Yoda:: If once you start down the dark path, forever it will dominate your destiny

Ed Shaya

U. Of Maryland

PROBING DARK MATTER PROPERTIES BY DYNAMICS OF THE GALAXY AND THE LOCAL GROUP

AGENDA

- Motivation for dynamical study of DM
- Theoretical Predictions
- Streams
- Dwarf Central Density
- High Velocity Stars
- Galaxy Motions
- Attempts to Fix CDM
- The Acceleration of the Sun by the Galaxy.

Luke: This R2 unit has a bad motivator, look!

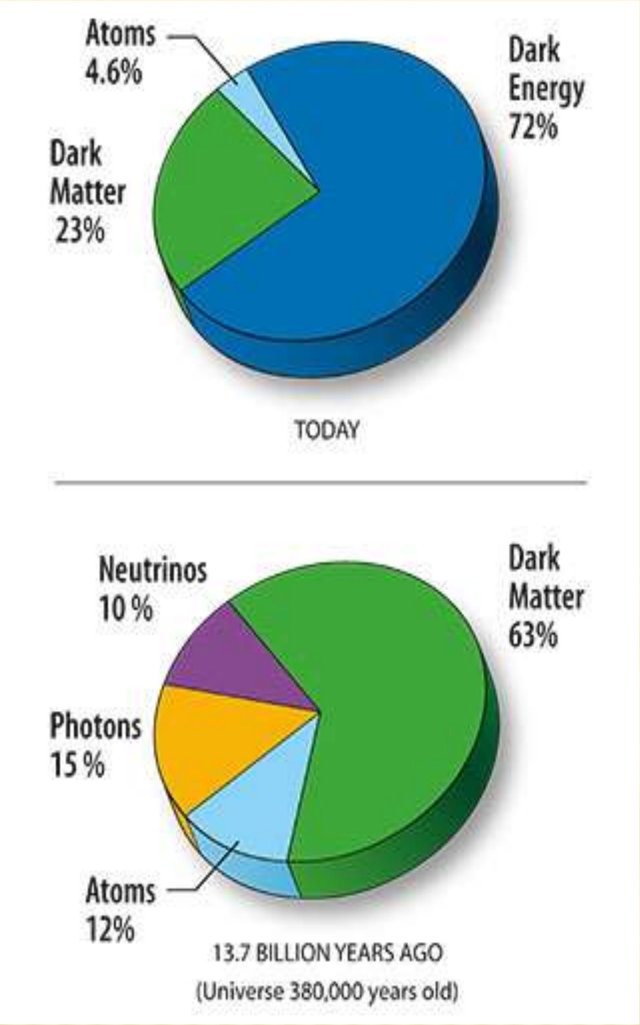
Uncle Owen: [*to Jawa*] Hey, what are you trying to push on us?

WHAT ARE THE BENEFITS OF DYNAMICAL STUDIES OF DM?

GOALS OF DYNAMIC STUDIES OF DM

I. What particle(s) comprise DM?

- What are the properties of the DM particle(s)?
  - Mass
    - Temperature (relates to Mass through cosmology)
      - Mass Distribution 10 Kpc to 5 Mpc gives clues.
      - What is small halo mass distribution?
      - What is orphan particle distribution?
      - DM cusps or cores at centers of galaxies?
  - Dissipation - Elastic Scattering or Low level Annihilation
    - Effects ratio of Dwarf to Giant Galaxies
    - Shape of Halo (Spherical vs Spheroidal) and core/cusp
    - Annihilation into photinos or other dark particle? Increase the hot dark matter component.



II. Hot Dark Matter (neutrinos)
- WMAP constrains $\Sigma m_\nu < 0.6$ ev or $\Omega_\nu < 0.015$ (Goobar et al 2006)
- MINOS oscillation experiment indicate $m_\nu > 0.04$ ev.
- But, does CDM convert to HDM over time?

III. Baryonic Dark Matter (0.02)
- Where is it?
- What form is it in?
- Temperature?

GOALS OF DM STUDY

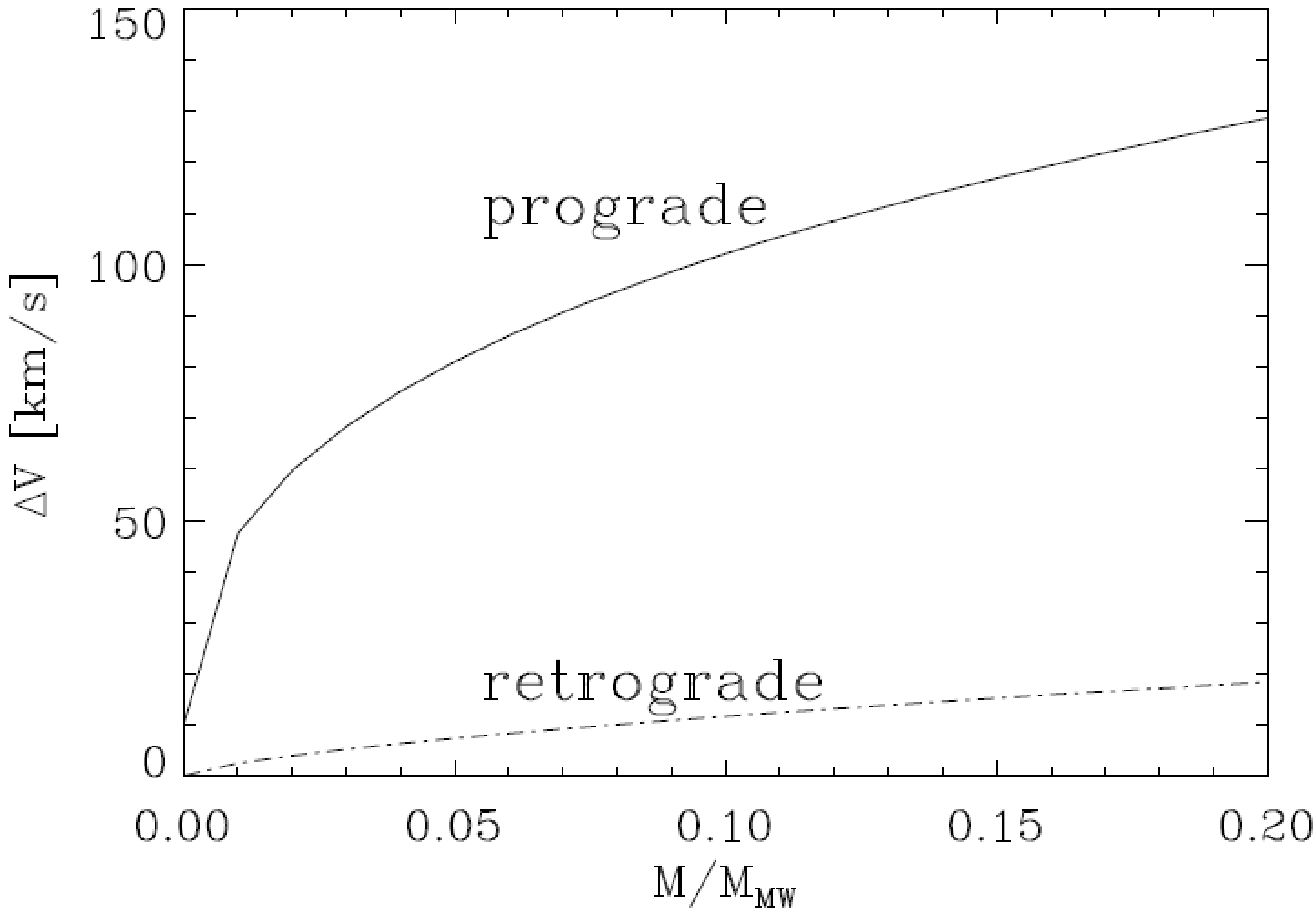
SENSING DARK MATTER

Obi-Wan: The [Gravity] Force is what gives a Jedi [aka Dynamicist] his/her power. It's an energy field created by all ... things. It surrounds us and penetrates us. It binds the galaxy together.

DYNAMICS AT 1 MICROAS/YR

- A GAIA/SIM combined baseline of 10-15 years:
- For some stars, can achieve ~2 μas/yr =
  - 10 km/s @ 1 Mpc
  - 1 km/s @ 100 Kpc
  - 100 m/s @ 10 Kpc
  - 10 m/s @ 1 Kpc
- Accelerations on galactic scales are too hard because time scales are >10 Myr (except, perhaps for acceleration of Sun around Galaxy: time dependence of stellar aberration (~4 cos θ [μas/yr] from v^2/R_{MW}, θ – direction of Sun's motion wrt GC).

Velocity Change at Center of Subhalos



Stars that happen to be traveling through a subhalo will have substantial velocity dispersions.

DARK MATTER ESSENTIALS

- The matter/energy density of the universe divides up accordingly: Ω_{baryon}=0.04, Ω_{DM}=0.22, Ω_{Λ}=.74.
- Only 0.02 (half of the baryons) are seen, so far. Dark Baryons lurk somewhere.
- Dark matter particle cross-section with normal matter may be very small but finite (WIMPs) and thus astronomically observable, or it may be essentially zero (eg supersymmetric particle).
- There may be more than 1 species. So, if we detect DM in lab, there is still more to do.
- Therefore: observations of dynamical effects on stars and galaxies are crucial for learning the whole story.

TOP CANDIDATES FOR CDM

- **Neutralino** – Each particle in Standard Model has a heavier (supersymmetric) partner of different spin. Unifies 3 forces of nature. Lightest one is Neutralino, m = 60 GeV – 10TeV. US and EU embarking on effort to detect SUSY down to level of 10^{-46} cm^2.
- **Lightest Kaluza-Klein particle** – massive particles occupying tiny rings in a compactified dimension. Need Fermi Satellite plus ground-based Cerenkov detectors to see annhilation (Nuss et al 2006).
- **Axion** – Particle hypothesized to explain "CP symmetry" and lack of electric dipole moment in neutron. Very light (< 0.01eV) but couples so weakly it was never in thermal equilibrium, thus cold. Lab experiment - Photons turn into axions in strong magetic field.

Princess Leia: I don't know where you get your delusions, laser brain.

THEORETICAL/SIMULATION PREDICTIONS OF MASS DISTRIBUTIONS

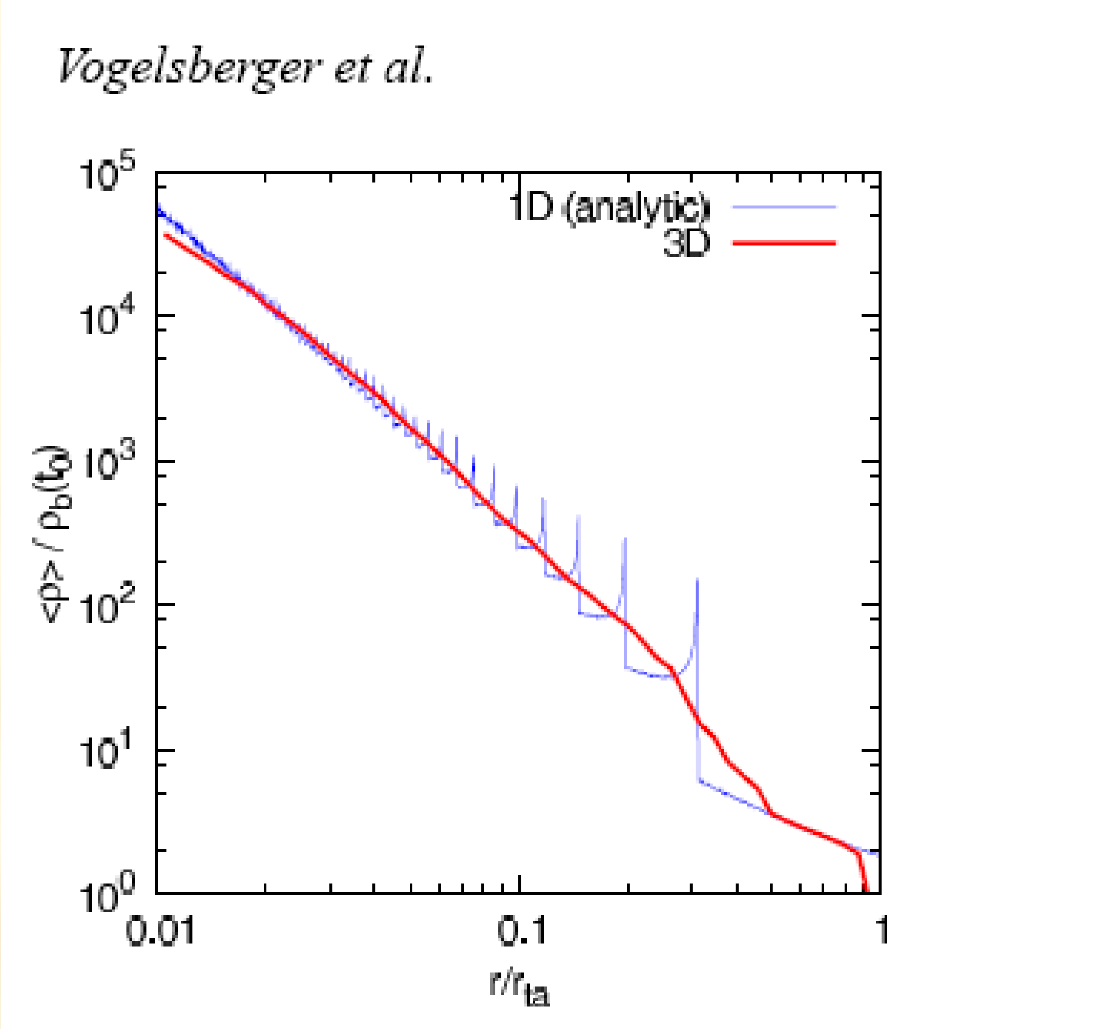
In 1-d there are strong caustics.

In 3-d simulation focused on diminishing the problems arising from softening parameter, caustics are mostly washed out by strong bar.

Both follow $\rho \sim r^{-9/4}$

Typical N-body Simulations give

$\rho \sim r^{-1.5}$



DENSITY PROFILE OF CDM HALO SIMULATION

MARK VOGELSBERGER, SIMON D.M. WHITE, ROYA MOHAYAEE, VOLKER SPRINGEL SUBMITTED TO MNRAS

- For MW r_{2t} is near 250 kpc (Xue et al 2008) so velocity profile should fall slowly inside this then quickly outside.

- DM anisotropy low (0.3) until 80 kpc and nearly radial beyond that.

- DM forms bar at center and this washes out caustics.

VELOCITY AND ANISOTROPY

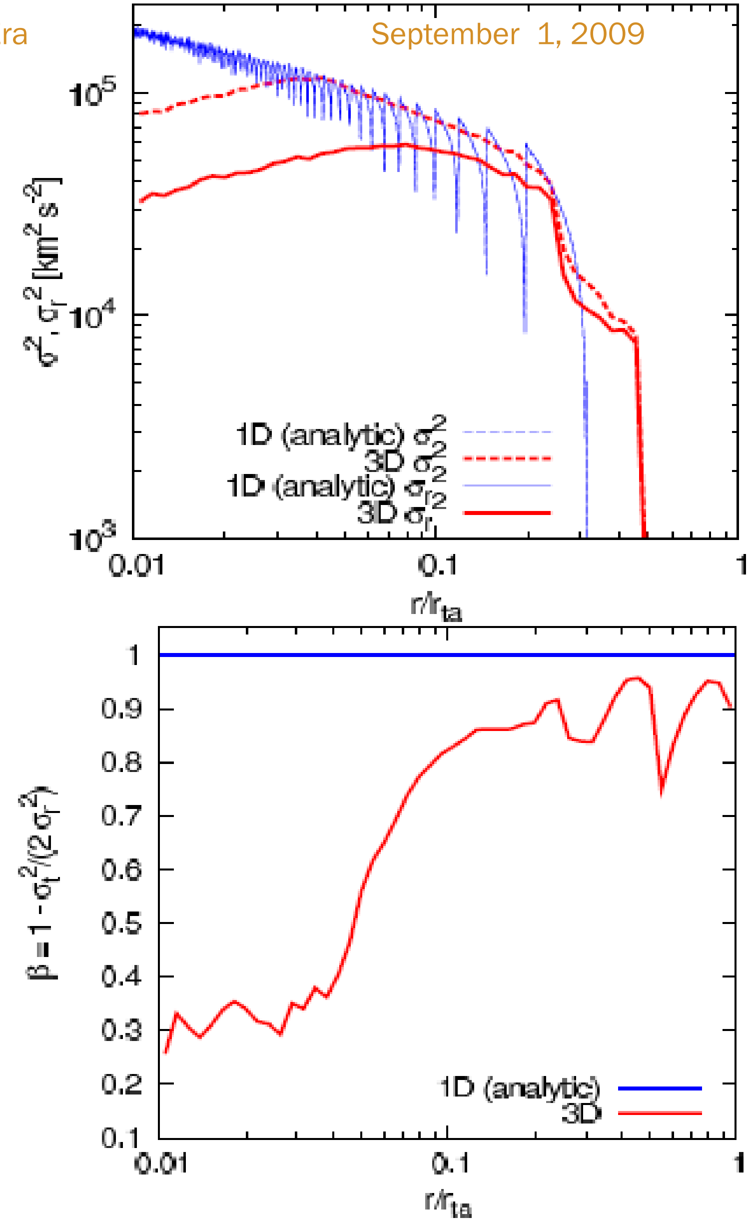
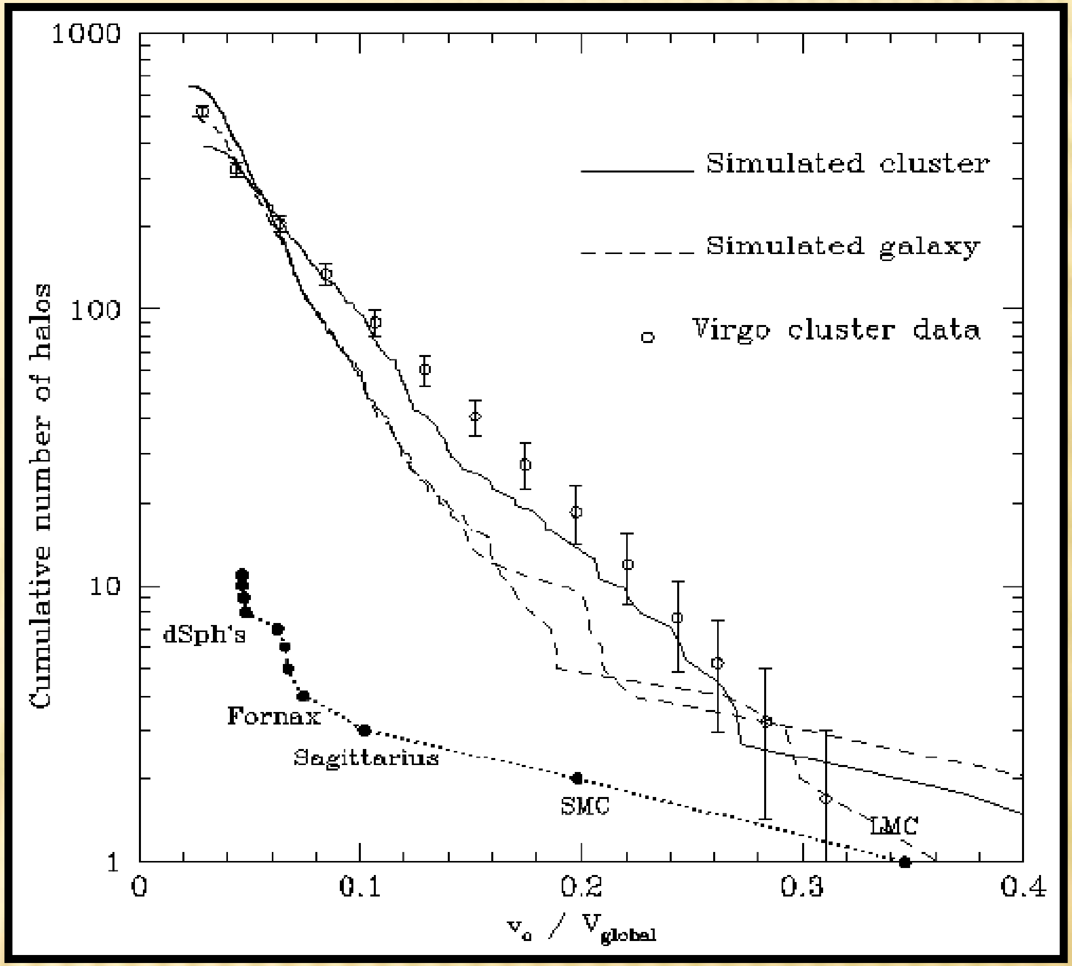


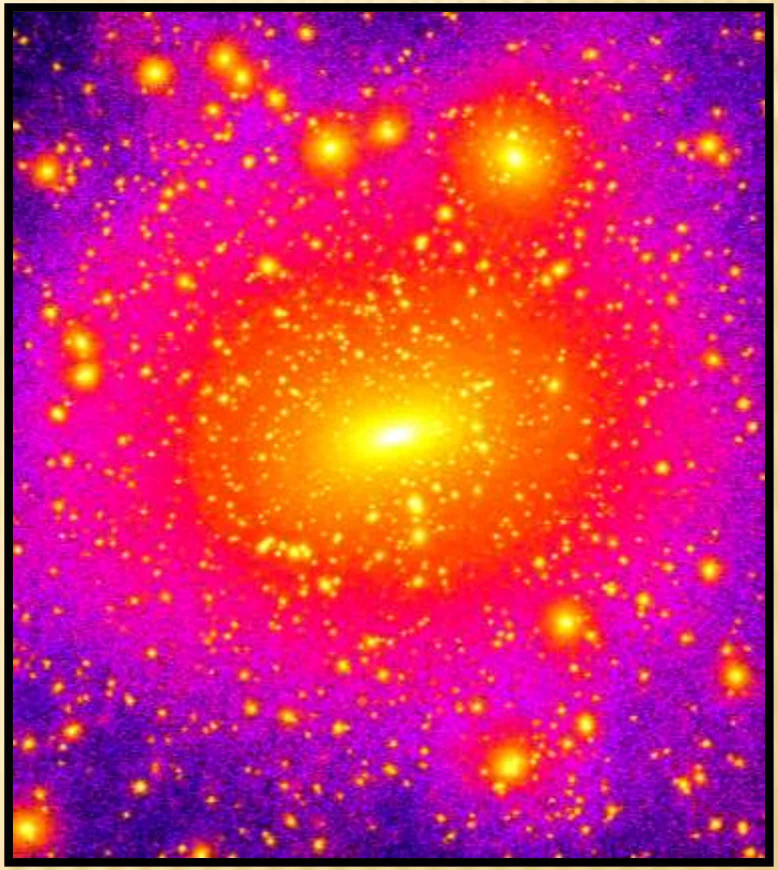
Figure 7. Top panel: Total ($\sigma^2 = \sigma_r^2 + \sigma_t^2$, where σ_r and σ_t are the velocity dispersions in the radial and tangential directions, respectively) and radial (σ_r^2) velocity dispersion profiles for the 3D halo are compared to the radial velocity dispersion profile of the FG similarity solution. Bottom panel: Velocity anisotropy profile $\beta = 1 - \sigma_t^2/(2\sigma_r^2)$. Apart from caustic features the total velocity dispersion behaviour is very similar in the two

Many small mass halos are predicted but have not (yet?) been seen. Perhaps stars and gas were blown out of most small halos. Perhaps DM particle is warm creating a lower limit to halo mass.



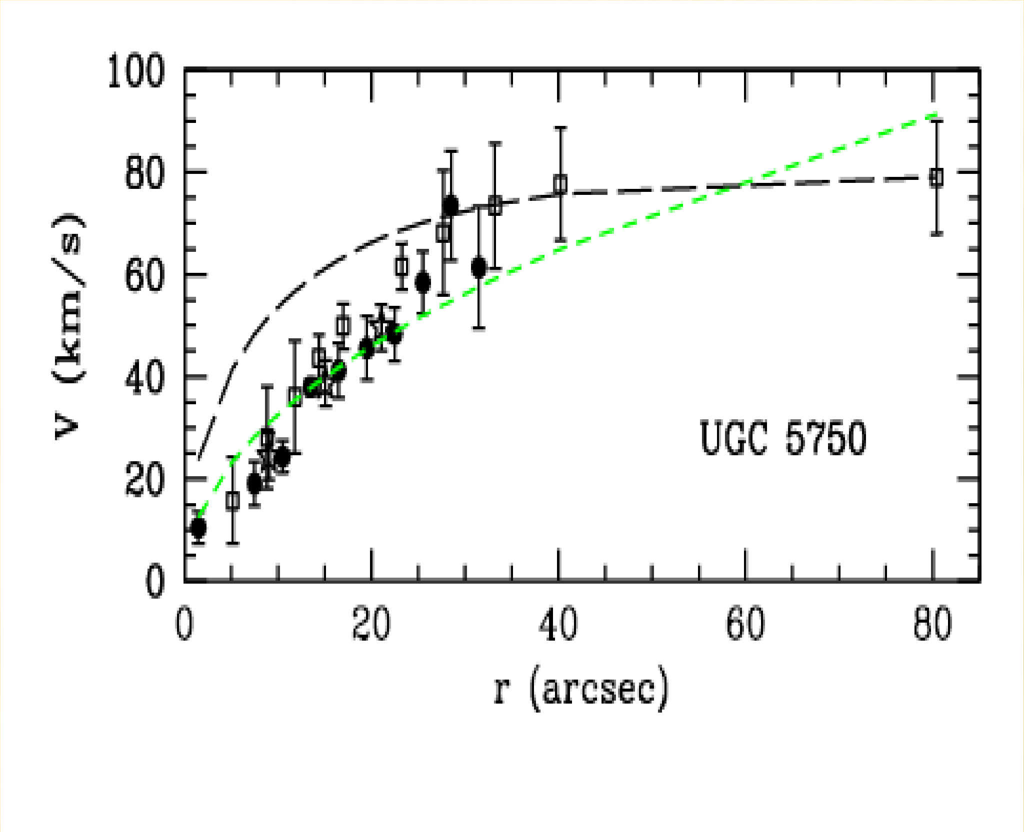
SIMULATIONS PREDICT MANY SUBHALOS: OBSERVED IN CLUSTERS, PROBLEM FOR GALAXIES

Small scale structure fall into the Galaxy. High density centers of small halos survive in great abundance. The outer envelopes of DM are destroyed and strewn around the outer halo.



MANY SMALL HALOS FALL INTO GALAXIES

Density profiles of halos in simulations have NFW Profiles (also fit by $r^{1/4}$ De Vaucouleur's Law). However, warm DMs result in flatter profiles.



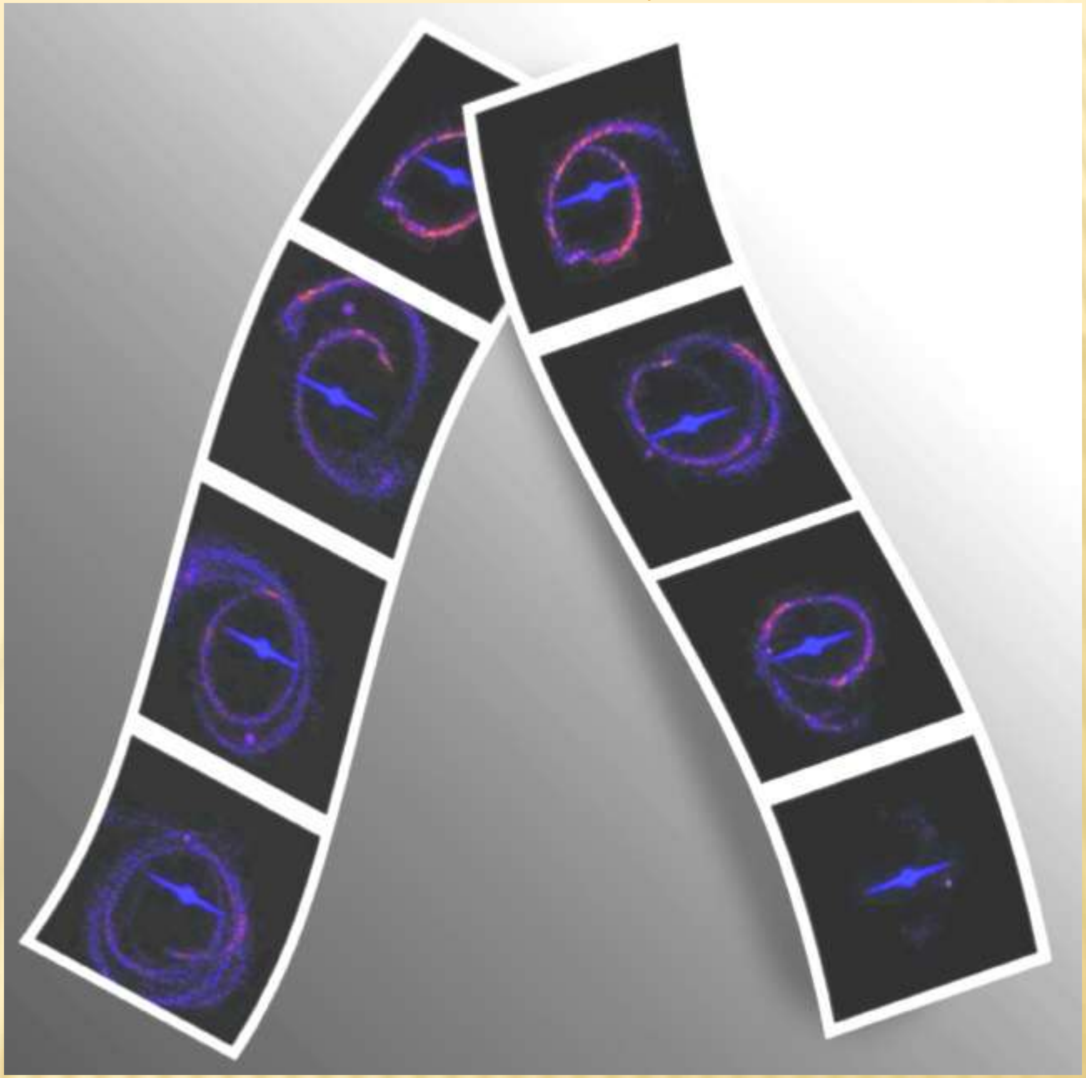
Centers of simulated halos have steep slope in density profiles (cusps). Dwarf galaxies usually have slowly rising velocity profiles.

Rachel de Naray, UMD PhD Thesis 2007

Darth Vader Galaxy: Your powers are weak, old man.
Obi-Wan Dwarf Galaxy: You can't win, Darth. If you strike me down, I shall become more powerful than you could possibly imagine.

STREAMS OF STARS

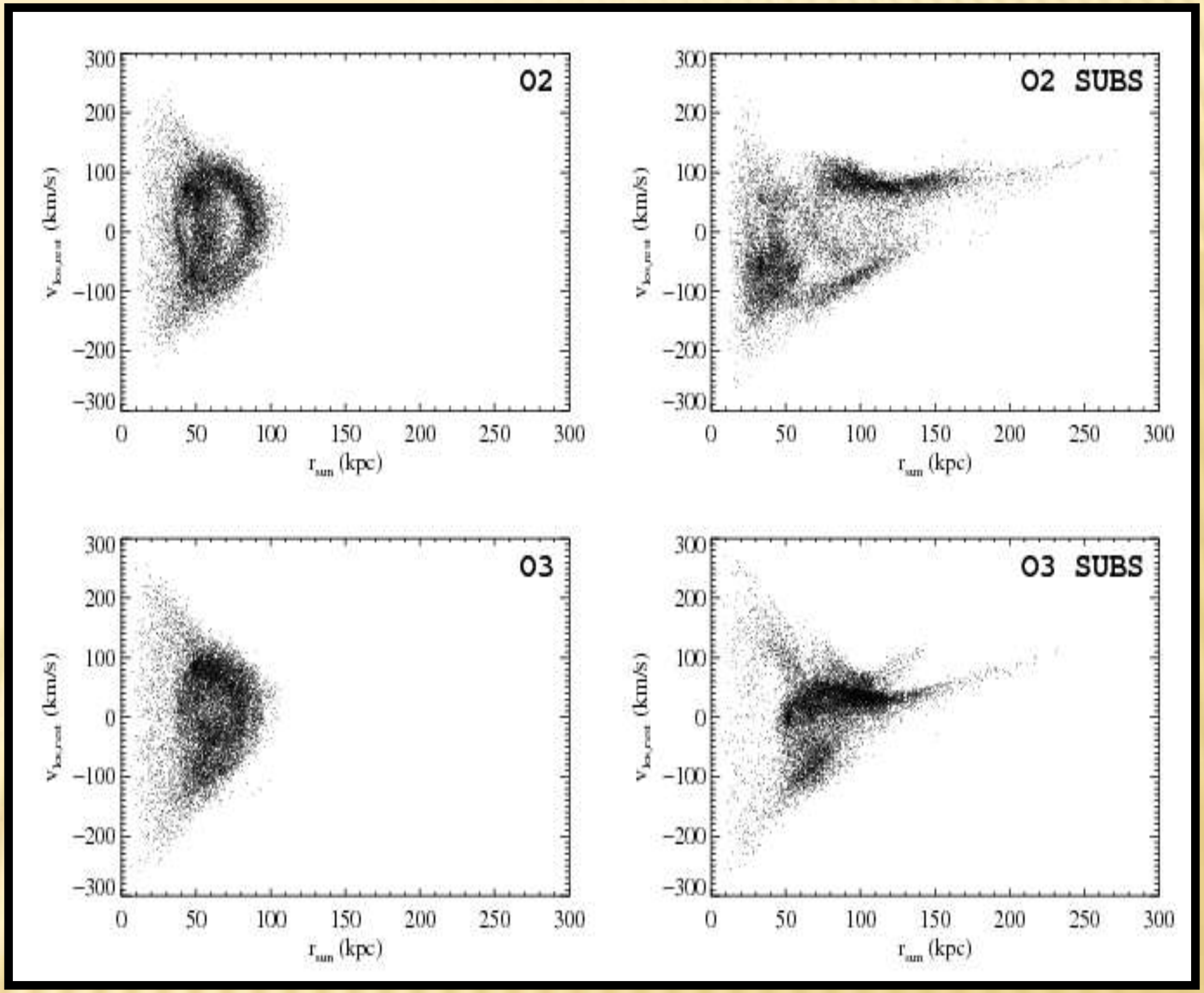
With an accurate model of the MW one can create trajectories of stream stars back in time that all come together. If the model is not highly realistic the orbits do not merge.



OBTAINING AN ACCURATE MODEL OF THE MW'S POTENTIAL MAJEWSKI ET AL

If many subhalos exist in the MW, the streams will be heated and spread out in the phase-space diagram.

Without Substructure With Substructure



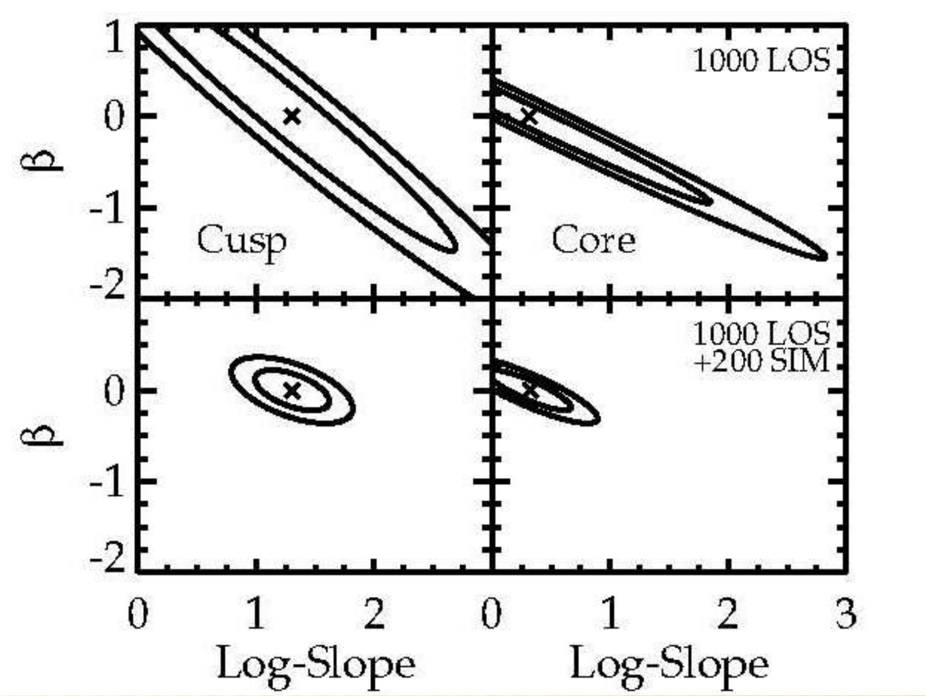
Substructure affects phase-space of stellar streams

Jennifer SiegalGaskins & Monica Valluri 2007

Han Solo: Kid, I've flown from one side of this galaxy to the other, and I've seen a lot of strange stuff, but I've never seen **anything** to make me believe that there's one all-powerful Force controlling everything. 'Cause no mystical energy field controls **my** destiny. It's all a lot of simple tricks and nonsense.

CENTRAL CUSPS AND CORES: IS THERE MORE THAN GRAVITY PHYSICS GOING ON?

Present observations of velocity dispersions indicate cores in their centers provided that velocities are isotropic. But, radial velocity data would be consistent with cuspy cores if the velocities were anisotropic. By observing proper motions of 200 stars using SIM, one could determine definitively if a nearby galaxy has a DM cusp or core at its center.

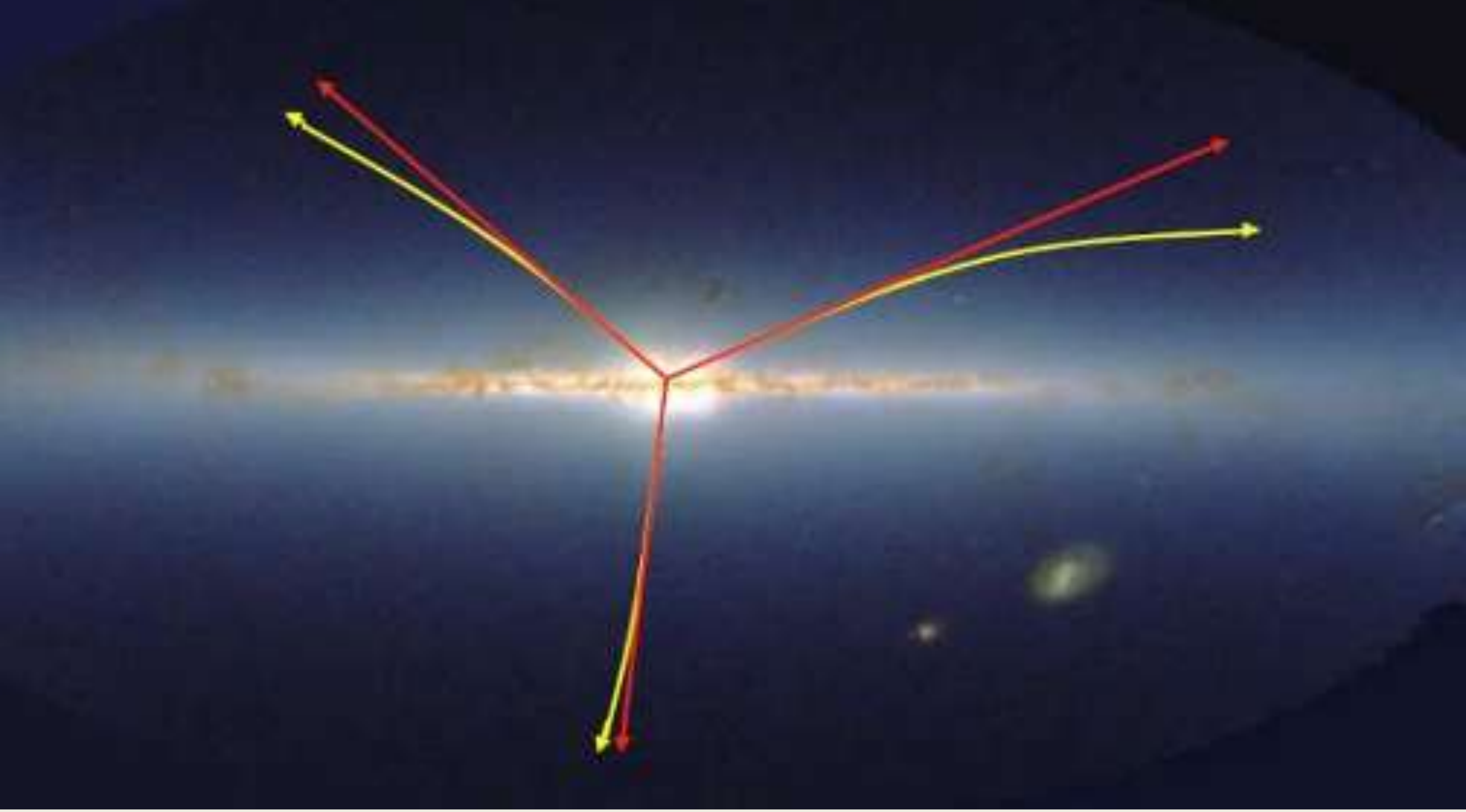


Top panels - Error ellipses with just radial velocities include both cusp and core slopes. Bottom panels - A significant improvement is derived from the addition of 200 SIM proper motions with 5 km/s precision.

ANALYZE VELOCITY SPHEROID OF DWARF GALAXIES

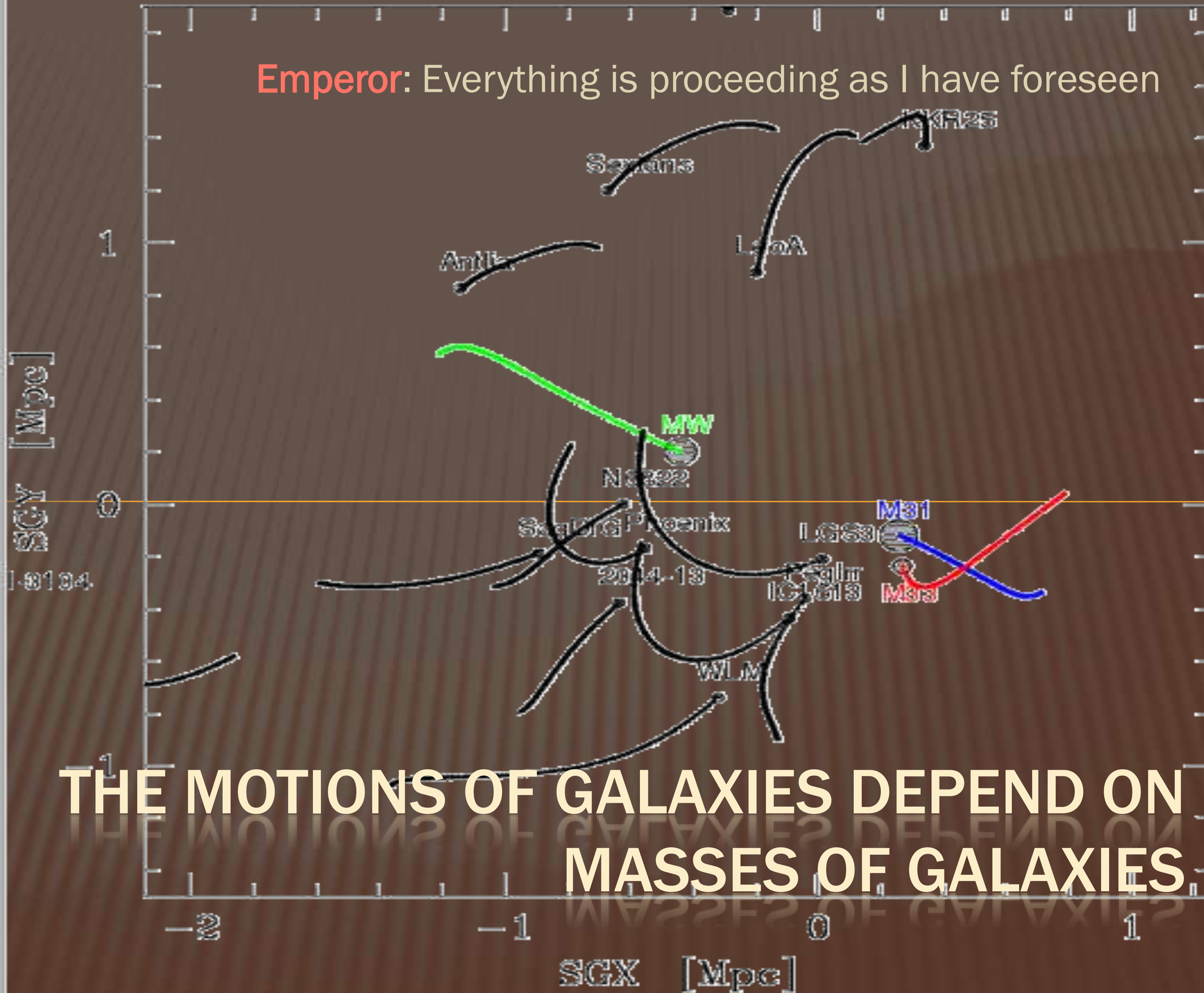
Princess Leia: The more you tighten your grip, Tarkin, the more star systems will slip through your fingers.

THE GALACTIC POTENTIAL FROM HIGH VELOCITY STARS



SHAPE OF GALAXY CAN BE DETERMINED FROM HIGH VELOCITY STARS

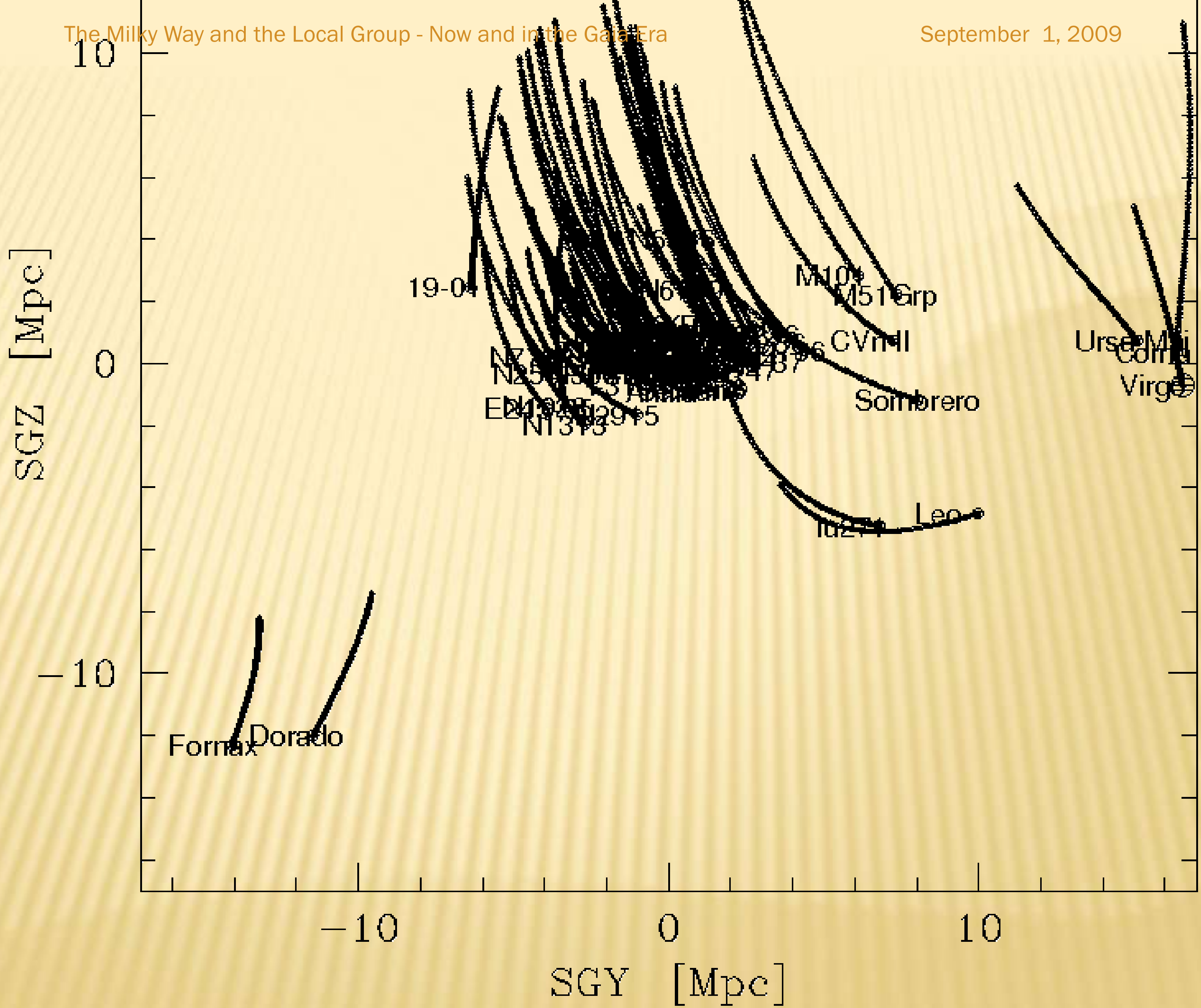
Emperor: Everything is proceeding as I have foreseen

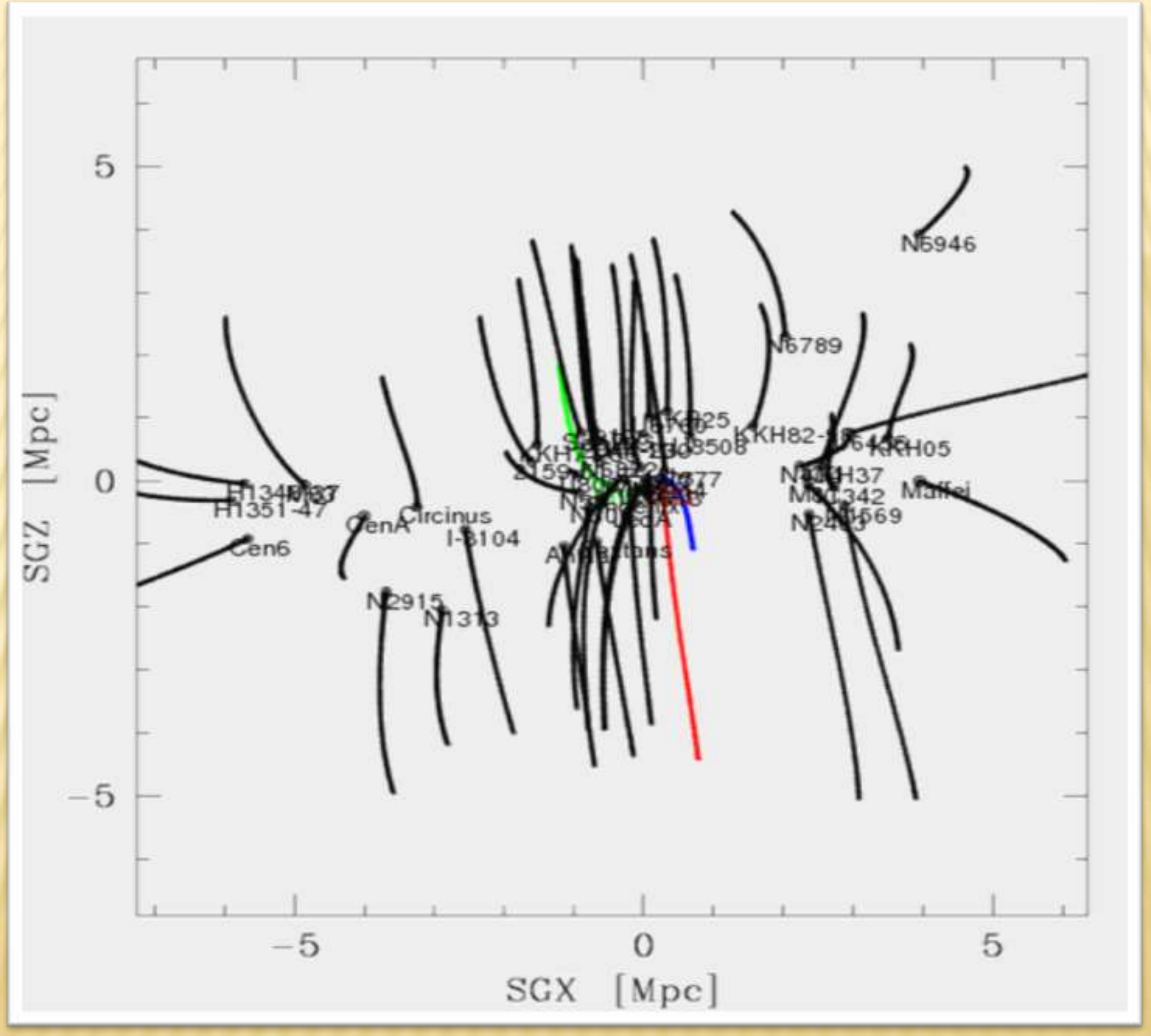


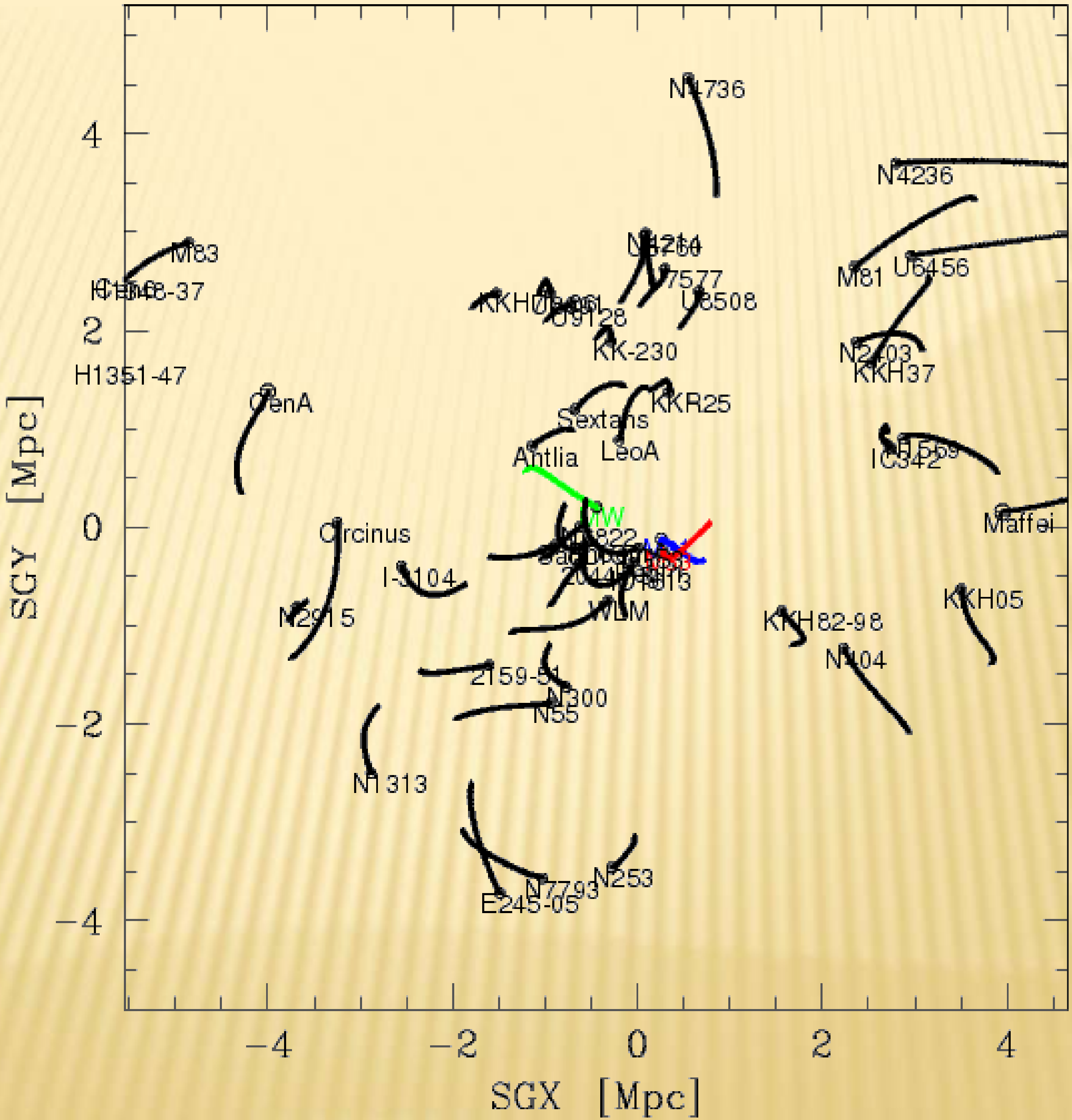
THE MOTIONS OF GALAXIES DEPEND ON MASSES OF GALAXIES

EXTRAGALACTIC PROPER MOTIONS

- SIM can obtain proper motions (~3 μas/yr) for a sample of 27 nearby (<5 Mpc) galaxies.
- These measurements complete our knowledge of the 6-dimensional position and velocity vector for each galaxy.
- In conjunction with advanced gravitational flow models (NAM + constrained N-body), the result will be total mass measurements of individual galaxies and a few groups.
- Observe 5-20 stars per galaxy to beat down scatter from internal motions and measurement error.


SGZ [Mpc]
SGY [Mpc]
10
0
−10
19-04
M101
M51 Grp
CVnII
Sombrero
Leo
UrsaMaj
Coma
Virgo
Fornax
Dorado
N1313


N6946
N6789
KK225
KKH82
KKH05
N6503
N3109
M81
Maffei
H1348-37
H1351-47
CenA
Circinus
Cen6
I-3104
N2915
N1313
N2403
IC1569
NGC342
SGZ [Mpc]
SGX [Mpc]
5
0
−5
−5
0
5


N4736
N4236
M83
M81
U6456
U8508
KK-230
H1351-47
CenA
KKR25
Sextans
N2403
KKH37
Antlia
LeoA
IC342
MW
Maffei
Circinus
I-5104
KKH05
N2915
WLM
KKH82-98
N404
2159-51
N300
N55
N1313
N253
N7793
E245-05
SGY [Mpc]
SGX [Mpc]

Tracing the Magellanic Clouds Back in Time
P. J. E. Peebles, arXiv:0907.5207

Figure 4 shows an example of an orbit for the SMC that fits the K06b SMC velocity measurement. The SMC is assigned zero mass — it is a test particle — so it can be added to any of the solutions discussed in the last section. This example uses solution 220a.

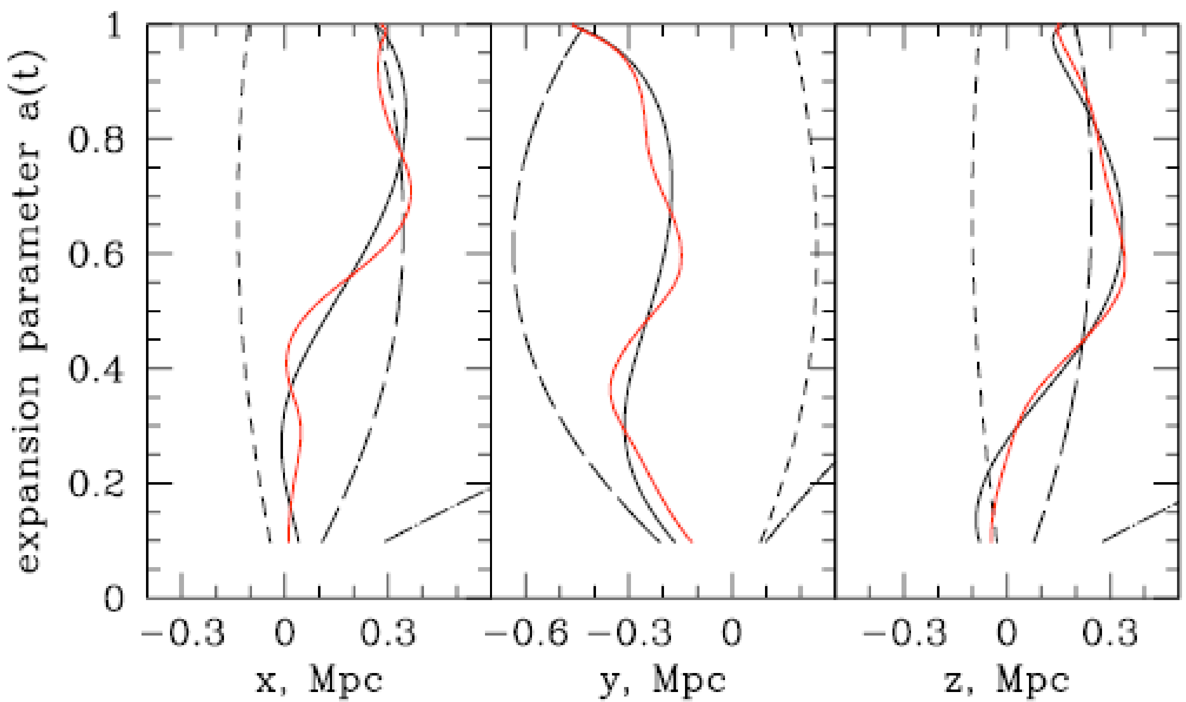


Fig. 4.— Motions relative to the center of mass of the LG in solution 220a, as in Figures 2 and 3, except here plotted in physical coordinates. The red curve is the path of the SMC in example (a).

Admiral Motti: Don't try to frighten us with your sorcerous ways, Lord Vader. Your sad devotion to that ancient religion has not helped you ...

ATTEMPTS TO FIX CDM

FIXING CDM (EITHER WITH PHYSICS OR ASTRO)

- Warm Dark Matter
  - Solves cusp/core problem and small halo problem and lack of damped La systems at z > 1.5 (Prochaska and Wolfe, 2001)
  - But, then formation of dwarf galaxies suppressed until too late (Silk, 2001)
  - Dynamics: detect no cusps in dwarfs, no subhalos, spheroidal potentials
- Self-interacting CDM
  - Avoid core by elastic scattering
  - But, creates spherical halo (Miralda-Escude, 2000)
  - Dynamics: detect cores in dwarfs, no subhalos, spherical potentials
- SMBHs
  - SMBHs throw stars out and heat DM at core as galaxies merge
  - But, dwarfs have unimportant BHs.
  - Dynamics: detect no cusps, but some subhalos.
- Stellar Feedback
  - Makes small halos dark (satellites become invisible)
  - But, may cause giant disks to form late
  - Dynamics: detect cusps and subhalos.