Lecture 2

Galaxy Formation Theory: Simulations and Semi-Analytic Models

Joel Primack, UCSC

The ΛCDM theory of a universe dominated by dark energy and dark matter (the "Double Dark" standard cosmological model) is supported by a vast variety of observational data, and there is no convincing data known that disagrees with predictions of this theory. The goals of cosmology now are to discover the nature of the dark energy and dark matter, and to understand the formation of galaxies and clusters within the cosmic web gravitational backbone formed by the dark matter in our expanding universe with an increasing fraction of dark energy. This lecture will discuss the current state of the art in galaxy formation, and describe the successes and challenges for the best current ΛCDM models of the roles of baryonic physics and supermassive black holes in the formation of galaxies.

I thank my collaborators Avishai Dekel, Sandra Faber, and Rachel Somerville for help with this lecture.

What We Know About Galaxy Formation

- Initial Conditions: WMAP5 cosmology

CMB + galaxy P(k) + Type Ia SNe →

Ω_Λ=0.72, Ω_m=0.28, Ω_b=0.046, H_0=70 km/s/Mpc, σ_8=0.82

What We Know About Galaxy Formation

- Initial Conditions: WMAP cosmology
- Final Conditions: Low-z galaxy properties

Well-studied in Milky Way and nearby galaxies

What We Know About Galaxy Formation

- Initial Conditions: WMAP cosmology
- Final Conditions: Low-z galaxies
- Integral Constraints: Cosmological quantities

Star Formation Rate Density (SFRD) vs. redshift ($M_\odot$/yr/Mpc^3) - Madau plot

Stellar Mass Density (SMD) vs. redshift ($M_\odot$/Mpc^3) - Dickinson plot

SMD should = integrated SFRD: $\rho_*(t) = \int_0^t dt\ \ d\rho_*/dt$

Extragalactic Background Light (EBL) - constrains integrated SFRD

What We Know About Galaxy Formation

- Initial Conditions: WMAP cosmology
- Final Conditions: Low-z galaxies
- Integral Constraints: Cosmological quantities
- Well-studied galaxy evolution at z<1

  SDSS clarified galaxy scaling relations, galaxy color bimodality

  COMBO-17, DEEP, COSMOS surveys measuring star formation rates, etc.

What We Know About Galaxy Formation

- Initial Conditions: WMAP cosmology
- Final Conditions: Low-z galaxies
- Integral Constraints: Cosmological quantities
- Well-studied galaxy evolution at $z<1$
- Identified Galaxy Zoo at $z=2-3$

Lyman break galaxies, Lyman alpha emitters, Distant red galaxies, Active Galactic Nuclei, Damped Lyman alpha systems, Submillimeter galaxies

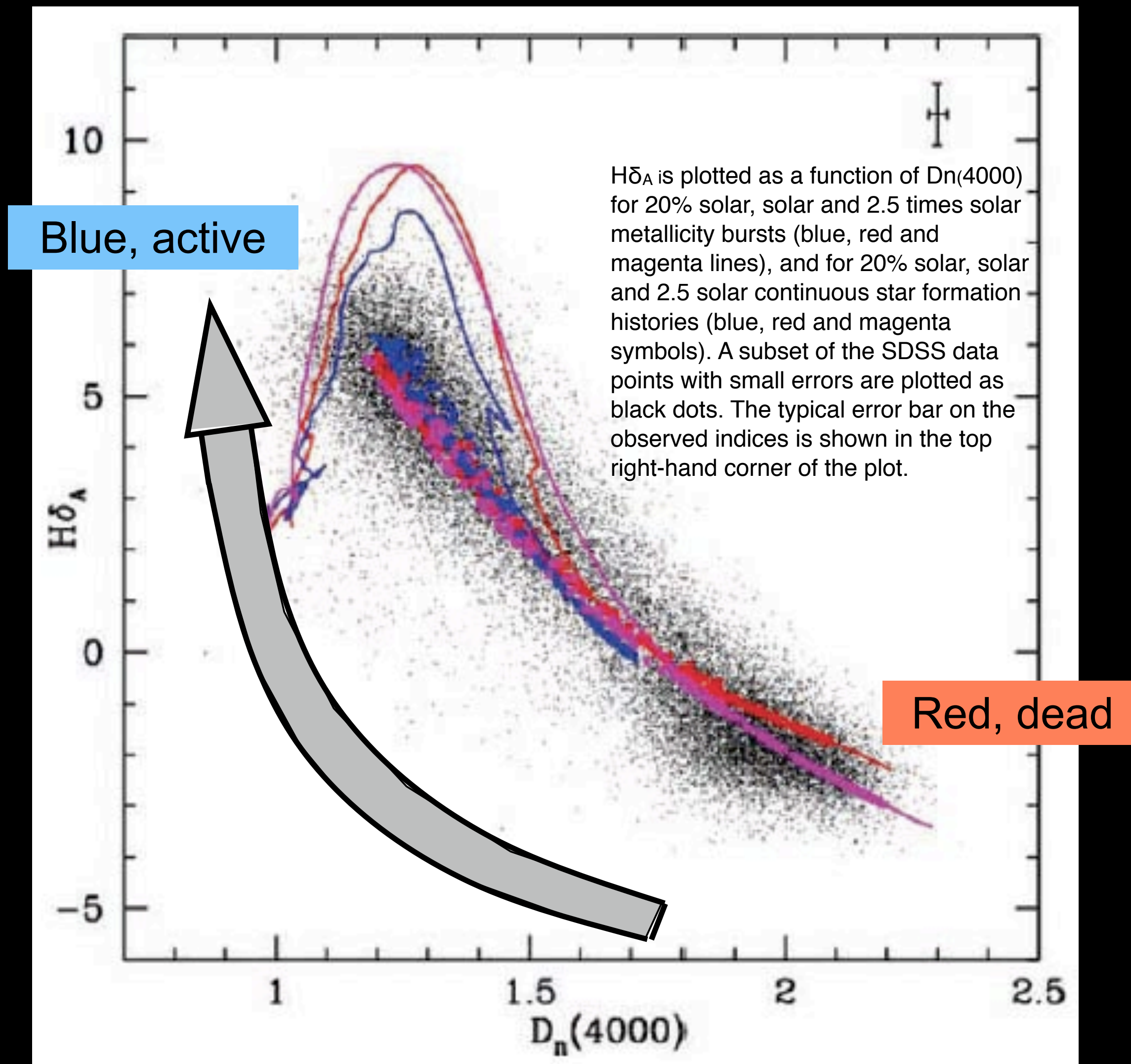
However: Evolutionary sequence unclear, which (if any) are progenitors of typical galaxies like the Milky Way?

with thanks to Eric Gawiser

Revolutionizing new developments

- **Large redshift surveys:**
  - **Sloan Digital Sky Survey:** 1 million spectra to z = 0.3, 3.4 Gyr back in time

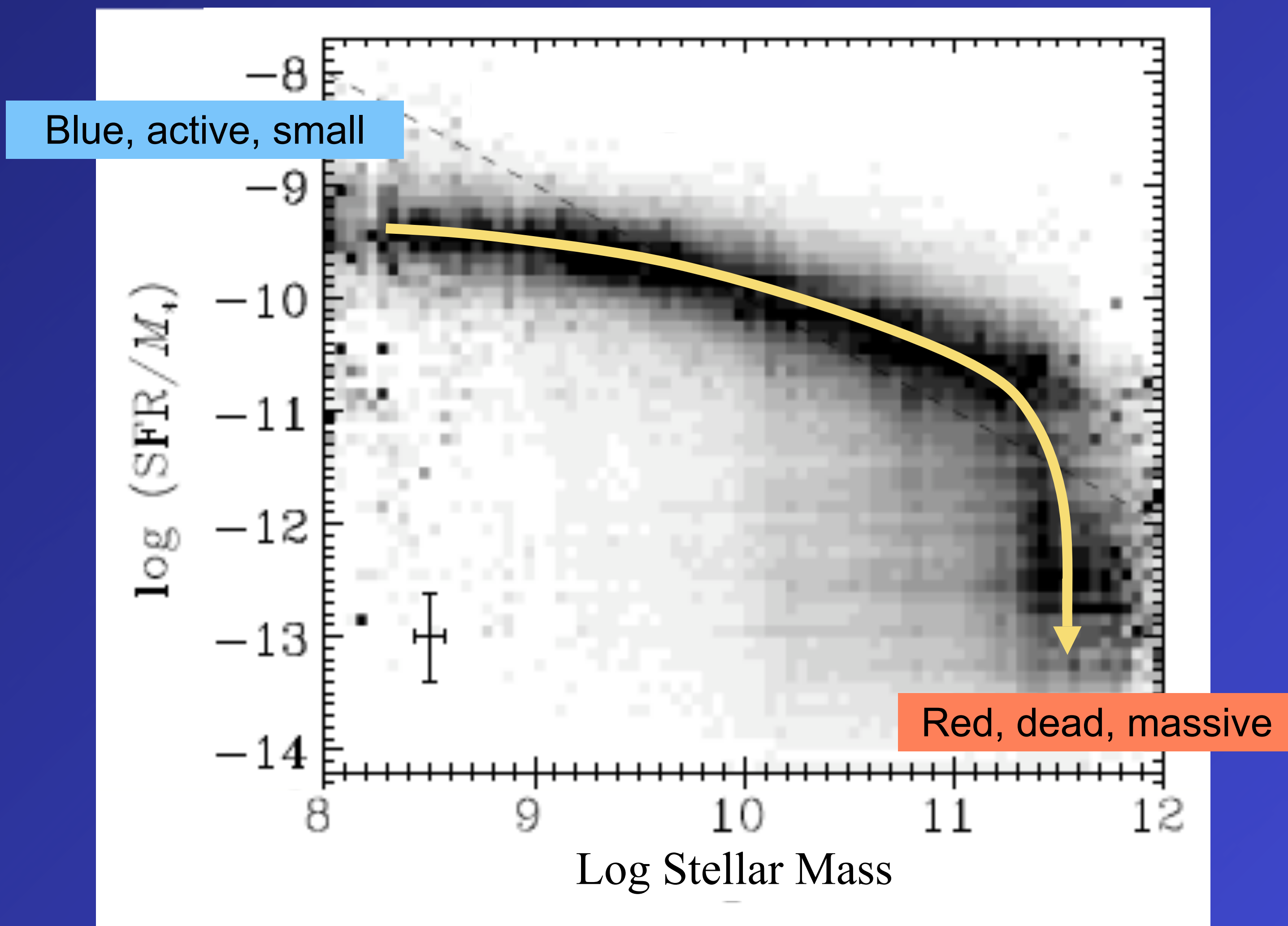
The Star-Forming Sequence in Stellar Population Indices



Kauffmann et al. 2003

The star-forming sequence is also a mass sequence

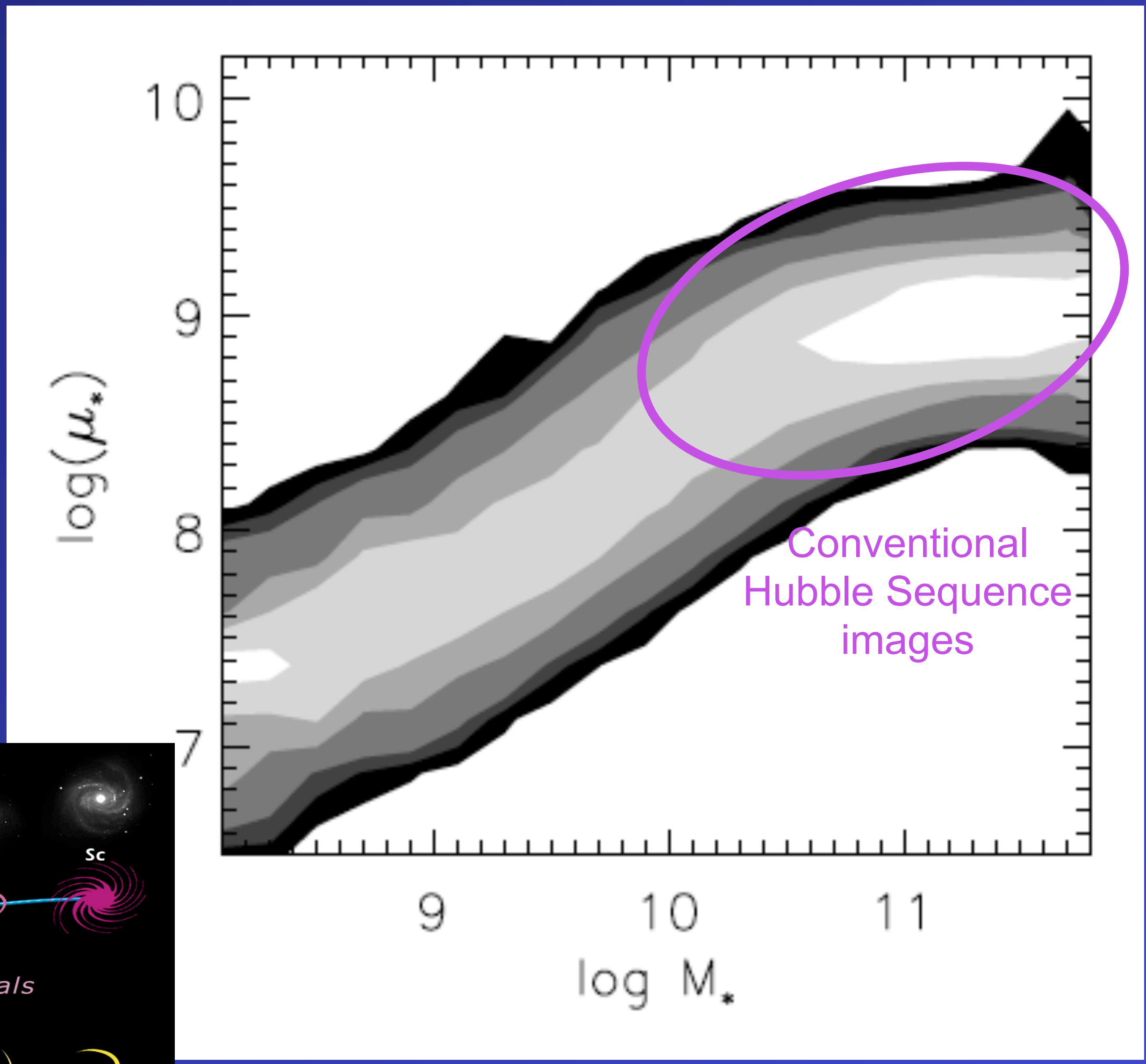
Specific SFR based on absorption-corrected GALEX UV flux

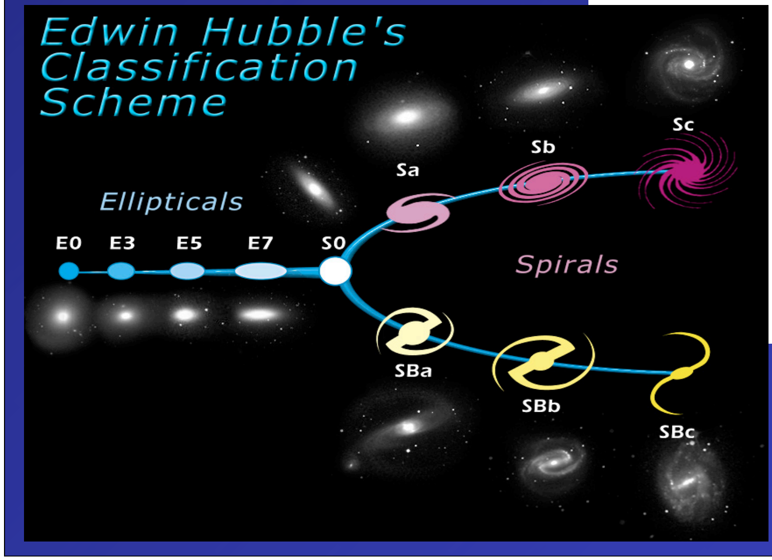


Samir et al. 2007

Other trends vs. stellar mass --

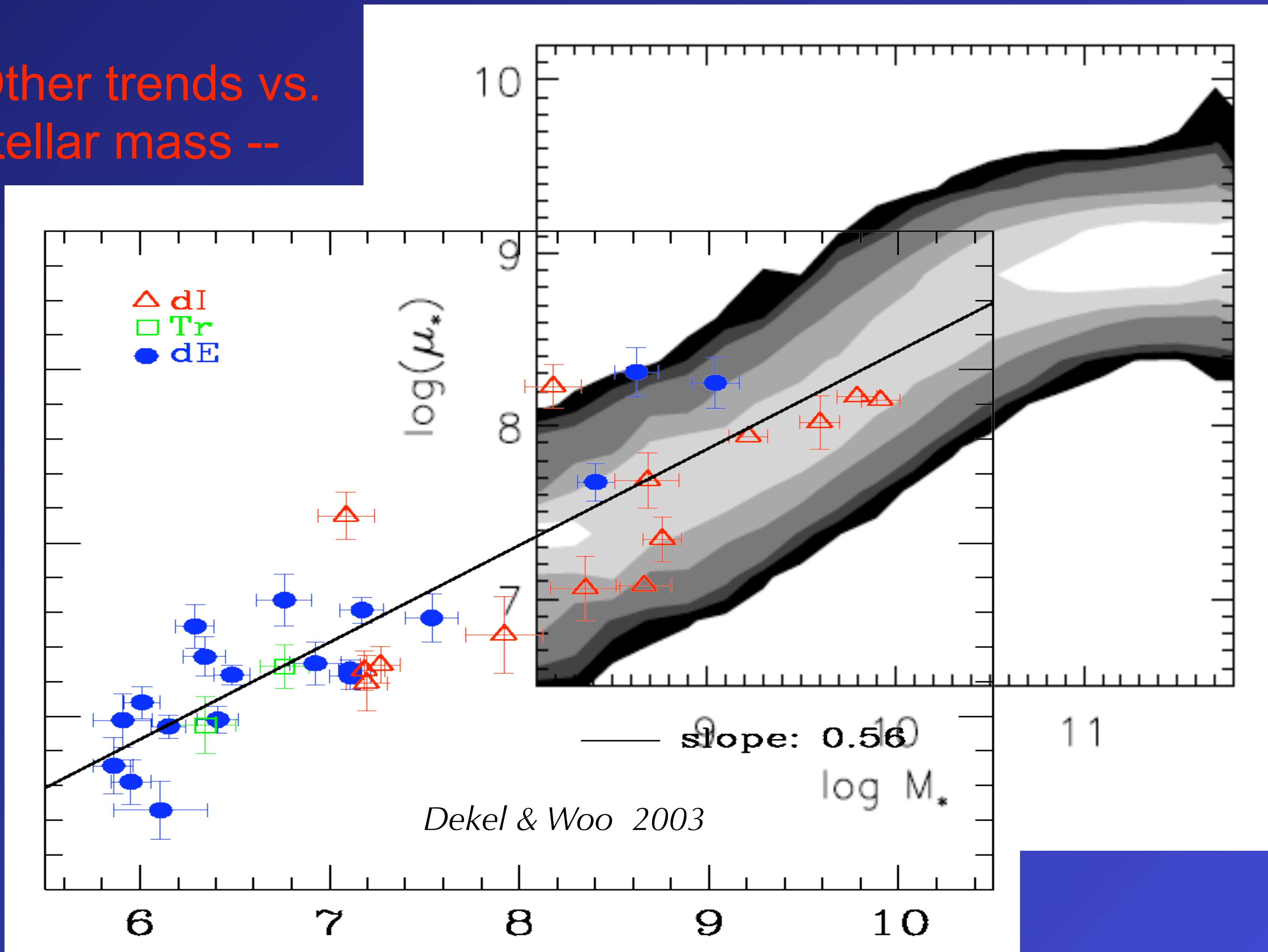
Surface mass density





Kauffmann et al. 2003: Sloan Survey

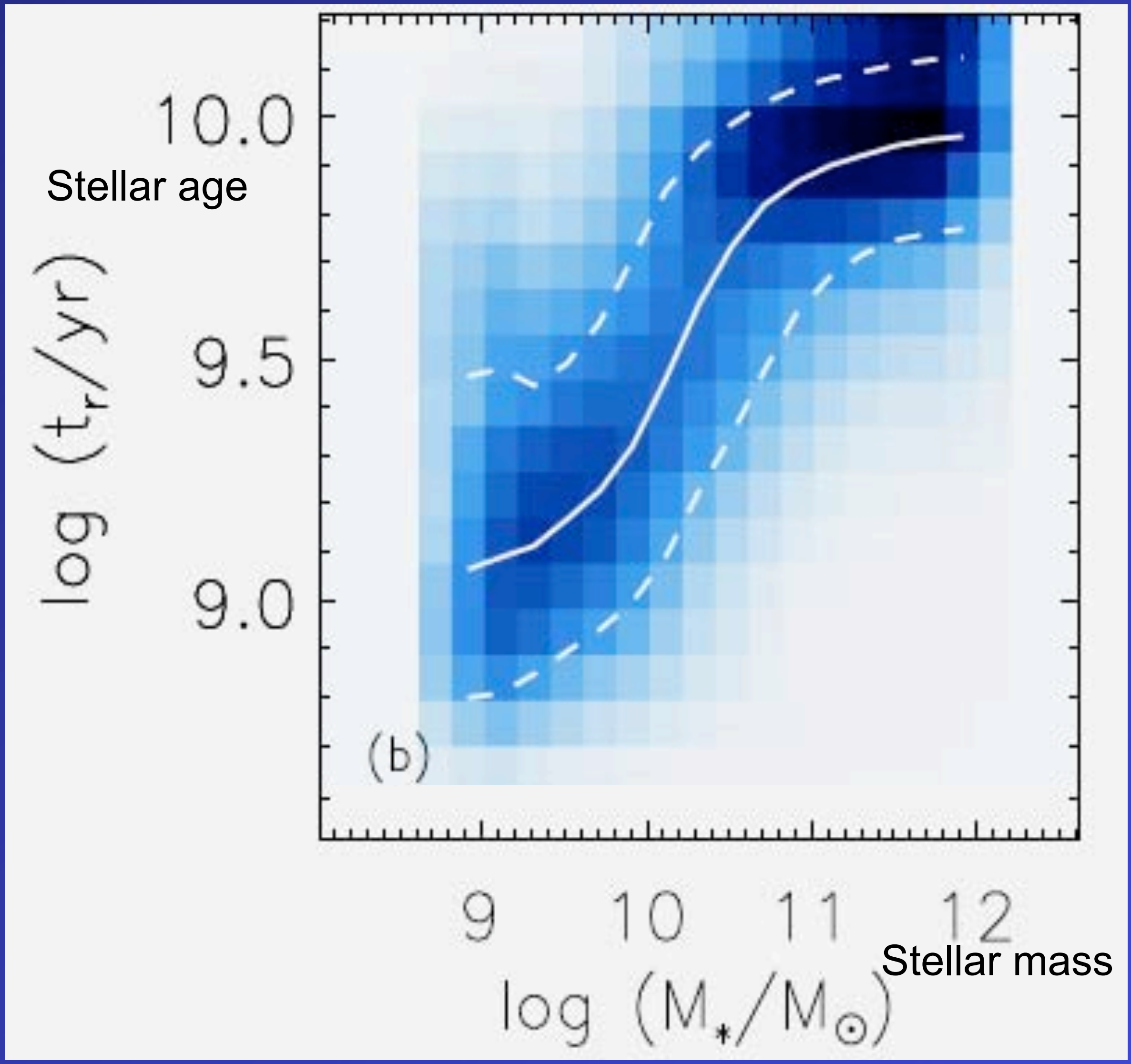
Other trends vs. stellar mass --



Other trends vs. stellar mass --

Mean stellar age

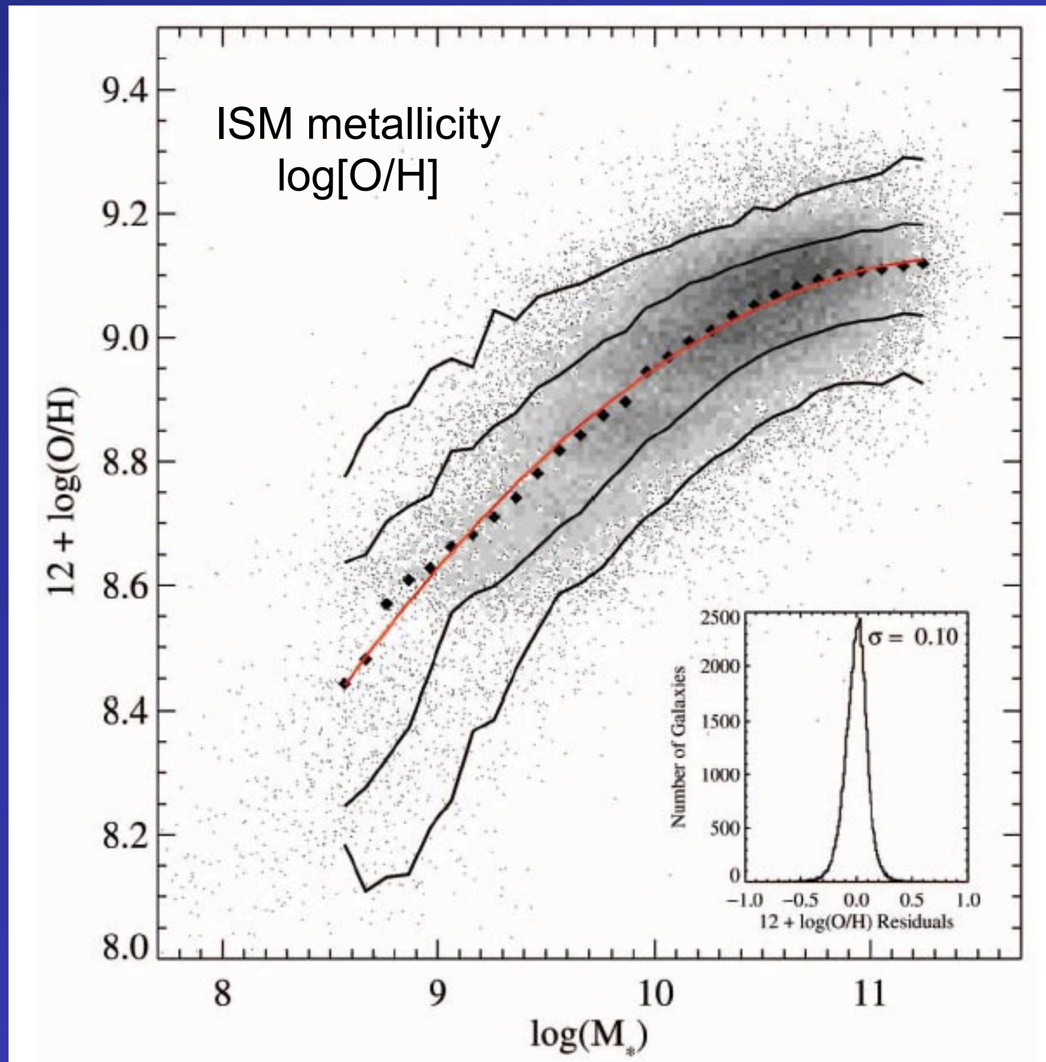
Stars in more massive galaxies are older.



Gallazzi et al. 2005: Sloan Survey

Other trends vs. stellar mass --

Interstellar gas metallicity



Stars in more massive galaxies are more metal rich.

Tremonti et al. 2004: Sloan Survey

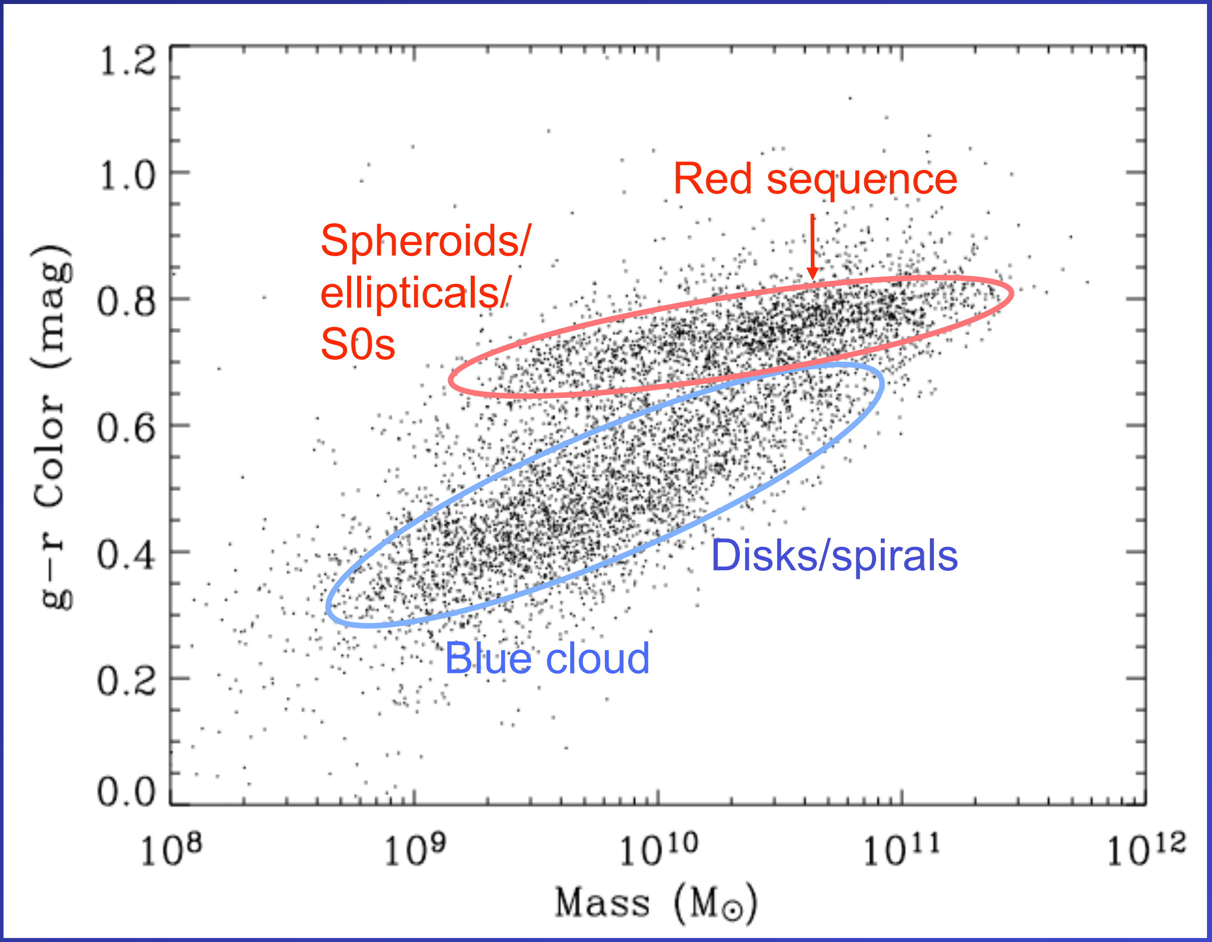
Color bimodality seen in Sloan galaxies

"Red-and dead" ellipticals/S0s populate the red sequence

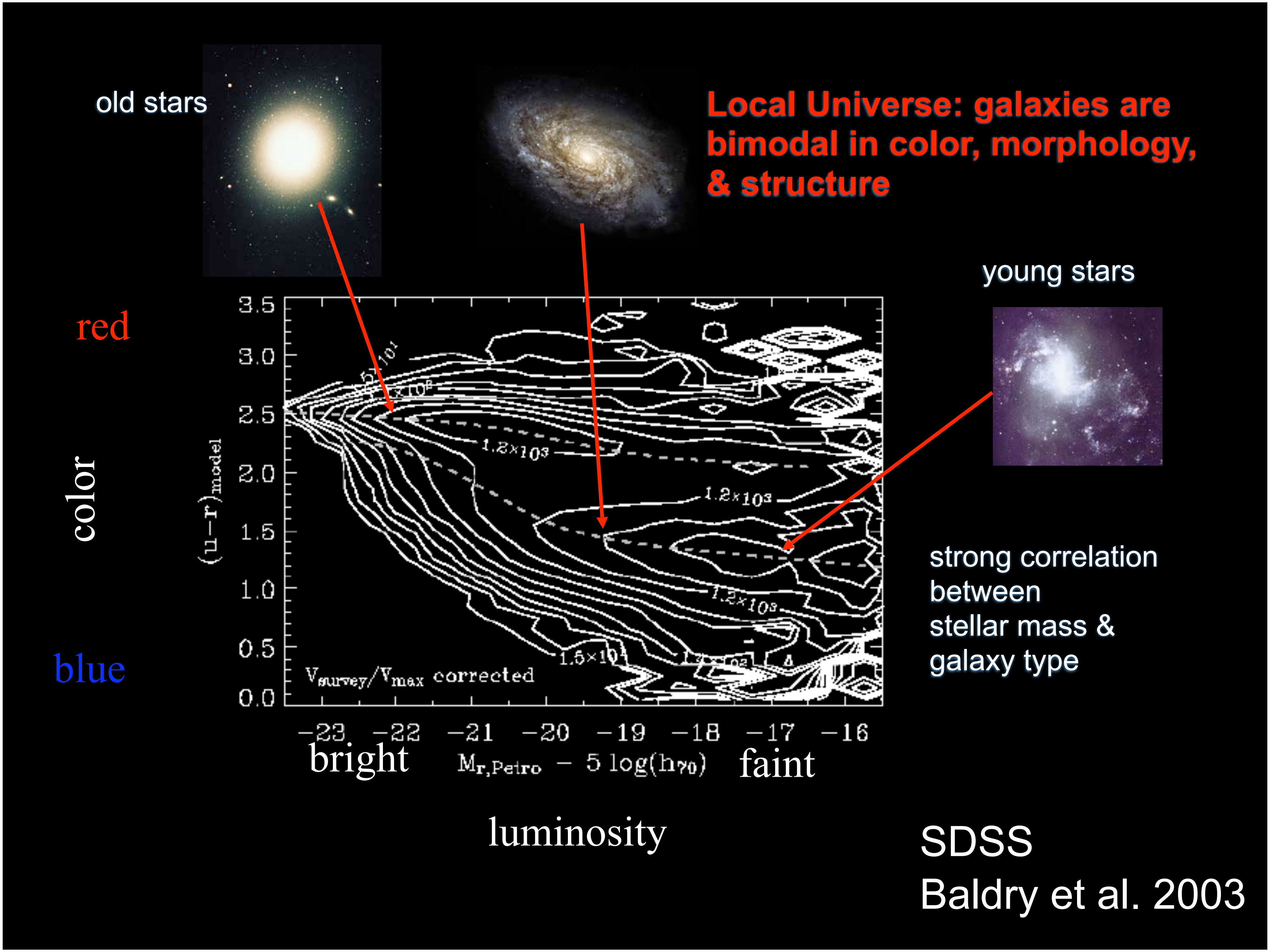
Star-forming blue, disky galaxies populate the "blue cloud"

Red

Blue



Color vs. stellar mass for Sloan Digital Sky Survey galaxies



Local Universe: galaxies are bimodal in color, morphology, & structure
old stars
young stars
red
color
blue
$(u-r)_{model}$
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−23
−22
−21
−20
−19
−18
−17
−16
$M_{r,Petro} - 5\log(h_{70})$
V_{survey}/V_{max} corrected
1.2×10³
1.2×10³
1.2×10³
1.5×10¹
bright
faint
luminosity
strong correlation between stellar mass & galaxy type
SDSS
Baldry et al. 2003

Revolutionizing new developments

- **Large redshift surveys:**
  - **Sloan Digital Sky Survey:** 1 million spectra to z = 0.3, 3.4 Gyr back in time
  - **DEEP2 Survey:** 50,000 spectra to z = 1.4, 9.0 Gyr back

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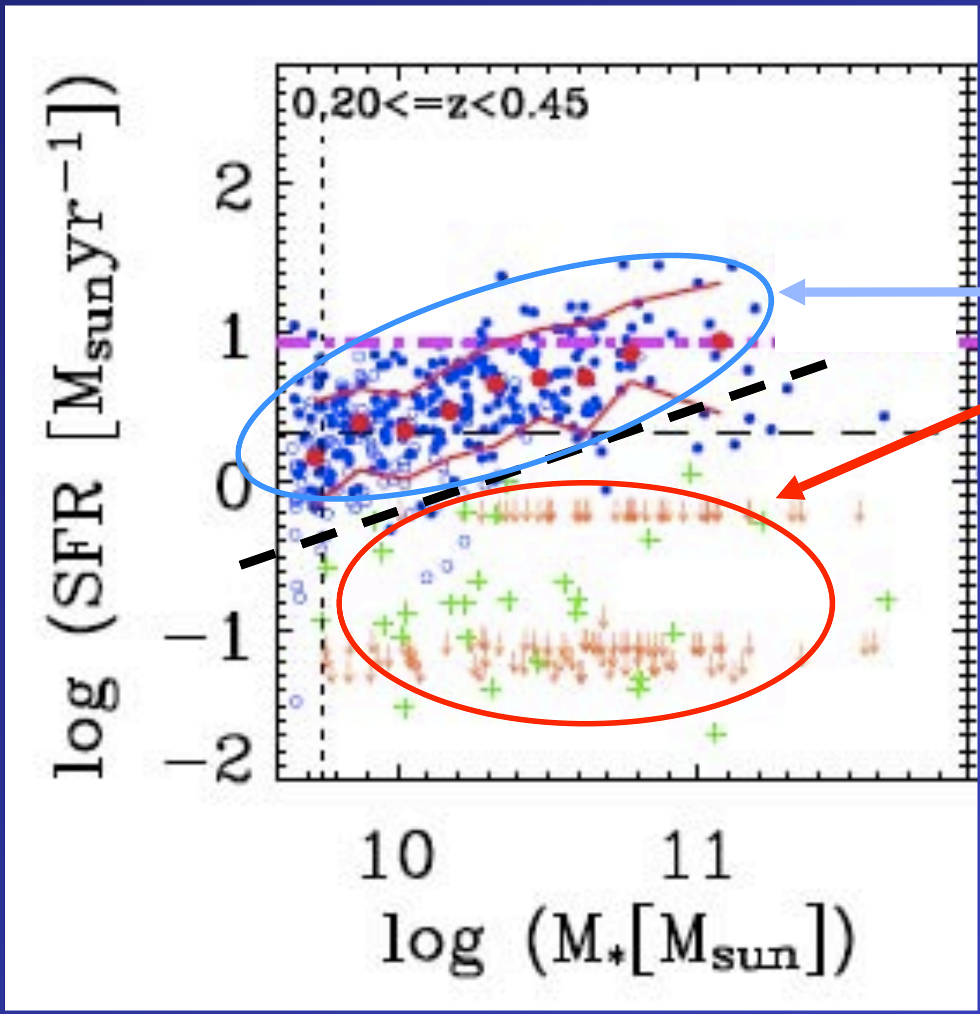
- **Broad wavelength coverage**
  - Old stars, young stars, star-formation rates, dust and gas, accreting BHs
  - Example: AEGIS Survey, outgrowth of DEEP2 in Groth Strip
  - Chandra (X-rays), GALEX (UV), Hubble (optical), SIRTF (IR), VLA (radio)


AEGIS
All-wavelength Extended Groth strip International Survey
Home
AEGIS Teams
For the Public
Papers & Talks
For Astronomers
Team Site
New: AEGIS is in Google Sky!
Click here to explore X-ray, ultraviolet, visible, and infrared images.
VLA
Spitzer
Palomar
CFHT
Keck
Hubble
News
Images
EGS Map
The AEGIS Survey...
...is unlocking the secrets of galaxy and large-scale structure formation over the last 9 billion years.

Star-formation rate from AEGIS



Galaxies are in two groups:

Blue: star-forming

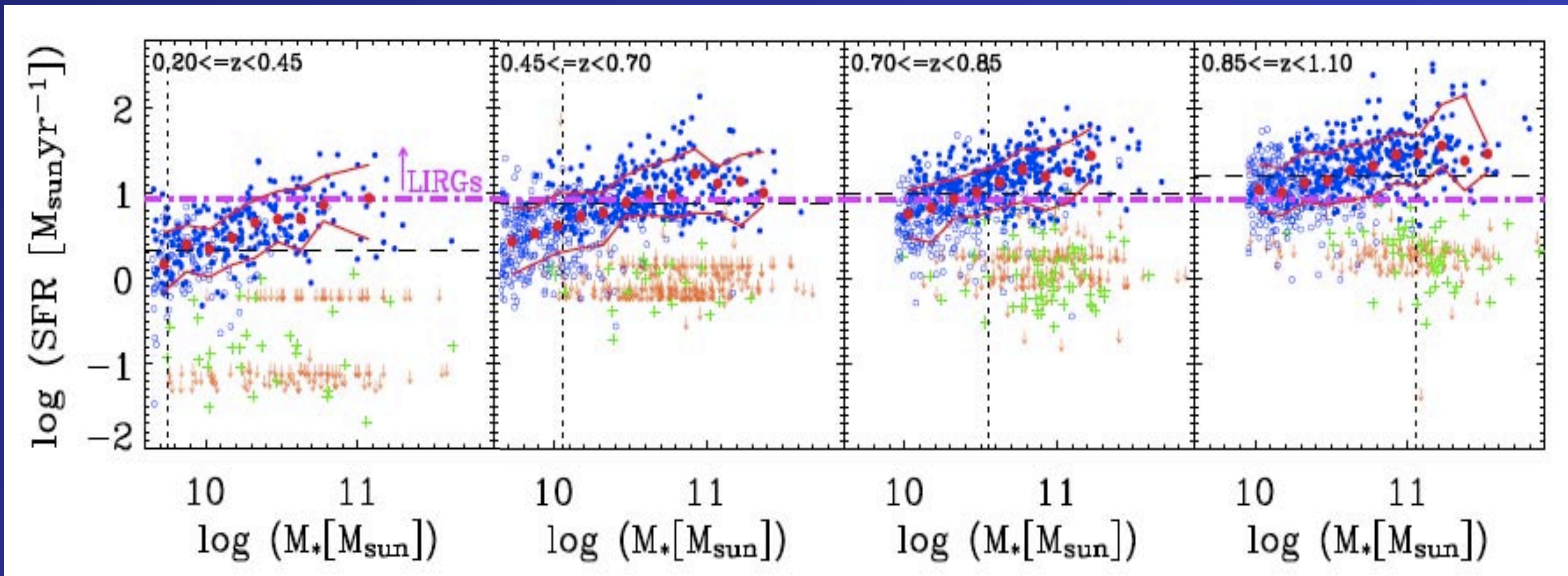
Red: quenched

For blue galaxies, star formation rate (SFR) has rms scatter of only:

± 0.3 dex

Noeske et al. 2007

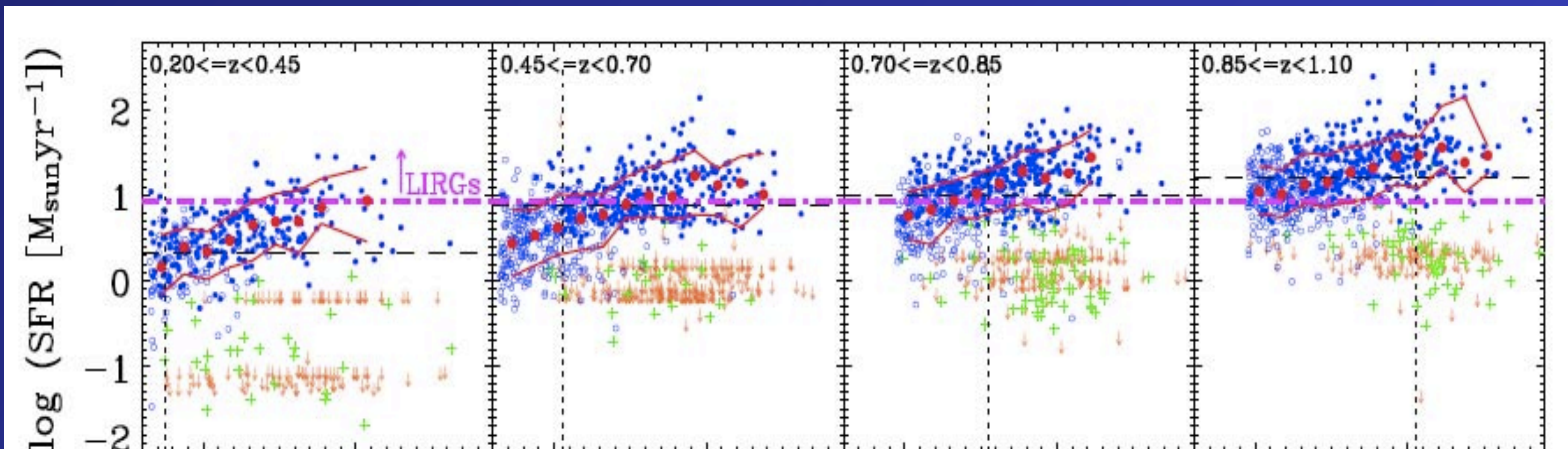
Star-formation rate from AEGIS

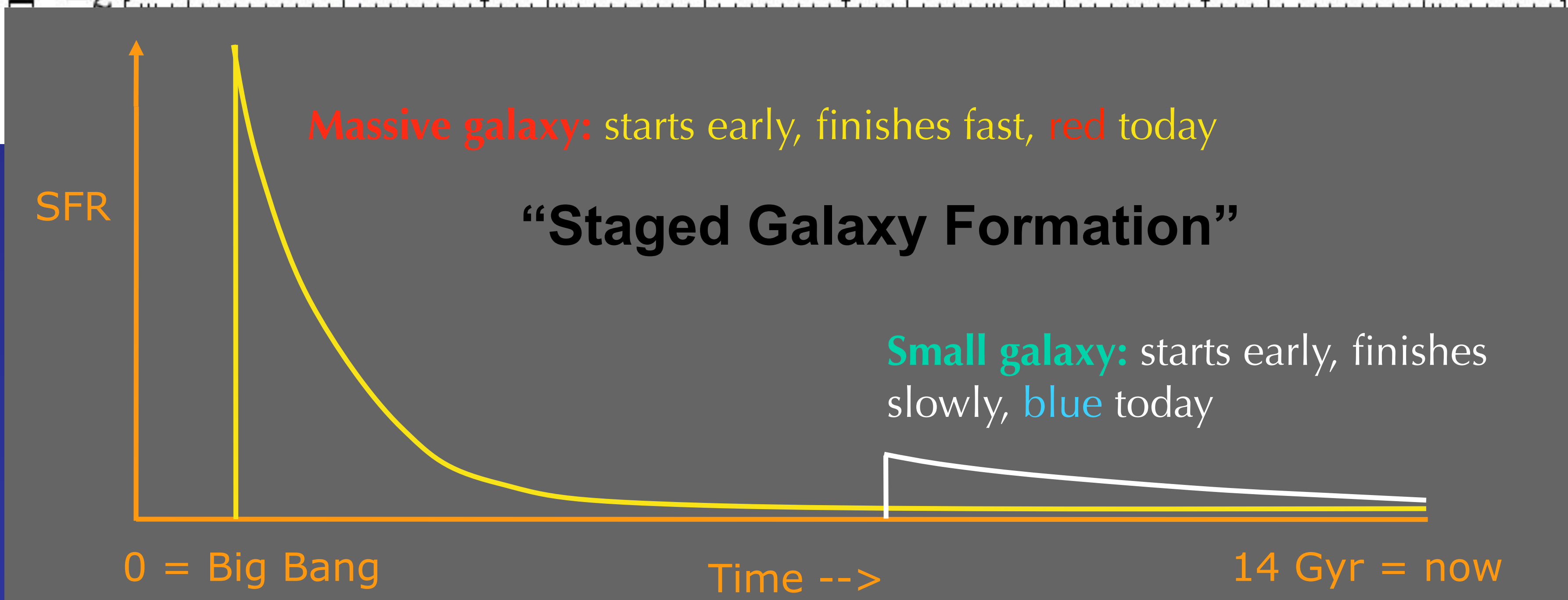


Star-forming **"main sequence":** (Noeske et al. 2007)

- Star formation declines exponentially in each galaxy
- Bigger galaxies turn on sooner and decay faster
- Downsizing!

Star-formation rate from AEGIS





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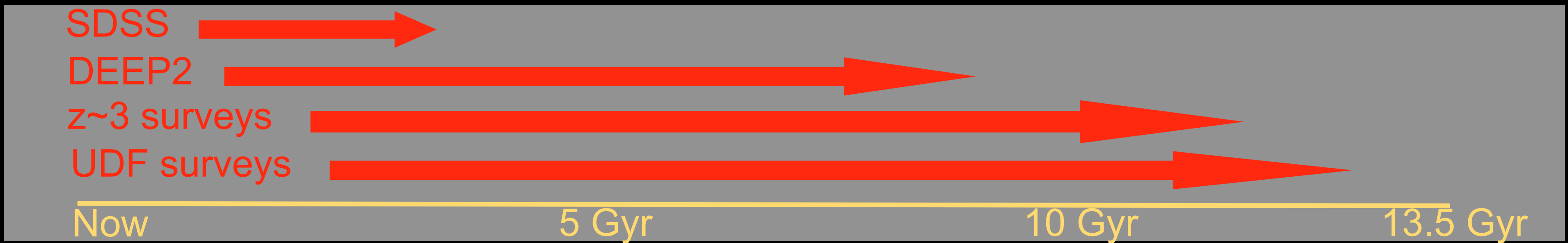
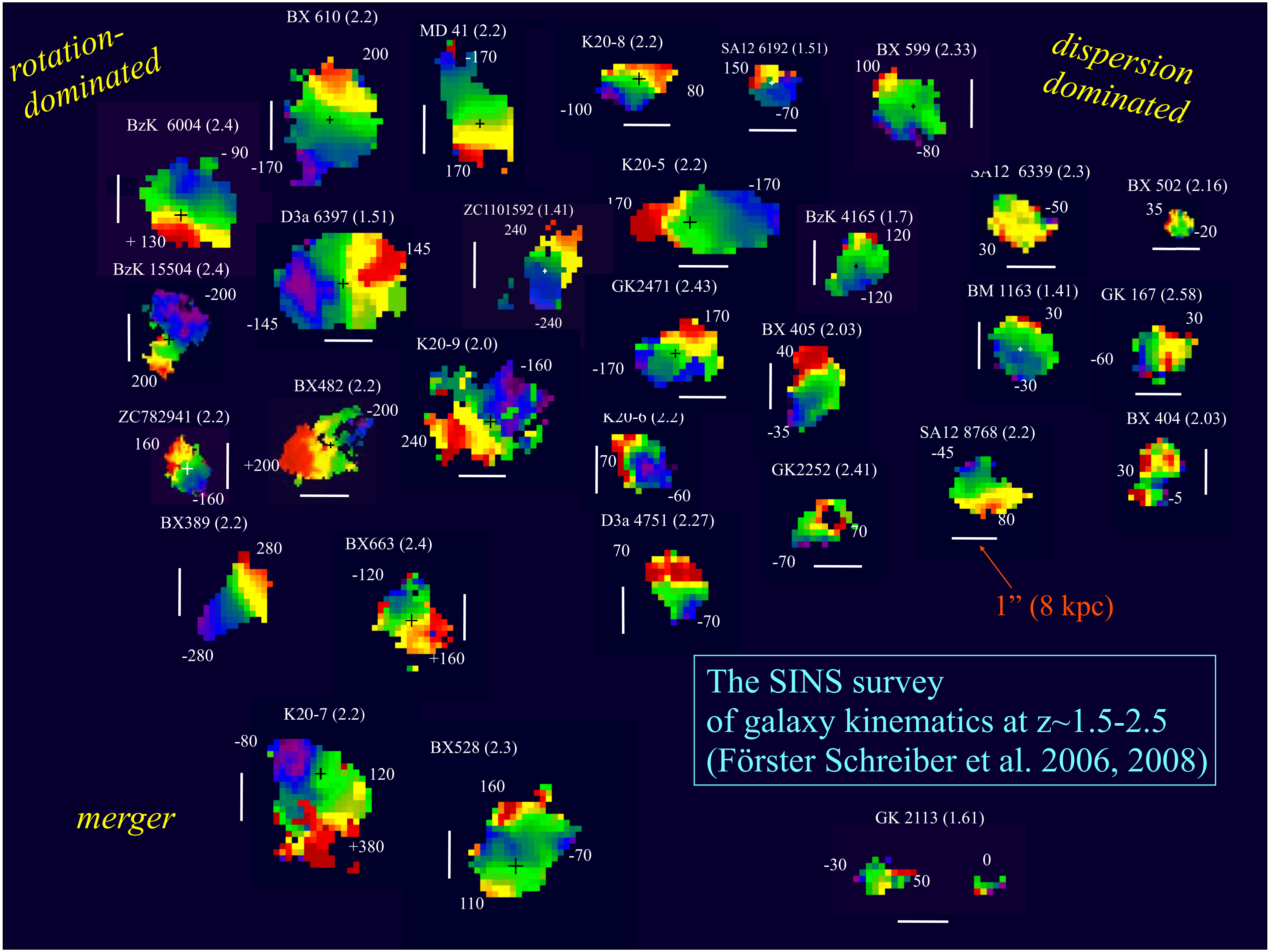
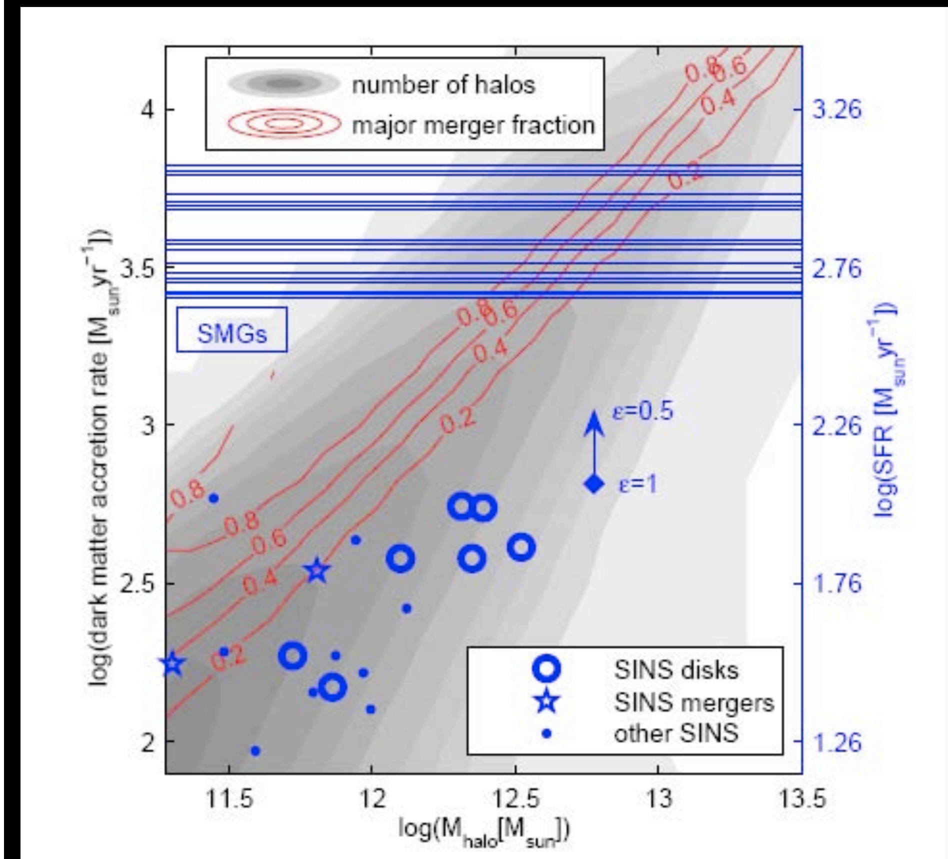
  - Example: AEGIS Survey, outgrowth of DEEP2 in Groth Strip
  - Chandra (X-rays), GALEX (UV), Hubble (optical), SIRTF (IR), VLA (radio)
- **Deep redshift penetration back in time**
  - Large surveys like DEEP2 to z ~ 1.5 — 9.0 Gyr
  - Several ~1,000-galaxy surveys to z ~ 4 — 11.9 Gyr
  - Handfuls of galaxies to z ~ 7 — 12.7 Gyr

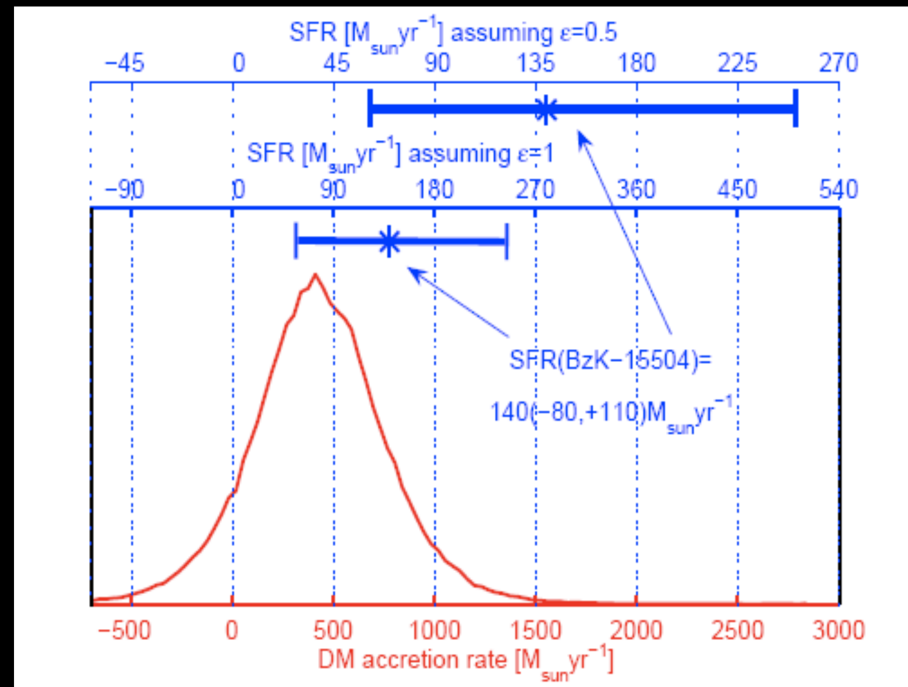



rotation-dominated
dispersion dominated
merger
BX 610 (2.2)
MD 41 (2.2)
K20-8 (2.2)
SA12 6192 (1.51)
BX 599 (2.33)
BzK 6004 (2.4)
K20-5 (2.2)
SA12 6339 (2.3)
BX 502 (2.16)
D3a 6397 (1.51)
ZC1101592 (1.41)
BzK 4165 (1.7)
BzK 15504 (2.4)
GK2471 (2.43)
BM 1163 (1.41)
GK 167 (2.58)
K20-9 (2.0)
BX 405 (2.03)
BX482 (2.2)
ZC782941 (2.2)
BX 404 (2.03)
SA12 8768 (2.2)
GK2252 (2.41)
BX389 (2.2)
BX663 (2.4)
D3a 4751 (2.27)
1” (8 kpc)
K20-7 (2.2)
BX528 (2.3)
GK 2113 (1.61)
The SINS survey
of galaxy kinematics at z~1.5-2.5
(Förster Schreiber et al. 2006, 2008)

The large star formation rates are consistent with CDM simulations (even) without (major) mergers



Genel et al. 2008, astro-ph 0808.0194, Dekel et al. 2008



observed SFR can be accounted for by DM simulations for

- $SFR \sim \left(\frac{\varepsilon_{SFR}}{0.5}\right)\left(\frac{b}{0.18}\right)\left(\dot{M}_{dm}\right)_{z,M}$
- cold flow regime
- mostly gaseous accretion

R. Genzel 2008

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- **Better models**
  - Cosmology & clustering of Dark Matter are understood: “GRAVITY BACKBONE”
  - Gas and star-formation are still a challenge; semi-analytic models are advancing

-- Sandra Faber

Recent Progress in Simulations

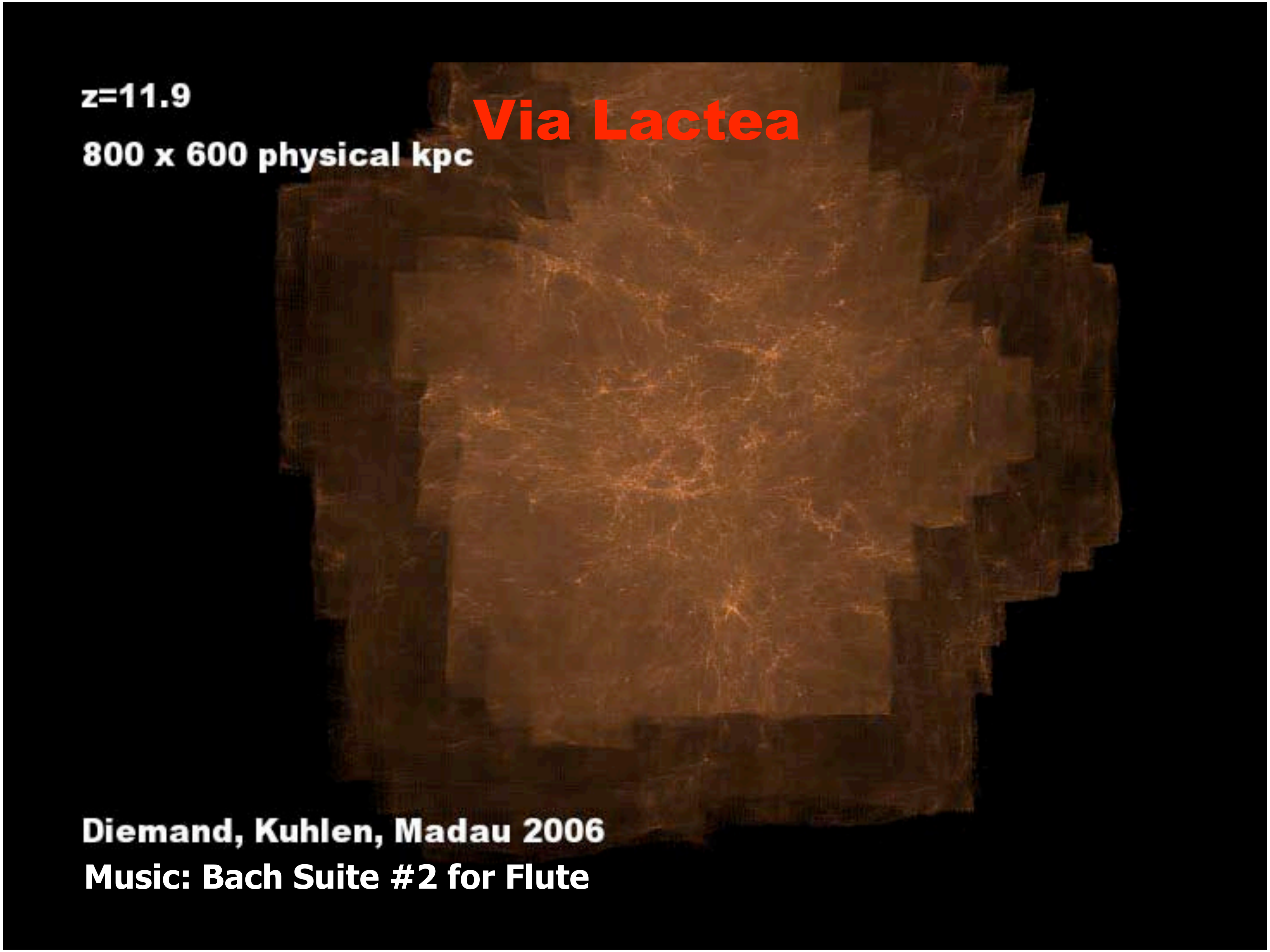
Improvements in resolution in DM simulations Diemand, Madau, Zemp; Springel, Aquarius simulations, ...

Stream-fed galaxies form most of the stars in the universe Birnboim & Dekel 03+, Keres+05, Dekel+08

Improvements in resolution and feedback treatment leading to formation of more realistic disk galaxies Fabio Governato's group, Klypin & Ceverino, ...

Predict appearance of interacting galaxies, AGN formation, and properties of merger remnants TJ Cox04, Cox+06,+08, Patrik Jonsson04,06, Hernquist's group+05++, Jonsson +06, Greg Novak+06,08, Matt Covington08,+08, ...

Statistically compare to observations (GOODS and AEGIS) Jennifer Lotz, Madau, & Primack 04; Lotz et al. 05, 06, 08; Cristy Pierce+06,... Nandra+06, Georgakakis+08, Pierce+08


z=11.9
800 x 600 physical kpc
Via Lactea
Diemand, Kuhlen, Madau 2006
Music: Bach Suite #2 for Flute

At High z, in Massive Halos: Cold Streams in Hot Halos

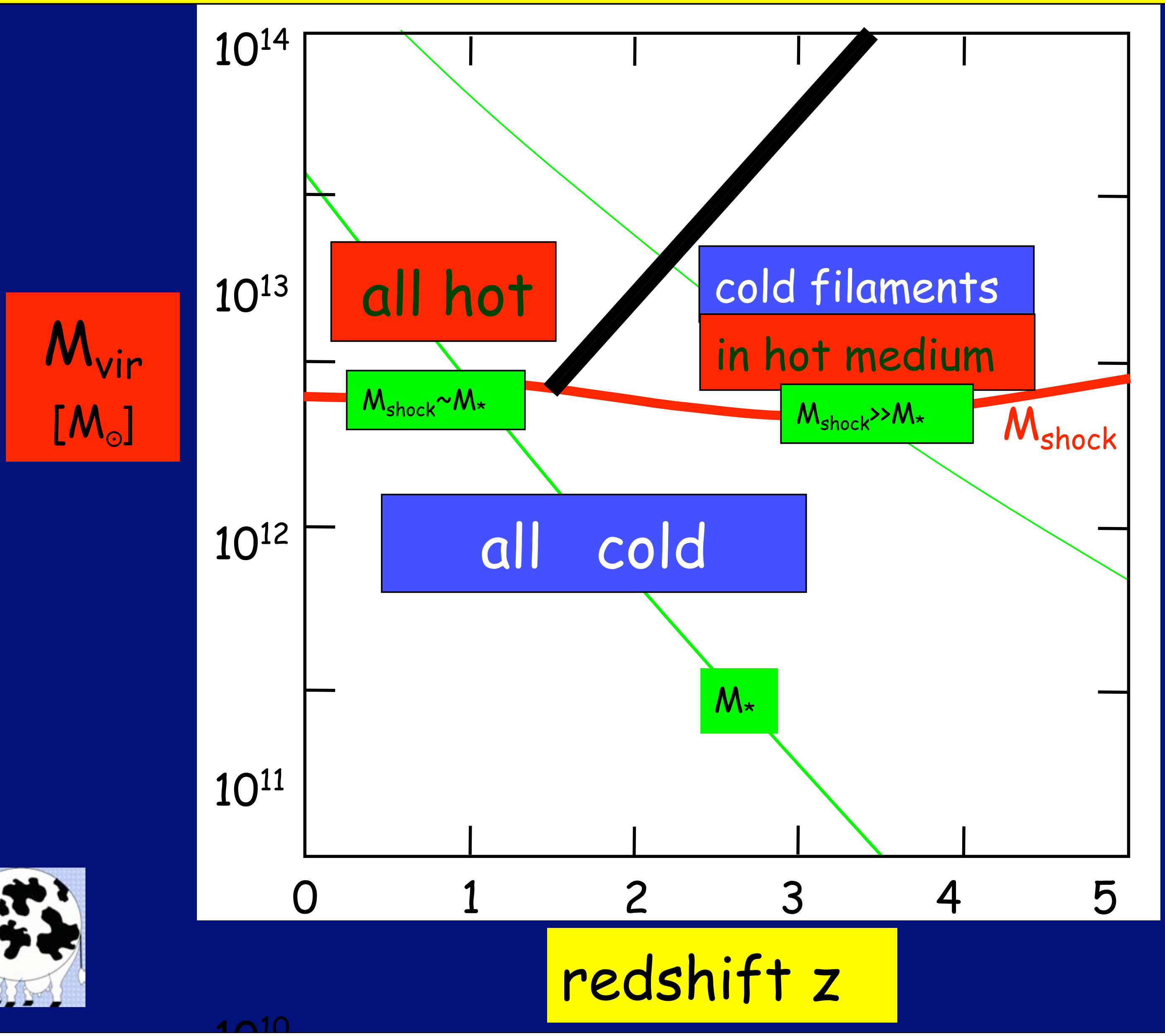
in M>M_{shock}

Totally hot at z<1

Cold streams at z>2

Dekel & Birnboim 2006

Cold Streams in Big Galaxies at High z



Dekel & Birnboim 06 Fig. 7

Improvements in resolution and feedback are leading to formation of more realistic disk galaxies in hydro simulations

The formation of a Milky Way size disk galaxy ...

Gas is GREEN

Stars are WHITE

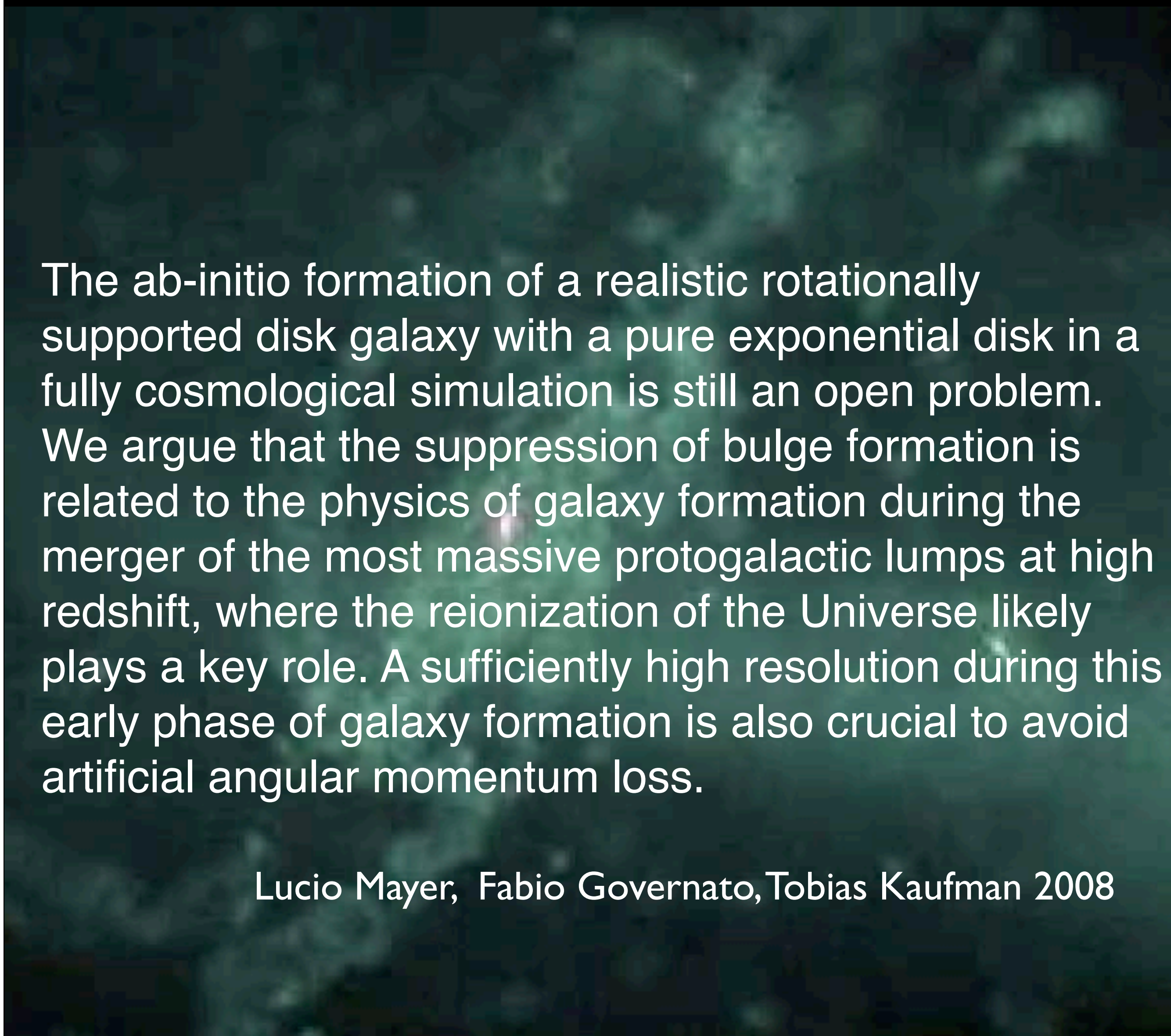
(DM not shown)

Music: Peter Podobry, Ya-Mamma

Courtesy of

Fabio Governato, UW

Improvements in resolution and feedback are leading to formation of more realistic disk galaxies in hydro simulations



The ab-initio formation of a realistic rotationally supported disk galaxy with a pure exponential disk in a fully cosmological simulation is still an open problem. We argue that the suppression of bulge formation is related to the physics of galaxy formation during the merger of the most massive protogalactic lumps at high redshift, where the reionization of the Universe likely plays a key role. A sufficiently high resolution during this early phase of galaxy formation is also crucial to avoid artificial angular momentum loss.

Lucio Mayer, Fabio Governato, Tobias Kaufman 2008

The formation of a Milky Way size disk galaxy

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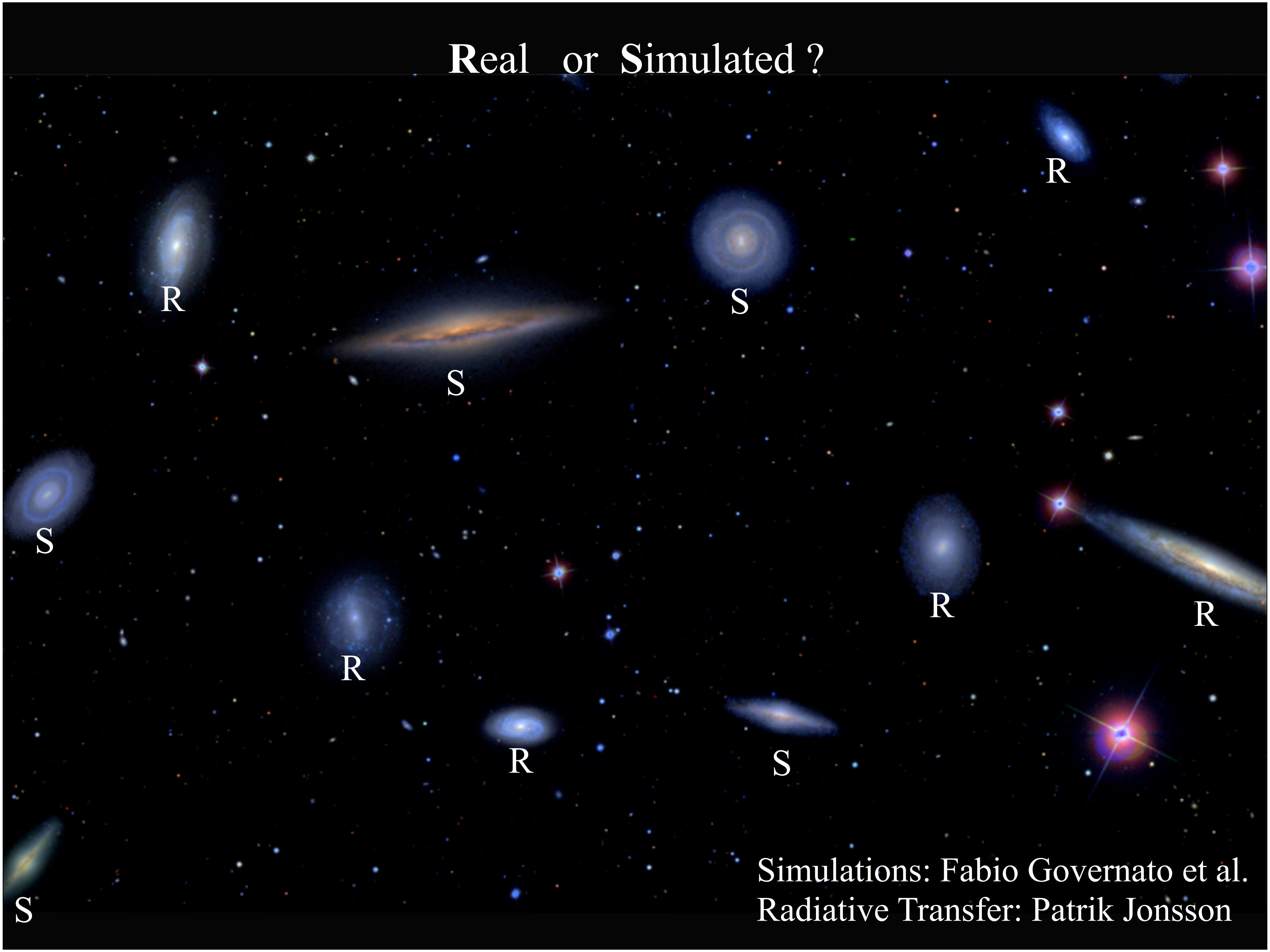
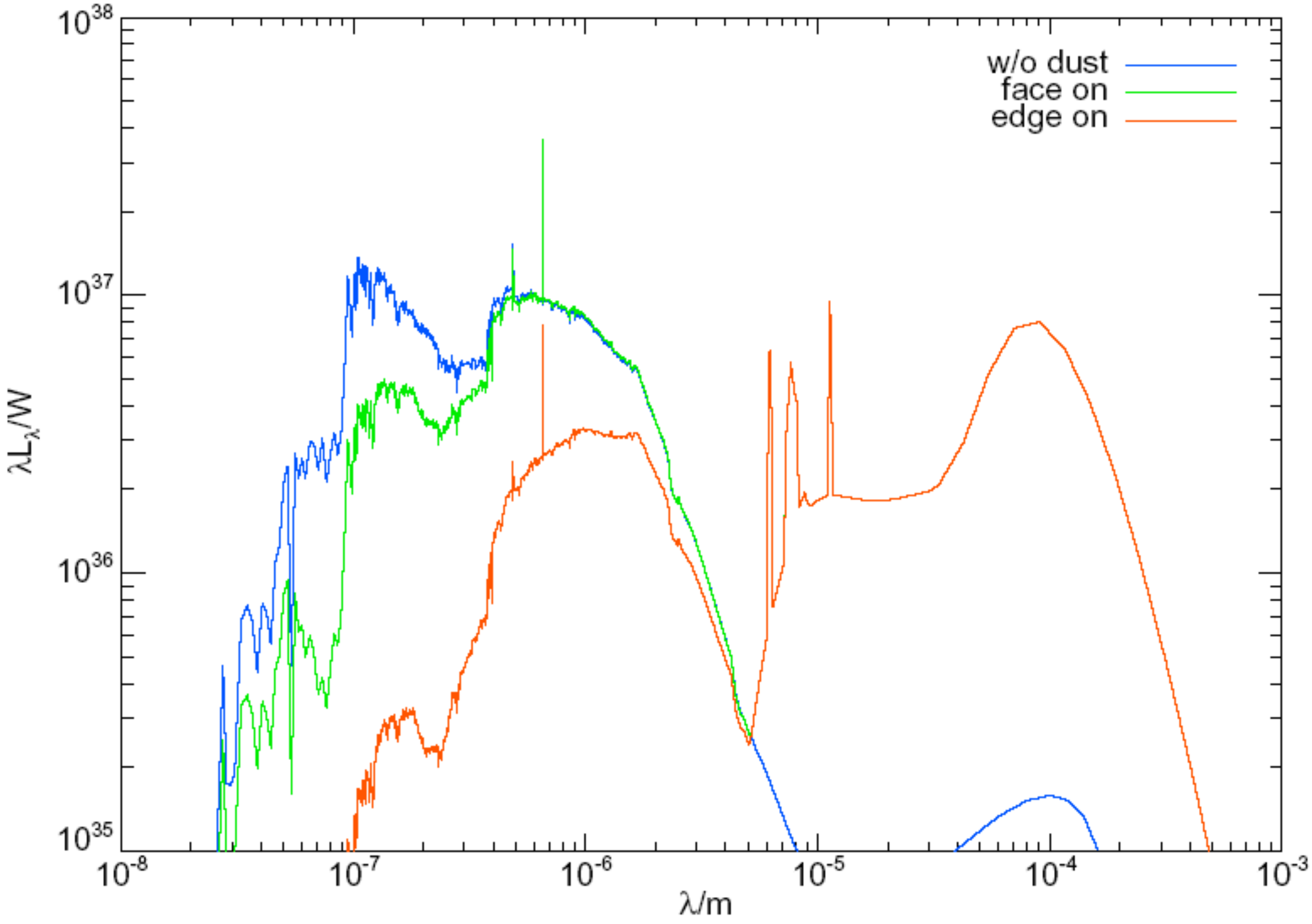
(DM not shown)


Real or Simulated ?
R
S
S
R
S
R
R
R
R
S
S
Simulations: Fabio Governato et al.
Radiative Transfer: Patrik Jonsson

Sunrise Code for Radiative Transfer through Dust

- Dust in galaxies is important
  - Absorbs about 40% of the local bolometric luminosity
  - Makes brightness of spirals inclination-dependent
  - Completely hides the most spectacular bursts of star formation
  - Makes high-redshift SF history very uncertain
- Dust in galaxies is complicated
  - The mixed geometry of stars and dust makes dust effects geometry-dependent and nontrivial to deduce
  - Needs full radiative transfer model to calculate realistically
- Previous efforts have used 2 strategies
  - Assume a simple, schematic geometry like exponential disks, or
  - Simulate star-forming regions in some detail, assuming the galaxy is made up of such independent regions
- *Sunrise* approach - Patrik Jonsson
  - For every simulation snapshot: SED calculation, adaptive grid
  - Monte Carlo radiative transfer
  - "Polychromatic" approach saves factor of ~100 in CPU time

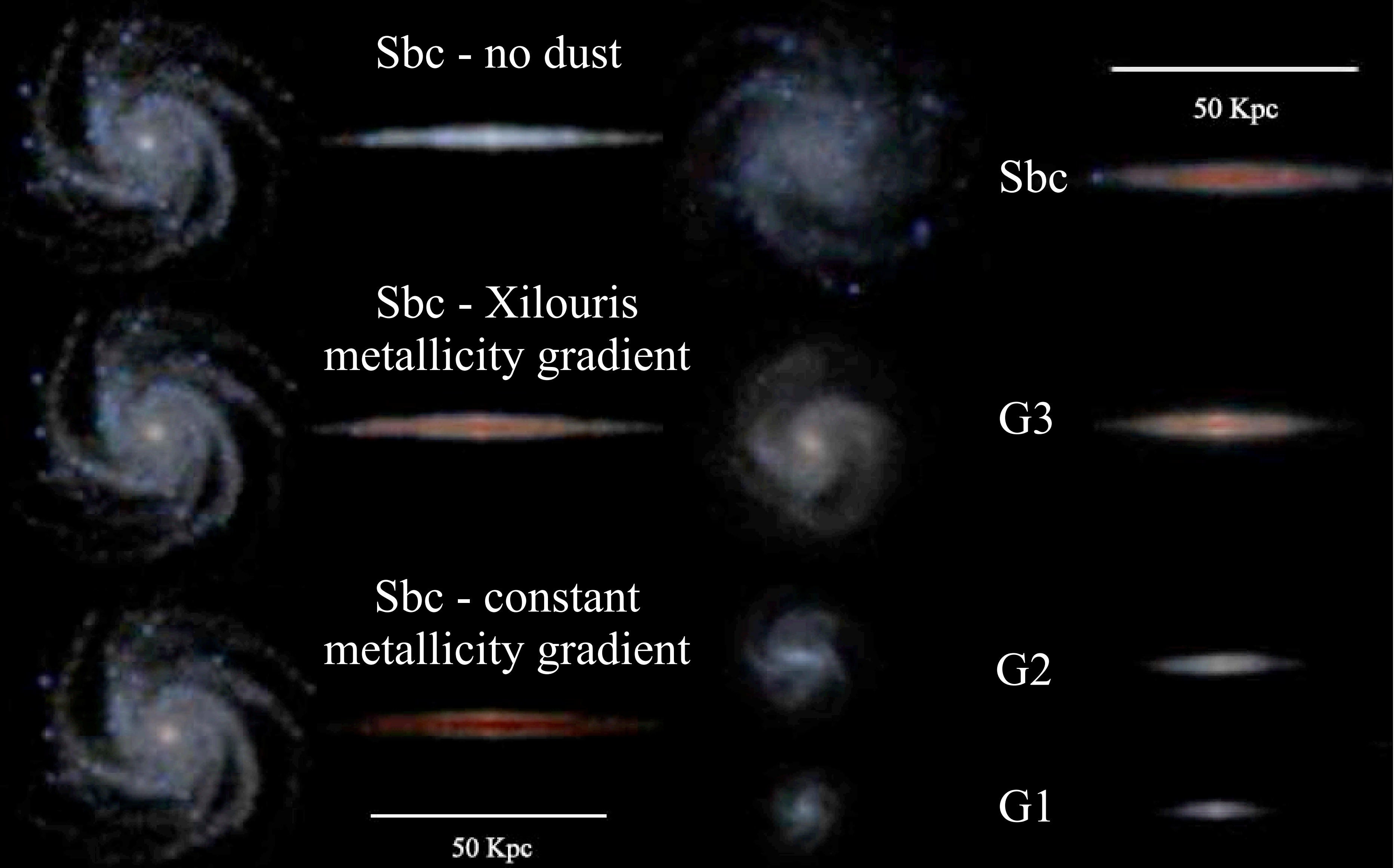
Spectral Energy Distribution

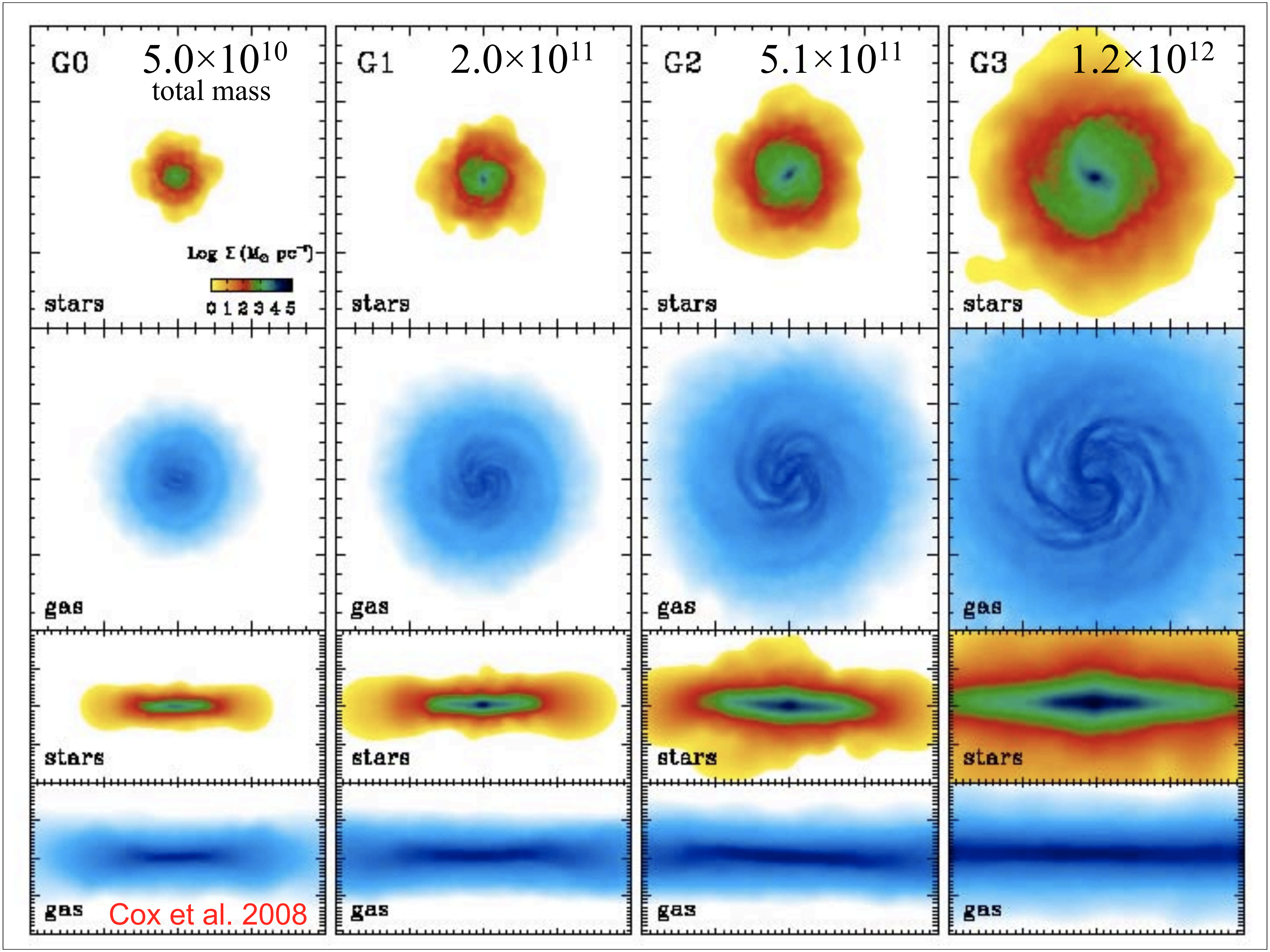


Dust Attenuation in Hydrodynamic Simulations of Spiral Galaxies

Rocha, Jonsson, Primack, & Cox 2008 MN

Right hand side:
Xilouris et al. 1999
metallicity gradient





G0
5.0×10^10
total mass
G1
2.0×10^11
G2
5.1×10^11
G3
1.2×10^12
Log Σ (M☉ pc⁻²)
0 1 2 3 4 5
stars
gas
stars
gas
Cox et al. 2008

Stellar mass is mostly in galactic spheroids

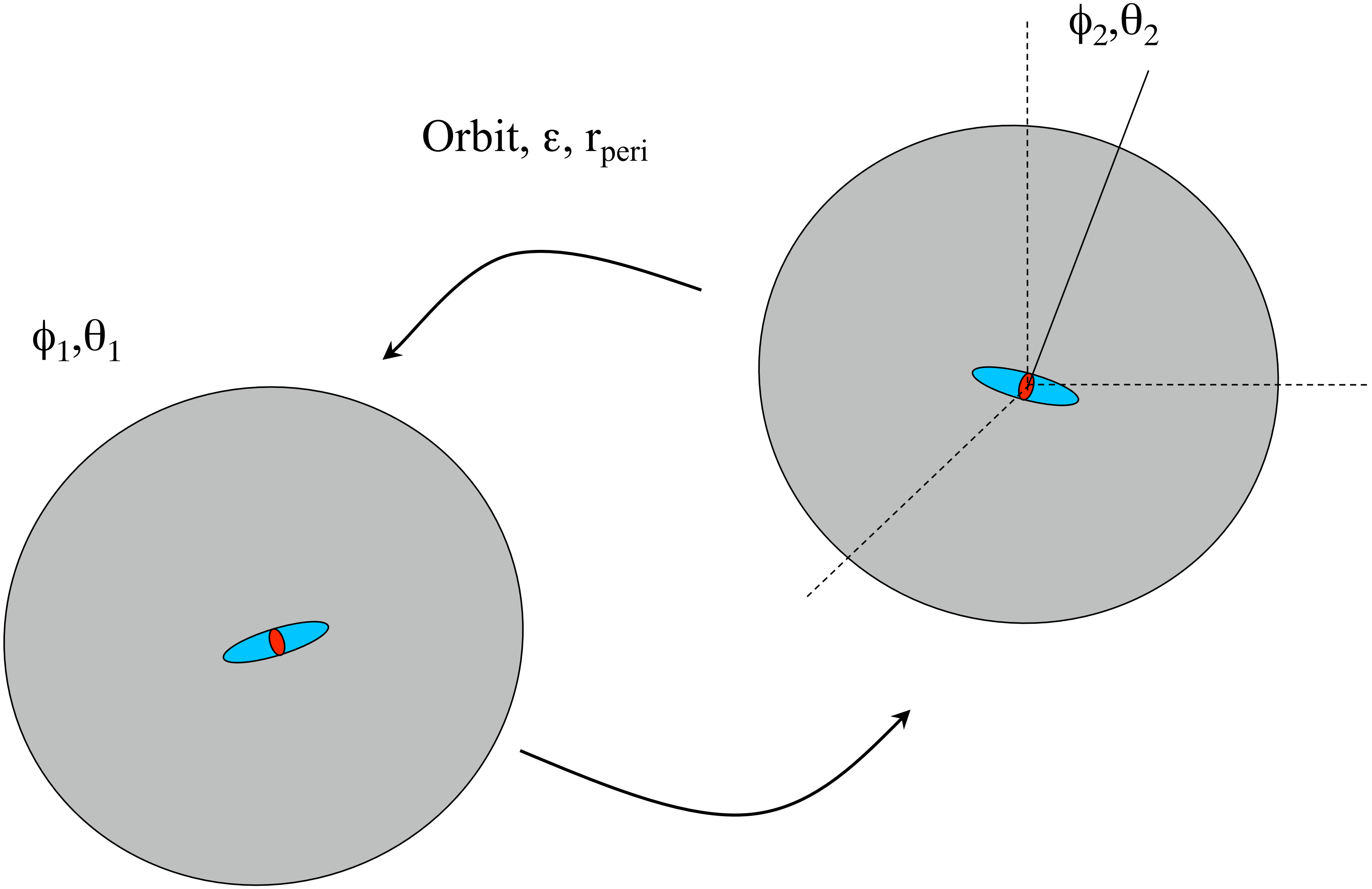
spheroid:disk = 0.74:0.26 Fukugita & Peebles 2004

Stellar galaxy mergers make spheroids

Disk galaxy mergers make both
rotating elliptical spheroids and disks

Multiple galaxy mergers, common at high z,
can make round, slowly rotating spheroids
and also gaseous disks

So Let's Merge Two Disks

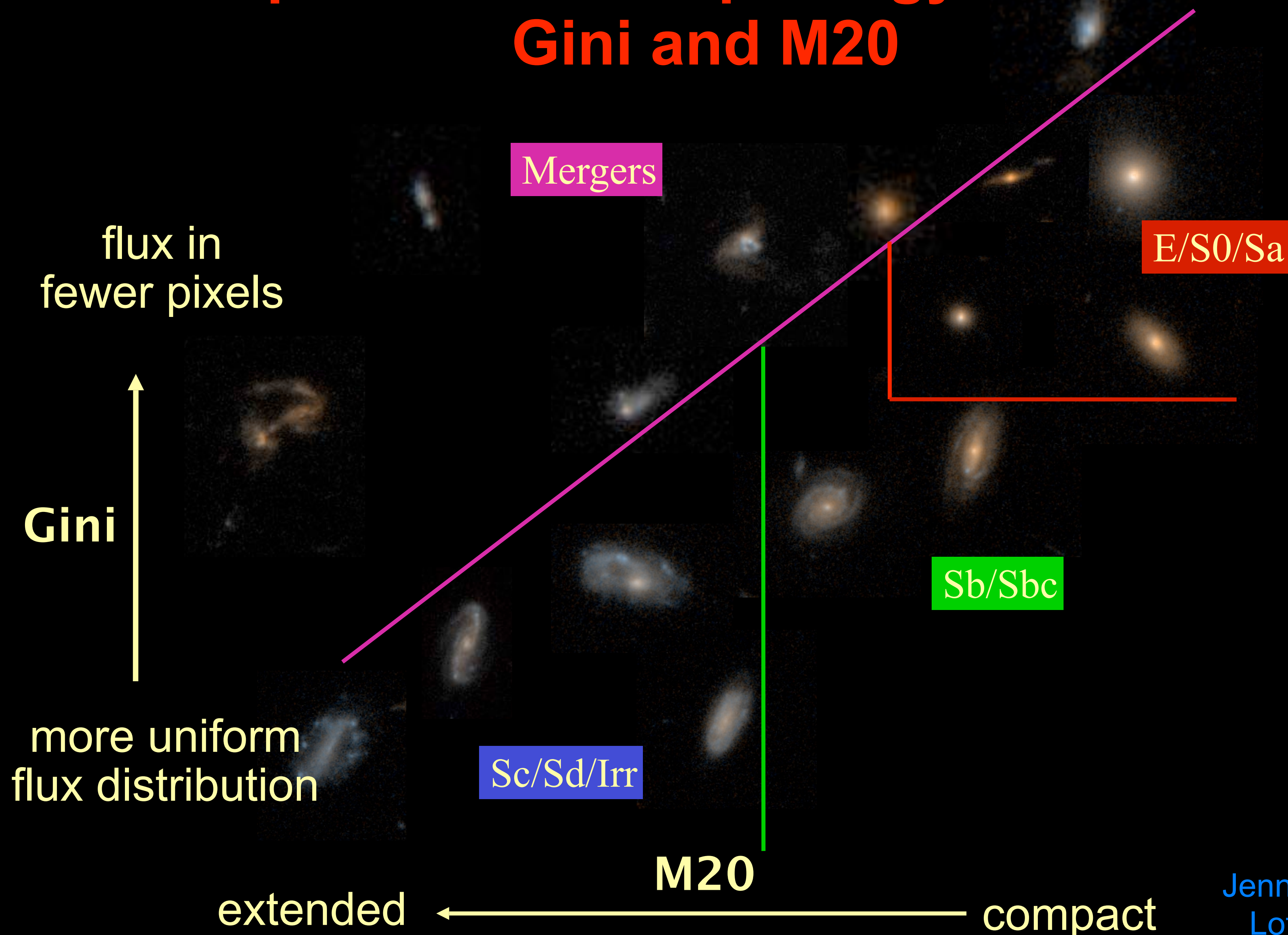


Galaxy Merger Simulation

Patrik Jonsson, Greg Novak, Joel Primack

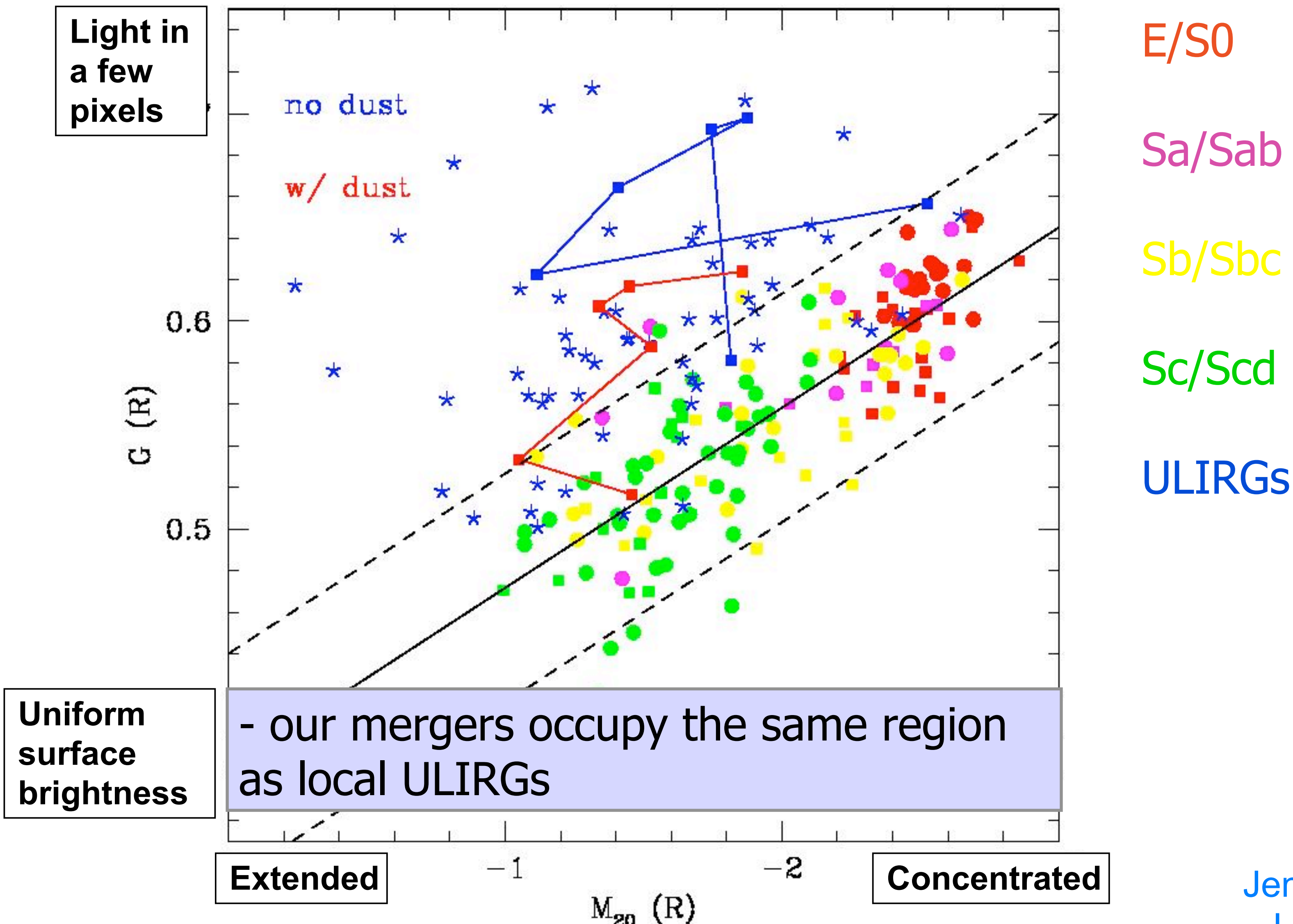
music by Nancy Abrams

Nonparametric Morphology Measures
Gini and M20



Jennifer Lotz

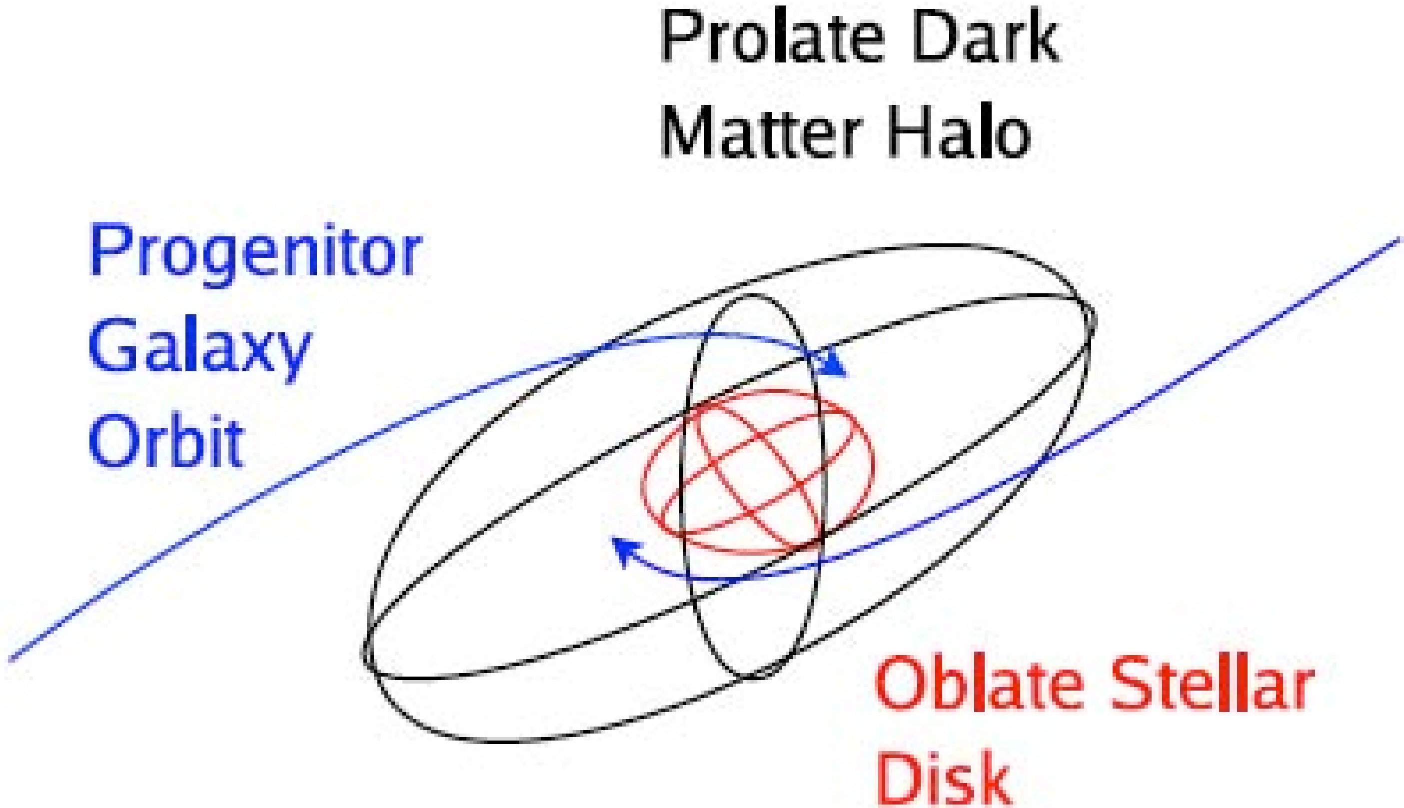
Modeling Merger Morphologies



- our mergers occupy the same region as local ULIRGs

Jennifer Lotz

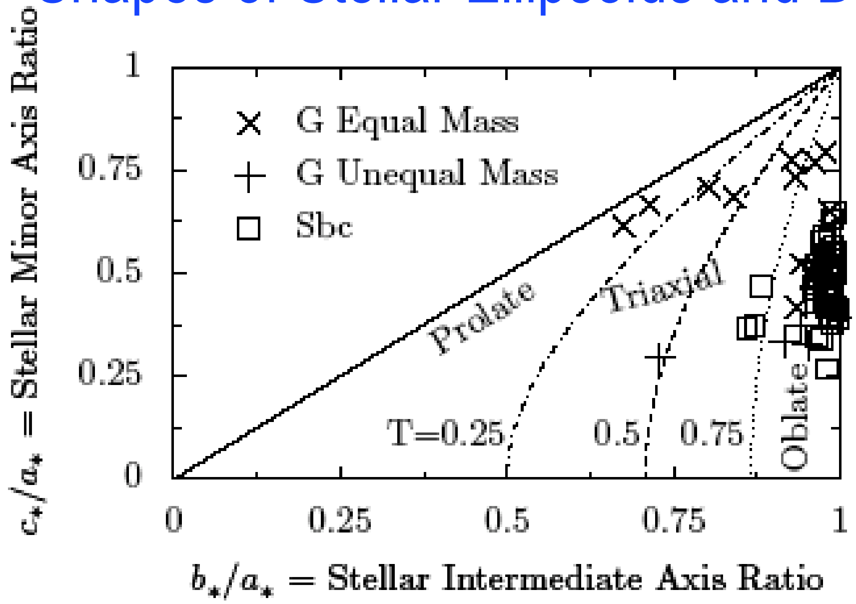
The short (rotation) axis of the visible elliptical galaxy is perpendicular to the long axis of its dark matter halo. Why? The long axis of the halo is along the merger axis, while the angular momentum axis is perpendicular to that axis.

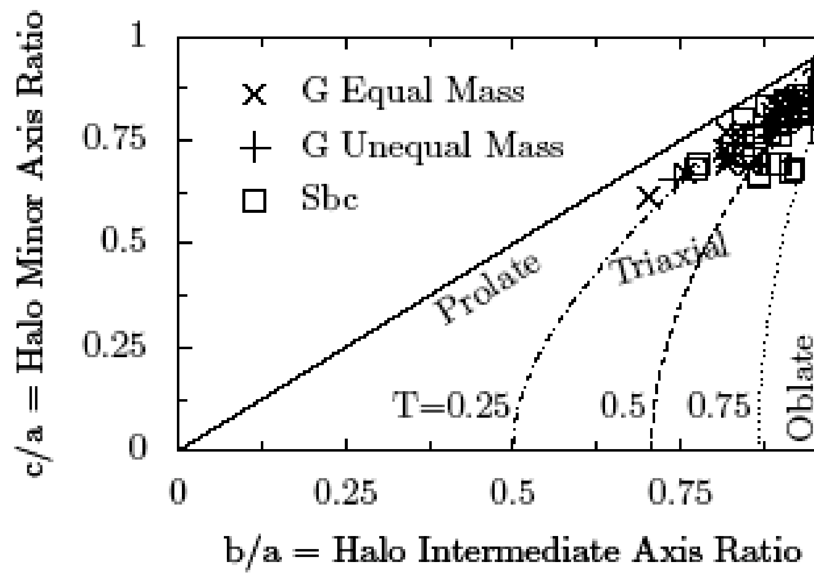


Novak, Cox, Primack, Jonsson, & Dekel, ApJ Letters 2006

We include detailed predictions testable via weak lensing

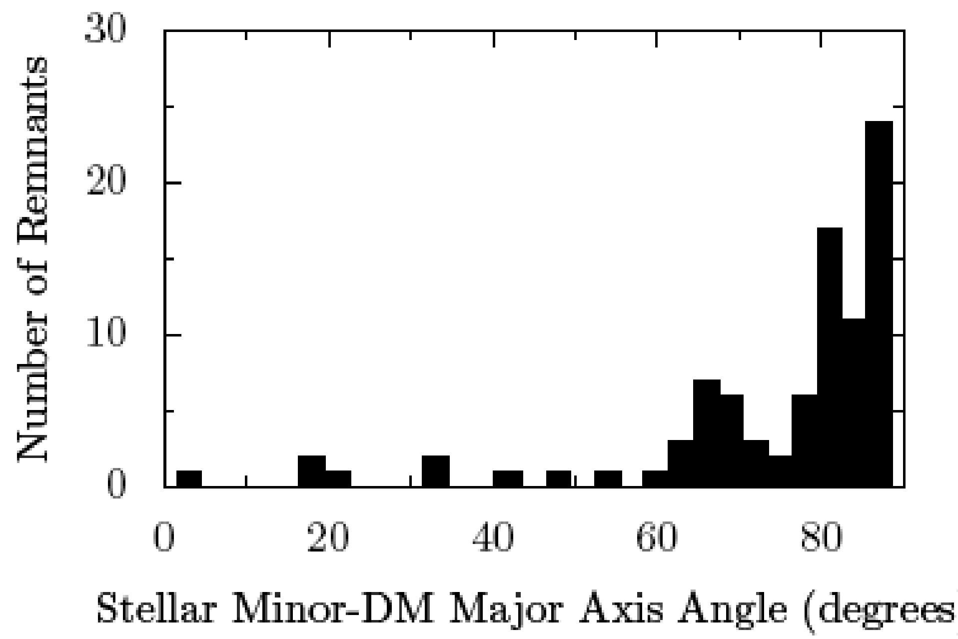
Shapes of Stellar Ellipsoids and Dark Halos of Major Merger Remnants





The stellar ellipsoids are mostly oblate but the dark matter halo is usually triaxial or prolate.

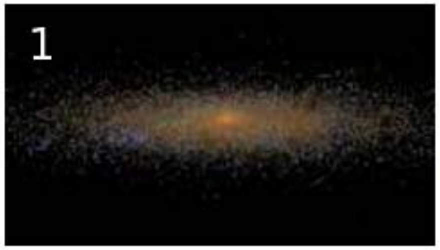
The stellar minor axis usually aligns with the angular momentum axis, which aligns with the dark matter smallest axis, perpendicular to the dark matter major axis.

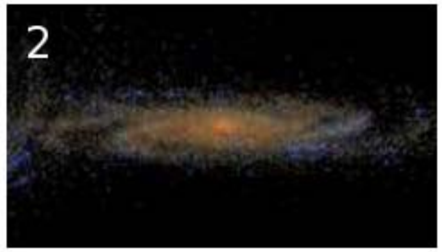


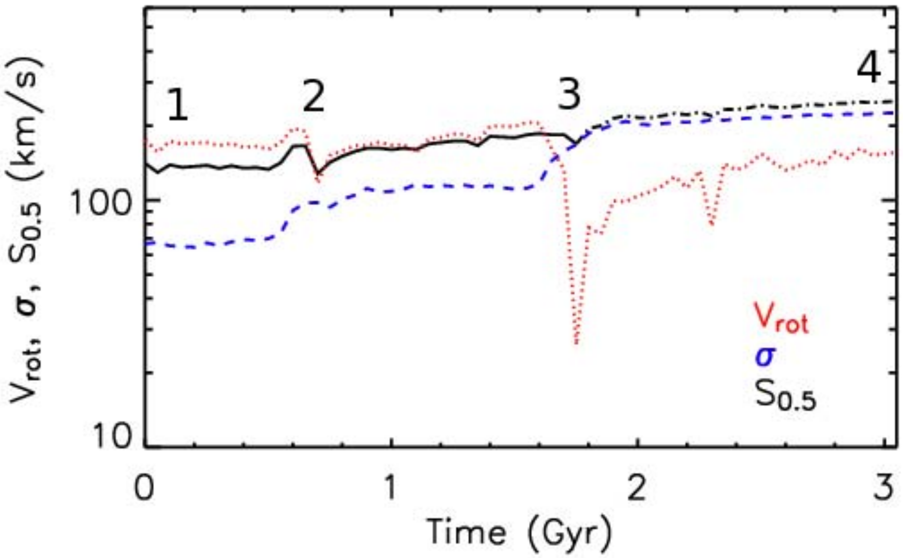
Novak, Cox, Primack, Jonsson, & Dekel, ApJ Letters 2006

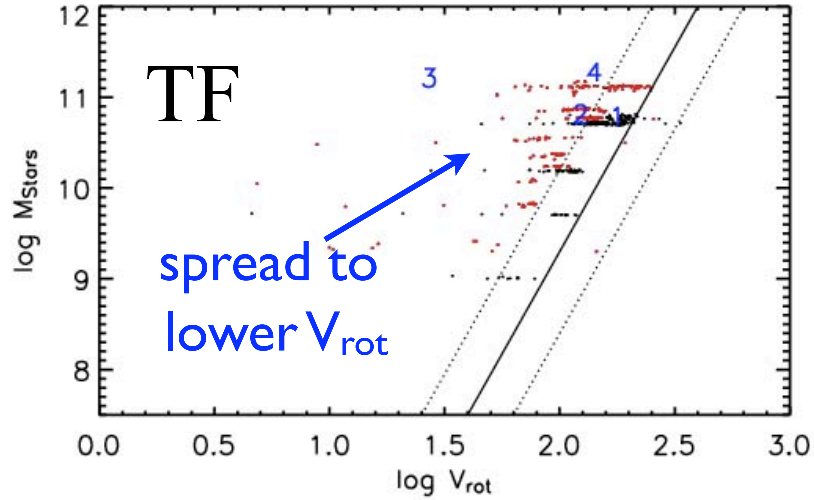
Stellar Mass Tully-Fisher Relation Evolution in Disk Galaxy Merger Simulations Reproduces Observed Behavior

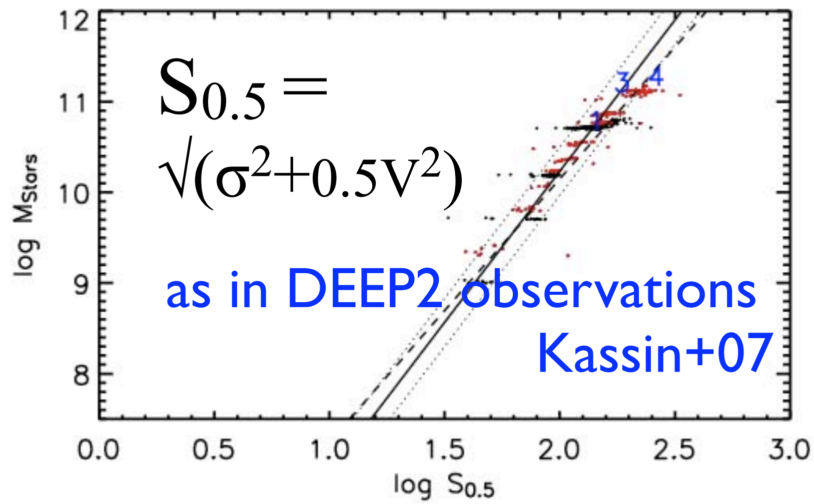
Matthew D. Covington, Susan A. Kassin, Aaron A. Dutton, Benjamin J. Weiner, T. J. Cox, Patrik Jonsson, Joel R. Primack, Sandra M. Faber, & David C. Koo in prep.











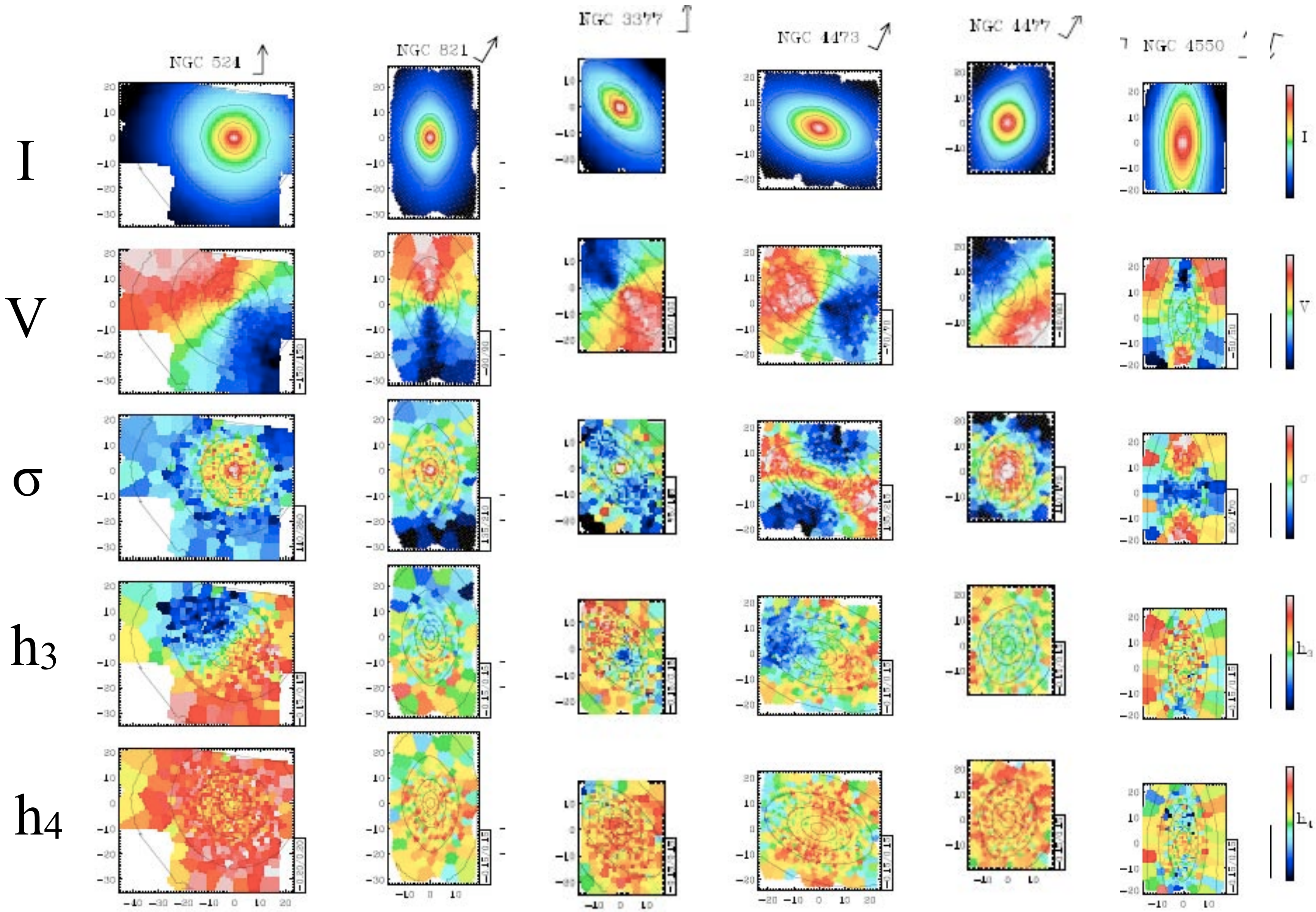
Remnant elliptical galaxies from binary gas-rich disk galaxy mergers

- Gas-rich binary major merger remnants look like SAURON fast rotators
- Easily understood in terms of orbital angular momentum; predictions for weak lensing
- Very few good candidates for slow rotators

Novak+08 in prep

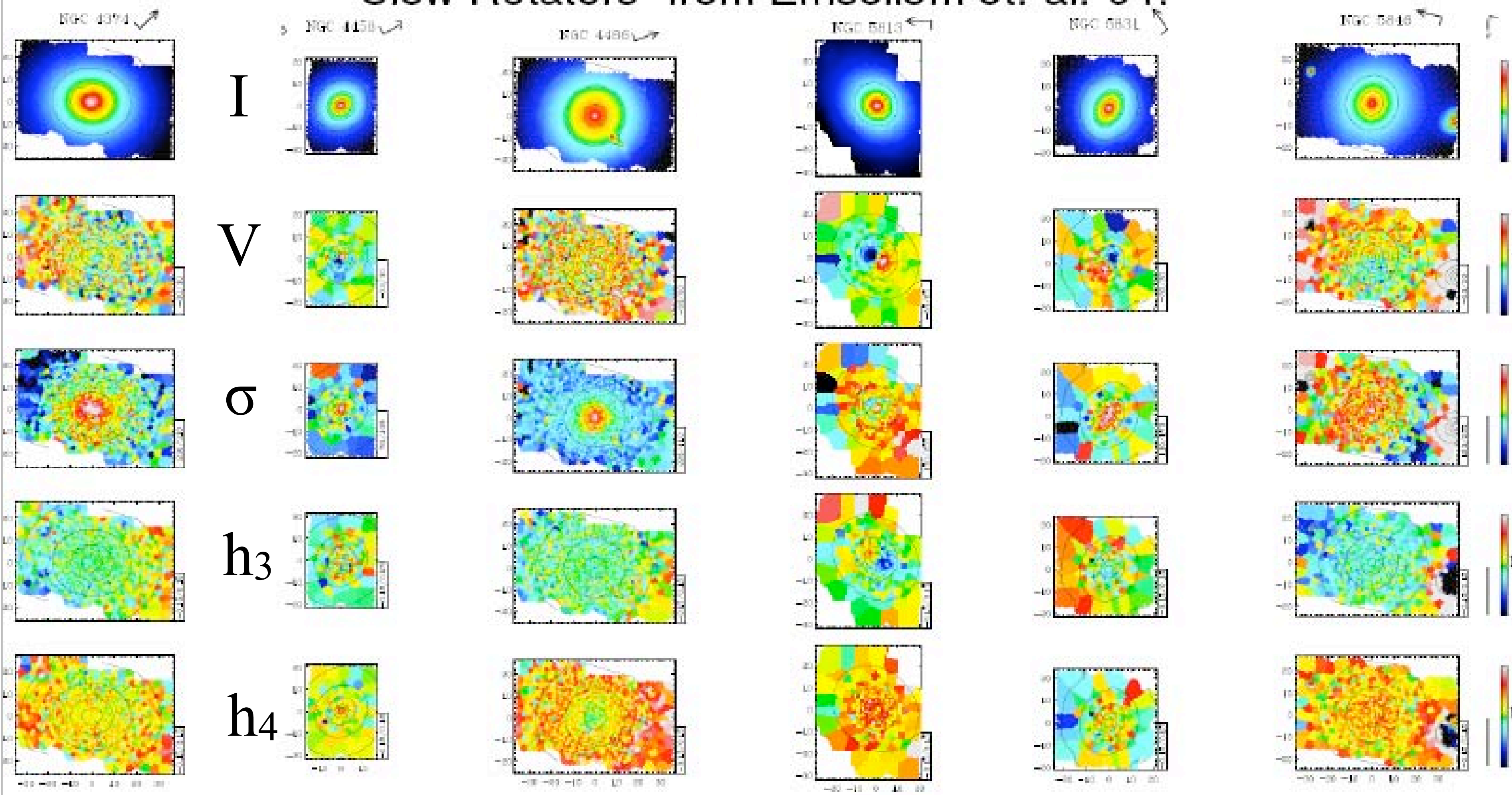
SAURON Data

"Fast Rotators" from Emsellem et al. 2003



SAURON Data

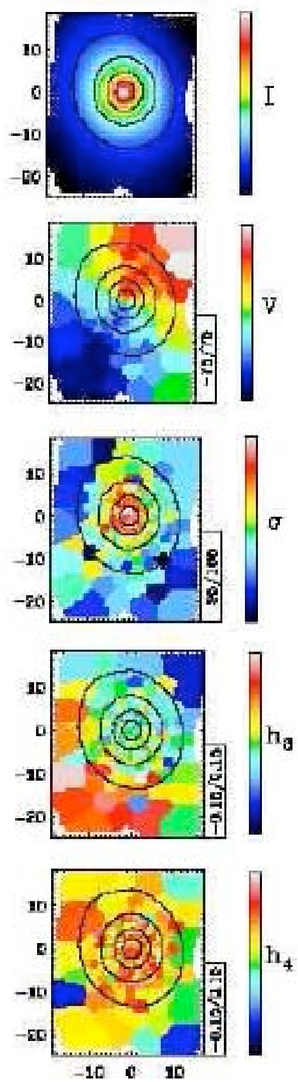
"Slow Rotators" from Emsellem et. al. 04.



SAURON
Fast Rotator
NGC 474

Comparison with SAURON data in progress by Greg Novak working with Cox, Jonsson, Faber, and Primack

Different Views of a G3G3 merger, plotted like SAURON data.



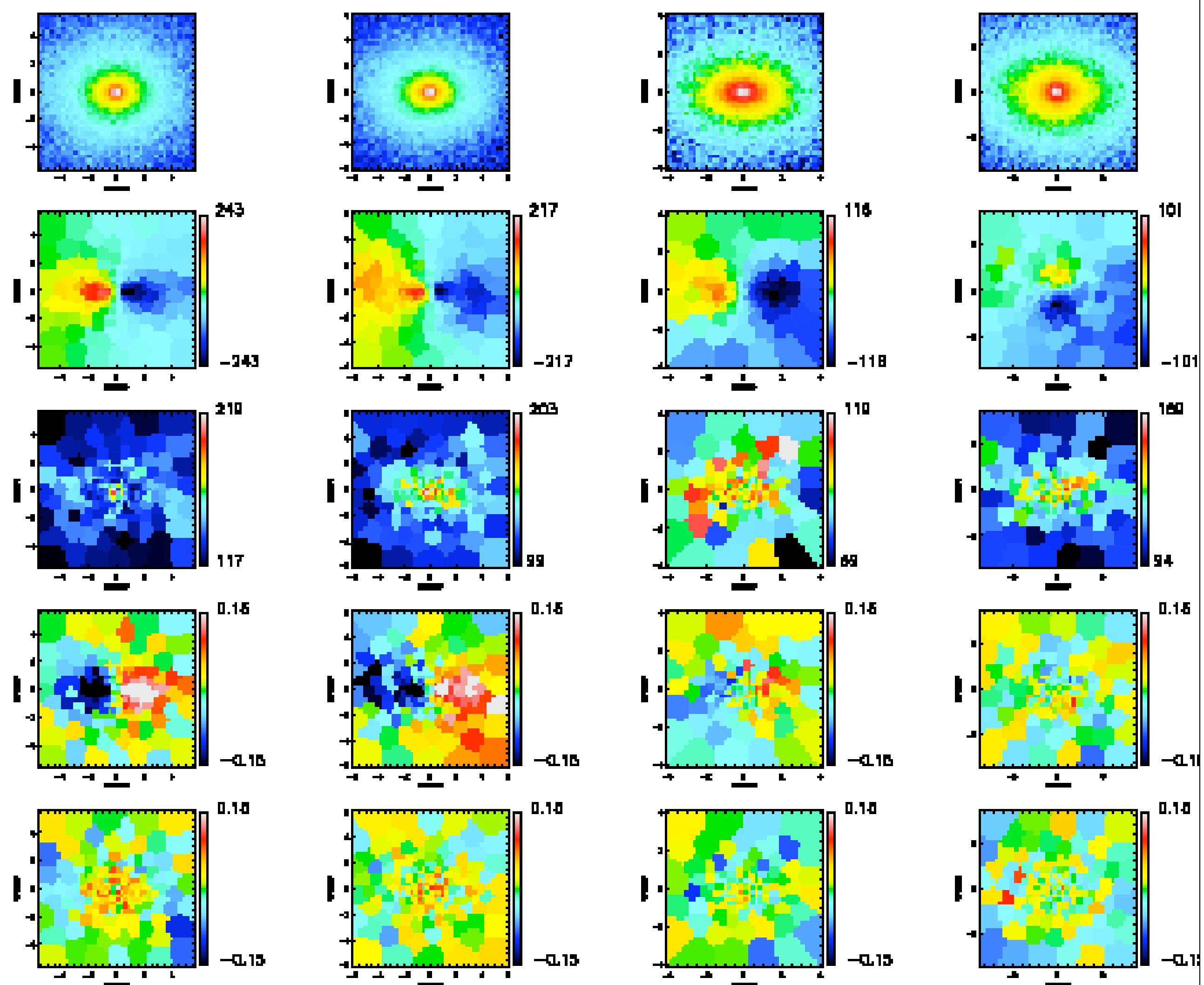
I

V

σ

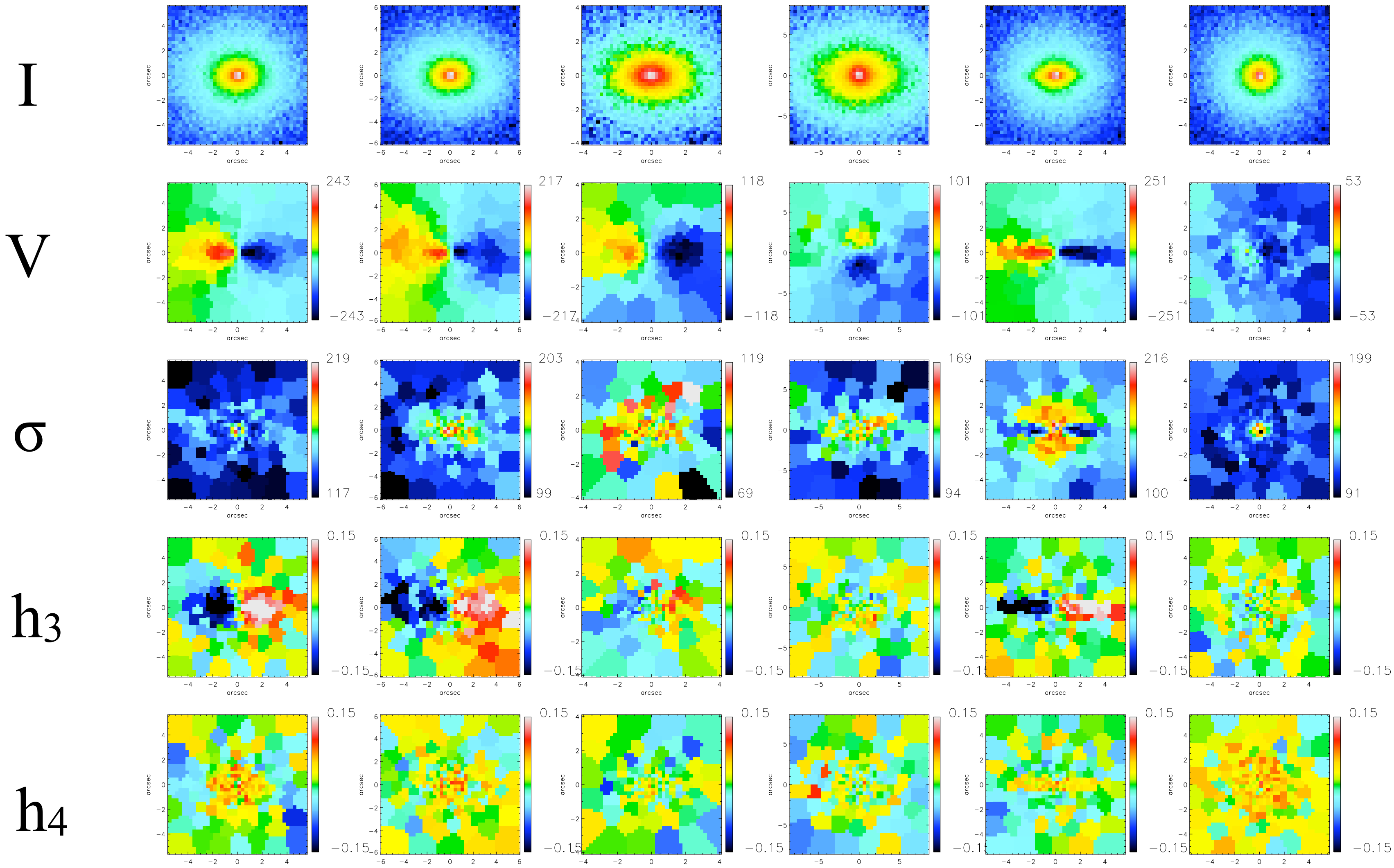
h_3

h_4



Our detailed comparison uses “kinemetry” (Krajnovic et al. 2006)

Binary Merger Simulations Produce Fast Rotators



Novak+08 in prep

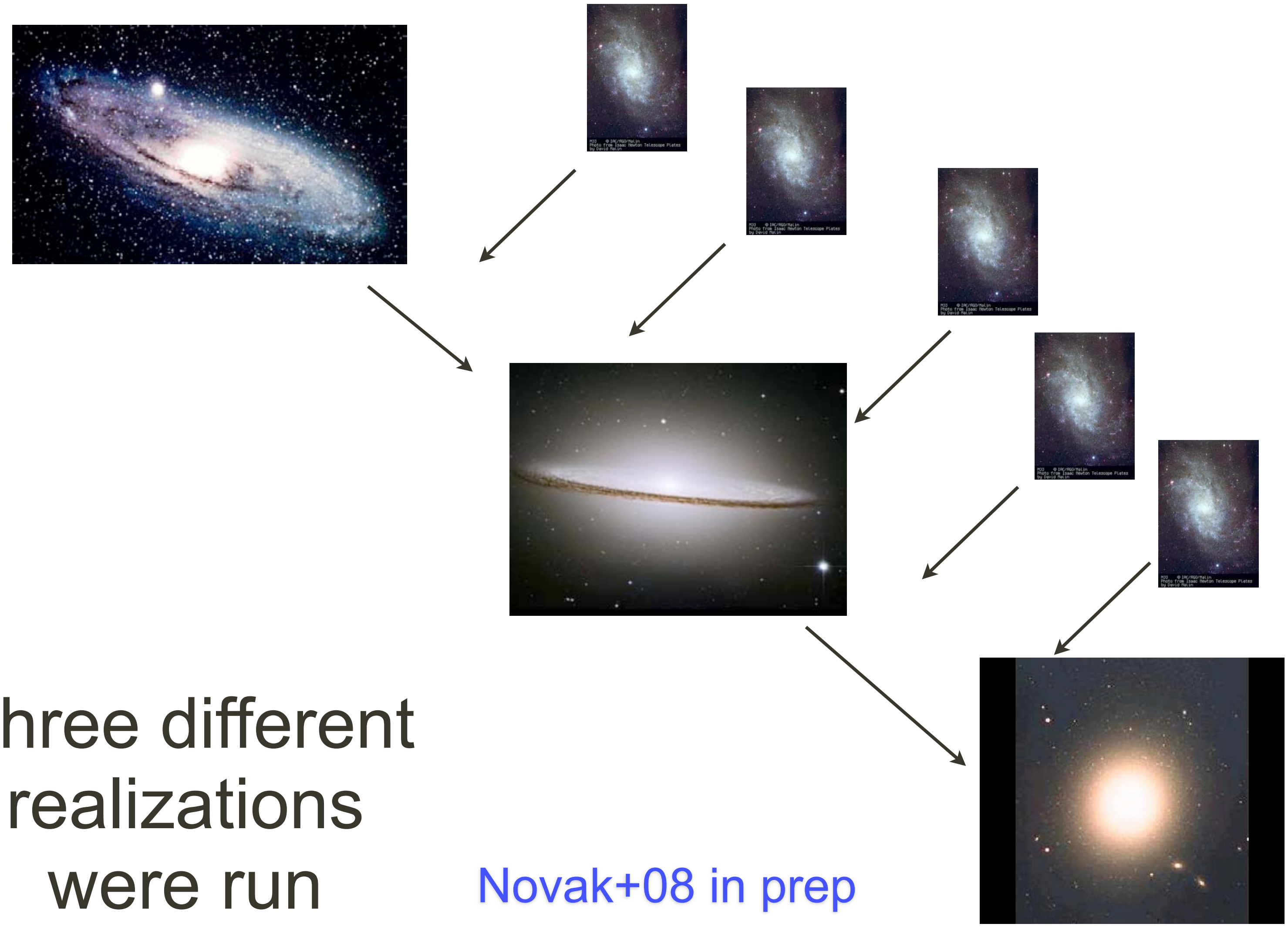
This movitated a study of multiple mergers, which are very likely at $z \gtrsim 2$, when the merger time ~ Hubble time

Both (1) simplified simulations with just galaxies and no gas environment,

(2) resimulations of groups selected at $z \gtrsim 2$ from a cosmological hydro simulation

(both, using GADGET) Novak+08 in prep

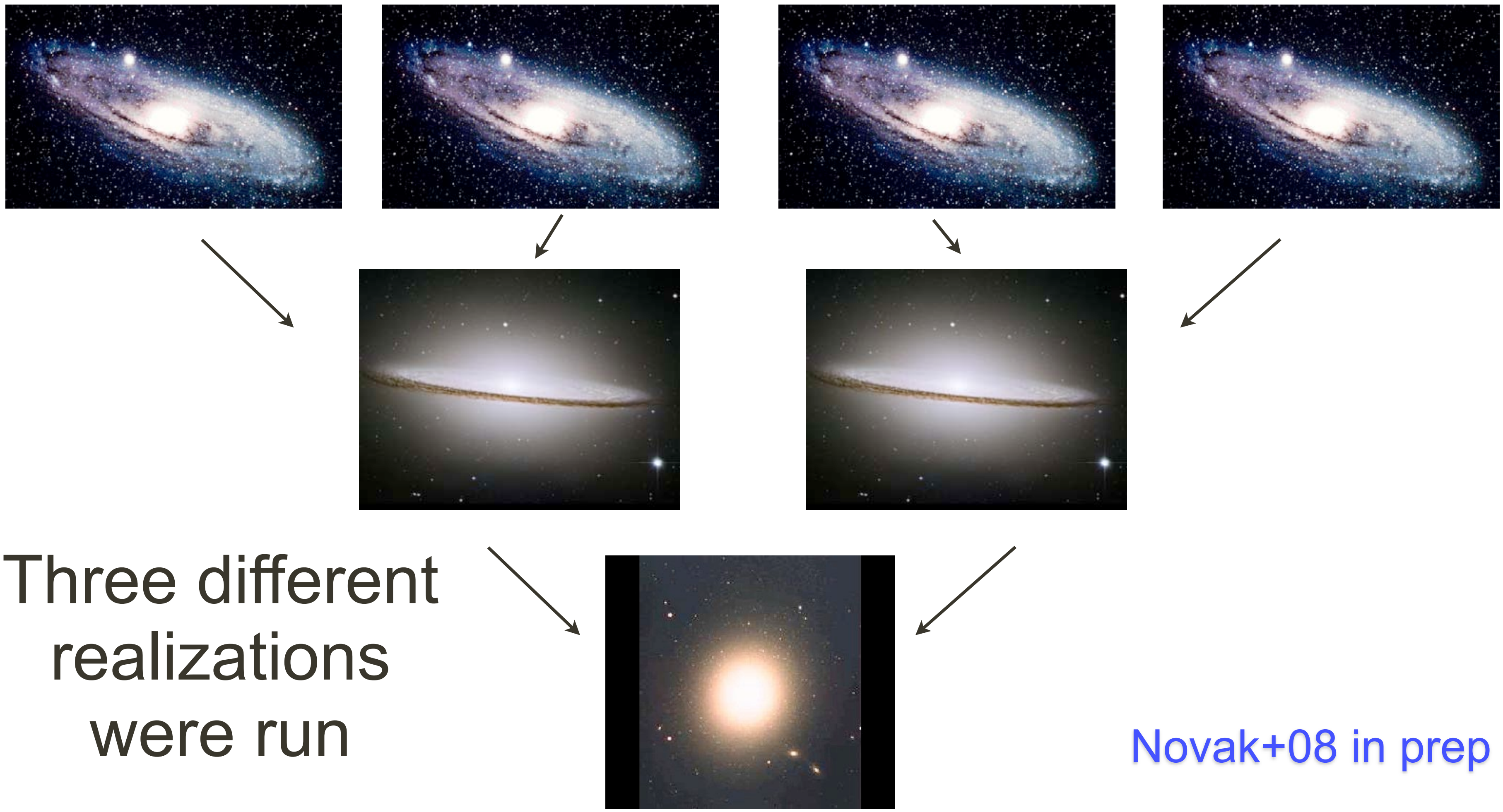
Multi-Minor Mergers



Three different realizations were run

Novak+08 in prep

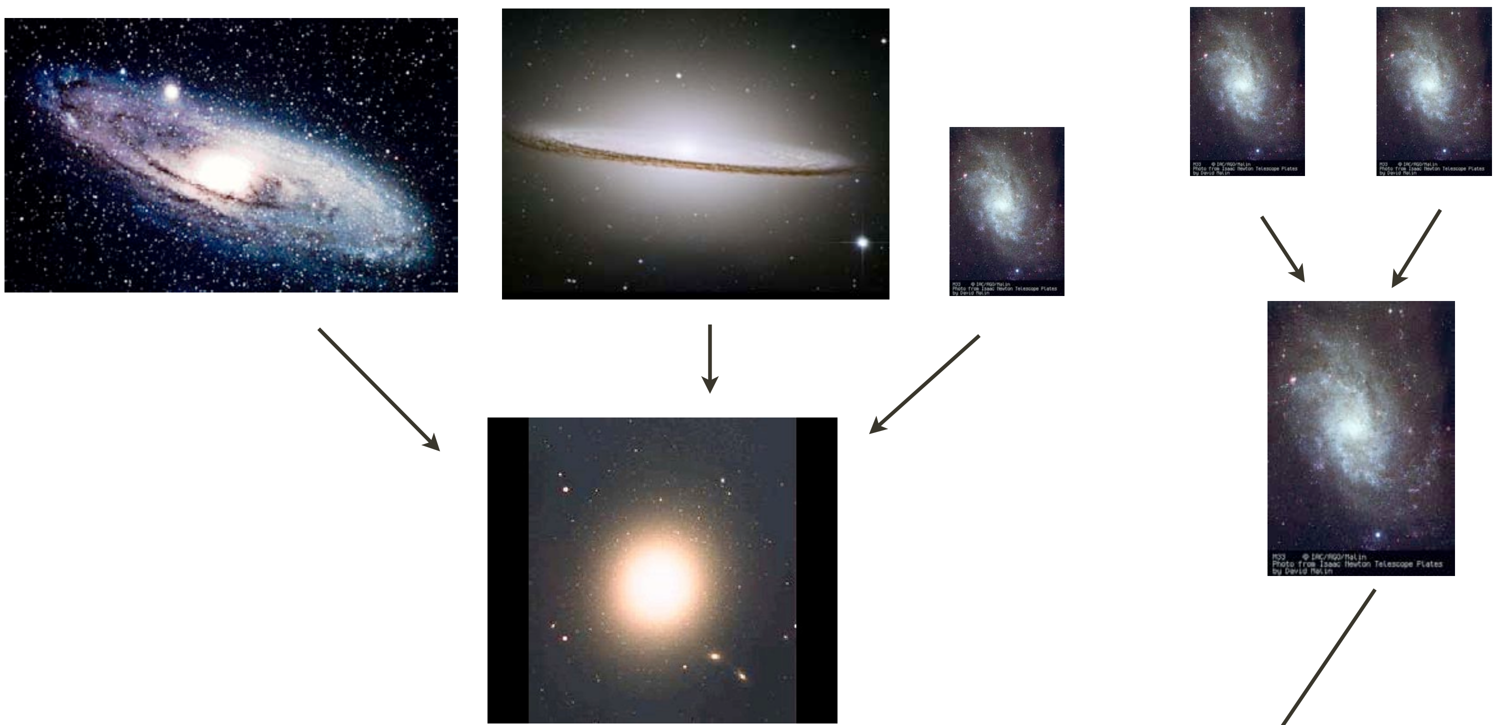
Multi-Major Mergers

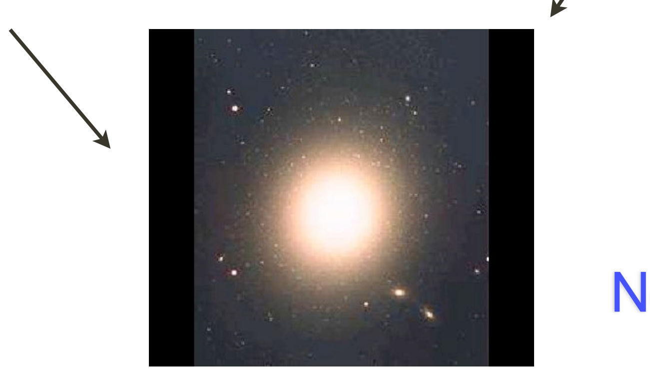


Three different realizations were run

Novak+08 in prep

Cosmological ICs



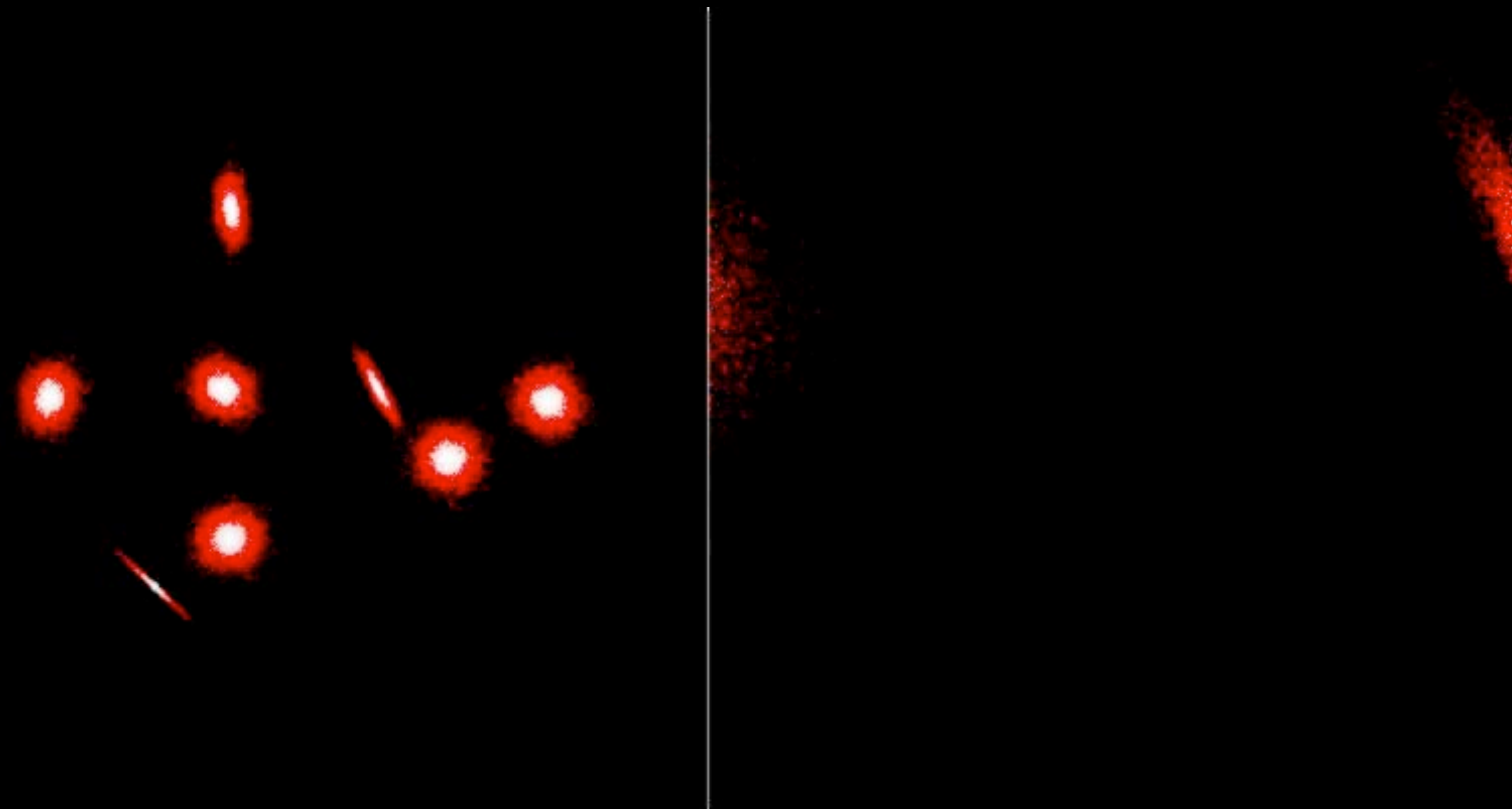


Results now for
six different
regions, more
in progress...

Novak+08 in prep

Multi-Minor Mergers

Stars are white Gas is red



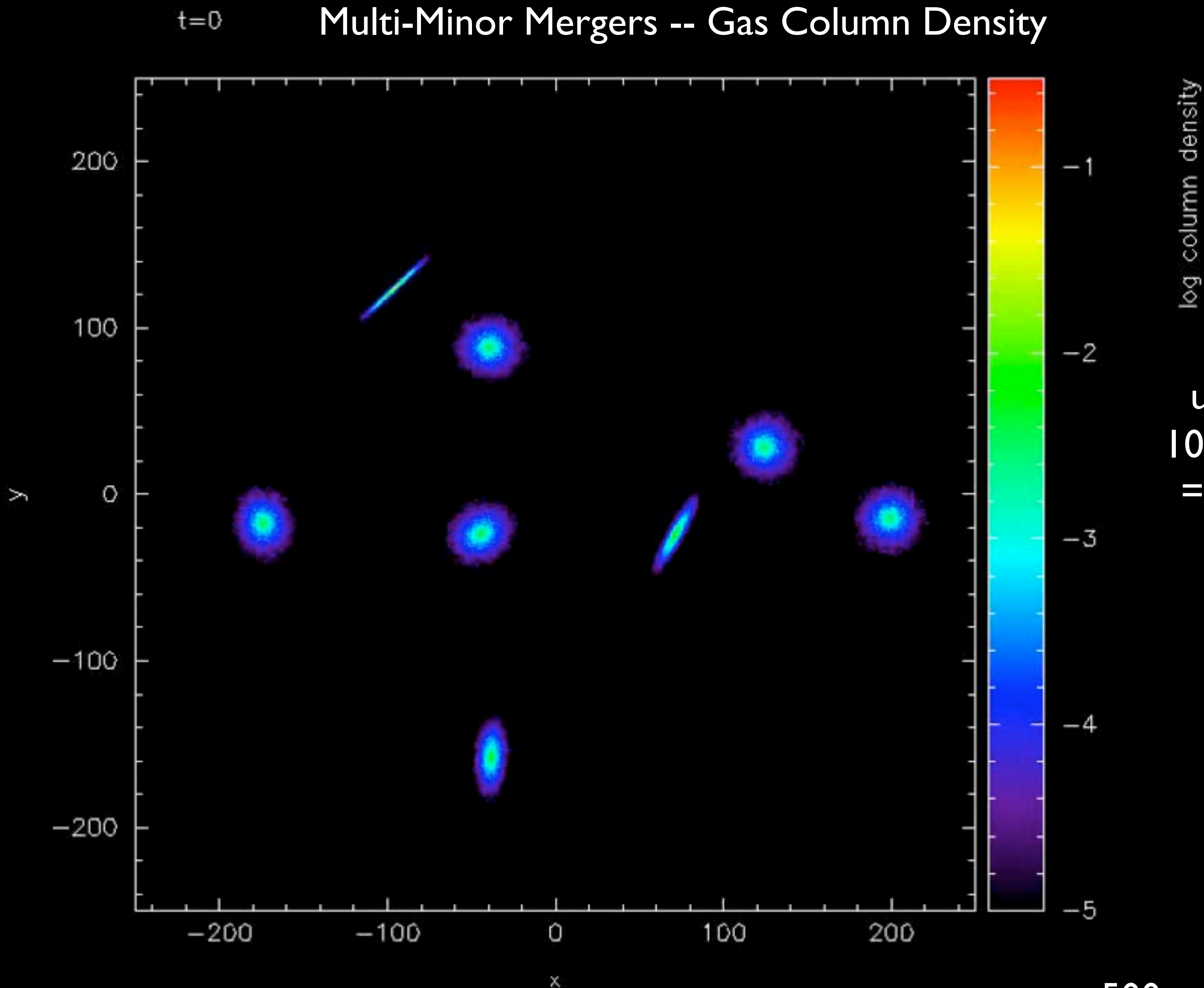
zoomed out

central region

Simulation: Greg Novak

Music: Sheldon Mirowitz, Since You Asked

Multi-Minor Mergers -- Gas Column Density



units are $10^{10}\ M_o/kpc$
$=1.3 \times 10^{24}\ cm^{-2}$

500 x 500 kpc

Cosmological Sims by Greg Novak

- **Start with 80/h Mpc adaptive mesh ART-hydro sim run by Doug Rudd (UChicago, IAS) on Columbia (NASA), with WMAP3 parameters Ω_m=0.24, Ω_Λ=0.76, Ω_b=0.04, σ_8 = 0.75, h=0.73; N_{dm} = 512^3, resolution=1.6 kpc, star formation + feedback**

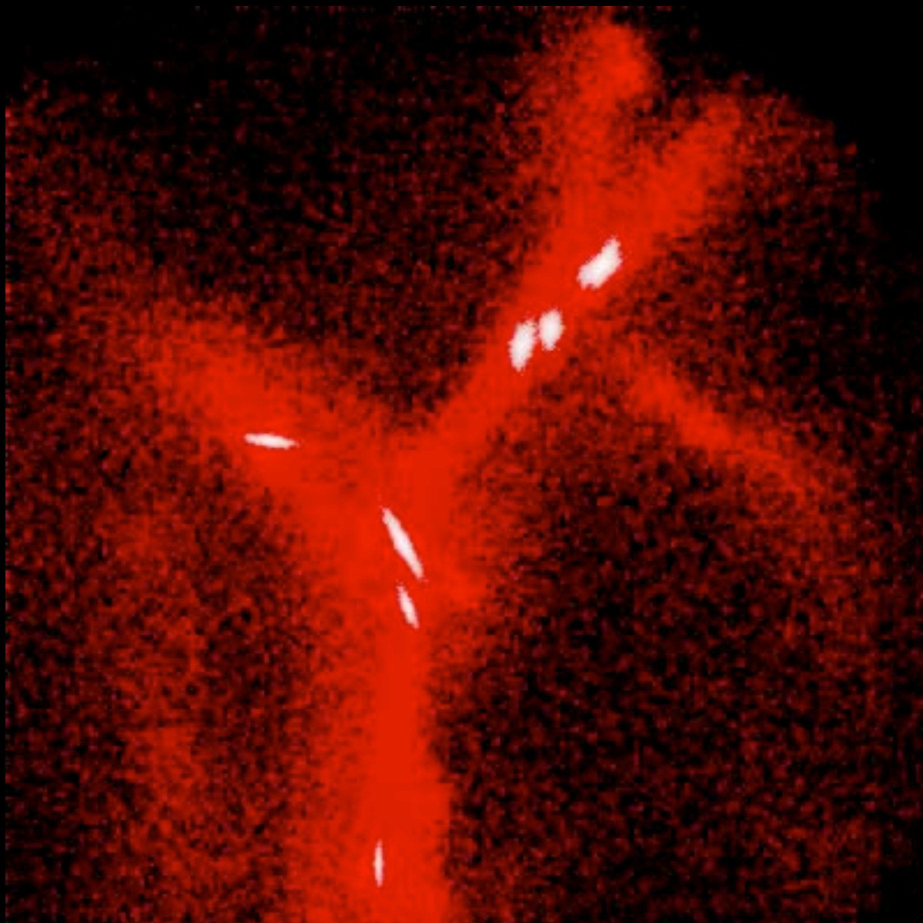
- **Extract "interesting" group halos, replace baryonic lumps with model galaxies, and include 1 proper Mpc high res region + 5 Mpc low res region (1.2 - 2.5 million particles total)**

- **Require ~40 khr on Columbia per simulation; current sims will require ~600 khr**

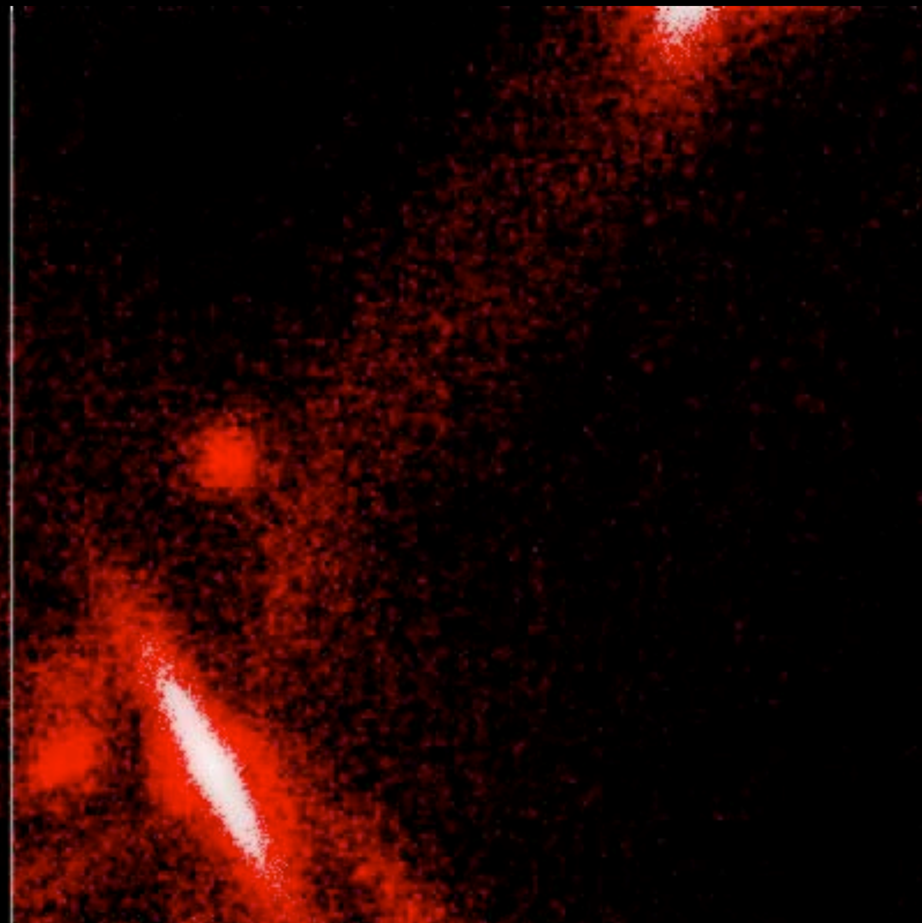
Cosmological Multi-Merger

cos7

Stars are white Gas is red



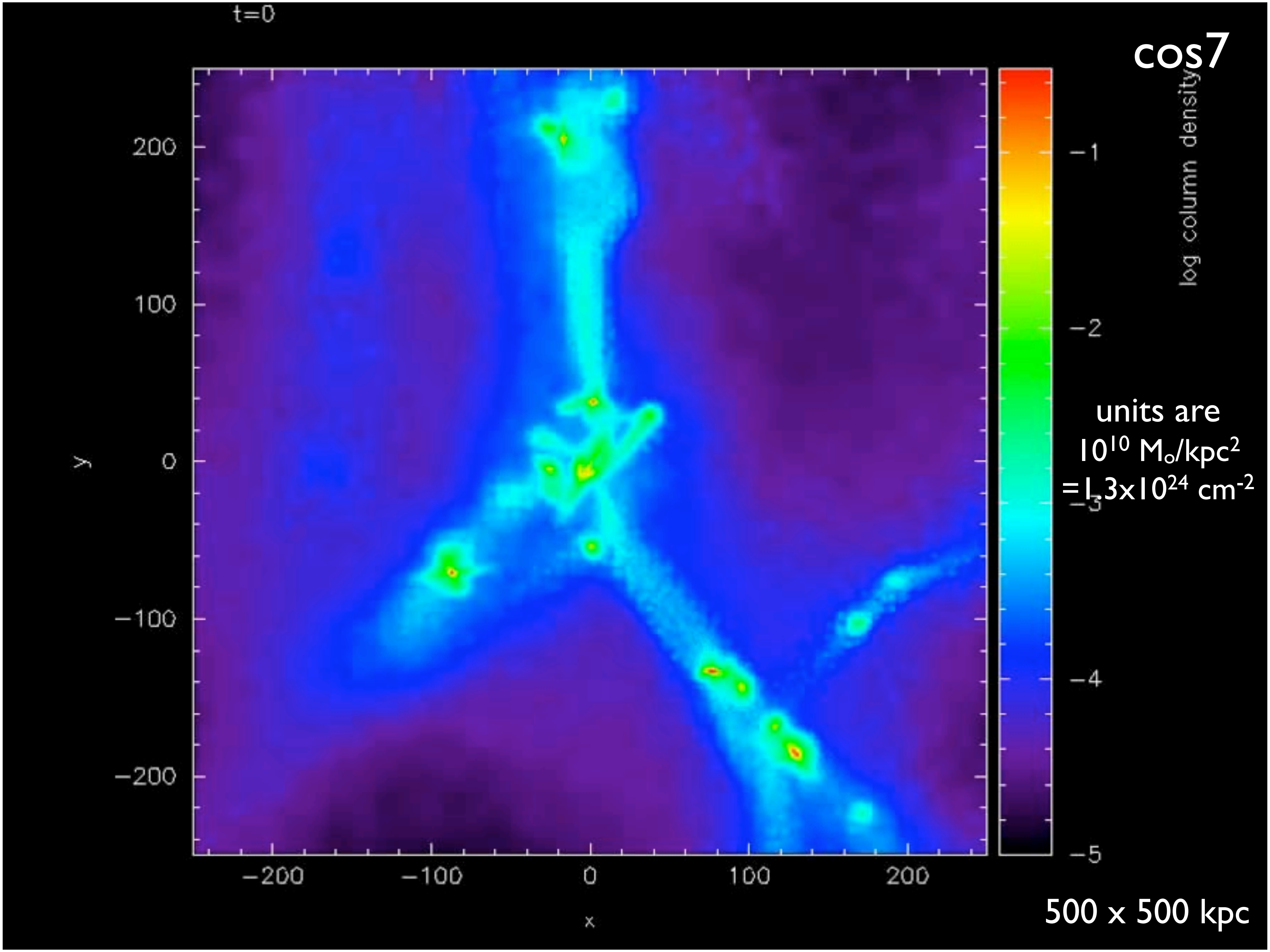
zoomed out

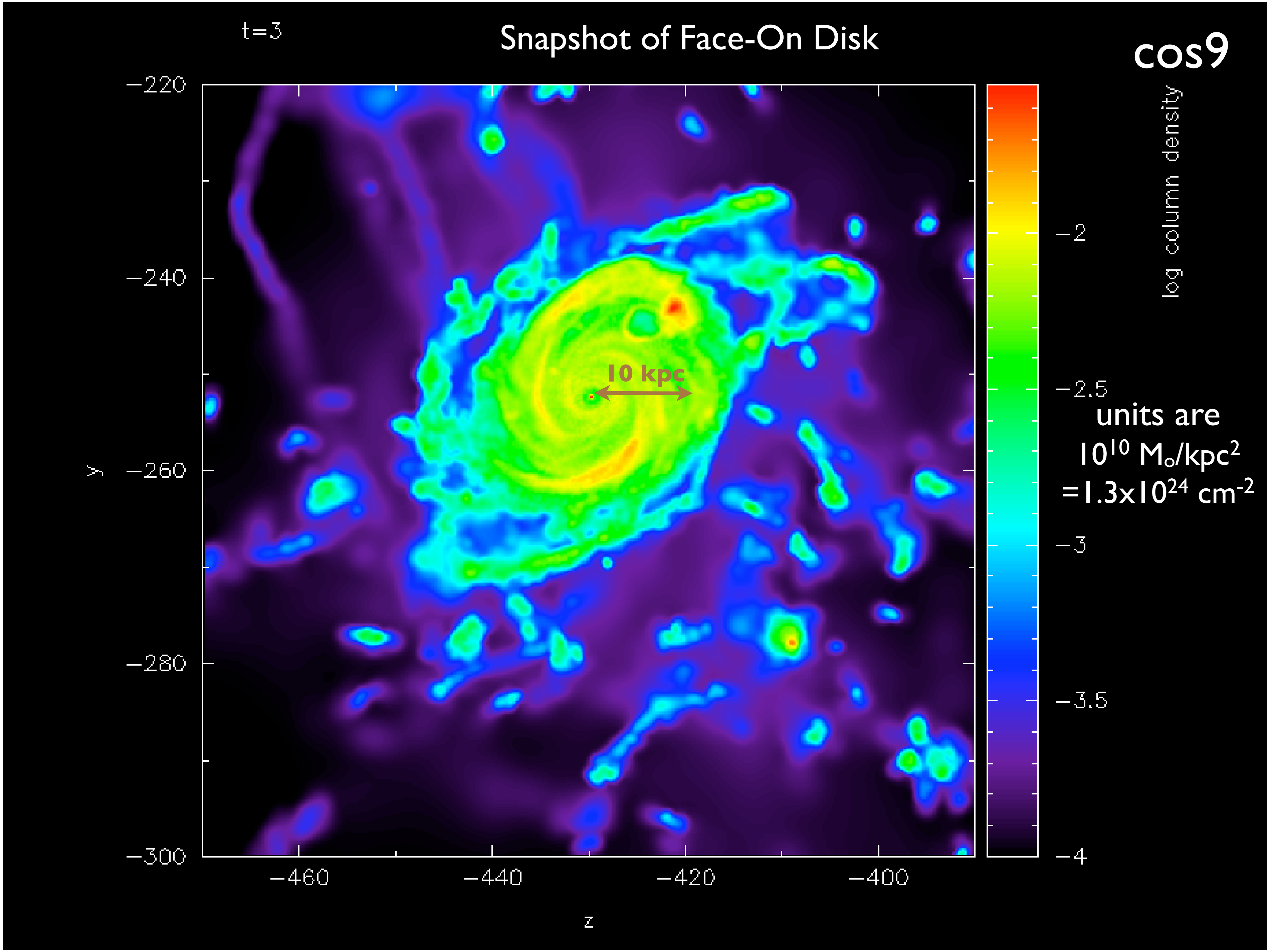


central region

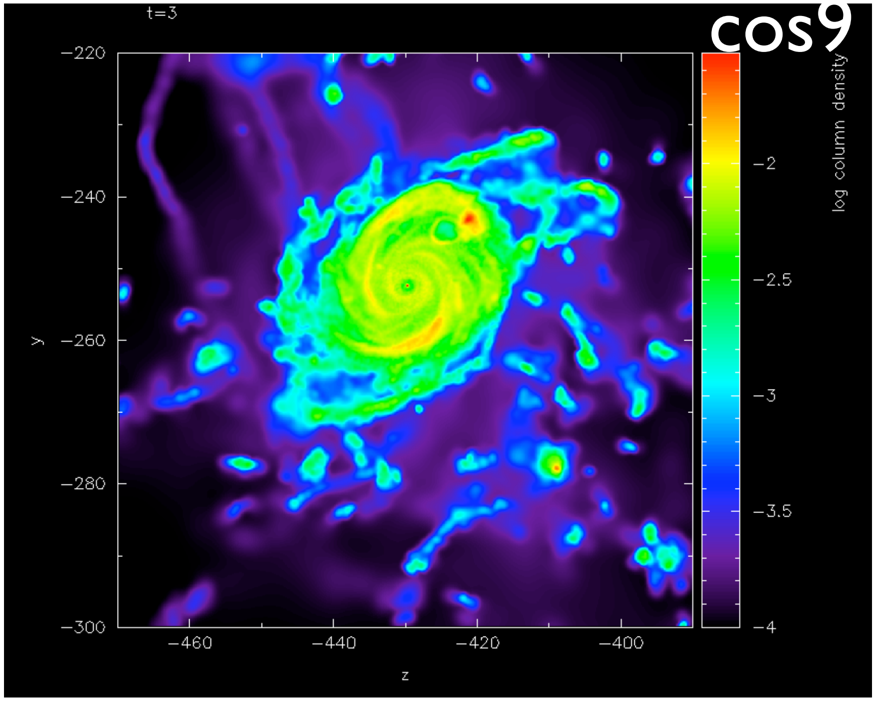
Simulation: Greg Novak

Music: J. S. Bach, from Cantata #22

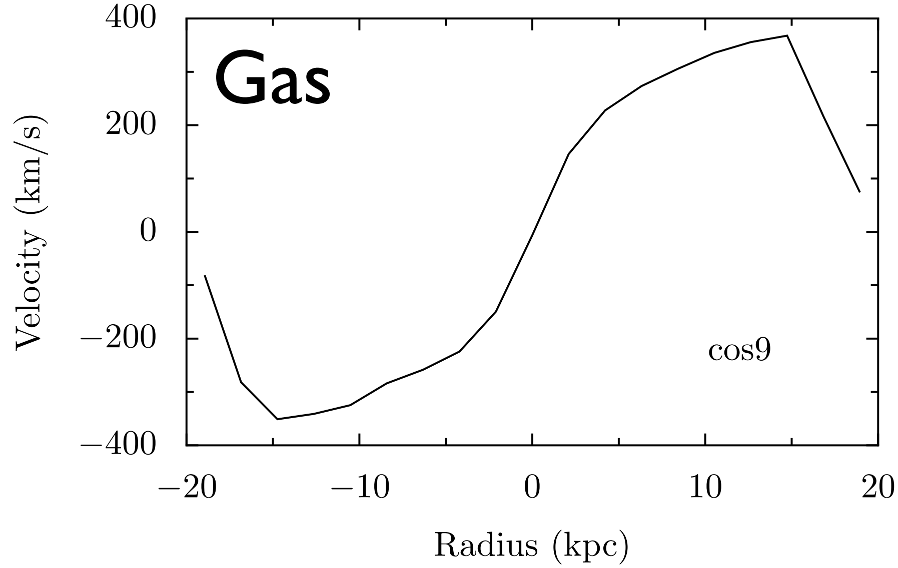

t=0
cos7
log column density
units are
10^10 M_o/kpc^2
=1.3x10^24 cm^-2
500 x 500 kpc
x
y

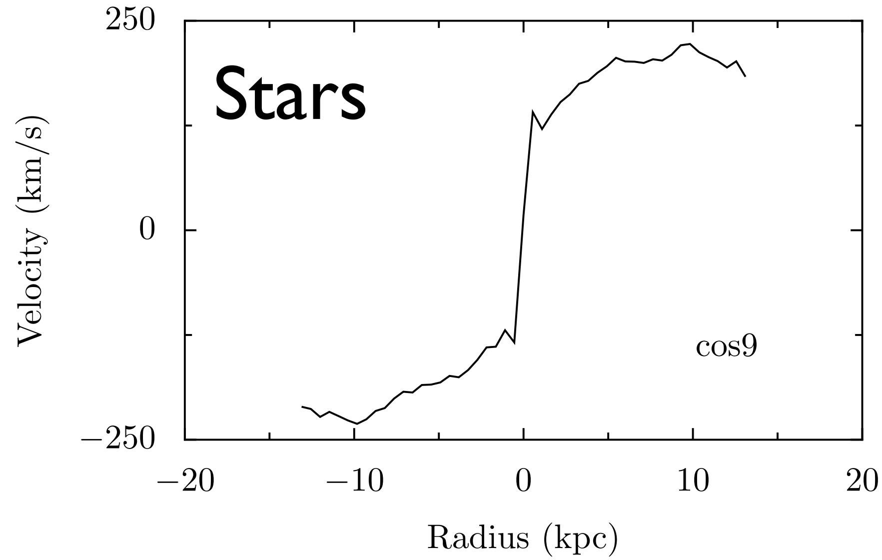


t=3
Snapshot of Face-On Disk
cos9
log column density
10 kpc
units are
10^10 Mo/kpc^2
=1.3x10^24 cm^-2
y
z
−220
−240
−260
−280
−300
−460
−440
−420
−400
−2
−2.5
−3
−3.5
−4



Rotation Curves

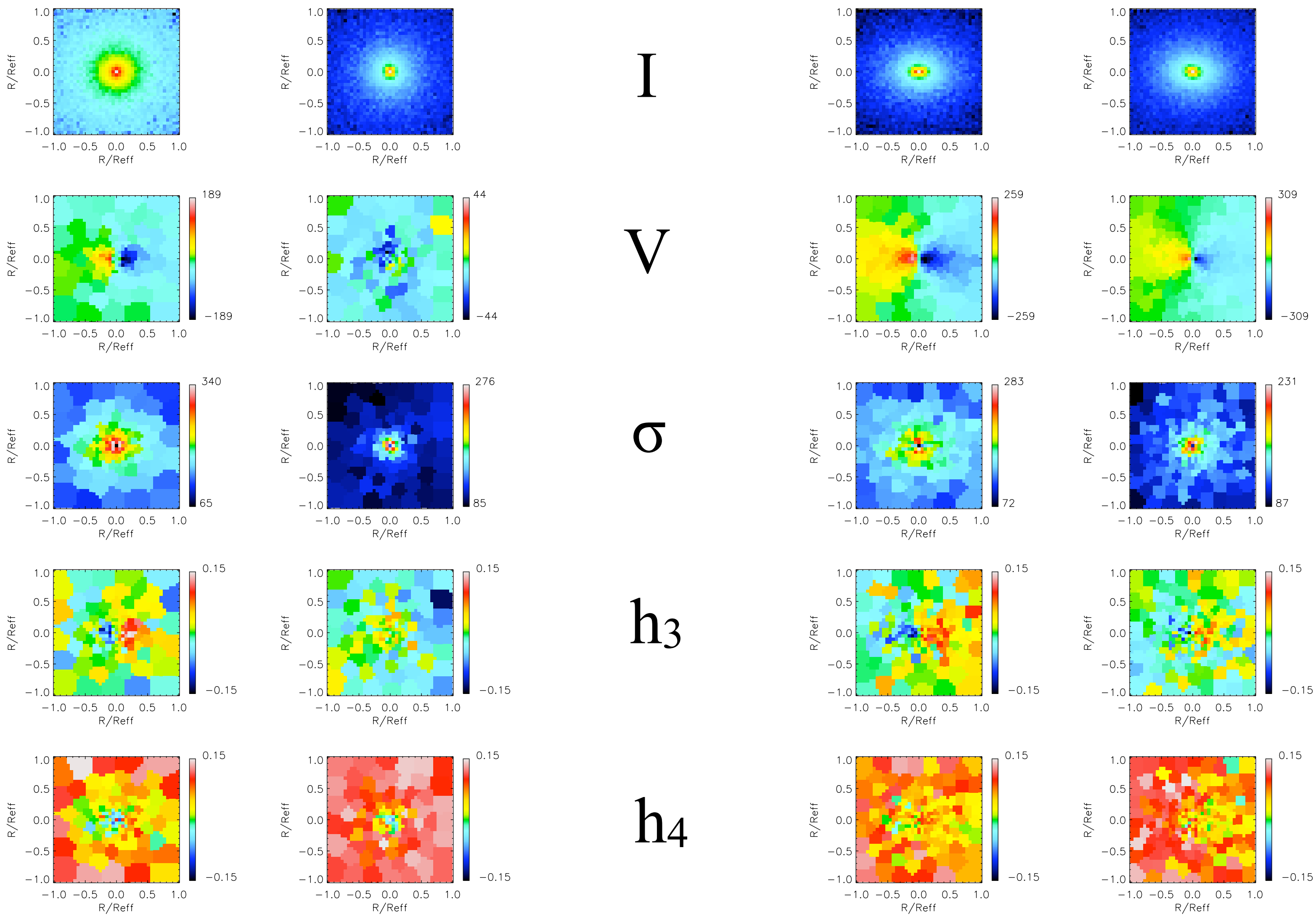




Many of the Galaxies Formed in Our Cosmological Simulations Appear to Resemble SINFONI Observations

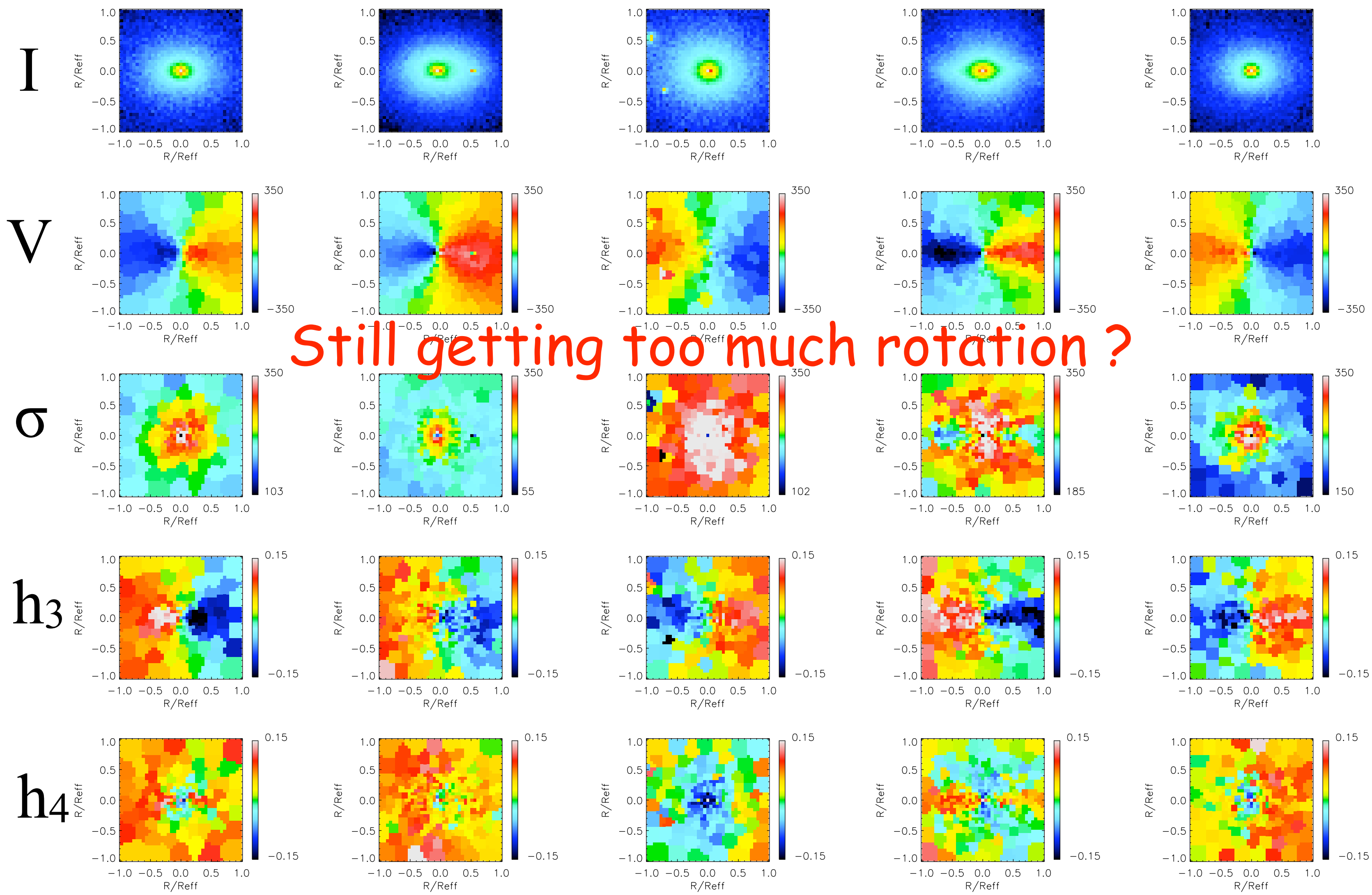
Novak+08 in prep

Multi-Minors Multi-Majors



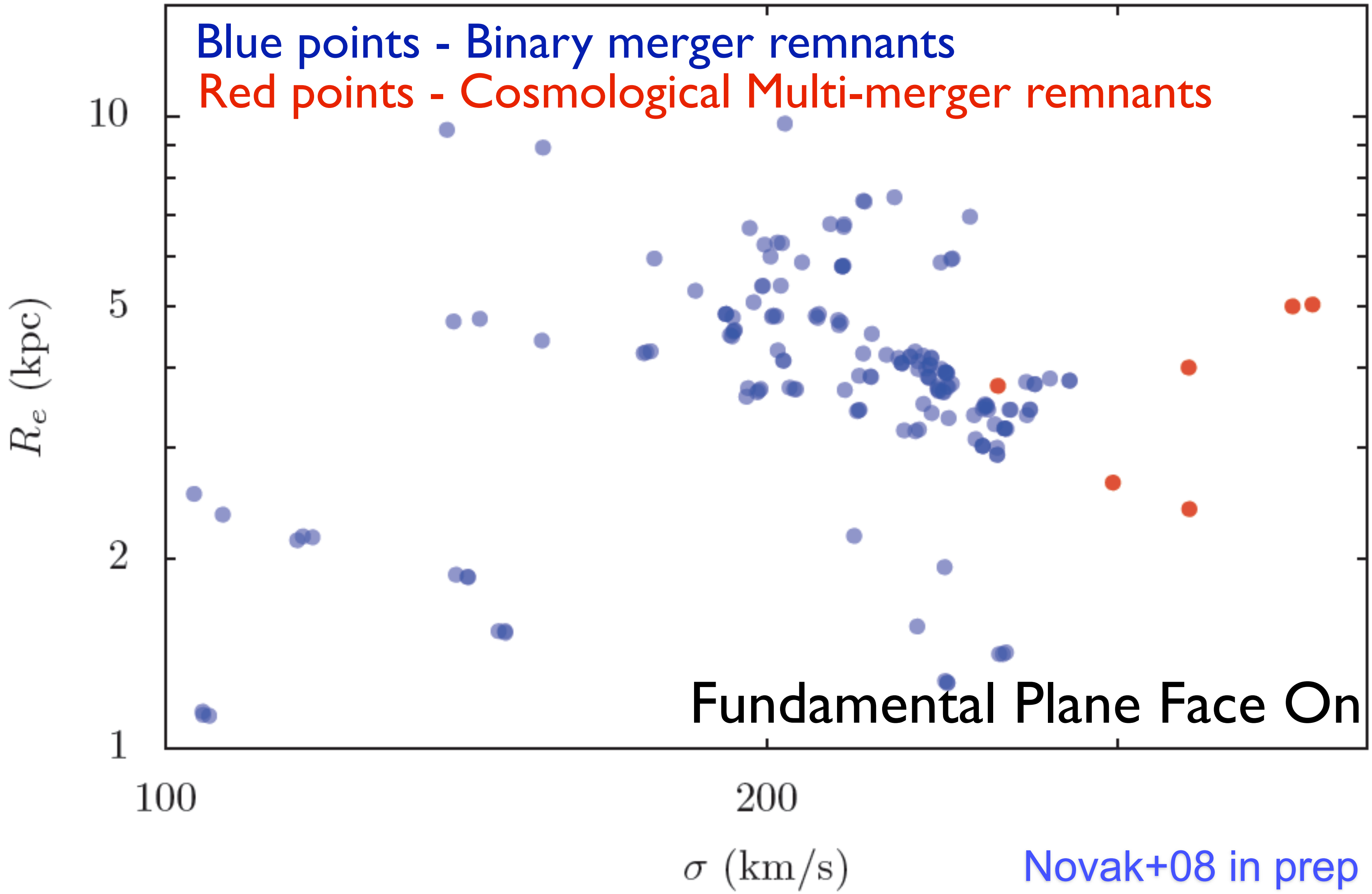
Produce Spheroids with Little or No Rotation

Cosmological Multi-Merger Simulations



Novak+08 in prep

Effective Radius vs. Velocity Dispersion for Merger Remnants



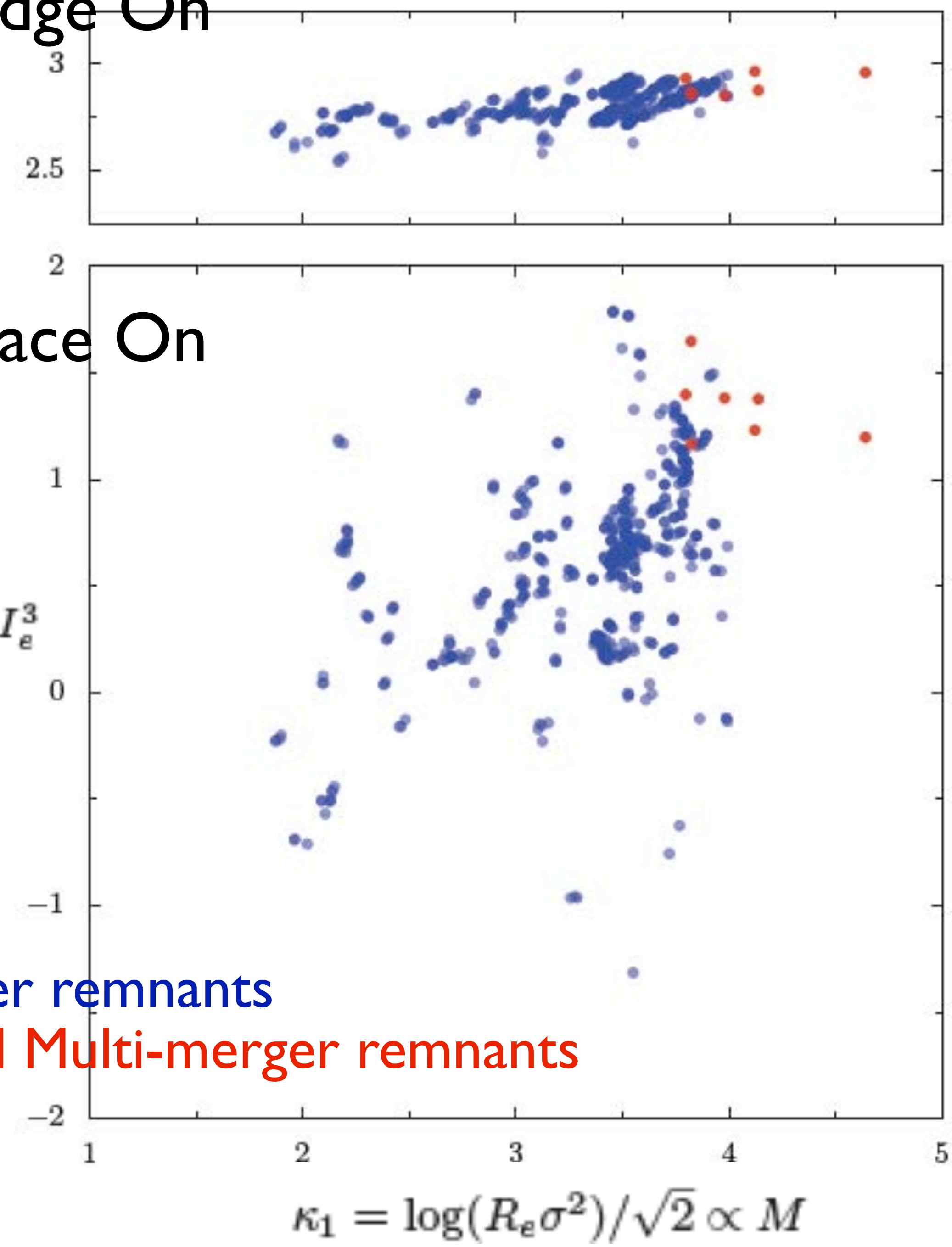
Novak+08 in prep

Fundamental Plane Edge On

$\kappa_3 = \log(\sigma^2/I_e R_e)/\sqrt{3} \propto M/L$

Fundamental Plane Face On

$\kappa_2 = \log(\sigma^2 I_e^2/R_e)/\sqrt{6} \propto (M/L)I_e^3$



Blue points - Binary merger remnants

Red points - Cosmological Multi-merger remnants

A Physical Model for Predicting the Properties of Spheroidal Remnants of Binary Mergers of Gas Rich Disk Galaxies

We might expect that a more energetic encounter will cause increased tidal stripping and puff up the remnant.

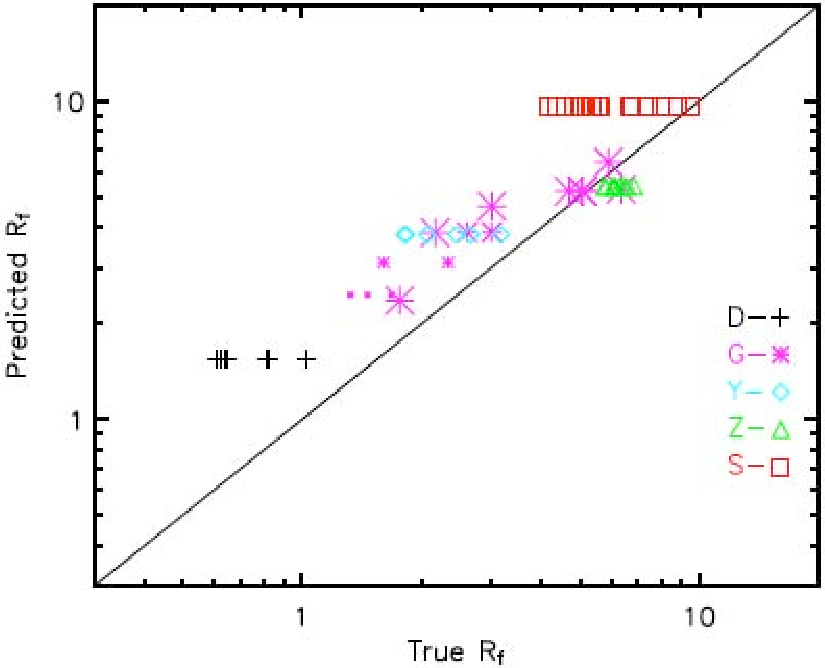
NO! For our simulations, more energetic encounters create more compact remnants.

Why? Dissipative effects cause more energetic encounters to result in smaller remnants.

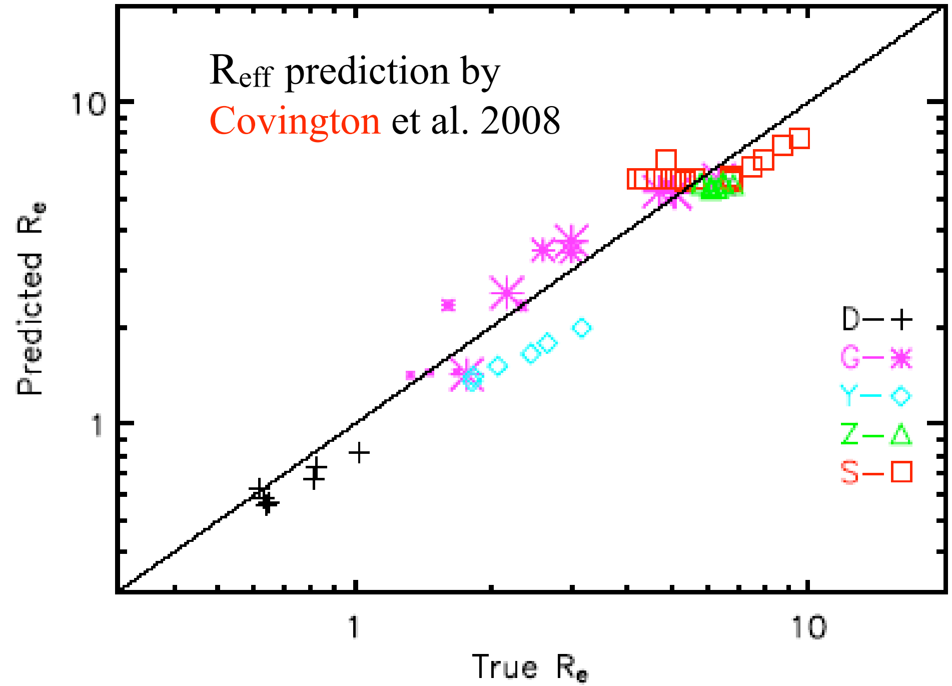
Impulse provides a measure of merger "violence." The greater the impulse, the more the gas is disturbed, therefore the more it can radiate and form stars.

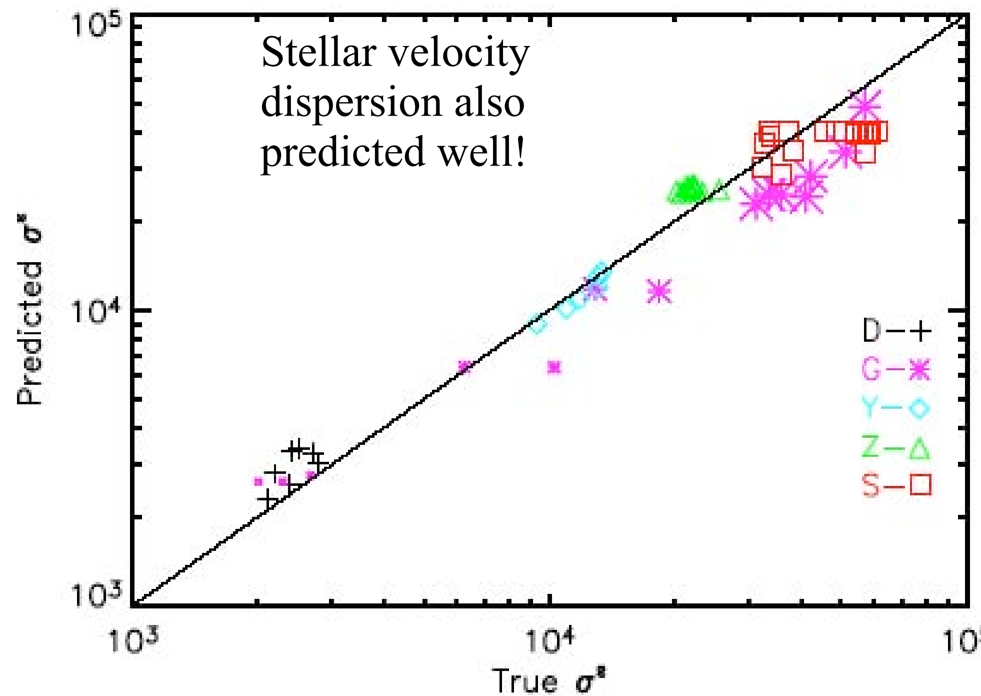
A number of physical mechanisms conspire to make this so (e.g. greater tidal effects, lower angular momentum, and more gas disk overlap).

Matt Covington, Cox, Dekel, & Primack MNRAS 2008



R_{eff} prediction by
Cole et al. 2000
dissipationless model





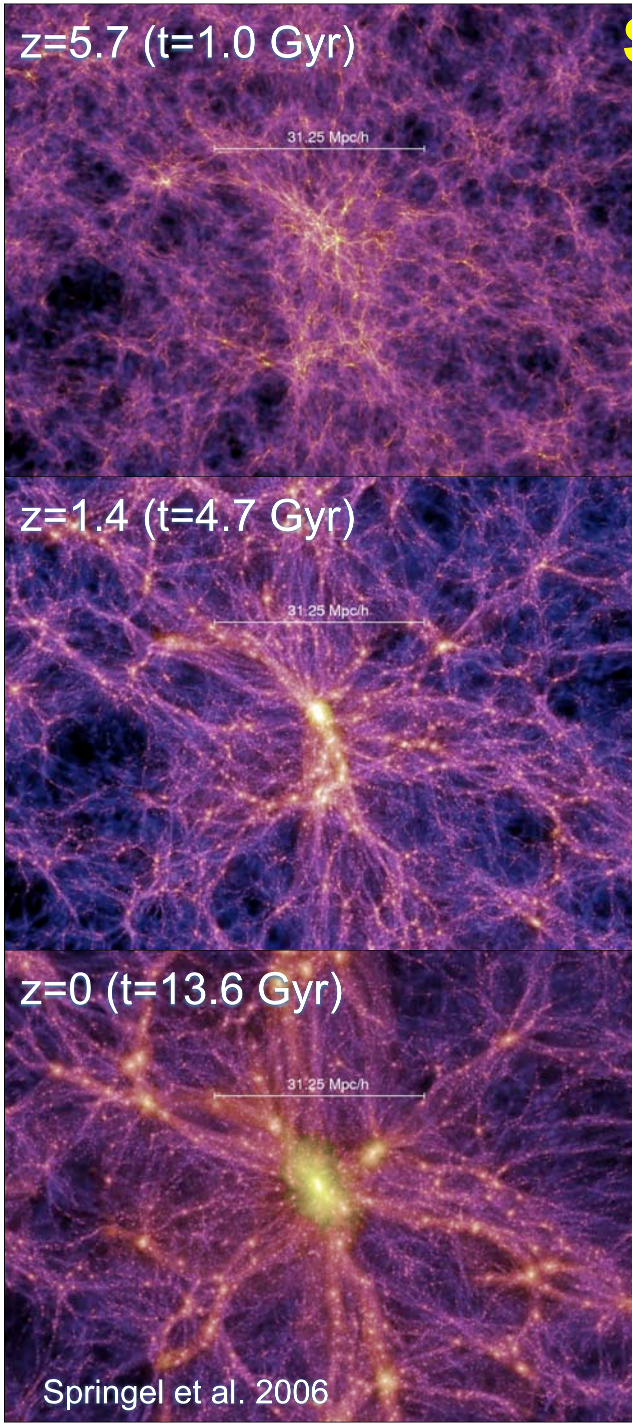
Covington et al. 2008 model also works well for non-equal mass mergers, including minor mergers!

New Improved Semi-Analytic Models Work!

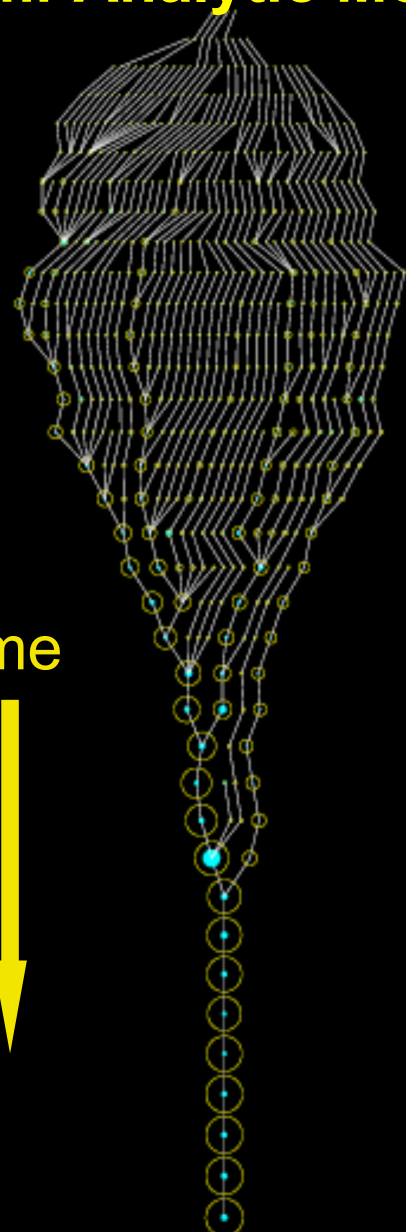
- Earlier CDM-based galaxy formation models suffered from a set of interlinked problems
  - overcooling/cooling flow problems in galaxies and clusters
  - failure to produce observed color bimodality
- ‘Bright mode’ AGN feedback may regulate BH formation & temporarily quench star formation, but is not a viable ‘maintenance’ mechanism
- Low-accretion rate ‘radio mode’ feedback is a promising mechanism for counteracting cooling flows over long time scales
- New self-consistent ‘hybrid’ models based on physical scaling from numerical simulations and calibrated against empirical constraints now enable us to predict/interpret the relationship between galaxies, BH, and AGN across cosmic history

-- Rachel Somerville

Semi-Analytic Models of Galaxy Formation



time



Wechsler et al. 2002

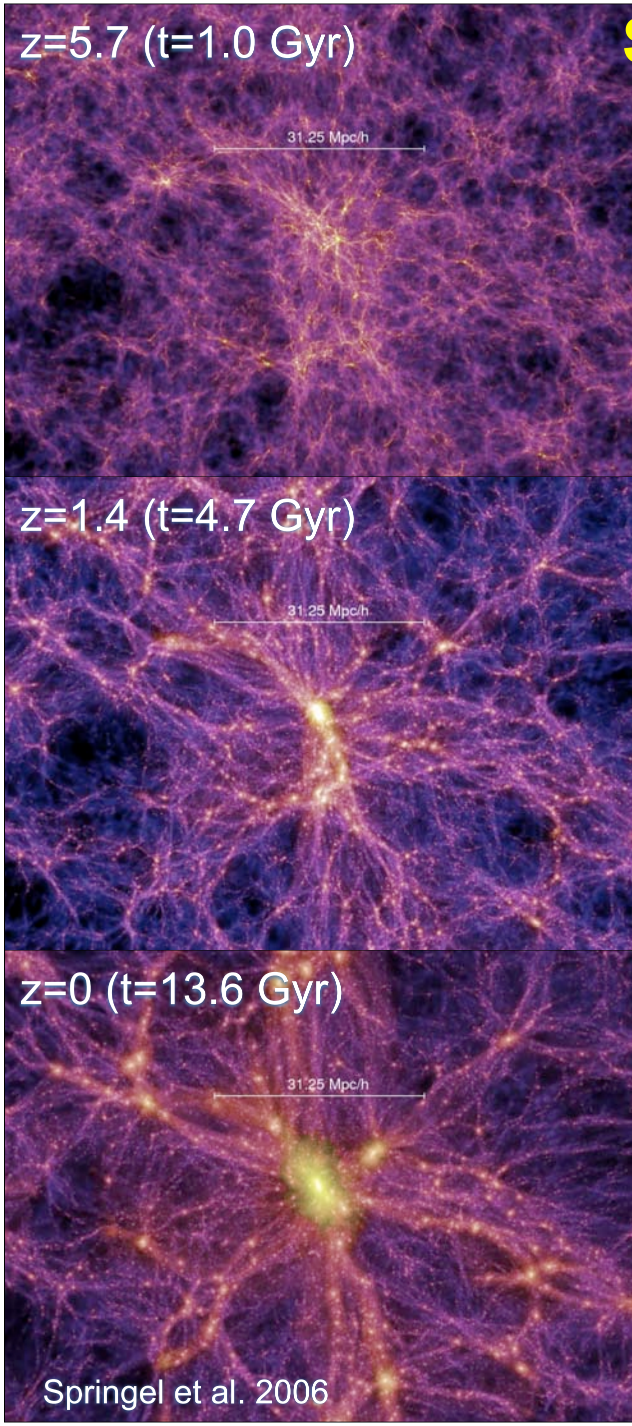
Present status of ΛCDM
“Double Dark” theory:

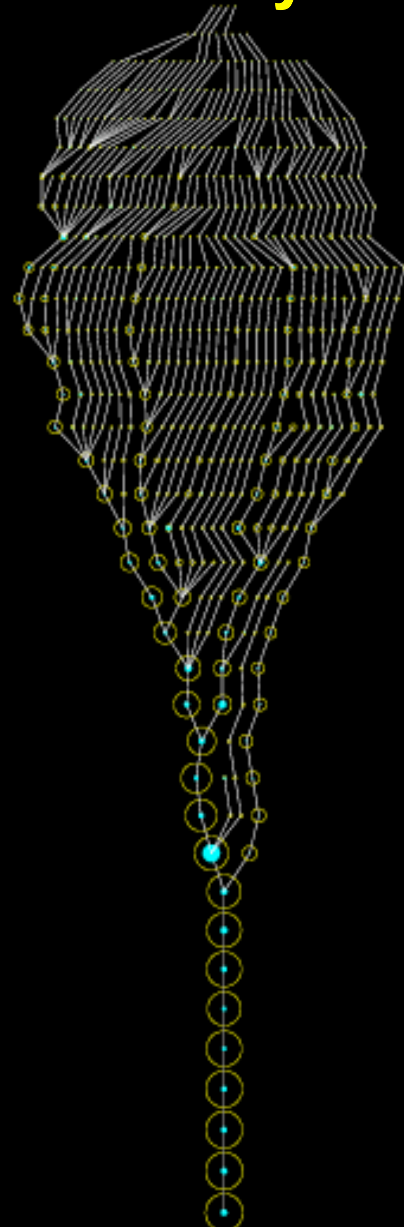
- cosmological parameters are now
well constrained by observations

- structure formation in dominant dark matter component accurately quantified

- mass accretion history of dark matter halos is represented by ‘merger trees’

Semi-Analytic Models of Galaxy Formation

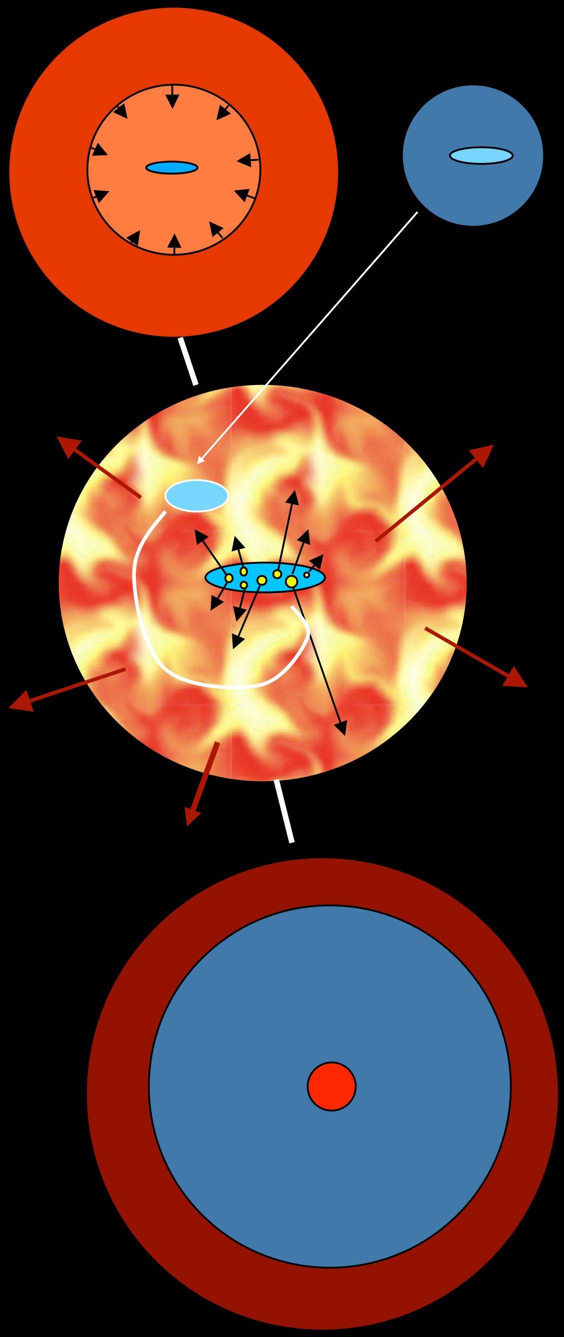




Astrophysical processes modeled:

- 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

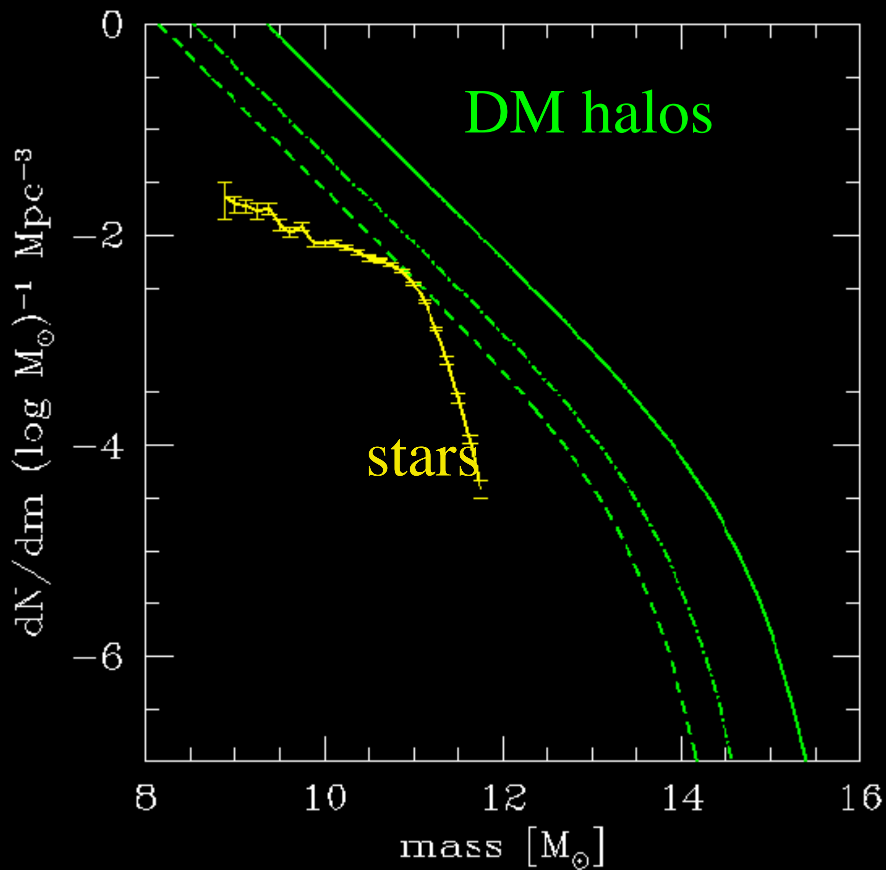
Semi-Analytic Models of Galaxy Formation



- 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)
- massive stars and SNae reheat (and expel?) cold gas and some metals
- galaxy mergers trigger bursts of star formation; 'major' mergers transform disks into spheroids

White & Frenk 1991; Kauffmann et al. 93; Cole et al. 94; Somerville & Primack 99; Cole et al. 2000; Somerville, Primack, & Faber 01; Cattaneo et al. 07, Somerville et al. 08

Baryons in Dark Matter Halos

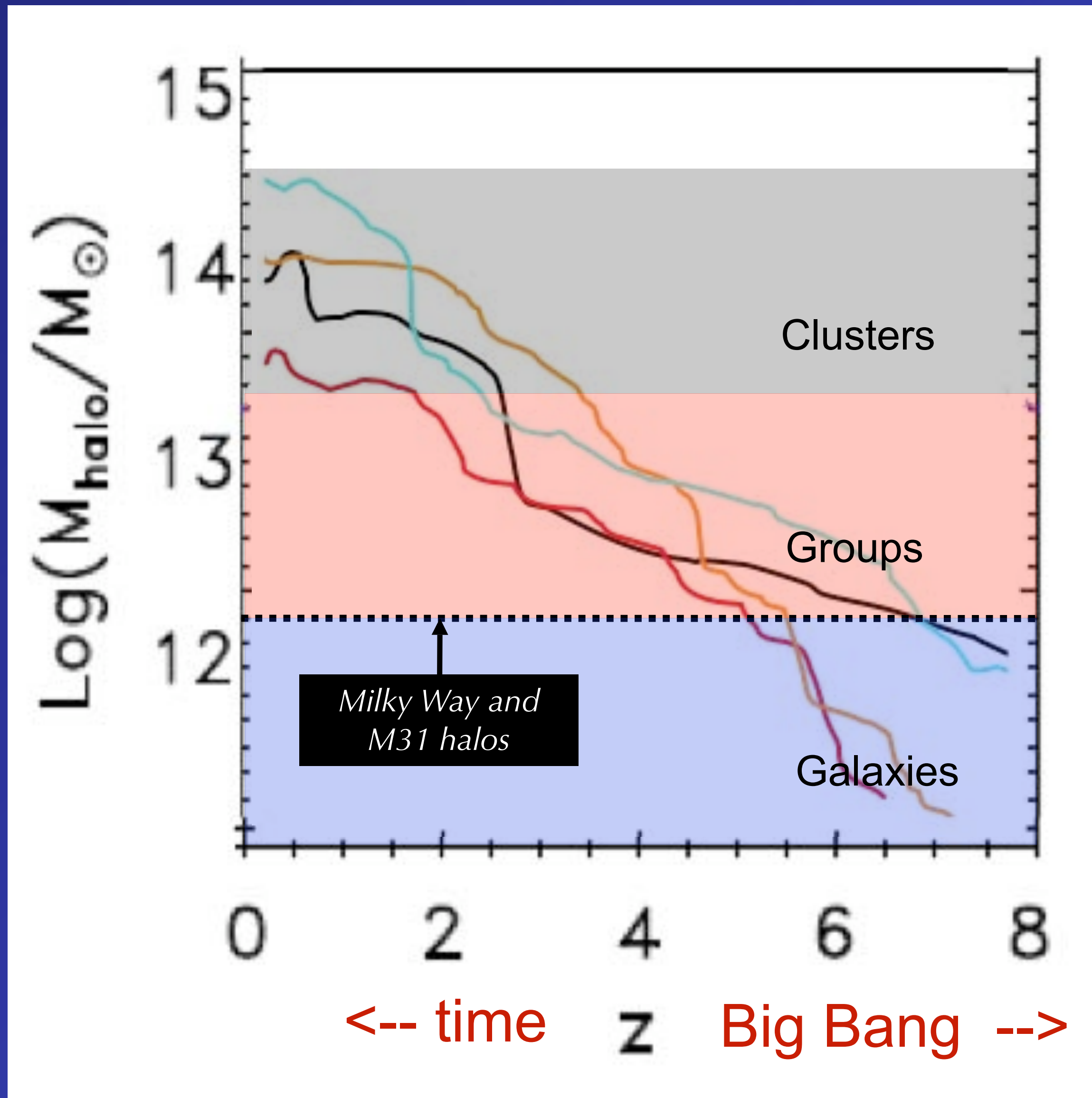


- in order to reconcile CDM (sub)halo mass function with galaxy LF or stellar MF, cooling/star formation must be inefficient overall, most efficient at 10^{12} M_{sun}
- baryon/DM ratio must be a strongly non-linear (& non-monotonic) function of halo mass

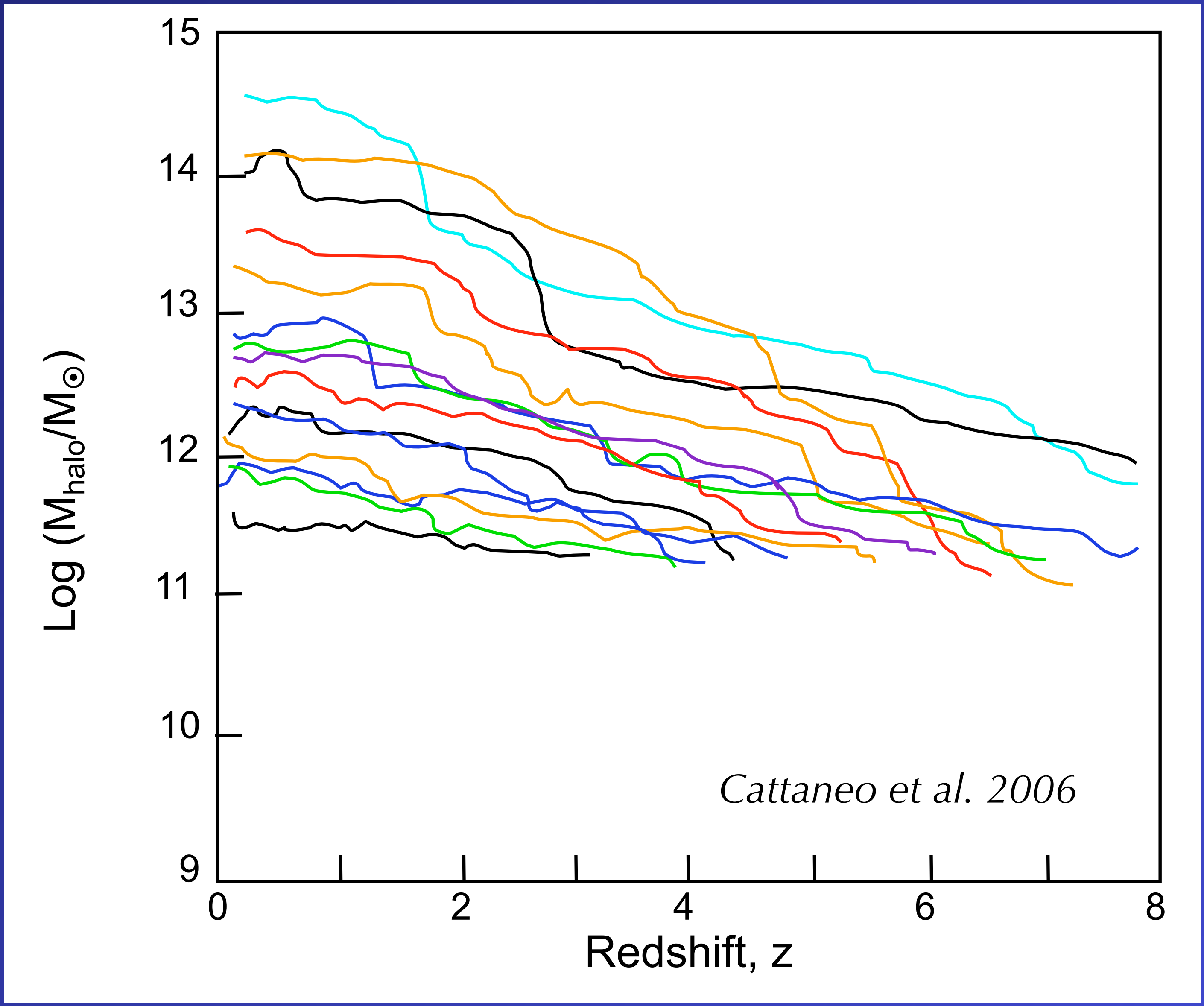
Somerville & Primack 1999; Benson et al. 2003

Dark halo mass growth vs. time: 4 examples

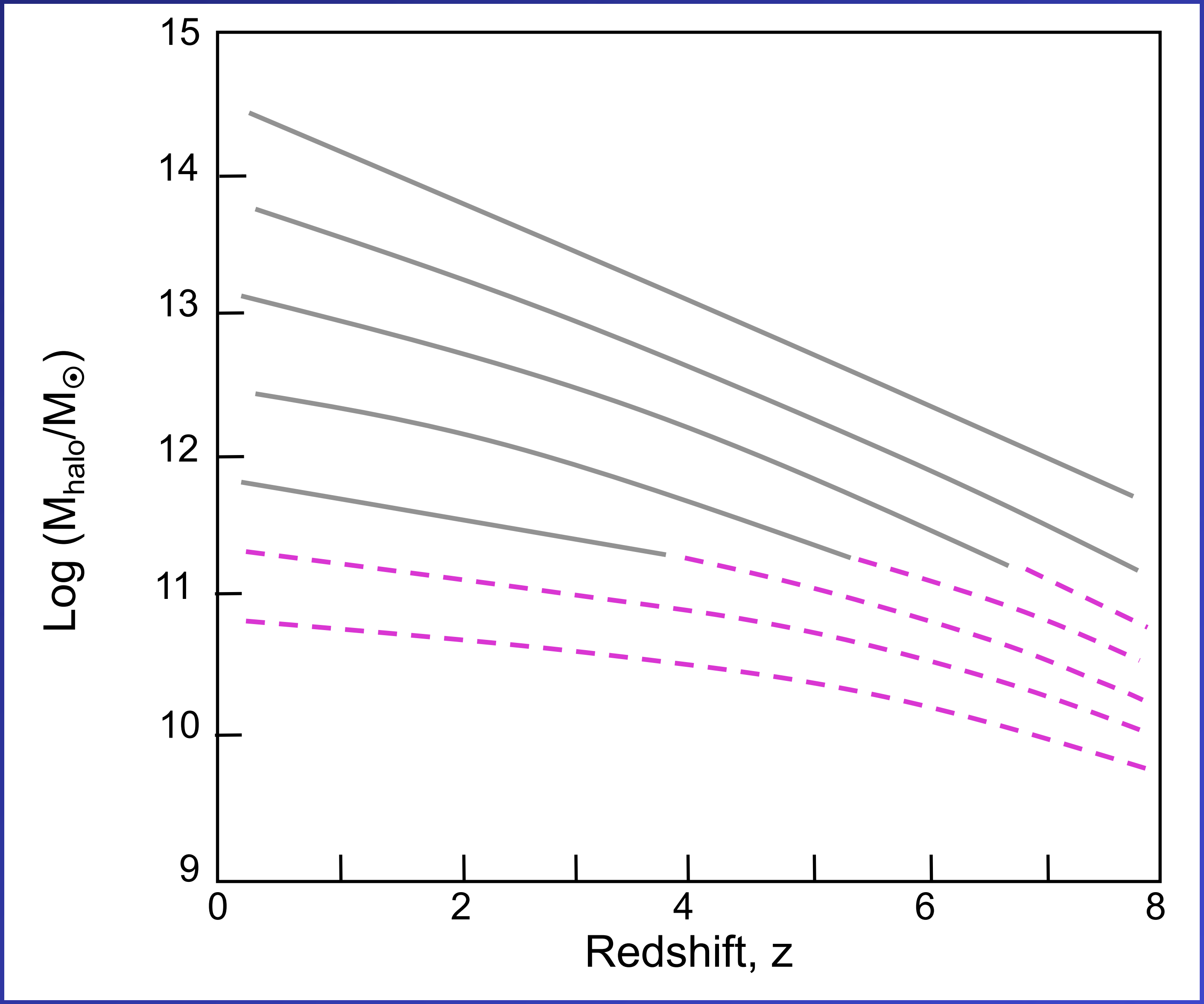
GALics DM halos by Cattaneo et al. 2006



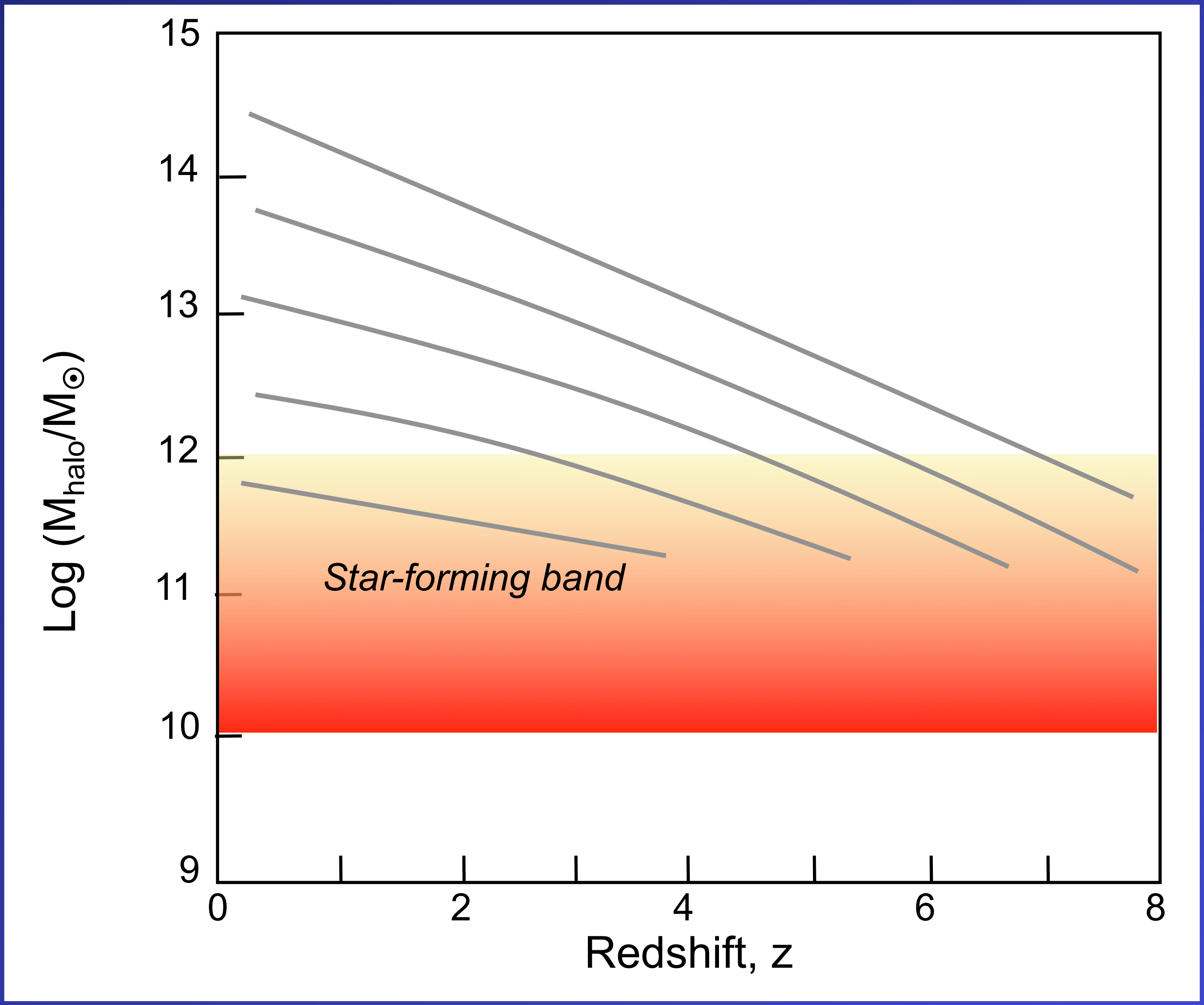
Dark halos of progressively smaller mass



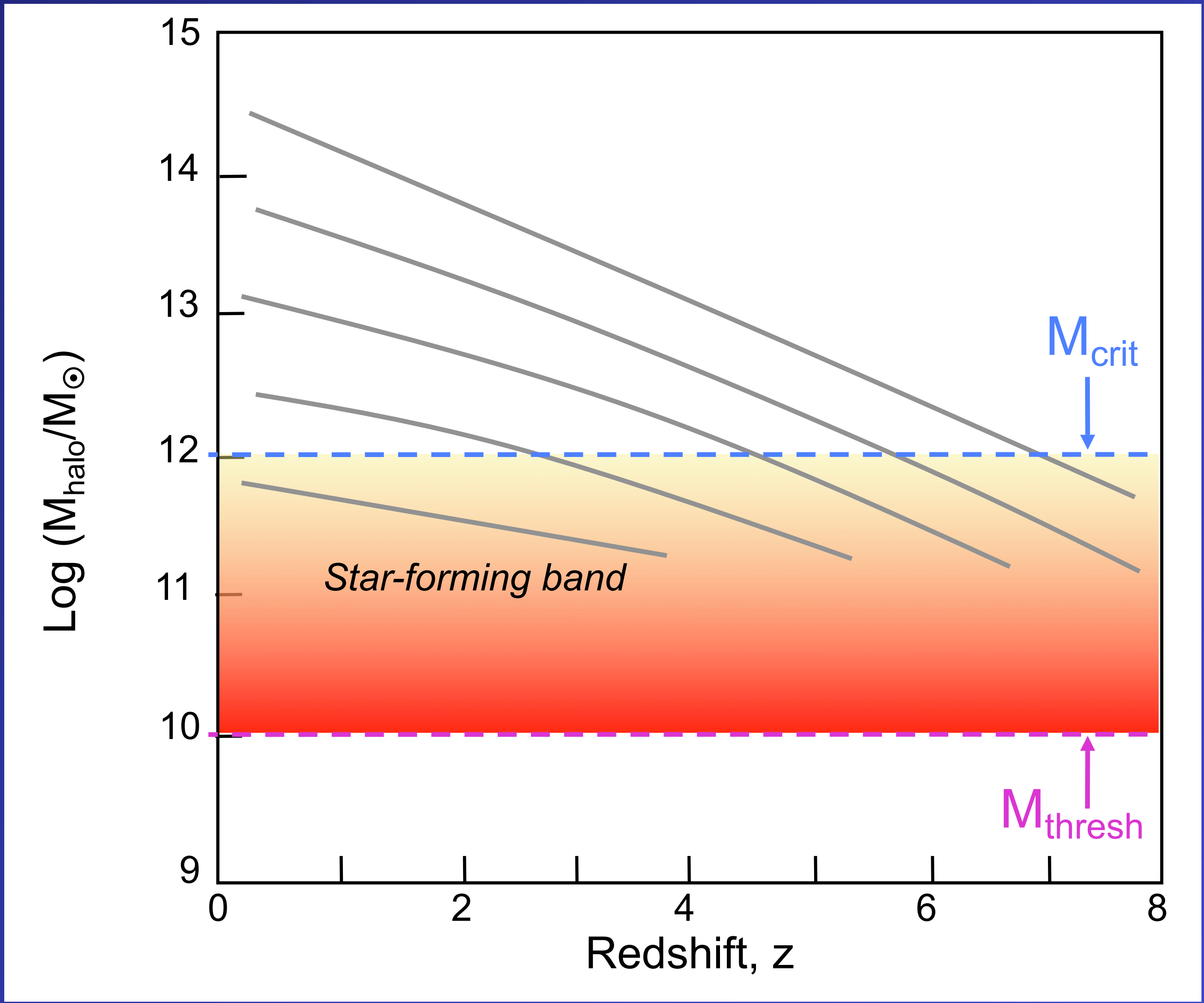
A schematic model of average halo mass growth



Key assumption: ***star-forming band*** in dark-halo mass



Key assumption: ***star-forming band*** in dark-halo mass



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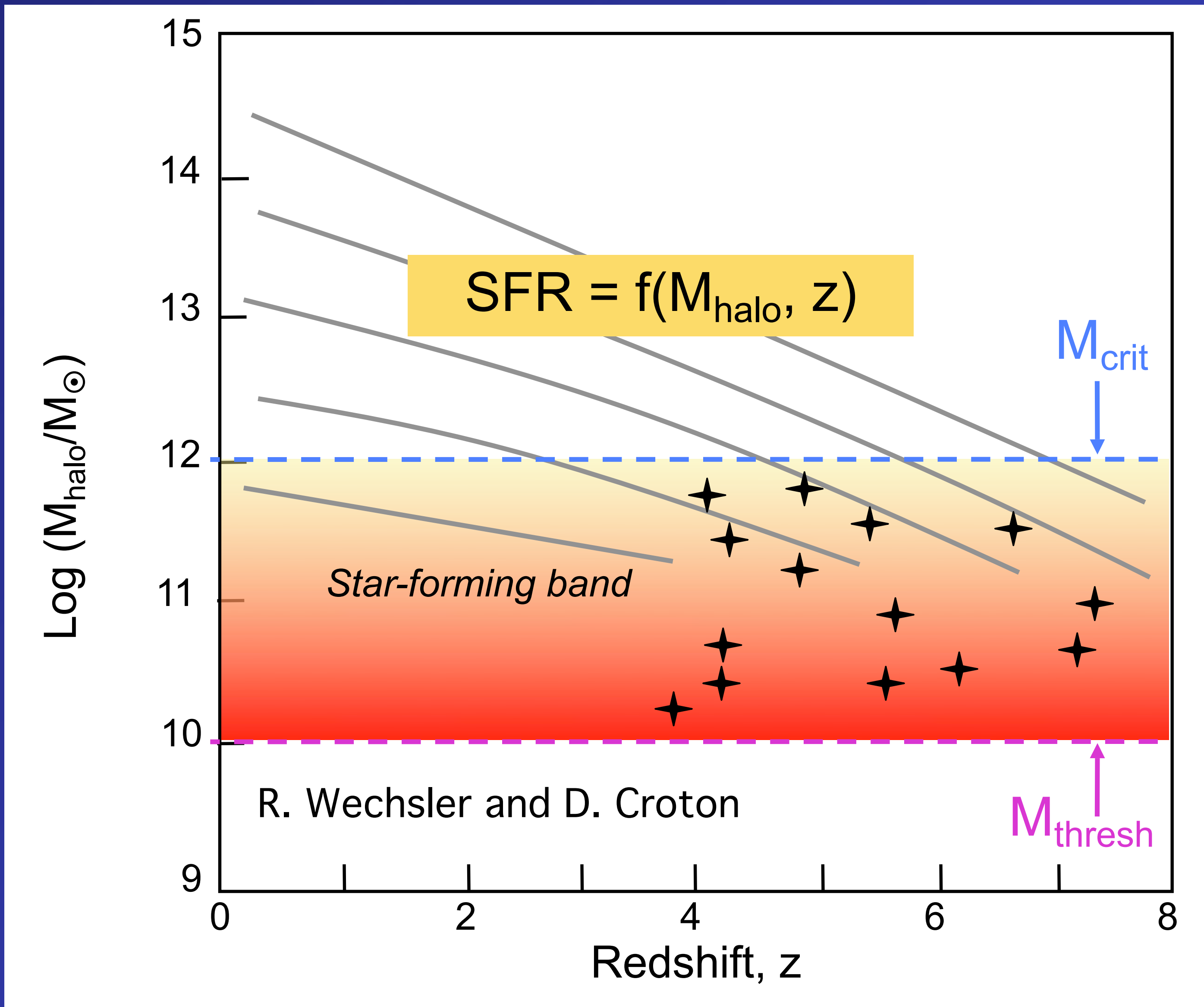
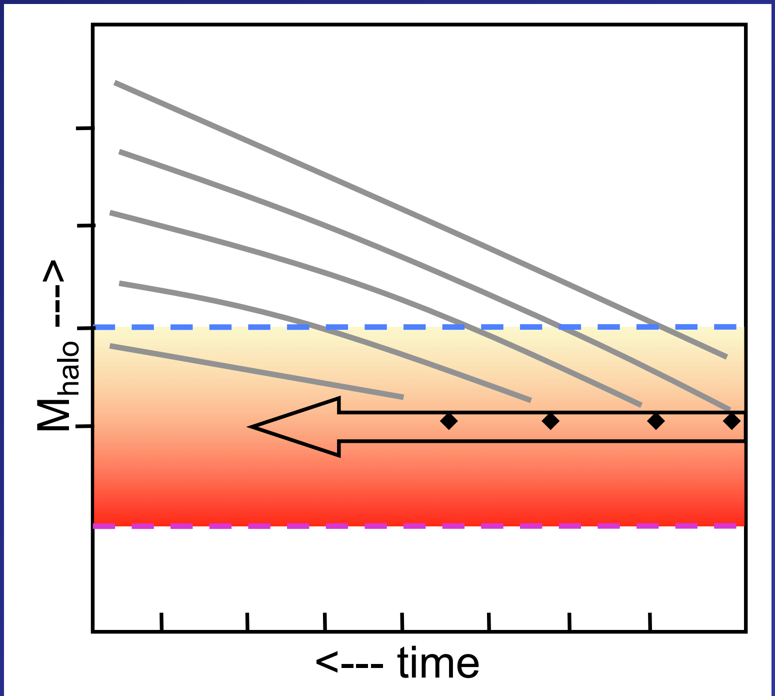


Implications and Predictions of the Model



1) Each halo has a unique dark-matter growth path and associated stellar mass growth path.

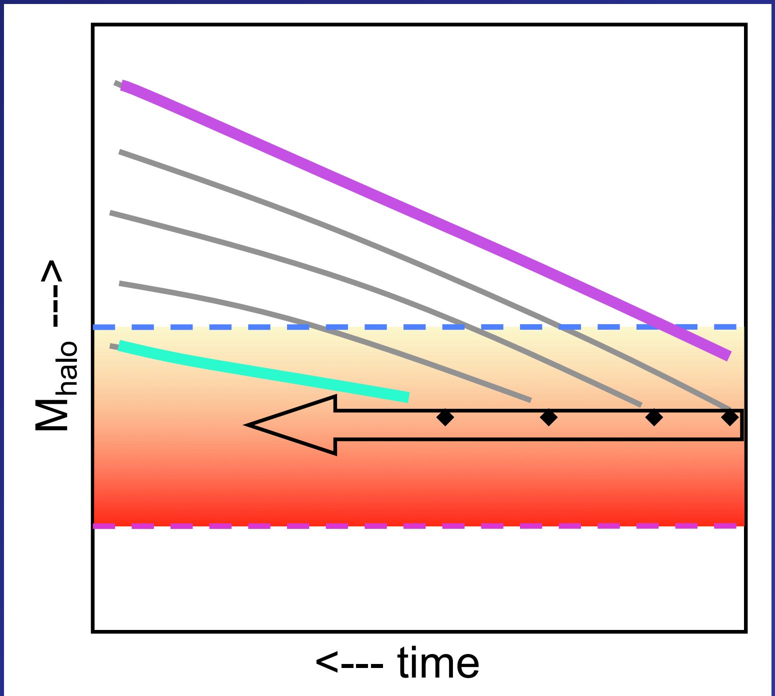
2) Stellar mass follows halo mass until M_{halo} crosses M_{crit}.

SAMs: $M_{star} \sim 0.05\ M_{halo}$

3) A ***mass sequence*** comes from the fact that different halo masses enter the star-forming band at different times. A galaxy's position is determined by its ***entry redshift*** into the band. More massive galaxies enter earlier. Thus:

z_{entry} <--> M_{halo} <--> M_{star}

Implications and Predictions of the Model



Massive galaxies:

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

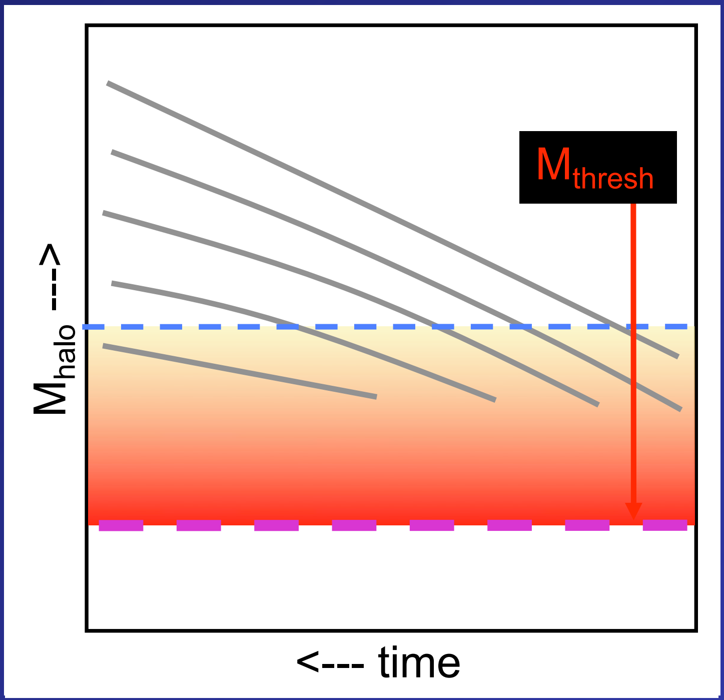
Small galaxies:

- 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).

Theories for the ***lower*** halo star-formation boundary



M_{thresh} is the halo mass at the LOWER edge of the star-formation band, roughly 10^{10} $M_{\odot}$.

Not yet well understood

1. Supernova feedback (Dekel & Silk 1985):

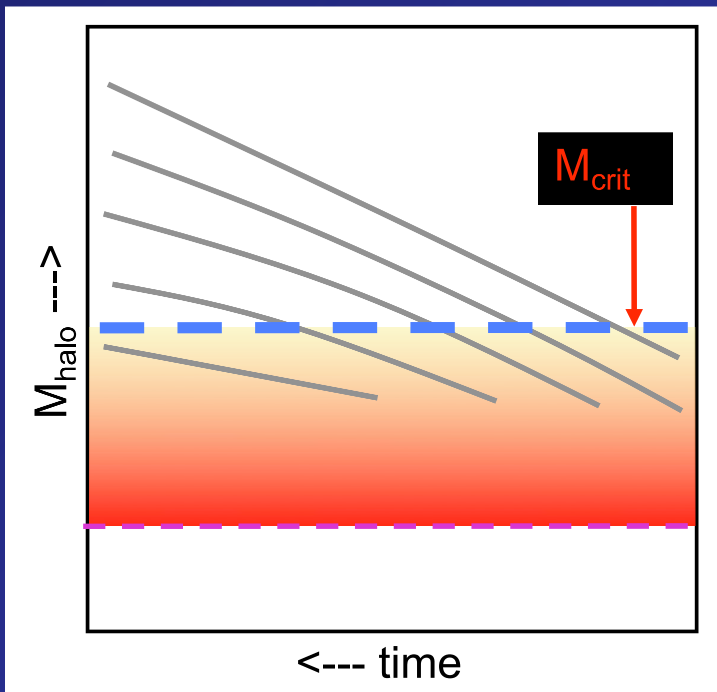
   $v_{lim} < 100$ km/sec

2. Early Universe reionization (e.g., Somerville 2002):

   $v_{lim} < 30$ km/sec

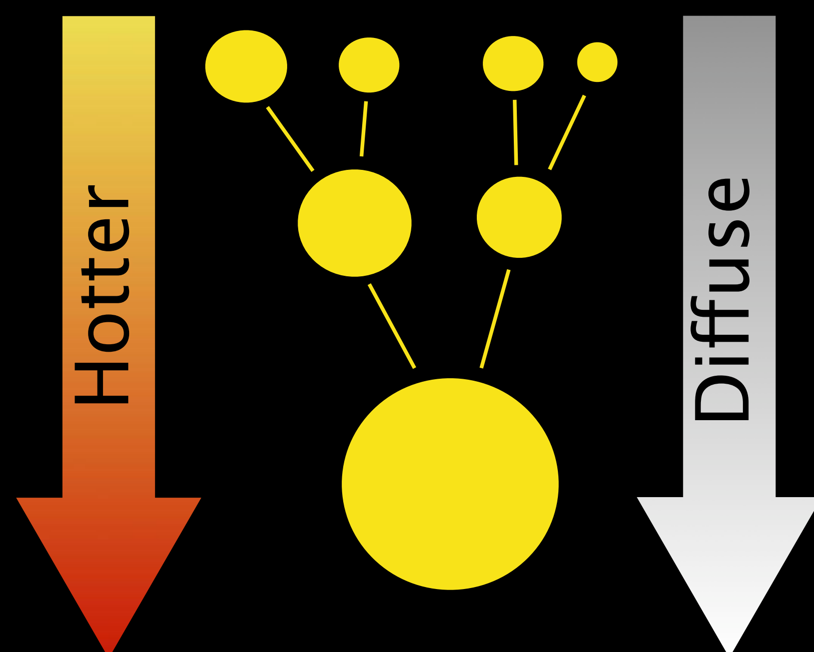
3. Plus tidal destruction!

Theories for the ***upper*** halo star-formation boundary

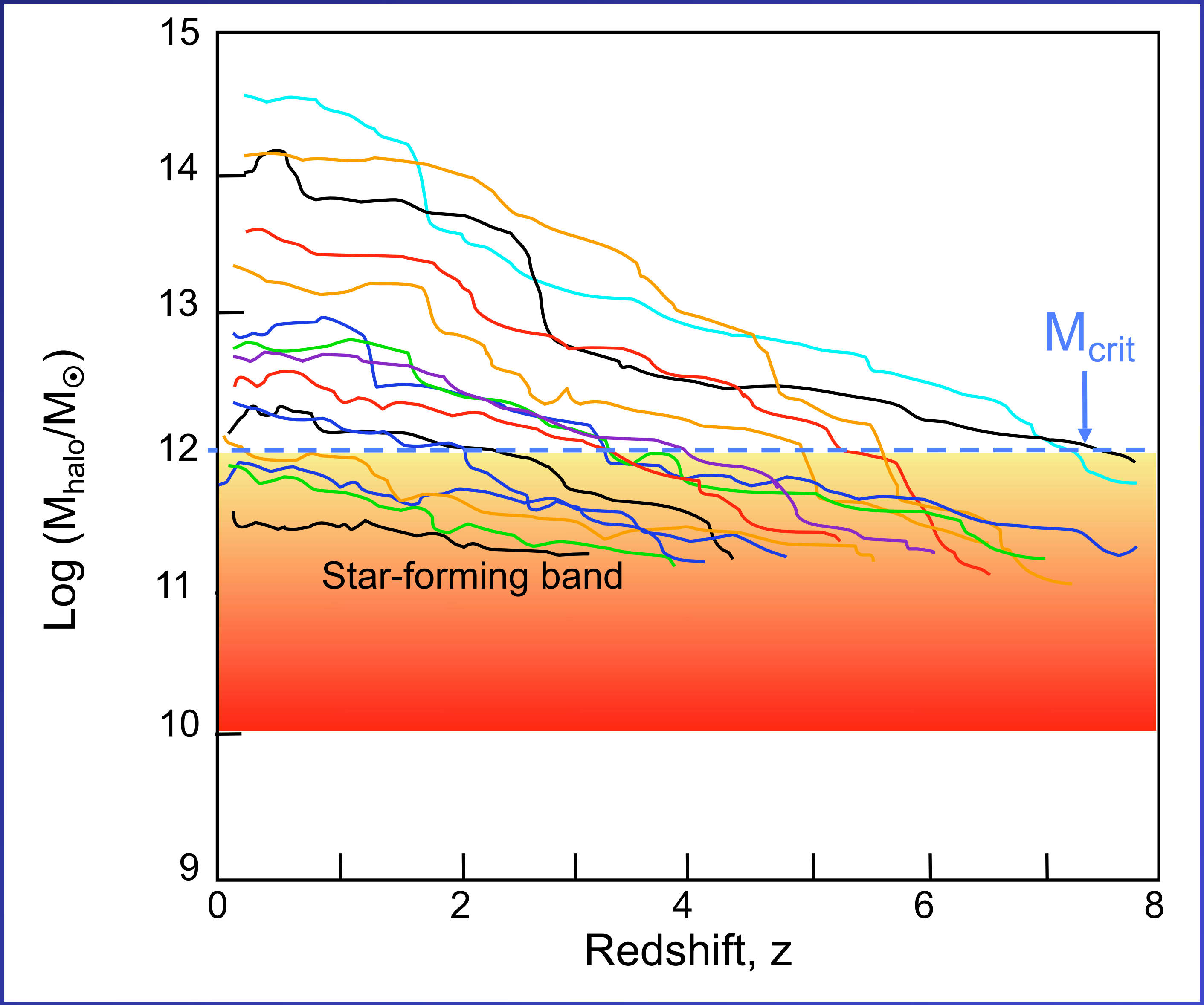


M_{crit} is the halo mass at the UPPER edge of the star-formation band, roughly 10^{12} $M_{¤}$.

1 Gas in halos above the critical halo mass M_{crit} ~ 10^{12} $M_{\odot}$ cannot cool (Ostriker & Rees 1978, Blumenthal et al. 1984, Dekel & Birnboim 2007).



More realistic model of halo-cooling boundary



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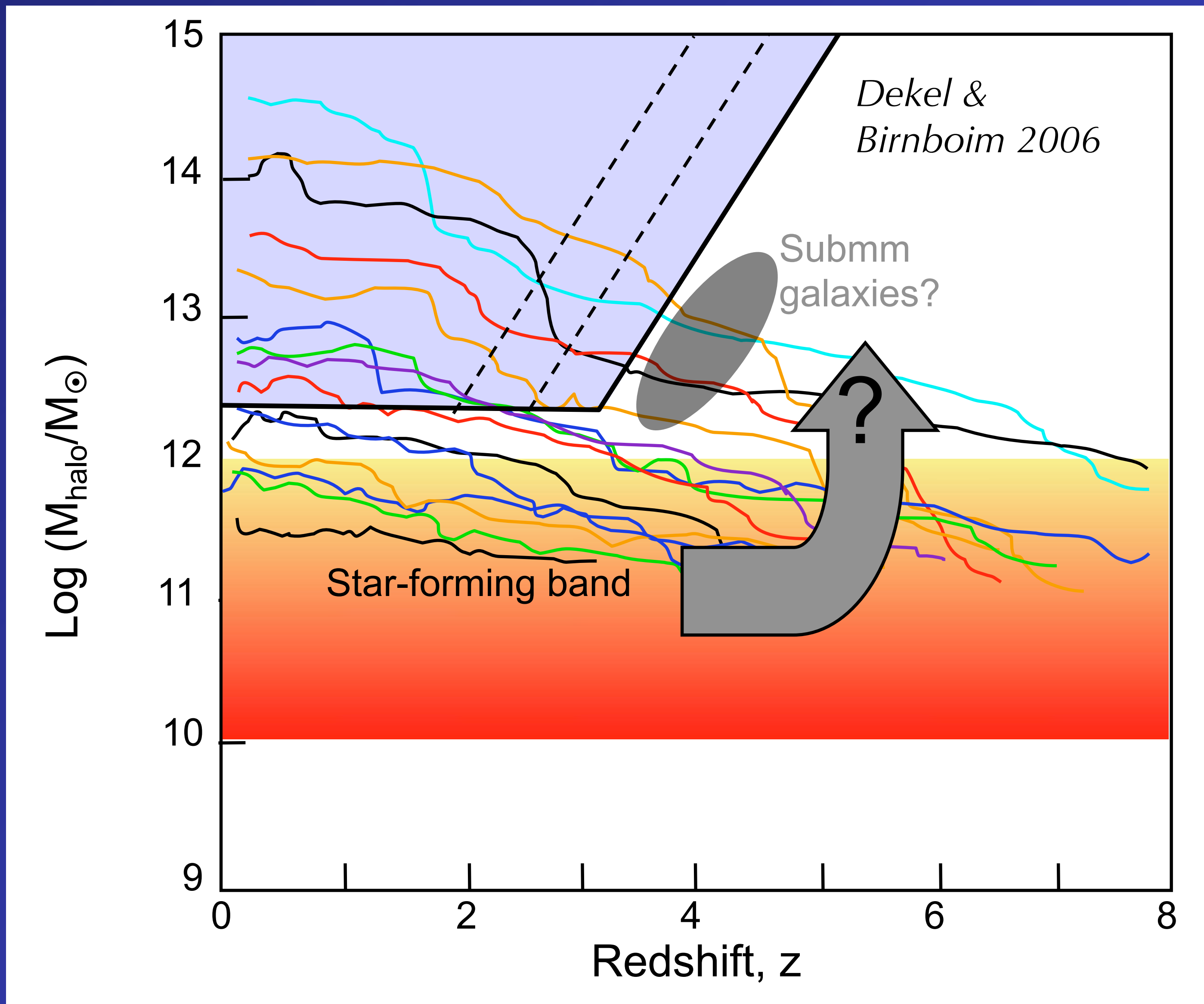
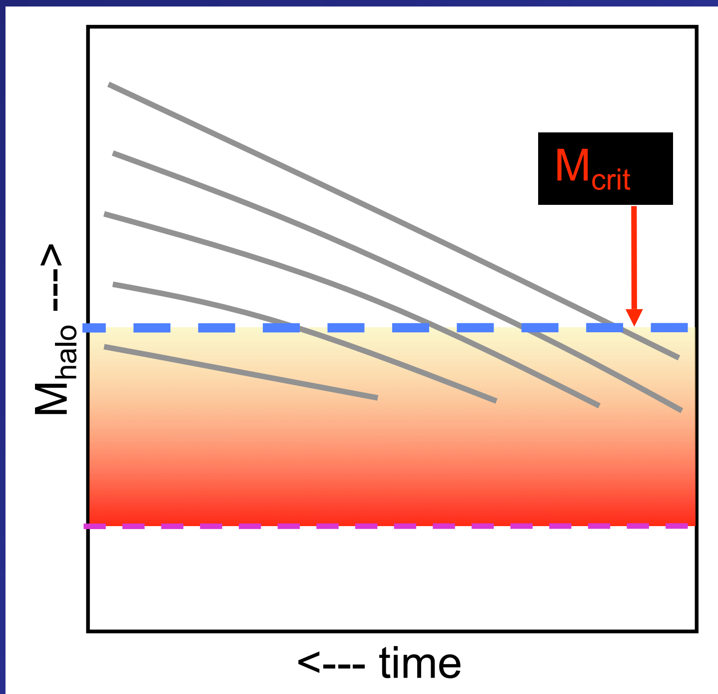
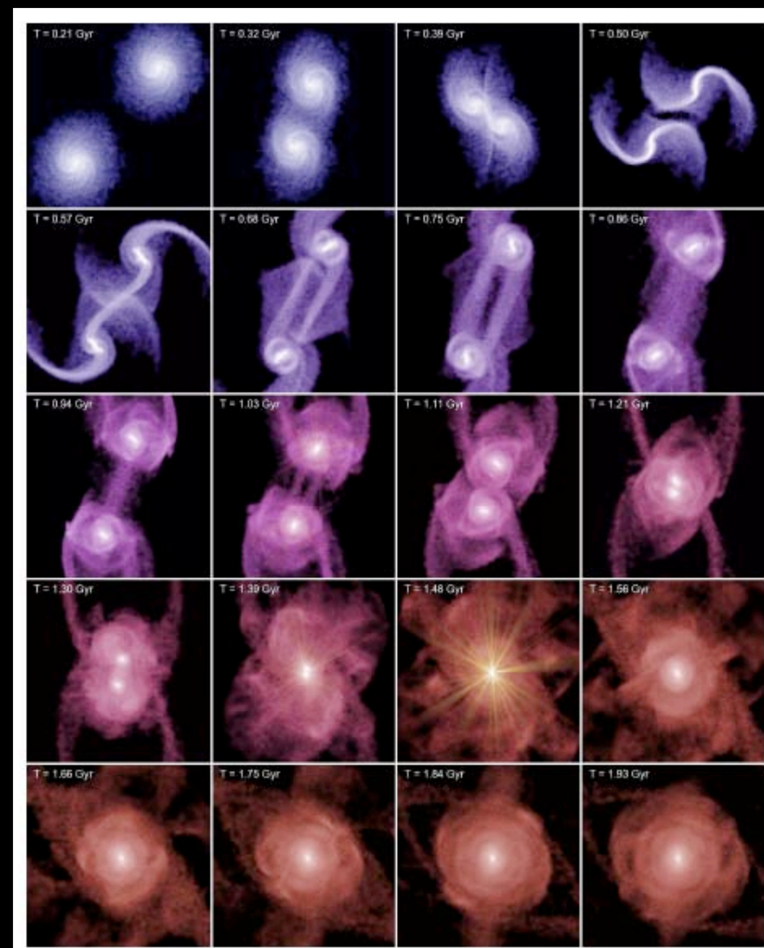


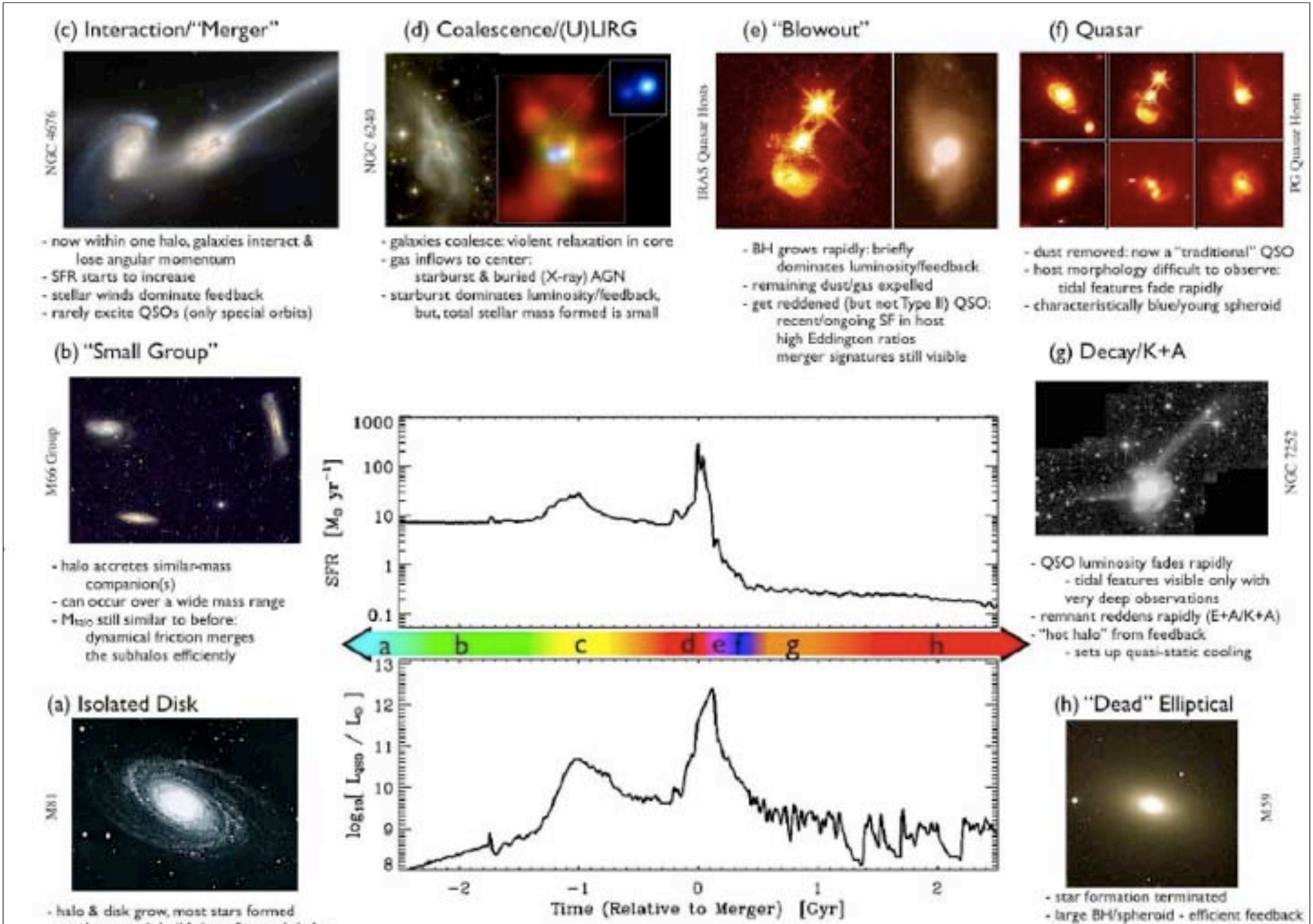
Theories for the ***upper*** halo star-formation boundary



M_{crit} is the halo mass at the UPPER edge of the star-formation band, roughly 10^{12} $M_{¤}$.

2 Merging galaxies trigger BH growth. AGN feedback drives out galaxy gas (Hopkins et al 2006).

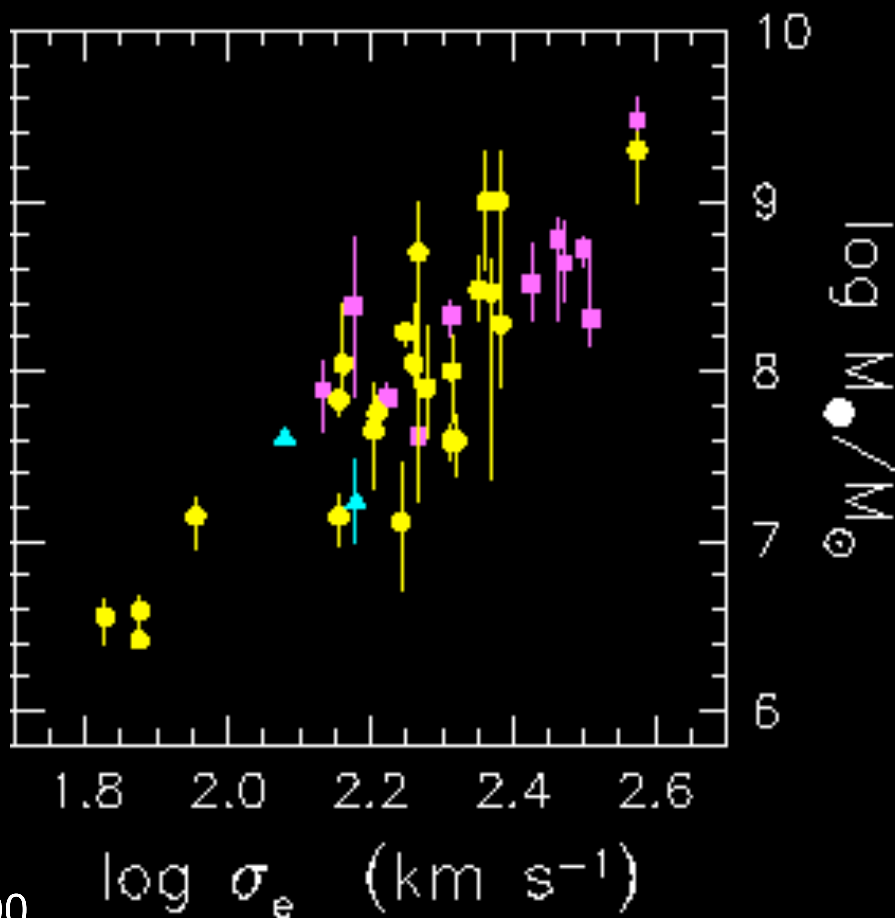




Hopkins et al. 2008 ApJS

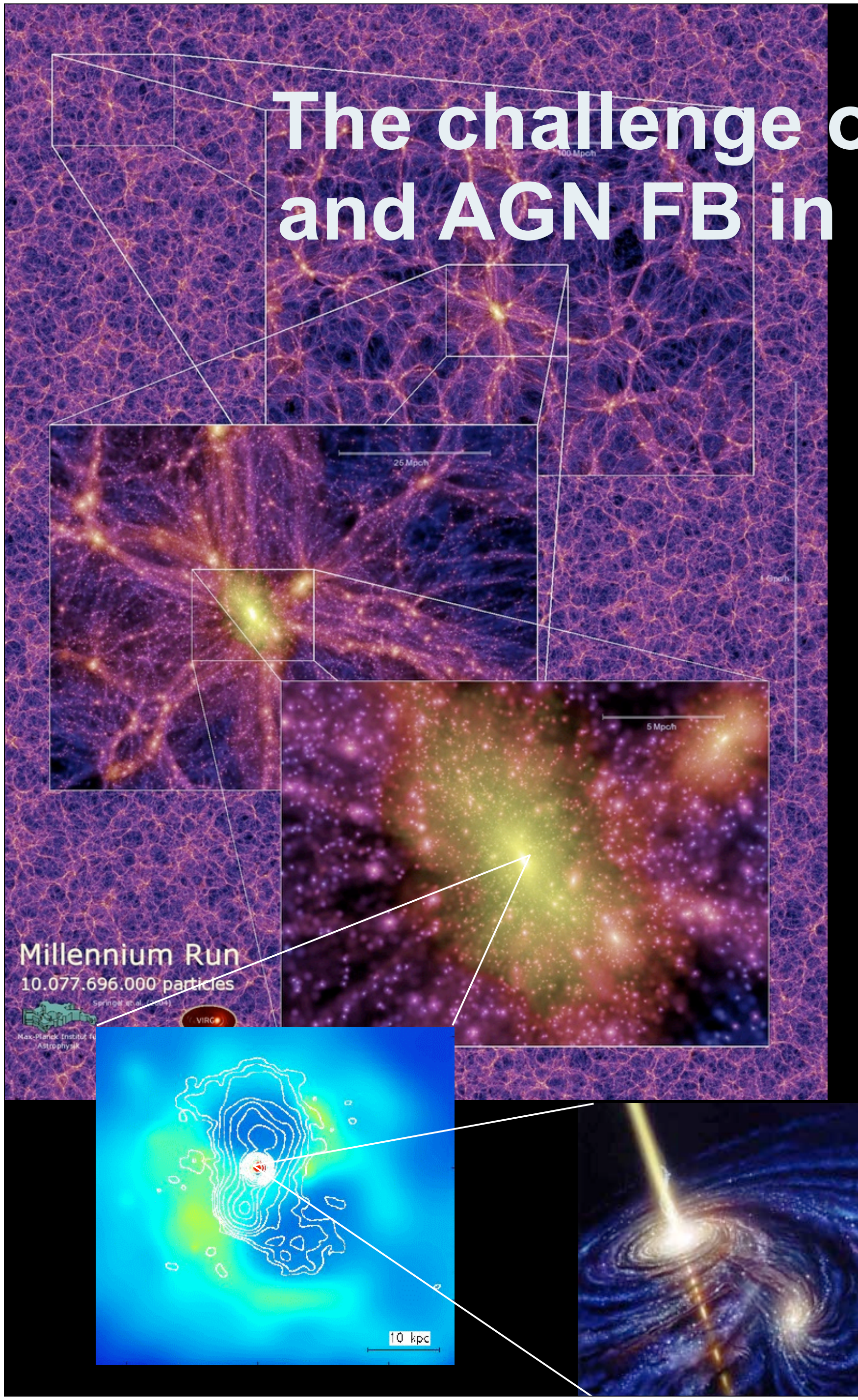
Why AGN Feedback Can Make Massive Galaxies Red/Dead

- Need mechanism to
  - quench star formation in massive galaxies
  - stop cooling in clusters
- SN feedback inadequate: not enough energy, little star formation in red galaxies
- BH mass closely connected with host galaxy's spheroid mass
- Bigger BH ⇒ more energy
  (L_{max} ~ L_{Edd} ~ M_{BH})



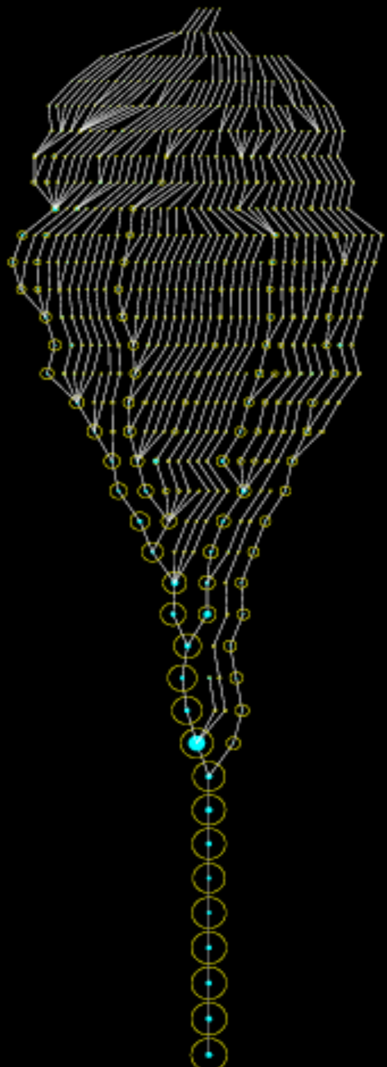
Magorrian et al. 1998;
Gebhardt et al. 2000,
Ferrarese & Merritt 2000

The challenge of simulating BH growth and AGN FB in a cosmological context



- dynamic range:
  - Gpc (luminous QSO)
  - few 100 Mpc (LSS)
  - 10's of kpc (ICM, jets)
  - sub-kpc (star formation, stellar FB)
  - few 100 pc (nuclear gas inflows, starbursts, AGN feeding, winds)
  - pc & sub-pc (accretion disk, BH mergers, etc)
- poorly understood physics (B-fields, conduction, cosmic ray pressure, turbulence, feeding problem, ...)

NEW Self-Consistent Model for the Co-Evolution of Galaxies, Black Holes, and AGN



- Top-level halos start with a ~100 M_{sun} seed BH
- Mergers trigger bursts of star formation and accretion onto BH; efficiency and timescale parameterized based on hydrodynamical merger simulations (μ, B/T, V_c, f_g, z; Cox et al., Robertson et al.)
- BH accrete at Eddington rate until they reach ‘critical mass’, then enter ‘blowout’ (power-law decline) phase

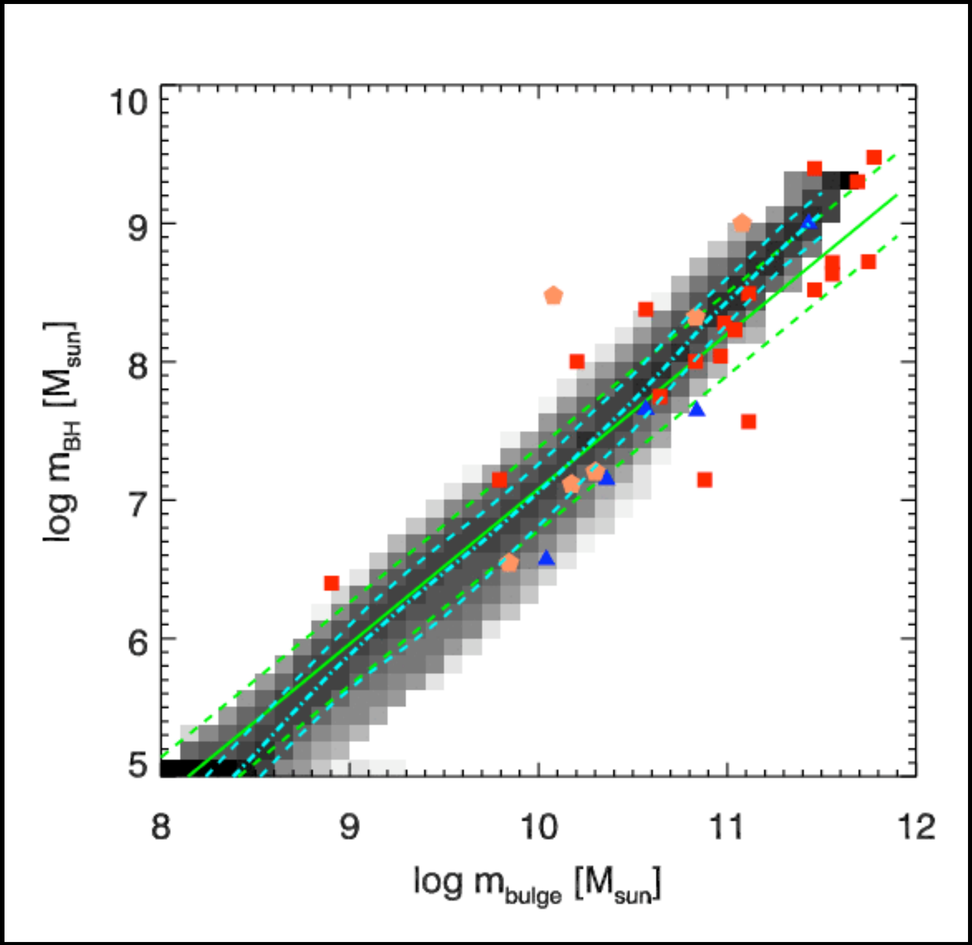
$$dm_{acc}/dt = \dot{m}_{Edd}/[1+(t/t_Q)^{\beta}]$$

- Energy released by accretion drives a wind
- BH merge when their galaxies merge; mass is conserved

Somerville, Hopkins, Cox, et al. 2008 MN in press

Predicted M_{BH}-M_{bulge} relationship

in Somerville+08 model, arises from 'bright mode' feedback



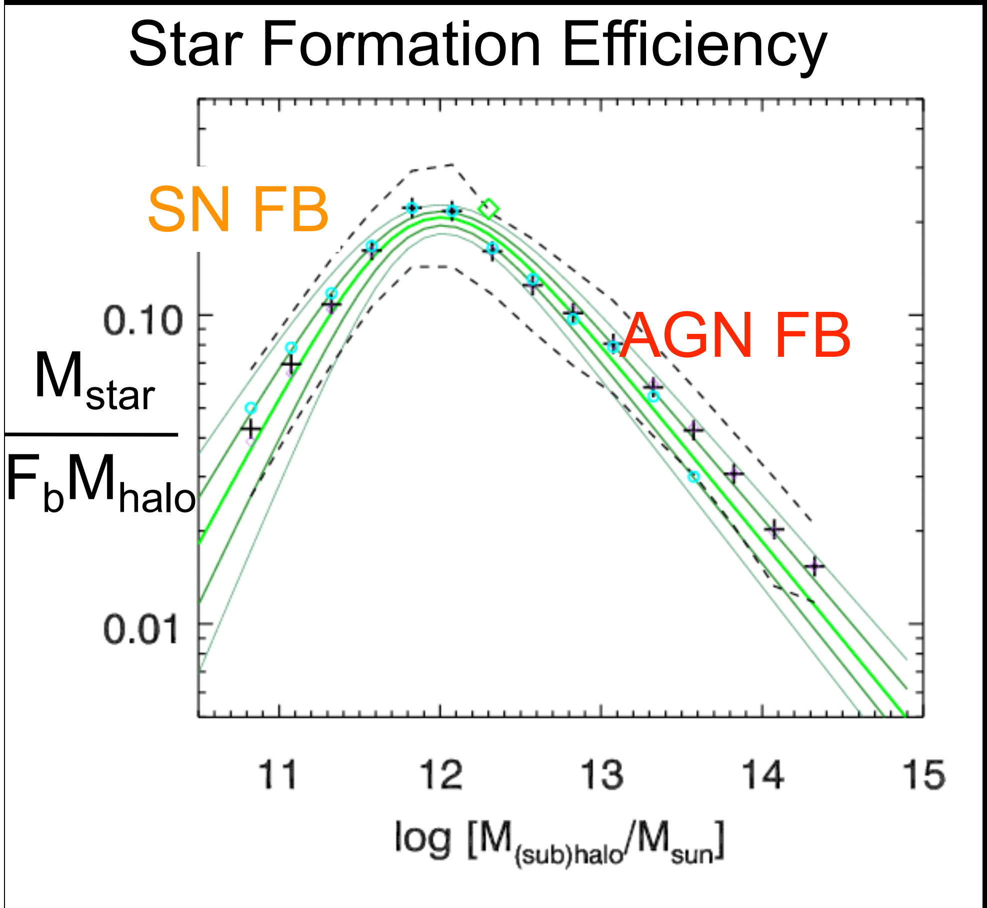
matches slope & scatter of observed relation

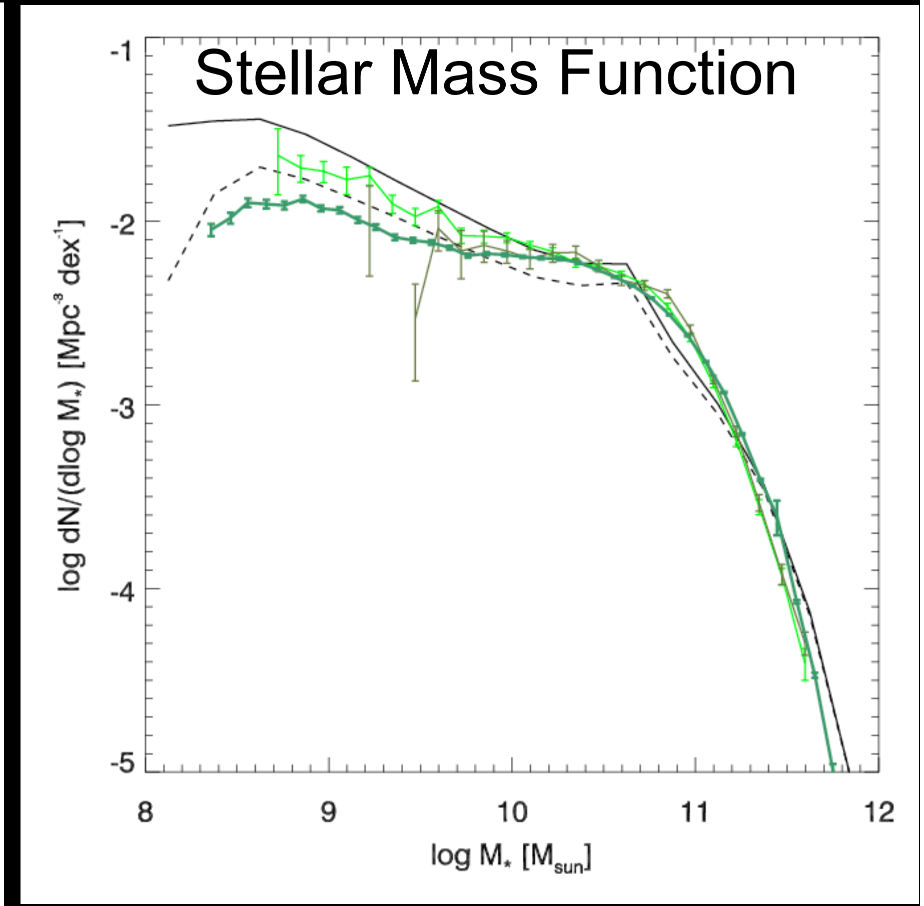
large symbols:
Haering & Rix data
green: H&R fit + scatter
intrinsic scatter: 0.3 dex

cyan: predicted median, 10th, & 90th percentile
predicted scatter: ~0.15 dex

Somerville et al. 2008

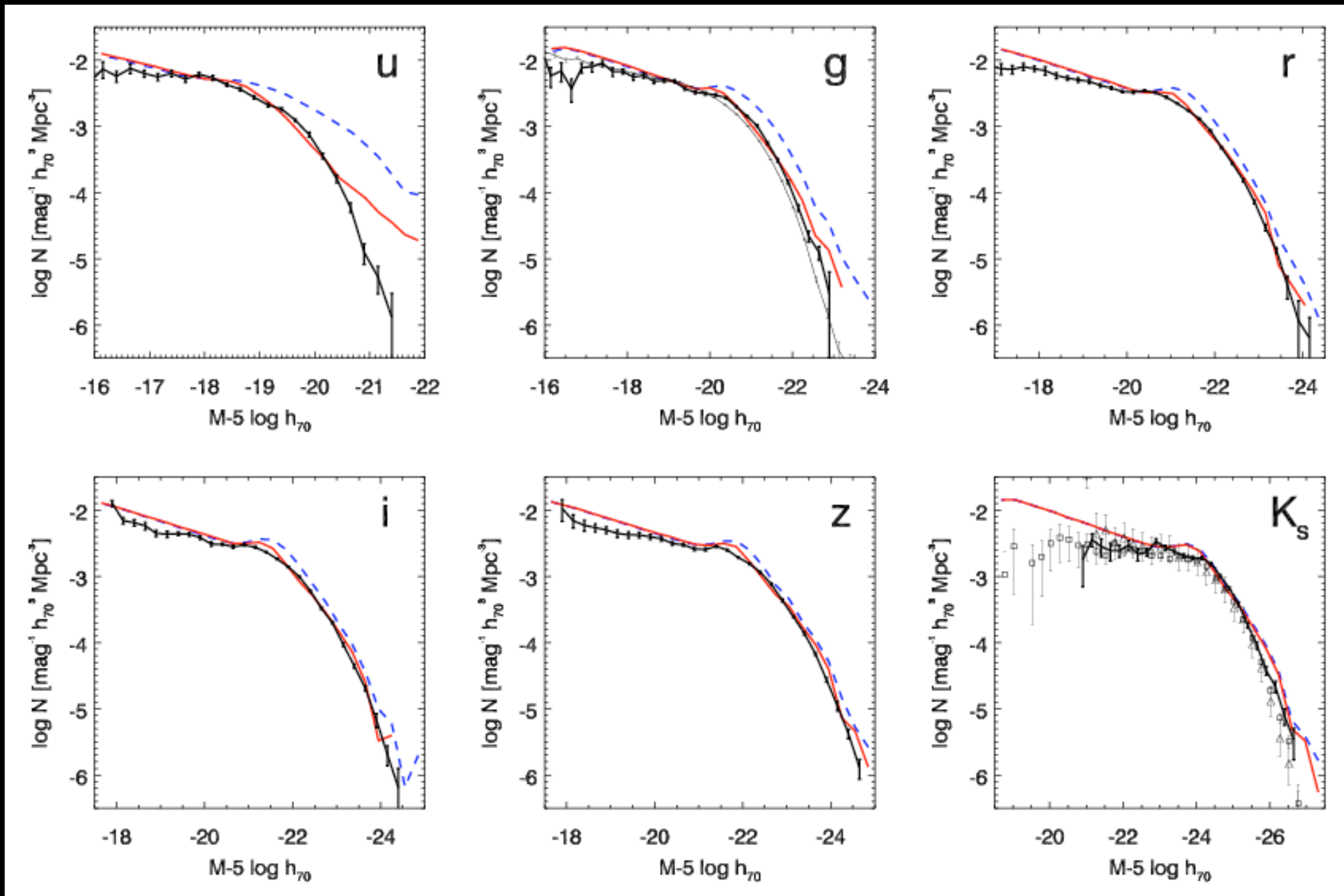
AGN Heating Leads to Galaxy Mass Functions at z~0 in Agreement with Observations





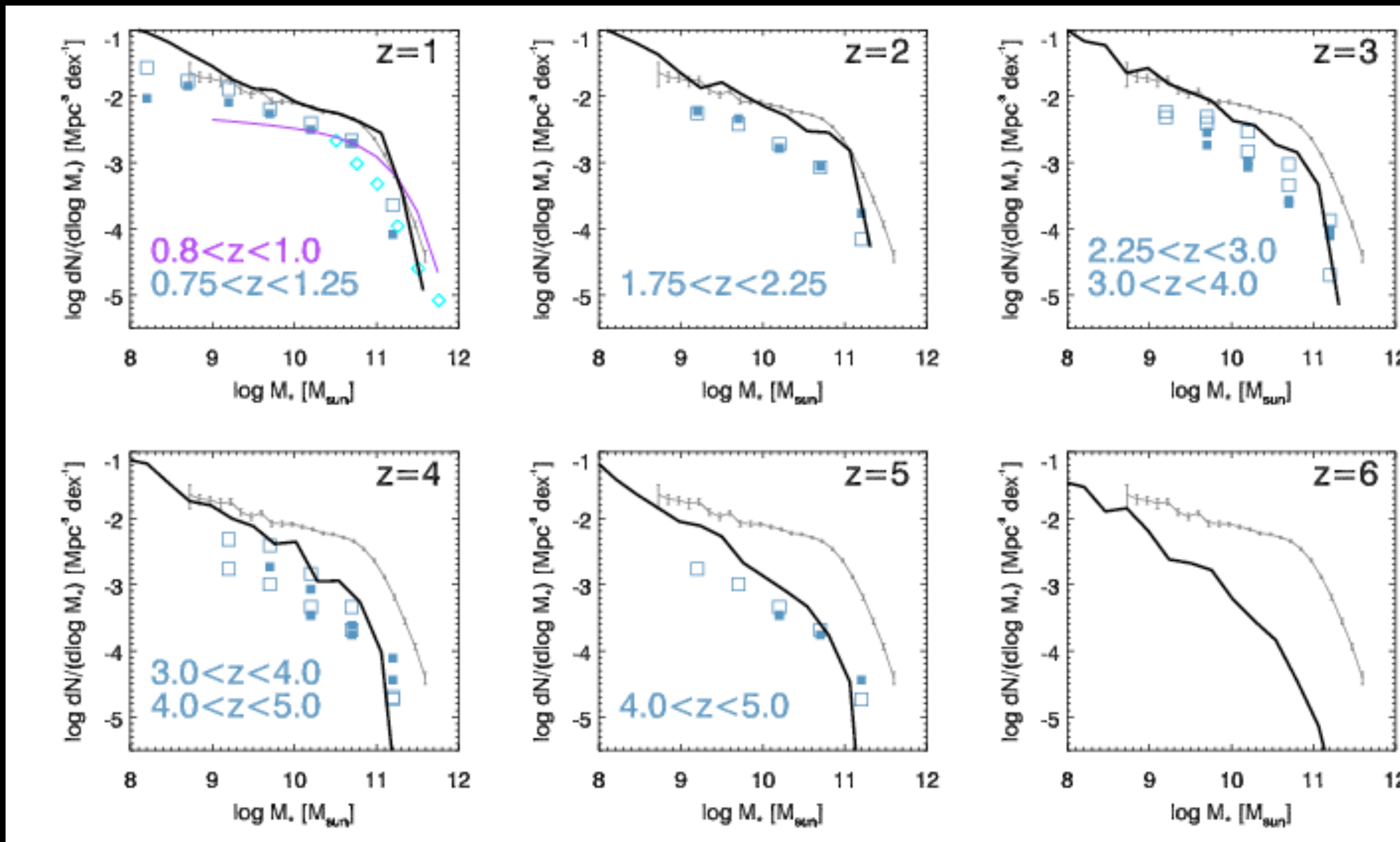
Somerville et al. 2008

Luminosity Functions



Somerville et al. 2008

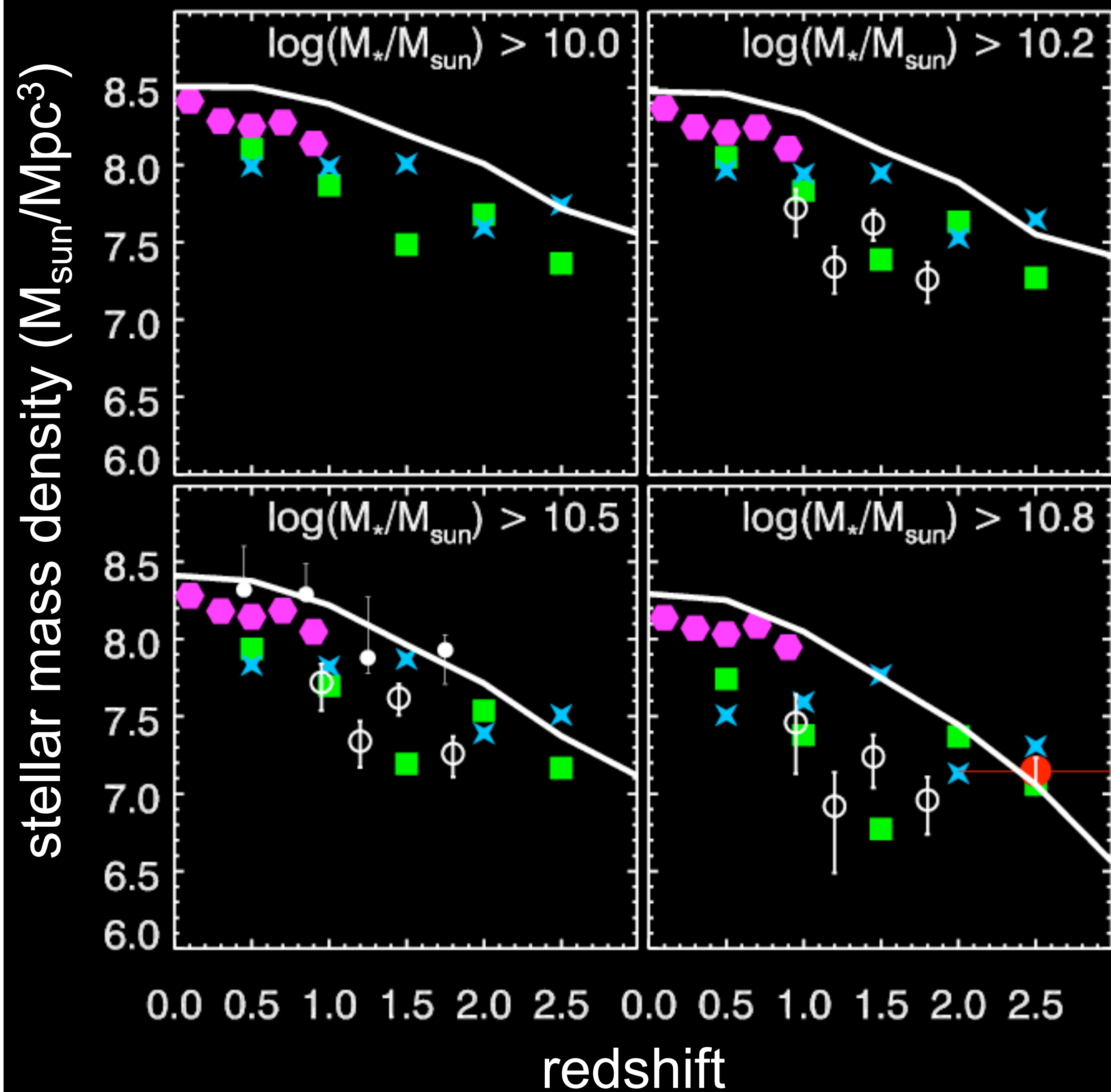
Stellar Mass Function Evolution



data from Borch et al. (COMBO-17);
Drory et al. (MUNICS, GOODS, FDF)

Somerville et al. in prep

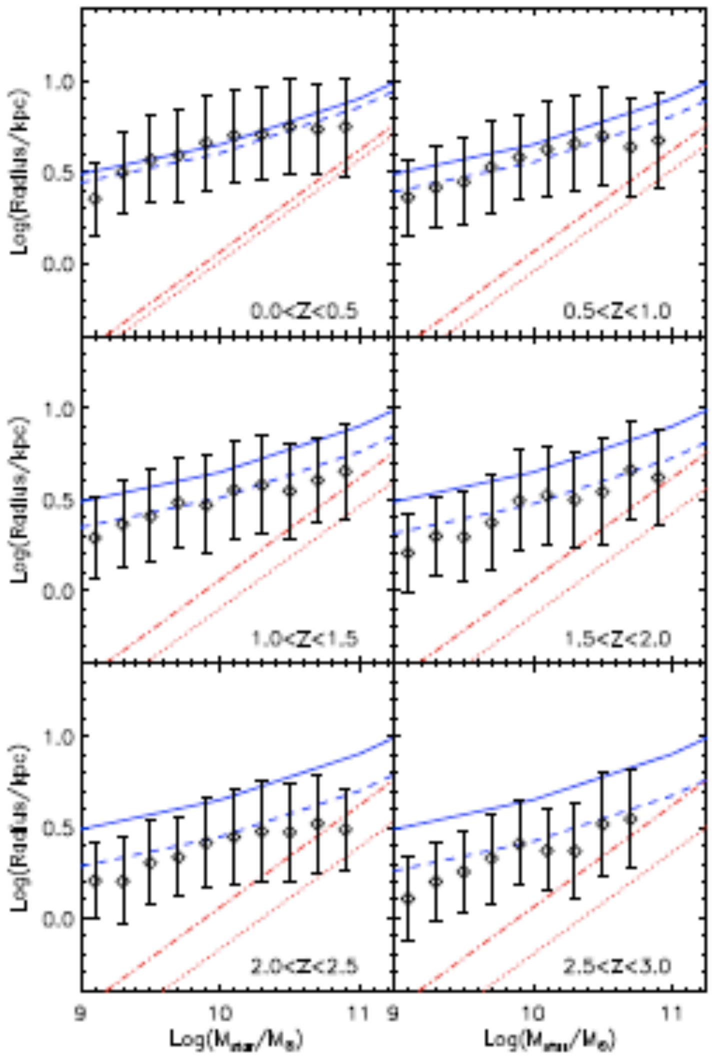
Model produces enough massive galaxies at high redshift



observations:
Borch et al. (COMBO-17)
Drory et al. (GOODS)
Glazebrook et al. (GDDS)
Fontana et al. (K20)
Papovich et al. (GOODS DRGs)

Somerville et al. 2008;
see also Bower et al.2006;
Kitzblicher & White 2006

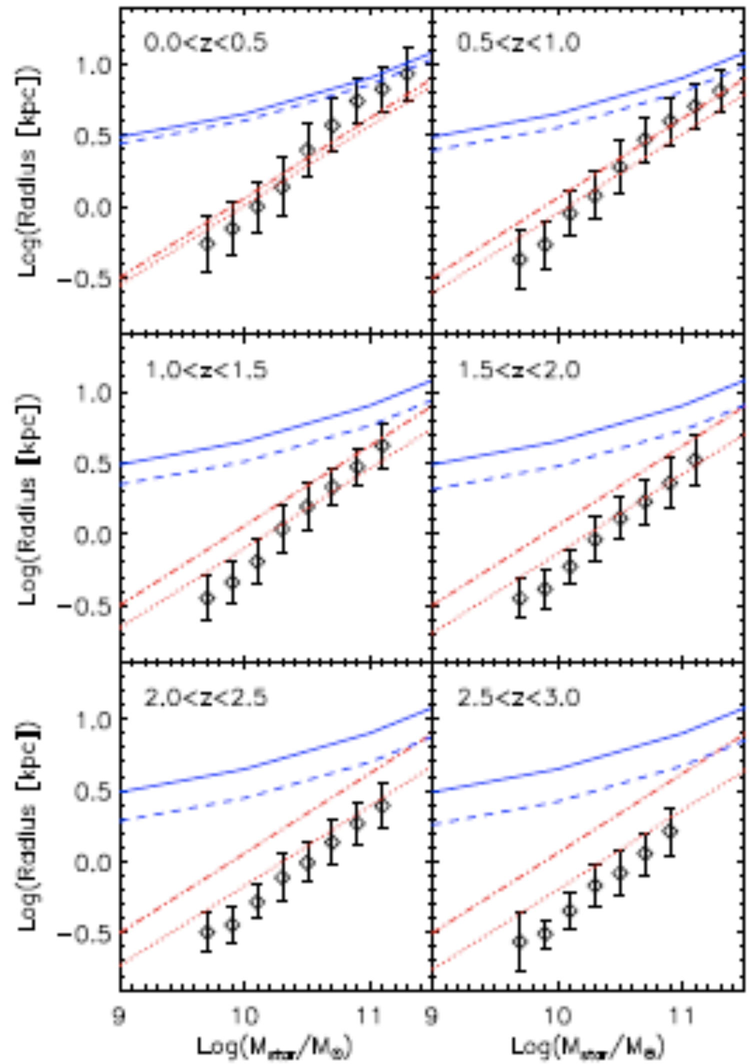
Somerville+08 SAM + Mergers Predict Observed Size-Mass



DISKS

z ~ 0 observations SDSS

higher z data Trujillo+06

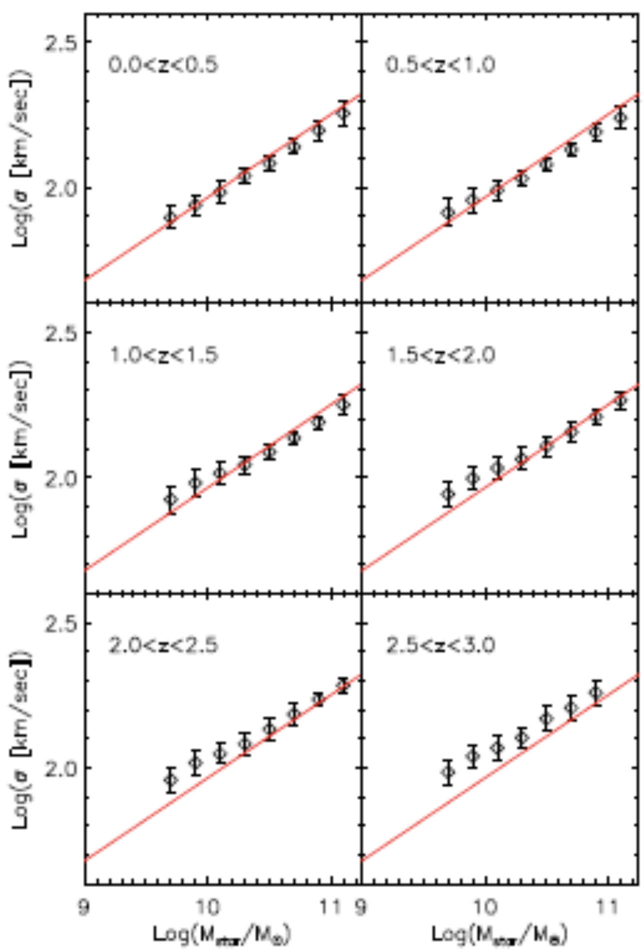


SPHEROIDS

z ~ 0 observations SDSS

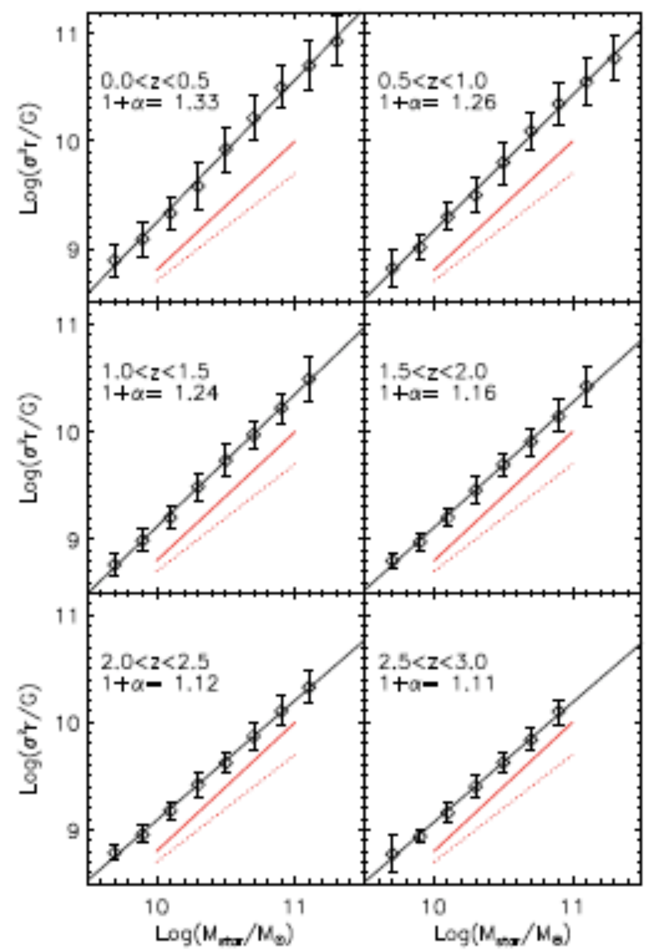
higher z data Trujillo+06

Faber-Jackson relations for the remnants in the S08 SAM, binned by redshift. Model predicts little F-J evolution.



Red line is the observed relation at low redshift (Gallazzi et al., 2006).

Fundamental Plane plotted as M_* vs. M_{dyn} for the remnants in the S08 SAM, binned by redshift. Model reproduces observed tilt of the Fundamental Plane.



observed scaling $M_{dyn} \propto M_*^{1.2}$

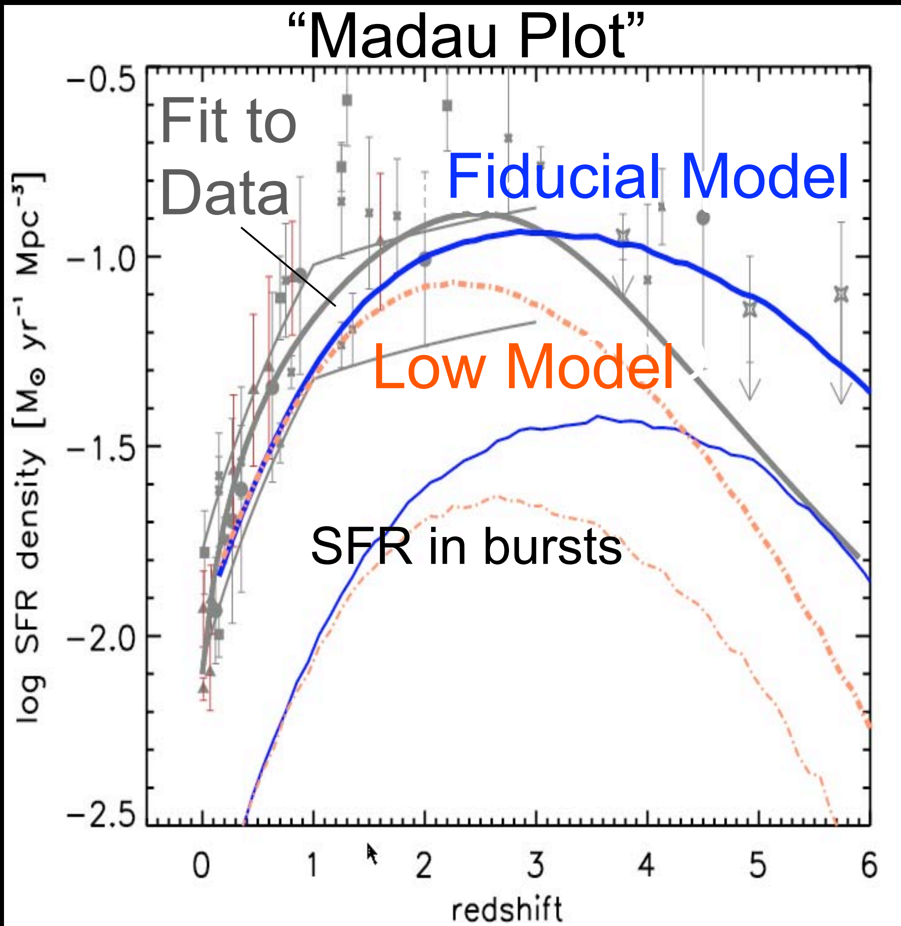
virial scaling

Matt Covington dissertation 08, Covington et al. in prep.

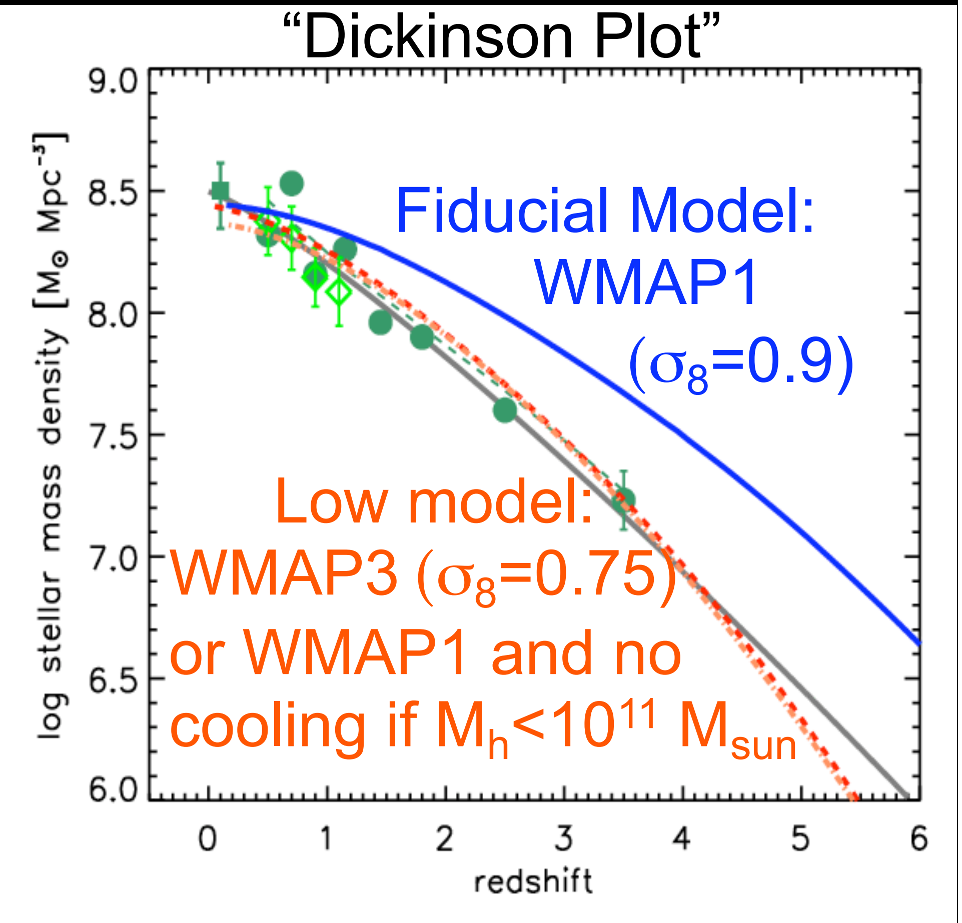
The black line is fit to the SAM remnants with $M_{dyn} \propto M_*^{1+\alpha}$ ($1 + \alpha$ is shown on the figure).

History of Star Formation and Stellar Mass Build-up

Star Formation History

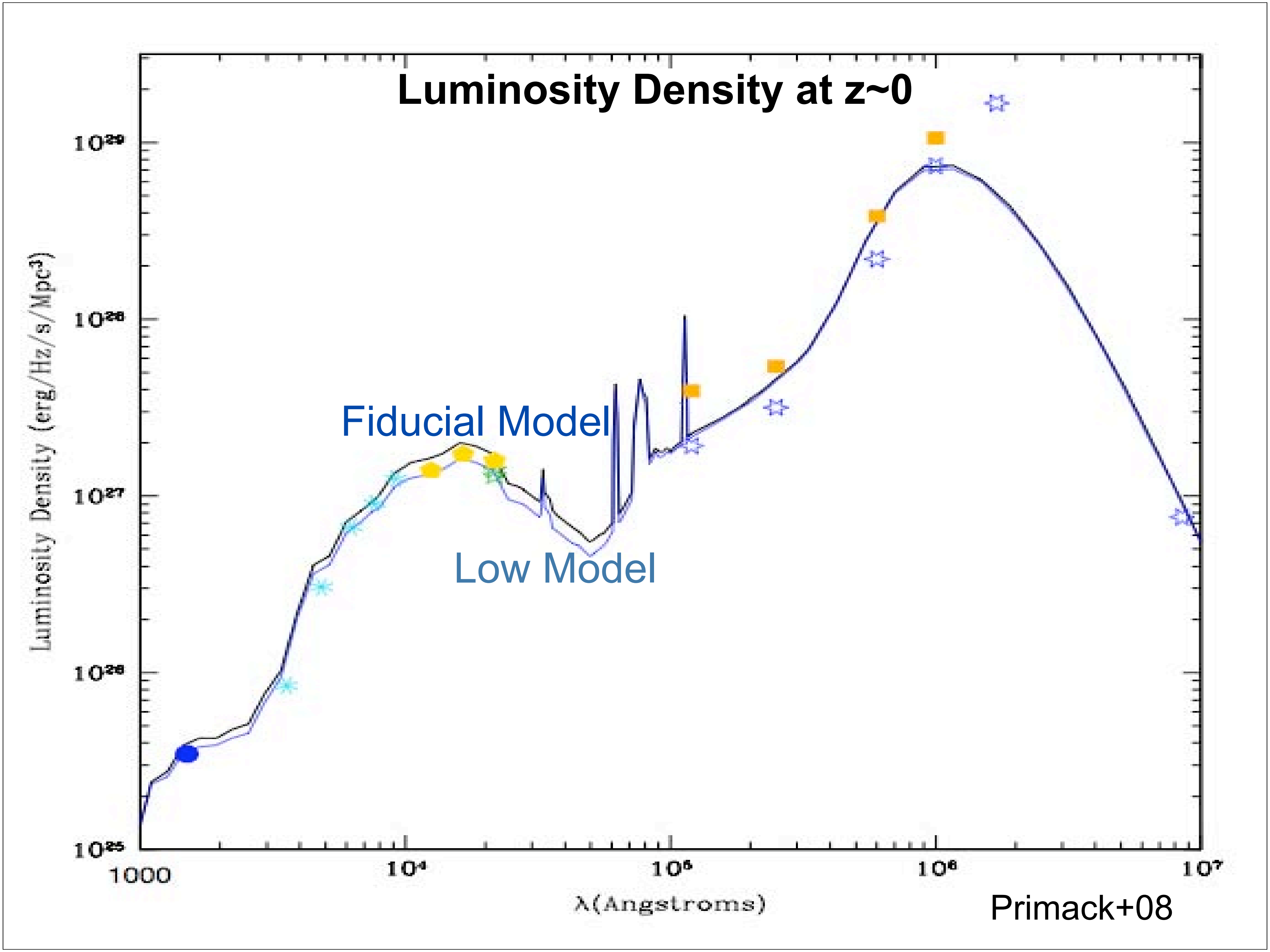


Stellar Mass Build-up



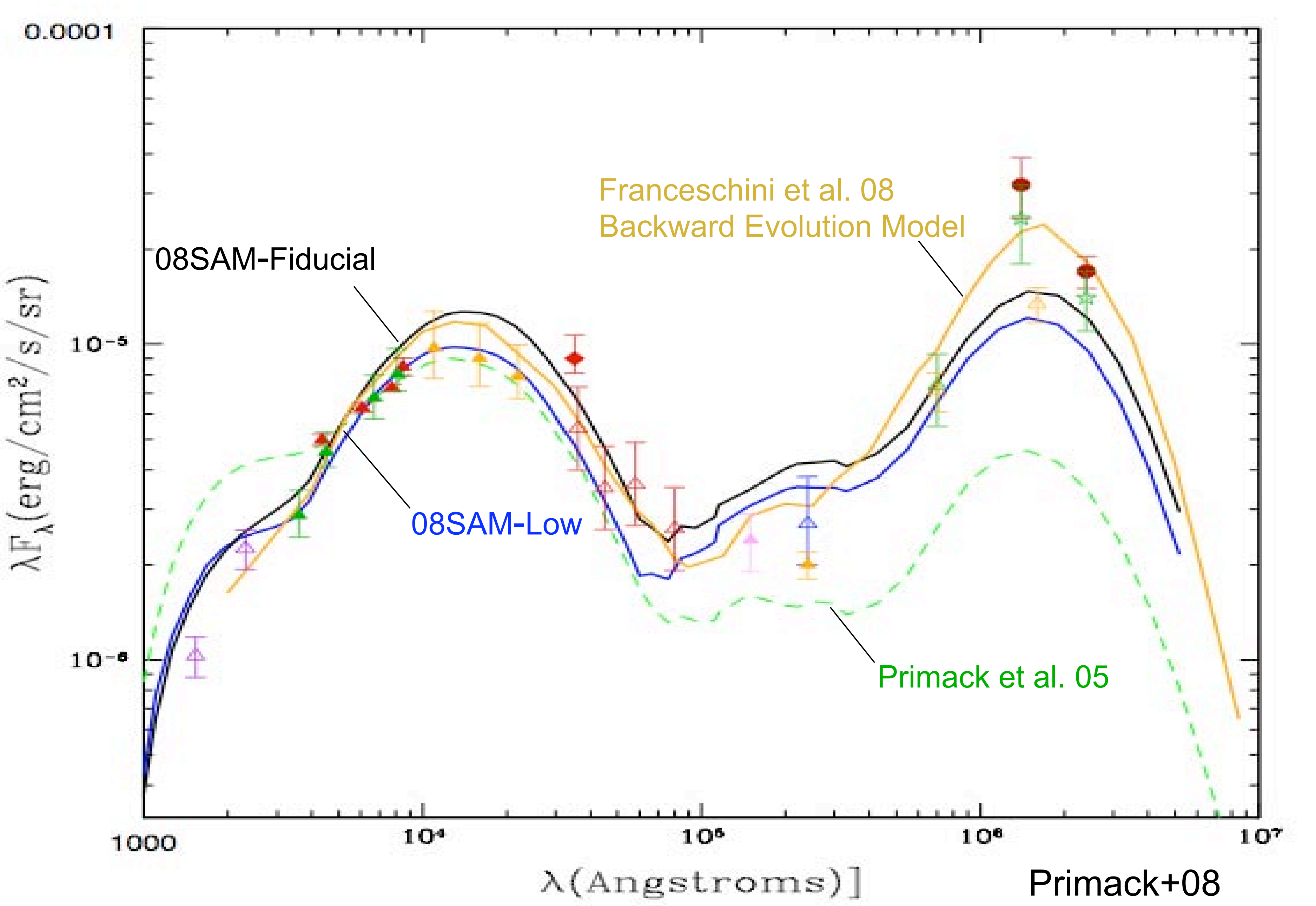
Discrepancy: SFR indicators or IMF evolution?

Somerville et al. 2008

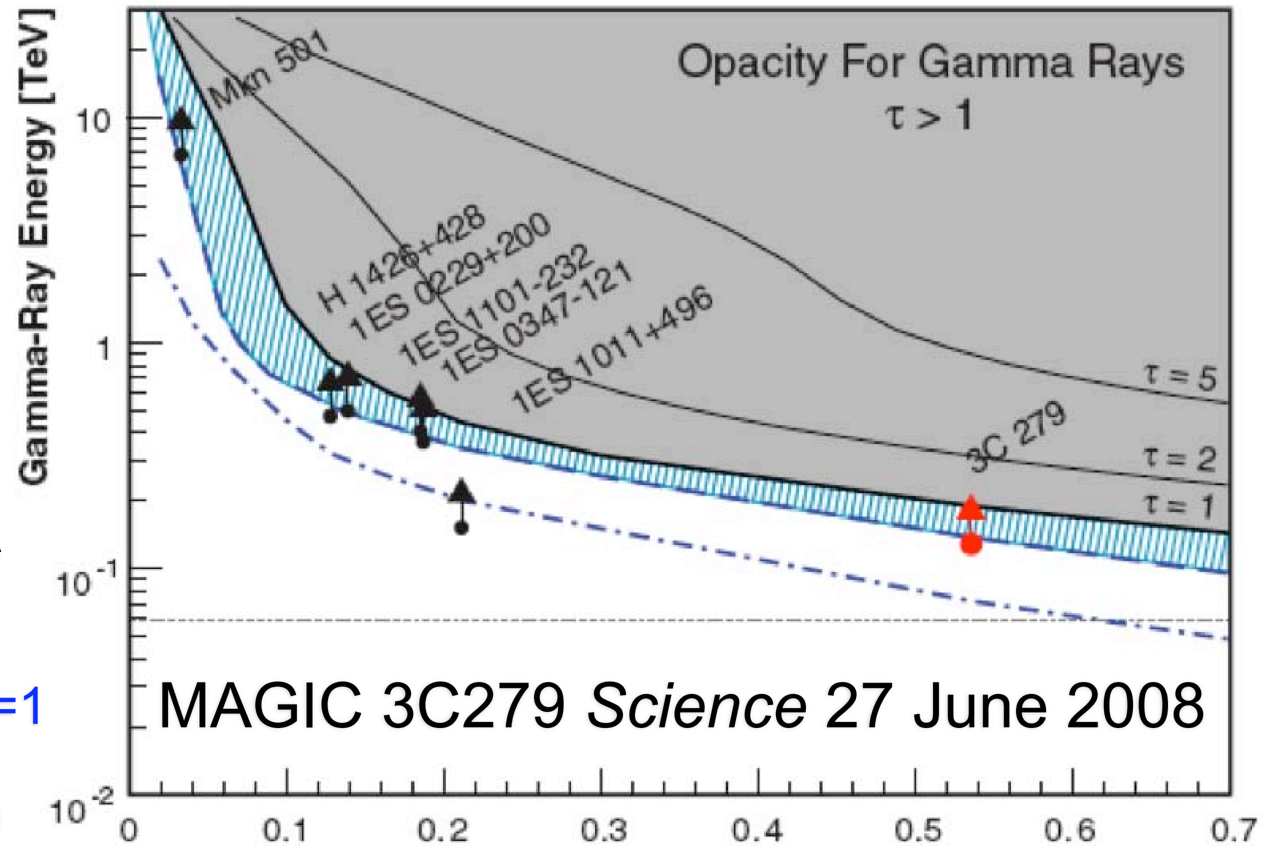


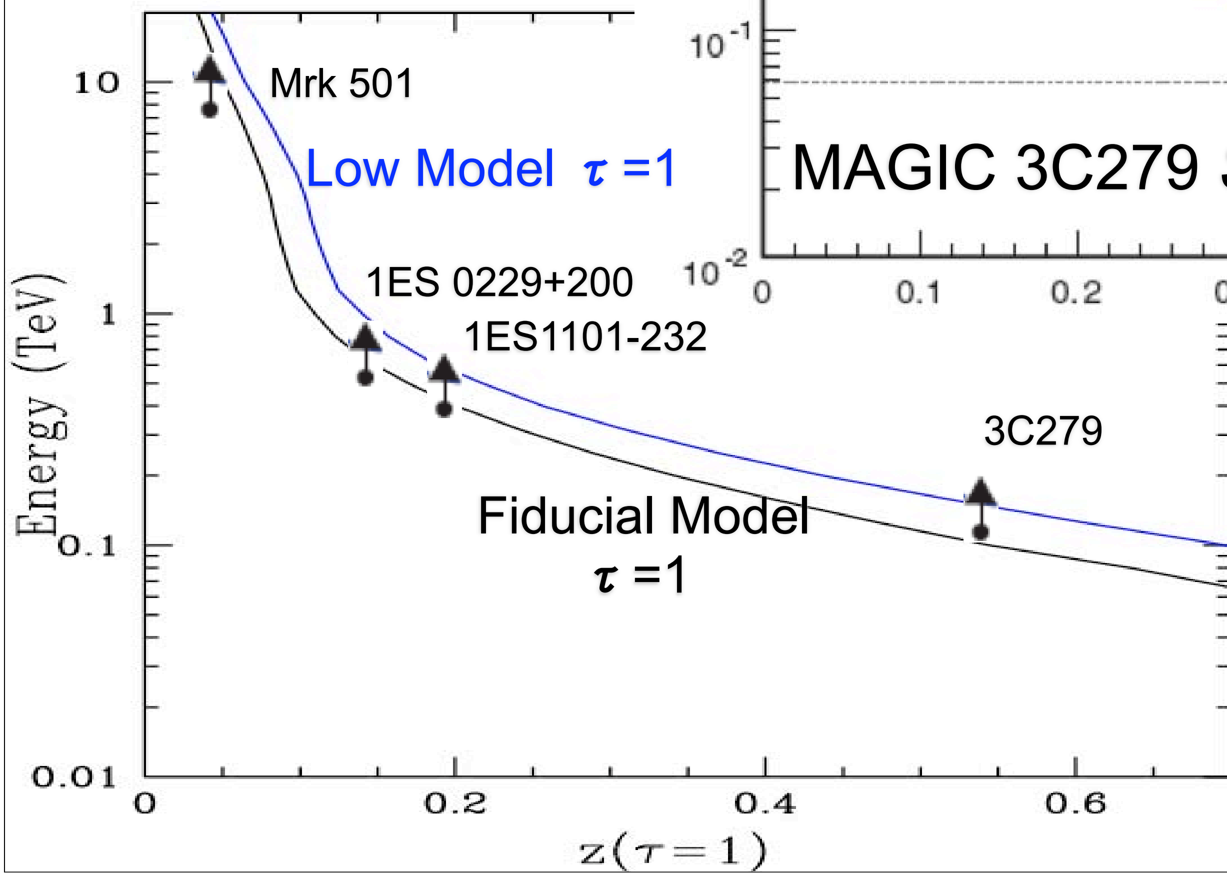
Luminosity Density at z~0
Fiducial Model
Low Model
Luminosity Density (erg/Hz/s/Mpc^3)
10^{29}
10^{28}
10^{27}
10^{26}
10^{25}
1000
10^4
10^5
10^6
10^7
λ(Angstroms)
Primack+08

Extragalactic Background Light



Gamma Ray Attenuation Due to **Fiducial** and Low Models





Low Model is well within observational constraints

Fiducial Model also looks OK!

Conclusions

- **High resolution DM simulations show halo substructure. New hydrodynamic simulations are increasingly able to explain galaxy formation. At z>2, even massive halos have cold streams bringing in gas that quickly forms stars. At z<2 this only happens for $M_{halo} < 10^{12}$.**
- **Spheroids from mergers have observed size-mass relation and lie in observed Fundamental Plane.**
- **New self-consistent semi-analytic galaxy formation models based on physical scaling from numerical simulations and calibrated against empirical constraints now enable us to predict/interpret the relationship between galaxies, BH, and AGN across cosmic history.**
- **Such models accurately predict number counts and luminosity functions in all spectral bands and all redshifts except for sub-mm galaxies.**
- **The predicted range of EBLs is consistent with the best estimates of EBL evolution inferred from observations.**

[redacted]