Outer HI Disks in the Local Volume & Beyond

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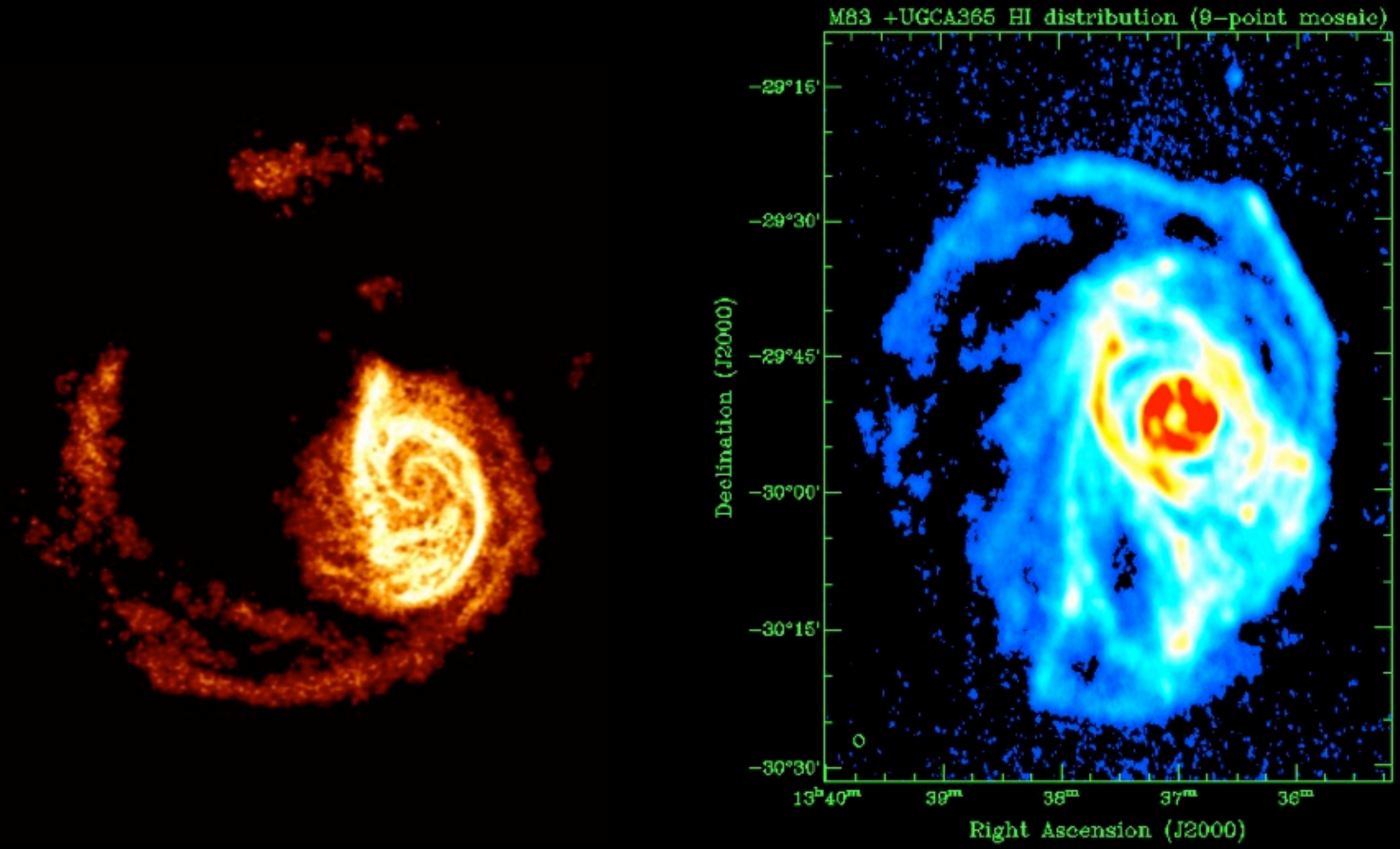
Overview

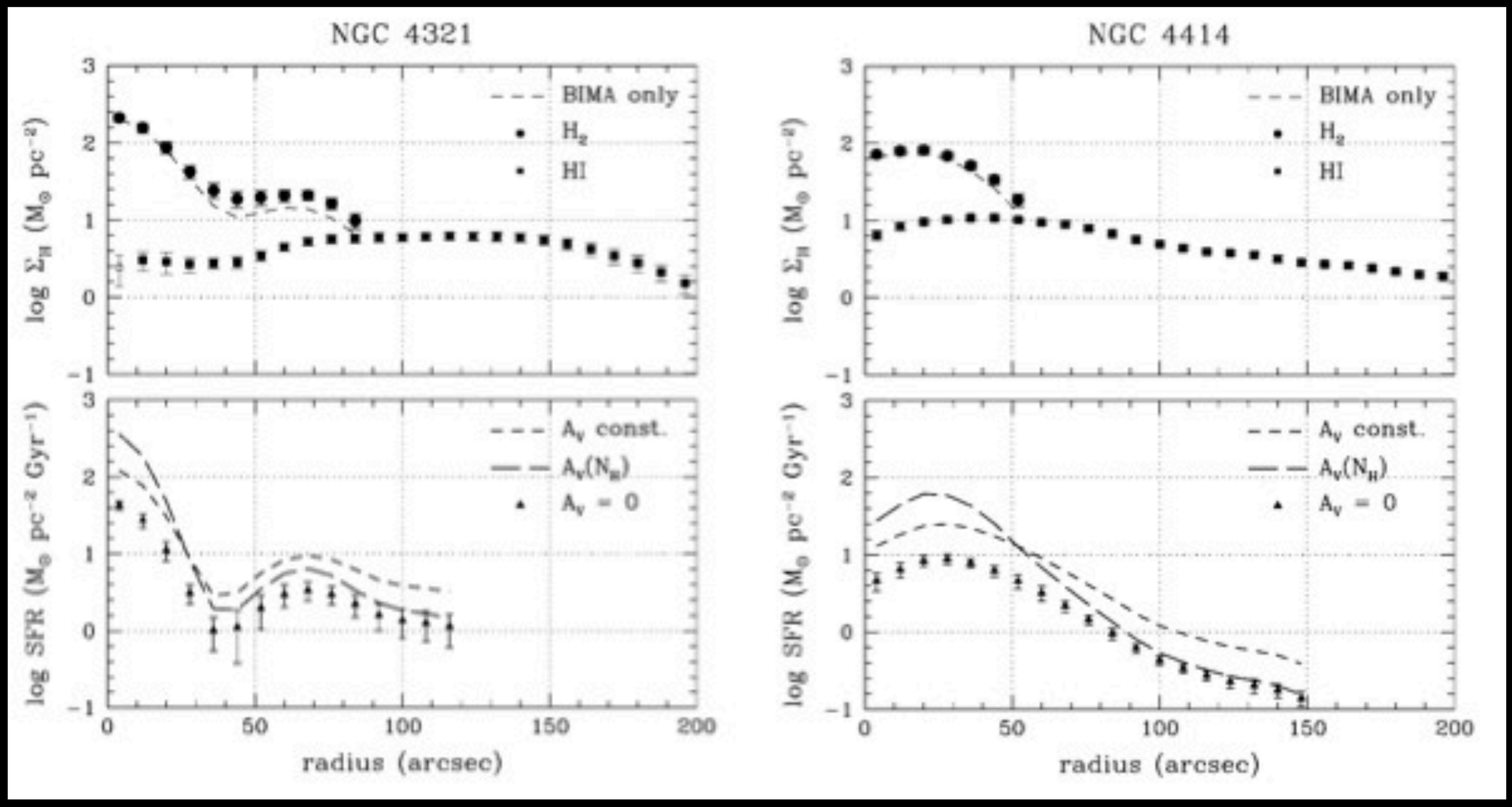
- Properties of outer HI disks
- HI & FUV, low SFR
- Radial Gas Inflows
- Analyzing HI maps to characterize dark matter sub-structure & density profile
- Beyond the Local Volume
- Future

Extended HI Disks



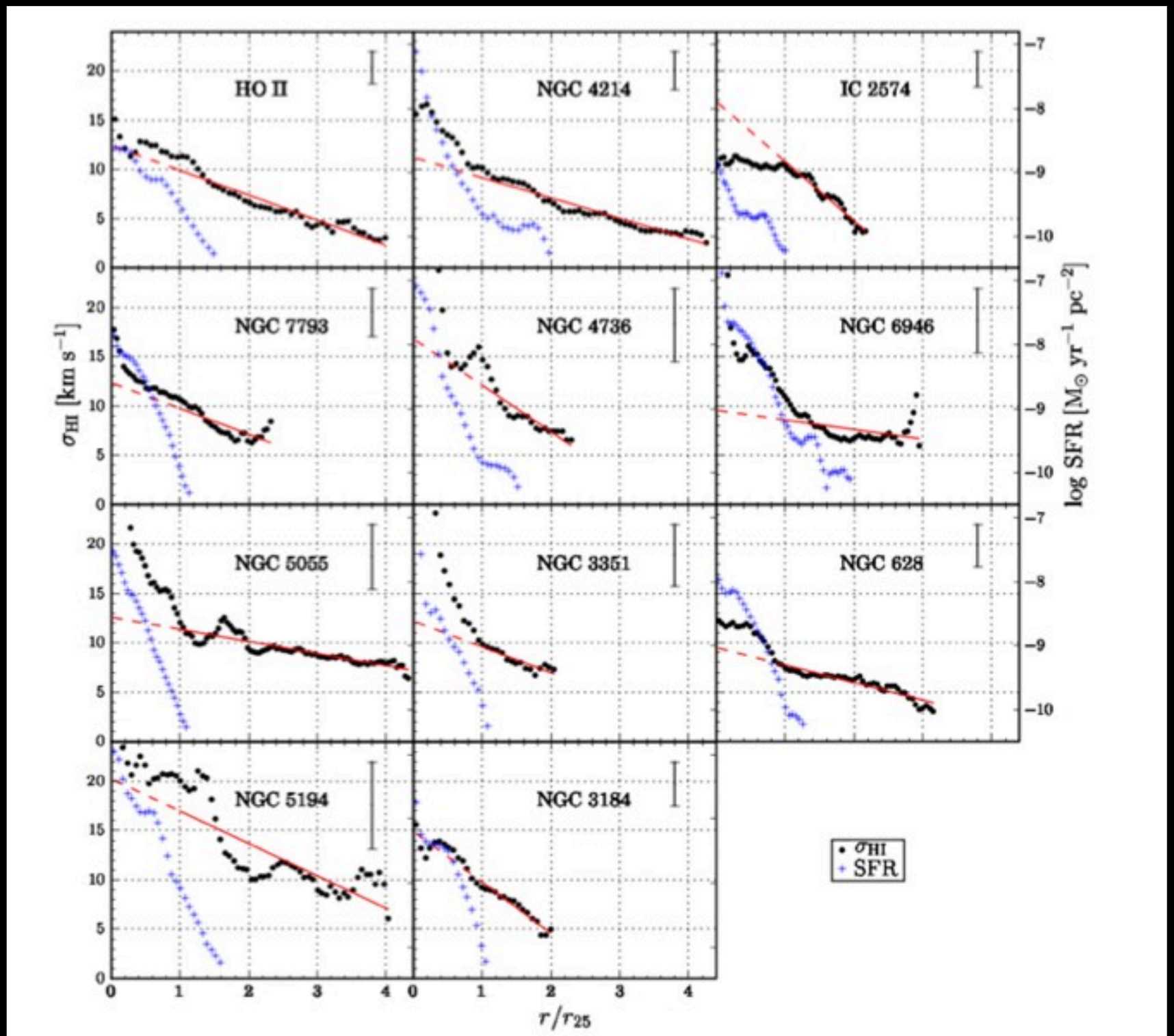
THINGS; Walter et al. 08

Radial Profiles



Wong & Blitz 2002

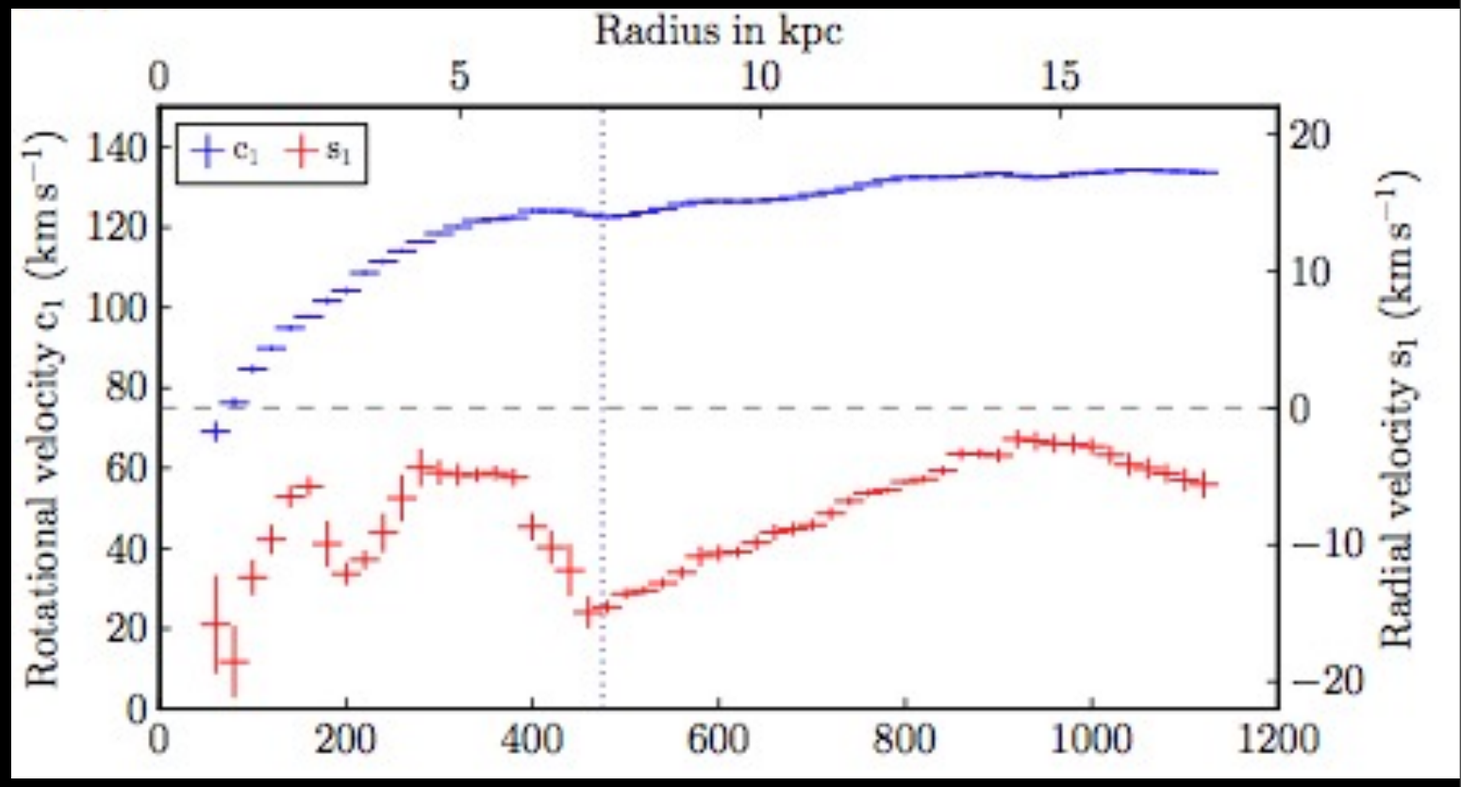
Velocity dispersion



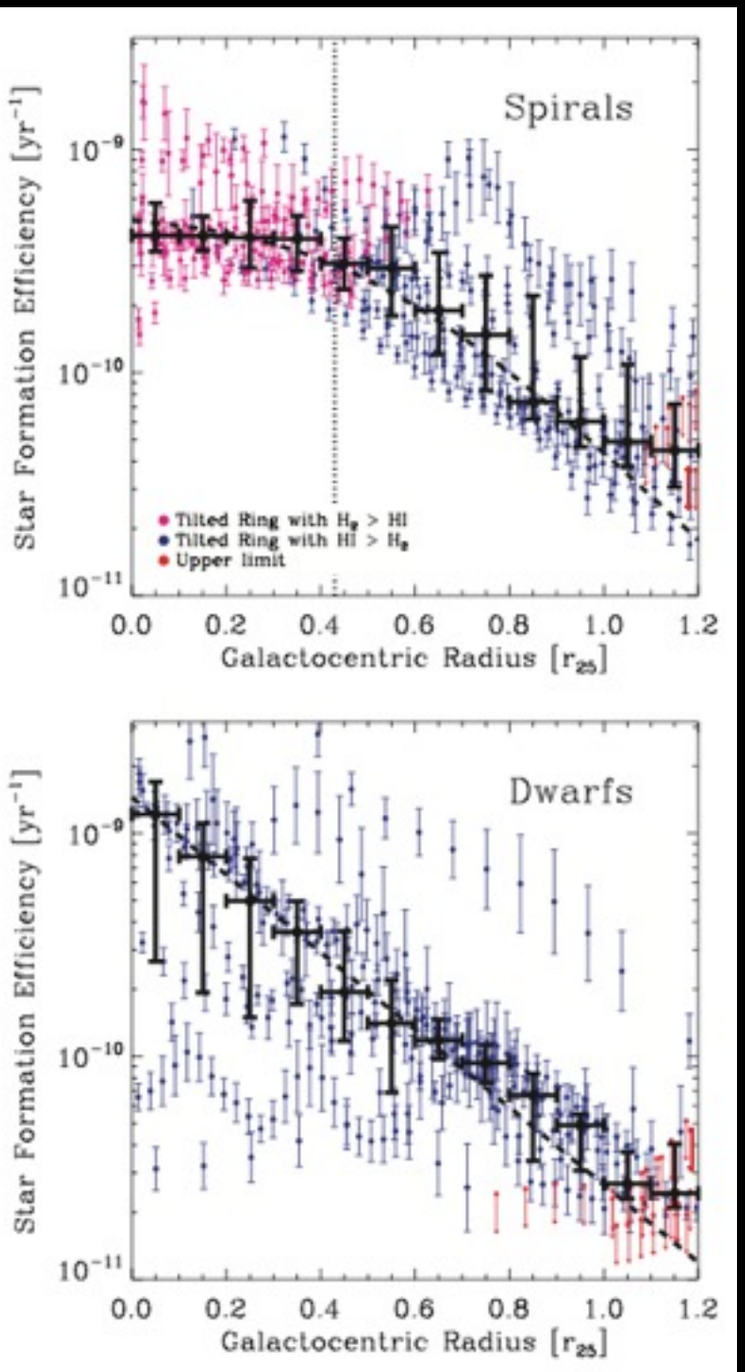
Tamburro et al. 2009

Radial Gas Flows

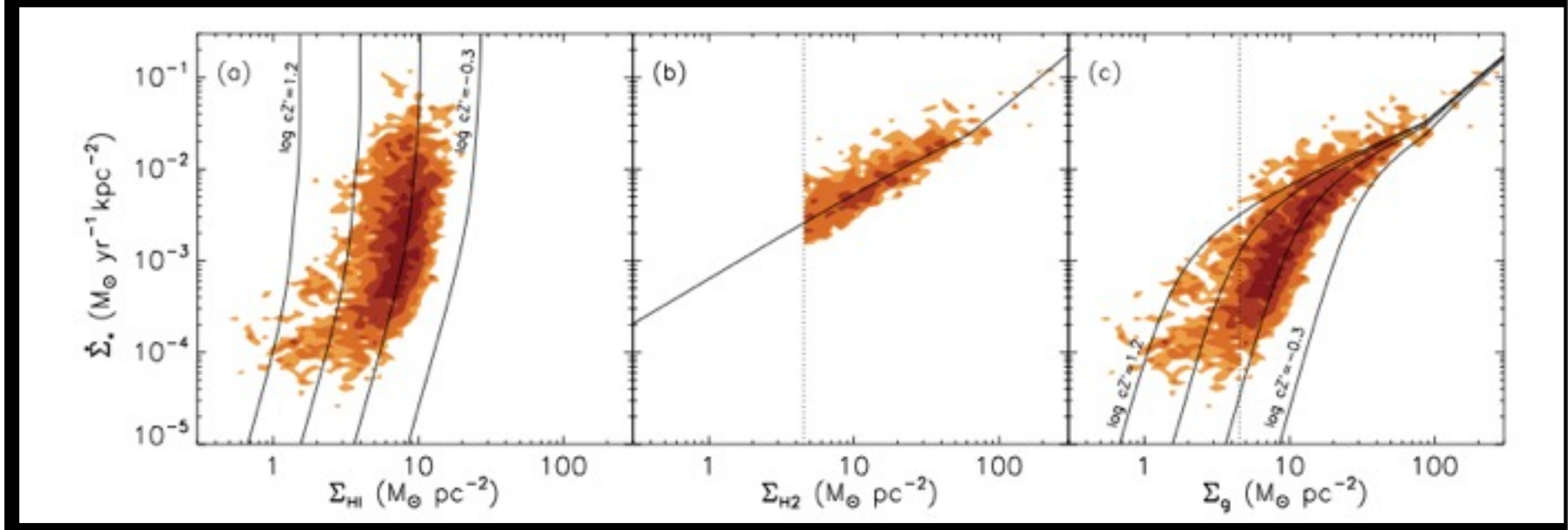
- Gas depletion time ~ few Gyr. Replenish gas reservoir?
- Wong, Blitz & Bosma 04 -- upper limits of 5 - 10 km/s in inner regions of nearby spirals



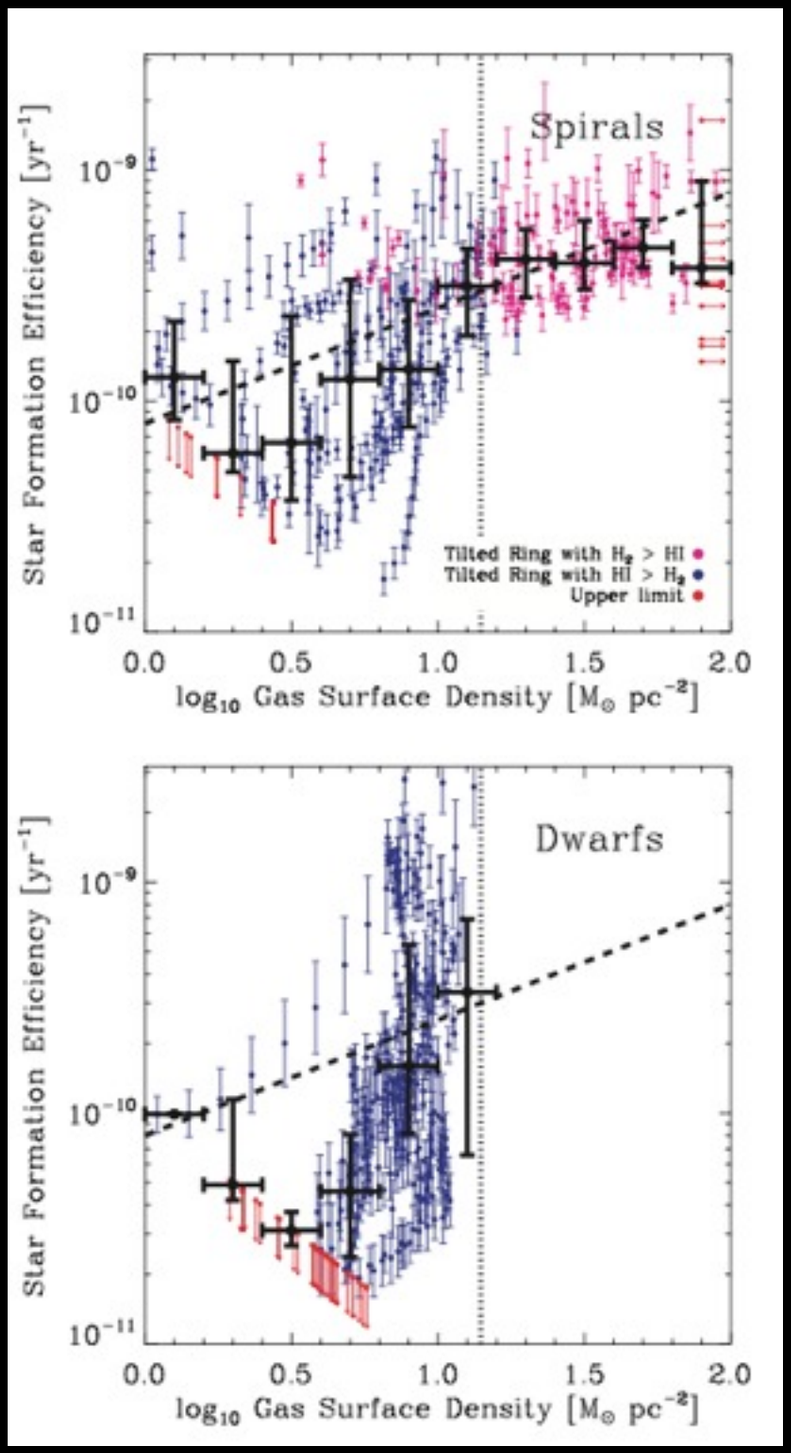
- Schmidt et al. 2015 -- radial inflows of ~ 15 km/s detected in outer HI disks of some THINGS galaxies (mass flow rate of ~ 3 M_{sun}/yr)



Star formation efficiency = SF/per unit neutral gas (Leroy et al. 2008) -- combining THINGS, GALEX, Spitzer, CO data)



Krumholz et al 2009; see also Tan 2000; Suwannajak, Tan & Leroy 2014: SFE : cloud-cloud collisions; Blitz & Rosolowsky 2006: pressure



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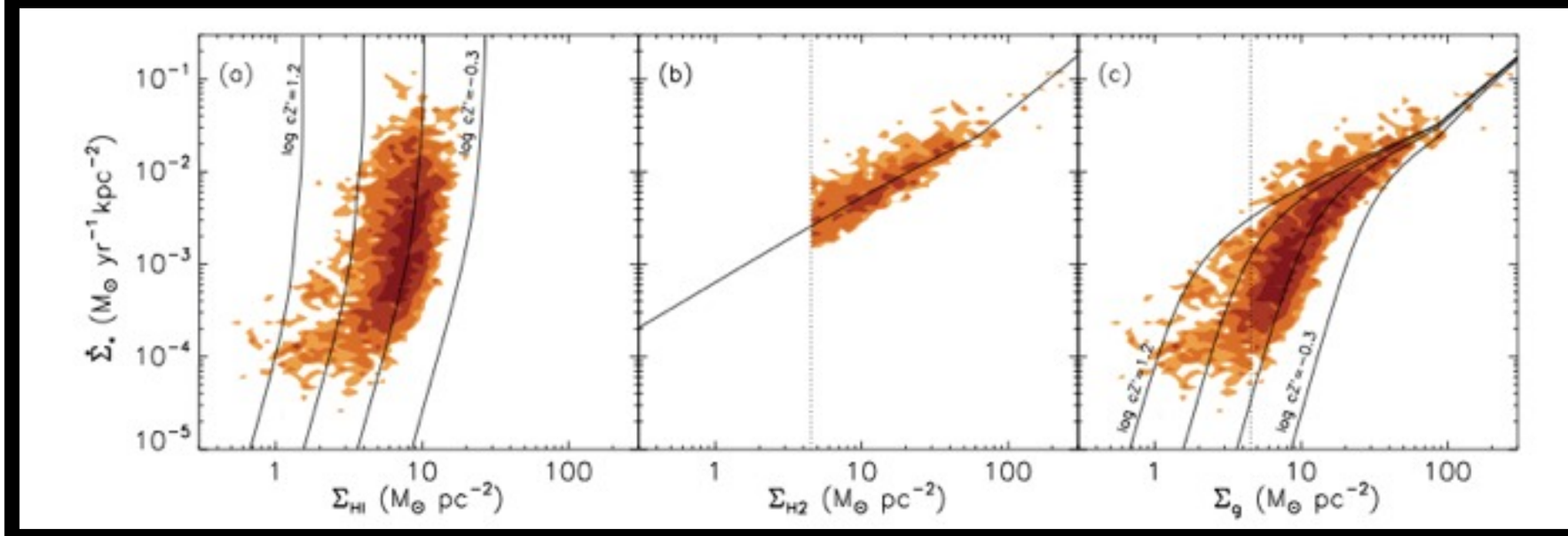

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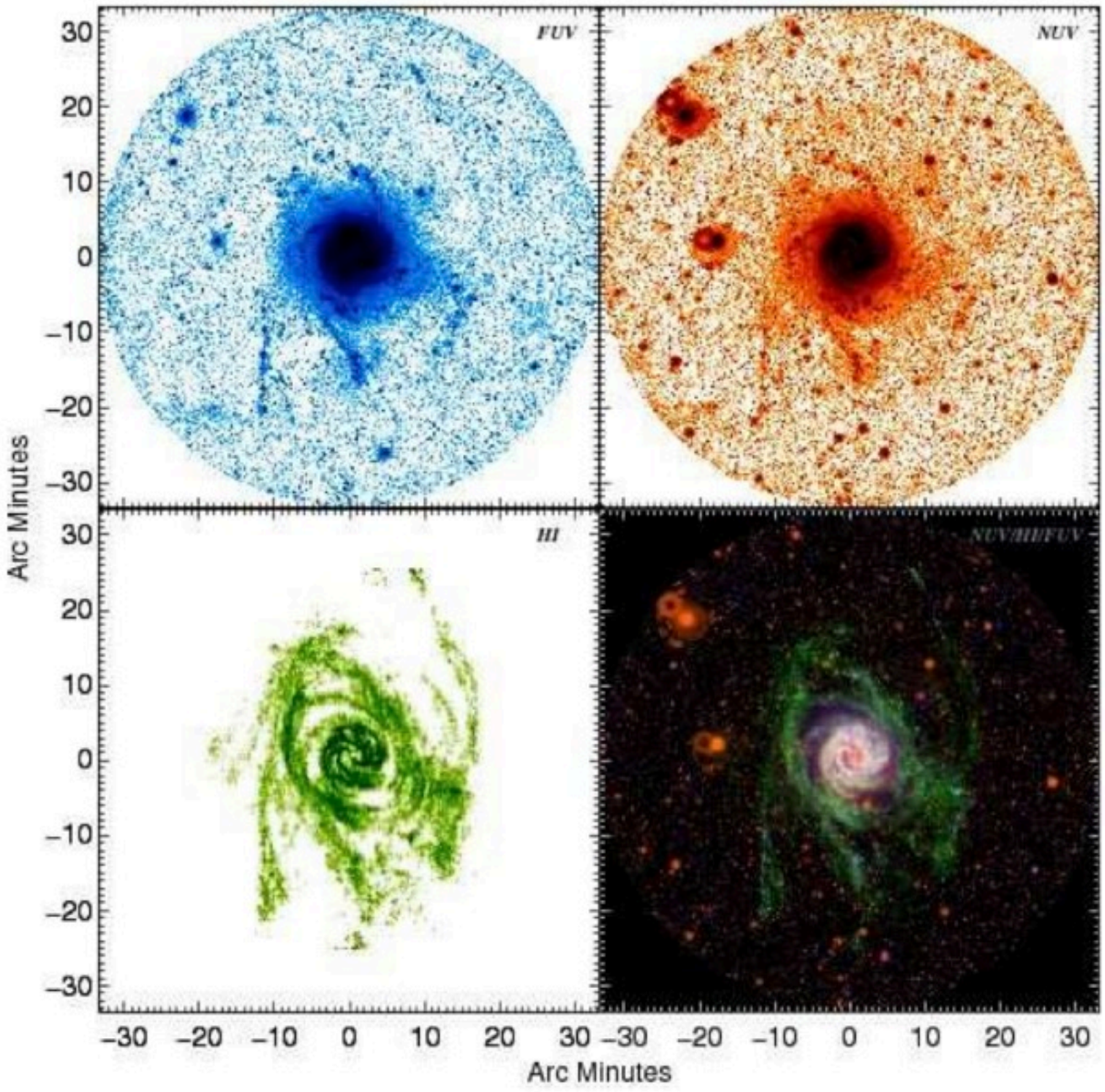
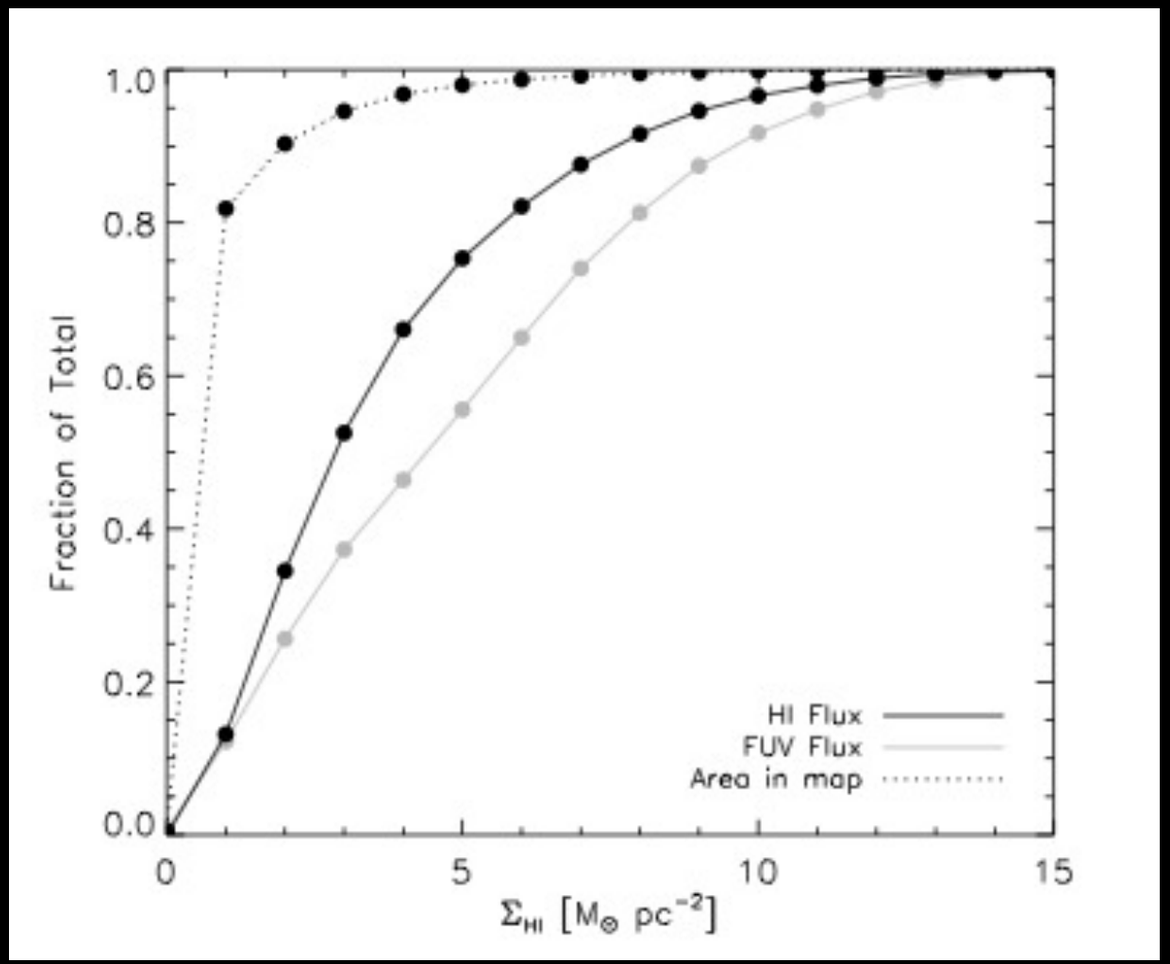


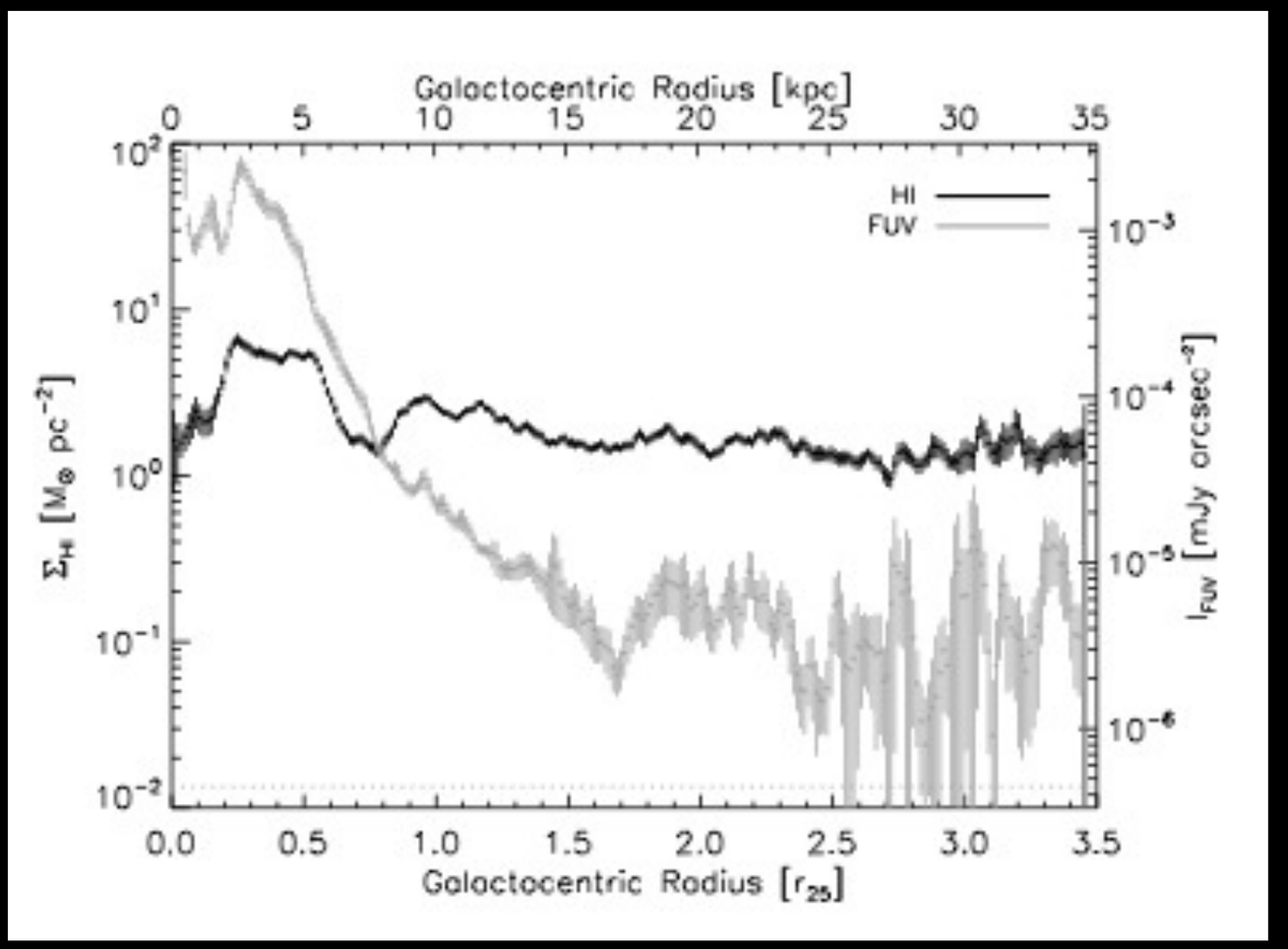
HI & FUV are correlated

Thilker et al. 2005; Bigiel et al. 2010



FUV tracks HI

Bigiel et al. 2010

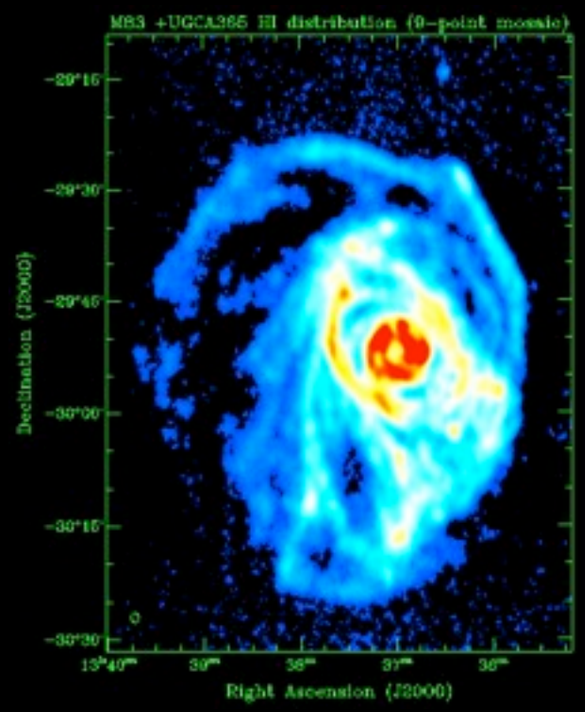


FUV corresponds to high surface density HI & falls off sharply radially relative to HI, flattening to low level of FUV (SF) in outer parts


THINGS
The HI Nearby Galaxy Survey
NGC 2841
NGC 3621
NGC 7331
NGC 4826 (M64)
NGC 6946
NGC 3184
NGC 925
NGC 3351 (M95)
NGC 3198
NGC 5194 (M51)
NGC 3521
NGC 4214
NGC 2976
DDO 53
NGC 1569
M81dwB
M81dwA
NGC 5236 (M83)
NGC 2366
Our Galaxy HI stars
IC 2574
NGC 4449
NGC 3627 (M66)
Holmberg II
NGC 7793
DDO 154
NGC 4736 (M94)
NGC 3077
Holmberg I
NGC 5055
NGC 2903
10 kpc
NGC 628 (M74)
NGC 5457 (M101)
NGC 3031 (M81)
NGC 2403
THINGS
Data: Walter et al 2008
Milky Way HI map: Oort et al (1958)
Milky Way art: NASA/JPL, R. Hurt (SSC)

Imprints of dwarf galaxies on outskirts of spirals

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

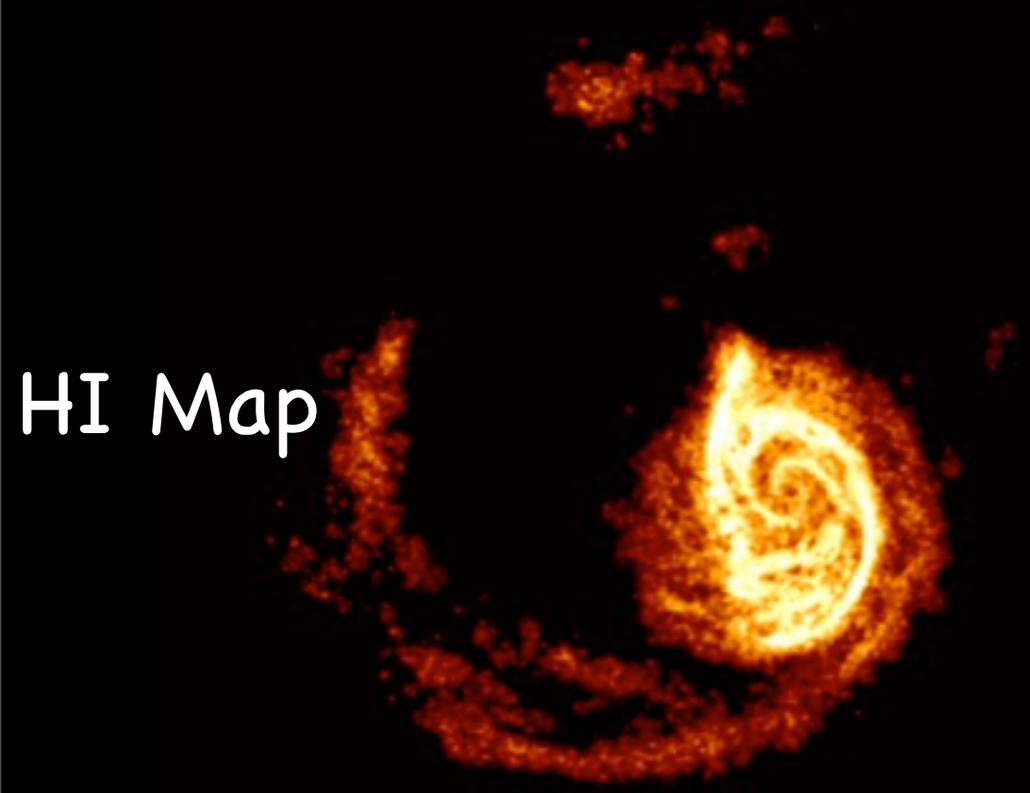


HI Maps

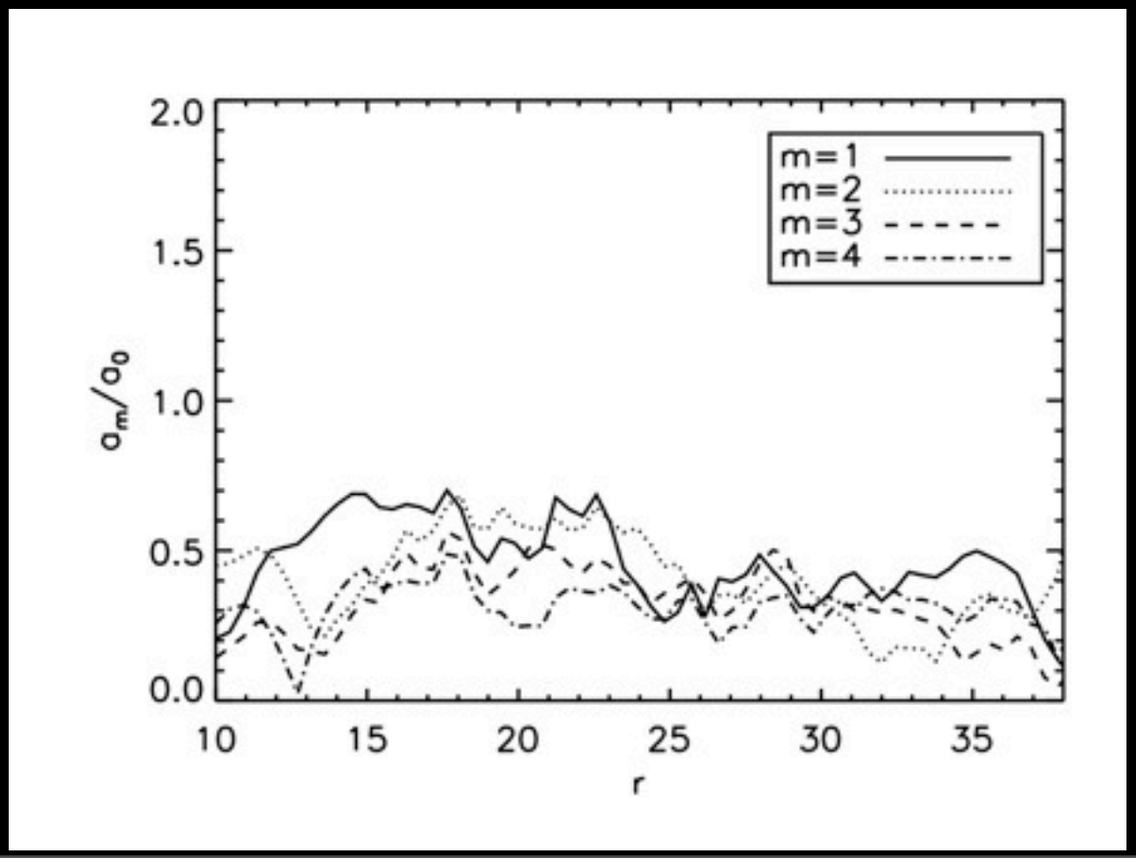
Footprints of Dark Sub-Halos

M51

HI Map



optical image

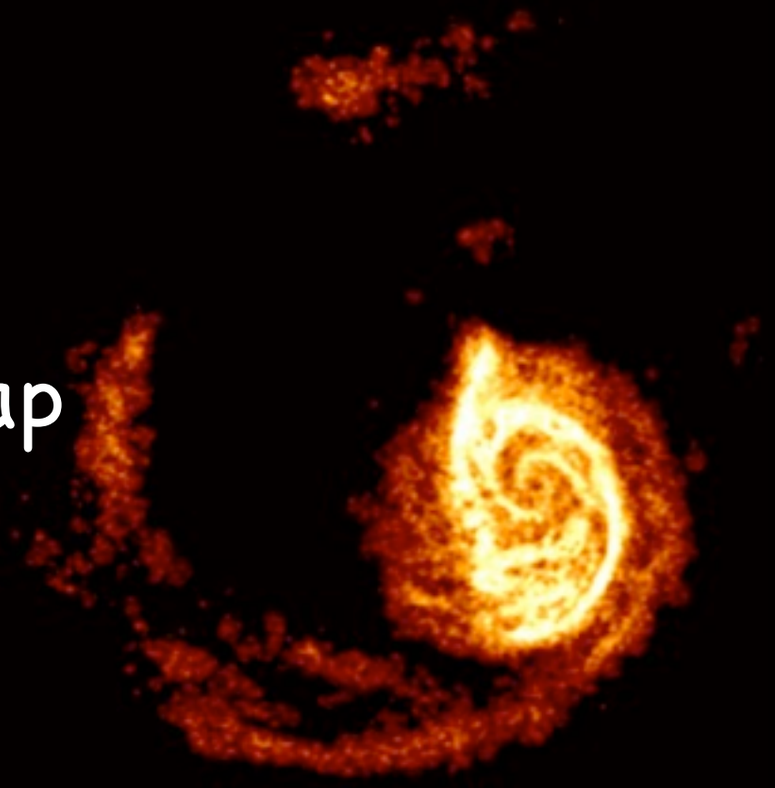


$$a_m(r)=\int \Sigma(r,\varphi)e^{-im\varphi}d\varphi$$

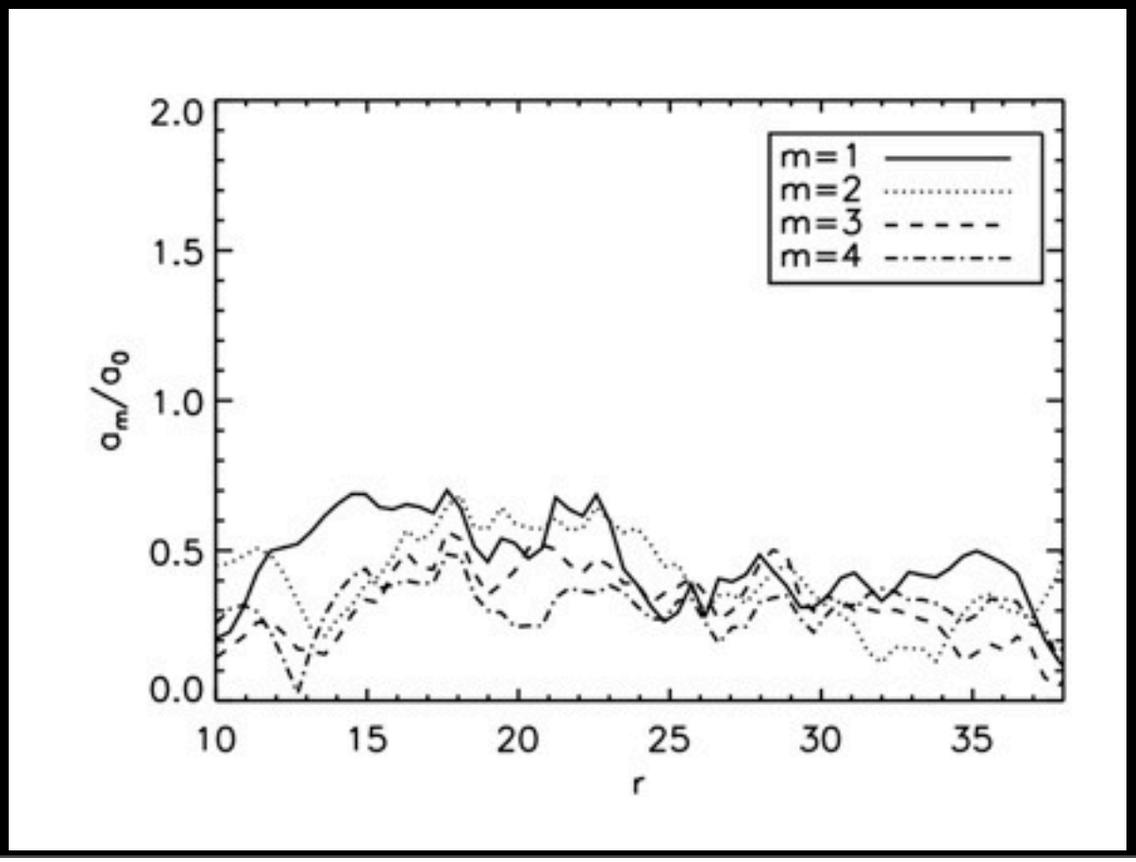
Local Fourier Amplitudes of HI data: Metric of Comparison to simulations

M51

HI Map



optical image



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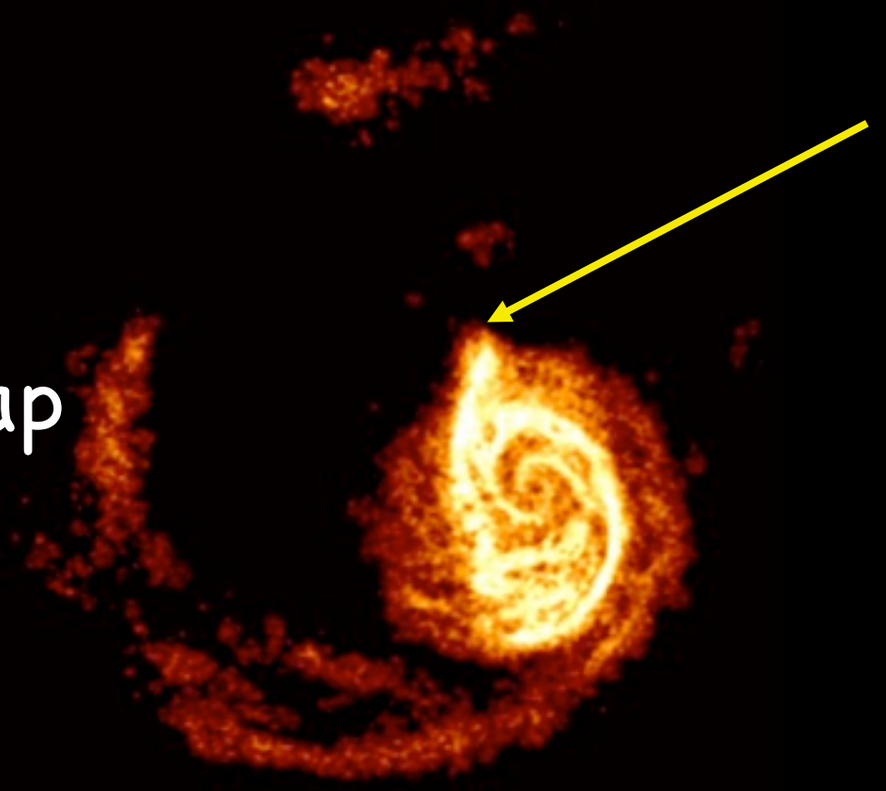
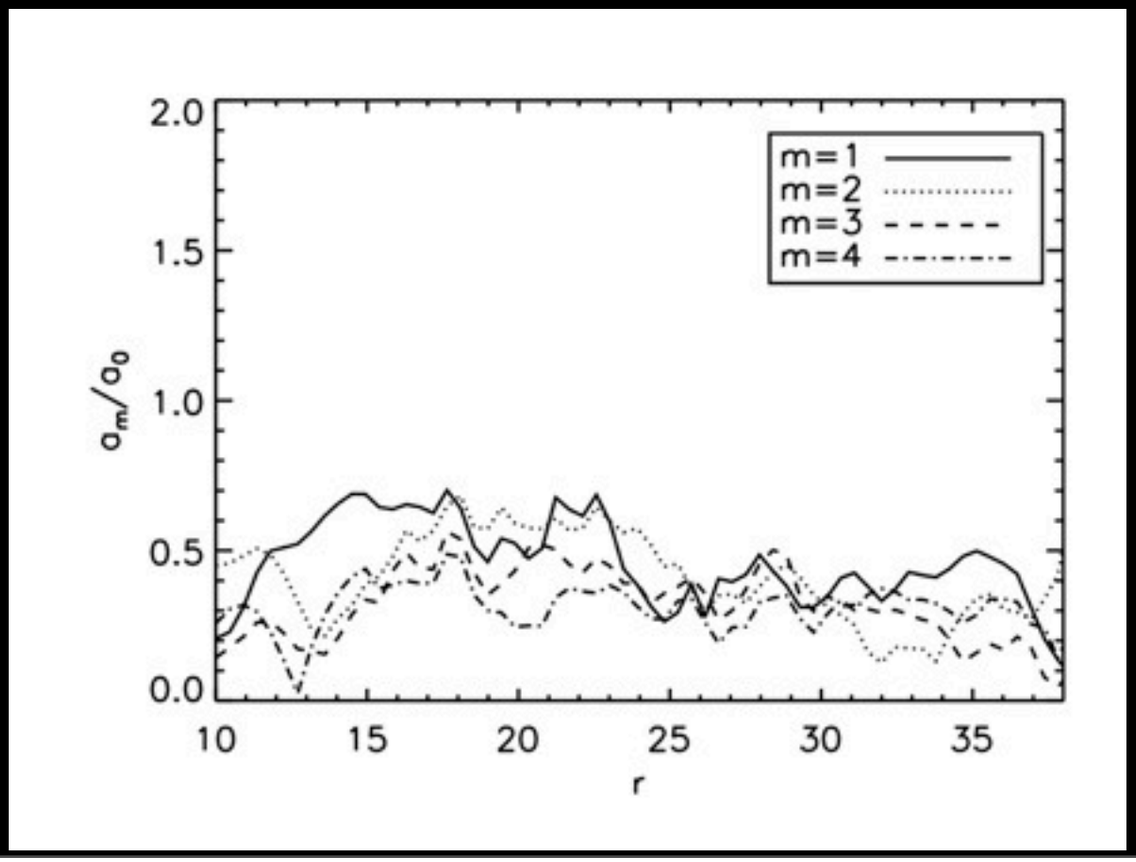


optical image



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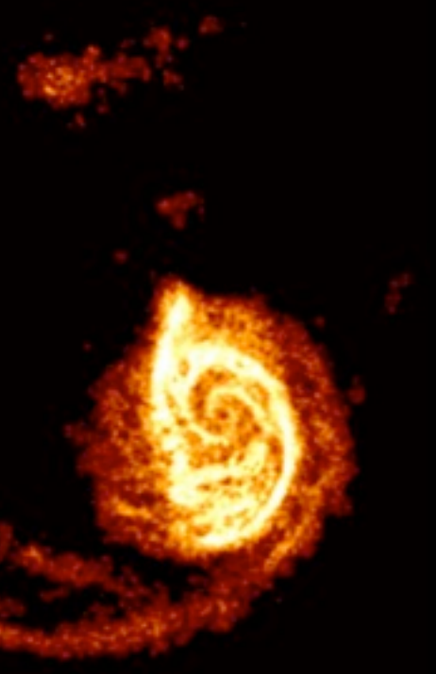
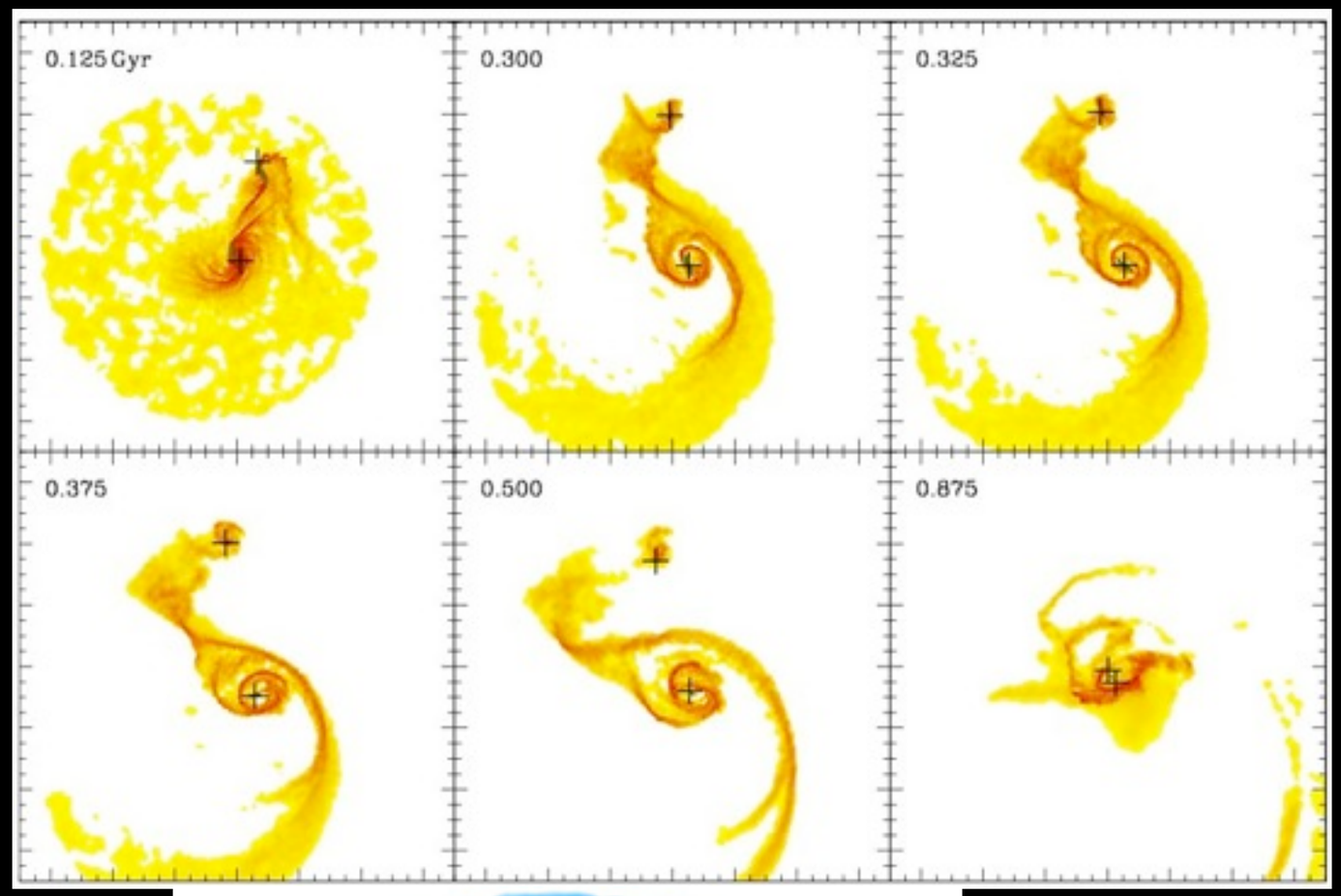
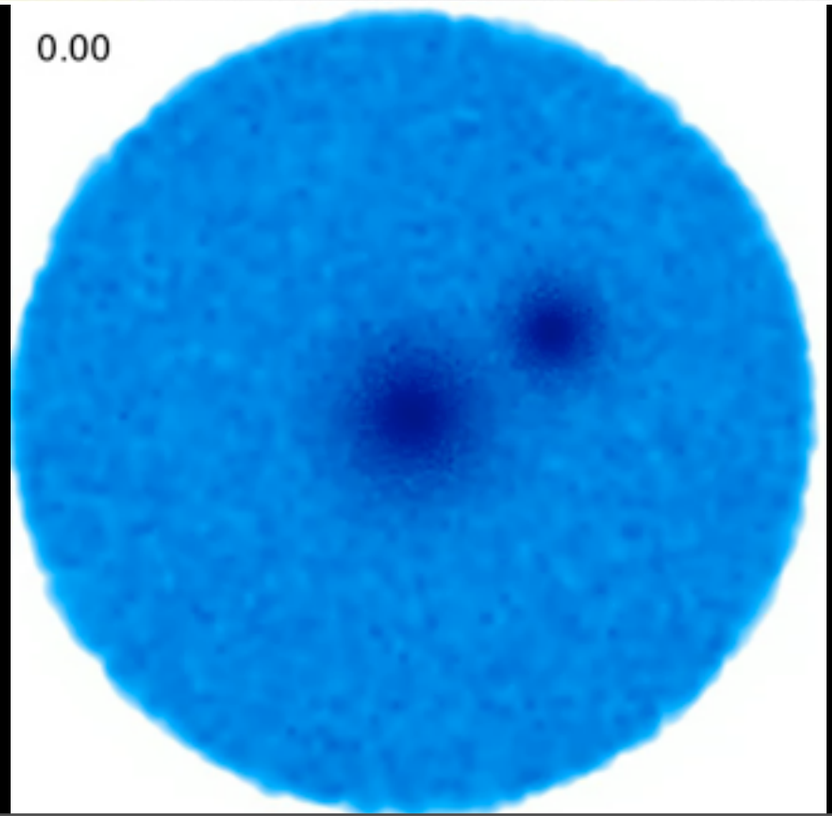
Local Fourier Amplitudes of HI data: Metric of Comparison to simulations

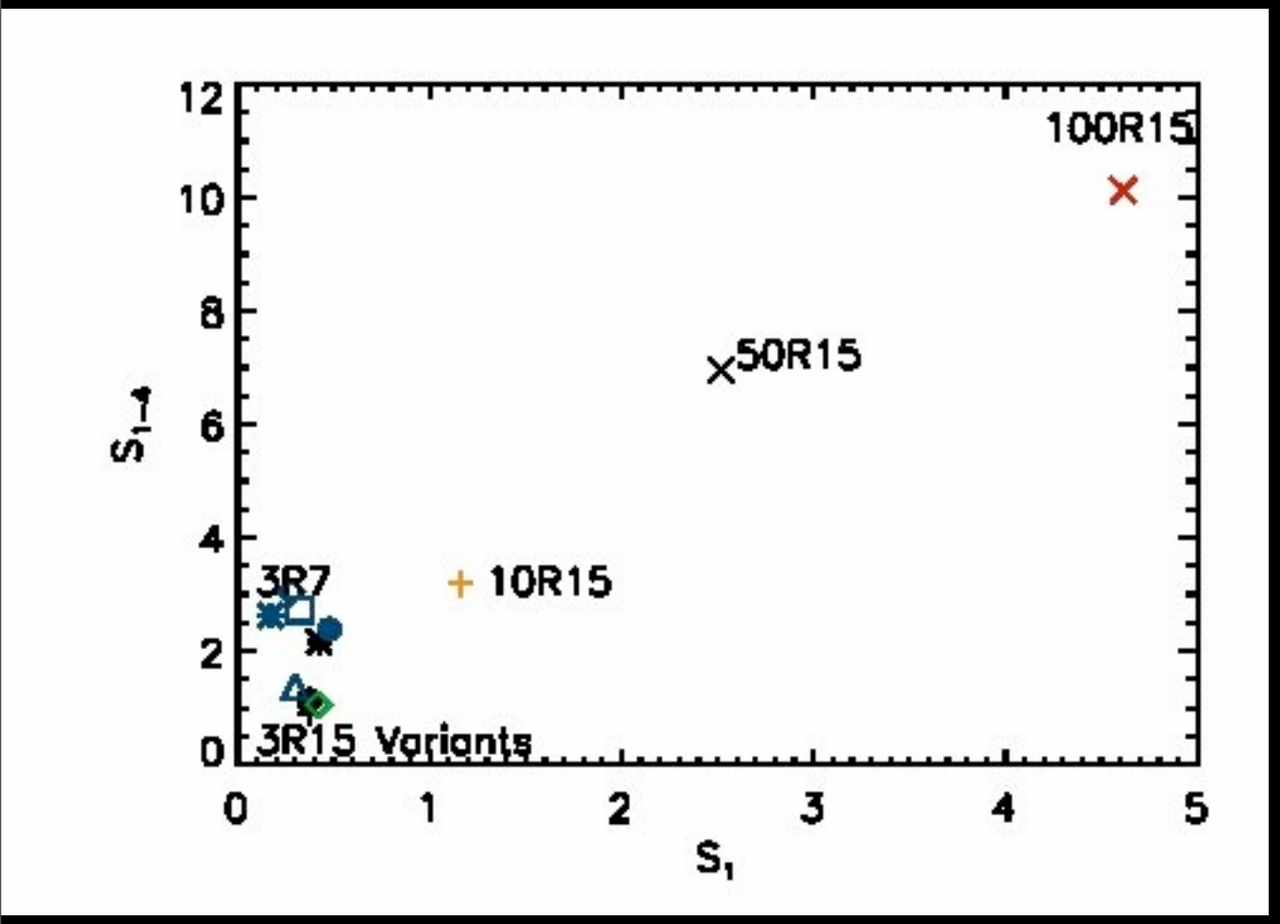
M51 : Proof of Principle



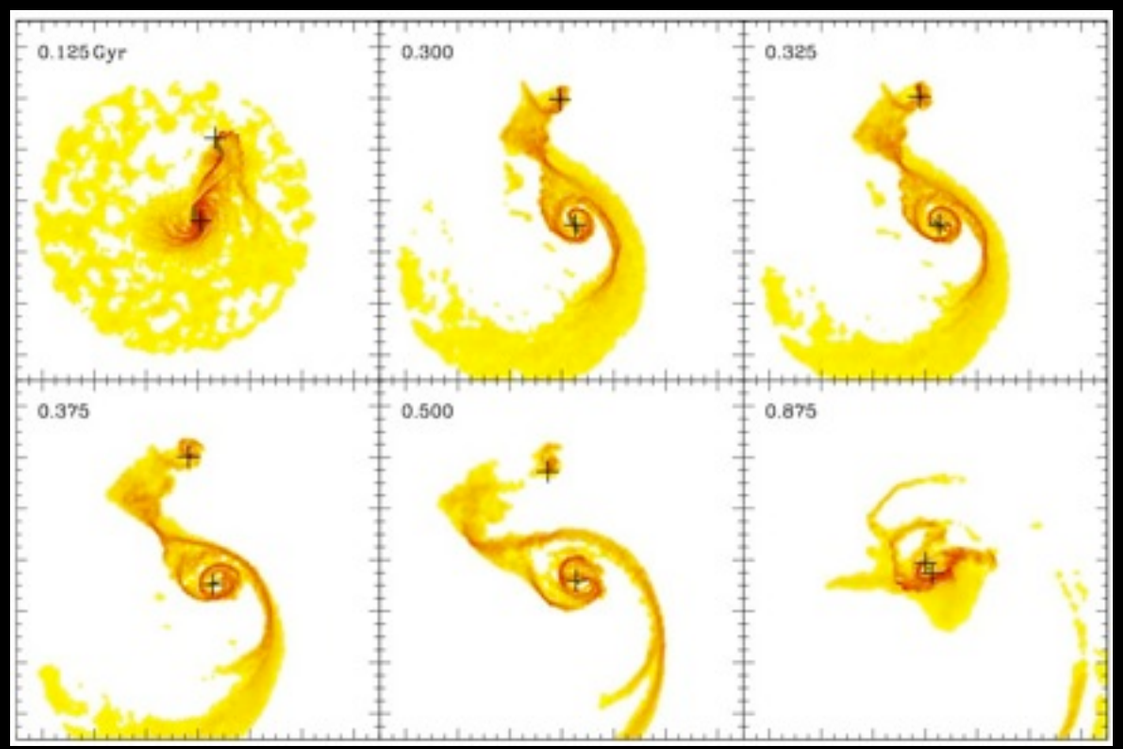


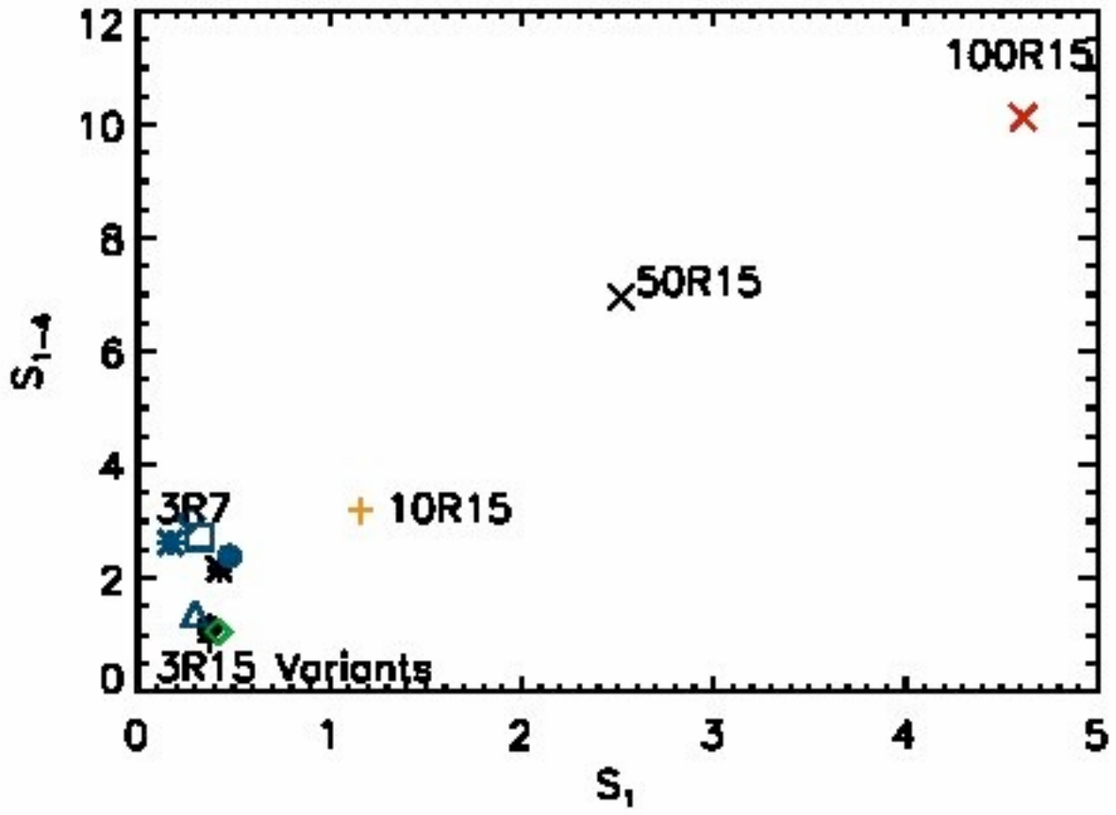


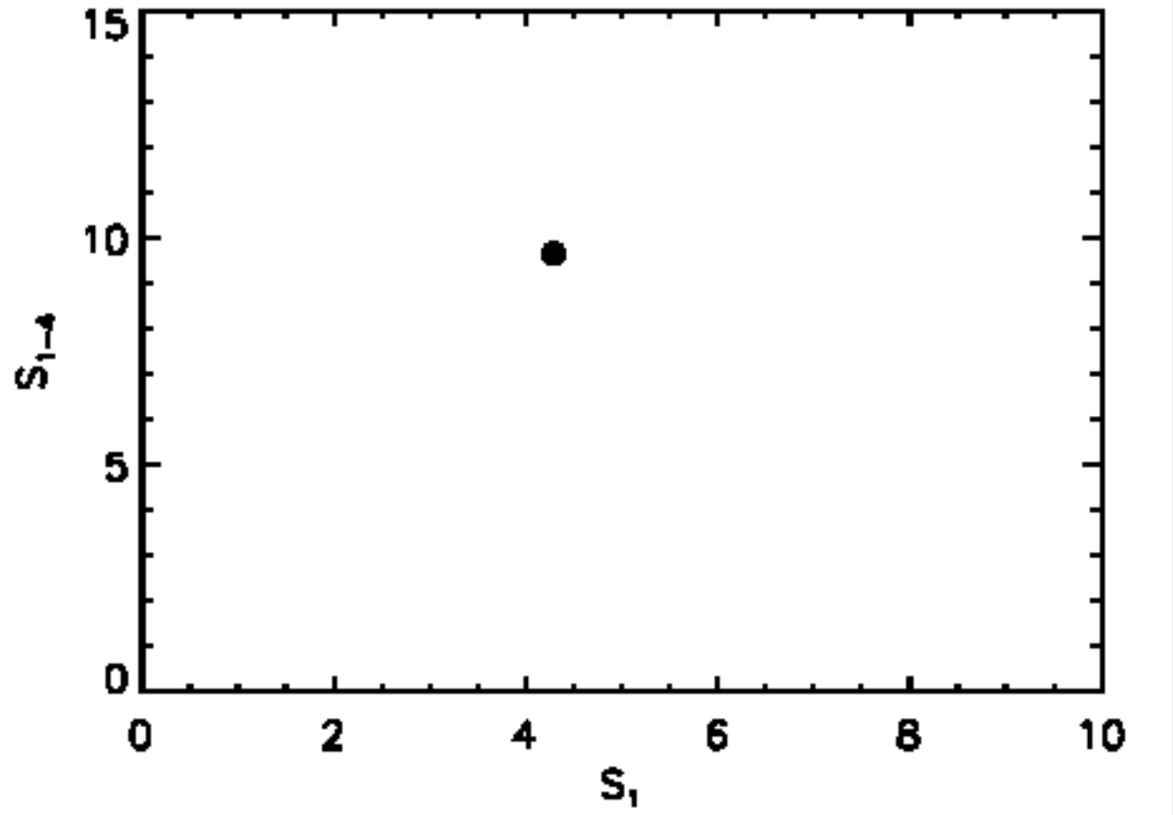
Chakrabarti, Bigiel,
Chang & Blitz, 2011



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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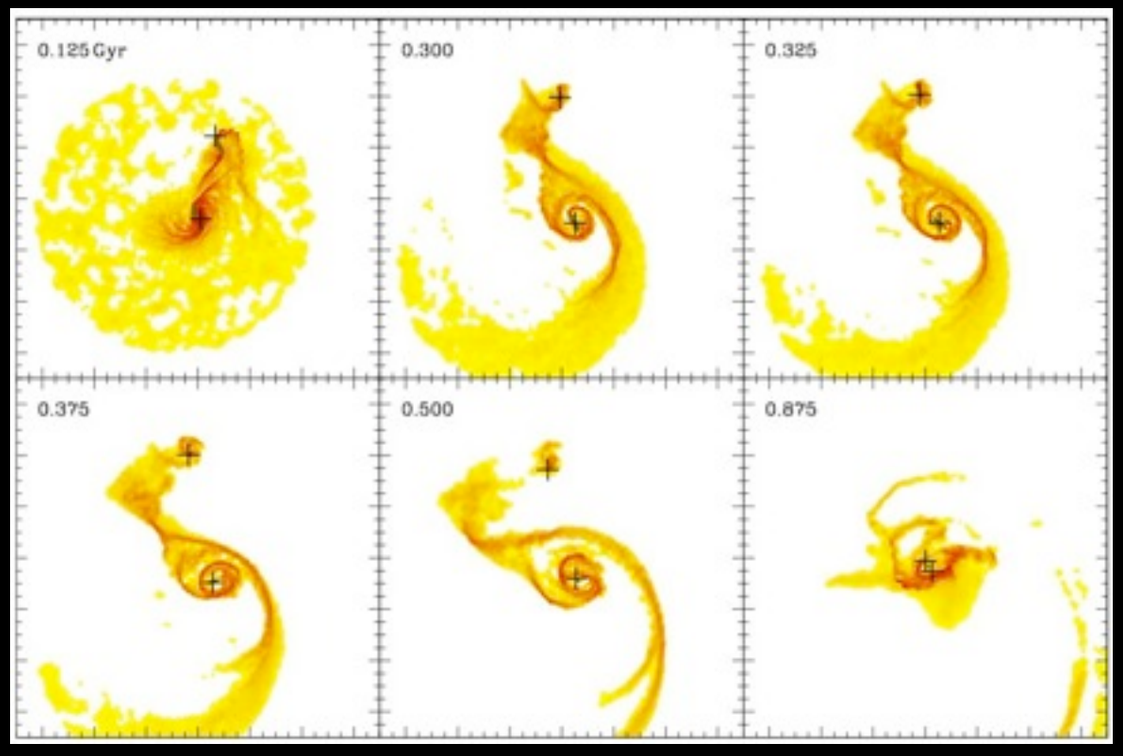
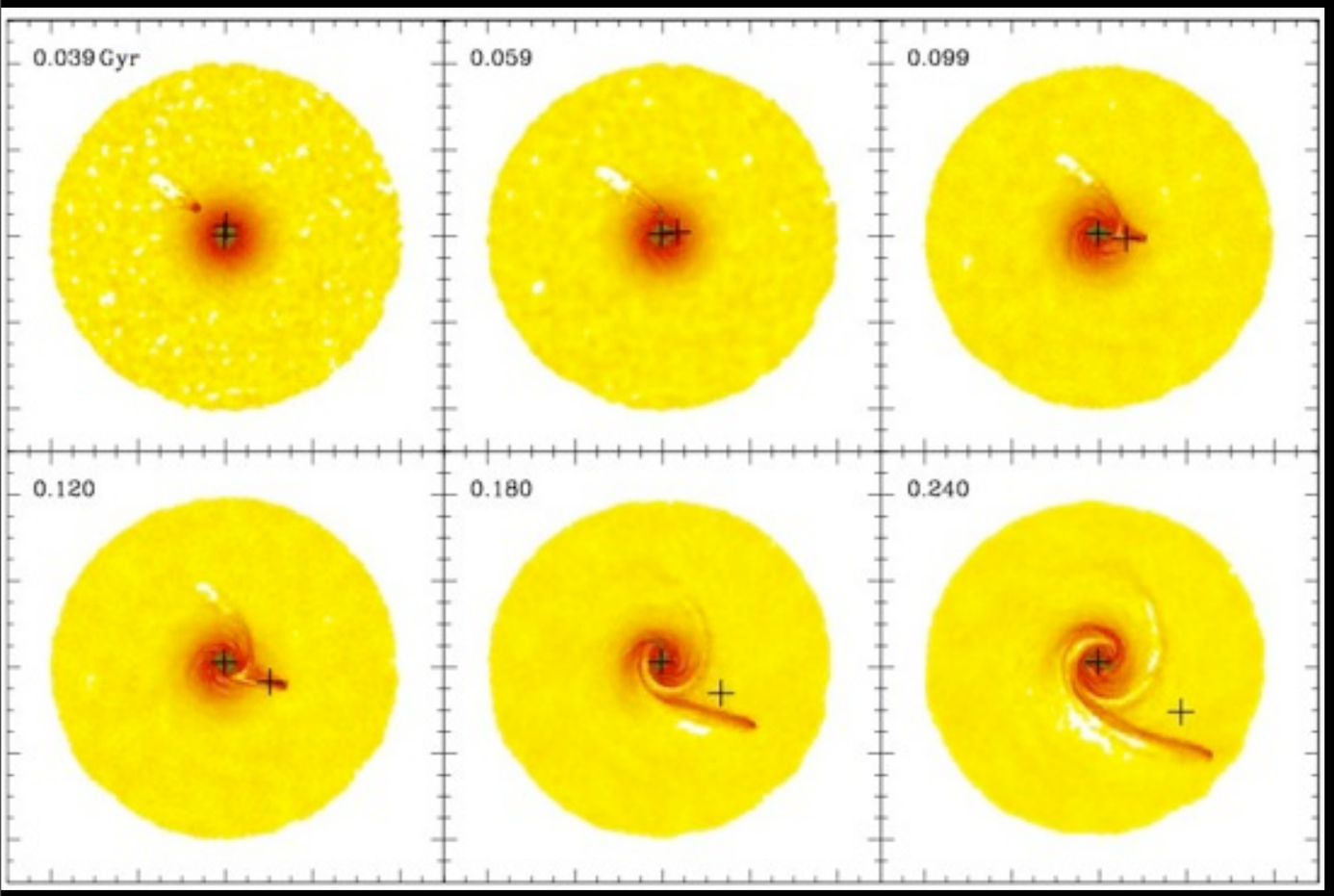
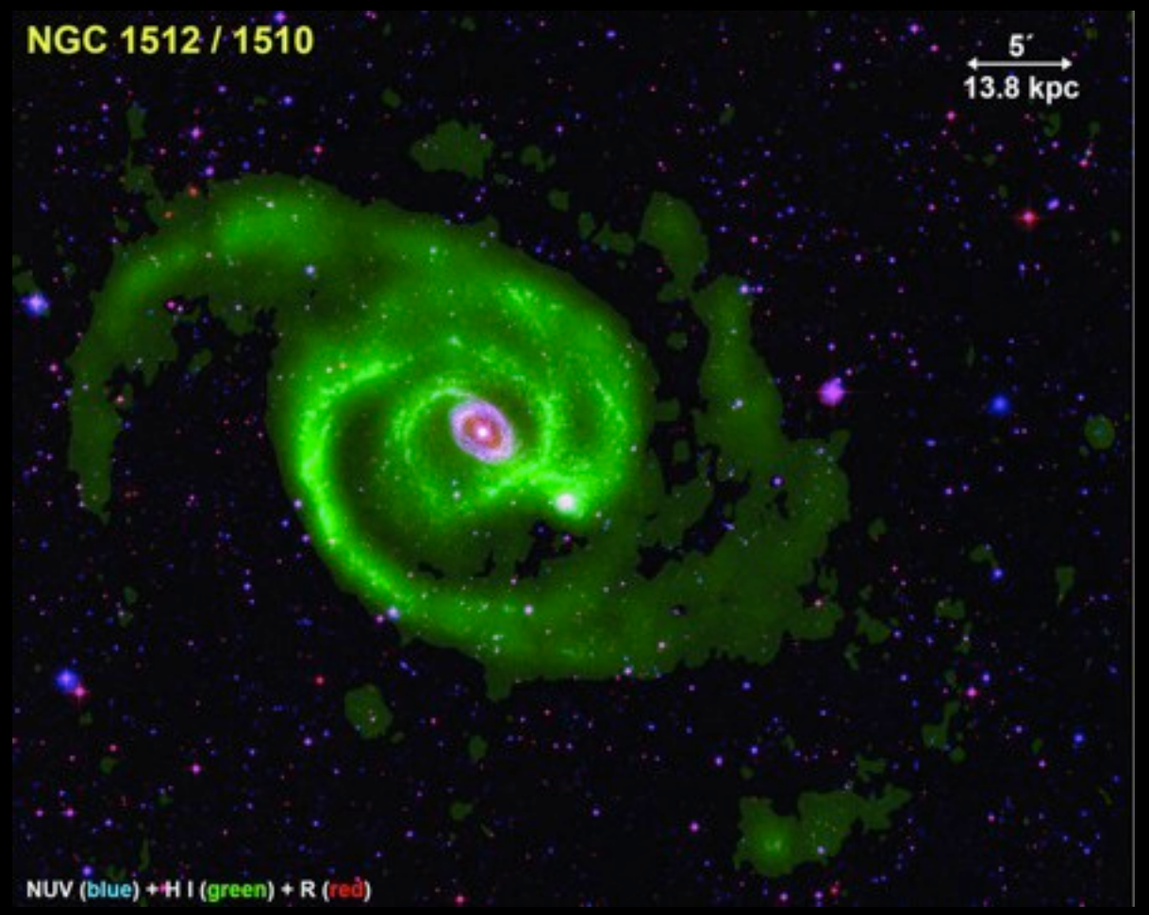


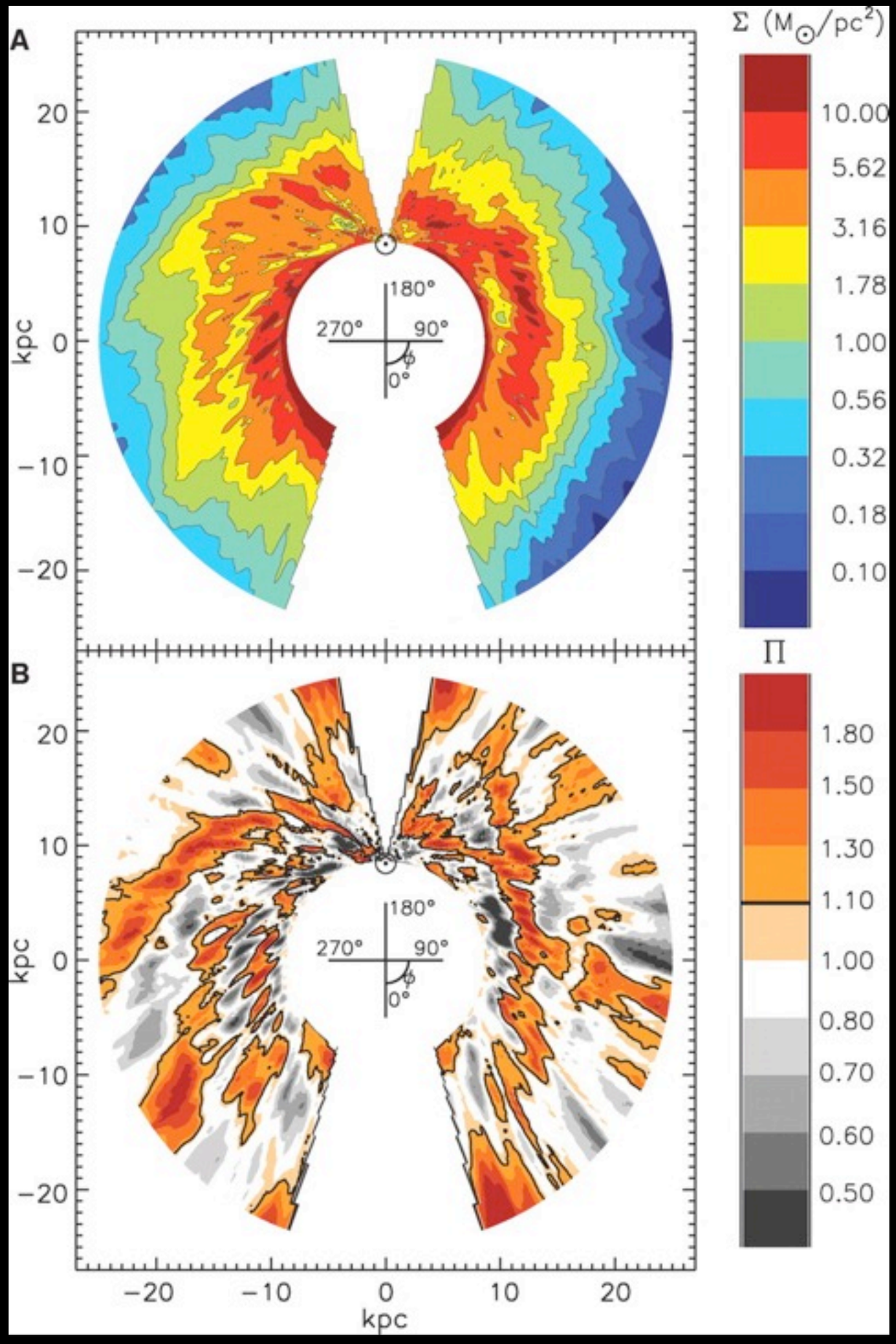
Galaxies with known optical companions contd.





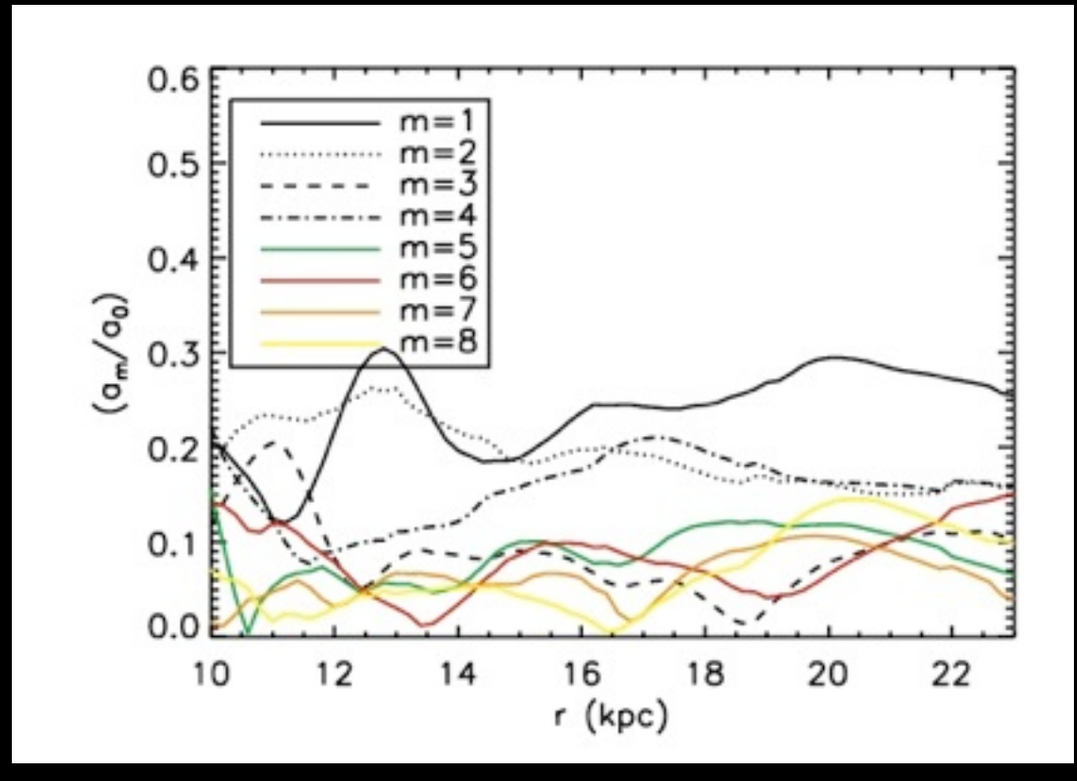
- ~1:100 satellite, R_{peri} = 7kpc (close agreement with Koribalski & Sanchez 09) (global fourier amplitudes)
- Method works for 1:3 - 1:100 mass ratio satellites
- Chang & Chakrabarti (2011) : scaling relations for satellite mass from HI map

HI Map of Milky Way



Levine, Blitz & Heiles 2006

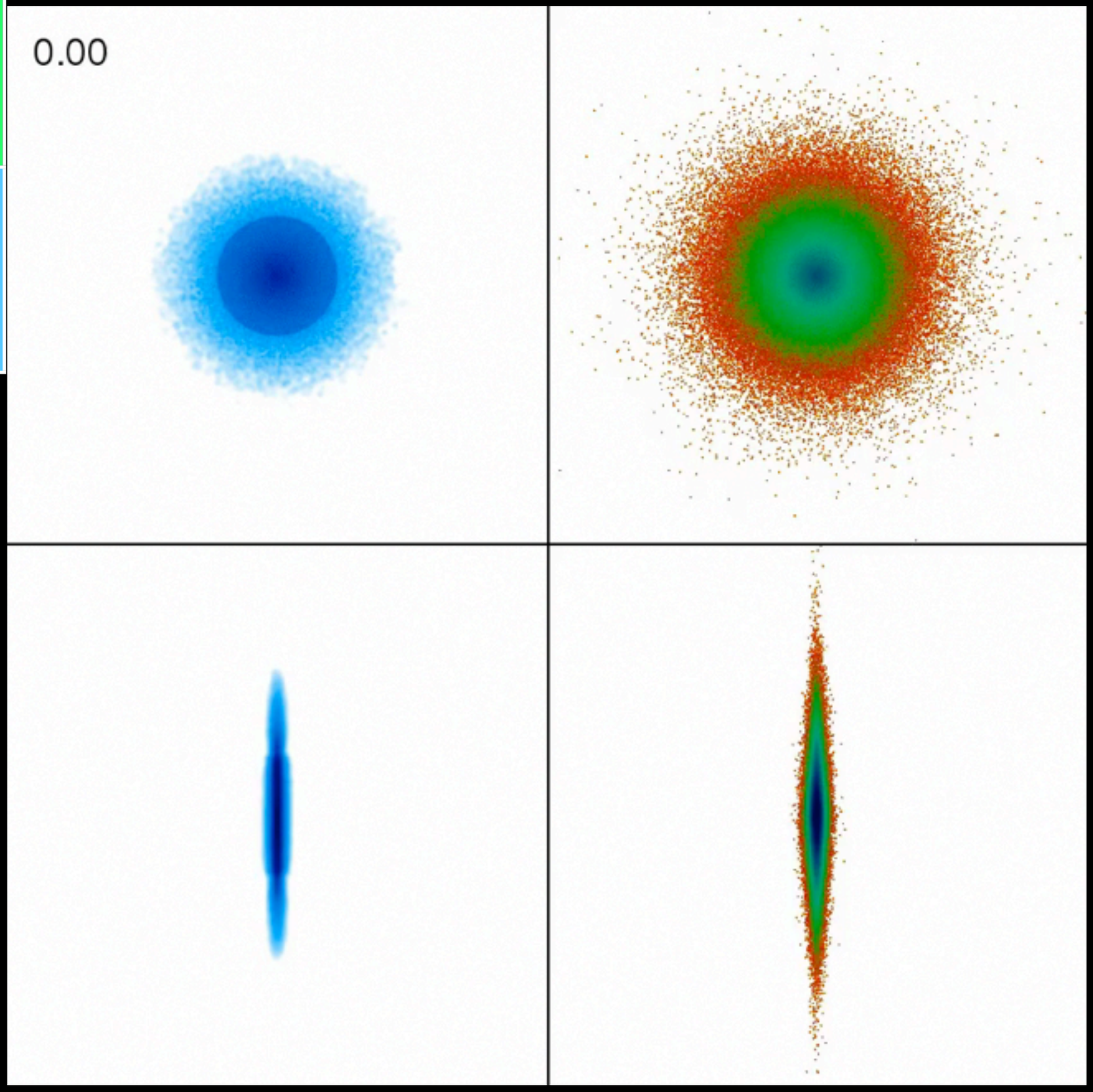
$$a_m(r)=\int \Sigma(r,\varphi)e^{-im\varphi}d\varphi$$



M_s	R_{peri}	inclinat-ion
1:10-1:1000	0.1-50kpc	f_{gas} (0.1-0.3), EQ)

Parameter space survey of simulations. Chakrabarti & Blitz 2009, Chakrabarti & Blitz 2011.

Note Monoceros like structure in stellar disk & vertical oscillations



Initial Conditions, Orbits -- what really matters?

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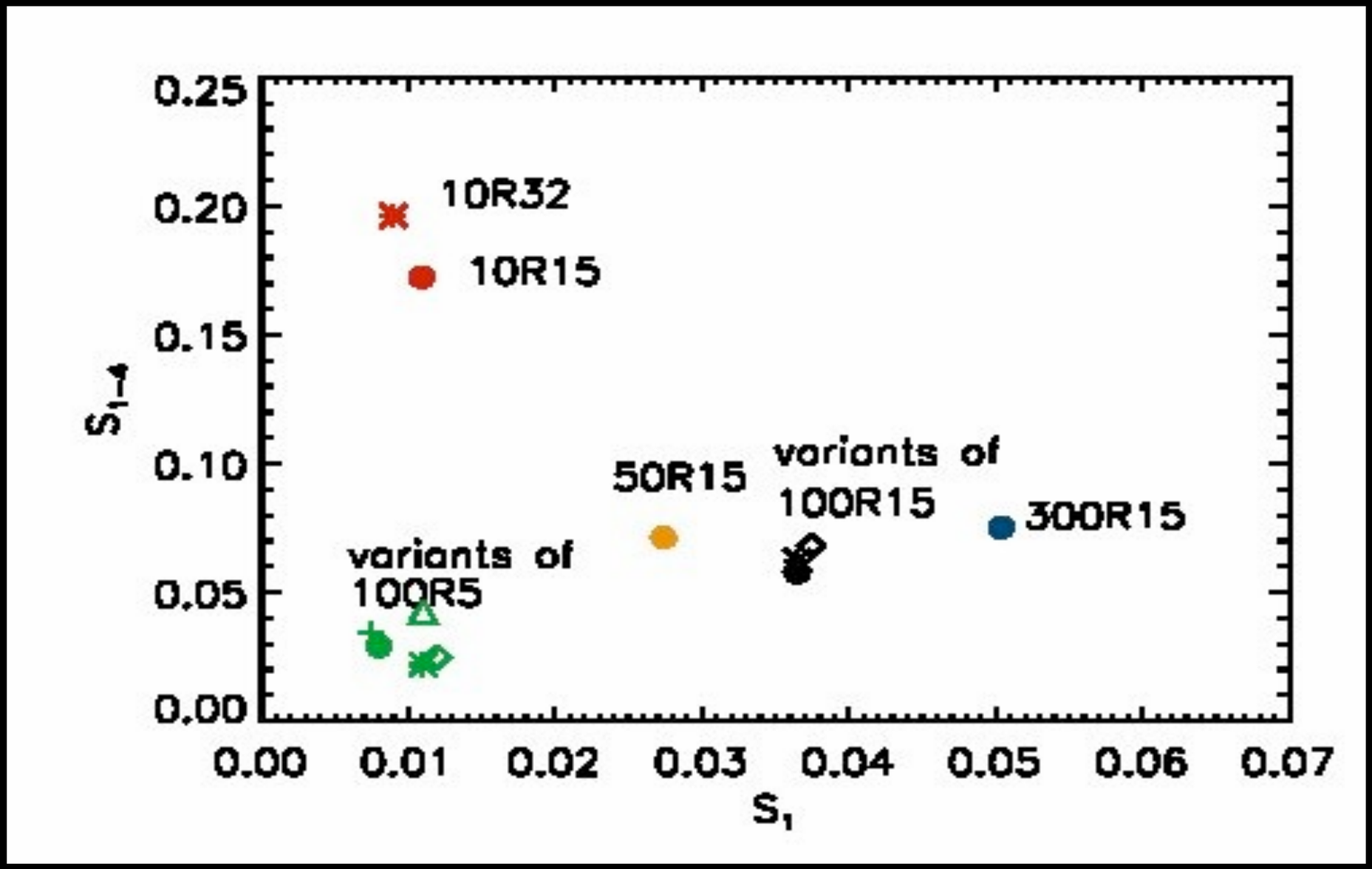

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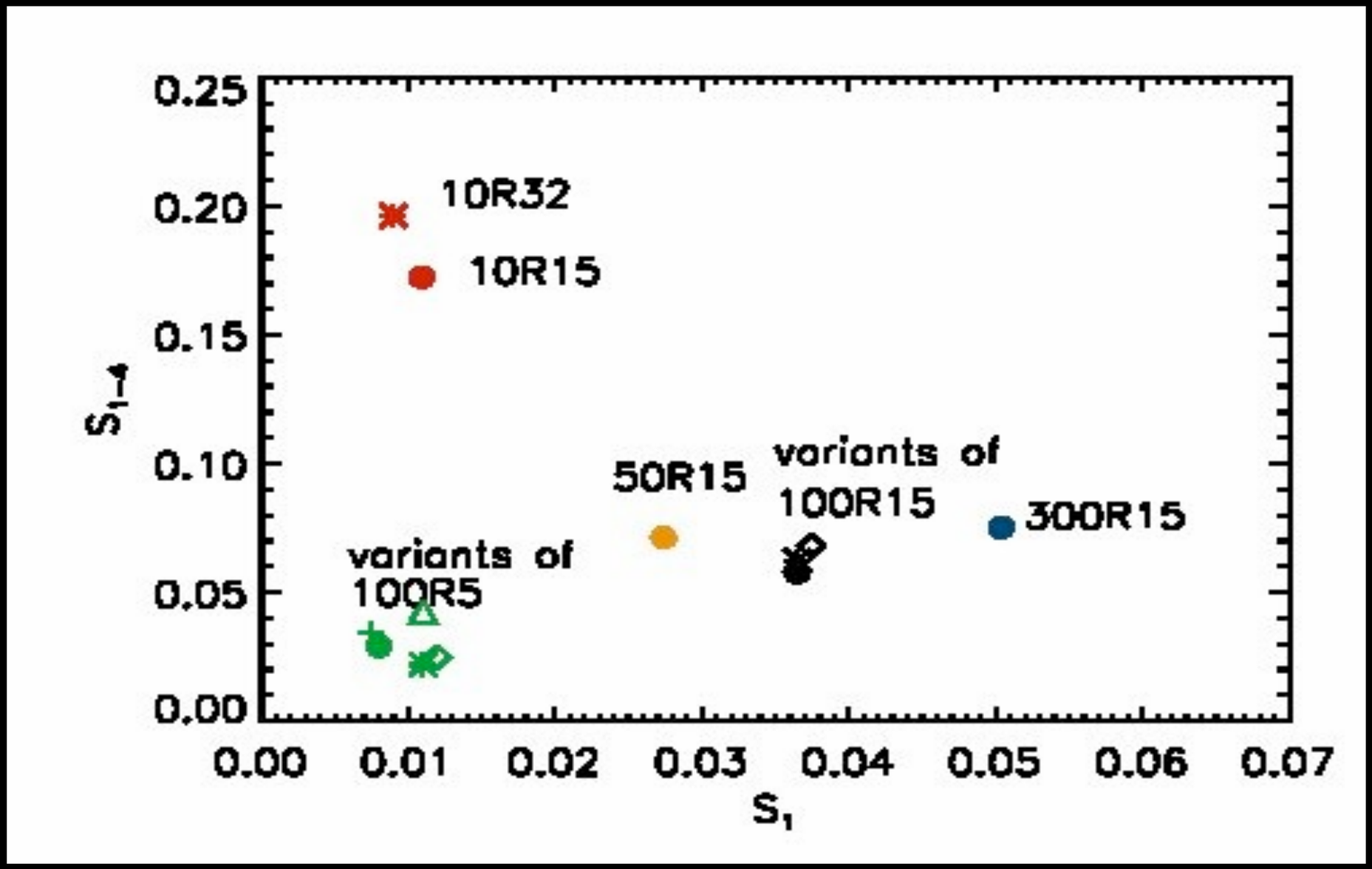
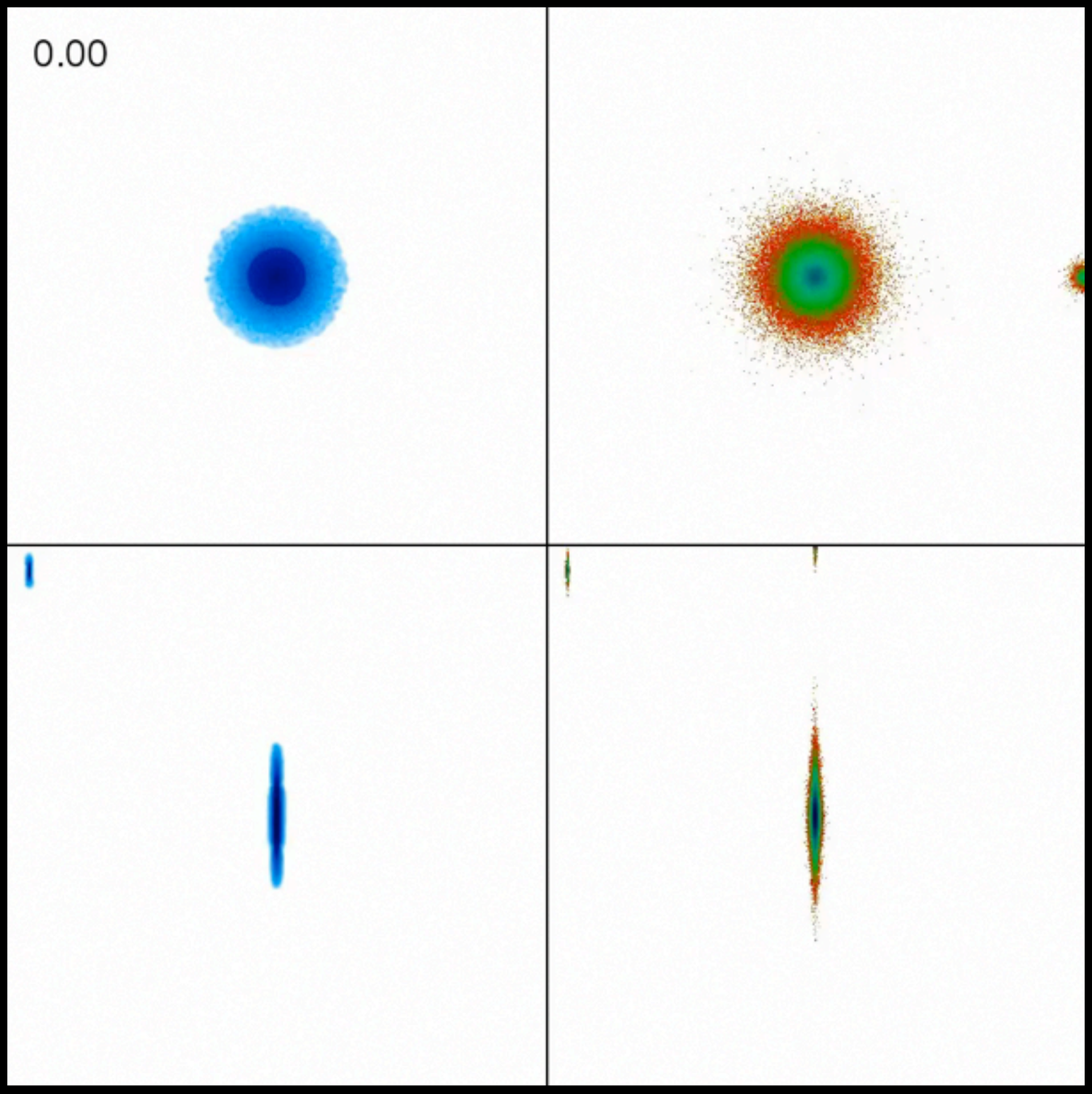


- Not very sensitive to initial conditions (for parameters comparable to spirals). CB09 -- M_s and R_{peri} are what really matter.

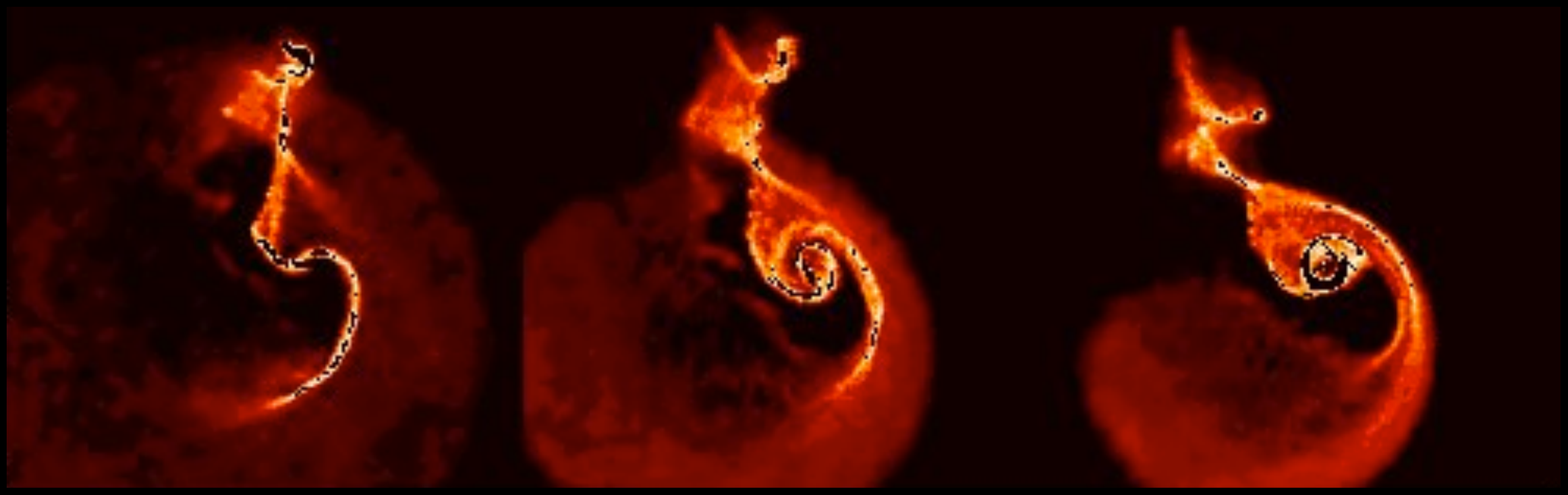
The Tidal Players of the Milky Way



Chakrabarti et al. in prep

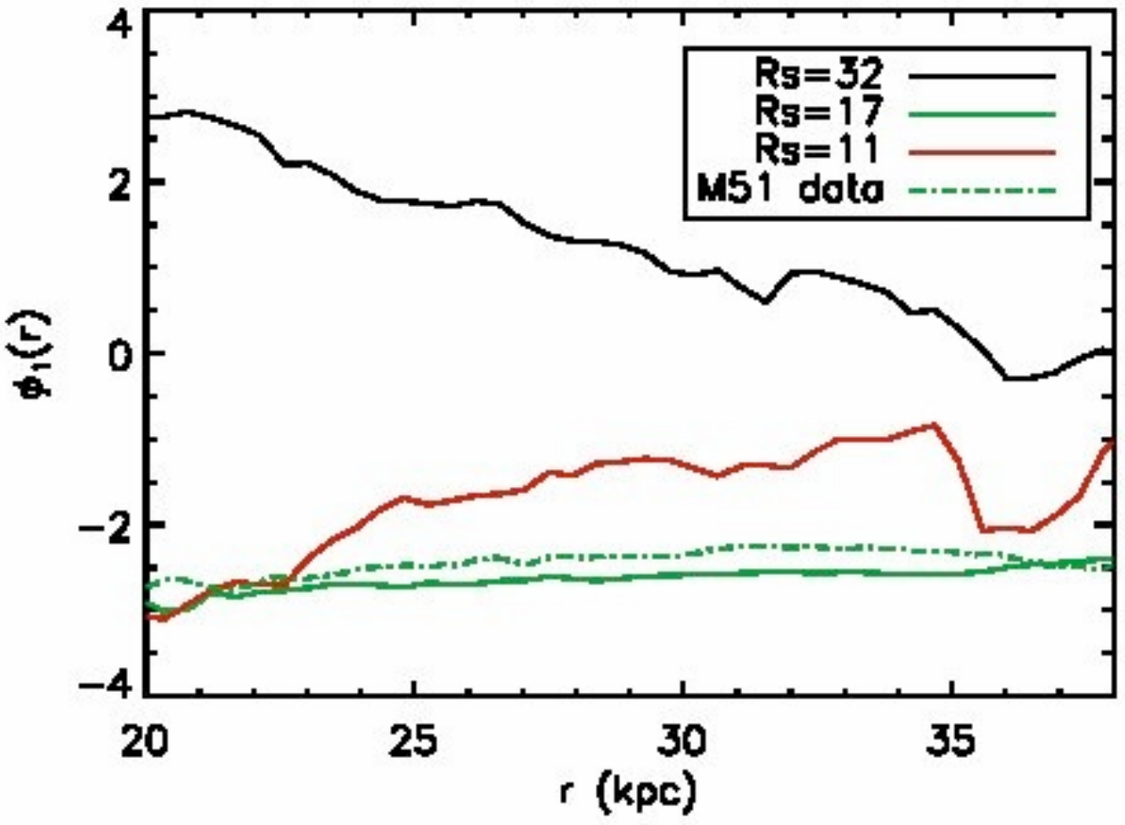
Inferring the distribution of DM in galaxies

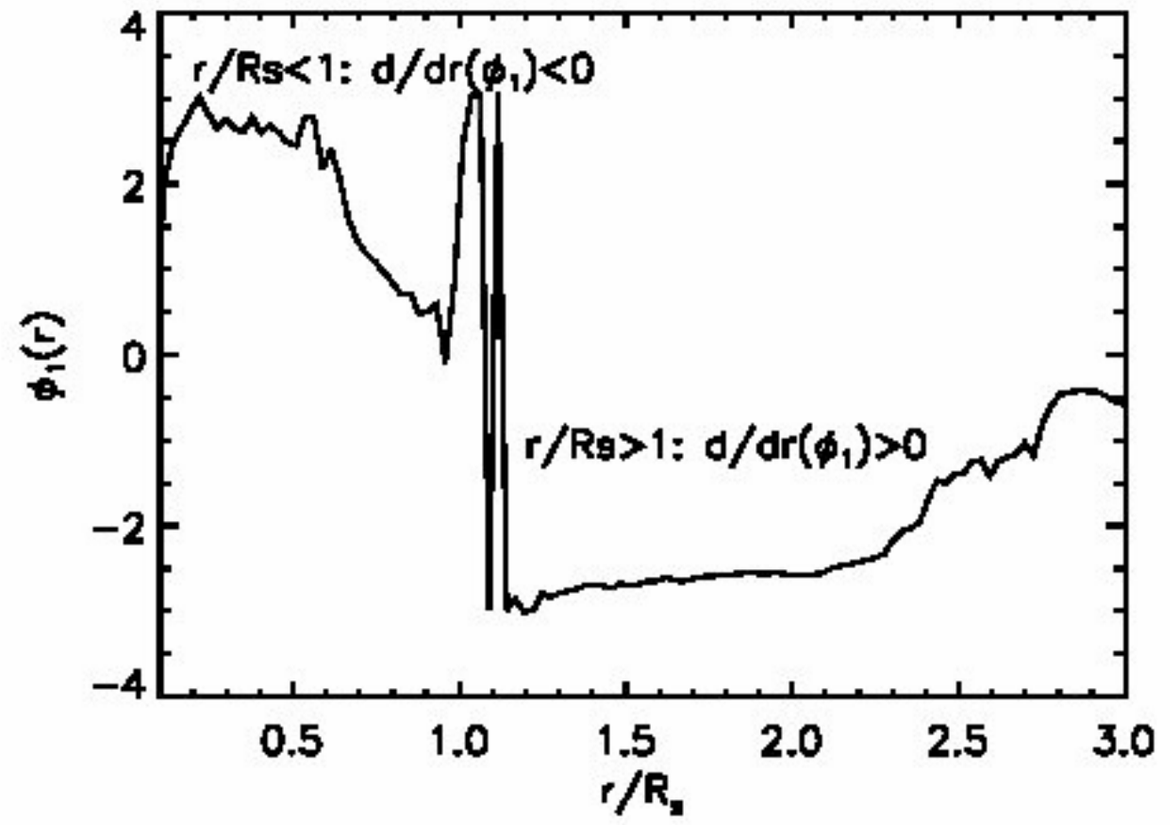
- How is the dark matter distributed? Early N-body simulations found it is (NFW):
  $\rho(r) = \delta_c \rho_c / [(r/R_s)(1+(r/R_s)^2]$ ($\rho \propto r^{-1}$ for $r < R_s$ and $\propto r^{-3}$ for $r > R_s$)



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

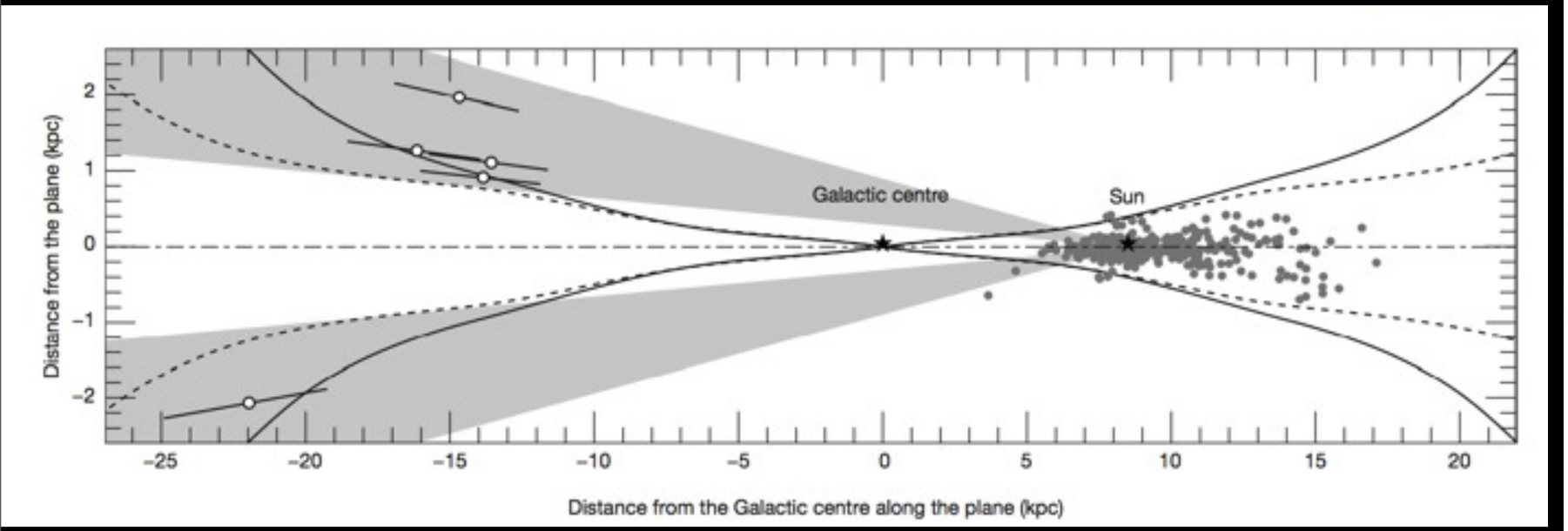
Inferring the scale radius of the dark matter halo

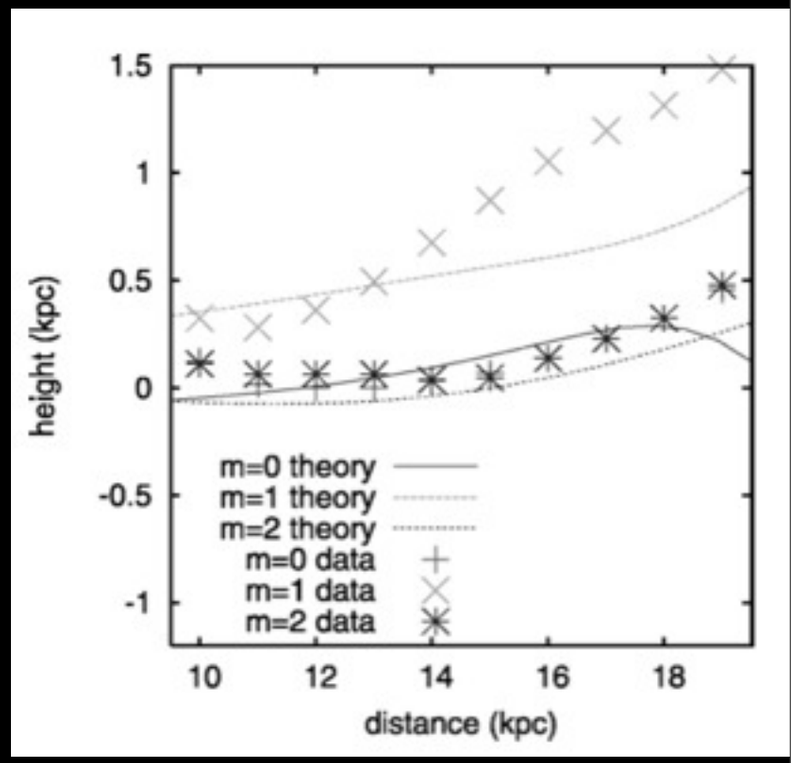




- Three distinct regimes: for $r < R_s$, $d\Phi/dr < 0$, for $r > R_s$, $d\Phi/dr > 0$, and for $r \sim R_s$, $d\Phi/dr$ transitions (Chakrabarti 2013)

Milky Way's Flared, Warped HI Disk

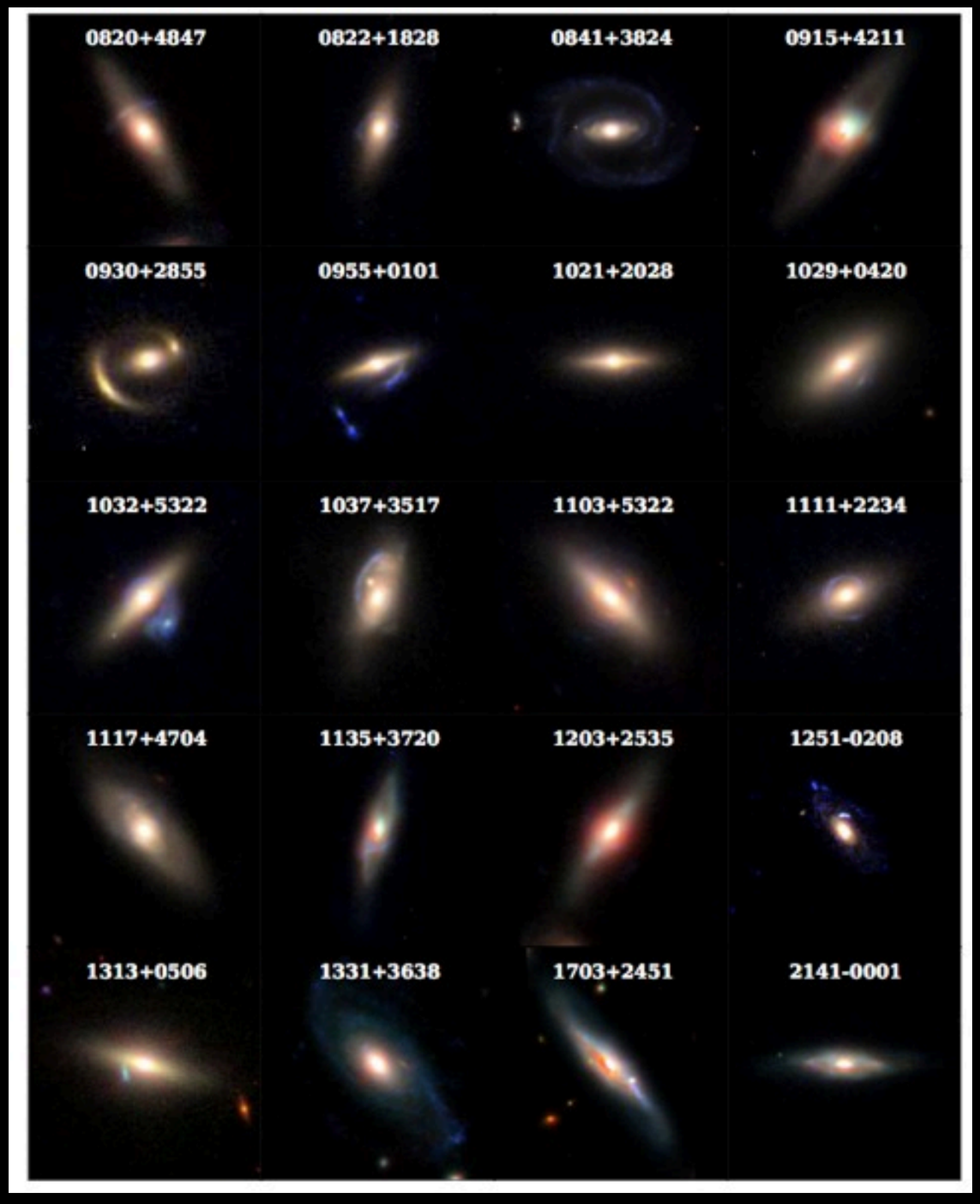




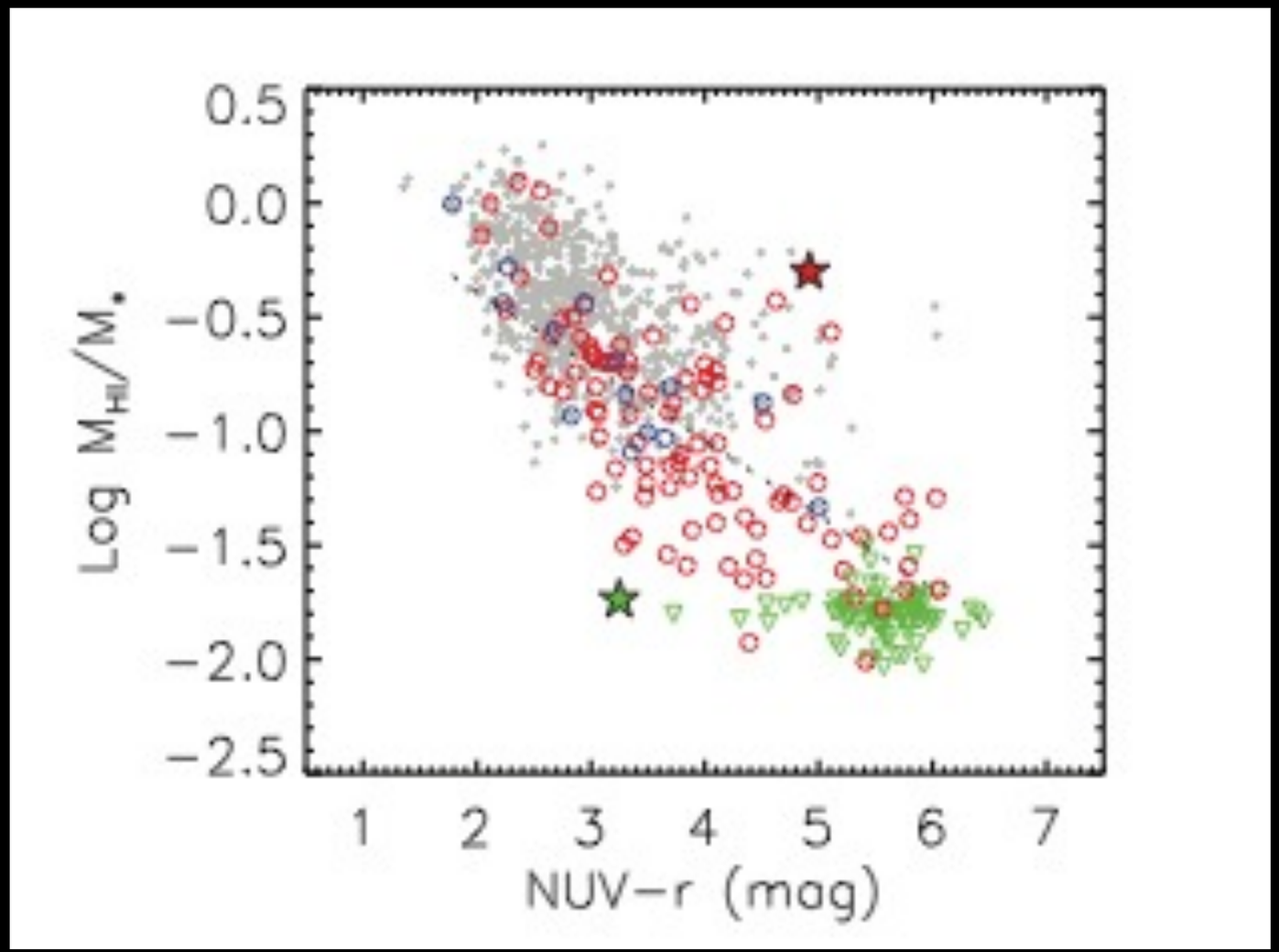
Cepheids tracing flared HI disk at ~15 kpc (Feast et al. 2014), follow-up spectroscopic observations of ~ 30 candidate Cepheids identified by OGLE -- 5 are confirmed spectroscopically. Prospects with GAIA.

Weinberg & Blitz 06

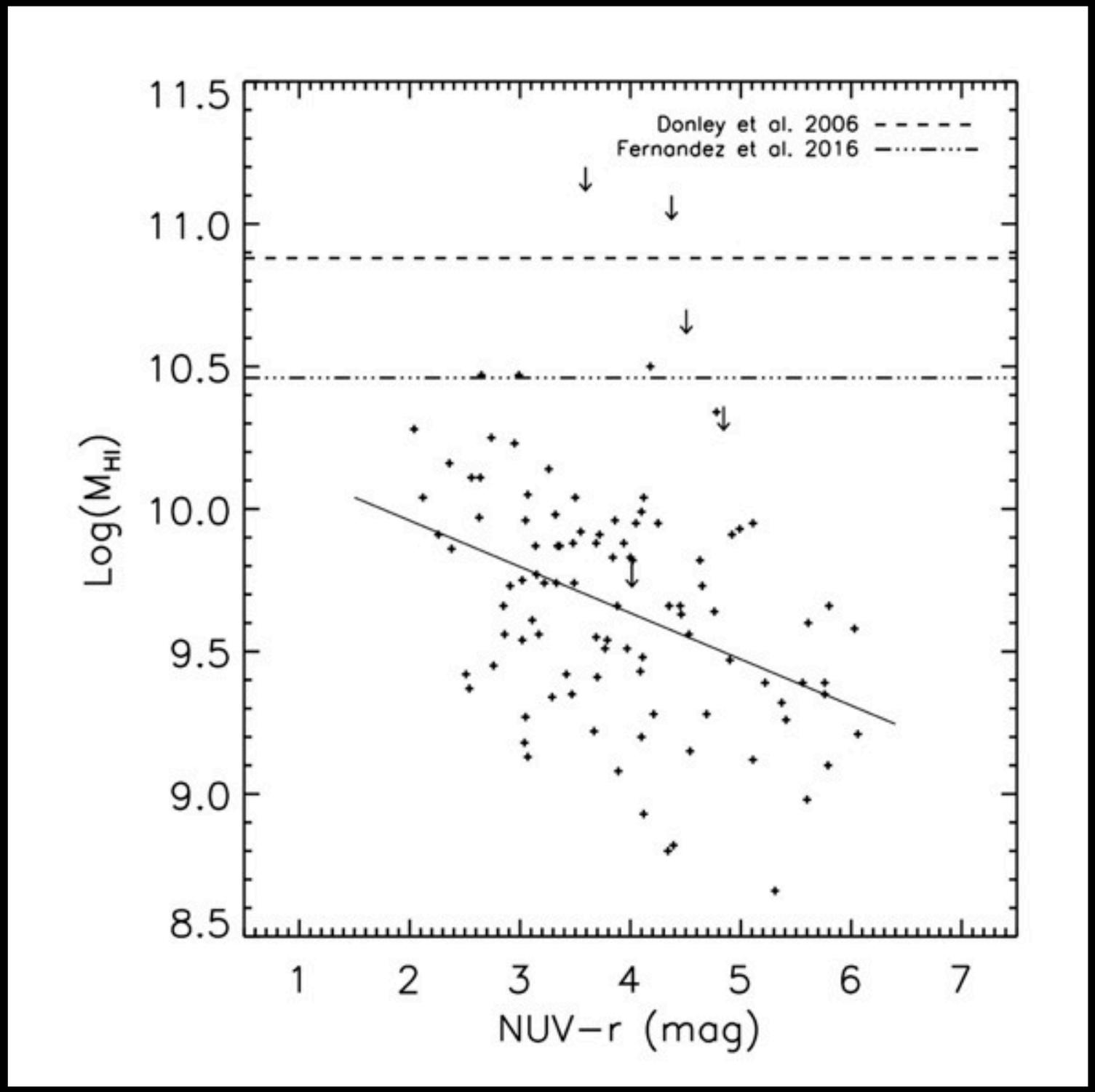
Beyond the Local Volume



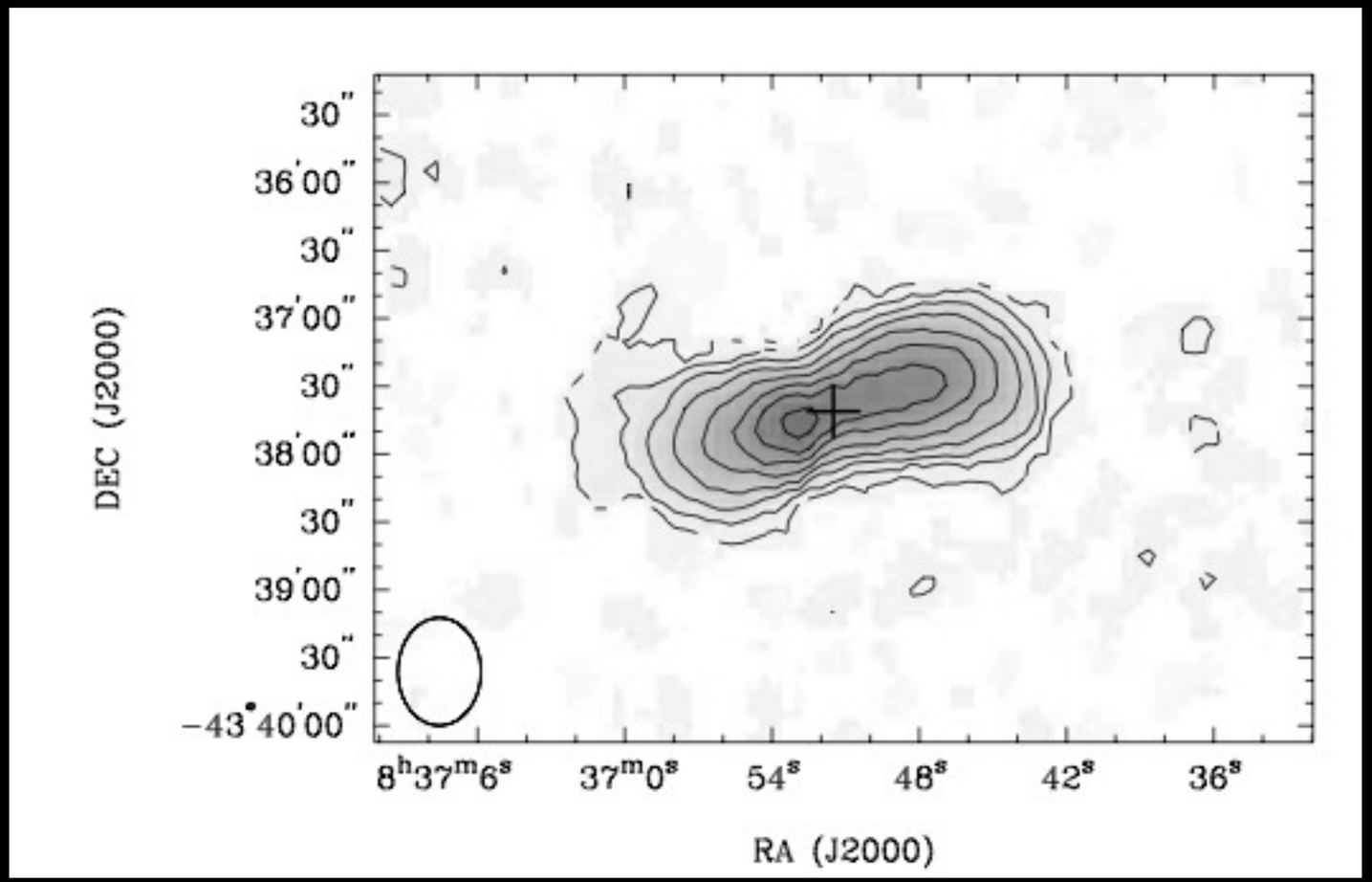
SWELLS: sample of strong spiral lenses (Brewer et al. 2012)



Catinella et al. 2010
GASS survey - HI spectra of galaxies between 0.025 < z < 0.05

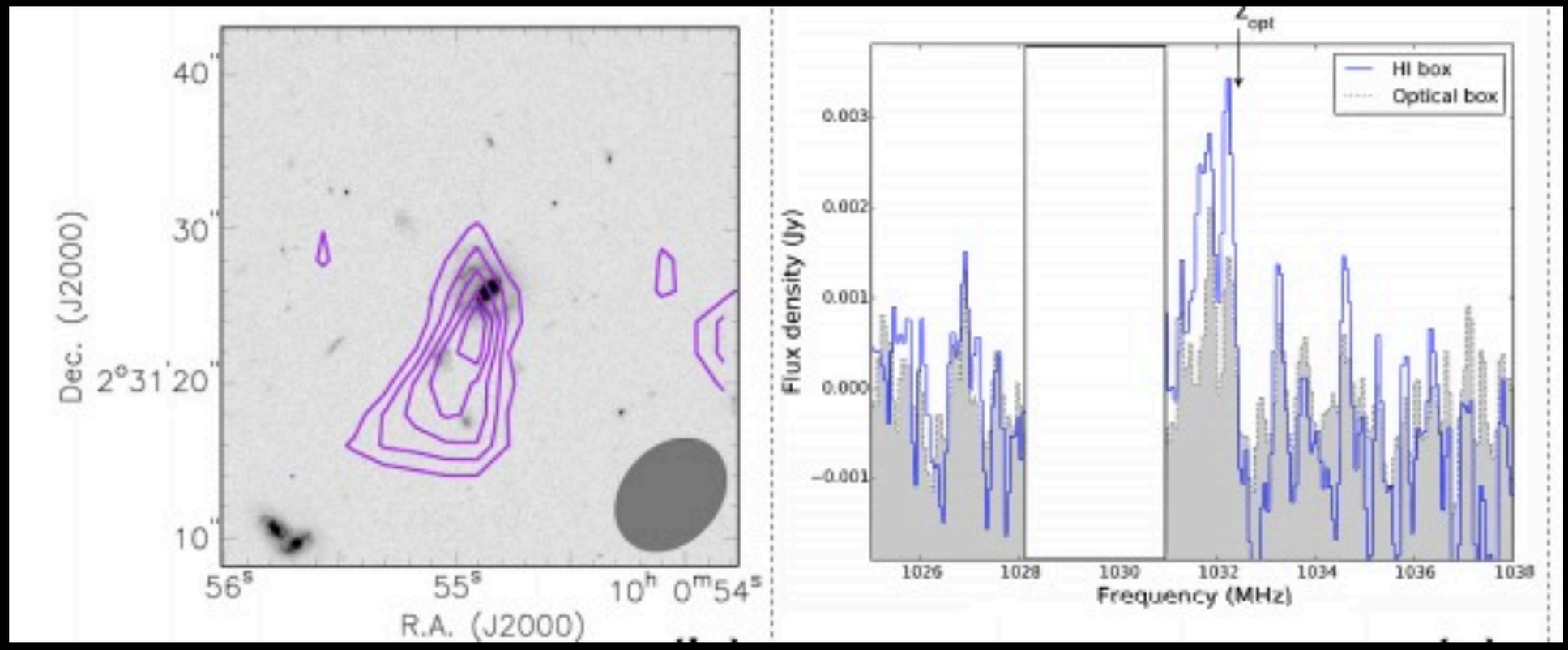


Upper limits for SWELLS sample from GBT and Arecibo observations (Lipnicky et al., in prep)



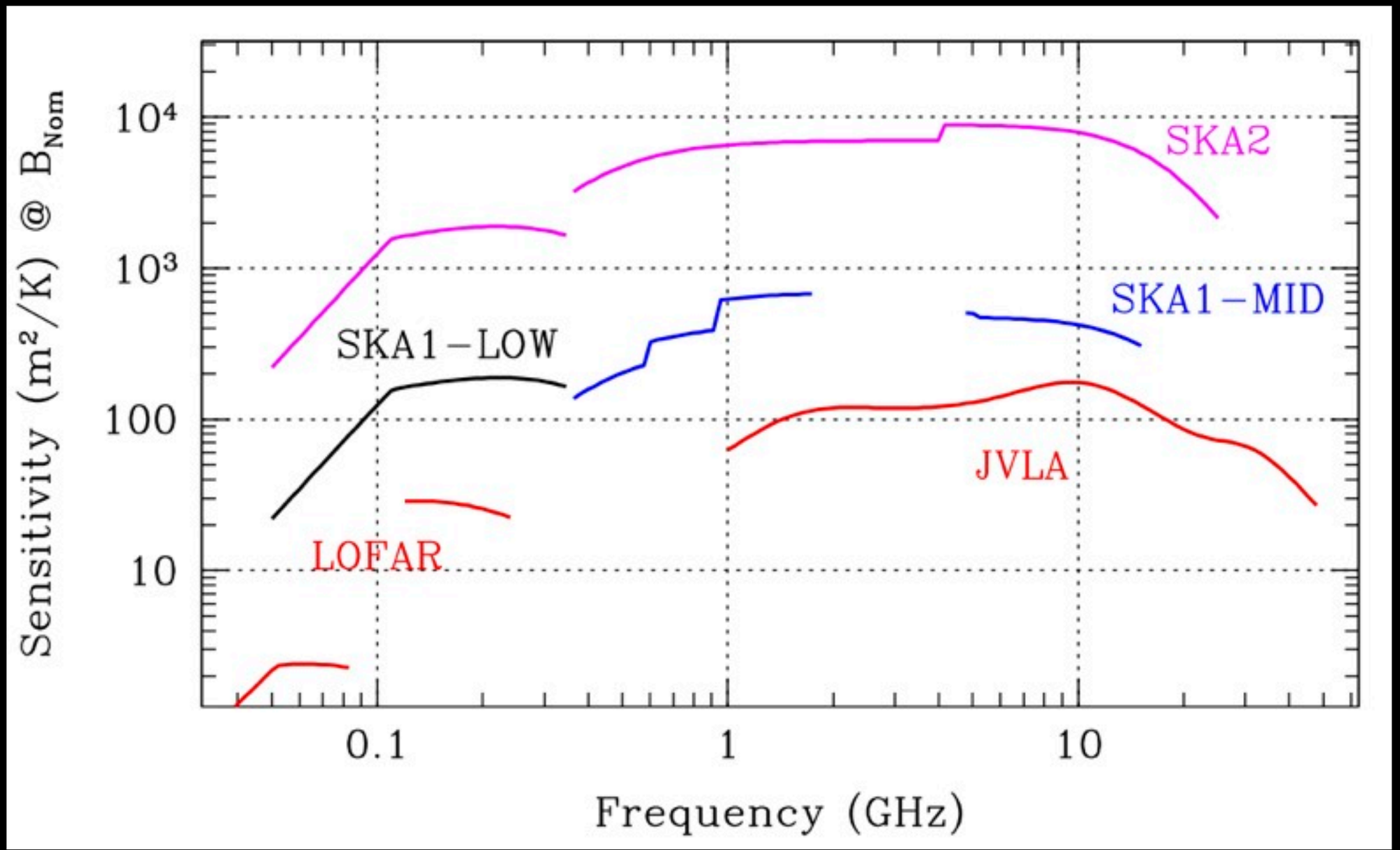
Donley et al. 2006, z = 0.036, M_{HI} = 7.5 x 10^{10} M_{sun}, diameter ~ 120 kpc, SFR ~ 35 M_{sun}/yr (Broeils & Rhee 97: relation between HI mass and diameter of HI disk)

CHILES survey



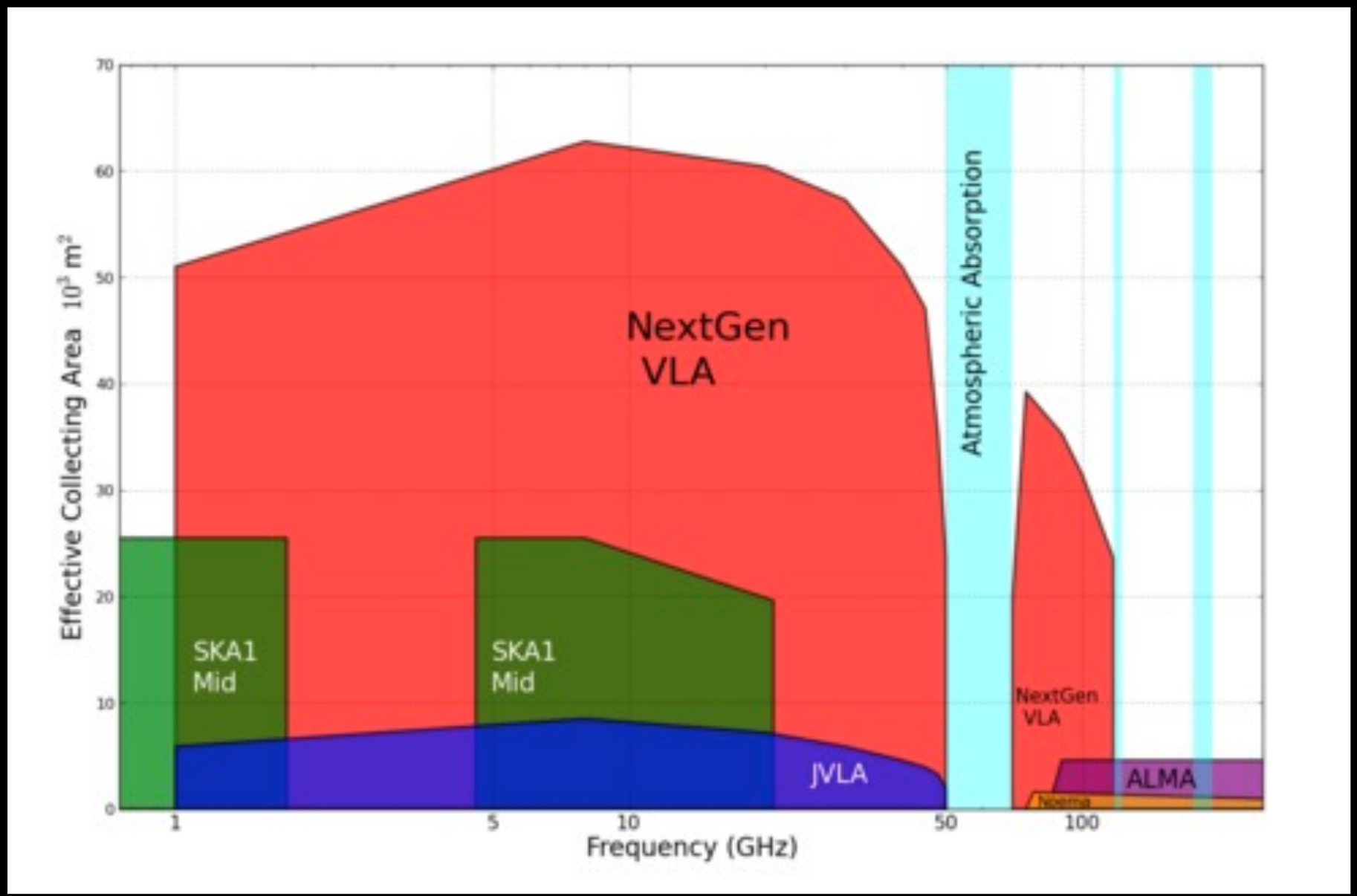
z = 0.376 - highest redshift HI map to date, 178 hours on JVLA, LIRG, M_{HI} = 2.9 x 10^{10} M_{sun} , SFR_{IR} = 85 M_{sun}/yr (Fernandez et al. 2016)

Future



SKA scientific operations to begin in early 2020s

Beyond SKA


Effective Collecting Area 10^3 m^2
70
60
50
40
30
20
10
0
1
5
10
50
100
Frequency (GHz)
NextGen
VLA
SKA1
Mid
SKA1
Mid
JVLA
Atmospheric Absorption
NextGen
VLA
ALMA
Nobeyama

Summary

- HI, FUV tightly correlated. HI disks are a gas reservoir. Radial gas inflows of ~ 15 km/s detected in some THINGS galaxies
- Many spirals in Local Volume show perturbed morphologies
- HI map can be analyzed to infer properties about dwarf companion and galactic potential
- HI maps obtained beyond the Local Volume for **massive** spirals
- SKA, ngVLA