Outer disks and rings of the lenticular galaxies

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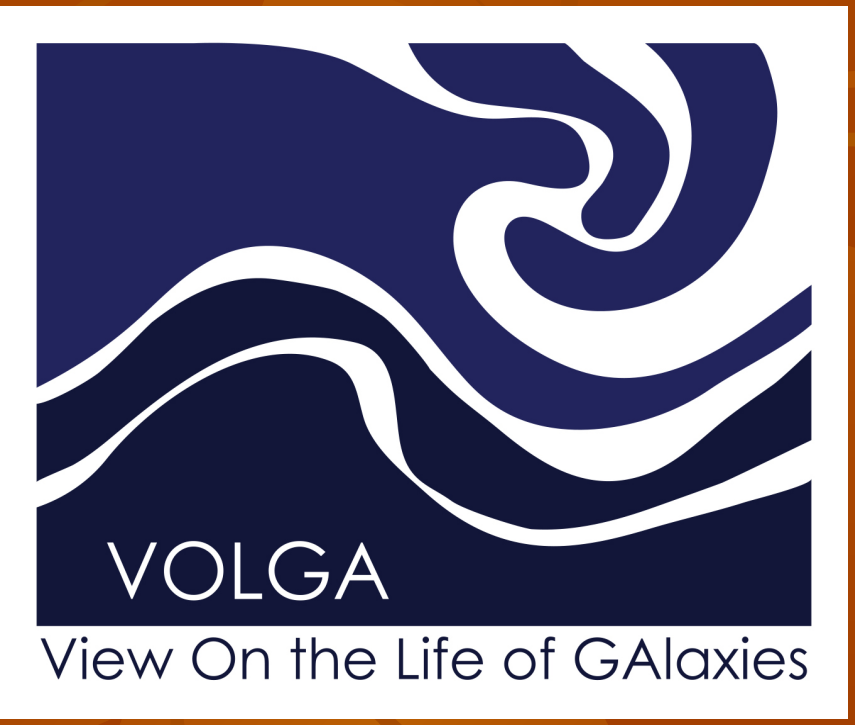
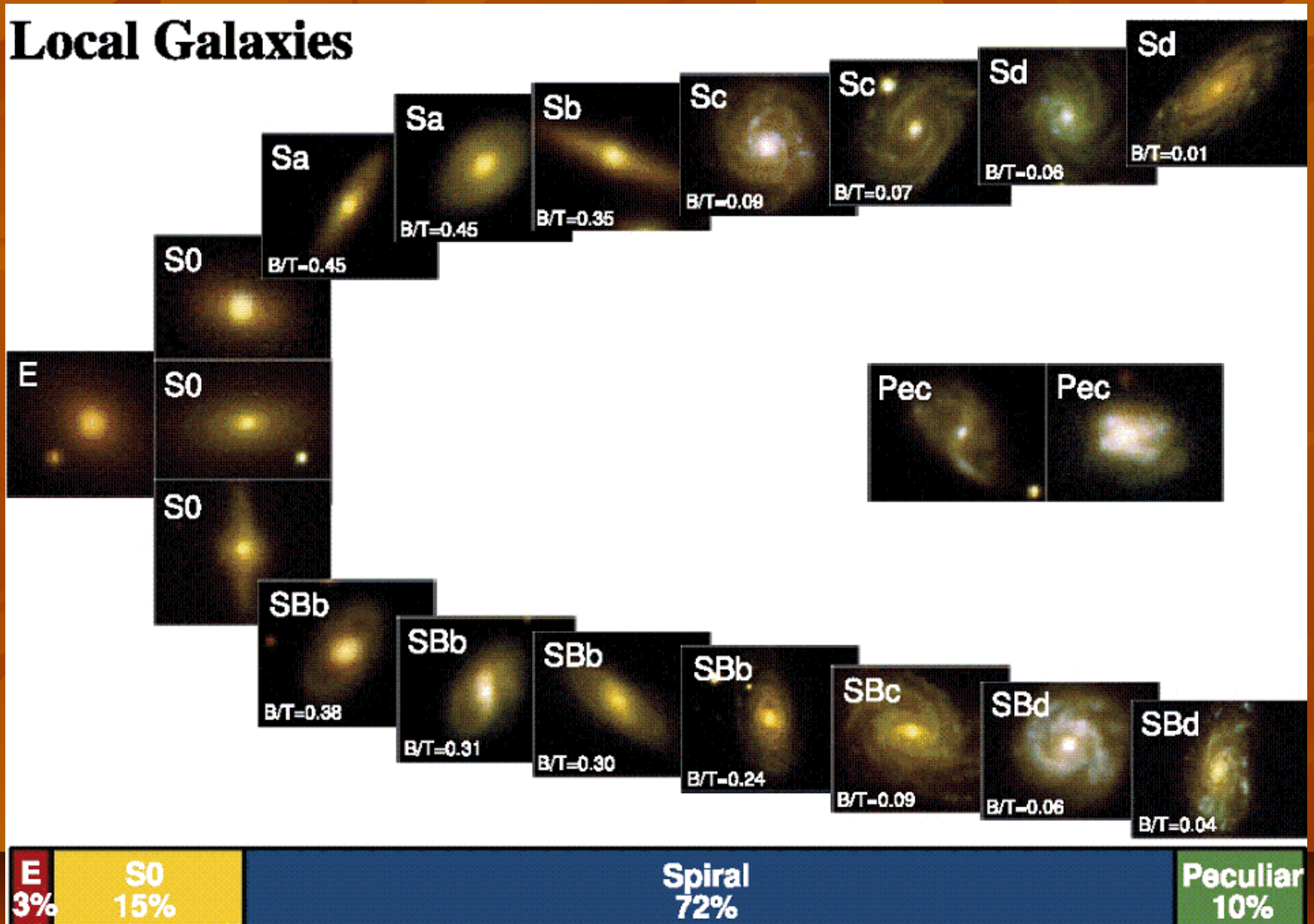
In collaboration with:

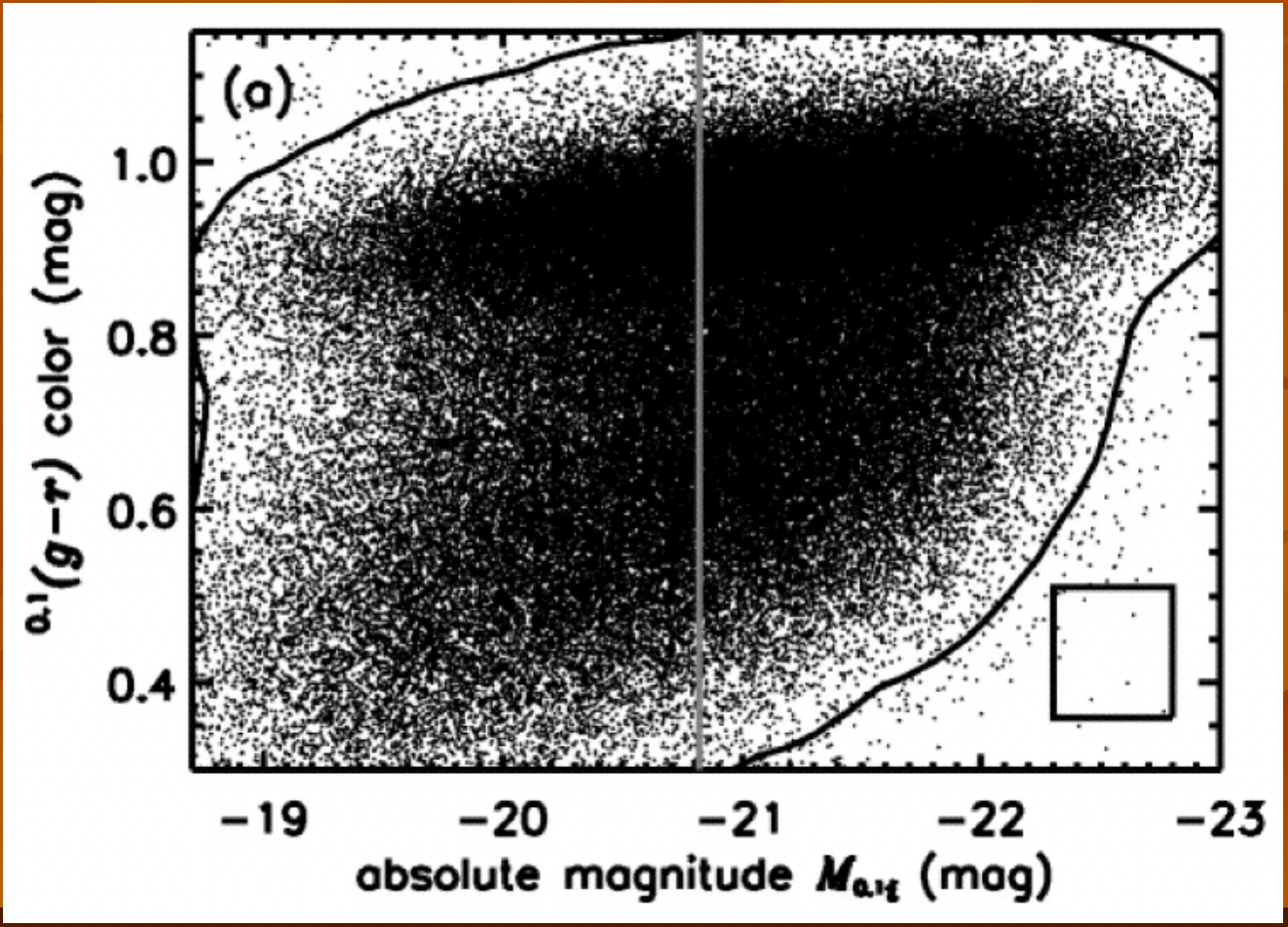


- Alexei Kniazev (SAAO, SAI MSU)
- Ivan Katkov (SAI MSU)
- Irina Proshina (SAI MSU)
- Irina Kostiuk (SAO RAS)
- Marina Ilyina (SAI MSU)
- Victor Afanasiev (SAO RAS)

Hubble `fork': evolutionary sequence?



From the blue cloud to the red sequence – quenching? Or from the red sequence to the blue cloud – gas accretion and SF ignition?

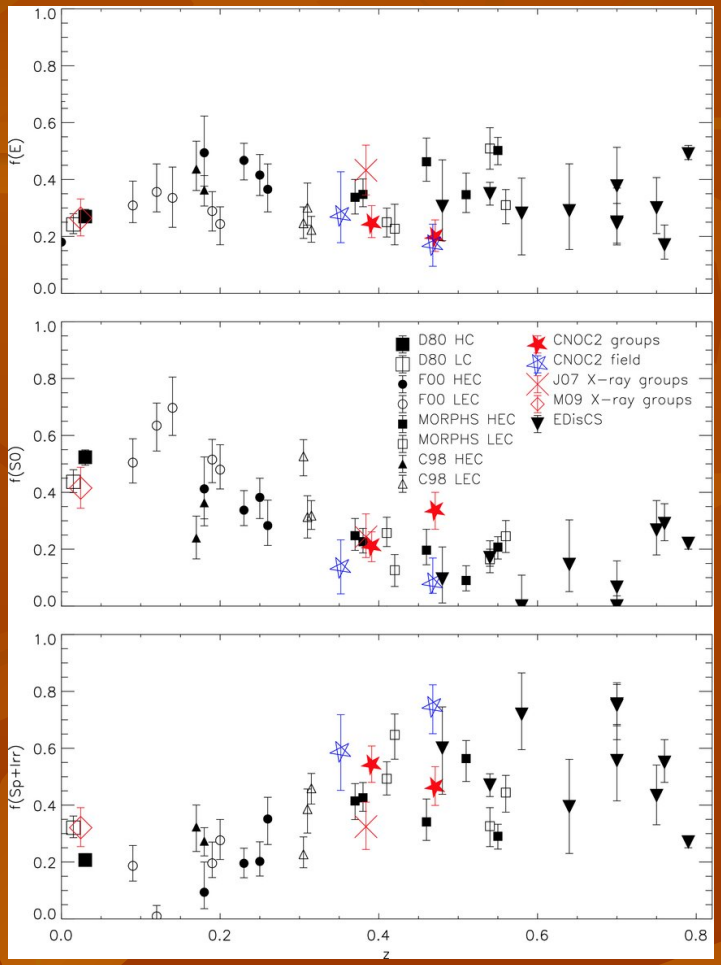


Hogg et al. 2003

S0s and Ss are relatives; but what type was first?

- The common point of view: S0s are formed from spirals, and it is known even the exact epoch and place of the event…

Surveys of galaxies at intermediate redshifts: S0 galaxies arise in groups and clusters just at z=0.4



- Wilman et al. (2009)

"Morphological Composition of z ~ 0.4 Groups: The Site of S0 Formation"

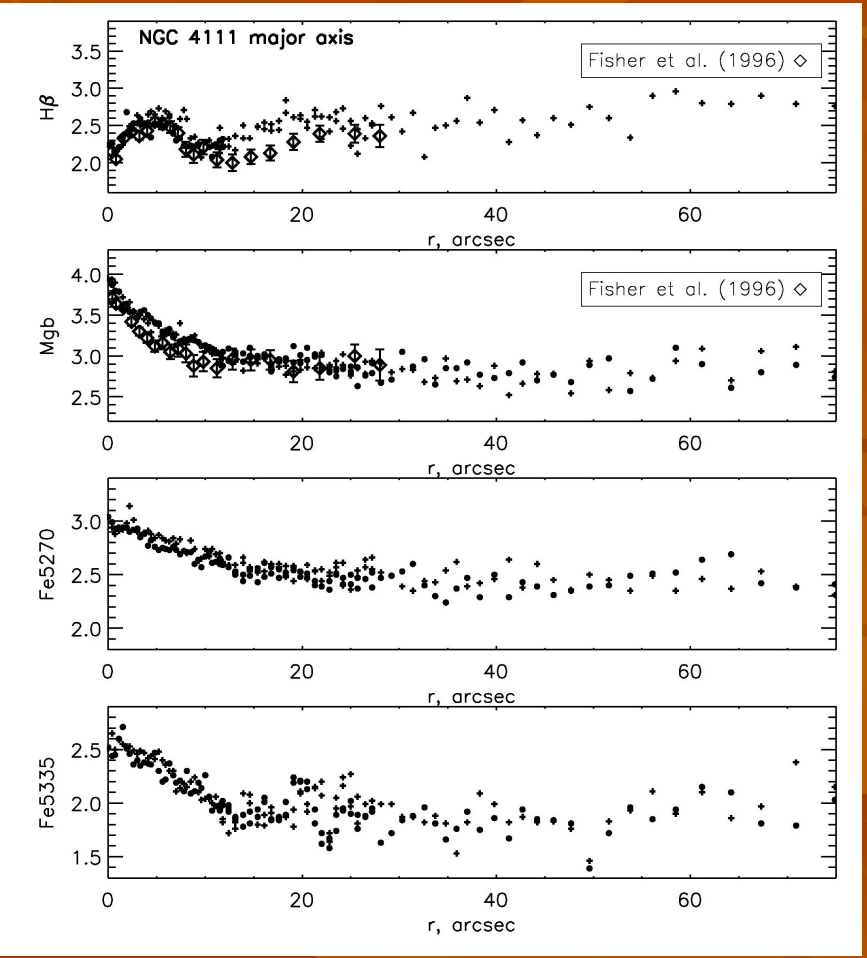
So do we see directly when S0s formed?

- z=0.4 – it is only 4 Gyr ago!
- So star formation proceeded in the most cluster S0 disks only 4 Gyr ago? And at z=0.4-0.5 it was quenched? Then the stellar disks of nearby lenticulars must have rather young stellar populations! And we can check that.

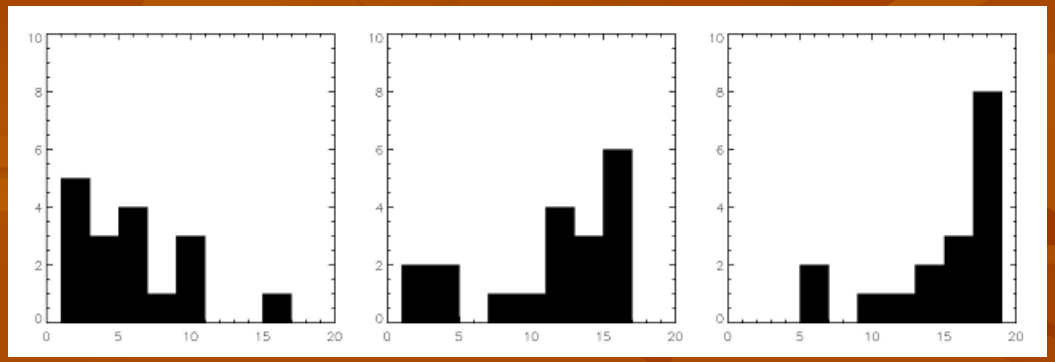
Deep long-slit spectroscopy of nearby S0 galaxies: Observations at the Russian 6m telescope

- SCORPIO of the Russian 6m telescope: long-slit mode
- Green (4700-5500 A) and red (5900-7100) spectral ranges, spectral resolution of 2.2 A in the green
- Exposures from 60 to 180 minutes
- Later SCORPIO-2: 3700-7100 AA, sp res of 4.5 A
- Lick indices Hβ, Mgb, Fe5270, Fe5335 measured

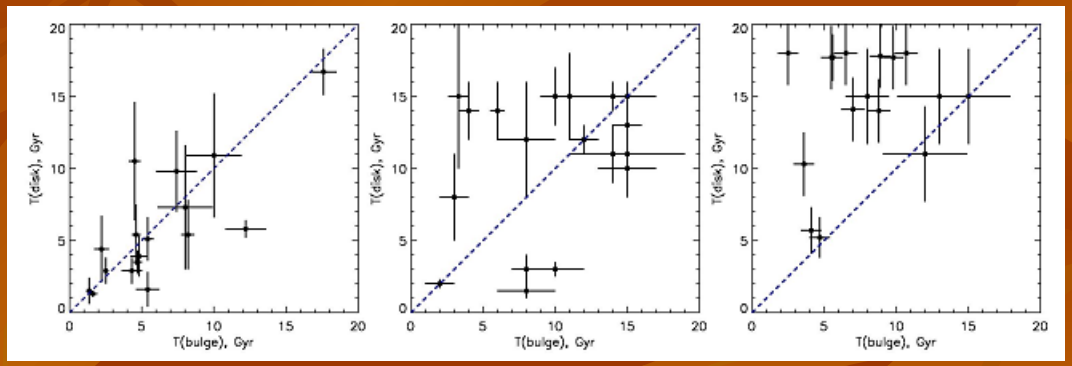
Lick index profiles up to 2-4 exponential scalelengths



The denser environments, the older are the disks of S0s



Isolated In groups Virgo



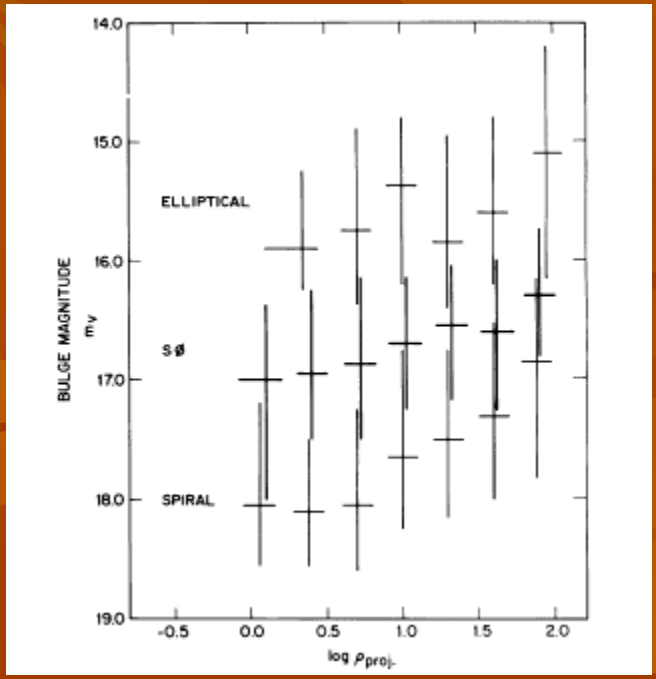
- Three samples:
- Isolated S0s (Katkov, Kniazev, Sil'chenko 2015);
- S0s in rich groups (Sil'chenko et al. 2012 and after that);
- - S0s in Virgo (Johnston et al. 2014 + 4 S0s observed with the SCORPIO-2).

Burstein et al. (2005):

- The Butcher-Oemler effect is only rejuvenation in pre-existing S0s.

- And it is now shown that the rejuvenation affects mostly the inner parts – bulges; the most OUTER DISKS REMAIN OLD!

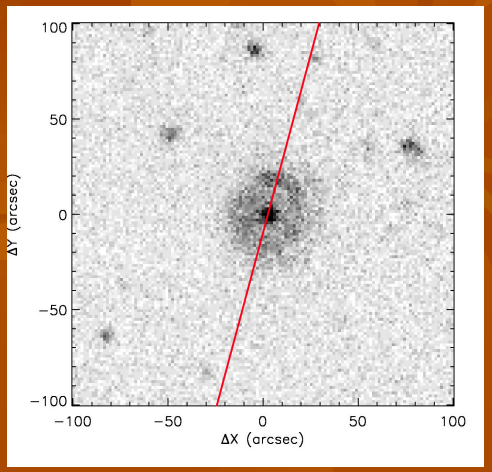
Old finding by Dressler (1980): the bulges of BOTH spirals and S0s are larger in dense environments



New view on the S0 origin and evolution:

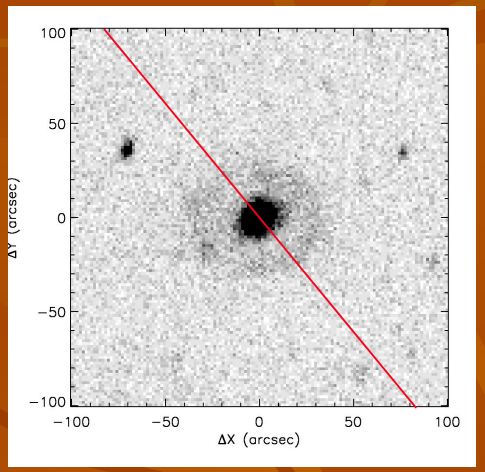
- All disk galaxies were initially S0s, with their thick stellar disks built in short intense star formation bursts at z~2.
- Later, at z<1, most of them acquired some sources of prolonged cold gas accretion from outside (e.g. Dekel's cold gas filaments? Multiple gas-rich satellite accretion?); those became **spirals**.
- Within dense environments, in clusters and in massive groups with their hot intra-cluster/group medium, it is difficult for the outer gas to remain cold – so the most primary S0s in clusters and groups have to remain **S0s** up to now.

However disk rejuvenation is possible too…



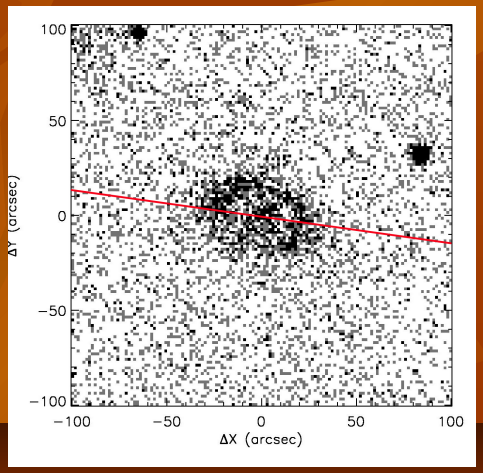
IC 522

NGC 446



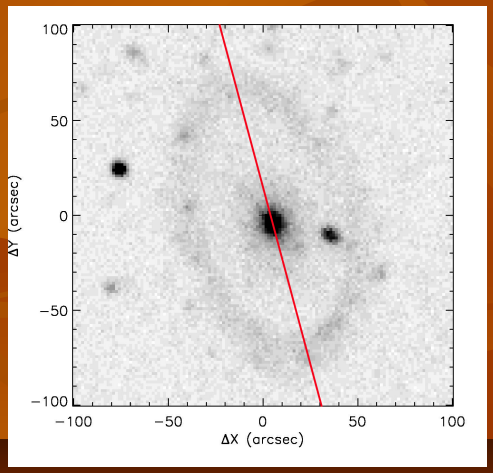
NUV-rings!

GALEX



NGC 252

NGC 4513



Ilyina, Sil’chenko, Afanasiev 2014

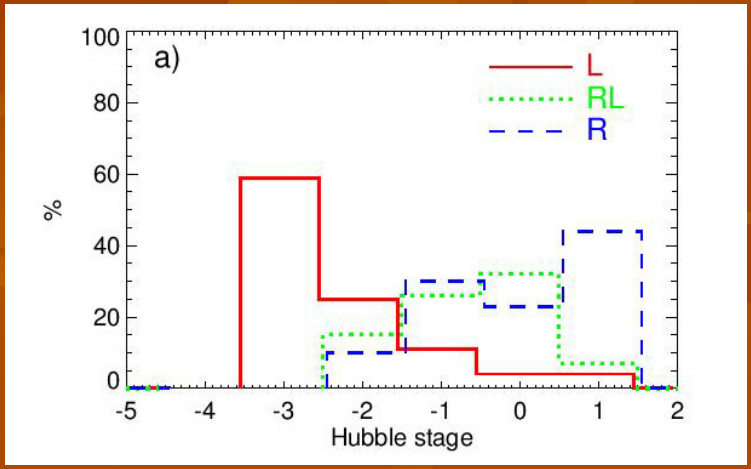
There are two commonly accepted types and origins of outer rings:

- «Resonance rings» are formed from the proper gas of the galaxy which is pushed out and compressed at the outer Lindblad resonance, at the fixed radius, by the bar dynamical influence.
- «Impact rings» – also from the proper gas of the galaxy which is pushed out by the shock produced by vertical impact of the falling satellite; the radius may change with time.

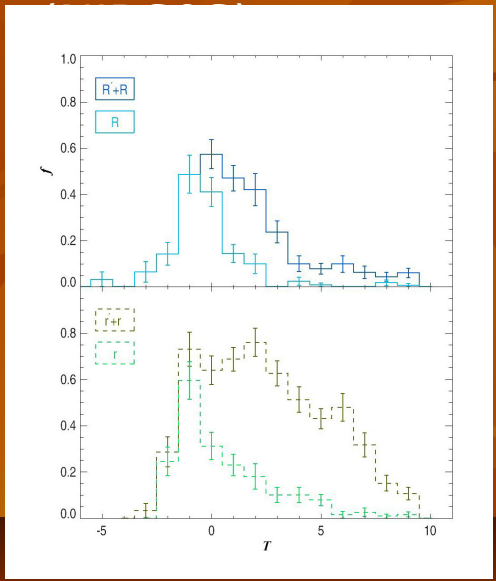
Is this list full?

- Let us try to relate the possible origin of the rings with the observational statistics of the host galaxy properties.

Among disk galaxies, the outer rings are most common in S0s



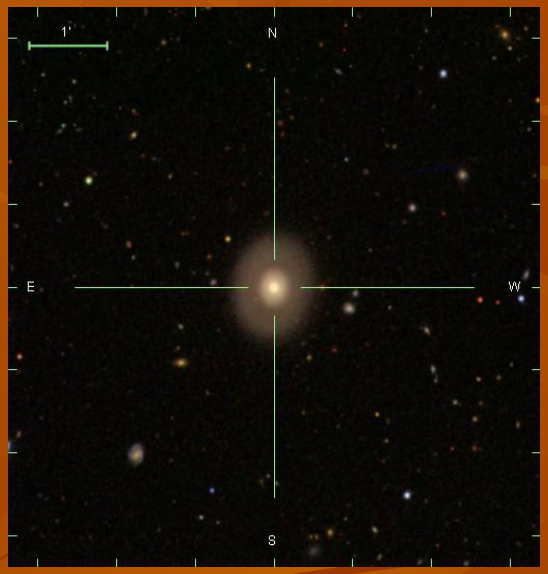
Laurikainen et al. (2011,2013)

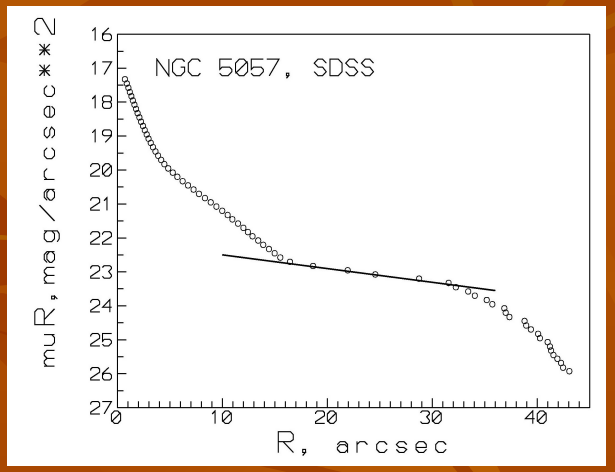


Comeron et al. 2014 (S4G)

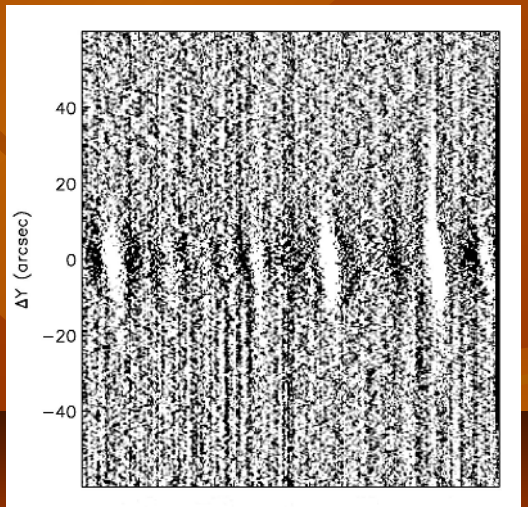
- 1) In S0s there are much less bars than in spirals: 35% of all S0 vs 80% of all Sp reveal bar presence in NIR (K-band);
- 2) instead, the presence of rings and lenses is enhanced just in S0-Sa

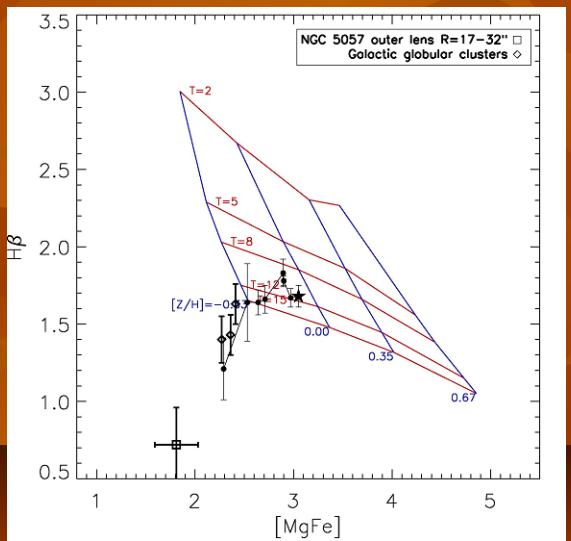
There are pure STELLAR outer rings in S0s: NGC 5057, 1 arcsec=400pc





SCORPIO-2, Russian 6m telescope





Statistics of the UV-visibility in the S4G sample of the outer rings:

- Among S0, the outer rings (R and RL) are seen by GALEX in 56% ; if only R, without RL, - in 86%.
- Among S0/a and Sa, the outer rings (R, RL, R_1 R_2) are seen by GALEX in 81%; 90%-100%, if without RL.

Kostiuk and Sil’chenko (2015)

Salim et al. (2012) have made HST imaging of the ETGs having UV-excess in the integrated light

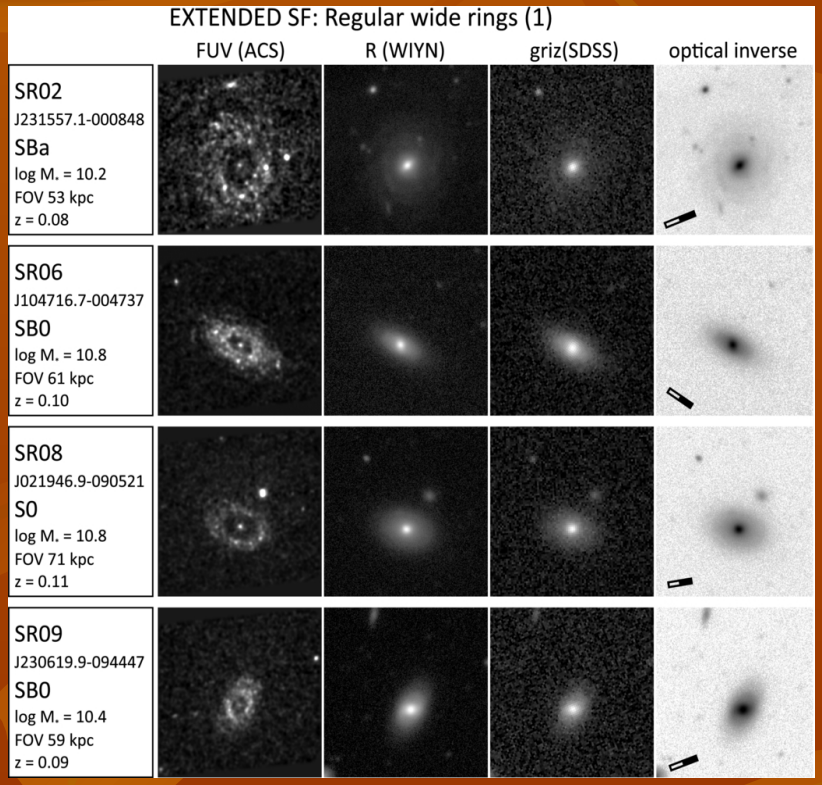
	Sa	S0	E	Total
Extended SF	**4**	**15**	**0**	**19**
Wide rings	1	7	0	8
Disks w/holes	1	2	0	3
Narrow rings	0	4	0	4
Irregular rings	0	2	0	2
Arms	2	0	0	2
Small-scale SF	**0**	**1**	**5**	**6**
Off-center	0	1	3	4
Central	0	0	2	2
Compact	**0**	**1**	**1**	**2**

	non barred	barred
Extended SF	**11**	**8**
Wide rings	4	4
Disks w/holes	2	1
Narrow rings	2	2
Irregular rings	2	0
Arms	1	1
Small-scale SF	**6**	**0**
Off-center	4	0
Central	2	0
Compact	**2**	**0**

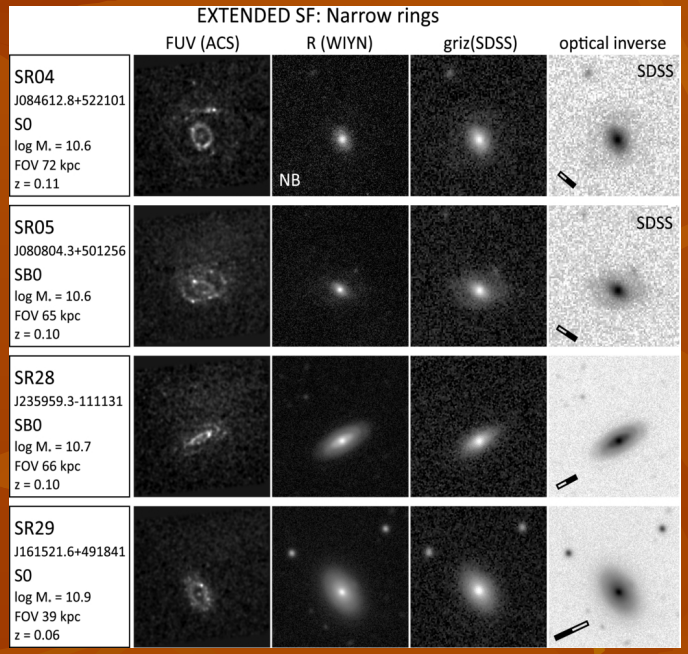
In 20% of ALL S0s the GALEX reveal extended star formation – with the same frequency in barred and unbarred ones

Salim et al. (2012): extended star formation in S0s

SF – Only rings

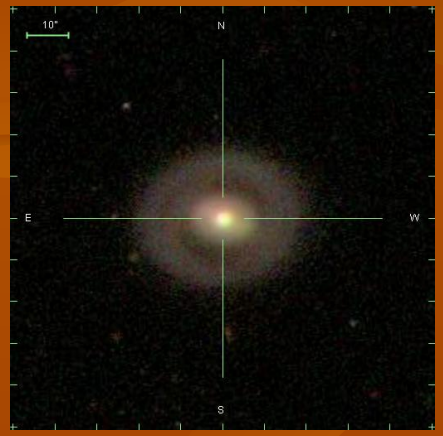


Broad rings with a typical radius of 16-20 kpc

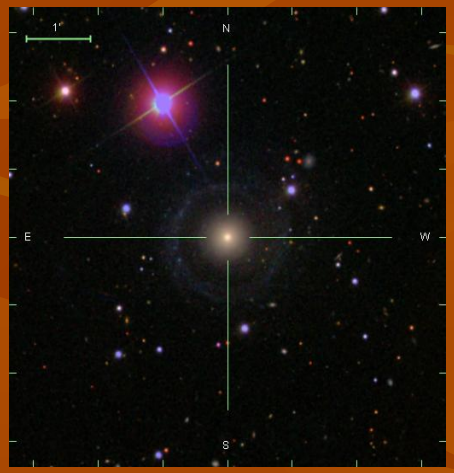


Narrow rings with a typical radius of 6.5 kpc

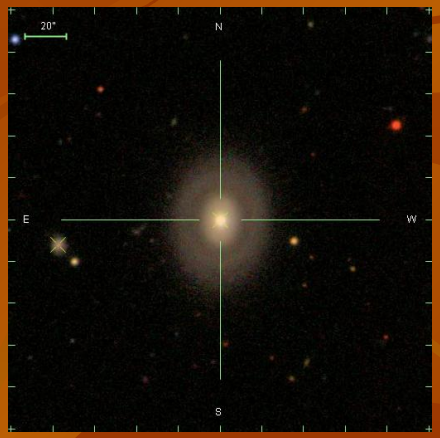
Ilyina & Sil'chenko (2011): a list of UV-rings in unbarred S0s



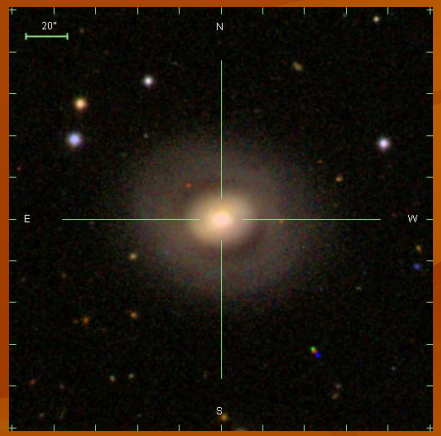
PGC 48114



UGC 4599



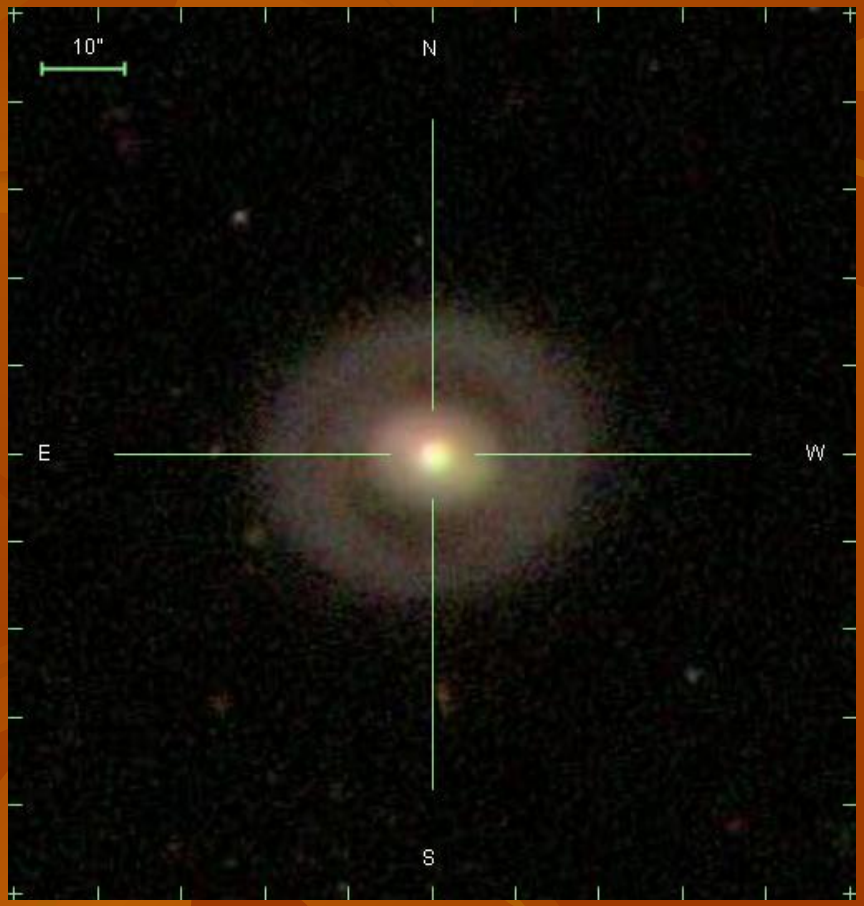
NGC 809



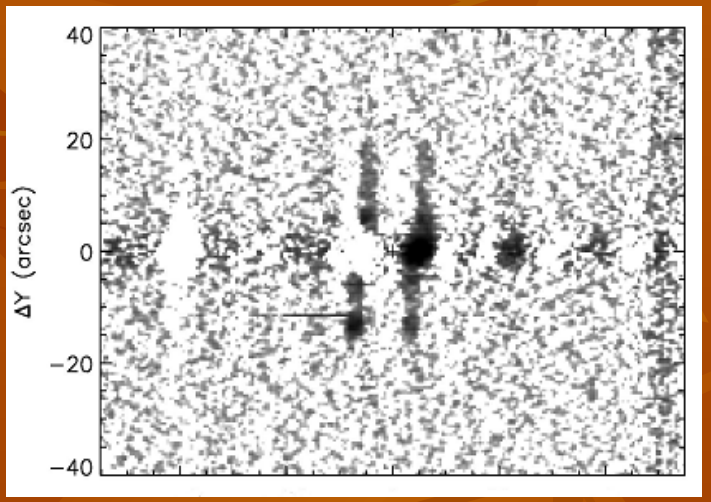
NGC 446

SDSS colour-combined images

UV→ recent star formation→ emission lines? Yes!

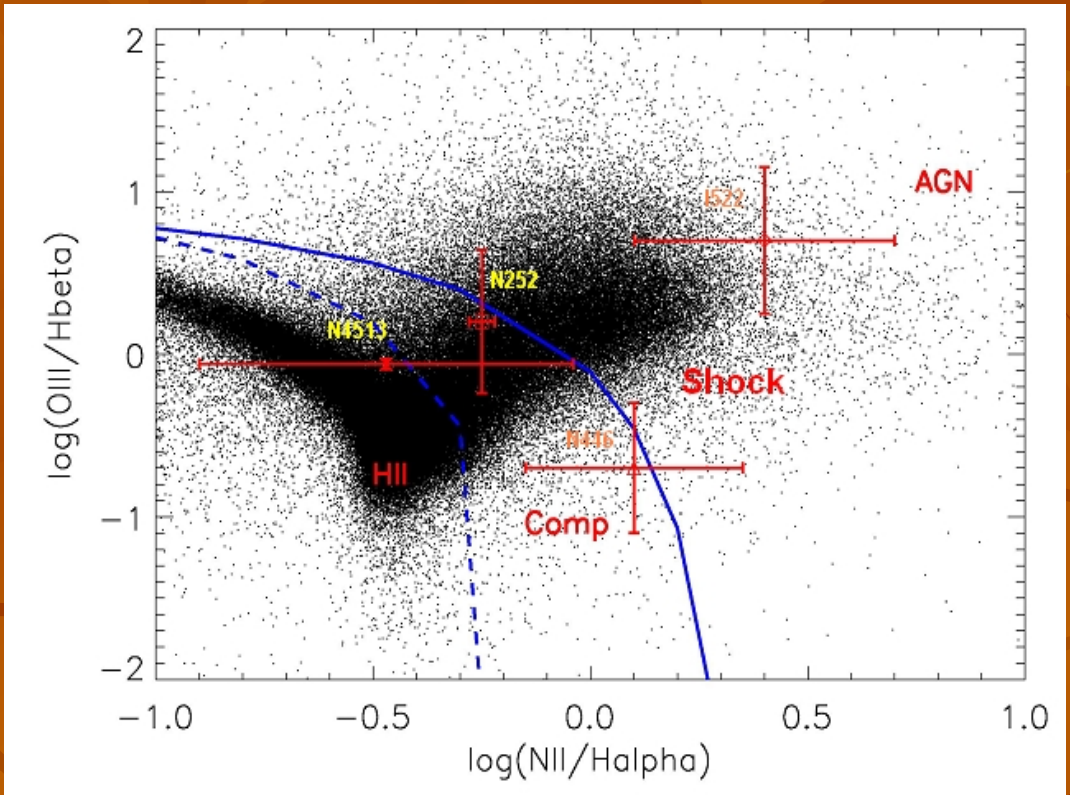


SDSS-image



Long-slit spectrum with the subtracted continuum, RSS/SALT

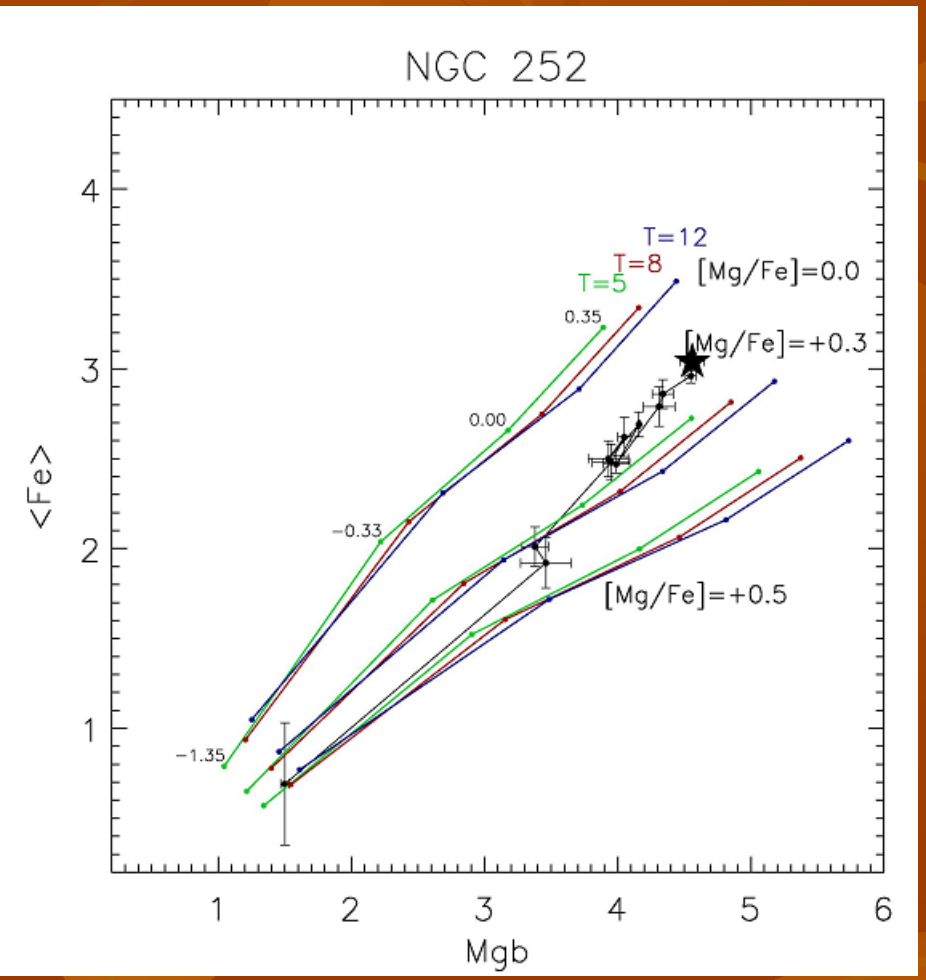
Different gas excitation in the rings:

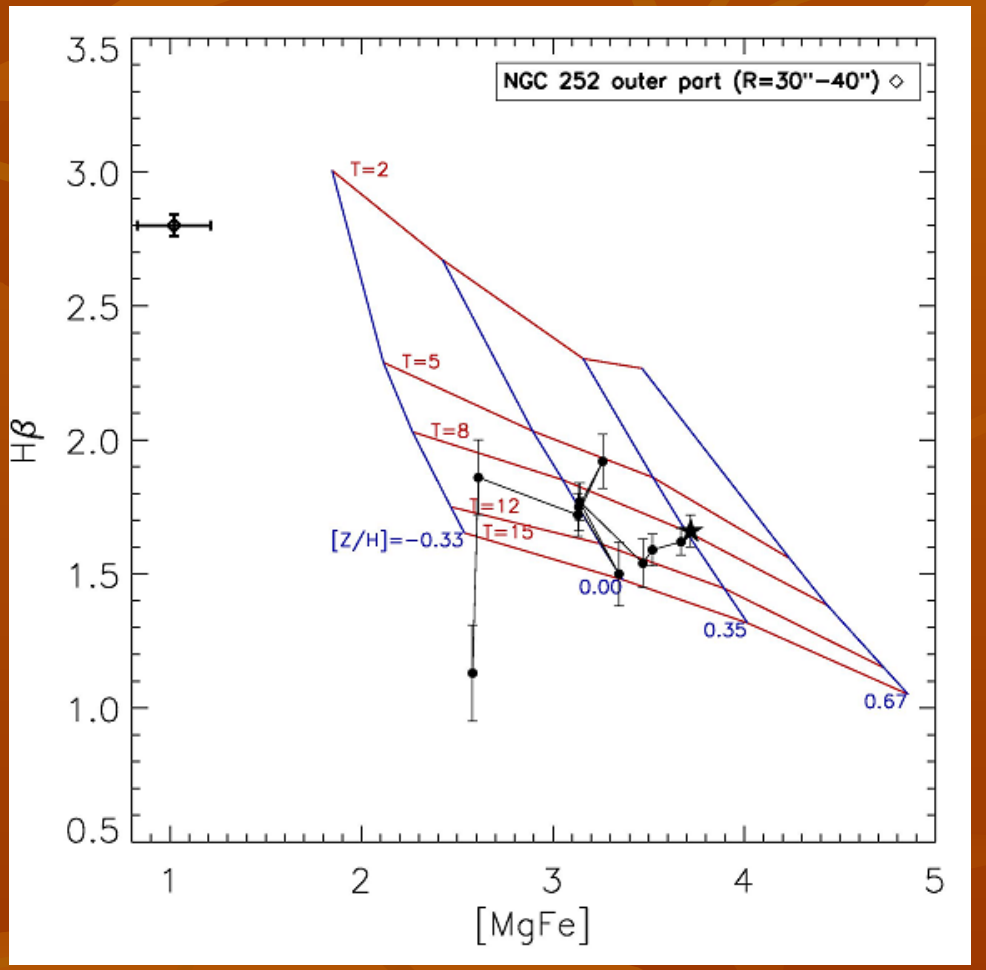


Ilyina, Sil'chenko, Afanasiev (2014)

But always solar O/H!

While the stellar components of the rings are rather metal-poor:





Full chemical evolution after discrete accretion events

The third possibility for a S0 galaxy to form an outer ring: ACCRETION

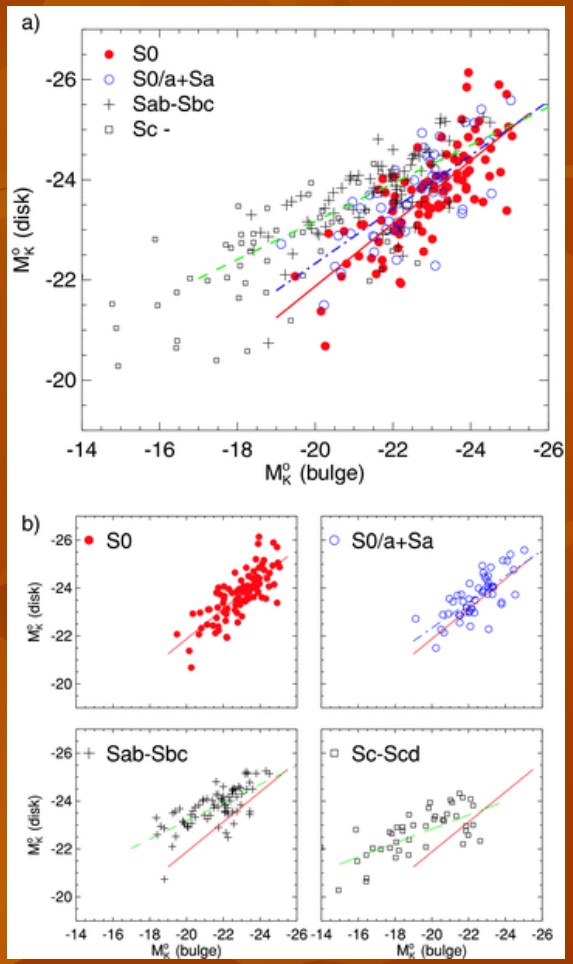
- Since outer gas accretion is a necessary condition of the disk galaxy evolution:

in S0s the accretion events may be more rare with respect to the spirals so the accreted gas is not enough to fill the whole disk, so it is concentrated in the outer rings;

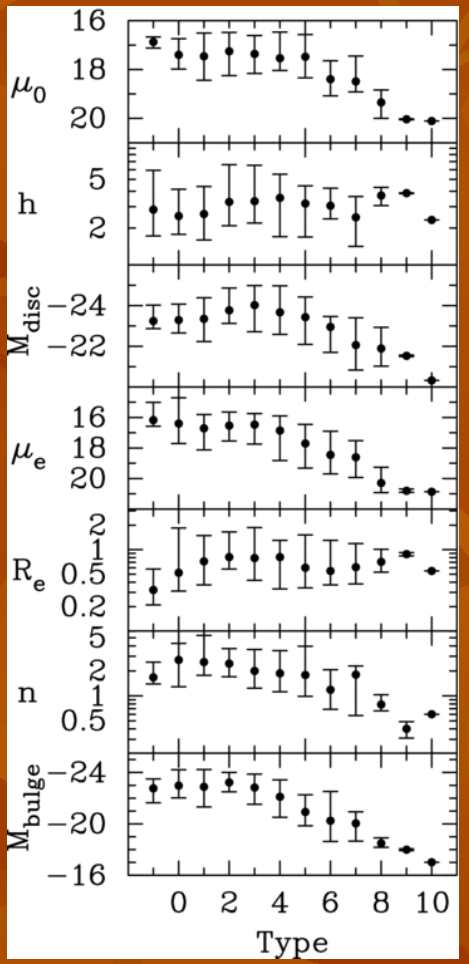
the gas can be accreted from different directions – various geometry of accretion is the reason for a diversity of kinematics and excitation;

the possible source of the outer gas accretion may be dwarf gas-rich satellites.

What can we explain with the new paradigm?

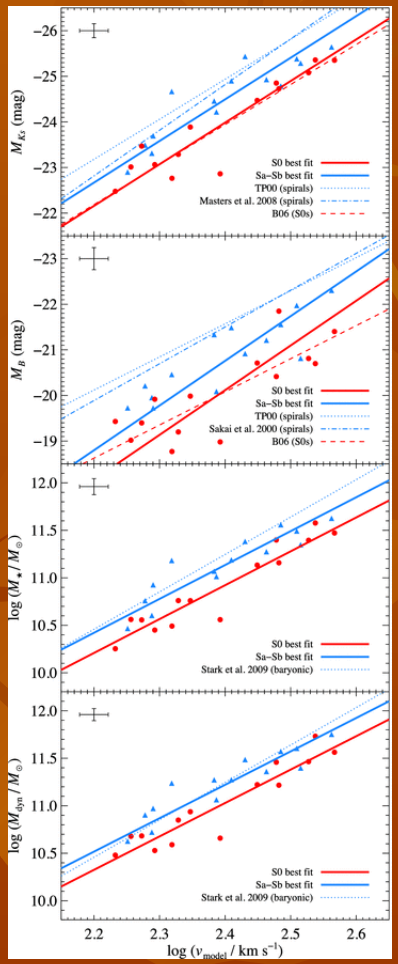


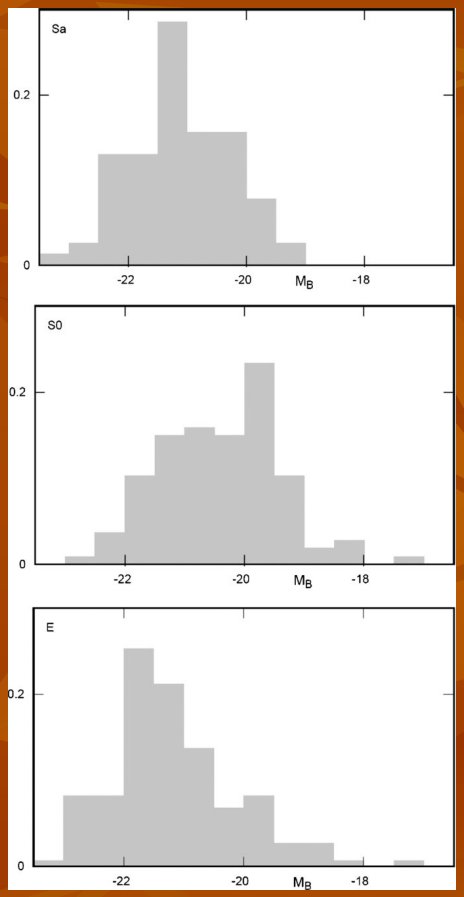
Laurikainen et al. 2010



Graham and Worley 2008

What can we explain with the new paradigm?

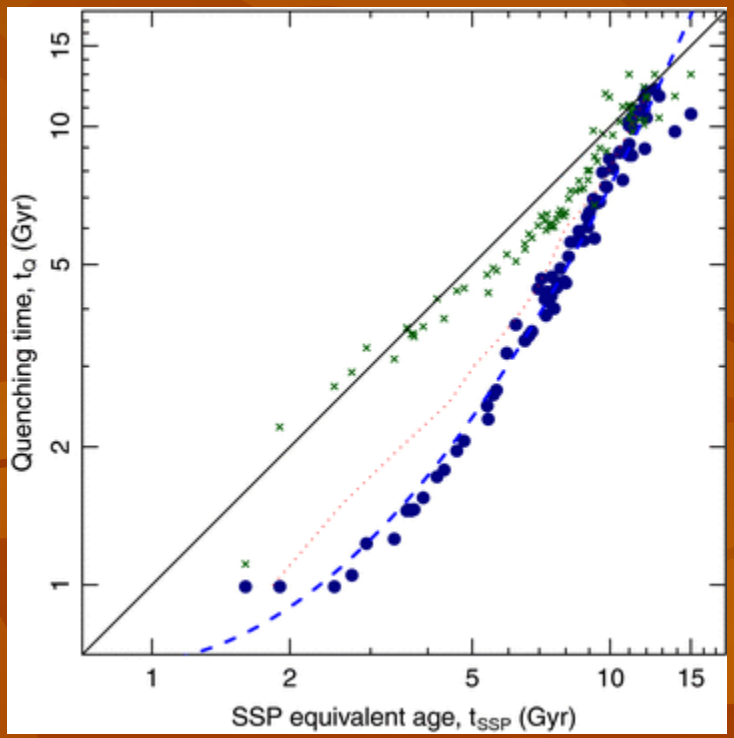




Williams et al. 2010

S. Van den Bergh 2009

So the star formation in S0 disks cannot be quenched at z=0.4!



Smith et al. 2009