The Role of Gas in Spiral Galaxies

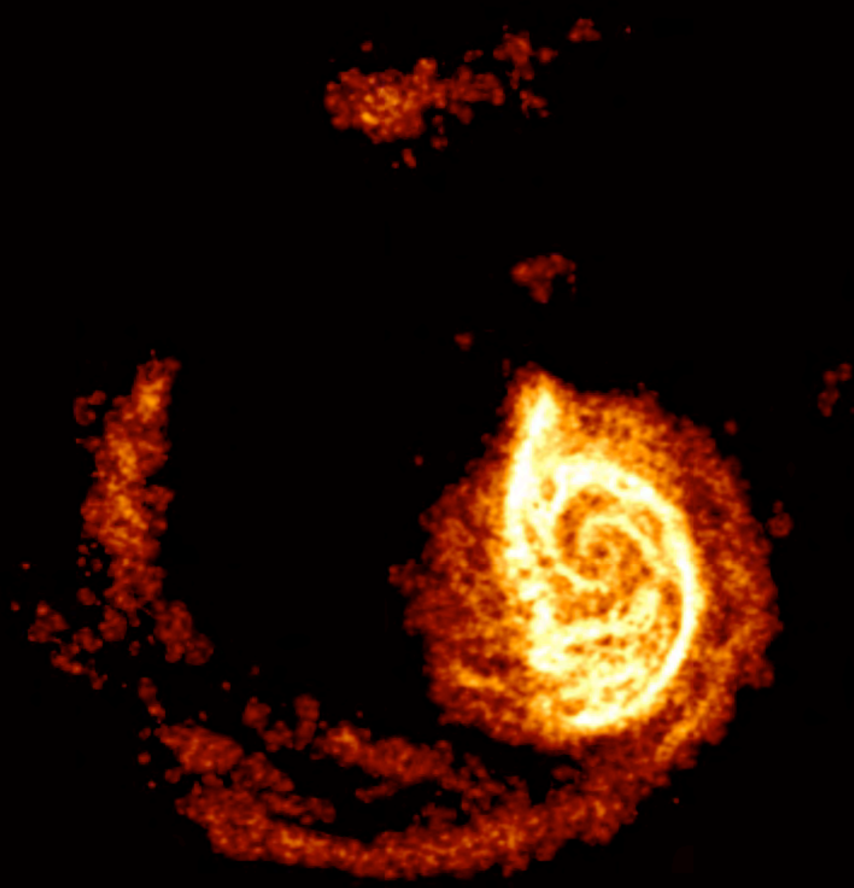
Sukanya Chakrabarti (RIT)
Collaborators: Leo Blitz (UCB), Frank Bigiel (Heidelberg), Phil Chang (UWM), David Merritt (RIT), Alice Quillen (UR)

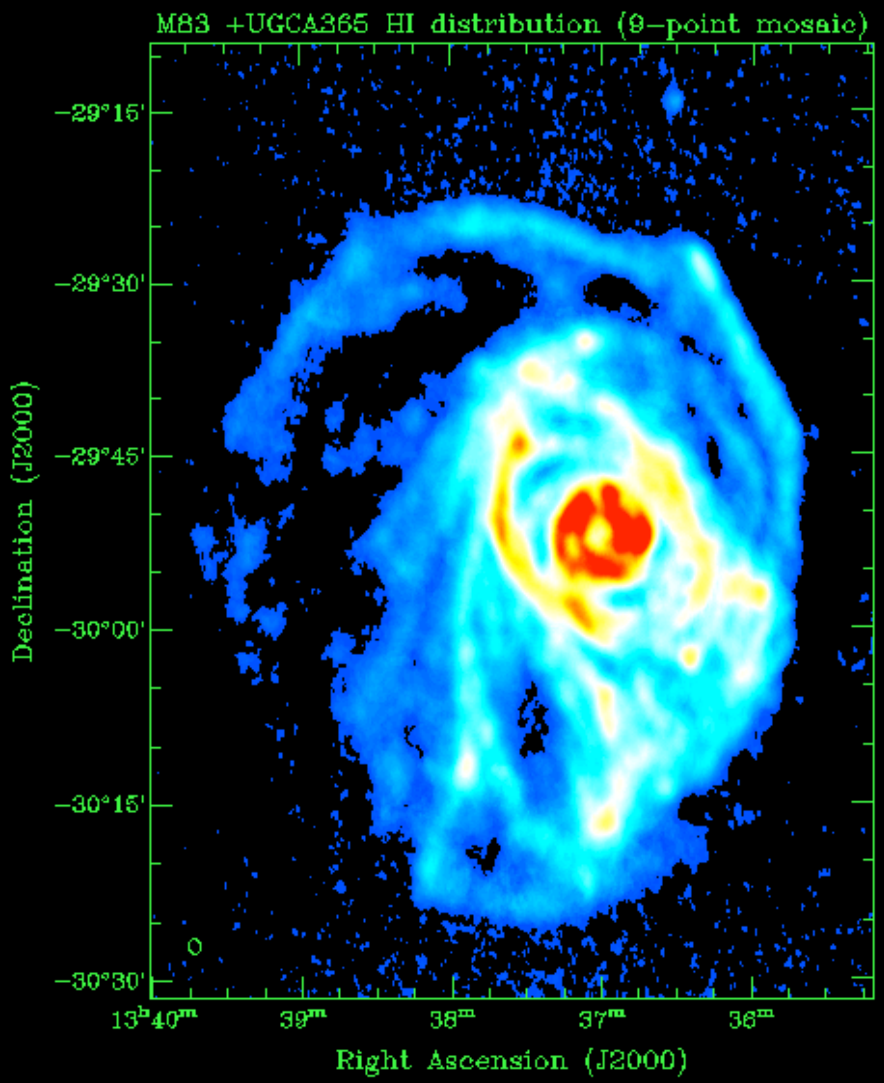
Quasi-Steady Spiral Structure in Stellar Disks (the two faces of spirals)

K-band

B-band

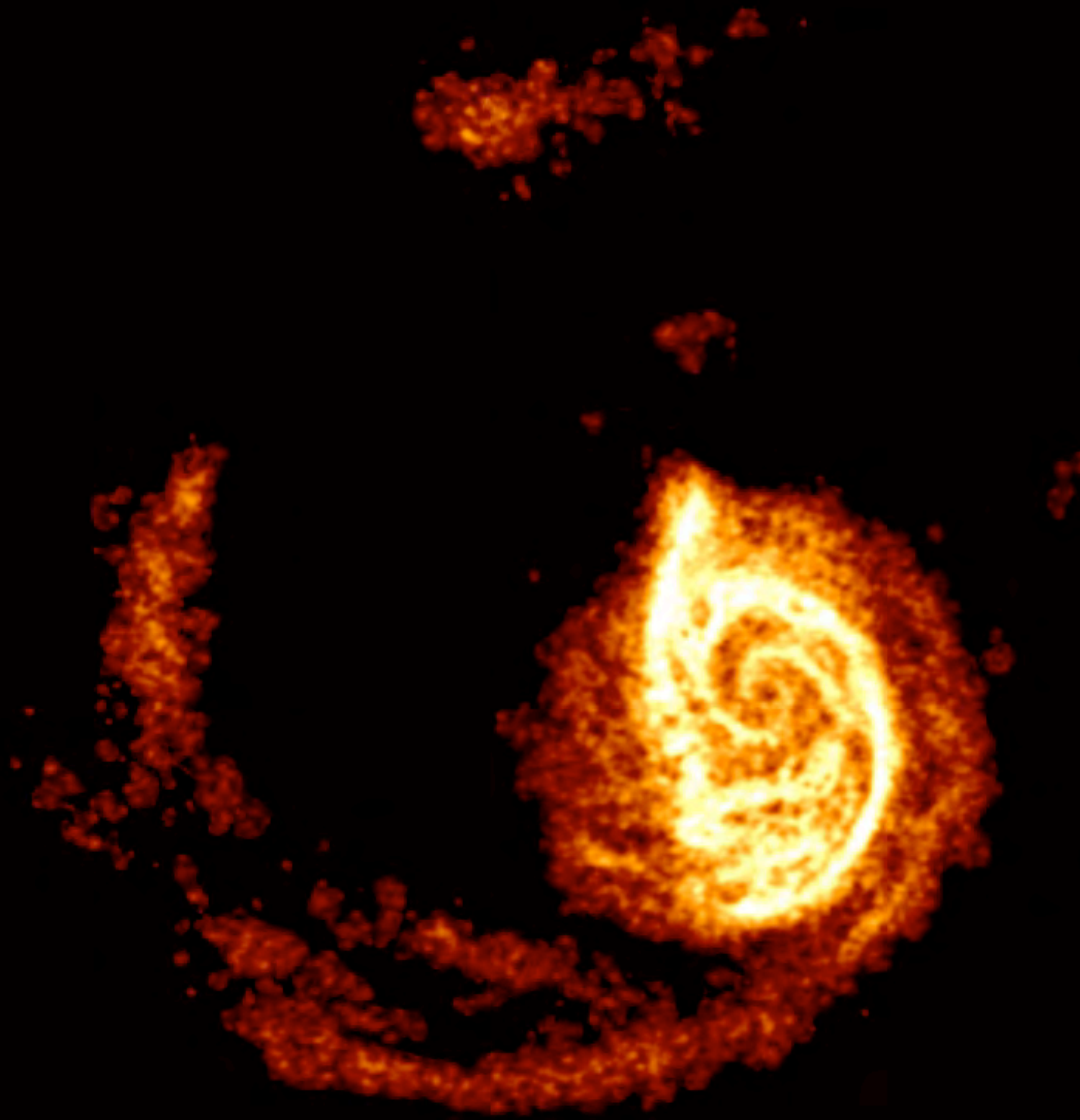
Extended HI Disks as Tracers of Tidal Interactions





- Galaxies with optical companions : Proof of Principle

Overview



Overview

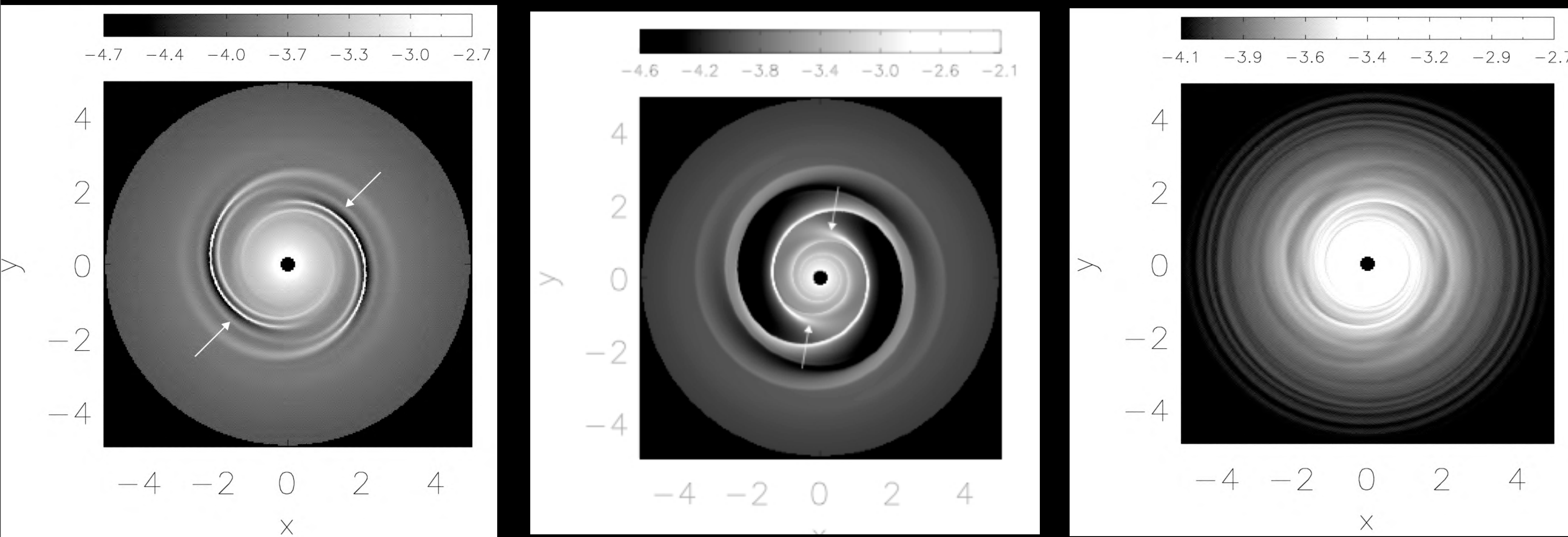
- Cold gas (in inner regions of spirals) as donor of angular momentum : long-lived, self-excited, spiral structure in stellar disks

Overview

- Cold gas (in inner regions of spirals) as donor of angular momentum : long-lived, self-excited, spiral structure in stellar disks

- Cold gas in extended HI disks as tracer of perturbing dark sub-halos ($r > r_{OLR}$)

Spiral sub-structure in gas disks

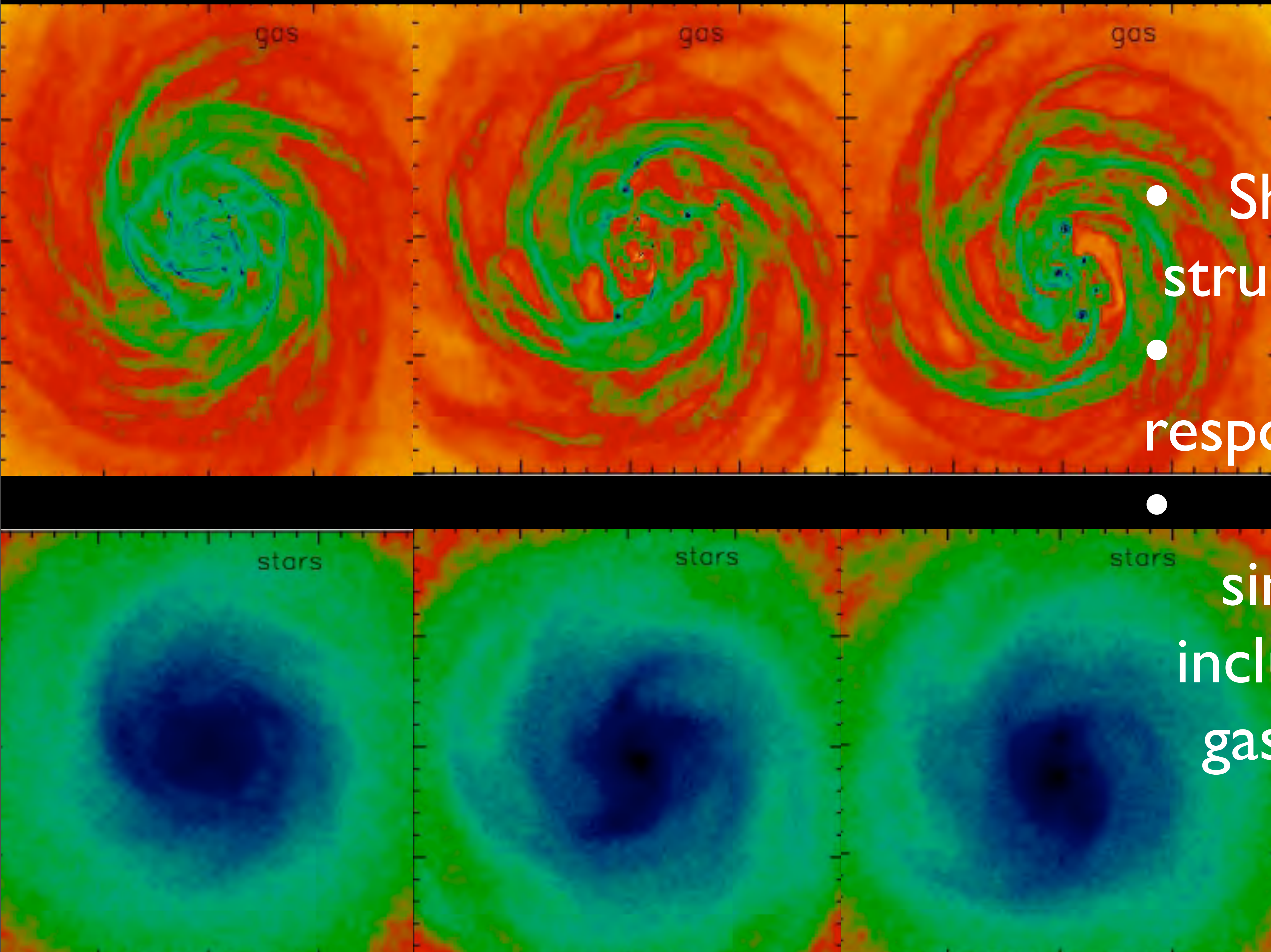


- Shu, Milione & Roberts 1973: effects of ultra-harmonic resonances
- Chakrabarti, Laughlin & Shu 2003 (simplified model looking at gas response when driven by stellar spiral potential): Density wave theory can produce the "backbone" *and* the disorder

Self-excited spiral structure

- Does the stellar disk continue to be unstable to spiral structure for many Gyr?
- SPH simulations with gas, stars, dark matter halo
- differences between the gas response and stellar response

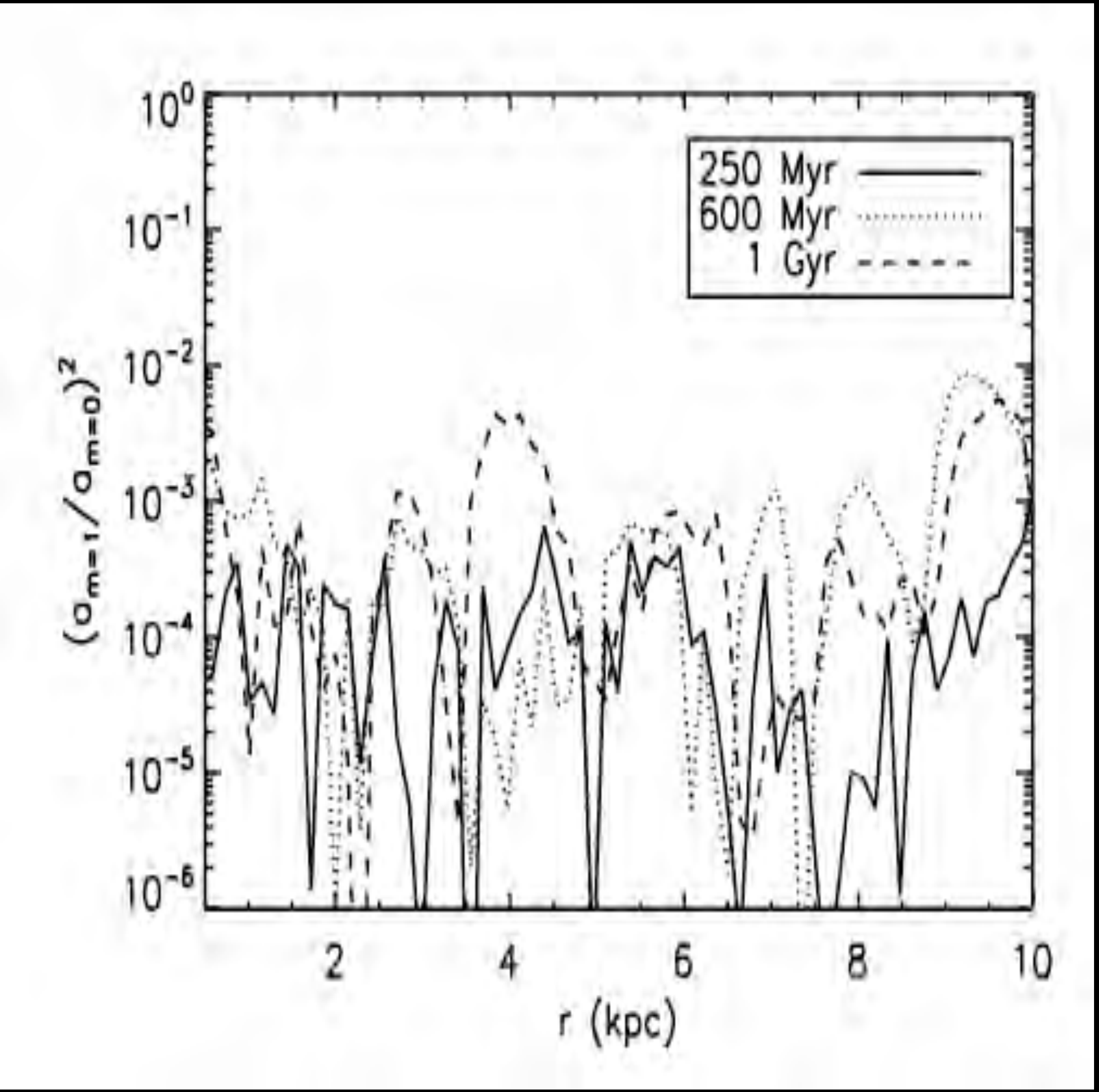
Self-excited spiral structure

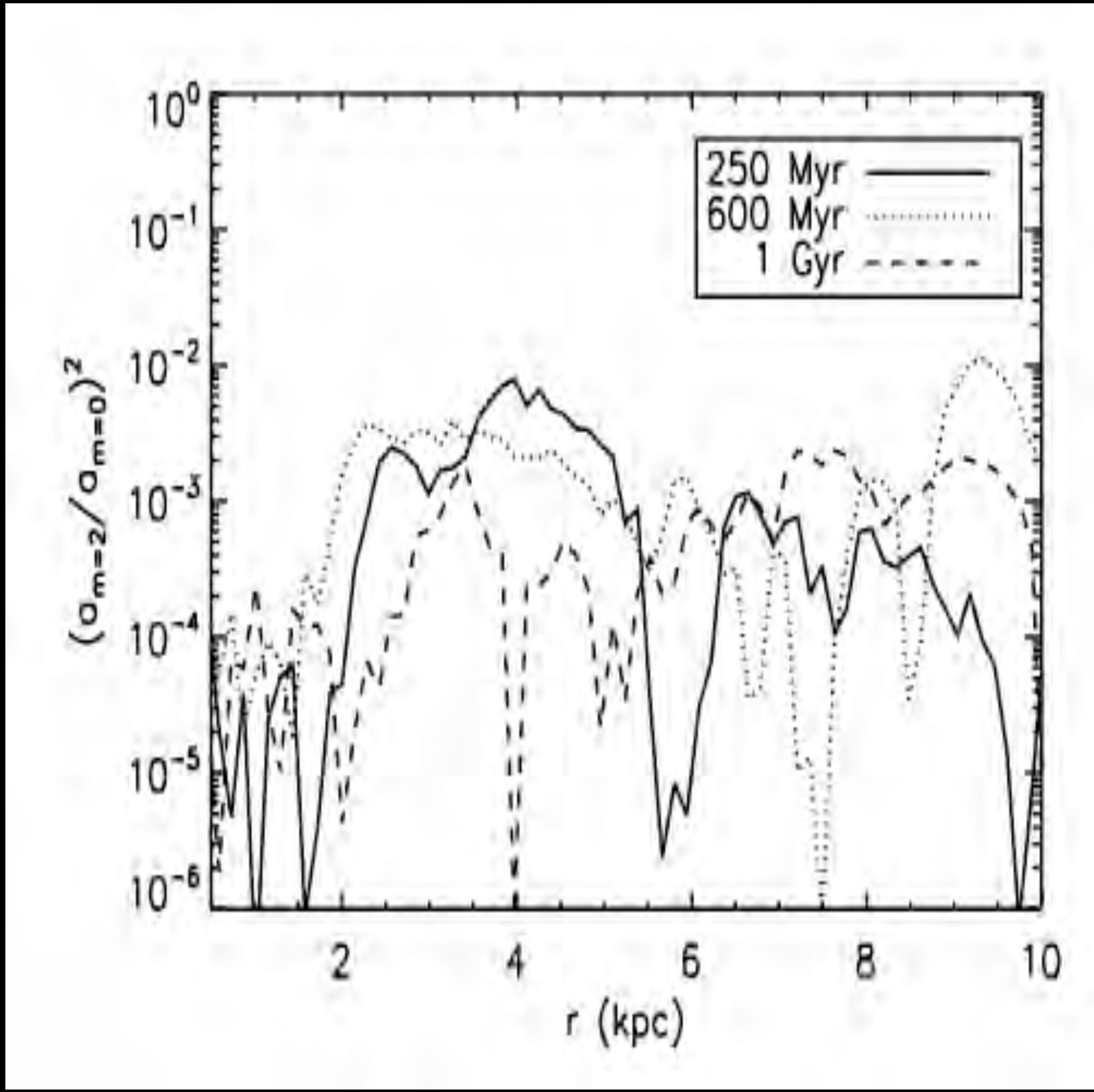


250 Myr 1 Gyr 1.5 Gyr

- Sharp spiral structure in gas
- Smooth response in stars
- SPH simulations including stars, gas and dark matter

Roughly steady m=2 disturbance in stellar disk

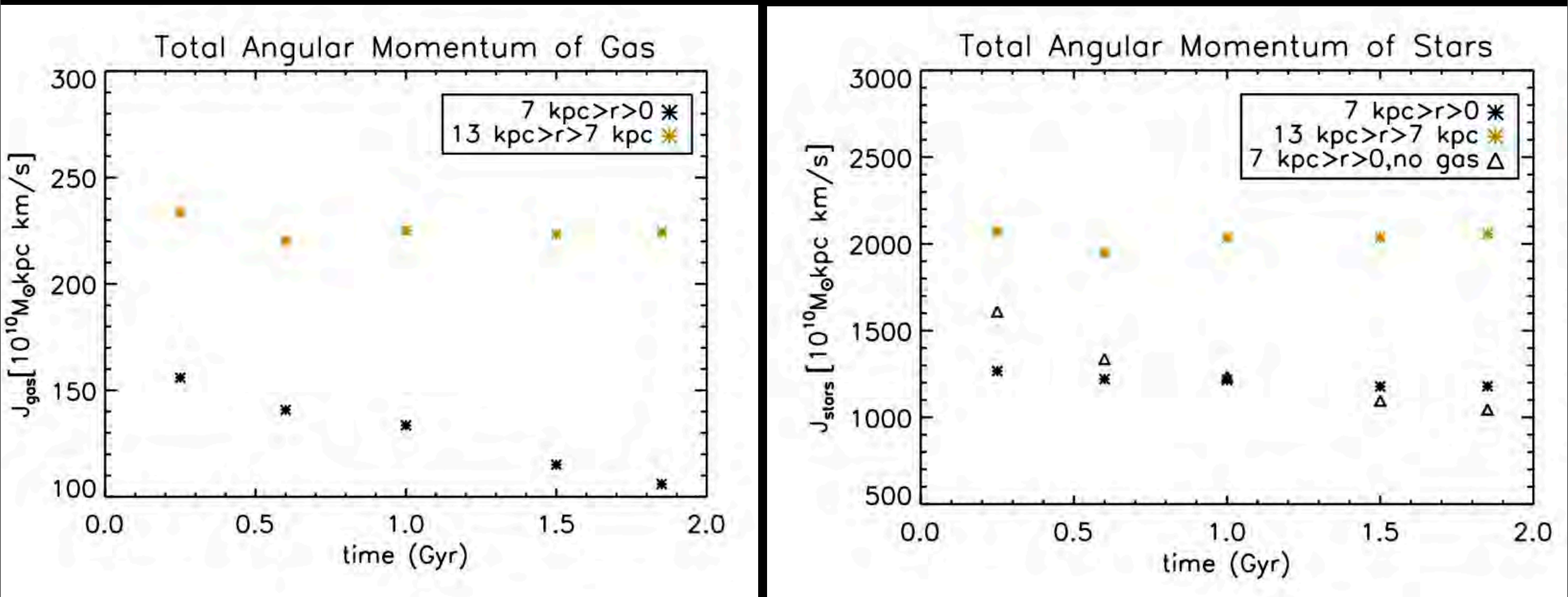




m=1 Fourier amplitude

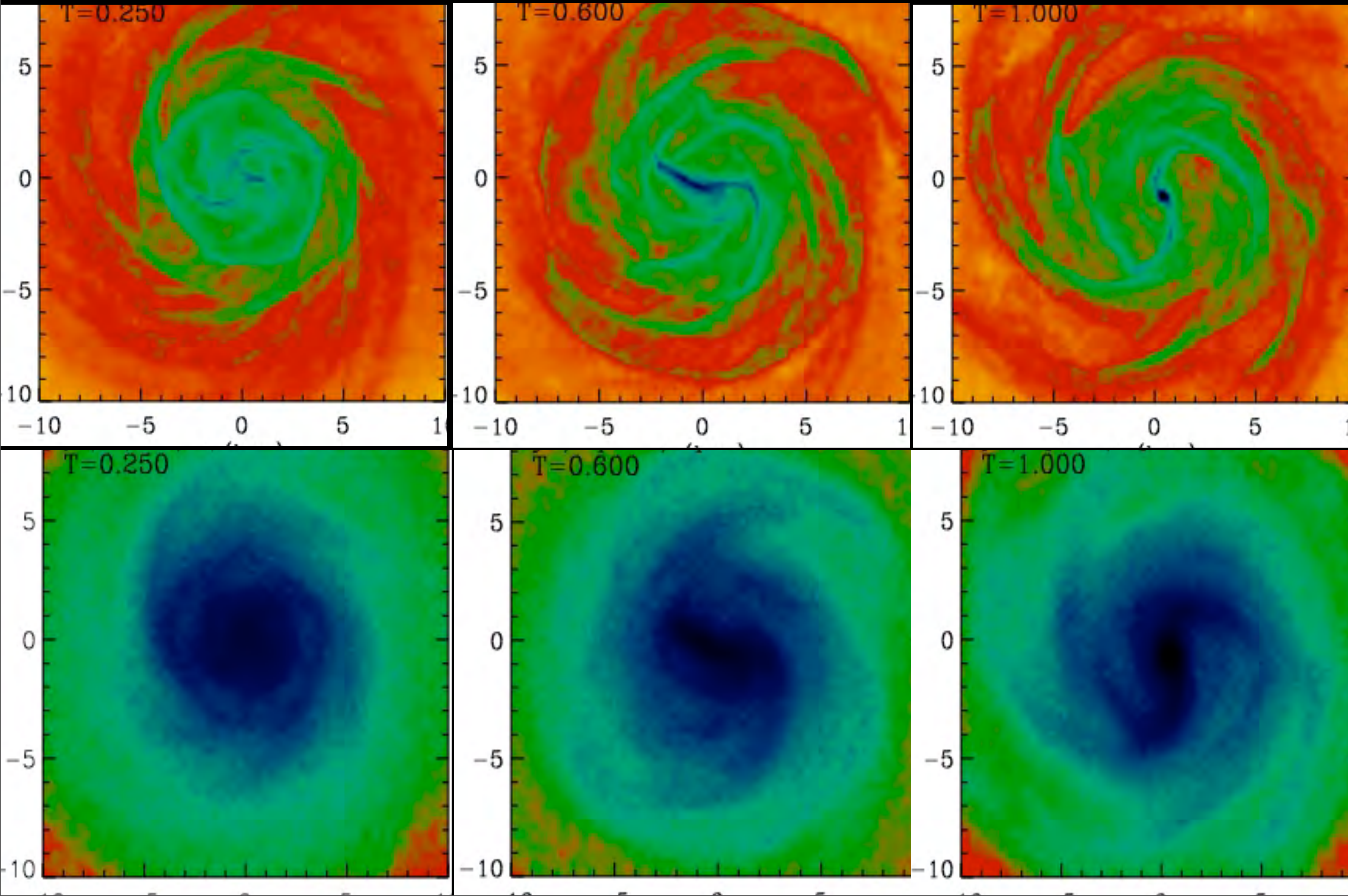
m=2 Fourier amplitude

Angular Momentum Transport

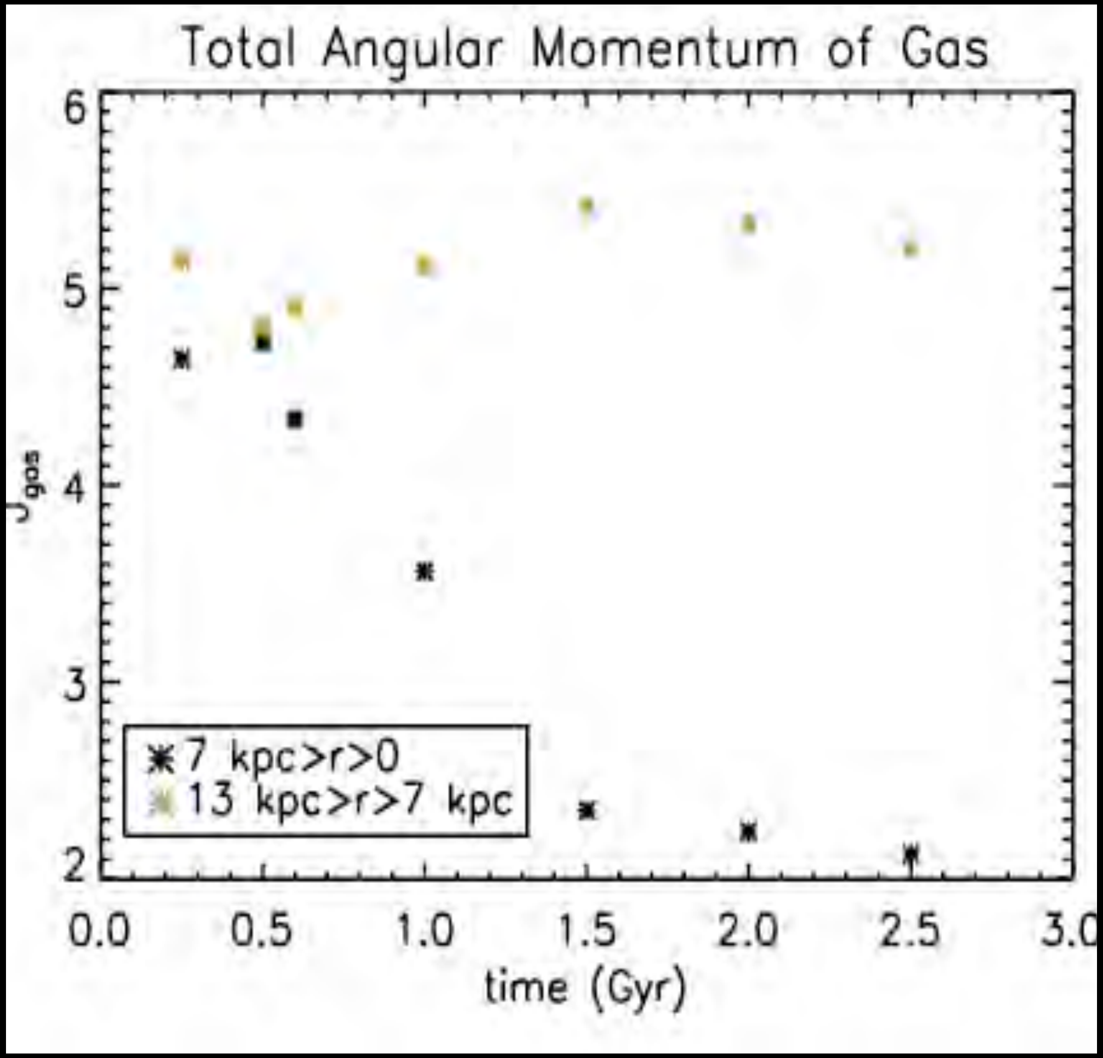


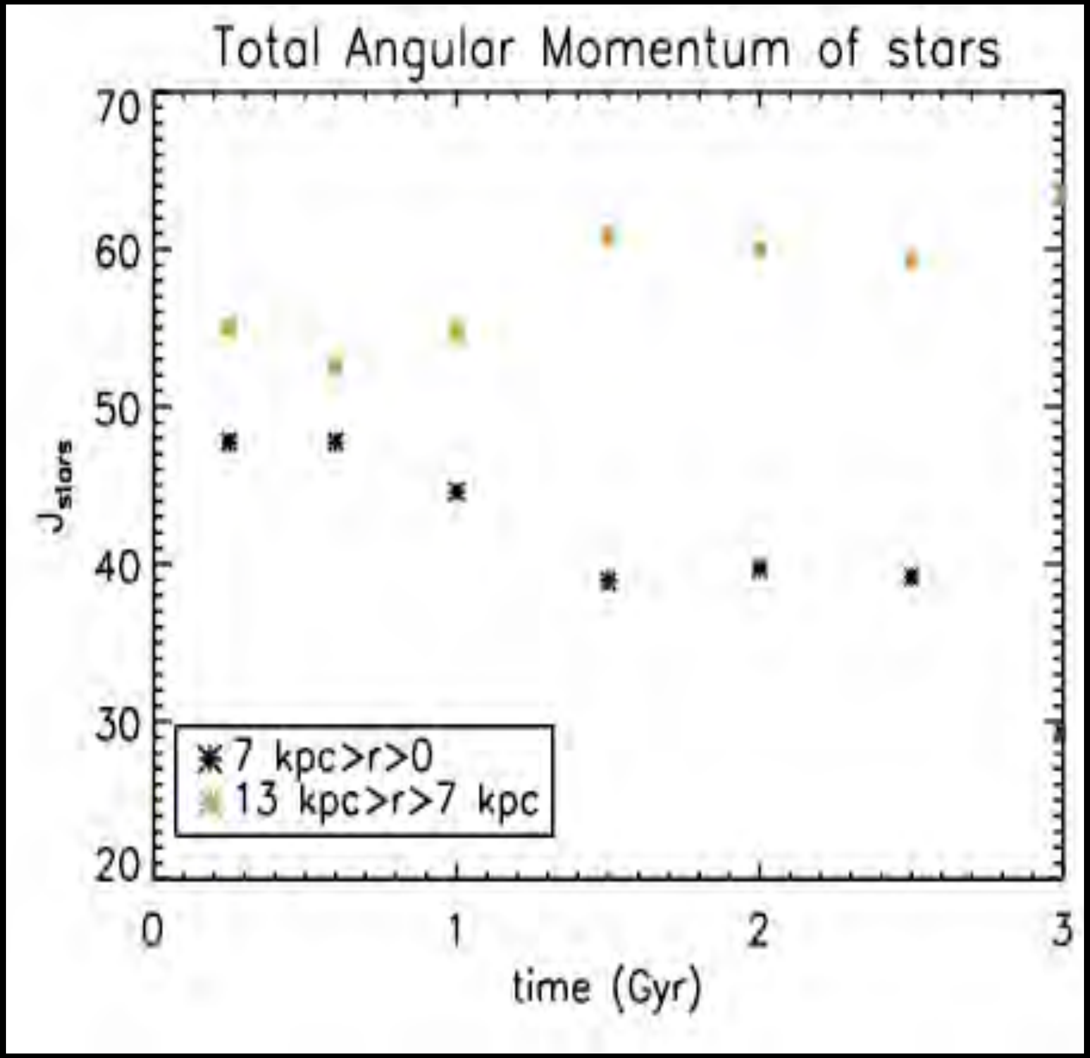
- gas is more susceptible to spiral instability
- flow of J: gas -->stars (with star formation turned off). Stars don't lose as much J as in simulations w.out gas (7% vs 35 %) (Chakrabarti, in prep)

Simulations with star formation turned on

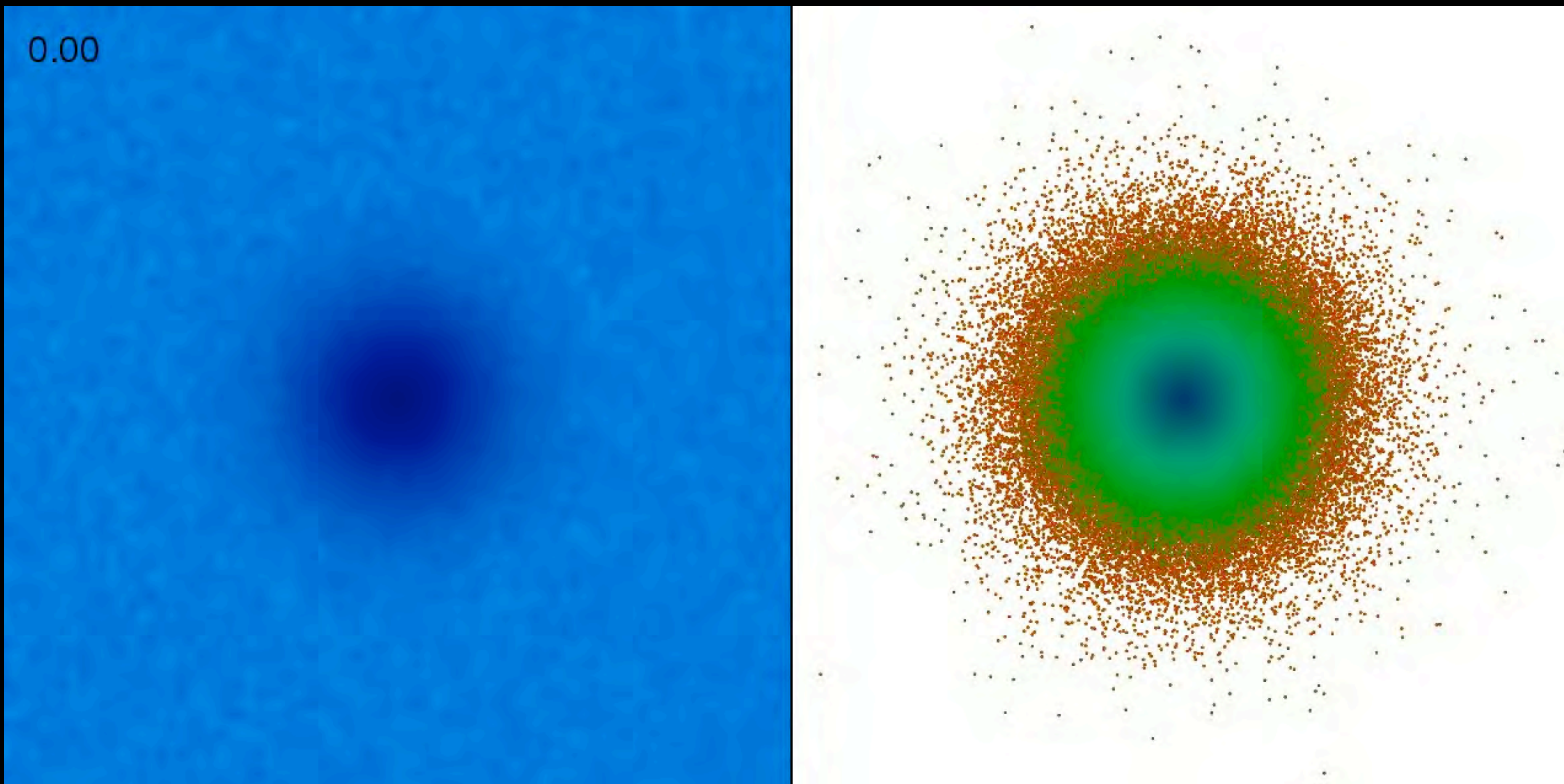


Angular momentum transport





- angular momentum of stars not as constant as with star formation turned off.
- gas consumption time-scale



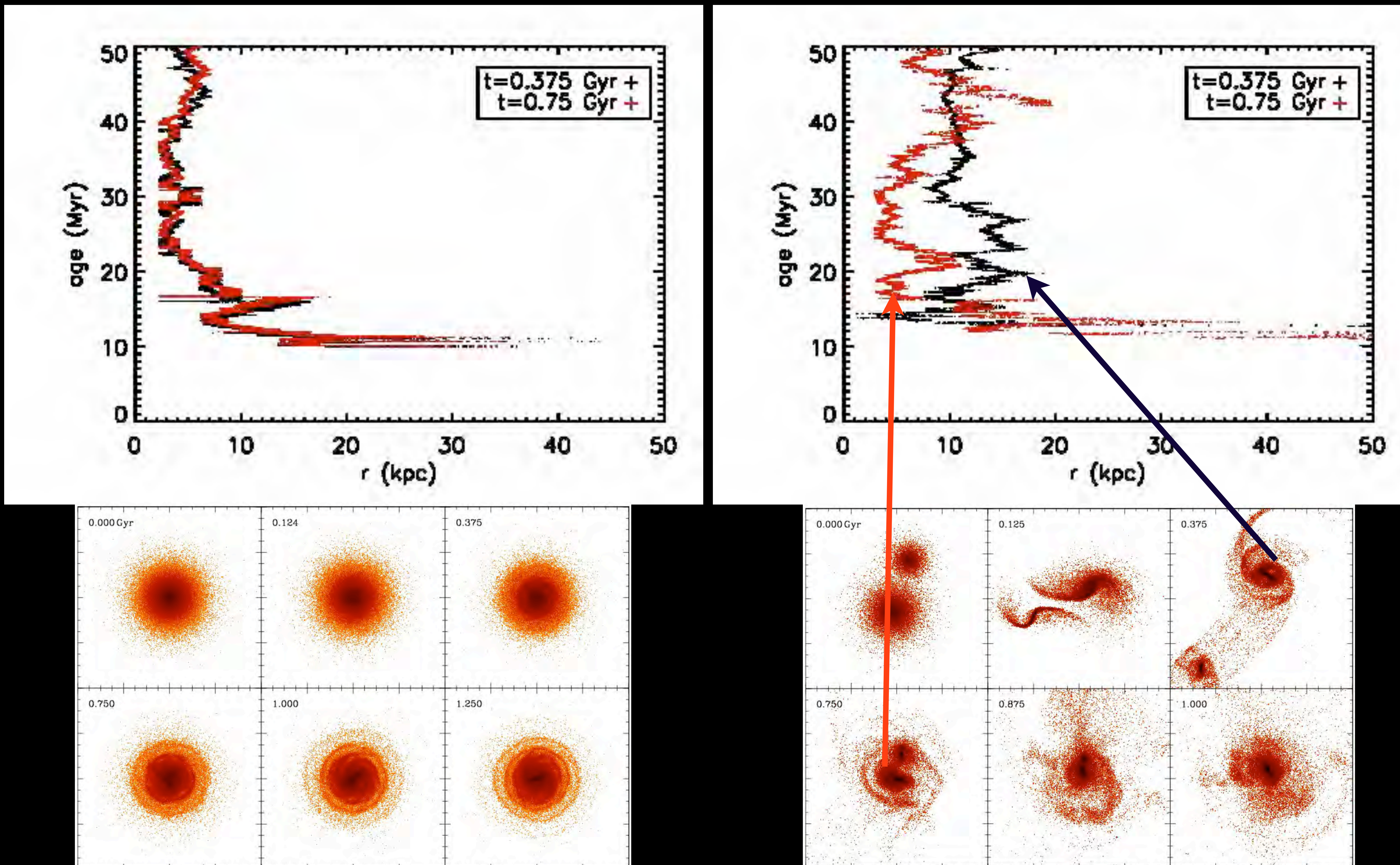
gas

stars

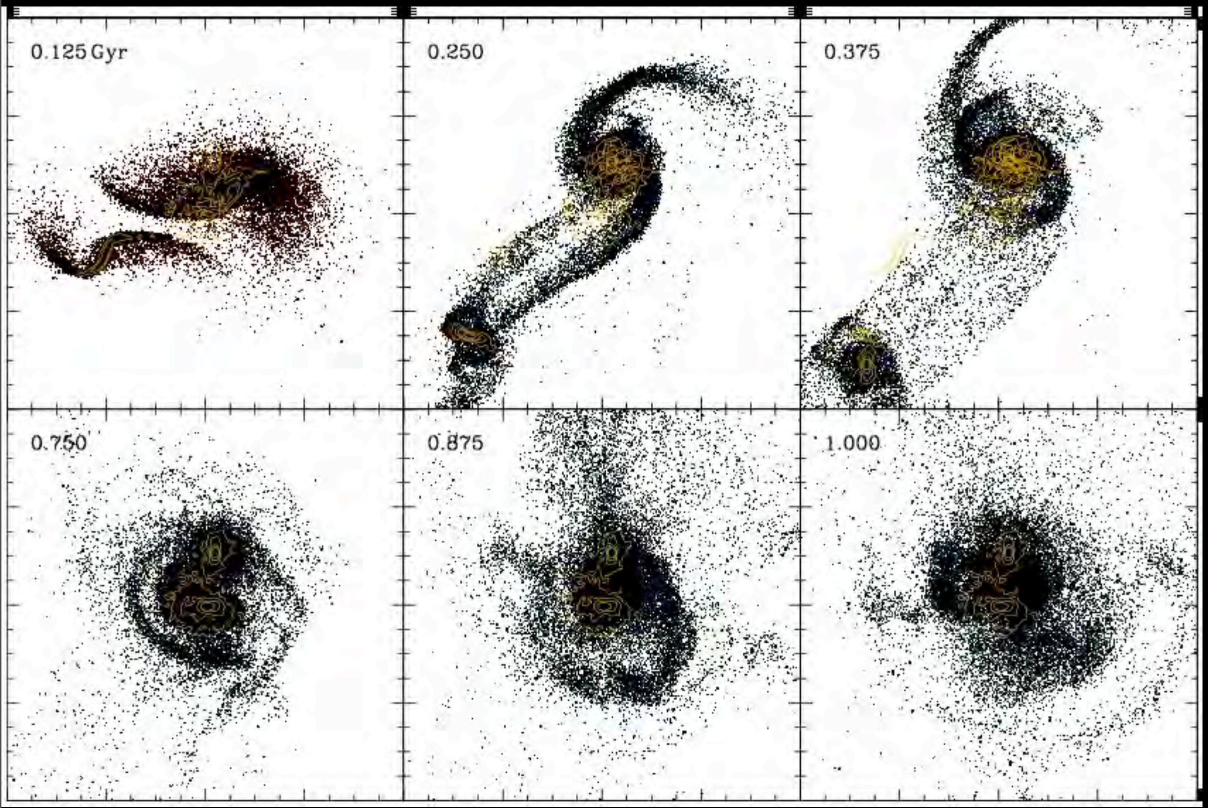
Lin & Shu 1964

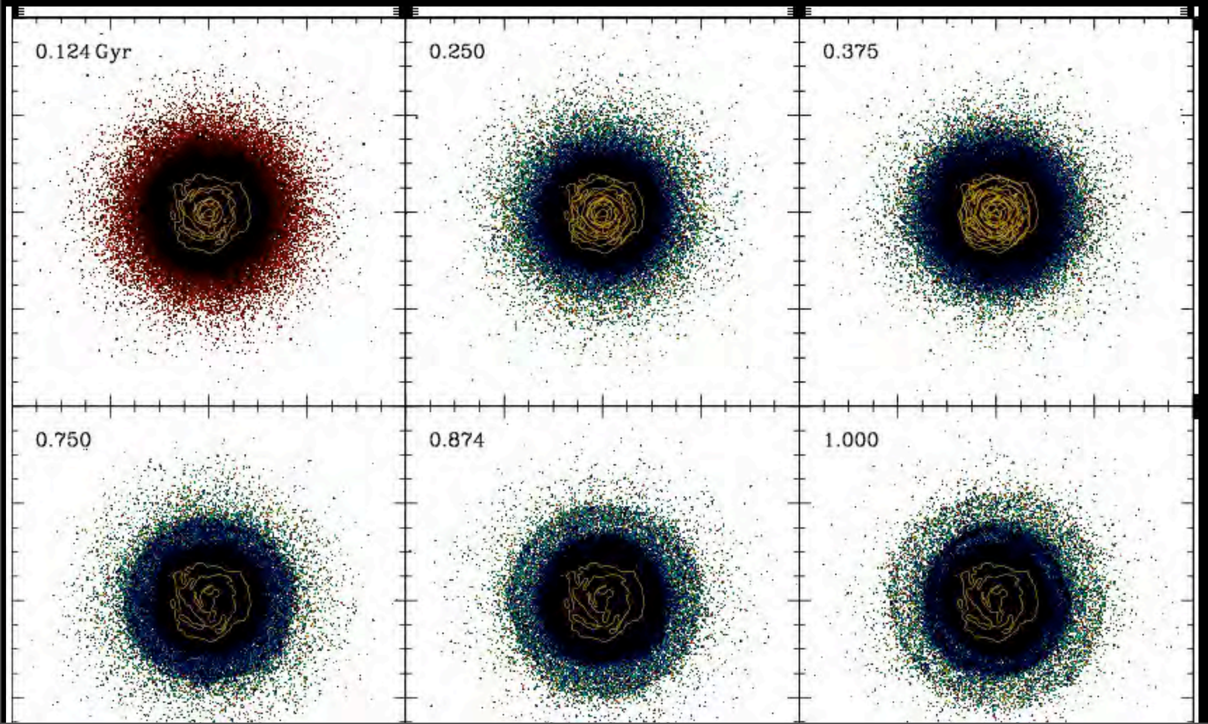
- "Different stellar components with different extent of velocity dispersion, should lie on somewhat different spirals and exhibit different degrees of unevenness. As an extreme case, one may even attempt to analyze the behavior of the gas, which has very little pressure, and is subject to the action of the spiral gravitational field as produced by the rest of the galactic population. Its density contrast may therefore be expected to be far larger than that known in the stellar components. These discussions should be supplemented by a consideration of the reaction of the gas on the stellar population."

Age distribution of stars in isolated vs interacting models



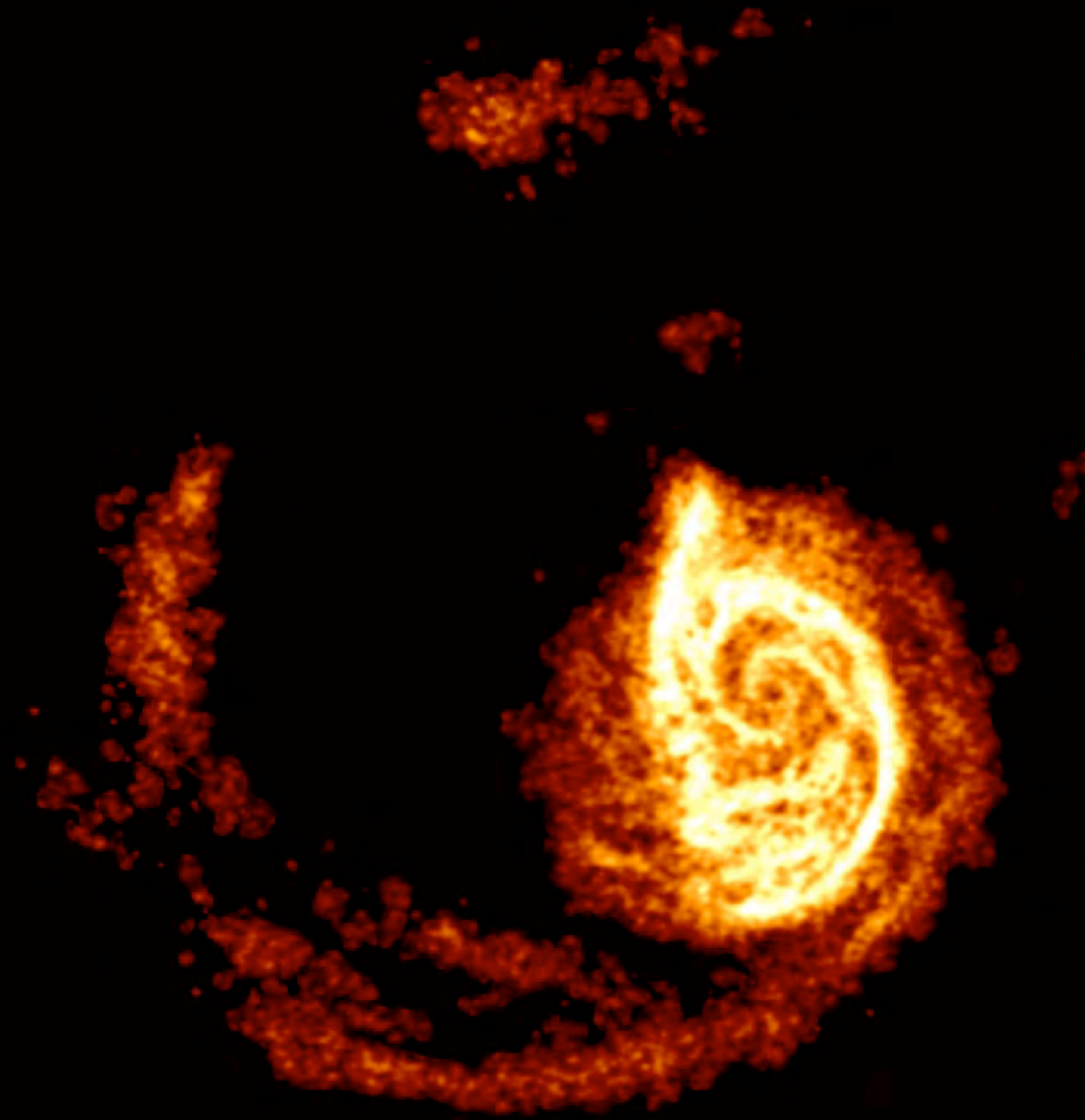
future -- constraining evolutionary models





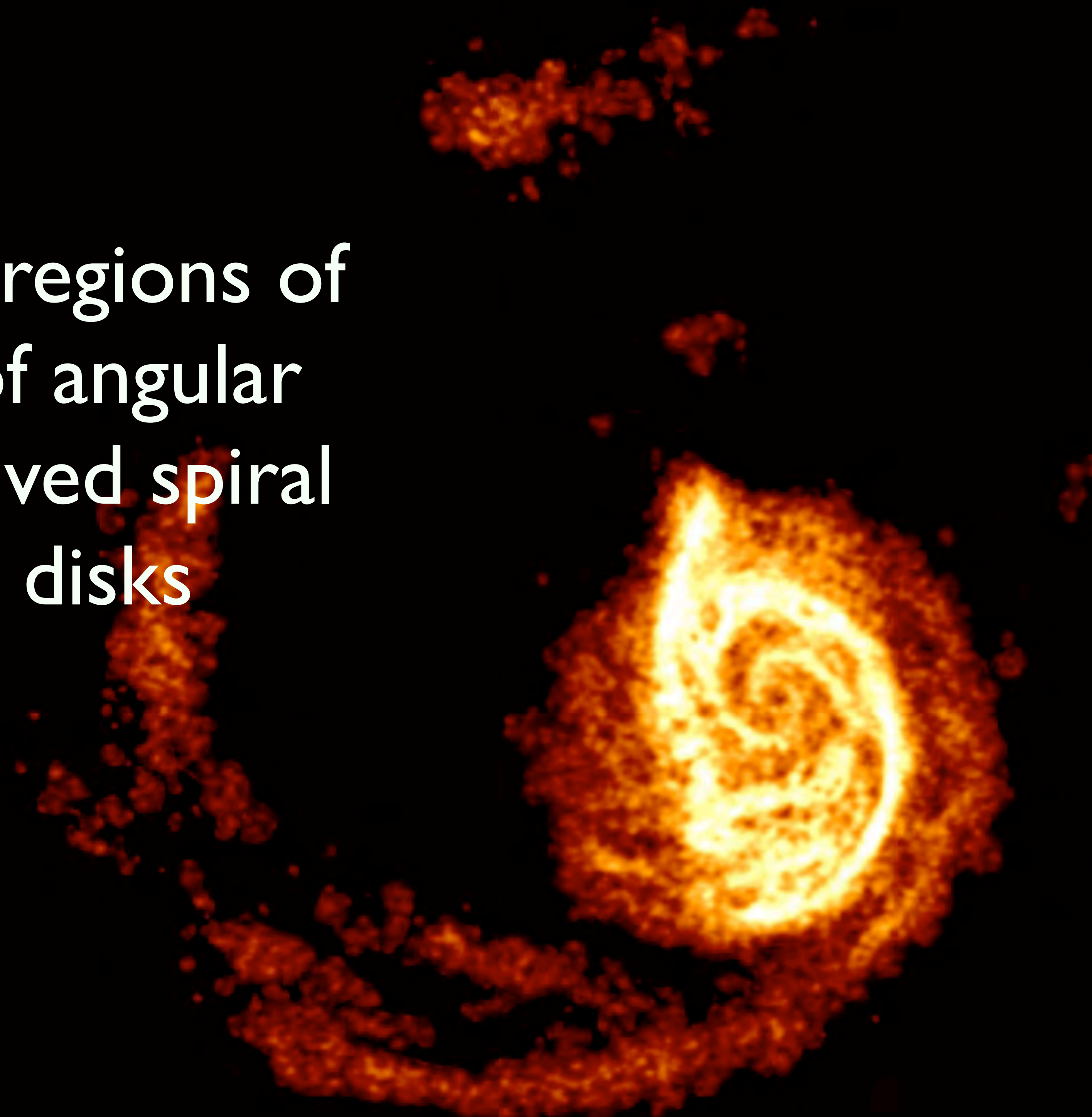
- Caveats: initial conditions
- star formation prescriptions
- multiple constraints: fit to HI maps, GALEX images (recent star formation), *and* age distributions of star clusters (following Gonzalez et al.)

Overview



Overview

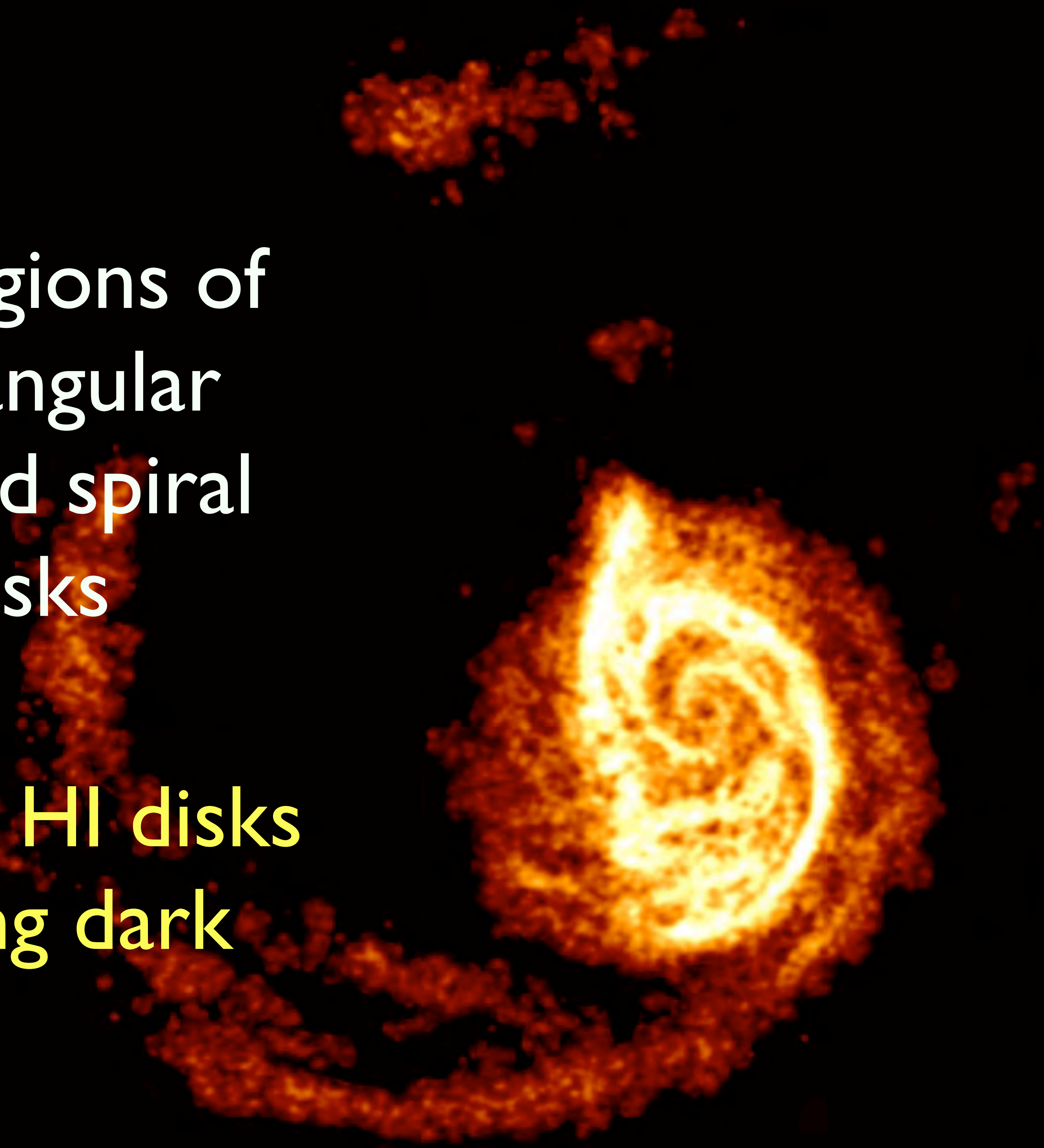
- Cold gas (in inner regions of spirals) as donor of angular momentum, long-lived spiral structure in stellar disks



Overview

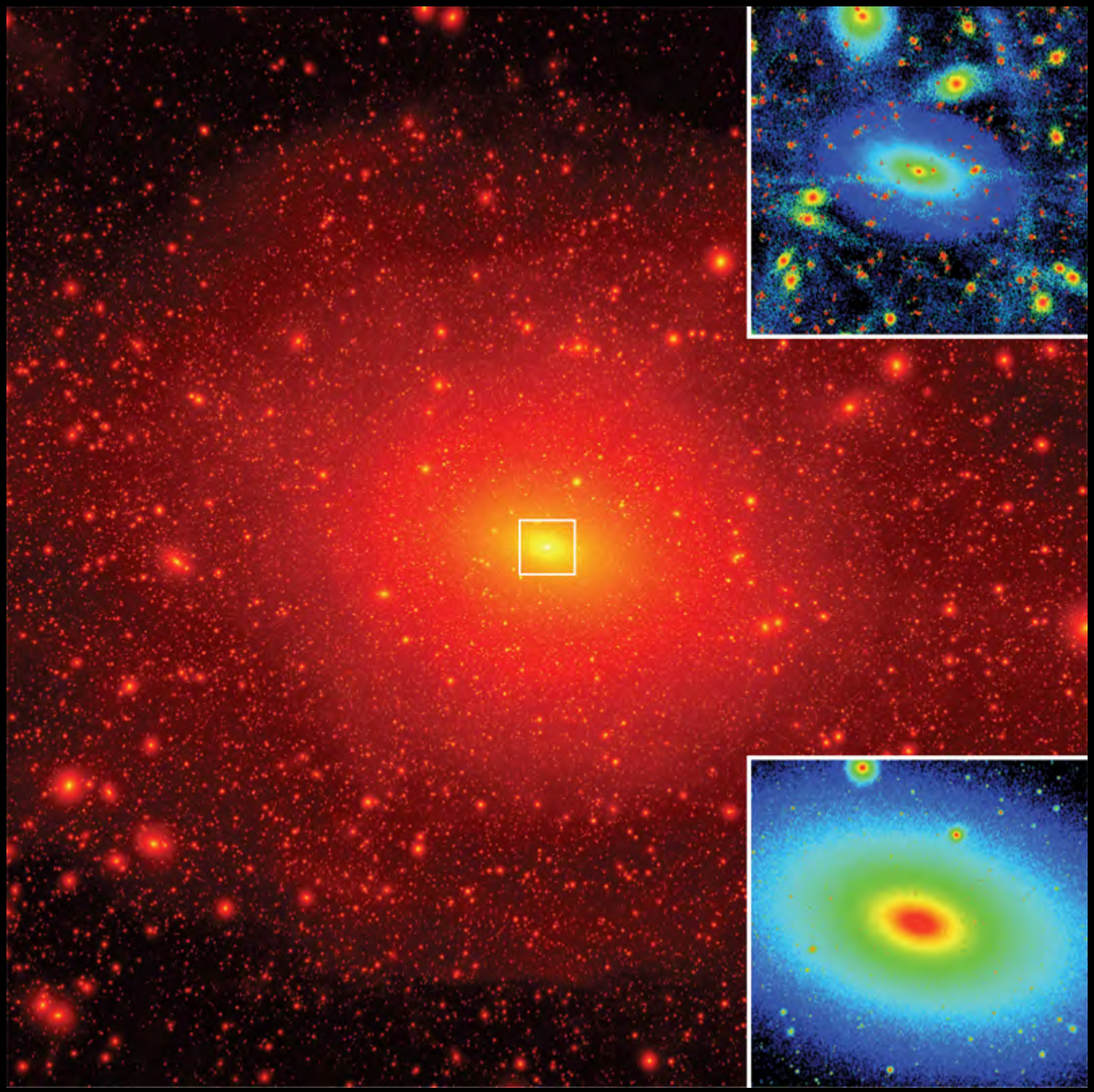
- Cold gas (in inner regions of spirals) as donor of angular momentum, long-lived spiral structure in stellar disks

- Cold gas in extended HI disks as tracer of perturbing dark sub-halos

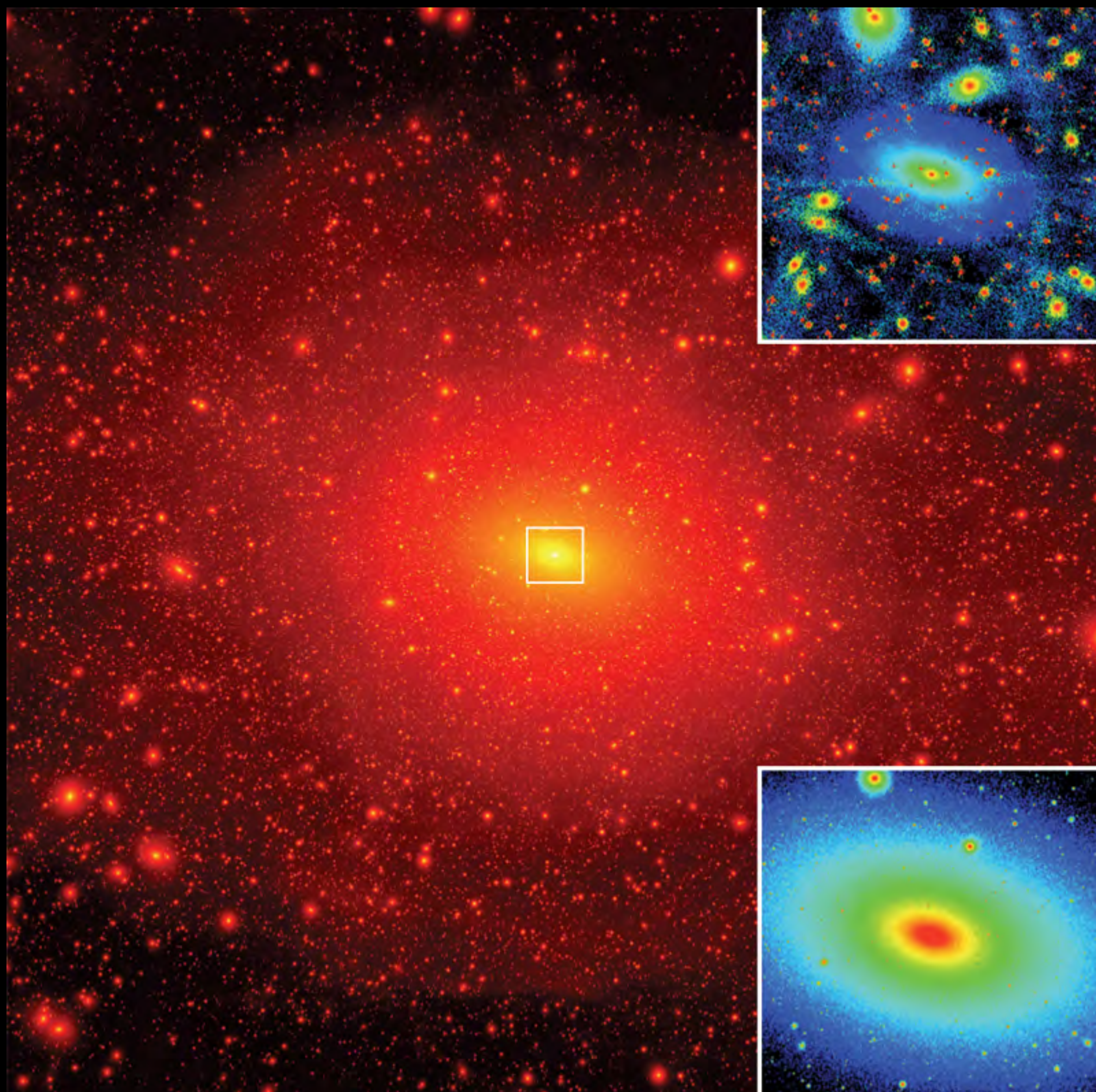


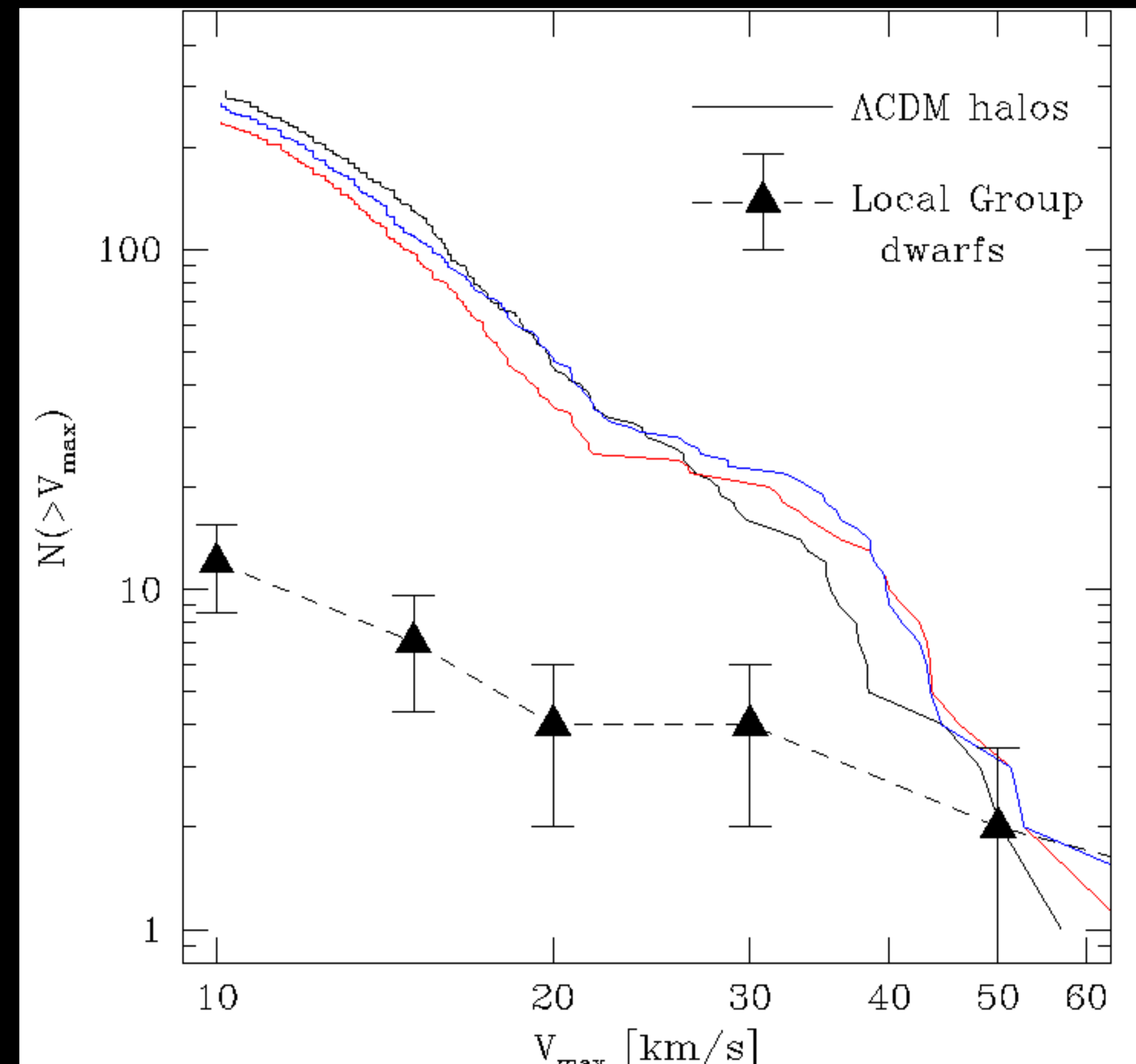
Dark Sub-Halos: Expectations from Simulations

Dark Sub-Halos: Expectations from Simulations

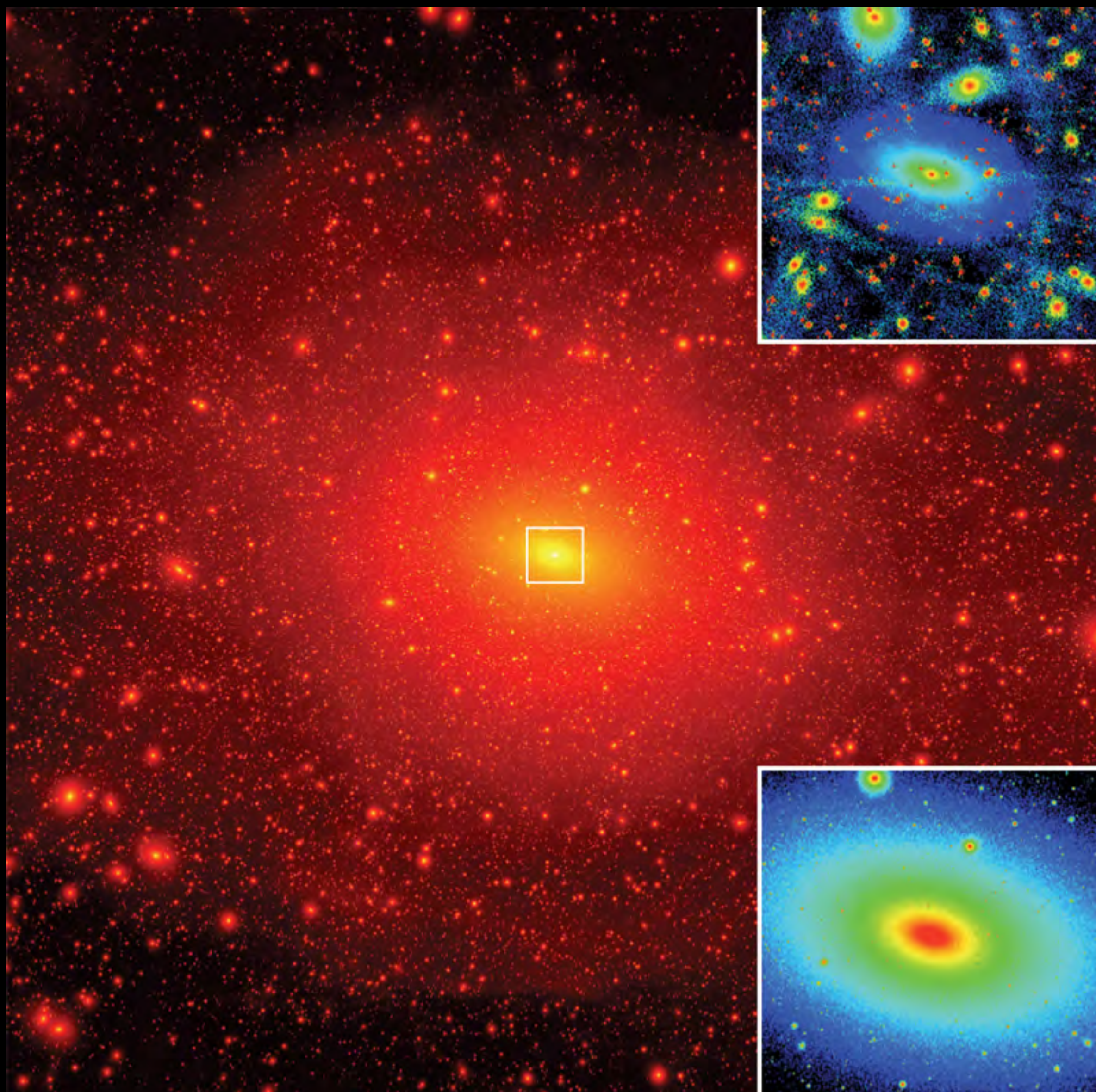


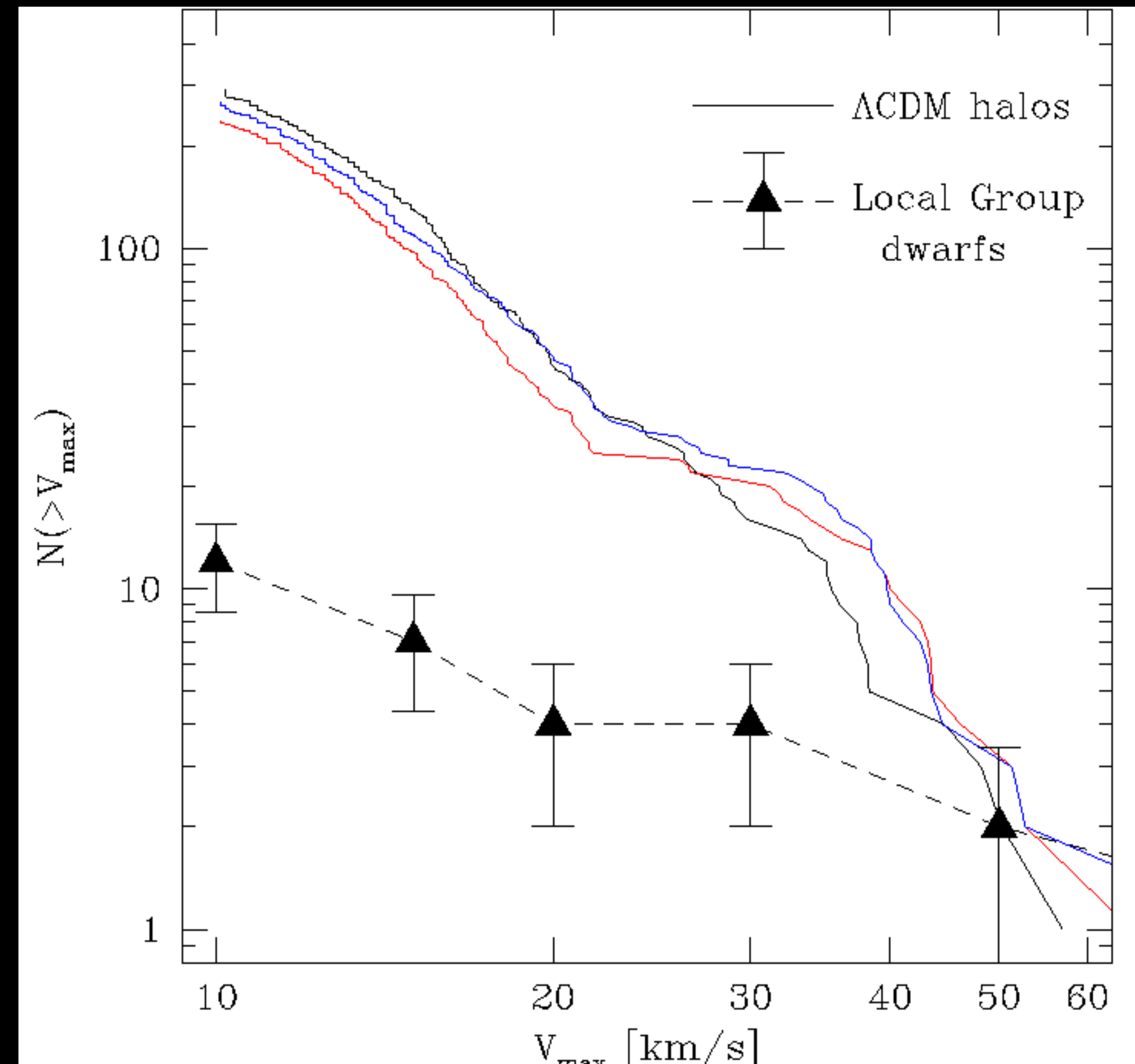
Dark Sub-Halos: Expectations from Simulations





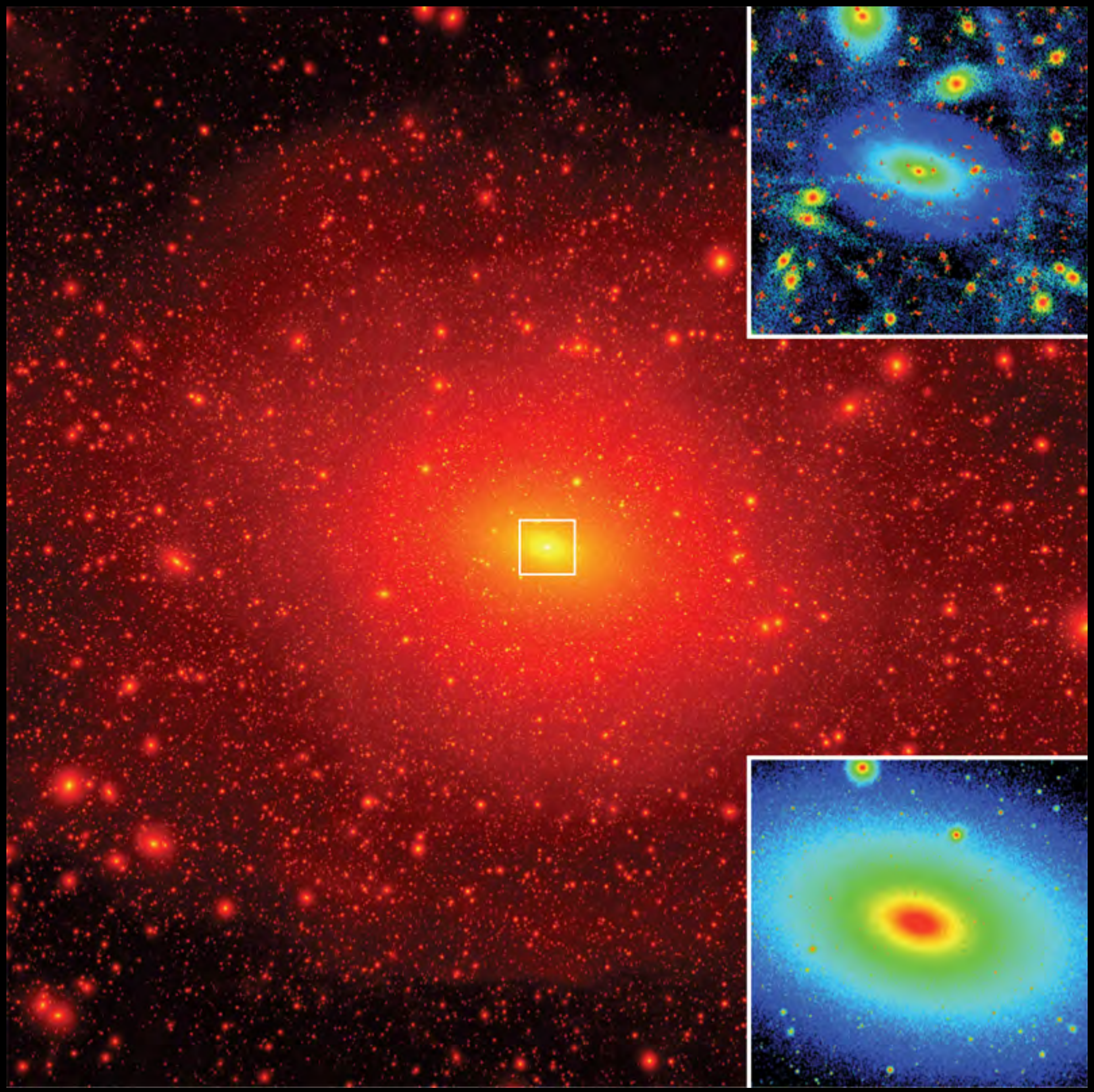
Dark Sub-Halos: Expectations from Simulations

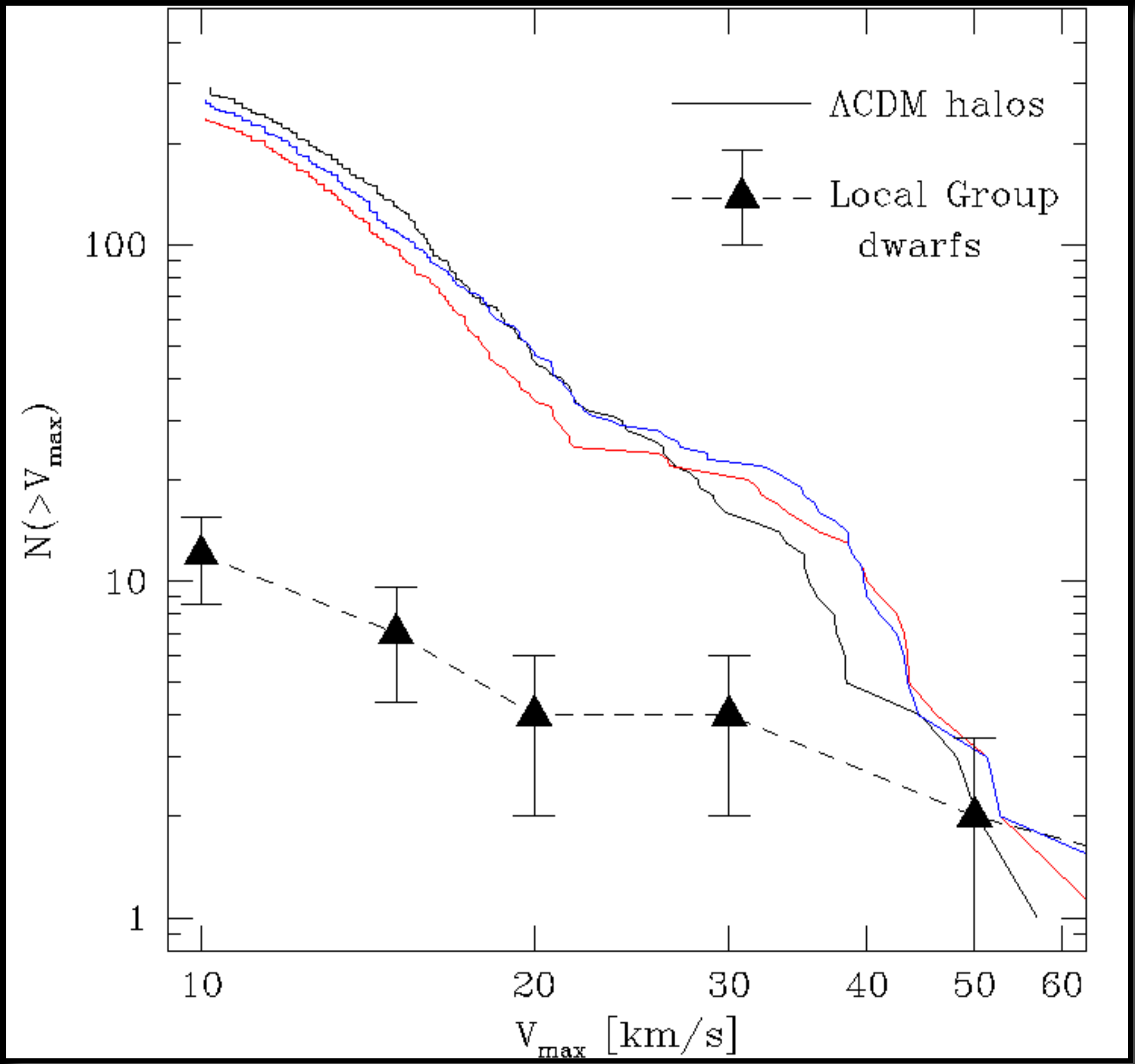




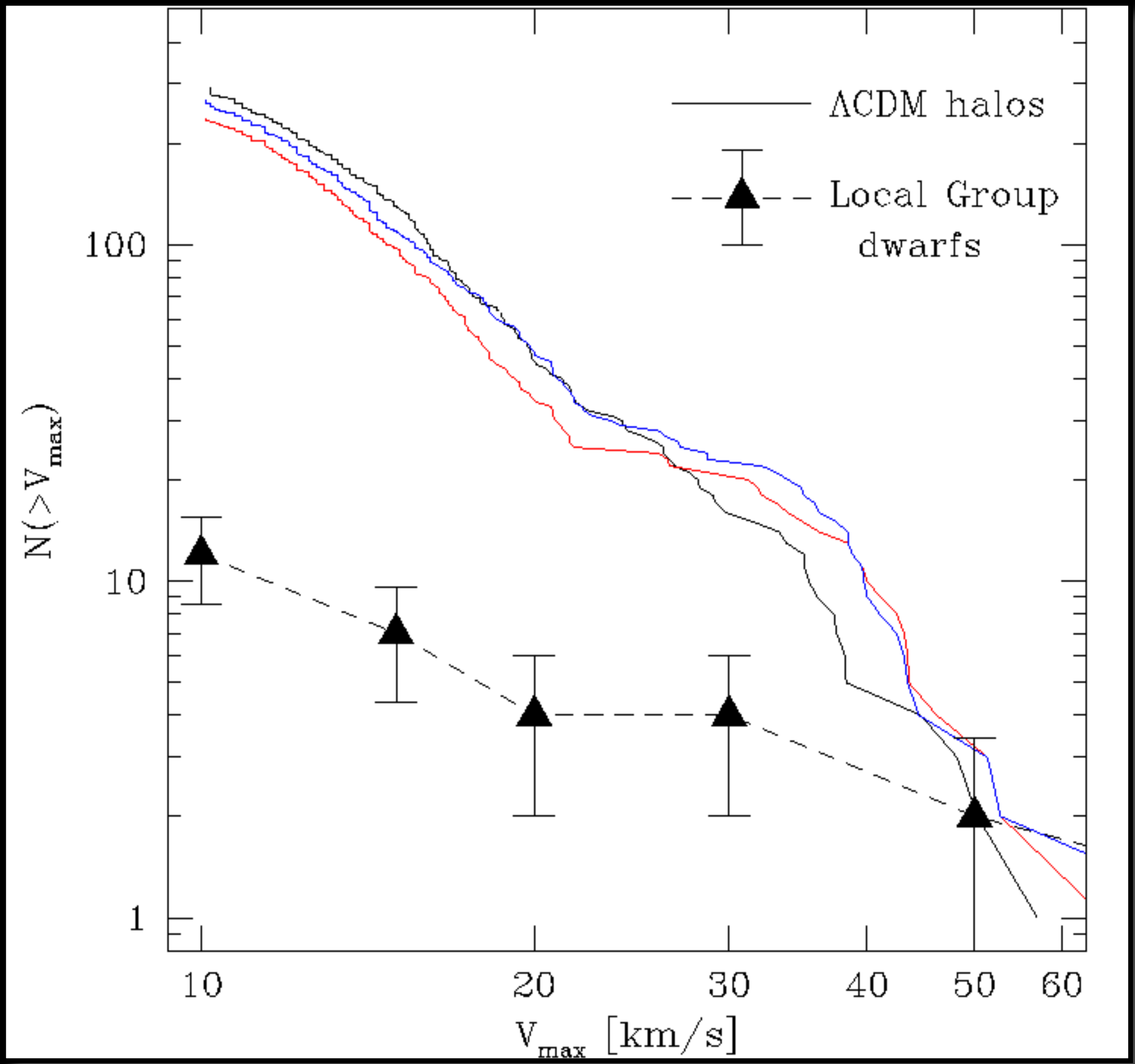
- Missing satellites problem (Klypin et al. 1999; Diemand et al. 2008)

Dark Sub-Halos: Expectations from Simulations





Dark Sub-Halos: Expectations from Simulations



Dark Sub-Halos: Expectations from Simulations

Dark Sub-Halos: Expectations from Simulations

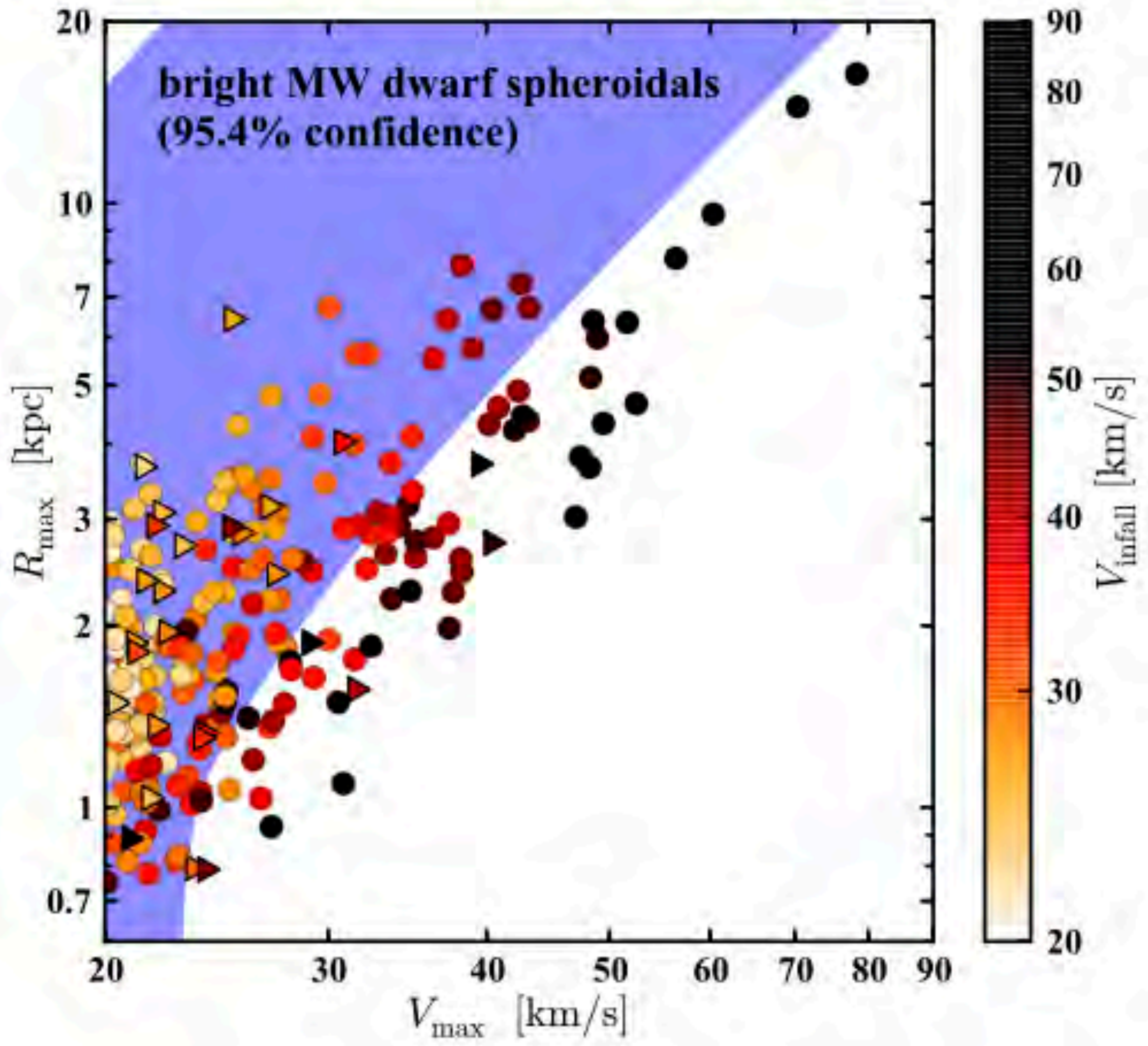


Figure 2. Subhalos from all six Aquarius simulations (circles) and Via Lactea II (triangles), color-coded according to V_{infall}. The shaded blue region shows the $2\,\sigma$ confidence interval for possible hosts of the bright MW dwarf spheroidals (see Fig. 1).

Dark Sub-Halos: Expectations from Simulations

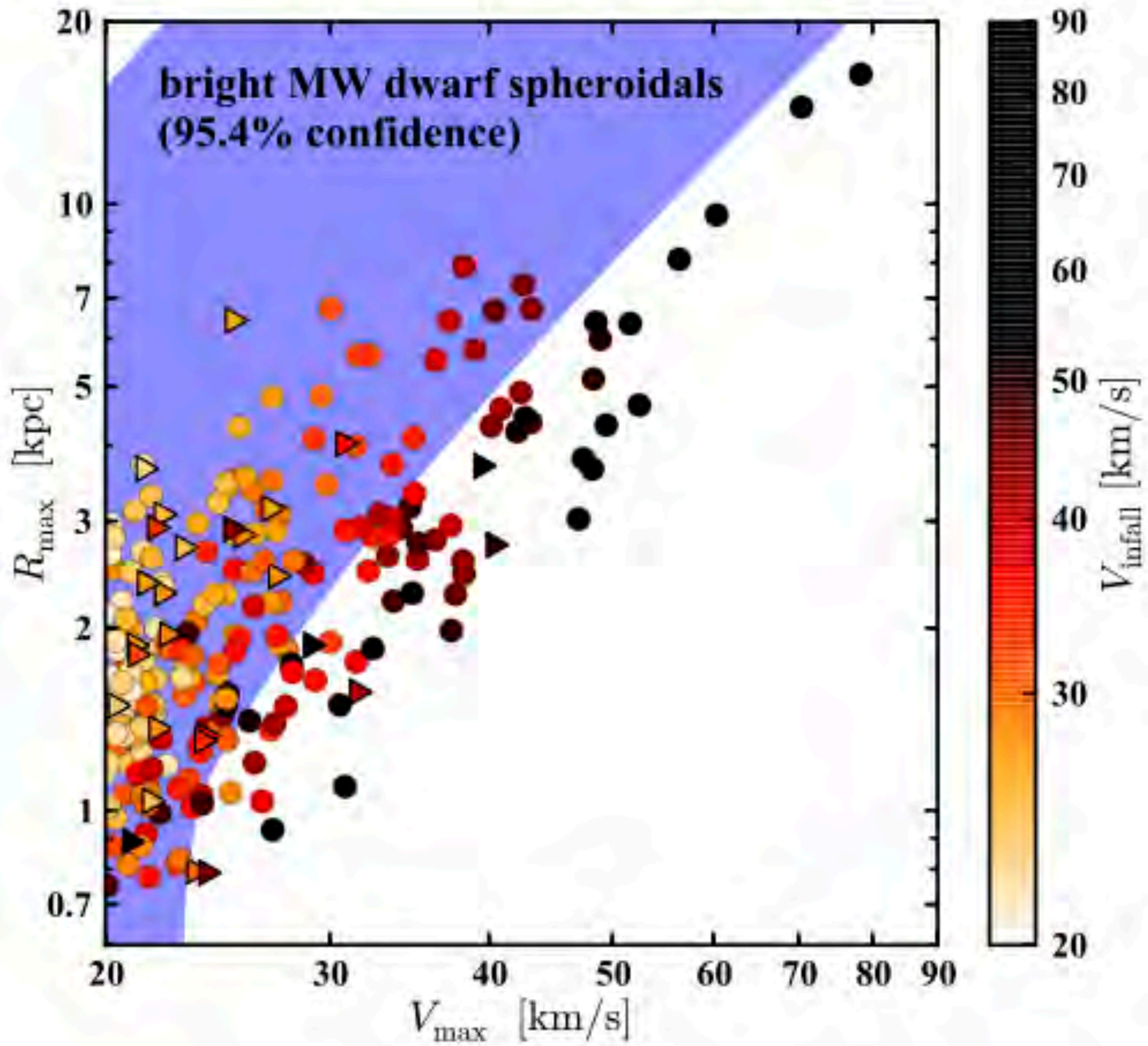
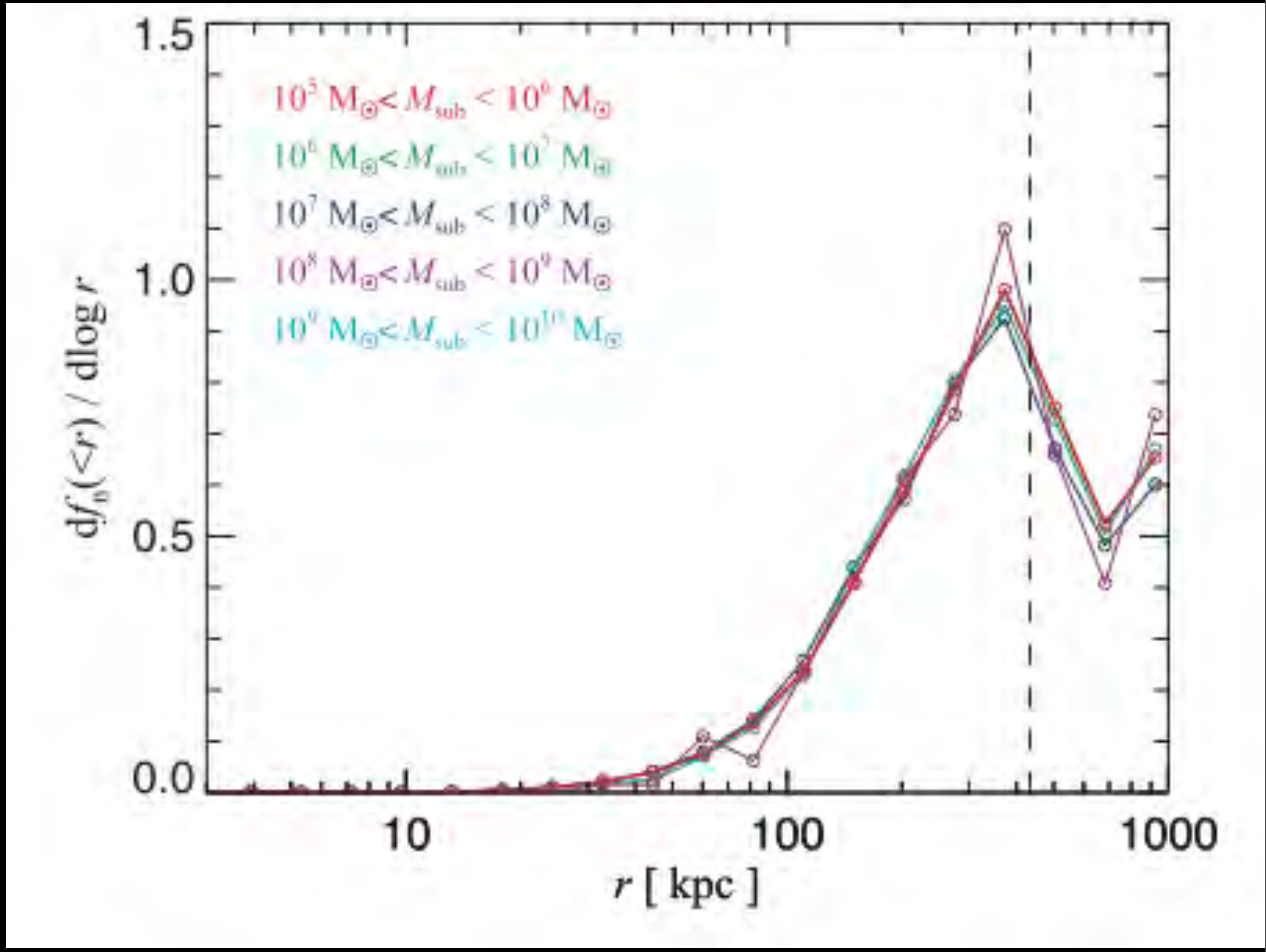


Figure 2. Subhalos from all six Aquarius simulations (circles) and Via Lactea II (triangles), color-coded according to V_{infall}. The shaded blue region shows the $2\,\sigma$ confidence interval for possible hosts of the bright MW dwarf spheroidals (see Fig. 1).

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

Extended HI disks as tracer of sub-halo interactions

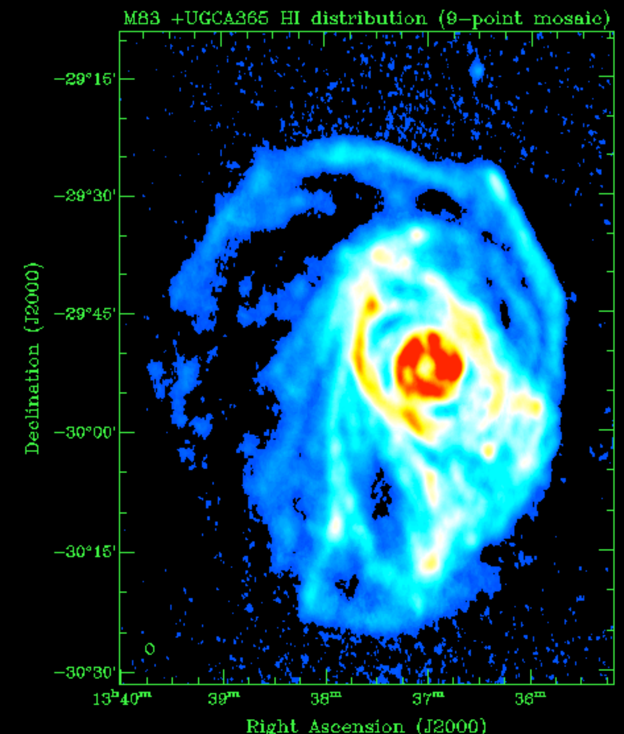
- cosmological simulations predict most sub-halos of a given mass are in the outer parts of the halo
- M83's HI disk reaches to ~ 100 kpc -- where simulations *expect* the sub-structure to be



Springel et al. 2008

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

- Coldest Component Responds the Most!
- Extended HI disks reach to several times the optical radius -- <u>largest</u> cross-section for interaction
- Gas has short-term memory.
- **The *best* of hydrodynamics!**



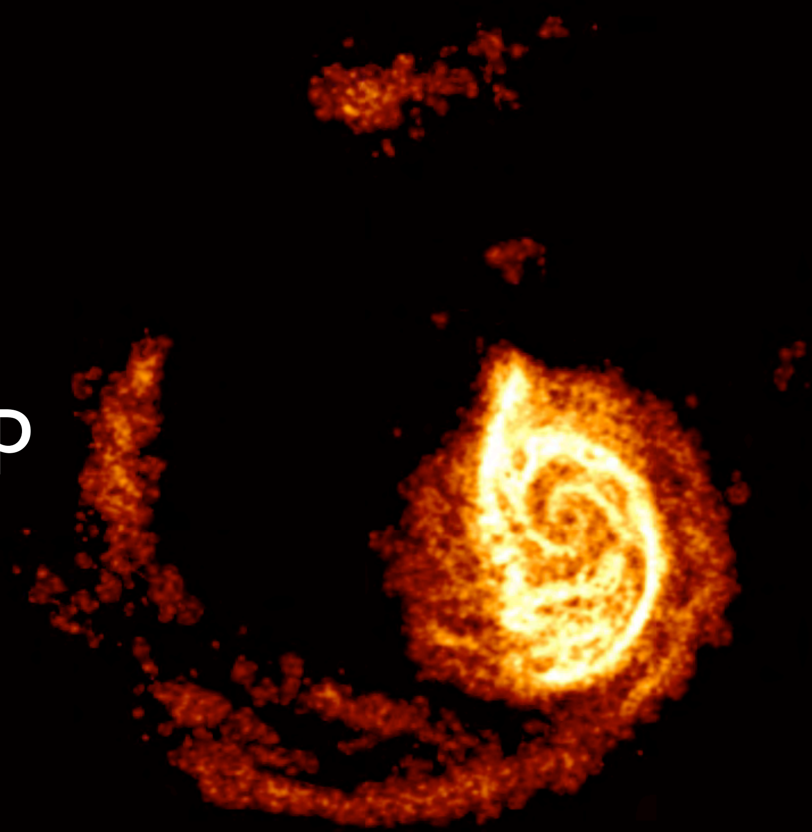
Atomic hydrogen (HI) Maps

Footprints of Dark Sub-Halos

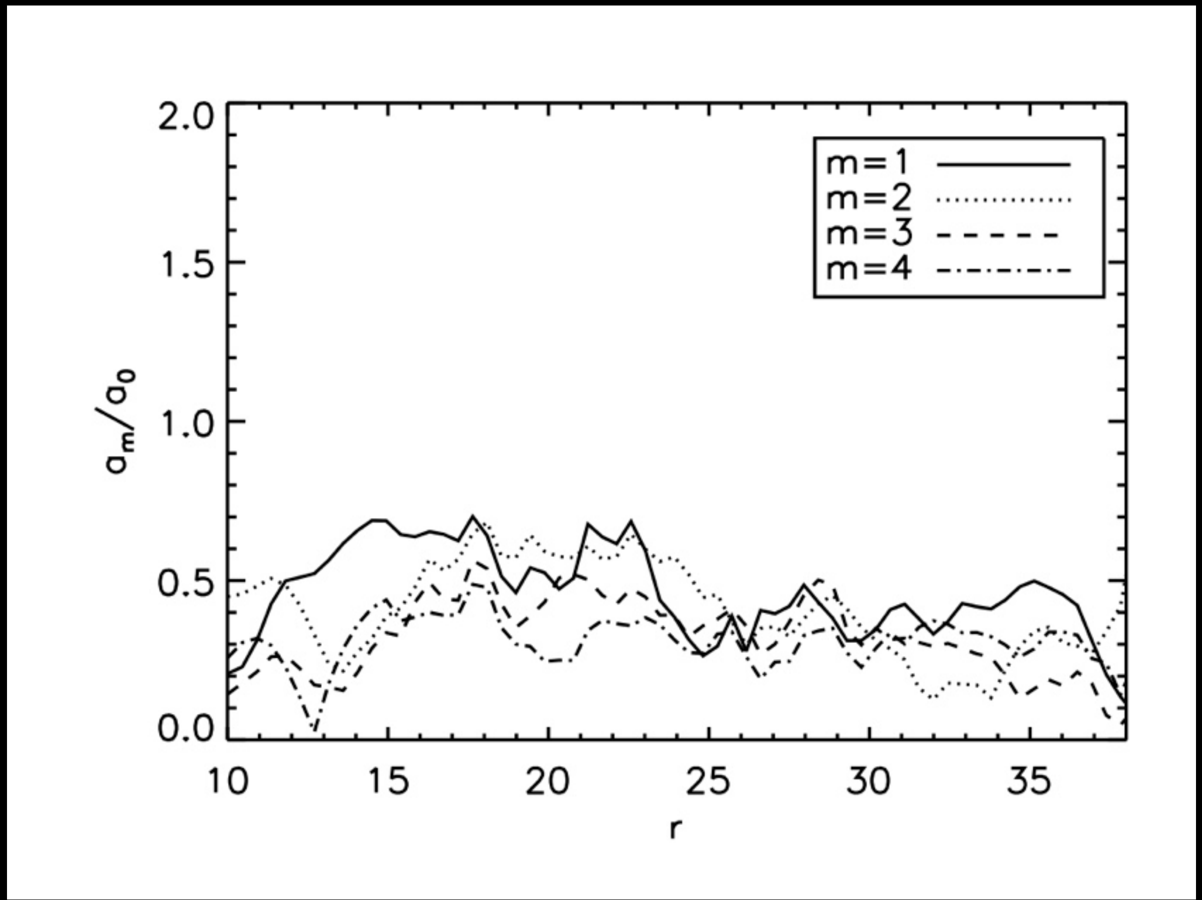
Disturbances in HI disks in Local Spirals: Proof of Principle

M51

HI Map



optical image

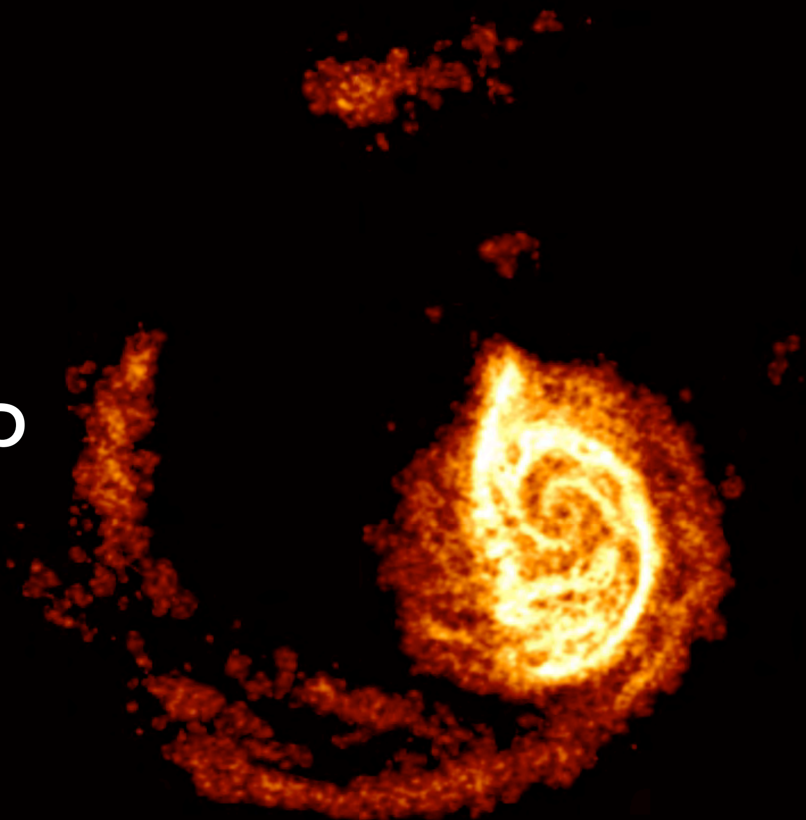


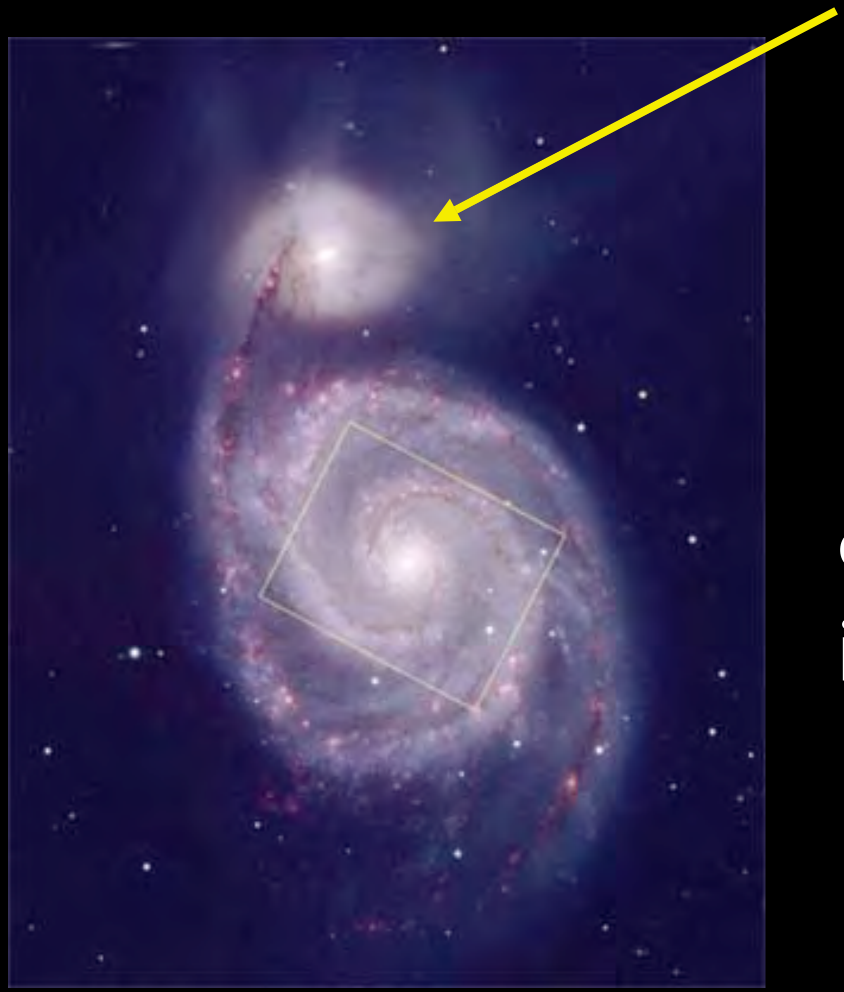
$$a_m(r) = \int \Sigma(r,\phi) e^{-im\phi} d\phi$$

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

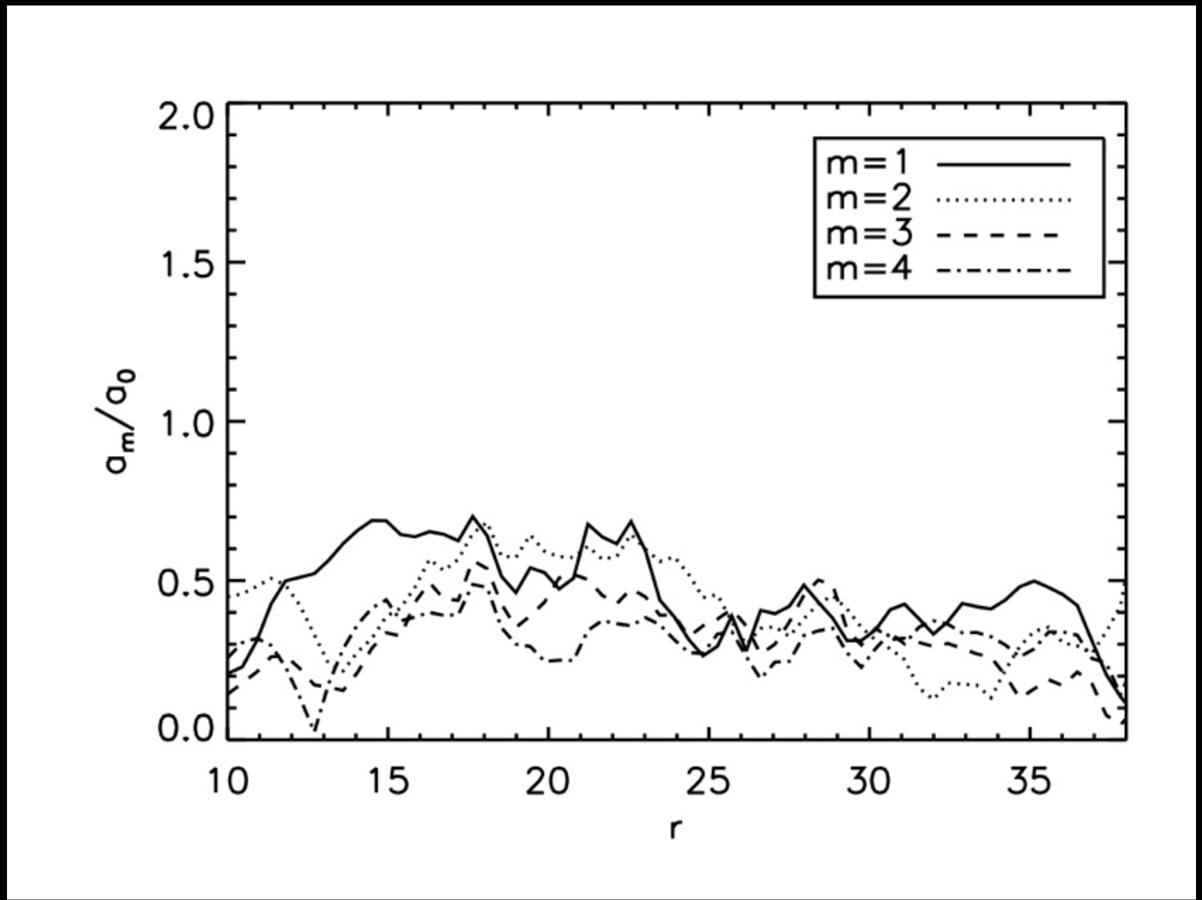
M51

HI Map





optical image

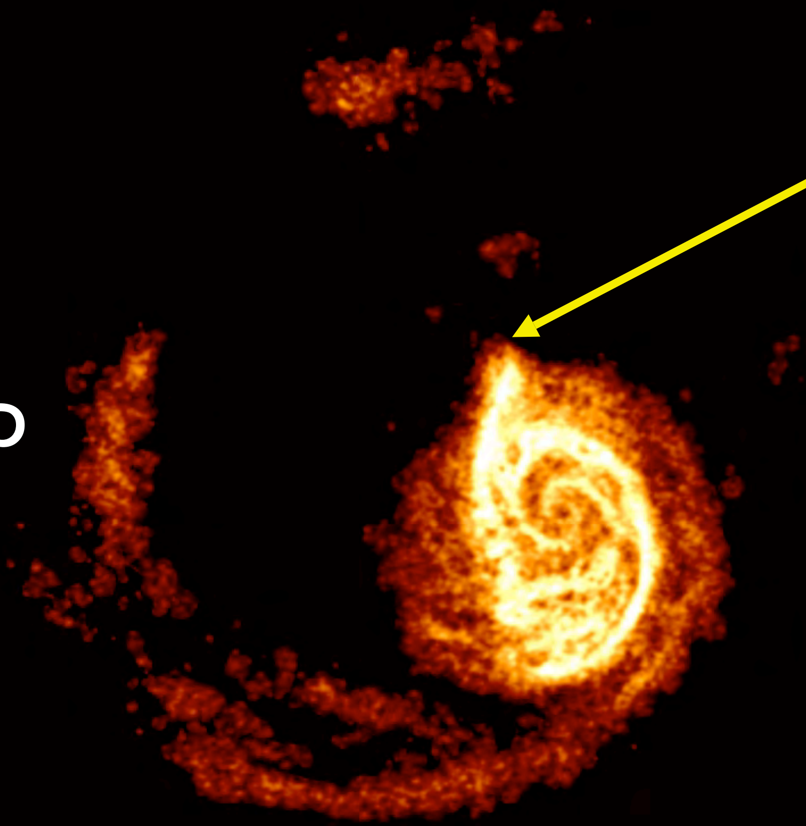


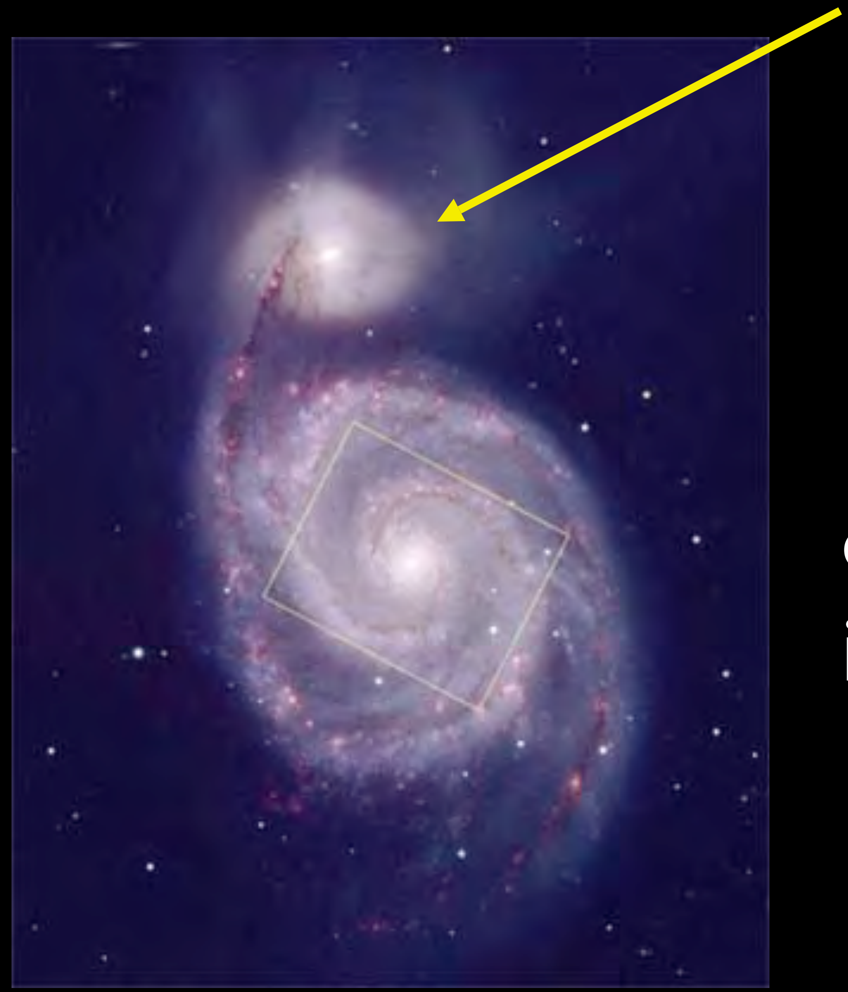
$$a_m(r)=\int \Sigma(r,\phi)e^{-im\phi}d\phi$$

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

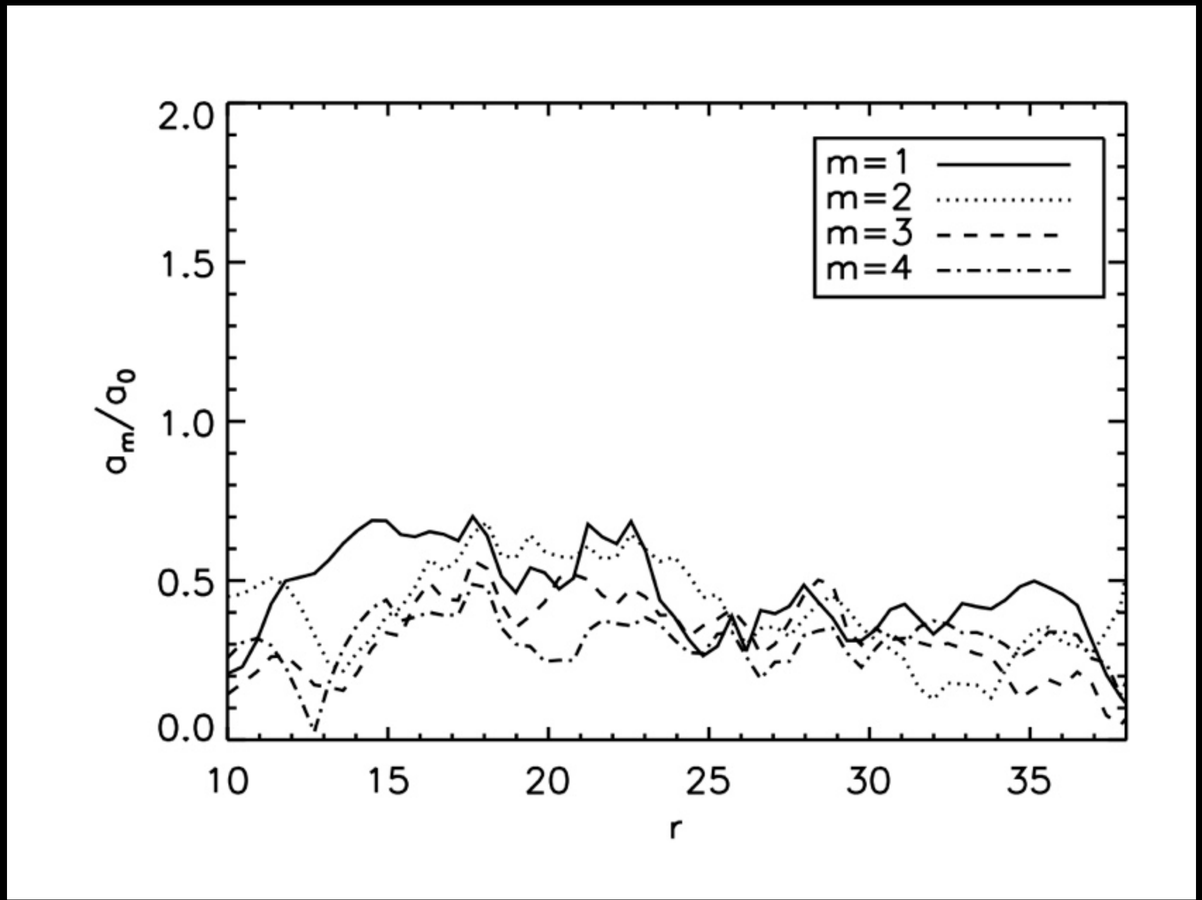
M51

HI Map





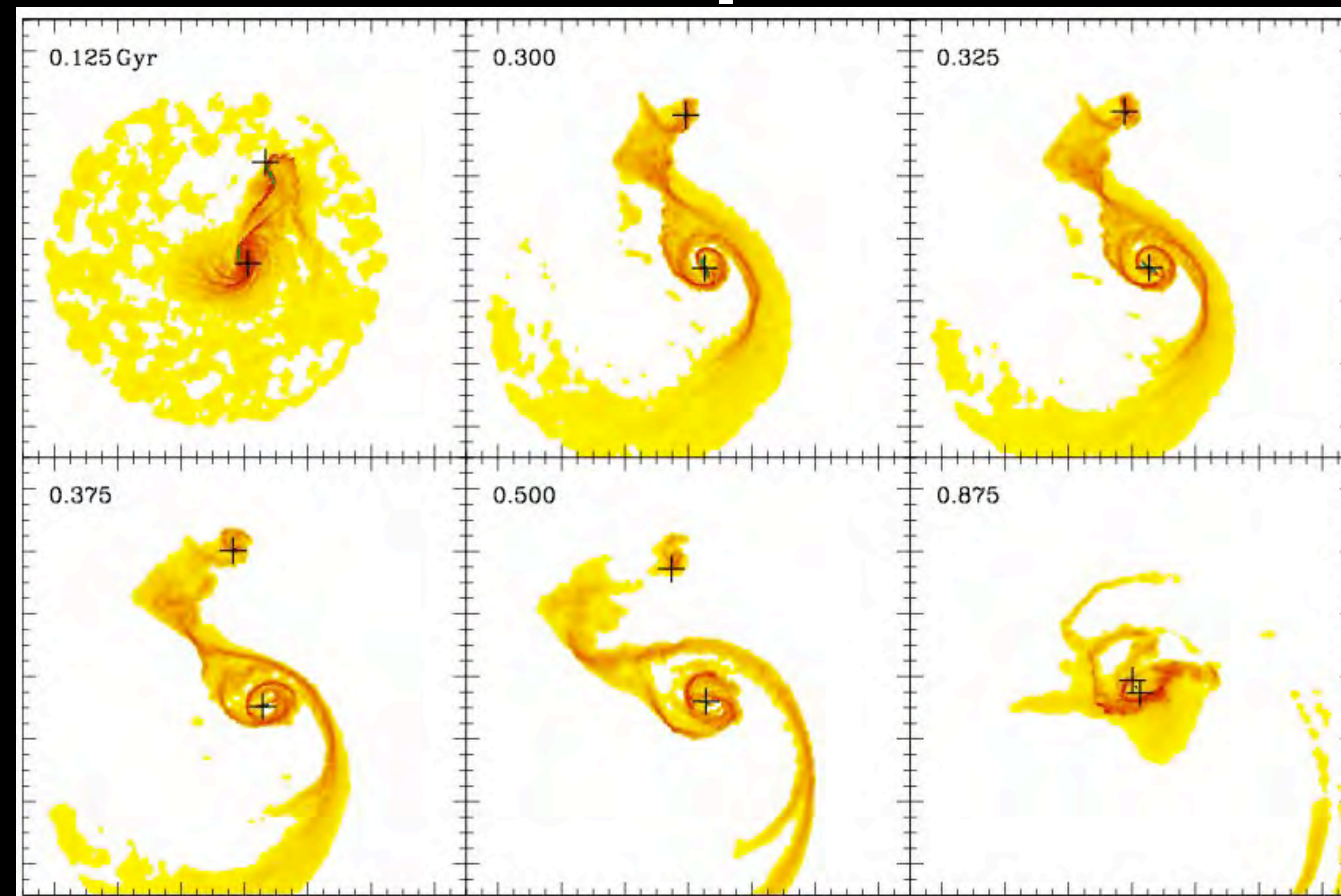
optical image

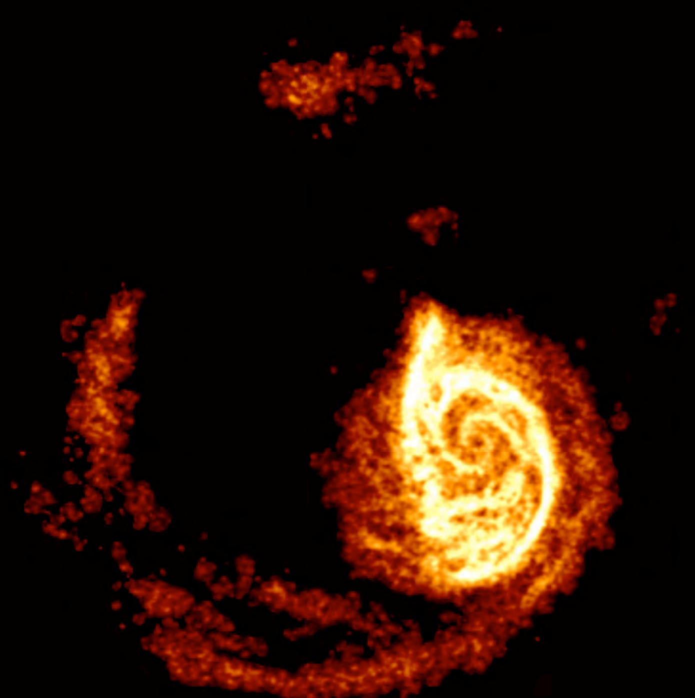


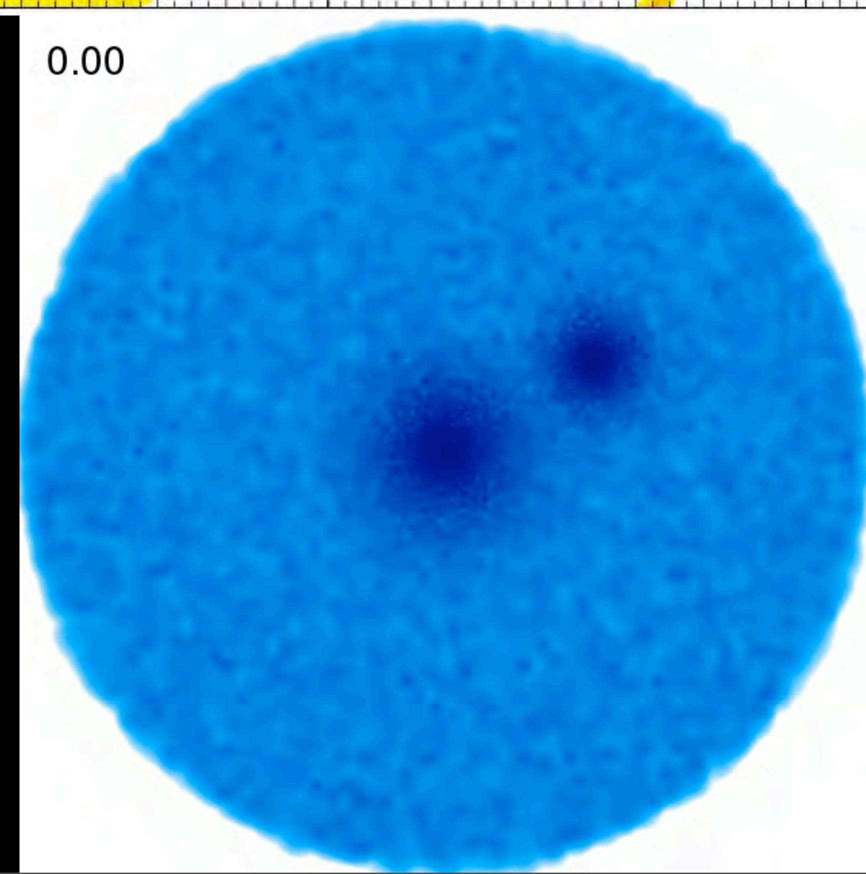
$$a_m(r) = \int \Sigma(r,\phi) e^{-im\phi} d\phi$$

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

M51 Simulation Comparison



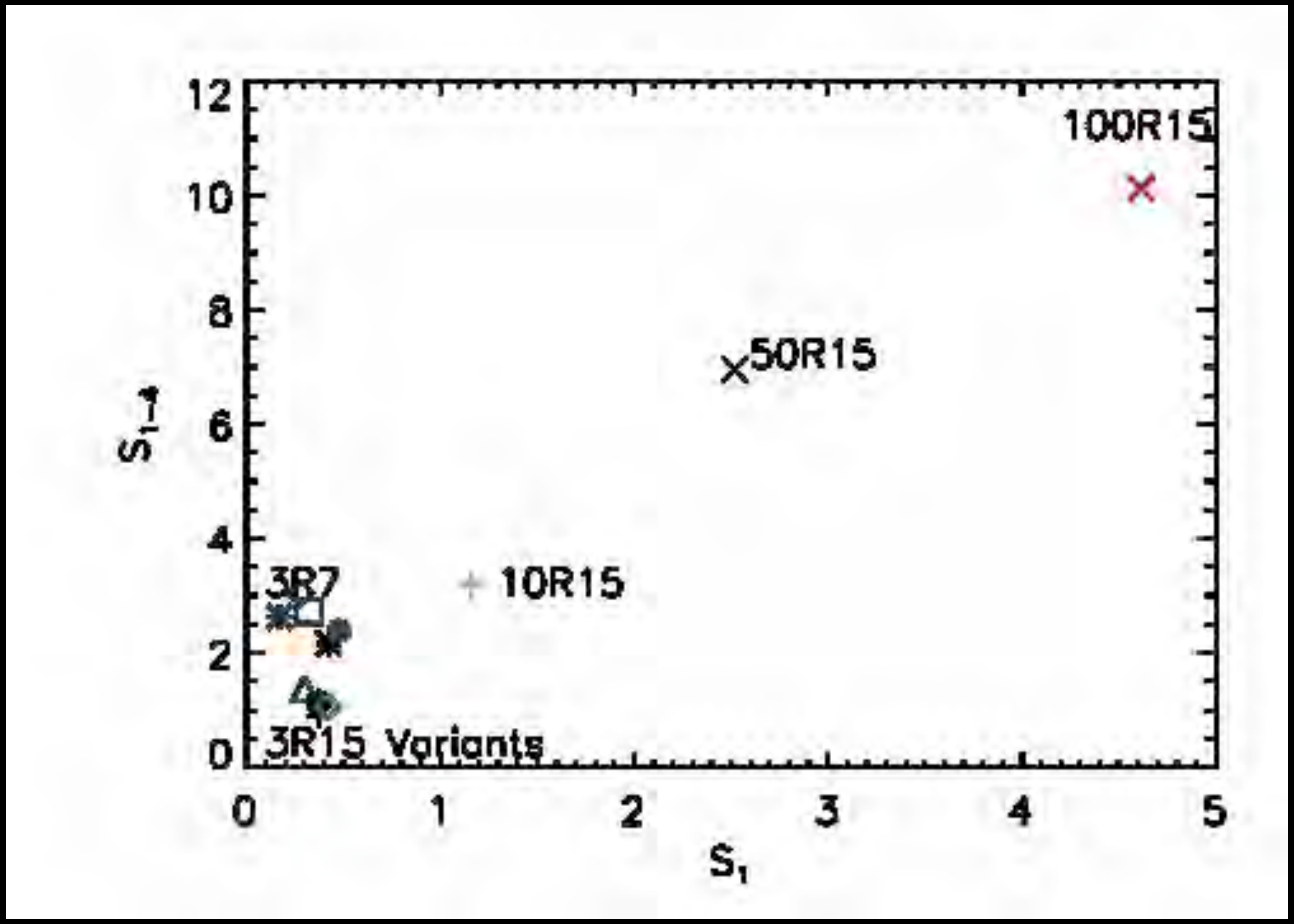




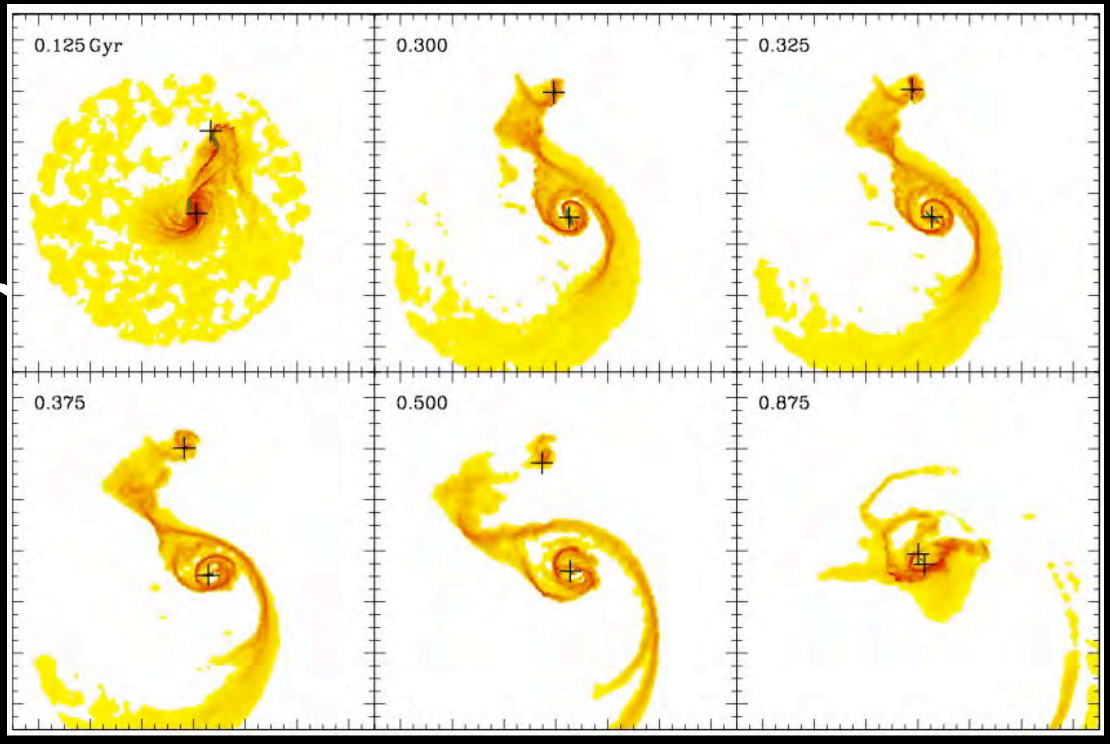
Chakrabarti, Bigiel, Chang & Blitz, 2011

3-D stereoscopic rendering shown at AAS 2011

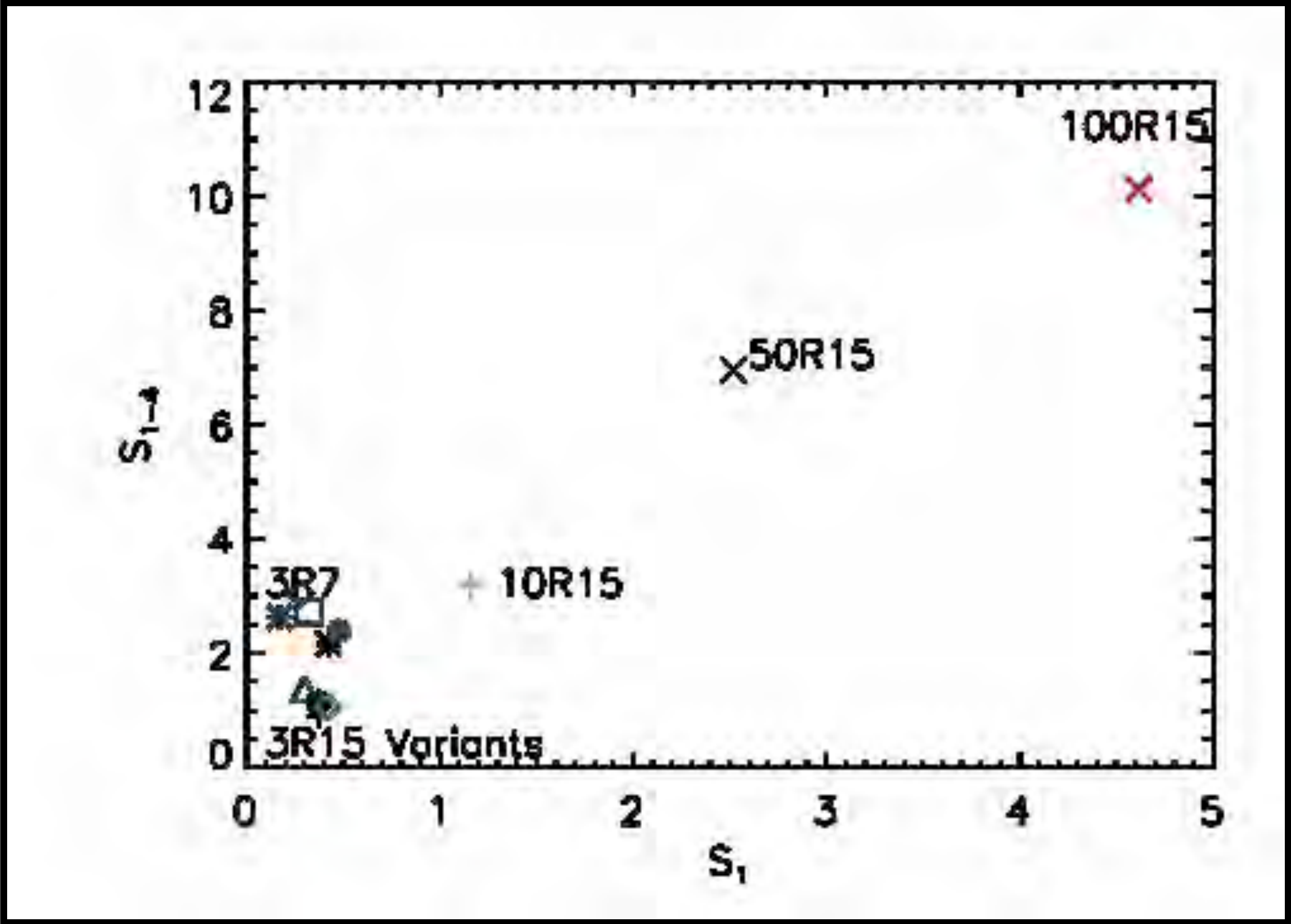
Variance Vs Variance

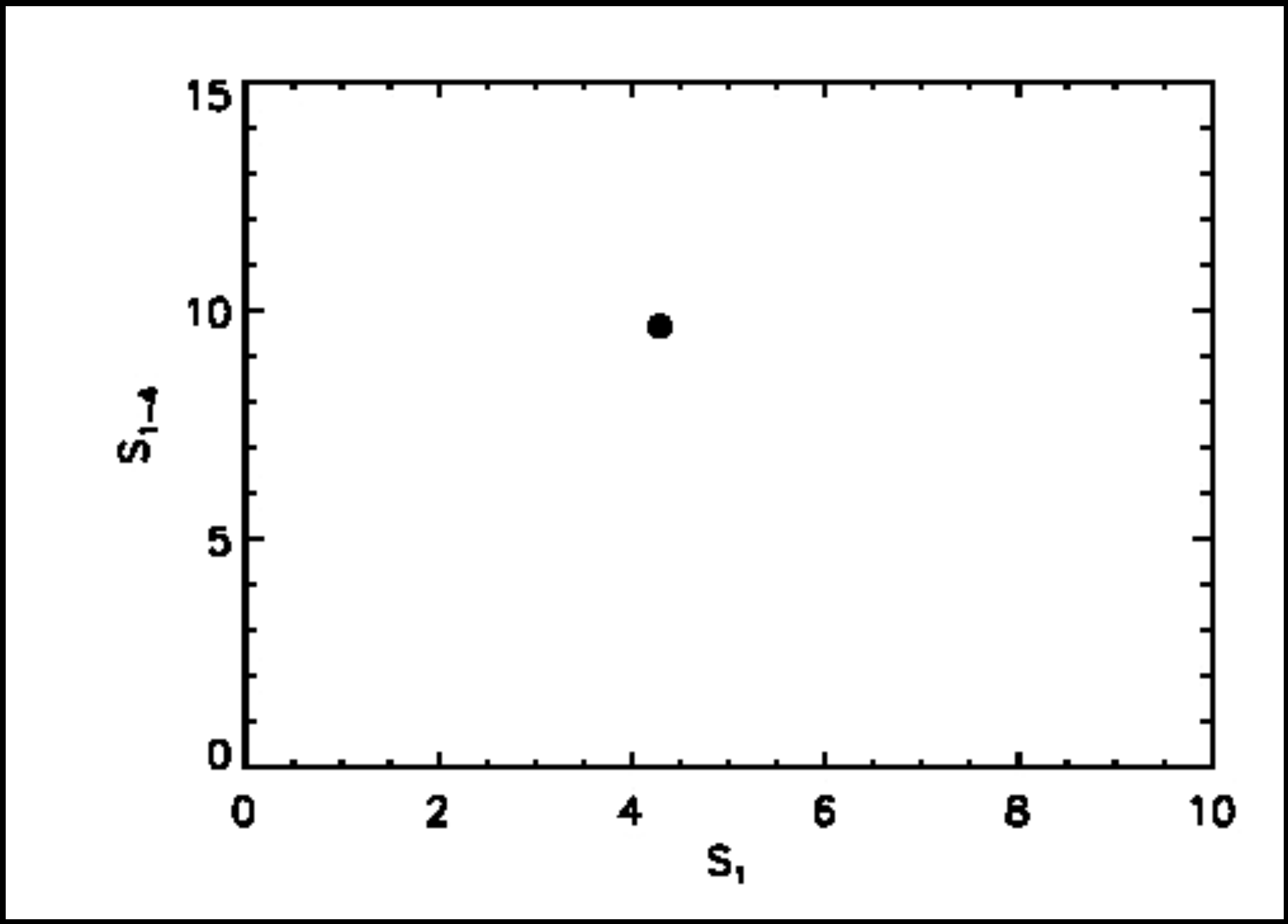


Best-fits -- close to origin on variance vs variance plot (S_1-S_{1-4}), shown at best-fit time. "Variants" include varying initial conditions (ICs), interstellar medium (ISM), star formation prescription, orbital inclination, etc. Our estimate of M_s (1:3) close to observational numbers.

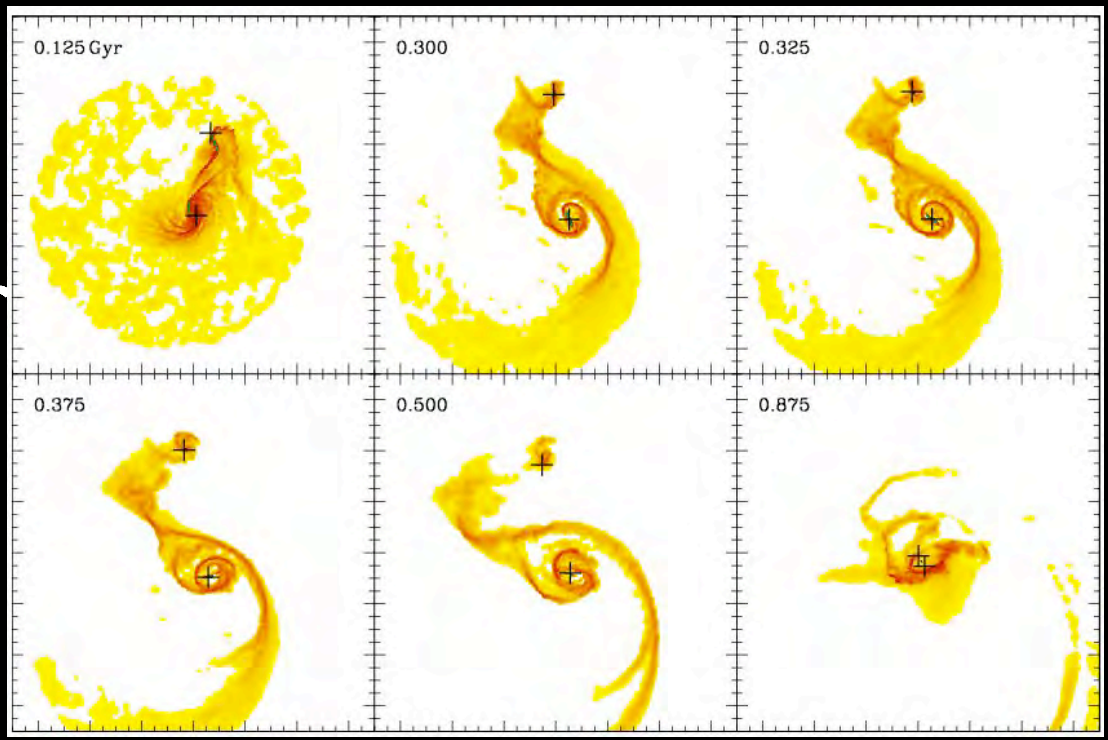


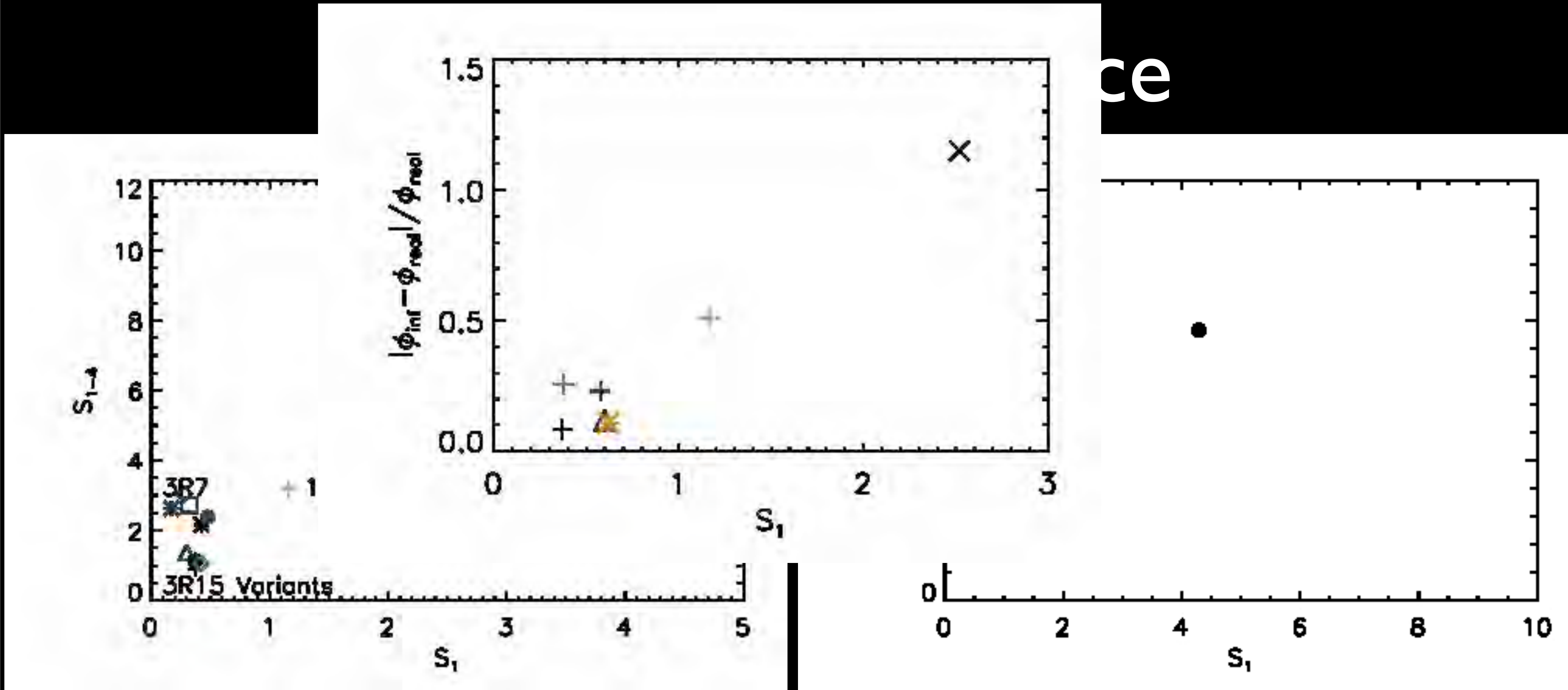
Variance Vs Variance



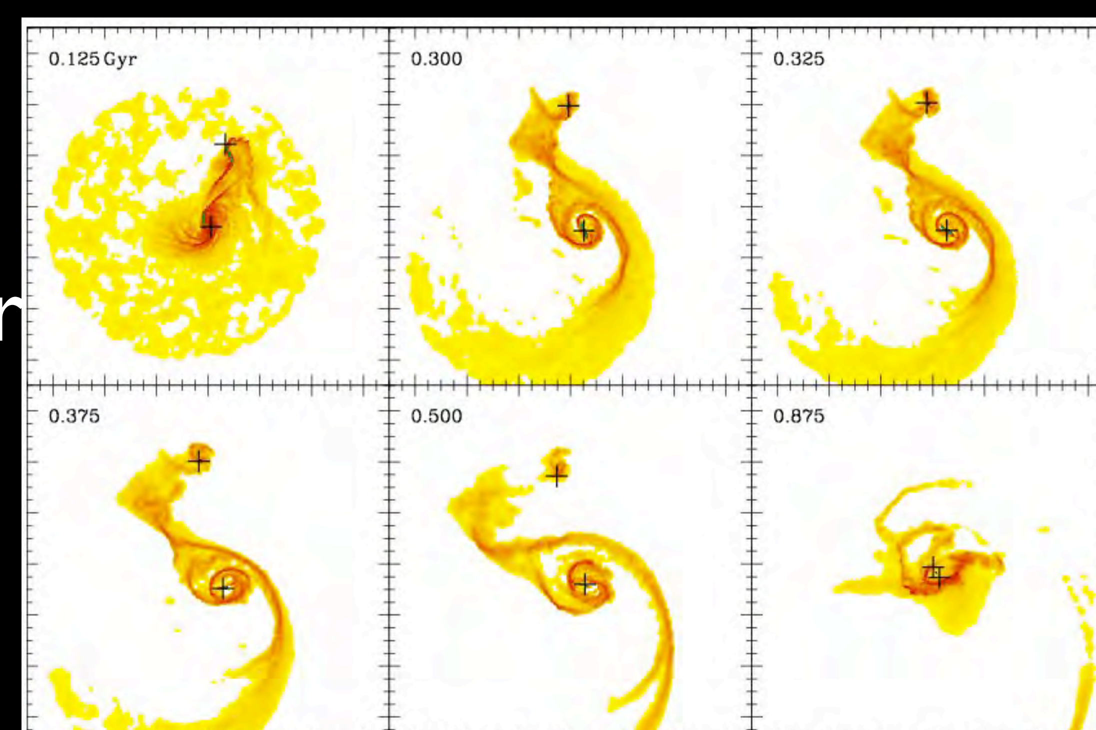


Best-fits -- close to origin on variance vs variance plot (S_1-S_{1-4}), shown at best-fit time. "Variants" include varying initial conditions (ICs), interstellar medium (ISM), star formation prescription, orbital inclination, etc. Our estimate of M_s (1:3) close to observational numbers.

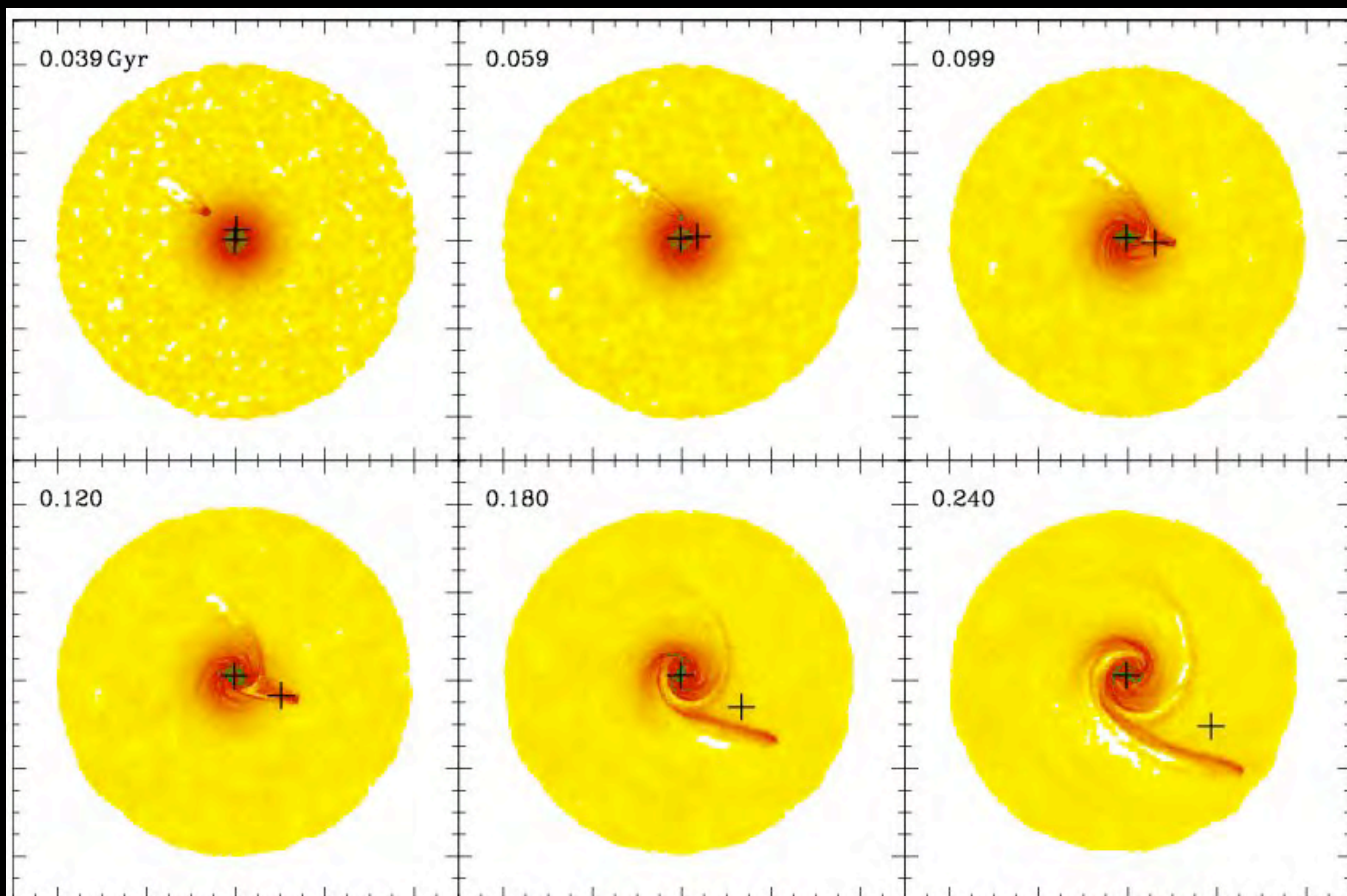


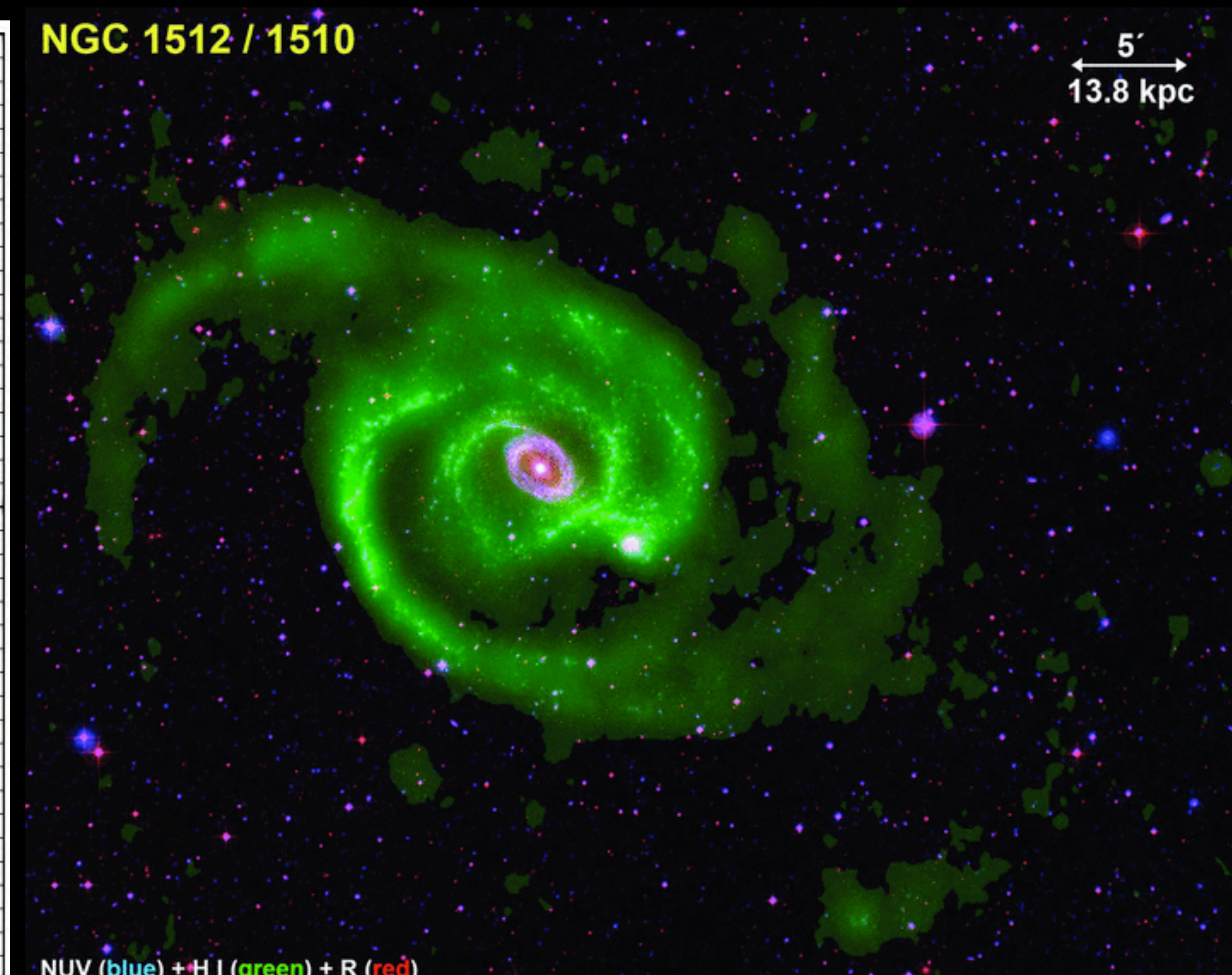


Best-fits -- close to origin on variance vs variance plot (S_1-$S_{1\text{-}4}$), shown at best-fit time. “Variants” include varying initial conditions (ICs), interstellar medium (ISM), star formation prescription, orbital inclination, etc. Our estimate of M_s (1:3) close to observational numbers.



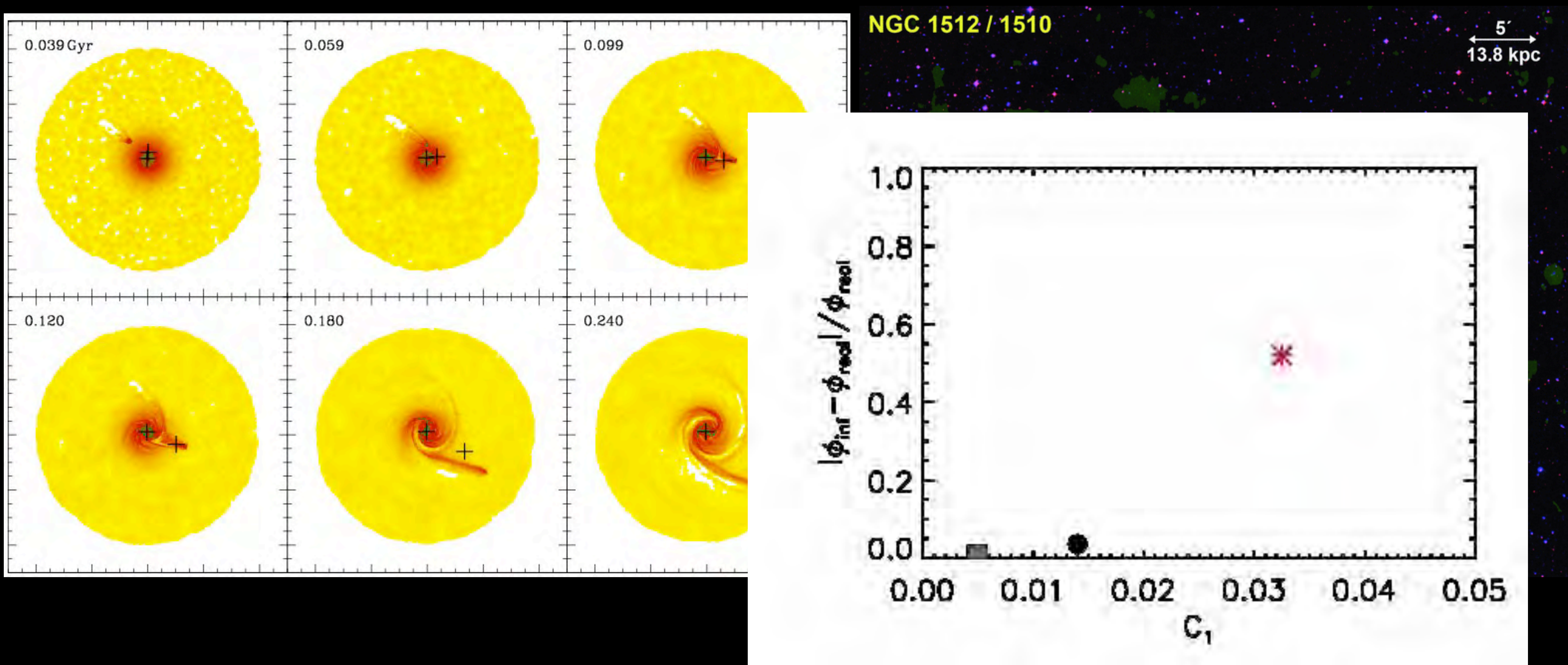
Galaxies with known optical companions contd.



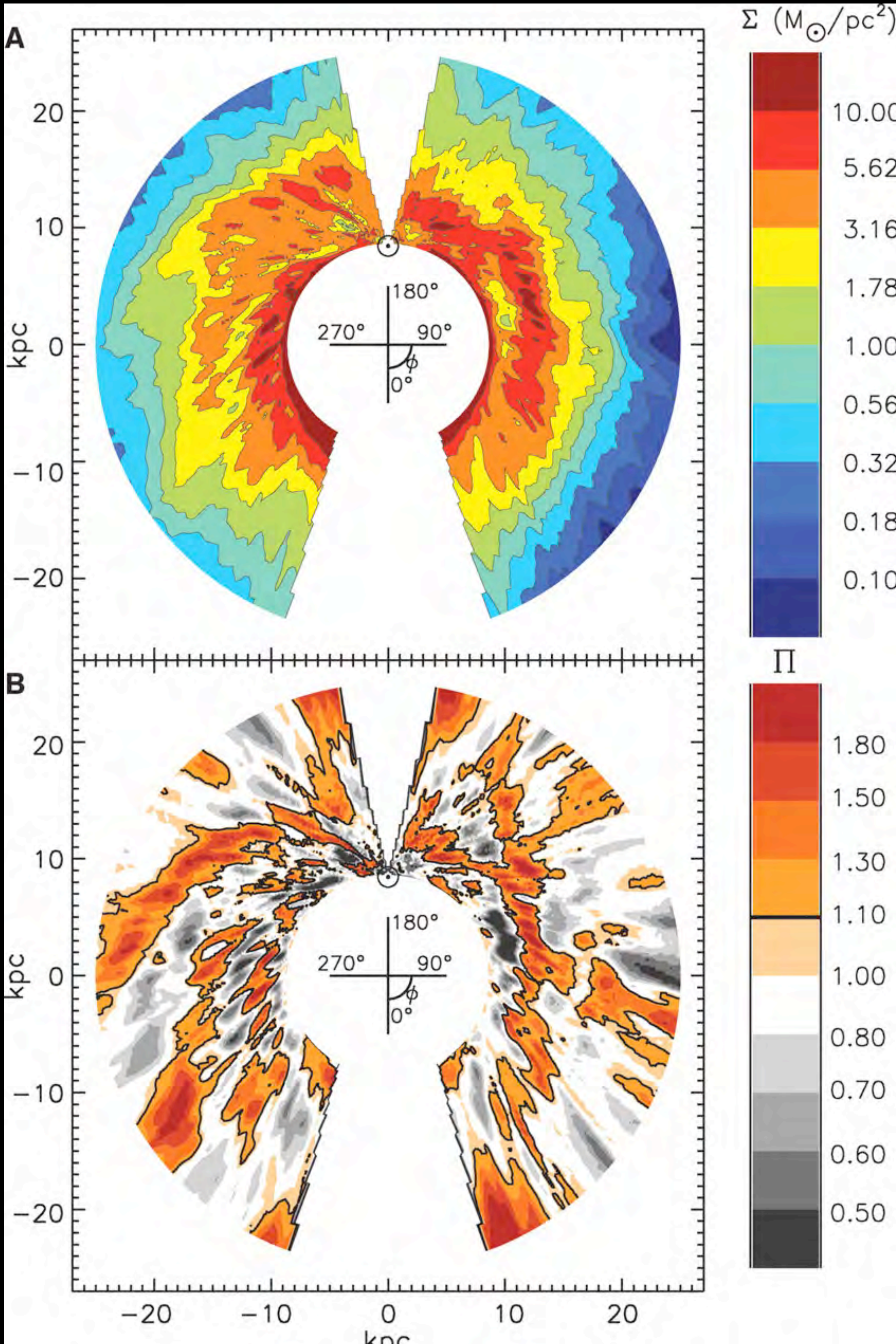


- ~1:100 satellite, R_{peri} = 7kpc (close agreement with Koribalski & Sanchez 09) (global fourier amplitudes)
- Method works for 1:3 - 1:100 mass ratio satellites

Galaxies with known optical companions contd.



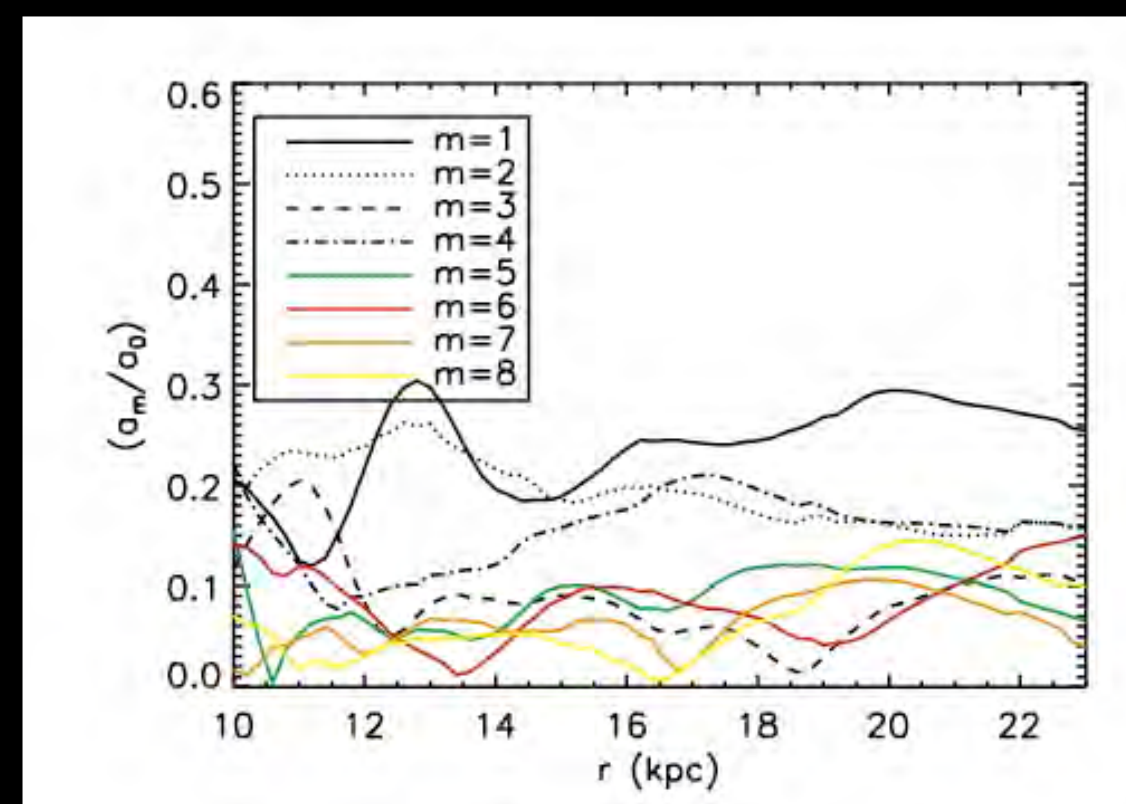
- ~1:100 satellite, R_{peri} = 7kpc (close agreement with Koribalski & Sanchez 09) (global fourier amplitudes)
- Method works for 1:3 - 1:100 mass ratio satellites



HI Map of Milky Way

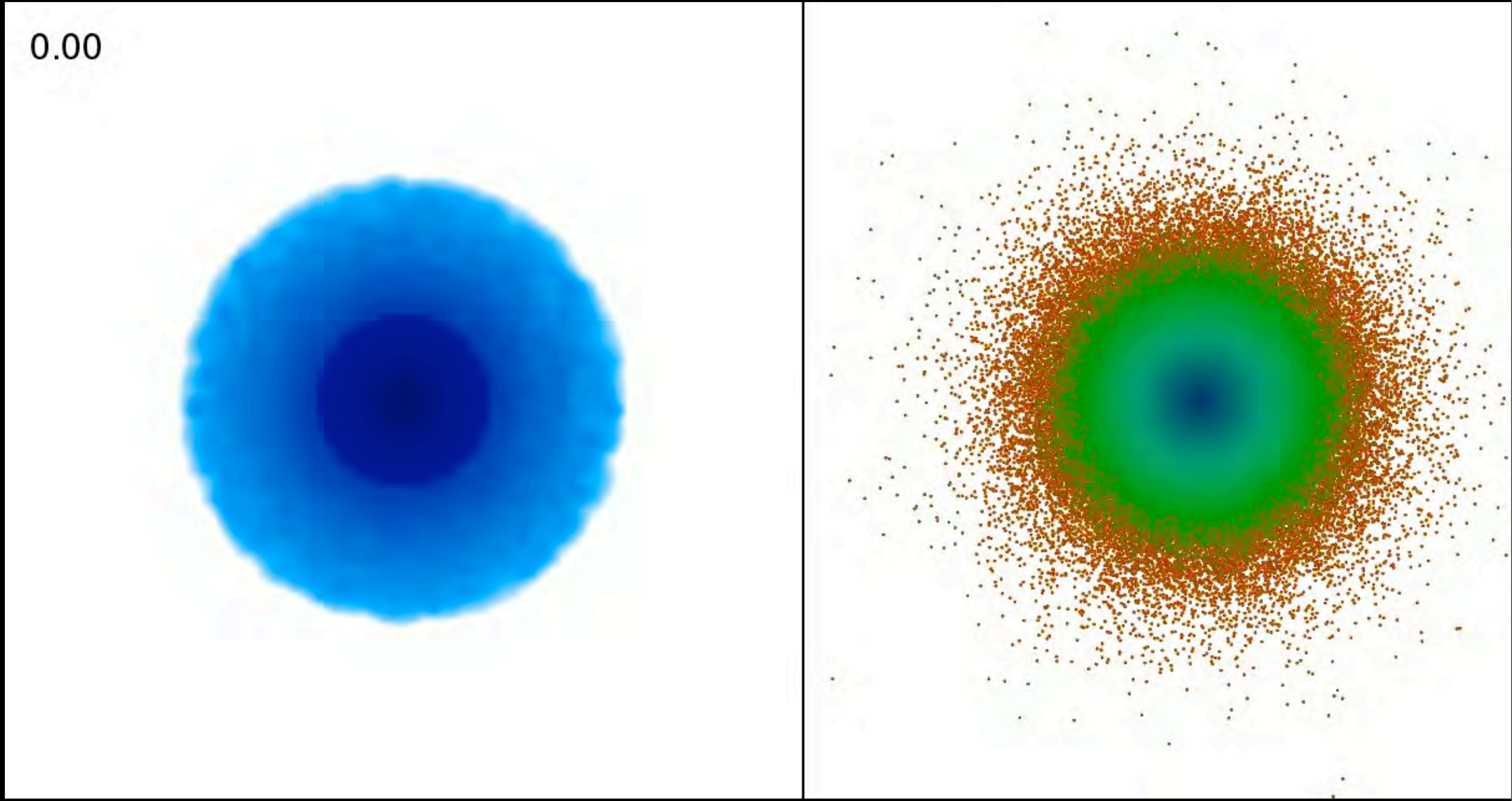
HI maps: Levine, Blitz & Heiles 2006. What caused these structures well outside the solar circle?

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



Simulations

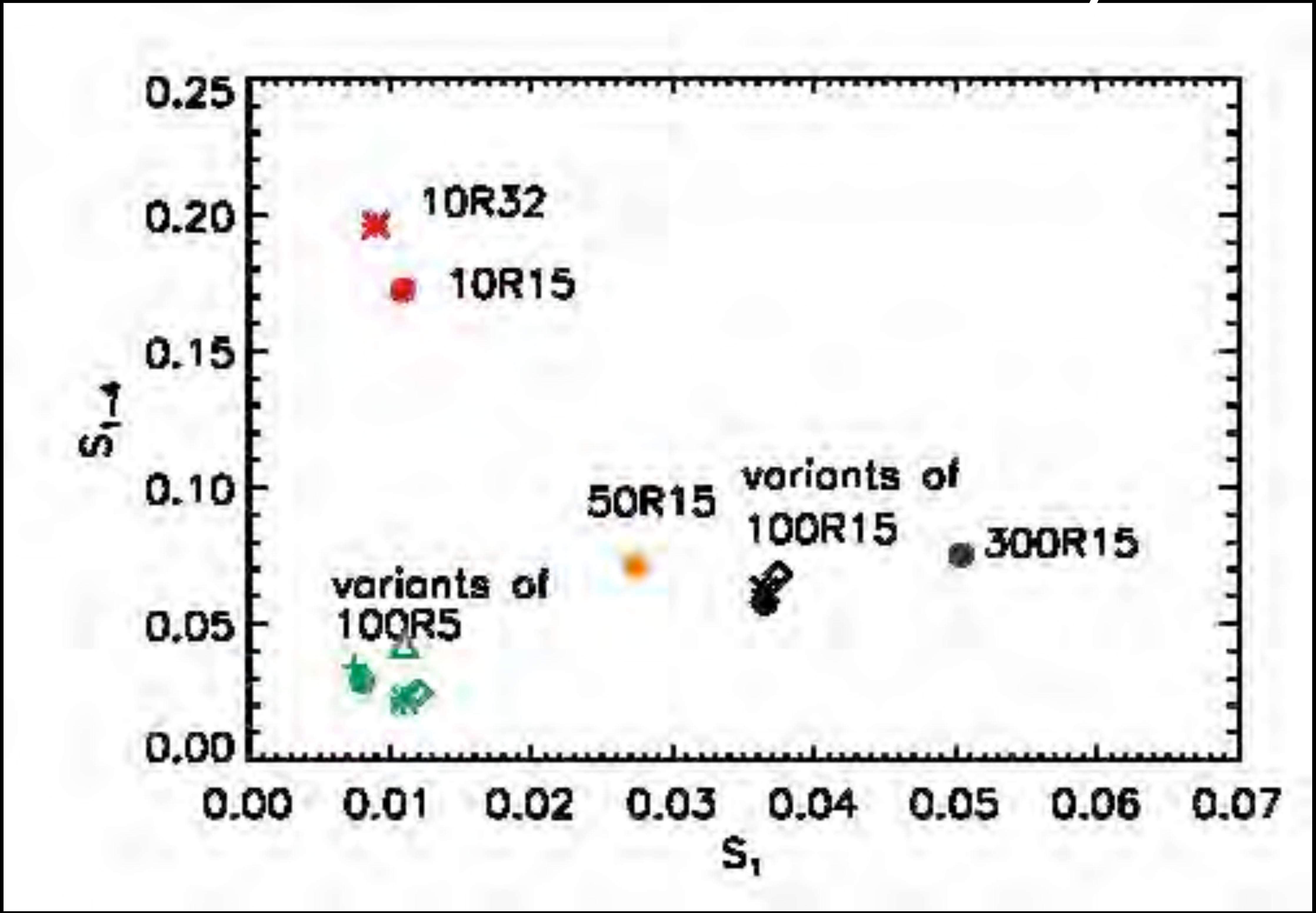
M_s	R_{peri}	inclination
1:10-1:1000	0.1-50kpc	f_{gas} (0.1-0.3), EQS



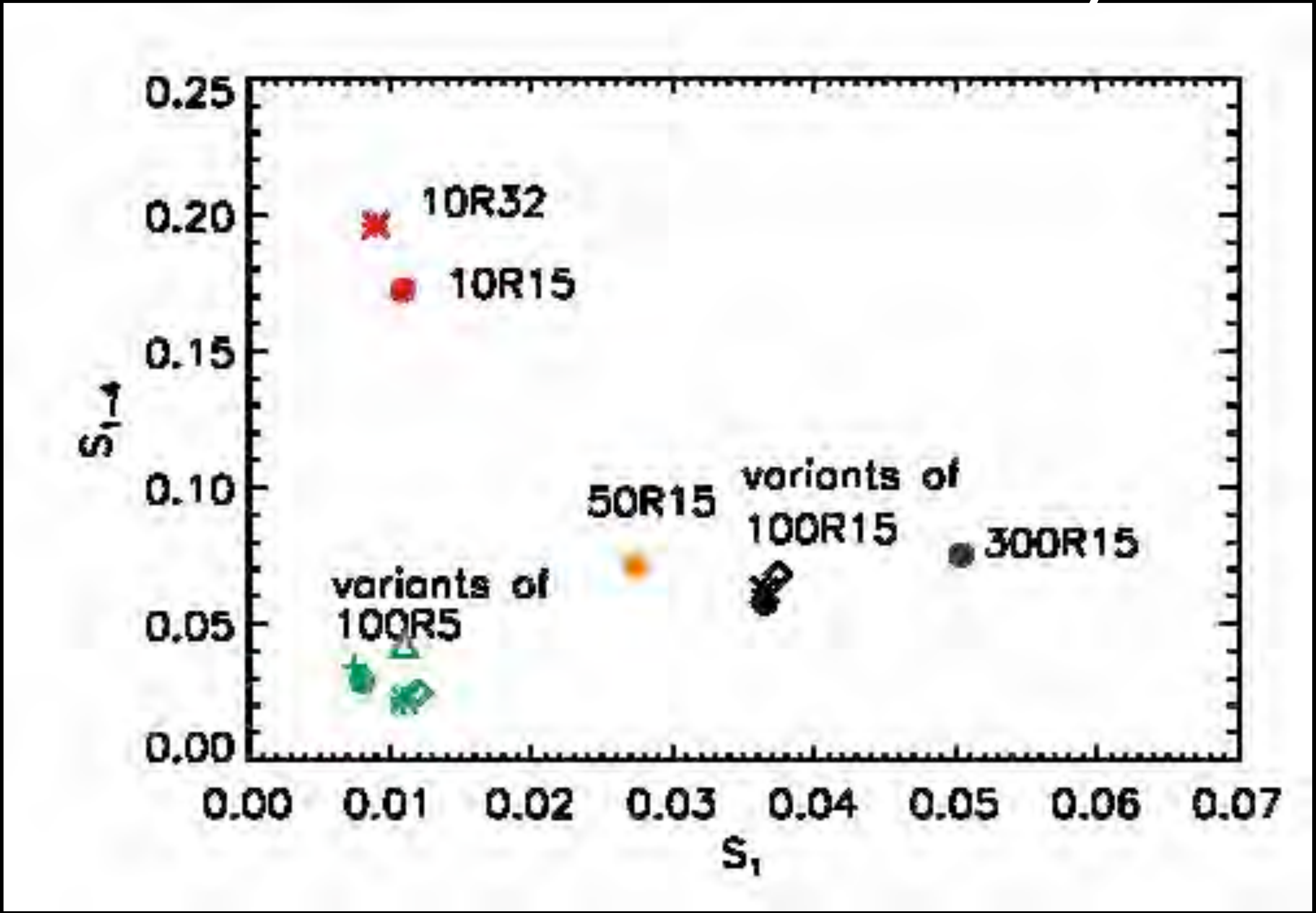
Parameter space survey of simulations to explain observed disturbances in HI map of Milky Way. Chakrabarti & Blitz 2009.

Initial Conditions, Orbits -- what really matters?

Initial Conditions, Orbits -- what really matters?



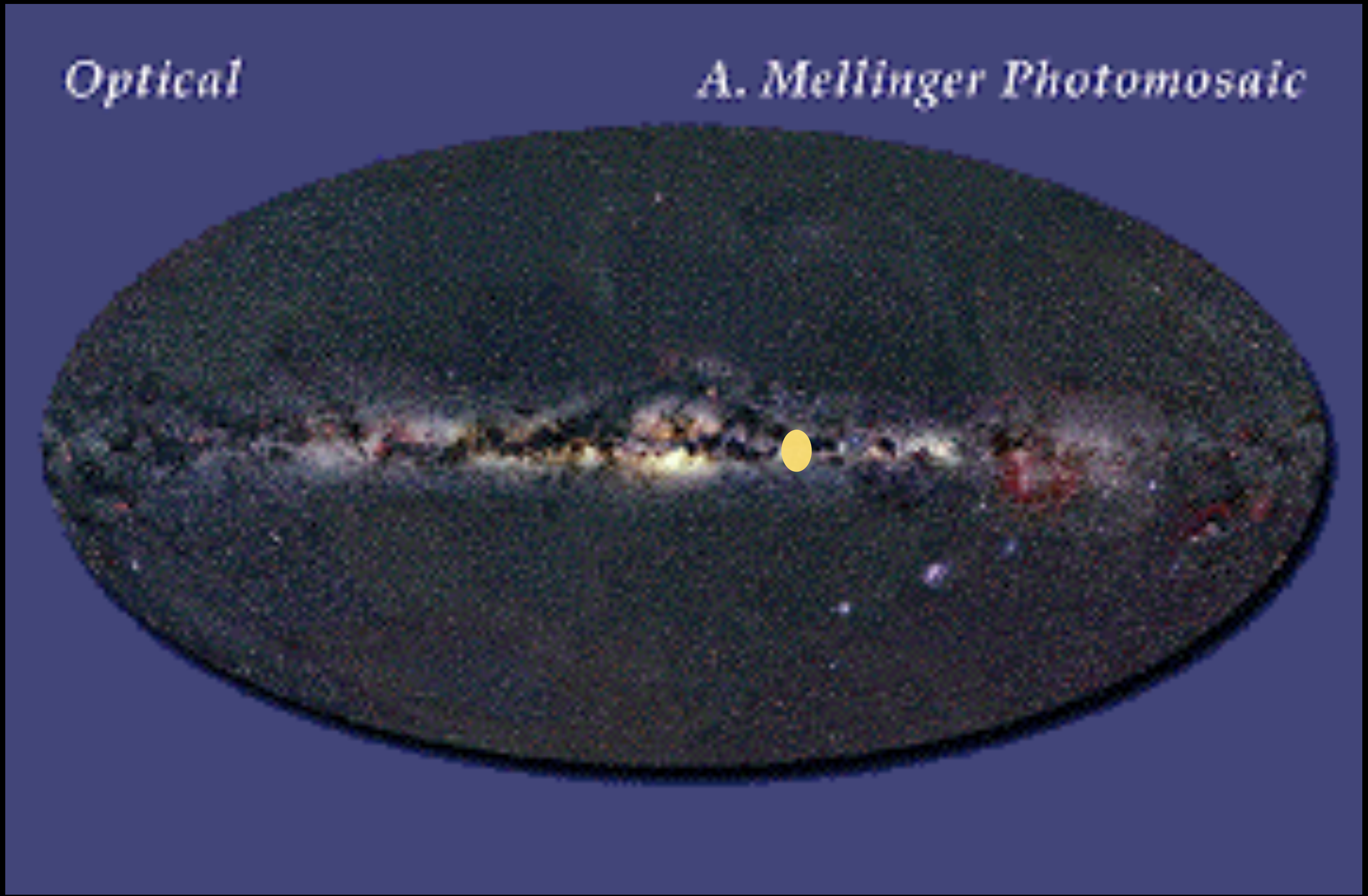
Initial Conditions, Orbits -- what really matters?



- Not very sensitive to initial conditions (for parameters comparable to spirals). CB09 -- M_s and R_{peri} are what really matter

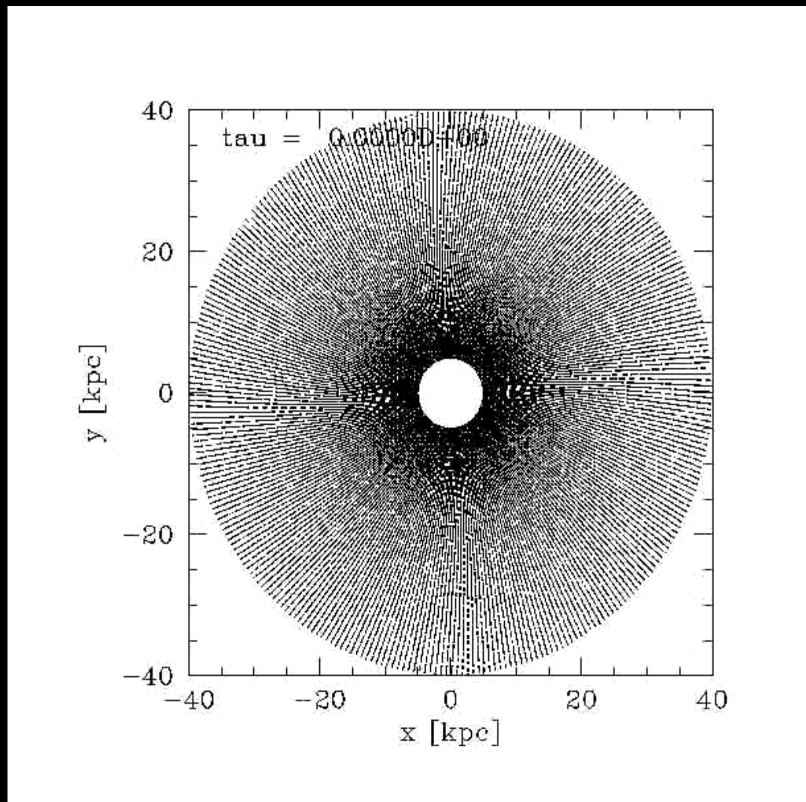
Hunting for the Dark Dwarf Galaxy

- Why haven't we seen it yet?
- Known Milky Way companions have been discovered so far in the optical bands. Huge obscuration in the plane! Prediction for azimuth of satellite (Chakrabarti & Blitz 2011)

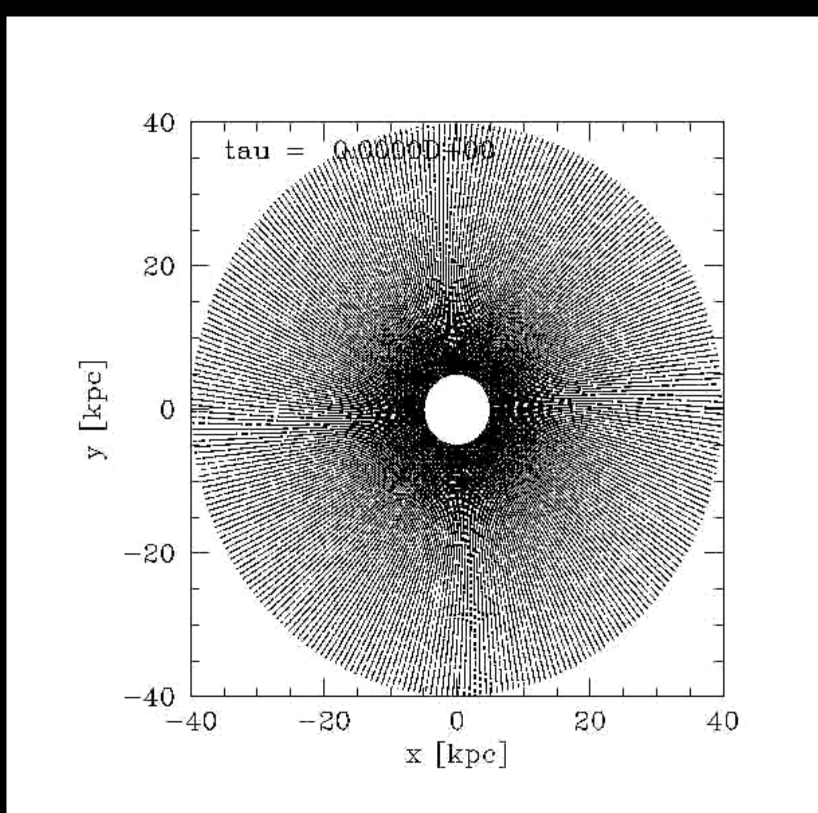


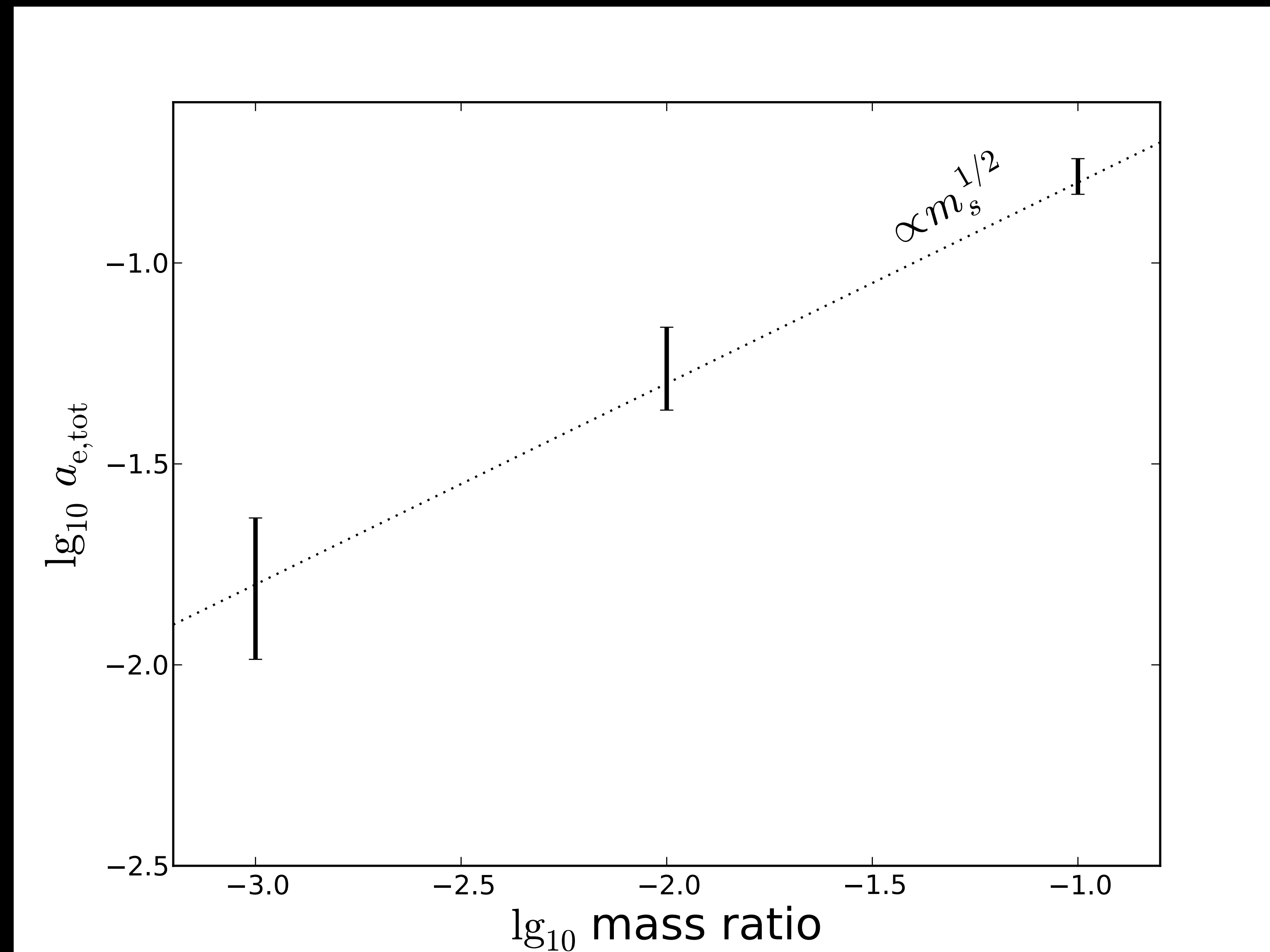
A Simplified Approach

Test Particles



Mode Reconstruction





Fitting relations for satellite mass from Fourier amplitudes

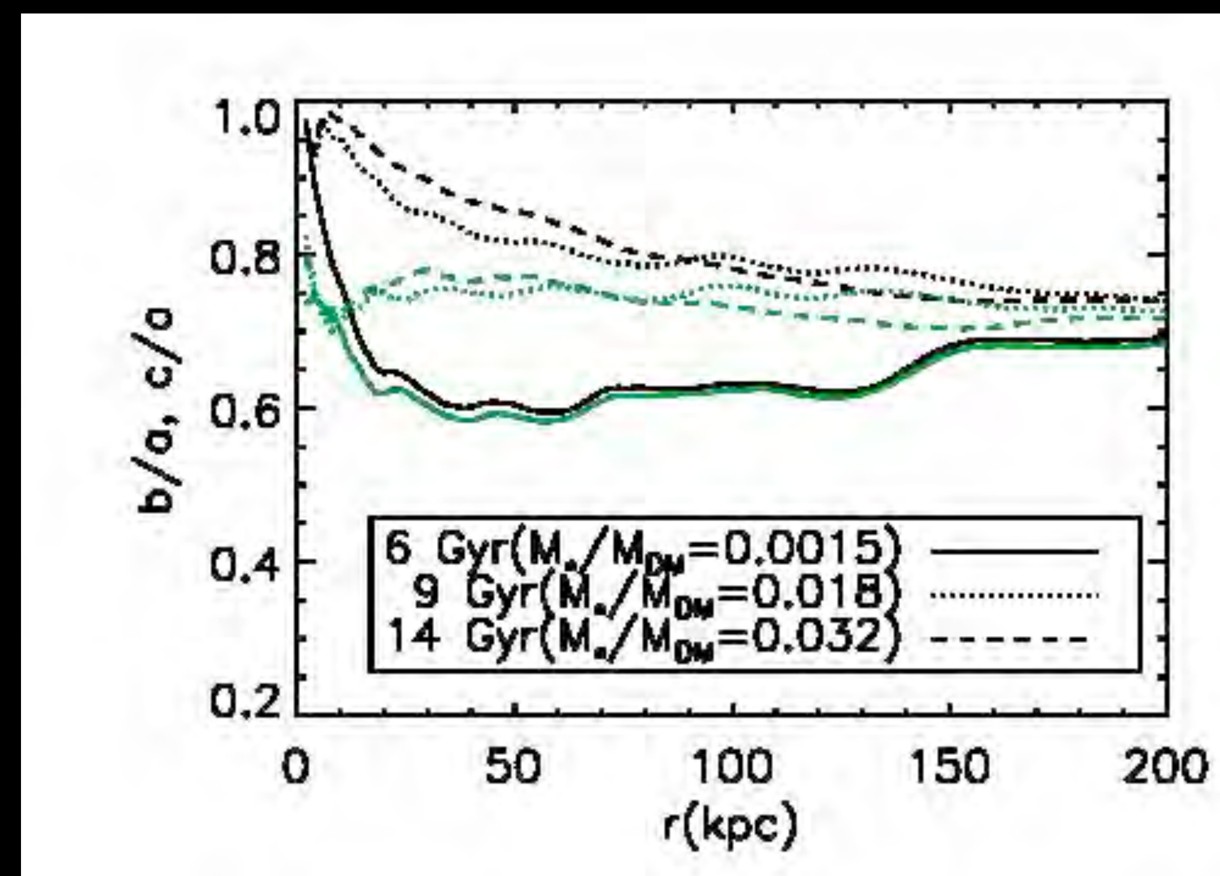
Chang & Chakrabarti 2011

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)

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)

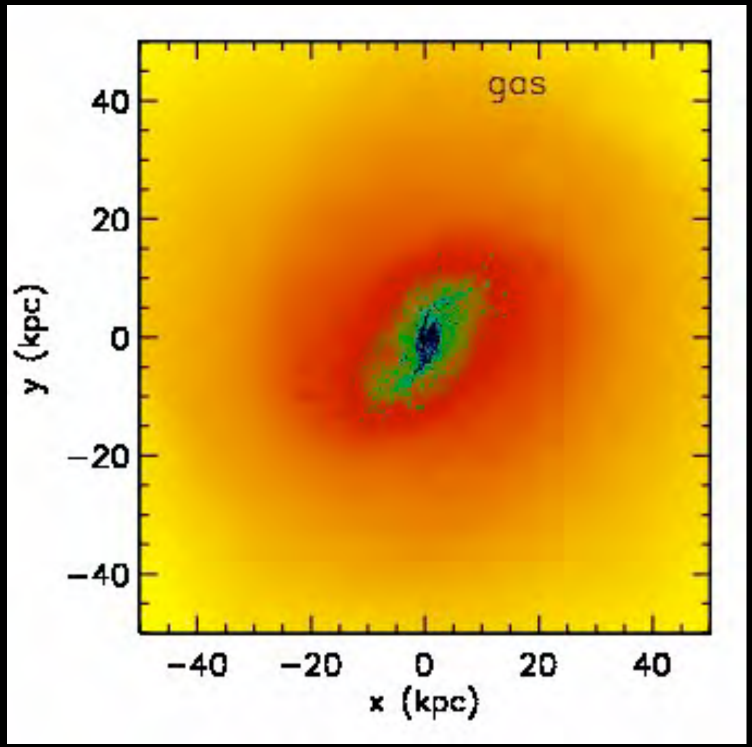


Halo shapes contd.

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)

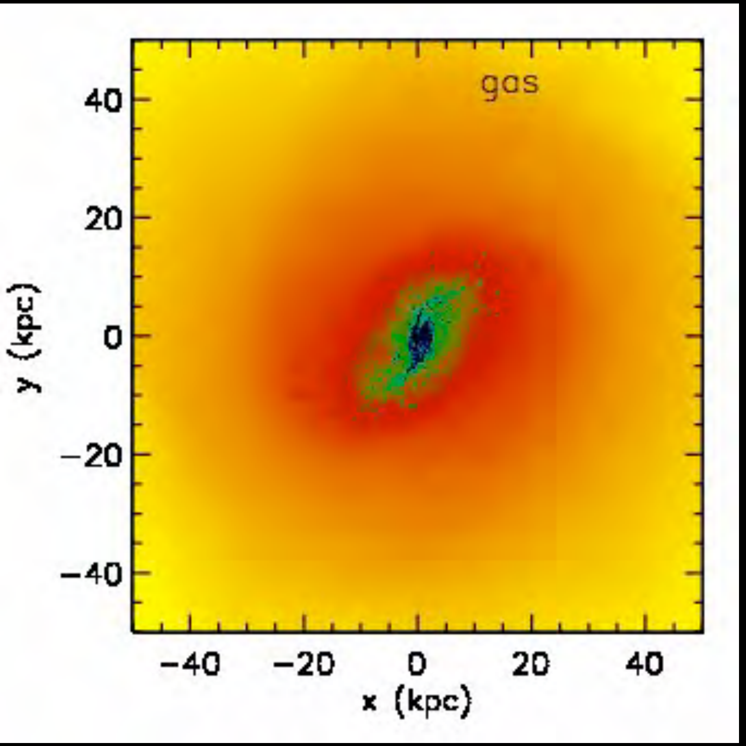
Halo shapes contd.

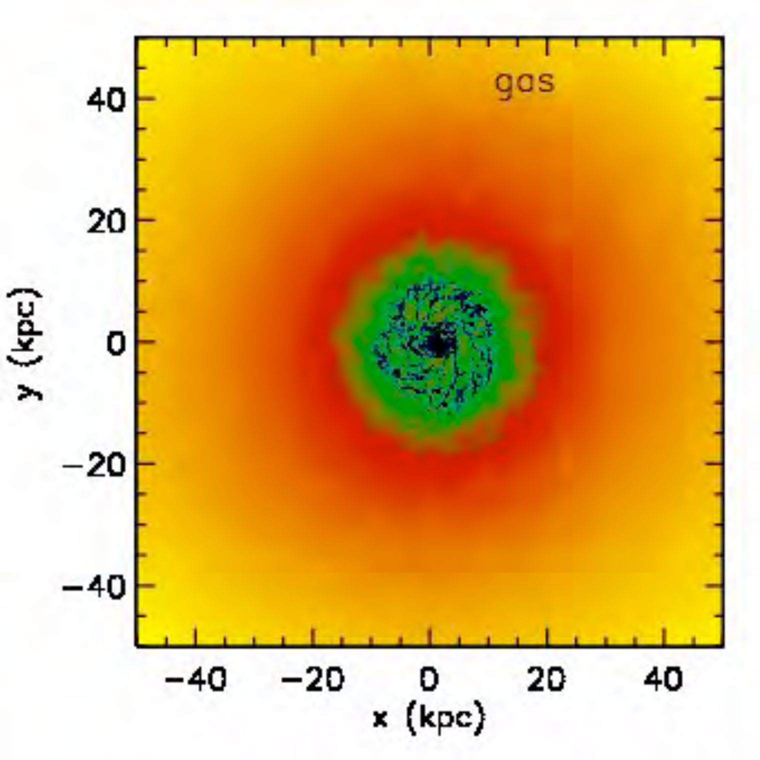
Fourier amplitudes of planar disturbances low in outskirts (less than 10 %) close to present day, but warp survives in some simulations (where gas and halo angular momenta are misaligned)



Halo shapes contd.

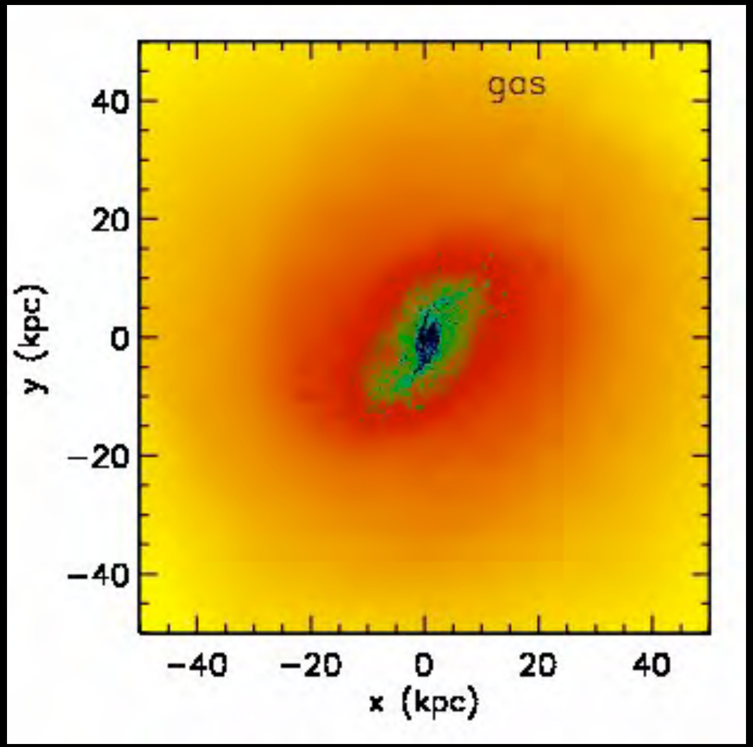
Fourier amplitudes of planar disturbances low in outskirts (less than 10 %) close to present day, but warp survives in some simulations (where gas and halo angular momenta are misaligned)

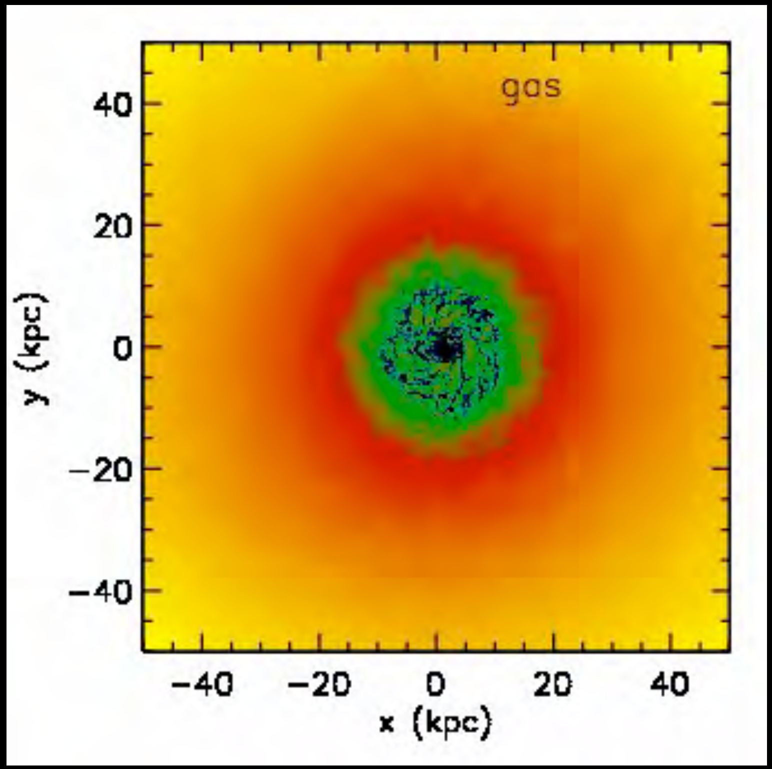


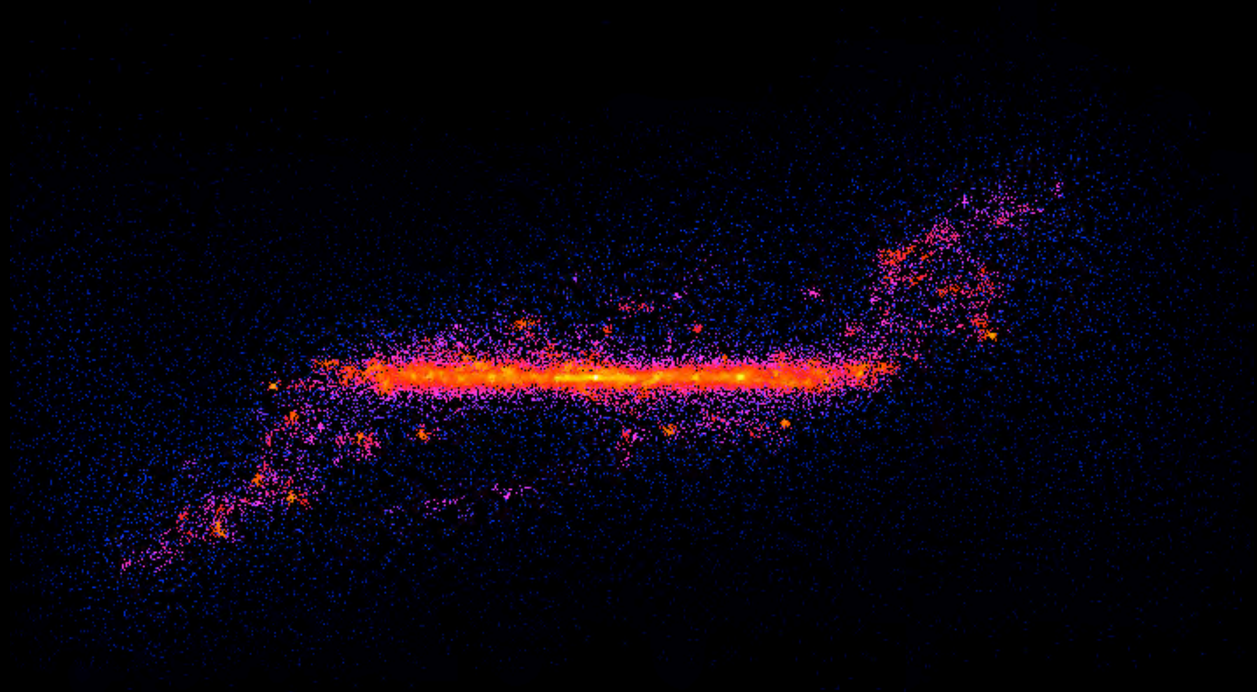


Halo shapes contd.

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)

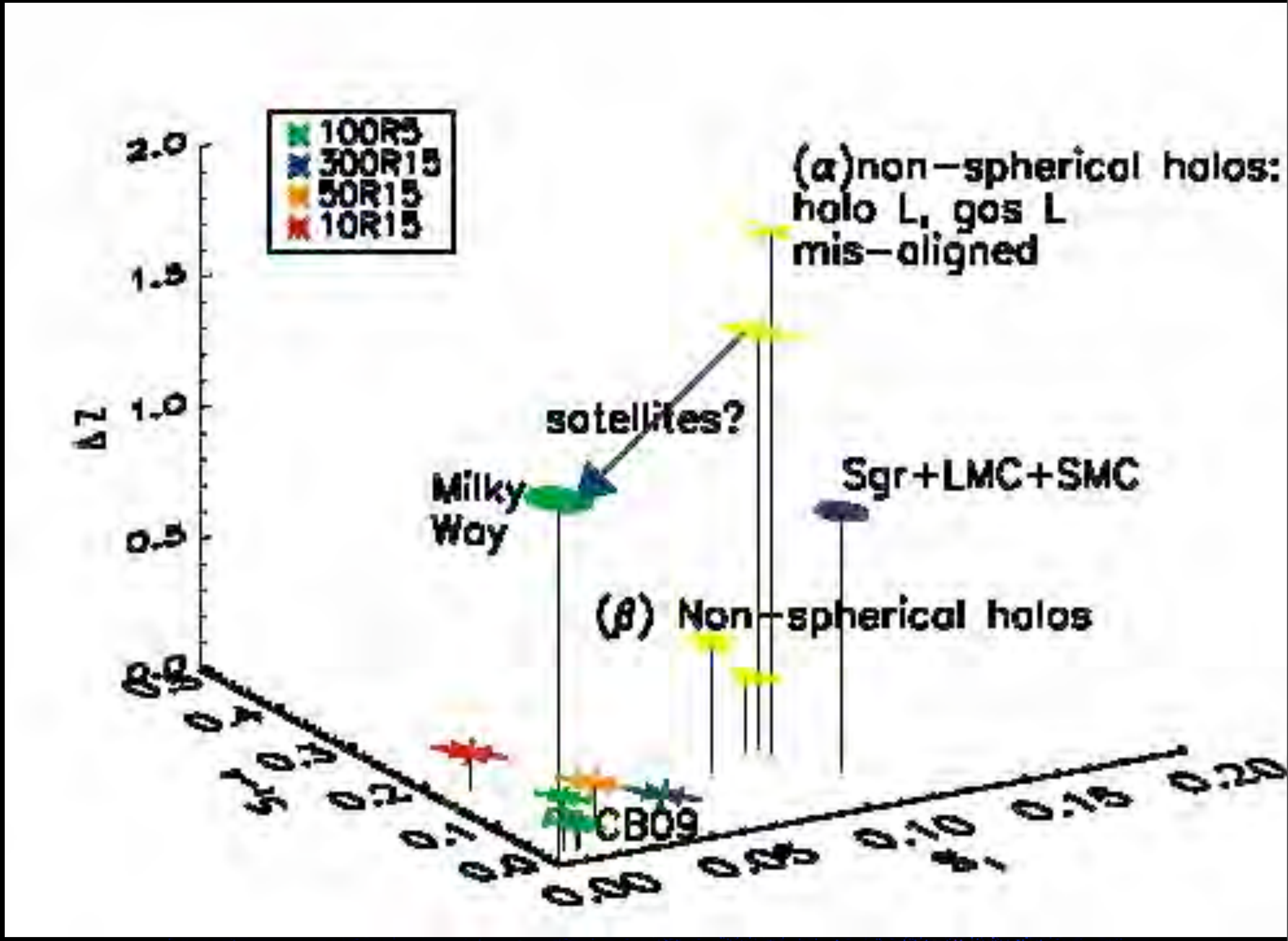


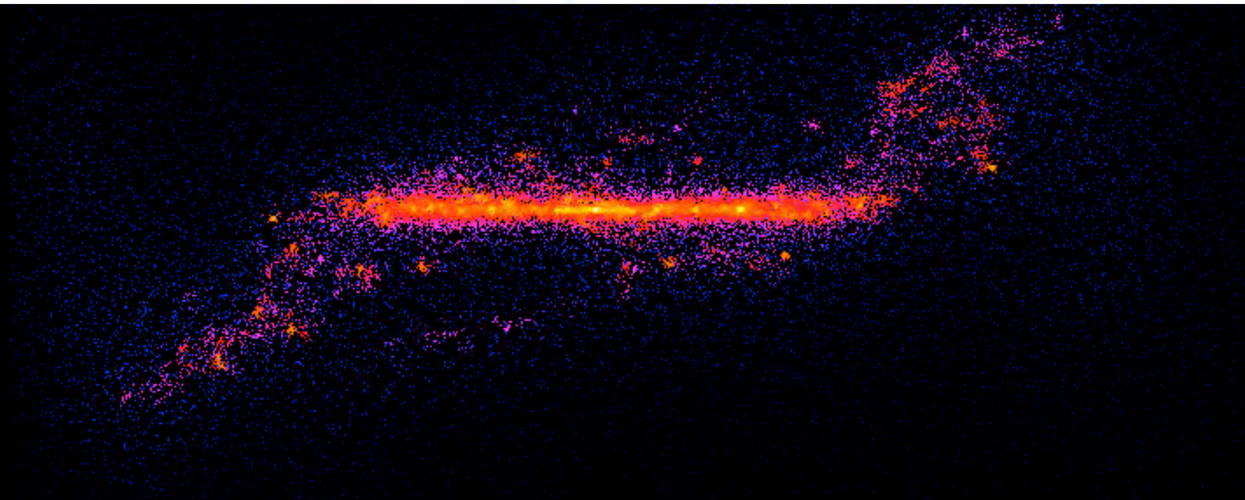




Halo shapes contd.

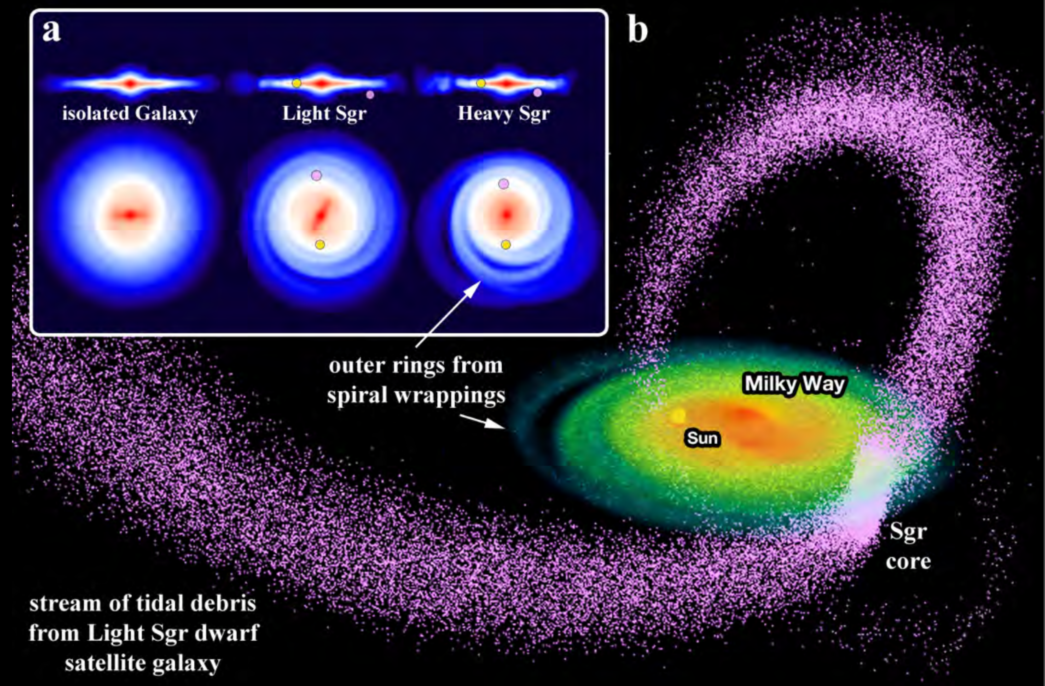
Fourier amplitudes of planar disturbances low in outskirts (less than 10 %) close to present day, <u>but warp survives in some simulations</u> (where gas and halo angular momenta are misaligned)





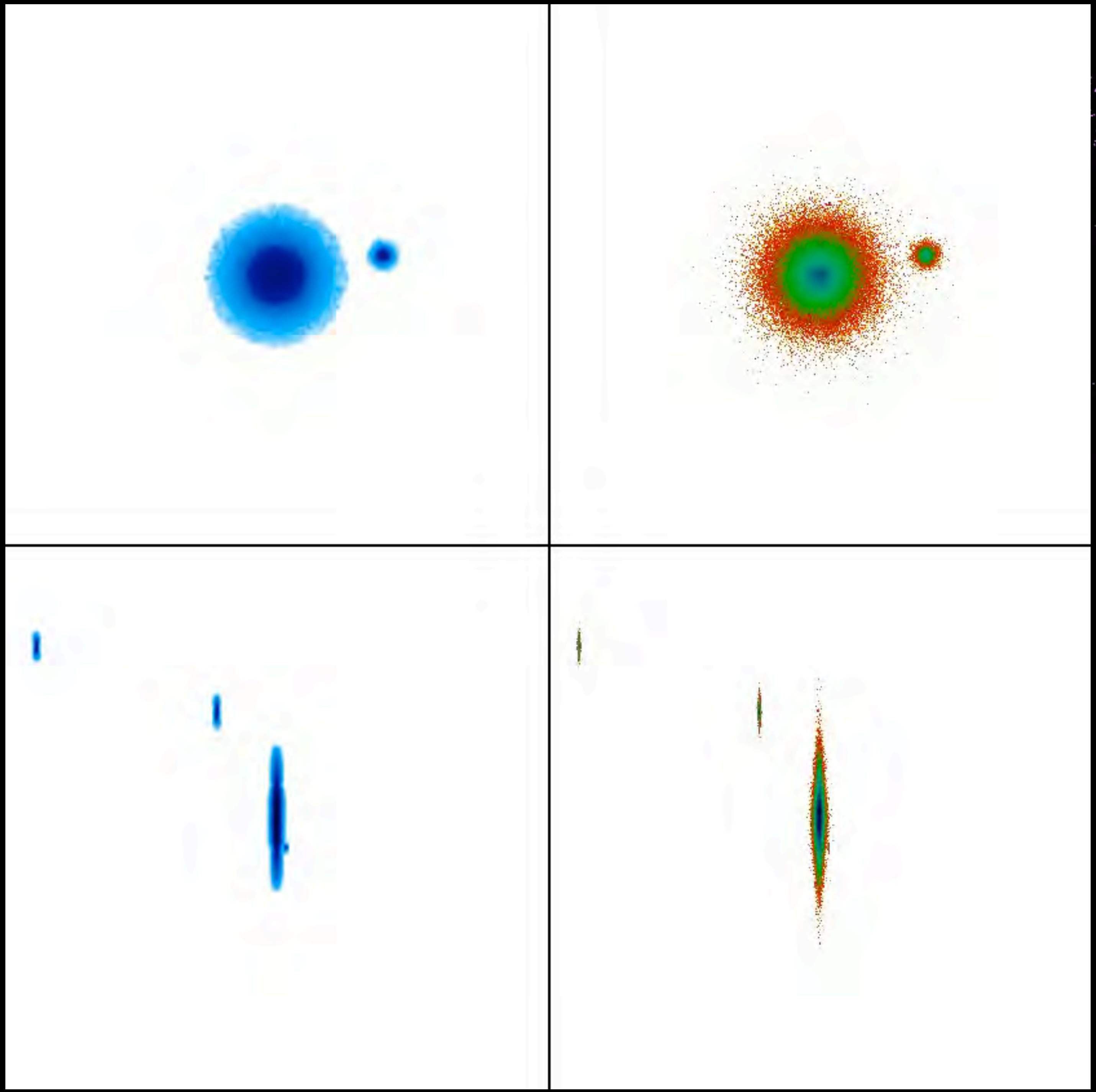
Current/Future Work

- Focus on low-order modes means that we study the larger scale disturbances (for the Milky Way: Chakrabarti & Blitz 2009; Chakrabarti & Blitz 2011)
- Example: high-res N-body sim of interaction of Milky Way w. Sgr. Purcell et al. (+Chakrabarti), Nature 2011.
- Current & future work: effects of **all** the known Milky Way satellites on the disk (Chakrabarti et al., in prep)



Current/Future Work

- Focus on low-order modes means that we study the larger scale disturbances (for the Milky Way: Chakrabarti & Blitz 2009; Chakrabarti & Blitz 2011)
- Example: high-res N-body sim of interaction of Milky Way w. Sgr. Purcell et al. (+Chakrabarti), Nature 2011.
- Current & future work: effects of **all** the known Milky Way satellites on the disk (Chakrabarti et al., in prep)



Summary

- Gas serves as an efficient angular momentum donor to the stars, leading to longer lived spiral structure in the stellar disk than simulations w.out gas.
- dependence on star formation rate (multiple constraints needed to quantify)
- extended HI disks as tracer of tidal interactions: can constrain mass and location (radius & azimuth) of galactic satellites from the HI map
- can you have self-excited, long-lived spiral structure and a tidally forced response in the *same* galaxy?