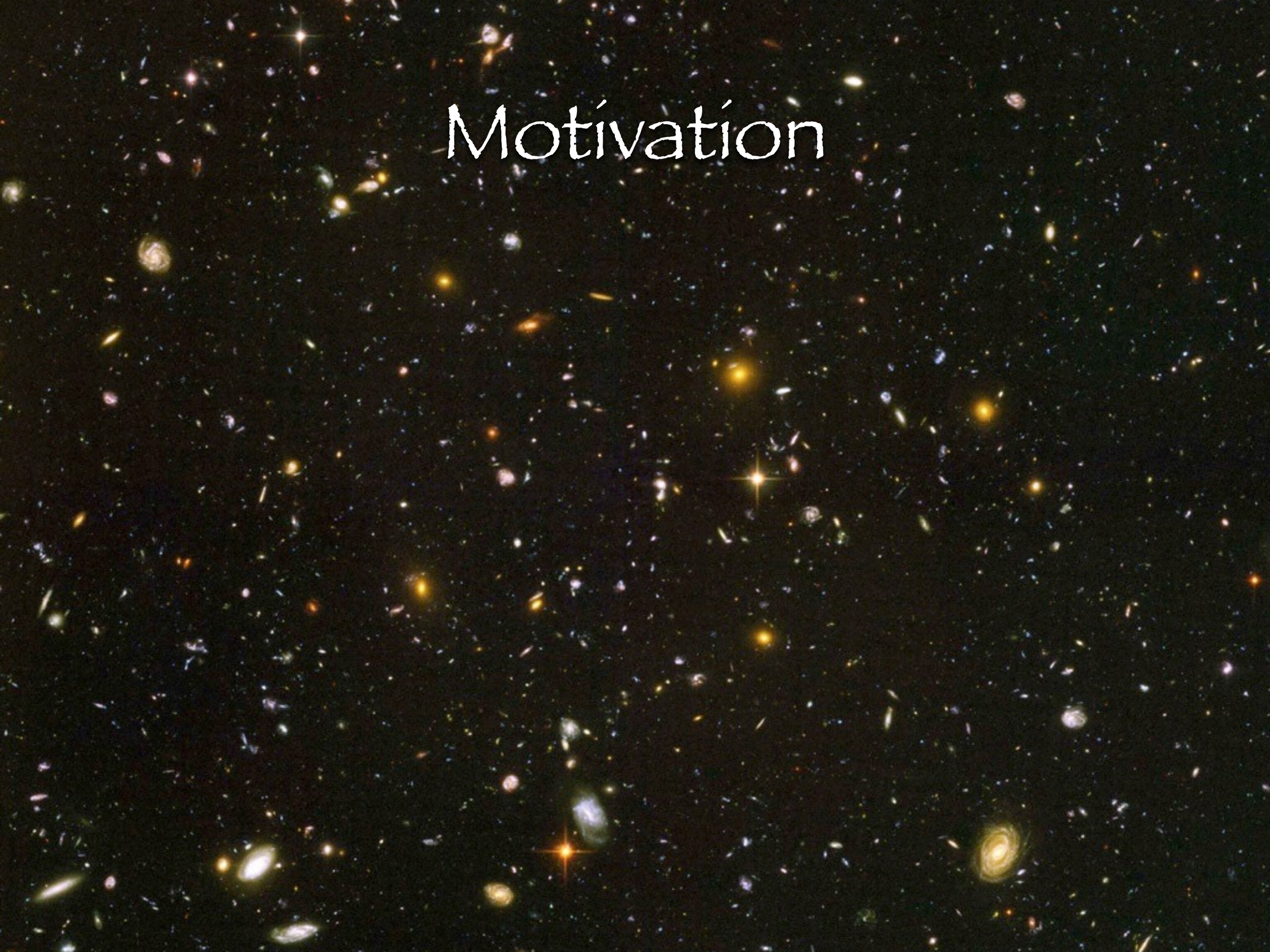
Populating the Hubble sequence in cosmological simulations

Paul Torrey

In collaboration with:

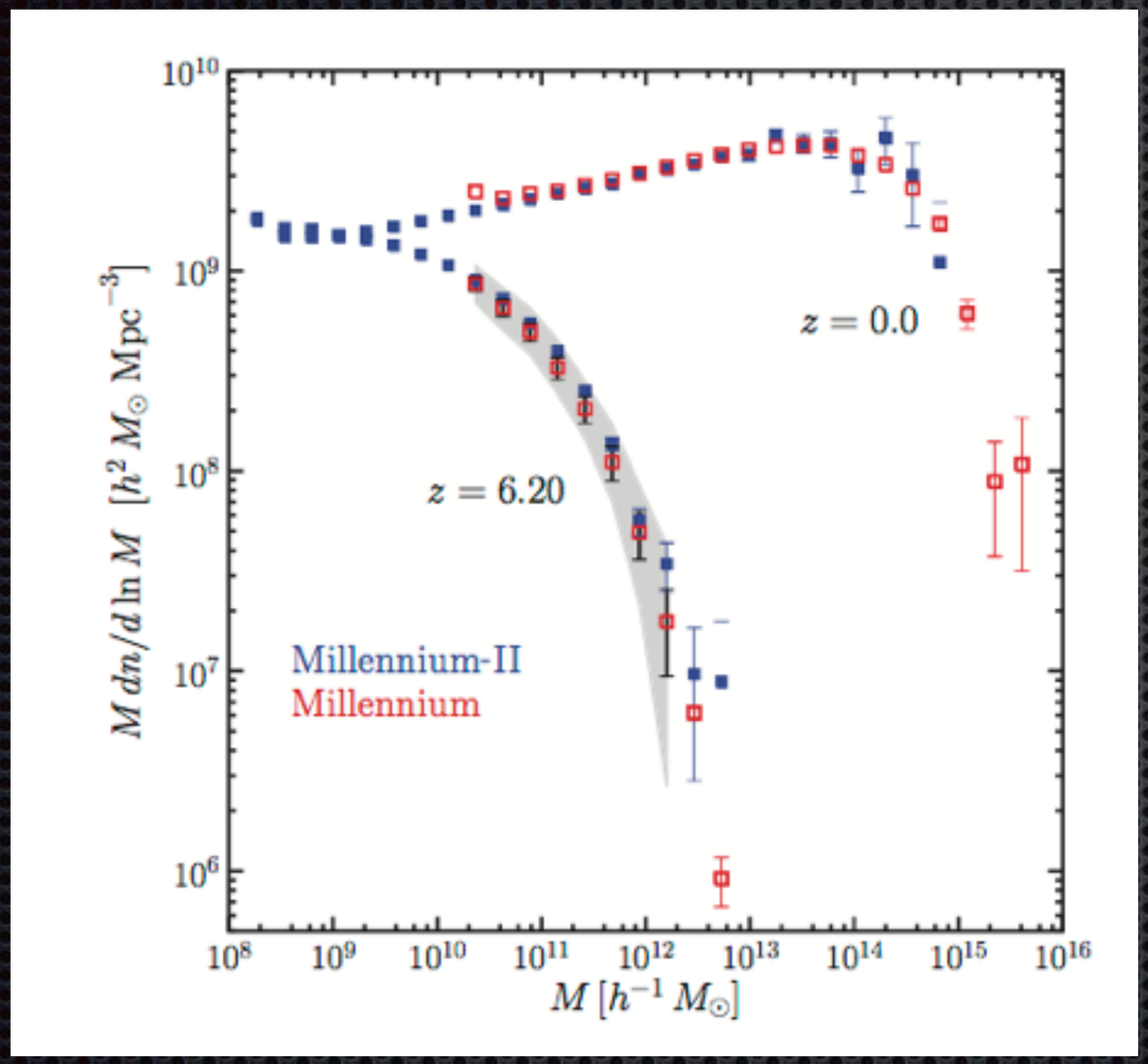
Mark Vogelsberger, Shy Genel, Debora Sijacki, Volker Springel, Lars Hernquist

Motivation



Structure Formation

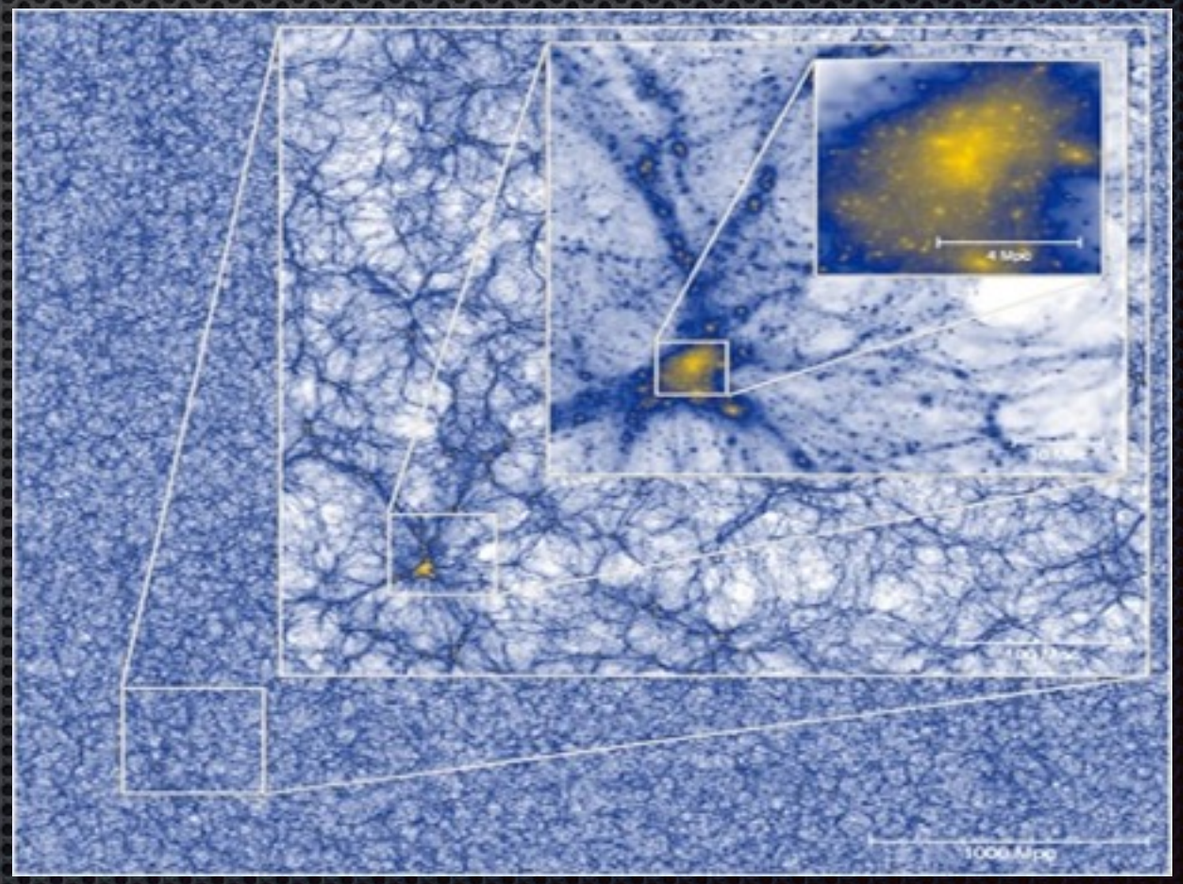
Millennium-1 & II



Boylan-Kolchin+ (2009)

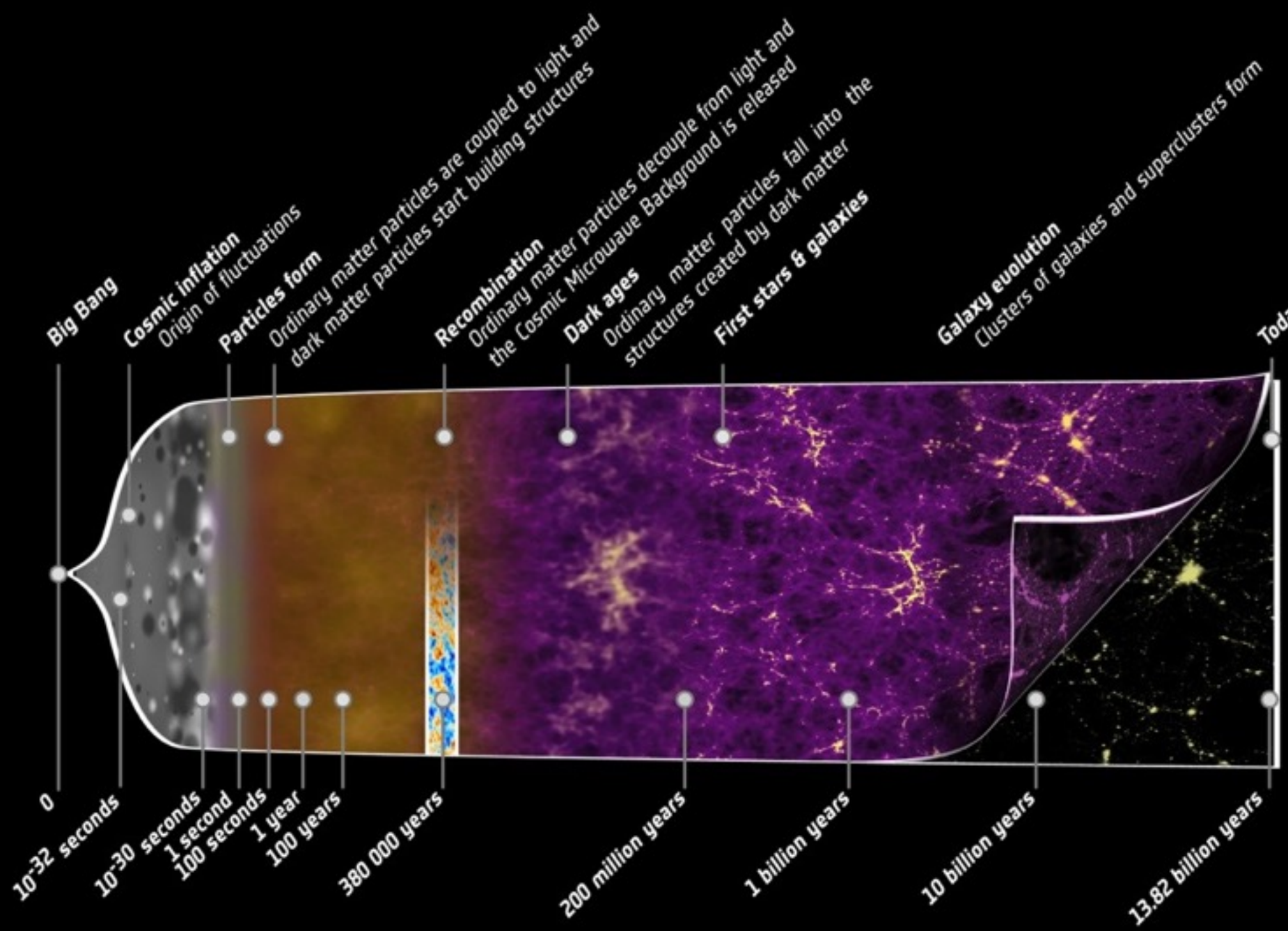
Springel+ (2005)

Millennium-XXL

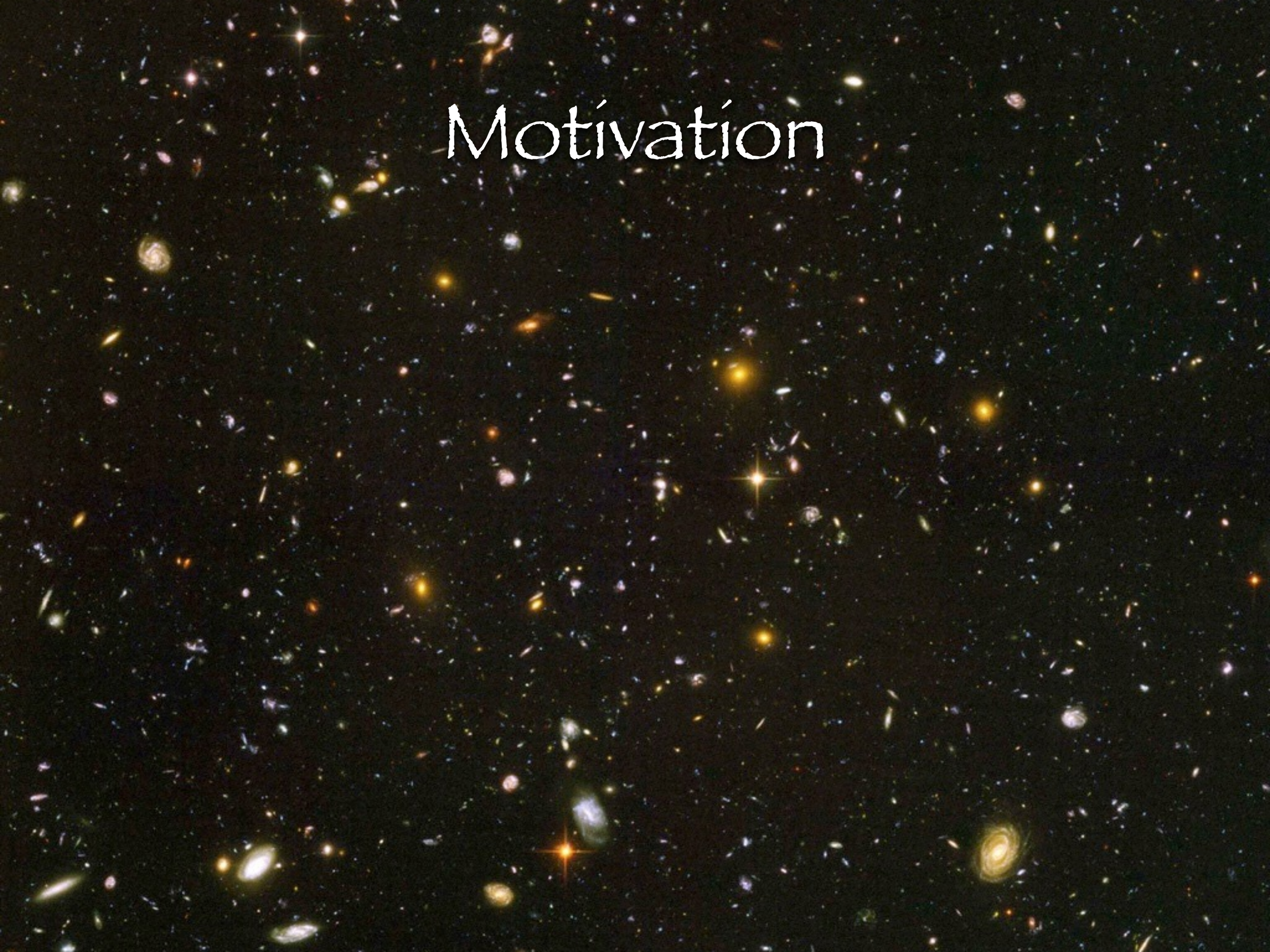


Angulo+ (2012)

Structure Formation



Motivation



Motivation

- Start from early universe initial conditions
- Build simulation which includes relevant physics
- Allow galaxies to “self-consistently” evolve
- Analyze results; Redefine “relevant physics”

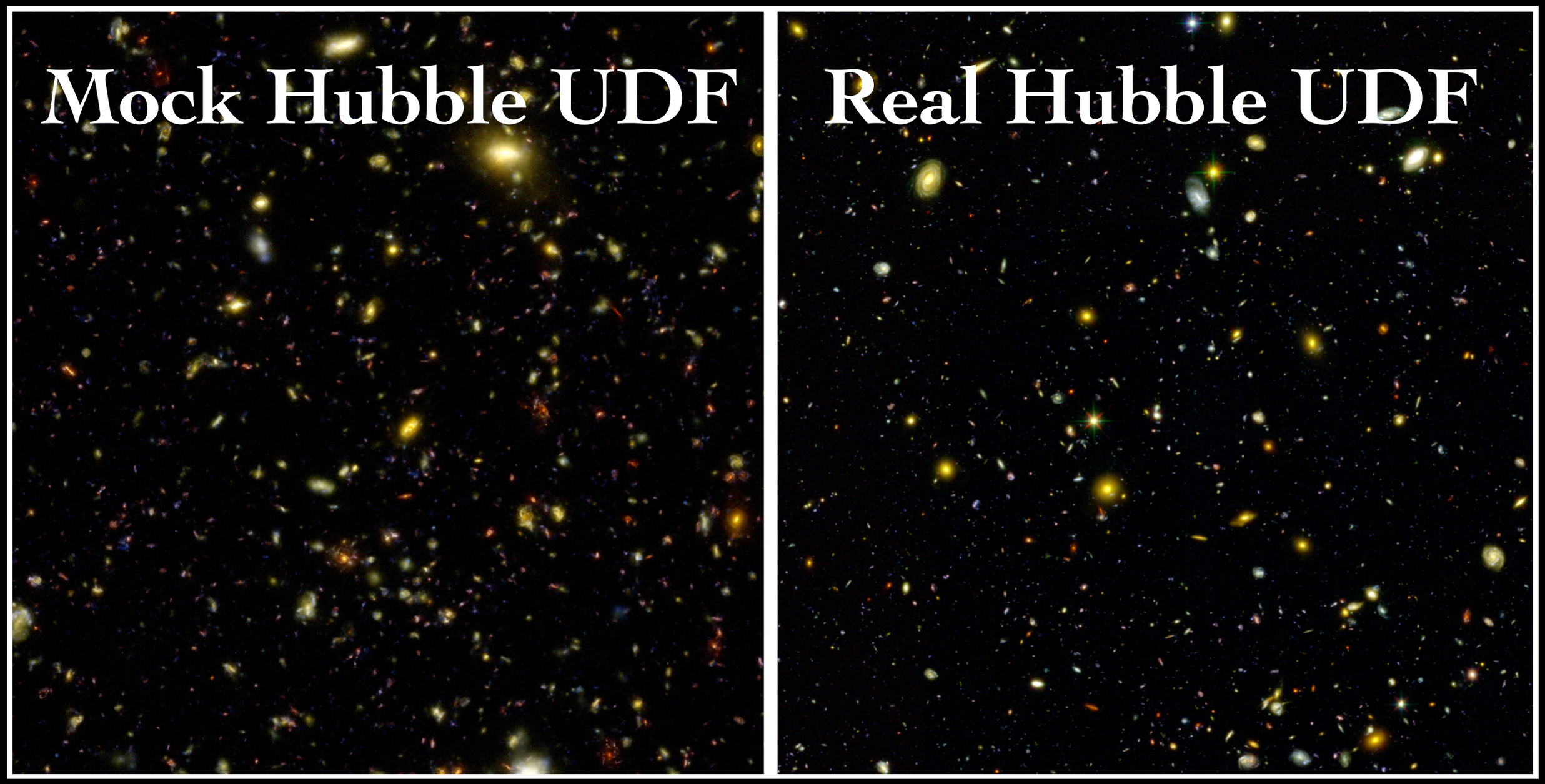


Image Credit: Greg Snyder

Talk Outline:

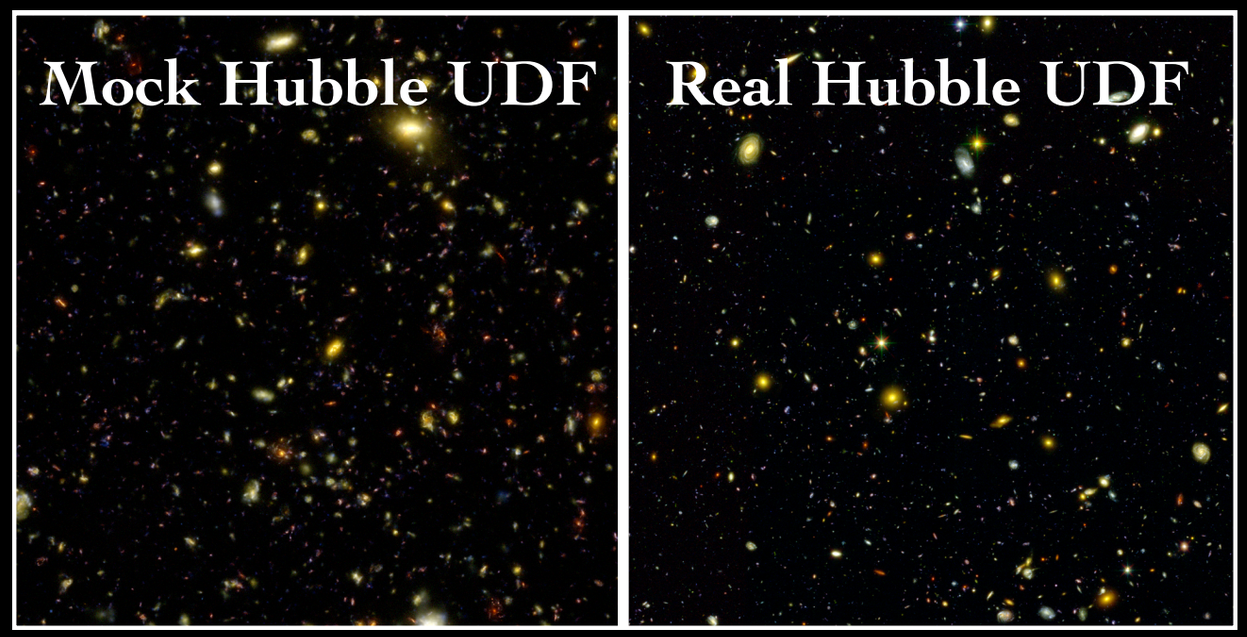


Image Credit: Greg Snyder

1. Description of simulation methods

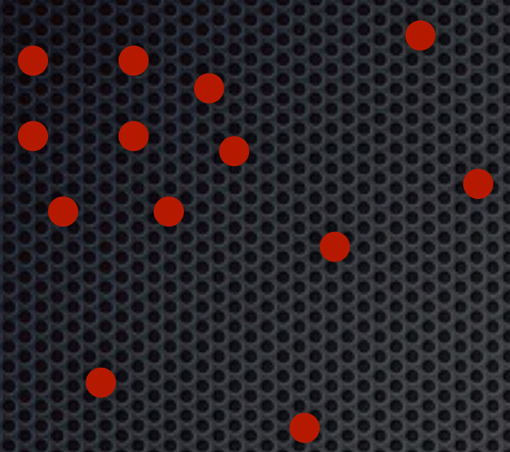
2.Importance and implementation of feedback from stars and AGN

3. Doing science with mock observations

Methods: AREPO

Lagrangian Methods

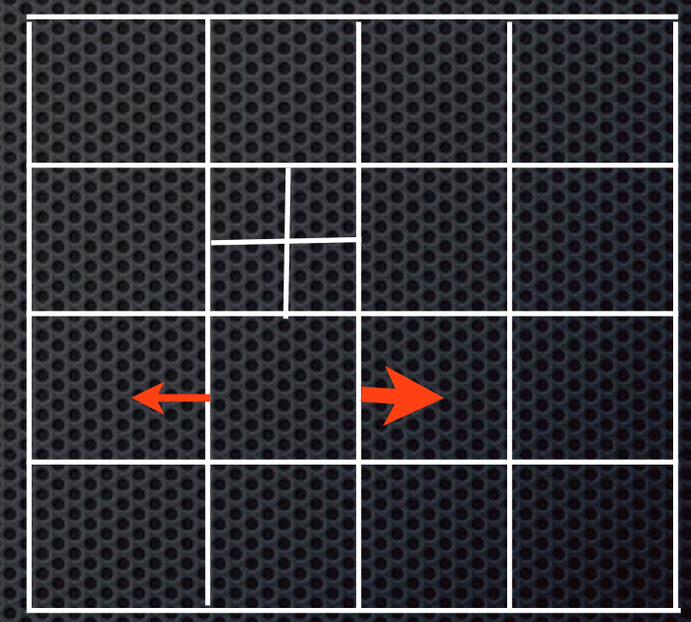
(SPH) e.g., GADGET



- Geometrically flexible
- Naturally adaptive resolution
- Galilean invariant

Eulerian Methods

(AMR) e.g., ENZO



- Instability handling
- Natural shock capturing
- Phase boundary resolution

Methods: AREPO

Lagrangian Methods

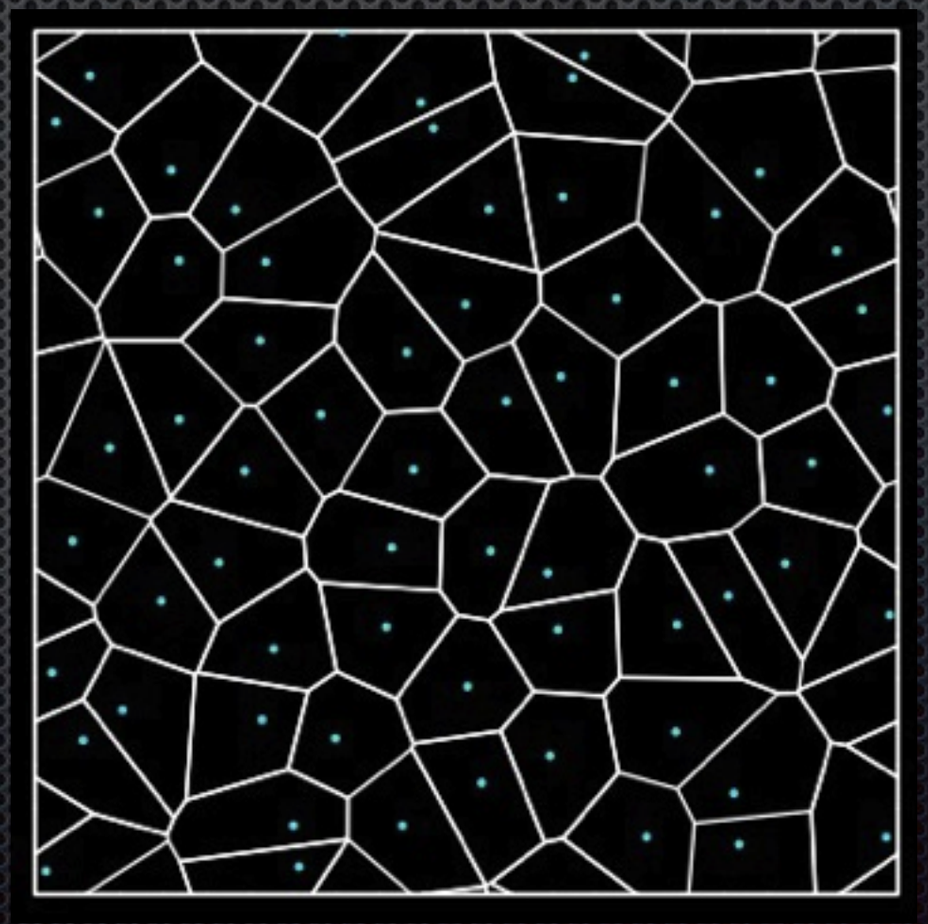
(SPH) e.g., GADGET

Eulerian Methods

(AMR) e.g., ENZO

Quasi-Lagrangian Finite-Volume

(moving mesh) e.g., AREPO



Springel (2010)

Methods: AREPO

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(SPH) e.g., GADGET

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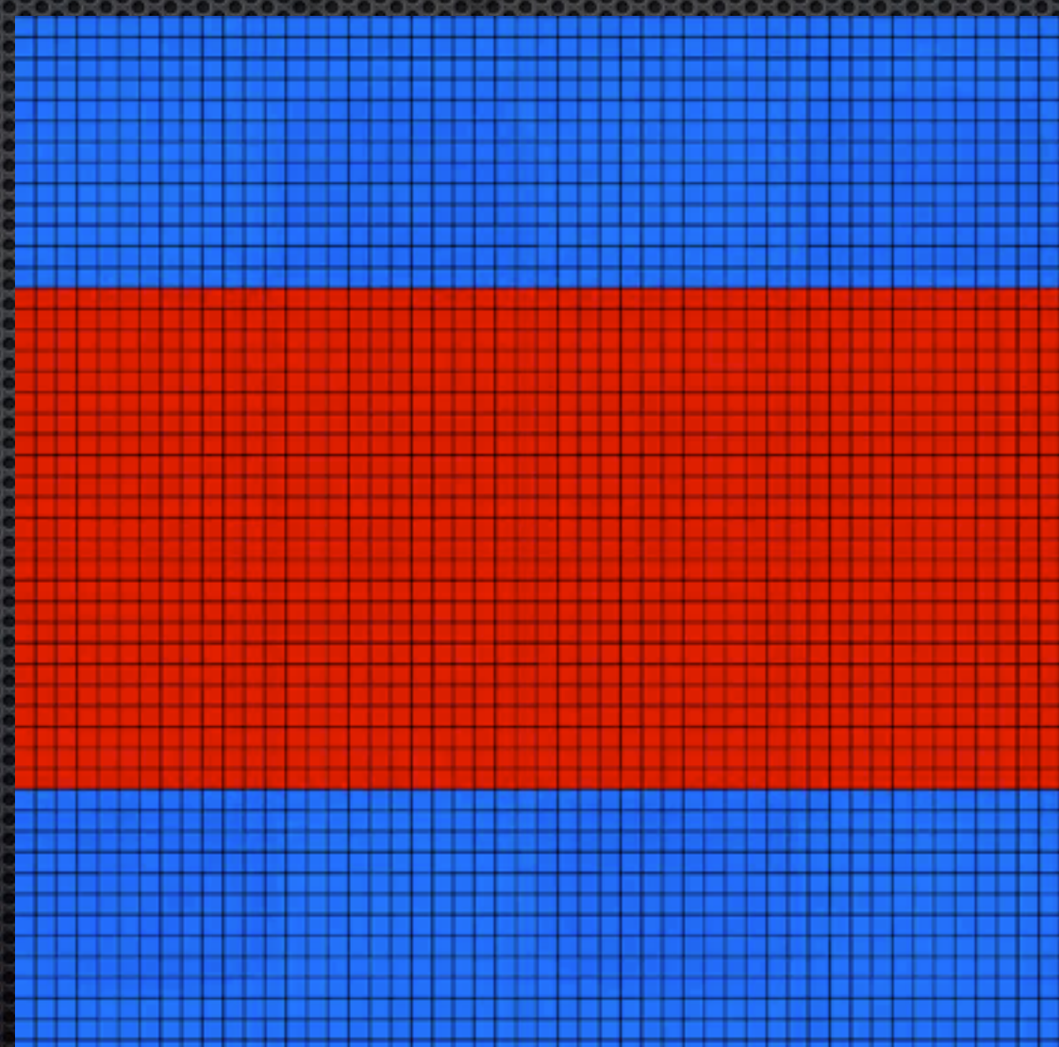
Quasi-Lagrangian Finite-Volume



Springel (2010)

Methods: AREPO

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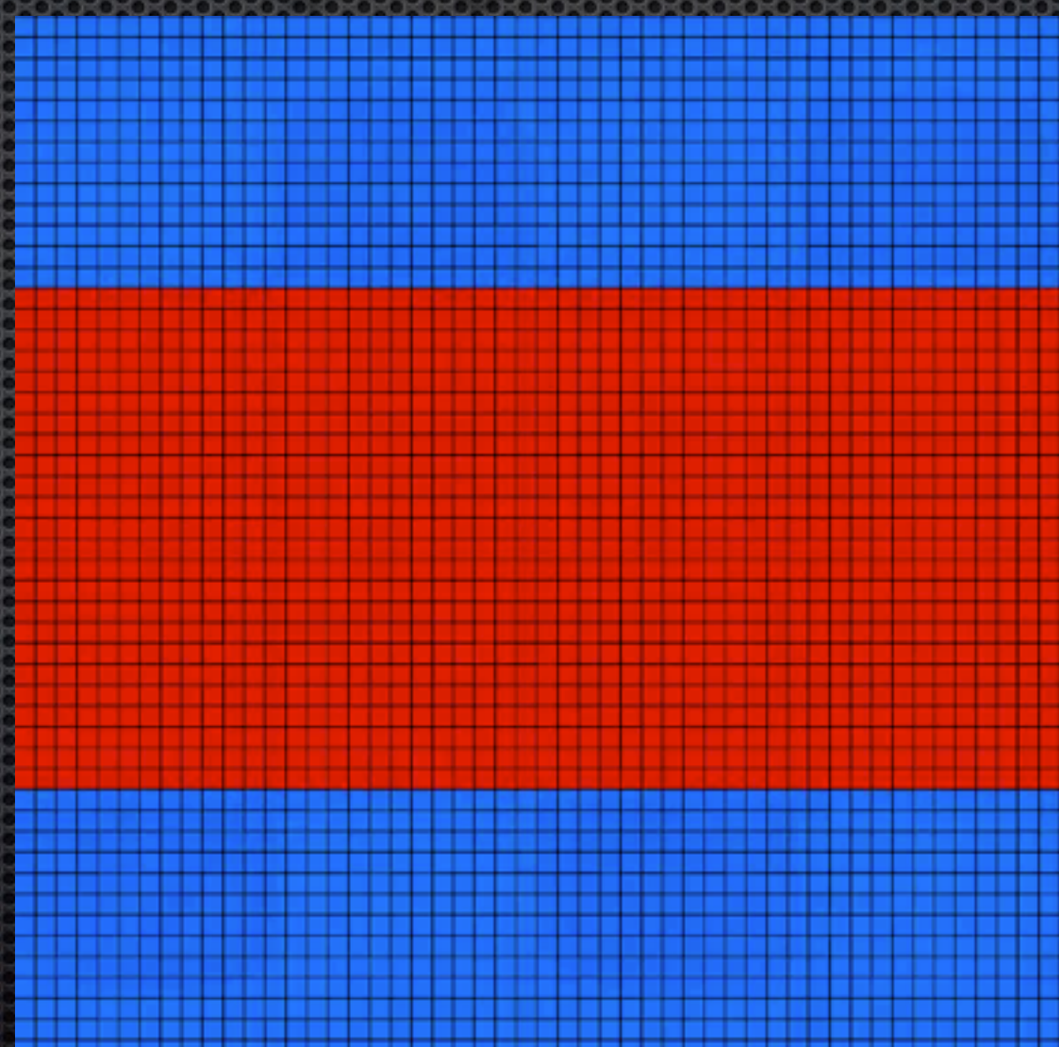
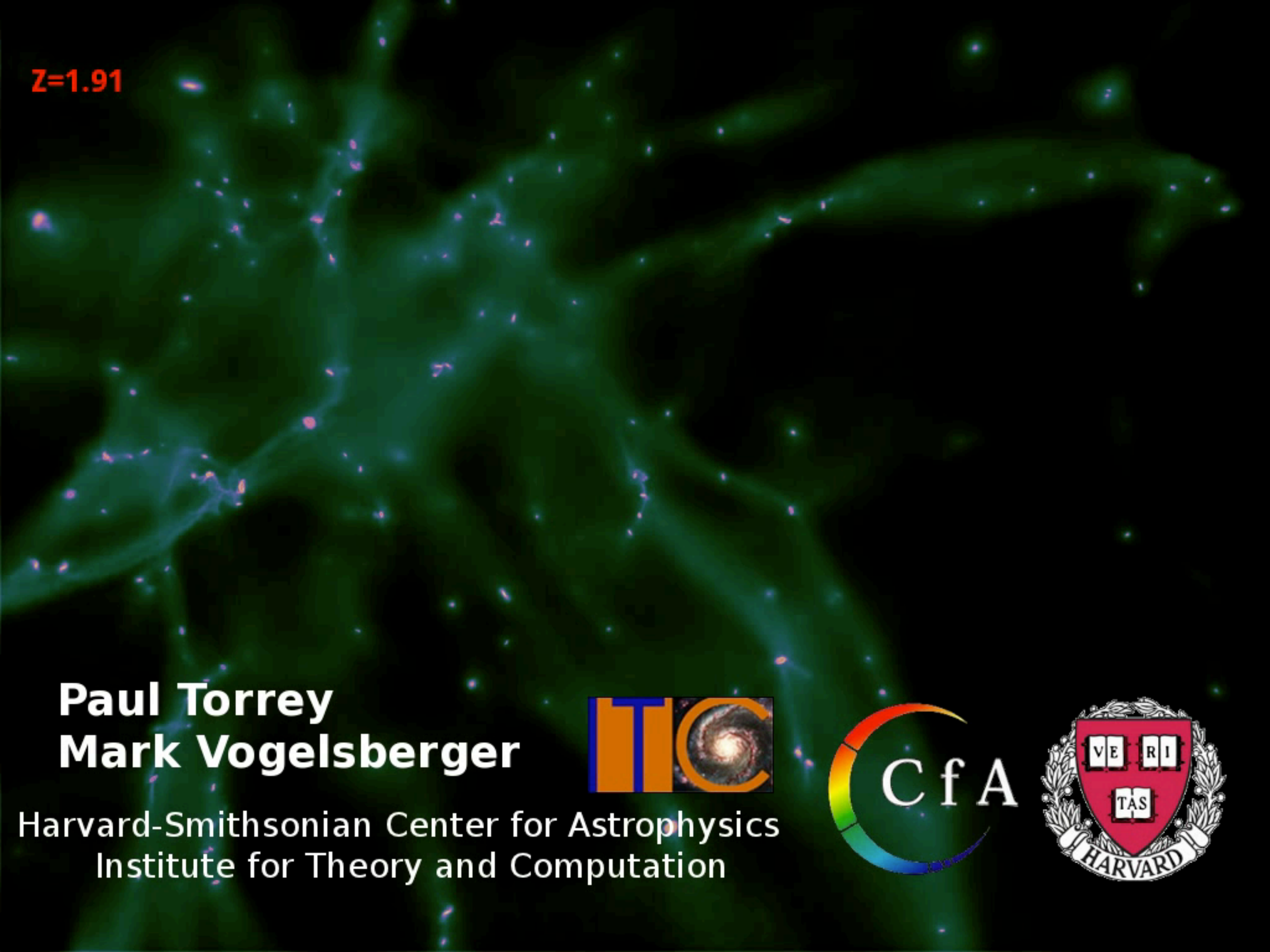
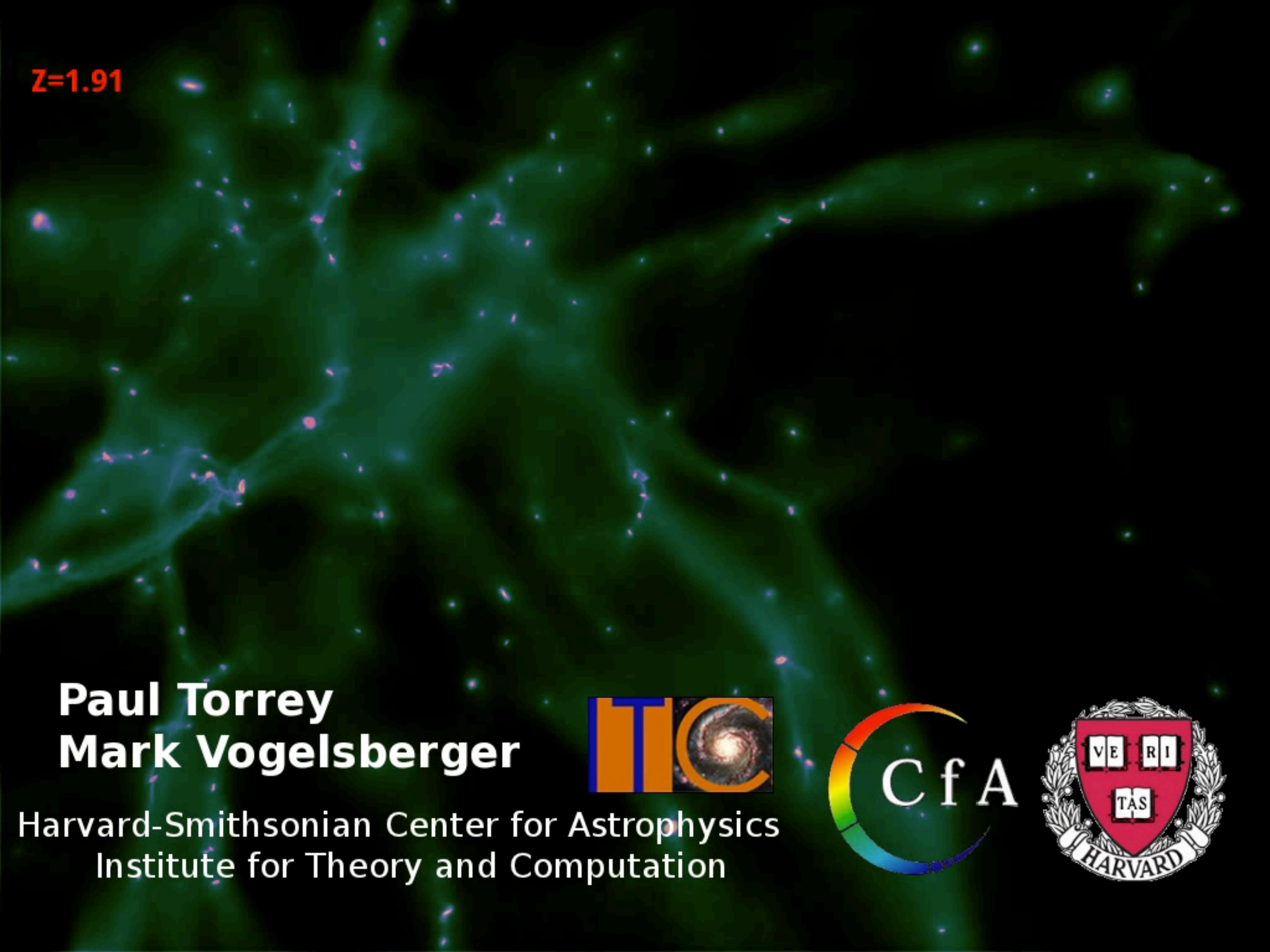


Springel (2010)



Paul Torrey
Mark Vogelsberger

Harvard-Smithsonian Center for Astrophysics
Institute for Theory and Computation



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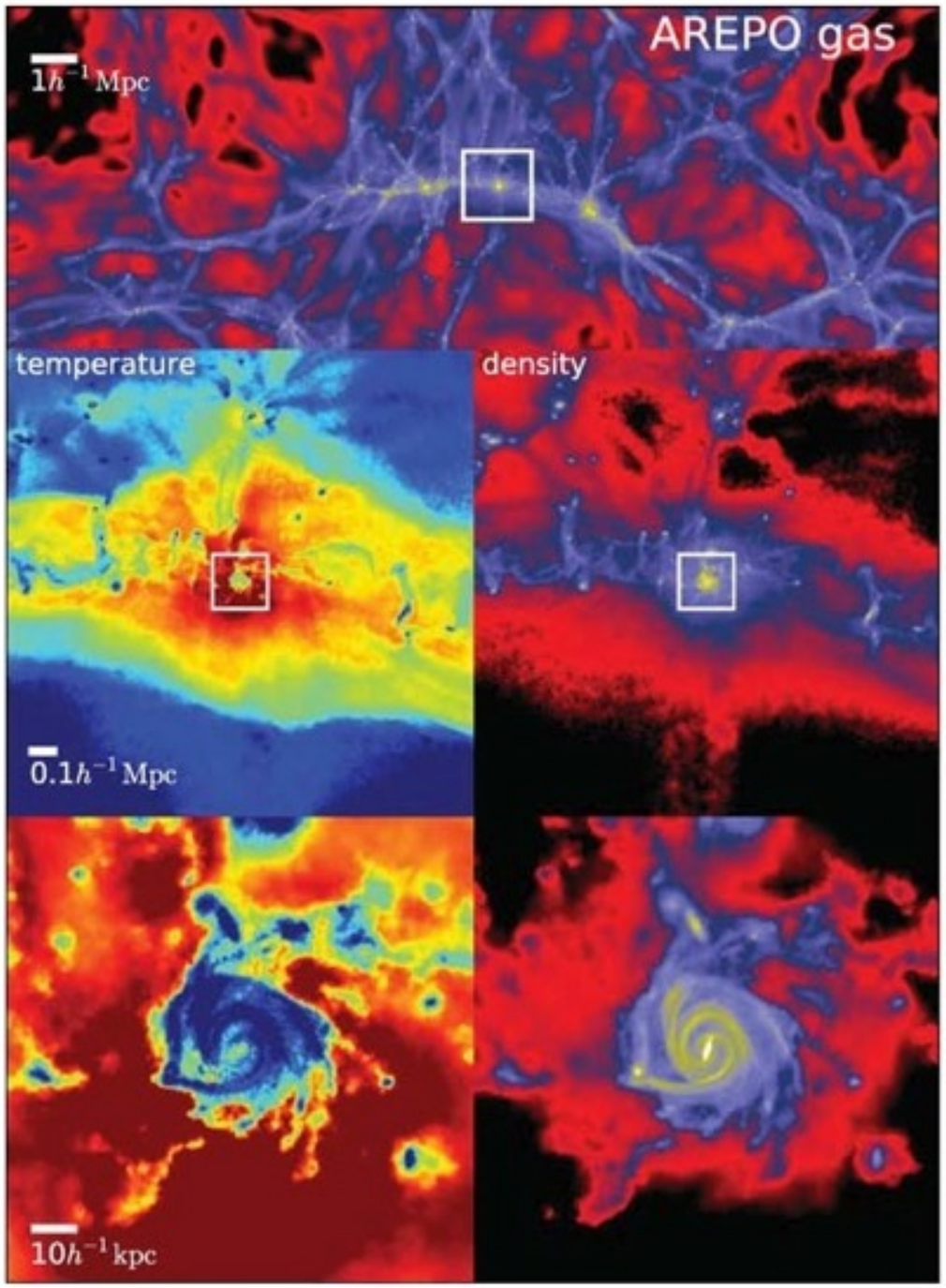
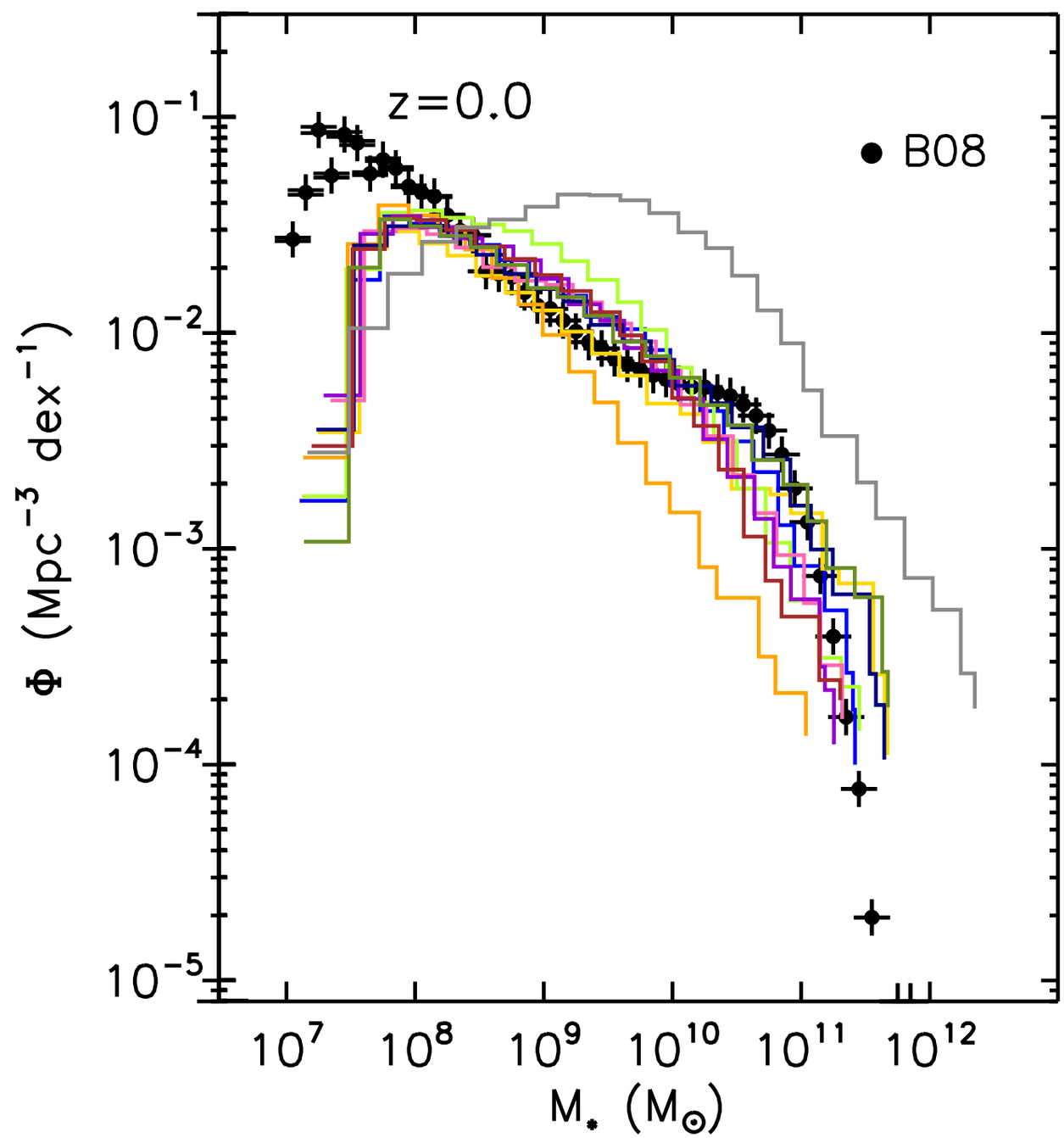
Need for Feedback Physics





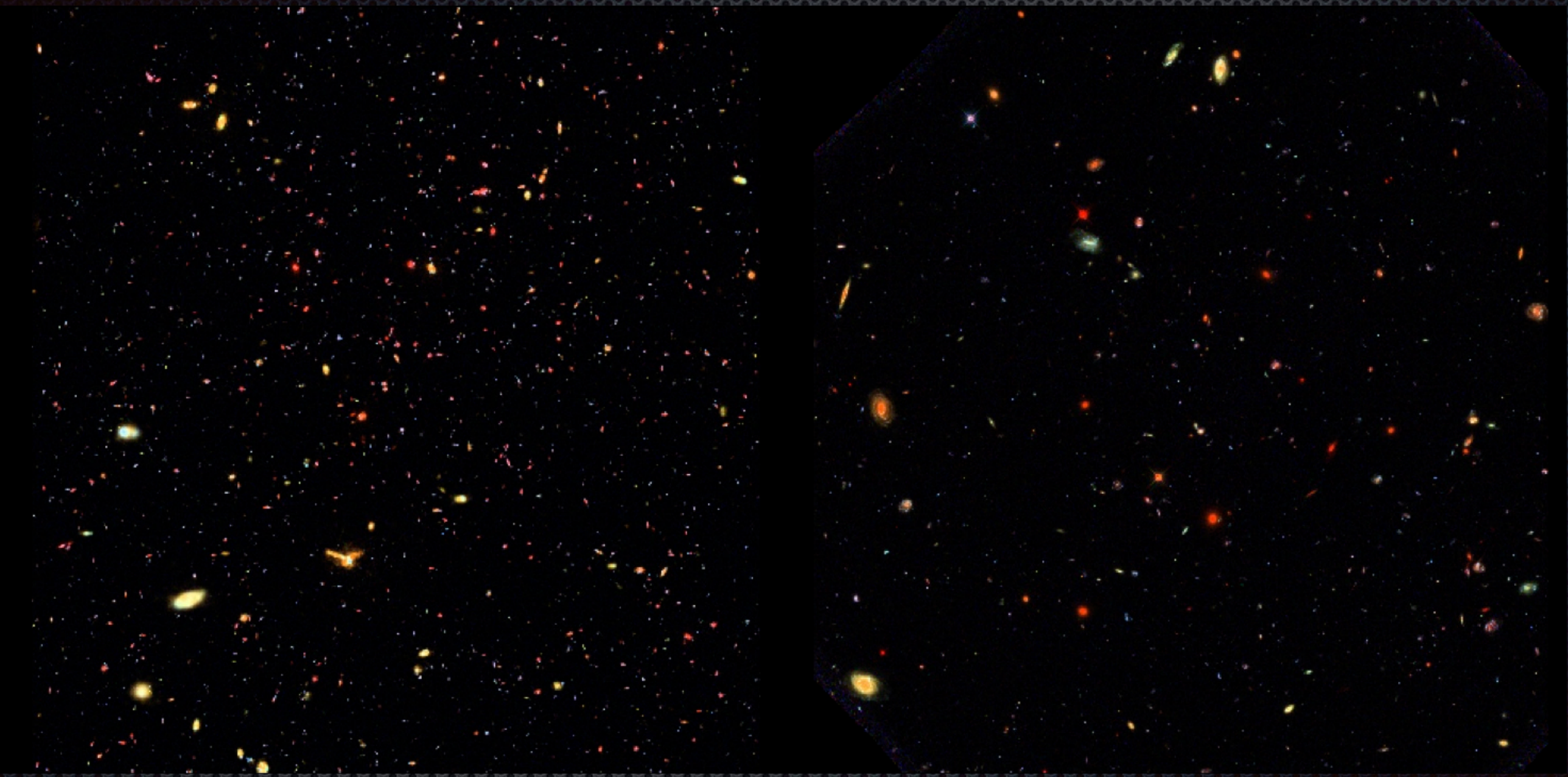
Feedback Physics

- **Incorporate comprehensive physics/feedback model:**
  - ***Stellar Evolution***
    - Chabrier IMF
    - Time dependent mass/metal return from Core Colapse SN, AGB winds, and Type Ia
    - 9 species metal enrichment
  - ***Metal Line Cooling***
    - Cloudy photoionization model tabulated (redshift, density, temperature, metallicity)
    - Only one “metallicity” used for cooling
  - ***Galactic Winds***
    - Kinetic winds launched with ~10^{51} erg per supernova
    - Wind speed scaled with local DM velocity dispersion (~0.75 of halo escape velocity)
    - Lower velocities/Higher mass loadings for low mass galaxies
  - ***AGN Feedback***
    - Quasar mode — continuously dumps thermal energy for high Eddington ratios
    - Radio mode — periodically inflates mechanical bubbles for low Eddington ratios
    - Electromagnitic — gas cooling rates recalculated with ionizing AGN radiation

Vogelsberger et al., (2013)

Torrey et al., (2013)

Feedback Physics

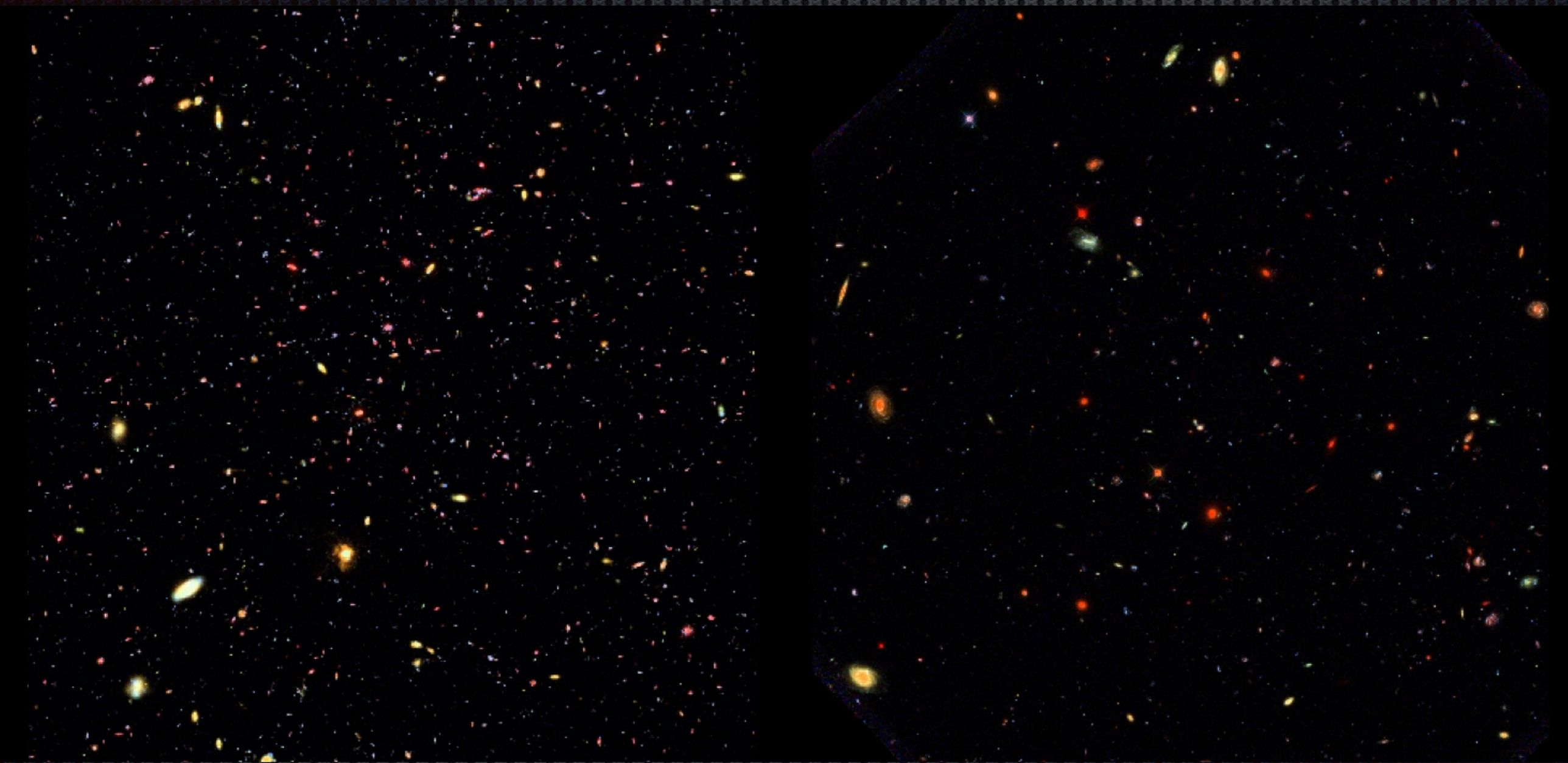


No Feedback

HUDF

Image Credit: Greg Snyder

Feedback Physics

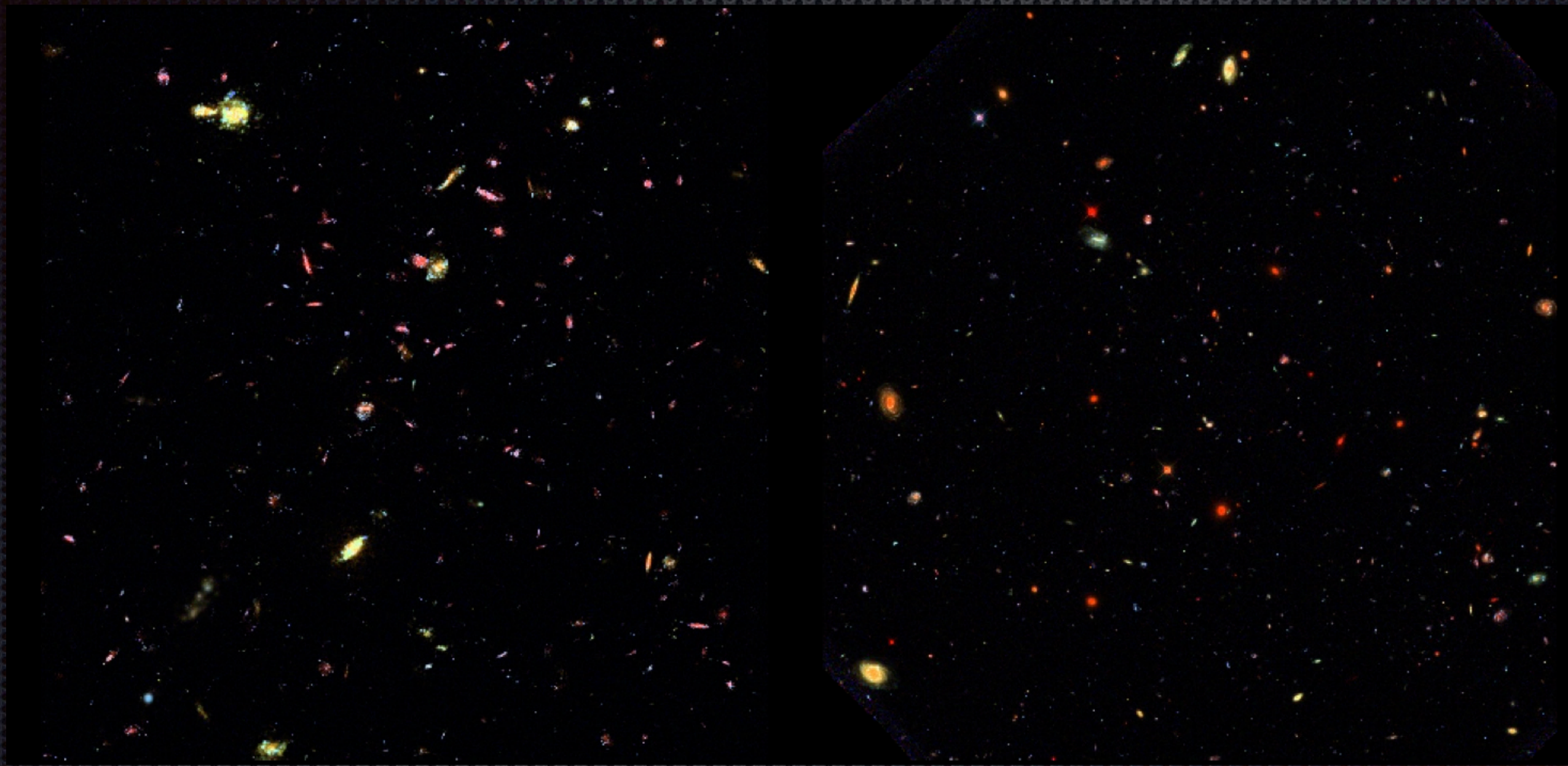


+ Metal Line Cooling
+ Stellar Mass Loss

HUDF

Image Credit: Greg Snyder

Feedback Physics

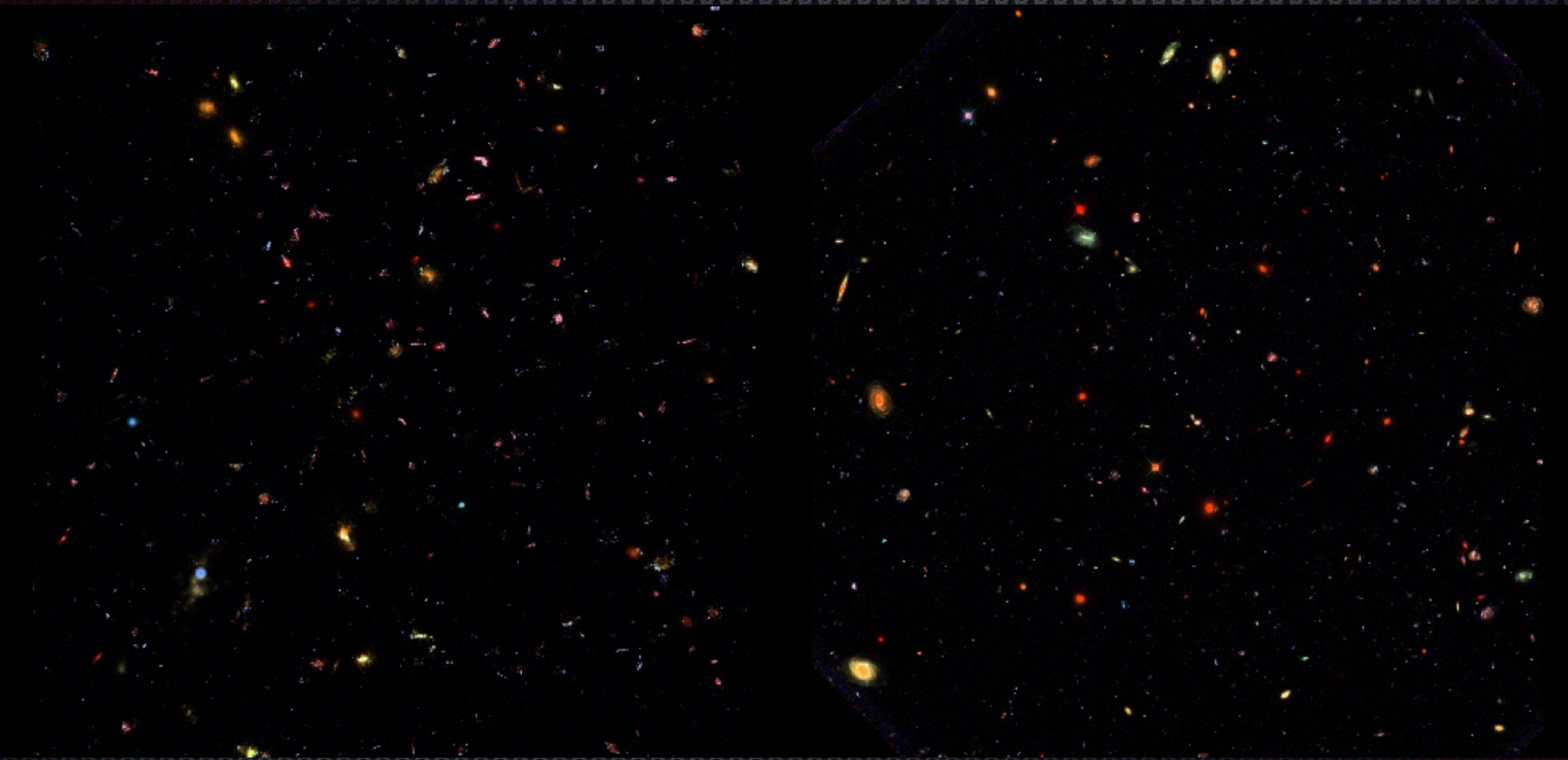


+ Galactic Winds

HUDF

Image Credit: Greg Snyder

Feedback Physics

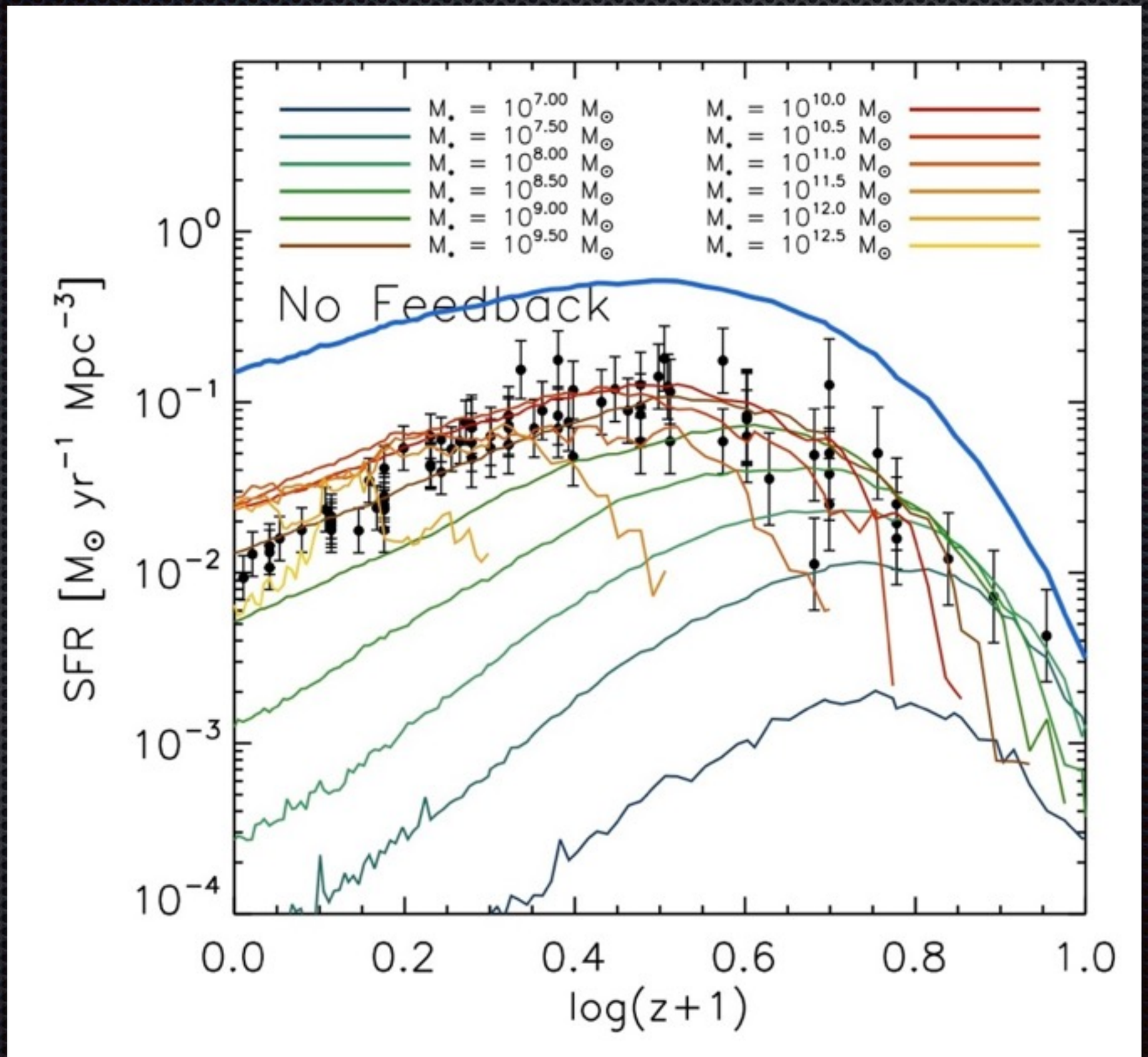


+ AGN Feedback

HUDF

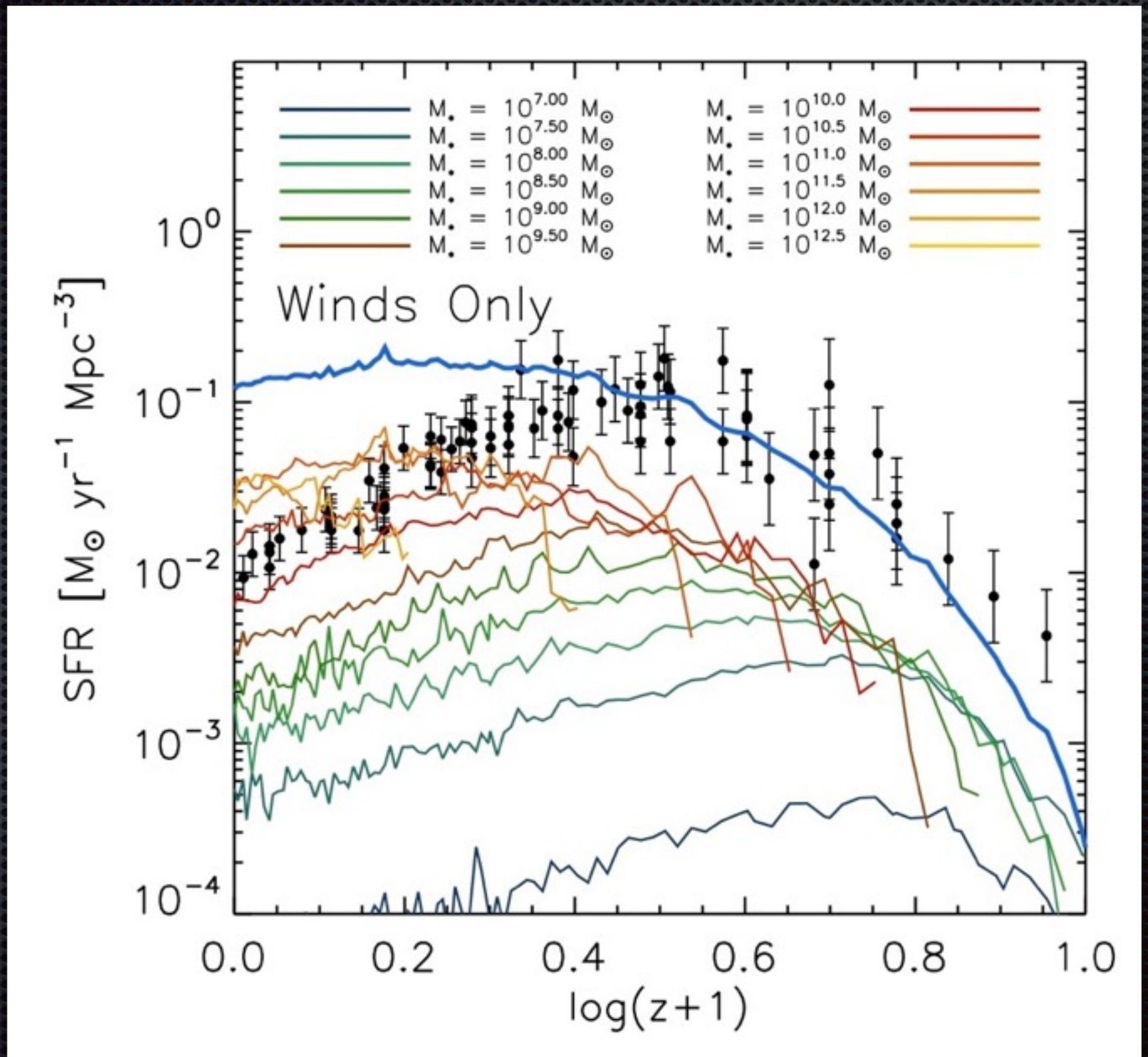
Image Credit: Greg Snyder

Feedback Physics



Torrey+ (2013)

Feedback Physics



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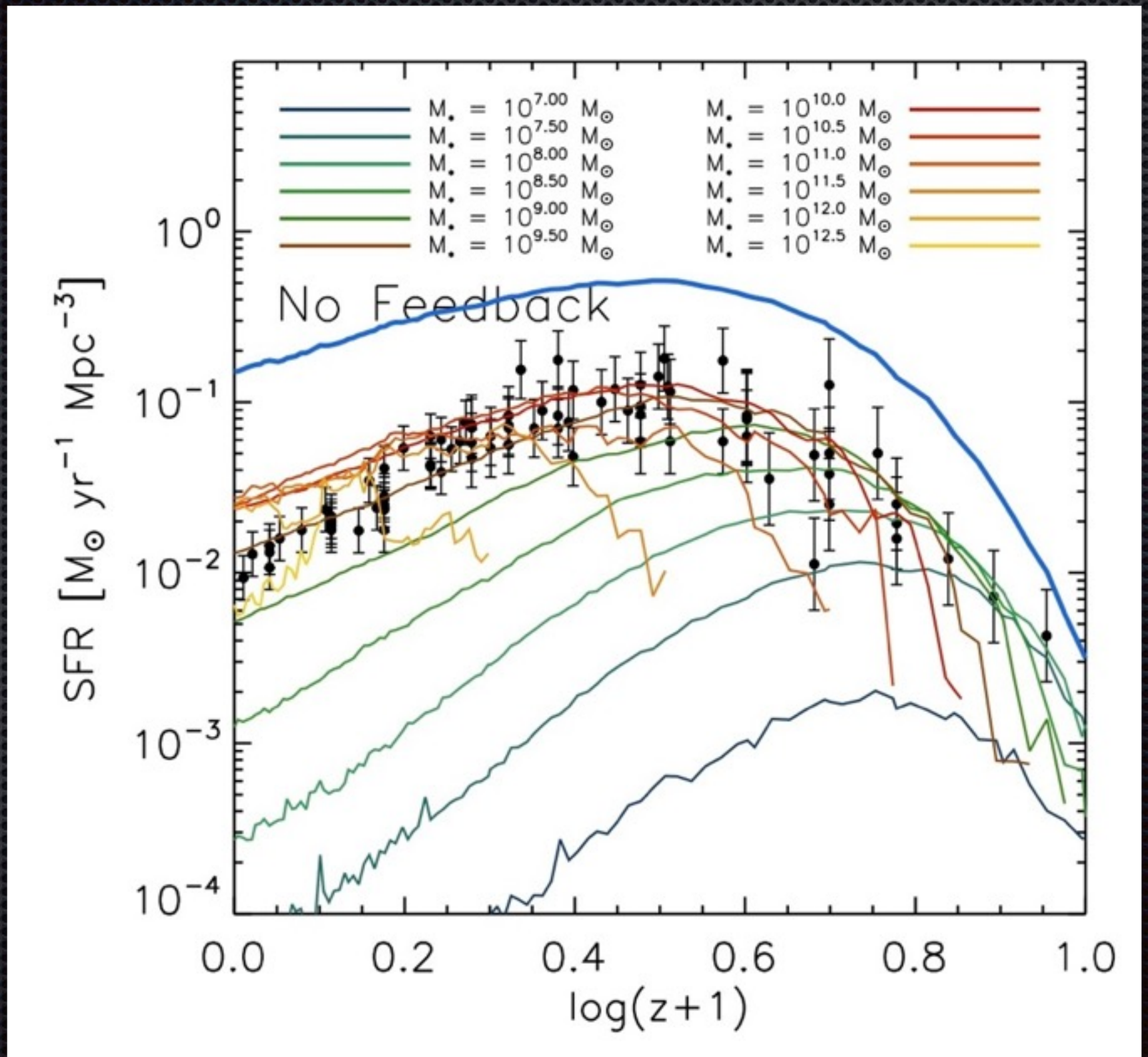

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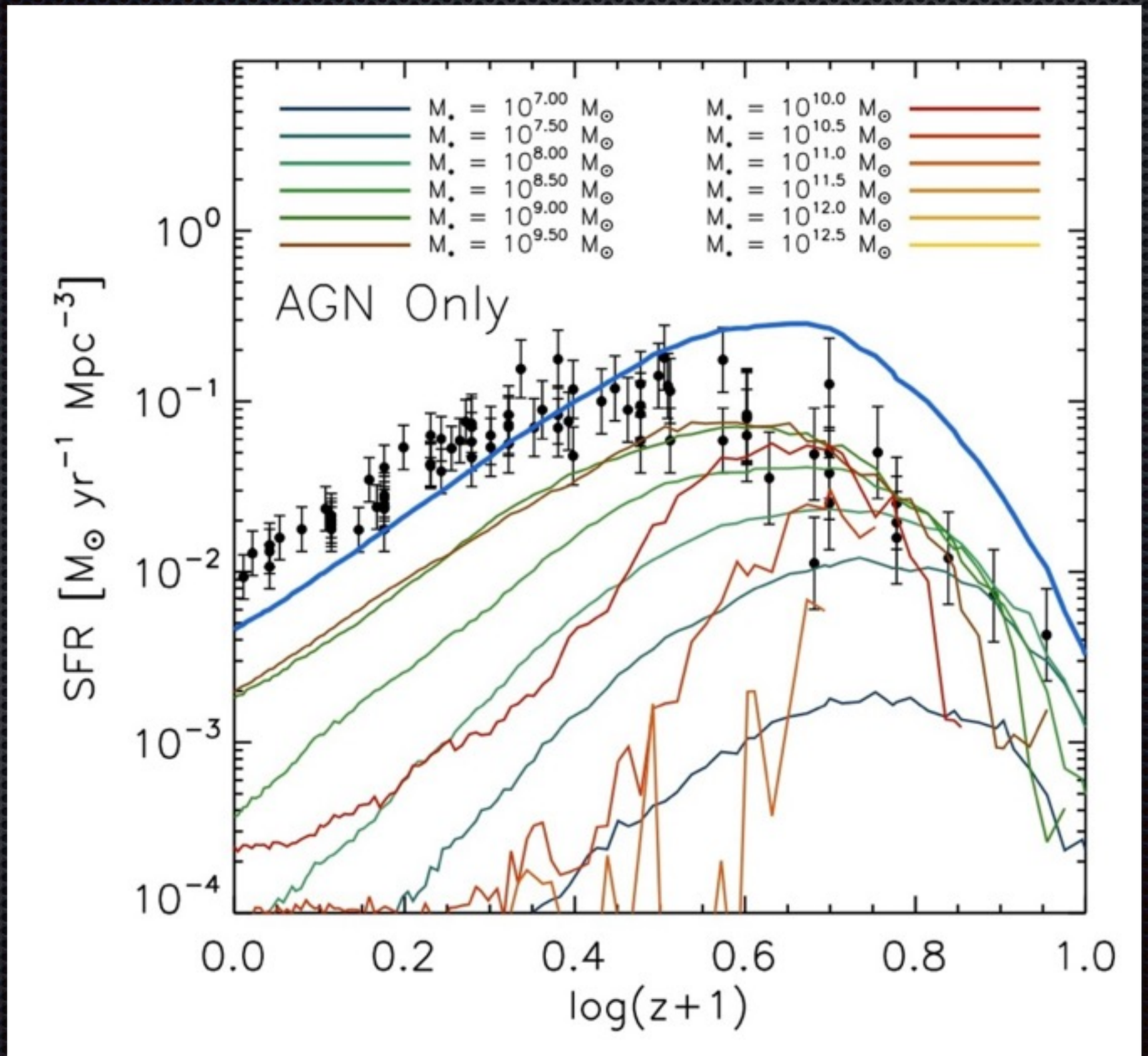

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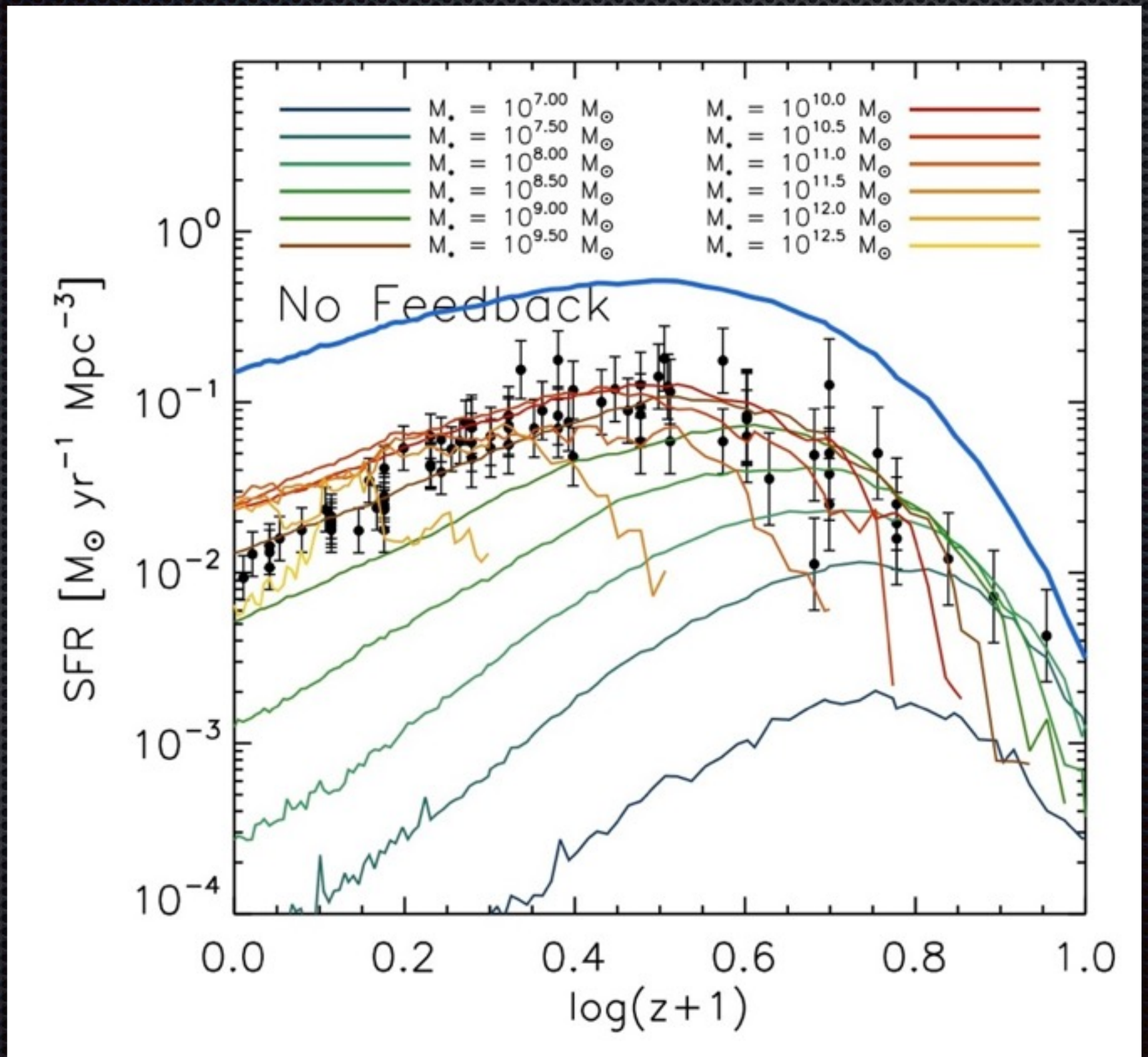

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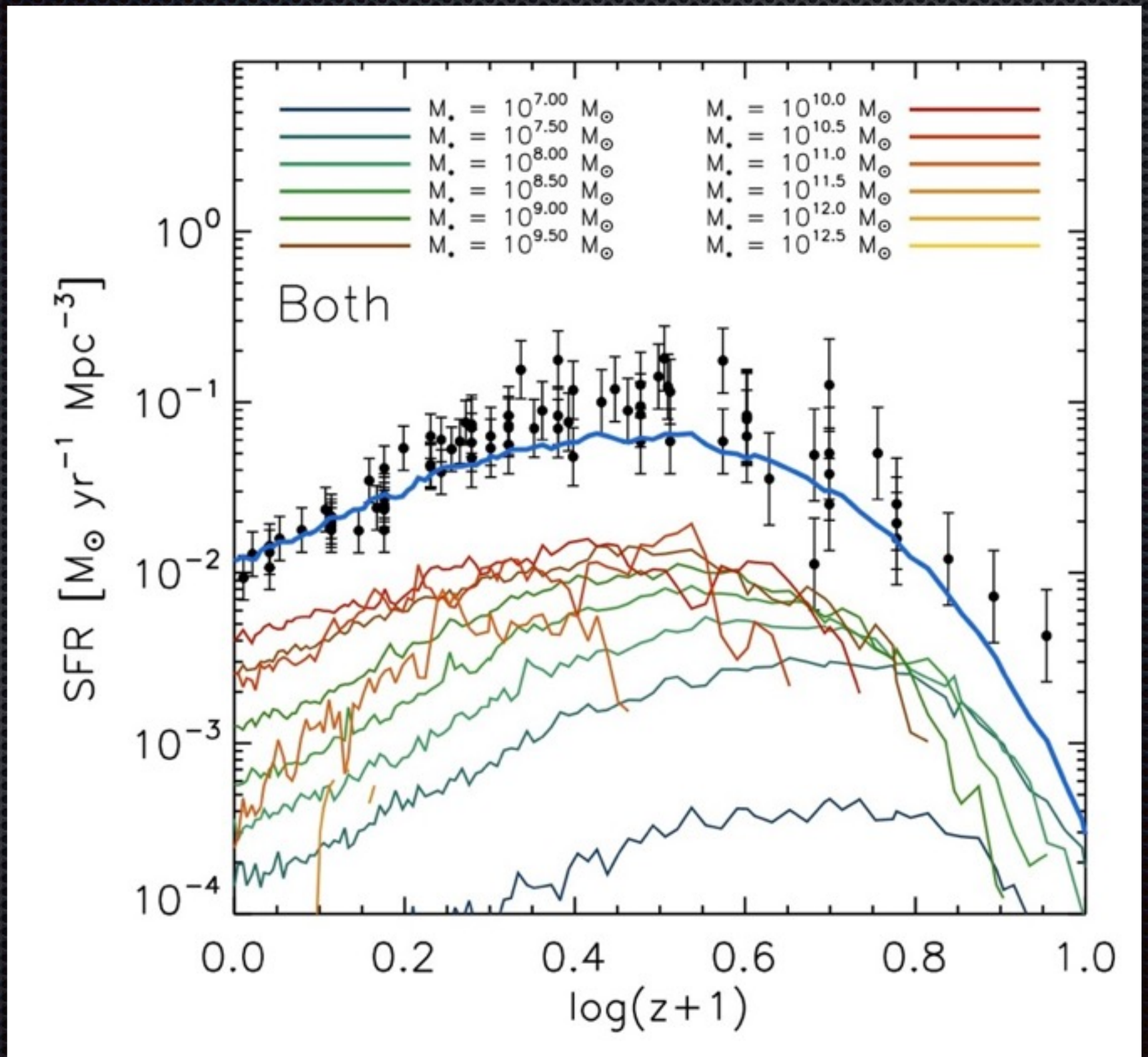


Torrey+ (2013)

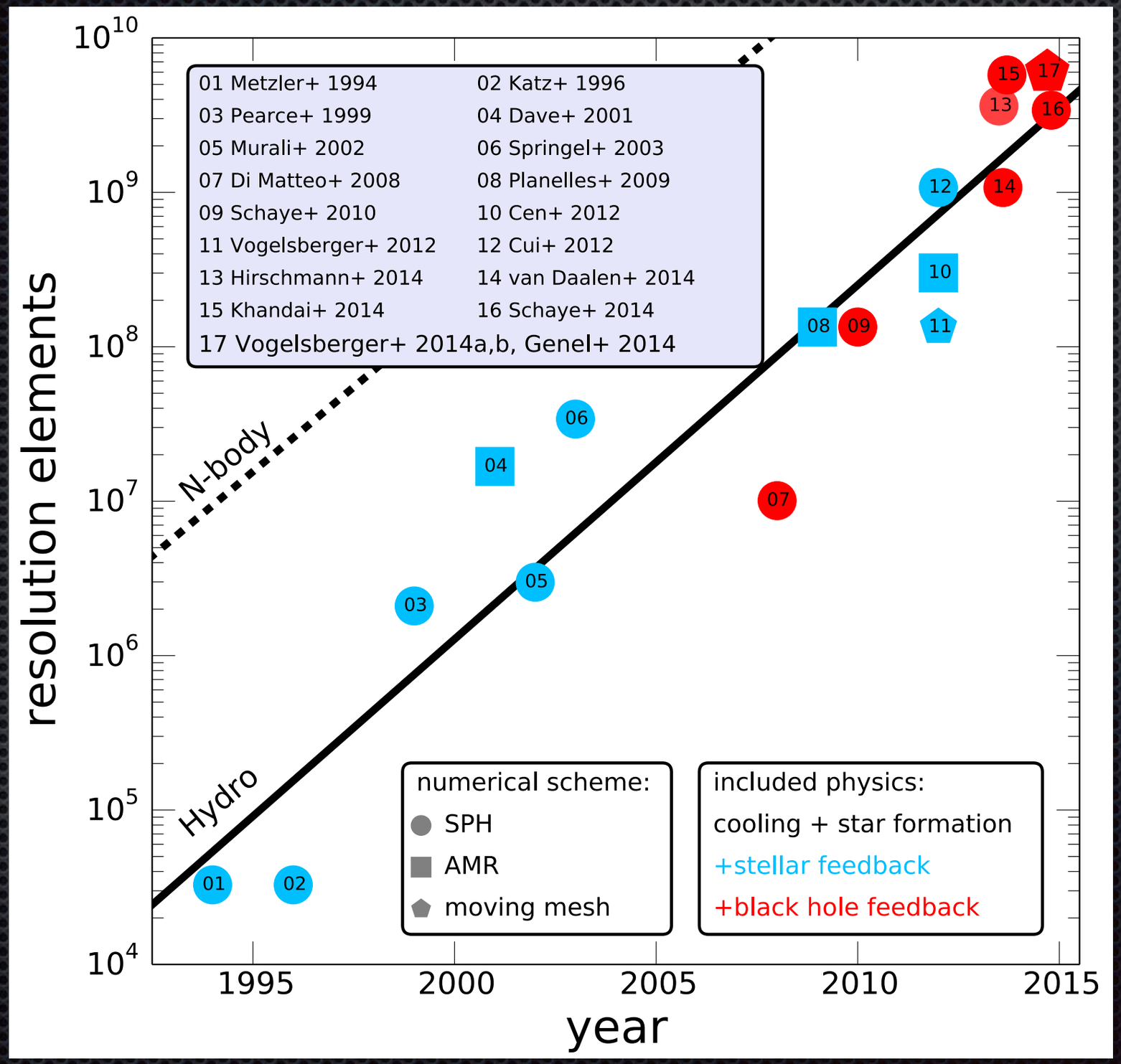
Principle Components of Illustris

1. **AREPO Moving Mesh Code:**
   - Computationally efficient — scales to 10k+ MPI tasks
   - Numerically sound — accurate gravity and hydro solvers

2. **Incorporated comprehensive physics/feedback model:**
   - Stellar Evolution
   - Metal Line Cooling
   - Galactic Winds
   - AGN Feedback

3. **Large Simulation Volumes, “high" resolution:**
   - L=75 Mpc/h periodic boxes
   - Three Resolution Levels:
     - **2×455^3** ($M_{DM} = 4.0 \times 10^8$; $M_{Baryon} = 8.1 \times 10^7$; $\varepsilon = 4.0$ kpc/h co-moving)
     - **2×910^3** ($M_{DM} = 5.0 \times 10^7$; $M_{Baryon} = 1.0 \times 10^7$; $\varepsilon = 2.0$ kpc/h co-moving)
     - **2×1820^3** ($M_{DM} = 6.2 \times 10^6$; $M_{Baryon} = 1.2 \times 10^6$; $\varepsilon = 1.0$ kpc/h co-moving)

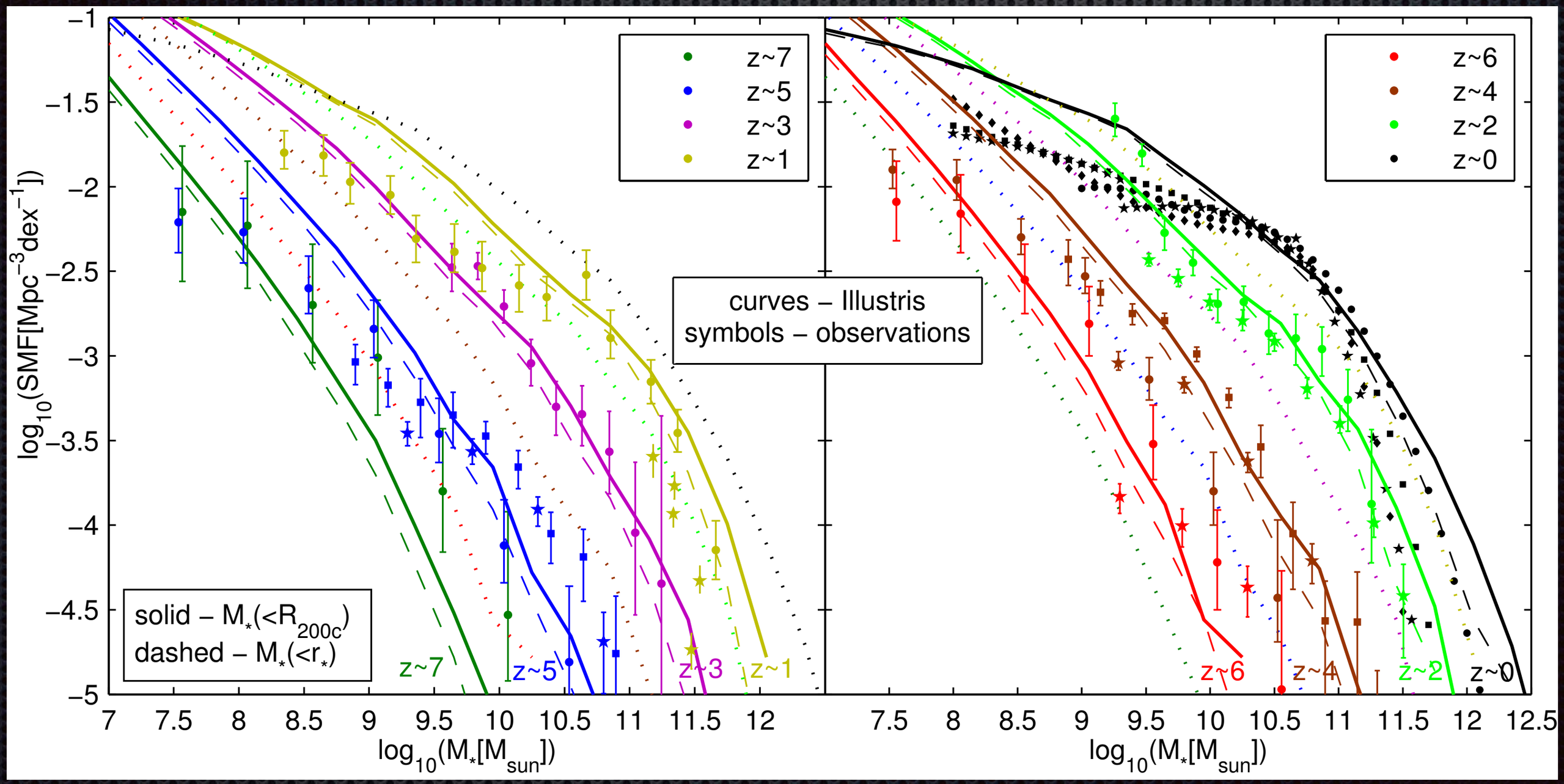
Principle Components of Illustris



The Illustris Simulation

The Illustris Simulation

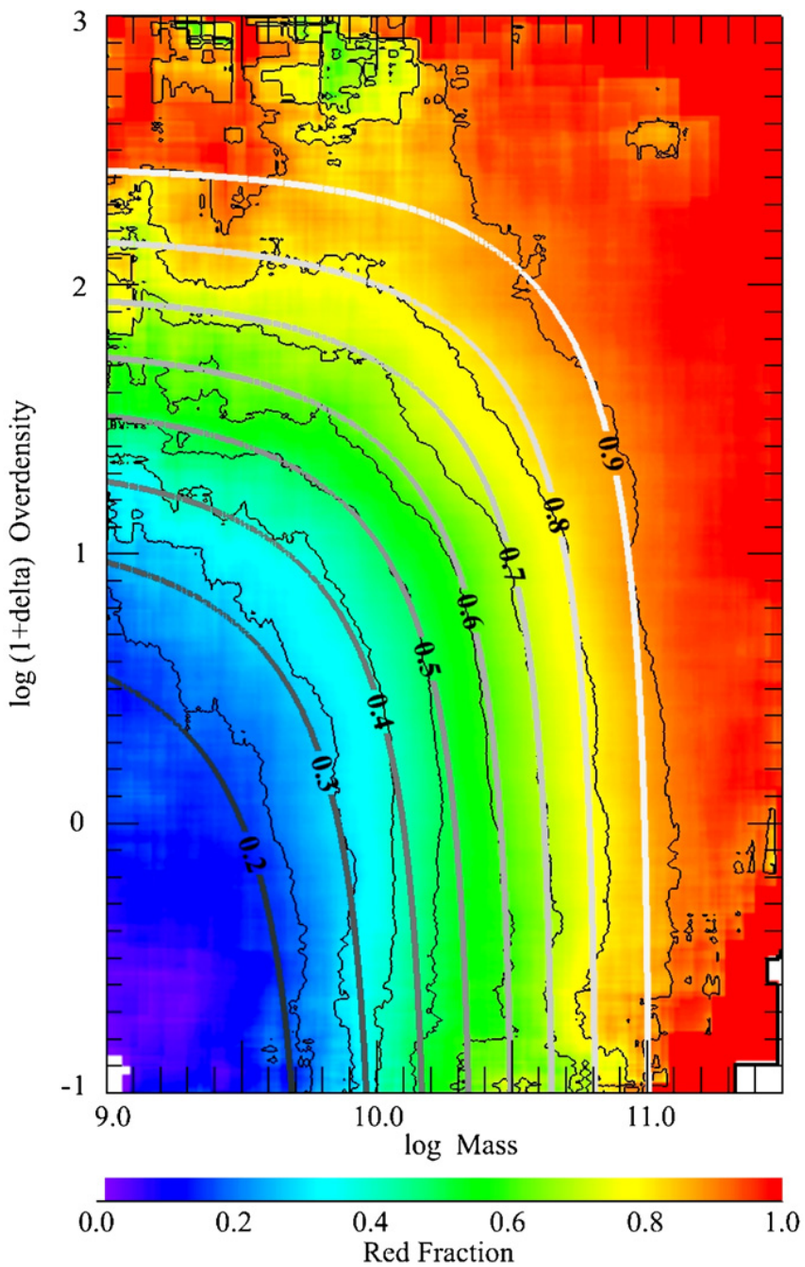
Galaxy Stellar Mass Function



Genel+ (2014)

Illustris Project:

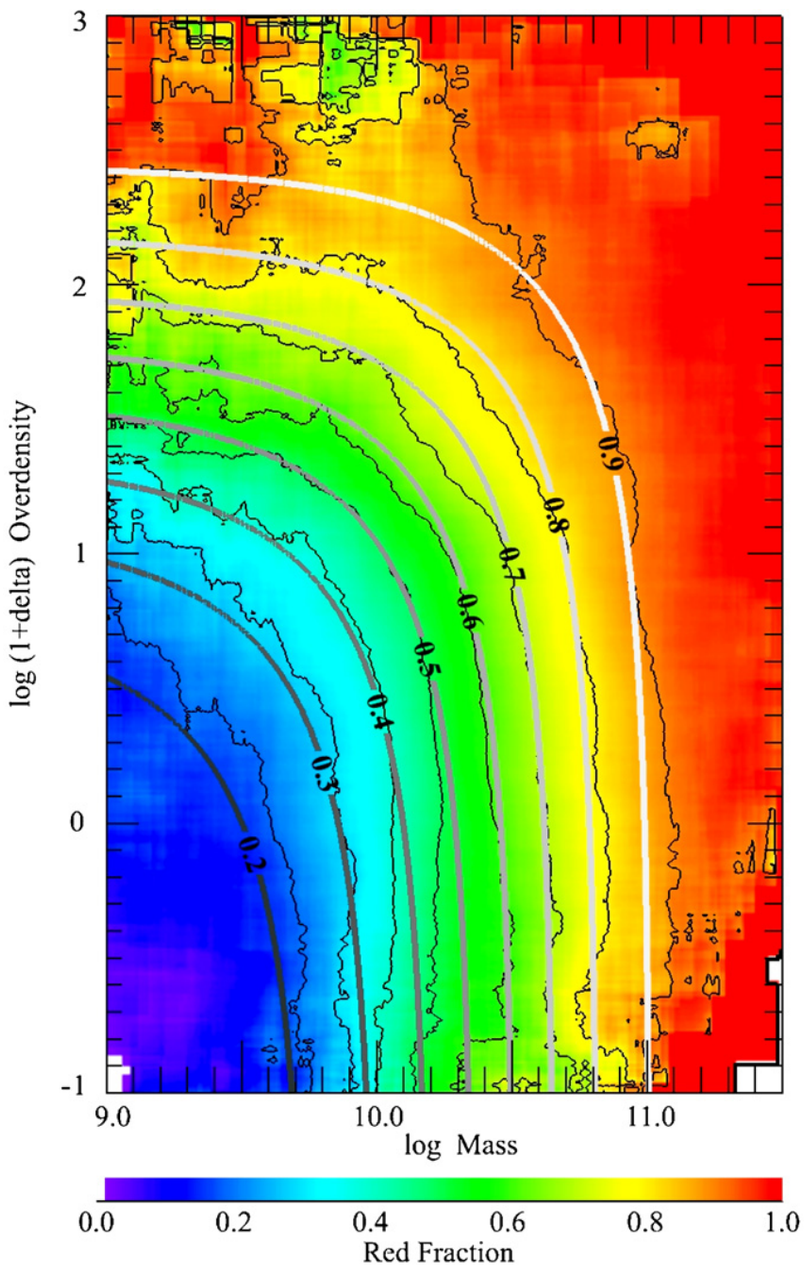
SDSS red fraction



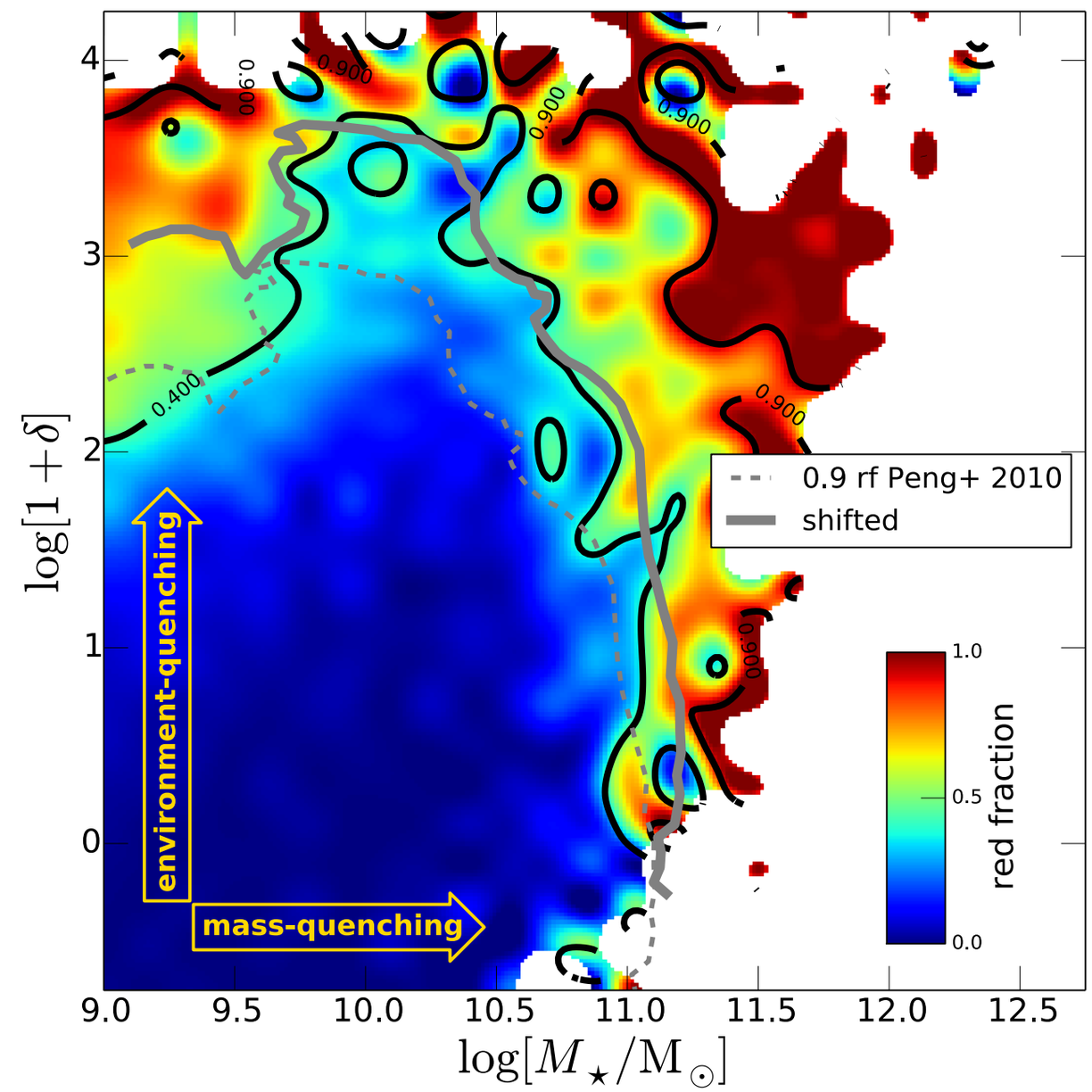
Peng+ (2010)

Illustris Project:

SDSS red fraction



Illustris red fraction

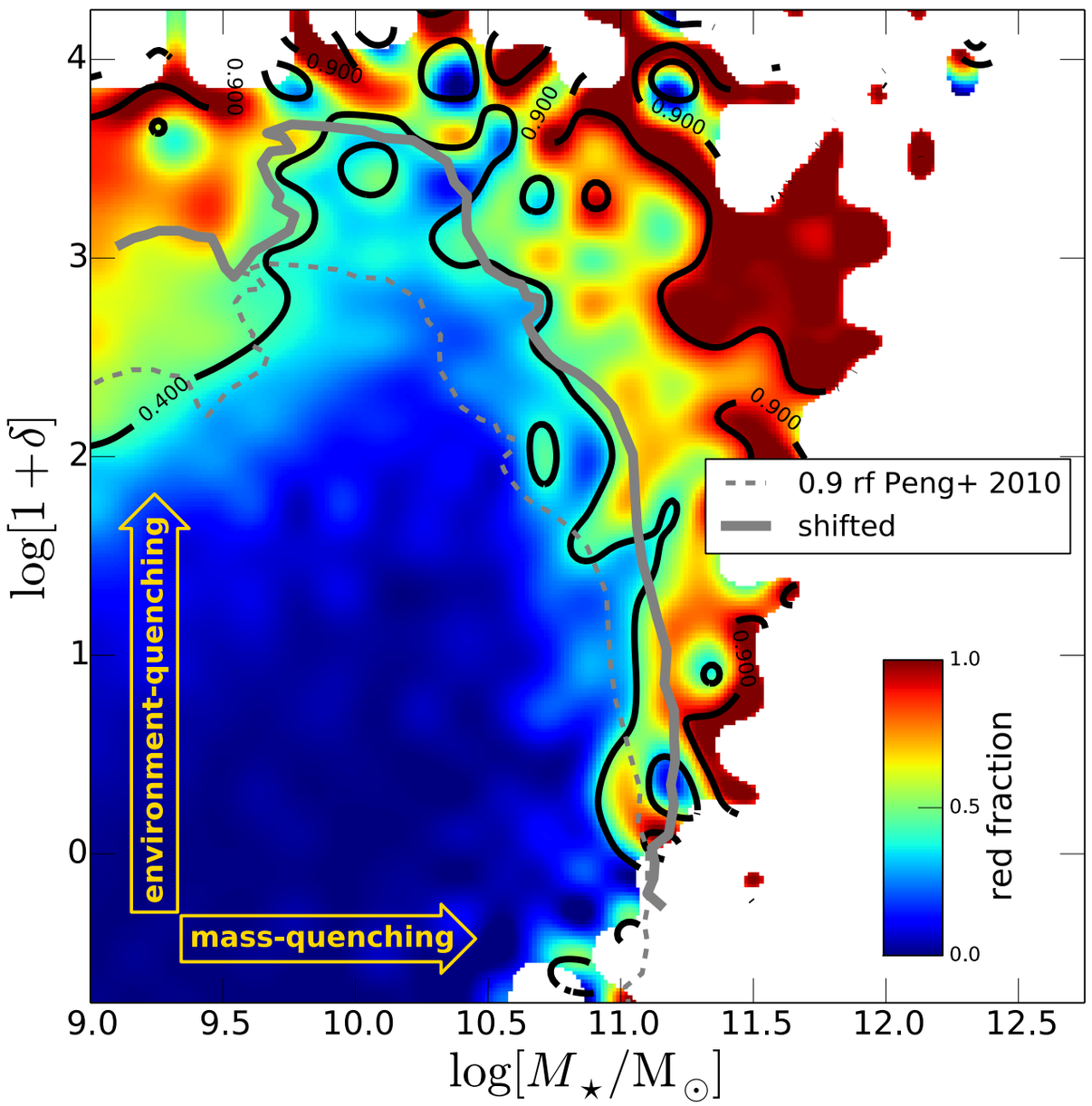


Peng+ (2010)

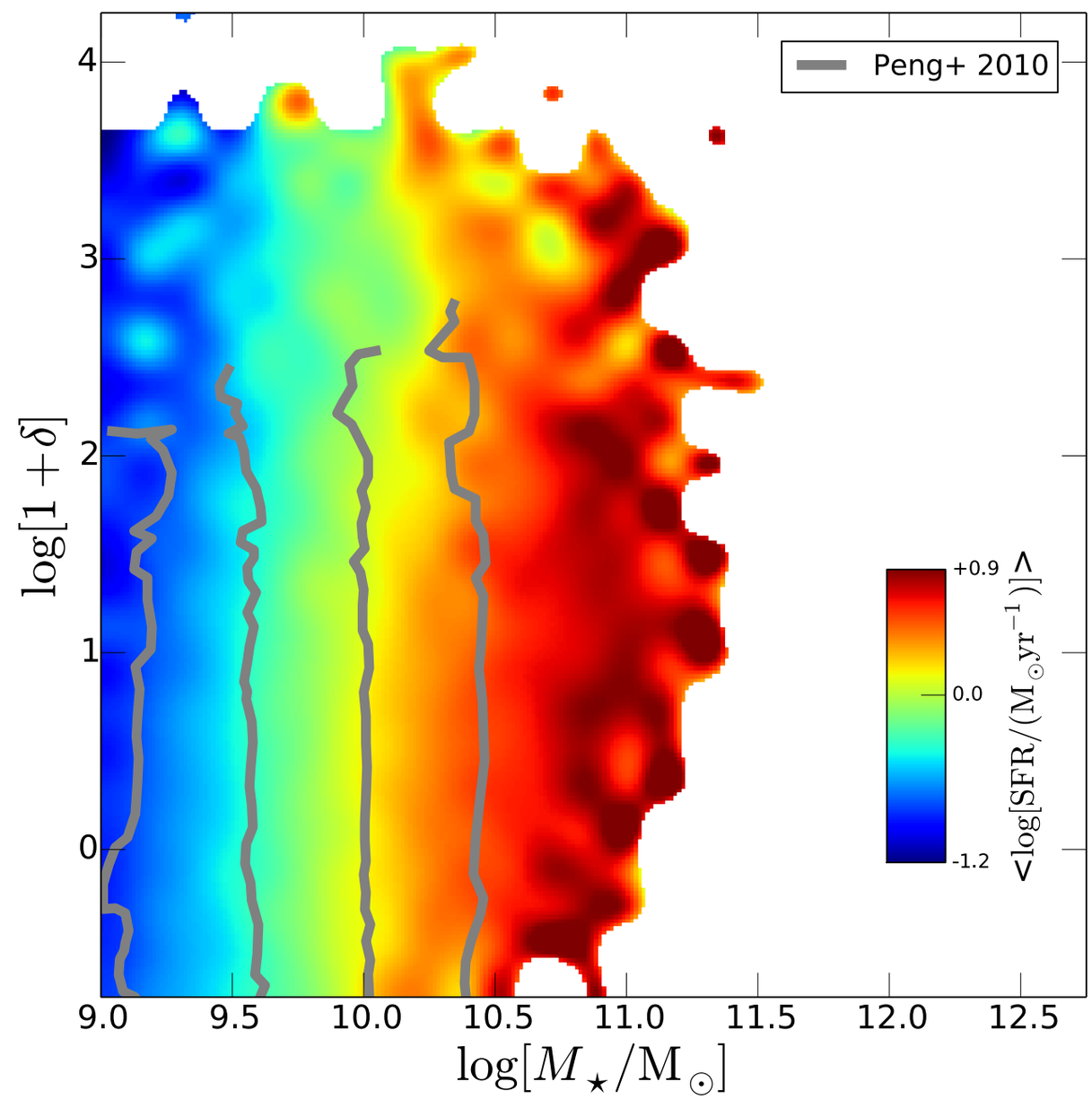
Vogelsberger+ (2014)

Illustris Project:

Illustris red fraction

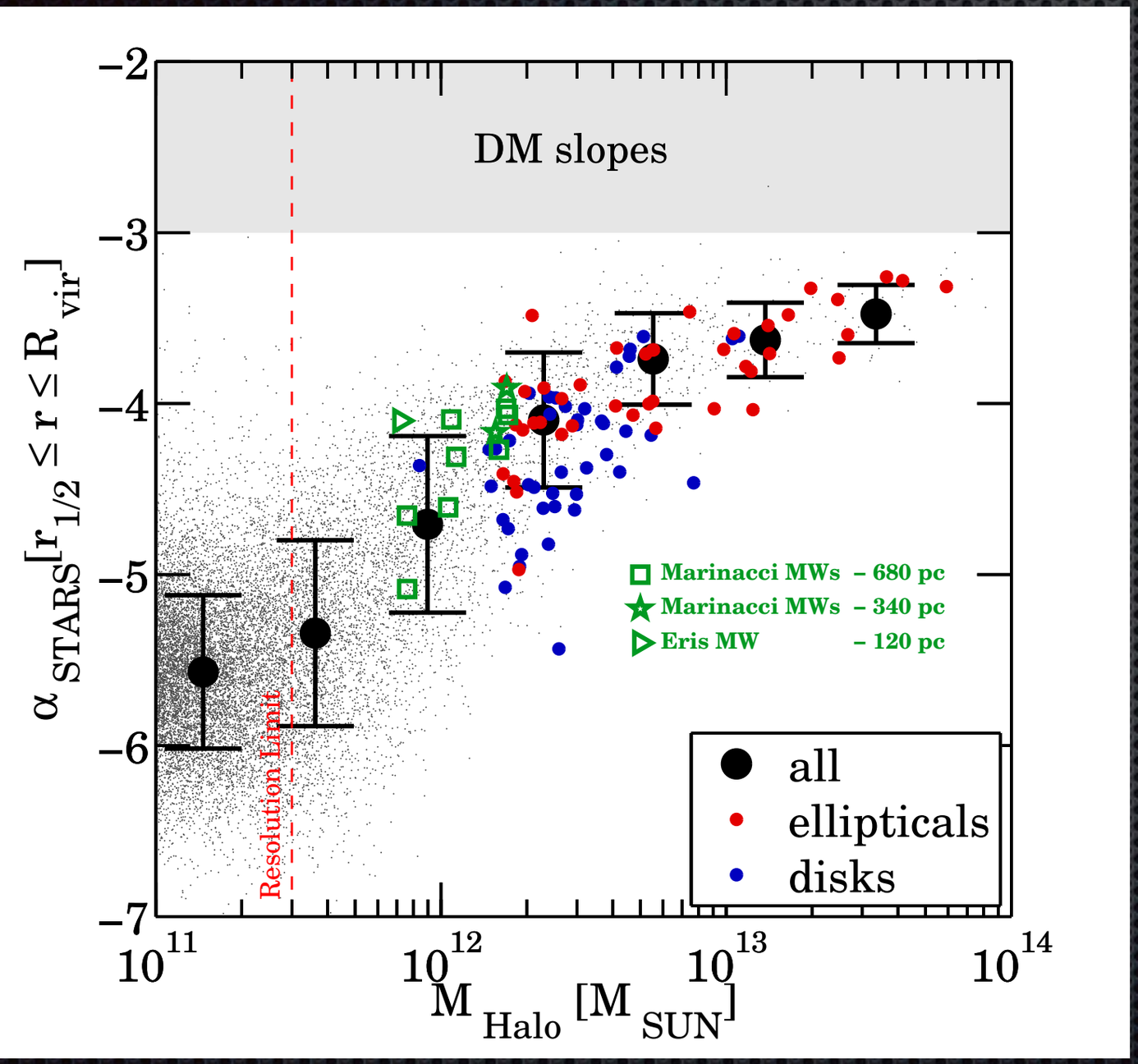


Avgerage SFR



Vogelsberger+ (2014)

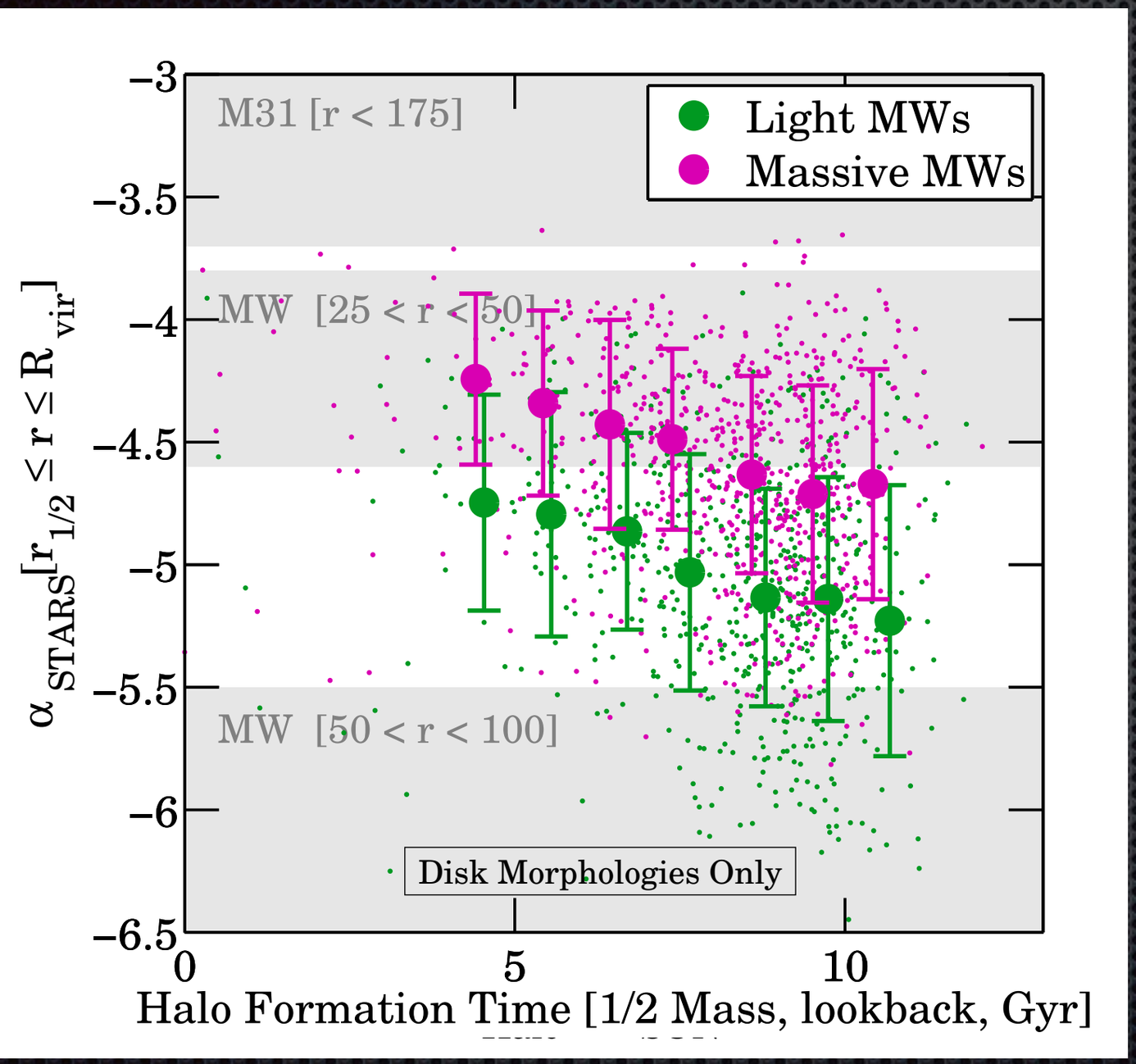
Illustris Project:



- Alpha = power law slope of outer stellar profile
- Steeper slope at low mass end
- Slope approaches DM halo slope as "ex-situ" fraction increases
- Analysis in thin mass bins predicts stellar haloes can probe galaxy formation time.

Pillepich+ (2014)

Illustris Project:



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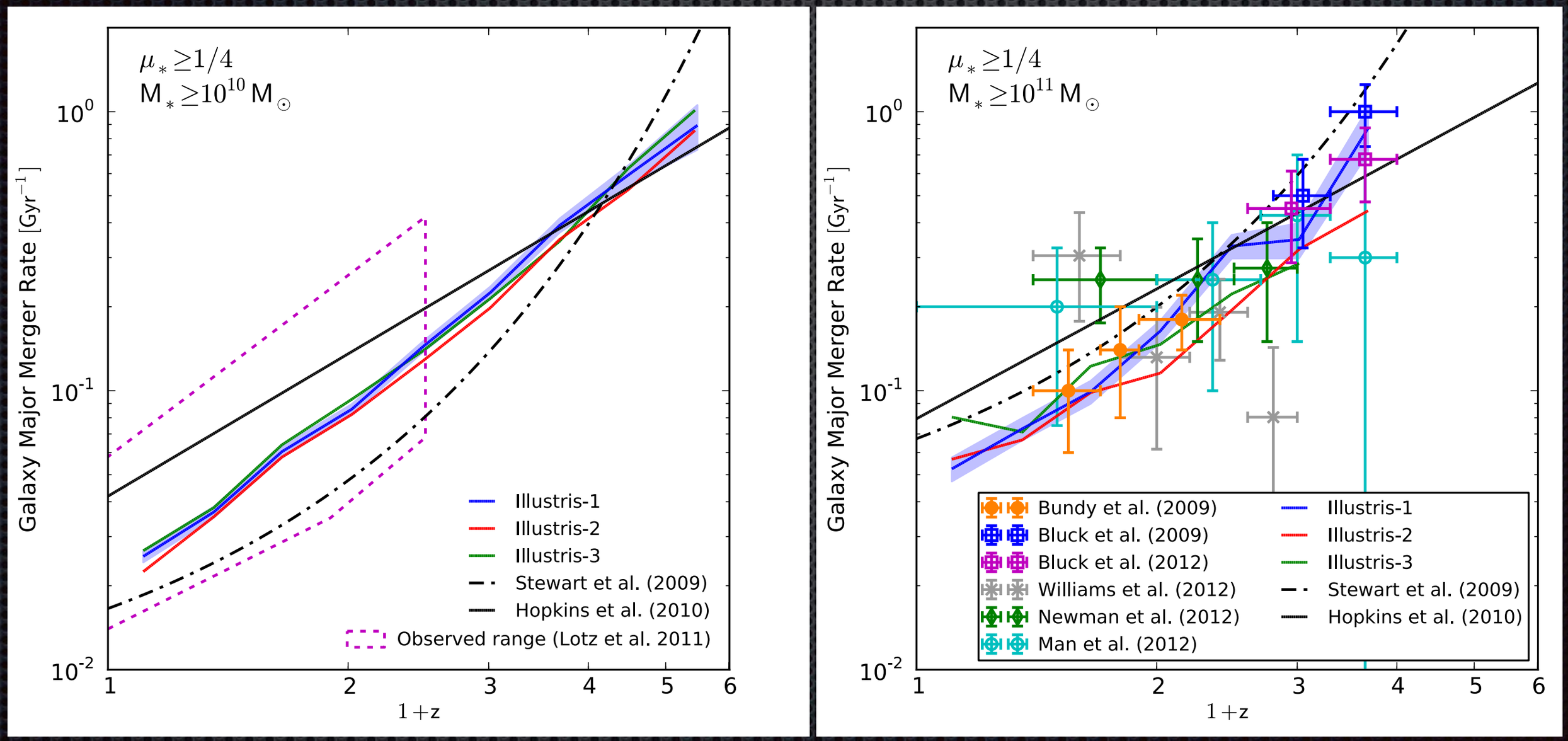
Pillepich+ (2014)

Illustris Project:

Major Merger Rate



Rodriguez-Gomez+ (2015)

Image Pipeline: General Summary

- Goals:
  - Convert simulated galaxy population into mock survey data
  - Place in accessible format for observers to access and compare
  - Analyze in even handed comparison using observational tools

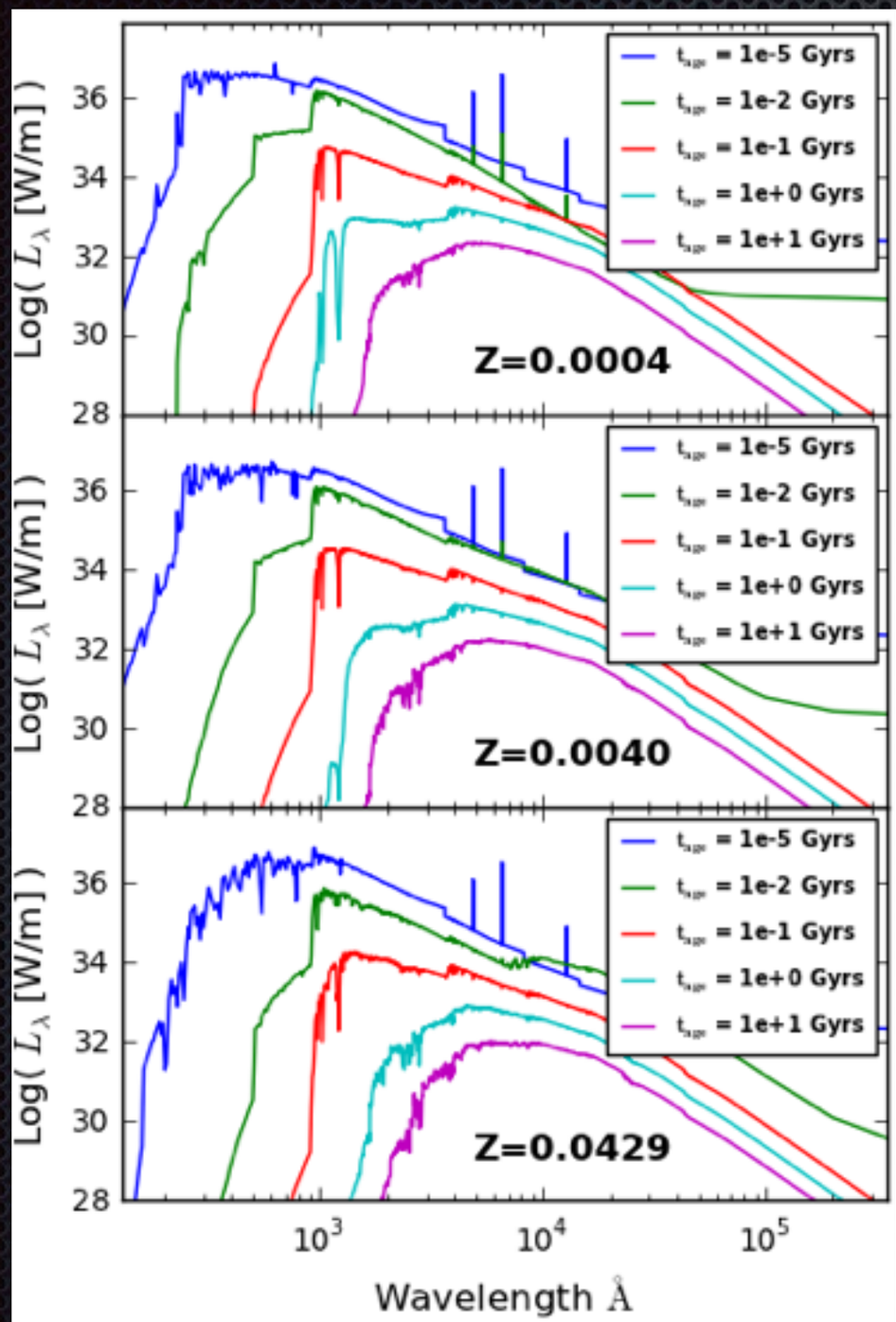
- Methods:
  - Assign light sources (stars only; can be generalized)
  - BC03 & SB99 SPS models employed
  - Observe with mock-telescopes/mock-filters

- Resulting Current and Completed Projects:
  - Accuracy of photometric stellar mass determinations
  - Gini-M20 non-parametric structural fits
  - Compact massive galaxy analysis
  - gim2d galaxy structural analysis

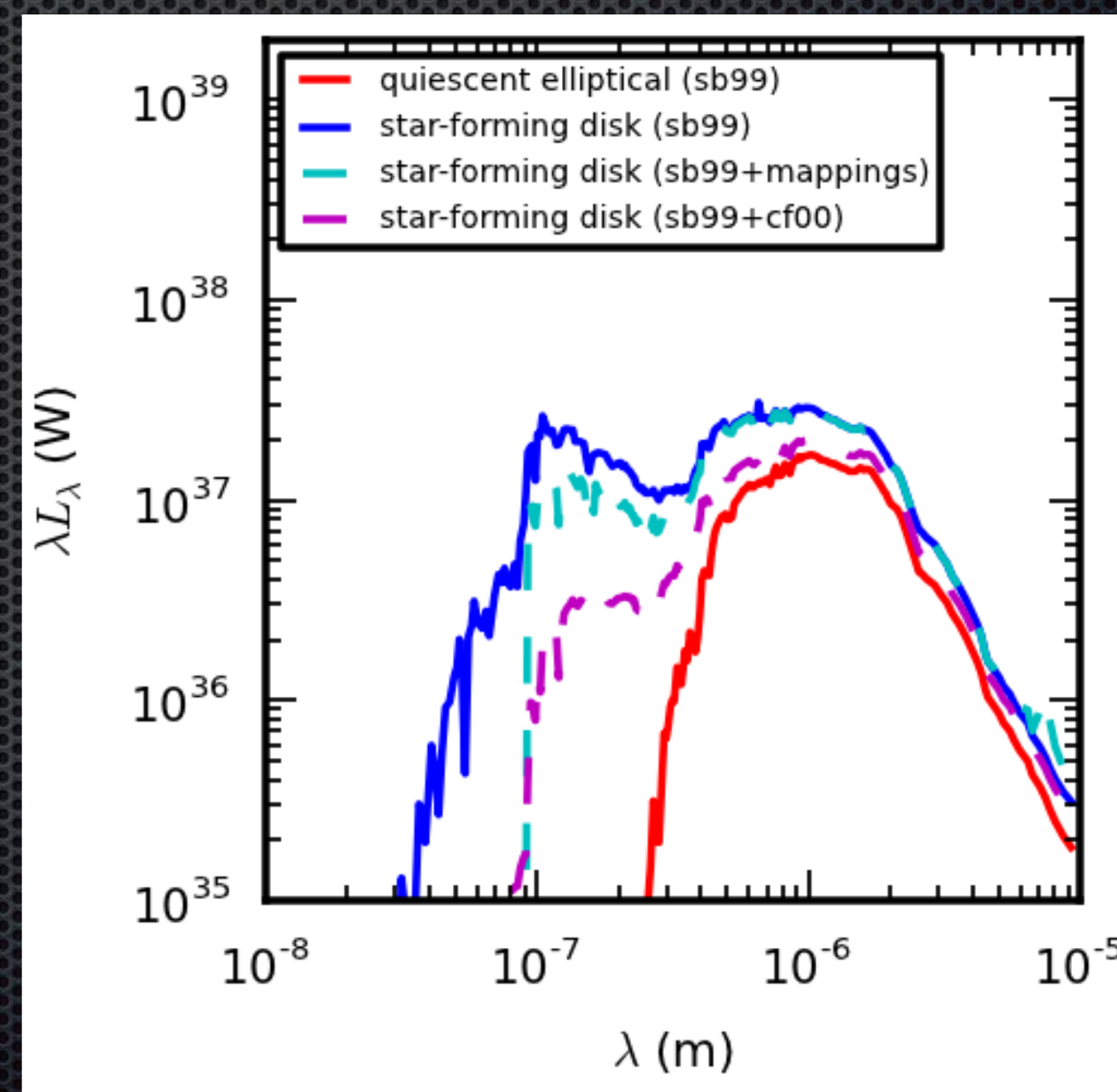
Torrey, Snyder+ (2015)
Synder, Torrey+ (2015)

Illustris Simulation Observatory

SPS Spectrum



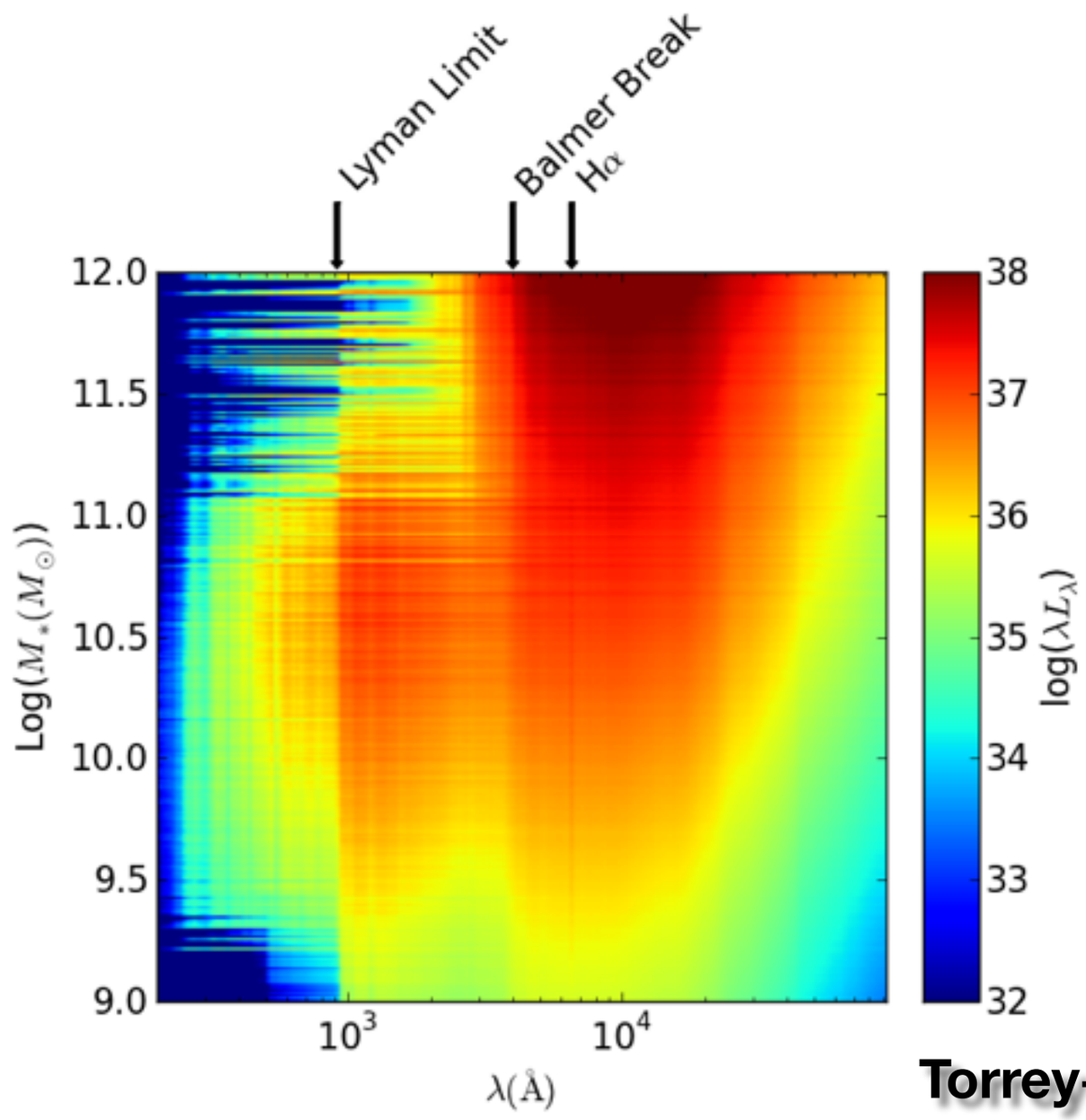
Galaxy Spectrum

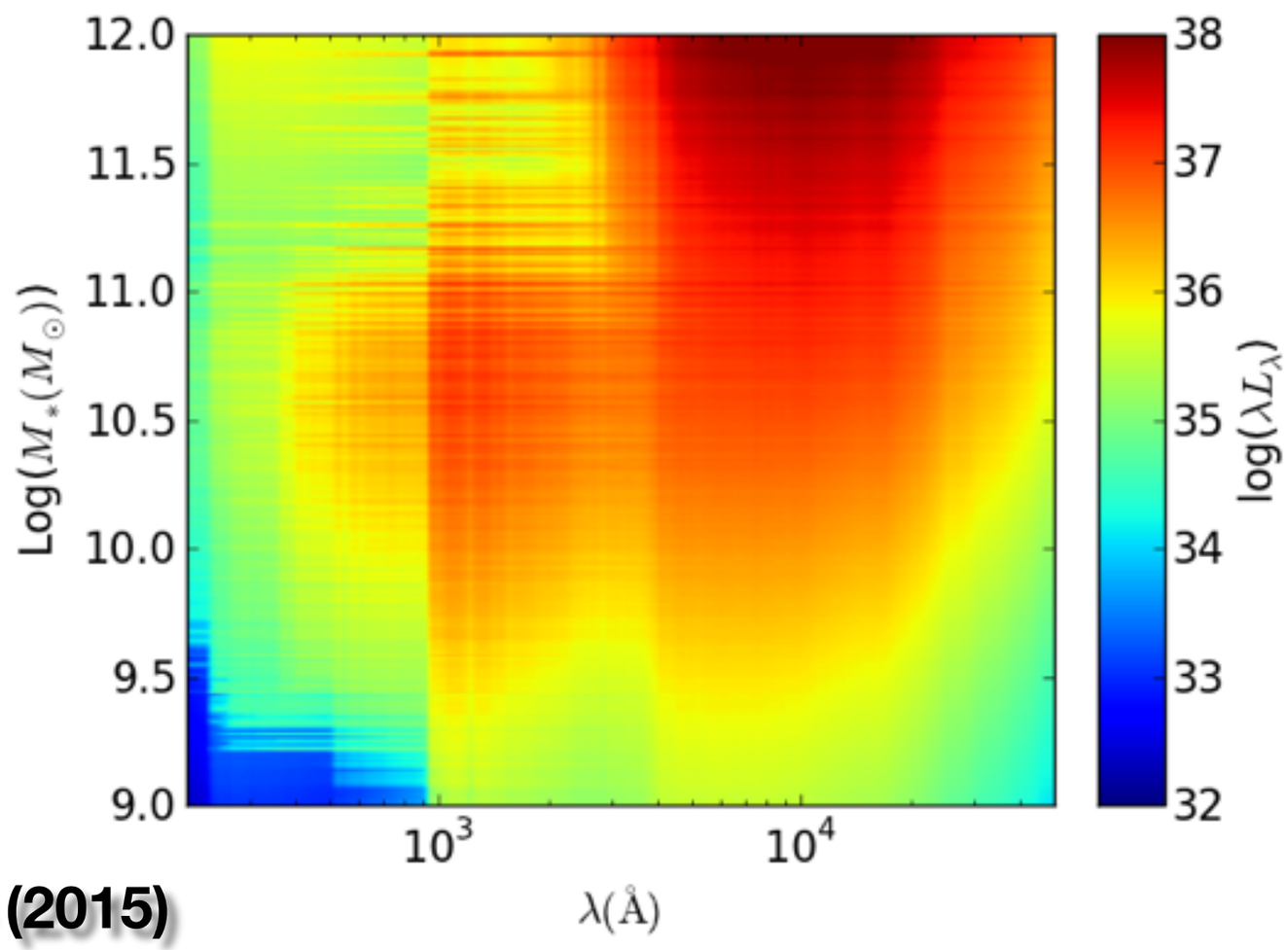


Torrey+ (2015)

Illustris Simulation Observatory

SB99 BC03

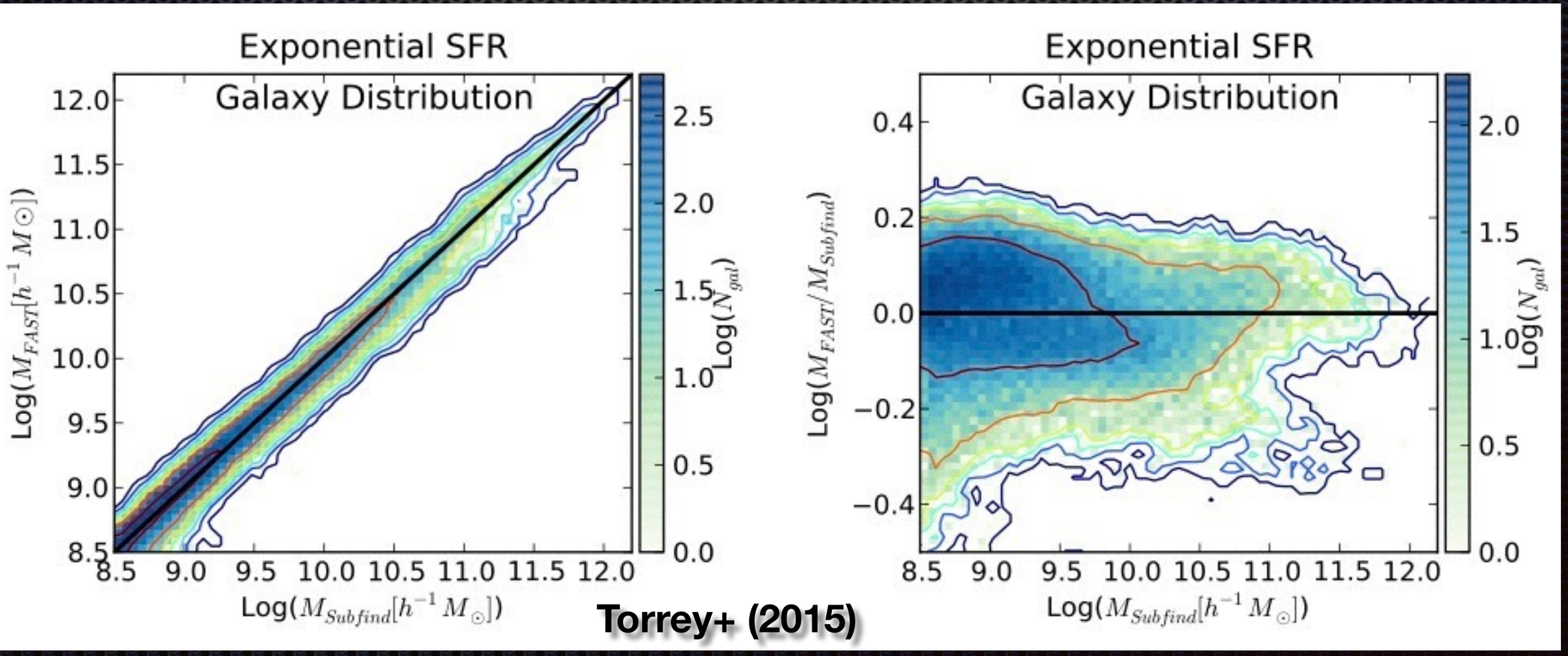




Torrey+ (2015)

Stellar Mass Fitting

- Stellar masses re-derived from mock photometric data using FAST
- Compare re-derived stellar masses vs. simulated stellar masses

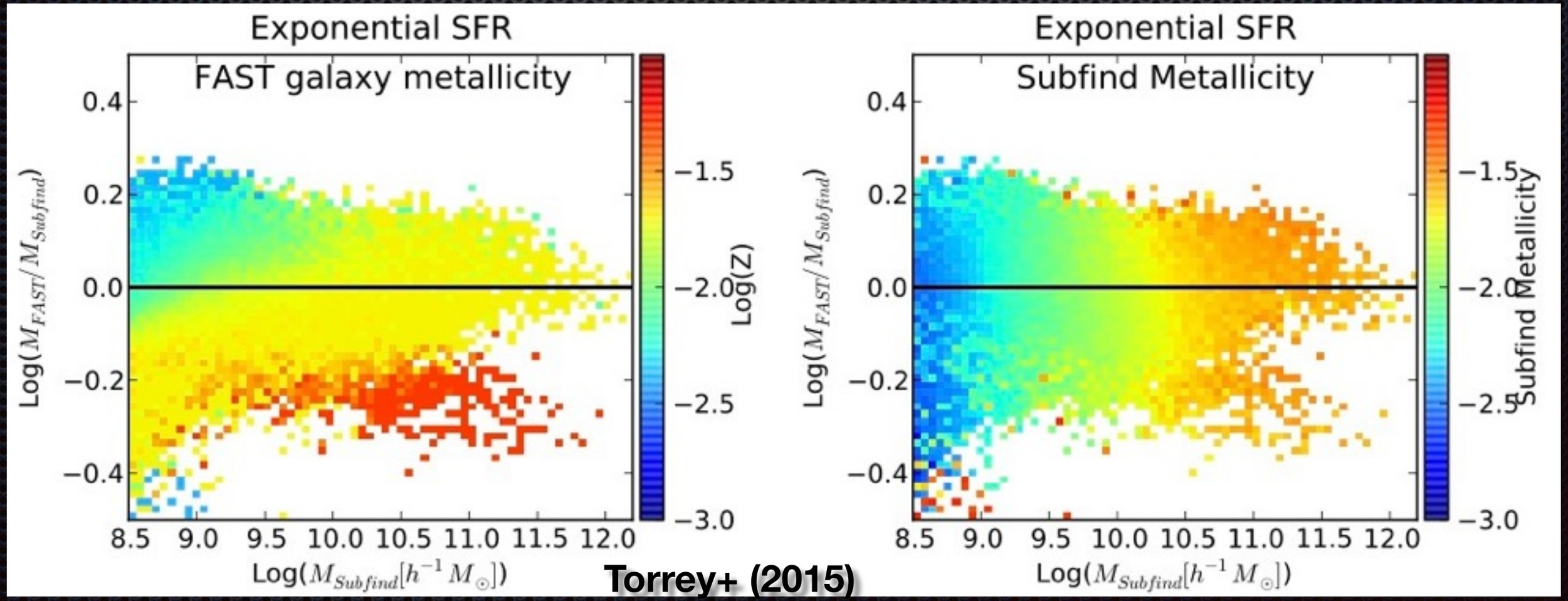


Torrey+ (2015)

Stellar Mass Fitting

- Stellar masses re-derived from mock photometric data using FAST
- Compare re-derived stellar masses vs. simulated stellar masses

Result: At a fixed "true" galaxy mass, the derived mass will depend on the assigned metallicity

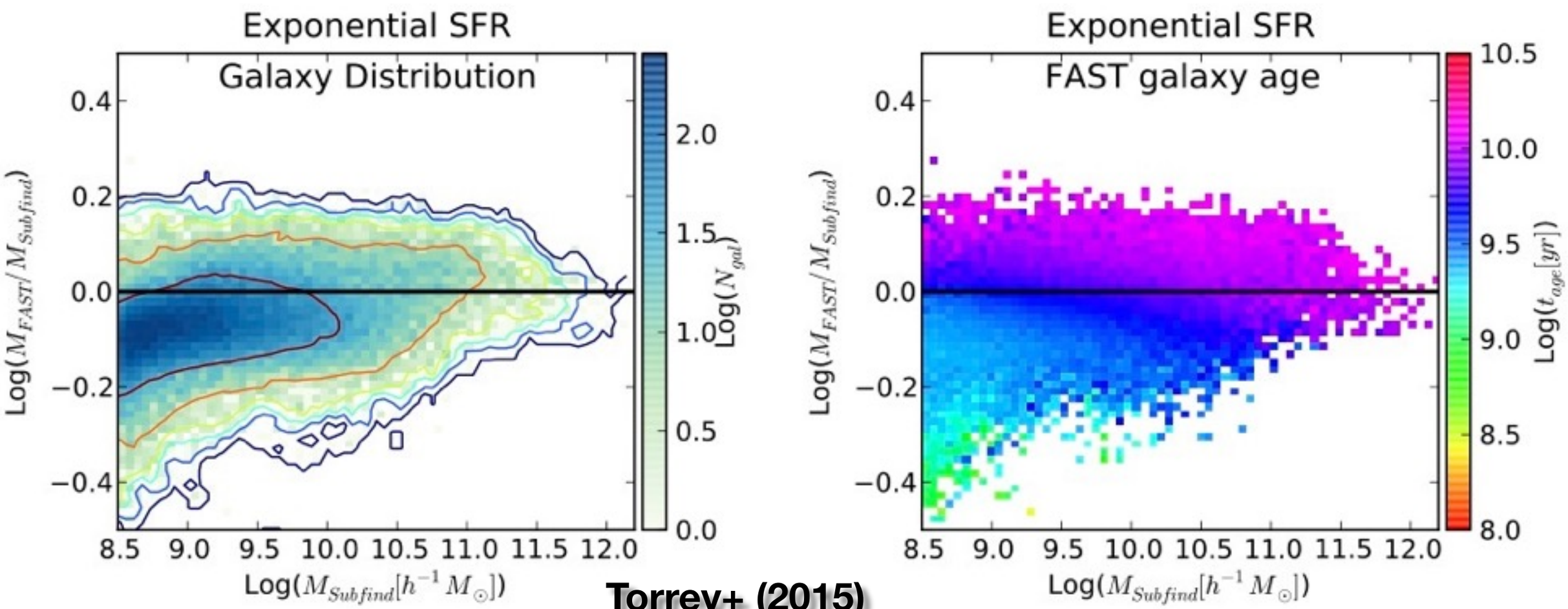


Torrey+ (2015)

Stellar Mass Fitting

- Stellar masses re-derived from mock photometric data using FAST
- Compare re-derived stellar masses vs. simulated stellar masses

Result: The error in the SED derived stellar mass depends on the inferred galaxy age

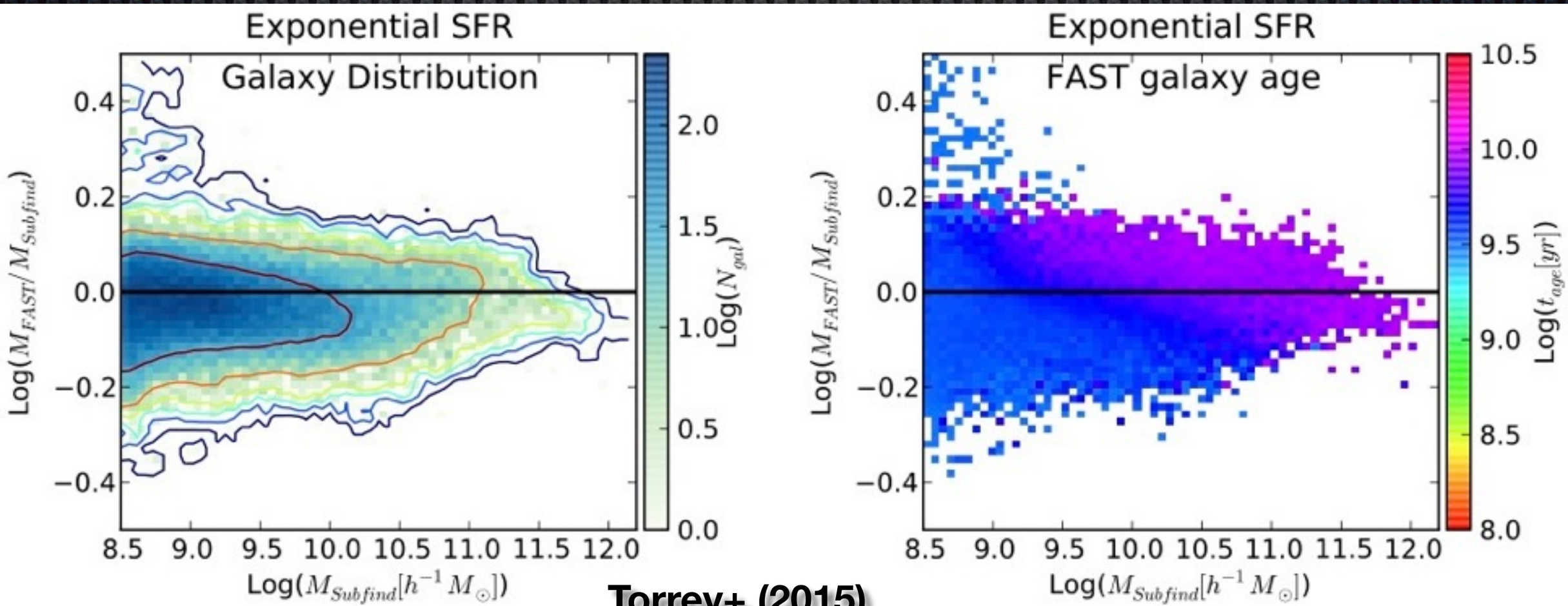


Torrey+ (2015)

Stellar Mass Fitting

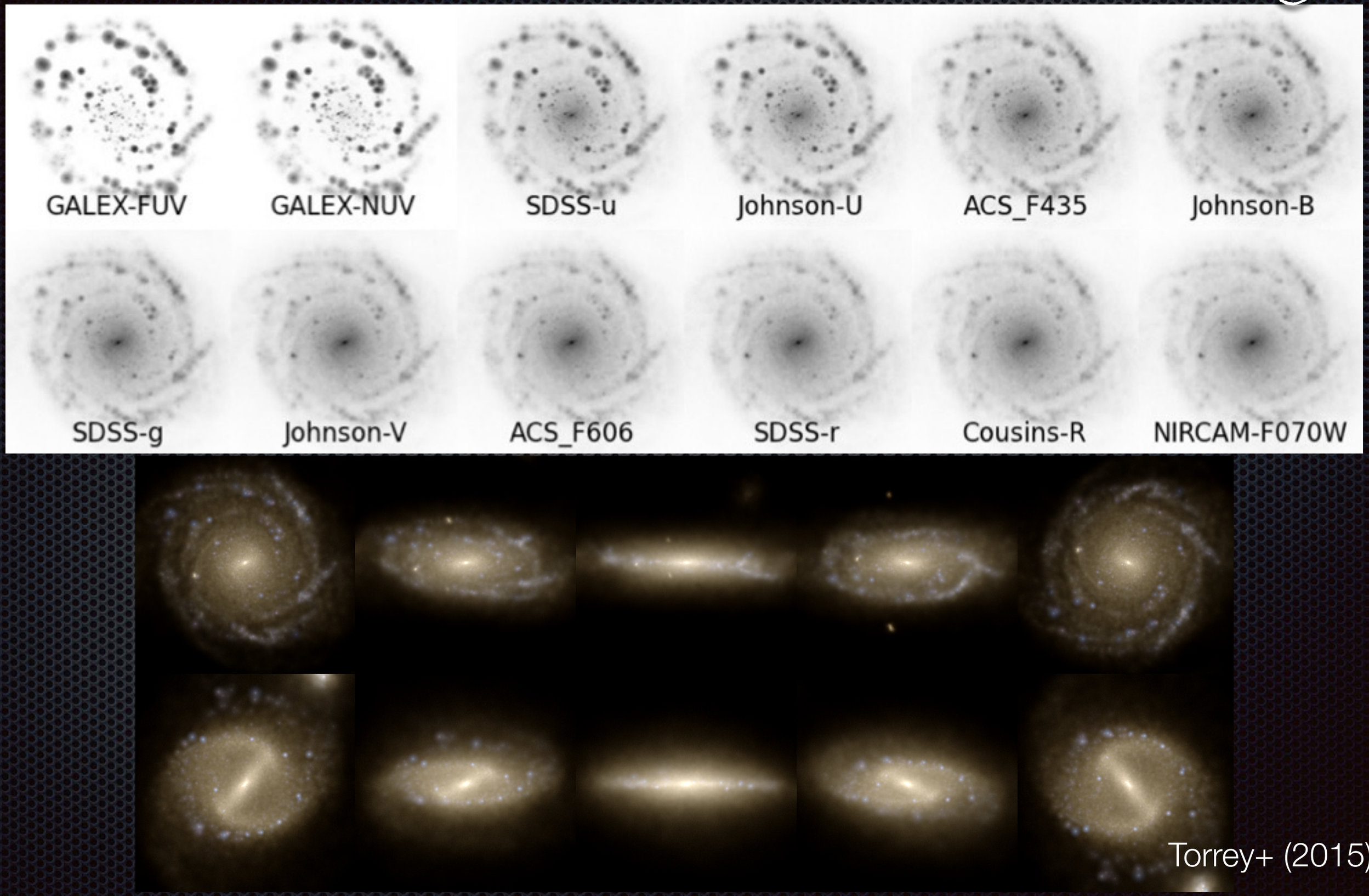
- Stellar masses re-derived from mock photometric data using FAST
- Compare re-derived stellar masses vs. simulated stellar masses

Result: Limiting the minimum assigned galaxy age reduces the error in the assigned galaxy mass.



Torrey+ (2015)

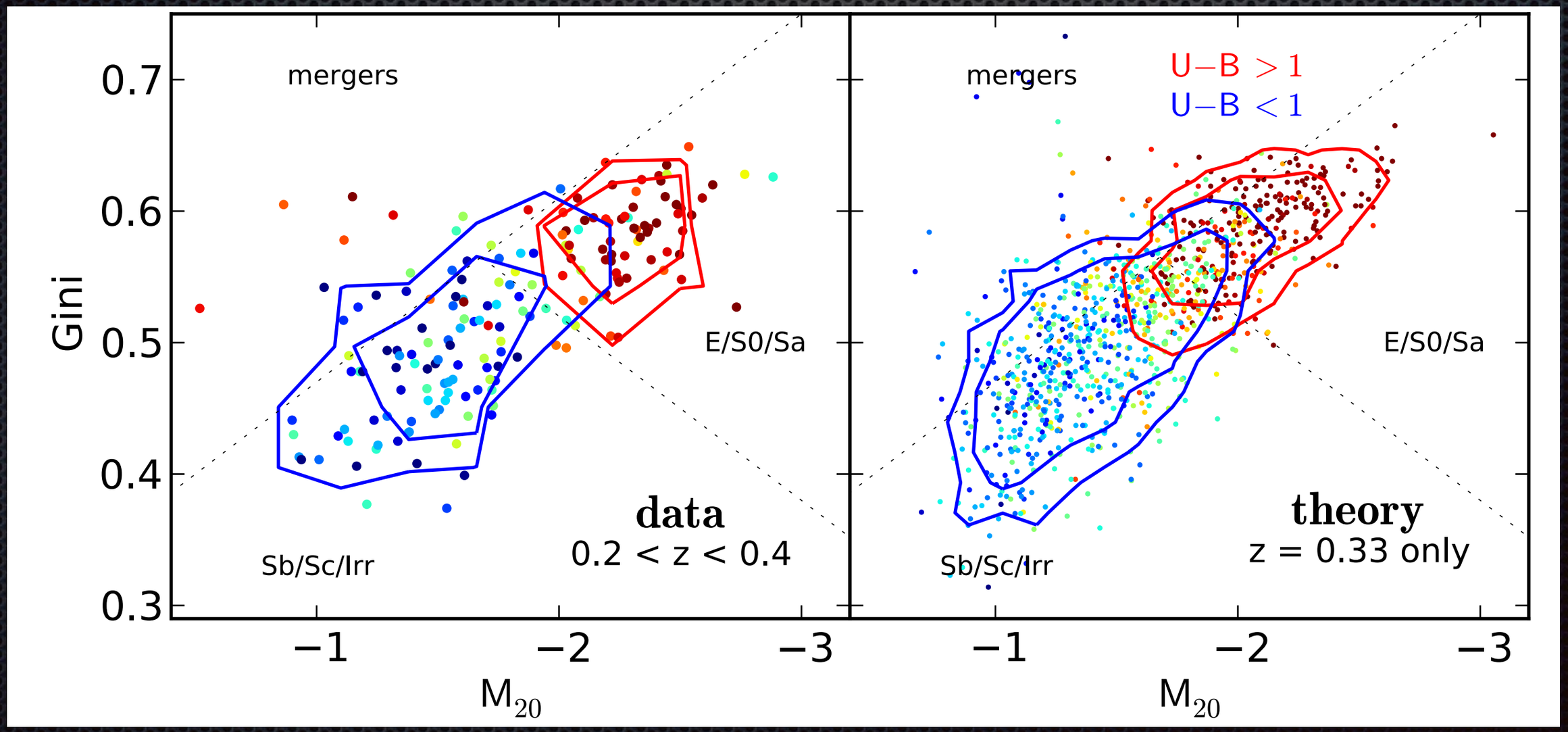
Illustris Simulation Observatory



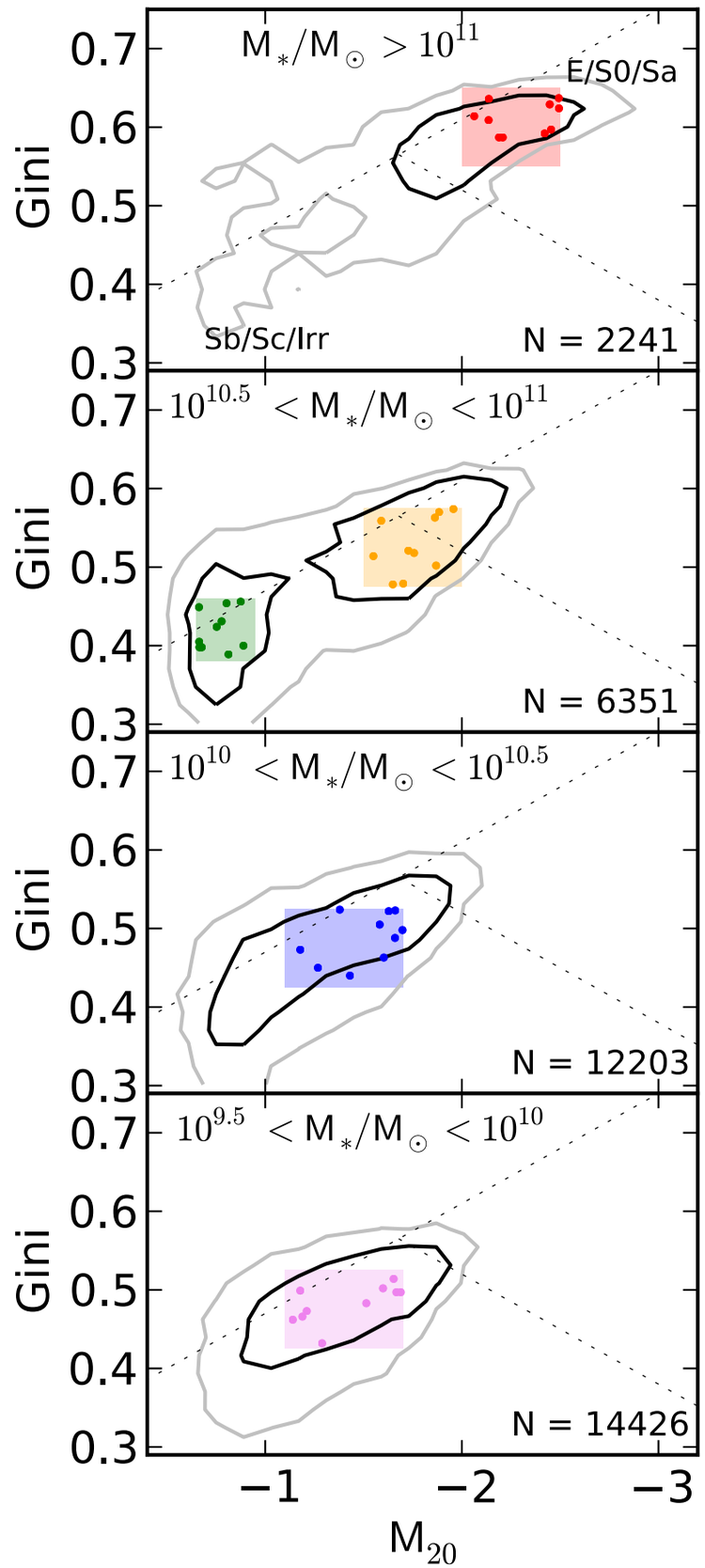
Torrey+ (2015)

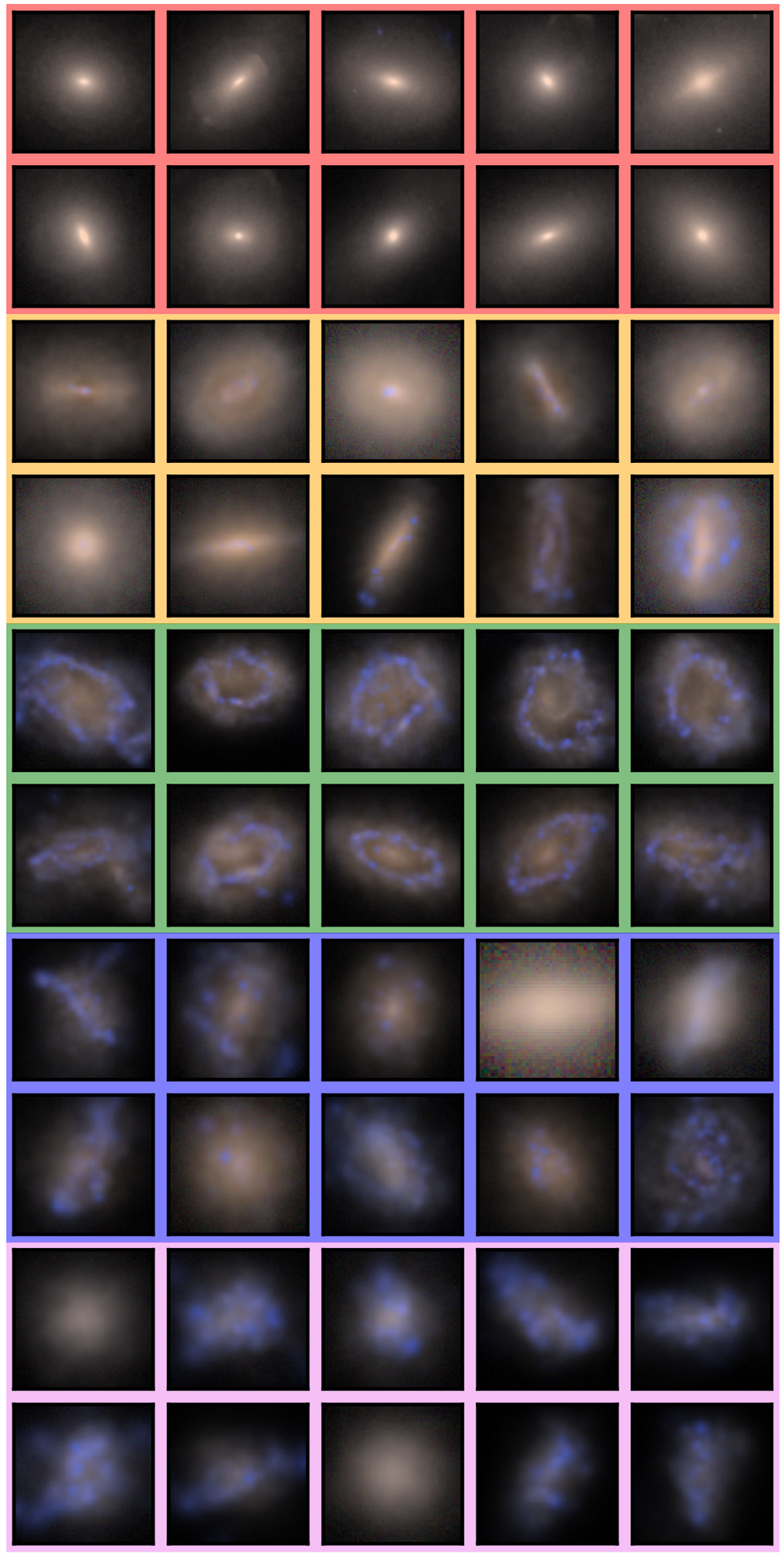
Image Pipeline: Application

- Employed image catalog for non-parametric galaxy morphology
- Compare against Extended Groth Strip data



Snyder, Torrey+ (2015)



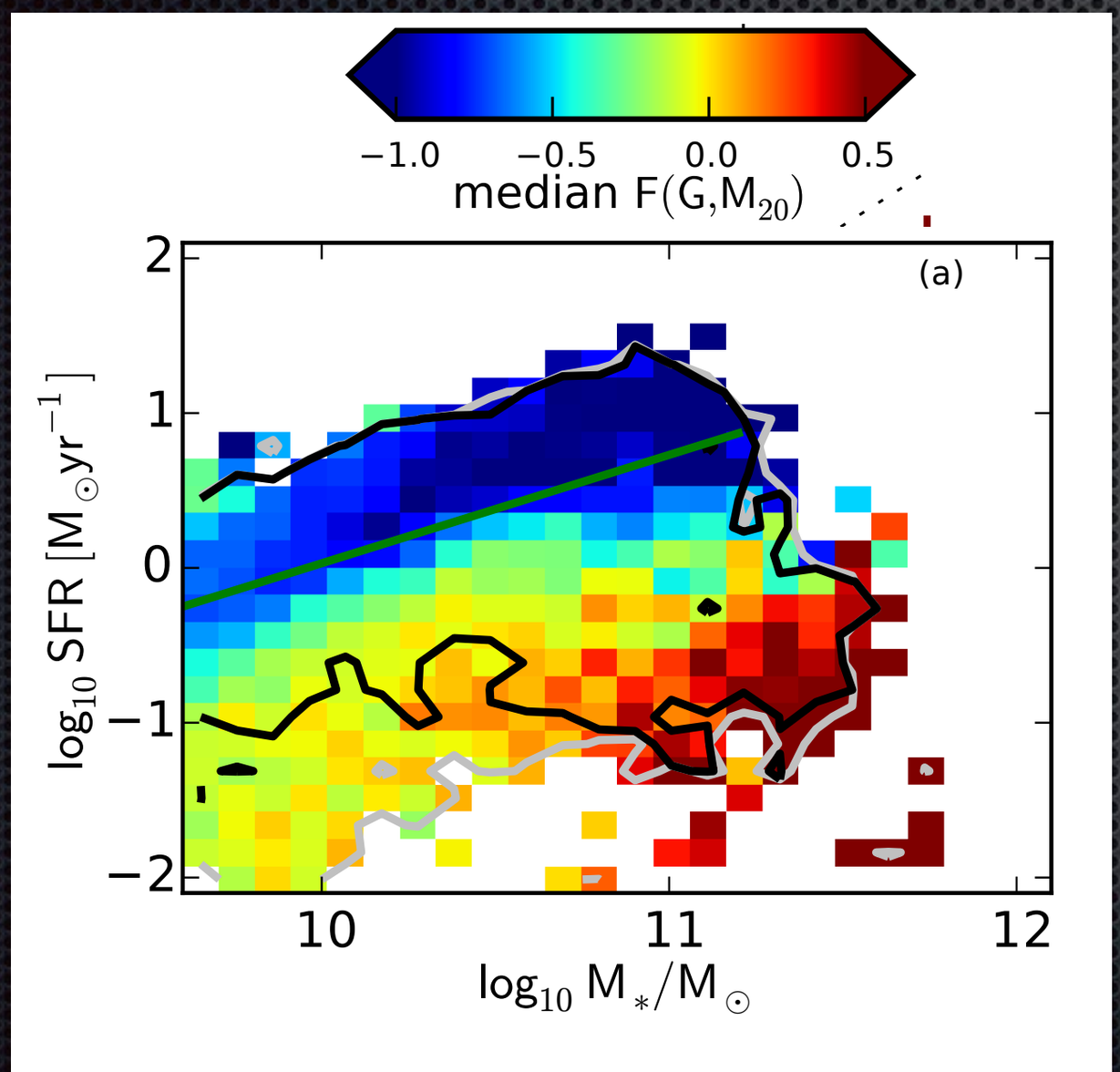


- Distribution of galaxies changes with mass
- Low mass galaxies disk dominated; high mass galaxies bulge dominated
- Interesting “ringed” galaxies at MW mass scale (more than observed)
- Rings indicate need for refining feedback model

Snyder, Torrey+ (2013)

Image Pipeline: Application

- Non-parametric fits of galaxy morphology vs simulated properties

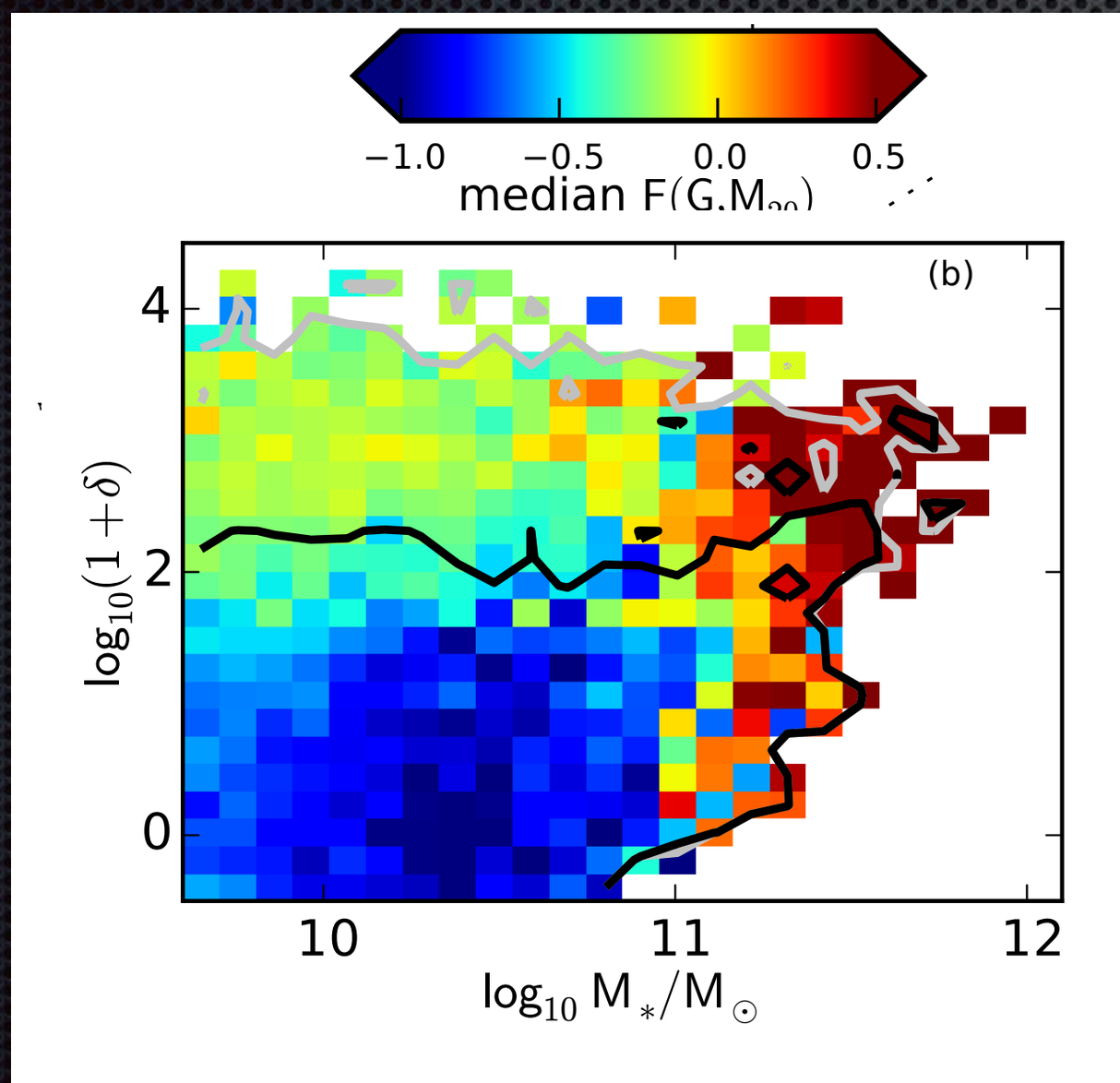


1. Disks are predominately found along SFMS. Systems significantly below SFMS tend to be spheroid dominated.

Snyder, Torrey+ (2015)

Image Pipeline: Application

- Non-parametric fits of galaxy morphology vs simulated properties



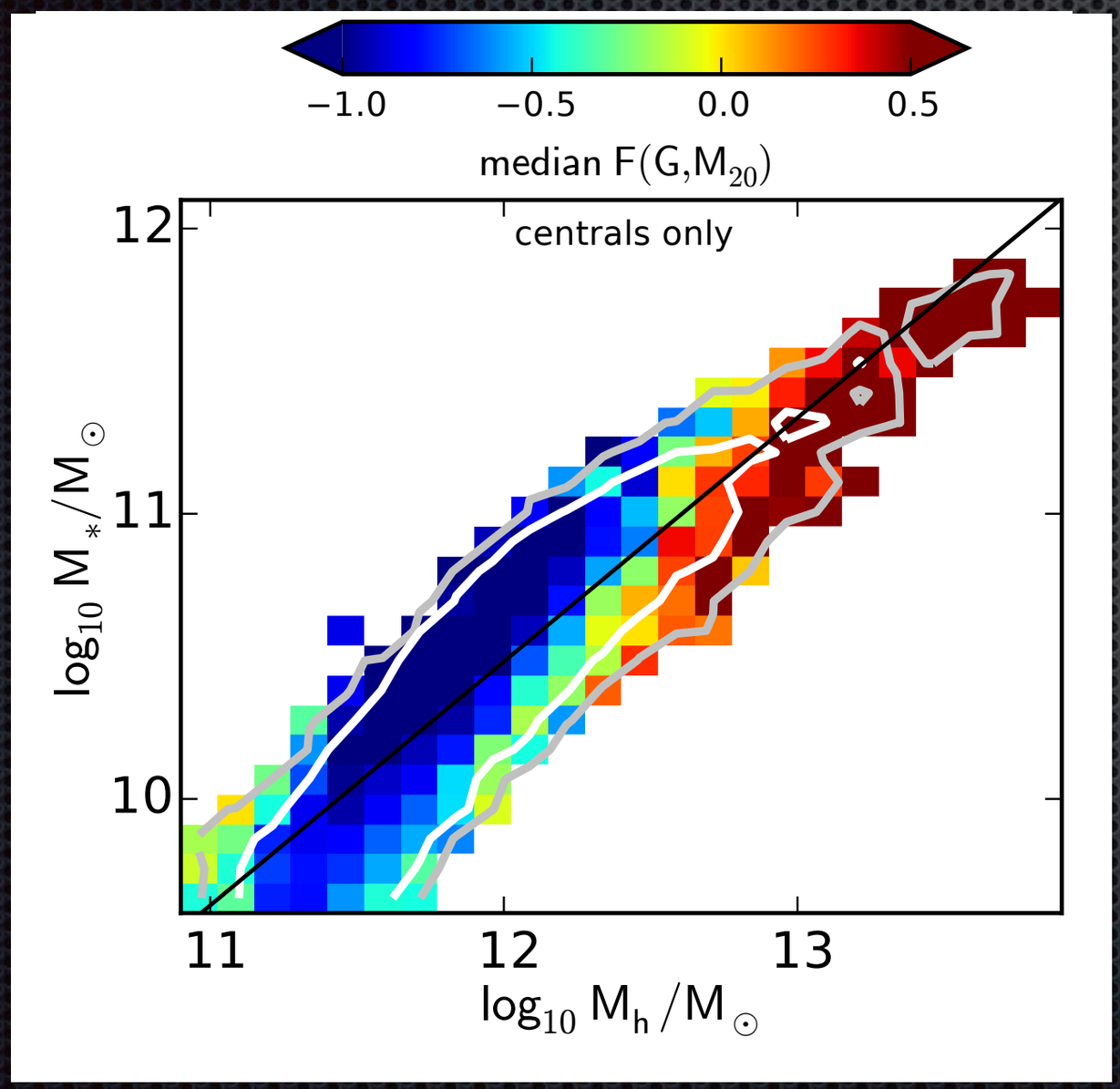
1. Disks are predominately found along SFMS. Systems significantly below SFMS tend to be spheroid dominated.

2. Galaxies in overdense environments tends to be more bulge dominated. Relation to merger history or quenched fraction still being investigated.

Snyder, Torrey+ (2015)

Image Pipeline: Application

- Non-parametric fits of galaxy morphology vs simulated properties



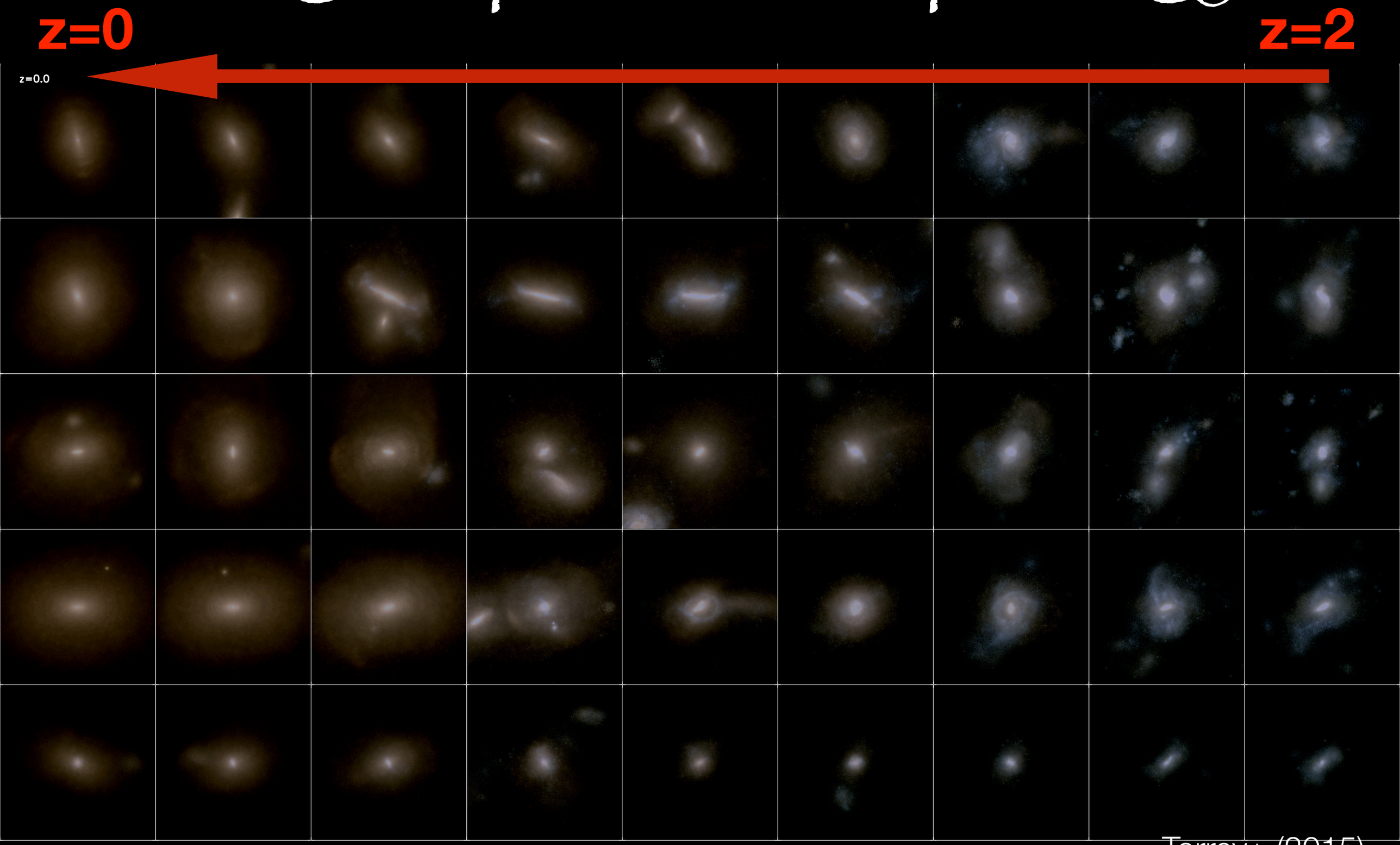
1. Disks are predominately found along SFMS. Systems significantly below SFMS tend to be spheroid dominated.

2. Galaxies in overdense environments tends to be more bulge dominated. Relation to merger history or quenched fraction still being investigated.

3. More massive galaxies also tend to be more bulge dominated

Snyder, Torrey+ (2015)

Image Pipeline: Morphology



Torrey+ (2015)

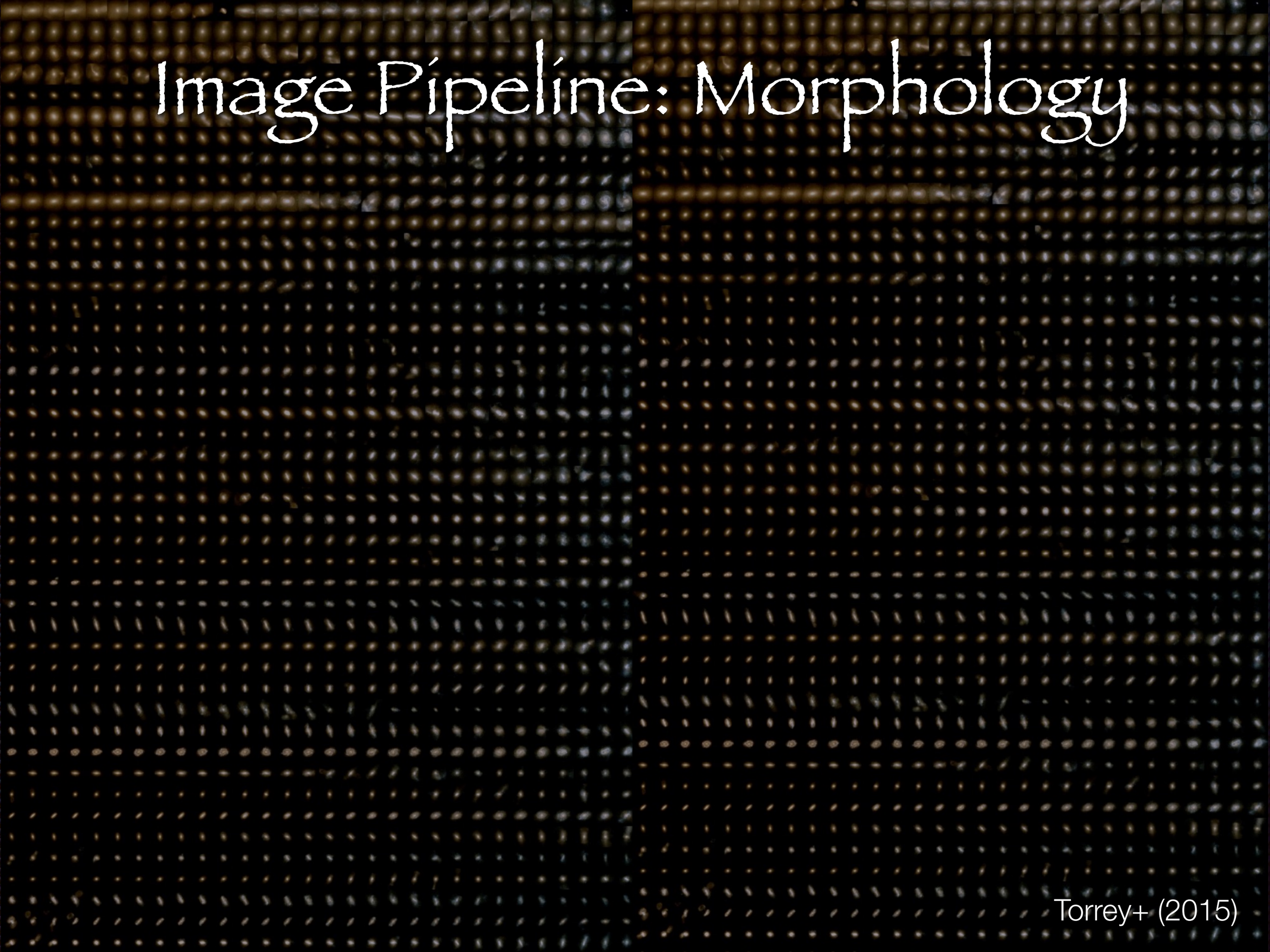
Image Pipeline: Morphology

Torrey+ (2015)

Image Pipeline: Morphology

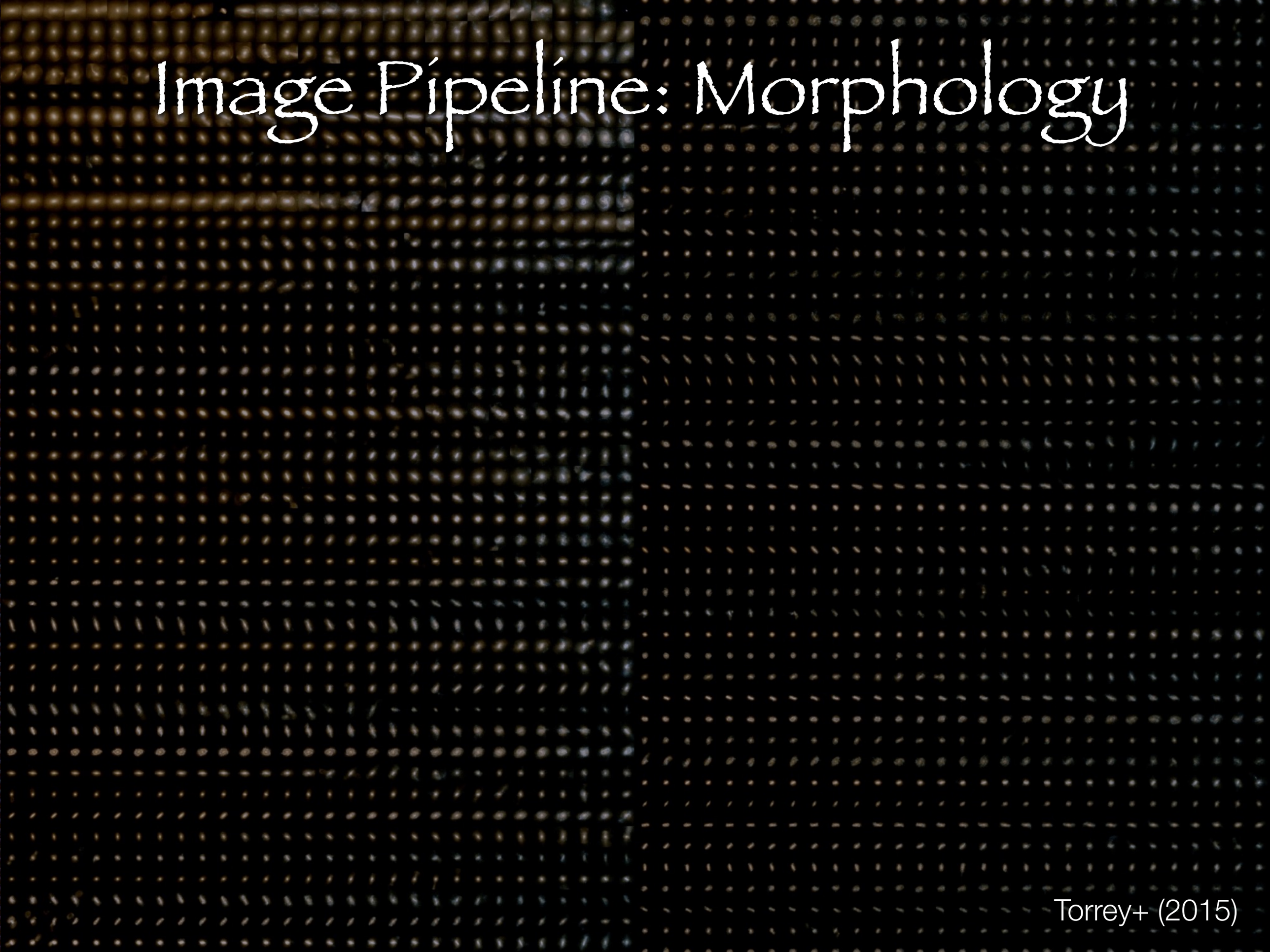
Torrey+ (2015)

Image Pipeline: Morphology



Torrey+ (2015)

Image Pipeline: Morphology



Torrey+ (2015)

Image Pipeline: Morphology

- For L=75 Mpc/h simulation volumes
  - 7000 galaxies with stellar masses >10^{10} M_solar
  - Some group/clusters available for study
  - Published and publicly available online

    illustris-project.org
  - Tools for opening/plotting/manipulating data

    github.com/ptorrey/sunpy

Torrey+ (2015)

Image Pipeline

- Lots of science questions to be addressed:
  - How do SED derived stellar masses compare against simulation value?
    - Factor of 2 errors common. Residual trends from discrete metallicity in SPS.
    - Reasonable constraints on parameter range help
  - How does galaxy morphology correlate with galactic properties?
    - SFMS populated by disks
    - Bulges more prevalent in dense environments
    - Scatter in Stellar Mass-Halo Mass relation correlated with morphology
  - Visual classification underway with Galaxy Zoo
  - How are high-z merger rates impacted by low S/N and PSF blurring?
  - Formation and evolution of unique galaxy classes (e.g., compact ellipticals)
  - ...

Illustris Project Select Science

- Properties of Galactic Stellar Haloes (Pillepich+ 2014)
- Galaxy-Galaxy Merger Rate Evolution (Rodriguez-Gomez+ 2014)
- Black Hole Scaling Relation (Sijacki+ 2014)
- Damped Lyman Alpha Properties (Bird+ 2014)
- Properties and Evolution of the SFMS (Sparre+ 2014)
- Impact of Feedback on Gas Accretion (Nelson+ 2014)
- Colors of Satellite Galaxies (Sales+ 2014)
- Metal Distribution and Ionization in the CGM (Suresh+ 2014)
- …
- DES image galaxy structural property comparison?
- DM Annihilation maps?
- Illustris Image Pipeline

Conclusions

- Described our numerical methods for running cosmological simulations including novel "Moving Mesh" hydro solver & feedback methods
- Presented AREPO simulations including strong feedback including the large volume Illustris cosmological simulations
- Argued that feedback yields realistic mass buildup of galaxy populations
  - Mass and Environmental Quenching
  - Galaxy Galaxy Merger Rate calculations
  - Buildup of Stellar Halo Profiles
- Outlined methods for producing synthetic galaxy image catalog
  - Idealized exploration of SED Fitting
  - Gini-M20 galaxy structural analysis and correlation with galaxy properties