Deciphering the Dynamical Echoes of Dwarf Galaxies on Galactic Disks

Sukanya Chakrabarti (RIT)
Collaborators: Frank Bigiel (Heidelberg) Leo Blitz (UCB), Philip Chang (UWM), Victor Debattista (UCLan), Alice Quillen (U.Rochester), Roberto Saito (PUC, Chile), Evan Kirby (Caltech)

Overview

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

- Galaxies with optical companions : Proof of Principle

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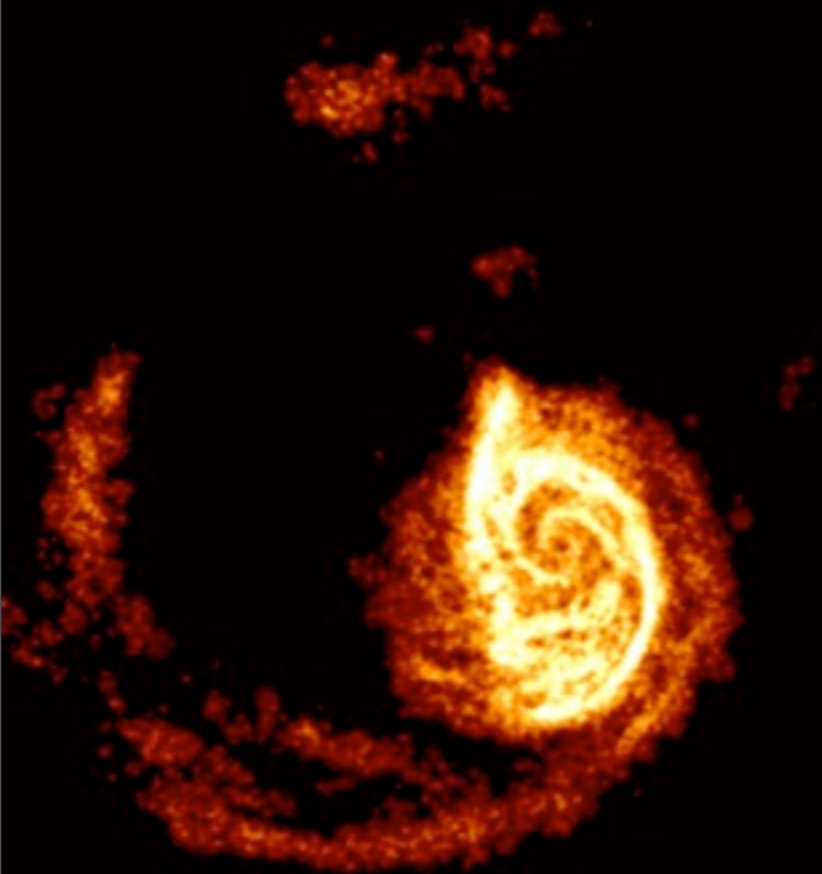

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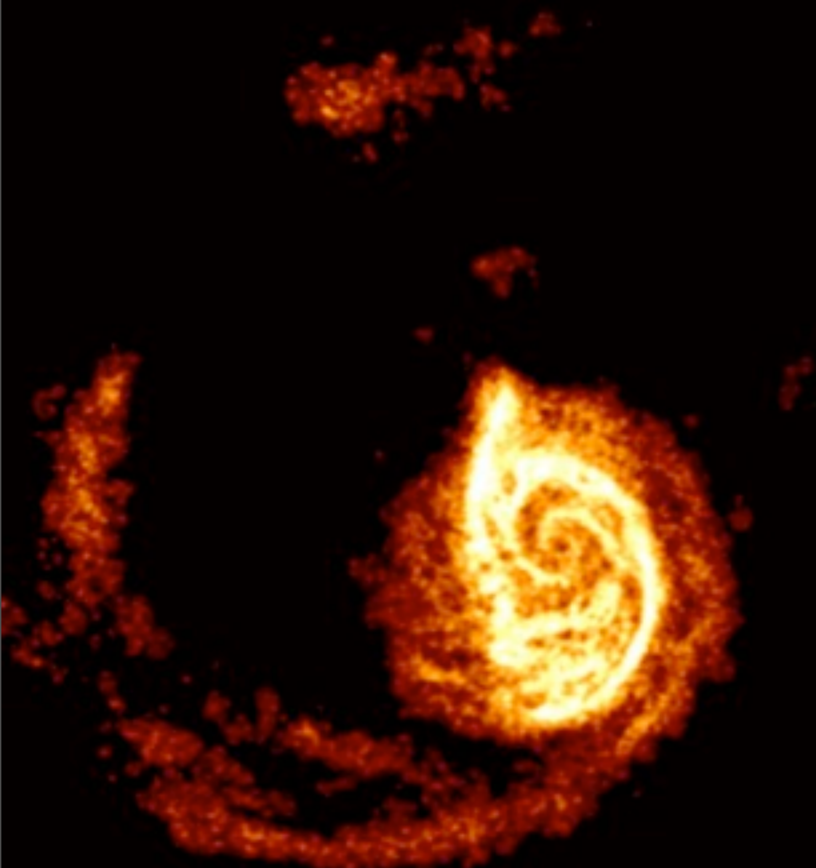

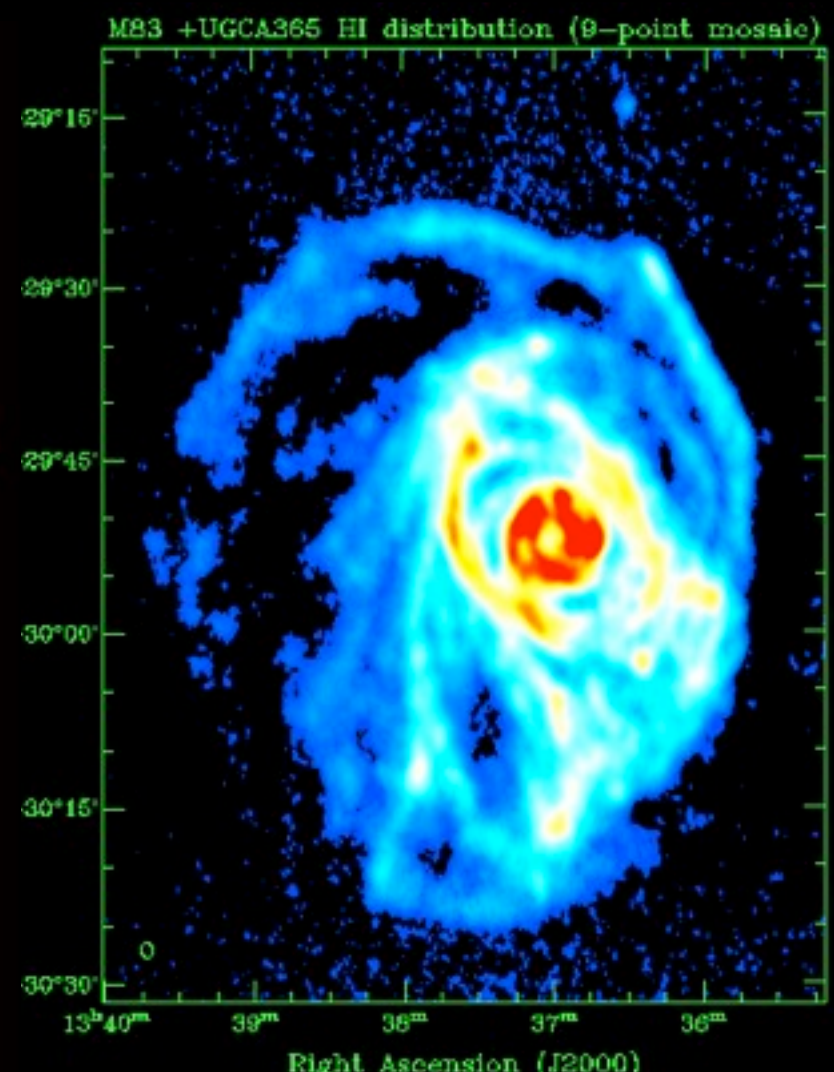

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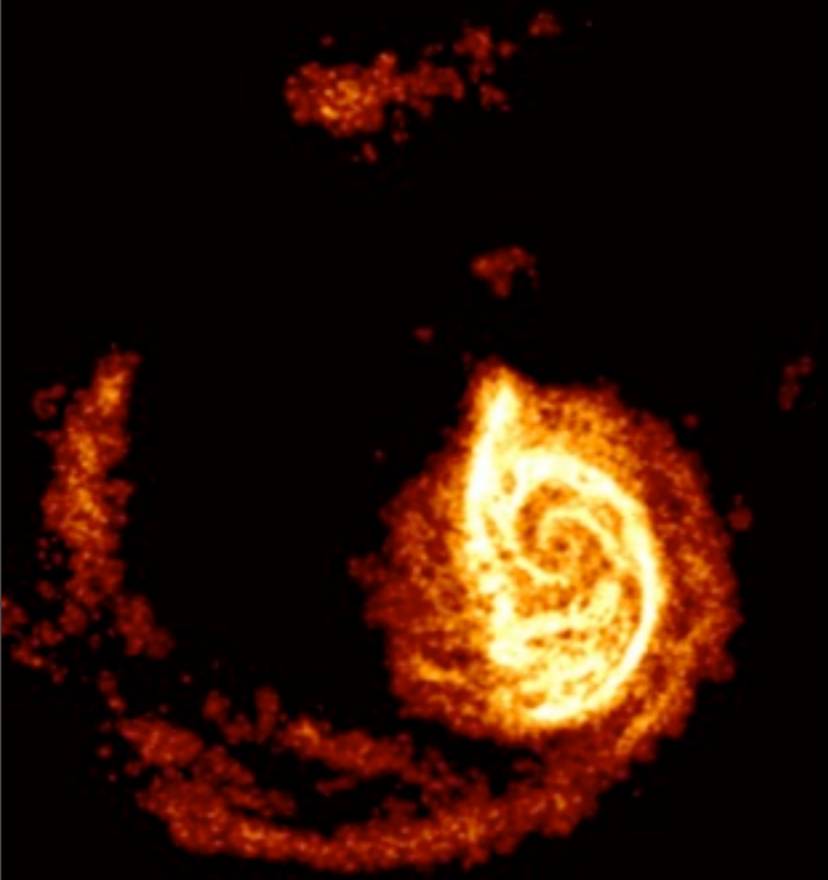

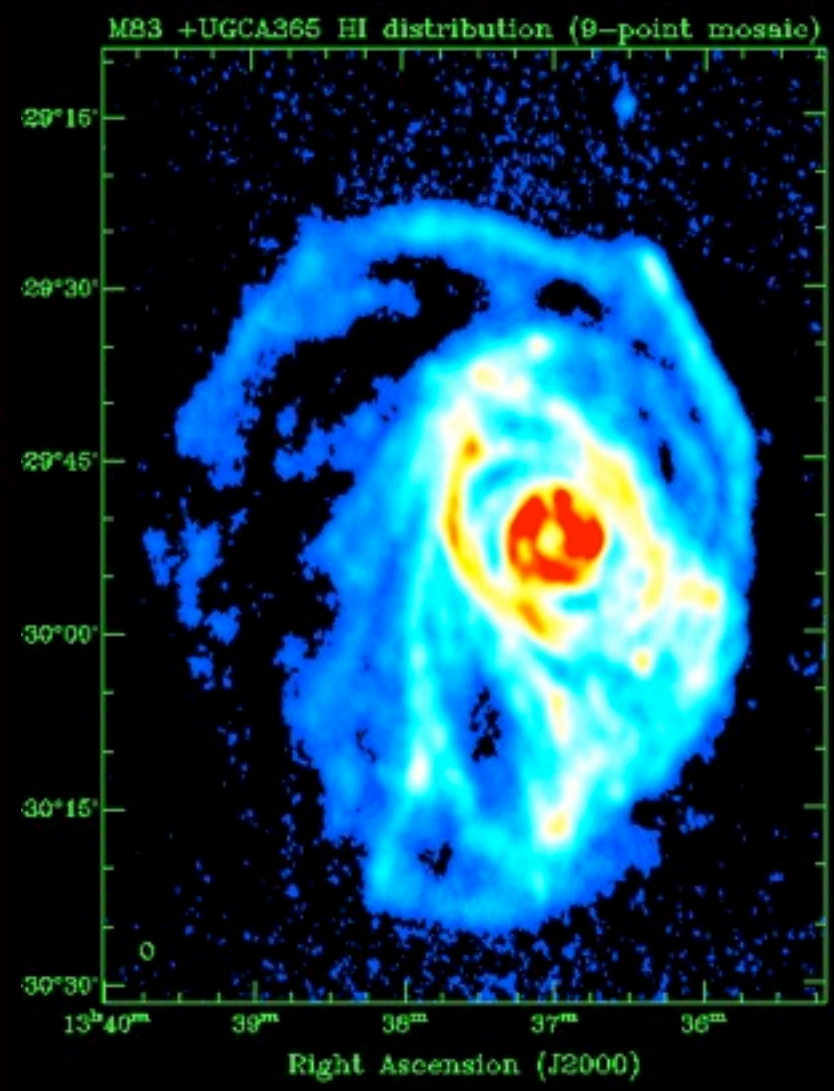

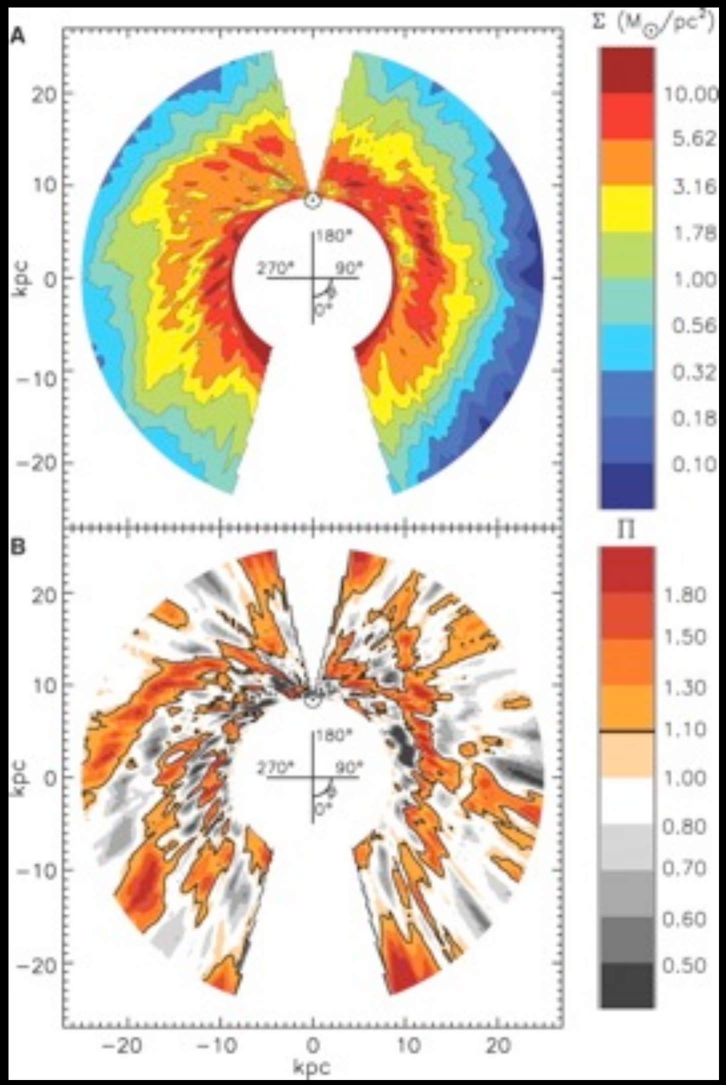

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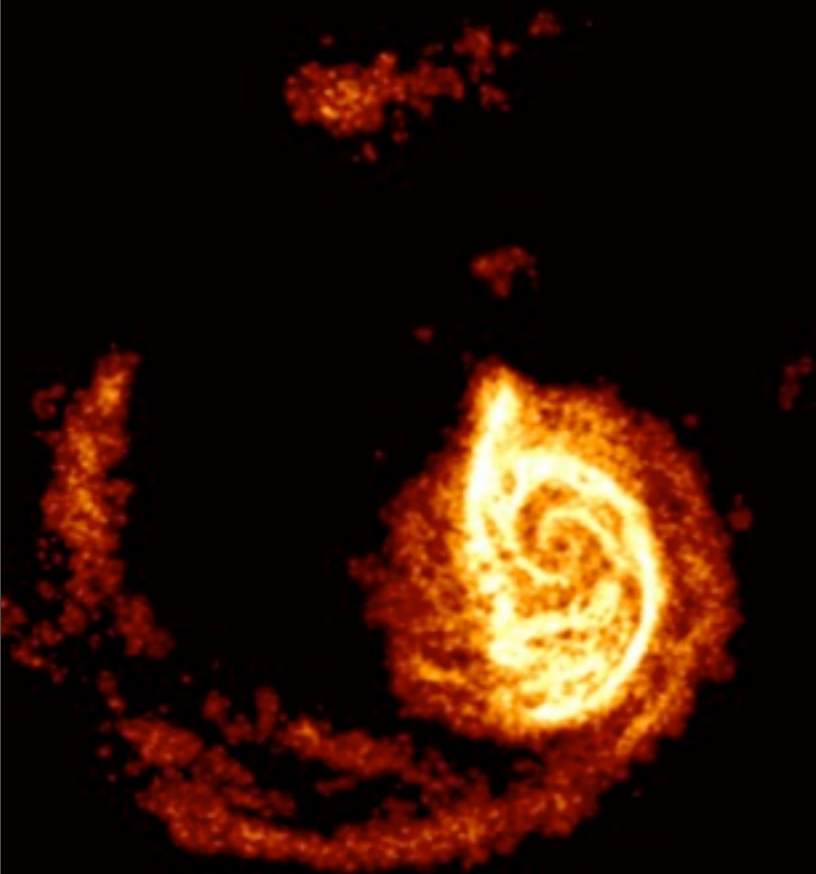

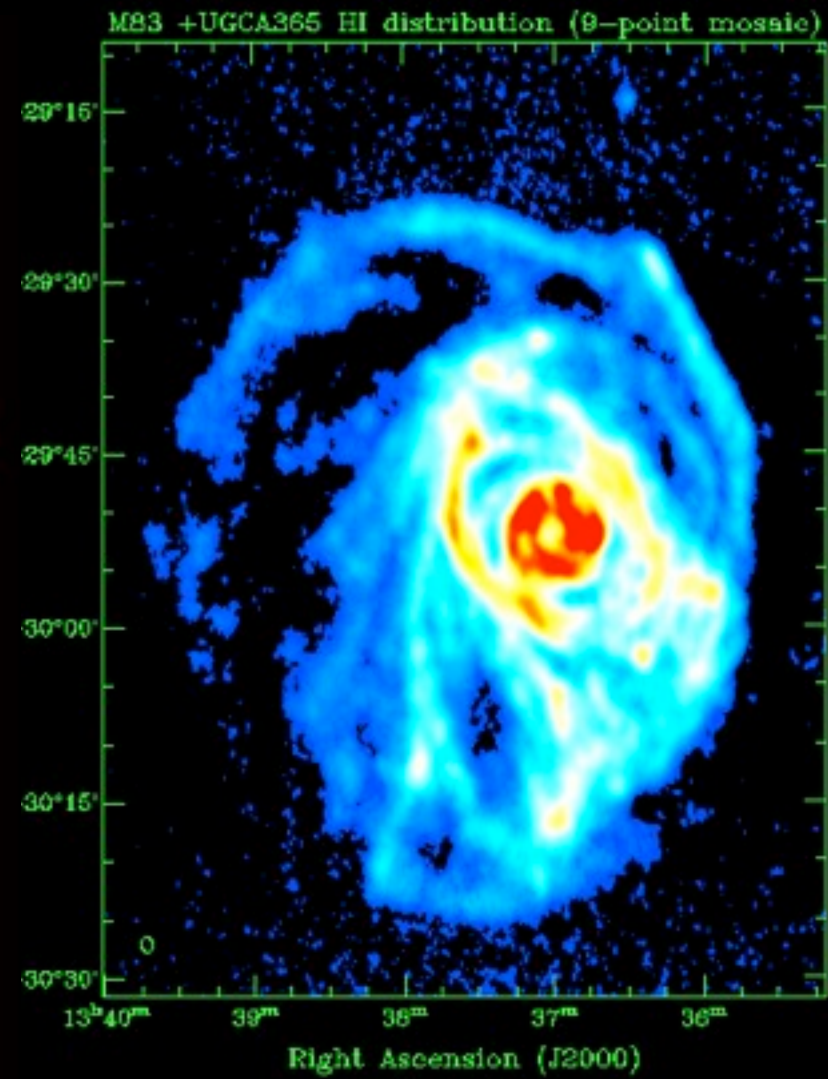

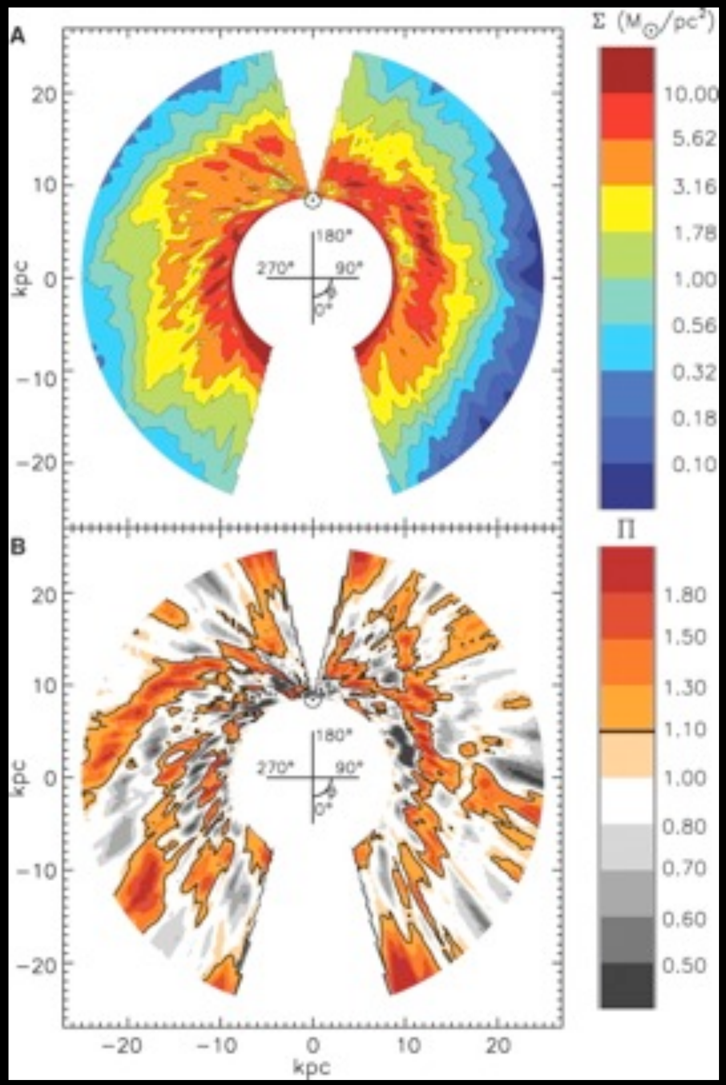

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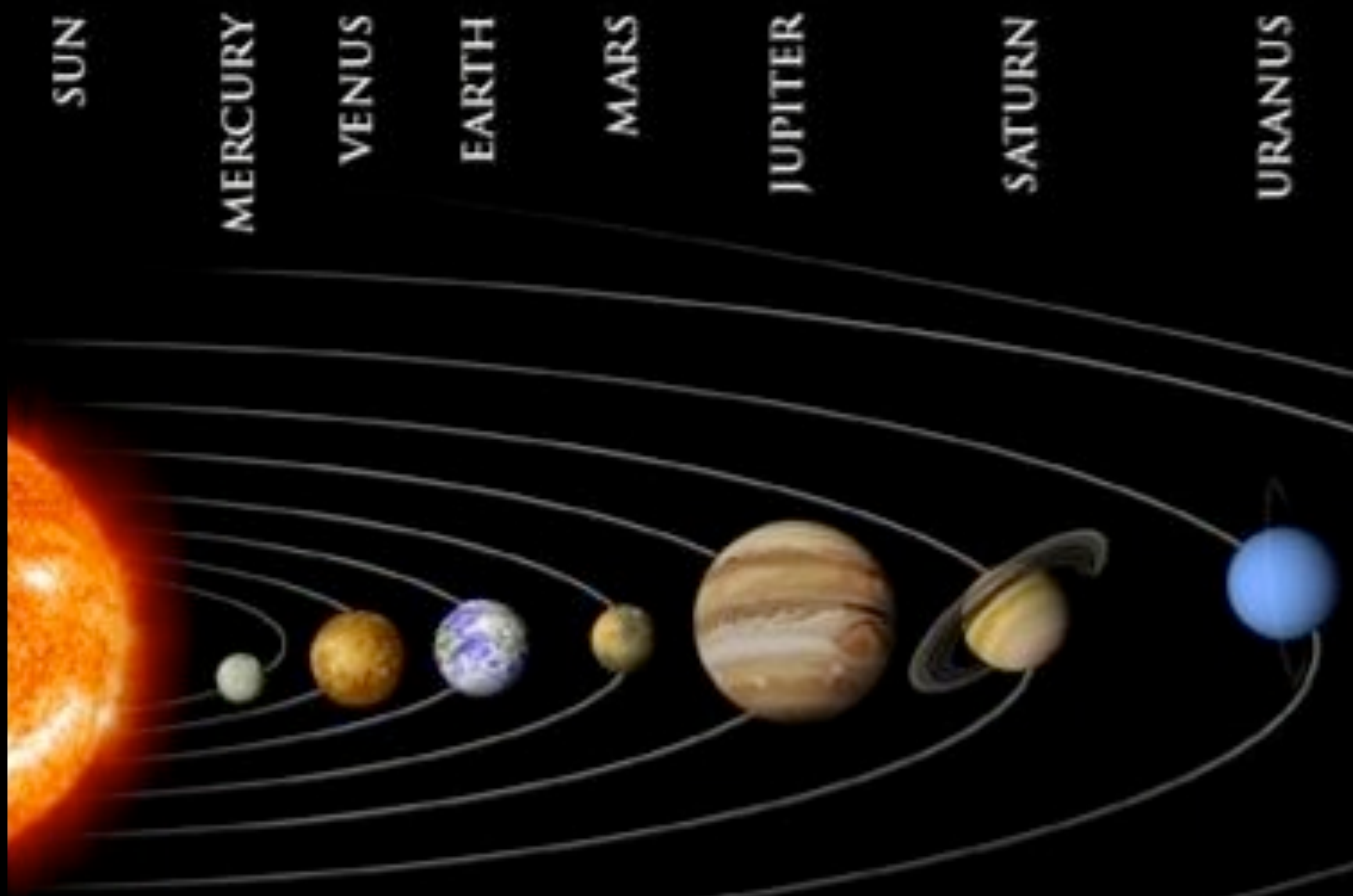
- The Milky Way

Analogy with Planetary Dynamics: Discovery of Neptune



- Urbain Le Verrier: Aug 13 1846: predicted azimuth of Neptune

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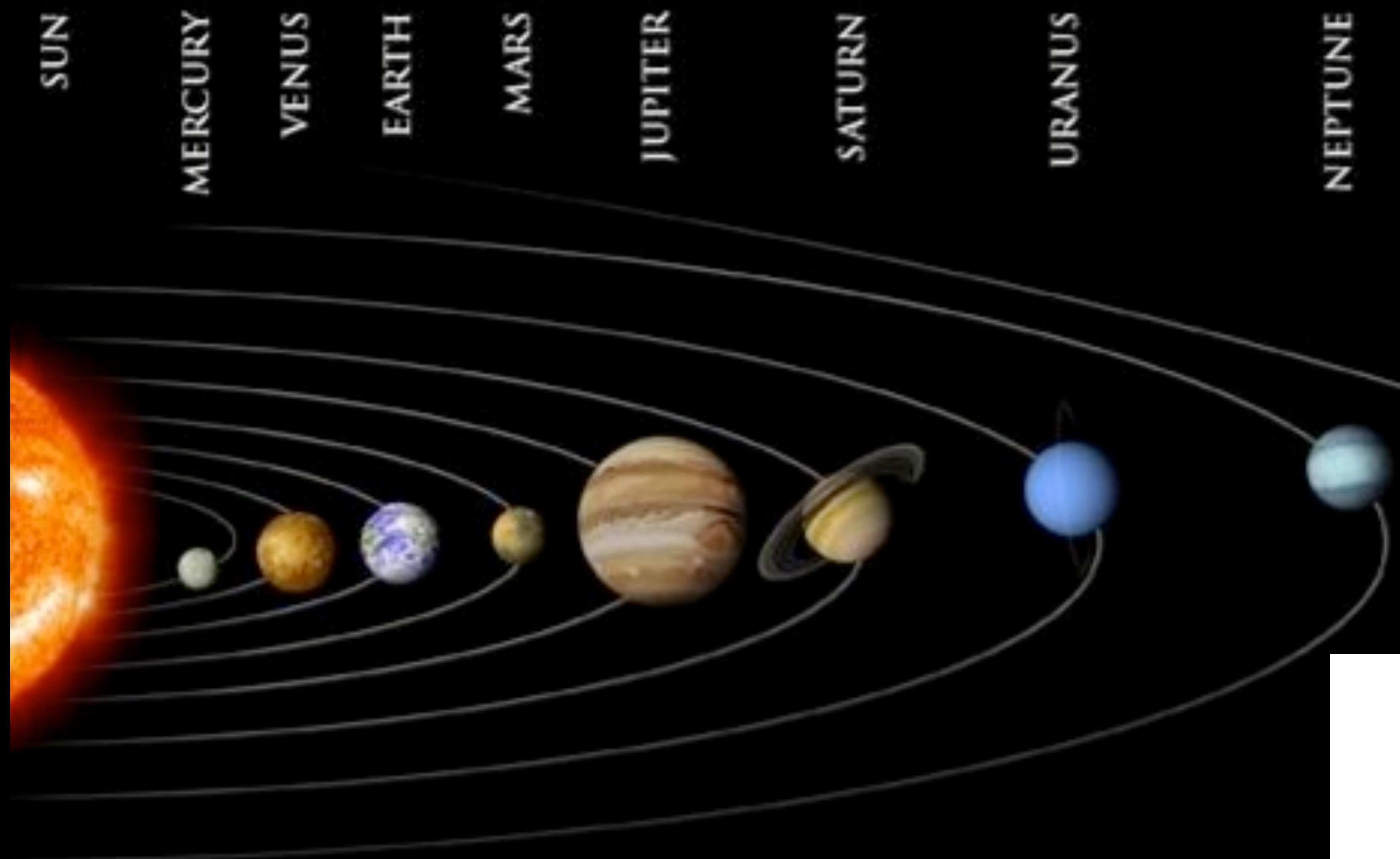

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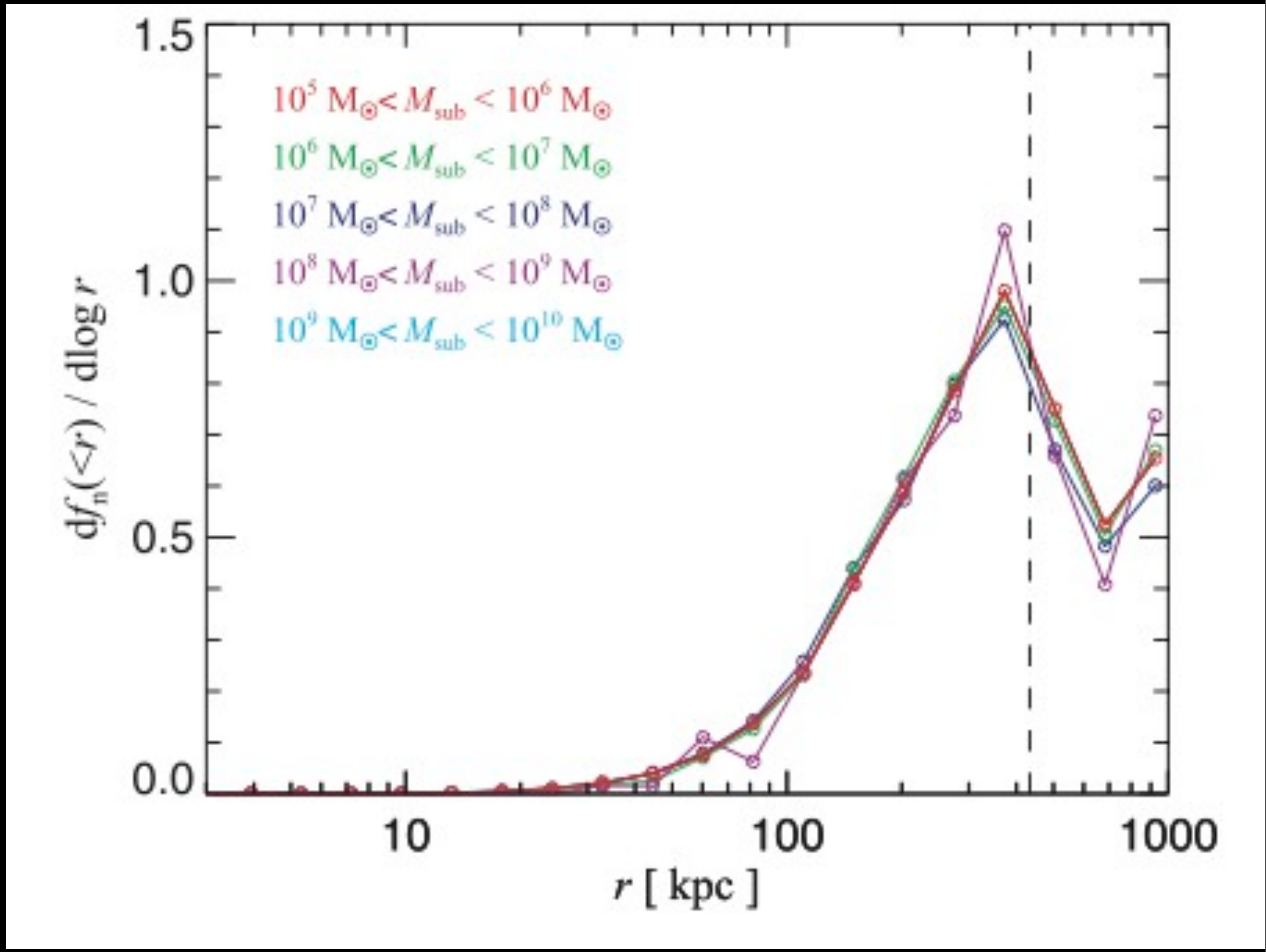
Extended HI disks as tracer of sub-halo interactions

- cosmological simulations predict most sub-halos of a given mass are in the outer parts of the halo

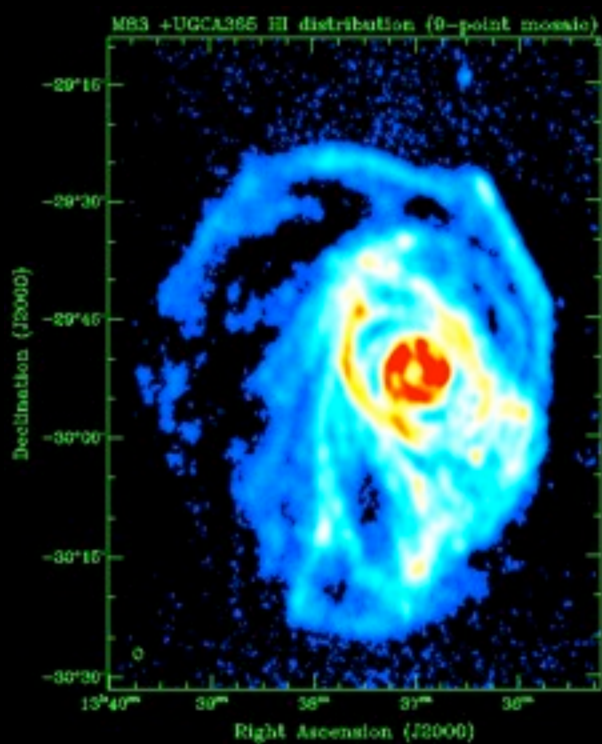
- M83's HI disk reaches to ~ 100 kpc -- where simulations *expect* the sub-structure to be



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!**



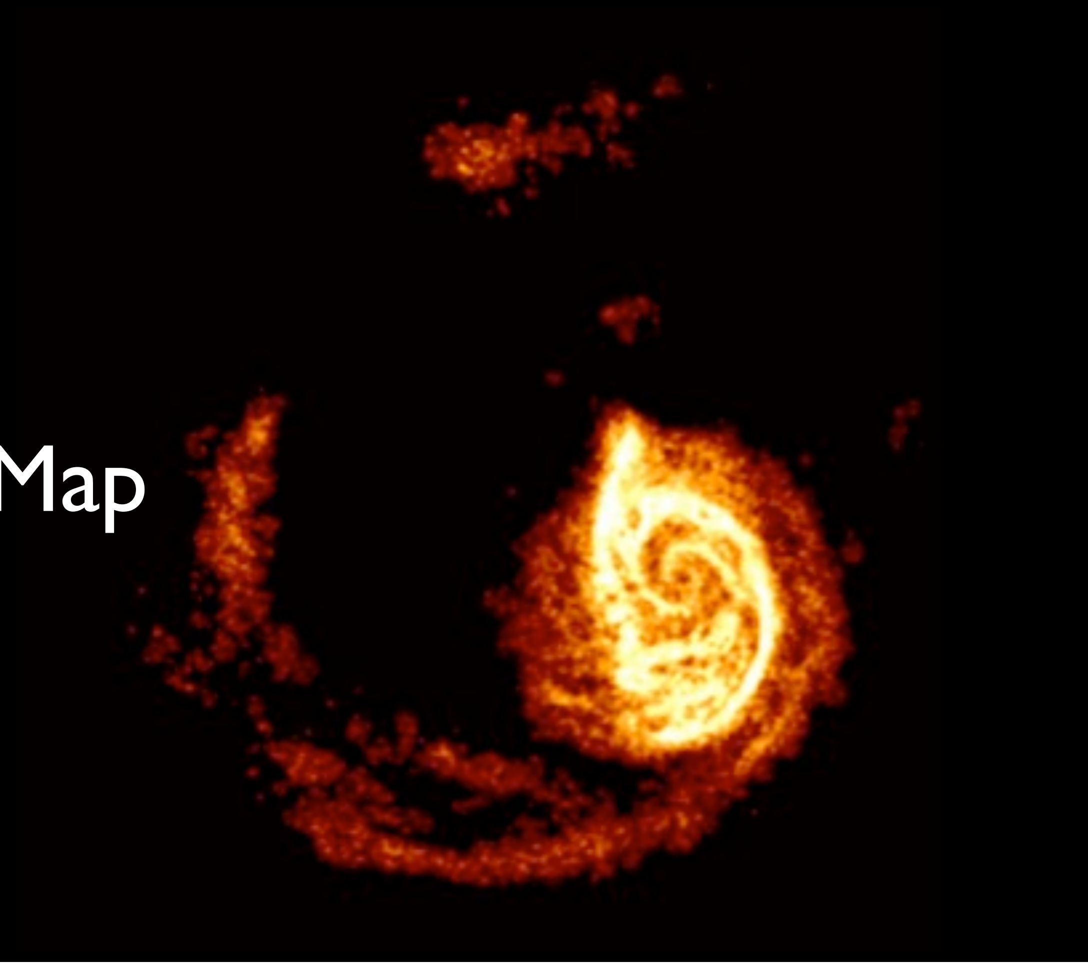
Atomic hydrogen (HI) Maps

Footprints of Dark Sub-Halos

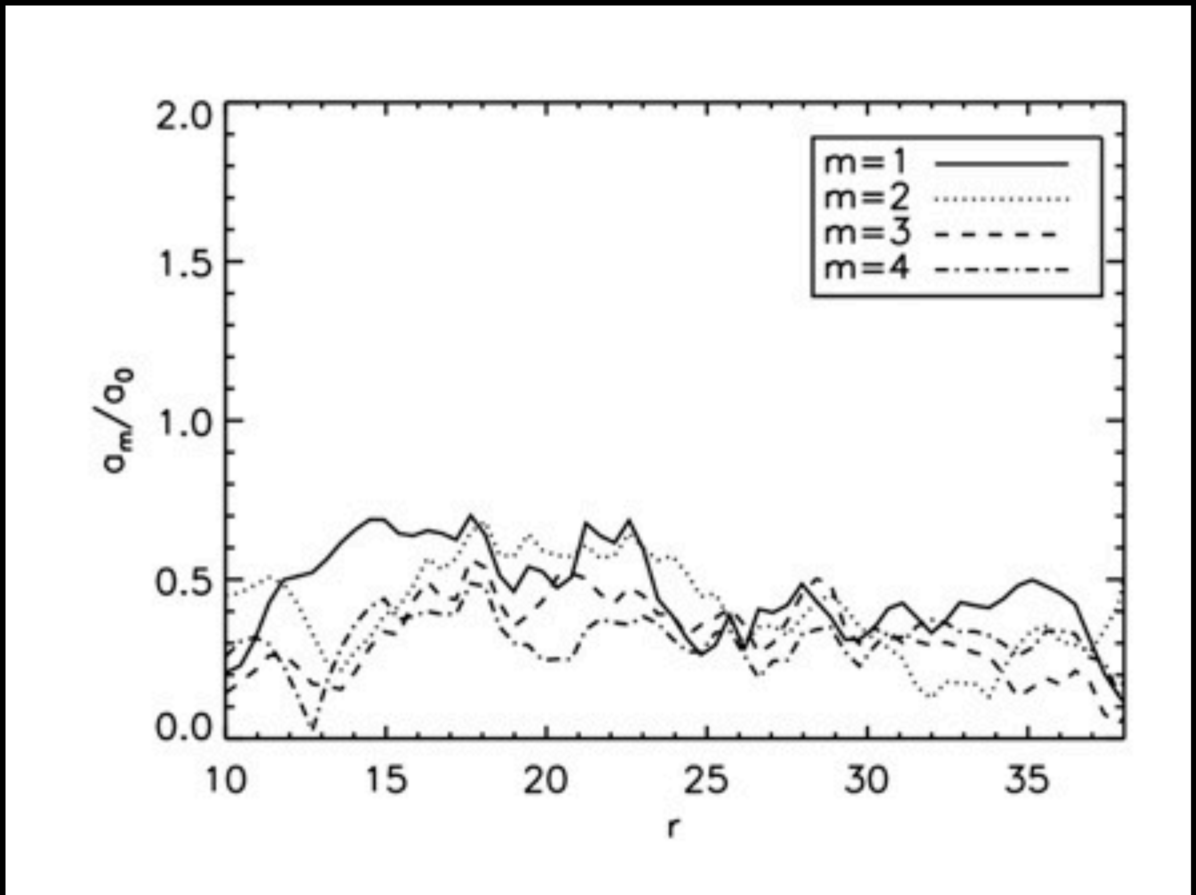
Disturbances in HI disks in Local Spirals: Proof of Principle

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

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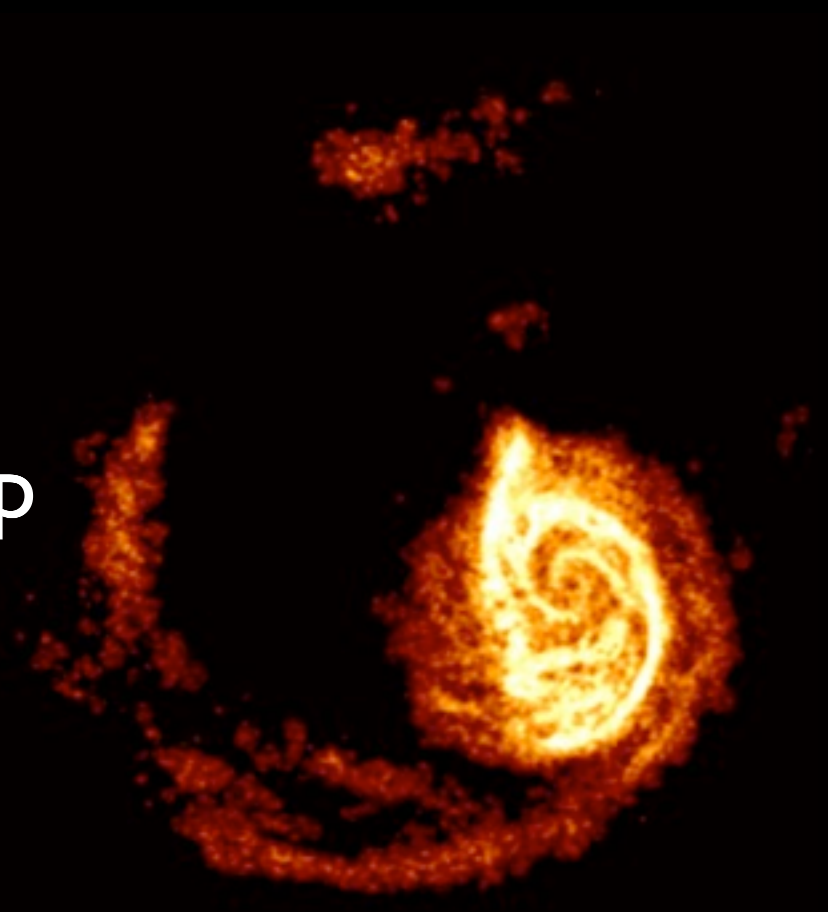

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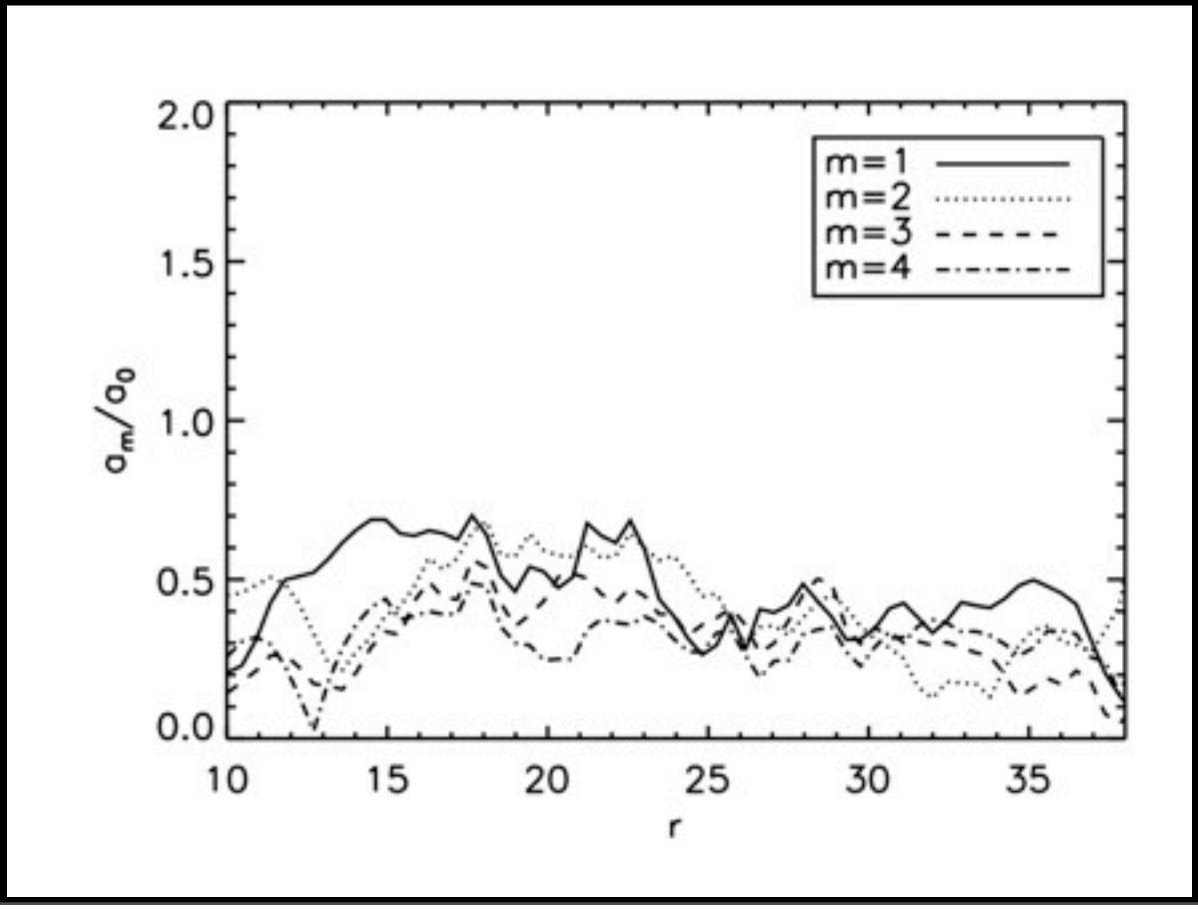

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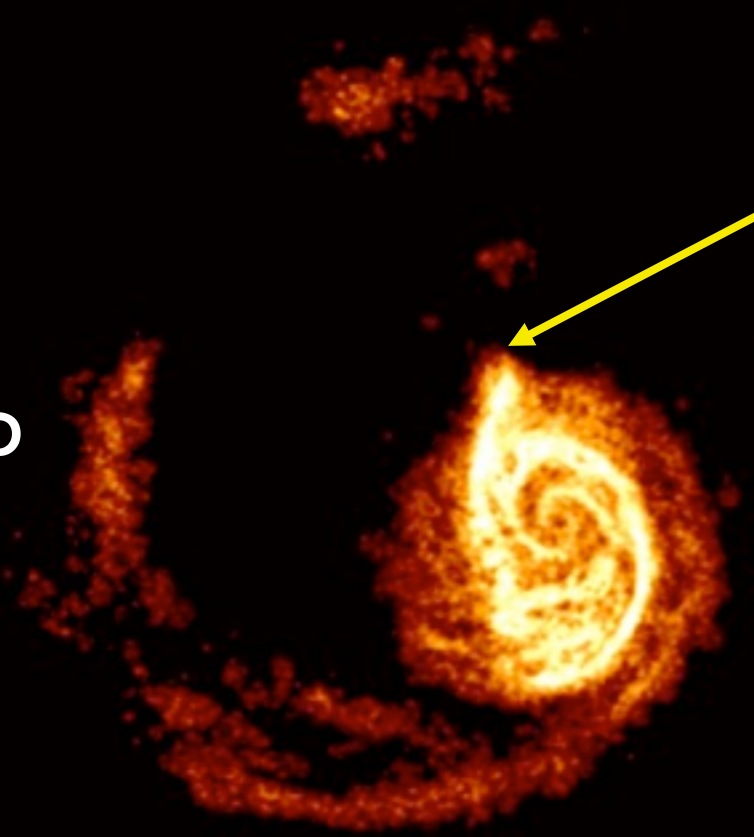

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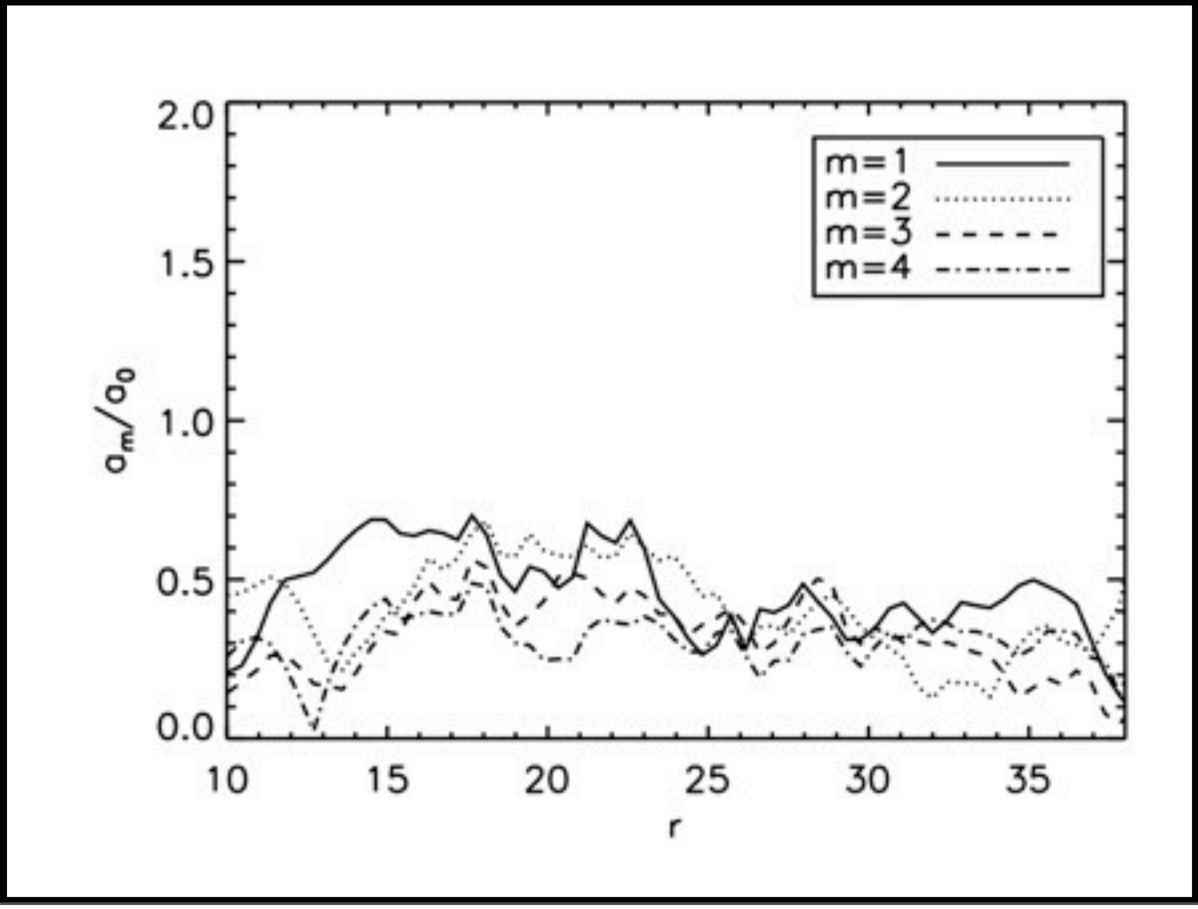

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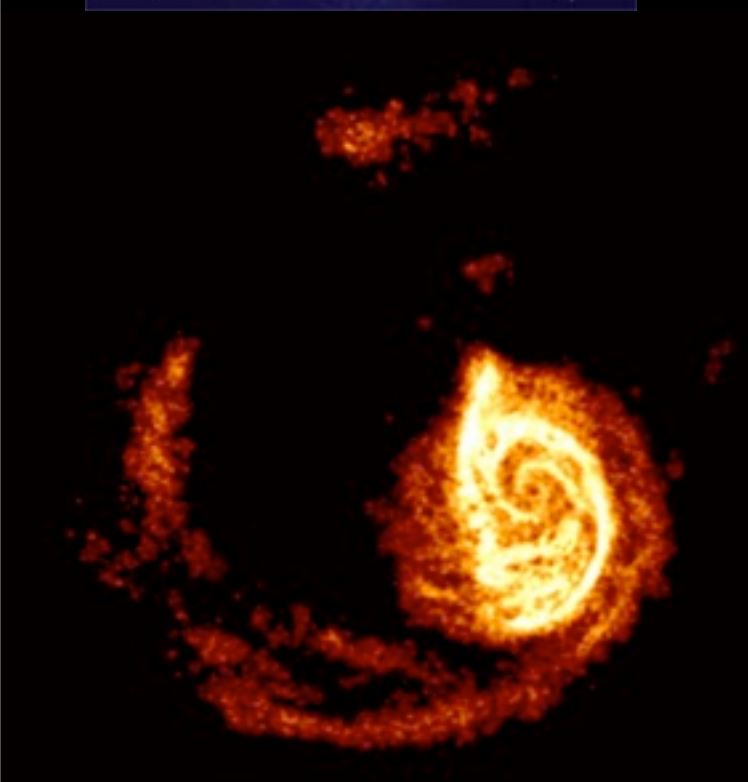
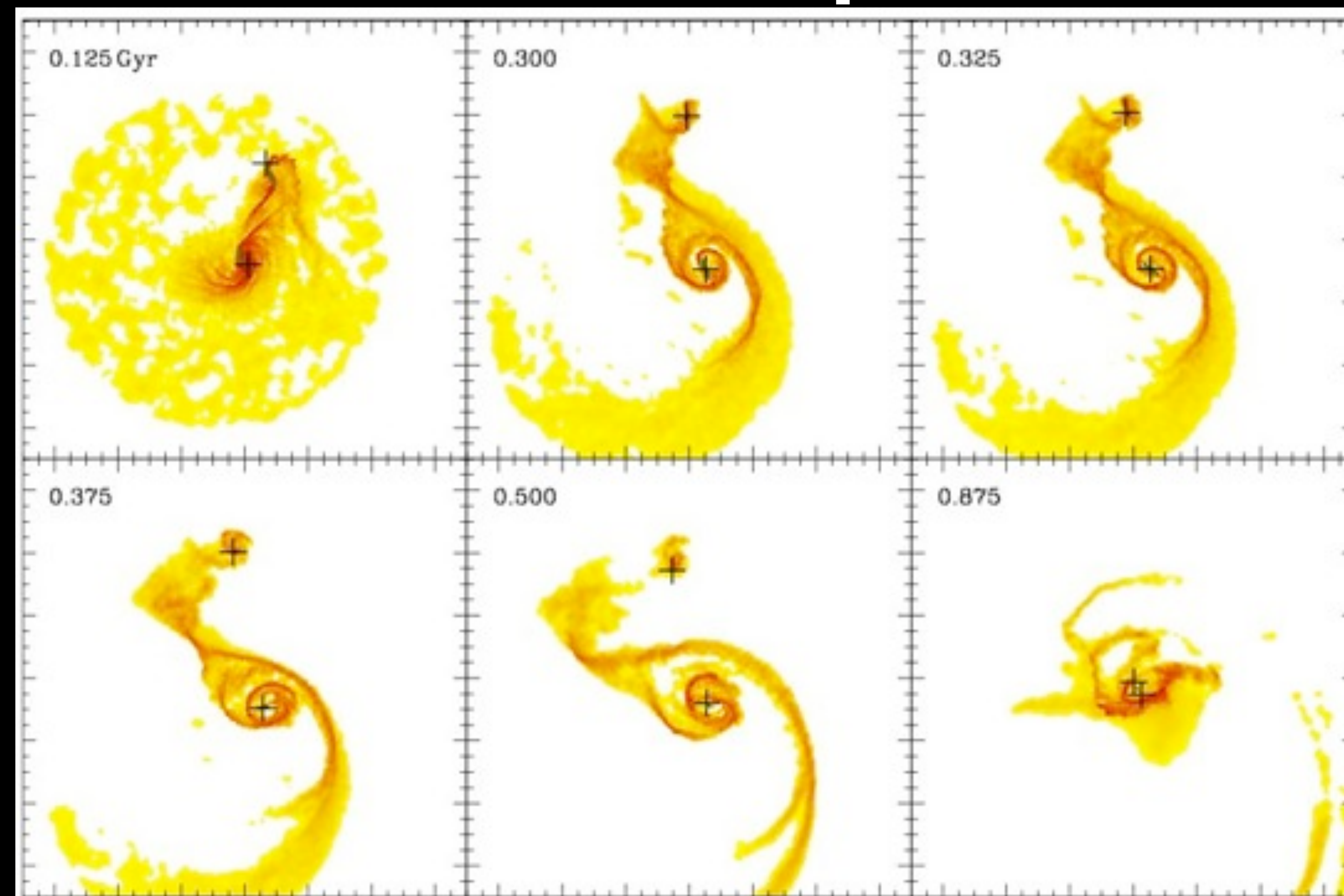
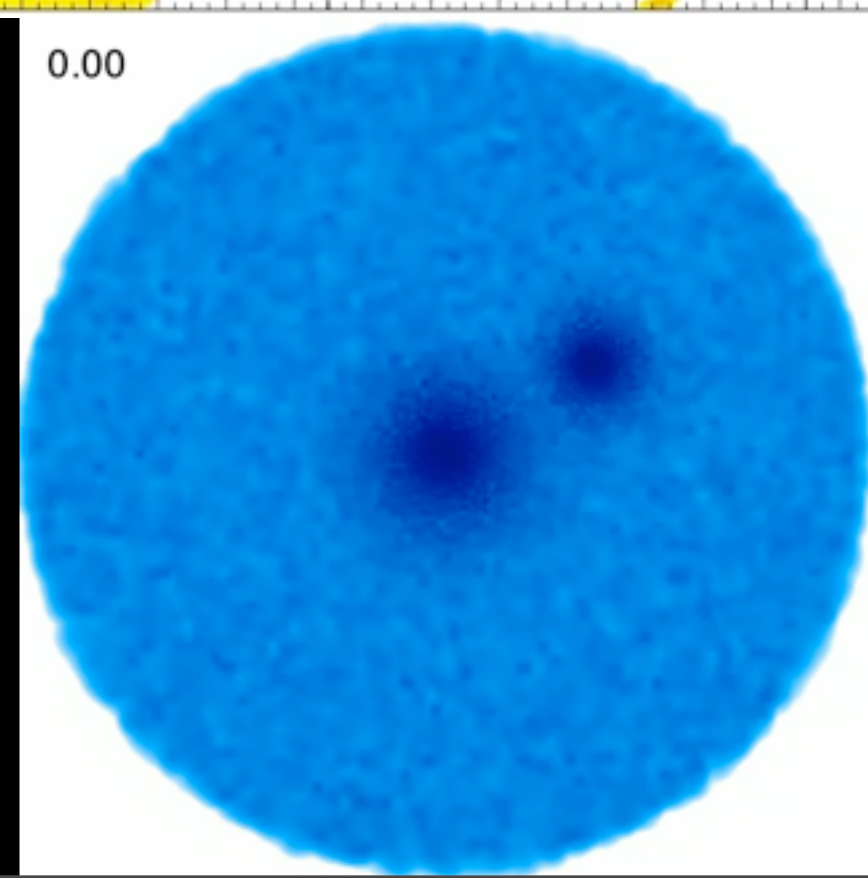
M51 : Proof of Principle

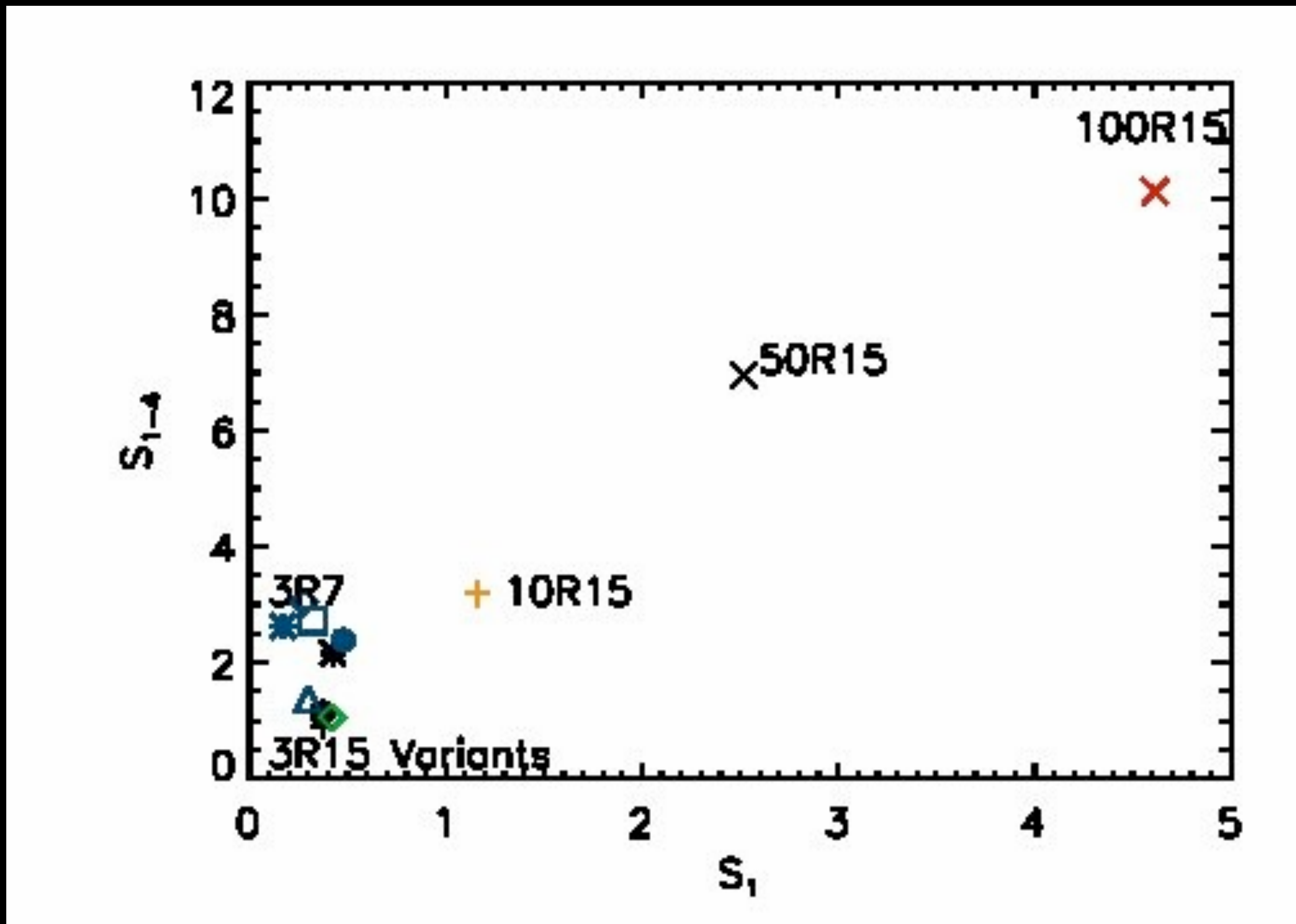




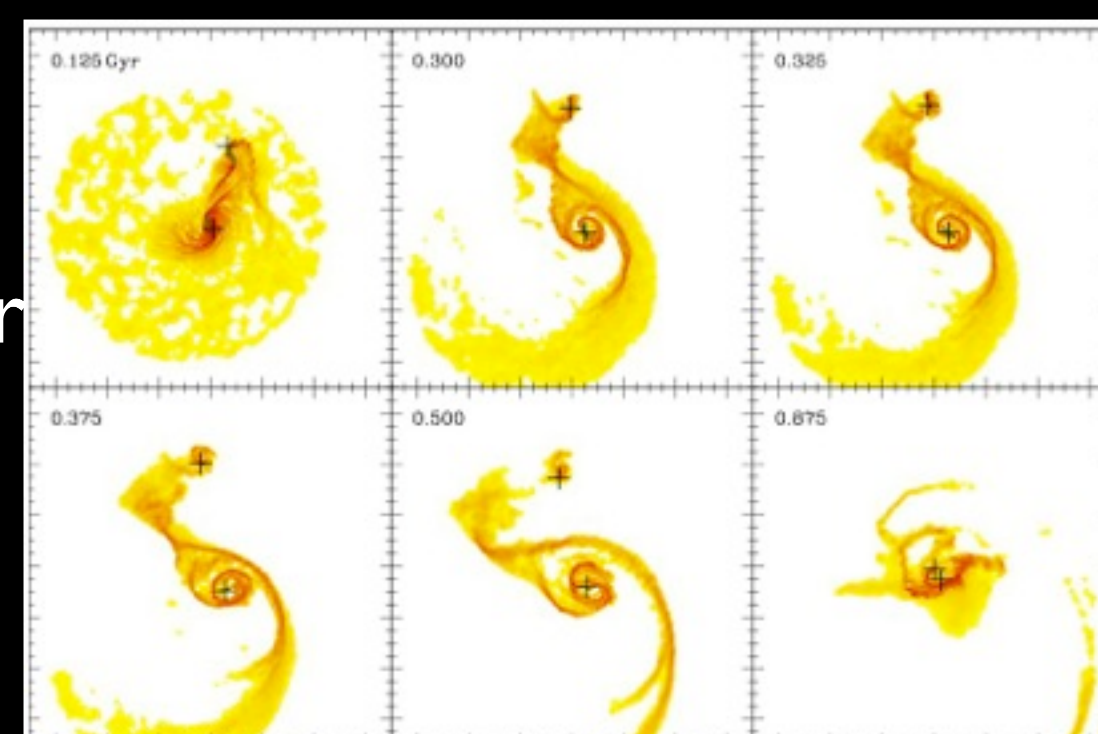


Chakrabarti, Bigiel, Chang & Blitz, 2011

Variance Vs Variance



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.



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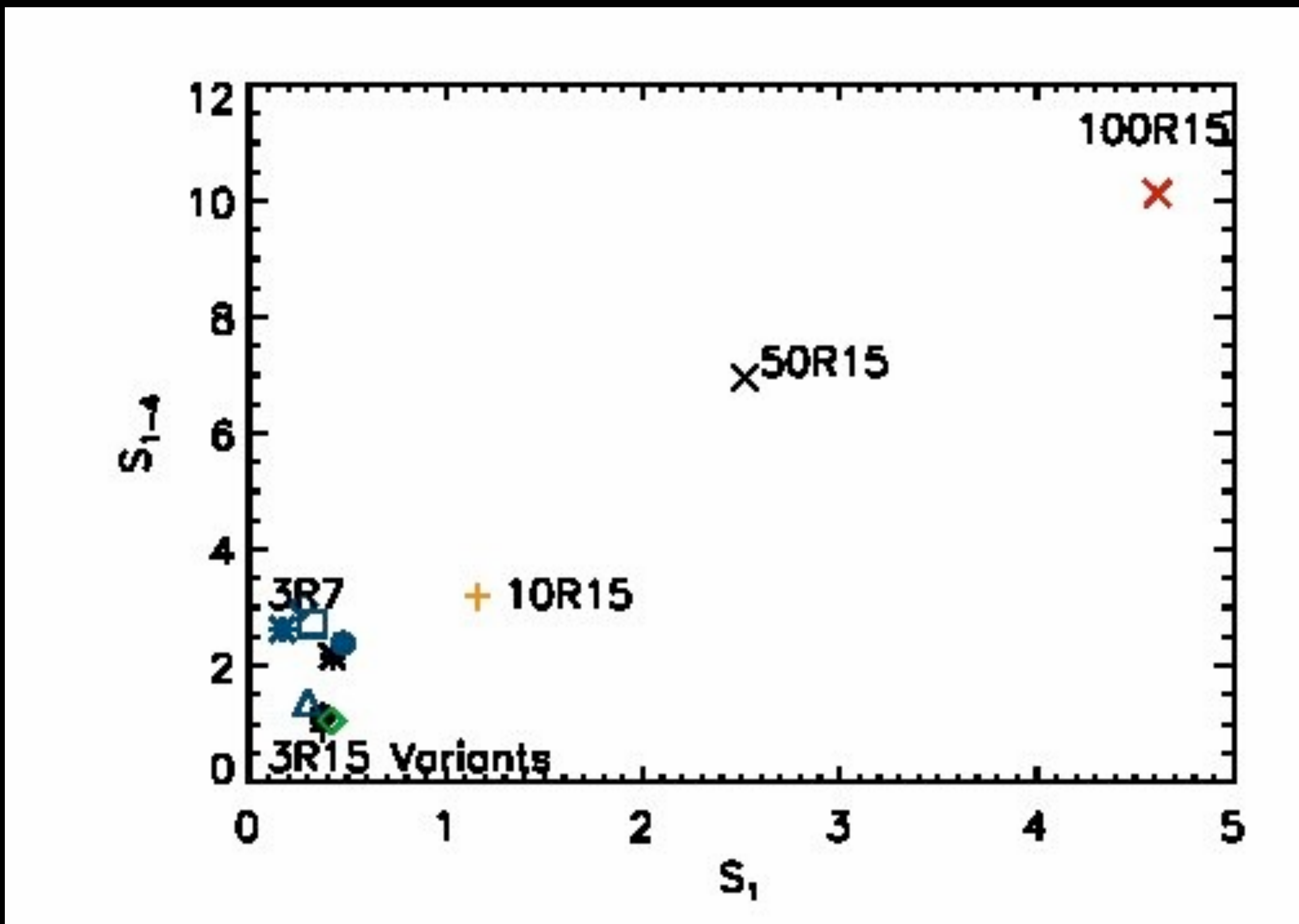

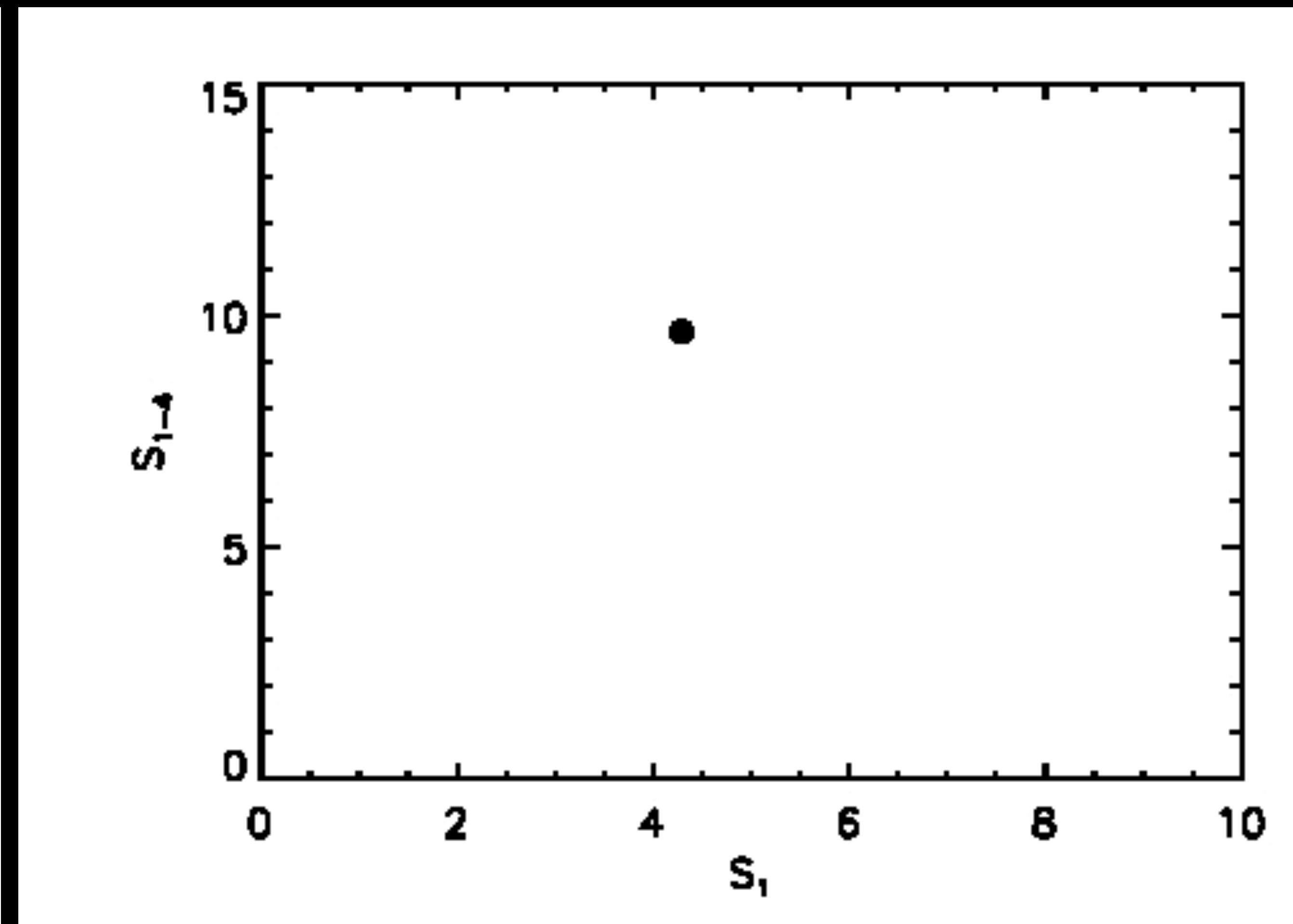

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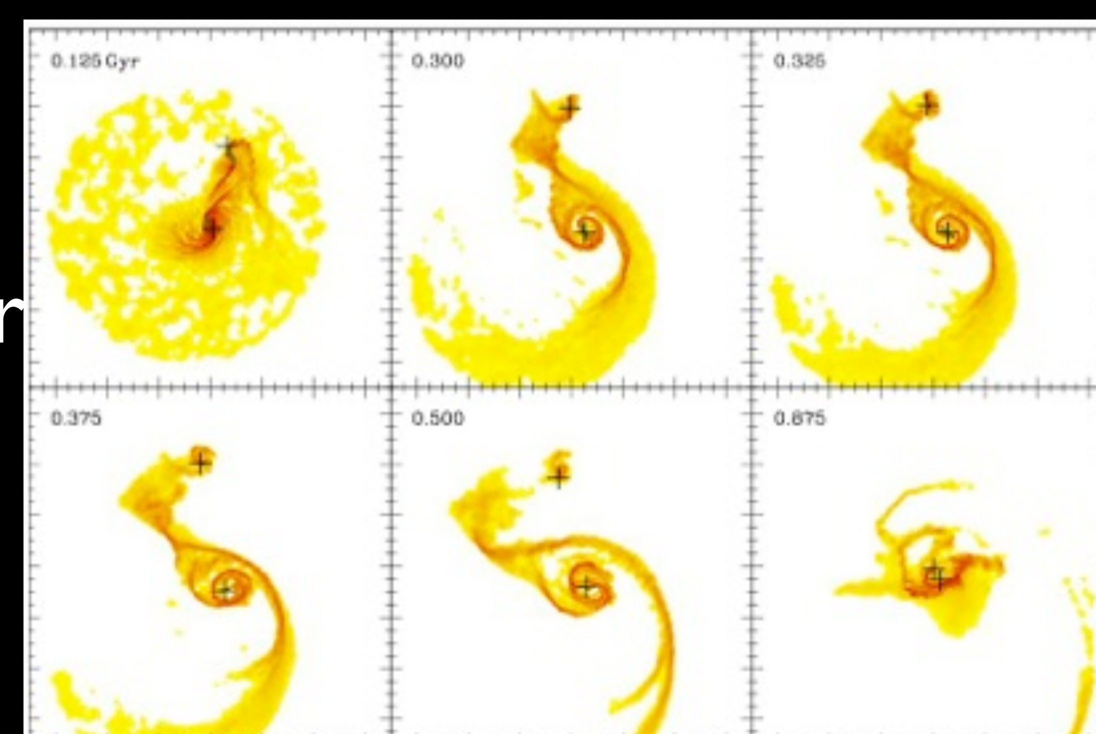

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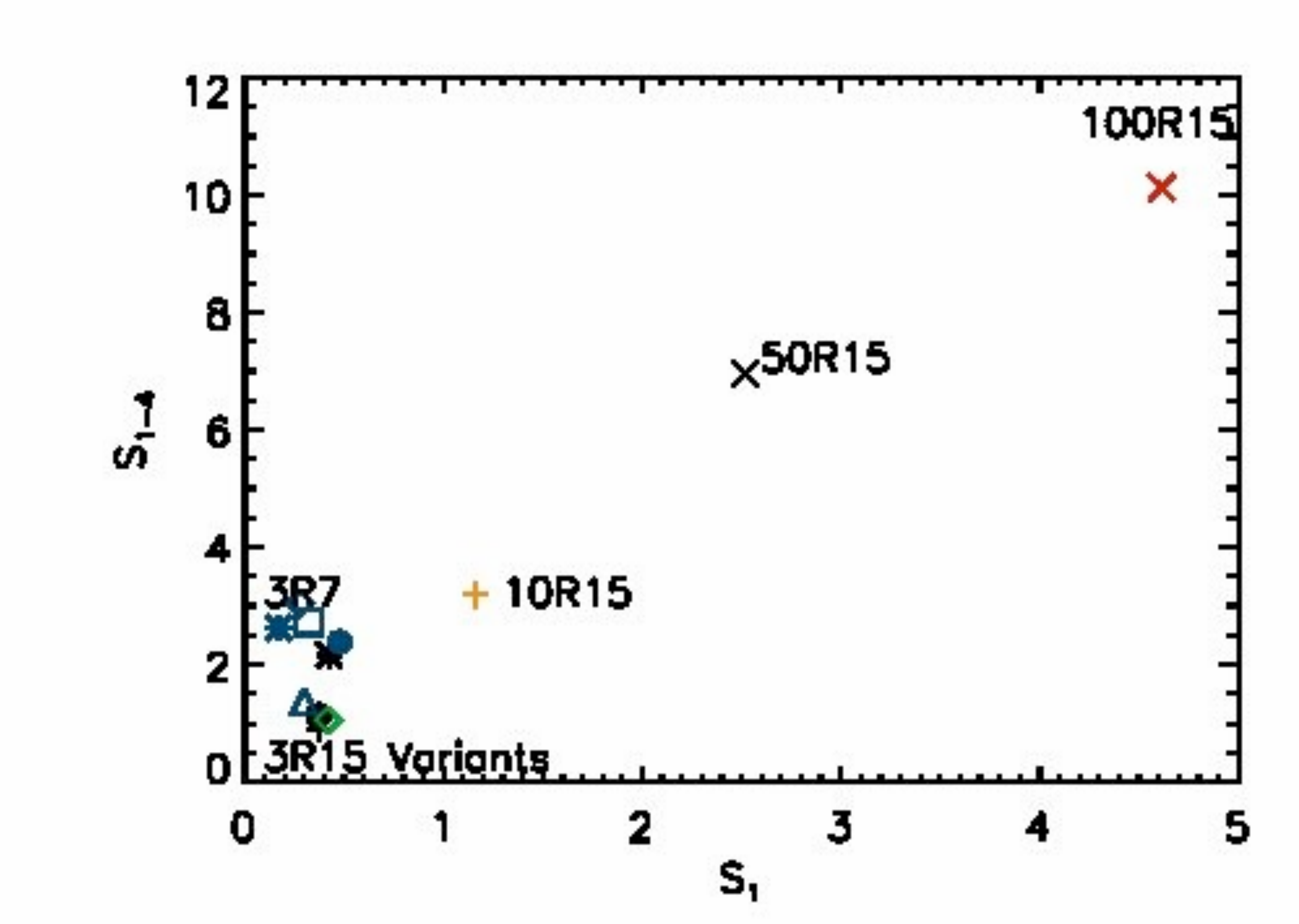

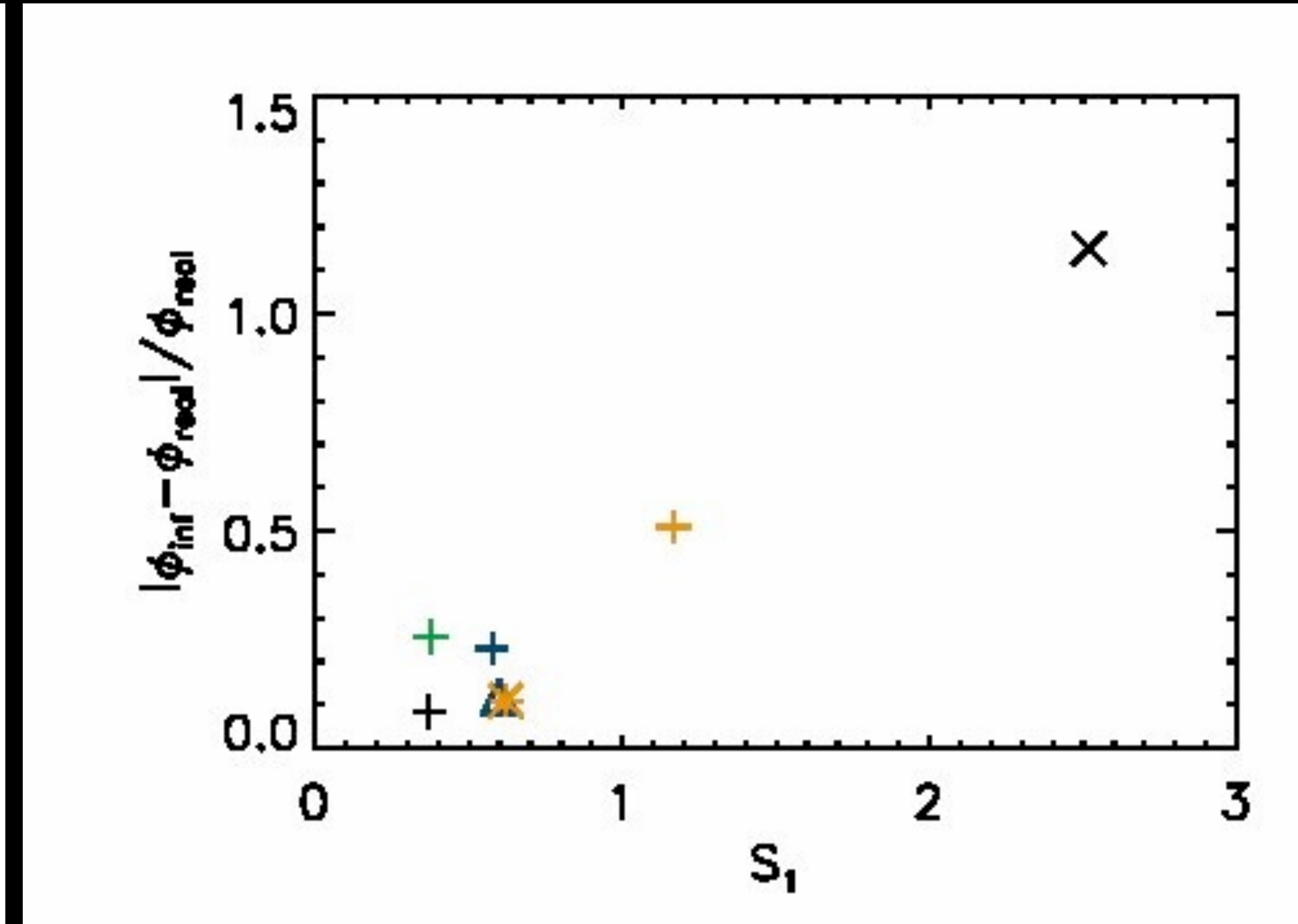

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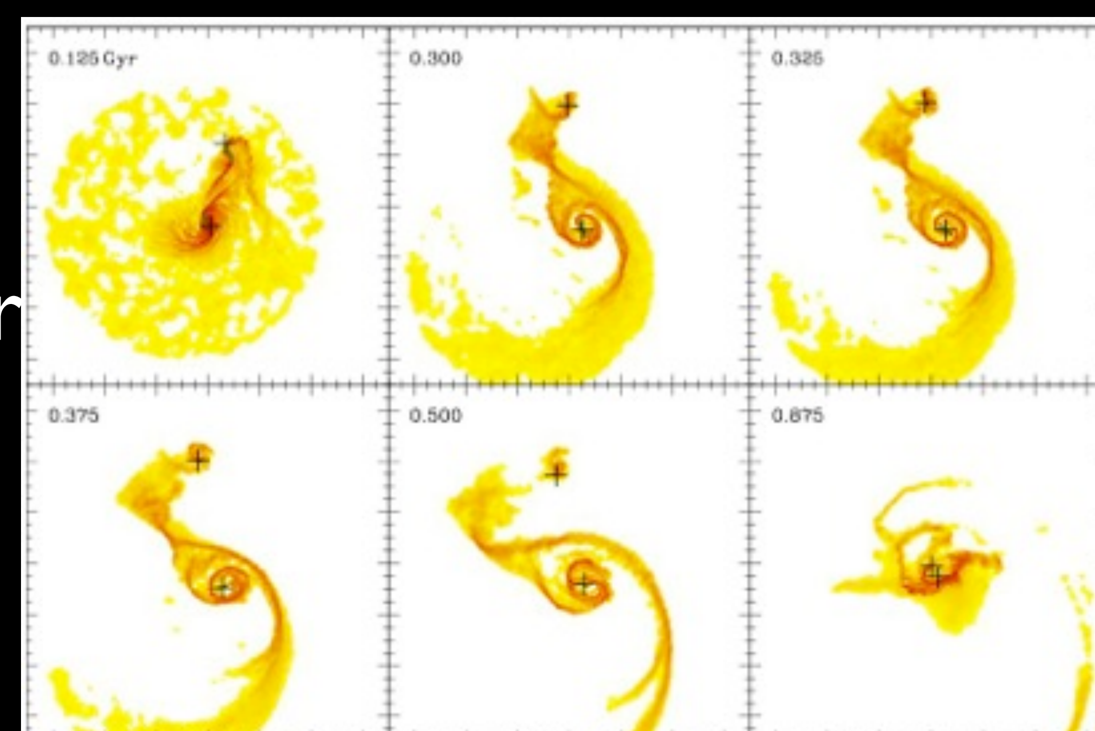
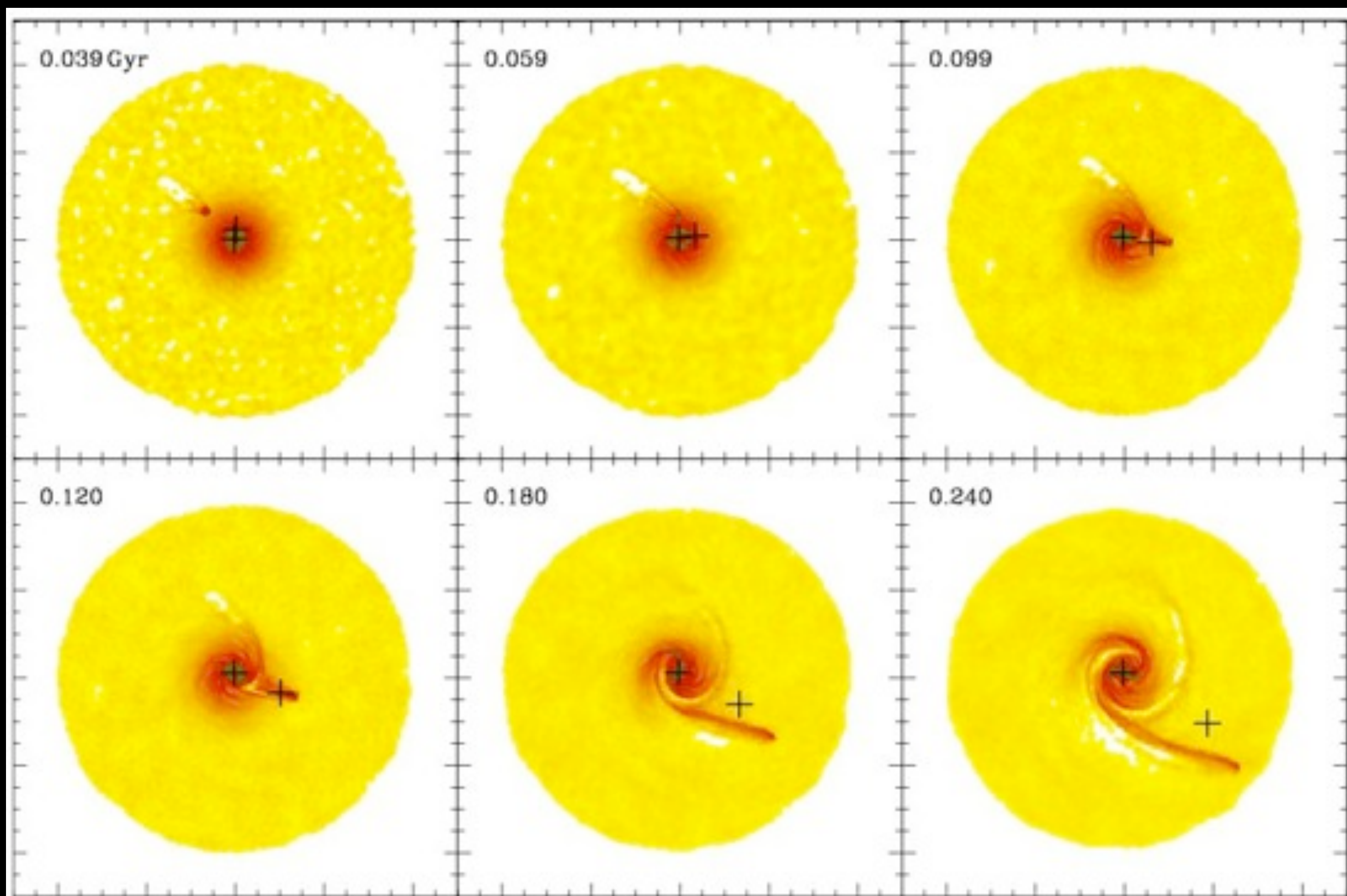
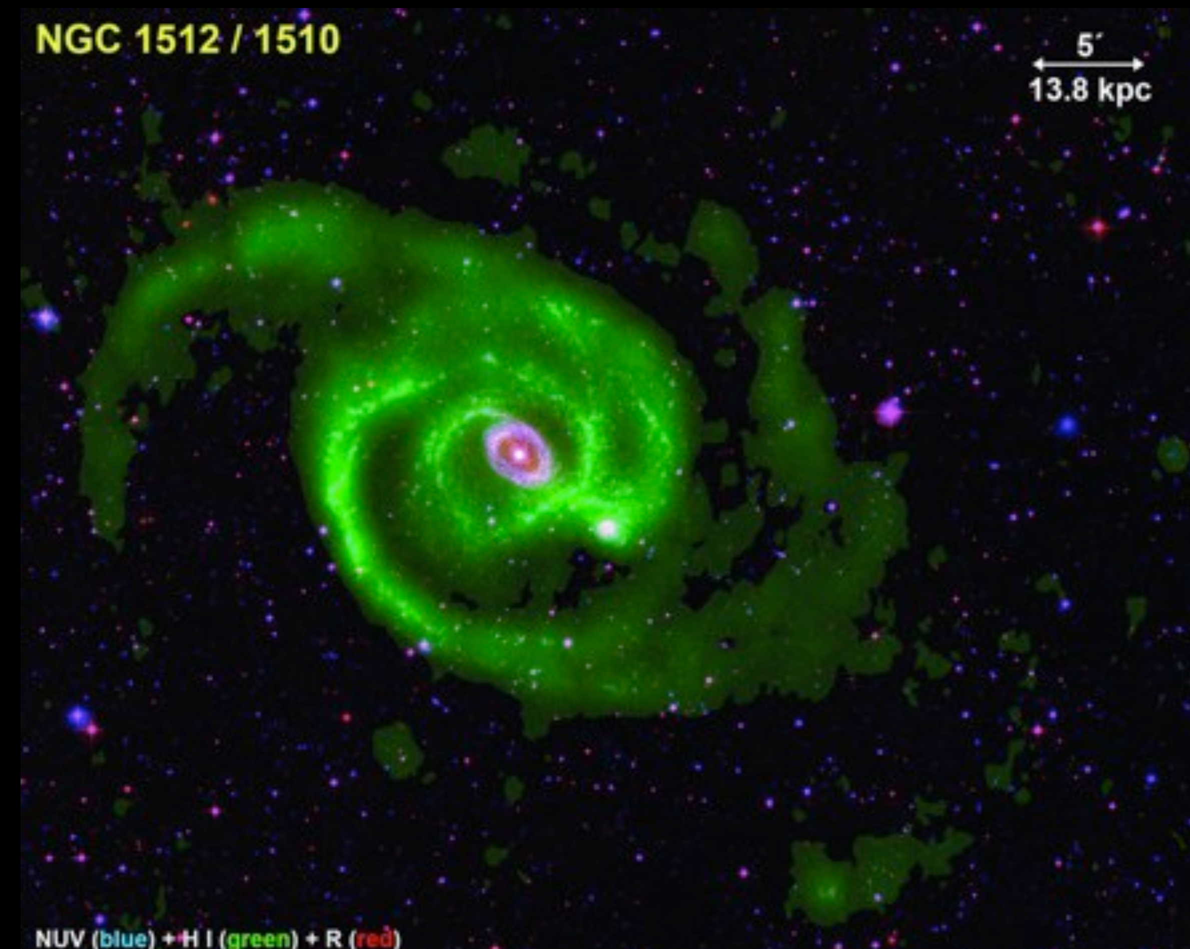


Galaxies with known optical companions contd.





- ~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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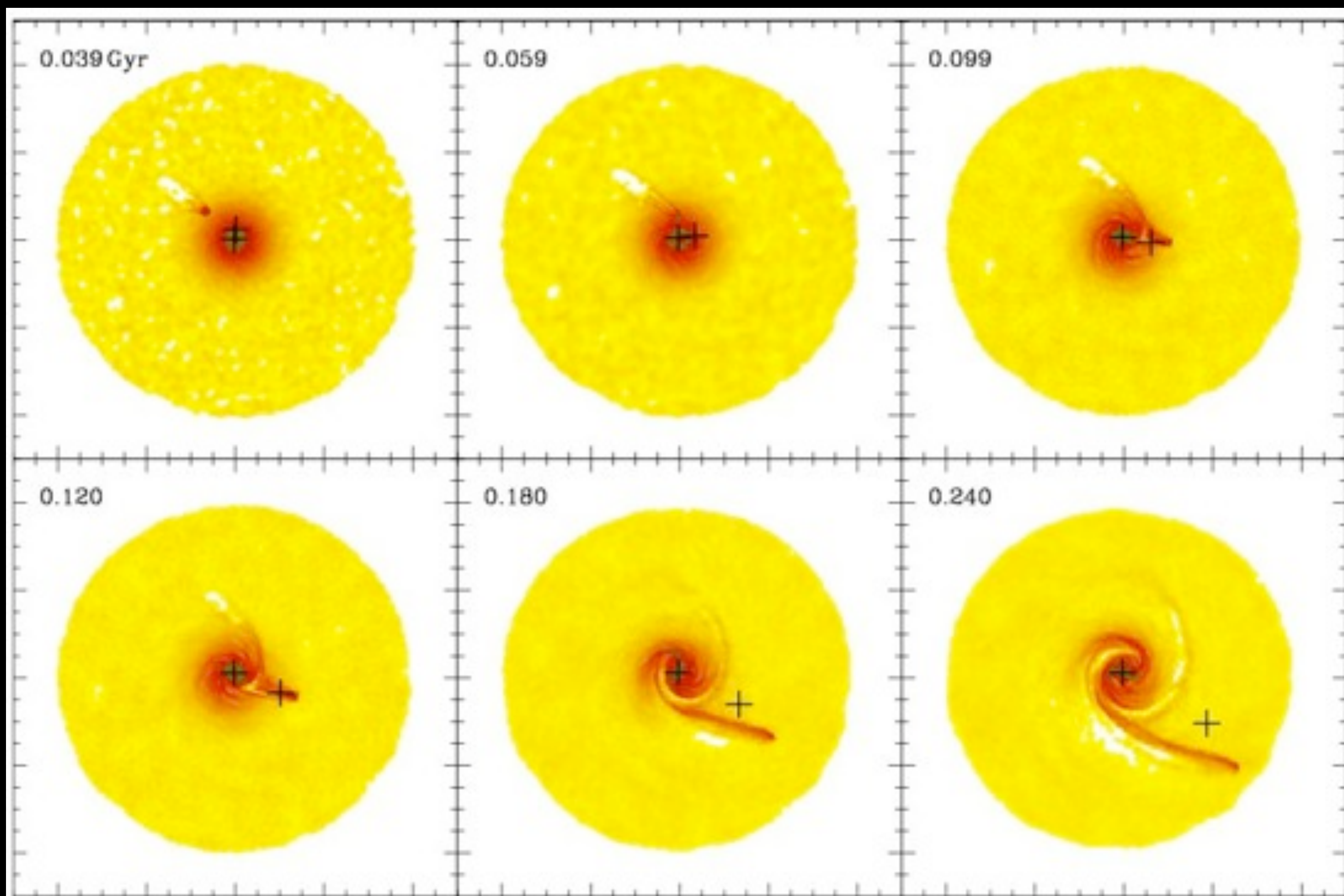

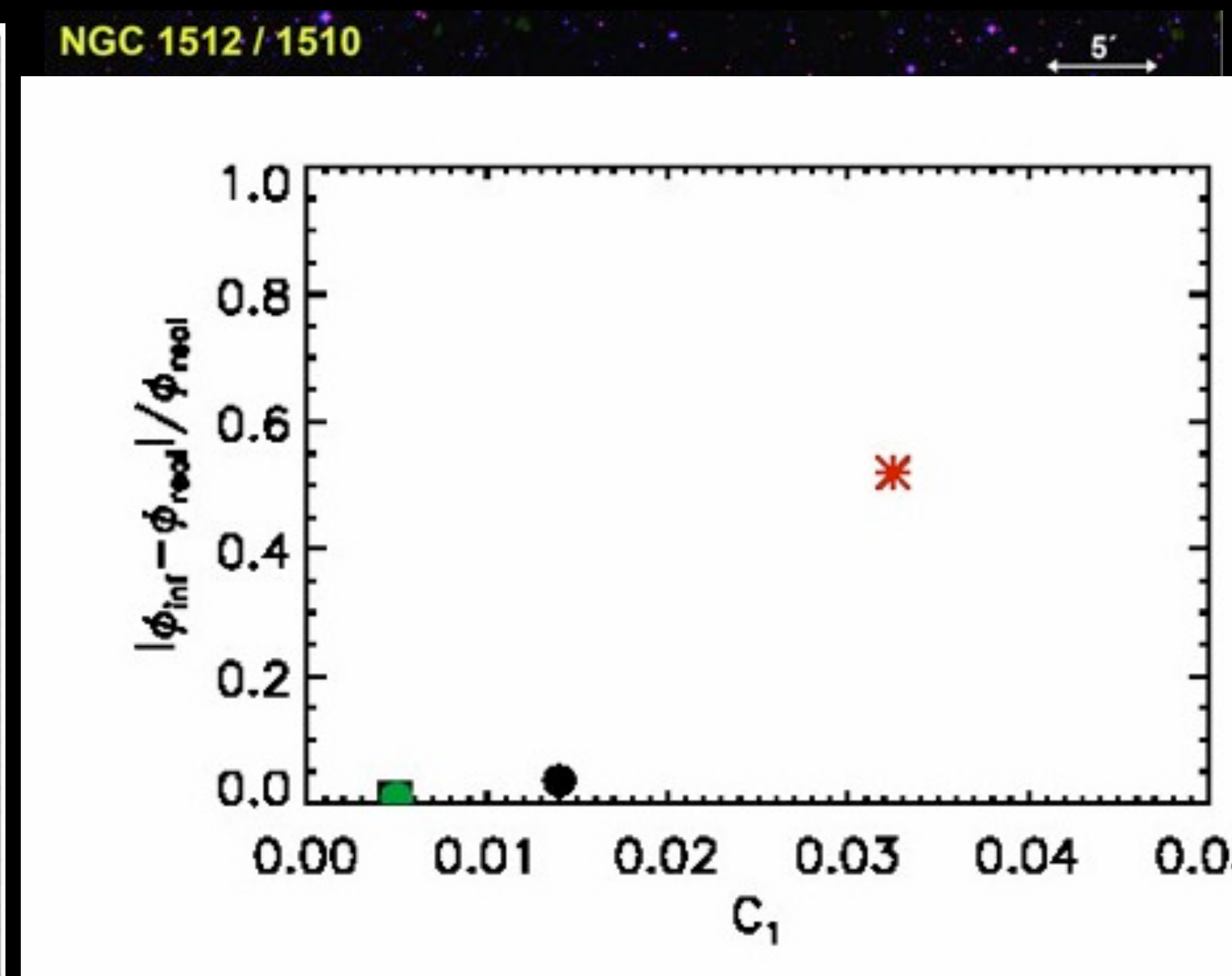

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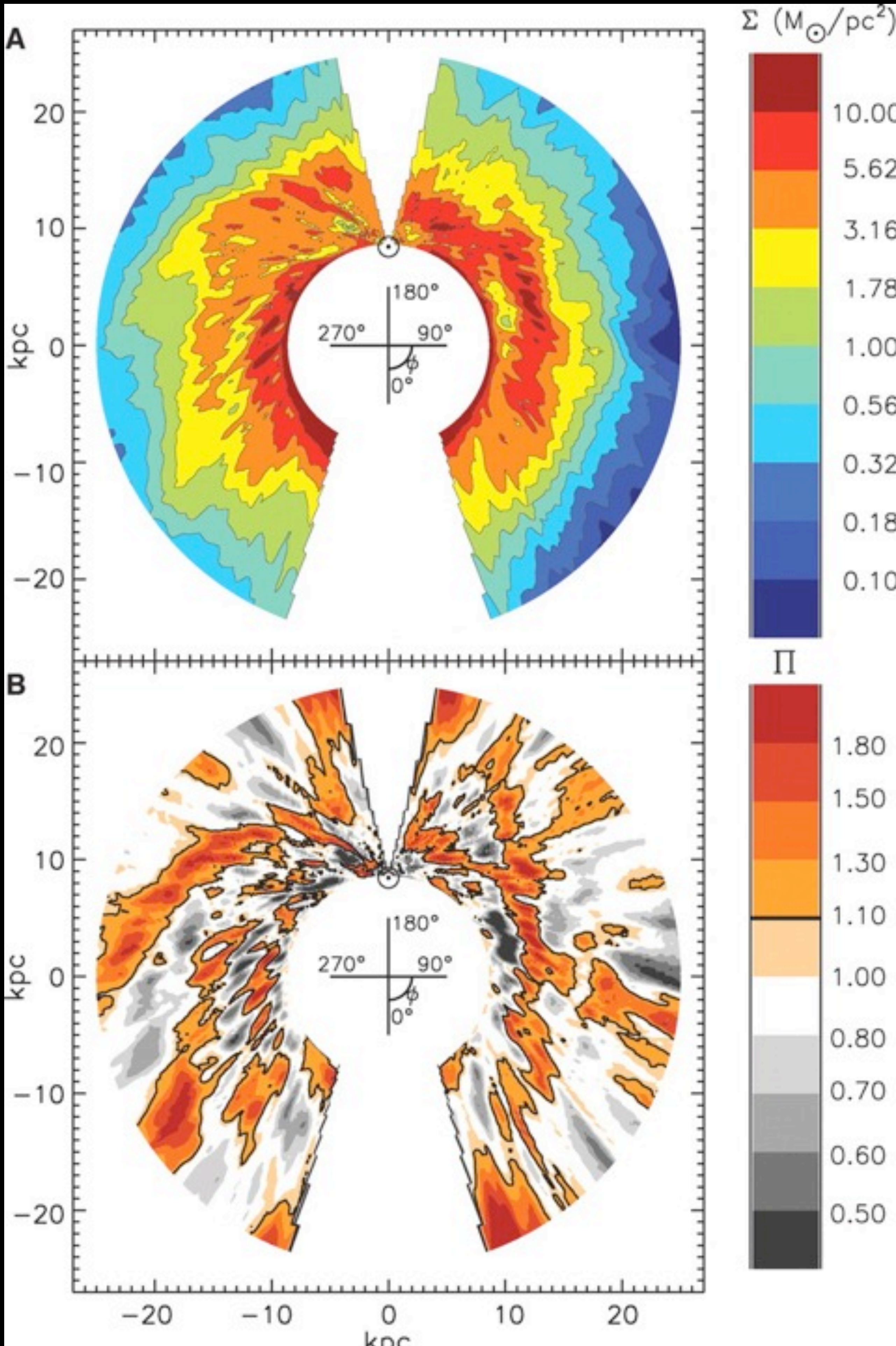
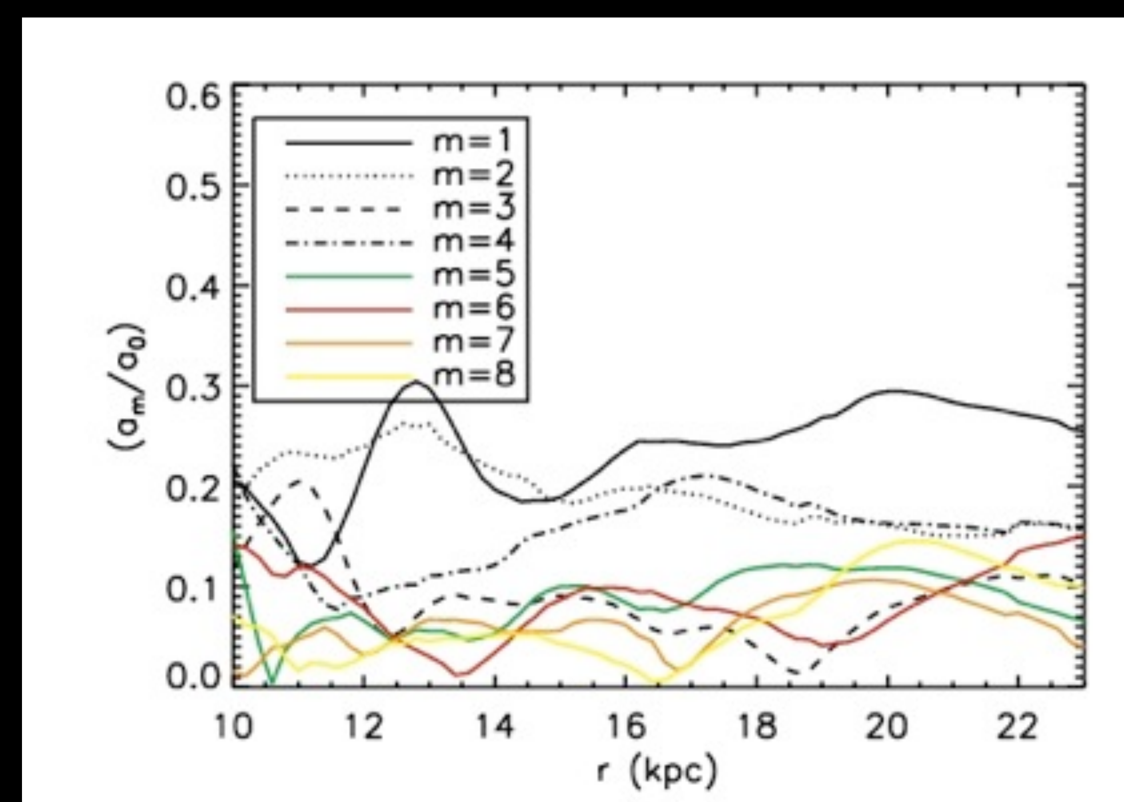


HI Map of Milky Way

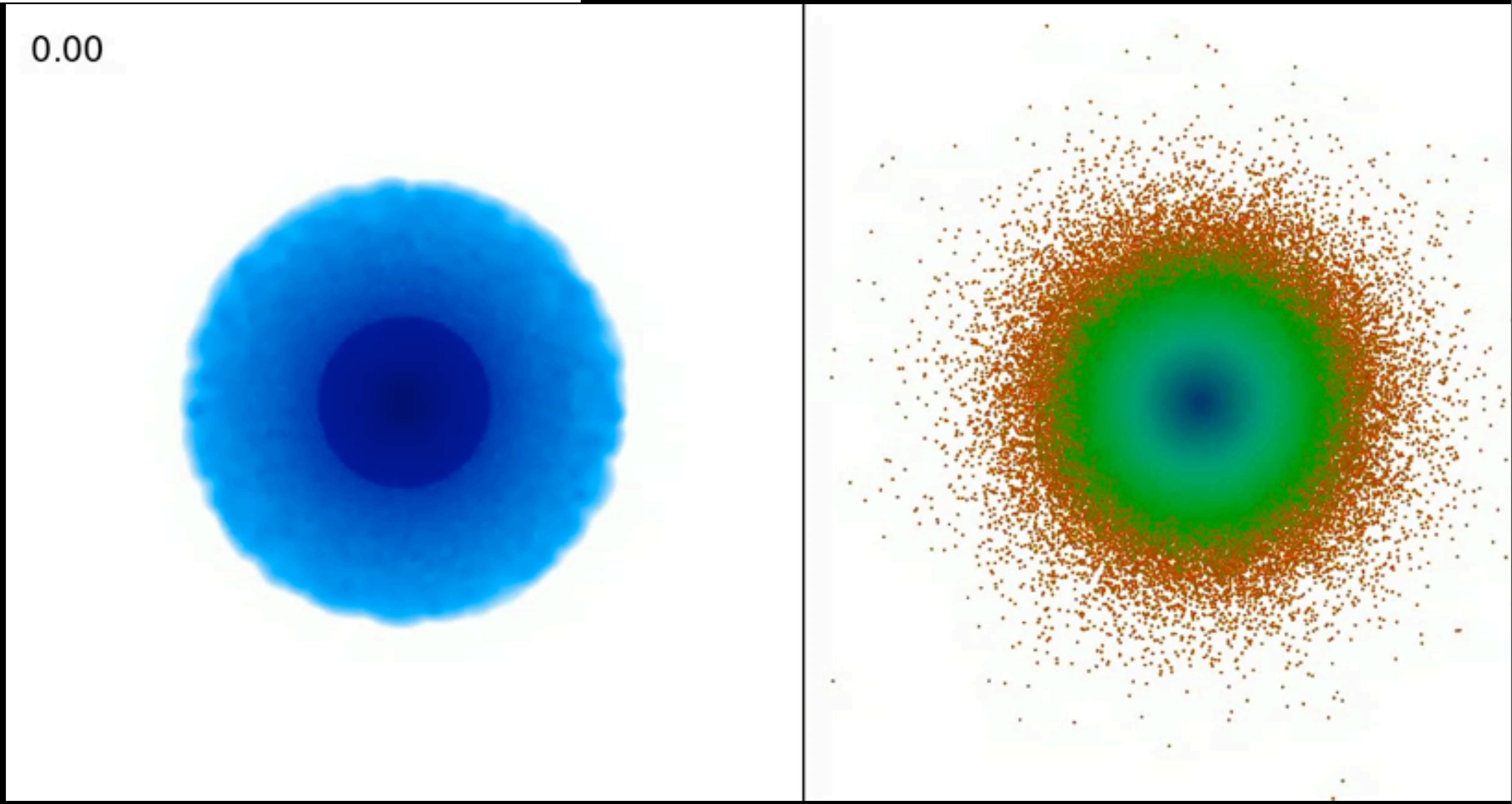
HI maps: Levine, Blitz & Heiles 2006. What caused these structures well outside the solar circle?

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



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 to explain observed disturbances in HI map of Milky Way. Chakrabarti & Blitz 2009, Chakrabarti & Blitz 2011.

Initial Conditions, Orbits -- what really matters?

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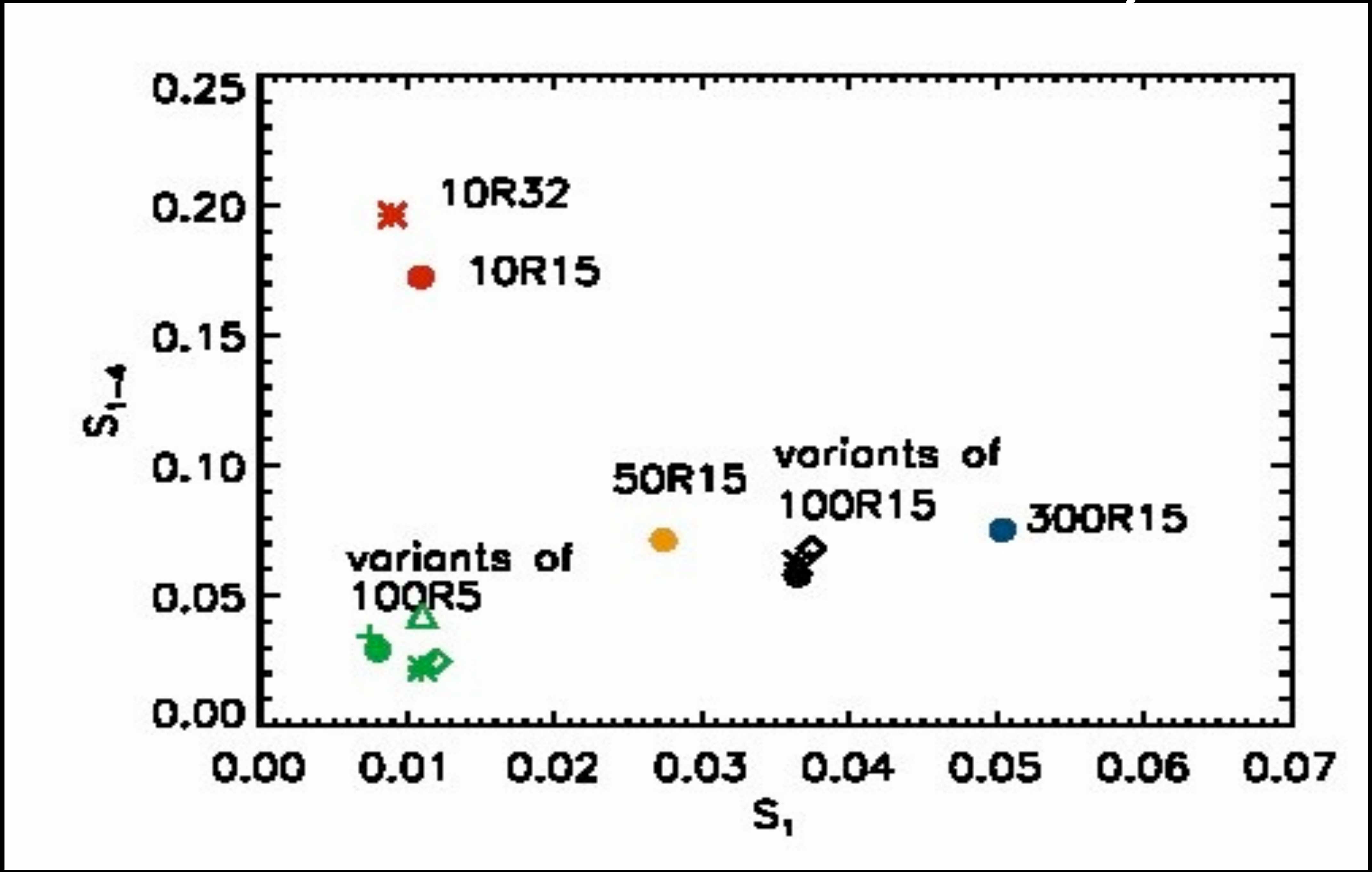

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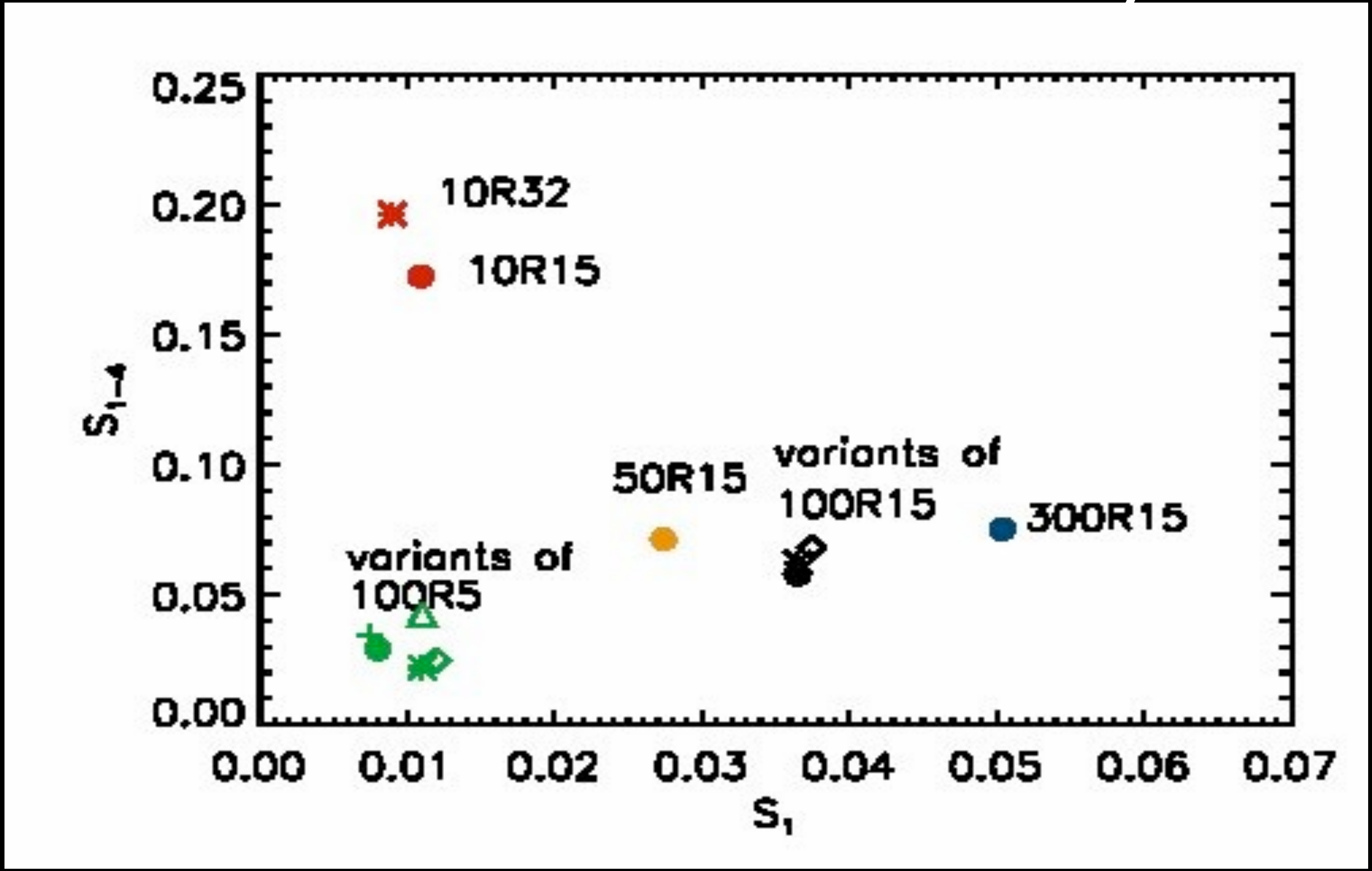
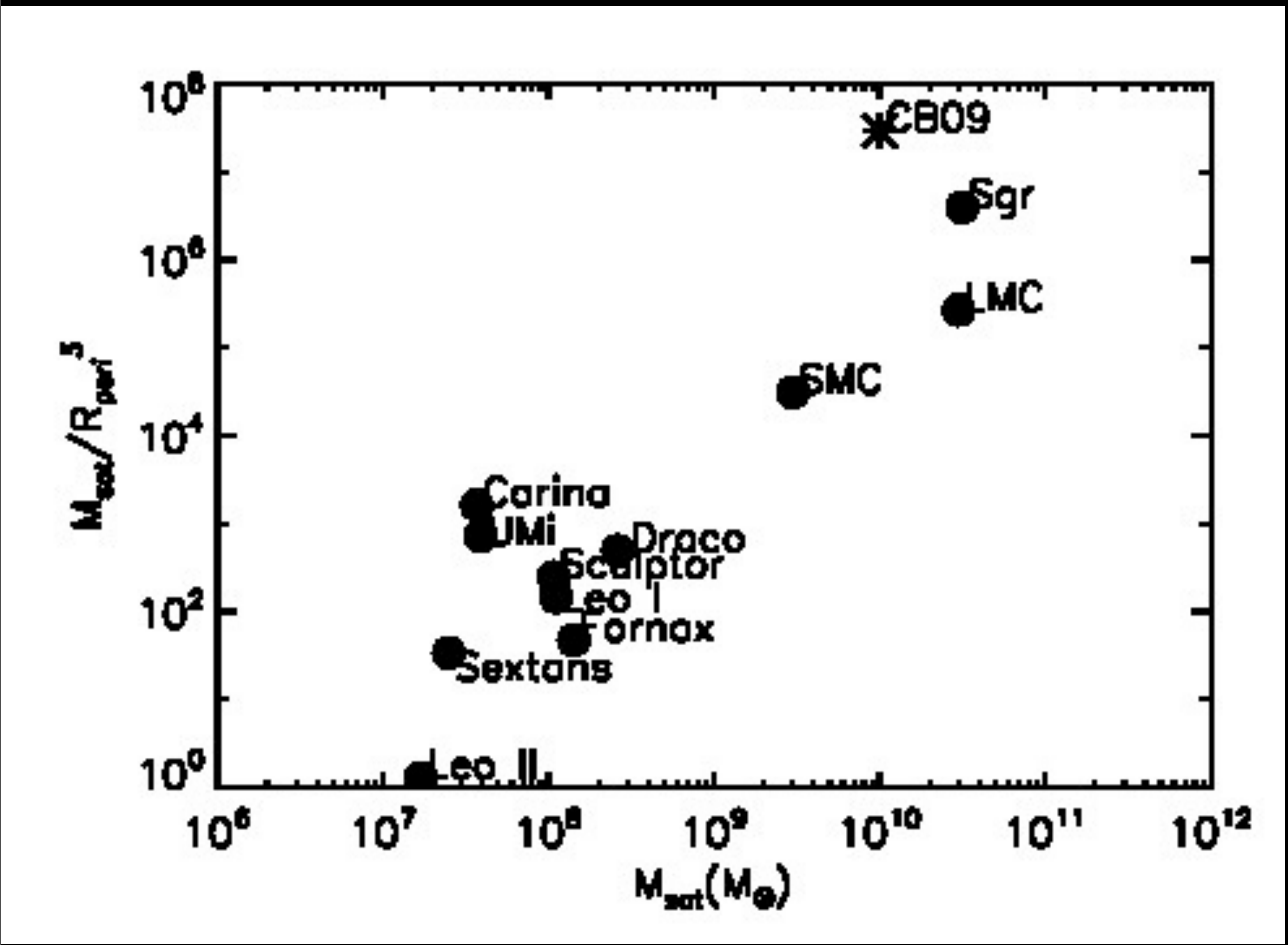


- Not very sensitive to initial conditions (for parameters comparable to spirals). CB09 -- M_s and R_{peri} are what really matter. Quillen et al. 2009 -- radial mixing of stellar metallicities caused by satellite of comparable mass and pericenter distance

The classical Milky Way Satellites: from Orbits to Tides



The Tidal Players: LMC, Sgr, CB09's putative satellite

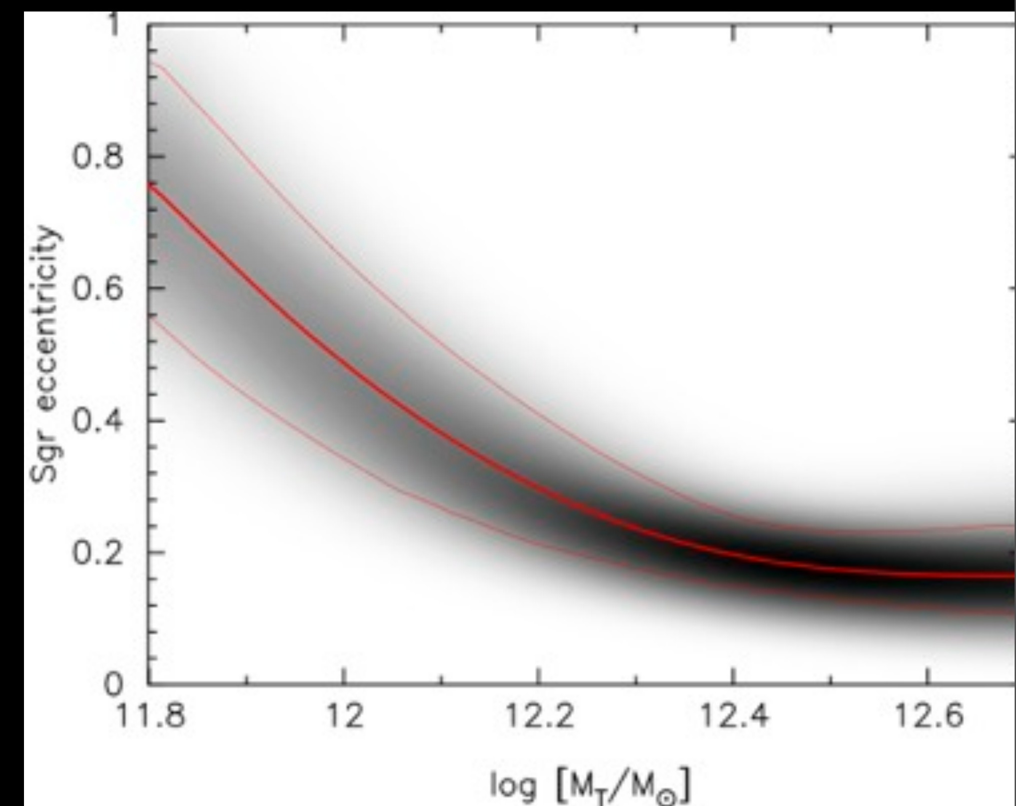
Chakrabarti et al., 2014b

- Integrate backwards the equation of motion for known Milky Way satellites including dynamical friction in orbit integrator test particle code.
  $\ddot{r} = \partial/\partial r\ \phi_{MW} + F_{DF}/M_{sat}$
- Observational constraints: HST proper motions + Sgr tidal stream stream. Take HST proper motion uncertainties into account by randomly sampling the distribution

but how can we get masses of *tidally disrupting* satellites??

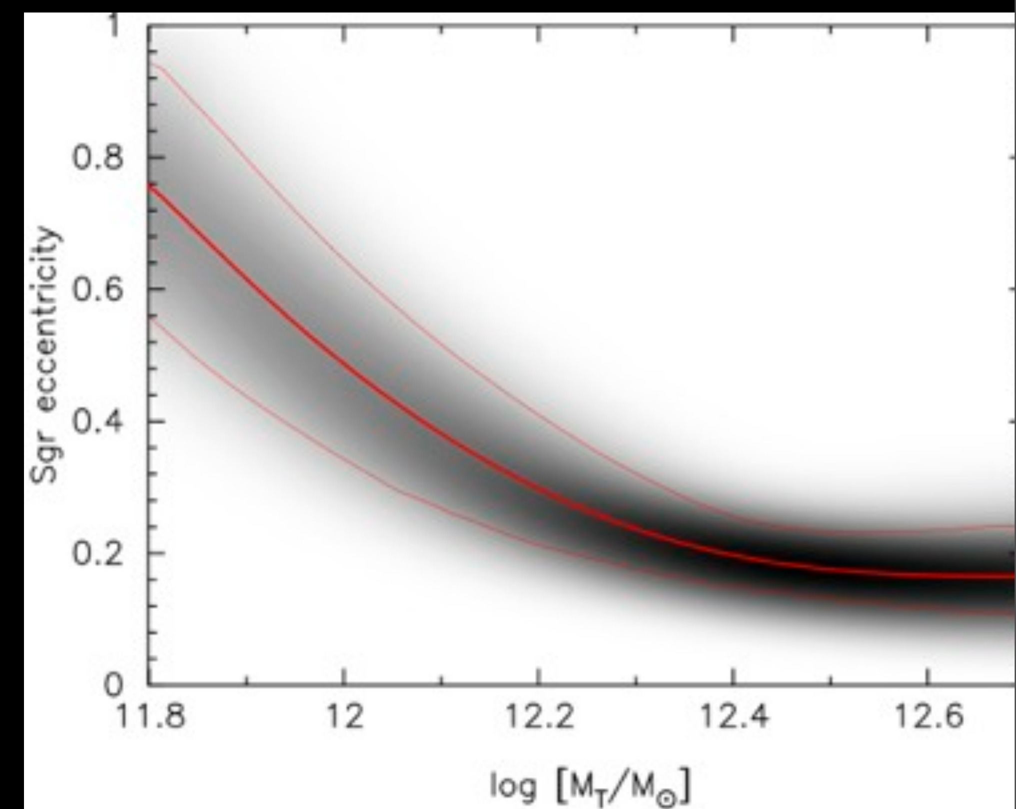
- the Sgr dwarf galaxy is ... the closest, most massive known Milky Way satellite. To study the tidal effect of the known satellites on the Milky Way disk, we need to figure out a way to get the progenitor mass of Sgr!

An Eccentricity-Mass Relation for Galaxies



An Eccentricity-Mass Relation for Galaxies

- Satellite at pericenter, know its **x**, **v.** Assume $\phi(r)$, with normalization (total mass, M_T) undetermined. Relate M_T to orbital eccentricity, e. $e = (R_a - R_p)/(R_a + R_p)$
- $E = 1/2\ v_r^2 + 1/2\ v_t^2 + \phi(r)$, $L = v_t r$, $E = 1/2\ v_r^2 + L^2/2r^2 + \phi(r)$



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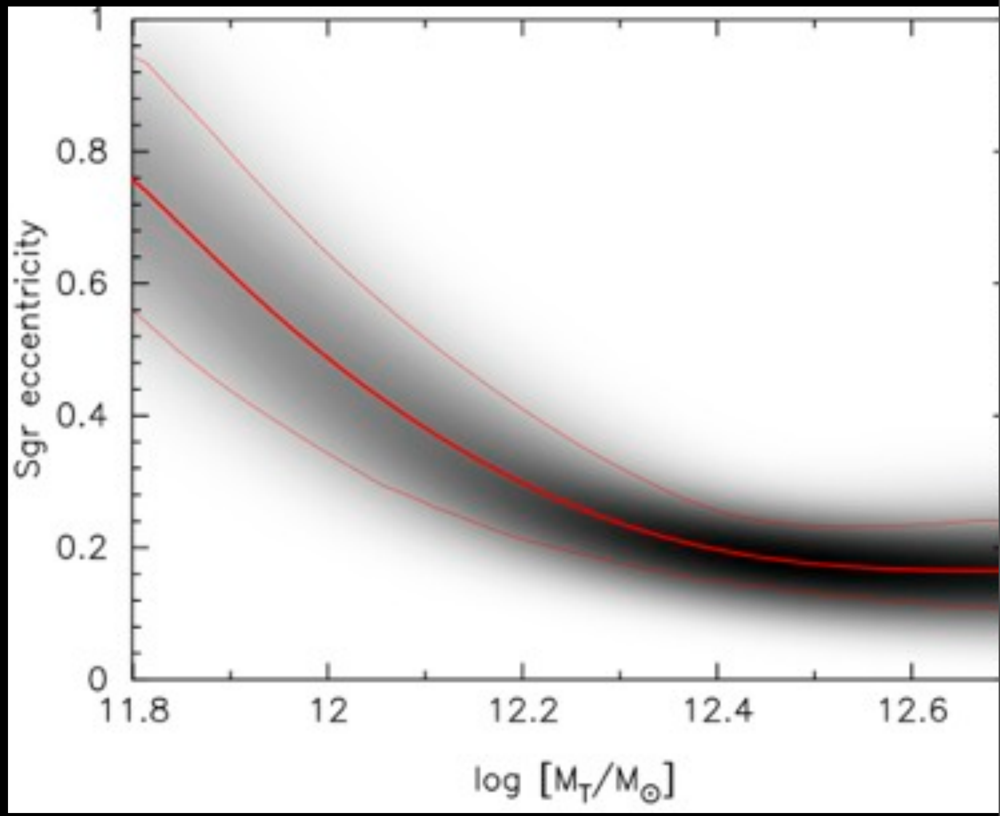

- Assume Hernquist form for potential: $E = 1/2\, v_r^2 + L^2/2r^2 - GM_T/(r+a)$

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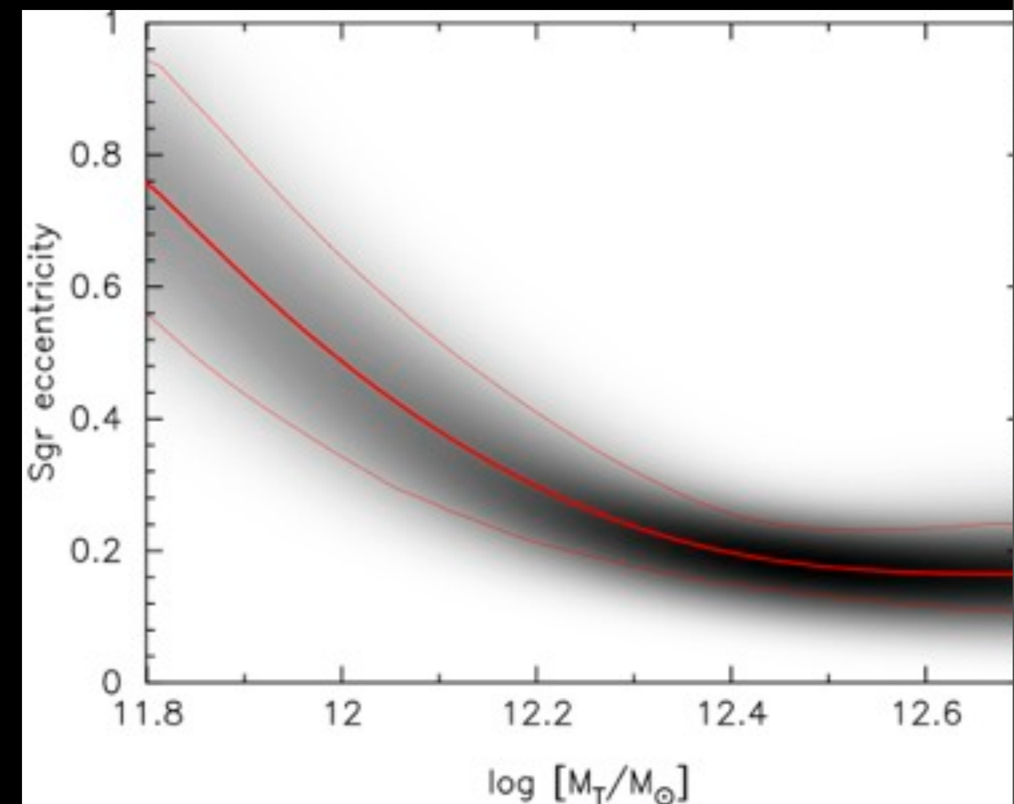

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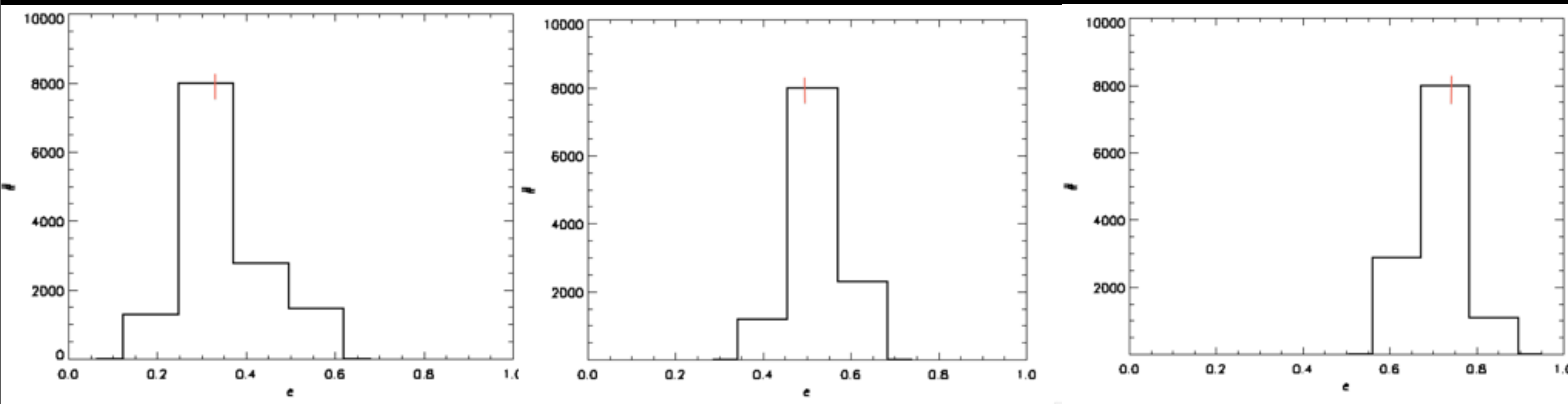
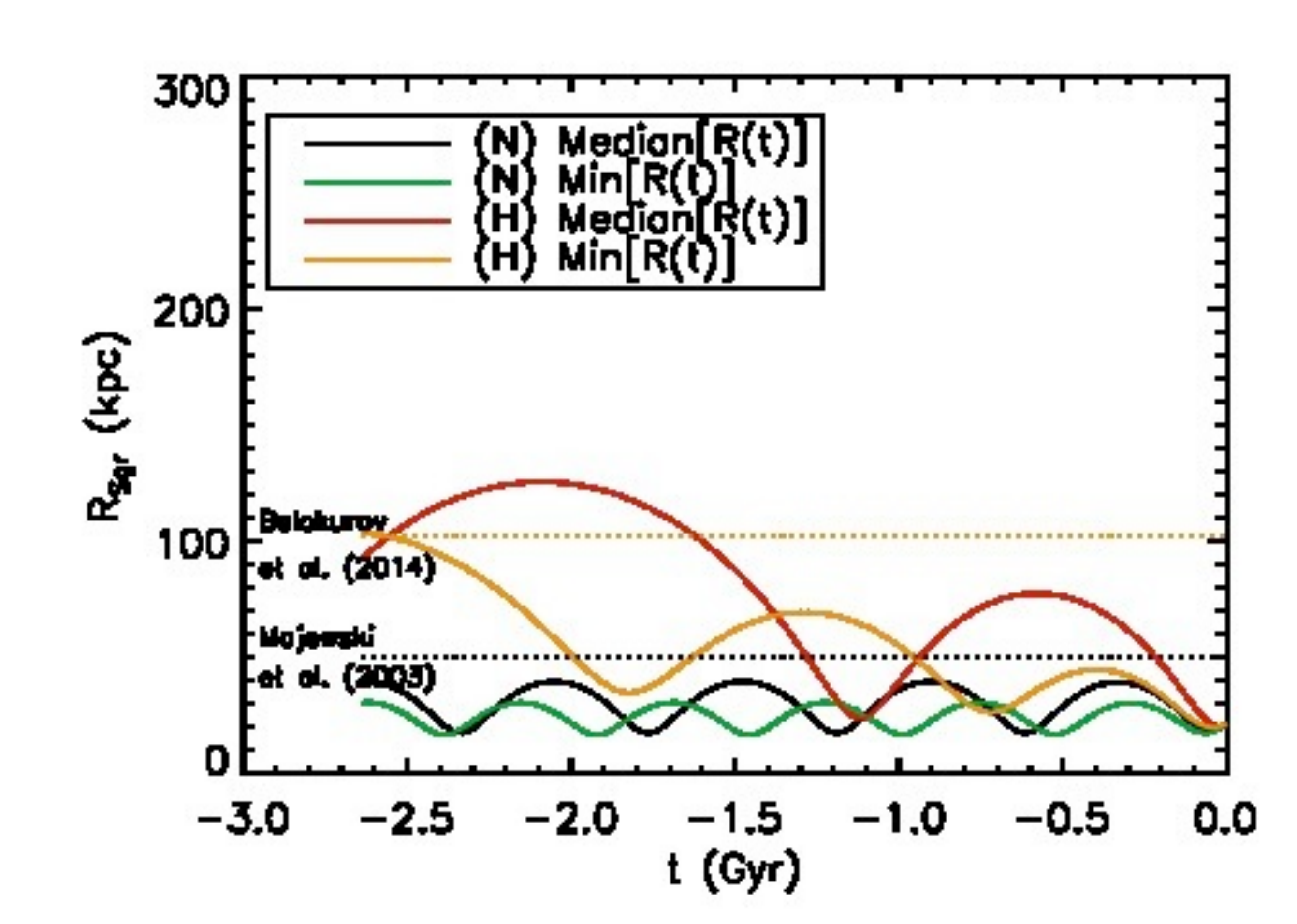
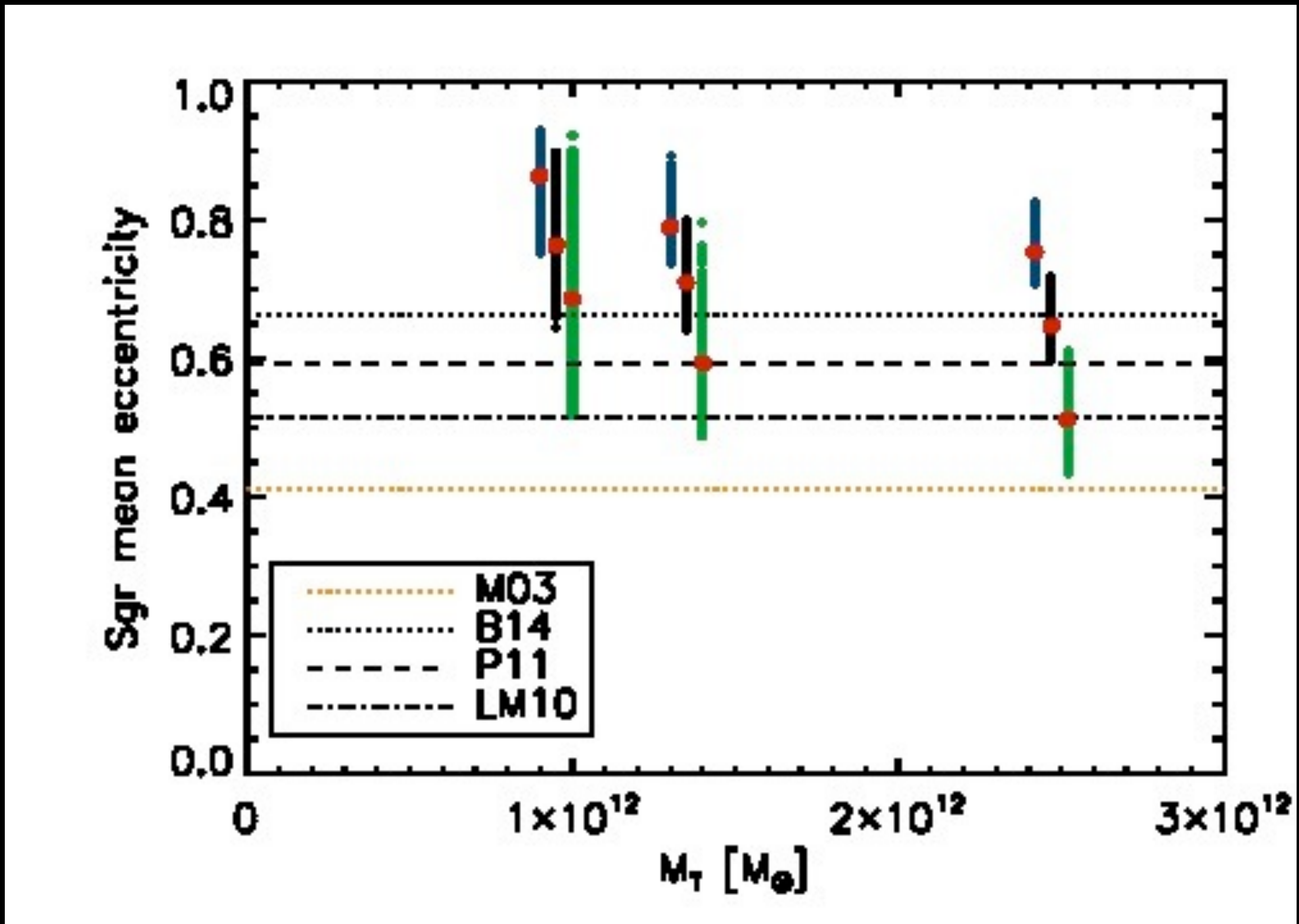
- Given **x**, **v**, assumed $\phi(r)$: in the absence of dynamical friction: unique relation between e and M_T. (Chakrabarti et al. 2014a, arXiv: 1401.4182)

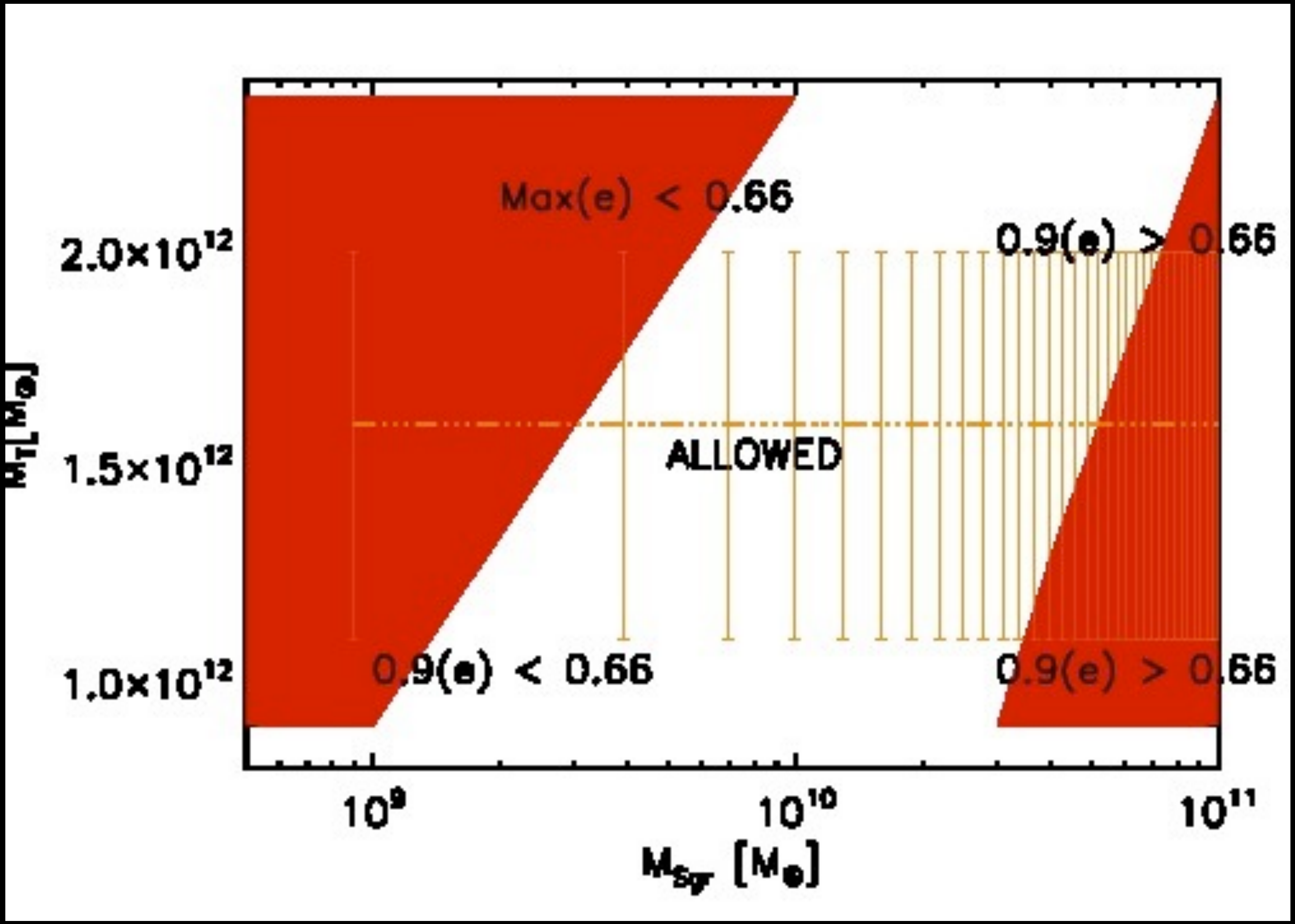


- Given a satellite's current X and V, its past orbit depends on the MW mass and on its mass thru dynamical friction and tides
- Average eccentricity of orbit in GADGET simulations agrees closely with orbit integration calculations, which we can use to sample the parameter space



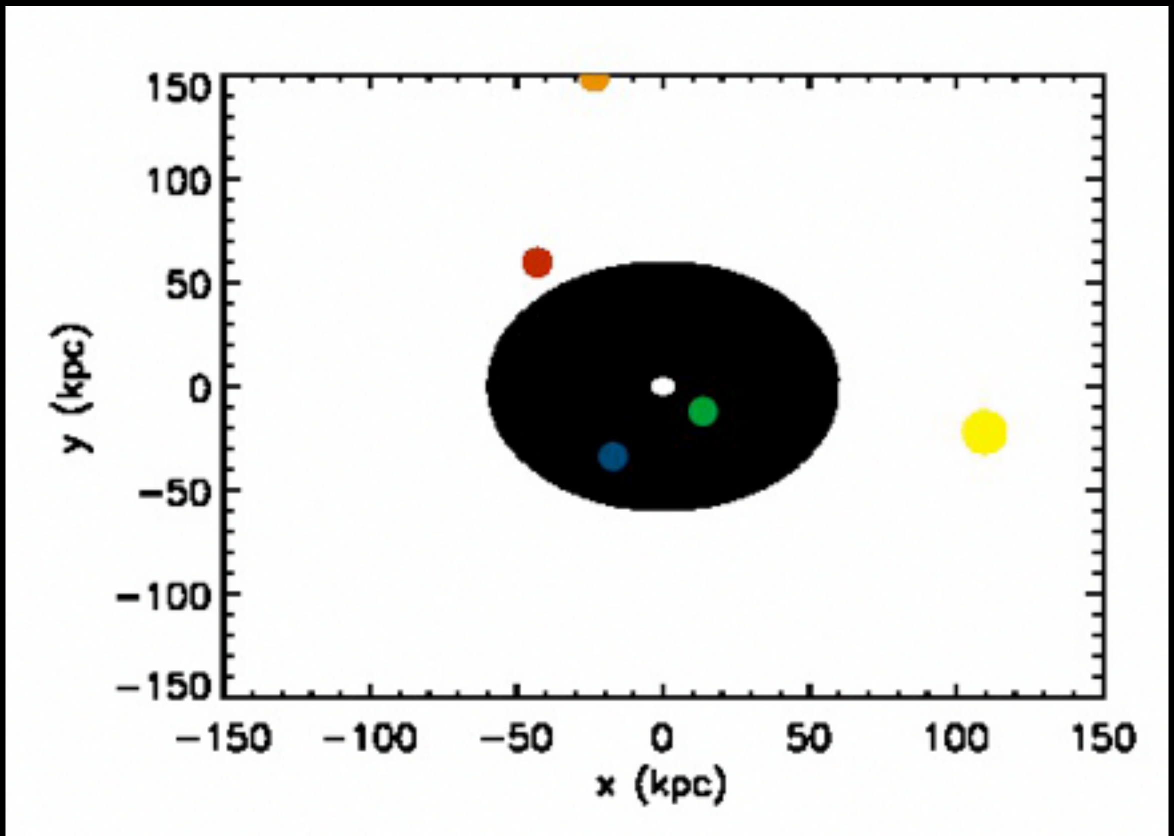


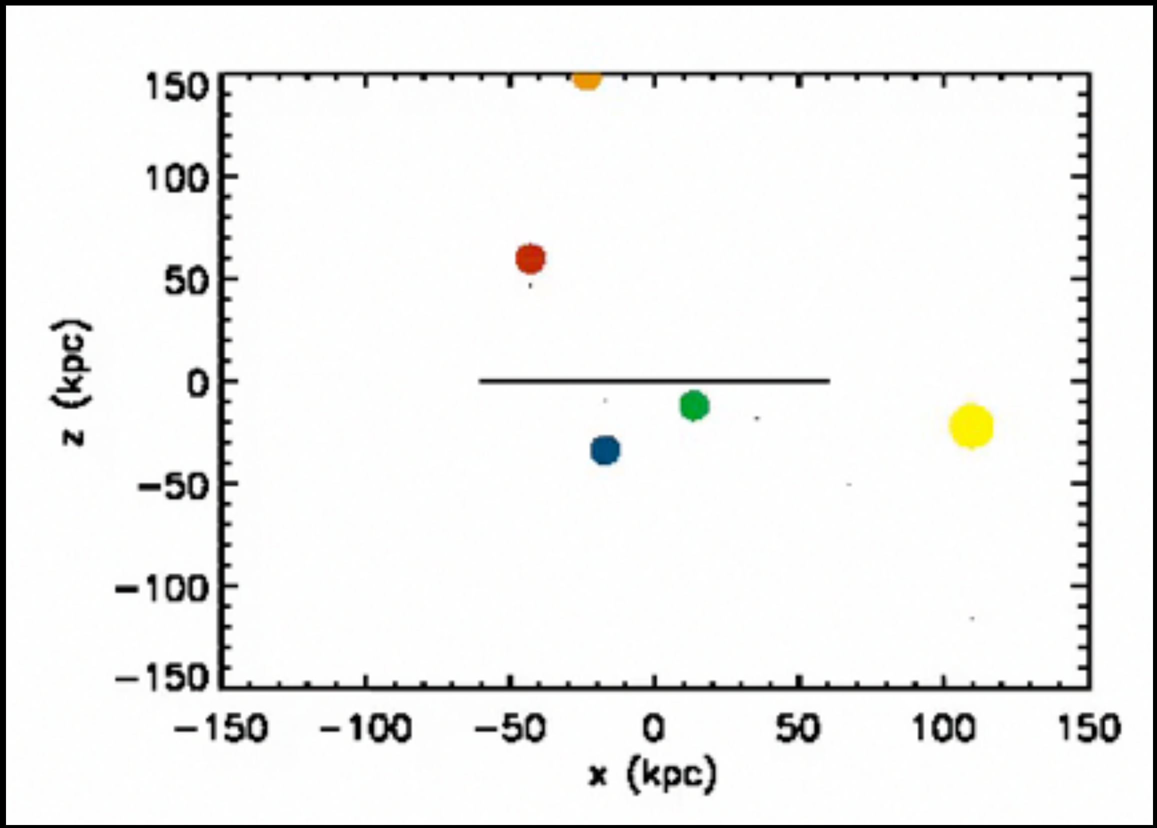
- <u>The maximum excursion of a satellite's orbit (when you include dynamical friction) gives you a measure of its progenitor mass.</u> Can explain the Belokurov et al. 2014 data.
- Main uncertainty in Sgr progenitor mass due to the fact that observational uncertainties in apocenters have not been quantified!
- Deeper observations (GAIA) should improve constraints on Sgr mass



- Sgr masses less than 10^9 M_{sun} and greater than 5×10^{10} M_{sun} ruled out for likely MW masses ~ 1 - 2.5 x 10^{12} M_{sun}.
- This is a robust and efficient method to estimate masses of tidally disrupting satellites (Chakrabarti et al. 2014a).

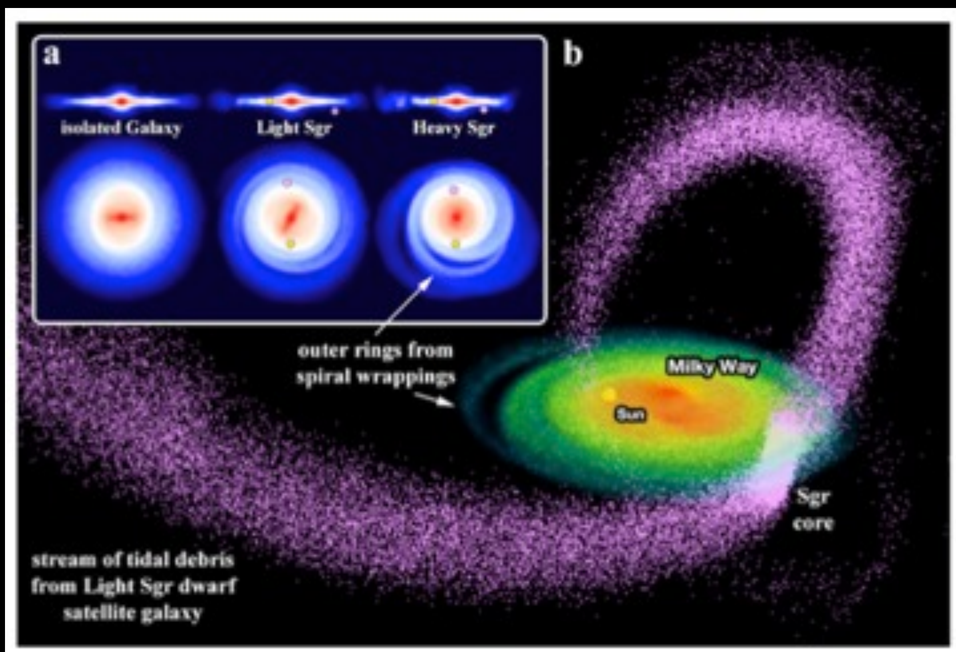
From Orbits to Tides

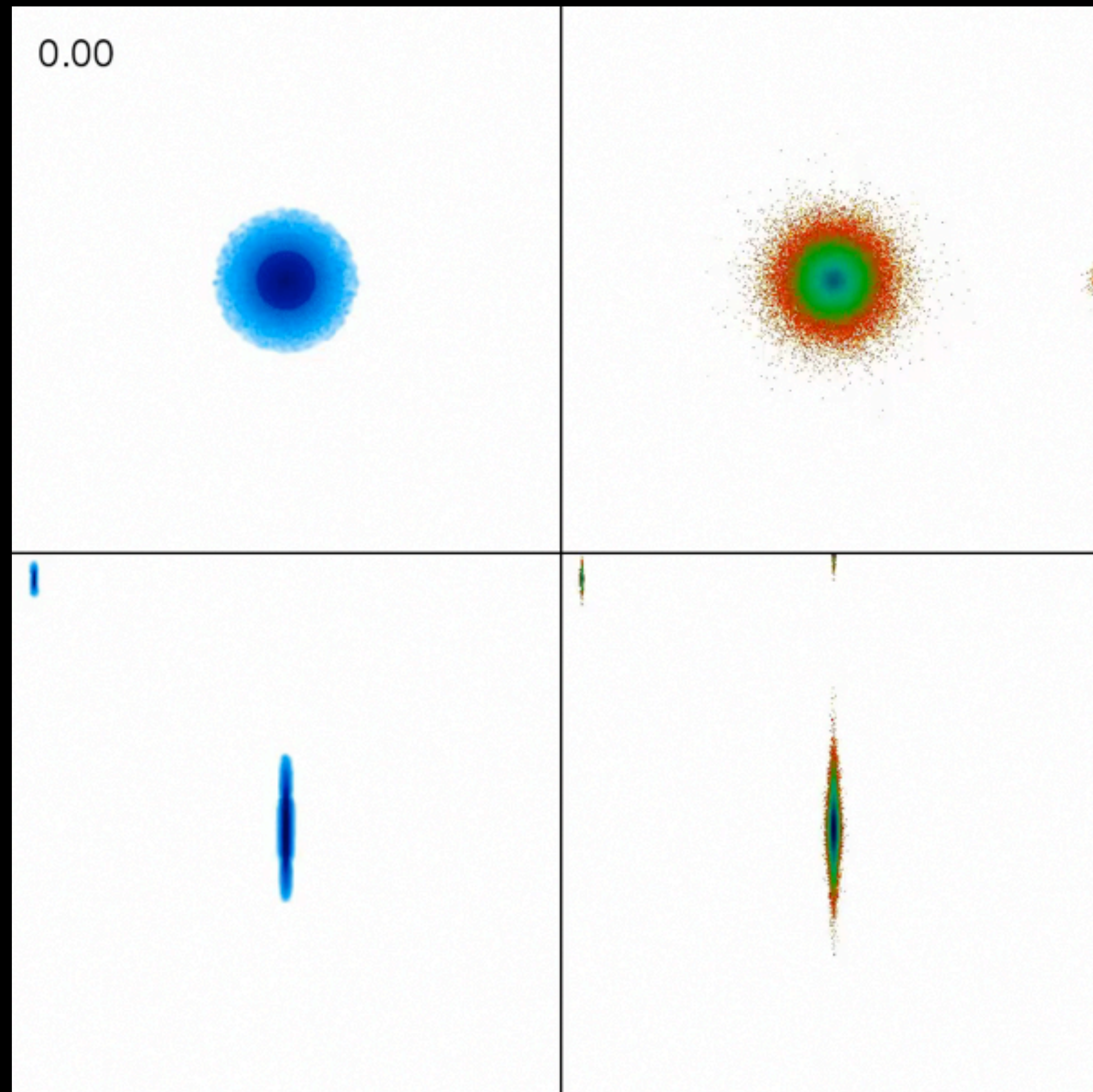




Test particle calculations to survey the parameter space and follow up interesting regions with full SPH simulations (Chakrabarti et al. 2014b)

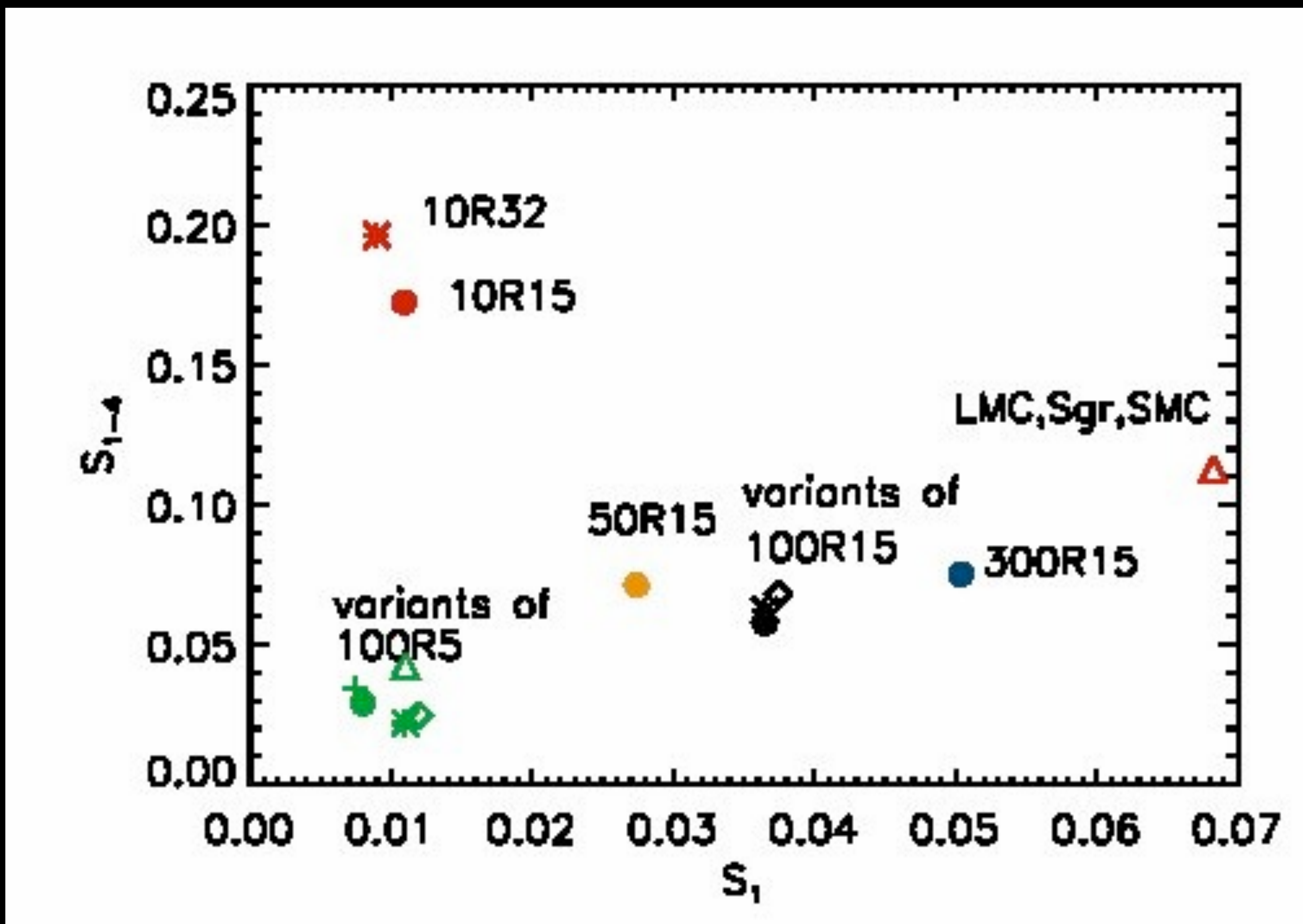
The Tidal Players of the Milky Way





Purcell et al. (+Chakrabarti) 2011
Previous work has focused on single satellites and/or N-body only with ad-hoc initial conditions

Are the known satellites enough?



known satellites alone do not match the planar disturbances

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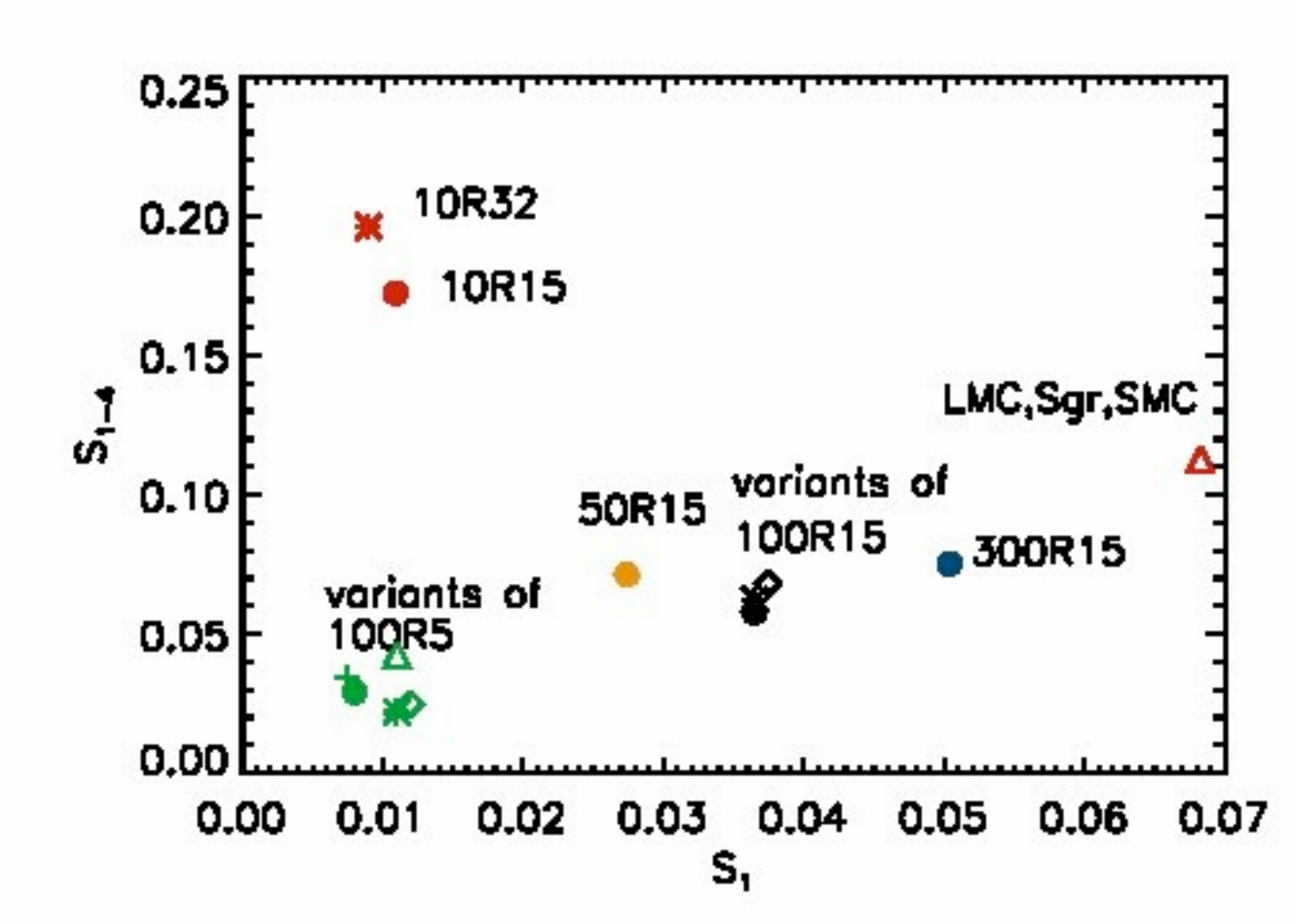
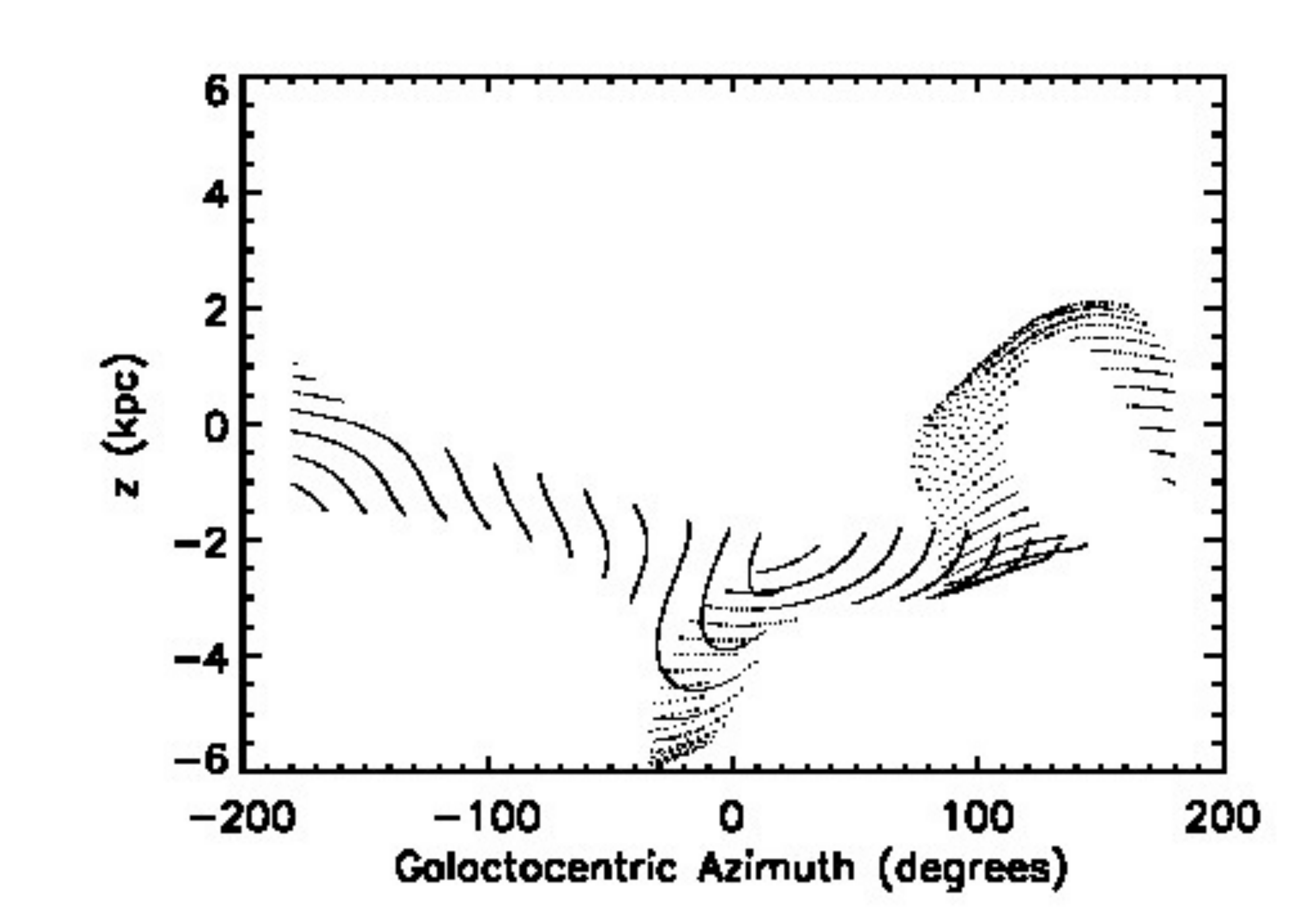
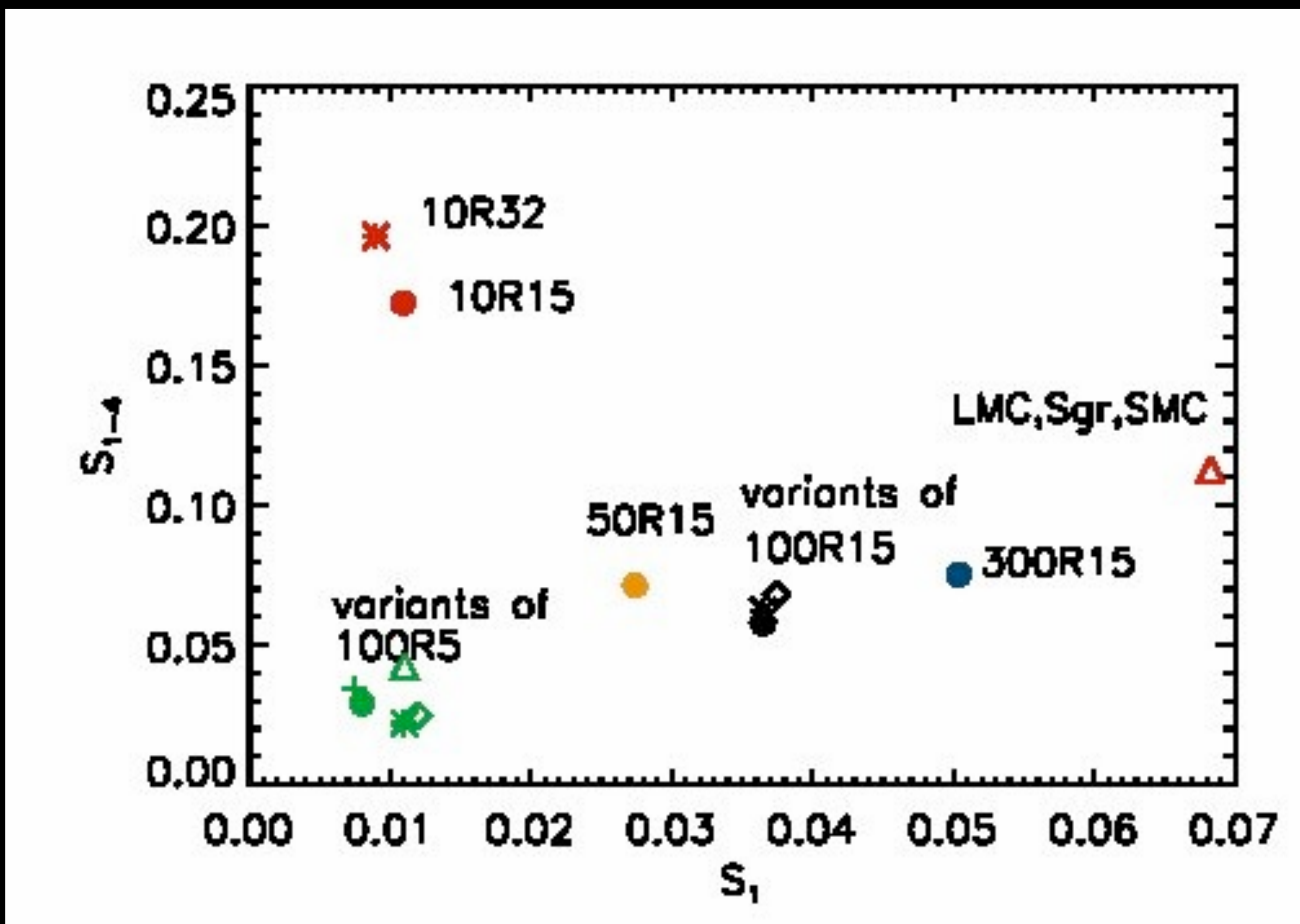
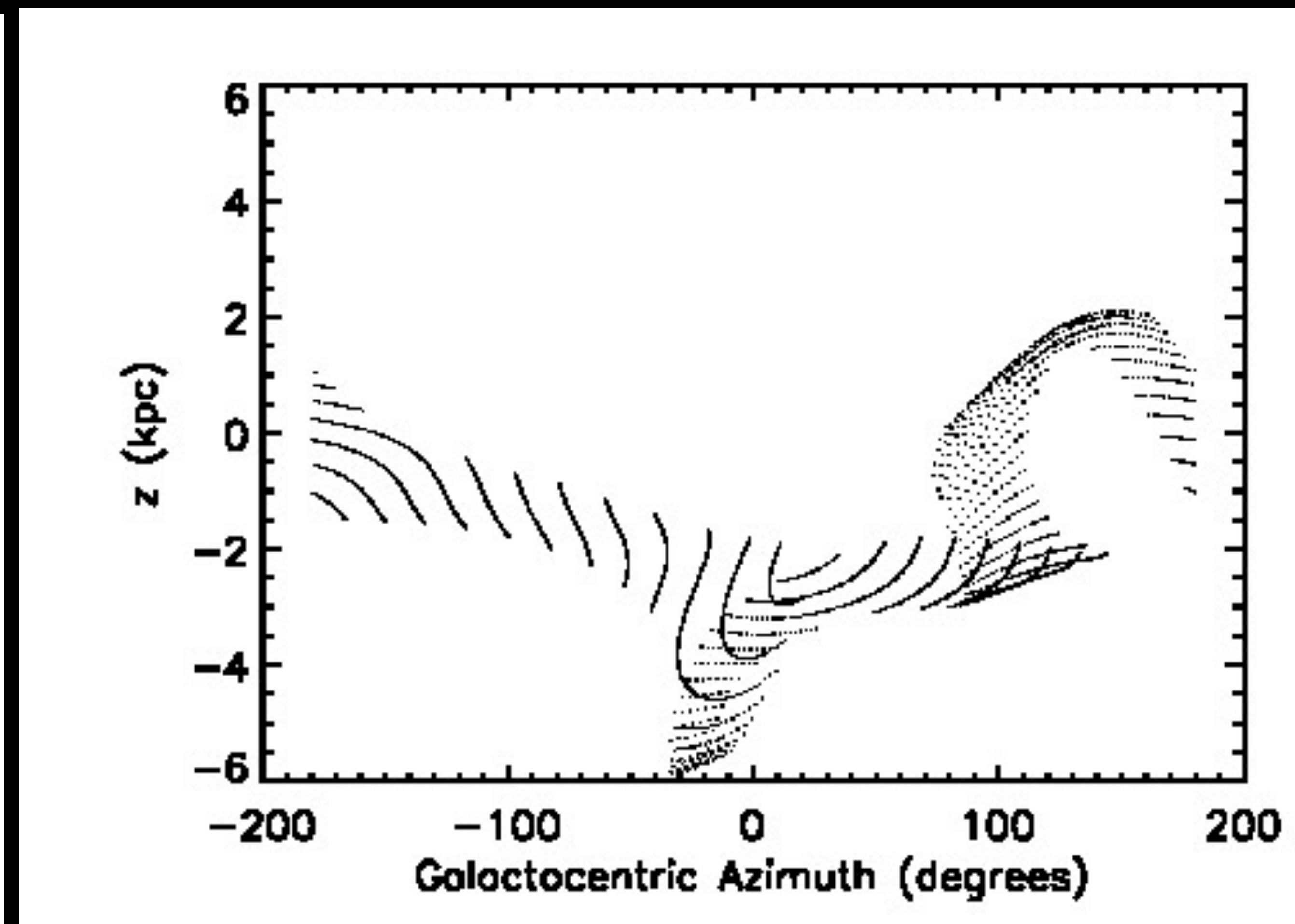




known satellites alone do not match the planar disturbances

Are the known satellites enough?





known satellites alone do not match the planar disturbances

But -- Sgr does produce a warp that's pretty close to the data

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.

- Using robust initial conditions (*simulations can't be used to make accurate predictions unless they start correctly!*) and reliable mass estimates, we find that the classical MW satellites can't explain observed disturbances.

Search for putative satellite in VISTA data