The Mystery of Star-forming S0 Galaxies

Insights from Modern Integral Field Spectroscopic Surveys

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National Initiative for Undergraduate Sciences

- An yearly initiative led by HBCSE - TIFR, to promote undergraduate research in India
- Organize funded research projects in various institutions across the country
- Faculty/postdocs can sign up as mentors

Kavin Kumar, IISERB

Yogesh Wadadekar, NCRA

Preetish Mishra, IUCAA

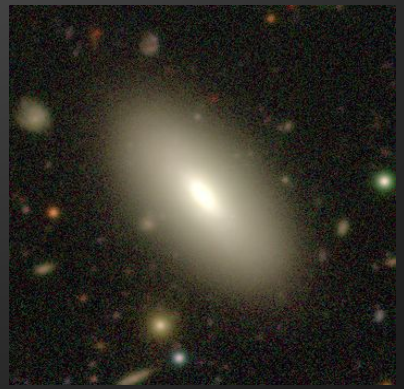
Omkar Bait, Univ. of Geneva

NCRA • TIFR

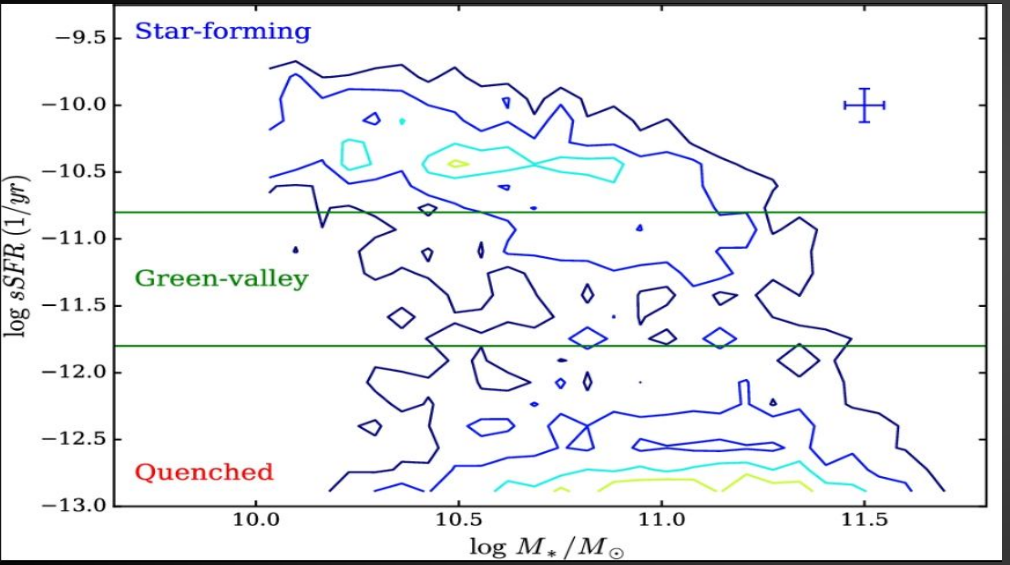
tifr HBCSE

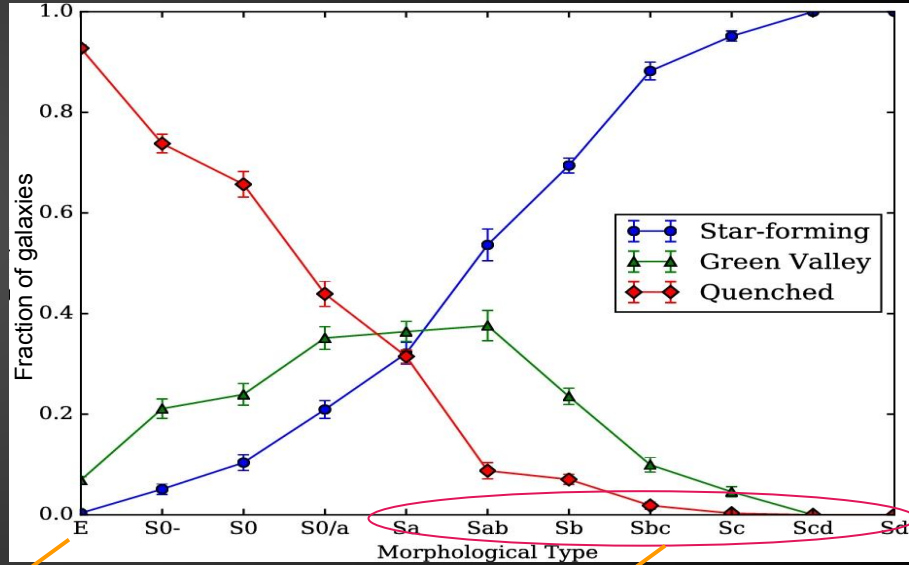
Morphological Classification

- Late Type
  - Disk + Spiral arms
    - Spirals
  - No defined shape
    - Irregulars
- Early Type
  - Disk w/o spirals
    - S0/Lenticulars
  - 3-D Ellipsoidal
    - Ellipticals



Early Types (including S0s) are generally quenched





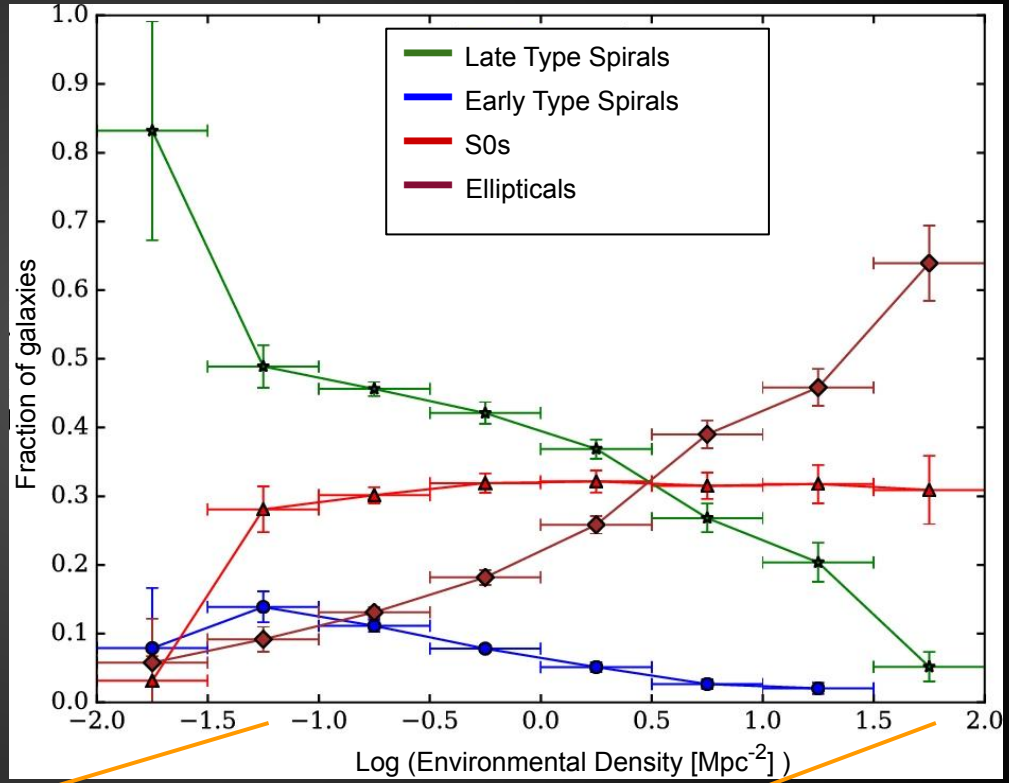
Ellipticals

Spirals

Bait+2017

How do S0s form ?

- Theories rely on strong quenching processes on spiral galaxies
- S0s are found in both low density environments as well as high density environments
- **There must be quenching mechanisms operating in both low and high density environments**

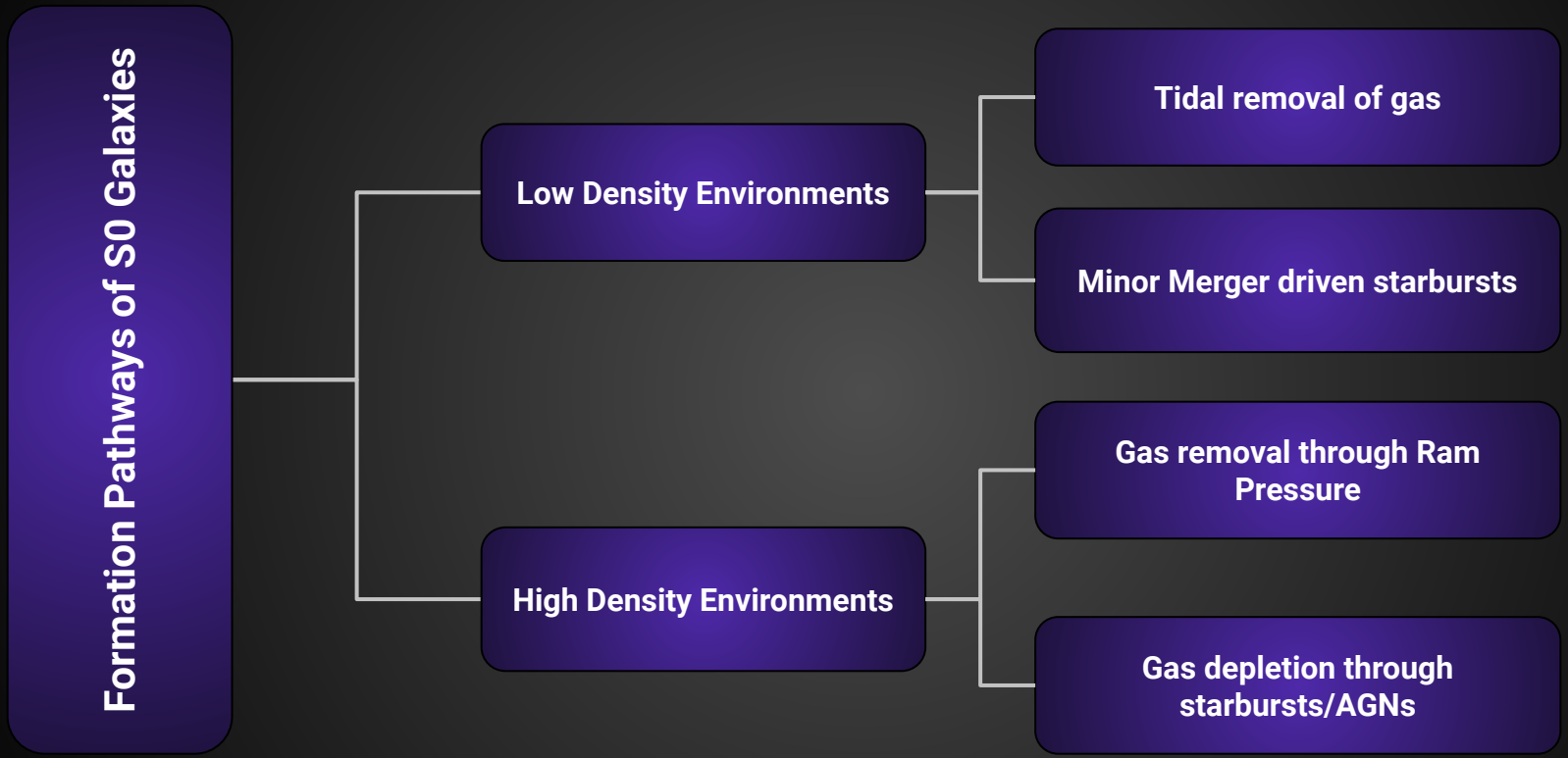


Low density

High density

Bait+2017

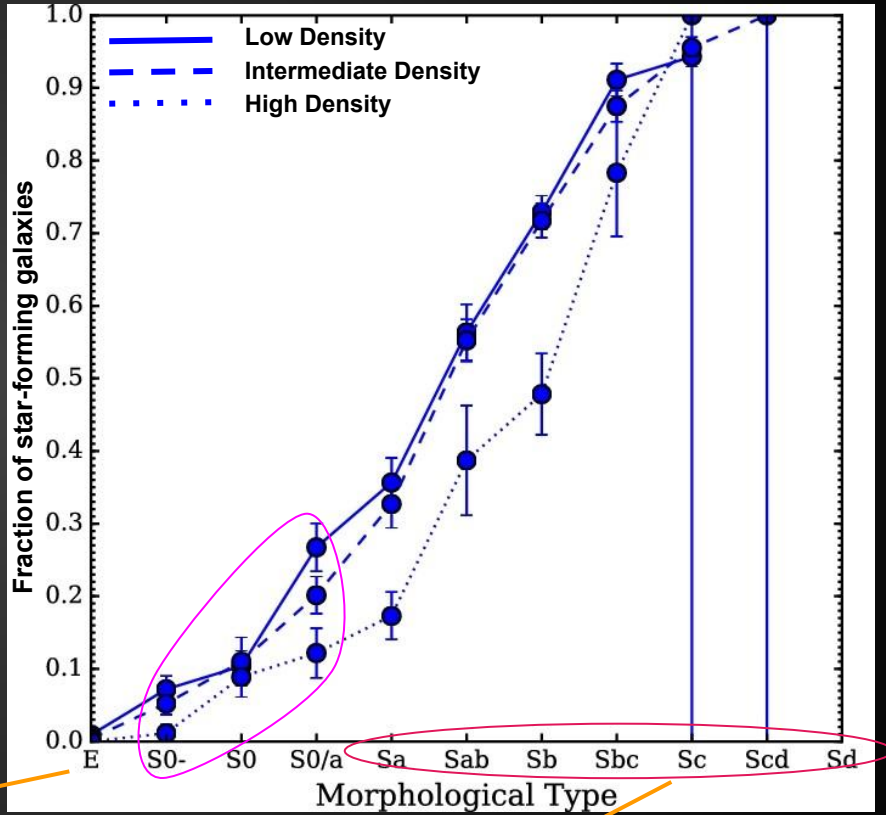
Quenching Mechanisms are Environment Dependent



Coccato+2020

But a significant number of S0s are star-forming !

- Formation of S0s is a quenching process
- However, the fraction of S0s that are star-forming can range from 10% - 30%
- How to explain the existence of star-forming S0s, given that the formation theory of S0s rely on strong quenching mechanisms ?



Ellipticals

Spirals

Bait+2017

Past attempts - first statistical samples

- Schawinski et al. 2009 - for the first time constructed a statistical sample (~ 200 galaxies) of blue **early types**
- Morphology identification based on SDSS images
- UV color taken as a proxy for star-formation
- Most of these galaxies have stellar masses below 10^{11} solar masses

Schawinski+2009

Past attempts - multiple scenarios possible

Could be spiral galaxies which are about to fade to the quenched sequence, and are experiencing their final stage of star-formation along with transformation to S0 morphology.

Eg. Kannappan+2009, Johnston+2014

Fading spirals ?

Could be quenched S0s in the past in which star-formation has been rejuvenated. The galaxy will become a quenched S0 again, after star-formation stops.

Eg. Wei+2009, George+2017

Rejuvenated S0s ?

Limitations of the past studies

- Selections were based on UV color, which can be affected by dust extinction.
- Lack of deep images, making morphology identification difficult. Significant spiral contamination could be present.
- Resolved spectroscopic data not available, so spatial location of star-formation difficult to identify.
- Studied star-forming early types, which comprise of both S0s and Ellipticals. However, both can be very different.

Shallow Imaging (SDSS)

Modern Prospects

- SED fits on large catalogs available
  - Selection based on SFR possible, do not have to rely on colors
- Deep images, like that from the DECam, or Subaru available.
  - So, accurate morphology identification possible.
- Resolved spectroscopic data available from IFS surveys like SDSS -MaNGA
  - Spatially resolved analysis of star-formation possible

In our work, we specifically try to understand the star-forming S0 galaxies, using the SDSS-MaNGA survey

SDSS MaNGA

Subaru Program

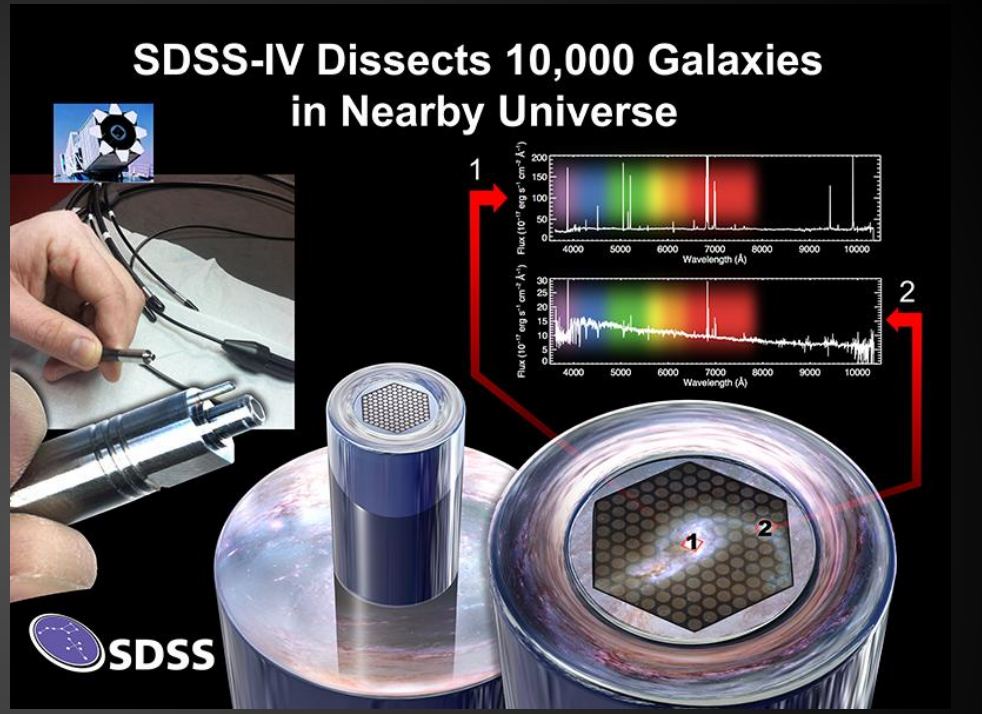
Questions we ask

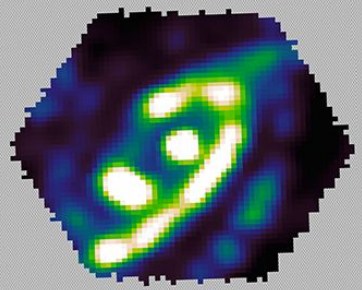
- Where is the star-formation happening in star-forming S0 galaxies ?
- Why are some of the S0s star-forming, even though we generally expect them to be quenched ?
- Can we reconcile star-forming S0s with the standard theory of how S0s form ? Or do we need a new theory ?

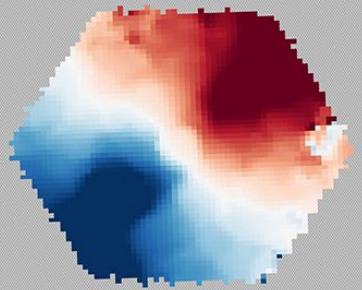
Rathore, Himansh; Kumar, Kavin; Mishra, Preetish Kumar; Wadadekar, Yogesh; Bait, Omkar; Star-forming S0 Galaxies in SDSS-MaNGA: Fading Spirals or Rejuvenated S0s? MNRAS, Volume 513, Issue 1, June 2022, Pages 389–404

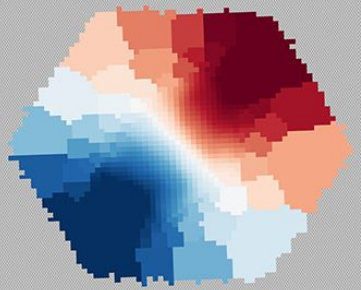
SDSS-MaNGA: peeking inside galaxies made possible !!!

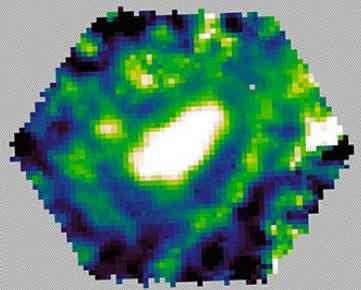
Bundy+2015; Blanton+2017







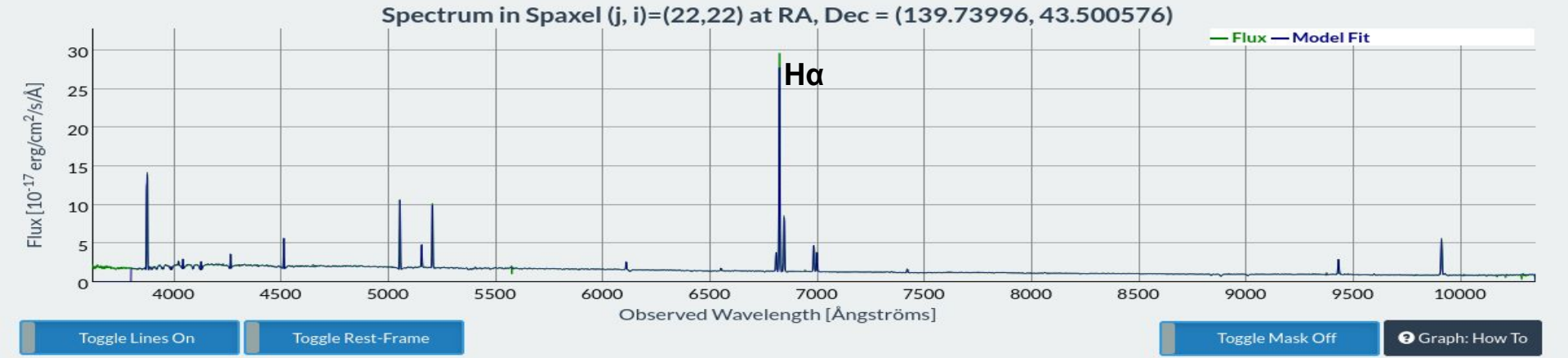




SDSS-MARVIN

The hunt for outlying galaxies begins !

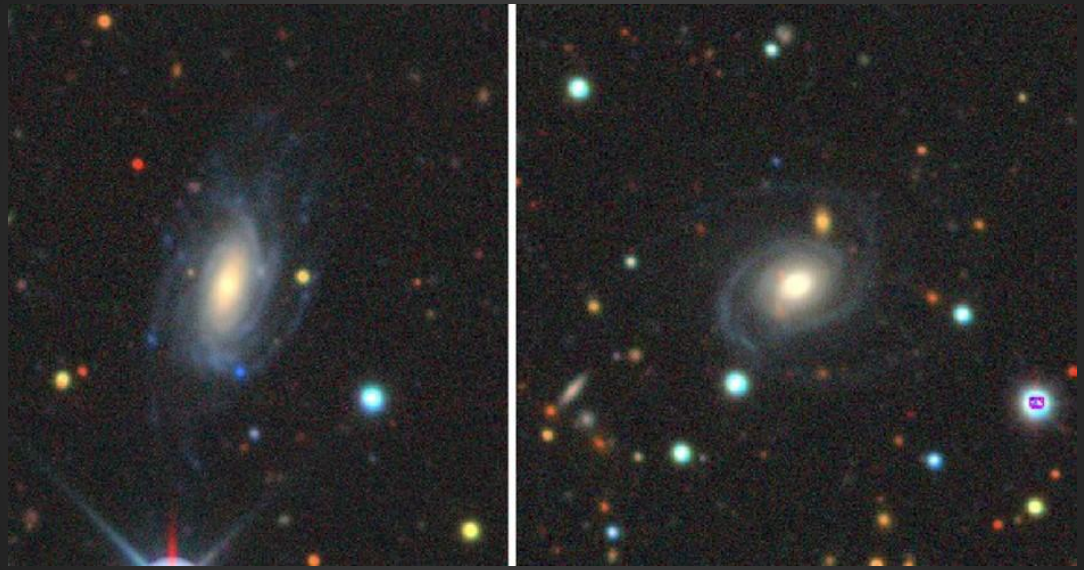
MaNGA 8250-3703



Identification of a clean star-forming S0 sample in MaNGA

- Entire MaNGA sample has > 5000 objects. We first use Deep Learning based catalogs to narrow down to ~ 200 objects.
- Deep learning catalogs are trained on shallow SDSS imaging. In some cases, spiral arms may not be visible resulting in misclassification as S0.
- We perform a visual inspection using deep images from DECam and Subaru.
- **Around 30% of our initial sample turned out to be spiral contaminants !**
- Finally, we have ~ 120 star-forming S0s in a redshift range ($z < 0.1$). We also construct control samples of star-forming spirals and quenched S0s.

Do not always rely on Machines !!!



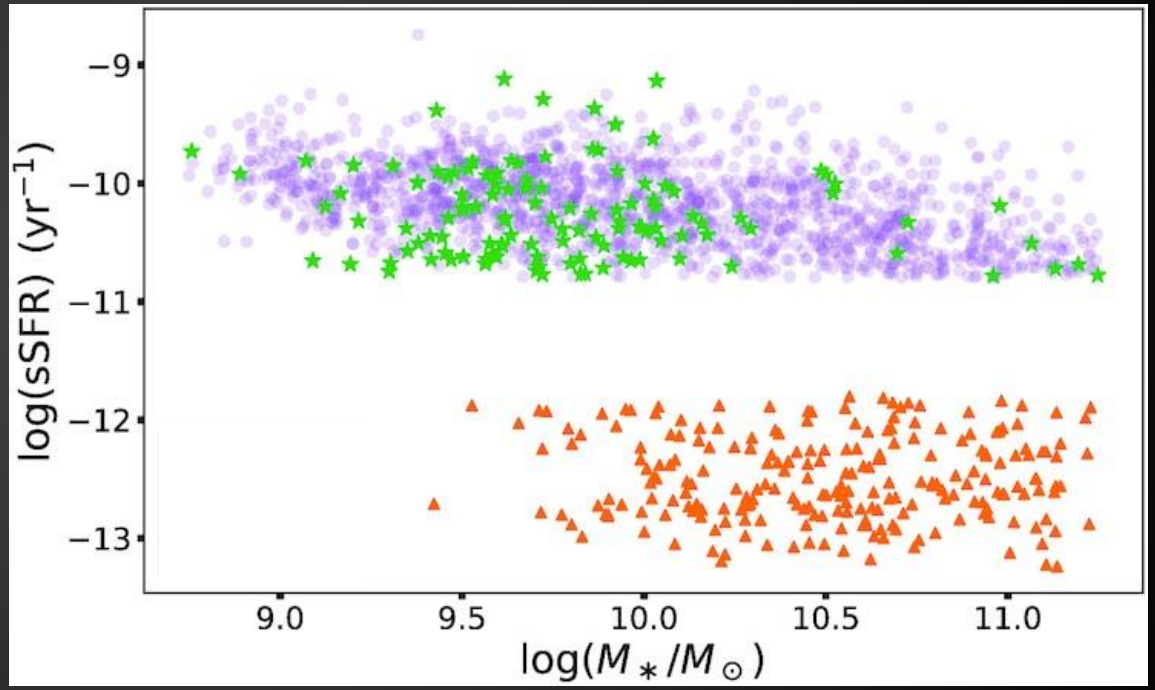
SDSS images of two galaxies. The above were classified as S0s by the DL model !!!

Our star-forming S0 sample

Star-forming S0s

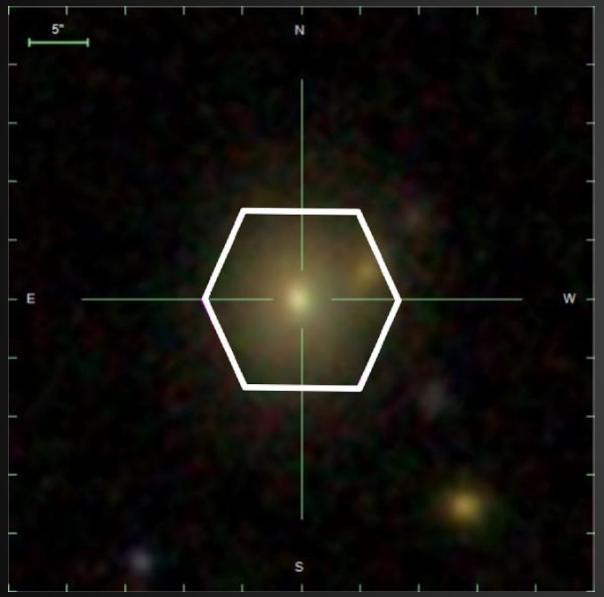
Star-forming Spirals (a control sample)

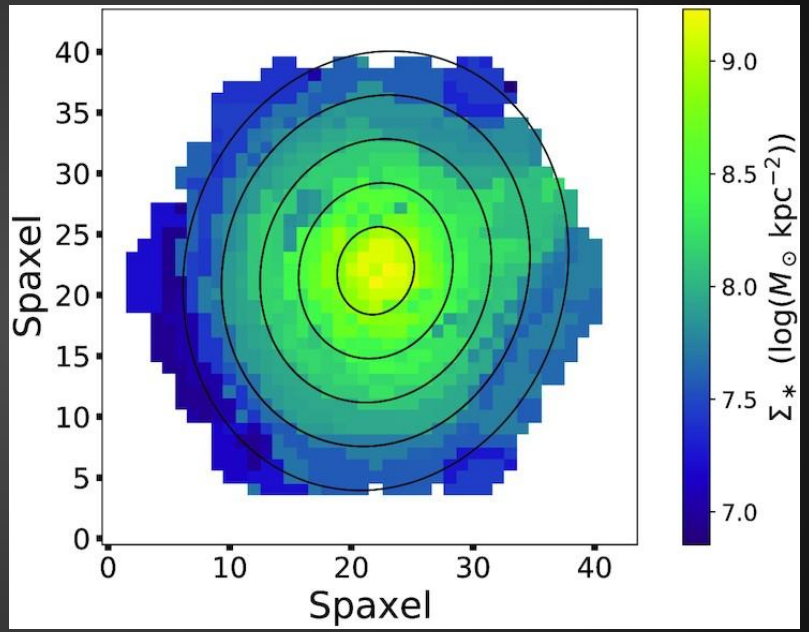
Quenched S0s (a control sample)



Rathore+2022

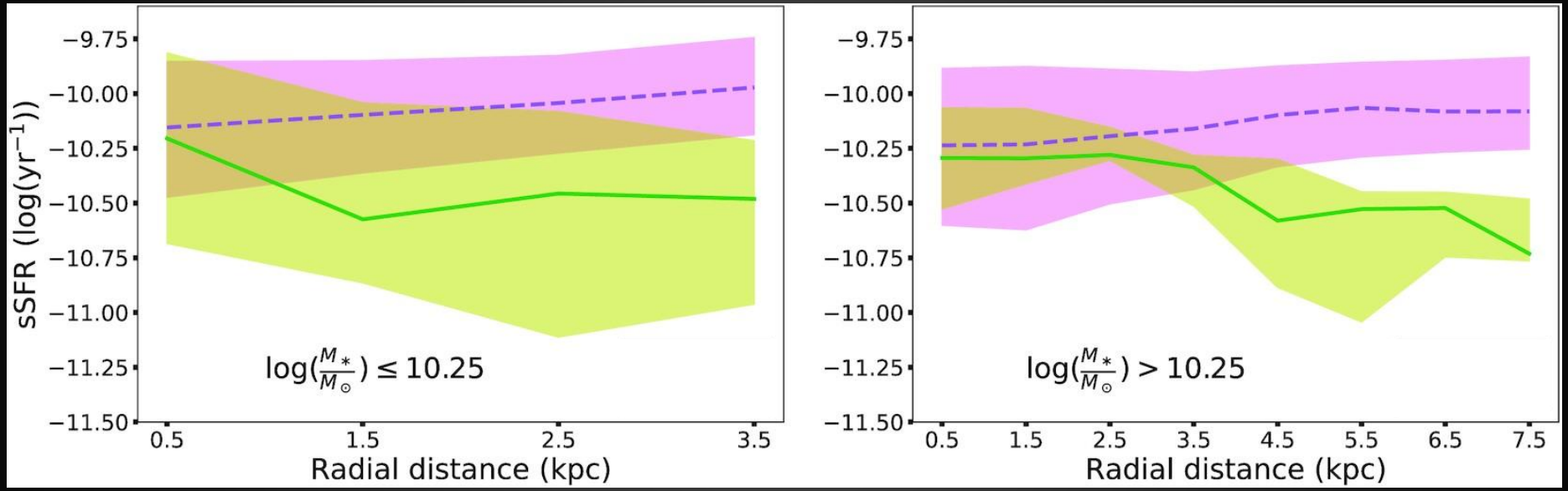
Utilizing MaNGA for resolved properties





Rathore+2022

Where is the star-formation happening in SF-S0s ?



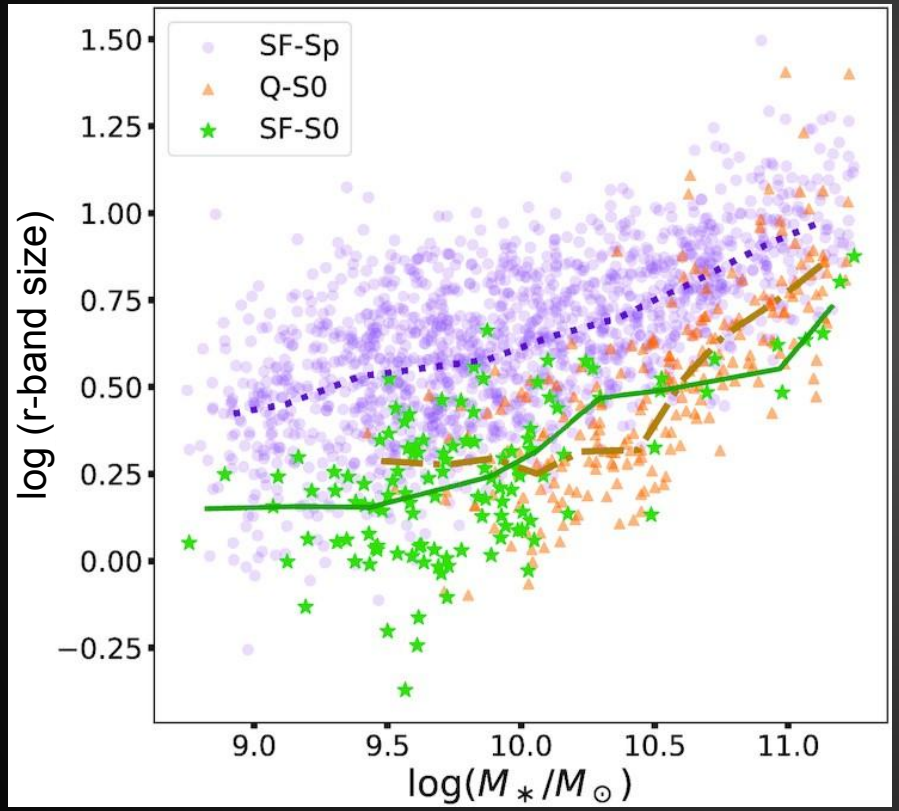
Unlike spirals, the star-forming S0s have centrally driven star-formation ! This was not known before !!!

Star-forming S0s

Star-forming Spirals

Rathore+2022

Star-forming S0s: fading spirals or rejuvenated S0s ?



Star-forming S0s

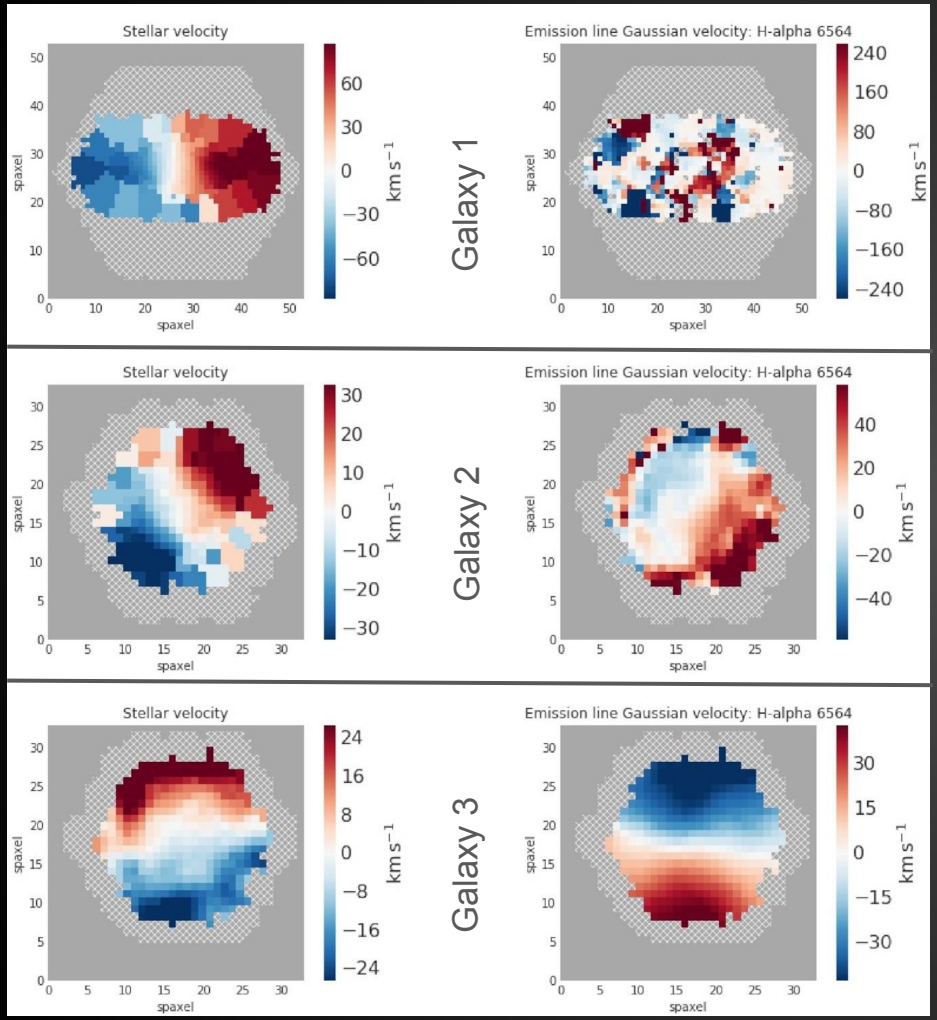
Star-forming Spirals (a control sample)

Quenched S0s (a control sample)

Star-forming S0s are structurally more similar to the quenched S0s and are different from spirals

Star-forming S0s were most likely quenched S0s in the past, whose star-formation has been rejuvenated !

Rathore+2022



What rejuvenated the star-formation in SF-S0s ?

- More than half of our SF-S0 sample shows disturbed gas kinematics, including misalignment and counter-rotation
- This suggests the gas has been brought in by minor mergers

Gas Rich Minor mergers have most likely rejuvenated the star-formation

Rathore+2022

Moral of the story…

Background

S0 galaxies are generally quenched, but there exists a significant number of S0s showing active star-formation.

Key Question

Key question: how to explain the existence of star-forming S0s ?

Findings

The star-forming S0s were most likely quenched S0s in the past, whose star-formation has been rejuvenated. Gas rich minor mergers are likely responsible for this rejuvenation.

Broader Context

The very idea of a uniform “flow” of galaxies from the star-formation sequence to the quenched sequence needs revision. Galaxies can “flow” in the reverse direction as well through rejuvenation processes.

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Backup slides