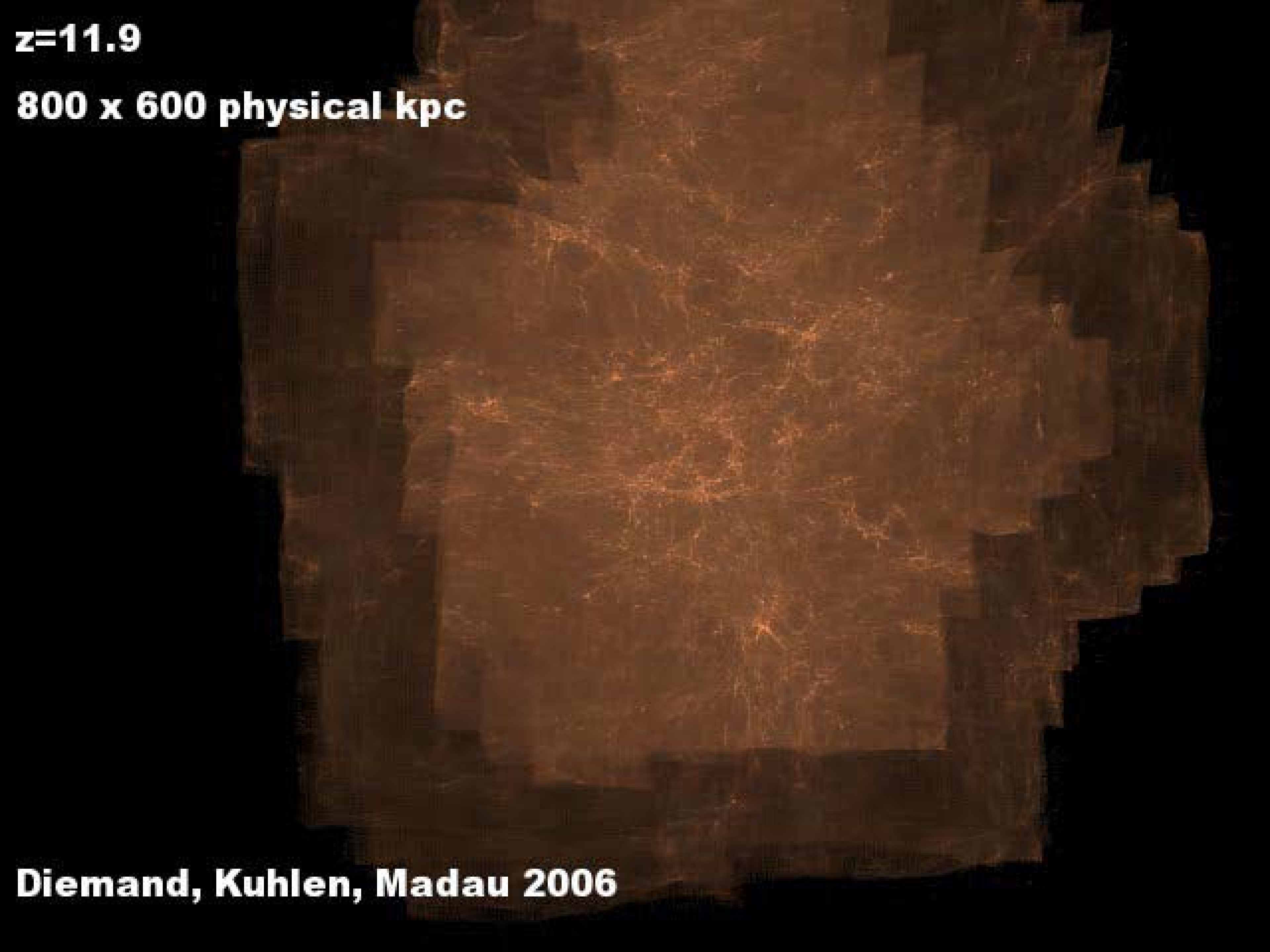
6th Patras Workshop on Axions, WIMPs and WISPs

News from structure and galaxy formation

Ben Moore, Institute for Theoretical Physics, University of Zurich

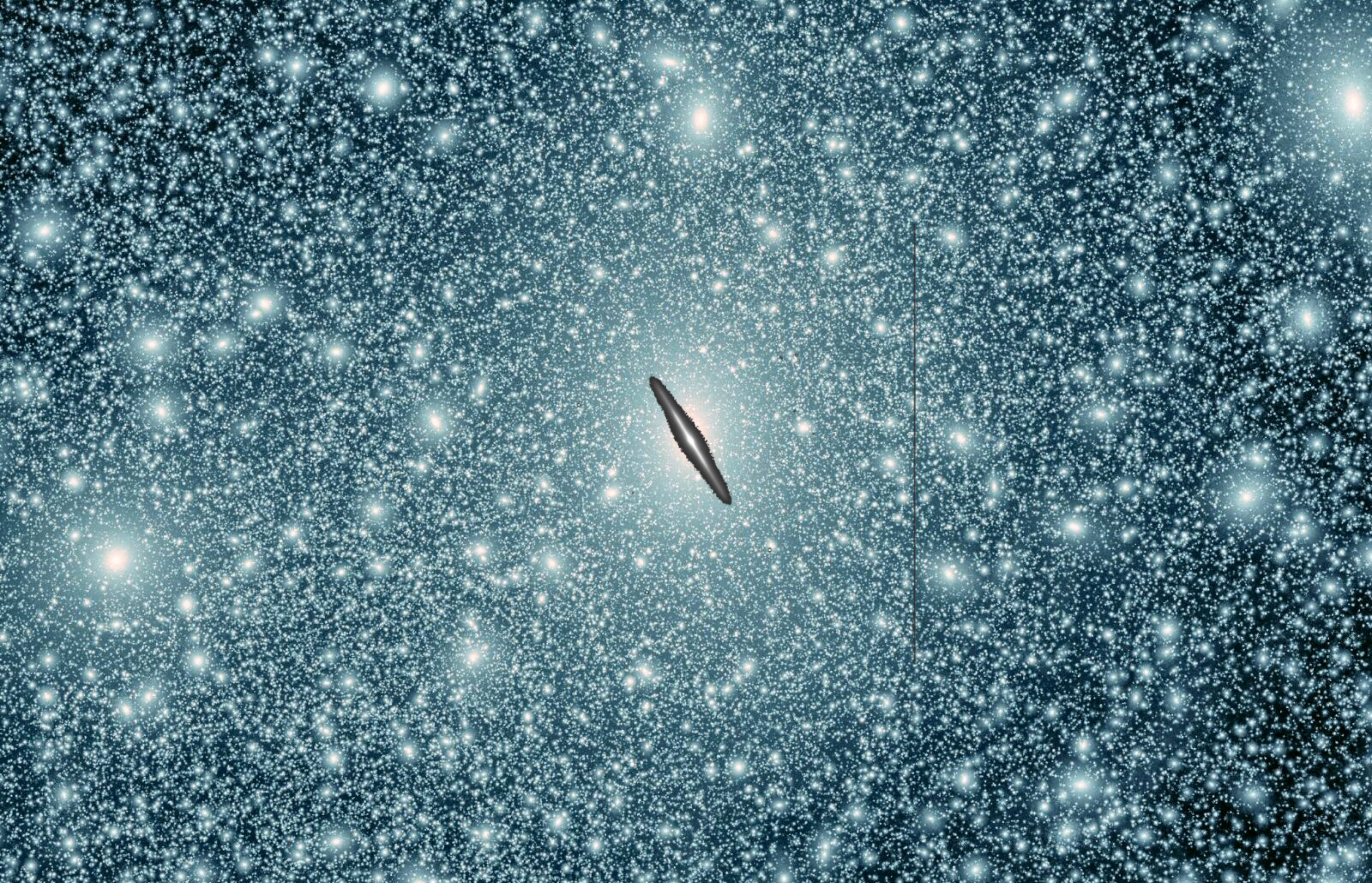
I. Dark matter

(Joachim Stadel, Aurel Schneider, Doug Potter, Juerg Diemand, Mike Kuhlen, Marcel Zemp, Piero Madau, Victor Debatistta)


z=11.9
800 x 600 physical kpc
Diemand, Kuhlen, Madau 2006

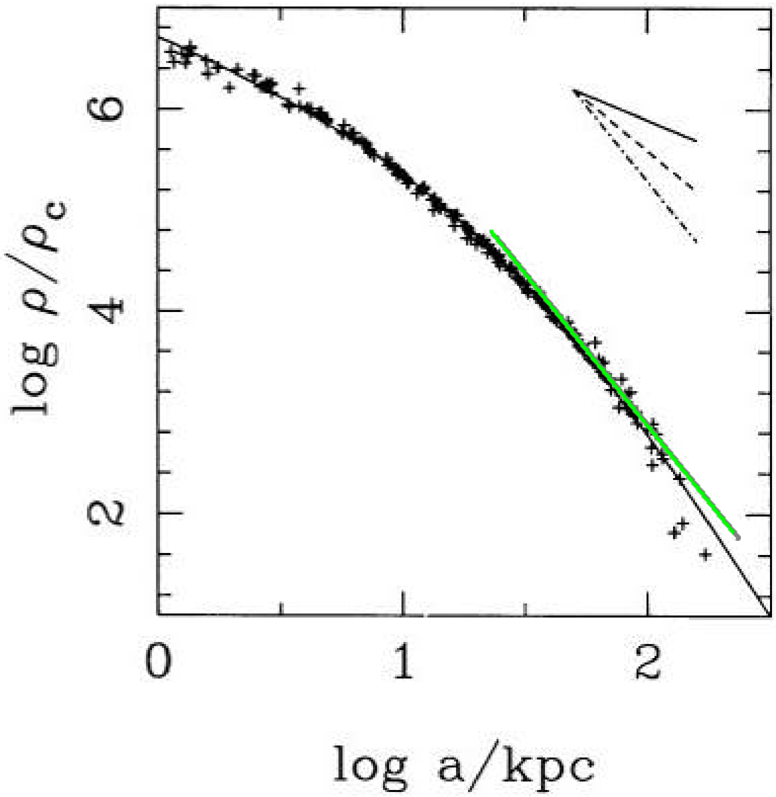
GHALO: A billion particle simulation of the dark matter distribution surrounding a galaxy. 3 million cpu hours with the parallel gravity code pkdgrav (Stadel et al 2008)

50 parsec, 1000Mo resolution, 100,000 substructures



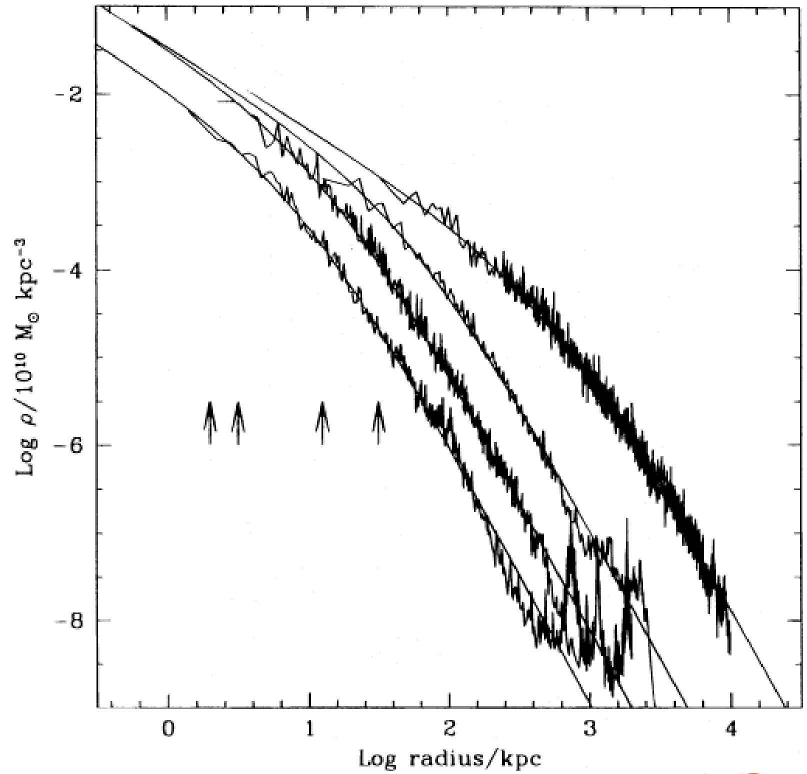
GHALO: A billion particle simulation of the dark matter distribution surrounding a galaxy. 3 million cpu hours with the parallel gravity code pkdgrav (Stadel et al 2008)

50 parsec, 1000Mo resolution, 100,000 substructures



Dubinski & Carlberg (1991)

One of the most important unsolved problems in dynamics is to understand the end state of collapsed structures.



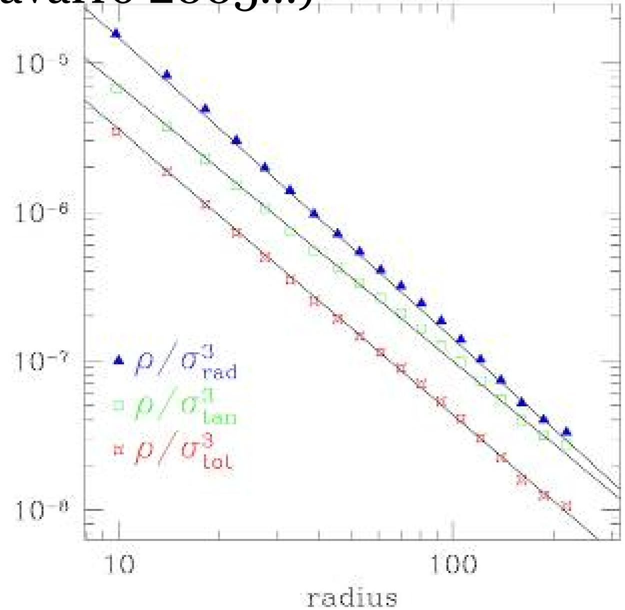
NFW (1996)

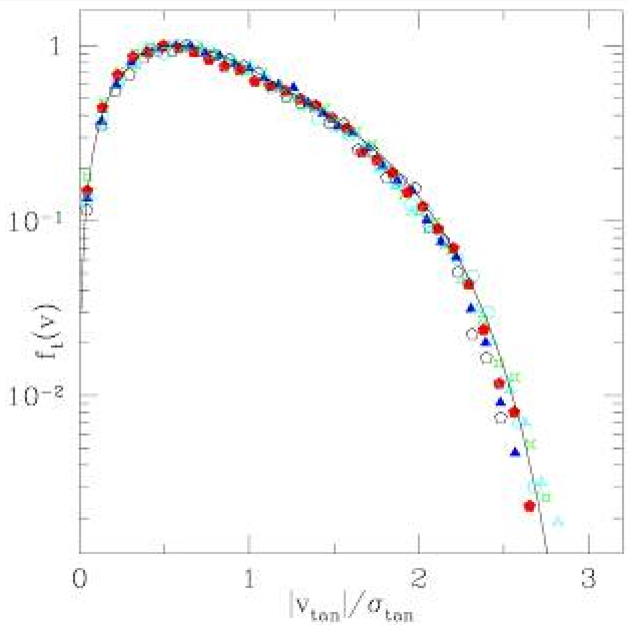
$$\frac{\rho(r)}{\rho_{\rm crit}} = \frac{\delta_c}{(r/r_s)(1 + r/r_s)^2},$$

$$\rho(r) = \rho_{\rm e} \exp\left\{-d_n\left[(r/r_{\rm e})^{1/n} - 1\right]\right\}$$

Einasto (1965) fits everything...

Universal density, f(v), alpa-beta, phase space profiles from spherical collapse simulations with different initial radial profiles… (Hansen & Moore 2006, Taylor & Navarro 2005…)





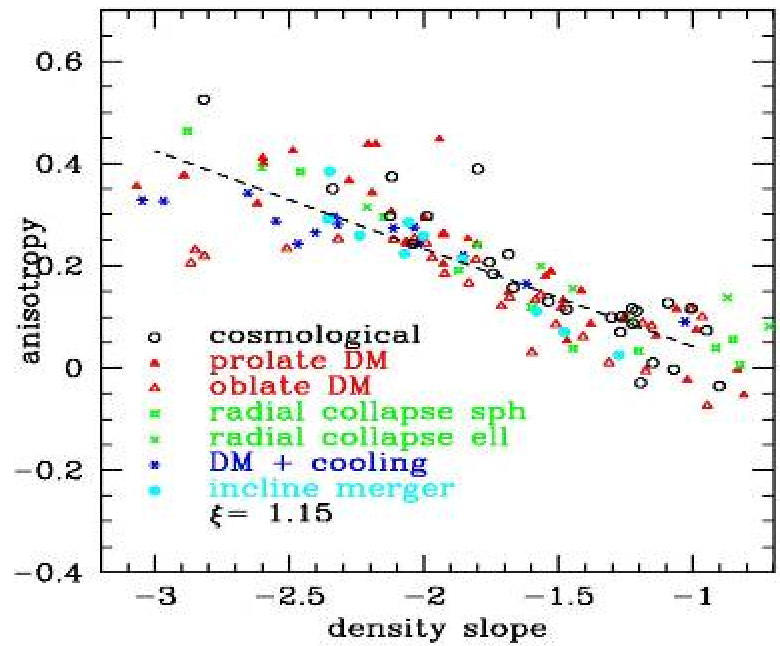
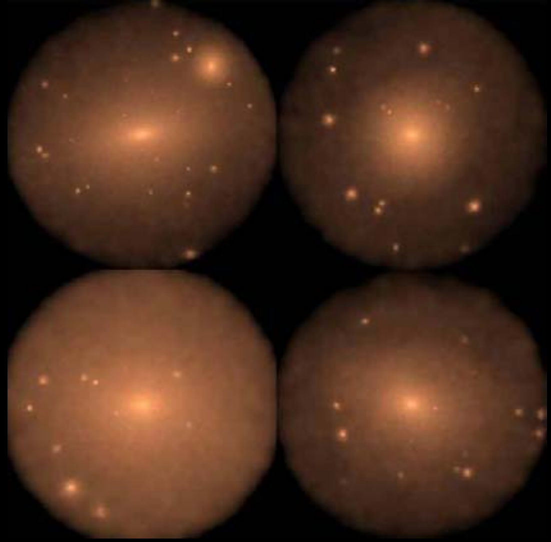
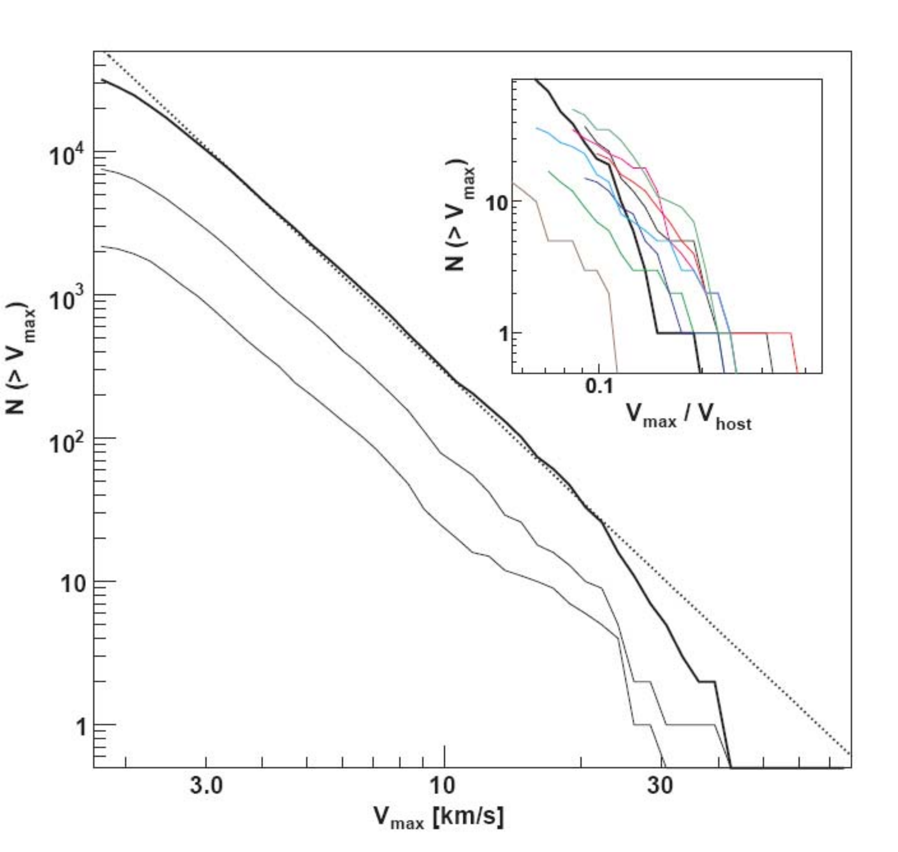
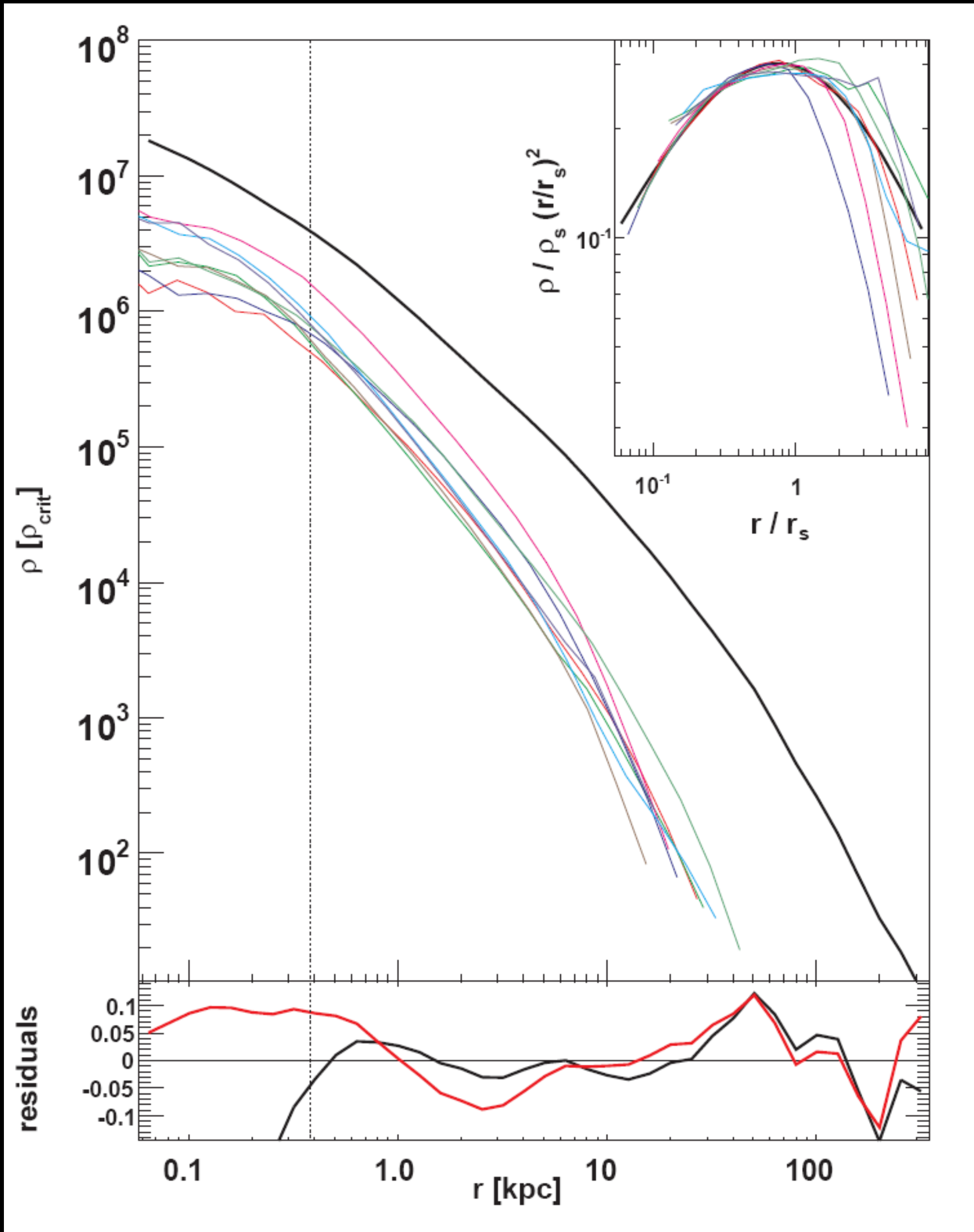


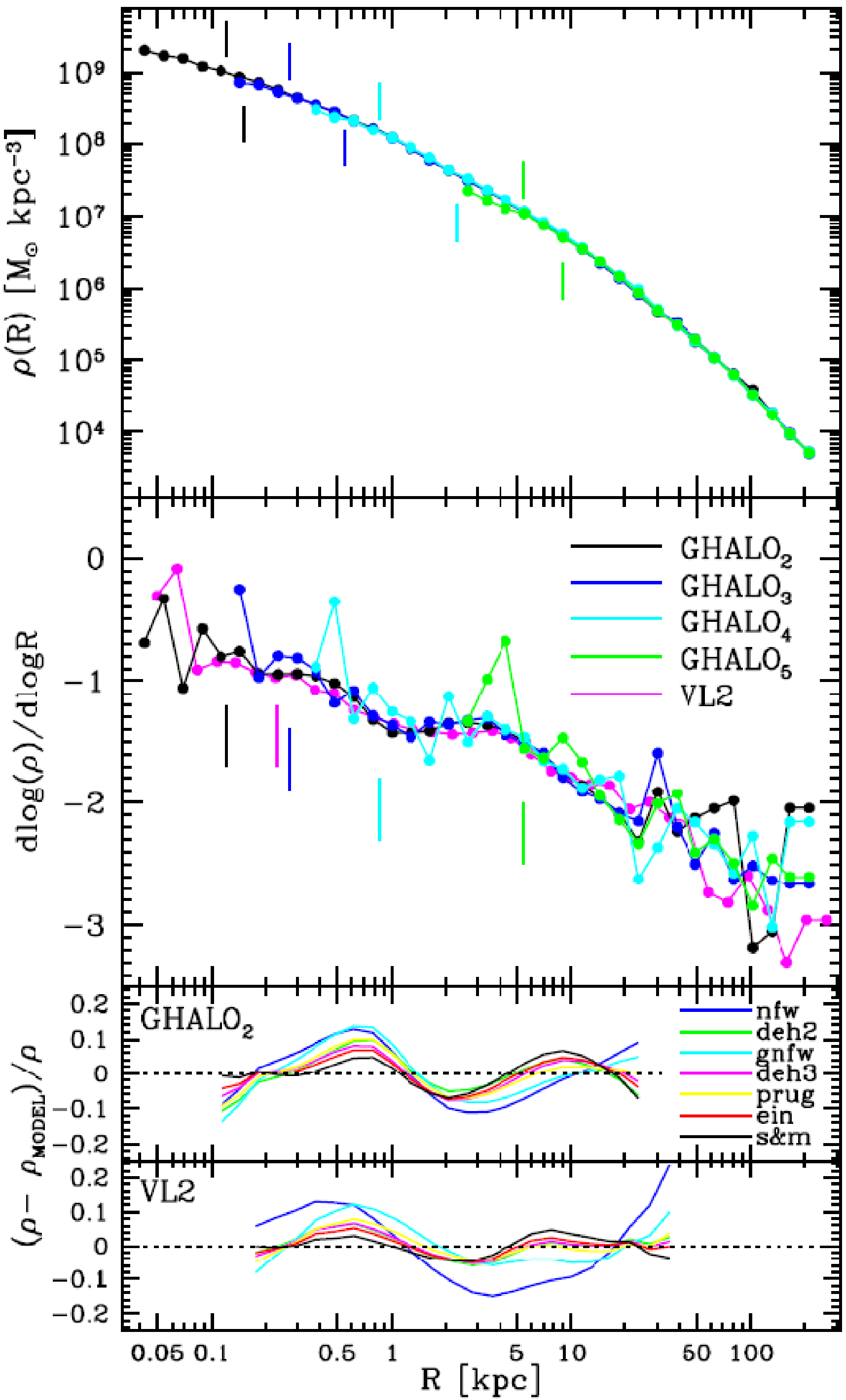
Figure 2. The final density slope versus velocity anisotropy for the six different simulations (coloured symbols) discussed in the text. For the spherical collapse calculation we plot the result using both spherical and elliptical bins. A general relation is clear with the slope in the range -3 to -1. The shape of the relation is reasonably well fit with 2 parameters, $\beta = \eta_1 - \eta_2\,\alpha$, where approximately $-0.45 < \eta_1 < 0.05$ and $0.1 < \eta_2 < 0.35$. The dashed (black) line is a one parameter fit as discussed in section 4, with the parameter $\xi = 1.15$.



Substructures have there own "sub-substructure"







The inner slope of GHALO is -0.8 at 160pc=0.067%R_{vir}

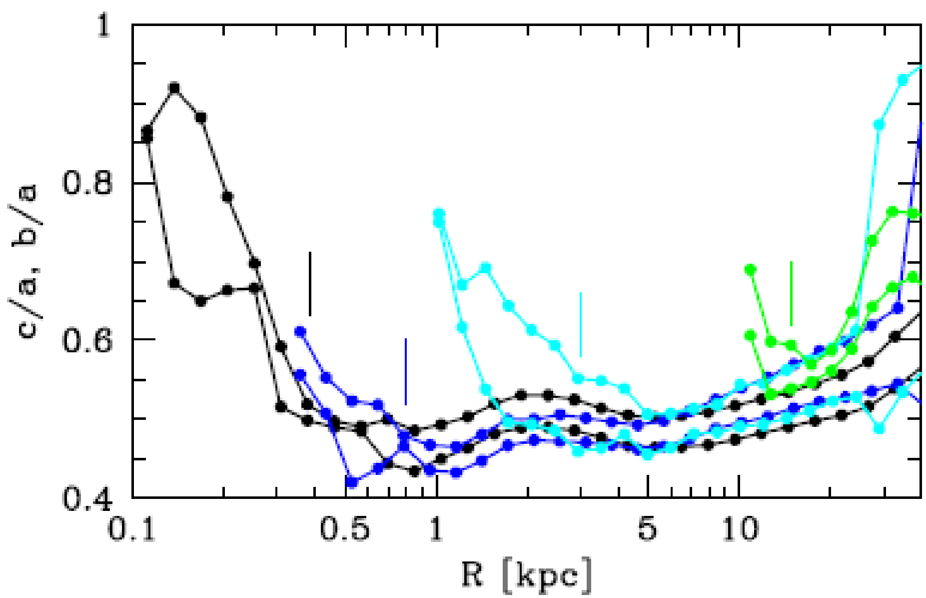
Between 0.5-1.5% of the virial radius the slope is -1.4

The best fitting density profile is the function:

$$\rho(r) = \rho_0 e^{-\lambda(\ln(1-r/R_\lambda))^2}$$

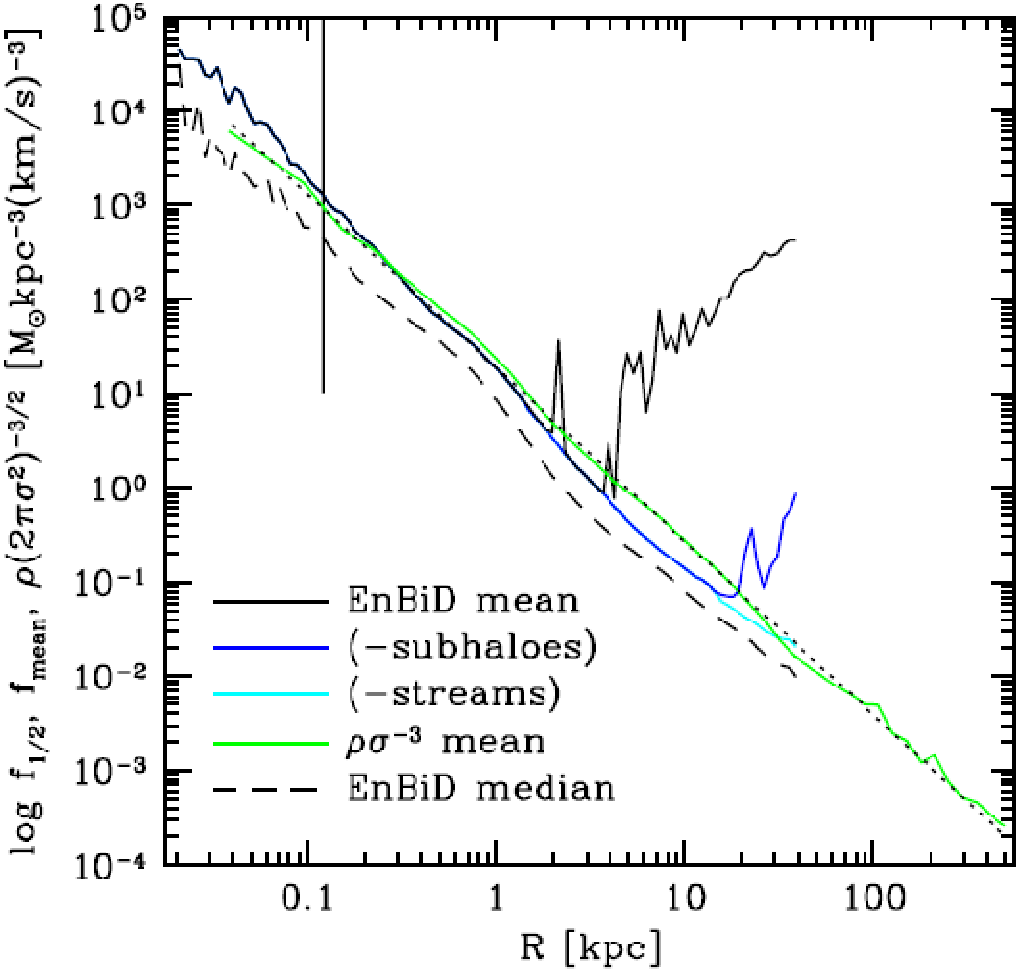
which is linear in a slope vs log(R) plot down to a scale R_λ beyond which it approaches the maximum density as r→0

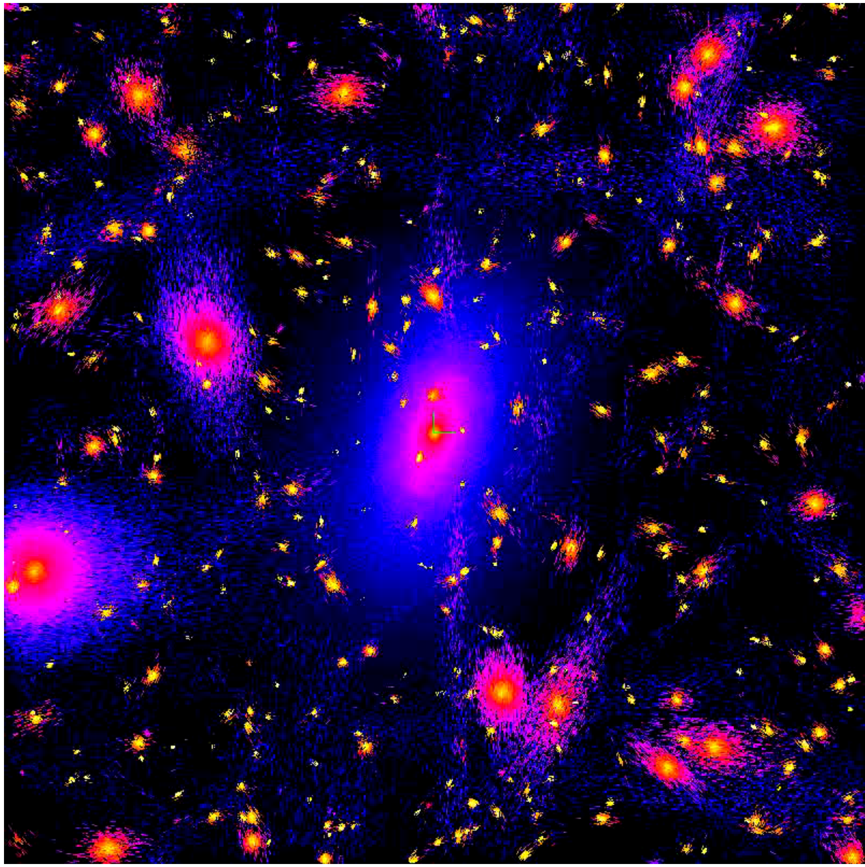
Halo density profile and shape



Phase space structure and streams of dark matter

(Diemand et al 2008)





One gets different profiles if you include/exclude substructures or streams

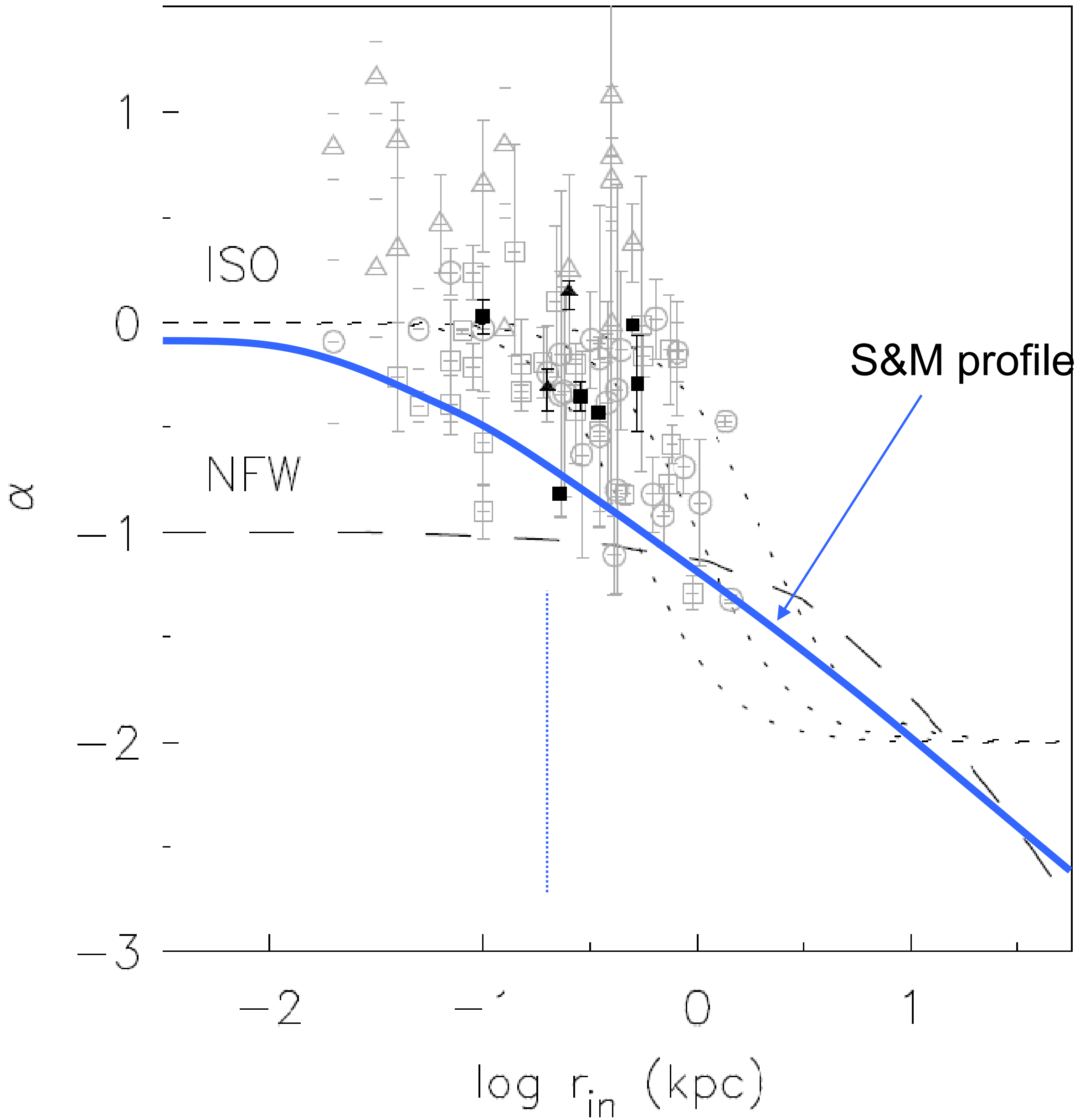
Computer calculations have given robust predictions for how dark matter assembles into 'haloes'

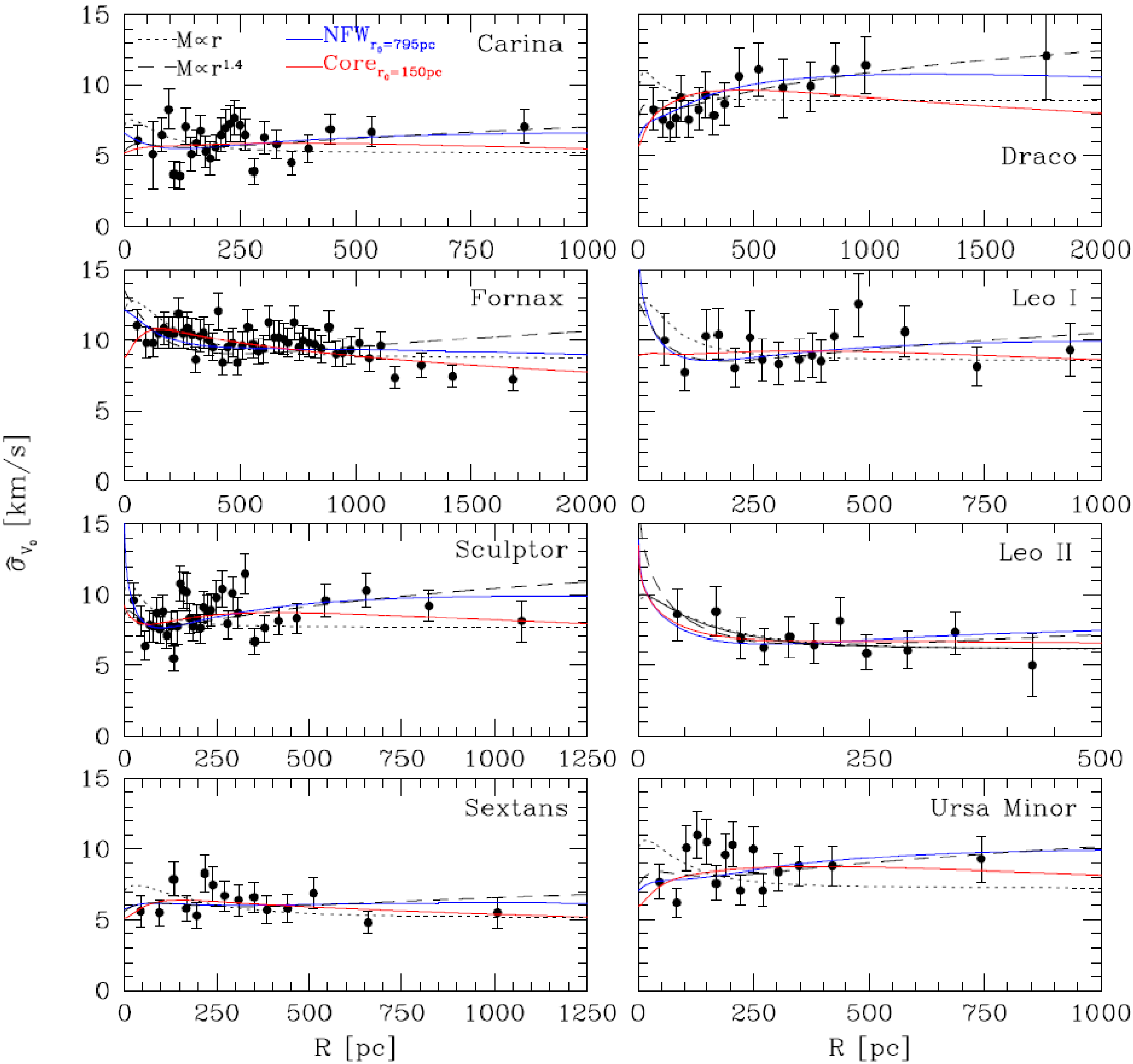
- Masses range from about $10^{-6}M_\odot$ to $10^{15}M_\odot$
- Self similar hierarchy of substructure $n(m) \sim m^{-2}$
- Universal density profiles, small dependence on halo mass
- Triaxial shape distribution on all scales
- Small amount of rotation, 90% random motions

What is the evidence for Cold Dark Matter?

- There is no strong evidence for any of these predictions (lots of data but galaxy formation is complicated). Neither is there strong dissagreement.
- It is also possible that the cross section to interact with baryons is so small that WIMPS can never be detected in laboratory experiments
- We might be left with astrophysical constraints on its nature – these are complicated by 'galaxy formation'

De Block, McGaugh et al.

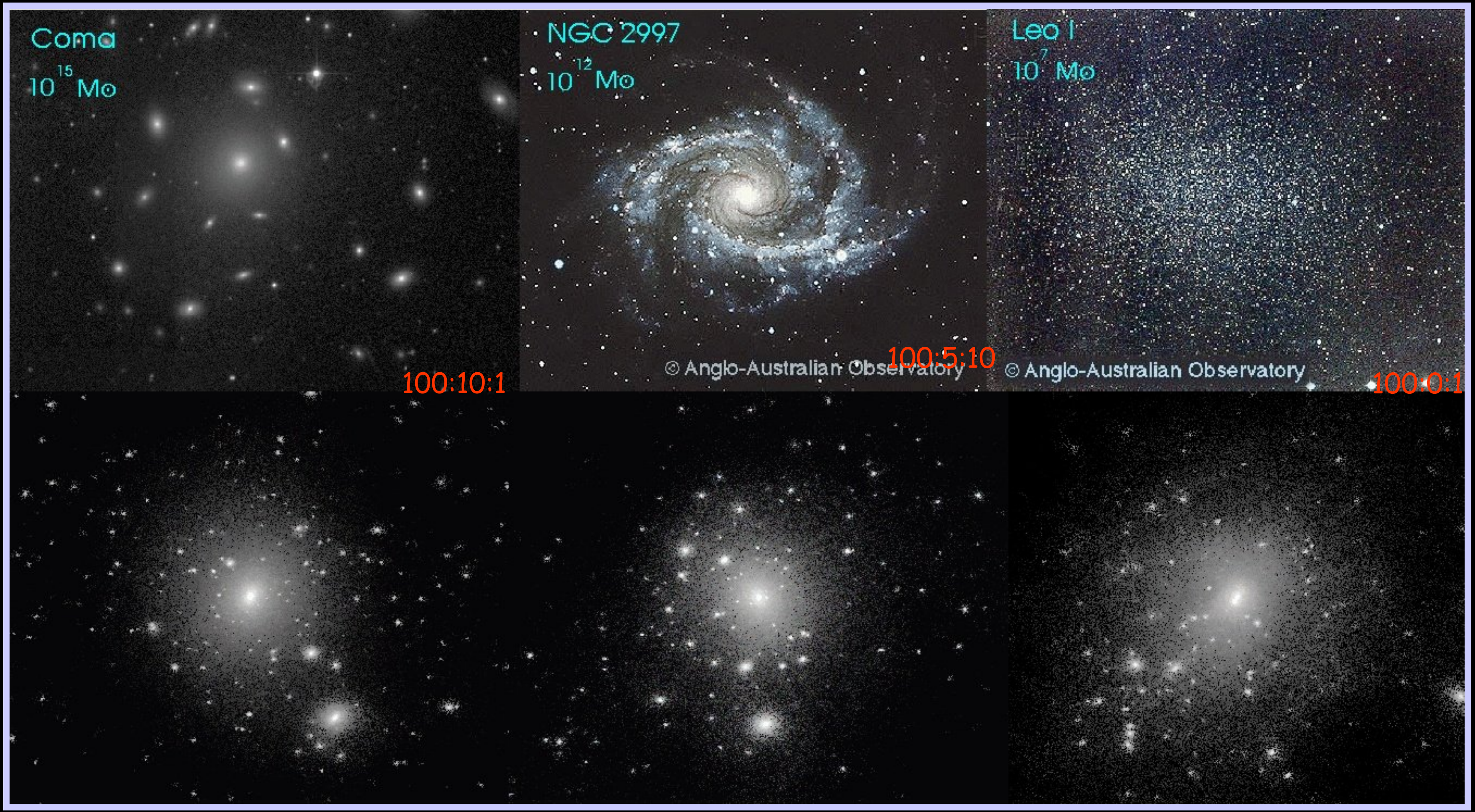




Gilmore et al (2009)

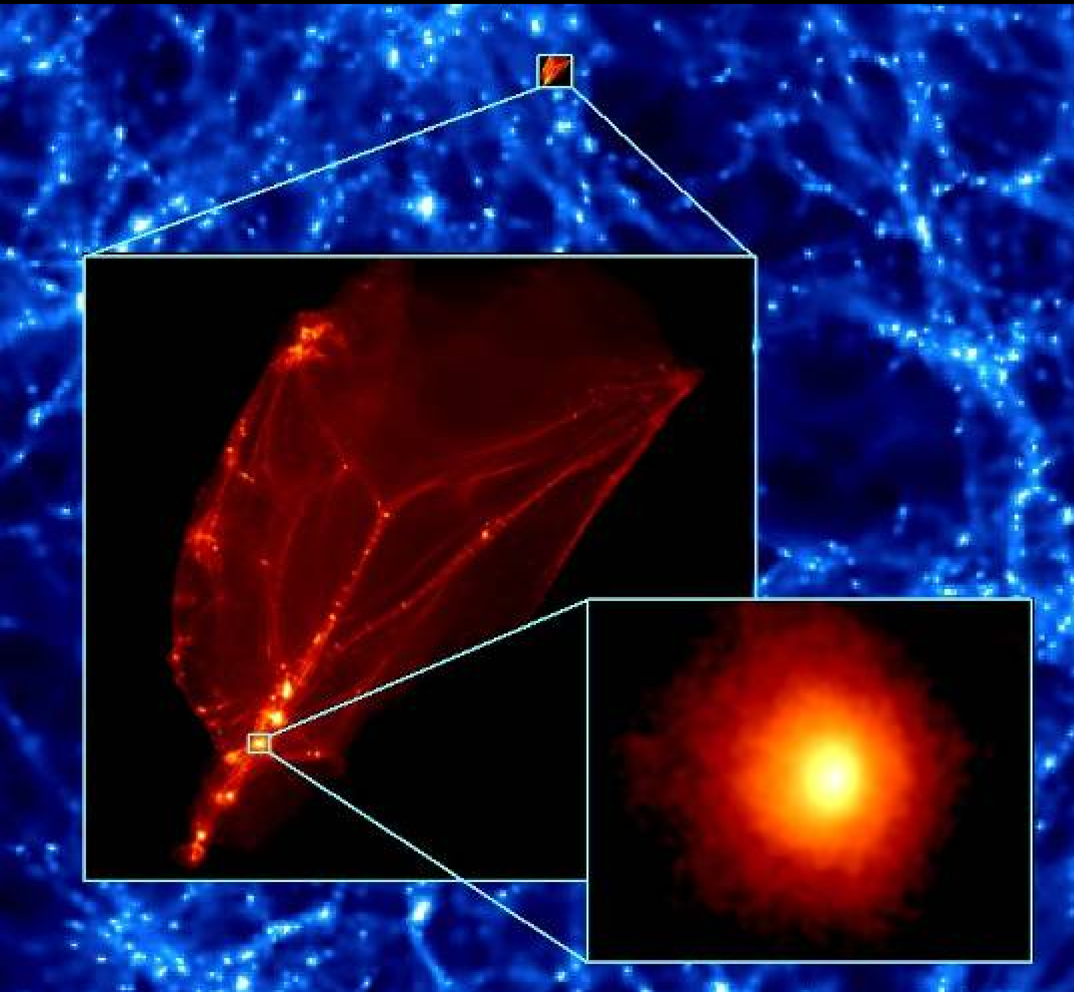
dSph mass profiles are unconstrained by the current data…

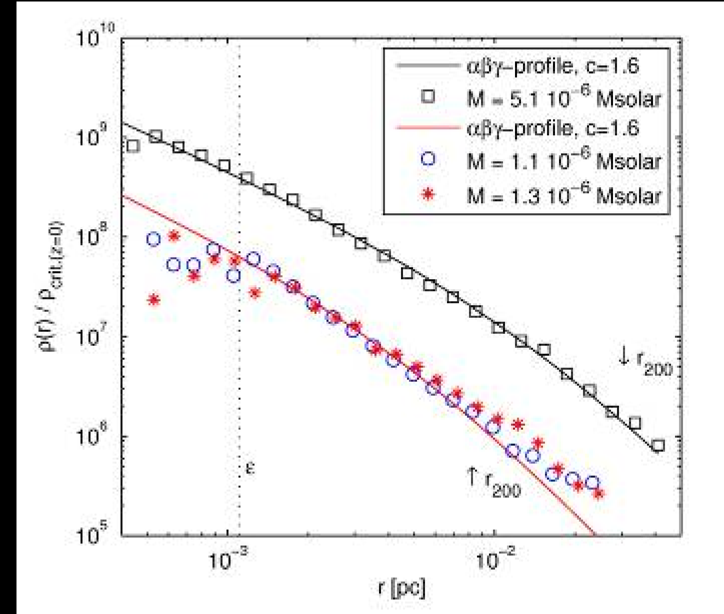
All galaxies, groups and clusters are dominated by dark matter; the dark matter structures form in a similar way on all mass scales

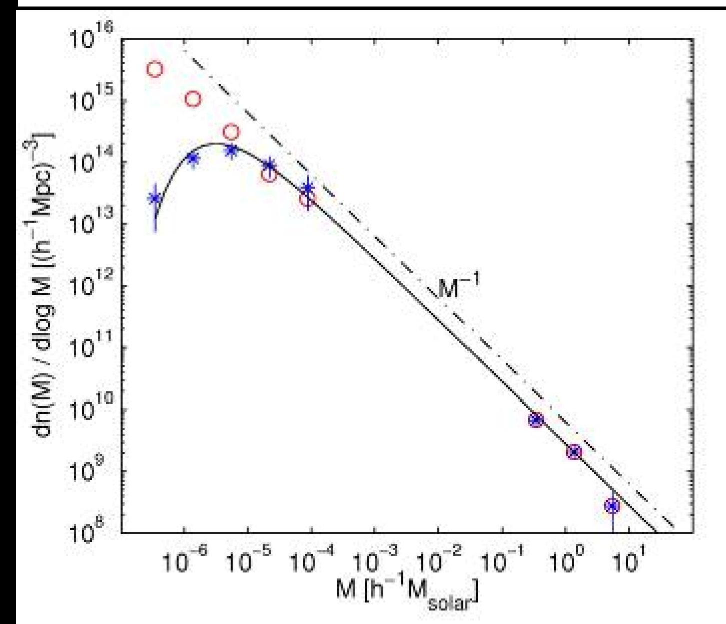


The baryons introduce a scale due to hydrodynamic and radiative processes

Diemand, Moore & Stadel (2005)

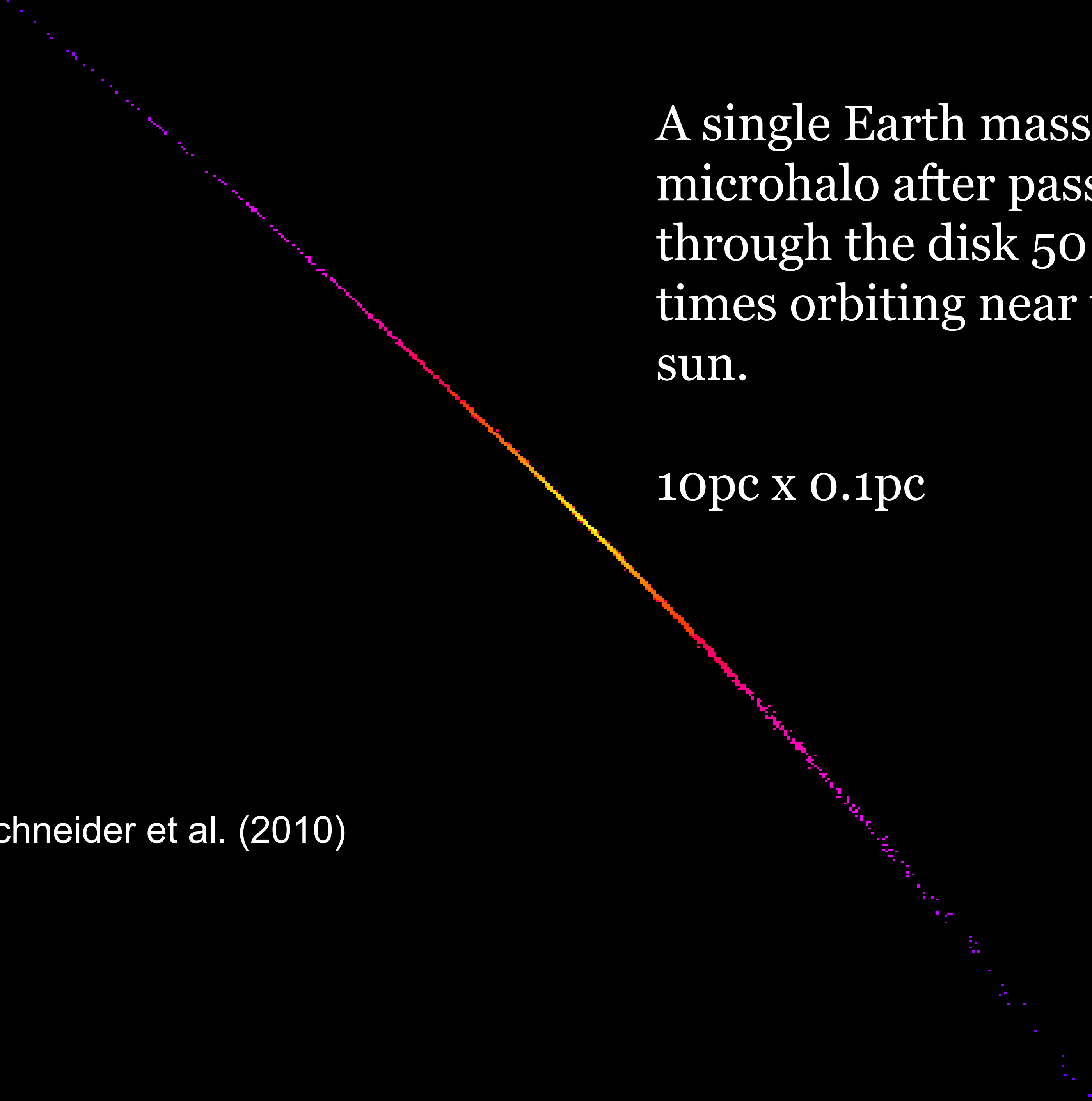






This is the one of the first objects to form in the Universe at z=60. The halo is smooth, has a cuspy density profile, has an earth mass 10^-6Mo and a size of the solar system.

Can be detected as high proper motion gamma-ray sources (Moore et al 2005).



A single Earth mass microhalo after passing through the disk 50 times orbiting near the sun.

10pc x 0.1pc

Aurel Schneider et al. (2010)

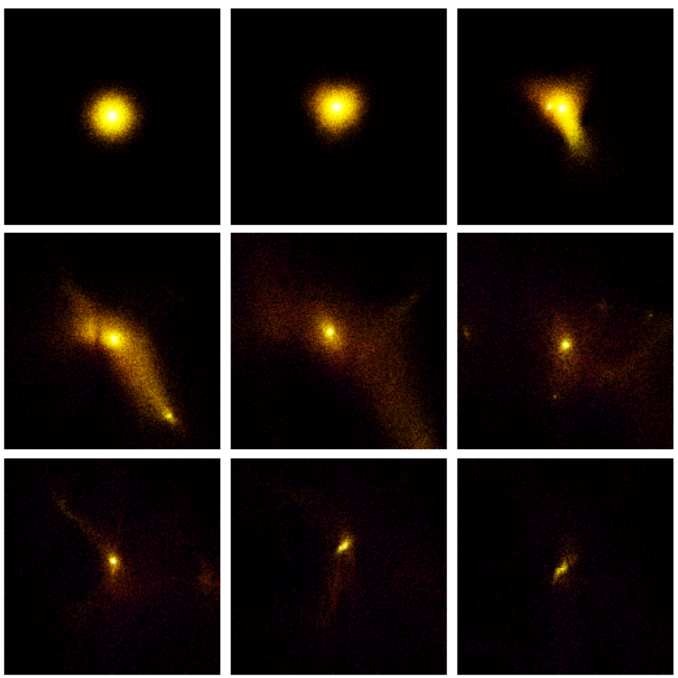
Impact of Dark Matter Microhalos on Signatures for Direct and Indirect Detection

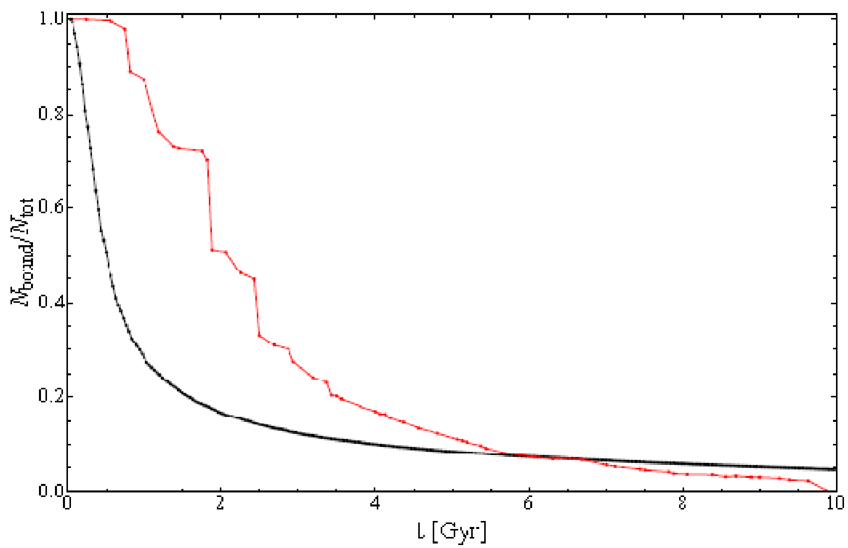
Aurel Schneider[1], Lawrence Krauss[1,2] and Ben Moore[1]

[1] *Institute for Theoretical Physics, University of Zurich, Zurich, Switzerland* [2]*School of Earth and Space Exploration and Department of Physics, Arizona State University, PO Box 871404, Tempe, AZ 85287;*

(Dated: May 3, 2010)

Detecting dark matter as it streams through detectors on Earth relies on know-ledge of its phase space density on a scale comparable to the size of our solar system. Numerical simulations predict that our Galactic halo contains an enormous hierarchy of substructures, streams and caustics, the remnants of the merging hierarchy [1, 2] that began with tiny Earth mass microhalos [3–5]. If these bound or coherent structures persist until the present time, they could dramatically alter signatures for the detection of weakly interacting elementary particle dark matter (WIMP). Using numerical simulations that follow the coarse grained tidal disruption within the Galactic potential and fine grained heating from stellar encounters, we find that microhalos, streams and caustics have a negligible likelihood of impacting direct detection signatures implying that dark matter constraints derived using simple smooth halo models are relatively robust. We also find that many dense central cusps survive, yielding a small enhancement in the signal for indirect detection experiments.





Density of a single stream

~10^-6Mo/10x0.1x0.1pc^3 = 10^4Mo/kpc^3 = 0.0003GeV/cm^3

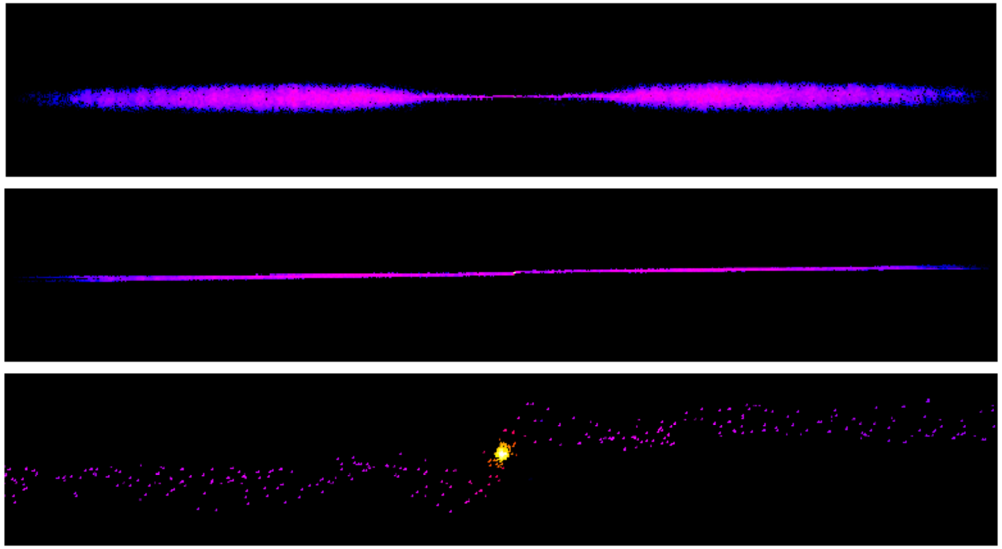
→ Single streams, such as from Sagittarius are irrelevant (fluctuations are < 1% of local dark matter density)

Number of overlapping streams ~1000

→ Fluctuations in density are very small

→ Central limit theorem implies close to Gaussian/Maxwellian velocity distribution

→ Annual modulation signal is not phase shifted



The fine grained phase space density (on scales above the radius of a star) decreases by two orders of magnitude.

Lowers the annihilation flux from finely wrapped caustics.

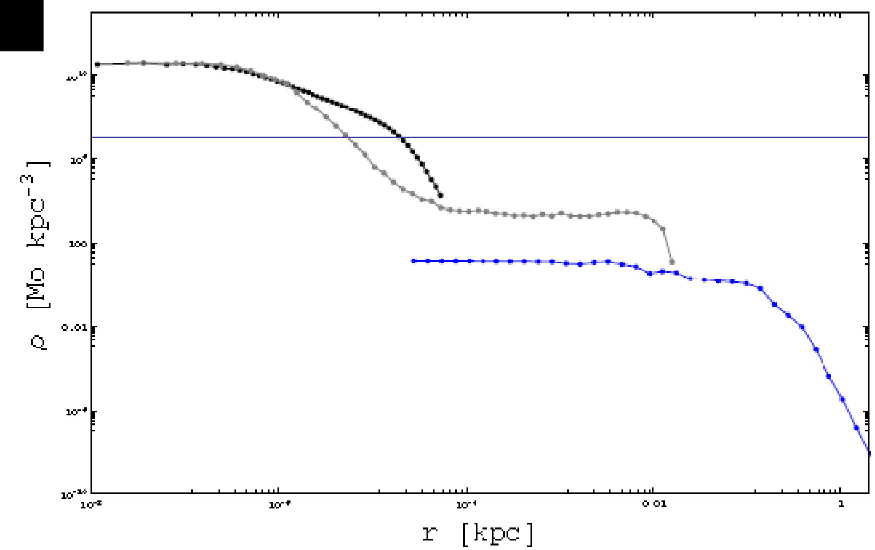
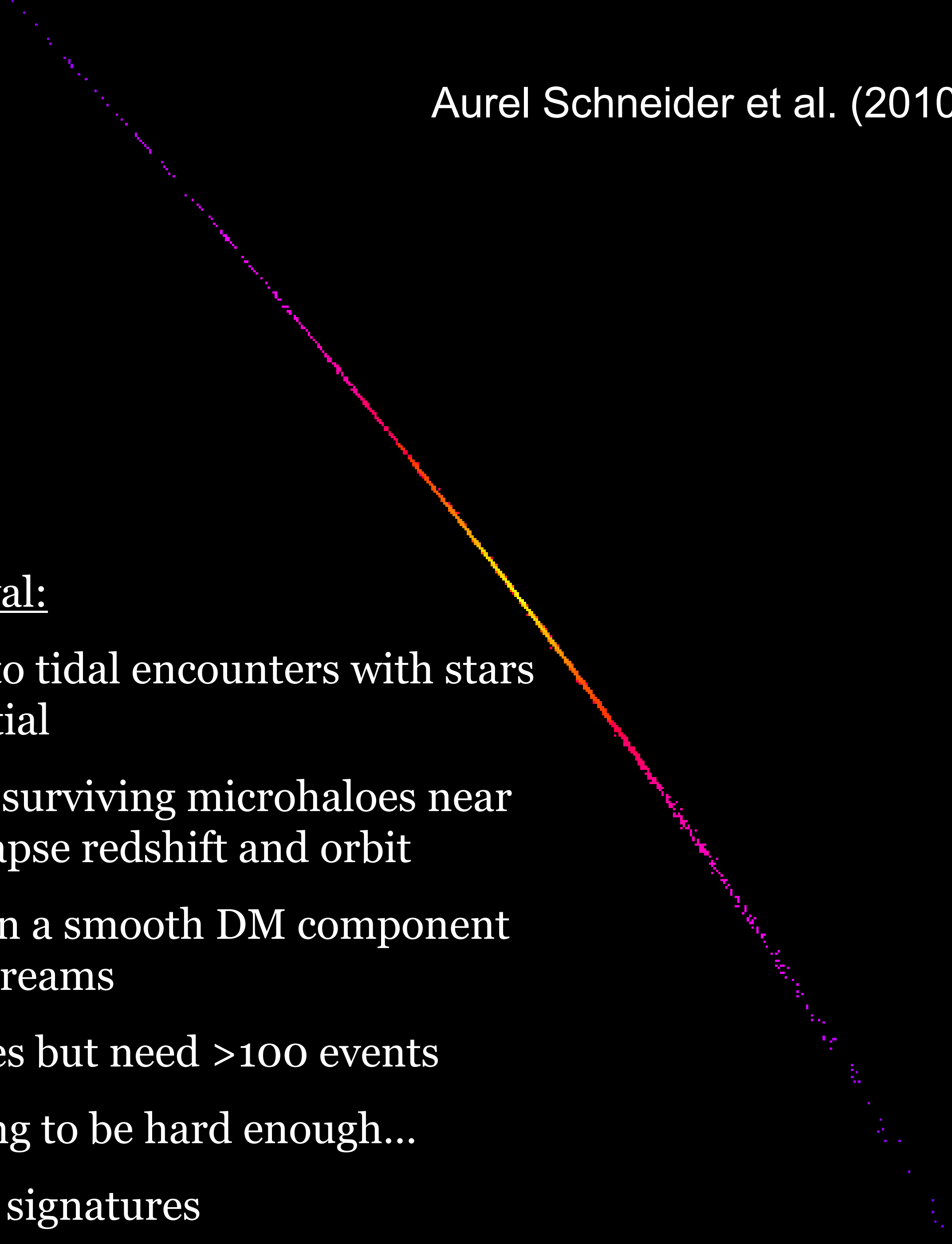


FIG. 2: *Radial densities along the tidal streams of an initially undisrupted microhalo (gray) and a disrupted microhalo (blue) compared to the density of a totally unperturbed microhalo (black). The blue straight line corresponds to the average dark matter density around the sun. After 10 Gyrs in the Milky Way potential the initially undisrupted halo still has a bound core with the same density as the unperturbed halo.*



Aurel Schneider et al. (2010)

<u>Summary of microhalo survival:</u>

Lose>90% of their mass due to tidal encounters with stars and the global Galactic potential

The mass loss and number of surviving microhaloes near the sun depends on their collapse redshift and orbit

Most of mass in this room is in a smooth DM component made of overlapping debris streams

Some non-Gaussian signatures but need >100 events

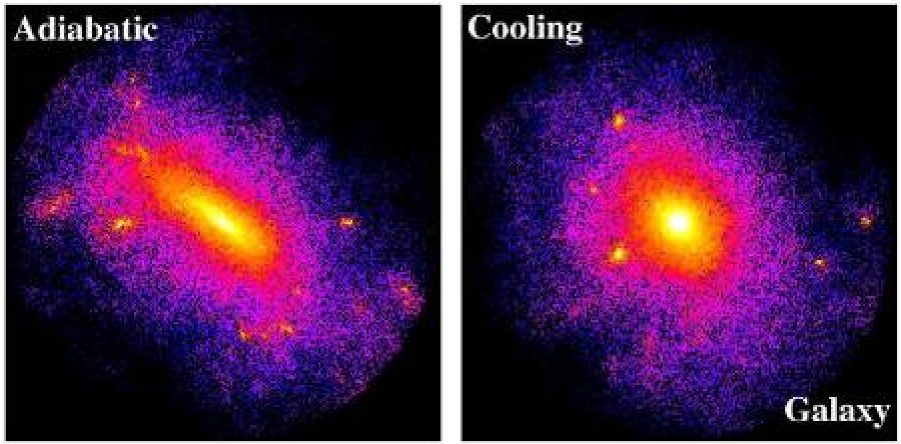
Detecting single events is going to be hard enough…

Indirect detection has unique signatures

II. Dark matter + baryons

(Oscar Agertz, Romain Teyssier, Victor Debatisttta, Gianfranco Bertone, Miguel Pato)

Kazantzidis etal (2004)



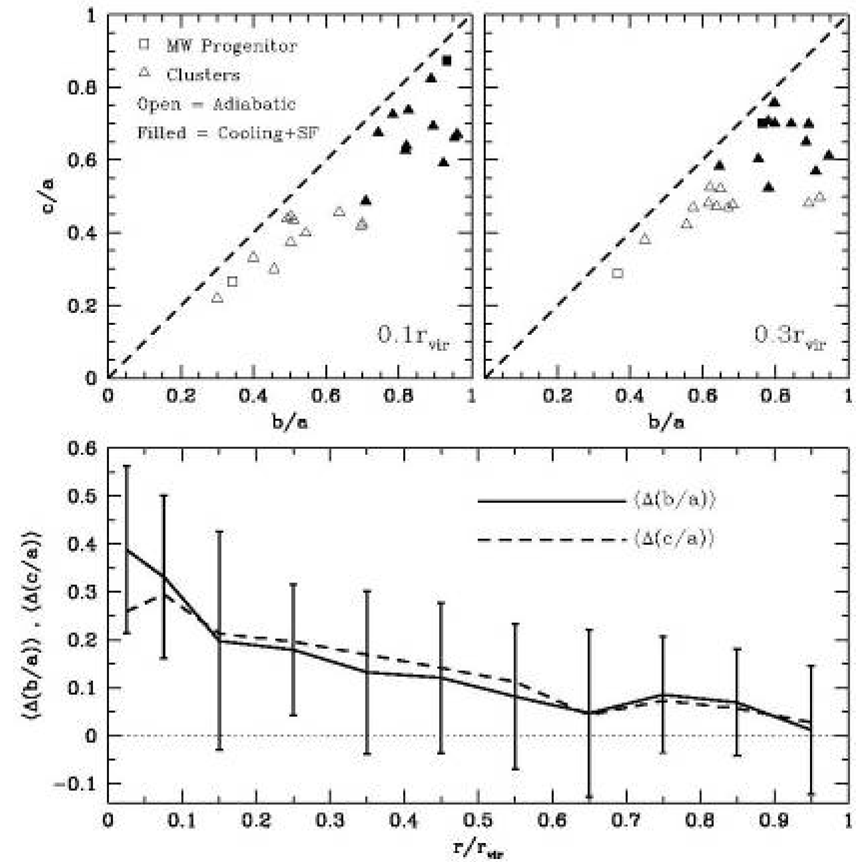
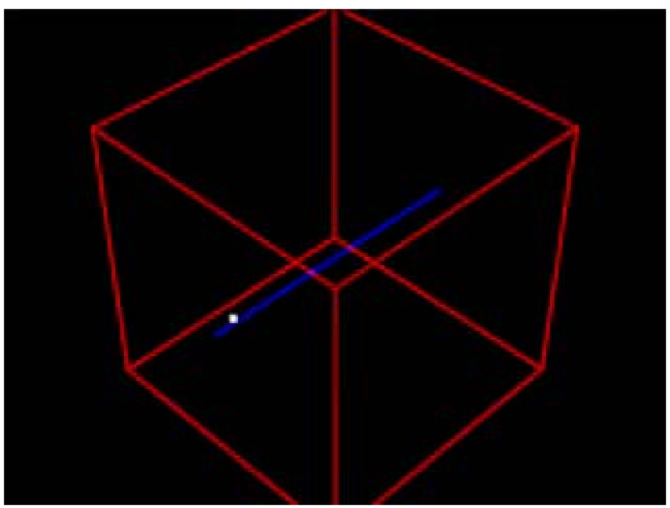
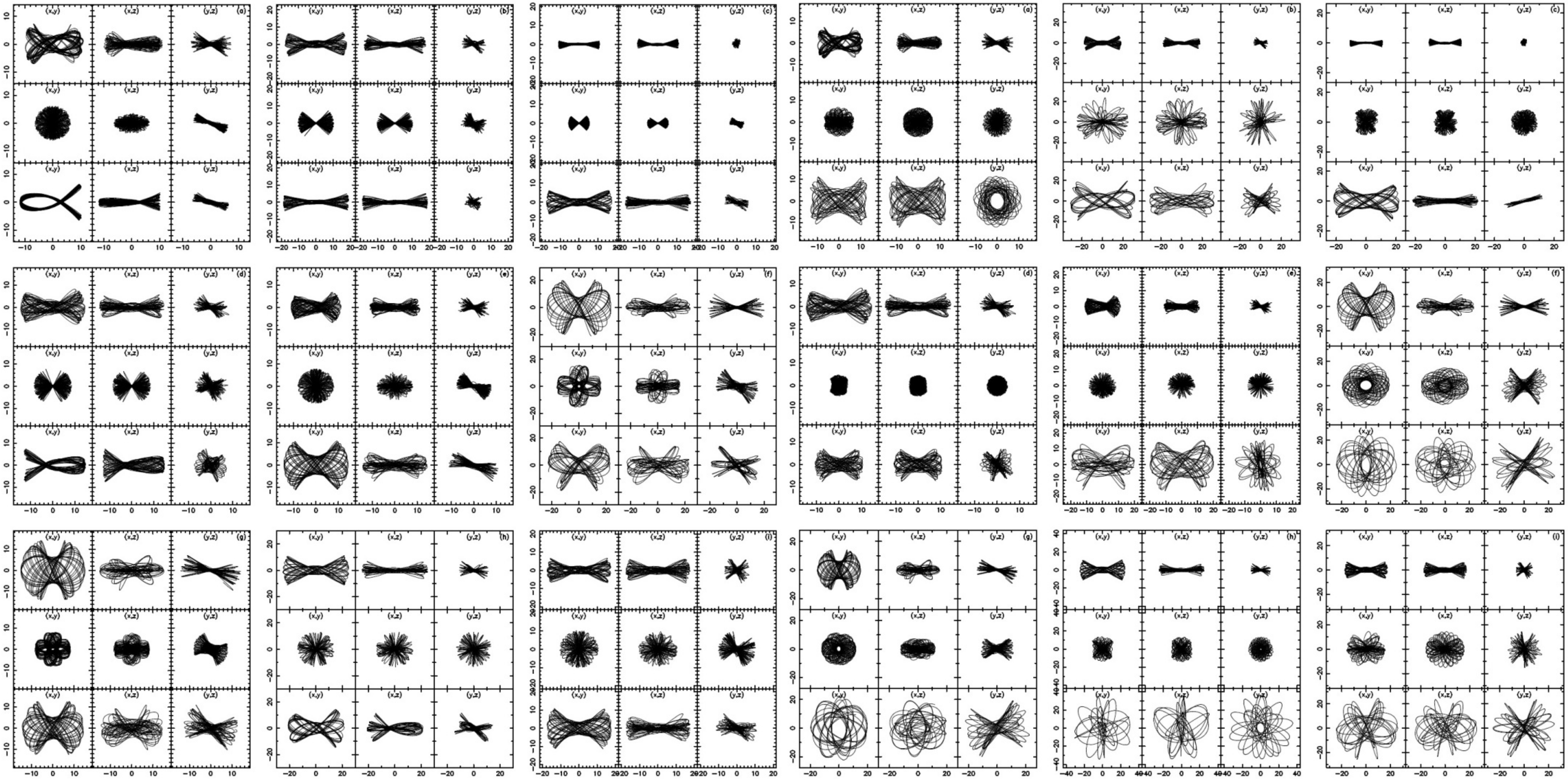


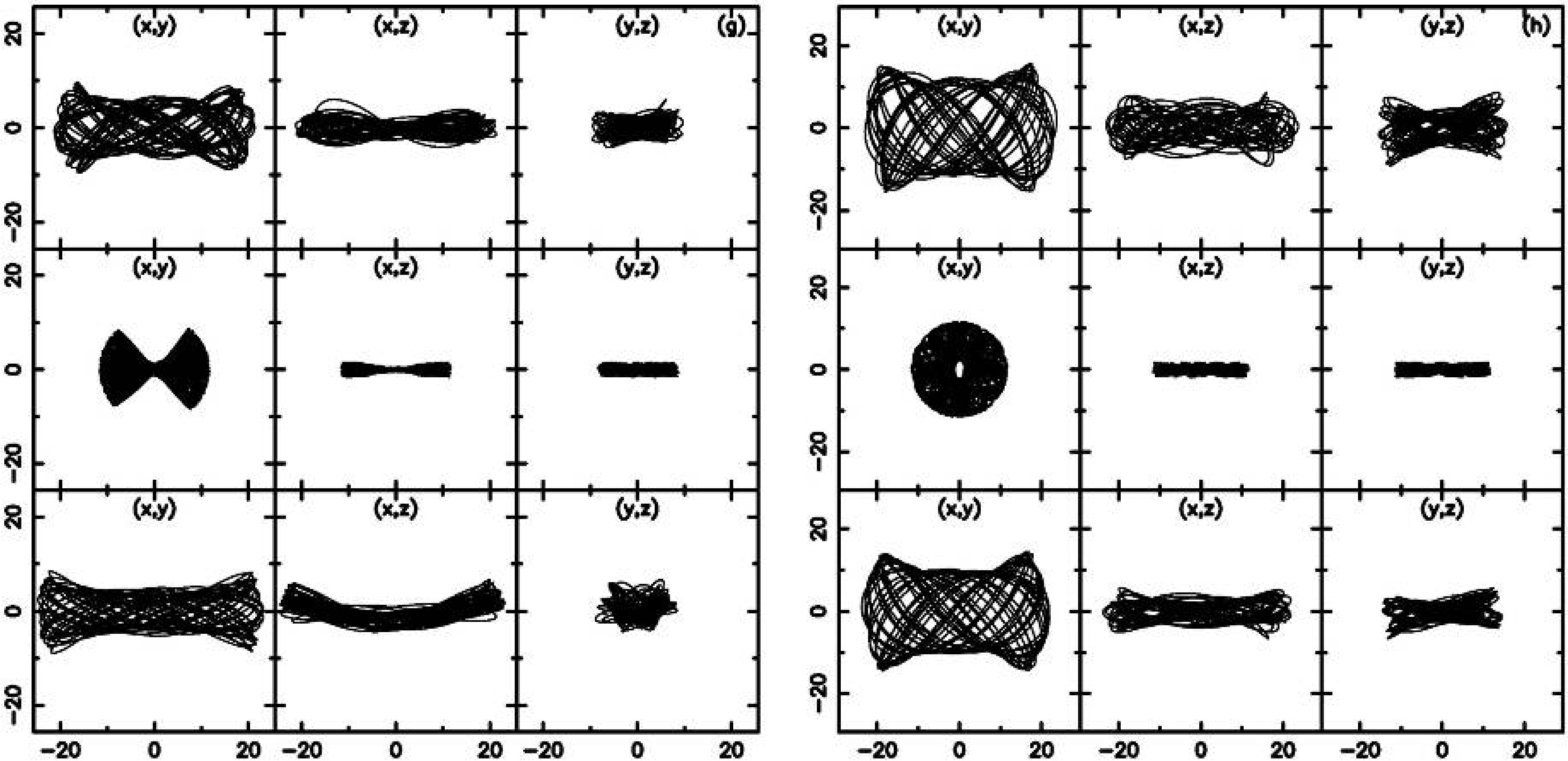
FIG. 1.— *Top panels:* Axis ratios c/a vs. b/a for halos in cosmological simulations. Open symbols show adiabatic simulations and solid symbols correspond to simulations with gas cooling and star formation. The galaxy simulation is shown by a square and the clusters by triangles. *Bottom panel:* the average difference between axis ratios in cooling and adiabatic runs as a function of radius. The error bars show the 1σ scatter in $\Delta(b/a)$ the mean in each bin. The scatter in $\Delta(c/a)$ is similar.



As baryons cool within dark matter halos, the central potential becomes more spherical. The box orbits which support the triaxial shape are destroyed and the entire system becomes more spherical – even at radii 10x beyond the baryons

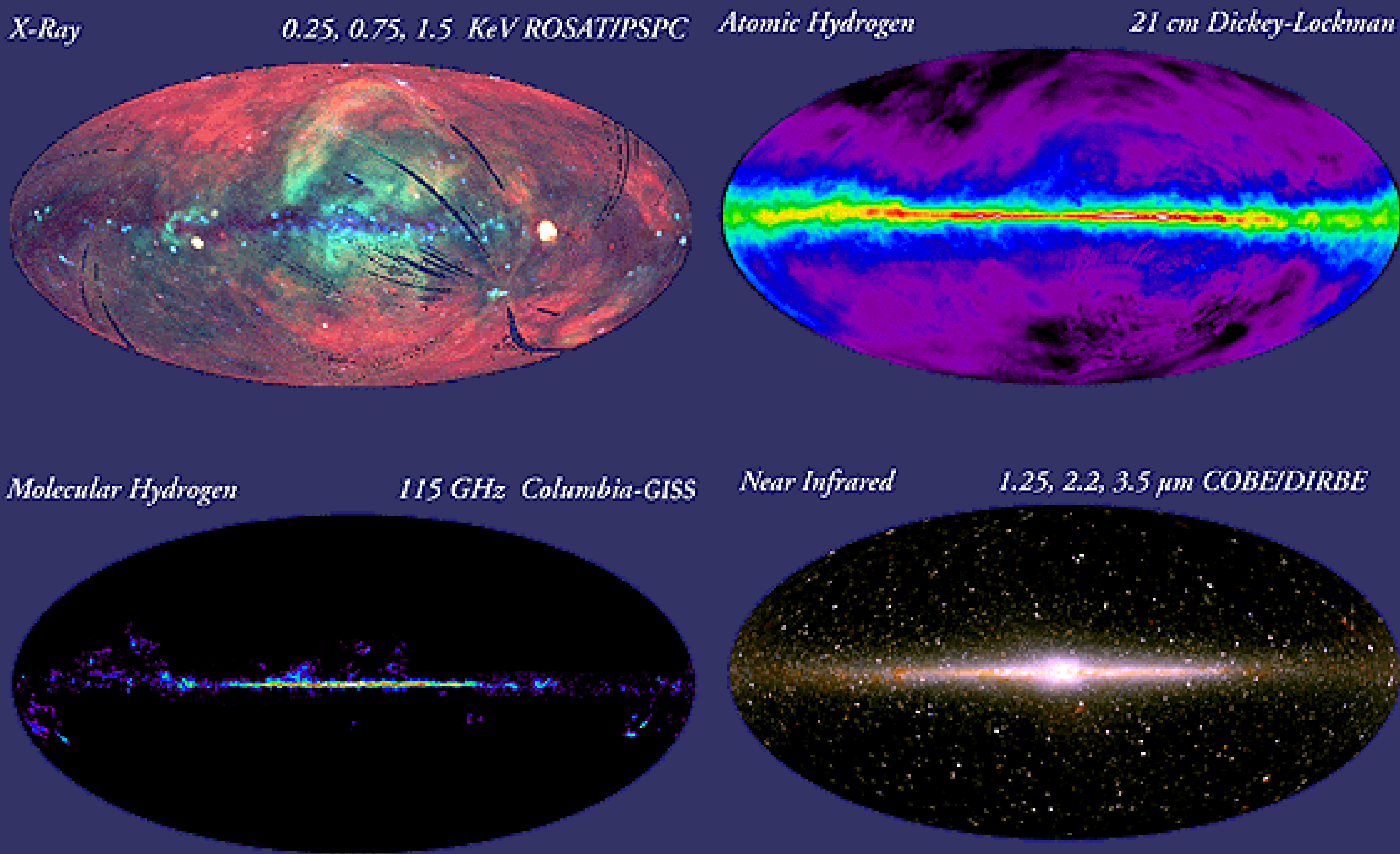


Debatistta et al (2008), Valluri et al. (2010)



Reason for shape change is destruction of box orbits that maintain the triaxial shape.

Remarkably, this is a reversible process - Debattista etal (2008)



Here are some of the key baryonic components of galaxies that we need to simulate correctly

No thin disk dominated system, no morphological detail, no spiral patterns, bulge/spheroid dominated systems.

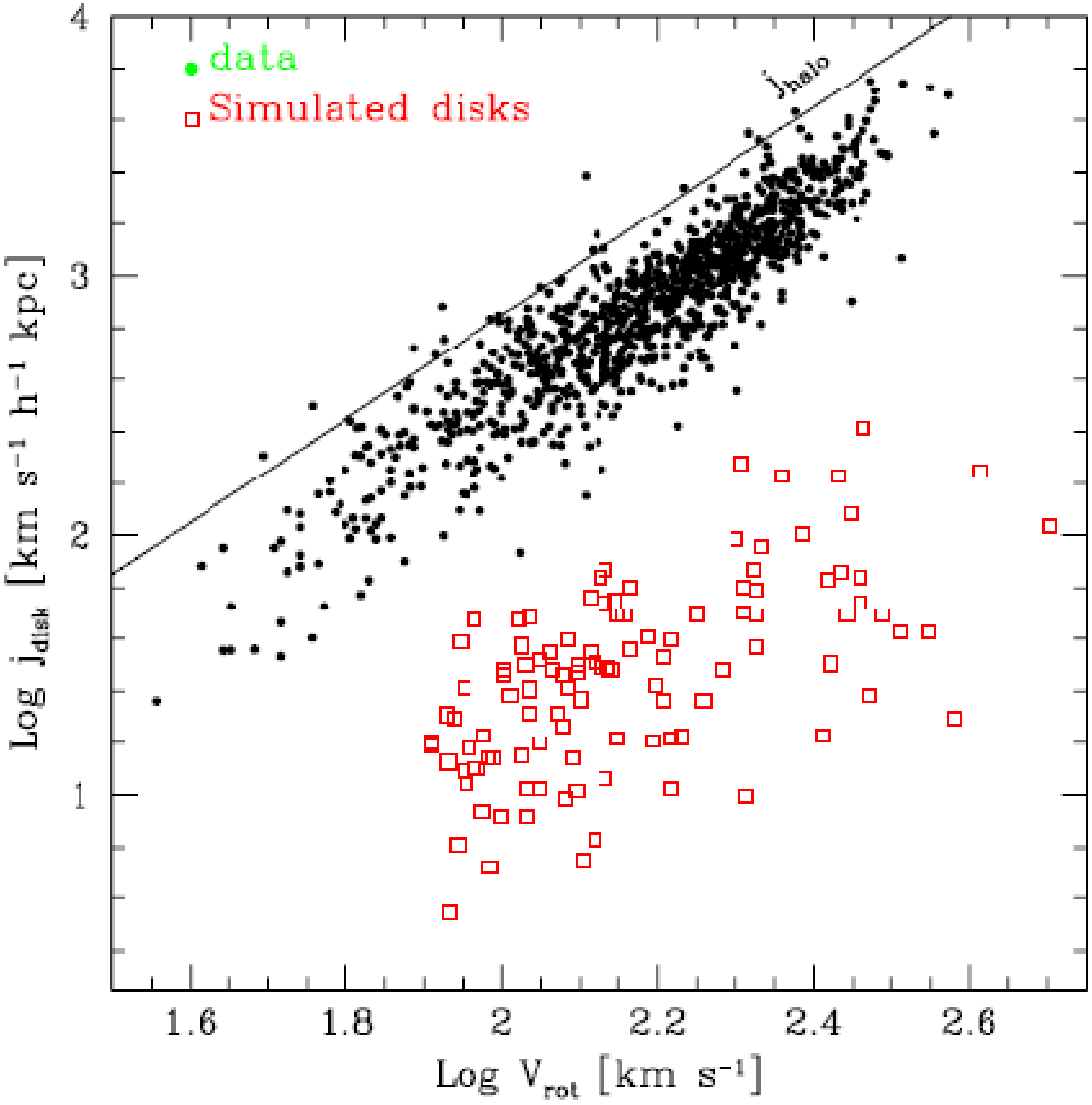
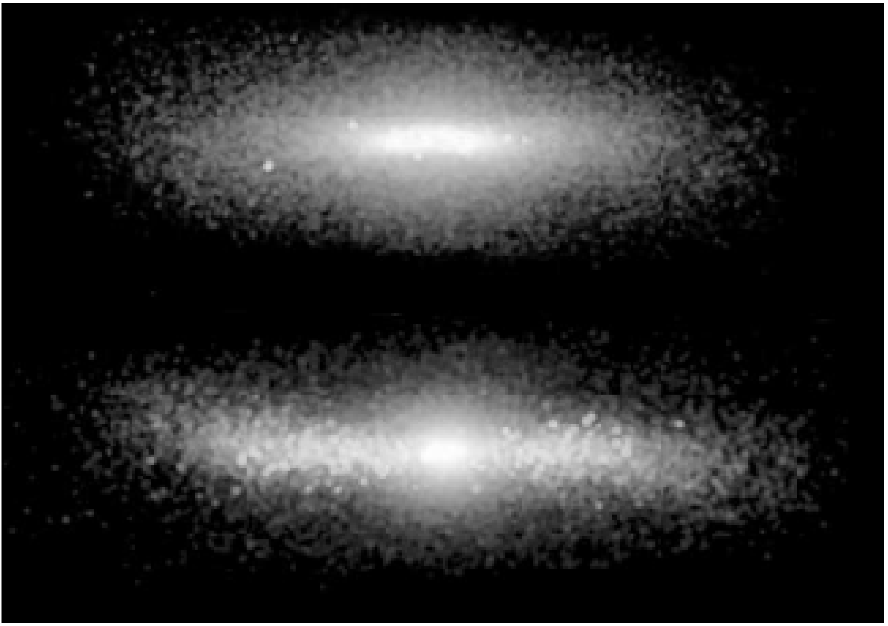
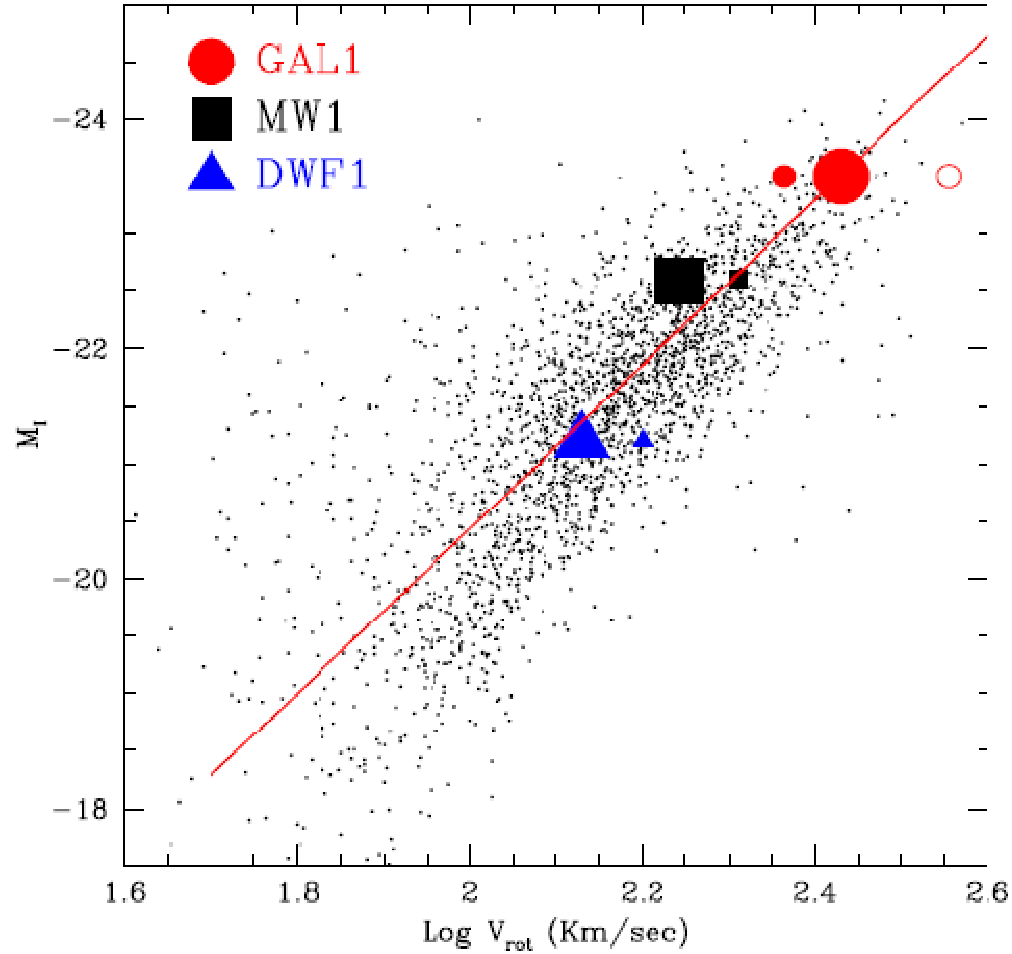


FIG. 3.—Specific angular momentum vs circular velocity of model galaxies compared to observational data.

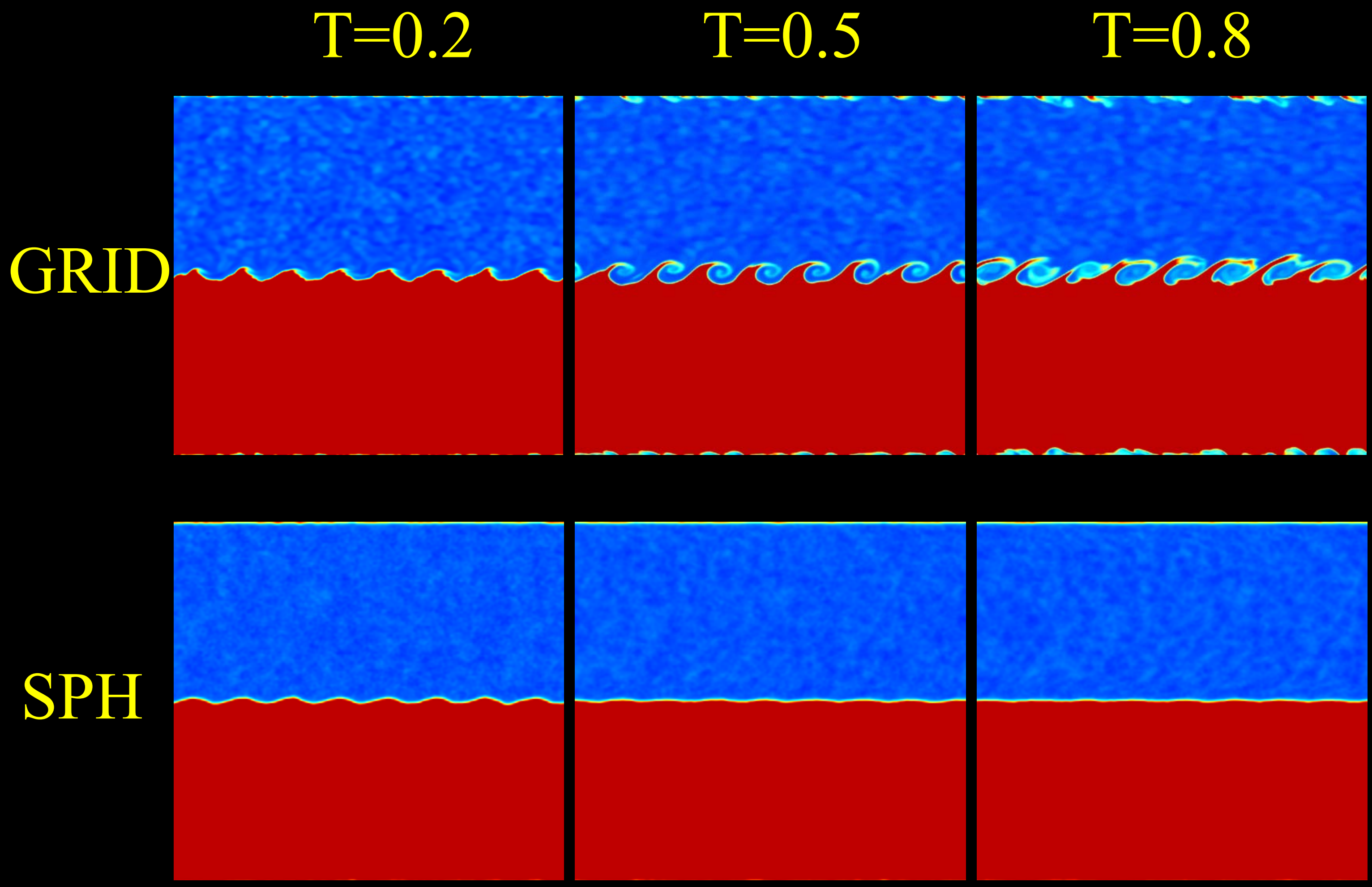
Steinmetz & Navarro 1998

1000-10000 SPH particles





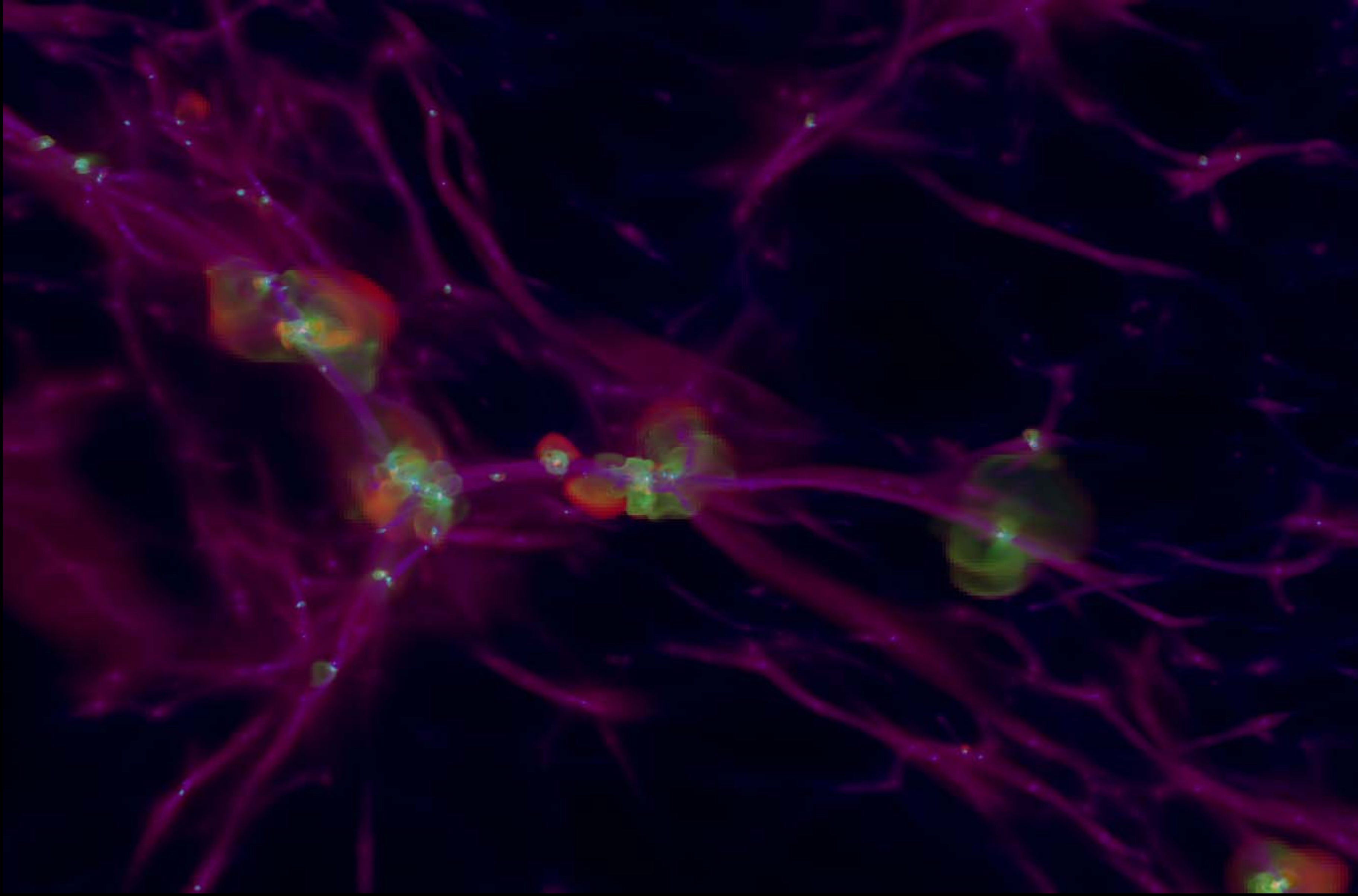
Governato et al 2006
10^5 SPH particles in total, 500pc resolution
Better match with T-F.
Huge spheroid, disk is unresolved single phase cold gas



Use high resolution AMR simulations, follow radiative cooling, shocks, multi-phase gas, stellar mass loss, supernovae feedback

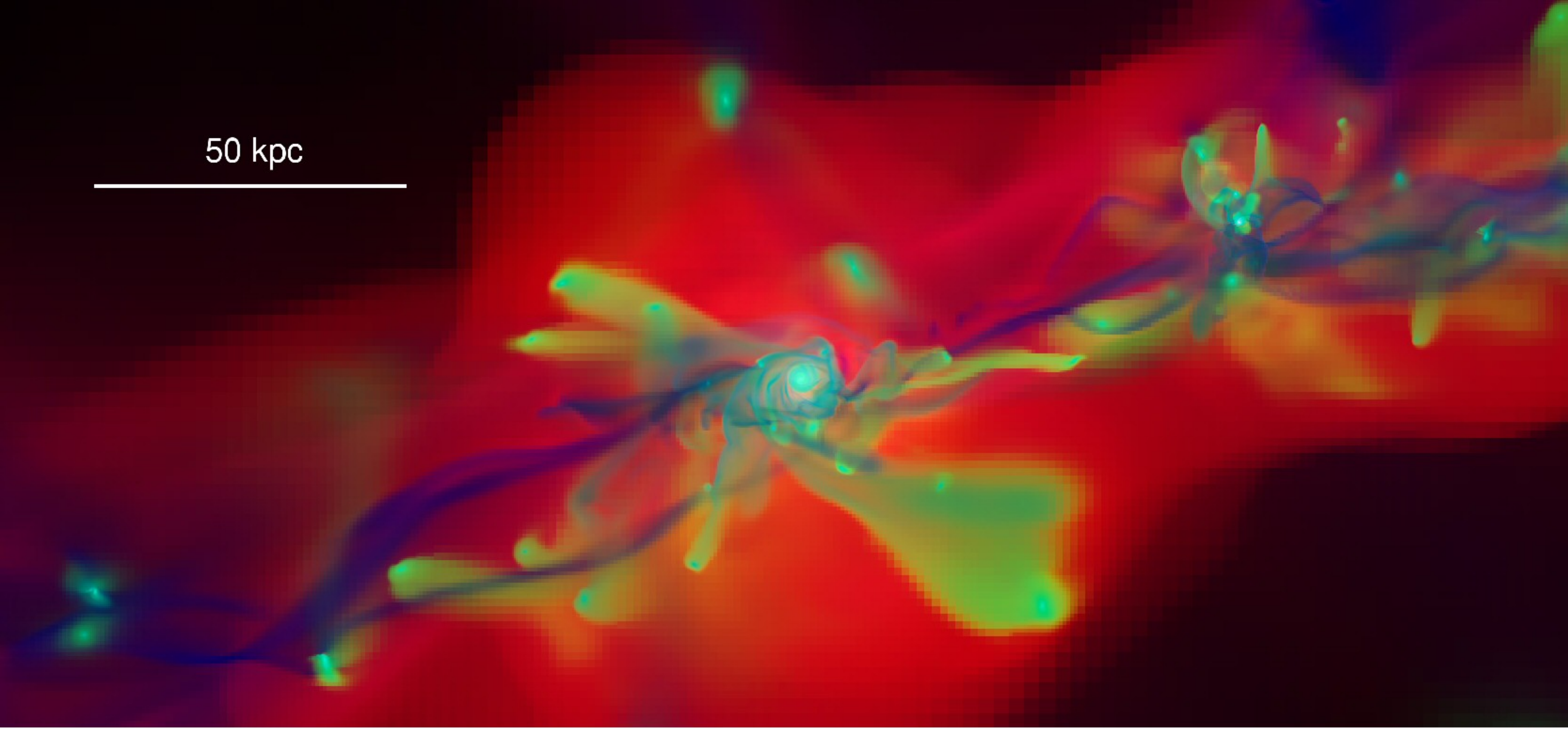
Test subgrid model parameters, search parameter space

Eventually resolve the full molecular cloud mass spectrum

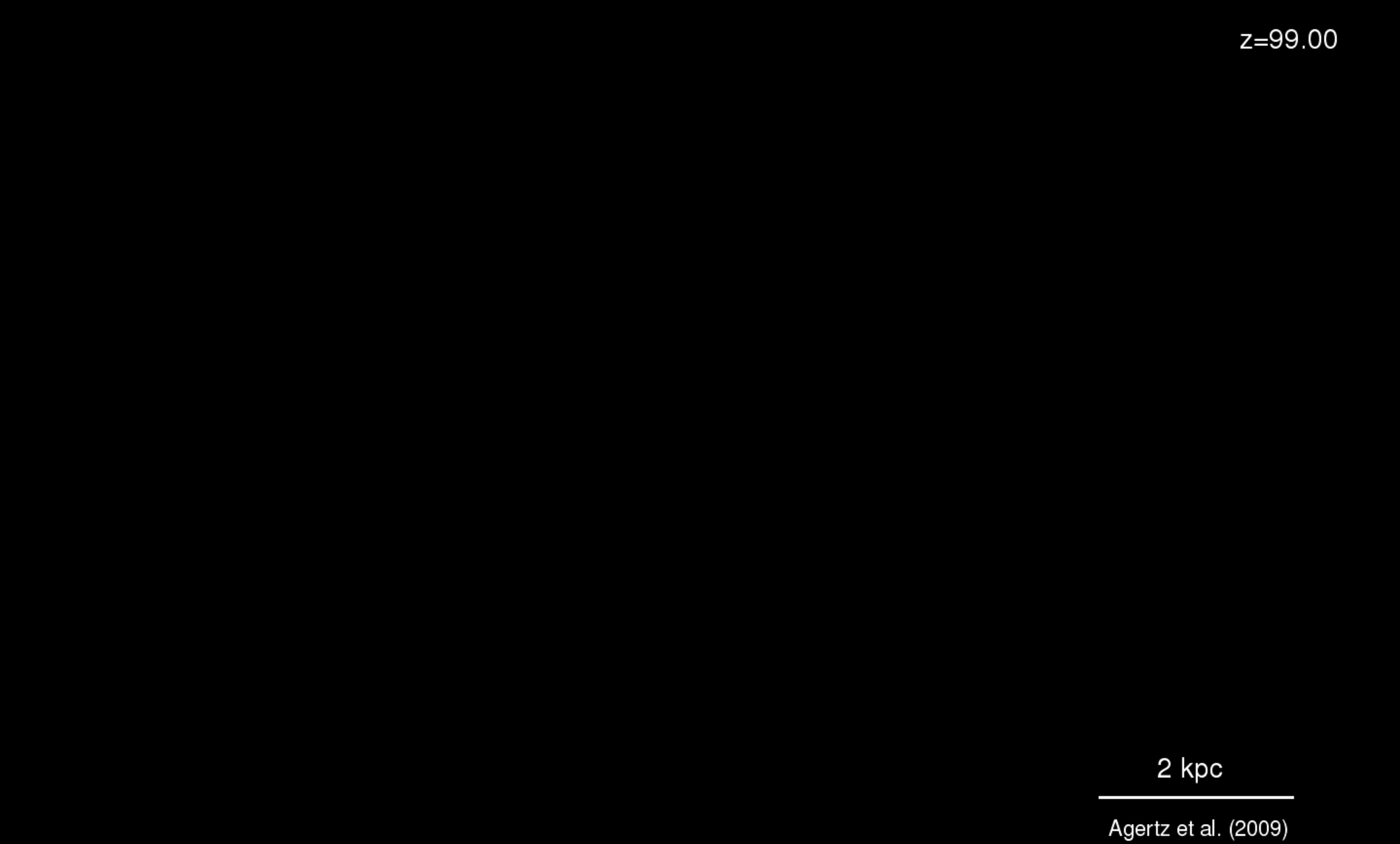


SN Feedback Thermal Dump and Delayed Cooling z=10

Agertz, Teyssier et al.



The complex gas flows into a dark matter halo with a forming disk galaxy at a redshift z=3. R=temperature, G=metals and B=density. (Agertz, Teyssier & Moore 2009). One can clearly distinguish the cold pristine gas streams in blue connecting directly onto the edge of the disk, the shock heated gas in red surrounding the disk and metal rich gas in green being stripped from smaller galaxies interacting with the hot halo and cold streams of gas. The disk and the interacting satellites stand out since they are cold, dense and metal rich.



The complex gas flows into a dark matter halo forming a disk galaxy

R=temperature, G=metals and B=density

Agertz et al (2009)

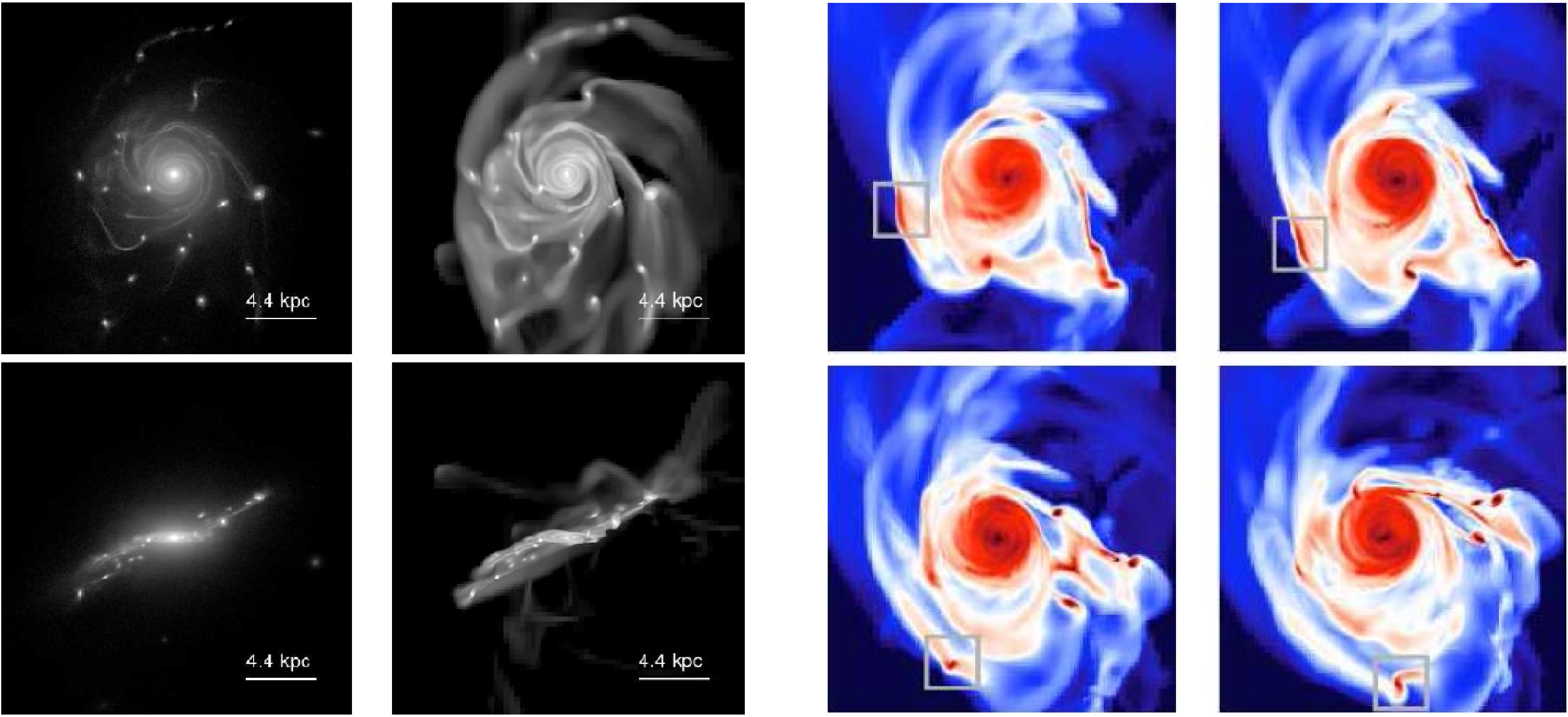
Disk formation and the origin of clumpy galaxies at high redshift

Oscar Agertz[1⋆], Romain Teyssier[1,2], Ben Moore[1]

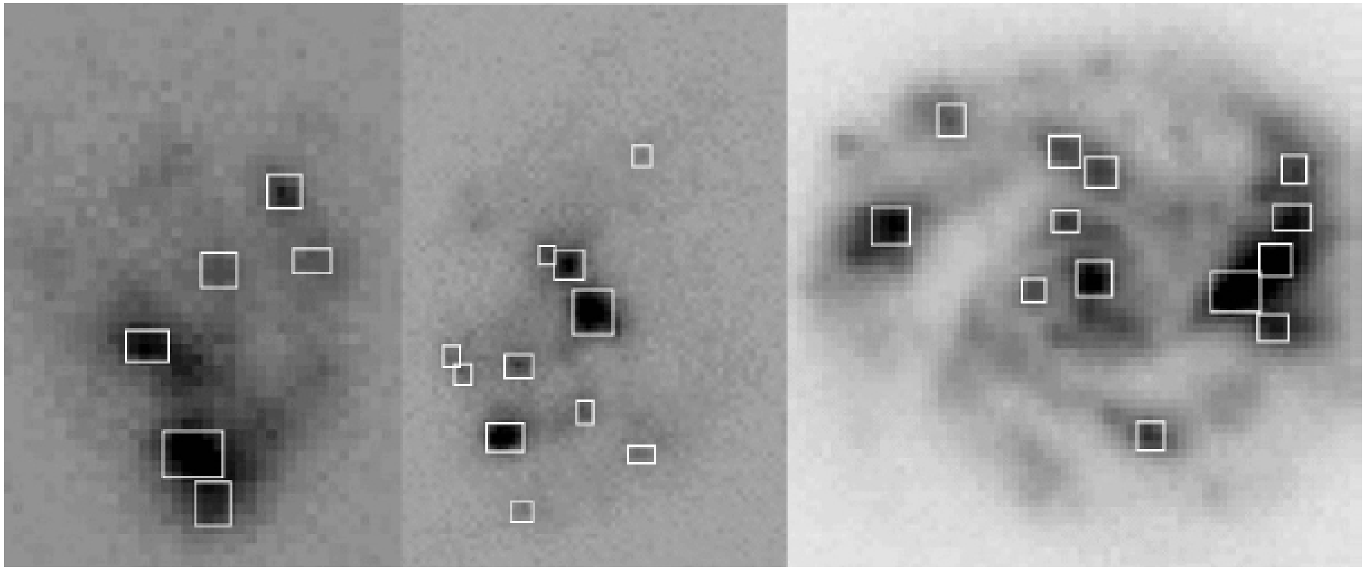
[1] *Institute for Theoretical Physics, University of Zürich, CH-8057 Zürich, Switzerland*
[2] *CEA Saclay, DSM/IRFU/SAp, Batiment 709, 91191 Gif-sur-Yvette Cedex, France*

31 July 2009

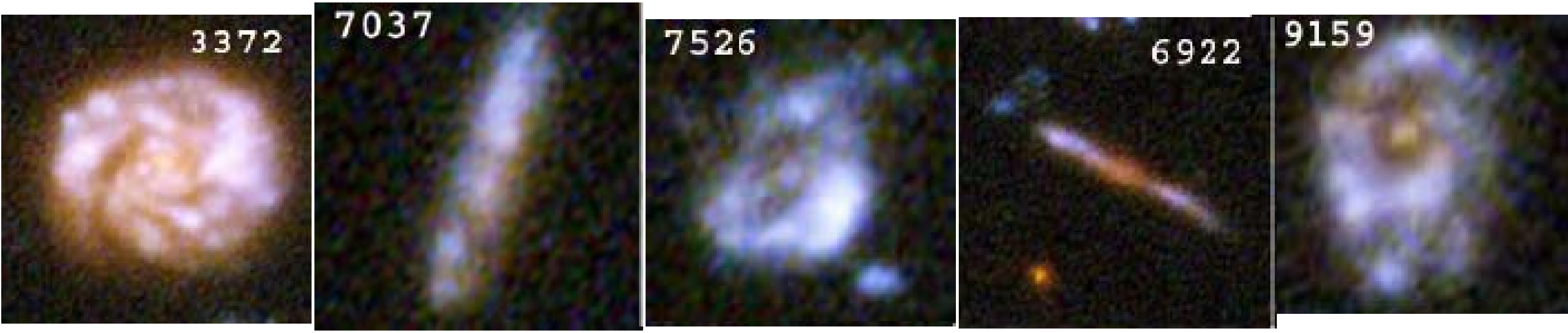
ABSTRACT
Observations of high redshift galaxies have revealed a multitude of large clumpy rapidly star-forming galaxies. Their formation scenario and their link to present day spirals is still unknown. In this *Letter* we perform adaptive mesh refinement simulations of disk formation in a cosmological context that are unrivalled in terms of mass and spatial resolution. We find that the so called 'chain-galaxies' and 'clump-clusters' are a natural outcome of early epochs of enhanced gas accretion from cold dense streams as well as tidally and ram-pressured stripped material from minor mergers and satellites. Through interaction with the hot halo gas, this freshly accreted cold gas settles into a large disk-like system, not necessarily aligned to an older stellar component, that undergoes fragmentation and subsequent star formation, forming large clumps in the mass range $10^7 - 10^9\ M_\odot$. Galaxy formation is a complex process at this important epoch when most of the central baryons are being acquired through a range of different mechanisms - we highlight that a rapid mass loading epoch is required to fuel the fragmentation taking place in the massive arms in the outskirts of extended disks, an accretion mode that occurs naturally in the hierarchical assembly process at early epochs.



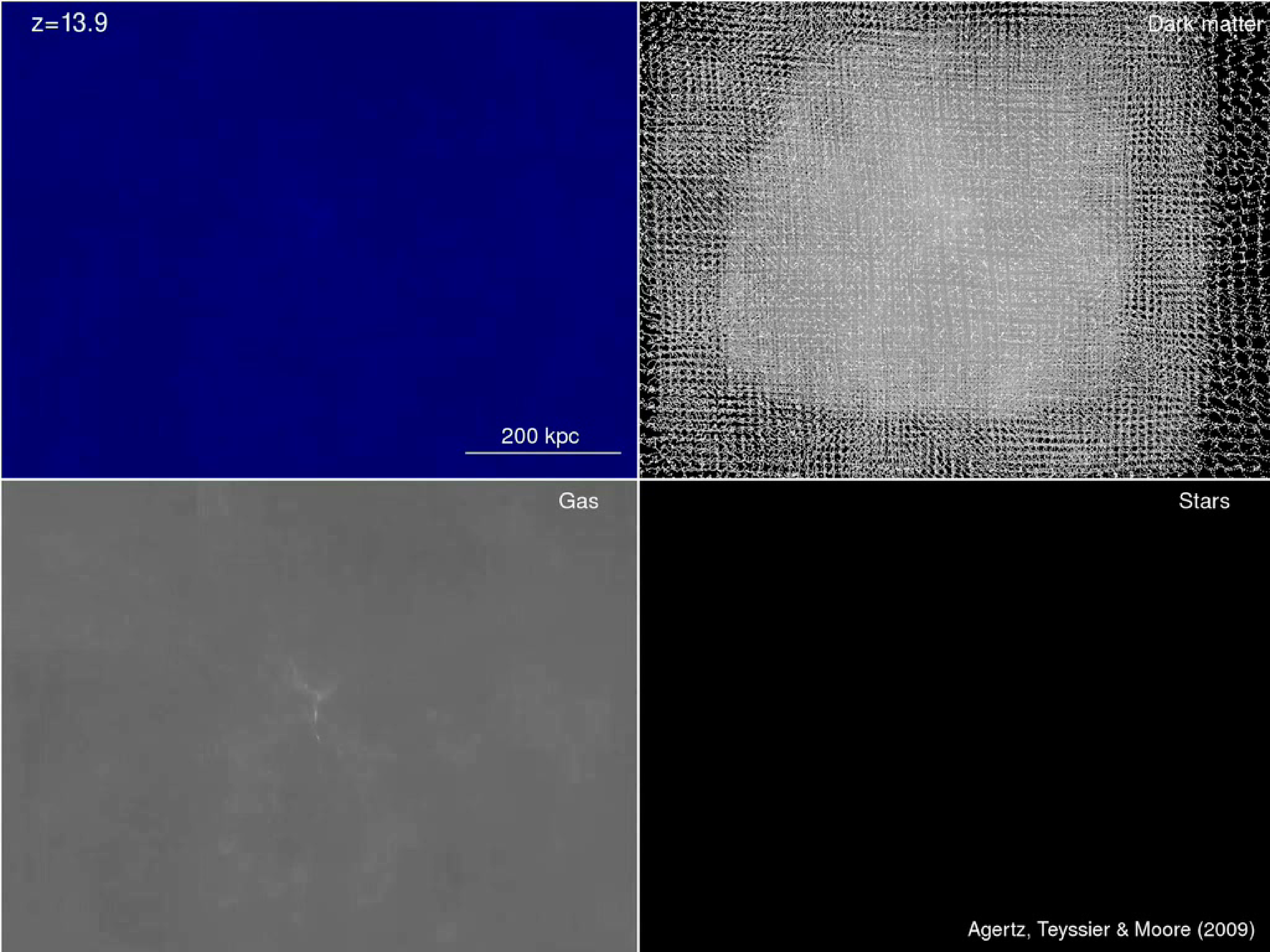
Elmegreen et al 2009: Clumpy high redshift galaxies – chains, clusters etc.

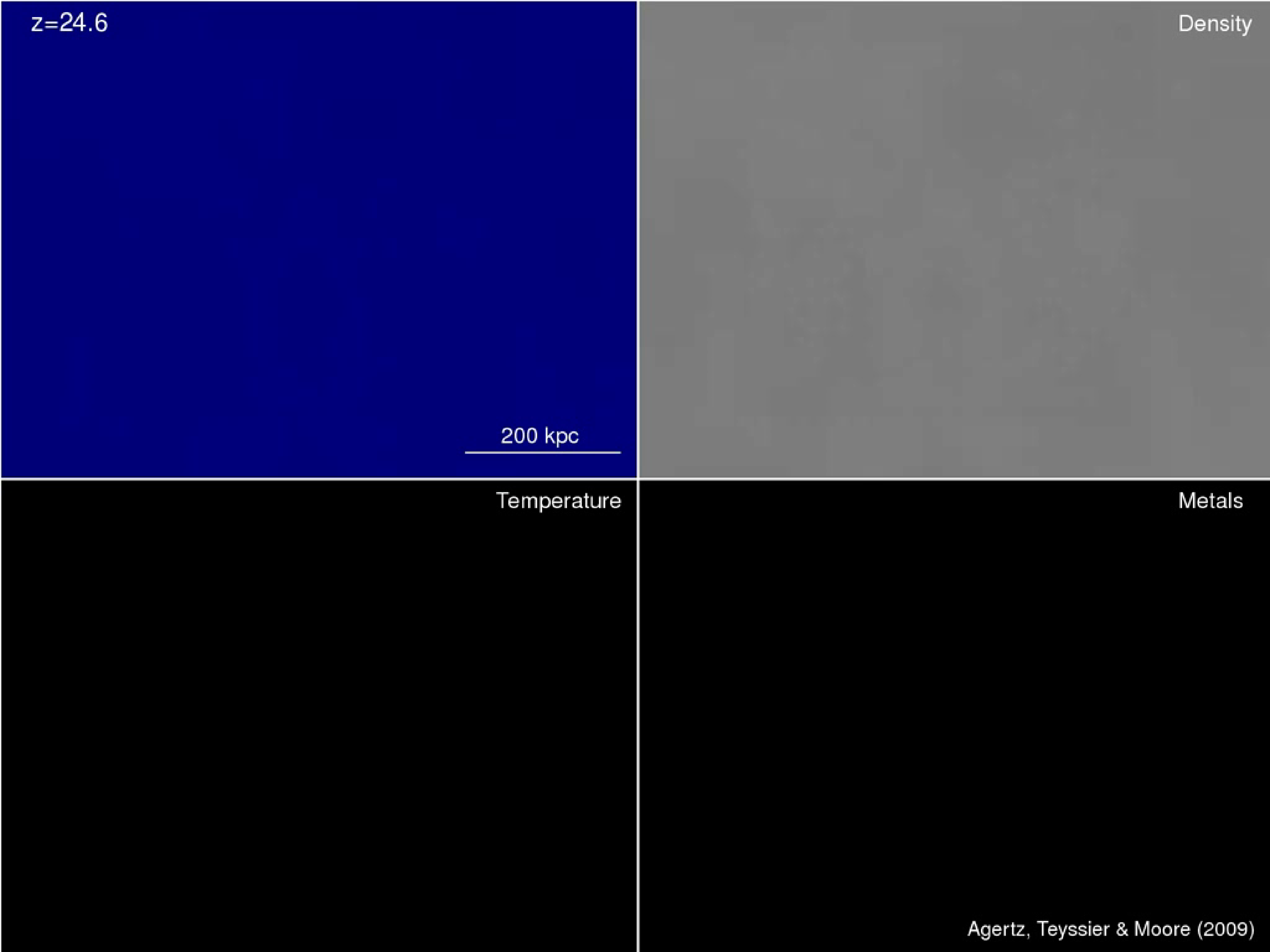


Clumpy (10^8Mo), high star-formation rates, extended over ~10kpc radii



ACS images (Elmegreen et al)


z=13.9
200 kpc
Dark matter
Gas
Stars
Agertz, Teyssier & Moore (2009)


z=24.6
Density
200 kpc
Temperature
Metals
Agertz, Teyssier & Moore (2009)

Parameter study

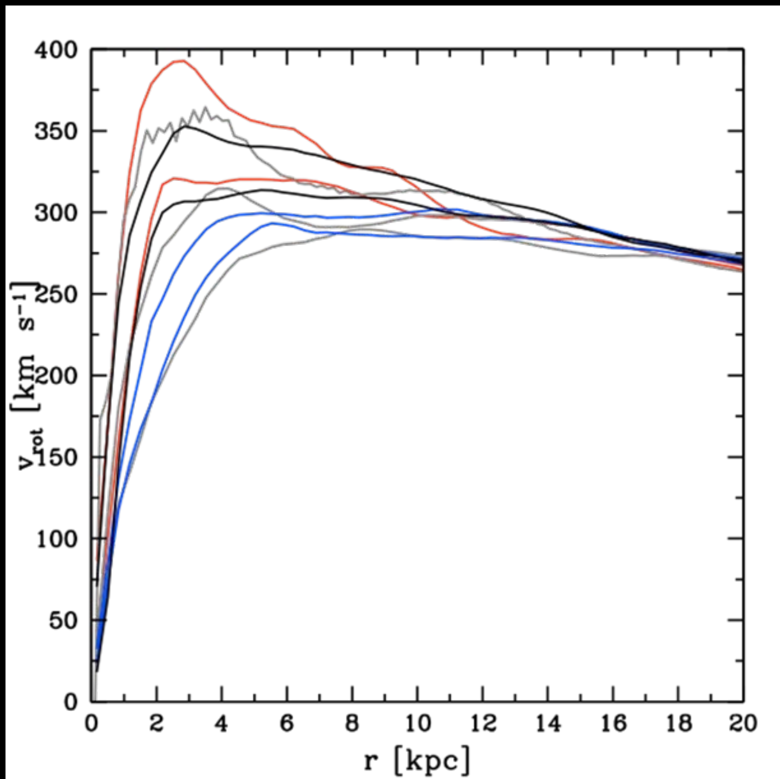
$$\dot{\rho}_* = \epsilon_{\rm ff} \frac{\rho_{\rm gas}}{t_{\rm ff}}$$

- Resolution
- Star formation threshold
- Star formation efficiency
- Inclusion of SN 1 events and wind mass-loss

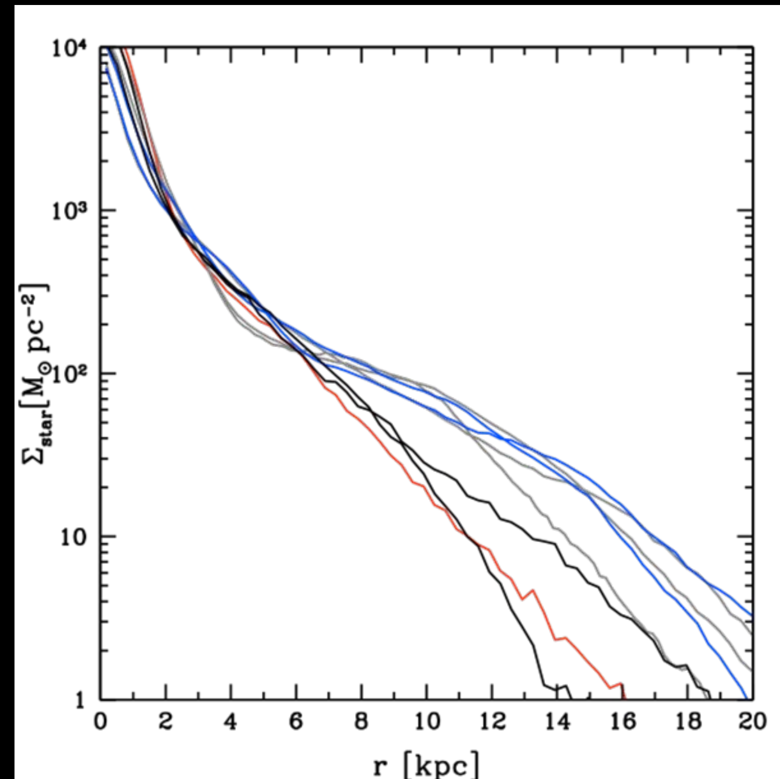
Run	$M_{\rm disk,s}$	$M_{\rm disk,g}$	$M_{\rm disk,tot}$	$M_{\rm bulge}$	$f_{\rm gas,disk}$	B/D
SR6_n1e1	4.9	3.3	8.2	4.5	0.4	0.55
SR6_n1e2	6.1	2.1	8.2	6.4	0.2	0.78
SR6_n1e5	4.1	2.1	6.2	7.0	0.34	1.1
SR6_n01e1	7.0	1.6	8.6	3.0	0.19	0.35
SR6_n01e2	6.7	1.3	8.0	5.0	0.16	0.63
SR6_n01e5	6.0	0.72	6.7	6.5	0.12	0.97
SR6_ML_n1e1	4.9	3.6	8.5	4.2	0.41	0.49
SR6_ML_n1e2	4.9	2.9	7.8	5.8	0.37	0.74
SR6_ML_n1e5	-	-	-	-	-	-
SR6_ML_n01e1	7.0	2.3	9.3	3.0	0.25	0.32
SR6_ML_n01e2	7.3	1.6	8.9	4.4	0.18	0.49
SR6_ML_n01e5	-	-	-	-	-	-
SR6_n01e1p1	-	-	-	-	-	-
SR6_MLT_n1e1	5.0	3.6	8.6	4.1	0.42	0.48
SR6_n1e1ND	-	-	-			
SR6_adiab	-	-	-			
SR5_ML_n1e1	6.6	2.0	8.6	4.5	0.23	0.52
SR5_ML_n01e1p1	-	-	-	-	-	-

- For realistic choices we always get nice disk galaxies.
- Due to regulation (balance of star formation and destructive feedback), a resolved disk is less sensitive to the actual choice of parameters.
- If the disk is under-resolved, the efficiency sets the bulge to disk ration. The threshold for star formation must be set low enough to avoid “missed star formation events” in the outer disk.

Gas rotational velocity



Gas surface density

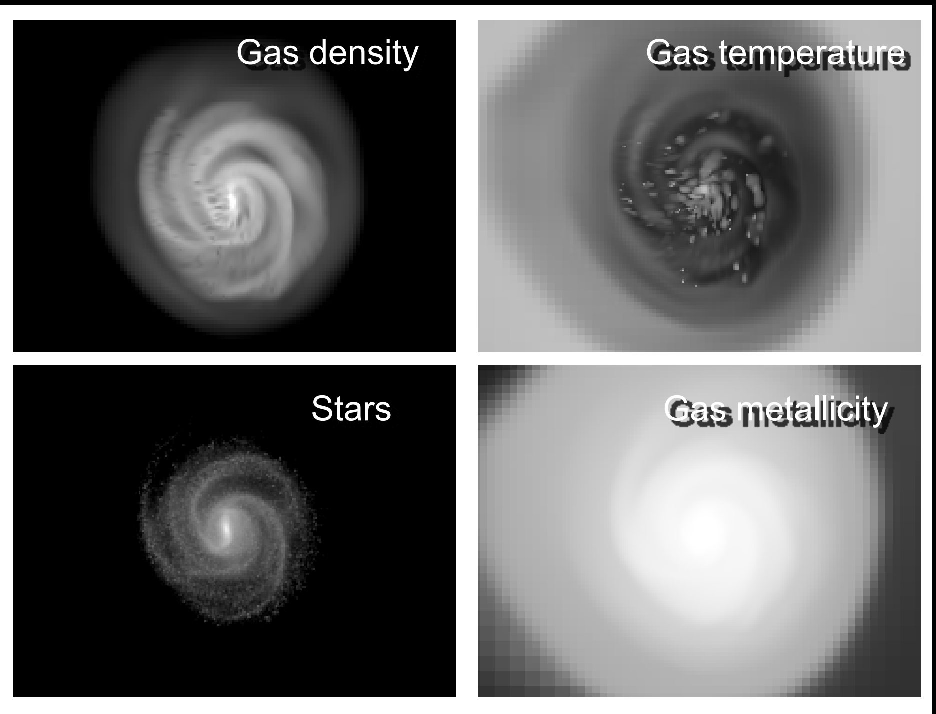


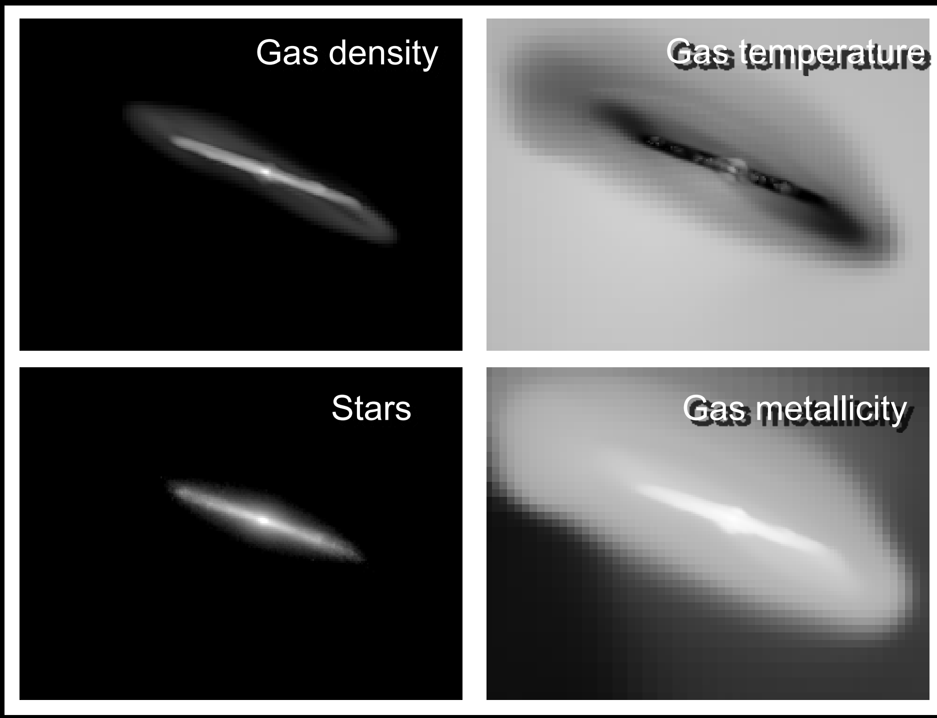
Regardless of parameter choice, all disks get roughly the same global properties. Disks with low B/D ratios are obtained when star formation is resolved at large disk radii and when the efficiency per free fall time is kept below 2%.

Detailed properties are unconstrained…..i.e. Sa - Sc

The disk, SR6n01e1ML

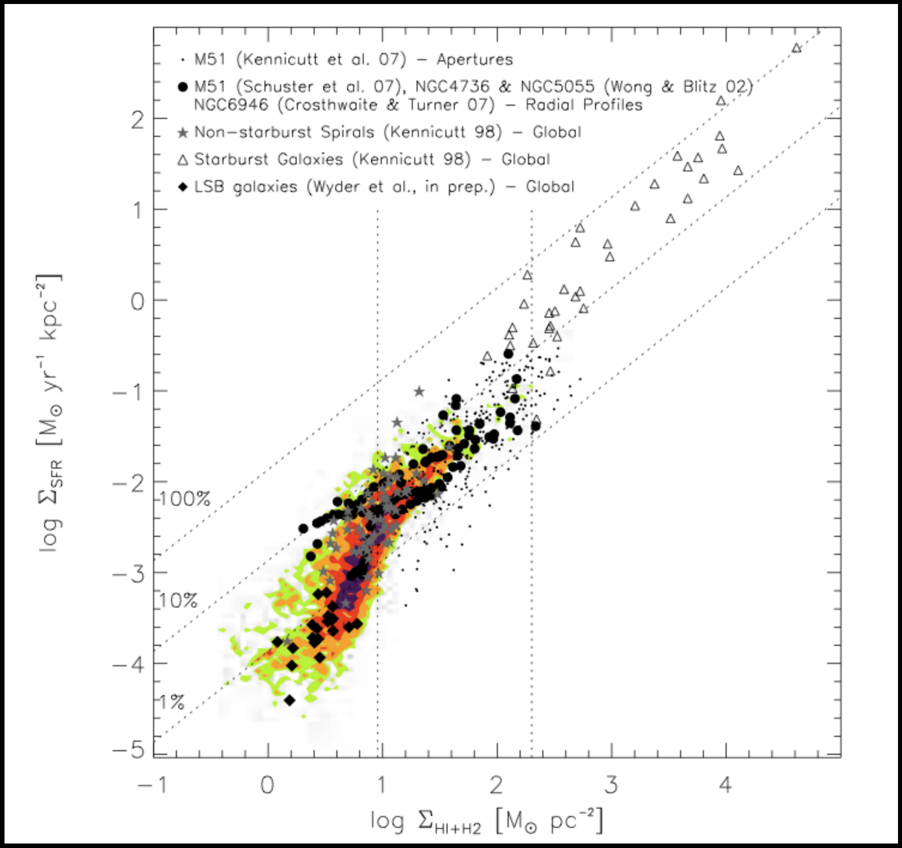
No dominating bulge!
Sb galaxy where the bulge forms from a buckled bar.



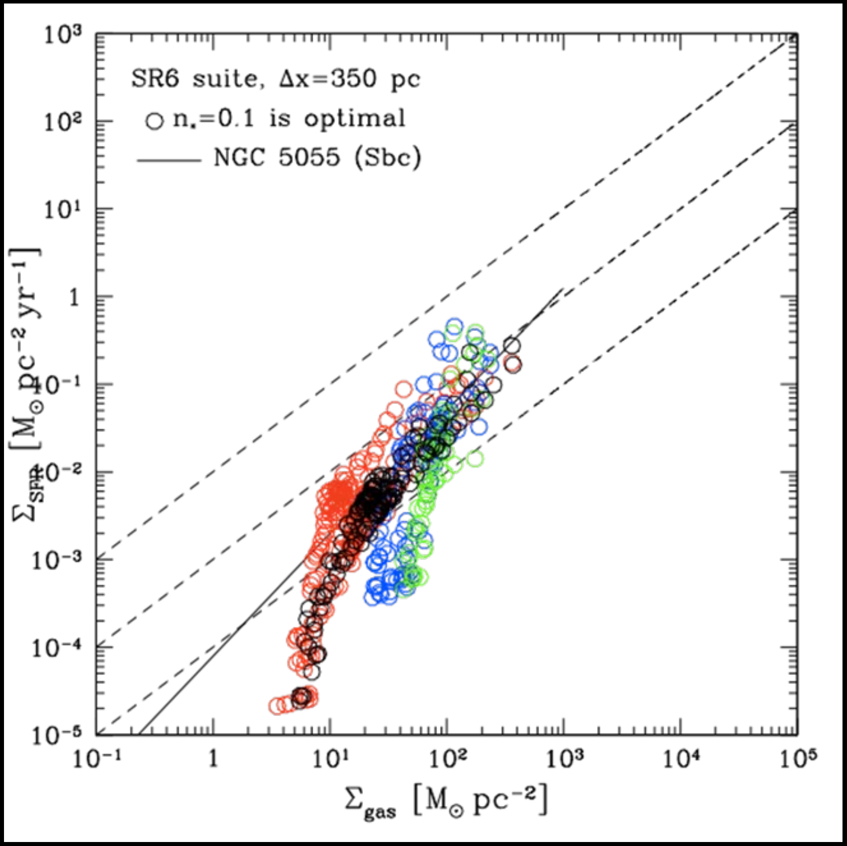


- Thin extended disk of stars and gas
- Thick stellar disk and bulge
- Hot pockets of gas from supernovae
- Massive hot gaseous halo
- Gravitational instability: we resolve spiral structure
- Stars preferentially form in the arms
- Galactic fountain
- Realistic metallicity gradient

The Kennicutt-Schmidt law



Bigiel (2009), fig. 15. Compilation using THINGS data + other



Our AMR simulations – different colours are different star formation efficiencies

Systematic uncertainties in the determination of the local dark matter density

Miguel Pato,[1,2,3,*] Oscar Agertz,[1] Gianfranco Bertone,[1,2] Ben Moore,[1] and Romain Teyssier[1]

[1]*Institute for Theoretical Physics, Univ. of Zürich, Winterthurerst. 190, 8057 Zürich CH*

[2]*Institut d'Astrophysique de Paris, UMR 7095-CNRS, Univ. Pierre & Marie Curie, 98bis Bd Arago 75014 Paris, France*

[3]*Dipartimento di Fisica, Università degli Studi di Padova, via Marzolo 8, I-35131, Padova, Italy*

(Dated: June 1, 2010)

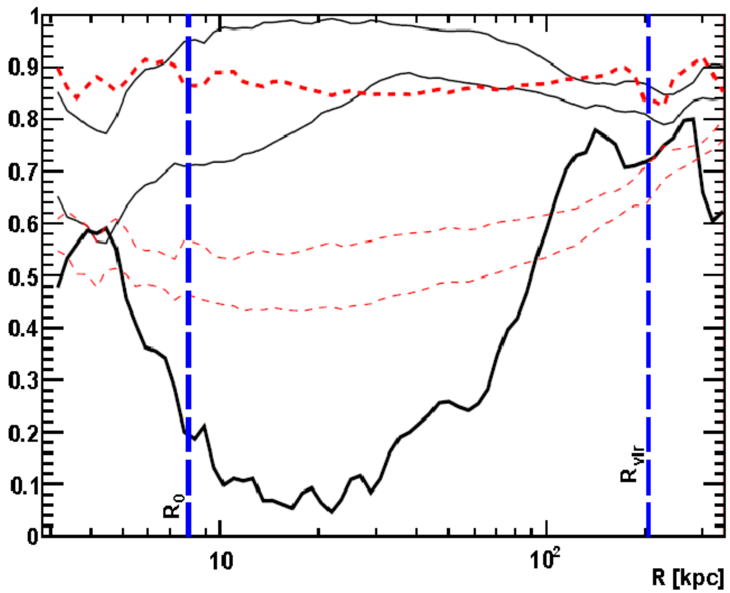


FIG. 1: The shape parameters b/a, c/a and T for SR6-n01e1ML (solid black lines) and the corresponding pure dark matter realization (dashed red lines), both at $z = 0$. Upper (Lower) thin lines show b/a (c/a), whereas thick curves represent the triaxiality parameter T. Also shown are the Sun galactocentric distance $R_0 \simeq 8$ kpc and the virial radius $R_{vir} \equiv R_{200c}$.

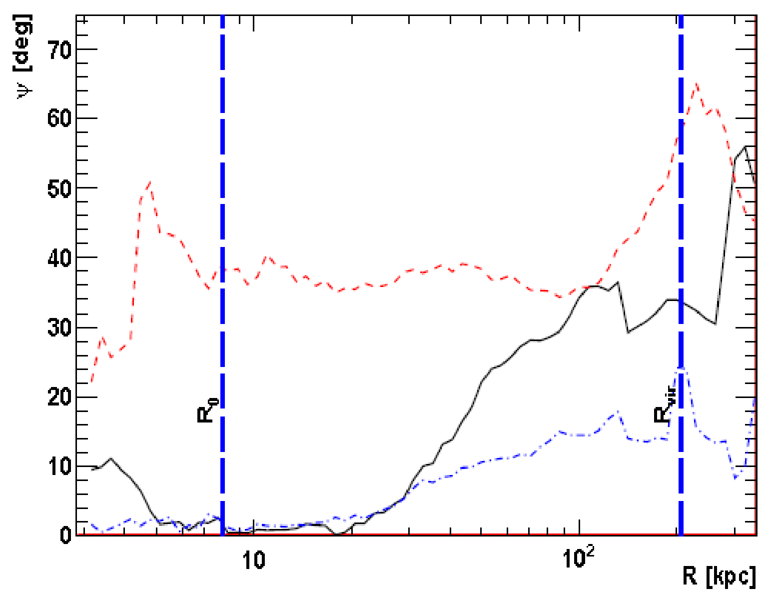


FIG. 2: The angle between the normal to the stellar disk $\vec{n}_{sd}$ and the minor axis $\vec{j}_c$. The solid black (dot-dashed blue) line corresponds to SR6-n01e1ML (SR6-n01e5ML) at z=0. The dashed red line shows the angle between the minor axis in the pure dark matter simulation and the normal to the stellar disk in SR6-n01e1ML. Also shown are the Sun galactocentric distance $R_0 \simeq 8$ kpc and the virial radius $R_{vir} \equiv R_{200c}$.

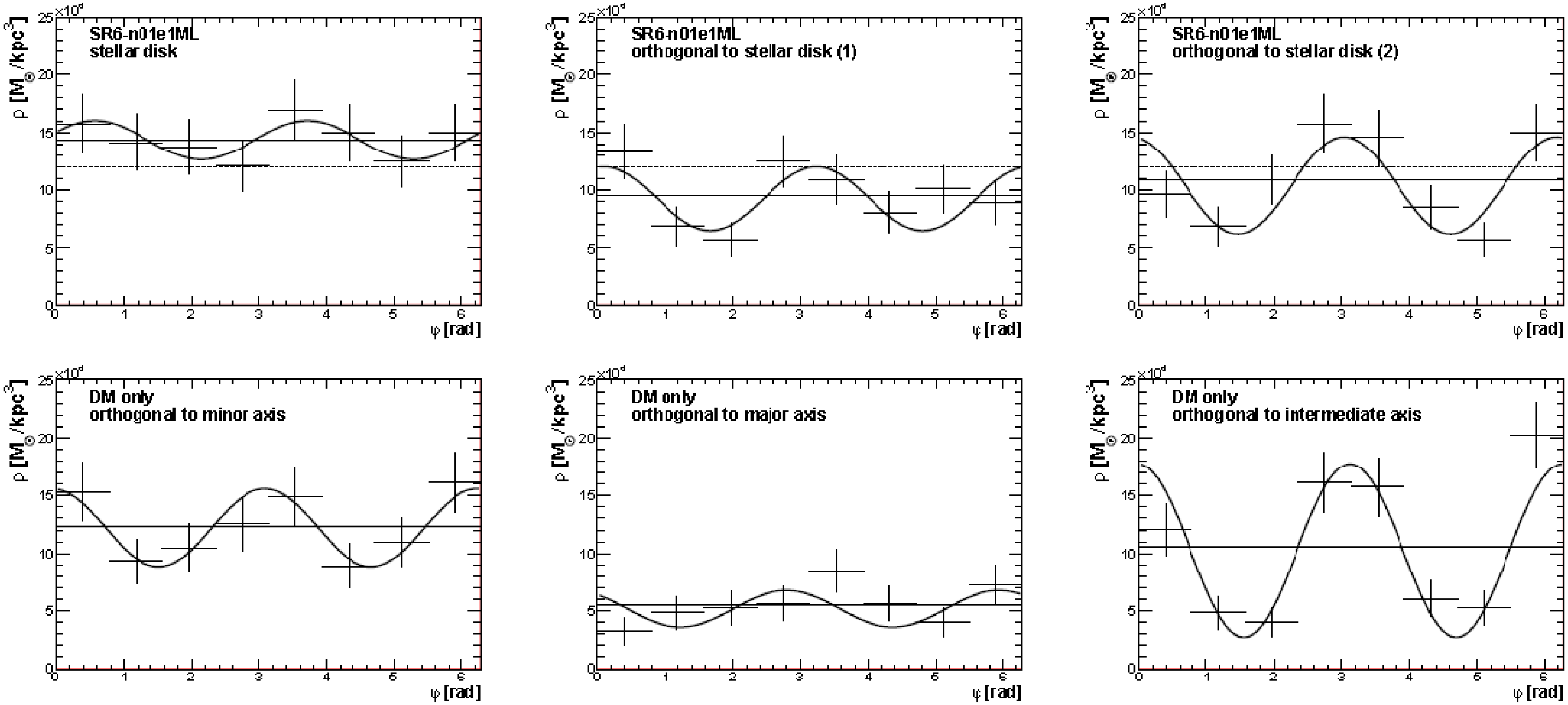
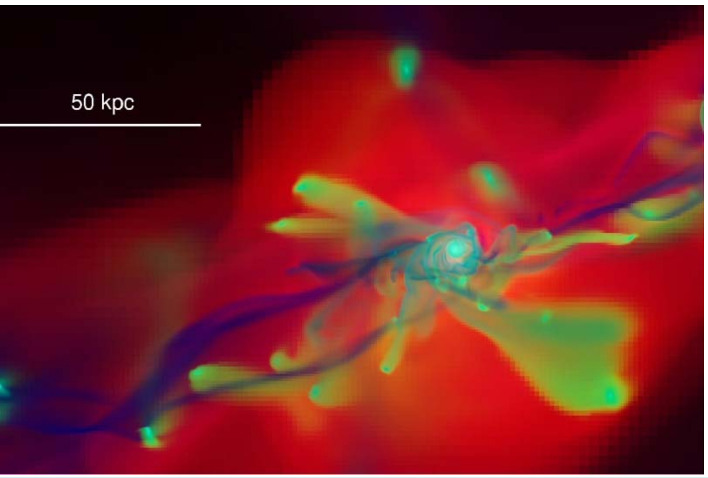


FIG. 3: The dark matter density in the spherical shell $7.5 < R/\mathrm{kpc} < 8.5$ along the stellar disk plane and two perpendicular planes for SR6-n01e1ML (top), and along the planes perpendicular to the principle axes for the pure dark matter simulation (bottom). The solid horizontal line represents the mean of the points and the dashed line shows the value of the mean density in the whole shell, dubbed $\bar{\rho}_0$. The sinusoidal curve shown in each plot is the best fit to the points in the form $c_1 + c_2 \sin\left(2\left(\varphi + c_3\right)\right)$.



Lots of predictions, no evidence for CDM yet, no strong counter evidence. Complicated by galaxy formation

Dark matter distribution near the solar is probably smooth. Lots of surviving substructures/microhaloes

A new complex model of galaxy formation is emerging in which baryons accrete to the halo center in three ways – cold streams, cooling flow, metal enriched stripped debris.

At z=2 we can match the clumpy morphology of HST galaxies.

At z=0 we can make thin disks with small bulges and nice spiral patterns. The global properties are believable but details are uncertain.

DM distribution is oblate within the disk. No core - slightly steeper central density profile.

By 2015 we will reach the 1 parsec resolution required to resolve the molecular disks and spatially resolved star formation.