ON
OBSERVATÓRIO NACIONAL

Divisão de Programas
de Pós-graduação

XIII Ciclo de Cursos Especiais

27 a 31 de outubro de 2008

Lecture 3 - Galaxy Data and Galaxy Formation Theory: Simulations

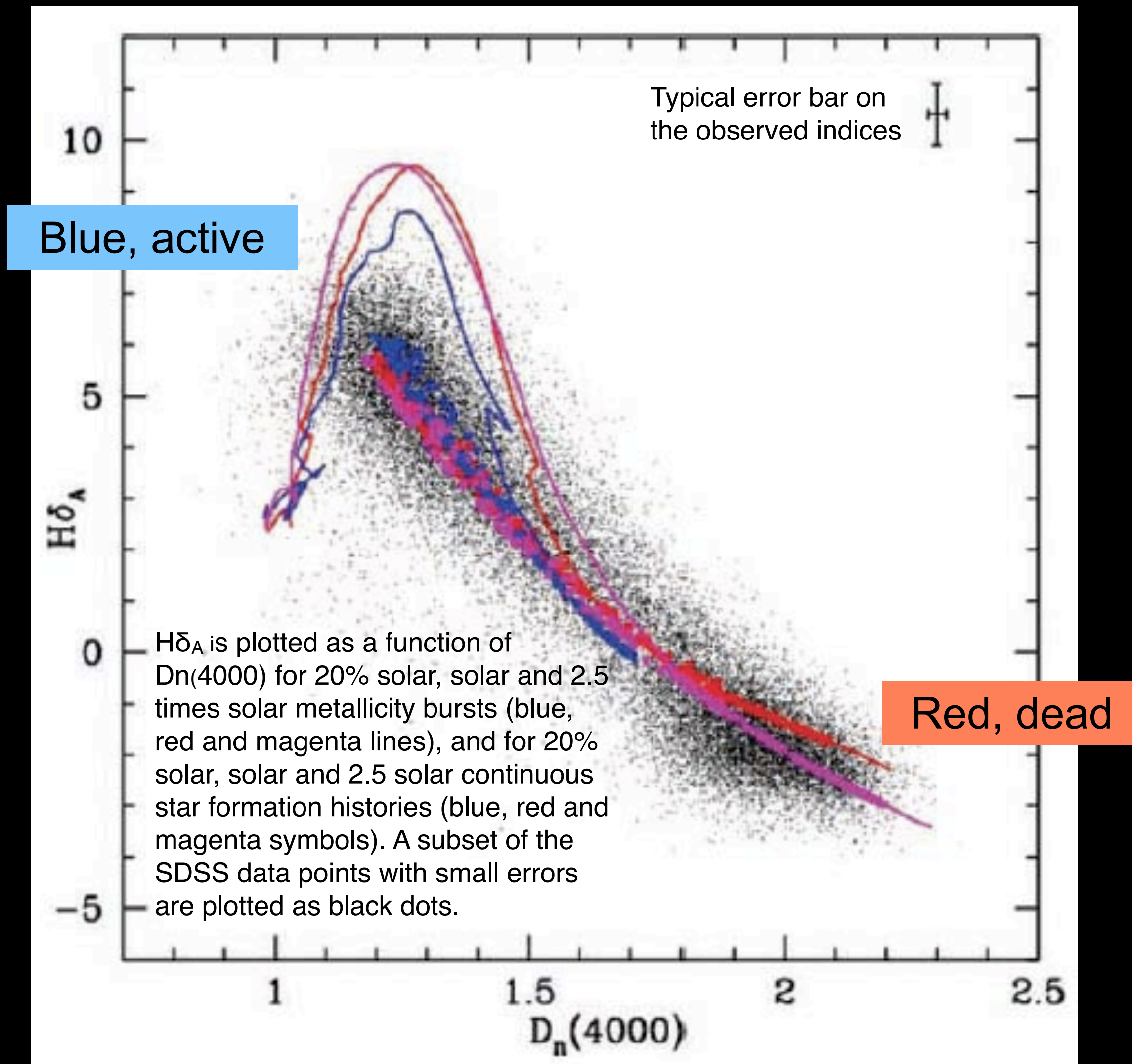
Joel Primack, UCSC

As I have discussed in Lectures 1 and 2, 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 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 discusses the currently available data on galaxies both nearby and at high redshifts, and the state of the art in galaxy formation simulations. I thank my collaborators Avishai Dekel, Aaron Dutton, and Sandra Faber for some of the slides in this lecture.

Revolutionizing new developments

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

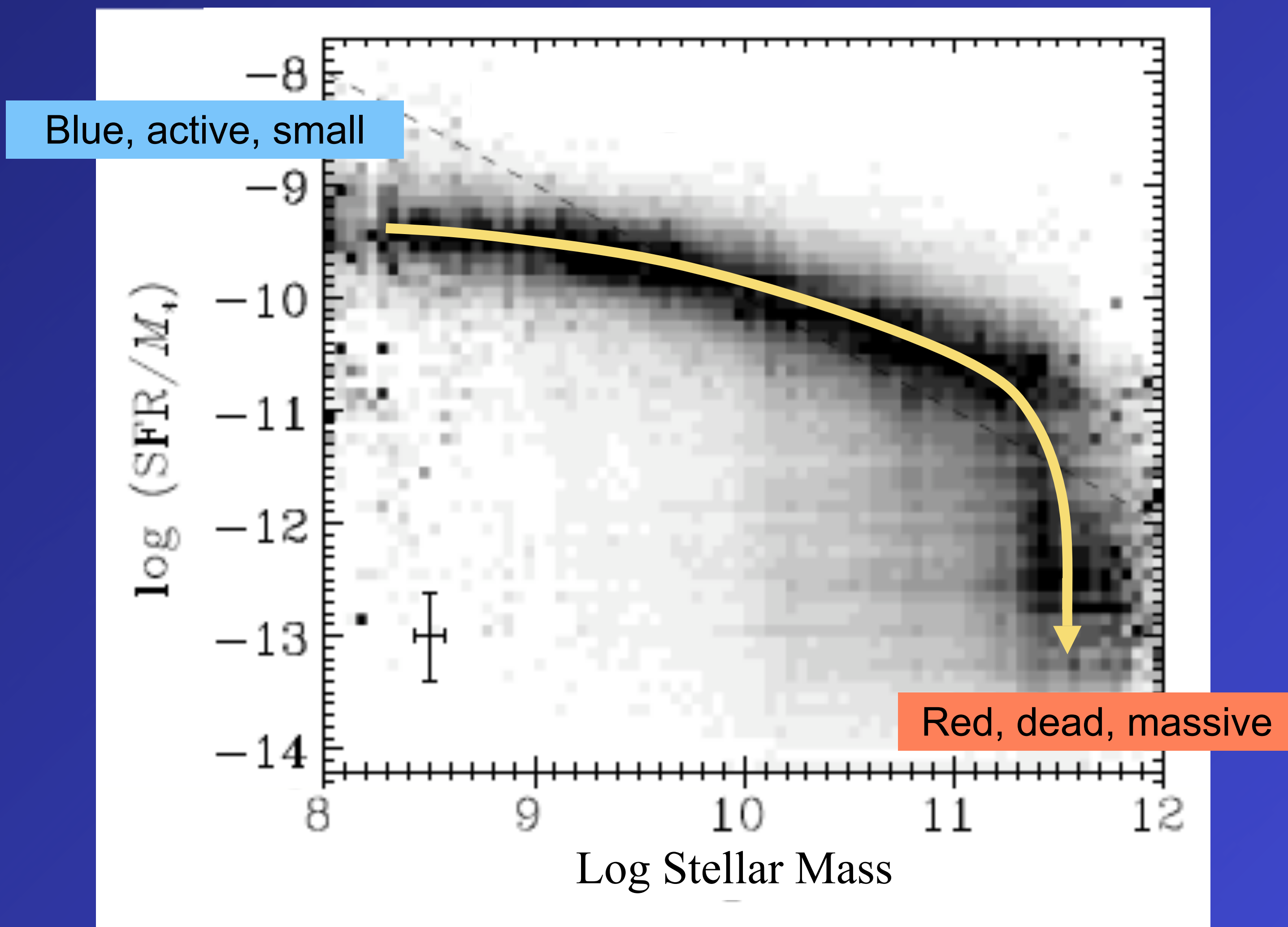
The Star-Forming Sequence in Stellar Population Indices



Kauffmann et al. 2003

The star-forming sequence is also a mass sequence

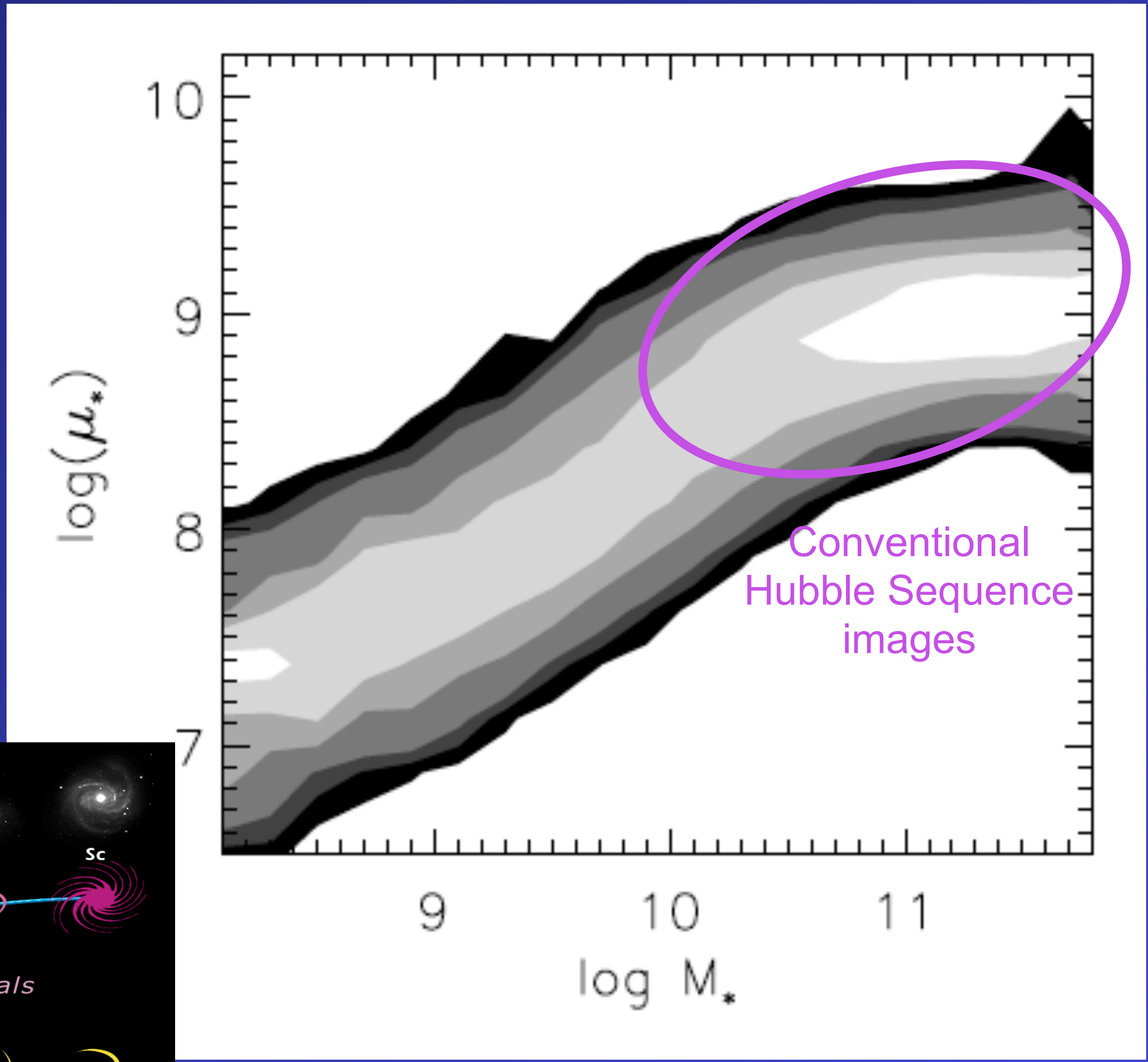
Specific SFR based on absorption-corrected GALEX UV flux

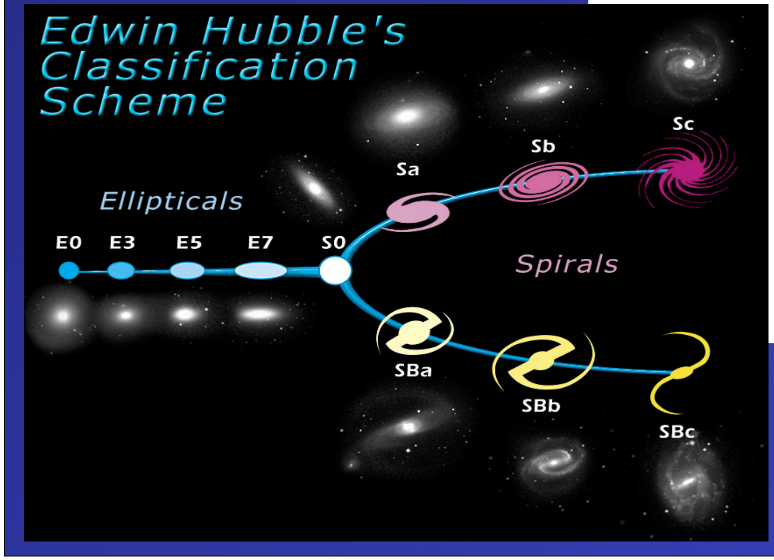


Samir et al. 2007

Other trends vs. stellar mass --

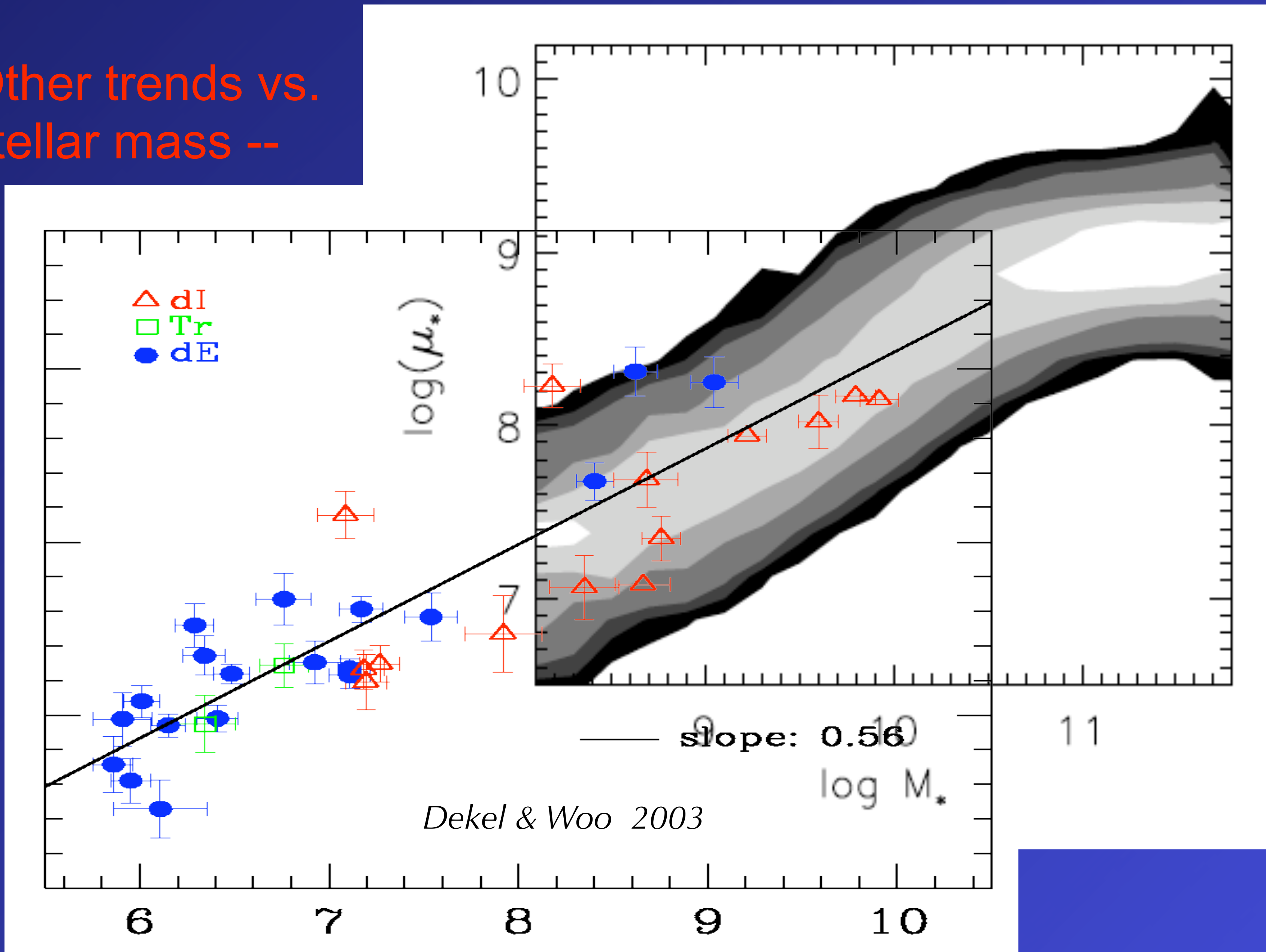
Surface mass density





Kauffmann et al. 2003: Sloan Survey

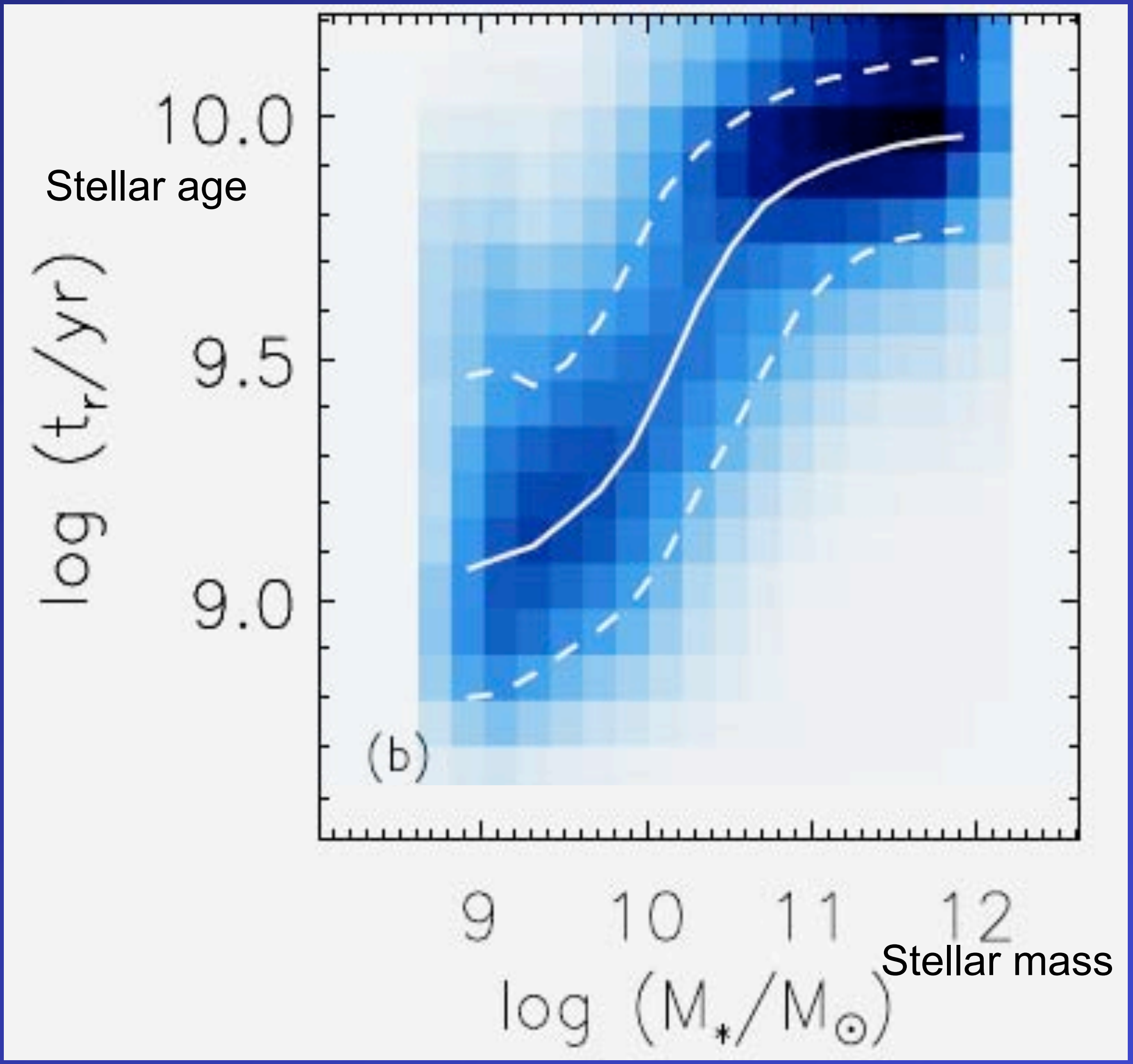
Other trends vs. stellar mass --



Other trends vs. stellar mass --

Mean stellar age

Stars in more massive galaxies are older.

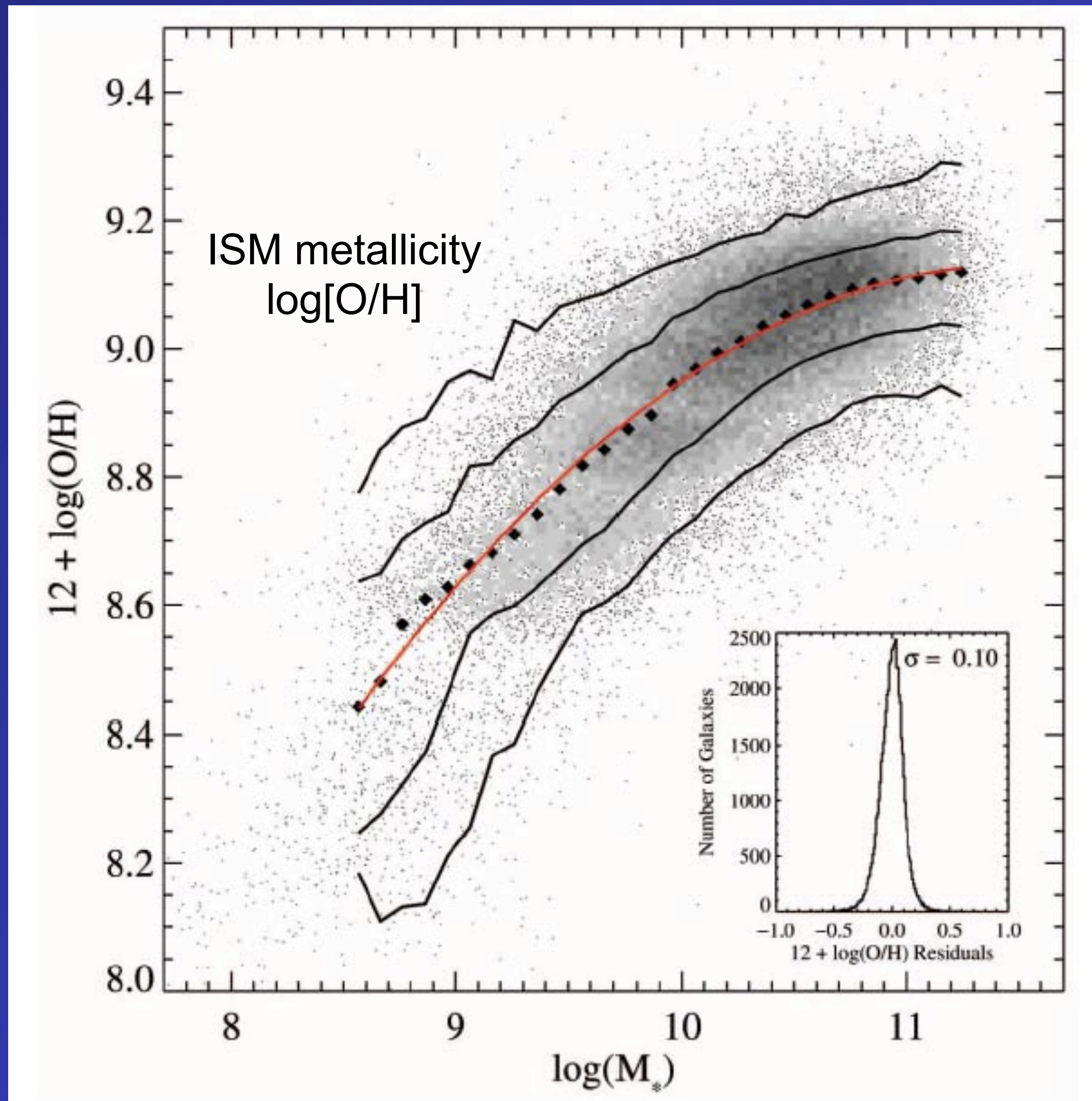


Gallazzi et al. 2005: Sloan Survey

Other trends vs. stellar mass --

Interstellar gas metallicity

Stars in more massive galaxies are more metal rich.

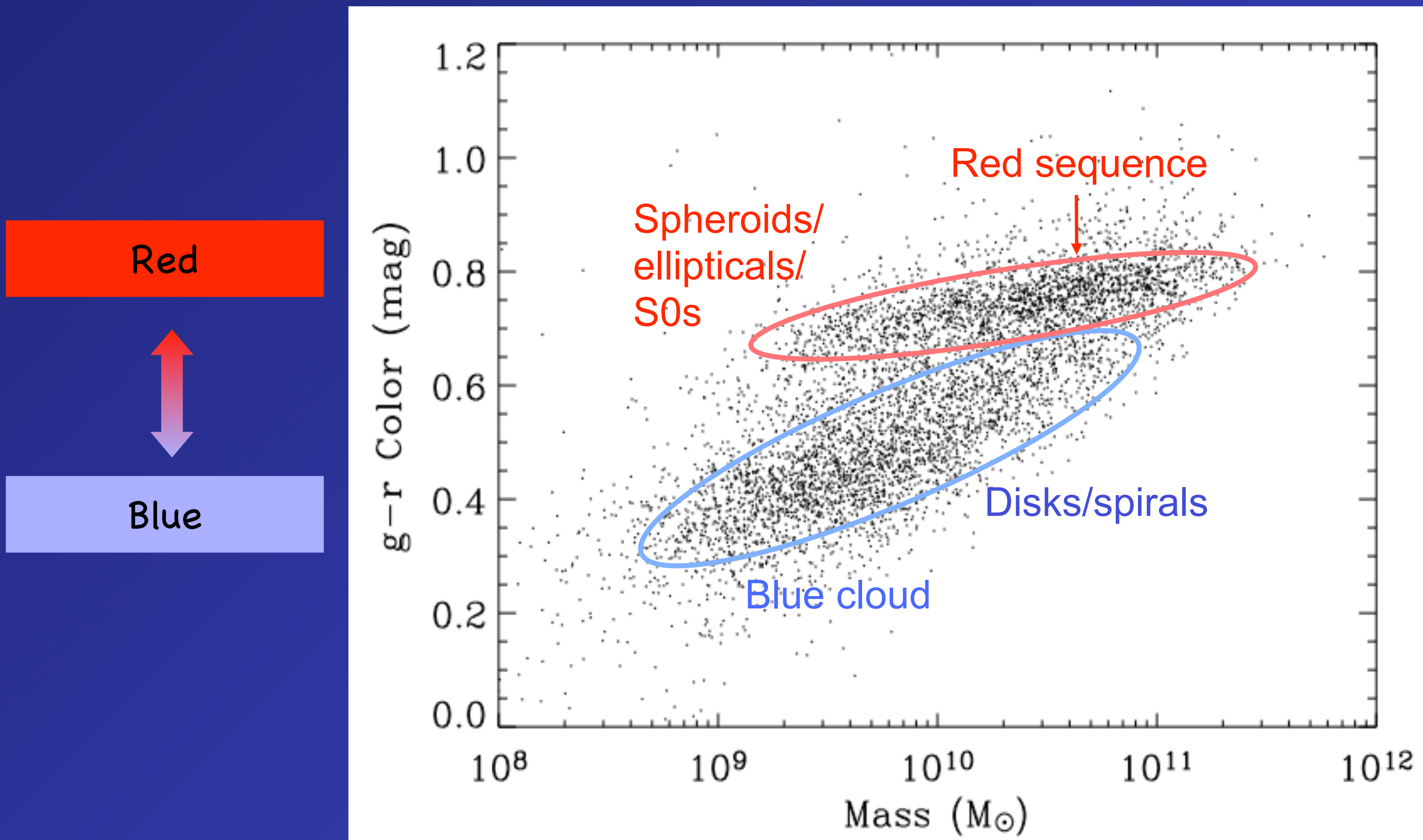


Tremonti et al. 2004: Sloan Survey

Color bimodality seen in Sloan galaxies

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

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

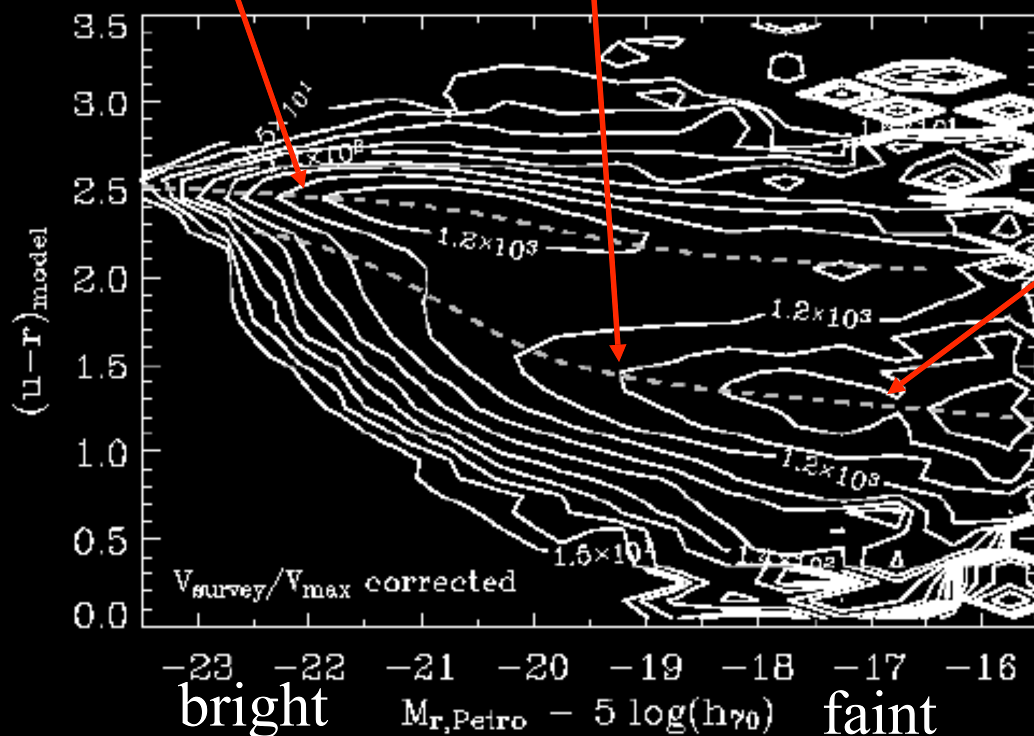


Color vs. stellar mass for Sloan Digital Sky Survey galaxies

Local Universe: galaxies are bimodal in color, morphology, & structure

old stars

young stars



strong correlation
between
stellar mass &
galaxy type

SDSS
Baldry et al. 2003

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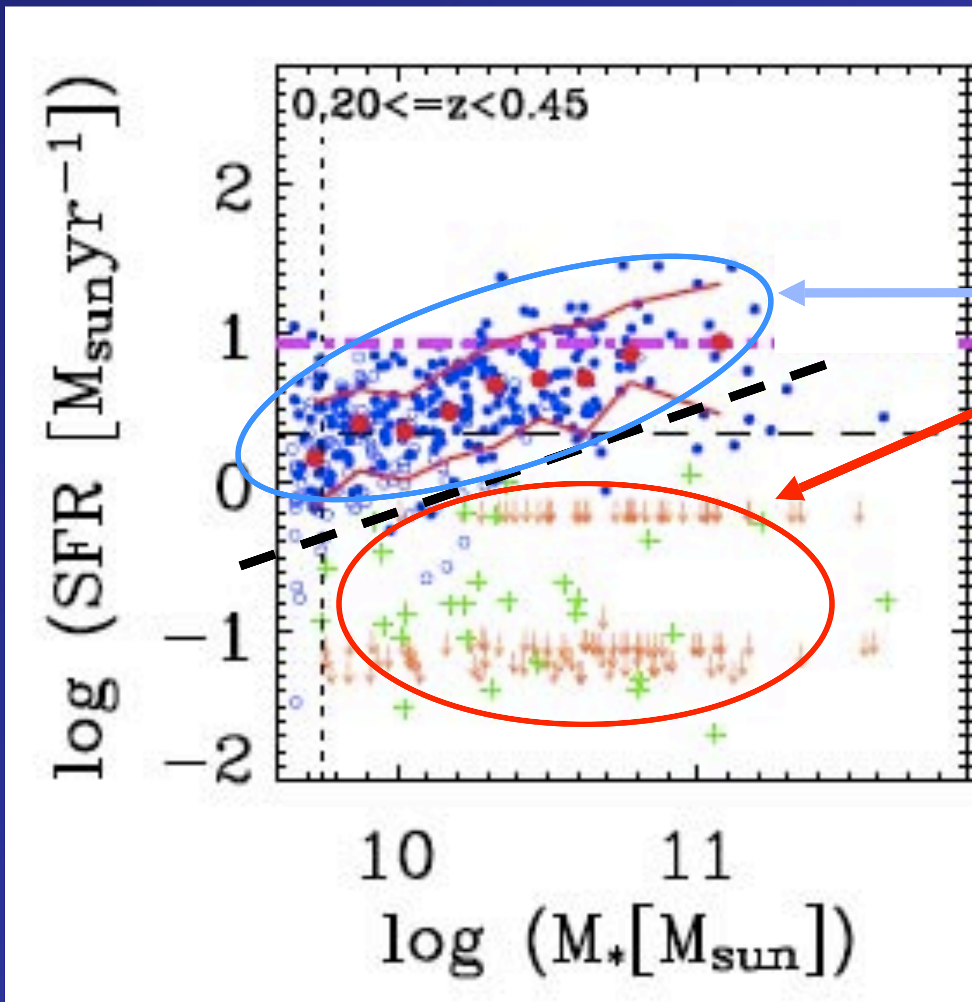
- **Broad wavelength coverage**
  - Old stars, young stars, star-formation rates, dust and gas, accreting BHs
  - Example: AEGIS Survey, outgrowth of DEEP2 in Groth Strip
  - Chandra (X-rays), GALEX (UV), Hubble (optical), SIRTF (IR), VLA (radio)


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

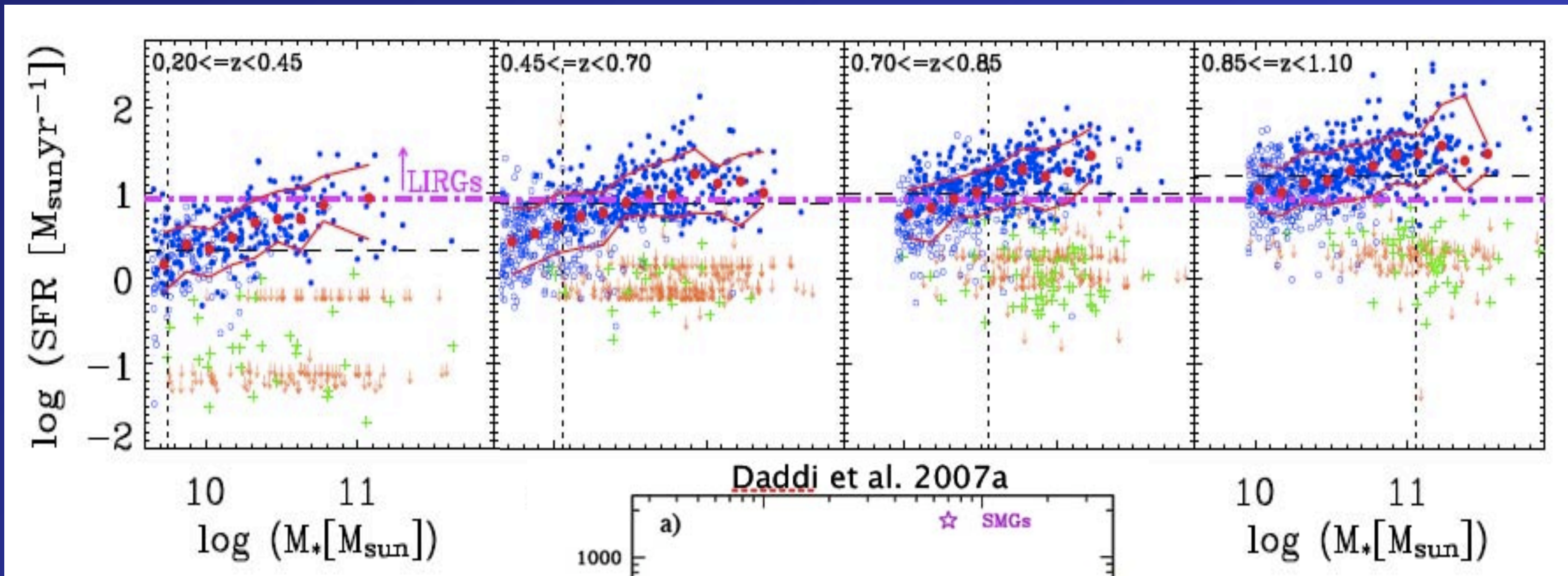
Red: quenched

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

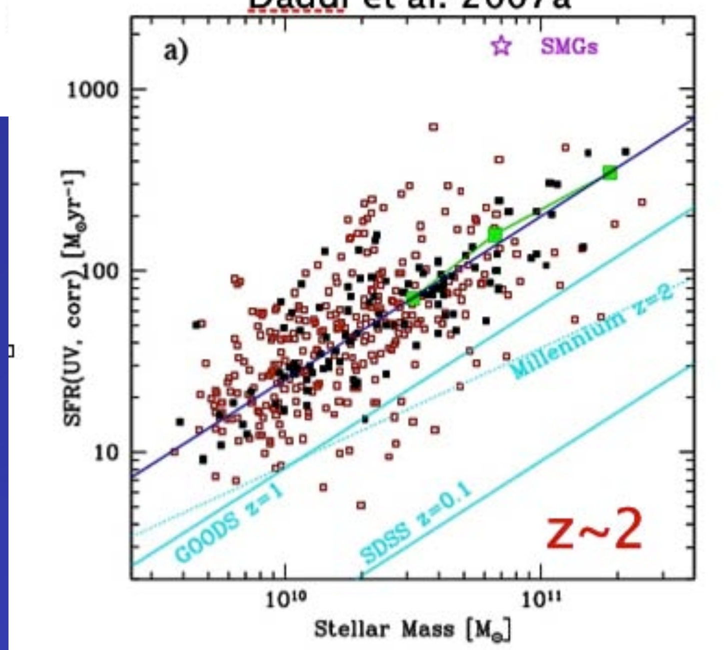
± 0.3 dex

Noeske et al. 2007

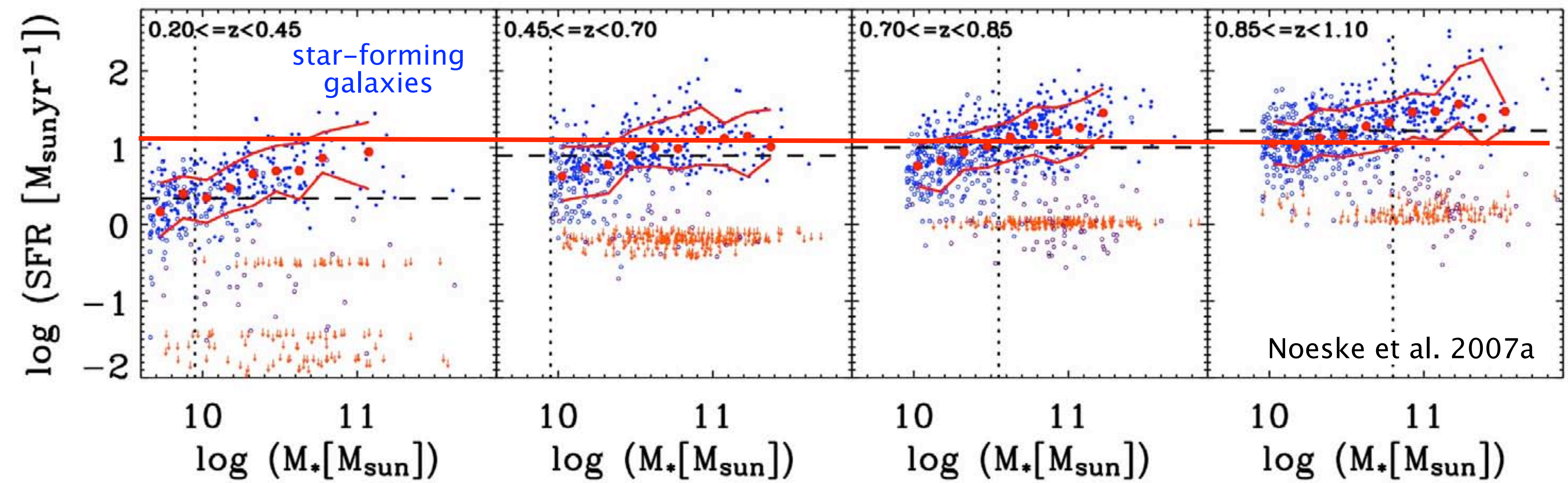
Star-formation rate from AEGIS



Daddi et al. 2007a



The Star Formation Rate–Stellar Mass Relation("Main Sequence")



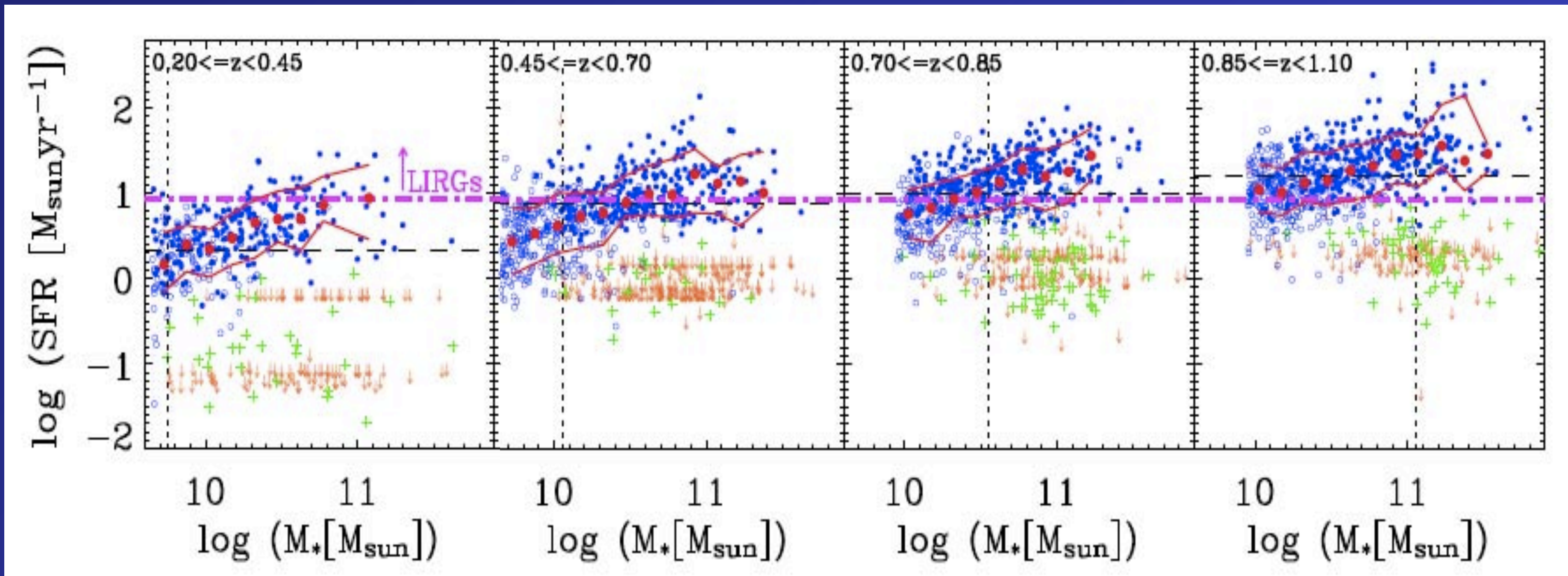
1) Star-forming galaxies form a defined relation:
SFR – stellar mass out to z>2.

2) Range of log(SFR) ~±0.3 dex (1σ) at all z:

starbursts had only a modest, barely evolving role out to z~2

3) Normalization evolves strongly with z:
evolution of SF since z~2 dominated by a gradual decrease of SFR

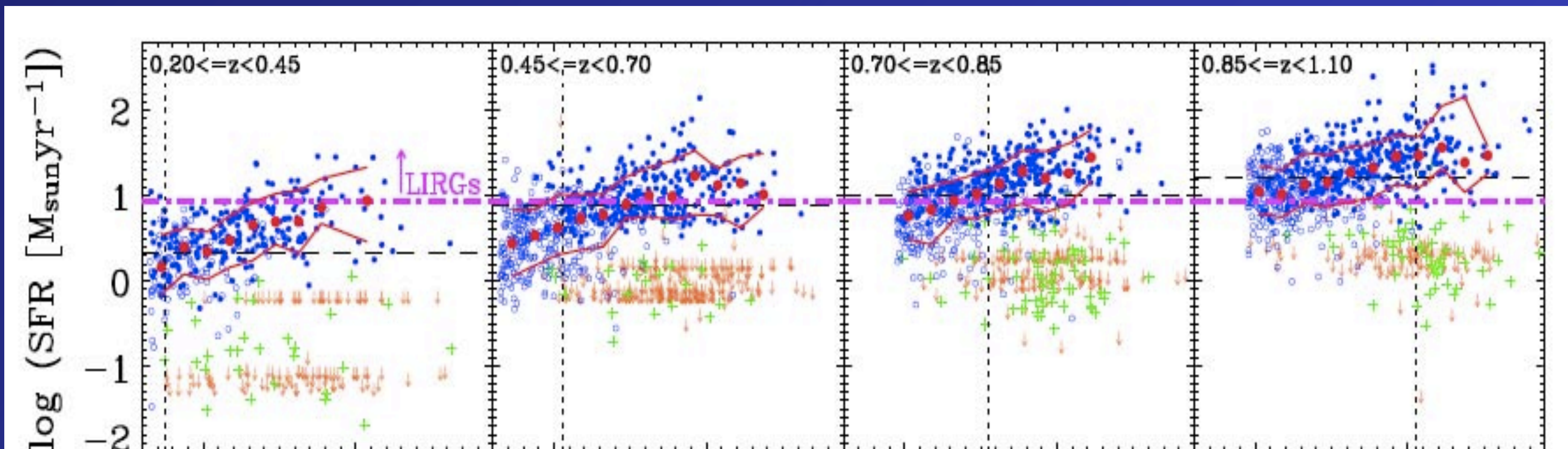
Star-formation rate from AEGIS

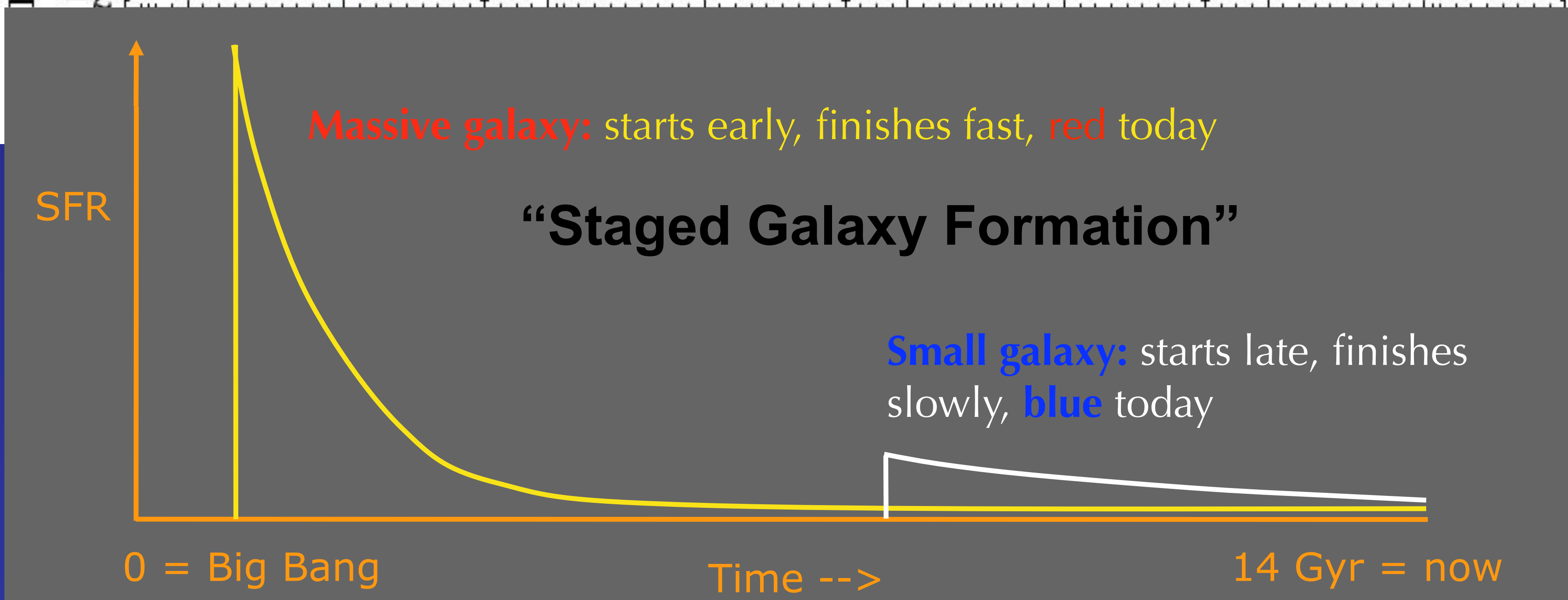


Star-forming **"main sequence":** (Noeske et al. 2007)

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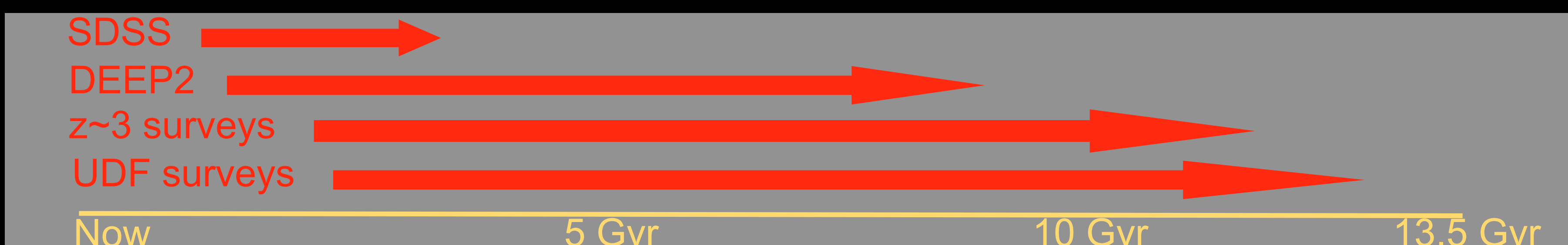
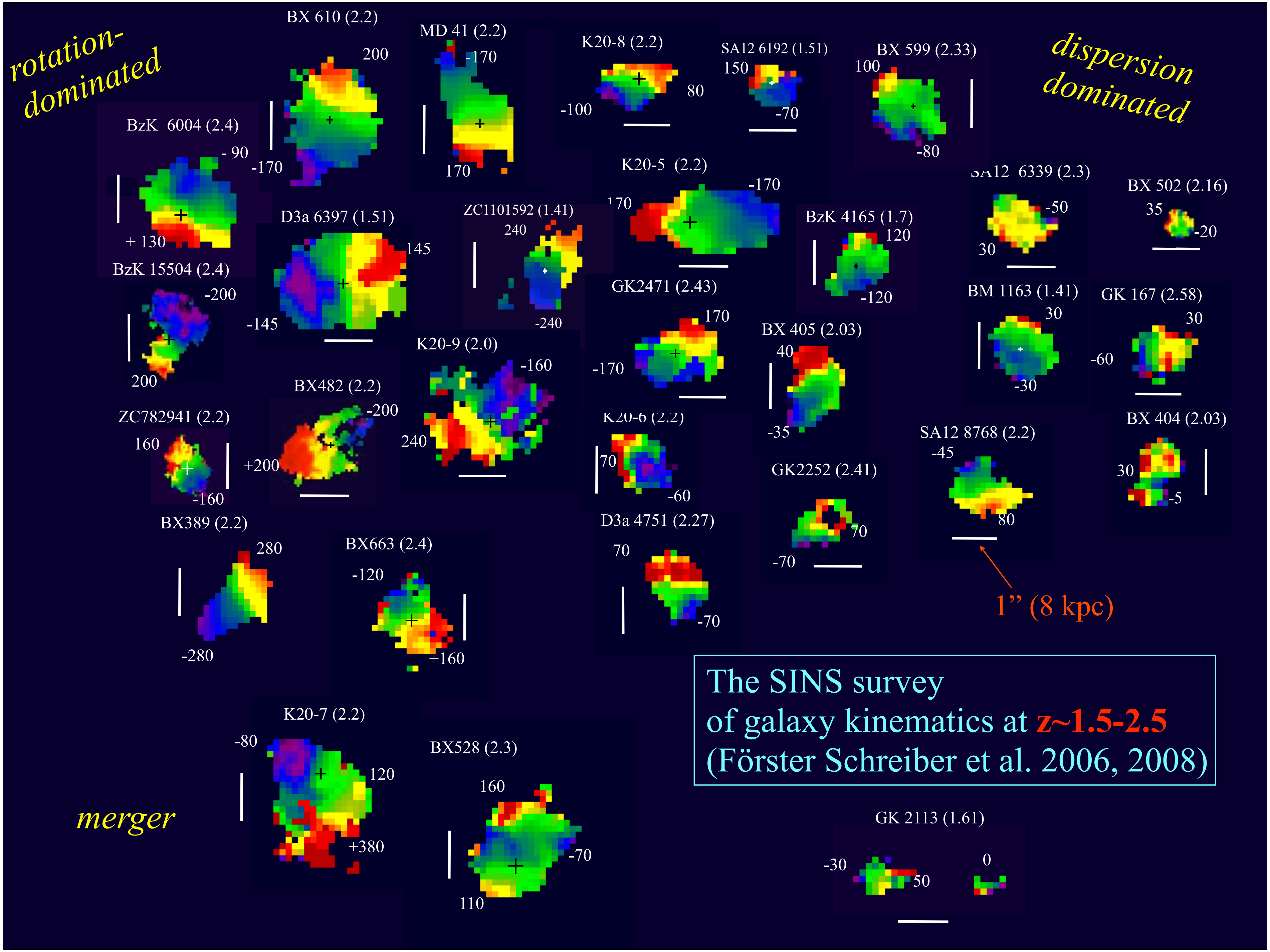
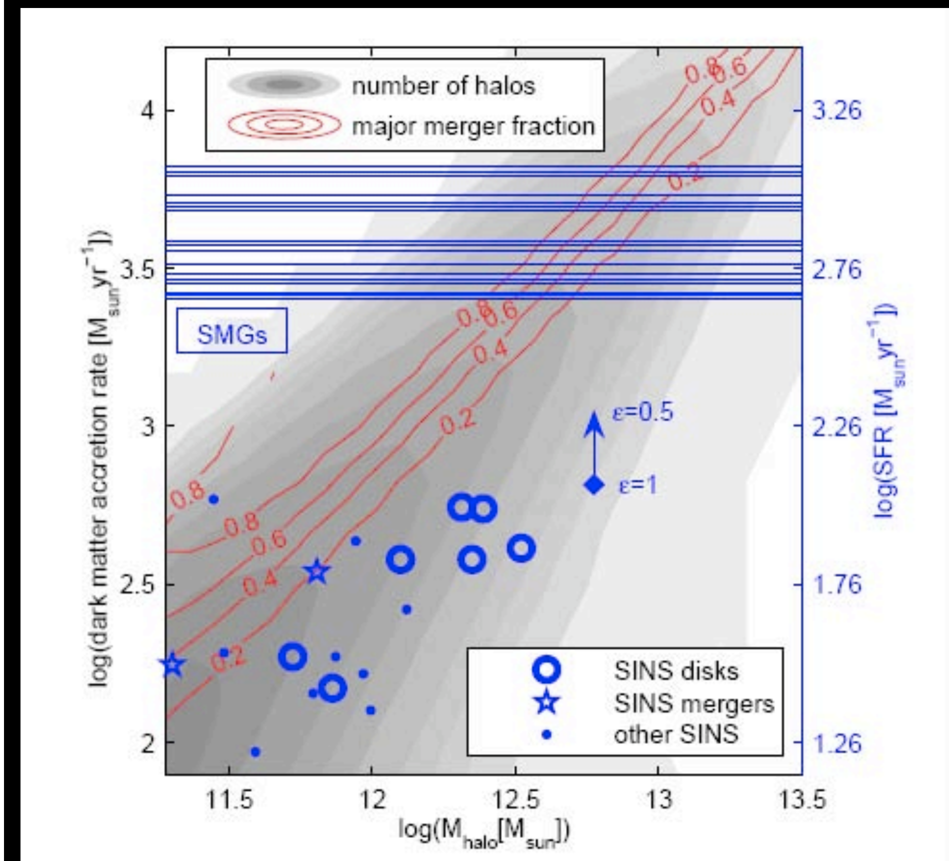
  - Example: AEGIS Survey, outgrowth of DEEP2 in Groth Strip
  - Chandra (X-rays), GALEX (UV), Hubble (optical), SIRTF (IR), VLA (radio)
- **Deep redshift penetration back in time**
  - Large surveys like DEEP2 to z ~ 1.5 — 9.0 Gyr
  - Several ~1,000-galaxy surveys to z ~ 4 — 11.9 Gyr
  - Handfuls of galaxies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

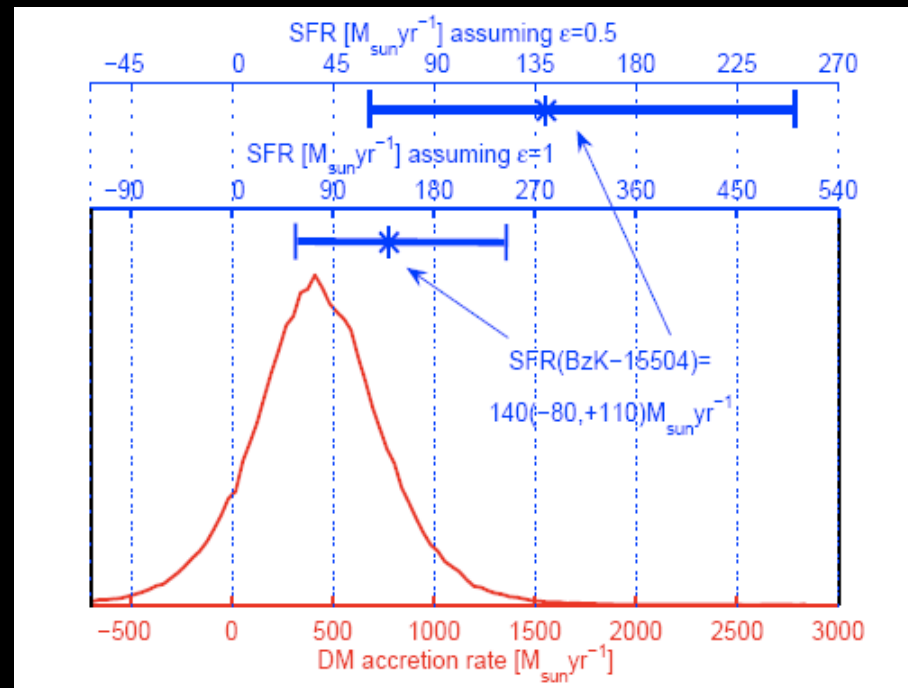



rotation-dominated
dispersion dominated
merger
BX 610 (2.2)
MD 41 (2.2)
K20-8 (2.2)
SA12 6192 (1.51)
BX 599 (2.33)
BzK 6004 (2.4)
K20-5 (2.2)
BX 502 (2.16)
D3a 6397 (1.51)
ZC1101592 (1.41)
BzK 4165 (1.7)
BzK 15504 (2.4)
GK2471 (2.43)
BM 1163 (1.41)
GK 167 (2.58)
BX 405 (2.03)
K20-9 (2.0)
BX482 (2.2)
ZC782941 (2.2)
BX 404 (2.03)
SA12 8768 (2.2)
GK2252 (2.41)
BX389 (2.2)
D3a 4751 (2.27)
BX663 (2.4)
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

- $$\mathrm{SFR} \sim \left(\frac{\varepsilon_{SFR}}{0.5}\right)\left(\frac{b}{0.18}\right)\left(\dot{M}_{dm}\right)_{z,M}$$
- 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

Cosmological Simulation Methods

Dissipationless Simulations

Particle-Particle (PP) - Aarseth NbodyN, N=1,...,6
Particle Mesh (PM) - see Klypin & Holtzman 1997
Adaptive PM (P3M) - Efstathiou et al.
Tree - Barnes & Hut 1986, PKDGRAV Stadel
TreePM - GADGET2, Springel 2005
Adaptive Mesh Refinement (AMR) - Klypin (ART)

Hydrodynamical Simulations

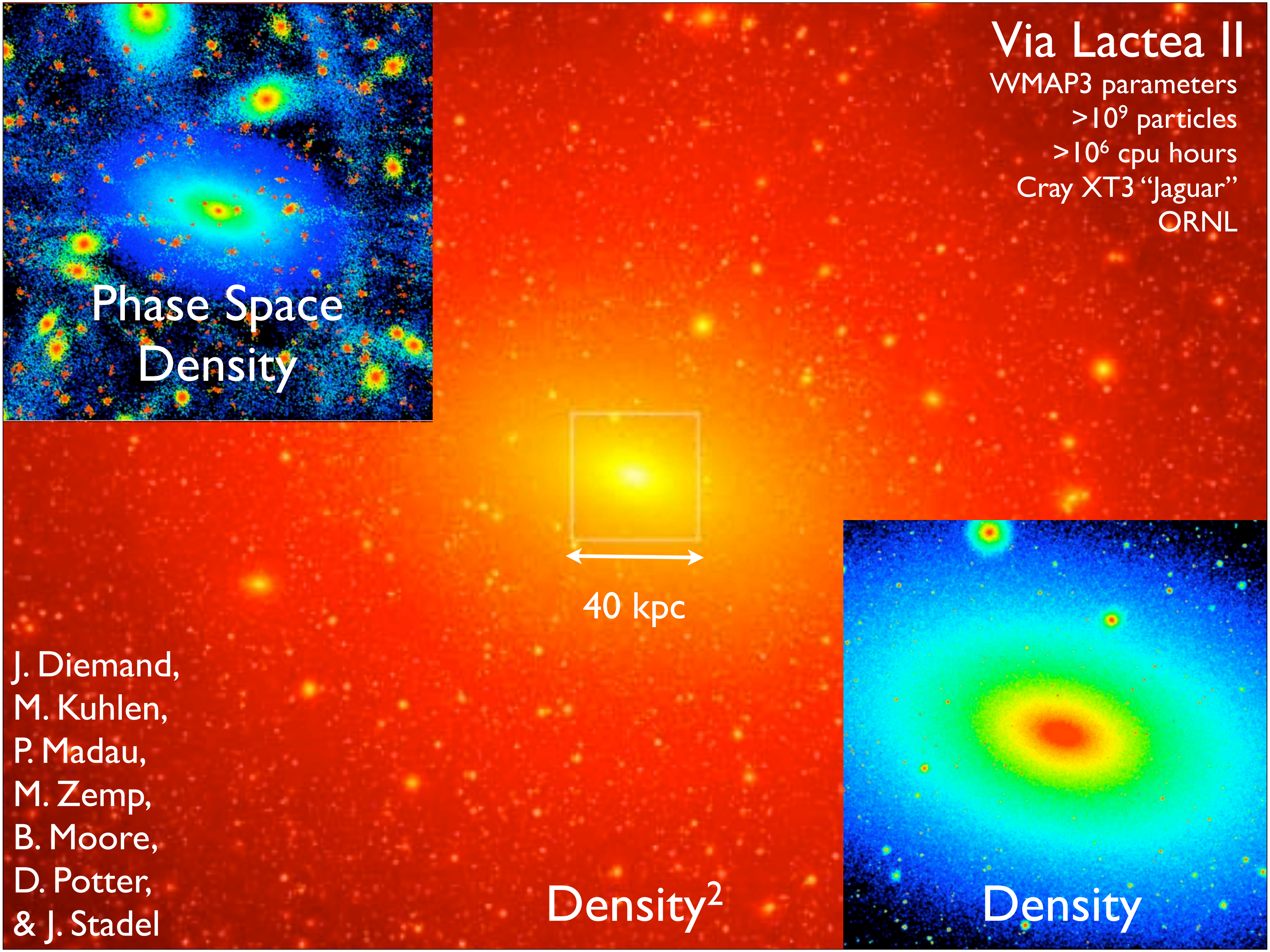
Fixed Grid - Cen & Ostriker
Smooth Particle Hydrodynamics (SPH) - Springel 2005 (GADGET2)
- Wadsley, Stadel, & Quinn (Gasoline)
Adaptive Grid - Klypin & Kravtsov (ART+hydro), Tessier (RAMSES)

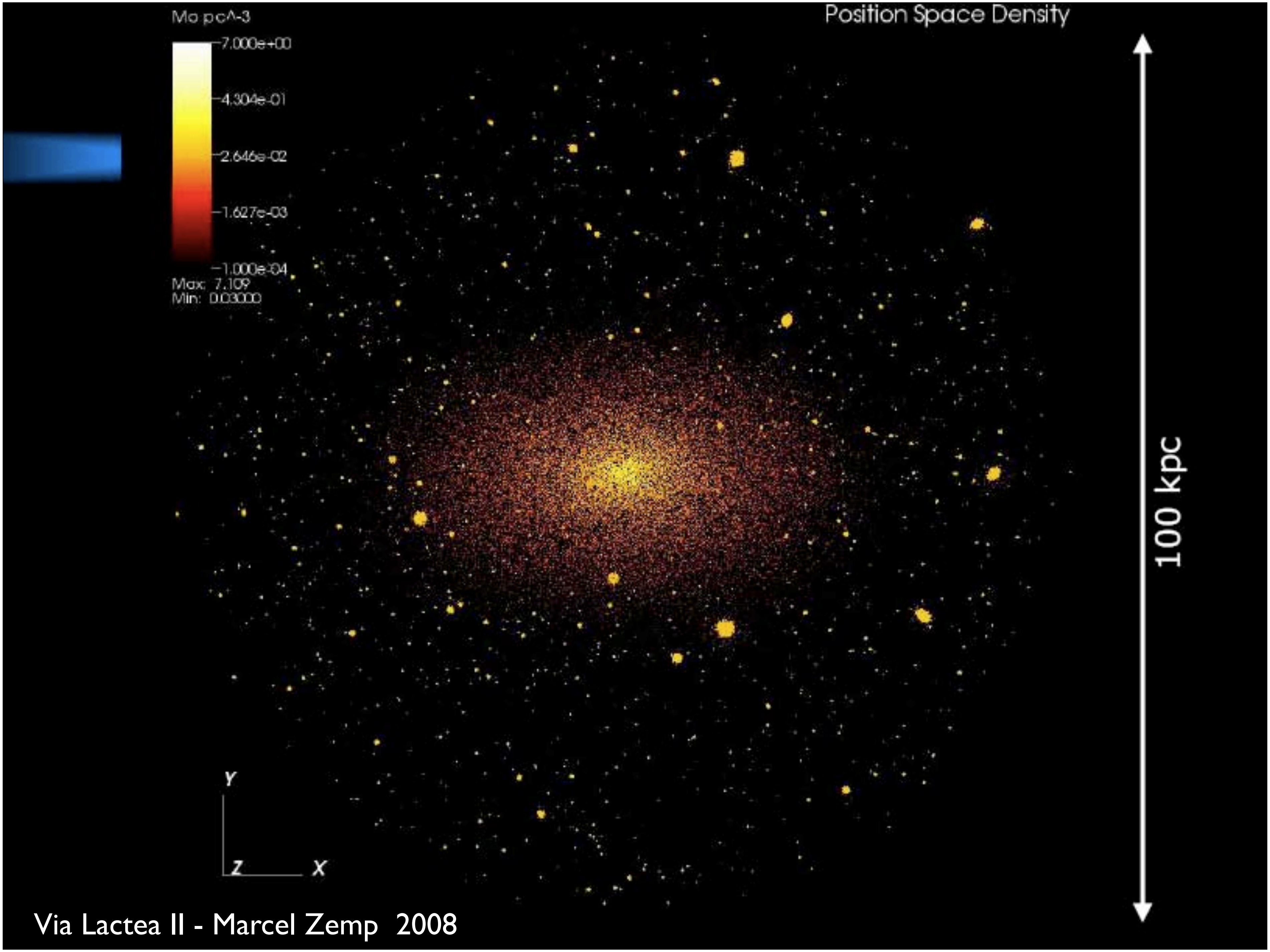
Initial Conditions

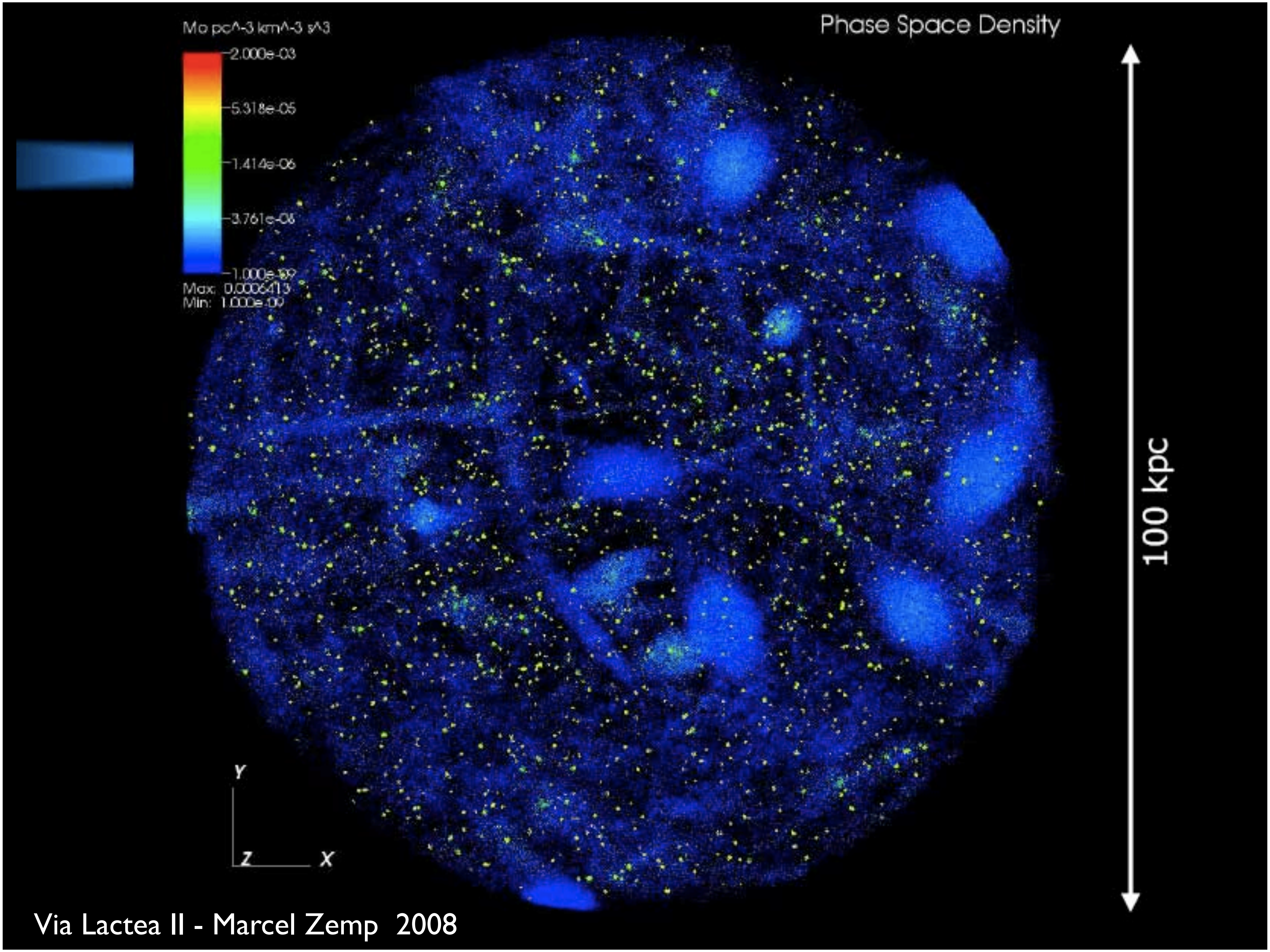
Standard: Gaussian P(k) realized uniformly, Zel'dovich displacement
Multimass - put lower mass particles in a small part of sim volume
Constrained Realization - large scale: simulate particular region
small scale: generate fluctuations from P(k)

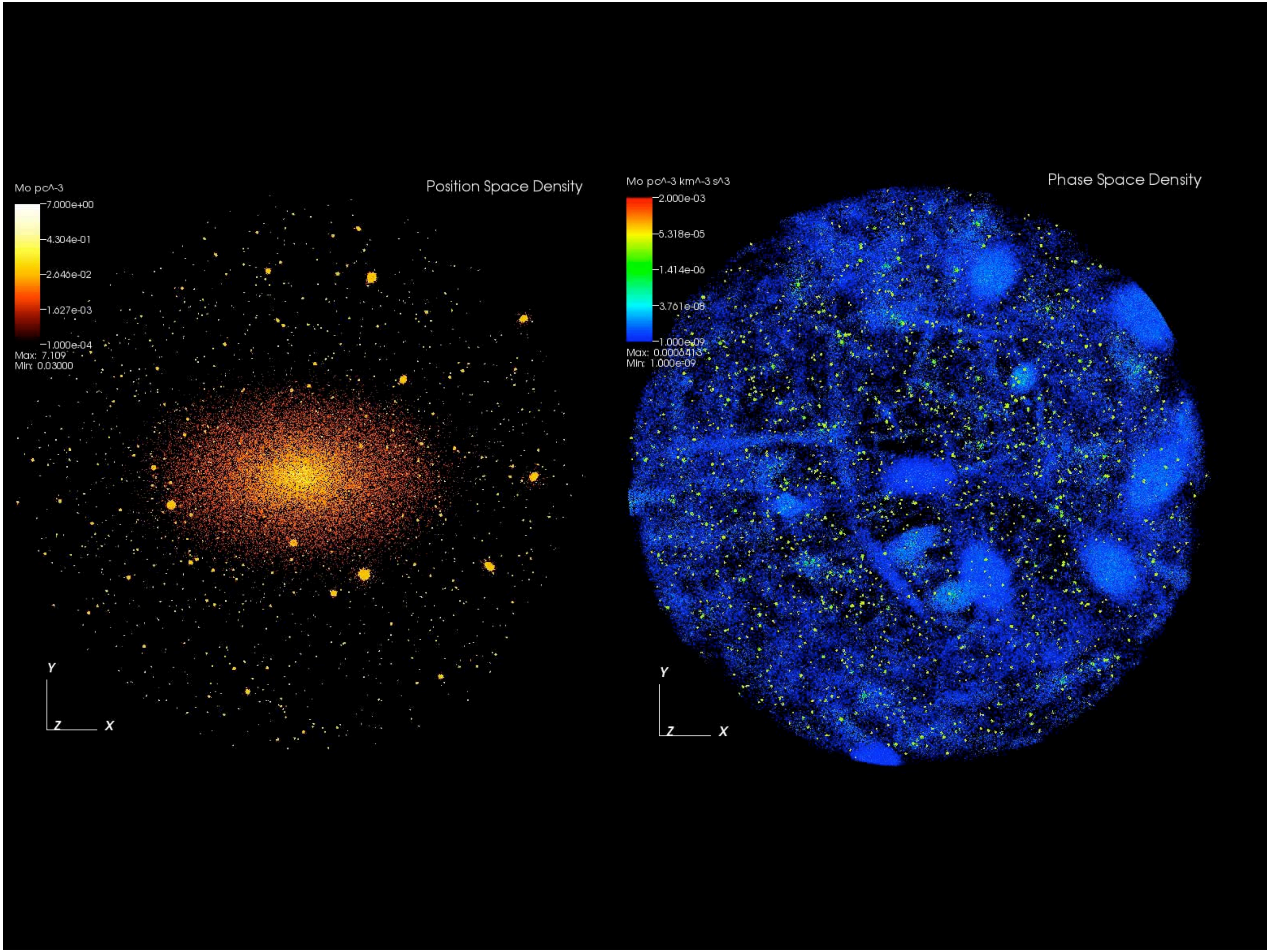
Reviews

Bertschinger ARAA 1998, Klypin lectures 2002, U Washington website


Via Lactea II
WMAP3 parameters
>10^9 particles
>10^6 cpu hours
Cray XT3 "Jaguar"
ORNL
Phase Space Density
40 kpc
J. Diemand,
M. Kuhlen,
P. Madau,
M. Zemp,
B. Moore,
D. Potter,
& J. Stadel
Density^2
Density


Mo pc^-3
7.000e+00
4.304e-01
2.646e-02
1.627e-03
1.000e-04
Max: 7.109
Min: 0.03000
Position Space Density
100 kpc
Y
Z
X
Via Lactea II - Marcel Zemp 2008


Mo pc^-3 km^-3 s^3
2.000e-03
5.318e-05
1.414e-06
3.761e-08
1.000e-09
Max: 0.0006413
Min: 1.000e-09
Phase Space Density
100 kpc
Y
Z
X
Via Lactea II - Marcel Zemp 2008


Position Space Density
Mo pc^-3
7.000e+00
4.304e-01
2.646e-02
1.627e-03
1.000e-04
Max: 7.109
Min: 0.03000
Y
Z
X
Phase Space Density
Mo pc^-3 km^-3 s^3
2.000e-03
5.318e-05
1.414e-06
3.761e-08
1.000e-09
Min: 1.000e-09
Y
Z
X

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

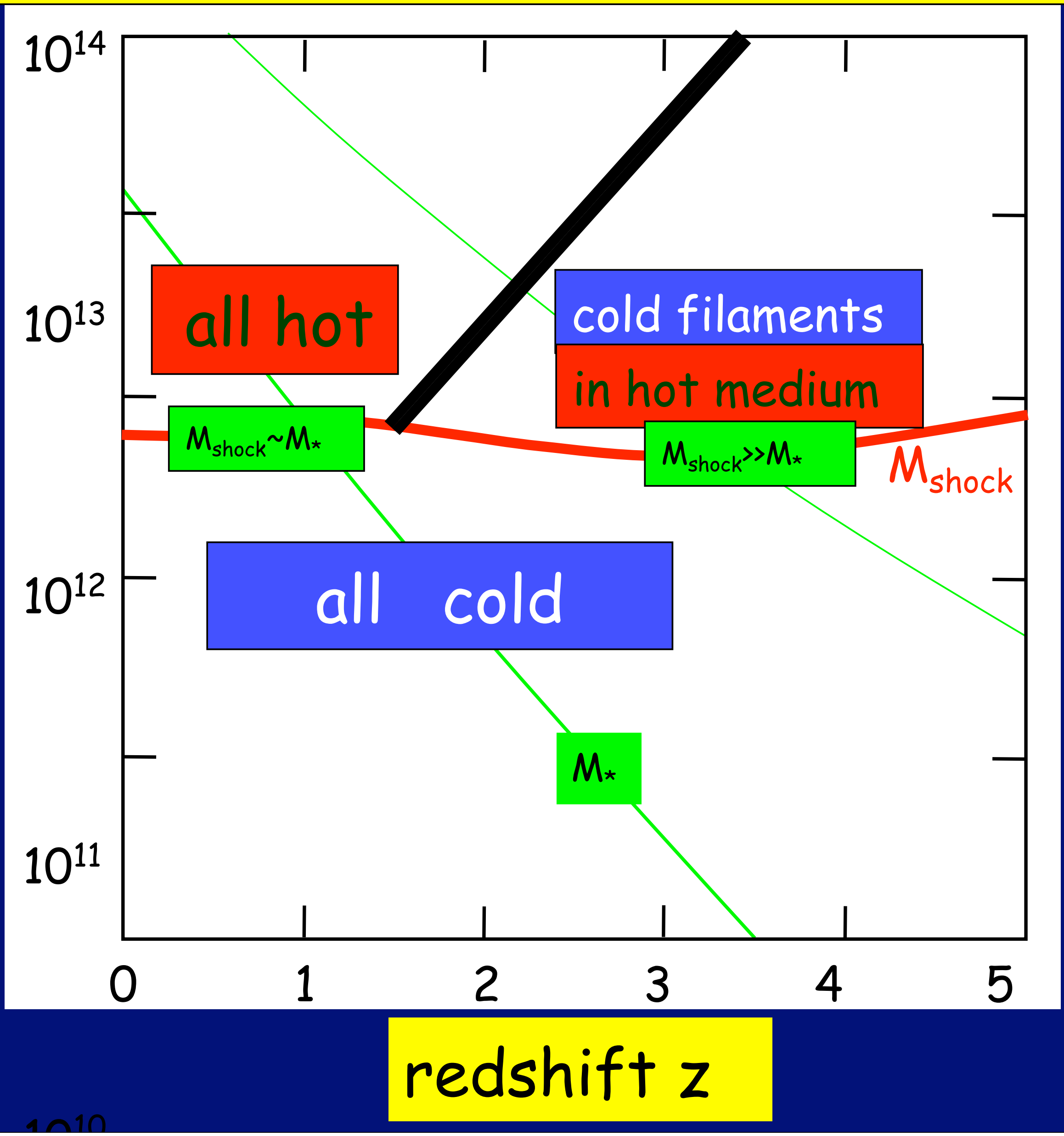
in $M>M_{shock}$

Totally hot at z<1

Cold streams at z>2

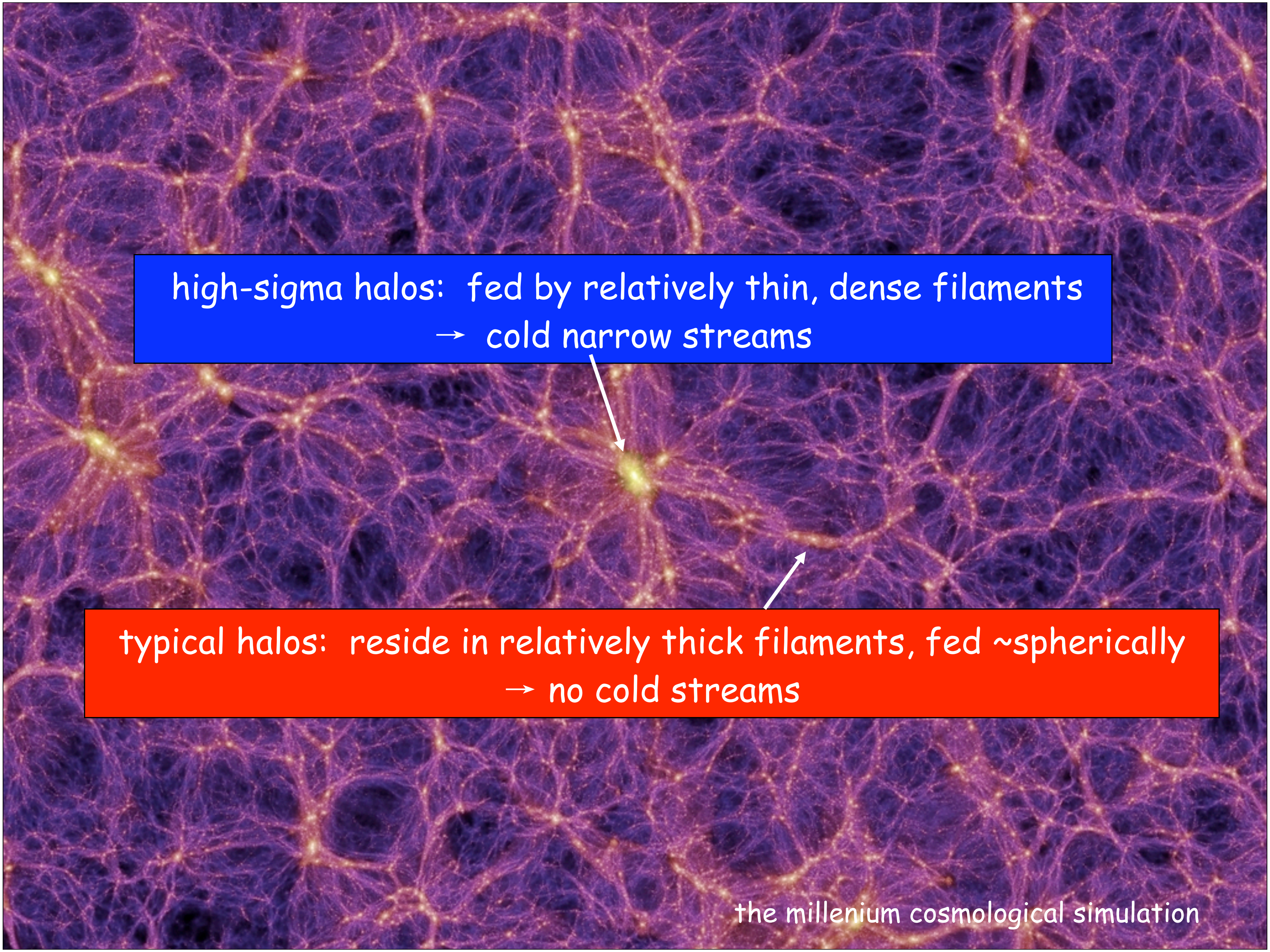
Dekel & Birnboim 2006

Cold Streams in Big Galaxies at High z



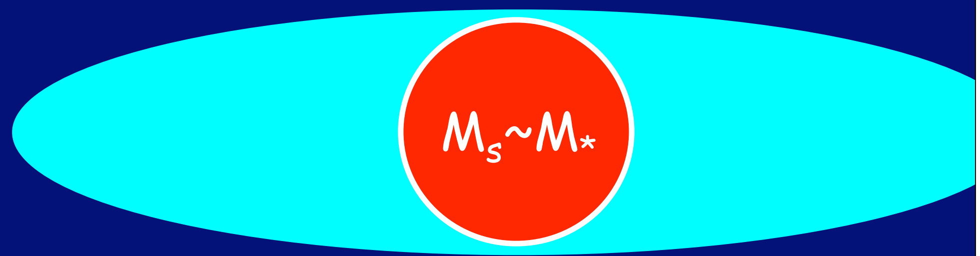
spherical cow approximation

Dekel & Birnboim 06 Fig. 7


high-sigma halos: fed by relatively thin, dense filaments
→ cold narrow streams
typical halos: reside in relatively thick filaments, fed ~spherically
→ no cold streams
the millenium cosmological simulation

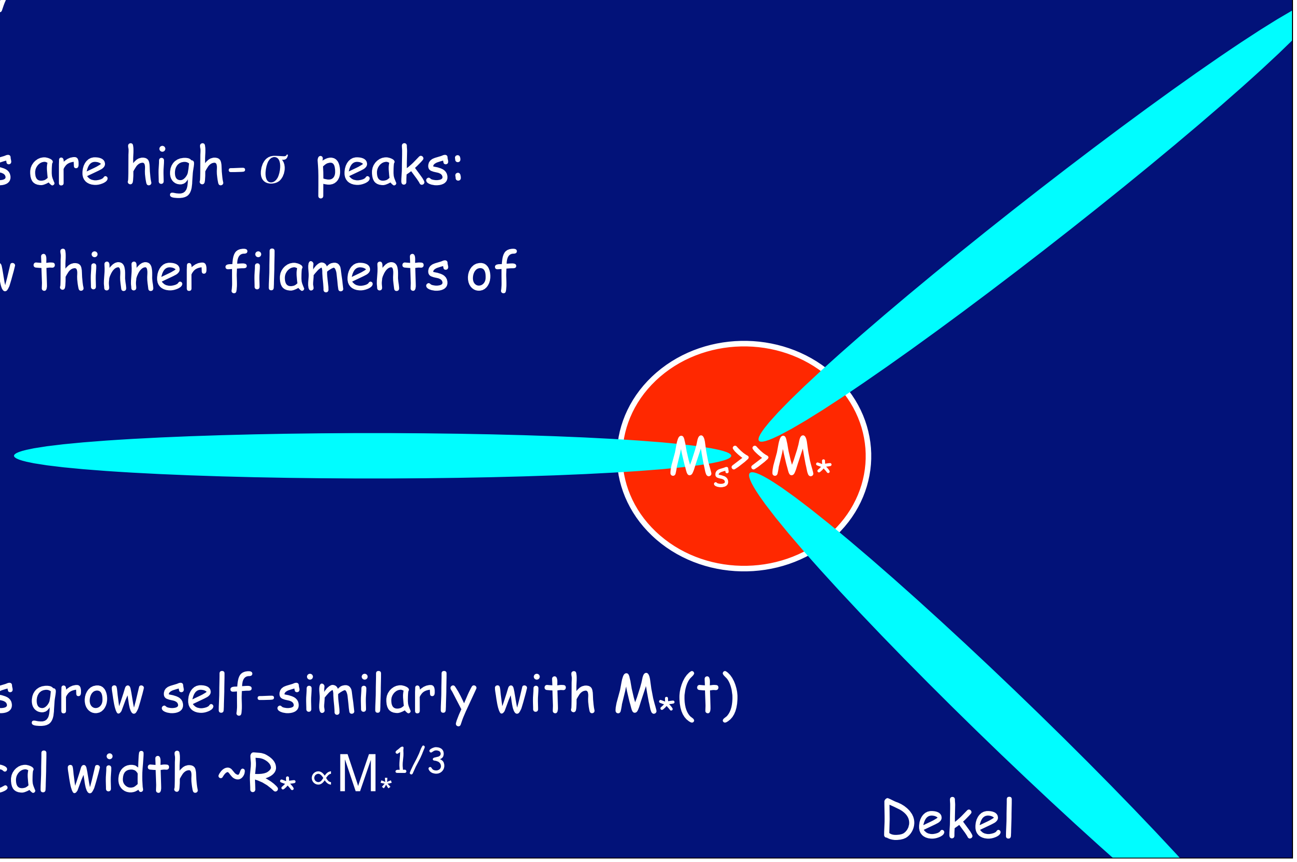
Origin of dense filaments in hot halos ($M \geq M_{shock}$) at high z

At low z, M_{shock} halos are typical:
they reside in thicker filaments
of comparable density



At high z, M_{shock} halos are high-σ peaks:

they are fed by a few thinner filaments of
higher density

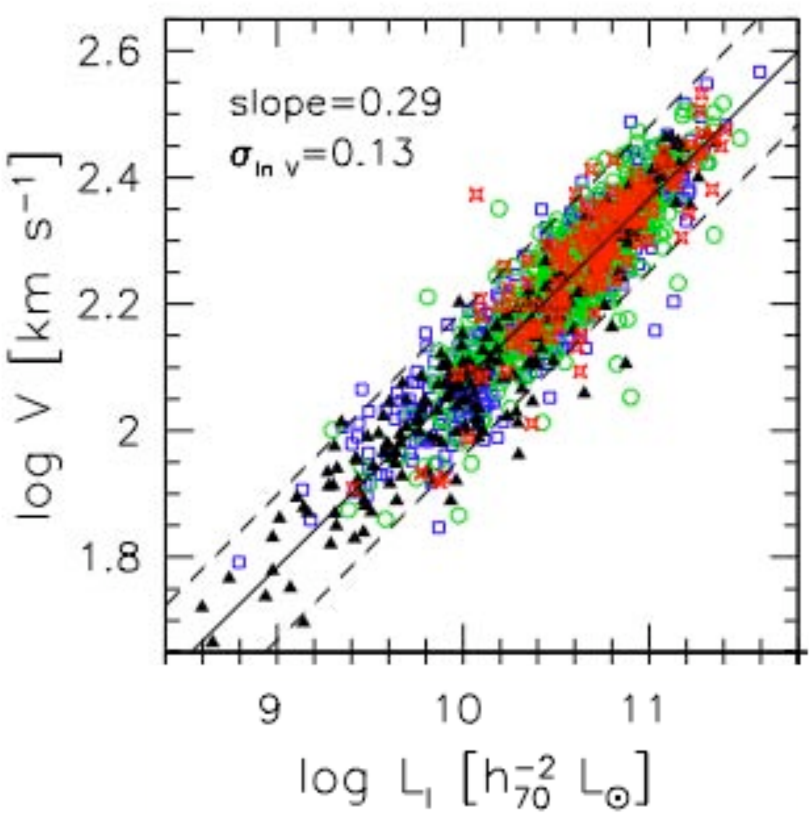


Large-scale filaments grow self-similarly with $M_*(t)$
and always have typical width $\sim R_* \propto M_*^{1/3}$

Dekel

The Tully-Fisher Relation

- A correlation between the rotation velocity, V, and luminosity, L, of disk galaxies (Tully & Fisher 1977).
- Small intrinsic scatter 0.05 dex in V|L (cf. 0.15 dex in R|L)
- Scatter is independent of surface brightness (e.g. Courteau & Rix 1997).



Courteau et al. 2007

slide: Aaron Dutton

The Tully-Fisher Zero Point Problem

- Reproducing the zero point of the TF relation has been a long standing problem for CDM based galaxy formation models (e.g. Van den Bosch 2000; Mo & Mao 2000; Cole et al 2000; Eke, Navarro & Steinmetz 2001).

- Semi-Analytic models can reproduce the TF relation and galaxy luminosity function ONLY IF $V_{obs}=V_{vir}$ (e.g. Somerville & Primack 1999) or $\mathbf{V_{obs}=V_{max,h}}$ (e.g. Croton et al. 2006).

- Measurements of halo masses from groups and isolated galaxies/halos also supports $\mathbf{V_{obs}=V_{max,h}}$ (Eke et al 2006; Blanton et al. 2007)

slide: Aaron Dutton

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

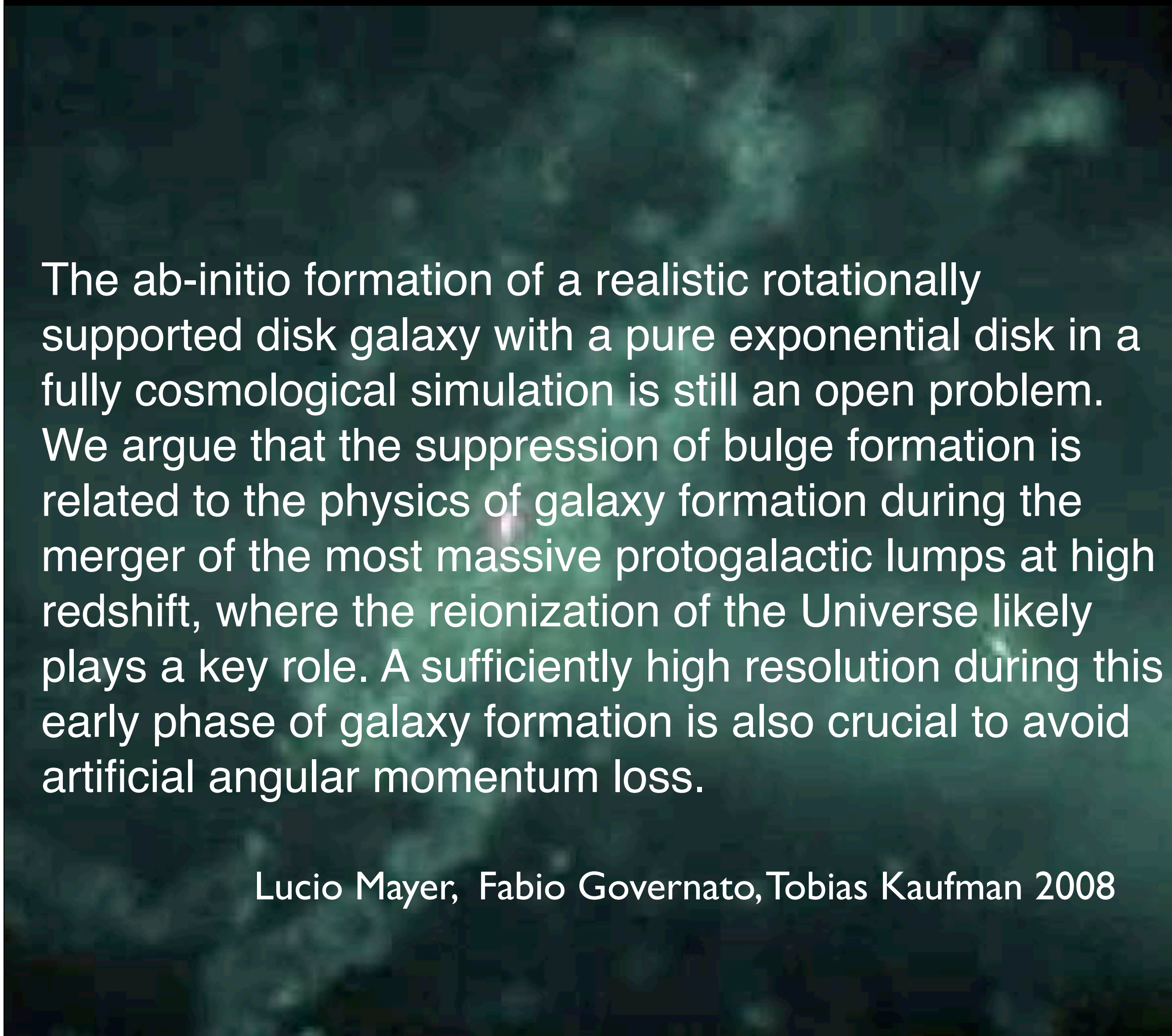
(DM not shown)

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

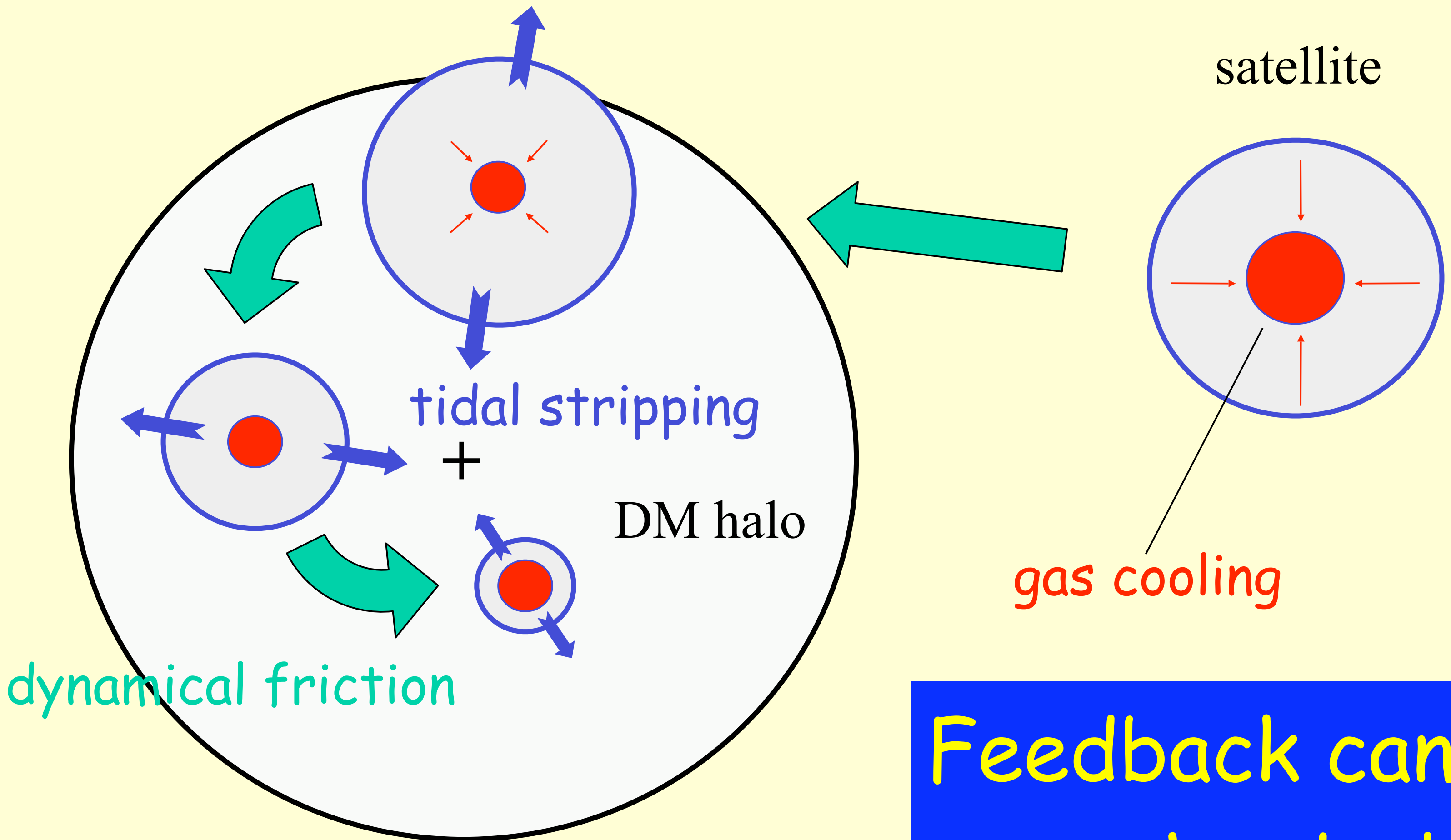
The formation of a Milky Way size disk galaxy

Gas is GREEN

Stars are WHITE

(DM not shown)

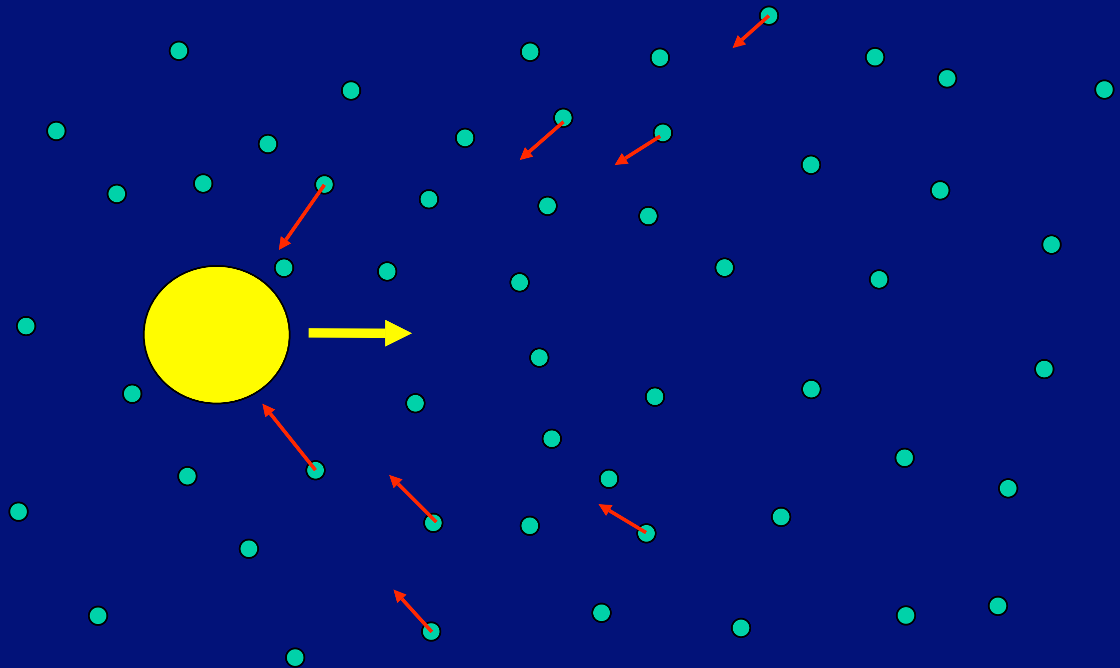
Avoiding the spin catastrophe: over-cooling and feedback



Feedback can save the day!

Maller & Dekel 2002

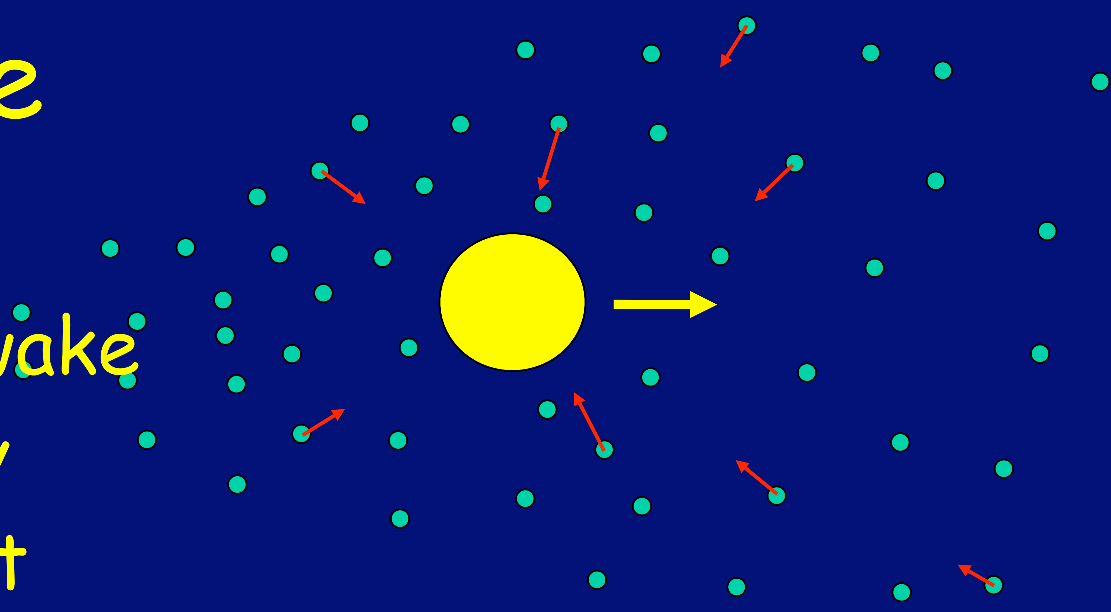
Dynamical Friction



Dynamical Friction

Force

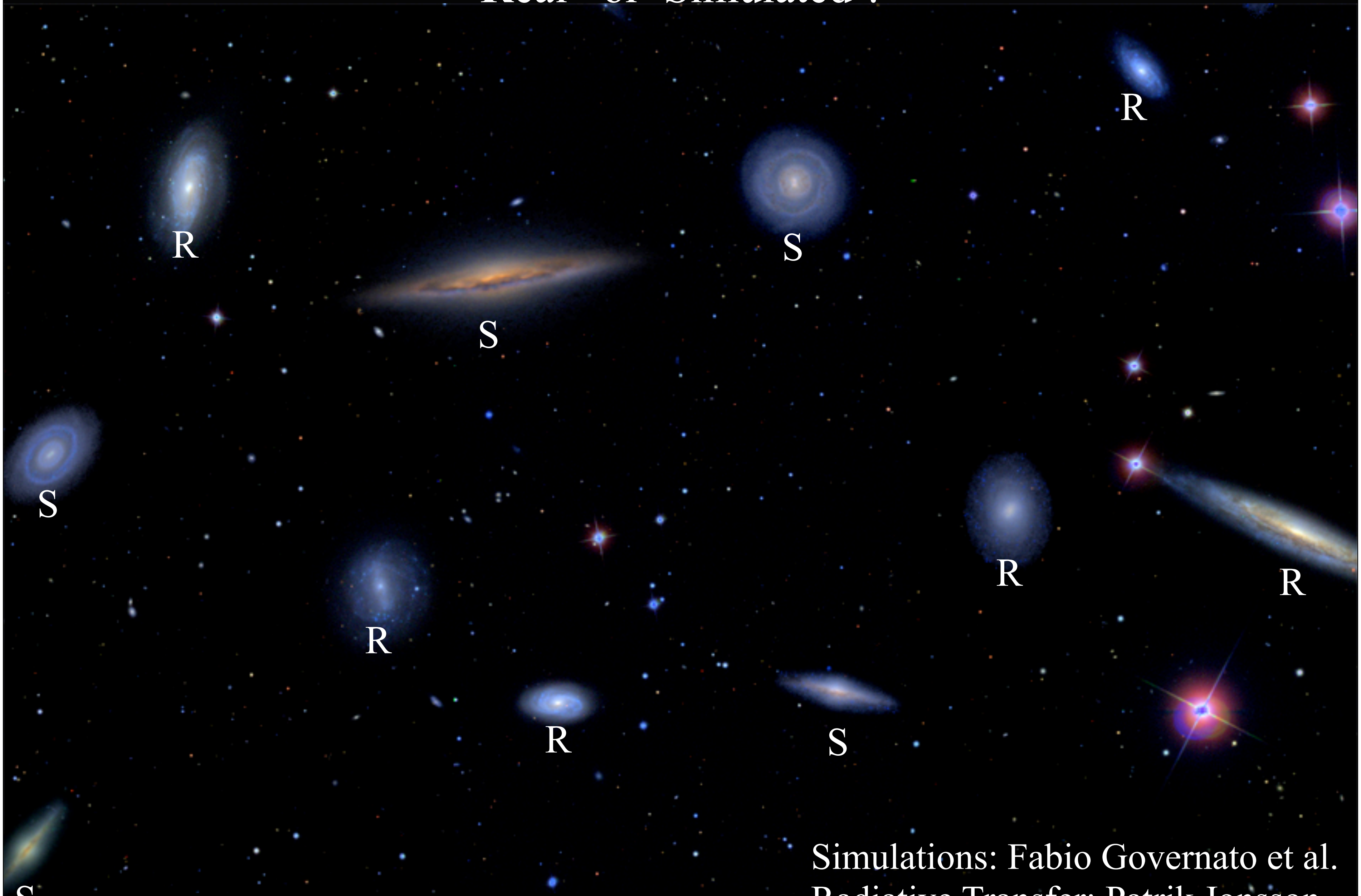
Ball's wake gravity slows it down



Energy

$KE_{\text{Little Balls}}$ from KE_{BigBall}

Real or **S**imulated ?

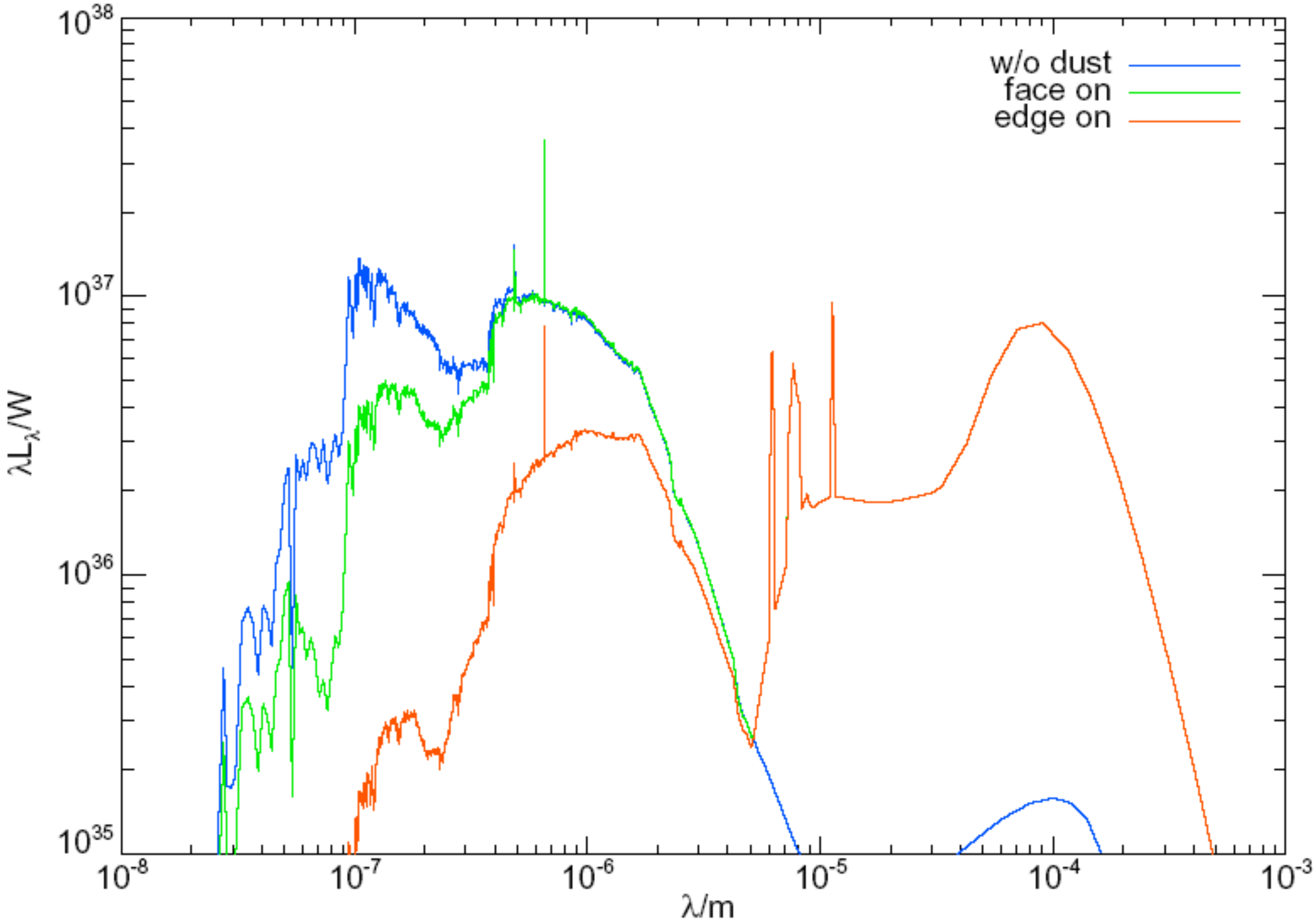


Simulations: Fabio Governato et al.
Radiative Transfer: Patrik Jonsson

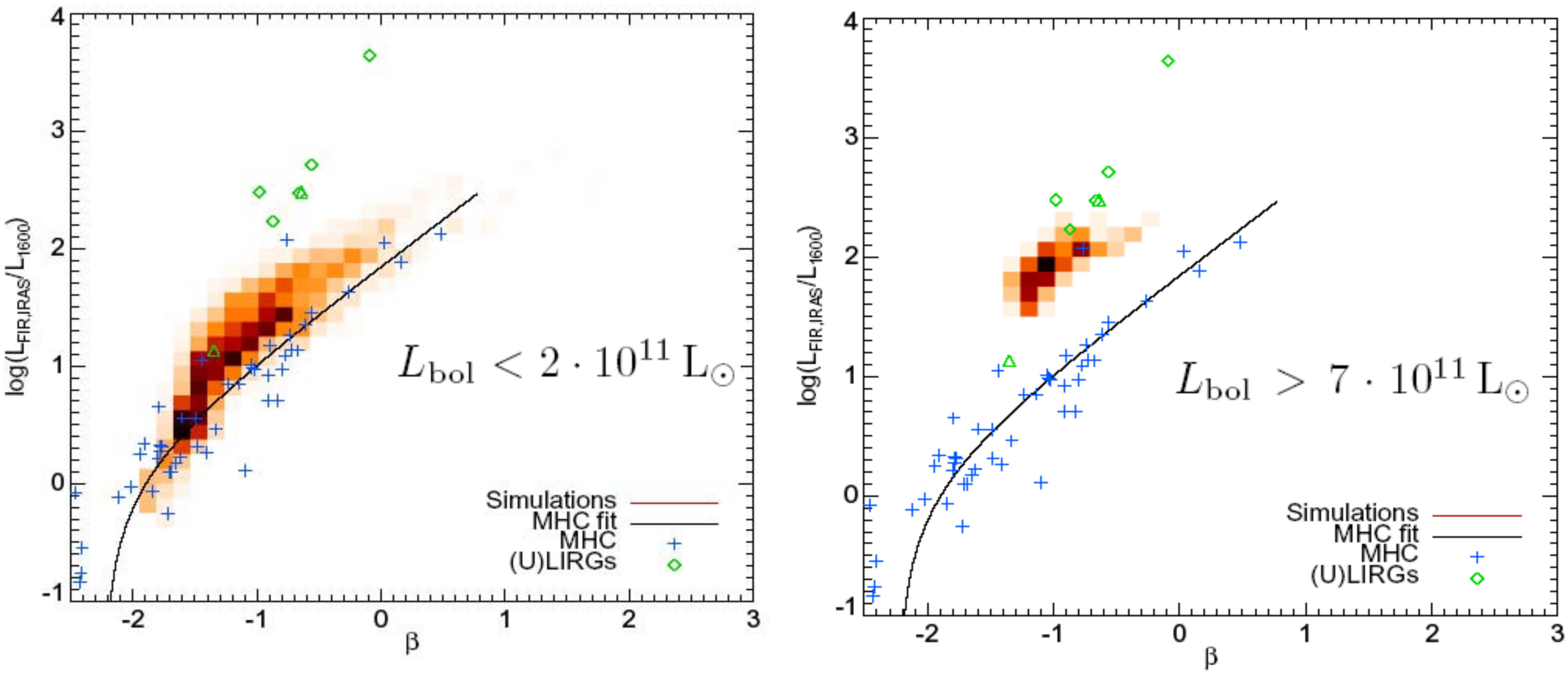
Sunrise Code for Radiative Transfer through Dust

- 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



Split by Luminosity



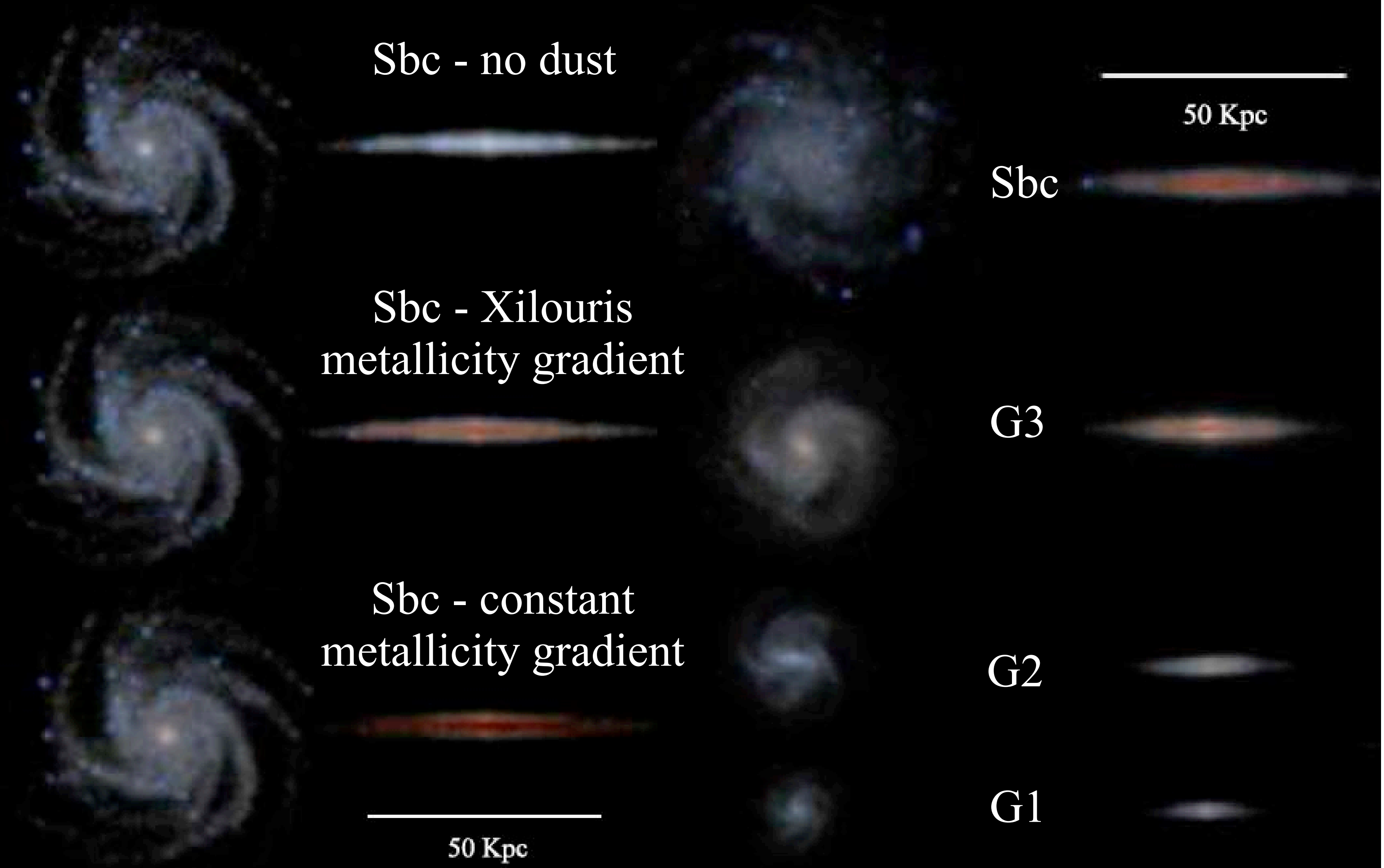
- Simulated lower-luminosity galaxies follow an IRX-β relation similar to the observed MHC99 galaxies
- Higher-luminosity galaxies occupy the UIRG region
- Note that these were predictions: no parameter fitting!

Jonsson et al. 2006

Dust Attenuation in Hydrodynamic Simulations of Spiral Galaxies

Rocha, Jonsson, Primack, & Cox 2008 MN

Right hand side:
Xilouris et al. 1999
metallicity gradient



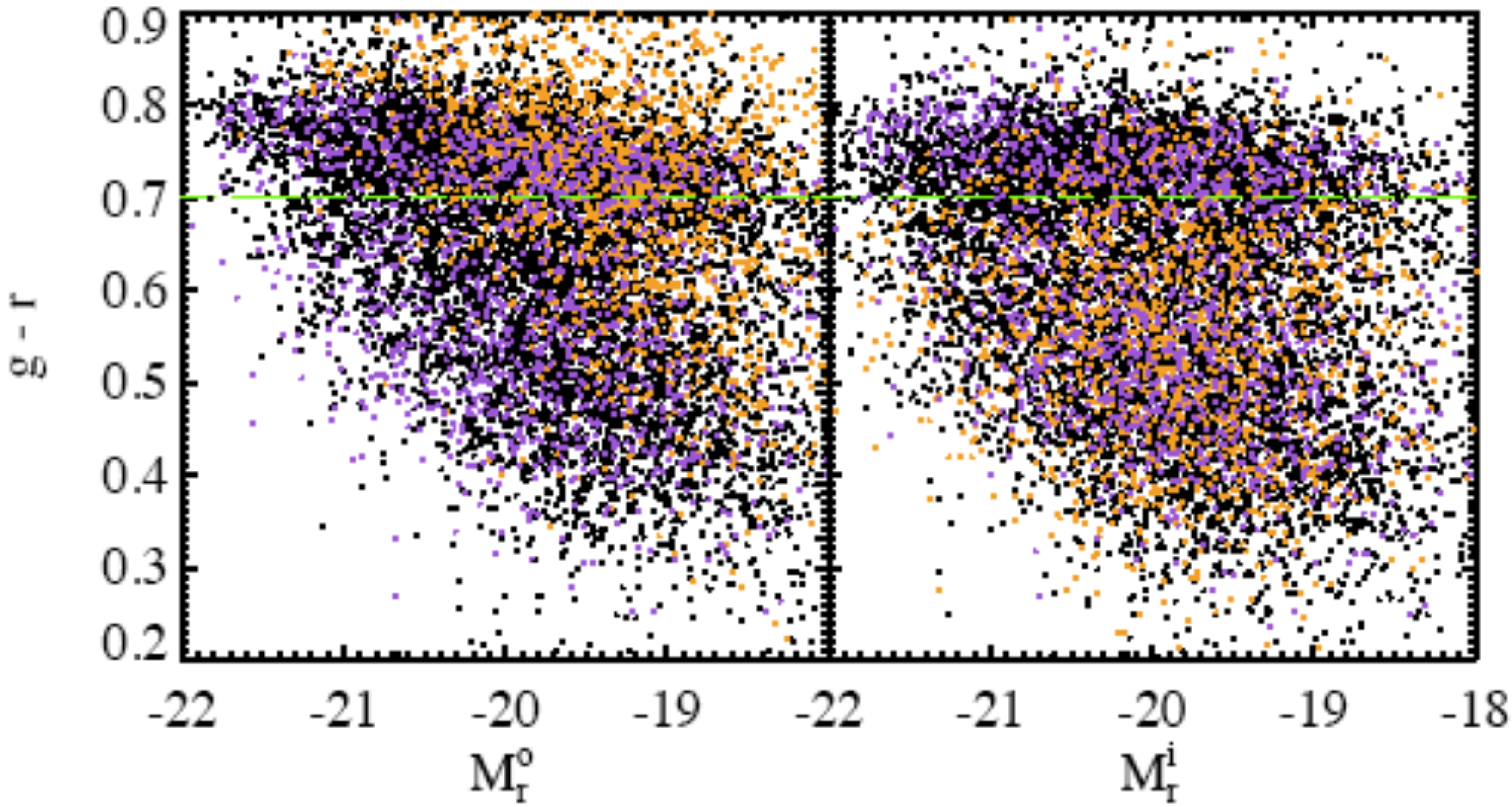
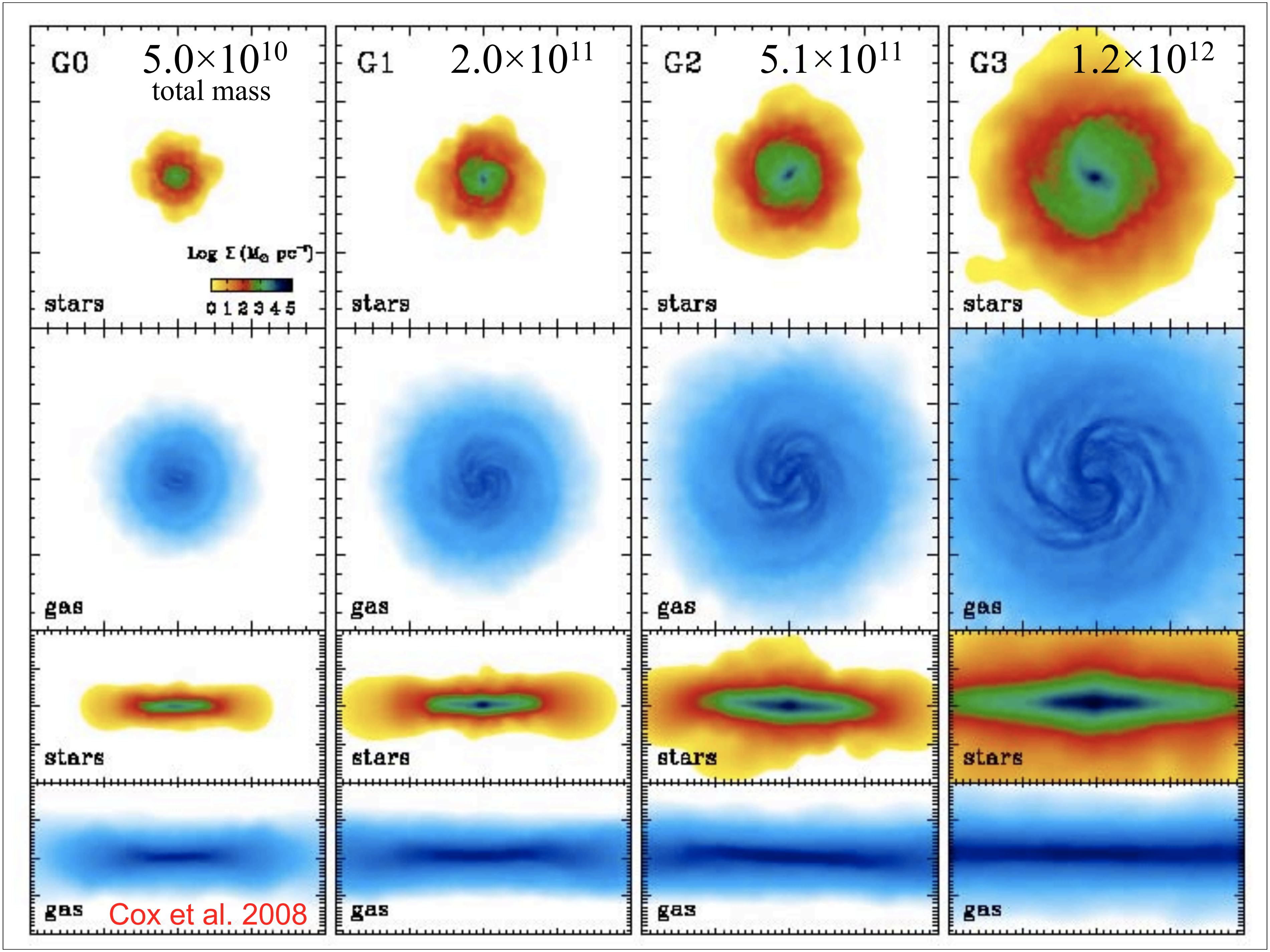


Figure 1. Color-magnitude diagrams for the observed (left panel) and intrinsic (right panel) galaxies in our sample. Purple points are face-on ($b/a > 0.85$) while orange points highly inclined ($b/a < 0.35$). Clearly, the observed properties of face-on and edge-on galaxies differ, with edge-on galaxies being fainter and redder. However, when inclination corrections are applied the two show a comparable distribution in the color-magnitude diagram. Also, the fraction of galaxies that one would consider red decreases when going from observed to intrinsic color.

SDSS - Maller, Berlind, Blanton, & Hogg 2008


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

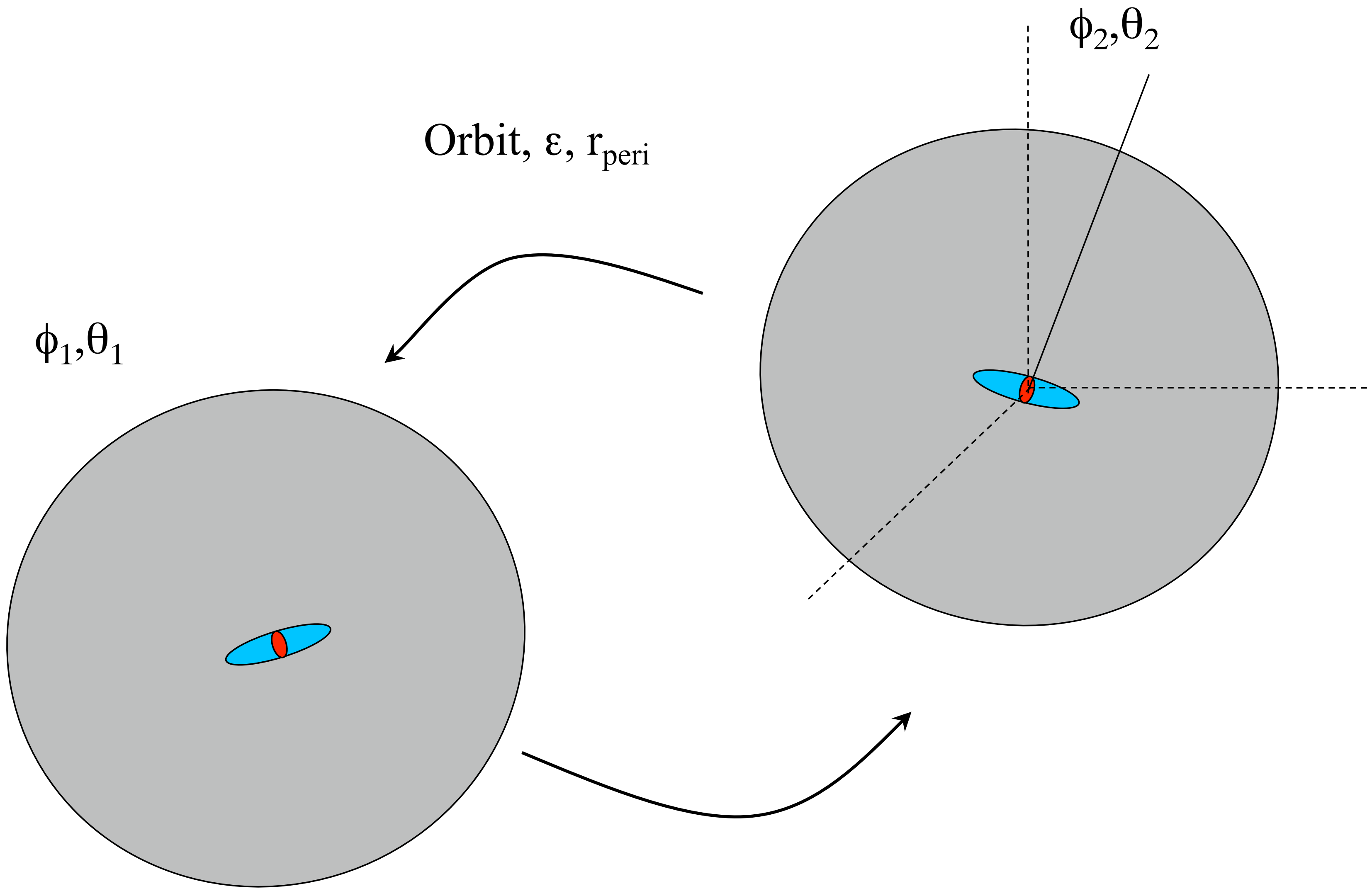
spheroid:disk = 0.74:0.26   Fukugita & Peebles 2004

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

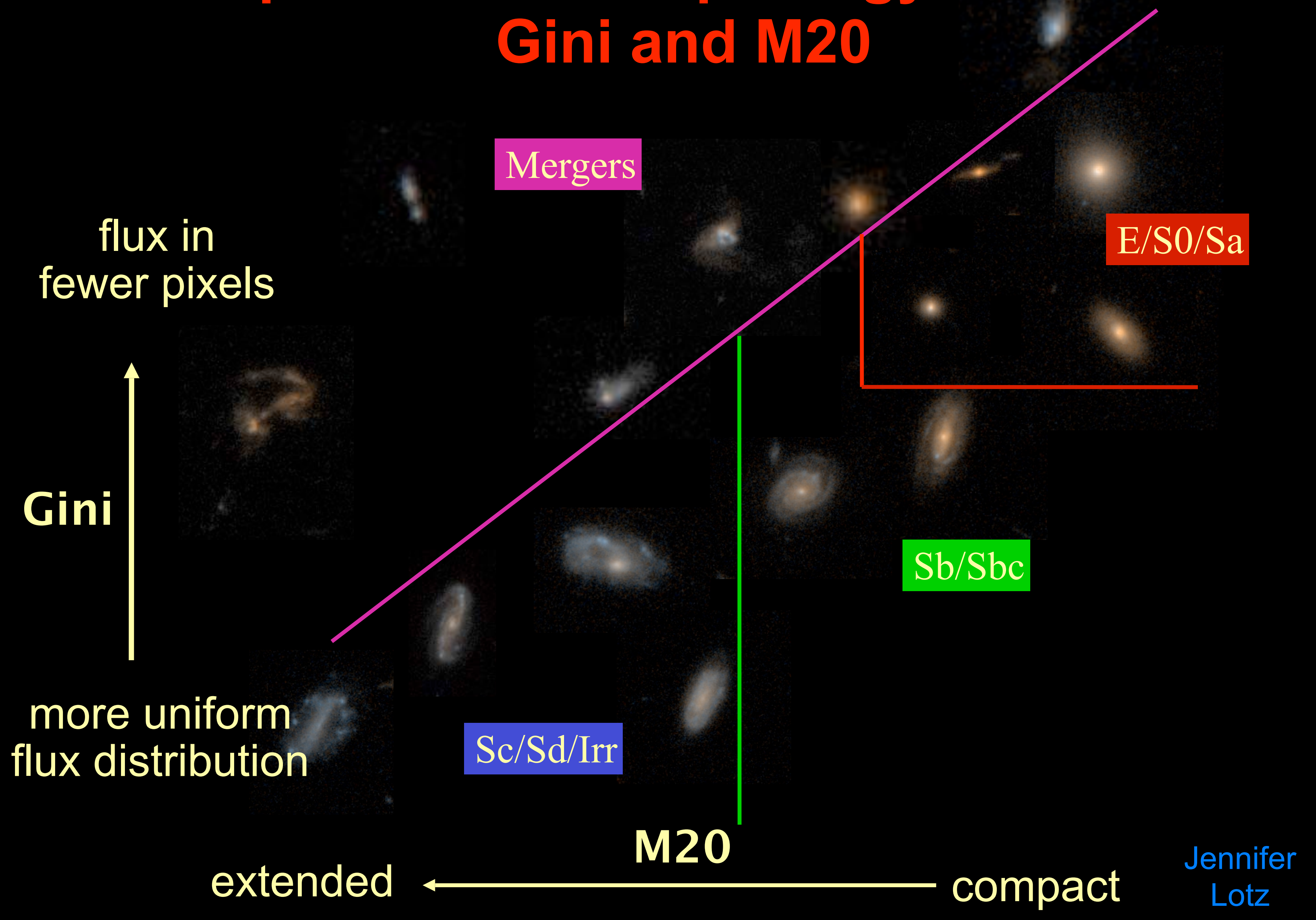
So Let's Merge Two Disks



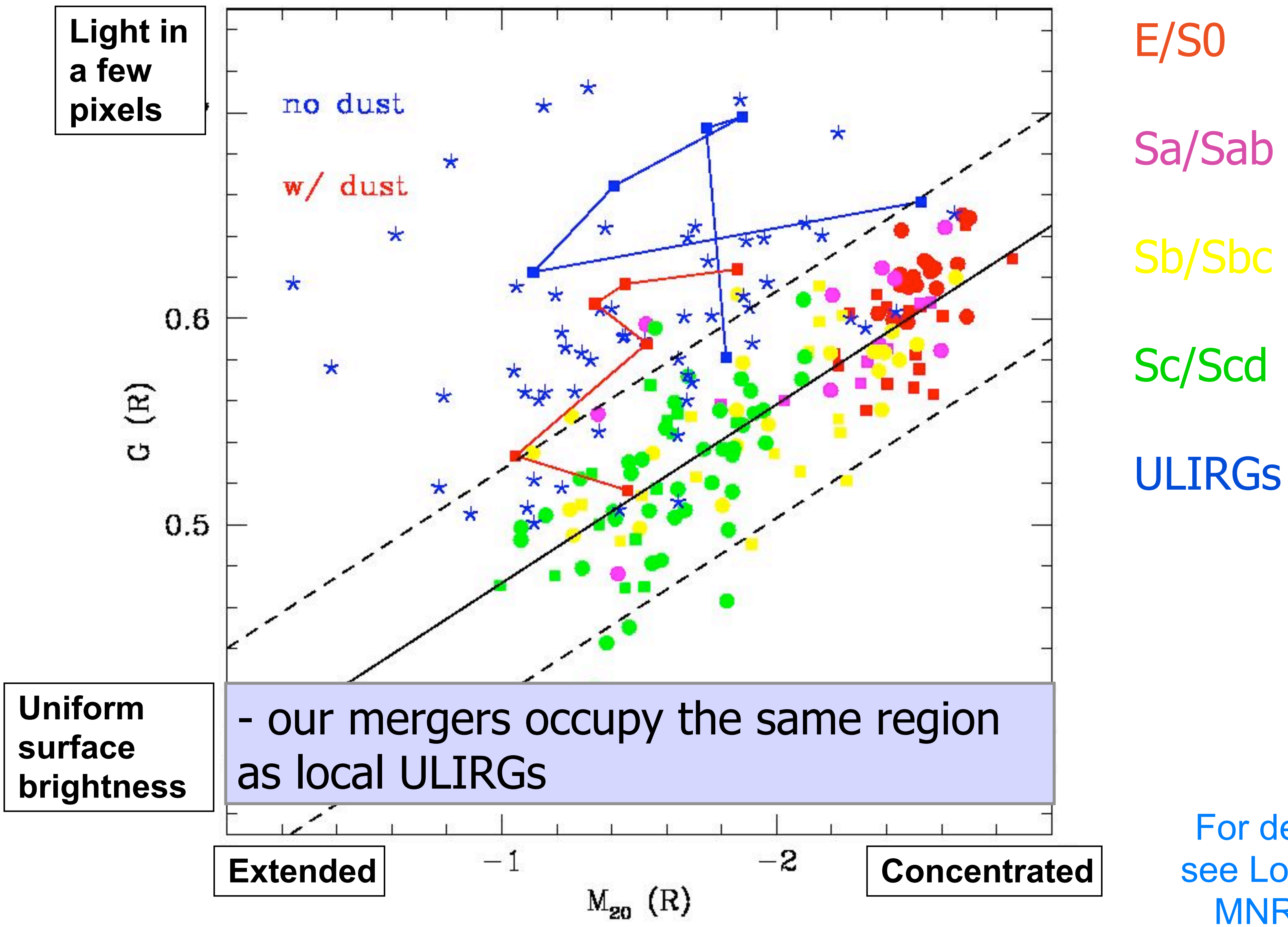
Galaxy Merger Simulation

Patrik Jonsson, Greg Novak, Joel Primack
music by Nancy Abrams

Nonparametric Morphology Measures
Gini and M20



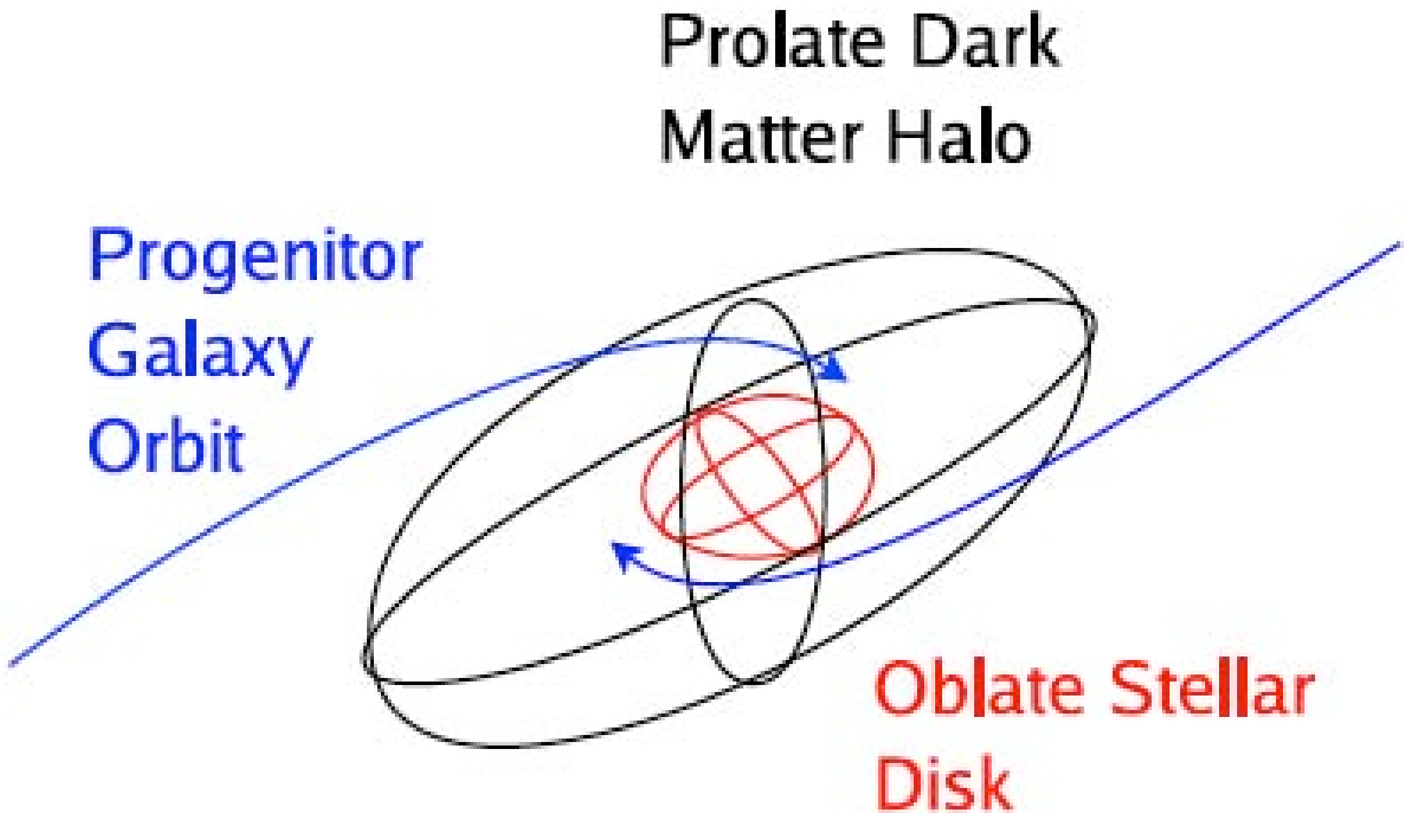
Modeling Merger Morphologies



- our mergers occupy the same region as local ULIRGs

For details see Lotz+08 MNRAS

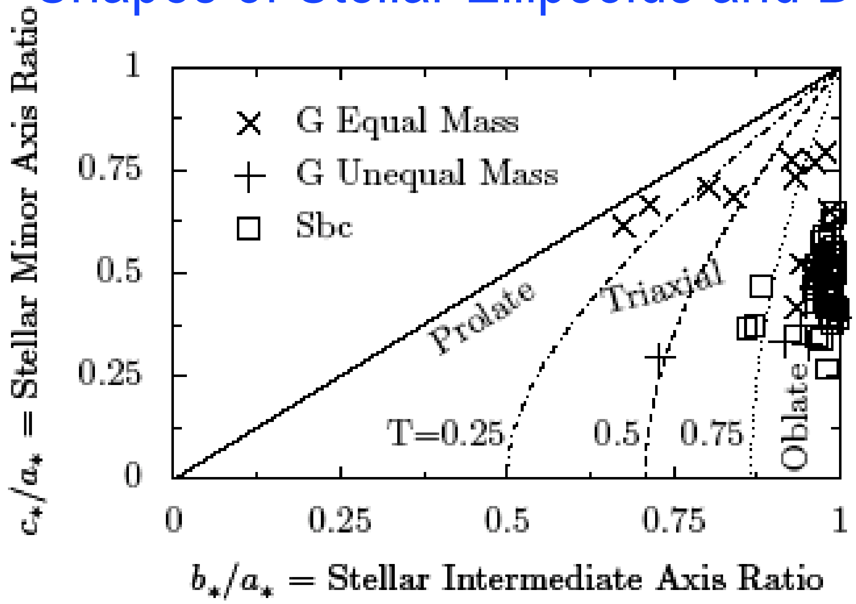
The short (rotation) axis of the visible elliptical galaxy is perpendicular to the long axis of its dark matter halo. Why? The long axis of the halo is along the merger axis, while the angular momentum axis is perpendicular to that axis.

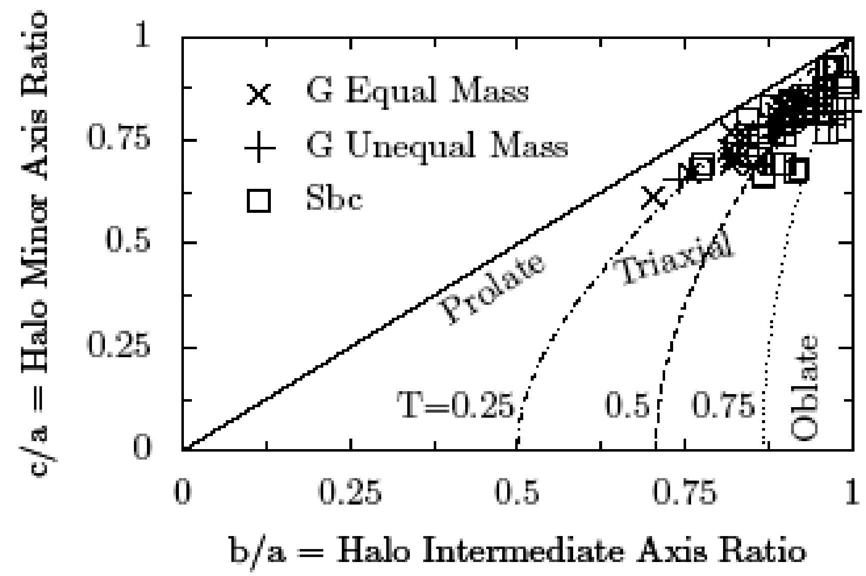


Novak, Cox, Primack, Jonsson, & Dekel, ApJ Letters 2006

We include detailed predictions testable via weak lensing

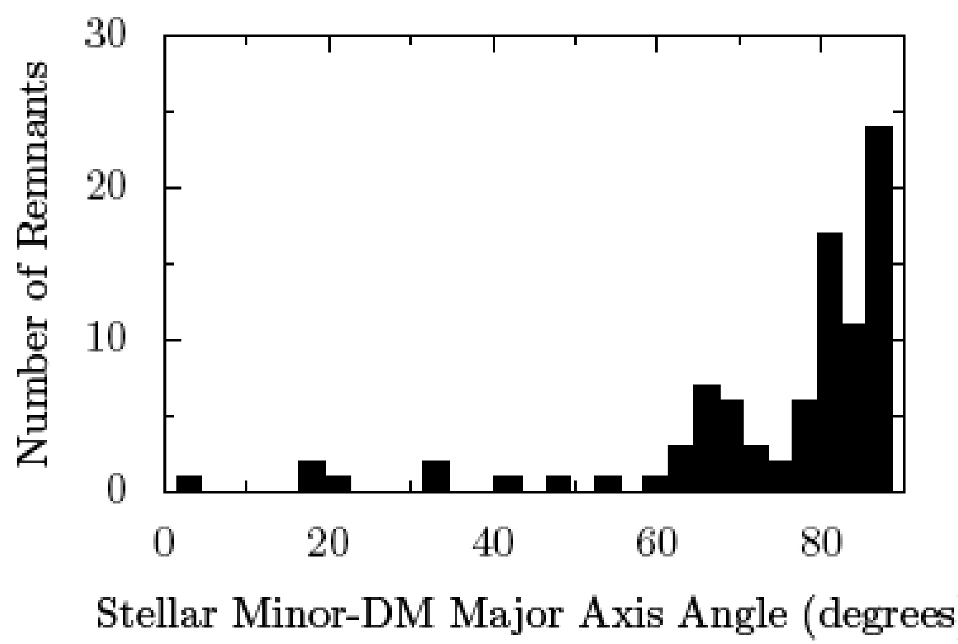
Shapes of Stellar Ellipsoids and Dark Halos of Major Merger Remnants





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

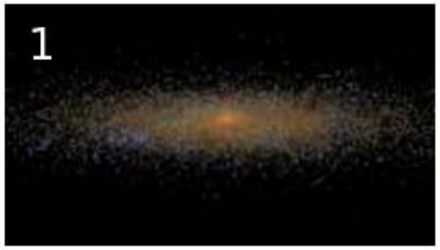
The stellar minor axis usually aligns with the angular momentum axis, which aligns with the dark matter smallest axis, perpendicular to the dark matter major axis.

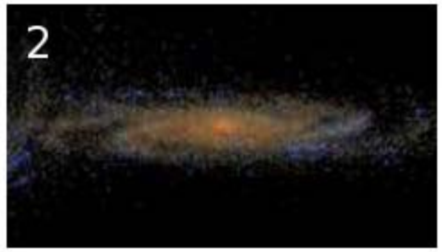


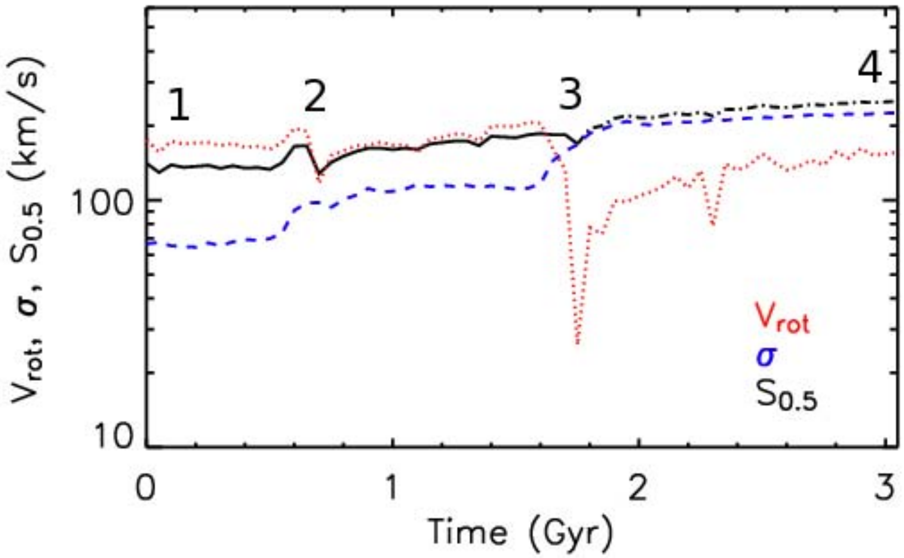
Novak, Cox, Primack, Jonsson, & Dekel, ApJ Letters 2006

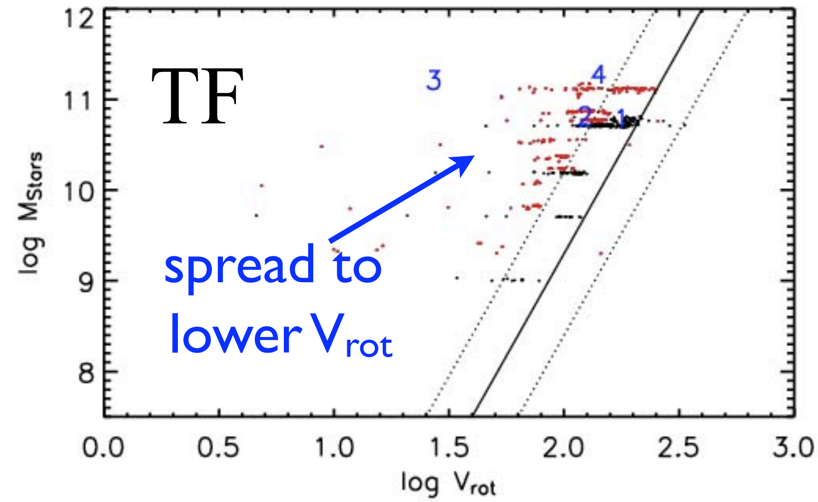
Stellar Mass Tully-Fisher Relation Evolution in Disk Galaxy Merger Simulations Reproduces Observed Behavior

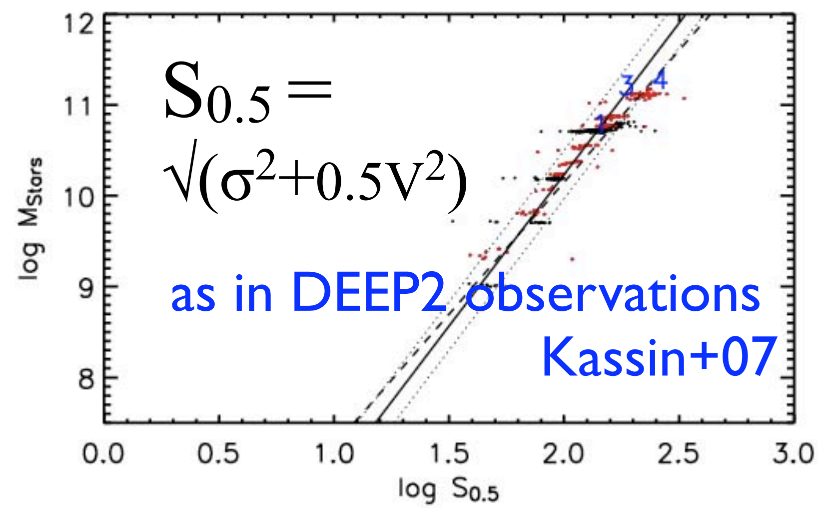
Matthew D. Covington, Susan A. Kassin, Aaron A. Dutton, Benjamin J. Weiner, T. J. Cox, Patrik Jonsson, Joel R. Primack, Sandra M. Faber, & David C. Koo in prep.











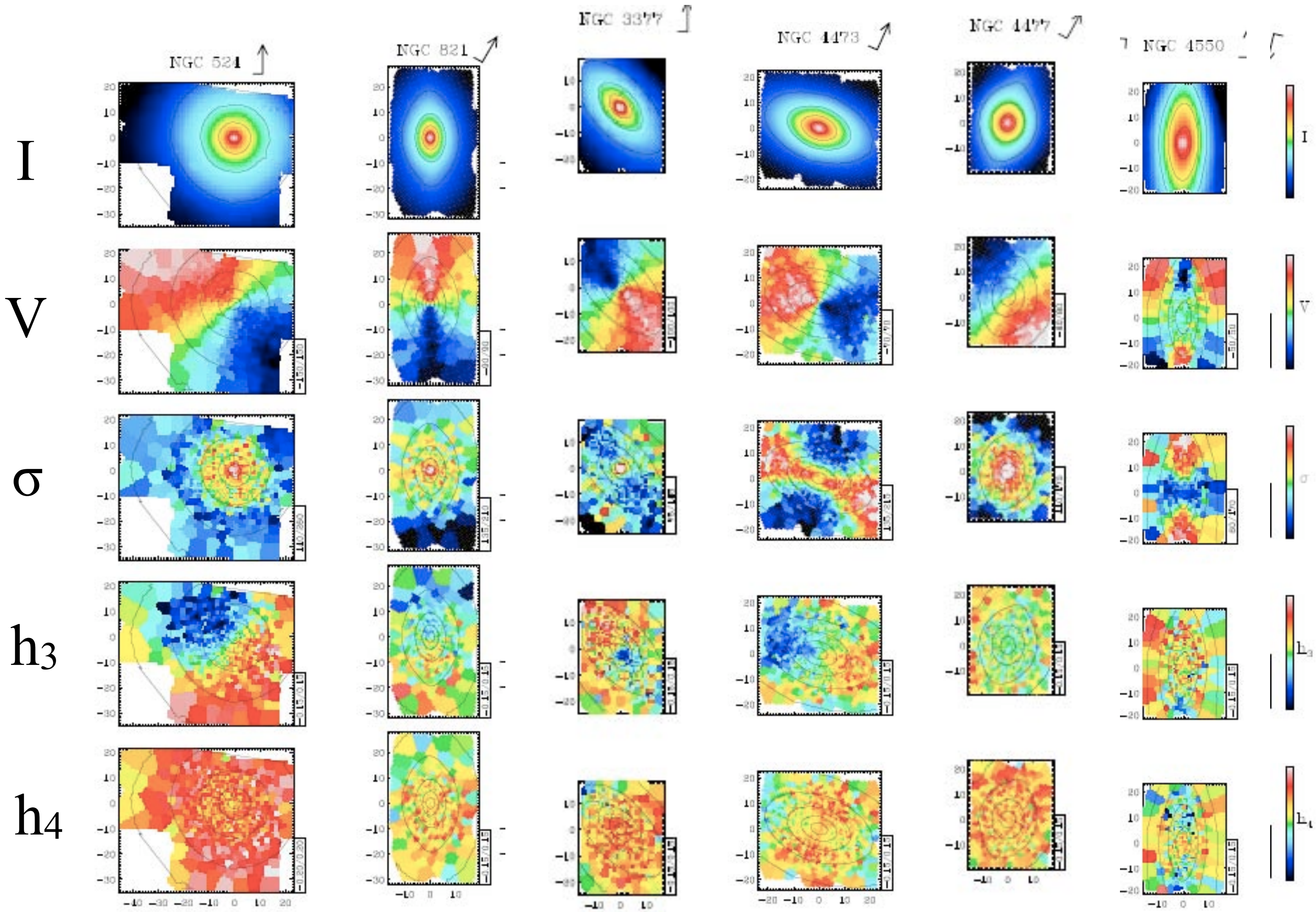
Remnant elliptical galaxies from binary gas-rich disk galaxy mergers

- 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

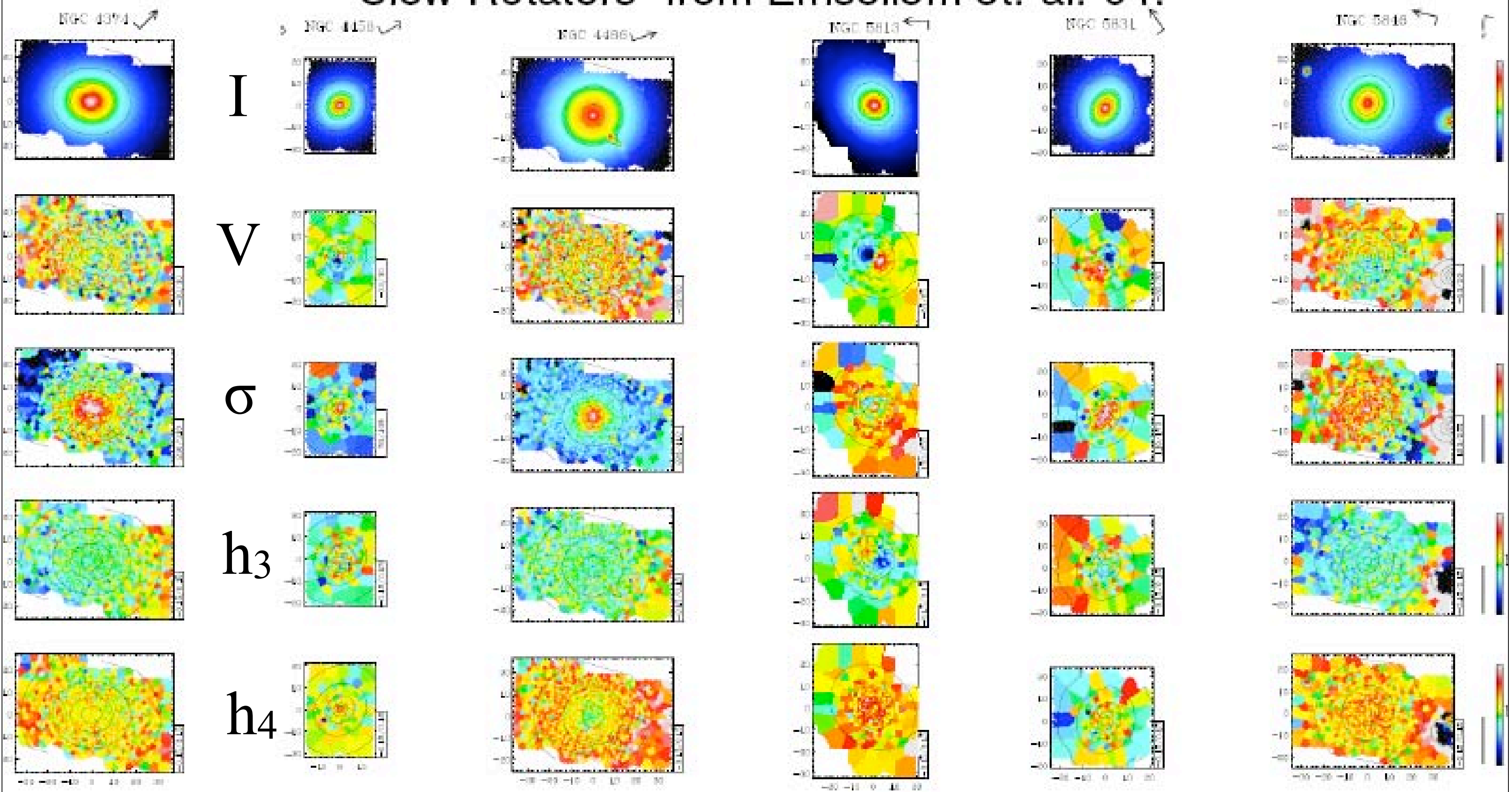
SAURON Data

"Fast Rotators" from Emsellem et al. 2003



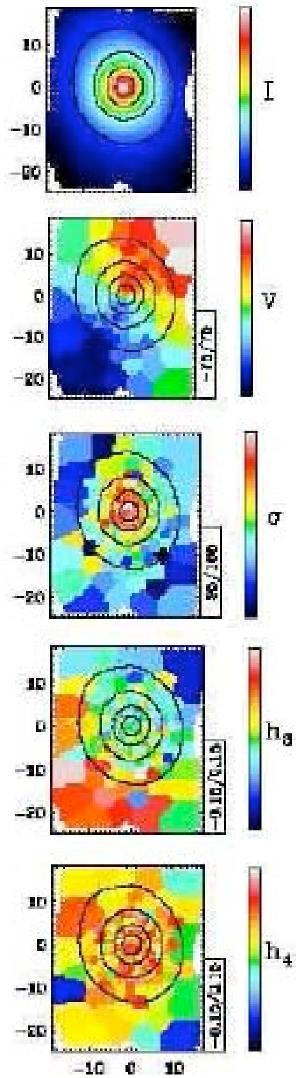
SAURON Data

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



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

SAURON Fast Rotator NGC 474



I

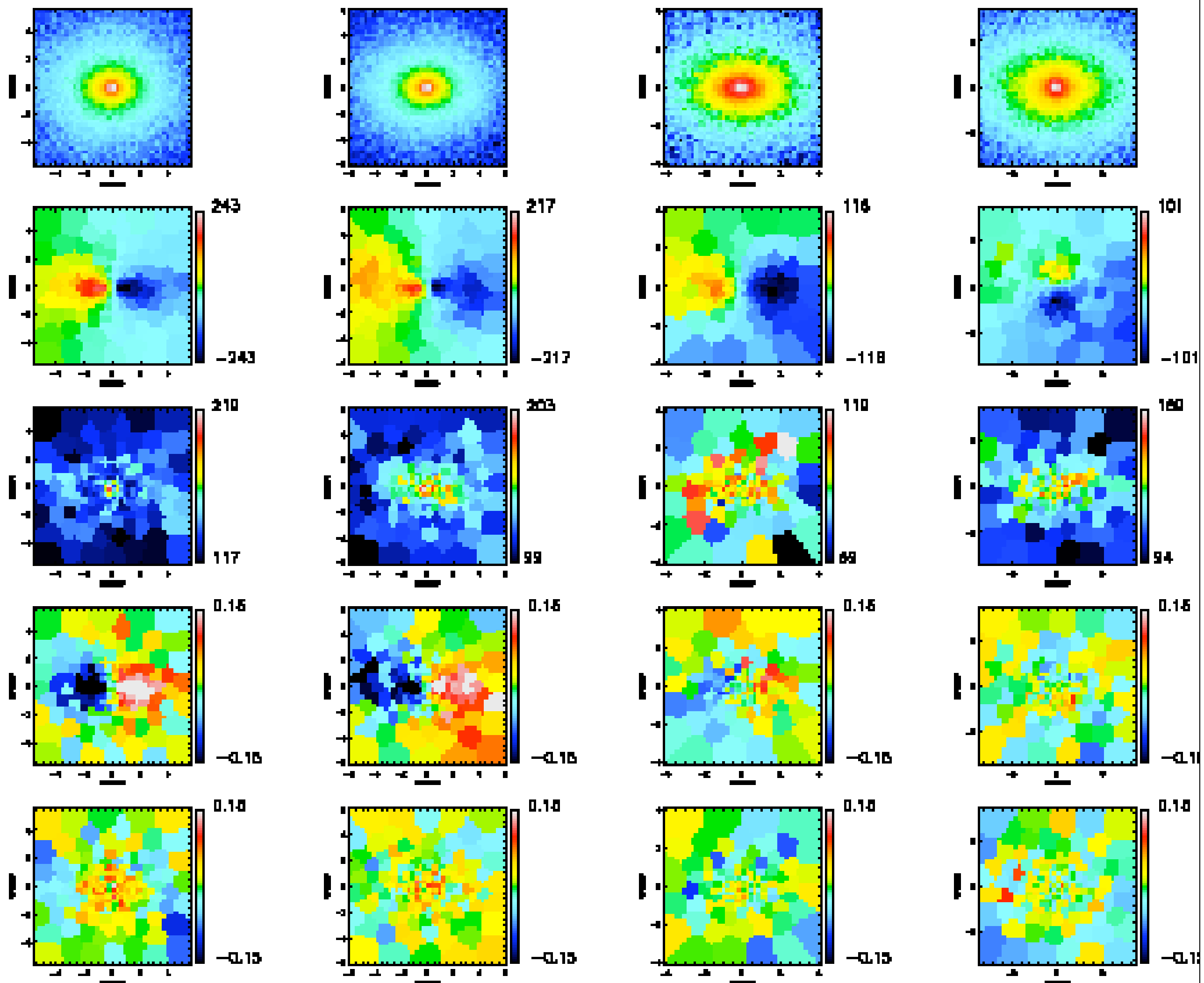
V

σ

h_3

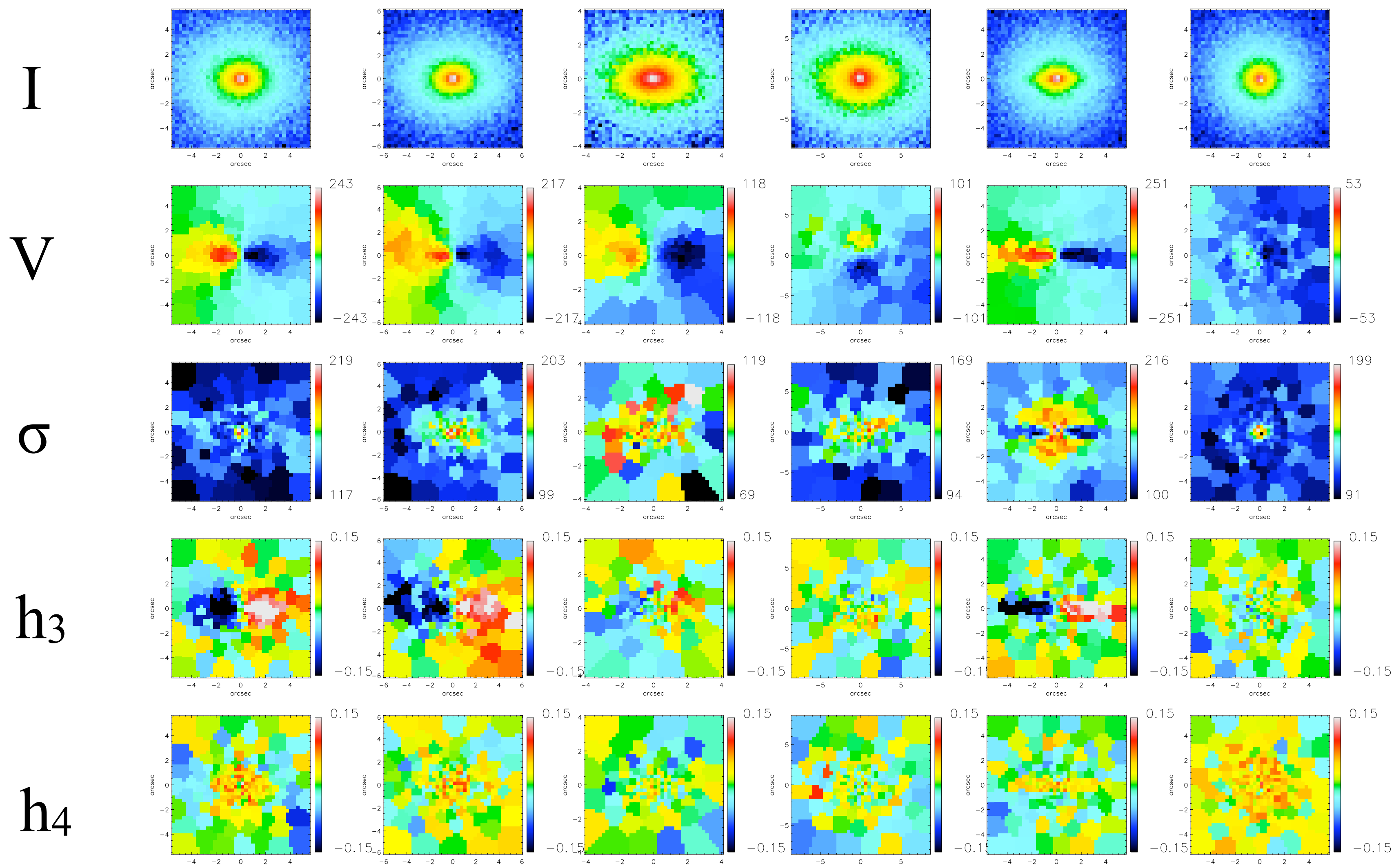
h_4

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



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

Binary Merger Simulations Produce Fast Rotators



Novak+08 in prep

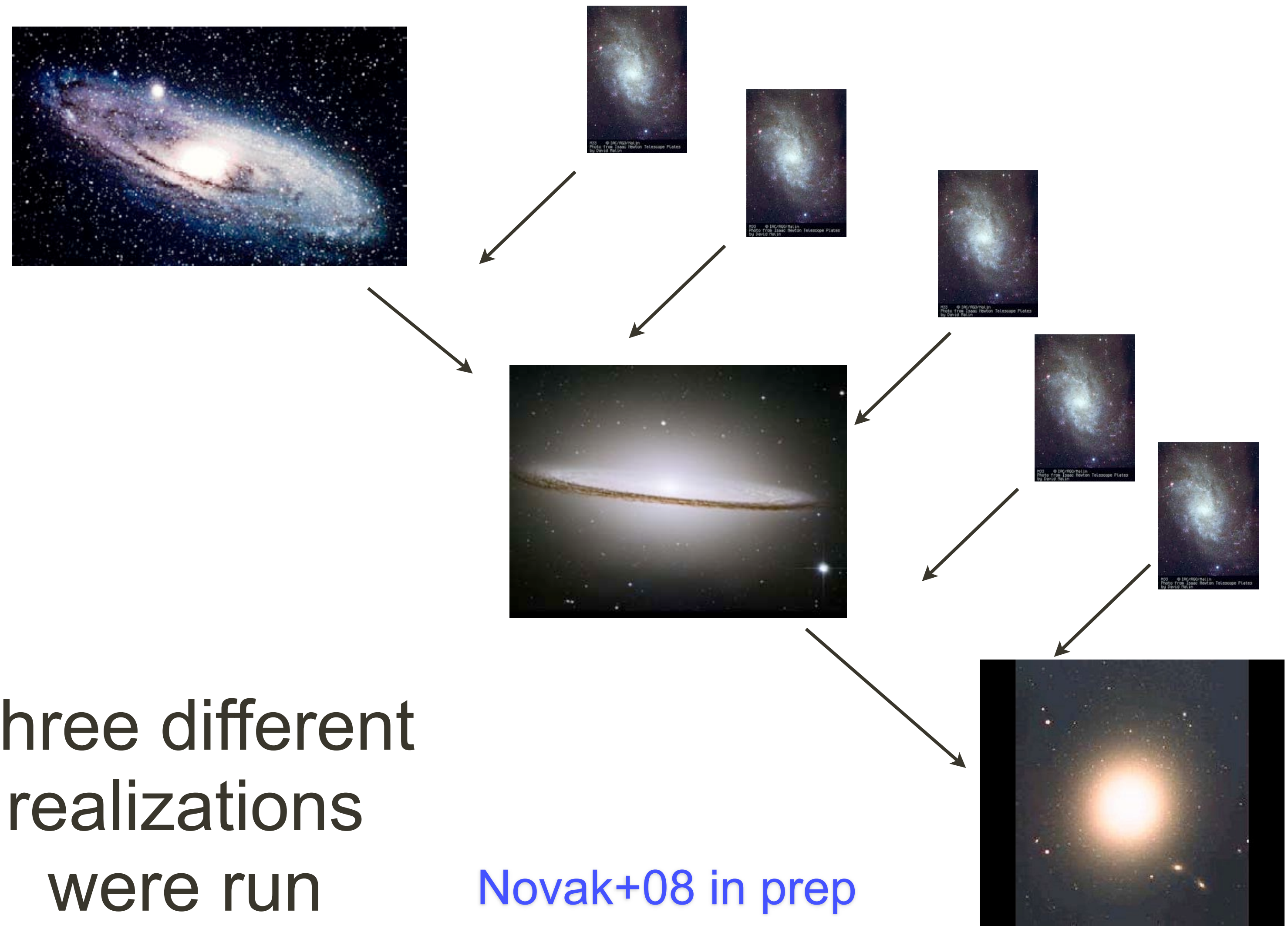
This movitated a study of multiple mergers, which are very likely at $z \gtrsim 2$, when the merger time ~ Hubble time

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

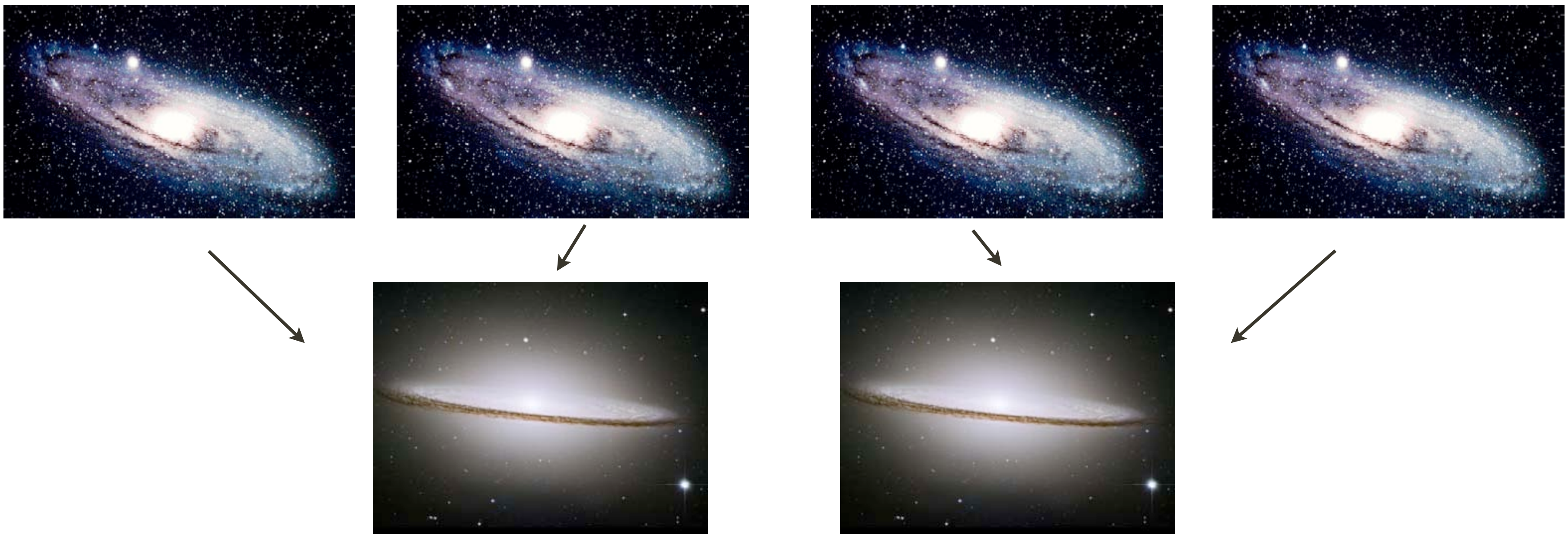
Multi-Minor Mergers



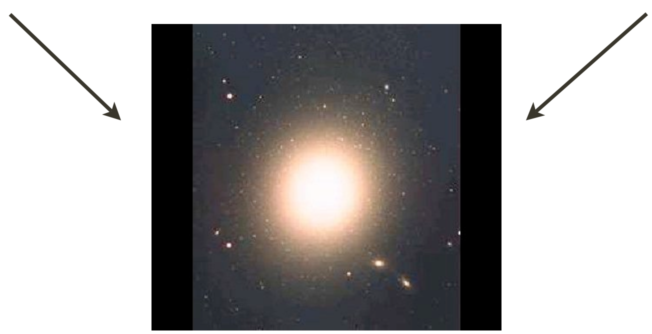
Three different realizations were run

Novak+08 in prep

Multi-Major Mergers

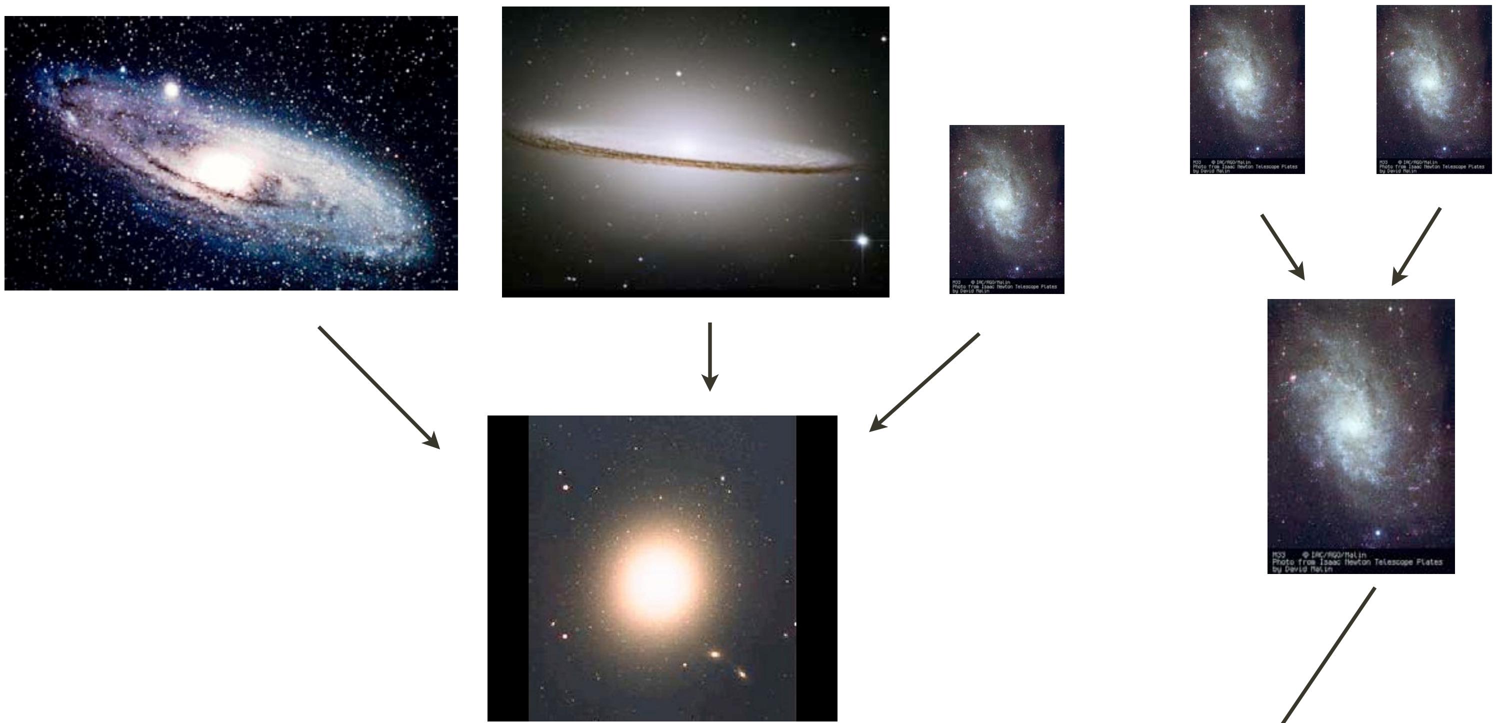


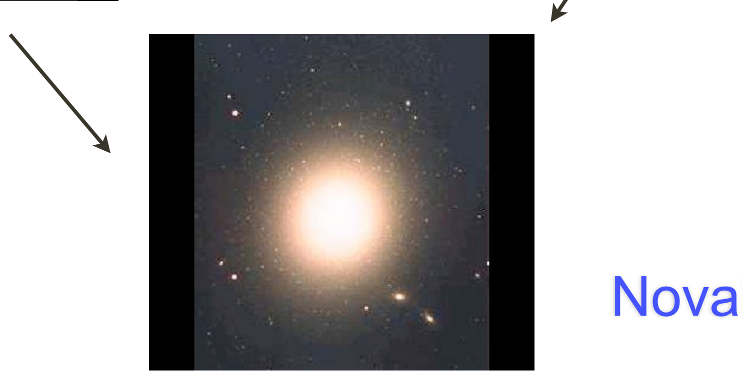
Three different realizations were run



Novak+08 in prep

Cosmological ICs



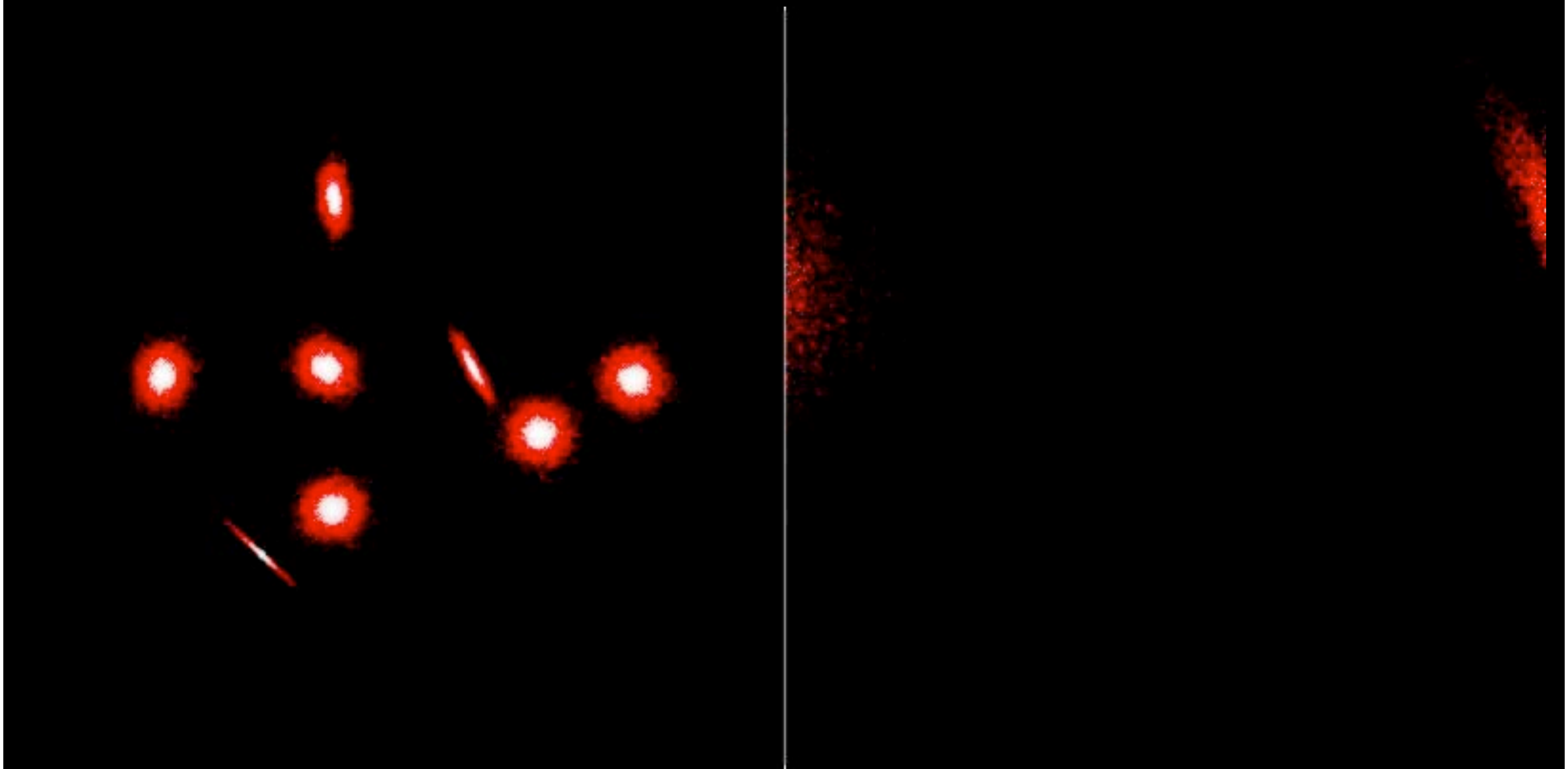


Results now for six different regions, more in progress...

Novak+08 in prep

Multi-Minor Mergers

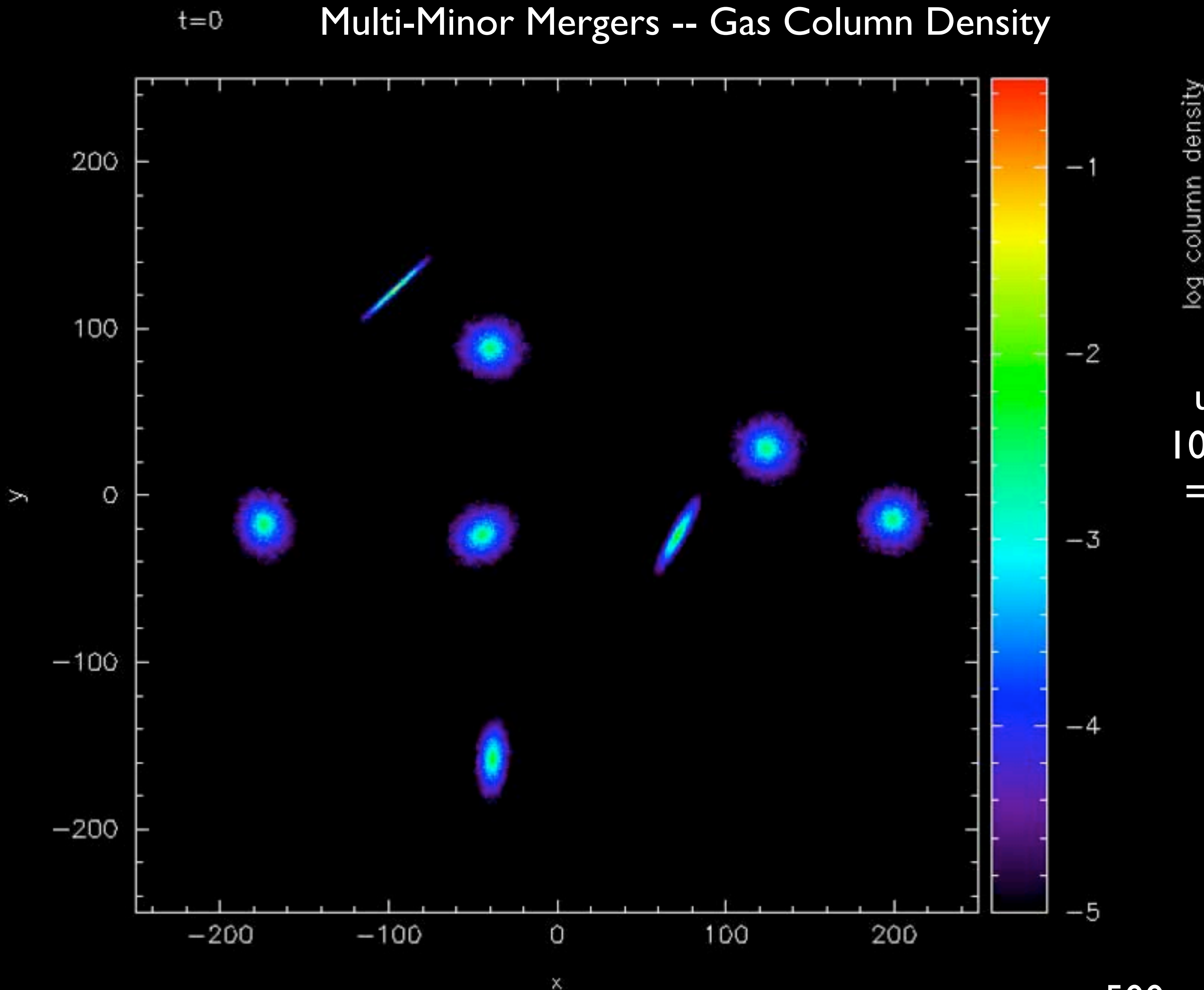
Stars are white   Gas is red



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
$=1.3\times10^{24}$ 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**

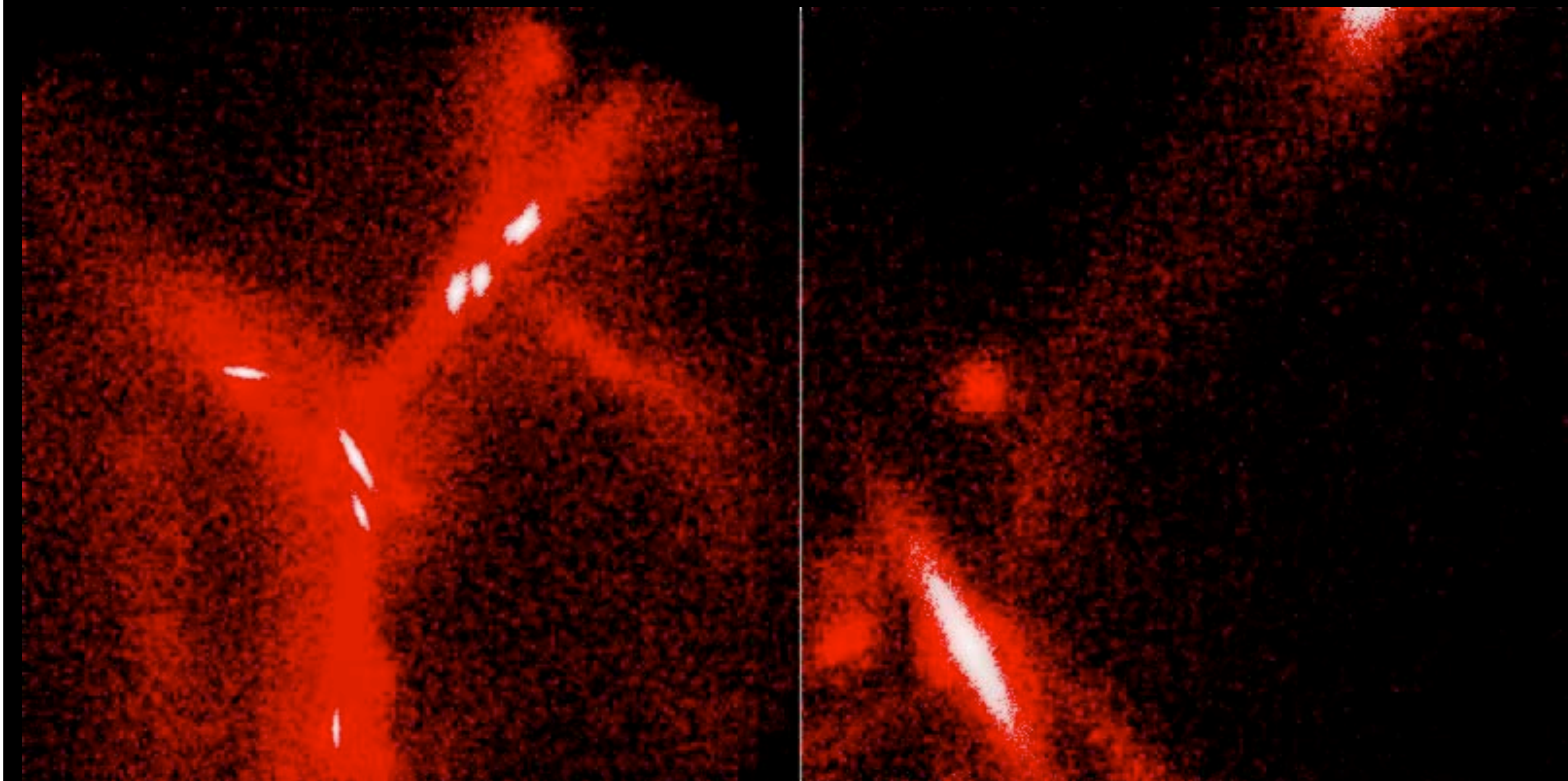
- **Extract "interesting" group halos, replace baryonic lumps with model galaxies, and include 1 proper Mpc high res region + 5 Mpc low res region (1.2 - 2.5 million particles total)**

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

Cosmological Multi-Merger

cos7

Stars are white Gas is red

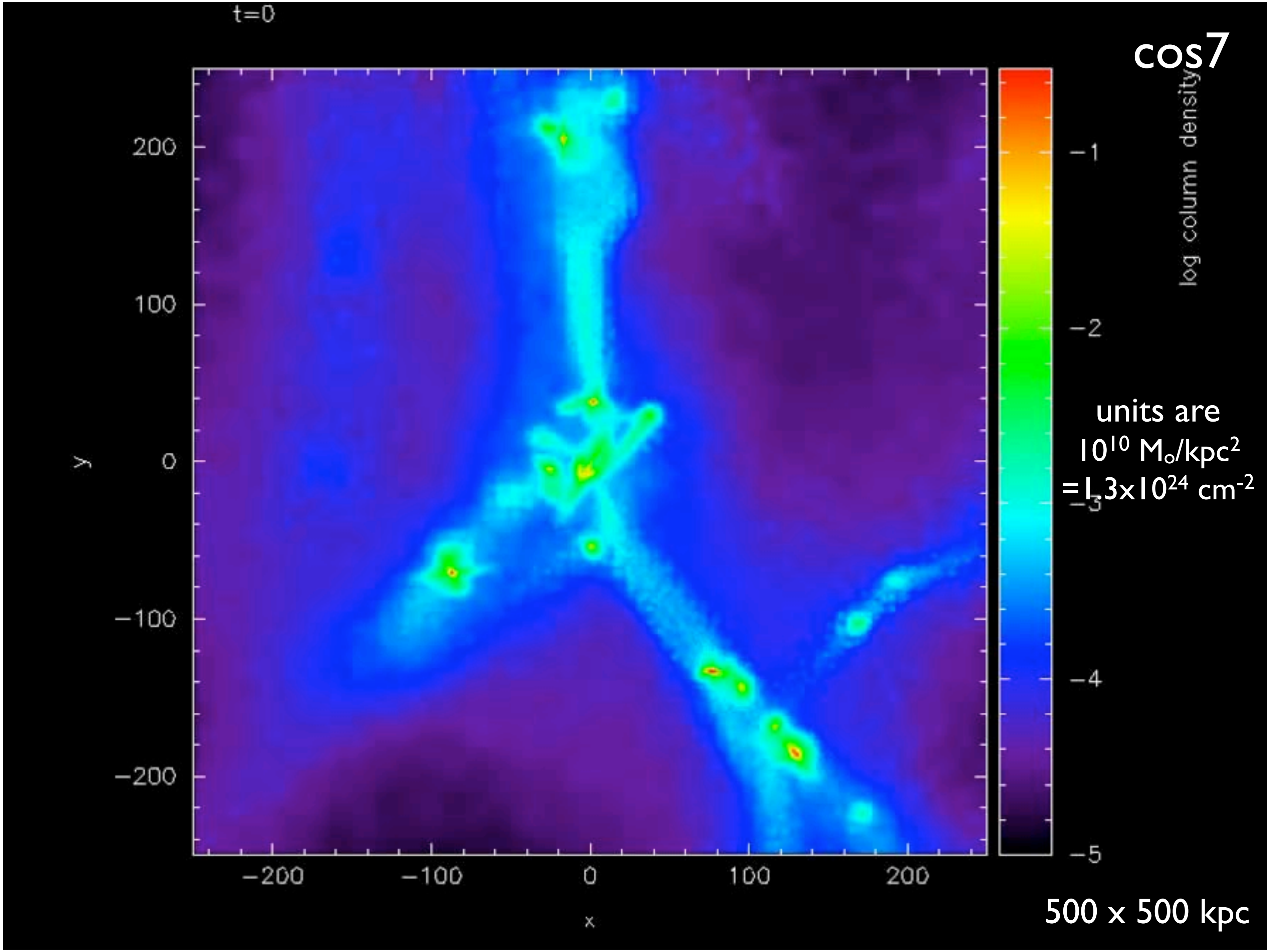


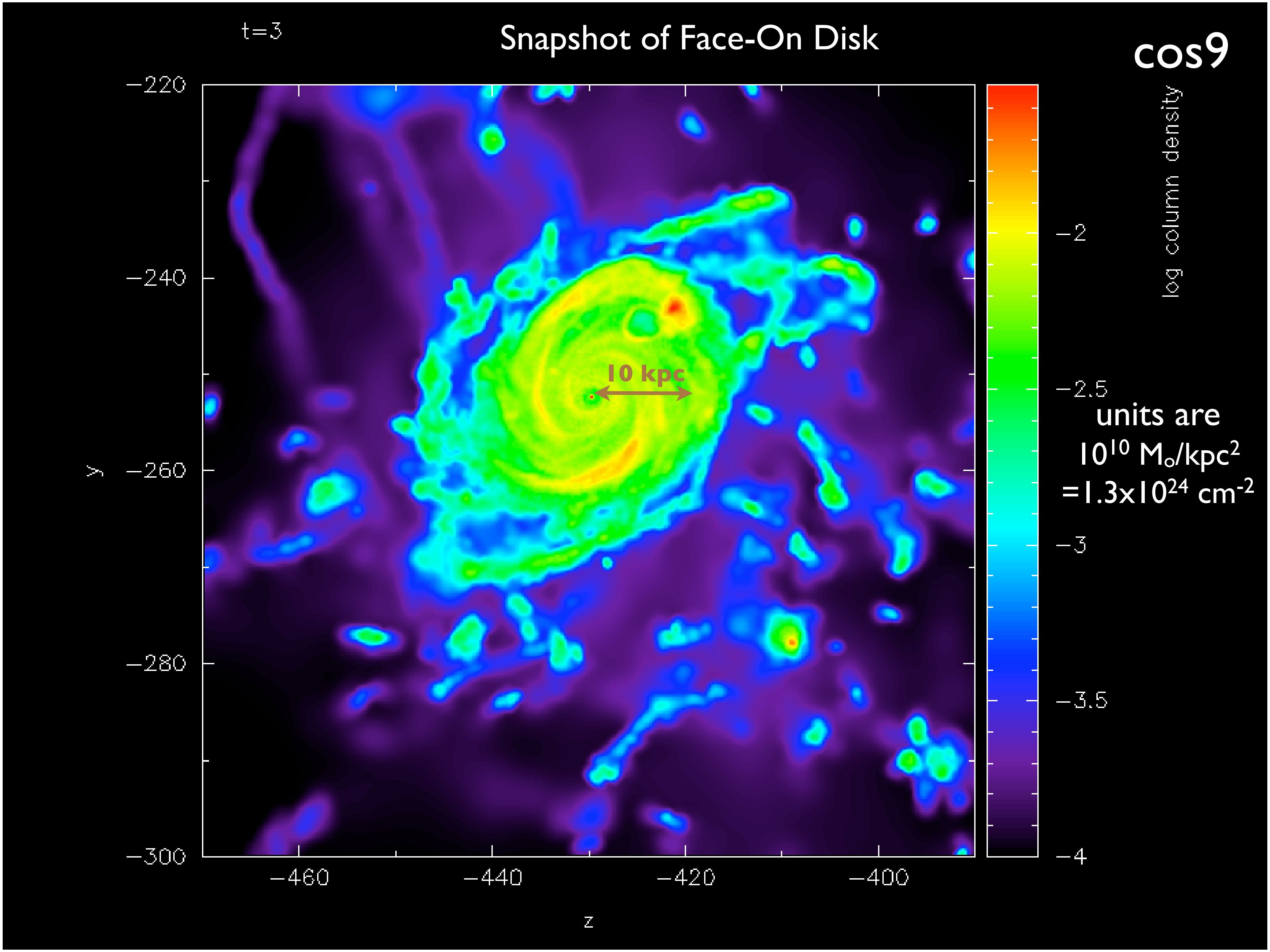
zoomed out

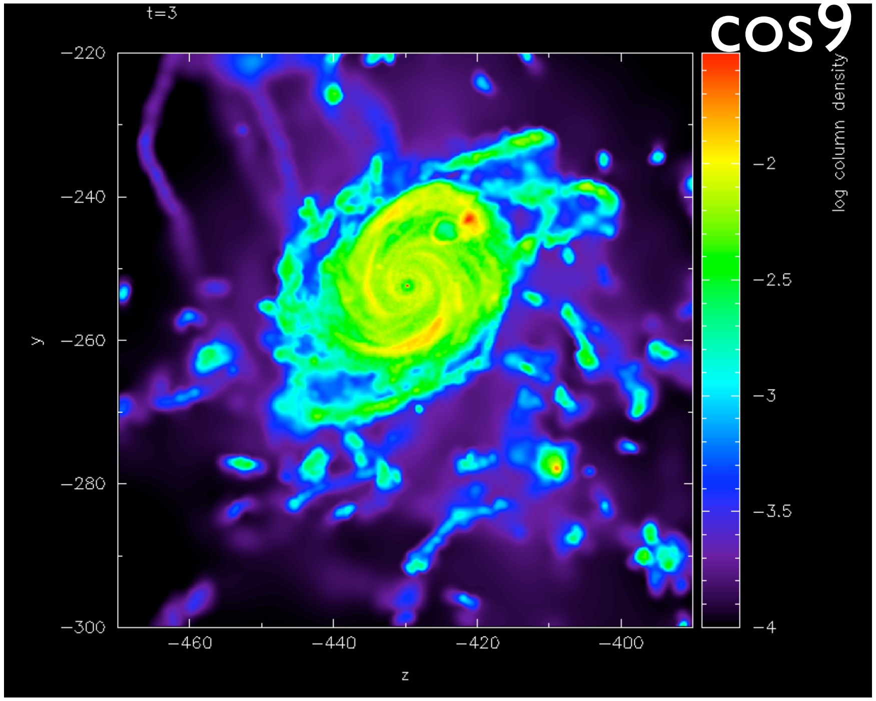
central region

Simulation: Greg Novak

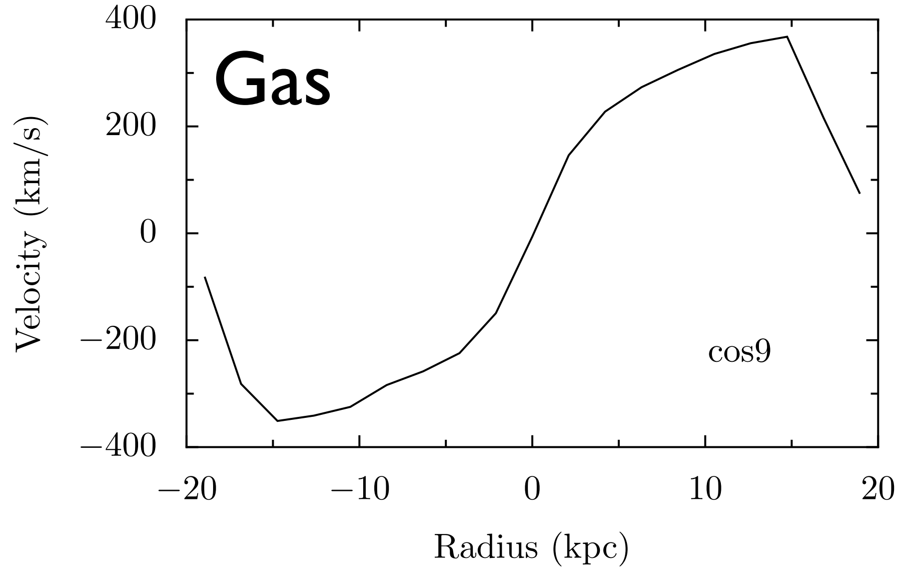
Music: J. S. Bach, from Cantata #22

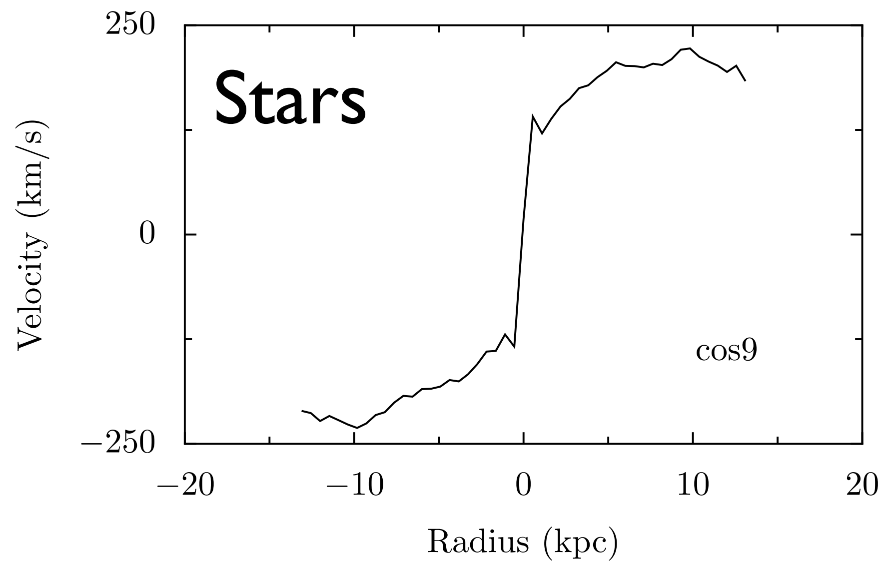

t=0
cos7
log column density
units are
10^{10} M_o/kpc^2
=1.3x10^{24} cm^{-2}
200
100
0
−100
−200
y
x
−1
−2
−3
−4
−5
500 x 500 kpc


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



Rotation Curves

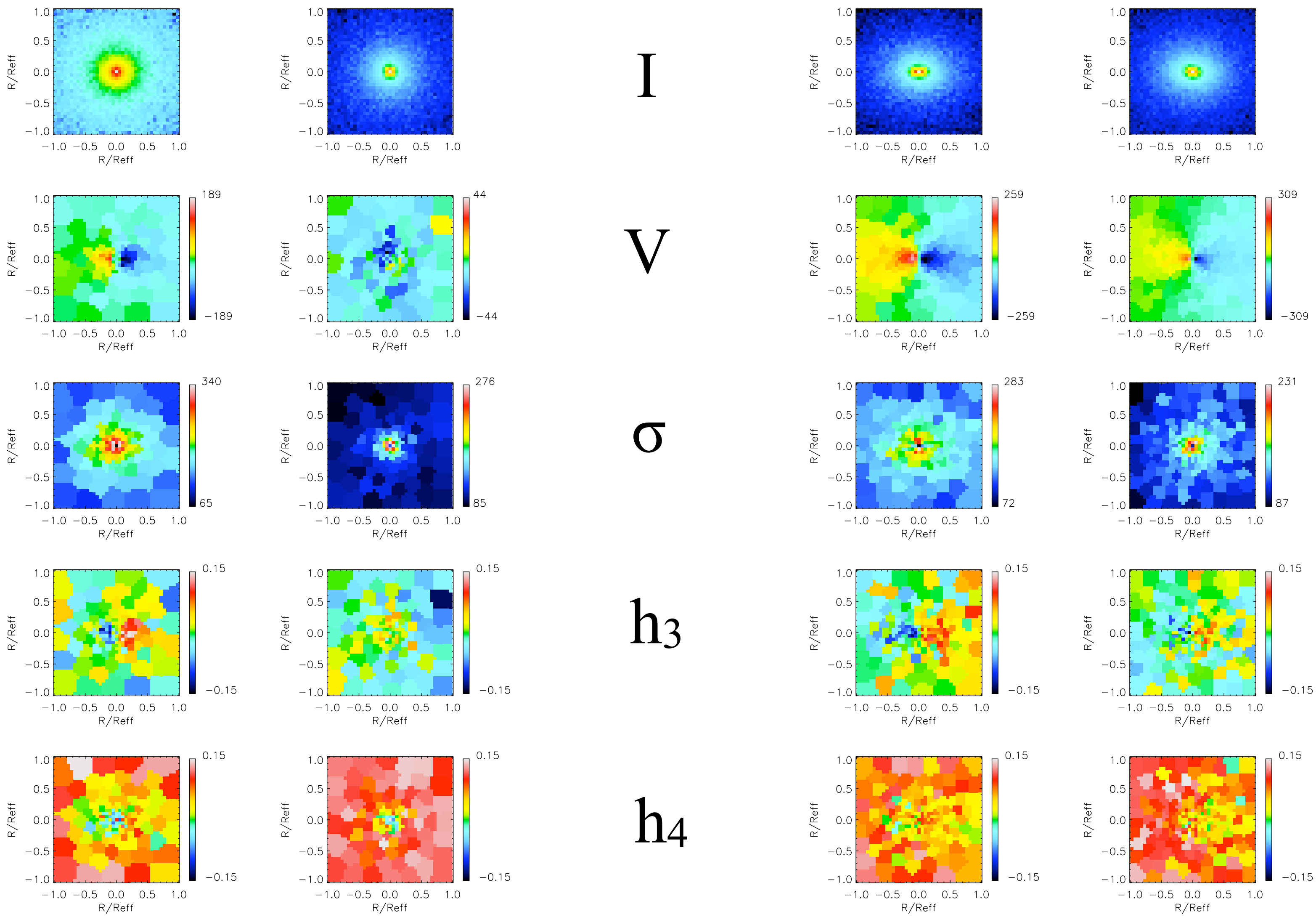




Many of the Galaxies Formed in Our Cosmological Simulations Appear to Resemble SINFONI Observations

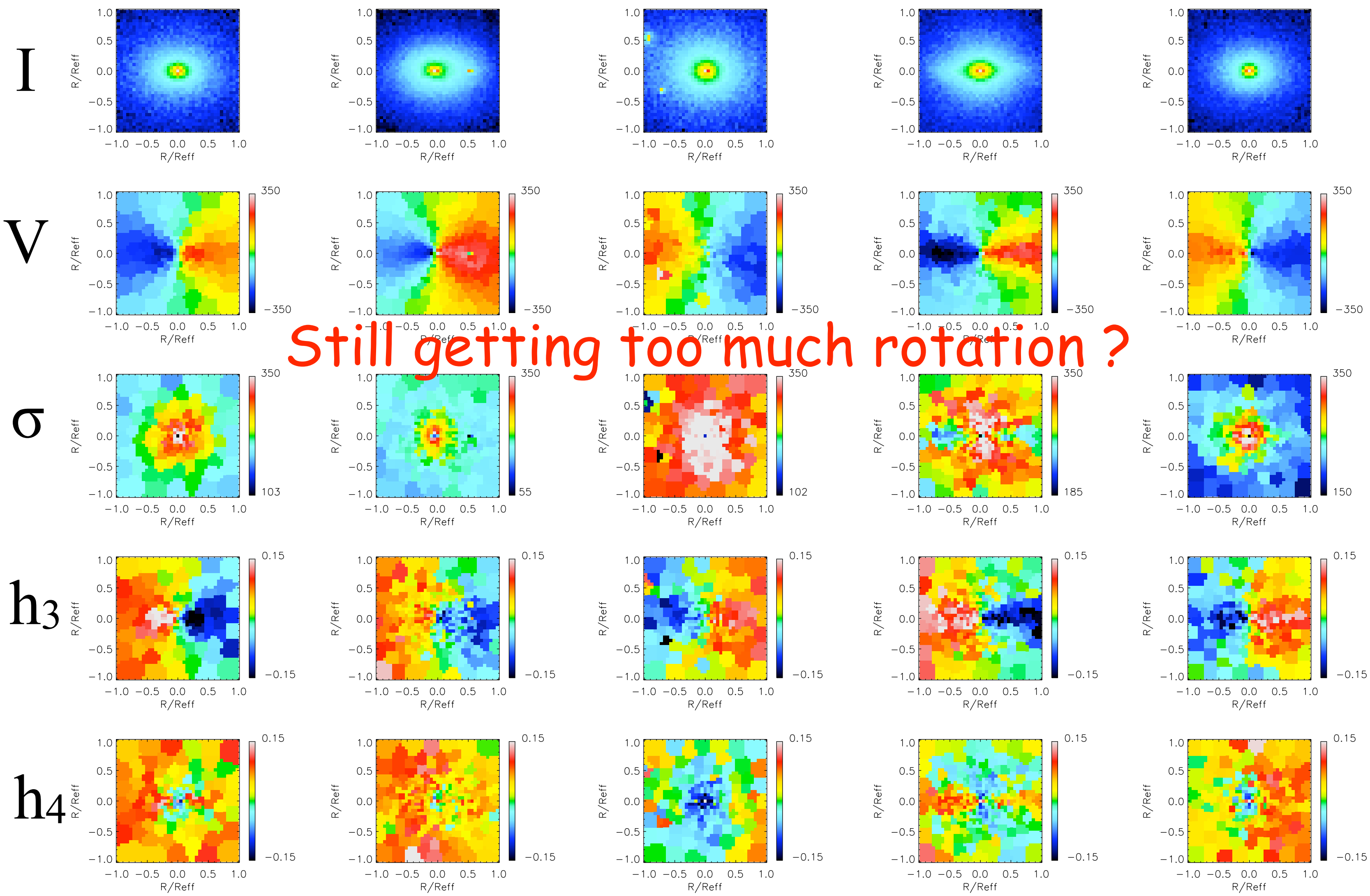
Novak+08 in prep

Multi-Minors   Multi-Majors



Produce Spheroids with Little or No Rotation

Cosmological Multi-Merger Simulations



Still getting too much rotation ?

Novak+08 in prep

Conclusions

- New galaxy surveys are greatly improving our picture of the evolution of galaxy properties. Key results include the red/blue color bimodality to at least $z \sim 1.4$, the small range of star formation rates (SFR) in star forming galaxies at a given z, and SFR increase with increasing z.
- Just as mass is the controlling parameter for stars, the key parameter that controls galaxy evolution appears to be the mass of its dark matter halo.
- Dissipationless simulations now resolve substructure in galaxy halos within the solar radius in a MWy size galaxy.
- Cold gas flows into galaxies if $M_{halo} < 10^{12}\ M_{sun}$ or at $z > 2$.
- Improved resolution and feedback are producing more realistic spiral galaxies, although further work is needed.
- Most small elliptical galaxies appear to be produced by binary mergers of gas-rich disks (Lecture 4). Most larger ellipticals may be produced by multiple mergers at $z>2$.