Infalling Satellites and Structure of Galactic Disks in CDM Models

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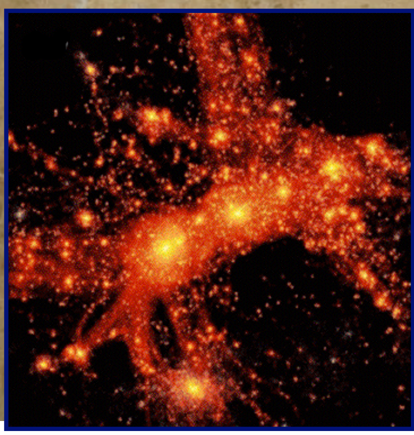
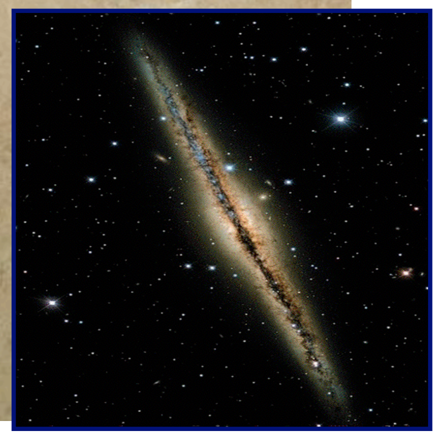




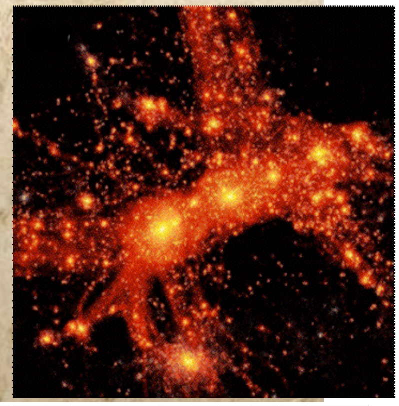
Collaborators

Andrey Kravtsov
University of Chicago

Andrew Zentner
University of Chicago

James Bullock (UC Irvine)

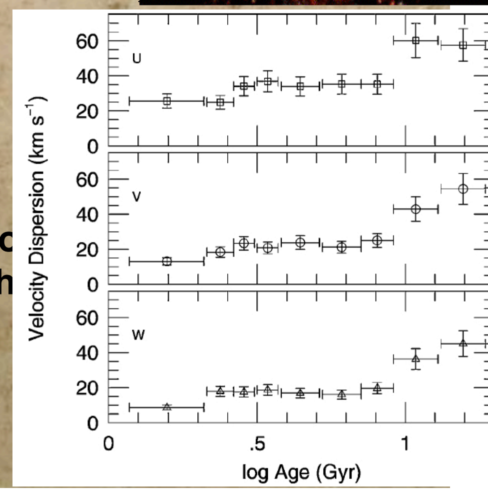
Motivation



❑ CDM structure formation models generically predict large amounts of substructure in the form of small, dense gravitationally bound subhalos orbiting within the larger potential.

❑ Various observations and mass modeling indicate that the Milky Way has a rather thin stellar disk with a scale height of ~ 250 ± 60 pc (e.g., Kent et al. 1991; Freudenreich 1998; Dehnen & Binney 1998; Vallenari et al. 2000).

❑ In the Milky Way disk a strong correlatic exists between the three components of th velocity dispersion and stellar age (e.g., Quillen & Garnet 2000; Freeman & Bland-Hawthorn 2002).

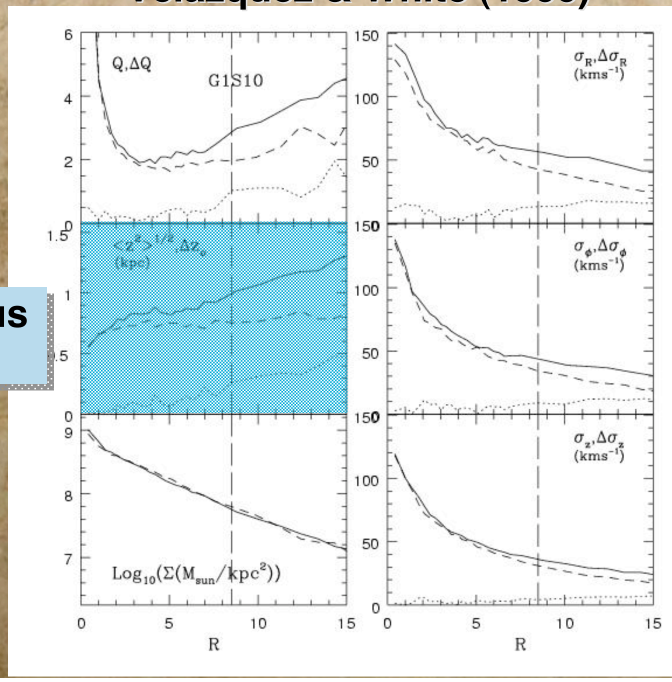


Overview

Previous Studies: Quinn & Goodman 1986; Toth & Ostriker 1992; Quinn et al. 1993; Walker et al. 1996; Sellwood et al. 1998; Huang & Carlberg 1997; Velazquez & White 1999; Font et al. 2001; Ardi et al. 2003; Benson et al. 2004; Gaunthier et al. 2006

Interaction of Disk Galaxies with Single Satellites

Velazquez & White (1999)

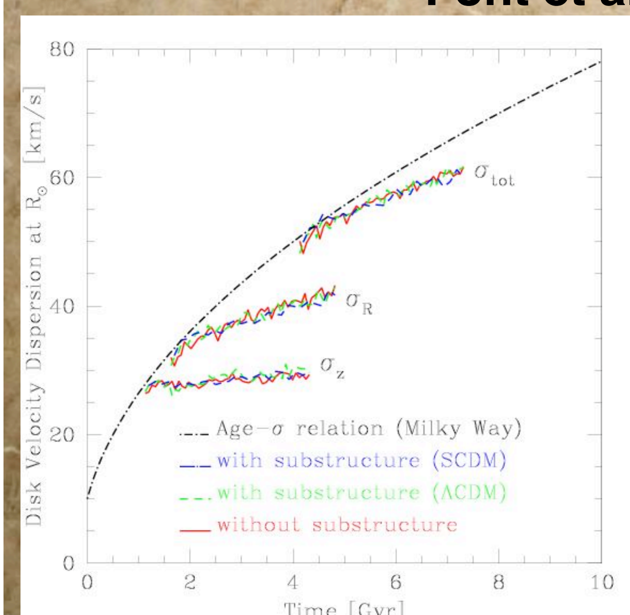


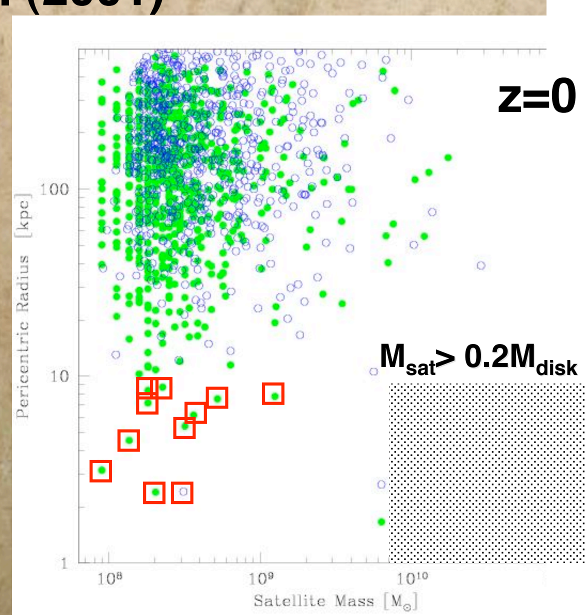
@ Solar Radius
Δz_o= 40%

M_{sat}= 0.2M_{disk}

Interaction of Disk Galaxies with Ensembles of CDM Satellites

Font et al. (2001)

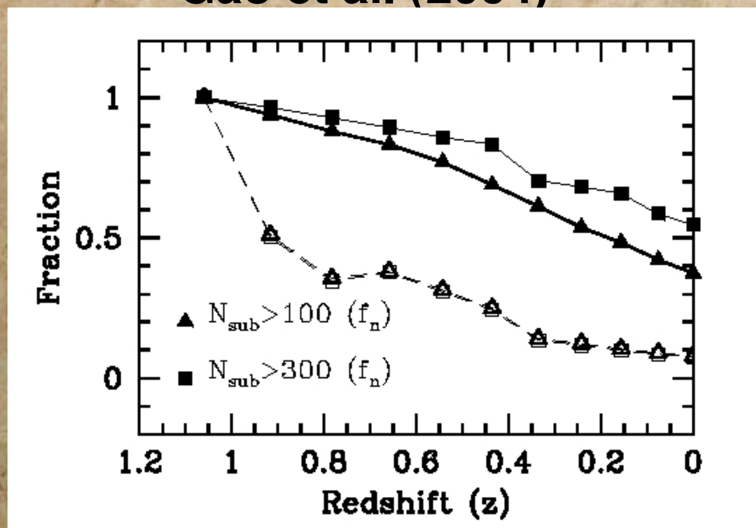




M_{sat}> 0.2M_{disk}

Interaction of Disk Galaxies with Ensembles of CDM Satellites

Gao et al. (2004)



❑ **A significant fraction of CDM subhalos on typical orbits present at z=1 are destroyed by z=0 which biases the present-day satellite orbital distribution against central mergers.**

Disks in Hierarchical Cosmologies

❑ **Disk galaxies have been notoriously difficult to form in _CDM cosmological simulations (angular momentum catastrophe-e.g., Navarro & Steinmetz 1997).**

❑ **More recent investigations with higher resolution and new astrophysics (e.g., SNe feedback to delay cooling) have had more success but we are not there yet.**

Abadi et al. (2003)
Governato et al. (2004,2006)
Robertson et al. (2004)
Sommer-Larsen et al. (2005)

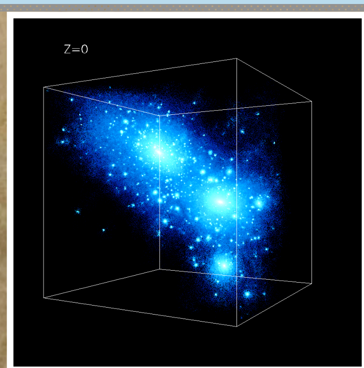
q **Given the uncertain astrophysical inputs, we may ask a more conservative question: Even if a thin disk could form... could it ever survive the expected bombardment?**

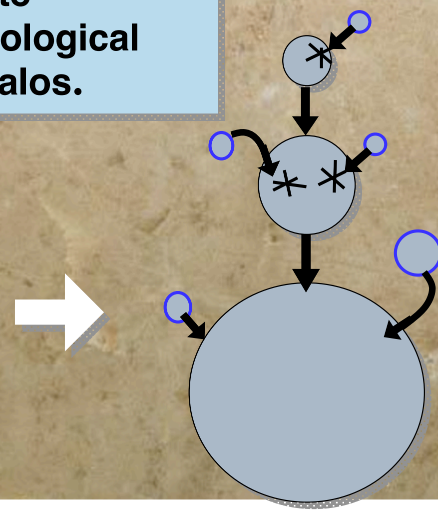
Modeling Satellite-Disk Encounters in a Hierarchical Cosmology: Our Method

Fully self-consistent cosmological simulations with the dynamic range needed are effectively impossible.

In order to overcome this difficulty, we adopt a hybrid approach:

1. Extract merger histories and satellite properties from high-resolution cosmological N-body simulations of Galaxy-sized halos.



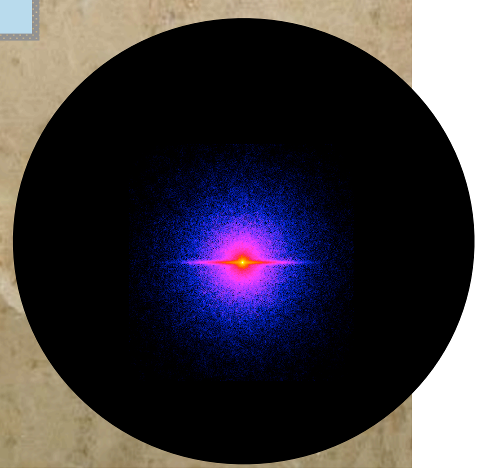


Modeling Satellite-Disk Encounters in a Hierarchical Cosmology: Our Method

Fully self-consistent cosmological simulations with the dynamic range needed are effectively impossible.

In order to overcome this difficulty, we adopt a hybrid approach:

2. Construct high-resolution N-body models of Galaxy-sized disks.

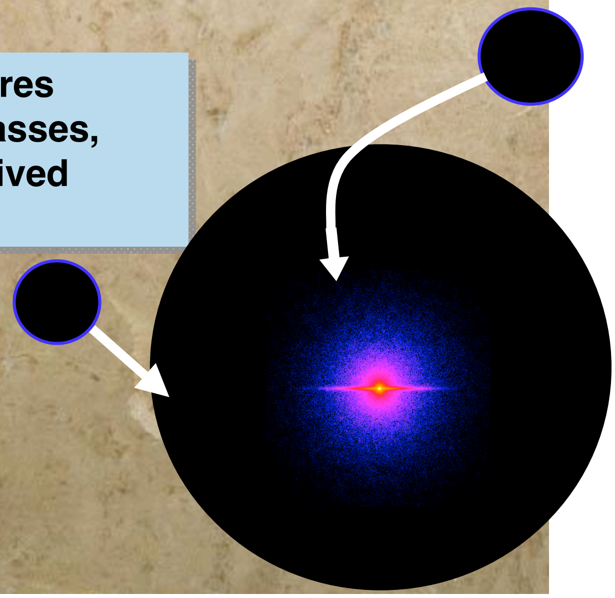


Modeling Satellite-Disk Encounters in a Hierarchical Cosmology: Our Method

Fully self-consistent cosmological simulations with the dynamic range needed are effectively impossible.

In order to overcome this difficulty, we adopt a hybrid approach:

3. Simulate impacts of substructures with the disk using properties (masses, orbits, density structures etc) derived from cosmological simulations.



Advantages of the Current Study

Satellite Orbital Distribution: Realistic orbital parameters for the infalling satellite systems consistent with the evolution of substructure throughout cosmic time.

Primary Galaxy Models:

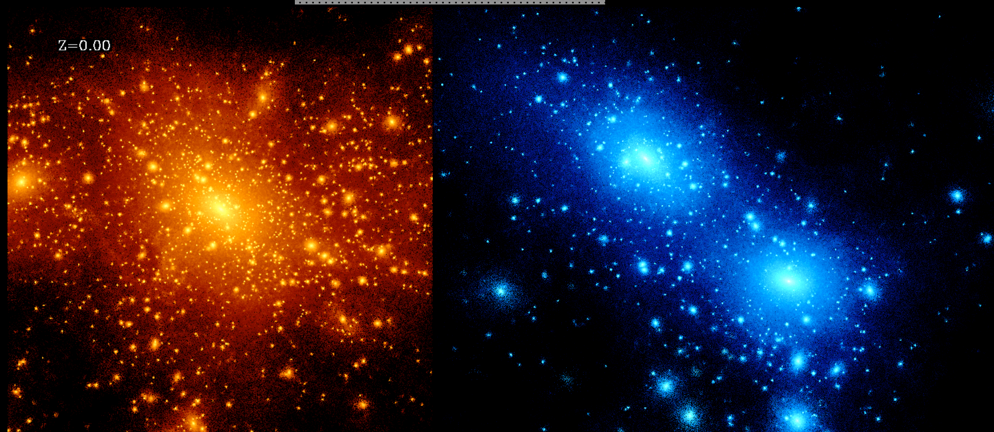
- Self-consistent, multicomponent galaxy models derived from explicit distribution functions for each component (Widrow & Dubinski 2005).
- Models satisfying a broad range of observational constraints available for the Milky Way galaxy (e.g., total mass surface density and stellar kinematics in the solar neighbourhood, mass measurements at large radii via satellite kinematics).

Satellite Galaxy Models:

- Self-consistent models initialized according to the density structure of satellites found in high-resolution cosmological N-body simulations (Kazantzidis et al. 2004).

Cosmological Simulations

Density Maps

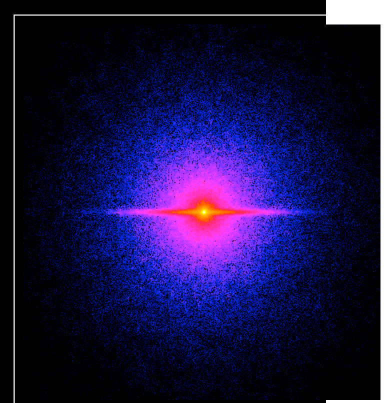


ART code simulations (Kravtsov 1999):

$$\Lambda\mathrm{CDM}: \Omega_\mathrm{m} = 0.3; \Omega_\Lambda = 0.7$$
$$\mathrm{h}=0.7; \quad \sigma_8 = 0.9; n = 1.0$$

Mass Resolution:

- $N_{dm} = 2x10^6$ particles
- $N_{disk} = 10^6$ particles
- $N_{bulge} = 5x10^5$ particles
- $N_{sat} = 5x10^5$ particles



Roughly 25 times higher mass resolution in the disk compared to Font et al. and Velazquez & White.

Force Resolution:

- ε_{dm} = 100 pc
- $\varepsilon_{disk} = \varepsilon_{bulge}$ = 50 pc
- ε_{sat} = 150 pc

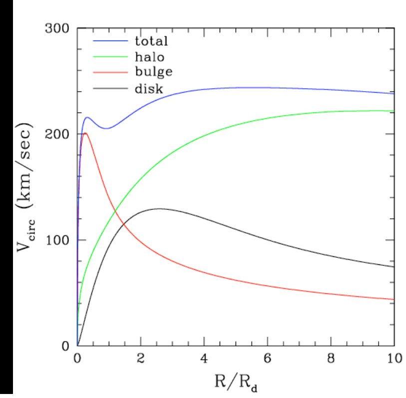
Initial conditions and resolution (mass and force resolution) adequate to set up thin equilibrium disk models.

<u>Primary Galaxy Model:</u>

Halo: $M_{vir} = 7.4x10^{11} M_o$, r_{vir}=240 kpc

Disk: $M_{disk} = 3.5x10^{10} M_o$, R_d =2.8 kpc, z_d = 0.4 kpc, Q = 1.6

Bulge: $M_{bulge} = 1.1x10^{10} M_o$, a_b = 0.88 kpc.



To investigate the effect of the initial disk thickness on the results we also constructed an identical galaxy model but with a factor of 2.5 thicker disk.

Gasoline

(Stadel 2001; Wadsley, Stadel & Quinn 2003)

Conspirators:

James Wadsley	McMaster
Joachim Stadel	University of Zürich
Thomas Quinn	University of Washington
Fabio Governato	University of Washington
Ben Moore	University of Zürich
Jeff Gardner	University of Pittsburgh
George Lake	University of Zürich
Stelios Kazantzidis	KIPAC/Stanford University
Lucio Mayer	ETH, Zürich

- **Fully parallelized multi-stepping tree+SPH code. Portable on all supercomputer architectures with efficient modular structure. Modules exist for cosmology, galaxy formation (radiative cooling, sta formation, SNe/AGN feedback, UV background), star/planet formation planetesimal formation, collisions of asteroids etc**

Properties of Cosmological Satellites and Orbits

Model	z	t (Gyr)	M_{sat} (10^{10}M$_\odot$)	V_{peak} (km s^{-1})	r_{peak} (kpc)	d (kpc)	r_{tid} (kpc)	r_{peri} (R_d)	r_{apo} (R_d)	θ (°)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
G1S1	0.96	7.6	1.14 (32.6%)	42.4	6.9	45.2	24.8	2.6	17.7	93.3
G1S2	0.89	7.3	1.98 (56.6%)	59.8	8.1	40.7	21.5	2.6	15.7	86.6
G1S3	0.54	5.3	1.48 (42.3%)	50.3	7.6	34.0	23.0	6.2	19.8	45.1
G1S4	0.32	3.6	1.57 (44.8%)	42.2	4.1	28.8	19.6	0.5	10.3	59.9
G1S5	0.20	2.4	0.75 (21.4%)	41.5	5.7	50.3	27.3	3.7	34.3	117.7
G1S6	0.11	1.4	0.73 (20.9%)	39.8	3.7	50.8	23.2	1.1	21.6	144.5

Very massive satellites with M_{sub} > 20 % M_{disk}

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Impacts are generally quite radial, with $r_{apo}/r_{peri} > 6/1$

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Prograde orbits (_ < 90^0)
Retrograde orbits (_ > 90^0),
and polar orbits (_ ~ 90^0)

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Very extended satellites with $r_{tid} \geq 20$ kpc

Properties of Cosmological Satellites and Orbits

Model	z	t (Gyr)	M_{sat} ($10^{10} M_\odot$)	V_{peak} ($km s^{-1}$)	r_{peak} (kpc)	(k	[illegible]
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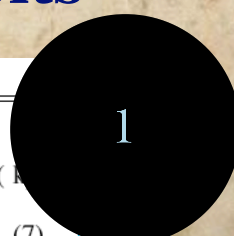
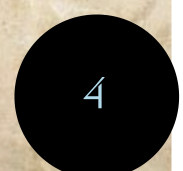
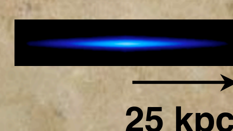
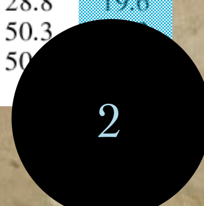
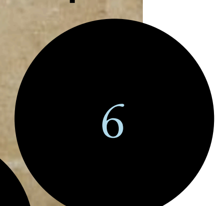




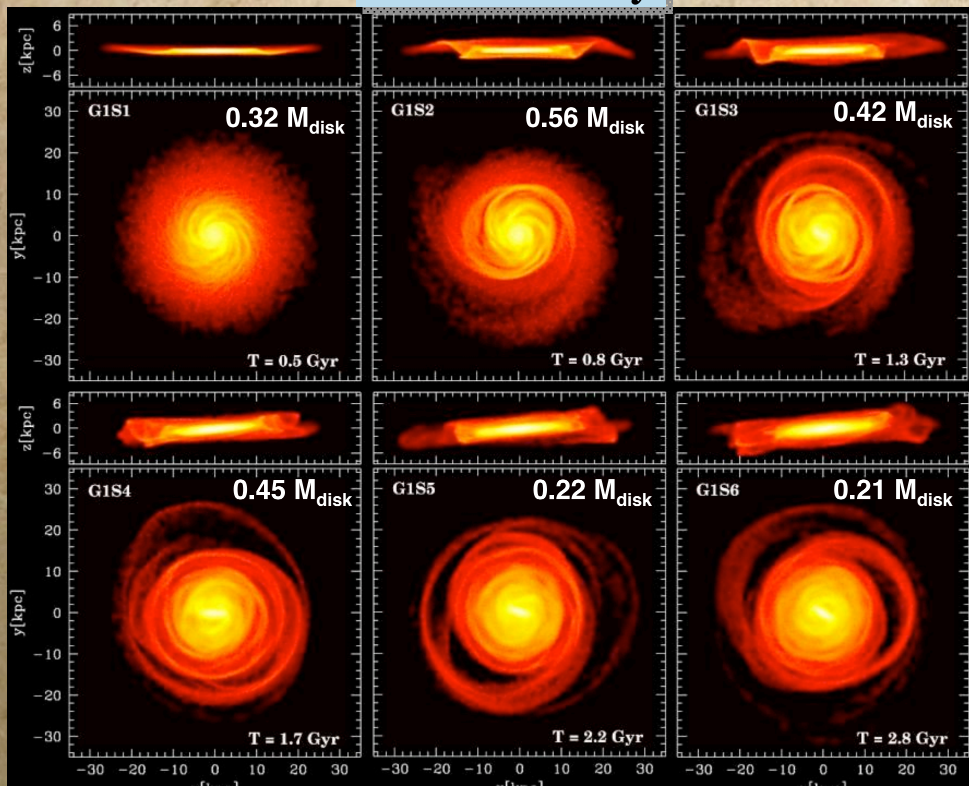




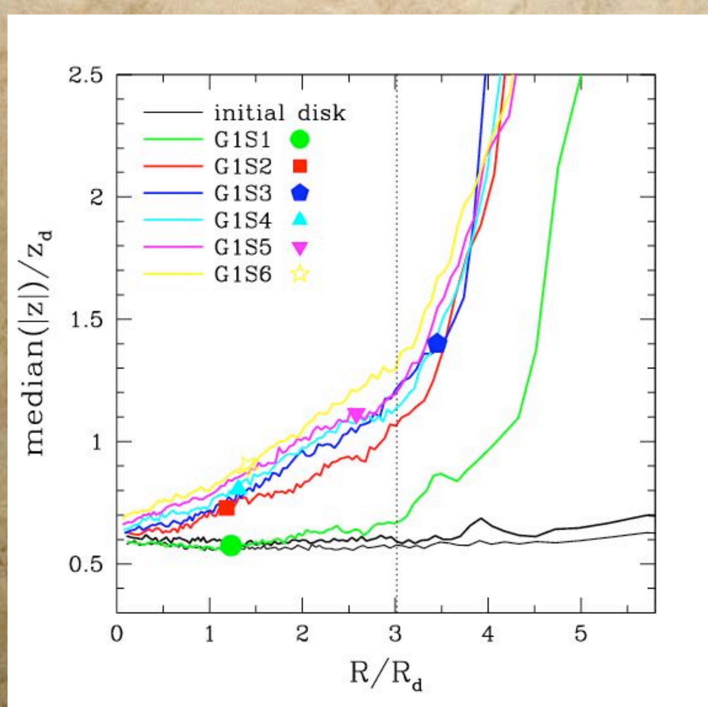


Fragility of Galactic Disks

Stellar Density



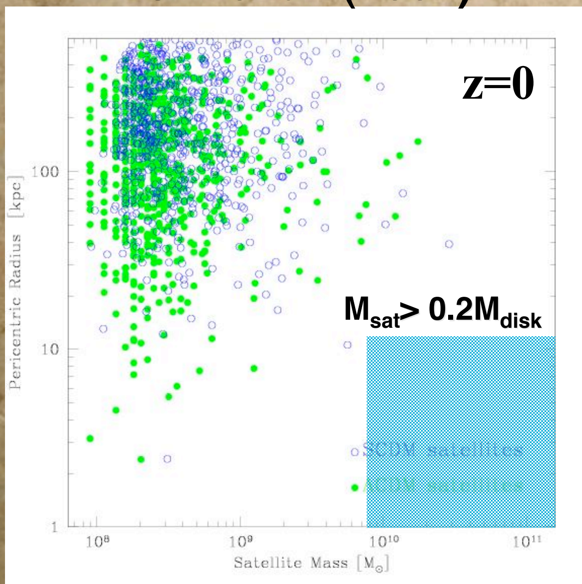
Disk Thickening and Satellite Accretion



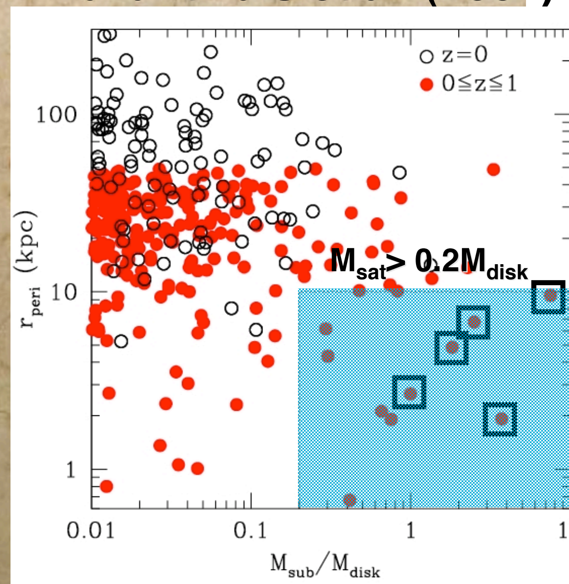
Kazantzidis et al. (2007)

Subhalo Pericenters vs Subhalo Masses in CDM Models

Font et al. (2001)

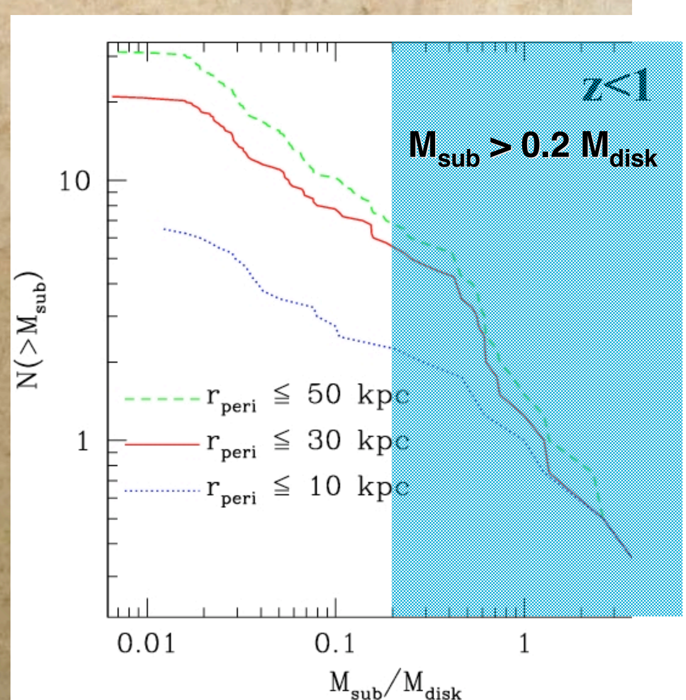


Kazantzidis et al. (2007)



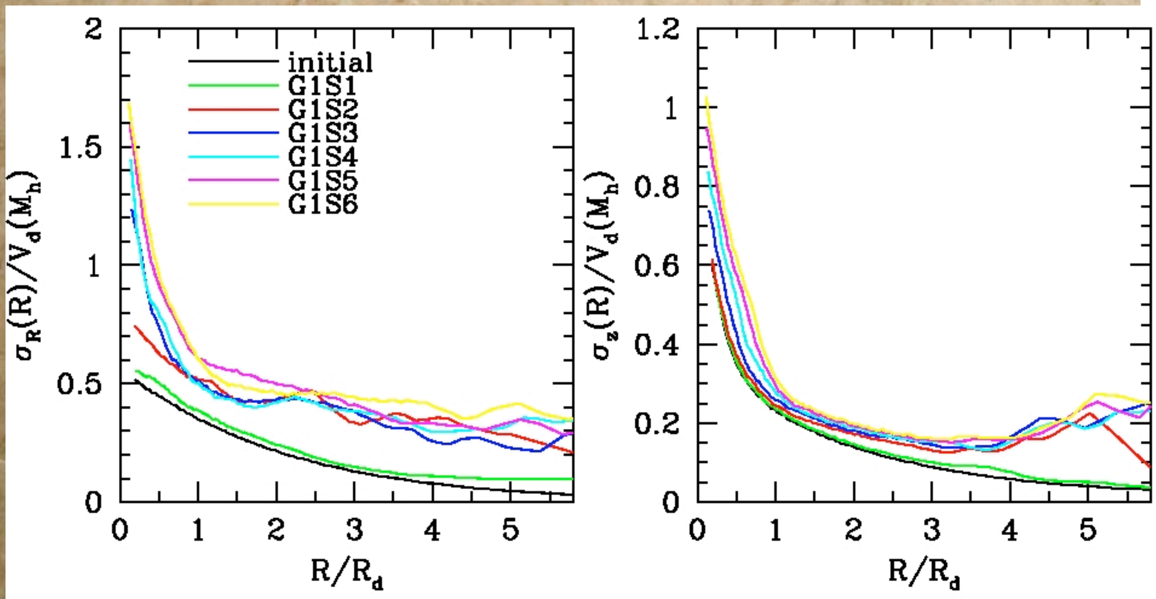
Cumulative Mass Functions of Subhalos in CDM Models

❑ Close encounters of massive subhalos with the Galactic disk since z=1 are common.



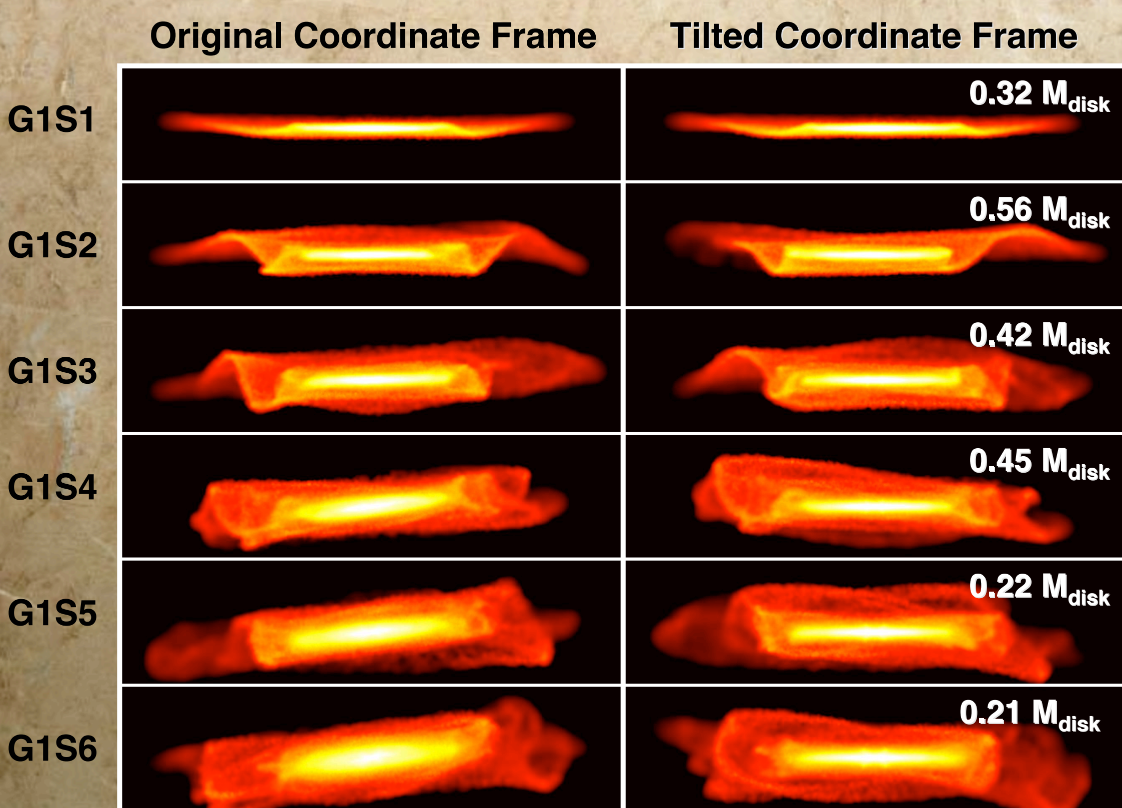
Kazantzidis et al. (2007)

Disk Heating and Satellite Accretion



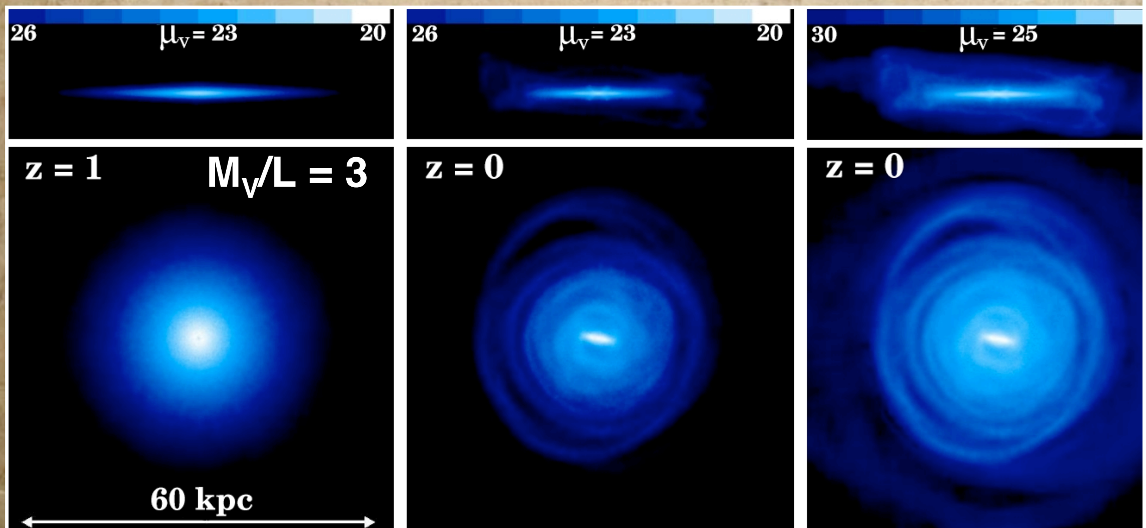
Kazantzidis et al. (2007)

Disk Tilting and Satellite Accretion

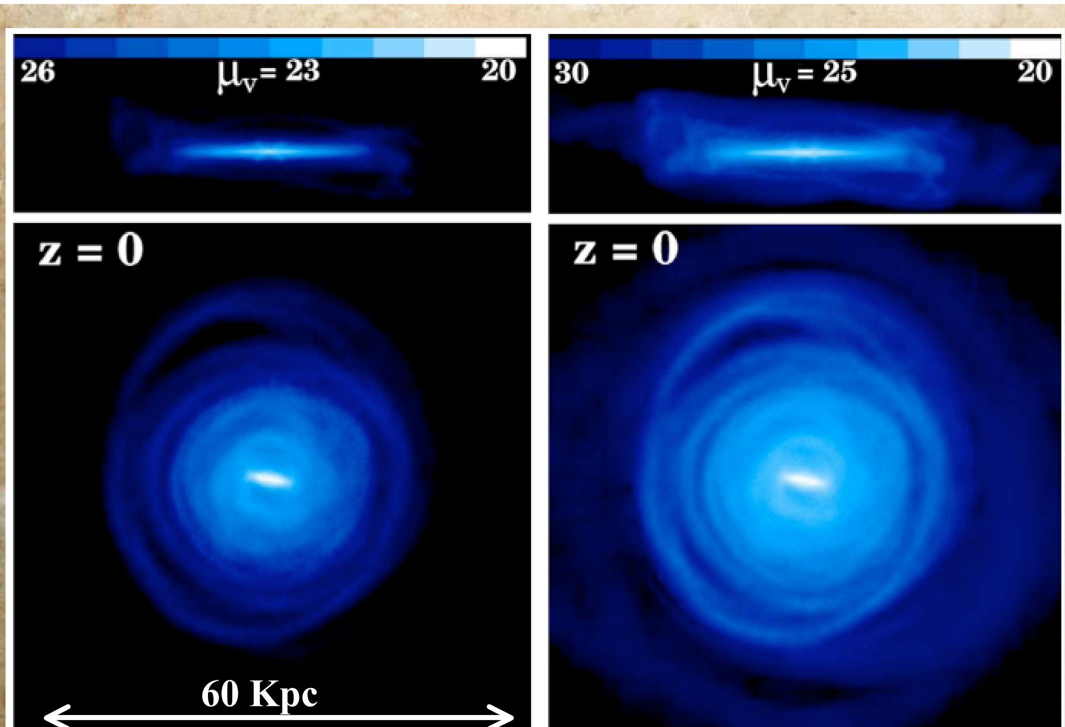


Surface Brightness Maps

Kazantzidis et al. (2007)

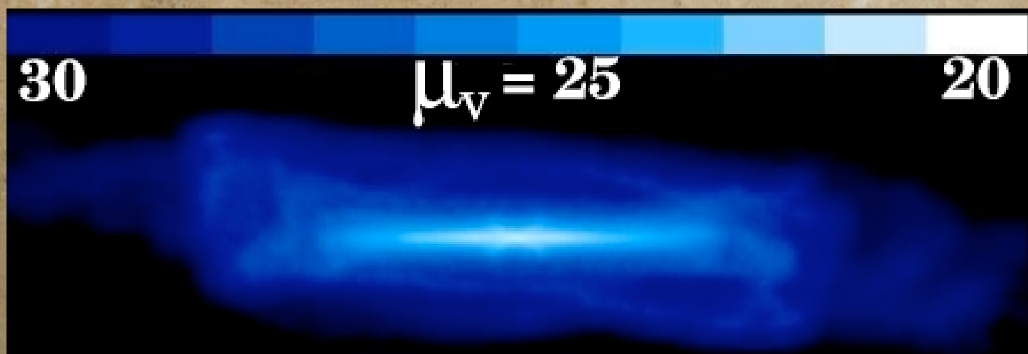


❑ **Satellite accretion leads to several observational signatures (e.g., disk flaring) that can be used to test the predictions of the proposed model.**



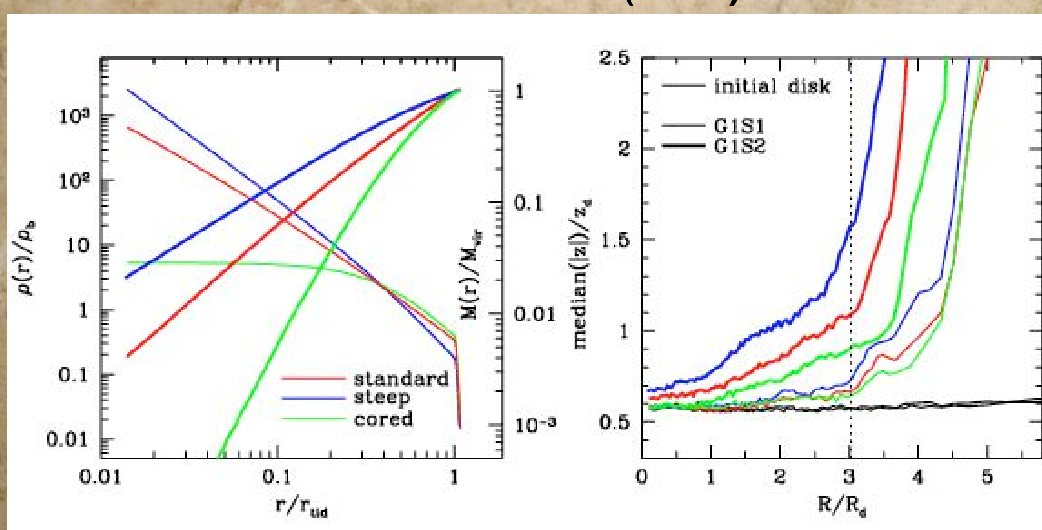
❑ **Satellite accretion excites significant disk substructure (outer "rings", central bar etc). Future observations (e.g. the SEGUE extension of SDSS) could help test whether disk structure is as excited as theory predicts.**

Surface Brightness Maps



Effect of Satellite Density Structure on Disk Thickening

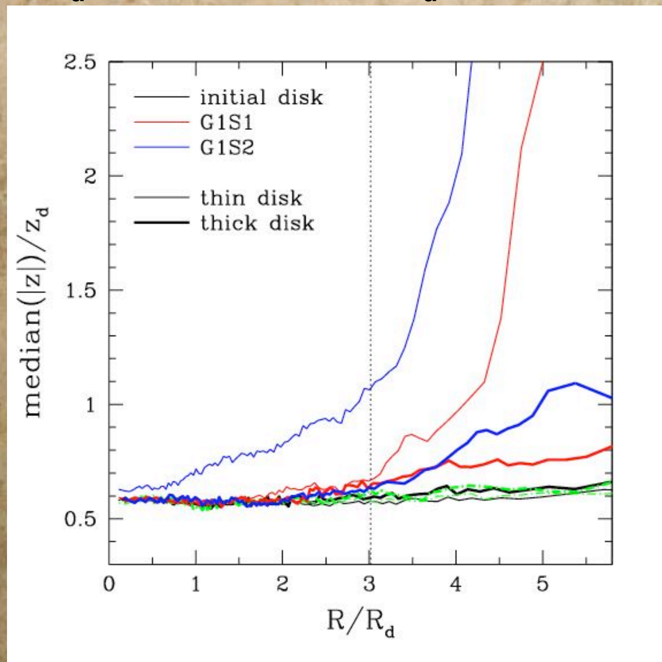
Kazantzidis et al. (2007)



- Satellite internal mass distribution is important in determining the amount of damage to the disk.

Effect of Initial Thickness on Disk Thickening

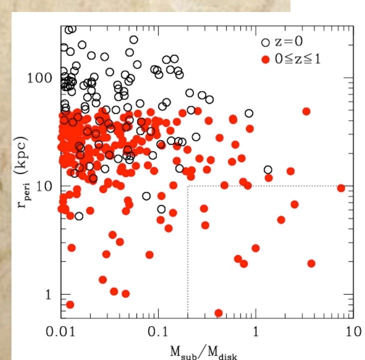
z_d (thick disk) = 2.5 z_d (thin disk)



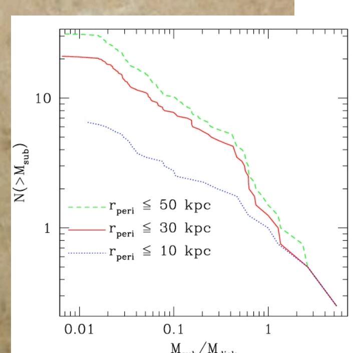
Kazantzidis et al. (2007)

Conclusions

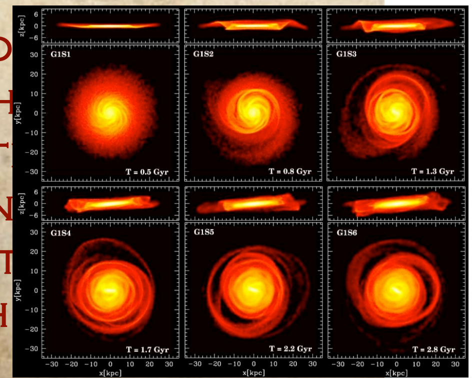
- Elucidating the dynamical response of a thin stellar disk to CDM substructures requires a realistic treatment of the evolution of the Subhalo populations over time.



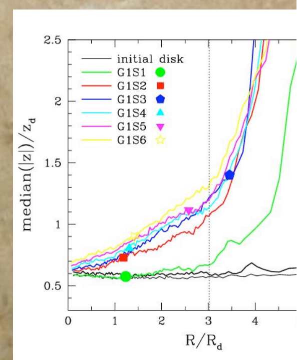
- CDM models predict several close encounters of massive subhalos with the galactic disks since z<1.



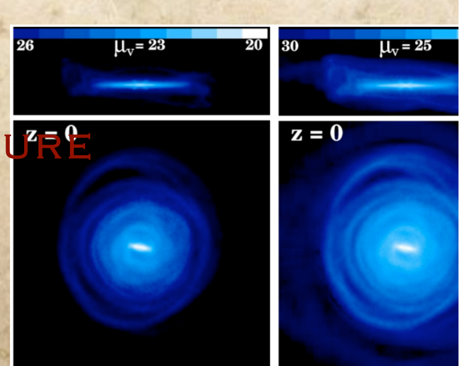
- CDM satellites have a profo
Effect on the structure of th
Stellar disks and can be Part
responsible for the formation
thick disks. Disks become hott
Thicker, tilted, warped and th
Axisymmetry is destroyed.



- Unless a mechanism (gas accretion?) can somehow stabilize the disks to these violent gravitational encounters stellar disks as old and thin as the Milky Way's will have severe difficulties to survive typical satellite accretion within _CDM.



- CDM satellites excite substantial disk substructure (e.g., flaring, outer rings). detailed observations of galactic structure (gaia, rave, segue) can be used to Distinguish between competing cosmological models and elucidate the nature of dark matter.



- Thicker disks are less sensitive to accretion events and suffer l
heating. Subsequent satellite
accretion by already thickened d
produce much smaller changes in
thickness and velocity ellipsoid.