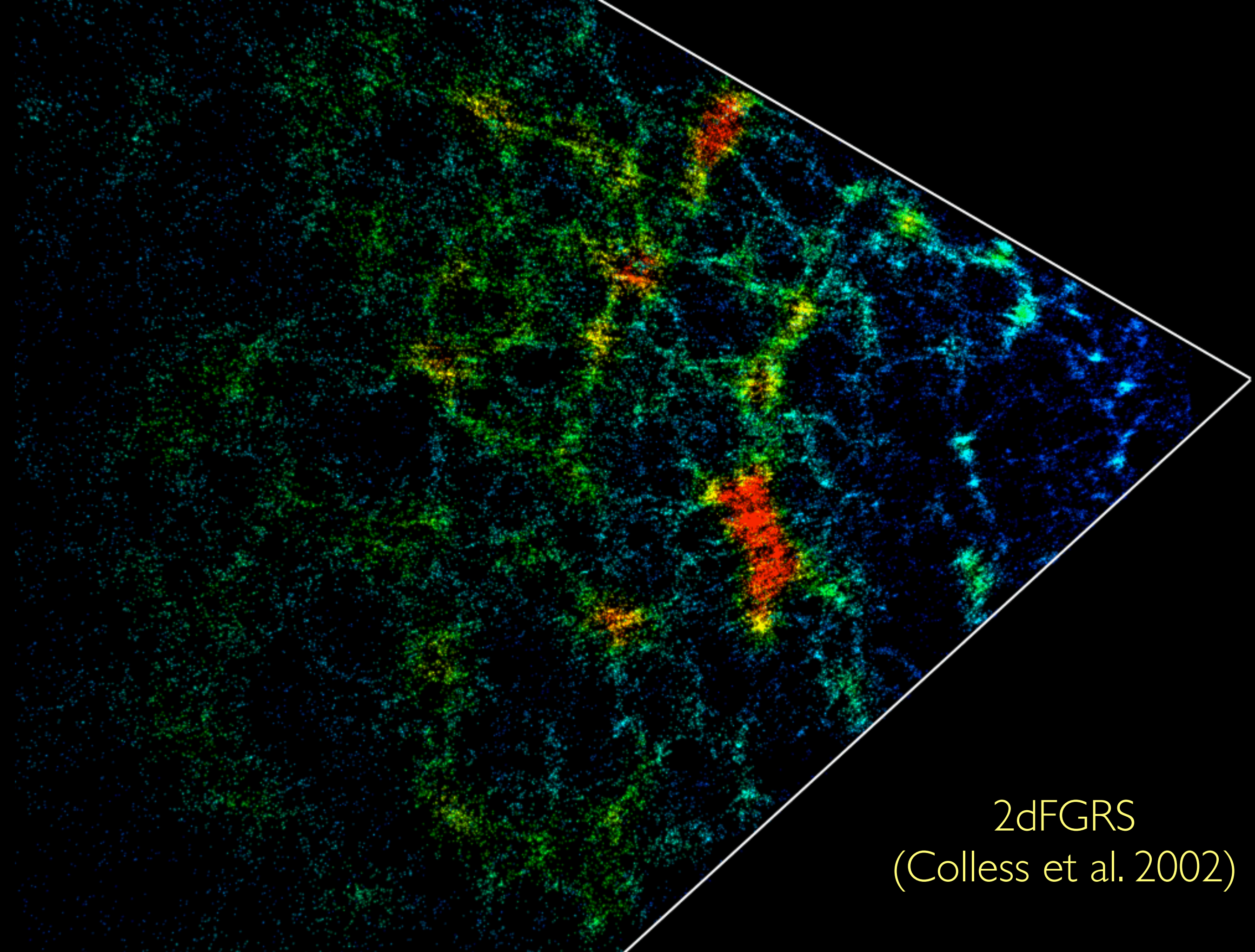


1.5 Gyr

New Simulations in Galaxy Evolution

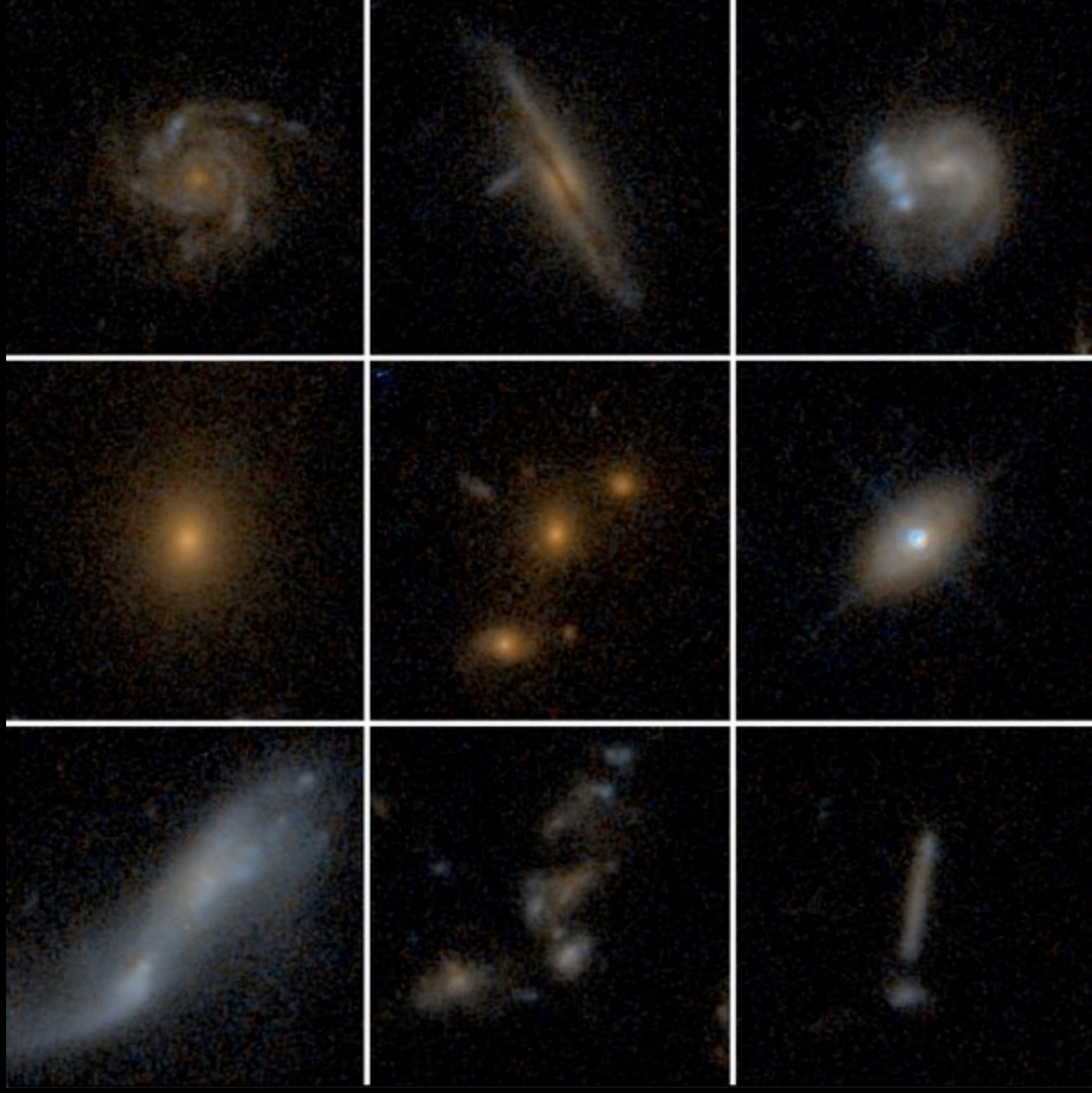
Darren Croton

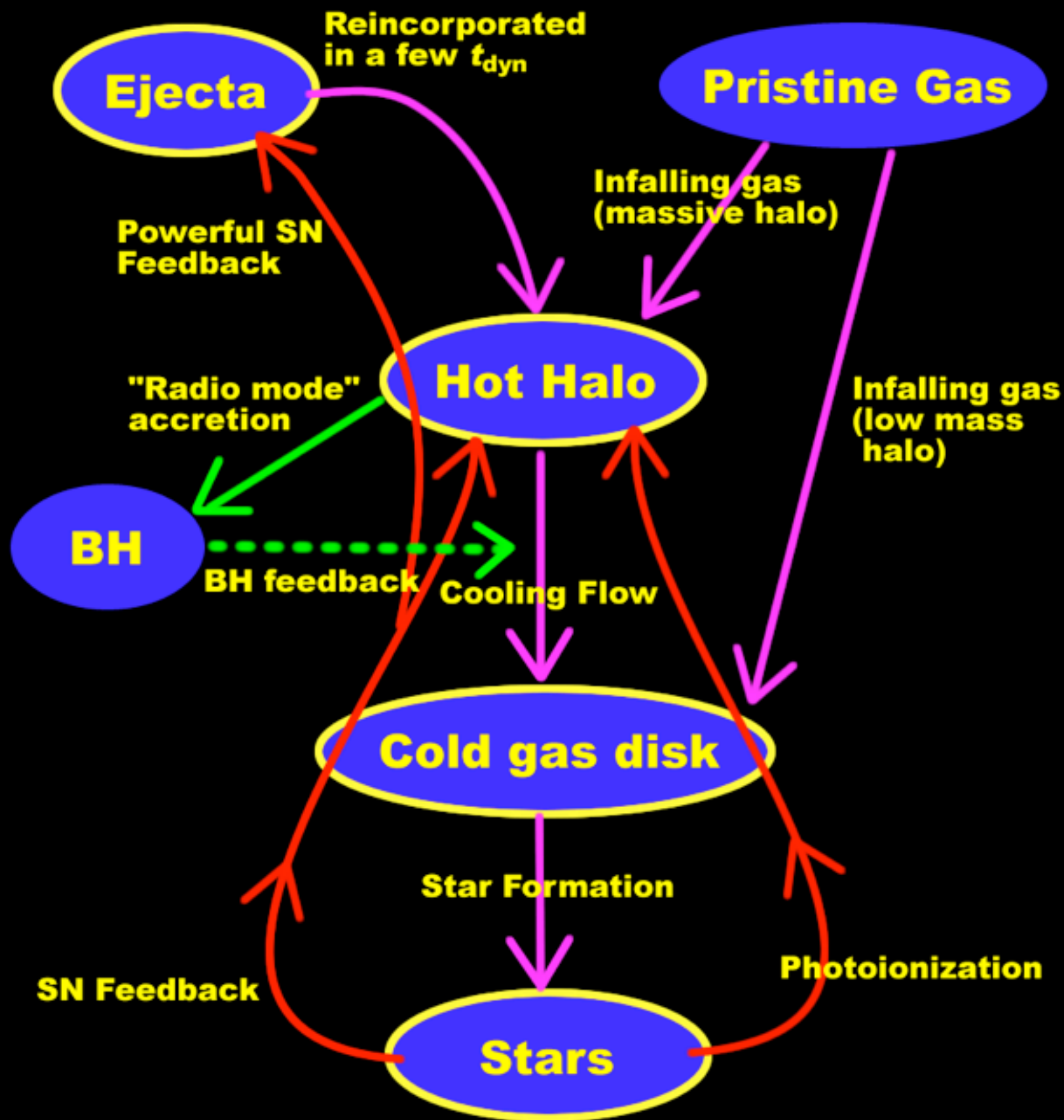
Centre for Astrophysics and Supercomputing
Swinburne University



2dFGRS
(Colless et al. 2002)

DEEP2





- Schmidt law star formation
- SFR dependent SN winds
- satellite gas stripping
- morphological transformation
- assembly through mergers
- starbursts through mergers
- Magorrian relation BH growth
- jet & bubble AGN feedback

morphological transformation

Quiescent star formation occurs in the disk

Burst star formation adds to the bulge

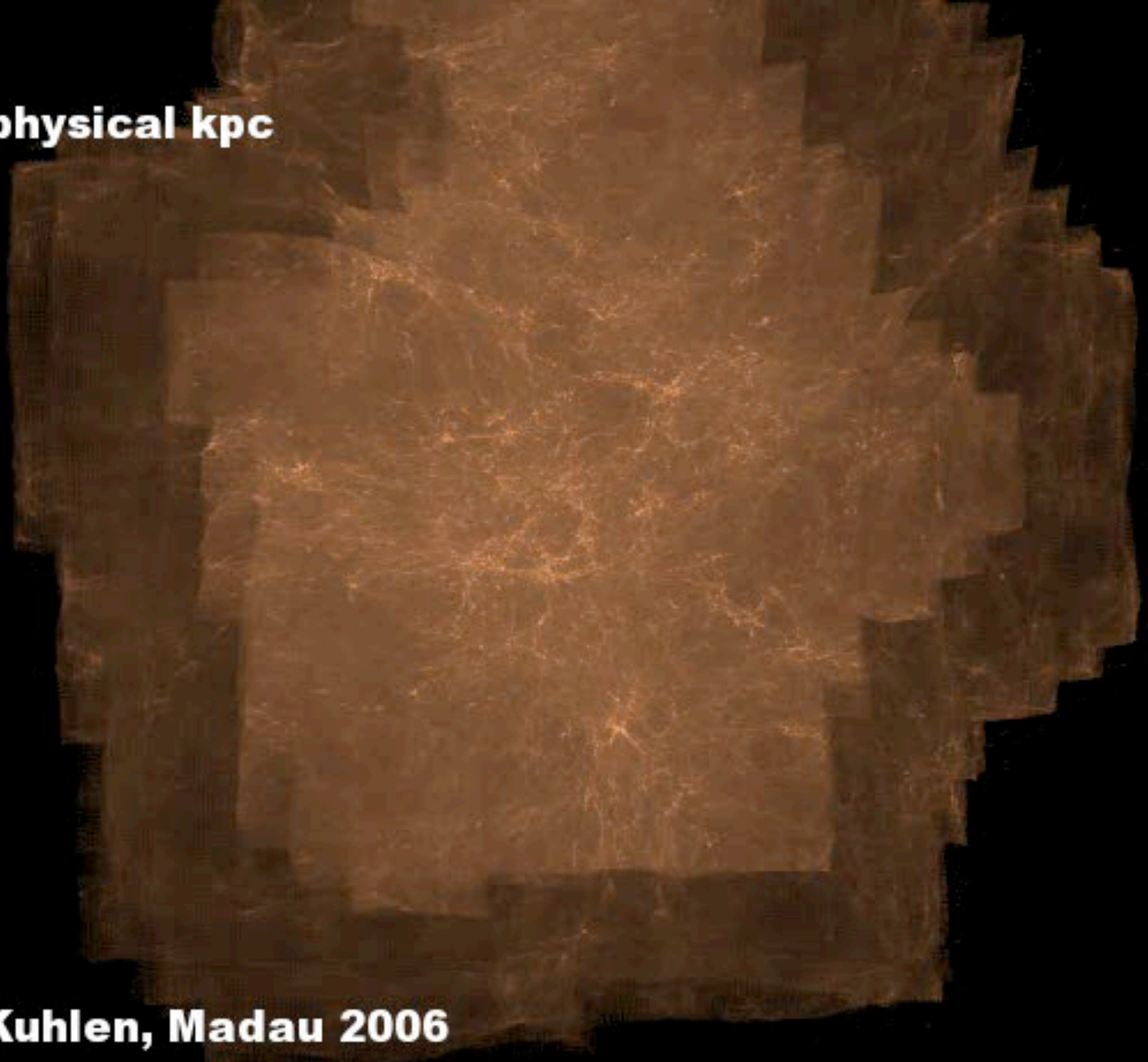
Disk instabilities move disk stars to the bulge

Minor galaxy mergers add satellite stars to the disk

Major galaxy mergers move disk stars to the bulge

$z=11.9$

800 x 600 physical kpc

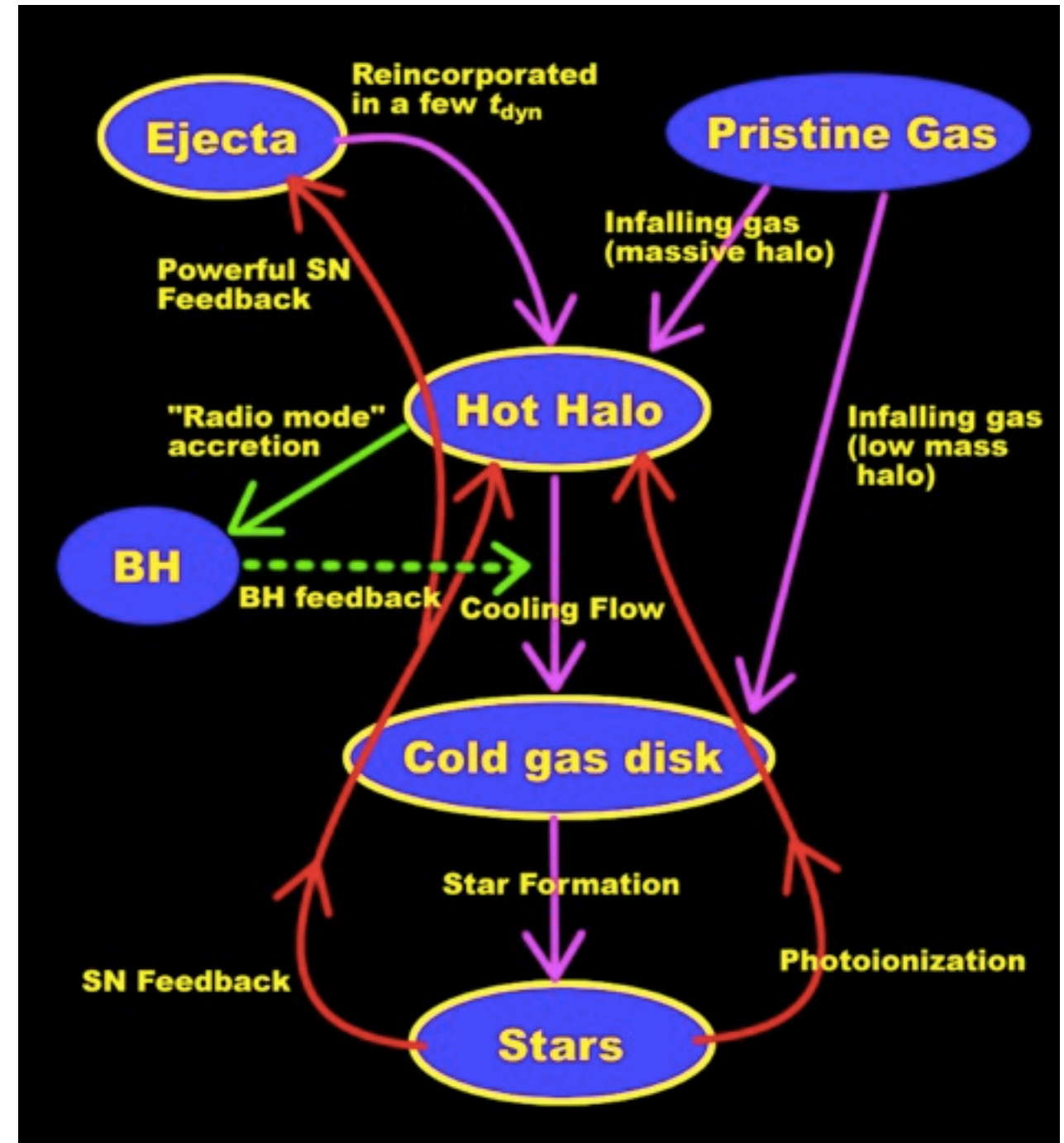
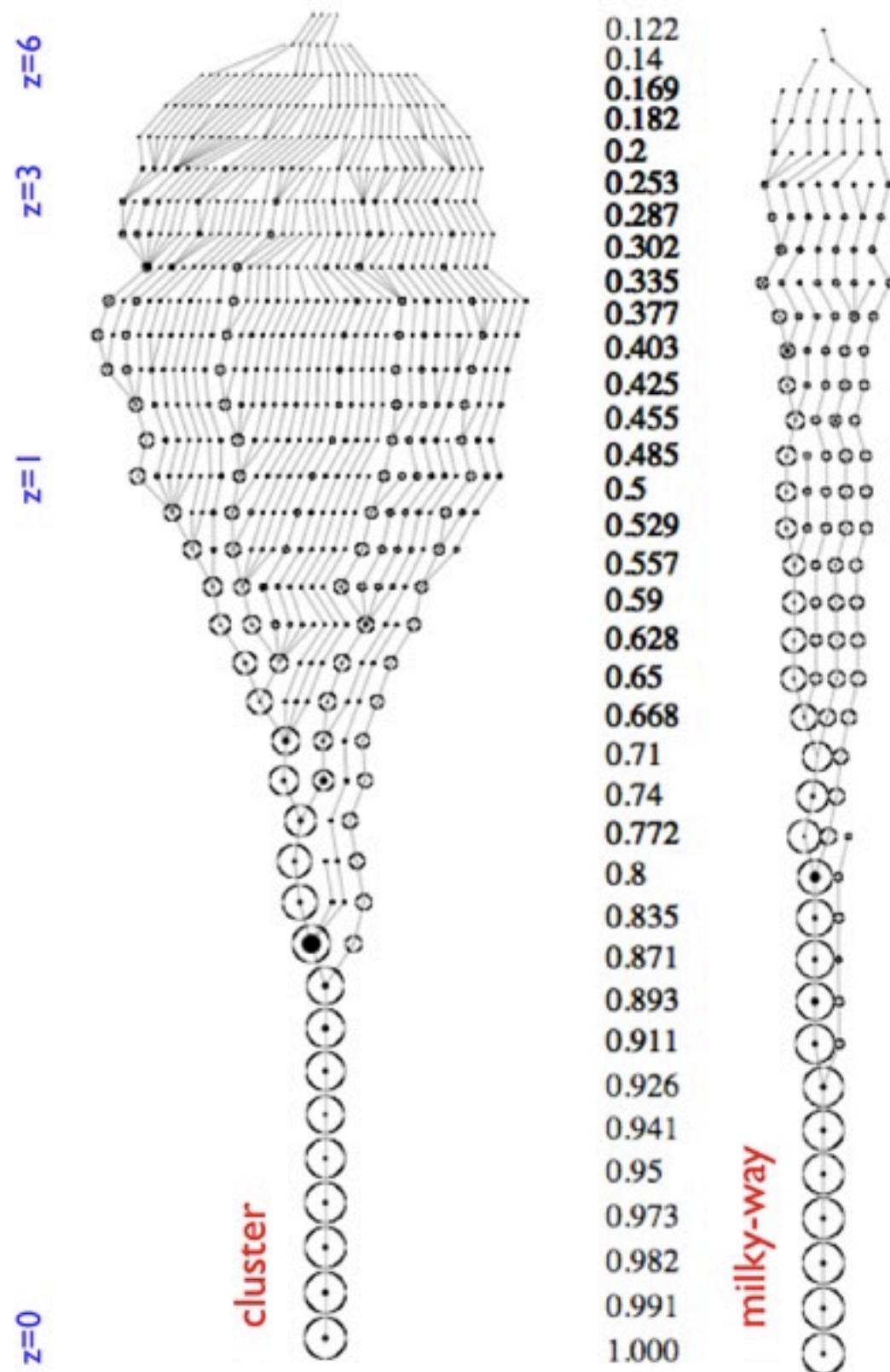


Diemand, Kuhlen, Madau 2006

Numerical Simulation

+

Analytic Simulation

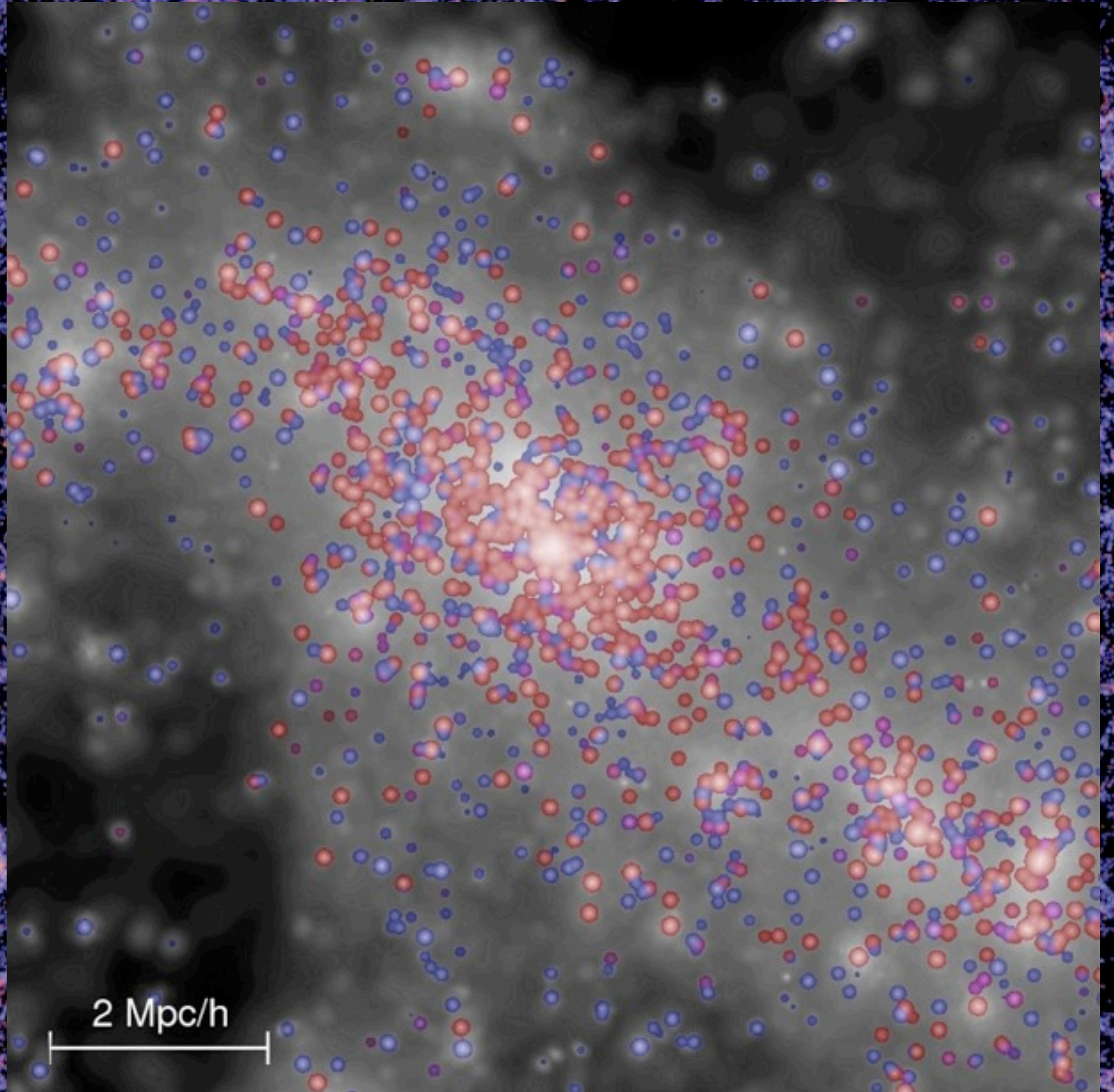


$z=0$ dark matter

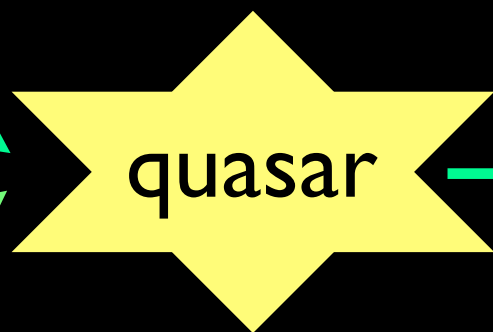
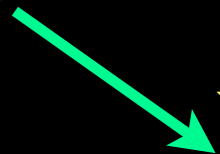
125 Mpc/h

The image displays a dense, interconnected network of dark matter filaments and clusters at redshift z=0. The filaments are represented by thin, branching lines of purple and blue, while the clusters are shown as brighter, more concentrated regions of yellow and orange. A horizontal scale bar with vertical end caps is positioned in the upper-middle section, labeled "125 Mpc/h".

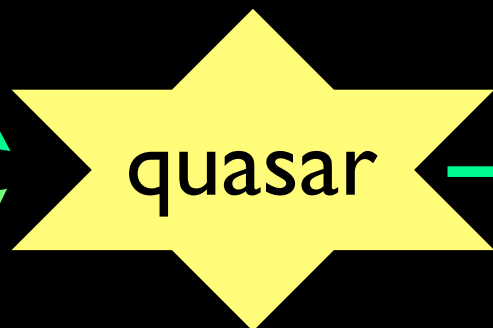
$z=0$ galaxy light



$z > 1$: Quasar Epoch



$z > 1$: Quasar Epoch



infalling gas, hot
halo build-up,
cooling gas

$z < 1$: hierarchical
growth



black hole accretion toy model (radio mode)

assumption: the hot gas around the black hole
is static and has uniform density

assumption: **maximal cooling flow** - at the
Bondi radius, the gas density is determined by
equating the cooling time to the free fall time

$$\dot{m}_{\text{Bondi}} = 2.5\pi G^2 \frac{m_{\text{BH}}^2 \rho_0}{c_s^3}$$

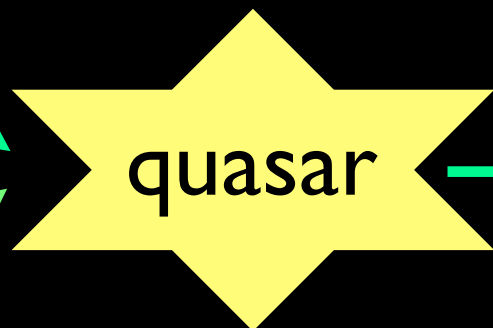
$$\frac{2r_{\text{Bondi}}}{c_s} \approx \frac{4Gm_{\text{BH}}}{V_{\text{vir}}^3} = \frac{3}{2} \frac{\bar{\mu} m_p kT}{\rho_g(r_{\text{Bondi}}) \Lambda(T, Z)}$$

$$\rho_0 = \rho_g(r_{\text{Bondi}}) = \frac{3\mu m_p}{8G} \frac{kT}{\Lambda} \frac{V_{\text{vir}}^3}{m_{\text{BH}}}$$

$$\dot{m}_{\text{Bondi}} \approx G\mu m_p \frac{kT}{\Lambda} m_{\text{BH}}$$

Croton et al. 2006

$z > 1$: Quasar Epoch

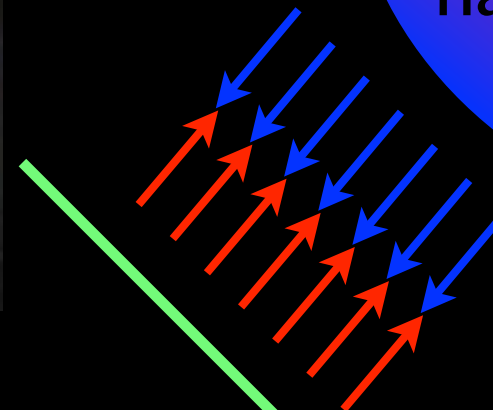
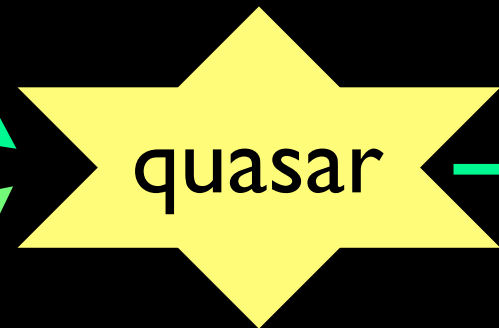


infalling gas, hot
halo build-up,
cooling gas

$z < 1$: hierarchical
growth

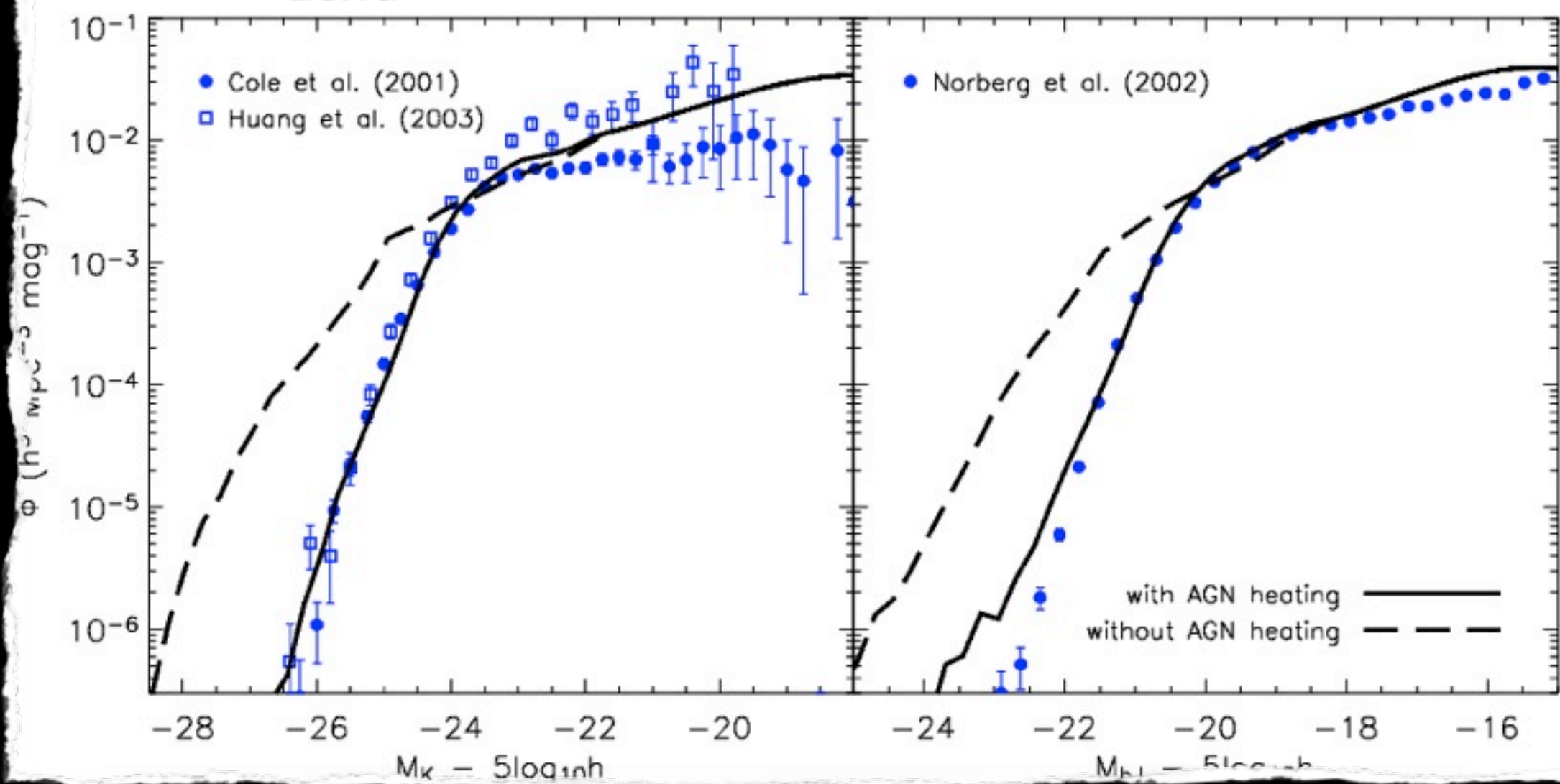


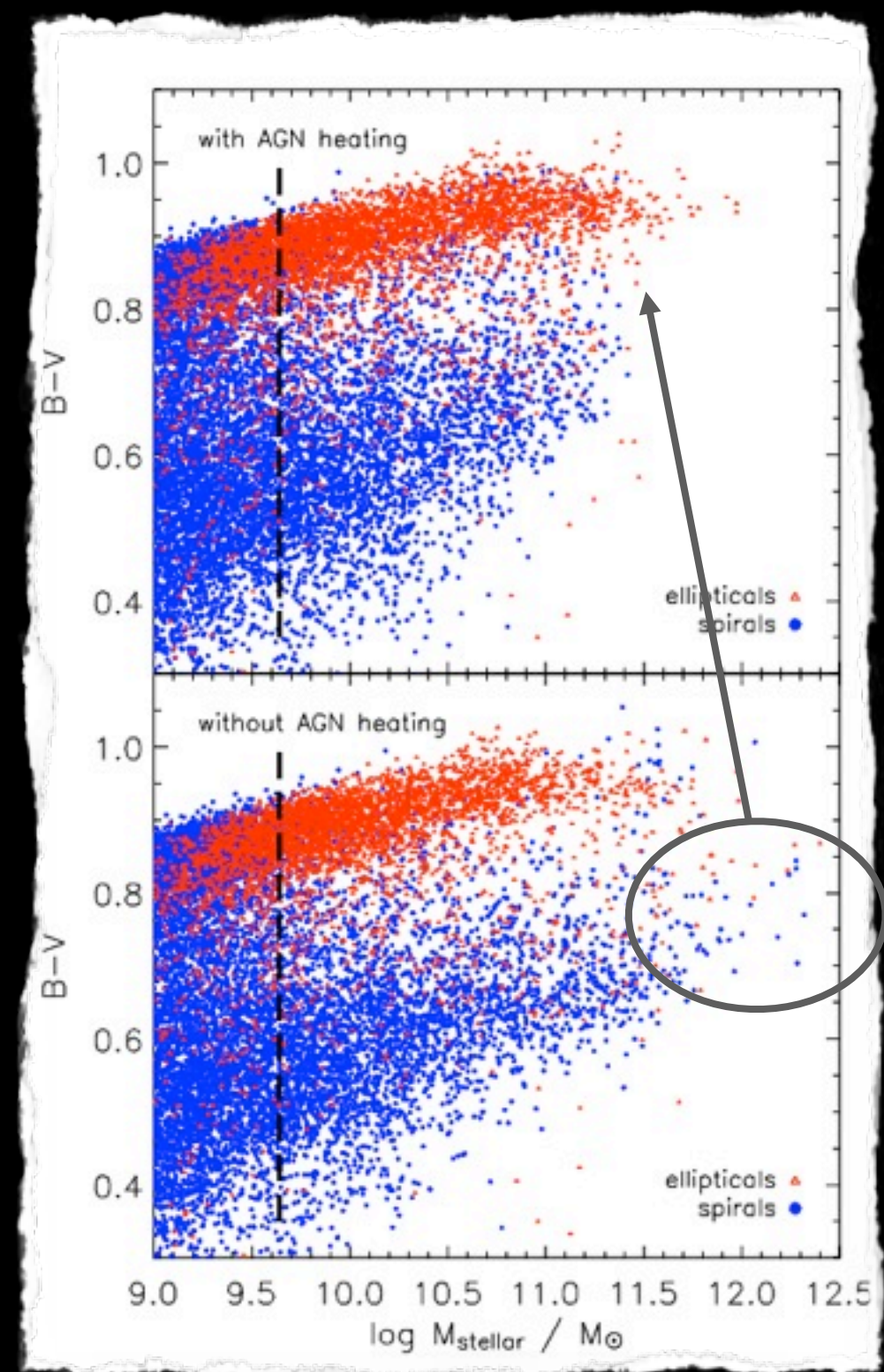
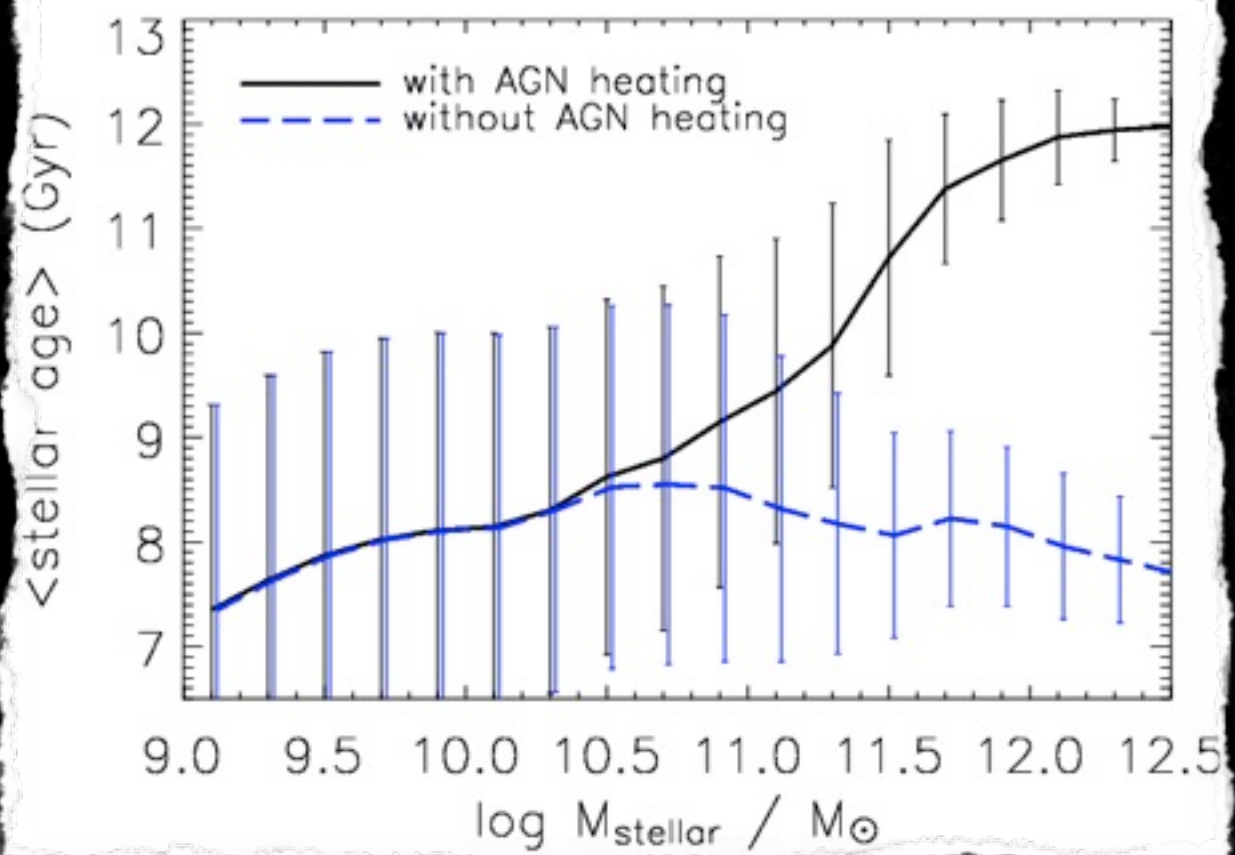
$z > 1$: Quasar Epoch



$z < 1$: Radio Mode







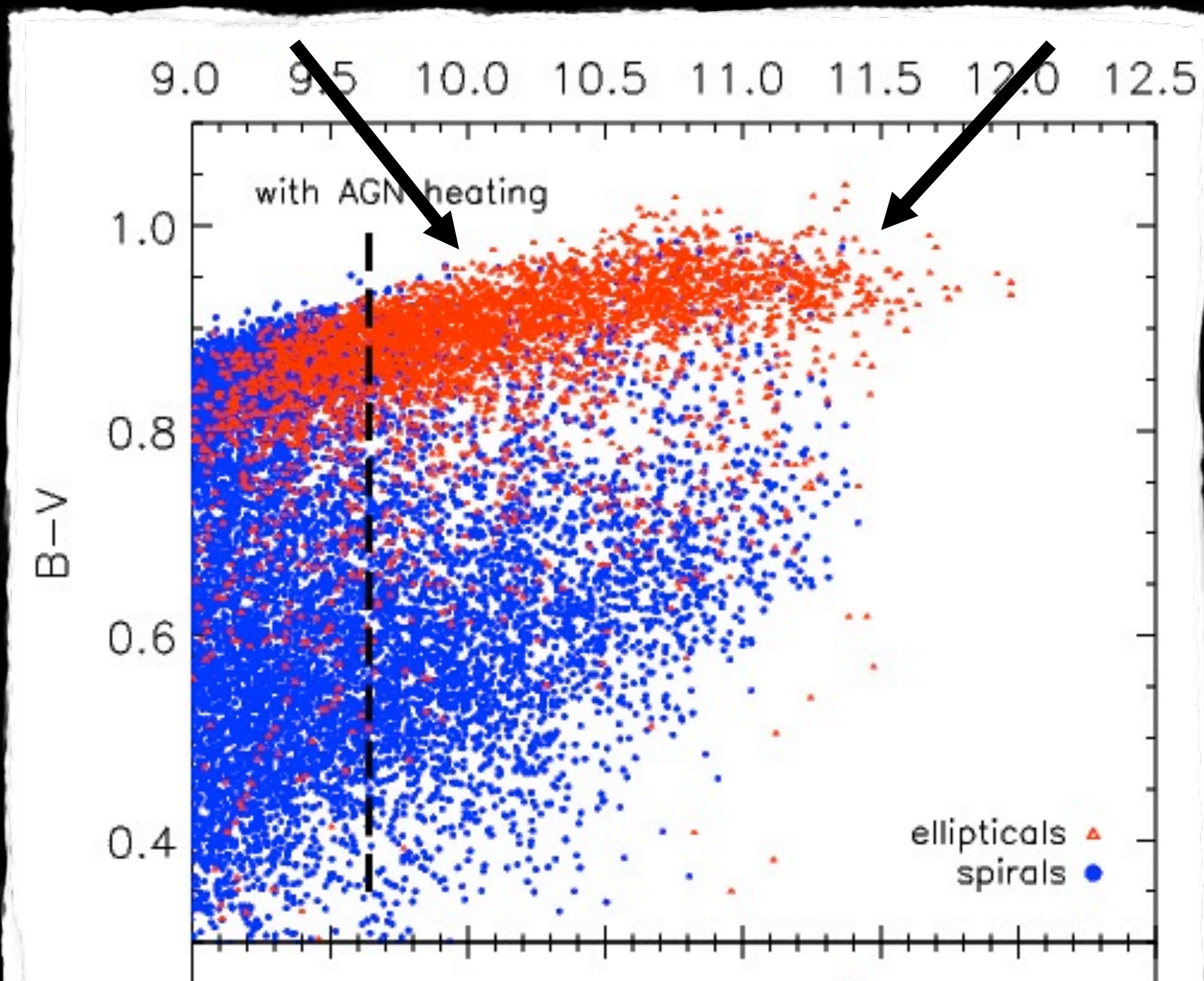
Croton et al. 2006

	When?	Trigger?	Feeding?	Consequence?
Quasar Mode	at early times	gas rich mergers	cold gas	BH growth, sets properties of ellipticals
Radio Mode	at late times	BH & hot halo large enough?	hot gas? stellar winds?	suppresses cooling gas, shuts down SF

Importantly, some kind of quenching is needed to get the low-z morphologies right

environment quenching
(satellite galaxies)

AGN quenching
(central galaxies)



GALAXY ZOO

SYDNEY 2013



RUNNING RINGS AROUND

URANUS

SYDNEY 2013

CLEARWAY
SPECIAL EVENTS
1AM TO 10AM
22 SEPTEMBER 2003

BLACKMORES

asics asics

110

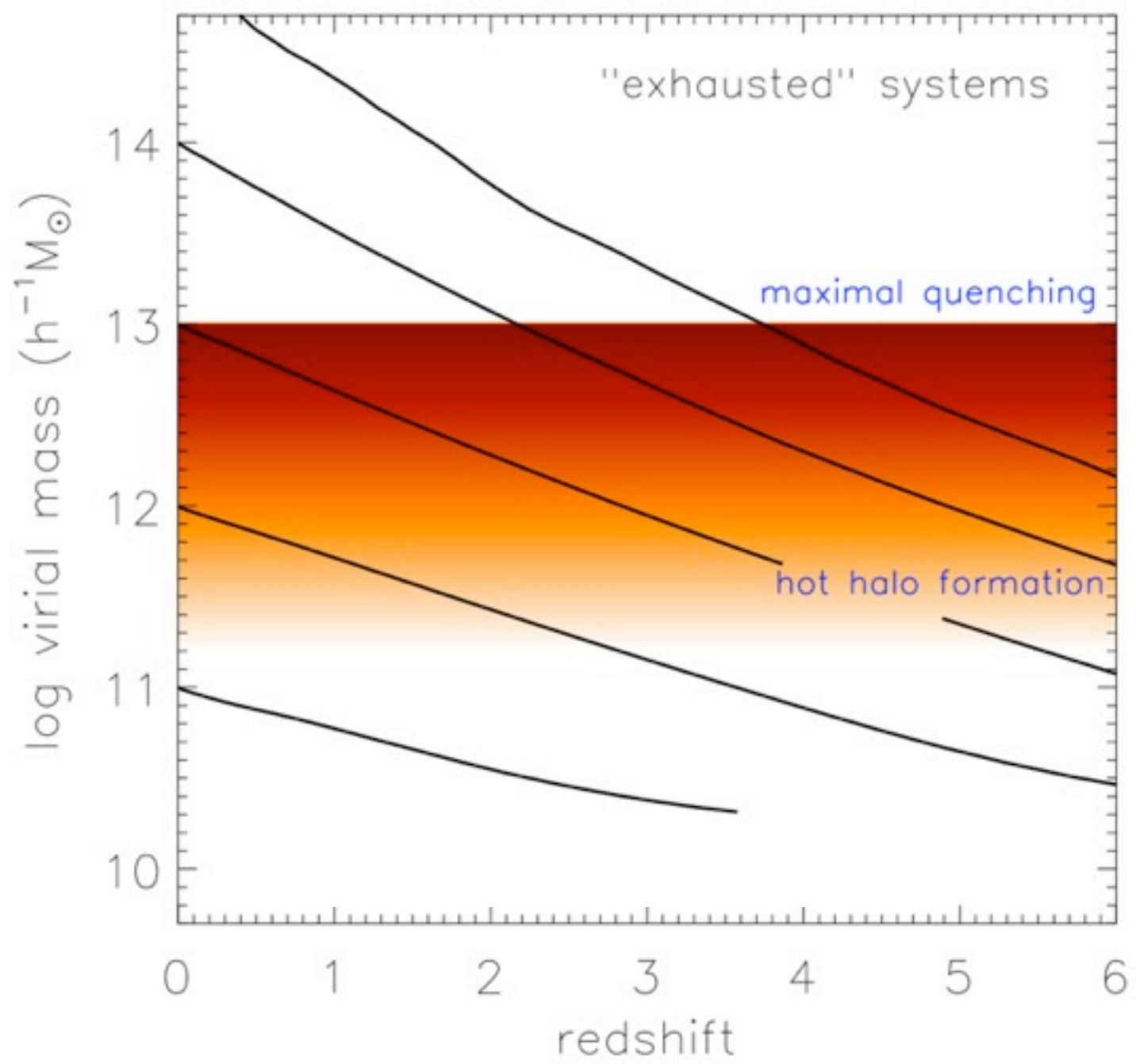
110

The Sydney Morning Herald

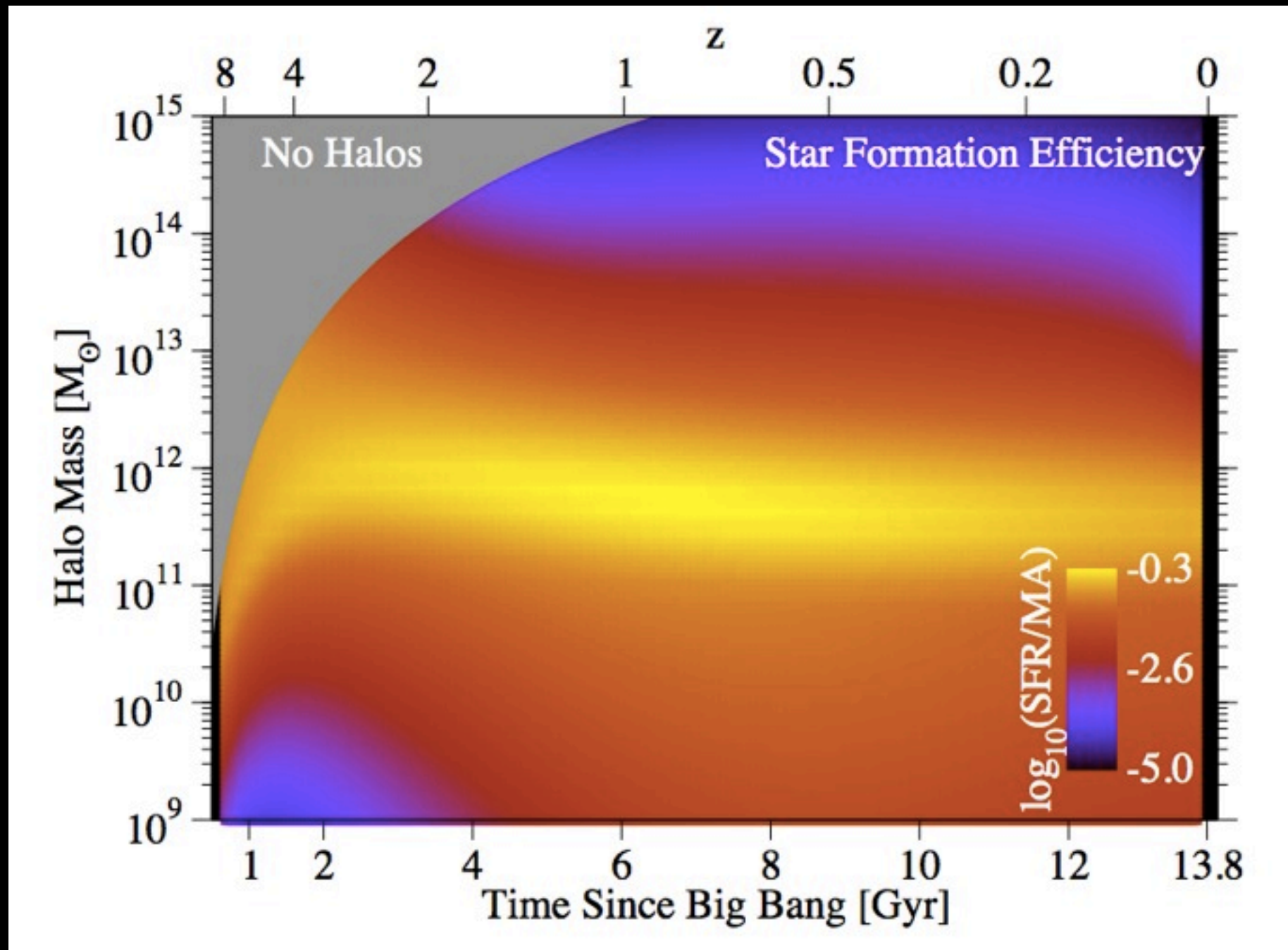


Amanda Bauer, Kelly Borden, Darren Croton, Sara Ellison,
Amit Kapadia, Amy Kimbal, Naomi McClure-Griffiths, Bob
Nichol, Jenna Ryon, Chris Snyder, Christopher Usher,
Anna Weigel.

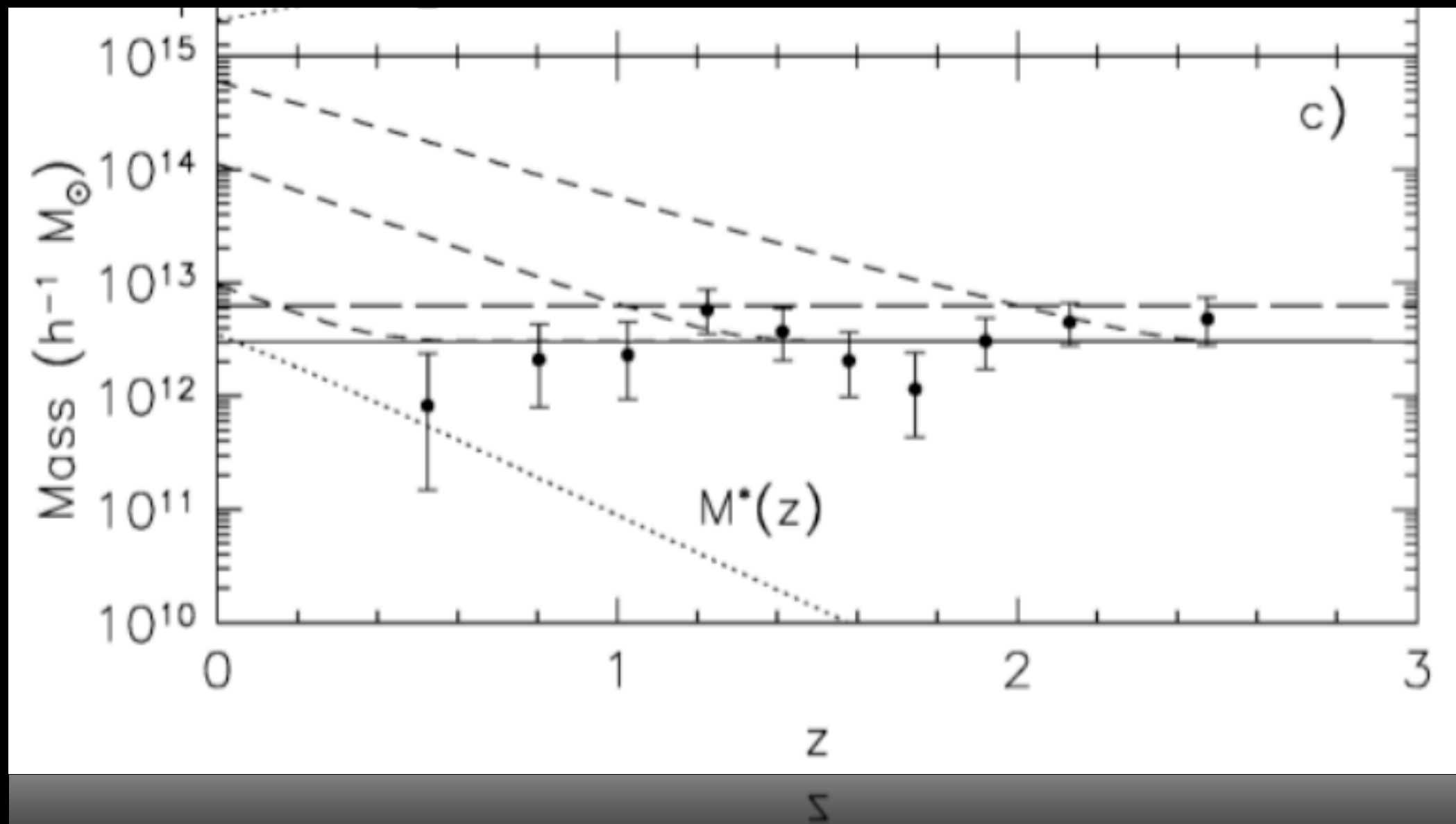




Galaxies



Quasars



The simplest model of galaxy formation I: A formation history model of galaxy stellar mass growth

Simon J. Mutch^{1,2*}, Darren J. Croton² and Gregory B. Poole¹

¹*School of Physics, The University of Melbourne, Parkville, Victoria 3010, Australia*

²*Centre for Astrophysics & Supercomputing, Swinburne University of Technology, PO Box 218, Hawthorn, VIC 3122, Australia*

See also:

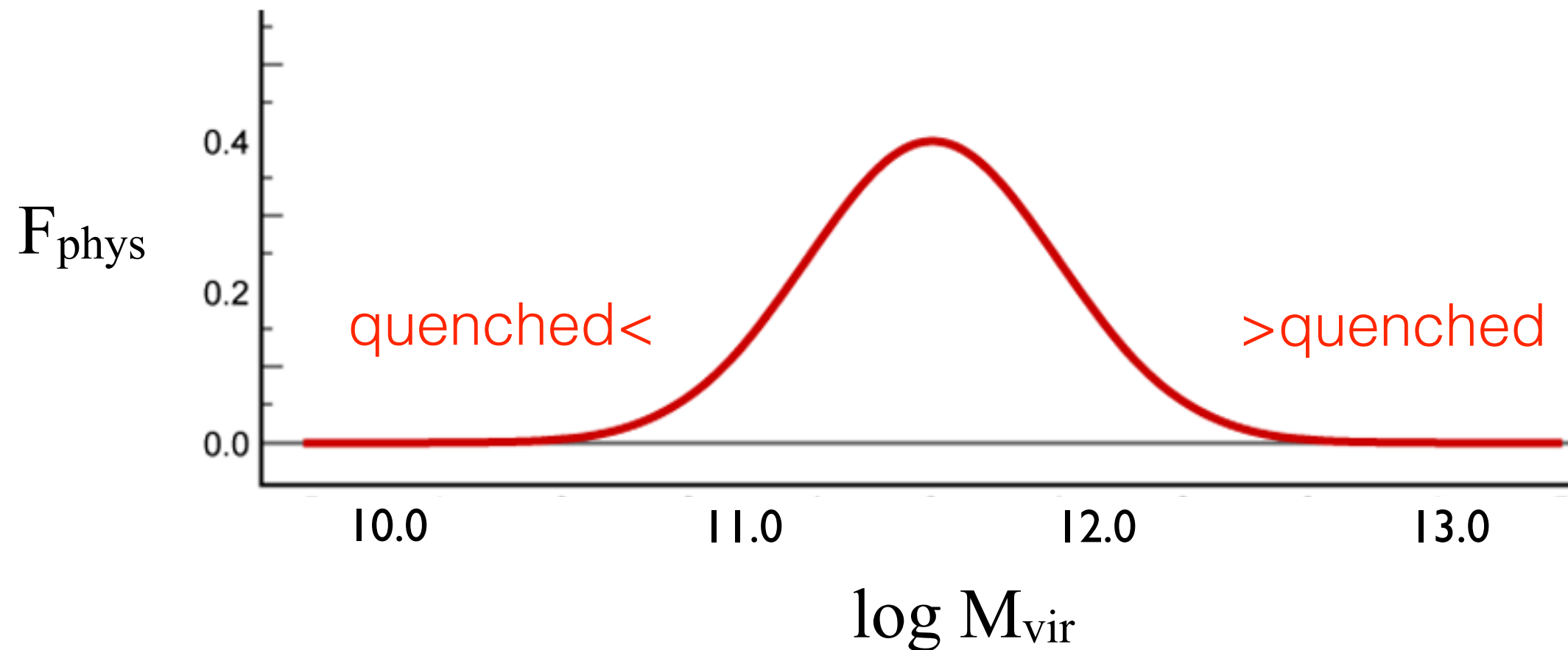
Peng et al. 2010 (Schechter function)

Driver et al. 2013 (morphology/SFR)

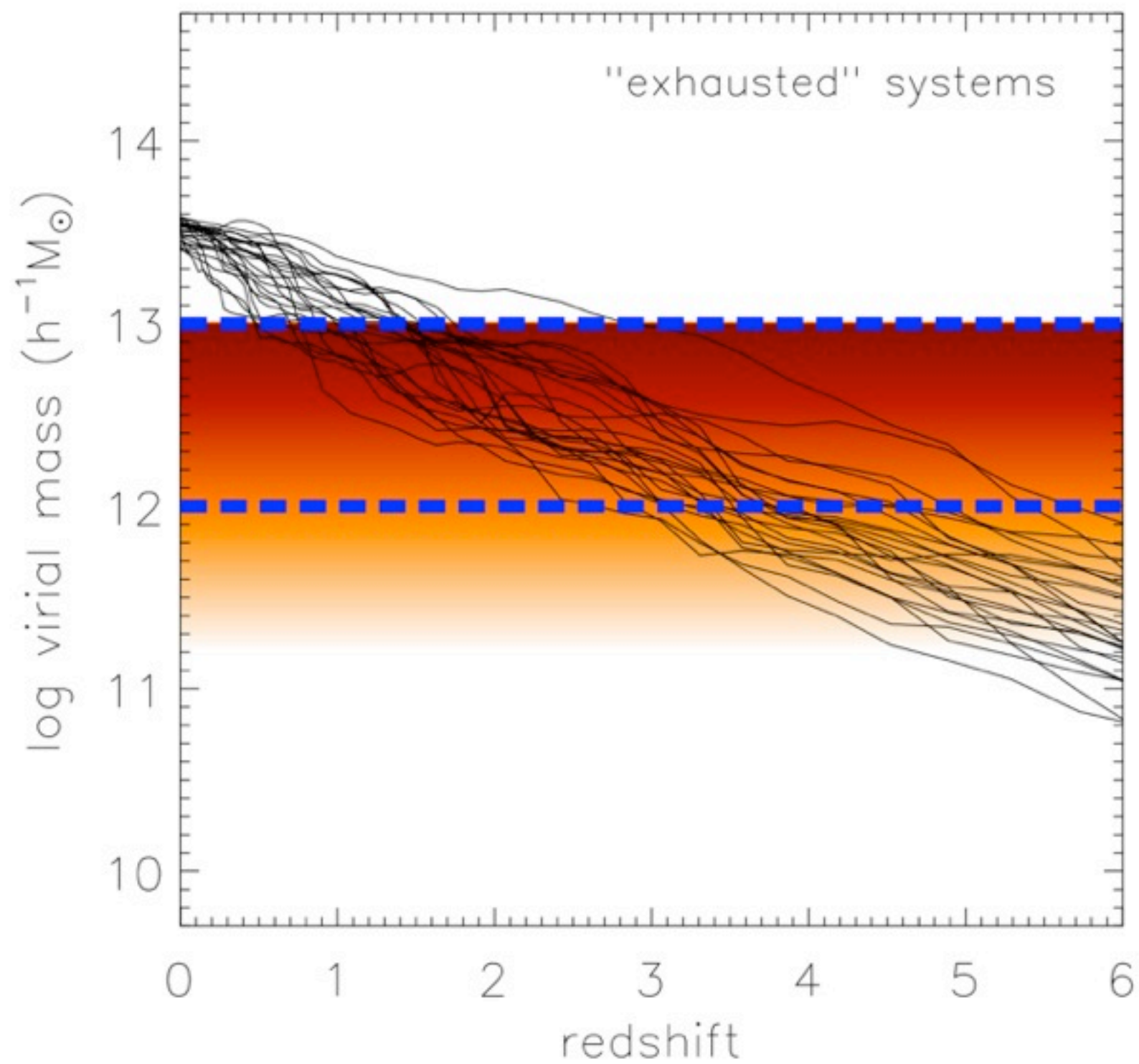


Mutch, Croton & Poole 2013

$$\dot{M}_* = f_b \frac{dM_{\text{vir}}}{dt} F_{\text{phys}}$$



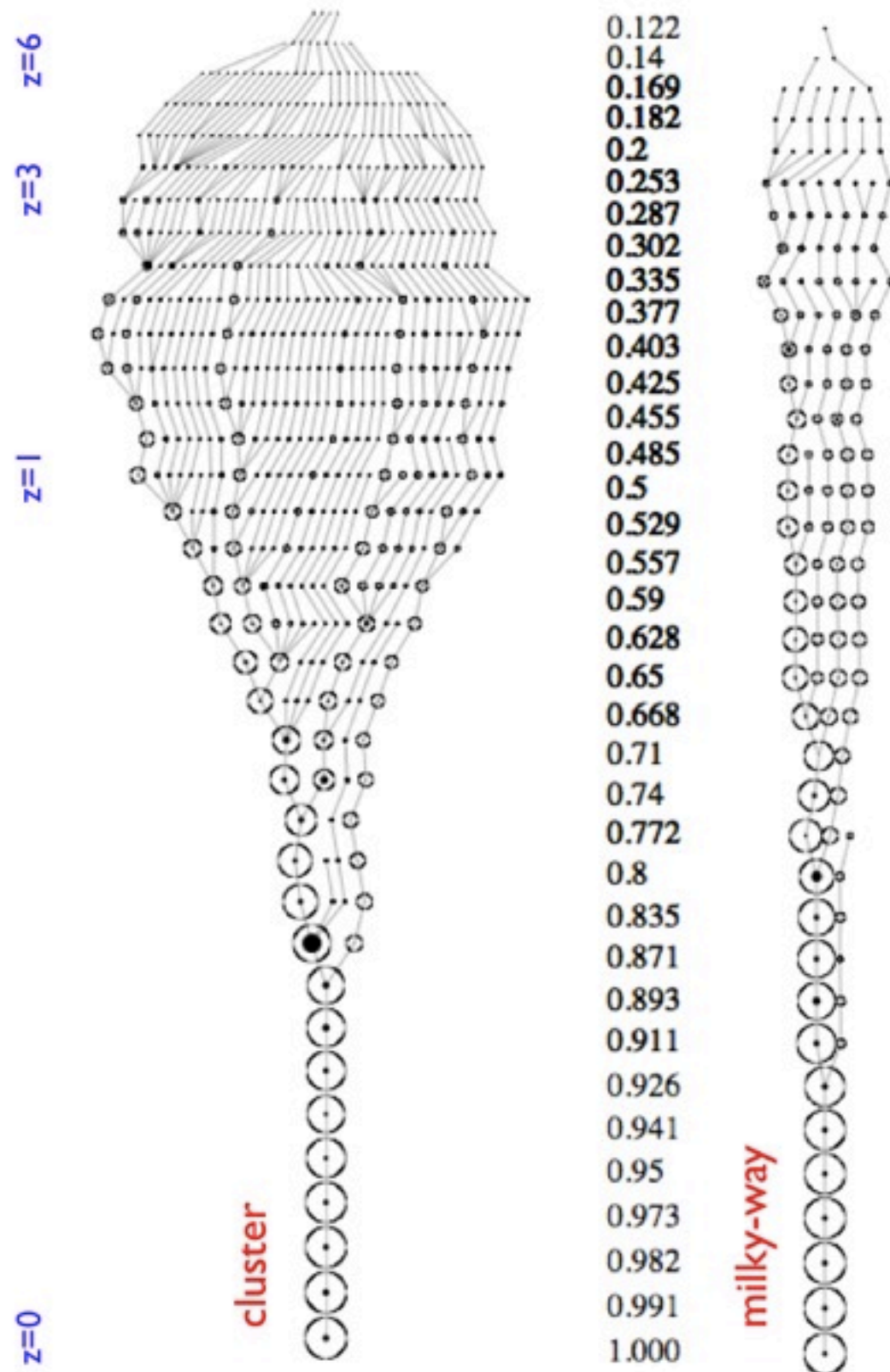
Mutch, Croton & Poole 2013



Numerical Simulation

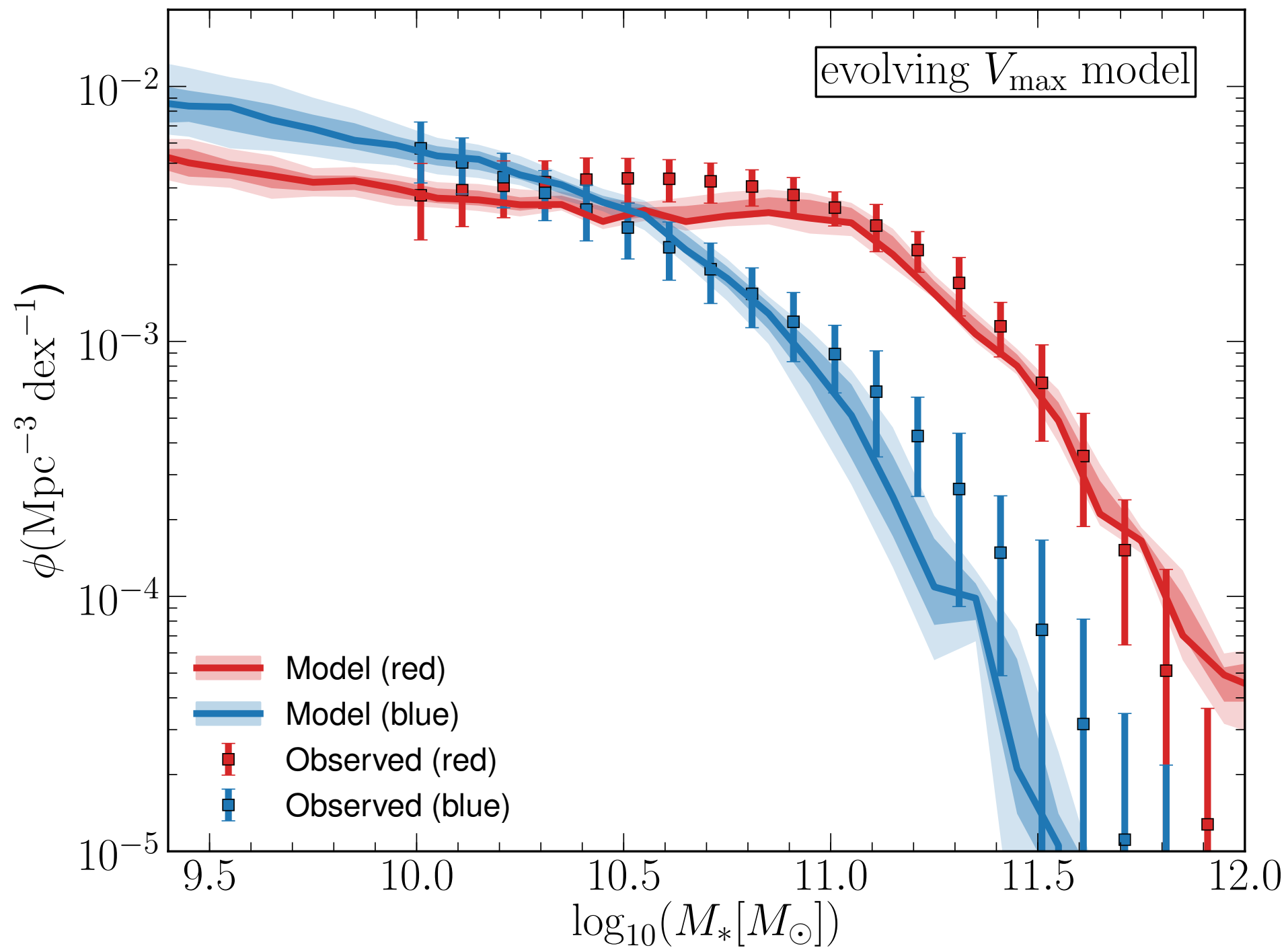
+

Analytic Simulation

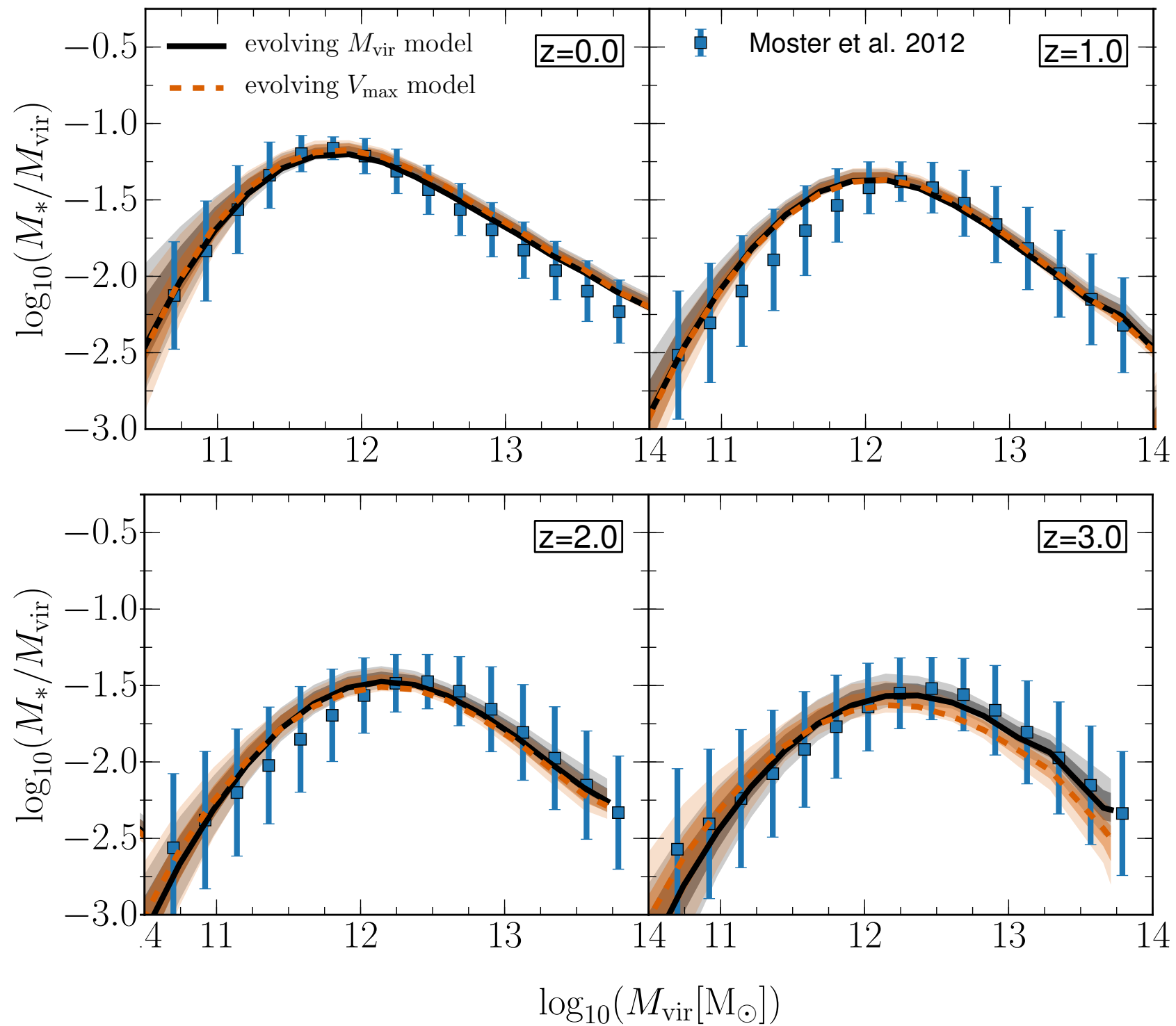


$$\dot{M}_* = f_b \frac{dM_{\text{vir}}}{dt} F_{\text{phys}}$$

Mutch, Croton & Poole 2013



Mutch, Croton & Poole 2013



$$\dot{M}_* = f_b \frac{dM_{\text{vir}}}{dt} F_{\text{phys}}$$

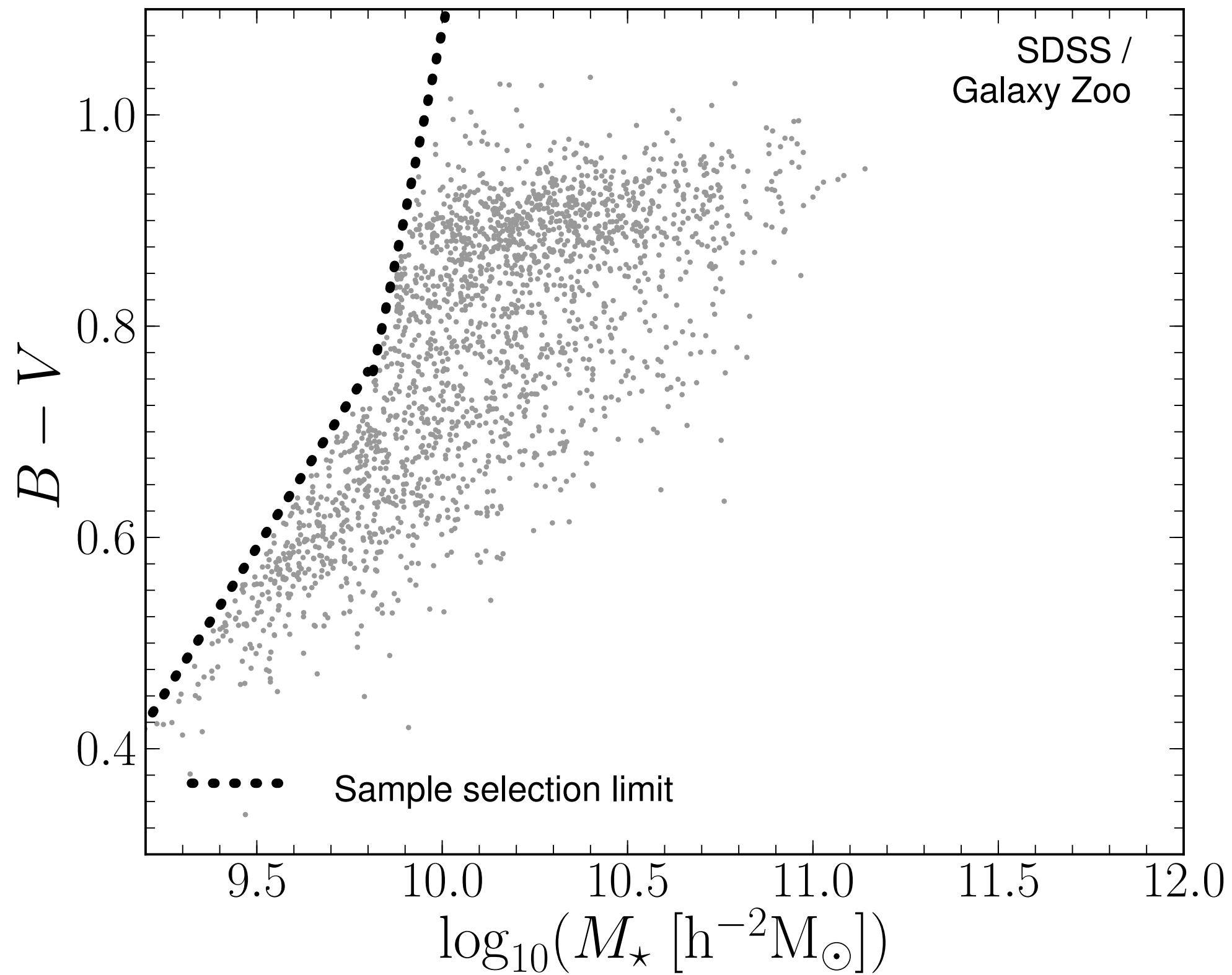
1. Can be applied to any simulation
2. Physics function can be arbitrarily complex
3. Statistically constrained
4. Full formation histories

the mid-life crisis of the Milky Way?

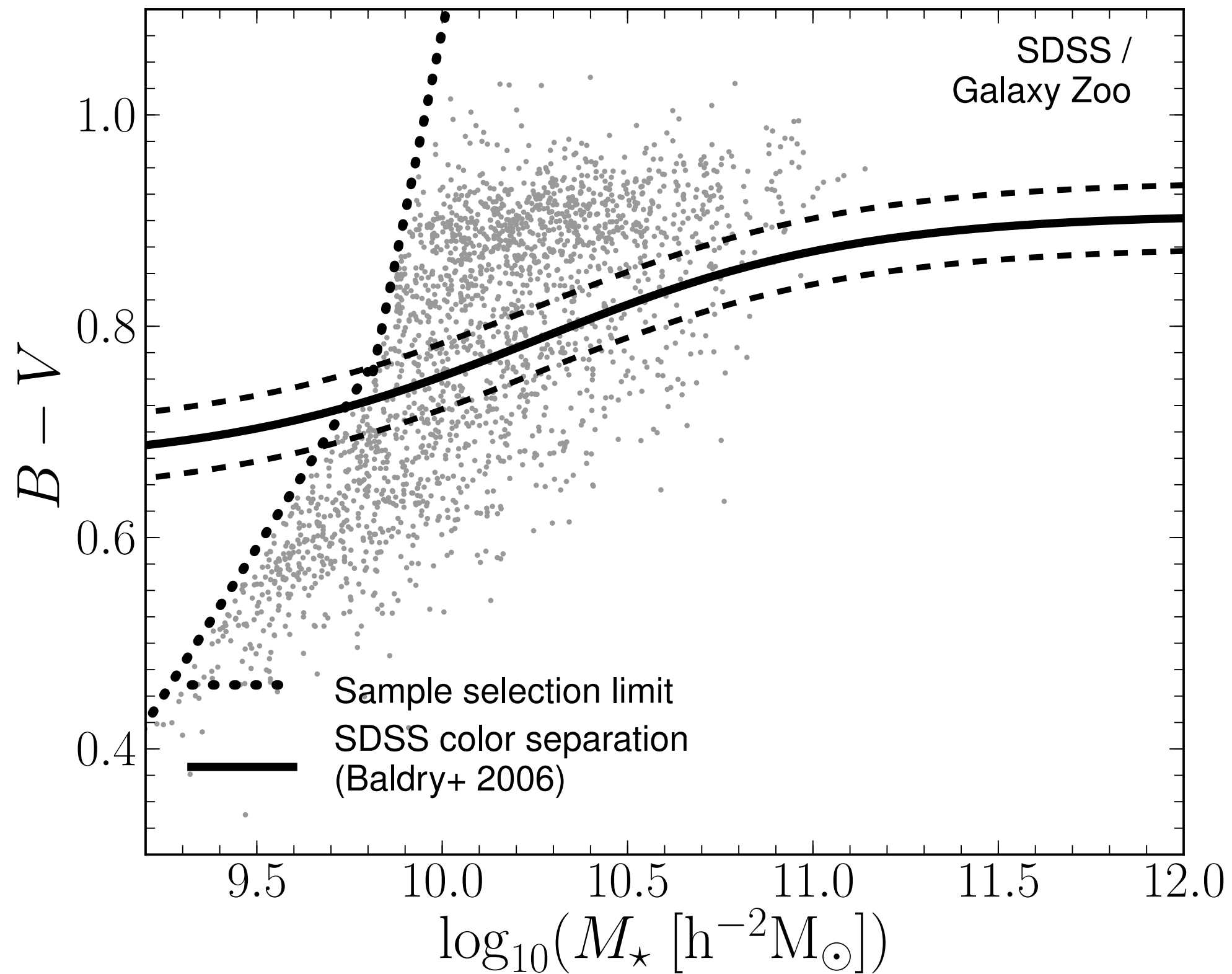
QUESTION: Where does the Milky Way and M31 lie in the traditional colour-magnitude diagram?

QUESTION: How would we interpret the MW if we were an alien race and included it in one of our galaxy surveys?

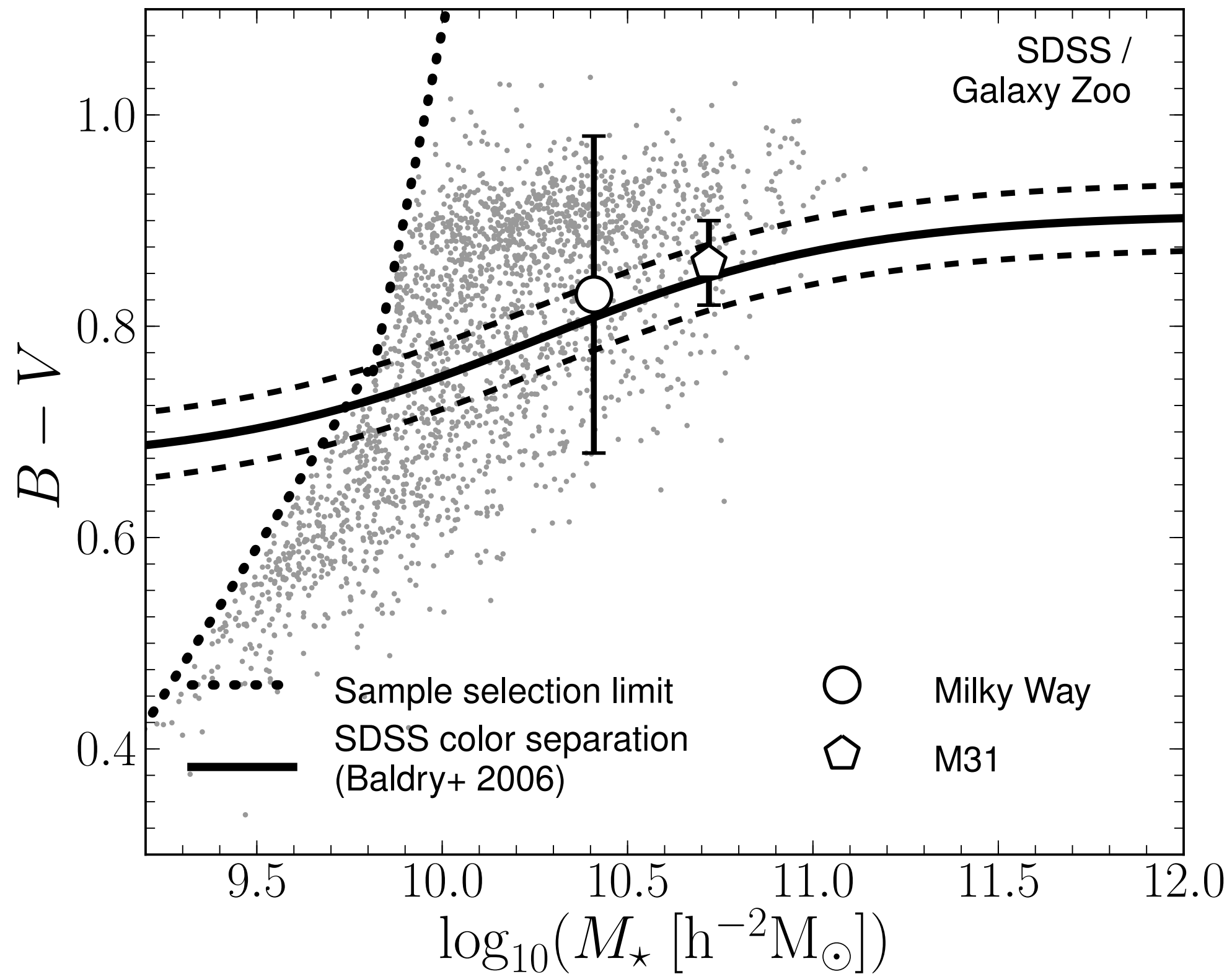
Mutch, Croton & Poole 2013



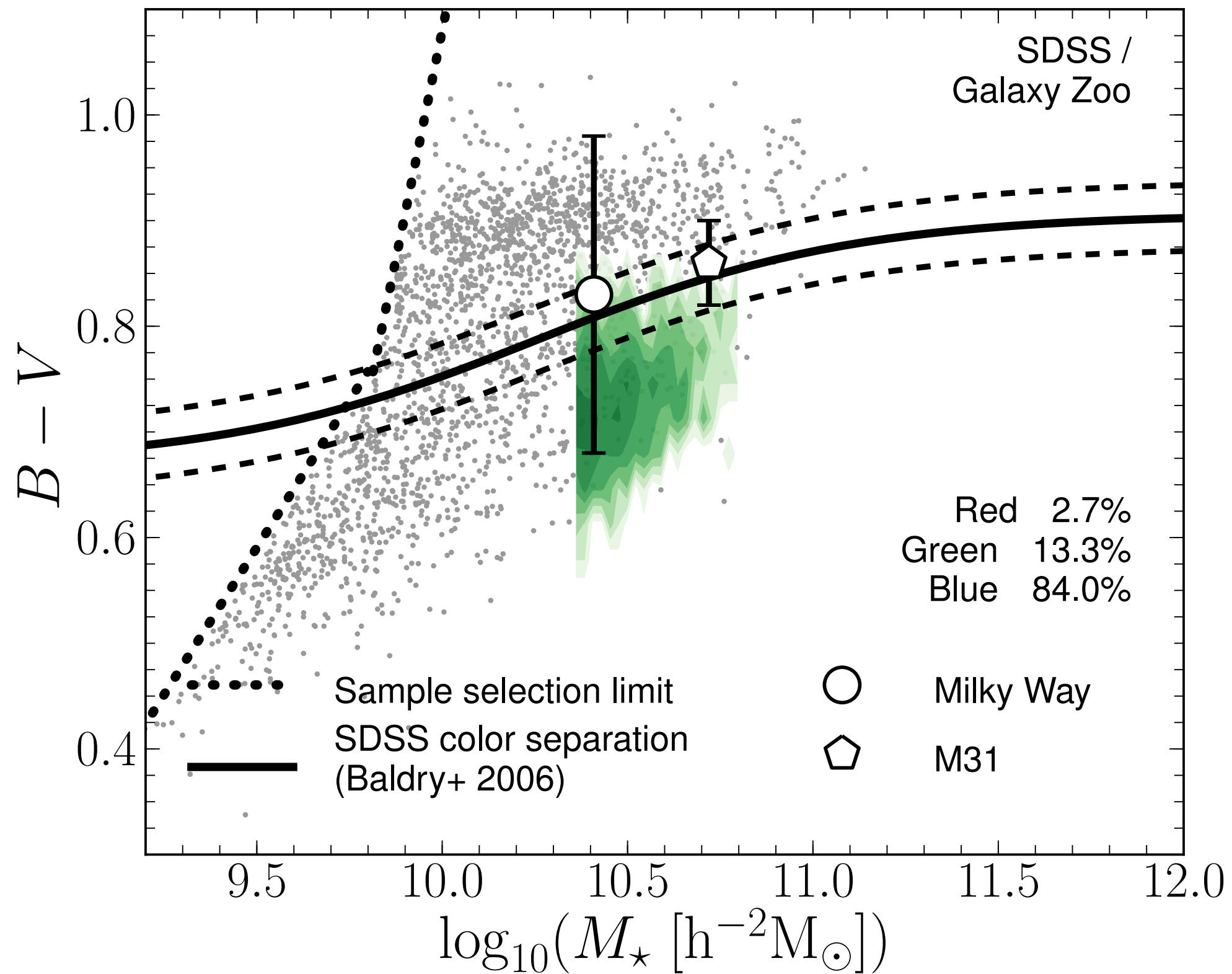
Mutch, Croton & Poole 2013



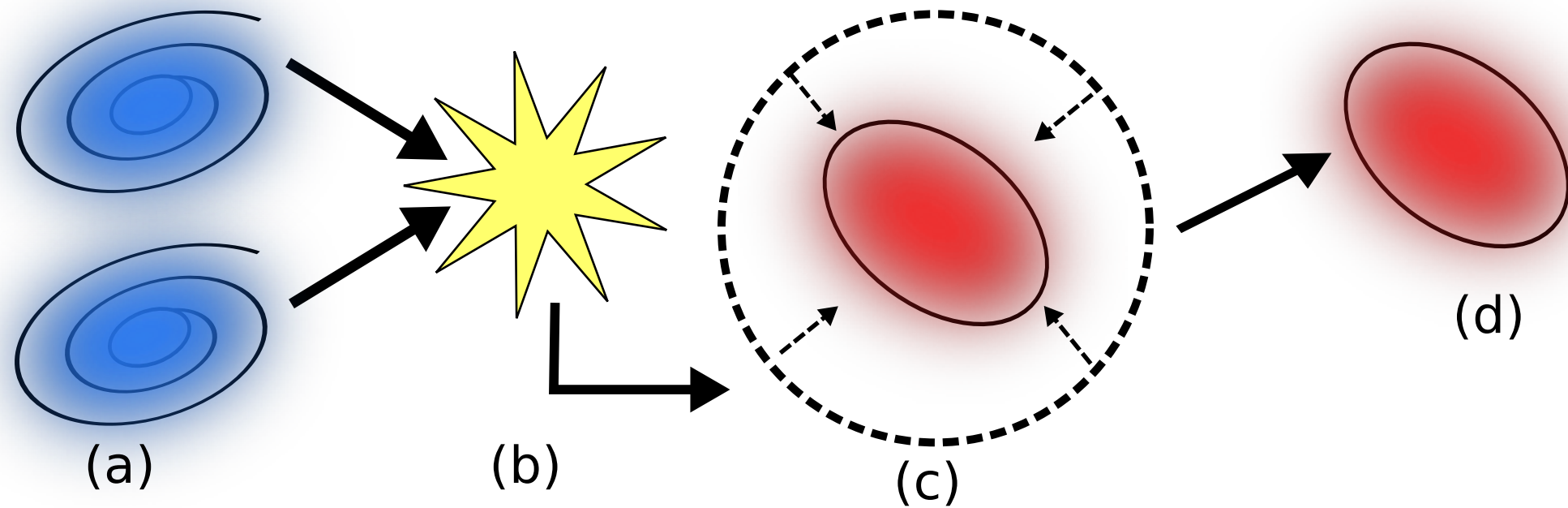
Mutch, Croton & Poole 2013



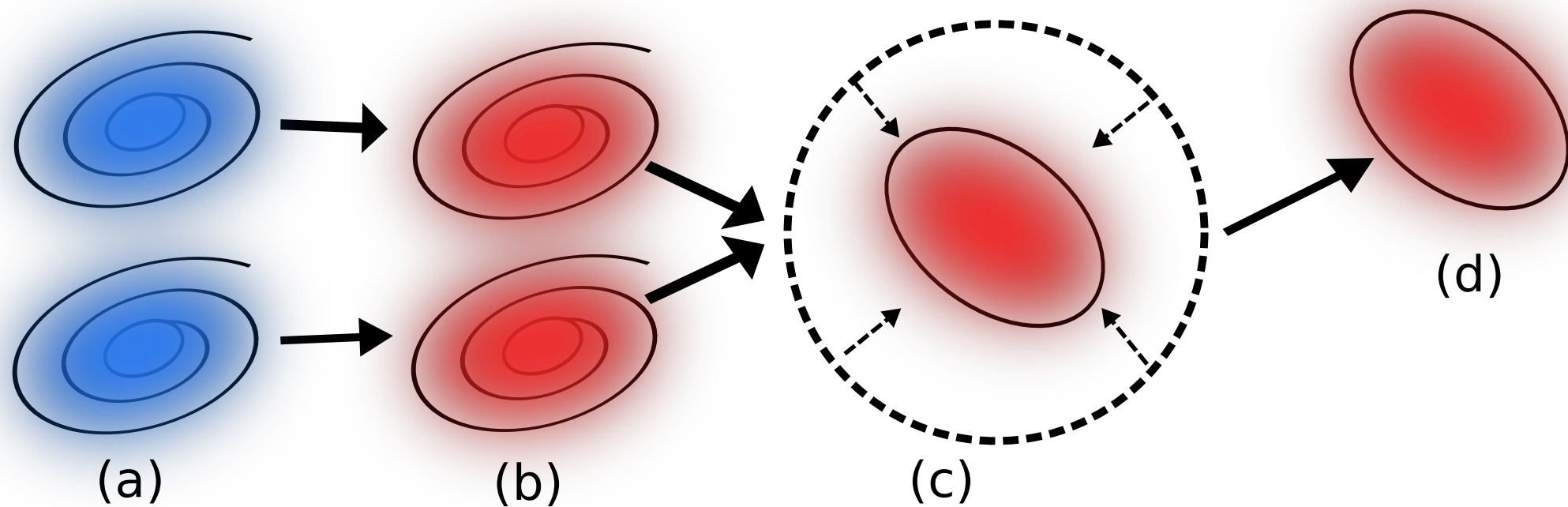
Mutch, Croton & Poole 2013



Traditional picture



Possible alternative



...and finally



nectar

<https://www.nectar.org.au/all-sky-virtual-observatory>

connecting • sharing • collaborating

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[RFP](#)

[news](#)

[researchers](#)

[documents](#)

[about NeCTAR](#)

The All Sky Virtual Observatory

What is the All-Sky Virtual Observatory

New telescopes and facilities coming online in the next three to five years will produce data in volumes never previously experienced in Australian astronomy. To gain maximum scientific benefit from this data flood, the federation of datasets from all types of astronomical facilities in Australia will be needed. This will involve creating the hardware, tools and services to bring together data from radio telescopes, optical telescopes and supercomputers, covering all parts of the southern sky, under a Virtual Observatory.

After extensive consultation with the entire astronomy community, two Australian astronomical facilities were chosen to form the first pillar of the All-Sky Virtual Observatory:

The primary observational dataset will come from the SkyMapper facility, an optical telescope located at Siding Spring Observatory, NSW, built by the Australian National University. SkyMapper is producing the most detailed and sensitive digitized map of the southern sky at optical wavelengths. This nationally significant dataset will be a fundamental reference for astronomers in Australia, and internationally, for many decades.

The Theoretical Astrophysical Observatory (TAO), being developed at Swinburne University of Technology, will house the growing ensemble of Australian theory data sets and galaxy formation models, with value-add tools that will allow astronomers to observe each virtual universe as if it was real. This will be achieved by mapping the simulated data onto an observer's viewpoint and the application of custom telescope simulators, beginning with SkyMapper. TAO provides a direct and vital link between the theoretical and observational aspects of data collection and analysis.

Who is Astronomy Australia?

Astronomy Australia Ltd (AAL) is a not-for-profit company whose members are all the Australian universities and research organisations with a significant astronomical research capability.

Our vision is that astronomers in Australia will have access to the best astronomical research infrastructure. AAL will achieve its



Search

VLs in project negotiation

[The All Sky Virtual Observatory](#)

[Climate and Weather Science Laboratory](#)

[Humanities Networked Infrastructure \(HuNI\) unlocking and uniting Australia's cultural data](#)

[The Genomics Virtual Laboratory](#)

[The Characterisation Virtual Laboratory: research environments for exploring inner space](#)

[Early Activities](#)

[CSIRO - Virtual Geophysics Laboratory](#)

[University of Queensland - Virtual Genomics Laboratory](#)

[University of Tasmania - Marine Virtual Laboratory](#)

[Latest News ...](#)

FAH

Telescope simulator

Image generation

Light cone generation

SEDs + Filters

Web form data query

Simulation database

TAO – Mock Galaxy Factory

ASVOTheoretical Astrophysical Observatory (Beta)New CatalogueHistoryAdminDocumentationSupportdarrencroton

New Catalogue

(Required Fields are marked with an asterisk)

Job TypeGeneral PropertiesSpectral Energy DistributionMock ImageSelectionOutput formatSummary and submit

< PreviousNext >

Data Selection

Catalogue geometry *
Box

Dark matter simulation *
Bolshoi

Box Size (Mpc/h) *
250.000

Redshift *
0.1132

Galaxy model *
SAGE

Output properties

Output properties *

AvailableSelected

Filter

Galaxy Properties
Galaxy Classification
Disk Scale Radius
Total Star Formation Rate

>>

Galaxy Masses
Total Stellar Mass
Bulge Stellar Mass
Black Hole Mass
Cold Gas Mass
Hot Gas Mass
Firsted Gas Mass

Selected simulation details

Bolshoi

Cosmology: WMAP5
Cosmological parameters: $\Omega_m = 0.27$, $\Omega_\Lambda = 0.73$,
 $\Omega_b = 0.0469$, $\sigma_8 = 0.82$, $h = 0.70$, $n=0.95$
Box Size: 250 Mpc/h
Mass resolution: 1.35×10^8 Msun/h
Force resolution: 1 kpc/h

Web Site: Bolshoi Cosmological Simulations
Paper: Klypin, Trujillo-Gomez & Primack 2011

Selected galaxy model details

SAGE

Kind: semi-analytic model
Paper: Croton et al. 2006

<https://tao.asvo.org.au/tao/>

TAO – Mock Galaxy Factory

ASVOTheoretical Astrophysical Observatory (Beta)New CatalogueHistoryAdminDocumentationSupportdarrencroton

New Catalogue

(Required Fields are marked with an asterisk)

Job TypeGeneral PropertiesSpectral Energy DistributionMock ImageSelectionOutput formatSummary and submit

< PreviousNext >

Data Selection

Catalogue geometry *

Light-Cone

Dark matter simulation *

Millennium

Right Ascension Opening Angle (degrees) *

20

Redshift Min *

0

Estimated job size: 7%

Unique

☒ Random

Galaxy model *

SAGE

Declination Opening Angle (degrees) *

20

Redshift Max *

0.5

Select the number of light-cones: *

3

maximum is 10

Output properties

Output properties *

Selected simulation details

Millennium

Cosmology: WMAP-1
Cosmological parameters: $\Omega_m = 0.25$, $\Omega_\Lambda = 0.75$,
 $\Omega_b = 0.045$, $\sigma_8 = 0.9$, $h = 0.73$, $n = 1$
Box size: 500 Mpc/h
Mass resolution: 8.6×10^8 Msun/h
Force resolution: 5 kpc/h

Paper: Springel et al. 2005
External link: Simulating the joint evolution of

Selected galaxy model details

SAGE

Kind: semi-analytic model
Paper: Croton et al. 2006

<https://tao.asvo.org.au/tao/>

The Future

1. Toy AGN heating models work, but how can we know the actual quenching mechanism(s)?
2. Quenching shapes morphology.
3. How simple is too simple when it comes to modelling galaxies?
4. Is the MW a green valley galaxy? What does this mean?