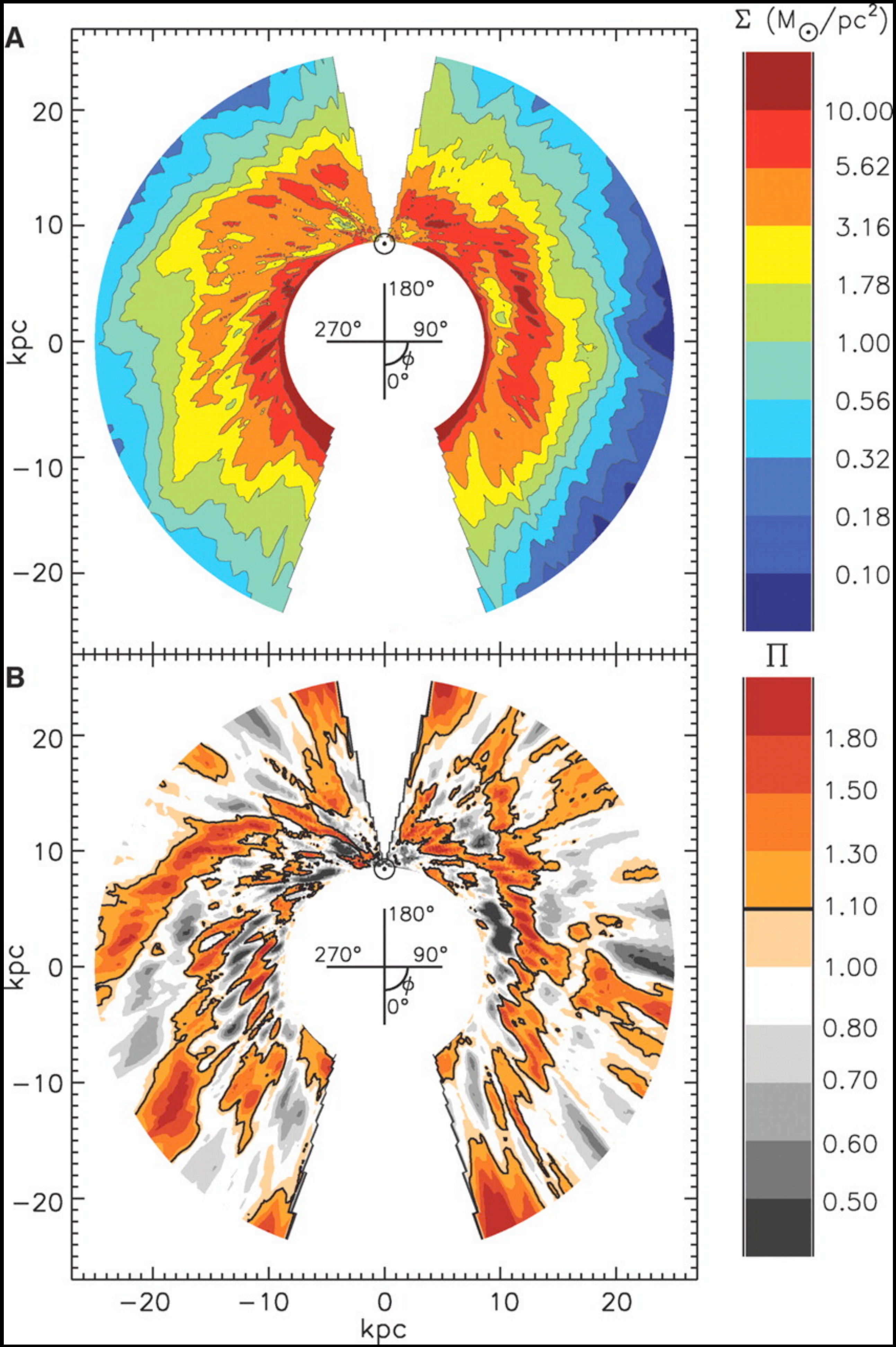
Tidal Imprints of a Dark Sub-Halo on the Outskirts of the Milky Way

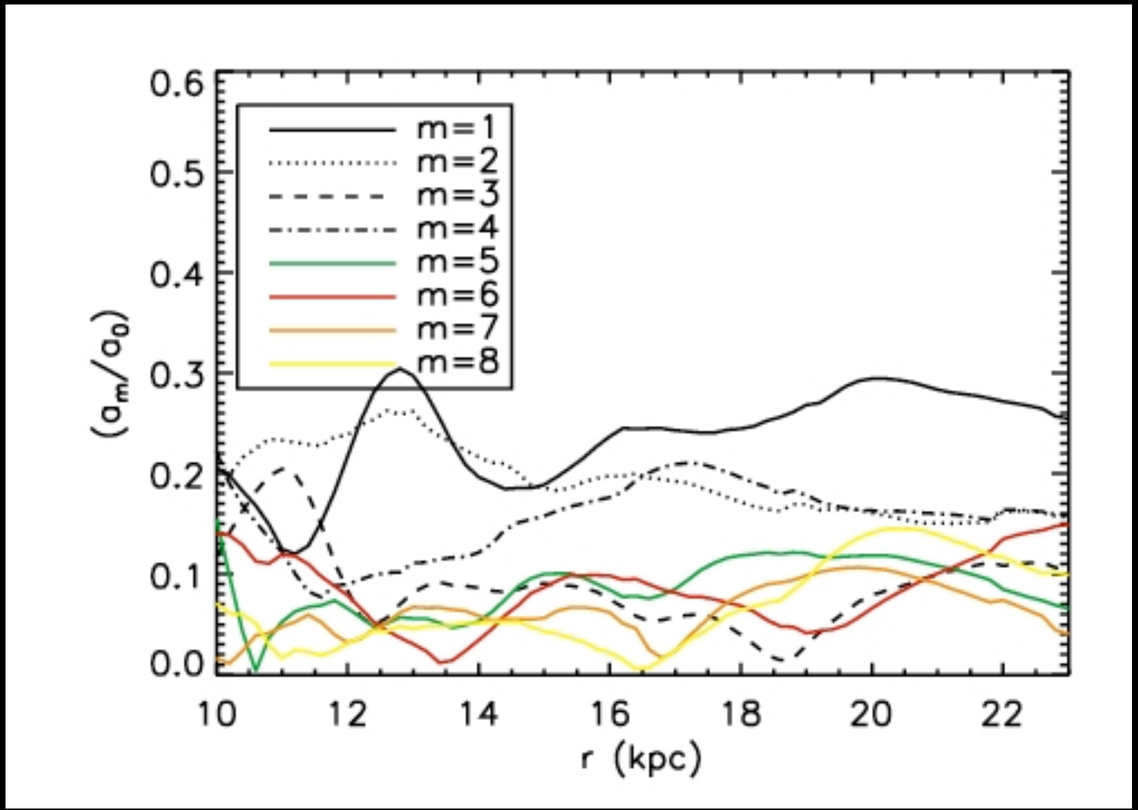
Sukanya Chakrabarti & Leo Blitz
UC Berkeley



HI Map of Milky Way

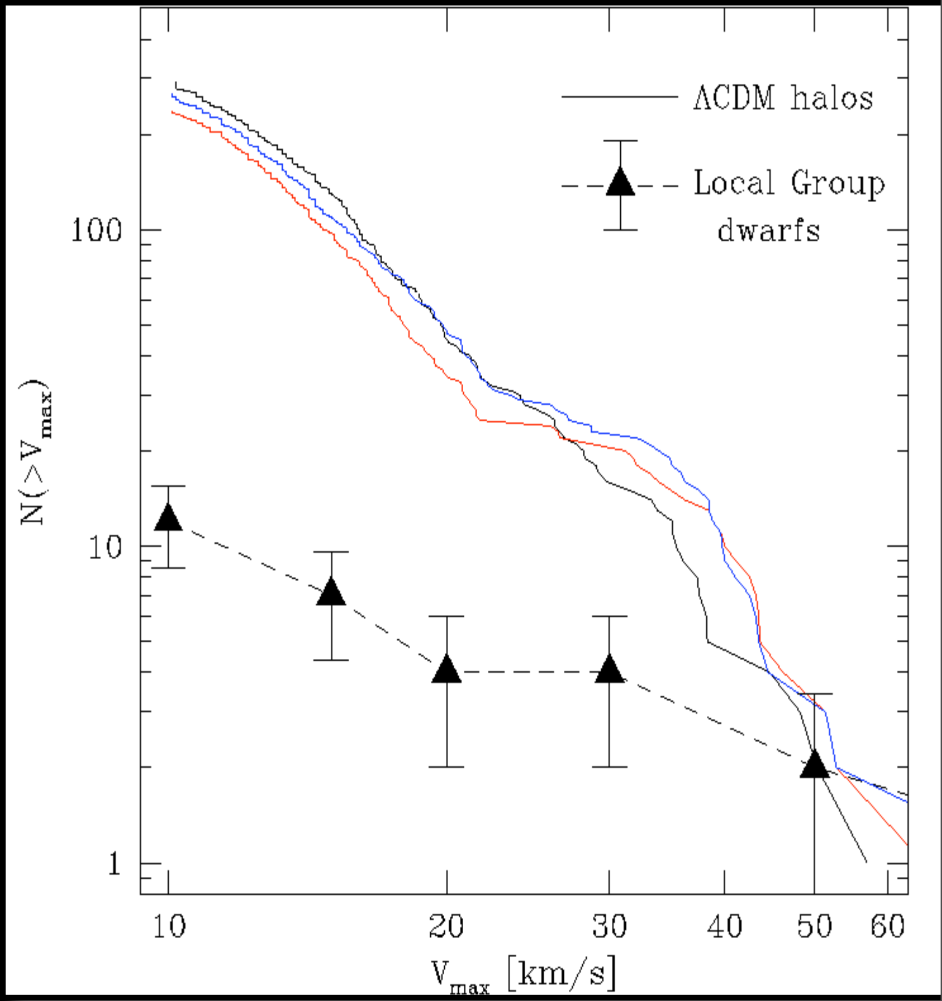
HI maps: Levine, Blitz & Heiles 2006. What caused these structures well outside the solar circle?

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

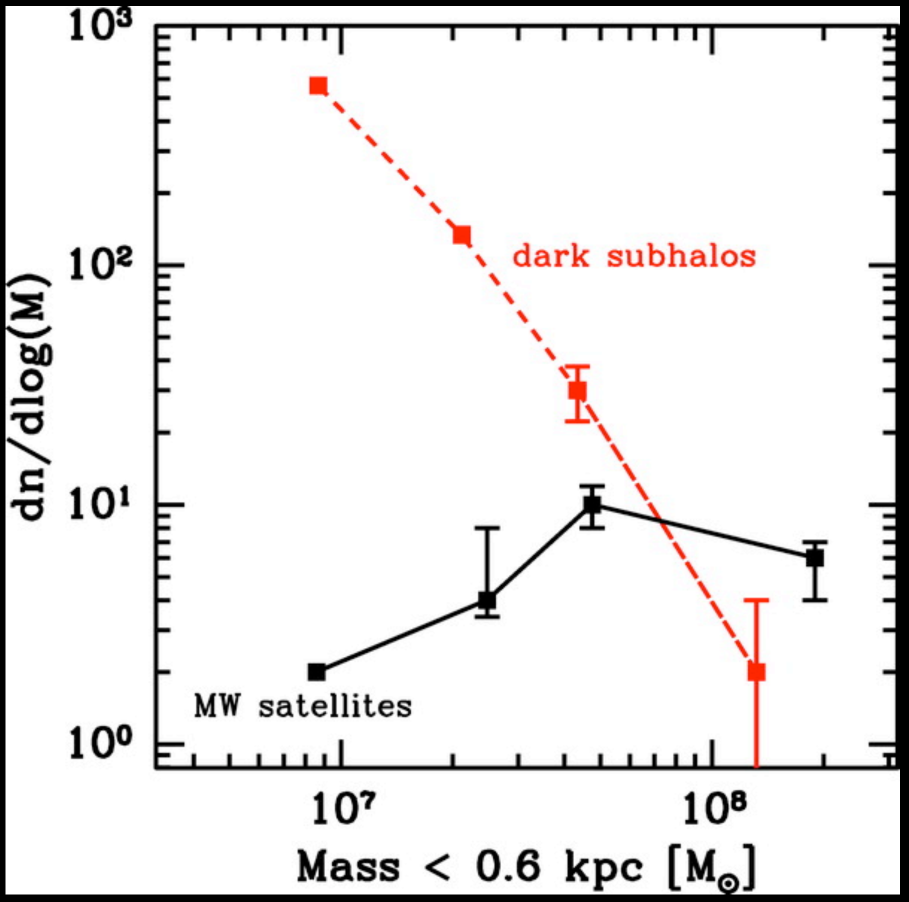


Motivation for New MW Analysis

- 60 - 70 dwarfs down to magnitude limit observed
- Via Lactea predicts hundreds of halos with $M_{halo} > 10^7 M_{sun}$
- Where are the rest?
- Can one find dark galaxies by their interaction with gas disks?



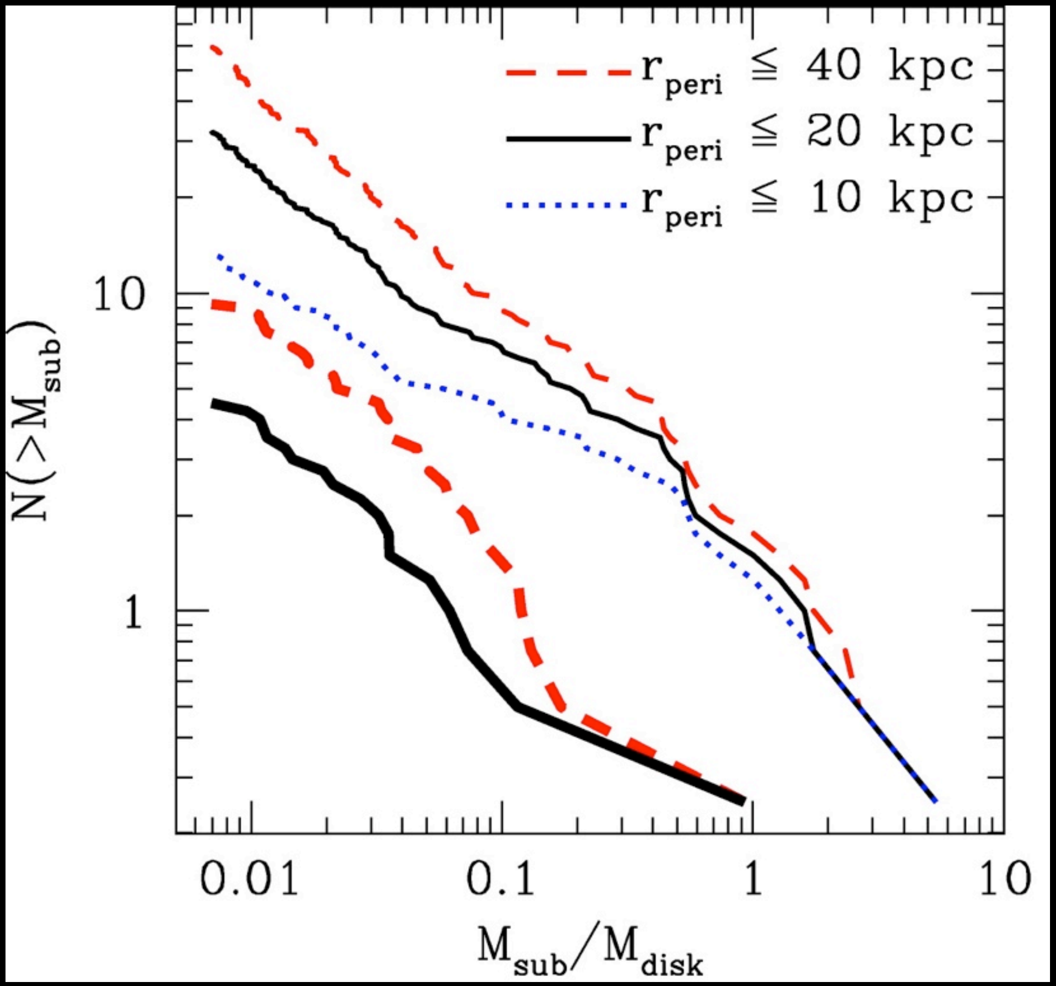
Klypin (2003)



Strigari et al. (2007)

Signatures of CDM Sub-structure on Collisionless Component

- $n(M) \propto M^{-\alpha}$, $\alpha \sim 1.8\text{-}1.9$, 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 effect of CDM sub-structure on stellar disks. Disk 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)
- 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

Simulations

High-Resolution SPH simulations of galaxy collisions with dark sub-halos performed with GADGET-2. Note long wavelength disturbances: morphological signature of tidal interactions

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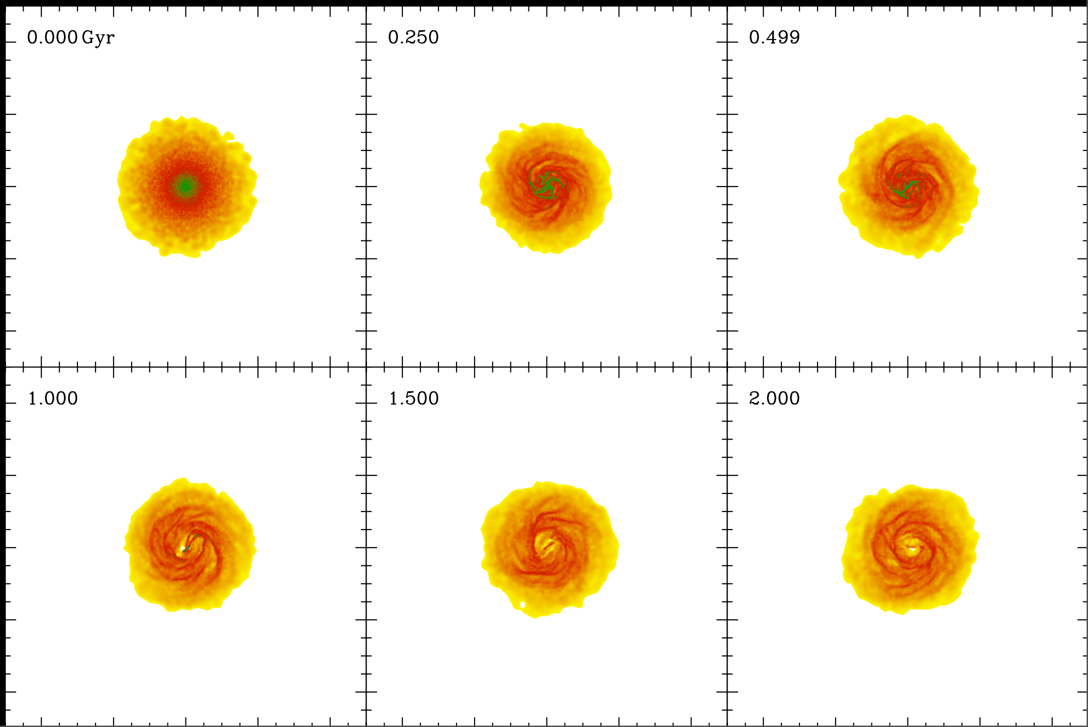
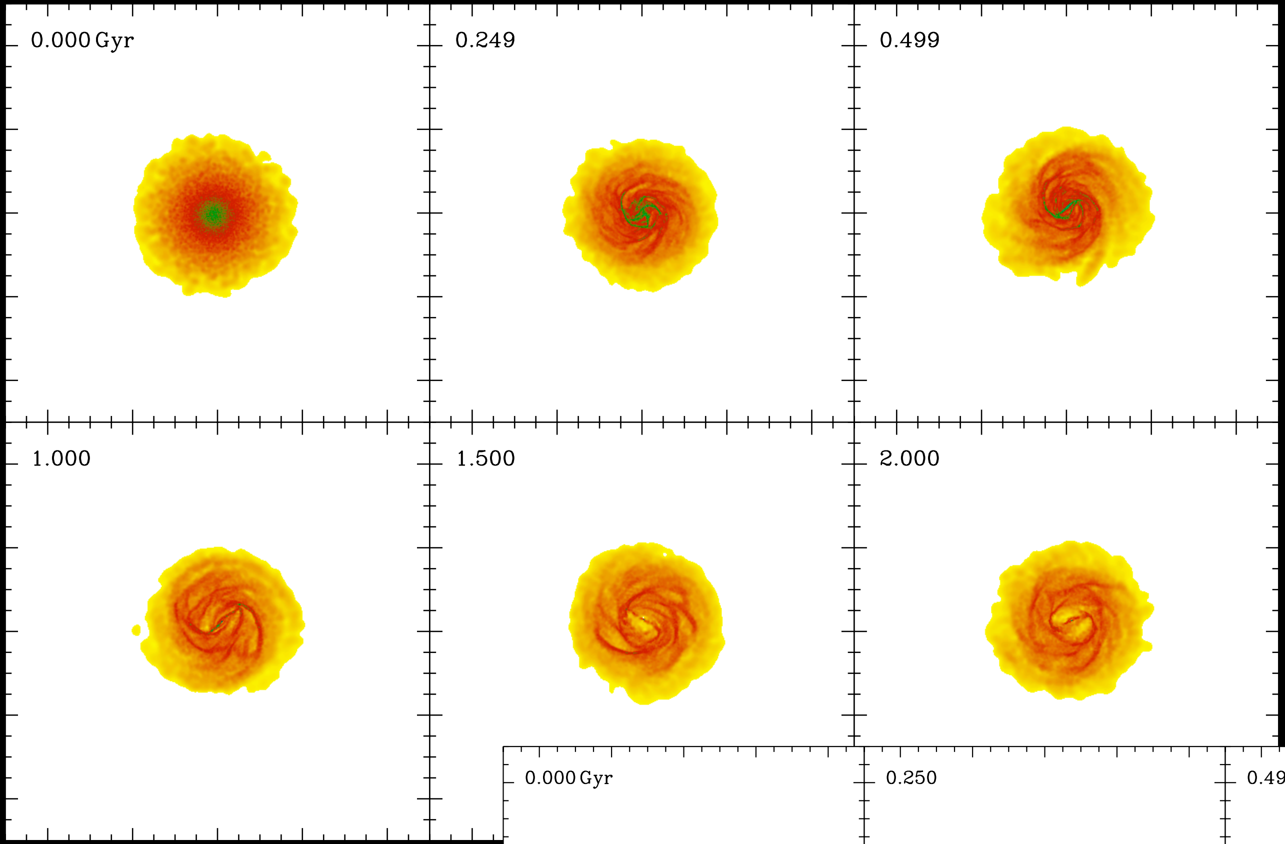
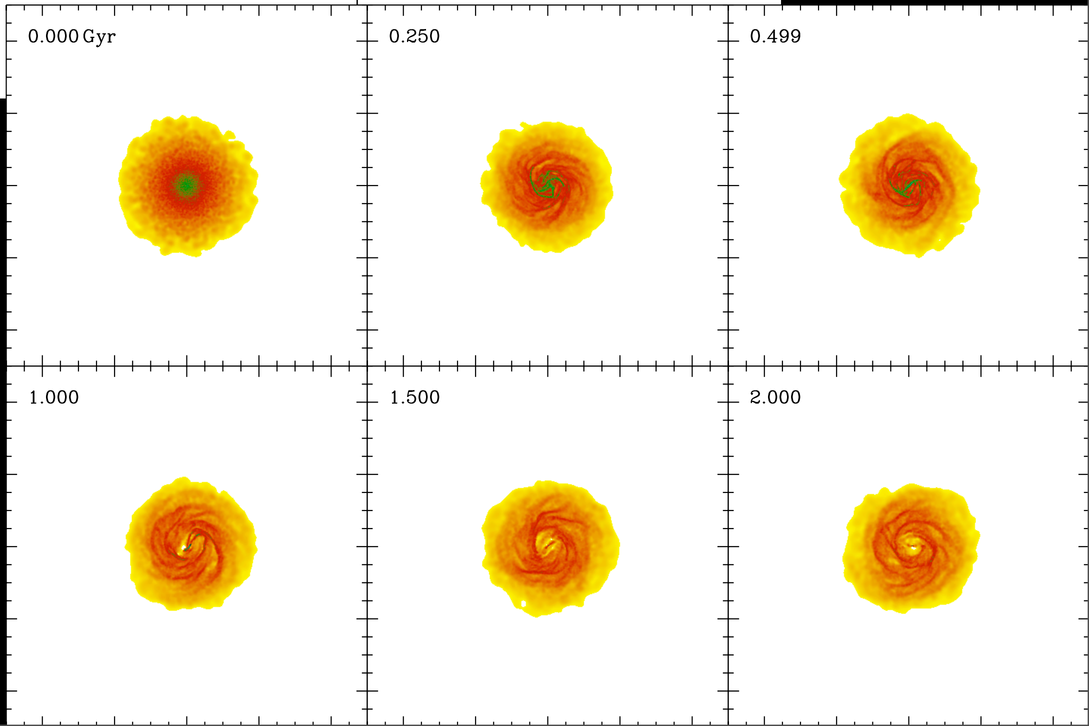


Simulations





High-Resolution SPH simulations of galaxy collisions with dark sub-halos performed with GADGET-2. Note long wavelength disturbances: morphological signature of tidal interactions

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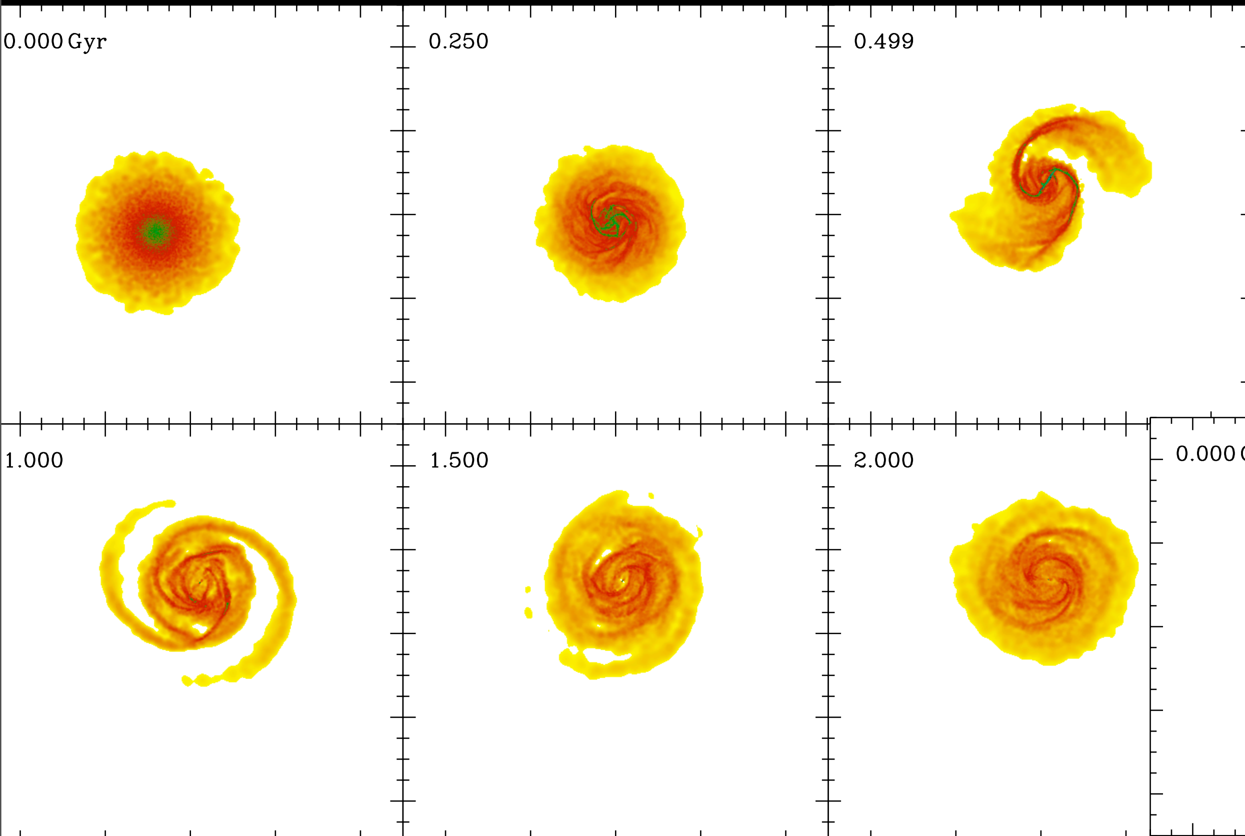

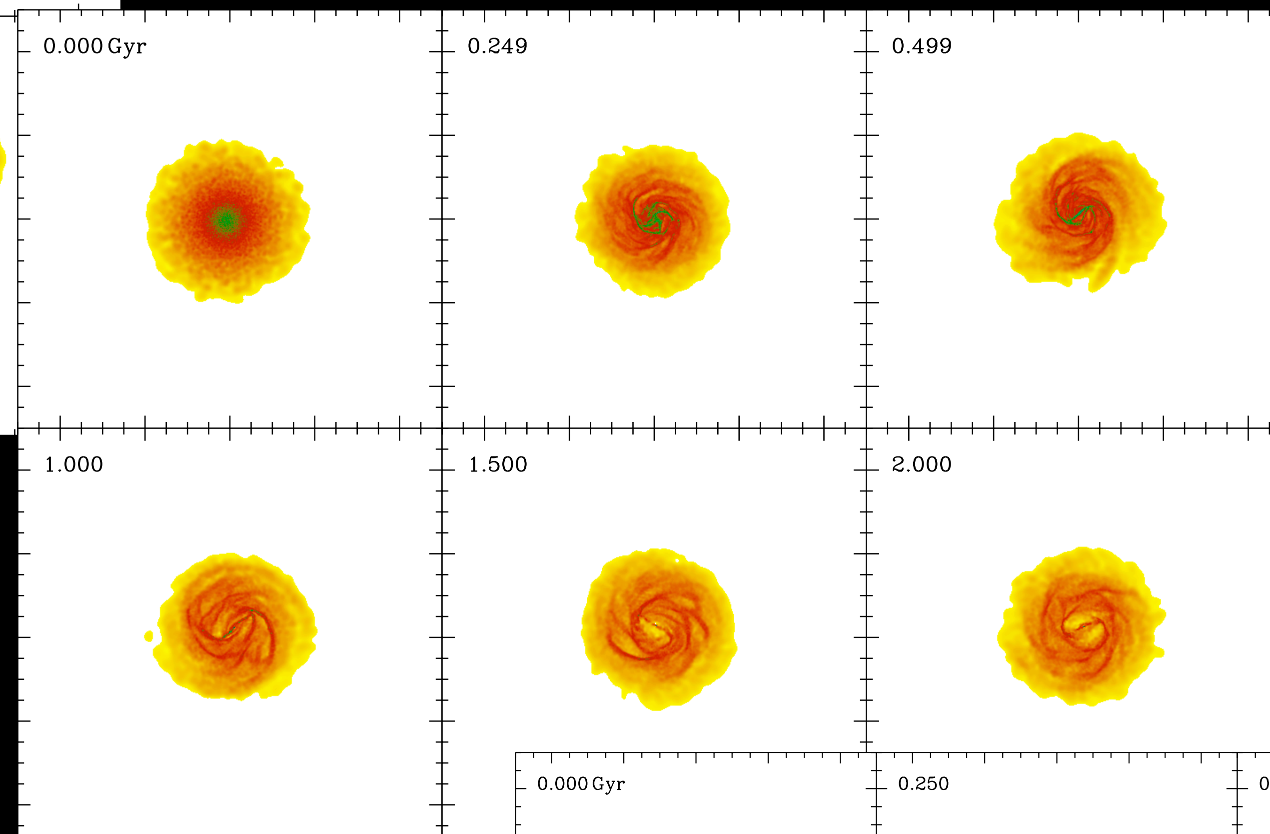

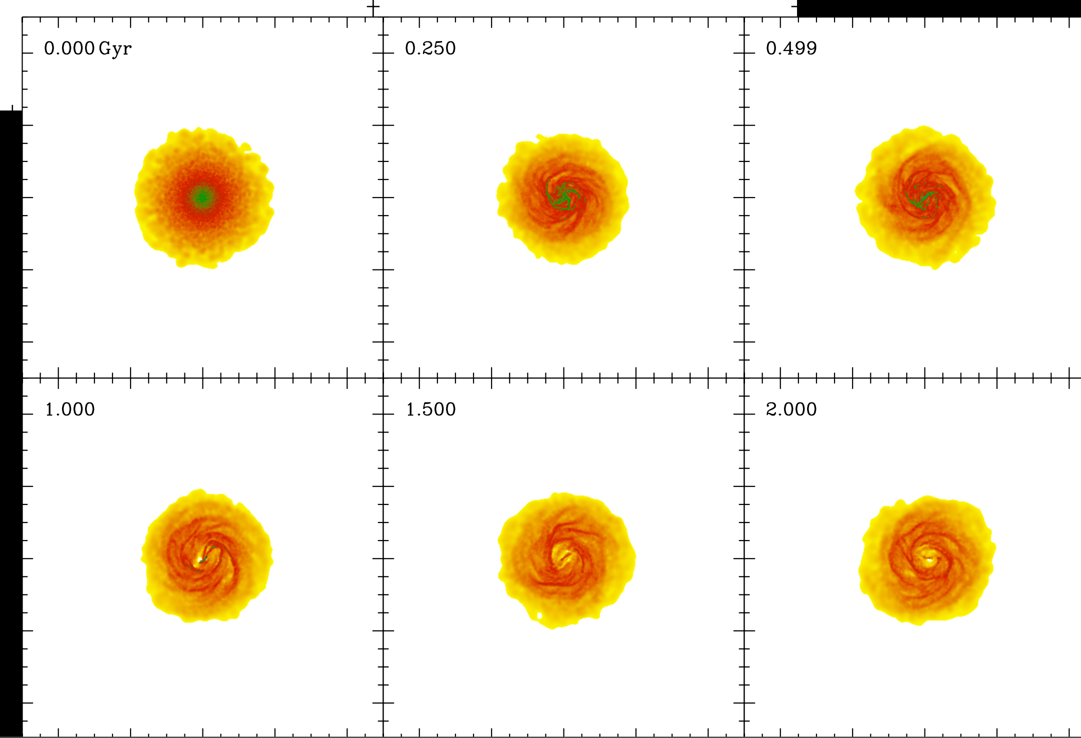

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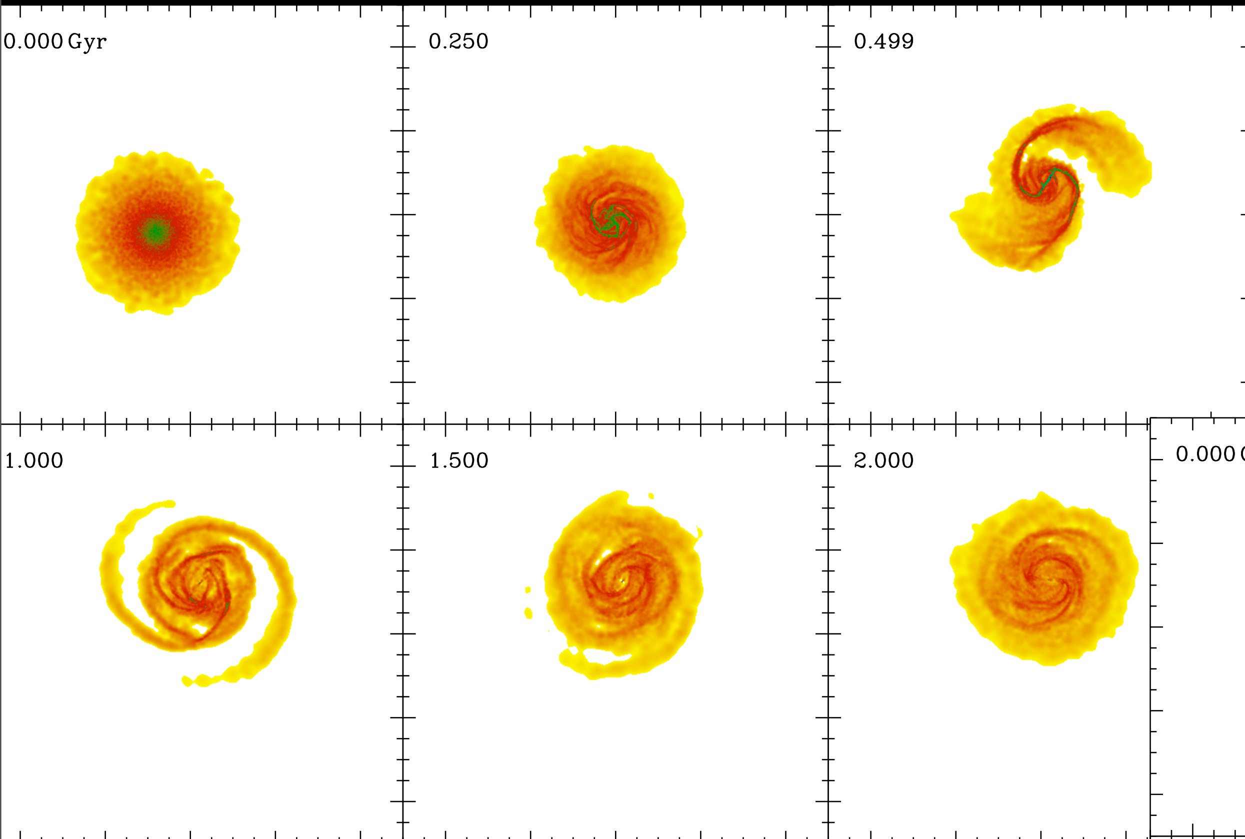
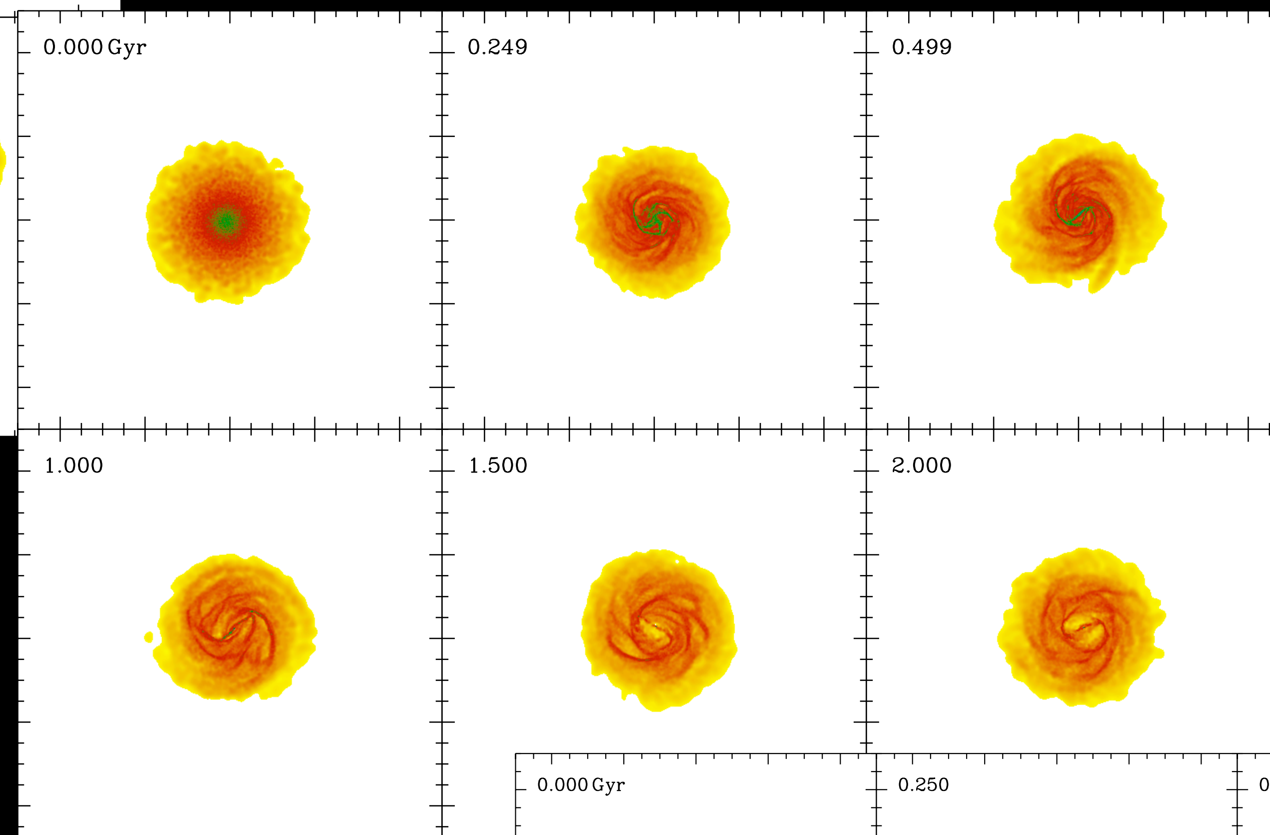
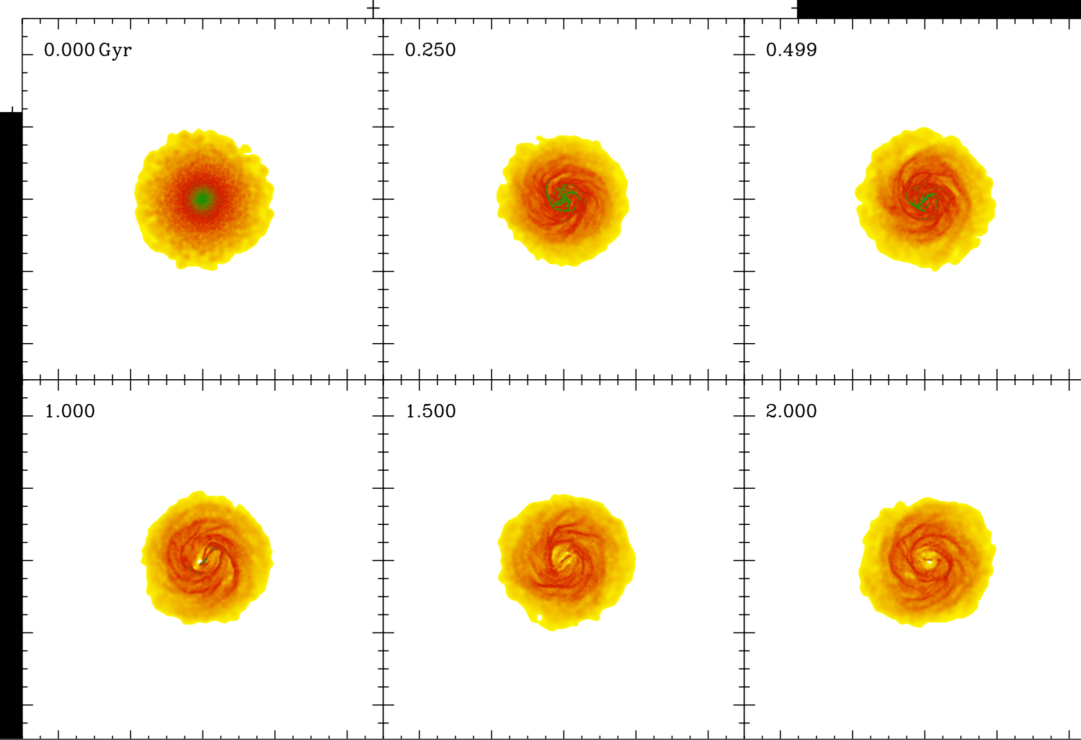


to higher M_s:
1:10, 1:100, isolated





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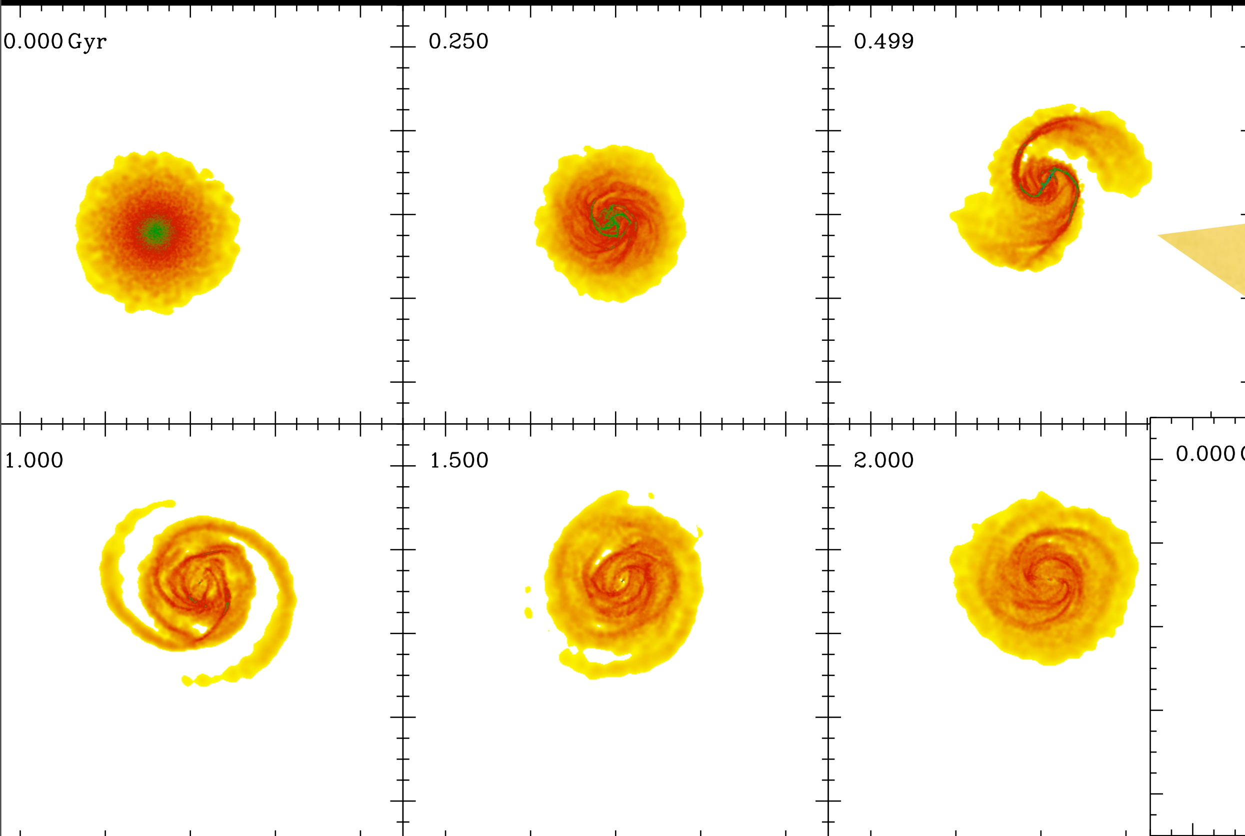
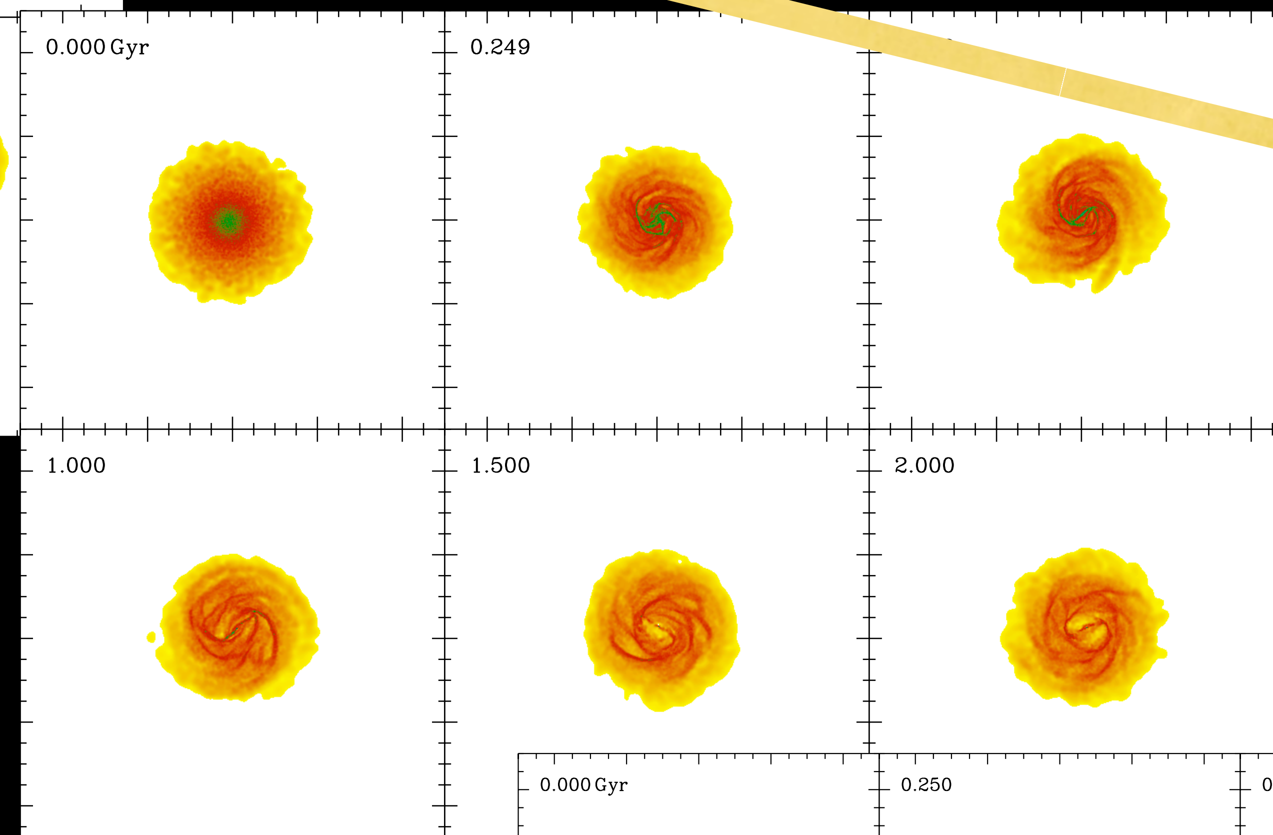
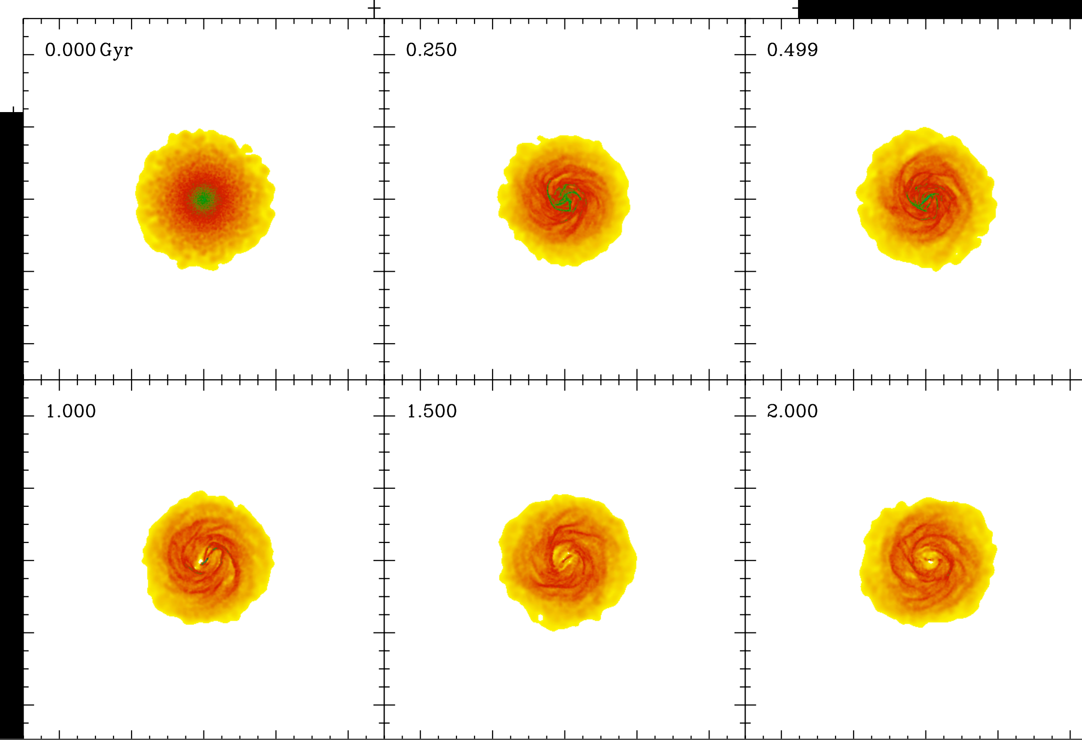


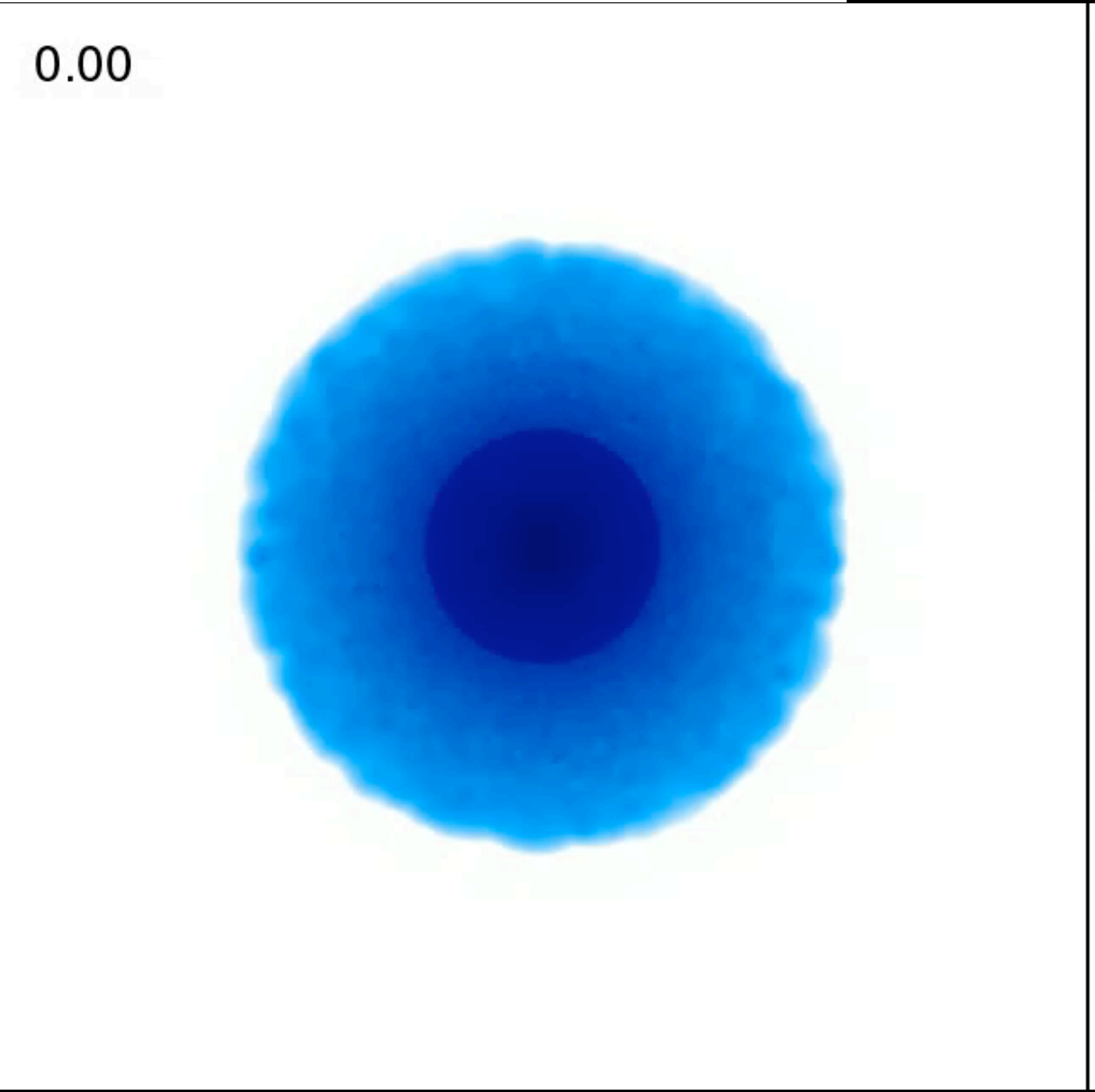


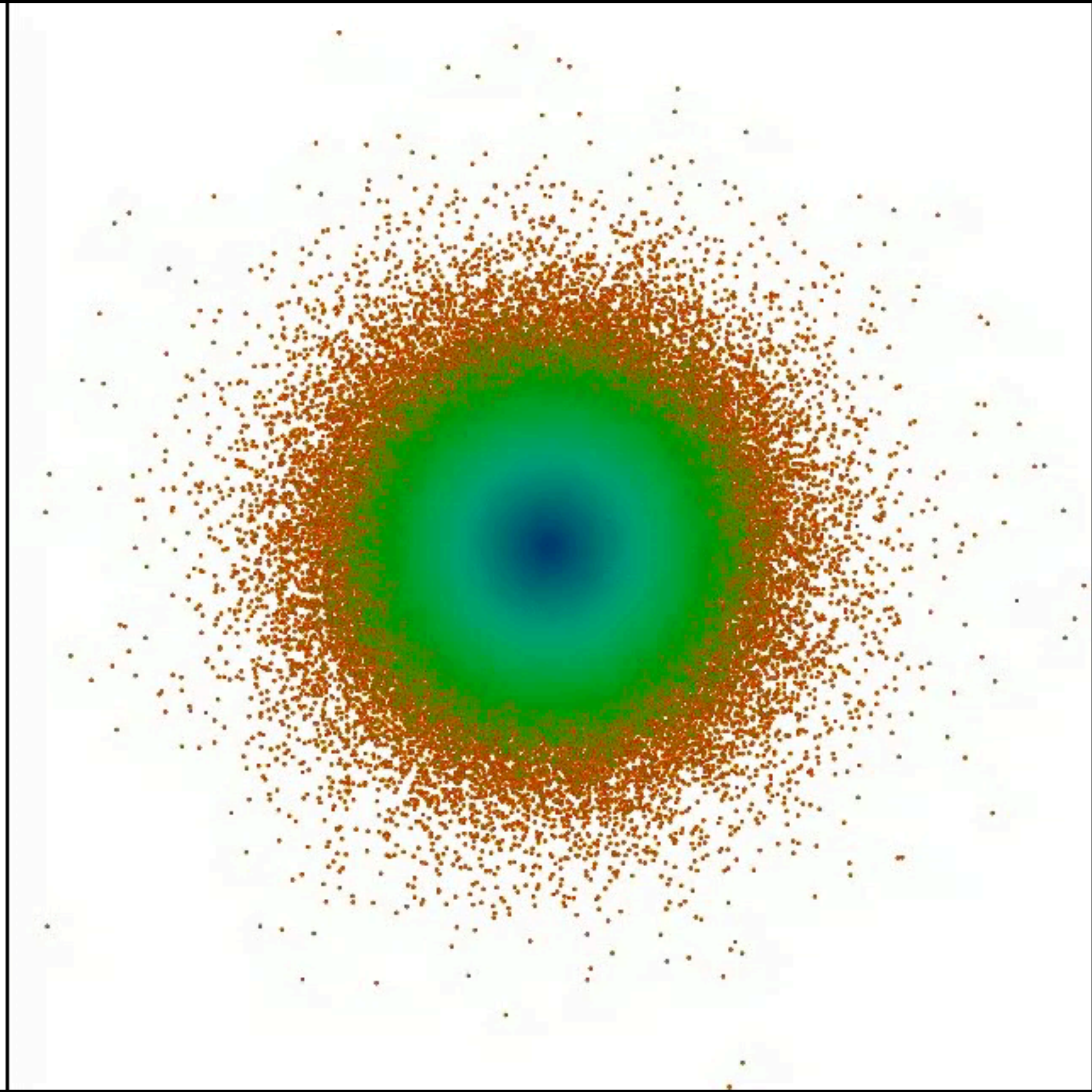


High-Resolution SPH simulations of galaxy collisions with dark sub-halos performed with GADGET-2. Note long wavelength disturbances: morphological signature of tidal interactions

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

Simulations

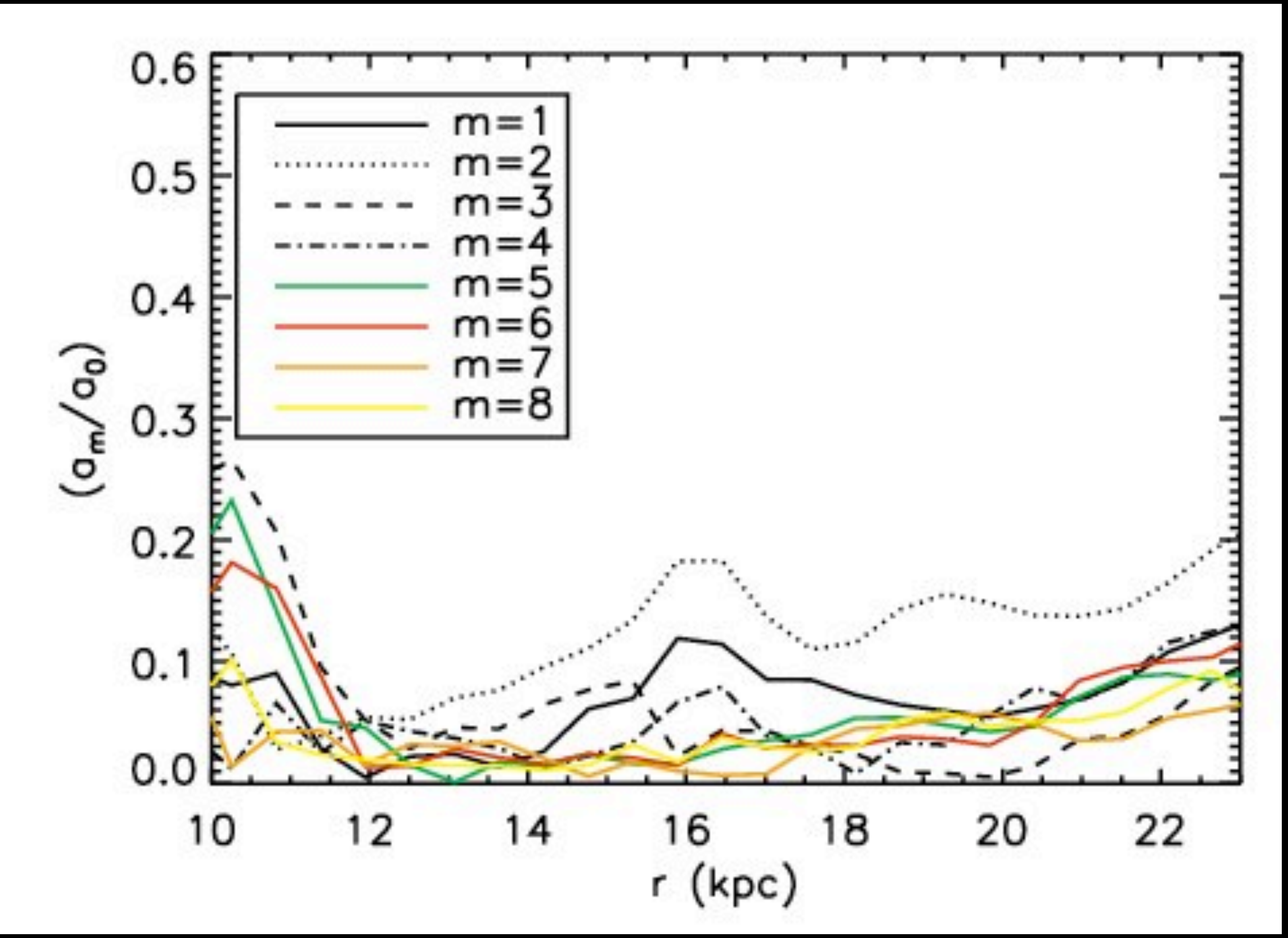




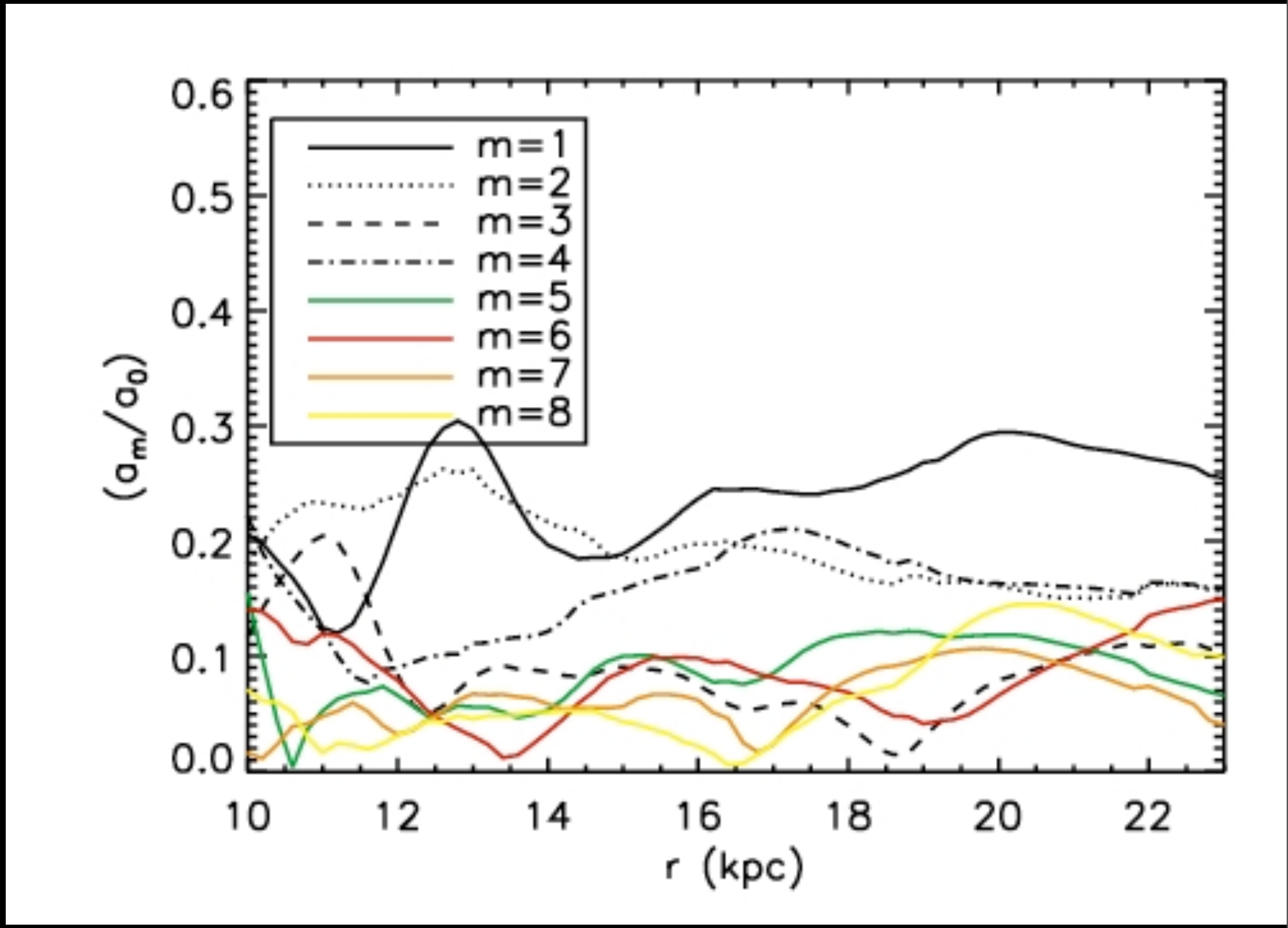
Parameter Space Survey of Simulations. Total ~ 50. Chakrabarti & Blitz 2009, submitted.

Goldilocks--what's not too cold and not too hot?

Simulation



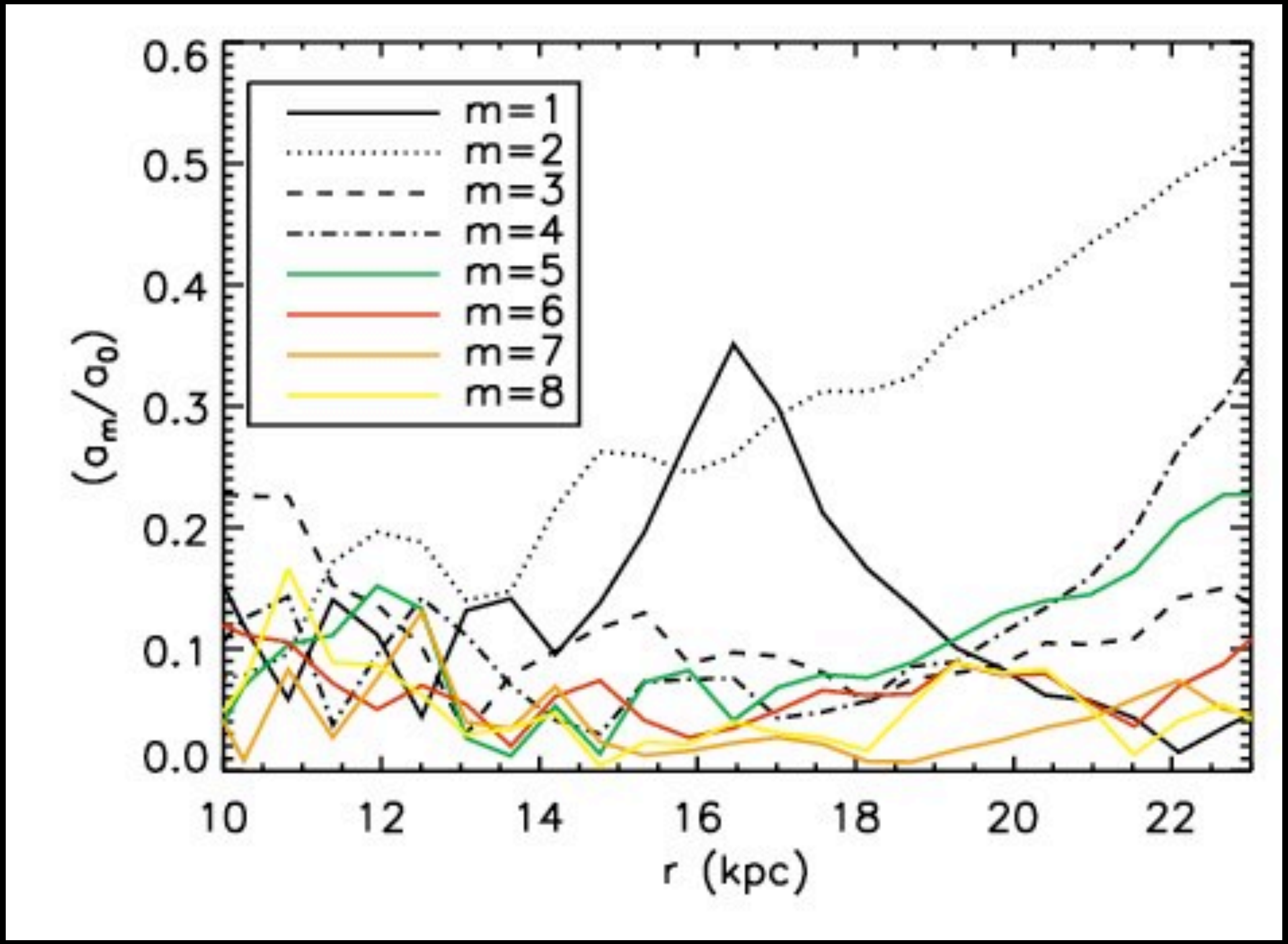
Data



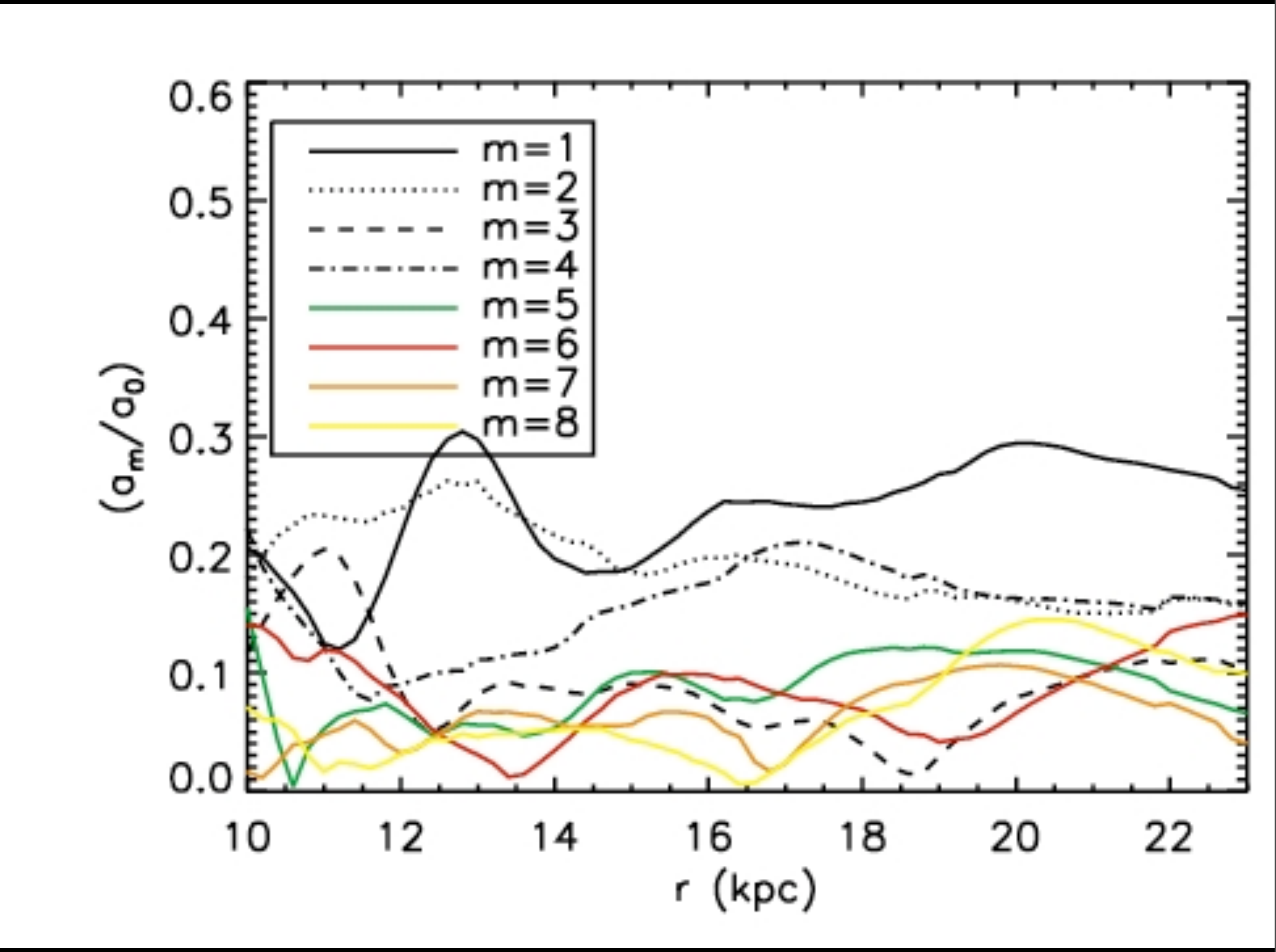
Isolated - 1:300 mass ratio interactions --
"Troppo Freddo! (too cold)!"

Troppo Caldo! (Too hot!)

Simulation



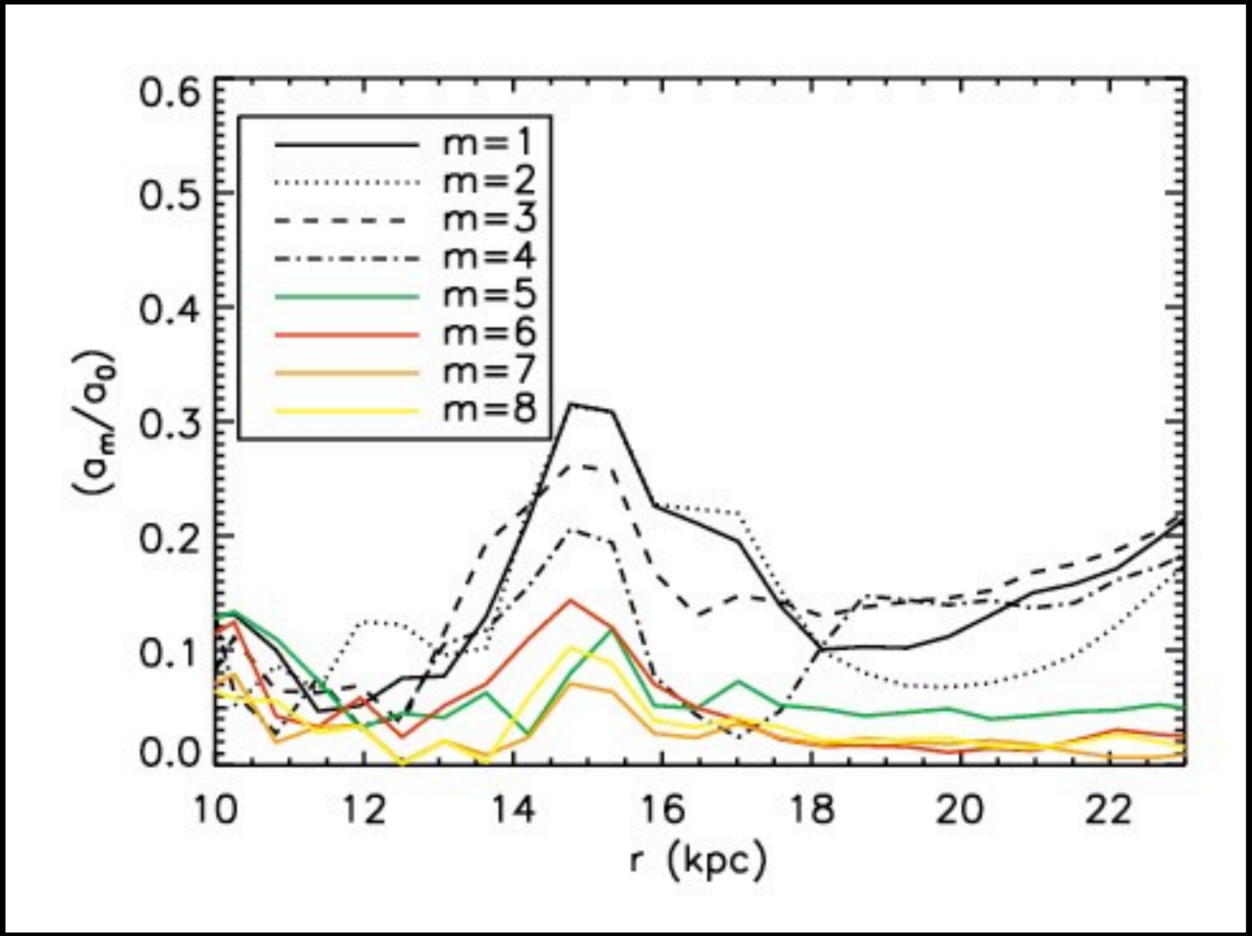
Data



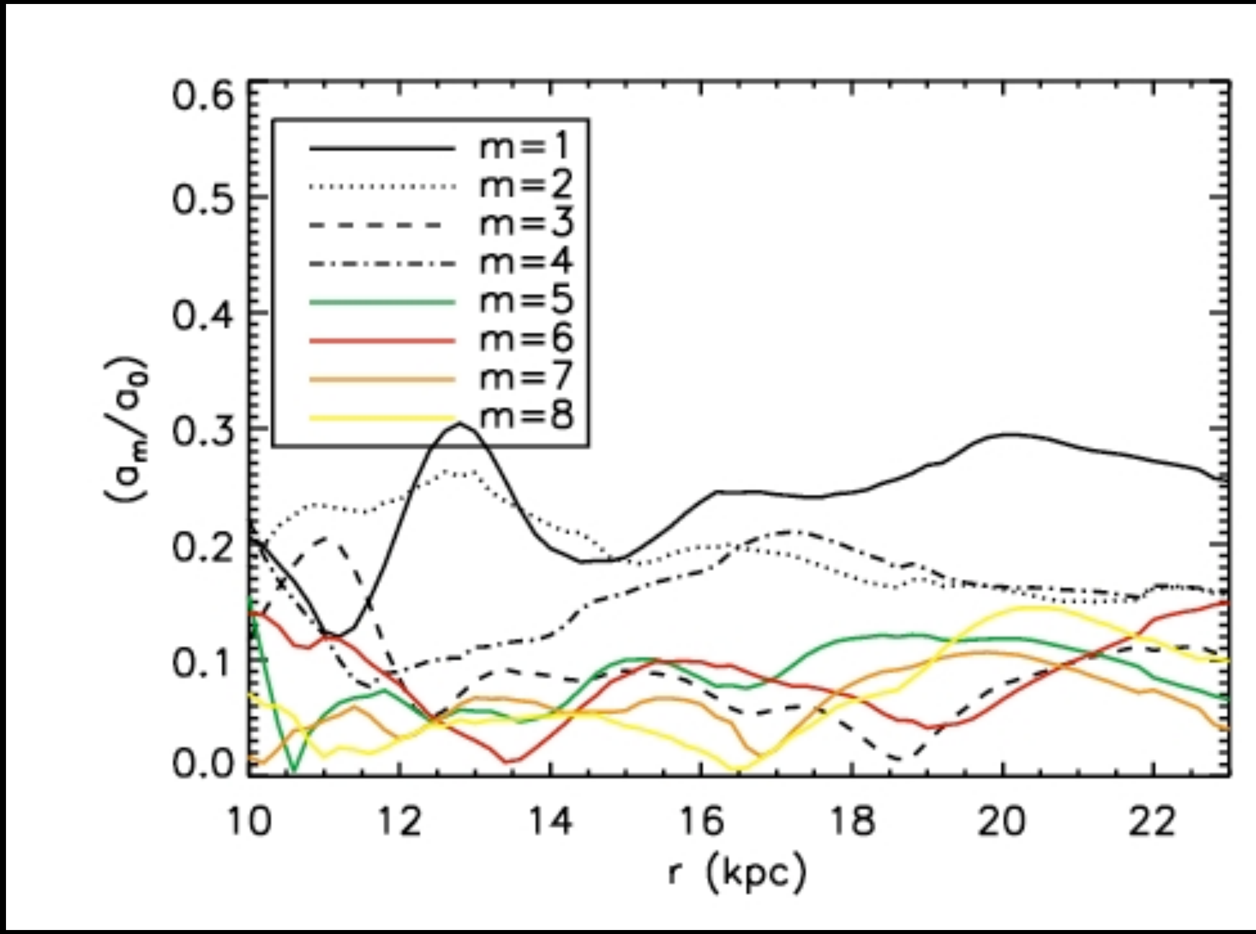
1:50 is too hot!

Circa Giusto!
(Just about right)

Simulation

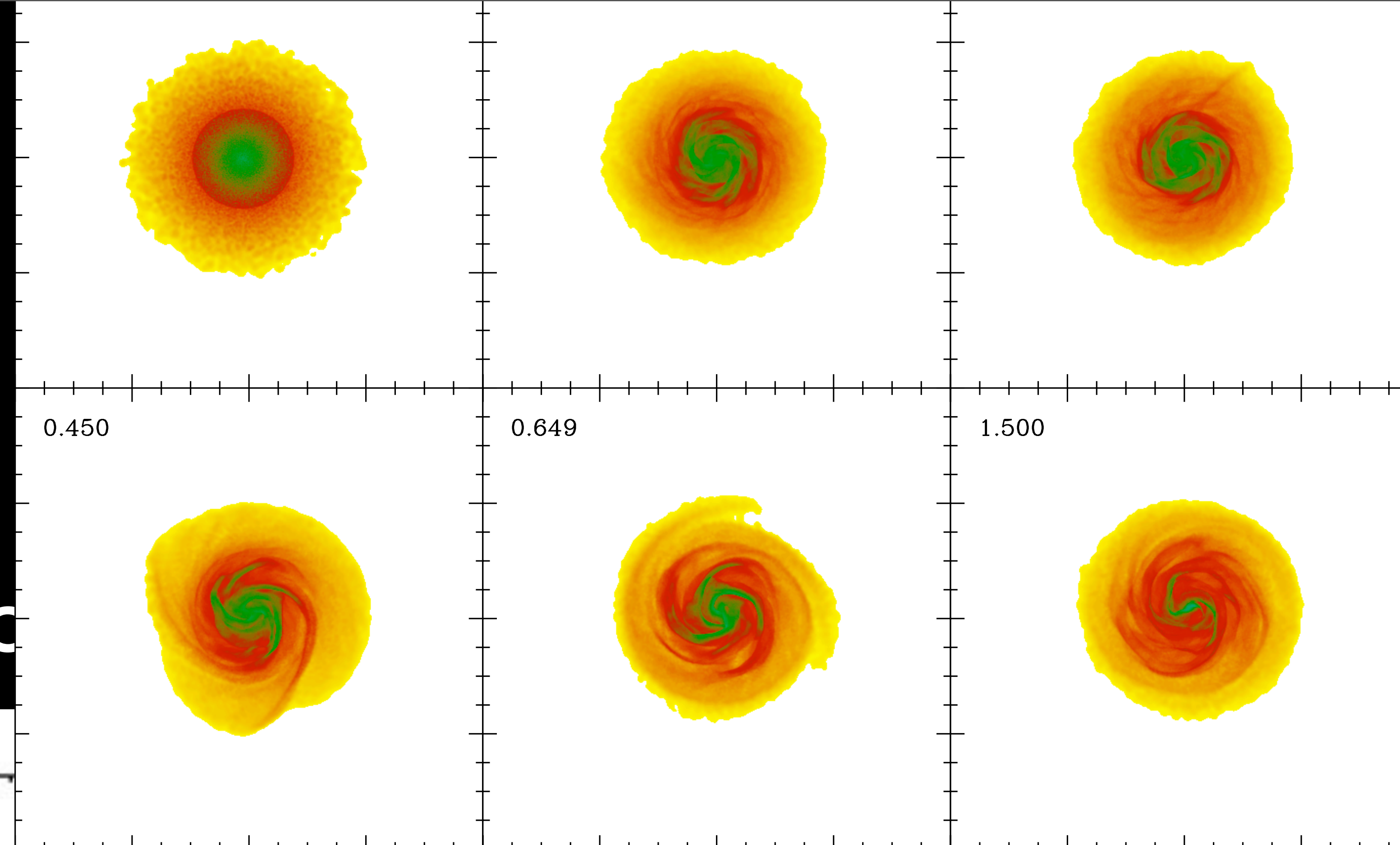


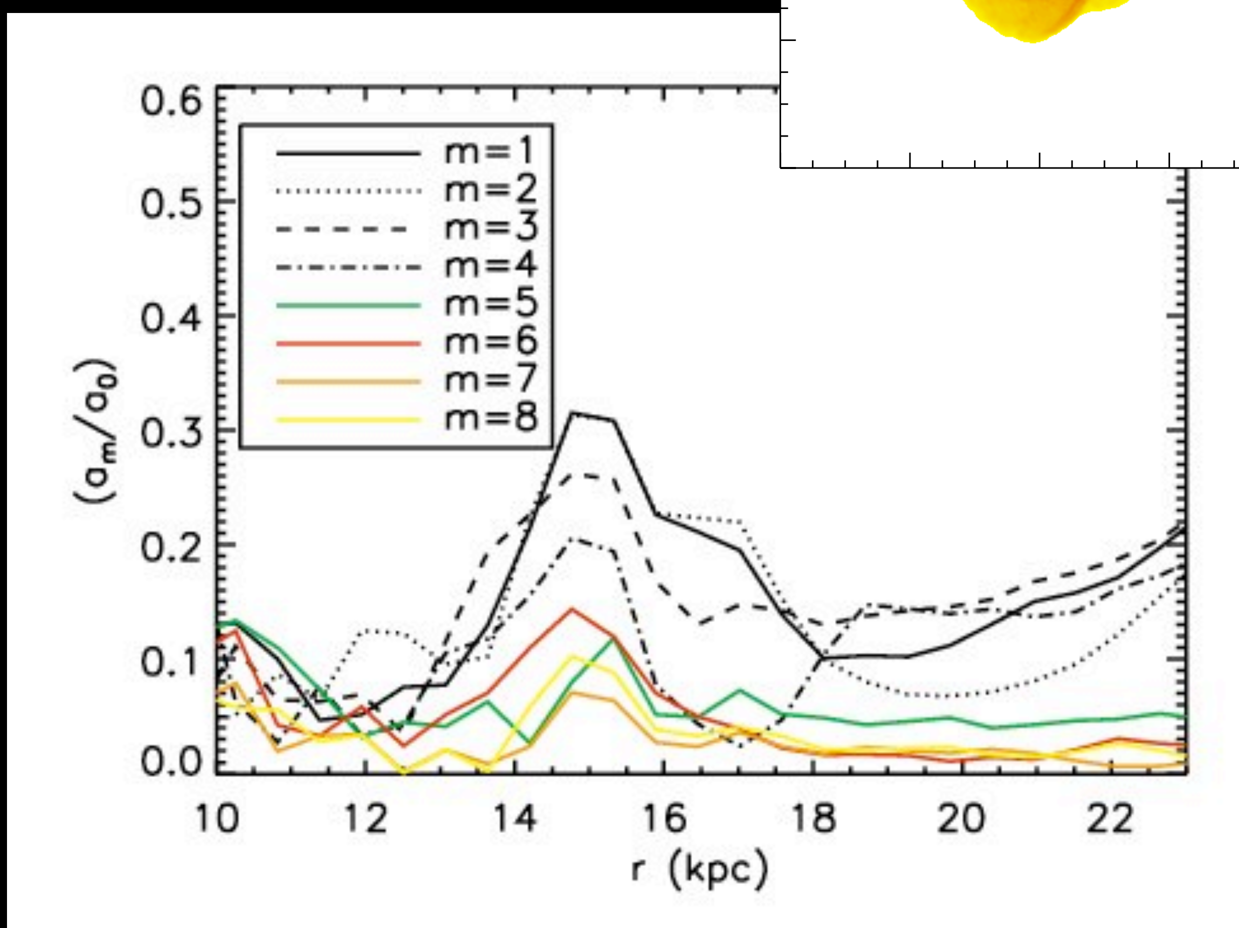
Data

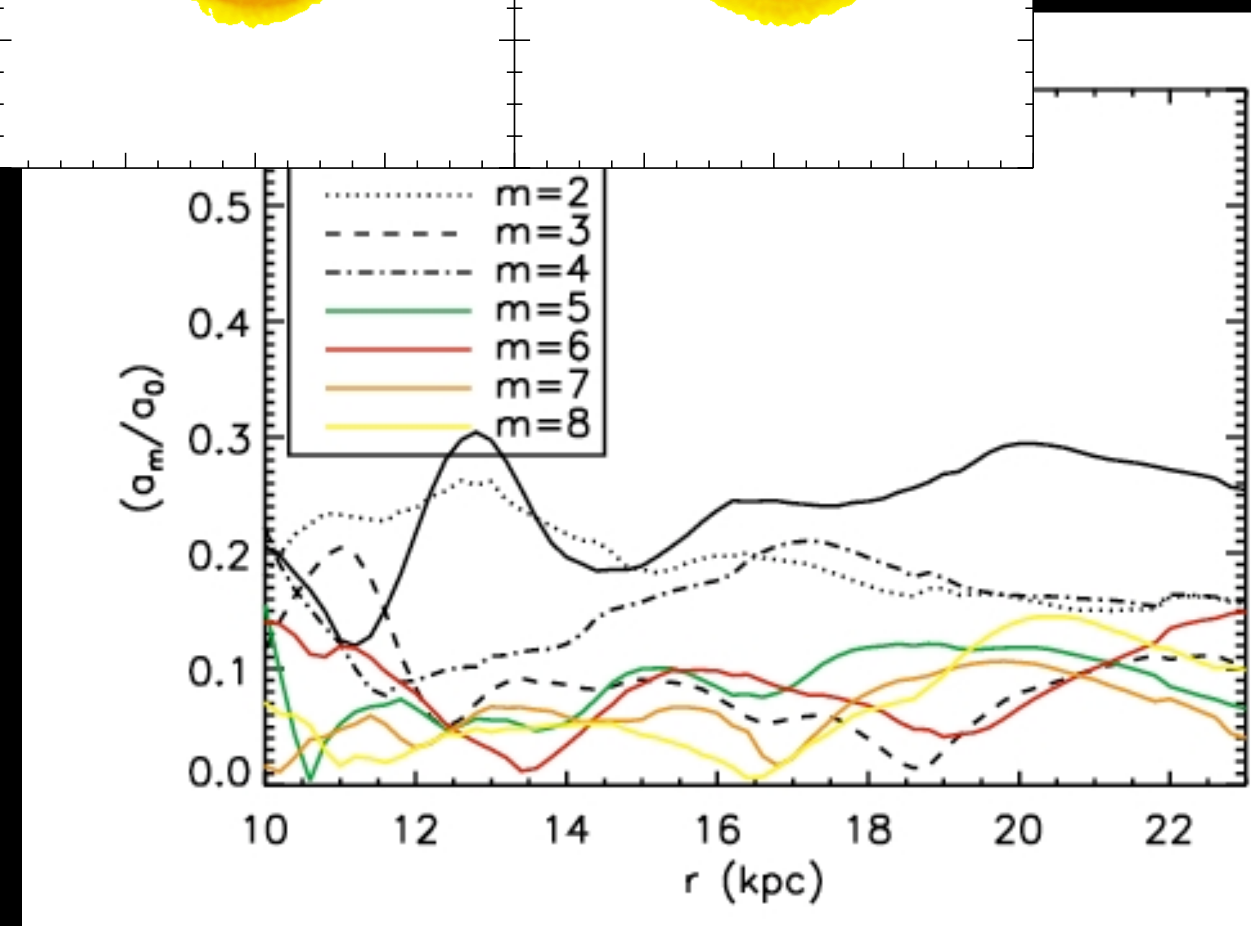


1:100, R_{peri}=5 kpc - the best-fit case. Chakrabarti & Blitz 09

Simulatic







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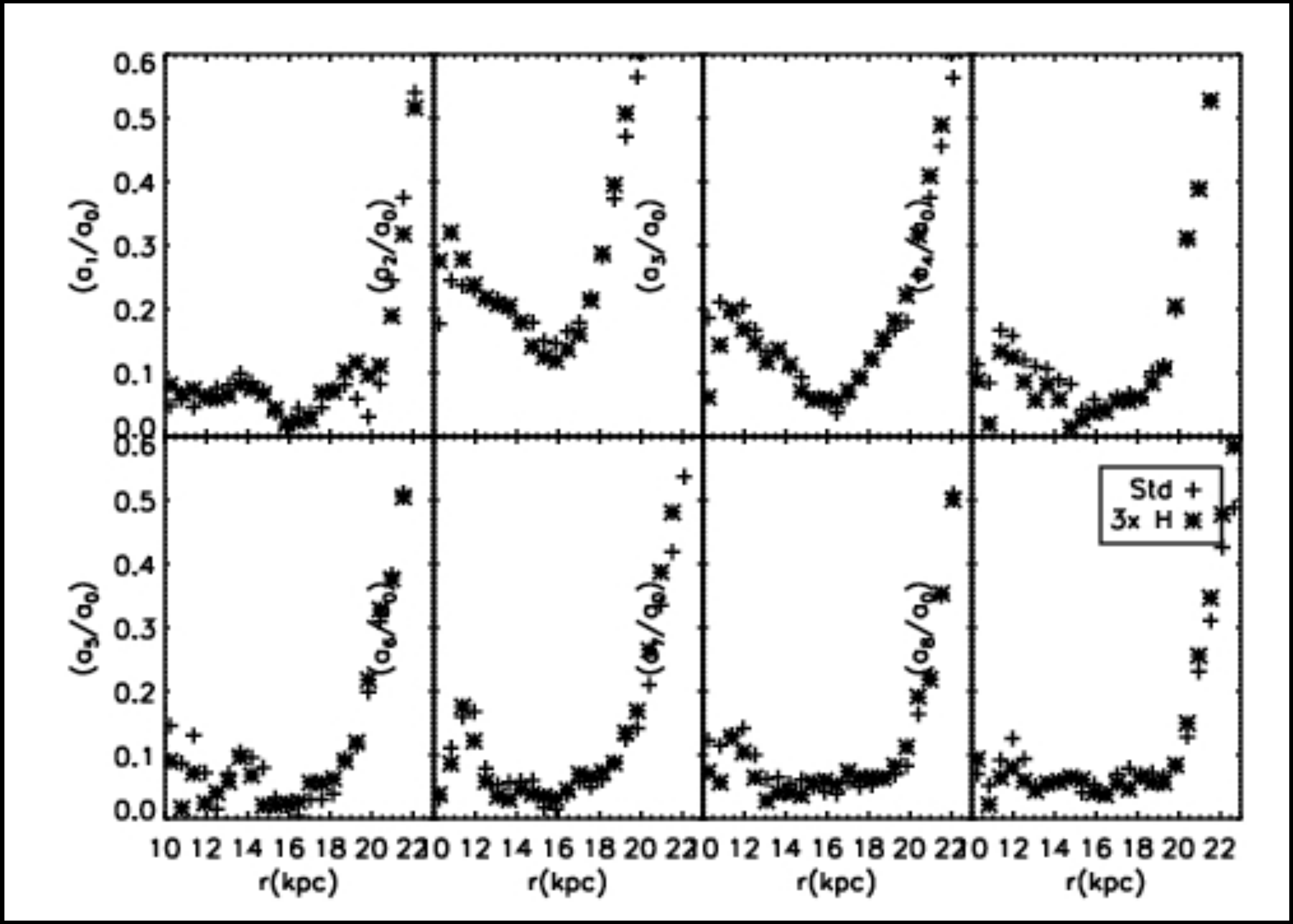
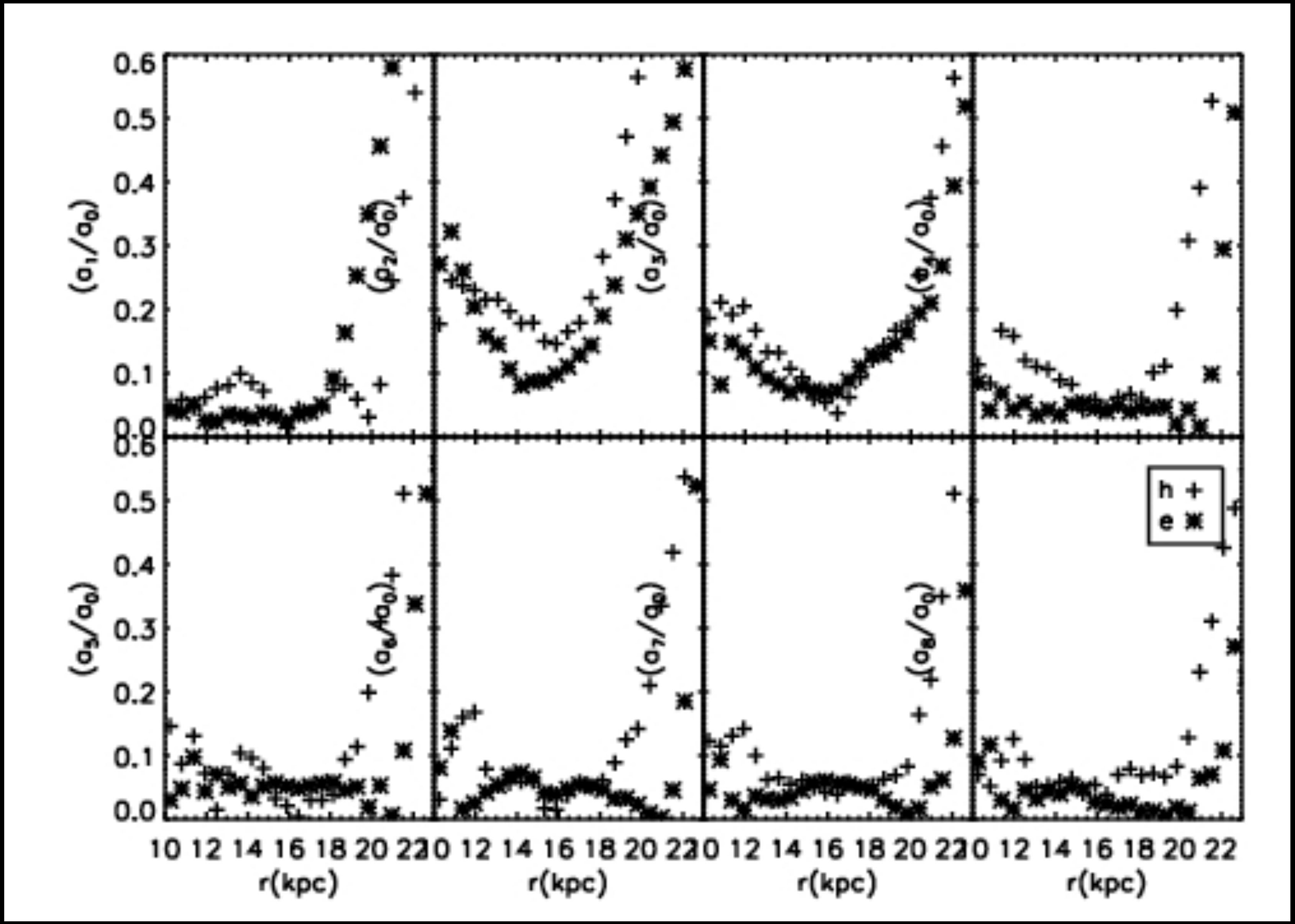
Are the results converged?



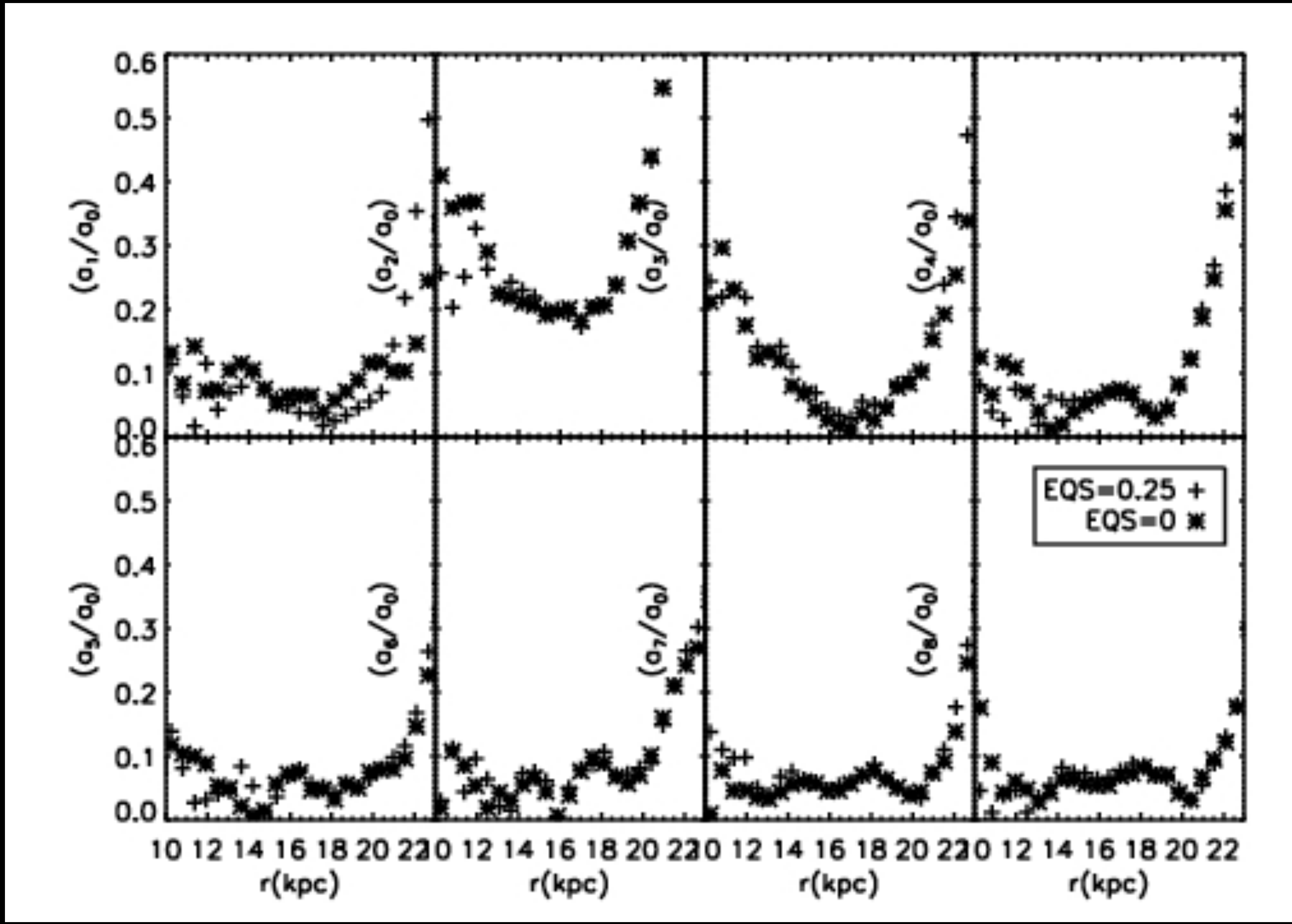
- Yes. 3 x higher res case w.in 1.3 of standard res.

Do different inclinations matter?



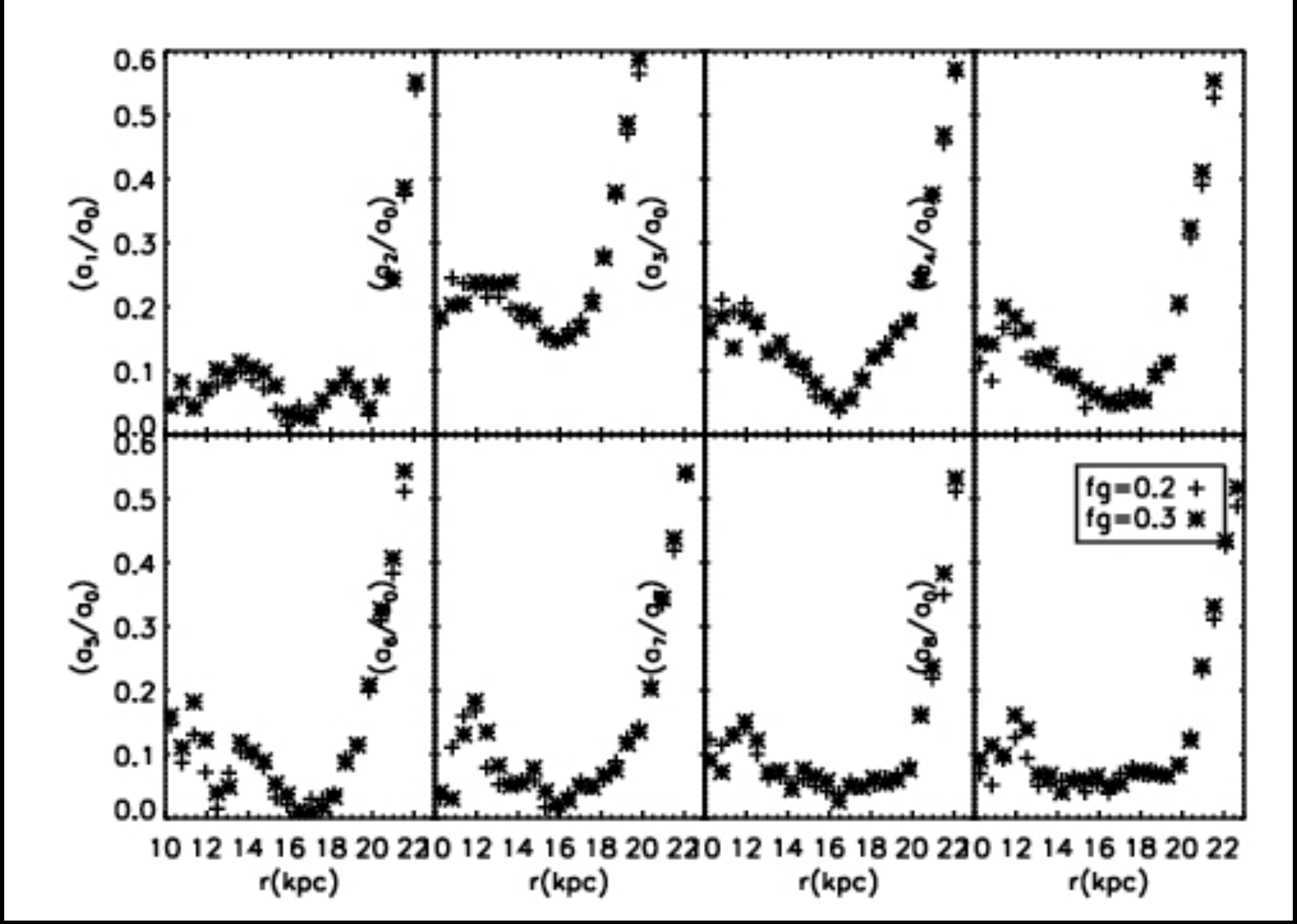
- co-planar and tilted (θ_1=30,φ_1=60,θ_2=-30,φ_2=45). co-planar produces largest amplitude.

Does Equation of State Matter?



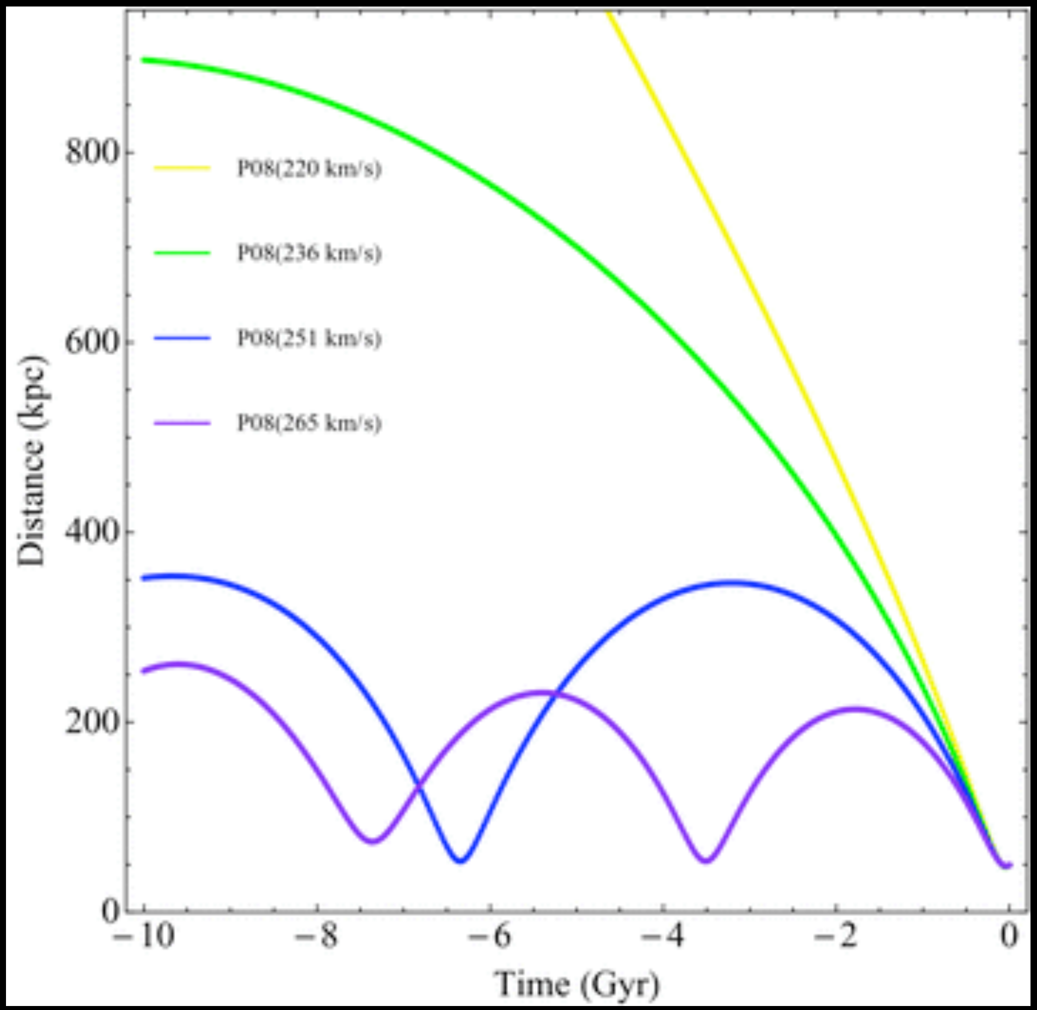
- Isothermal equation (EQS=0) of state bit more responsive

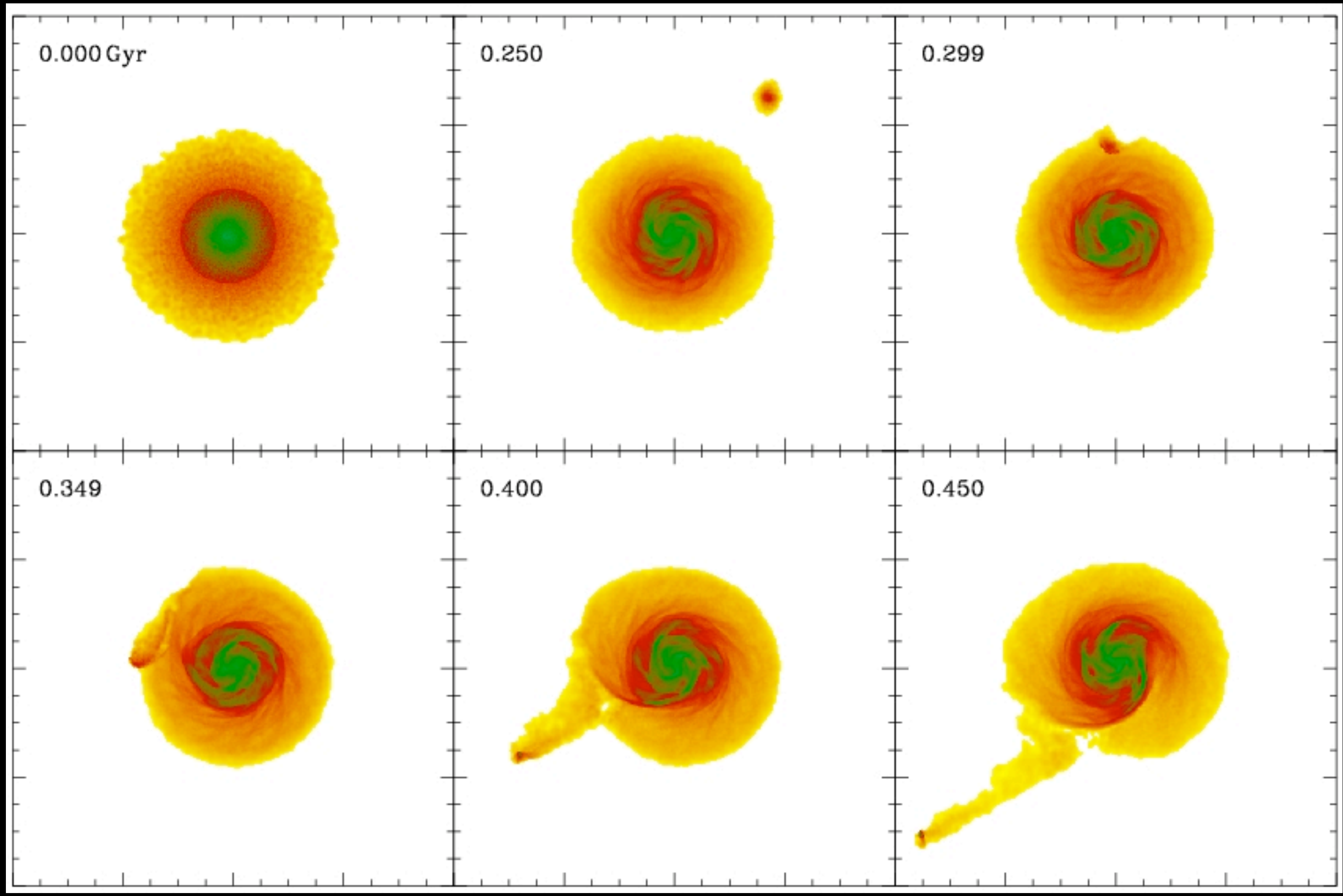
Does gas fraction matter?



- very little difference between f_{gas}=0.2 and f_{gas}=0.3. Summary: not very sensitive to ICs (for parameters comparable to spirals)

Can the LMC be the culprit?





Shattow & Loeb 2009

Proper motions from Kalivayil et al. 2006 and estimates of orbits of LMC show that it cannot have come closer than 50 kpc. LMC can't be the culprit.

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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can break degeneracy betwen M & R if:

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

Breaking the degeneracy between M & R

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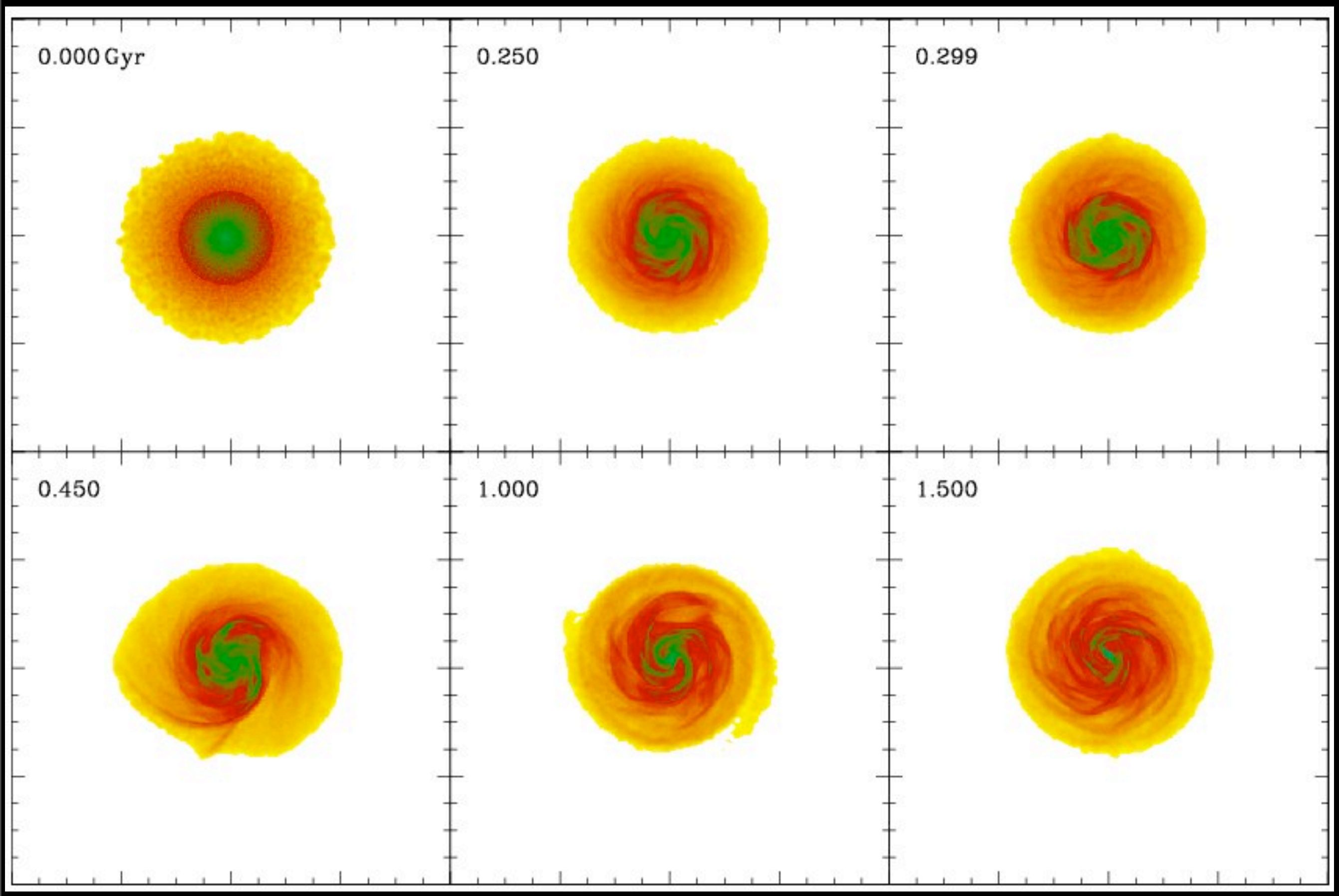

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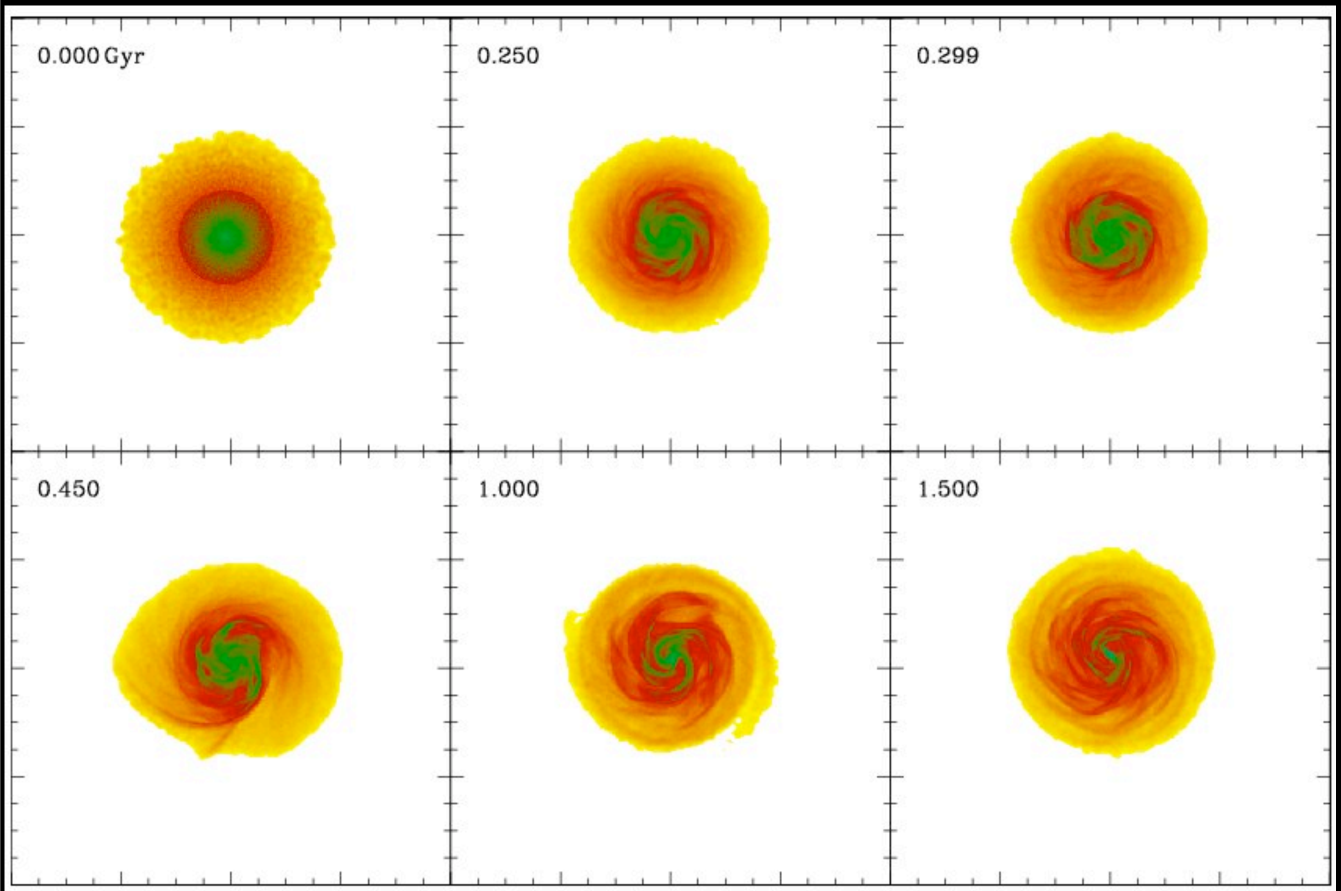
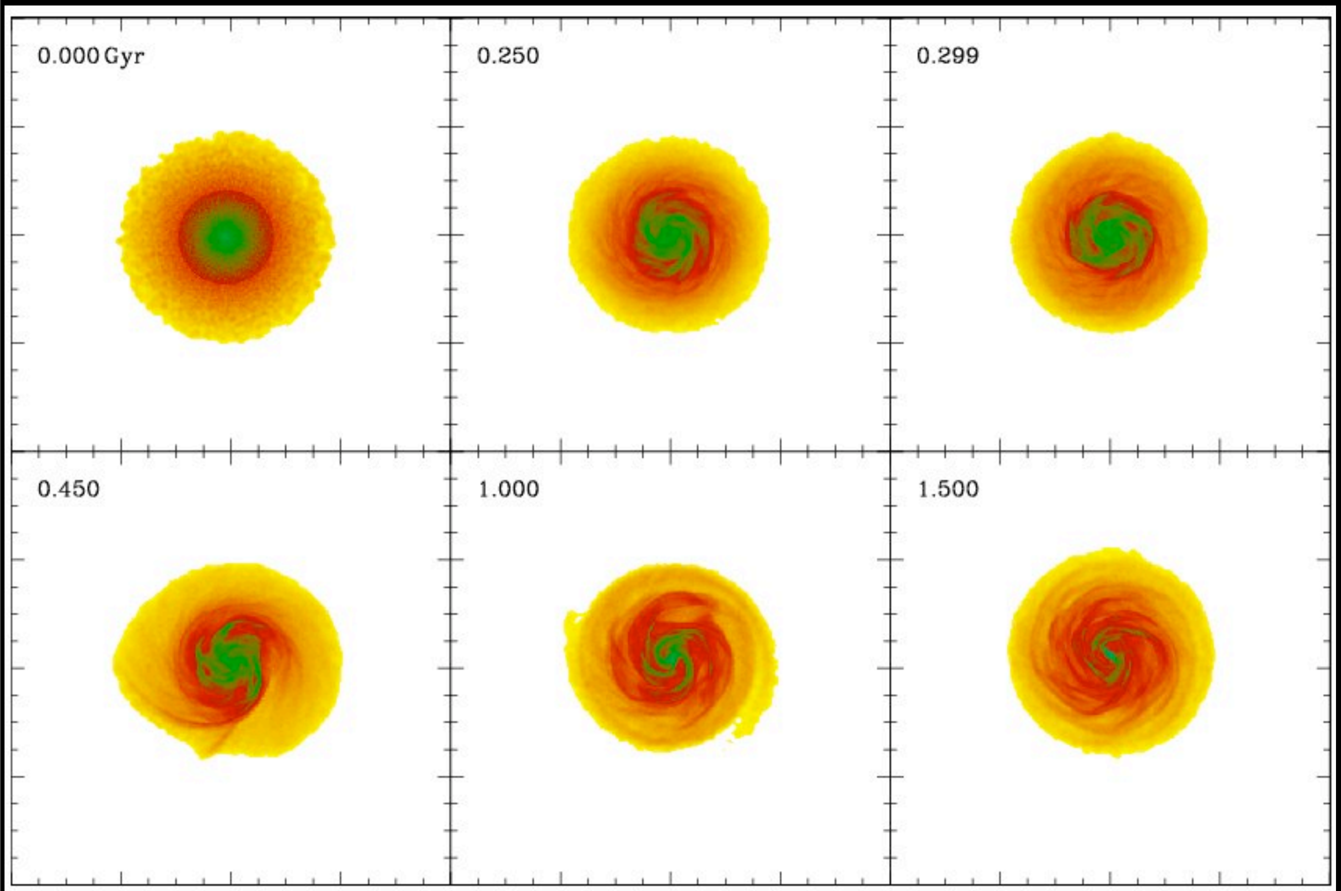


1:100 with R_{peri}=5 kpc

Breaking the degeneracy between M & R



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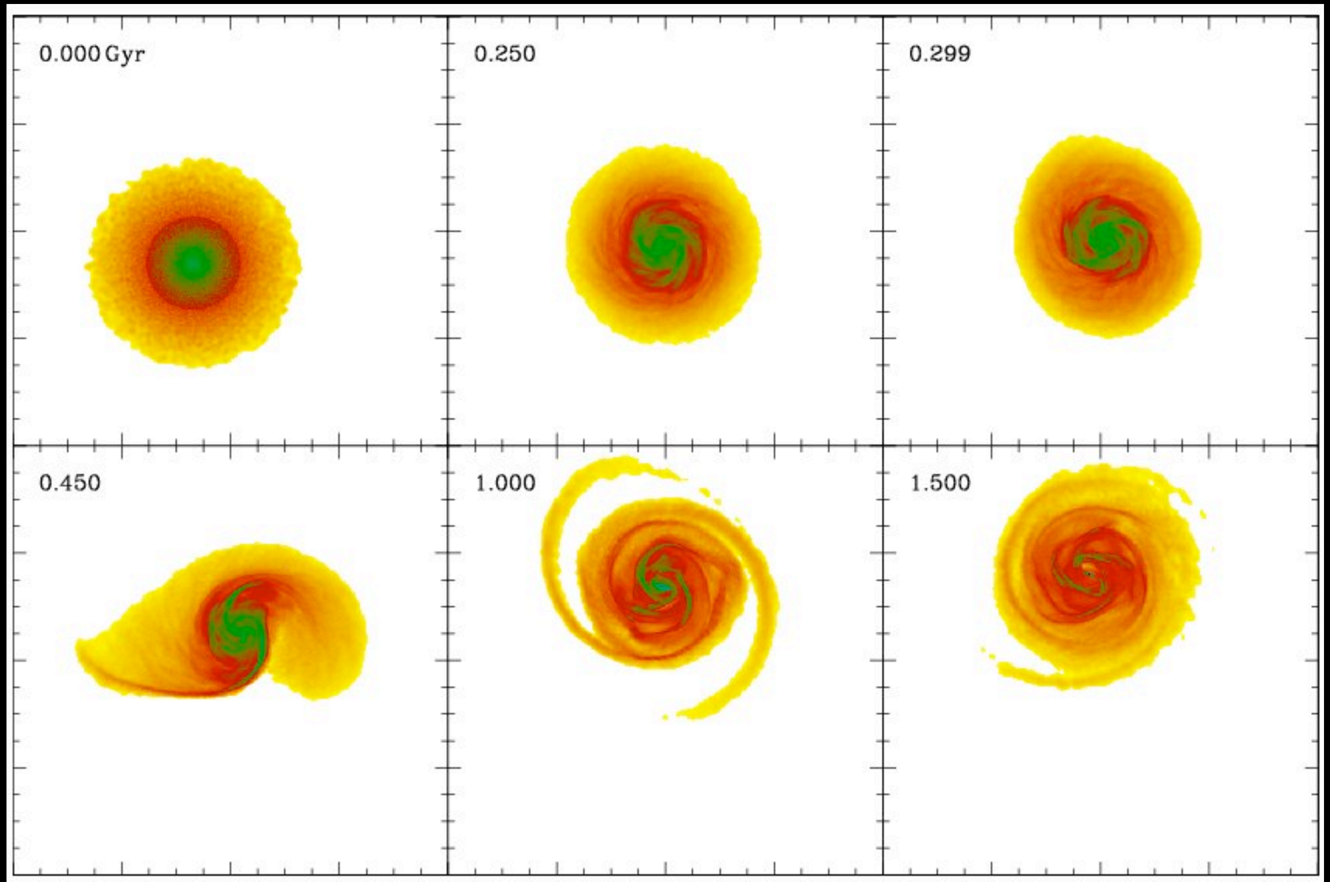

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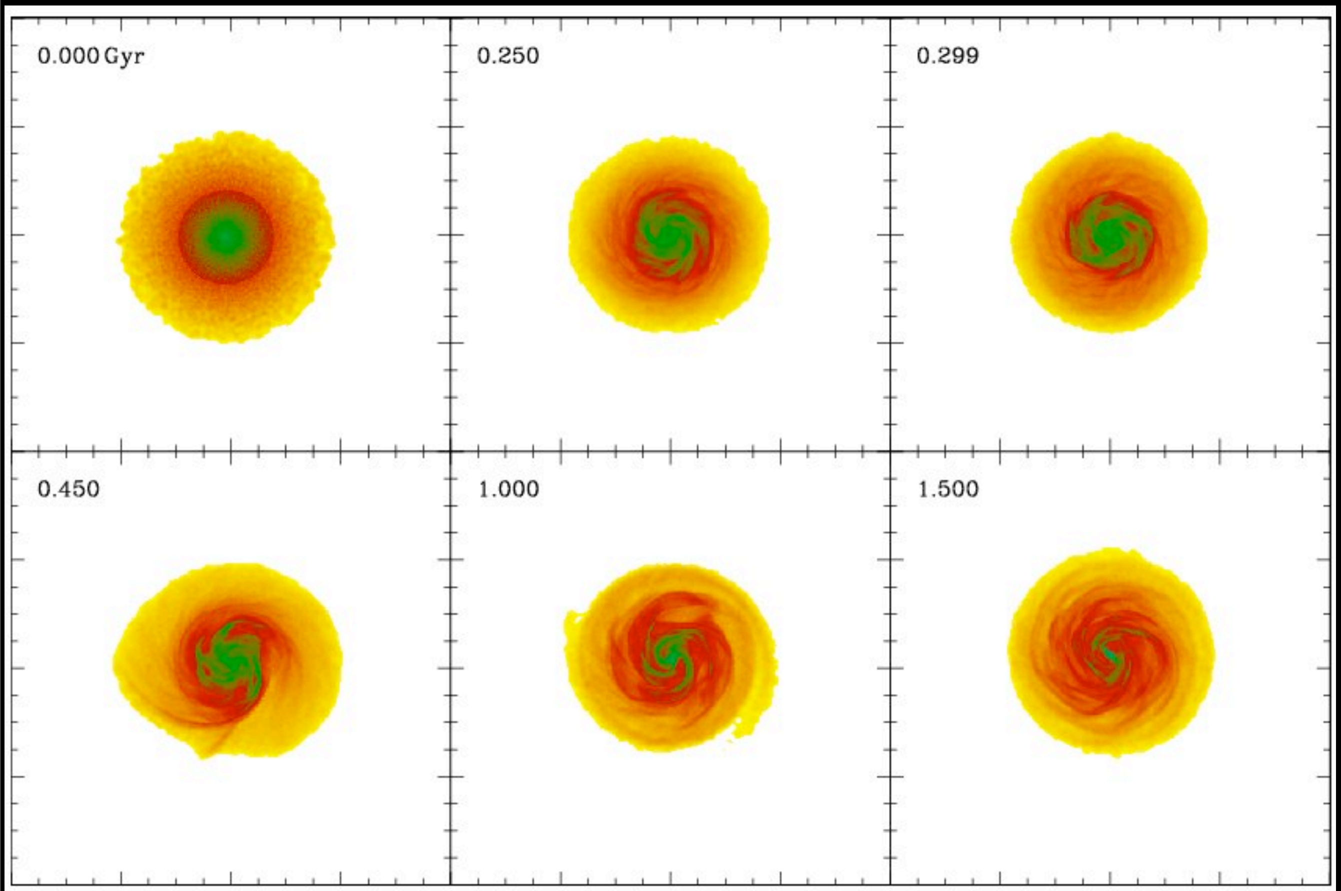

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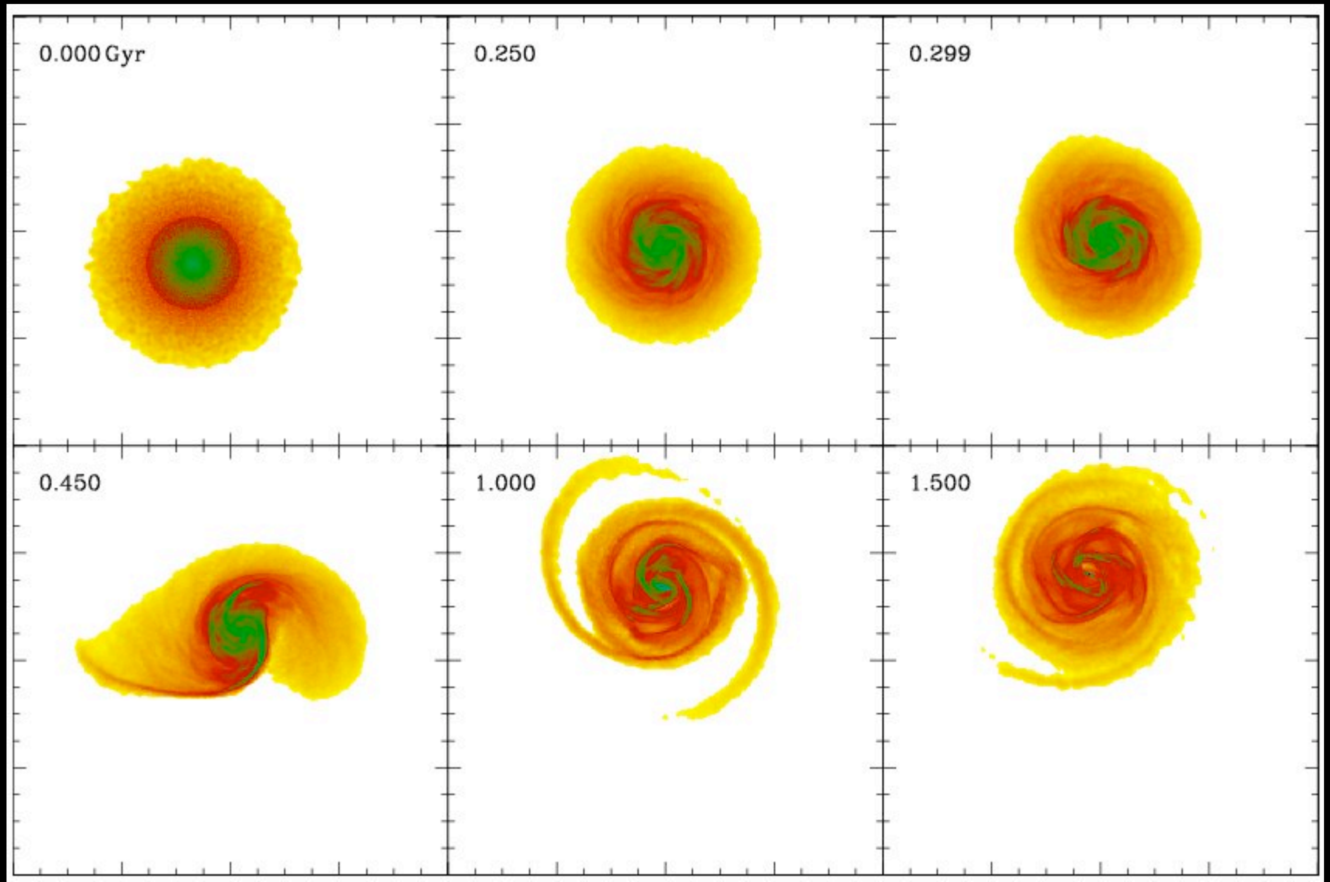
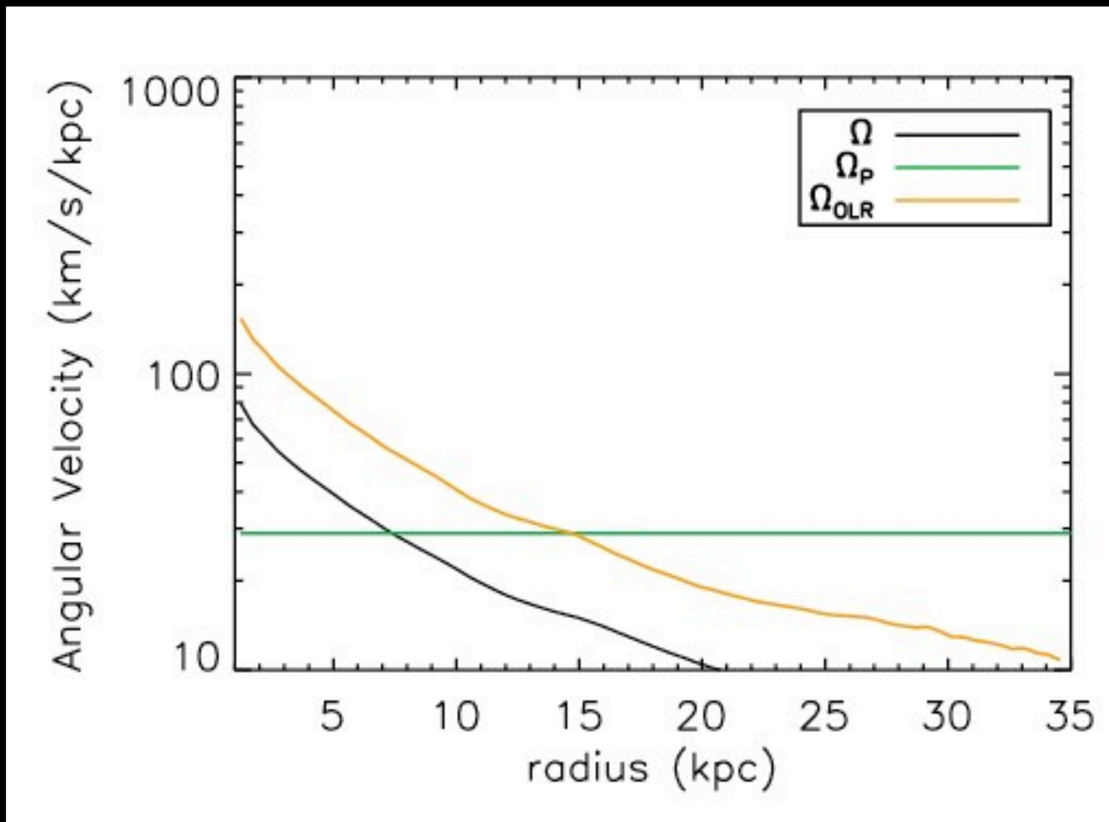
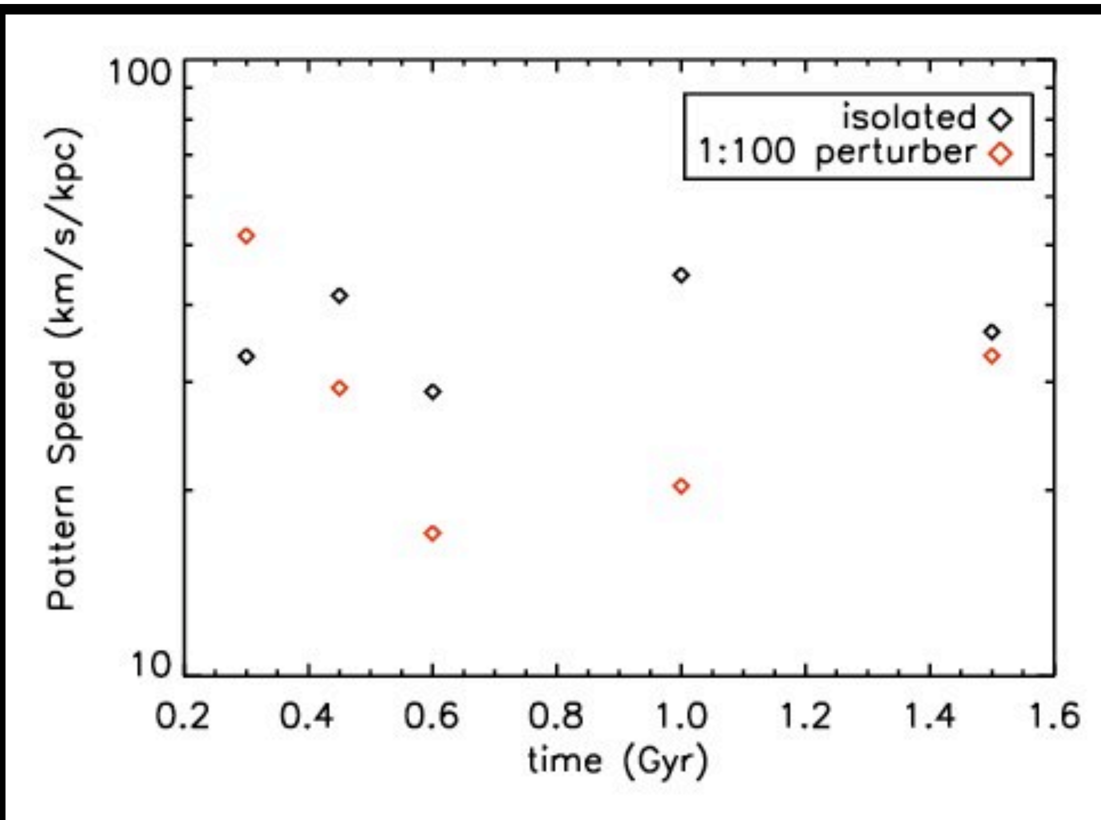


1:10 at equivalent tidal distance as 1:100

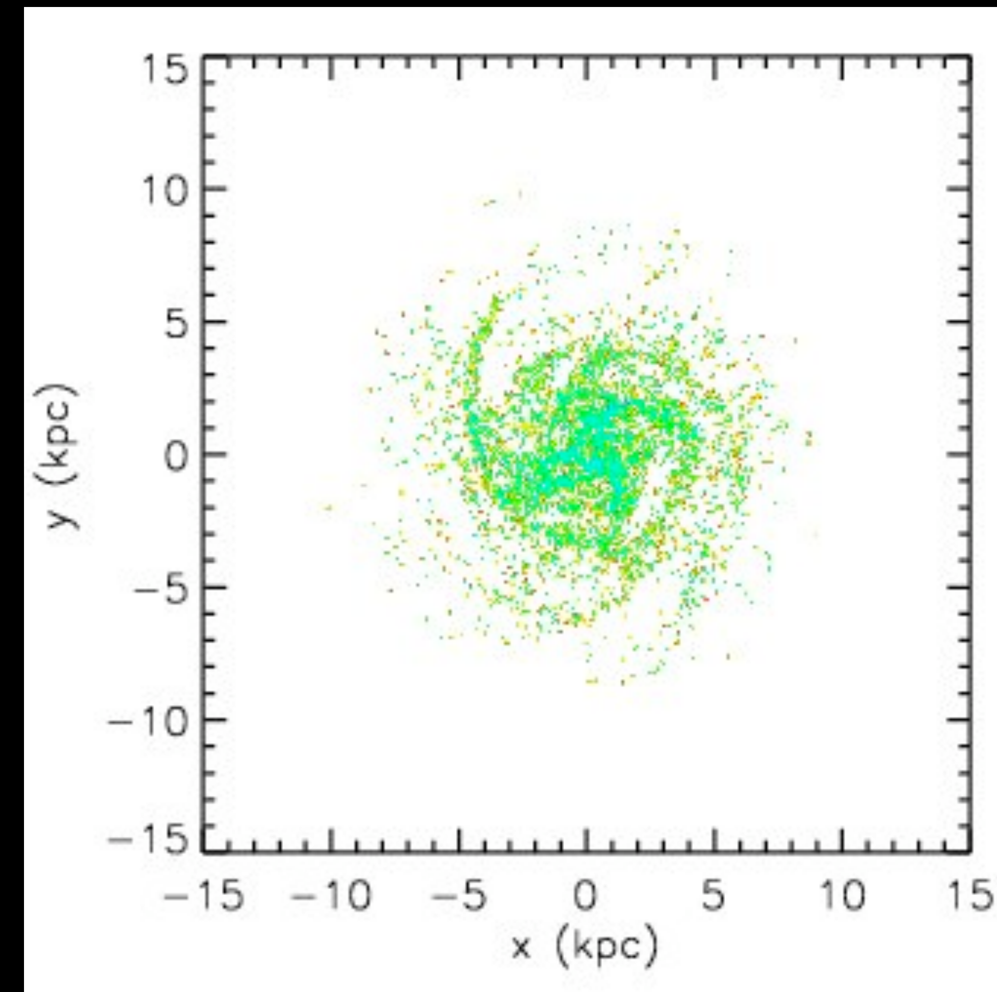
Resonances

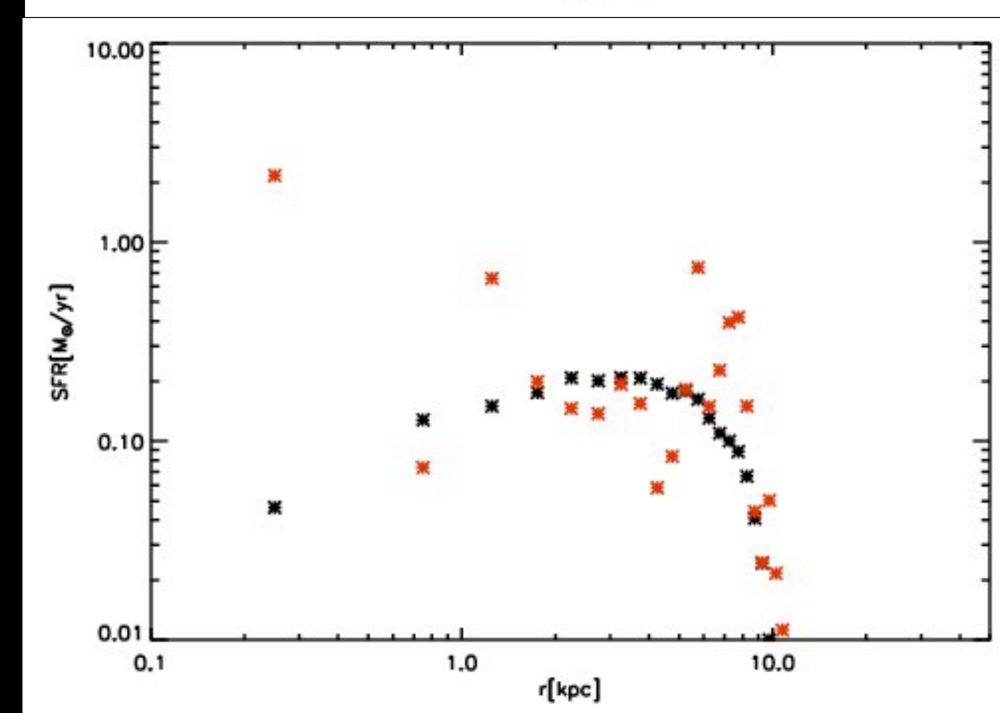




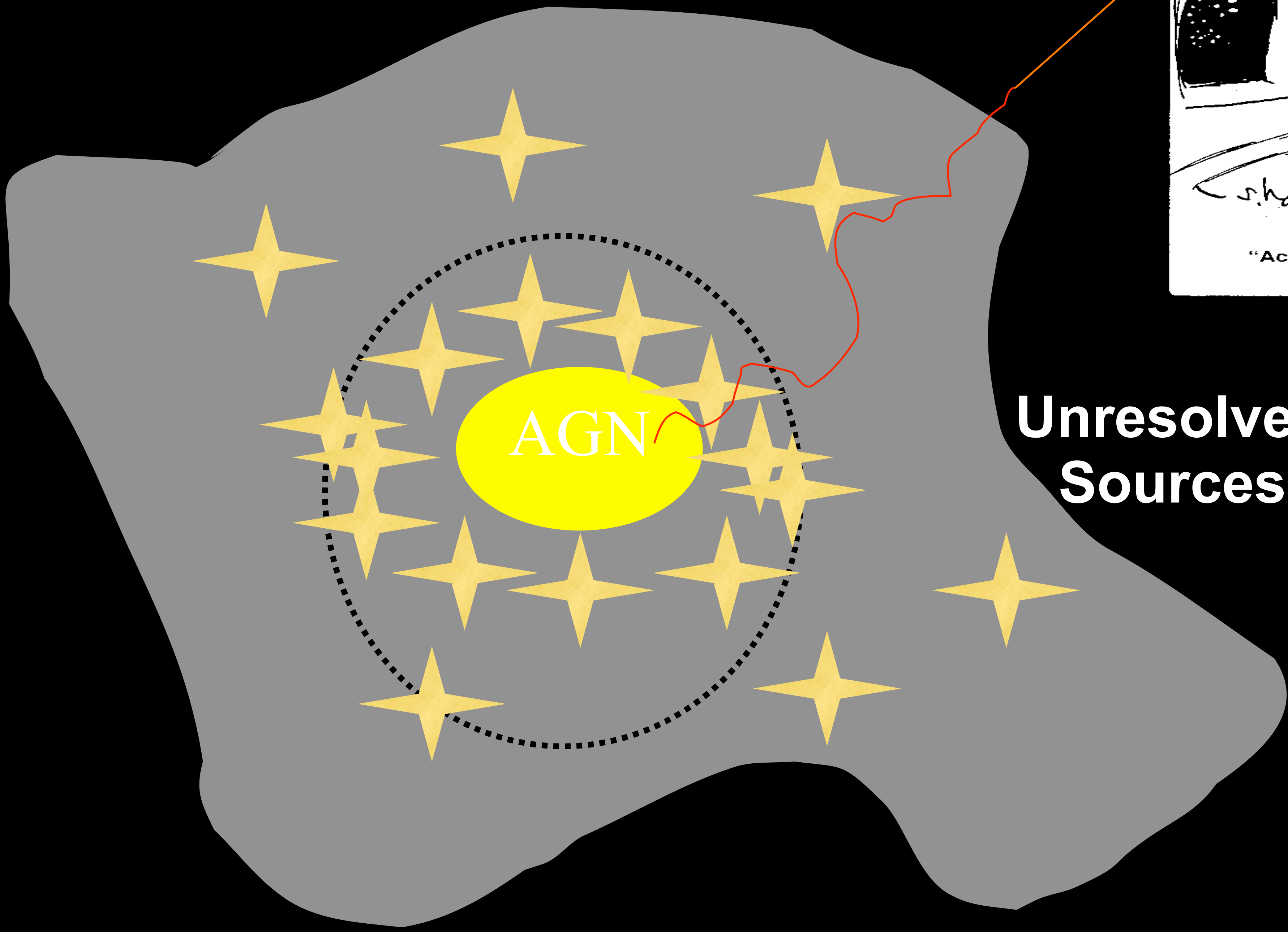
Long-term persistence of spiral structure: Chakrabarti 2009

Star Formation (preliminary)

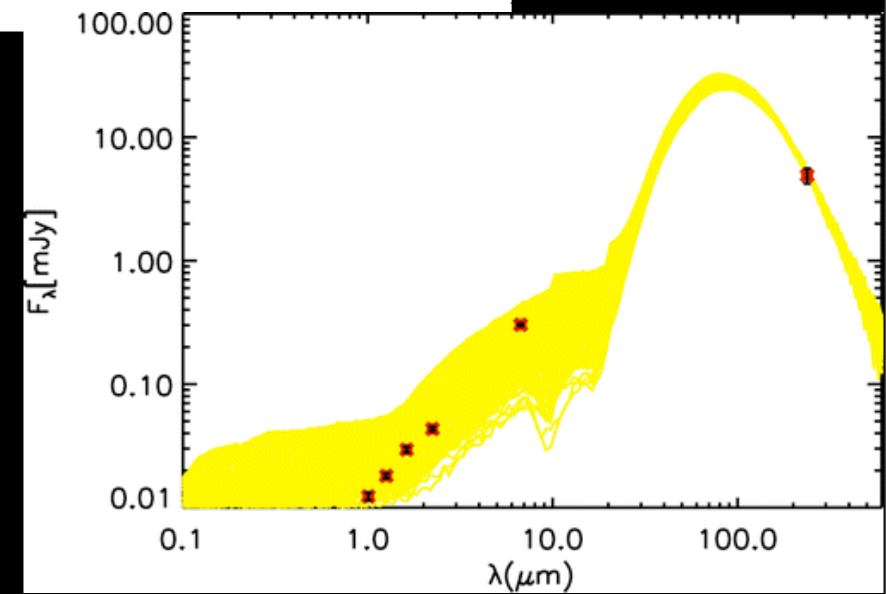




RADISHE: Photons that emerge undergo: attenuation,scattering, reemission



Unresolved Sources



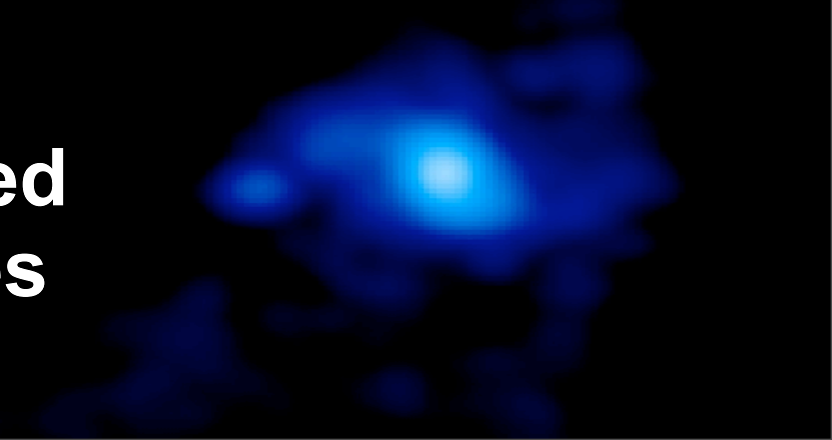
Chakrabarti & Whitney 09; Chakrabarti et al. 2008, Chakrabarti et al. 2007

Temperature: Radiative Equilibrium:

Energy Balance:

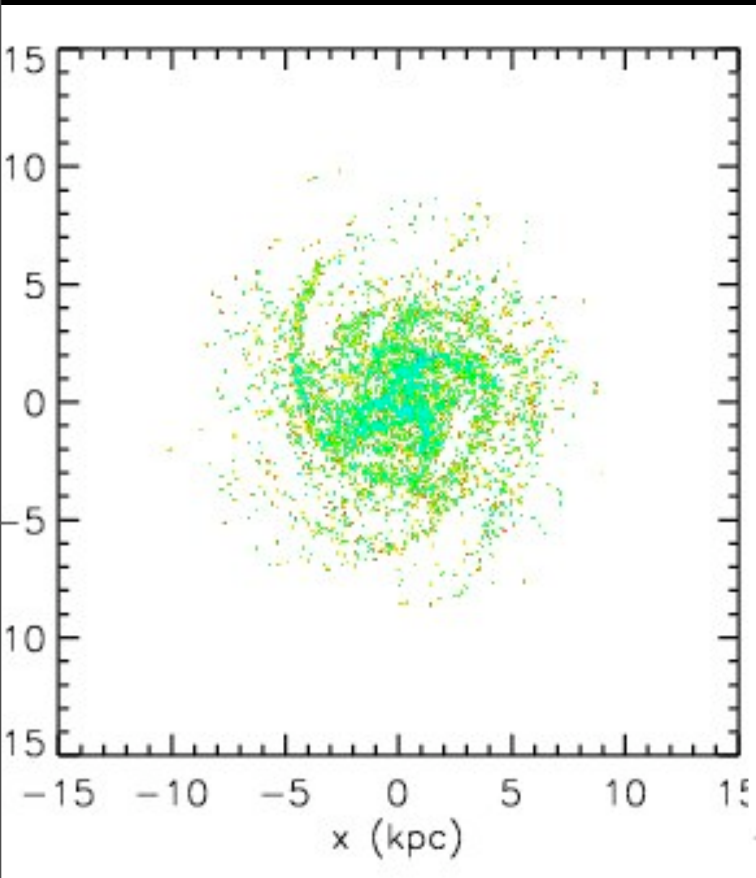
$$\int \kappa_\nu B_\nu(T) d\nu = \int \kappa_\nu J_\nu d\nu$$

Resolved Sources

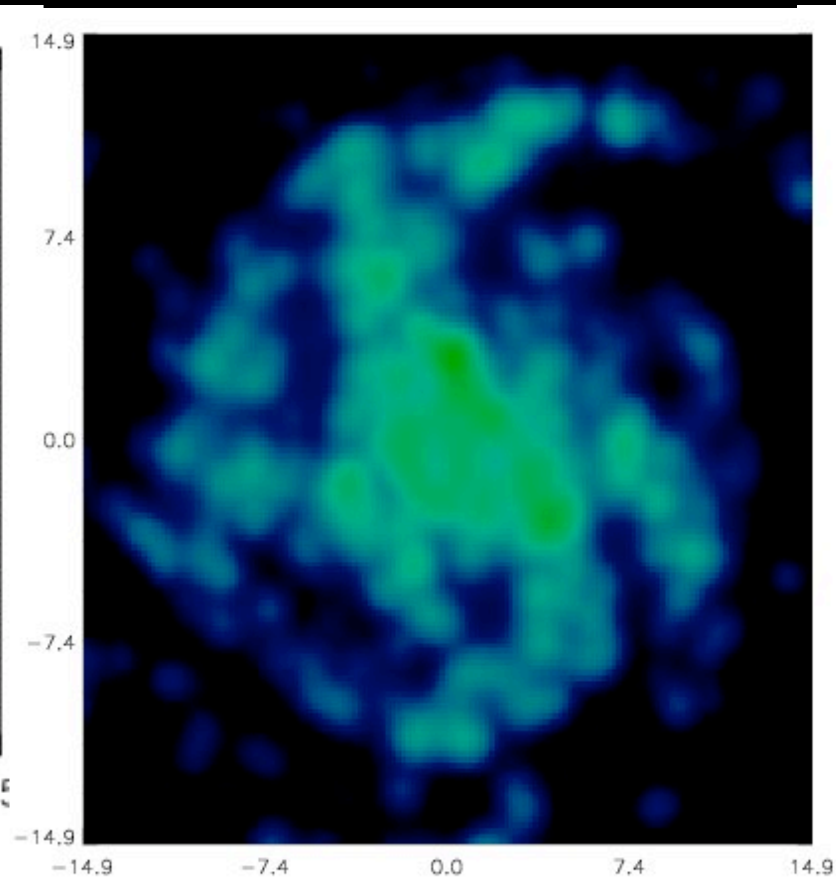


Star Formation & IR Emission

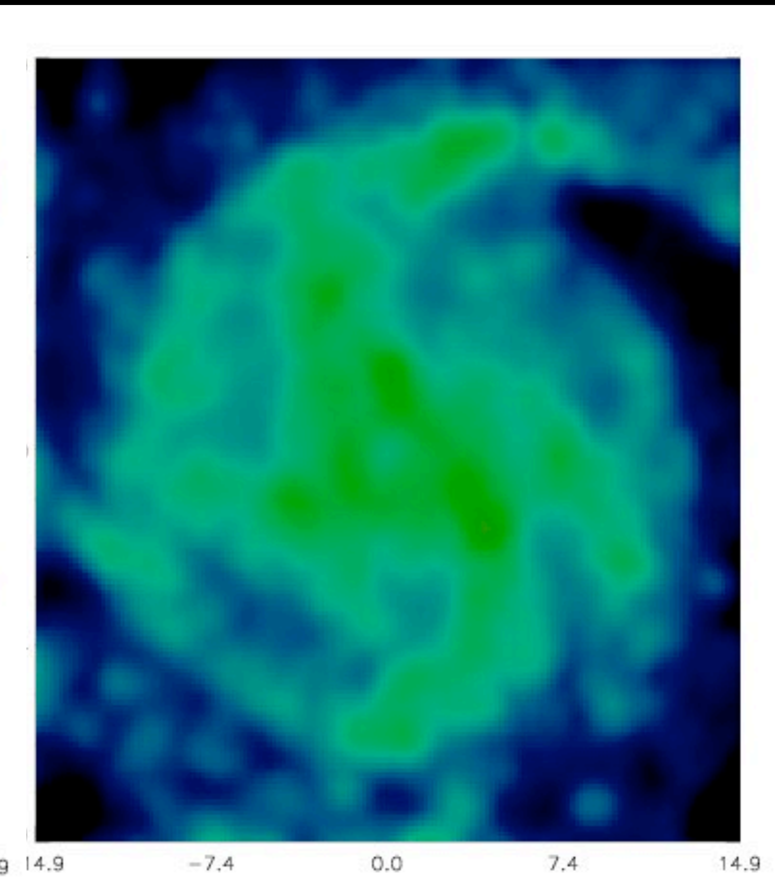
New Stars



70 µm

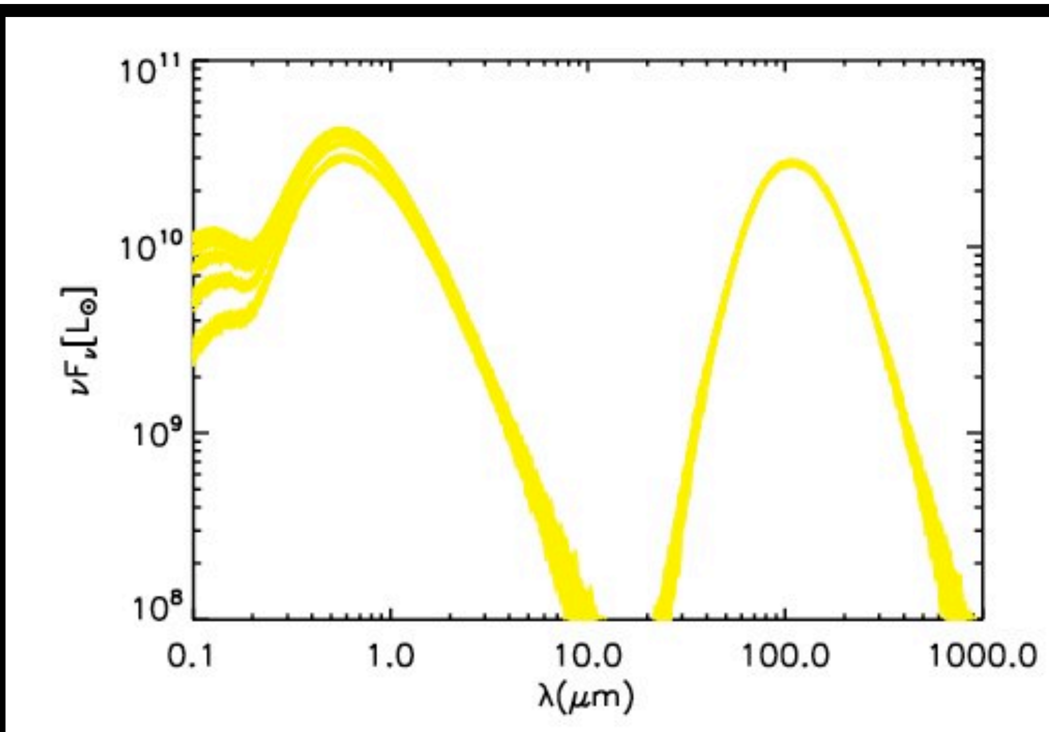


160 µm



Images & SED from RADISHE

Note diffuse emission from longer wavelengths (Chakrabarti & McKee 2005)



In Preparation: (Chakrabarti, Whitney et al.)

Can we quantify SFR profiles from the IR emission images & SED?

Summary & Future Work

- Analysis of perturbations in cold gas on outskirts of galaxies →constrains mass of dark perturbers.
- In preparation: quantify relations between star formation rate (profiles) in simulations and IR emission and compare to sub-kpc observations of spirals