The Quenching of Massive Spiral Galaxies

MNRAS Letter(arxiv: 2005.09663)
+ working in progress

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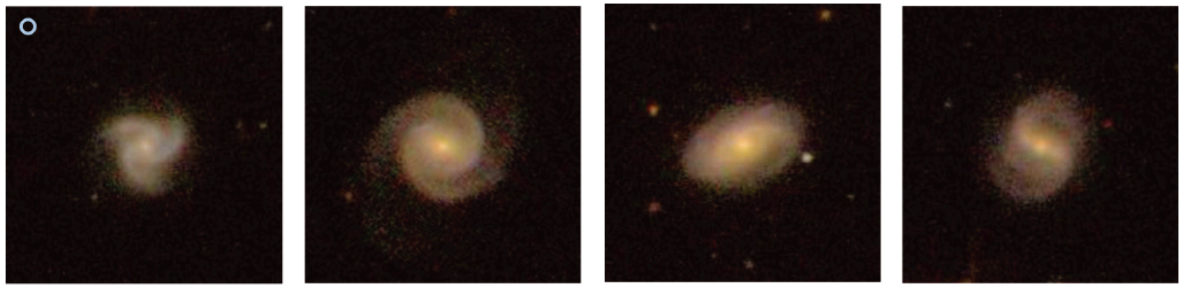

Tsinghua, Nov, 12, 2020

The quenching of massive spiral galaxies
---Background and motivation

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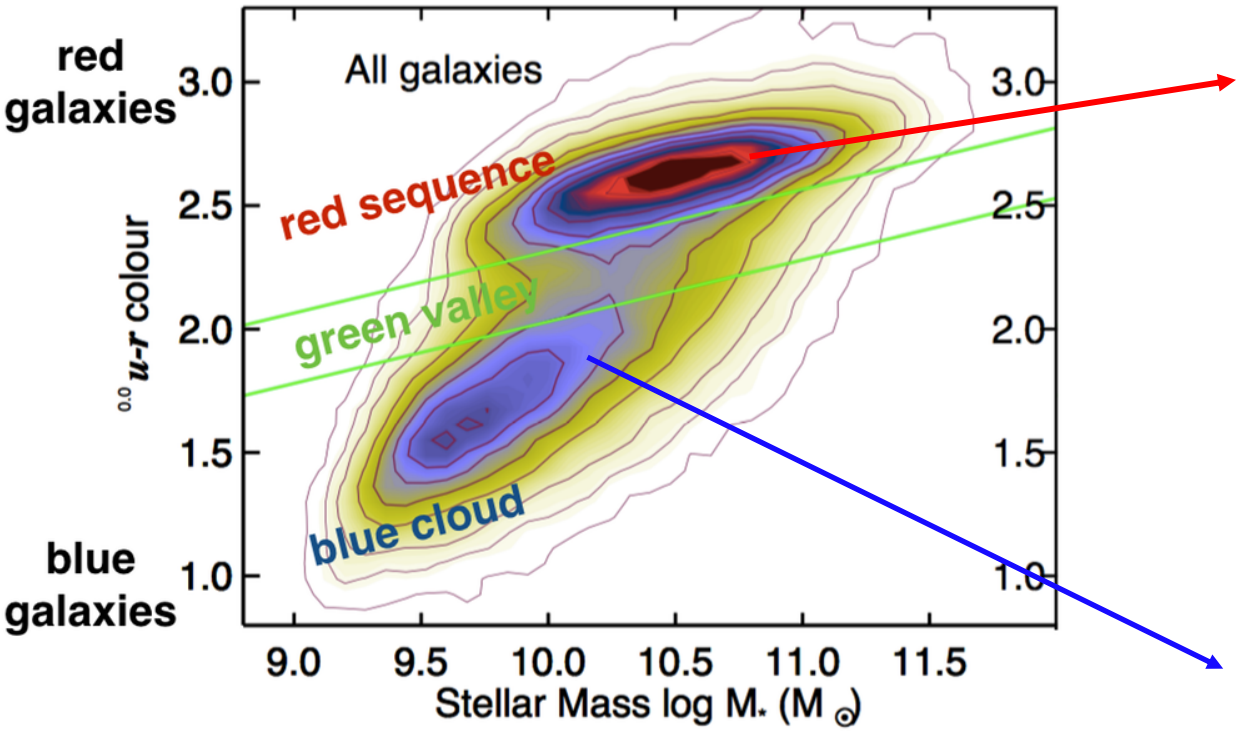
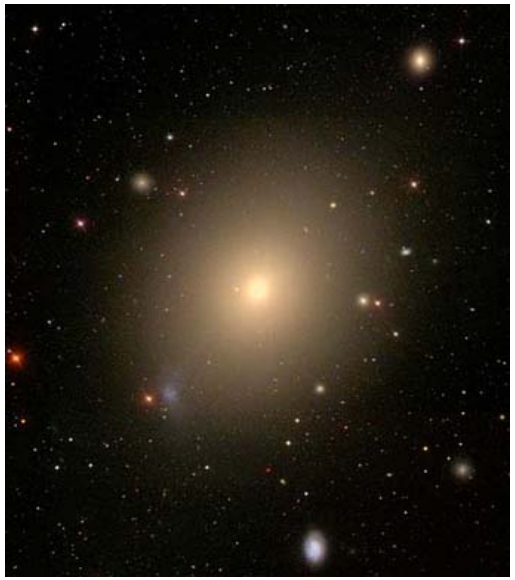
Galaxy color/morphology bimodality



Schawinski+ 2014



Most elliptical galaxies are quenched
Most spirals are star forming
True vice versa

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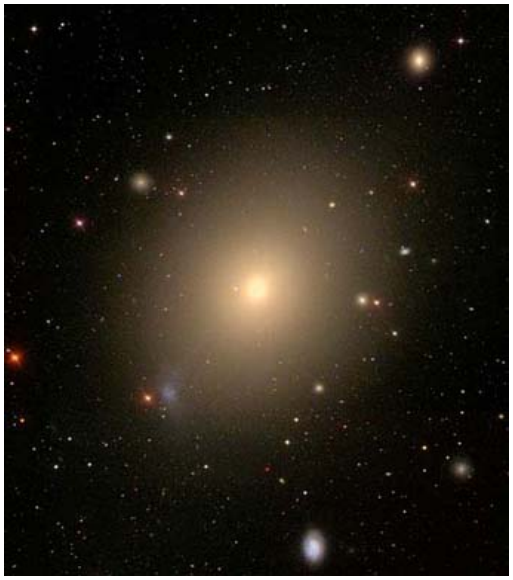
More observational facts about elliptical and spiral galaxies



Elliptical galaxies:
Live in massive haloes
Early formation time
Existence of hot circular galactical medium (CGM)
No fresh cold gas

Spiral galaxies:
Halo mass is lower
Late formation time
Not clear of the existent of hot CGM
Plenty cold gas

Fundamental question: Why the two populations are different?
Or What determines their diversities?

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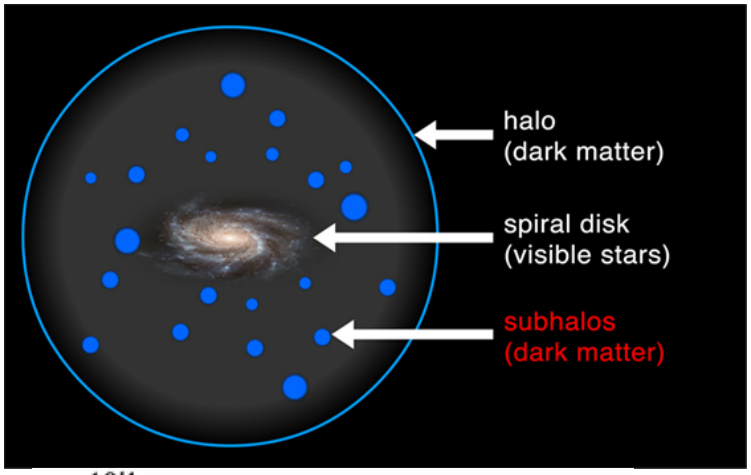
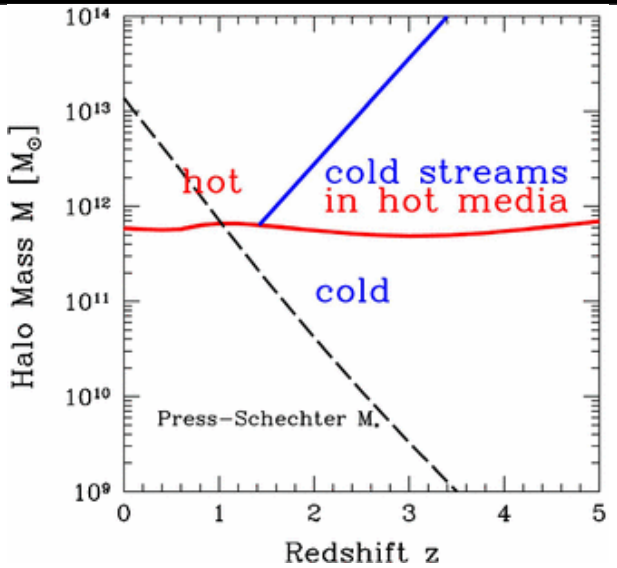
Galaxy formation is close linked to halo mass/accretion history





Dekel et al. 2009

Halo mass/accretion history matters:

- Baryon budget in the galaxy
- Gas accretion pattern (cold accretion or cooling from hot gas)
- Galaxy morphology
- Galaxy star formation history

General expectation:

Spiral: in quiet and low-mass halo where cold accretion is efficient-→ star forming

Massive galaxies: in massive halo where merger and feedback (AGN or others) to quench star formation→ red

Note: mass quenching-->nonsense

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How to quench a massive galaxy?

- Satellite galaxy: environmental quenching---tidal/ram-pressure stripping

- Central galaxy

Ellipticals: all gas consumed/expelled during merger and hot gas does not cool (energy source: starburst or AGN)

Red Spirals:

- No star formation in disc
  - no cold gas→no quenching needed
  - with gas →morphology quenching?
- No hot CGM hot→no cooling
- With hot CGM→ How to suppress cooling? (no energy source)

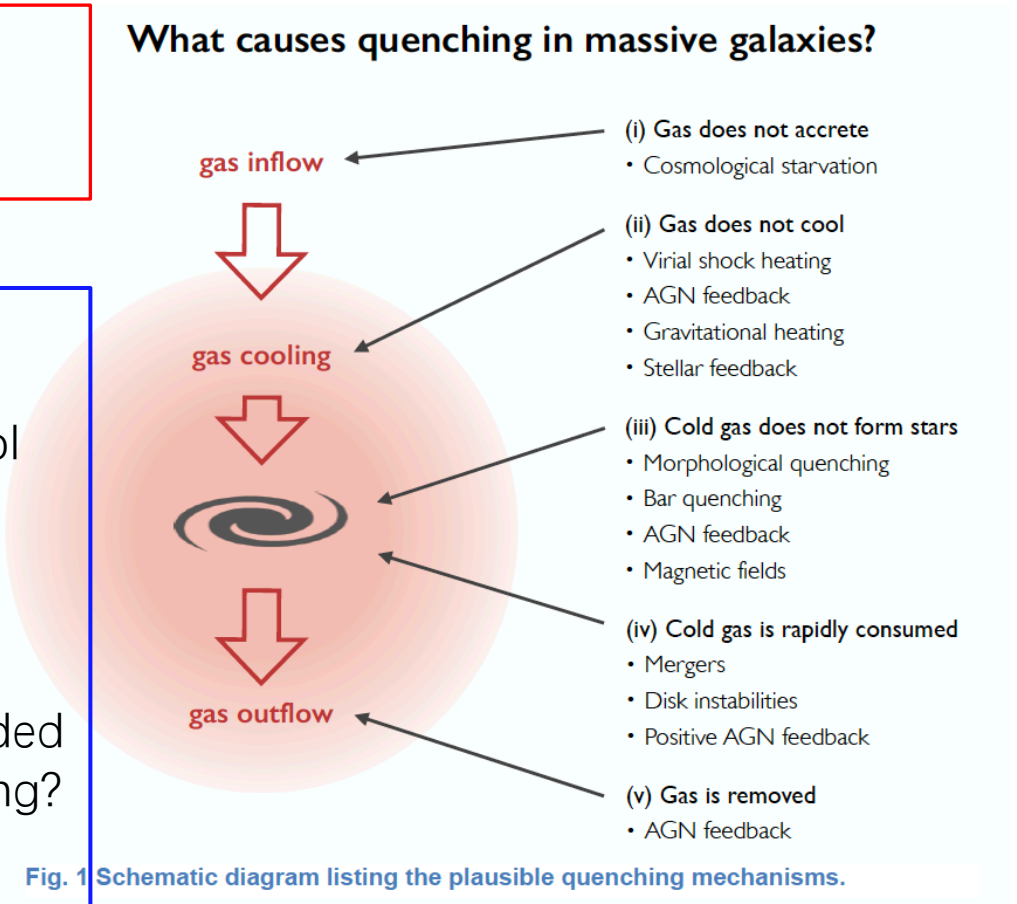

Fig. 1 Schematic diagram listing the plausible quenching mechanisms.

Man & Belli 2019

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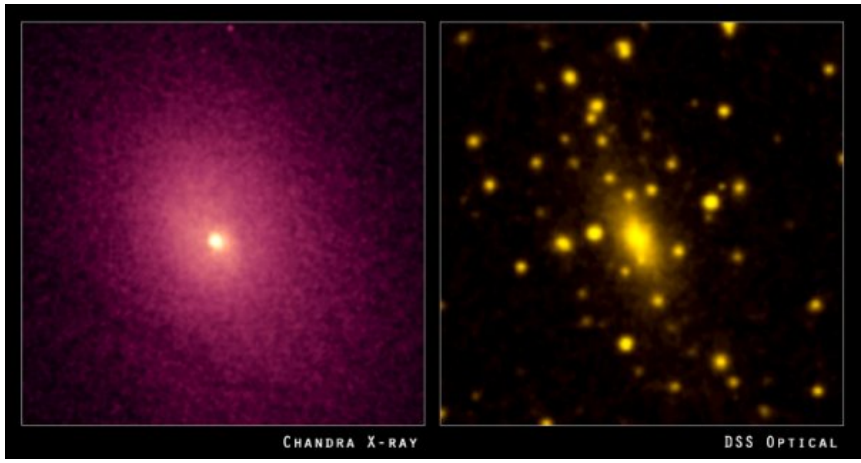
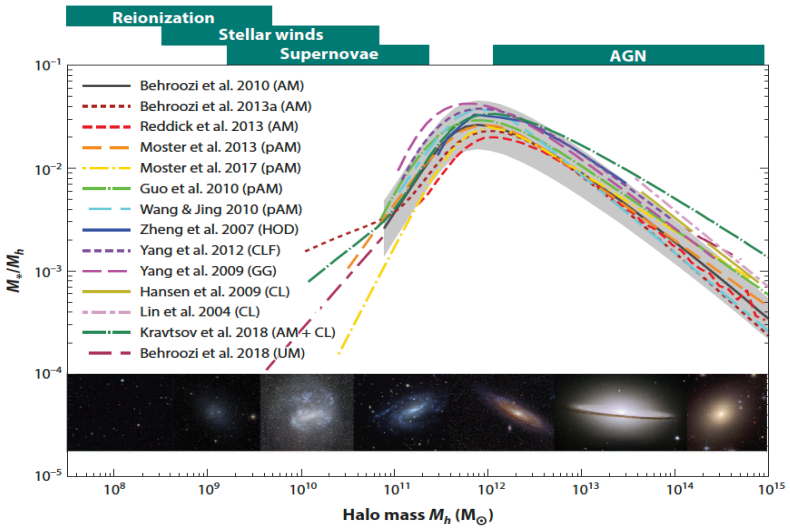
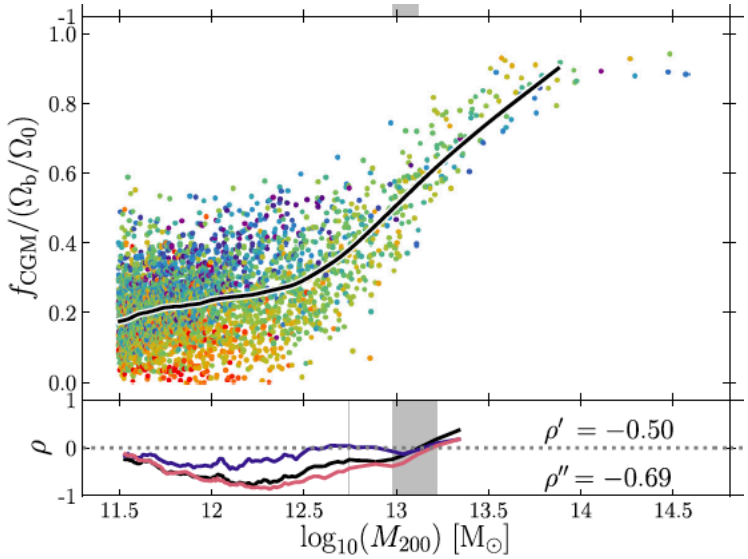
Quenching of massive (elliptical) galaxies-- a long last challenge !

- Massive halos contain nearly universal baryon, most in hot gas
- Stellar mass is at most 10% of gas in massive galaxies --- Quenching is needed





Wechsler & Tinker 2018



Eagle simulation, Davis+ 2020

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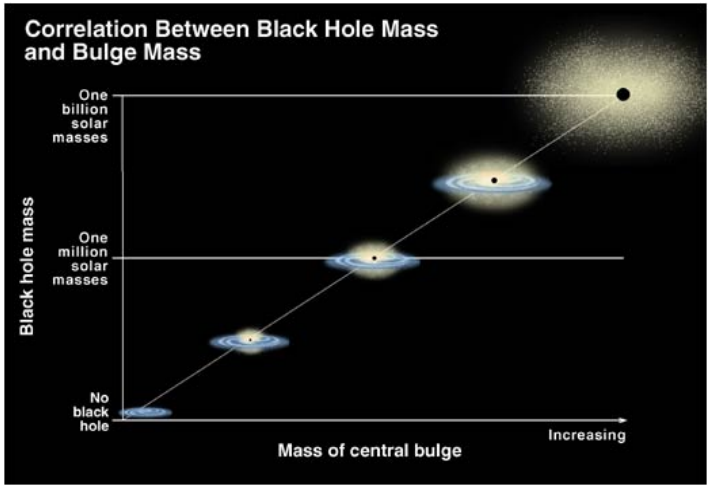
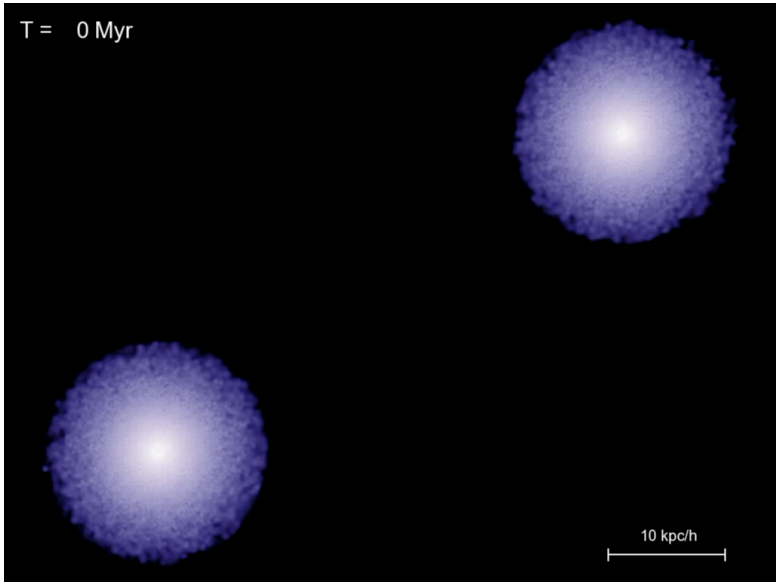
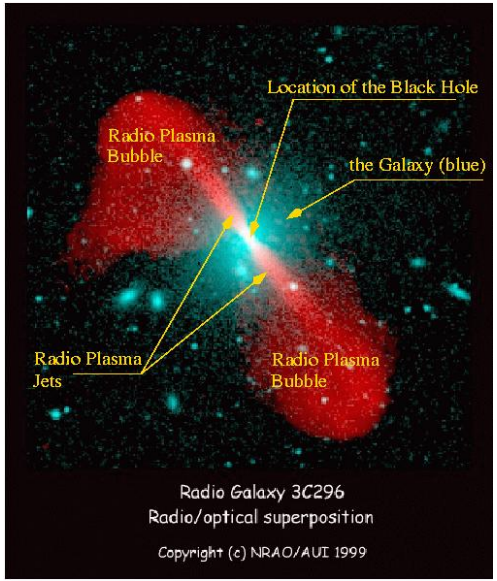
Black hole and AGN feedback in elliptical galaxies







- Almost all elliptical galaxies have massive black holes
- Feedback from radio AGN/QSO can effectively quench star formation (not clear in detail)

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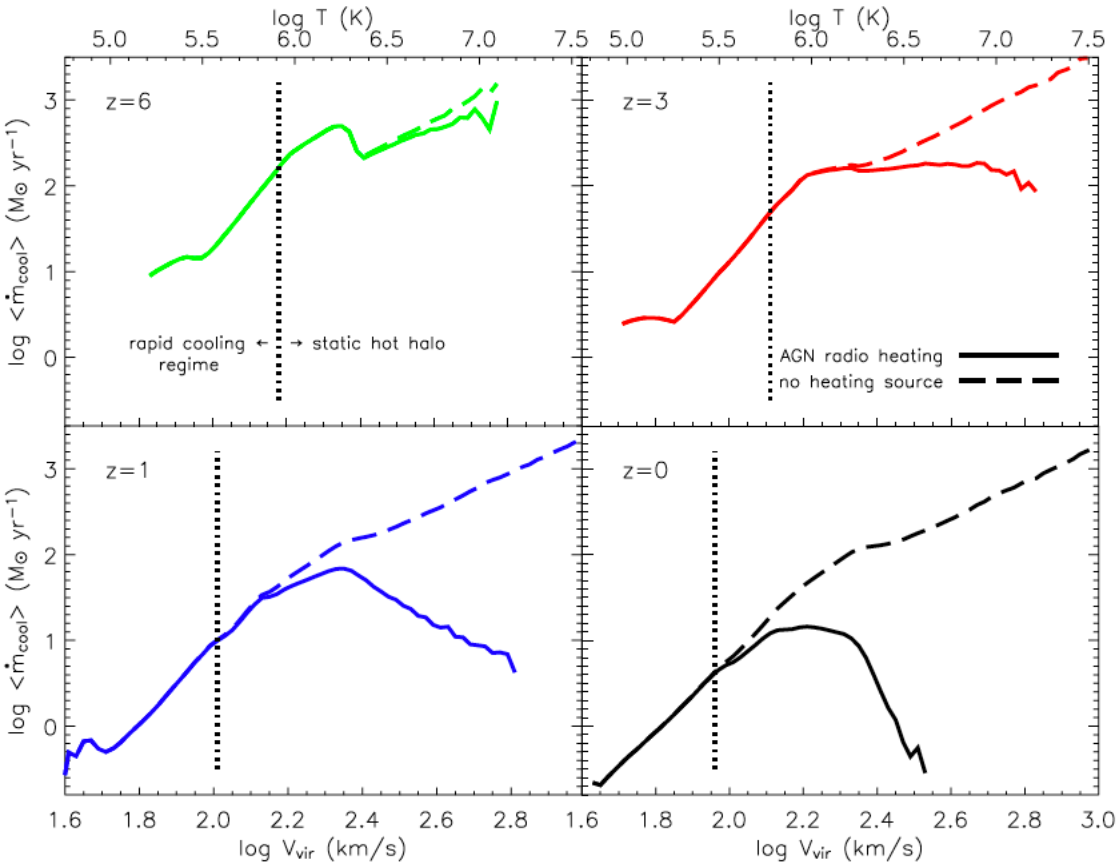
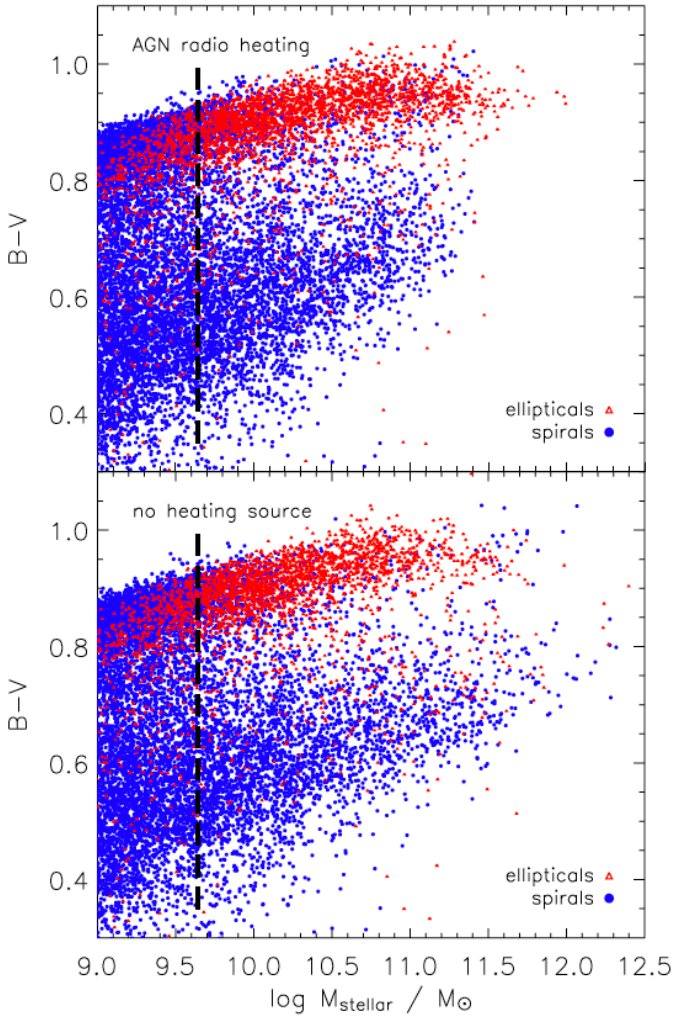
Models of galaxy formation including AGN feedback to suppress gas cooling

---Ellipticals are quenched and red





Croton et al. 2006

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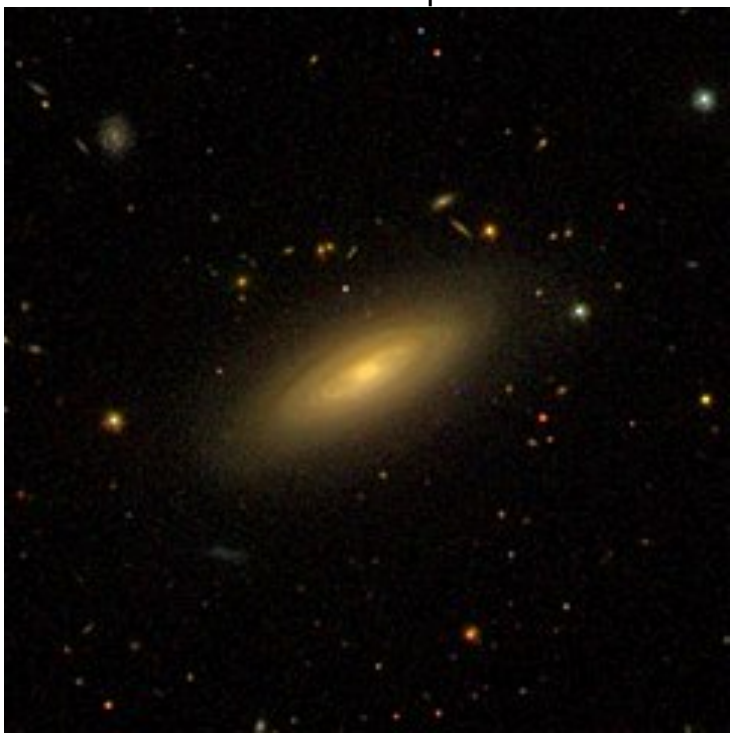
Why the two spirals are different?

Blue spiral

Red spiral



Simple but meaningless answer: red spiral has consumed all its gas

For most galaxies, stellar mass is at most ~30% of its universal baryonic mass
Where is the other baryon component?
Why no new cold gas supply?

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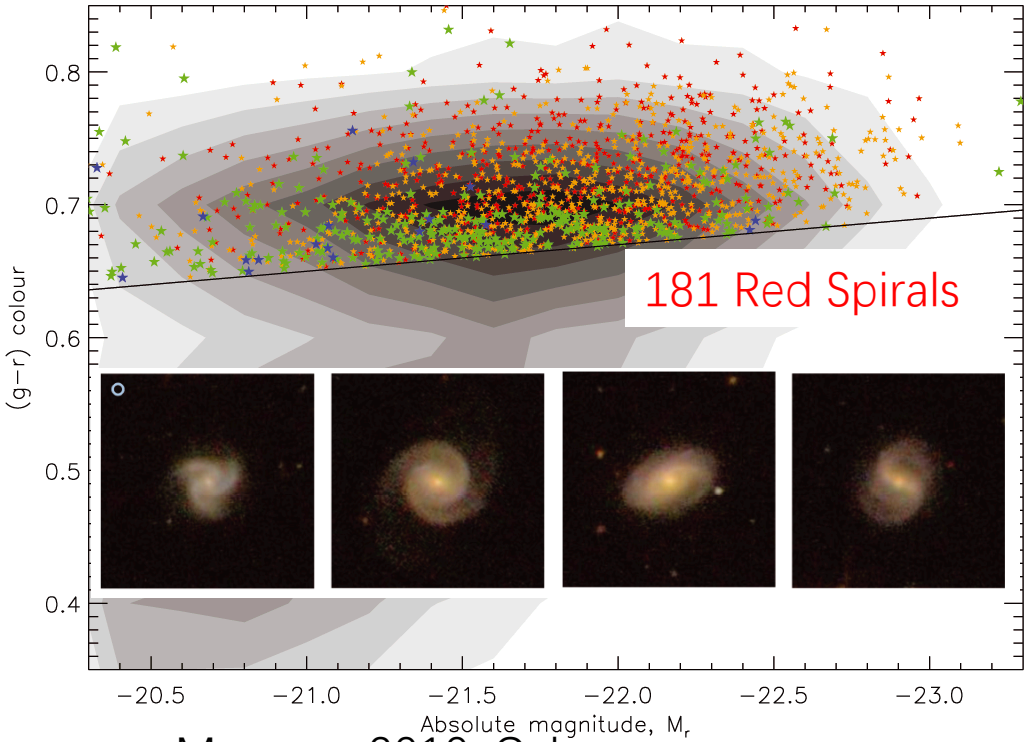
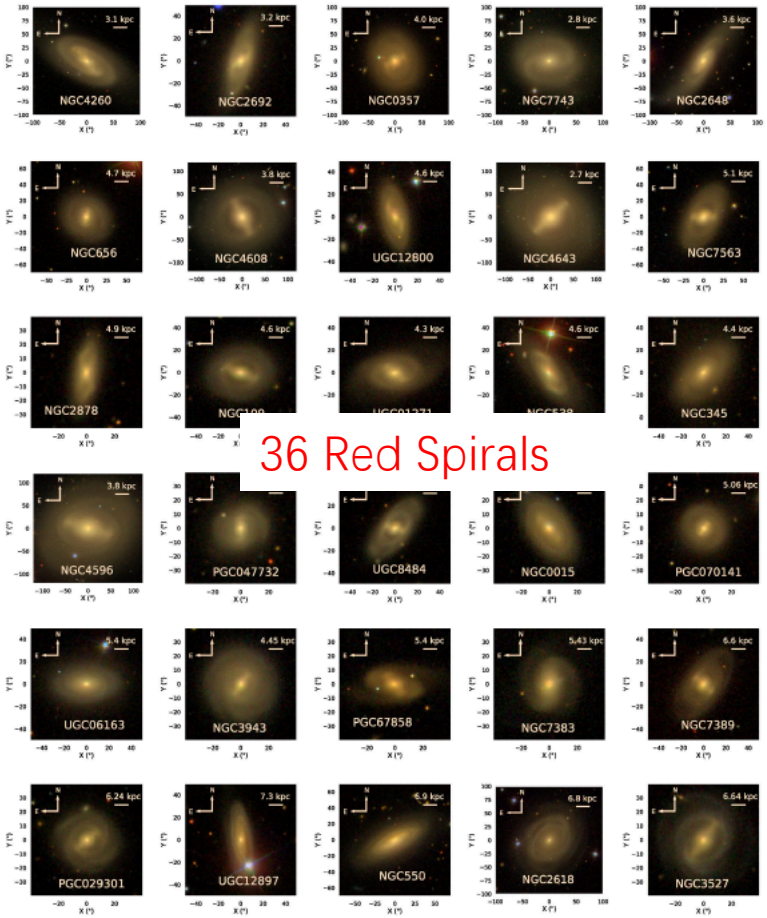
Passive spiral galaxies are rare & not well selected (contaminated)

- dozens of passive spirals are found in galaxy clusters until SDSS
- some are not really passive, but red because of dust



Masters+2010, Galaxy zoo

Fraser-McKelvie+ 2017
From 2MASS+SDSS



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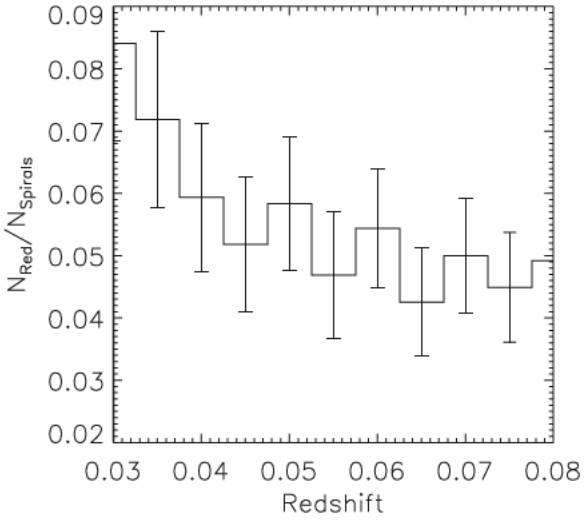
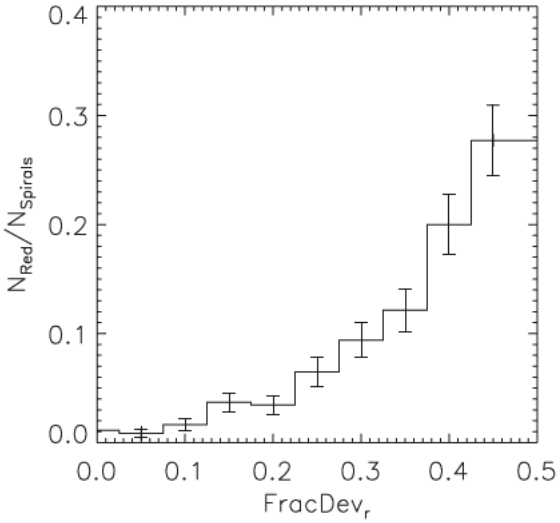
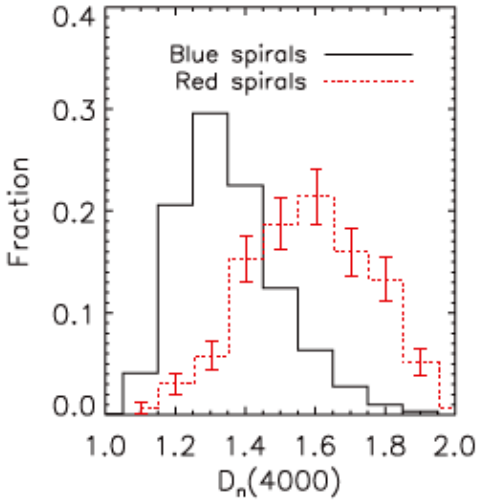
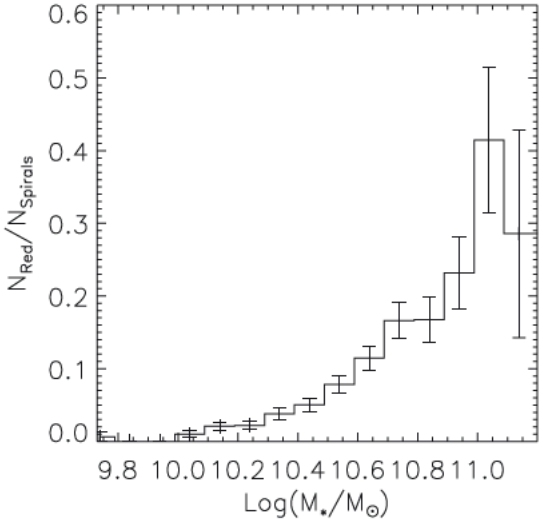
Properties of red spirals

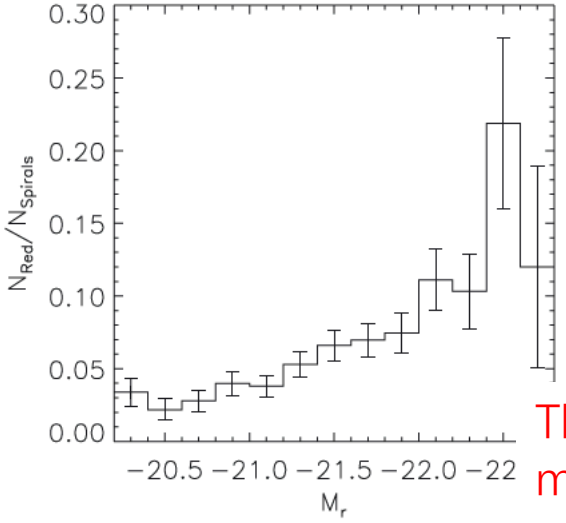
Masters+2010, from galaxy zoo











- Red spirals have old ages
- More red spirals at low-z
- High-mass spirals are more likely to be red

Their bar fraction is too high, most have fracDev>0.1

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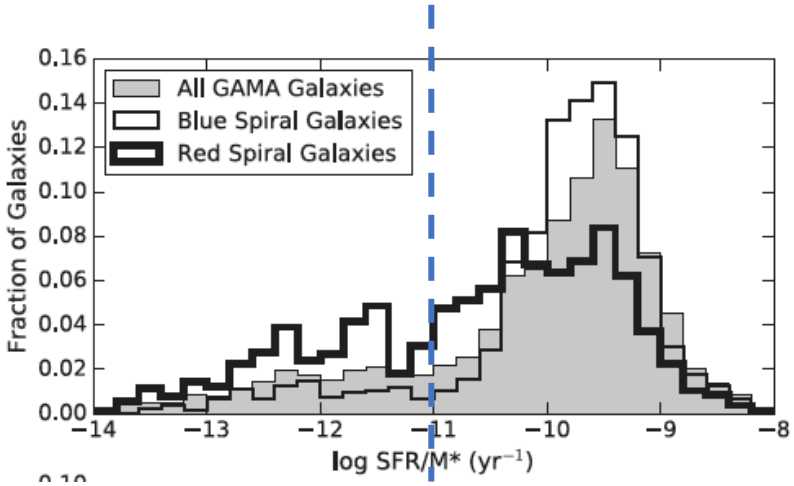
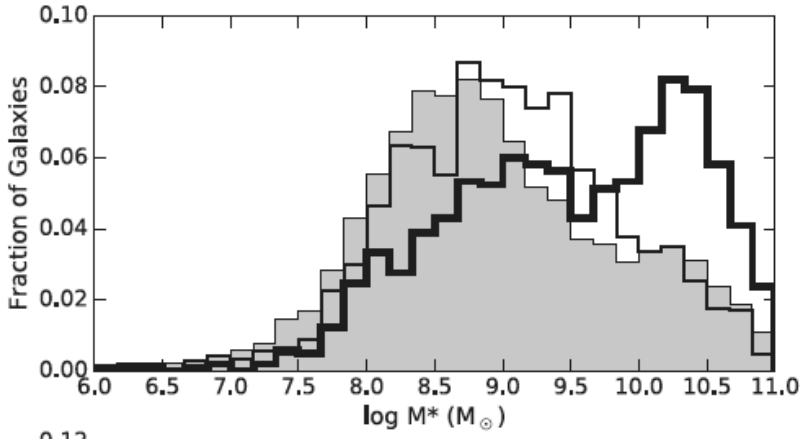
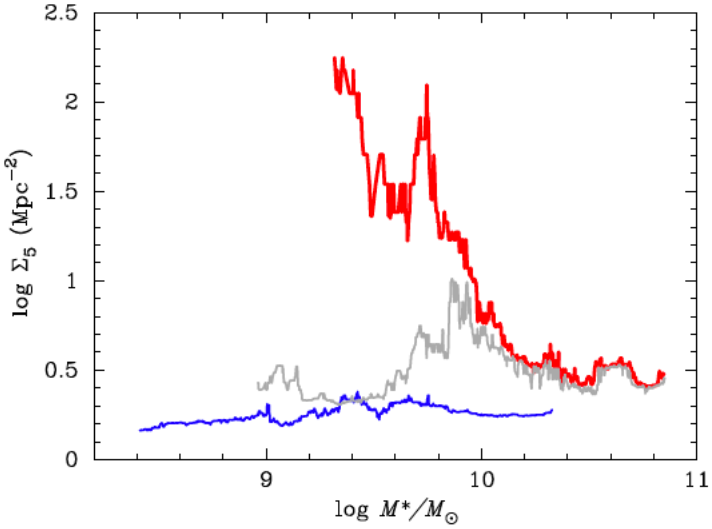
Properties of red spirals

Red ≠ passive

Mahajan+19, Red spiral from GAMA







- Optically selected red spiral has non-negligible SFR
- Red spirals live in more dense region

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Quenching does not mean no gas.
Any cold gas in passive spirals?

https://doi.org/10.3847/2041-8213/ab4ae4

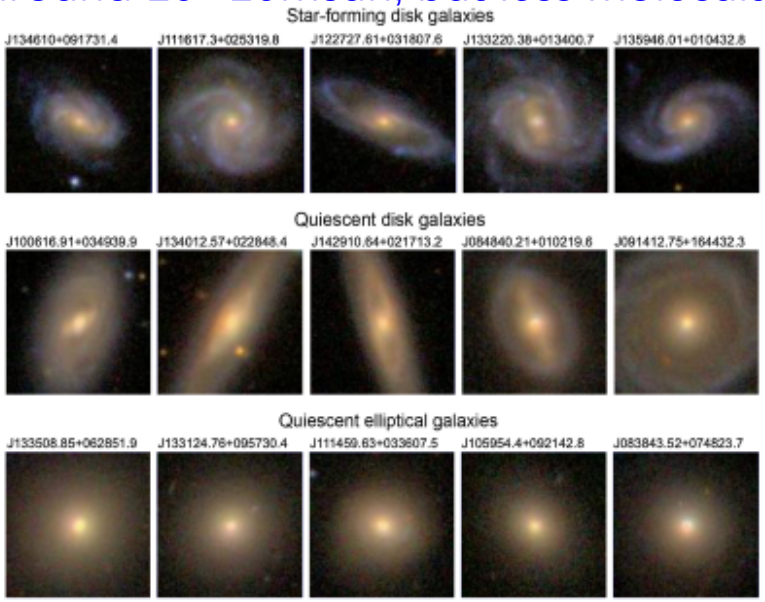
CrossMark

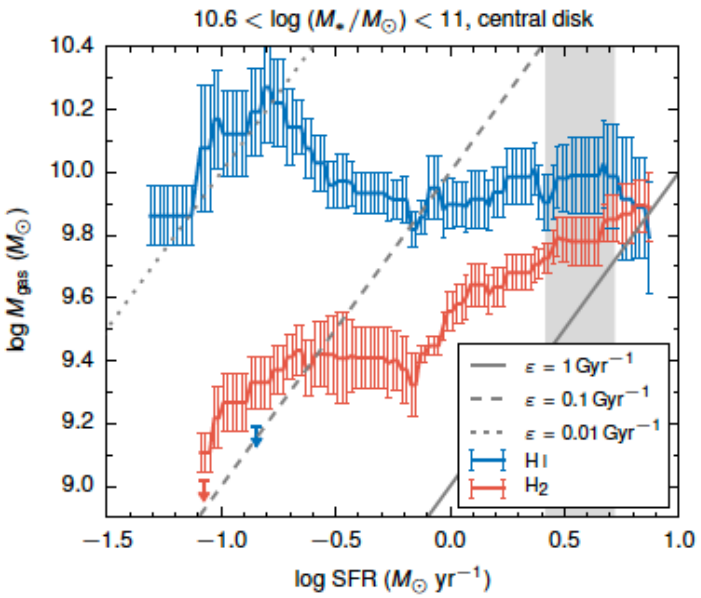
Nearly all Massive Quiescent Disk Galaxies Have a Surprisingly Large Atomic Gas Reservoir

Chengpeng Zhang[1,2], Yingjie Peng[1], Luis C. Ho[1,2], Roberto Maiolino[3,4], Avishai Dekel[5,6], Qi Guo[7,8], Filippo Mannucci[9], Di Li[8,10], Feng Yuan[11], Alvio Renzini[12], Jing Dou[1,2], Kexin Guo[1,13], Zhongyi Man[1,2], Qiong Li[1,2]

Data from SDSS, ALFALFA, GASS, COLD GASS surveys

Passive Spirals (10.6<lgM<11) have HI gas around 10^10Msun, but less molecular gas





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Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **494,** L42–L47 (2020)
Advance Access publication 2020 February 19

doi:10.1093/mnrasl/slaa032

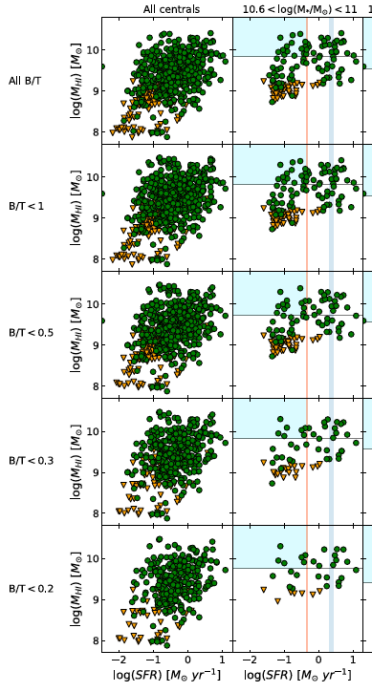
xGASS: passive discs do not host unexpectedly large reservoirs of cold atomic hydrogen

L. Cortese [1,2★] B. Catinella [1,2] R. H. W. Cook [1,2] and S. Janowiecki [3]

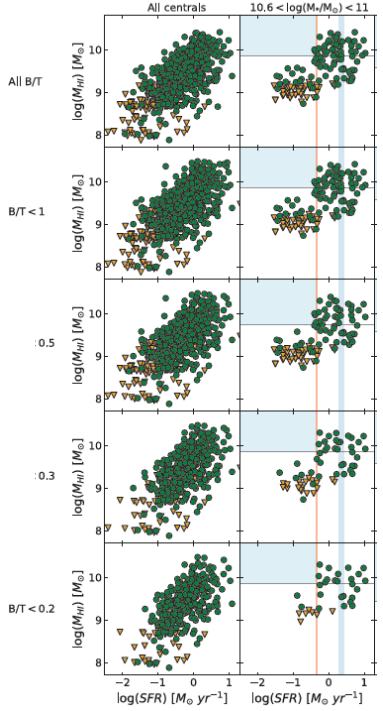
[1] *International Centre for Radio Astronomy Research, The University of Western Australia, 35 Stirling Hw, 6009 Crawley, WA, Australia*
[2] *ARC Centre of Excellence for All Sky Astrophysics in 3 Dimensions (ASTRO 3D), Australia*
[3] *Hobby–Eberly Telescope, McDonald Observatory, University of Texas, TX 79734 Austin, USA*

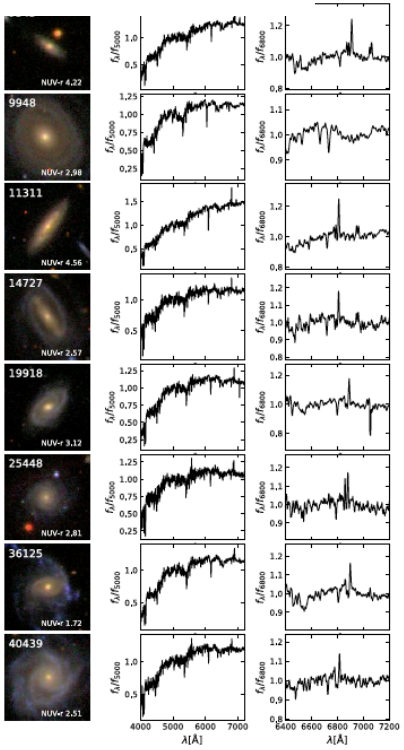
Cortese et al. used the same data set, but SFR from NUV+MIR

SFR from SDSS



SFR from NUV+ MIR



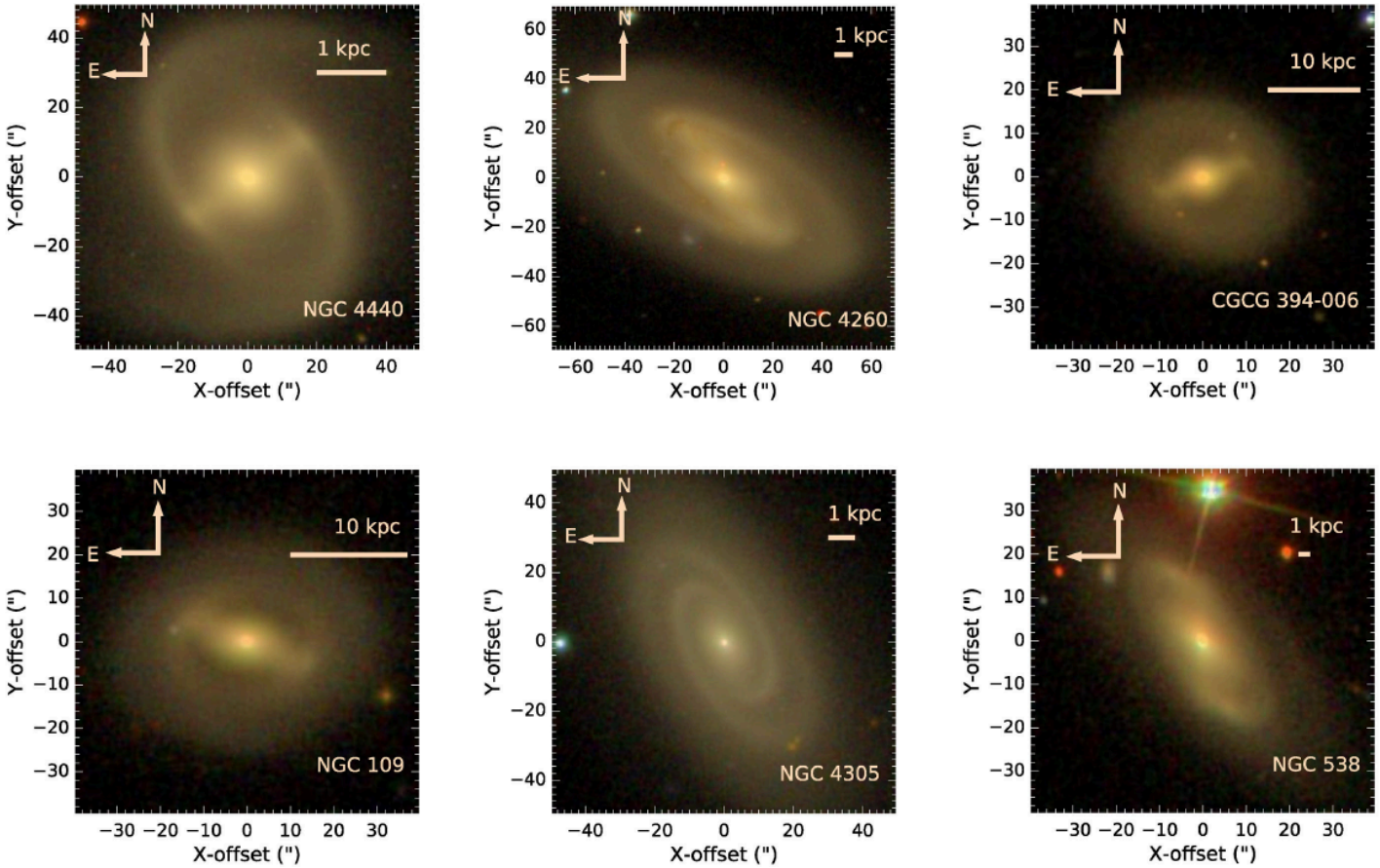


Zhang+ use fiber SFR

Many quenched spirals from Zhang+ show blue spiral arms and Ha lines

Morphology of Red Spirals

- Most studies show high bar fraction
- Bar can stabilize the gas disk, suppressing star formation



Bar is present even they select spiral using small fracDev parameter

Fraser-McKelvie+16

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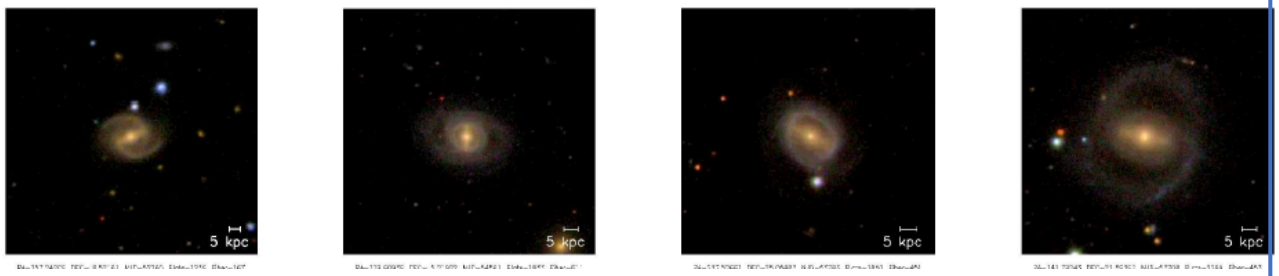
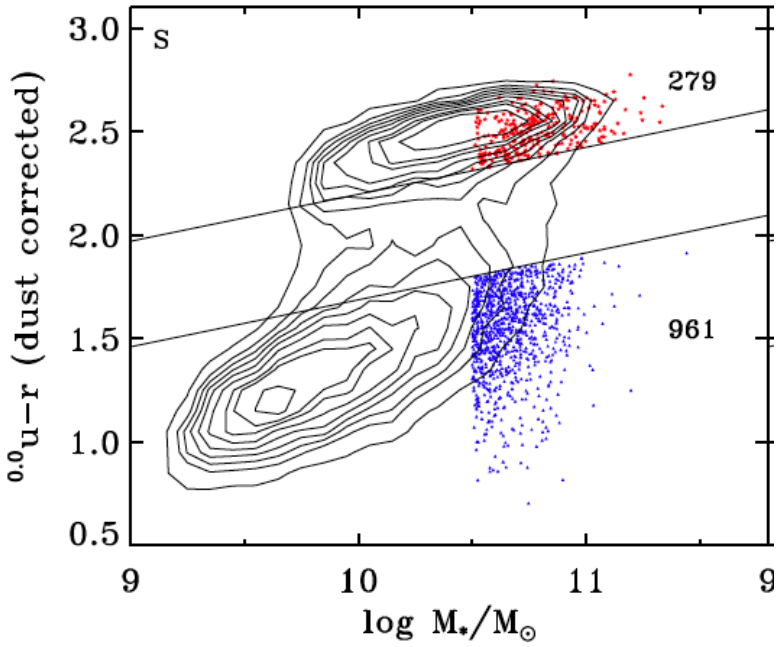
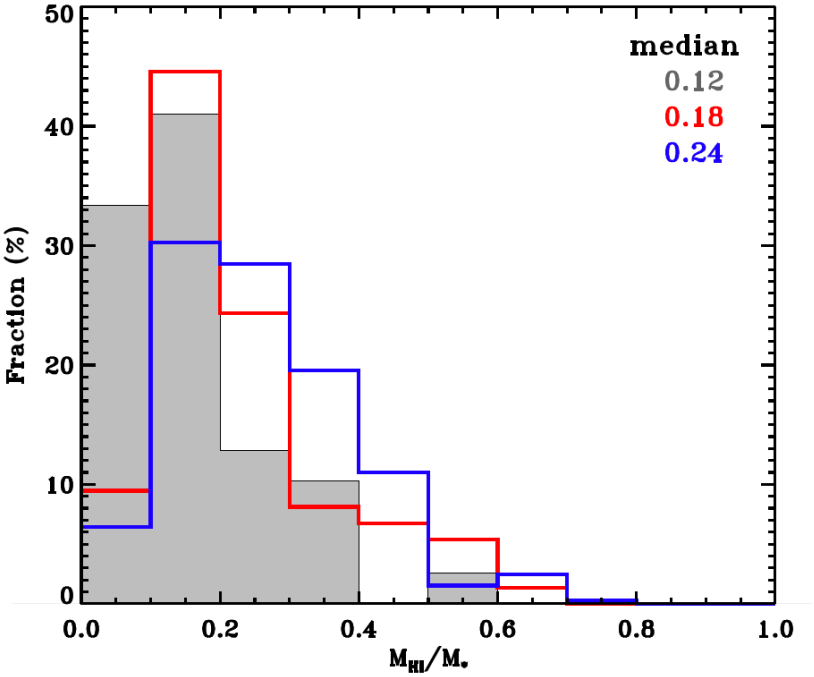
Morphology of Red Spirals

Guo, Xia+2020, arXiv:2006.05462



- 279 red spiral from 1914 spirals
- Significant bulge/bar in red spirals than in blue spirals
- Cold gas~10%





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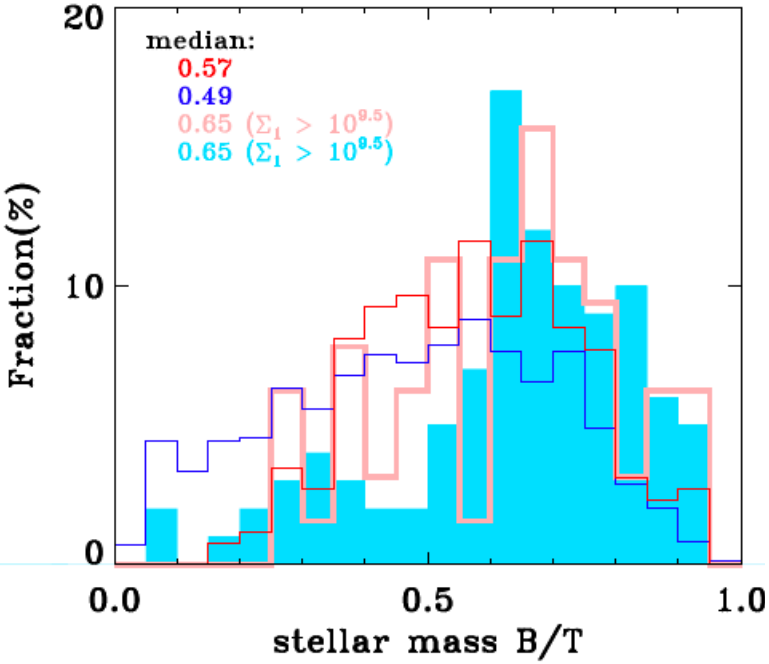
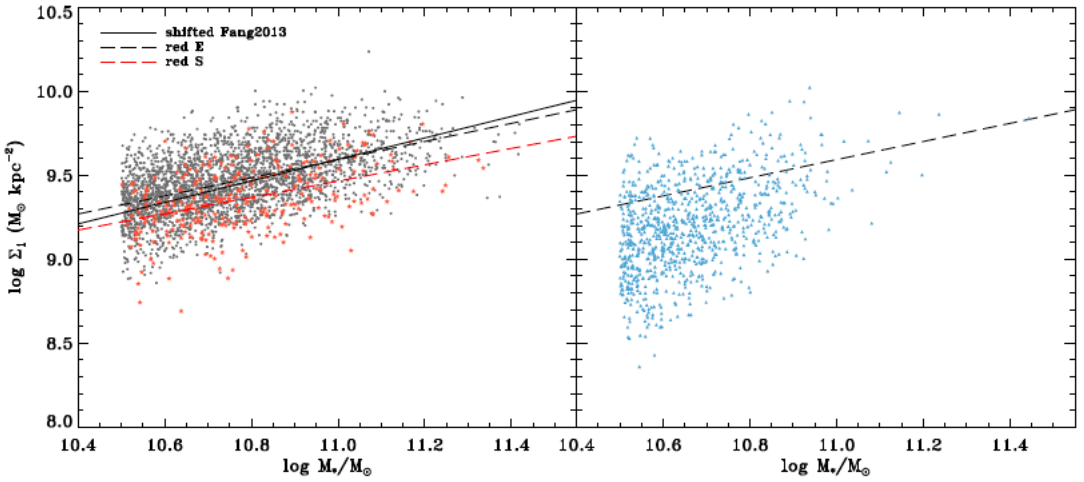
Bulge and central density of red spirals

- Quenched spirals have larger bulge/bar
- Quenched spirals have higher central density





Guo+2020, arXiv:2006.05462

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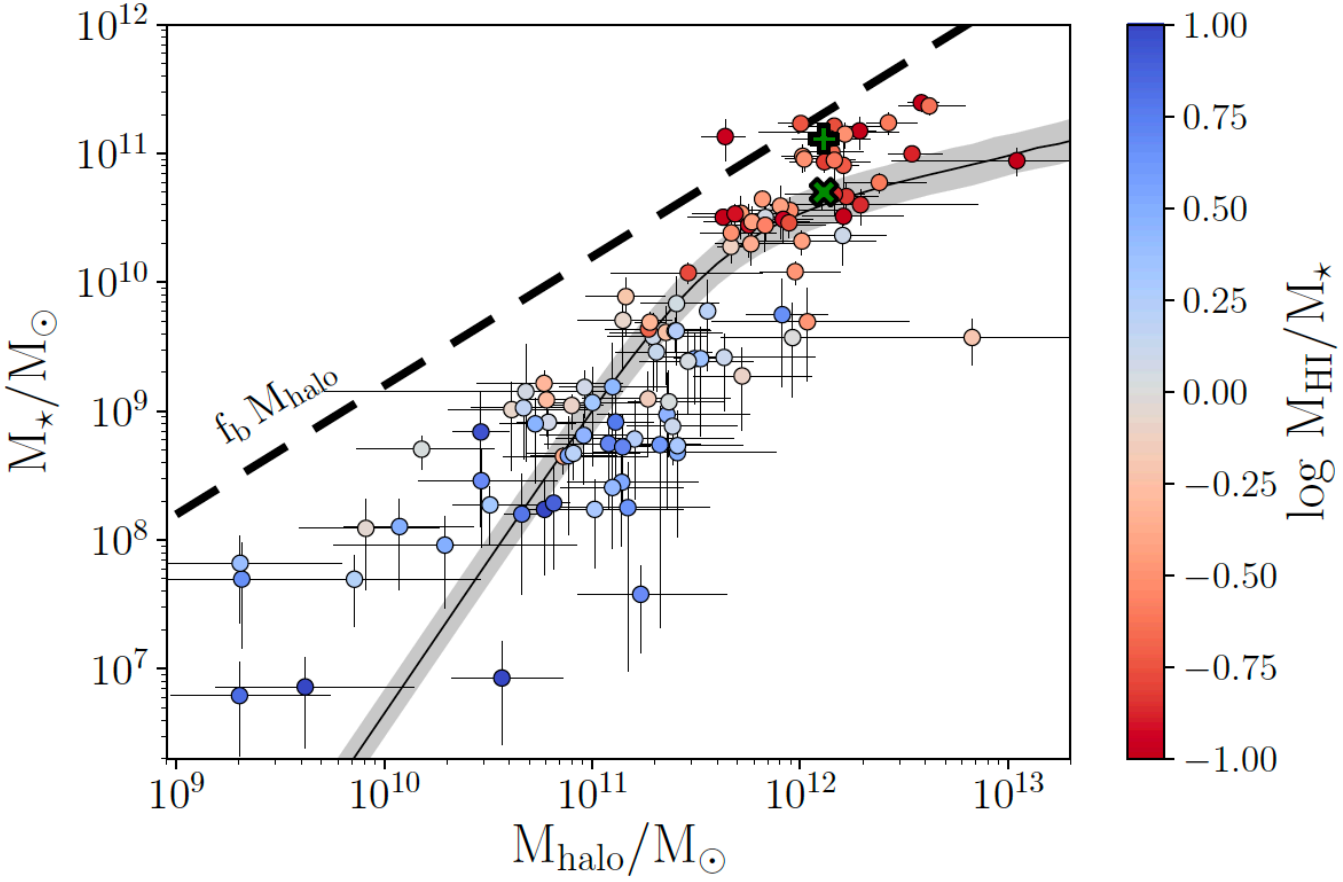
Halo mass of Massive blue spirals

No miss baryon in some massive spirals



Posti et al. 2019

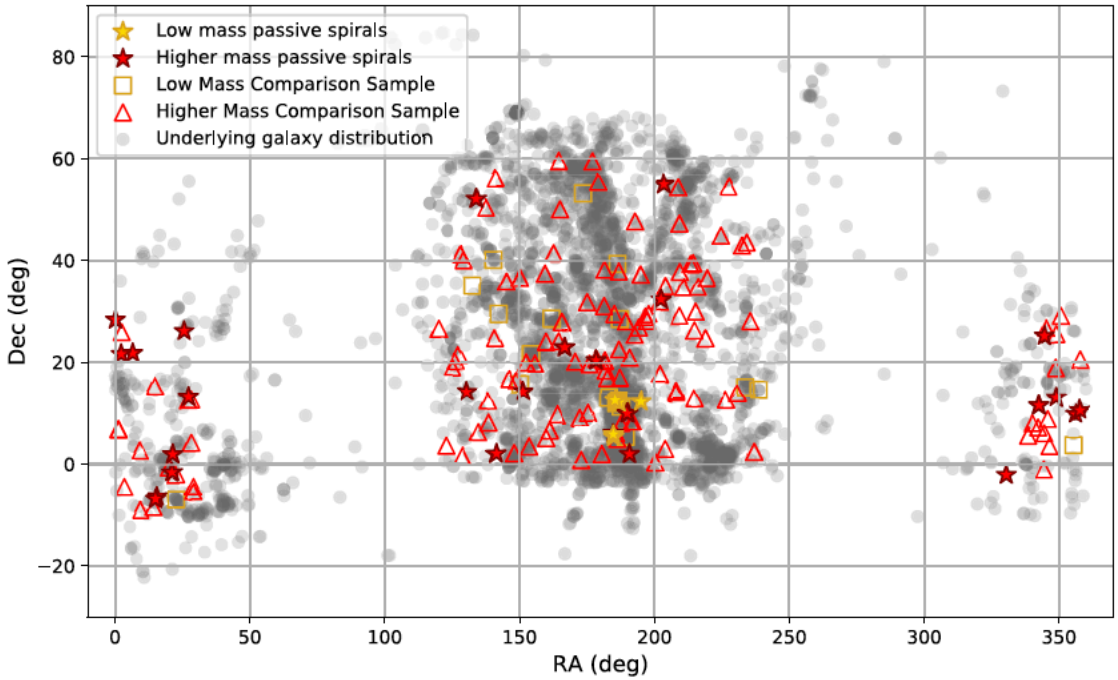
- 175 disc galaxies with near-infrared photometry and HI rotation curves
- Massive blue spirals are in halos mass<$3*10^{12}M_{sun}$, where quick cold accretion is expected

Quenching of low-mass spirals

For satellite galaxies, environmental effect (tidal stripping/ram-pressure) will reduce the gas content

---most low-mass passive spirals are found in/around clusters

(Bamford+2009, Wolf+2009, Fraser-McKelvie+2010)



The quenching of massive spiral galaxies ---Our results

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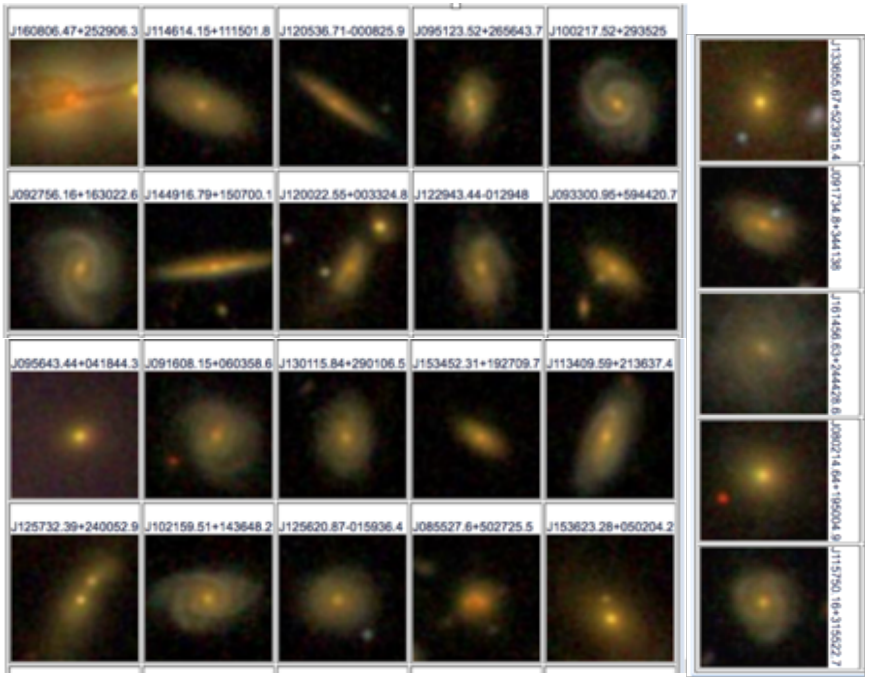
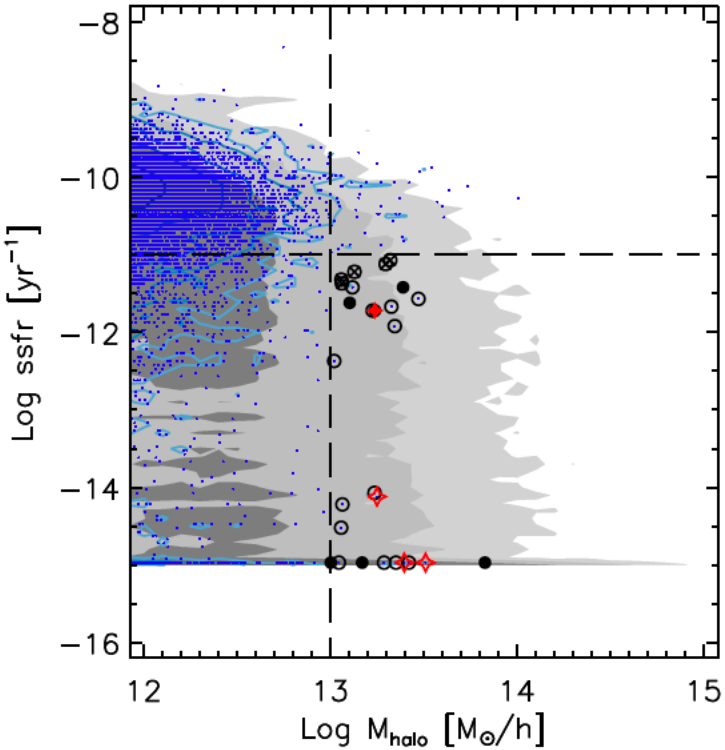
Our Observational Sample

- SDSS+Yang Group catalog+Chang catalog (WISE)
- Central Galaxies with Mhalo>10^{13} Msun & fdev<0.1
  72 galaxies in total
- sSFR<10^{-11}
  27 Quenched, 52 star forming



Luo, KX+, 2020, MNRAS Letter



The quenching of massive spiral galaxies ---Our results

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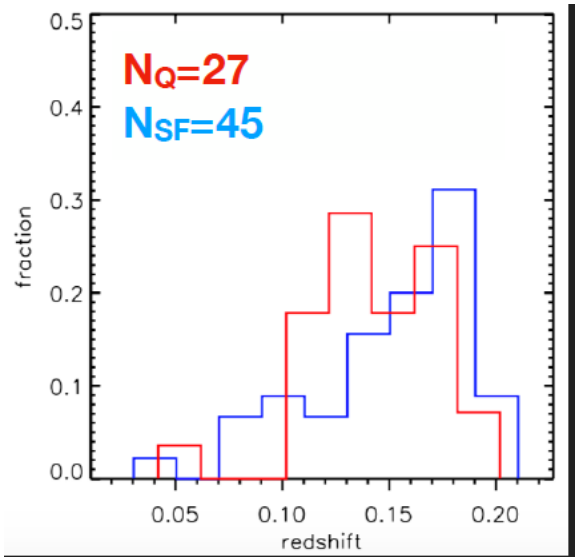
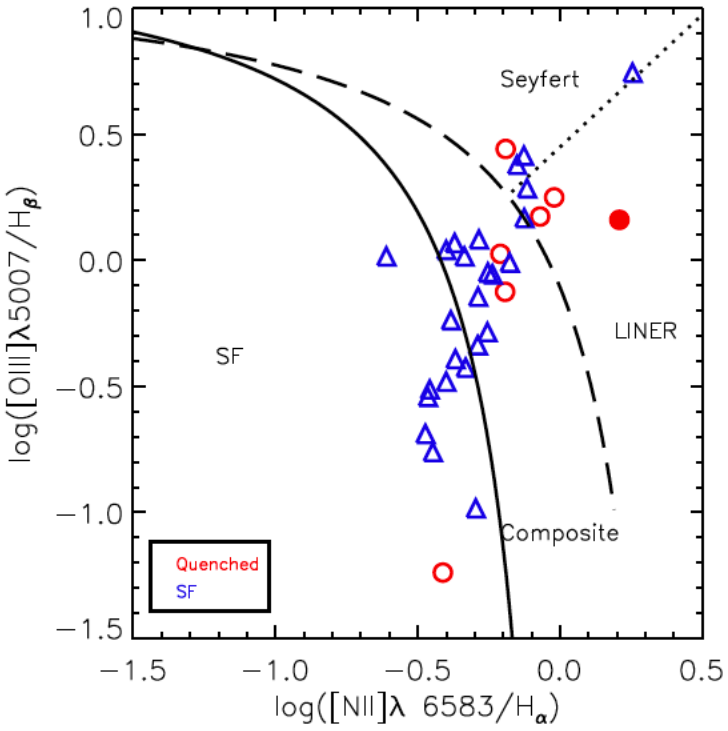
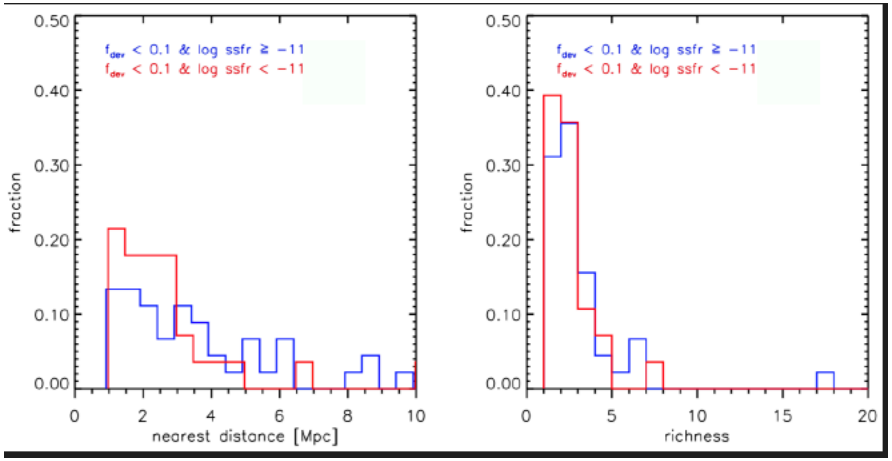
Our sample

- Most at z>0.1 (no cold gas data)
- In isolated environment
- 6 among 27 quenched galaxies show AGN activities, others lack emission lines



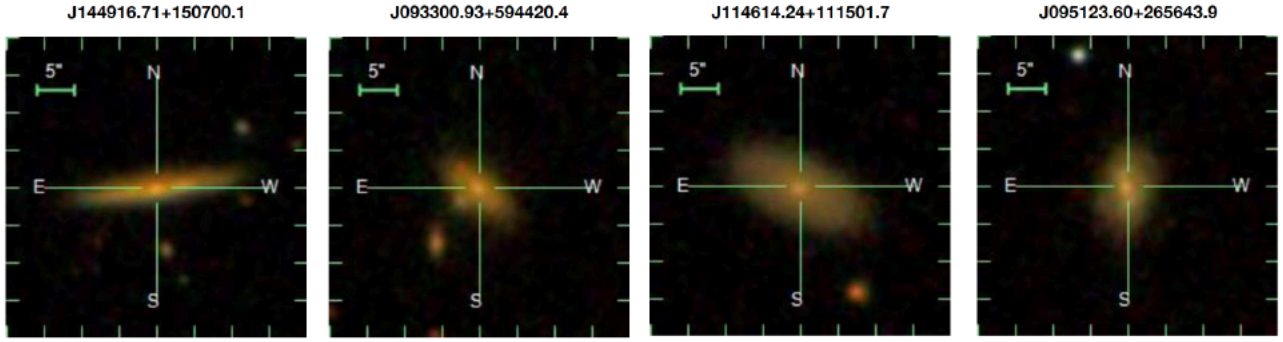


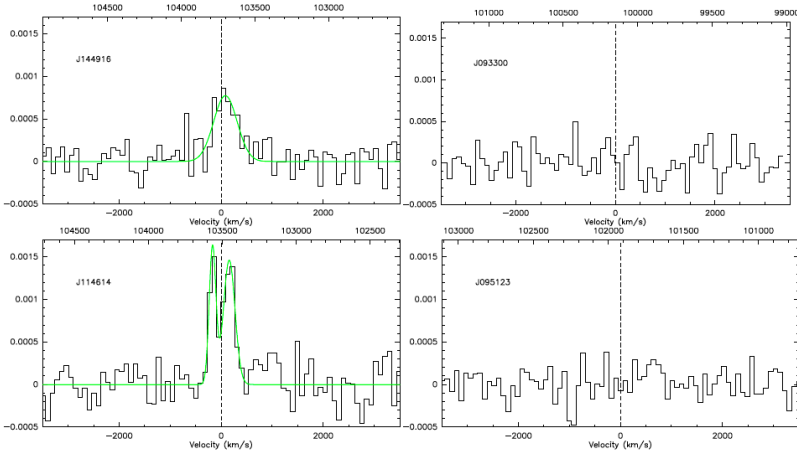
Distances to nearest neighbor



The quenching of massive spiral galaxies
---Our results

We randomly select 4 quenched galaxies for CO detection using IRAM 30m for 20 hours





CO(1-0) spectra

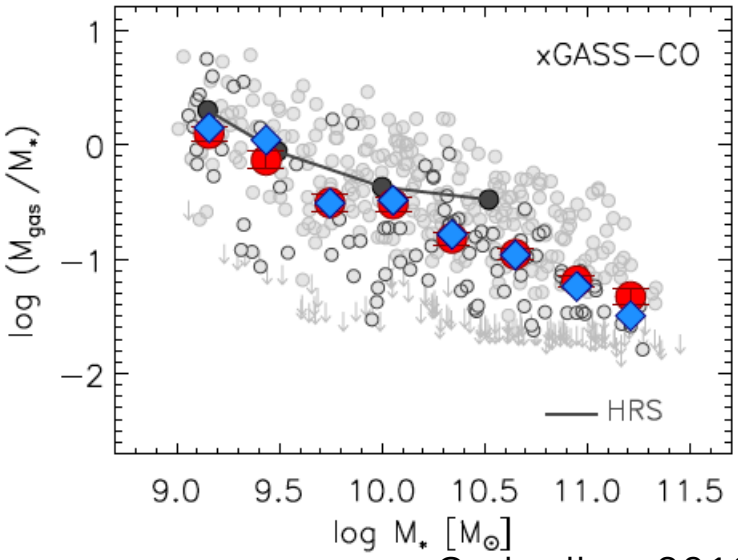
Two have CO detection. All have cold gas $<10^{10}$Msun ($M_{cold}/M*<0.05$)

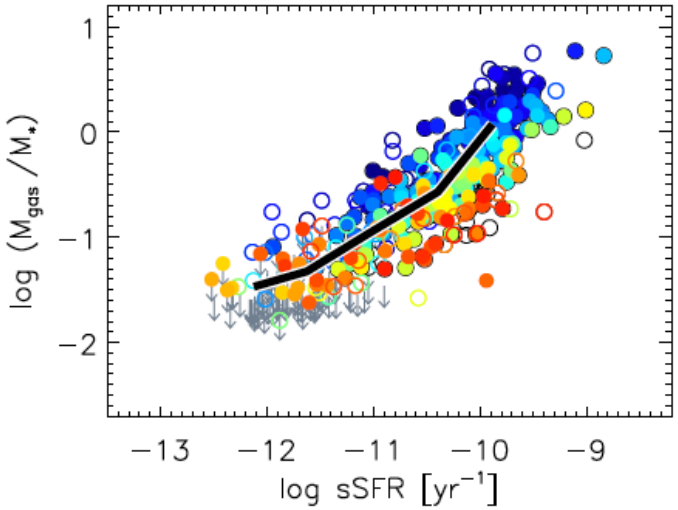
Table 1. Basic information and observation log of our target galaxies.

Name	J144916.71+150700.1	J093300.93+594420.4	J114614.24+111501.7	J095123.60+265643.9
RA (J2000)	222.320	143.254	176.559	147.848
Dec. (J2000)	15.117	59.739	11.251	26.946
z	0.111	0.151	0.114	0.131
$\log M_{halo}$ ($M_\odot$)[a]	~~13.40~~ 13.1	13.55	13.66	~~13.29~~ 13
$\log M_*$ ($M_\odot$)[b]	11.20	11.29	11.12	11.02
$\log$ sSFR (yr^{-1})[c]	−14.12	−14.97	−14.97	−11.72
Frequency (GHz)	103.75	100.15	103.48	101.92
T_{int} (h)[d]	4.5	5	3	4.4
rms[e] (mK)	0.15	0.17	0.22	0.15
Velocity[f] (km s^{-1})	82.47 ± 34.21	–	−169.40 ± 12.31 157.77 ± 17.30	–
FWHM[g] (km s^{-1})	547.74 ± 100.90	–	155.36 ± 36.09 267.31 ± 43.26	–
$T_{mb,peak}$[h] (mK)	0.93 ± 0.15	–	1.95 ± 0.22 1.76 ± 0.22	–
I_{CO}[i] (K km s^{-1})	0.54 ± 0.07	<0.31[j]	0.33 ± 0.06 0.51 ± 0.07	<0.28[j]
$\log L_{CO}$ ($L_\odot$)[k]	9.20 ± 0.06	< 9.24	9.41 ± 0.05	< 9.06
$\log M_{H_2,o}$ ($M_\odot$)[l]	9.84 ± 0.06	< 9.88	10.05 ± 0.05	< 9.70
$\log M_{gas,p}$ ($M_\odot$)[m]	9.98	10.02	9.95	9.91

The quenching of massive spiral galaxies
---Our results

We lack HI data. The Catinella+ results suggest that for massive, passive galaxies, total gas fraction is at most 10%





Catinella+ 2018
For galaxies with both CO and HI detection

For our sample, halo mass is around 10^13 solar mass
No massive cold gas
→what has quenched the cooling of halo hot gas?

The quenching of massive spiral galaxies
---Our results

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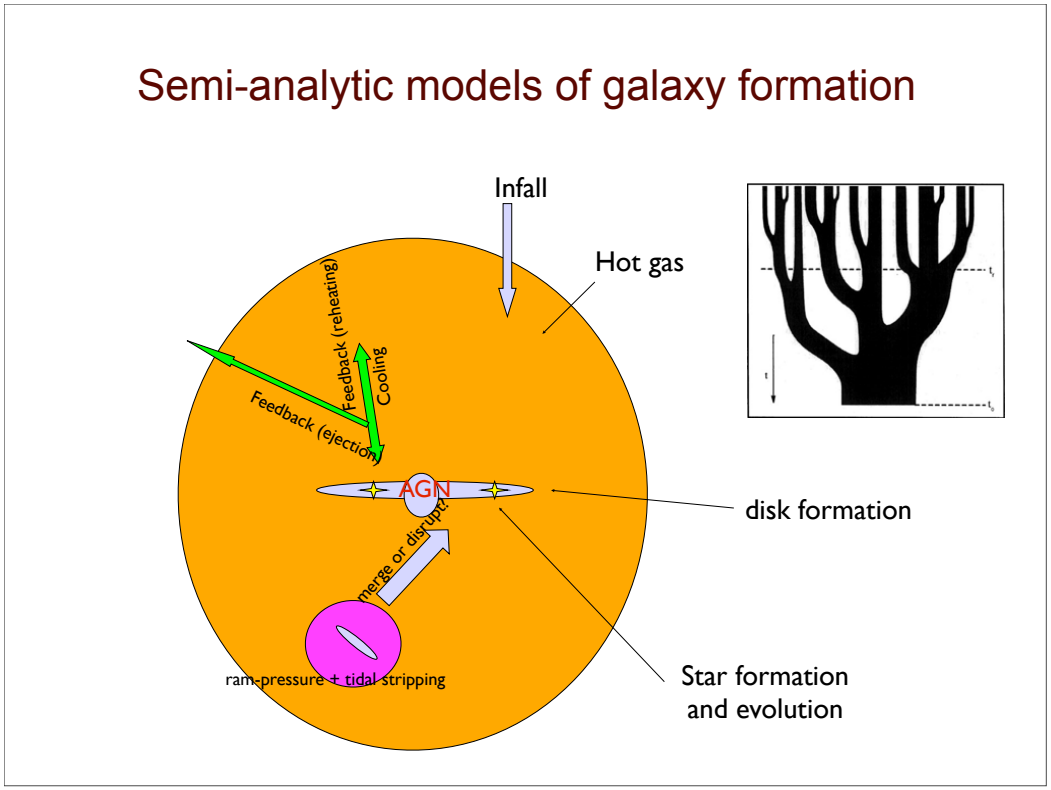
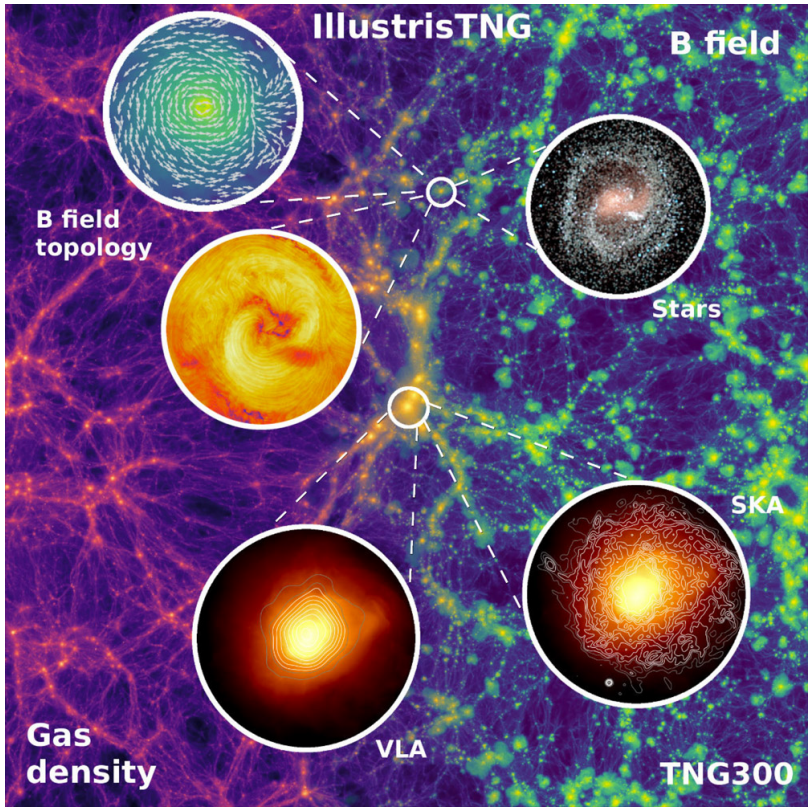
We use both semi-analytical model and hydro-simulation to see

- If models predict such massive quenched spiral galaxies
- If any, Why they are quenched?





The quenching of massive spiral galaxies
---Model predictions

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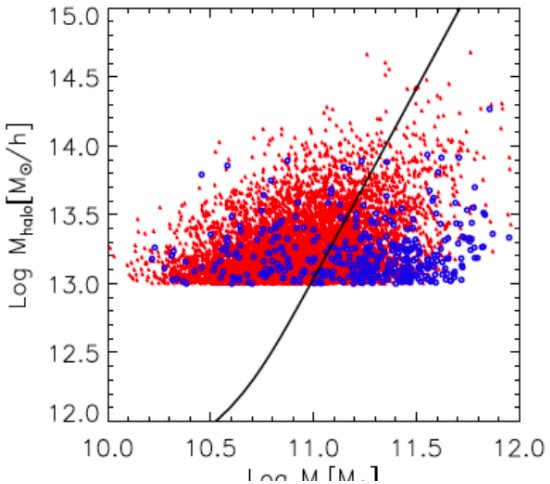
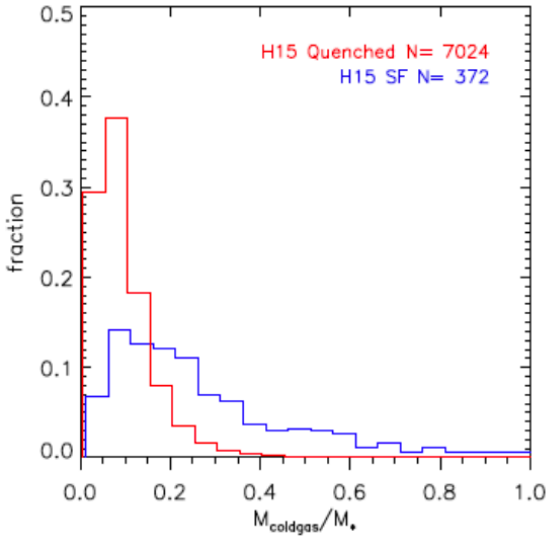
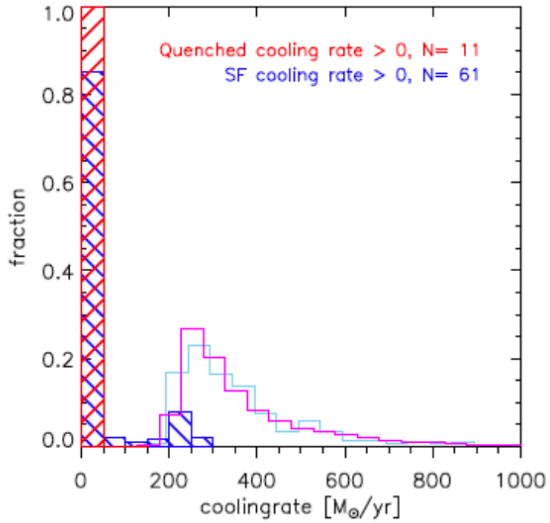
We use the SAM data from Henriques+2015 and apply the same criteria to select massive spiral galaxies

- The fraction of quenched spiral galaxies is too high in the model
- Quenched spirals have slightly more hot gas, but cooling rate is ~ 0
- By turning off AGN feedback, all spirals have cooling rate above 200M_{sun}/year and they becomes blue







The quenching of massive spiral galaxies
---Model predictions

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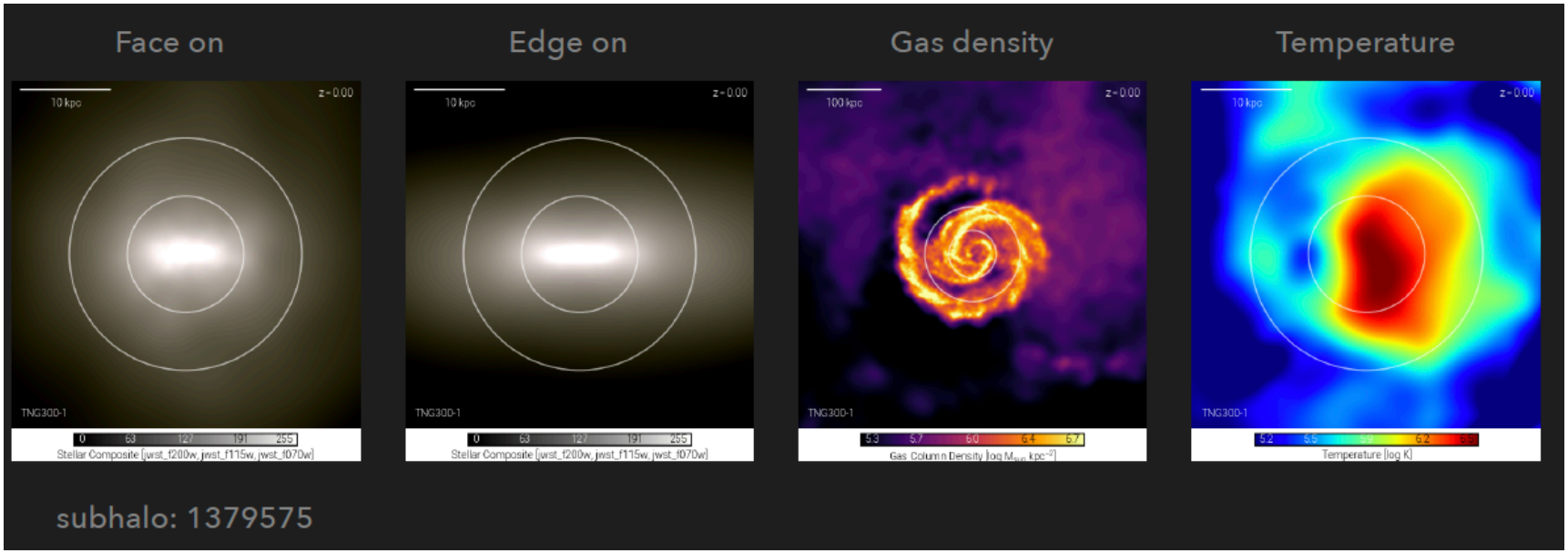
Using the TNG simulation, we find the quenched spirals

- TNG300-1 data, galaxies with $M_* > 10^{11}$ solar mass
- We decompose stellar into bulge+disk, select fdev<0.1
- There are 8 quenched spiral galaxies

One of our 8 galaxies



The quenching of massive spiral galaxies

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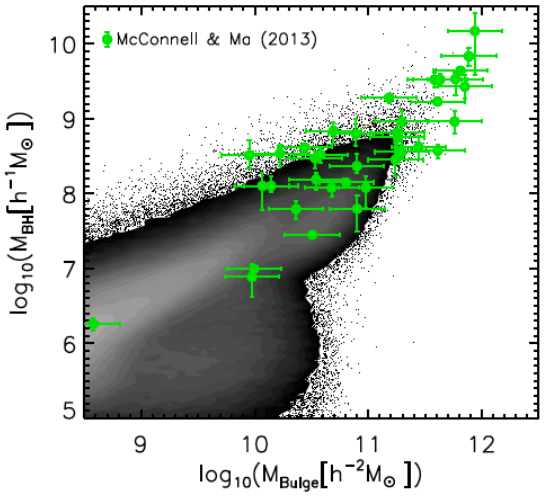
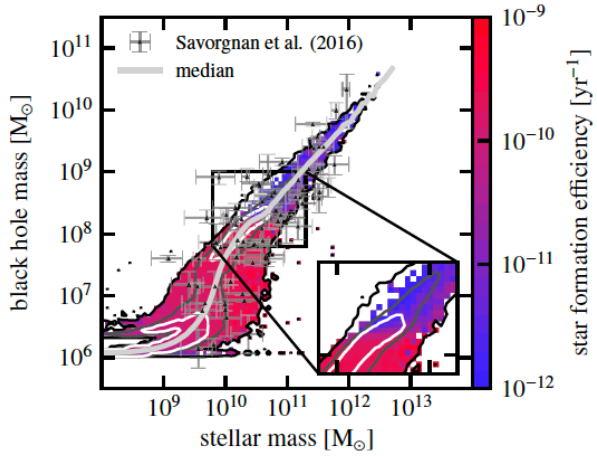
Black hole mass-Bulge mass relation in SAM and Simulations

All galaxies: BH mass are not over-predicted

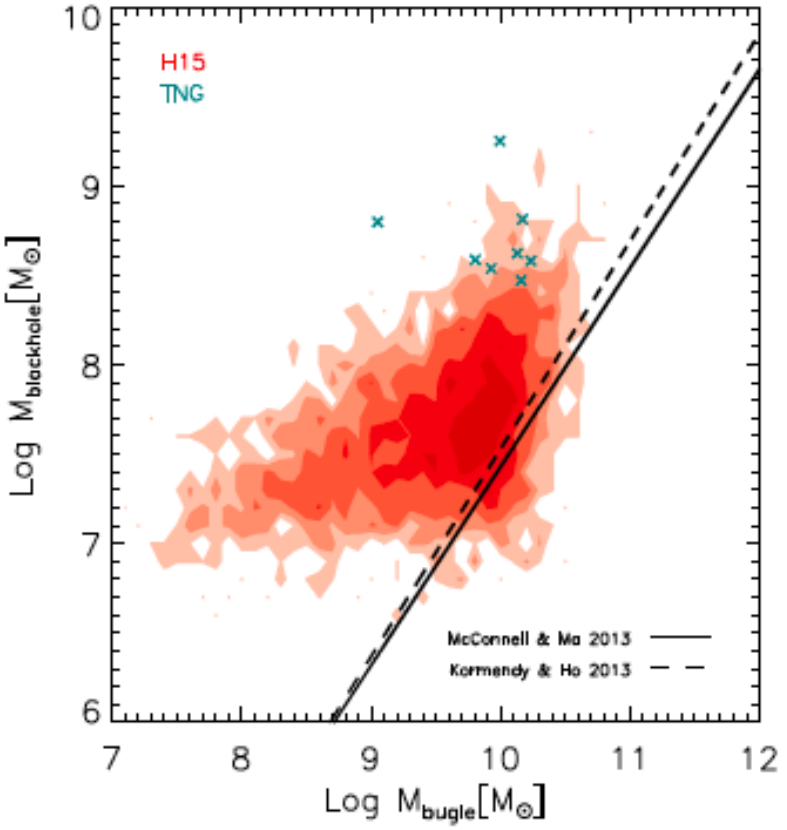
S
A
M



Hydro-simulations



Quenched spiral galaxies



Quenched spirals have massive black holes compared to their bulges

The quenching of massive spiral galaxies

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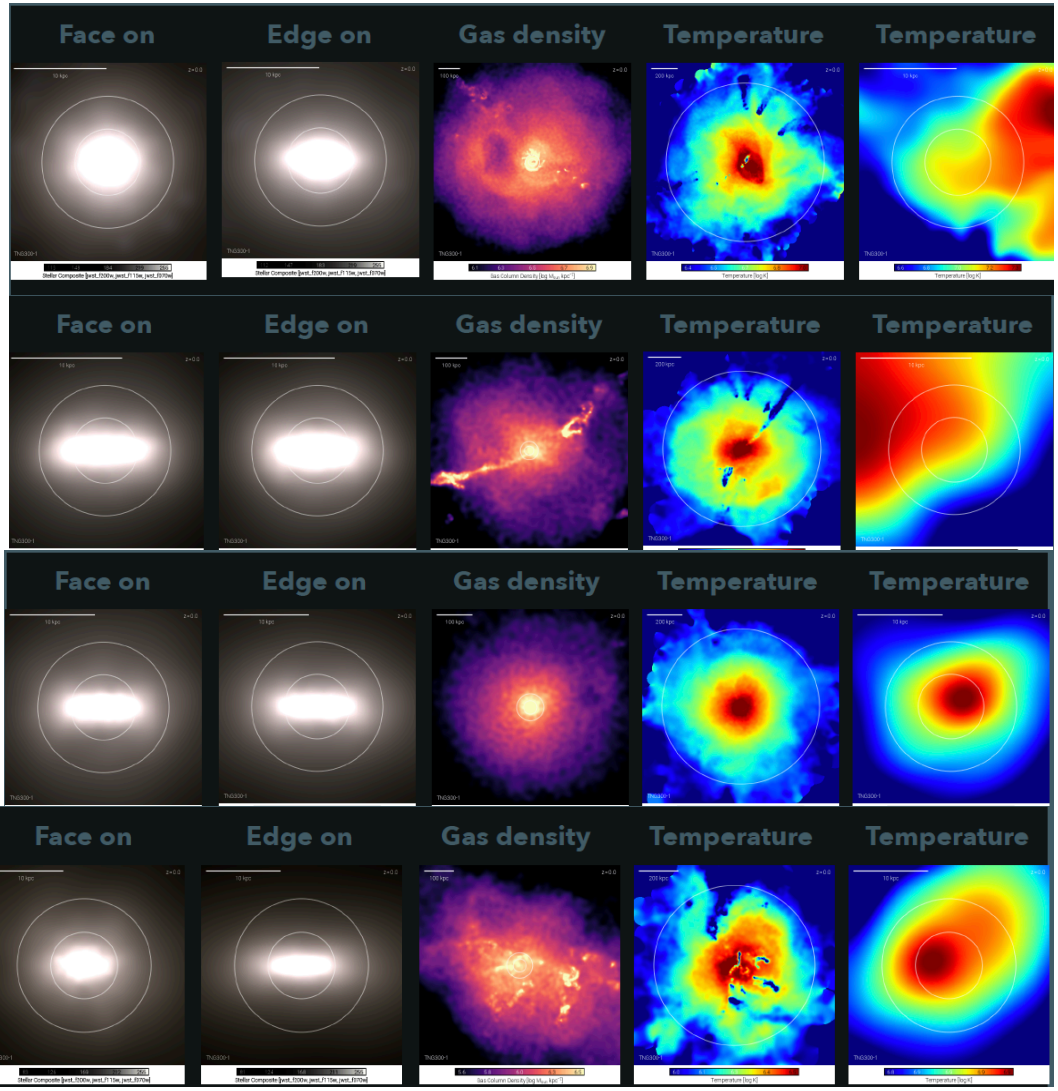
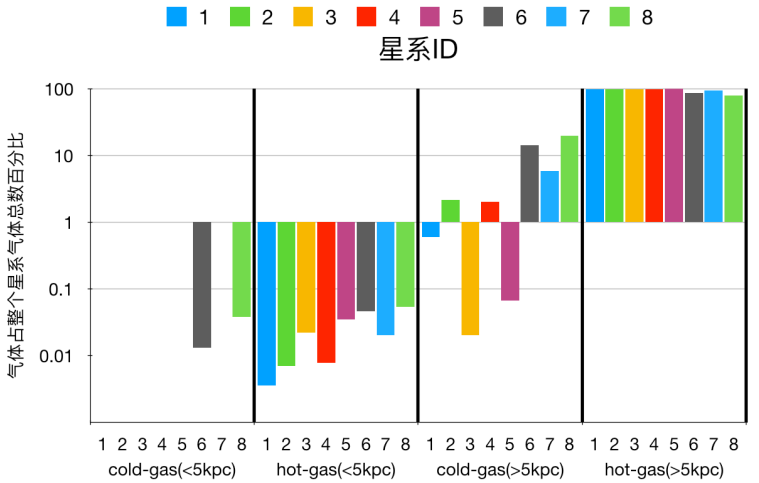
Content of hot gas around passive spirals in Illustris-TNG:

Baryon fraction ~0.3-0.5, most in hot phase





ID	Mh/fb*Mh (10^10)	Stellar mass(10^10)	Hot baryon fraction
1	2511/416	18.9	0.47
2	1000/166	12.6	0.34
3	912/151	15.04	0.28
4	776/128	10.96	0.39
5	707/117	11.22	0.38
6	588/97.6	13.22	0.25
7	446/74	11.6	0.26

The quenching of massive spiral galaxies

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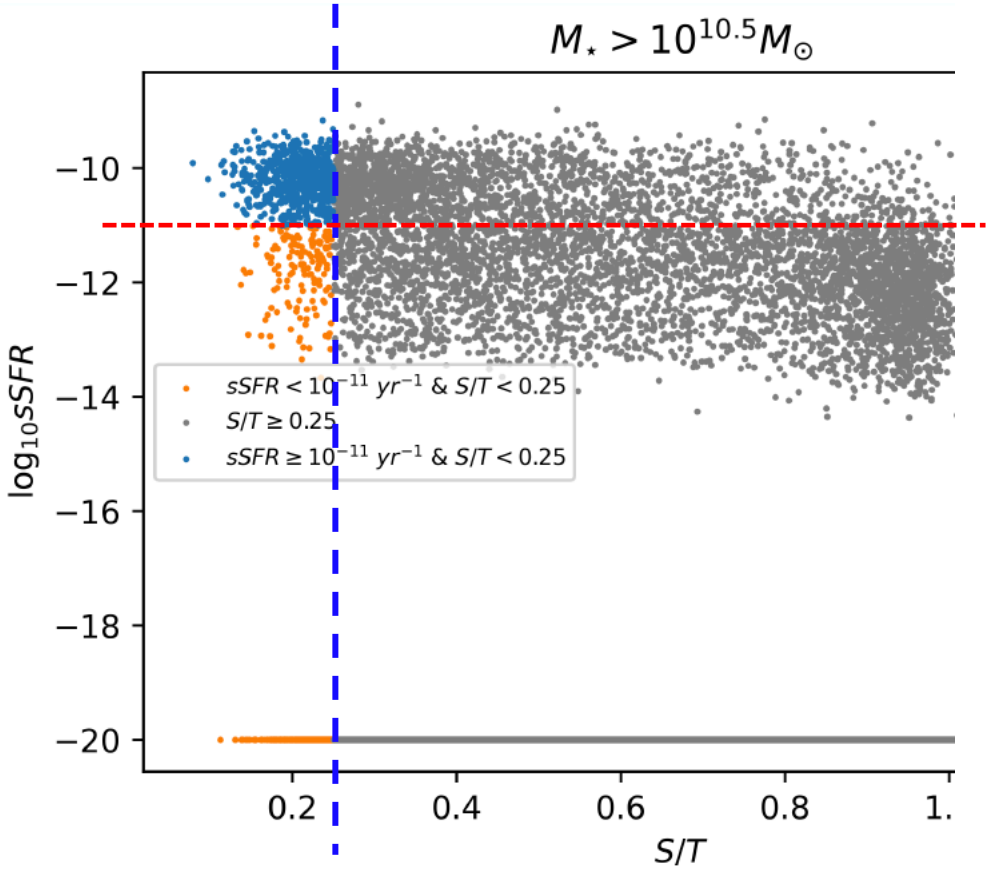
Recent work using TNG300-1

- Increase the sample size by selecting galaxies with M*>10.5 solar mass
- Select galaxies with disk morphology (S/T <0.25)
- Classify galaxies into star forming and quenched (sSFR = 10^{-11})



Simulation reproduces observational trend that sSFR is correlated with bulge mass

The quenching of massive spiral galaxies

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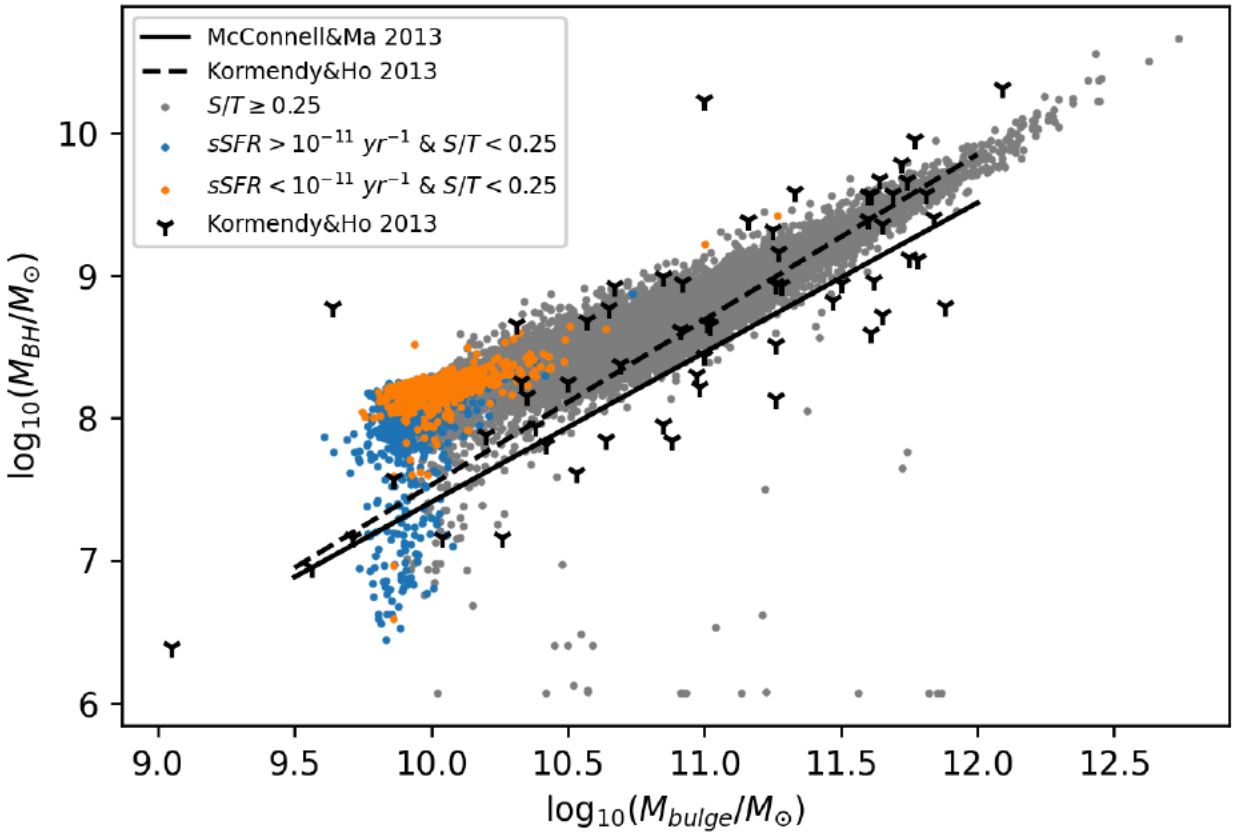
Results from TNG300-1



BH mass- bulge mass relation

- Quenched disks have higher BH mass than than the data
- Star forming disks have larger scatter.

The quenching of massive spiral galaxies

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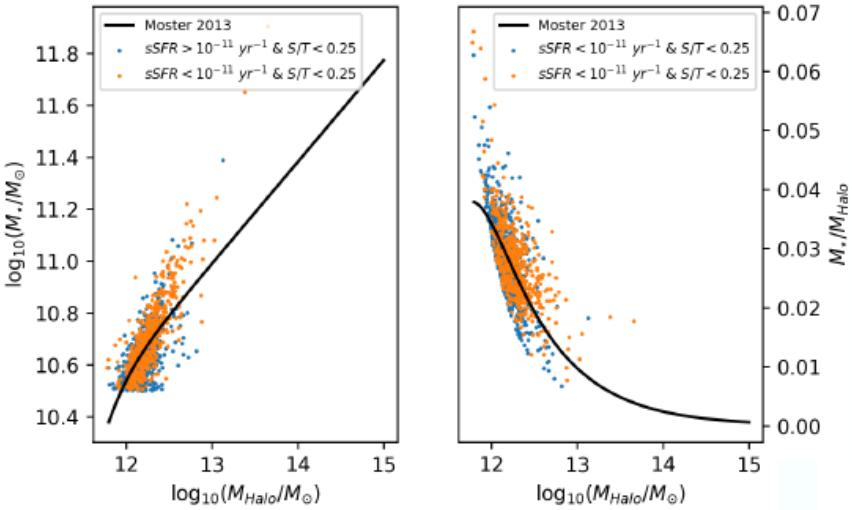
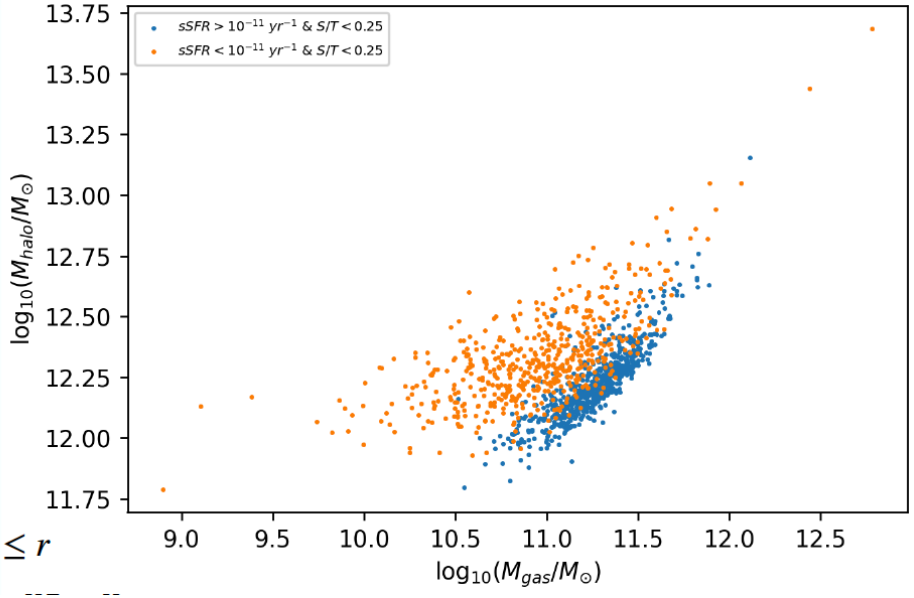
Results from TNG300-1



- SF disk and quenched disk have similar halo mass
- Quenched disks have less gas (cold+hot)
  - SF: baryonic fraction ~0.8
  - Quenched: ~0.4



$0 \leq r$

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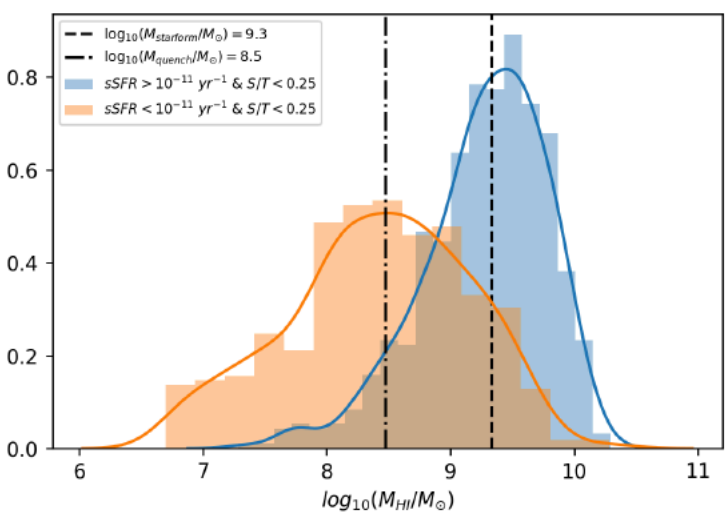
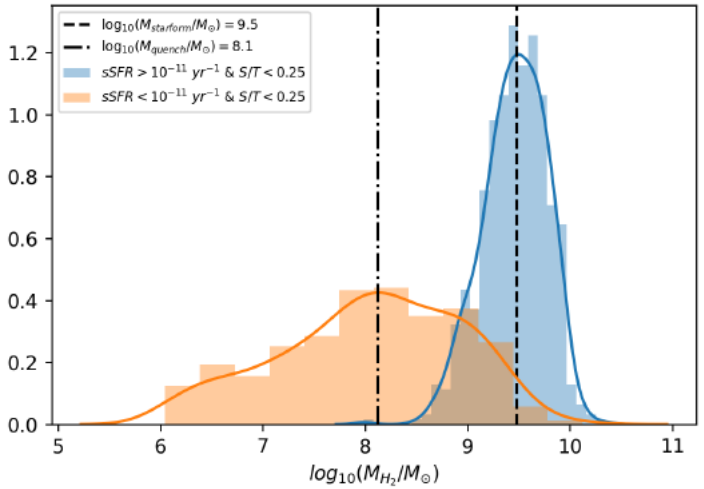
Results from TNG300-1

Gas content within r<2Re



HI Gas



H2 Gas

- Quenched spirals have considerable less HI and H2 gas than star forming ones
- Only a few percent quenched galaxies have HI $>10^{9.5}$ (value used in Zhang+ 2019)

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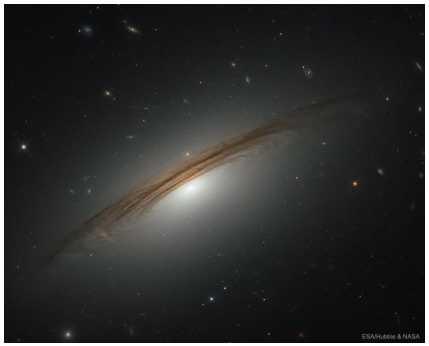
Content of hot gas around local very massive spirals in X-ray observations

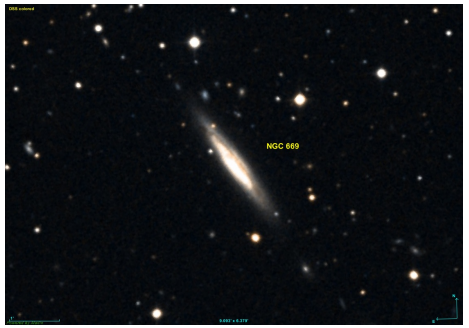
All are passive with sSFR<10^{-11}

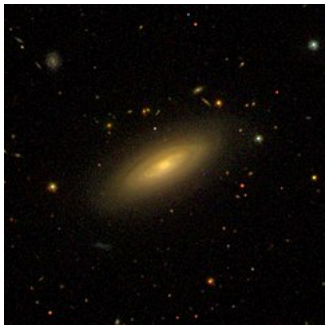
Table 1
Properties of the CGM-MASS Galaxies

Galaxy	Scale kpc arcm^{-1}	M_* $10^{11}\,M_\odot$	M_*/L_K $M_\odot/L_\odot$	SFR $M_\odot\ yr^{-1}$	M_{TF} $10^{11}\,M_\odot$
UGC 12591	27.45	$5.92^{+0.14}_{-0.74}$	0.773	1.17 ± 0.13	16.1 ± 1.5
NGC 669	22.63	$3.32^{+0.02}_{-0.17}$	0.893	0.77 ± 0.07	5.32
ESO142-G019	18.78	$2.49^{+0.05}_{-0.24}$	1.137	0.37 ± 0.06	5.07 ± 0.90
NGC 5908	15.10	$2.56^{+0.02}_{-0.15}$	0.842	3.81 ± 0.09	4.88 ± 0.60
UGCA 145	20.17	$1.47^{+0.01}_{-0.08}$	0.595	2.75 ± 0.11	4.03
NGC 550	27.09	$2.58^{+0.04}_{-0.28}$	0.773	0.38 ± 0.09	5.08 ± 1.81

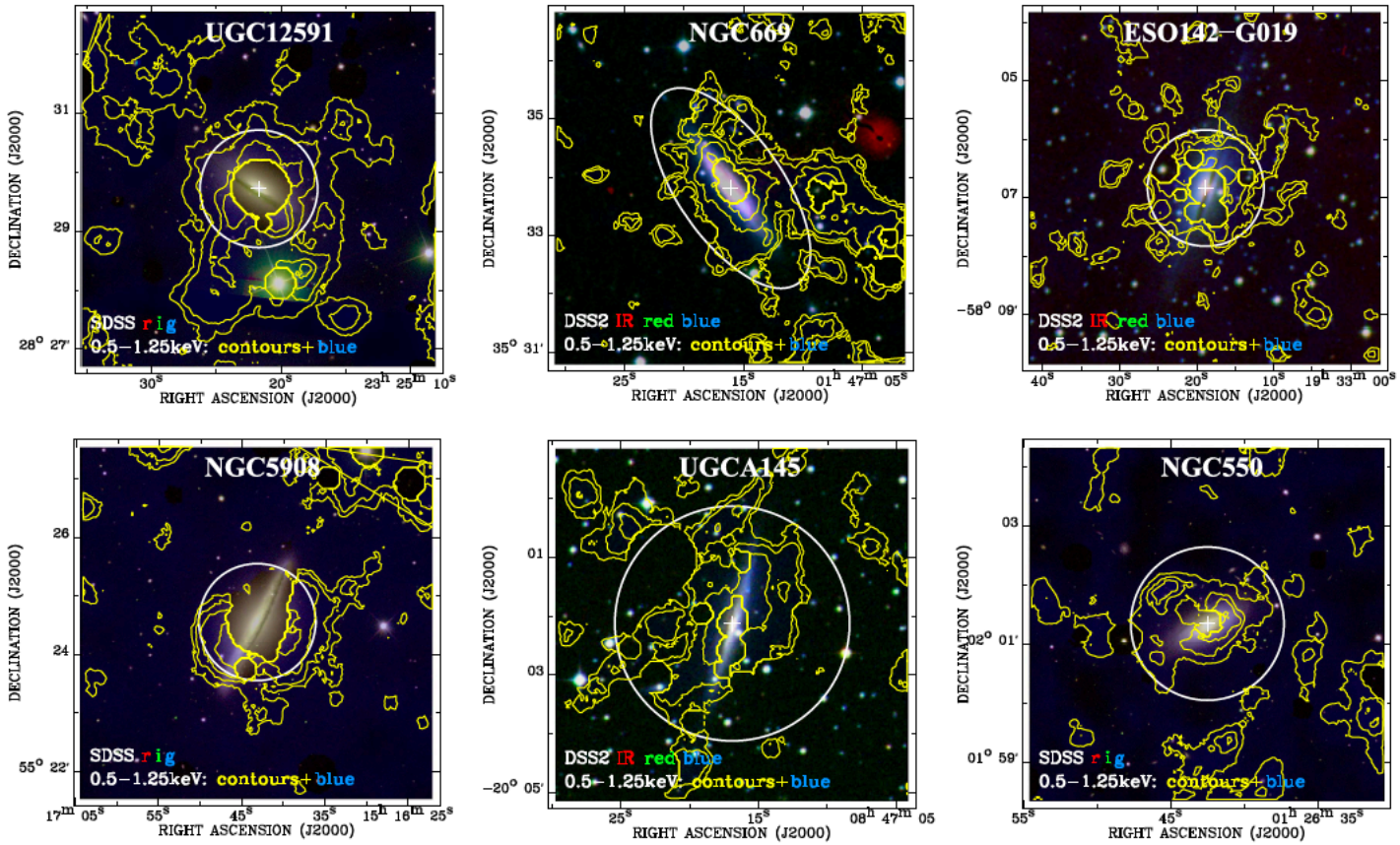
Li J.T et al. 2017







Content of hot gas around passive spirals---Xray images



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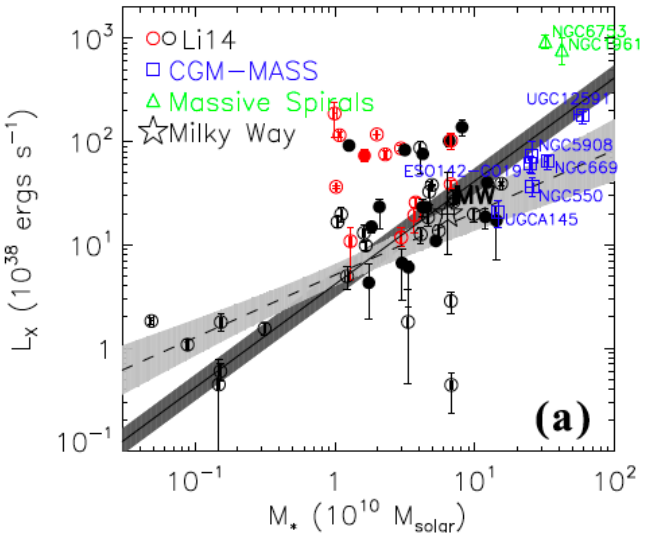
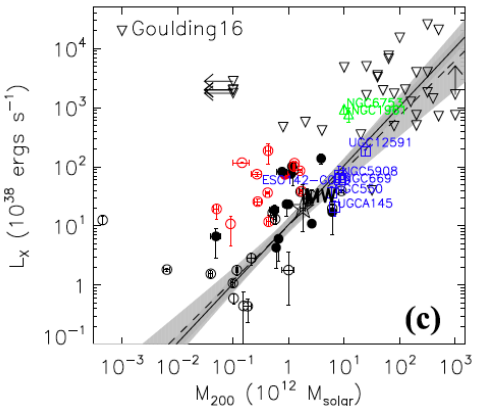
Content of hot gas around passive spirals---Xray images

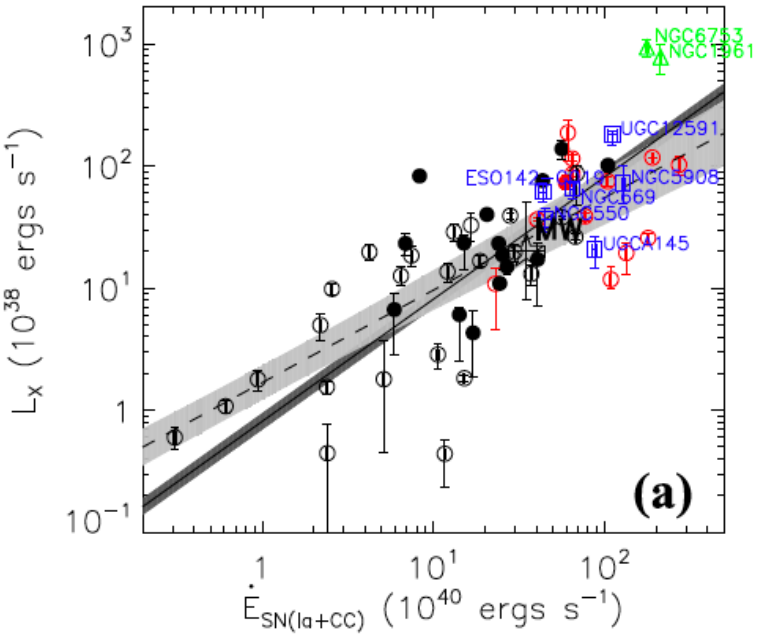




Gas cooling time is long

1% of SNe energy can explain the x-ray luminosity

No additional energy source is needed



The quenching of massive spiral galaxies

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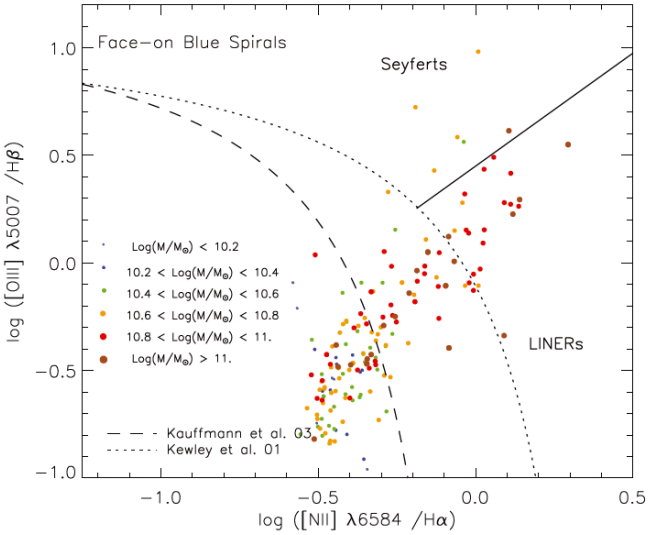
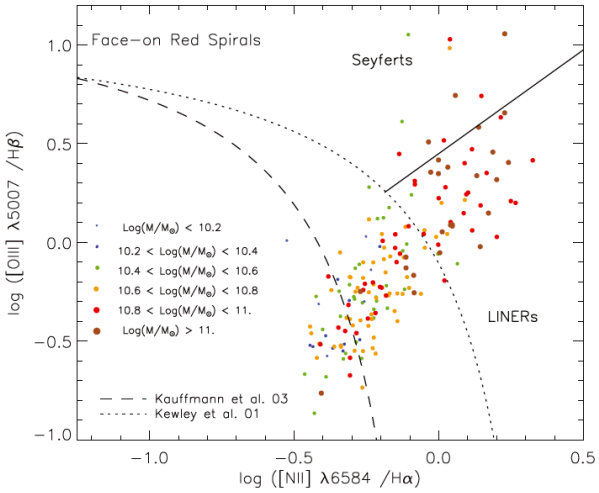
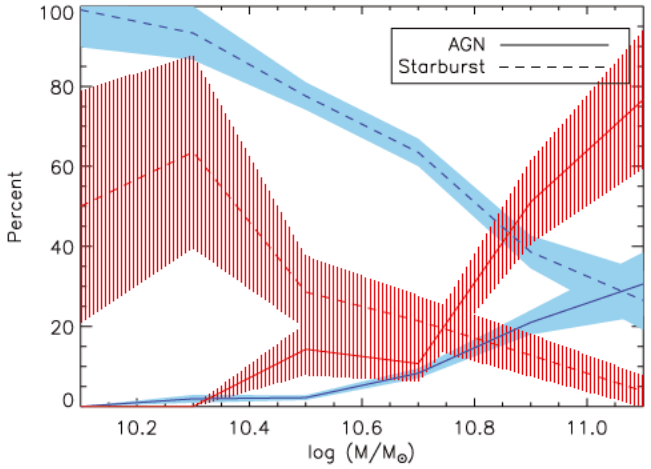
AGN activities in local passive spirals?





Masters+2010, from galaxy zoo



AGN fraction increases in quenched massive spirals

The quenching of massive spiral galaxies

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AGN in spirals at moderate redshifts?

Bizzocchi+2014 identify 19,225 bulgeless galaxies from COSMOS, AEGIS, GEMS, GOODS at 0.4<z<1.0

Most spirals are not quenched, but red

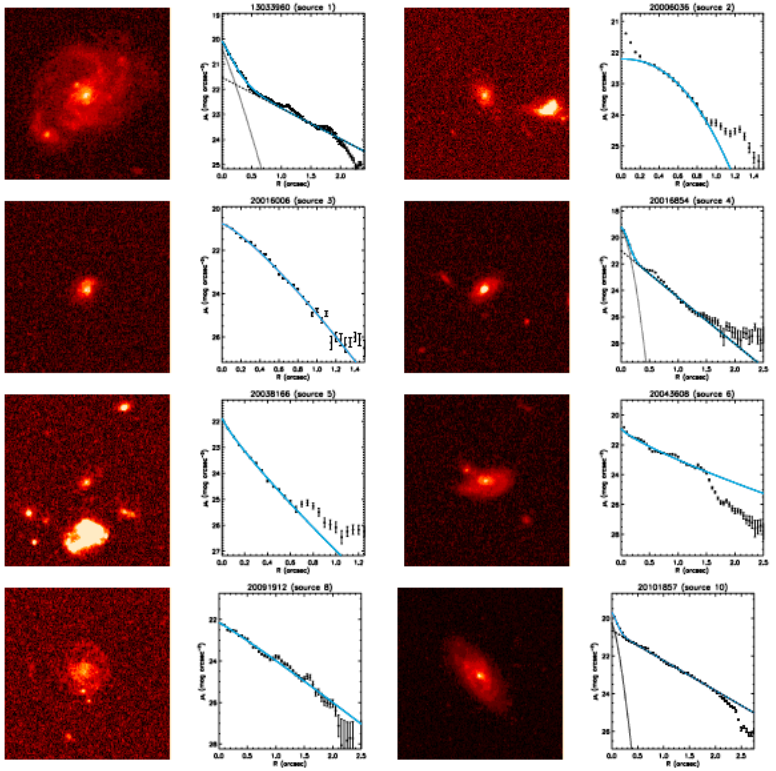


Figure 11. *HST*/ACS images and surface brightness profile of the AGN bulgeless host galaxy candidates with $n < 1.5$ and disk/irregular morphology. (A color version of this figure is available in the online journal.)

Table 2
Catalog Selection Statistics Split by Field ($0.4 \leqslant z \leqslant 1.0$)

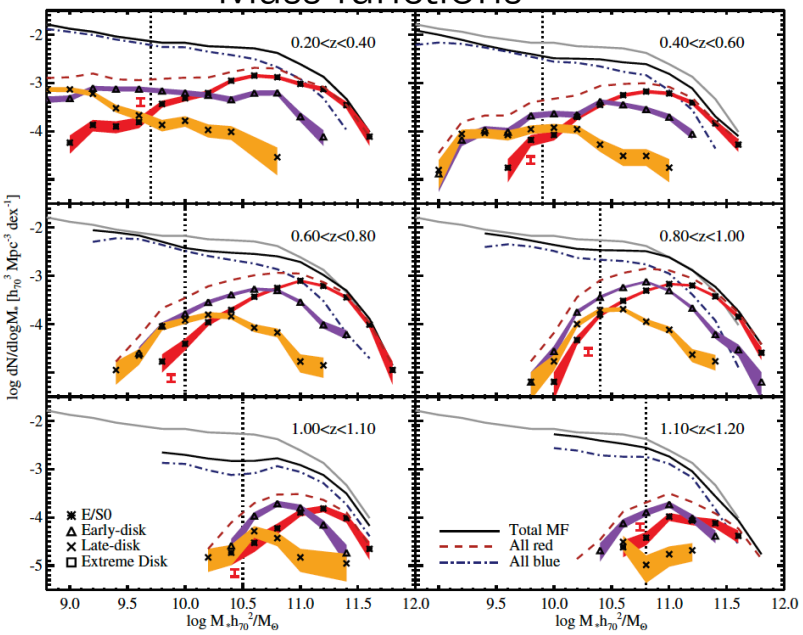
Field	Total	spec-z	$n \leqslant 1.5$	$1.5 < n \leqslant 3.0$	$n > 3.0$
COSMOS	31714	3116	14139	7259	10316
AEGIS	2848	1451	1588	576	684
GEMS	3595	1382	2267	793	535
GOODS-S	852	524	482	199	171
GOODS-N	843	648	749	74	20
Total	39852	7121	19225	8901	11726

Only 30 (0.2%) massive quenched spirals have AGN

The quenching of massive spiral galaxies

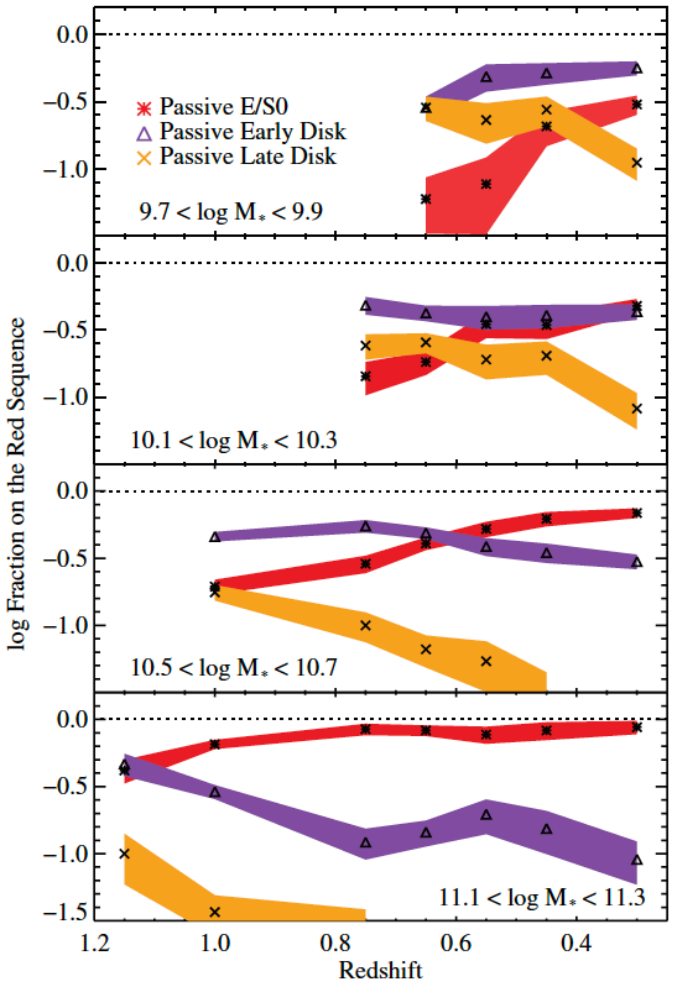
evolution of passive spirals population
Bundy et al. 2010 using COSMOS data

Mass functions



- Absolute number density of passive disks increase with time (more at low-z)
- Fraction of passive disk declines with z, as more quenched disks turn into passive E/S0 at low-z

Fraction of red galaxy



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Summary

Observational results:

- Quenched spirals are rare, but more frequent in high-mass spirals
- Most red spirals have bars, indicating bar can suppress star formation in the disk
- Contradictory results on HI gas content in quenched galaxies

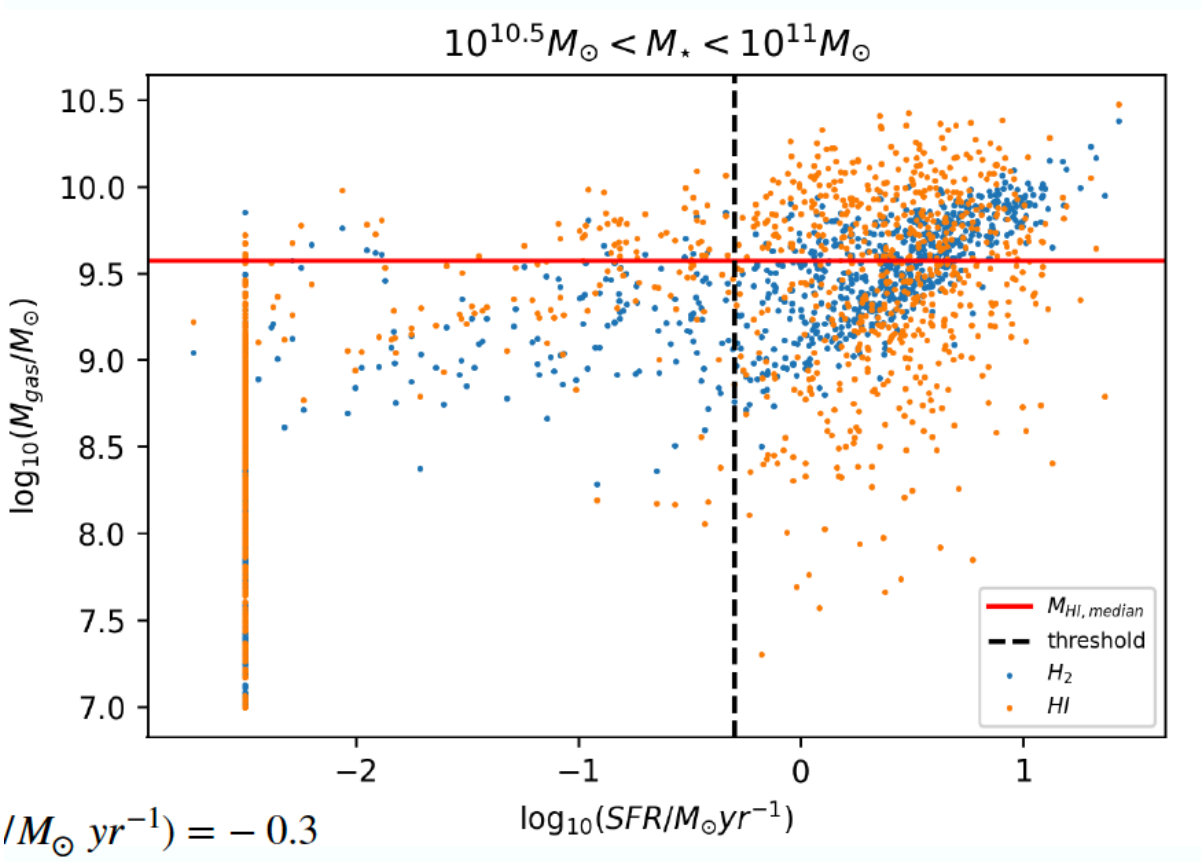
Simulation and Model results

- Quenched spirals have larger BH mass than the Magorrian relation, suggesting AGN feedback might be effective
- Quenched spirals have less cold and hot gas than star forming ones

Future: need to know why Quenched spirals have less hot gas
Searching AGN activity and X-ray observation are important

Thanks for your attention

The quenching of massive spiral galaxies



$/M_\odot\ yr^{-1}) = -0.3$

~1 percent quenched have HI>10^9.5

If using SFR within 1Re, Some star forming galaxies become quenched