A New Probe of Dark Matter in Spirals

Sukanya Chakrabarti (FAU); Leo Blitz (UCB); Phil Chang (University of Wisconsin-Milwaukee); Frank Bigiel (Heidelberg)

Overview

- Cold gas as tracer of perturbing dark-matter dominated dwarf galaxies

- Galaxies with optical companions : Proof of Principle

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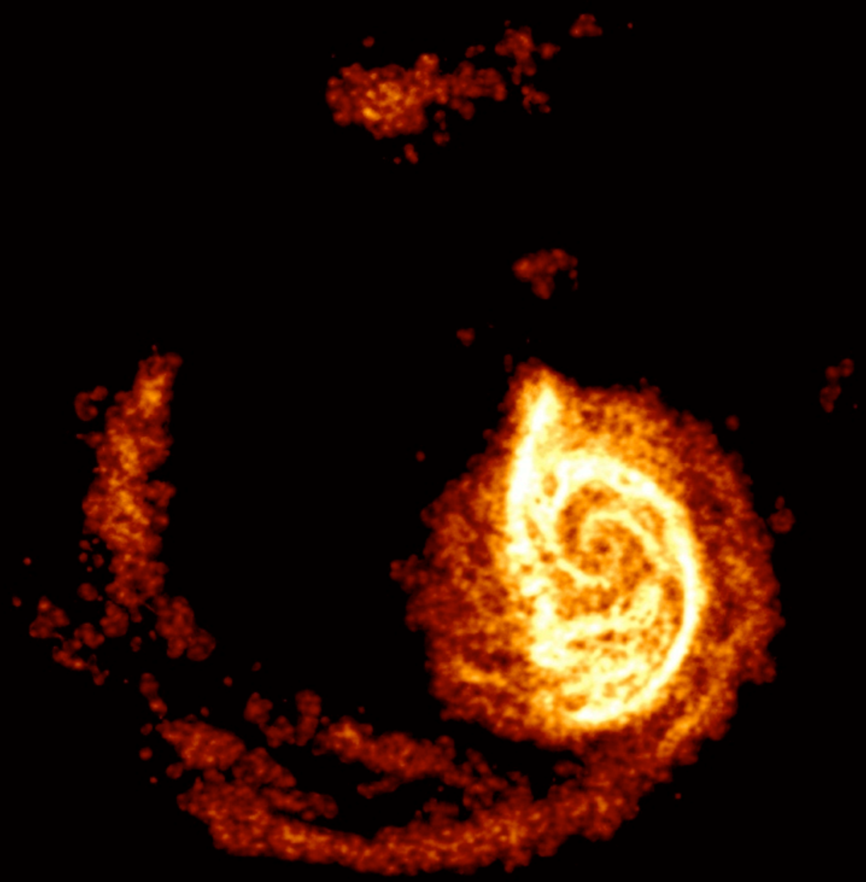

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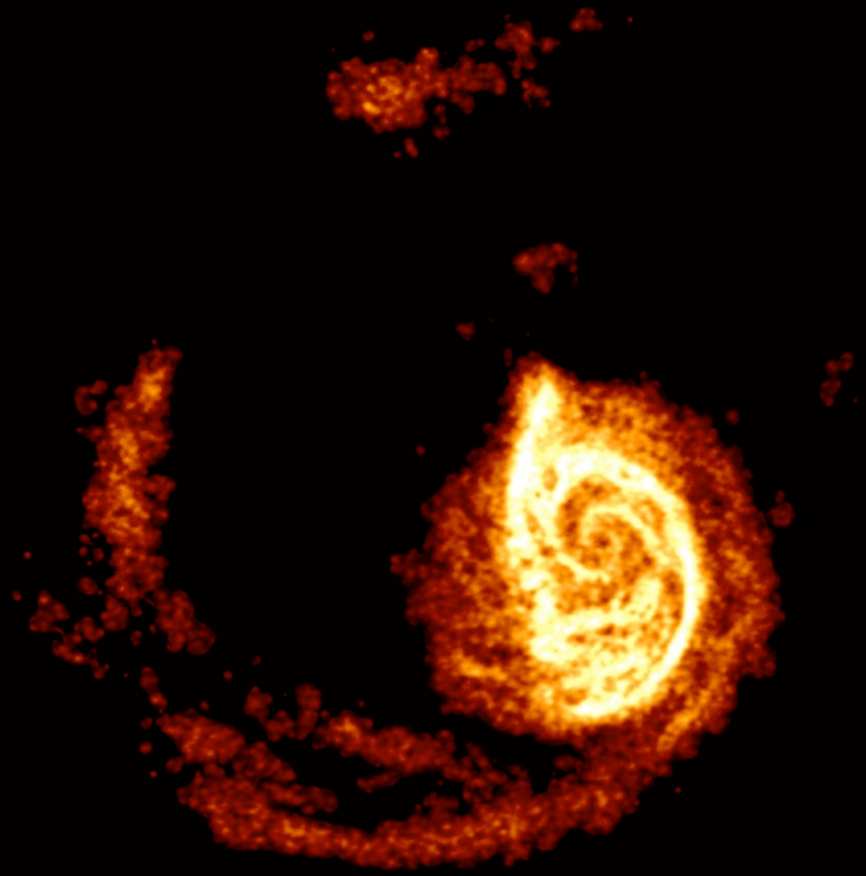

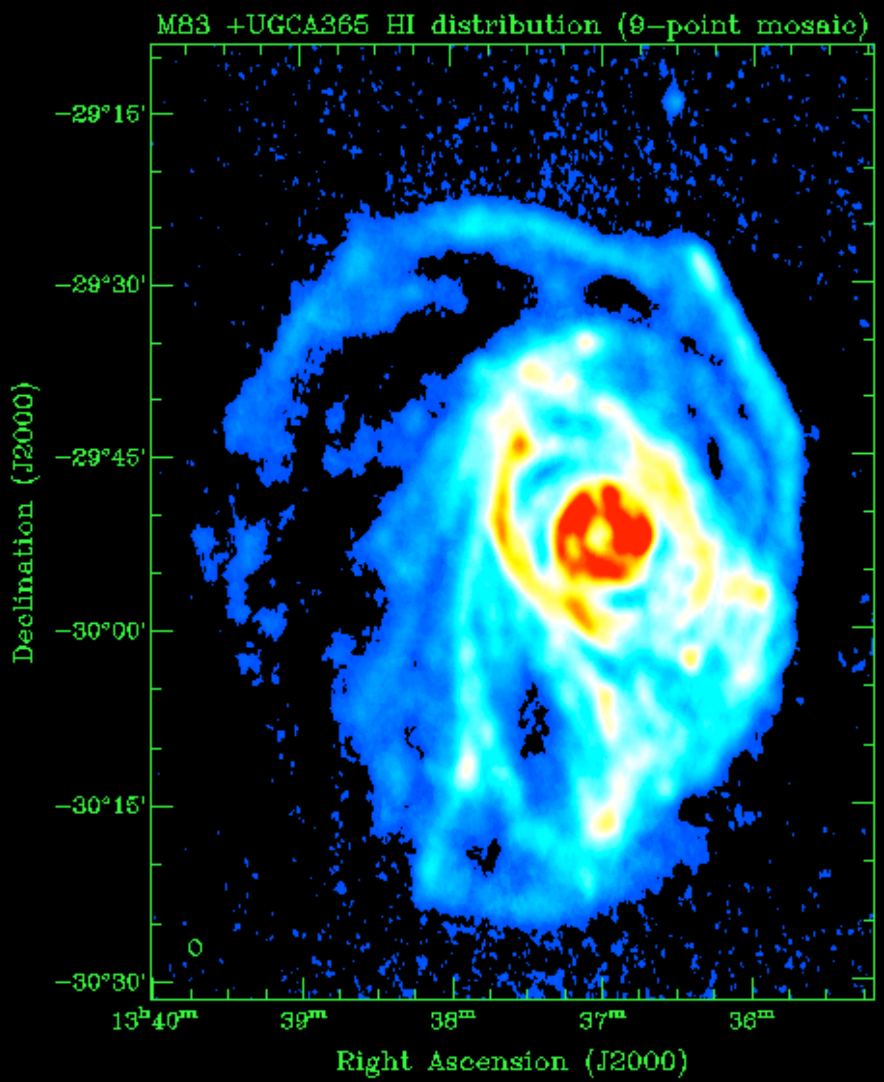

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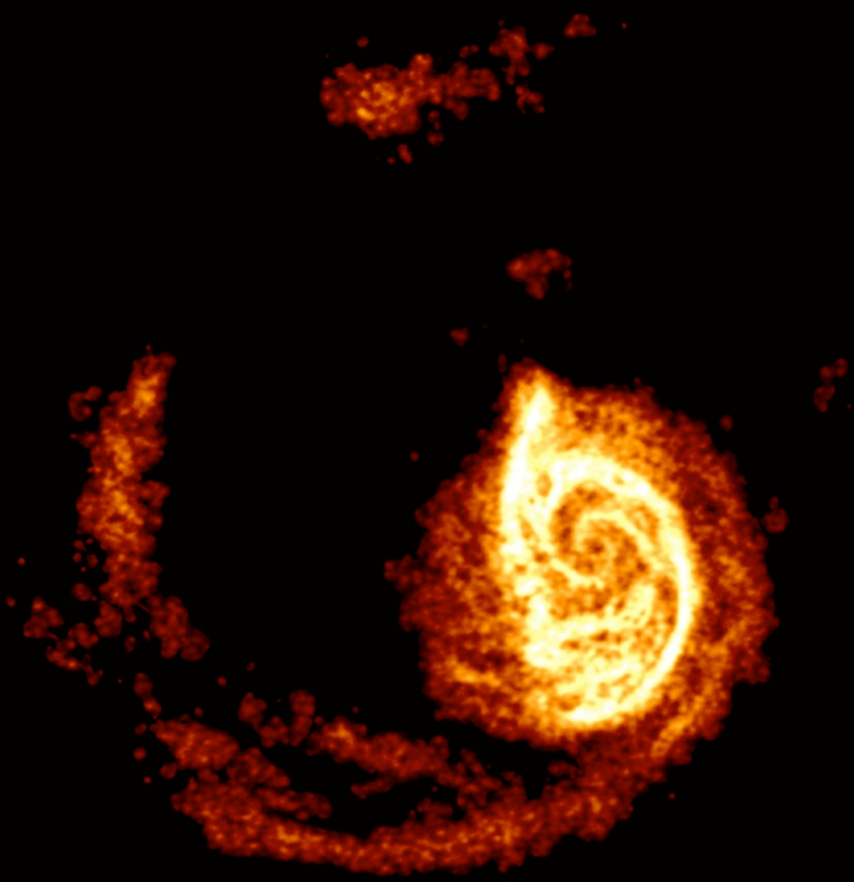

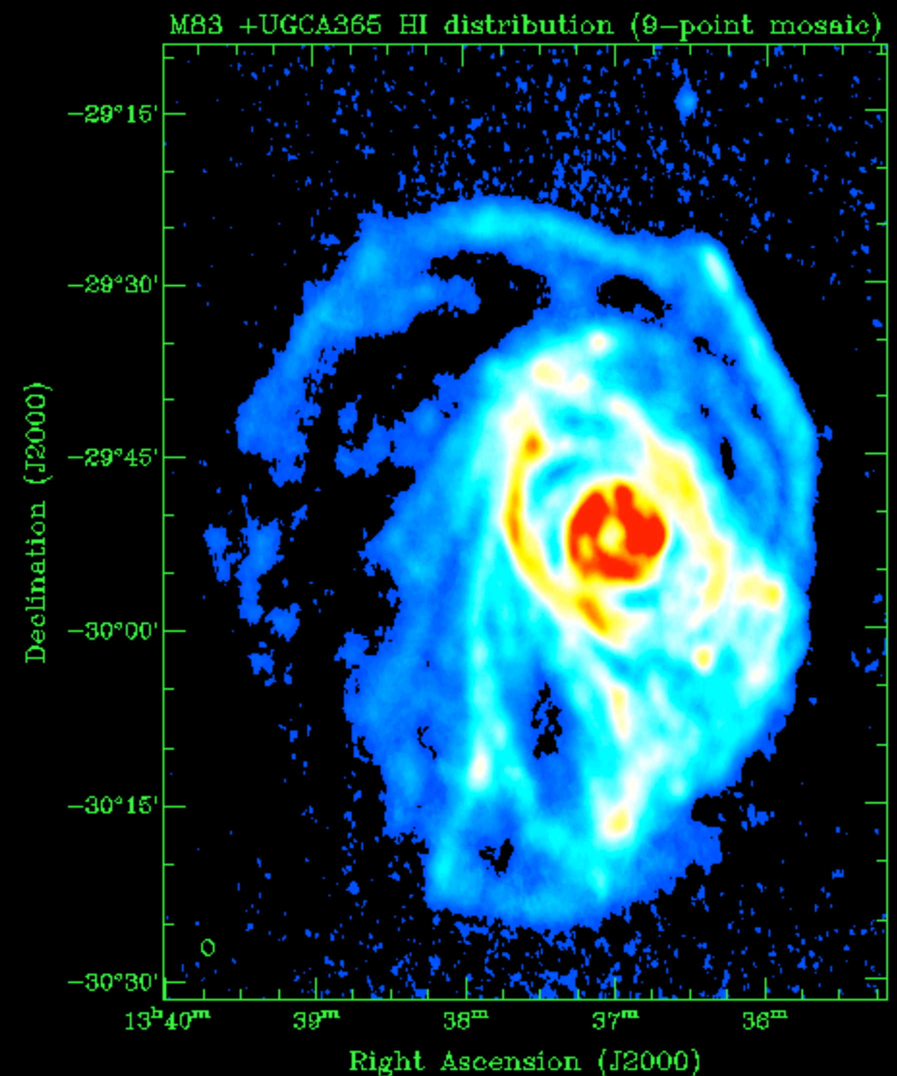

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Dark Sub-Halos: Expectations from Simulations

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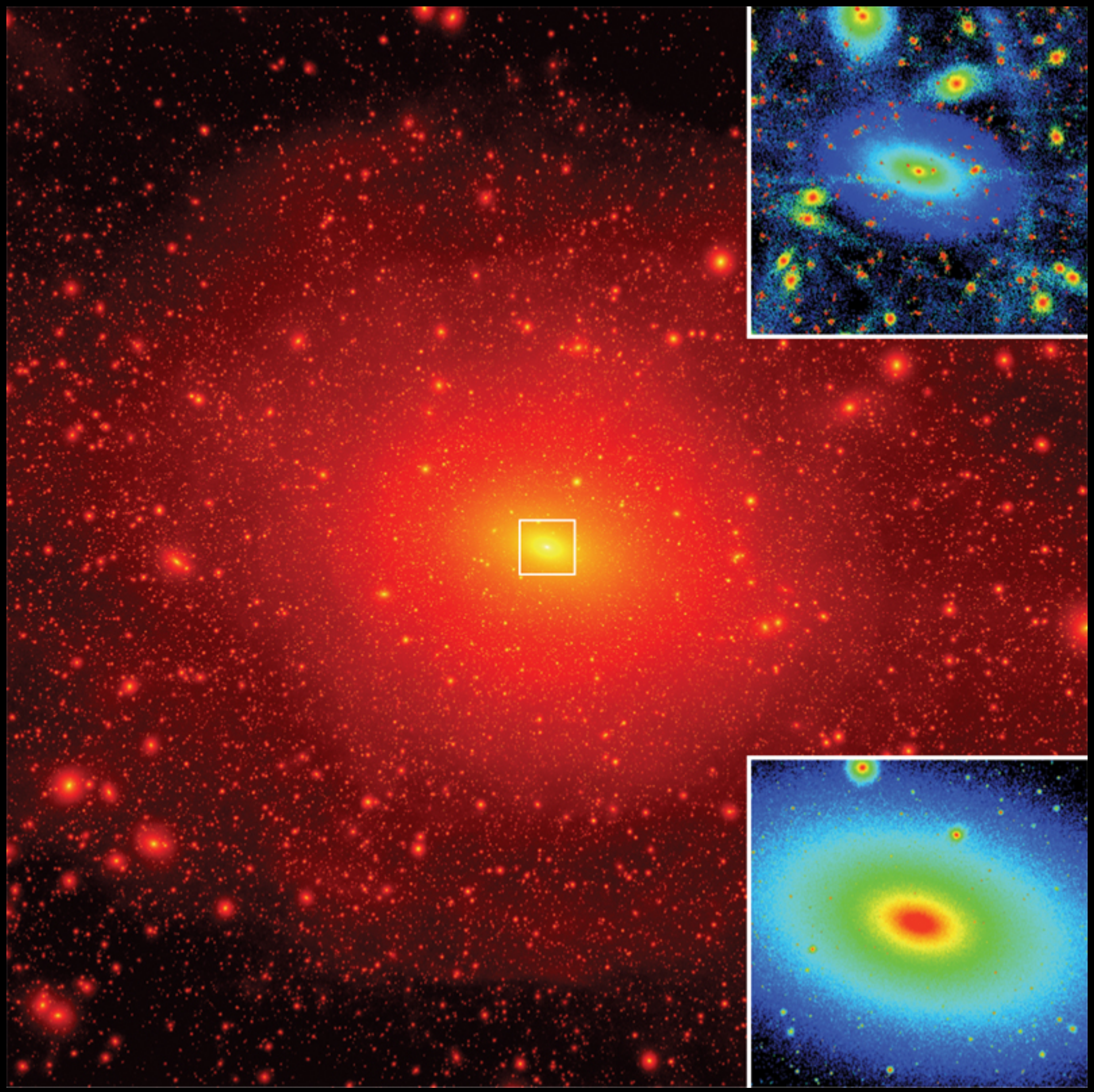

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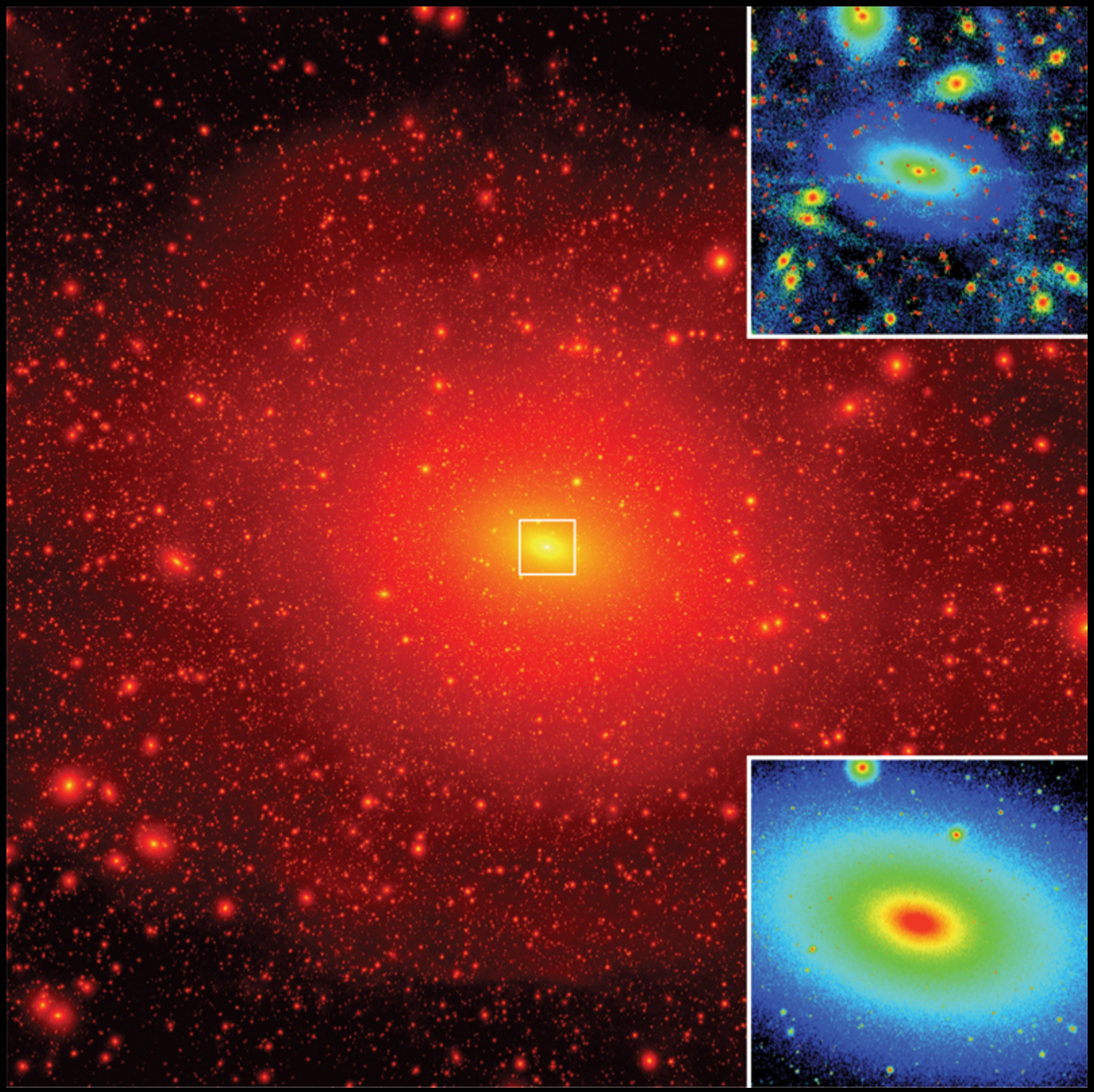

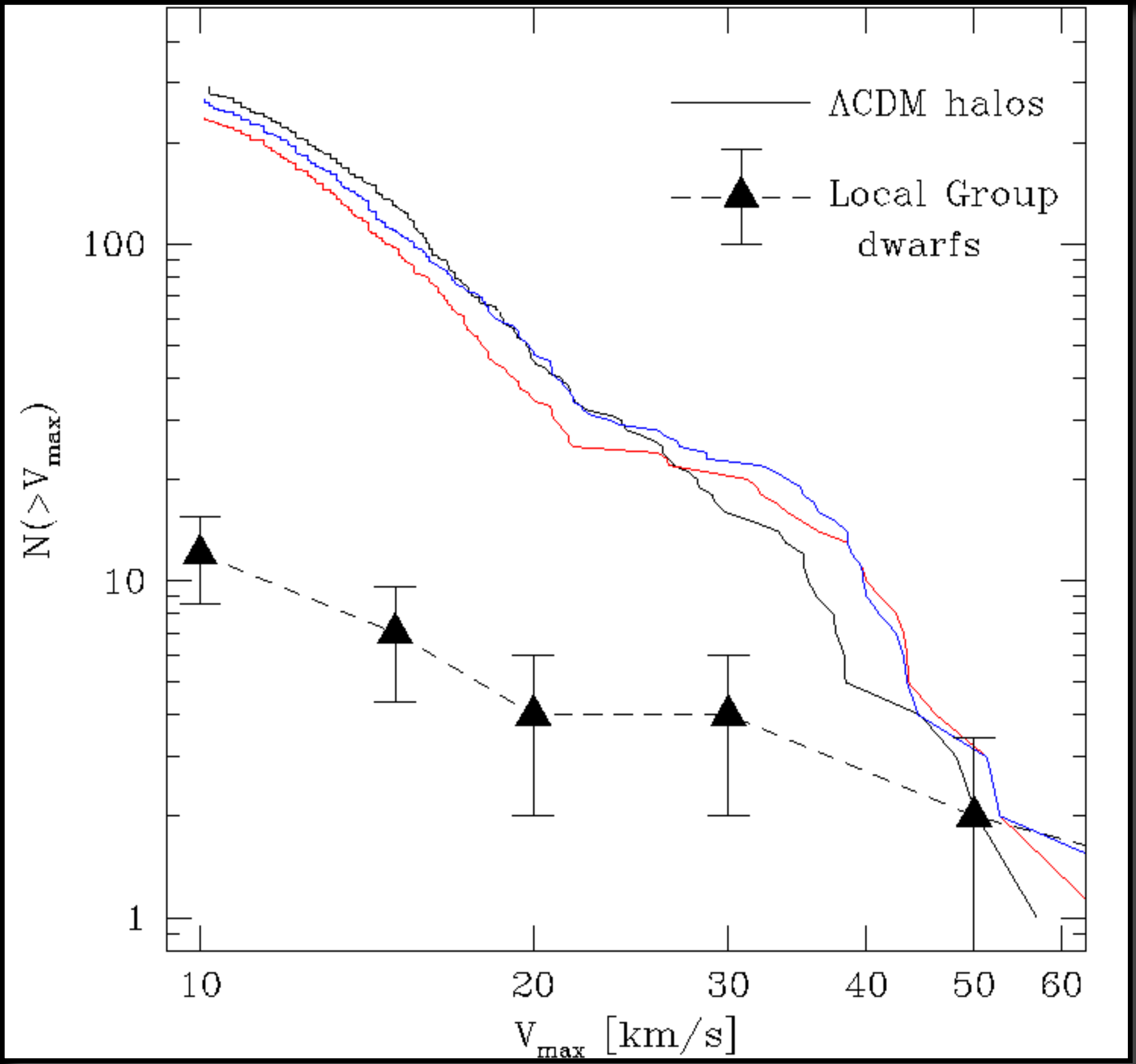

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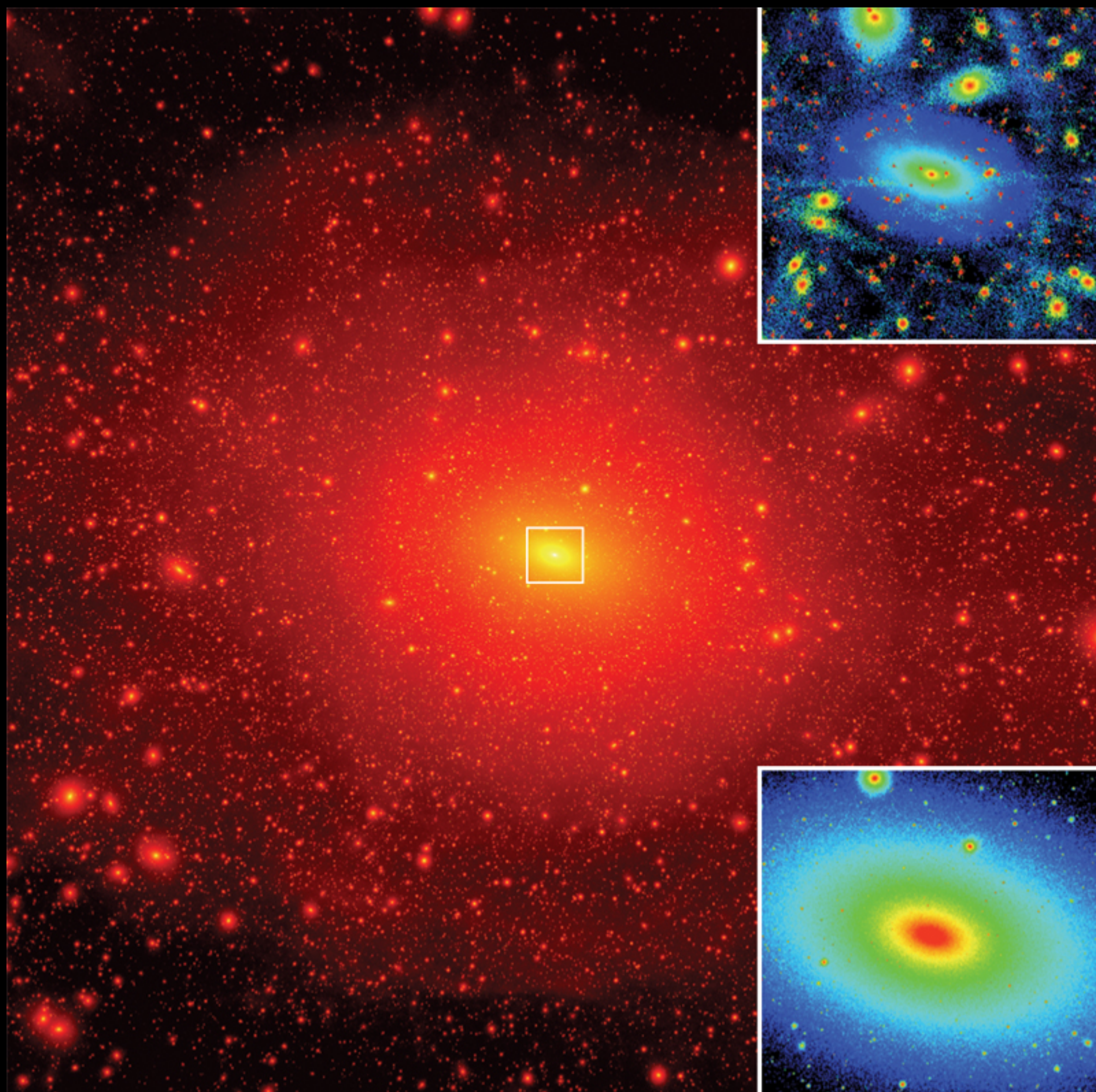

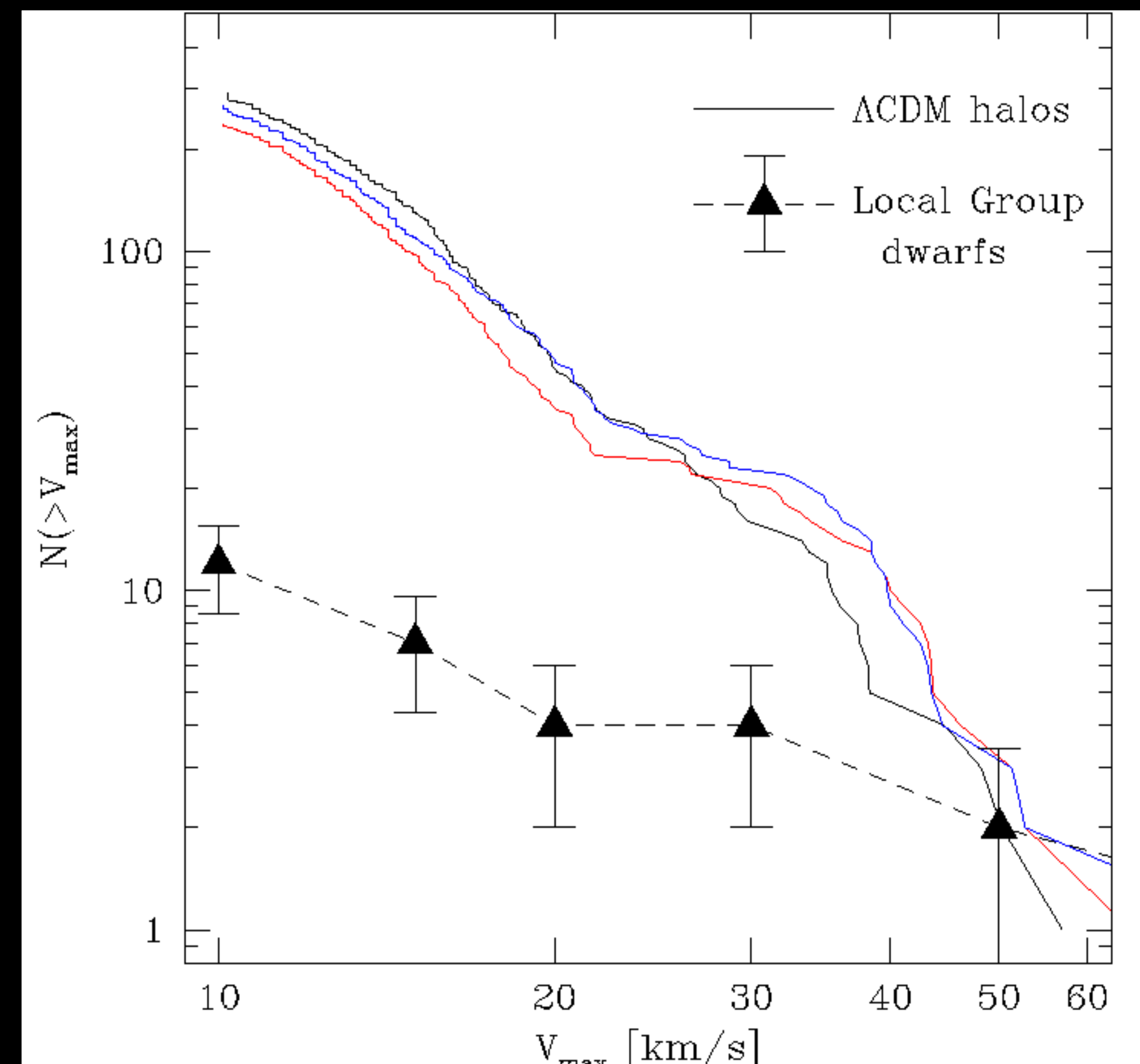

- Missing satellites problem (Klypin et al. 1999; Diemand et al. 2008)

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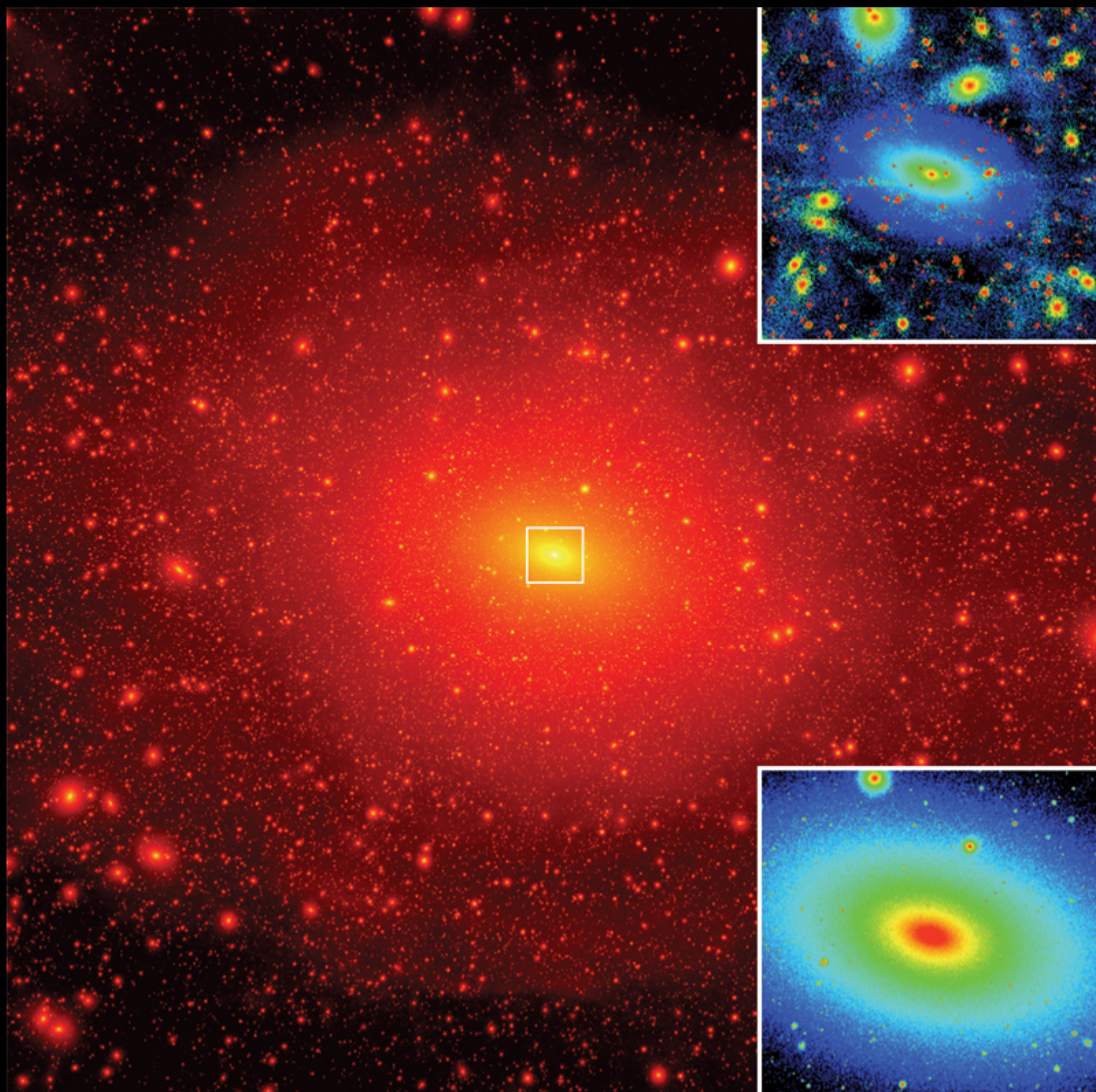

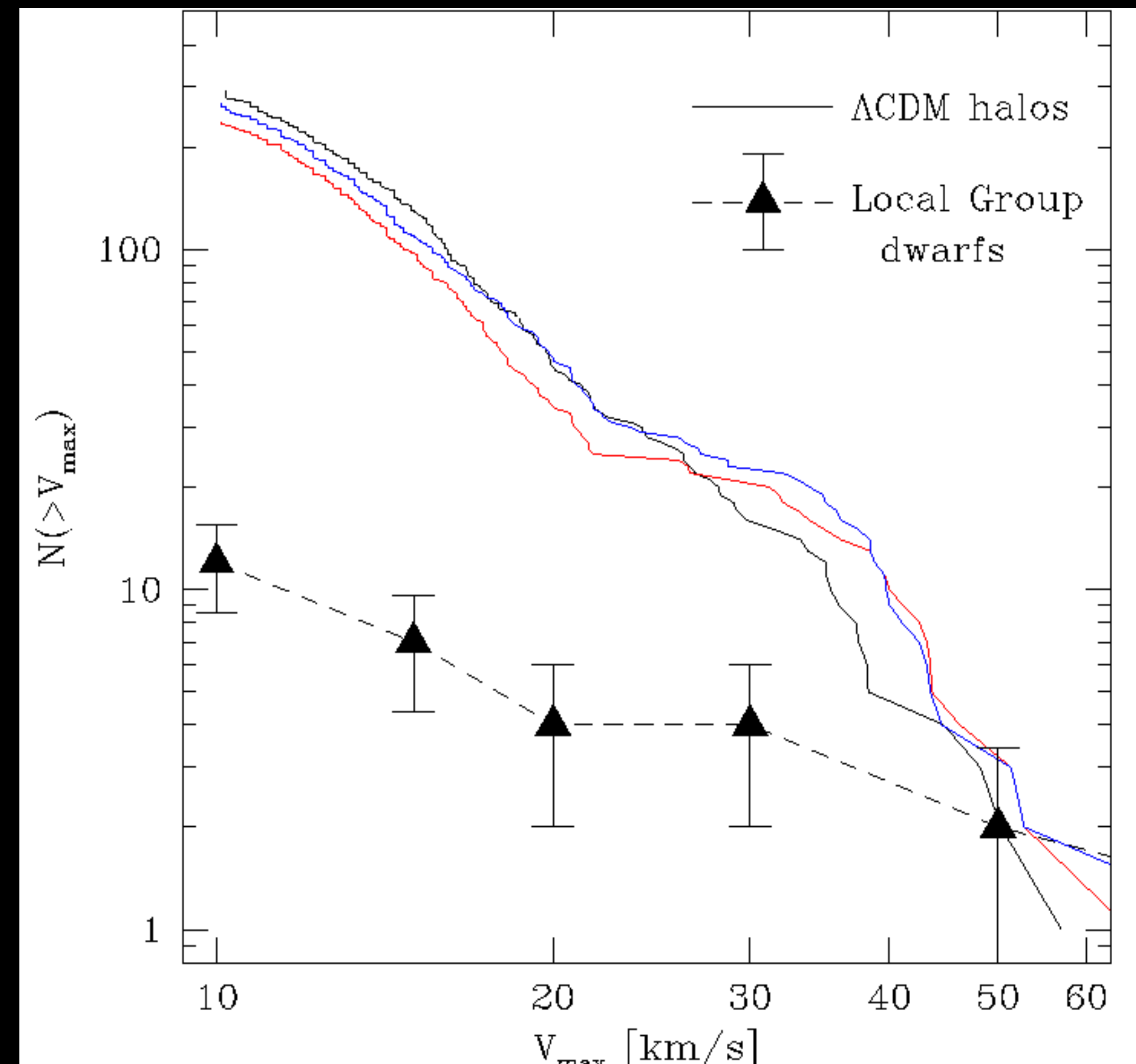

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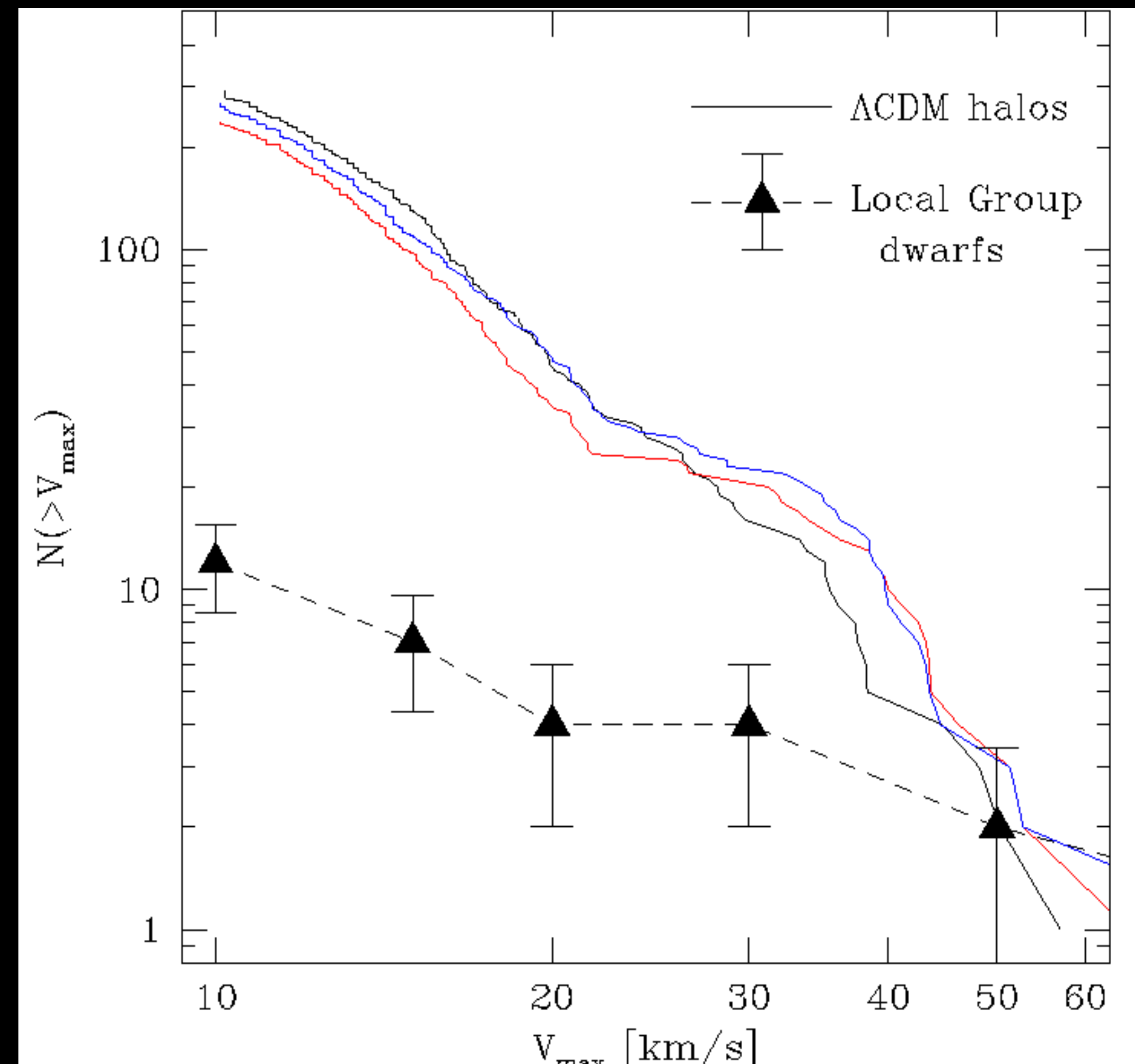

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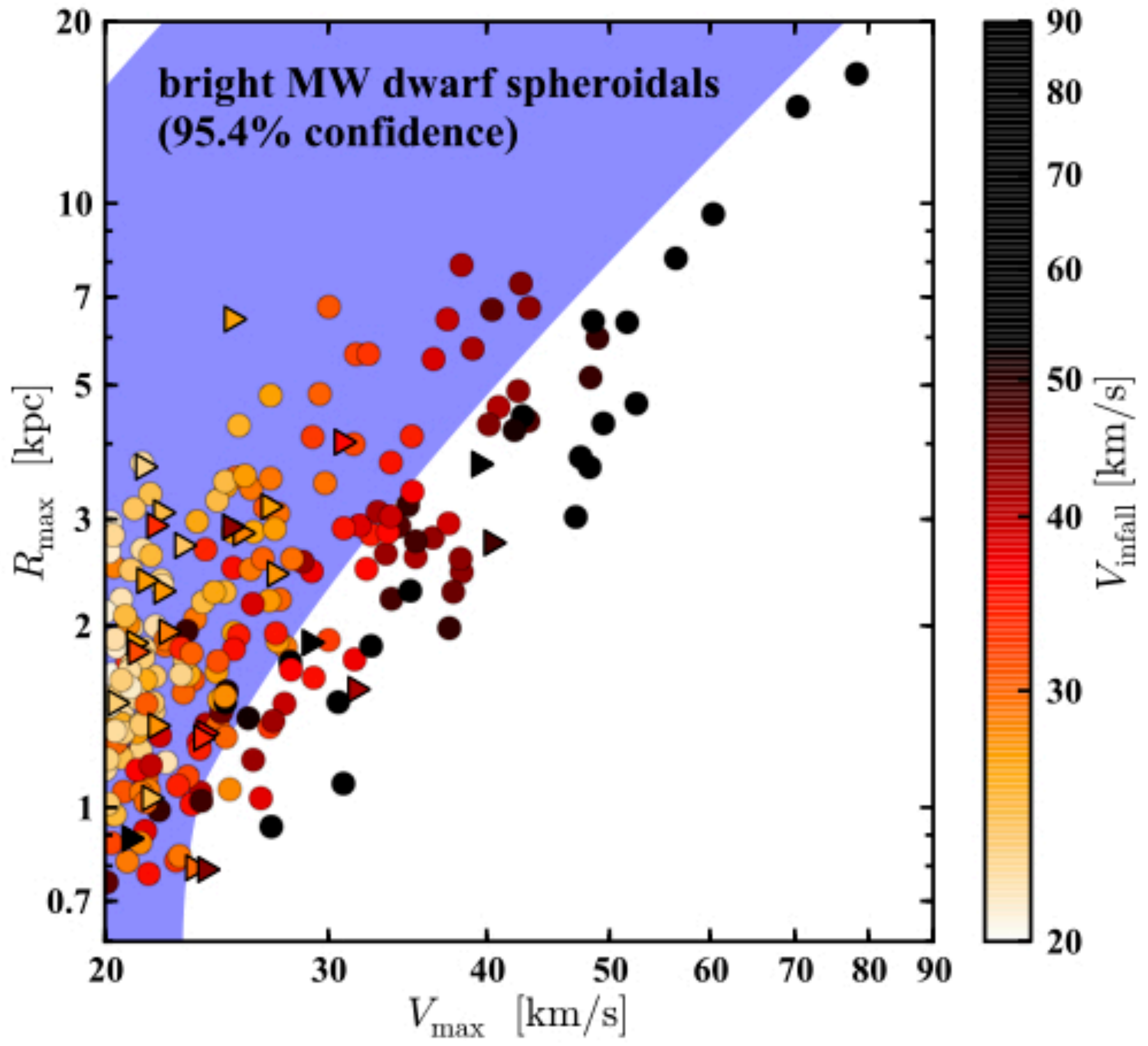

Figure 2. Subhalos from all six Aquarius simulations (circles) and Via Lactea II (triangles), color-coded according to V_{infall}. The shaded blue region shows the $2\,\sigma$ confidence interval for possible hosts of the bright MW dwarf spheroidals (see Fig. 1).

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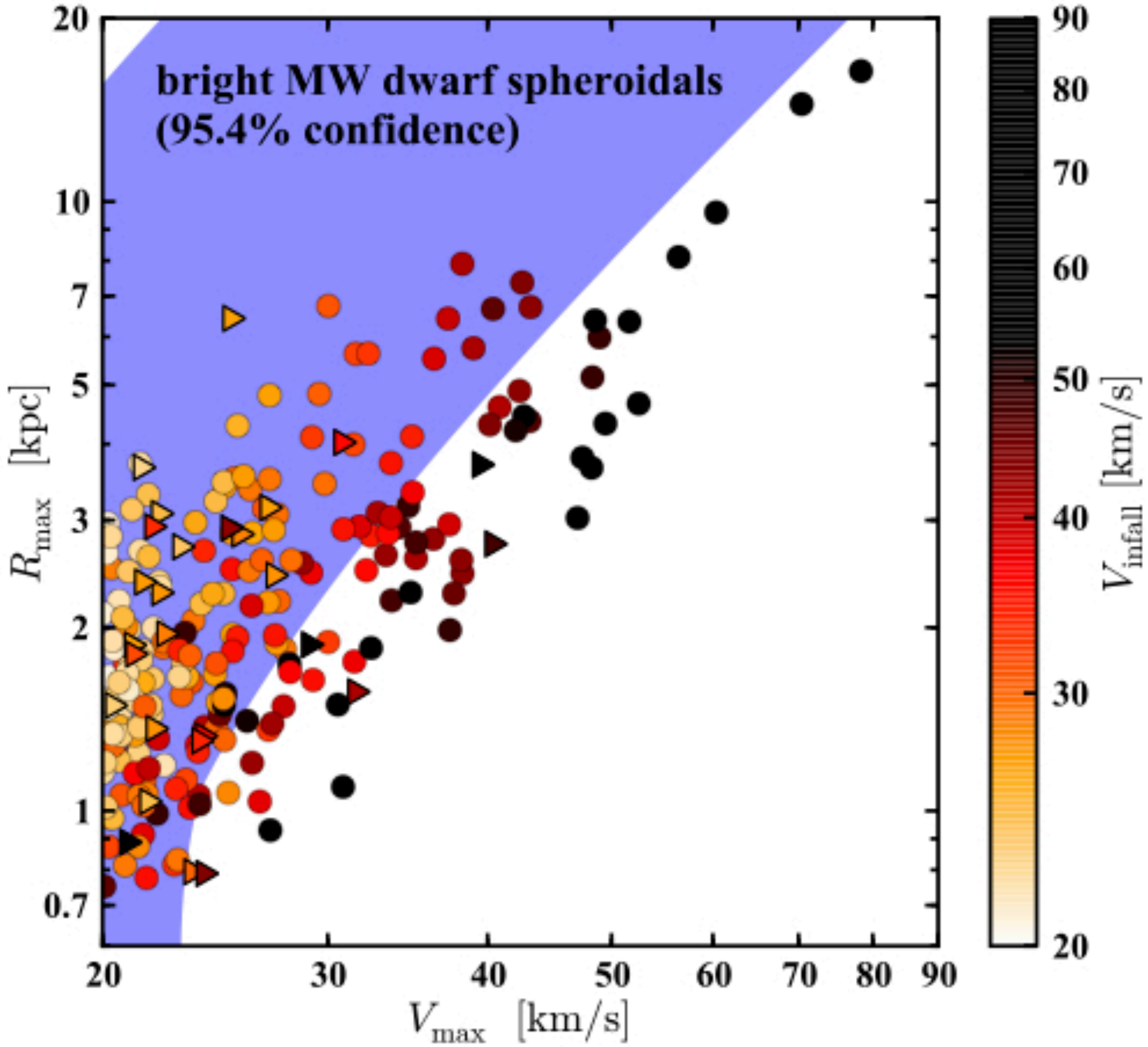

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- Massive satellites too dense to host known MW satellites (Boylan-Kolchin et al. 2011)

Tidal Imprints of dark-matter dominated dwarf galaxies on outskirts of Spirals

- Coldest Component Responds the Most! (by ratio of inverse sound speed squared). Gas has short-term memory.
- Maximize rate of detection of dim dwarf galaxies by looking for their tidal footprints on atomic hydrogen gas disks.

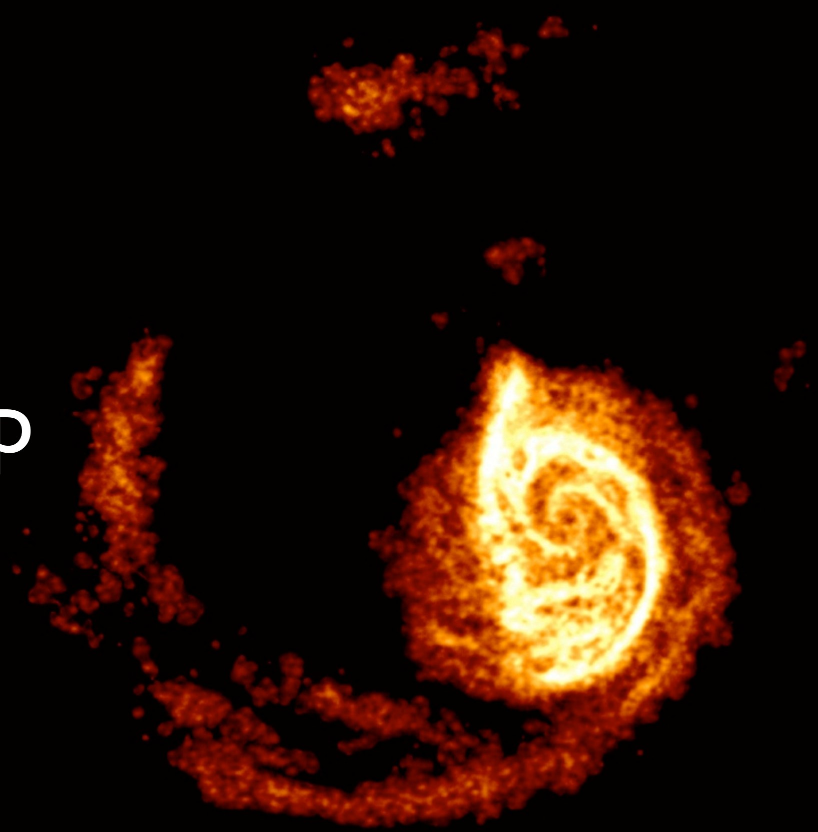
Atomic hydrogen (HI) Maps!

Footprints of Dark Sub-Halos

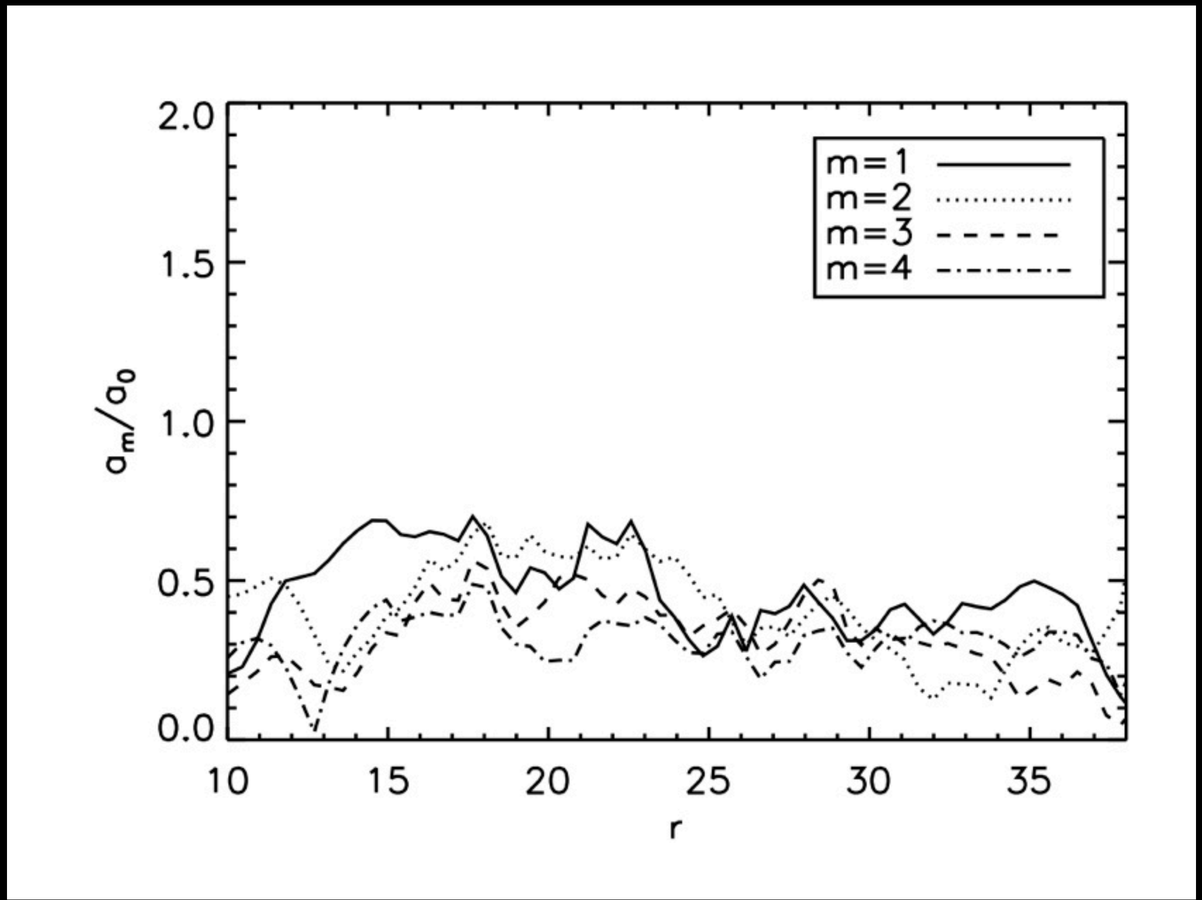
Disturbances in HI disks in Local Spirals: Proof of Principle

M51

HI Map



optical image



$$a_m(r) = \int \Sigma(r,\phi) e^{-im\phi} d\phi$$

Local Fourier Amplitudes of HI data: Metric of Comparison to simulations

M51

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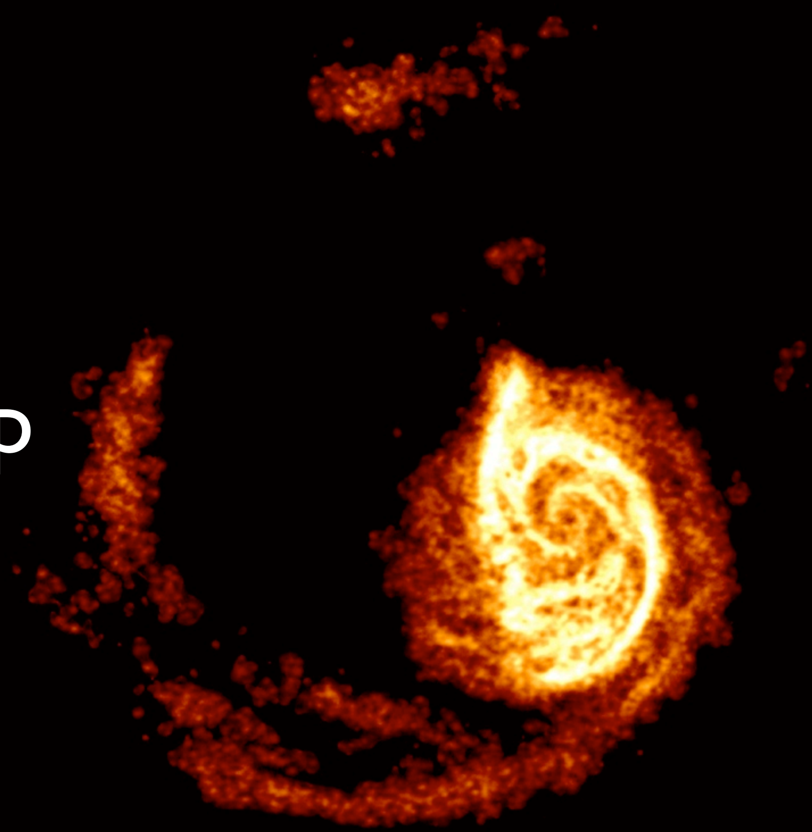

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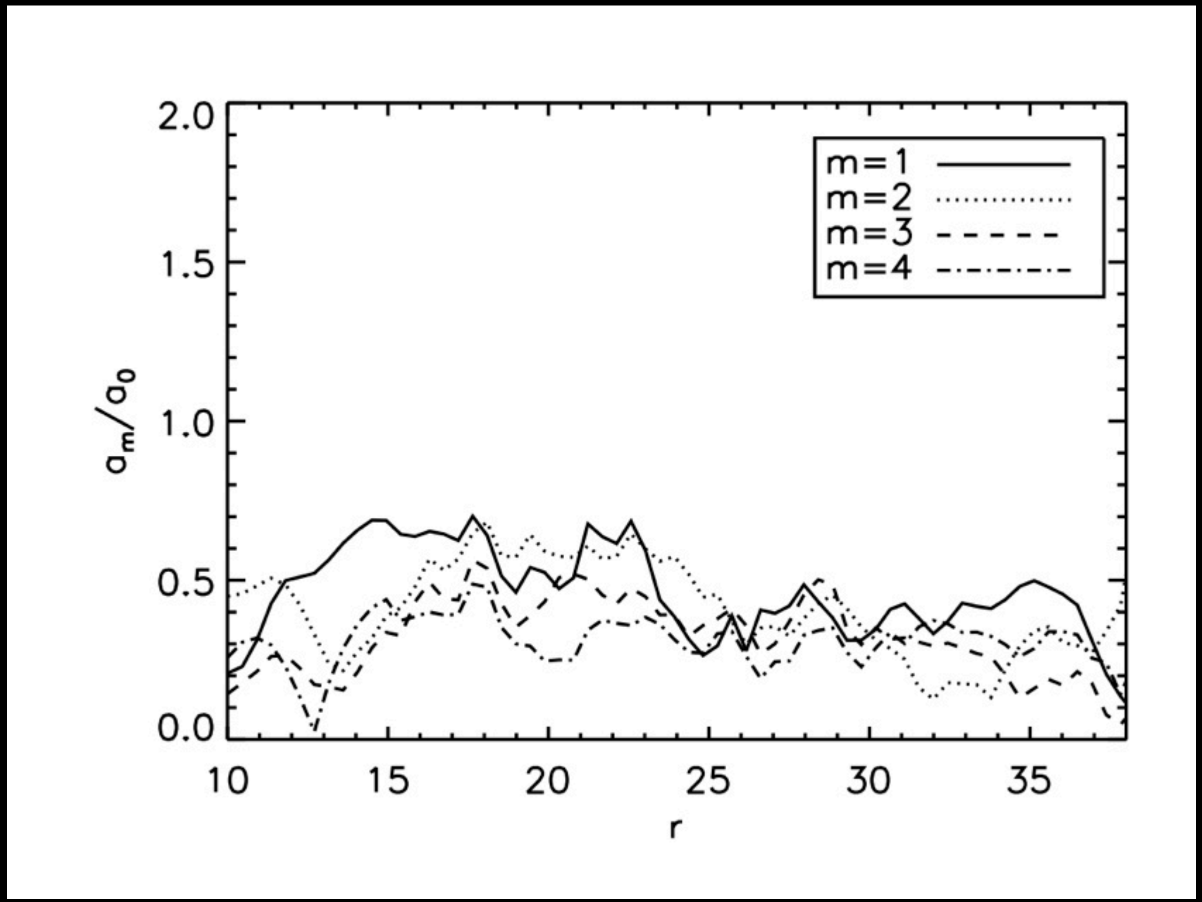

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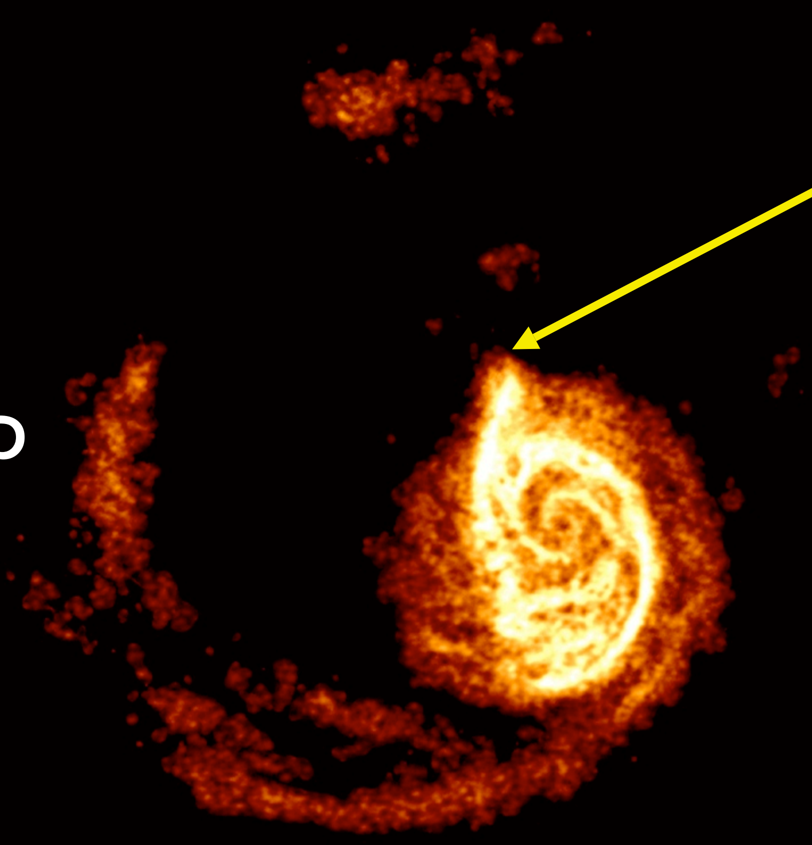

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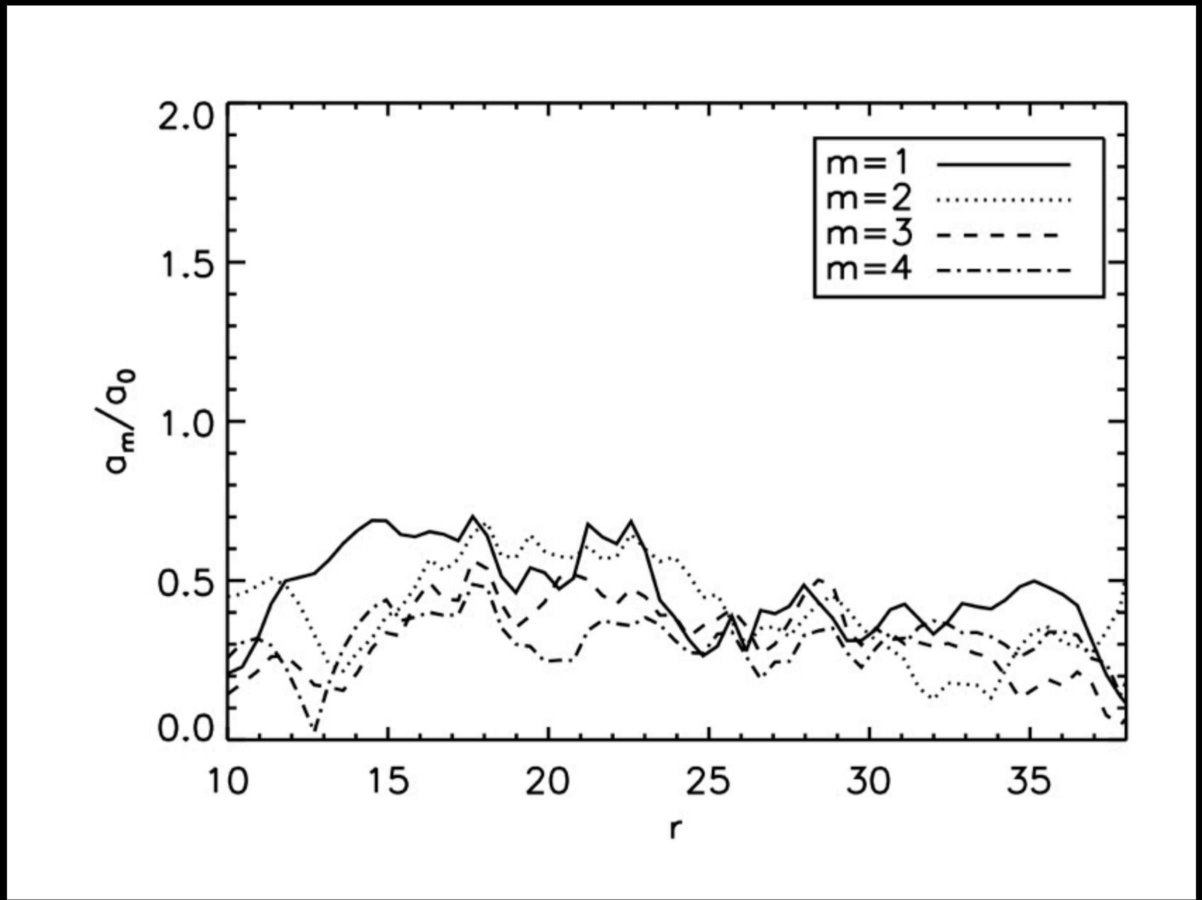

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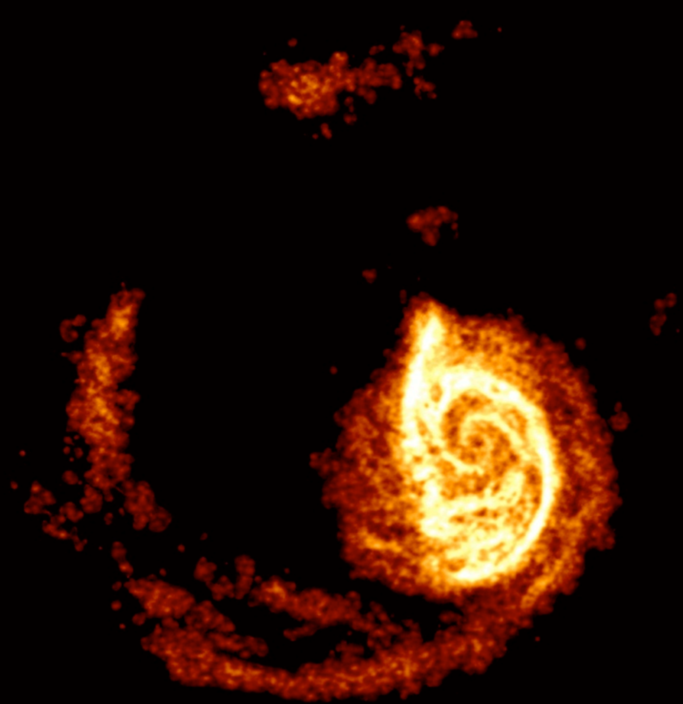
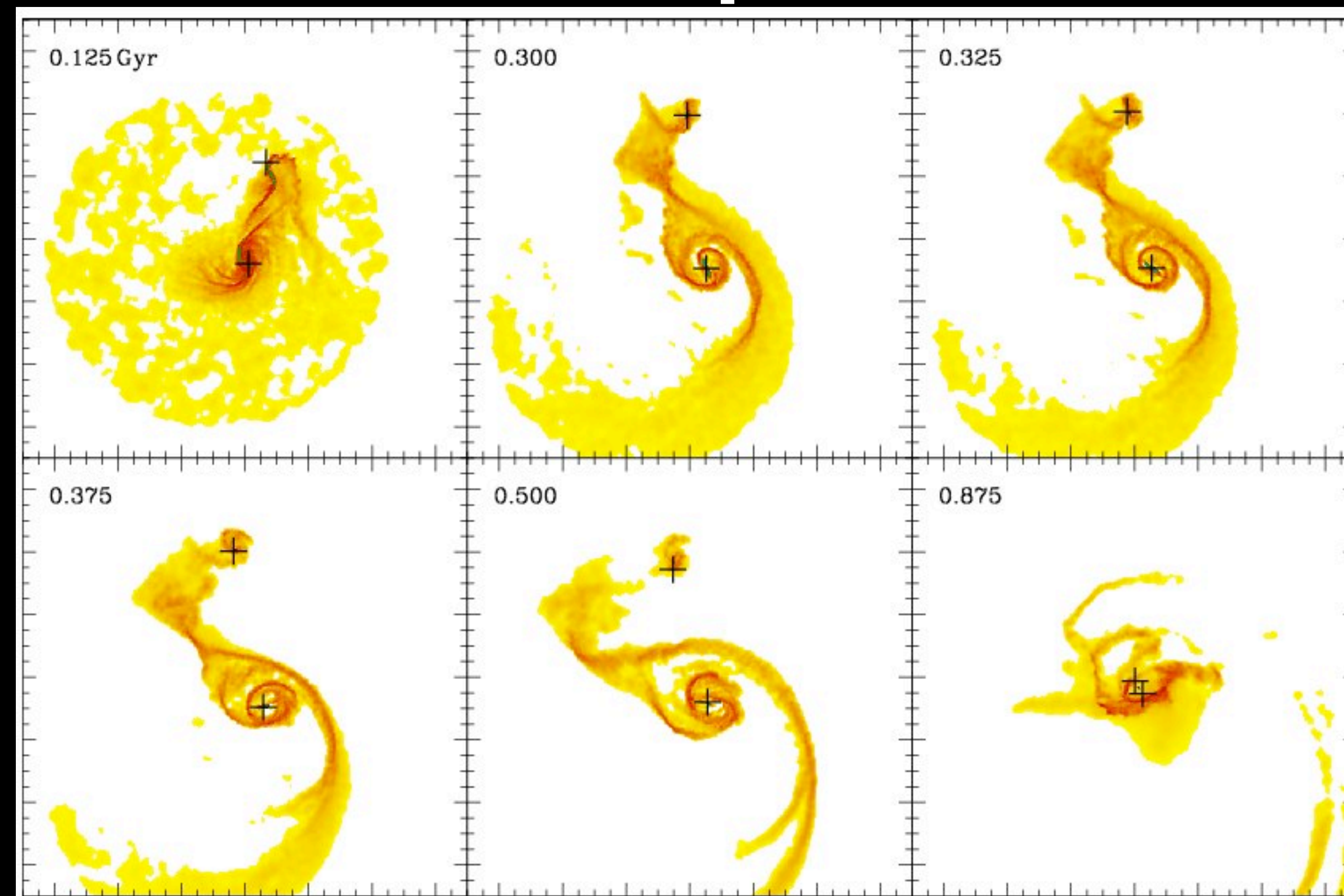
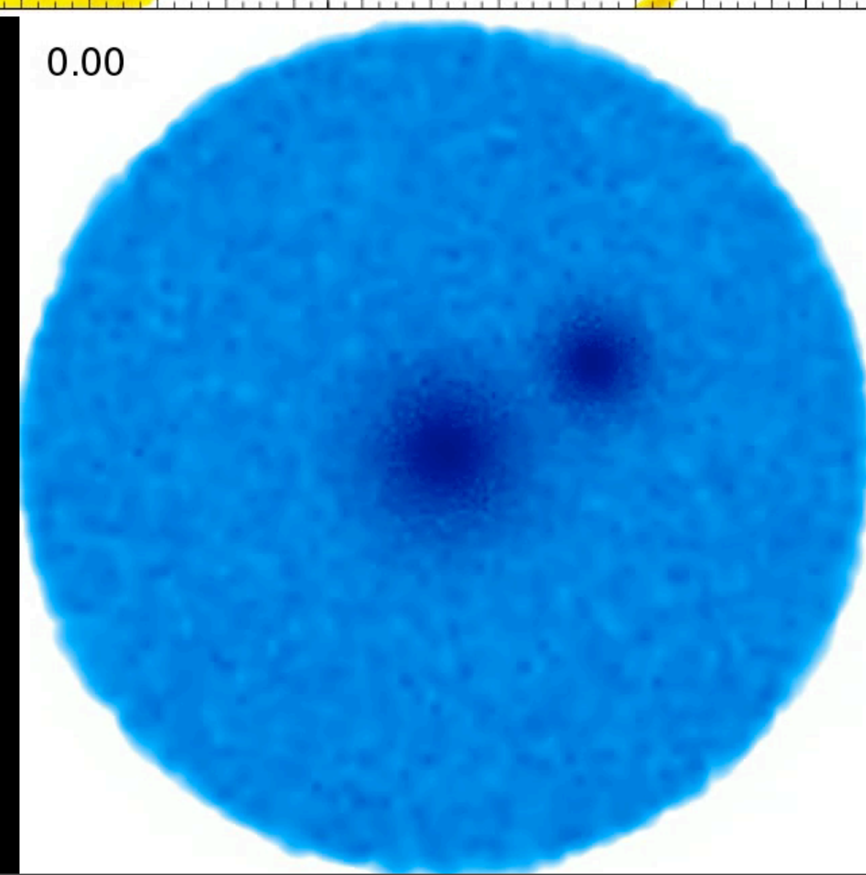
M51 Simulation Comparison



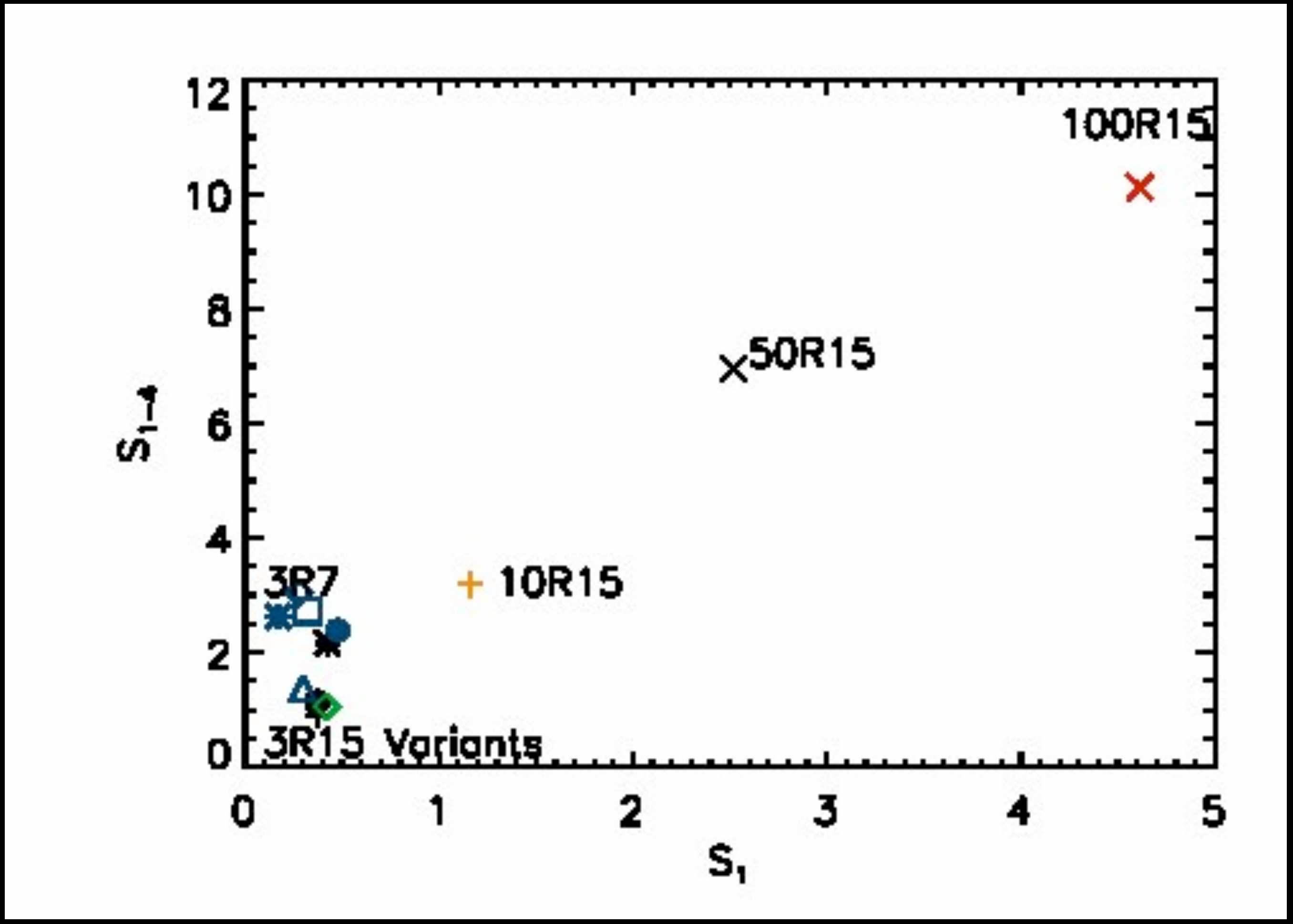




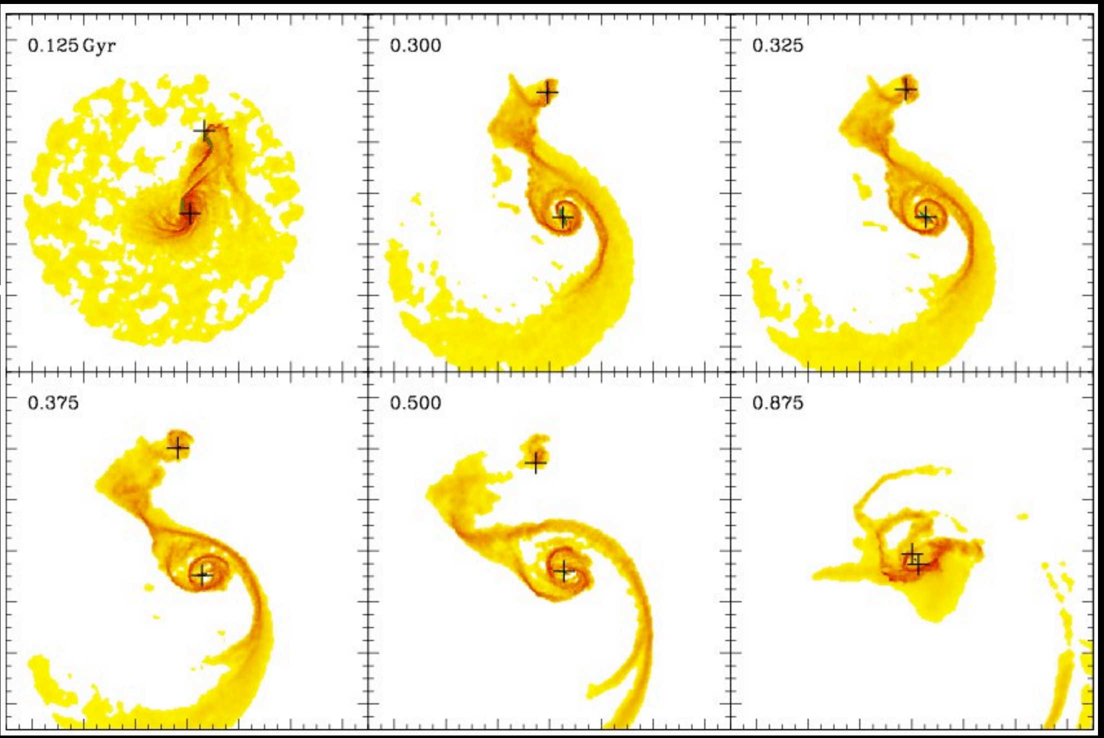
3-D stereoscopic rendering shown at AAS 2011

Chakrabarti, Bigiel, Chang & Blitz, 2011

Variance Vs Variance



Best-fits -- close to origin on variance vs variance plot (S_1-S_{1-4}), shown at best-fit time. "Variants" include varying initial conditions (ICs), interstellar medium (ISM), star formation prescription, orbital inclination, etc. Our estimate of M_s (1:3) close to observational numbers.



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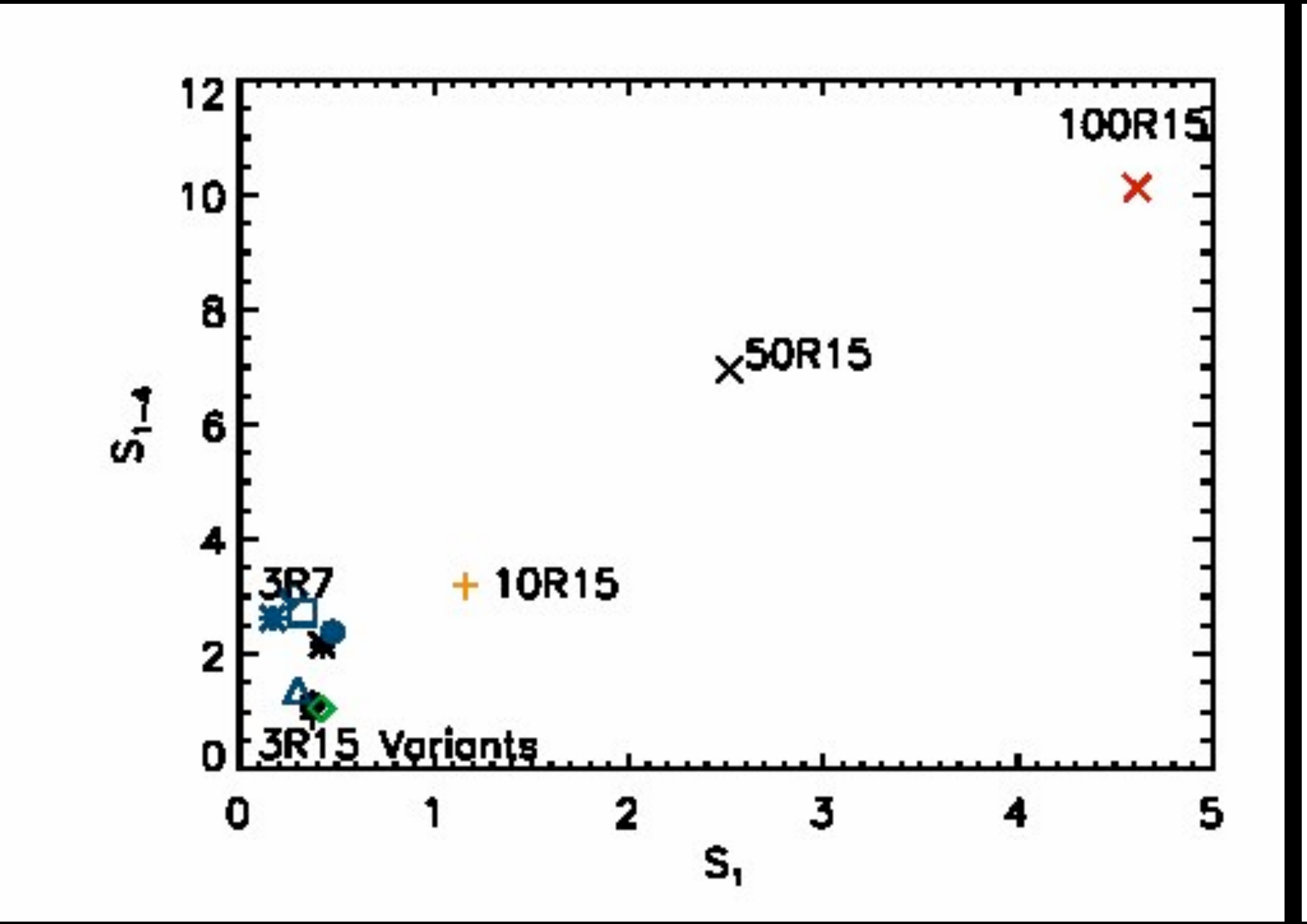

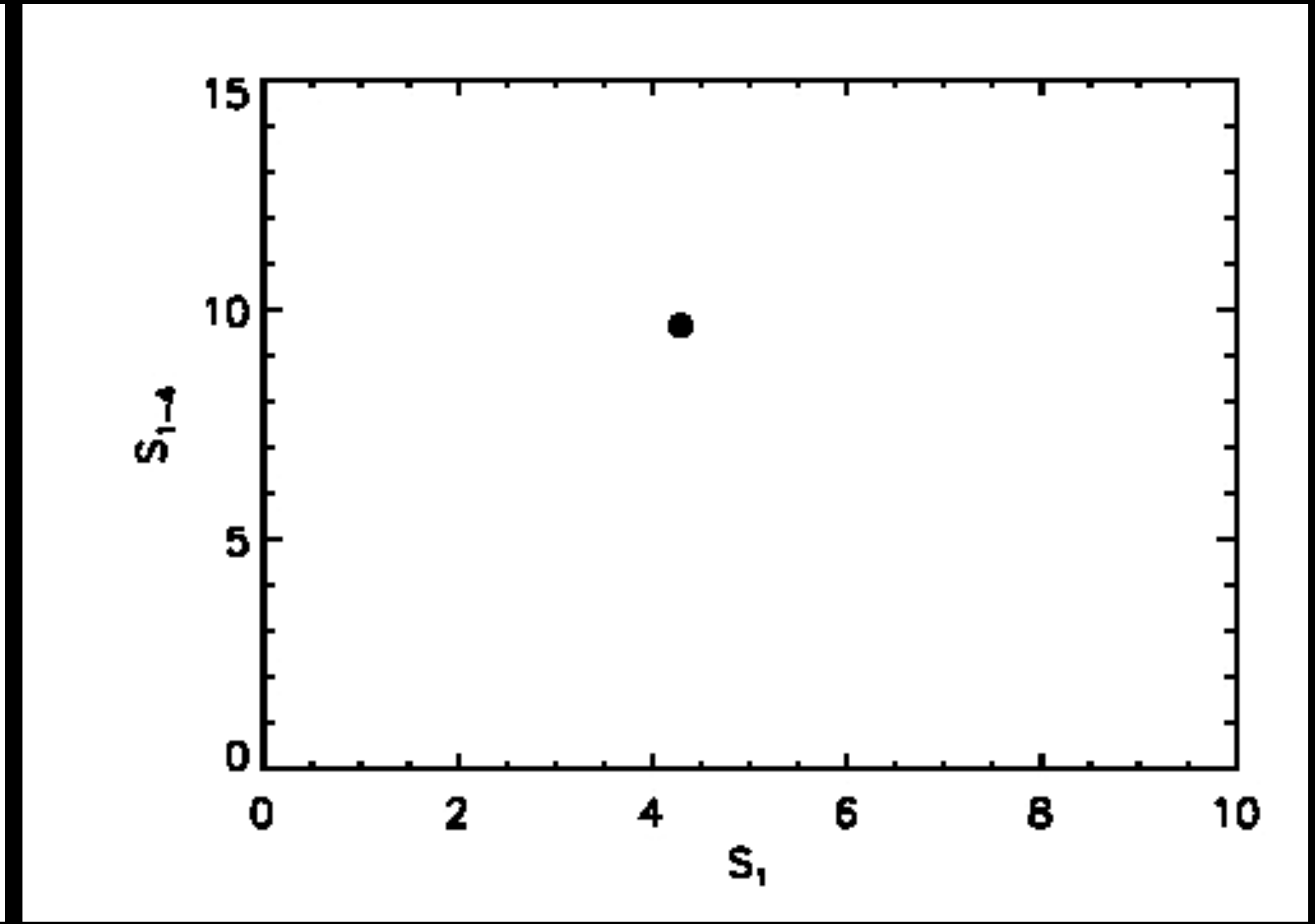

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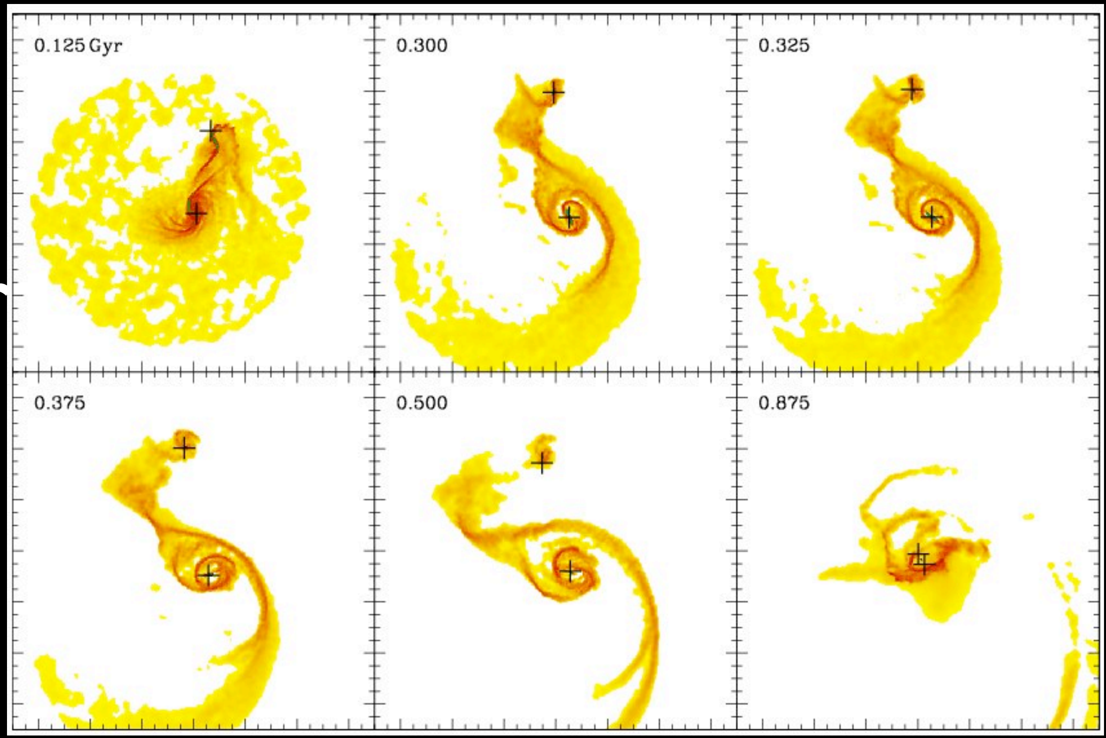

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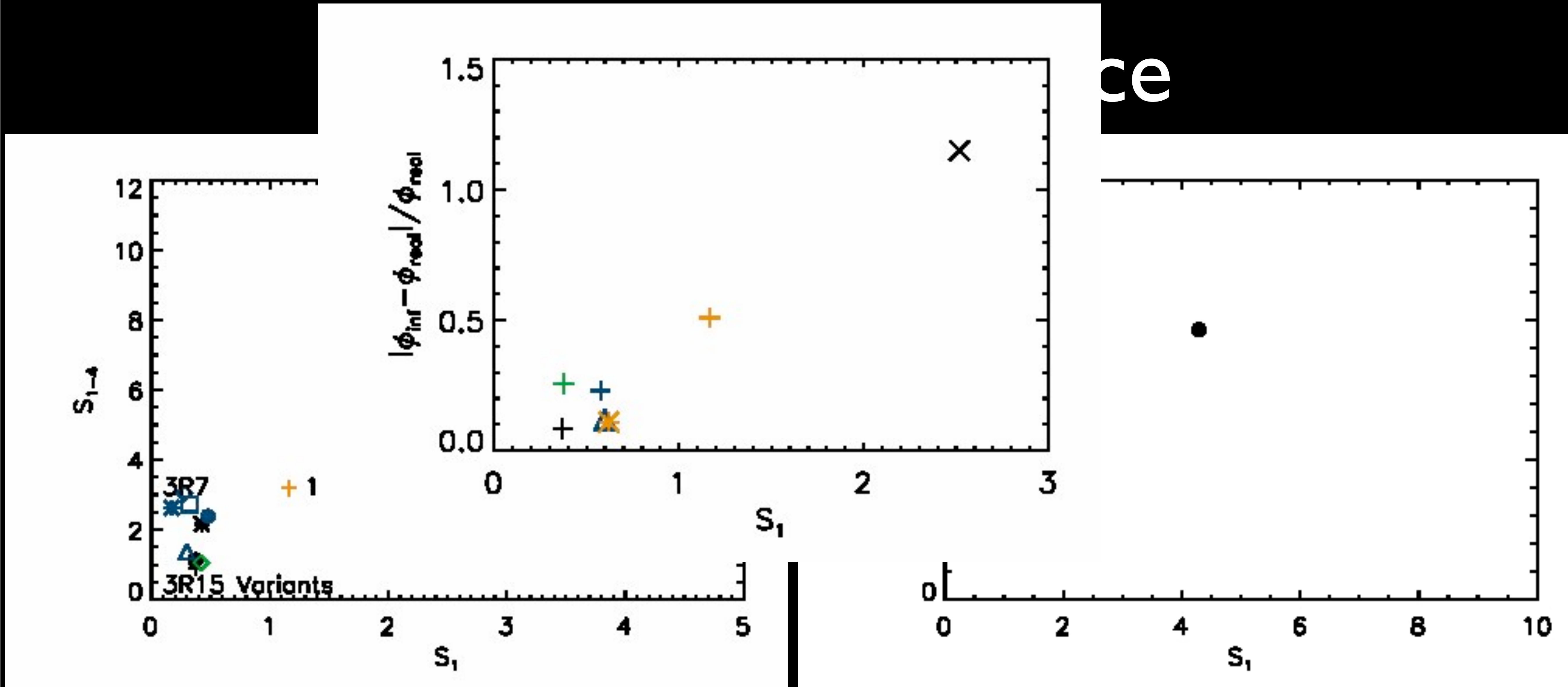

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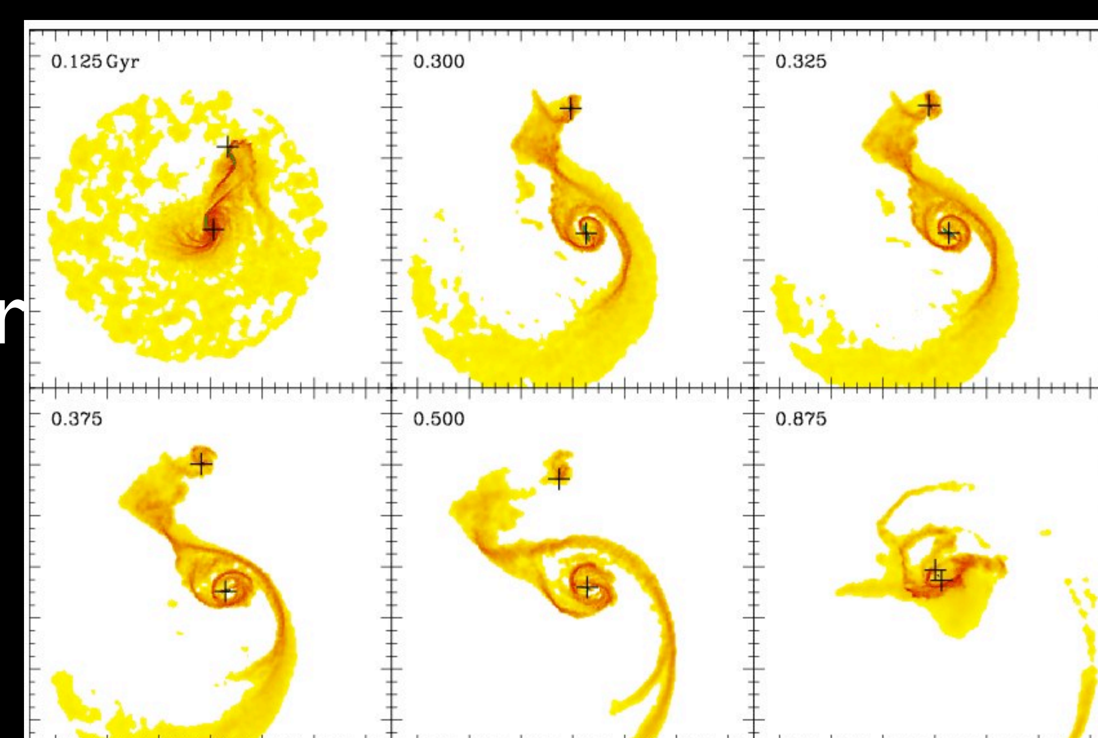
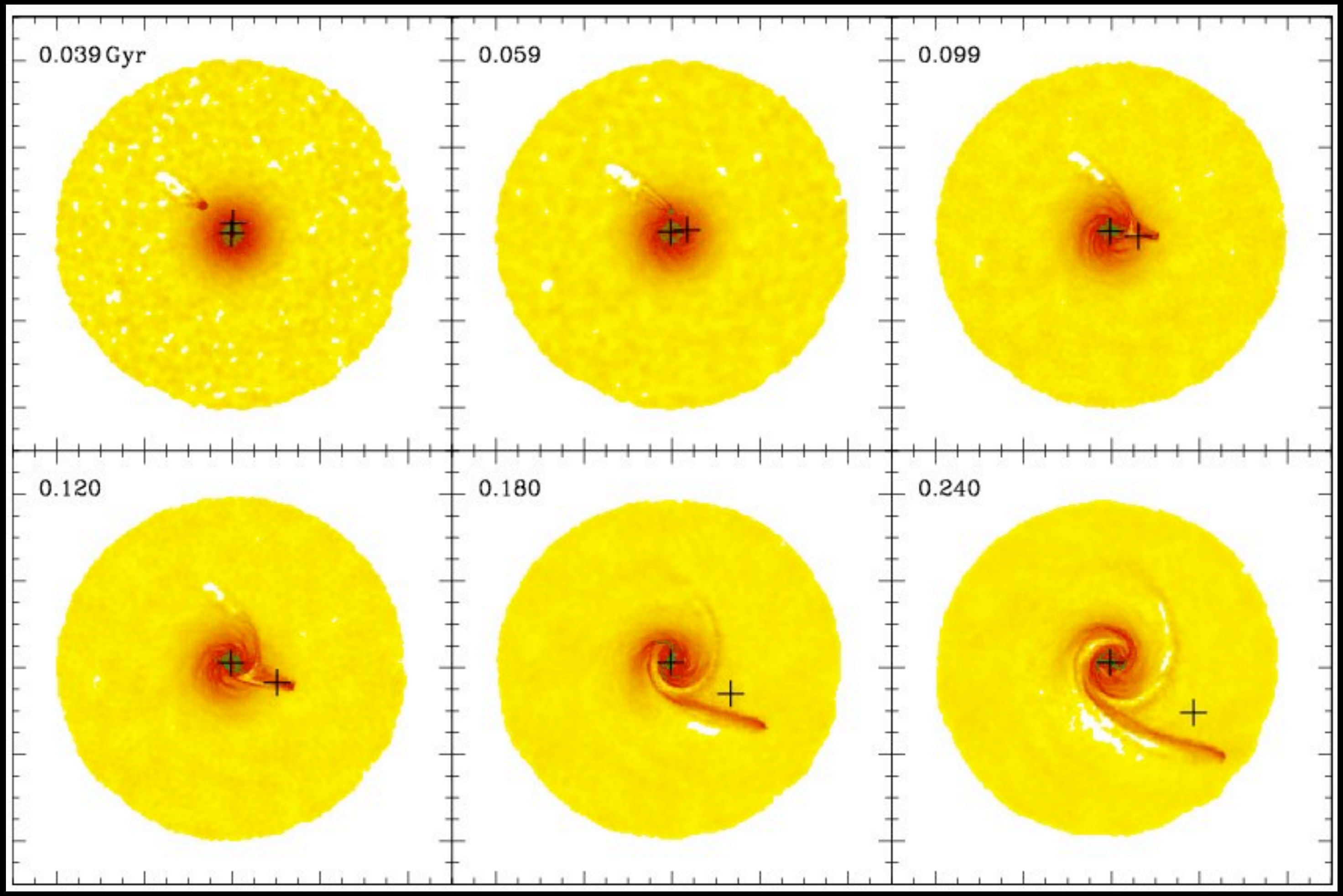
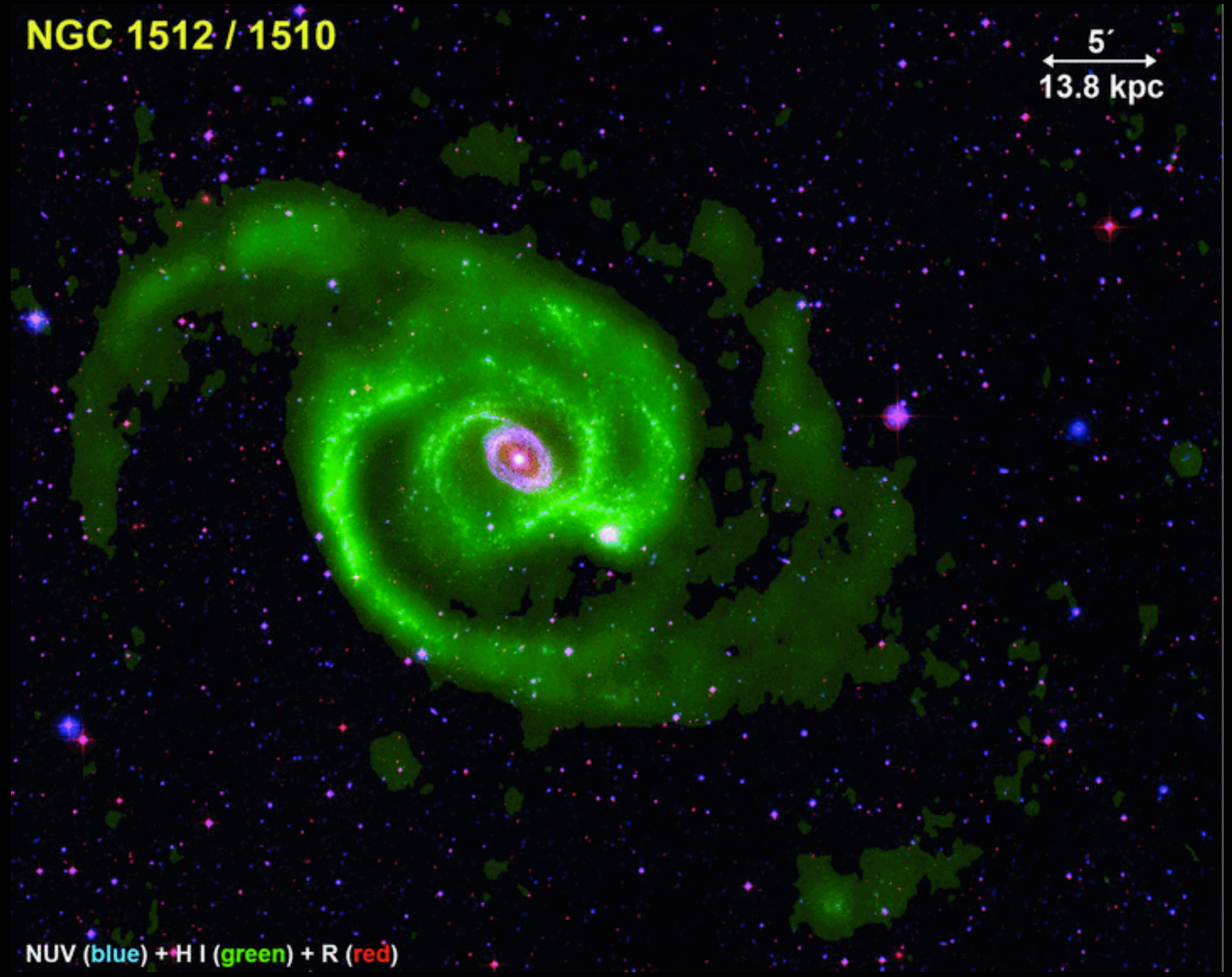


Galaxies with known optical companions contd.





- ~1:100 satellite, R_{peri} = 7kpc (close agreement with Koribalski & Sanchez 09) (global fourier amplitudes)
- Method works for 1:3 - 1:100 mass ratio satellites

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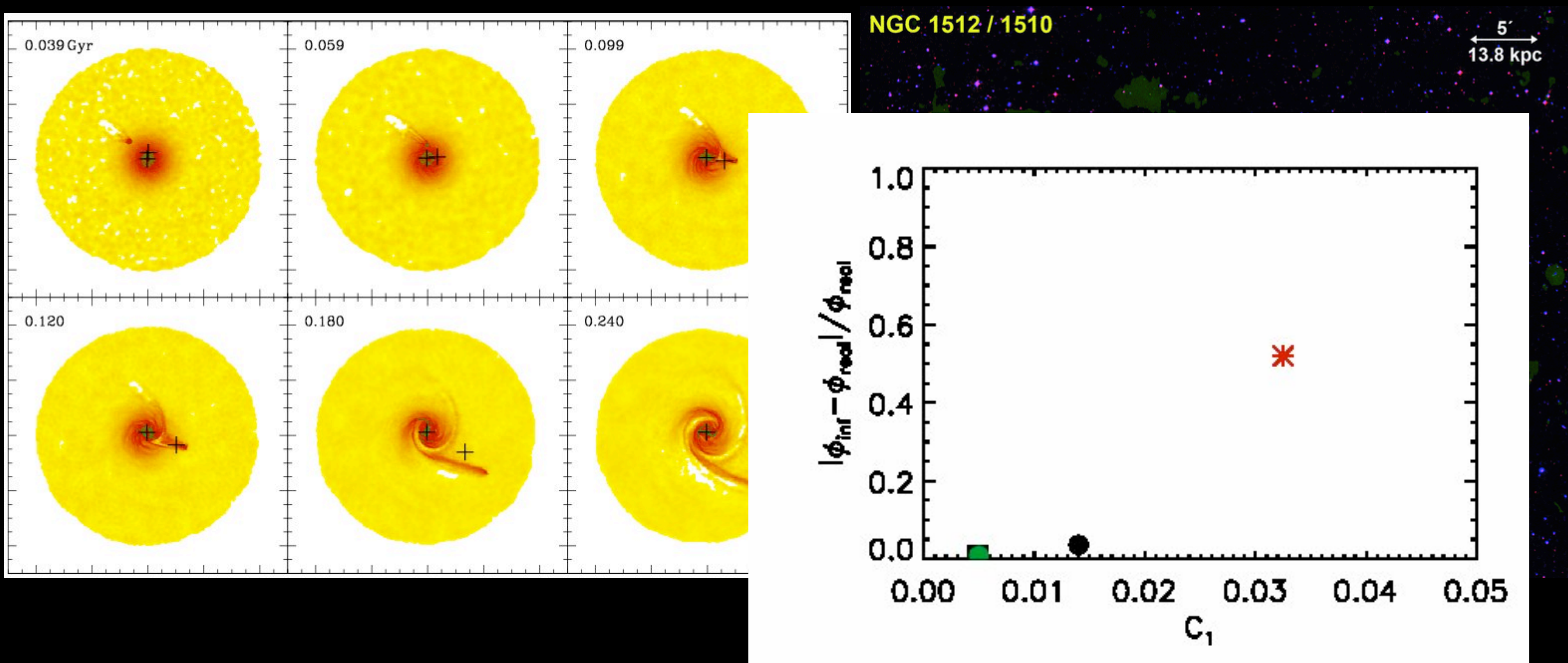

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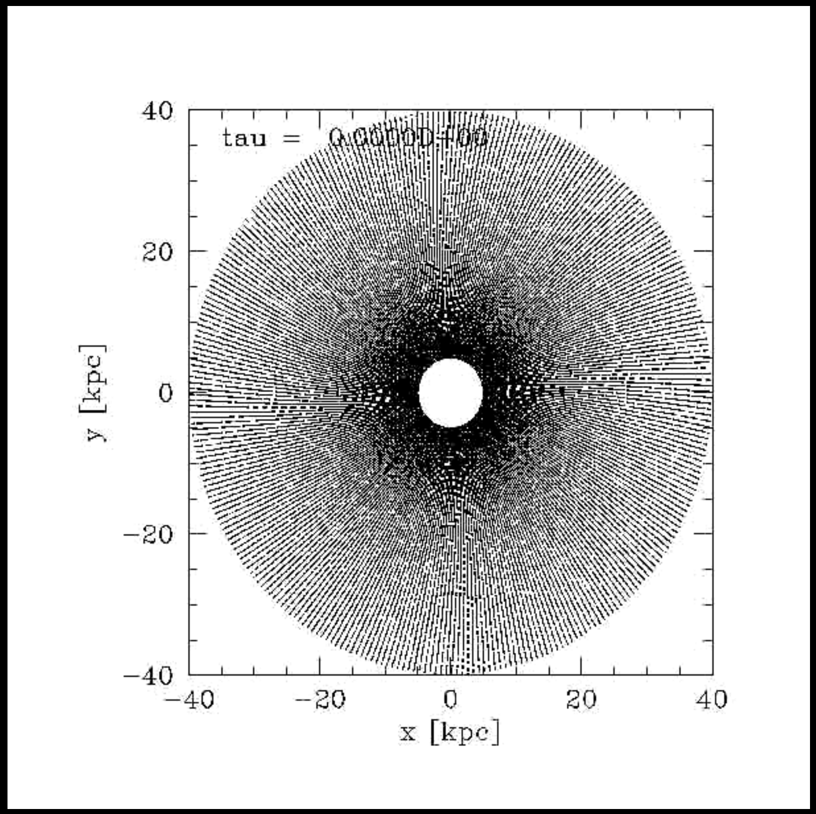
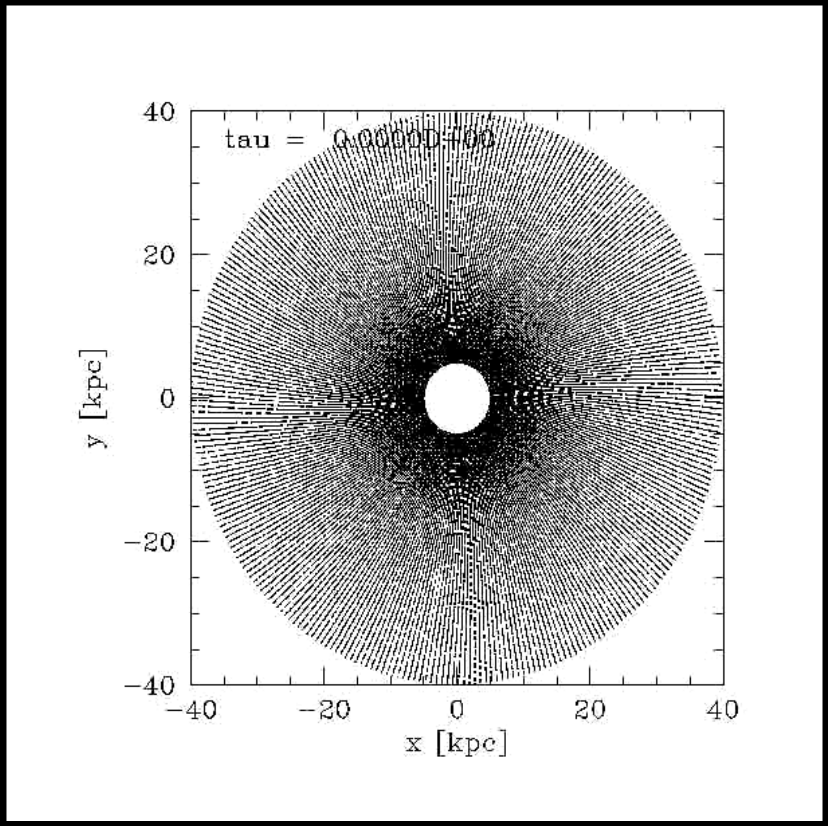
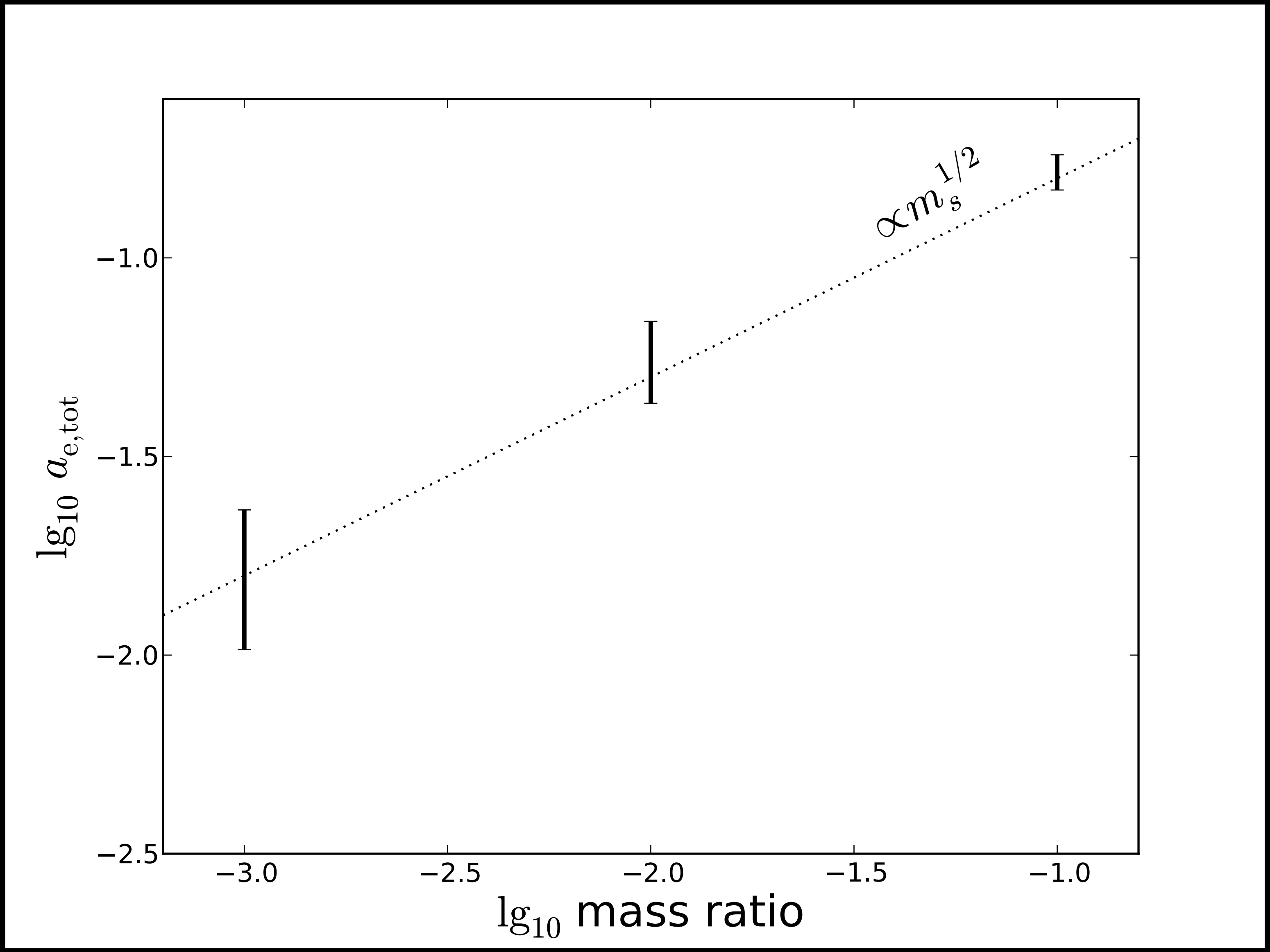
A Simplified Approach

Test Particles



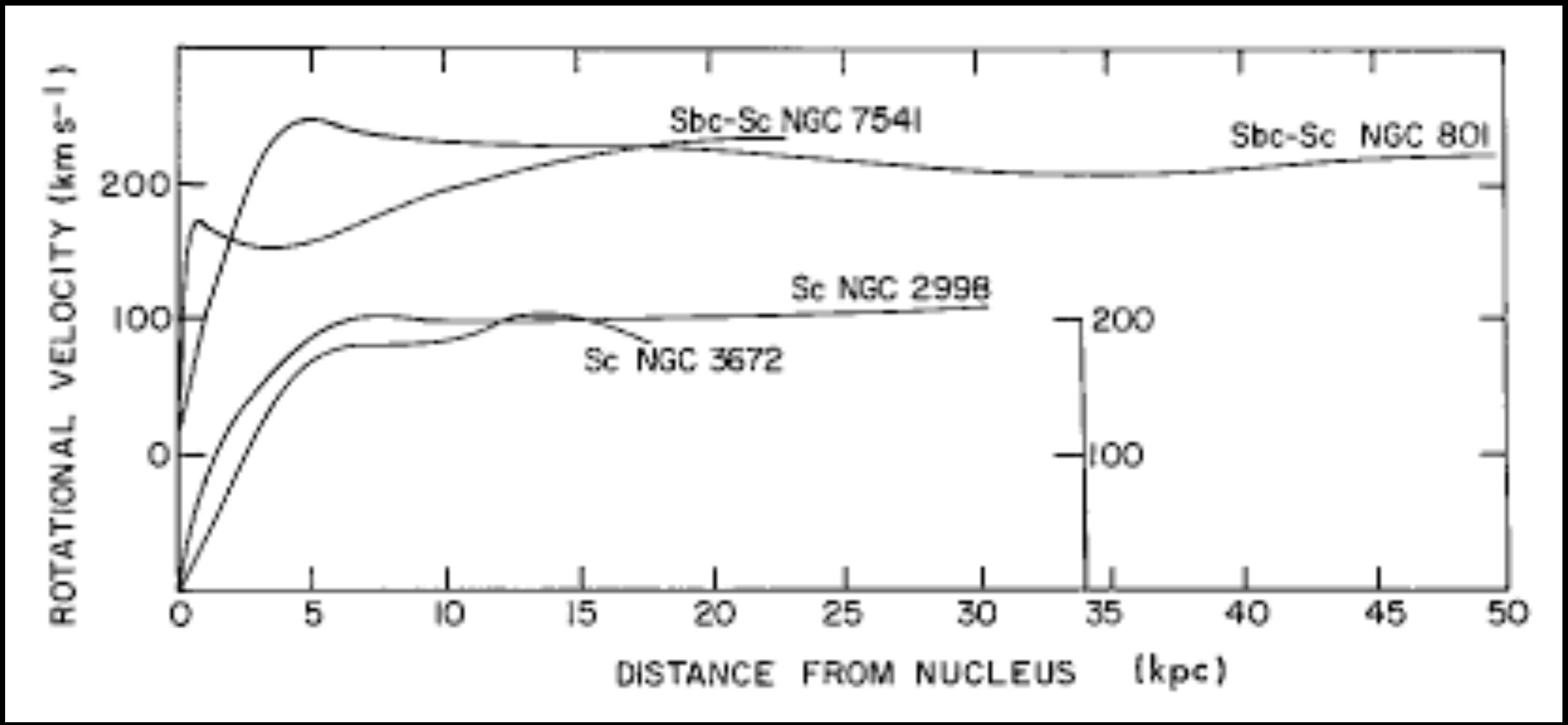
Mode Reconstruction





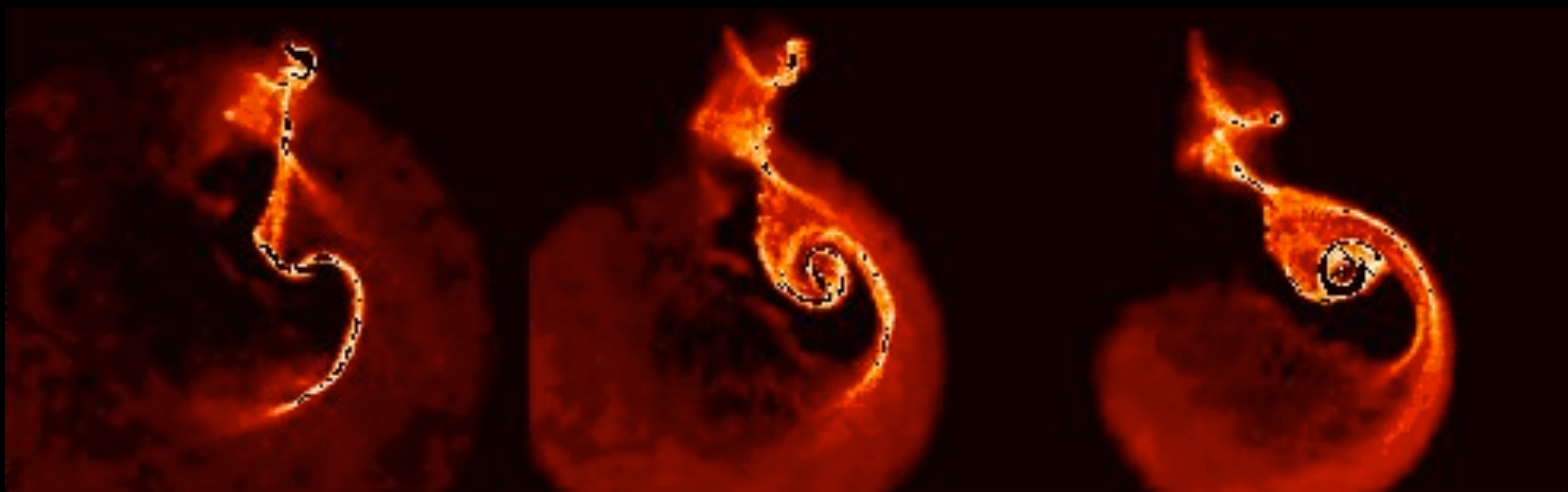
Fitting relations for satellite mass from Fourier amplitudes Chang & Chakrabarti 2011

Inferring the distribution of DM in galaxies



- Rotation curves -- infer the existence of dark matter halos in galaxies
- but how is it distributed? Theoretical N-body simulations find it should be (NFW): $\rho(r)=\delta_c\rho_c/[(r/R_s)(1+(r/R_s)^2]$ ($\rho \propto r^{-1}$ for $r < R_s$ and $\propto r^{-3}$ for $r > R_s$)

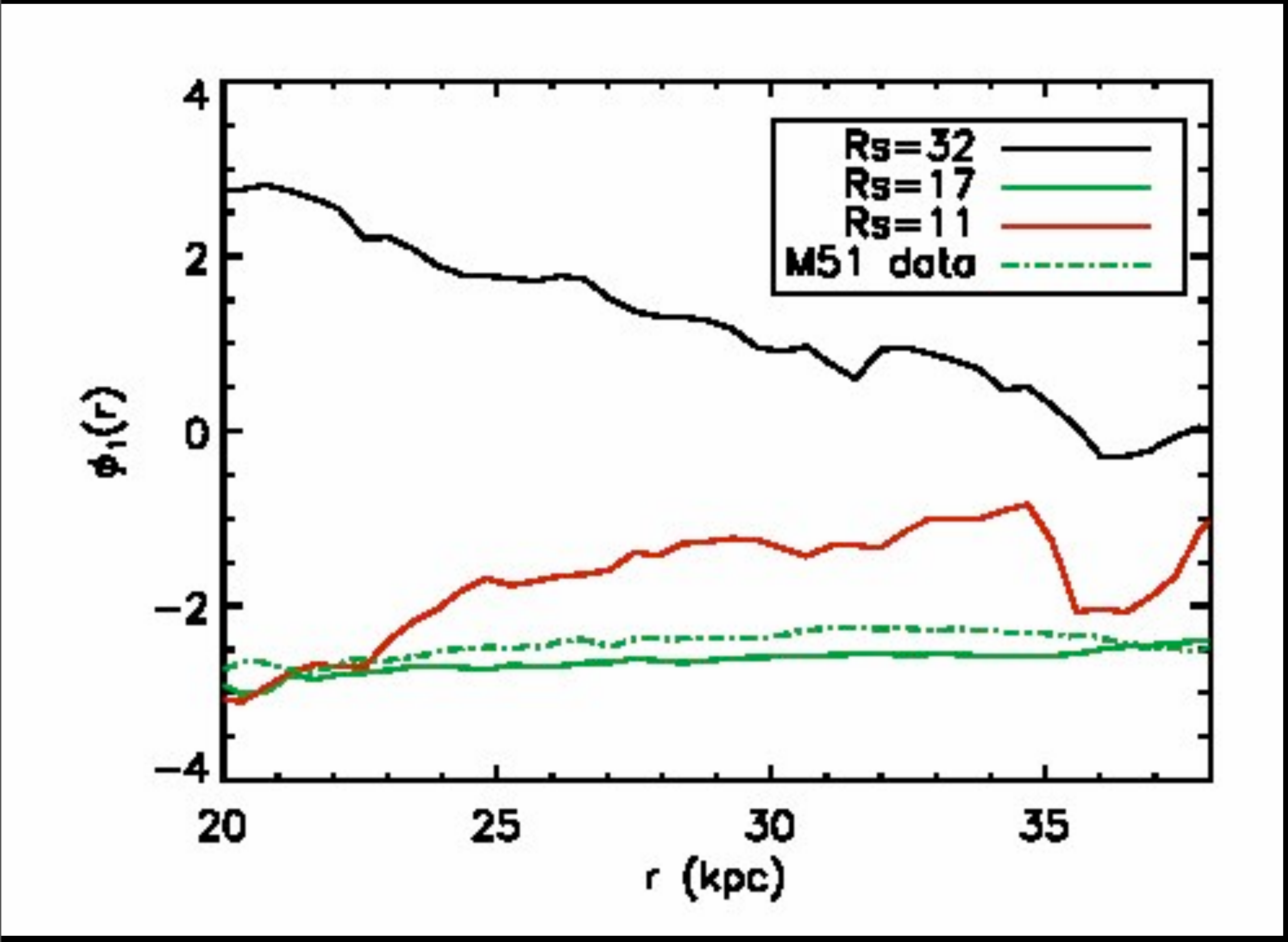
how can we get the scale radius?

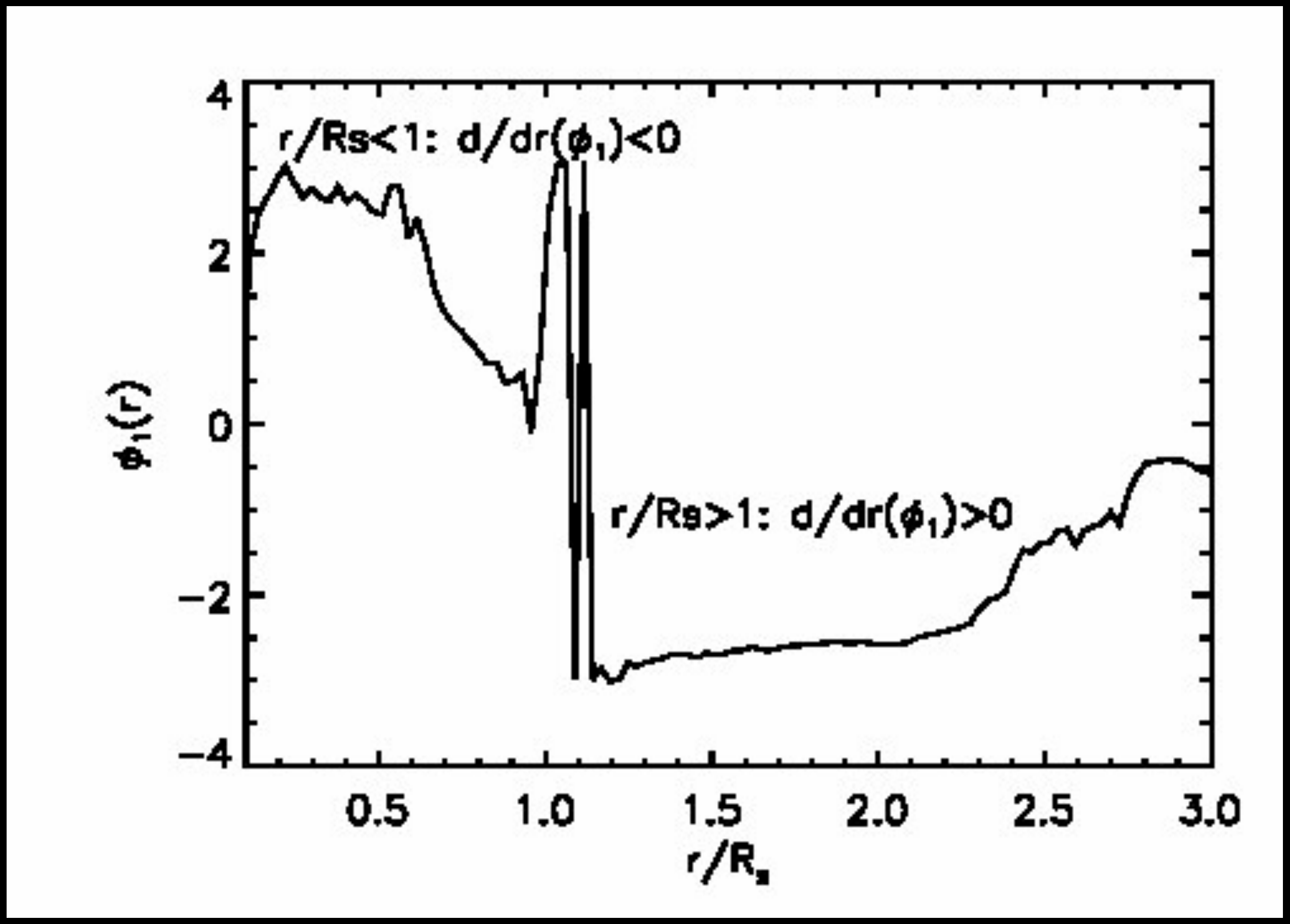


R_s=32 kpc R_s=17 kpc R_s=11 kpc

- build on previous results for M51. Use derived satellite mass and $R_{peri.}$ Varying the density profile varies the potential depth and the resultant disturbances

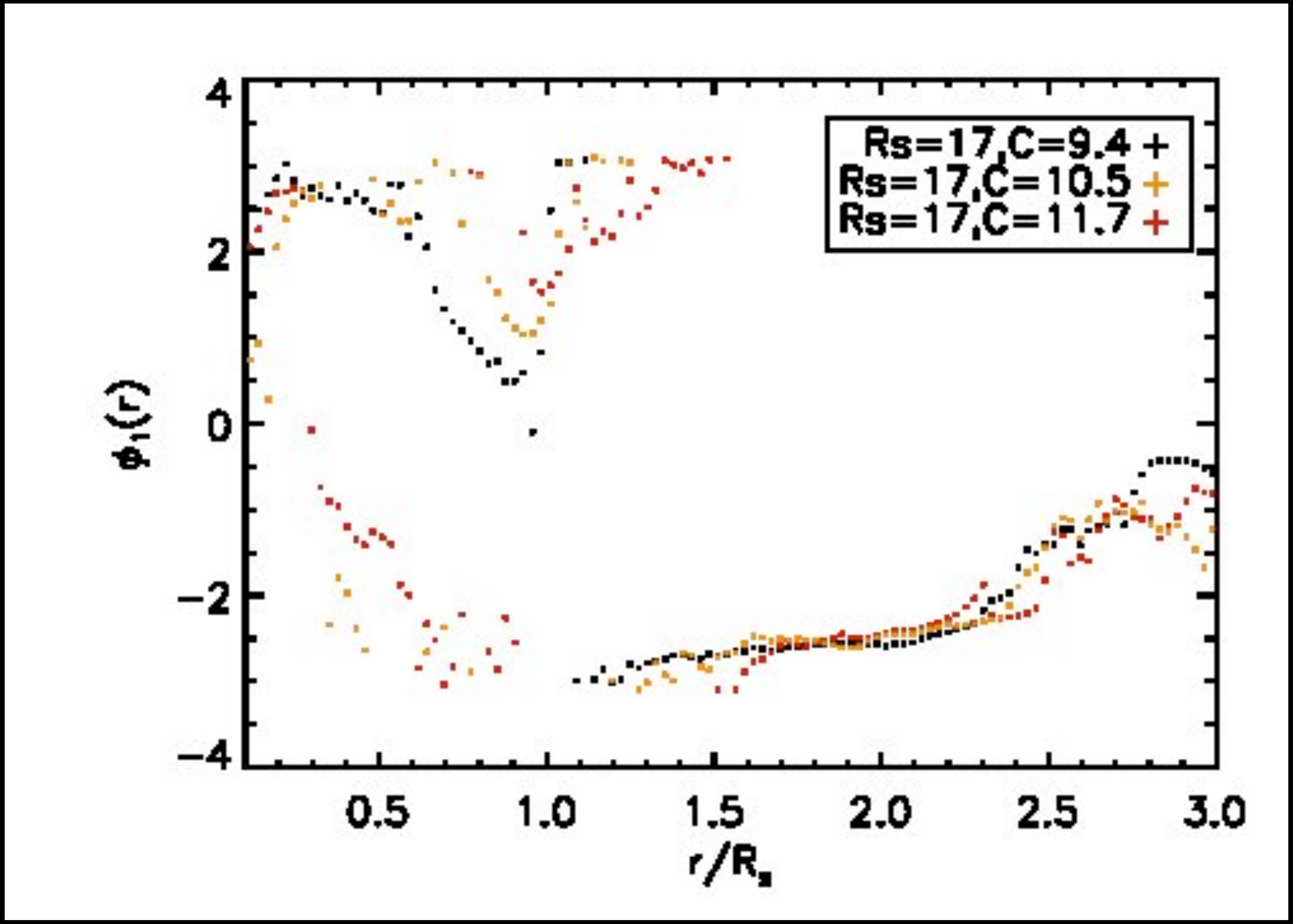
Inferring the scale radius of the dark matter halo





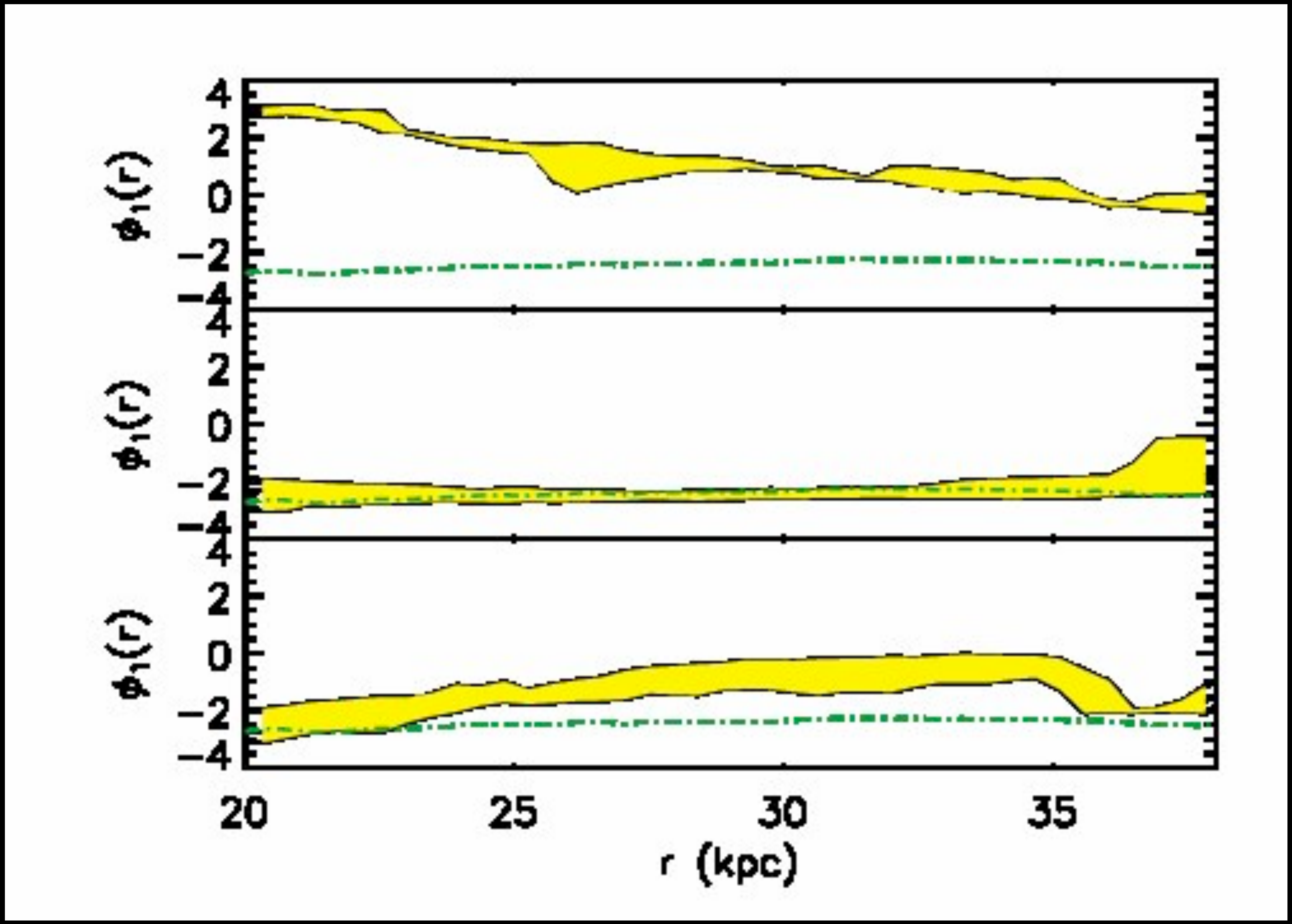
- Three distinct regimes: for $r < R_s$, $d\Phi/dr < 0$, for $r > R_s$, $d\Phi/dr > 0$, and for $r \sim R_s$, $d\Phi/dr$ transitions (Chakrabarti 2012, arXiv:1112.1416)

Inferring the scale radius



- if R_s is held constant, then different concentration values give nearly identical results for $r/R_s > 1$

Inferring the scale radius contd



- phase does depend on other parameters (ICs: bulge fraction, gas fraction, orbital inclination), but the dependence is not very large (Chakrabarti 2012)

Will halo shapes affect our analysis?

- In general, yes. But disturbances in tidally interacting systems like M51 are dominated by the companion, not intrinsic processes.
- Cosmological sims (Maccio et al. 2008): DM halos are non-spherical ... but including a baryonic stellar disk makes halos rounder (Debattista et al. 2008). Including gas cooling in such sims (Debattista et al., in prep; Chakrabarti et al. in prep)

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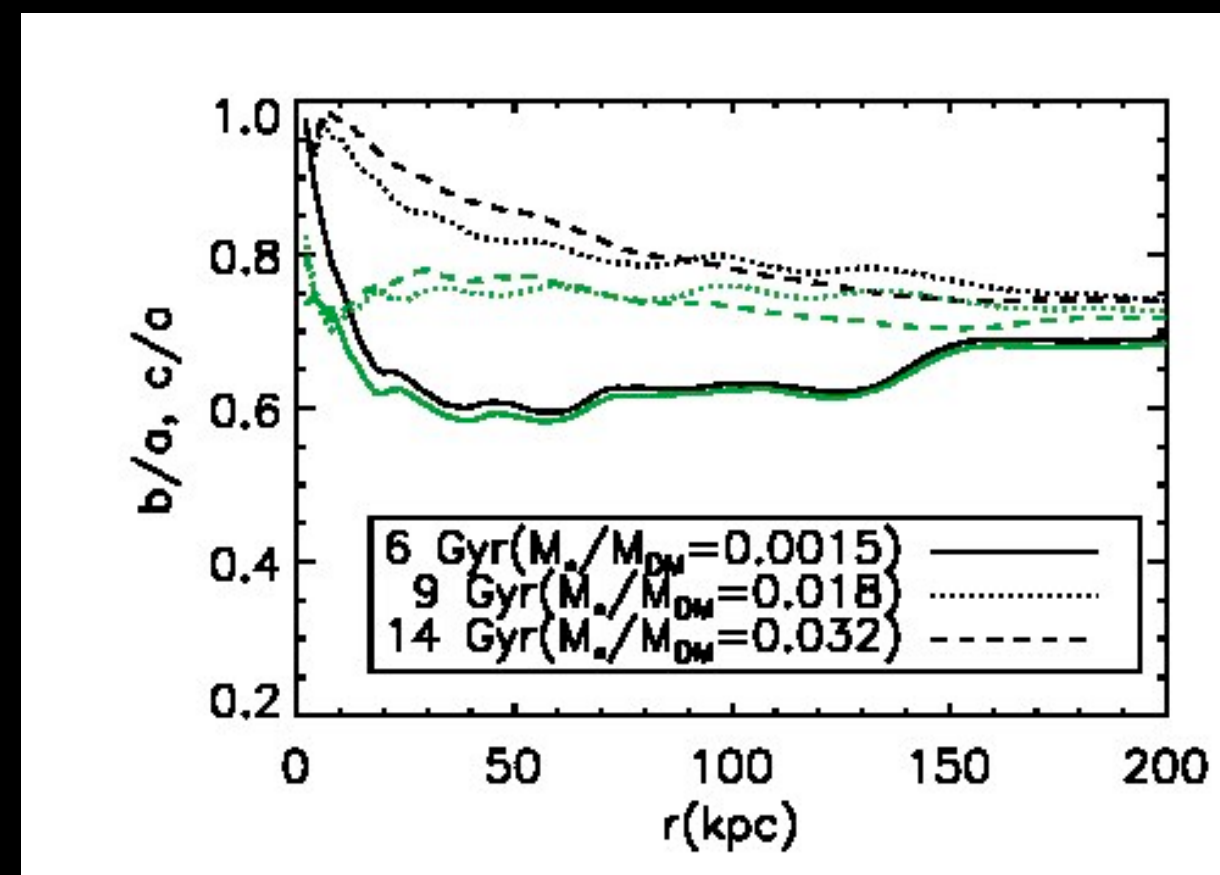

Halo shapes contd.

Fourier amplitudes of planar disturbances low in outskirts (less than 10 %) close to present day, but warp survives in some simulations (where gas and halo angular momenta are misaligned)

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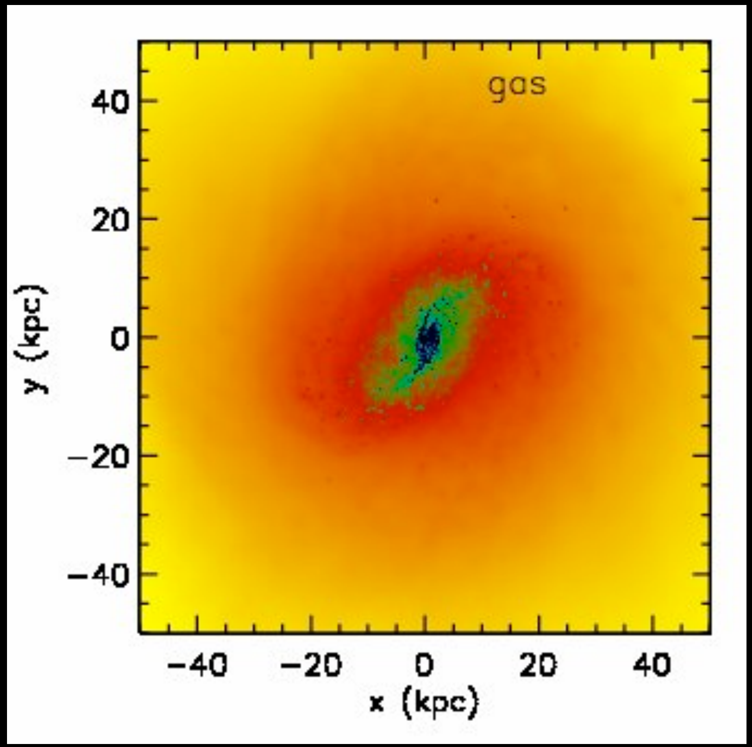

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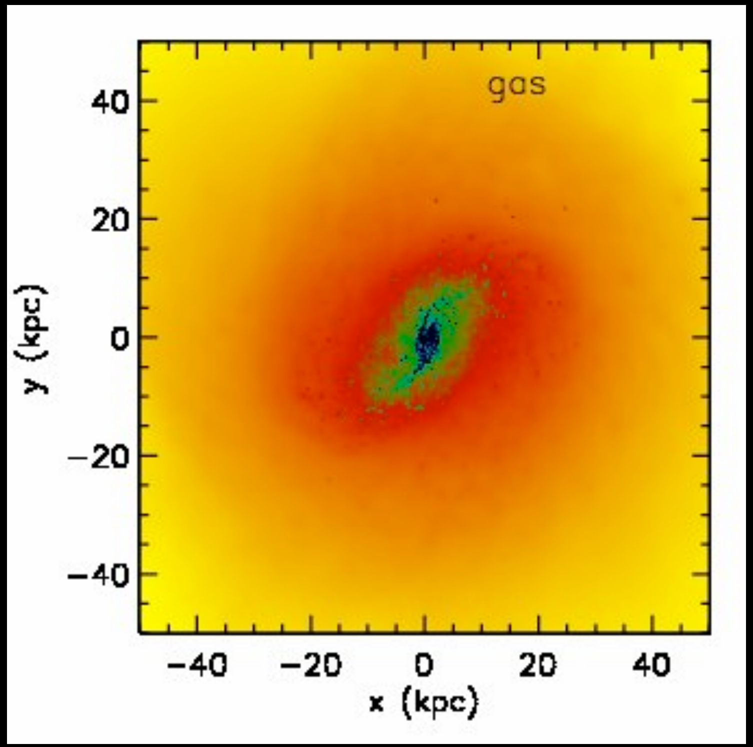

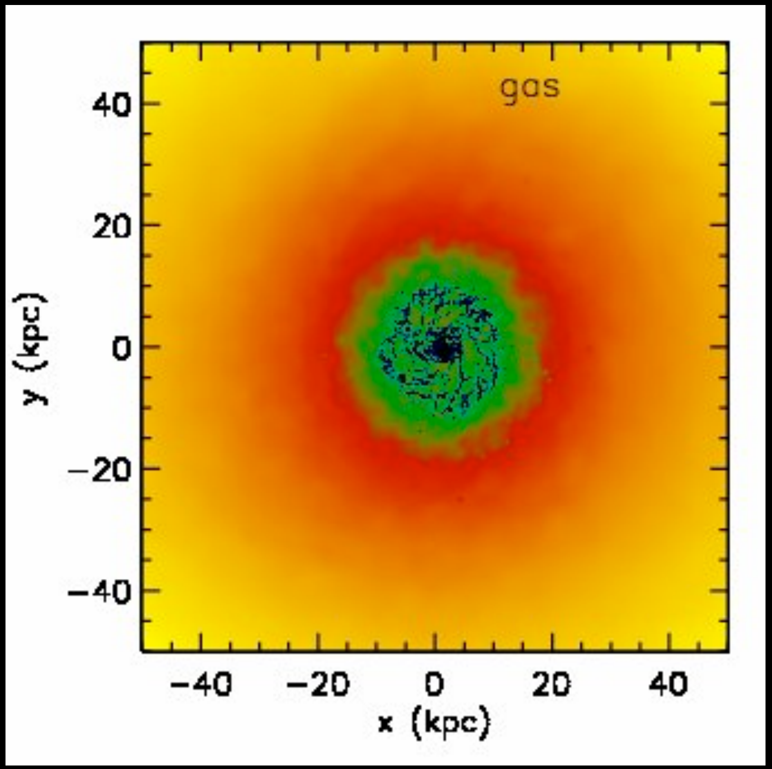

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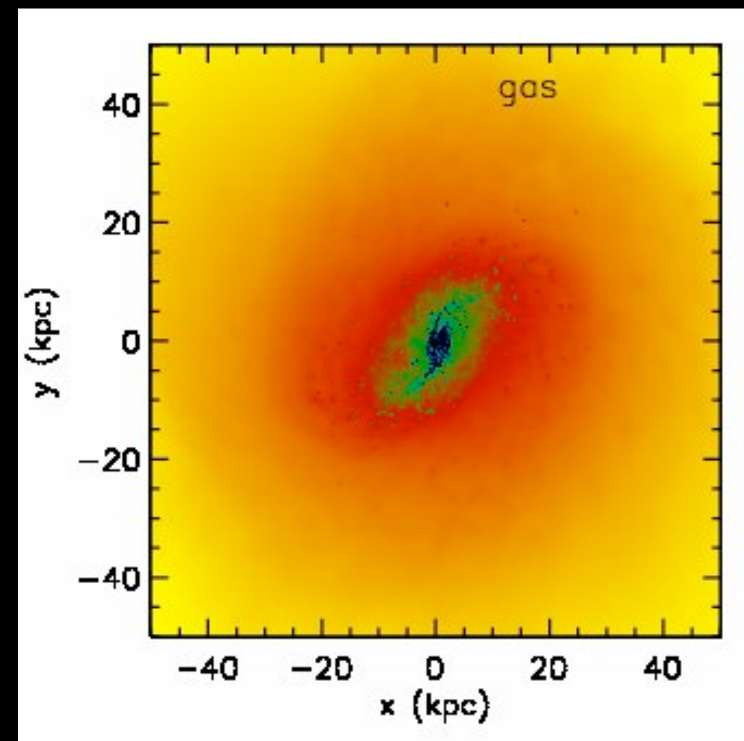
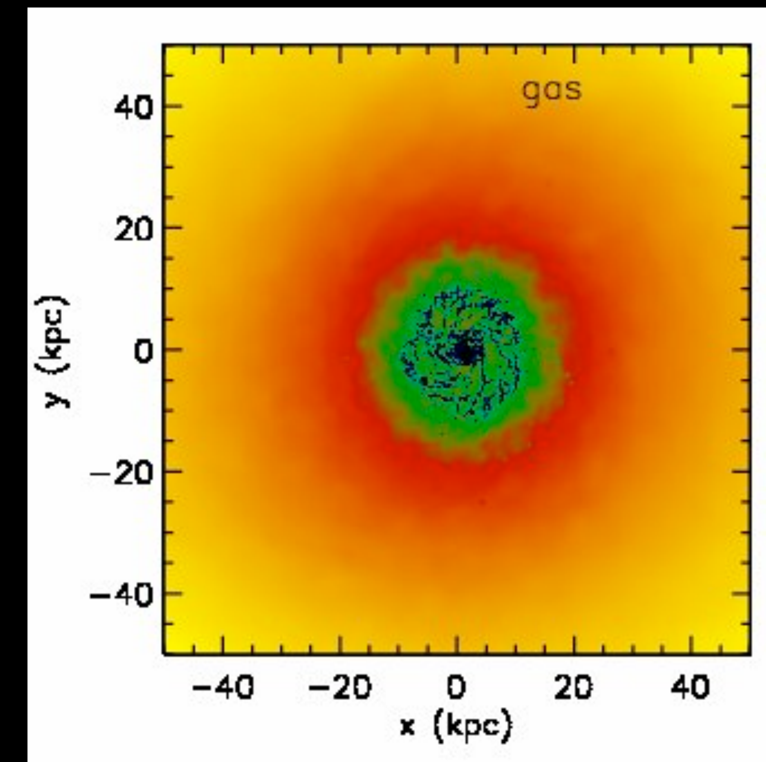
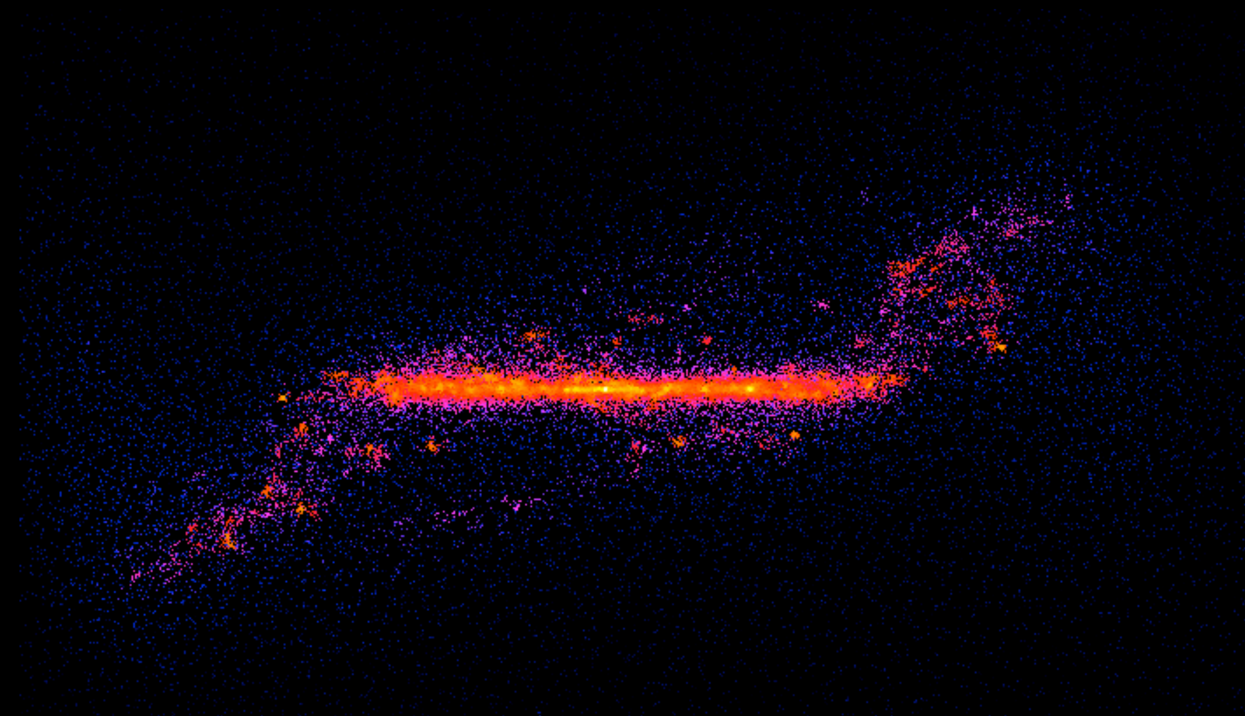
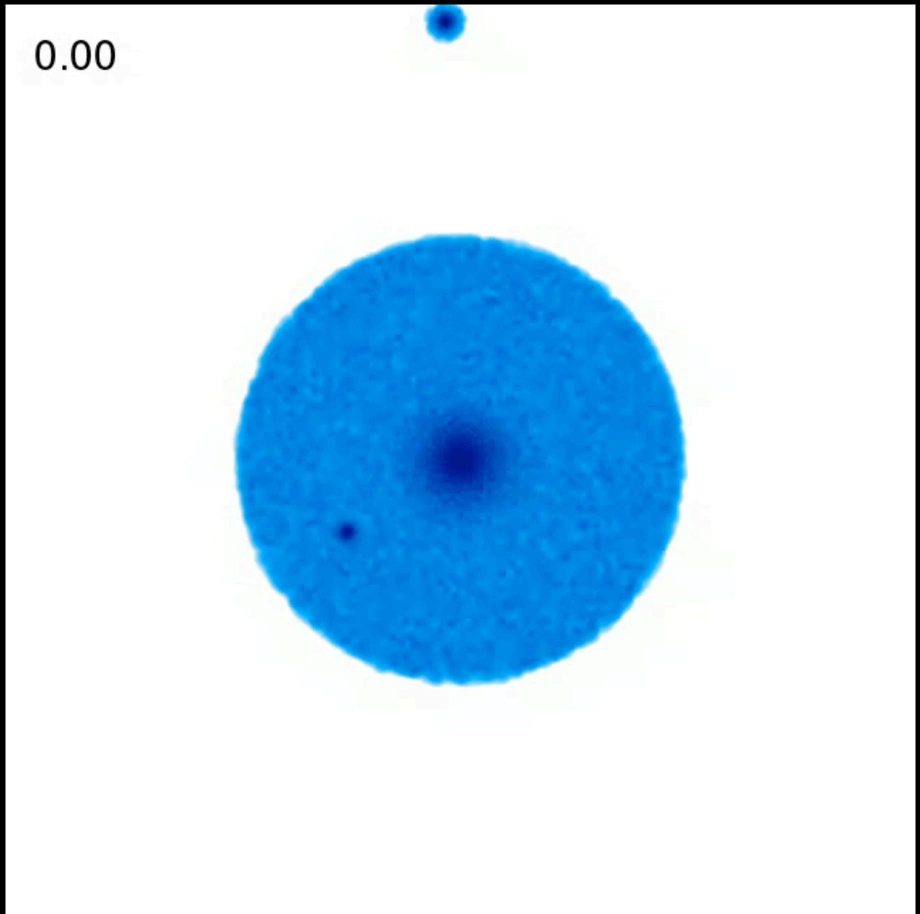




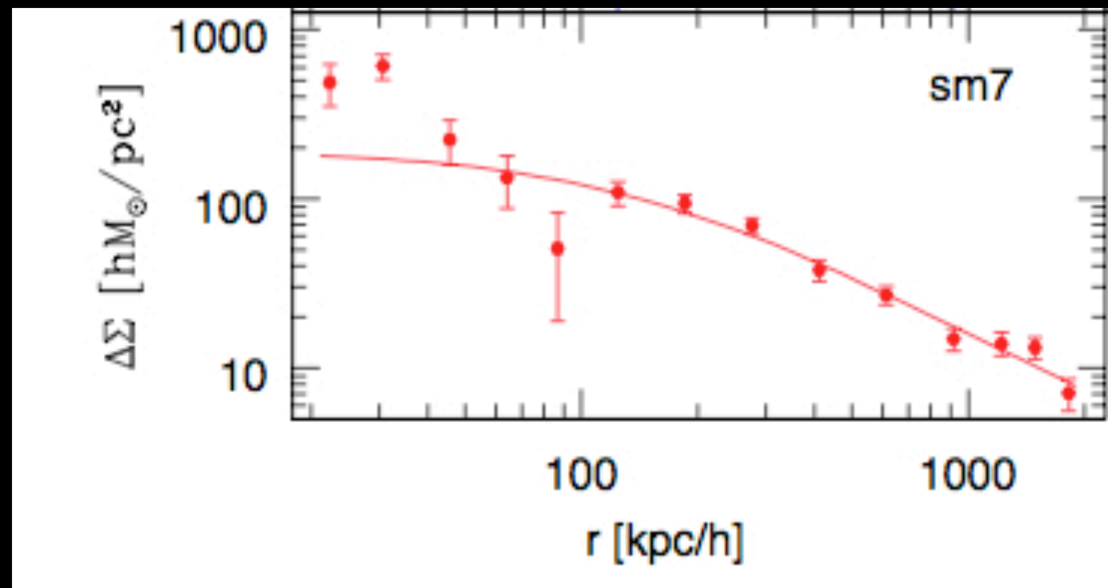


Future Work

- Focus on low-order modes means that we study the larger scale disturbances
- Current & future work: effects of even smaller (< 1:1000) perturbers, and multiple perturbers on the *higher order modes*. M83 - multiple satellite model (Chakrabarti et al., in prep). Scaling relations for multiple satellites
- Lensing - Tidal Analysis comparison for cosmological hydrodynamical simulations



N~10^4

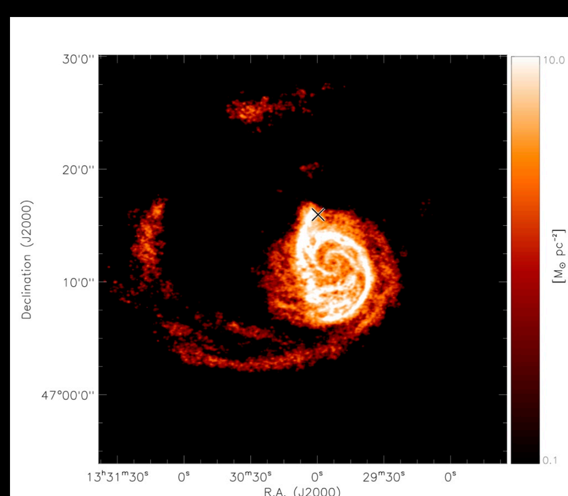


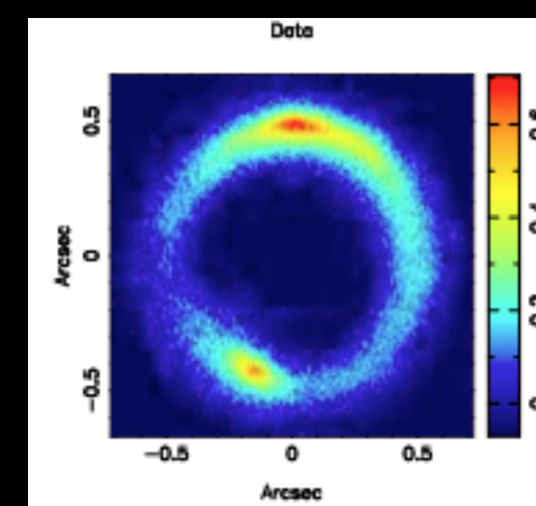
a) z~0.1, N~ 10^4
profiles in outskirts:
weak lensing
(Mandelbaum et al. 06)

N

Vegetti et al. 2012

N =1





z=0.8

b) Local volume
Tidal Analysis

z

c) sub-structure,
r < r_E: strong lensing

Summary & Future

- Analysis of perturbations in cold gas on outskirts of galaxies: constrains mass,R,and azimuth of dark (or luminous) perturbers. New method to characterize satellites (to see dark galaxies). Method tested for satellites with mass ratio: ~1:100 - 1:3. Extended to infer dark matter density profile of spirals.
    - Extending to include multiple satellites and non-spherical halos
    - comparison to lensing

Summary & Future

Summary & Future

Coming Soon!

AAS topical conference series (TCS) meeting on:
"**Probes of Dark Matter on Galaxy Scales**"

July 2013

SOC: SC, Leo Blitz, Lars Hernquist, Manoj Kaplinghat, Chris Fassnacht, Rachel Mandelbaum, Jay Gallagher, Martin Weinberg