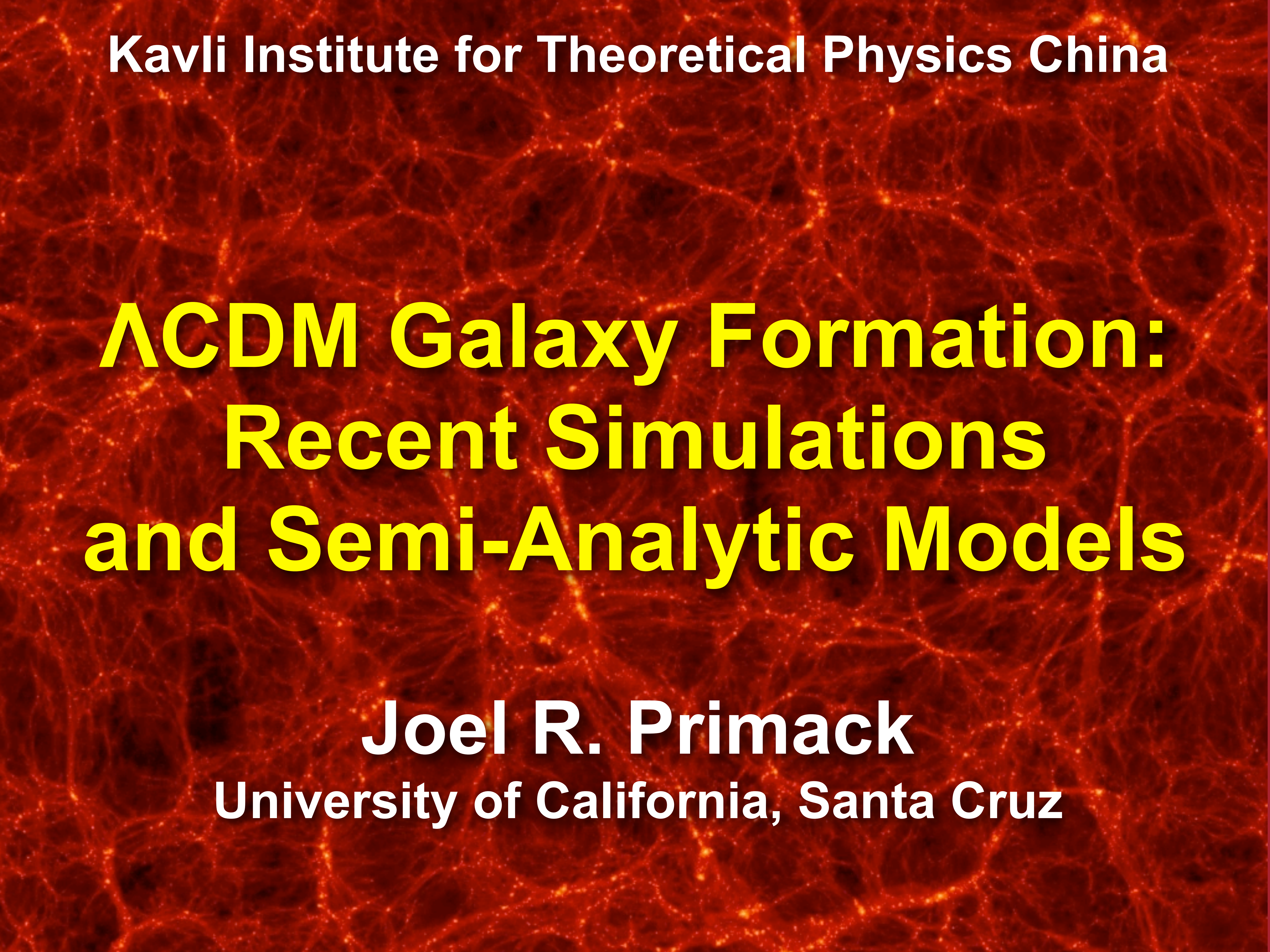


Kavli Institute for Theoretical Physics China

ΛCDM Galaxy Formation: Recent Simulations and Semi-Analytic Models

Joel R. Primack

University of California, Santa Cruz

Cosmological Simulations

Astronomical observations represent snapshots of moments in time. It is the role of astrophysical theory to produce movies -- both metaphorical and actual -- that link these snapshots together into a coherent physical theory.

Cosmological dark matter simulations show large scale structure, growth of structure, and dark matter halo properties and merger trees

Hydrodynamic galaxy formation simulations: evolution of galaxies, formation of galactic spheroids via mergers, galaxy images in all wavebands including stellar evolution and dust

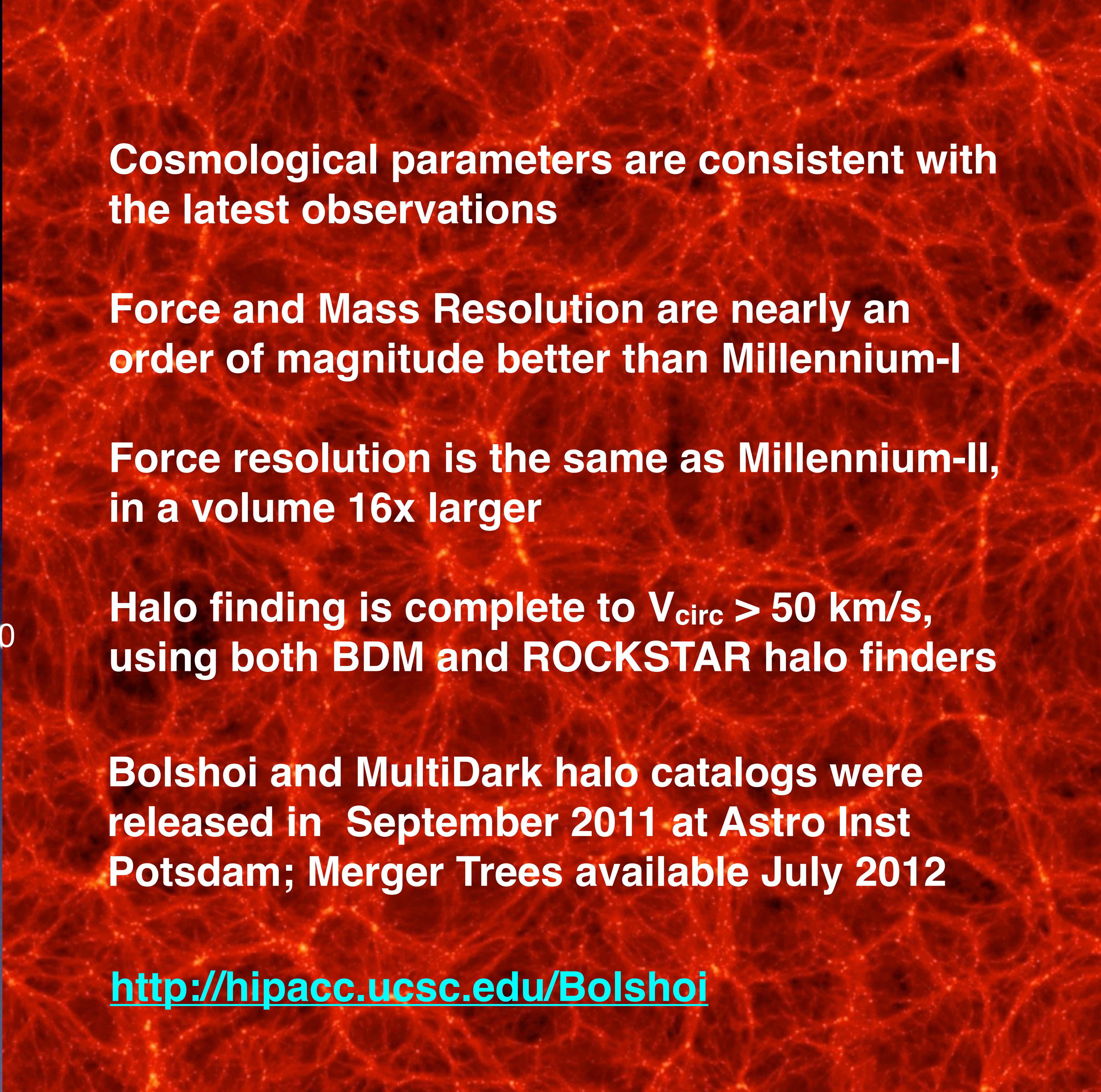
The Bolshoi simulation

ART code

250Mpc/h Box
LCDM
σ_8 = 0.82
h = 0.70
8G particles
1kpc/h force resolution
1e8 Msun/h mass res

dynamical range 262,000
time-steps = 400,000

NASA AMES
supercomputing center
Pleiades computer
13824 cores
12TB RAM
75TB disk storage
6M cpu hrs
18 days wall-clock time



Cosmological parameters are consistent with the latest observations

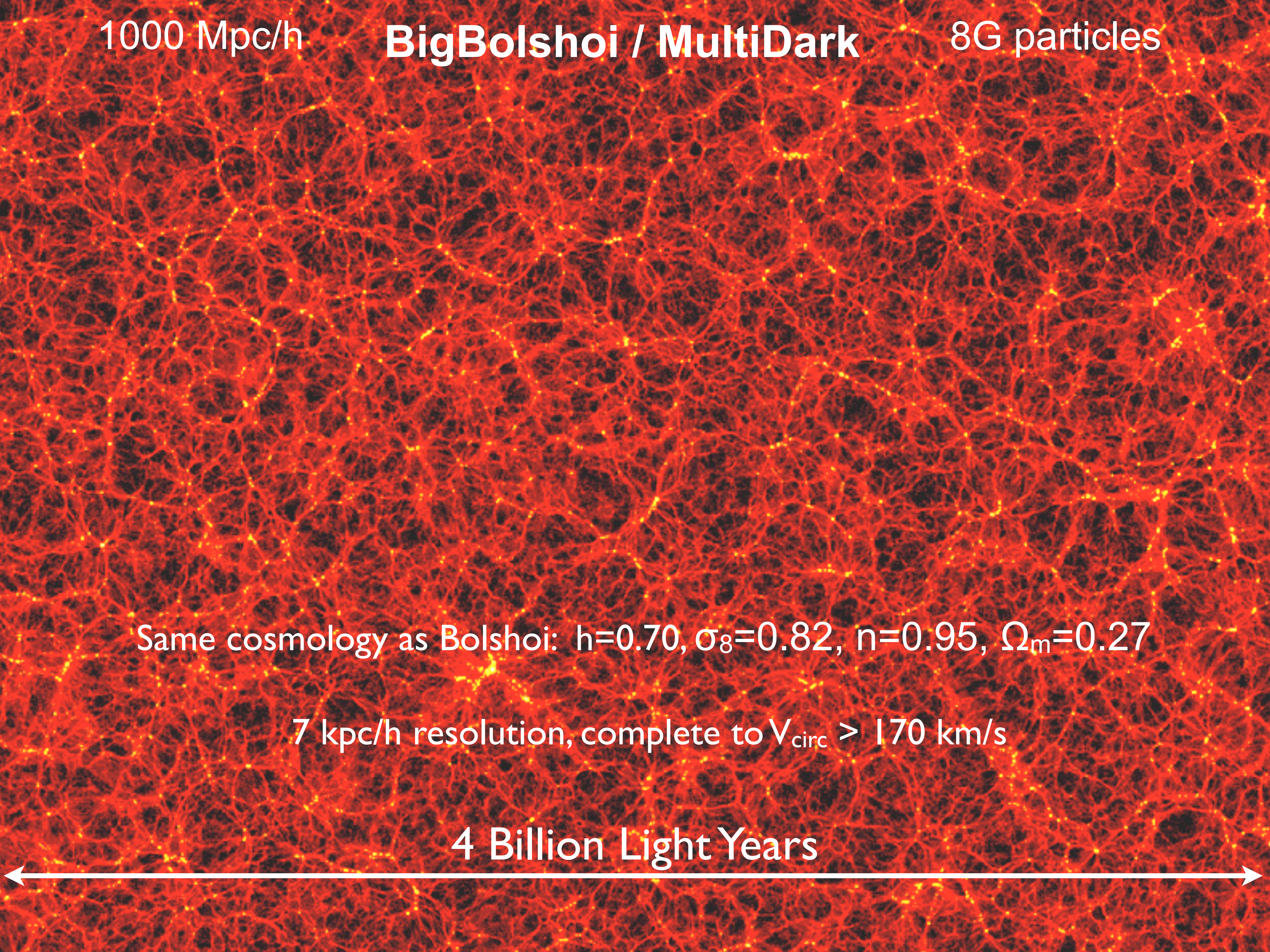
Force and Mass Resolution are nearly an order of magnitude better than Millennium-I

Force resolution is the same as Millennium-II, in a volume 16x larger

Halo finding is complete to V_{circ} > 50 km/s, using both BDM and ROCKSTAR halo finders

Bolshoi and MultiDark halo catalogs were released in September 2011 at Astro Inst Potsdam; Merger Trees available July 2012

http://hipacc.ucsc.edu/Bolshoi



BigBolshoi / MultiDark

1000 Mpc/h

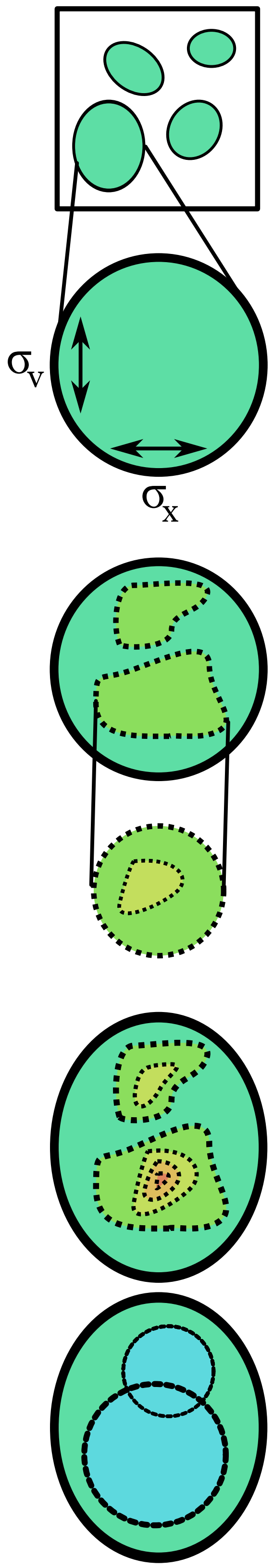
8G particles

Same cosmology as Bolshoi: $h=0.70$, $\sigma_8=0.82$, $n=0.95$, $\Omega_m=0.27$

7 kpc/h resolution, complete to $V_{circ} > 170$ km/s

4 Billion Light Years

The Rockstar Halo Finder



The simulation volume is divided into 3D Friends-of-Friends groups for easy parallelization.

For each group, particle positions and velocities are divided (normalized) by the group position and velocity dispersions, giving a natural phase-space metric.

A phase-space linking length is adaptively chosen such that 70% of the group's particles are linked together in subgroups.

The process repeats for each subgroup: renormalization, a new linking-length, and a new level of substructure calculated.

Once all levels of substructure are found, seed halos are placed at the lowest substructure levels and particles are assigned hierarchically to the closest seed halo center in phase space. (see Knebe et al. 2011 for specific details).

Once particles have been assigned to halos, unbound particles are removed and halo properties (positions, velocities, spherical masses, radii, spins, etc.) are calculated.

Behroozi et al.

HALO MERGER TREE ALGORITHM

1. Identify halo descendants using a traditional particle algorithm.

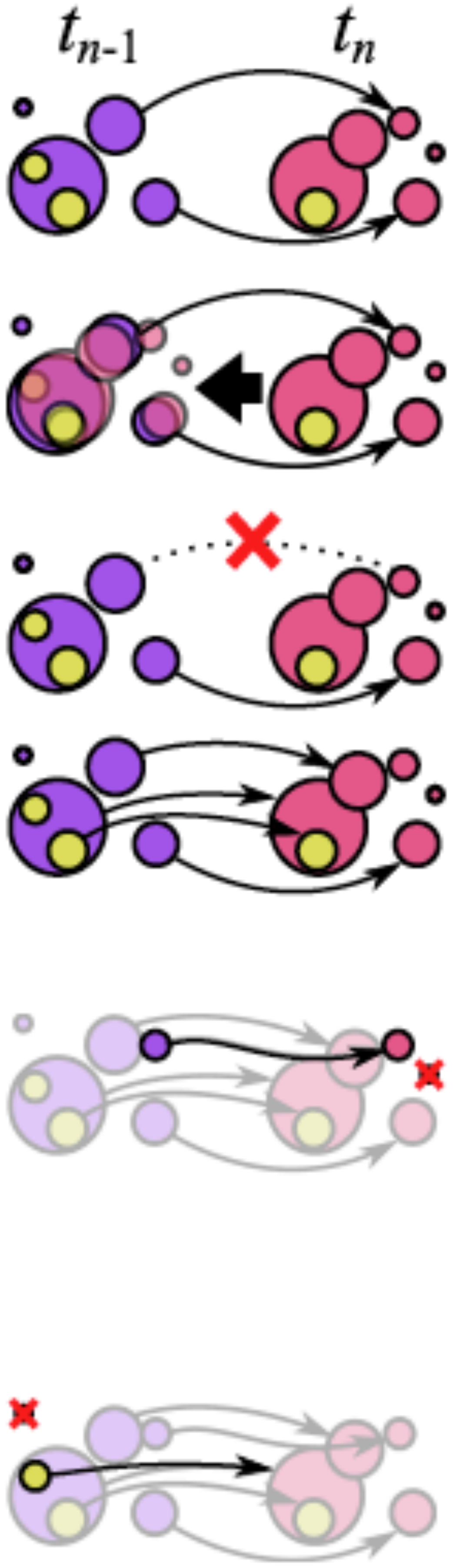
2. Gravitationally evolve the positions and velocities of all halos at the current timestep back in time to identify their most likely positions at the previous timestep.

3. Based on predicted progenitor halos in step (2), cut ties to spurious descendants.

4. Create links for halos with likely progenitors at the previous timestep for cases in which step (2) has identified a good match.

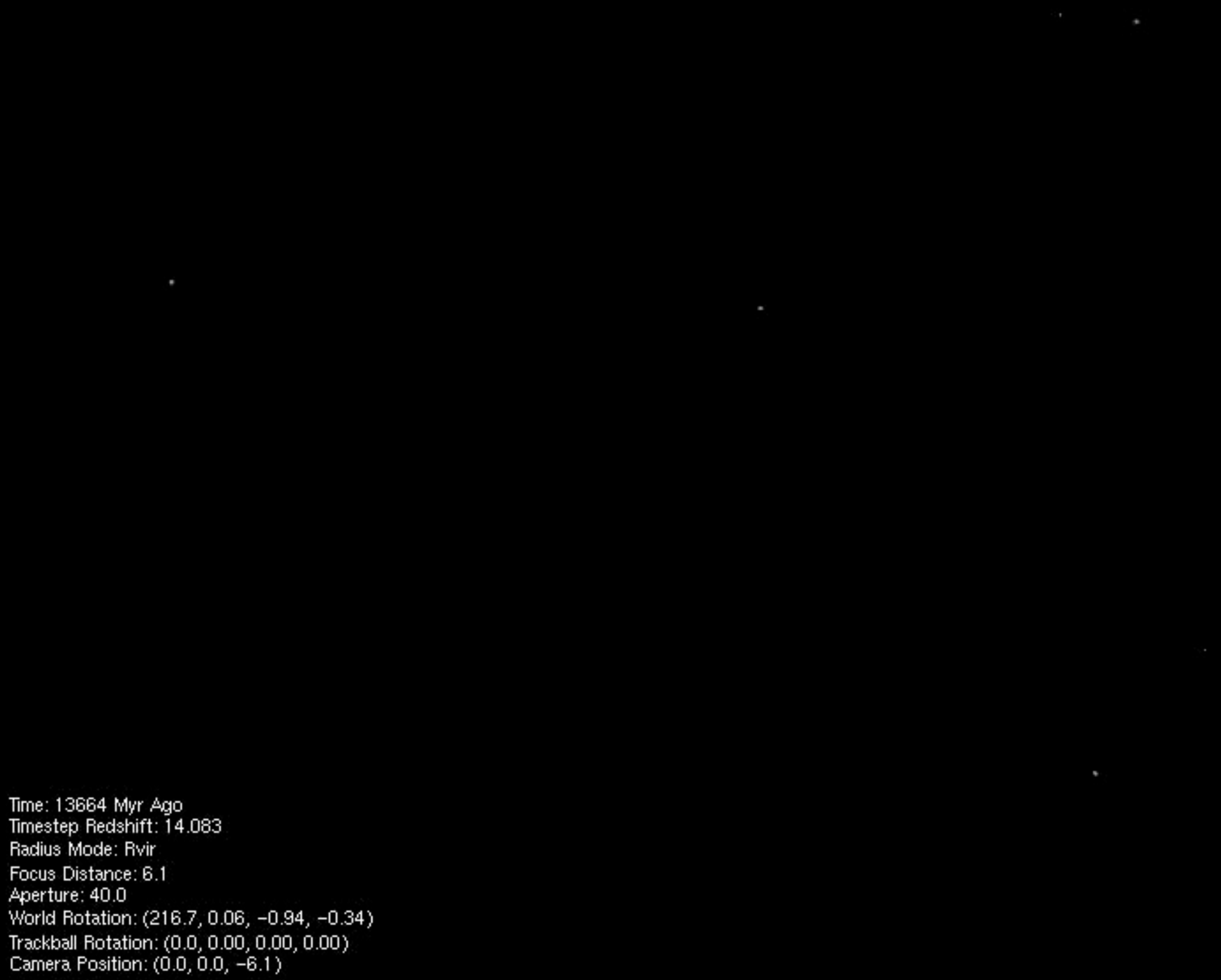
5. For halos in the current timestep without likely progenitors, create a new halo at the previous timestep with position and velocity given by the evolution in step (2). Remove any such halos generated from previous rounds if they have had no real progenitors for several timesteps.

6. For halos in the previous timesteps which have no descendants, assume that a merger occurred into the halo exerting the strongest tidal field across it at the previous timestep. If a halo with no descendant is too far removed from other halos to experience a significant tidal field, assume that it is a statistical fluctuation and remove it from the tree and catalogs.



Behroozi et al. in prep.

Bolshoi Merger Tree for the Formation of a Big Cluster Halo



Time: 13664 Myr Ago
Timestep Redshift: 14.083
Radius Mode: Rvir
Focus Distance: 6.1
Aperture: 40.0
World Rotation: (216.7, 0.06, −0.94, −0.34)
Trackball Rotation: (0.0, 0.00, 0.00, 0.00)
Camera Position: (0.0, 0.0, −6.1)

Peter Behroozi

Bolshoi simulations - recent progress

- Halo catalogs for all 180 stored timesteps of the **Bolshoi** and 50 timesteps of the **BigBolshoi/MultiDark** simulation are now available using both Anatoly Klypin's BDM halo finder and Peter Behroozi's powerful new phase-space halo finder ROCKSTAR.
- All catalogs are finished for **BigBolshoi/MultiDark**, which has the same cosmology as Bolshoi in a volume 64x larger. It has 7 kpc/h resolution, and is complete to Vcirc > 170 km/s (so all MWy-size halos are found). Anatoly Klypin's BDM halo catalog now includes the spin parameter, concentration, shape and orientation of all halos for both "virial" and overdensity-200 halo definitions. Merger trees are finished and were made available at the UC-HiPACC AstroInformatics summer school July 2012 at SDSC/UCSD.
- A new **miniBolshoi** simulation is running now. It will have a force resolution of about 100 pc and a mass resolution better than 2x10^6 M_{sun} and will be complete to 15 km/s or better. We will have complete merger histories and substructure for hundreds of MWy-size halos.
- Halo catalogs and particle data for z=0 etc. is available at Astro Inst Potsdam http://www.multidark.org/MultiDark/ (You have to get an account there.) Images, videos, and links to articles: http://hipacc.ucsc.edu/Bolshoi

Galaxy Formation - Introduction

An old criticism of ΛCDM has been that the order of cosmogony is wrong: halos grow from small to large by accretion in a hierarchical formation theory like ΛCDM, but the oldest stellar populations are found in the most massive galaxies -- suggesting that these massive galaxies form earliest, a phenomenon known as "downsizing." The key to explaining the downsizing phenomenon is the realization that **star formation is most efficient in dark matter halos with masses in the band between about 10^{10} and 10^{12} $M_\odot$**. This goes back at least as far as the original Cold Dark Matter paper (BFPR84), from which the following figure is reproduced.

Formation of galaxies and large-scale structure with cold dark matter

Blumenthal, Faber, Primack, & Rees -- Nature 311, 517 (1984)

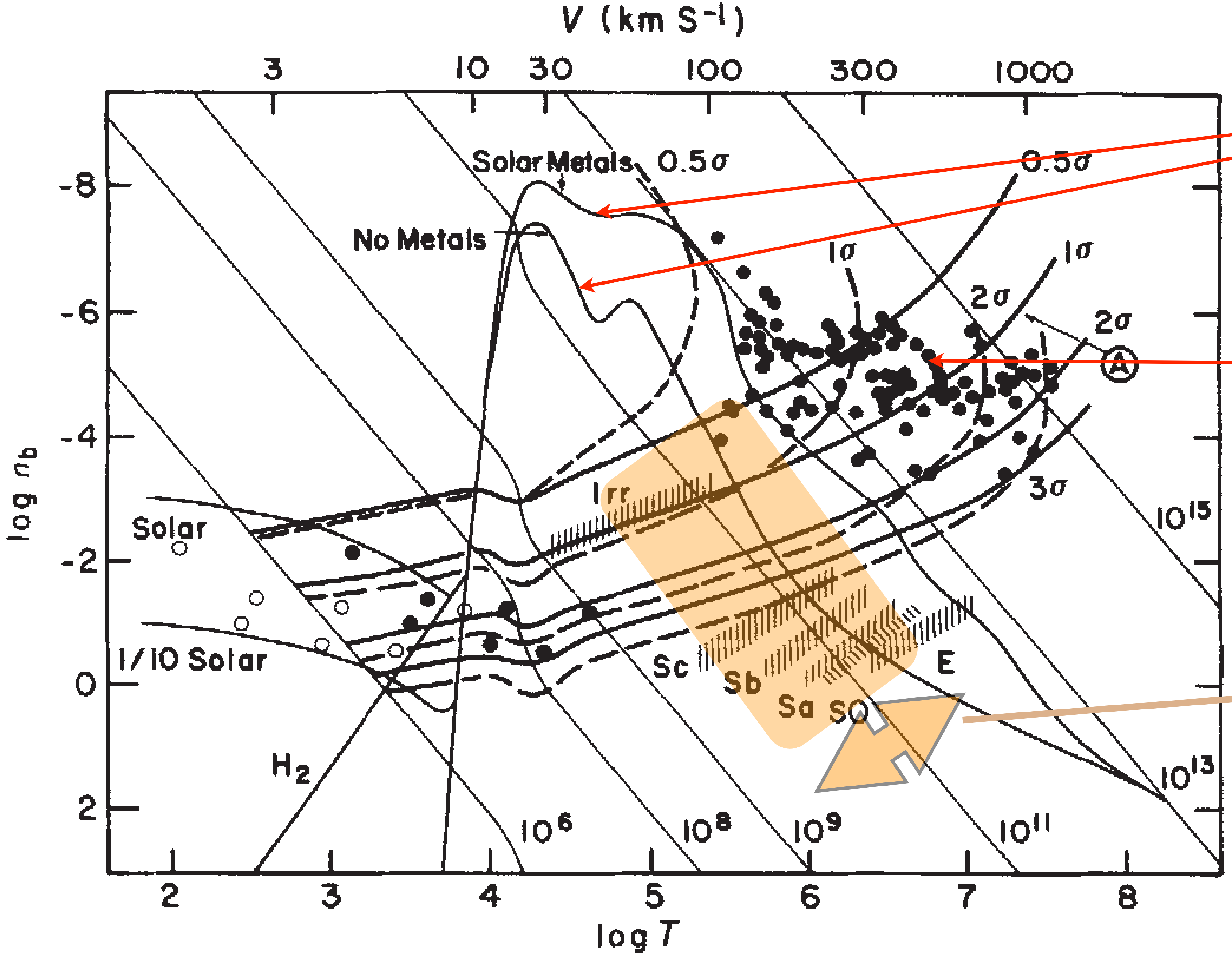


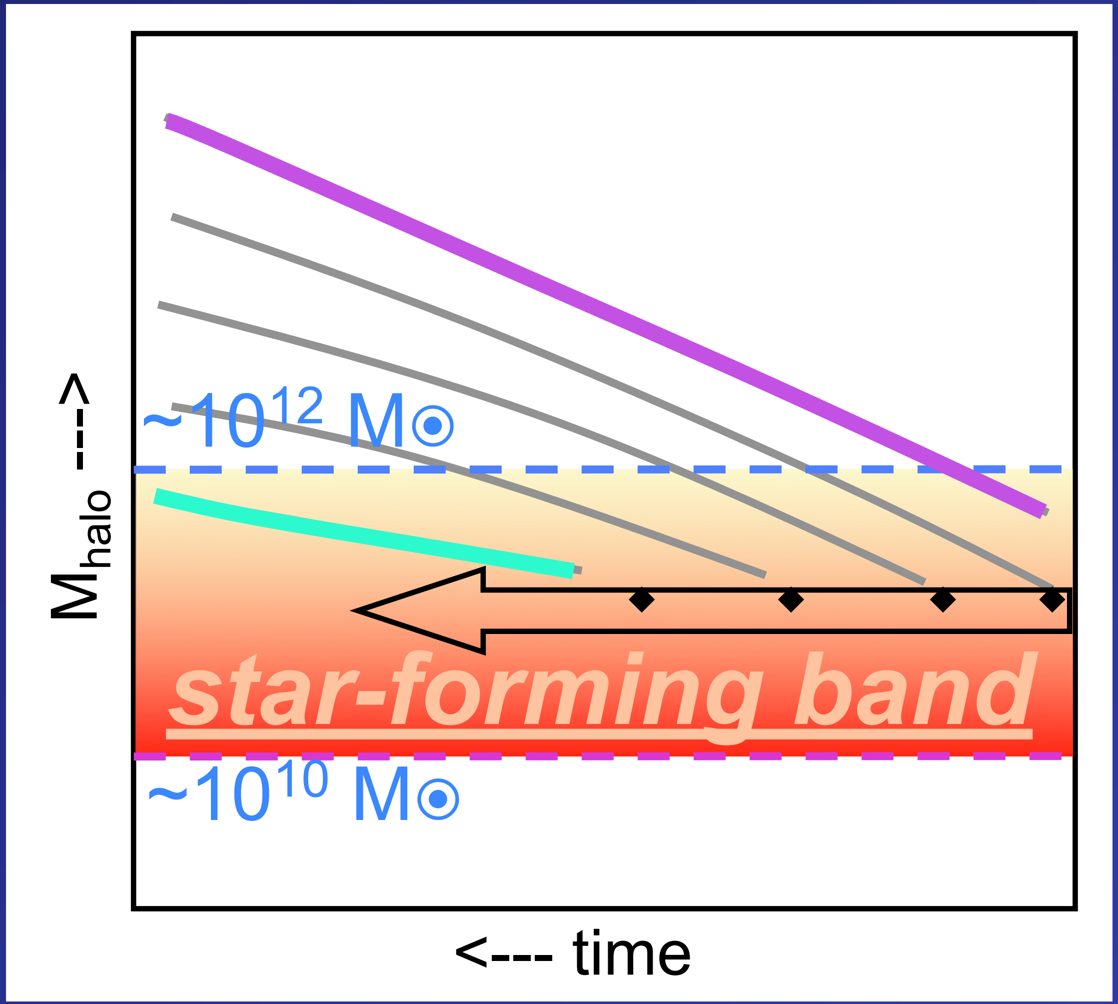
Fig. 3 Baryon density n_b versus three-dimensional, r.m.s. velocity dispersion V and virial temperature T for structures of various size in the Universe. The quantity T is $\mu V^2/3k$, where μ is mean molecular weight ($\approx$0.6 for ionized, primordial H+He) and k is Boltzmann's constant.

Galaxies form beneath the cooling curves

Galaxy groups and clusters form above the cooling curves

Star Forming Band: 10^{10} - 10^{12} Msun

Implications of the Star-Forming Band Model



Massive galaxies:

- Started forming stars early.
- Shut down early.
- Are red today.
- Populate dark halos that are much more massive than their stellar mass.

Small galaxies:

- Started forming stars late.
- Are still making stars today.
- Are blue today.
- Populate dark halos that match their stellar mass.

"Downsizing"

Star formation is a wave that started in the largest galaxies and swept down to smaller masses later (Cowie et al. 1996).

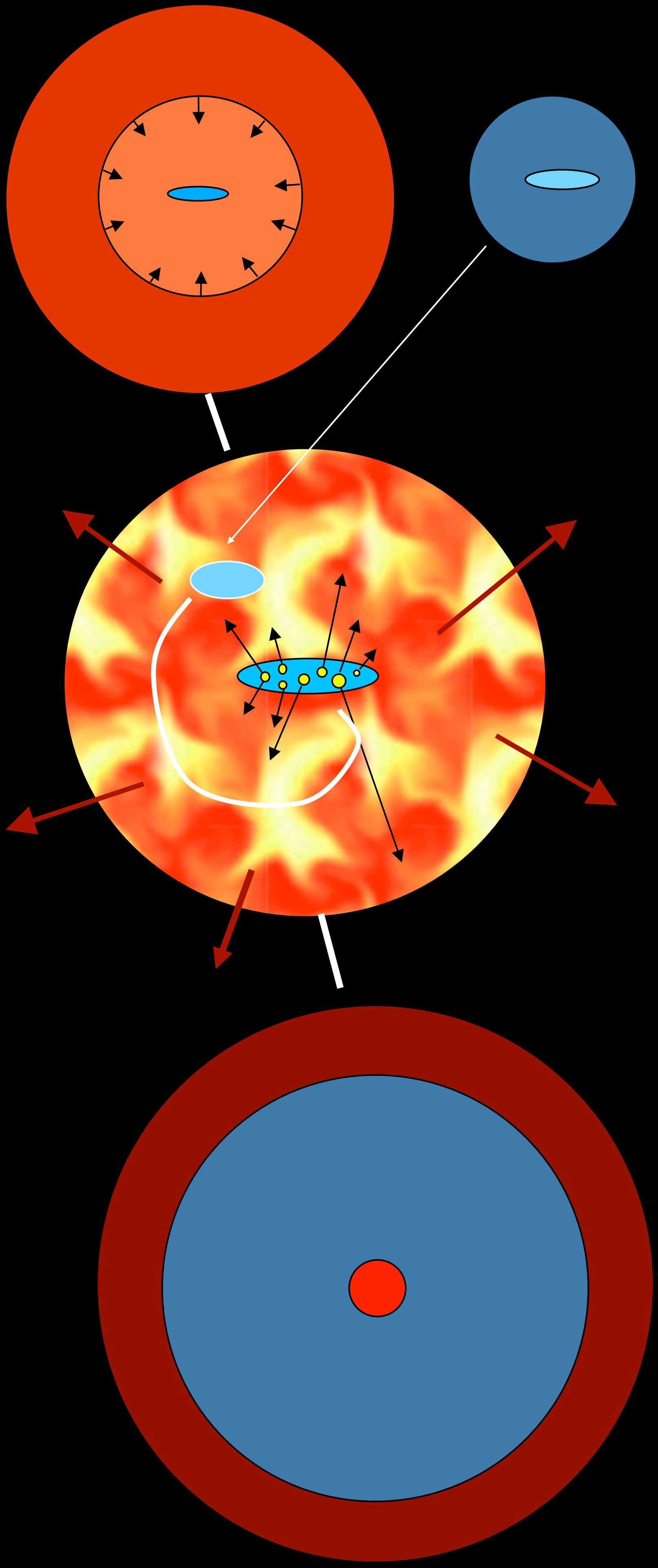
Sandy Faber

Galaxy Formation - Introduction

The details of the origin of the star-forming band are still being worked out. Back in 1984, we argued that cooling would be inefficient for masses greater than about 10^{12} $M_{\odot}$ because the density would be too low, and inefficient for masses less than about 10^8 $M_{\odot}$ because the gas would not be heated enough by falling into these small potential wells.

Now we know that reionization, supernovae, and other energy input additionally impedes star formation for halo masses below about 10^{10} $M_{\odot}$, that gas efficiently streams down filaments into halos up to about 10^{12} $M_{\odot}$, and that feedback from active galactic nuclei (AGN) impedes star formation for halo masses above about 10^{12} $M_{\odot}$. All of these processes and more are included in semi-analytic models (SAMs) of the evolution of galaxy populations.

Galaxy Formation via SAMs

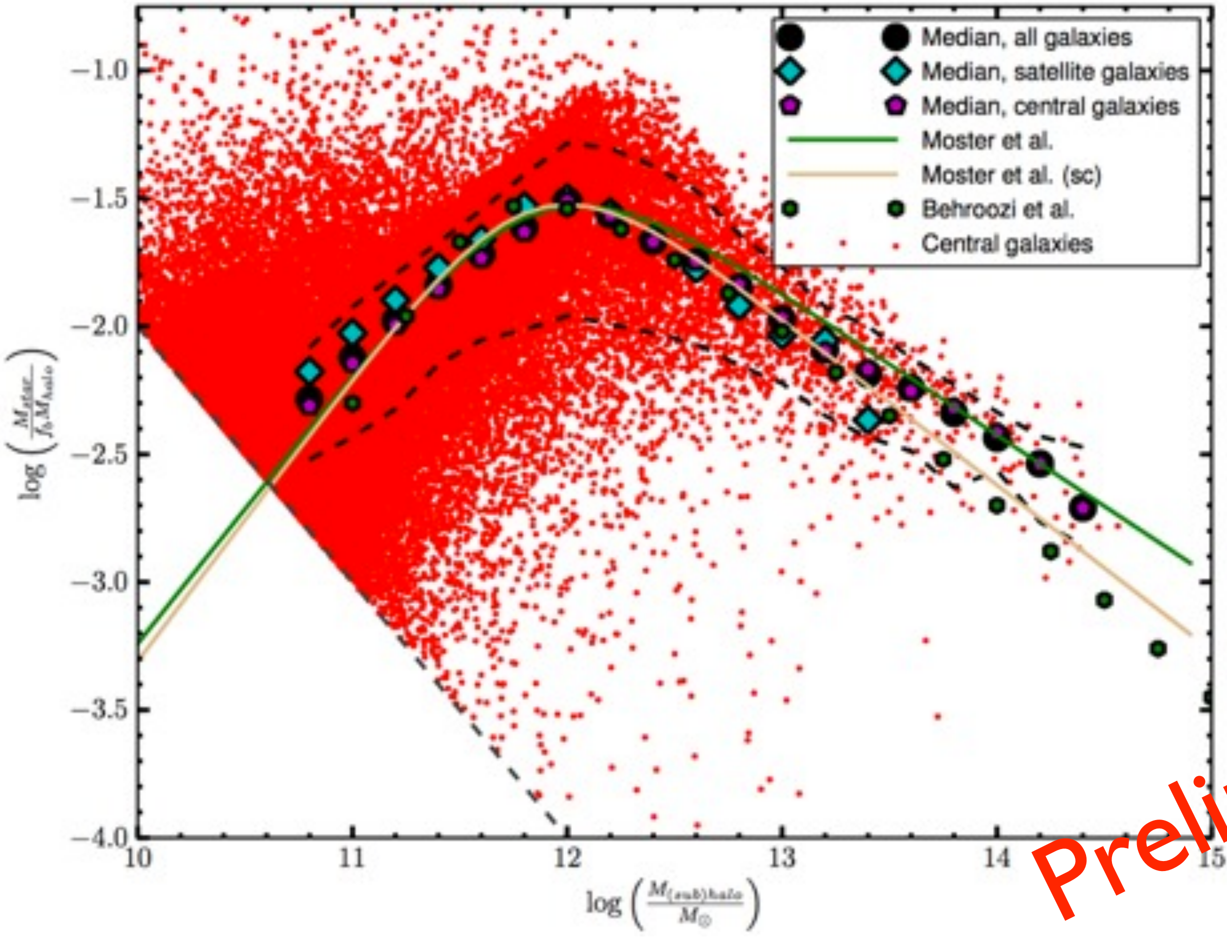


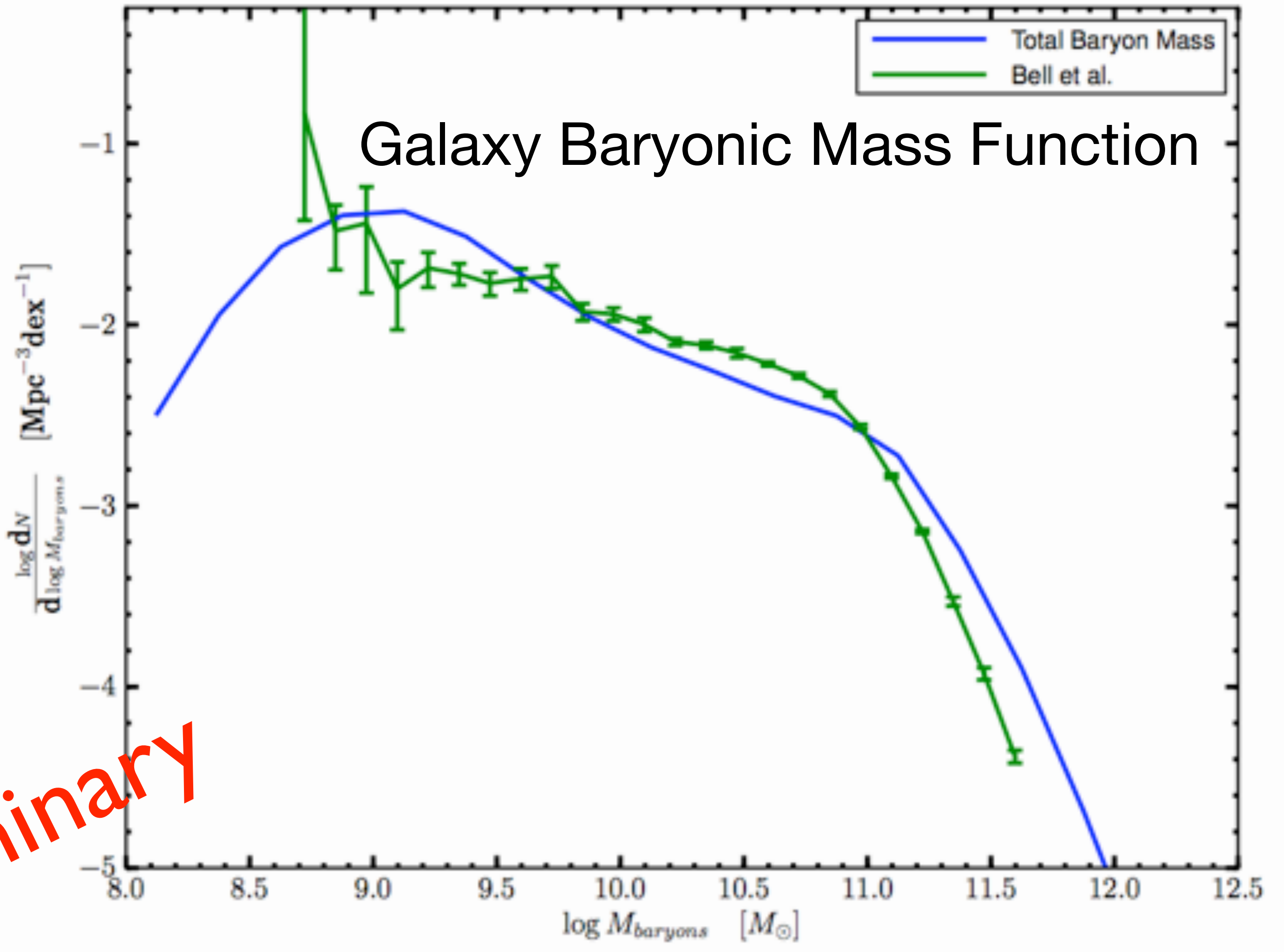
- gas is collisionally heated when perturbations 'turn around' and collapse to form gravitationally bound structures
- gas in halos cools via atomic line transitions (depends on density, temperature, and metallicity)
- cooled gas collapses to form a rotationally supported disk
- cold gas forms stars, with efficiency a function of gas density (e.g. Schmidt-Kennicutt Law, metallicity effects?)
- massive stars and SNe reheat (and in small halos expel) cold gas and some metals
- galaxy mergers trigger bursts of star formation; 'major' mergers transform disks into spheroids and fuel AGN
- AGN feedback cuts off star formation
- **including effects of dissipation in gas-rich galaxy mergers leads to observed elliptical size-mass relation**
- **including spheroid formation by disk instability is essential to reproduce the observed elliptical luminosity function**

White & Frenk 91; Kauffmann+93; Cole+94; Somerville & Primack 99; Cole+00; Somerville, Primack, & Faber 01; Croton et al. 2006; Somerville +08; Fanidakis+09; Covington et al. 10, 11; Somerville, Gilmore, Primack, & Dominguez 11; Porter et al.

First SAM galaxy results with Bolshoi - Rachel Somerville

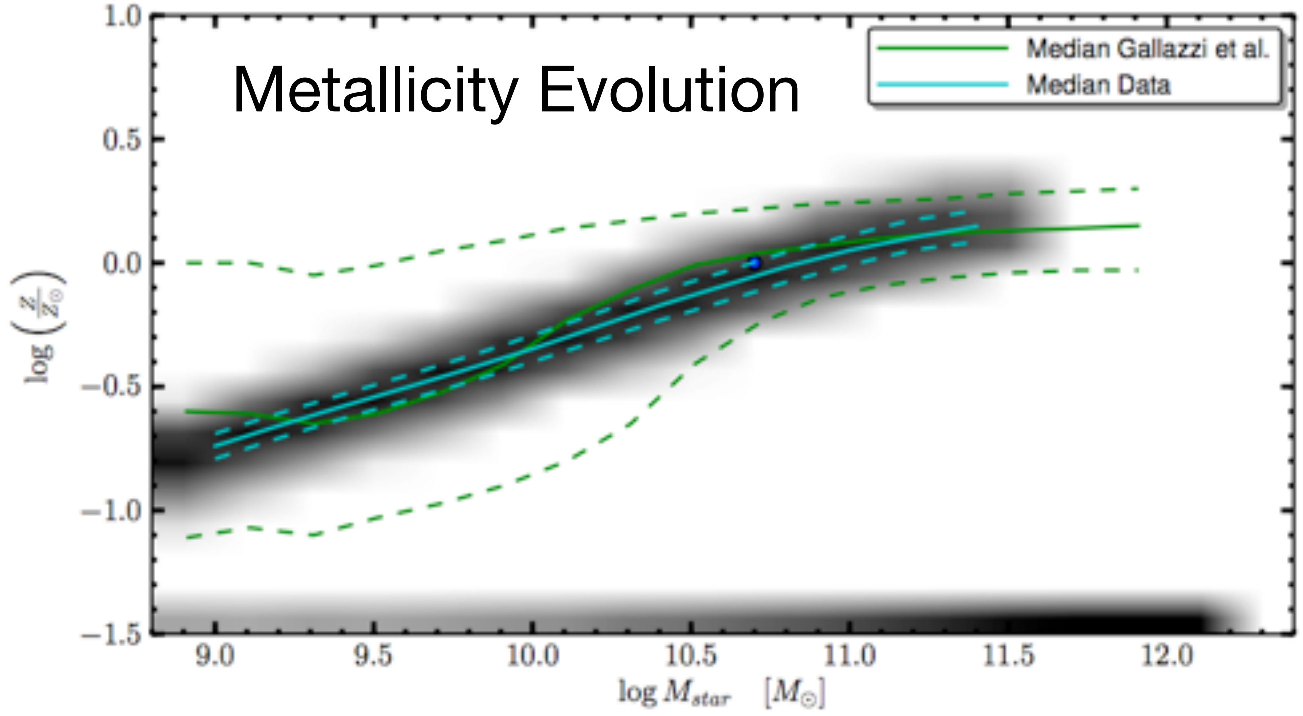
Star Formation Efficiency



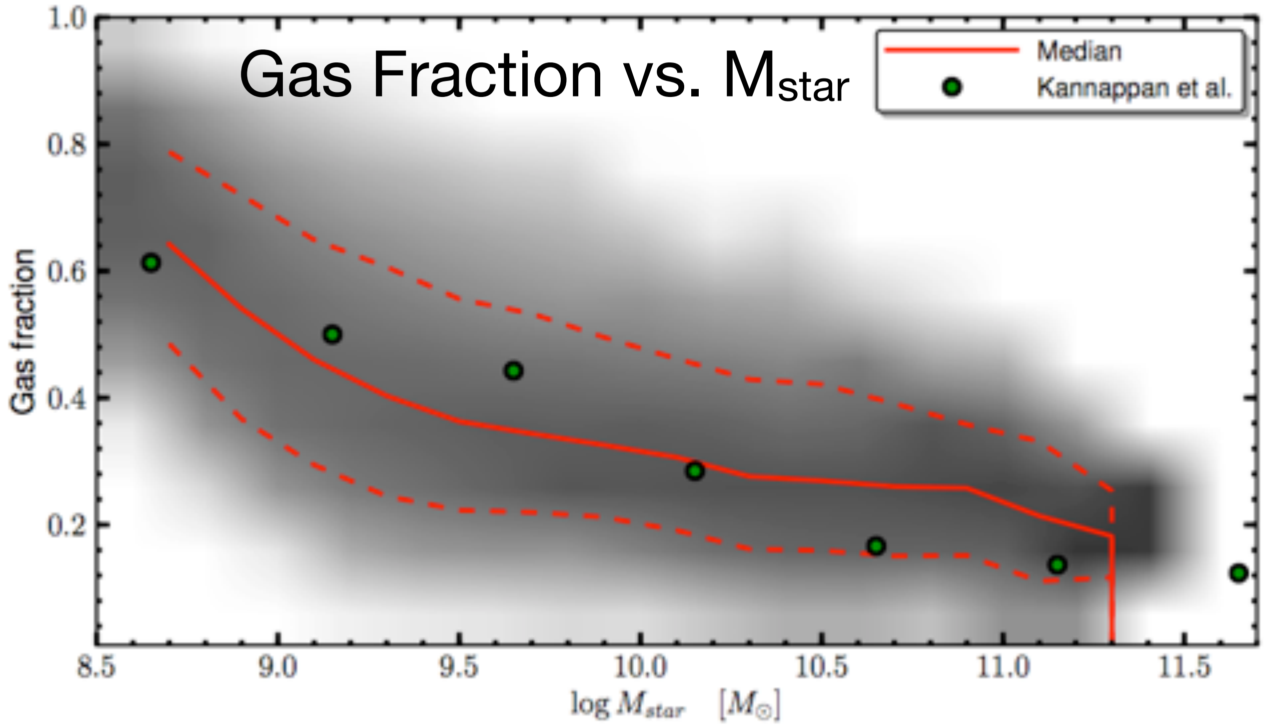

Galaxy Baryonic Mass Function

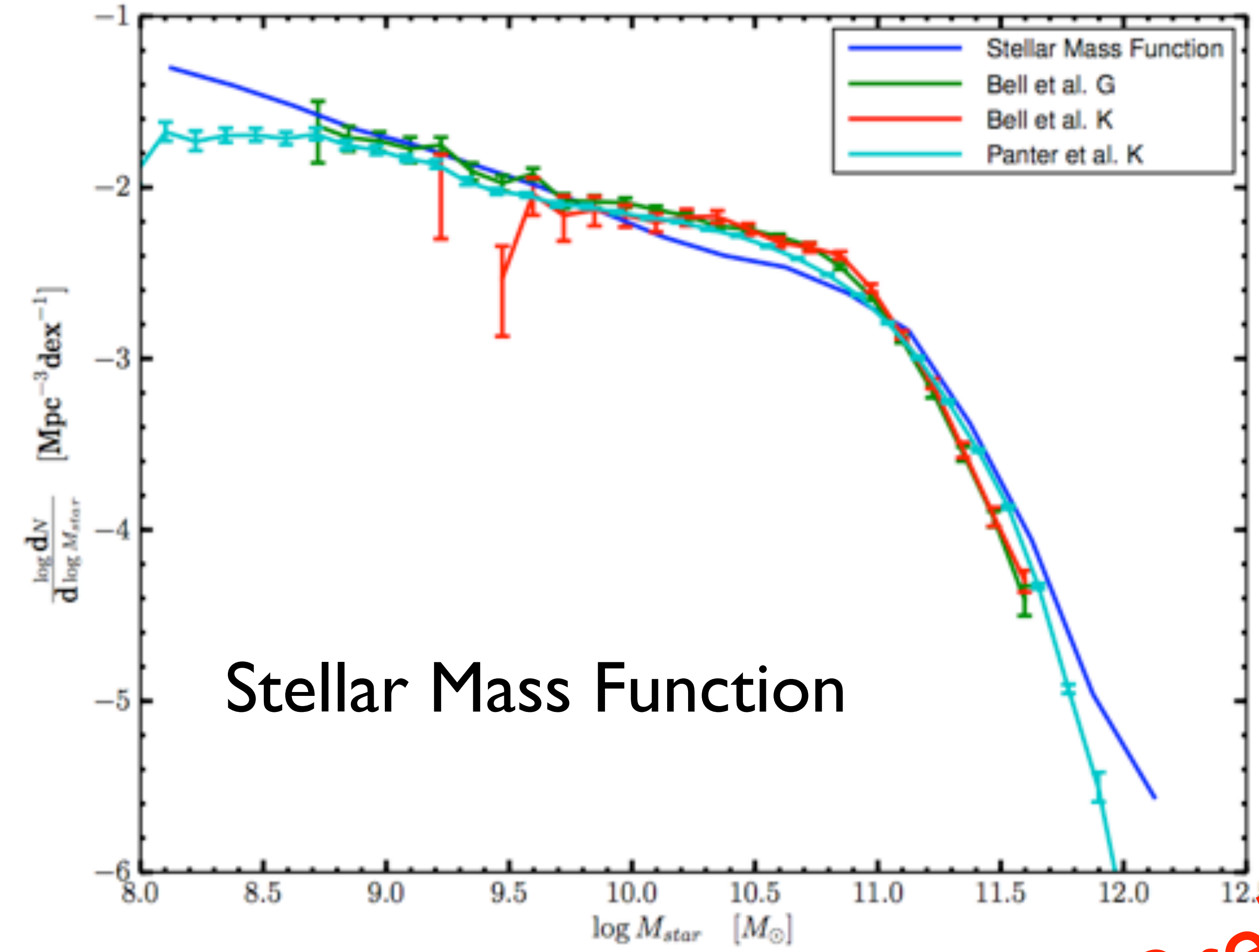
Preliminary

Metallicity Evolution

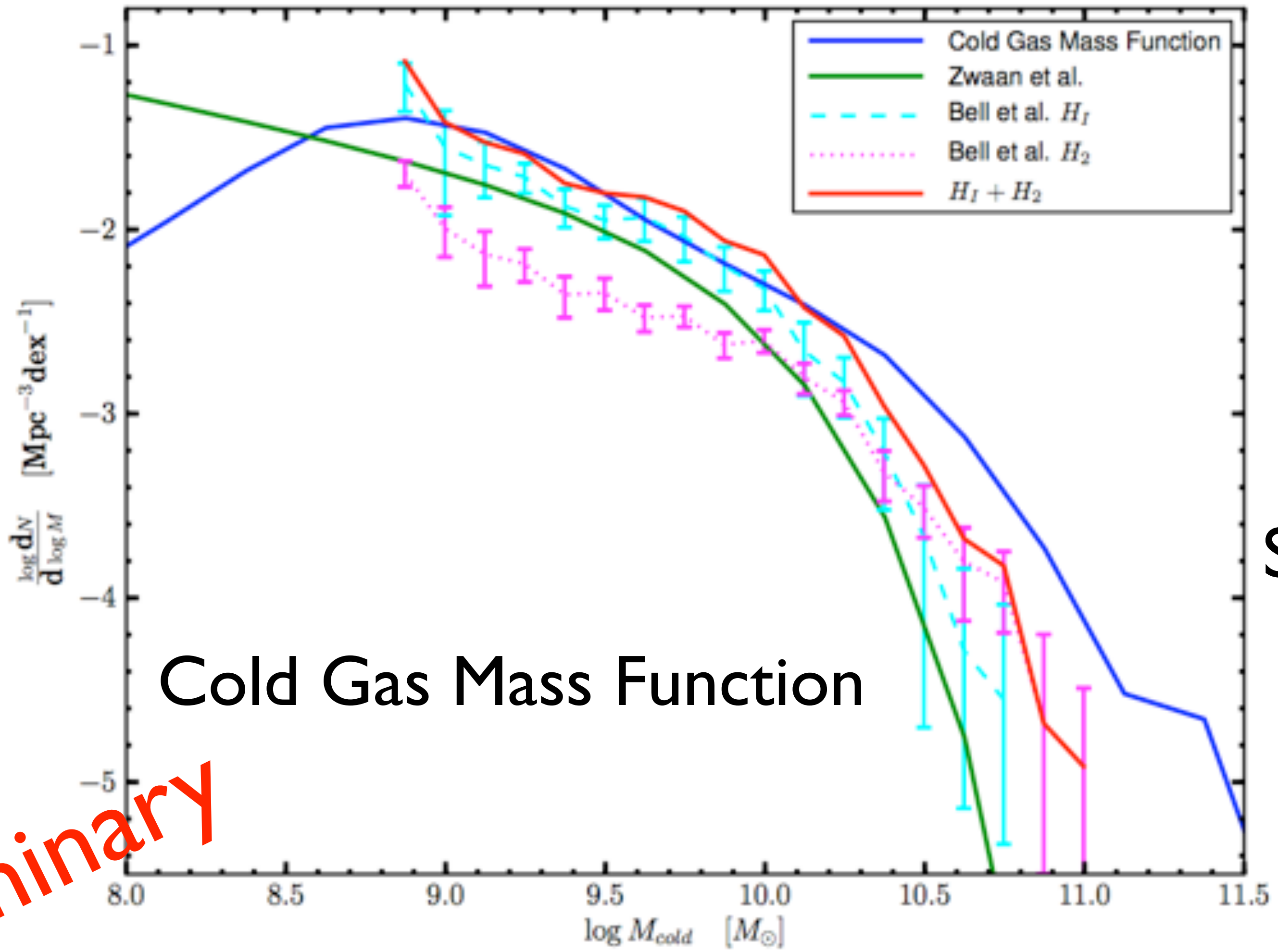


Gas Fraction vs. Mstar



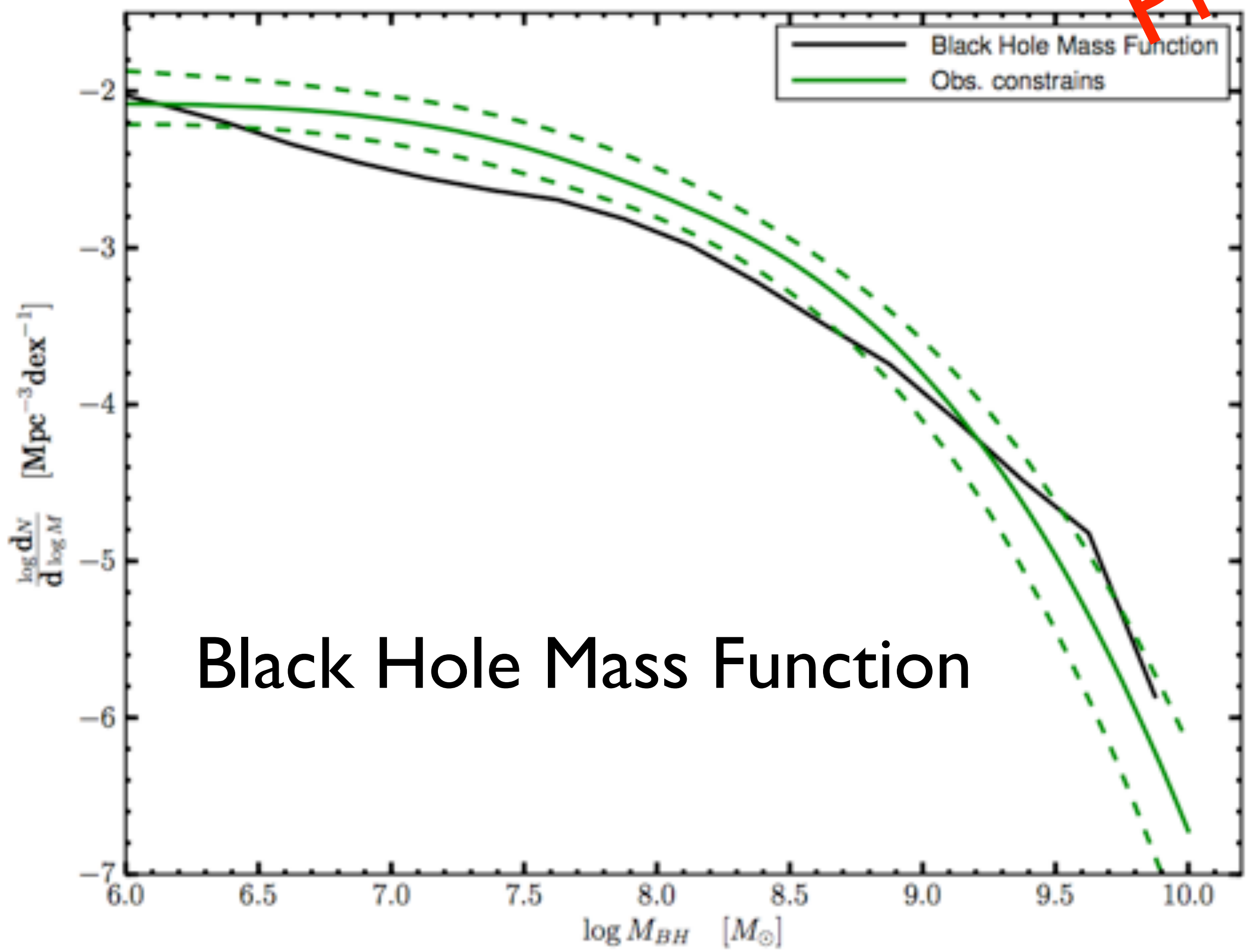


Stellar Mass Function

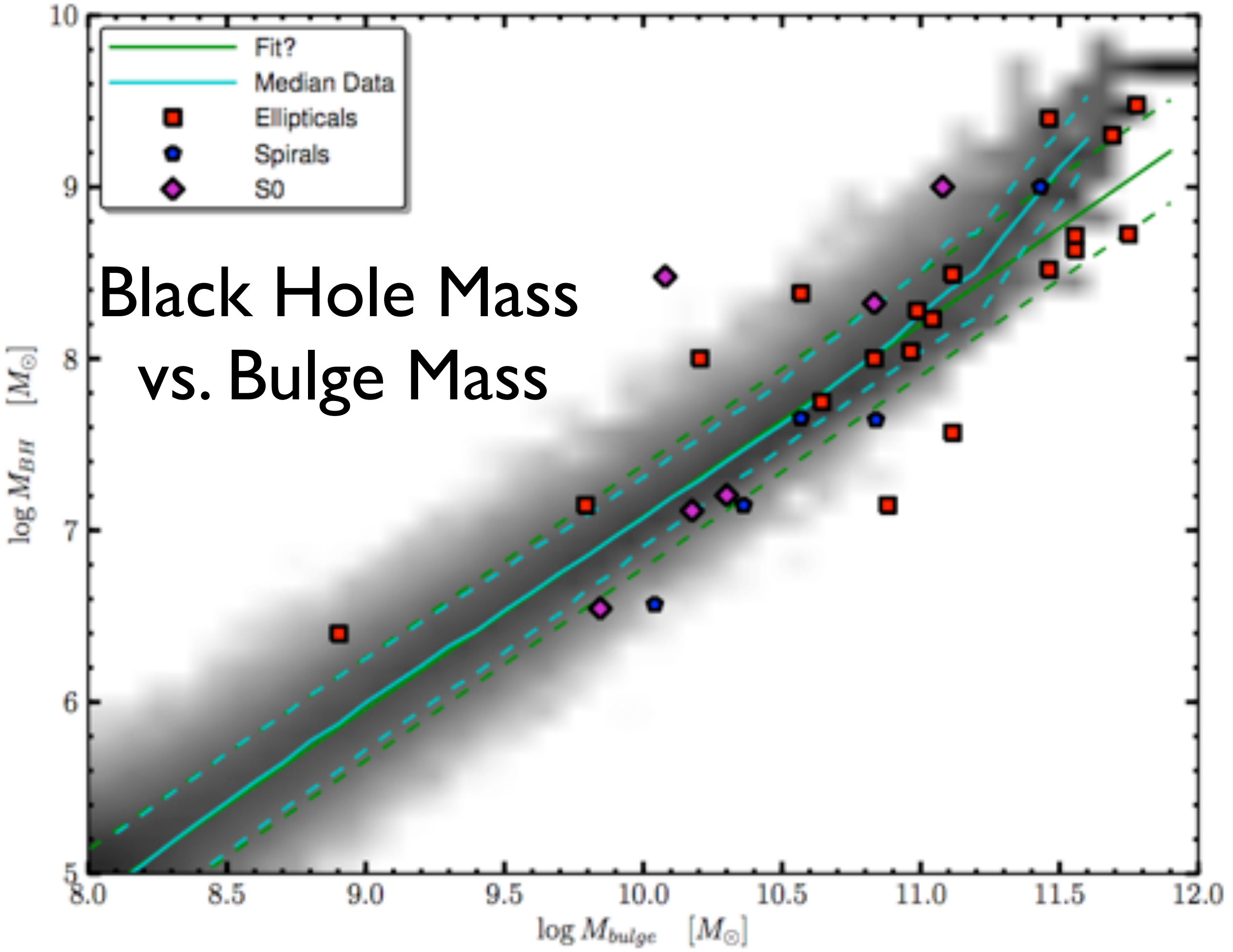


Cold Gas Mass Function

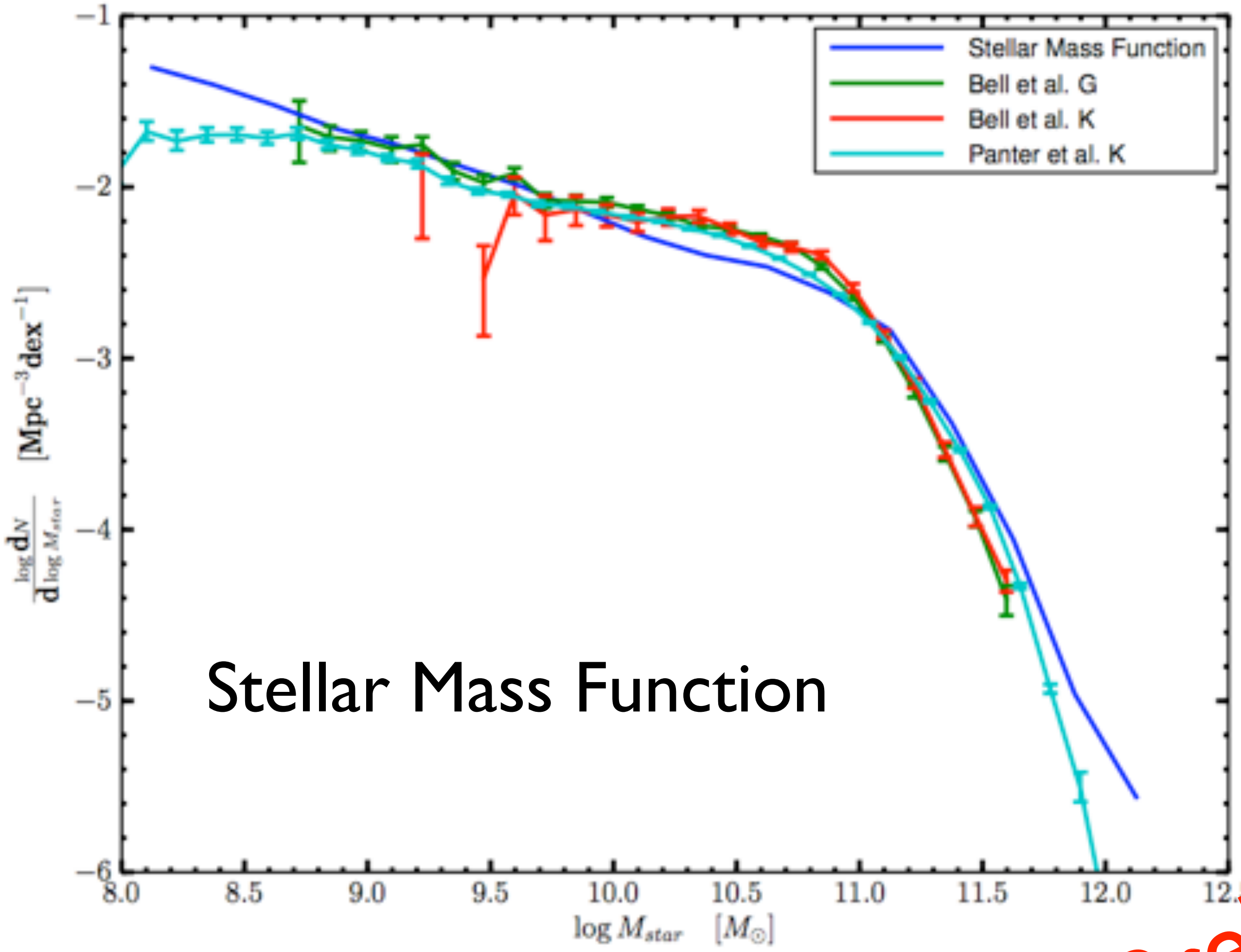
Preliminary



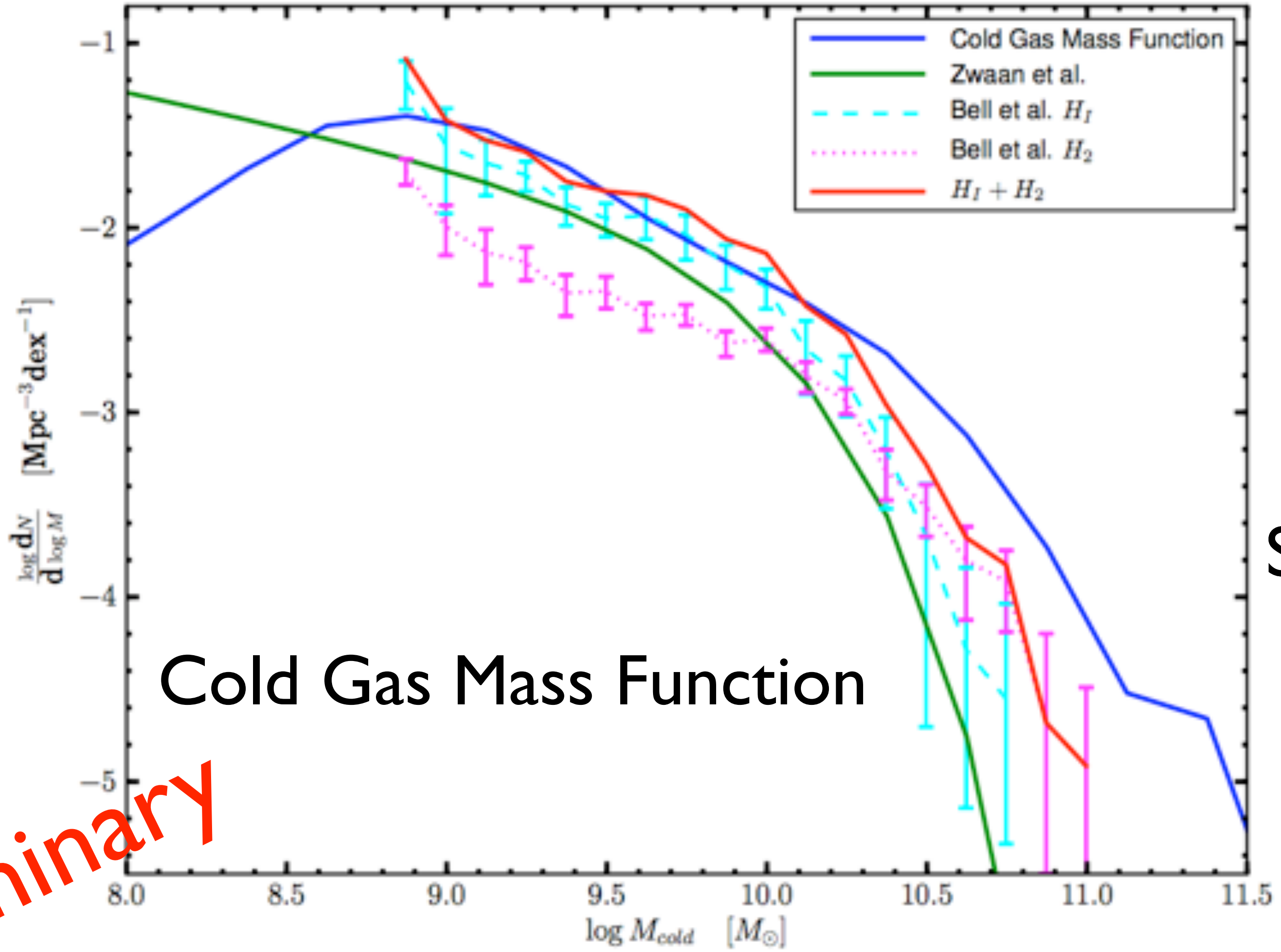
Black Hole Mass Function



Black Hole Mass
vs. Bulge Mass

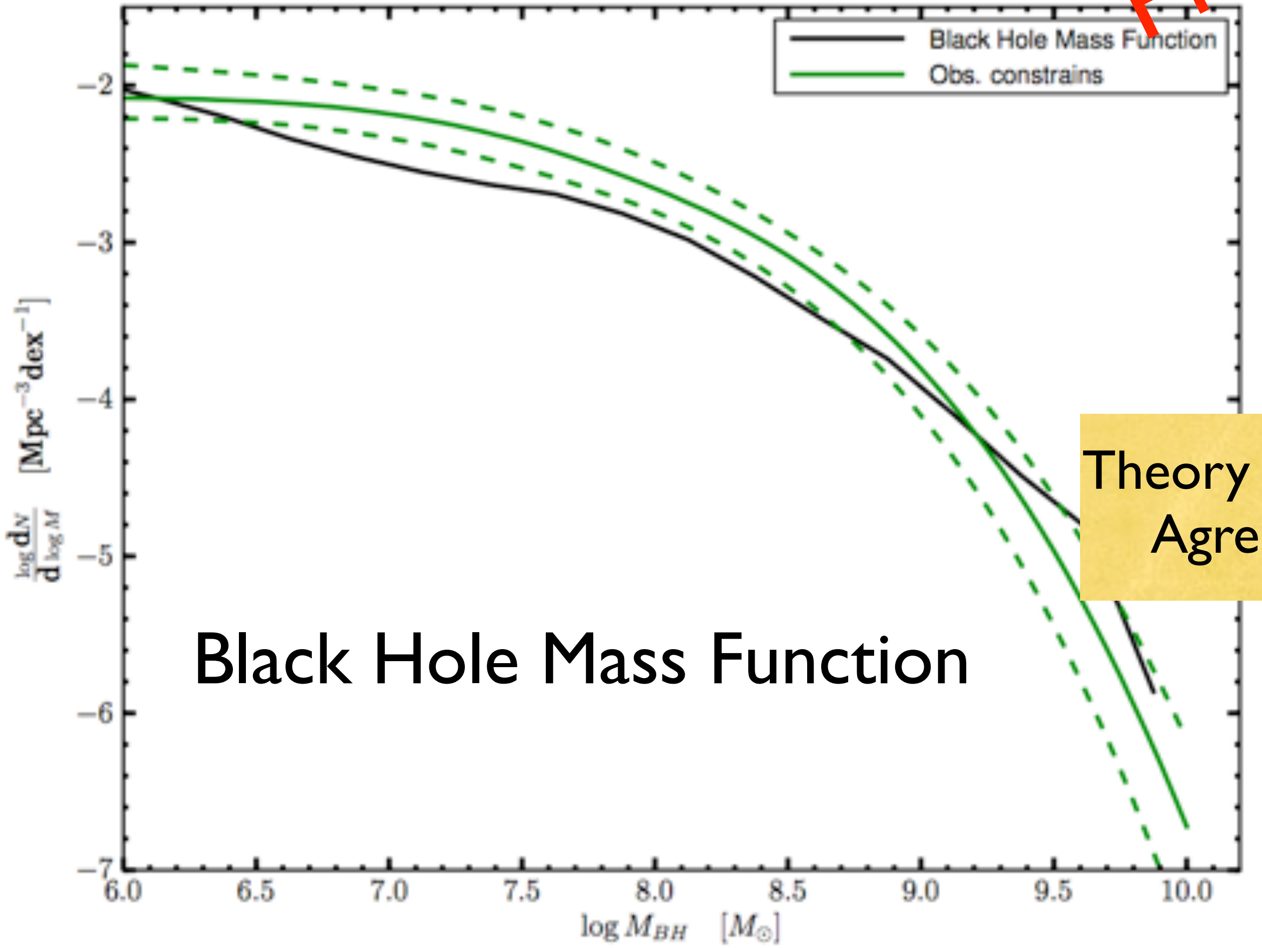


Stellar Mass Function

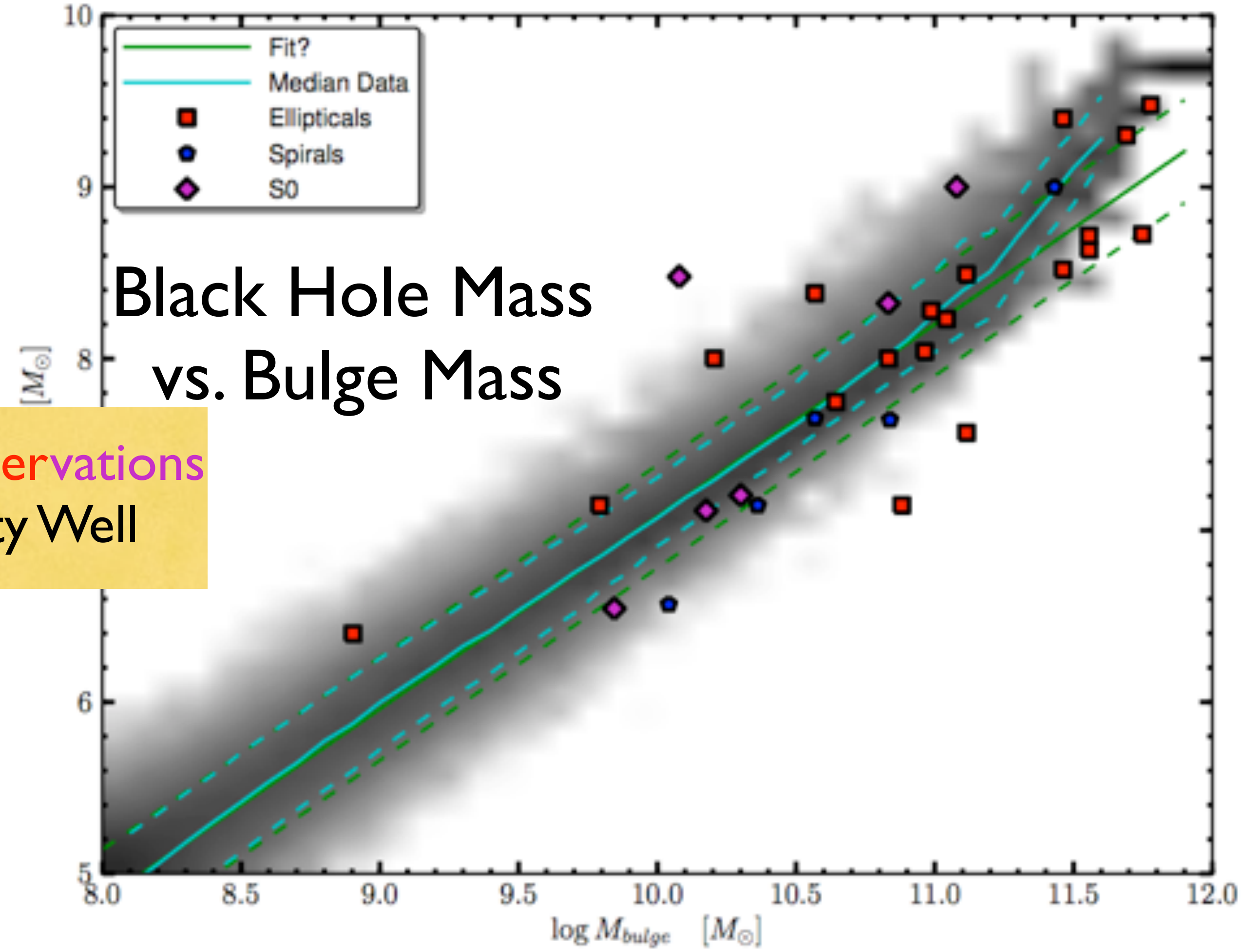


Cold Gas Mass Function

Preliminary



Black Hole Mass Function



Black Hole Mass vs. Bulge Mass

Theory & Observations Agree Pretty Well

Summary of problems with current SAMs

- no model simultaneously reproduces $f_*(M_h)$, $f_{gas}(m_*)$, and sSFR(m_*) at any redshift
- stellar population ages at z=0 too old for low mass galaxies (Somerville et al. 2008; Fontanot et al. 2009)
- low mass galaxies too numerous at high-z; low-mass halos at high-z have stellar fractions that are too high
- specific star formation rates too low at low z and too high at high z; no sSFR plateau at high z
- low mass galaxies become chemically enriched too early
- not enough cold gas at high redshift (z>3) – gas being consumed or expelled too efficiently?

CANDELS Bolshoi SAM comparison project underway: Yu Lu, Somerville, Croton, et al. 2012

Building the Model: Predicting Stellar Radii and Velocity Dispersions for Elliptical Galaxies

- Observations and high-resolution simulations have shown that major mergers of gas-rich spirals induce much star formation, typically consuming most of the gas from the progenitor galaxies (Cox et al. 2004, 2006; Dekel & Cox 2006, Robertson et al. 2006, Wuyts et al. 2010). Star formation ⇒ dissipative energy loss.

- Covington et al. (2008, 2011): including dissipation naturally reduces the sizes of elliptical galaxies, accounting for the smaller and steeper size-mass relation.

- Parameters for major (>1:3) mergers between spiral galaxies calibrated to results of GADGET simulations (Cox et al. 2008).

- Extending the model to include minor mergers and mergers involving bulge-dominated galaxies, using simulations of Johansson et al (2009).

Building the Model: Stellar Radius

- $E_{\mathrm{final}} = E_{\mathrm{init}} + E_{\mathrm{rad}}$
- $E_{\mathrm{init}} = C_{\mathrm{int}} G \sum_{i=1}^{2} \left(\frac{(M_{\mathrm{s},i} + M_{\mathrm{ns},i})^2}{R_i} \right)$
- $E_{\mathrm{rad}} = C_{\mathrm{rad}} \sum_{i=1}^{2} K_i f_{\mathrm{g},i} f_{\mathrm{k},i} (1 + f_{\mathrm{k},i})$
- $R_{\mathrm{final}} = G \sum_{i=1}^{2} \left(\frac{(M_{\mathrm{s},i} + M_{\mathrm{ns},i})^2}{E_{\mathrm{final}}} \right)$

Building the Model: Stellar Radius

- $E_{\rm final} = E_{\rm init} + E_{\rm rad}$
- $E_{\rm init} = C_{\rm int} G \sum_{i=1}^{2} \left(\frac{(M_{{\rm s},i} + M_{{\rm ns},i})^2}{R_i} \right)$
- $E_{\rm rad} = C_{\rm rad} \sum_{i=1}^{2} K_i f_{{\rm g},i} f_{{\rm k},i} (1 + f_{{\rm k},i})$
- $R_{\rm final} = G \sum_{i=1}^{2} \left(\frac{(M_{{\rm s},i} + M_{{\rm ns},i})^2}{E_{\rm final}} \right)$

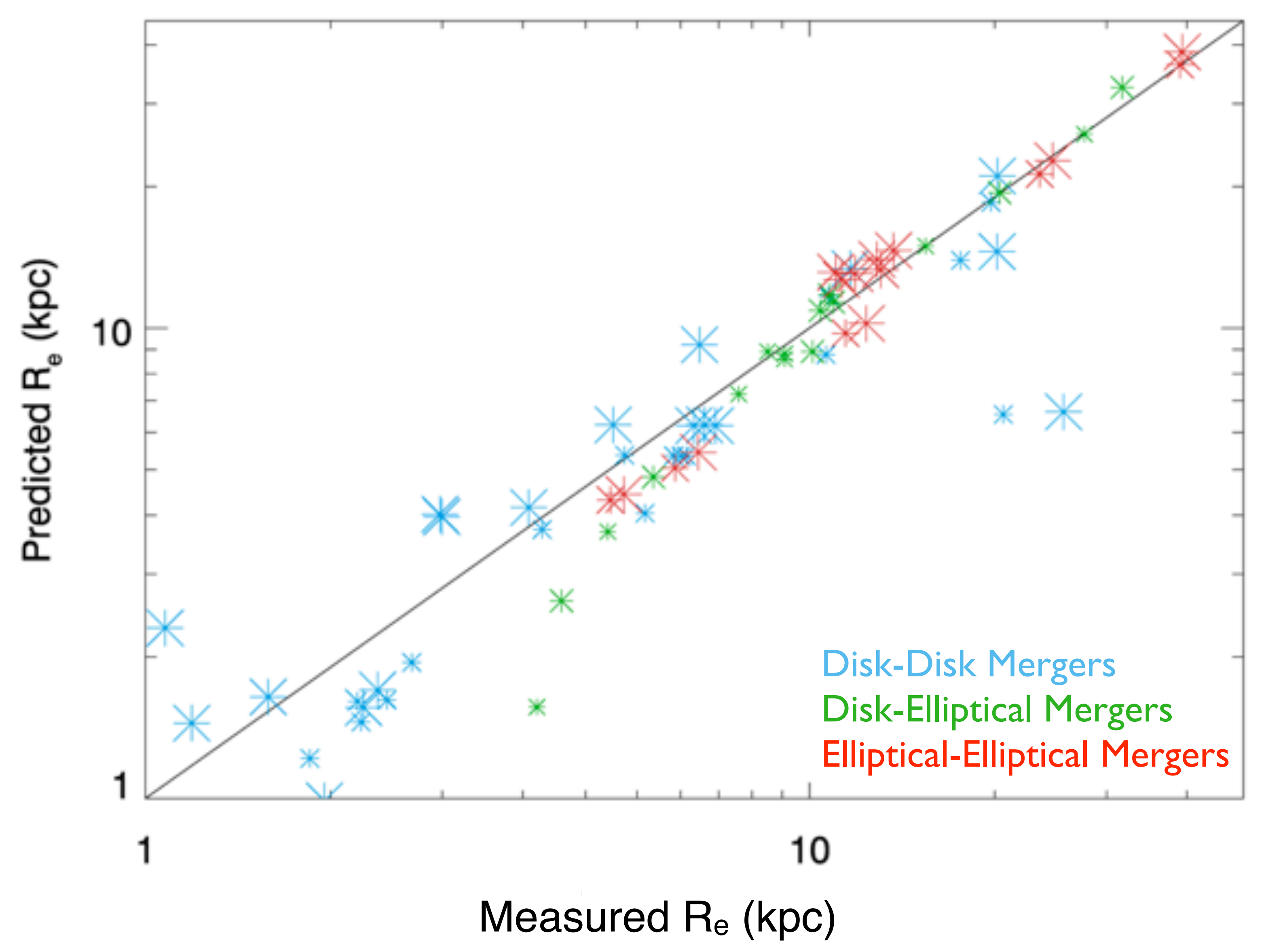
Kinetic Energy

Gas Fraction: higher gas fractions induce more dissipation

Impulse: taken from statistical distribution of orbital parameters (Wetzel 2010)

Building the Model: Spheroid Stellar Radius

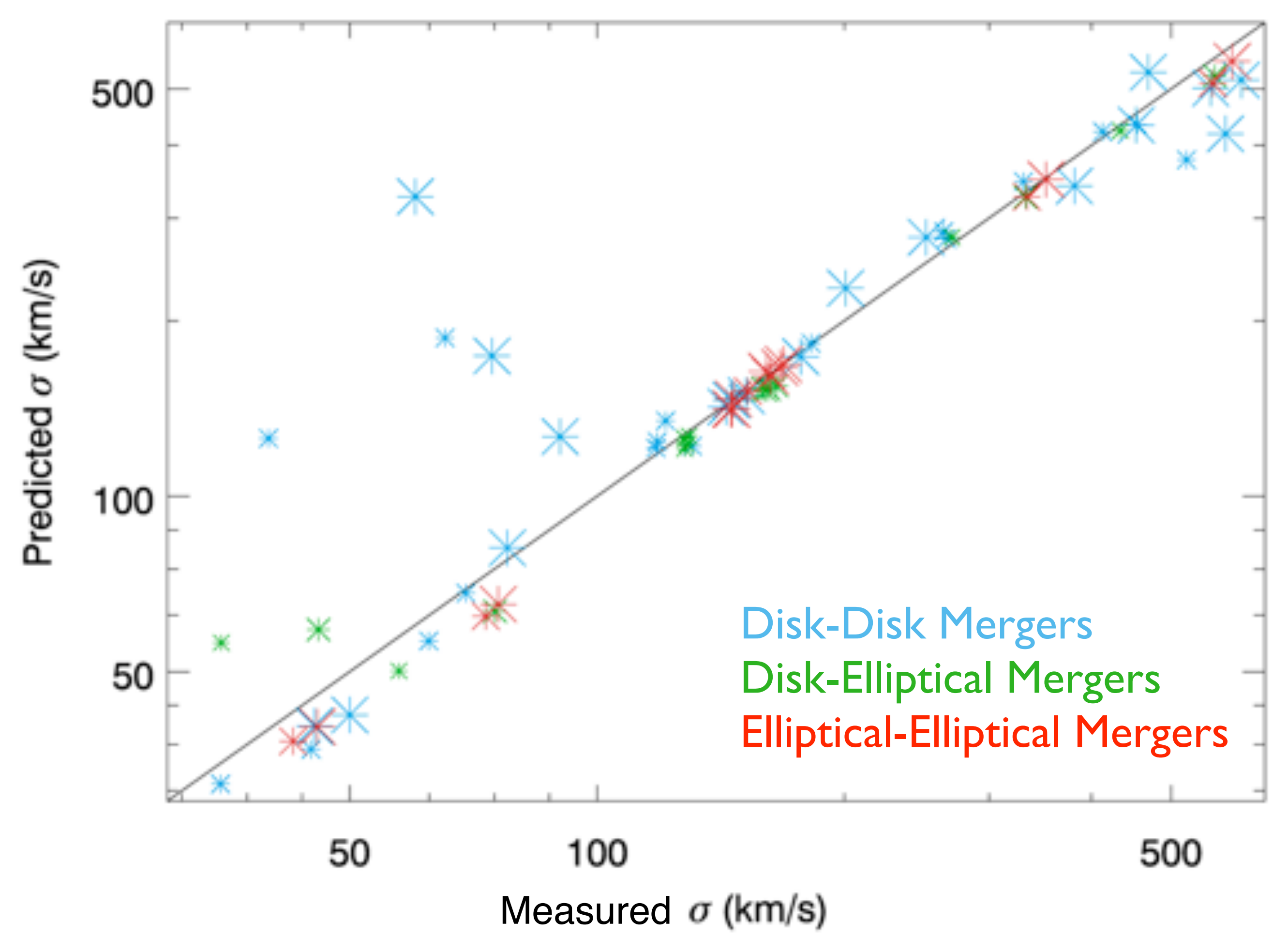
- Goal: Extend the model to include minor mergers and mergers involving bulge-dominated galaxies.
- Relative importance of dissipation parameterized by C_{int} and C_{rad}
  - Major disk-disk mergers: $C_{int} = 0.95$, $C_{rad} = 2.9$
  - Minor disk-disk mergers: $C_{int} = 1.0$, $C_{rad} = 2.7$
  - All other mergers: $C_{rad} = 0.0$ (dissipationless)



Simulations provided by Johansson et al. (2009). Each point represents a simulation of a merger between two galaxies. This extends earlier work (Covington et al. 2009, 2011) based on Cox+ simulations.

Lauren Porter + 2012

Building the Model: Velocity Dispersion



Simulations provided by Johansson et al. (2009). Each point represents a high-resolution simulation of a merger between two galaxies.

- Velocity dispersion is within half-mass radius
- $\sigma^2 = \dfrac{C_{sig} G M_{s,f}}{2R_f(1 - f_{dm,f})}$
- $C_{sig} = 0.20$ for all merger ratios and morphologies

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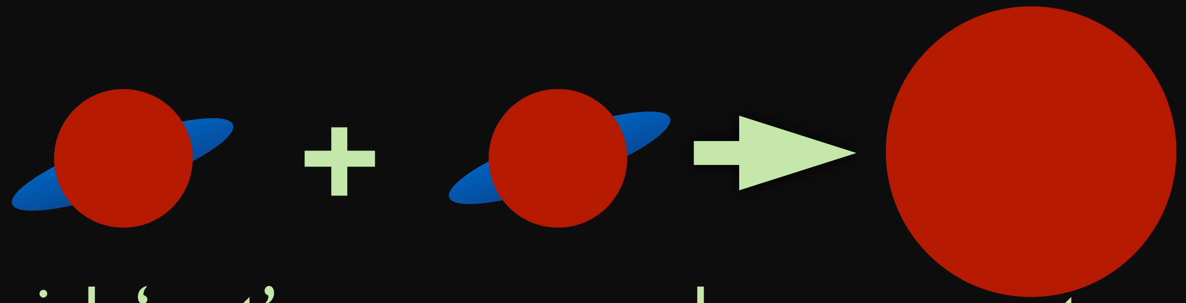
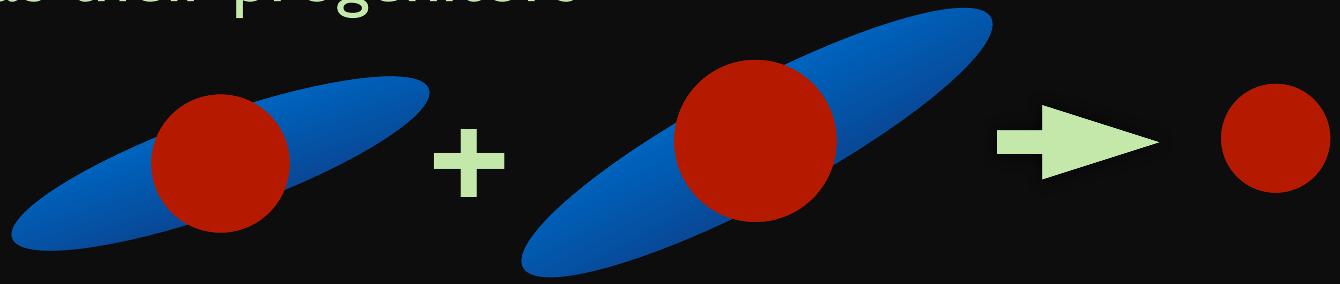
Building the Model: Predictions

- Gas-poor ‘dry’ mergers increase the radii of the remnants



- Gas-rich ‘wet’ mergers produce remnants with similar or smaller radii as their progenitors



- Gradient in gas fraction with stellar mass can introduce a tilt in the FP and account for the steepening of the size-mass relation from disks to ellipticals
- Gradient in gas fraction with respect to surface density reduces scatter in size-mass relation
- *Treat ‘classical’ disk instabilities the same as dissipationless mergers*

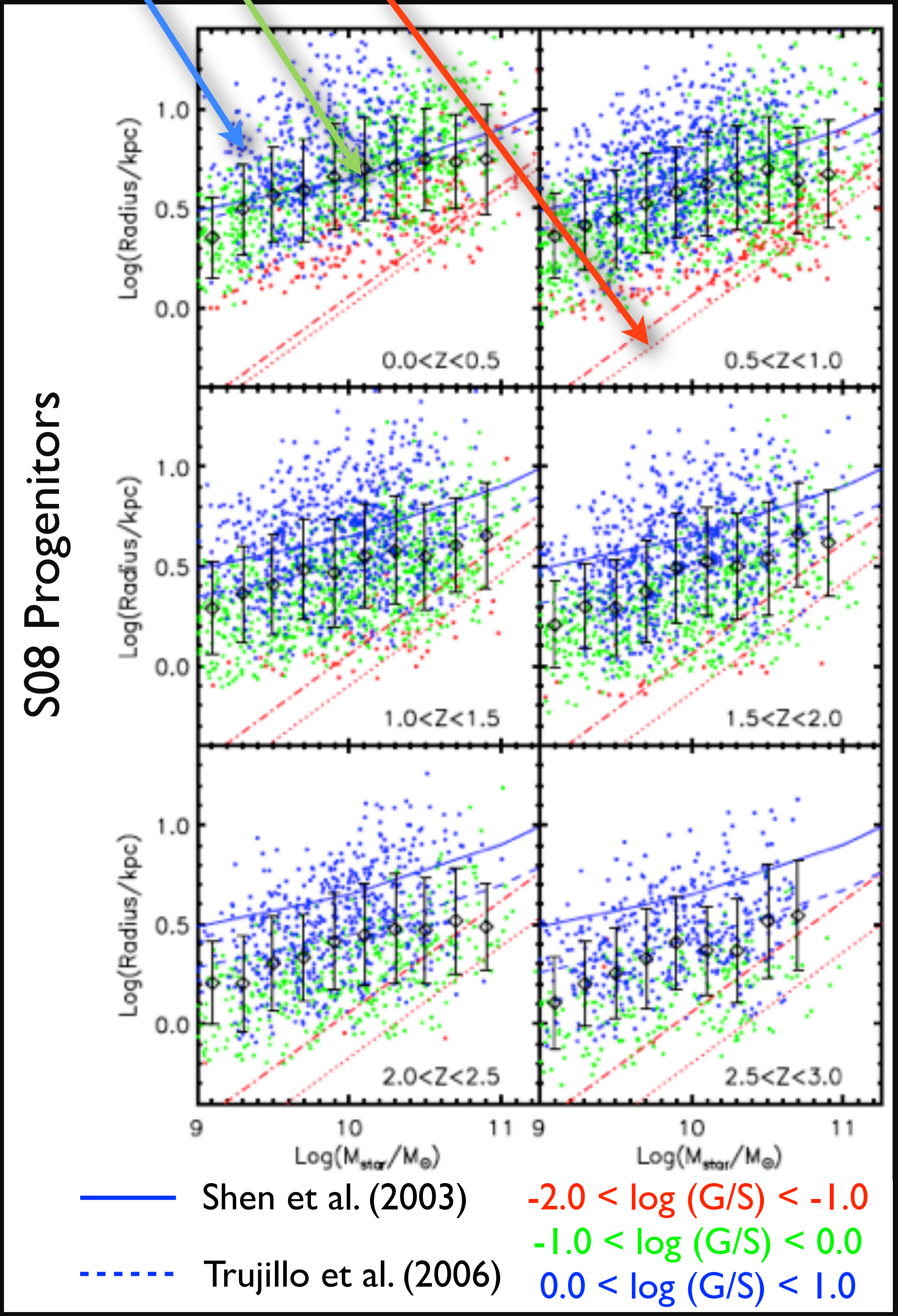
Building the model: Results

- Compared to the progenitors, remnants are:
    - More compact
    - Steeper size-mass relation
    - Greater evolution with redshift
- Subsequent minor mergers increase the effective radius and the scatter in radius while leaving the velocity dispersion relatively unchanged (Naab et. al 2009, Oser et al. 2012).

progenitor disks: gas rich

progenitor disks: less gas

resulting spheroids



Covington et al. (2011)

Building the model: Results

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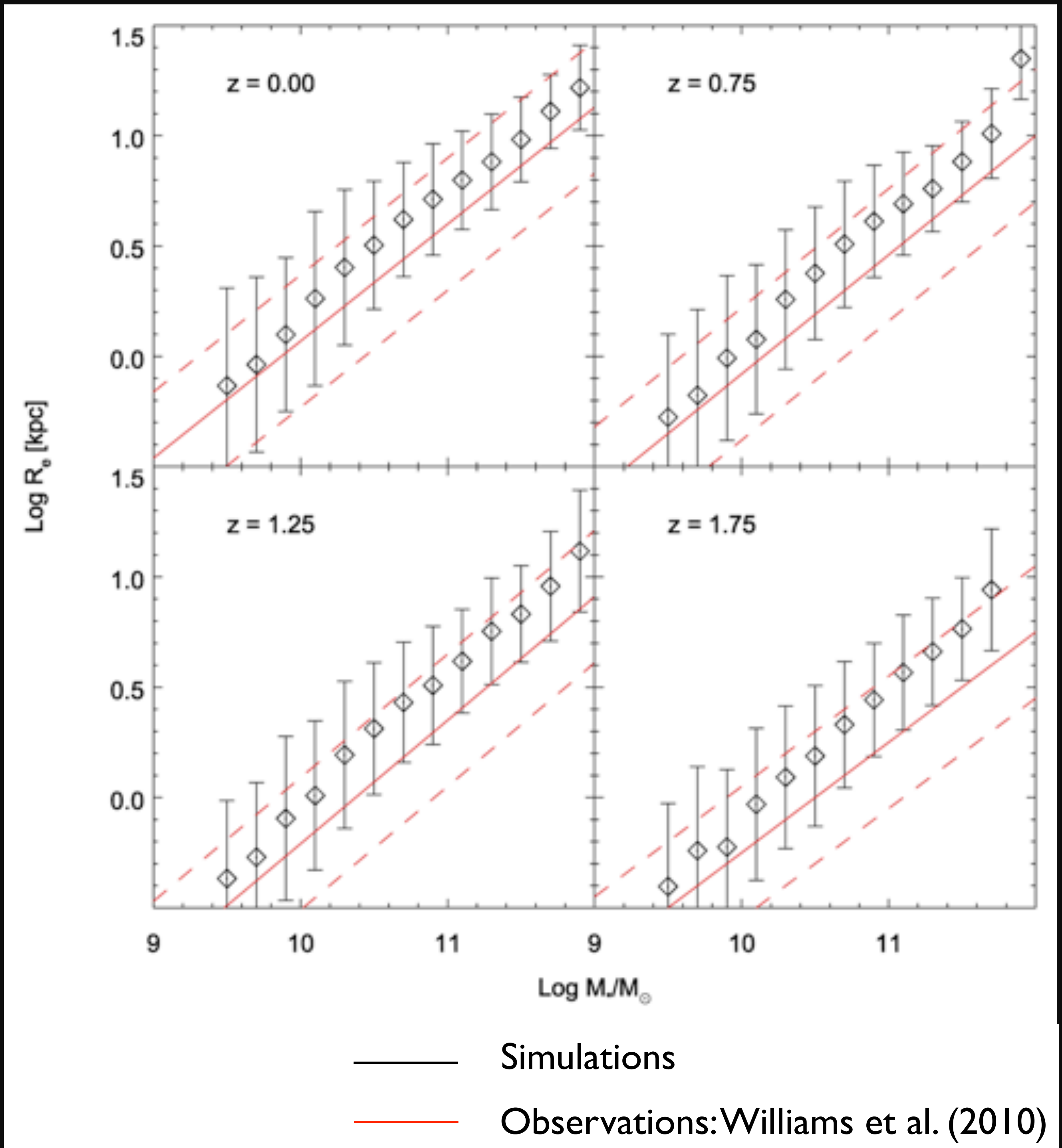


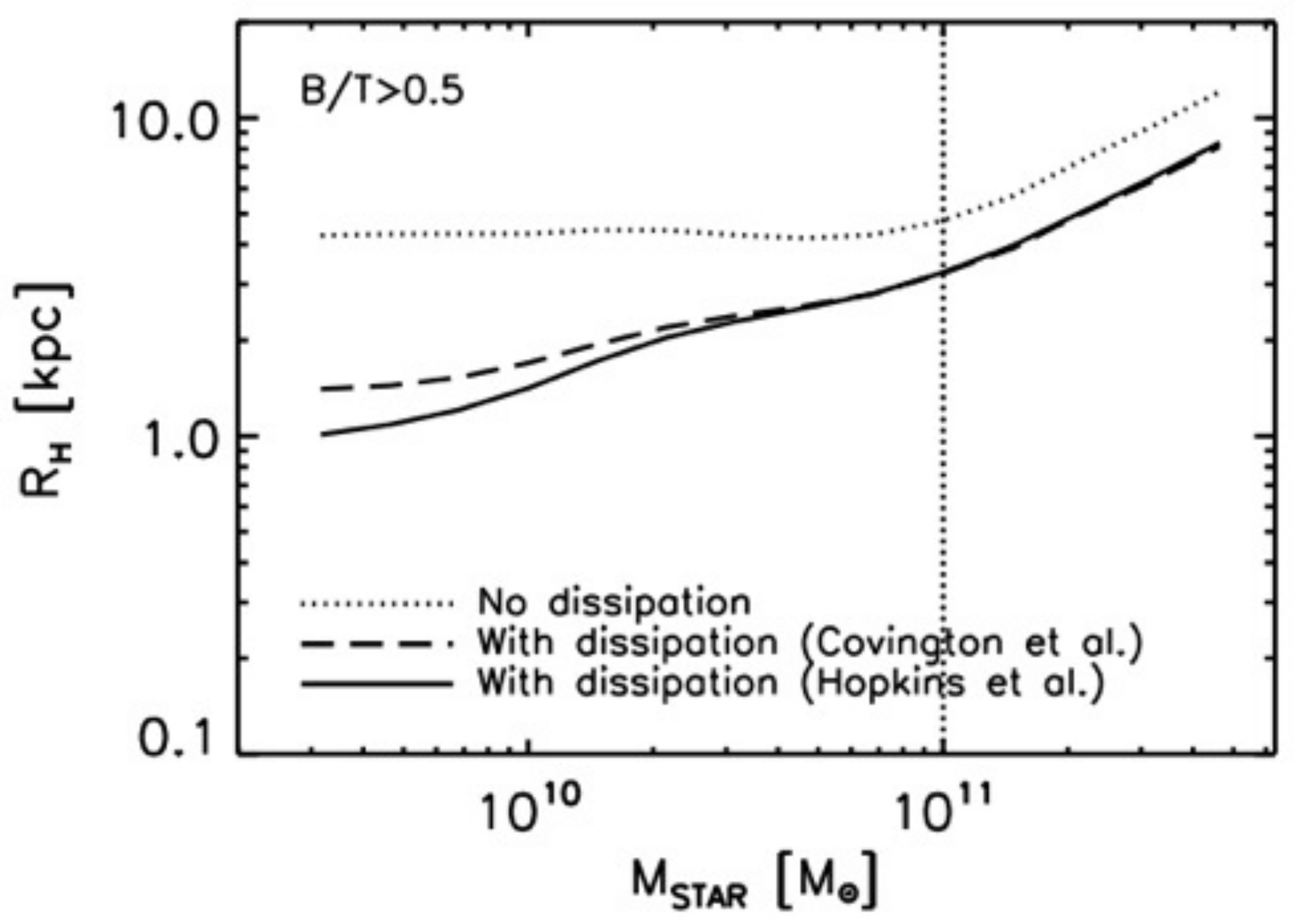
SAMs without dissipation predict a size-mass relation with a shallower slope and much greater dispersion than observed.

Lauren Porter + 2012

Building the model: Results

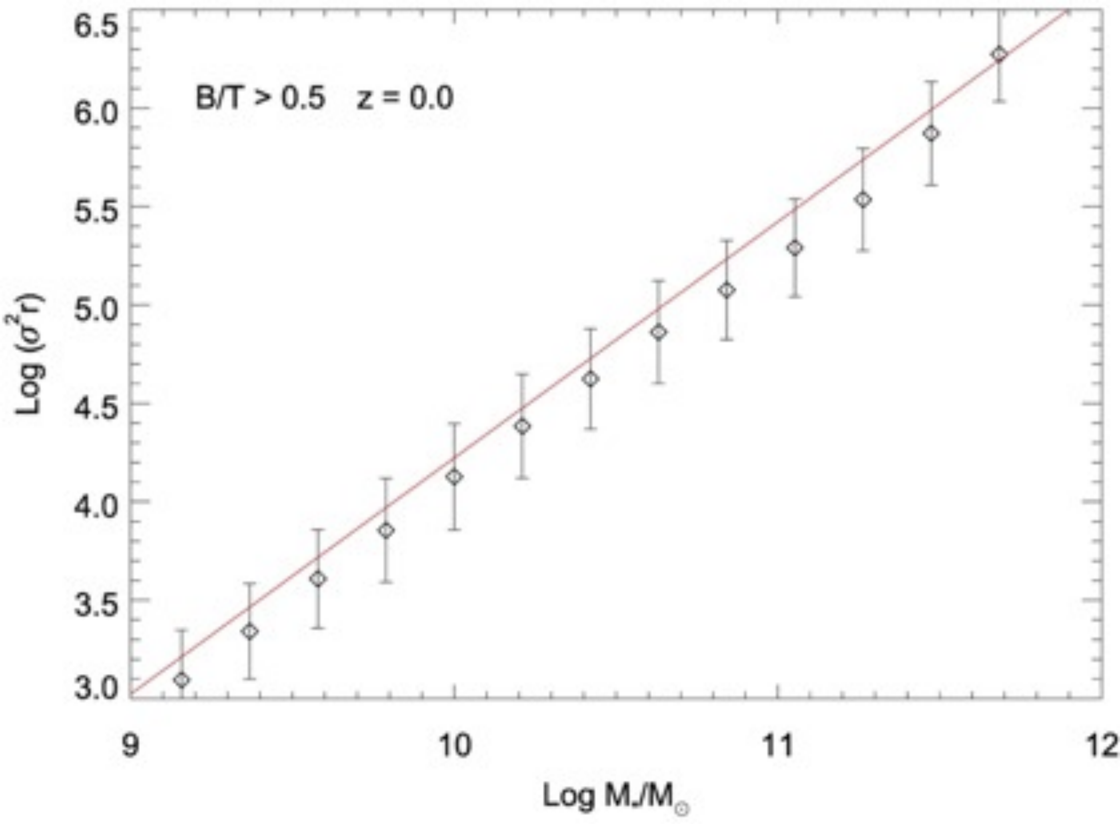
- Including dissipation is necessary to reproduce the size-mass relation for elliptical galaxies.
- Other recent SAMs that have included dissipation have found similar results (Shankar et al. 2011).
- For the first time, accurate predictions for the radii and velocity dispersions of elliptical galaxies enable SAMs to model and study the Fundamental Plane.

Spheroid Size-Mass Relation with and without dissipation

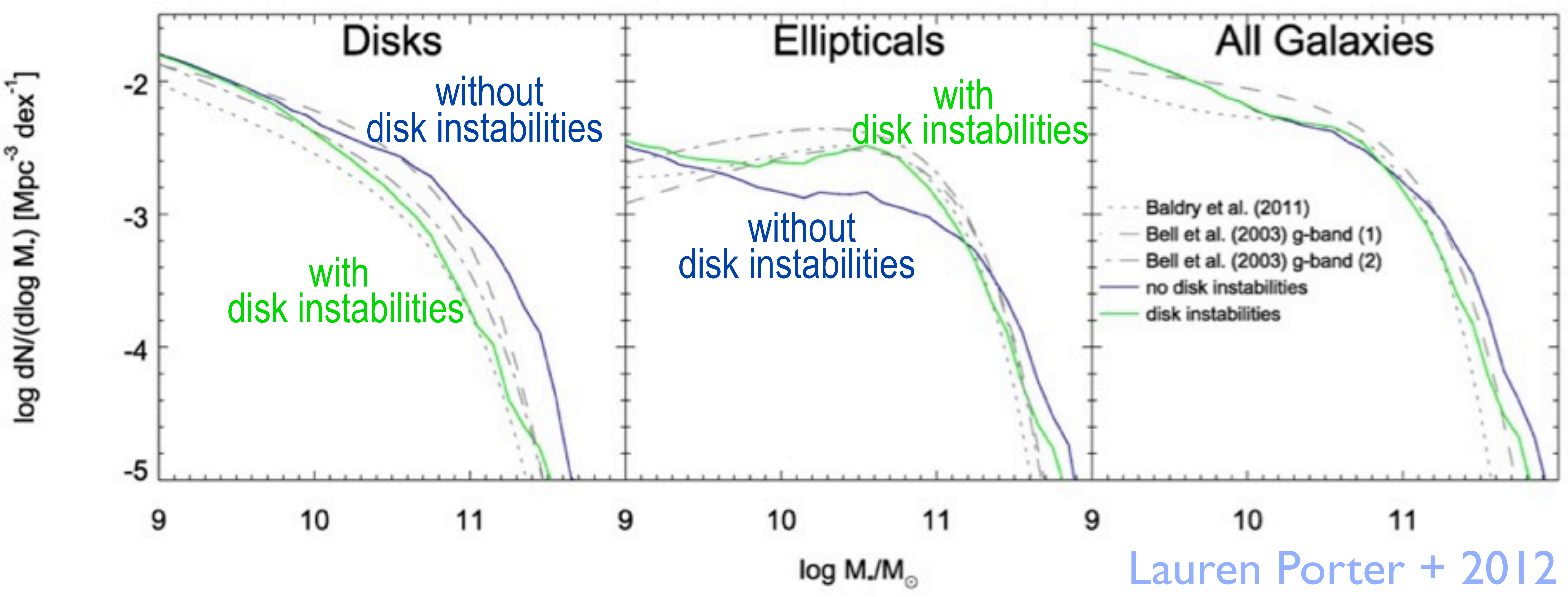


Shankar et al. (2011)

Low-redshift elliptical galaxies



- Correctly reproducing the z=0 size-mass, Faber-Jackson, and Fundamental Plane relations
- Including 'classical' disk instabilities reproduces the morphology-selected z=0 mass function



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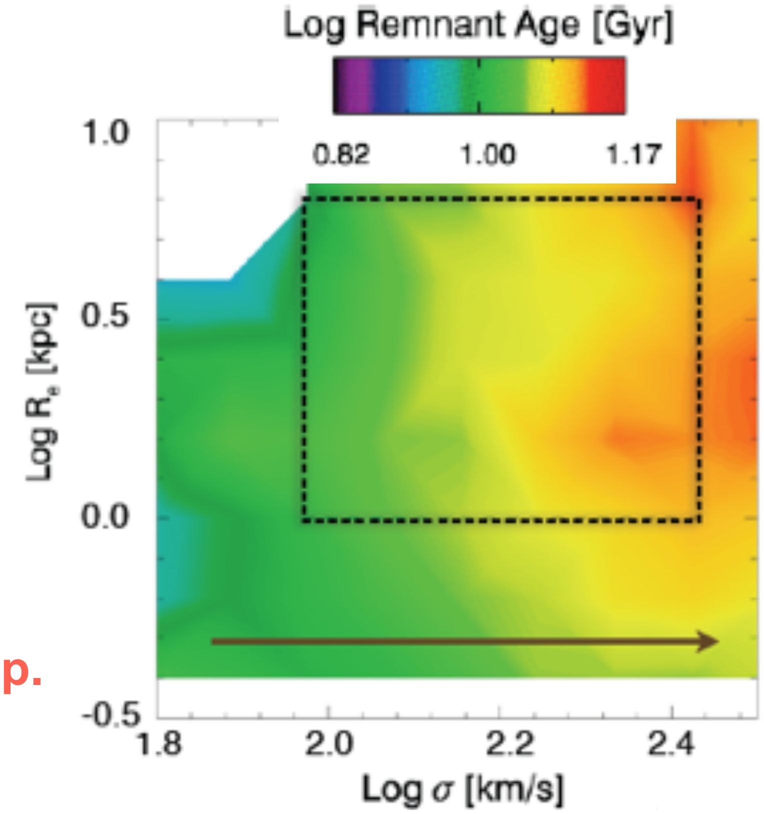
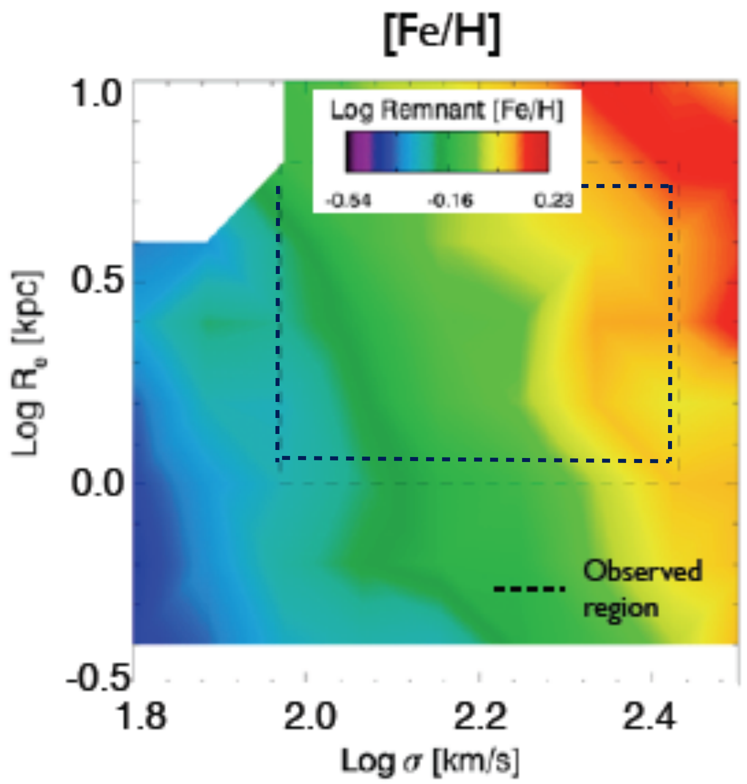
SAM Predictions vs. SDSS Observations

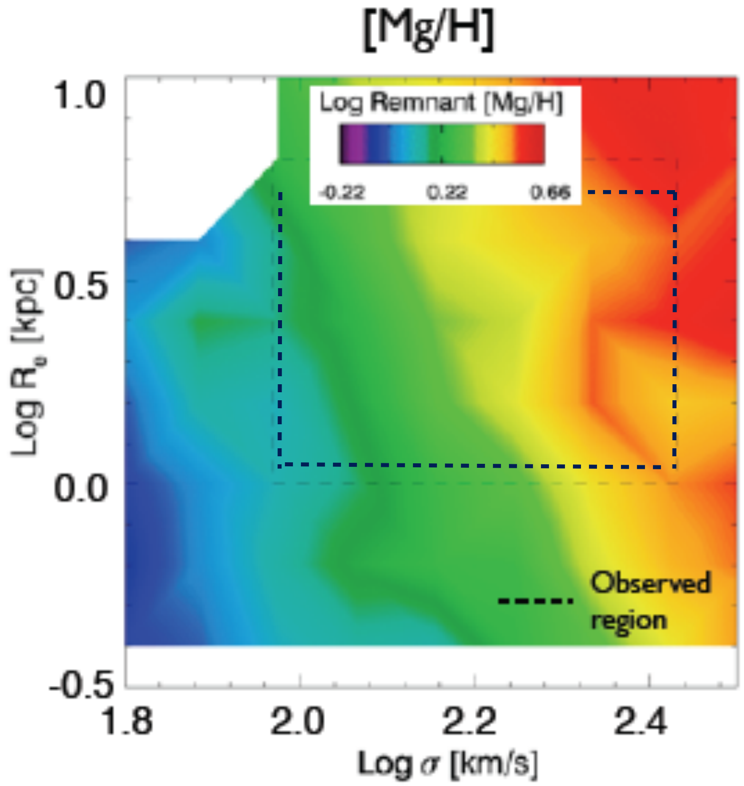
Galaxy Age

Galaxy Metallicity

SAM

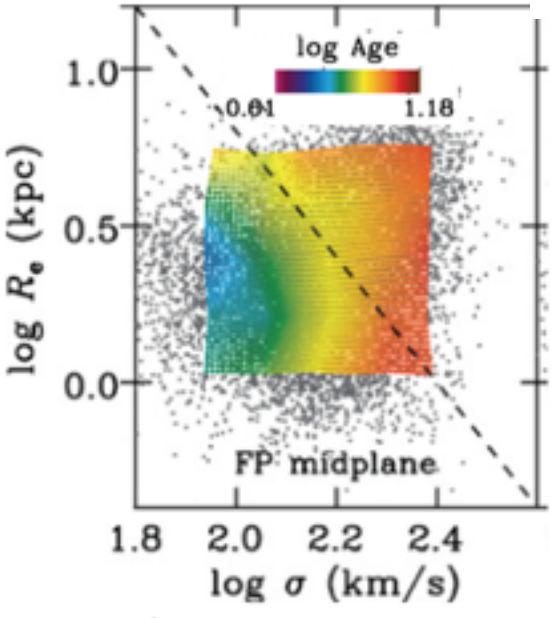


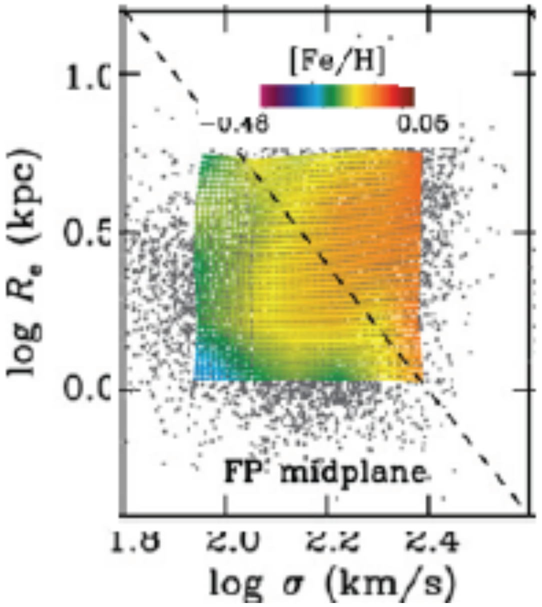


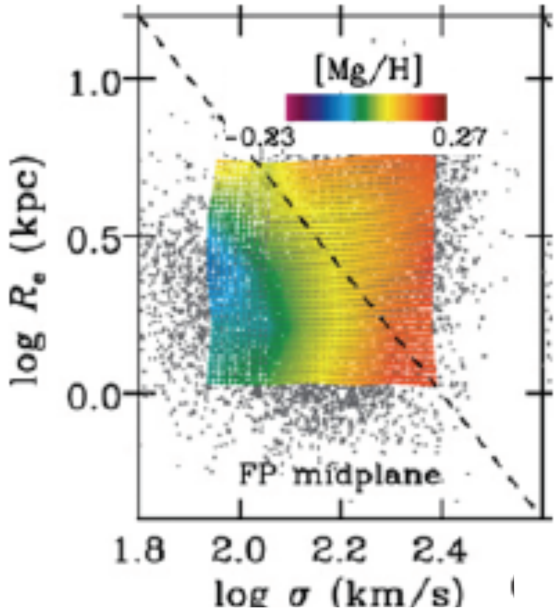


Lauren Porter et al. in prep.

SDSS







Jenny Graves et al. 2009

Lauren Porter + 2012

CANDELS: THE PROGENITORS OF COMPACT QUIESCENT GALAXIES AT $Z\sim2$

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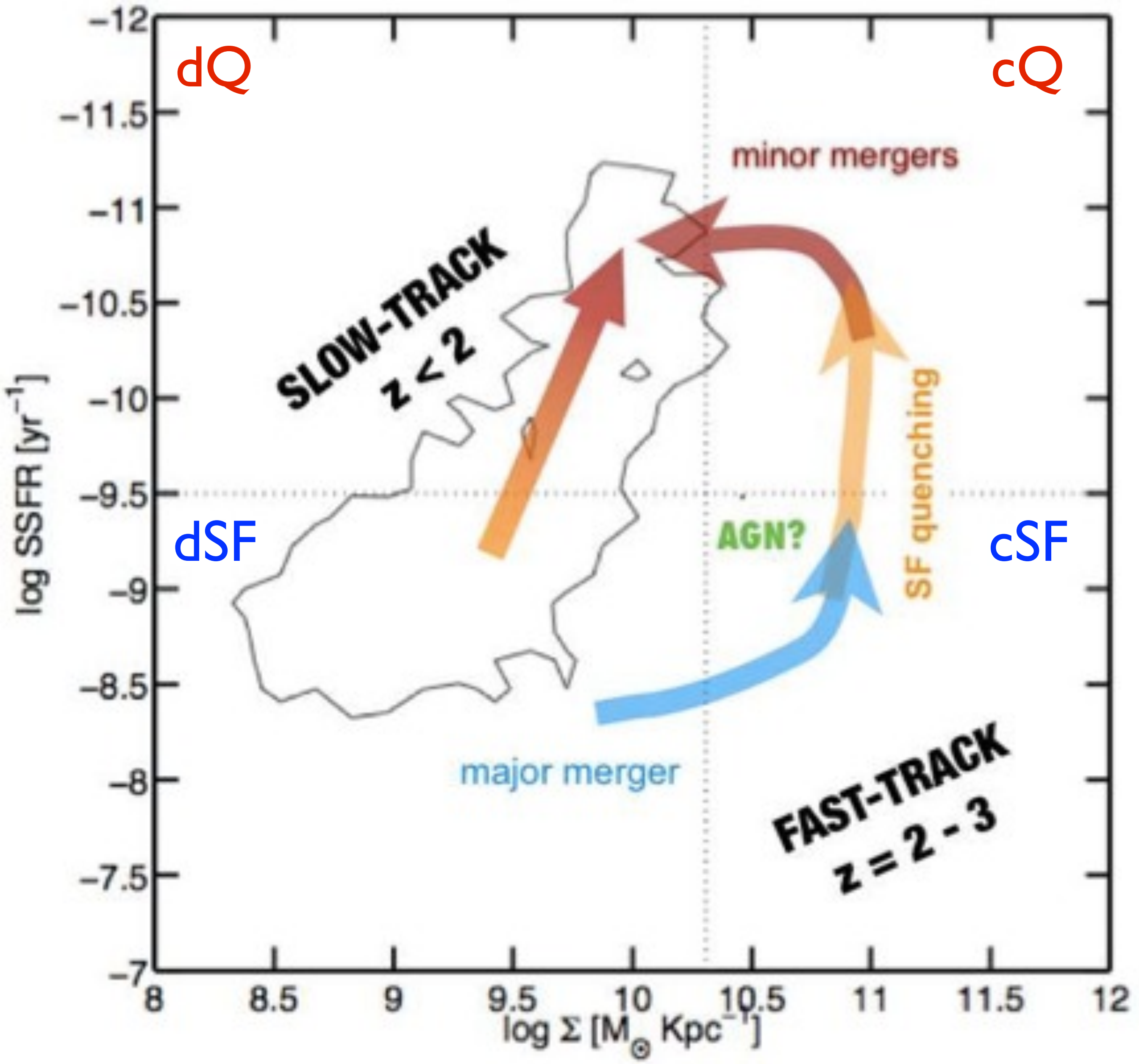
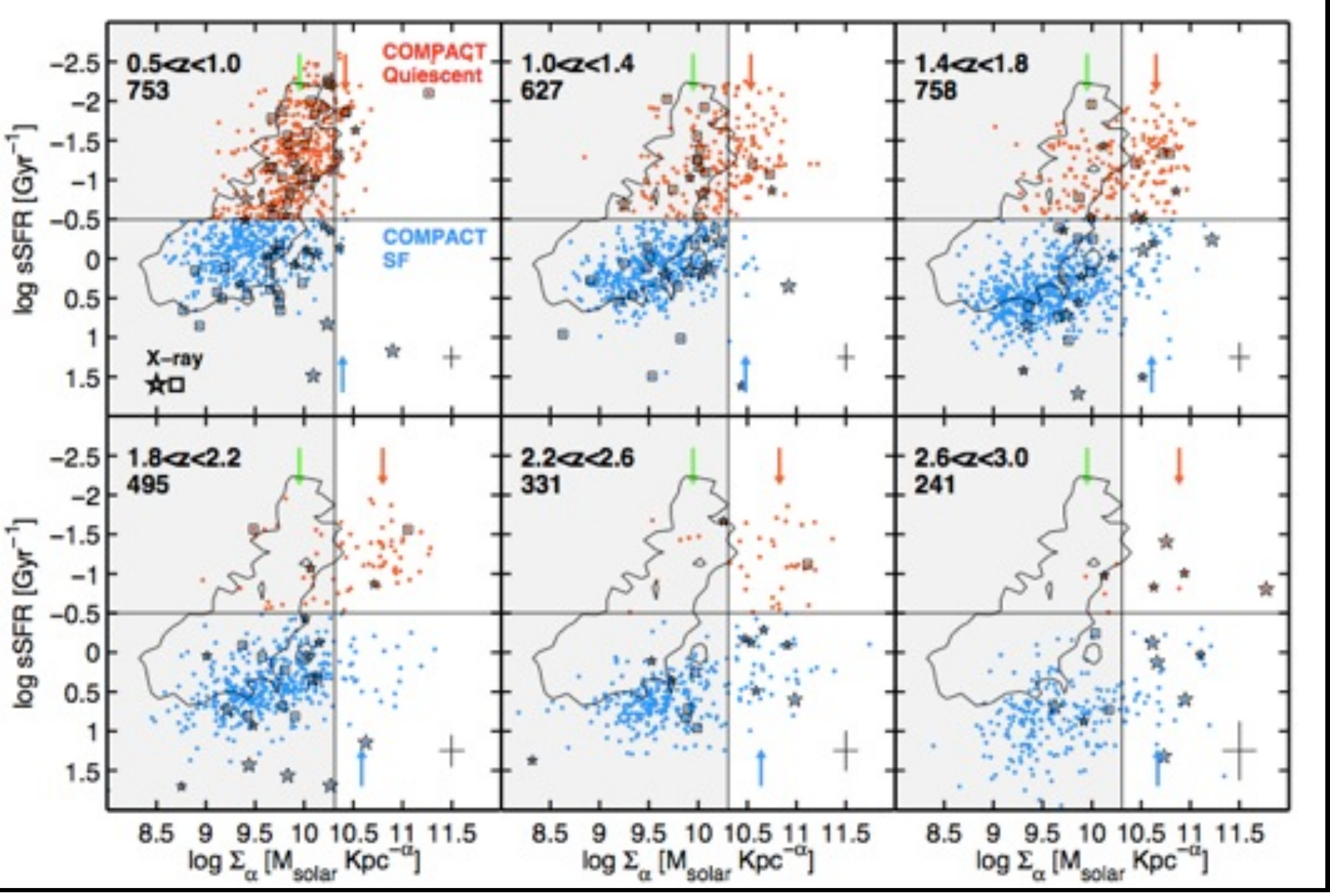
Submitted to the Astrophysical Journal Letters

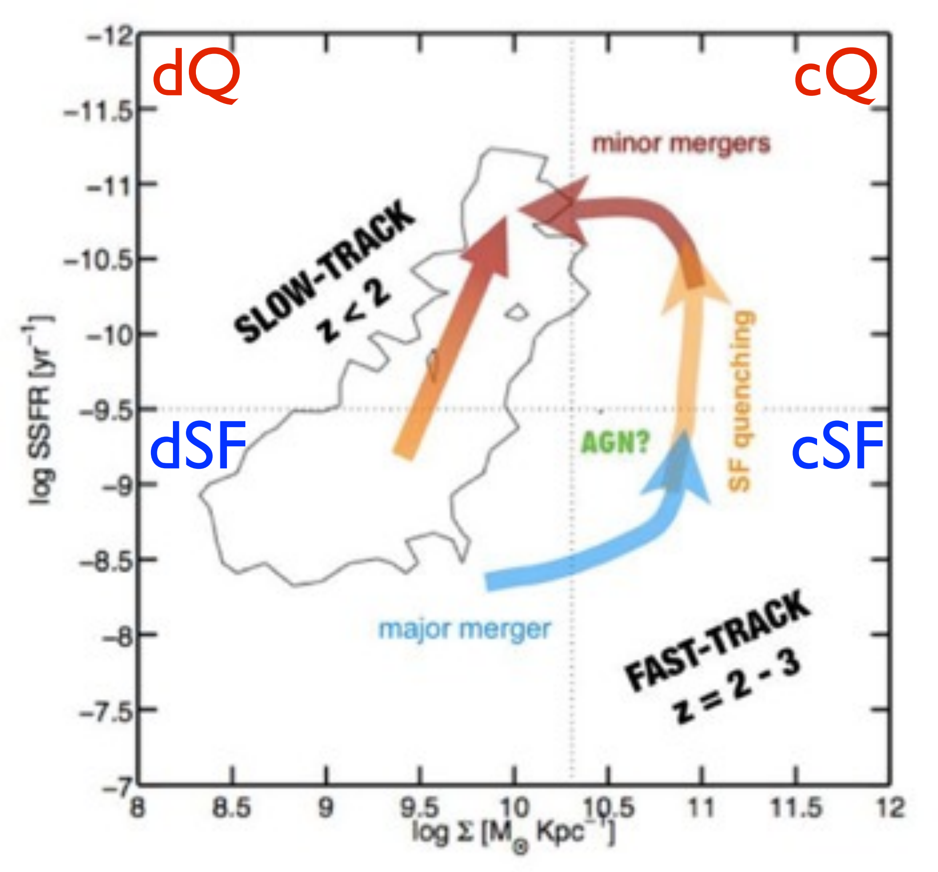
arXiv:1206.5000v1

ABSTRACT We combine high-resolution HST/WFC3 images with multi-wavelength photometry to track the evolution of structure and activity of massive ($M_\star > 10^{10} M_\odot$) galaxies at redshifts z = 1.4 − 3 in two fields of the Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey (CANDELS). We detect compact, star-forming galaxies (cSFGs) whose number densities, masses, sizes, and star formation rates qualify them as likely progenitors of compact, quiescent, massive galaxies (cQGs) at z = 1.5 − 3. At z > 2, most cSFGs have specific star-formation rates half that of typical massive SFGs, and host X-ray luminous AGNs 30 times more frequently. These properties suggest that cSFGs are formed by gas-rich processes (mergers or disk-instabilities) that induce a compact starburst and feed an AGN, which, in turn, quench the star formation on dynamical timescales (few 10^8yr). The cSFGs are continuously being formed at z = 2 − 3 and fade to cQGs down to z ~ 1.5. After this epoch, cSFGs are rare, thereby truncating the formation of new cQGs. In summary, we propose two evolutionary tracks of QG formation: an early (z > 2), fast-formation path of rapidly-quenched cSFGs fading into cQGs that later enlarge within the quiescent phase, and a slow, late-arrival (z < 2) path in which larger SFGs form extended QGs without passing through a compact state.

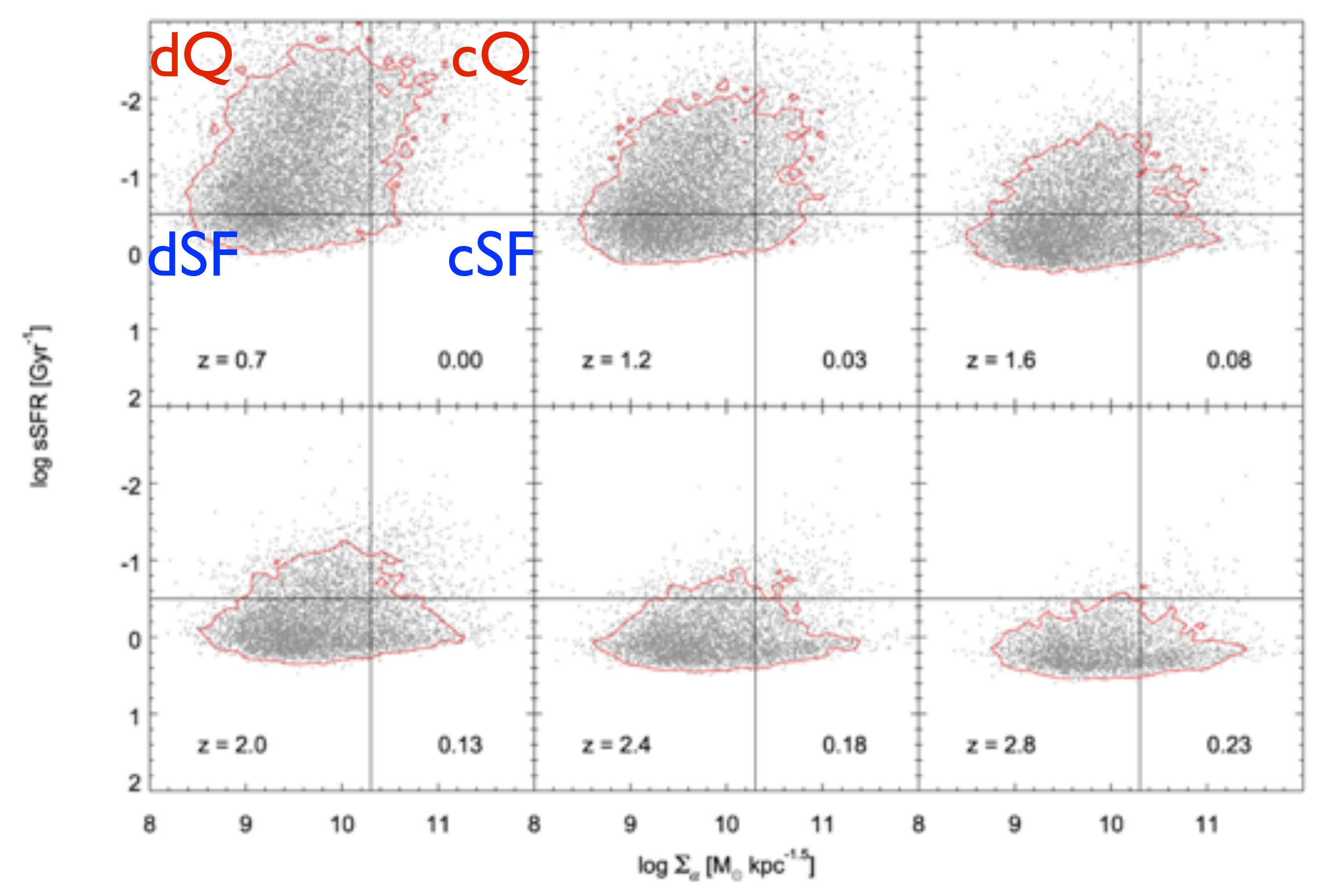


Evolution of Galaxies: Observations vs. Theory

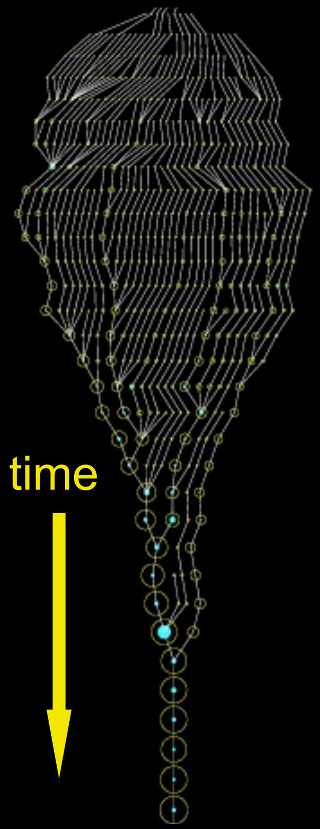




Barro et al. (2012 - Hubble Observations)



Bolshoi
DM Halo
Merger
Tree



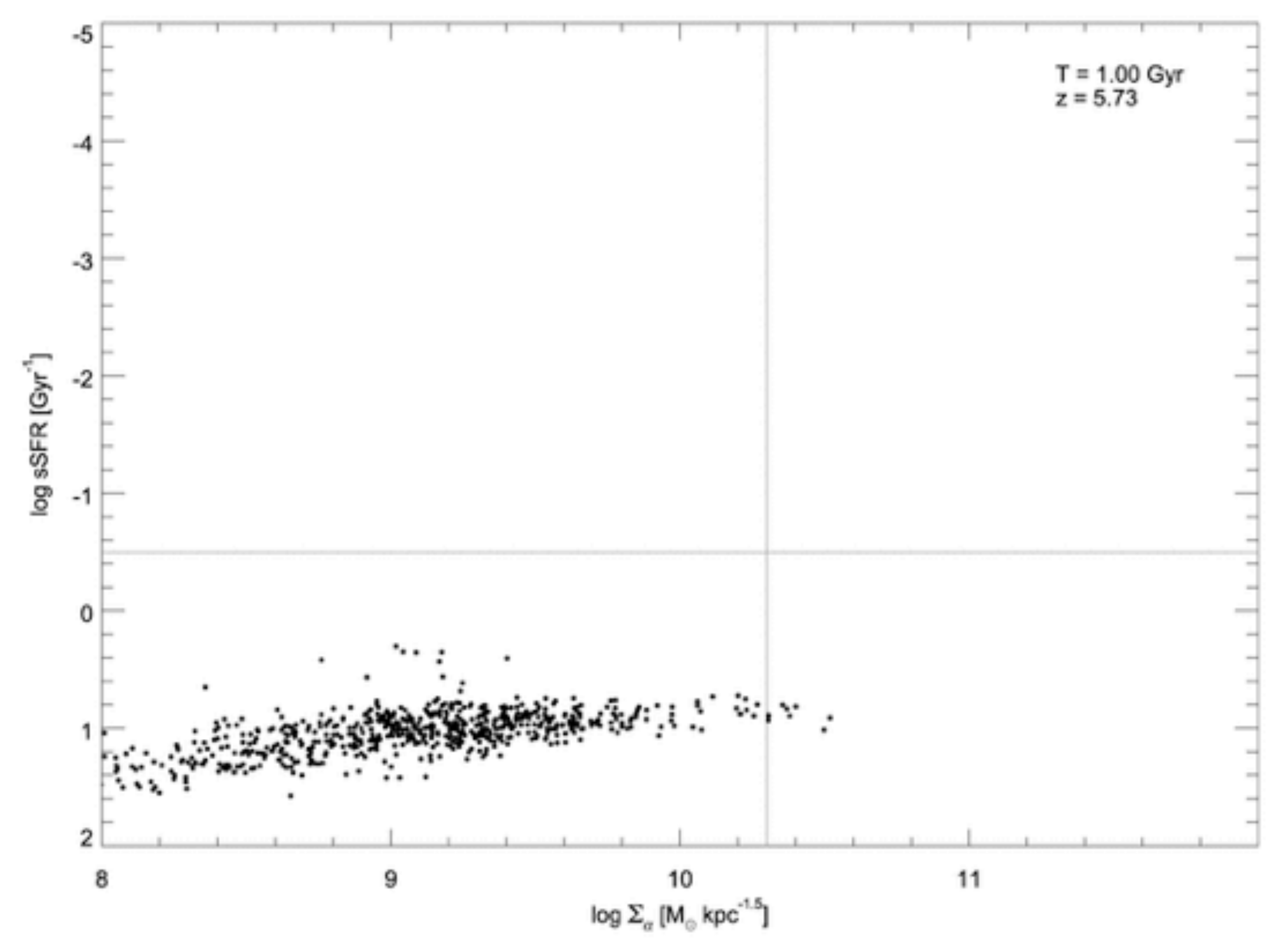
Astrophysical processes modeled:

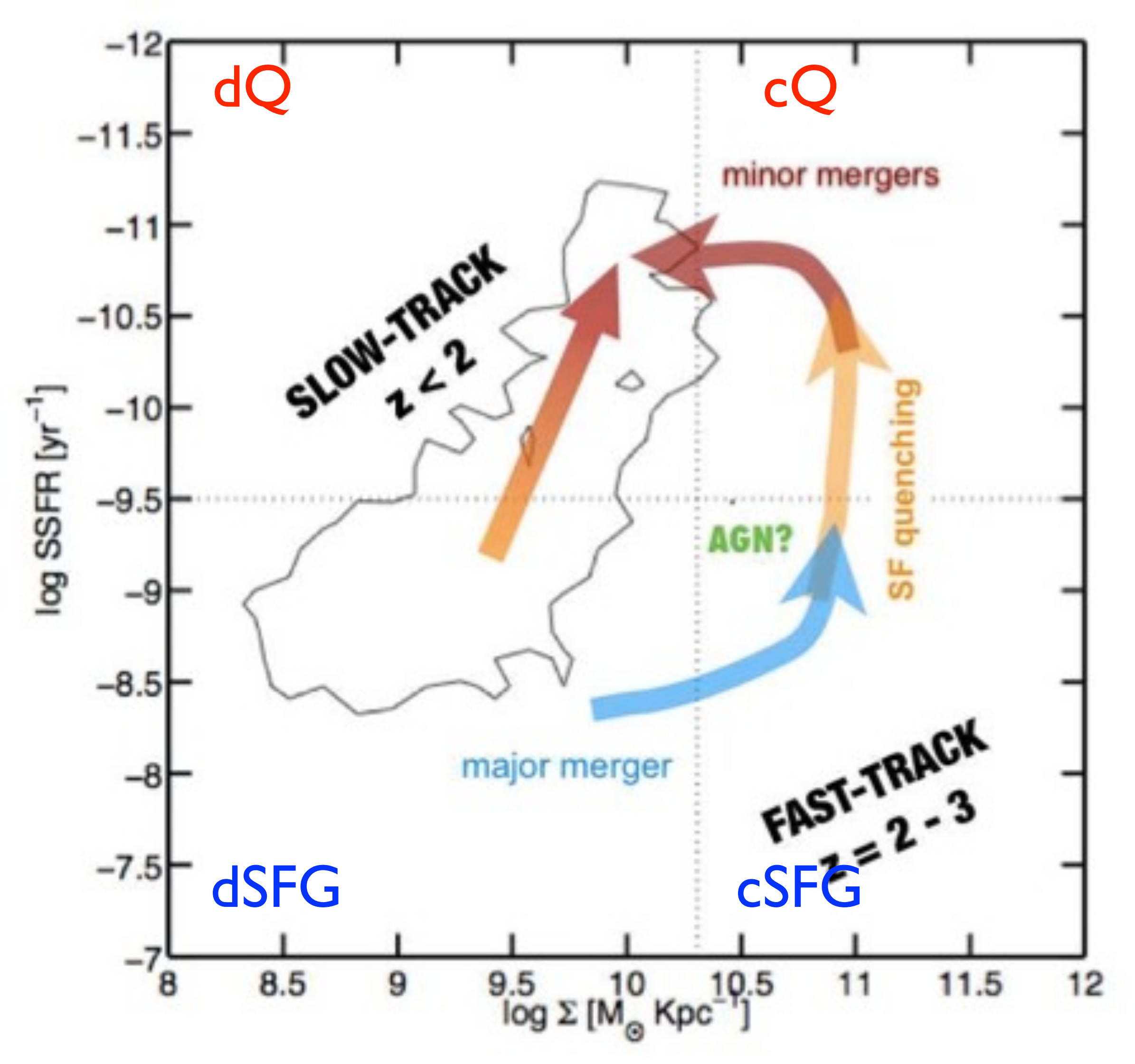
- shock heating & radiative cooling
- photoionization squelching
- merging
- star formation (quiescent & burst)
- SN heating & SN-driven winds
- AGN accretion and feedback
- chemical evolution
- stellar populations & dust

Porter et al. (in prep.) - Bolshoi SAM

Evolution of Compact Star-Forming Galaxies According to Bolshoi-based Semi-Analytic Model

Observed Evolution of Galaxies from Latest Hubble Telescope Data





Gas-rich merger in past Gyr
Gas-poor merger in past Gyr

cSFG at z = 2.4

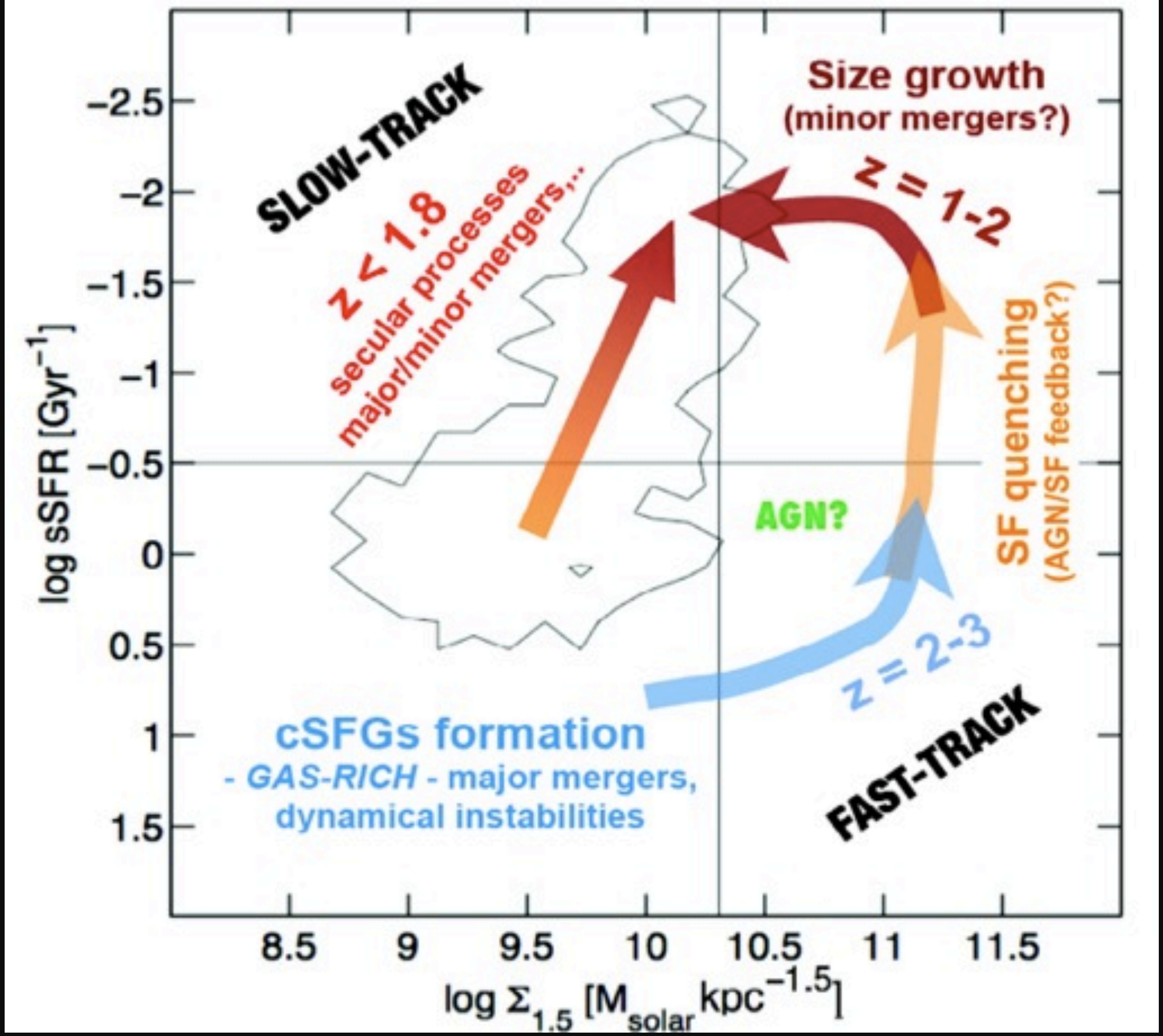
Barro et al. (2012 - Hubble Observations)

Porter et al. (in prep.) - Bolshoi SAM

Summary

SAM Predictions

- Galaxies move from dSFG to cSFG through gas-rich major and minor mergers, as well as classical disk instabilities. Major mergers may *not* be the dominant mechanism for creating compact galaxies.
- Diffuse and compact SFG may quench at similar redshifts, z ~ 1.5-1.7
- Minor mergers decrease the surface density of cSFG, but most remain compact down to redshift 0



Barro et al. (2012)

Porter et al. (in prep.) - Bolshoi SAM

Cosmological Simulations

Astronomical observations represent snapshots of moments in time. It is the role of astrophysical theory to produce movies -- both metaphorical and actual -- that link these snapshots together into a coherent physical theory.

Cosmological dark matter simulations show large scale structure, growth of structure, and dark matter halo properties and merger trees

Hydrodynamic galaxy formation simulations: evolution of galaxies, formation of galactic spheroids via mergers, galaxy images in all wavebands including stellar evolution and dust

Simulations of Galaxies Including Stellar Evolution and Dust

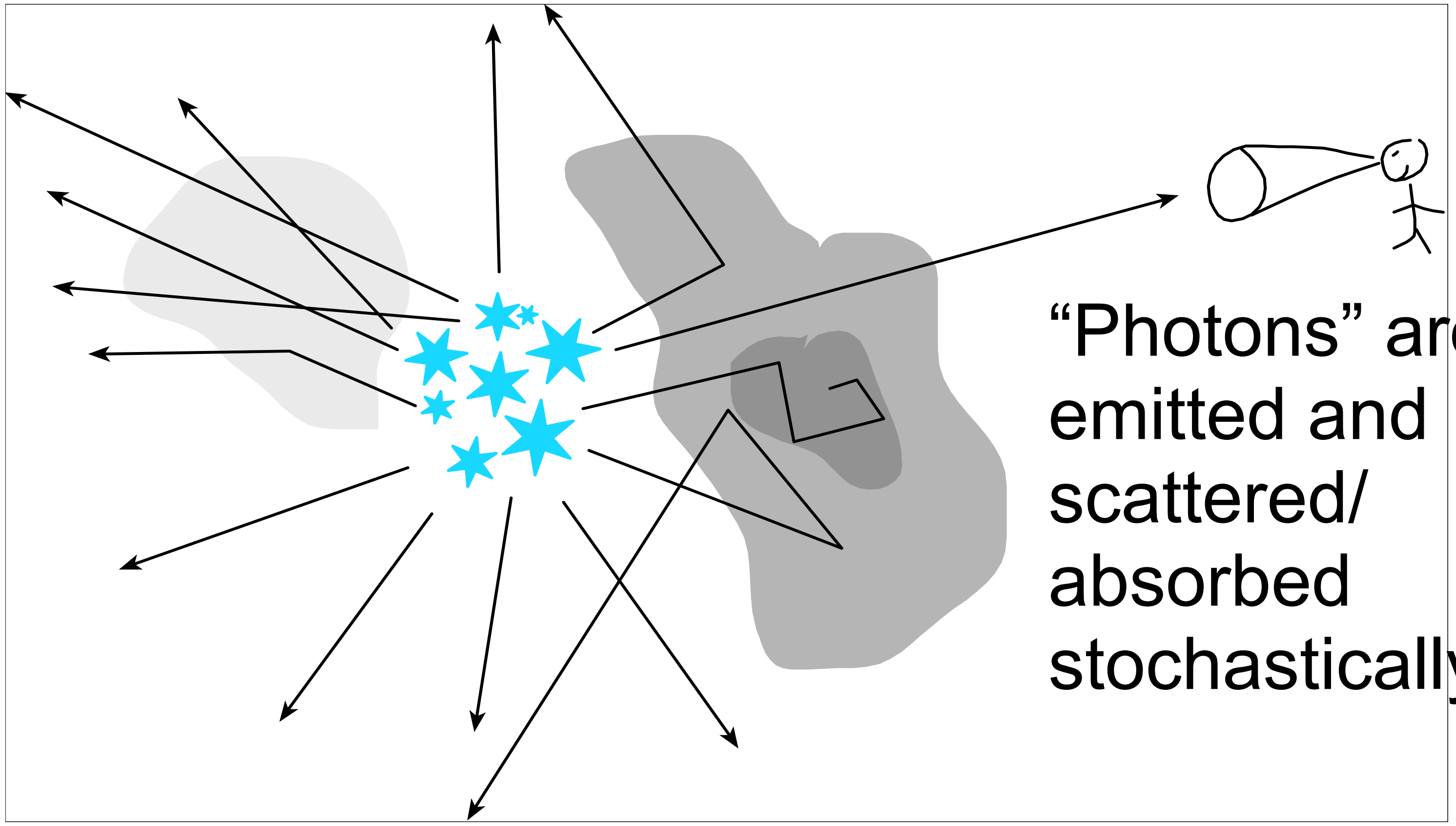
“The Antennae”

HST image of “The Antennae”

Sunrise Radiative Transfer Code

For every simulation snapshot:

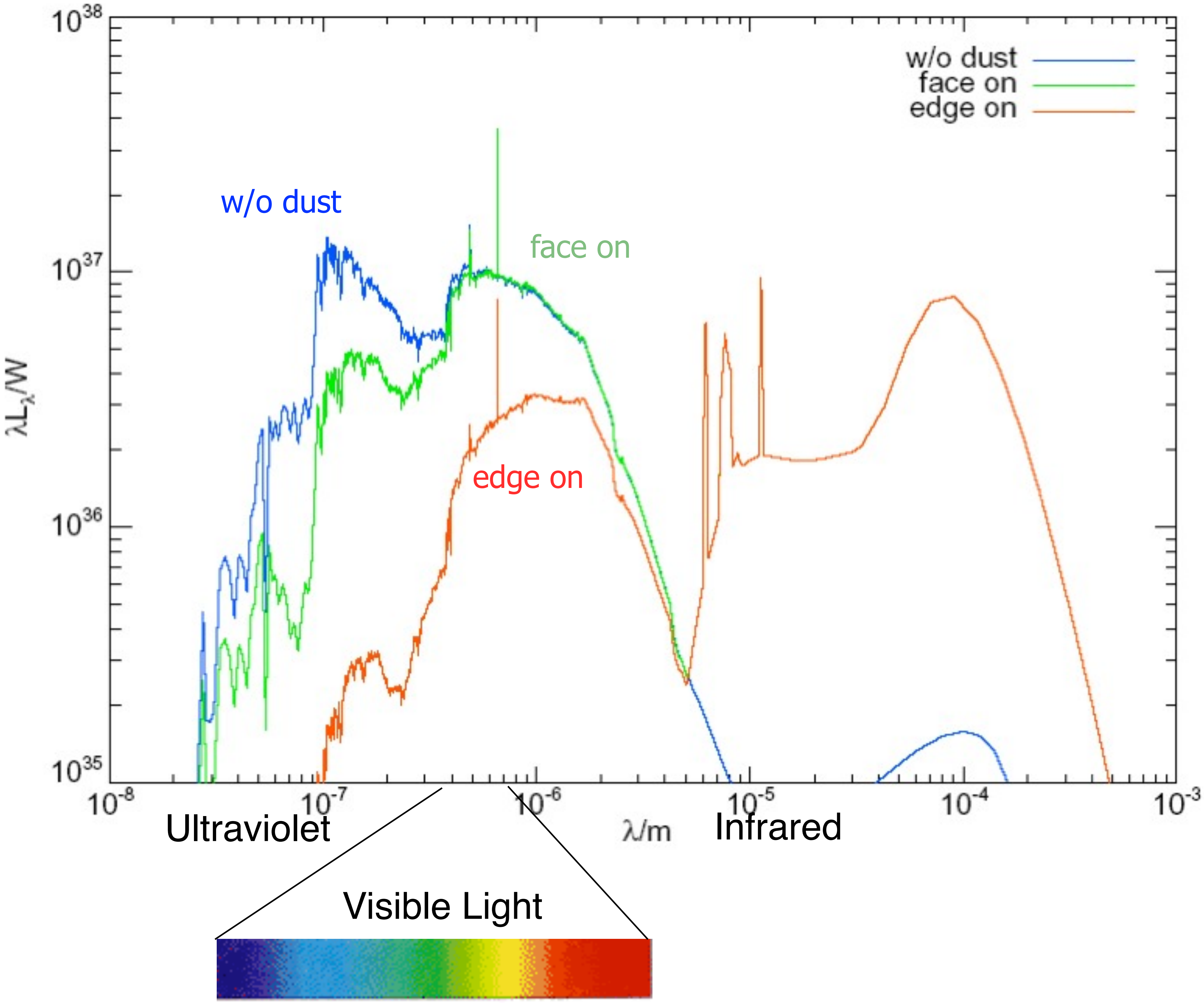
- Evolving stellar spectra calculation
- Adaptive grid construction
- Monte Carlo radiative transfer
- “Polychromatic” rays save 100x CPU time
- Graphic Processor Units give 10x speedup



“Photons” are emitted and scattered/ absorbed stochastically

Patrik Jonsson

Spectral Energy Distribution



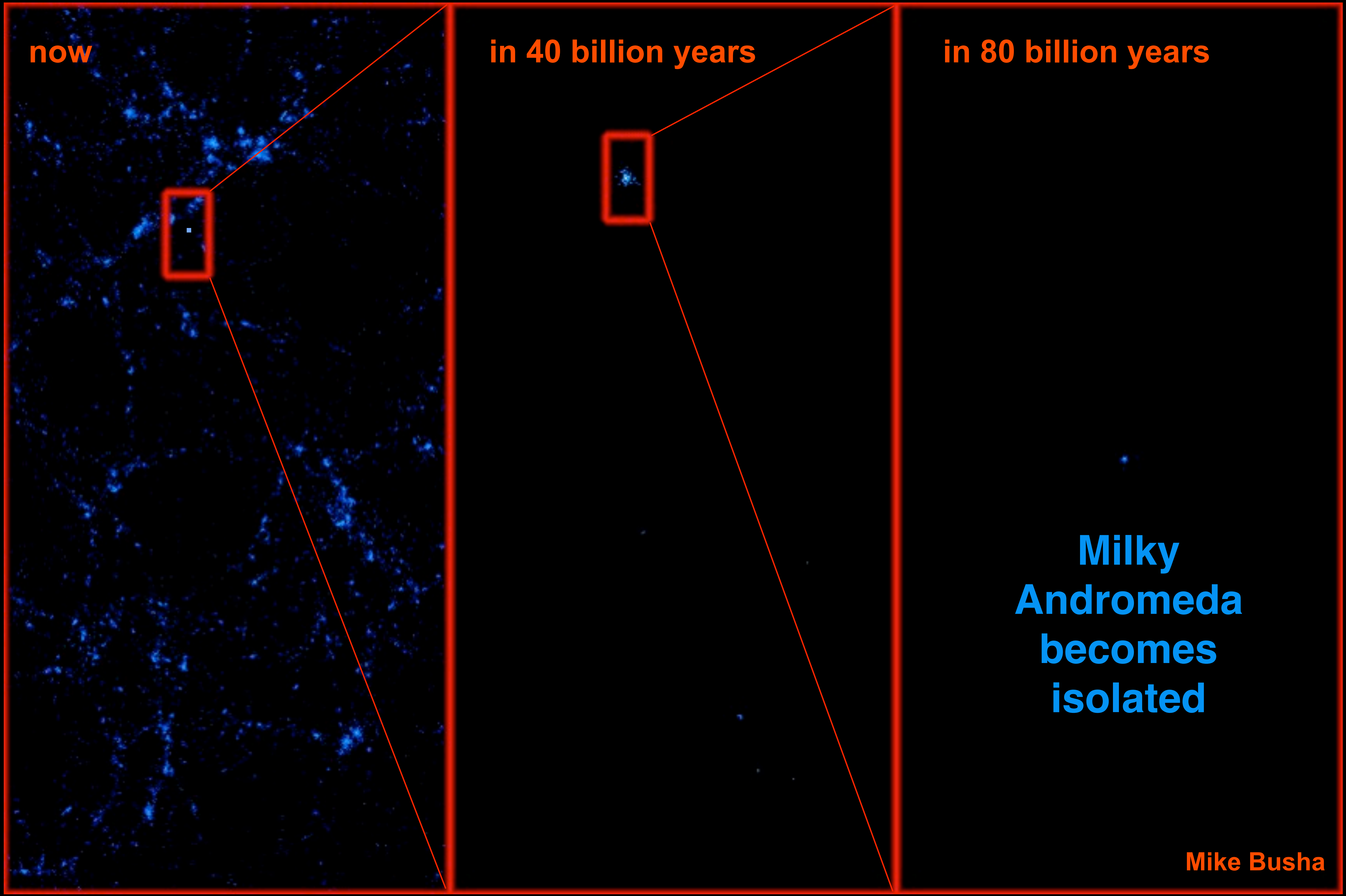
Galaxy Merger Simulation

A merger between galaxies like the Milky Way and the Andromeda galaxy. Galaxy mergers like this one trigger gigantic “starbursts” forming many millions of new stars (which look blue in these images). But dust (orange in the video) absorbs ~90% of the light, and reradiates the energy in invisible long wavelengths.

When the universe is twice its present age, the distant galaxies will have disappeared over the cosmic horizon.

Milky Andromeda will eventually become all that’s visible.

The Double Dark Future of the Universe



Milky Andromeda becomes isolated

Mike Busha

Accelerating Dust Temperature Calculations with Graphics Processing Units

Patrik Jonsson, Joel R. Primack

New Astronomy **15**, 509 (2010) (arXiv:0907.3768)

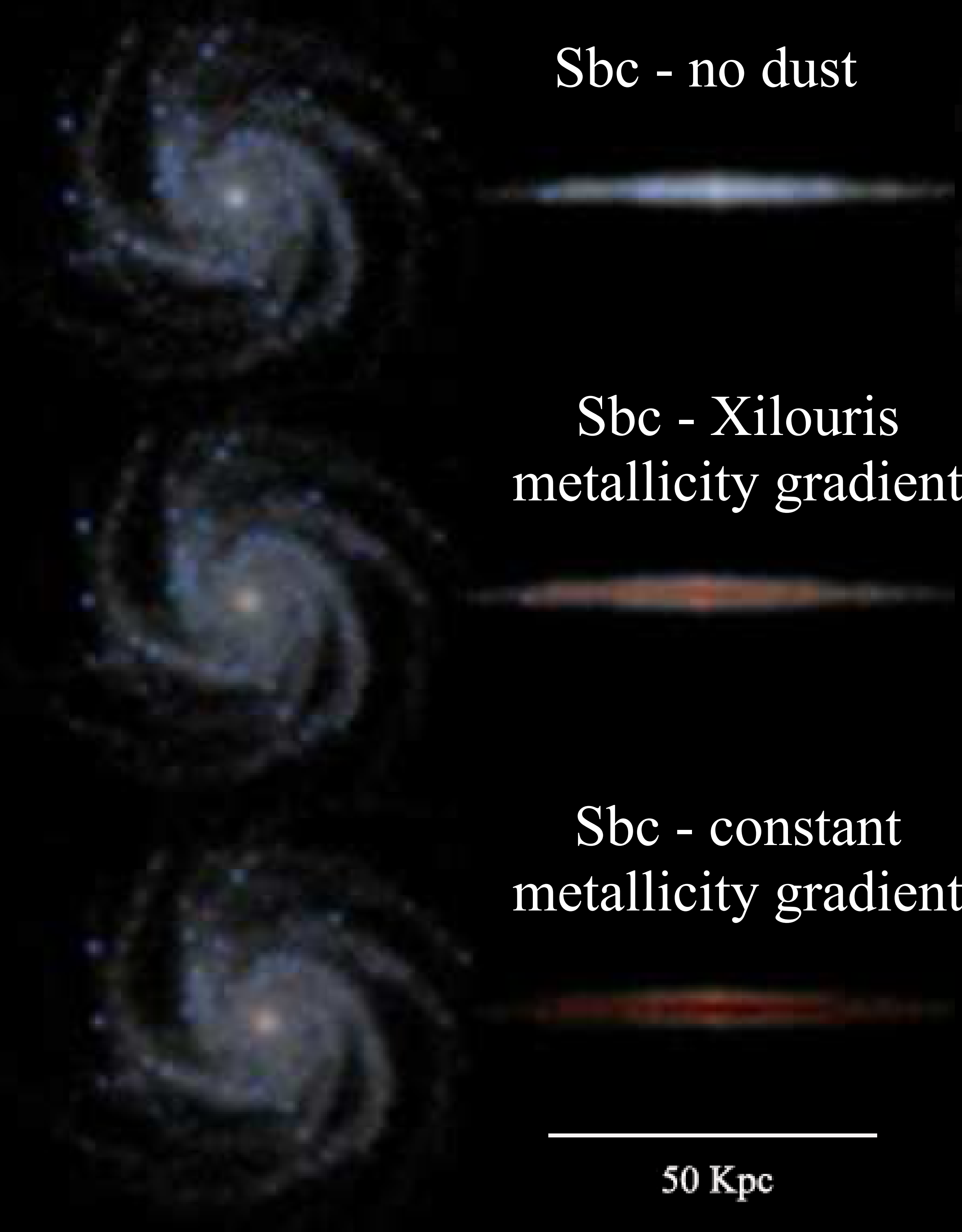
When calculating the infrared spectral energy distributions (SEDs) of galaxies in radiation-transfer models, the calculation of dust grain temperatures is generally the most time-consuming part of the calculation. Because of its highly parallel nature, this calculation is perfectly suited for massively parallel general-purpose Graphics Processing Units (GPUs). This paper presents an implementation of the calculation of dust grain equilibrium temperatures on GPUs in the Monte-Carlo radiation transfer code Sunrise, using the CUDA API. The Nvidia Tesla GPU can perform this calculation 55 times faster than the 8 CPU cores, showing great potential for accelerating calculations of galaxy SEDs.

On 64 special NAS Pleiades nodes with 2 Westmere chips (12 cores) and an Nvidia 2090 GPU, using the GPU makes the calculation run 12x faster.

Dust Attenuation in Hydrodynamic Simulations of Spiral Galaxies

Rocha, Jonsson, Primack, & Cox 2008 MN

Right hand side:
Xilouris et al. 1999
metallicity gradient

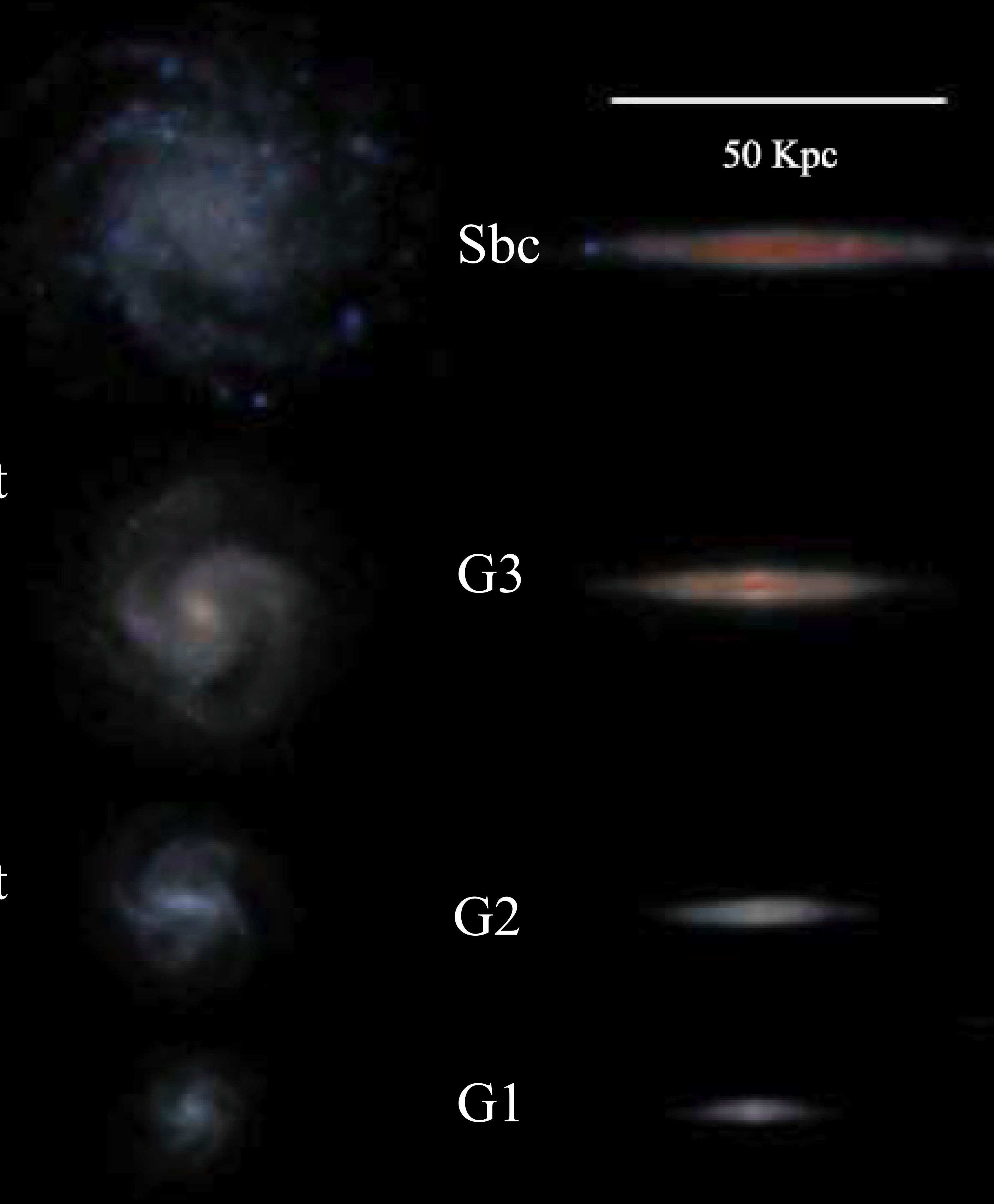


Sbc - no dust

Sbc - Xilouris
metallicity gradient

Sbc - constant
metallicity gradient

50 Kpc



50 Kpc

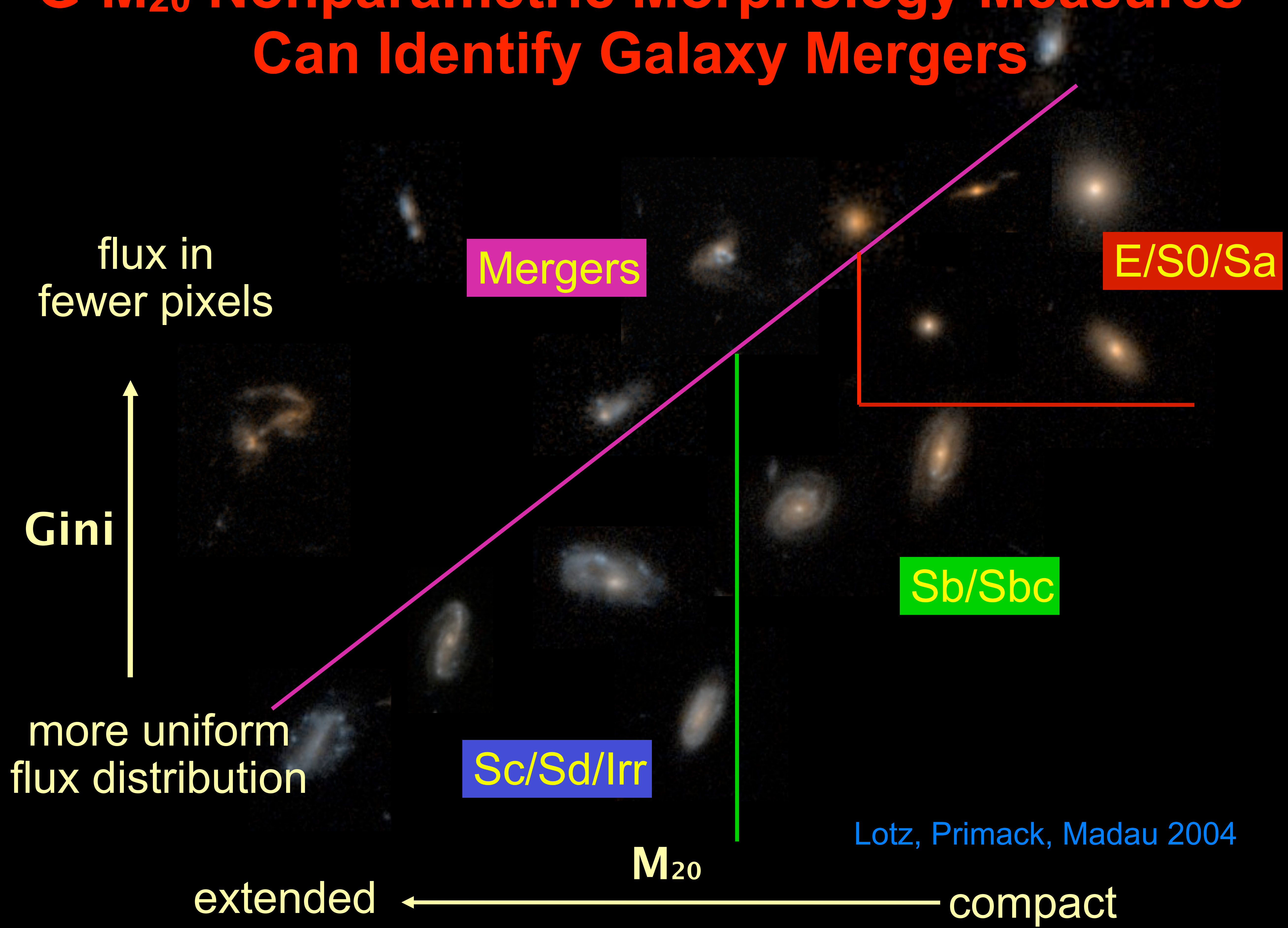
Sbc

G3

G2

G1

G-M_{20} Nonparametric Morphology Measures Can Identify Galaxy Mergers



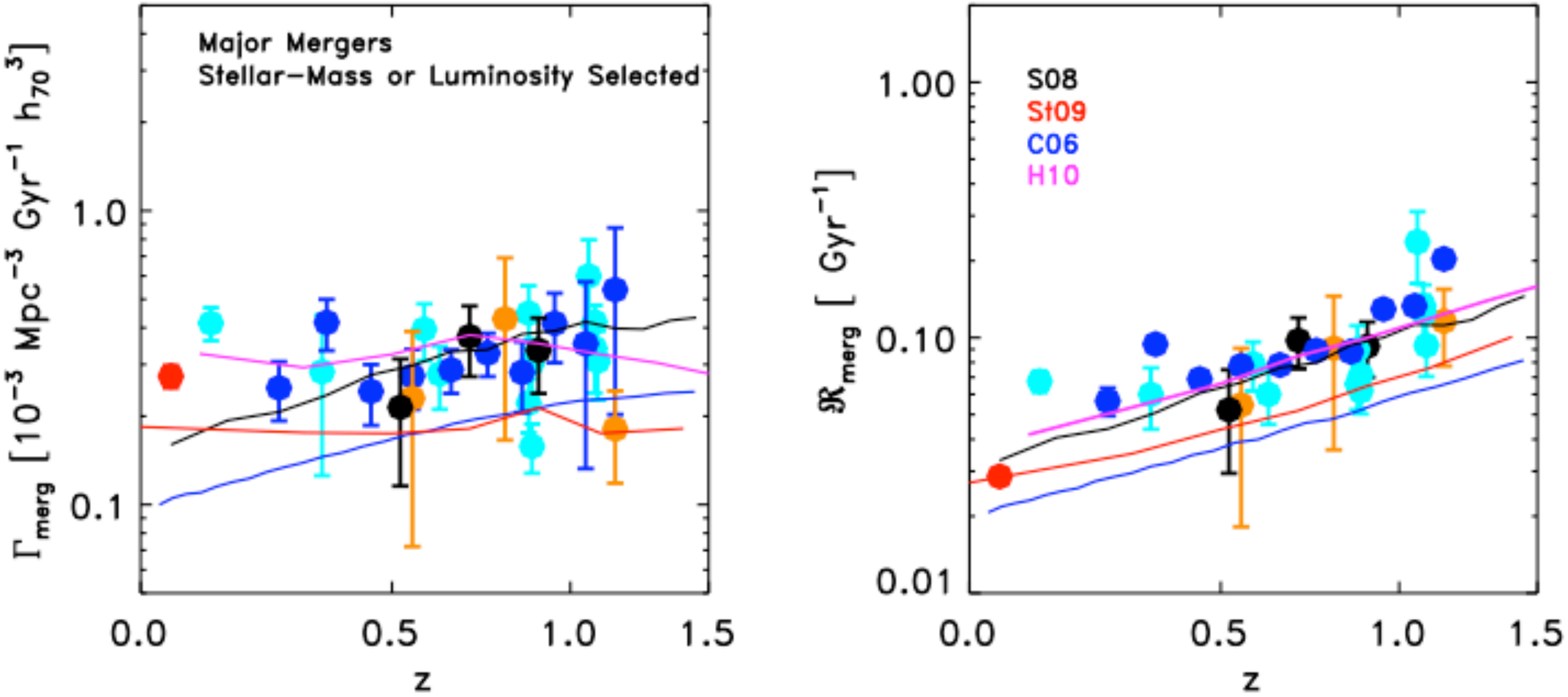
Lotz, Primack, Madau 2004

THE MAJOR AND MINOR GALAXY MERGER RATES AT Z < 1.5

Jennifer M. Lotz, Patrik Jonsson, T.J. Cox, Darren Croton, Joel R. Primack, Rachel S. Somerville, and Kyle Stewart

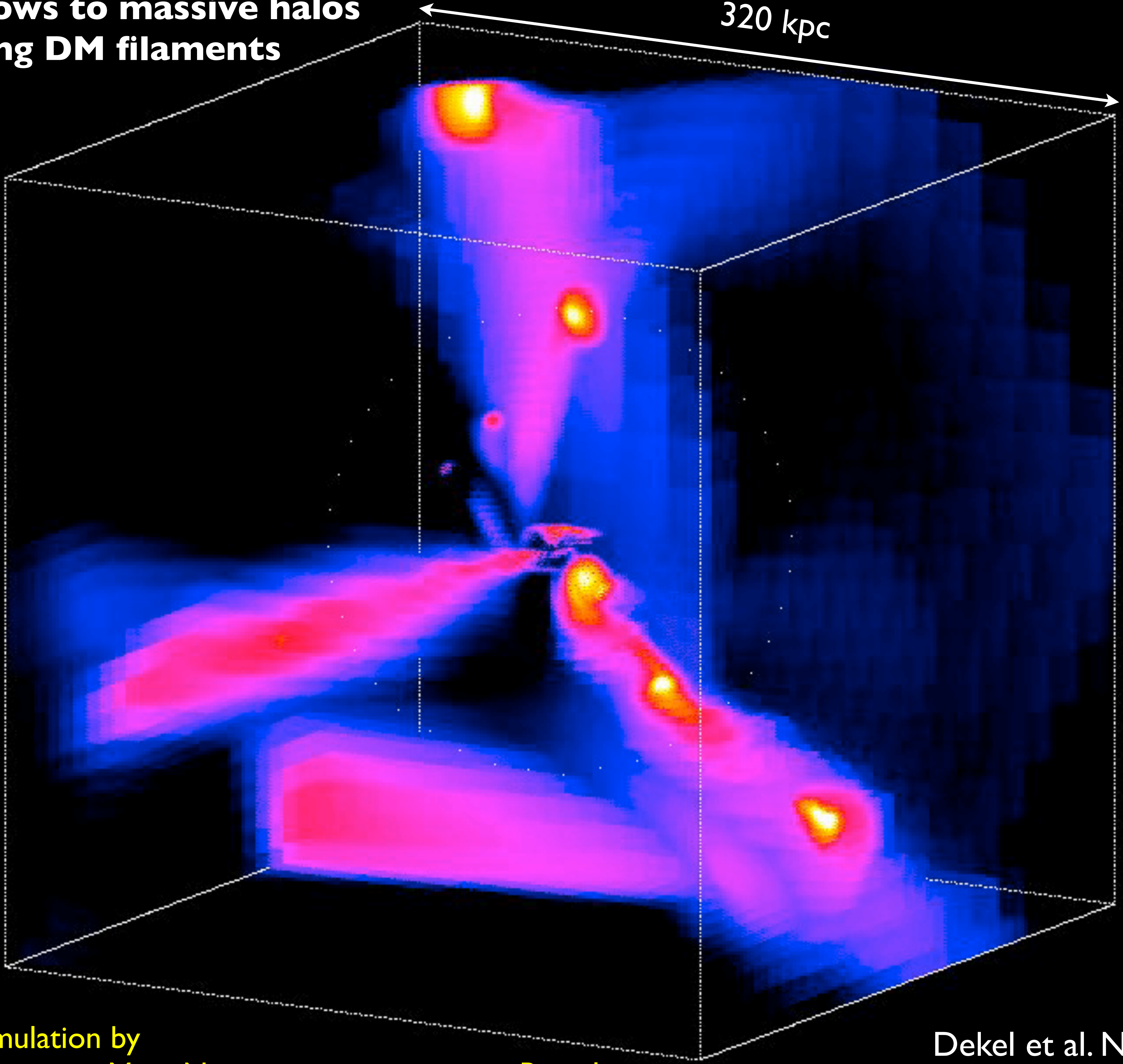
Astrophysical Journal December 2011

Calculating the galaxy merger rate requires both a census of galaxies identified as merger candidates, and a cosmologically-averaged 'observability' timescale $\langle T_{obs}(z) \rangle$ for identifying galaxy mergers. While many have counted galaxy mergers using a variety of techniques, $\langle T_{obs}(z) \rangle$ for these techniques have been poorly constrained. We address this problem by calibrating three merger rate estimators with a suite of hydrodynamic merger simulations and three galaxy formation models. When our physically-motivated timescales are adopted, the observed galaxy merger rates become largely consistent.



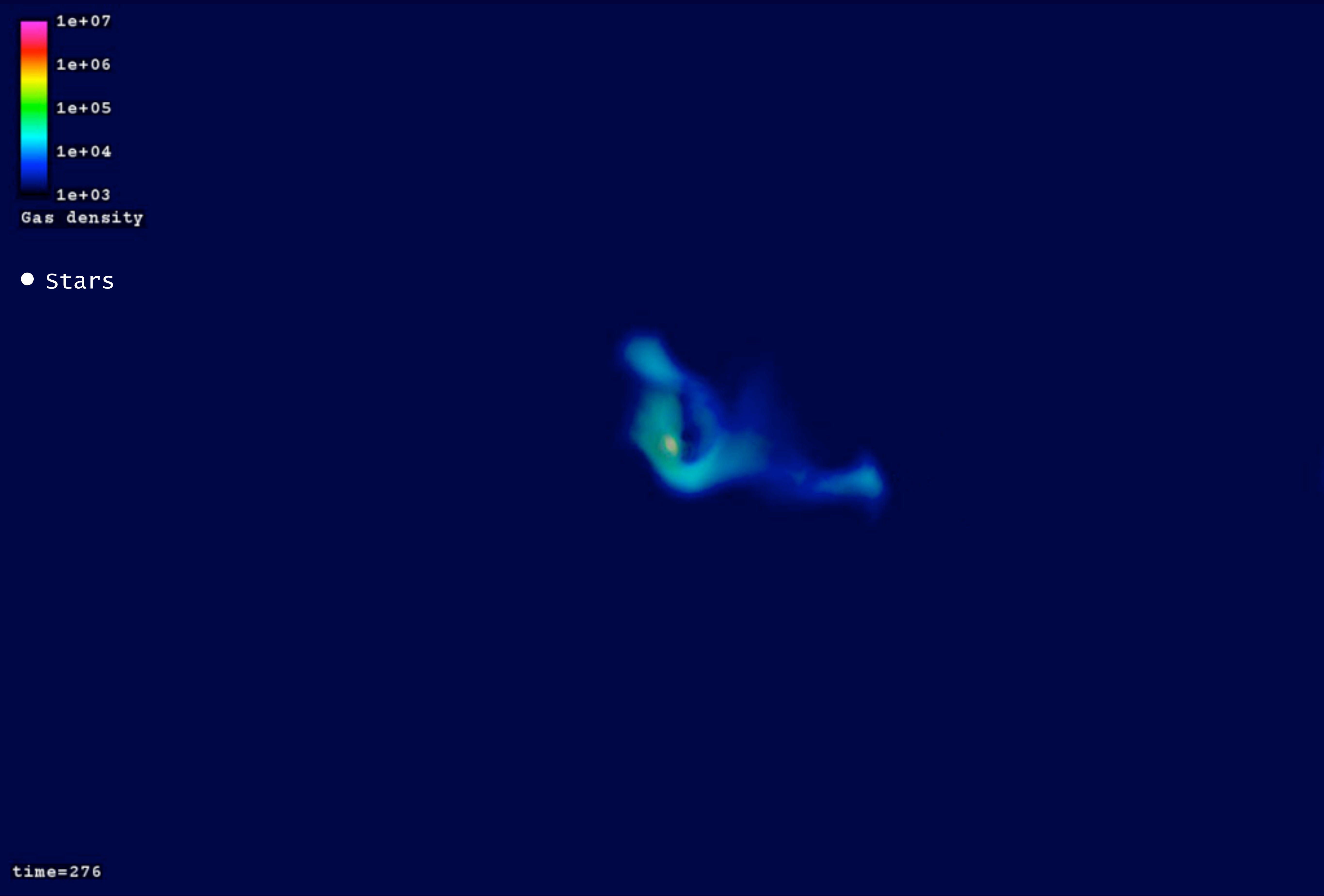
Observed Galaxy Merger Rates v. Theoretical Predictions. The volume-averaged (left) and fractional major merger (right) rates given by stellar-mass and luminosity-selected close pairs are compared to the major merger rates given by the S08 (black lines), St09 (red lines), C06 (blue line), and Hopkins et al. 2010b (magenta lines) models for 1:1 - 1:4 stellar mass ratio mergers and galaxies with $M_{star} > 10^{10}$ $M_{\odot}$. The theoretical predictions are in good agreement with the observed major merger rates.

Gas inflows to massive halos along DM filaments

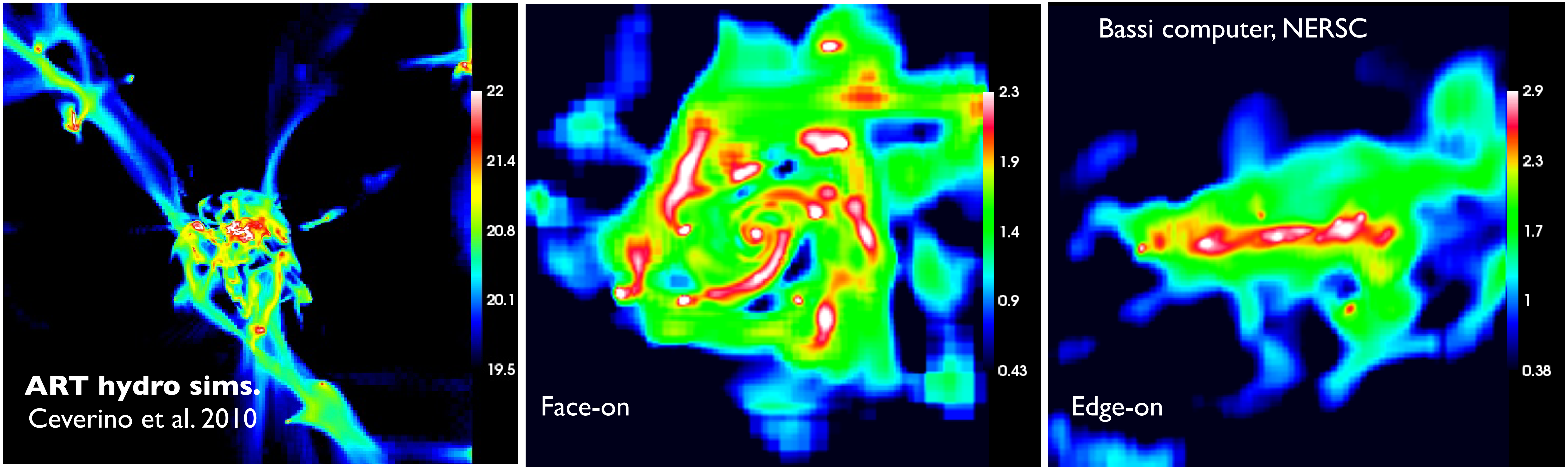


RAMSES simulation by
Romain Teyssier on Mare Nostrum supercomputer, Barcelona

Dekel et al. Nature 2009


1e+07
1e+06
1e+05
1e+04
1e+03
Gas density
● Stars
time=276

Simulated Evolution of an Elliptical Galaxy
U-V-J Images Every ~100 Million Years



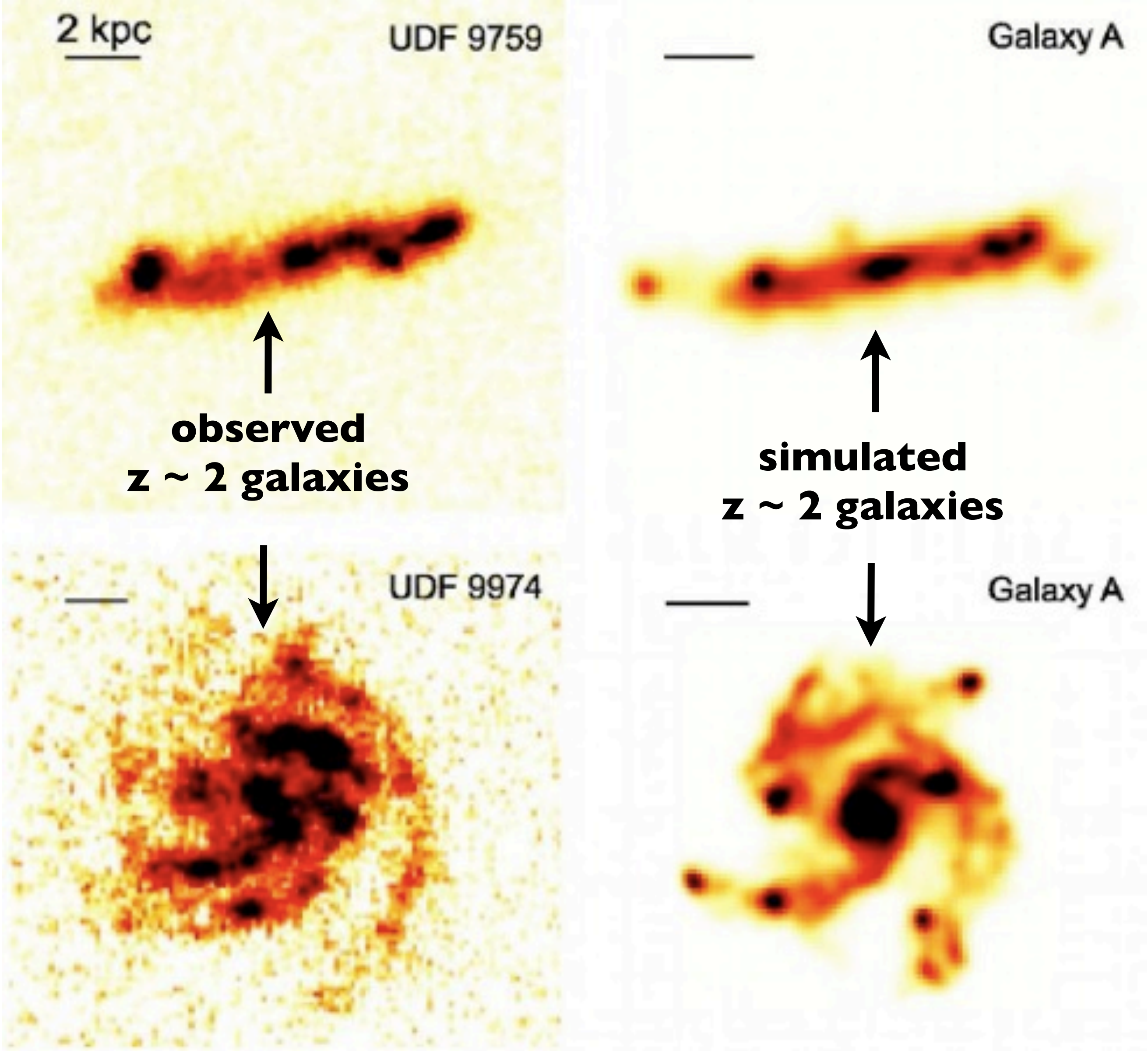
ART hydro sims.
Ceverino et al. 2010

Face-on

Bassi computer, NERSC

Edge-on

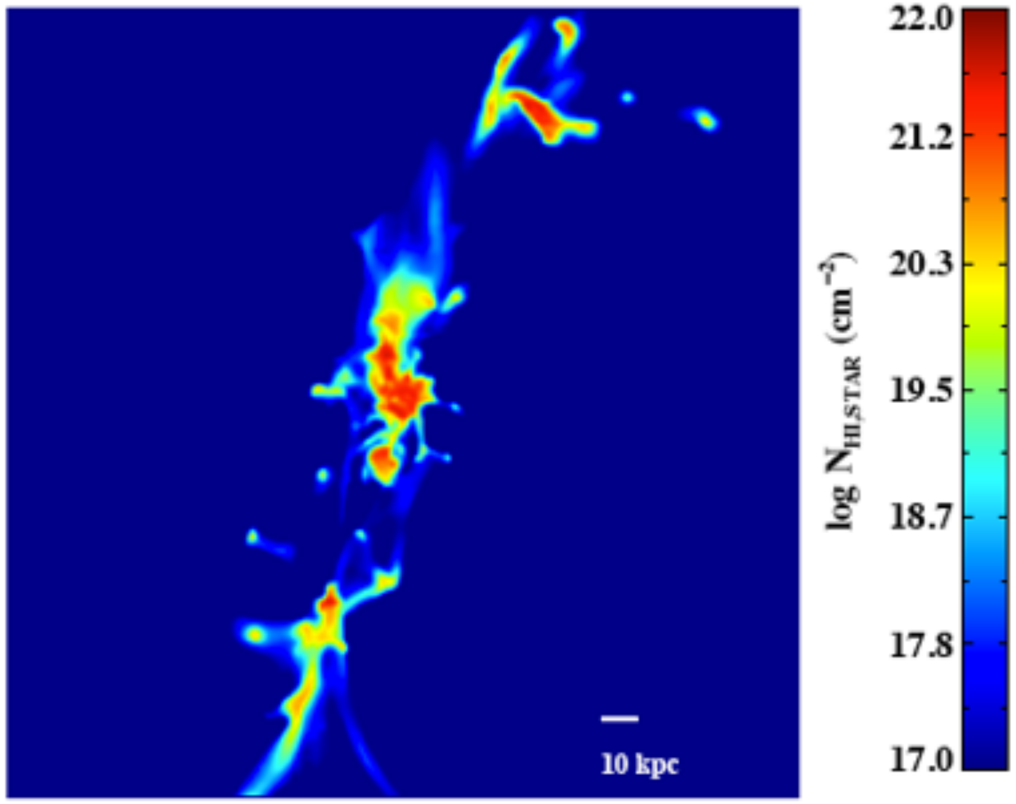
now running on NERSC Hopper-II
and NASA Ames Pleiades supercomputers



observed
z ~ 2 galaxies

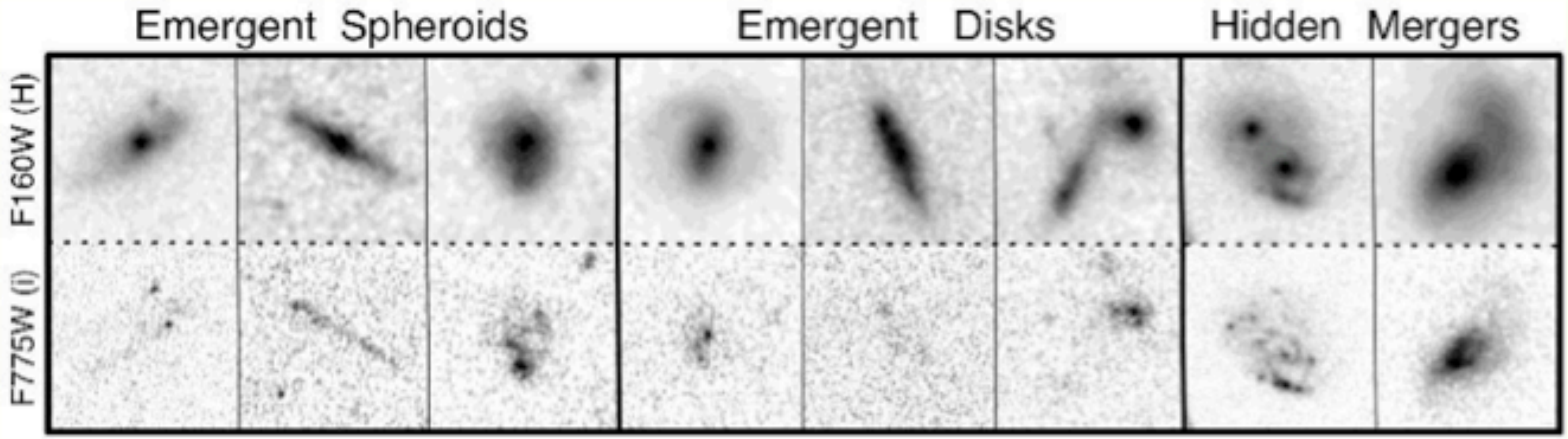
simulated
z ~ 2 galaxies

Ly alpha blobs from same simulation



Fumagalli, Prochaska, Kasen, Dekel, Ceverino, & Primack 2011

The CANDELS Survey



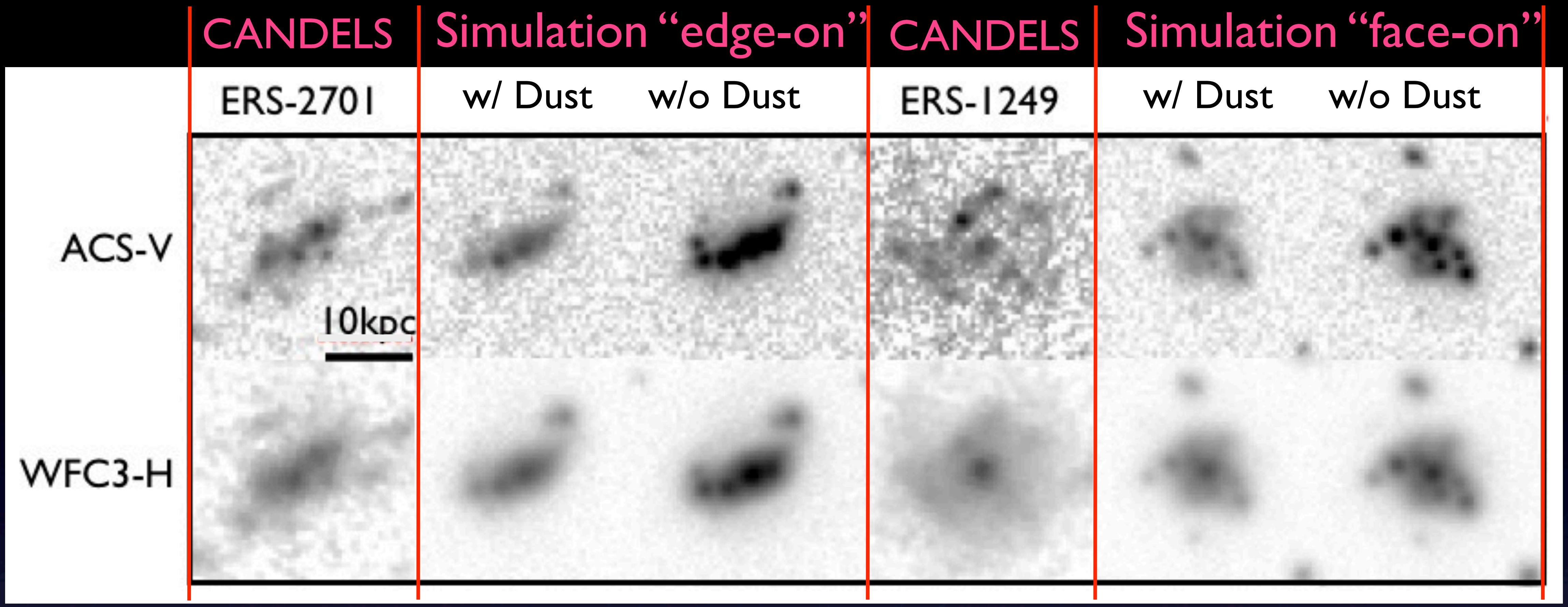
CANDELS makes use of the near-infrared WFC3 camera (top row) and the visible-light ACS camera (bottom row). Using these two cameras, CANDELS will reveal new details of the distant Universe and test the reality of cosmic dark energy.

http://candels.ucolick.org

CANDELS: A Cosmic Odyssey

CANDELS is a powerful imaging survey of the distant Universe being carried out with two cameras on board the Hubble Space Telescope.

- CANDELS is the largest project in the history of Hubble, with 902 assigned orbits of observing time. This is the equivalent of four months of Hubble time if executed consecutively, but in practice CANDELS will take three years to complete (2010-2013).
- The core of CANDELS is the revolutionary near-infrared WFC3 camera, installed on Hubble in May 2009. WFC3 is sensitive to longer, redder wavelengths, which permits it to follow the stretching of lightwaves caused by the expanding Universe. This enables CANDELS to detect and measure objects much farther out in space and nearer to the Big Bang than before. CANDELS also uses the visible-light ACS camera, and together the two cameras give unprecedented panchromatic coverage of galaxies from optical wavelengths to the near-IR.



Simulation shown is MW3 at z=2.33 ‘imaged’ to match the CANDELS observations in ACS-Vband and WFC3-Hband

- 0.06” Pixel scale
- convolved with simulated psfs
- noise and background derived from ERS observations (same field as examples shown)

MW3 was imaged at ‘face-on’ and ‘edge-on’ viewing angles both with and without including dust models

Summary: the big cosmic questions now

- The nature of the dark matter

- The nature of the dark energy (the future of the Universe)

- The early evolution of the Universe, including
  - Formation of the first tiny galaxies and the first stars
  - How the universe reionized

- How the entire population of galaxies forms and evolves
  - From direct observations from the ground and space
  - Interpreted with the help of cosmological simulations:
    - Resolving star formation with realistic feedback
    - Formation and feedback from supermassive black holes
    - etc.

University of California
High-Performance
AstroComputing Center
(UC-HiPACC)

University of California
Santa Cruz
Next Telescope Science
Institute (NEXSI)

The High-Resolution Galaxy Simulation Comparison Project

Joel R. Primack, UCSC (Director, UC-HiPACC)
Piero Madau, UCSC (Director, NEXSI)
Lucio Mayer, University of Zurich
Romain Teyssier, Saclay & Zurich
Ji-Hoon Kim, UCSC (Coordinator)

2012 Santa Cruz Galaxy Workshop

The High-Resolution Galaxy Simulation Comparison Project

Joel Primack, UCSC

The simulations to be discussed will all have resolution better than ~100 parsecs, which we hope will be enough to begin to resolve star formation in galactic disks. This project is motivated by recent improvements in hydrodynamical simulation codes, the availability of millions of cpu−hours for such simulations on high−performance computer systems, and the increasingly rapid acquisition of observational data on galaxies both nearby and out to very high redshifts. The discussions today and over the weekend will consider the current results and performance of various simulation approaches. We want to compare simulations of the same cosmological initial conditions by different codes to each other and to relevant observations. This will help to advance the state of the art of galaxy simulations and the understanding of the key astrophysical processes that control galaxy formation and evolution, including the flows of baryons into and out of galaxies, feedback from stars, supernovae, and massive black holes, and the impact of baryons on dark matter structure and substructure. We will try to model consistently similar recipes across codes, rather than allowing complete freedom in implementation. We will also discuss initial conditions for a range of galaxy masses, not just the Milky-Way-mass simulations that much earlier work has focused on.

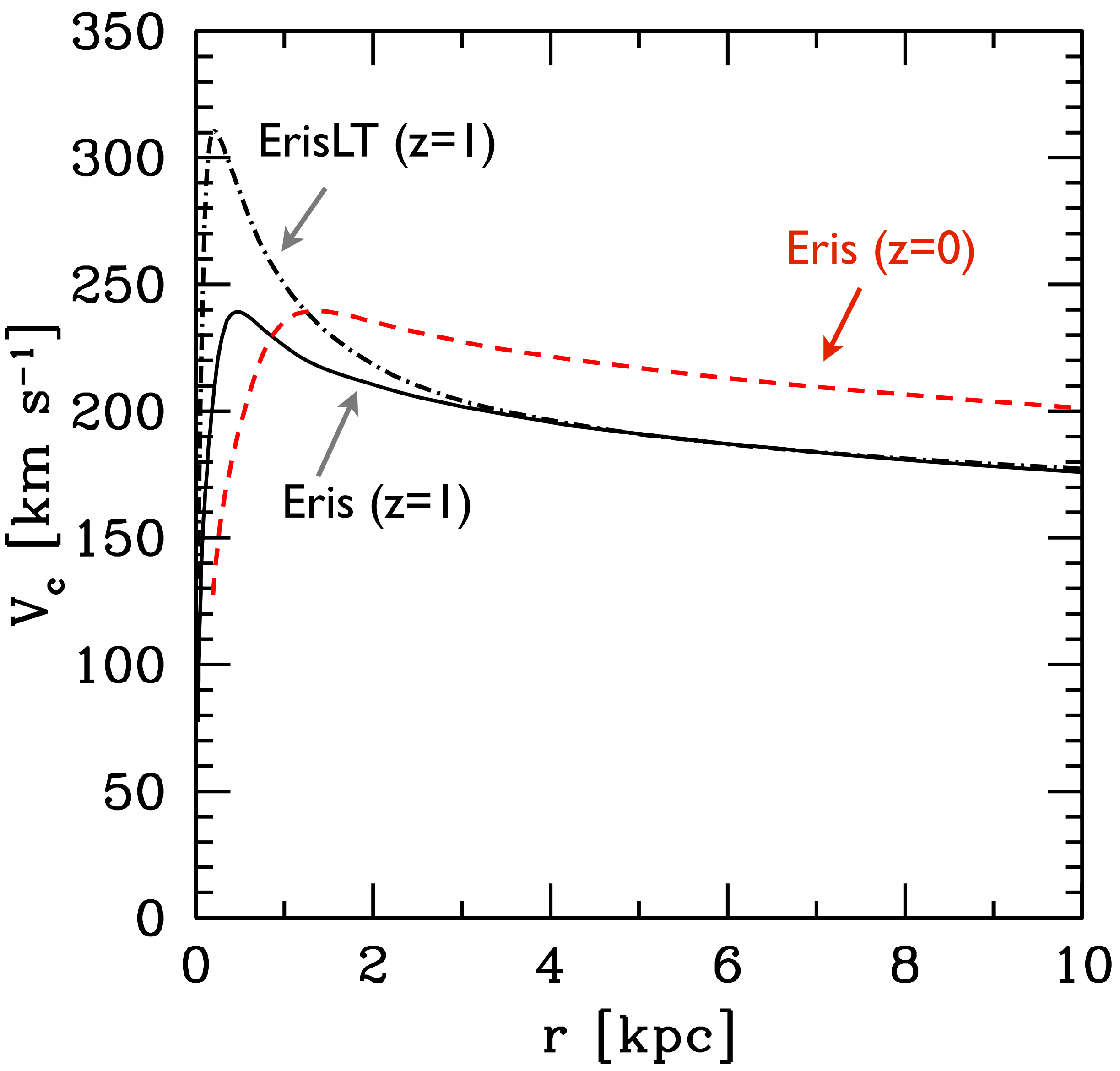
The High-Resolution Galaxy Simulation Comparison Project: Rationale

Key Earlier Simulation Comparisons

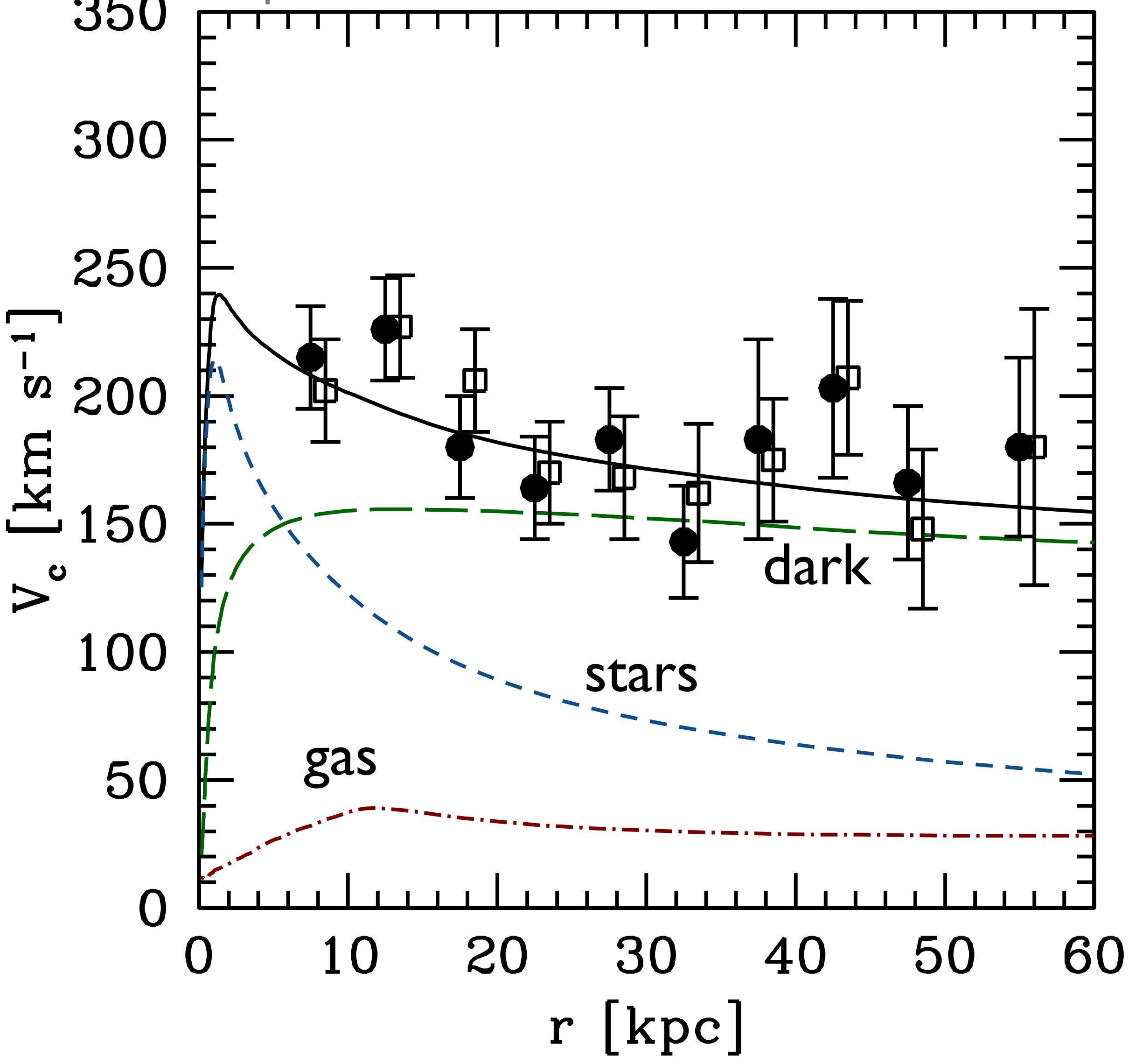
The paper led by Carlos Frenk, “The Santa Barbara Cluster Comparison Project: A Comparison of Hydrodynamics Simulations,” ApJ, 525, 554 (1999), which grew out of a workshop at the KITP in Santa Barbara, has now received 303 citations. Our HRGS program also follows an earlier galaxy simulation comparison project that resulted in the paper led by Cecilia Scannapieco, “The Aquila Comparison Project: The Effects of Feedback and Numerical Methods on Simulations of Galaxy Formation” (MNRAS 2012). The simulations there mostly used the Gadget smooth−particle−hydrodynamics code, and they had typical force resolutions of ~1 kiloparsec, with dark matter particle masses larger than 10^6 $M_\odot$ and gas particle masses mostly larger than 0.4×10^6 $M_\odot$. The one adaptive mesh refinement code used for these simulations, RAMSES, was run with relatively poor force resolution of 260 pc and dark matter particle mass 0.2×10^6 $M_\odot$. At these resolutions, all the key physics of star formation and feedback is sub−grid, and it is therefore not surprising that there were large code−to−code variations in the size, morphology, and stellar and gas masses of the simulated galaxies started from the same initial conditions, and rather poor agreement with observed galaxies. The success of recent higher−resolution simulations such as Eris (Javiera Guedes, Simone Gallegari, Piero Madau, & Lucio Mayer 2011, ApJ, 742, 76) in matching observed galaxies encourages us to hope for progress with the high−resolution simulations that will be discussed here.

Eris Rotation Curve

The z=0 is not highly peaked at the center, and falls slowly at large radii, in agreement with observations.



data points from SDSS blue HB stars Sofue et al. '09



Javiera Guedes, et al. 2011 ApJ

The Aquila comparison Project: The Effects of Feedback and Numerical Methods on Simulations of Galaxy Formation

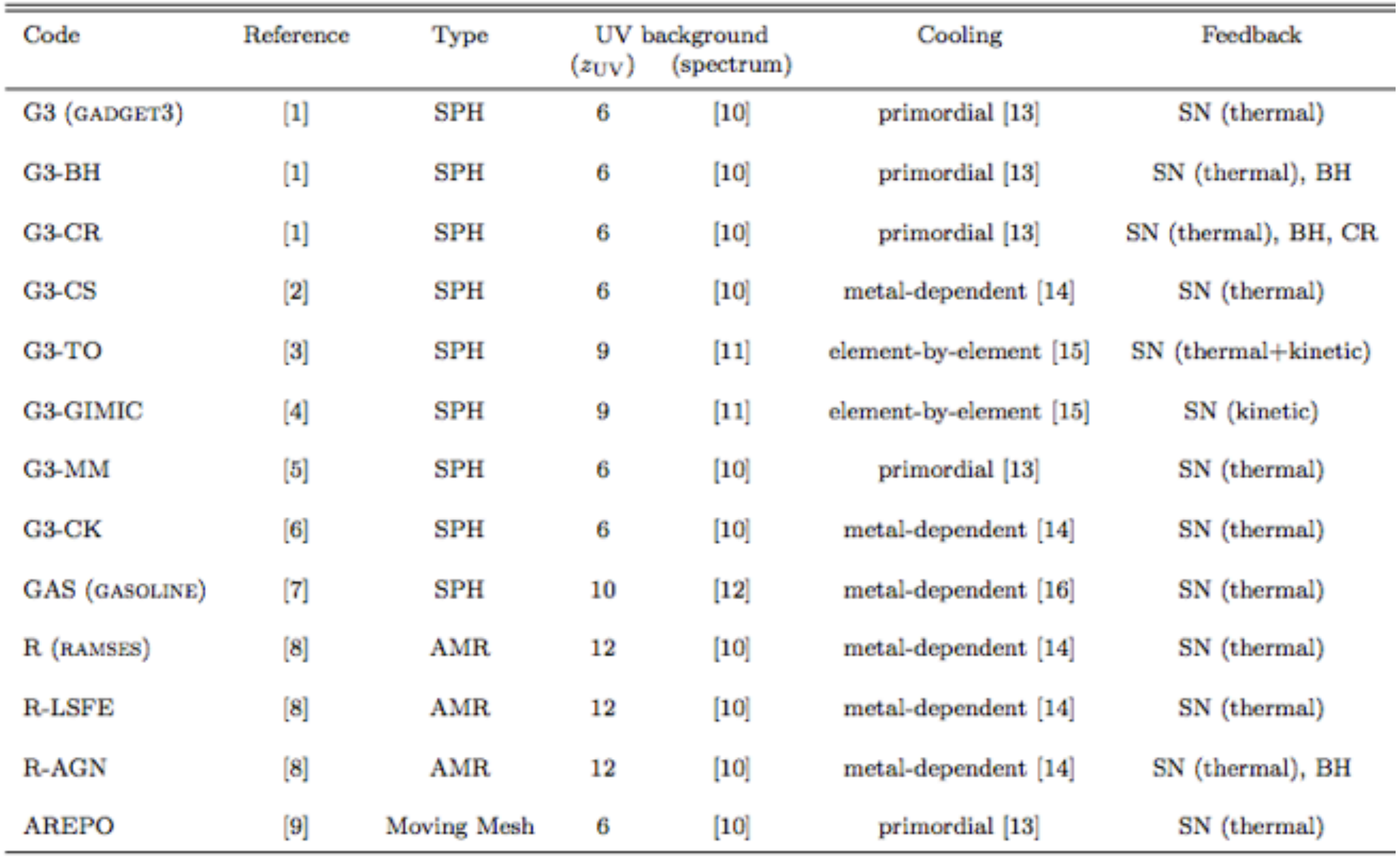
C. Scannapieco,[1] M. Wadepuhl,[2] O.H. Parry,[3,4] J.F. Navarro,[5] A. Jenkins,[3] V. Springel,[6,7] R. Teyssier,[8,9] E. Carlson,[10] H.M.P. Couchman,[11] R.A. Crain,[12,13] C. Dalla Vecchia,[14] C.S. Frenk,[3] C. Kobayashi,[15,16] P. Monaco,[17,18] G. Murante,[17,19] T. Okamoto,[20] T. Quinn,[10] J. Schaye,[13] G. S. Stinson,[21] T. Theuns,[3,22] J. Wadsley,[11] S.D.M. White,[2] R. Woods[11]

2012 MNRAS 423, 1726

ABSTRACT

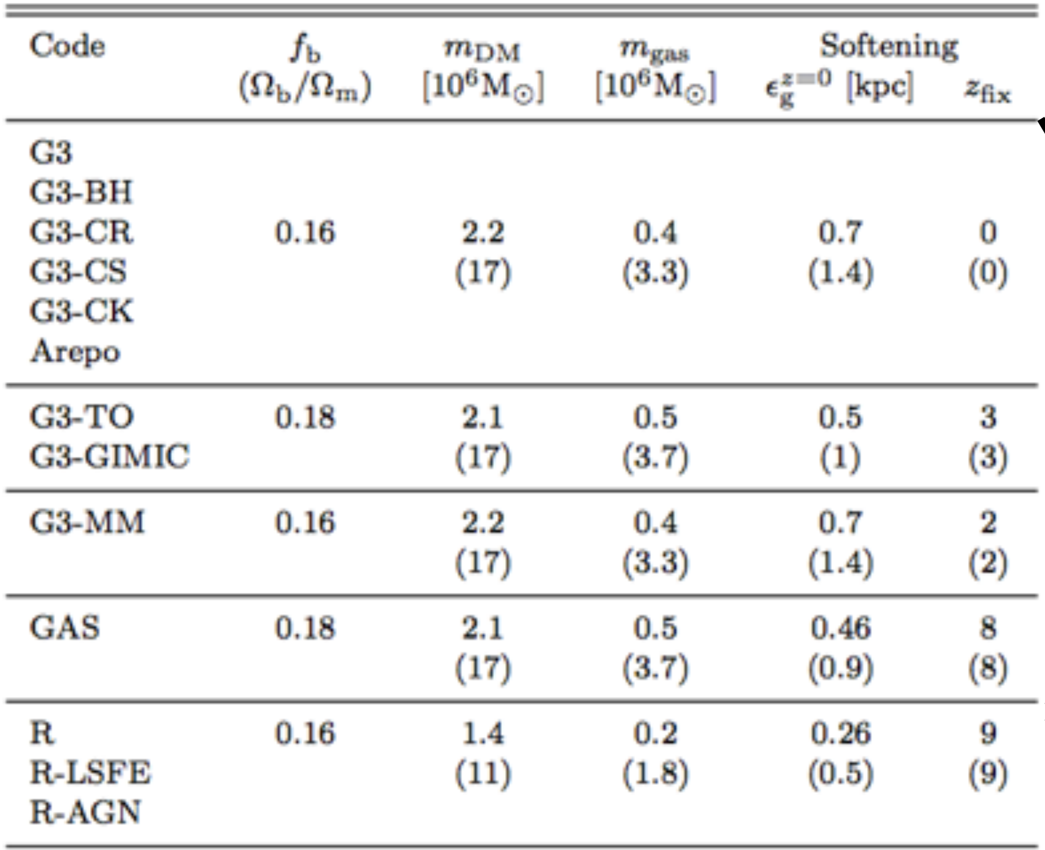
We compare the results of various cosmological gas-dynamical codes used to simulate the formation of a galaxy in the ΛCDM structure formation paradigm. **The various runs** (thirteen in total) differ in their numerical hydrodynamical treatment (SPH, moving-mesh and AMR) but **share the same initial conditions and adopt in each case their latest published model of gas cooling, star formation and feedback.** Despite the common halo assembly history, **we find large code-to-code variations in the stellar mass, size, morphology and gas content of the galaxy at $z = 0$, due mainly to the different implementations of star formation and feedback**. Compared with observation, **most codes tend to produce an overly massive galaxy, smaller and less gas-rich than typical spirals, with a massive bulge and a declining rotation curve**. A stellar disk is discernible in most simulations, although its prominence varies widely from code to code. There is a well-defined trend between the effects of feedback and the severity of the disagreement with observed spirals. In general, models that are more effective at limiting the baryonic mass of the galaxy come closer to matching observed galaxy scaling laws, but often to the detriment of the disk component. Although numerical convergence is not particularly good for any of the codes, our conclusions hold at two different numerical resolutions. Some differences can also be traced to the different numerical techniques; for example, more gas seems able to cool and become available for star formation in grid-based codes than in SPH. However, this effect is small compared to the variations induced by different feedback prescriptions. We conclude that state-of-the-art simulations cannot yet uniquely predict the properties of the baryonic component of a galaxy, even when the assembly history of its host halo is fully specified. **Developing feedback algorithms that can effectively regulate the mass of a galaxy without hindering the formation of high-angular momentum stellar disks remains a challenge.**

The Aquila Comparison Project



Code	Reference	Type	UV background ($z_{\rm UV}$)	UV background (spectrum)	Cooling	Feedback
G3 (GADGET3)	[1]	SPH	6	[10]	primordial [13]	SN (thermal)
G3-BH	[1]	SPH	6	[10]	primordial [13]	SN (thermal), BH
G3-CR	[1]	SPH	6	[10]	primordial [13]	SN (thermal), BH, CR
G3-CS	[2]	SPH	6	[10]	metal-dependent [14]	SN (thermal)
G3-TO	[3]	SPH	9	[11]	element-by-element [15]	SN (thermal+kinetic)
G3-GIMIC	[4]	SPH	9	[11]	element-by-element [15]	SN (kinetic)
G3-MM	[5]	SPH	6	[10]	primordial [13]	SN (thermal)
G3-CK	[6]	SPH	6	[10]	metal-dependent [14]	SN (thermal)
GAS (GASOLINE)	[7]	SPH	10	[12]	metal-dependent [16]	SN (thermal)
R (RAMSES)	[8]	AMR	12	[10]	metal-dependent [14]	SN (thermal)
R-LSFE	[8]	AMR	12	[10]	metal-dependent [14]	SN (thermal)
R-AGN	[8]	AMR	12	[10]	metal-dependent [14]	SN (thermal), BH
AREPO	[9]	Moving Mesh	6	[10]	primordial [13]	SN (thermal)

All simulations share the same initial conditions (ICs), a zoomed-in resimulation of one of the halos of the Aquarius Project (halo “Aq-C”, in the notation of Springel et al. 2008).



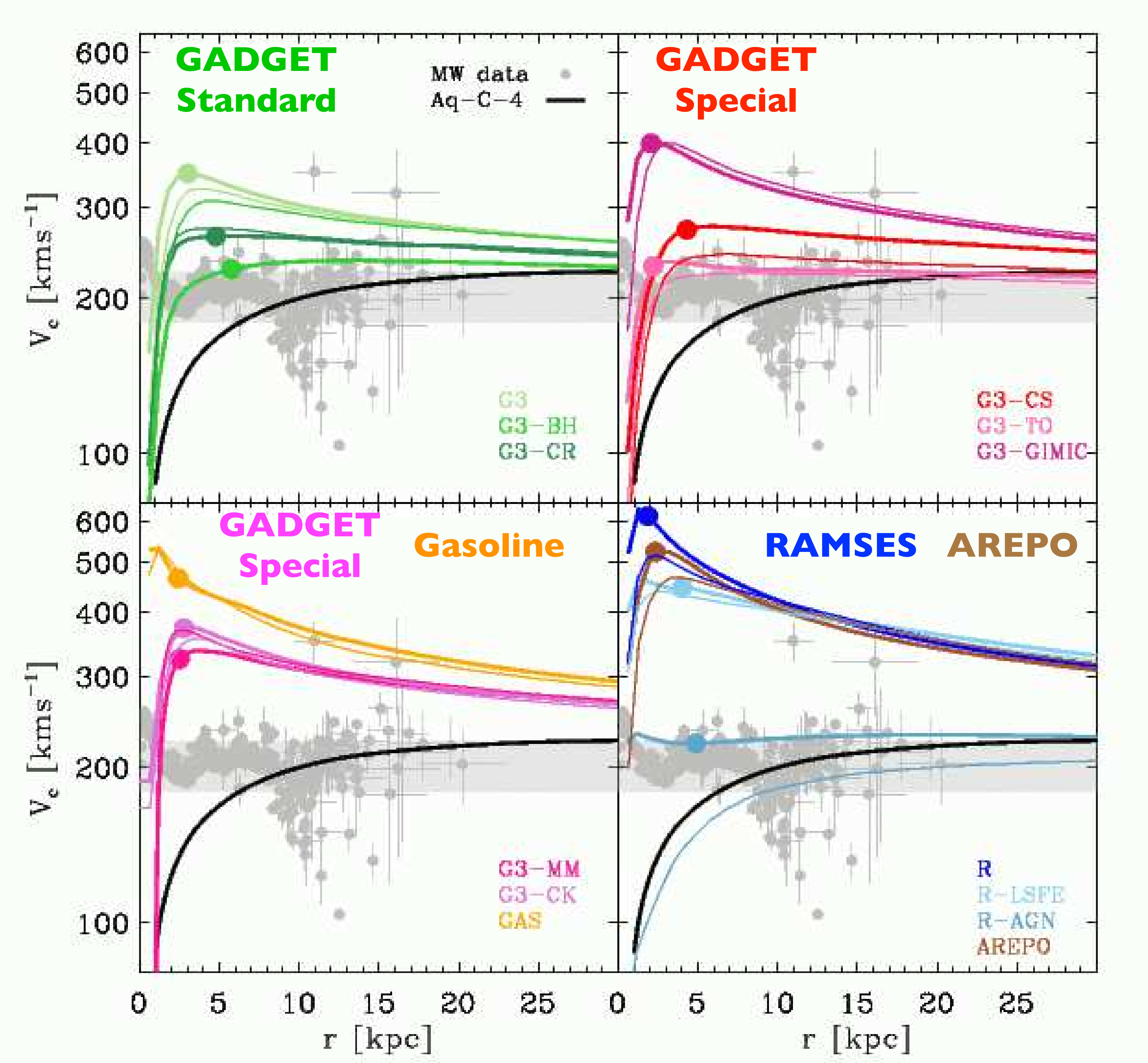
Code	$f_{\rm b}$ ($\Omega_{\rm b}/\Omega_{\rm m}$)	$m_{\rm DM}$ [$10^6 {\rm M}_\odot$]	$m_{\rm gas}$ [$10^6 {\rm M}_\odot$]	Softening $\epsilon_{\rm g}^{z=0}$ [kpc]	Softening $z_{\rm fix}$
G3 G3-BH G3-CR G3-CS G3-CK Arepo	0.16	2.2 (17)	0.4 (3.3)	0.7 (1.4)	0 (0)
G3-TO G3-GIMIC	0.18	2.1 (17)	0.5 (3.7)	0.5 (1)	3 (3)
G3-MM	0.16	2.2 (17)	0.4 (3.3)	0.7 (1.4)	2 (2)
GAS	0.18	2.1 (17)	0.5 (3.7)	0.46 (0.9)	8 (8)
R R-LSFE R-AGN	0.16	1.4 (11)	0.2 (1.8)	0.26 (0.5)	9 (9)

Most stars form in galactic disks, so it is essential to resolve disks. The scale height of the MWy disk is about 100 pc.

Softening is 500 pc or worse (fixed in comoving coordinates at $z = z_{\rm fix}$).

Softening is 260 pc (fixed in comoving coordinates at $z_{\rm fix} = 9$)

Aquila Comparison Project Rotation Curves - Scannapieco+2012



High-resolution Galaxy Simulation Comparison Project

(1) Inaugurate a set of frameworks for comparing high-resolution galaxy simulations (with resolution better than 100 parsecs) across different high-resolution numerical platforms.

(2) Establish isolated and cosmological initial conditions in the 1st workshop so each participating group can run a suite of simulations in the months to come.

(3) Maintain the collaboration online (telecon+webpage) between the two meetings.

(4) Measurable objectives: produce a set of comparison papers by the end of year 2013

Starting Workshop Summary

The **Starting Workshop** of the High-Resolution Galaxy Simulation Comparison (UCSC, Aug. 17-19, 2012) was a great success. All the main simulation groups in the world were represented (in many cases by their leaders), people behaved extremely constructively, and we were able to reach consensus on a wide variety of key issues including initial conditions for cosmological and isolated disk simulations (including separation criteria for the cosmological ICs), ultraviolet background and cooling functions, and common analysis tools including yt. People have signed up to be key contacts for all the simulation groups, titles of 7 or 8 major papers to be produced by this project were agreed on with at least one person tentatively agreeing to take charge of each, and the first of our follow-up web conferences has been set for Nov. 16 (Fri) at 9am PST, noon EST, and 6pm in Europe.

It is remarkable that we are launching this project at the time when several key technologies have just become available including the simulation codes, the MUlti-Scale Initial Conditions generator (MUSIC) for setting up the simulations, and the yt code for analyzing the outputs from all the simulations in a parallel way. This project will be state-of-the-art in every respect, and in fact it will surely advance the entire field of galaxy simulations.

Goals of the Project

[1] **Each of the participating code groups is invited (but not required) to perform two different types of high-resolution galaxy formation simulations: isolated galaxy and cosmological zoom-in galaxy.** These two types of simulations will be run and studied in parallel in the upcoming months. We will analyze and compare the results at several epochs and in multiple dimensions.

[2] **At the end we will go a step further to include comparisons with observational data.** We focus on science-based research, not just code-based comparison. We aim to use this project as a platform to launch many science-oriented studies of high-resolution galaxy simulations.

Point Persons for Participating Codes

CODE	Isolated Galaxy	Cosmological Zoom-in Galaxy
AREPO	Dusan Keres (to be confirmed)	Dusan Keres (to be confirmed)
ART-NMSU	Sebastian Trujillo-Gomez	Daniel Ceverino
ART-Chicago	Sam Leitner	Sam Leitner
ENZO	Ji-hoon Kim	John Wise
GADGET	Brant Robertson, Justin Read	Amit Kashi, Justin Read, Phil Hopkins
GADGET-SPHS	Justin Read	Justin Read
GASOLINE	James Wadsley, Lucio Mayer	Sijing Shen
RAMSES	Oscar Agertz, Romain Teyssier	Oscar Agertz, Romain Teyssier

Working Groups

We have formed 12 working groups including eight science-oriented working groups primarily focused on performing original research by comparing simulations across different codes and with observations. Most of the Working Groups are led by postdocs.

Task-oriented Working Groups (I-IV)
Working Group I – **Common Physics and Introduction to Project**
Working Group II – **Common ICs: Isolated Low Redshift Disk Galaxy**
Working Group III – **Common ICs: Cosmological Zoom-In**
Working Group IV – **Common Analysis**

Science-oriented Working Groups (V-XII)
Working Group V – **Isolated Galaxies and Subgrid Physics**
Working Group VI – **Dwarf Galaxies in Cosmological Simulations**
Working Group VII – **Dark Matter Issues**
Working Group VIII – **Satellite Galaxies**
Working Group IX – **Characteristics of Cosmological Galaxies**
Working Group X – **Outflows**
Working Group XI – **High-redshift Galaxies and Reionization**
Working Group XII – **Interstellar Medium**

High-Resolution Galaxy Simulation Comparison

Initial Conditions for Simulations

MUSIC galaxy masses at z~0: ~10^{10}, 10^{11}, 10^{12}, 10^{13} $M_\odot$

with both quiet and busy merging trees

isolation criteria agreed for Lagrangian regions

Isolated Spiral Galaxy at z ~ 1, M ~ 10^{10}, 10^{11}, 10^{12} $M_\odot$

Astrophysics that all groups will include

UV background (Haardt-Madau 2012)

cooling function

Tools to compare simulations based on *yt*, now available for all codes used here, also input for *Sunrise*

The High-Resolution Galaxy Simulation Comparison Project: Calendar

This Kickoff Meeting: August 17-18-19, 2012, at UCSC

Roughly every two months: simulation comparison telecon

Roughly January 2013: web conference on HRGS Comparison

Summer 2013:
UC-HiPACC Summer School on Star and Planet Formation
July 22 - August 9, at UCSC, directed by Mark Krumholz
Santa Cruz Galaxy Workshop - August 12-16 (by invitation)
Followup Conference for HRGS Comparison Project
August 19-23 at UCSC, and/or during
August 19 - September 6 at KITP Santa Barbara
(KITP will make 20 office spaces available during their Black Hole workshop, in response to proposal by Primack, Madau, Mayer, and Teyssier)

Summary: the big cosmic questions now

- The nature of the dark matter

- The nature of the dark energy (the future of the Universe)

- The early evolution of the Universe, including
  - Formation of the first tiny galaxies and the first stars
  - How the universe reionized

- How the entire population of galaxies forms and evolves
  - From direct observations from the ground and space
  - Interpreted with the help of cosmological simulations:
    - Resolving star formation with realistic feedback
    - Formation and feedback from supermassive black holes
    - etc.