ISM Properties at the disk-halo interface in Spiral Galaxies

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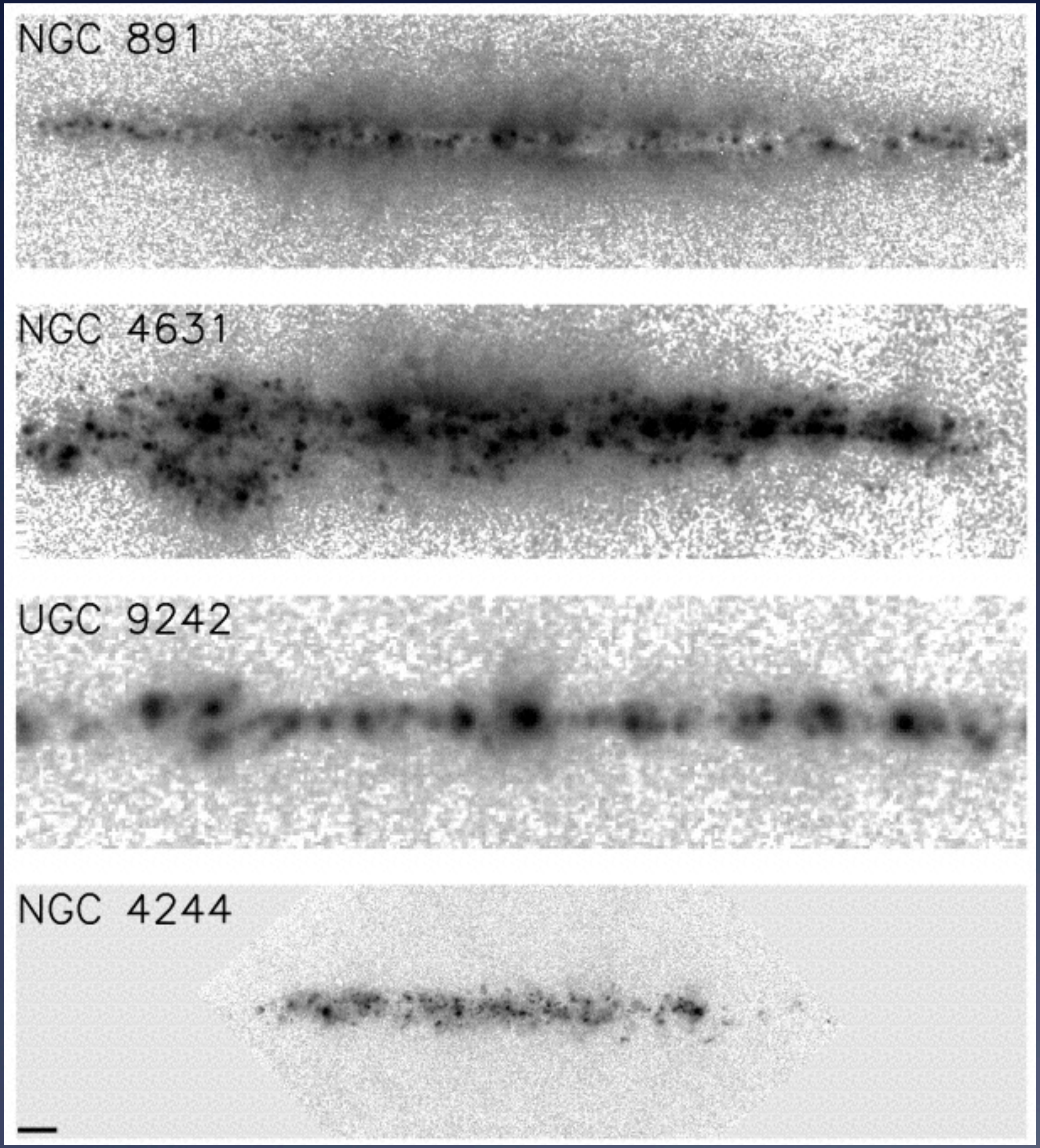
Topics

- Introduction
- Vertical kinematic lags in edge-on galaxies from HI and Hα observations
- Trends in lags, evidence for accretion(?)
- Future outlook

Disk-halo interaction and connection with accretion

- Observable manifestations of galactic fountains (in emission):
  - X-ray emission from hot gas
  - Thick disks of diffuse ionized gas (DIG) and HI disks with vertical kinematic lags
  - Outflows
  - Dust at large distances above disk
  - Magnetic fields and synchrotron halos

- Observable manifestations of accretion (in emission):
  - HI clouds/filaments in outer disks and halos
  - Tidal features in cases of galaxy interaction
  - Counter-rotating gas, radial motions, vertical kinematic lags

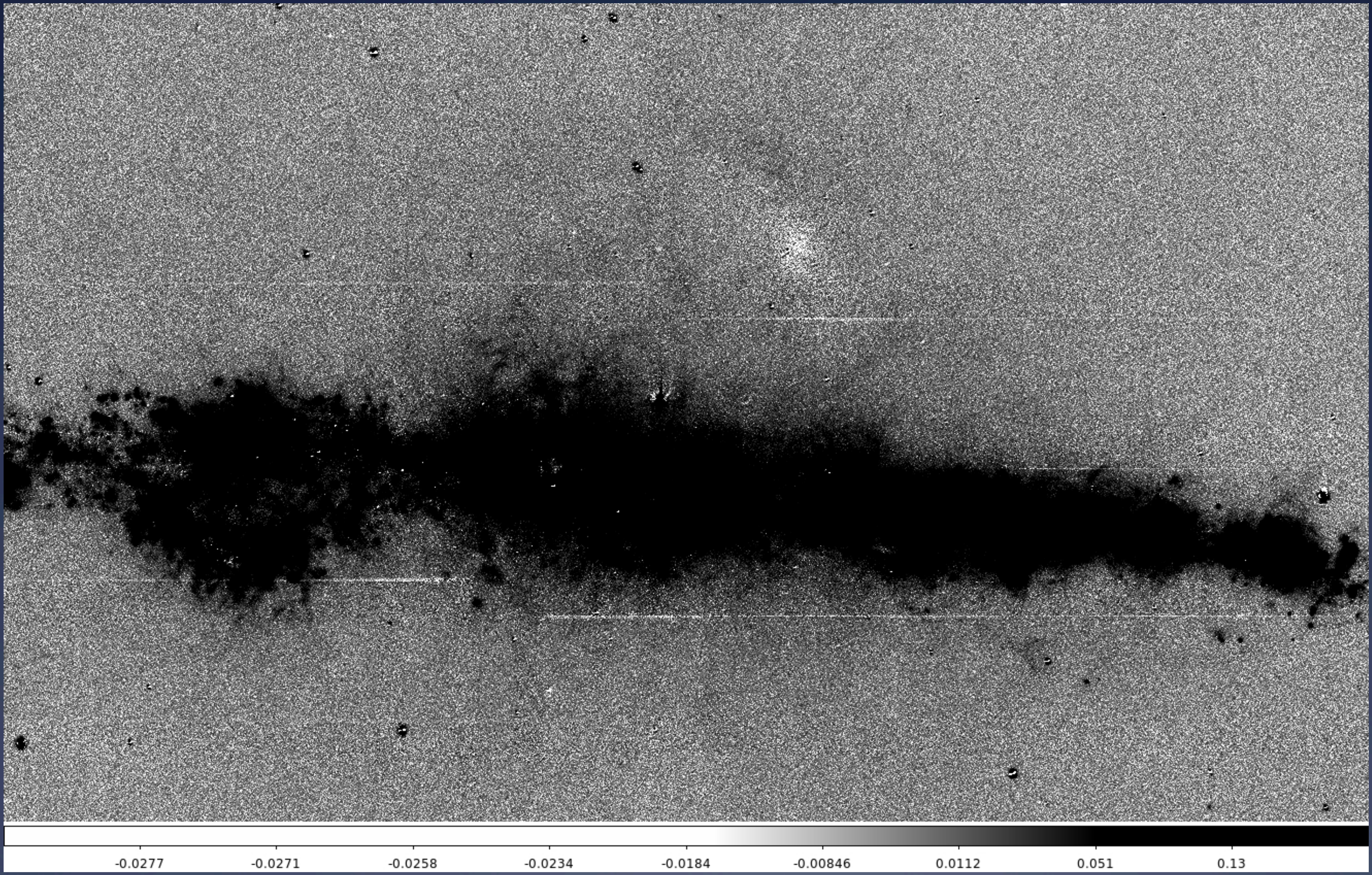


Edge-on galaxies in Hα

Four edge-on galaxies with very different SFRs per unit area, on same physical scale

From Hoopes et al. 1999

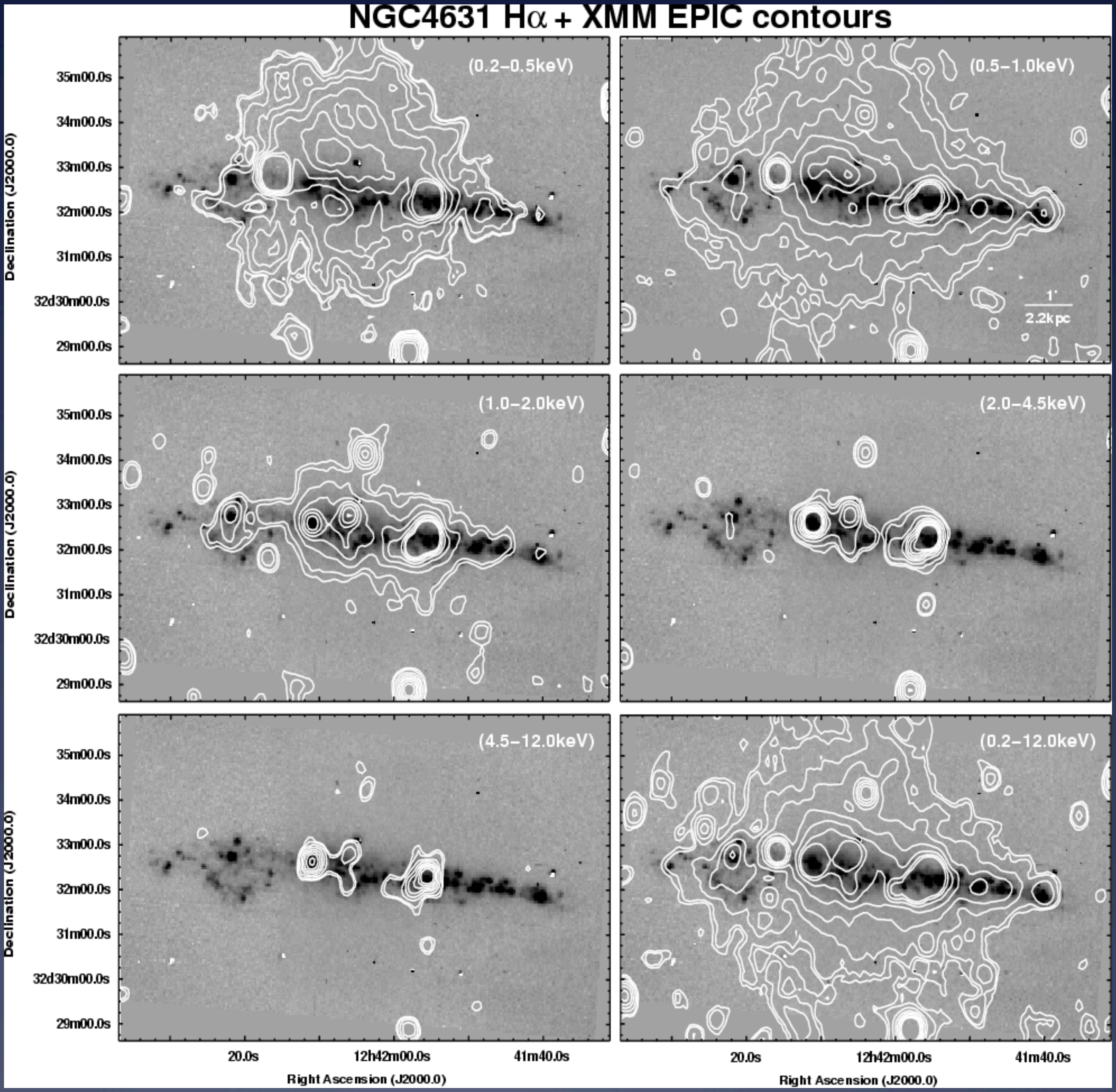
NGC4631, Hα+[NII] filter, KPNO 4-m



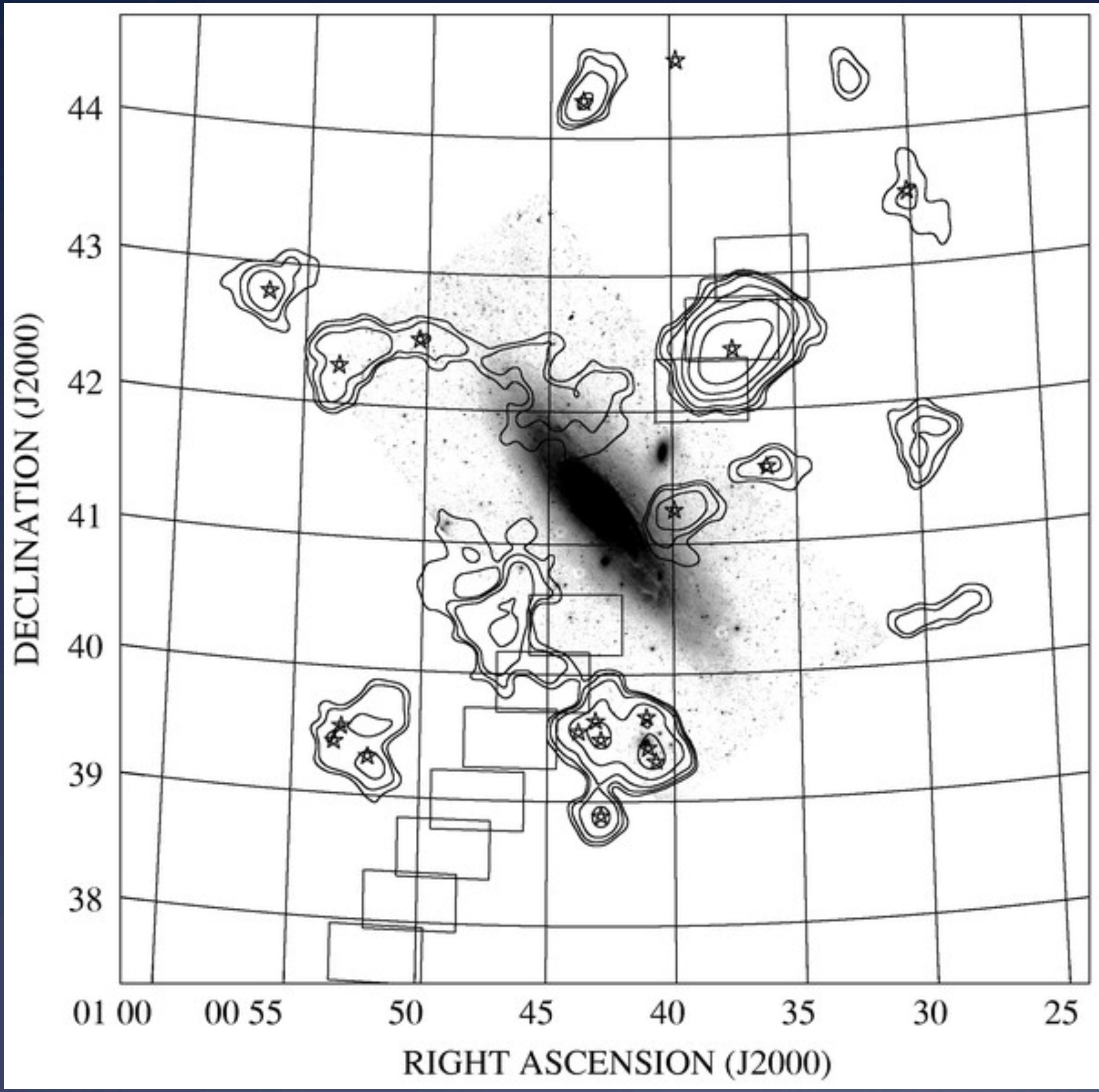
NGC4631 X-ray halo

(Tullman etal 2006)

About 8 kpc in radius, five times smaller than HI clouds around M31



M31 HI halo clouds

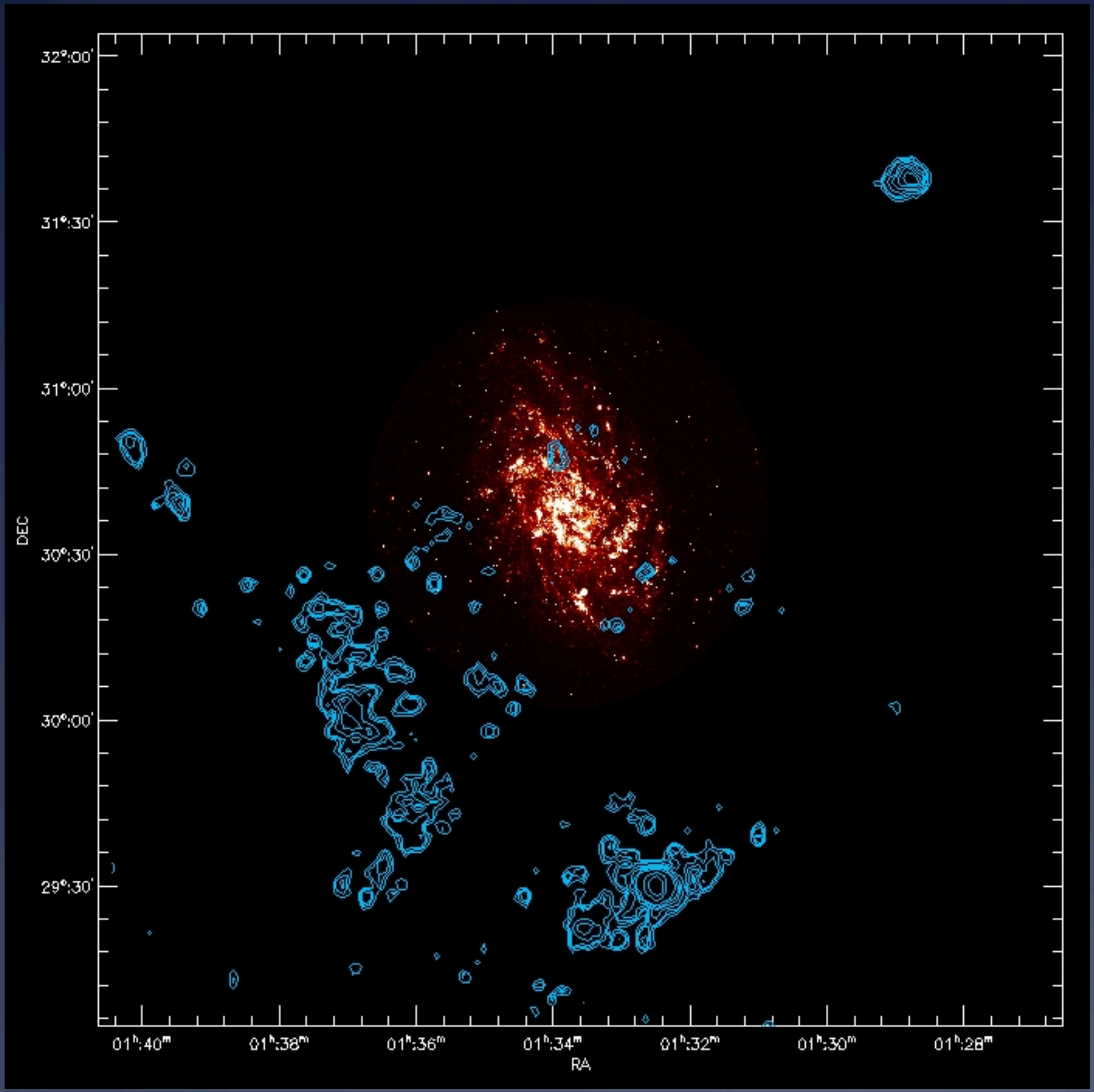


There may be some confusion with Galactic HI (e.g. Davies cloud)

1 degree = 13 kpc

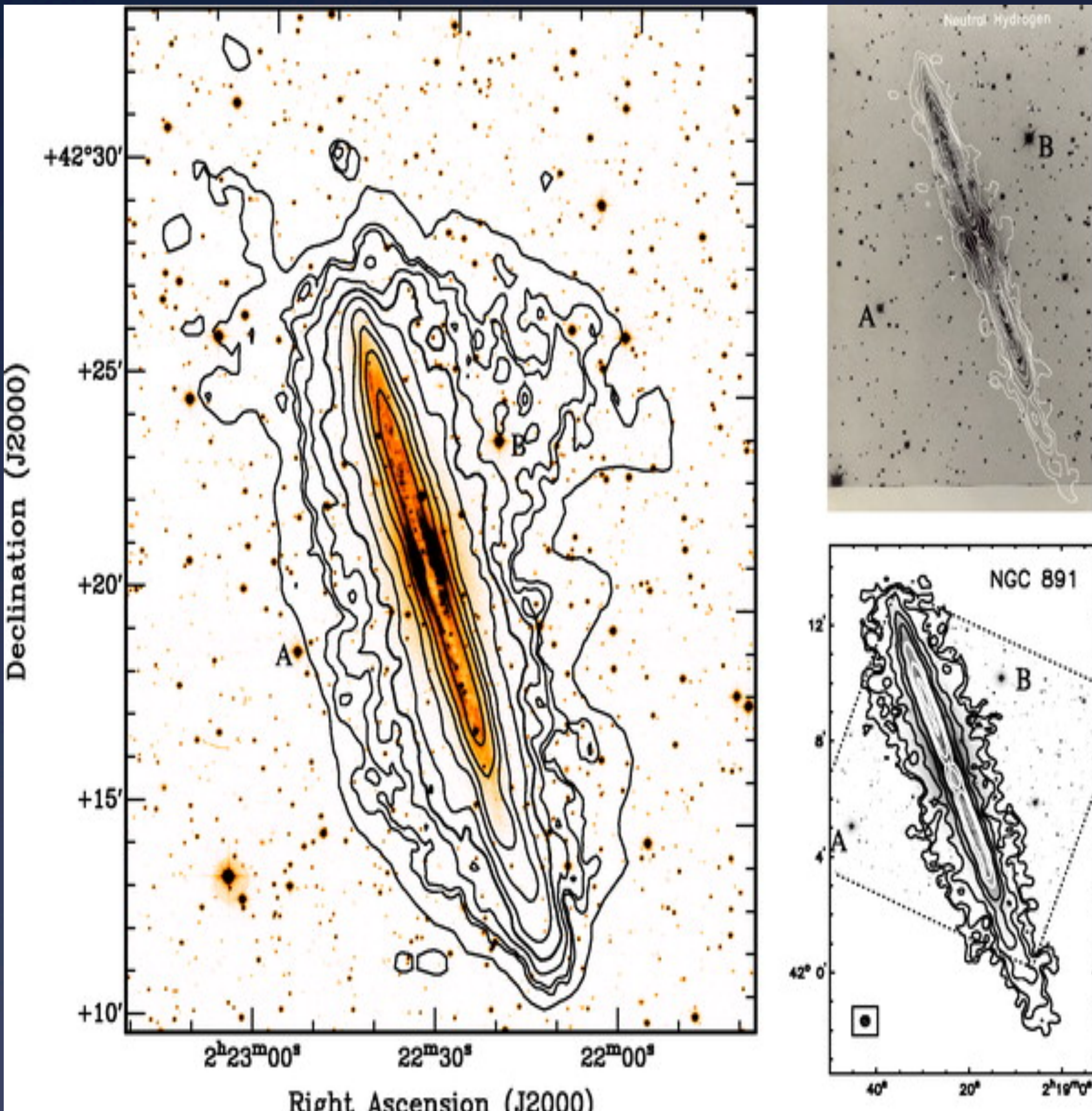
from Thilker etal 2004

HI in the outer reaches of M33



- Grossi etal., 2008

The poster child: NGC 891 in HI



Westerbork HI data for NGC891 shows extended halo and plume out to 20+ kpc above disk

from Oosterloo etal 2007

Kinematic signatures possibly related to accretion

- Counter-rotating gas
- Presence of a lag in the "halo" gas, i.e. slower rotation for gas above the disk than in the disk. Lag is expressed through the velocity gradient in z-direction, in km/s per kpc.
- Some lag is expected in galactic fountains due to conservation of angular momentum but observed lags seem to be larger than expected

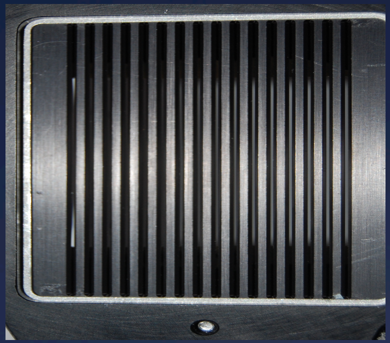
Galaxy samples

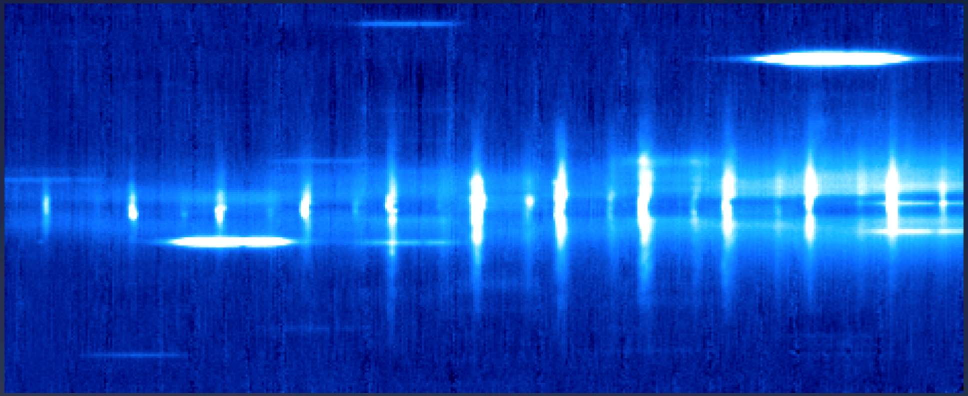
- Halogas: 22 galaxies, selected without bias to star formation, inclination range 50 – 75 degrees, and some edge-on (Heald et al 2011). Deep HI observations with WSRT (3000 hrs total).
- VLA B,C,D array HI observations to supplement Halogas sample with 3 more edge-on galaxies (Rand, Zschaechner, Walterbos)
- Optical Halpha kinematics, APO sample, 13 edge-on galaxies, some overlap with above samples (Wu, Walterbos, Rand)

Main questions

- How common are vertically extended HI or H+ disks with lagging velocities?
- Are counter-rotating clouds/filaments common? What about outflows?
- What is the origin of the vertical decrease in rotational velocity (lag)? Galactic fountain? Accretion? Other?

Multi-long-slit Spectroscopic Observations at APO (Ph D thesis, Catherine Wu)





Study of the kinematics of ionized, extra-planar gas to search for:

- extraplanar lagging component
- possible outflows via line widths

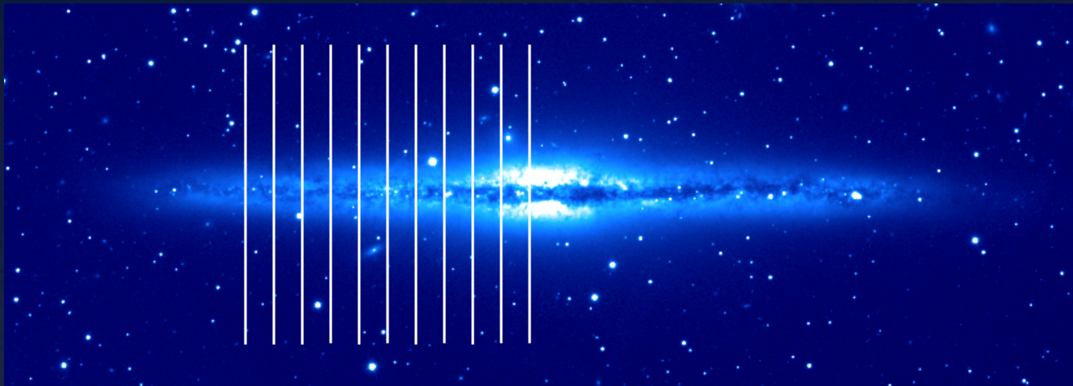
Sample of 13 nearby, edge-on galaxies

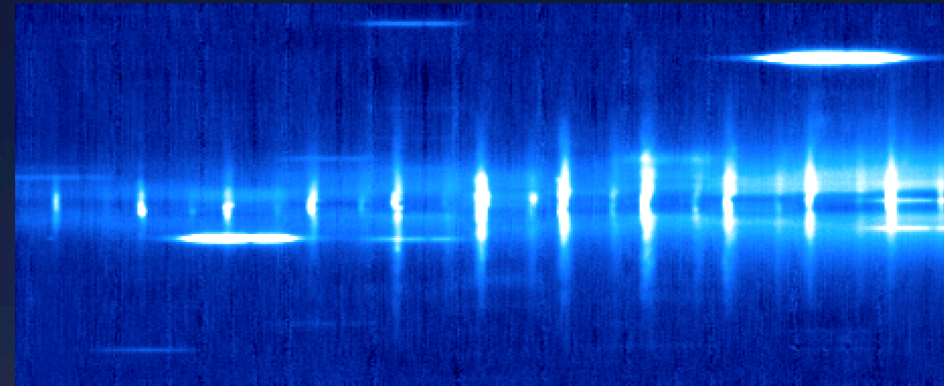
Multi-long-slit spectroscopic observations with ARC 3.5-m telescope

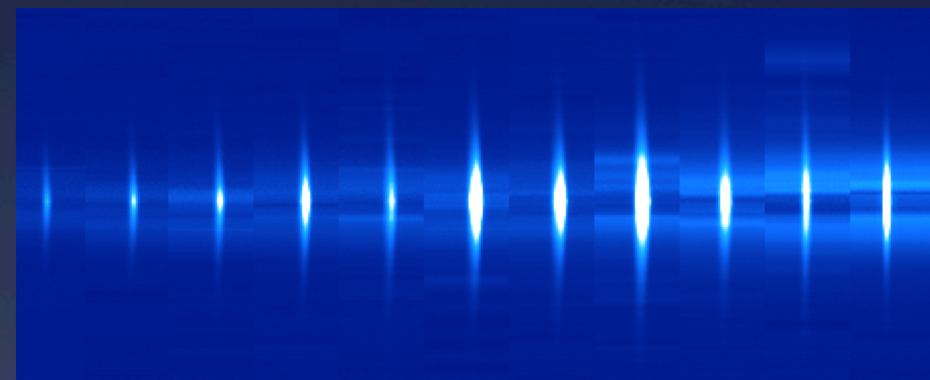
- 11 parallel slits, 1.5” wide, spaced 22.5” apart, 25 Å filter
- field of view: 3.75' wide, 4' tall
- 0.58 A/pix dispersion → 65 km/s resolution
  with centroid fitting → 5 km/s accuracy
- Exposure times from 3 to 10 hrs

Projection effects in Edge-on galaxies: modeling of optical spectra

- Inputs: HI rotation curve, Exponential ionized gas density distribution with r and z
- Line of sight integration to obtain model spectrum
- Introduce lag and inclination variations
- Convolve to spectral resolution, add noise, analyse same way as data
- Start from simplest models, add thick disk and lags if needed to represent the data.







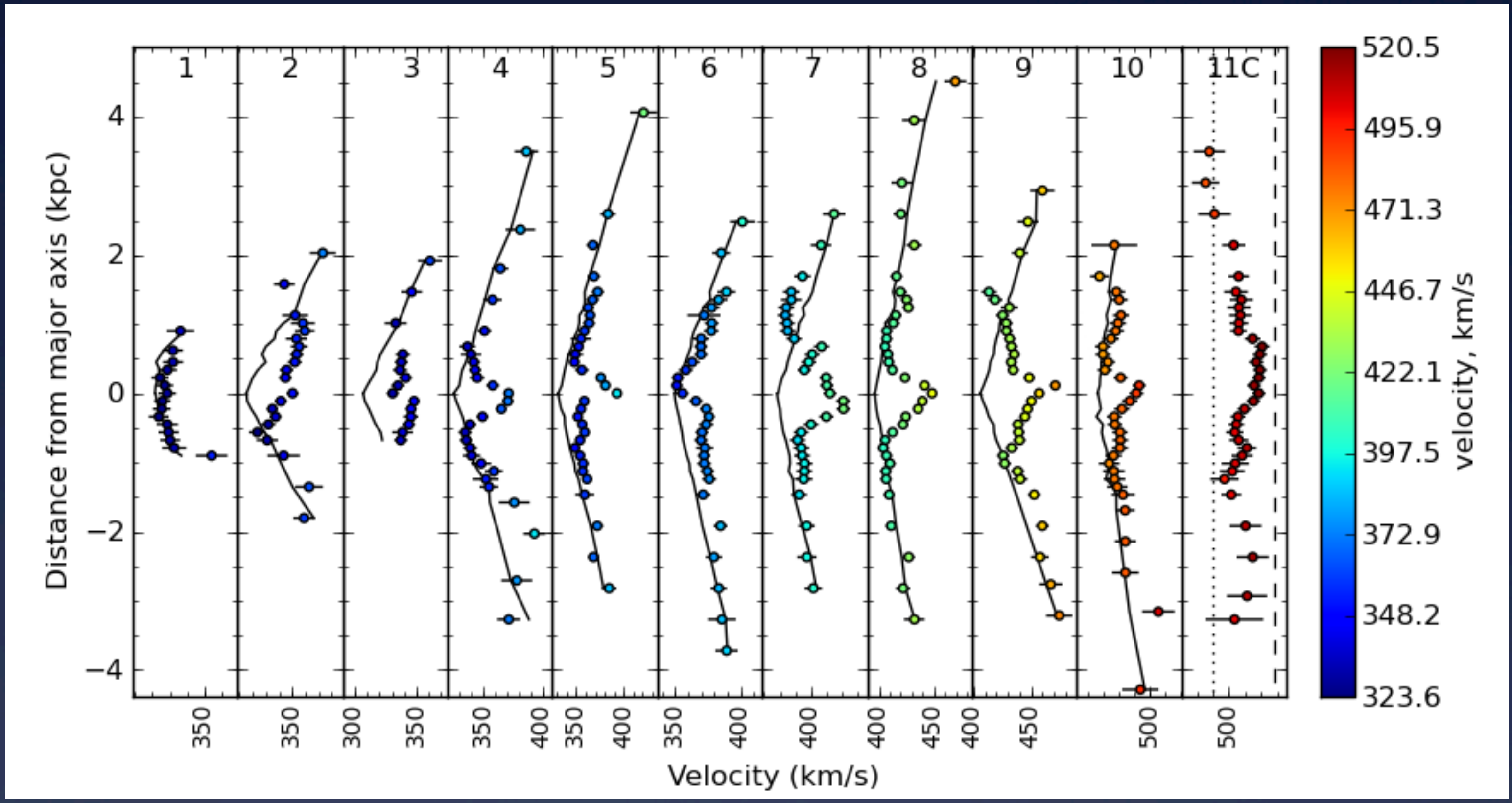
NGC 891

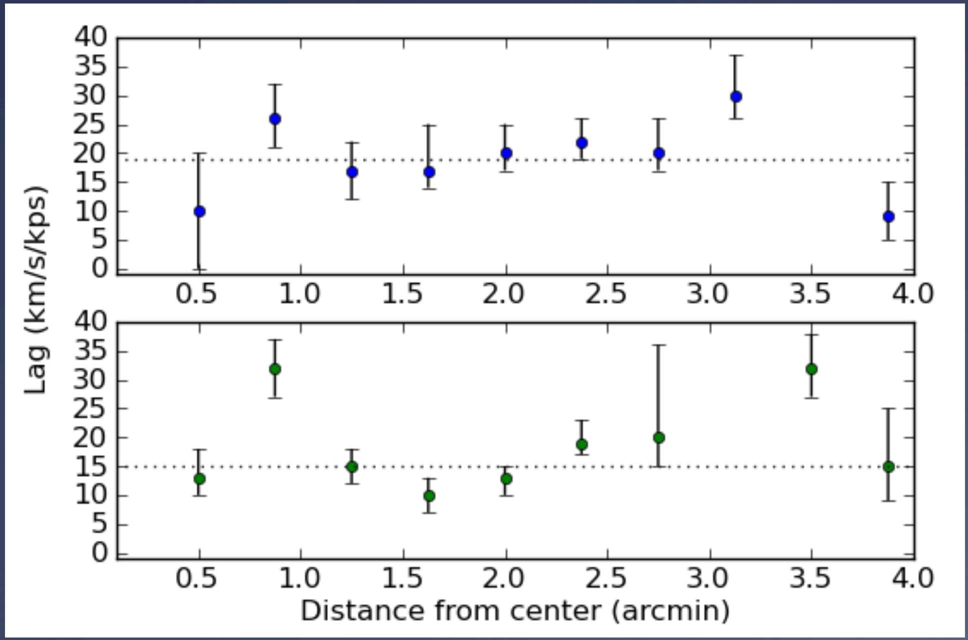
- Sb galaxy, $v_{rot=}$ 210 km/s
- D = 9.5 Mpc, incl=88-90^o
- moderate to high star formation rate (2.5)
- Known to have a lag in HI and H+ (15 – 20 km/s)

Top: 12.9 hour exposure
North approaching side
Emission extends +/- 4 kpc

Bottom: model spectrum

NGC 891

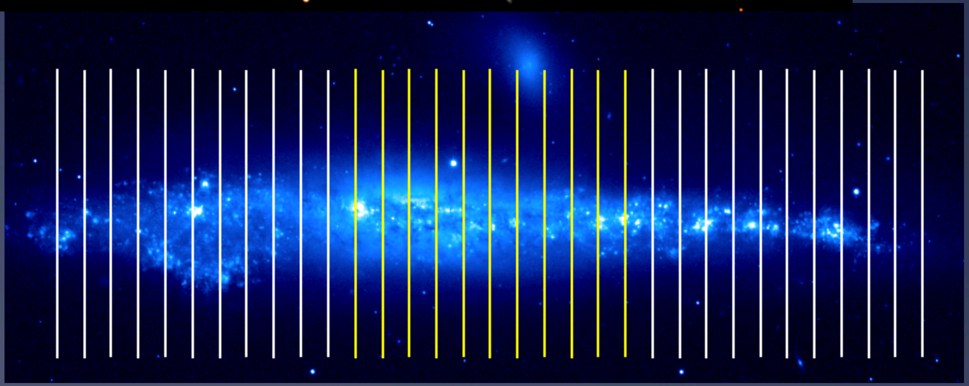




Model lags for upper and lower half of each slit, agrees with HI results

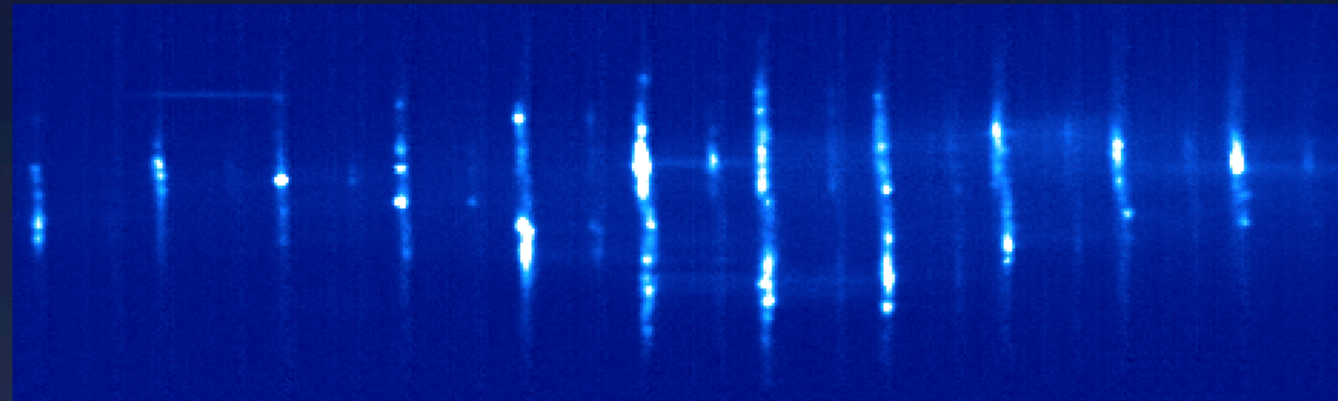
Top (blue): 19 km/s/kpc
Bottom (green): 15 km/s/kpc

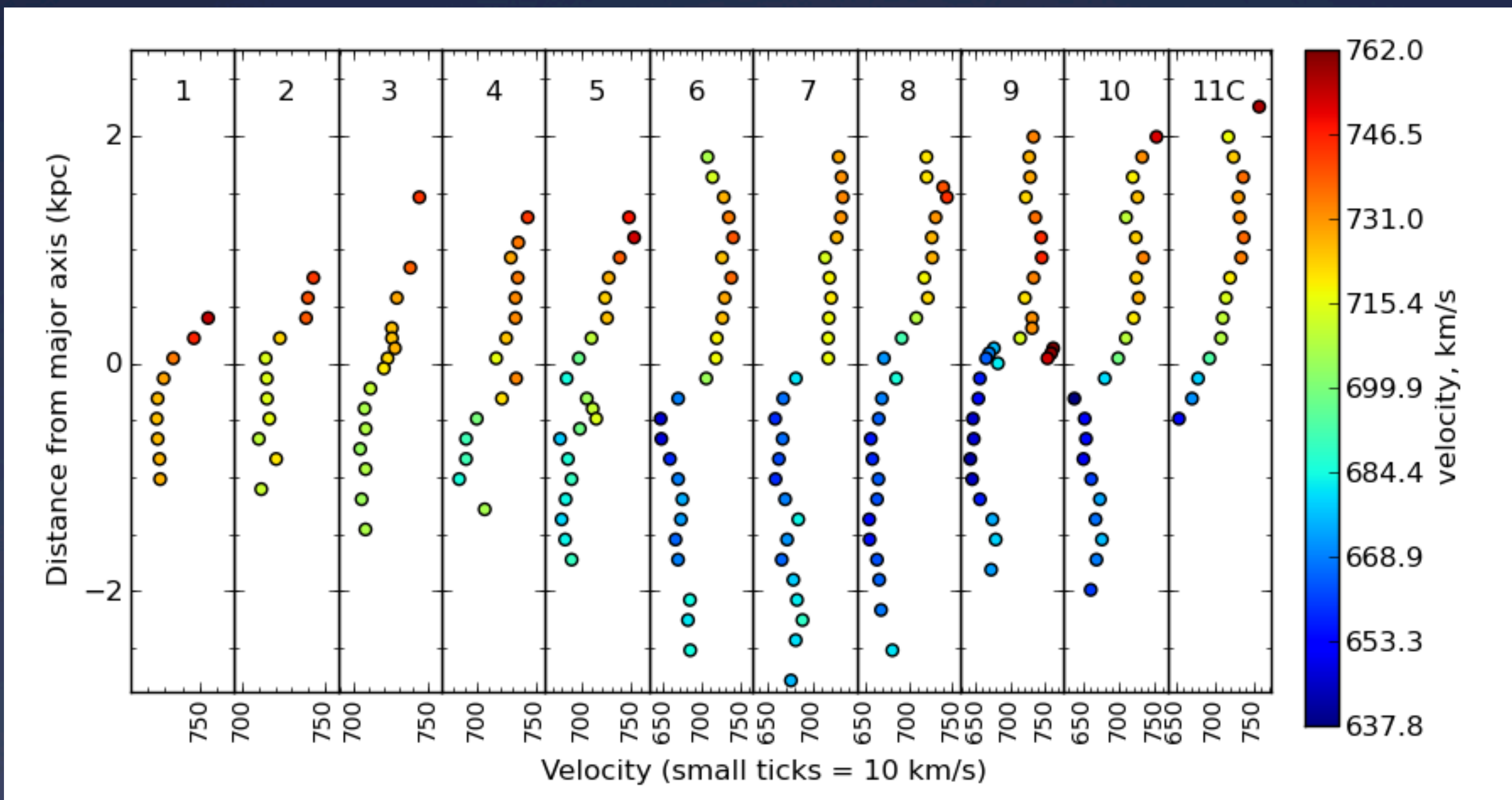
NGC 4631



- SBd, v_{rot} = 140 km/s
- 85-90^o inclination
- D = 7.6 Mpc
- moderate star formation rate
- interacting with companion galaxies
- 3 fields (east, central, west)

NGC 4631 East (receding)

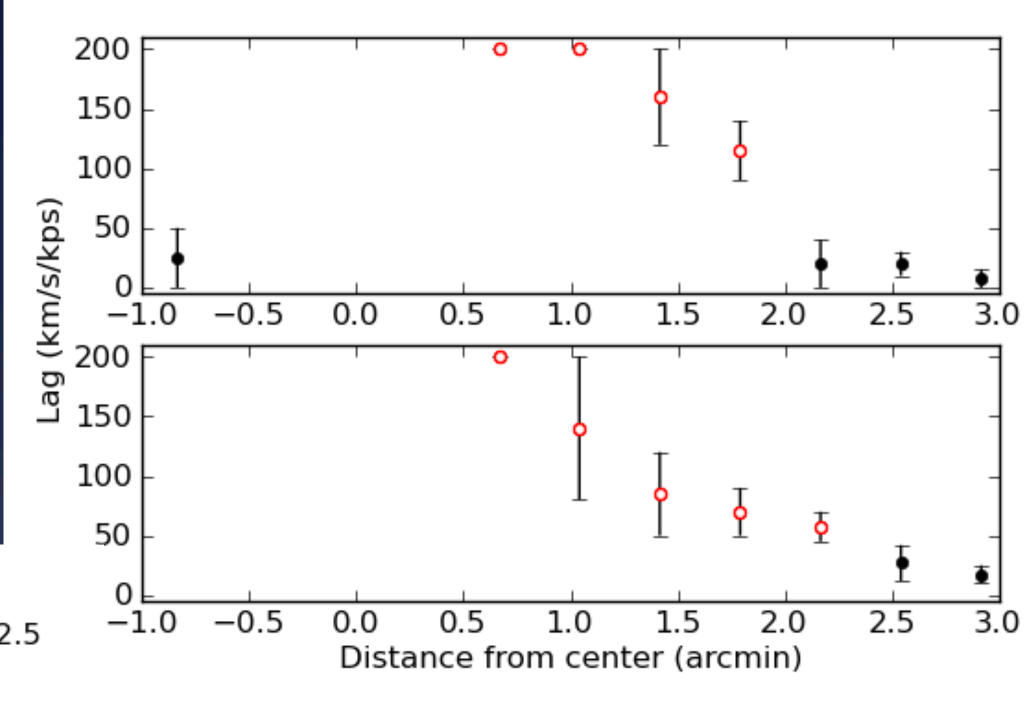


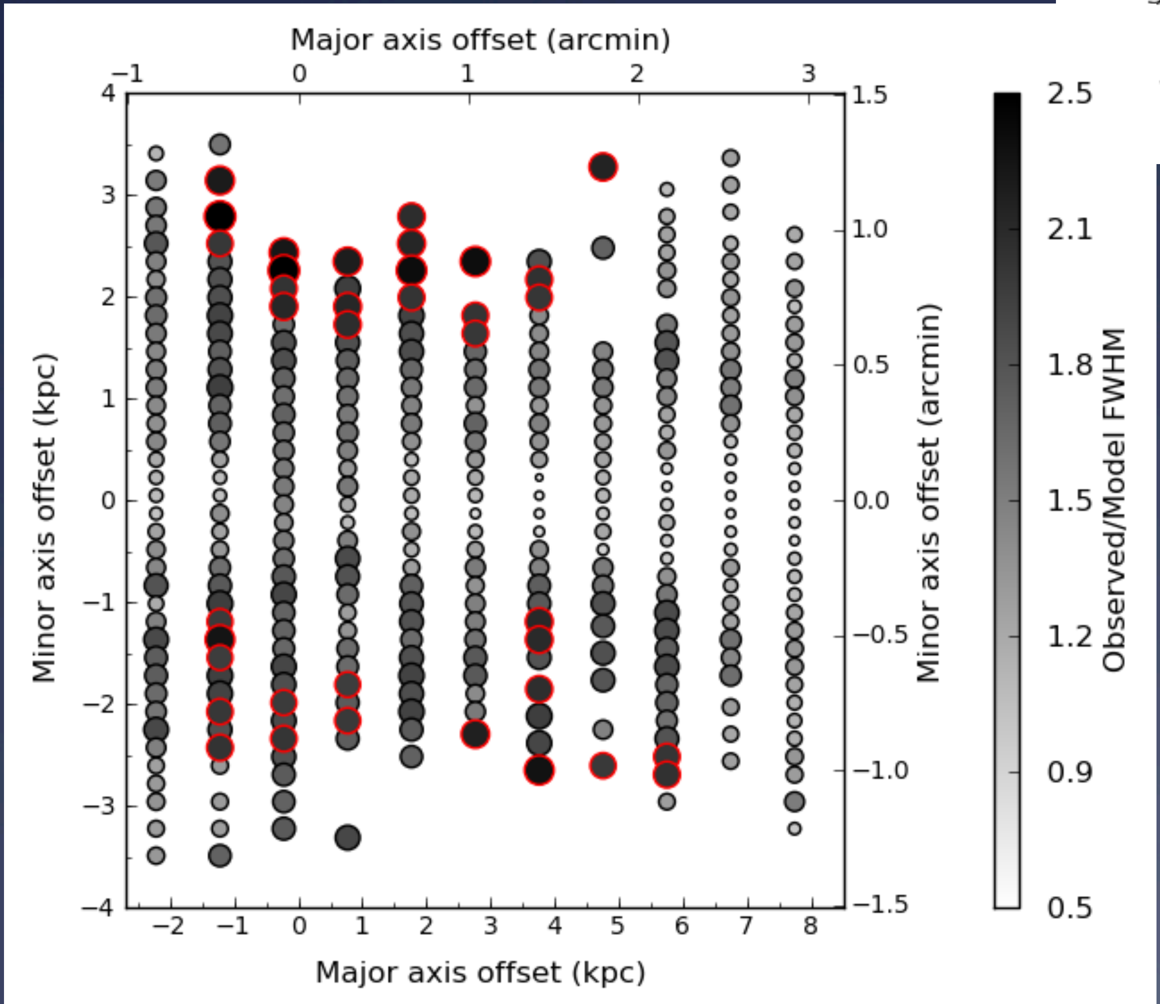


Significant warp in lower half (65º vs 85º): outer spiral arm

NGC 4631 Central

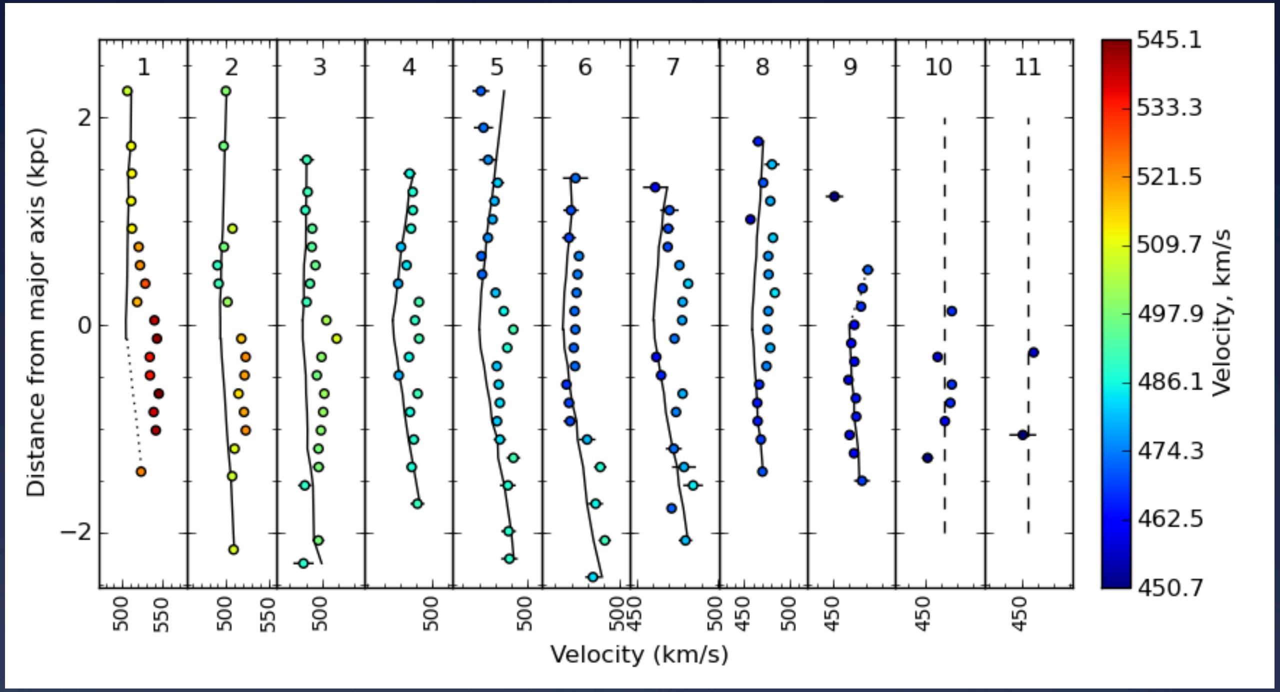
Slits 2-8: Large velocity widths over central area: likely a SF driven outflow



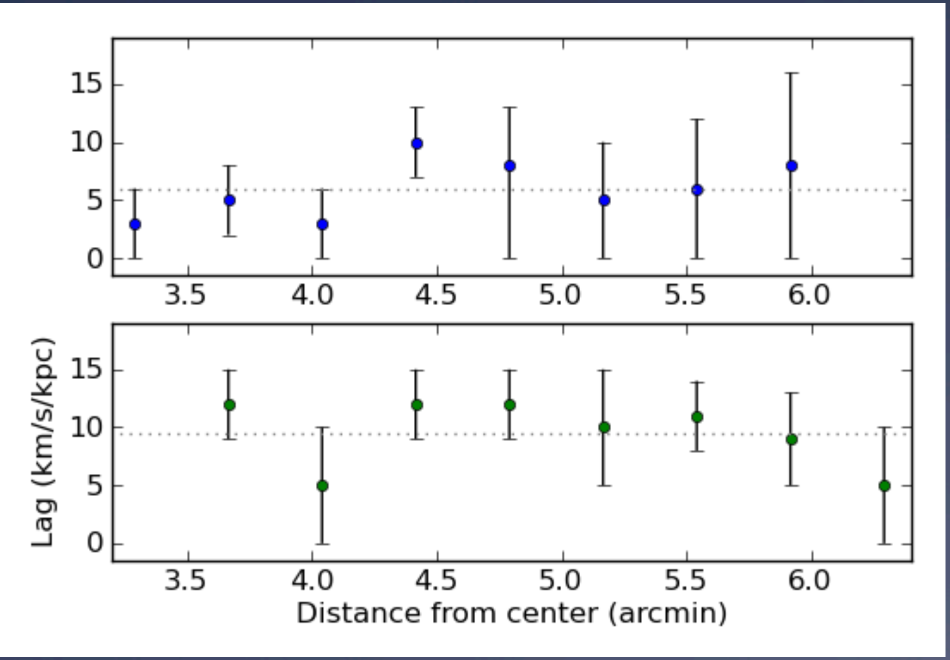


Inferred lags are unphysically large in outflow region, because we are dominated by outflow

NGC 4631 West (approaching)



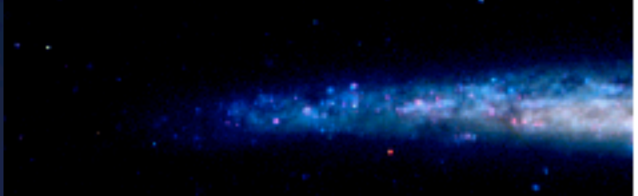
Models: 90º- inclination

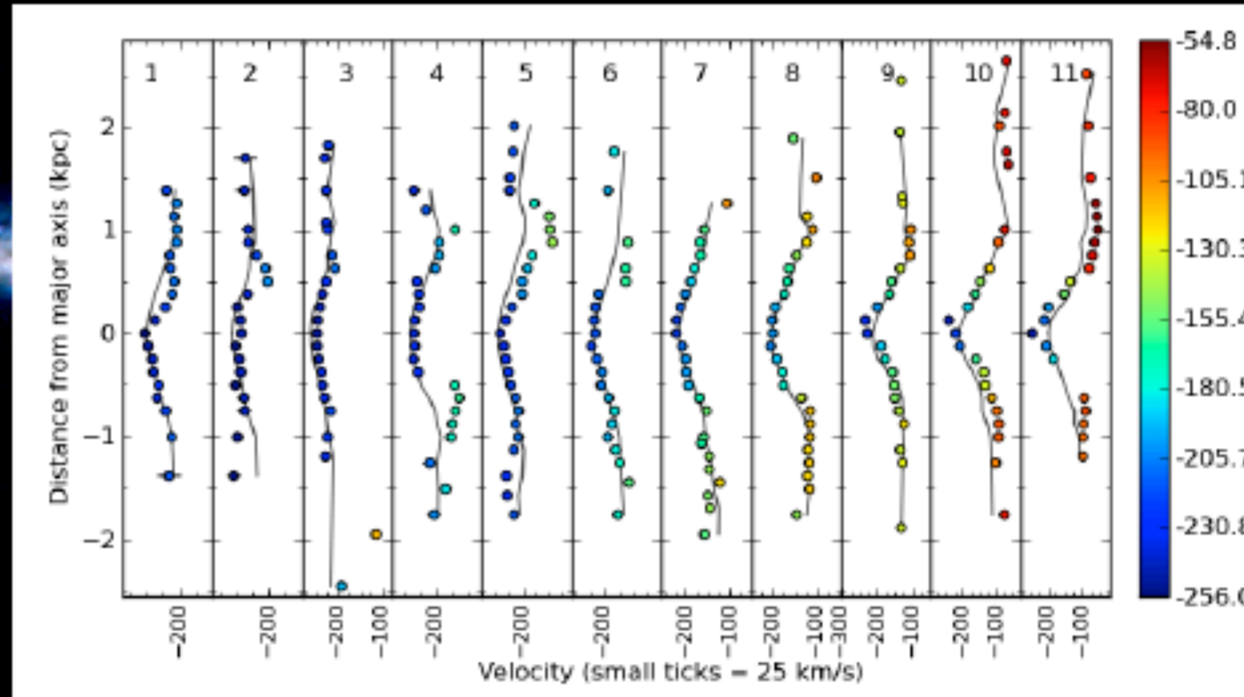


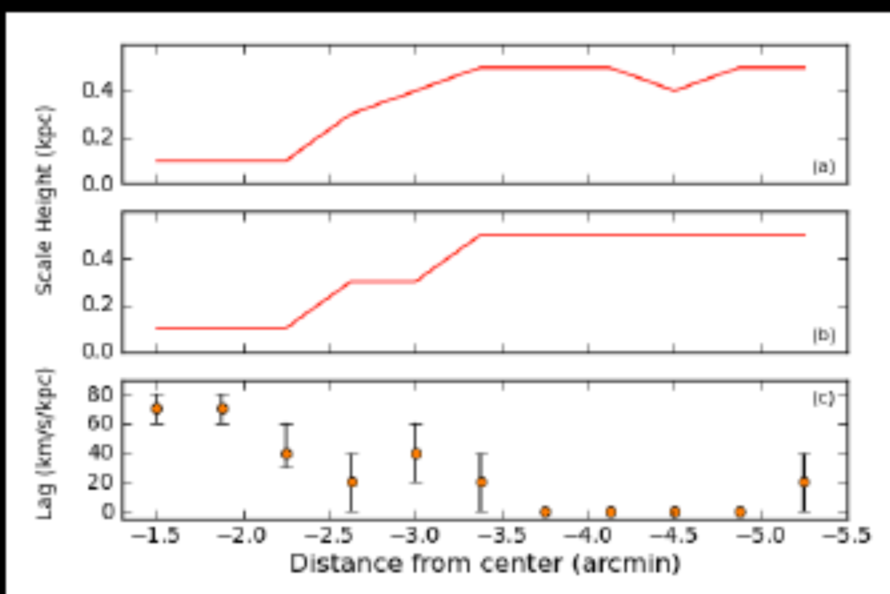
Model lags for upper and lower half of each slit.

Top (blue): 6.5 km/s/kpc
Bottom (green): 9.0 km/s/kpc

NGC 4565





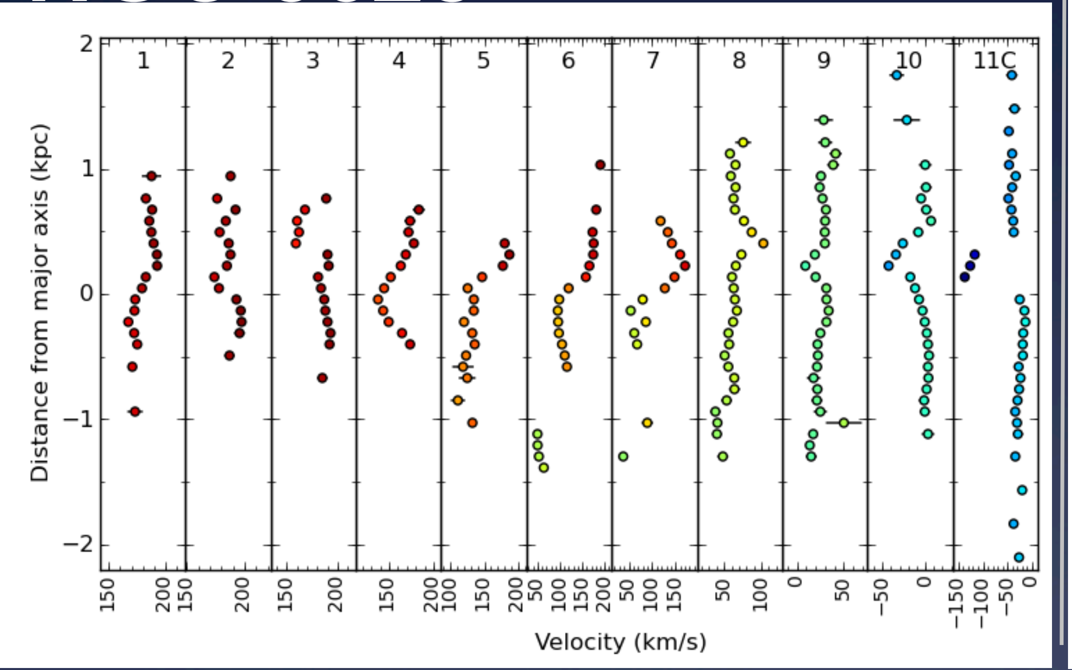


2-component model:

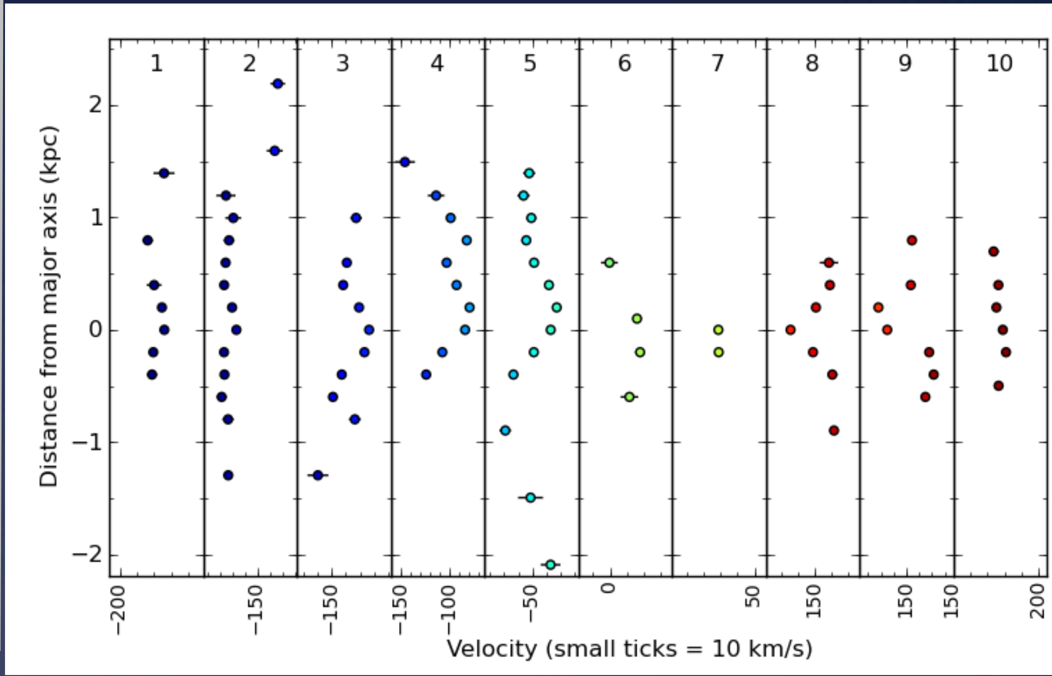
- Thin – flare
- Thick
  radially decreasing lag
- Both match HI models

Non-lagging extra-planar gas

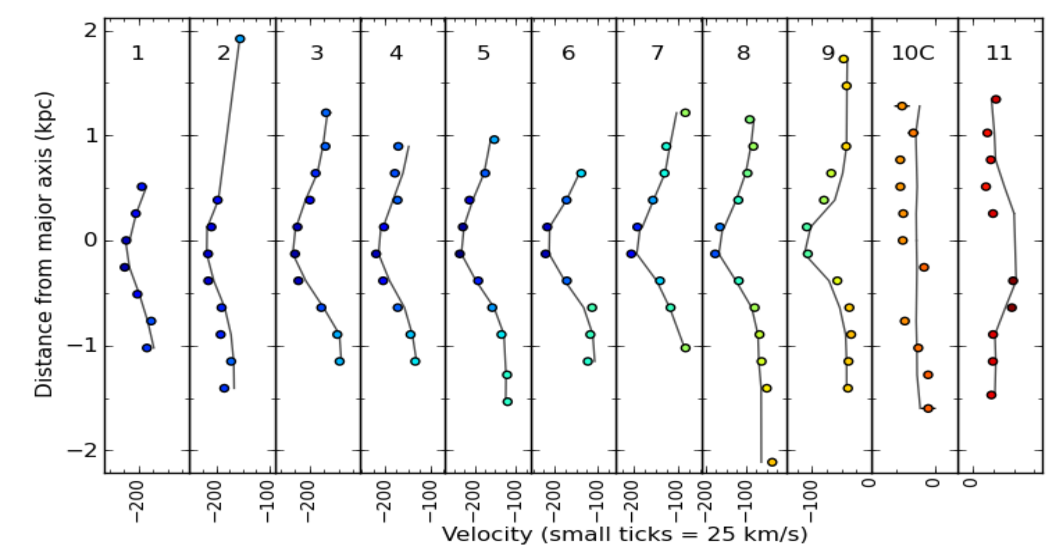
NGC 3628



NGC 4013



NGC 5907

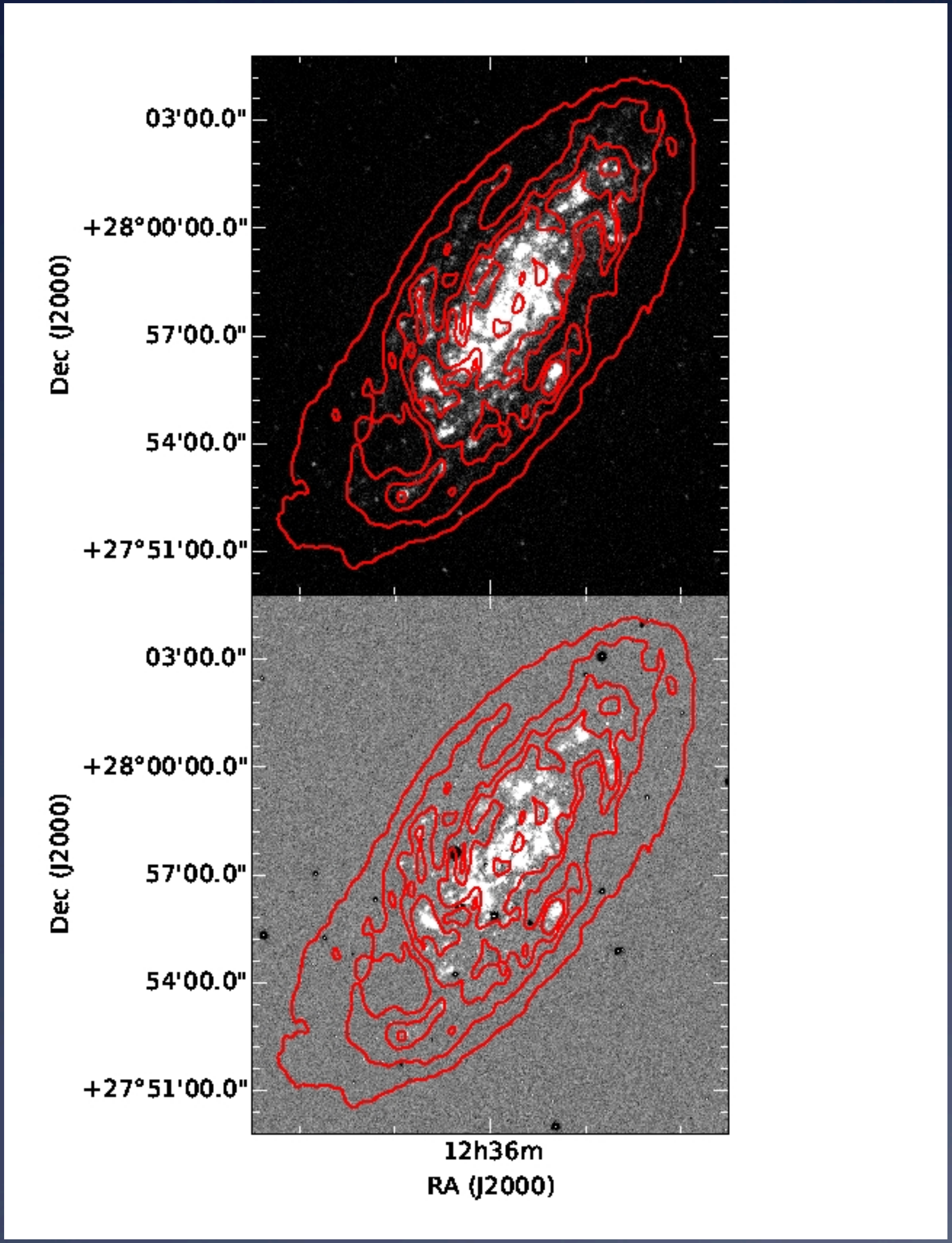


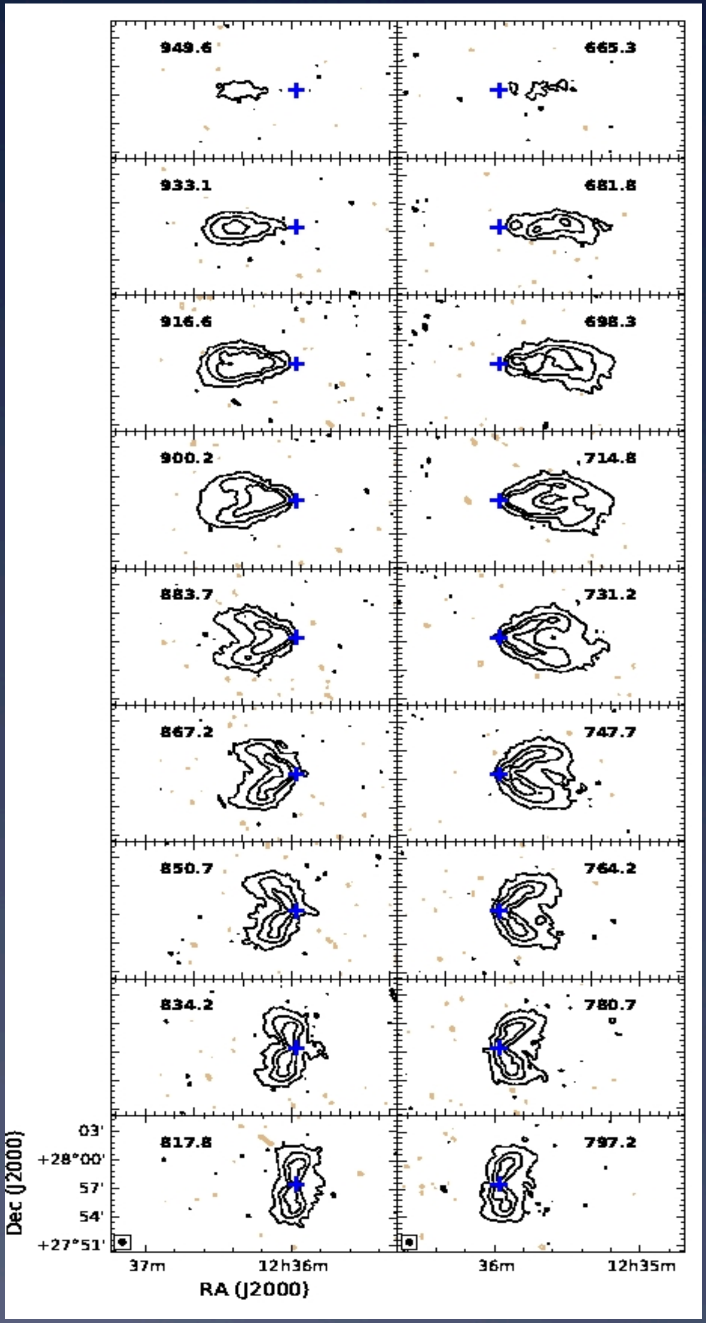
Models:
Thin disk, 87°

HI studies – Halogas, analysis method

- HI cubes, resolution is typically 15" to 30", velocity resolution is 4 km/s
- HI cloud mass sensitivity, typically few times 10^5 $M_{\odot}$, column density sensitivity: few 10^{19} at cm^{-2}, at full resolution
- HI distribution is modeled through use of "tilted ring fitting code", TiRiFiC (Jozsa et al. 2007), powerful way to obtain understanding of data
- Bottoms up approach, from simple to complex models:
    - Thin disk, tilted rings
    - Warp? Is it flaring?
    - Need thick disk? Is it lagging?
    - Add gas filaments ("arcs") and/or spiral arms
    - Radial infall?

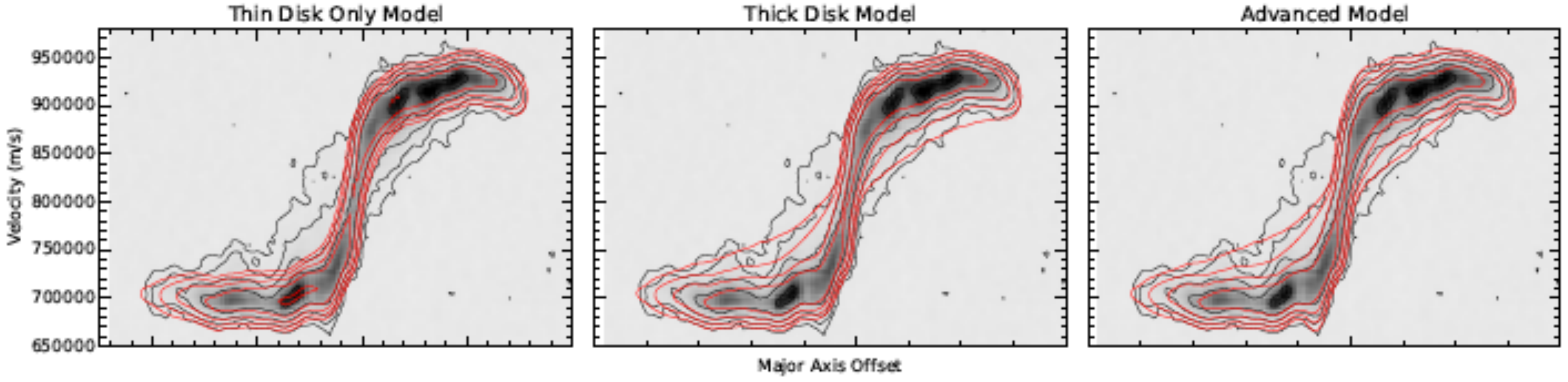
NGC4559 in HI (Carlos Vargas, follow-up study to Barbieri etal al. 2005)





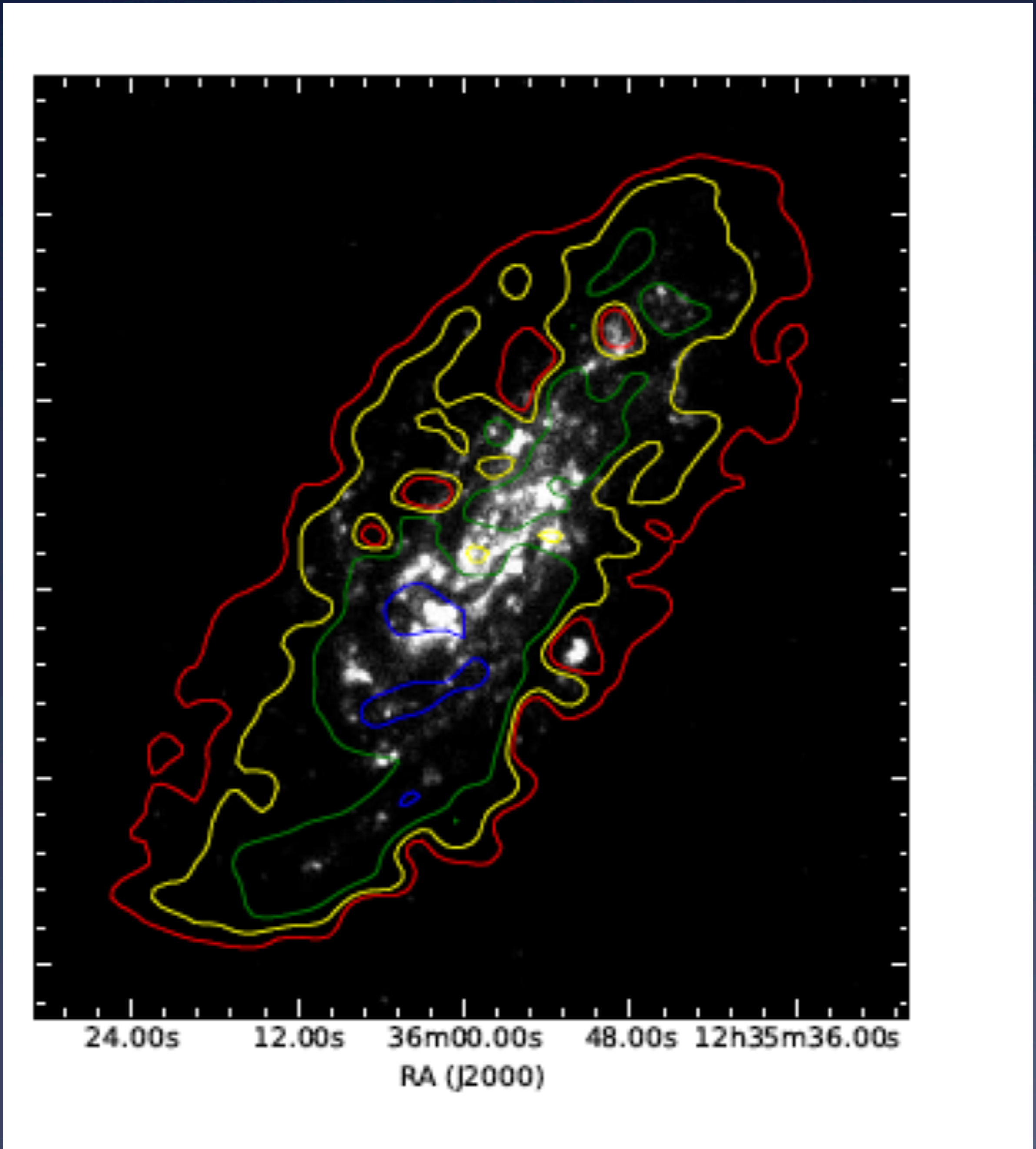
NGC 4559, Major axis position-velocity plots, with models

Thin disk model in red, thick disk model in blue, "halo gas" in yellow

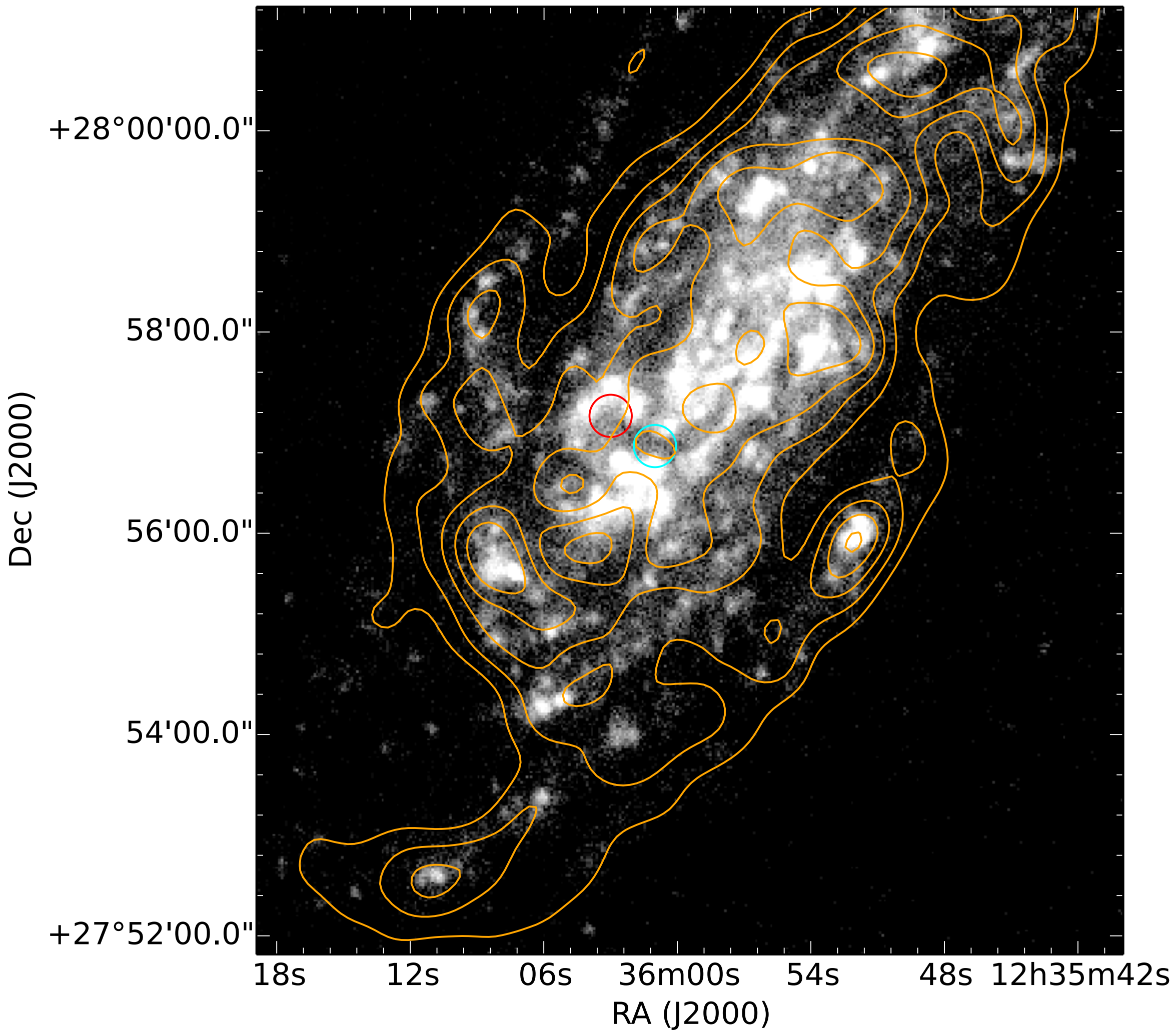


Conclusions: thick disk with lagging velocities fits better. There is some counter-rotating gas near central region.

NGC 4559, thick HI layer superposed on GALEX image



HI still correlated with the spiral arms;
if due to fountain then it is an entrained outflow, not returning cooled gas



NGC 4559, forbidden velocity region.

Red circle: prominent HI hole

Green circle: main region of forbidden gas

Dust lane and velocity suggest accretion

HI studies – NGC4244, low SFR Scd

Zschaechner et al. 2011

THE ASTROPHYSICAL JOURNAL, 740:35 (16pp), 2011 October 10 ZSCHAECHNER ET AL.

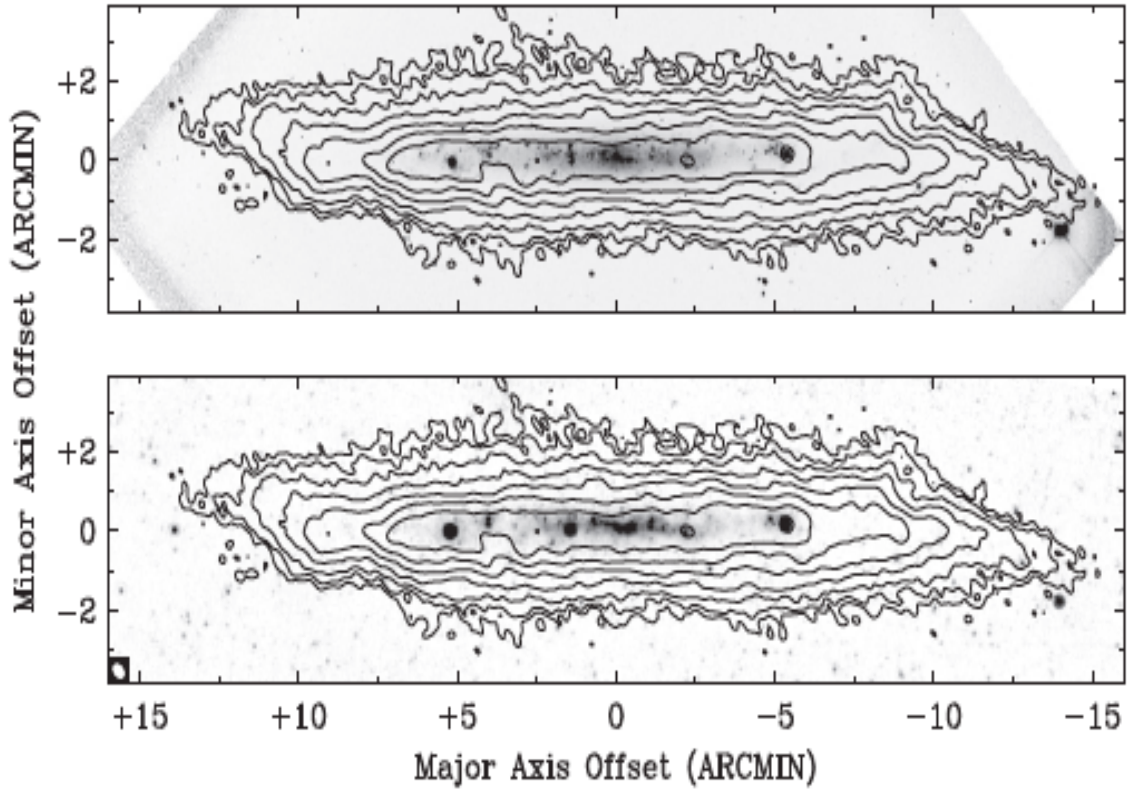
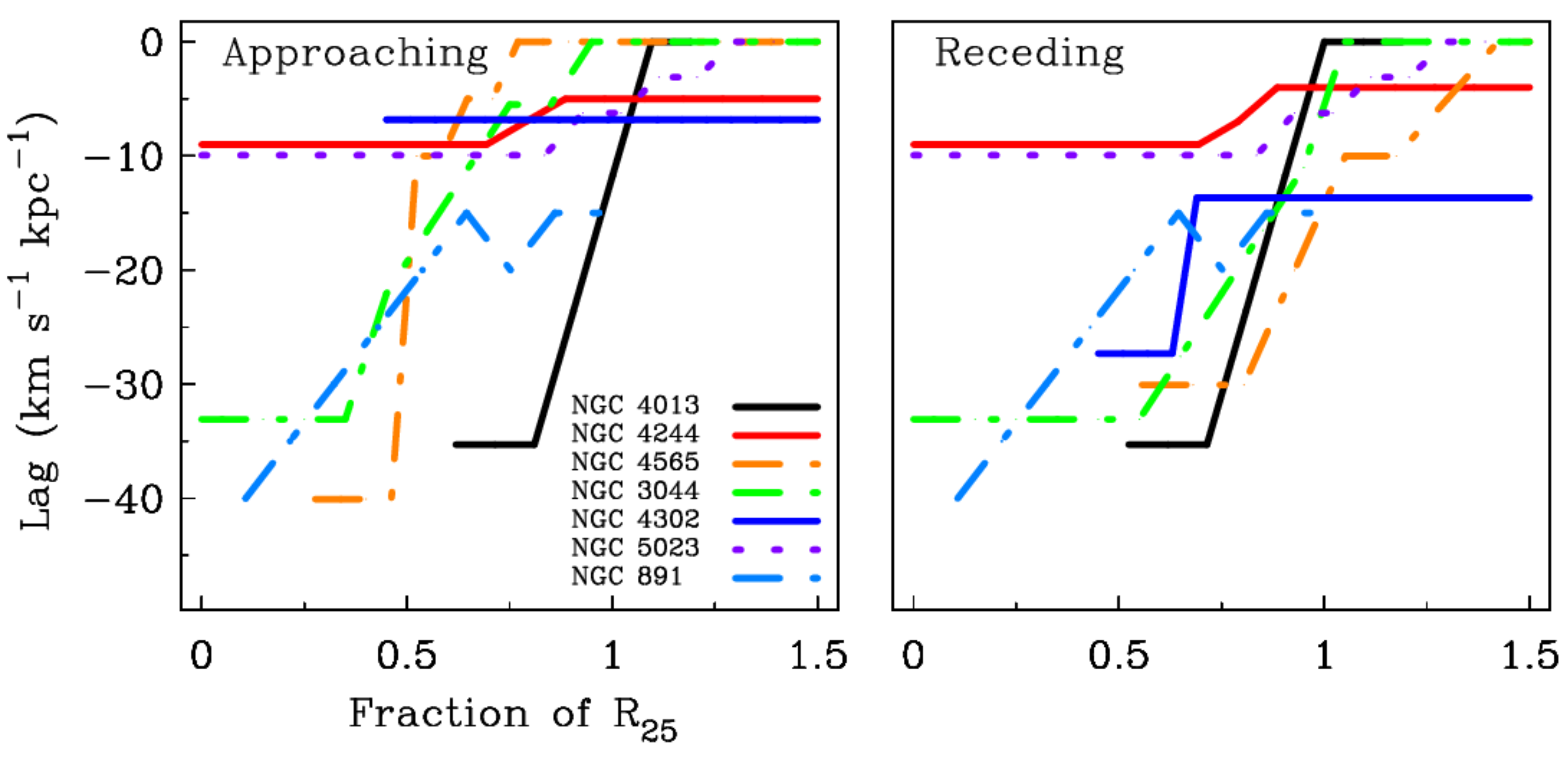


Figure 1. H I zeroth-moment map overlaid on Hα (top) and MIPS 24 μm (bottom) images. Each image is rotated counterclockwise by 43°. H I contours begin at 6.4×10^{19} cm^{-2} and increase by factors of two. The H I beam is shown in the lower left-hand corner in white. The Hα image is supplied by Rene Walterbos from Hoopes et al. (1999).

Large vertical extent in this case is mostly due to warp, as modeling shows, but lag in HI disk is also present

Radial Variations in Observed Lag (HI)

(Zschaechner et al., 2015, Zschaechner & Rand, 2015)



- Shallowing begins near 0.5 R_{25}
- Shallowest values reached near R_{25}
- If lag is accretion-related, there is accretion inside R_{25}

Optical Sample Conclusions

	v_{rot} (km/s)	L_{FIR}/D_{25}^2 (10^{40} erg/s/kpc^2)	Hα extent (kpc)	Lag (km/s/kpc)	Interacting?
NGC 3079	208.4	8.9	3.50	?/yes	Maybe
NGC 3044	153.1	3.3	3.00	?/yes	N
NGC 4013	181.7	2.7	2.00	0 (yes in HI)	N
NGC 891	212.1	2.2	4.25	15-20	N
NGC 3628	211.7	2.0	2.00	0	Y
NGC 4631	138.4	1.8	3.50	outflow; 6-9	Y
NGC 5907	226.7	0.8	2.00	0	N
NGC 4565	244.9	0.5	2.50	70 → 0	N
NGC 4517	139.8	0.5	2.50	20-60	N
UGC 4278	78.9	0.2	1.50	-	N
NGC 5229	55.8	> 0.2	0.35	-	N
UGC 7321	94.5	0.03	0.35	-	N

HI sample conclusions

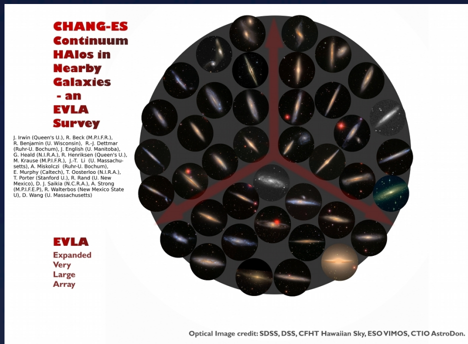
- Most, but not all, galaxies show vertical velocity gradients (“lagging thick disks”).
- Lags reduce with radial distance in several cases. Lags can be present even in rather thin disks with weak star formation, e.g. NGC4244, NGC4565
- Value of lags is higher than predicted in simple galactic fountain models. Need more realistic (M)HD models of gas flow (e.g. “halo drag”, Marinacci etal 2010, 2011). Or may indicate evidence for accretion (e.g. Fraternali & Binney, 2008).
- Direct detection of accreting clouds is rare. some cases may exist. Also evidence for extented arcs in some cases that could be accreting gas (E.g. Kampuhuis etal 2013, See also case of NGC2403)

Revisit the main questions

- How common are vertically extended HI or H+ disks with lagging velocities? Common, but the HI extent in NGC 891 is the exception, not the rule
- Are counter-rotating clouds/filaments common? No. What about outflows? No
- What is the origin of the vertical decrease in rotational velocity (lag)? Galactic fountain? Accretion? Other? Not yet clear. No clear correlations of lags with other galaxy properties.

Future

- Overall analysis of Halogas+ samples underway, papers on scale heights and lag correlations, as well as paper on clouds and individual features
- Large optical IFU surveys that will include many edge-ons (MaNGA (Rubin), CALIFA, SAMI); large interferometric HI surveys planned in North and South (WNSHS; WALLABY)
- CHANG-ES project (PI J. Irwin). VLA observations of 35 edge-on galaxies to study magnetic field structure and cosmic ray transport. Correlation with lagging gas velocities?



CHANGES VLA SURVEY OF RADIO SYNCHROTRON HALOS