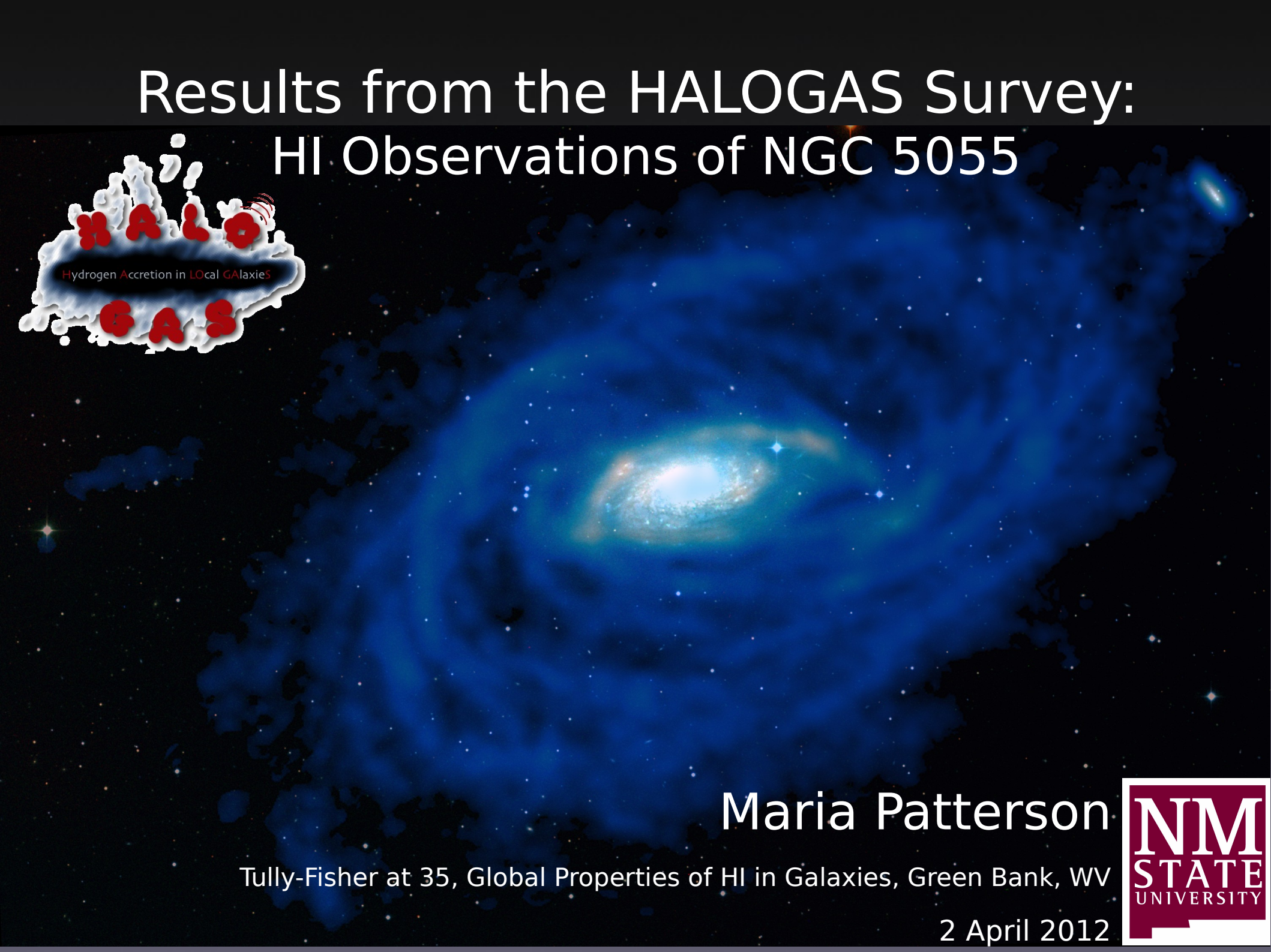
Results from the HALOGAS Survey:
HI Observations of NGC 5055



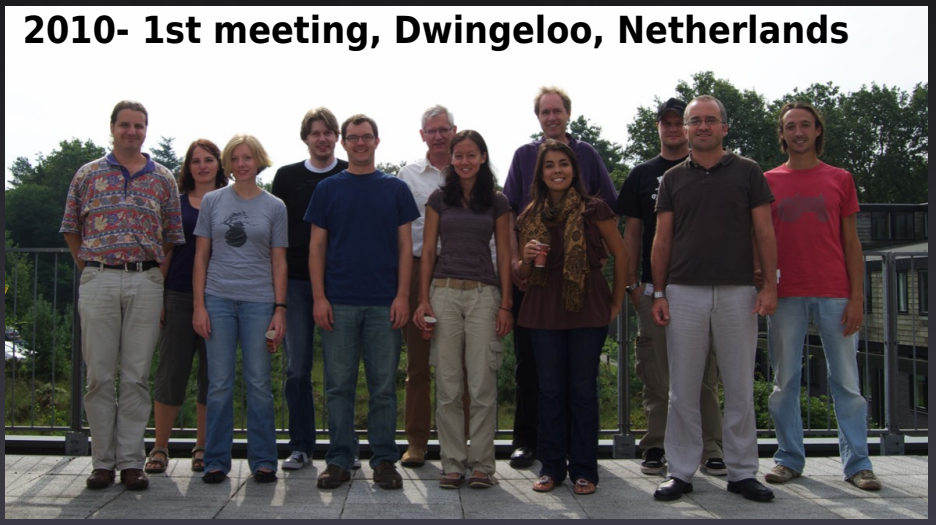
Maria Patterson

Tully-Fisher at 35, Global Properties of HI in Galaxies, Green Bank, WV

2 April 2012

NM STATE UNIVERSITY

HALOGAS Survey Team



http://www.astron.nl/halogas/

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HALO GAS
Hydrogen Accretion in LOcal GAlaxieS

Hydrogen **A**ccretion in **LO**cal **GA**laxie**S** Survey

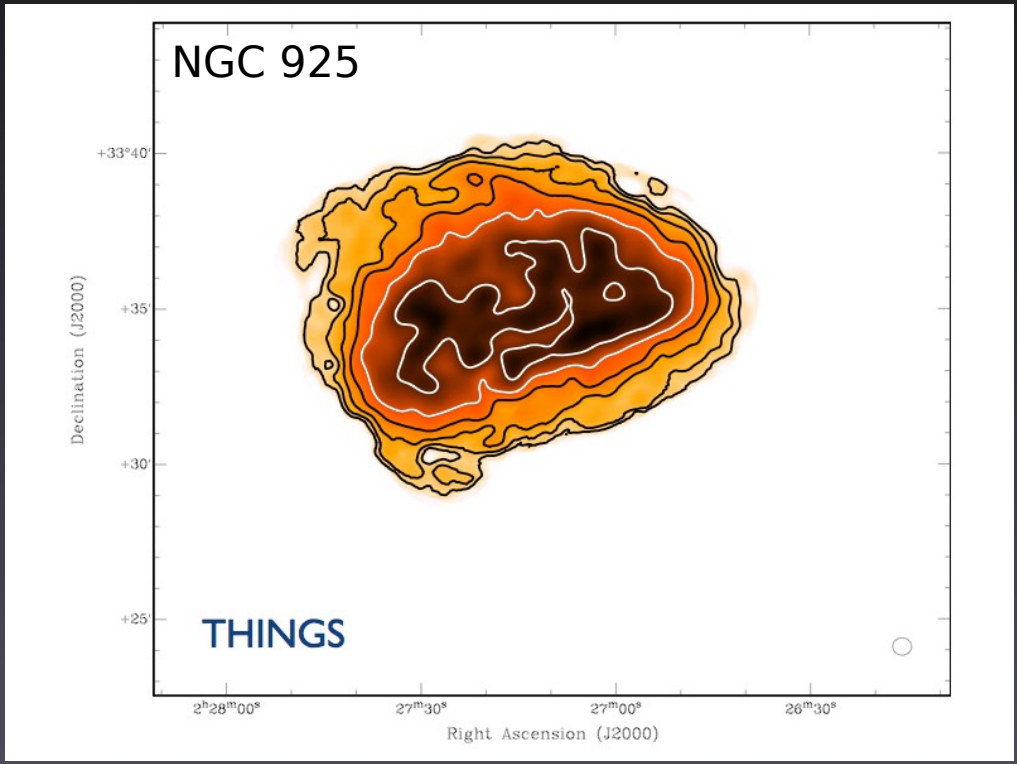
The HALOGAS Survey is a deep HI survey with the Westerbork Synthesis Radio Telescope of a sample of neutrally selected nearby spiral galaxies with the goal of detecting faint gas and characterizing accretion.

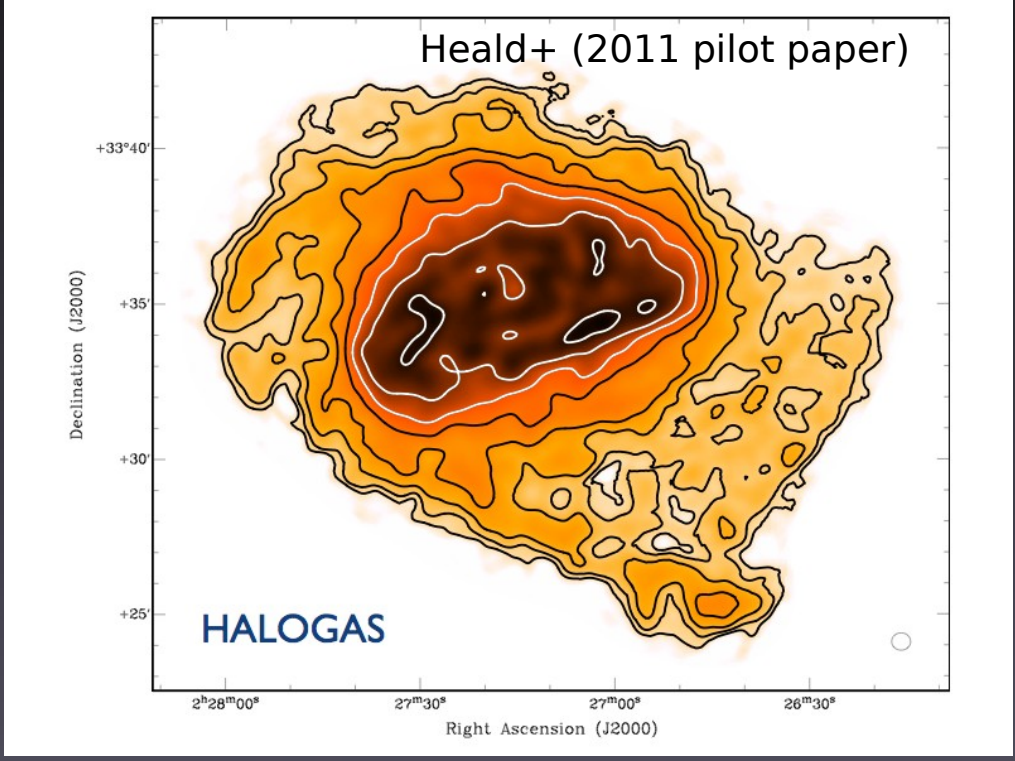
Neutral selection criteria:

- Barred and unbarred, Sa-Sd from Tully (1988) catalog
- Inclinations: moderately-inclined (50-75°) and edge-on (> 85°)
- Declination > +25° (synthesized beamsize < 30“)
- d_{TF88} < 11 Mpc (15“ = 0.7 kpc at 10 Mpc)
- D_{25} > 3' (well-resolved)
- V_{sys} > 100 km/s (avoid MW confusion)
  - → **20 spiral galaxies (+ NGC 891 (Oosterloo+ '07), NGC 2403 (Fraternali+ '02))**
  - → **120 hrs for each galaxy**
  - → **5 times deeper than THINGS**
  - → **Sensitivity of 3σ at ~1 x 10^{19} cm^{-2}**

HALOGAS survey sensitivity

The HALOGAS data are sensitive to ~1 x 10^5 $M_\odot$ clouds, at 3σ level for a typical line width of 16 km/s at 10 Mpc.





THINGS:

5σ column density limit of
~1 x 10^{20} cm^{-2}

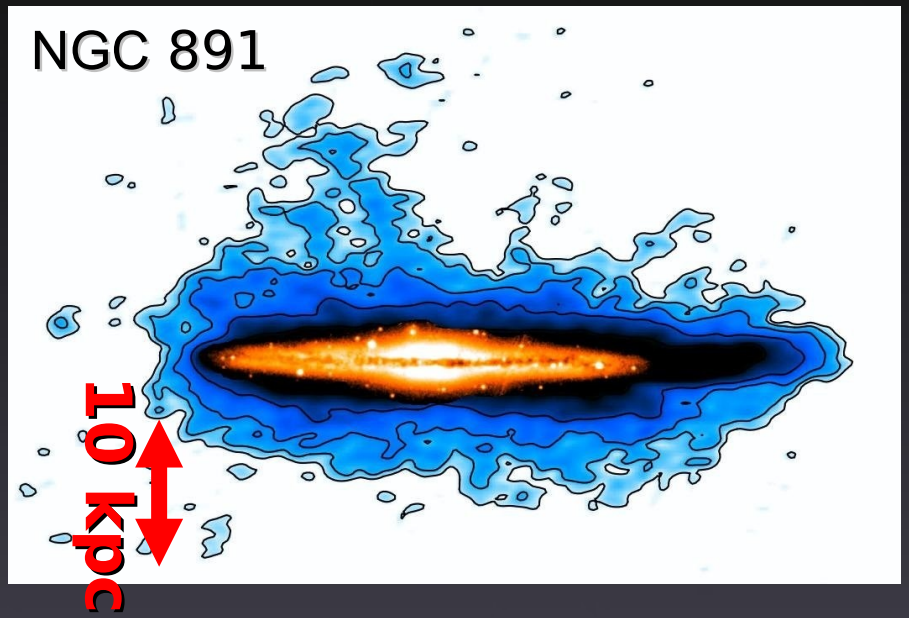
HALOGAS:

5σ column density limit of
~2.0 x 10^{19} cm^{-2}

Goal: Establish the importance of the role of accretion in galaxies

Accretion is key to...

- Maintaining a ~constant SFR
- Metallicity evolution in ISM
- Continuing buildup of galaxies- connection to warps and lopsidedness



How *many galaxies* show evidence for accreting gas?

How *much* accreting gas is there?

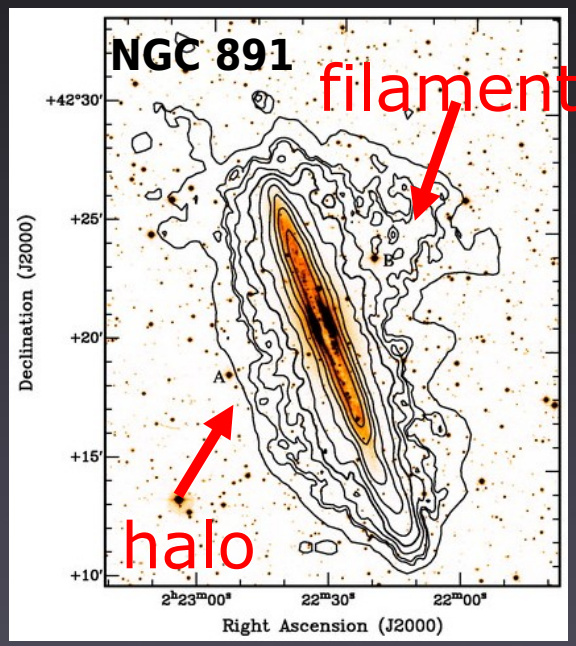
- Estimated 1-2 solar masses/yr (Sancisi+ 2008)

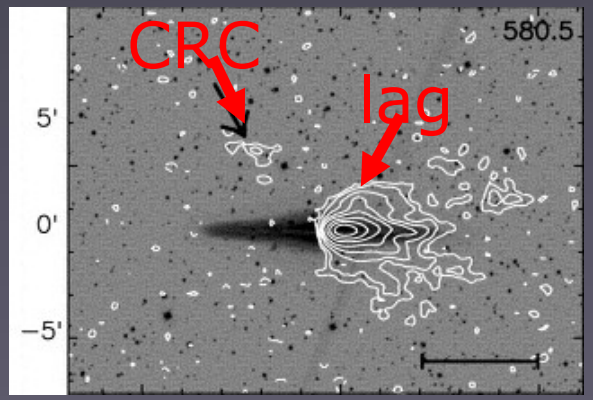
How *often* can 'halo' gas be associated with

- infall from the IGM?
- minor mergers with smaller satellite galaxies?
- returning galactic fountain gas?

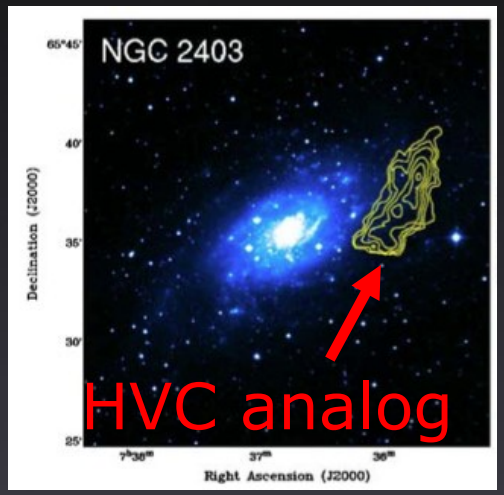
If we look deep enough, how many spiral galaxies look like this?

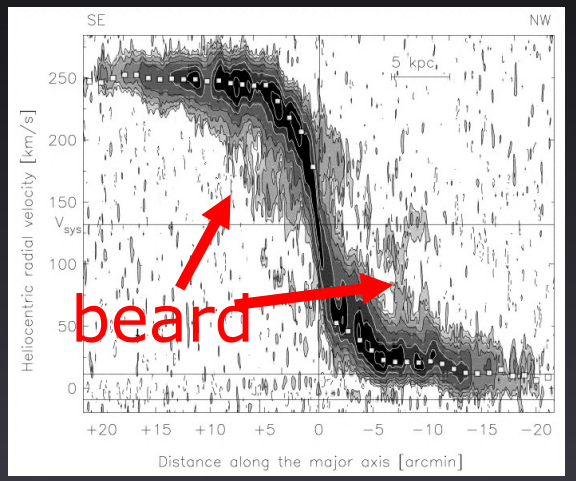
NGC 891:
30% (~1.2 x 10^9 solar masses) of the gas in extraplanar halo component

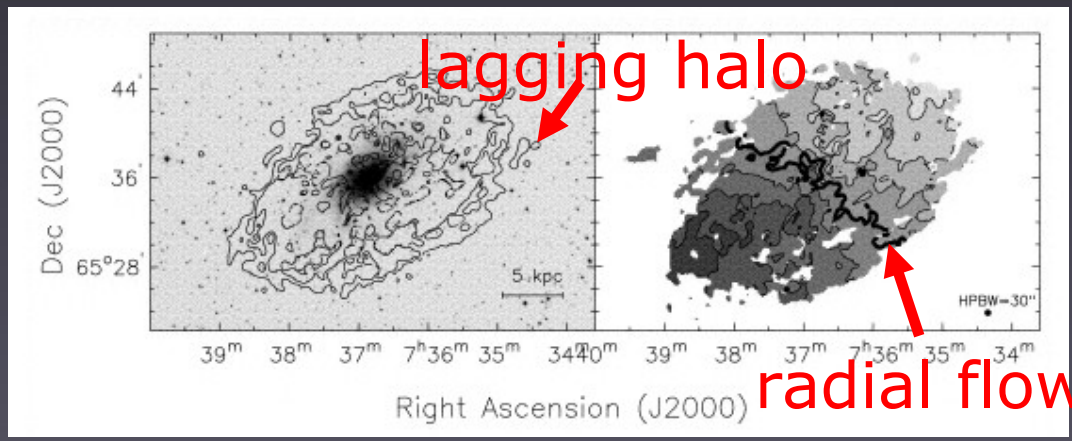




Oosterloo+ (2007)







Fraternali+ (2002)

NGC 2403:
10% (~3 x 10^8 solar masses) of the gas in extraplanar halo component (+ radial flow in halo)

Approach

- Develop a tilted-ring model for each galaxy
- Identify discrete clouds and streams to build an 'accretion catalog'
    - Mass, size, distance and kinematics relative to disk
    - Cross identify with optical and UV features
- Identify galaxies with thick disks / 'halos' for occurence statistics
    - Radial extent, vertical scaleheight, kinematics
- Compare gas properties with galaxy properties on individual basis
    - Complementary observing campaigns
- Compare gas properties with galaxies properties across sample

Status

All HI observations finished.

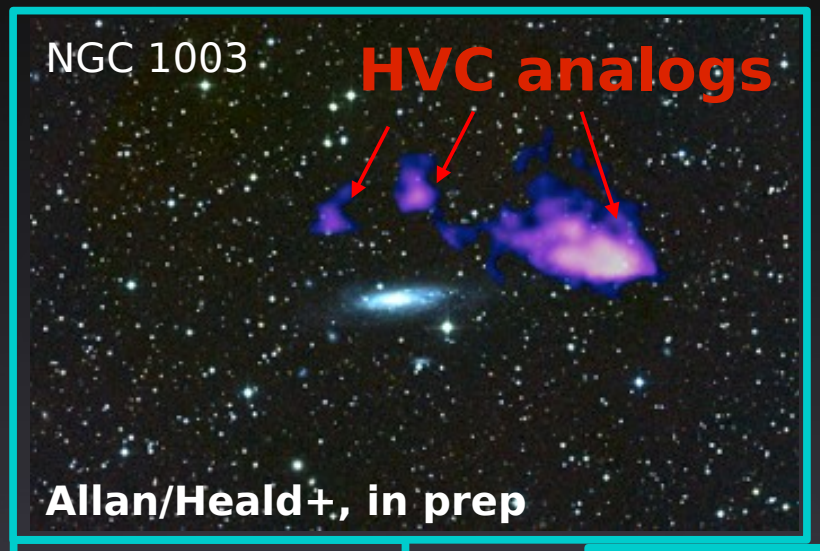
Modeling complete / near complete for many targets.

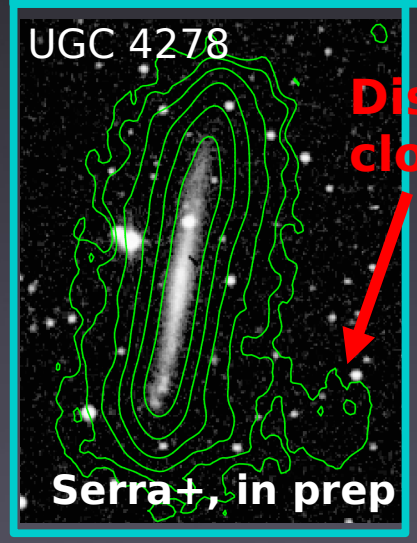
Individual galaxy analysis papers in prep.

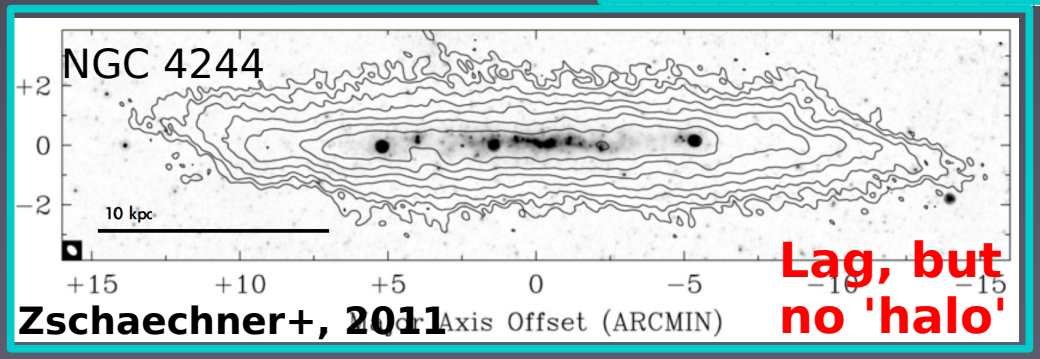
Beginning preliminary analysis of sample statistics.

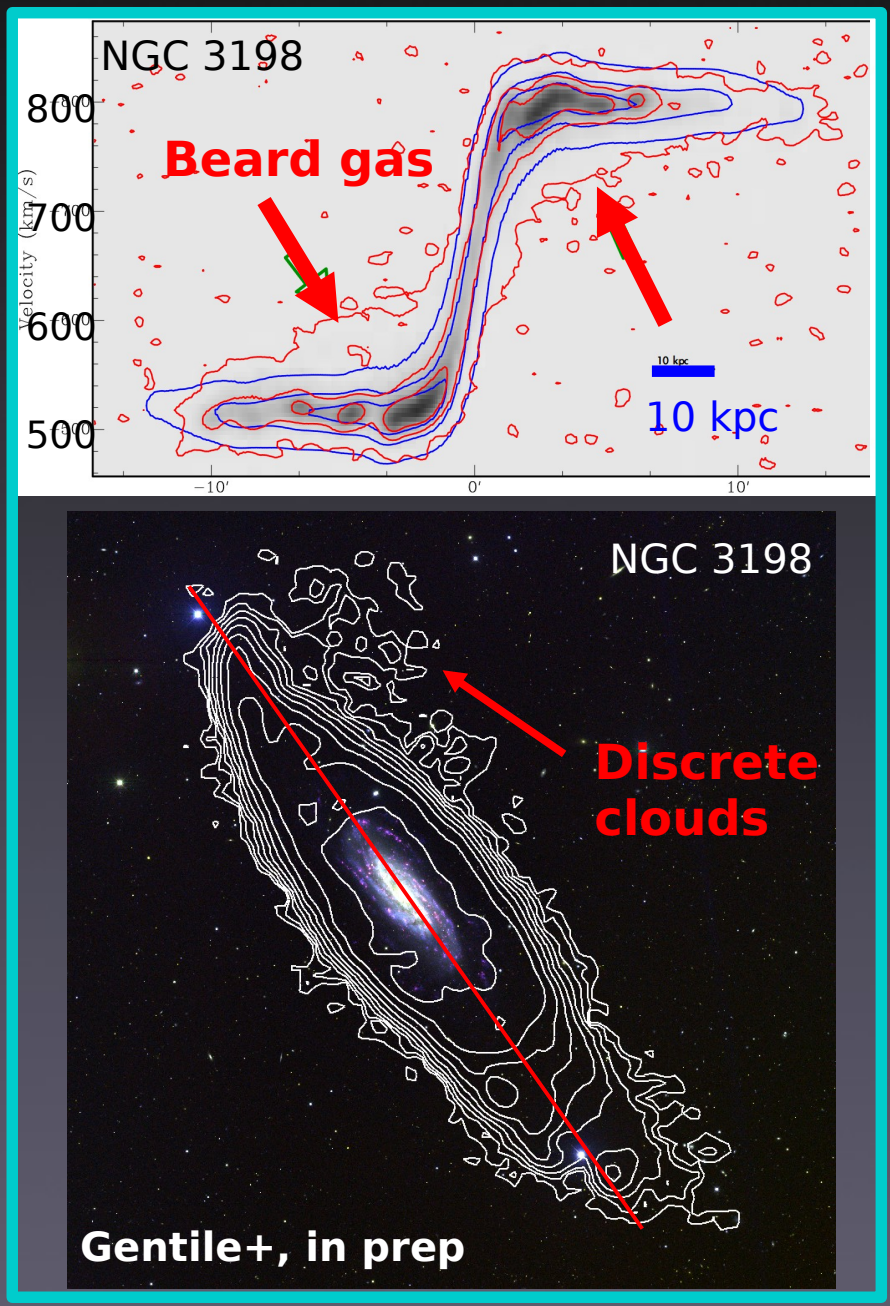
See survey website: **http://www.astron.nl/halogas/**

The HALOGAS data reveal a range of HI features...





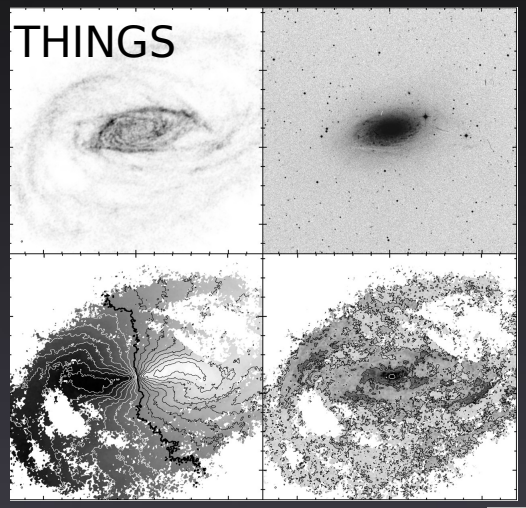




NGC 5055 (M63)

- SAbc
- Moderately-inclined (55°)
- d = 8.5 Mpc
- D_{25}=13'=32.5 kpc
- SFR= 2.1 solar masses/ yr

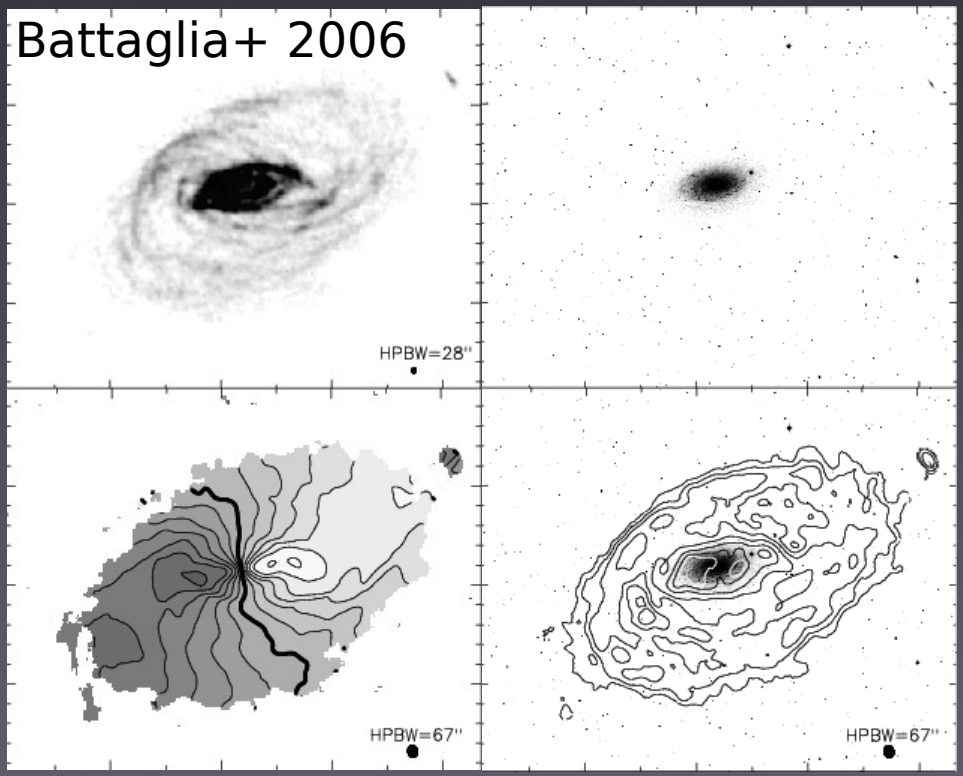
previous HI data



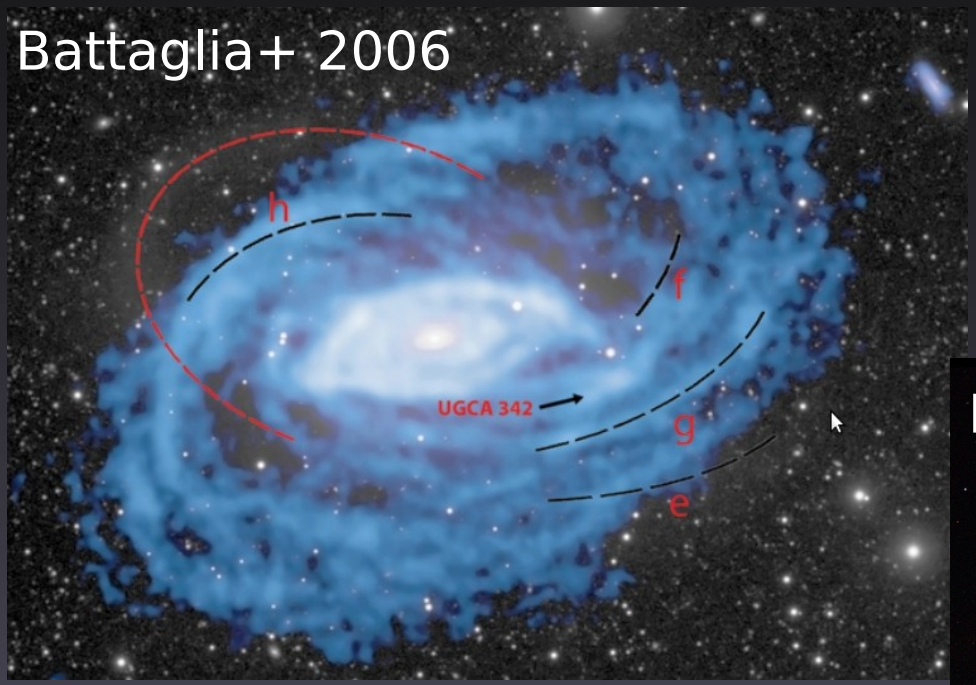
- Large HI disk

~3.5 x D_{25}

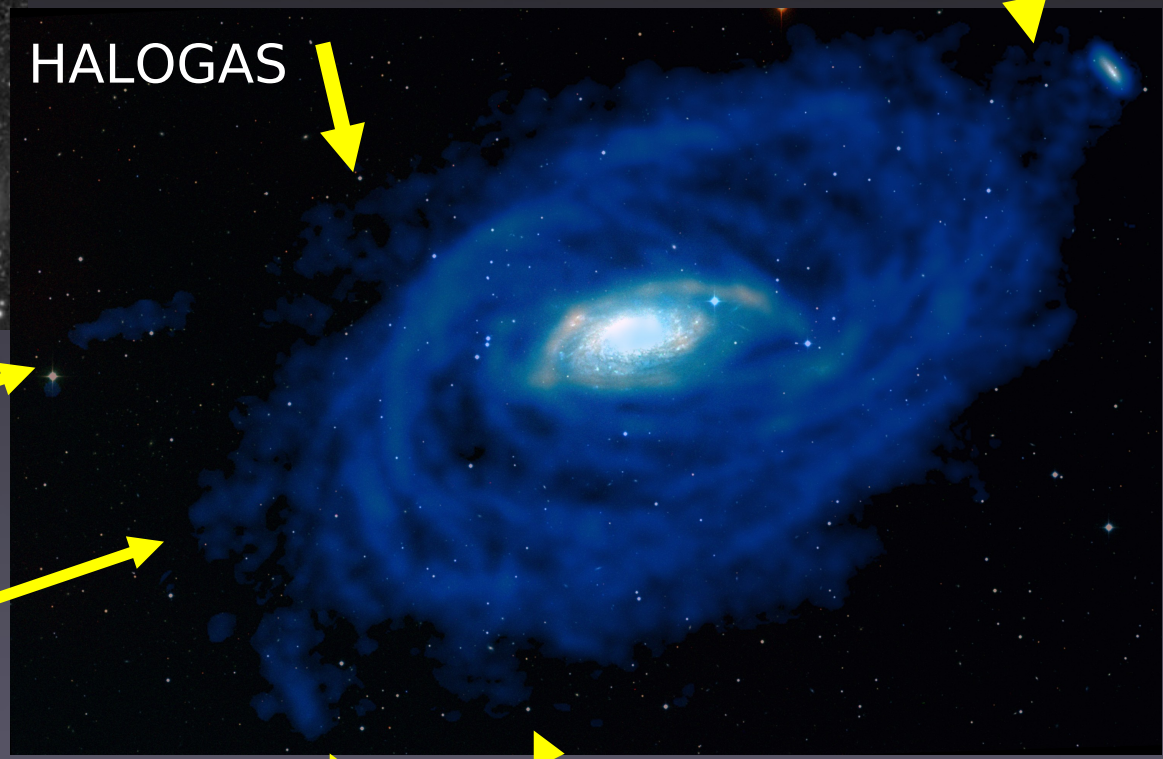
- Large HI warp



NGC 5055: HALOGAS



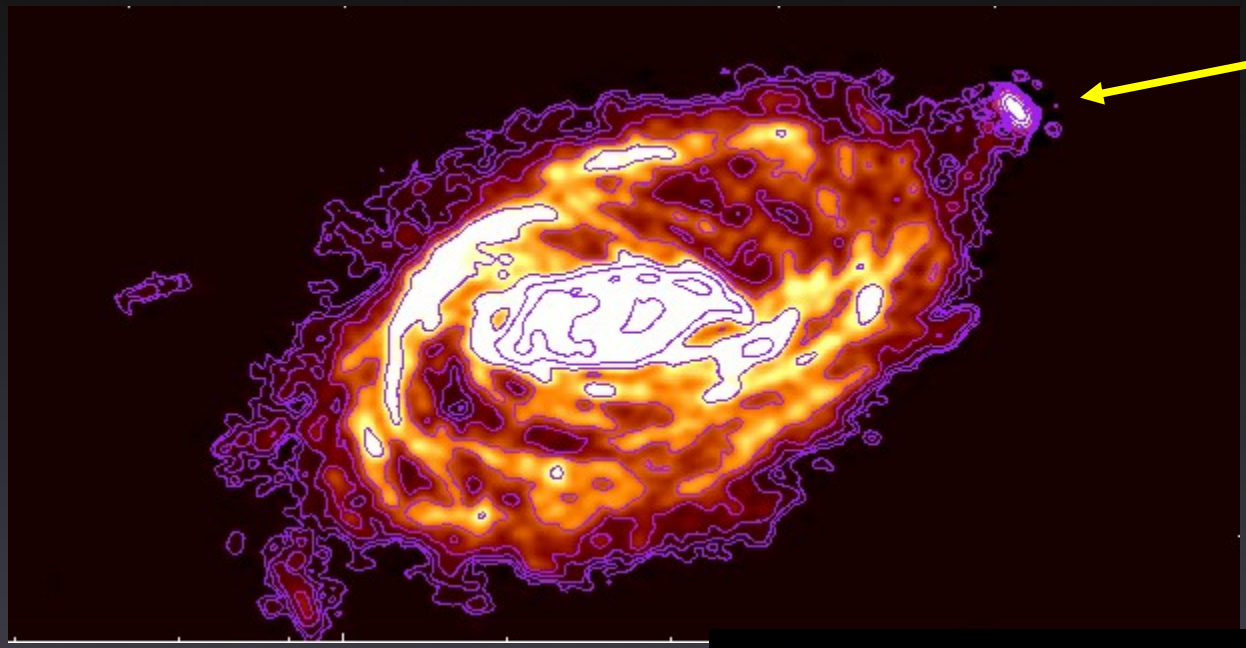
Total HI mass of galaxy:
~ 8.5 x 10^9 solar masses



14.5 kpc
~9.4×10^6 $M_\odot$

13 kpc
~2.7×10^7 $M_\odot$

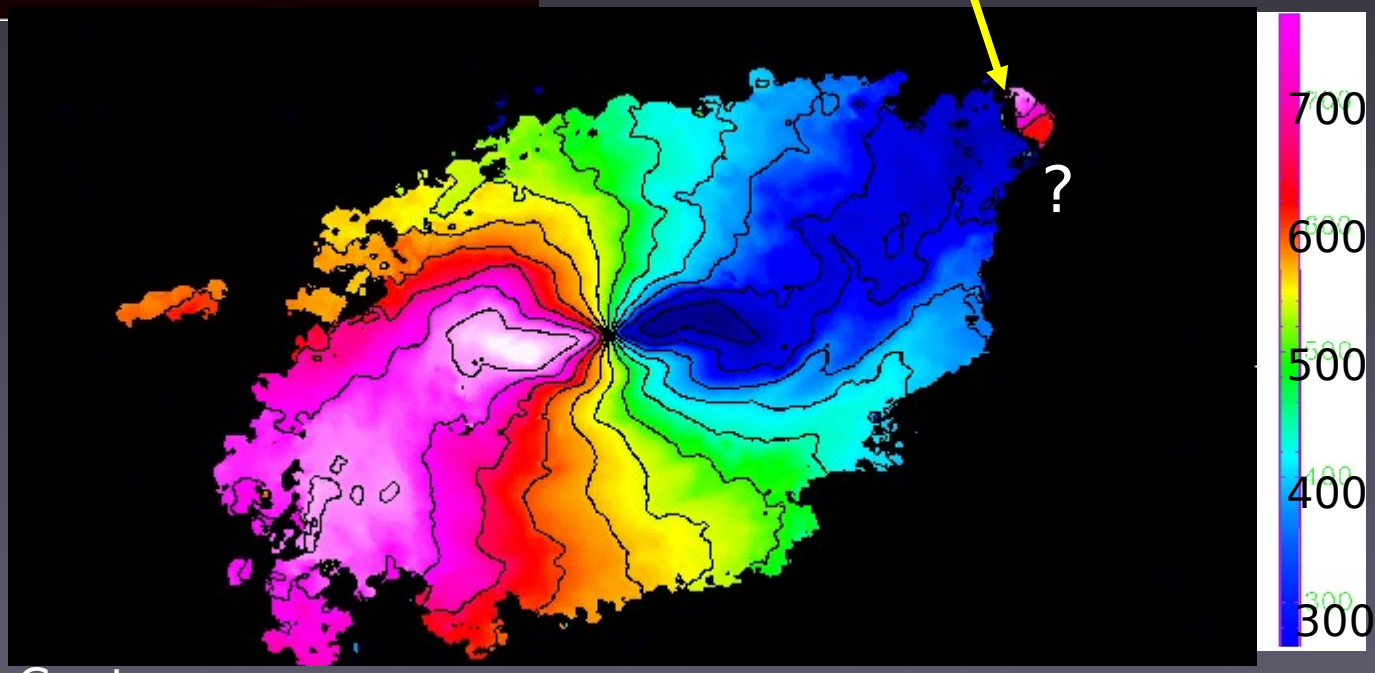
NGC 5055 moment maps



UGC 8313

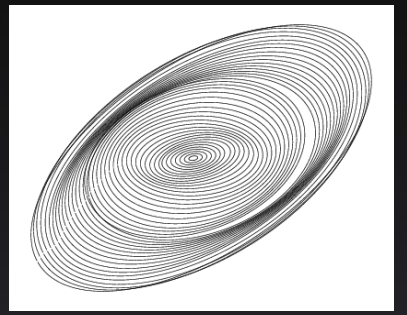
companion is separated in velocity, but may be a connection through the south

Contours:
2.7 x 2^n mJy/beam
(3σ x 2^n)
(1.0 x 10^{19} x 2^n cm^{-2})



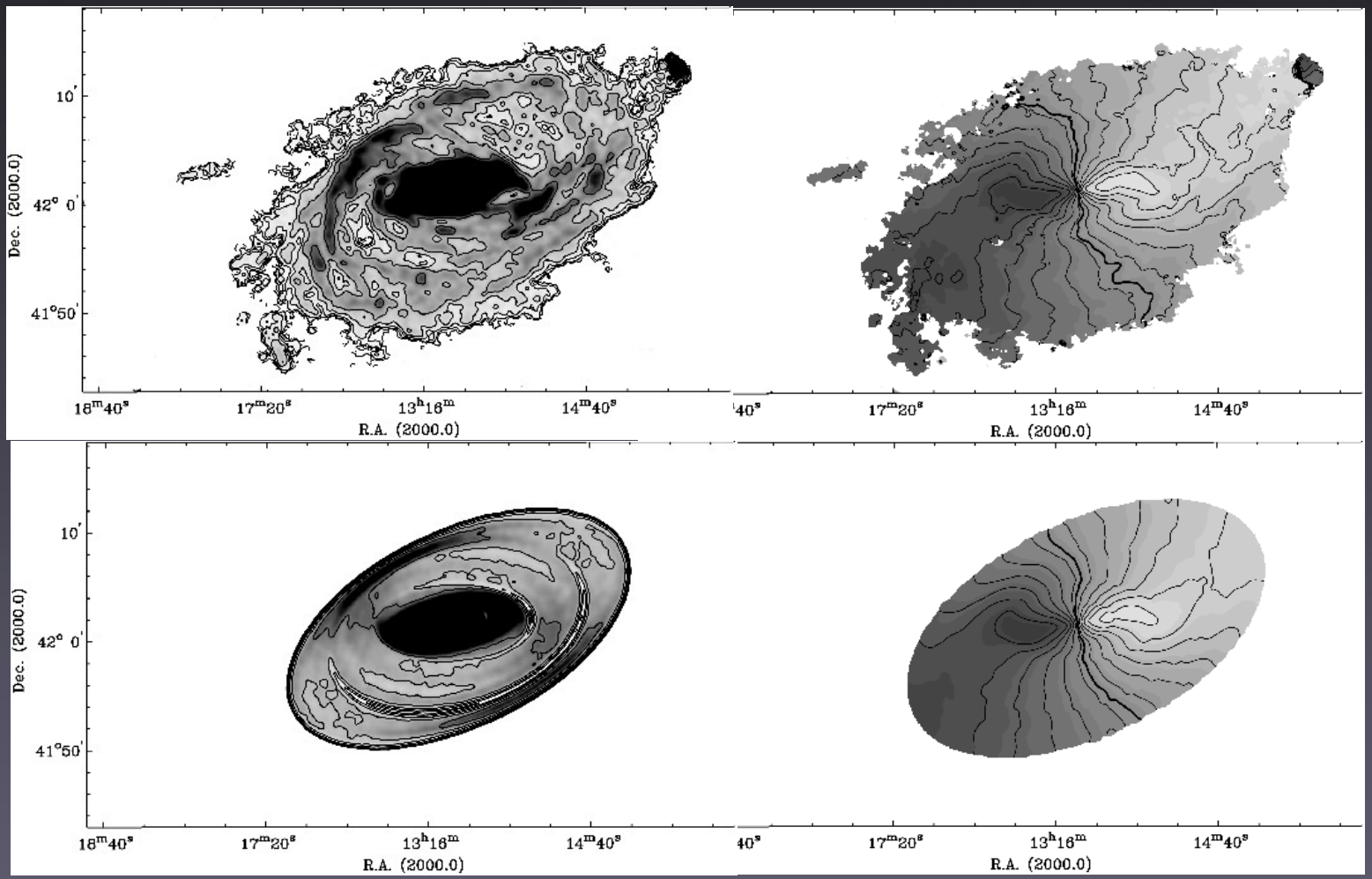
Contours:
270:780, +30 km/s

Tilted-Ring Modeling



Groningen Image Processing System (GIPSY) (van der Hulst+ 1992)

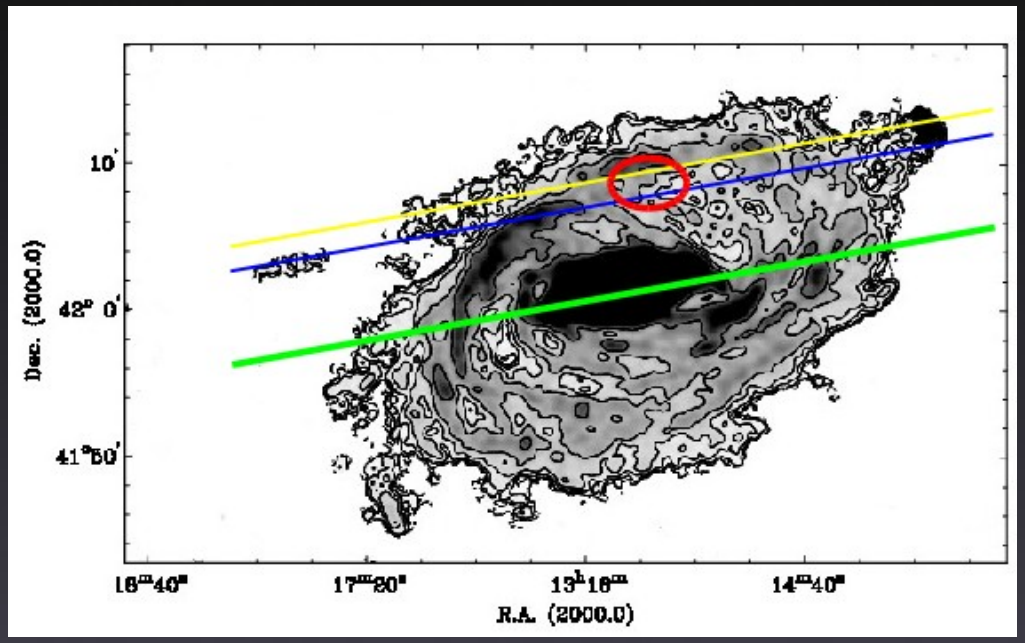
- GALMOD (and HALOGALMODZ) (Fraternali, Heald)
- Tilted Ring Fitting Code (TiRiFiC) (Jozsa et al., 2007)

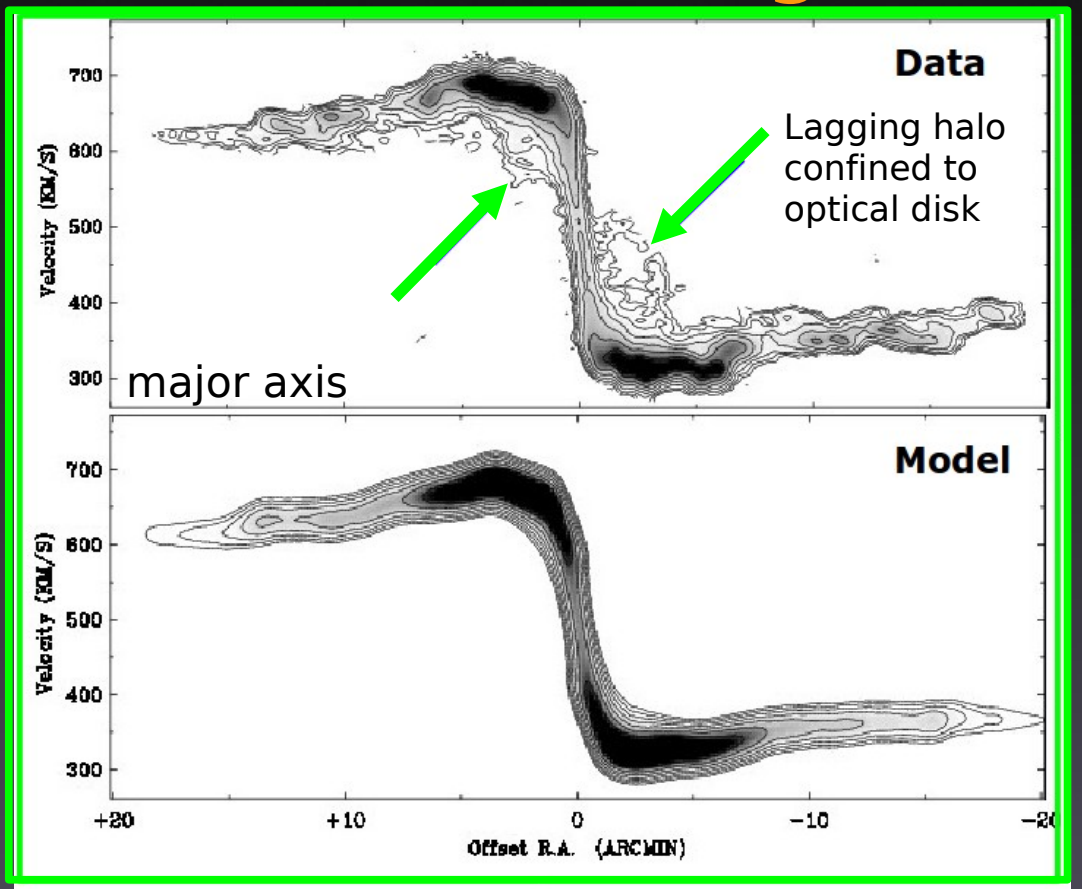


Contours: 2.7 x 2^n mJy/beam

Contours:270:780, +30 km/s

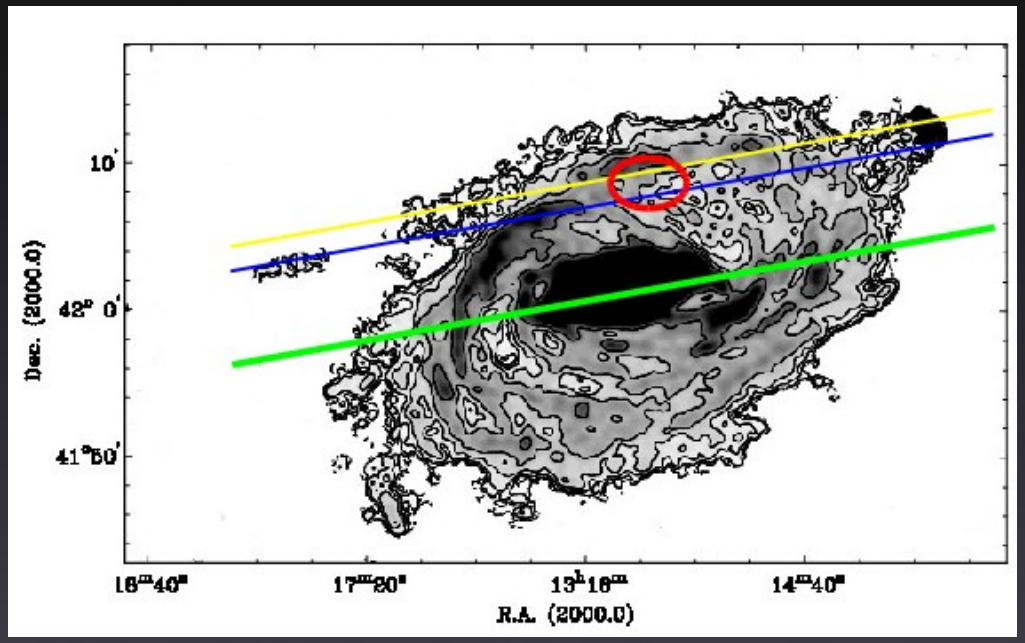
Position velocity plots: anomalous gas

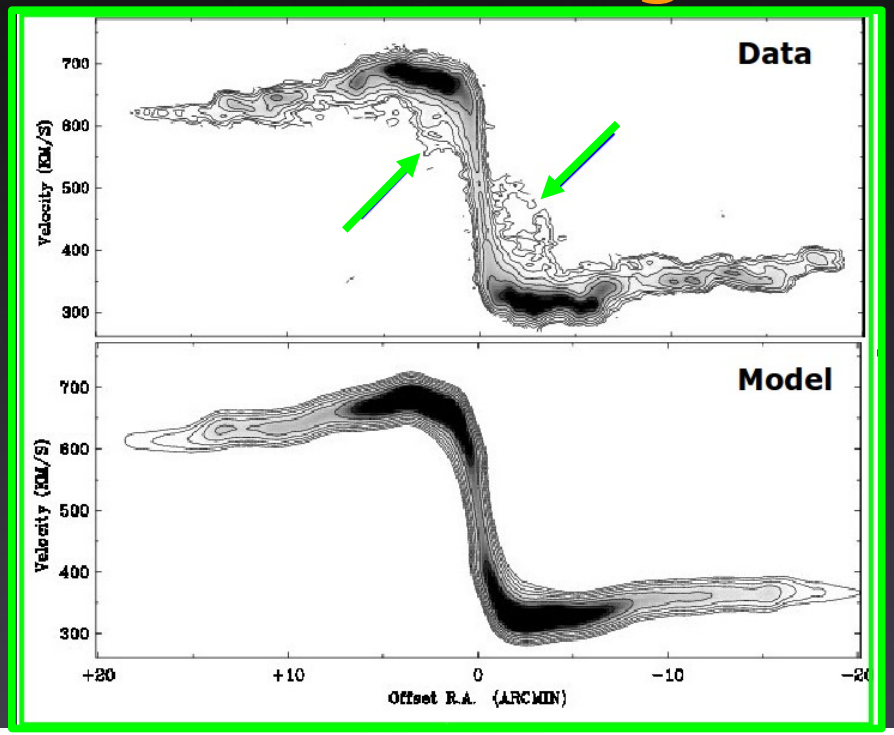


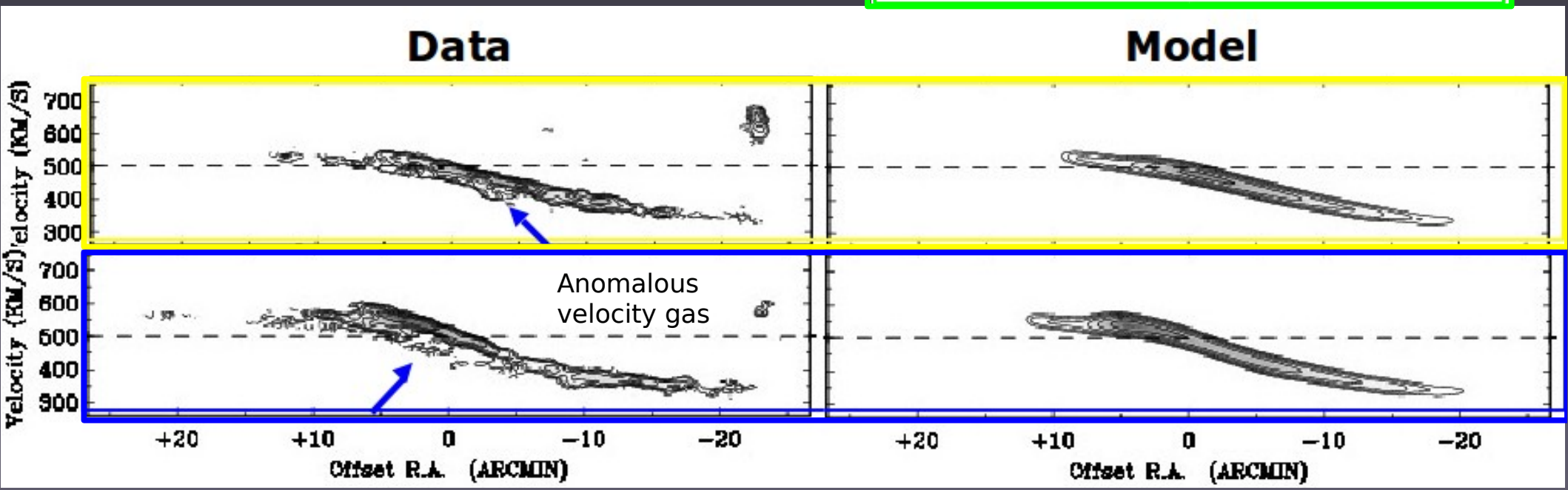


Contours: 0.36x2ⁿ mJy/beam

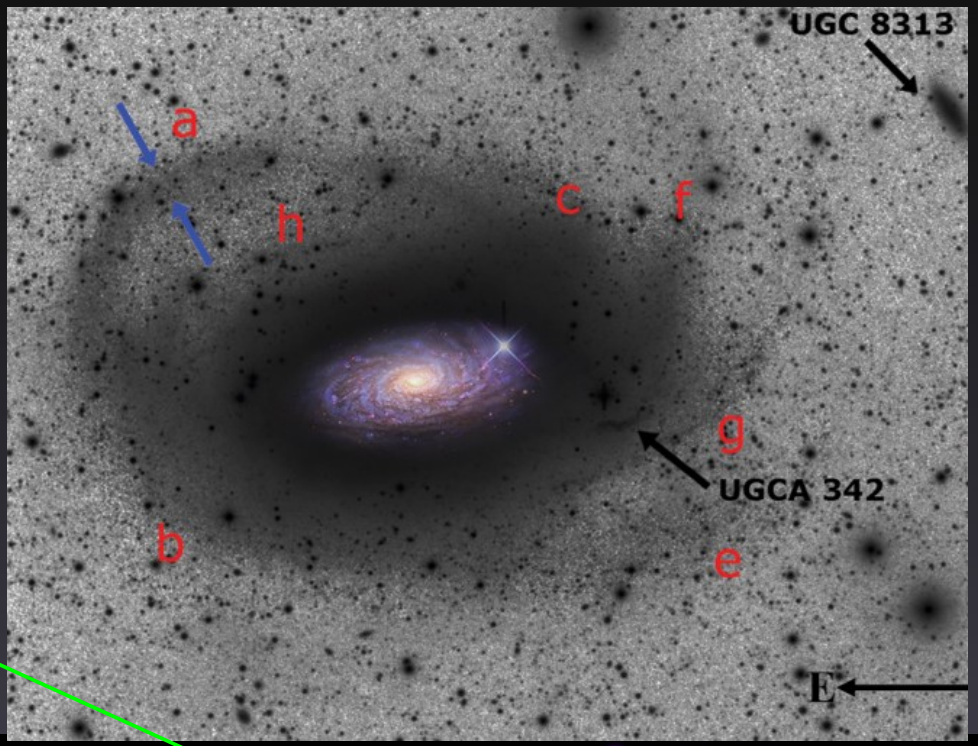
Position velocity plots: anomalous gas



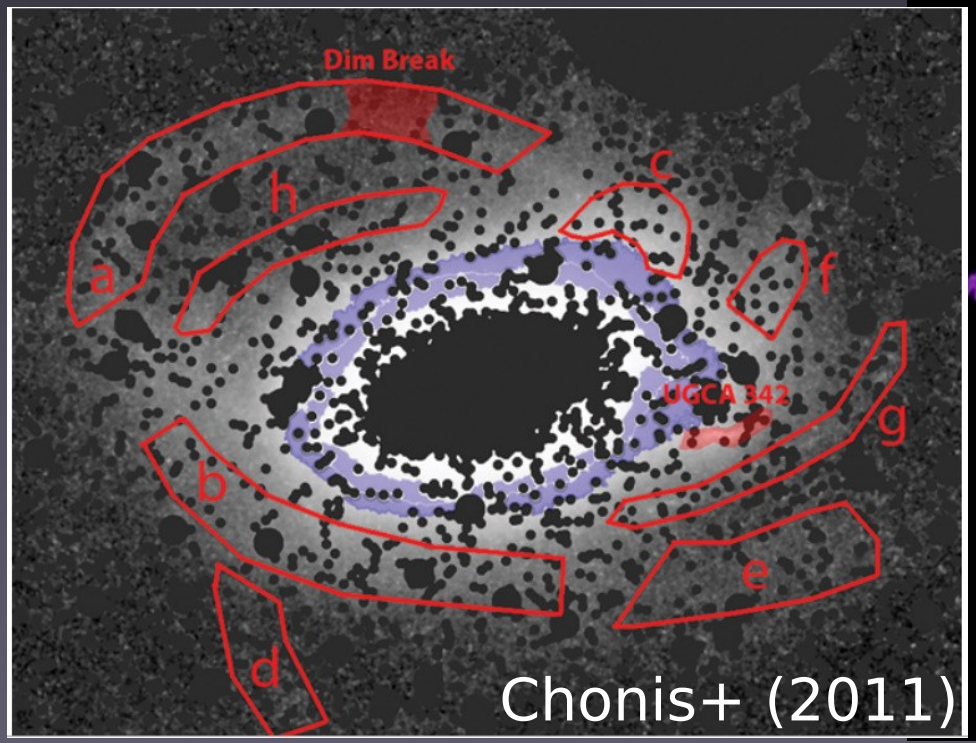


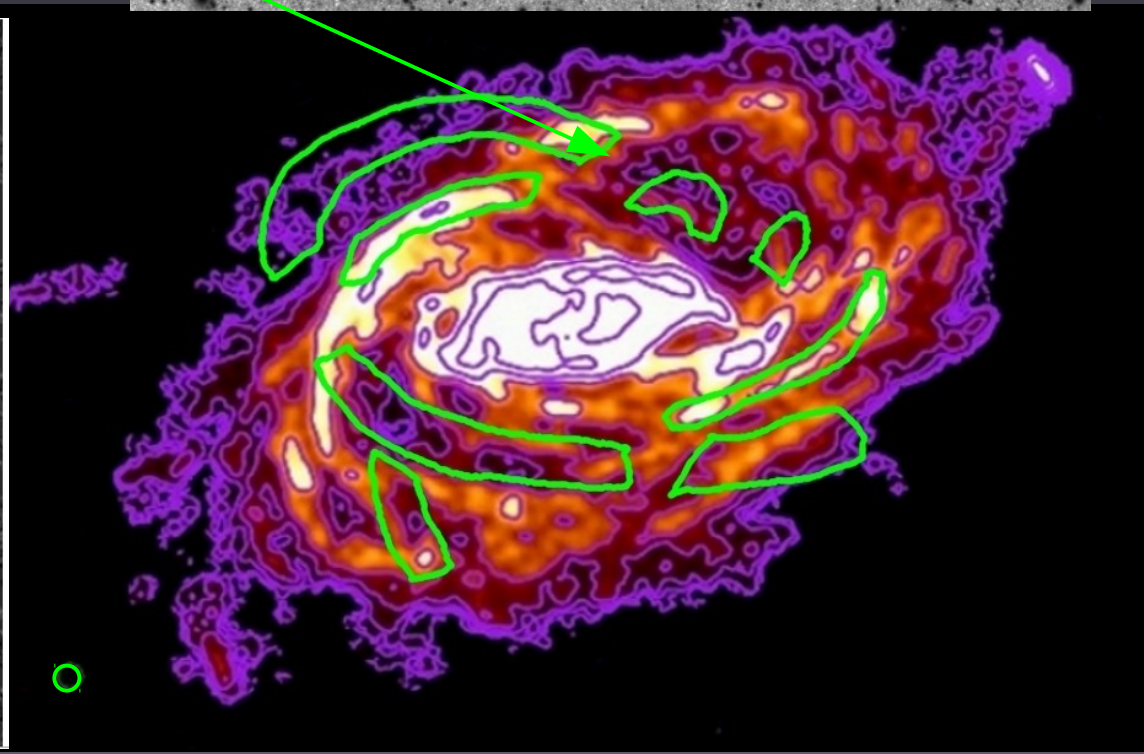


Deep optical imaging: stellar streams and accretion from minor mergers

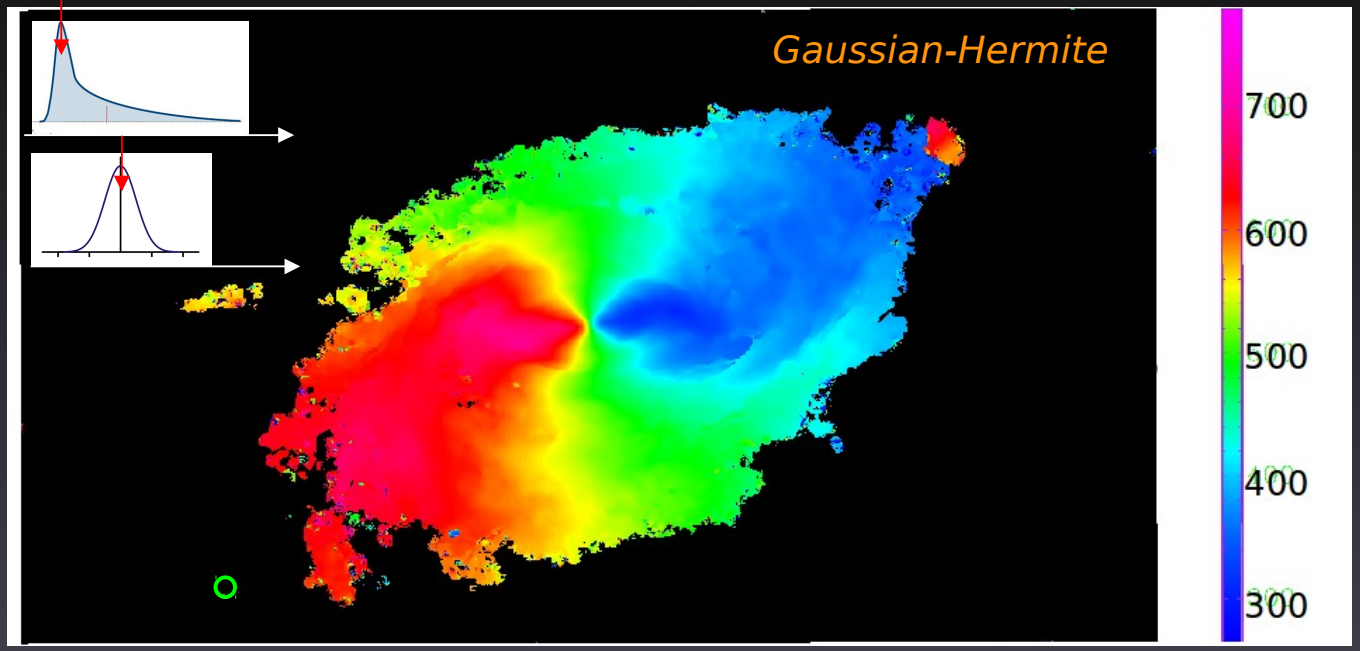


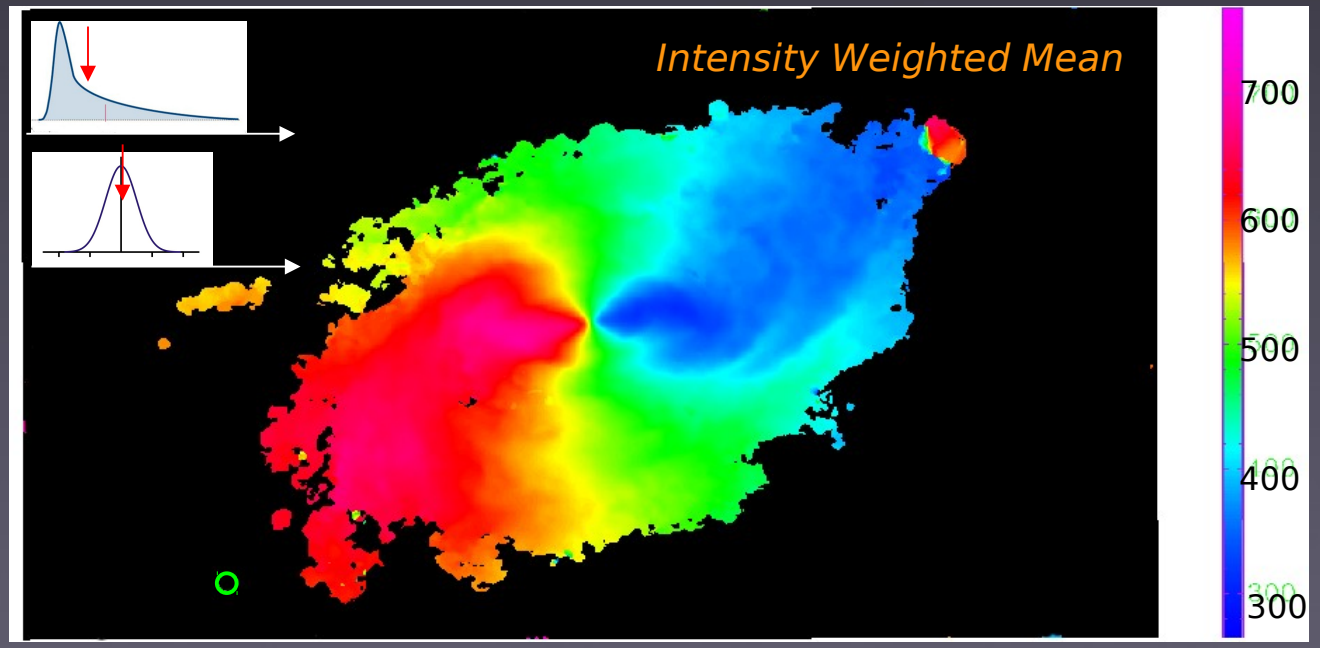
Chonis et al (2011) speculate the remnant of the 'a' loop stream could be located at the west end of the loop, just east of the 'c' feature.



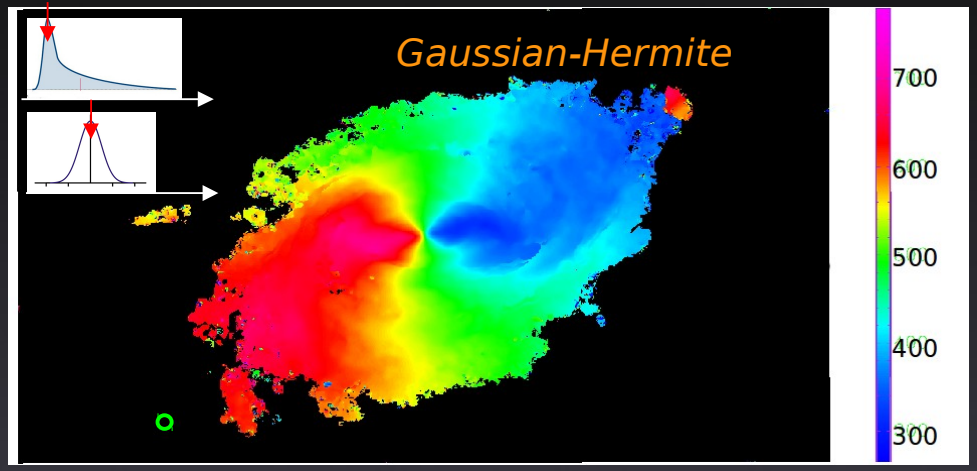


Searching for anomalous velocity gas





$(v_{GH} - v_{IWM})$ difference map



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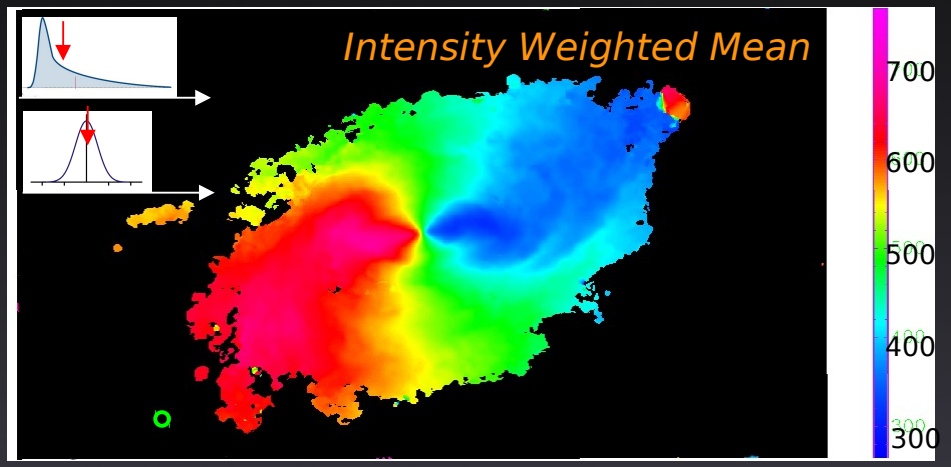

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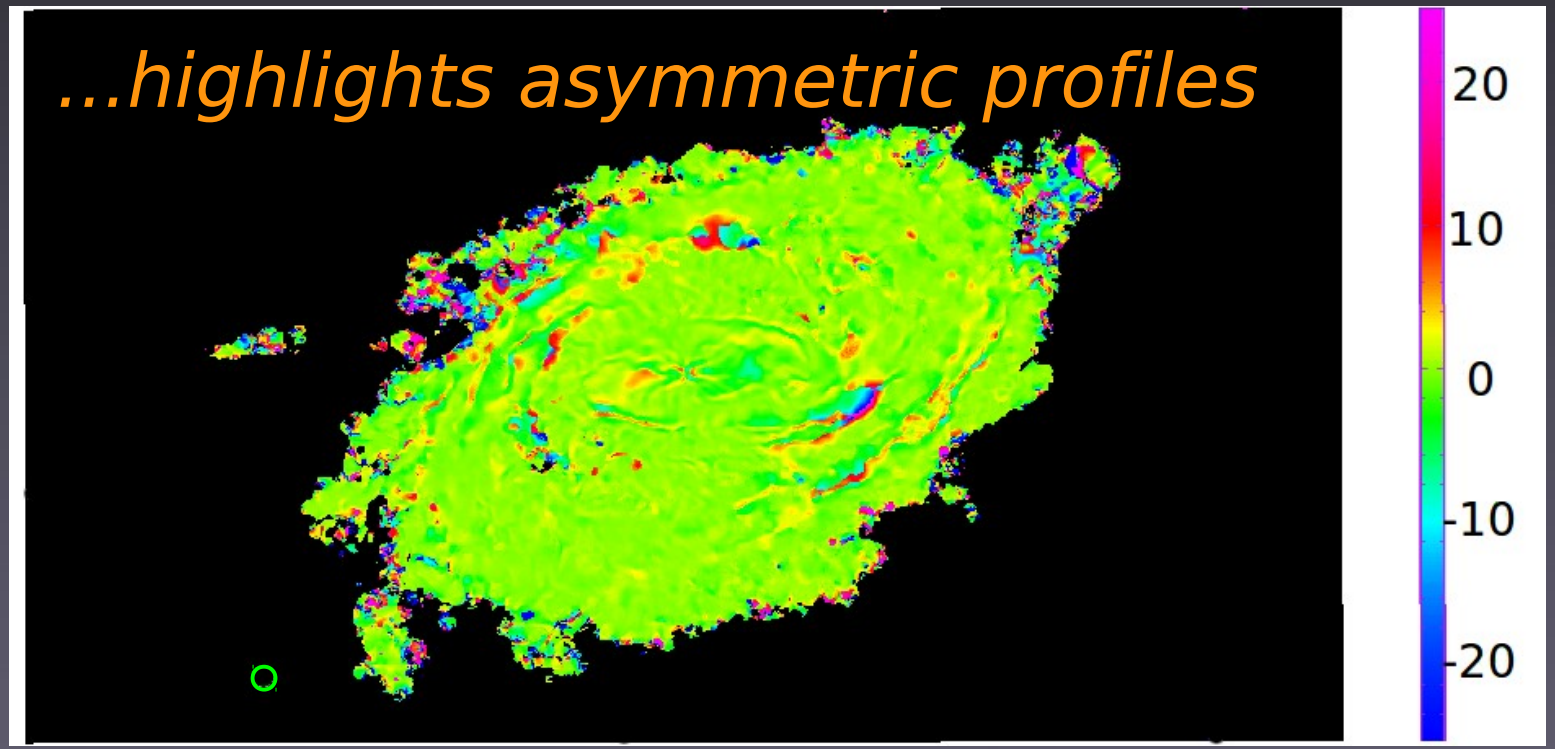
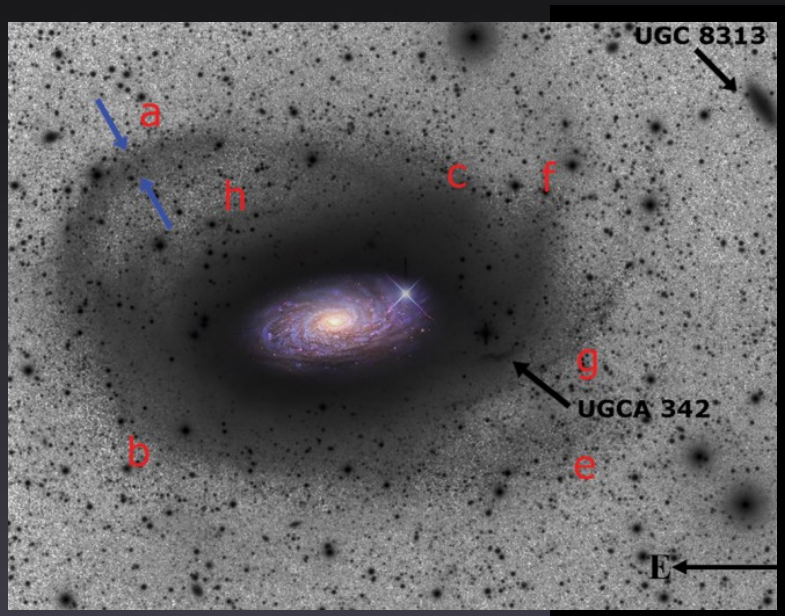
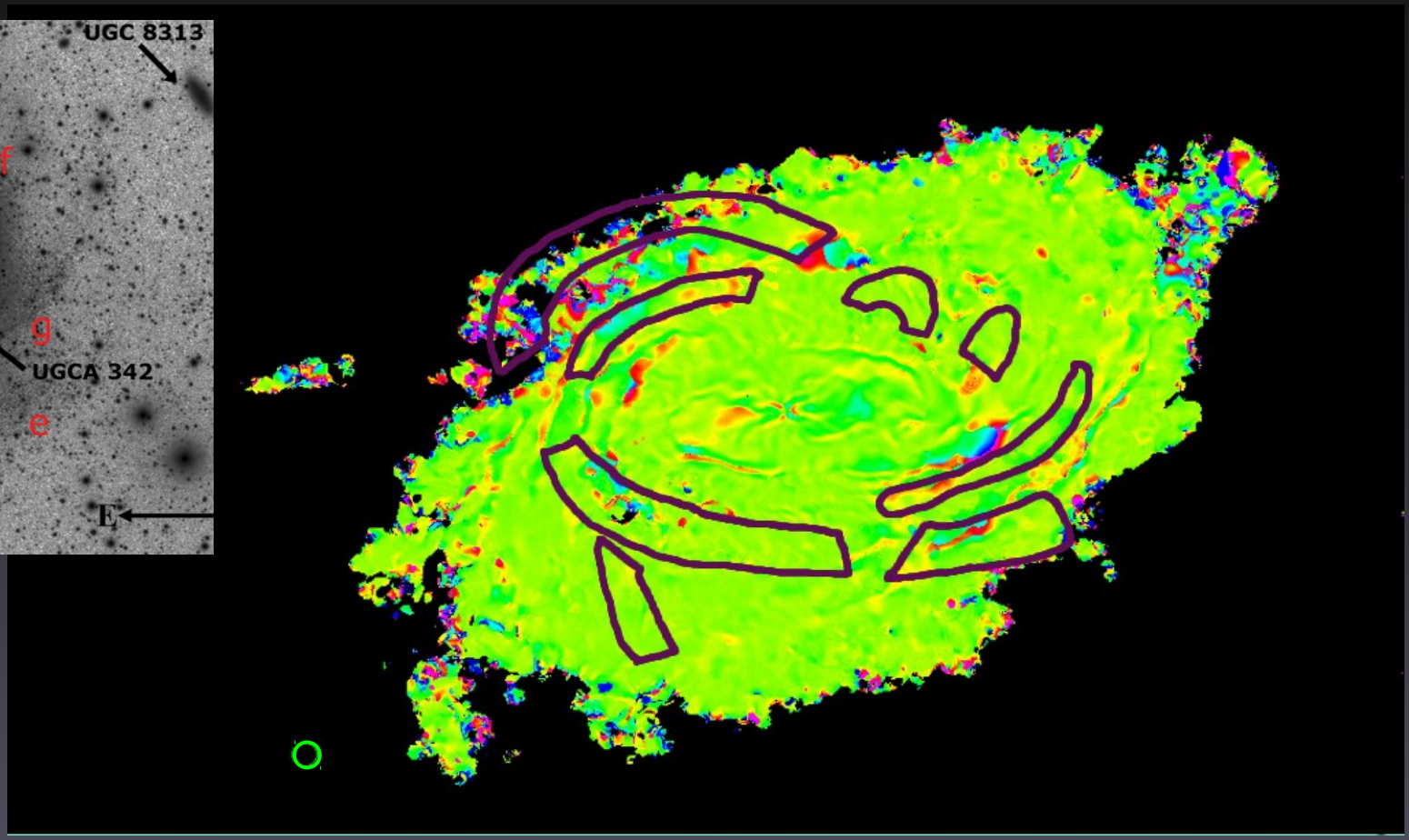
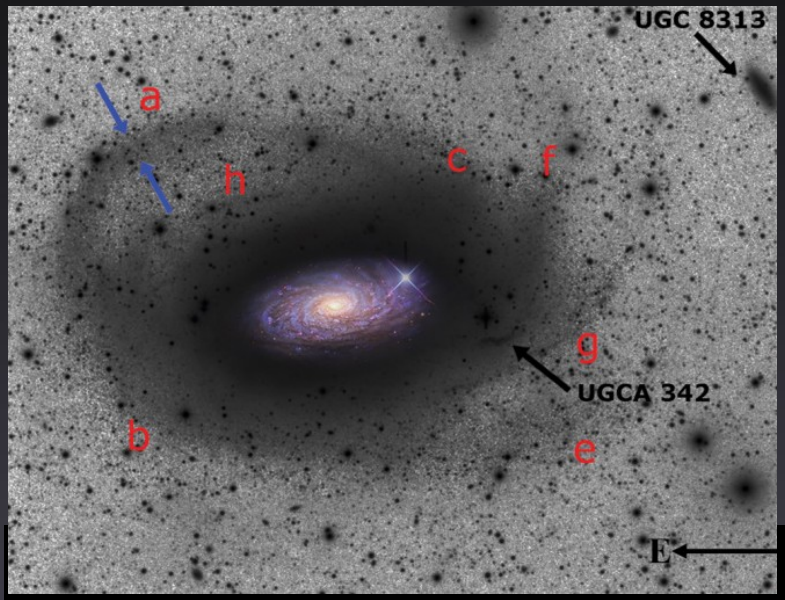


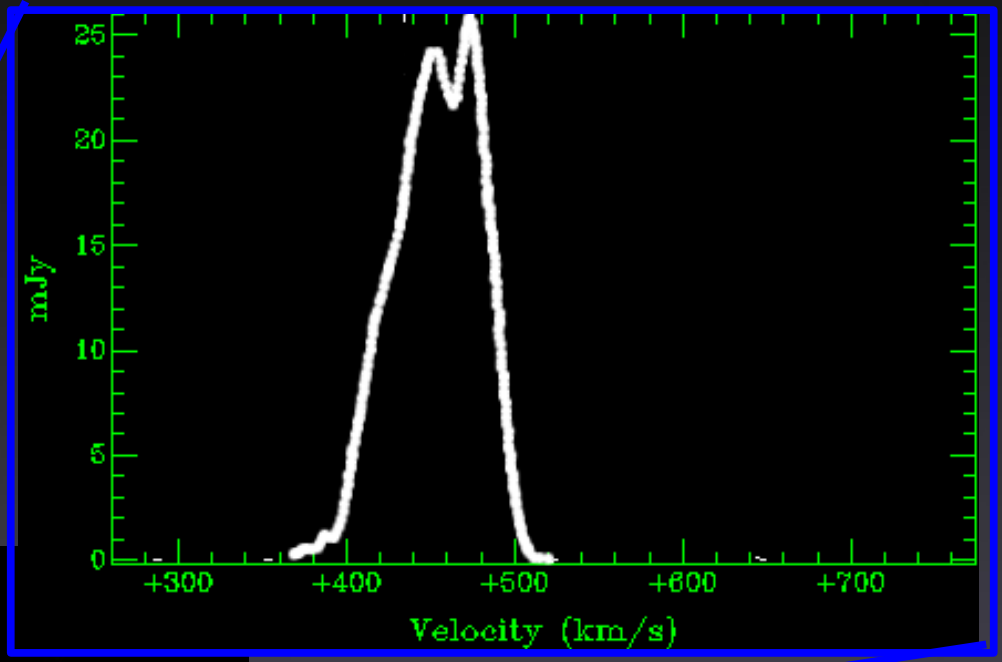
$(v_{GH} - v_{IWM})$ difference map

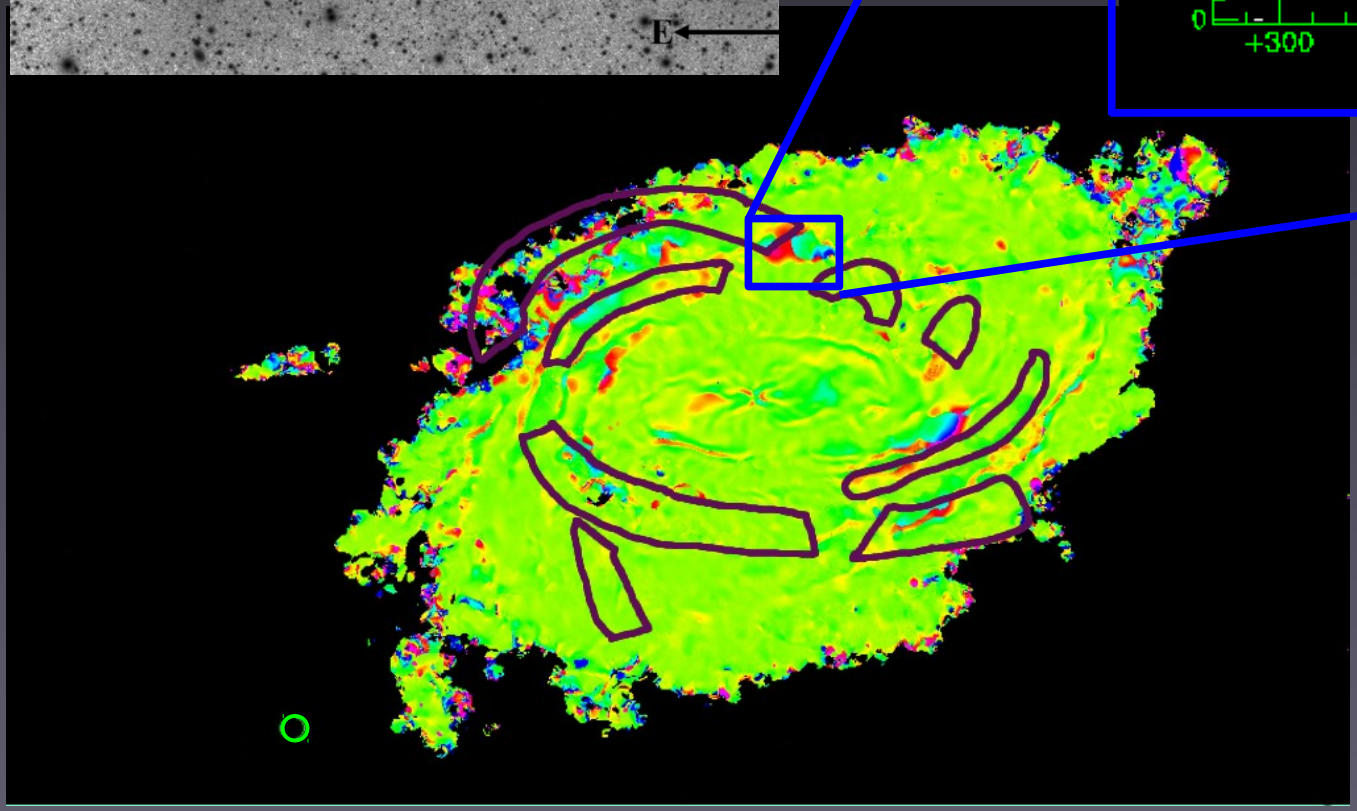




$(v_{GH} - v_{IWM})$ difference map





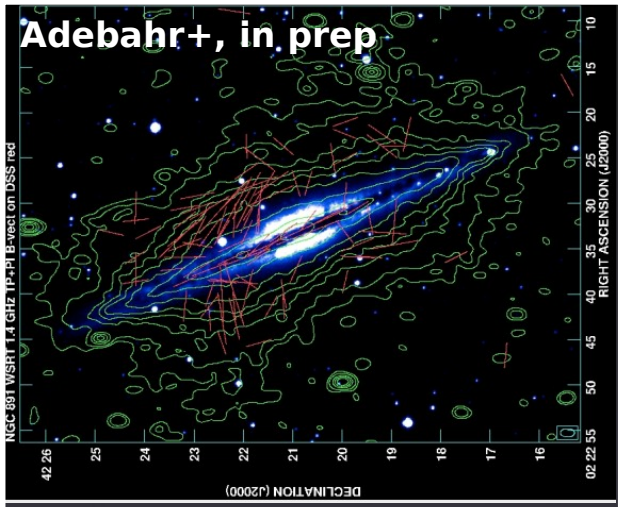


mass estimate of cloud:

~ 2 x10⁸ $M_\odot$

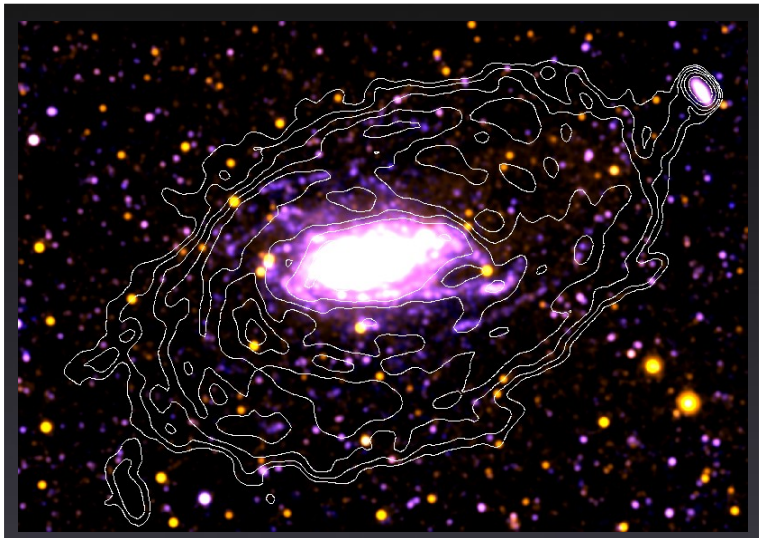
Possible remnant? Or gas pulled from the disk during an interaction?

Complementary observations



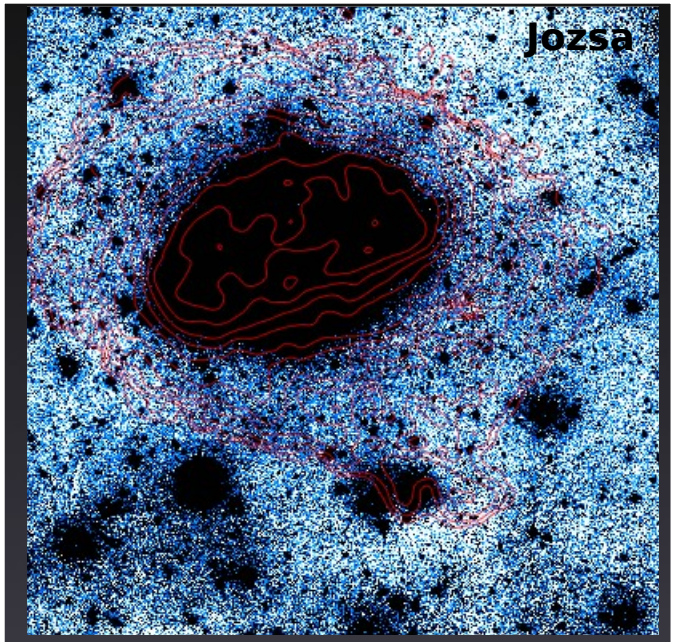
Radio continuum

5 MHz of effective continuum bandwidth for first half of targets
80 Mhz of full-polarization continuum bandwidth for second half



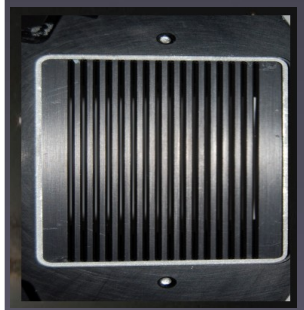
GALEX

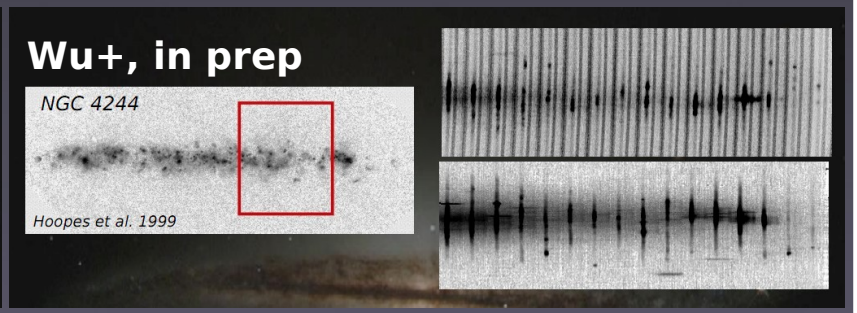
Deep NUV (+some FUV) observations:
Detect outer disk star formation
Detect UV emission reflected from dust grains in halo



HALOSTARS

Deep R-band imaging at INT:
Search for stellar streams and counterparts to HI features





APO Multi-longslit spectroscopy:

Build up 2D optical spectra of HALOGAS edge-ons; compare ionized gas with HALOGAS HI observations

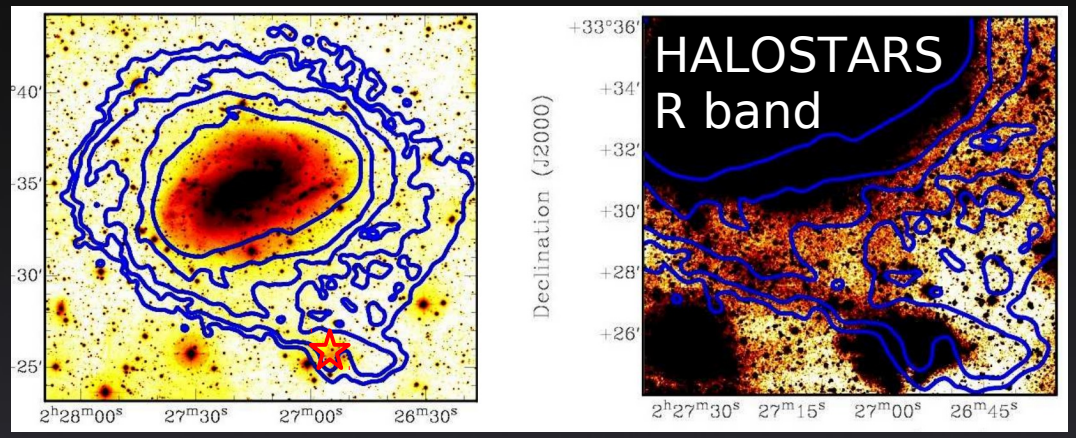
KPNO

4-meter Mosaic 1.1:
UBHaR imaging

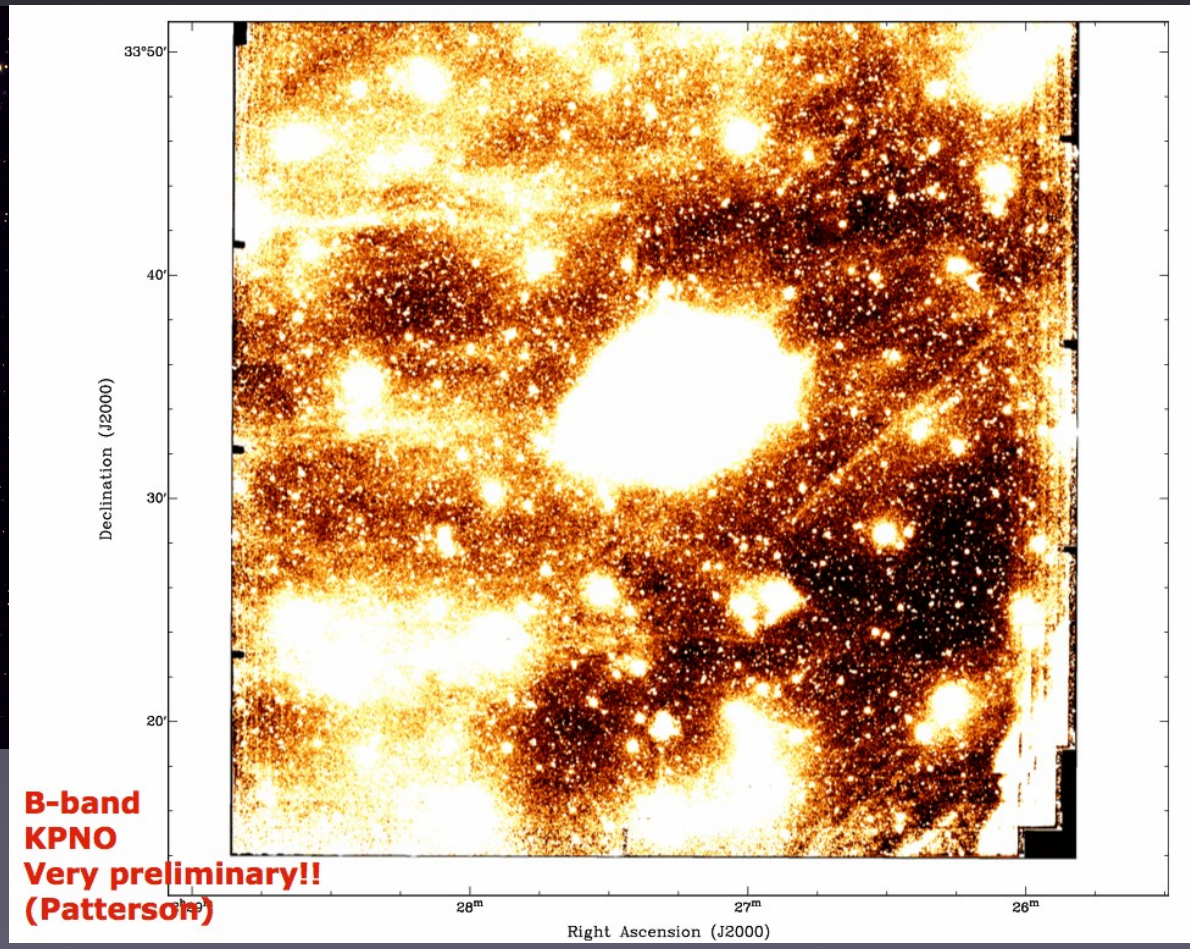
Plus deep B imaging for HALOSTARS complementary color information

Deep optical imaging of NGC 925

Dwarf companion and stellar stream detected in B and R, corresponding to HI feature



PRELIMINARY



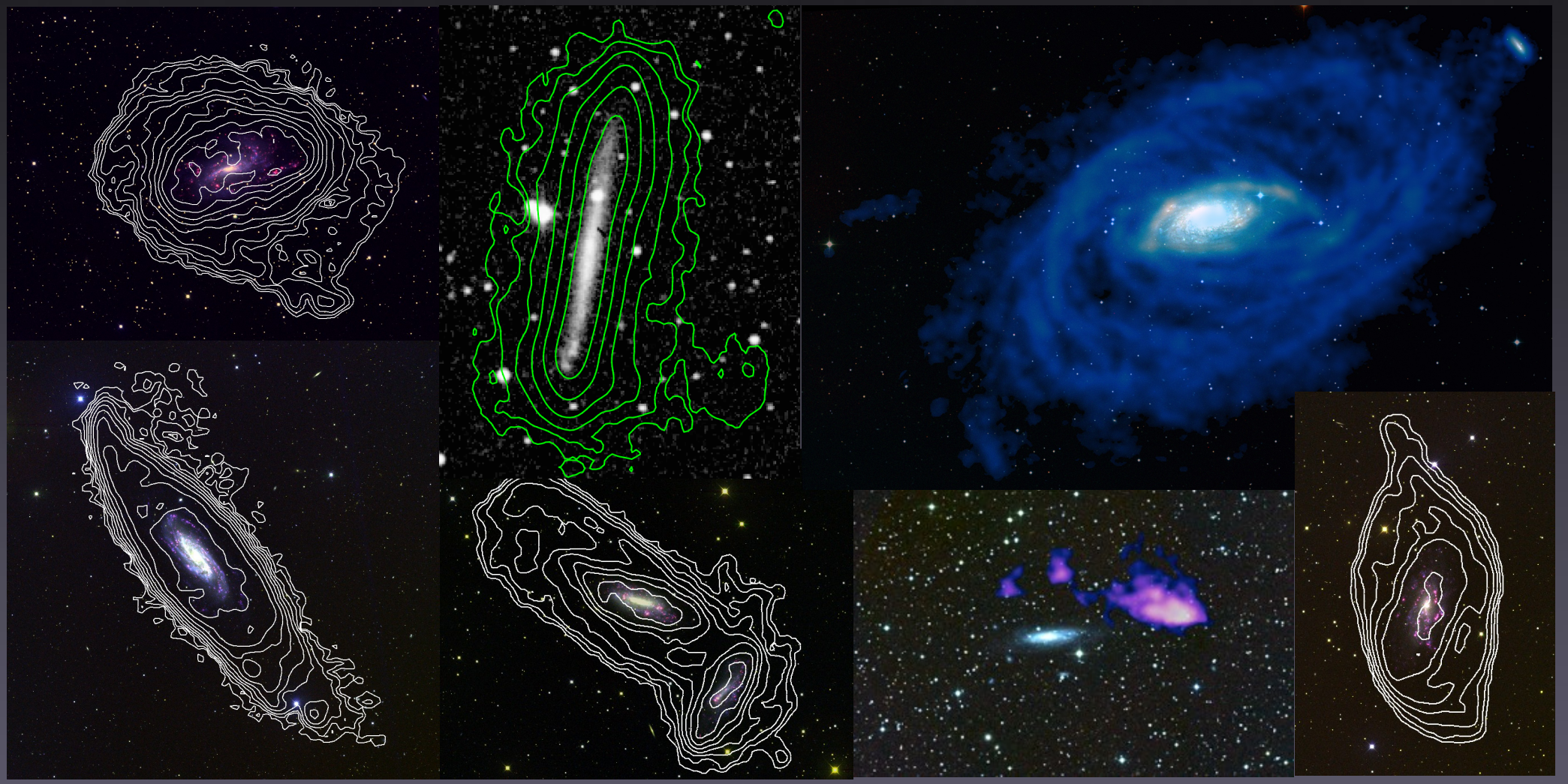
Companion:

$L_R \sim 1.85 \times 10^7 L\odot$

$M_{*,R} \sim 3 \times 10^6 M\odot$

In short...

the HALOGAS survey galaxies show a range of HI features:
HVC analogs, companions, thick disks, streams, and filaments.



Stay tuned for upcoming publications:

http://www.astron.nl/halogas/

Appendix: Full sample

UGC	Other IDs	Type	d_{T88} (Mpc)	d_{best} (Mpc)	d_{best} method	v_{sys} (km s^{-1})	i (°)	D_{25} (arcmin)	M_B (mag)	v_{rot} (km s^{-1})	SFR ($M_\odot$ yr^{-1})	SFR Refs.
1256	NGC 0672	SBcd	7.5	7.6	2	425	70	6.4	–18.65	130.7	0.2	H1, I2
1831	NGC 0891	SAb	9.6	9.2	1	529	84	12.2	–19.96	212.2	2	H1, I4
1913	NGC 0925	SABd	9.4	9.1	1	554	54	11.3	–19.66	102.4	0.3	H1, I4
1983	NGC 0949	SAd	10.3	11.3	2	610	52	3.5	–17.85	90.9	0.1	H1, I1
2082	–	SAc	10.7	14.4	3	710	89	5.8	–18.55	86.6	0.023	–, I1
2137	NGC 1003	SAcd	10.7	11.6	3	626	67	6.3	–18.61	95.5	0.1	H1, I2
3918	NGC 2403	SAcd	4.2	3.2	1	132	62	23.8	–19.68	121.9	1	H1, I4
4278	IC 2233	SAd	10.6	13.6	3	565	90	4.3	–17.45	79.2	0.1	H1, I5
4284	NGC 2541	SAcd	10.6	12.0	1	553	67	7.2	–18.37	92.1	<0.1[a]	H2, I2
5572	NGC 3198	SBc	10.8	14.5	1	660	71	8.8	–19.62	148.2	0.6	H2, I4
7045	NGC 4062	SAc	9.7	16.9	3	769	68	4.5	–18.27	140.5	0.2	H2, I2
7322	NGC 4244	SAcd	3.1	4.4	1	247	90	15.8	–17.60	89.0	0.08	H1, I5
7353	NGC 4258 (M 106)	SABbc	6.8	7.6	1	449	71	17.1	–20.59	208.0	1	H1,I3
7377	NGC 4274	SBab	9.7	19.4	3	922	72	6.5	–19.22	239.9	0.1	H3, I2
7539	NGC 4414	SAc	9.7	17.8	1	720	50	4.5	–19.12	224.7	1	H2, I4
7591[b]	NGC 4448	SBab	9.7	9.7	4	693	71	3.8	–18.43	221.6	0.06	–, I2
7766	NGC 4559	SABcd	9.7	7.9	3	816	69	11.3	–20.07	113.4	1	H4, I4
7772	NGC 4565	SAb	9.7	10.8	2	1228	90	16.2	–20.34	244.9	0.4	H5, I4
7774[b]	–	SAd	6.8	24.4	3	526	90	3.5	–15.57	79.4	0.074	H1, I5
7865	NGC 4631	SBd	6.9	7.6	1	613	85	14.7	–20.12	138.9	2	H1, I4
8286	NGC 5023	SAc	6.0	6.6	1	400	90	6.8	–17.29	80.3	0.02	H1, I5
8334	NGC 5055 (M 63)	SAbc	7.2	8.5	3	497	55	13.0	–20.14	215.5	1	H1, I4
8550	NGC 5229	SBc	6.4	5.1	2	365	90	3.5	–15.82	57.3	0.04	H1, I5
9179	NGC 5585	SABd	7.0	8.7	2	303	51	5.5	–17.96	79.1	0.1	H1, I1

Notes. [(a)] The SFR value for NGC 2541 is strictly speaking an upper limit, because the IRAS 25 μm flux is catalogued as a non-detection by Moshir et al. (1990). [(b)] No H I observing time granted yet.

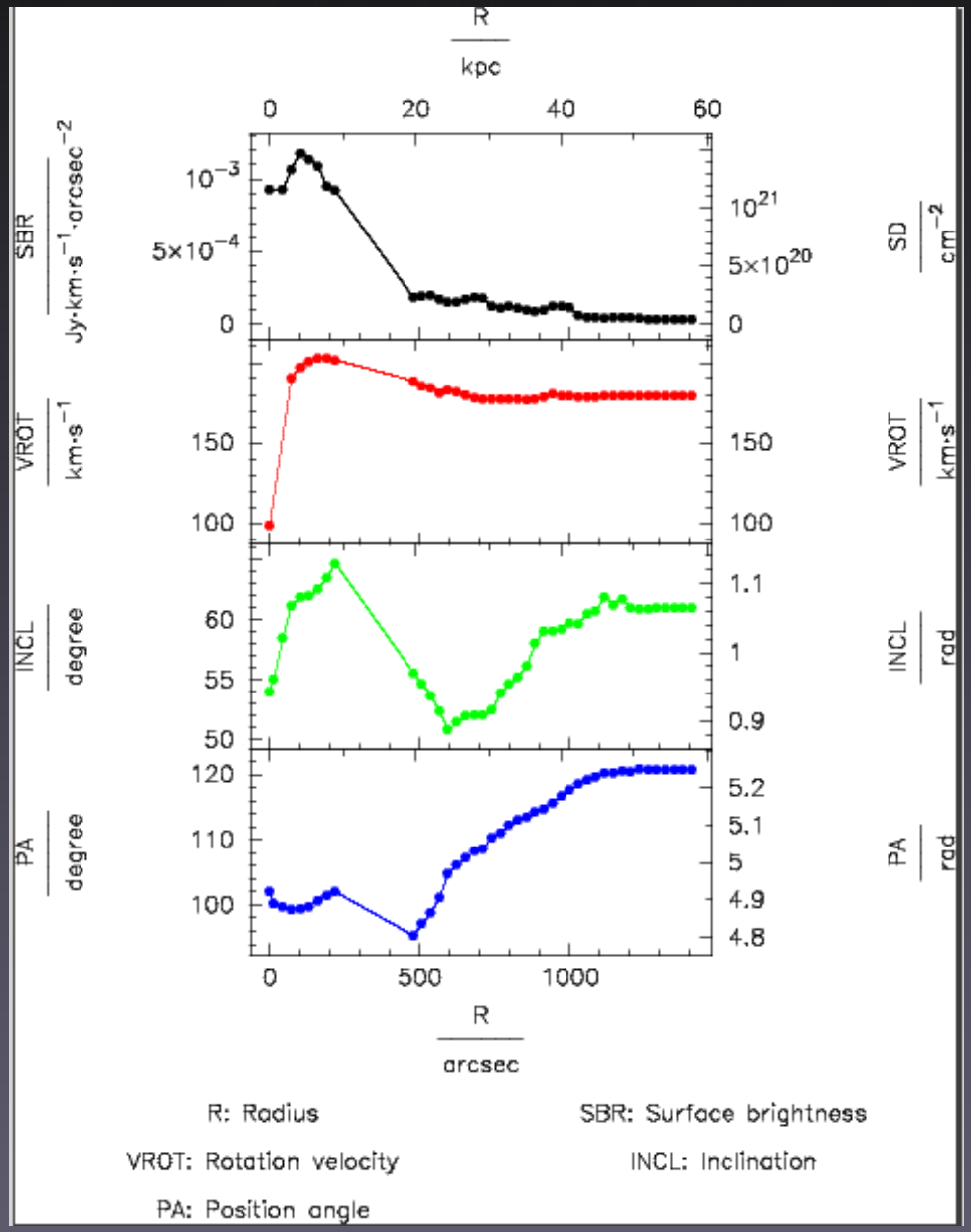
References. (H1) Kennicutt et al. (2008); (H2) Moustakas & Kennicutt (2006); (H3) Hameed & Devereux (2005); (H4) Kennicutt et al. (2009); (H5) Robitaille et al. (2007); (I1) Lisenfeld et al. (2007); (I2) Moshir et al. (1990); (I3) Rice et al. (1988); (I4) Sanders et al. (2003); (I5) Dale et al. (2009).

Appendix: SFR

UGC	Other IDs	d_{T88} (Mpc)	d_{best} (Mpc)	Old SFR ($M_\odot$ yr^{-1})	New SFR ($M_\odot$ yr^{-1})
1256	NGC 0672	7.5	7.6	0.22	0.23
1831	NGC 0891	9.6	9.2	2.4	2.2
1913	NGC 0925	9.4	9.1	0.83	0.77
1983	NGC 0949	10.3	11.3	0.26	0.31
2082	–	10.7	14.4	0.023	0.041
2137	NGC 1003	10.7	11.6	0.34	0.40
3918	NGC 2403	4.2	3.2	1.0	0.60
4278	IC 2233	10.6	13.6	0.11	0.18
4284	NGC 2541	10.6	12.0	< 0.27[a]	< 0.35[a]
5572	NGC 3198	10.8	14.5	0.61	1.1
7045	NGC 4062	9.7	16.9	0.22	0.67
7322	NGC 4244	3.1	4.4	0.058	0.12
7353	NGC 4258 (M106)	6.8	7.6	1.4	1.7
7377	NGC 4274	9.7	19.4	0.31	1.2
7539	NGC 4414	9.7	17.8	1.3	4.2
7591	NGC 4448	9.7	9.7	0.056	0.056
7766	NGC 4559	9.7	7.9	1.1	0.69
7772	NGC 4565	9.7	10.8	0.54	0.67
7774	–	6.8	24.4	0.0074	0.095
7865	NGC 4631	6.9	7.6	2.1	2.6
8286	NGC 5023	6.0	6.6	0.032	0.039
8334	NGC 5055 (M63)	7.2	8.5	1.5	2.1
8550	NGC 5229	6.4	5.1	0.014	0.0086
9179	NGC 5585	7.0	8.7	0.26	0.41

[a] The SFR value for NGC 2541 is strictly speaking an upper limit, because the IRAS 25μm flux is catalogued as a non-detection by Moshir et al. (1990).

Appendix: NGC 5055 model parameters



Appendix: Environmental properties

Galaxy ID	# Group members	NOGG number	$L_{B,\,\mathrm{group}}$ [$10^{10}\,M_{\odot}$]	R_{group} [Mpc]	$v_{\mathrm{min,\,group}}$ [km s^{-1}]	$v_{\mathrm{max,\,group}}$ [km s^{-1}]	$L_B/L_{B,\,\mathrm{group}}$	$L_B/L_{B,\,\mathrm{max}}$	R/R_{group}	v [km s^{-1}]
NGC 0672	2	88	1.3	0.01	–52	29	0.64	1.00	0.55	29
NGC 0891[a]	–	–	–	–	–	–	–	–	–	–
NGC 0925	6	149	3.1	0.56	–16	47	0.69	1.00	0.25	–16
NGC 0949	6	149	3.1	0.56	–16	47	0.15	0.21	1.00	47
UGC 2082[b]	–	–	–	–	–	–	–	–	–	–
NGC 1003[a]	–	–	–	–	–	–	–	–	–	–
NGC 2403	2	319	1.8	0.24	–14	1	0.88	1.00	0.13	1
UGC 4278	6	345	1.4	0.77	–90	35	0.30	1.00	0.44	21
NGC 2541	6	345	1.4	0.77	–90	35	0.24	0.79	0.21	35
NGC 3198	2	462	1.7	0.43	–25	1	0.96	1.00	0.05	1
NGC 4062	27	631[c]	21.0	1.27	–163	525	0.03	0.07	0.86	45
NGC 4244	16	636	3.1	0.80	–93	83	0.22	0.66	0.31	–42
NGC 4258	21	644	9.0	1.07	–103	160	0.51	1.00	0.24	–40
NGC 4274	27	631[c]	21.0	1.27	–163	525	0.04	0.10	0.45	194
NGC 4414	27	631[c]	21.0	1.27	–163	525	0.05	0.13	0.21	–3
NGC 4448	27	631[c]	21.0	1.27	–163	525	0.02	0.06	0.37	–79
NGC 4559	27	631[c]	21.0	1.27	–163	525	0.12	0.30	0.42	79
NGC 4565	3	648	14.9	0.26	–18	107	0.78	1.00	0.25	–18
UGC 7774	21	644	9.0	1.07	–103	160	0.01	0.01	0.74	3
NGC 4631	27	631[c]	21.0	1.27	–163	525	0.40	1.00	0.30	–91
NGC 5023	7	723	8.0	0.45	–94	131	0.04	0.09	0.68	–77
NGC 5055	7	723	8.0	0.45	–94	131	0.37	0.79	1.00	8
NGC 5229	7	723	8.0	0.45	–94	131	0.01	0.02	0.97	–94
NGC 5585	8	766	3.1	0.54	107	75	0.07	0.09	0.52	75

Notes. [(a)] Not included in the Giuricin et al. (2000) catalog due to low galactic latitude. [(b)] No environmental information available; UGC 2082 is isolated. [(c)] NOGG number 631 corresponds to Coma I.