Fifty Years of Secular Evolution in Galaxies

Where do we stand?

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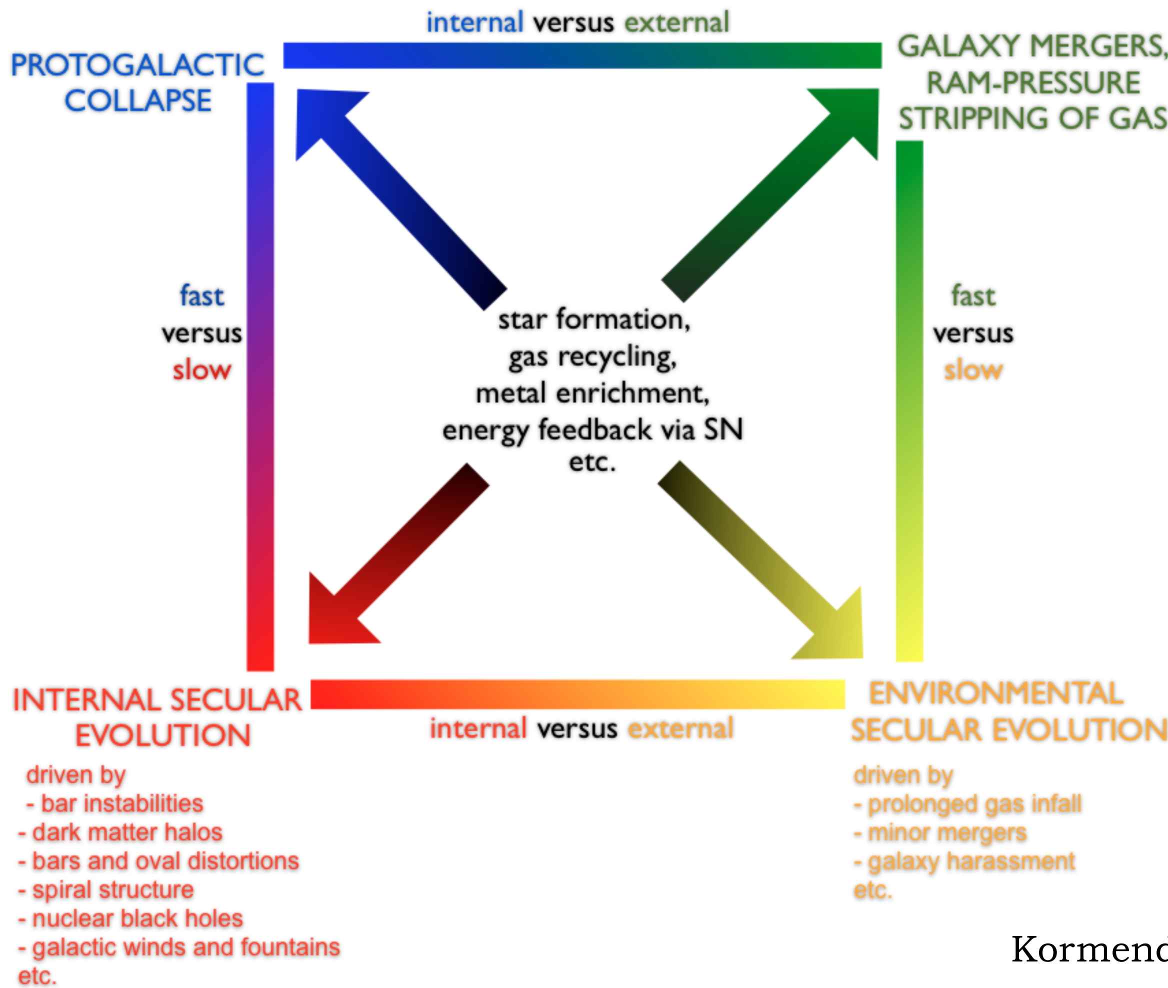
Questions for Discussion

- What do we expect from theoretical considerations?
  - How to compare observations with models?
- What aspects of secular evolution seem to be corroborated with observations?
- What observational results are apparently in contradiction with theoretical expectations?
- What aspects of secular evolution are important to investigate in depth now?

Nota Bene

This is about *internal* secular evolution.



Kormendy & Kennicutt 2004

A Bit of History

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STELLAR DYNAMICS

Potentials with Isolating Integrals

D. Lynden-Bell

(Received 1962 January 25)*

A Bit of History

GAS STREAMING IN BARRED SPIRAL GALAXIES

K. C. Freeman

(Communicated by L. Mestel)

(Received 1964 June 23)

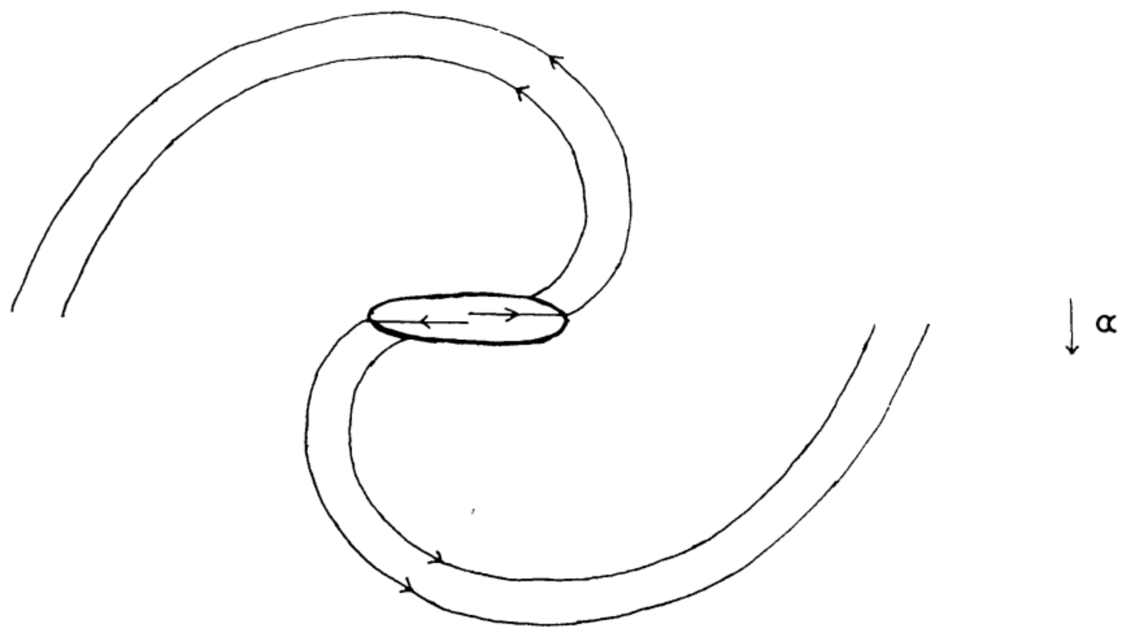


FIG. 1.—*Some streamlines for gas flow under the gravitational potential of a prolate spheroid with axial ratio 5.*

A Bit of History

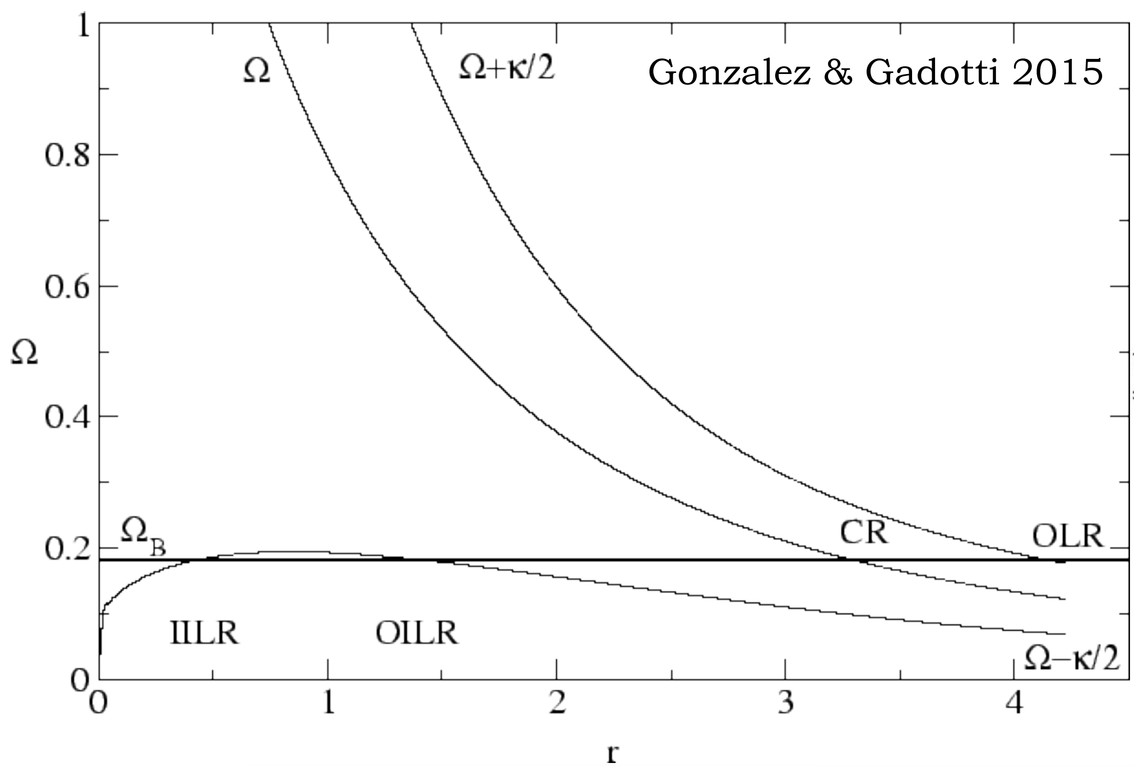
- Many subsequent studies adding more details such as the collisional nature of gas find that shocks lead to a net *inflow* of gas toward the central regions (e.g. Schwarz 1979; Prendergast 1983). These simulations had already shown that gas is brought to the centre fast (~ 10^8 yrs). This is corroborated with modern simulations (e.g. Berentzen+2003; Emsellem+2015).

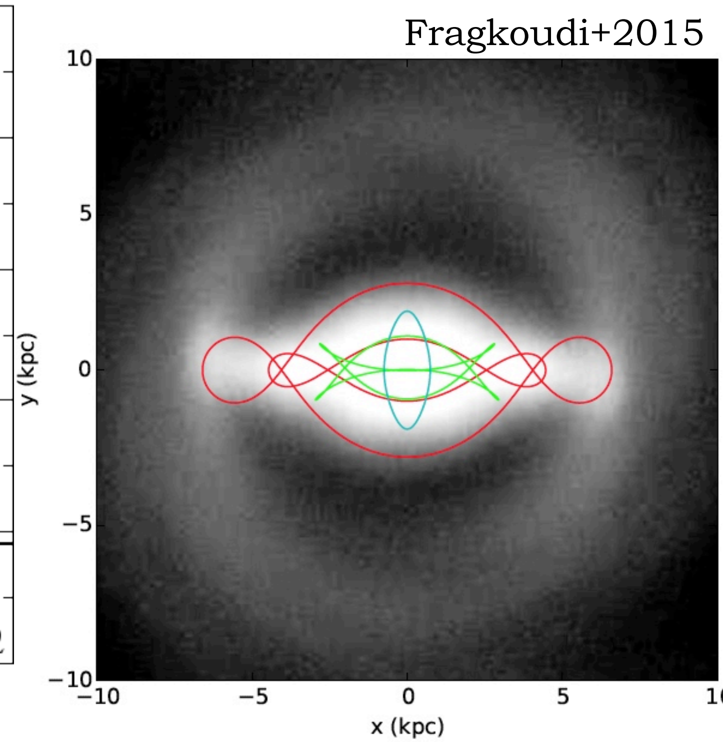
- Simkin, Shu and Schwarz (1980) suggest that bars can feed AGN.

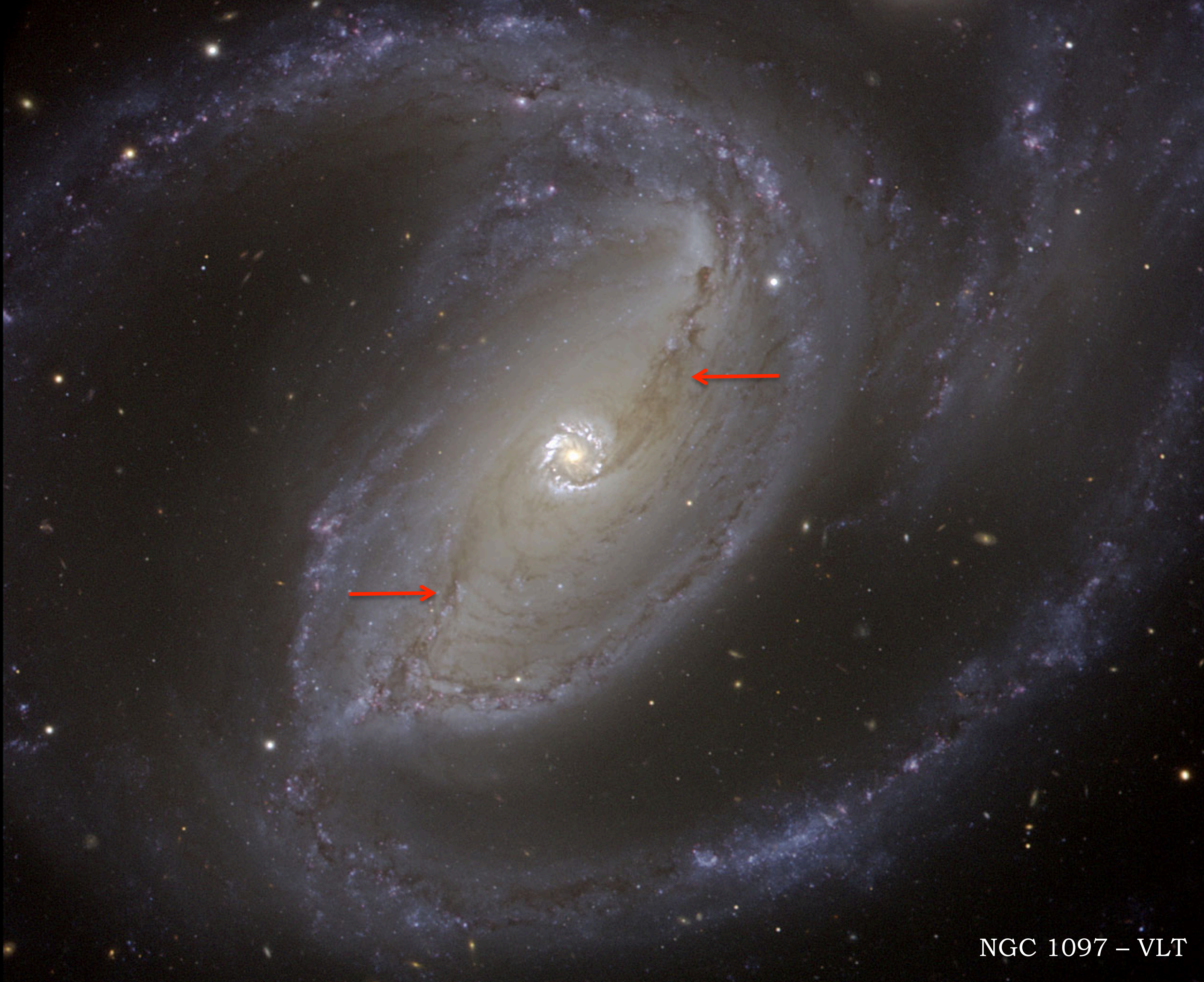
- Kormendy (1982) suggests that the gas inflow through the bar may originate a central stellar structure that rotates like a disc.

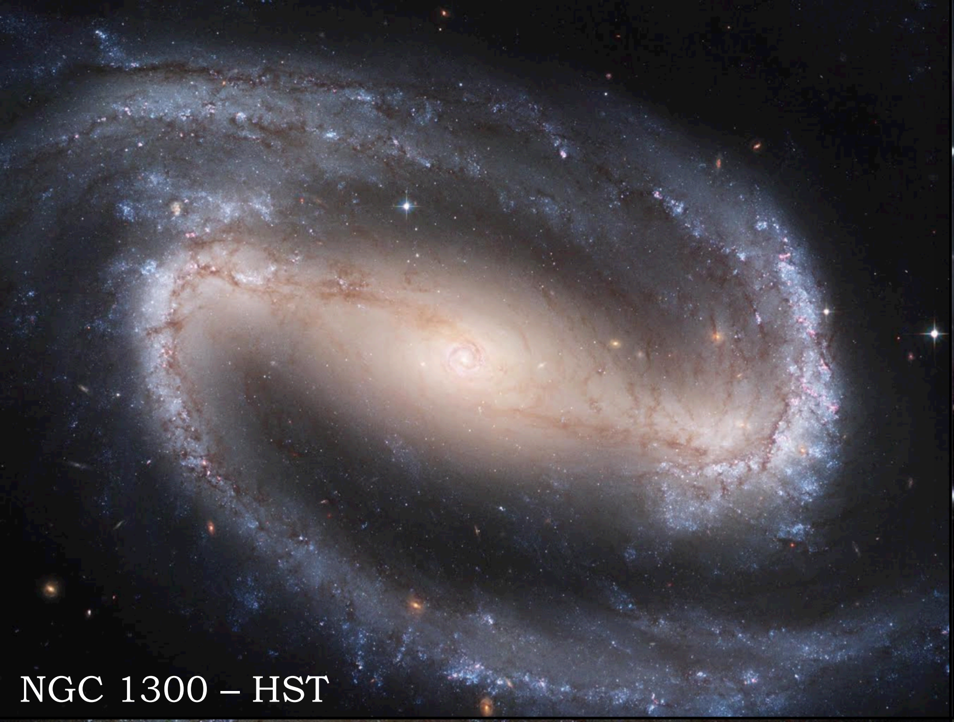
The Secular Evolution Paradigm

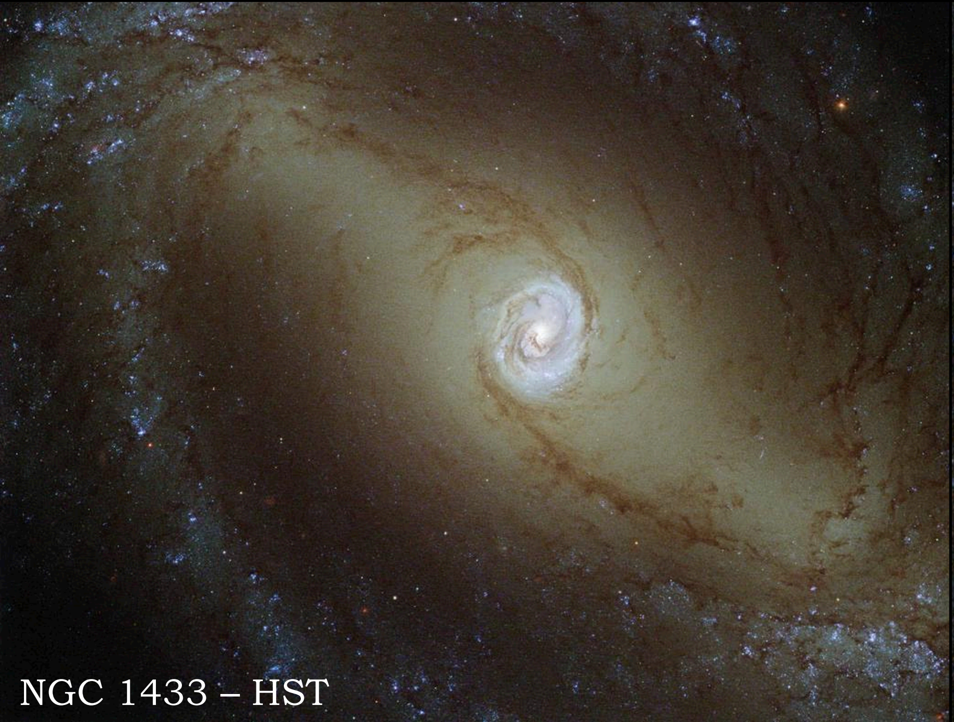
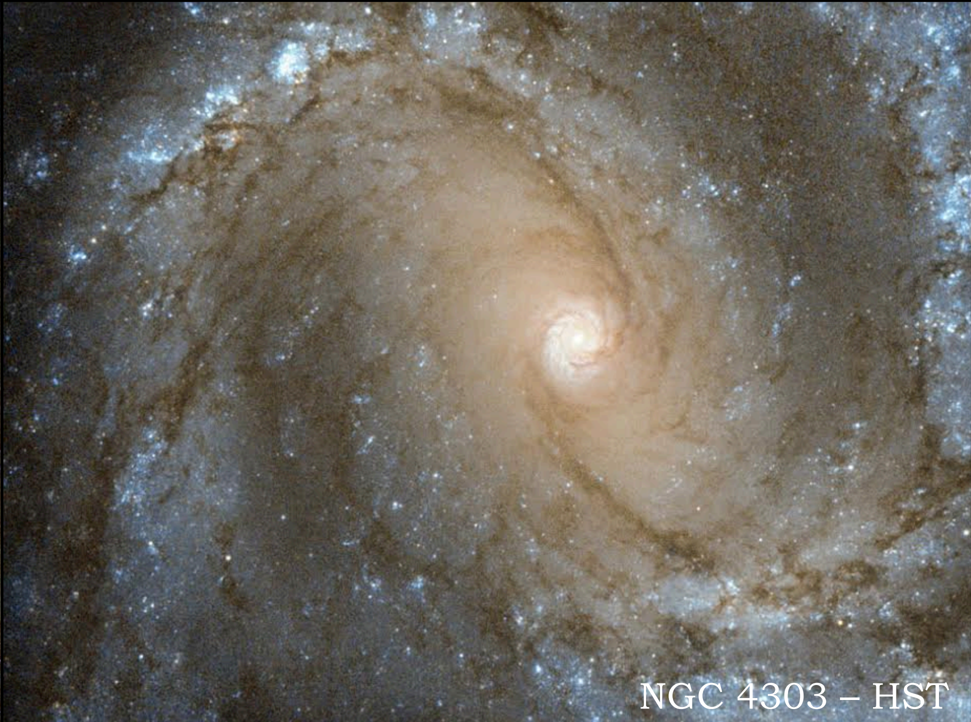
- Non-axisymmetric structures in disc galaxies – mostly bars but to some extent also spiral arms – drive angular momentum outwards. Stellar systems must evolve to a minimum energy state (see e.g. globular clusters: equipartition of energy, mass segregation, core-collapse). In disc galaxies, that's the role of internal secular evolution. (See e.g. Athanassoula 2003.)





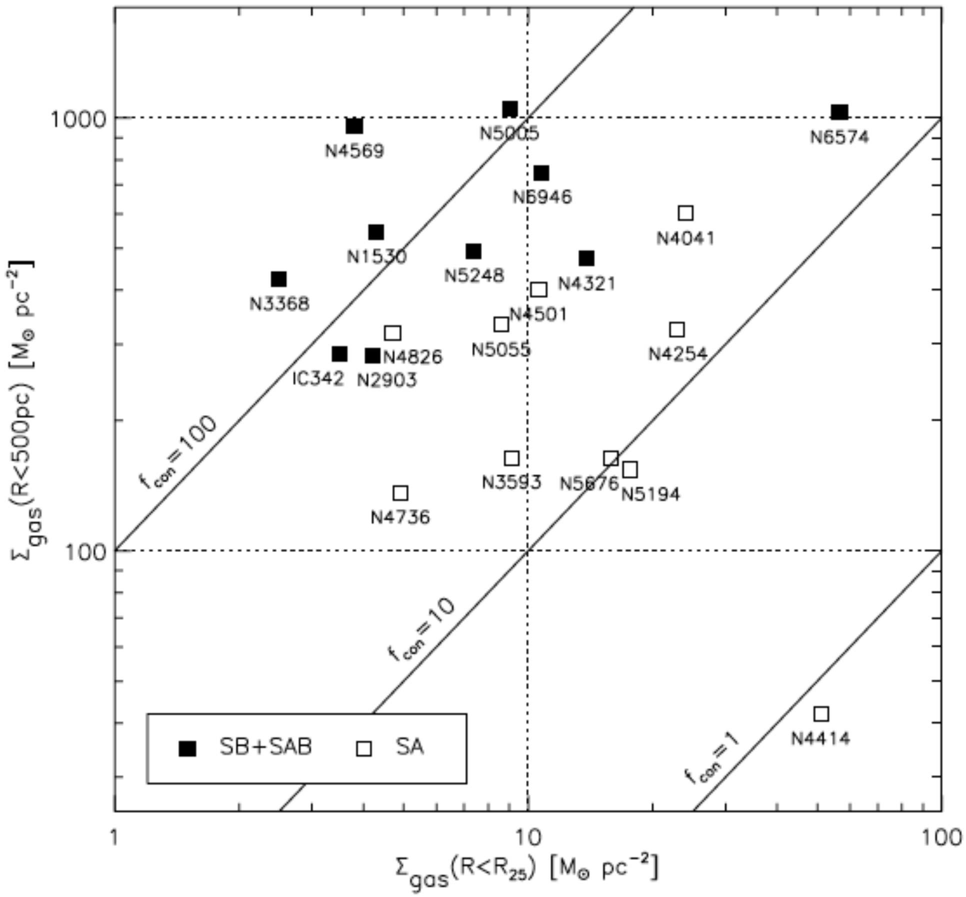

NGC 1097 – VLT


NGC 1300 – HST

NGC 1365 – SSRO

NGC 1433 – HST

NGC 4303 – HST

Secularly-Built Inner Structures

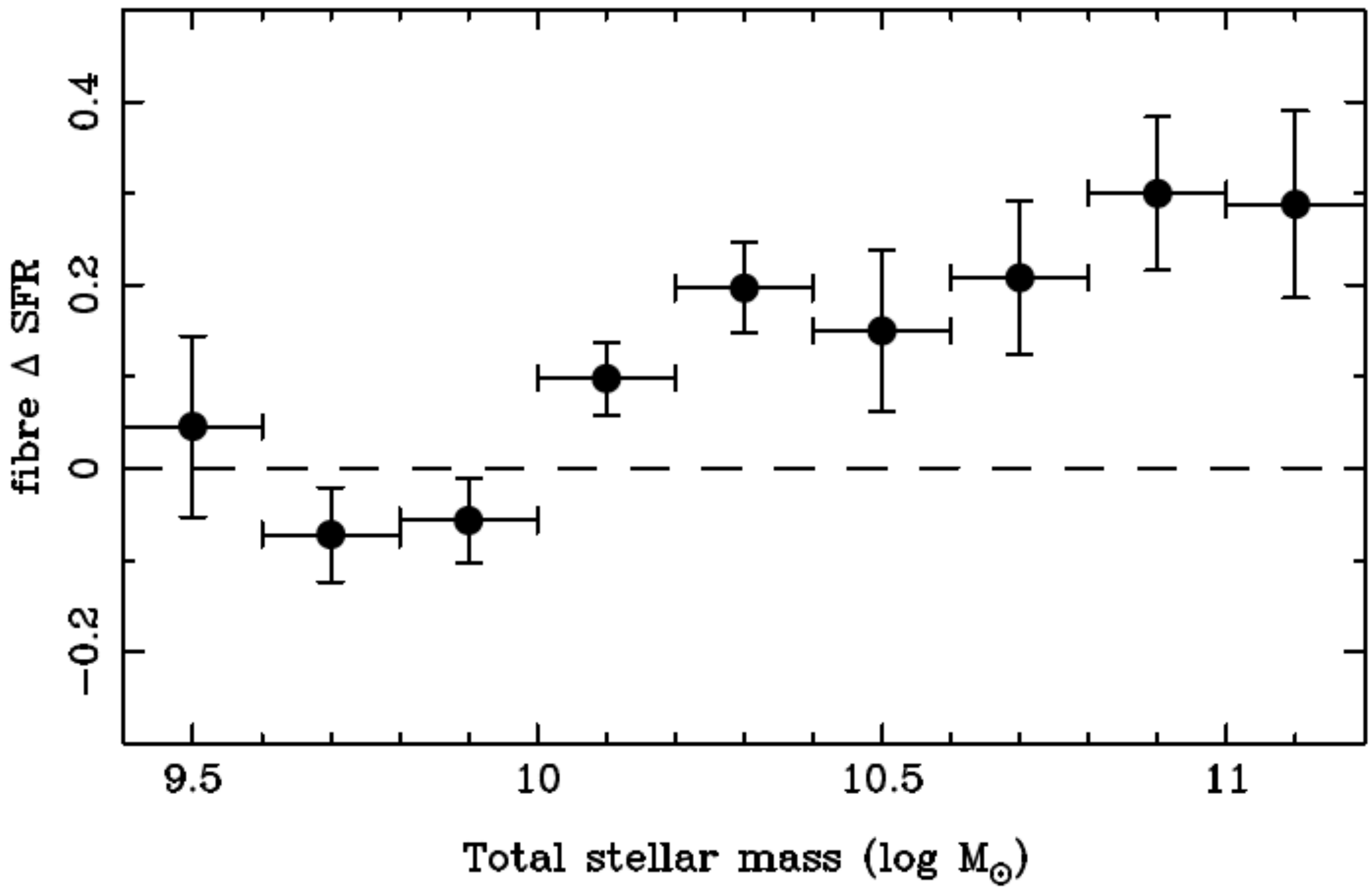
There is evidence for a net inflow of (molecular) gas to the central regions in barred galaxies, more important than in unbarred galaxies (see e.g. Sakamoto+1999; Sheth+2005).



Sakamoto+1999

Secularly-Built Inner Structures

Current formation of stars appears enhanced in the centres of barred galaxies (see Huang+1996; Ho+1997; Alonso-Herrero & Knapen 2001; Ellison+2011).



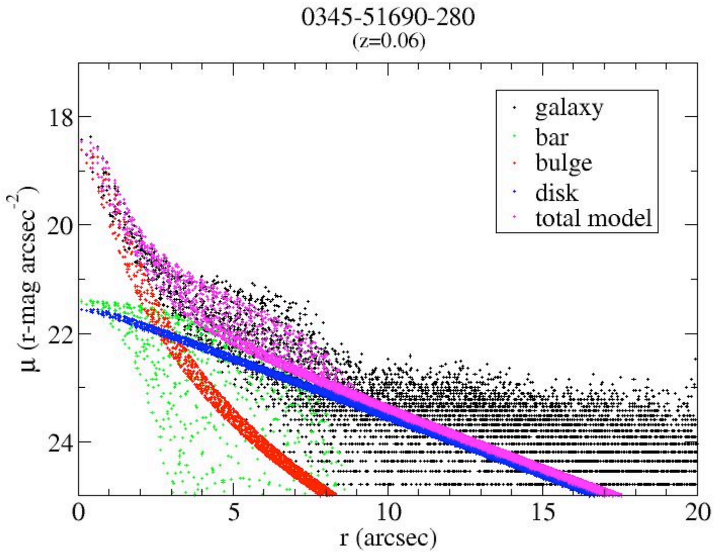
Ellison+2011

Secularly-Built Inner Structures

But are stars generally younger in the centres of barred galaxies? To answer this question one should compare the mean stellar ages of bulges in matched samples of barred and unbarred galaxies. That's what we did in Coelho & Gadotti (2011).

Secularly-Built Inner Structures

- SDSS data (Gadotti 2009)
  - $0.02 \leq z \leq 0.07$
  - $M_\star \geq 10^{10}\ M_\odot$
  - $b/a > 0.9$
  - 575 bulges
  - 2D *g*, *r*, *i* bulge/bar/disc – individually checked – decompositions with BUDDA (de Souza+2004; Gadotti 2008)



Secularly-Built Inner Structures

- Bar classification by visual inspection of image, 2D surface brightness radial profile and isophotal contours

- SDSS fibre spectra

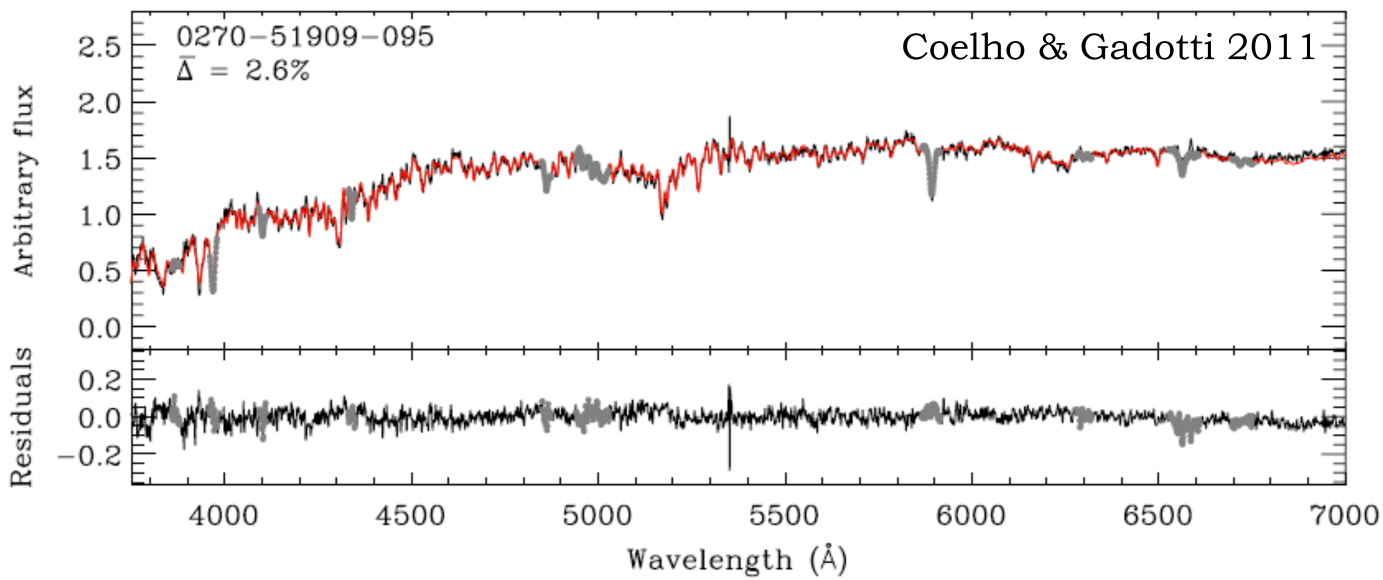
- Bulge stellar masses are determined

- Disc contamination inside the fibre is measured (it’s low, typically below 20%)

- Samples of barred and unbarred galaxies are matched in *bulge* mass and disc contamination in the fibre (never done previously)

Secularly-Built Inner Structures

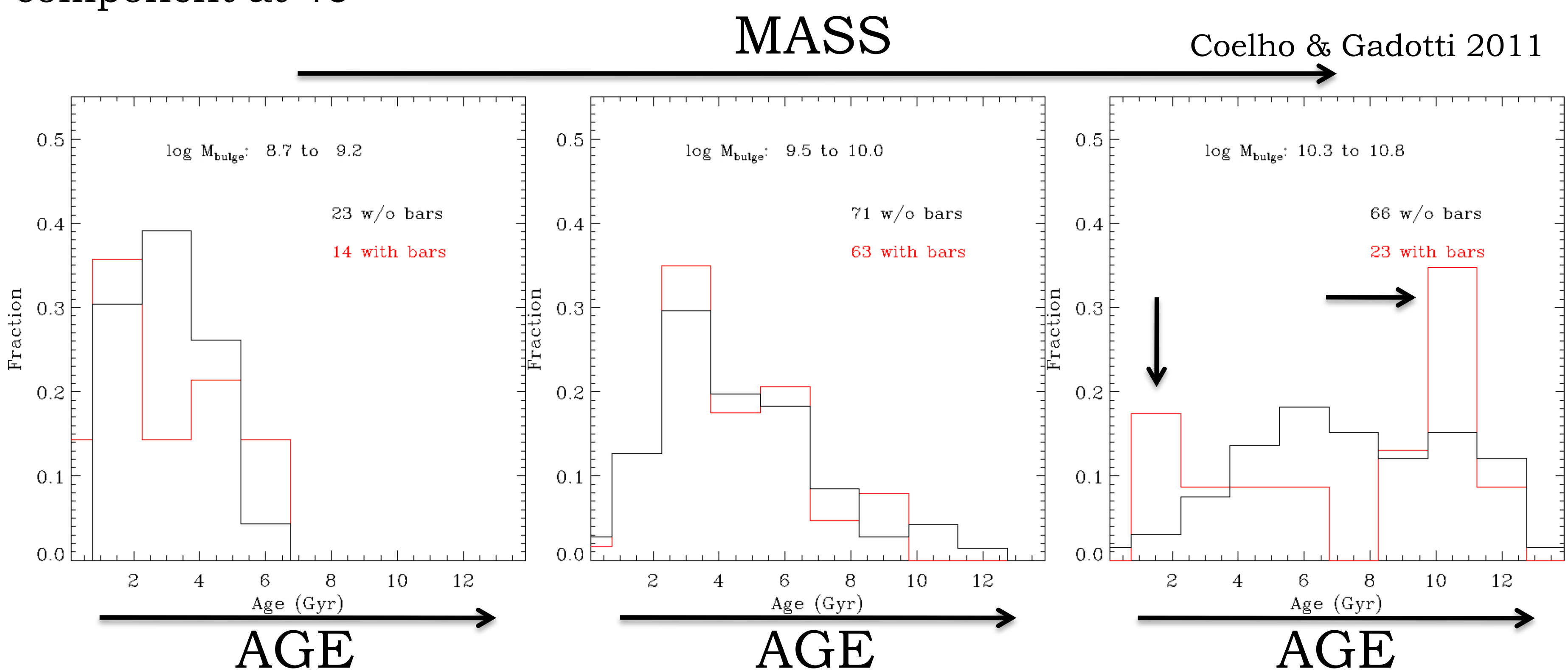
- Spectral fitting w/ STARLIGHT (Cid Fernandes+2005)
  - S/N > 10, typically ~ 20 per Angstrom



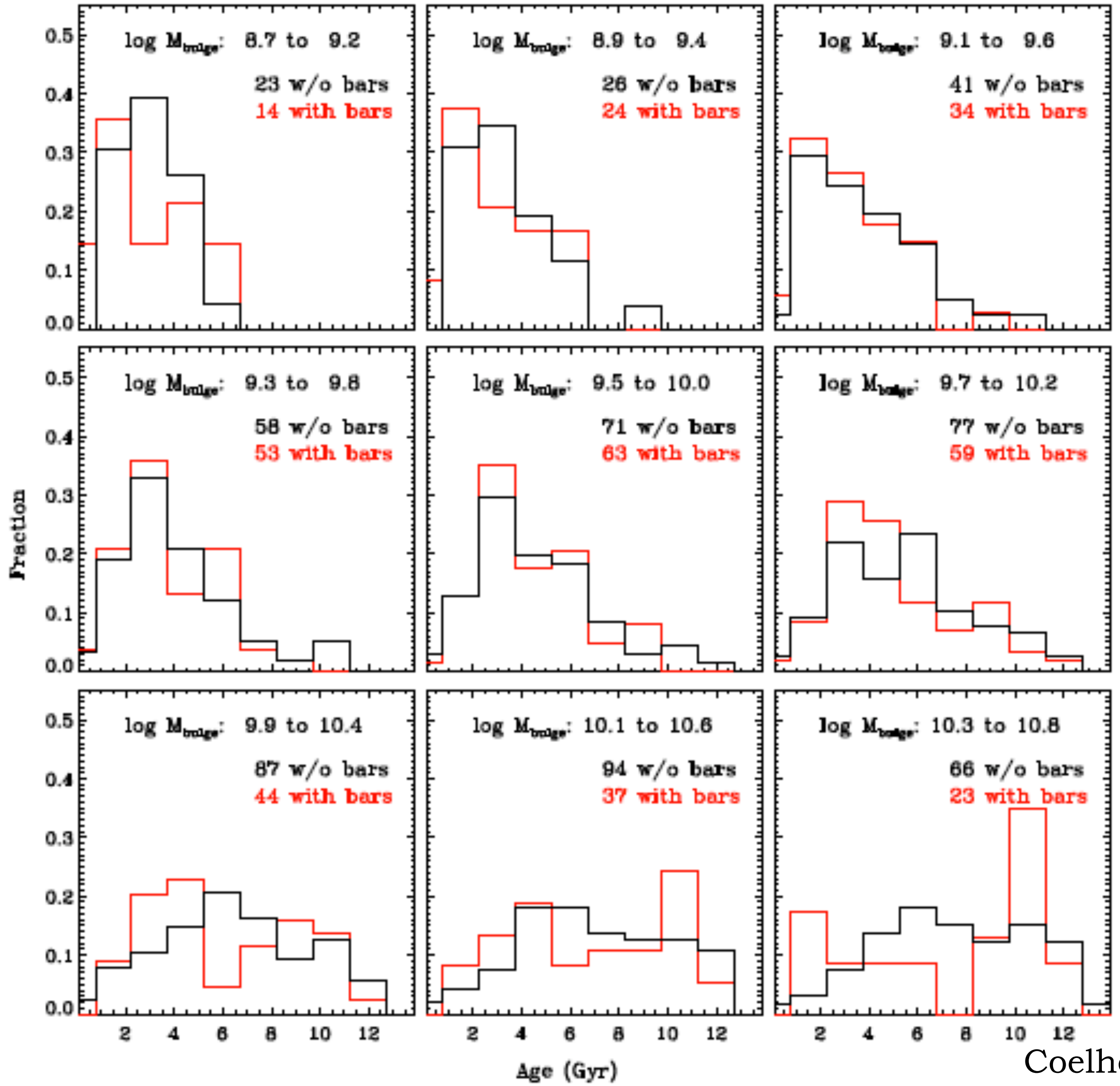
Secularly-Built Inner Structures

- ➢ Distributions of bulge mean stellar ages for barred and unbarred galaxies in bins of same bulge mass

- ➢ Bulges in non-AGN massive barred galaxies show bimodality and younger component at 4σ



Secularly-Built Inner Structures



Coelho & Gadotti 2011

Secularly-Built Inner Structures

- Bars feeding AGN:

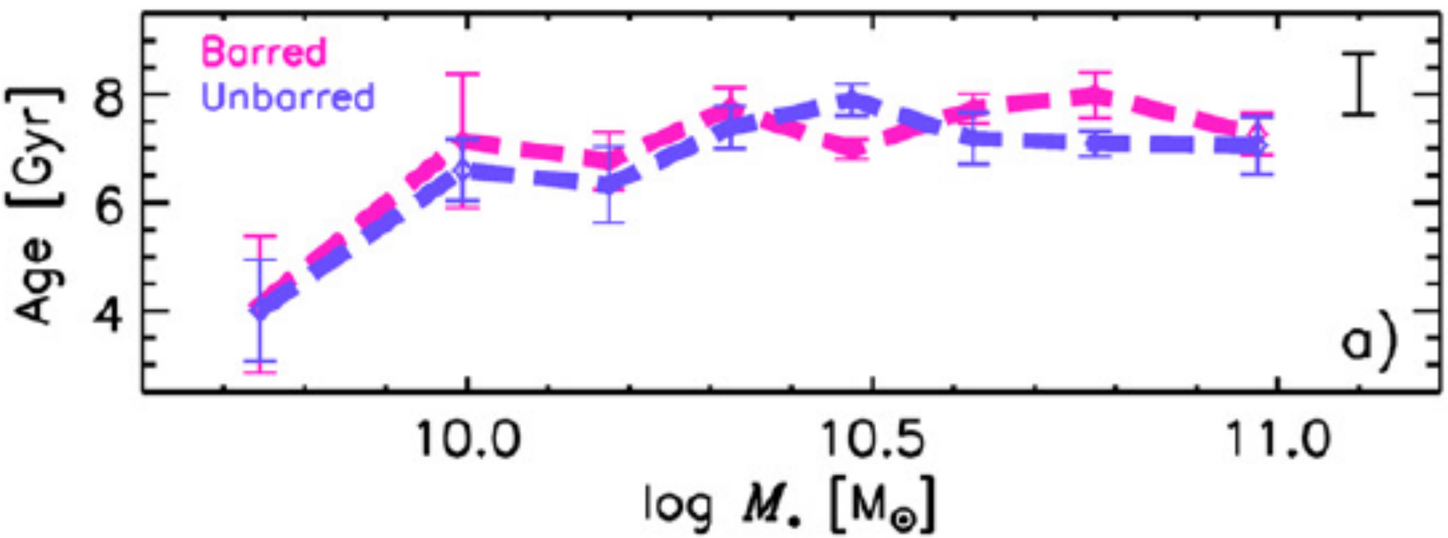
low bulge mass bin:	35% of barred galaxies are AGN 16% of unbarred galaxies are AGN
high bulge mass bin:	55% of barred galaxies are AGN 34% of unbarred galaxies are AGN

- How come we find this?

    - Homogeneous and good data
    - Sample selection
    - Bar and AGN classifications consistent (Gadotti 2009; Kauffmann +2003)

Secularly-Built Inner Structures

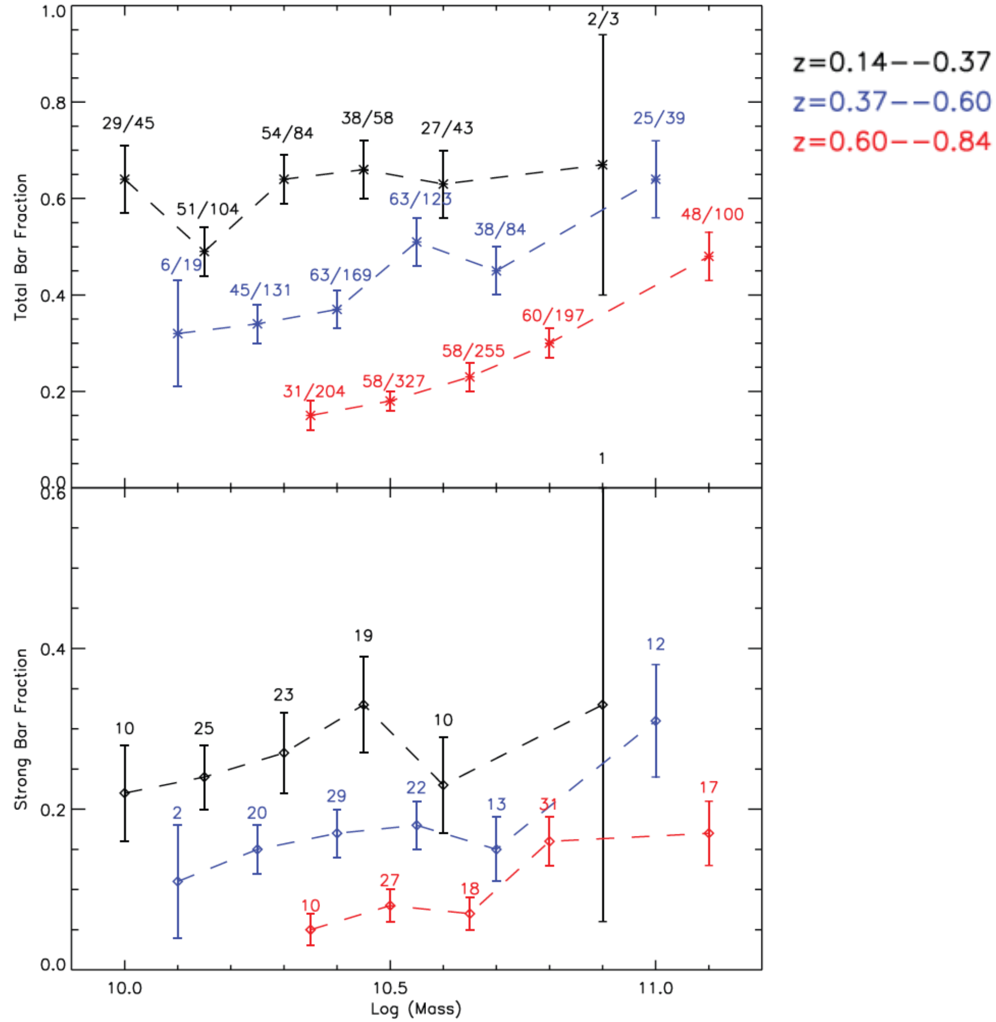
But there are opposing results in the literature (see e.g. Cacho+2014; Cheung+2015).



Cheung+2015

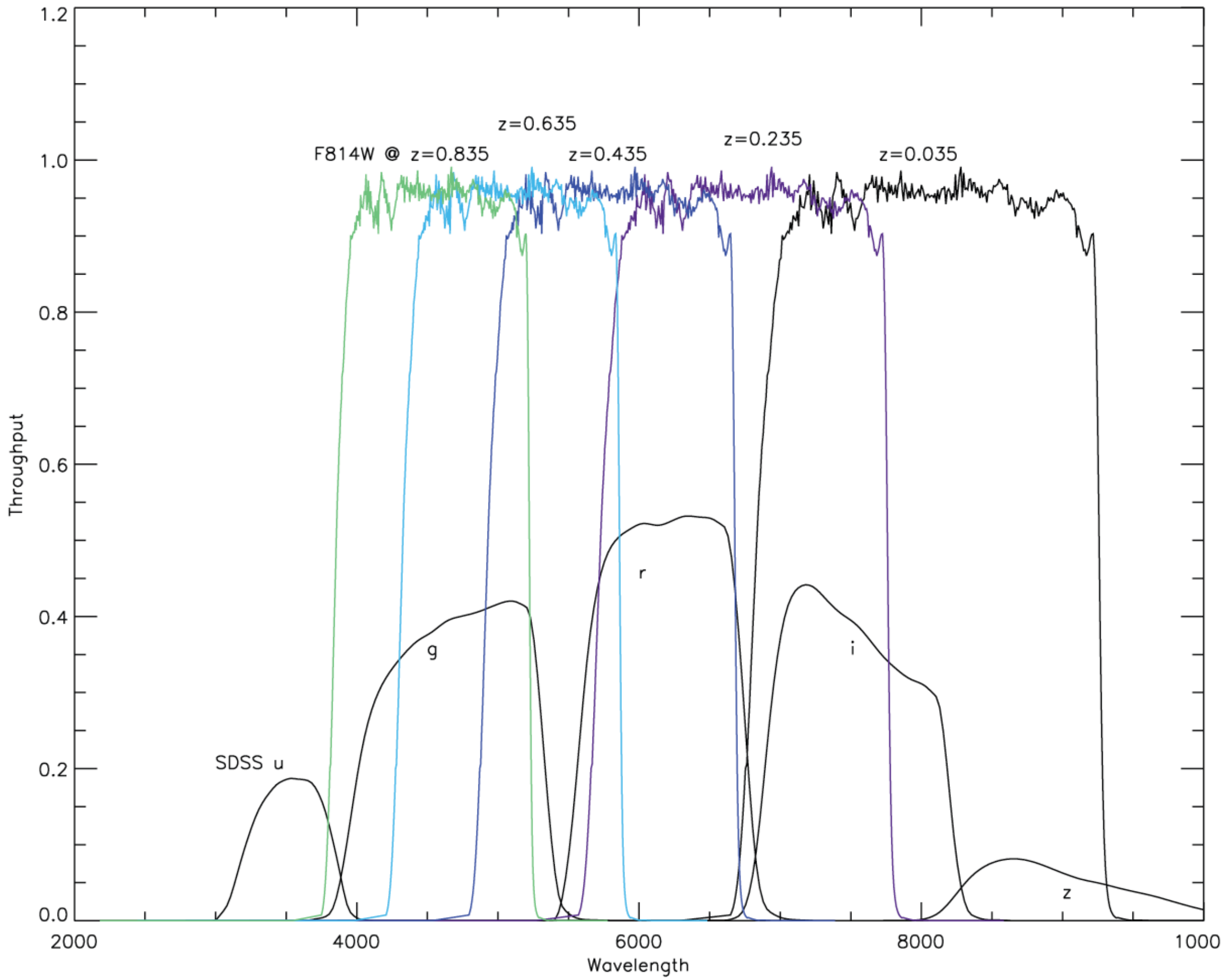
Bars at Higher Redshifts

The fraction of barred galaxies decreases with redshift (see e.g. Sheth +2008; Melvin+2014).



Bars at Higher Redshifts

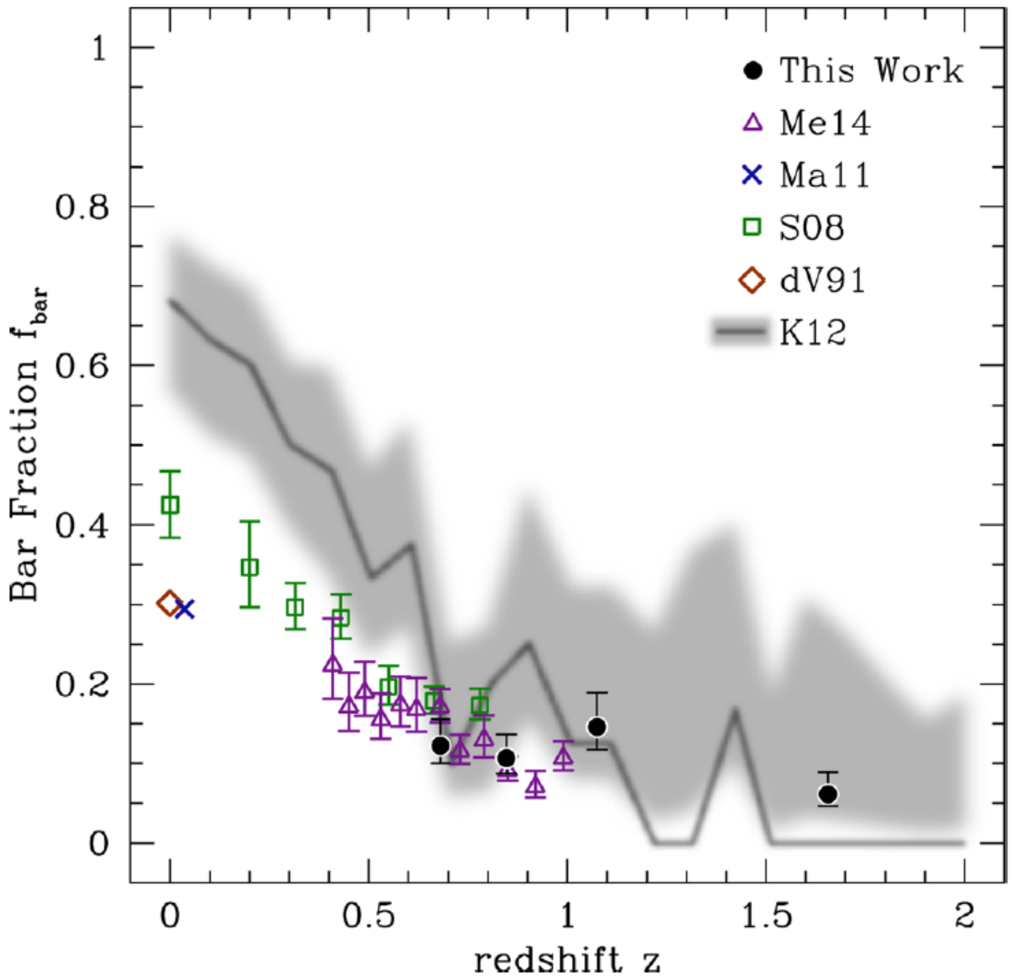
Near-infrared imaging is necessary to go beyond $z \approx 0.8$.



Sheth+2008

Bars at Higher Redshifts

The only study that goes with some reliability above $z = 0.8$ finds a constant (strong) bar fraction of about 10% up to $z \approx 2$ (Simmons+2014).



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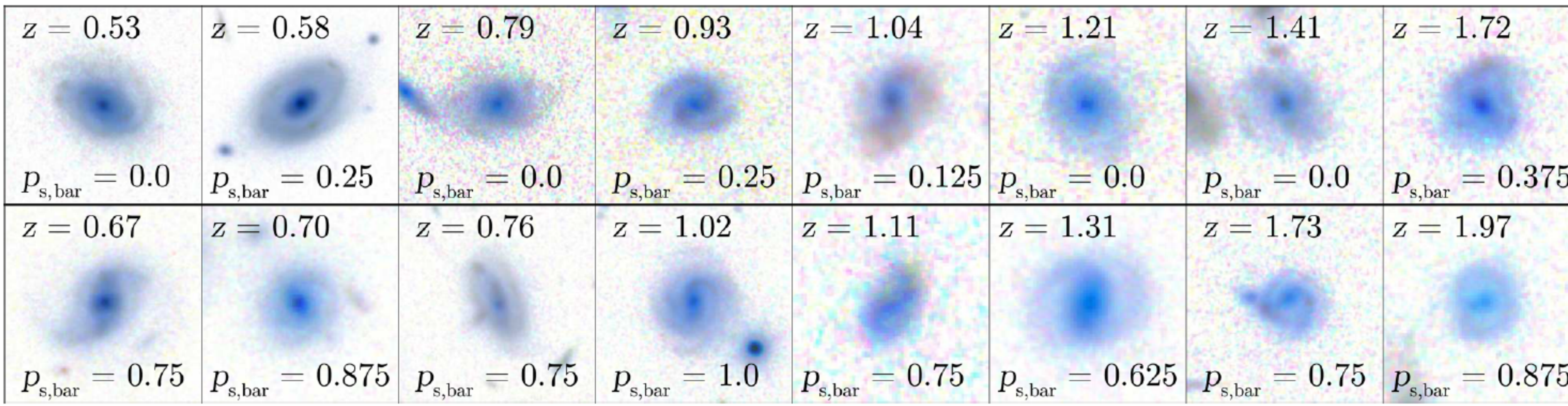
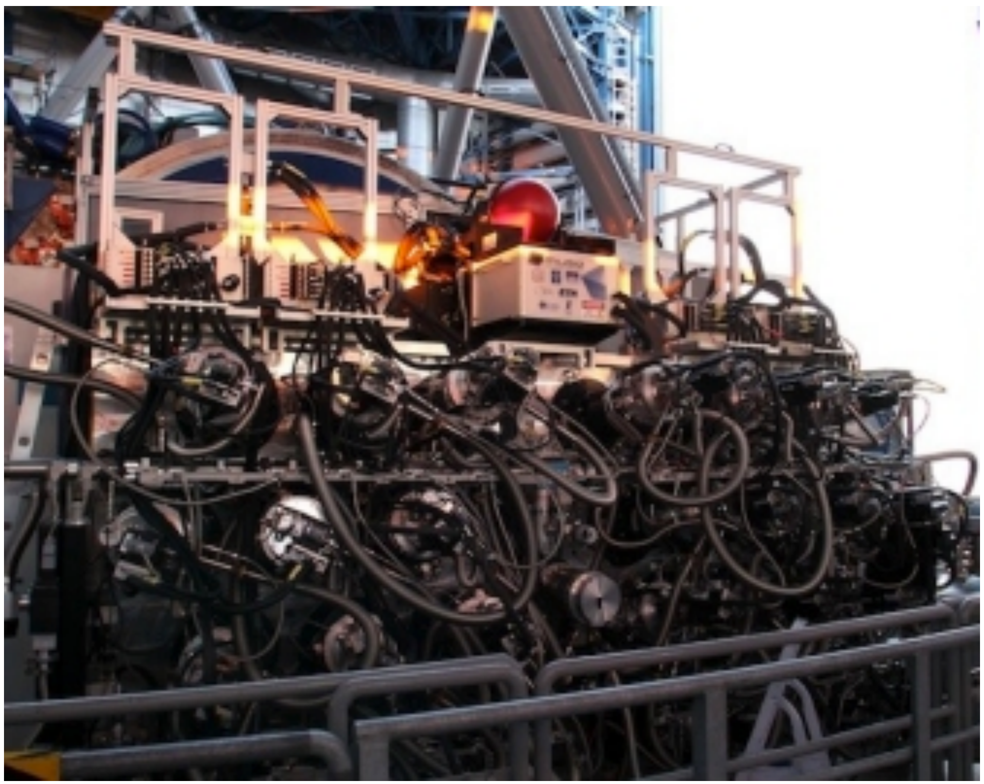


MUSE tells the story of NGC 4371: The dawning of secular evolution

Dimitri A. Gadotti[1], Marja K. Seidel[2,3], Patricia Sánchez-Blázquez[4], Jesus Falcón-Barroso[2,3], Bernd Husemann[5], Paula Coelho[6], and Isabel Pérez[7,8]

Multi Unit Spectroscopic Explorer



Observational Parameters	
Spectral range (simultaneous)	0.465-0.93 μm
Resolving power	2000@0.46 μm
	4000@0.93 μm
Wide Field Mode (WFM)	
Field of view	1x1 $arcmin^2$
Spatial sampling	0.2x0.2 $arcsec^2$
Spatial resolution (FWHM)	0.3-0.4 arcsec
Gain in ensquared energy within one pixel with respect to seeing	2
Condition of operation with AO	70%-ile
Sky coverage with AO	70% at Galactic Pole
Limiting magnitude in 80h	I_{AB} = 25.0 (R=3500)
	I_{AB} = 26.7 (R=180)
Limiting Flux in 80h	3.9 $10^{-19} erg.s^{-1}.cm^{-2}$
Narrow Field Mode (NFM)	
Field of view	7.5x7.5 $arcsec^2$
Spatial sampling	0.025x0.025 $arcsec^2$
Spatial resolution (FWHM)	0.030-0.050 arcsec
Strehl ratio	10-30%
Limiting Flux in 1h	2.3 $10^{-18} erg.s^{-1}.cm^{-2}$
Limiting magnitude in 1h	R_{AB} = 22.3
Limiting surface brightness in 1h	R_{AB} = 17.3 $arcsec^{-2}$

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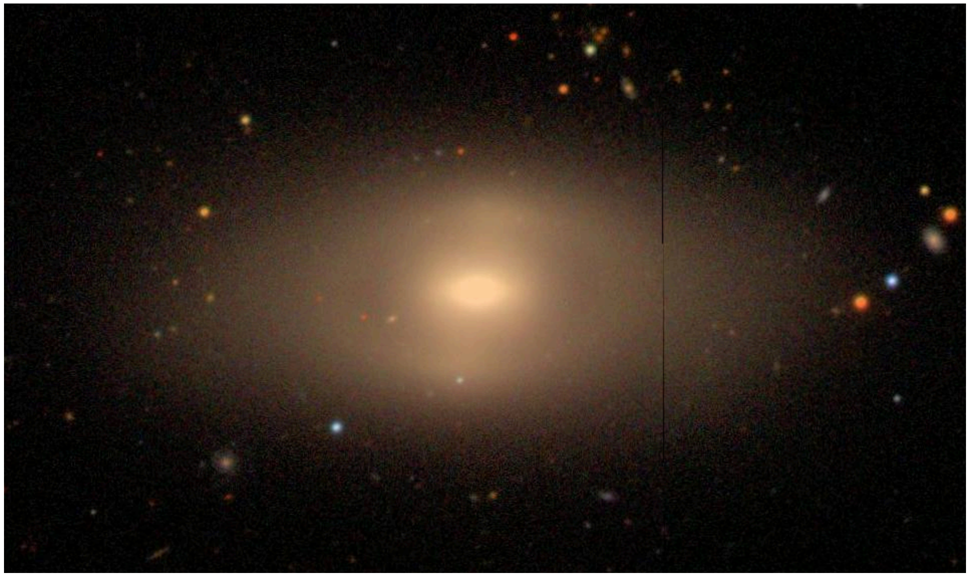

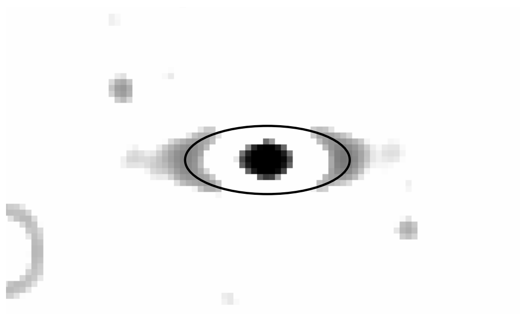

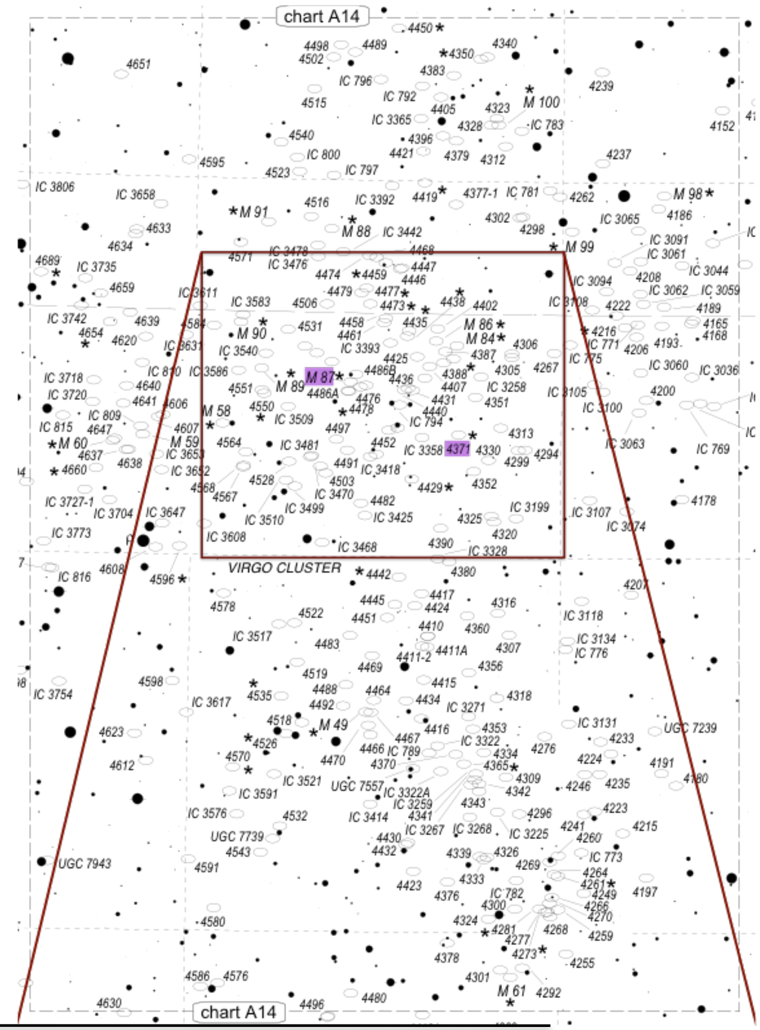

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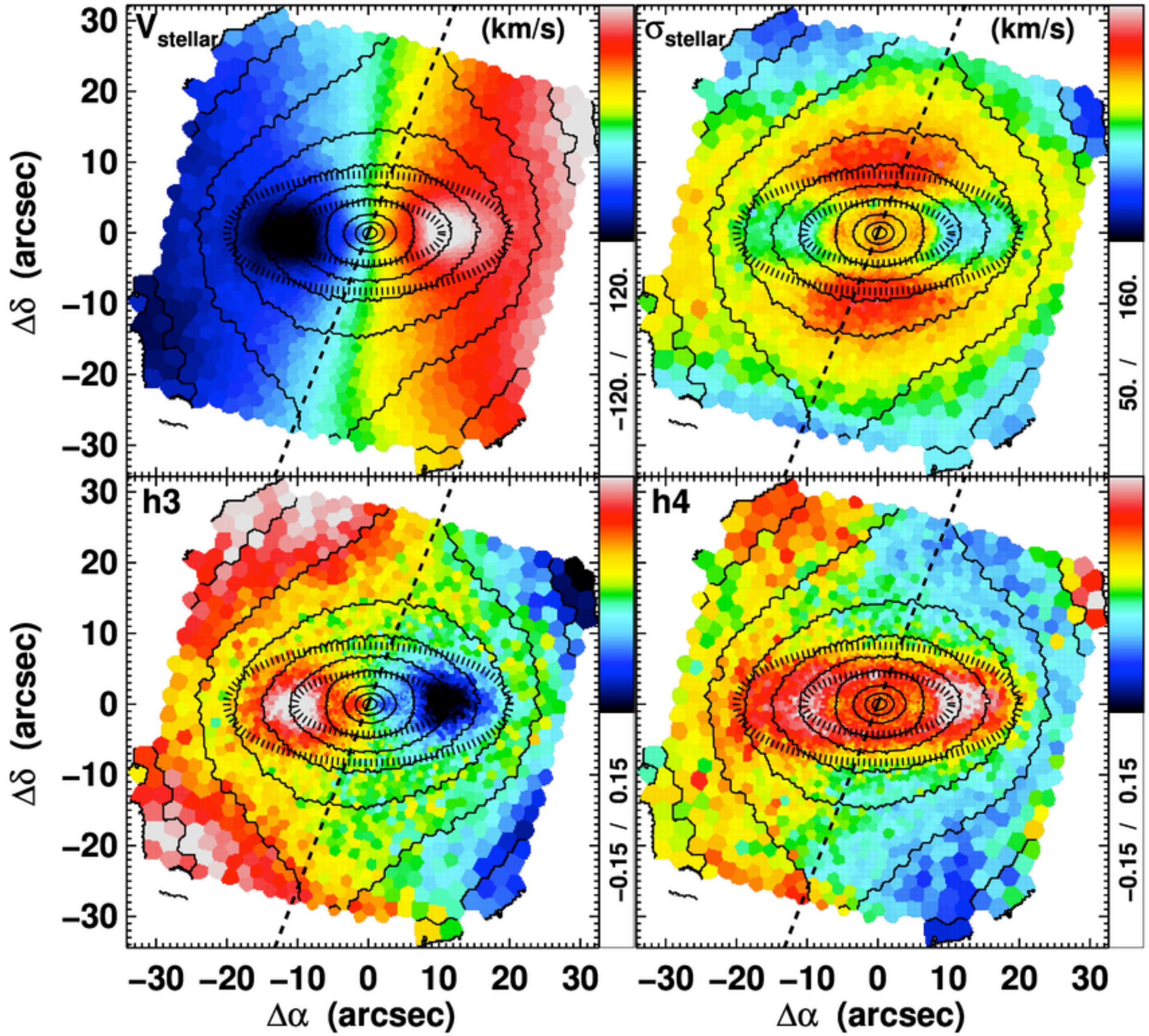

Gadotti+2015

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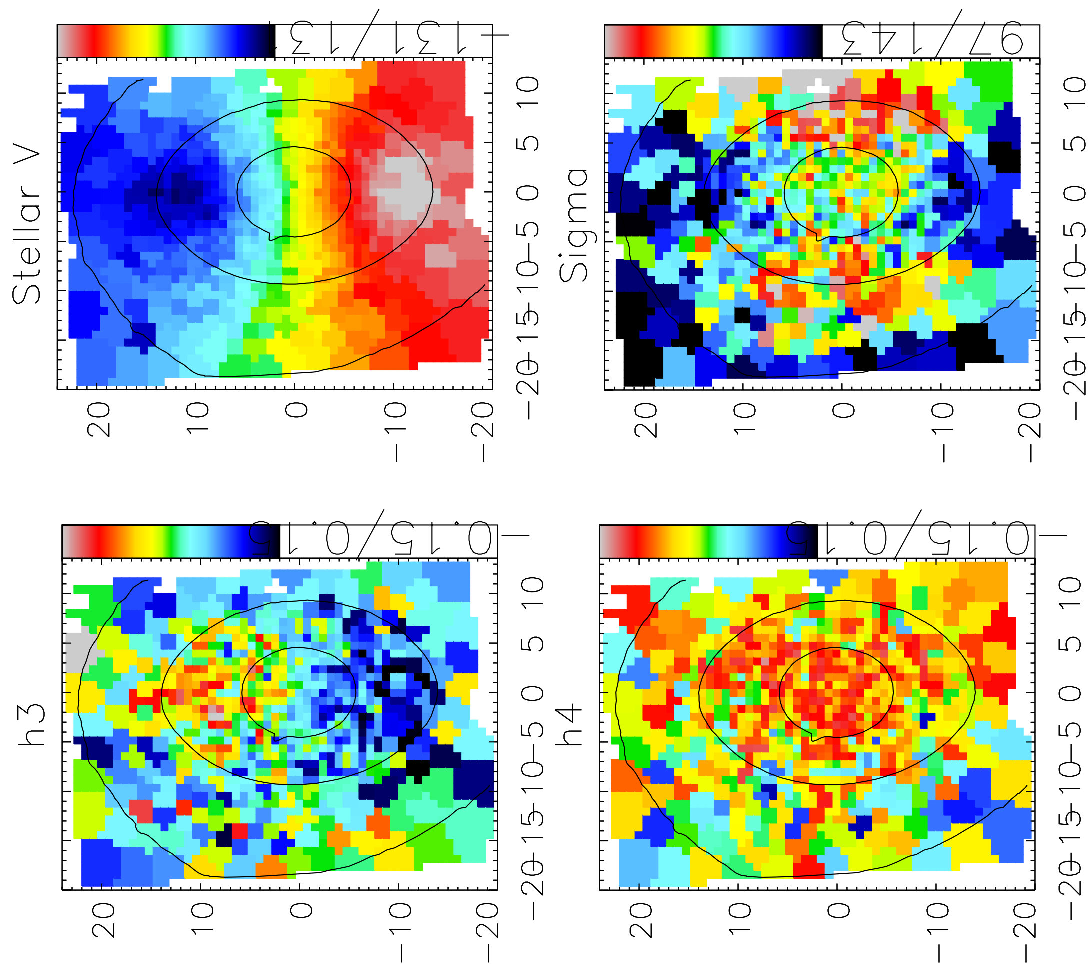
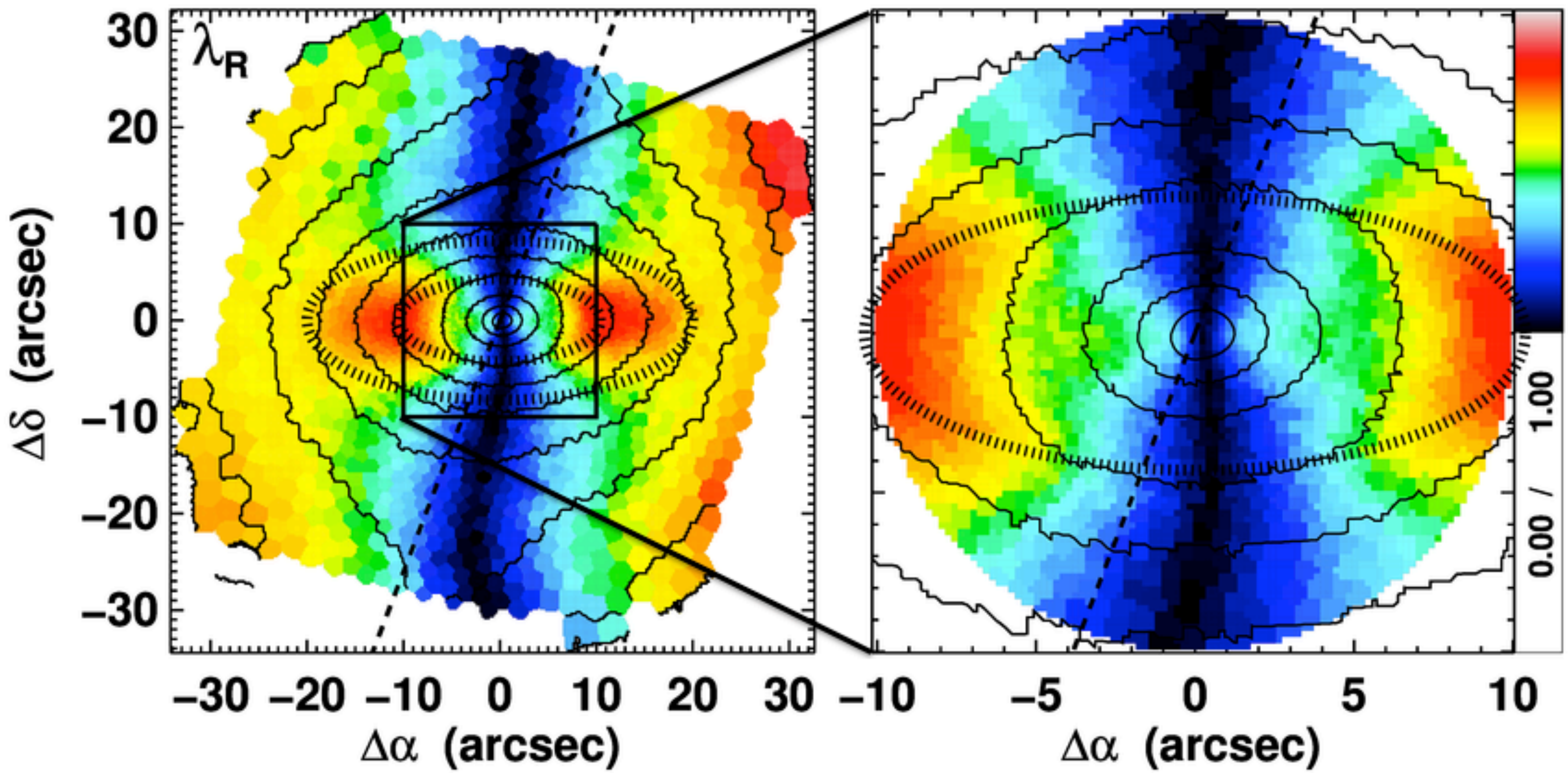


Atlas3D, SAURON
Cappellari+2011

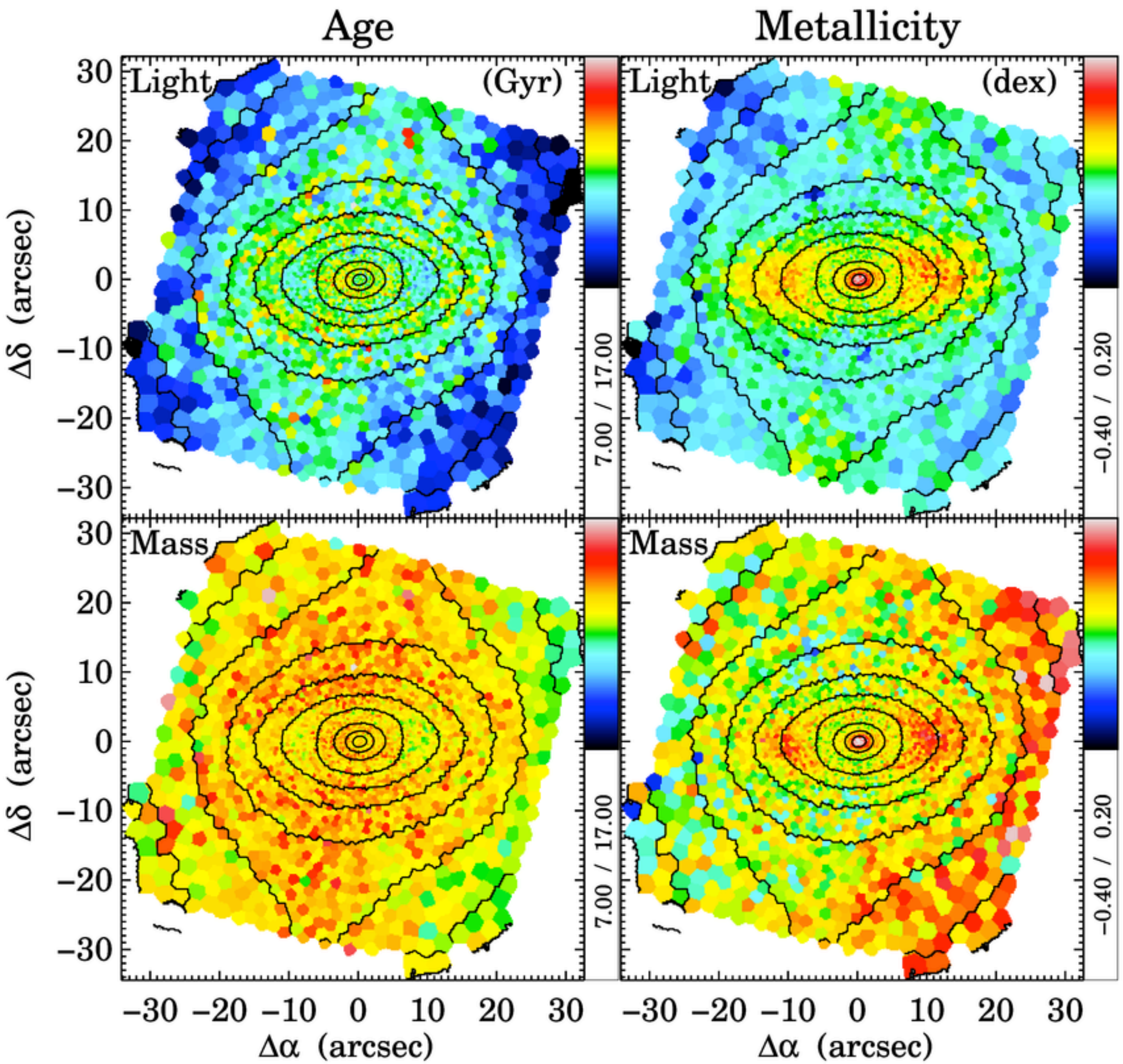
MUSE tells the story of NGC 4371: The dawning of secular evolution

NGC 4371 has an inner disc and a nuclear ring built by bar-driven gas inflow.



Gadotti+2015

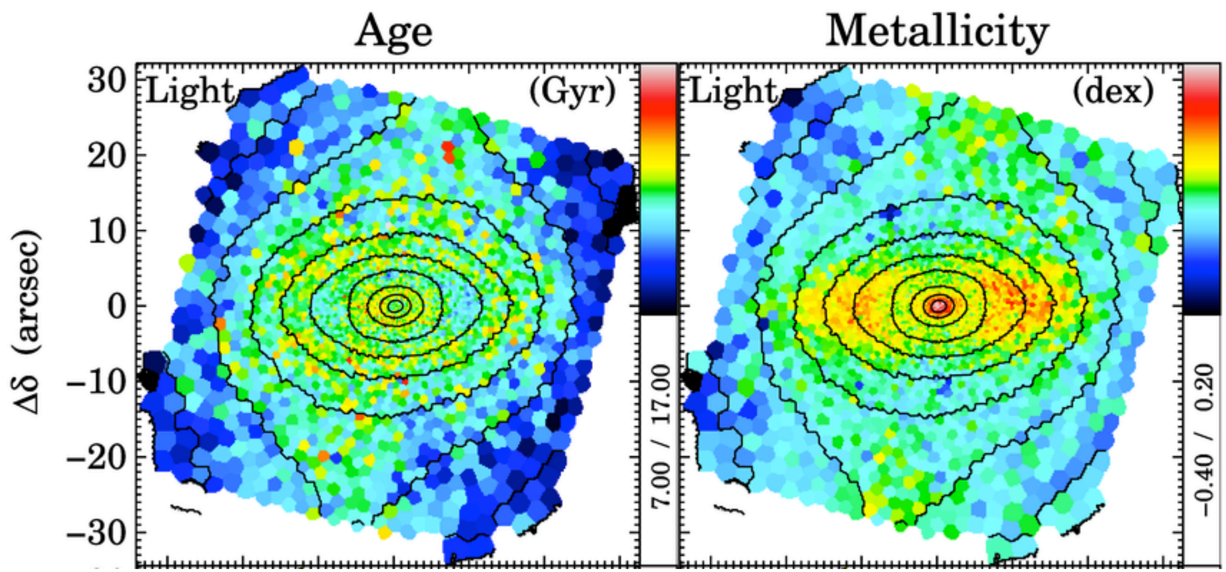
MUSE tells the story of NGC 4371: The dawning of secular evolution



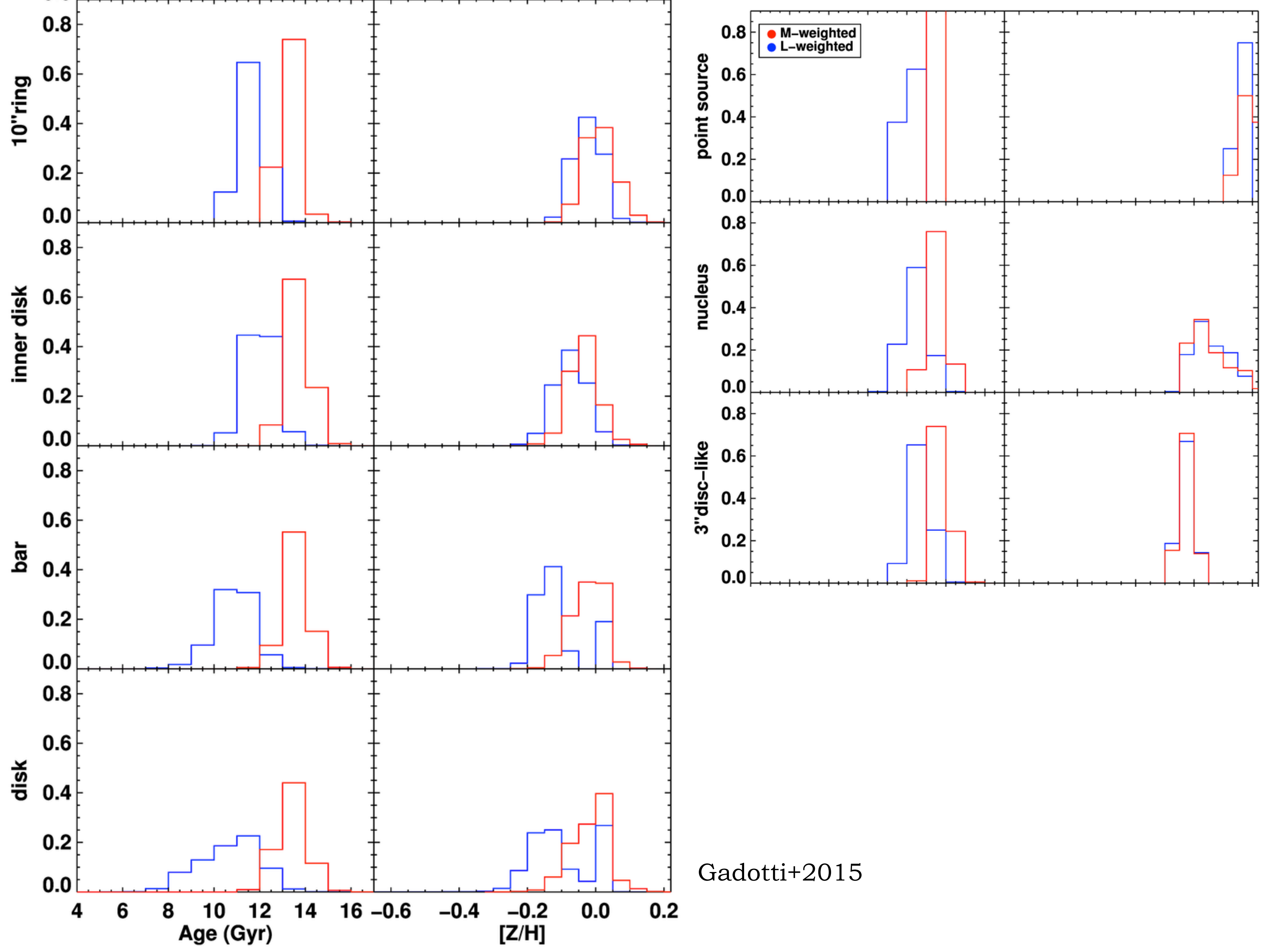
Gadotti+2015

MUSE tells the story of NGC 4371: The dawning of secular evolution

Using Spitzer and HST images, we built structural maps to study the distribution of mean stellar ages and metallicities in the spatial bins dominated by each structural component in the galaxy.



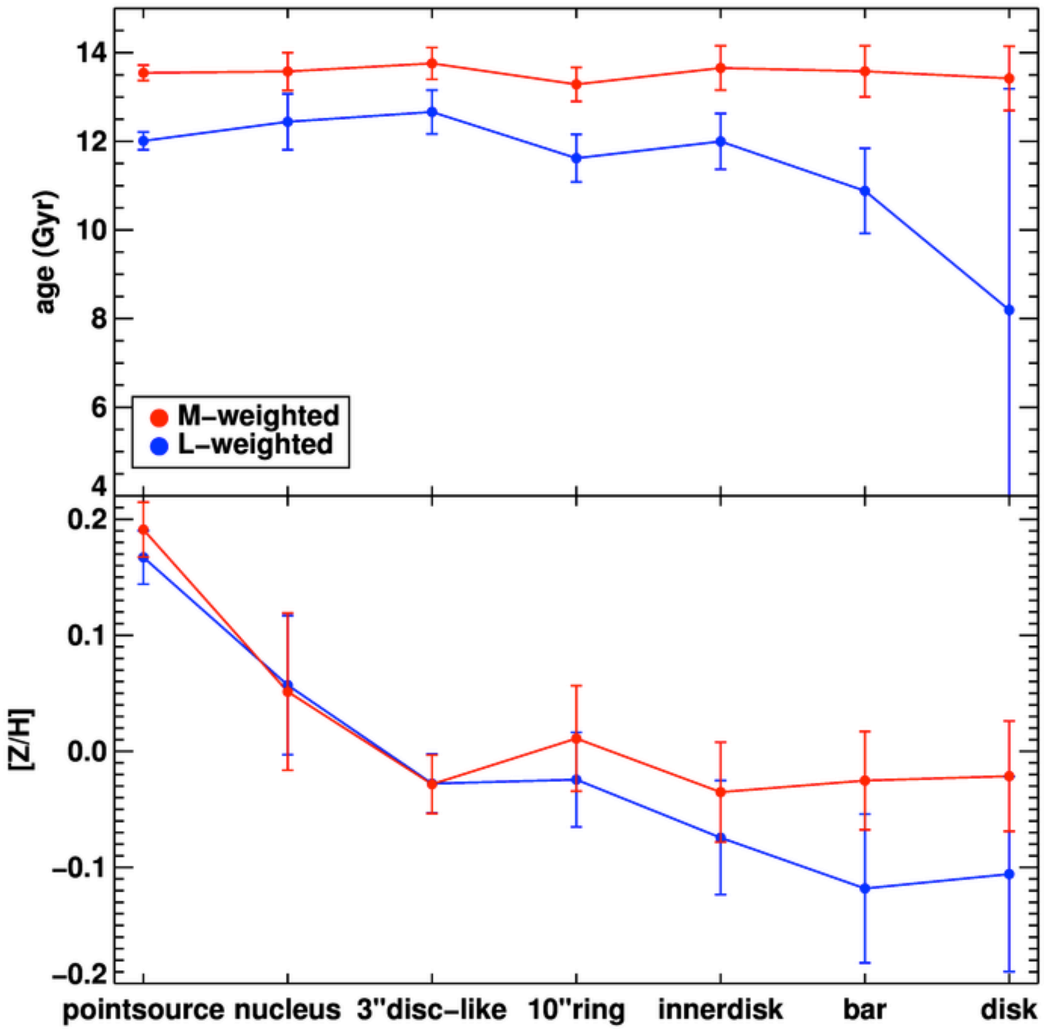
Gadotti+2015



Gadotti+2015

MUSE tells the story of NGC 4371: The dawning of secular evolution

This plot can be thought of as a radial profile of mean age and [Z/H].



Gadotti+2015

MUSE tells the story of NGC 4371: The dawning of secular evolution

- Stellar population in inner disc and nuclear ring vastly dominated by stars older than 10 Gyr old
  - Bar had to be there already to push gas inward

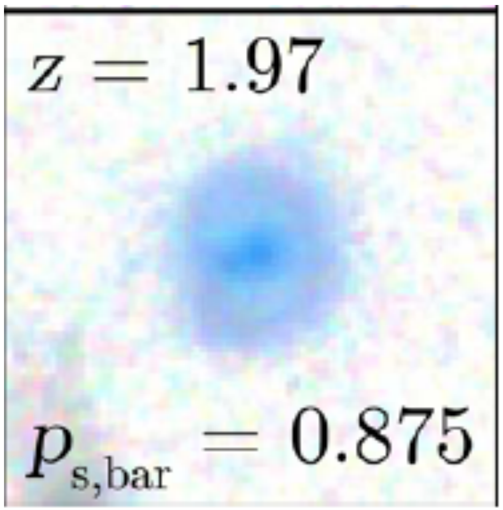
- Bar formation redshift is thus *at least* $z \approx 1.8$ ($1.4 < z < 2.3$)
  - This sets a benchmark as to when massive galaxies formed their bars: galaxies less massive than NGC 4371 ($\log M_\star = 10.8\ M_\odot$) form their bars at lower z (see Sheth+2012).

- Bar in NGC 4371 is a robust structure
  - Spontaneous bar dissolution and reformation seems unlikely in most galaxies (the idea that we have secured that all bars dissolve and form again recurrently is a misconception – this might be the case for a minority of galaxies, possibly more important at high z).

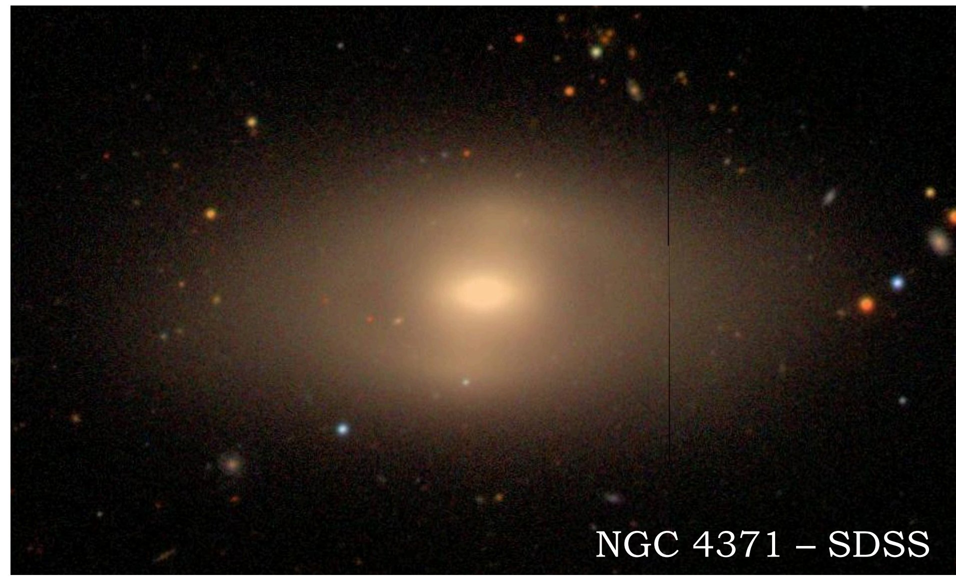
- Secularly-built structures (inner disc and nuclear ring) are old in NGC 4371
  - So called pseudobulges (or discy bulges) may be old (the idea that they must contain young stars is also a common misconception).

MUSE tells the story of NGC 4371: The dawning of secular evolution

NGC 4371 is thus a fossil record of the most distant and oldest barred galaxies known to date.



Simmons+2014



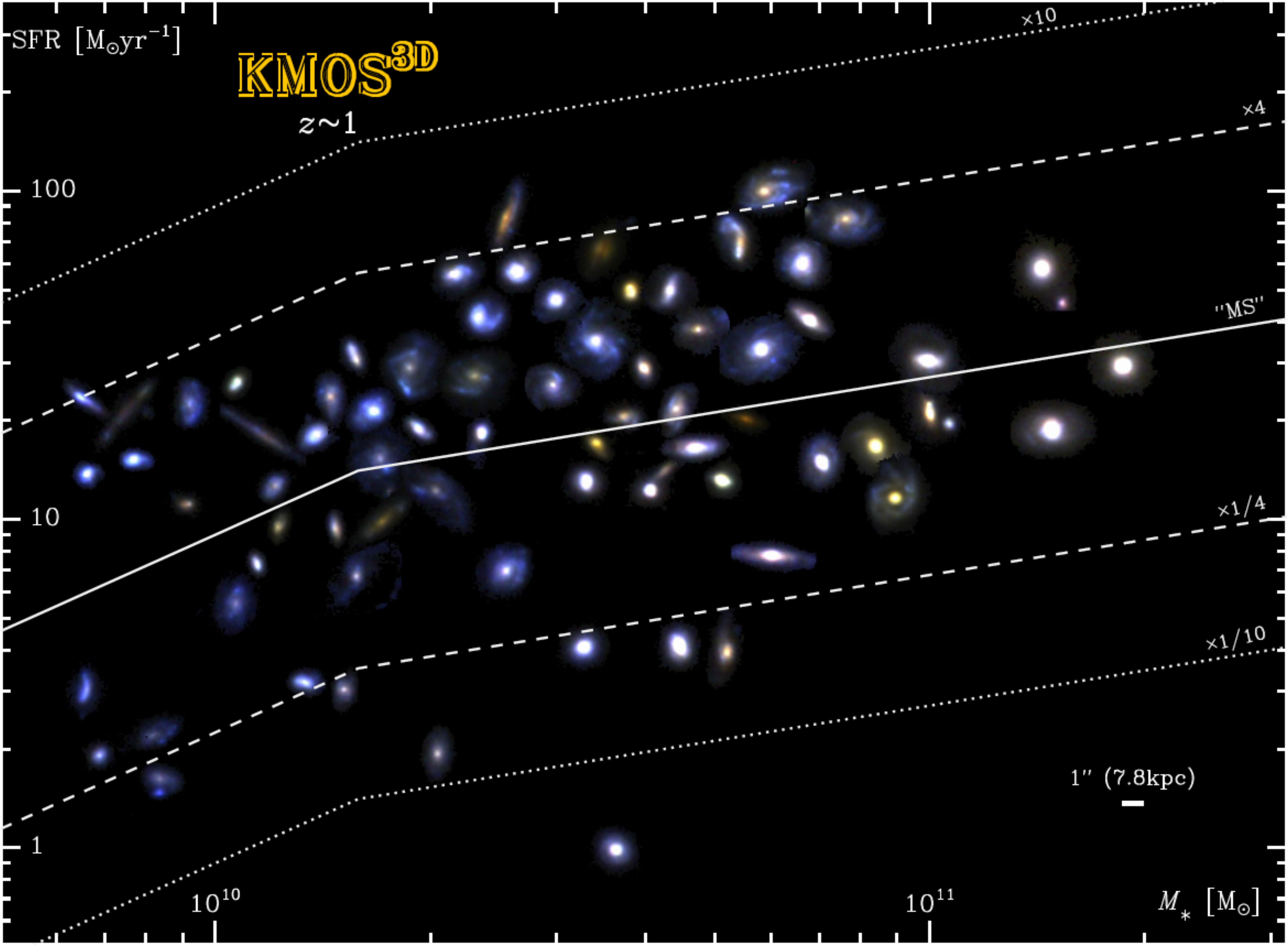
The Appearance of the First Dynamically Mature Discs

The implication is that at least NGC 4371 had a dynamically mature disc already about 10 Gyr ago.

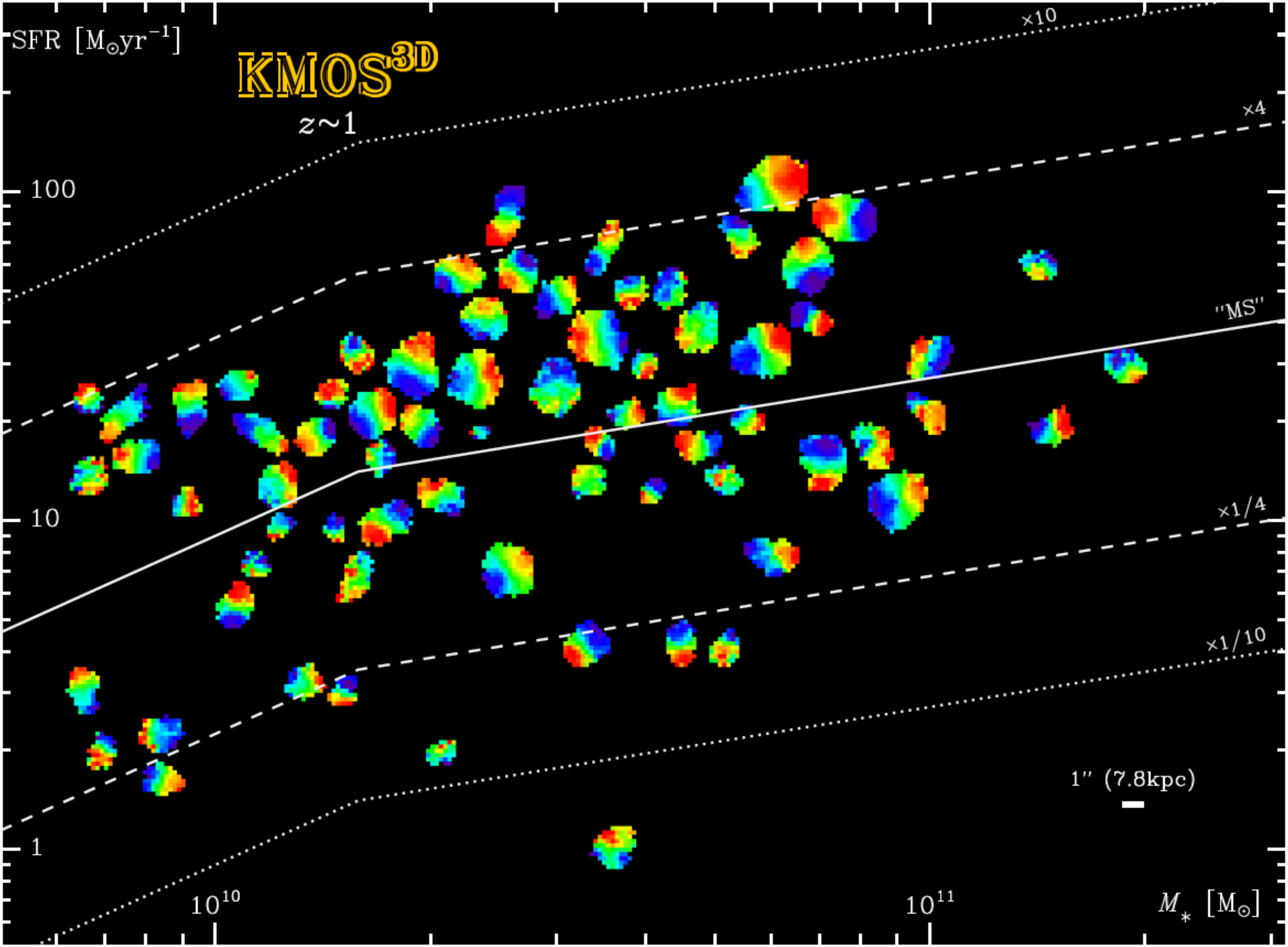
In this context, the KMOS^{3D} team (see e.g. Wisnioski+2014) find consistent results.

- 600 galaxies at $0.7 < z < 2.7$: mass, structure and dynamical evolution

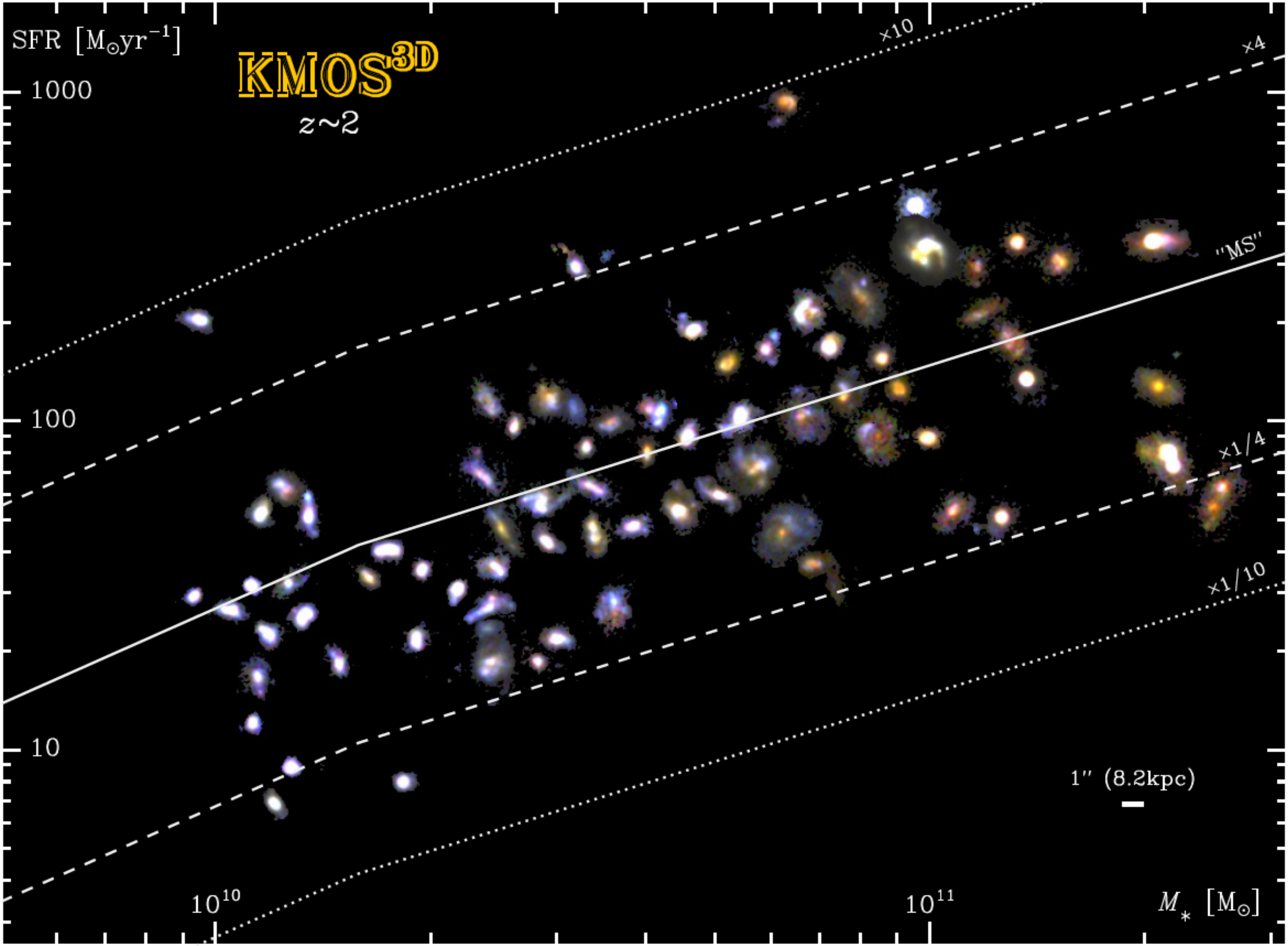
- Results so far:
  - 93% of galaxies at $z \sim 1$ are rotationally supported
  - 74% at $z \sim 2$



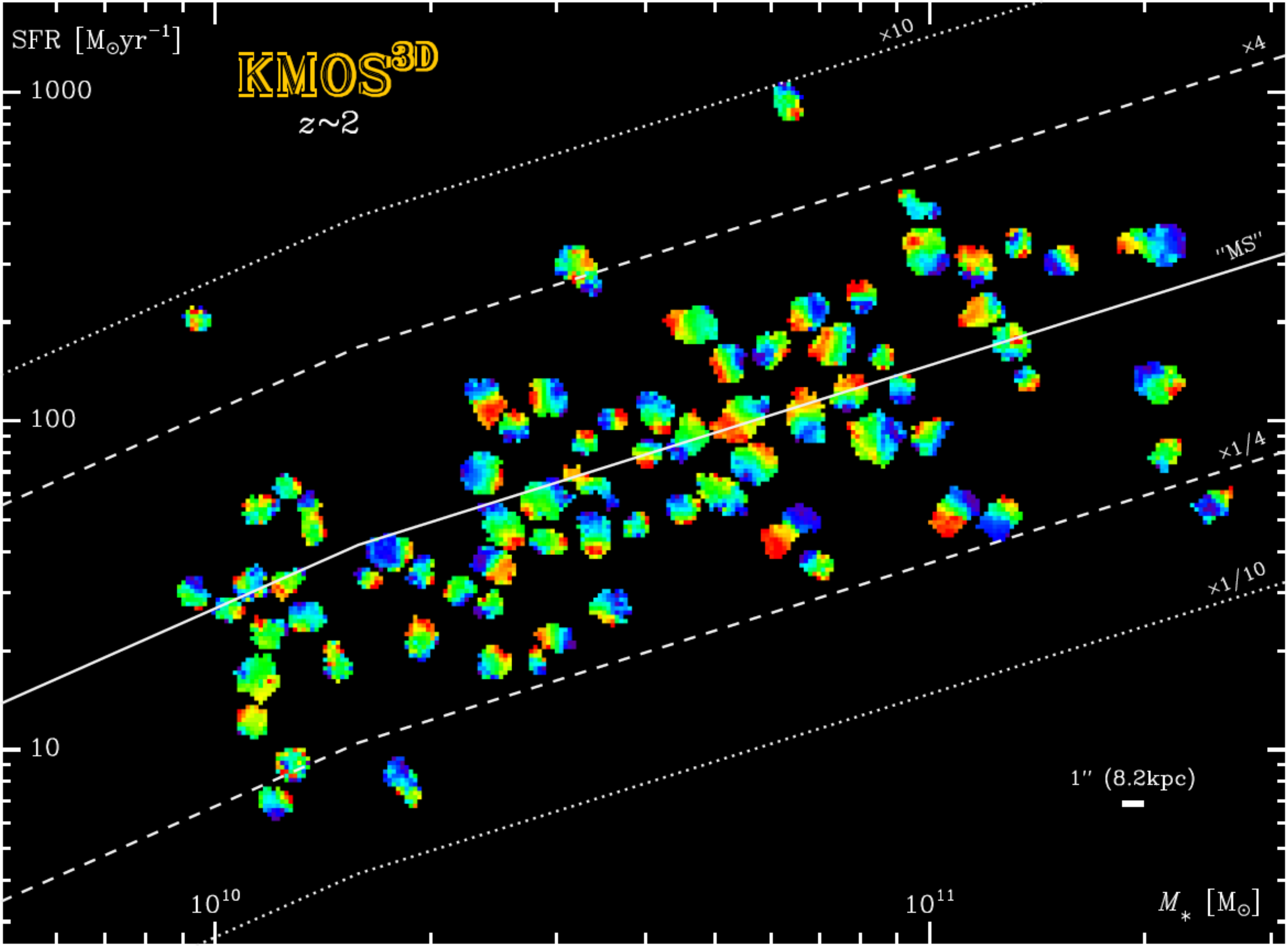
SFR [M$_\odot$yr^{-1}]
KMOS^{3D}
z~1
×10
×4
"MS"
×1/4
×1/10
100
10
1
10^{10}
10^{11}
1" (7.8kpc)
M_* [M$_\odot$]



SFR [M$_\odot$yr^{-1}]
KMOS^{3D}
$z\sim1$
×10
×4
"MS"
×1/4
×1/10
100
10
1
10^{10}
10^{11}
M_* [M$_\odot$]
1" (7.8kpc)



SFR [M$_\odot$yr^{-1}]
KMOS^{3D}
z~2
1000
100
10
×10
×4
"MS"
×1/4
×1/10
1″ (8.2kpc)
10^{10}
10^{11}
M_* [M$_\odot$]


SFR [$M_\odot yr^{-1}$]
KMOS^{3D}
$z\sim2$
1000
100
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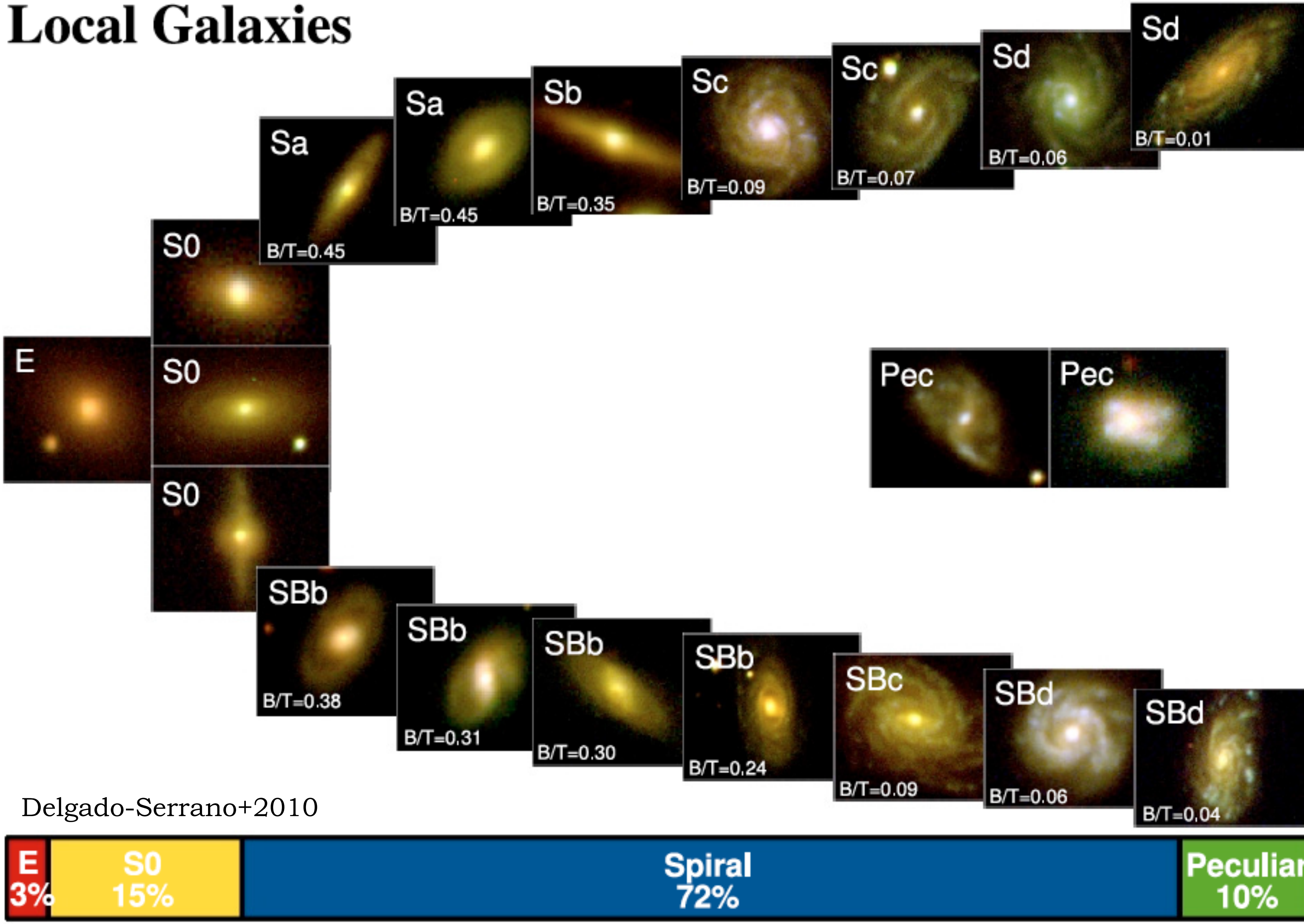
$\times10$
$\times4$
"MS"
$\times1/4$
$\times1/10$
1″ (8.2kpc)
10^{10}
10^{11}
M_* [$M_\odot$]

The Appearance of the First Dynamically Mature Discs

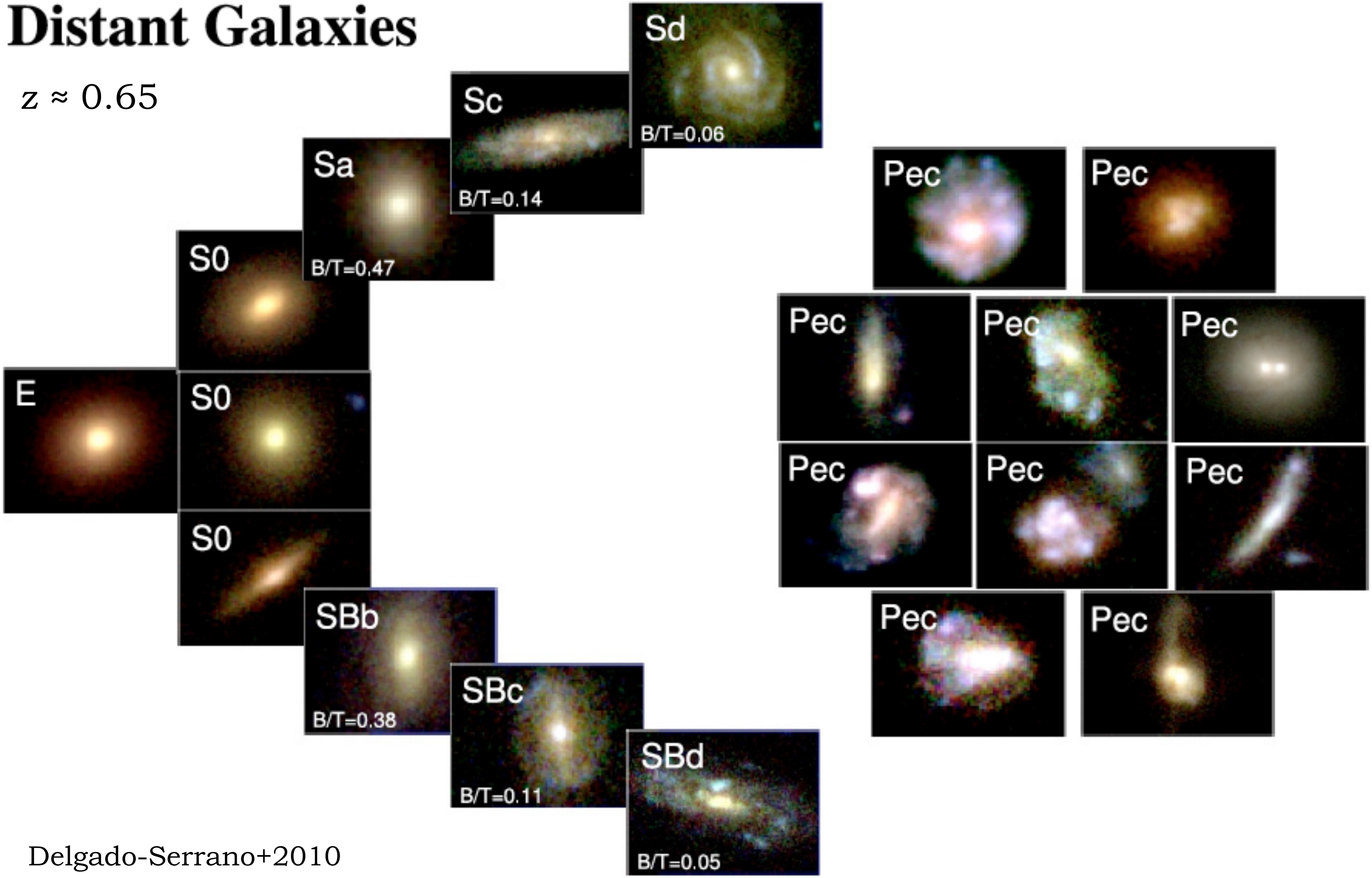
Result is still controversial (see e.g. Delgado-Serrano+2010): what about disc clumps and mergers?

Local Galaxies



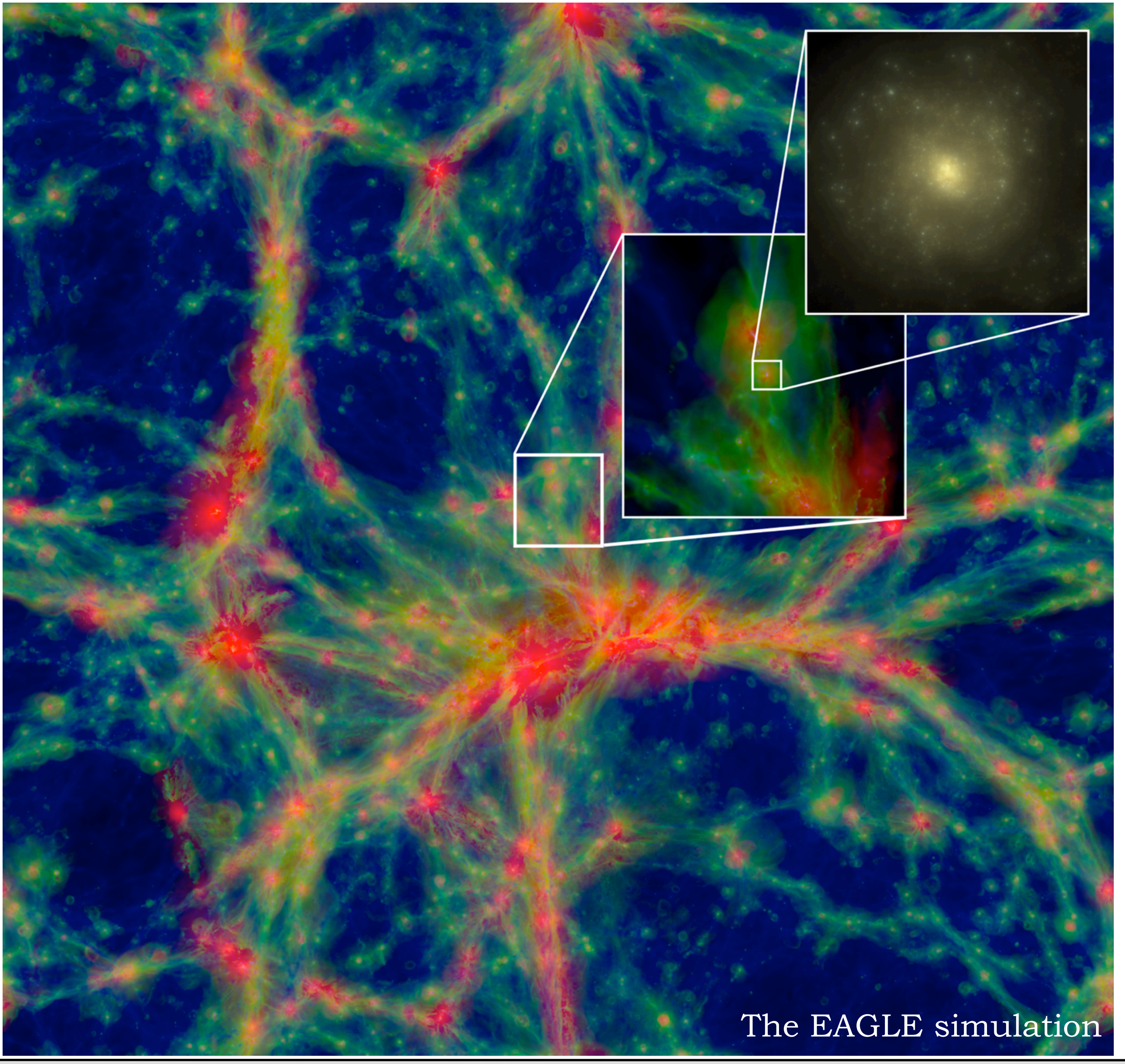
Distant Galaxies

$z \approx 0.65$



Delgado-Serrano+2010

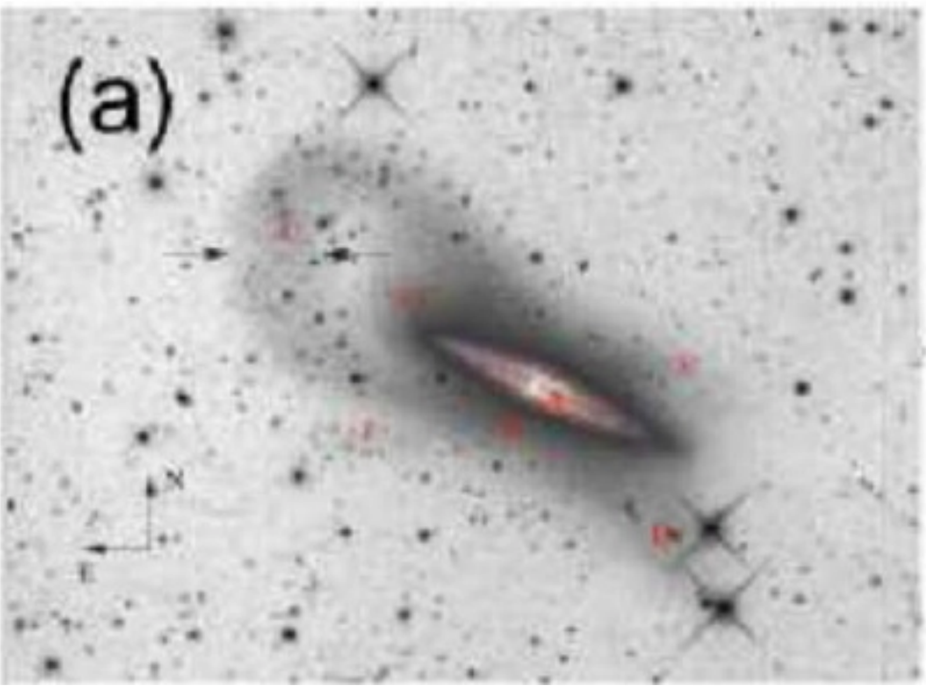
Galaxy Formation

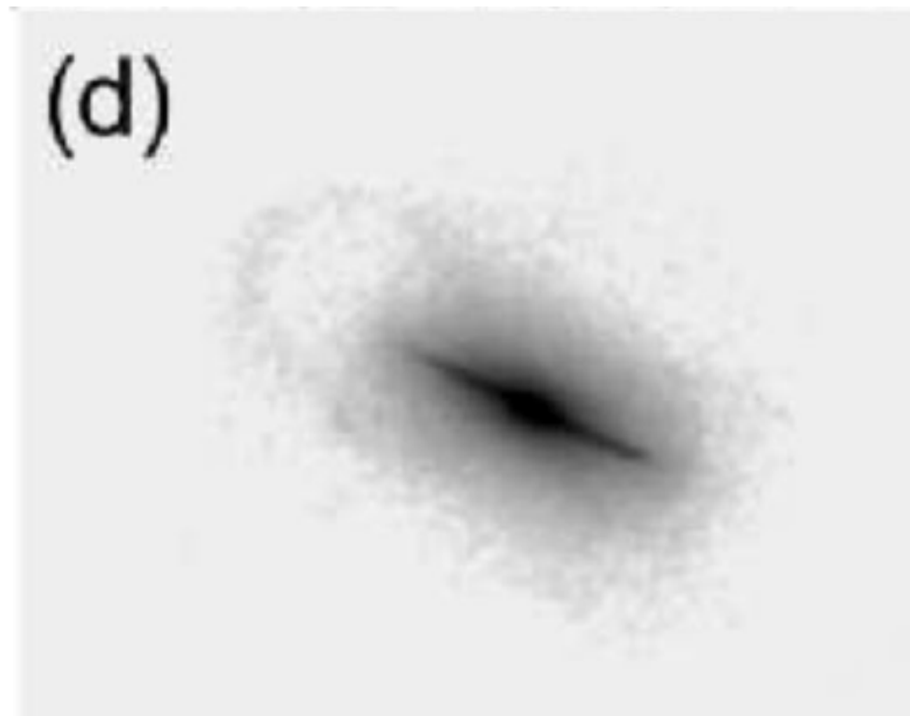


Galaxy Formation

We seem to live in a hierarchical universe, but fraction of galaxies with classical (i.e merger-built) bulges seems too low (see e.g. Kormendy 2015).

A possible way out is that in some conditions mergers lead to galaxies with no massive classical bulge (e.g. gas-rich mergers – Wang+2015) but more work is needed.





Conclusions
(Addressing Misconceptions)

- Bar-induced processes within the bar radius can be fast

- Pseudobulges are inner discs

- Most bars seem to be robust structures

- Inner discs built by bars can be old

Conclusions
(Open Questions)

- We still need to work out the details about how bars affect the ages and abundances of stars in the centres of discs, and help igniting AGN.

- What is the fraction of robust bars formed at z ~ 2 or more?

- When have the first dynamically mature discs formed?

- In how many different ways can we form inner discs?