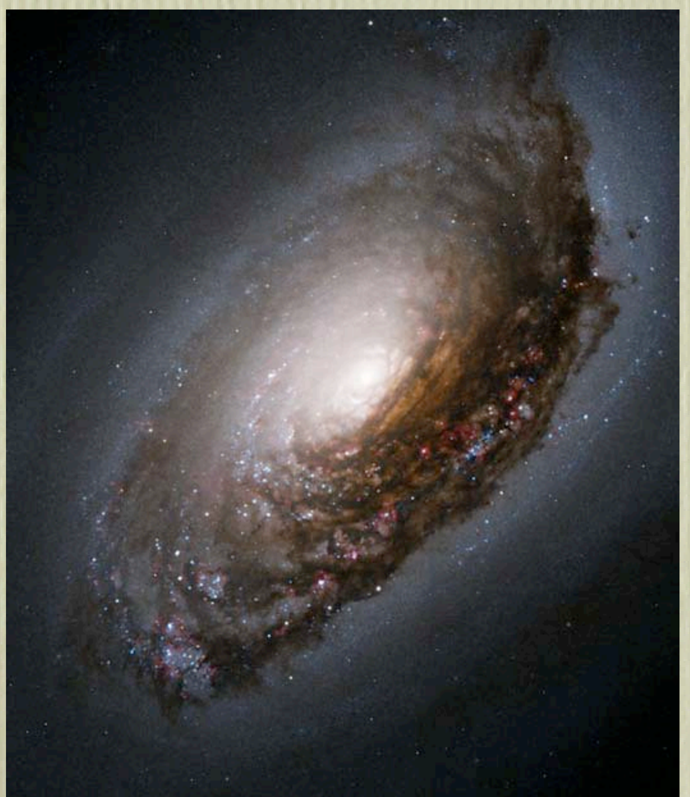
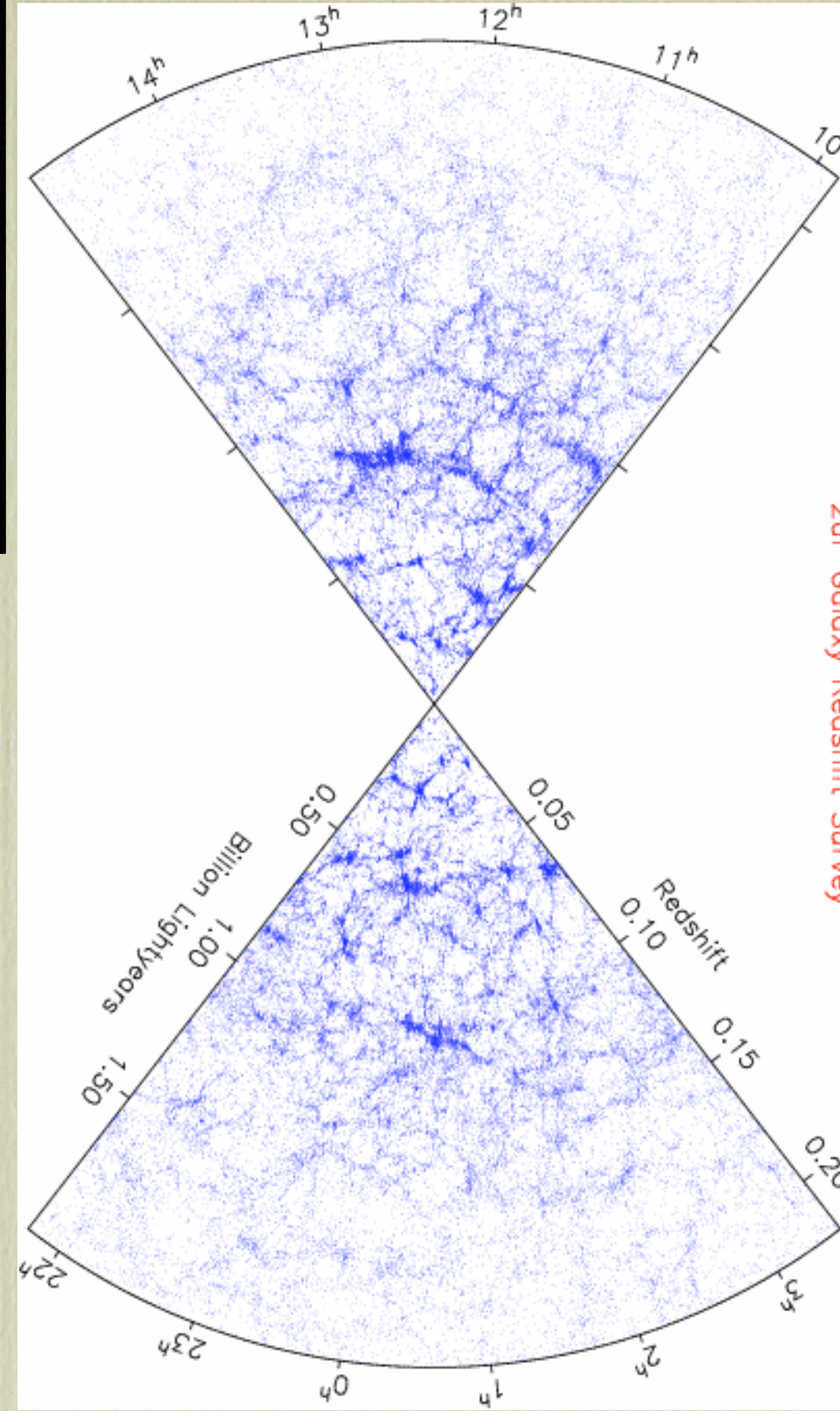
Dark Forces in the Visible Sector

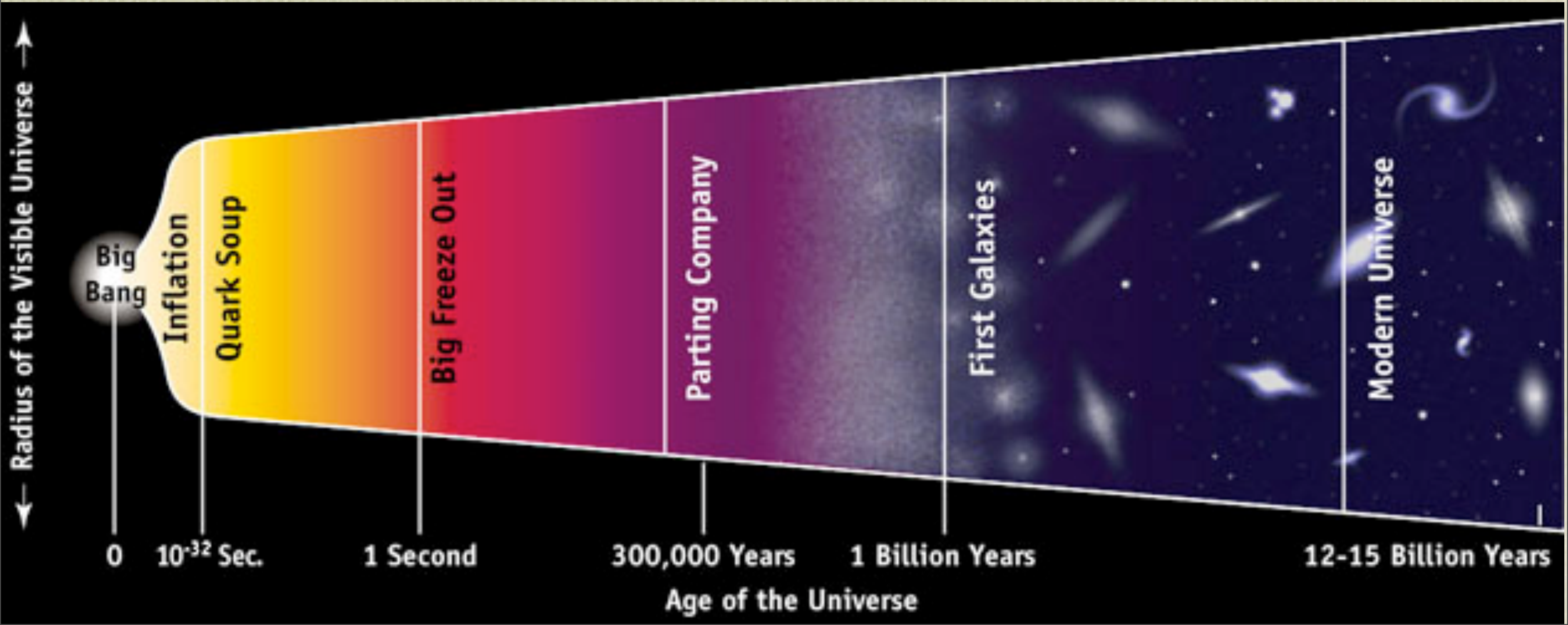
- Great success of the standard cosmological model (LCDM)
- Anomalies in the standard model
- Remedies by modifications in the Dark Sector physics
- Galactic Ghost Streams
- Predictions

Collaborators:
Ariel Keselman
Jim Peebles
Steve Gubser

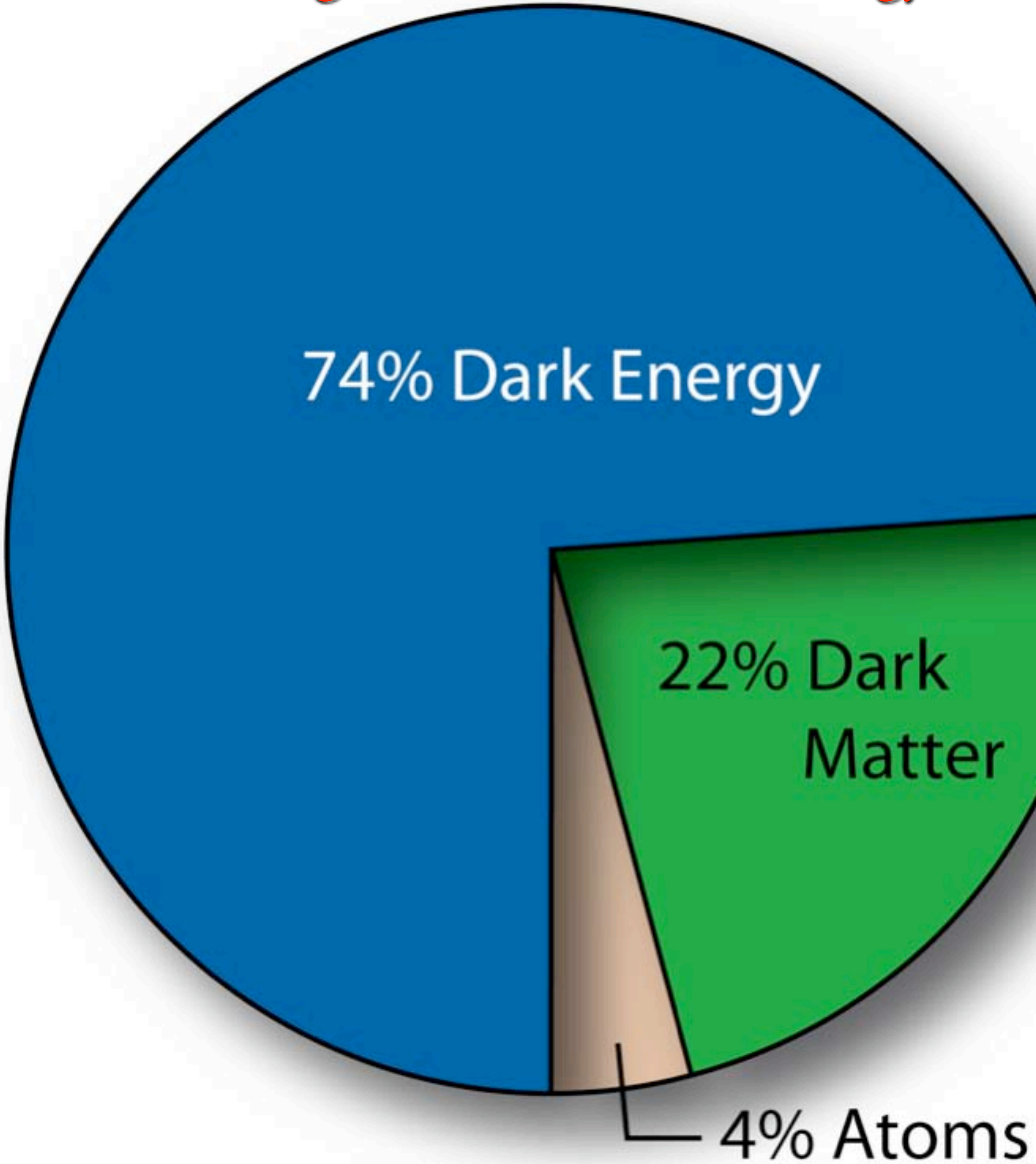



2dF Galaxy Redshift Survey
14h
13h
12h
11h
10h
Billion Lightyears
0.50
1.00
1.50
Redshift
0.05
0.10
0.15
0.20
22h
23h
0h
1h
2h
3h

What is the history of structure formation?



High Precision Cosmology



Gravity of Dark matter is the driver of structure formation

The Great Success of LCDM

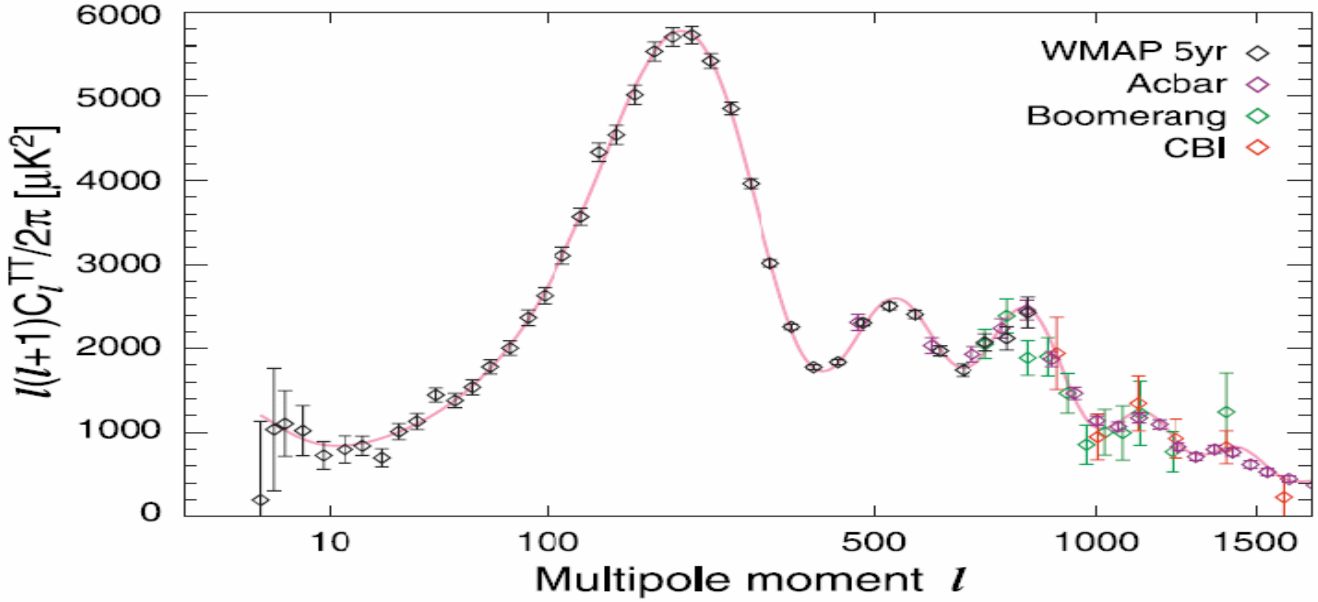
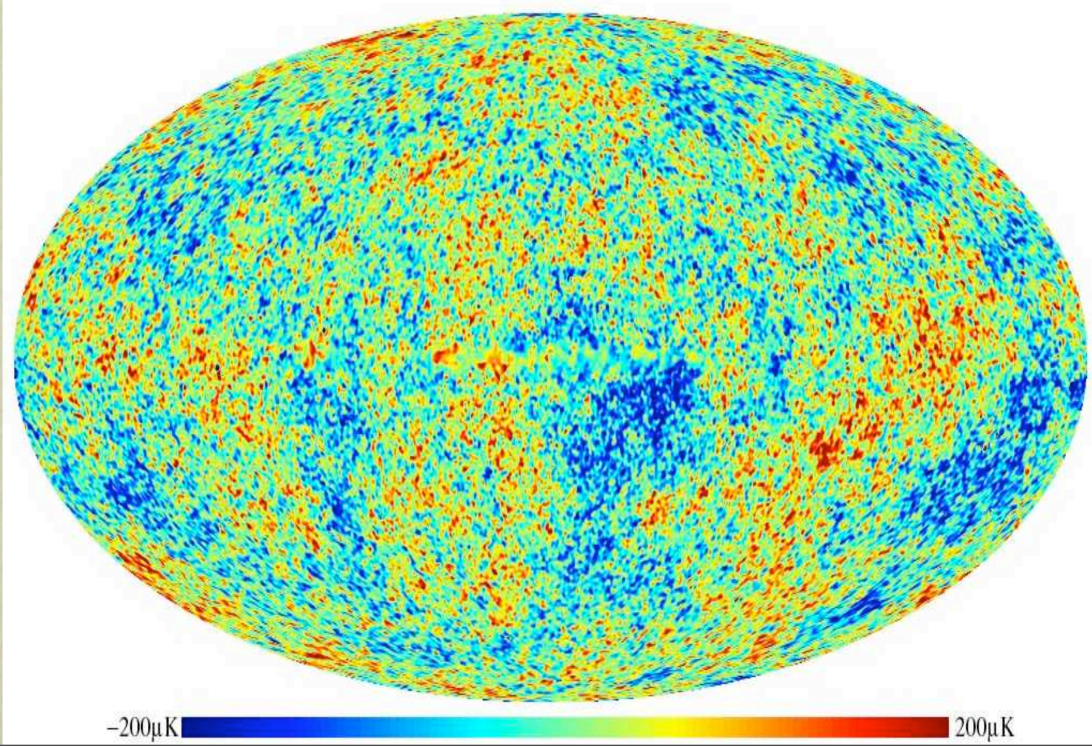


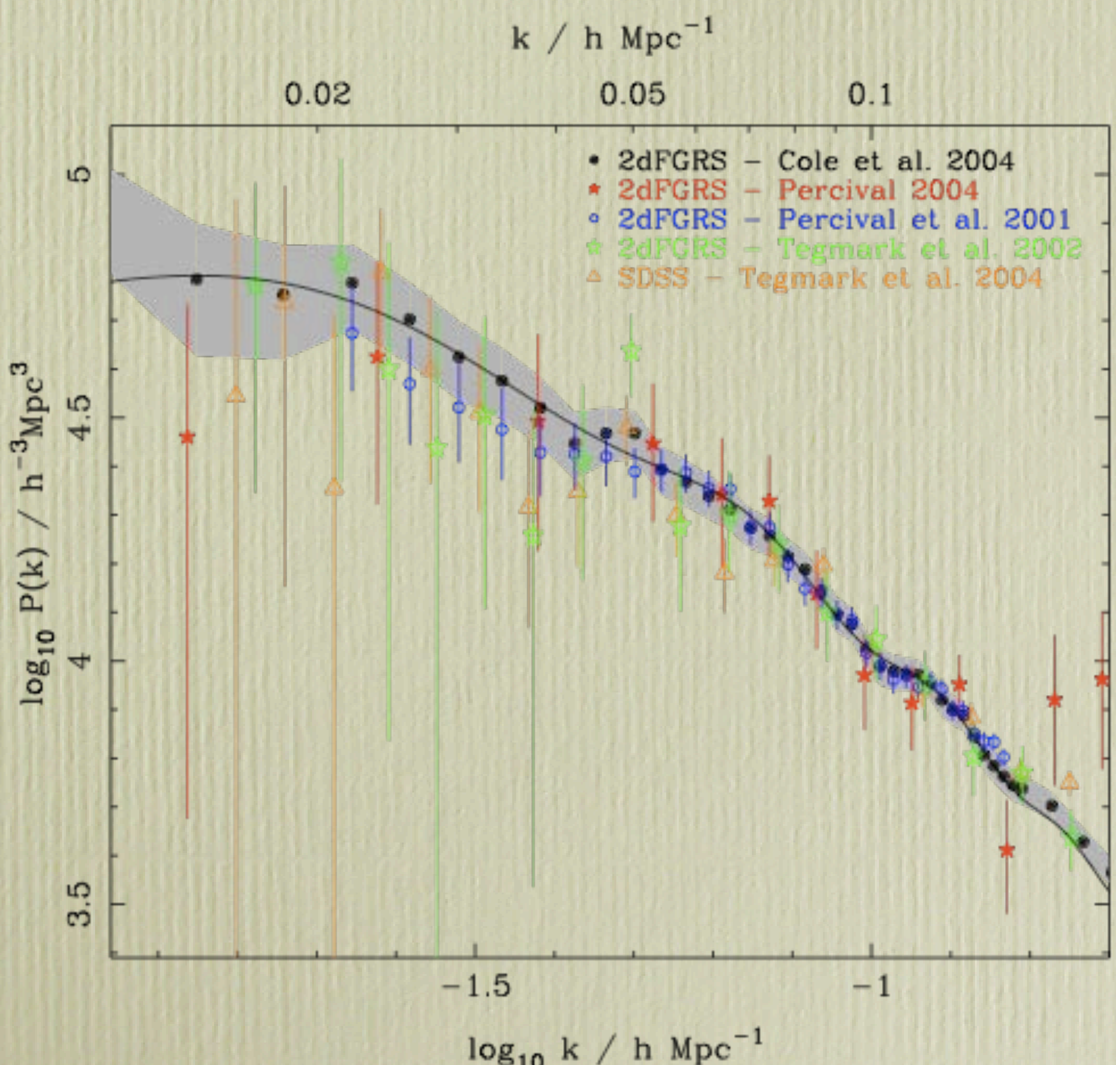
Fig. 2.— The *WMAP* 5-year TT power spectrum along with recent results from the ACBAR (Reichardt et al. 2008, purple), Boomerang (Jones et al. 2006, green), and CBI (Readhead et al. 2004, red) experiments. The other experiments calibrate with *WMAP* or *WMAP*'s measurement of Jupiter (CBI). The red curve is the best-fit ΛCDM model to the *WMAP* data, which agrees well with all data sets when extrapolated to higher-ℓ.



CMB Temperature fluctuations

The 2dF Galaxy Redshift Survey: Power-spectrum analysis of the final dataset and cosmological implications

Shaun Cole[1], Will J. Percival[2], John A. Peacock[2], Peder Norberg[3], Carlton M. Baugh[1], Carlos S. Frenk[1], Ivan Baldry[4], Joss Bland-Hawthorn[5], Terry Bridges[6], Russell Cannon[5], Matthew Colless[5], Chris Collins[7], Warrick Couch[8], Nicholas J.G. Cross[4,2], Gavin Dalton[9], V.R. Eke[1], Roberto De Propris[10], Simon P. Driver[11], George Efstathiou[12], Richard S. Ellis[13], Karl Glazebrook[4], Carole Jackson[14], Adrian Jenkins[1], Ofer Lahav[15], Ian Lewis[9], Stuart Lumsden[16], Steve Maddox[17], Darren Madgwick[12], Bruce A. Peterson[11], Will Sutherland[12], Keith Taylor[13] (The 2dF-GRS Team)



$$\Omega_\mathrm{m} = 0.231 \pm 0.021$$

$$\Omega_\mathrm{b} = 0.042 \pm 0.002$$

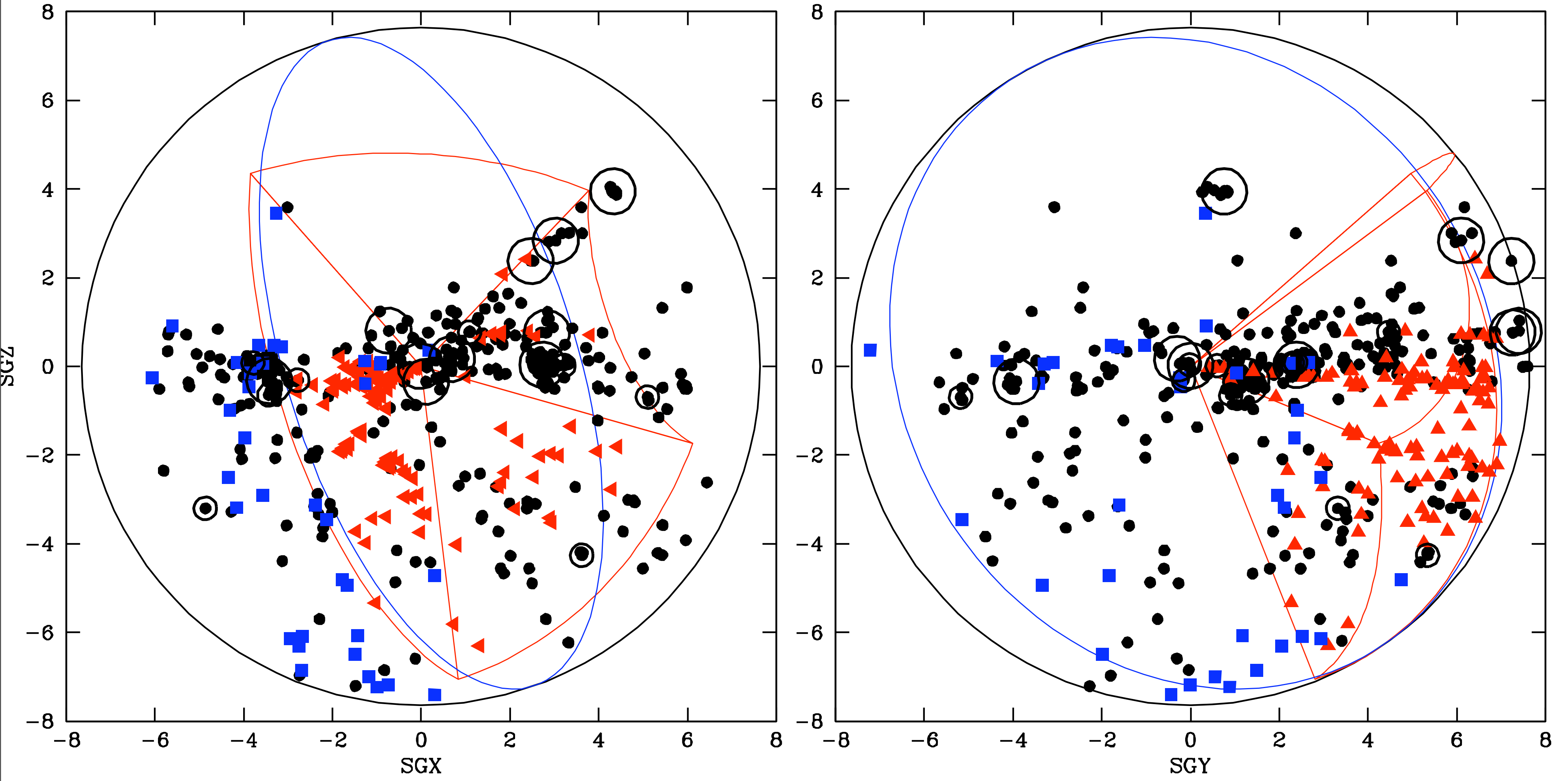
$$h = 0.766 \pm 0.032$$

$$n_\mathrm{s} = 1.027 \pm 0.050.$$

Anomalies of the ΛCDM model

The Local Void

Credit: Jim Peebles



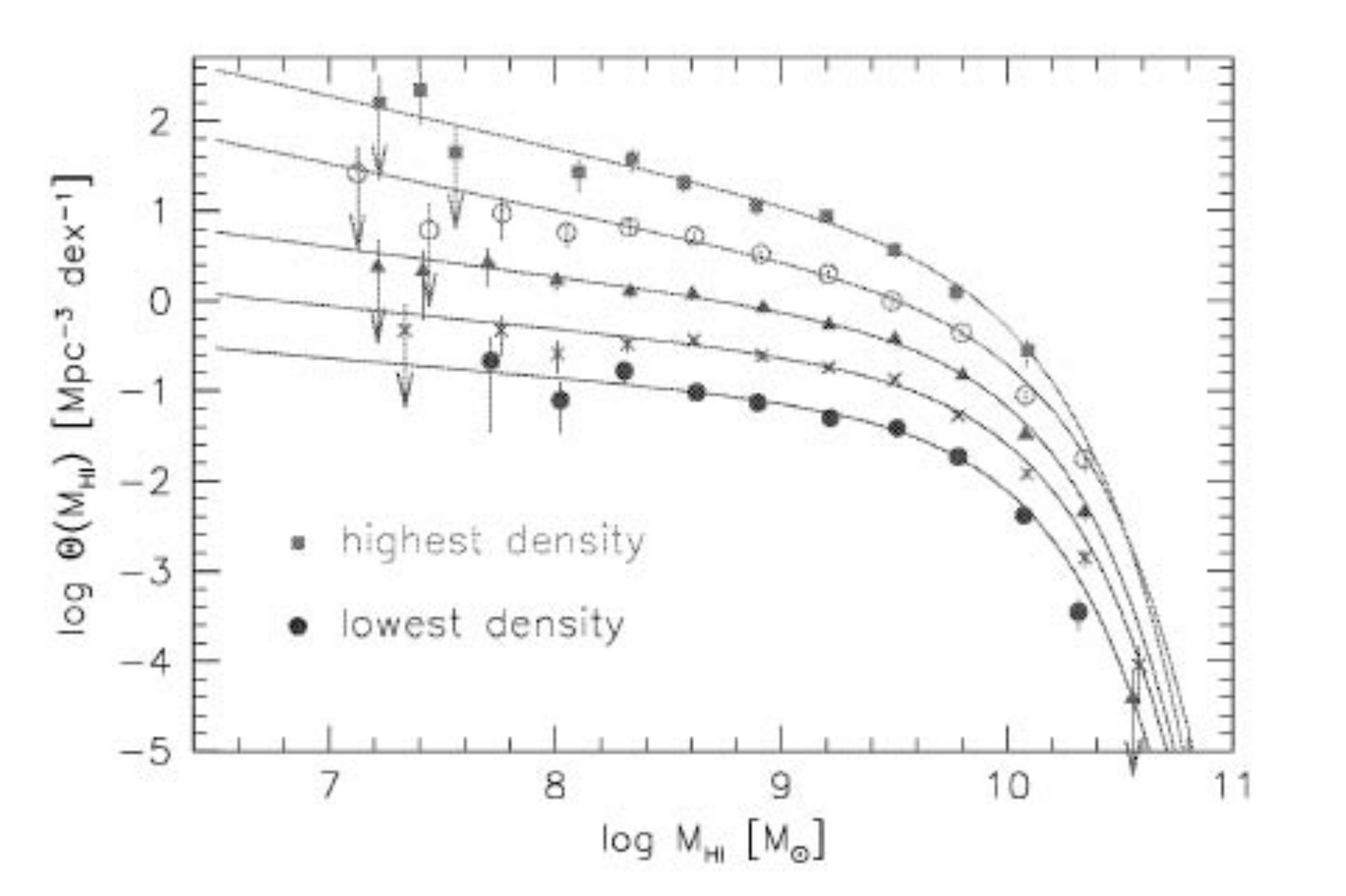
Only 2 dwarfs are observed in the void opposed to 15 expected in LCDM

red=SDSS
blue=HIPASS
black=Karachentsev etal

The LV phenomenon seems to be part of a bigger problem:

The HIPASS catalogue: $\Omega_{\mathrm{H\,I}}$ and environmental effects on the H I mass function of galaxies

M. A. Zwaan,[1★] M. J. Meyer,[2] L. Staveley-Smith[3] and R. L. Webster[4]

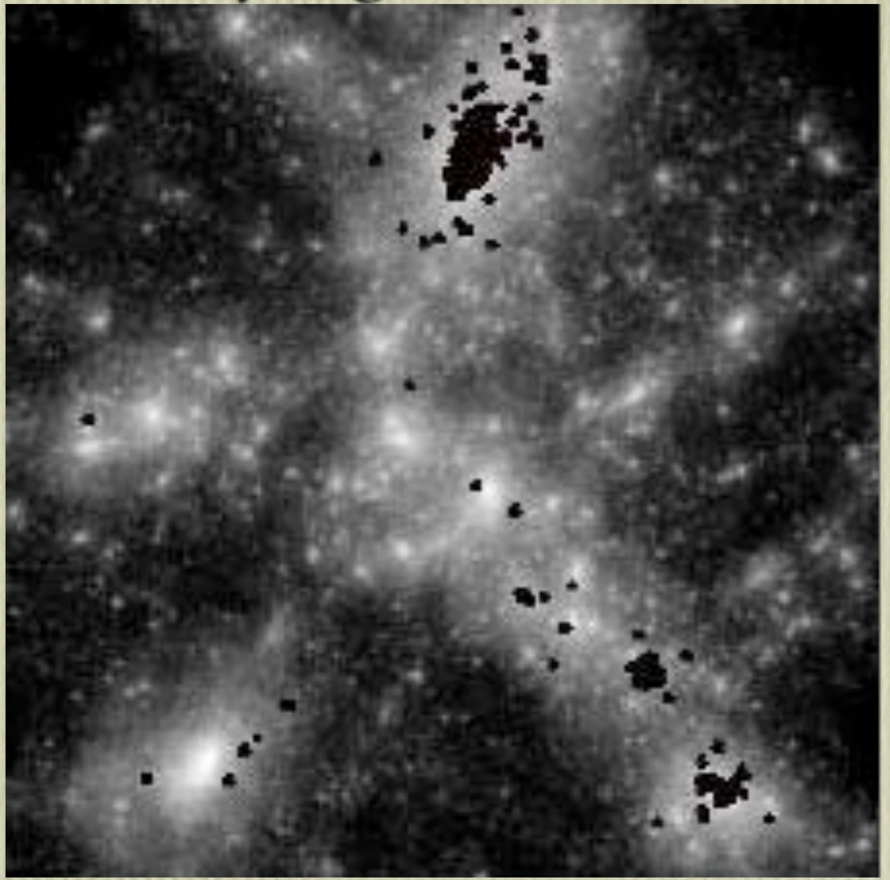


ΛCDM tends to produce too much merging at $z < 1$

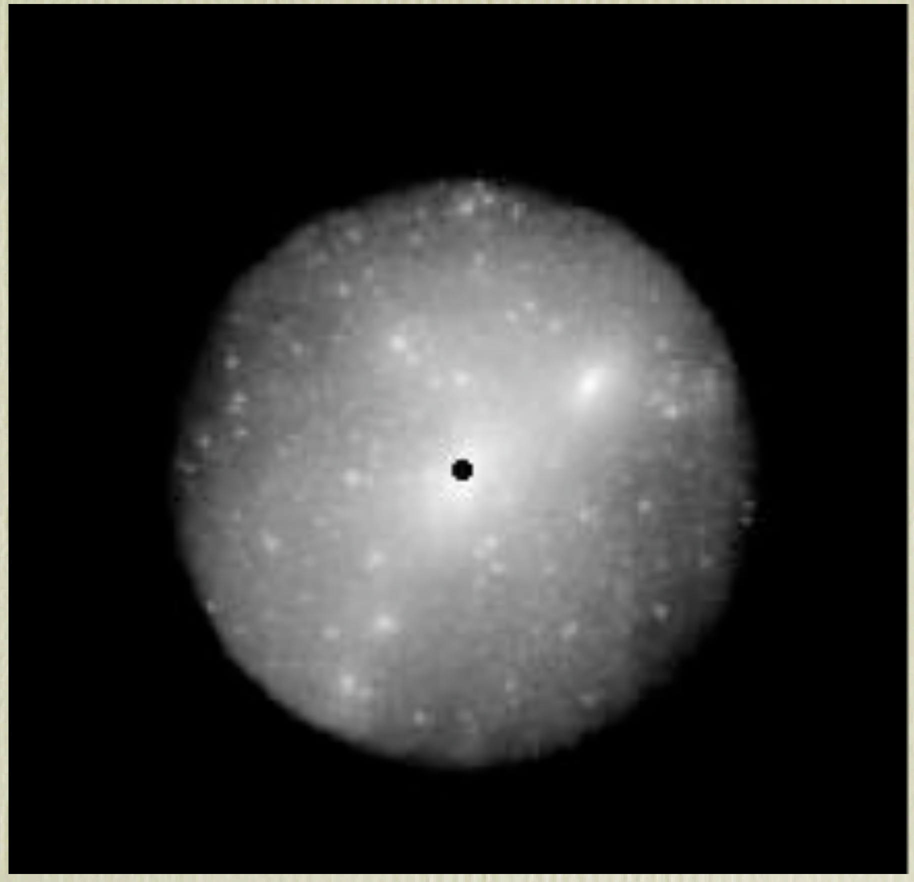
i.e. the last 8Gyr

Merging in a simulation

8Gyr ago (z=1)



Today (z=0)

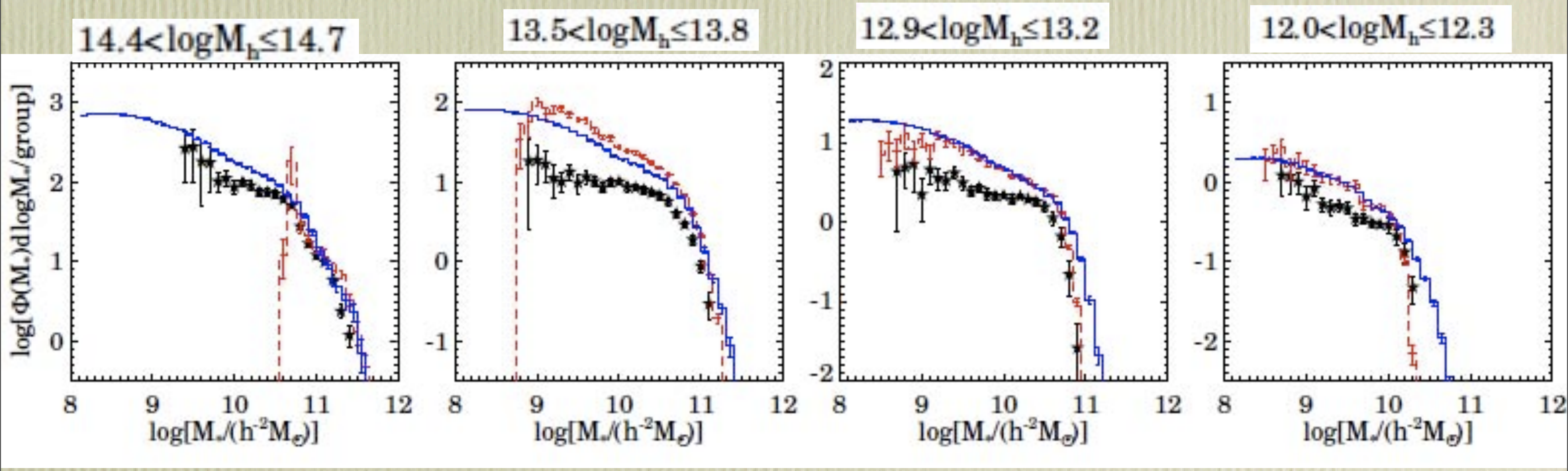


Gao etal 04

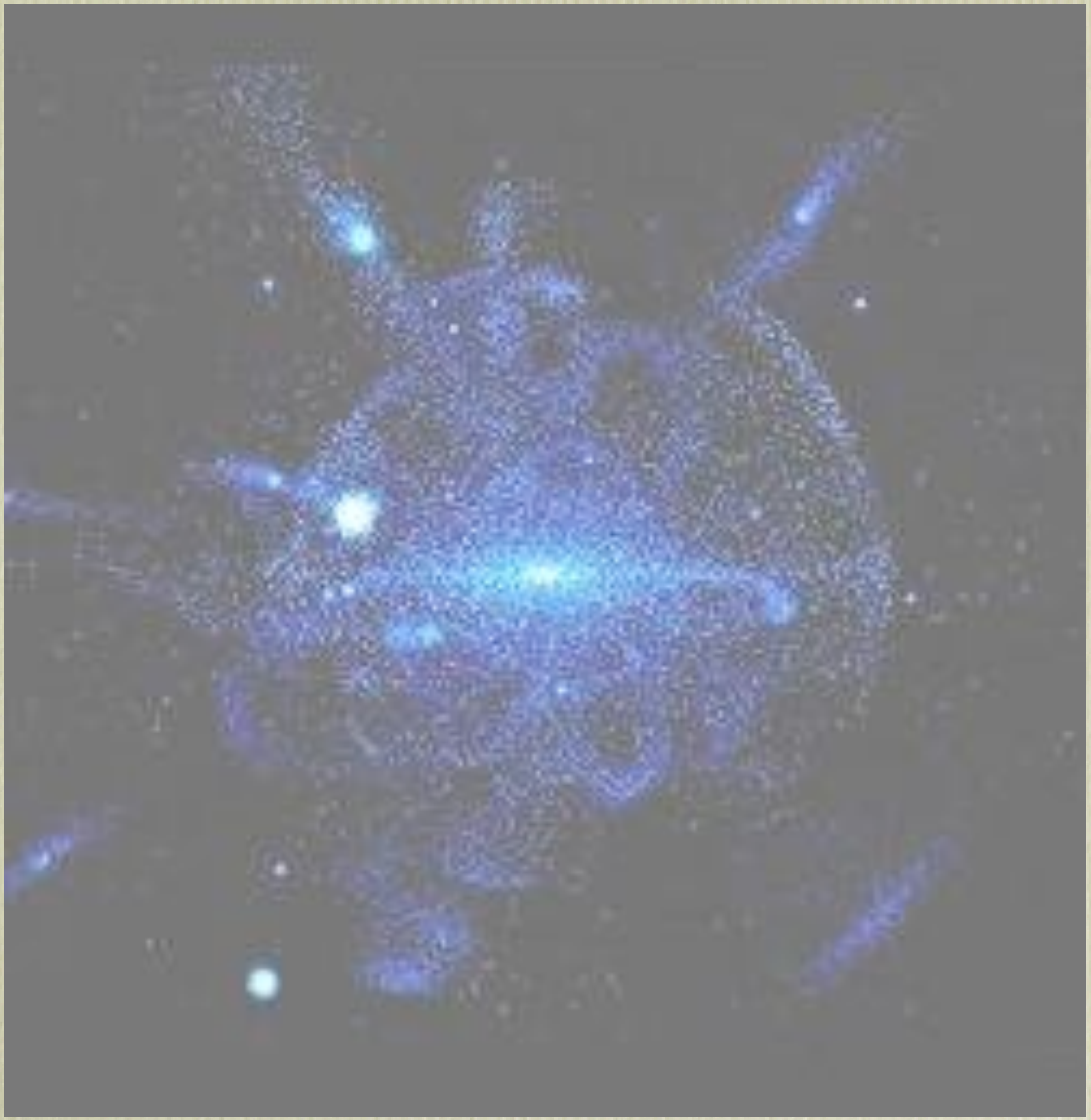
How do we know how much merging there is in the Universe?

THE STELLAR MASS COMPONENTS OF GALAXIES: COMPARING SEMI-ANALYTICAL MODELS WITH OBSERVATION

Lei Liu[1,5], Xiaohu Yang[1], H.J. Mo [2], Frank C. van den Bosch[3], Volker Springel[4]



Stellar streams in the Milky Way



Kinematics of stars a few kpc above the midplane of the disk:

DECIPHERING THE LAST MAJOR INVASION OF THE MILKY WAY

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Received 2002 May 10; accepted 2002 June 14; published 2002 June 25

ABSTRACT

We present first results from a spectroscopic survey of ~2000 F/G stars 0.5–5 kpc from the Galactic plane, obtained with the Two Degree Field facility on the Anglo-Australian Telescope. These data show the mean rotation velocity of the thick disk about the Galactic center a few kiloparsecs from the plane is very different than expected, being ~100 km s^{-1} rather than the predicted ~180 km s^{-1}. We propose that our sample is dominated by stars from a disrupted satellite that merged with the disk of the Milky Way some 10–12 Gyr ago. We do not find evidence for the many substantial mergers expected in hierarchical clustering theories. We find yet more evidence that the stellar halo retains kinematic substructure, indicative of minor mergers.

if LCDM

Pieces of the puzzle: Ancient substructure in the Galactic disk

Amina Helmi[*1], J. F. Navarro[†2,3], B. Nordström[4,5], J. Holmberg[6], M. G. Abadi[2‡] and M. Steinmetz[7§]

extra-Galactic provenance. It is possible to identify three coherent Groups among these stars, that, in all likelihood, correspond to the remains of disrupted satellites. The most metal-rich group ($[Fe/H] > -0.45$ dex) has 120 stars distributed into two stellar populations of ~ 8 Gyr (33%) and ~ 12 Gyr (67%) of age. The second Group with $\langle [Fe/H] \rangle \sim -0.6$ dex has 86 stars, and shows evidence of three populations of 8 Gyr (15%), 12 Gyr (36%) and 16 Gyr (49%) of age. Finally, the third Group has 68 stars, with typical metallicity around -0.8 dex, and a single age of ~ 14 Gyr. The identification of substantial amounts of debris in the Galactic disk whose origin can be traced back to more than one satellite galaxy, provides undisputable evidence of the hierarchical formation of the Milky Way.

probably not LCDM

About half of the brightest 20 galaxies with 8Mpc are pure disks just like the MW (Fisher & Kormendy 08)

Pure disk NGC4247

Andromeda

MERGER HISTORIES OF GALAXY HALOS AND IMPLICATIONS FOR DISK SURVIVAL

Kyle R. Stewart,[1] James S. Bullock,[1] Risa H. Wechsler,[2] Ariyeh H. Maller,[3] and Andrew R. Zentner[4]

Received 2007 November 30; accepted 2008 March 14

ABSTRACT

We study the merger histories of galaxy dark matter halos using a high-resolution ΛCDM *N*-body simulation. Our merger trees follow ~17,000 halos with masses $M_0 = 10^{11}$–$10^{13}\ h^{-1}\ M_\odot$ at $z = 0$ and track accretion events involving objects as small as $m \simeq 10^{10}\ h^{-1}\ M_\odot$. We find that mass assembly is remarkably self-similar in m/M_0 and dominated by mergers that are ~10% of the final halo mass. While very large mergers, $m \gtrsim 0.4M_0$, are quite rare, sizeable accretion events, $m \sim 0.1M_0$, are common. Over the last ~10 Gyr, an overwhelming majority (~95%) of Milky Way–sized halos with $M_0 = 10^{12}\ h^{-1}\ M_\odot$ have accreted at least one object with greater total mass than the Milky Way disk ($m > 5 \times 10^{10}\ h^{-1}\ M_\odot$), and approximately 70% have accreted an object with more than twice that mass ($m > 10^{11}\ h^{-1}\ M_\odot$). Our results raise serious concerns about the survival of thin-disk-dominated galaxies within the current paradigm for galaxy formation in a ΛCDM universe. In order to achieve a ~70% disk-dominated fraction in Milky Way–sized ΛCDM halos, mergers involving $m \simeq 2 \times 10^{11}\ h^{-1}\ M_\odot$ objects must not destroy disks. Considering that most thick disks and bulges contain old stellar populations, the situation is even more restrictive: these mergers must not heat disks or drive gas into their centers to create young bulges.

Merging At high z

A Comparison of Galaxy Merger History Observations and Predictions from Semi-Analytic Models

Serena Bertone[1⋆], Christopher J. Conselice[2]

(CAS) method. We examine the evolution of the predicted merger fraction and rate in the Millennium simulation for galaxies with stellar masses $M_\star \sim 10^9 - 10^{12}$ $M_\odot$. We find that the predicted merger rates and fractions match the observations well for galaxies with $M_\star > 10^{11}$ $M_\odot$ at $z < 2$, while significant discrepancies occur at lower stellar masses, and at $z > 2$ for $M_\star > 10^{11}$ $M_\odot$ systems. At $z > 2$ the simulations underpredict the observed merger fractions by a factor of 4-10. The shape of the predicted merger fraction and rate evolutions are similar to the observations up to $z \sim 2$, and peak at $1 < z < 2$ in almost all mass bins. The exception is the merger rate of galaxies with $M_\star > 10^{11}$ $M_\odot$, which remains high at $z < 1.5$. We discuss possible

Therefore:

There is an ``imbalance” between standard LCDM and observations on small scales.

Partial Remedy

Increase the clustering rate on small scales!

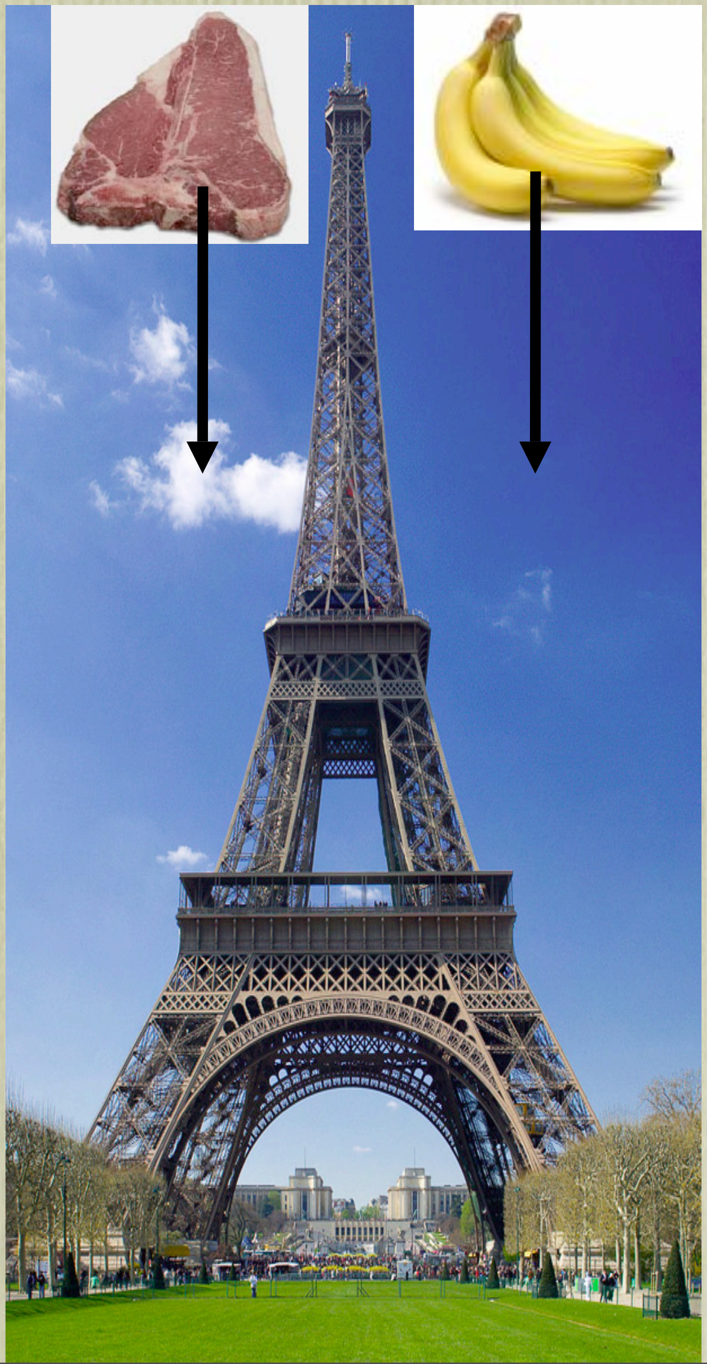
How do we do that?

$$V = -\frac{Gm^2}{r}\left(1 + \beta e^{-r/r_s}\right)$$

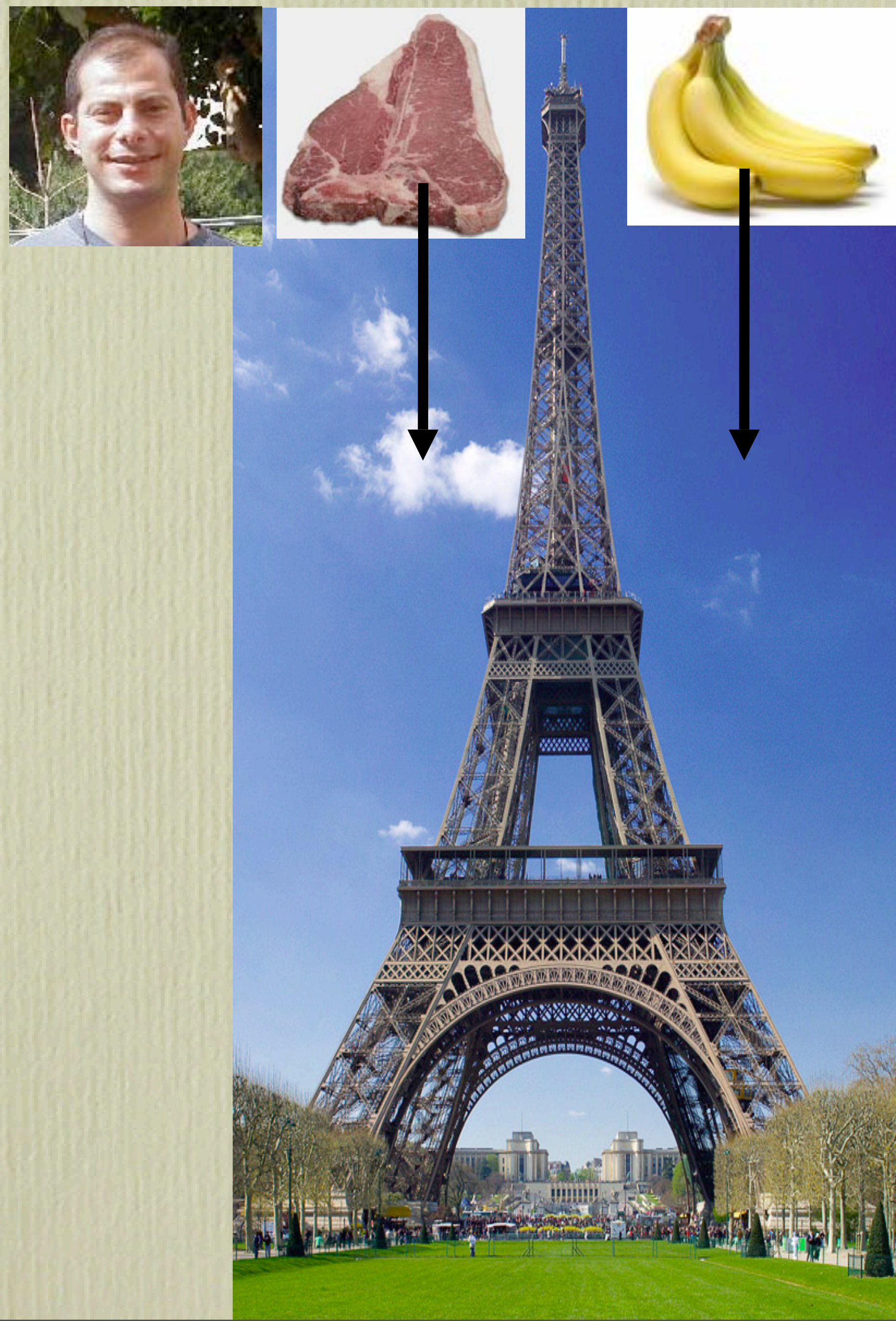
WARNING: ONLY BETWEEN DARK MATTER PARTICLES!!!!

The Baryons do not feel the extra term

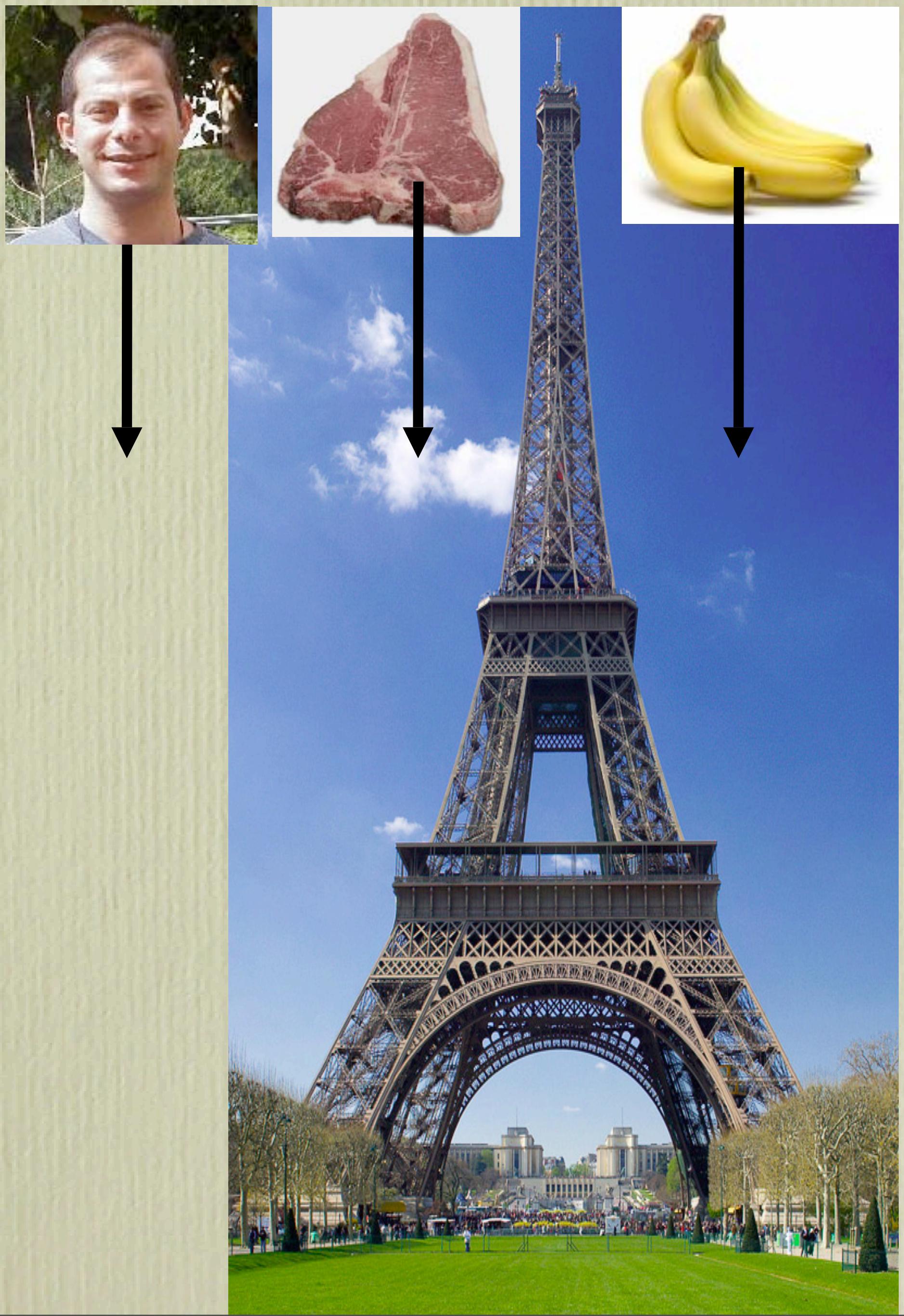
Violation of the Equivalence Principle



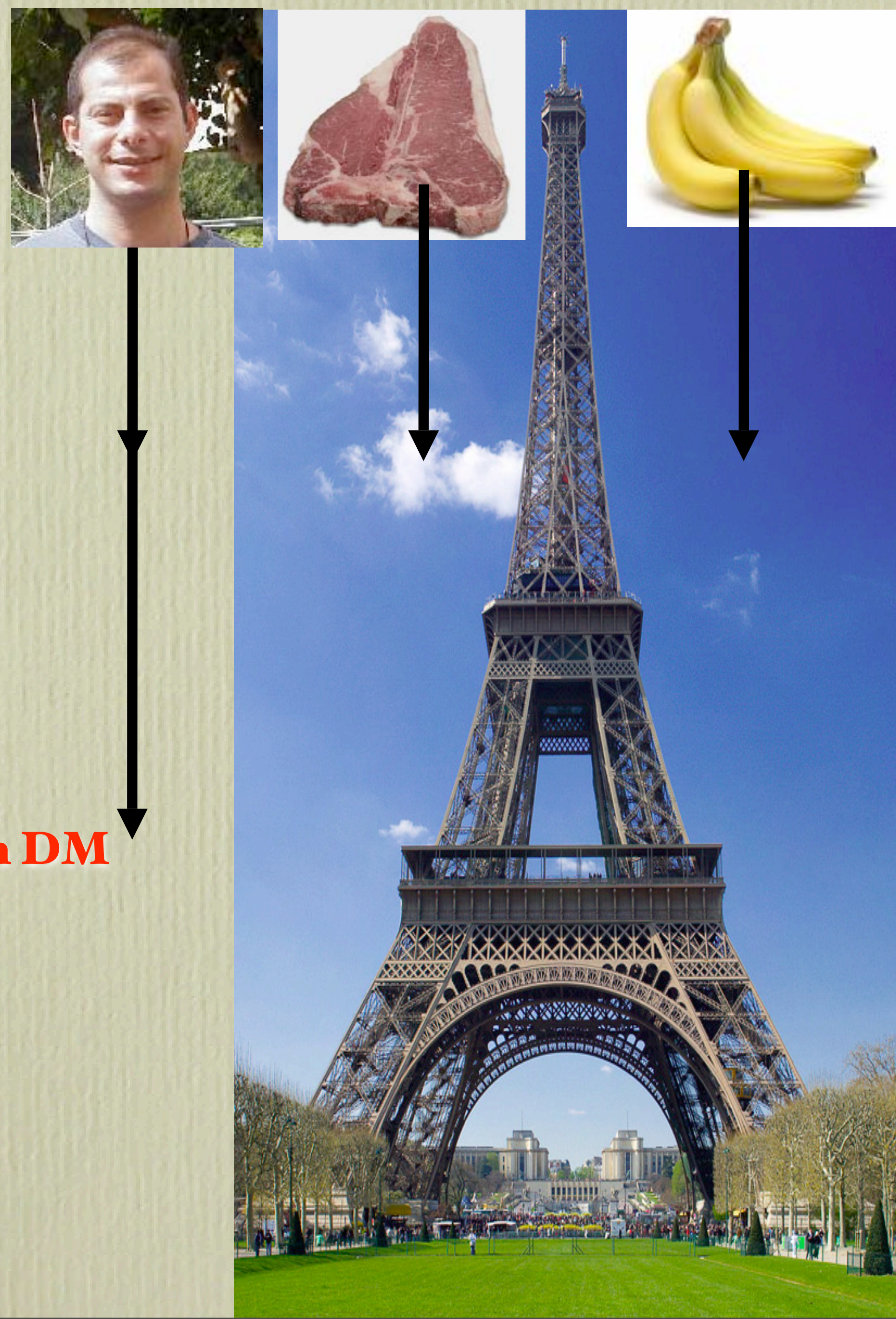
Violation of the Equivalence Principle



Violation of the Equivalence Principle



Violation of the Equivalence Principle



If A and E contain DM

Acronym

ReBEL=daRk Breaking Equivalence principLe

Long Range Interactions in the Dark Sector

Collaborators: Jim Peebles & Steve Gubser

Assume two species of dark matter particles of masses $M_+(\Phi)$ and $M_-(\Phi)$ that depend on a scalar field Φ. Consider the action

$$S = \int \mathrm{d}^3x\, \mathrm{d}t \Phi_{,i}\Phi^{,i} - \sum_{particles} \int \left[M_+(\Phi)\, \mathrm{d}t \sqrt{1 - v_+^2} + M_-(\Phi)\, \mathrm{d}t \sqrt{1 - v_-^2} \right]$$

Long Range Interactions in the Dark Sector

Collaborators: Jim Peebles & Steve Gubser

Assume two species of dark matter particles of masses $M_+(\Phi)$ and $M_-(\Phi)$ that depend on a scalar field Φ. Consider the action

Lorentz factor factor

$$S = \int \underbrace{\mathrm{d}^3x\,\mathrm{d}t\,\Phi_{,i}\Phi^{,i}} - \sum_{particles} \int \left[\underbrace{M_+(\Phi)\,\mathrm{d}t\sqrt{1-v_+^2}} + \underbrace{M_-(\Phi)\,\mathrm{d}t\sqrt{1-v_-^2}} \right]$$

kinetic term of the field

relativistic Lagrangian of a particle

History of scalar interactions (slide from J. Peebles):

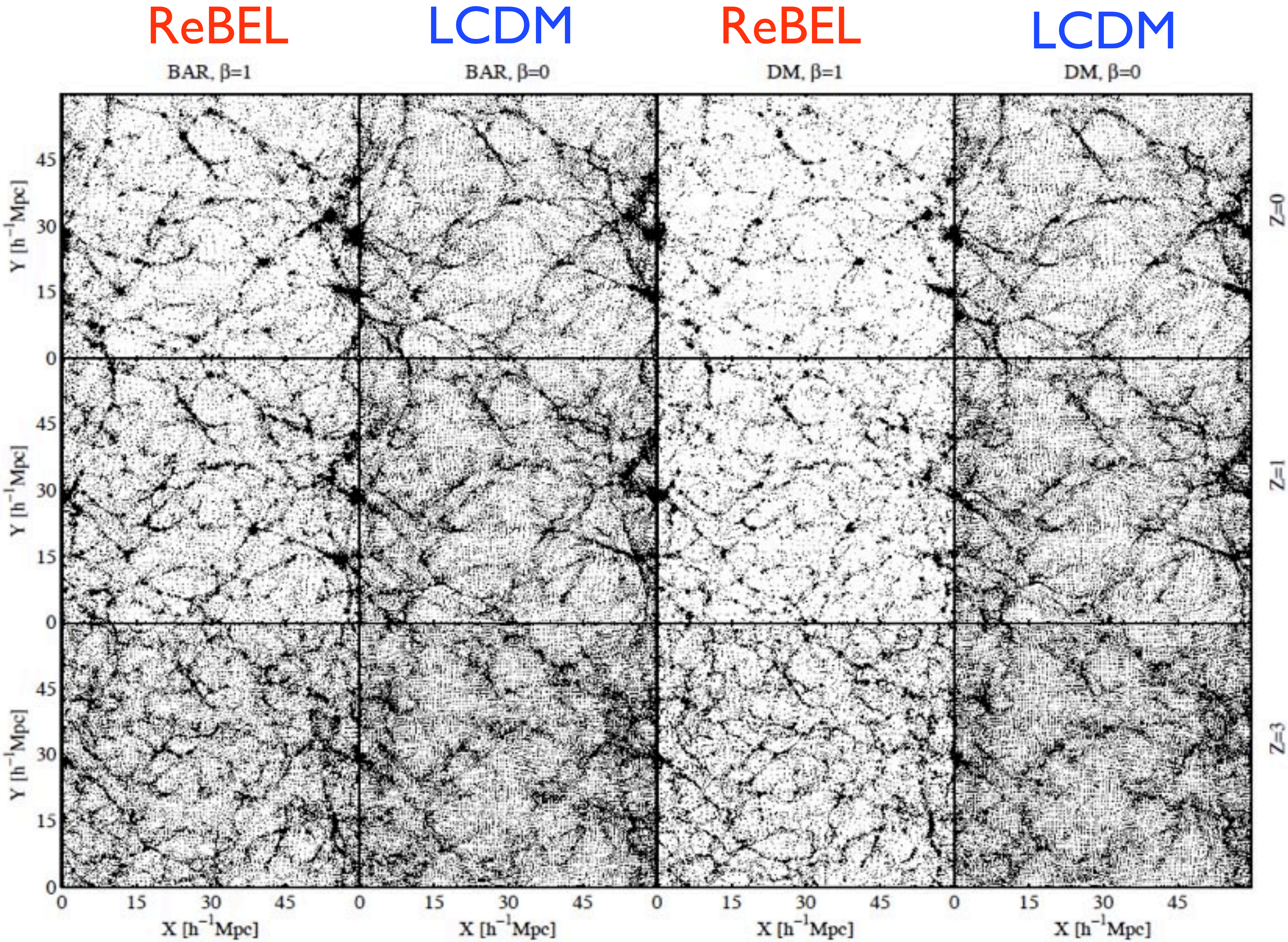
The idea has a long history: Nordström (1912) introduced the classical form (1), which is equivalent to Yukawa's (1935) form (2) when the de Broglie wavelength is small.

In the 1950s through 1970s Pascual Jordan and Bob Dicke led explorations of scalar-tensor gravity physics, with this action in the Einstein frame.

Damour, Gibbons & Gundlach (1990) noted that the tight empirical constraints we now have on a long-range scalar interaction in the visible sector allow a substantial scalar interaction in the dark sector.

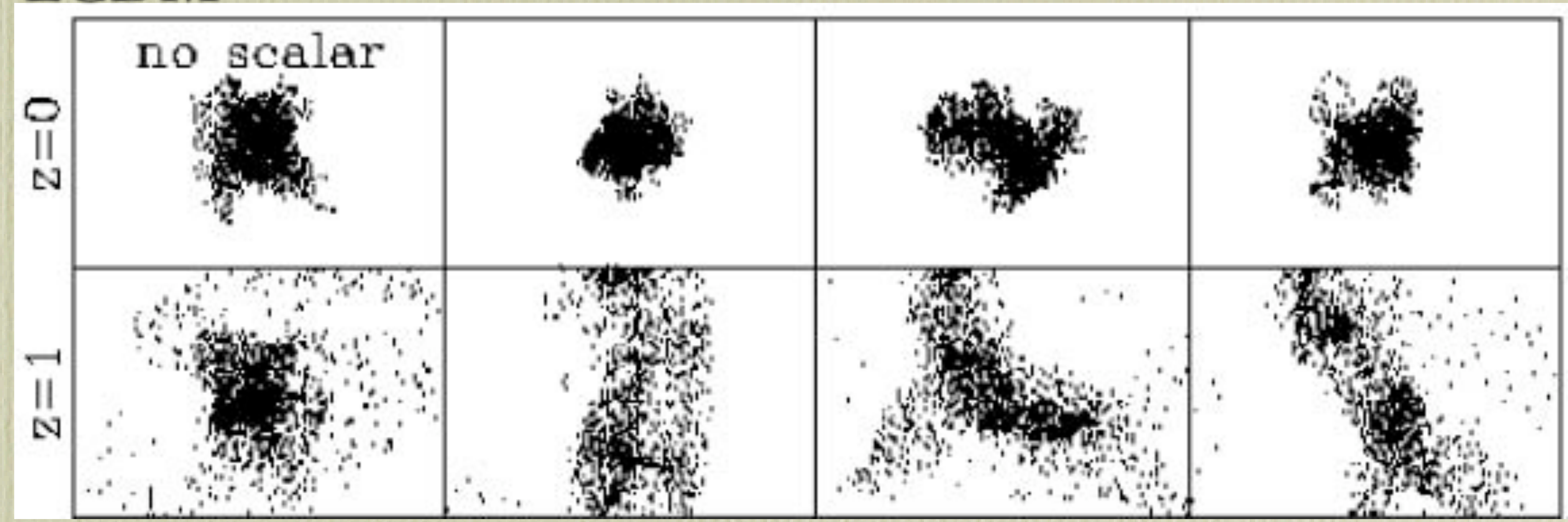
Recent discussions along this and similar similar lines of thought include Gradwohl & Frieman 1992; Casas, Garcia-Bellido & Quiros (1992); Damour & Polyakov (1994); Wetterich (1995); Anderson & Carroll (1997); Bean (2001); Amendola (2000); Amendola & Tocchini-Valentini (2002); França & Rosenfeld (2002); Damour, Piazza & Veneziano (2002); Comelli, Pietroni & Riotto (2003); Amendola, Gasperini & Piazza (2004).

Lets simulate ReBEL

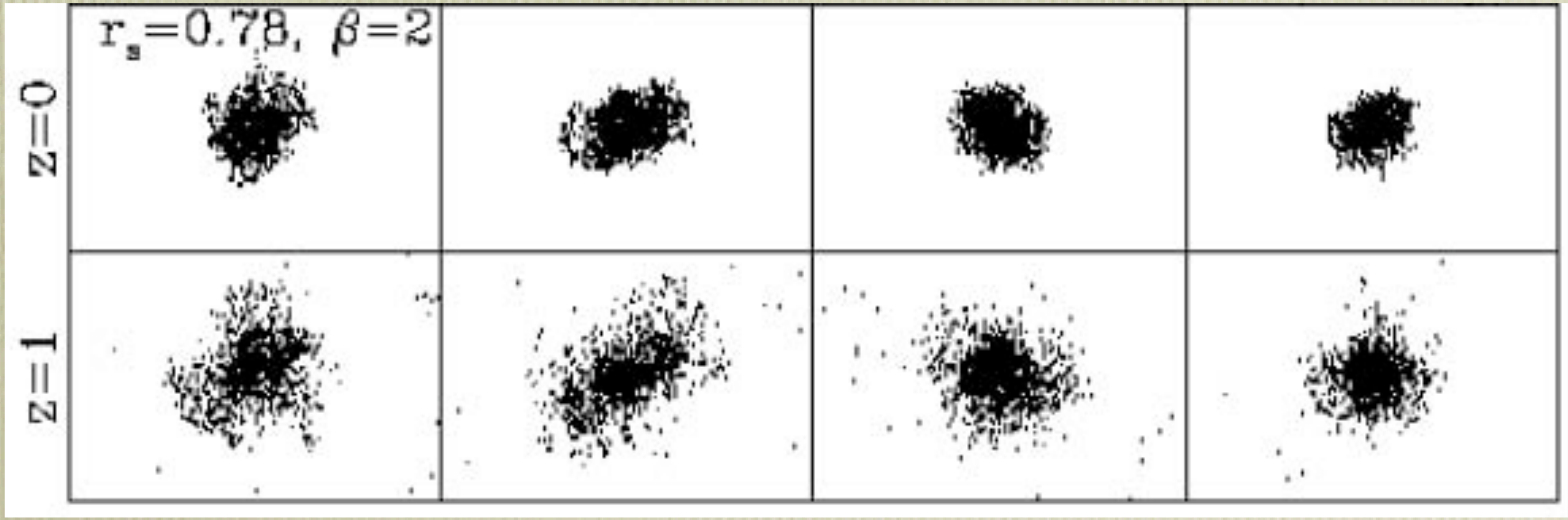


ReBEL
LCDM
ReBEL
LCDM
BAR, β=1
BAR, β=0
DM, β=1
DM, β=0
Y [h⁻¹Mpc]
X [h⁻¹Mpc]
0
15
30
45
Z=0
Z=1
Z=3

LCDM



LCDM+LRSI



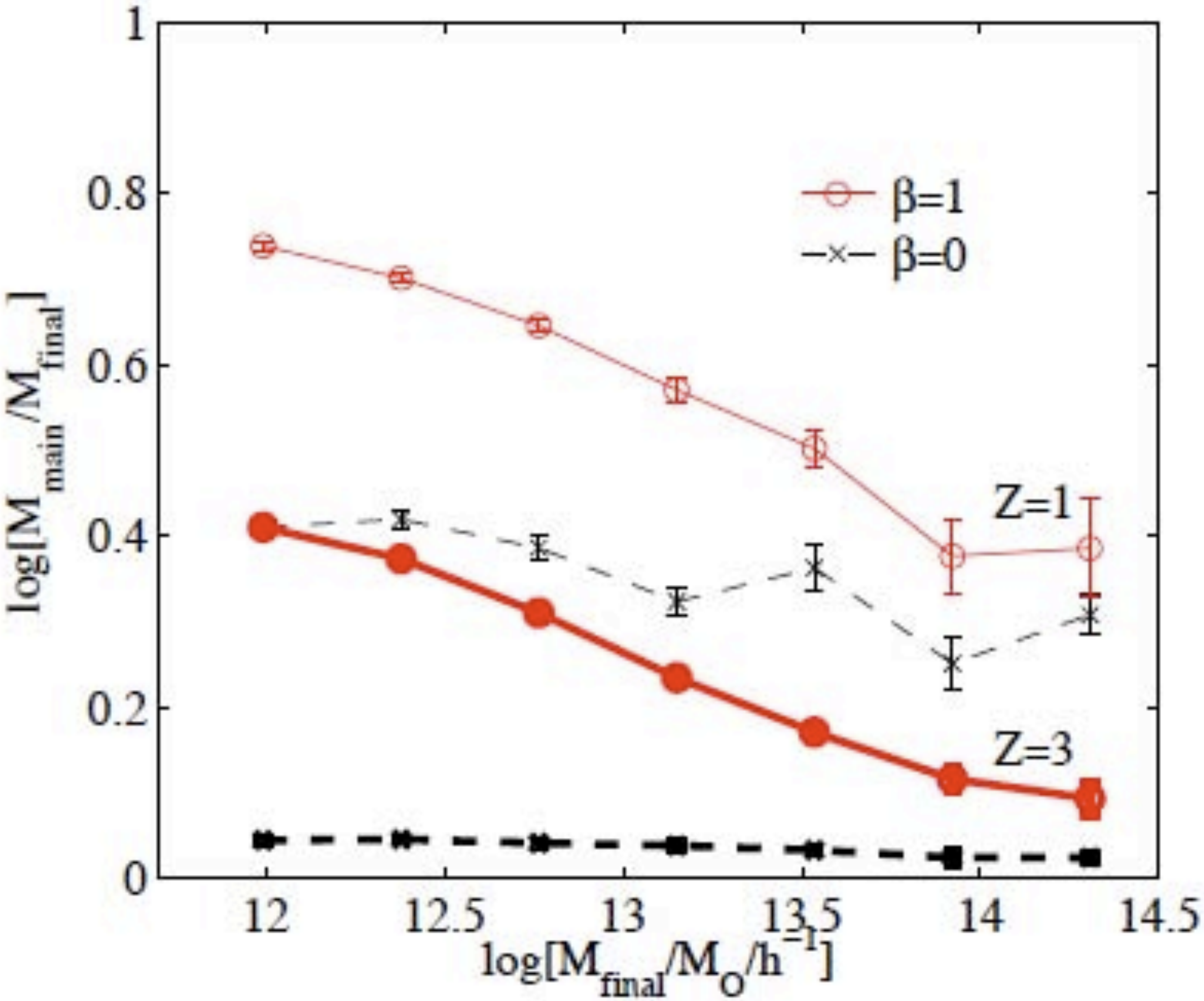


FIG. 9: Fraction of assembled mass by redshift $Z = 1$ and $Z = 3$, as function of the present halo mass.

Halo concentration

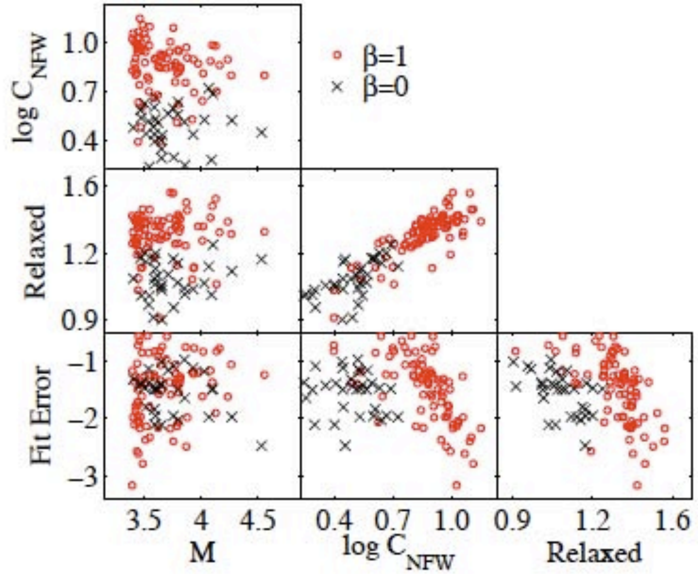
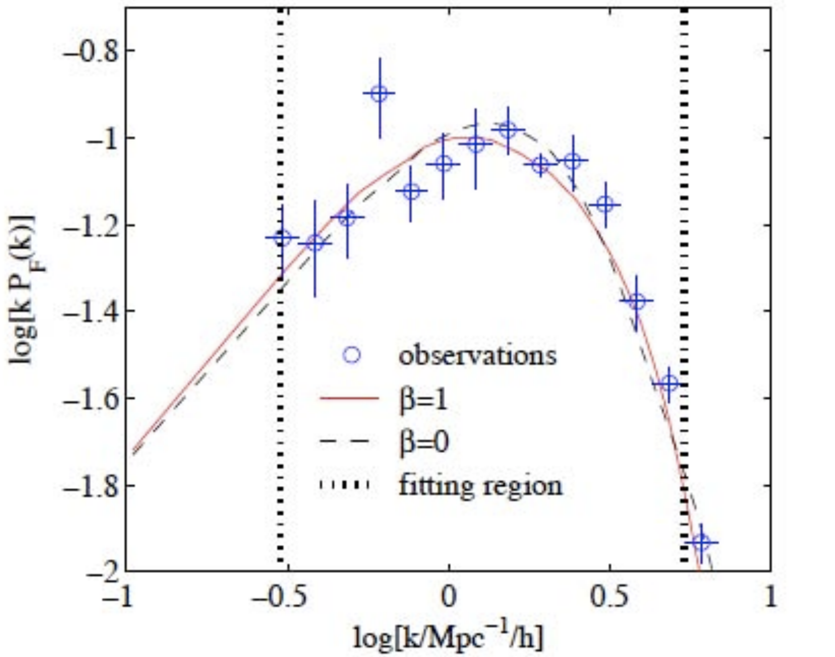
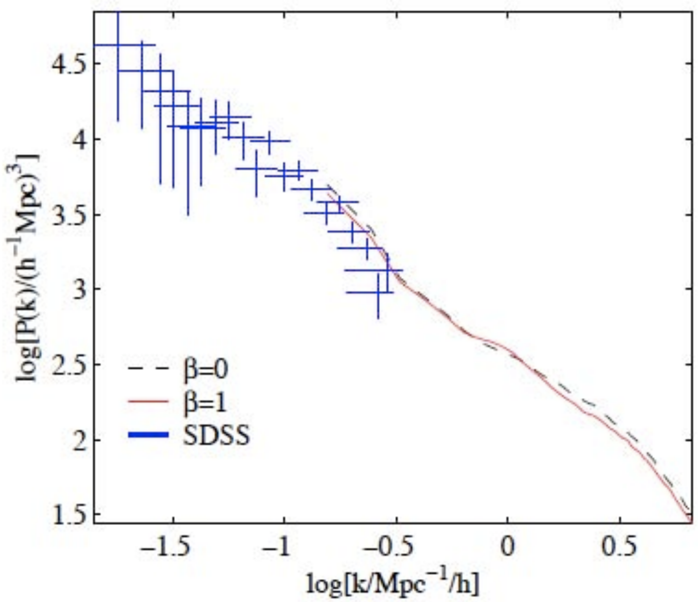


FIG. 11: Different correlation of halo properties for standard and ReBEL models.

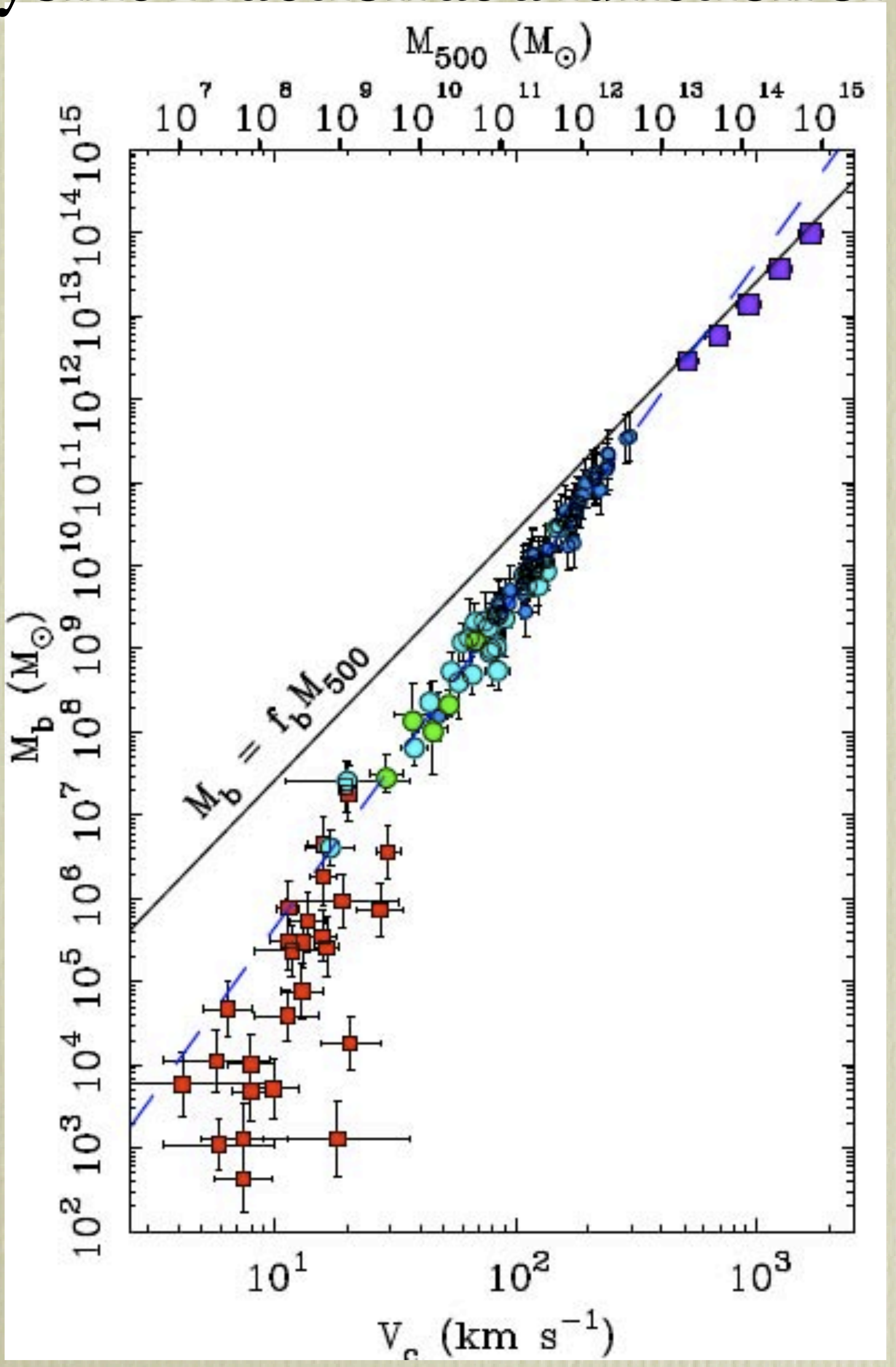
Ly-alpha forest



power spectrum

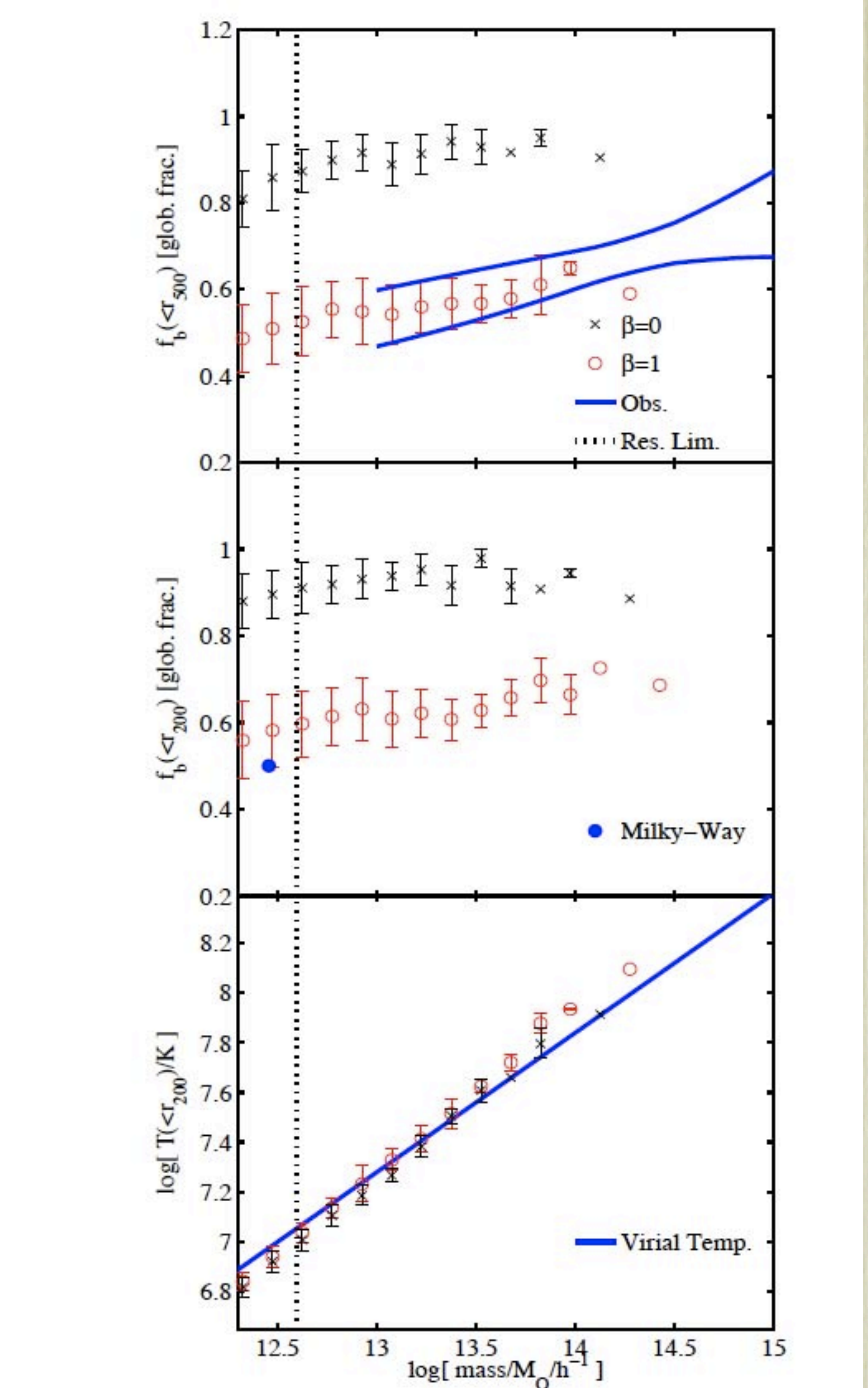


Baryonic Fraction as a function of mass



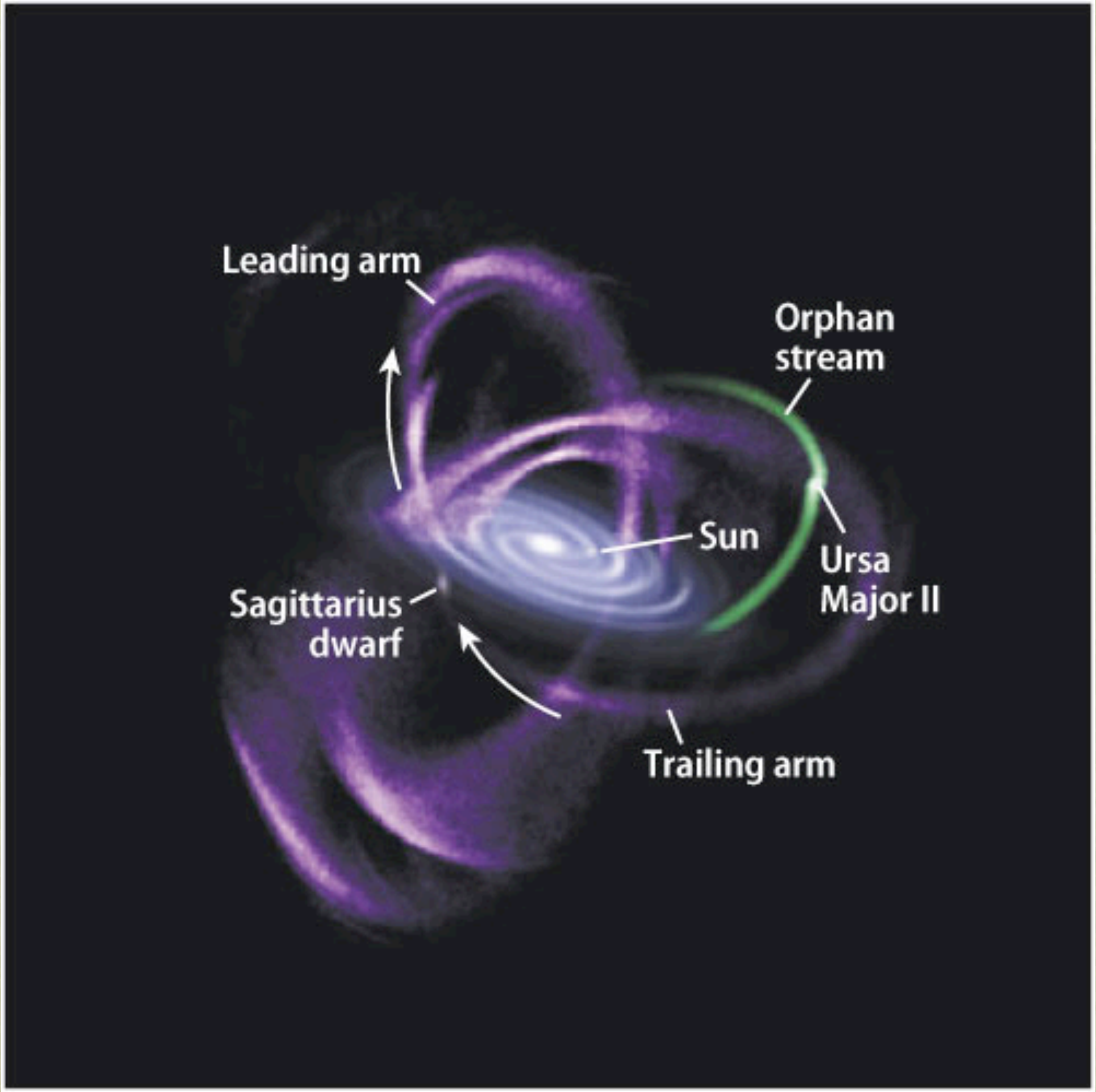
McGaugh et. al. 09

Baryonic Fraction as a function of mass from simulations

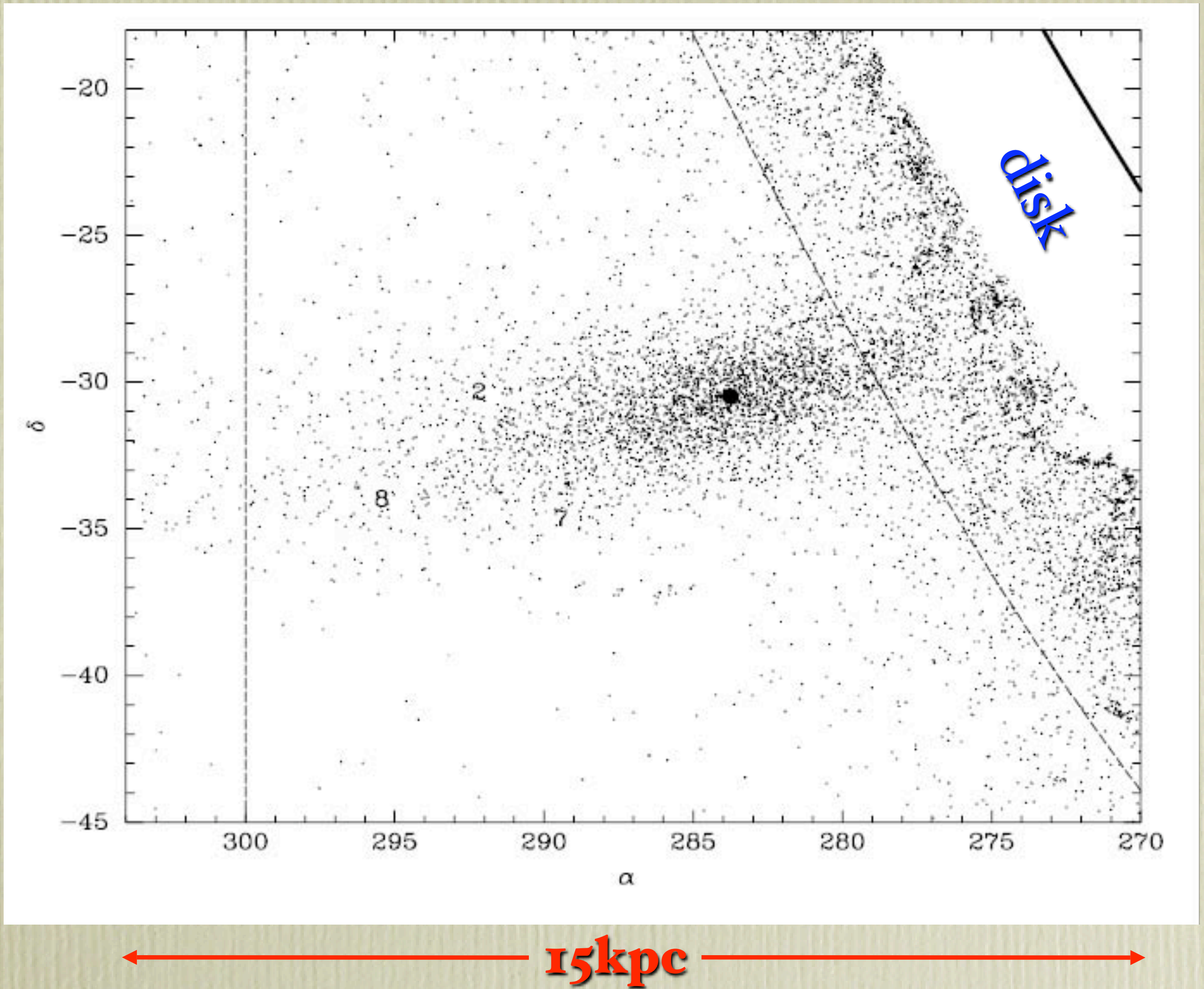


Dynamics of Galactic satellites

A test for ReBEL



The Sagittarius dwarf/stream



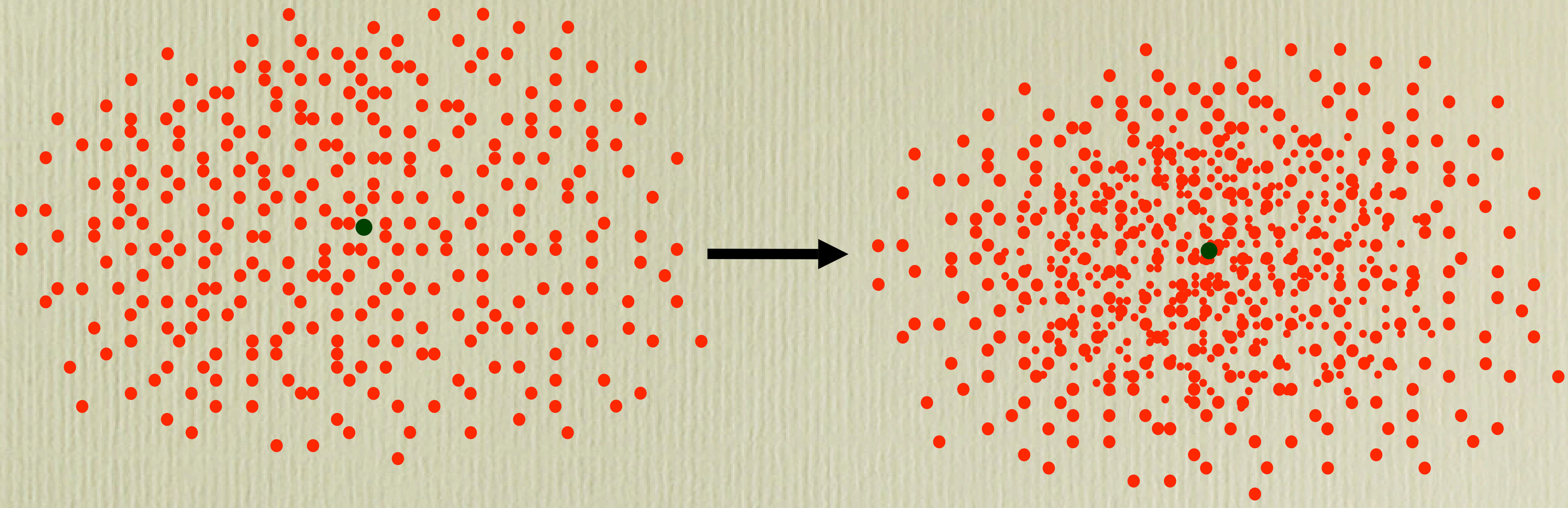
Dynamics of infalling satellite halos/galaxies

Two important processes:

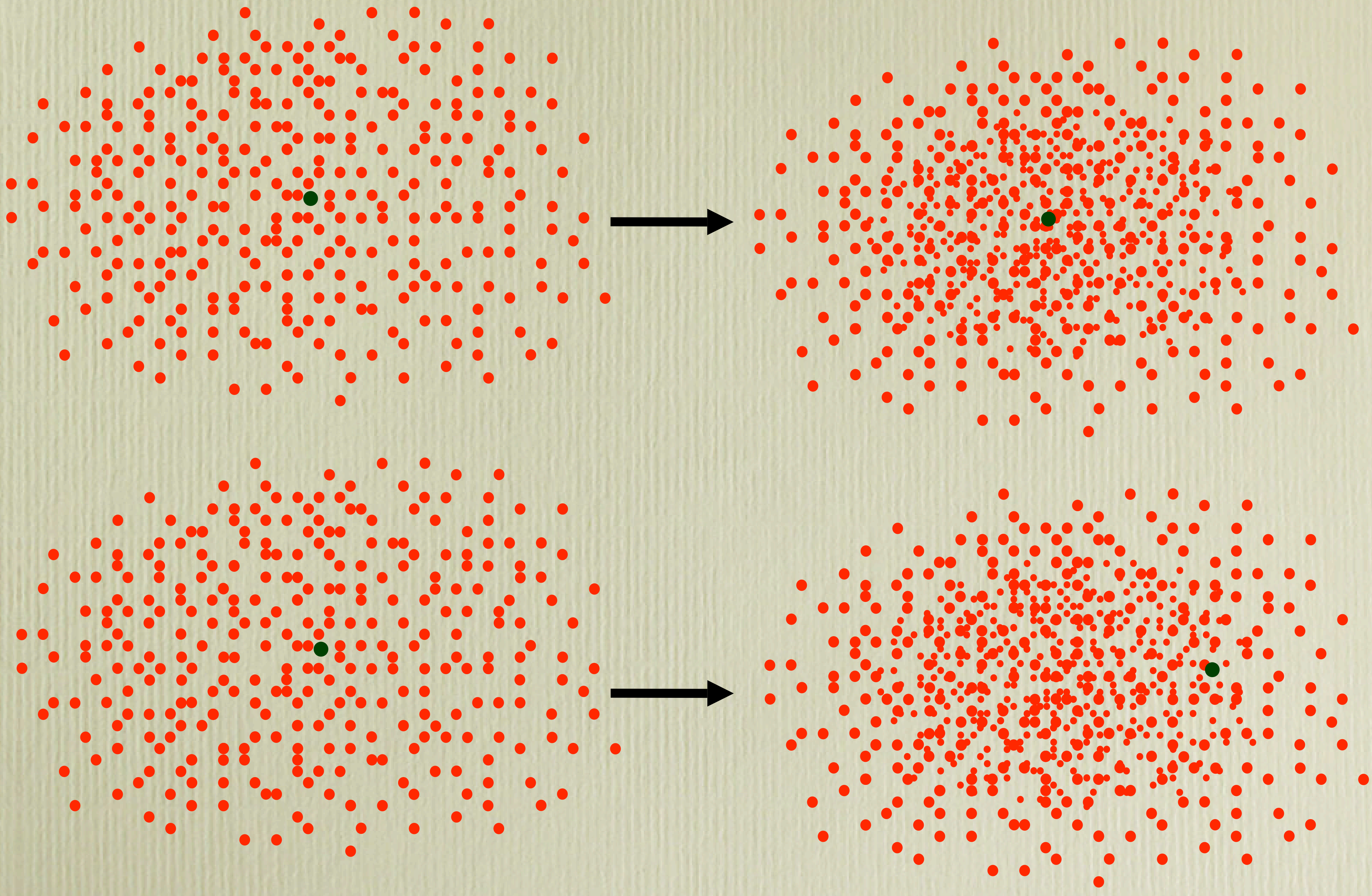
a. **dynamical friction**

b. **tidal stripping**

Dynamical friction (Chandrasekhar 44)



Dynamical friction (Chandrasekhar 44)



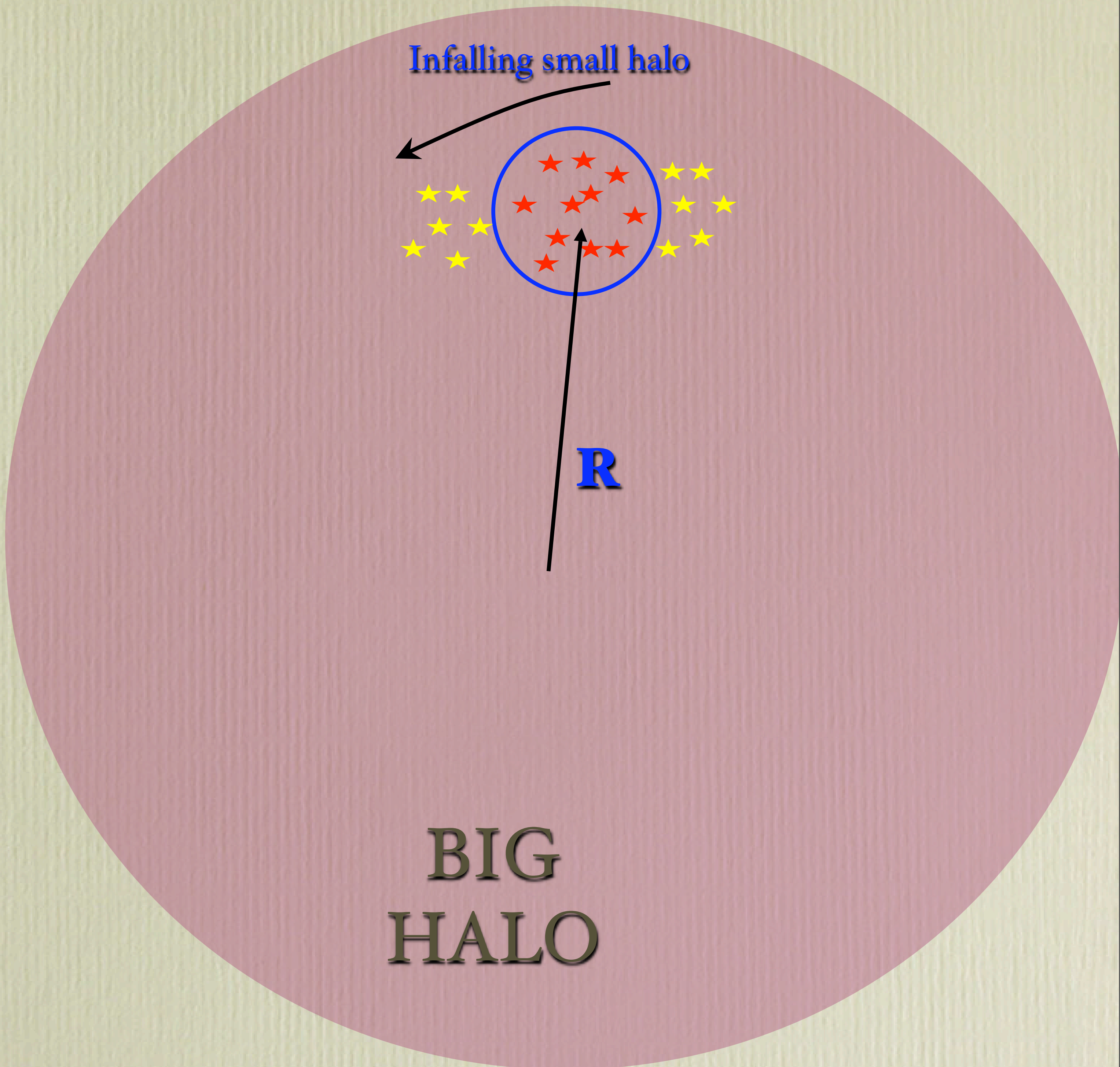
$$F_{df} \propto G^2 M^2 \rho / V^2$$

A very very side note:

Time scale for orbit decay by DF: V^3/(G^2 M rho)

Time scale for Bondi growth of BH: V^3/(G^2 Mbh rho)

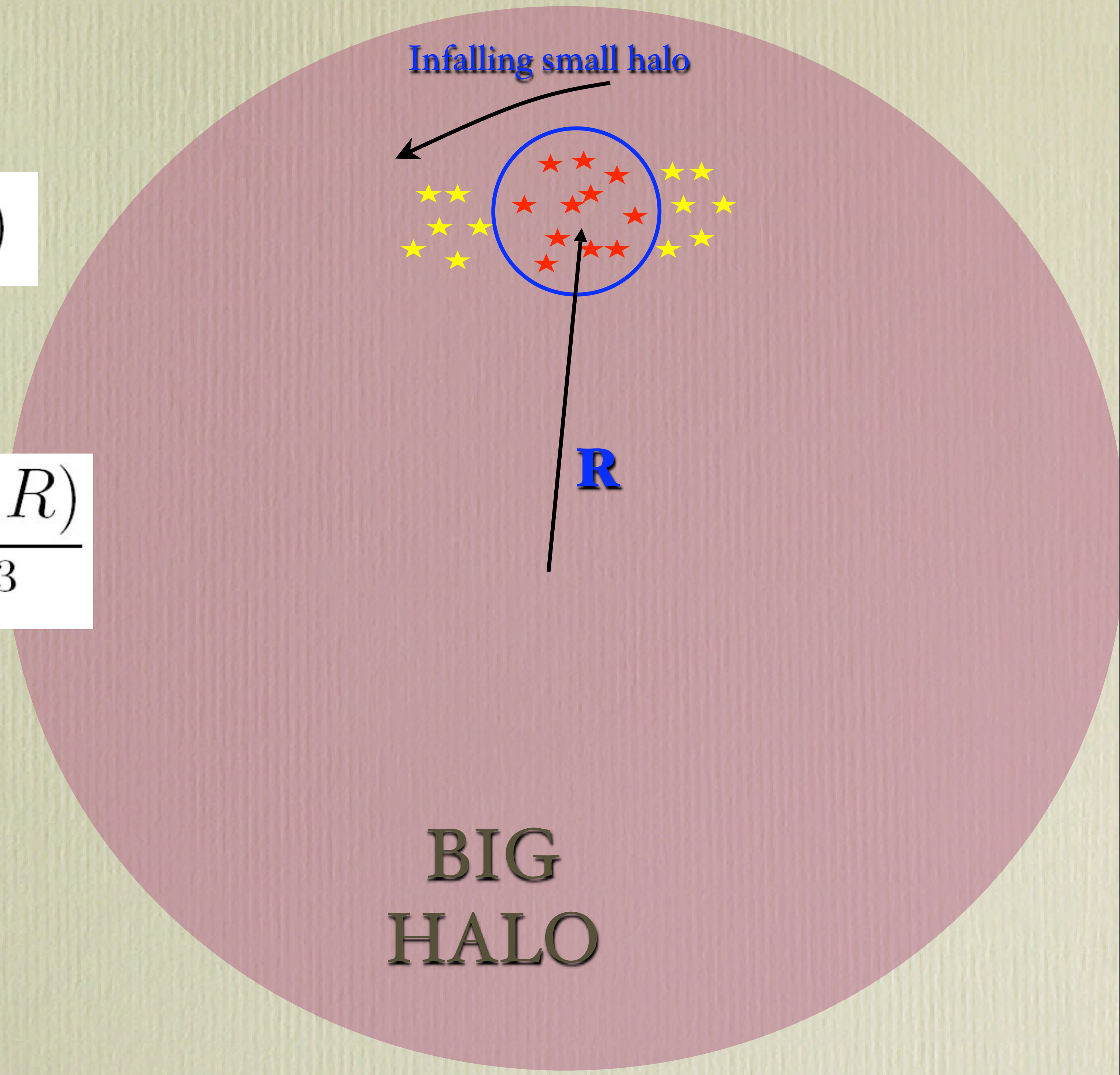
Tidal Stripping



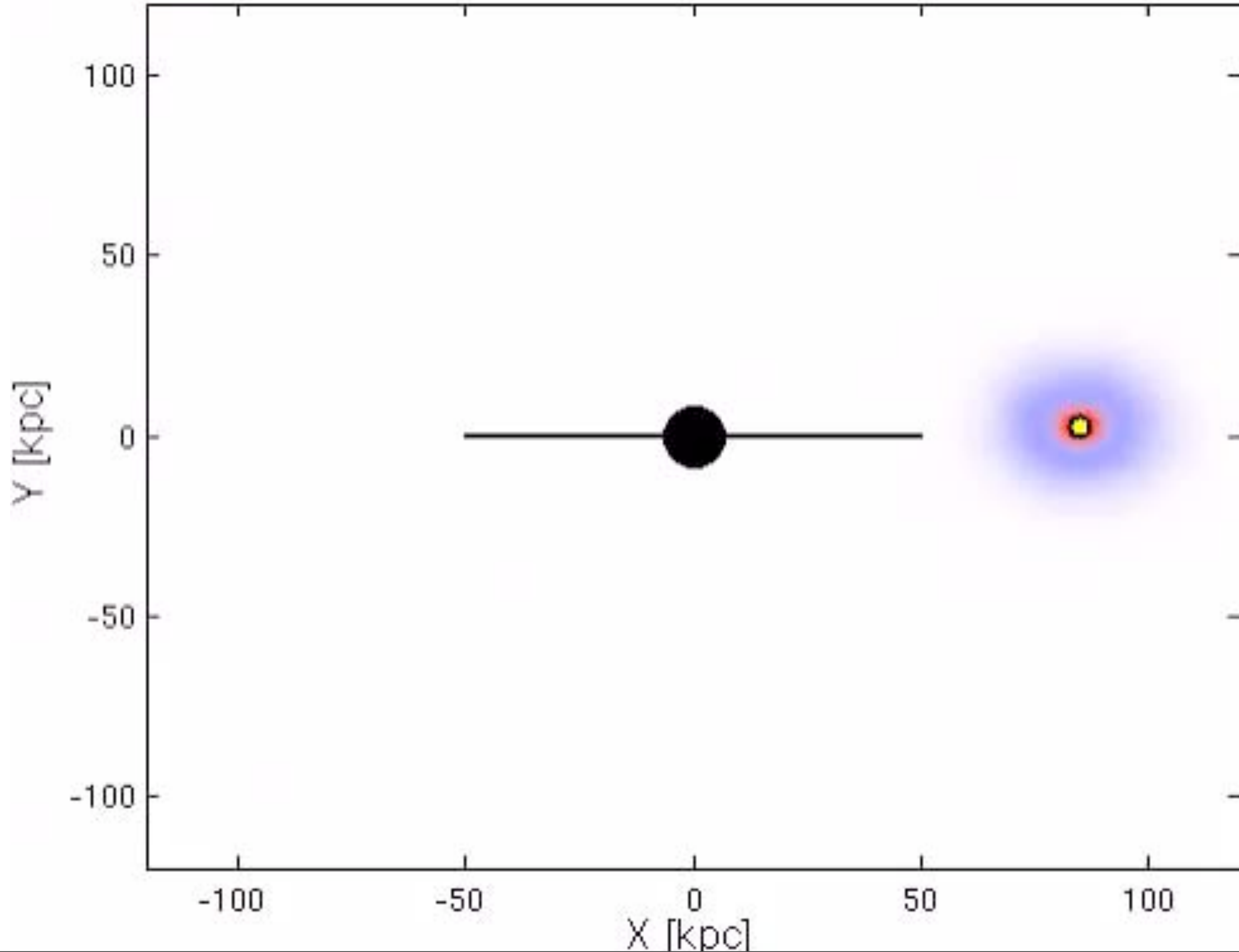
Tidal Stripping

$$T_s(r_t) \approx T_h(R)$$

$$\frac{M_s(r_t)}{r_t^3} \approx \frac{M_h(R)}{R^3}$$



Gravity alone

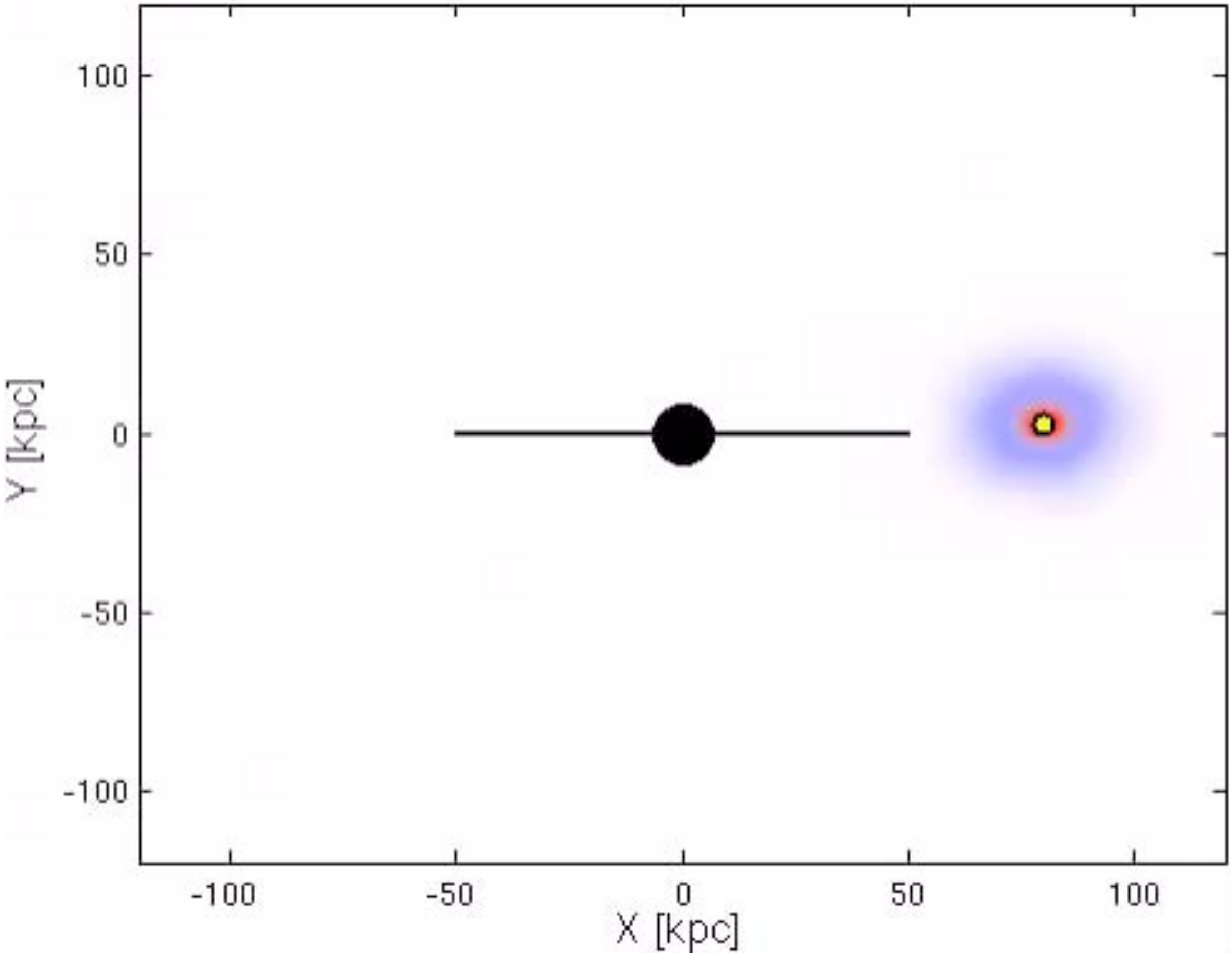


Frieman & Gradwohl 93 and Kesden & Kamionkowski 2006 test

Galactic tidal streams are not symmetric when a ReBEL force is added!
KK put a limit: *beta*$<$*0.05*

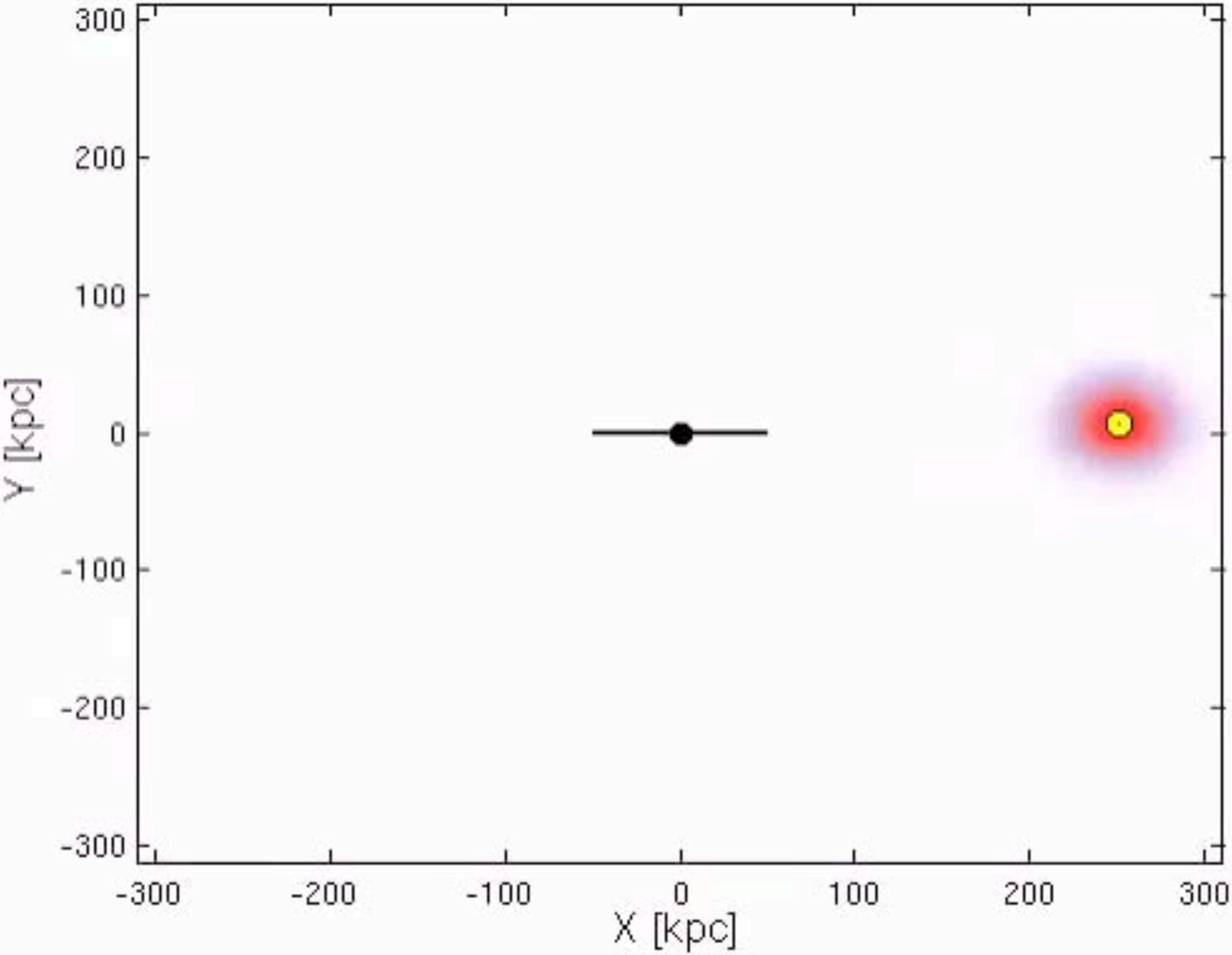
Gravity + weak ReBEL (beta<<1)

Gravity + strong ReBEL (beta=1)

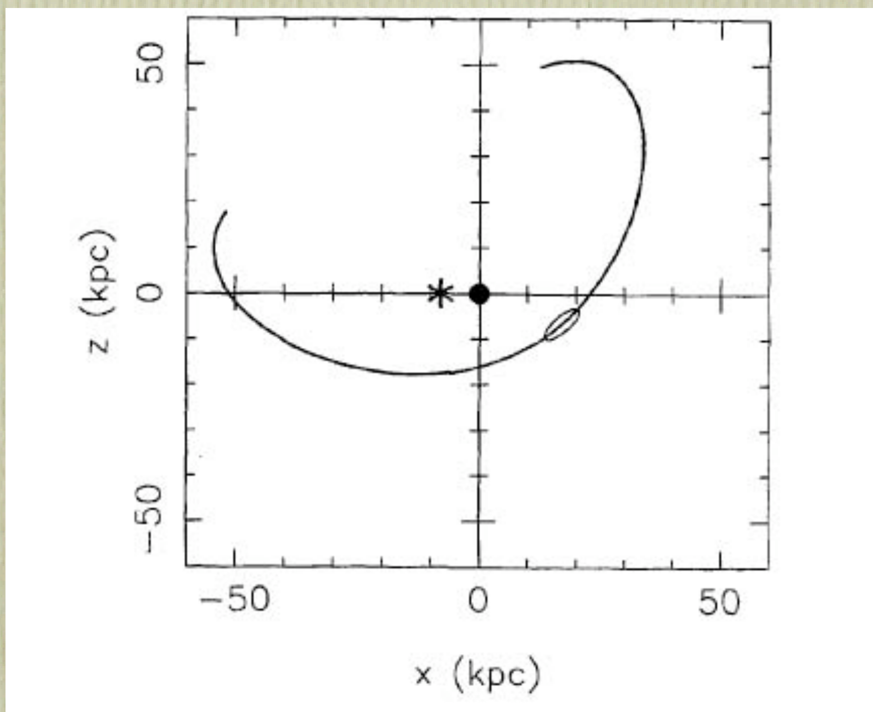


A demonstration of the Frieman & Gradwohl 93 and Kesden & Kamionkowski 2006 test

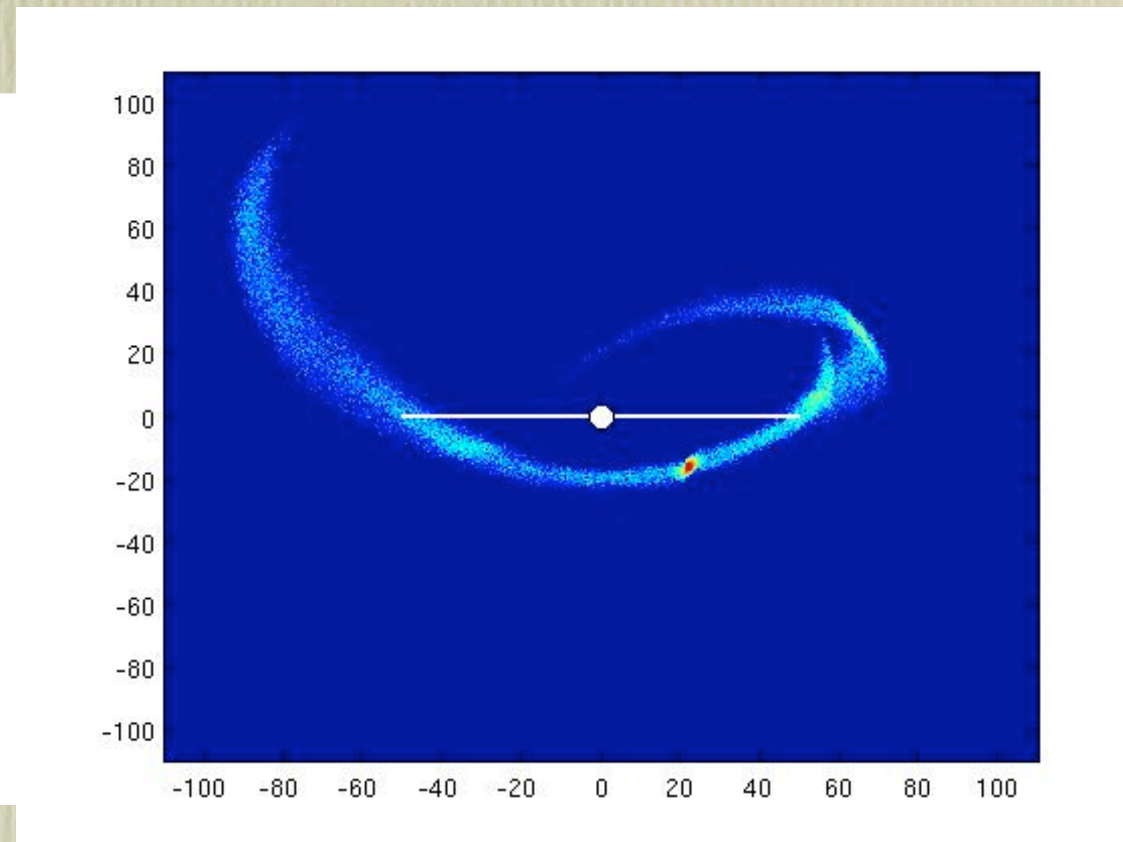
Criticism by Kesden 09: our initial conditions are fine tuned!



Comparison with observations: General Impression

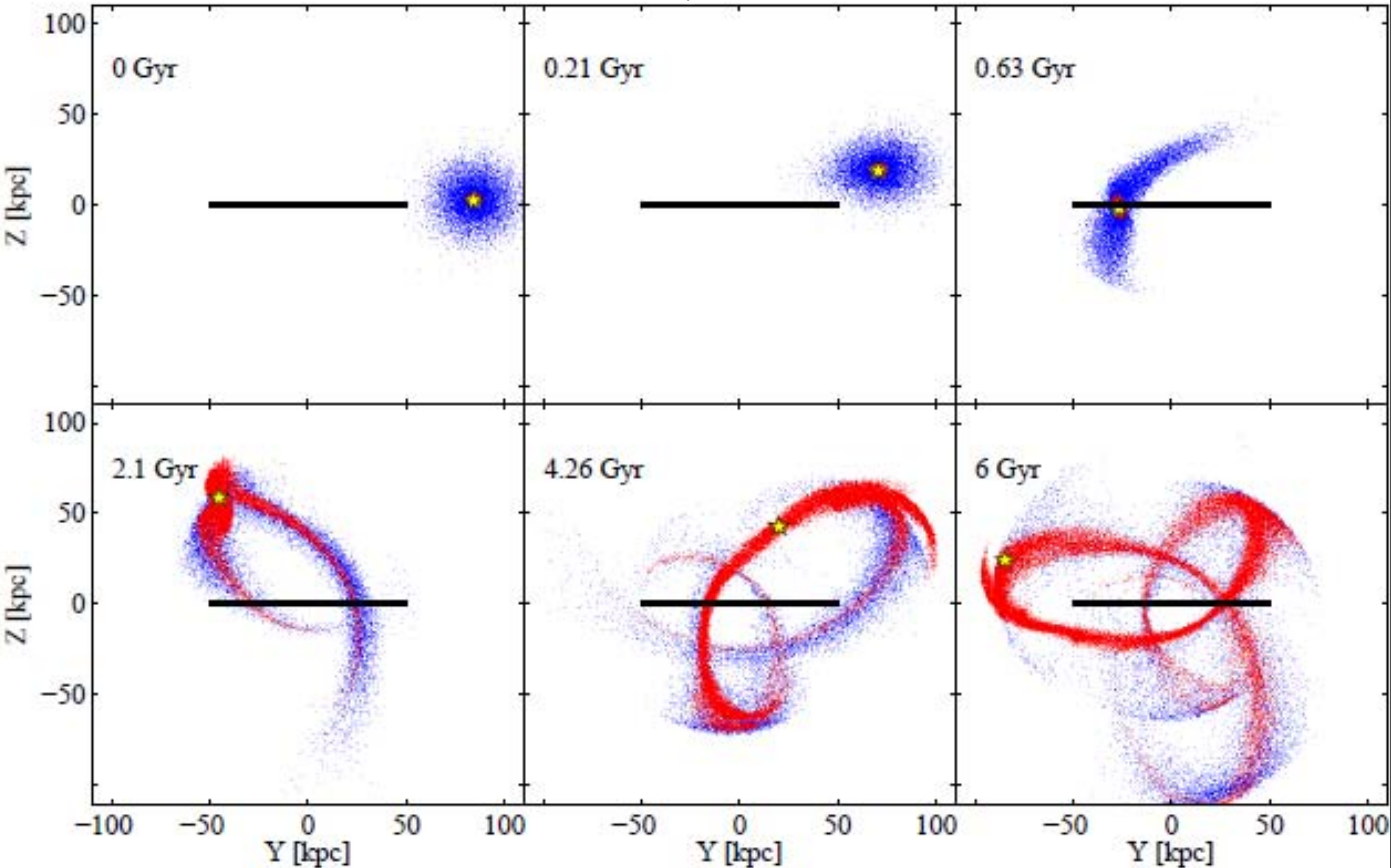


Ibata, 1997



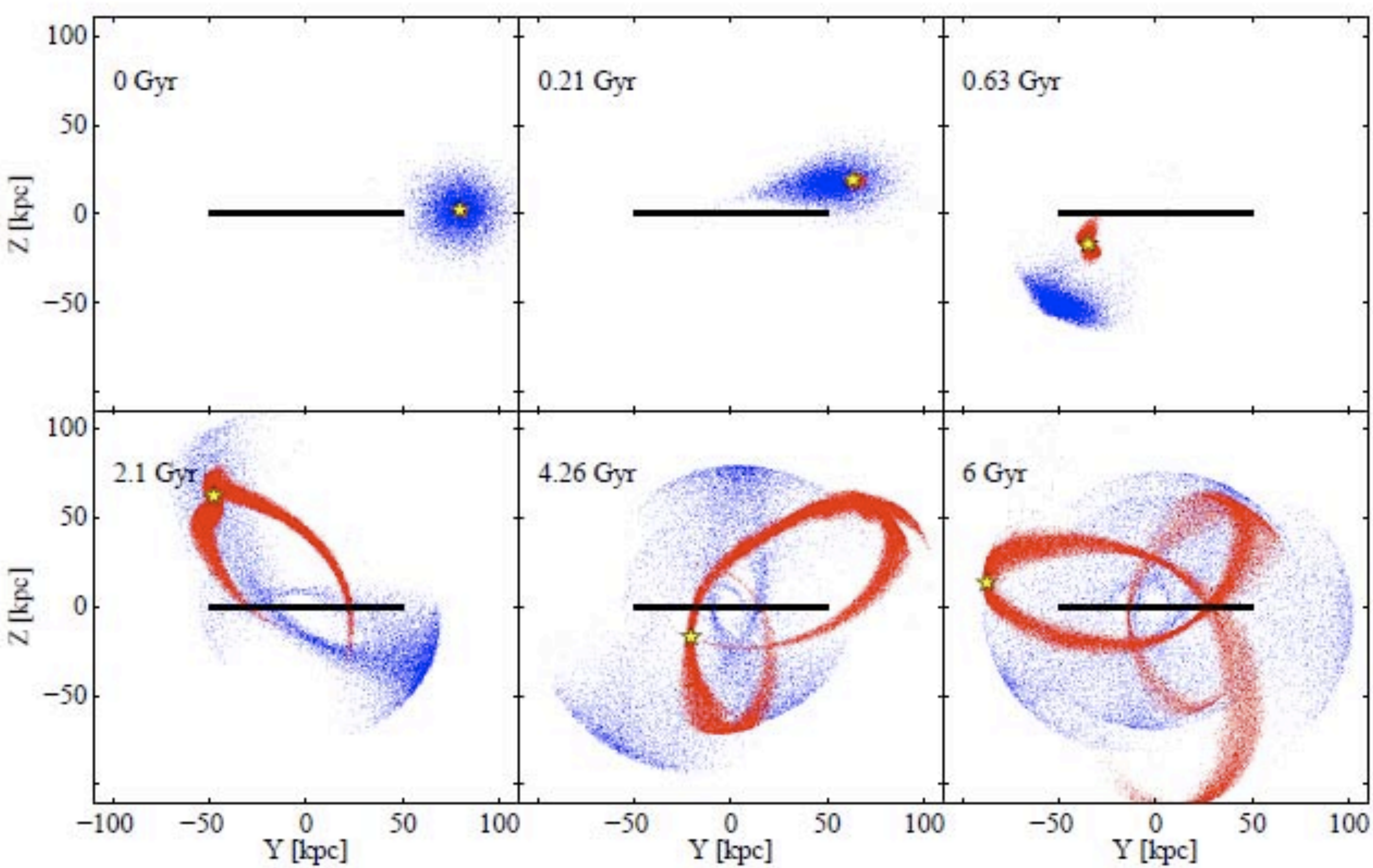
Simulation at 3 Gyrs

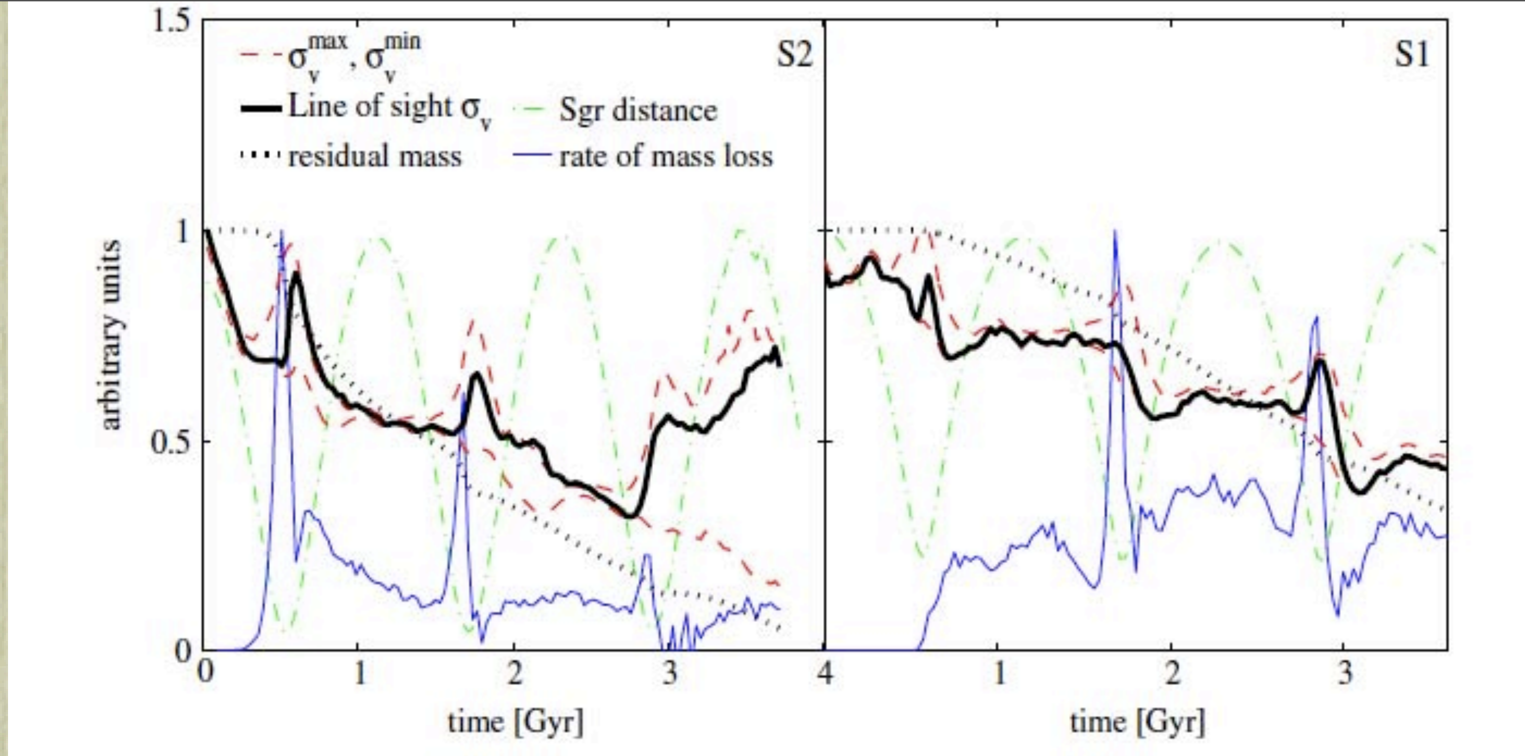
Gravity alone



Keselman, AN & Peebles 09

Gravity + ReBEL (beta=1)





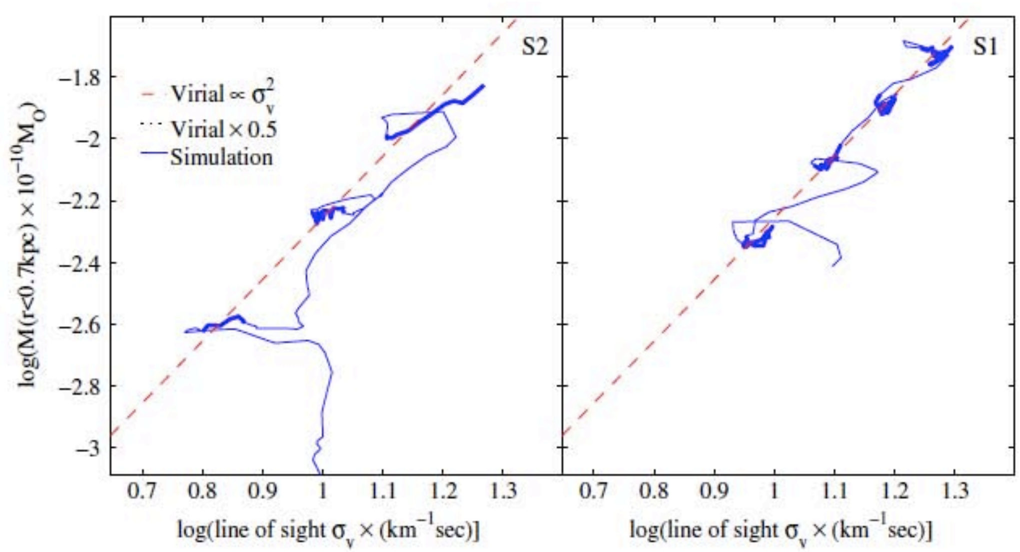


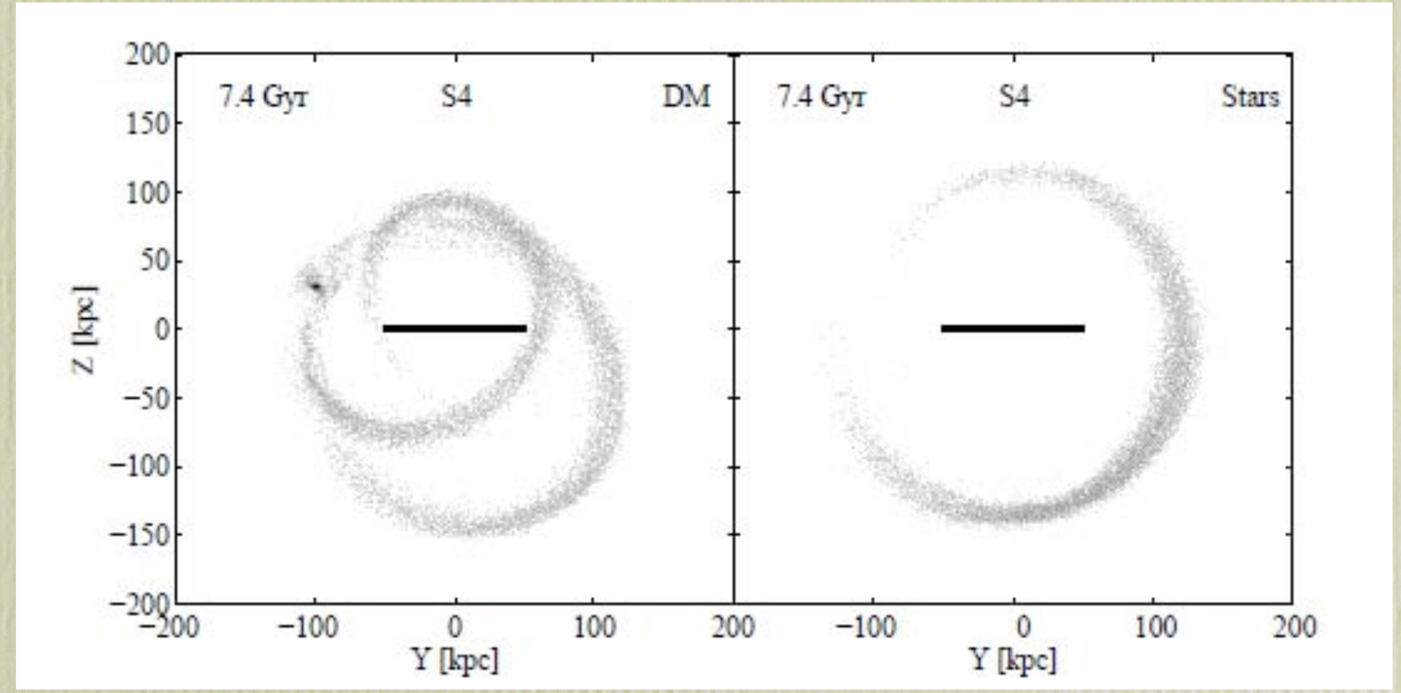
FIG. 5 (color online). Evolution of the satellite bound stellar mass and stellar line-of-sight velocity dispersion follows the blue lines commencing near the top-right corner of each panel and ending toward the lower left. At the thick portions, the velocity anisotropy is less than 15%. The dashed line varies as ${\sigma_v}^2$, as expected for dynamical equilibrium in a satellite with fixed size.

	Observations	Simulation (at 3 Gyrs)
Distance from center of galaxy	Close to pericenter, at 16 Kpc (Law et al., 2004)	Close to pericenter, at 18 Kpc
Luminosity, Assuming M/L=2.5 solar	2 to 5.8e7 (Ibata 97, Mateo 98)	8e7
Line of sight Velocity dispersion	9.6 Km/s, and constant (Bellazzini, 2008)	9.8 Km/s and constant

Observed core radius is about 1 Kpc (Majewski, 2003)
– matched well by the simulation.

Predictions

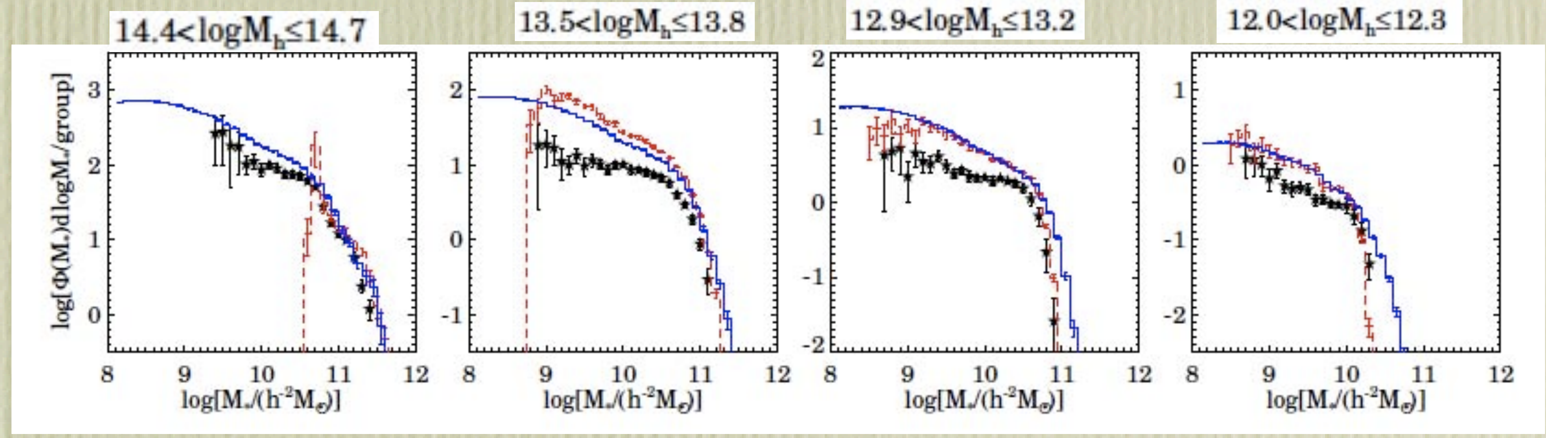
1. Orphan streams



2. Twin systems: DM dominated & baryon dominated

Some Other Implications

1. Reduces the number of observable Galactic satellites



2. Early structure formation: a solution to early reionization, supermassive black holes at high z?

Final Remarks

- LCDM is a good approximation to reality, but anomalies keep surfacing...
- Dark sector physics is extremely rich, but a simple modification could lead to major improvement.