Rapid, Recent Quenching within AGN Host Galaxies

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The Scientific Question

- How important is ANG feedback to star formation in Type 2 AGN galaxies?
  - Are galaxies hosting an AGN undergoing quenching?
  - If so, what is the rate at which this occurs?
  - Is this quenching occurring at different times and rates when compared to a control sample of inactive galaxies?
  - How does the morphology of a galaxy affect the quenching rate?

What is Galaxy Zoo?

- Started in 2007 to classify galaxy morphology from SDSS images
- Divided into multiple datasets and classification types
- Uses crowd-sourced data analysis to classify images
    - 70,000 classifications per hour
    - 50 million classifications per year
    - 150,000+ unique users
- Part of a series of other ‘citizen science’ projects run by Zooiverse
    - Gravitational waves, wildlife, encoded messages, and more!
- https://www.galaxyzoo.org/#/classify

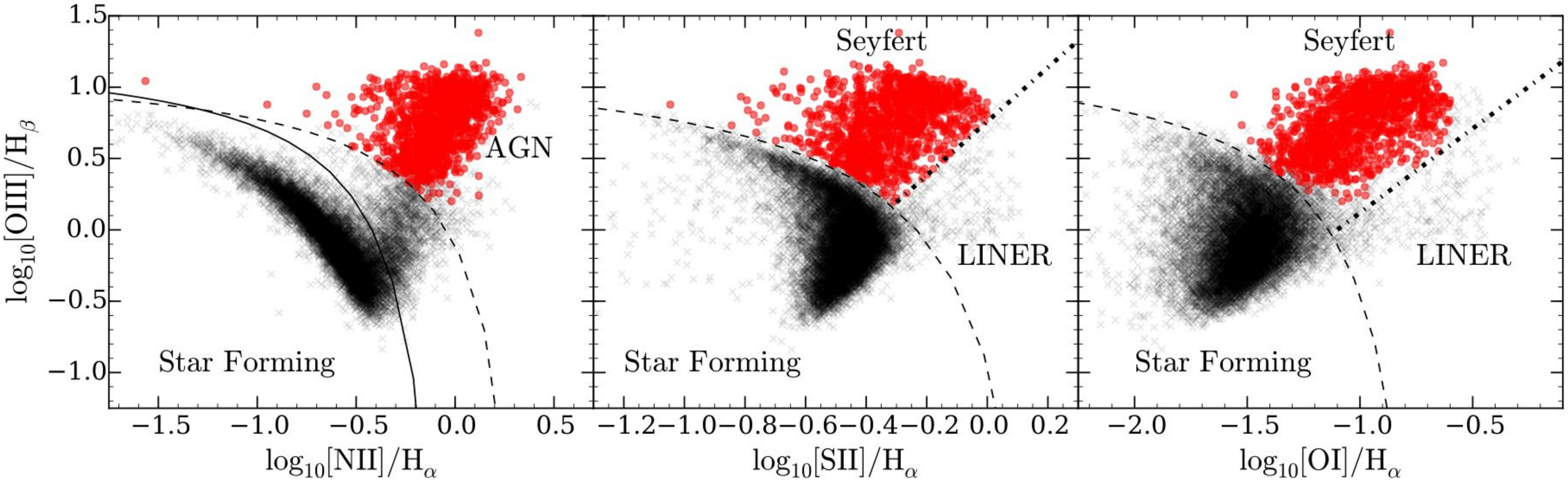
Data Sources

- Visual classifications from the Galaxy Zoo 2 survey were used
  - 304,022 Galaxies
  - >16 million morphological classifications
  - At least 17 independent classifications per image, with an average of 42
  - Uses both SDSS stripe82 and dr7 images
- NUV photometry from the GALAX survey was required
- The overlap between these sets is 126,316 galaxies (z: .01-.05)

Data Corrections

- Observed fluxes were corrected for galactic extinction using the Cardelli law
- *K*-corrections were applied to z=0
- Absolute magnitudes were obtained from NYU-VAGC

AGN Sample



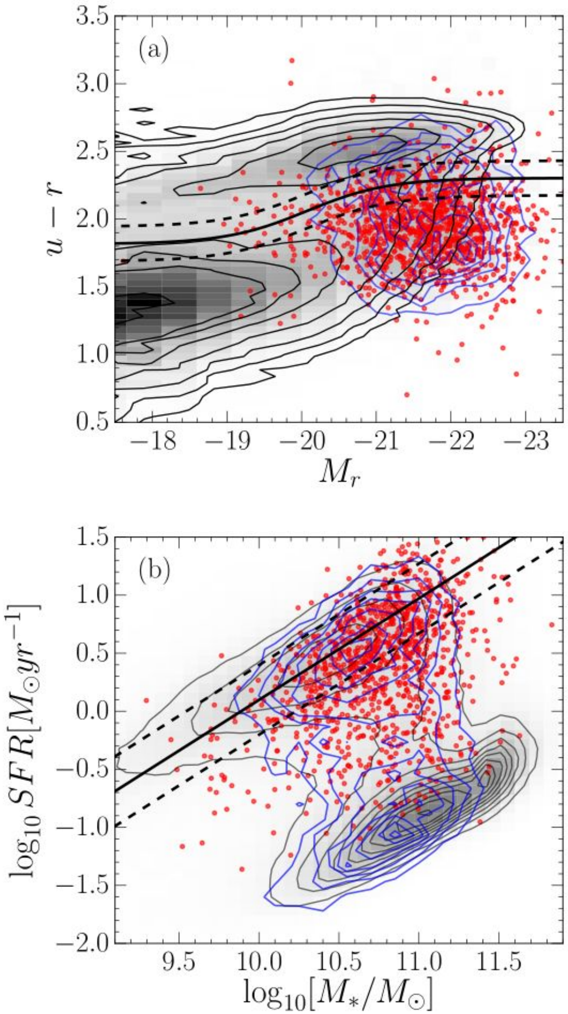
Seyfert
Seyfert
AGN
LINER
LINER
Star Forming
Star Forming
Star Forming
$\log_{10}[\mathrm{OIII}]/\mathrm{H}_\beta$
$\log_{10}[\mathrm{NII}]/\mathrm{H}_\alpha$
$\log_{10}[\mathrm{SII}]/\mathrm{H}_\alpha$
$\log_{10}[\mathrm{OI}]/\mathrm{H}_\alpha$
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−1.0
−0.5
0.0
0.5
−1.2
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
0.2
−2.0
−1.5
−1.0
−0.5

AGN Sample

- Type 2 AGN were selected using a BPT diagram with line and continuum strength for [OIII], [NII], [SII], and [OII] from MPA-JHU
- Type 2 AGN were required to have S/N > 3 for each emission line
- LINERS (**L**ow-**I**onization **N**uclear **E**mission-line **R**egion) are not powered by AGN so they are discluded
- The total number of galaxies remaining is 1,244

AGN Sample

- Type 1 AGN are rejected due to SFH contamination from NUV emission
- NUV emission in Type 2 AGN is negligible due to efficient obscuration of the nucleus
- Uncorrected colors related to residual AGN emission are used to avoid complexity and error propagation
  - Use of corrected colors do not change the results
- Colors were not corrected for intrinsic dust attenuation, so there is a strong possibility of biases due to dust



- Optical color-magnitude diagram of SDSS DR7
    - AGN-Host sample
    - Inactive sample

- SFR-stellar mass diagram of SDSS DR7
    - AGN-Host sample
    - Inactive sample

Corrections

- For higher-mass disc galaxies, earlier values of t and more rapid values of τ inferred from `STARPY`.
- However, these corrections did not change the main conclusions
- The results were consistent if the populations of edge-on and face-on galaxies were compared
- The results do not change if all galaxies were face-on, suggesting that internal galactic extinction does not systematically bias the results

Bayesian SFH Determination

- `STARPY` is a Python code that allows the user to derive the quenching SFH of a single galaxy through a Bayesian MCMC
- Uses observed *u-r* colors, *NUV-r* colors, redshift, and a stellar population model from Bruzual & Charlot (2003)
- Implemented using solar metallicity (which does not affect results) and Chaprier IMF
- Does not model for intrinsic dust

Calculation of SFH

- Exponential decline of the SFR described by the time at the onset of quenching (t_q,Gyr) and the exponential rate at which quenching occurs (τ,Gyr)
- Assuming all galaxies formed at t=0 with star formation

$$SFR = \begin{cases} i_{sfr}(t_q) & \text{if } t < t_q \\ i_{sfr}(t_q) \times exp\left(\frac{-(t-t_q)}{\tau}\right) & \text{if } t > t_q \end{cases}$$

Starpy

- The code run to analyze this data is Starpy
- It calculates quenched star formation history parameters of a galaxy using the MCMC algorithm emcee

```
from posterior import *
from astropy.cosmology import FlatLambdaCDM
import numpy as N
import sys

# Use sys to assign arguments for the galaxy data from the command line
u_r, err_u_r, nuv_u, err_nuv_u, z, dr8, ra, dec = sys.argv[1:]

# Use astropy to calculate the age from the redshift in the data
cosmo = FlatLambdaCDM(H0 = 71.0, Om0 = 0.26)
age = N.array(cosmo.age(float(z)))

# Define parameters needed for emcee
nwalkers = 100 # number of monte carlo chains
nsteps= 400 # number of steps in the monte carlo chain
start = [7.5, 1.5] # starting place of all the chains
burnin = 400 # number of steps in the burn in phase of the monte carlo chain

#The rest calls the emcee module which is initialised in the sample function of the posterior file.
samples, samples_save = sample(2, nwalkers, nsteps, burnin, start, float(u_r), float(err_u_r), float(nuv_u), float(err_nuv_u), age, dr8, ra, dec)
tq_mcmc, tau_mcmc,  = map(lambda v: (v[1], v[2]-v[1], v[1]-v[0]), zip(*N.percentile(samples, [16,50,84],axis=0)))
```

Assumptions

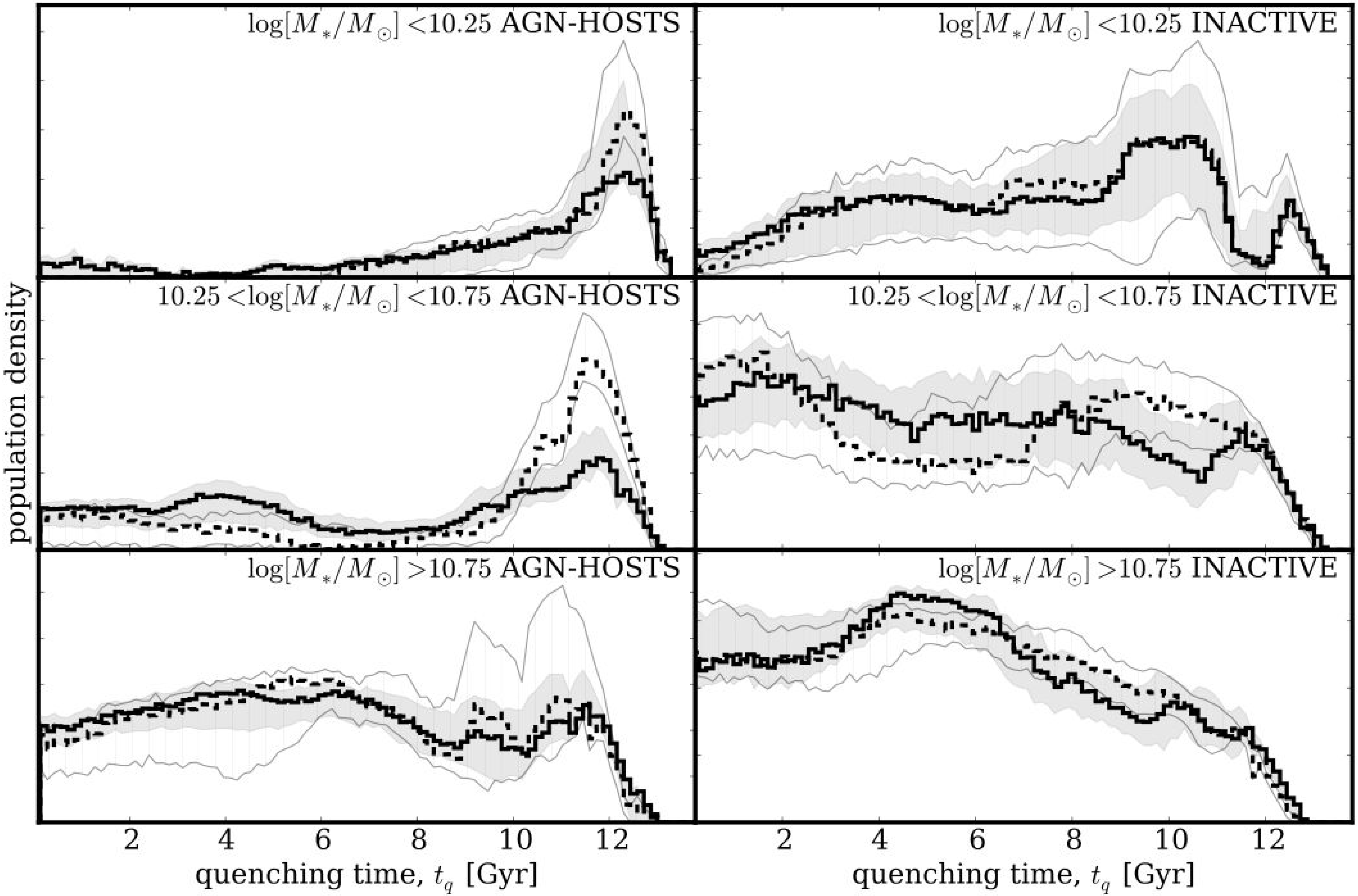
- Assumes all model parameters have a flat prior
- Difference between observed and predicted color sets are modelled as independent realizations of a double Gaussian
- Assumes that the age of each galaxy is the age of the universe at the observed redshift

Analysis

- Starpy output is probabilistic, and provides the posterior distribution across the two-parameter space for individual galaxies
- For studying the SFR of a population, individual galaxies are weighted by probability and stacked in $[t_q , \tau]$ space
- Minimizes contribution of poorly-fit galaxies that don't obey the exponential form of the SFH
- Morphologies of galaxies are used as weights when stacking, allowing separation into disc and smoothed populations
  - Prevents arbitrary morphology divisions (eg $p_d > .8$)

Alternative analysis

- Possible to perform inference on Bayesian parent parameters
  - Uses hyperparameters to determine parent distributions
- However, this requires initial decision on functional shape of the parent distribution
  - This requires non-trivial assumptions
  - e.g. hyper-distribution has the form of a multi-component Gaussian mixture model
  - Other hyper-distributions are possible but beyond scope
- This analysis was tested but did not fit the color distributions and was unsatisfactory



$\log[M_*/M_\odot] < 10.25$ AGN-HOSTS
$\log[M_*/M_\odot] < 10.25$ INACTIVE
$10.25 < \log[M_*/M_\odot] < 10.75$ AGN-HOSTS
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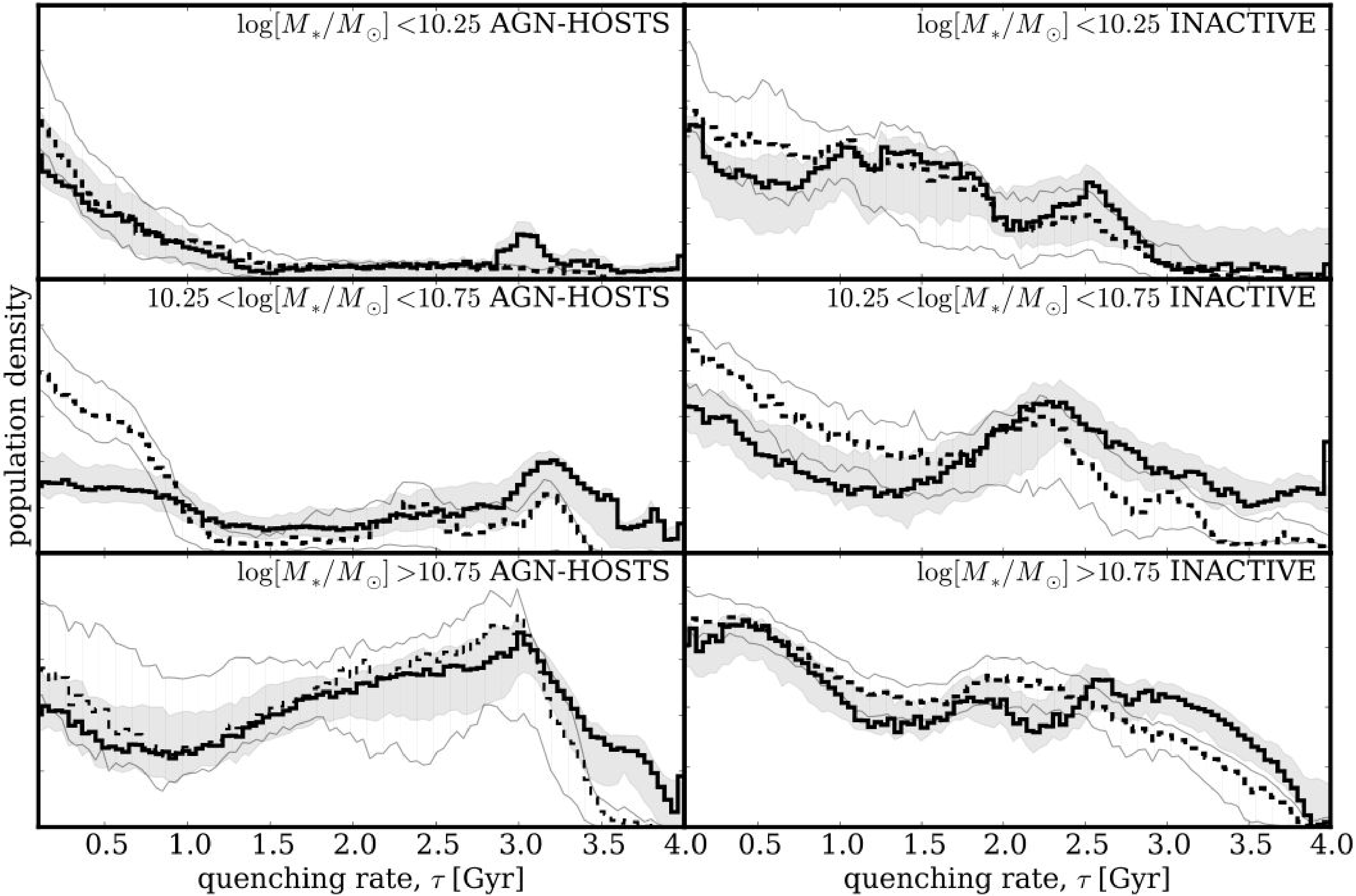
$\log[M_*/M_\odot] > 10.75$ INACTIVE
population density
2
4
6
8
10
12
quenching time, t_q [Gyr]

Quenching Time Results

- The results between AGN-Hosts and inactive galaxies are different
- Low-mid mass galaxies have much more recent quenching times
    - This is especially seen in smooth galaxies
- Less dominant for High mass galaxies due to earlier quenching times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$\log[M_*/M_\odot]$ >10.75 AGN-HOSTS
$\log[M_*/M_\odot]$ >10.75 INACTIVE
population density
0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0
0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0
quenching rate, τ [Gyr]
quenching rate, τ [Gyr]

Quenching Rate Results

- Quenching rate initially starts very high, particularly in smooth galaxies
- This quenching rate decreases with mass, particularly in disc galaxies
- The results are similar for the inactive galaxies, but the overall distribution is very different

Conclusions

- AGN has a significant effect on the SFH of the host galaxy
  - Includes both recent, rapid quenching and early, slow quenching
- Minimal differences in SFH between galaxy morphologies
  - This confirms earlier results that structural properties of AGN hosts depend very little on AGN power

Conclusions

- The differences in quenching rate are due to gas reservoirs
- Higher-mass AGN-hosts are dominated by slow, early quenching
  - This implies a a quenching mechanism before the AGN triggers
- This slow evolution agrees with the Kennicutt-Schmidt idea of previously isolated disks undergoing an interaction to reinvigorate SF and trigger AGN
- A large enough gas reservoir to fuel both SF and the recent SGN is needed
- The SFH challenges the usual explanation of co-evolution of luminous black holes and host galaxies being driven by merger growth

Conclusions

- In low-mass galaxies, rapid quenching is more dominant
  - Believed to be caused by negative feedback on the AGN
  - Lower gravitational potential allows easier expelled and heated gas
- This is believed to create more smooth galaxies, as it is believed that a merger causes the transition to a smooth galaxy and triggers an AGN

Conclusions

- It is still possible that AGN are the result of an alternative quenching method
- Exhaustion of gas due to a merger-caused starburst would cause a rapid quench and trigger an AGN
  - This is supported by the observation that AGN are more commonly found in post-starburst galaxies
- This possibility is not accounted for in these models, but the scenario is still consistent with the conclusions of this paper

References

Smethurst, R.J. et al (2016), MNRAS, 463 (3): 2986-2996. arXiv:1609.00023

https://www.galaxyzoo.org/

Willett, et al (2013) https://arxiv.org/abs/1308.3496

https://github.com/willettk/galaxyzoo2

https://github.com/rjsmethurst/starpy