# Finding Dwarf Galaxies from their Tidal Imprints

Sukanya Chakrabarti
UC Berkeley
Collaborators: Phil Chang, Frank Bigiel, Leo Blitz

# Overview

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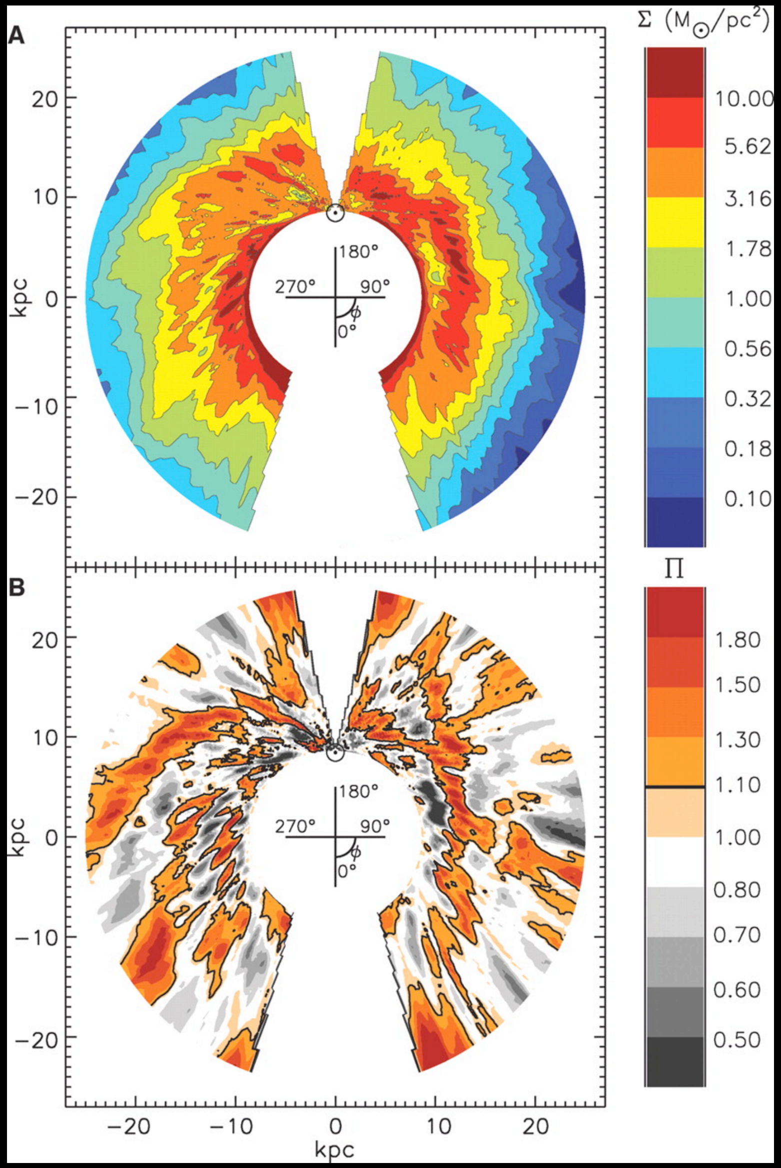

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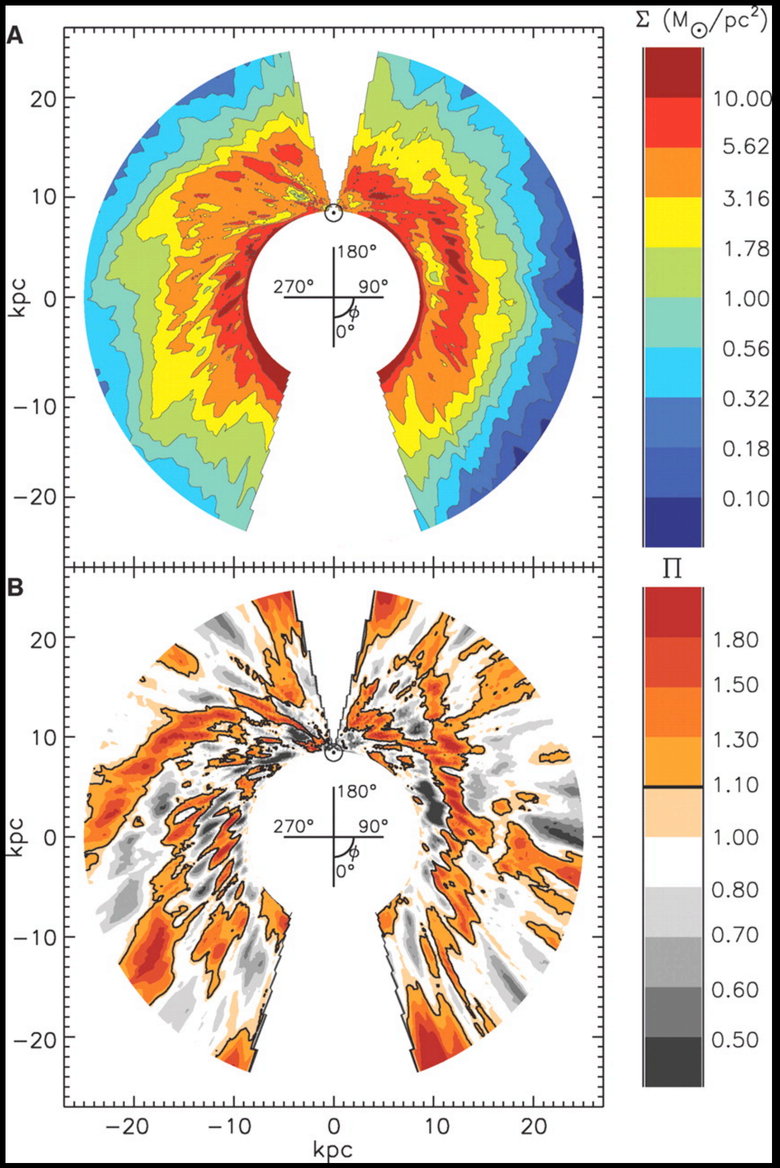


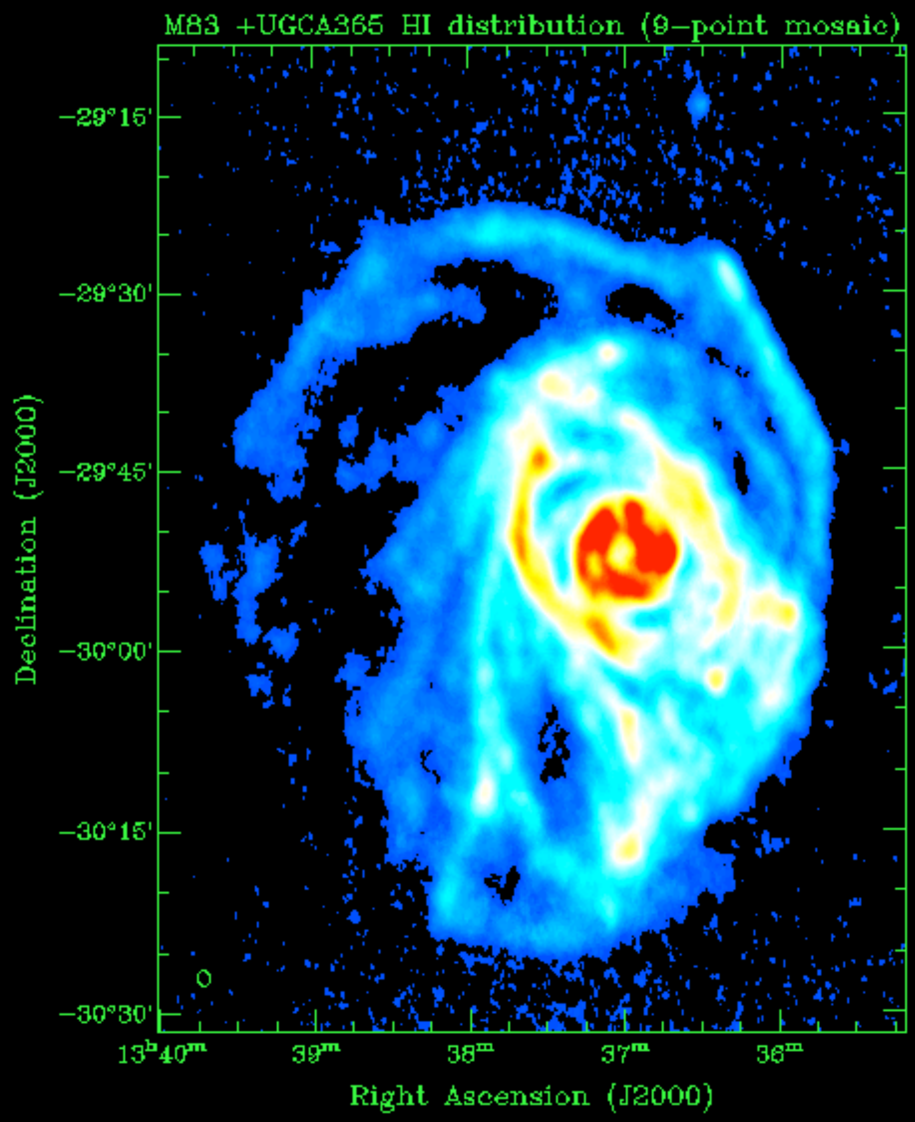

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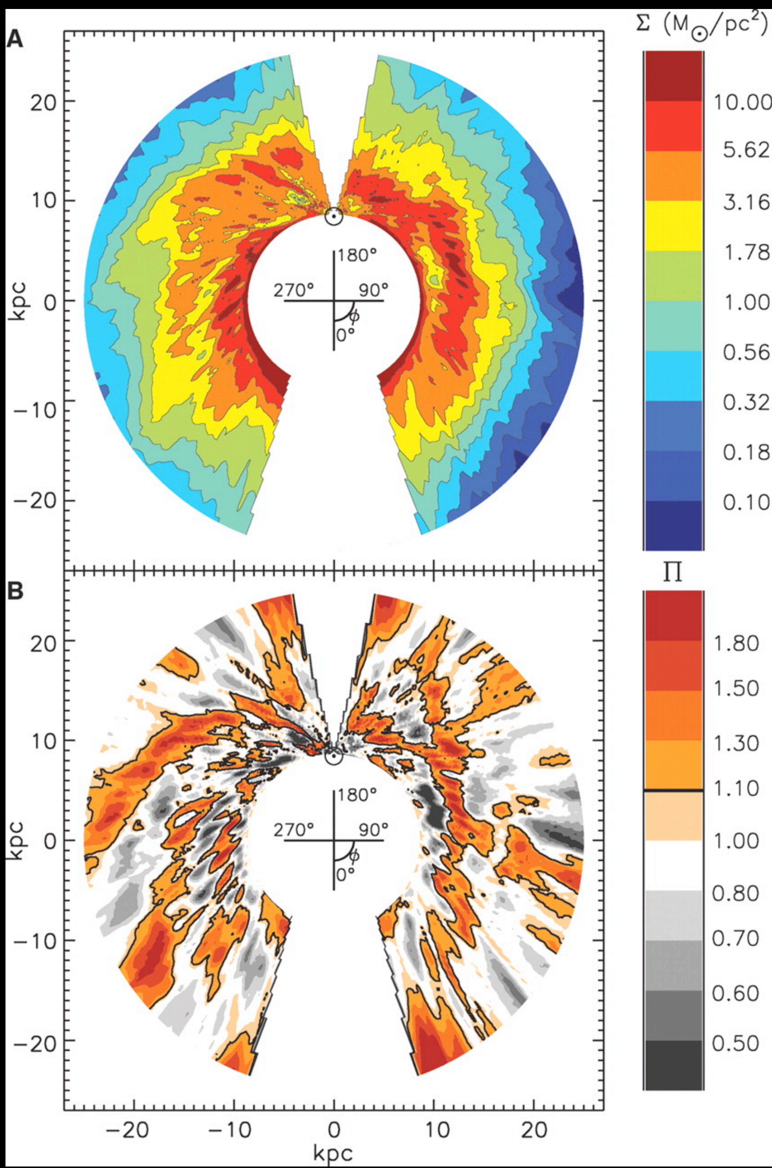
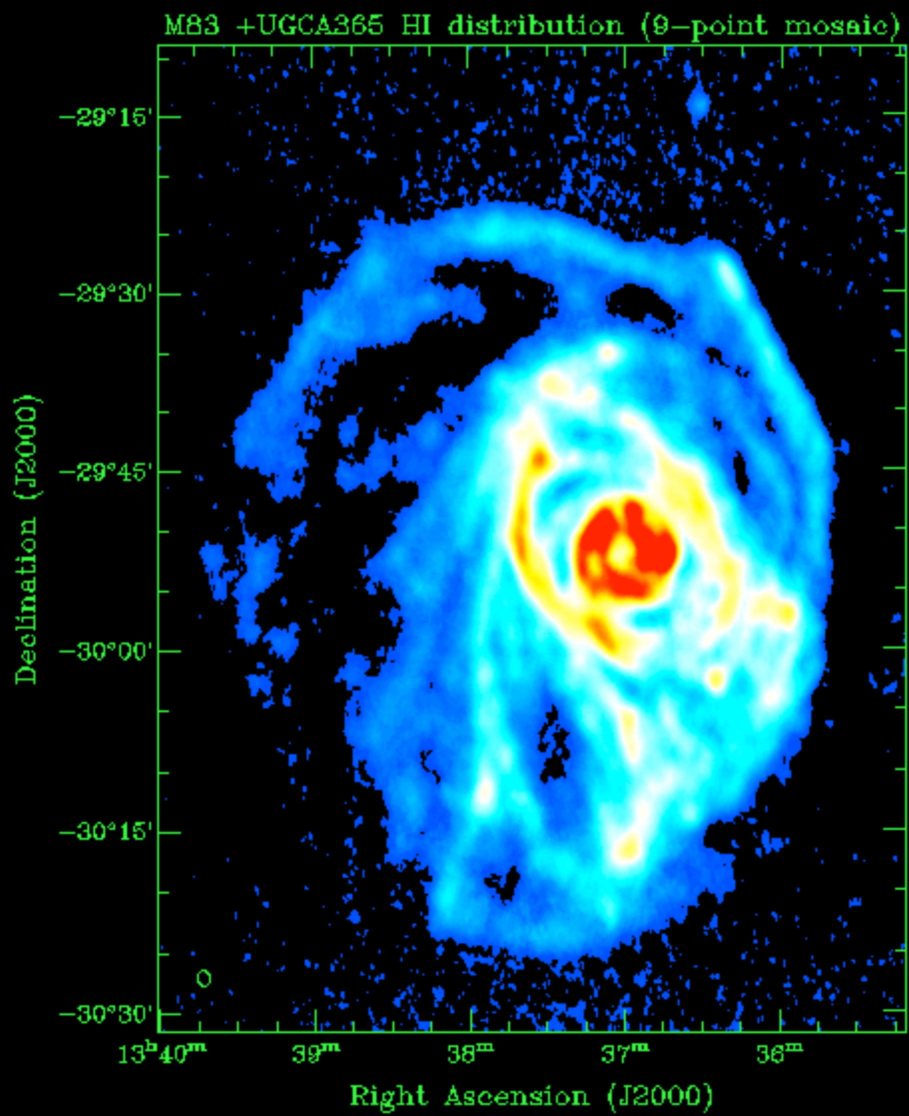
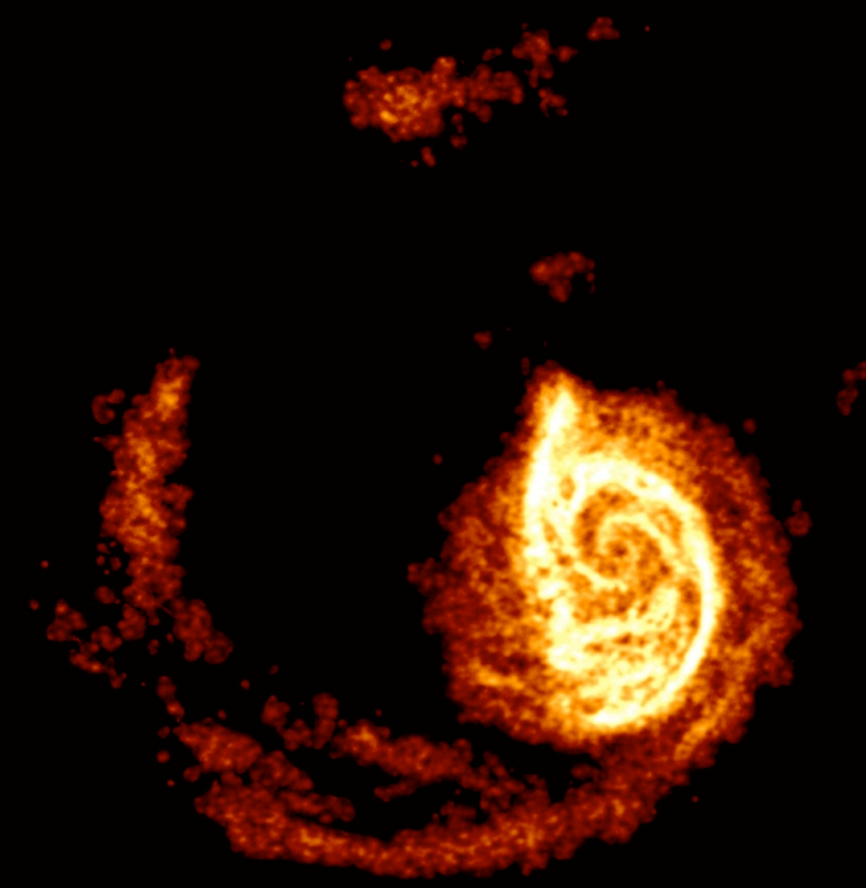
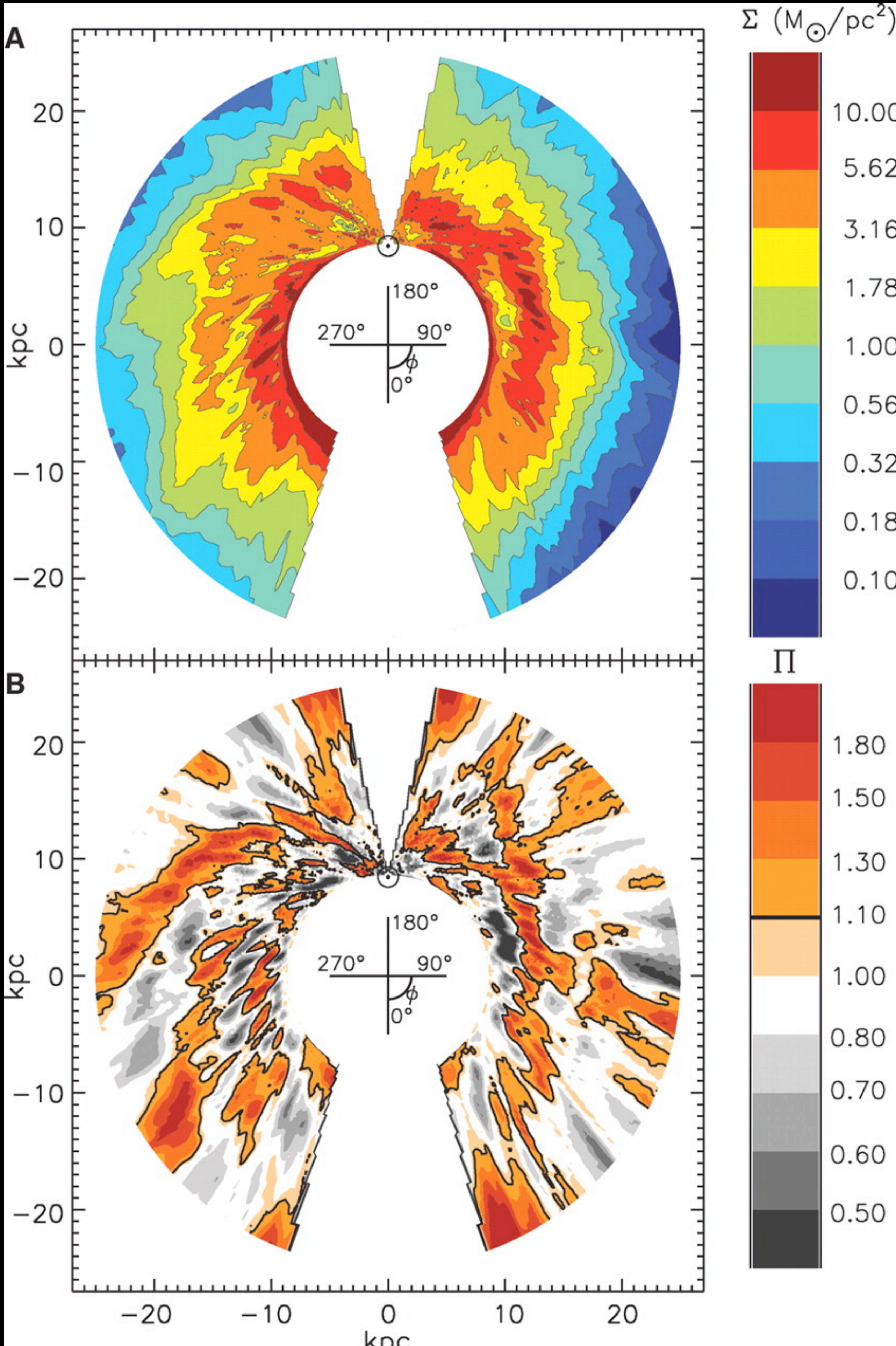


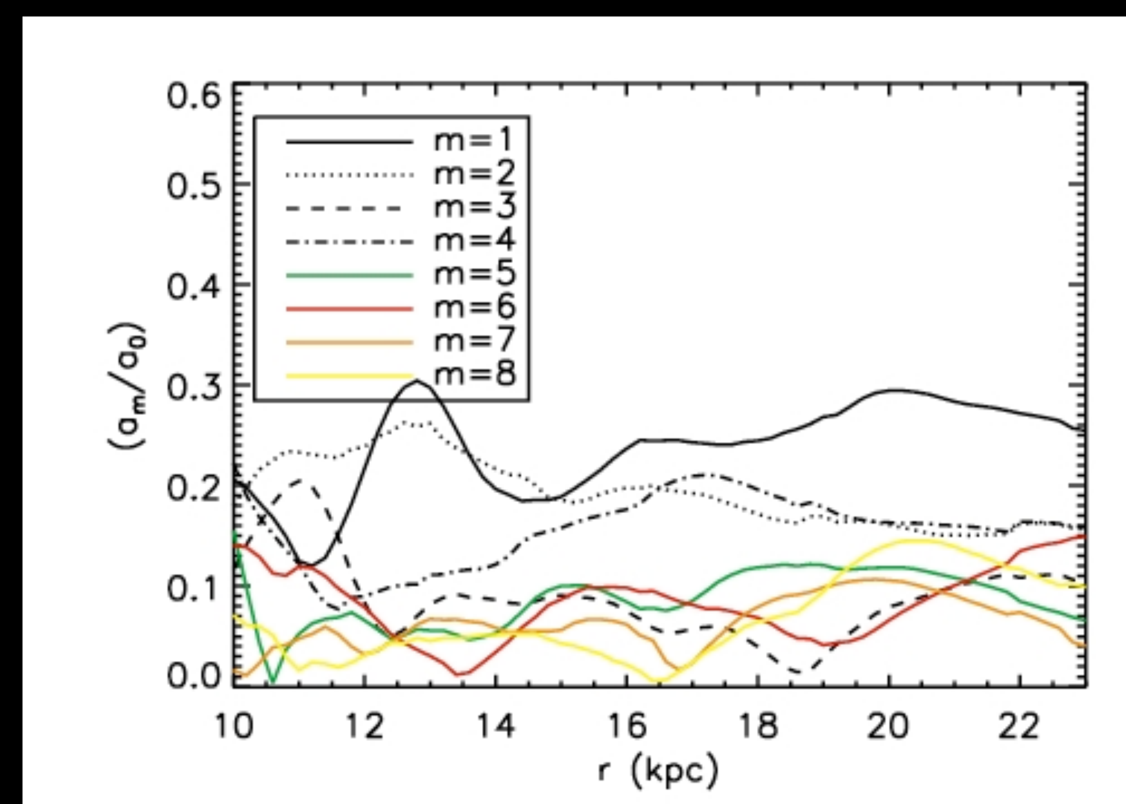



# HI Map of Milky Way

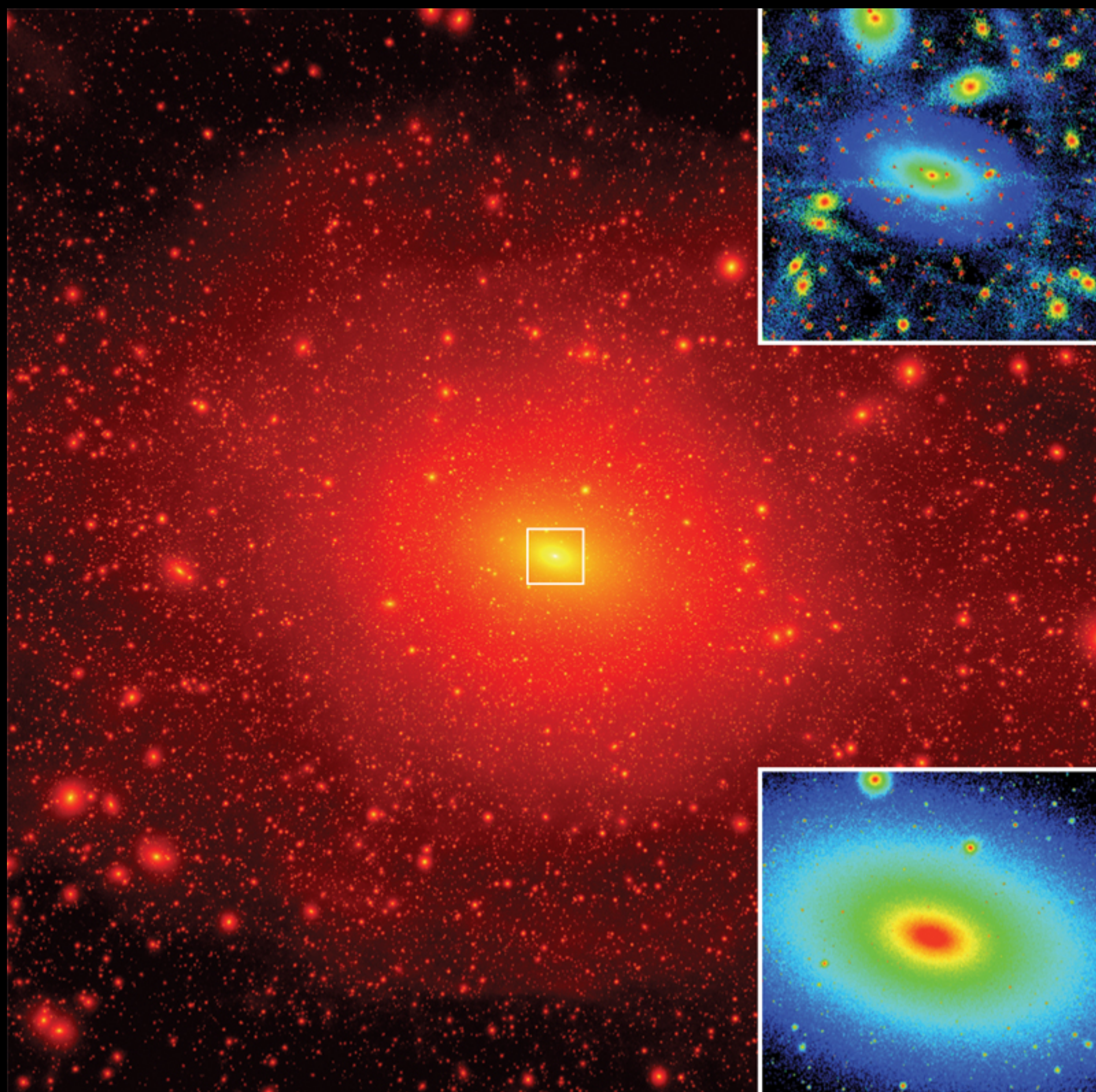


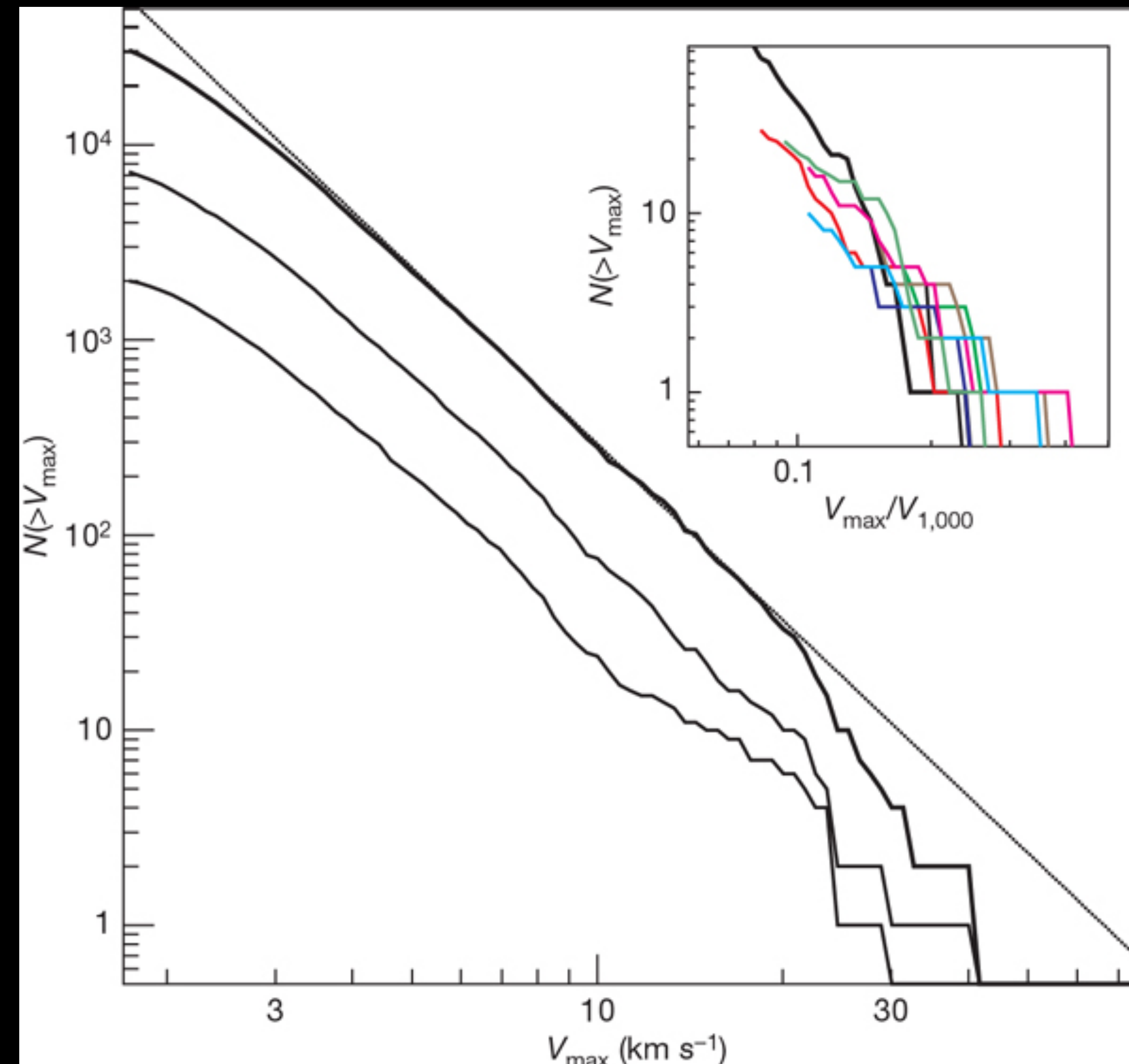

HI maps: Levine, Blitz & Heiles 2006. What caused these structures well outside the solar circle?

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



# Dark Sub-Halos: Expectations from Simulations






Klypin 2003

Diemand et al. 2008 - should be ~1000 sub-halos with M> $10^7$ $M_{sun}$, ~ 1 sub-halo of mass $10^{10} M_{sun}$ Where are the rest? Can you find dark galaxies by their interaction with gas disks?

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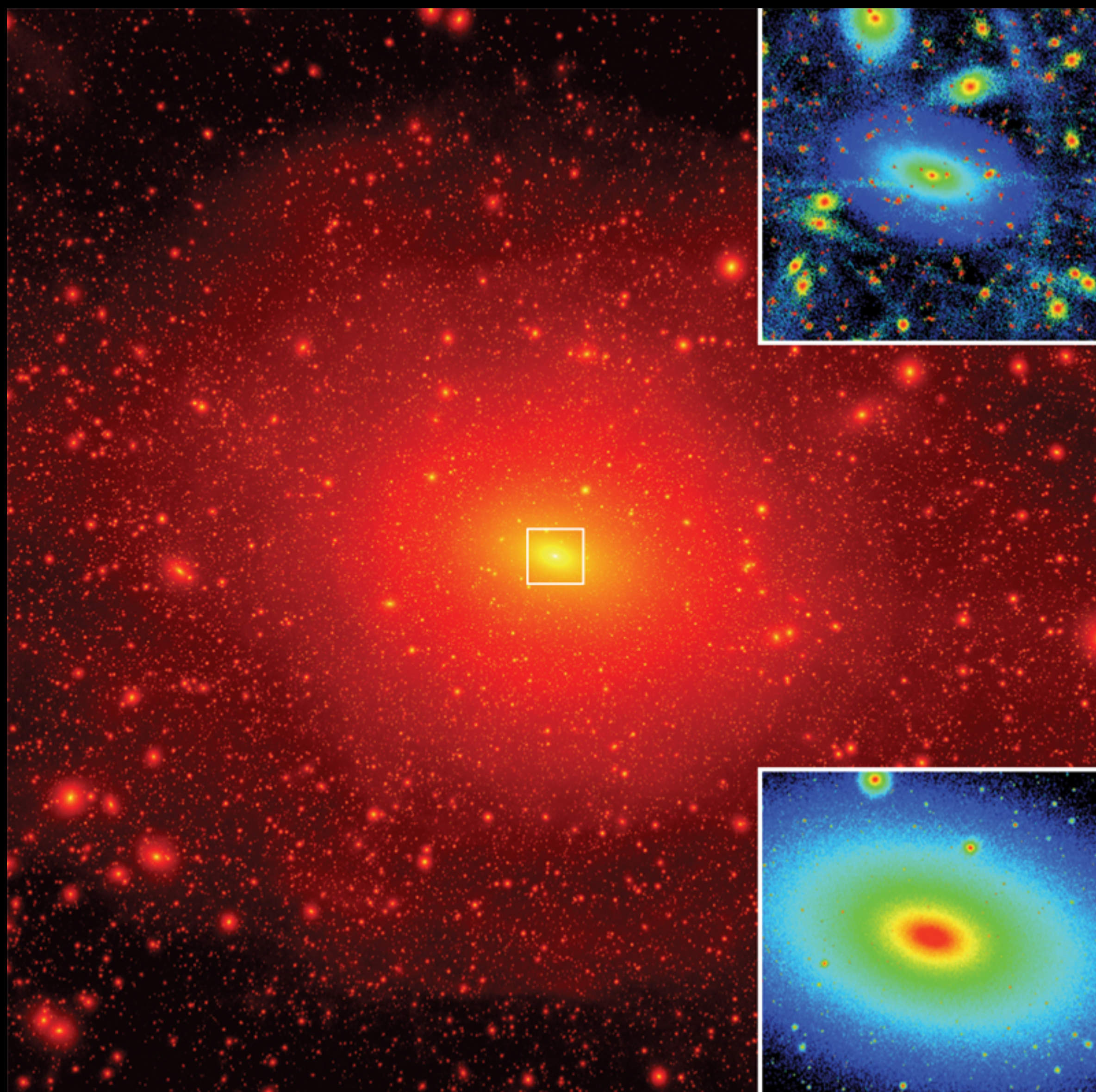

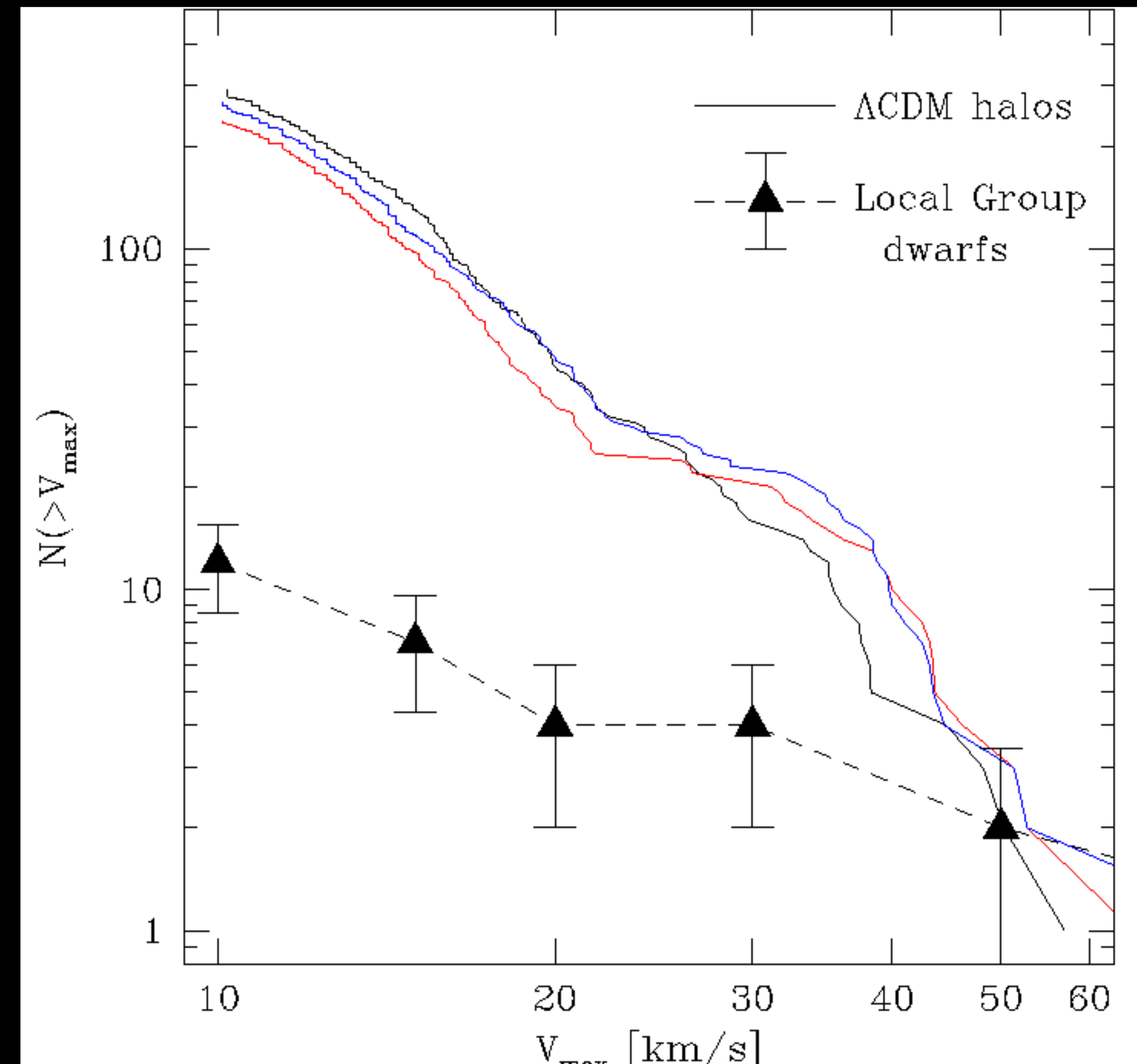


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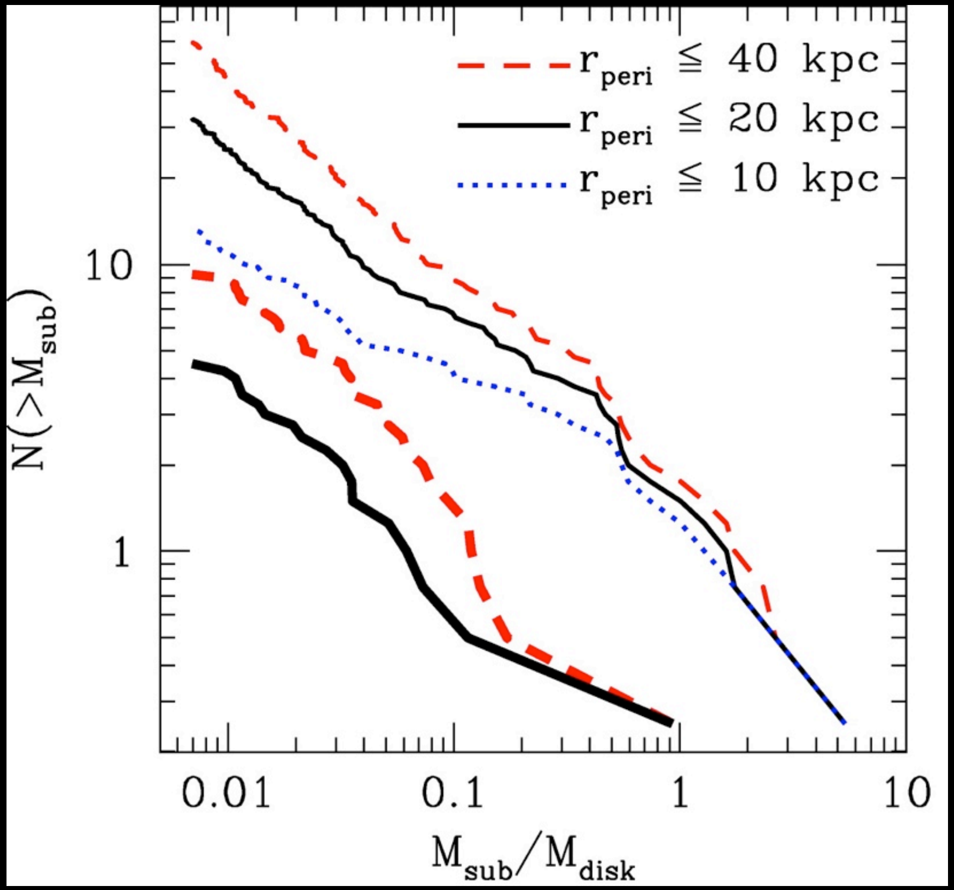
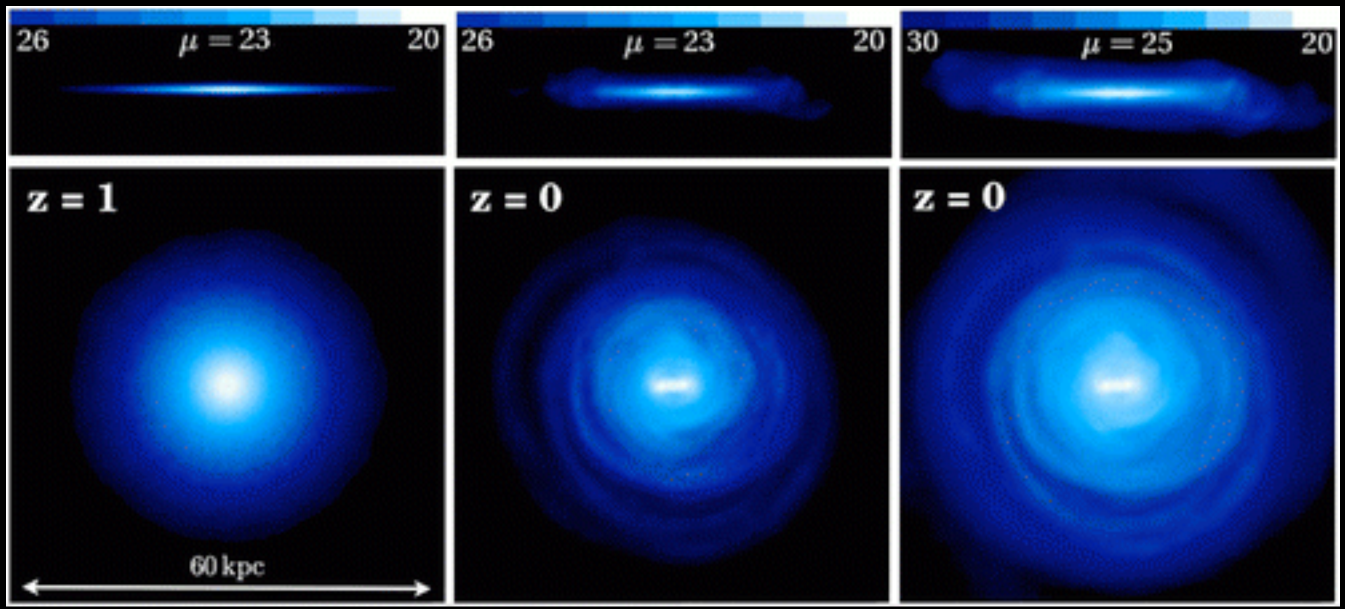
# Signatures of CDM Sub-structure on Collisionless Component




- $n(M) \propto M^{-\alpha}$, $\alpha \sim 1.8$-$1.9$, so dynamical effects will be dominated by most massive sub-structures. Tidal heating $\propto \int n(M)\, M^2\, dM$.

- Kazantzidis et al. 2008 - studied the effect of CDM sub-structure on stellar disks. thickening, flaring, surface density excesses.



# Tidal Imprints (footprints) of Dark Subhalos on Outskirts of Galaxies

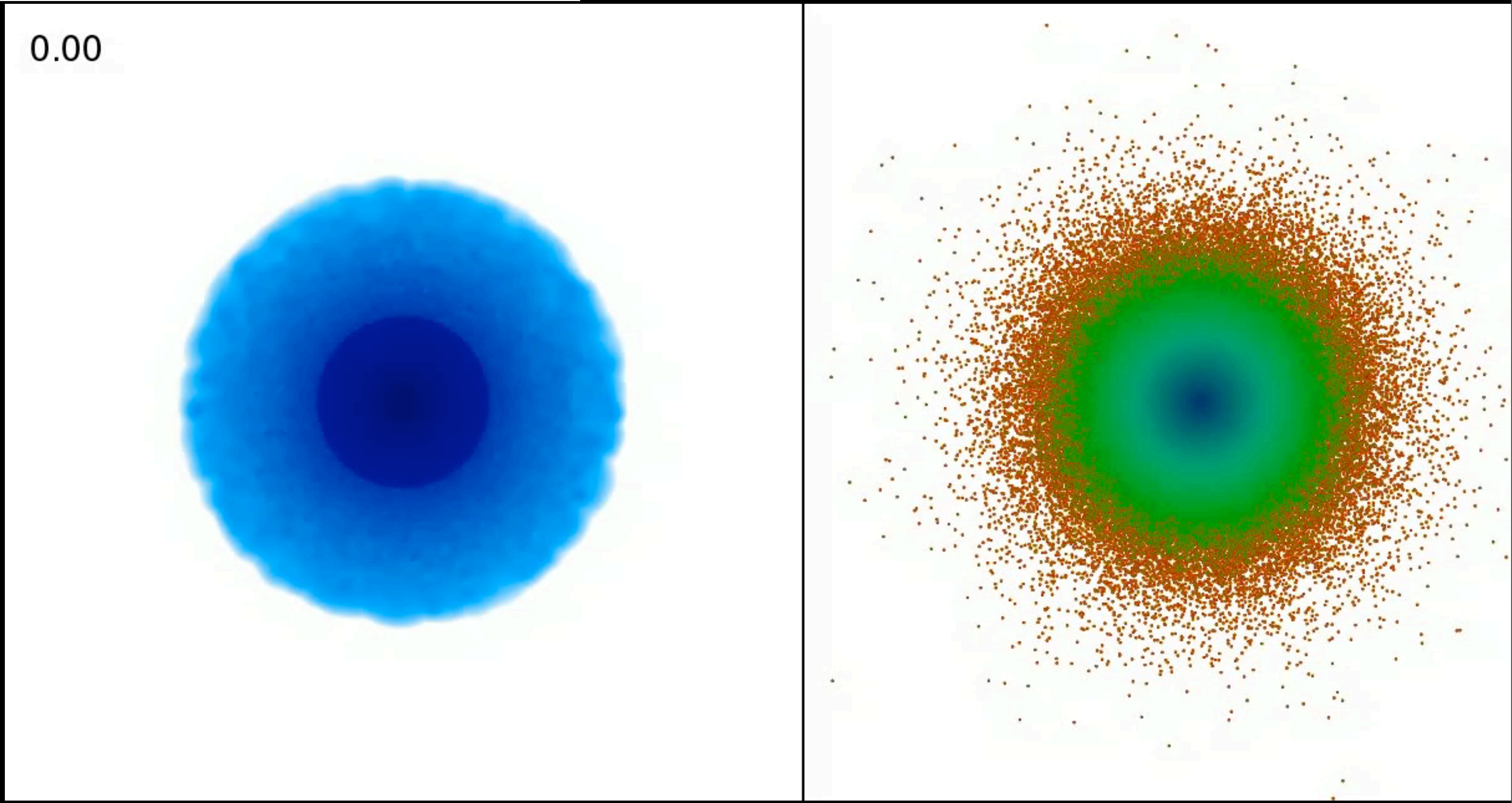
- Coldest Component Responds the Most! (by ratio of inverse sound speed squared). Gas has short-term memory.
- Maximize rate of detection of dark subhalos by looking for their tidal footprints on cold gas in extended HI

HI Maps!

Footprints of Dark Sub-Halos

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

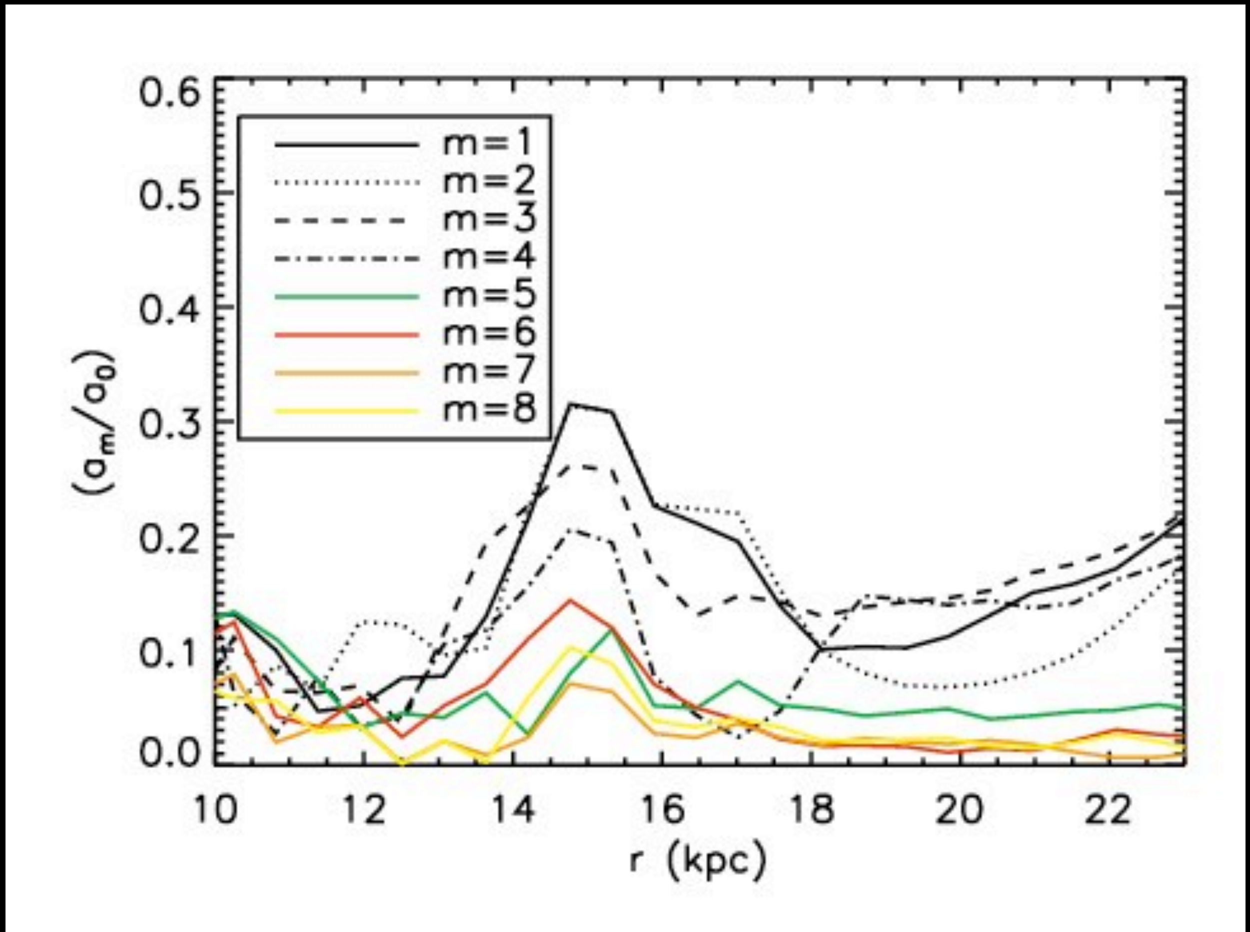
# Simulations



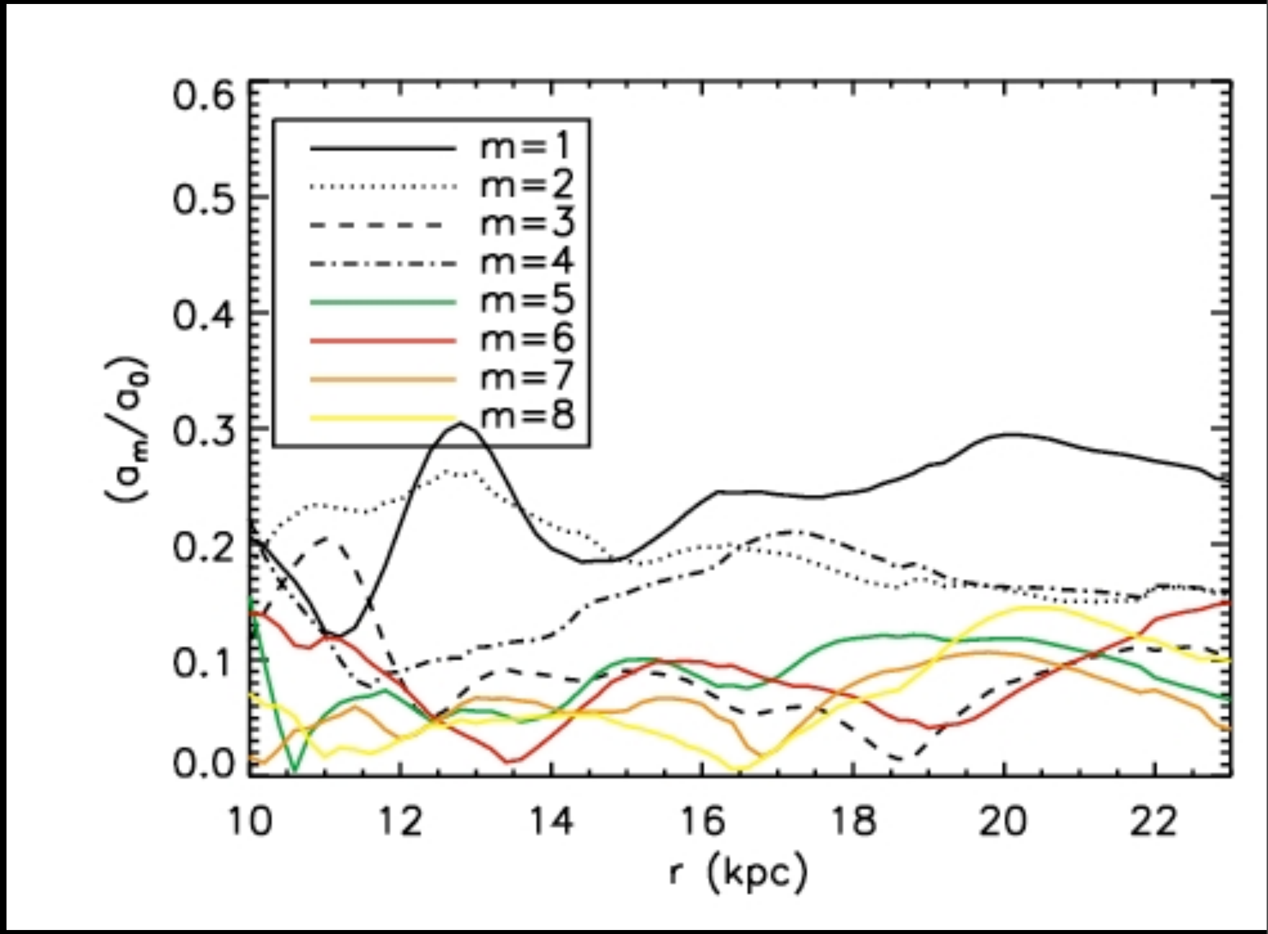

Parameter Space Survey of Simulations. Total ~ 50.
Chakrabarti & Blitz 2009.

# Just about right

Simulation




Data




1:100, $R_{peri}$~5-10 kpc - best-fit case. Chakrabarti & Blitz 09. Doesn't violate observed thickness.

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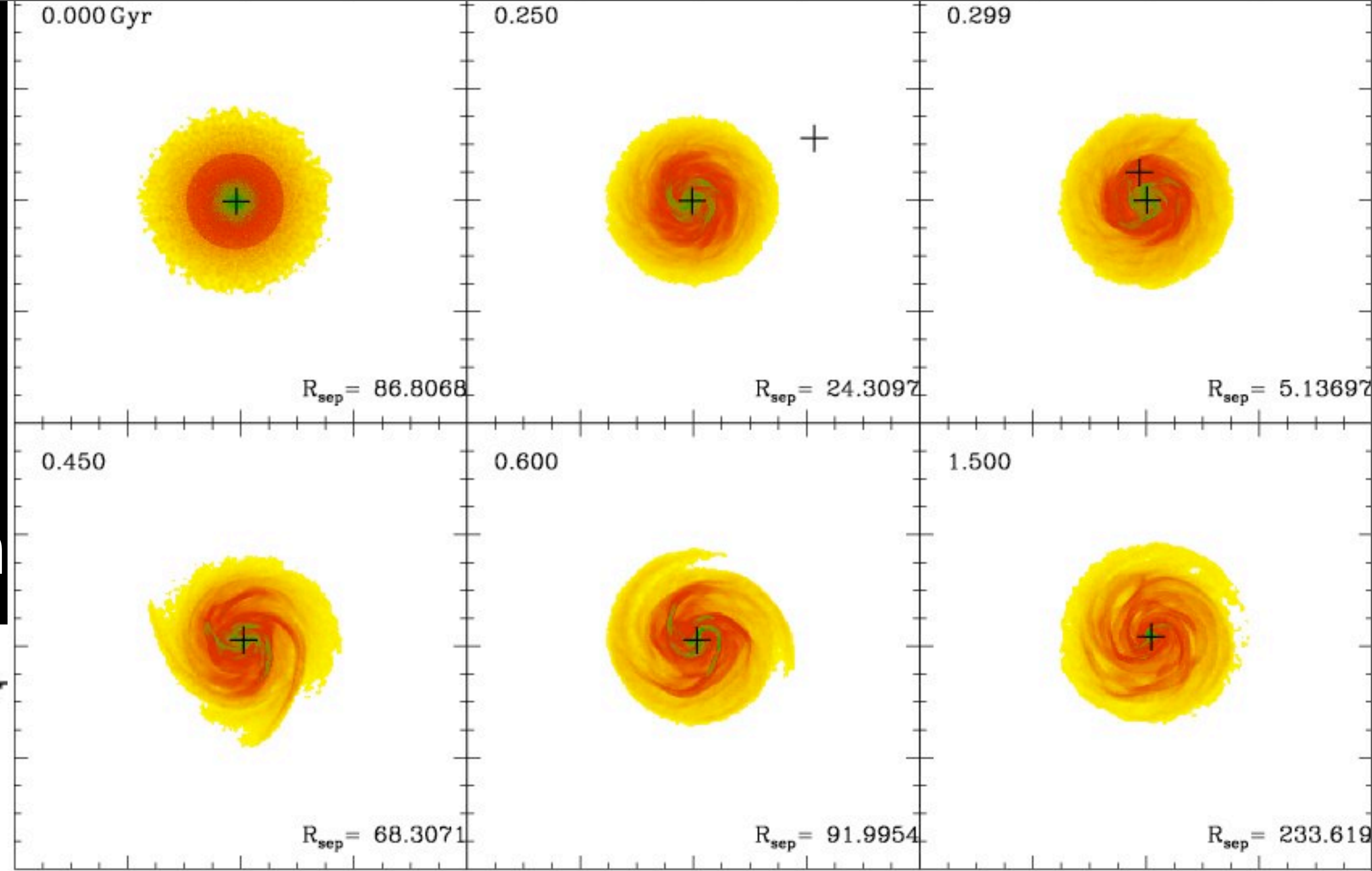


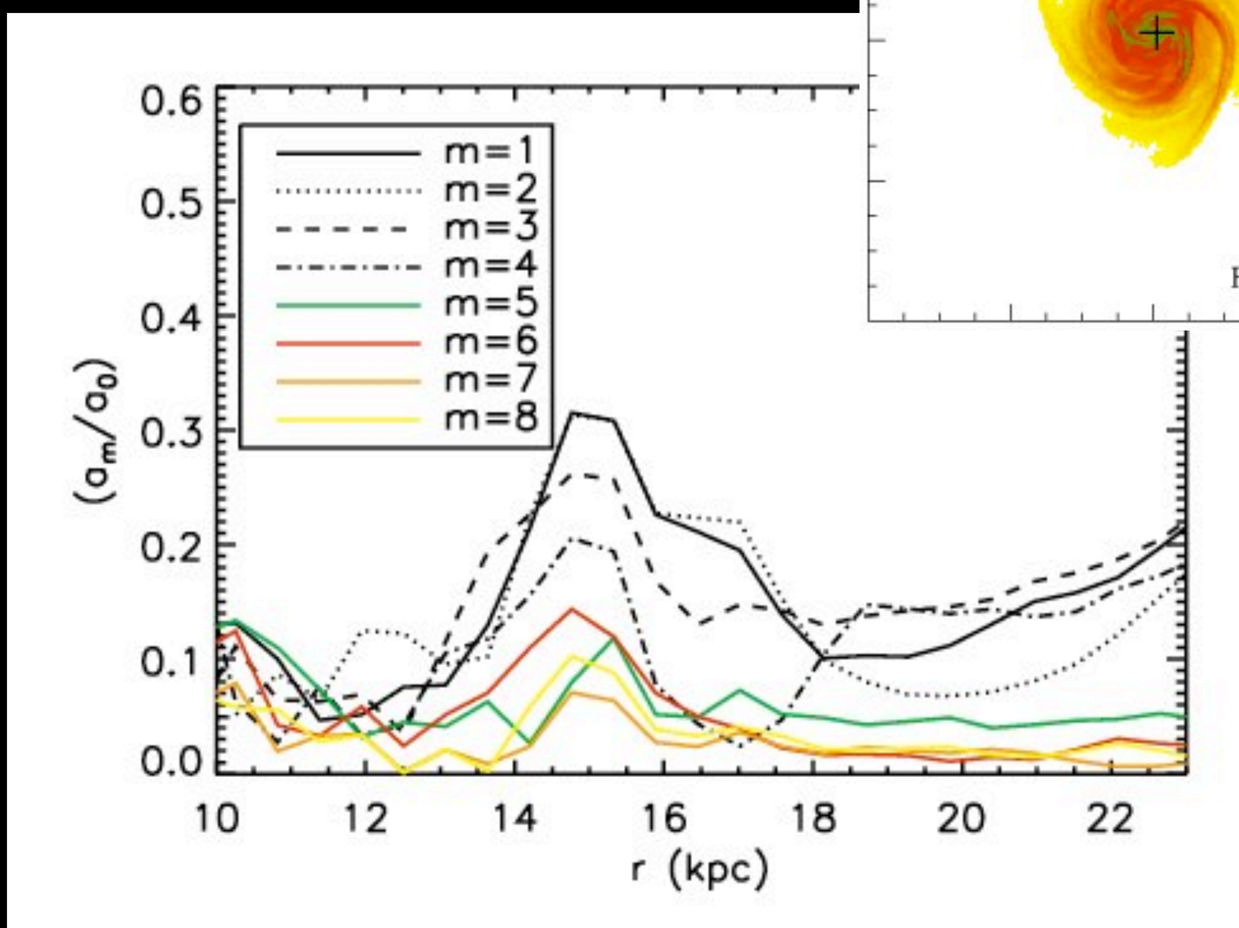


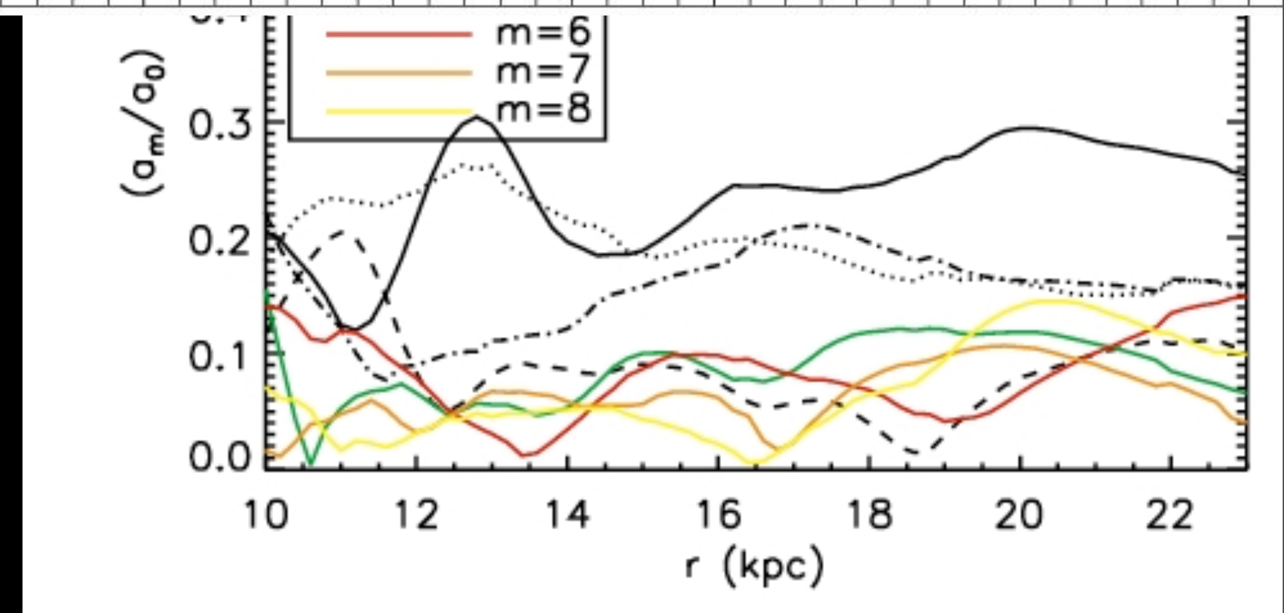


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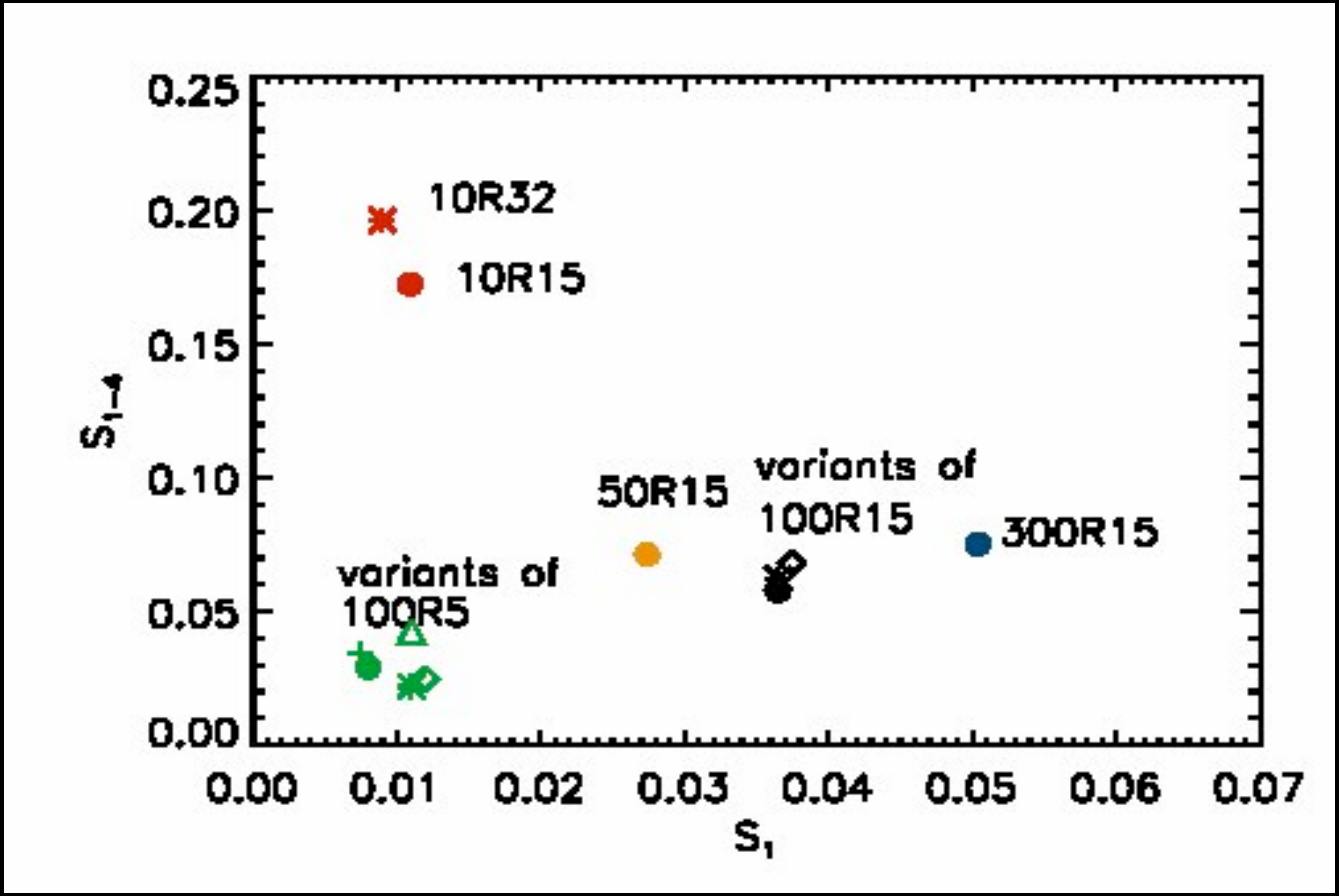

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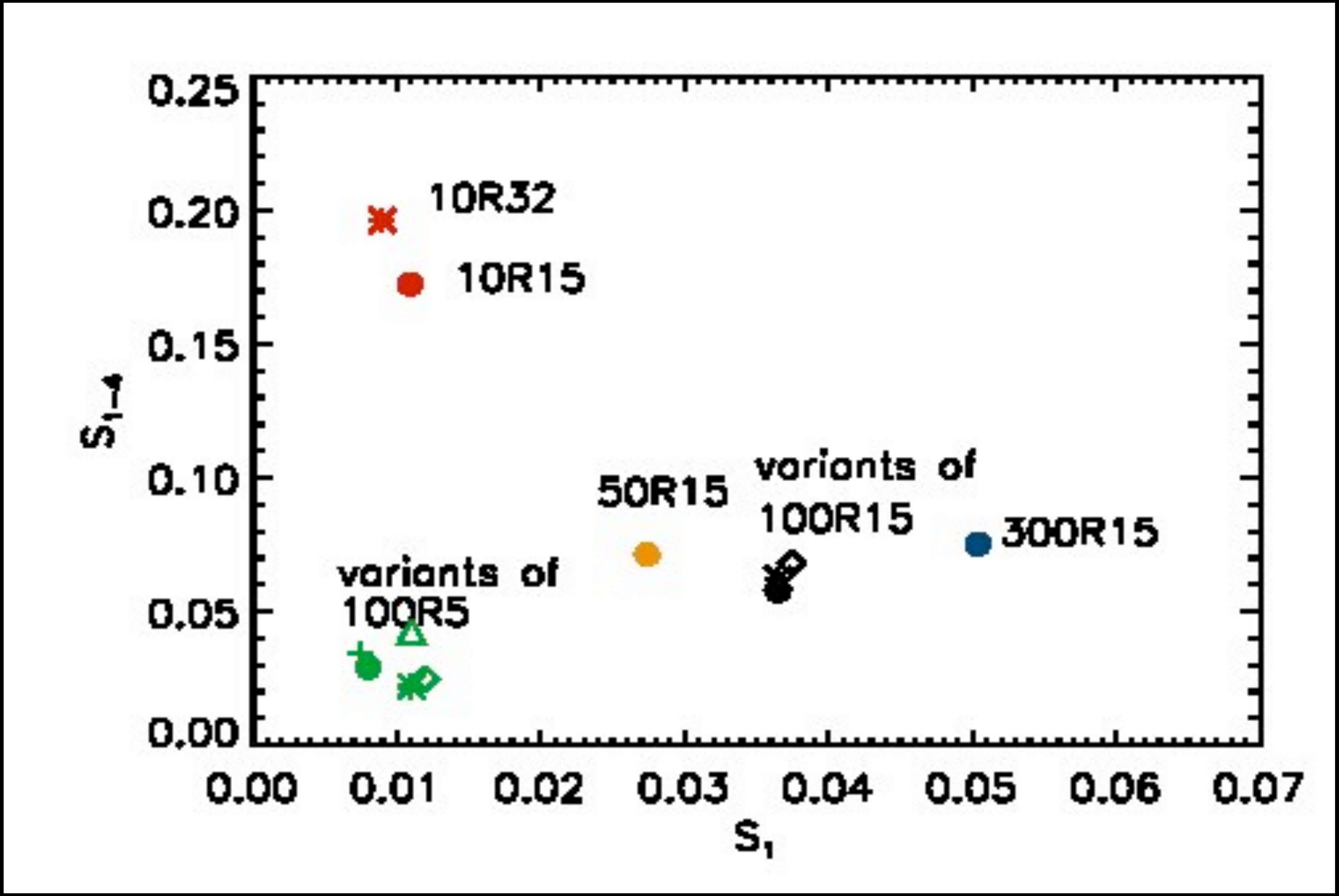


- Not very sensitive to ICs (for parameters comparable to spirals). CB09 -- $M_s$ and $R_{peri}$ are what really matter.

# Can you really figure out the perturber mass?

- $F_{tide} \propto M/R^3$. Can you tell the difference between a big perturber further out or a small perturber closer in?


$R_{peri}$

$R_0(M_s)$

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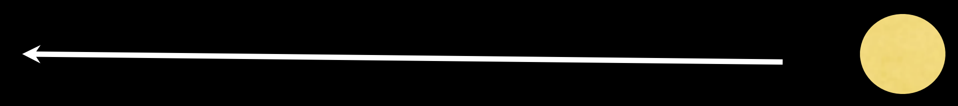

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can break degeneracy betwen M & R if:

$\Delta t = t(R_{peri}) - t(R_0) > t_{shock}$ (CB09)

# Breaking the degeneracy between M & R

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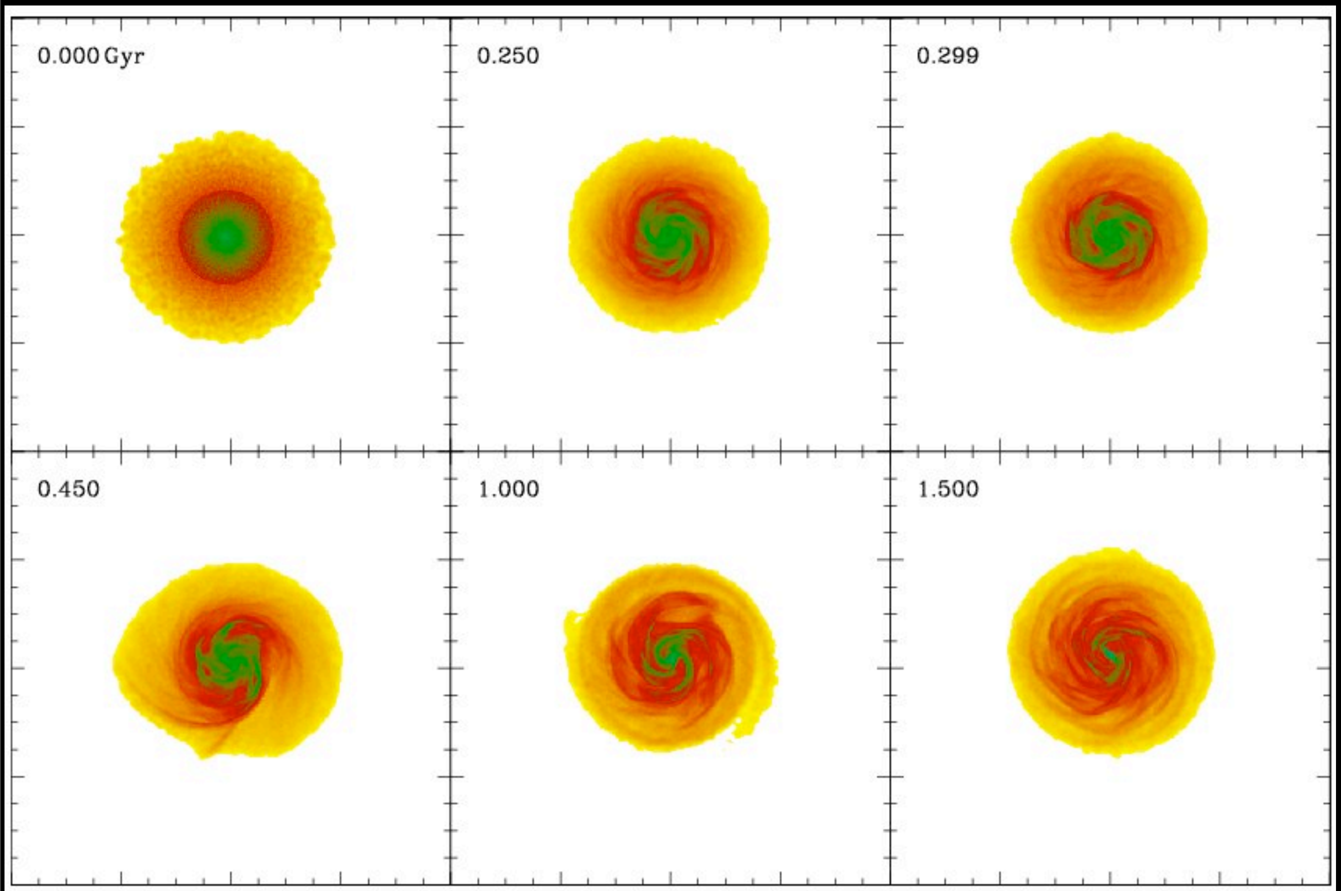

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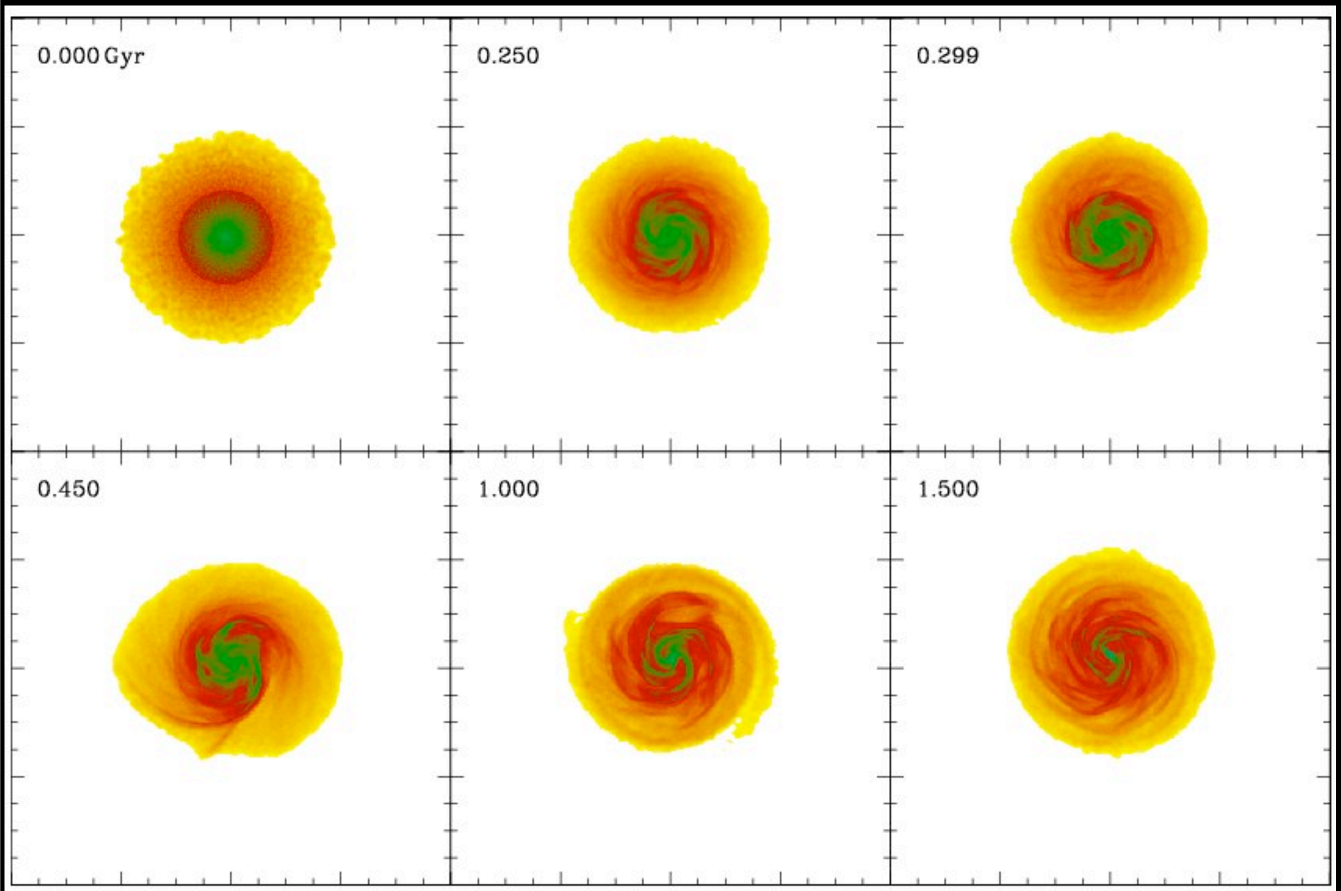


1:100 with $R_{peri}$=5 kpc

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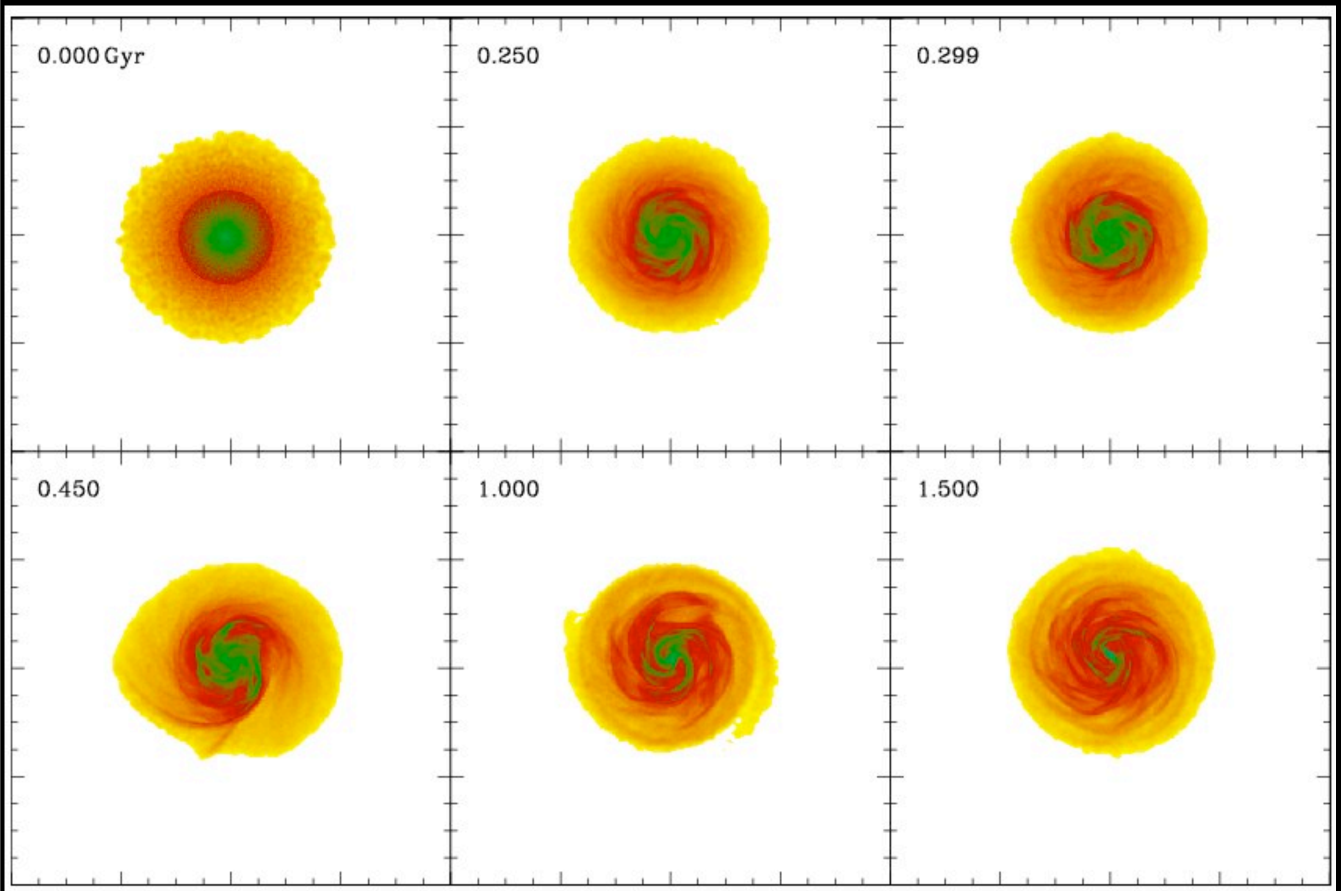


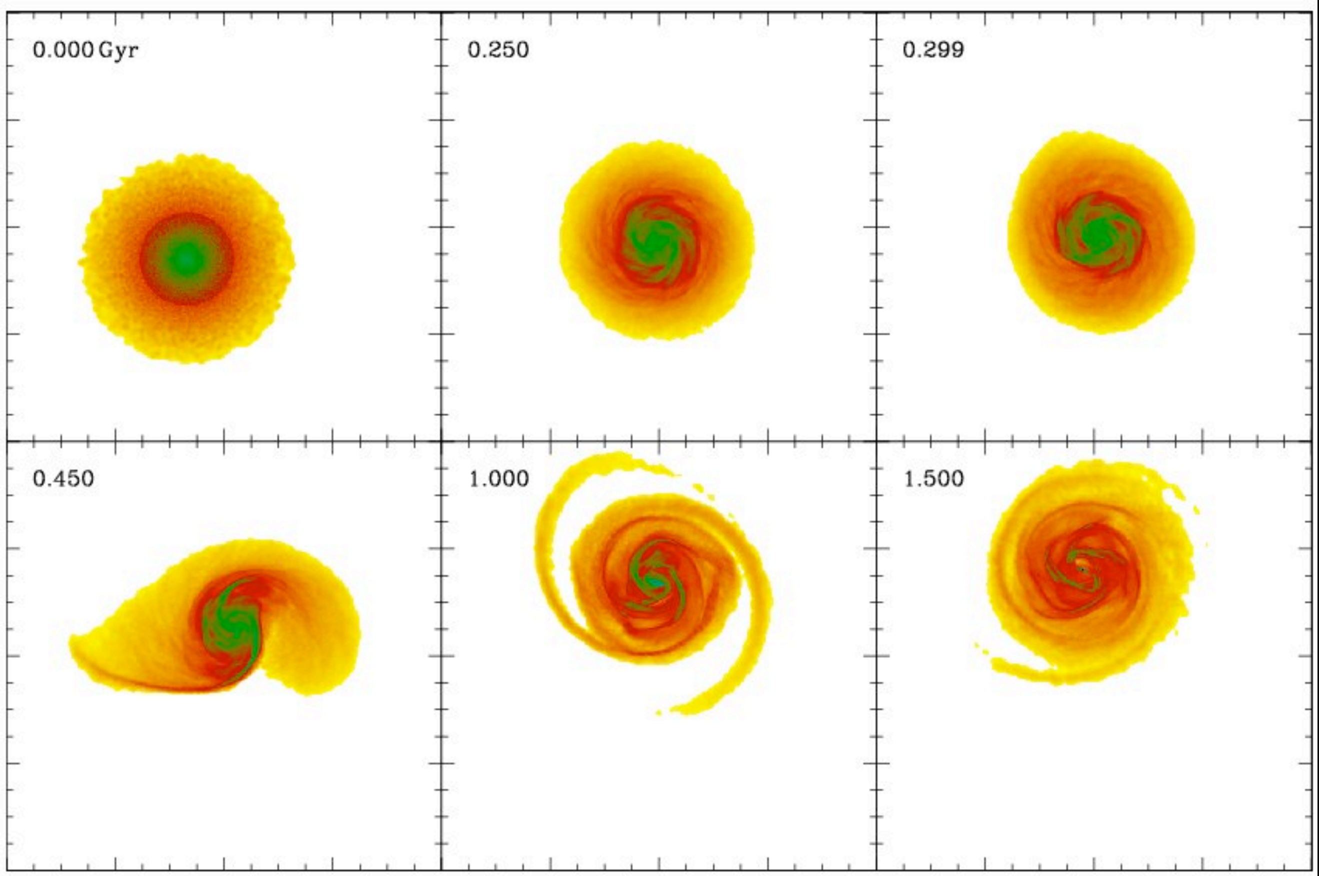


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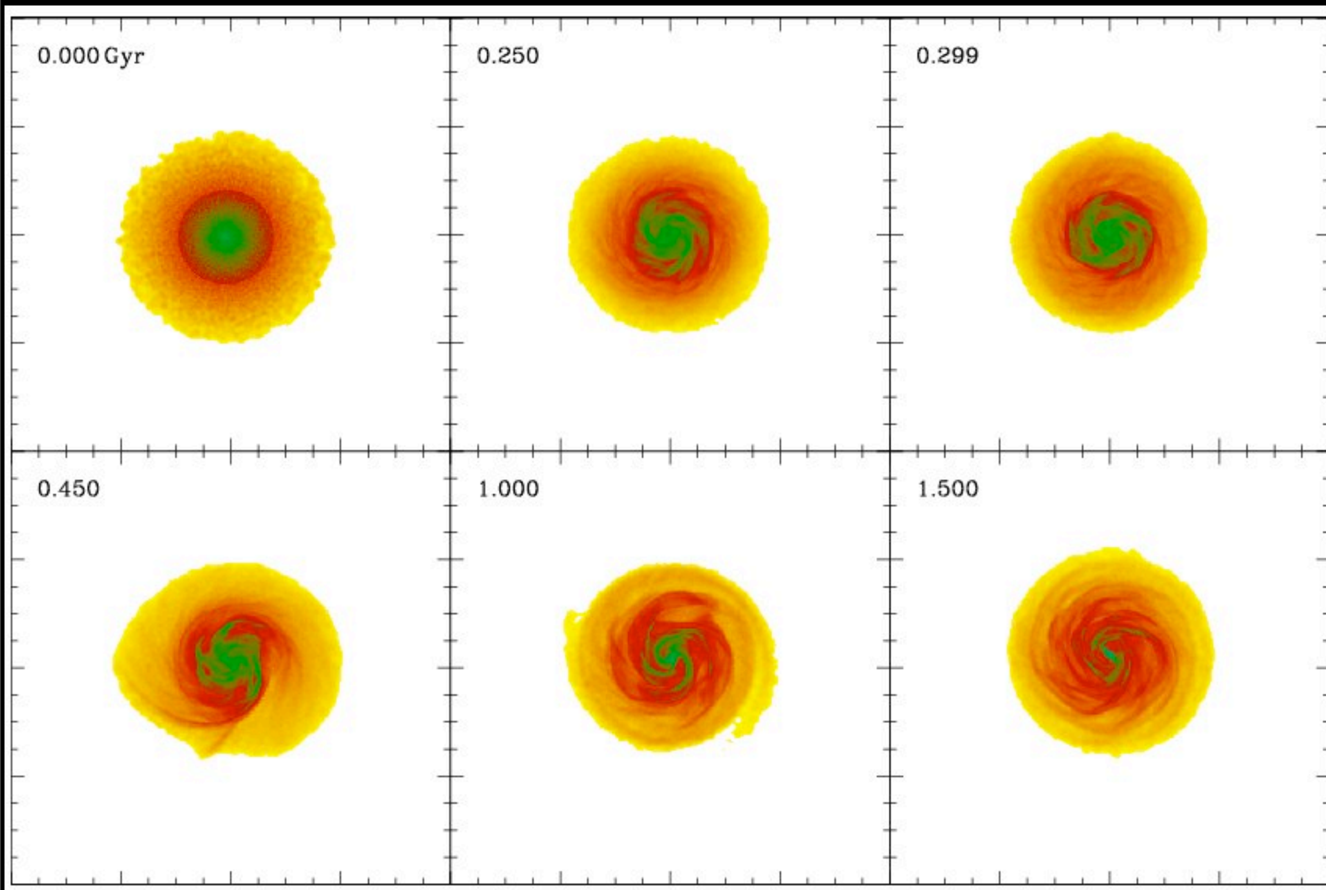


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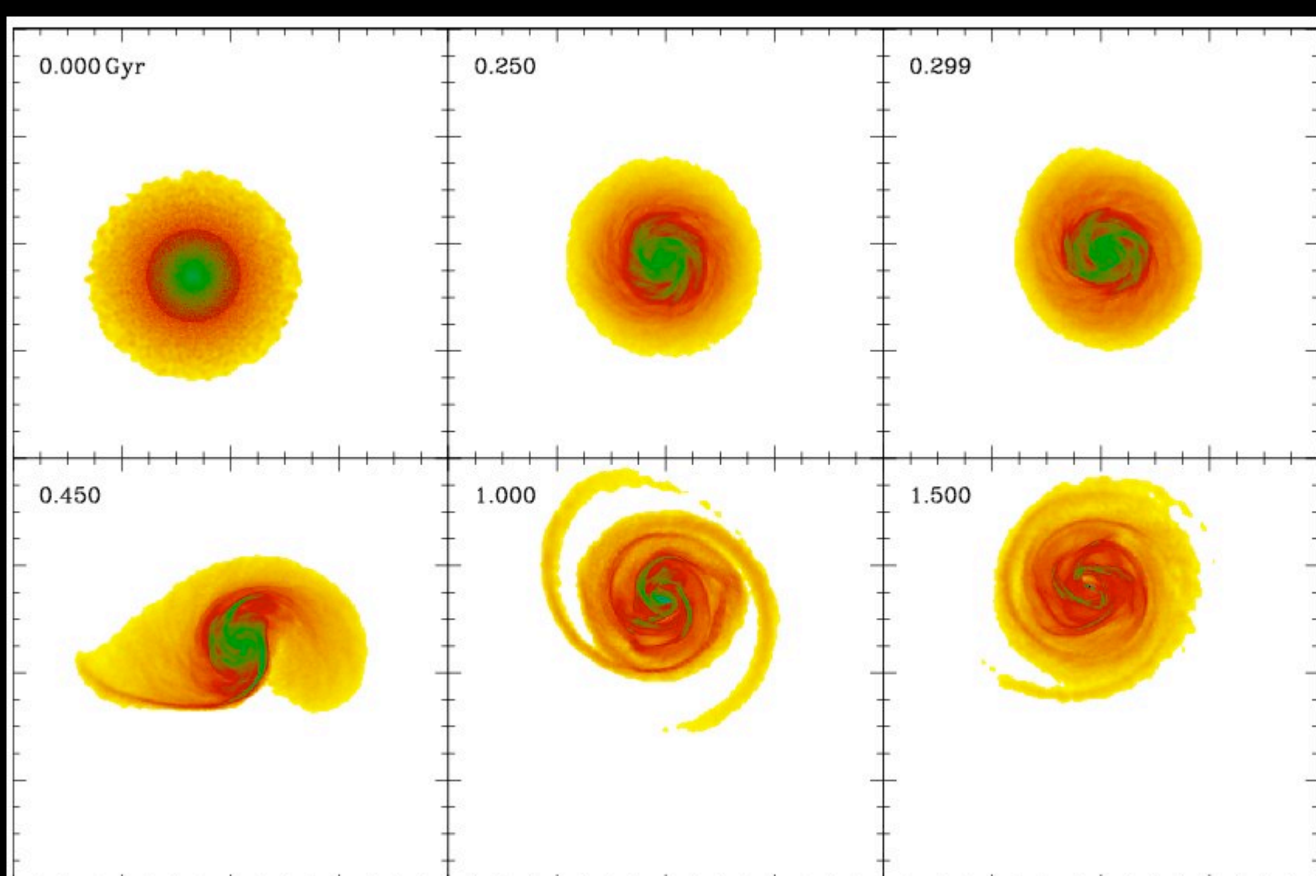


1:10 at equivalent tidal distance as 1:100

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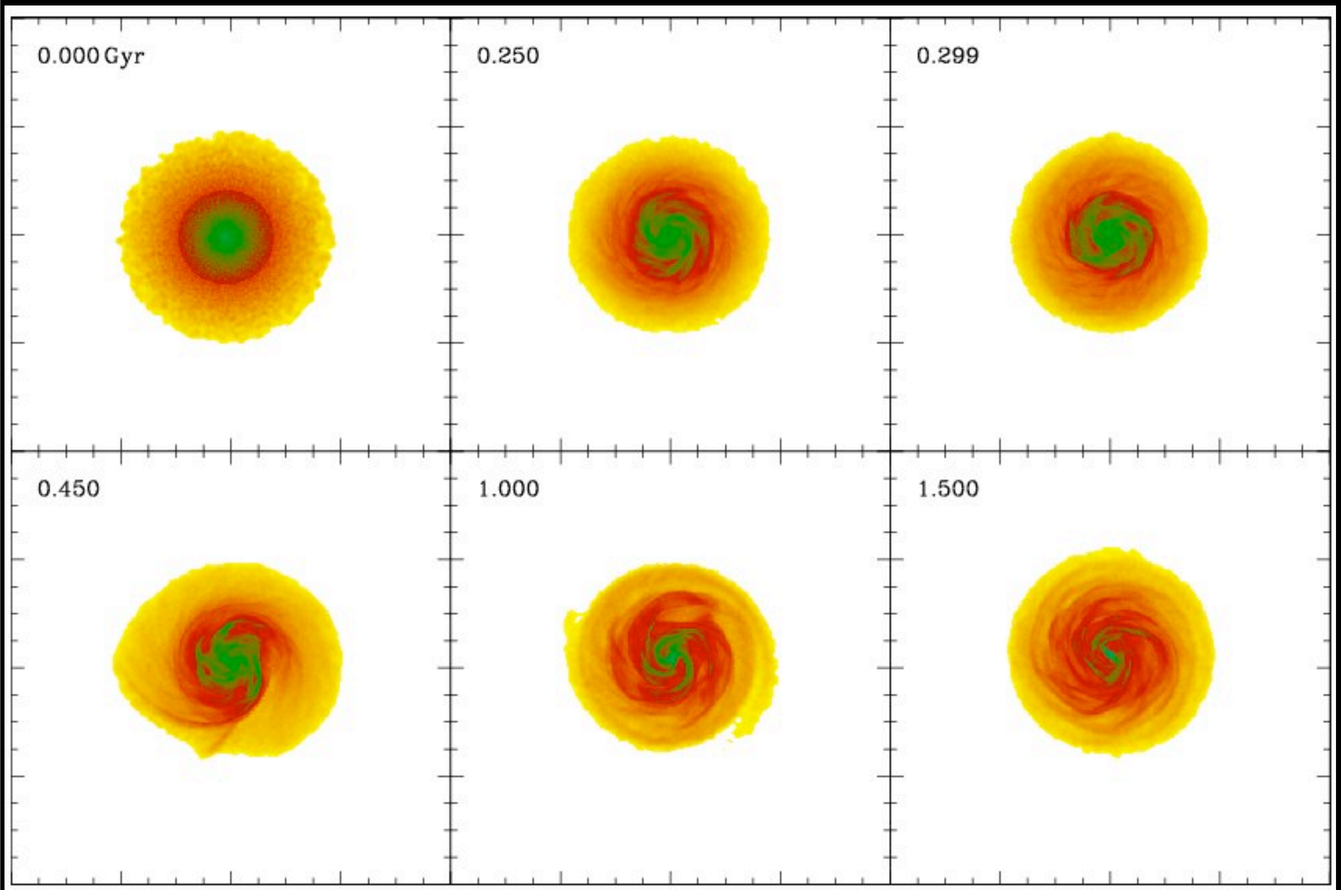


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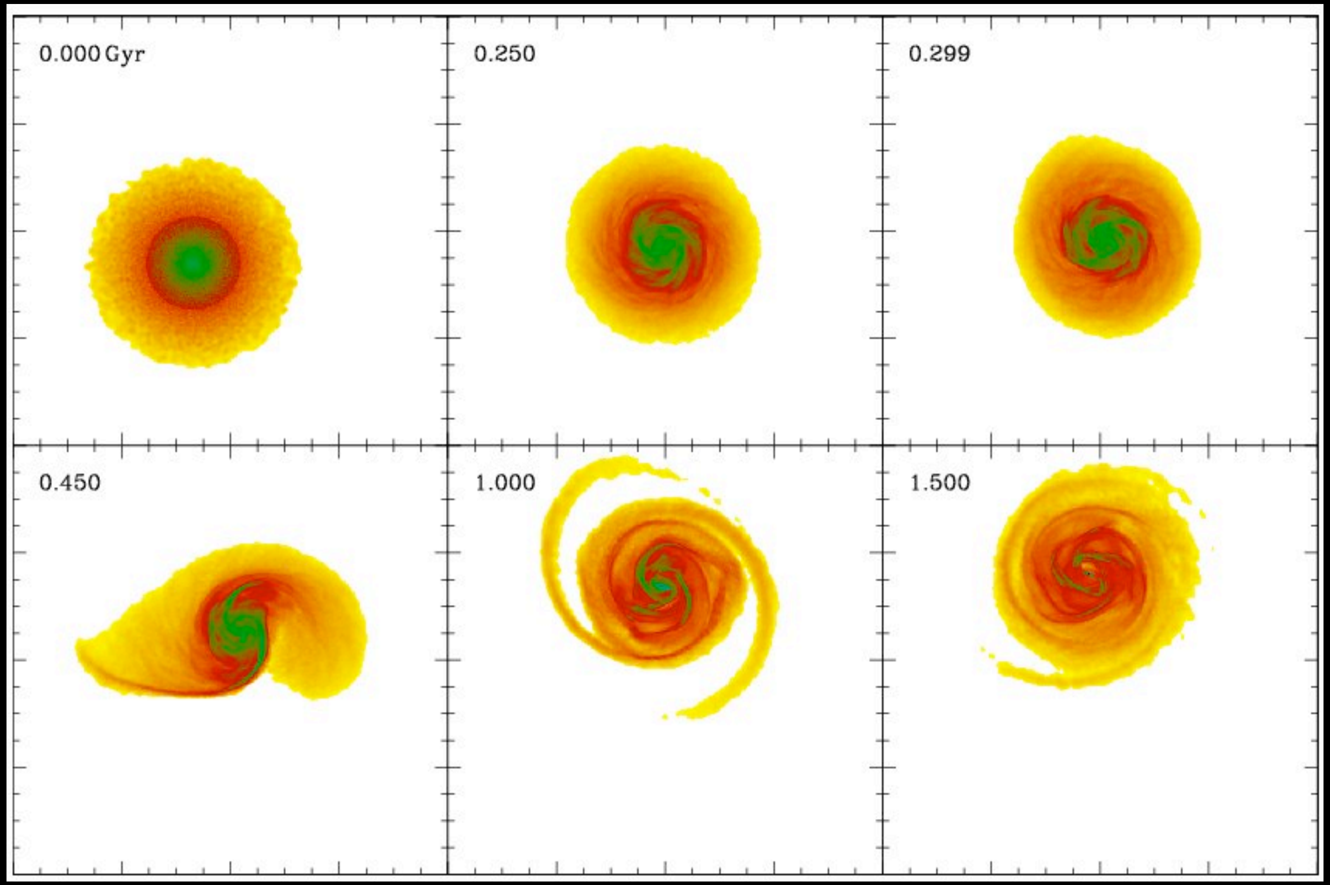


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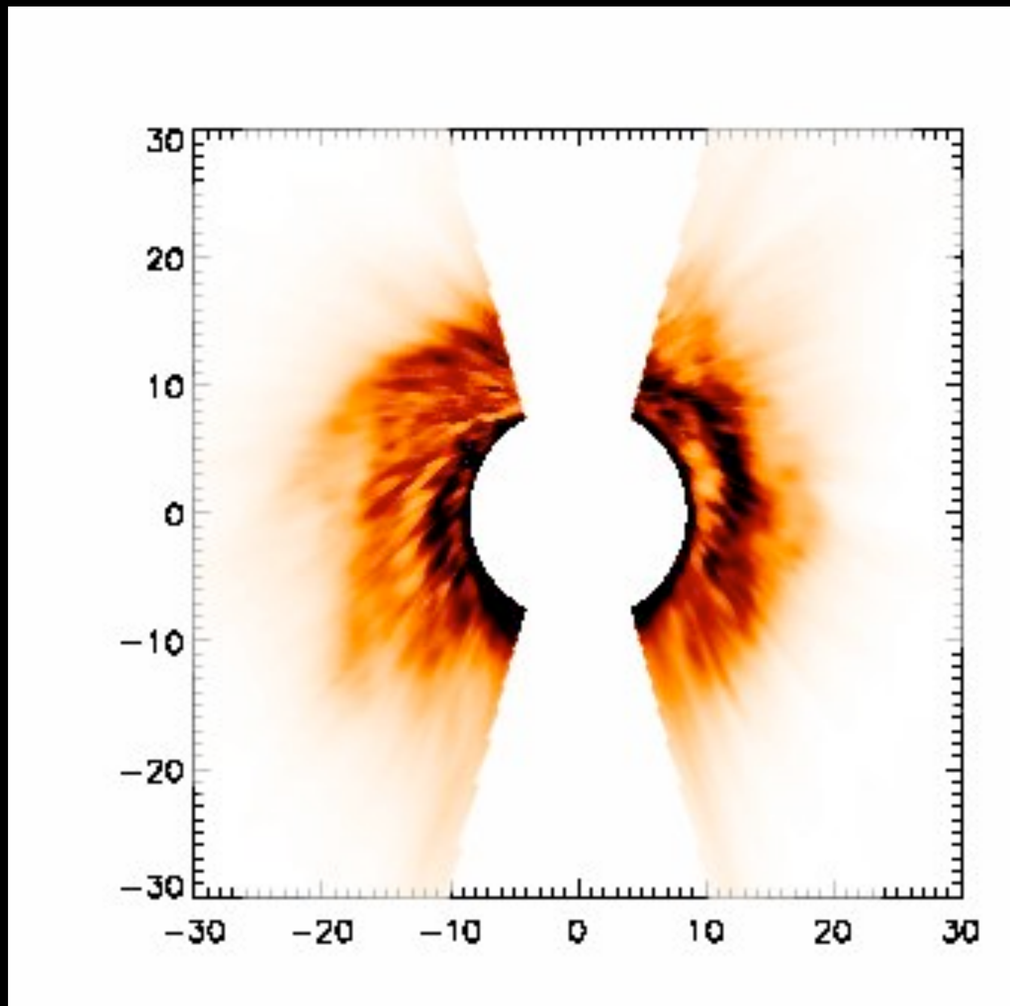
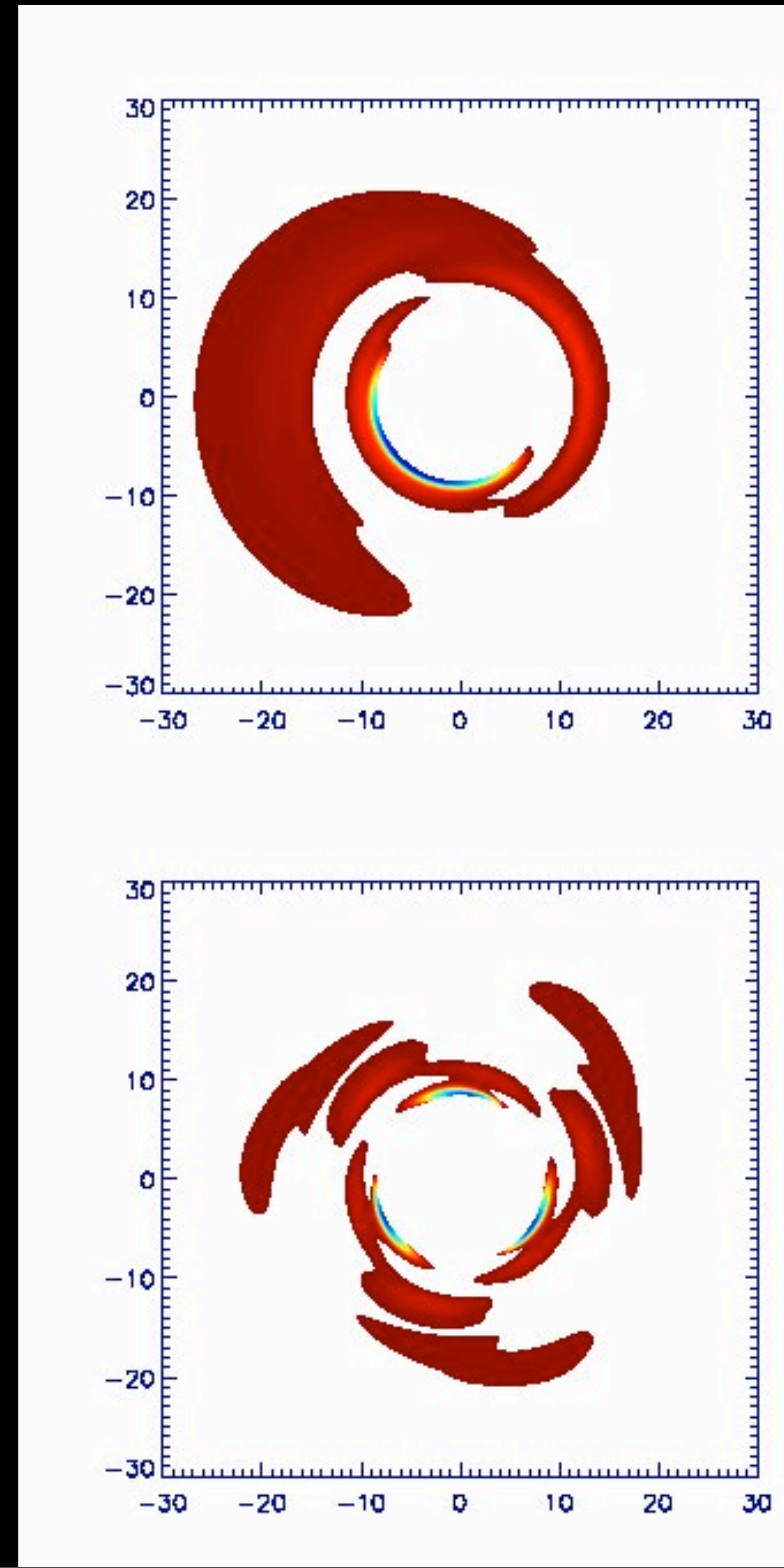
- Breaking of degeneracy + lack of dependence on ICs -- $M_s$,R (CB09)

# Azimuthal Location of Perturber




- Chakrabarti & Blitz 2010.
- determine azimuthal location of perturber from relative offset of phase in simulations vs data

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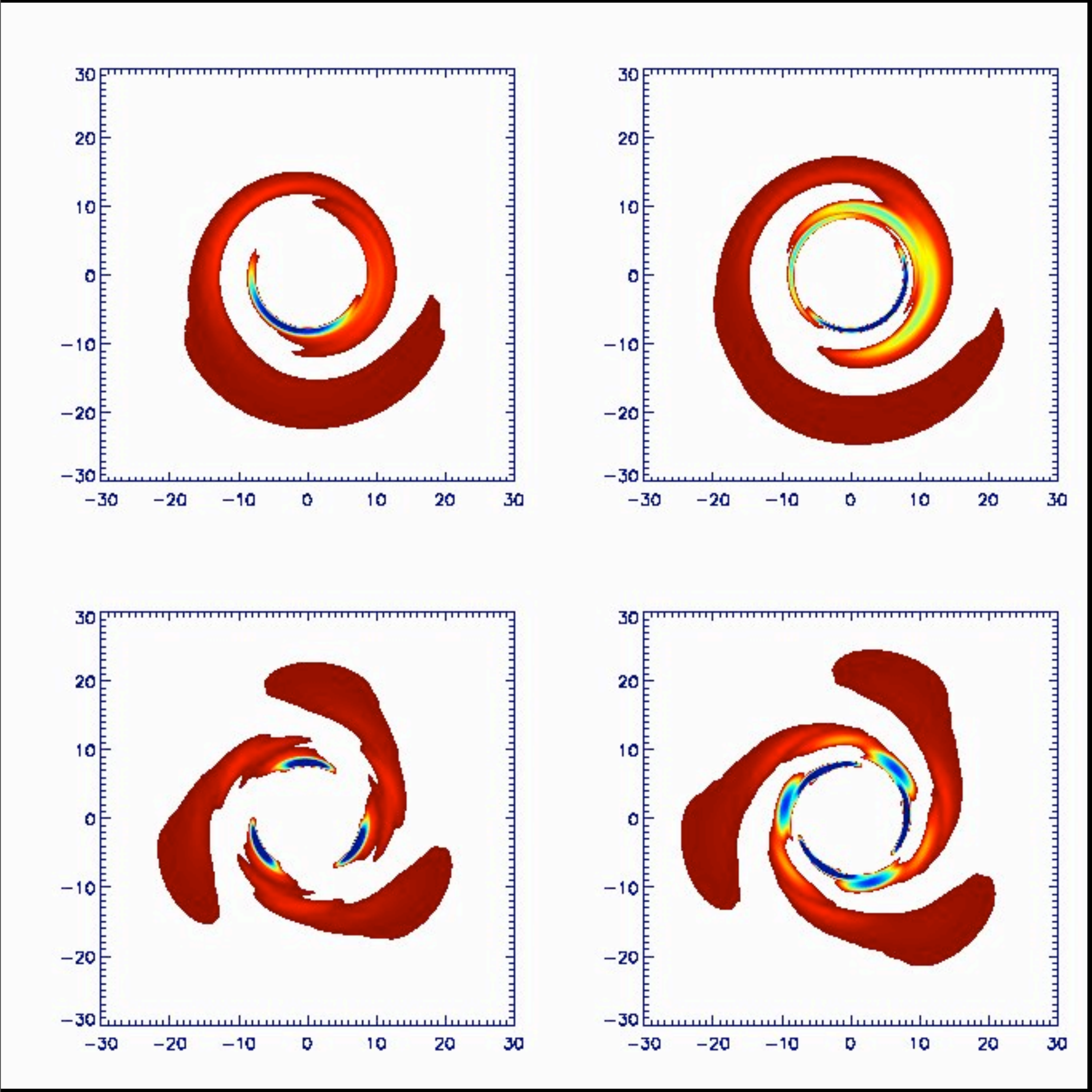


- Note similarity of phase of modes in outskirts of simulated galaxy -- little dependence on eq. of state.

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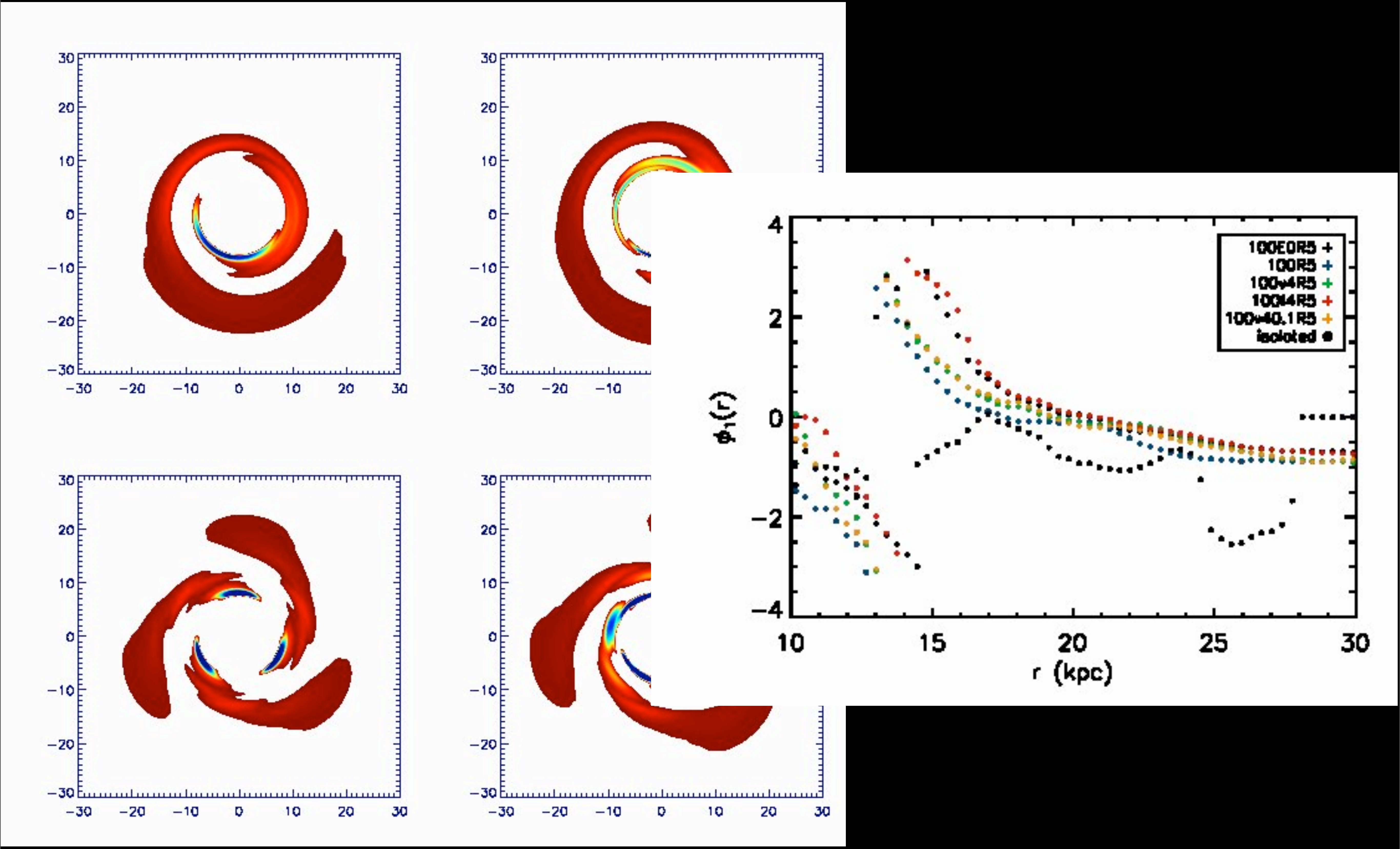


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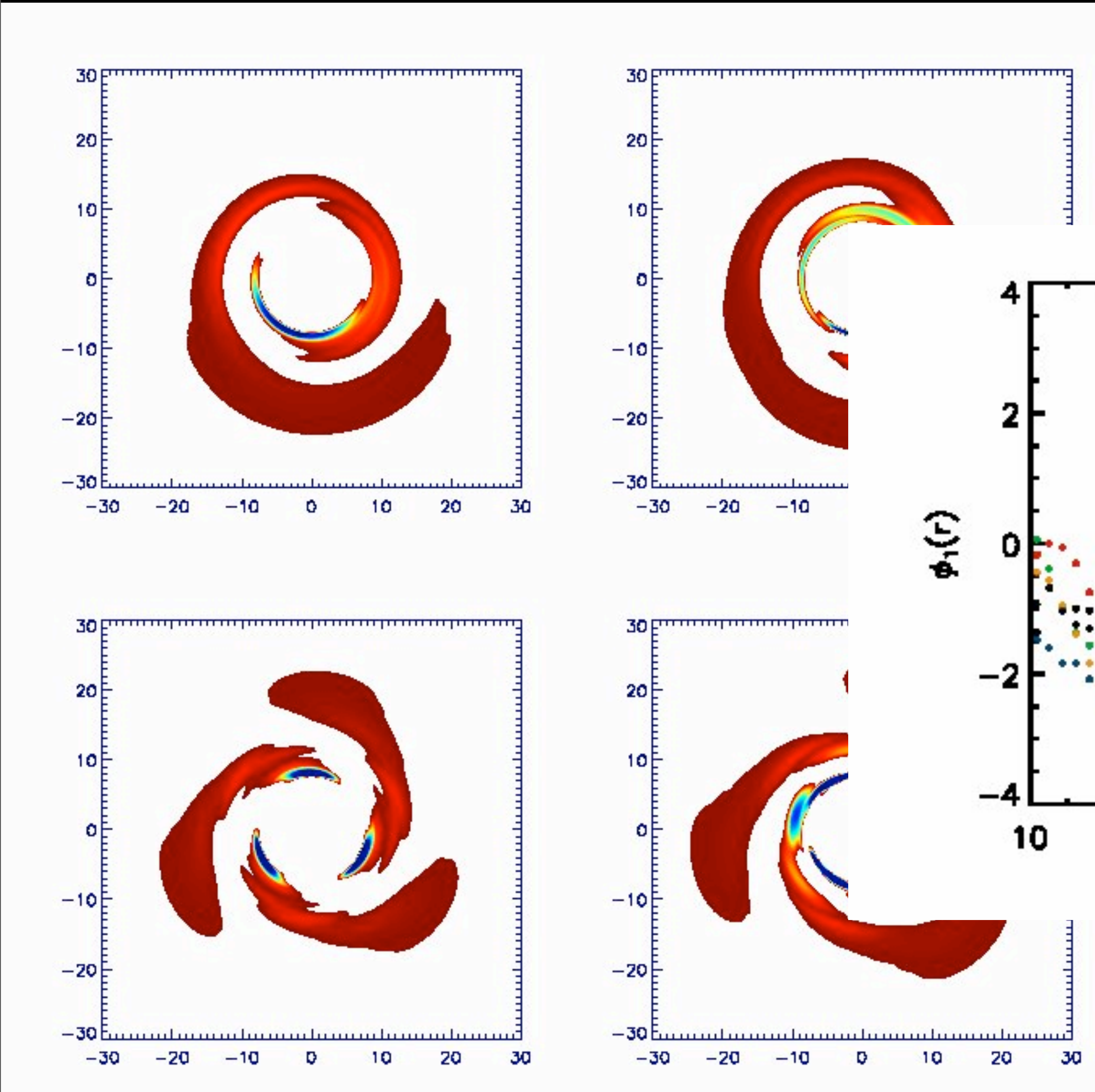


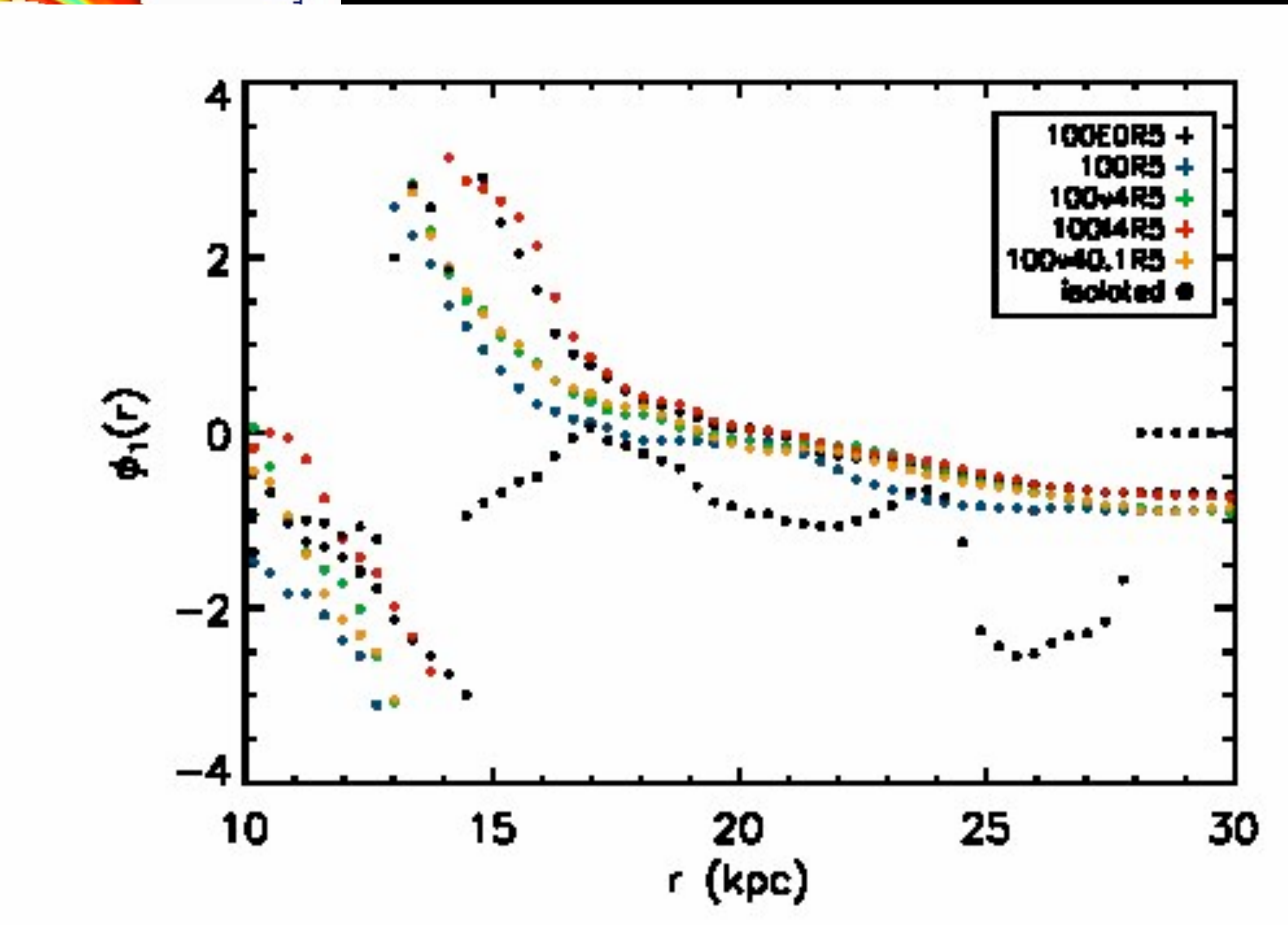


*Tidal interactions: flat phase variation*

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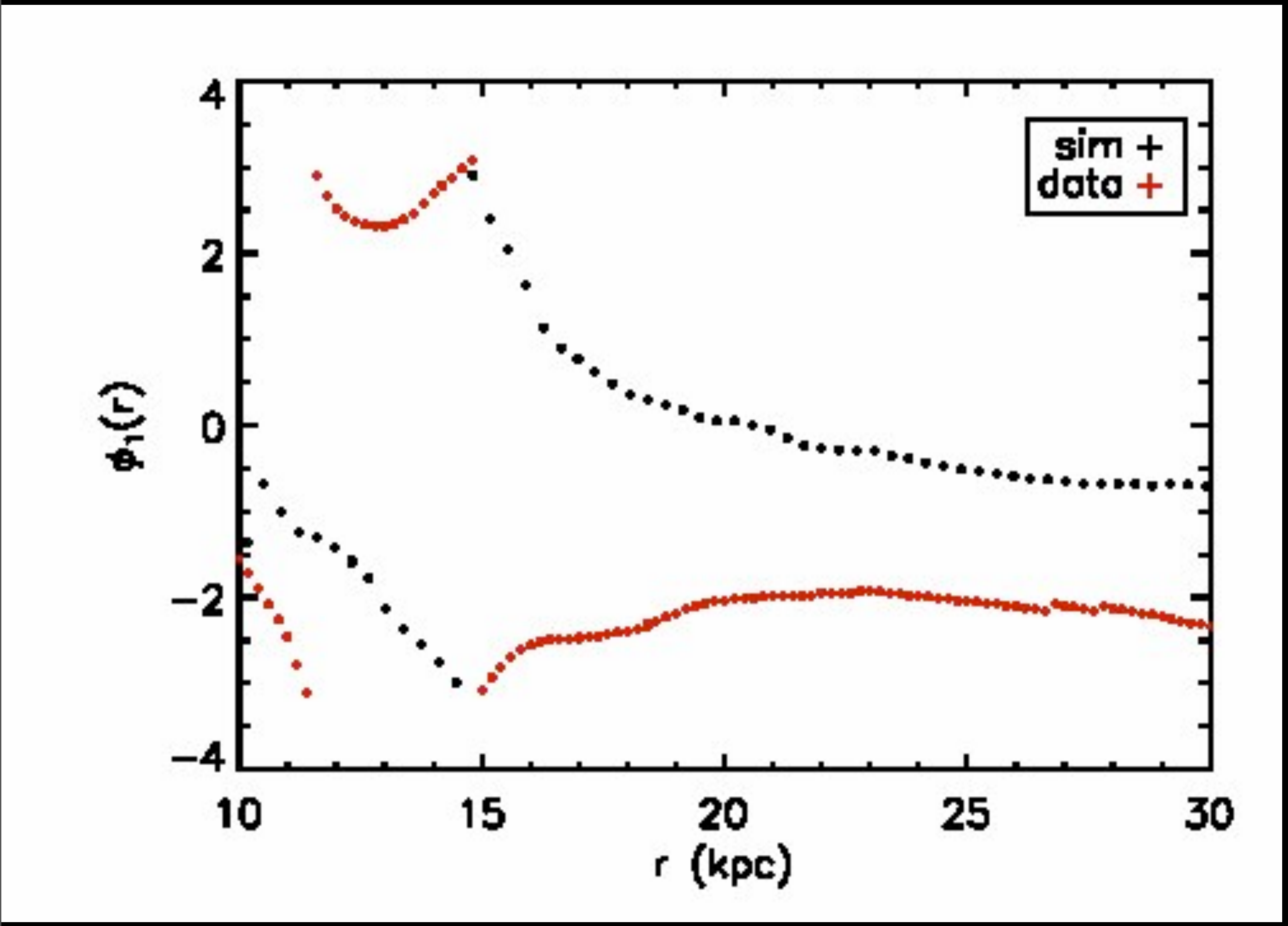
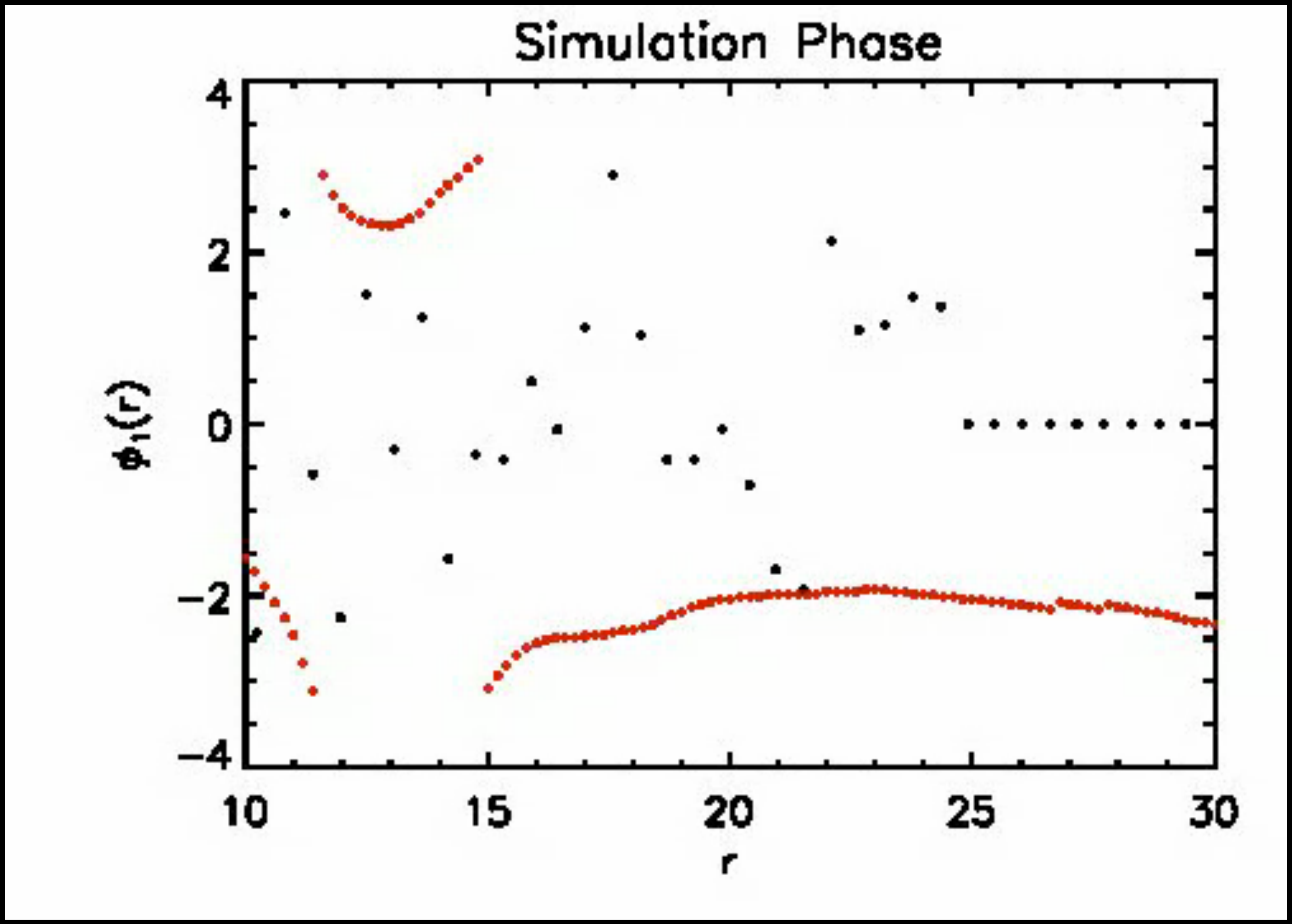
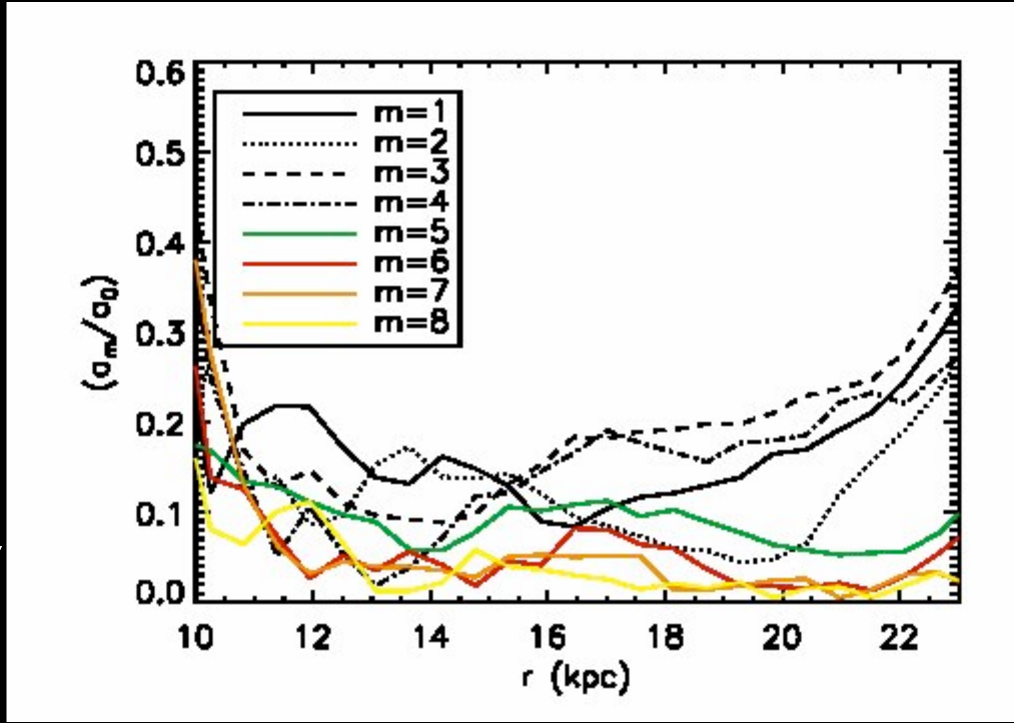


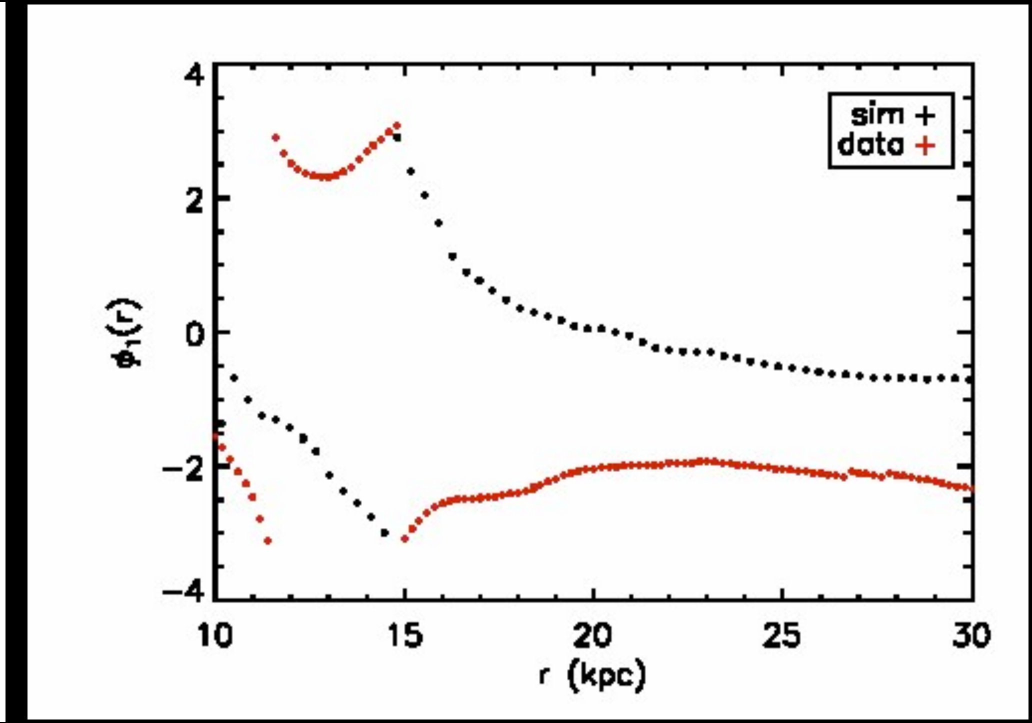



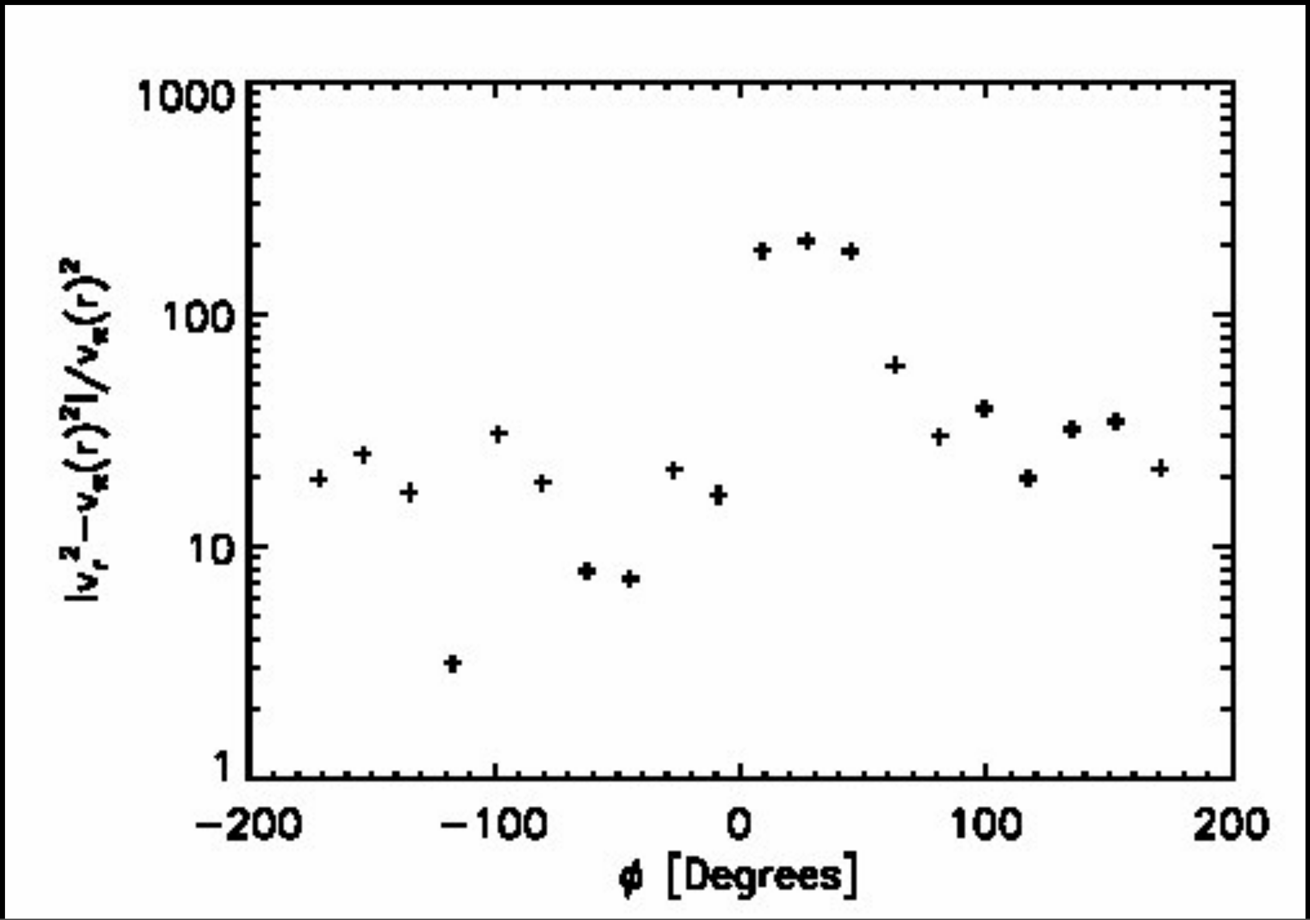

- Note flat variation of phase at best-fit time in outskirts; inner regions: tightly wrapped spiral -- sharp gradient in phase

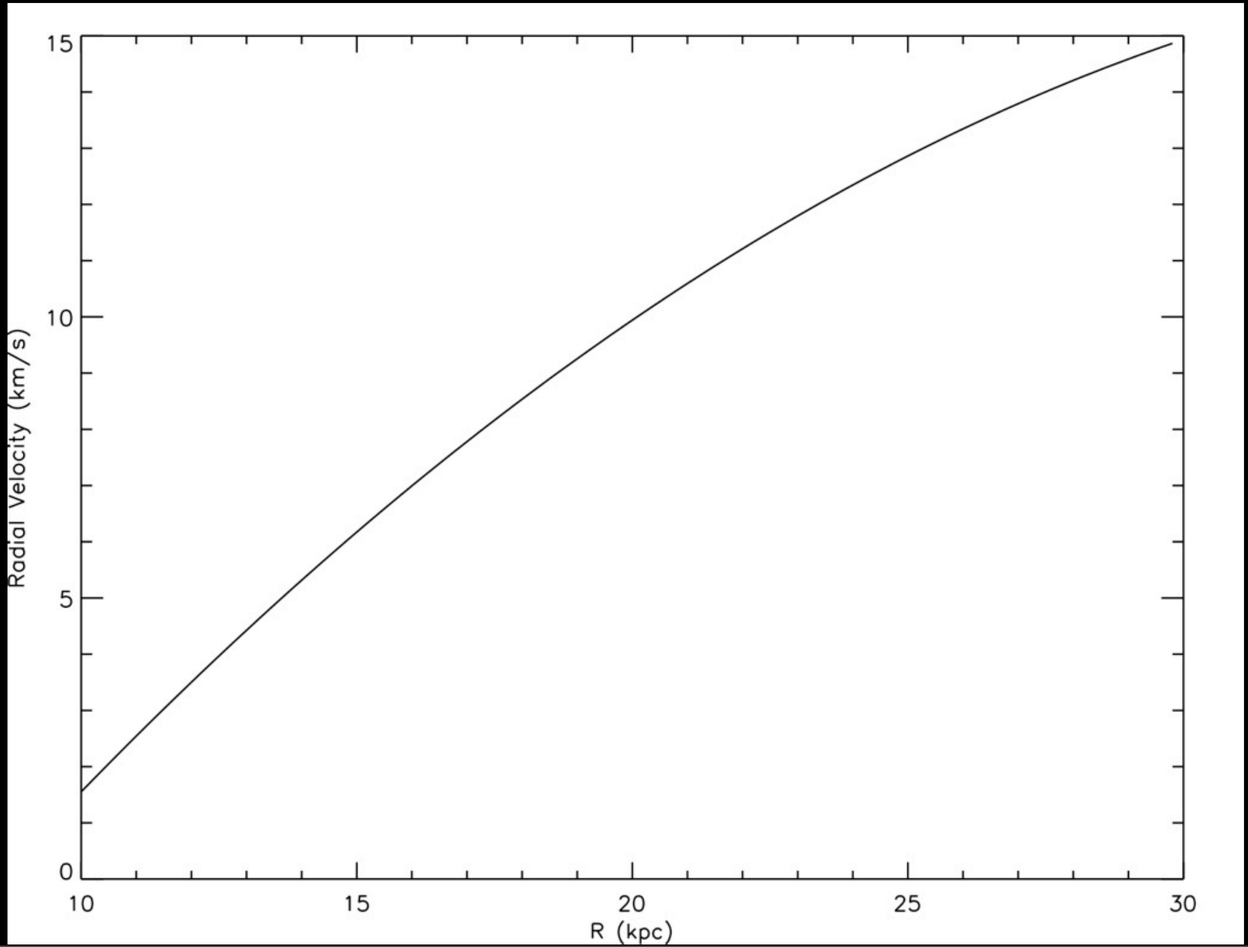
# 3 Independent Constraints

- Fourier Amplitudes
- Phase
- Asymmetry in radial velocity



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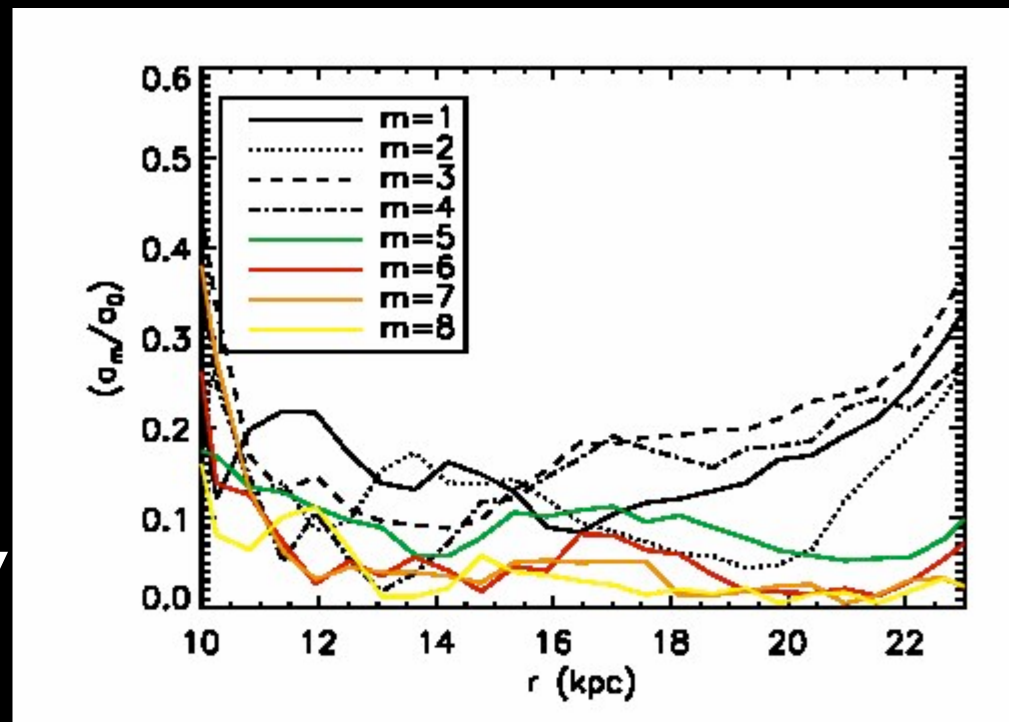
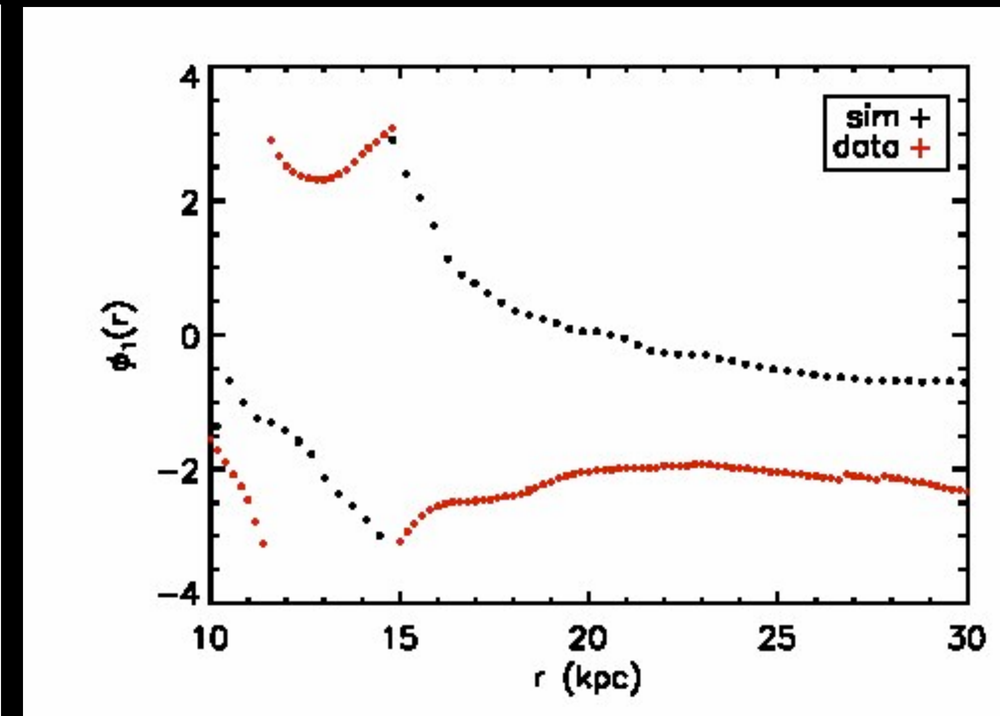
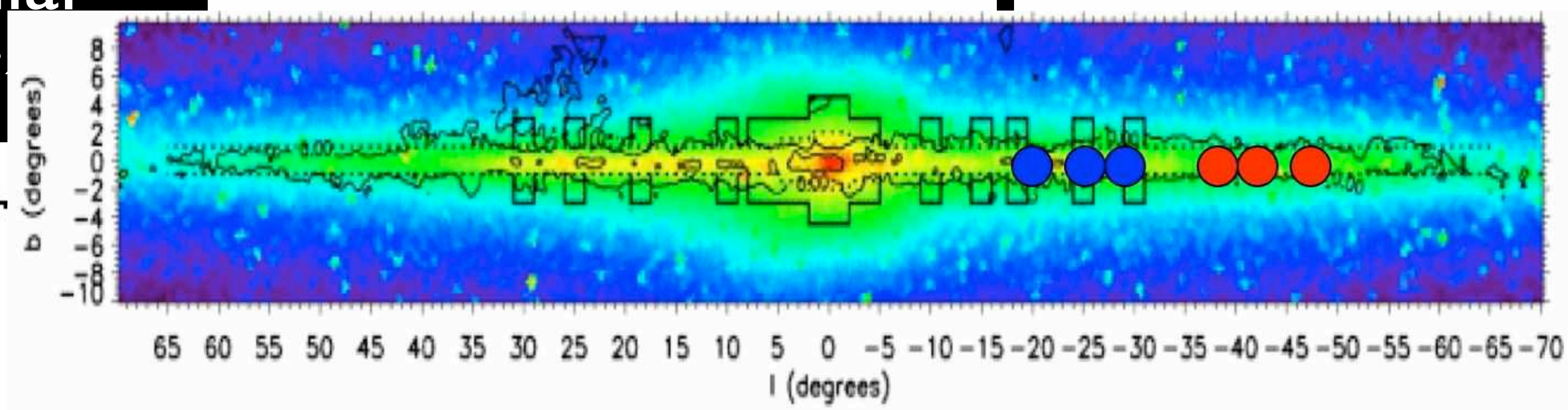
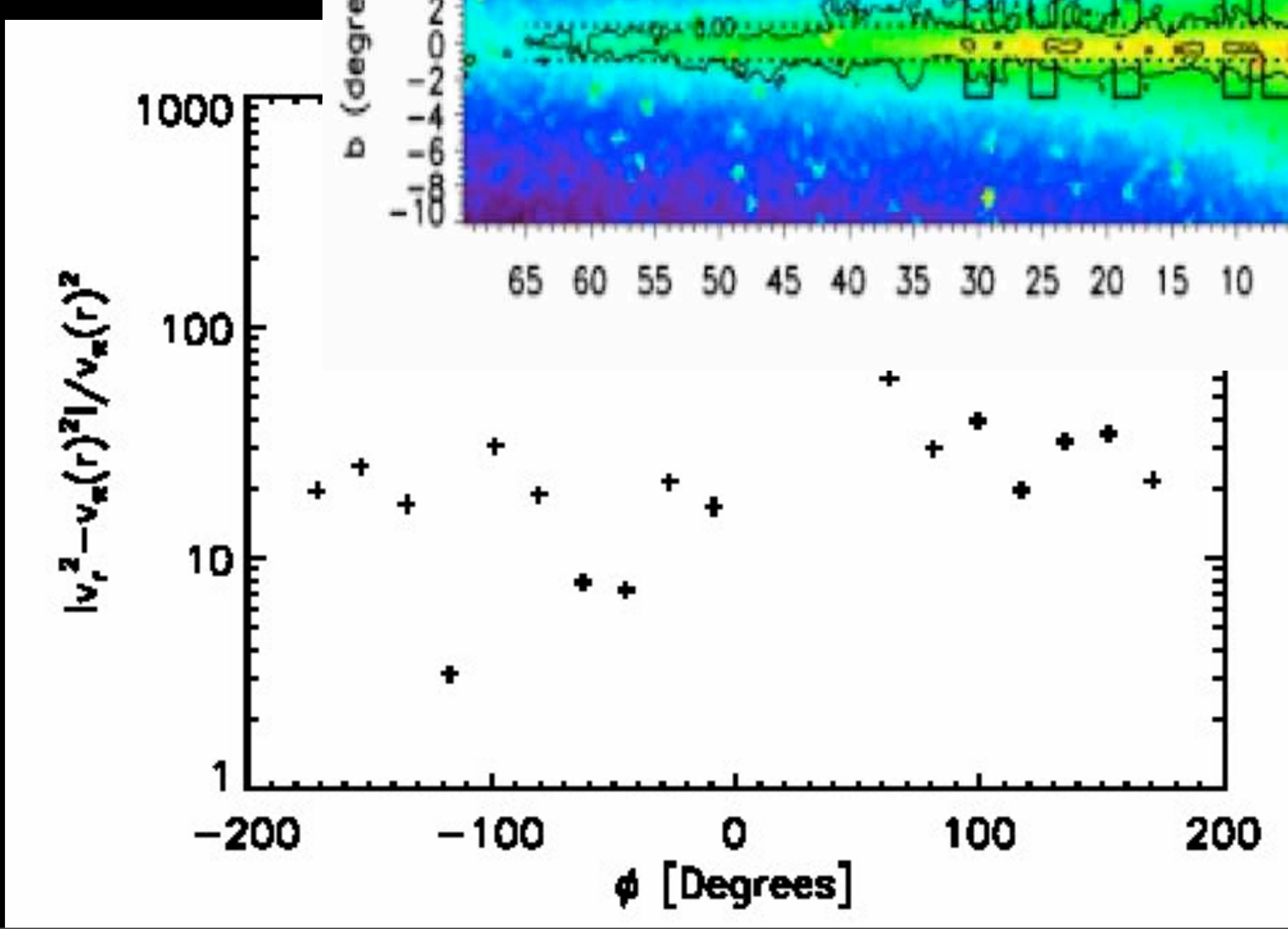
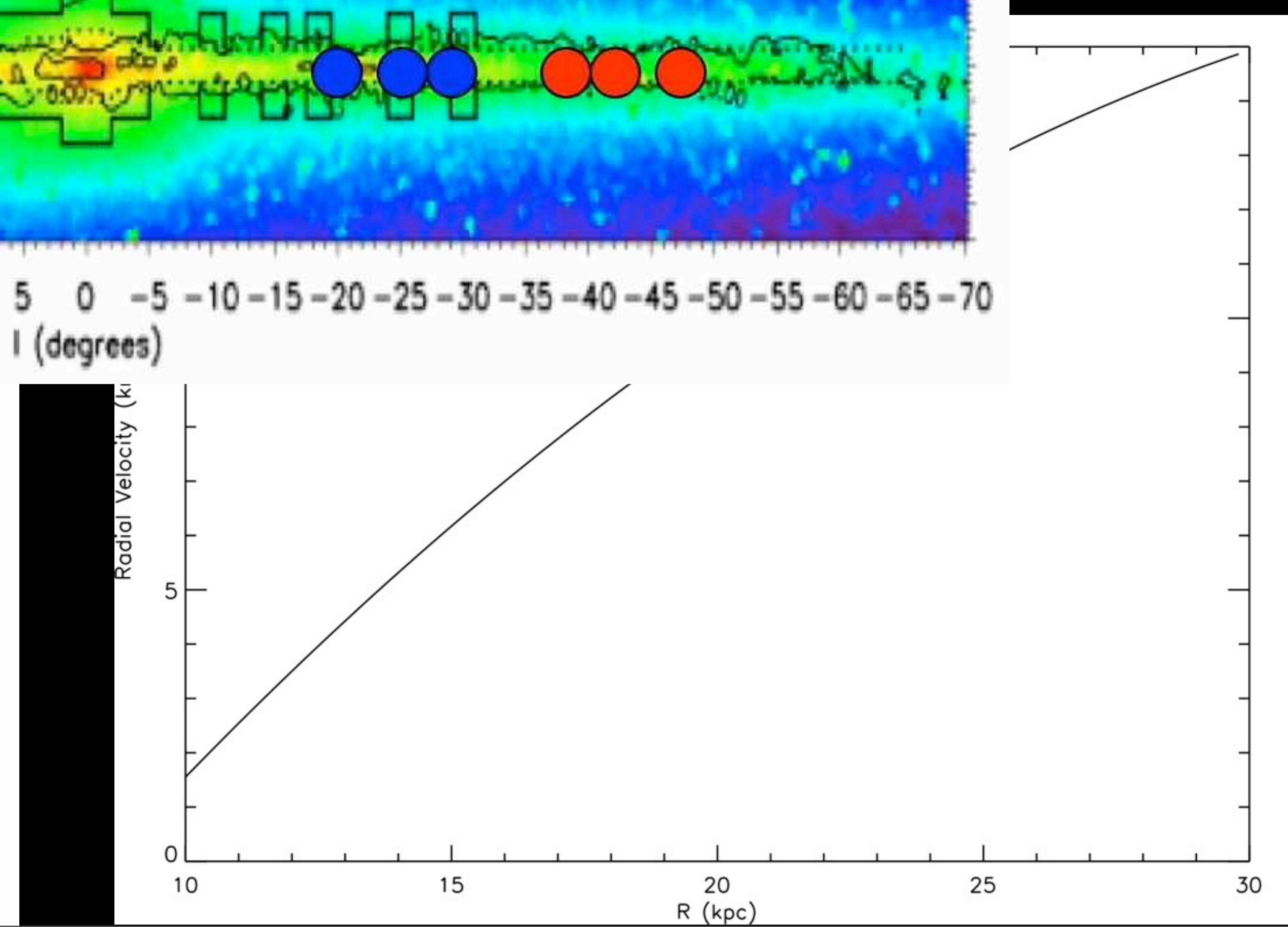


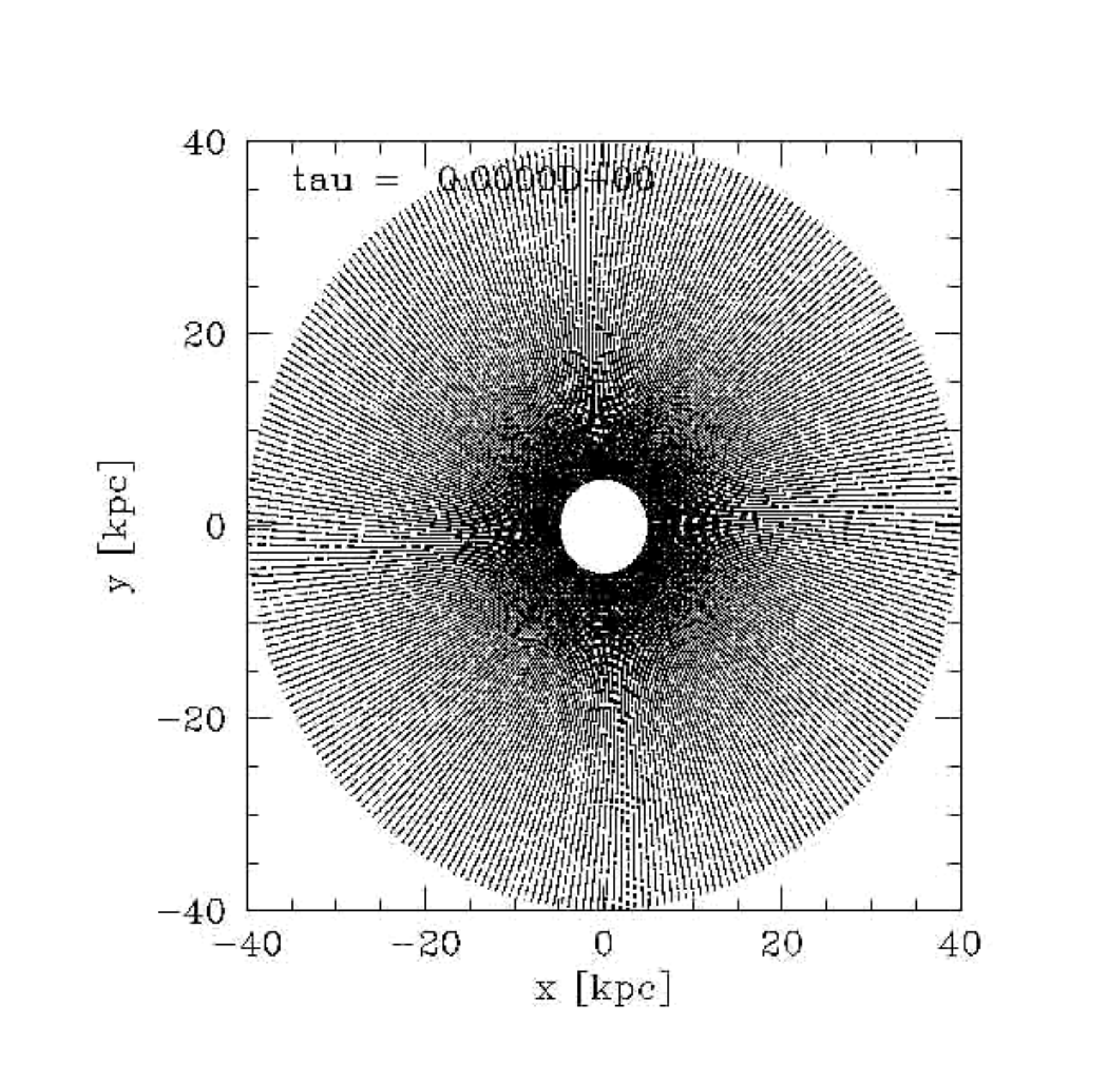



# Simplified Approach I

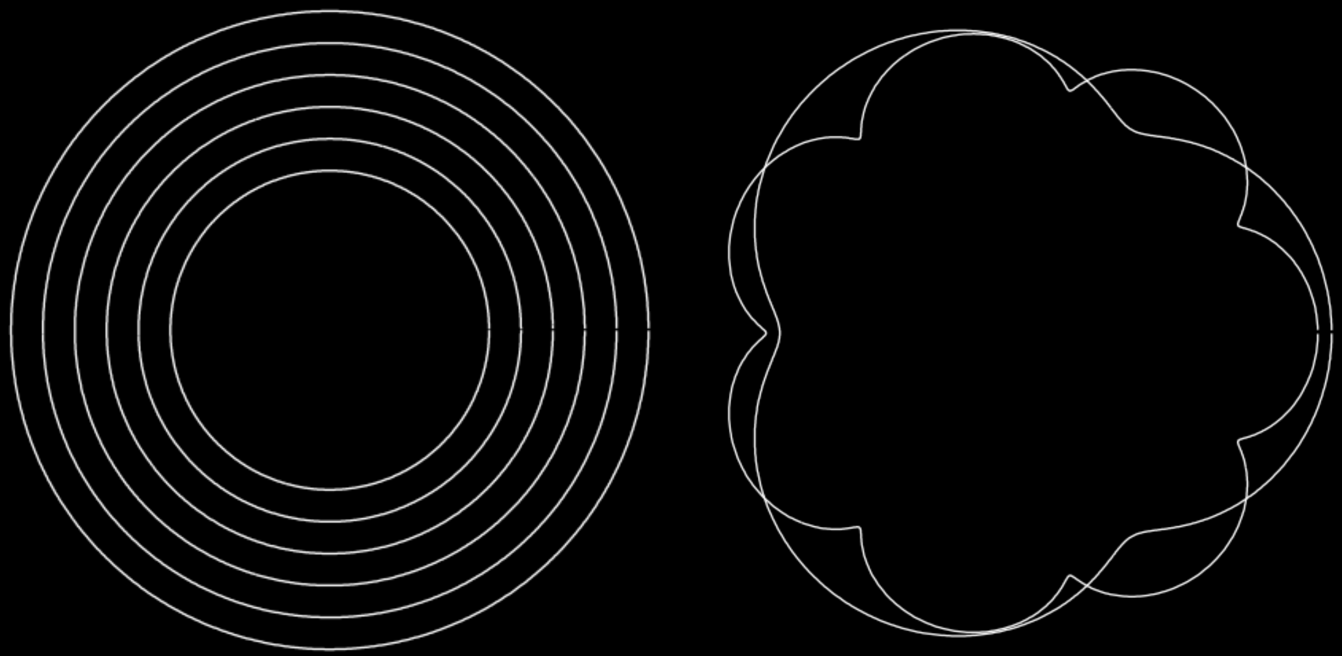
- With **Phil Chang**: strategy is to attack with a simplified approach that is computationally simpler.

- Describe a disk as bunch of test particles
- Consider the disturbance of these test particles by a passing subhalo.



# Simplified Approach II

- Describe a disk by N rings each with M modes



$$\frac{\partial^2 \delta r}{\partial t^2} + \kappa^2 \frac{\delta r}{r} = \frac{2\Omega \delta J}{r} - \frac{\partial \delta \Phi}{\partial r} \exp\left(im\Omega(r)t\right)$$

- The equations of each ring can be described as a series of harmonic oscillators of equal freqency

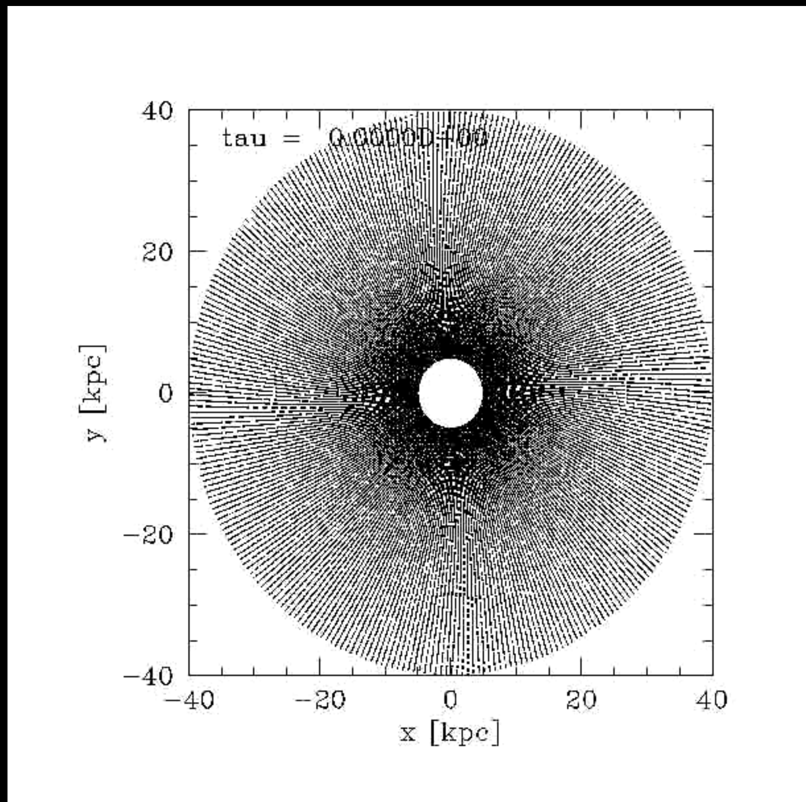
$$\ddot{x} + \omega^2 x = \omega^2 x_0 - f(t)$$

- A test particle's position can be determined by

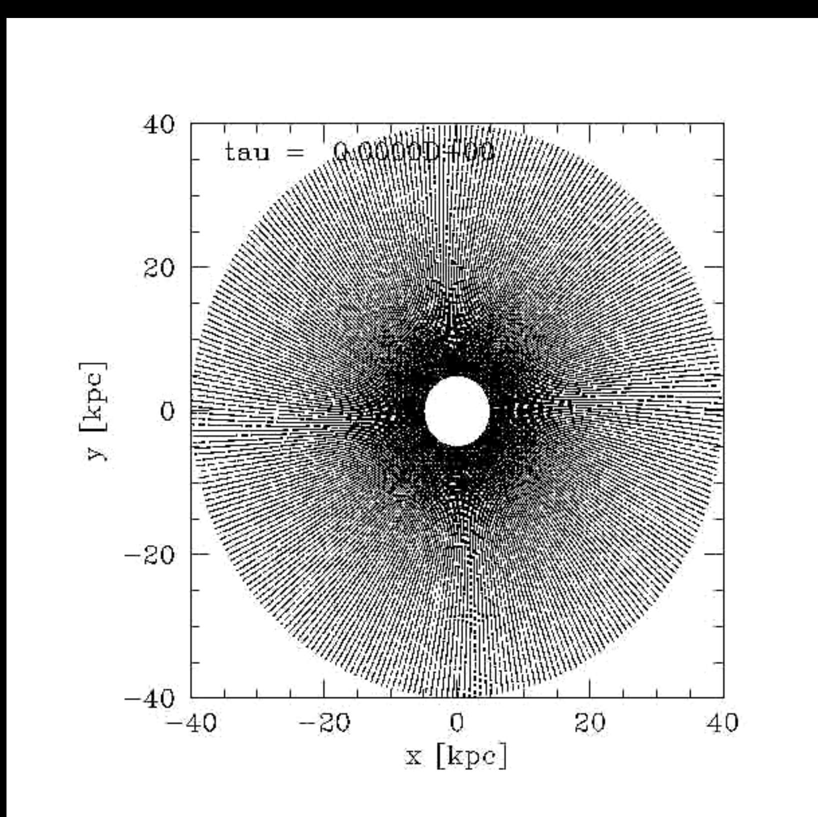
$$r(t) = r_0(t) + \sum_m \delta r_m(t) \exp(-im\Omega t)$$

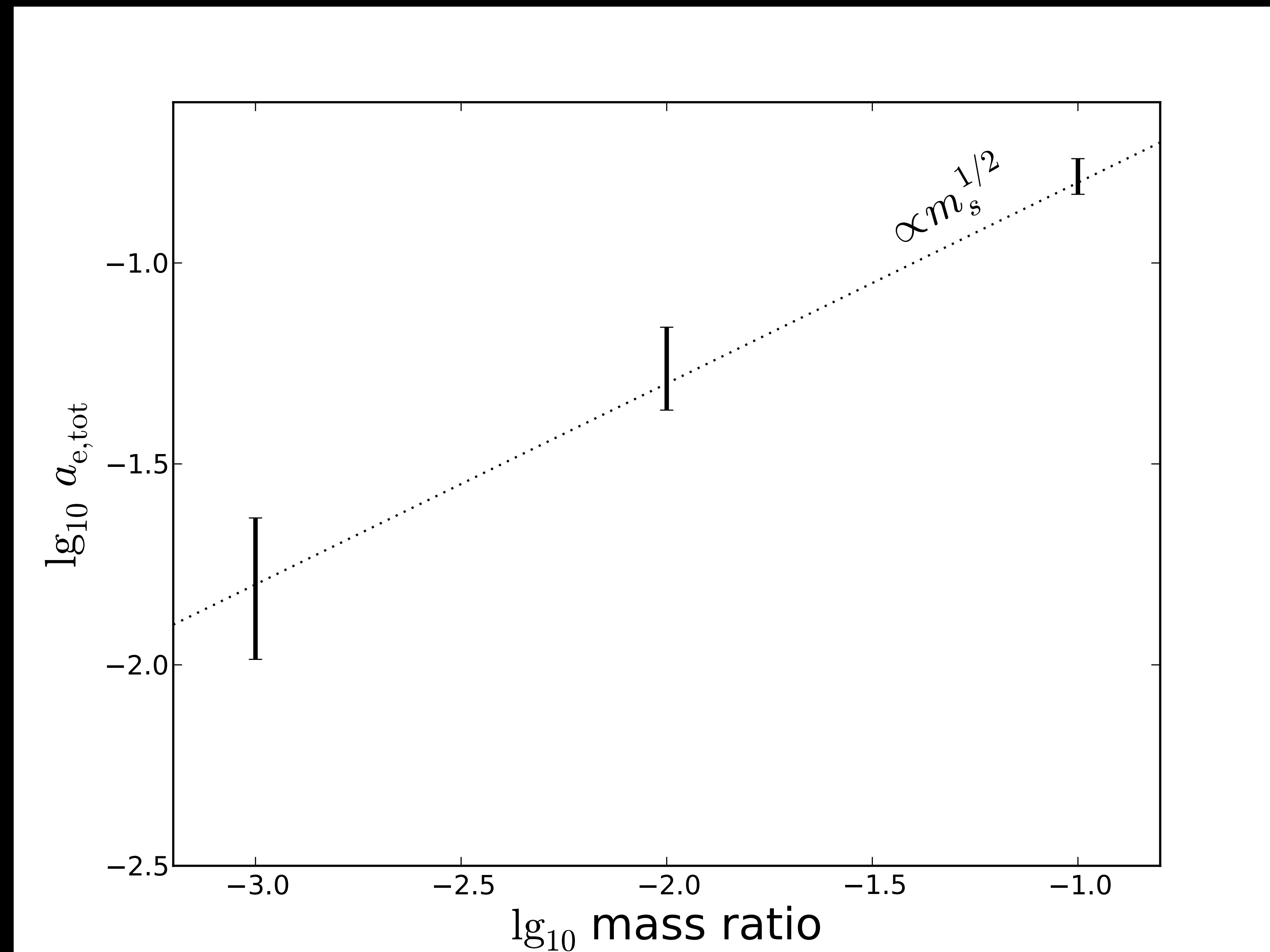
# Simplified Approach II

## Test Particles




## Mode Reconstruction




CC2010, in prep (fitting relations for satellite mass from Fourier amplitudes)

# Disturbances in HI disks in Local Spirals: Proof of Principle

# What about galaxies with known optical companions?

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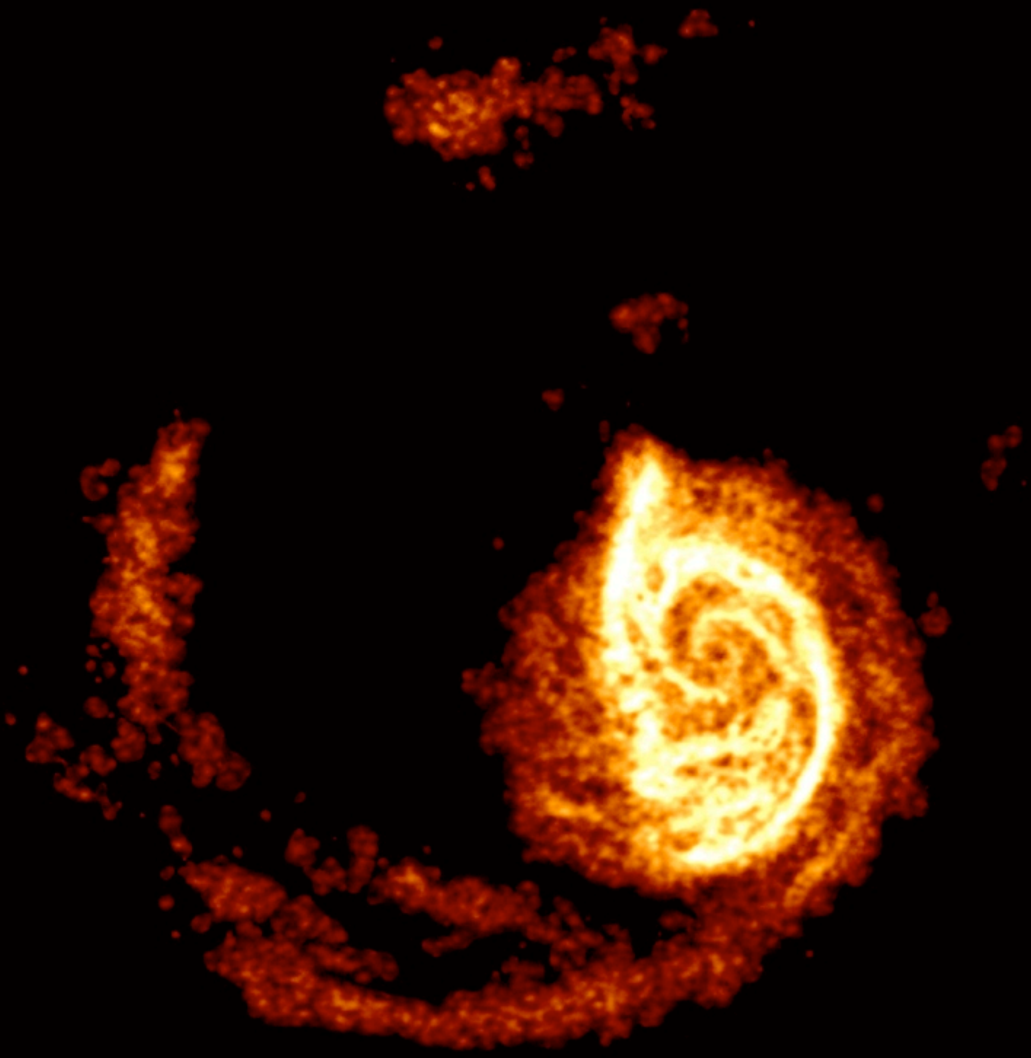

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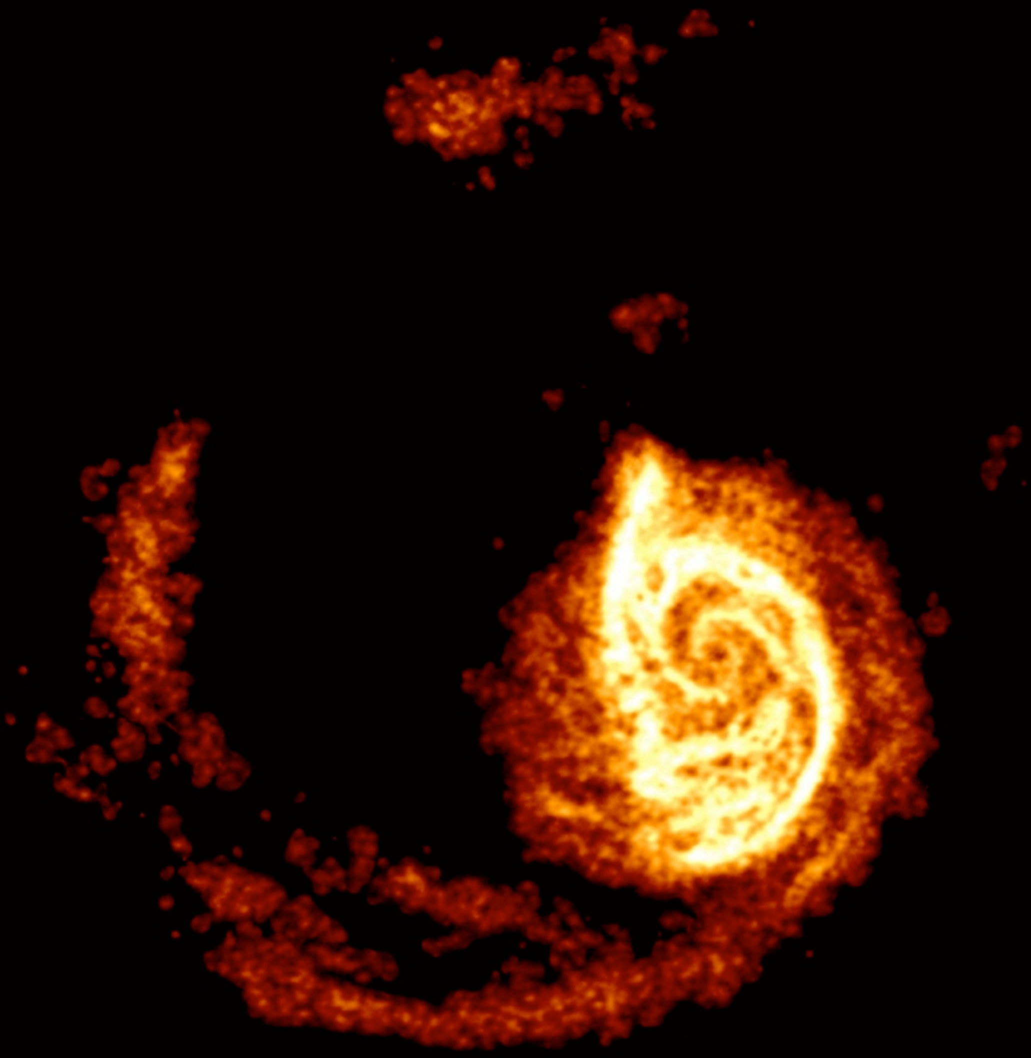

Bigiel: large VLA map of M51

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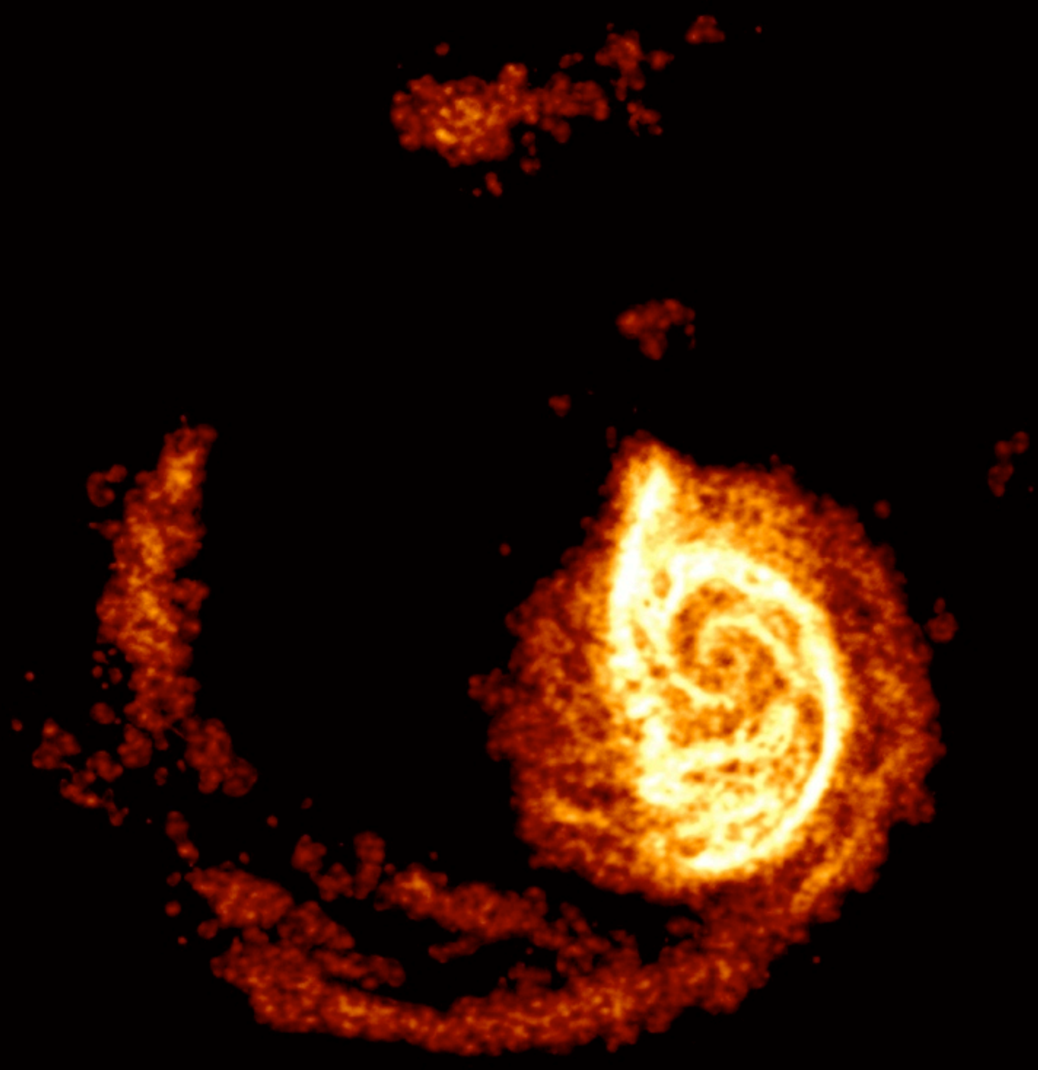

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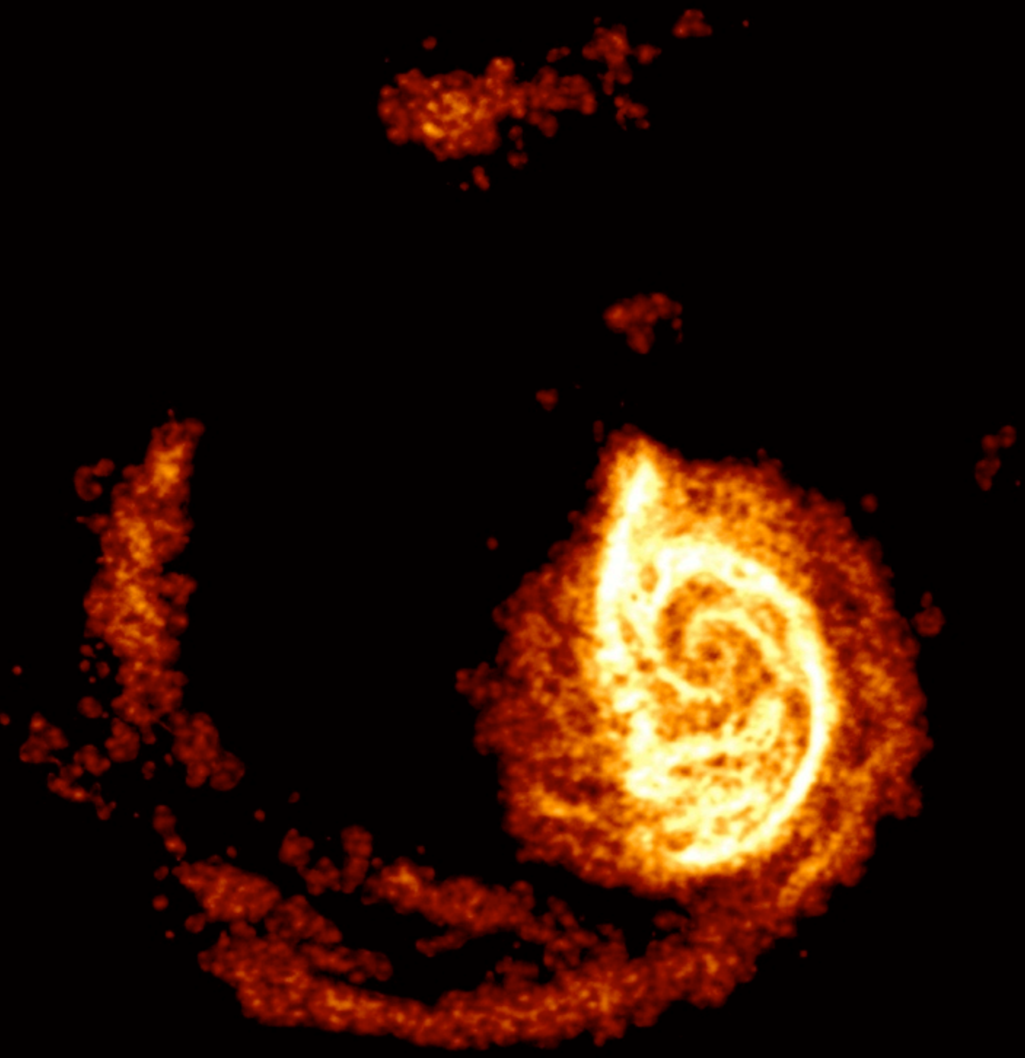
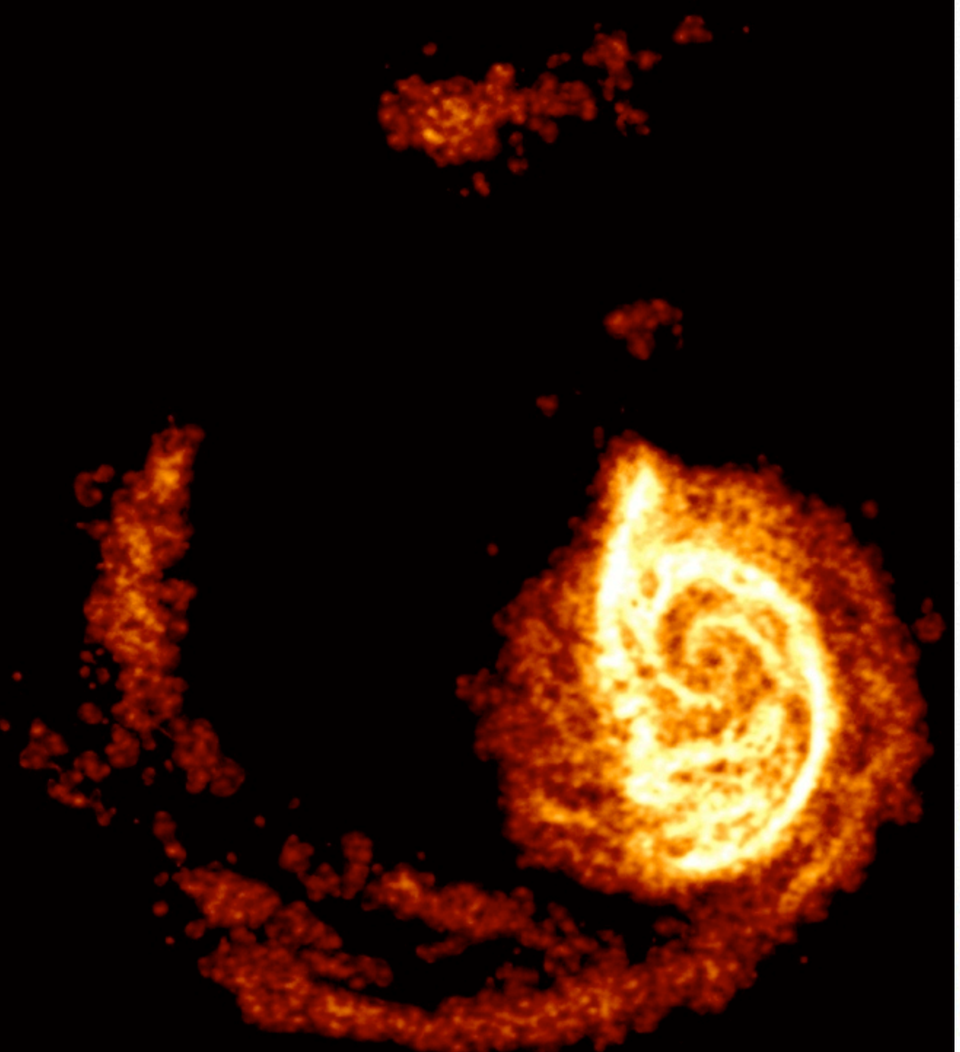
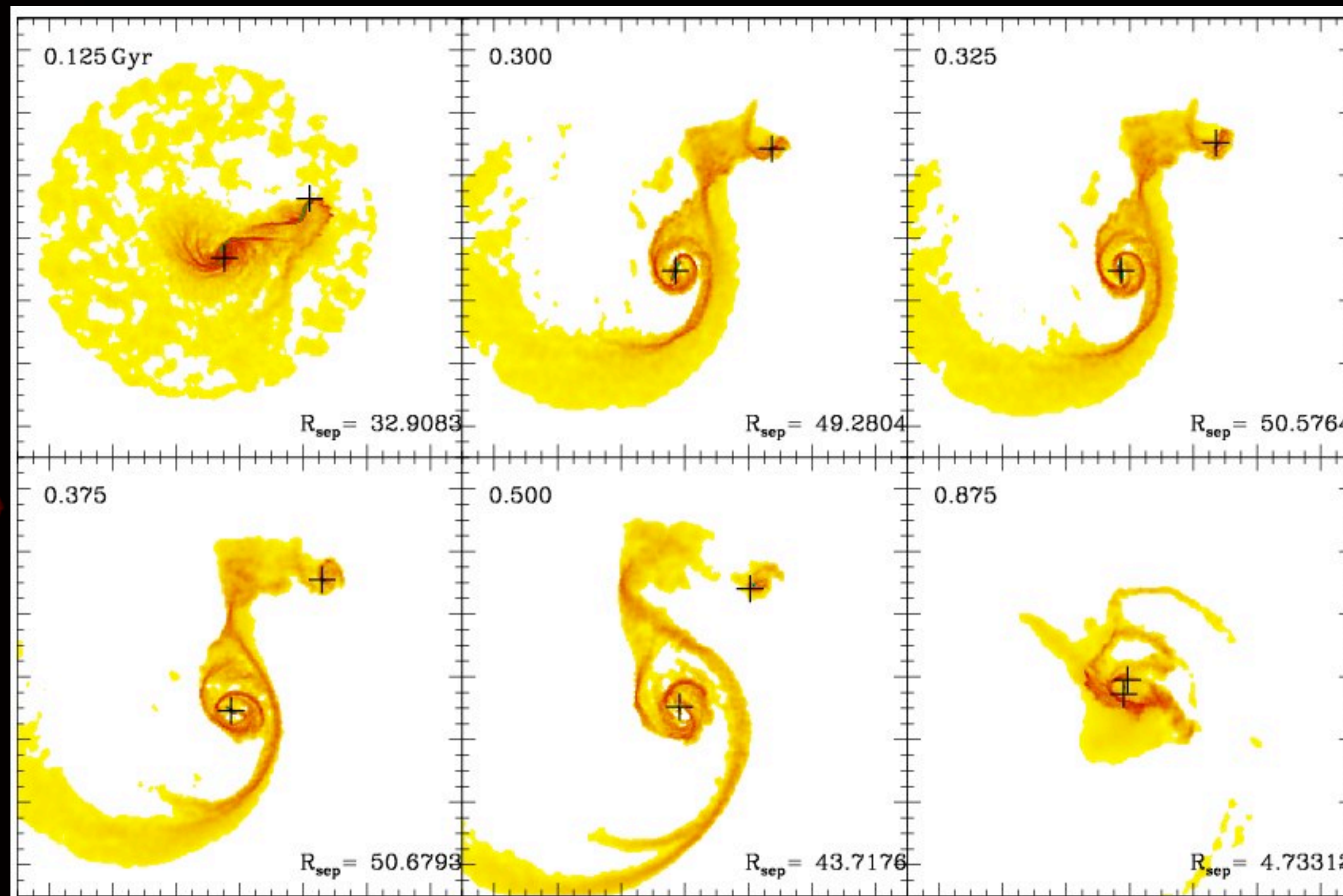


Bigiel: large VLA map of M51

- Chakrabarti et al. (with Frank Bigiel, Phil Chang, Leo Blitz)

# What about galaxies with known optical companions?

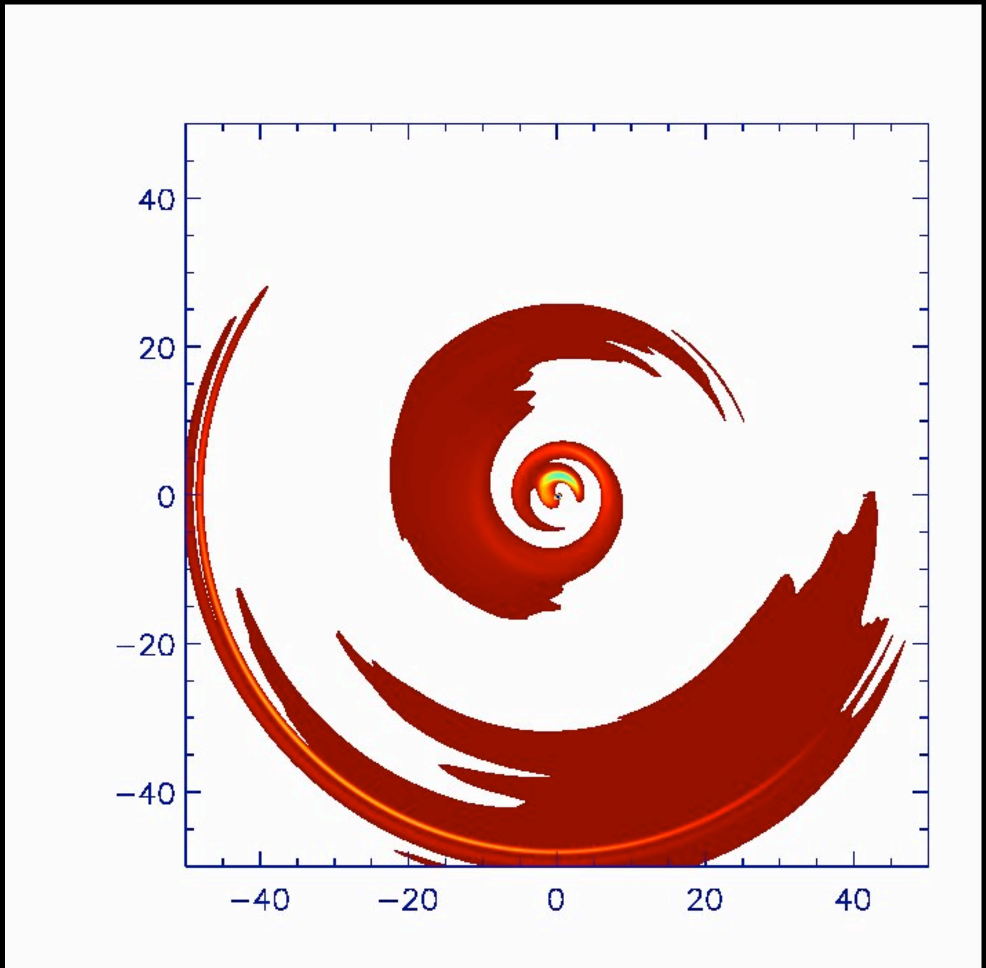


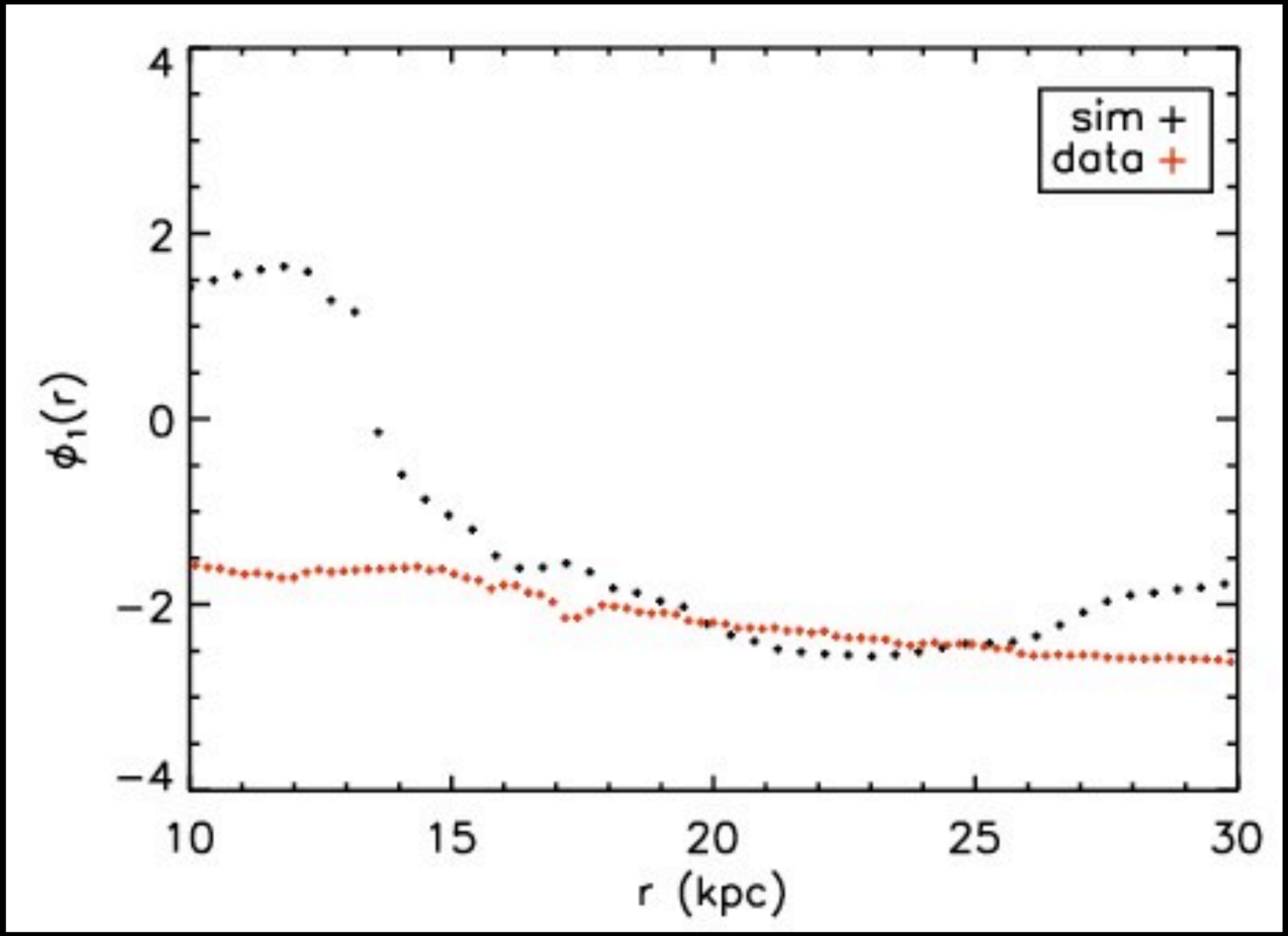


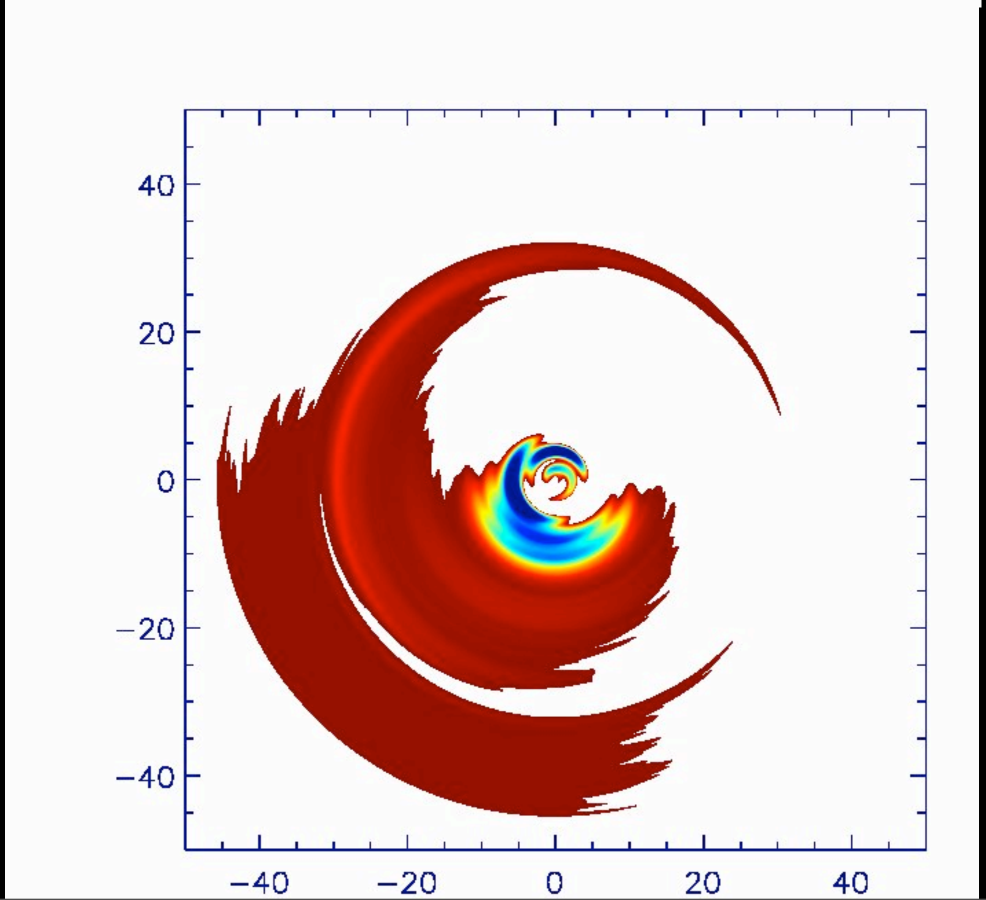

Bigiel: large VLA map of M51

- Chakrabarti et al. (with Frank Bigiel,Phil Chang,Leo Blitz)

# Galaxies with known optical companions

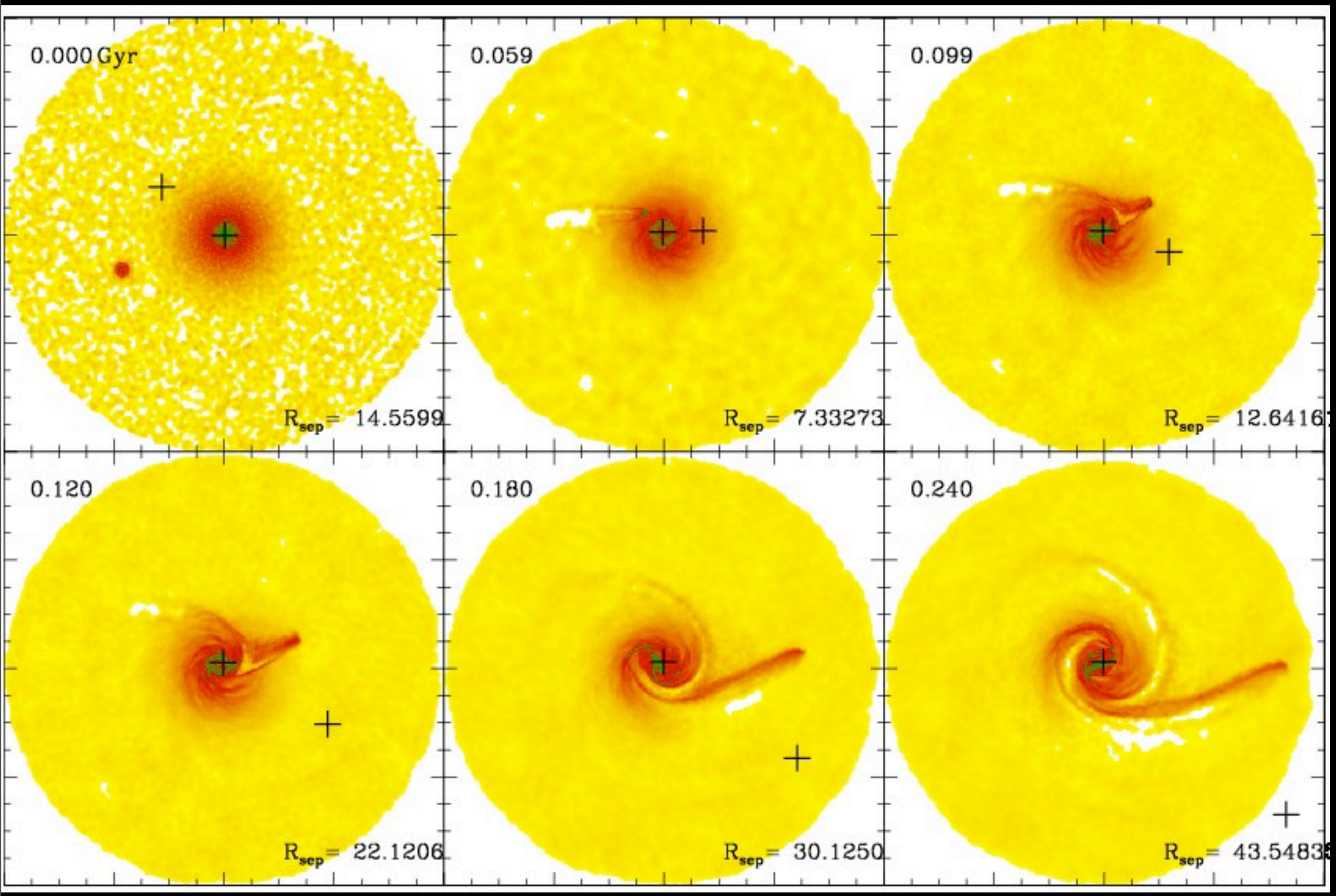


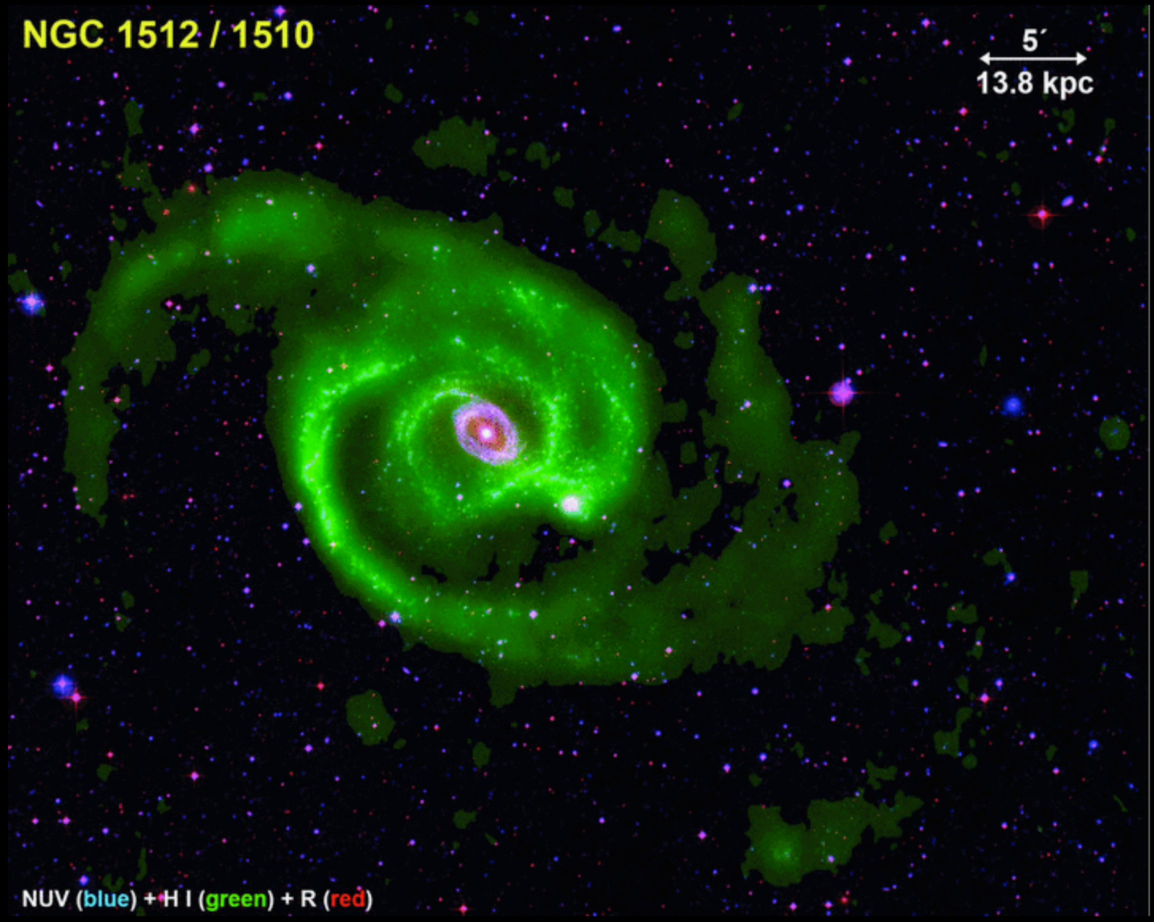



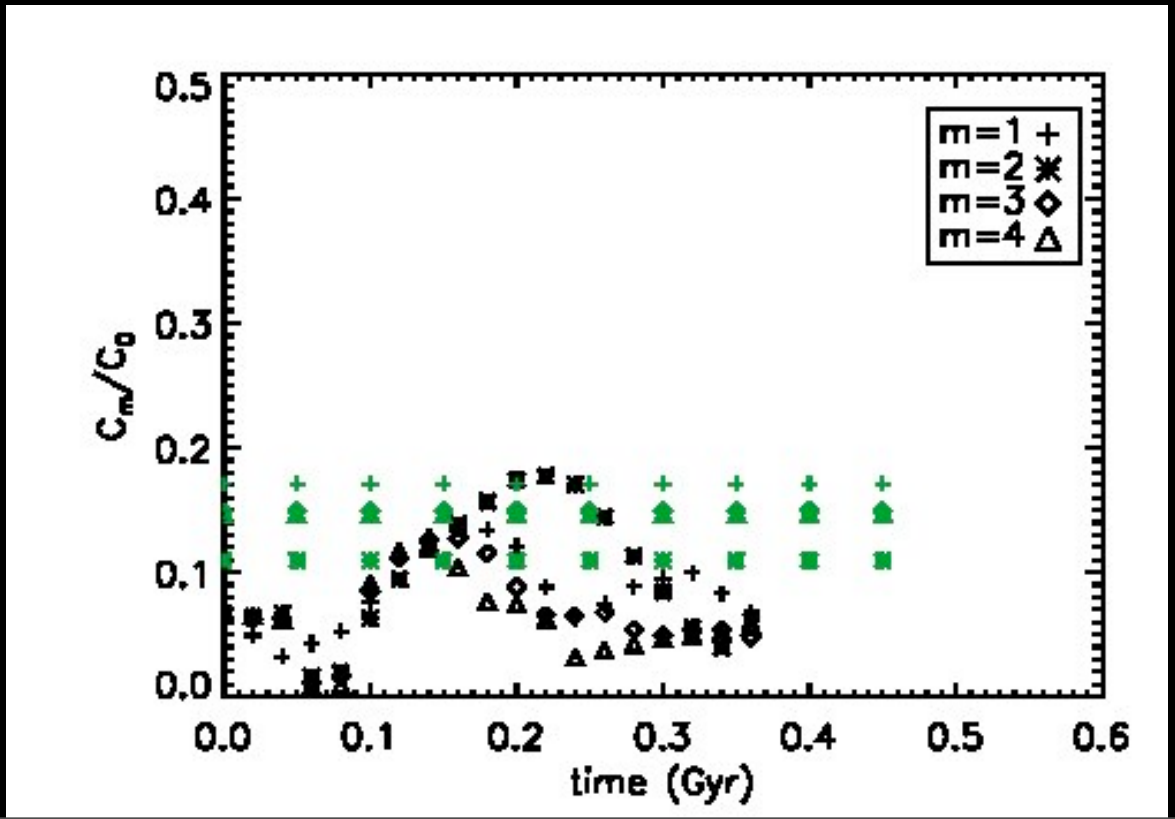

- Relative offset of phase → azimuth. Note flatness of phase
- Fourier amplitude: mass of satellite & R

# Galaxies with known optical companions contd.




- Global Fourier amplitudes



# Summary: Tidal Analysis

- 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. Does not require knowledge of optical light, analogous to gravitational lensing.

- DM -- what is it? No clear answer. We don't completely understand CDM sub-structure on sub-galactic scales. DM does respond to gravity

- Cold gas is one of the best tracers we have of the gravitational pull that dark subhalos exert on galactic disks.