

How to Quench a Galaxy

Michael Tremmel
University of Washington

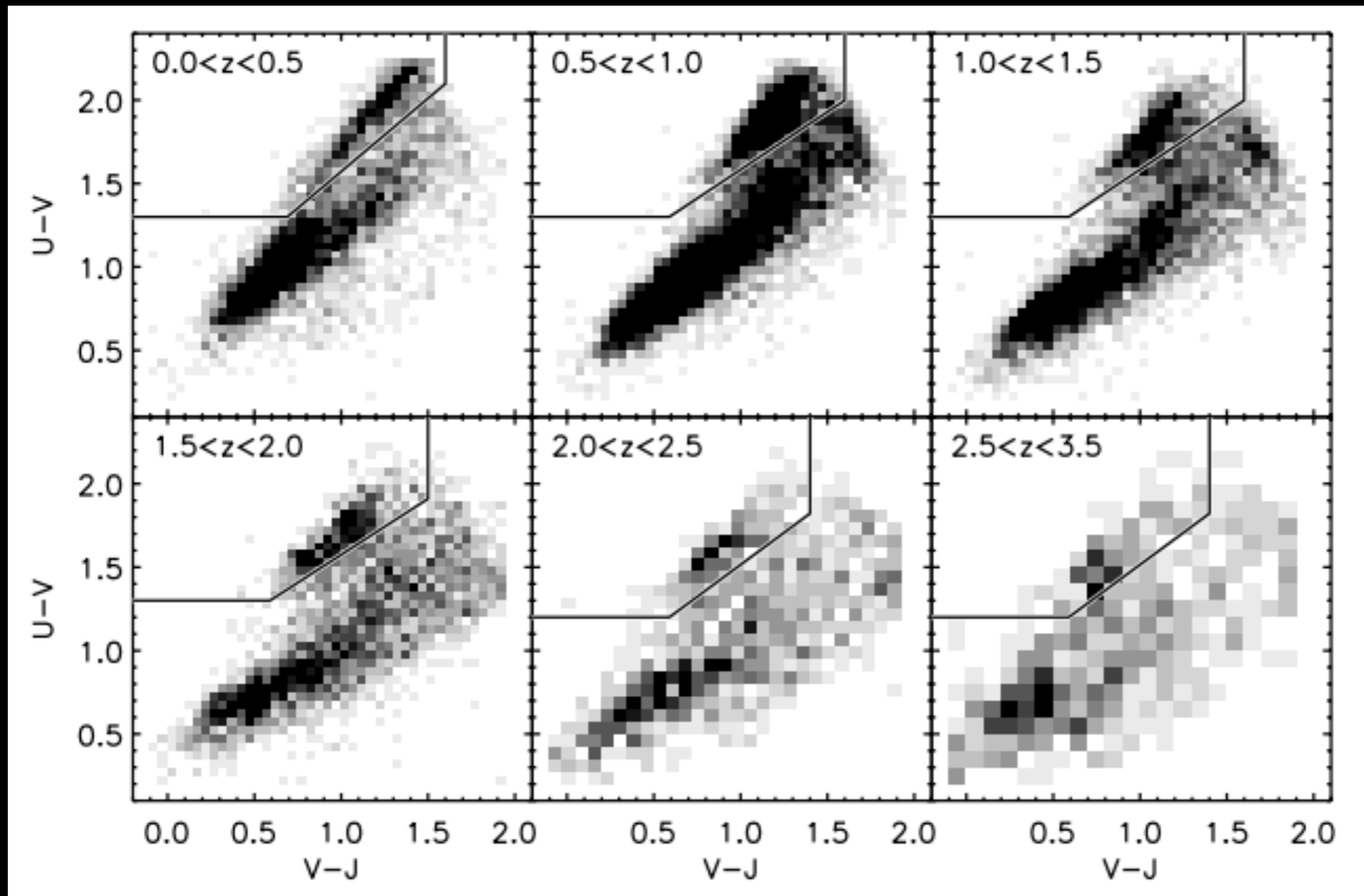
**Andrew Pontzen (UCL), Fabio Governato (UW),
Tom Quinn (UW), Marta Volonteri (IAP),
Nina Roth (AIA), Hiranya V. Peiris (UCL),
Amélie Saintonge (UCL)**

20 kpc



How to Quench a Galaxy

The growing population of massive, quenched galaxies



What shuts off star formation in massive galaxies?

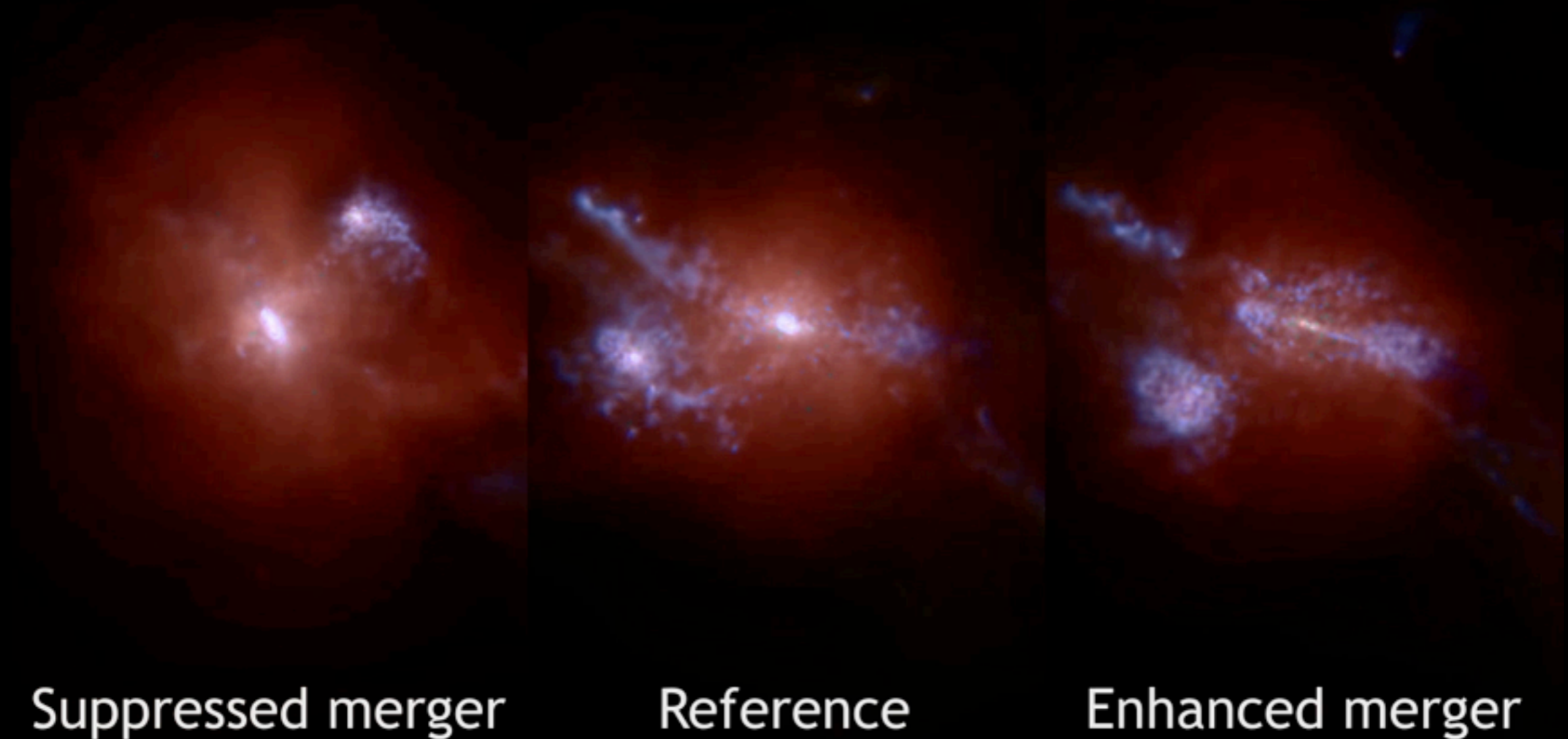
Is this transition (Blue -> Red) permanent?

Whitaker+ 2011

AGN Feedback and Quenching

Examining the interaction between AGN Feedback and Galaxy Merger History using **Genetic Modification** (Roth+ 2016)

Redshift 1.9
3.53 Gyr
Step 1024



SMBH Sub-Grid Physics

A novel, well-constrained model for SMBH formation, accretion, and dynamics

<https://arxiv.org/abs/1607.02151>

The Romulus Cosmological Simulations: A Physical Approach to the Formation, Dynamics and Accretion Models of SMBHs

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⁴*Department of Physics and Astronomy, University College London, 132 Hampstead Road, London, NW1 2PS, United Kingdom*

⁵*Department of Physics, Queensborough Community College, 222-05, 56th Avenue, Bayside, NY 11364*

- SMBHs seeded at early times without a priori assumptions of halo occupation
- Realistically follow the dynamical evolution of SMBHs (Tremmel+ 2015)
- Accretion that accounts for angular momentum of gas

SMBH Sub-Grid Physics

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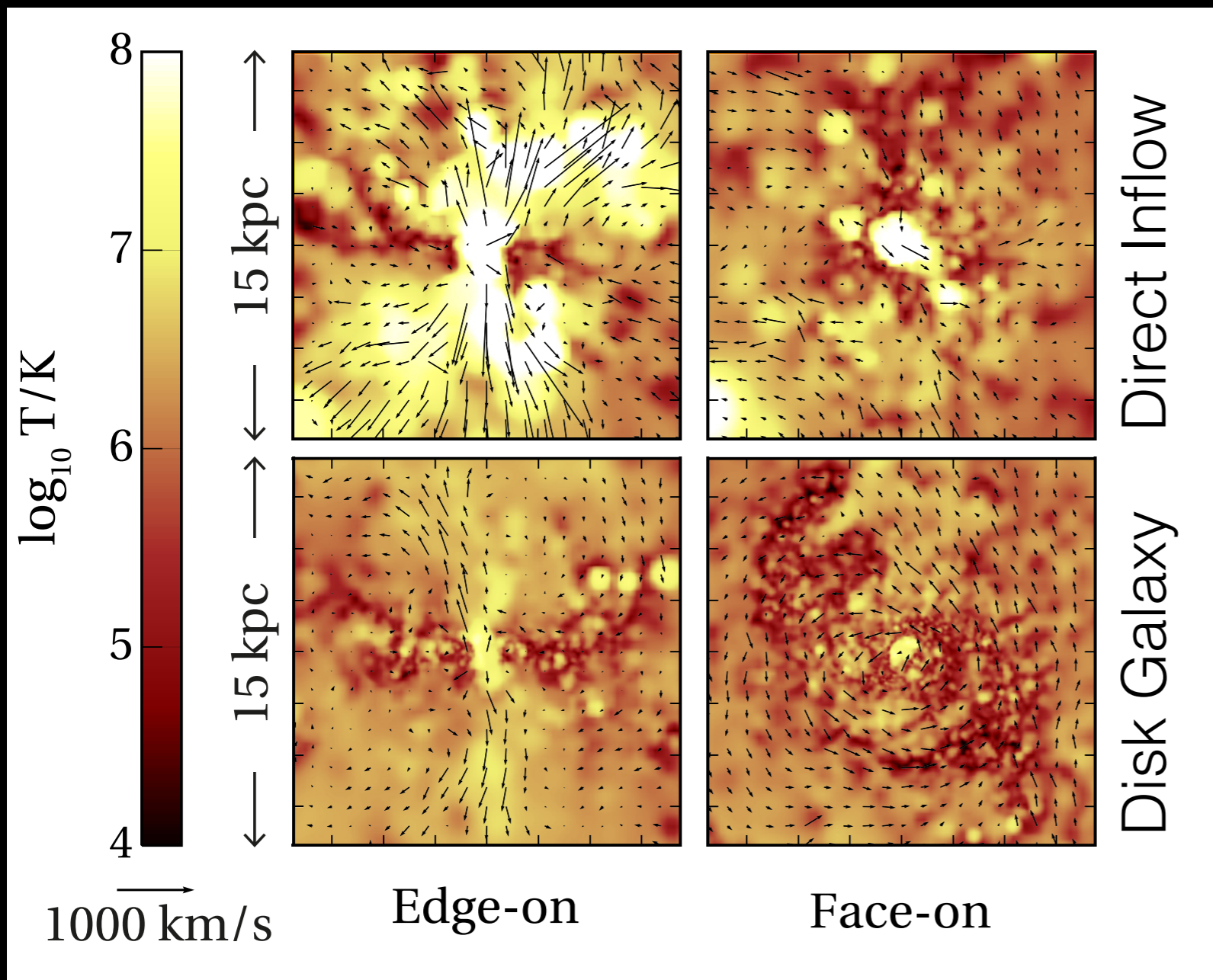
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- Realistically follow the dynamical evolution of SMBHs (Tremmel+ 2015)
- **Accretion that accounts for angular momentum of gas**

SMBH Sub-Grid Physics

Accretion that Accounts for Angular Momentum



- Account for Angular Momentum Support Tremmel + 2017
 - Estimate the effective potential due to rotation at resolved scales
 - Modify the Bondi radius accordingly
- 10% Radiative eff.
- 2% (thermal) gas coupling eff.

Pontzen, Tremmel+ 2017

AGN and Galaxy Mergers

Examining the interaction between AGN Feedback and Galaxy Merger History using **Genetic Modification** (Roth+ 2016)

- High resolution
(250 pc, $3 \times 10^5 M_{\text{sun}}$)
- SMBH dynamics and accretion that respond to the kinematics of their host
- Synergy with the **Romulus Simulations**
(Tremmel+ 2017)

Redshift 1.9
3.53 Gyr
Step 1024



To Quench or Not to Quench

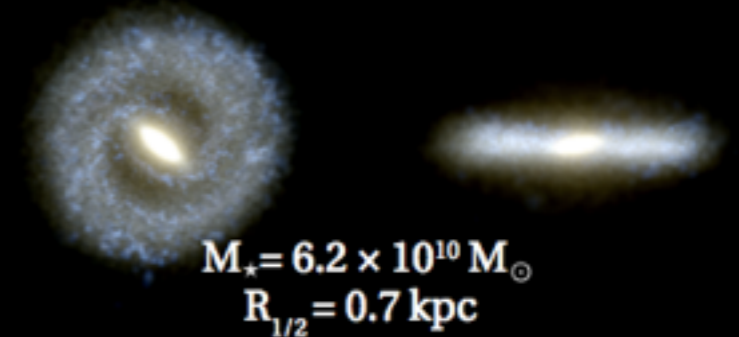
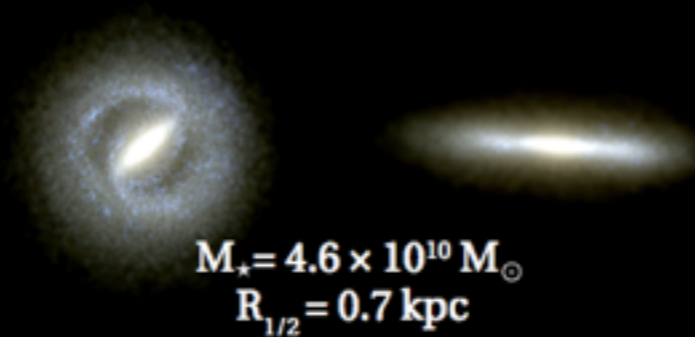
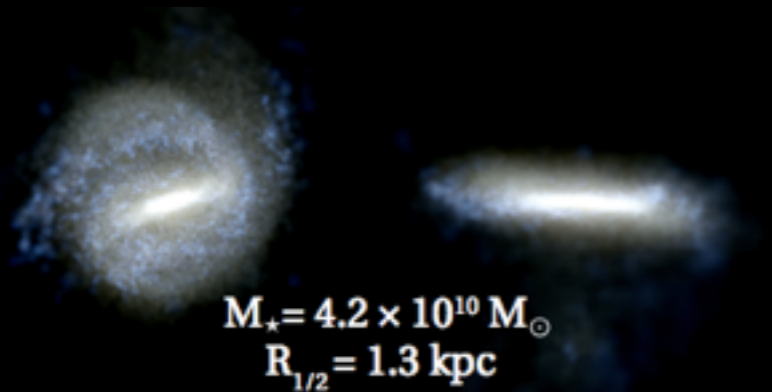
Galaxy mergers have drastic consequences for star formation and morphology.... **when coupled with AGN feedback**

Suppressed (1:10)
Merger

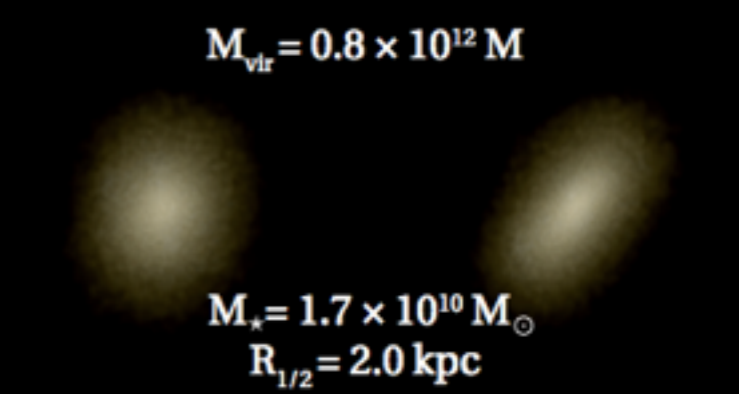
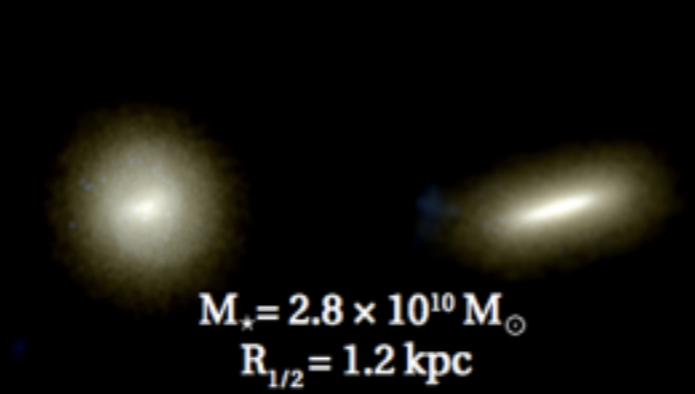
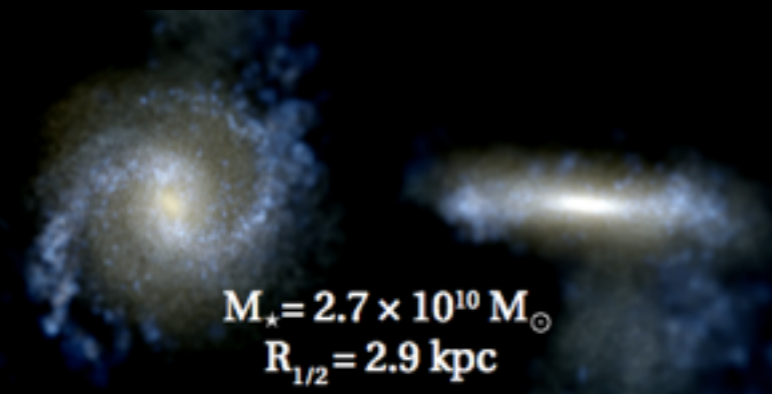
Reference (1:5)
Merger

Enhanced (2:3)
Merger

SN Only



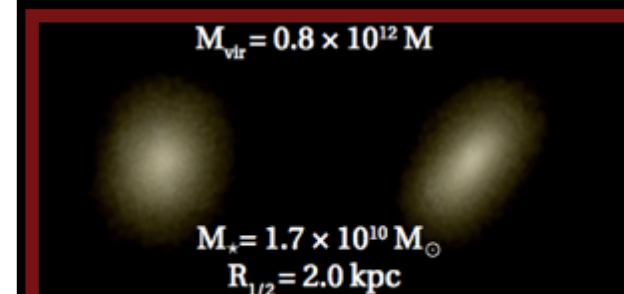
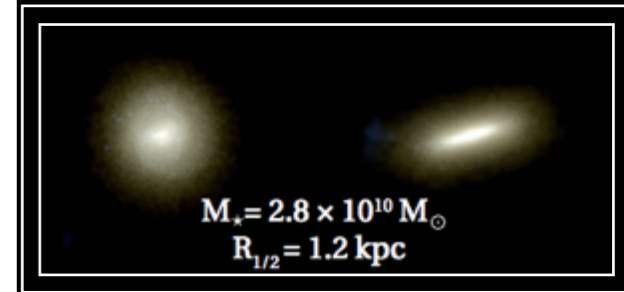
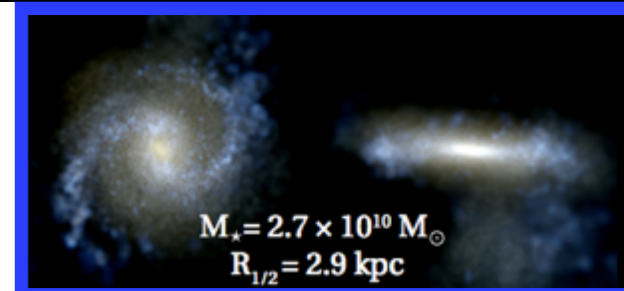
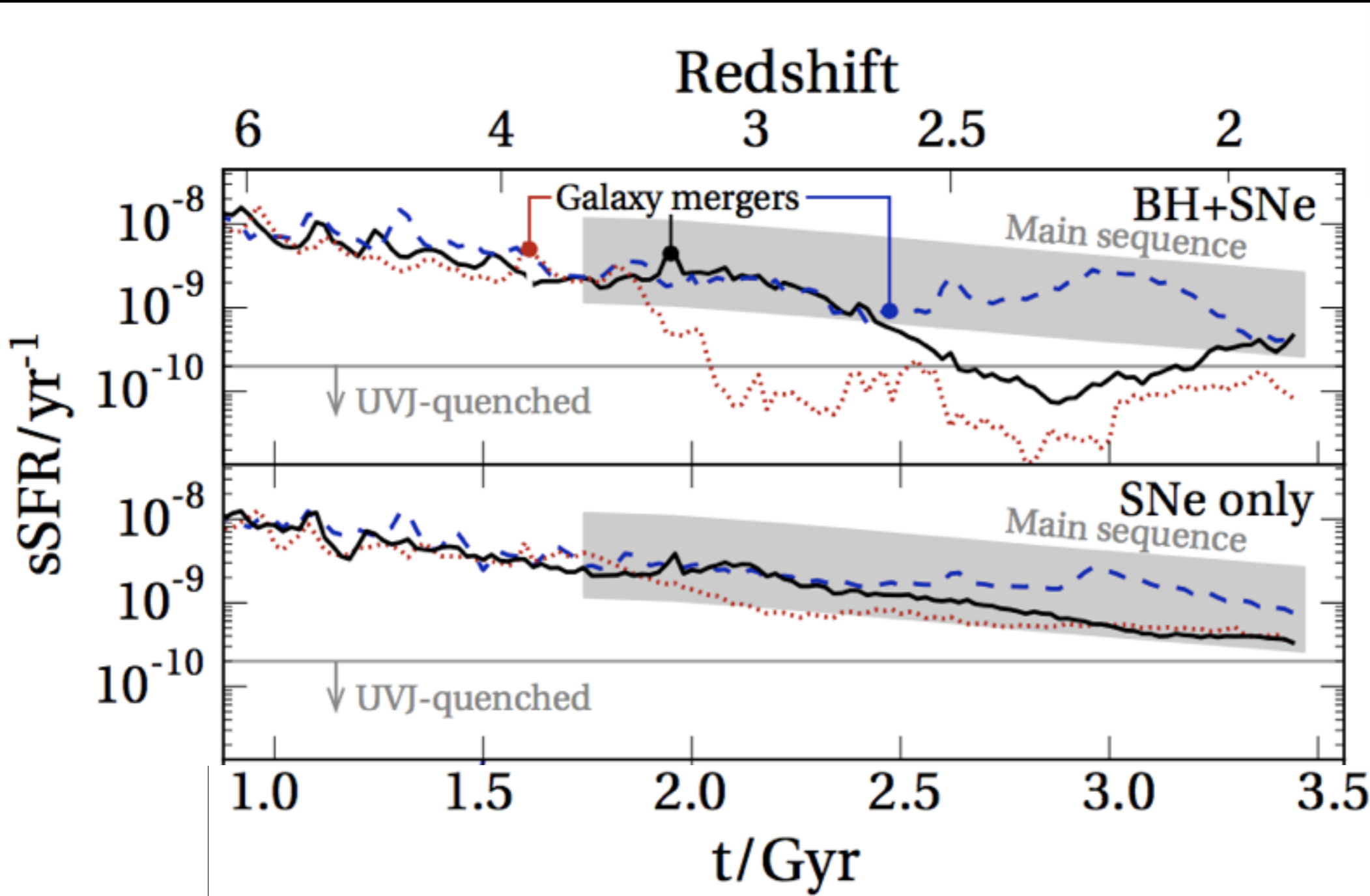
SN+AGN



Pontzen, Tremmel+ 2017

To Quench or Not to Quench

Galaxy mergers have drastic consequences for star formation and morphology.... when coupled with AGN feedback

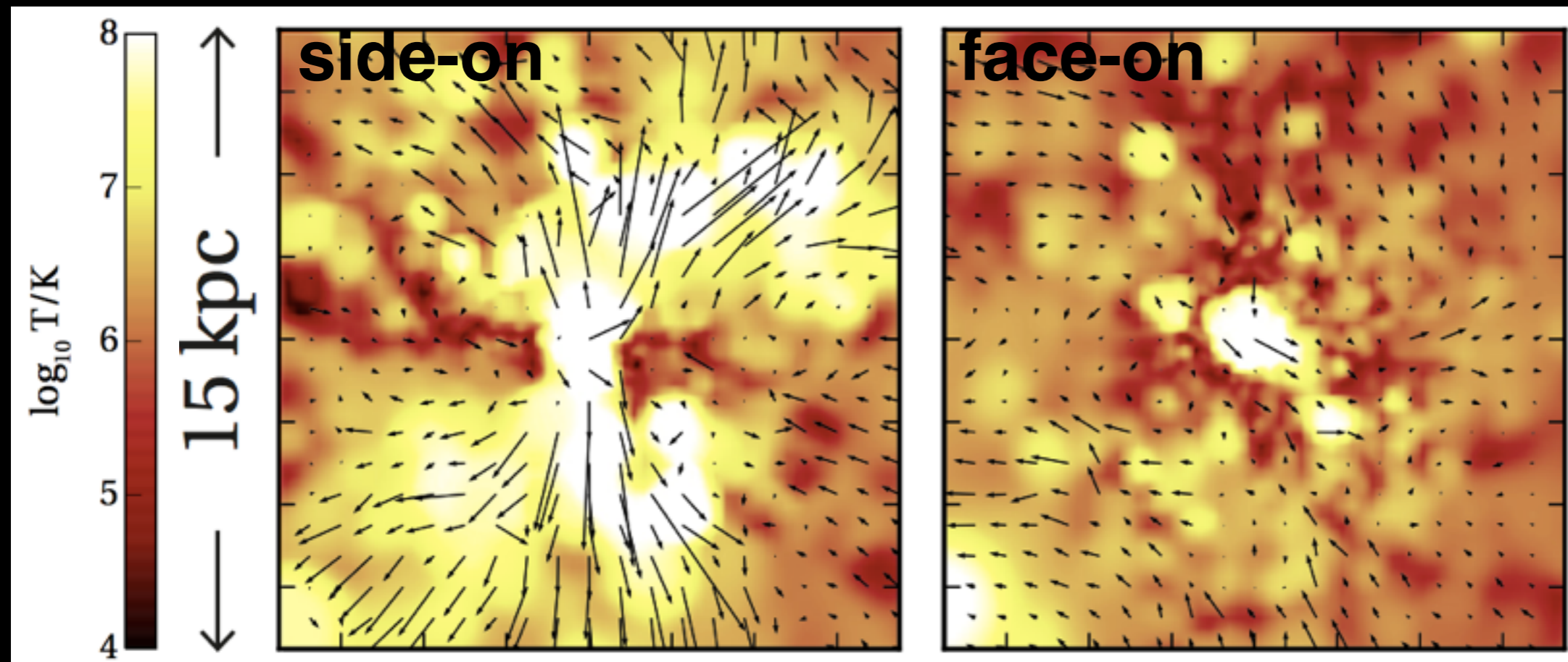


Pontzen,
Tremmel+
2017

Large-Scale Outflows

Energetic outflows prevent the reformation of a gaseous disk

Enhanced Merger simulation just after it becomes quenched

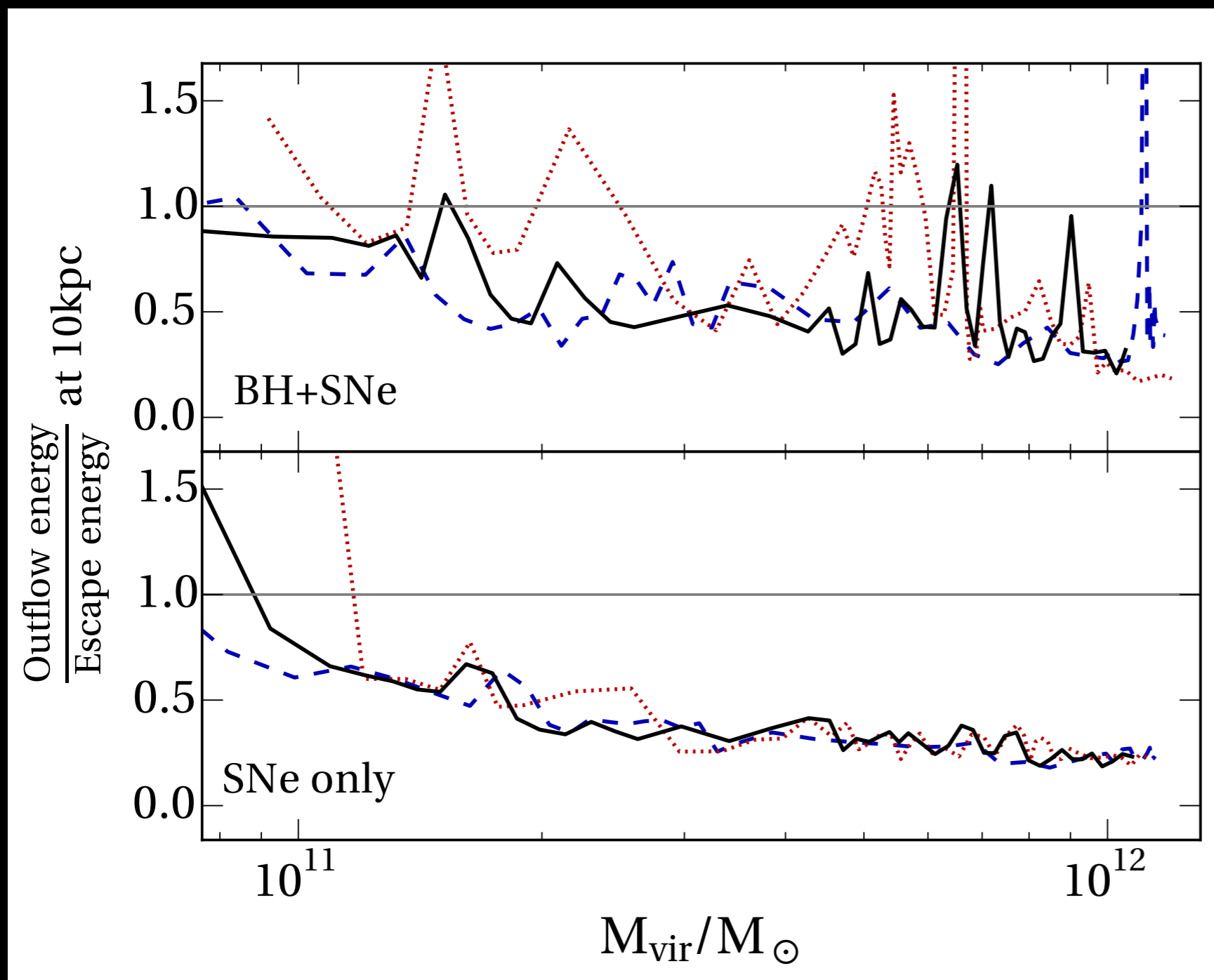


Inflowing gas fuels AGN activity, large-scale winds rather than form a new galactic disk

Pontzen, Tremmel+ 2017

Large-Scale Outflows

Outflows need to reach larger scales to suppress inflating gas

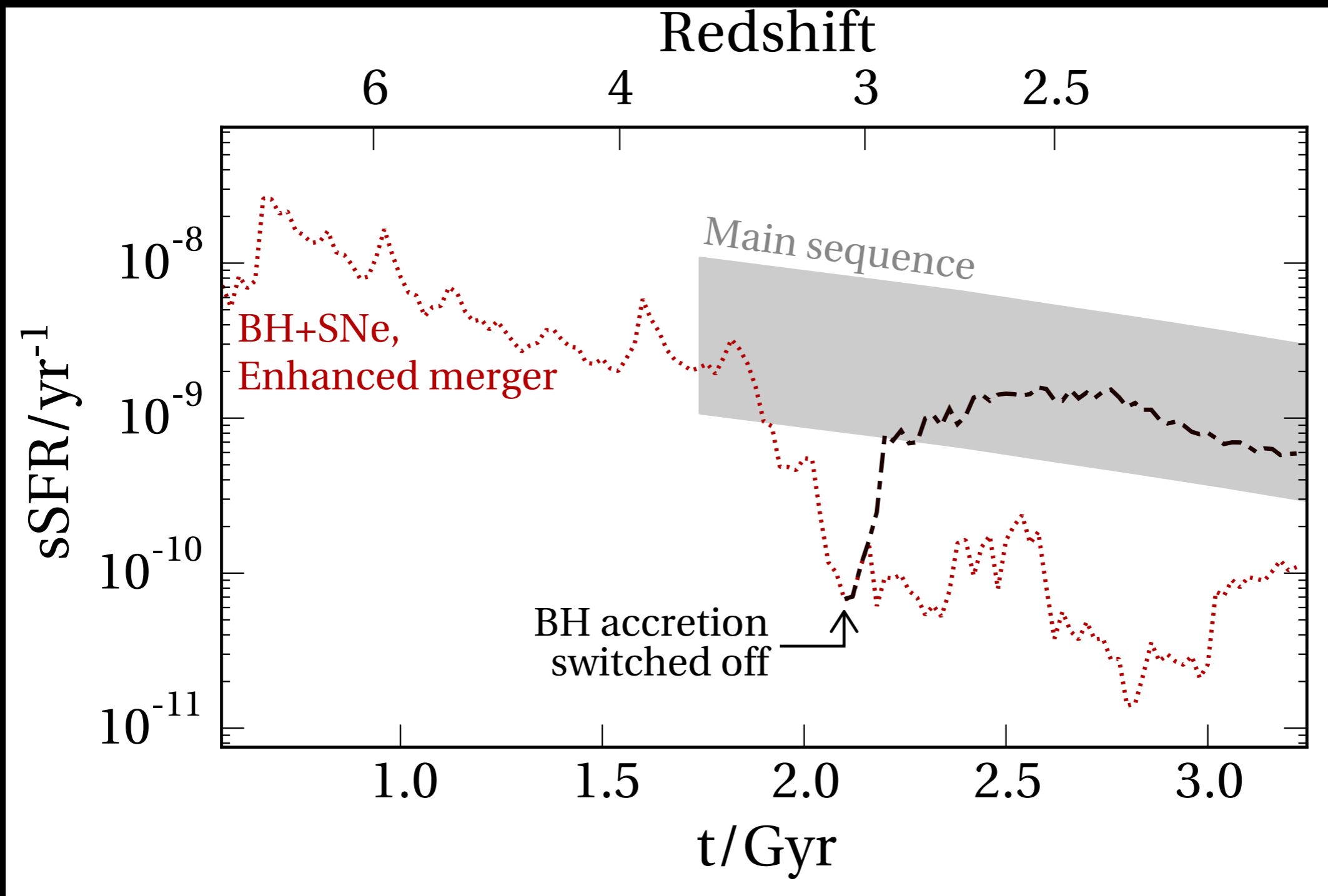


AGN that fail to drive such winds will eventually fail to prevent **rejuvenation**

Pontzen, Tremmel+ 2017

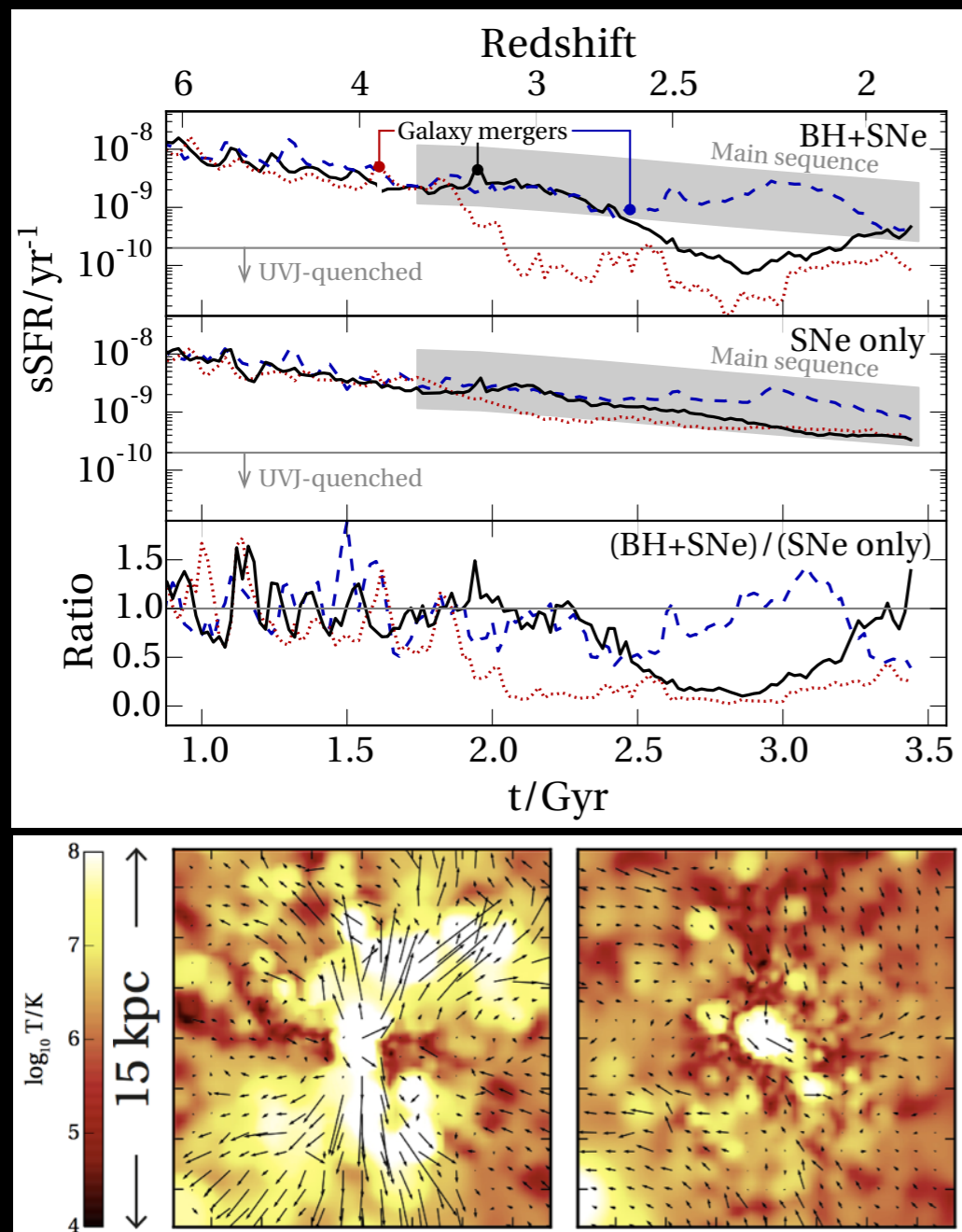
Large-Scale Outflows

Without AGN feedback, galaxy would **quickly rejuvenate**



Pontzen, Tremmel+ 2017

A Merger-Driven Quenching Scenario



Major merger disrupts galactic disk with help of AGN feedback

Further inflows feed SMBH, drive powerful winds

Large -scale AGN winds suppress gas inflow, prevent rejuvenation

Quenching Galaxies “In the Wild”

A wider exploration using the Romulus Simulations



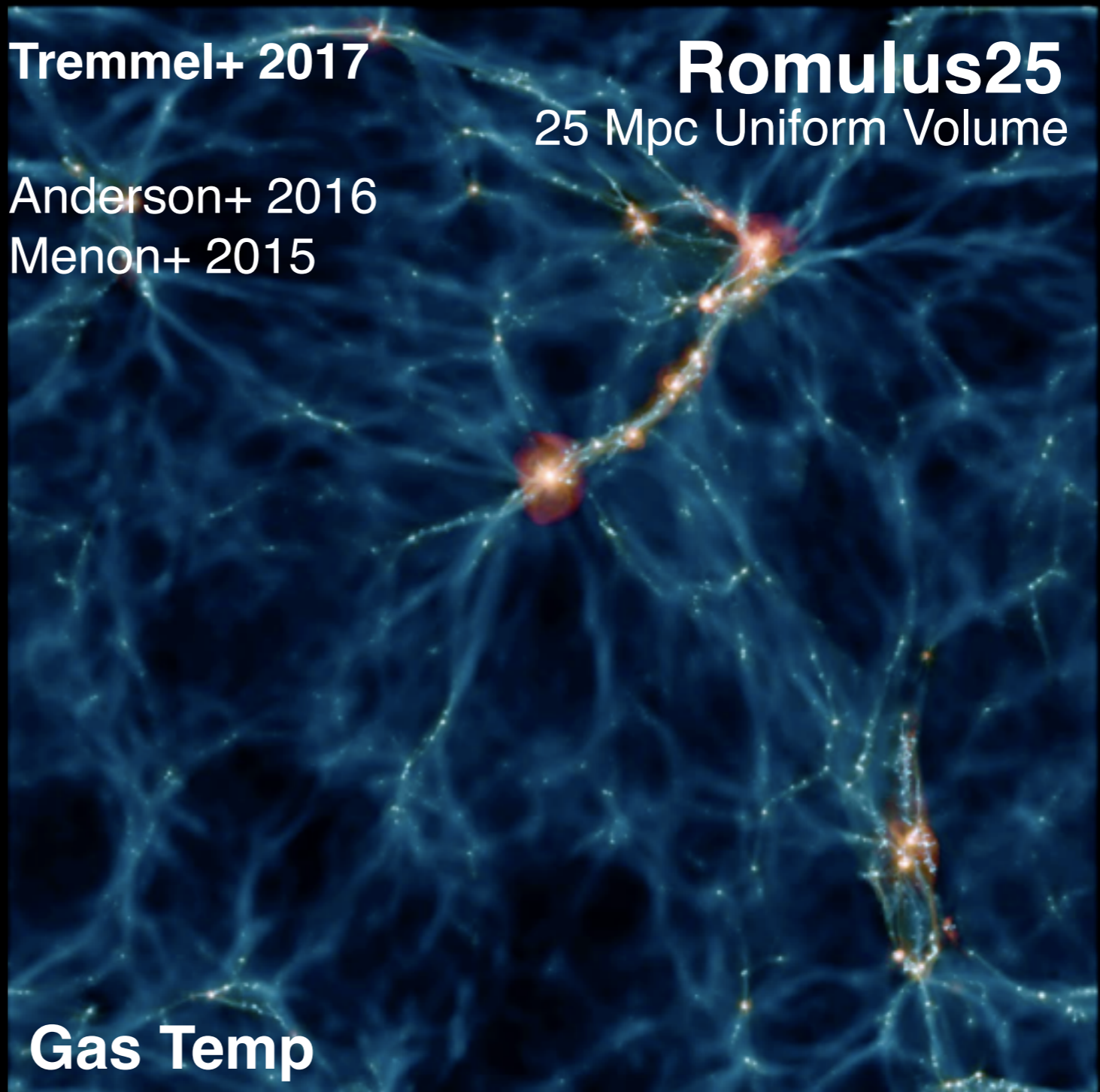
Tremmel+ 2017

Anderson+ 2016

Menon+ 2015

Romulus25
25 Mpc Uniform Volume

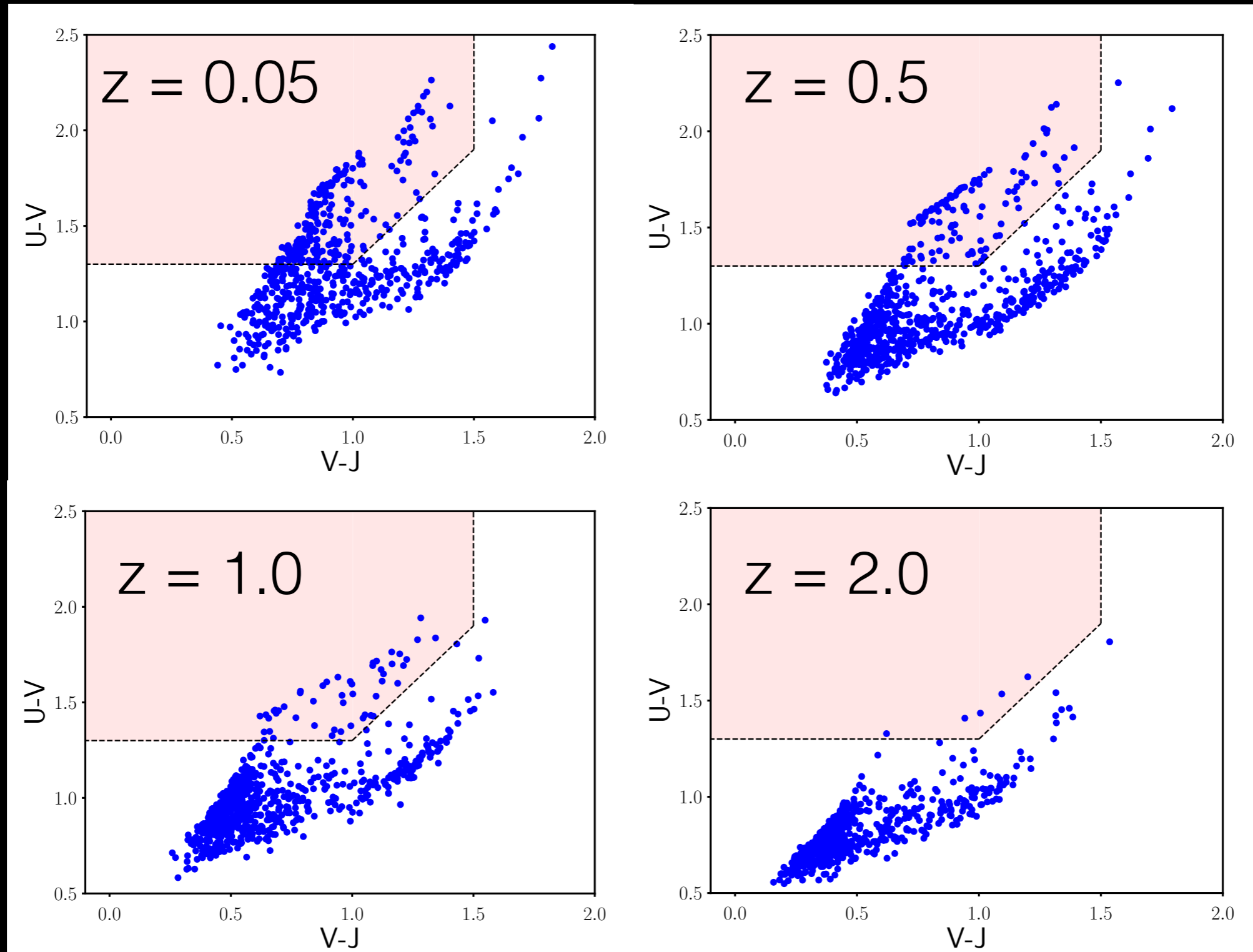
Gas Temp



Quenching Galaxies “In the Wild”

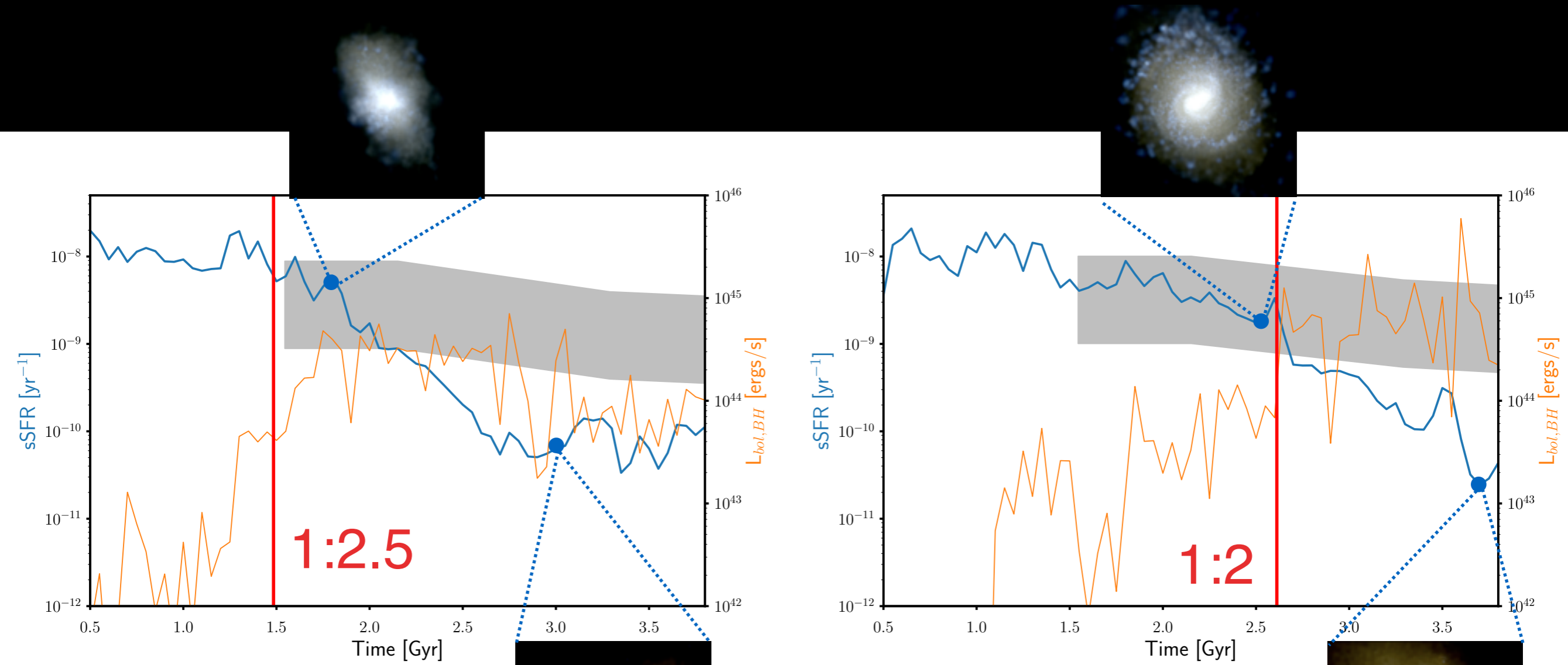
The rise of the red sequence in Romulus

Tremmel+, in prep



Merger Triggered Quenching at All Redshifts

Mergers cause quenching of massive galaxies at $z \sim 2$

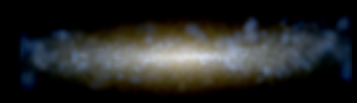


Tremmel+, in prep

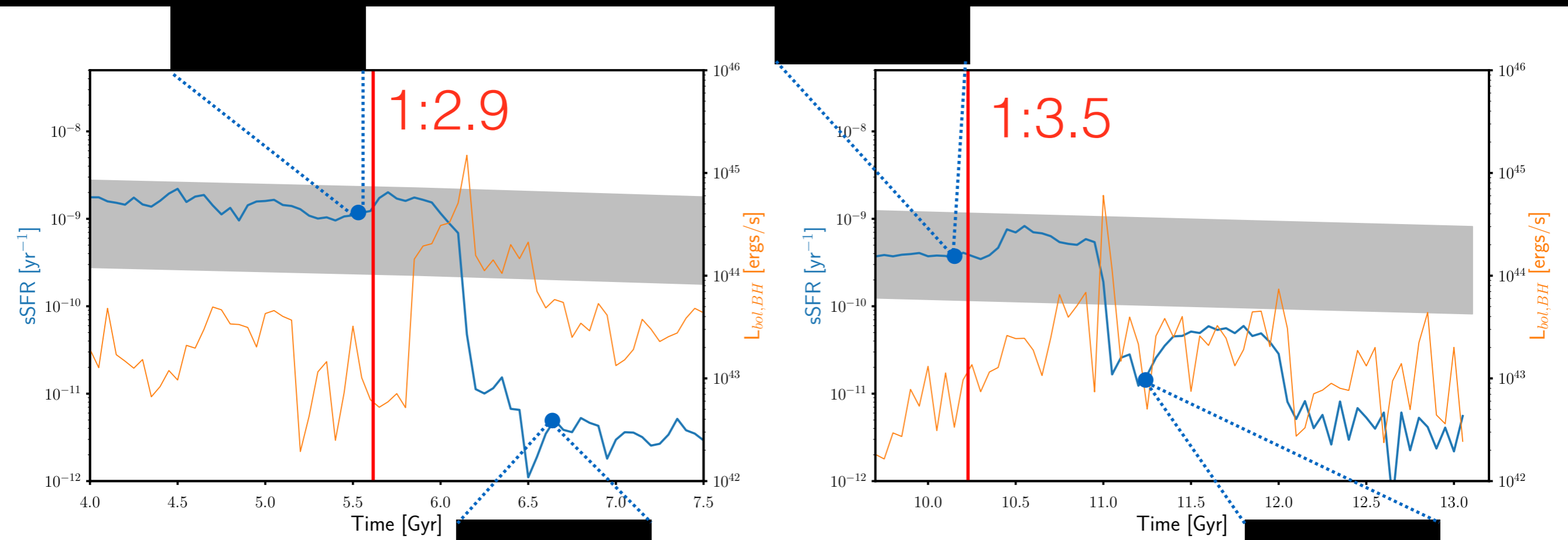
Merger Triggered Quenching at All Redshifts

Lower redshift mergers can also drive quenching

$z \sim 1$



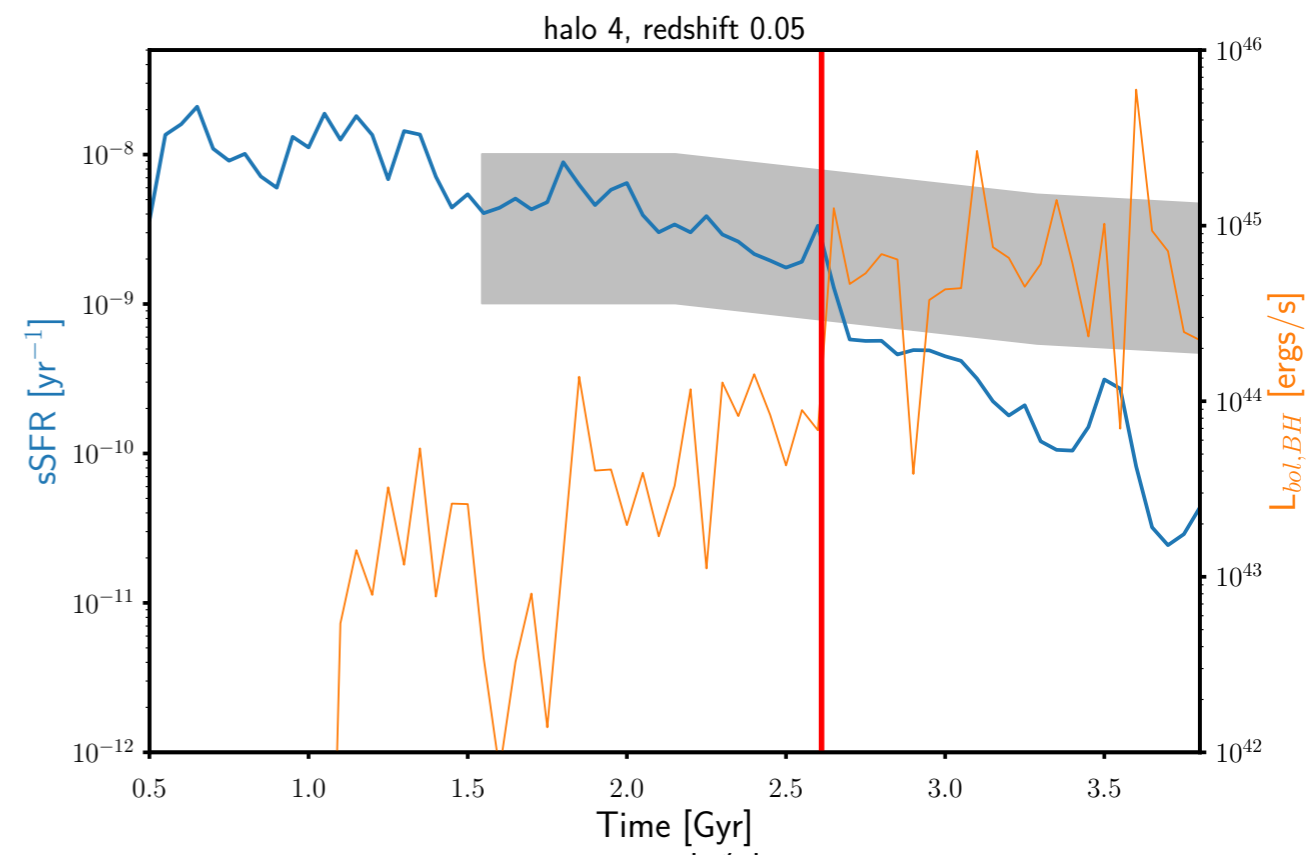
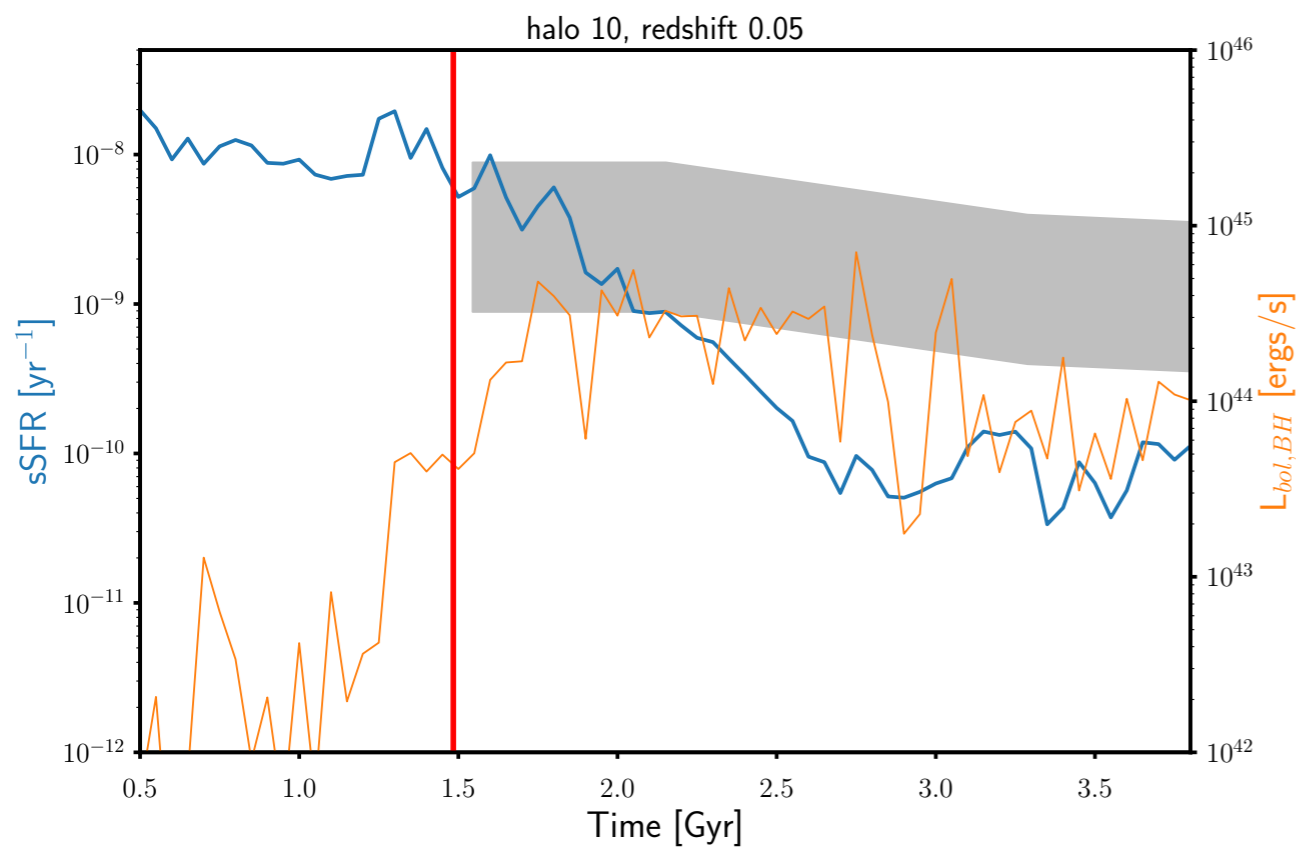
$z \sim 0.2$



Tremmel+, in prep

The Complicated History of Quenched Galaxies

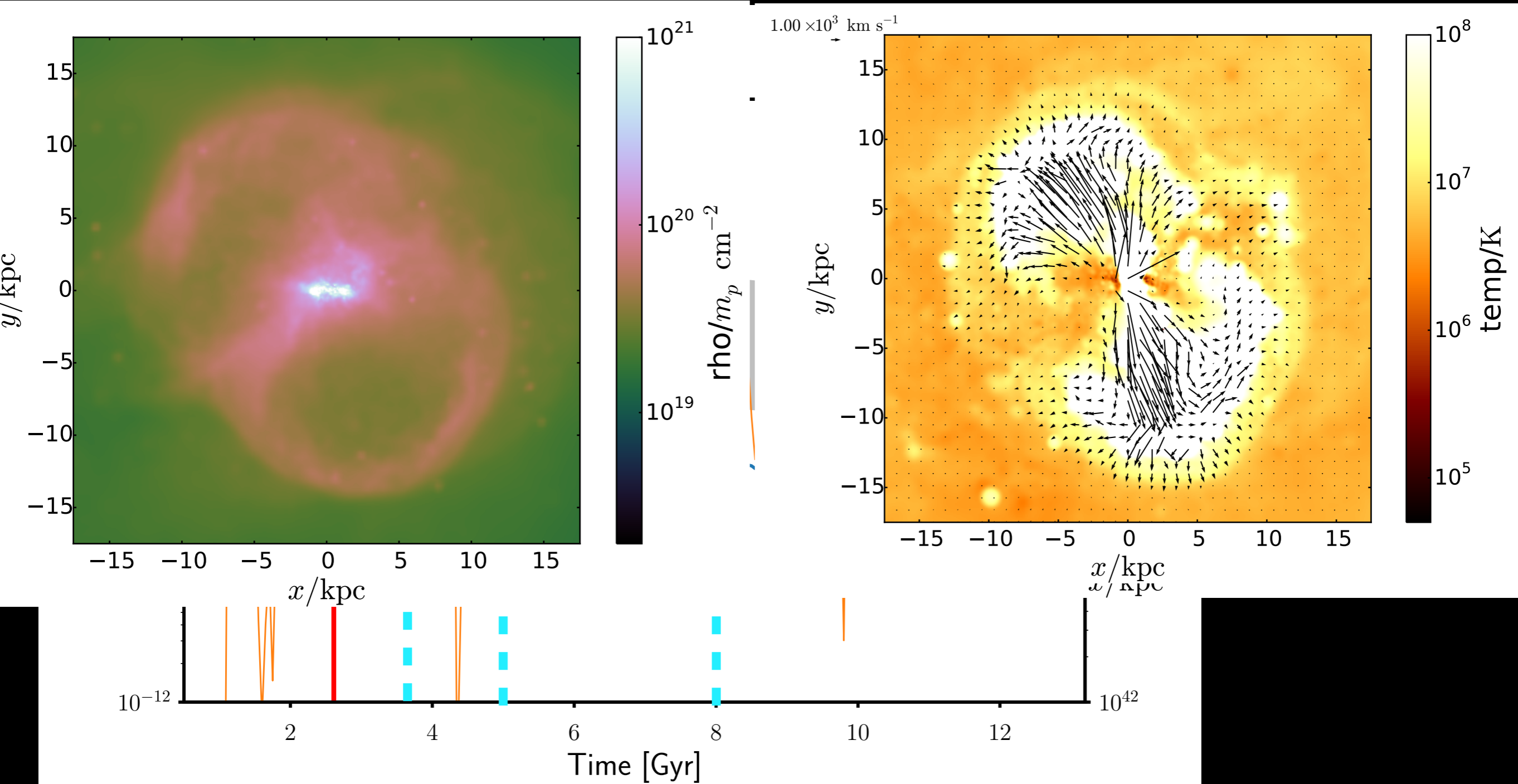
Rejuvenation/quenching can happen multiple times



Tremmel+, in prep

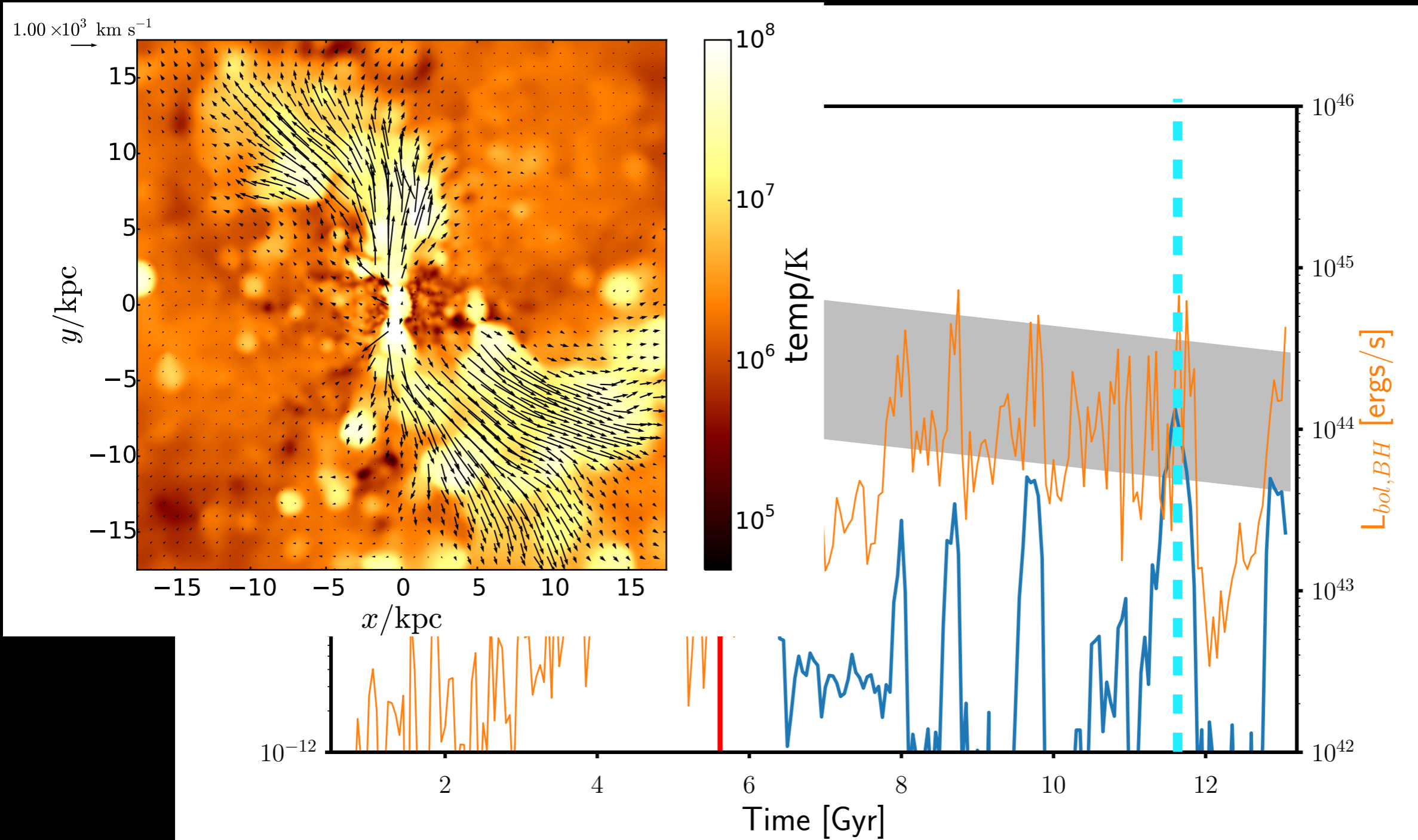
Large-Scale AGN-Driven Winds Prevent Disk Reformation

1000s km/s outflows at several to 10s kpc



Large-Scale AGN-Driven Winds Prevent Disk Reformation

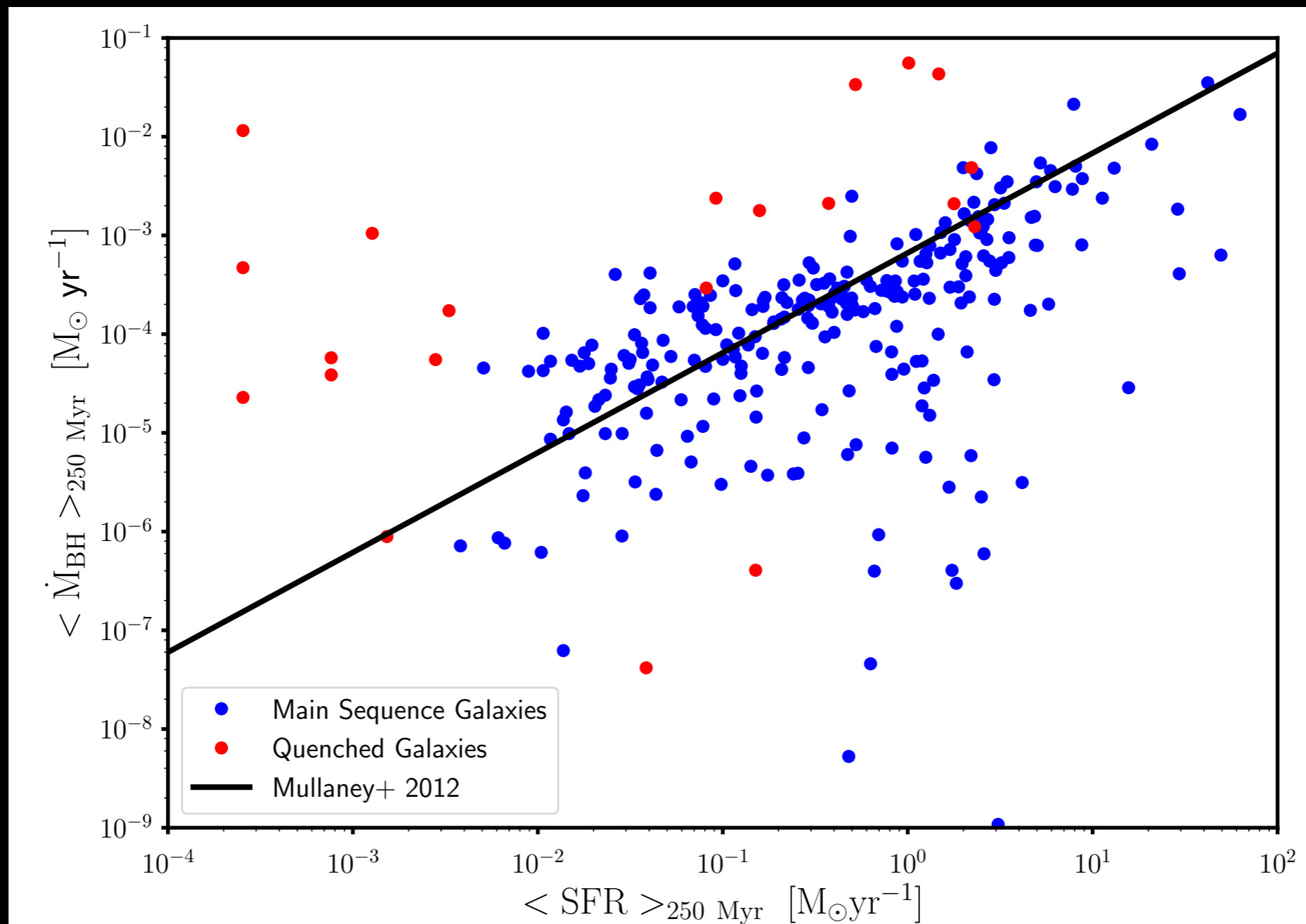
1000s km/s outflows at several to 10s kpc



Quenched Galaxies Have High AGN Activity Relative to Star Formation

Compared to Main Sequence Galaxies

Tremmel+, in prep



Conclusions

Large-scale (10s kpc), powerful winds driven by AGN are **required** to prevent rejuvenation in quenched galaxies

- Major mergers (ratio > 0.25) and AGN feedback disrupt disk, quench star formation
- Interaction with turbulent medium drives cooling gas onto SMBH
- AGN feedback removes gas, drives large-scale winds that prevent further inflow
- Mechanism robust at a variety of redshifts
- Repeated phases of powerful AGN feedback present in quenched galaxies

Looking Forward

Observational signatures of different phases of AGN feedback

- Effect of repeated outflows on CGM in massive galaxies
- Observational characteristics of outflows at different times
- Examine lower mass galaxies

Conclusions

Large-scale (10s kpc), powerful winds driven by AGN are required to prevent rejuvenation in quenched galaxies

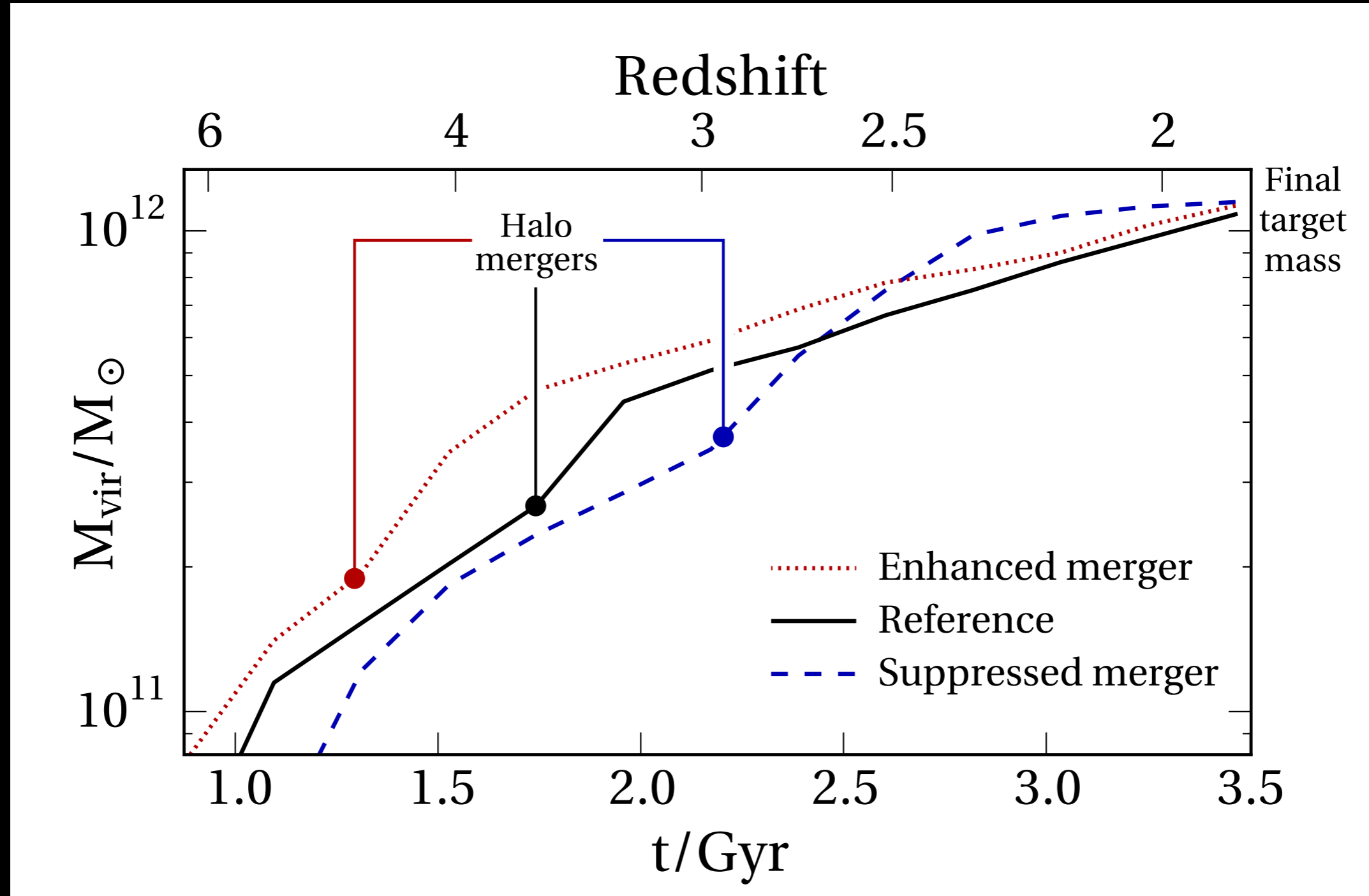
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Extra Slides

Genetically Modified Galaxies

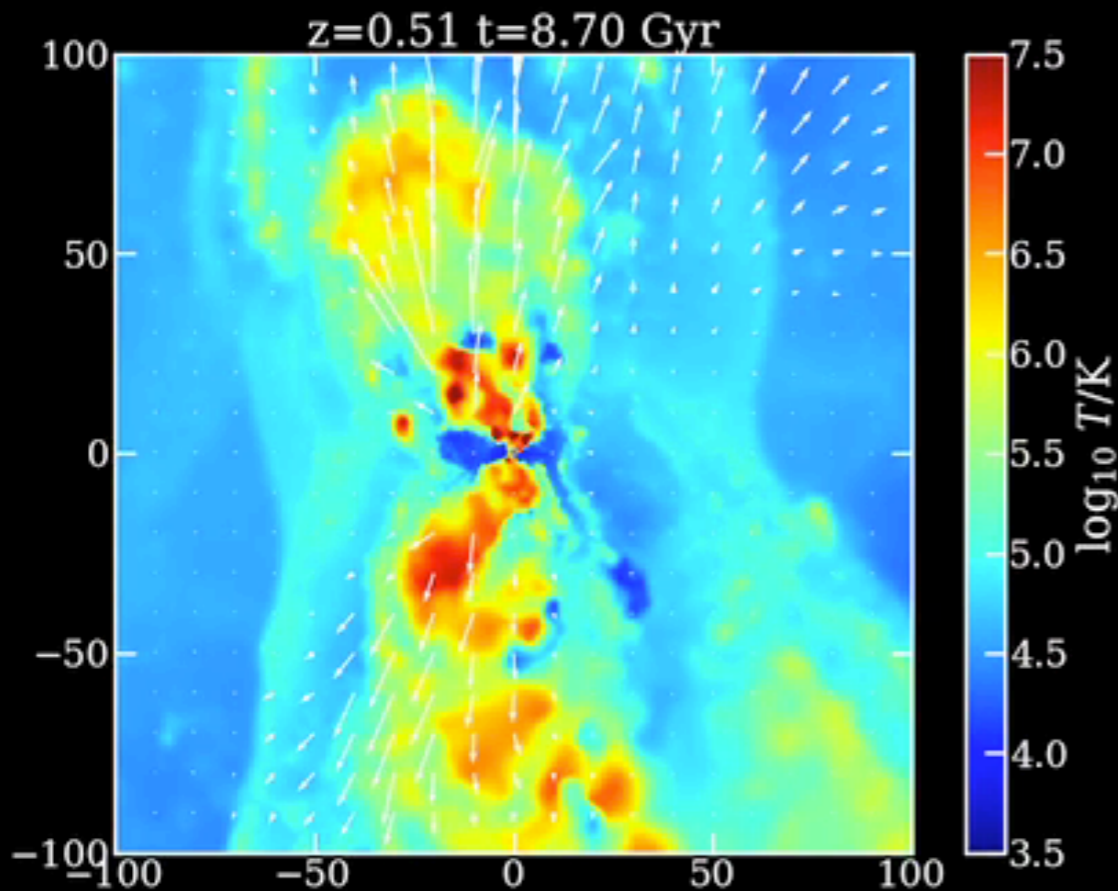
Controlled experiments on the dependence of galaxy properties on host halo assembly history

Pontzen, Tremmel+ 2017

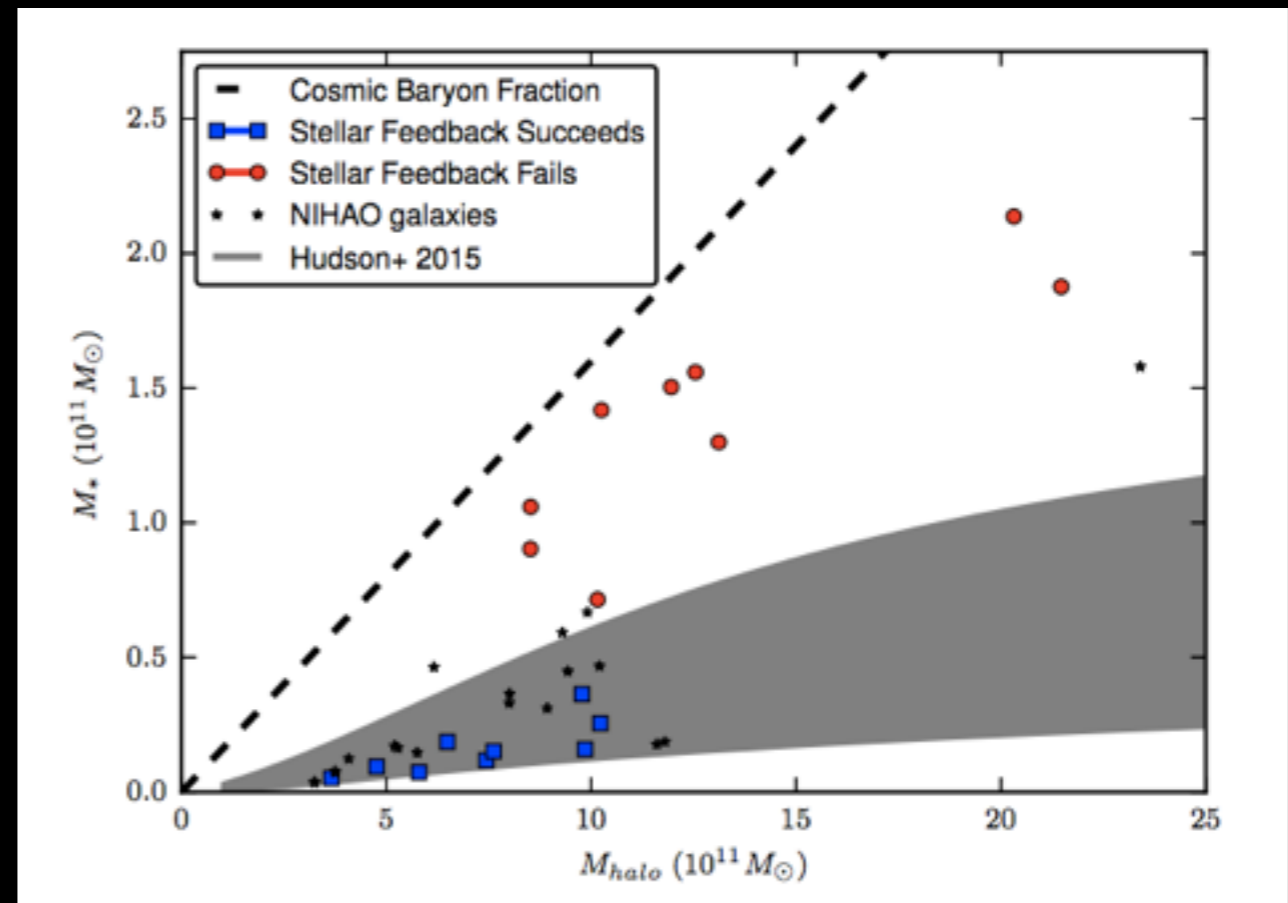


How to Quench a Galaxy

Feedback from Supernovae driven winds efficient only in low mass galaxies



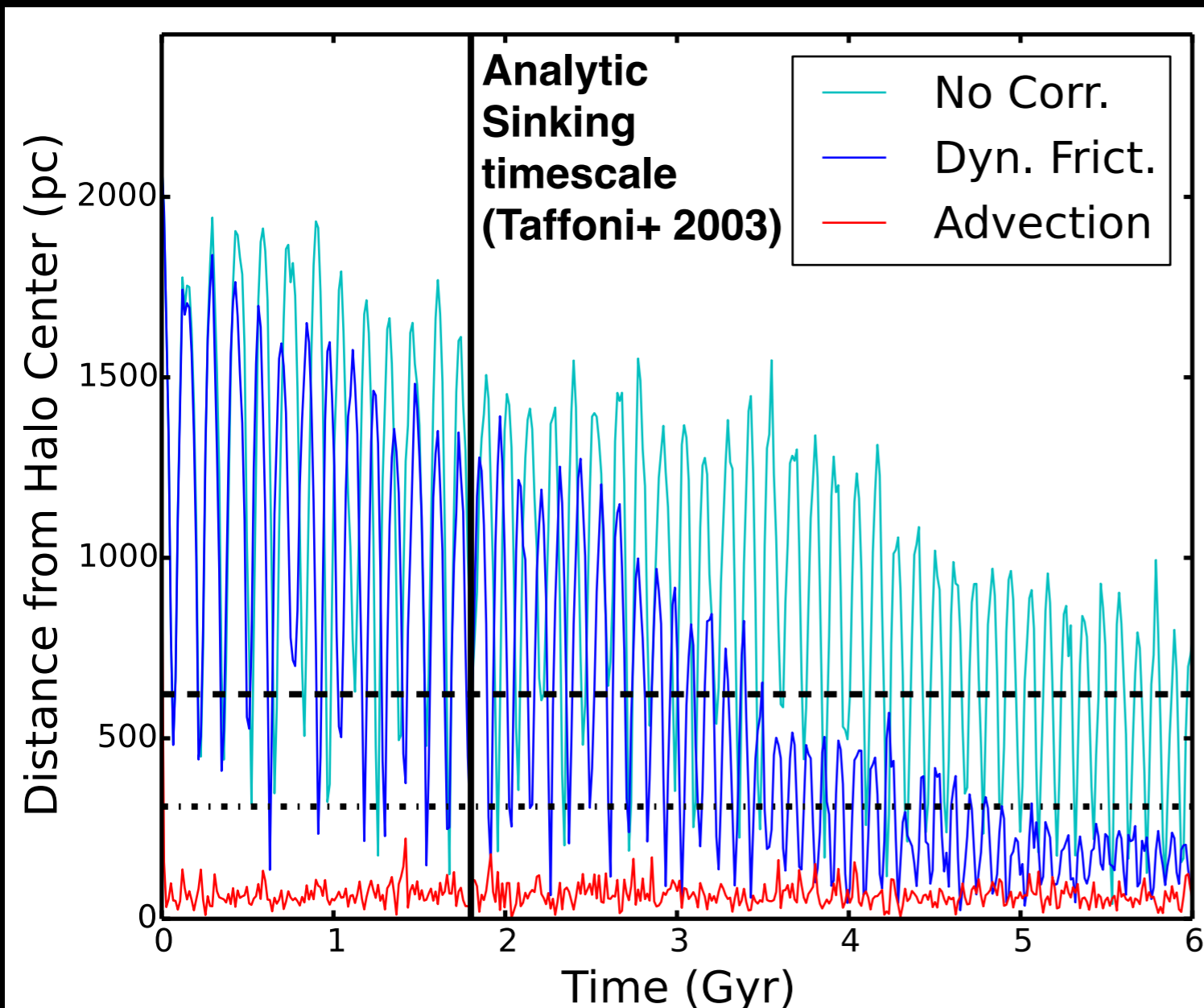
Movie courtesy A. Pontzen



Keller+ 2016

SMBH Sub-Grid Physics

Realistic SMBH Dynamical Evolution



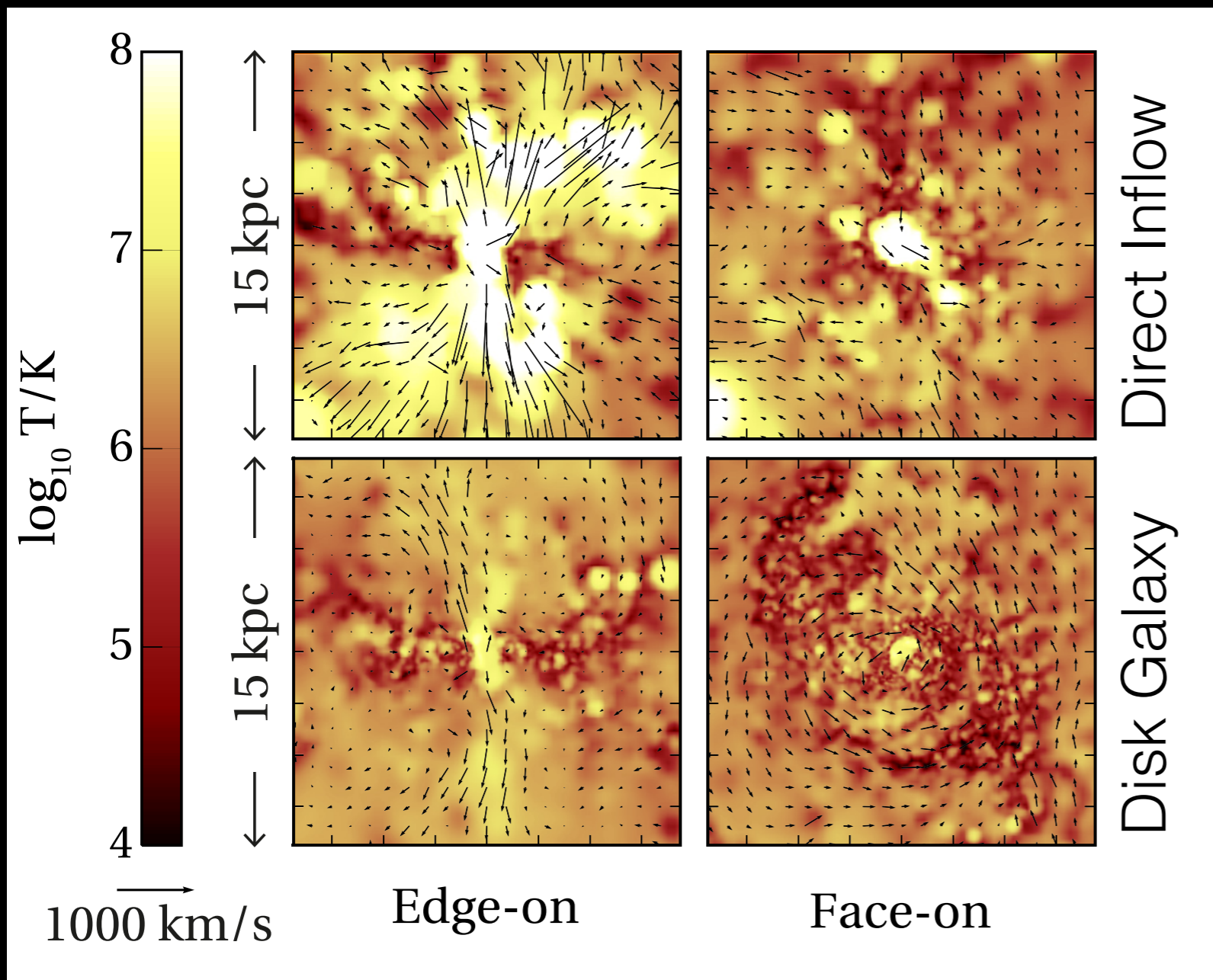
- Accurately follow the orbital evolution of SMBHs down to sub-kpc scales.
- Orbital evolution a prediction that naturally samples the underlying kinematics of host galaxy

Tremmel+ 2015
arxiv.org/abs/1501.07609

See also Hirschmann+ 2014

SMBH Sub-Grid Physics

Accretion that Accounts for Angular Momentum

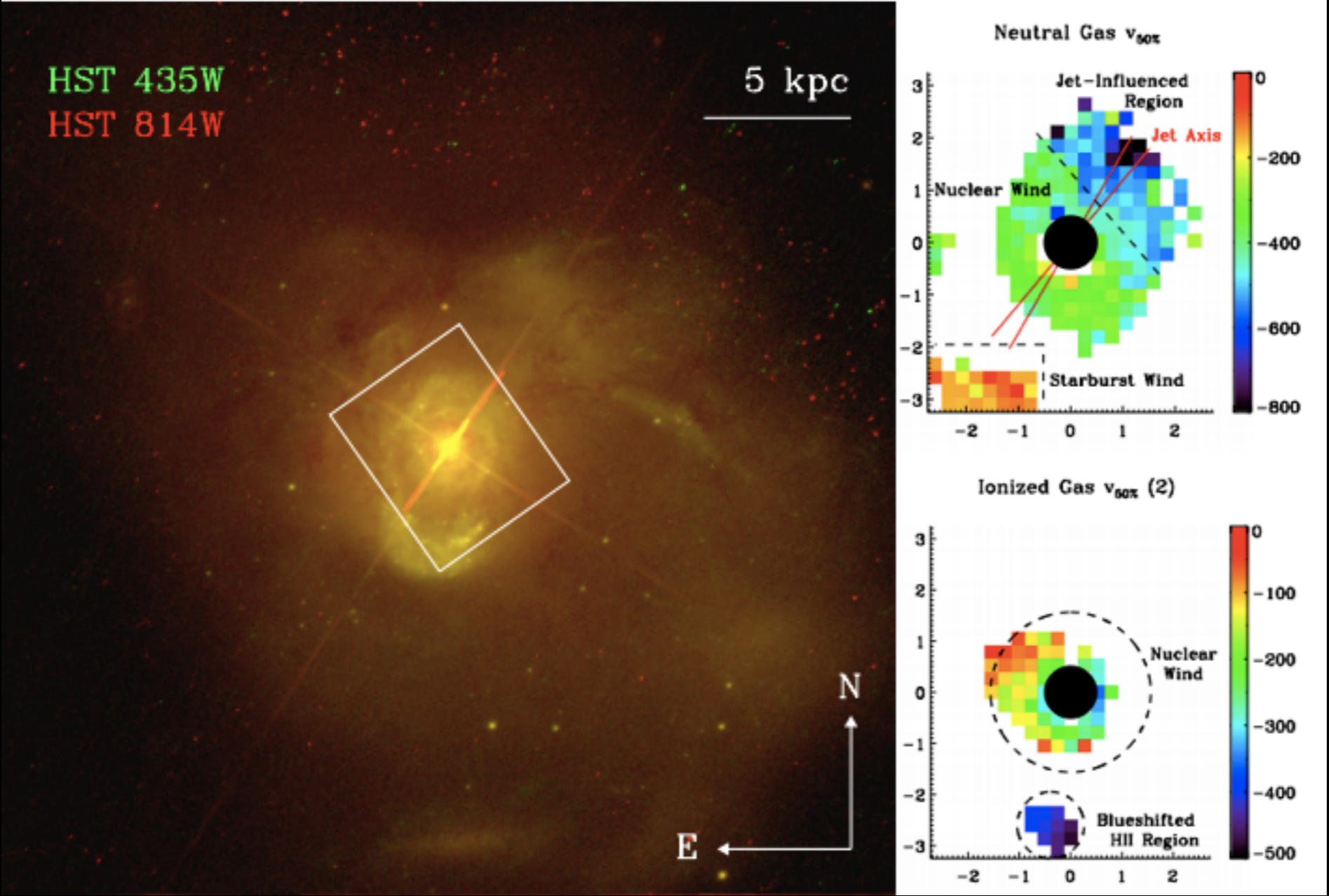


- Account for Angular Momentum Support
Tremmel+ 2017
- Estimate the effective potential due to rotation at resolved scales
- Modify the Bondi radius accordingly

Pontzen, Tremmel+ 2017

How to Quench a Galaxy

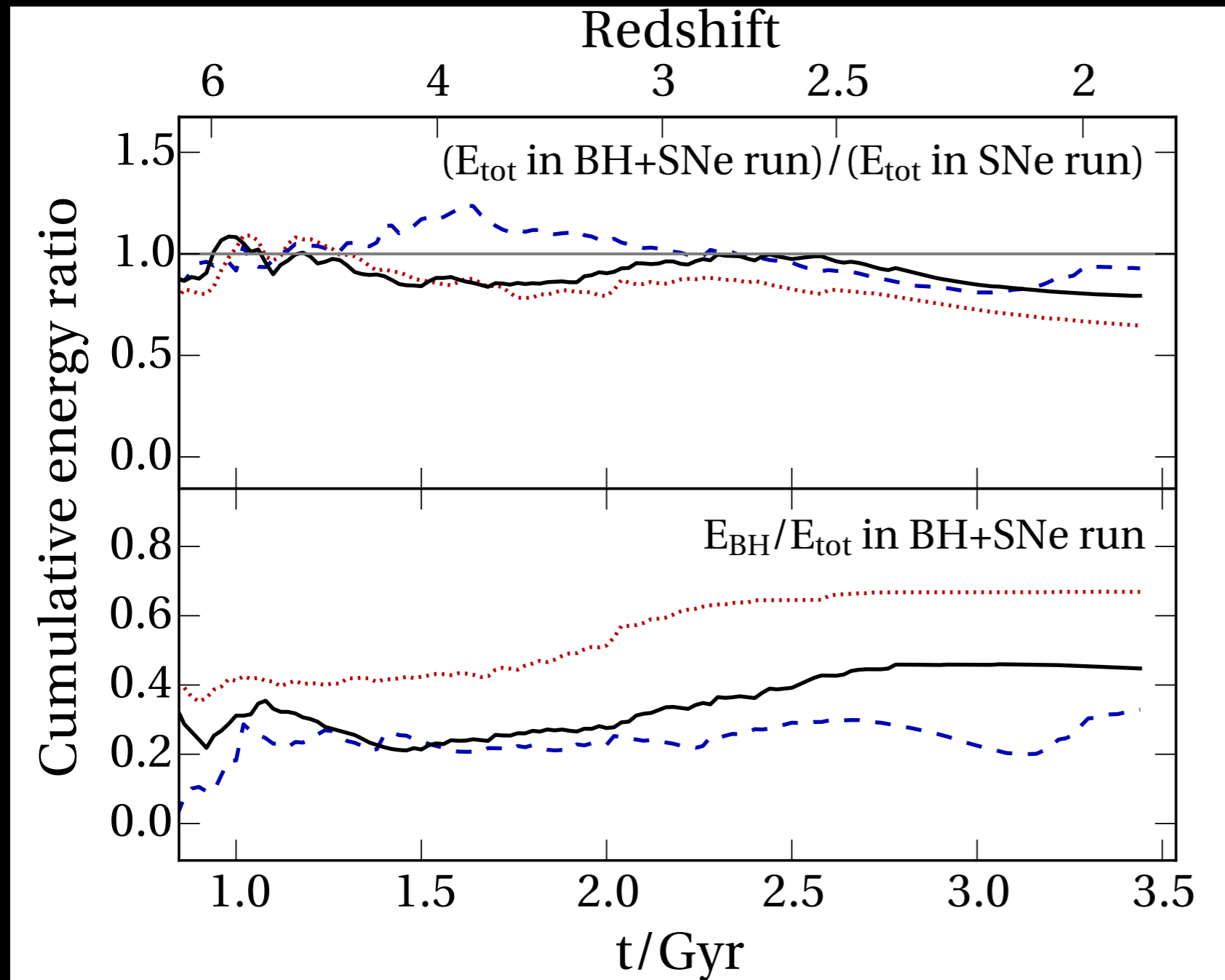
AGN can drive powerful winds in massive galaxies



Rupke & Veilleux 2011

To Quench or Not to Quench

Its not how much energy you get, but how it is distributed



SN and AGN+SN simulations have similar **total** feedback energy output

Quenching requires the **focused feedback** imparted by AGN

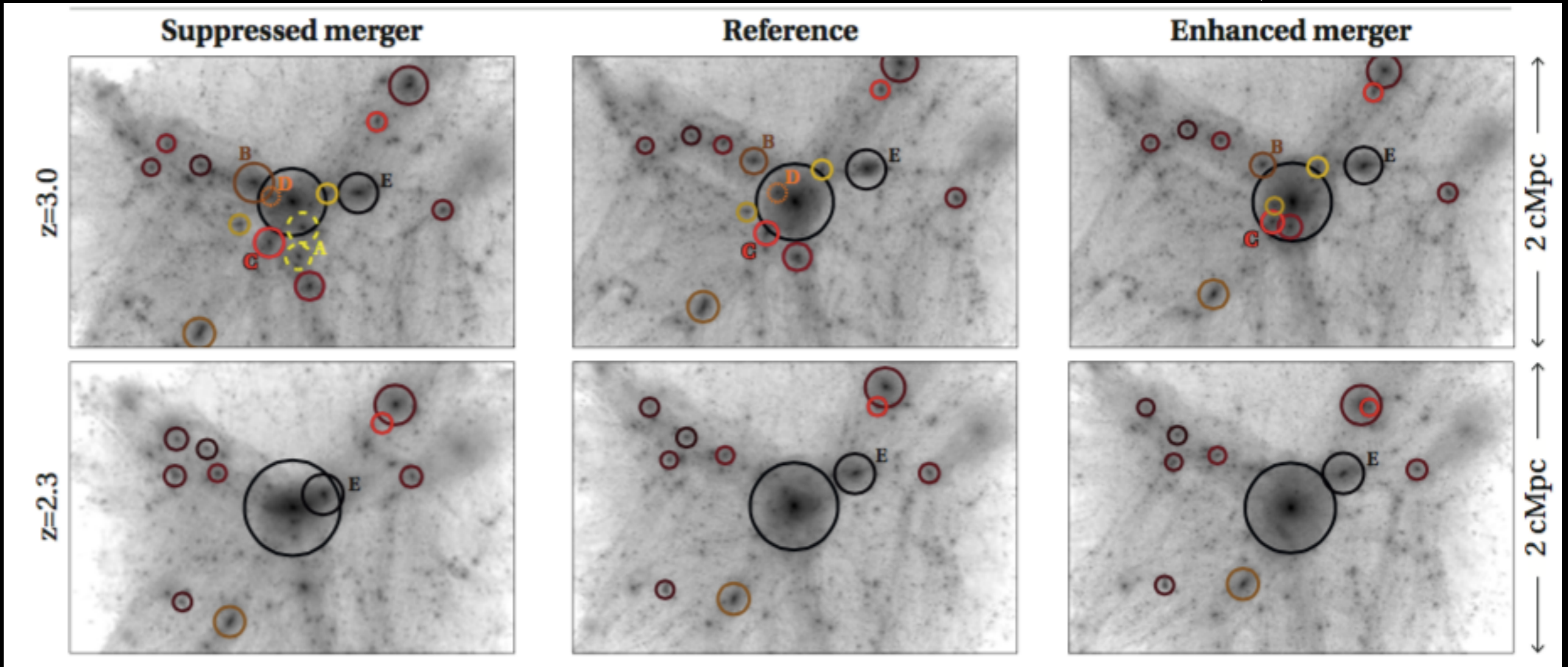
Enhanced
Suppressed

Pontzen, Tremmel+ 2017

Genetically Modified Galaxies

Controlled experiments on the dependence of galaxy properties on host halo assembly history

Pontzen, Tremmel+ 2017



1:10 at $z \sim 3$

1:5 at $z \sim 4$

2:3 at $z \sim 4.6$

