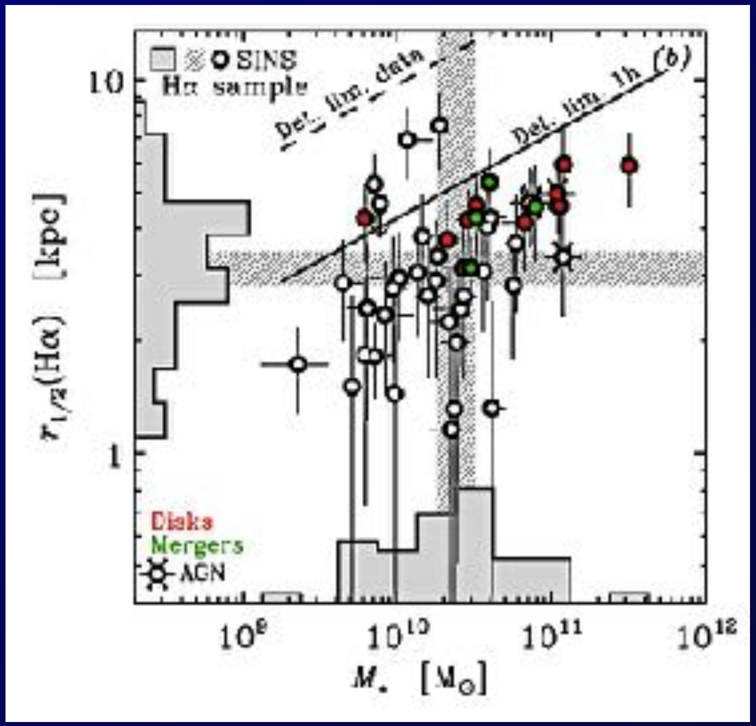


Law+09



FS09





Law09

FS09

High velocity dispersion

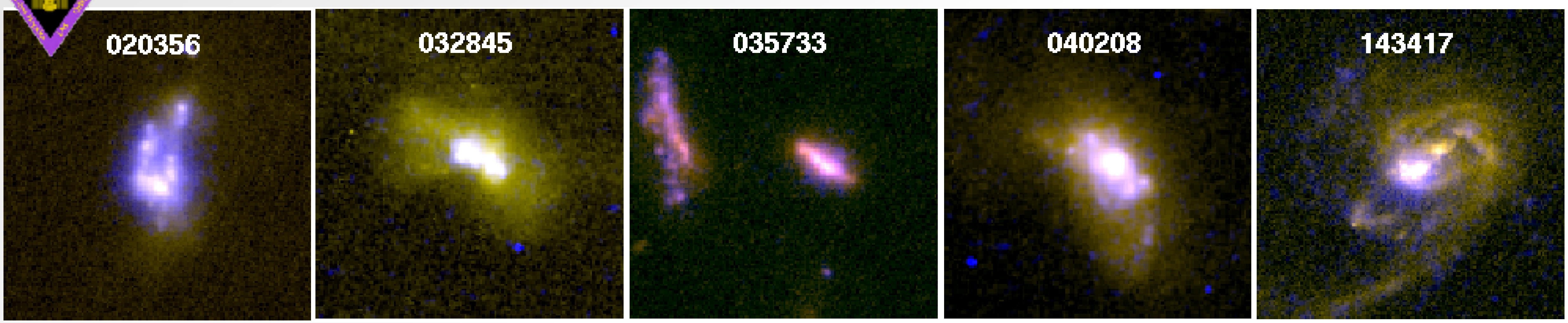
Stellar mass dependence of observables

Virial mass: 2K+U = 0

What is the main dynamical component?

Analogs at low redshift

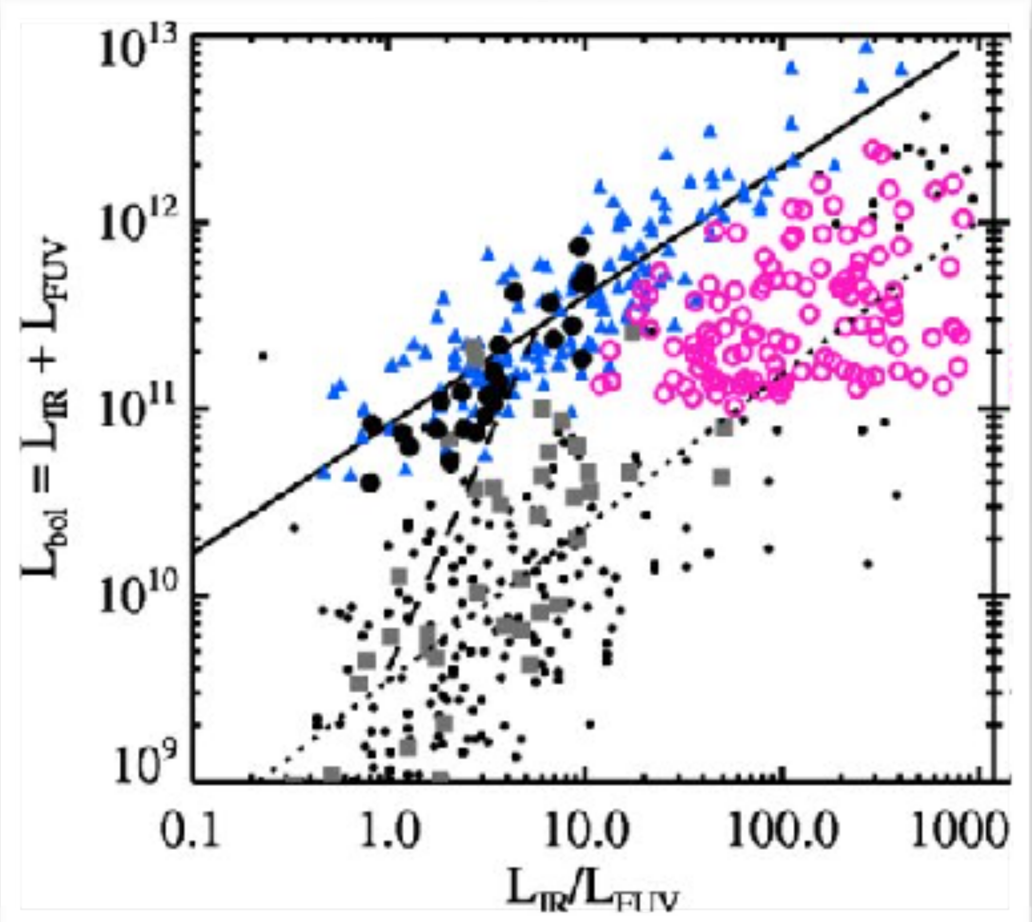
Hoopes+07
Overzier+09



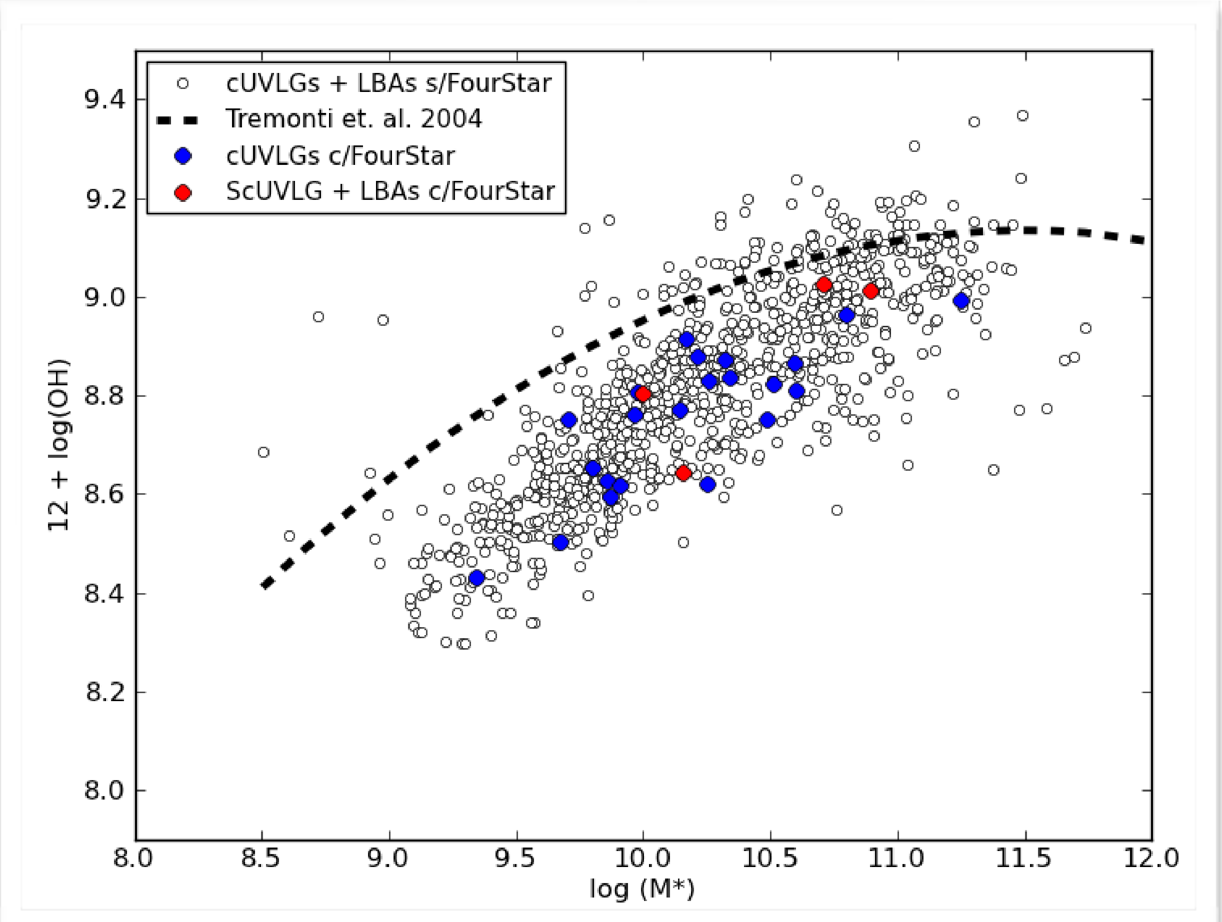
- z ~ 0.2
- Selected by ultraviolet luminosity and surface brightness

Analogs at low redshift

Overzier+11



Santos-de-Oliveira+ in prep

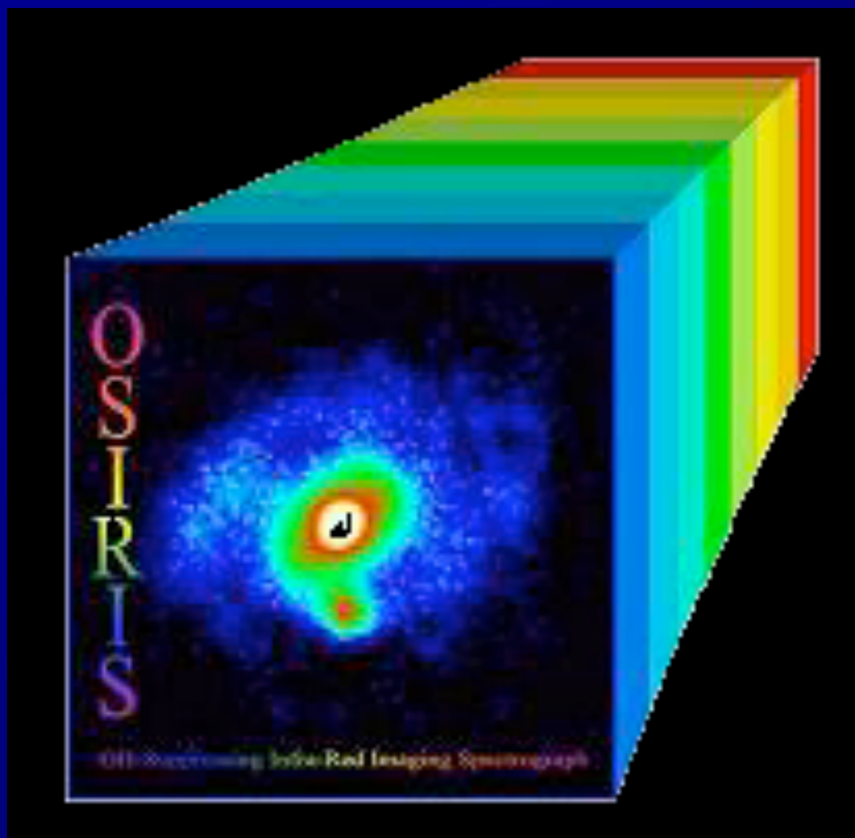


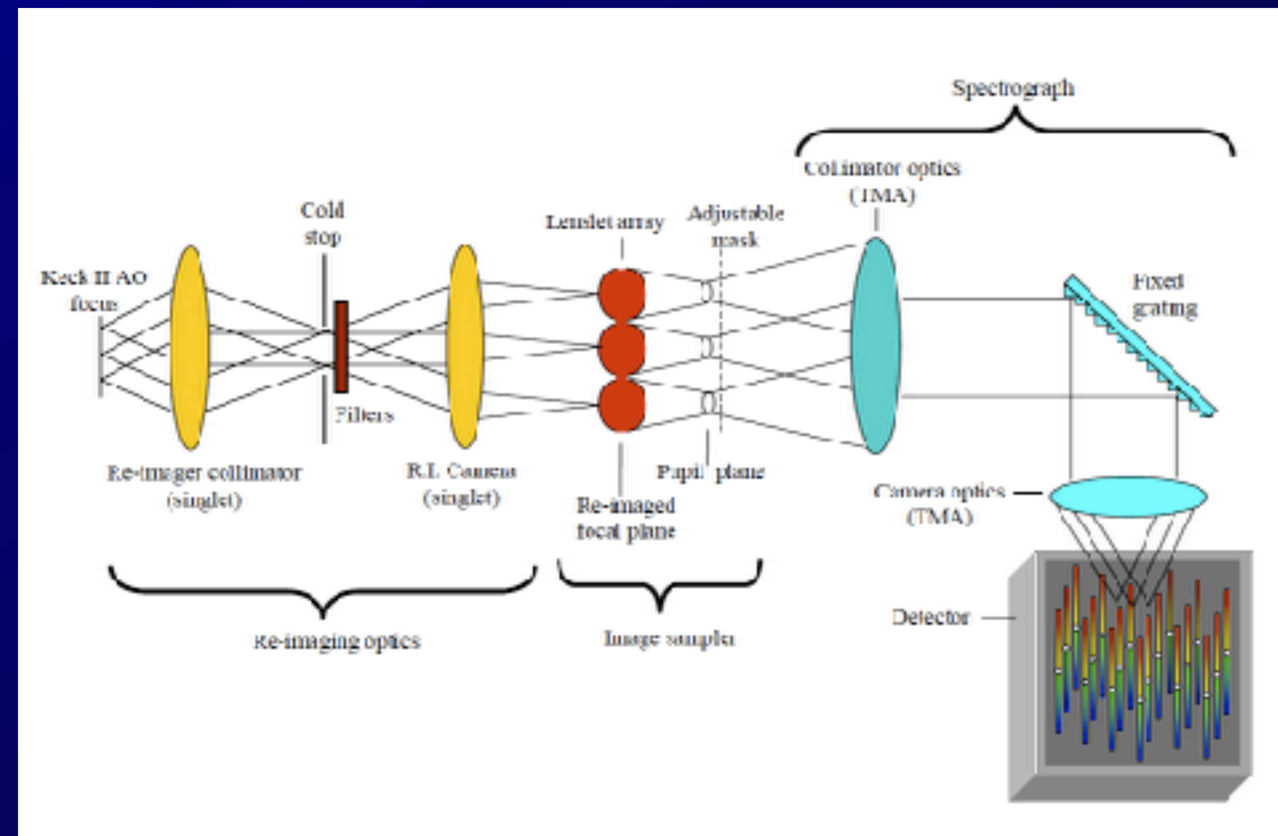
Low extinction

Low metallicities

Lyman break analogs (LBAs)

Keck IFU





- Compact objects, high SFR, strong line emission – great case!
- Resolution down to 200pc with AO, very close to diffraction limit in a 10m telescope
- Observed line: Pa-α in the K-band

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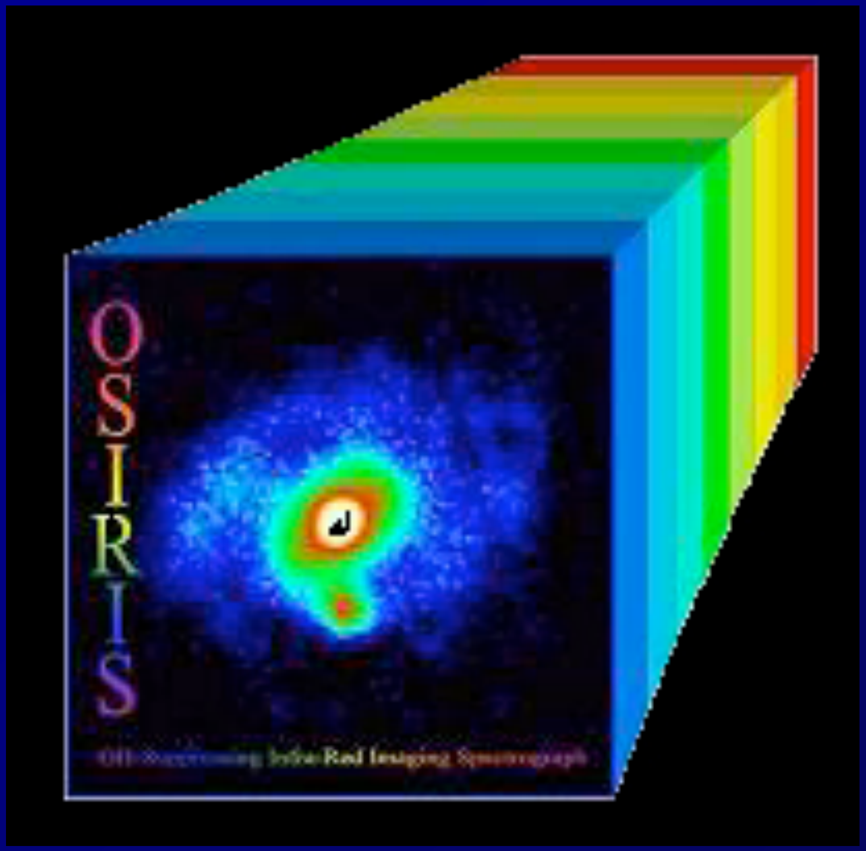

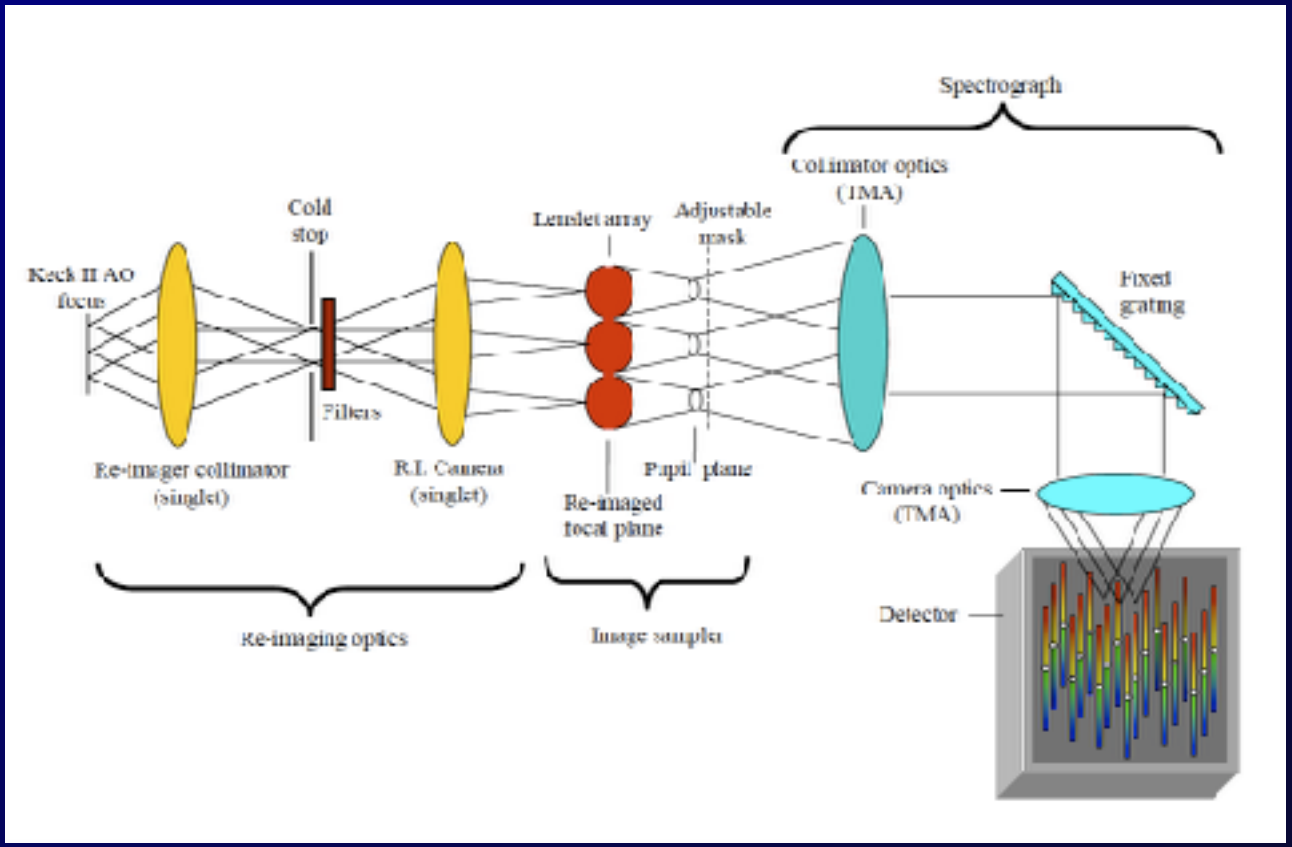

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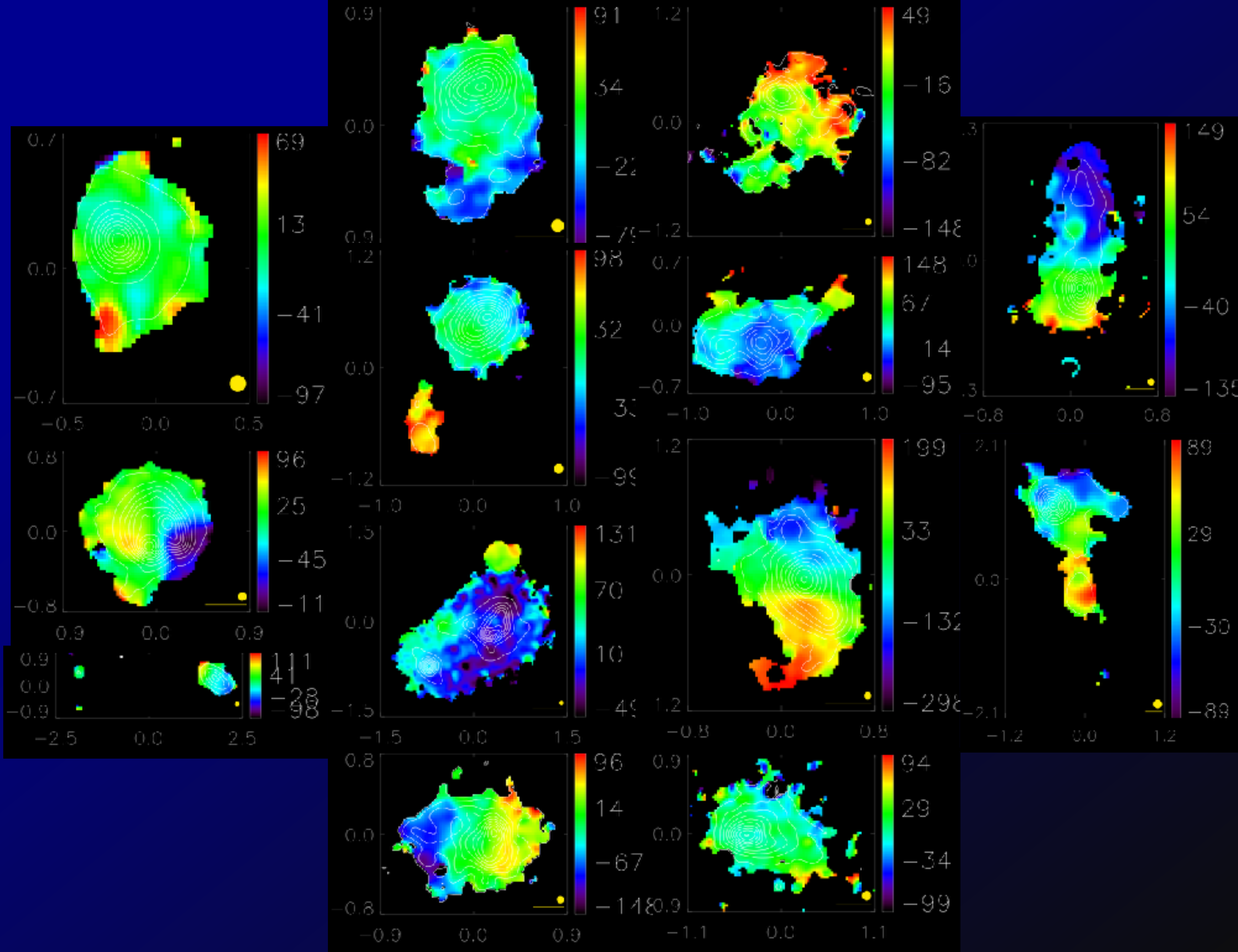

0.7
0.0
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13
−41
−97
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0.0
−0.8
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0.0
0.9
96
25
−45
−11
0.9
0.0
−0.9
−2.5
0.0
2.5
111
41
−28
−98
91
0.0
−1.2
1.2
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−1.0
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1.0
98
1.5
0.0
−1.5
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1.5
131
70
10
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0.0
−0.8
−0.9
0.0
0.9
96
14
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−148
1.2
0.0
−1.2
49
−16
−82
−148
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0.0
−0.7
−1.0
0.0
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148
67
14
−95
1.2
0.0
1.2
−0.8
0.0
0.8
199
33
0.9
0.0
0.9
−1.1
0.0
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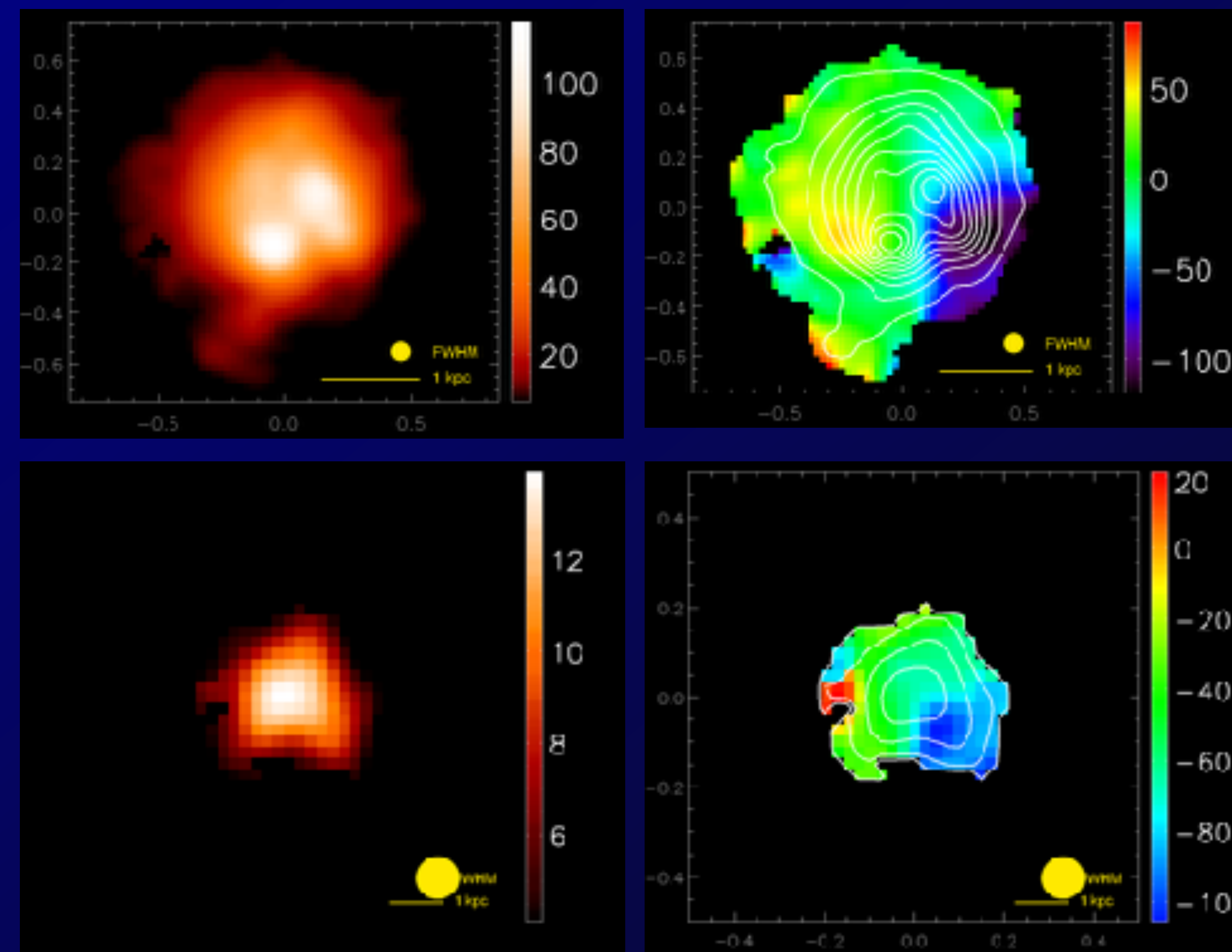
94
29
−34
−99
149
54
−40
−0.8
0.0
0.8
2.1
0.0
−2.1
−1.2
0.0
1.2
89
29
−30
−89

Data at high z?

S/N V (km/s)

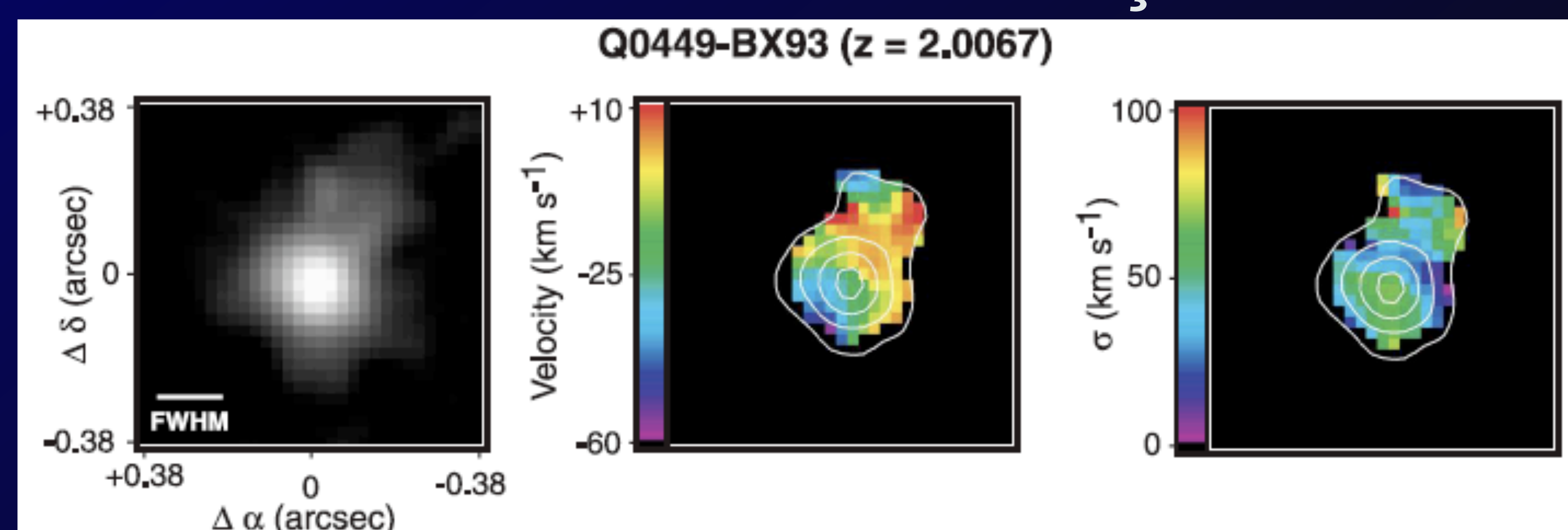
Real data

Artificially redshifted to z=2.2

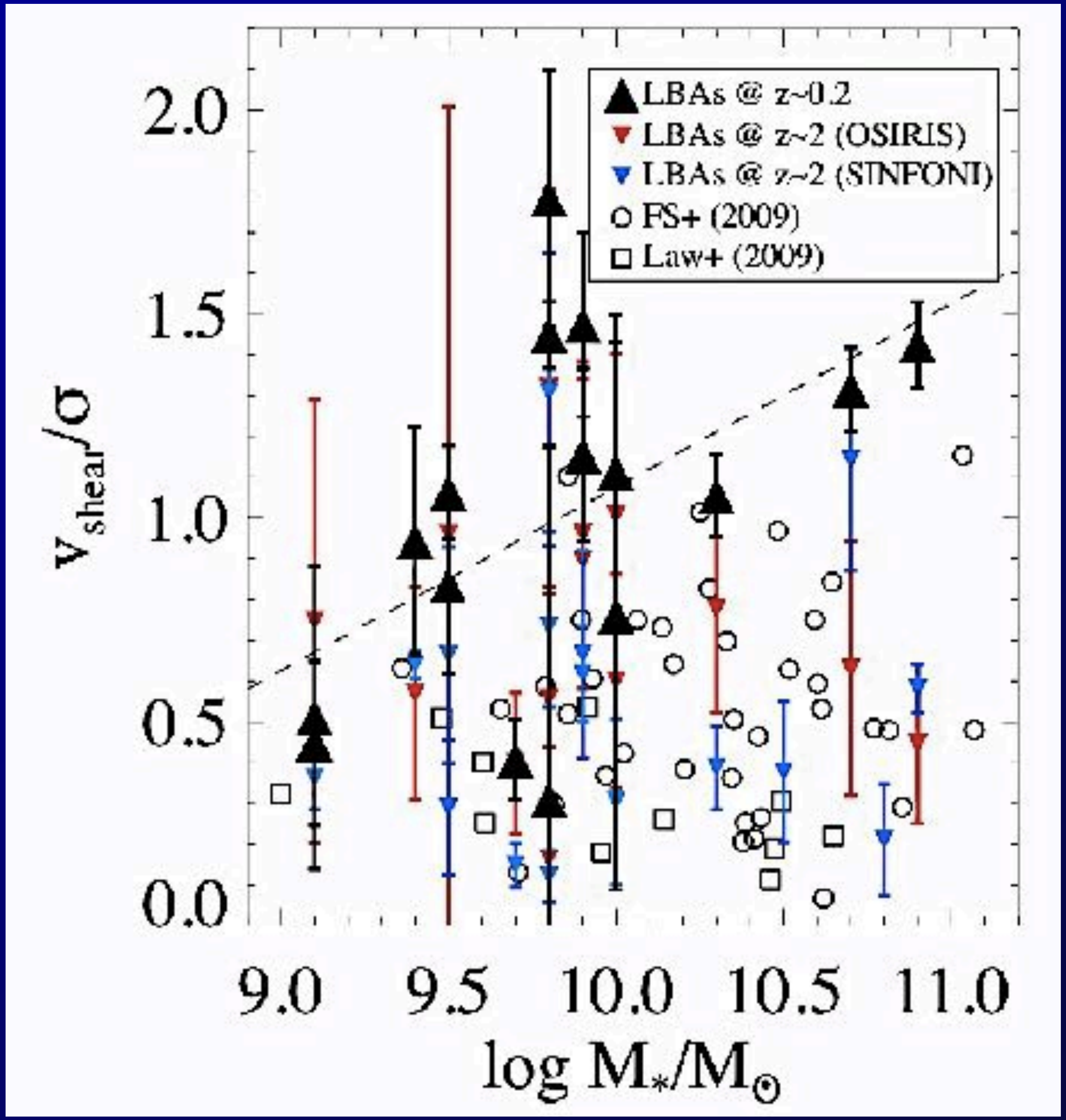


Gonçalves+10

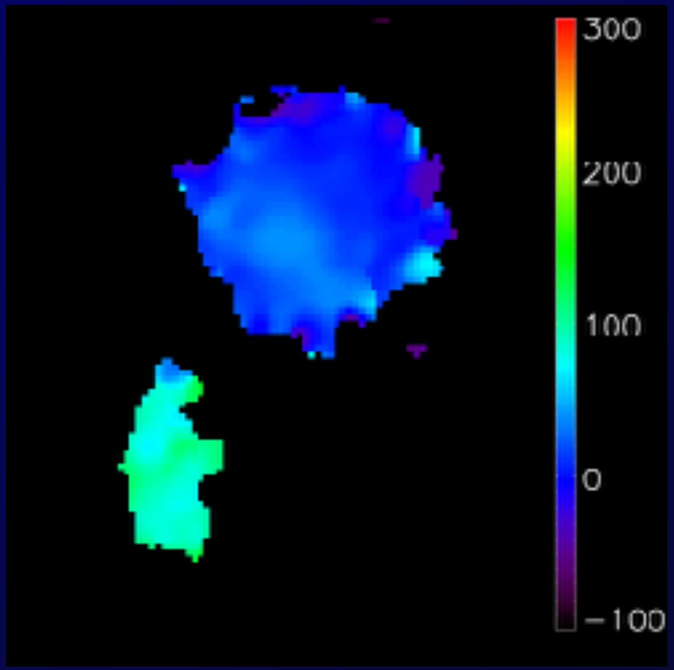
Law et al. 2007

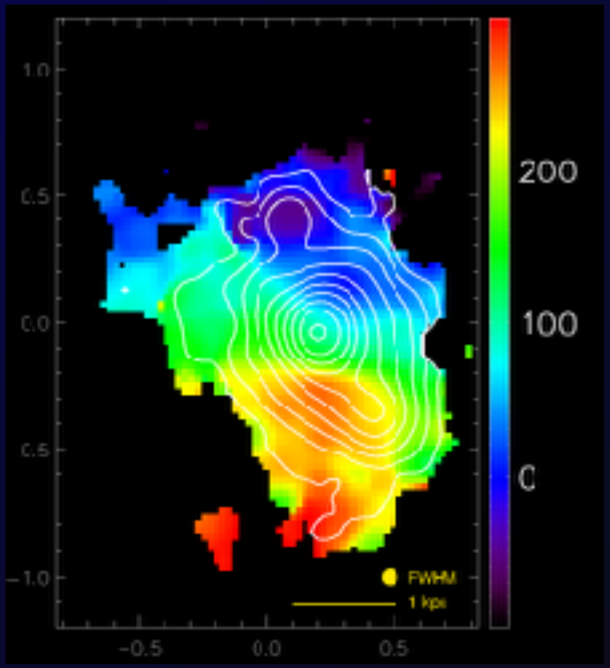


Stellar mass dependence



More massive objects show stronger velocity shears with similar values to high-z





Gonçalves+10

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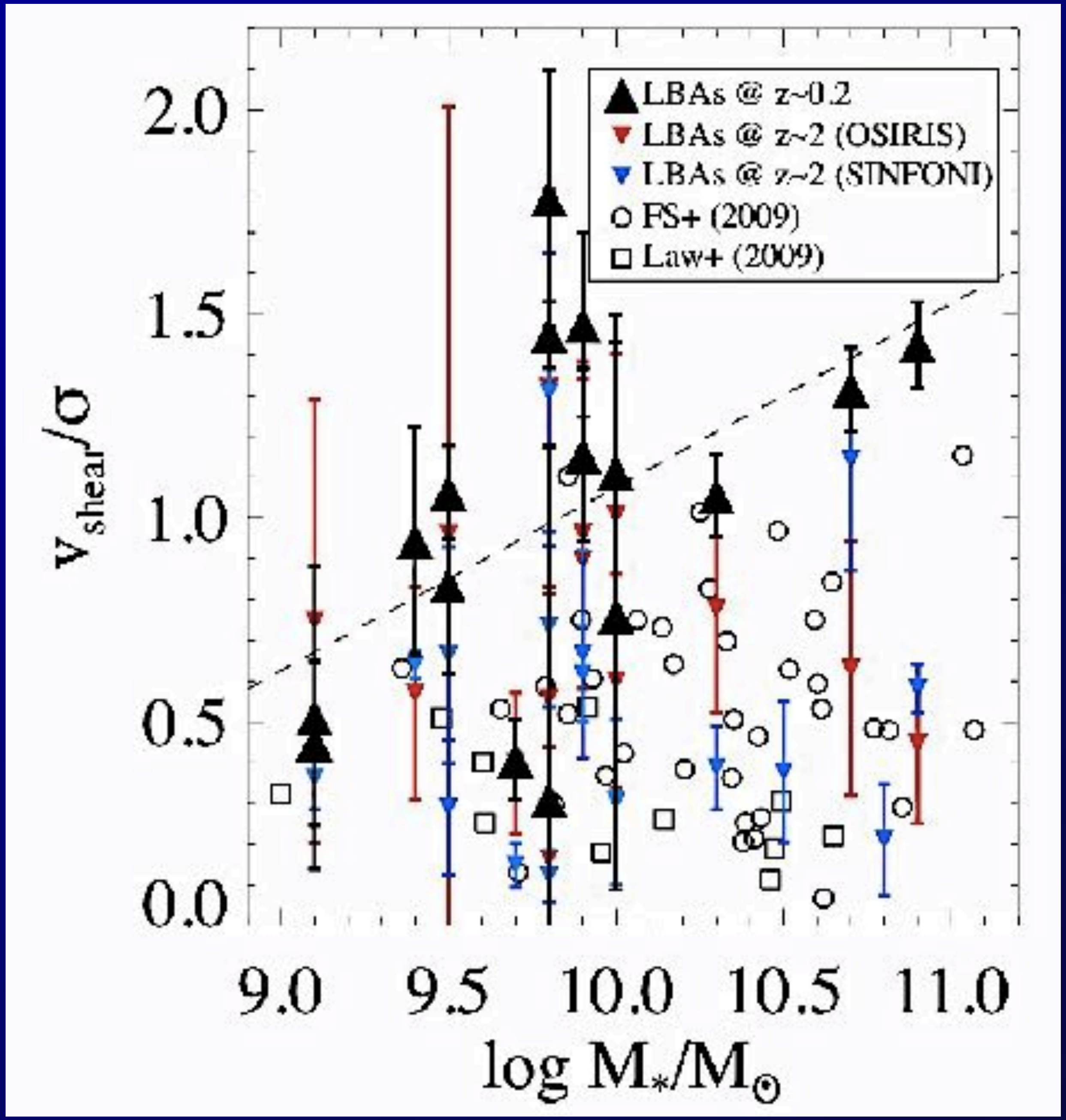

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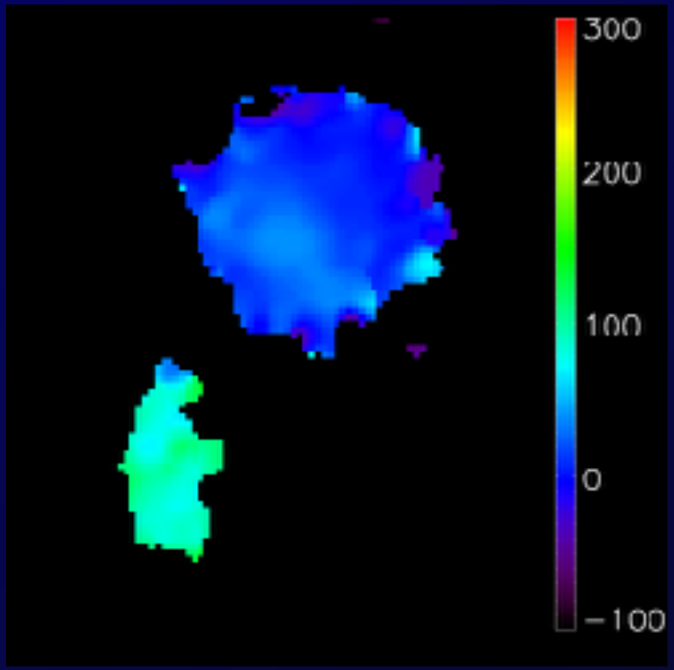
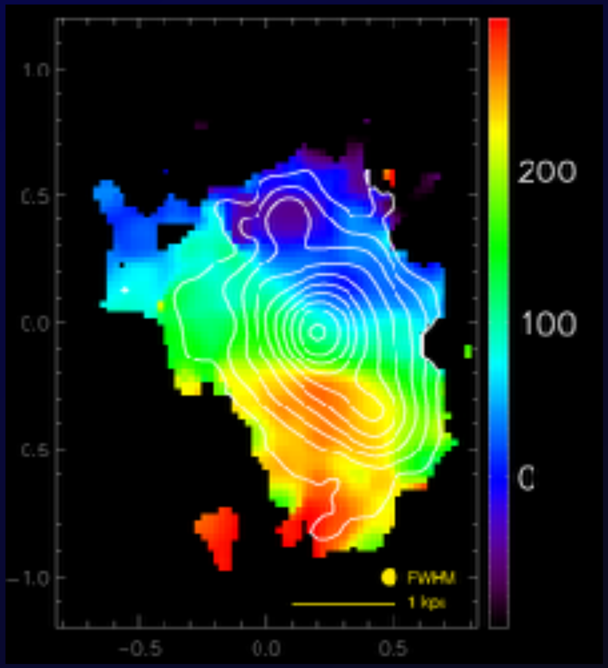
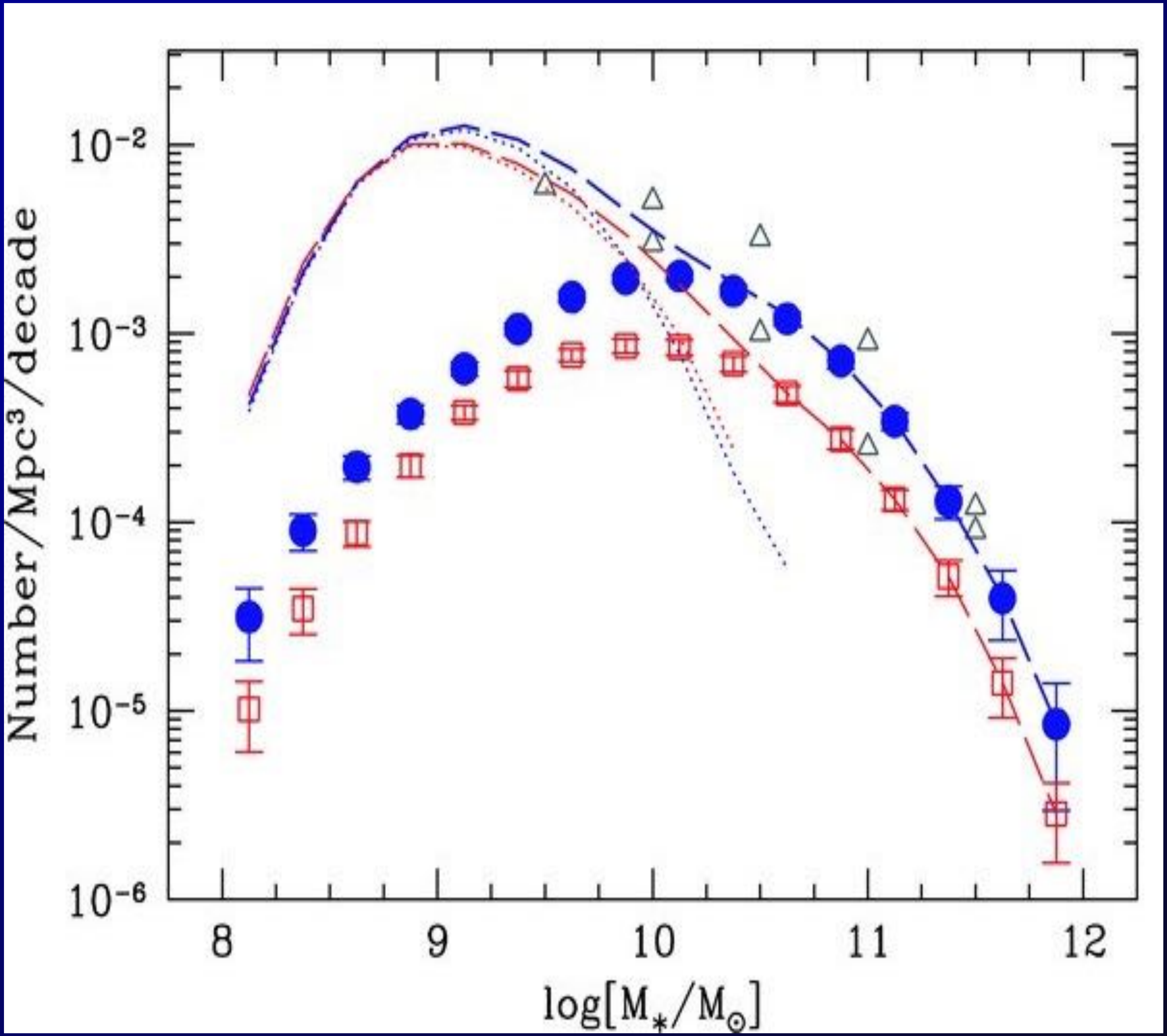
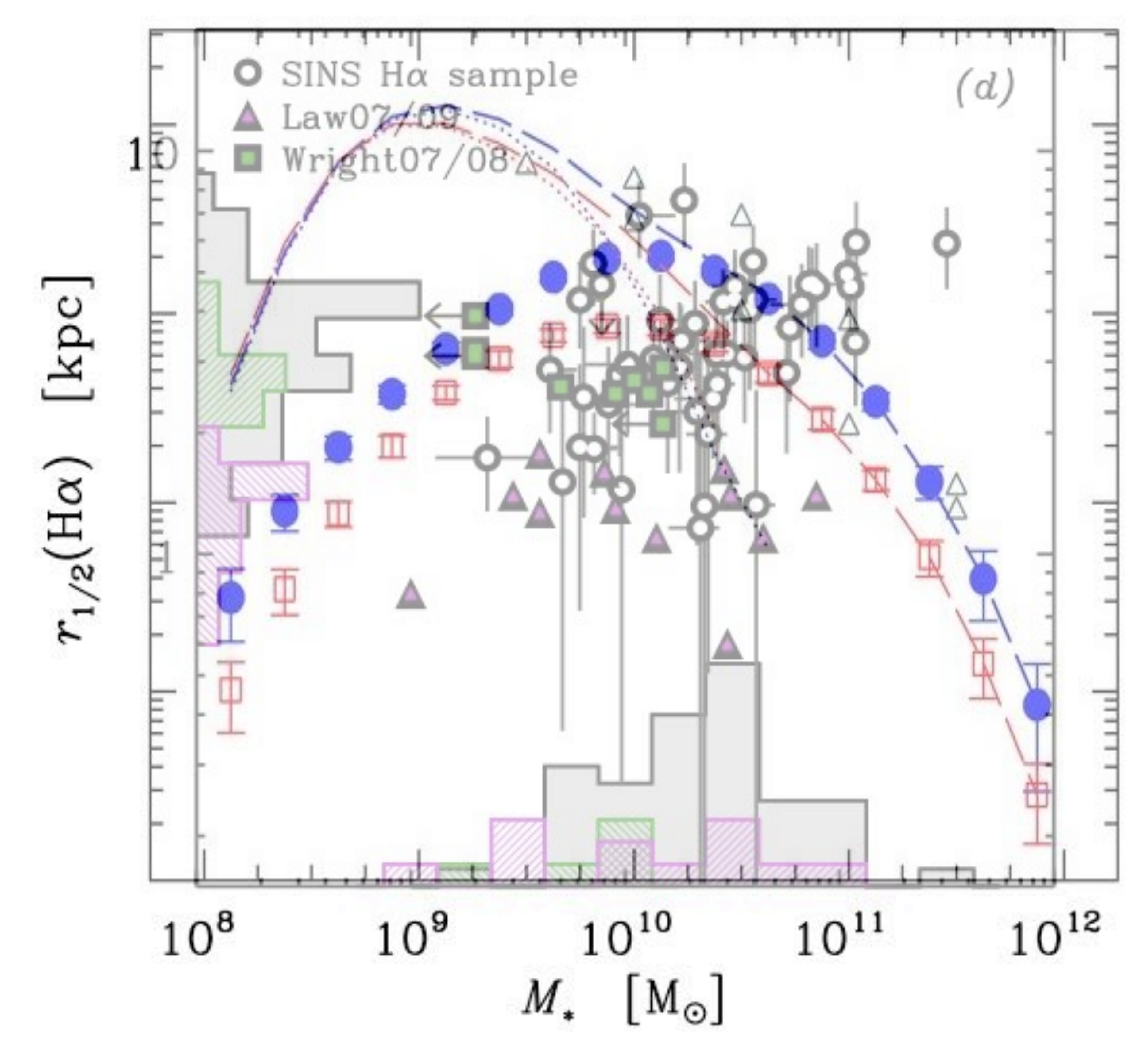




Gonçalves+10



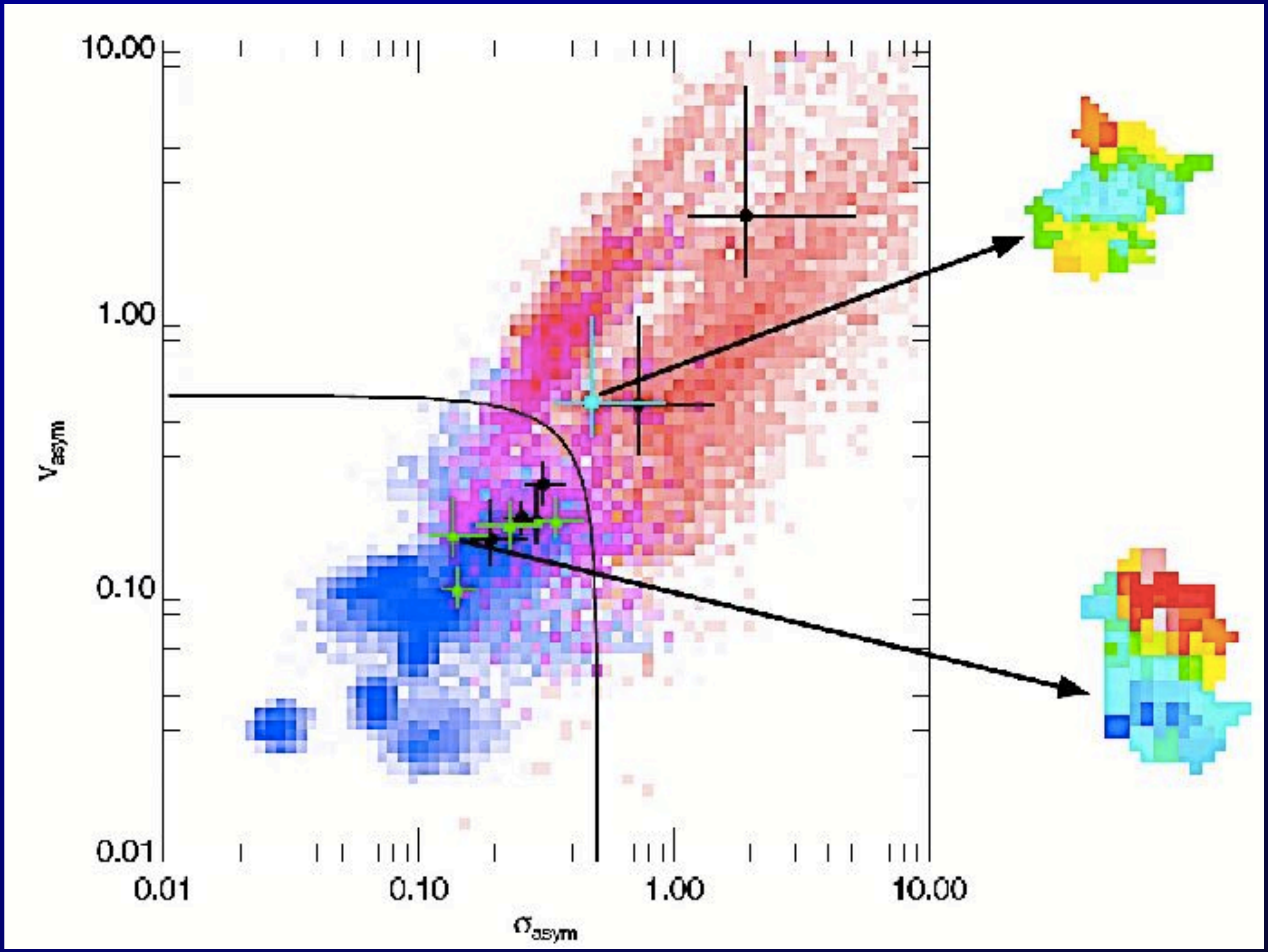
Reddy & Steidel, 2009



Reddy & Steidel, 2009

Kinemetry

Krajnović et al. 2006
Shapiro et al. 2008



- Asymmetry measurement
- Distinction between mergers and rotating disks

Kinemetry

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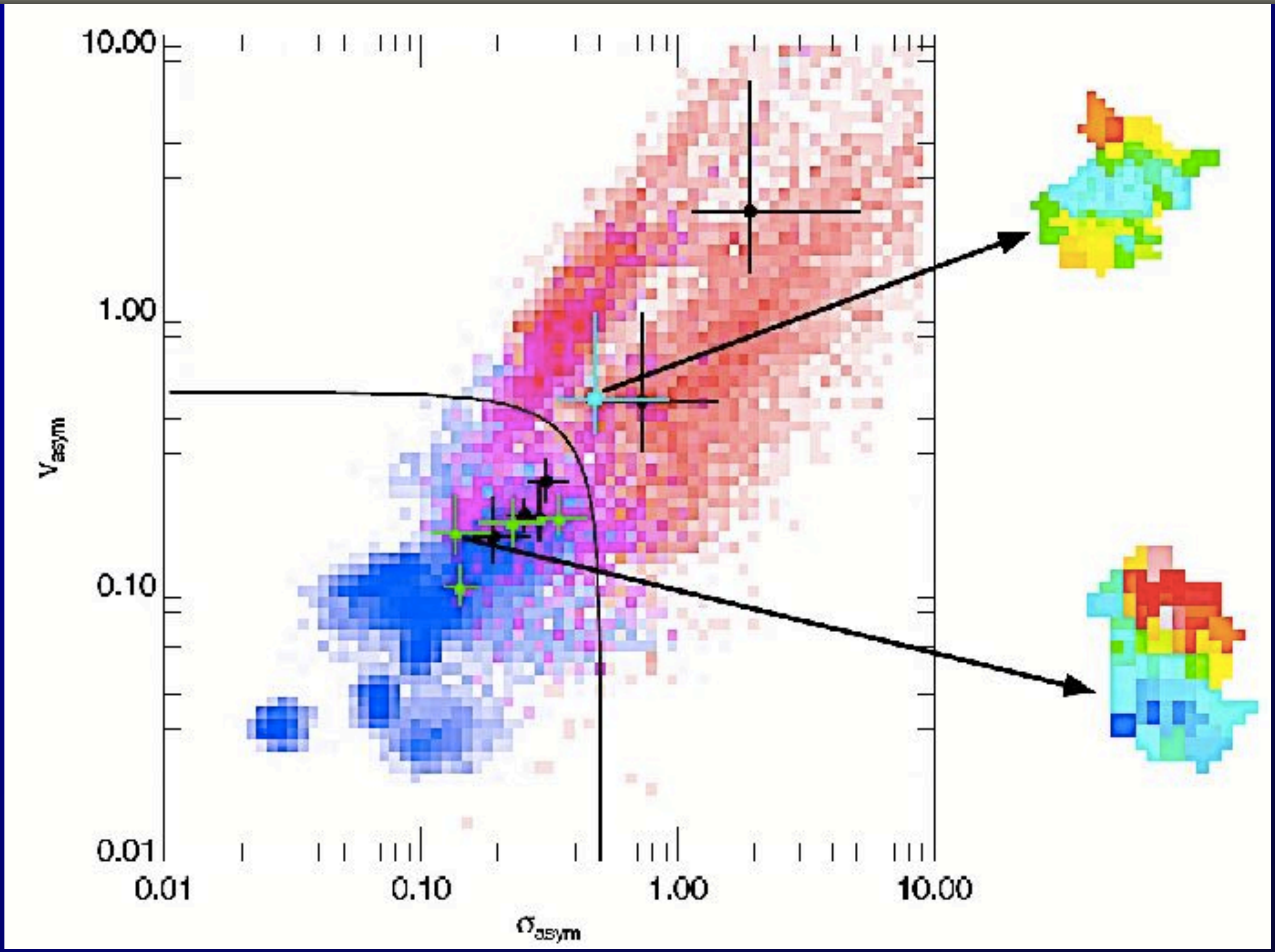

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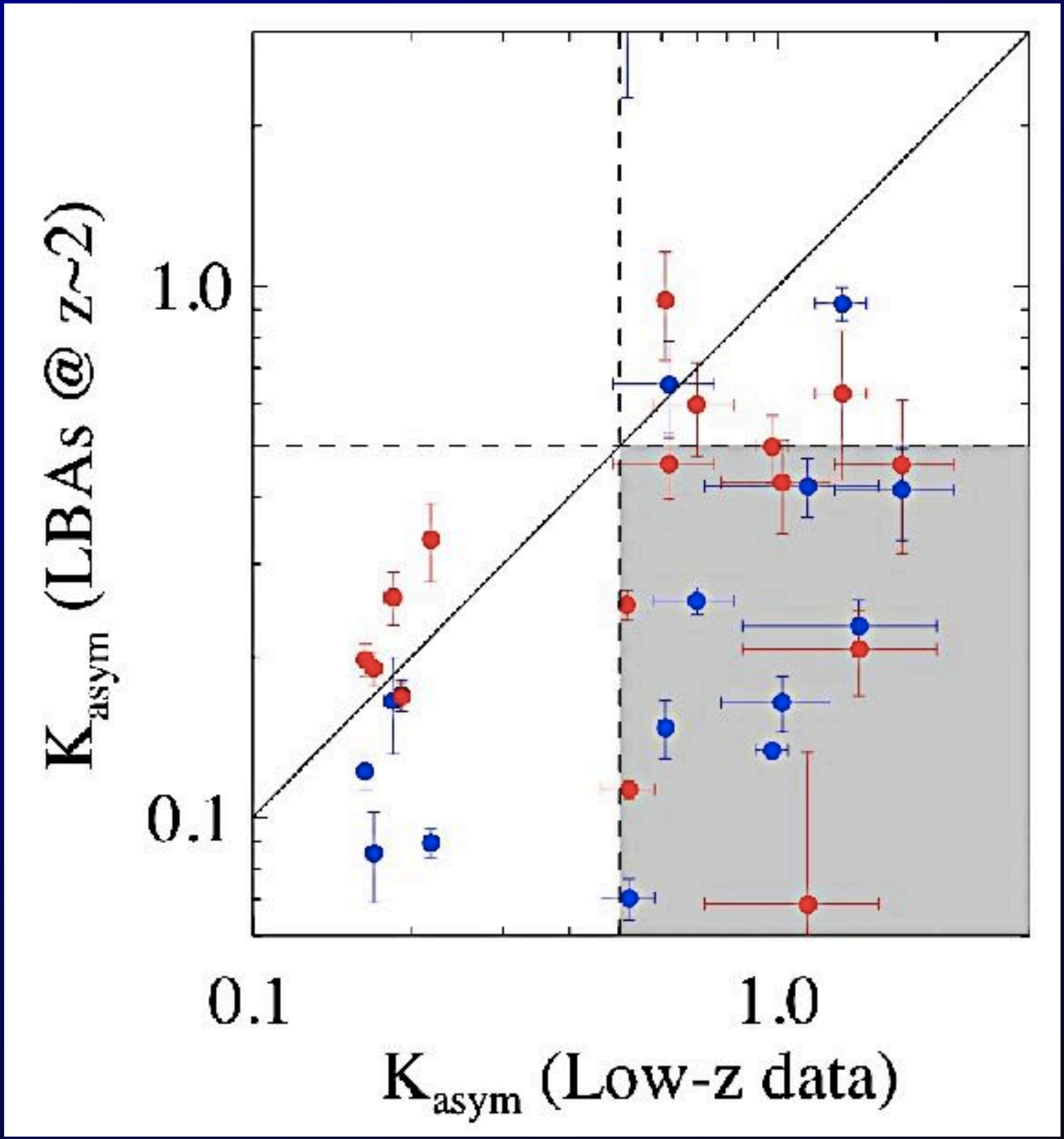
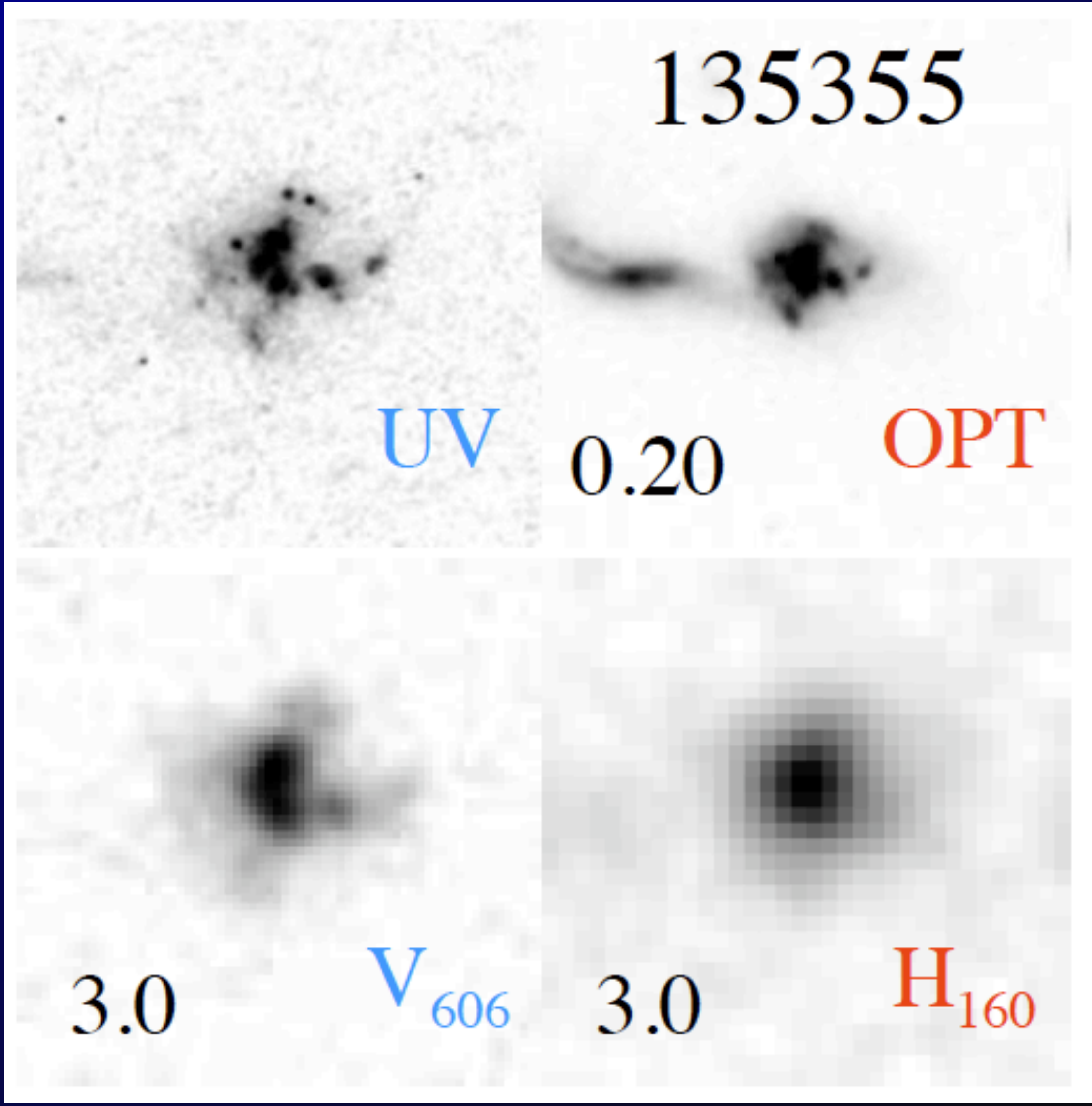


High-redshift data underestimates the asymmetry levels

Gonçalves+10

Detecting mergers

Can we detect mergers at high redshift?



Overzier et al. 2010

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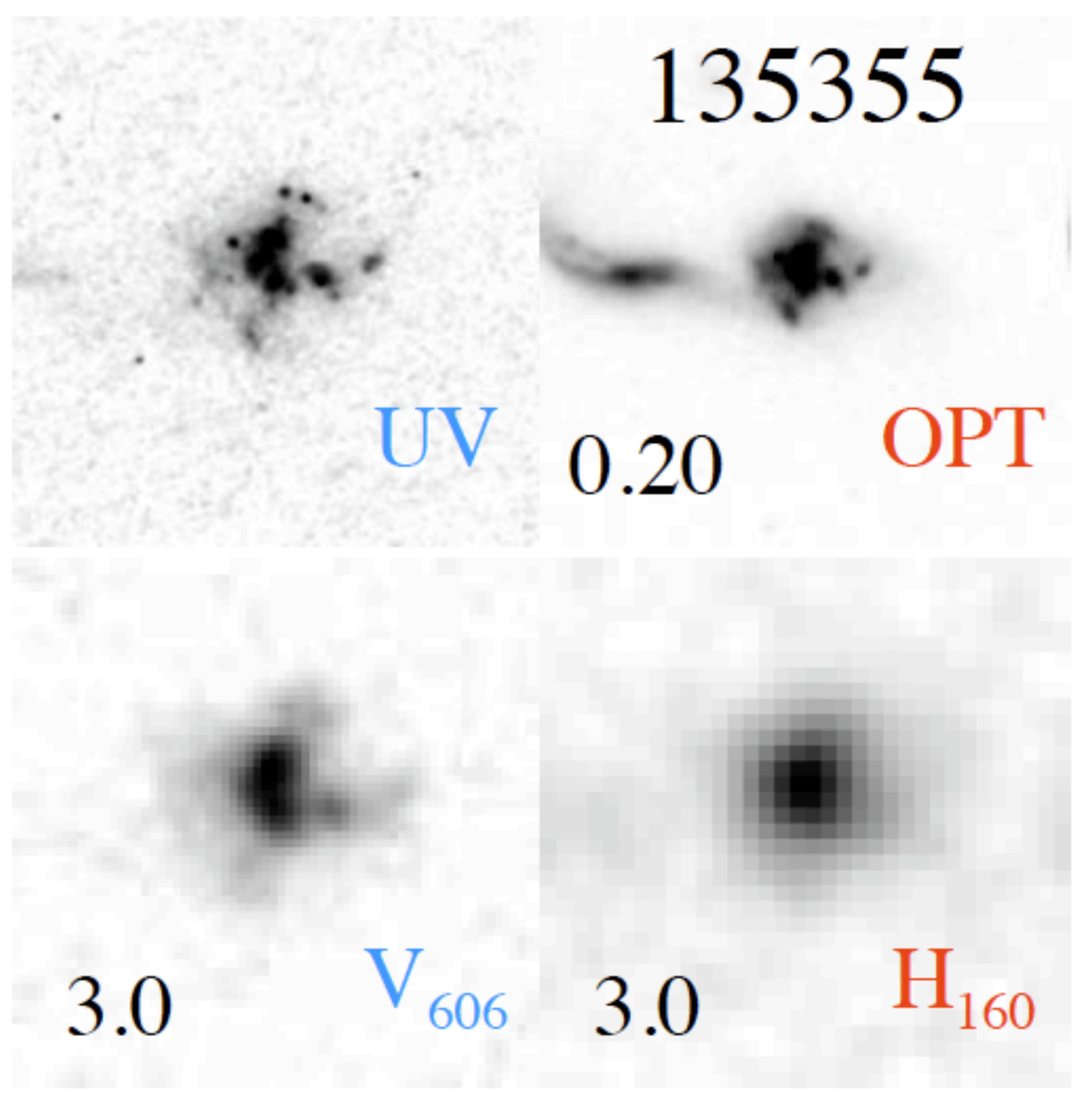

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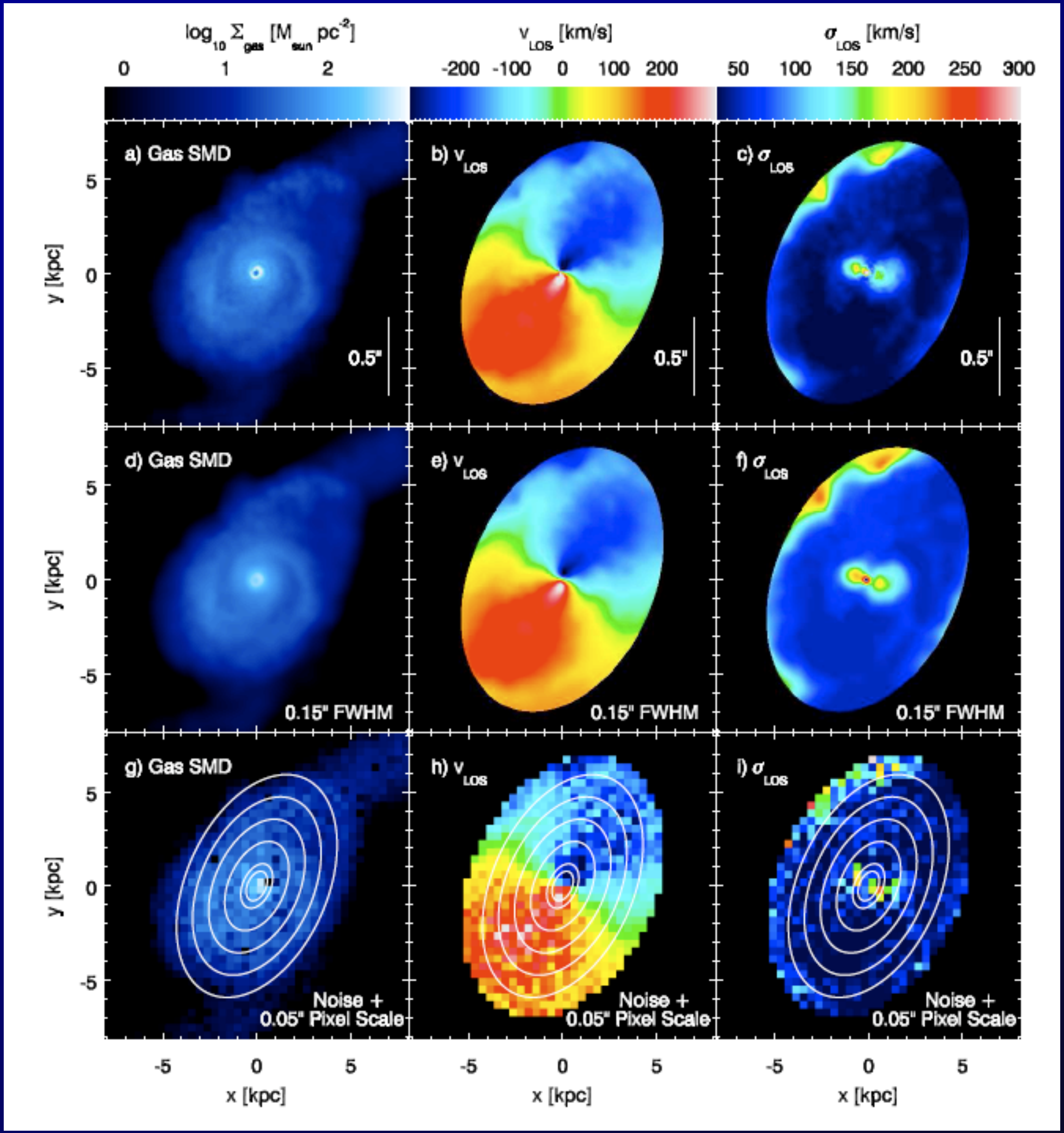

Robertson & Bullock (2008)

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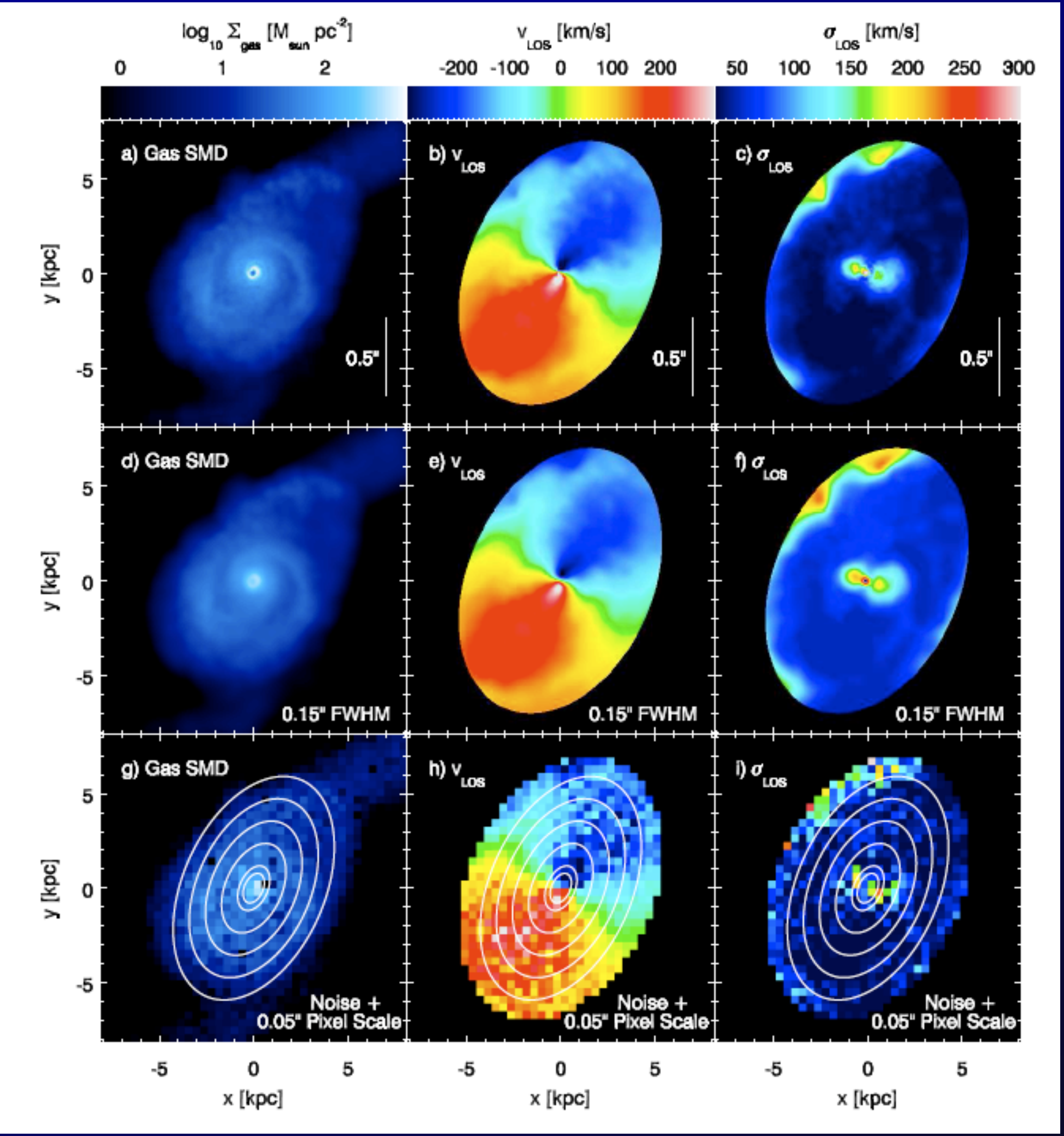
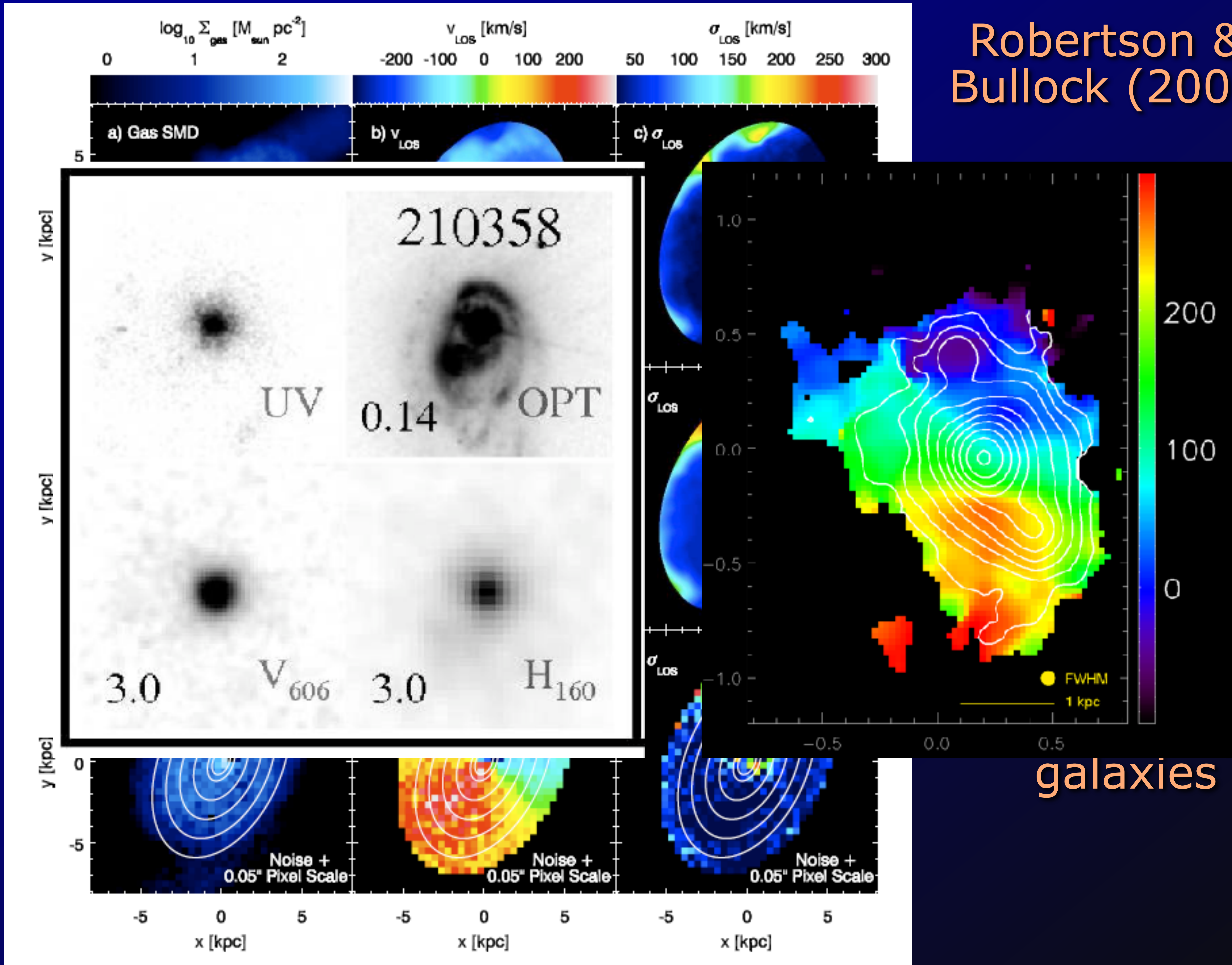


THIS IS A MERGER

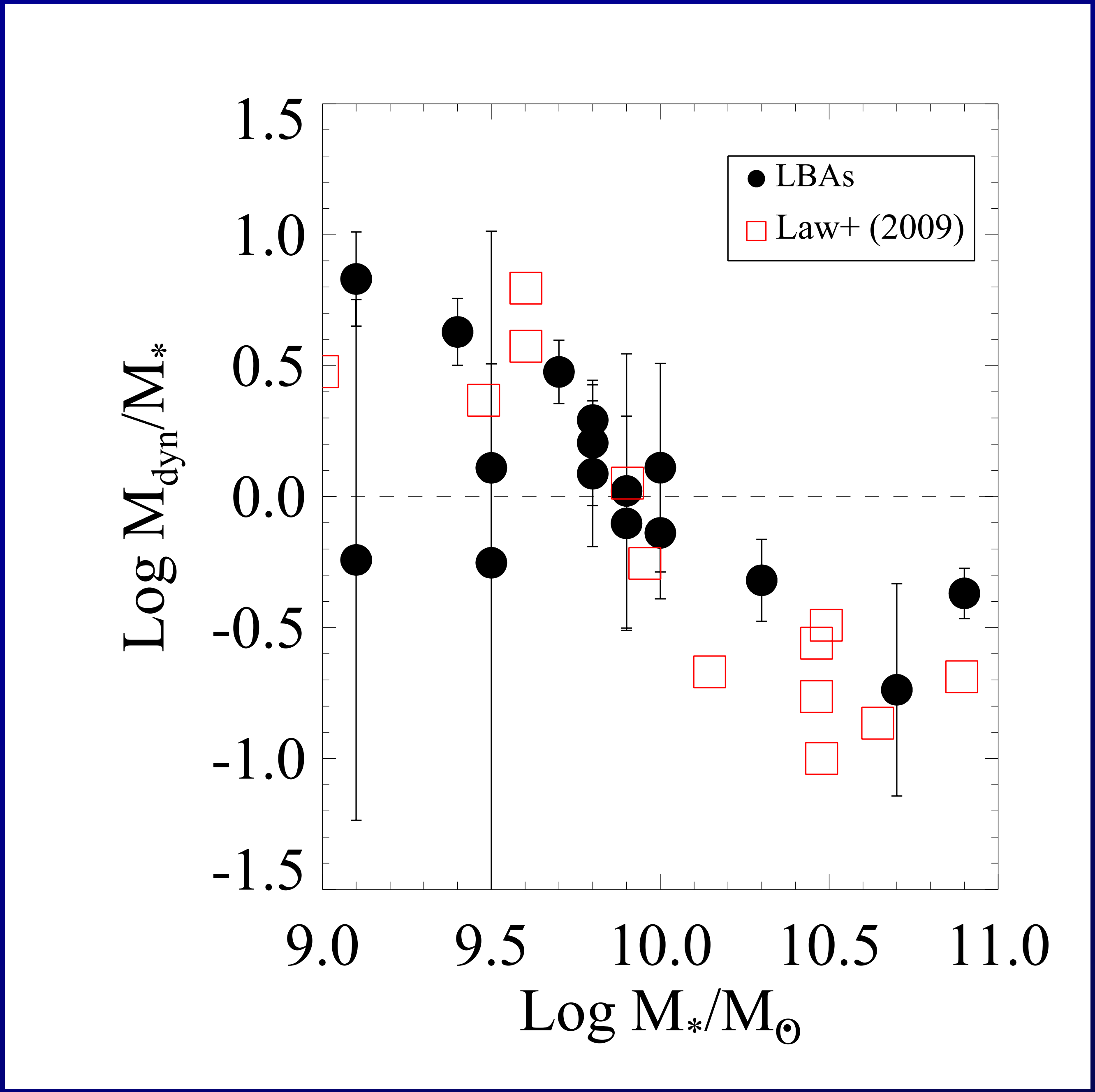
Kinematic properties depend on gas fraction of the interacting galaxies

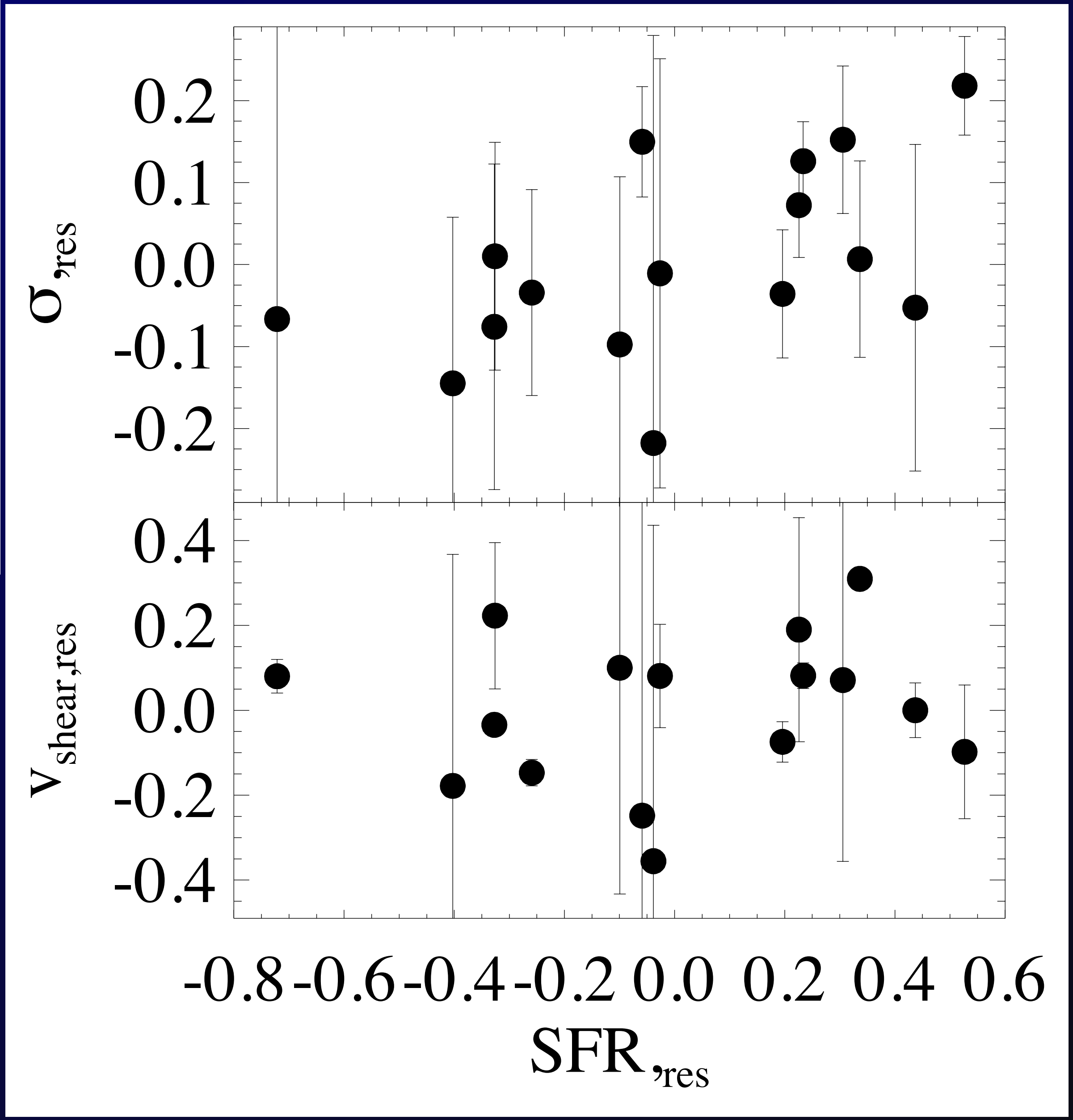
Robertson & Bullock (2008)



as
ne
galaxies

Dynamical mass (σ)





The impact of star formation

Gonçalves+10

Environment of LBAs

What is the environment of LBAs?

Luidhy Santana da Silva, PhD student

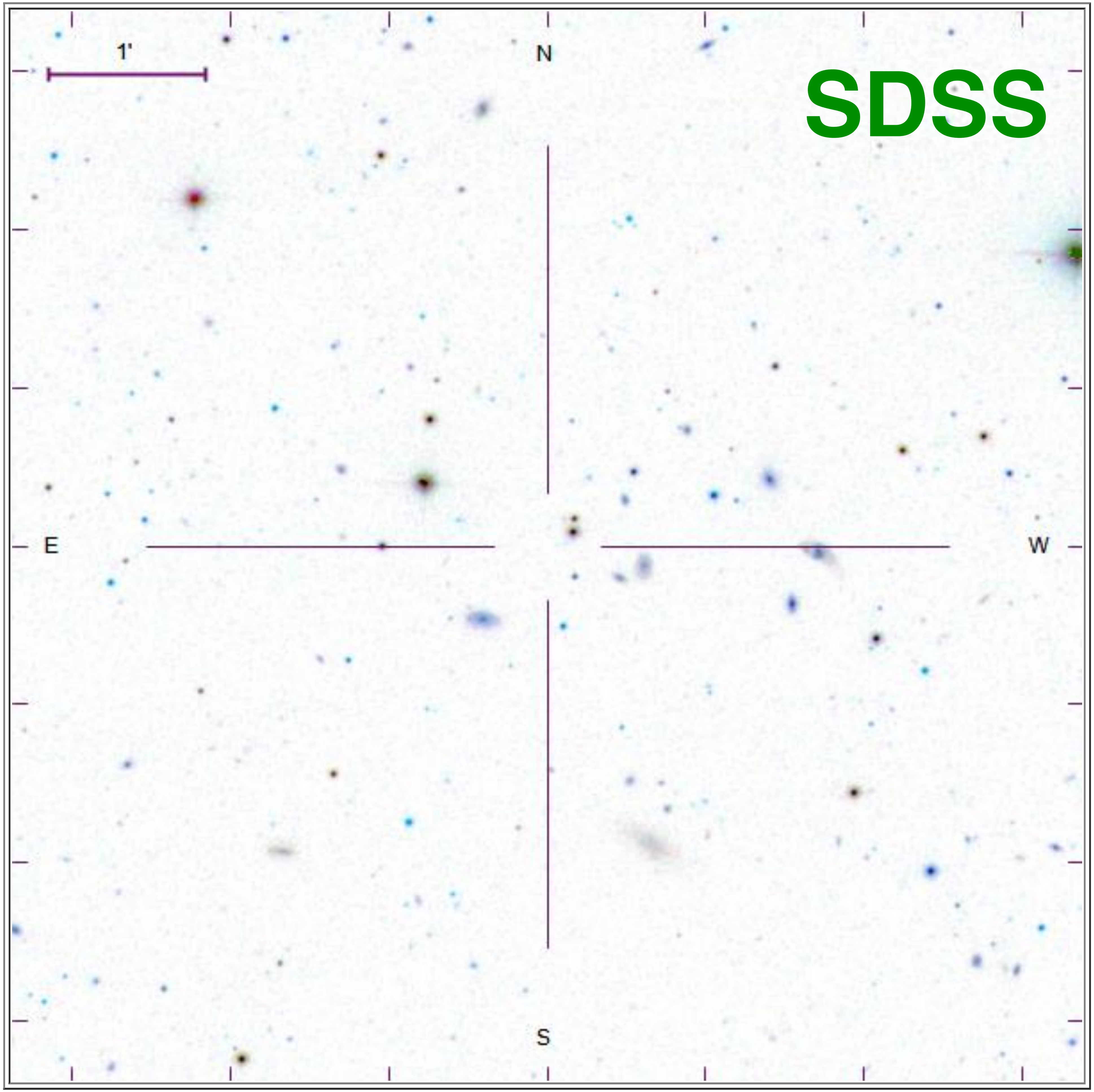
The ELBA/DECam survey:

- 3 sq. degrees at a time
- 4 bands (*u,g,r,i*)
- equatorial fields
- detection limits (10-σ AB, estimated):

25.0 (*u*), 26.0 (*g*), 25.5 (*r*), 24.5 (*i*)

(complete at z~0.2 down to 10^9 M_sun)

- 27 sq. degrees completed thus far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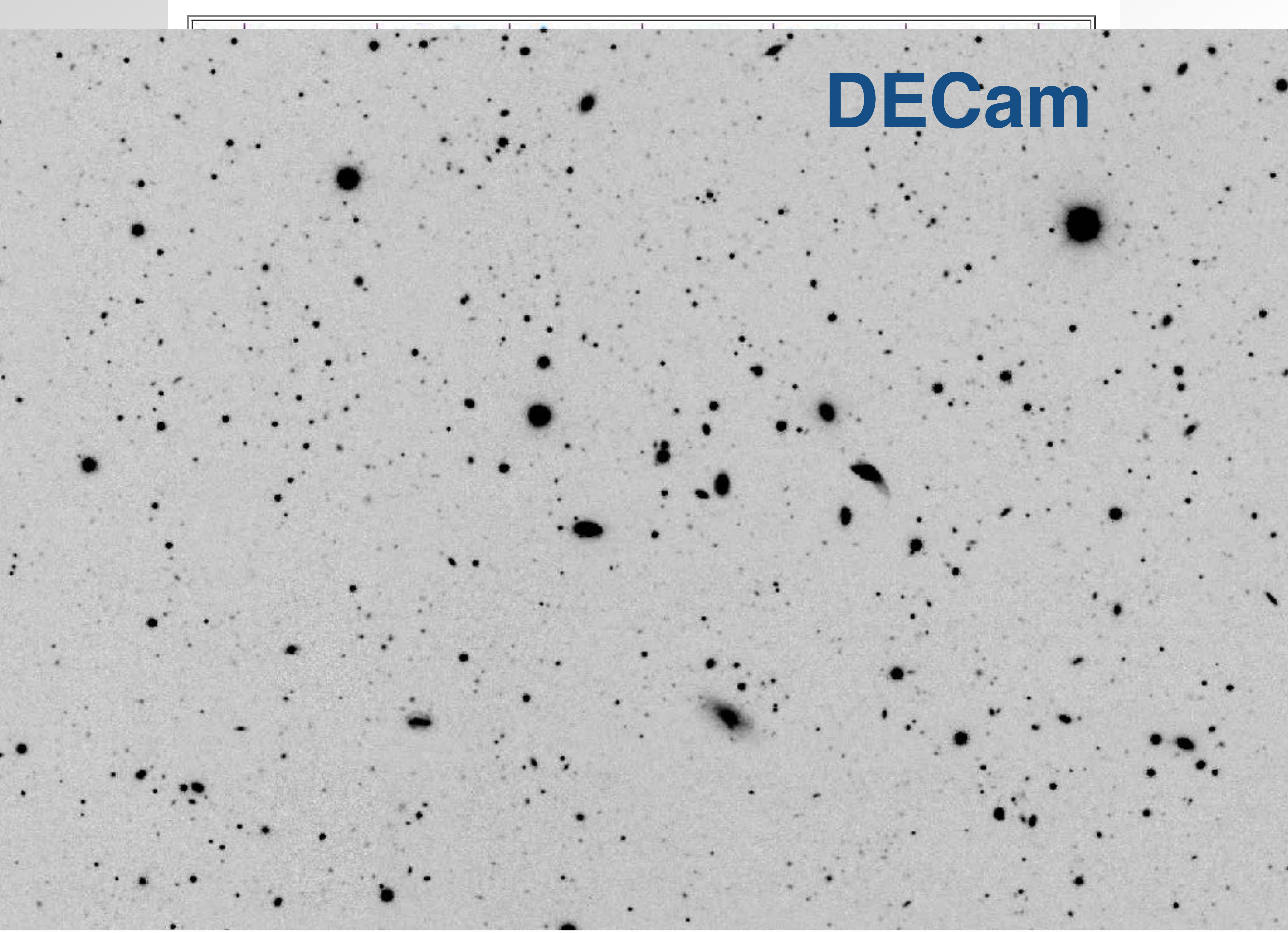
DECam

Summary

- Dark matter is taken for granted when it comes to galaxy formation studies, but it is fundamentally important
- The formation of structures across cosmic time is heavily influenced by the dark matter content. How can we measure this?
- The same is true for galaxy formation within dark matter haloes

Summary

- Dark matter is taken for granted when it comes to galaxy formation studies, but it is fundamentally important

- The formation of structures across cosmic time is heavily influenced by the dark matter content. How can we measure this?

- The same is true for galaxy formation within dark matter haloes