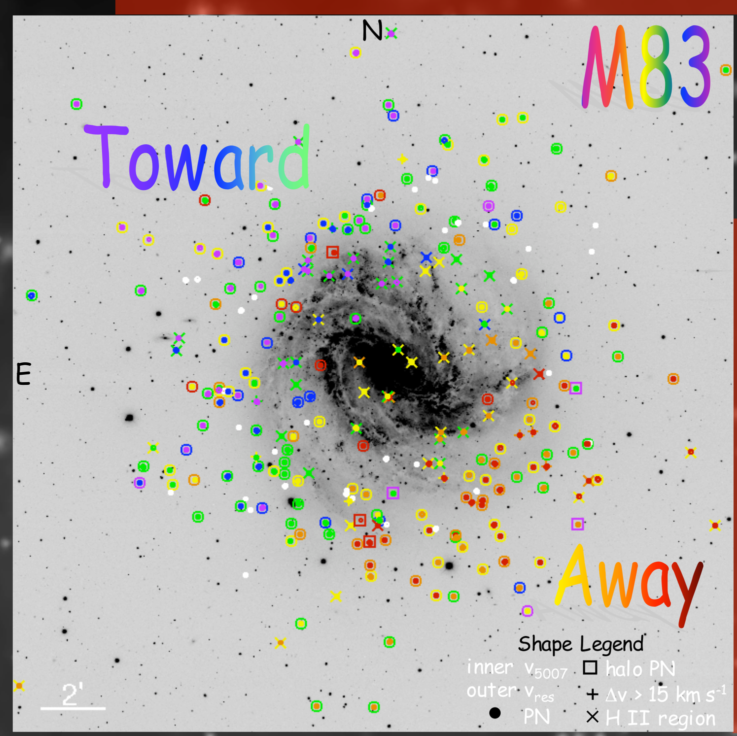
Kinematic Evidence for Halo Substructure in Spiral Galaxies



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We present the results from a kinematic study of planetary nebulae in the extreme outskirts of two spiral galaxies, M83 and M94. We find that in the inner regions of the galaxies, the vertical velocity dispersion (σ_z) falls off exponentially with the light, as expected for a constant mass-to-light ratio, constant scale height disk. However, starting at four optical scale lengths, σ_z asymptotes out at roughly 20 km s^{-1}. Our analysis finds evidence for significant flaring in the outer regions as well, especially in M94. Our observations are in excellent agreement with predictions derived from models of disk heating by halo substructure.

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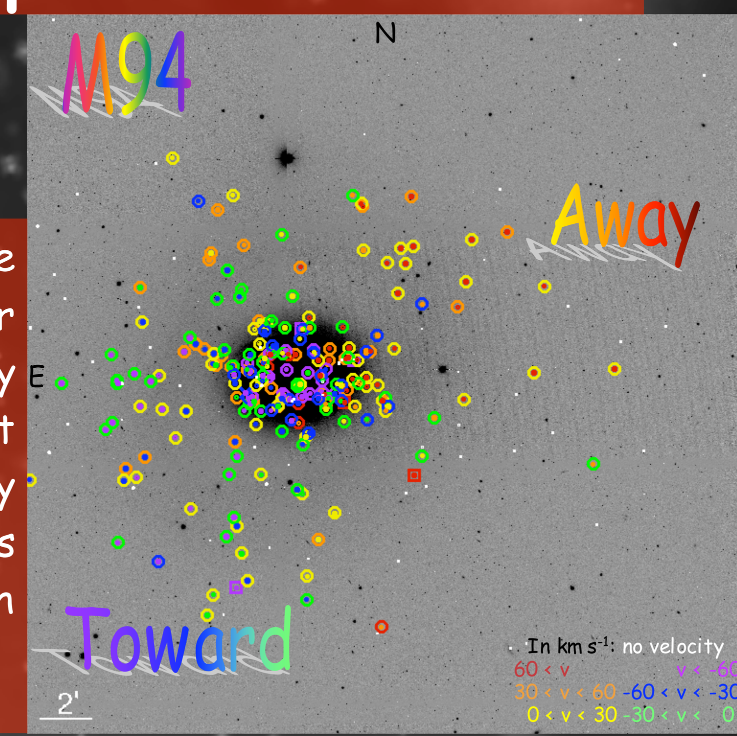

1. Introduction

- The cold dark matter (CDM) paradigm explains large scale structure and galactic clusters very well (Tegmark et al. 2004), yet problems still exist at the galactic level
- The "missing satellite" problem: according to simulations, a galactic halo should look like a galaxy cluster and contain many small subhalos (e.g., Moore et al. 1999; Klypin et al. 1999)
- Recent discoveries of tidally stripped satellite galaxies around the Milky Way and Andromeda galaxies (references in Kazantzidis et al. 2008) help to solve this problem
- *Small companions profoundly affect the morphology and kinematics of thin galactic disks*
- Specifically, numerical models of satellite halo bombardments predict:
  - faint stellar streams above the disk plane,
  - long-lived, low-surface brightness, cold, ring-like features in outer disks,
  - the growth of a strong bar, the production of a flare, and
  - the development of a thick disk (Kazantzidis et al. 2008, and references therein)
- Though many simulations (references in Kazantzidis et al. 2008) have explored disk heating by subhalos, *observationally the results have proven to be elusive*

2. The Survey

- Flat rotation curves indicate dark matter in the outer regions of spiral galaxies and determine total galactic mass (e.g., Sofue & Rubin 2001)
- Rotation curves cannot decouple the disk mass from the dark halo (Barnes et al. 2004)
- *The z-motions of old disk stars in low-inclination spirals measure disk mass directly*
- Planetary Nebulae (PNe) are ideal particles for this purpose because they are:
  - bright, abundant to >5 scale lengths, representative of the old disk,
  - easy to distinguish from H II regions (via the [O III]-Hα ratio; Ciardullo et al. 2002),
  - and amenable to precise (~2 km s^{-1}) radial velocities with fiber-fed spectrographs
- We presented a narrow-band imaging survey of six low-inclination nearby spirals in which we identified large samples of PNe (Herrmann et al. 2008, Paper I)
- Here, we focus on the two galaxies for which we have the largest radial coverage:
  - M83 (SBc): 162 PNe, 2.5 < R < 24.7 kpc, (~1 - 10 optical disk scale lengths)
    - Taken with the Hydra bench spectrograph on the CTIO 4-m telescope
    - Typical velocity uncertainty $\Delta v \sim 6.5$ km s^{-1}, and in all cases, $\Delta v < 15$ km s^{-1}
  - M94 (Sab): 192 PNe, 0.5 < R < 19.0 kpc (0.4 - 16 optical disk scale lengths),
    - Observed with the Hydra spectrograph on WIYN
    - Typically $\Delta v \sim 3$ km s^{-1}, again with $\Delta v < 15$ km s^{-1} for all objects
- Neither galaxy is exactly face-on, so we removed galactic rotation from the PN velocities by using velocity maps from The H I Nearby Galaxy Survey (THINGS; Walter et al. 2008) with corrections for asymmetric drift
- We then binned the PNe by radius (15-16 PNe in M83, and 16 PNe in M94), and excluded PNe more than ~2.5 σ away from the bin mean as possible halo contaminants
- This made very little difference to the analysis since the procedure eliminated only six objects in M83 and five in M94
- Finally, to extract the component of the velocity dispersion perpendicular to the galactic disk, σ_z, from the other two constituents of the velocity ellipsoid, we used the epicyclic approximation of near-circular orbits to couple σ_φ to σ_R, and then solved for σ_z via a maximum-likelihood analysis (Herrmann & Ciardullo in prep)
- Figure 1 shows example results of the fits for bins in the galaxies' outer disks

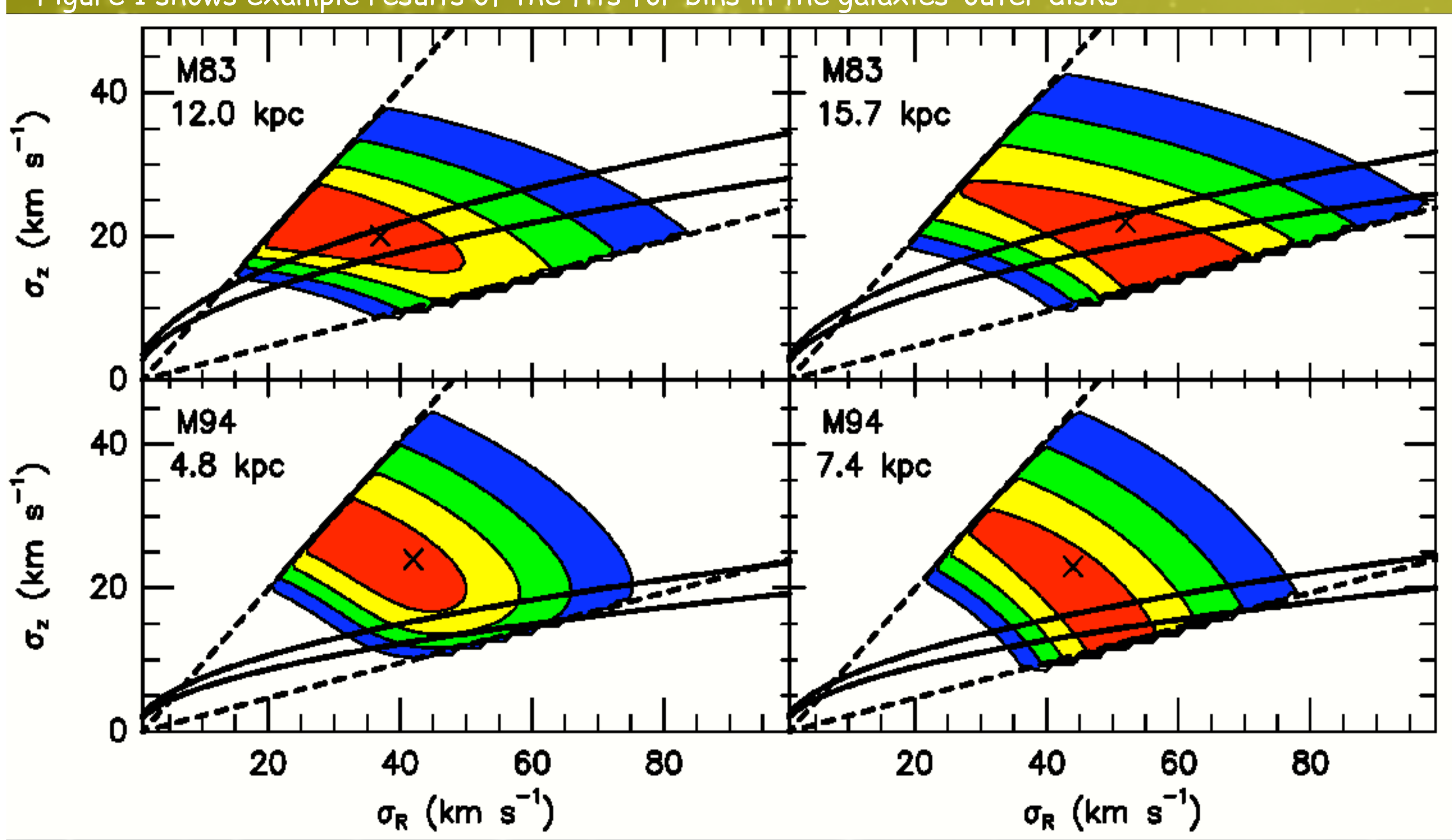

Fig. 1. Maximum likelihood probability contours for the outer disks of M83 and M94. From inner to outer, the contour regions enclose 38% (0.5σ), 68% (1σ), 86% (1.5σ) and 95% (2σ) of the probability. The dashed lines show the limits of our analysis. The black x indicates the most likely solution. The solid curves display the upper limits on σ_z derived from the additional constraint that the disk be stable against axisymmetric perturbations. The multiple curves represent intermediate (sech (z)) disks with scale heights of 200 and 300 pc. Note that for stability, h_z must be larger than these nominal values, especially in M94.

3. Results

- In spirals, the vertical velocity dispersion, σ_z, is related to disk surface mass, Σ(R), and the disk scale height, h_z, by: $\sigma_z^2(R) = K G \Sigma(R) h_z$
- K = 2π (isothermal), π (exponential) & π²/2 (intermediate sech(z)) (van der Kruit 1988)
- If (1) the light decays exponentially with a single scale length (h_R),
  (2) the disk mass-to-light ratio (M/L) is constant, and
  (3) the scale height is also constant,

then σ_z should decrease exponentially, with a scale length twice that of the light
- Fig 2 shows that σ_z *tracks the light in the inner regions, but flattens out at R > 4* h_R
- The minimum $\sigma_z \sim 15$ km s^{-1} is >> the typical measurement error, and cannot be due to dust, contamination by H II regions, or large scale warping (Herrmann & Ciardullo in prep)
- M94's flat profile is partially explained by its radial light profile: initially h_R = 1.22 kpc but then breaks to a shallower profile (h_R = 7.16 kpc) at R > 5 kpc (de Blok et al. 2008)
- However, σ_z is still much higher than possible for a constant M/L, constant h_z disk
- Moreover, *both disks have stability issues at large radii*: to be stable against axisymmetric perturbations, a thin stellar disk must obey the Toomre (1964) criterion:

$$\sigma_R > 3.36 G\Sigma/\kappa,$$

where κ is the epicyclic frequency of the orbits
- Combining this criterion with the equation above yields the strong constraint on σ_z:

$$\sigma_z < (K h_z \kappa \sigma_R / 3.36)^{1/2}$$

- Relations between h_z, h_R, Hubble type, and μ_0 (the central disk surface brightness) from edge-on galaxy studies (de Grijs & Peletier 1997; de Grijs 1998; Kregel et al. 2002; Bizyaev & Mitronova 2002) imply that h_z for both M83 and M94 is ~ 300 pc
- Yet, h_z in the outer regions must be >> 300 pc if one is to maintain stability (see Fig 1)
- *Could the flaring and high values of* σ_z *in the outer regions be due to subhalo heating?*
- Fig 2 compares our σ_z profiles to results from N-body simulations of dark subhalo interactions with a Milky Way-like galaxy (private communication with S. Kazantzidis)
- *The agreement between observations and theory is excellent*
- The simulations also predict a corresponding flaring of the disk

4. Conclusions

- The persistence of very thin spiral disks has long been recognized as a significant constraint for structure growth models (cf. Moore et al. 1999)
- We find kinematic evidence that *beyond ~4* h_R *disk thickness increases substantially and the z-velocity dispersion is independent of radius*
- This result is *consistent with cosmological models of hierarchical structure formation, where a thin disk is heated by a small number of massive subhalos*, which are initially on radial orbits (Hopkins et al. 2008) or orbiting coplanar to the disk (private communication with S. Kazantzidis)
- Since simulations show that disk heating does not scale linearly with the mass and number of subhalos, *this is potentially a strong constraint on substructure*
- More data is required to explore this constraint further

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The background image is from a simulation by the Via Lactea Project.

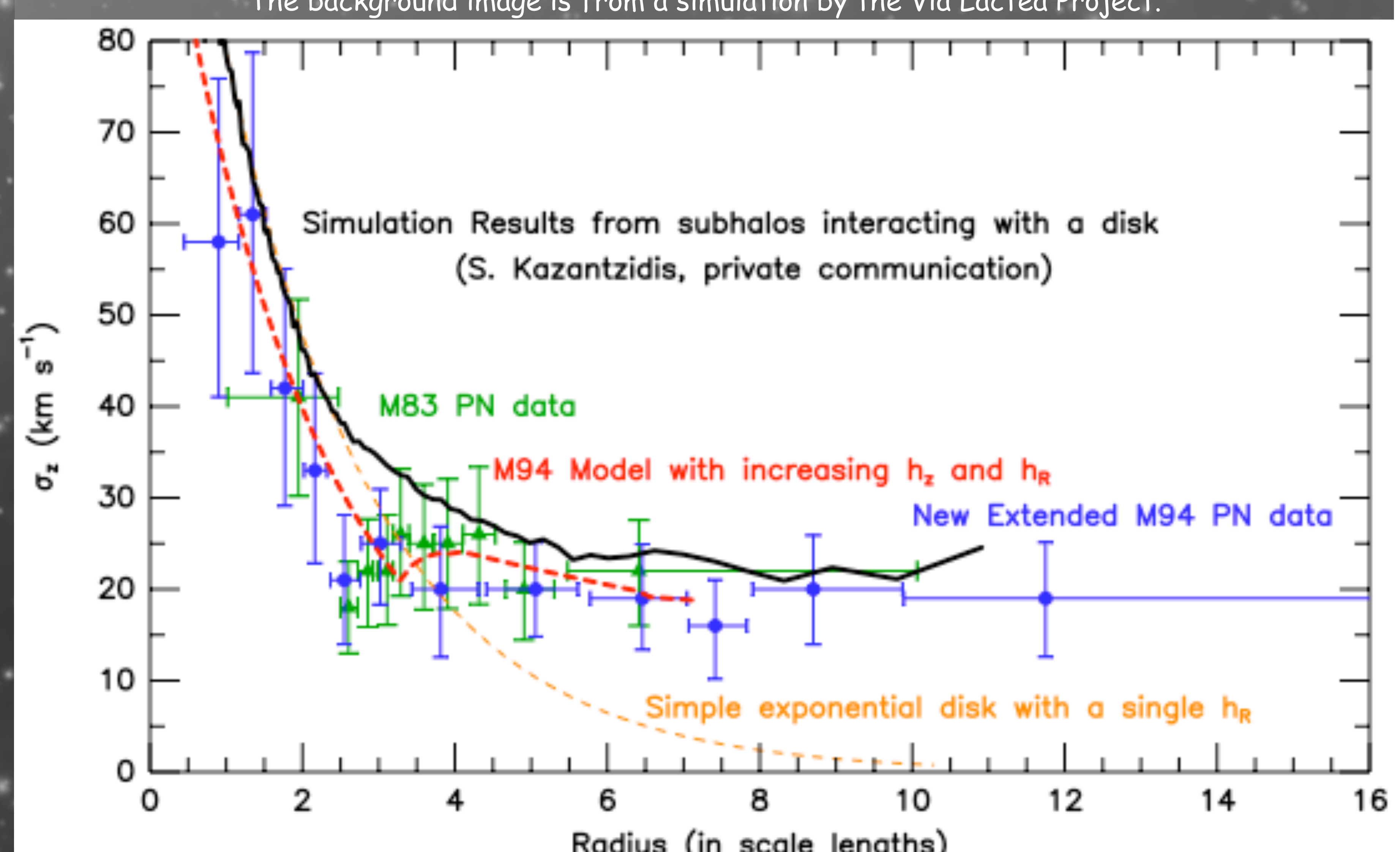

Fig. 2. Comparison of our M83 and M94 results to the σ_z values (solid black curve) determined from a numerical simulation of subhalos interacting with a disk. The data have not been rescaled in any way. The agreement between the data and model is much better than with the constant M/L, constant h_z exponential disk (dashed orange curve). A simple model with increasing scale height and scale length also fits the data very well (dashed red curve).

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