Properties of Star Formation and the Interstellar Medium in Galaxy Outskirts

Maria T. Patterson

Advisor: Rene Walterbos

Thesis Defense

5 April 2013

Credit: HALOGAS, KPNO

Acknowledgments

Committee Members

Rene Walterbos	New Mexico State University
Chris Churchill	New Mexico State University
Nicole Vogt	New Mexico State University
Jon Holtzman	New Mexico State University
Dan Dugas	New Mexico State University

Collaborators / Contributors

David Thilker	Johns Hopkins University
Robert Kennicutt	Institute of Astronomy
Cristina Chiappini	AIP, Potsdam
Robert Braun	ATNF/CSIRO
Taylor Chonis	UT, Austin

Family

Hi, Dad! Thanks for coming!

Office 108 4 Life

HALOGAS Survey Team

George Heald (PI)	ASTRON
Gyula Jozsa	ASTRON
Tom Oosterloo	ASTRON
Paolo Serra	ASTRON
Renzo Sancisi	Osservatorio Astronomico di Bologna
Filippo Fraternali	Bologna University
Erwin de Blok	University of Cape Town / ASTRON
Gianfranco Gentile	Ghent University
Rich Rand	University of New Mexico
Laura Zschaechner	University of New Mexico
Maria Patterson	New Mexico State University
Rene Walterbos	New Mexico State University
Cat Wu	New Mexico State University
Bjoern Adebahr	Ruhr-Universitat Bochum
Ralf-Juergen Dettmar	Ruhr-Universitat Bochum
Eva Juette	Ruhr-Universitat Bochum
Peter Kamphuis	Ruhr-Universitat Bochum/CSIRO
Bob Benjamin	University of Wisconsin- Whitewater

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

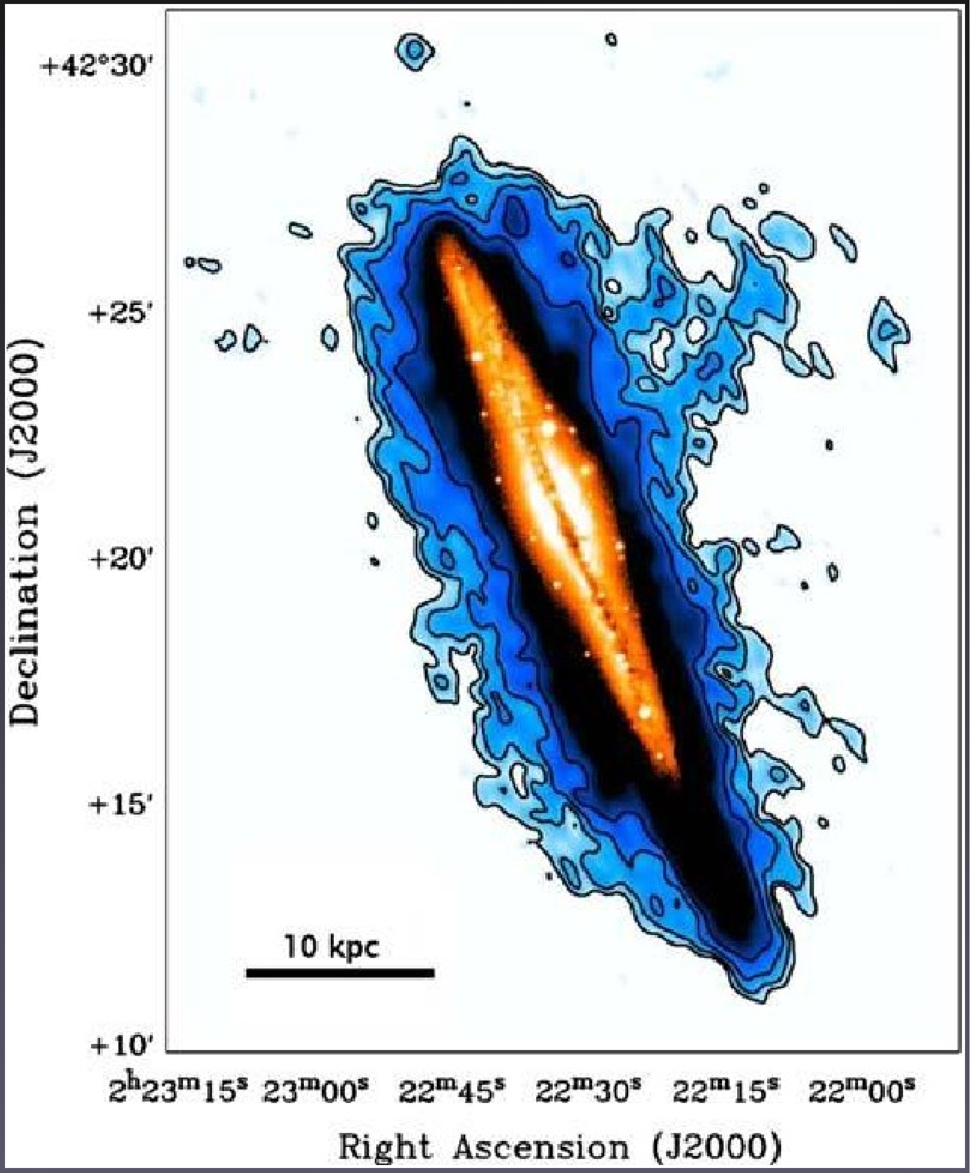
How do galaxies keep growing?

Spiral galaxies should have already converted all of their gas into stars. (Lacey & Fall, 1985)

→ Galaxies must be acquiring new material.

Recent observations show extended halos, possible evidence for accretion (see Sancisi+, 2008).

→ Where do these halos come from?



HI halo of NGC 891
(Oosterloo+, 2007; Sancisi+, 2008)

How do galaxies keep growing?

What are possible sources of halo gas?

Is halo gas expelled by stars in the disc? How much?

Is halo gas accreted externally? How much?

What are the properties of galaxy outer discs?

How metal rich are the outskirts of spiral galaxies?

What does metallicity imply about outer disc gas?

How much current star formation occurs in outer discs?

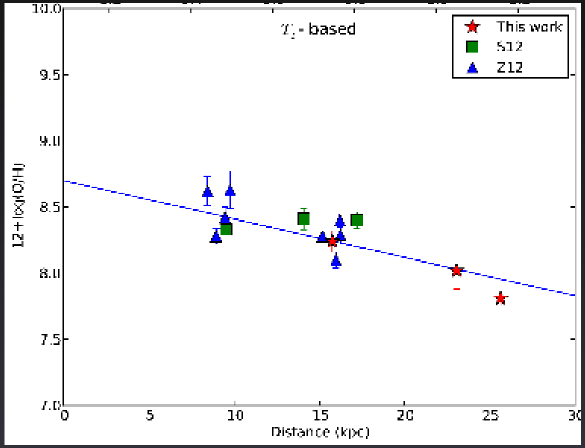
Under what conditions are stars forming?

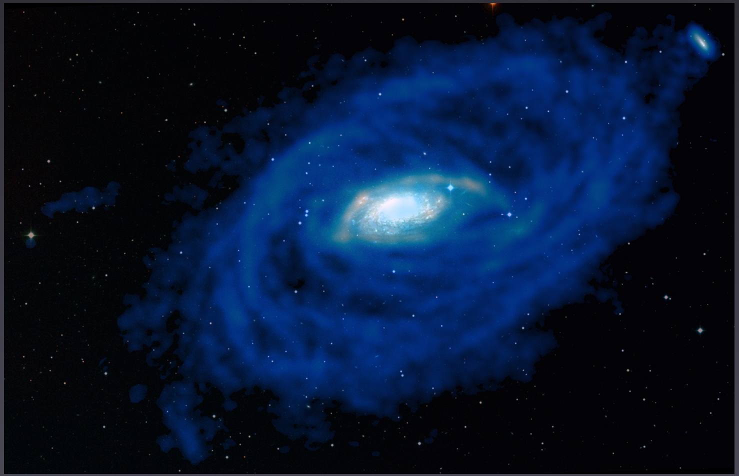
Thesis Projects

Extended metallicity gradients

of HII regions in the outer discs

of M81 and M31.





Tilted-ring modeling

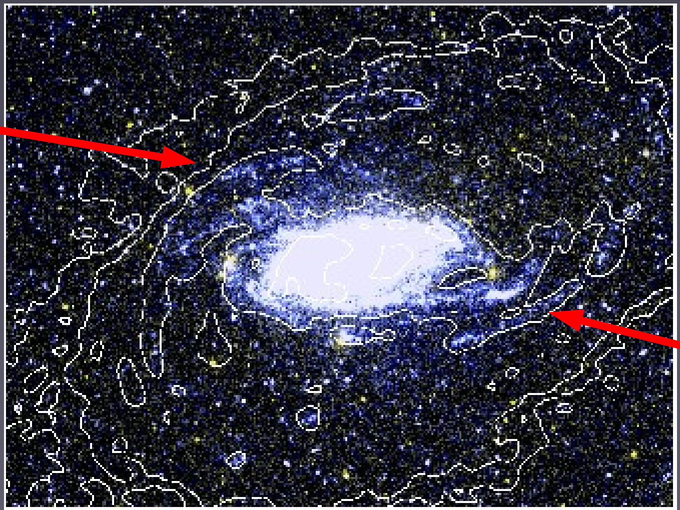
of the gaseous halo of NGC 5055

from the HALOGAS survey.

Outer disc star formation

from Halpha and GALEX UV imaging

of galaxies in the HALOGAS sample.

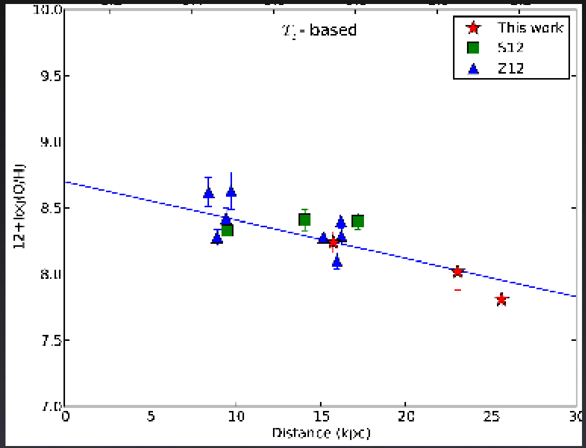


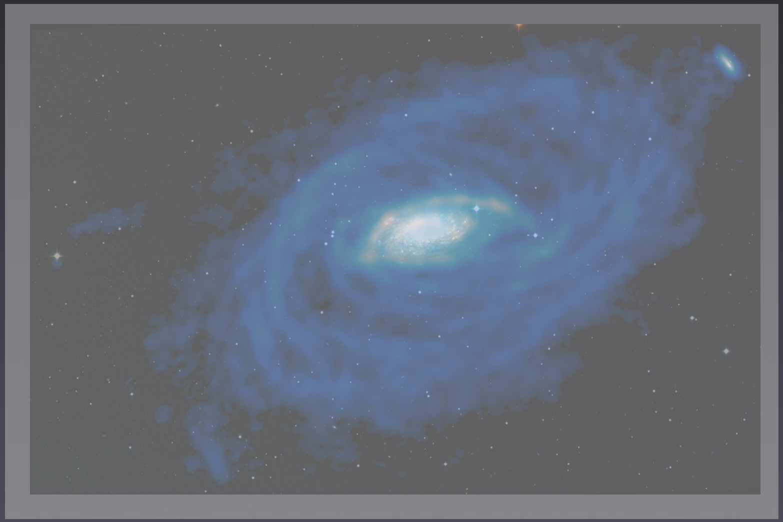
Thesis Projects

Extended metallicity gradients

of HII regions in the outer discs

of M81 and M31.

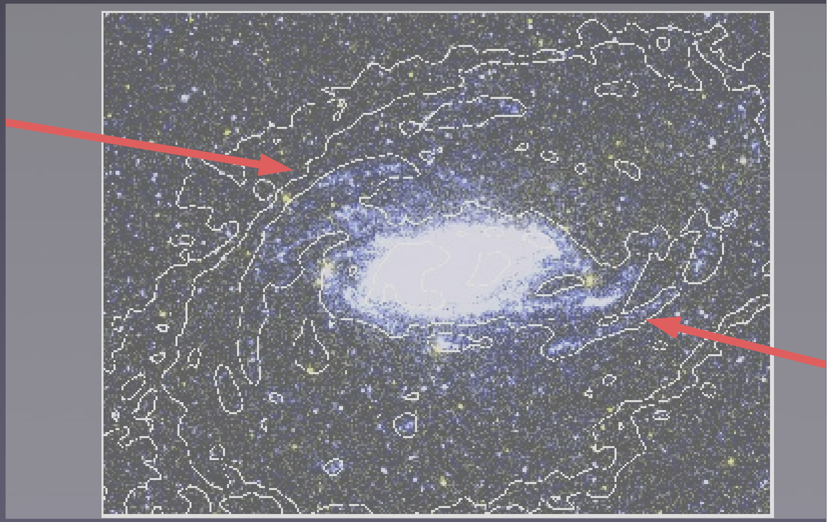




Tilted-ring modeling

of the gaseous halo of NGC 5055

from the HALOGAS survey.



Outer disc star formation

from Halpha and GALEX UV imaging

of galaxies in the HALOGAS sample.

HII regions

Ionized hydrogen gas hosting
star formation (O and B stars)

Temps ~ 10,000 K

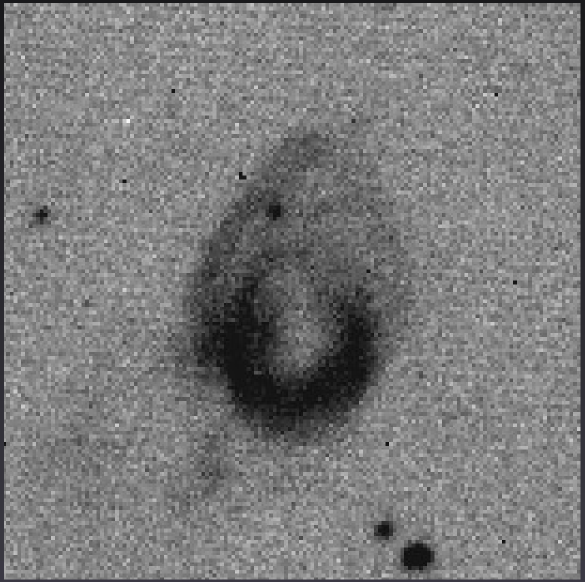
Emission line objects

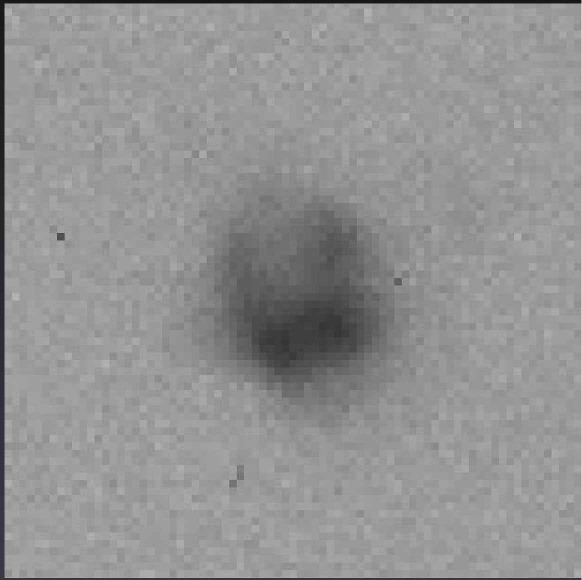
Glow in Hα

Recombination line

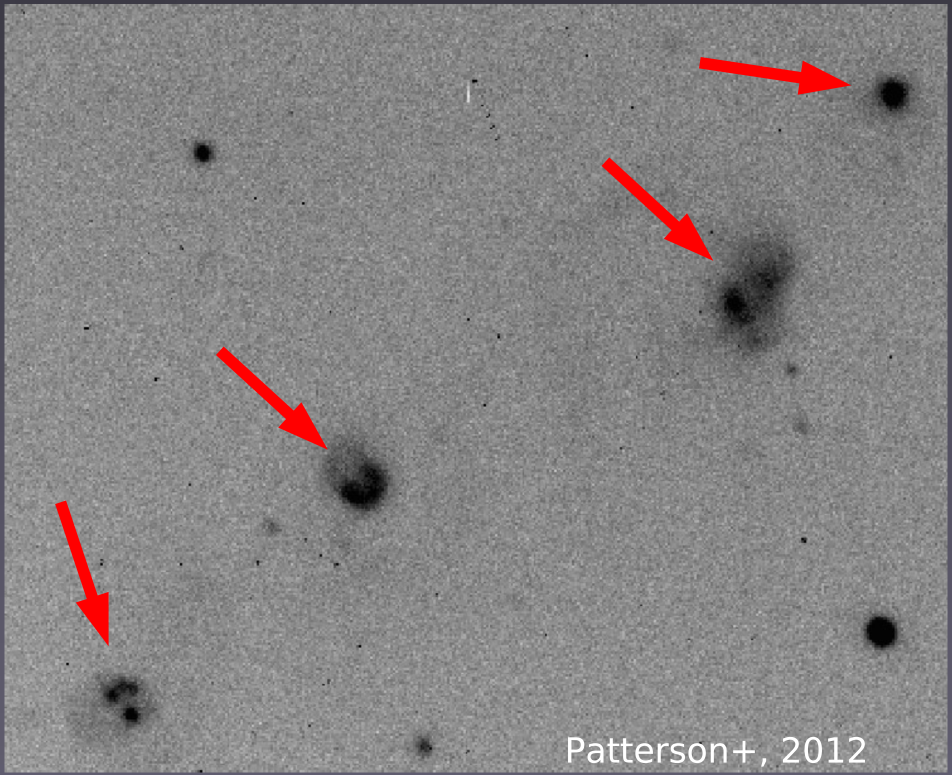
n=3 → n=2

6563 A





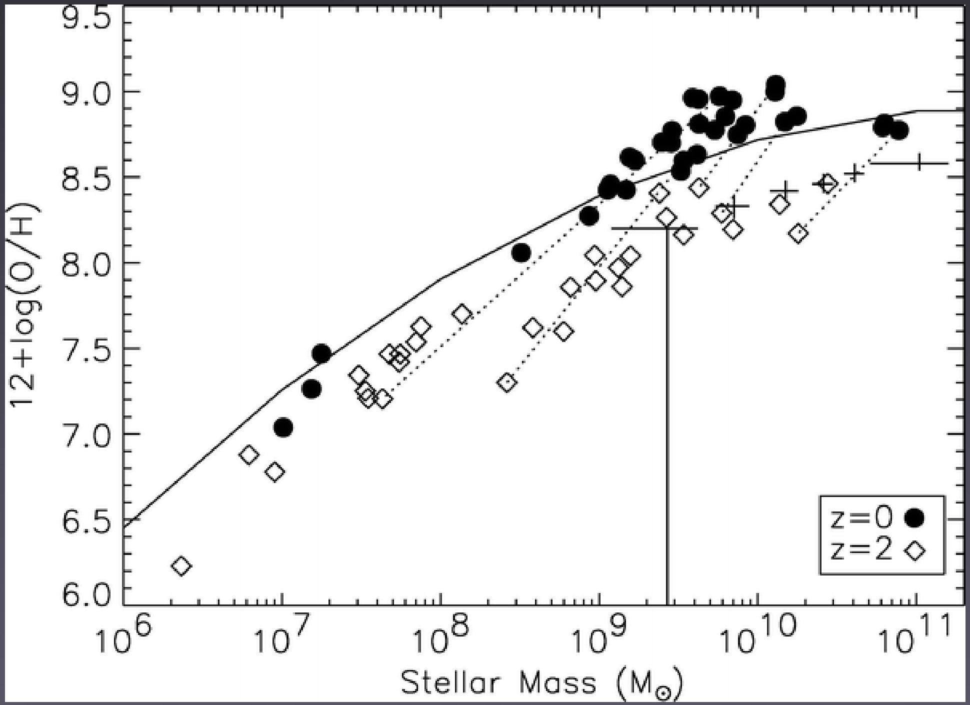
Orion Nebula, Credit: NASA/ESA



Patterson+, 2012

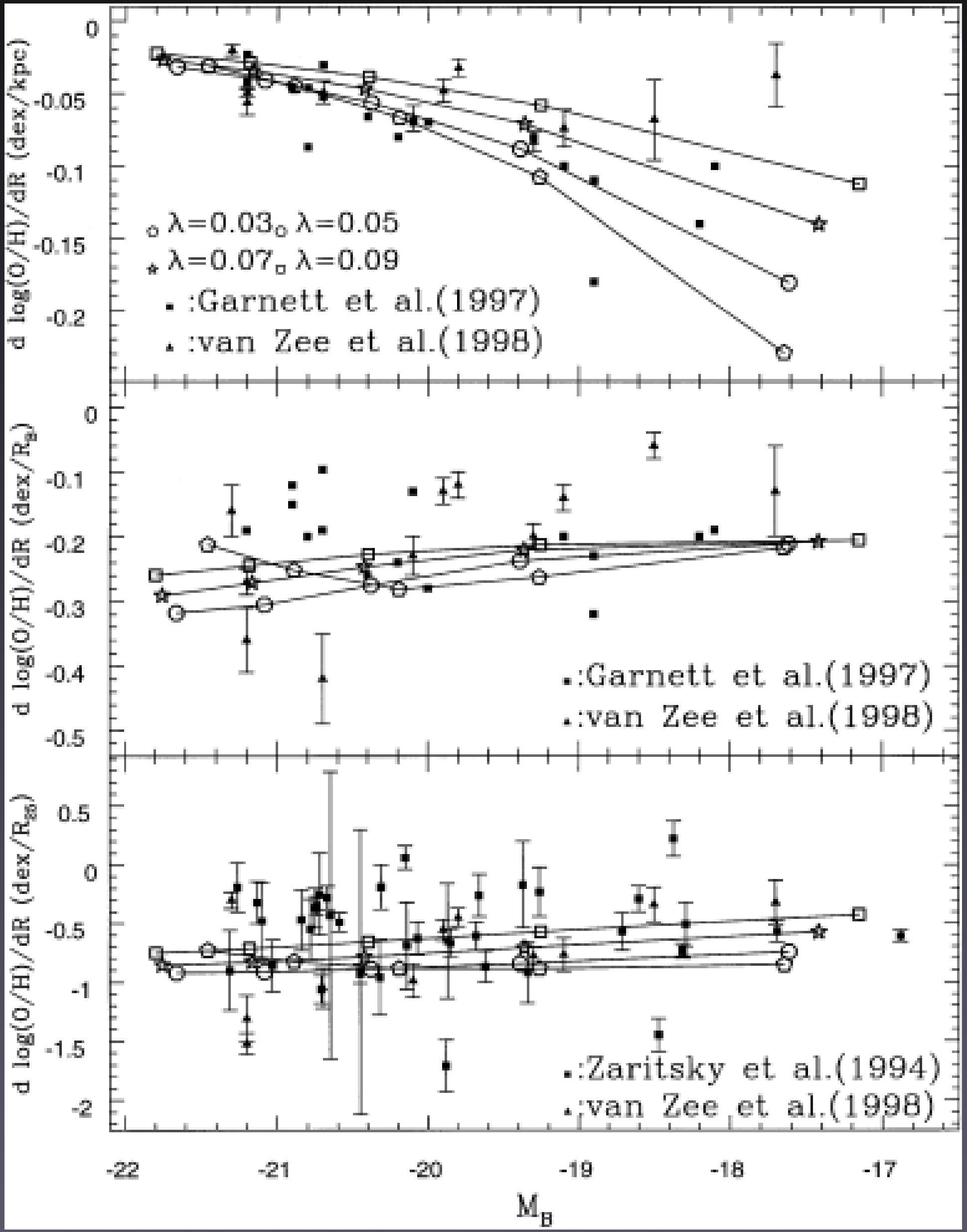
Metallicity

Use HII region emission lines to infer oxygen abundance, proxy for overall metallicity.



Mass-metallicity relation for galaxies

(Brooks+, 2007)



Abundance gradients of galaxies

(Prantzos & Boissier, 2000)

Metallicity Indicators

Electron temperature abundances

[NII] λ6583 and λ5755

[OIII] λ5007 and λ4363

→ *Direct indicator*

→ *Lines are weak*

Strong line oxygen abundances

R_{23} (Pagel et al., 1979)

[OII] λ3727, [OIII] λλ4959, 5007

Pilyugin & Thuan (PT05)

Kobulnicky & Kewley (KK04)

[NII] λ6583 / [OII] λ3727

Bresolin (B07)

Kewley & Dopita (KD02)

→ *Indirect indicators*

→ *Lines are strong*

M81 stats

Moderately-inclined (59°) Sa galaxy

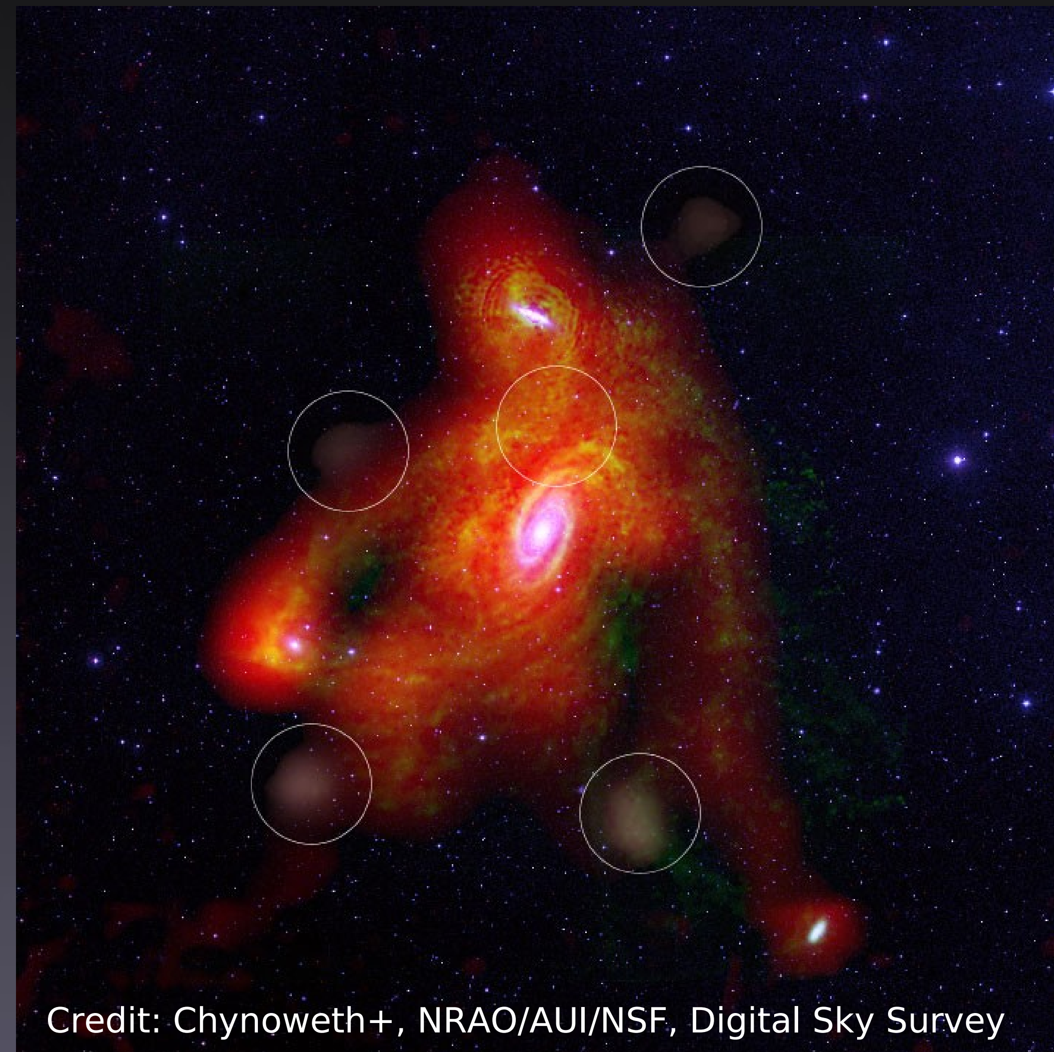
d = 3.63 Mpc (Freedman+, 2001)

R_{25}=13.8'=14.6 kpc

Mass = 2.6×10^{11} $M_{\odot}$ (Appleton+, 1981)

Type 1 XUV disc (Thilker+, 2007)


Credit: Gabany+


Credit: Chynoweth+, NRAO/AUI/NSF, Digital Sky Survey

M81 HII regions

MMT Blue Channel Spectrograph

Observed 21 HII regions:

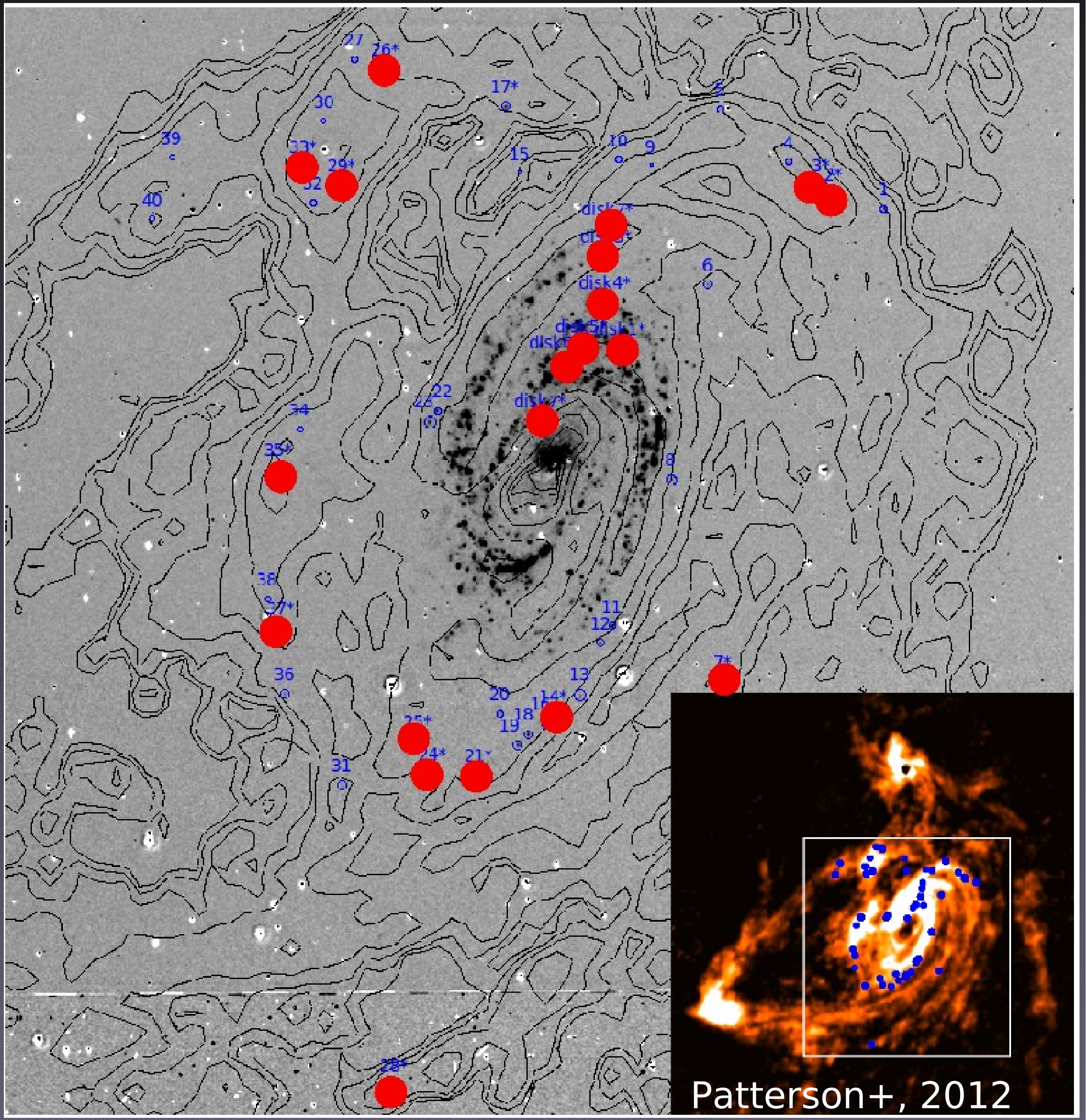
- 7 electron temperature abundances
- All strong line abundances

Supplementary data:

- Garnett & Shields, 1987
- Stanghellini+, 2010
- Croxall+, 2009

Distance range:

- ~2-35 kpc (~0.1-2.4 R_{25})



Shallow extended gradients: M81

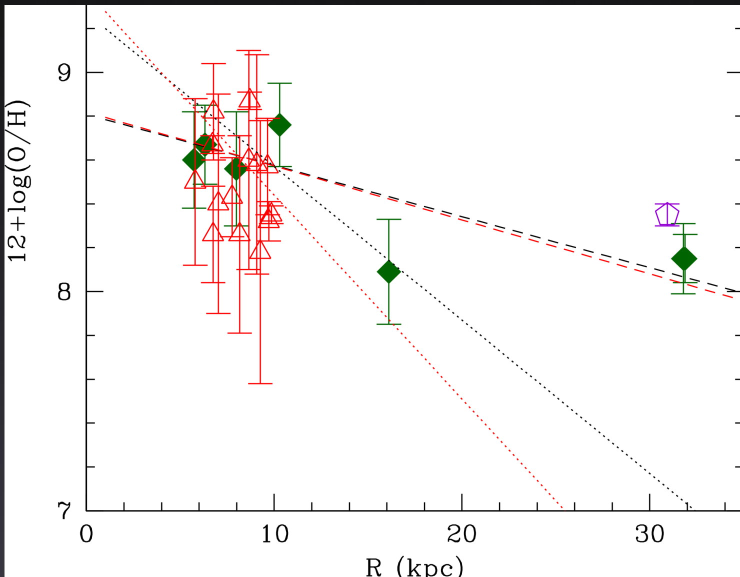
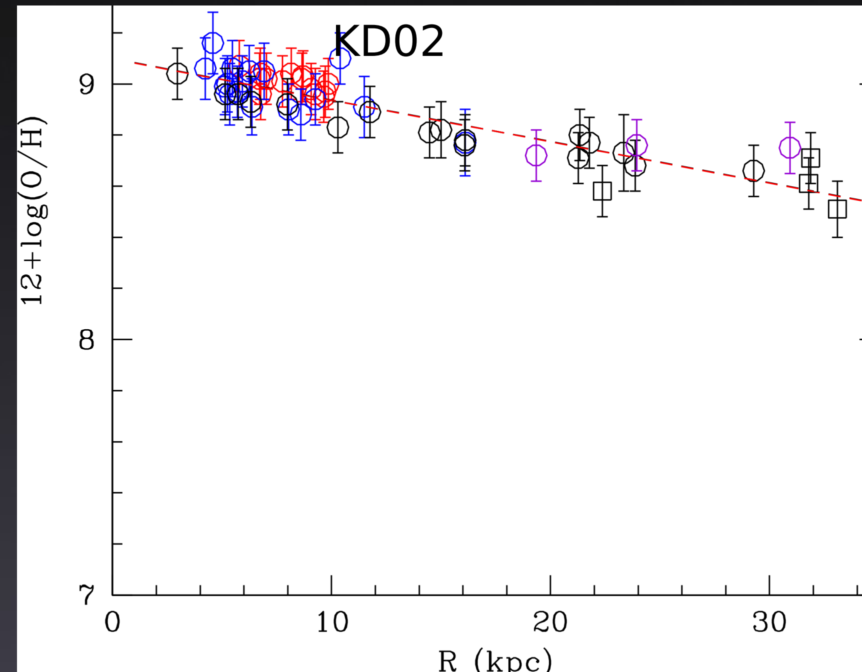
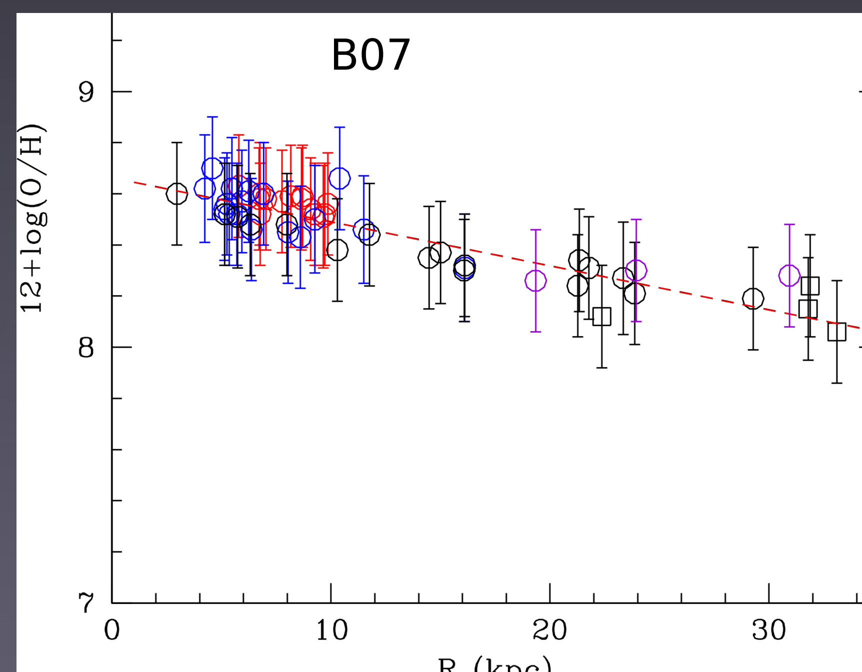


Table 6. Oxygen abundance gradients.

Method	N_{regions}	Δ (dex kpc^{-1})
	These data	
KK04	21	-0.014 ± 0.006
PT05	21	-0.013 ± 0.006
KD02	21	-0.013 ± 0.002
B07	21	-0.014 ± 0.005
T_{e}	7	-0.020 ± 0.006
	All four data sets	
KK04	49	-0.008 ± 0.005
PT05	49	-0.016 ± 0.004
KD02	49	-0.016 ± 0.002
B07	49	-0.017 ± 0.004





M31 stats

Sb galaxy

Moderately-inclined (77.7°)

dist = 770 kpc (Freedman & Madore, 1990)

R_{25}=100'=22.4 kpc

Mass = $3.4 \times 10^{11}\ M_{\odot}$ (Carignan+, 2006)

M31 HII regions

MMT Blue Channel Spectrograph

Observed 6 HII regions:

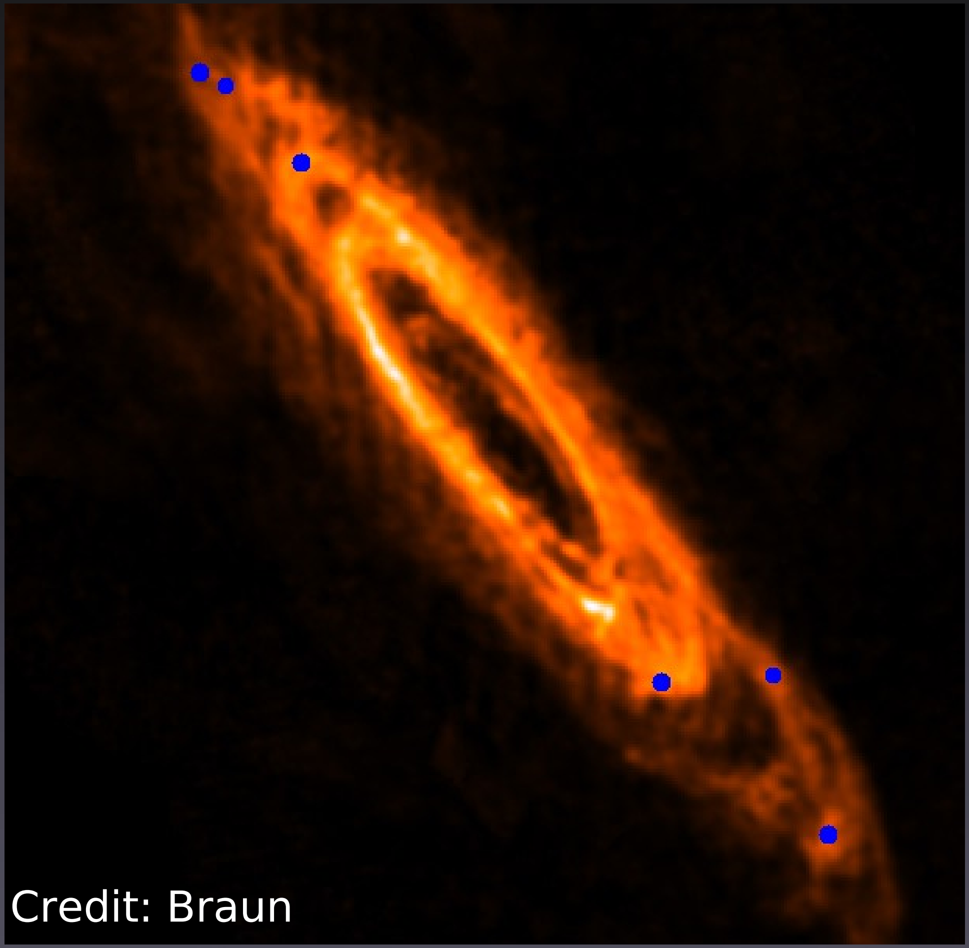
- 3 electron temperature abundances
- All strong line abundances

Supplementary data:

- Dennefeld & Kunth, 1981
- Blair+, 1982
- Galarza+, 1999
- (Sanders+, 2012)
- (Zurita & Bresolin, 2012)

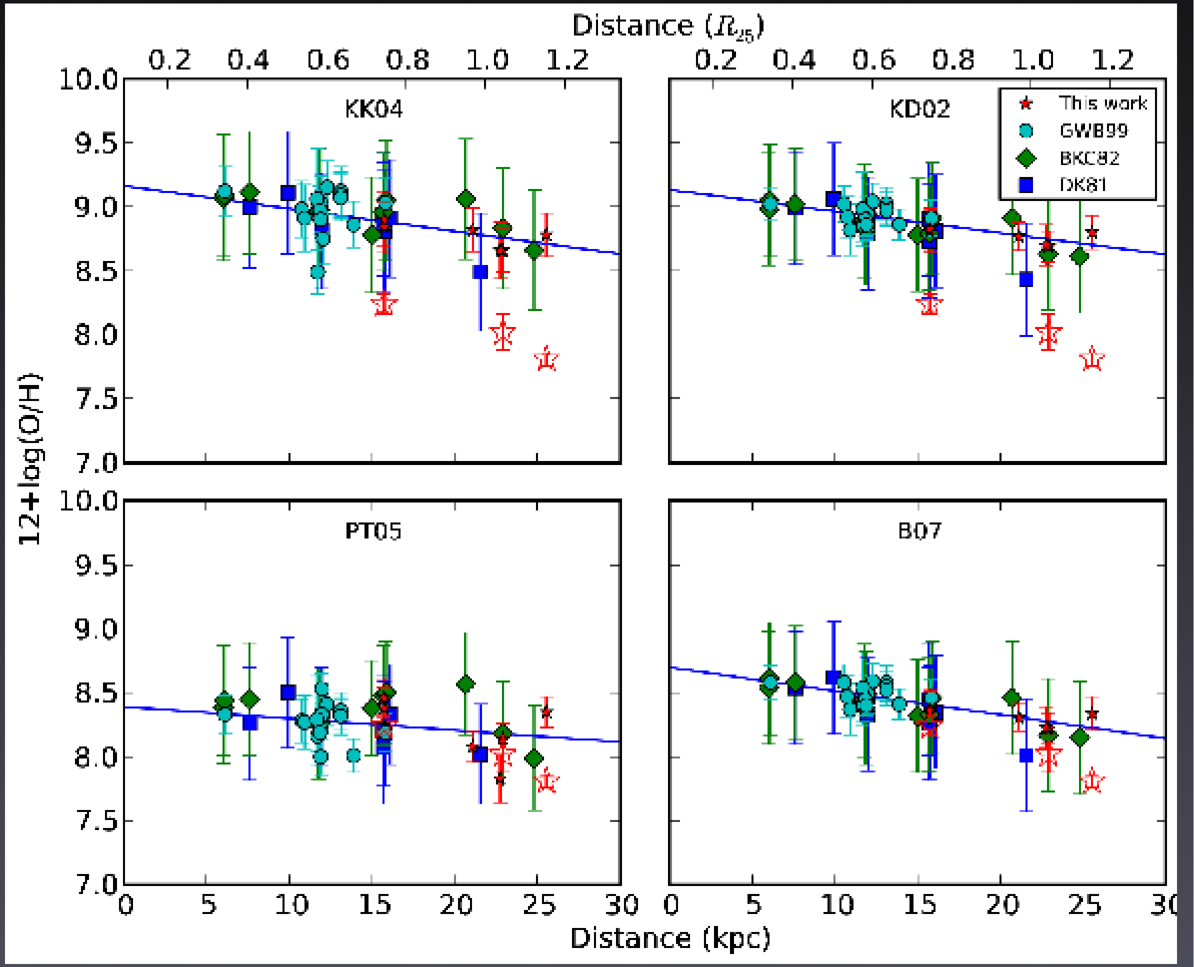
Distance range:

- ~6-26 kpc (~0.25-1.15 R_{25})



Shallow extended gradients: M31

Oxygen Abundance Gradients	
Method	Δ(dex kpc^{-1})
KK04	-0.018 ± 0.008
PT05	-0.009 ± 0.006
KD02	-0.017 ± 0.006
B07	-0.019 ± 0.009



Sanders+, 2012:

-0.020 +/- 0.006

Zurita & Bresolin, 2012:

-0.023 +/- 0.002

Shallow extended gradients: M31

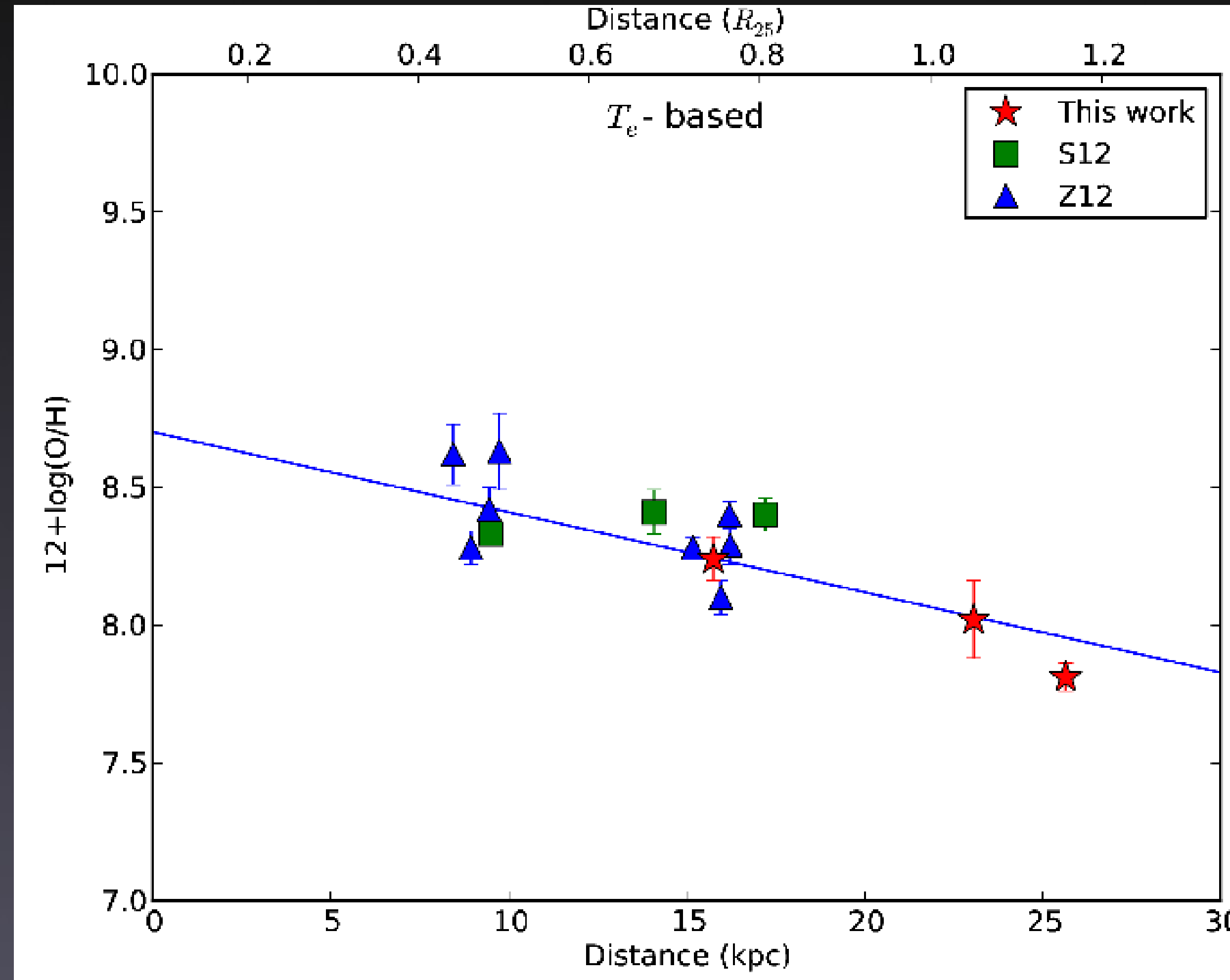
Oxygen Abundance Gradients	
Method	Δ(dex kpc^{-1})
KK04	−0.018±0.008
PT05	−0.009±0.006
KD02	−0.017±0.006
B07	−0.019±0.009

Sanders+, 2012:

-0.020 +/- 0.006

Zurita & Bresolin, 2012:

-0.023 +/- 0.002



Direct temperature gradient:

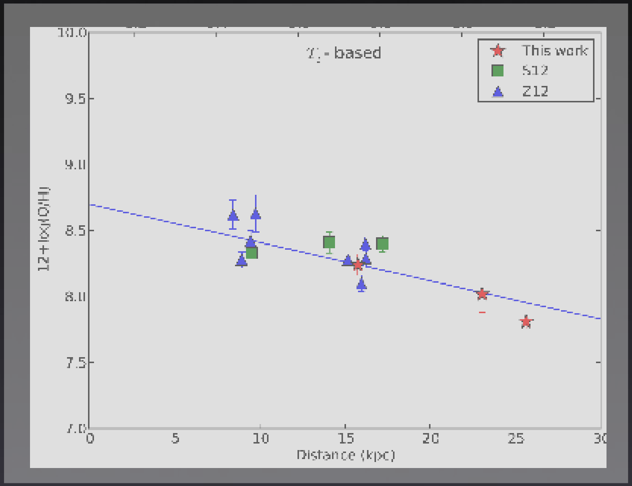
-0.028 +/- 0.003 dex/kpc

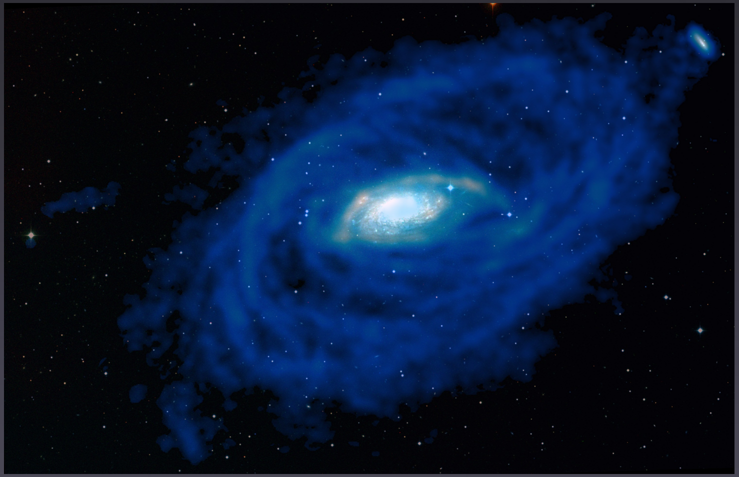
Thesis Projects

Extended metallicity gradients

of HII regions in the outer discs

of M81 and M31.





Tilted-ring modeling

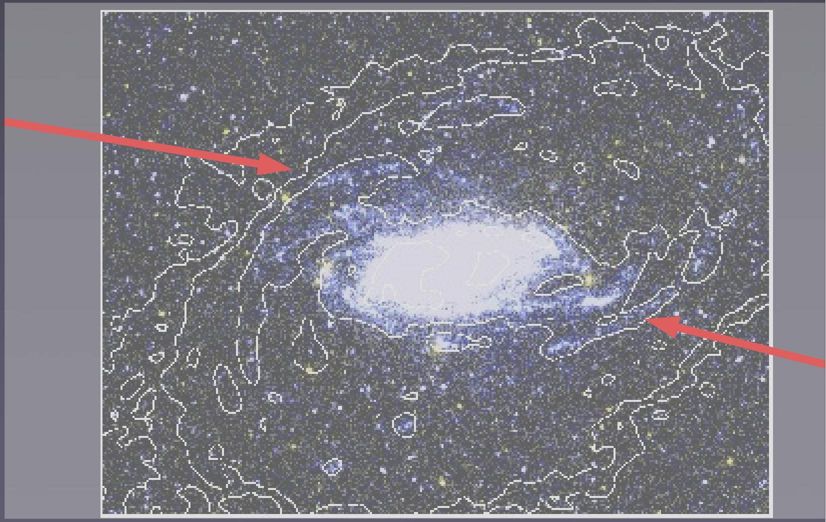
of the gaseous halo of NGC 5055

from the HALOGAS survey.

Outer disc star formation

from Halpha and GALEX UV imaging

of galaxies in the HALOGAS sample.



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

...is a deep cold hydrogen (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)

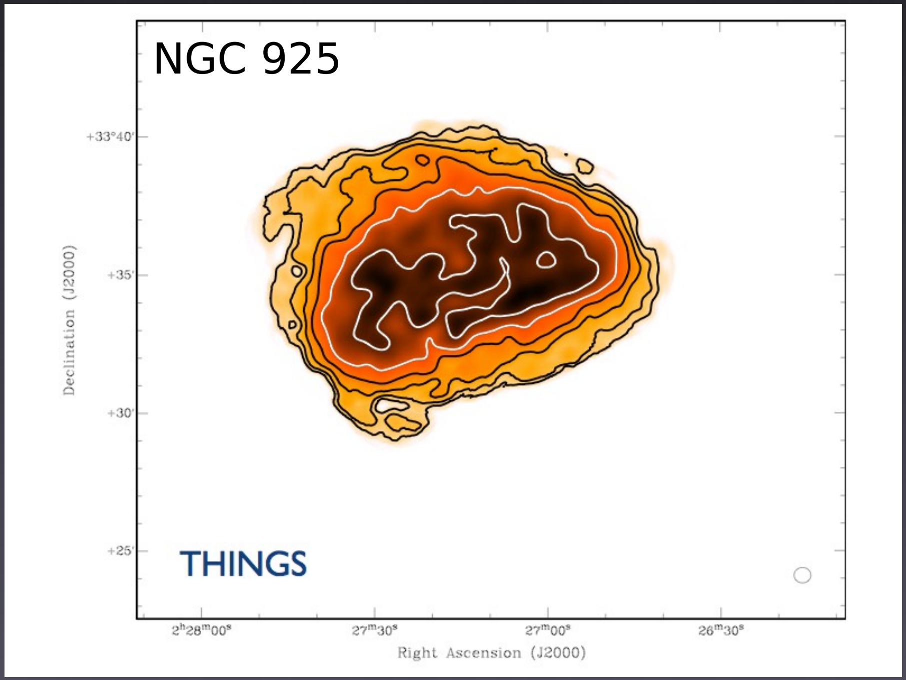
→ **20 spiral galaxies (+ NGC 891 (Oosterloo+ '07), NGC 2403 (Fraternali+ '02))**

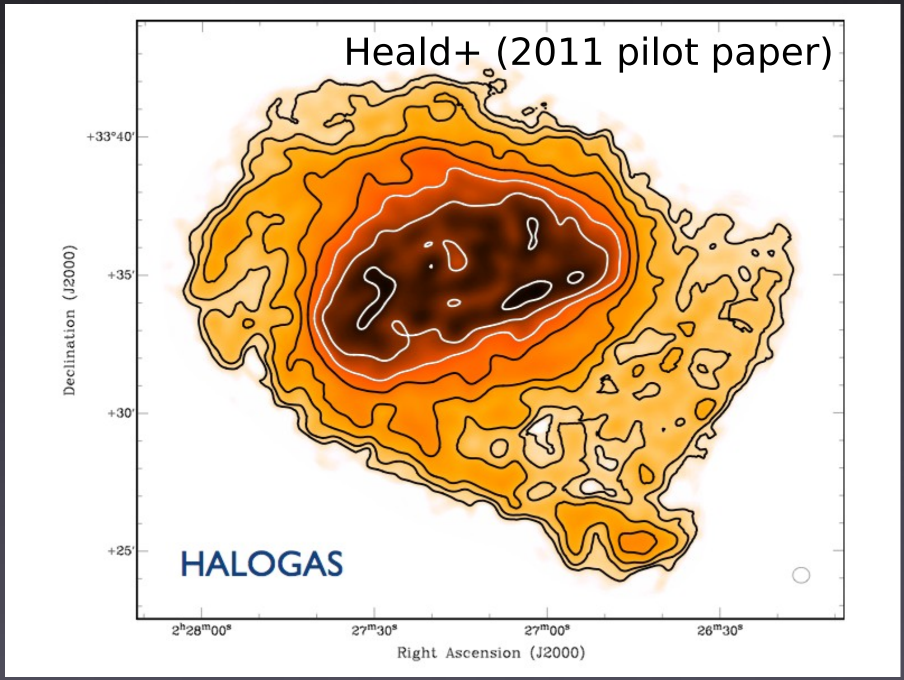
→ **120 hrs for each galaxy**

→ **5 times deeper than THINGS**

Hydrogen Accretion in LOcal GAlaxieS Survey

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:

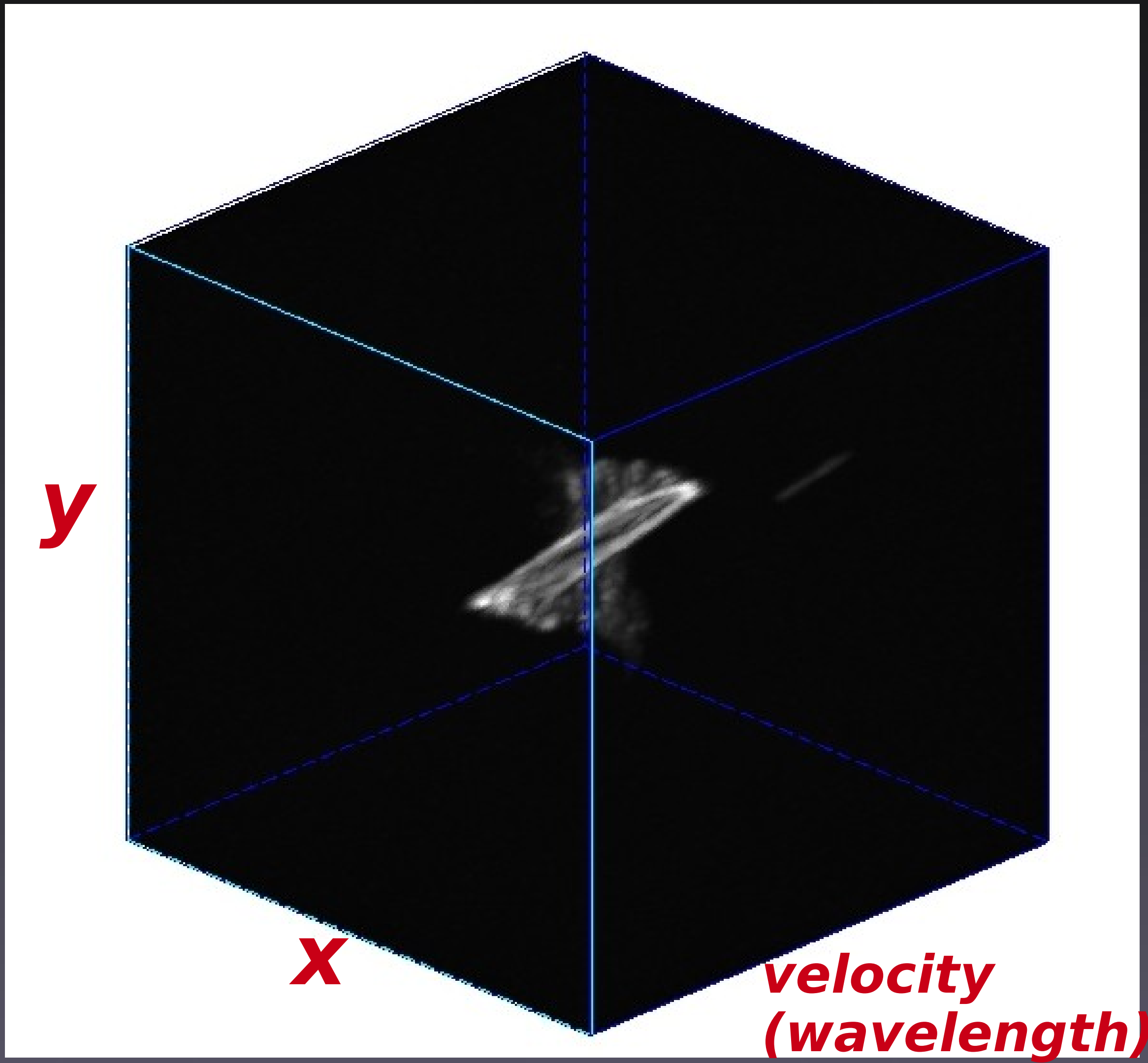
5σ column density limit of
~1 x 10^{20} cm^{-2}

HALOGAS:

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

Radio data cubes

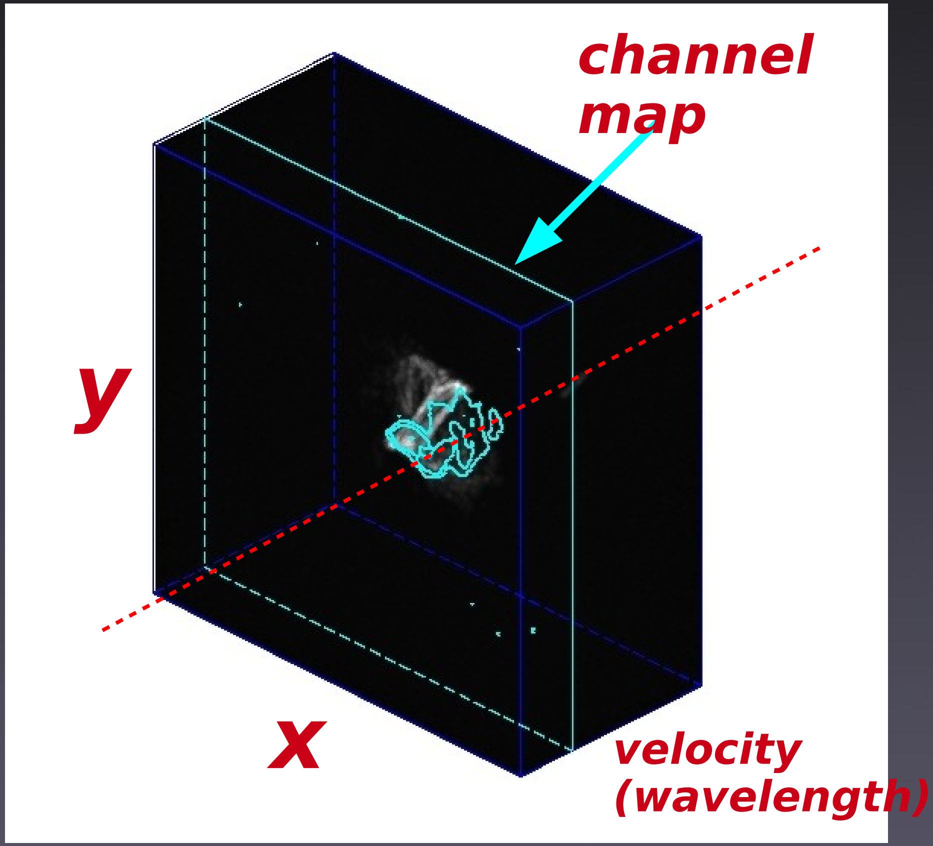
Westerbork Synthesis Radio Telescope

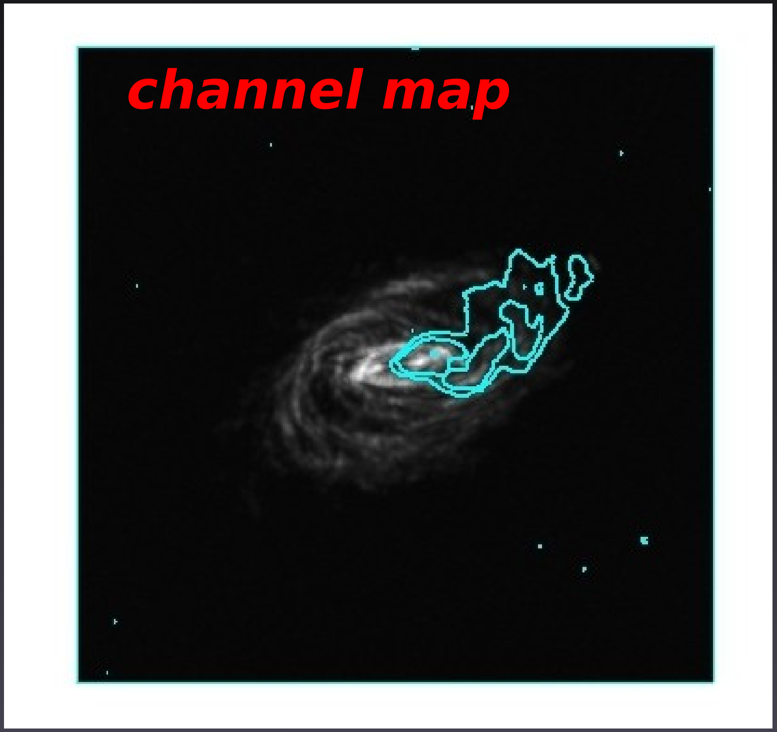


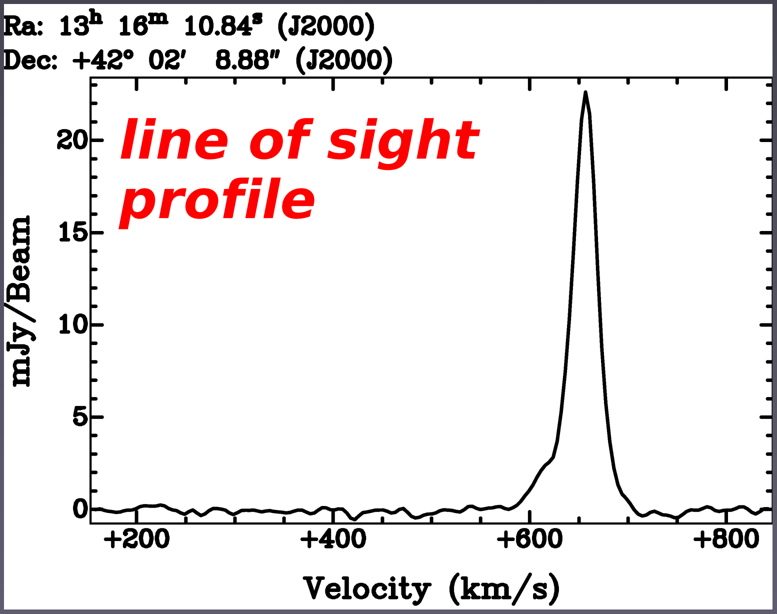
Radio data has a third dimension:

velocity

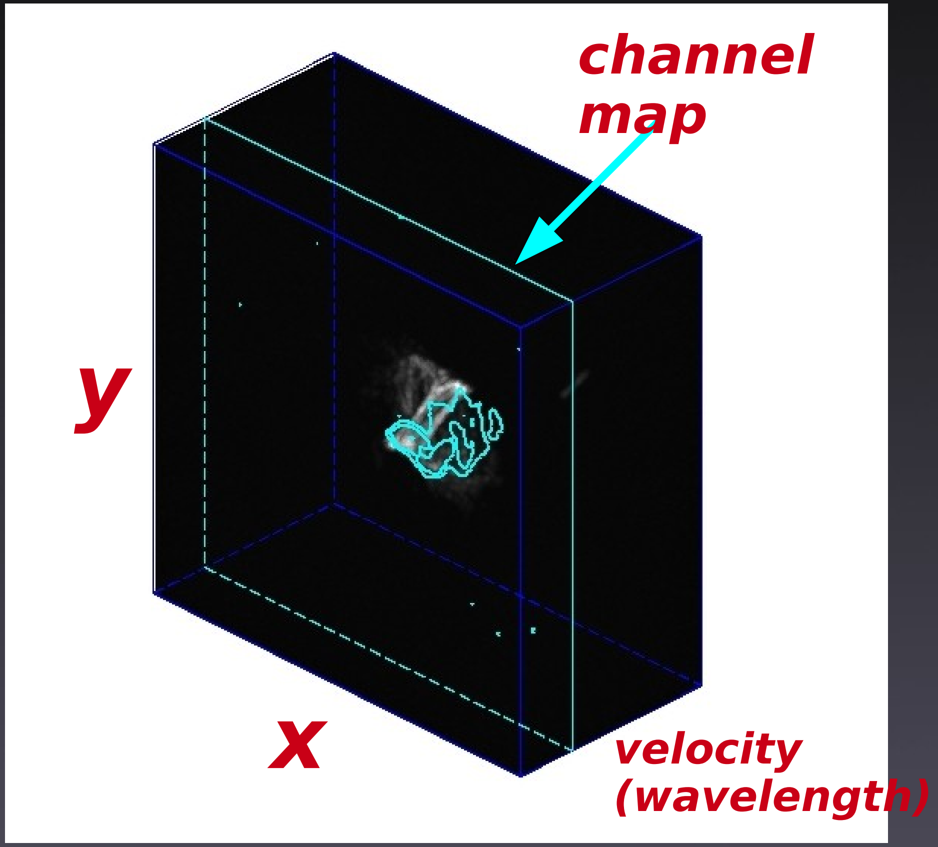
Types of radio data plots

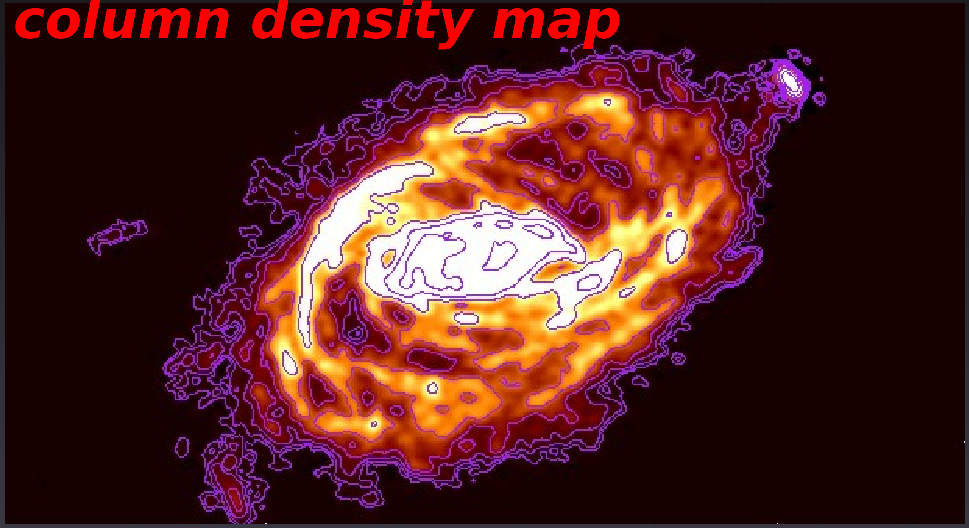


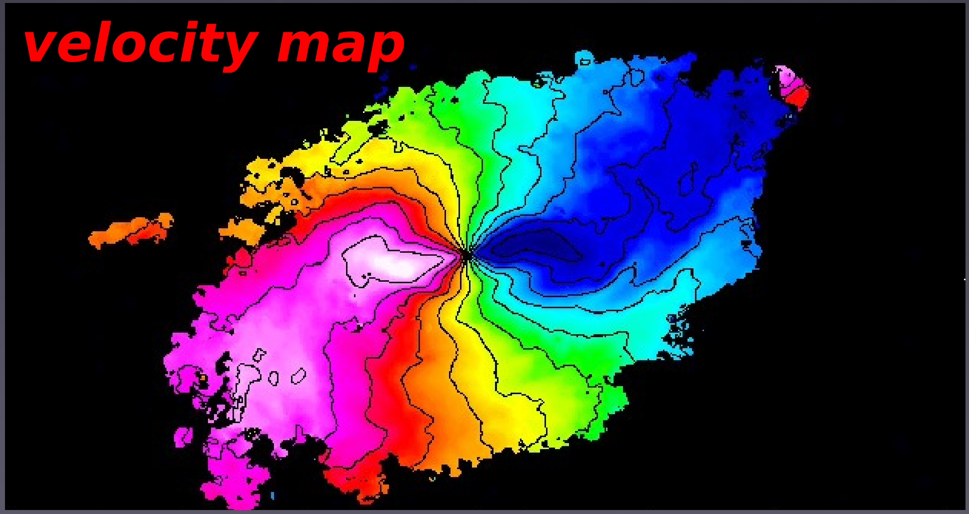




Types of radio data plots







NGC 5055

SAbc galaxy

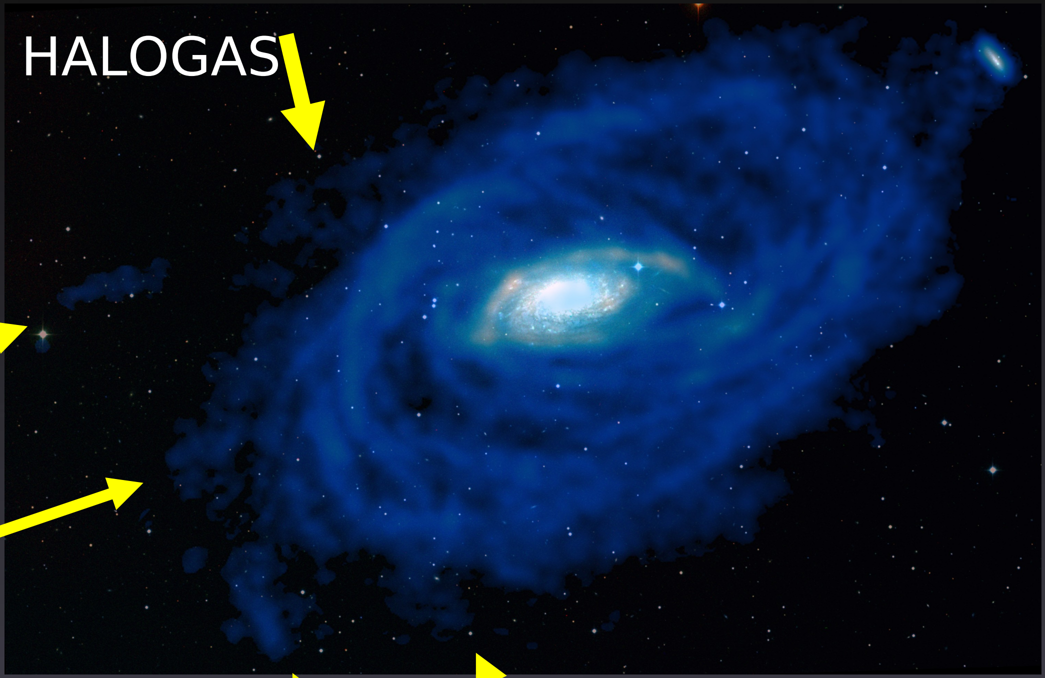
Moderately-inclined (55°)

d = 8.5 Mpc

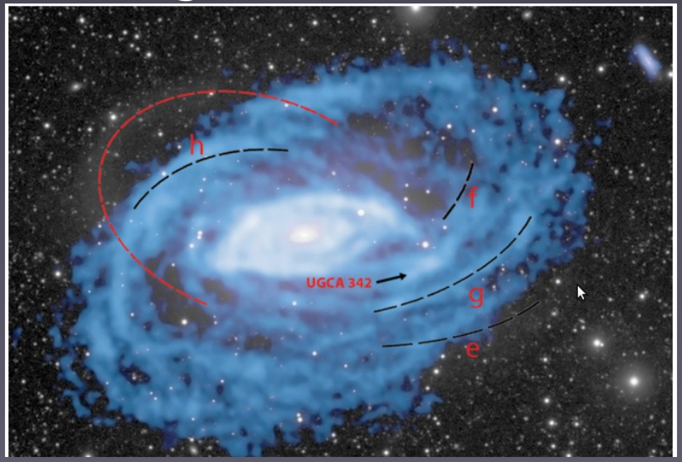
R_{25}=6.3'=15.6 kpc

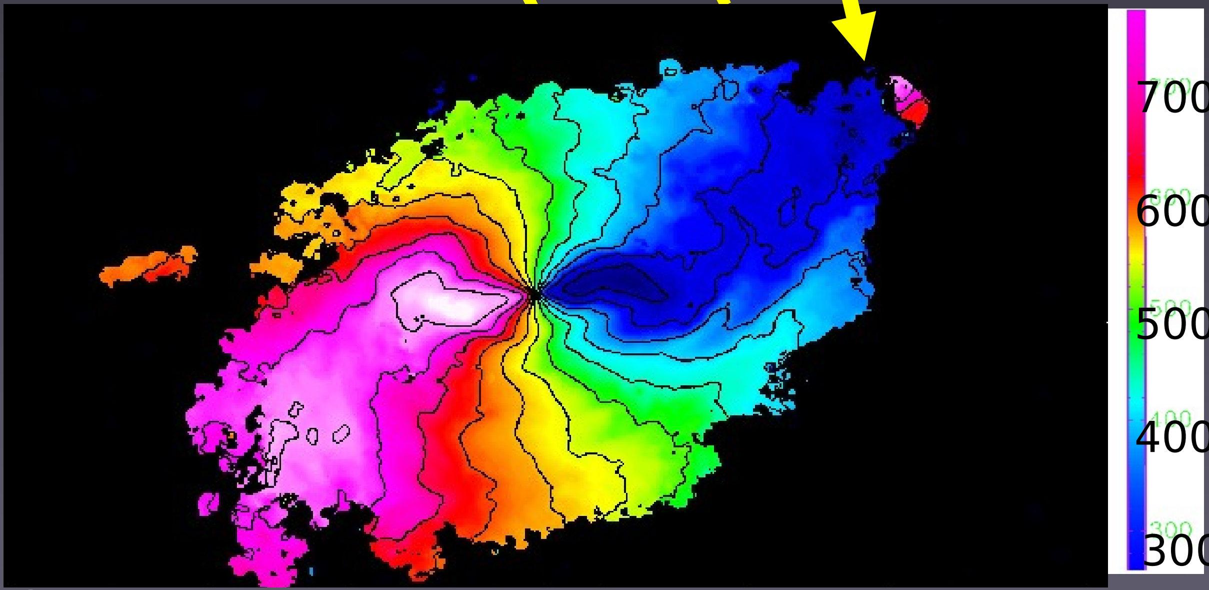
SFR= 2.5 solar masses/ yr

Gas extends 4 times the size of the optical disk.



Battaglia+, 2006 data





Contours:
270:780, +30 km/s

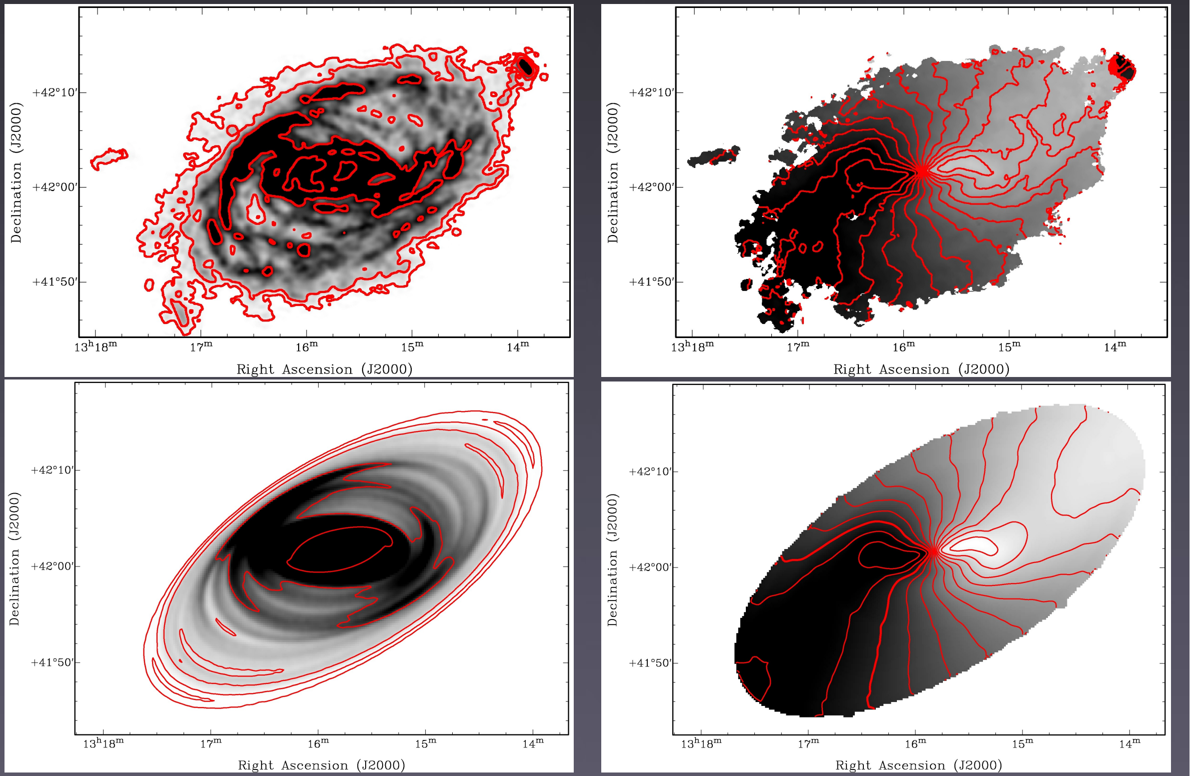
Tilted-Ring Modeling

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

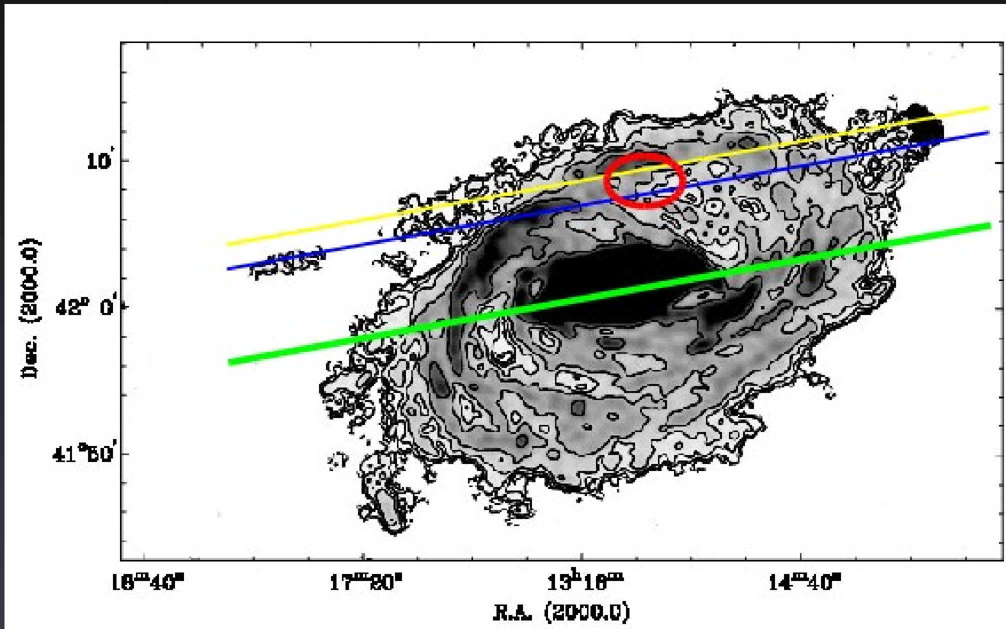
Tilted Ring Fitting Code (TiRiFiC) (Jozsa+, 2007)

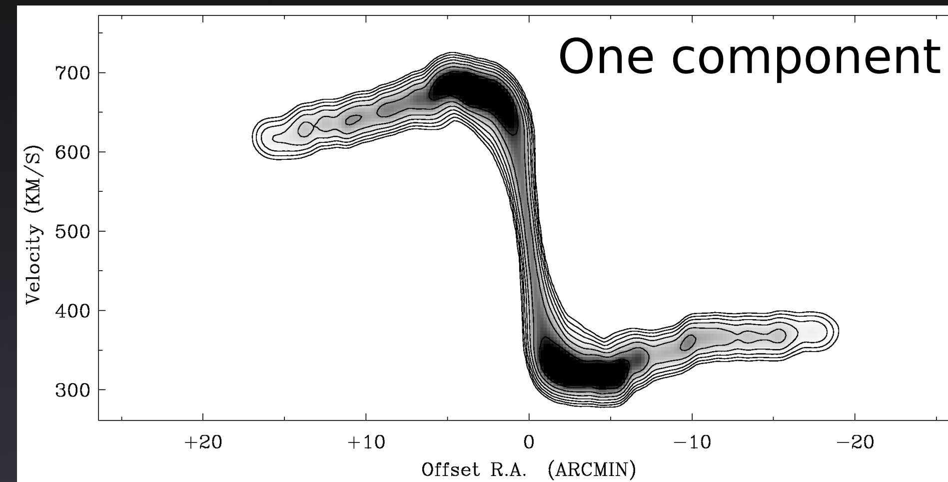
Fit for tilted ring parameters

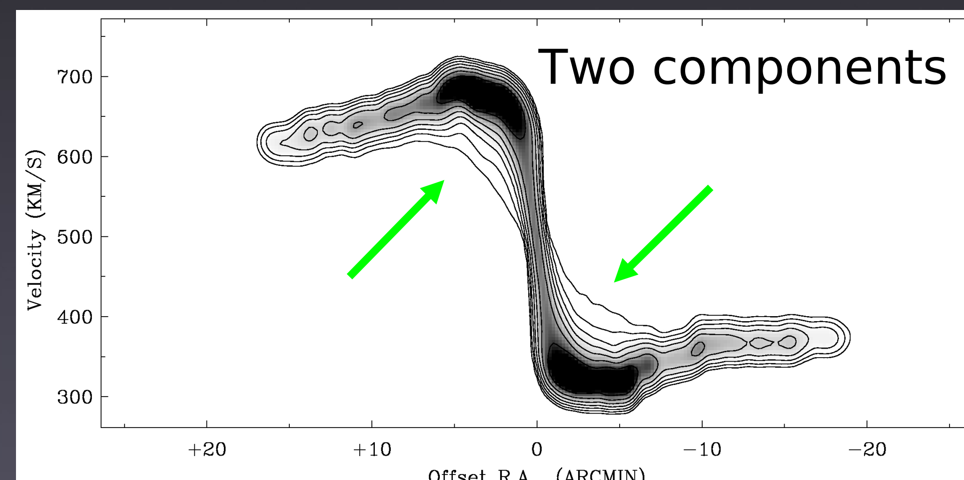
- Inclination
- Position angle
- Systemic velocity
- Rotational velocity
- Column density

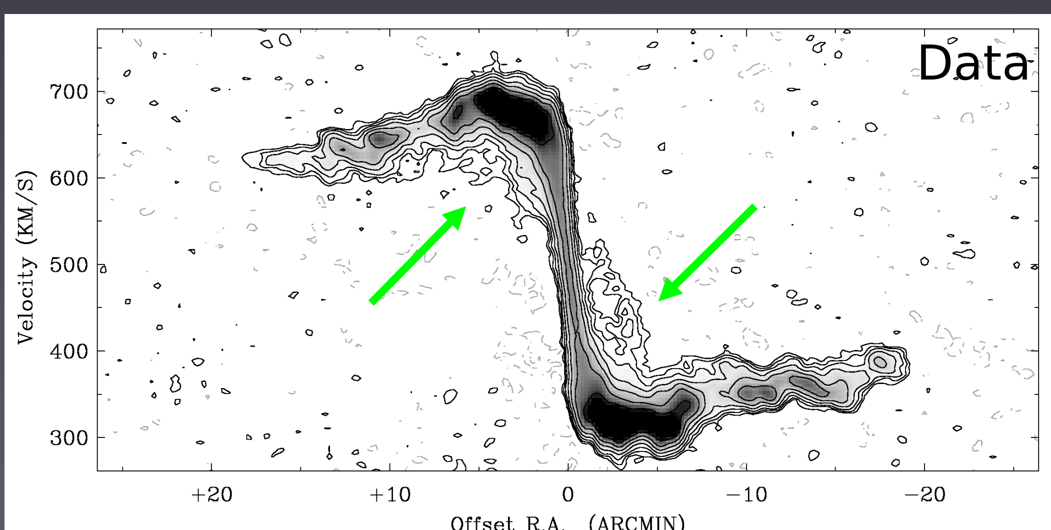


Anomalous gas- “Lagging halo”



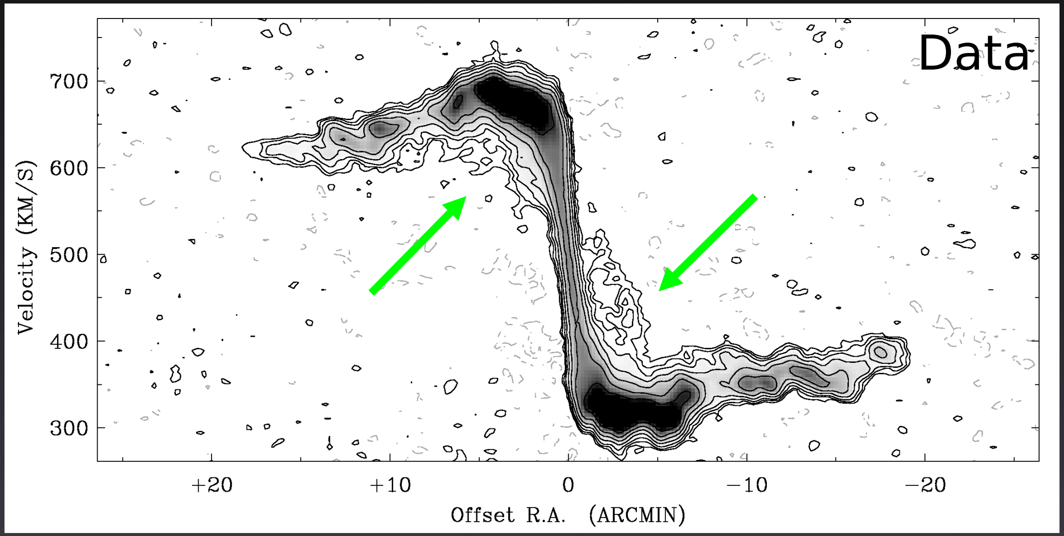


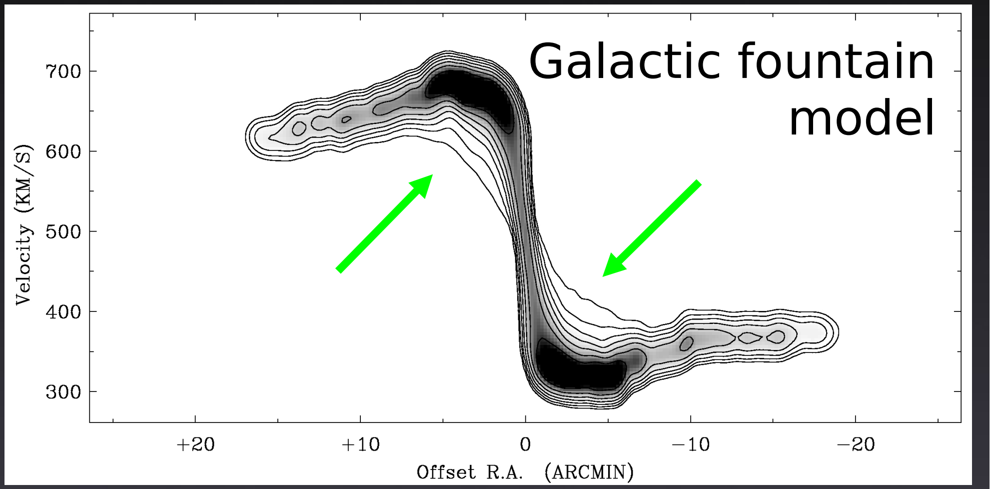


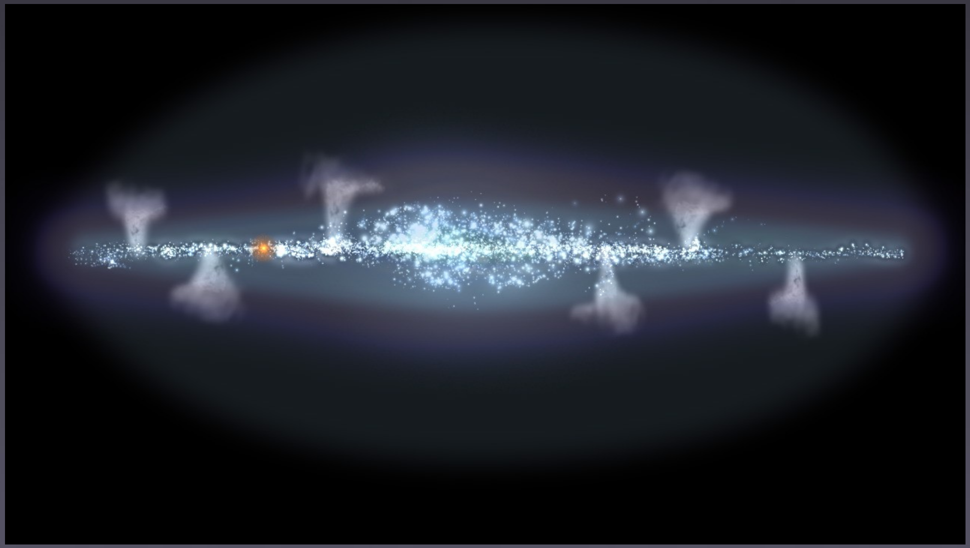


Thick second component with ~8% total gas mass needed to fit data.

"Lagging halo" = galactic fountain





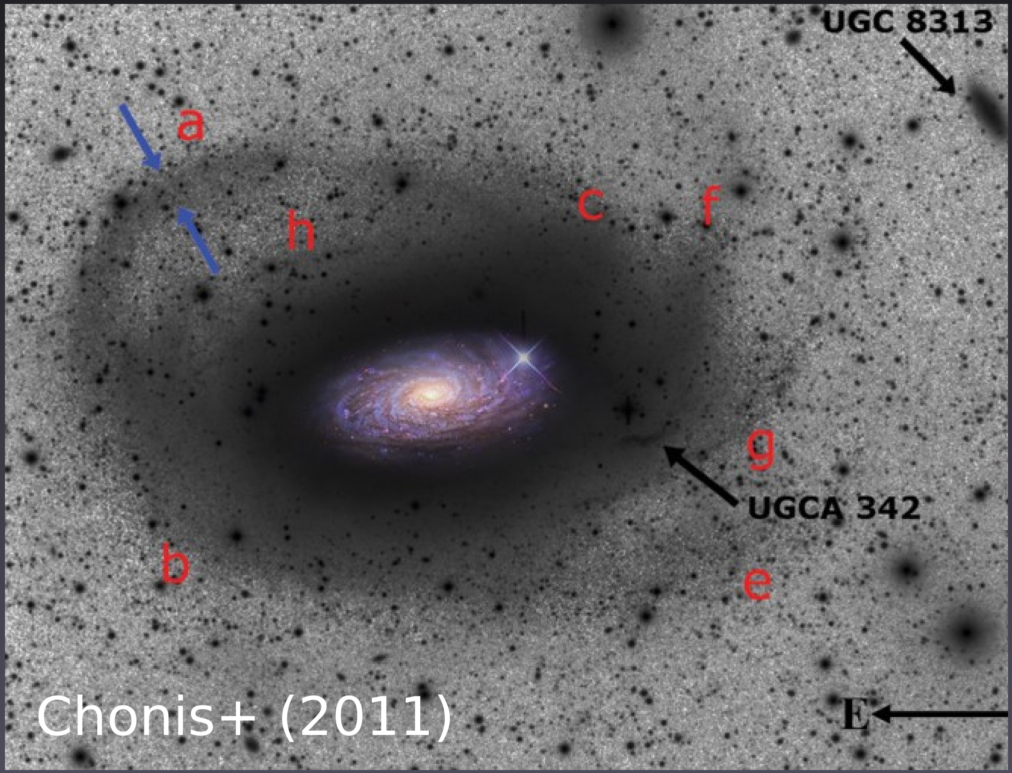


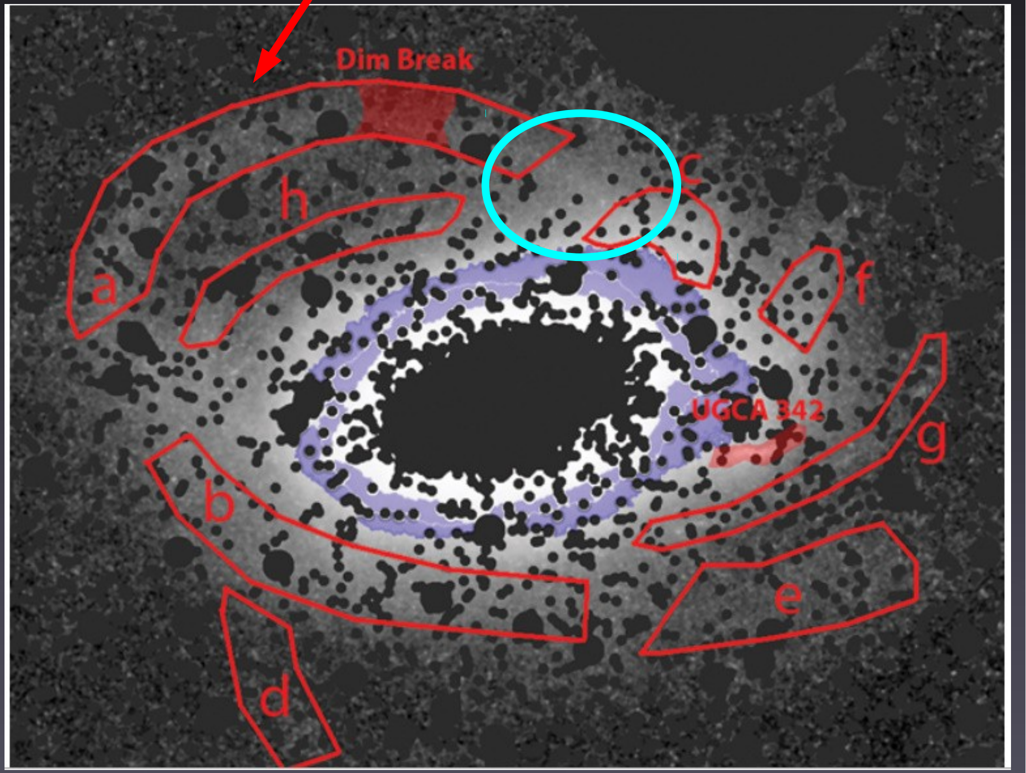
Extent of this gas is confined to the optical disk, likely from galactic fountain.

Galactic fountain theory:

- Massive stars blow gas out of the disk
- Gas slows, cools, condenses
- Falls back out onto the disk

Stellar stream around NGC 5055

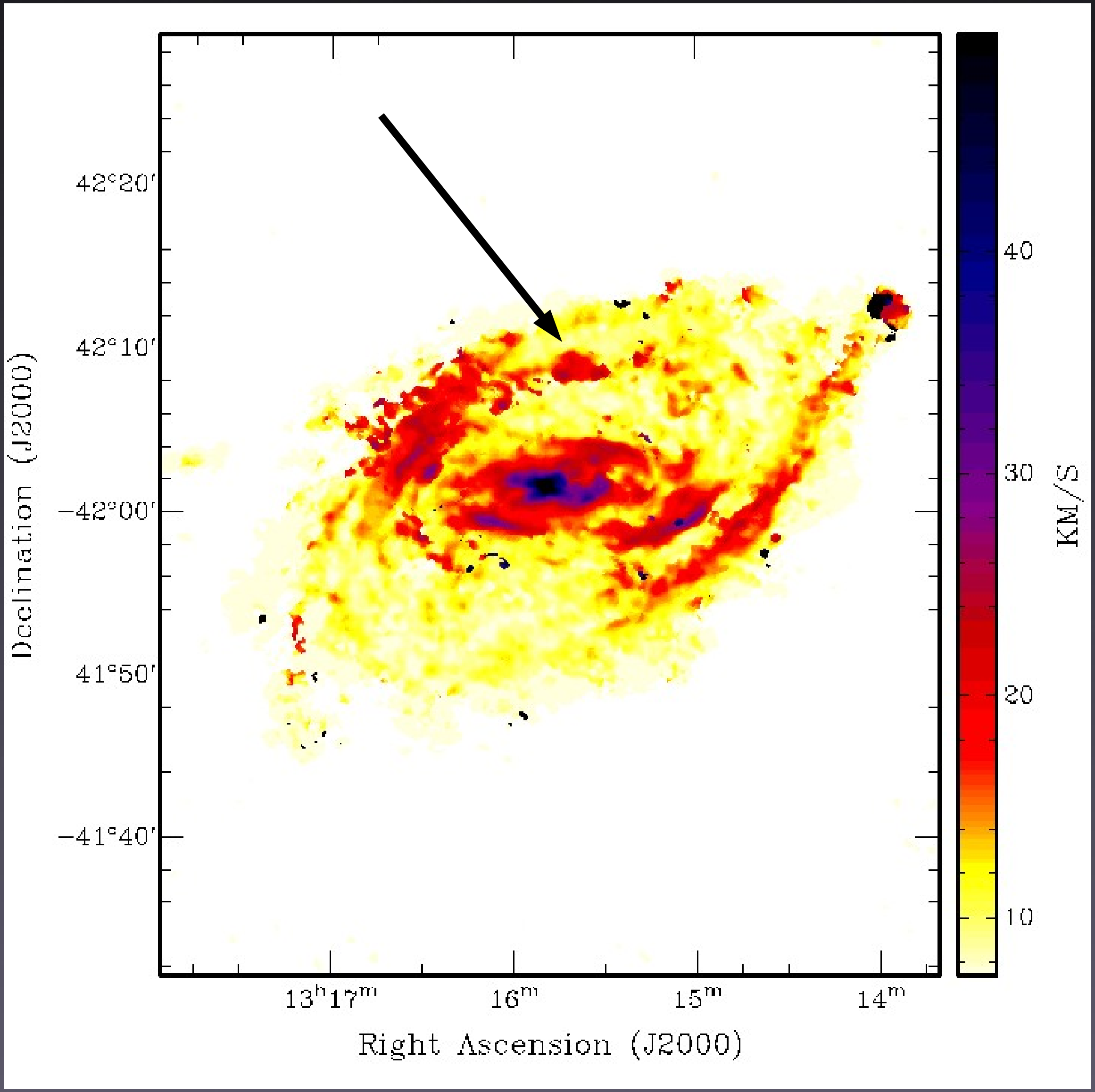


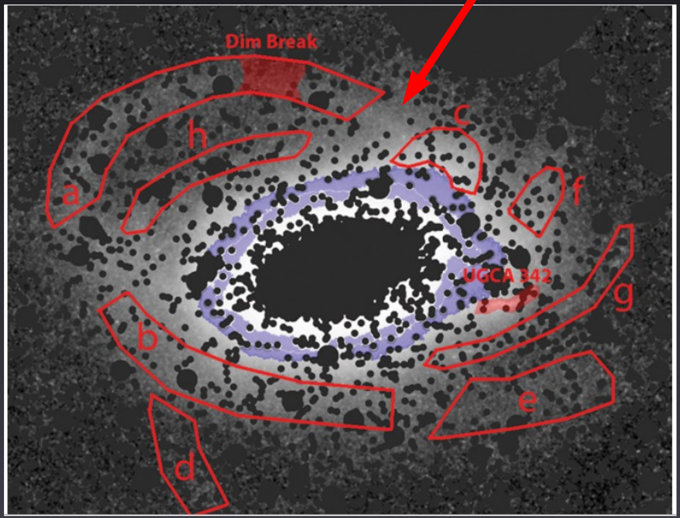


Eight low surface brightness features. (Chonis+, 2011).

One, the 'a' loop, is most likely a stellar stream.

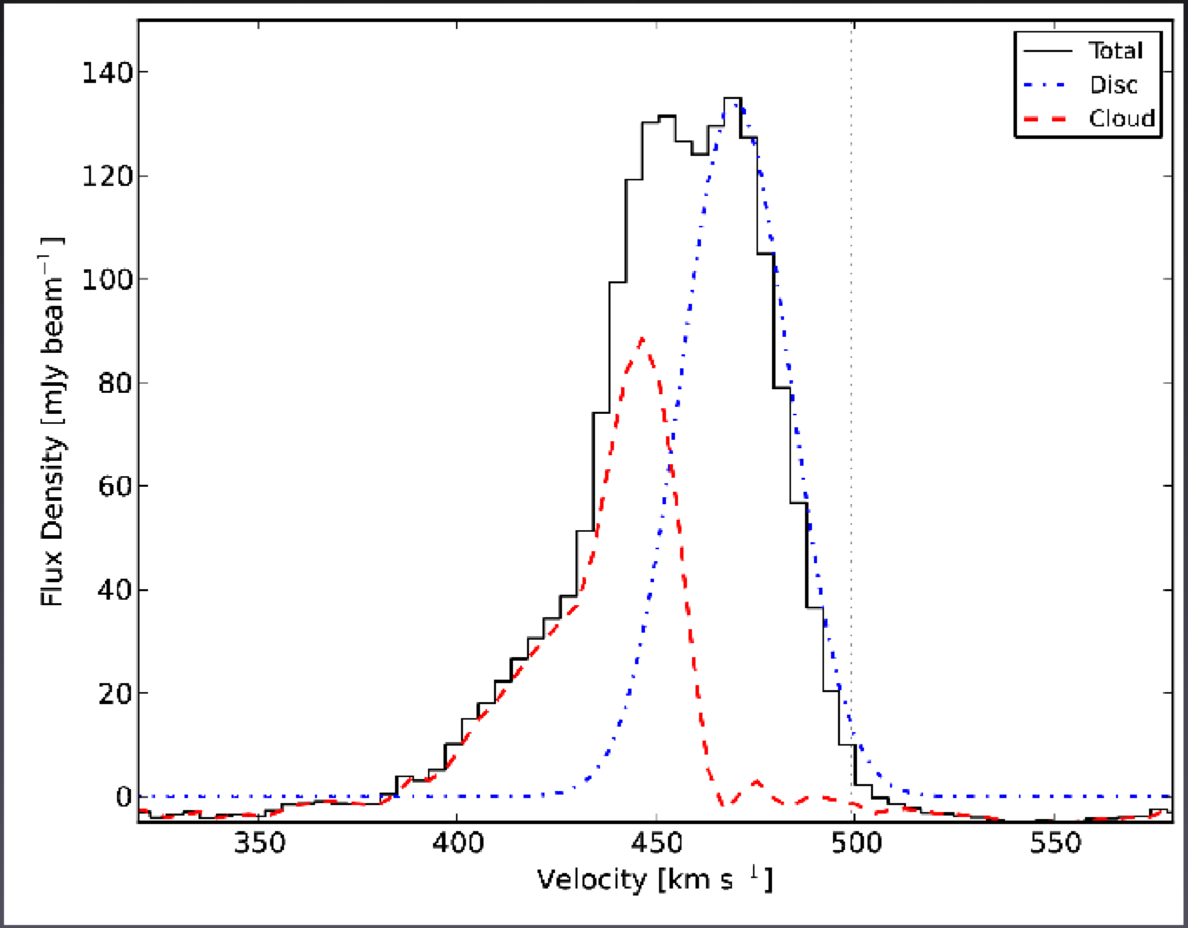
Anomalous velocity gas associated with stellar stream- remnant?

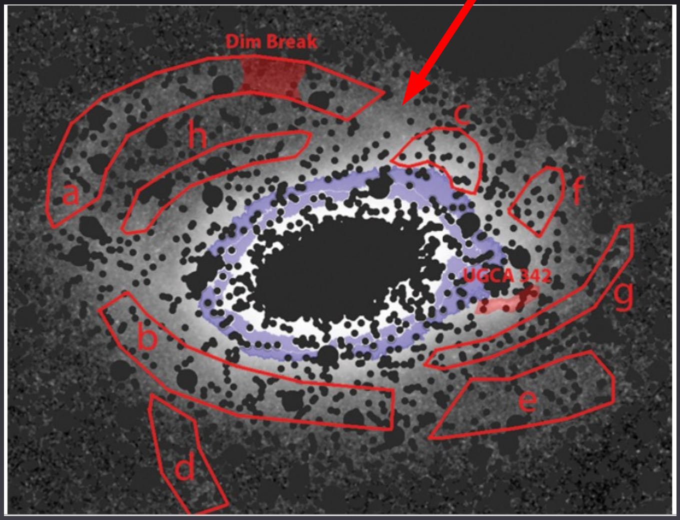


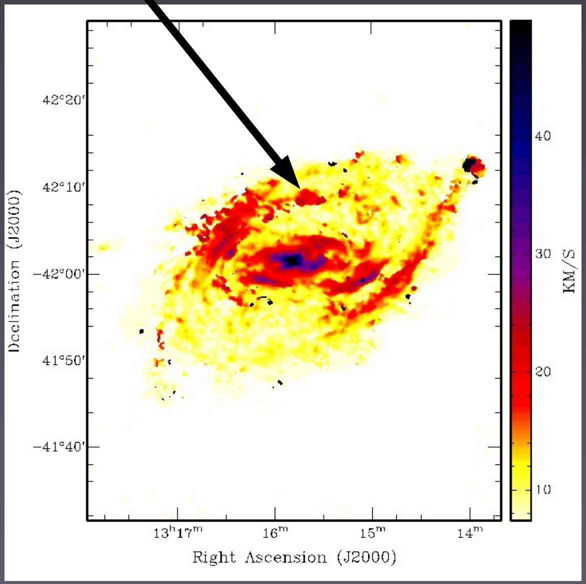


Map of velocity width shows anomalous velocity cloud, no associated star formation.

Anomalous velocity gas associated with stellar stream- remnant?

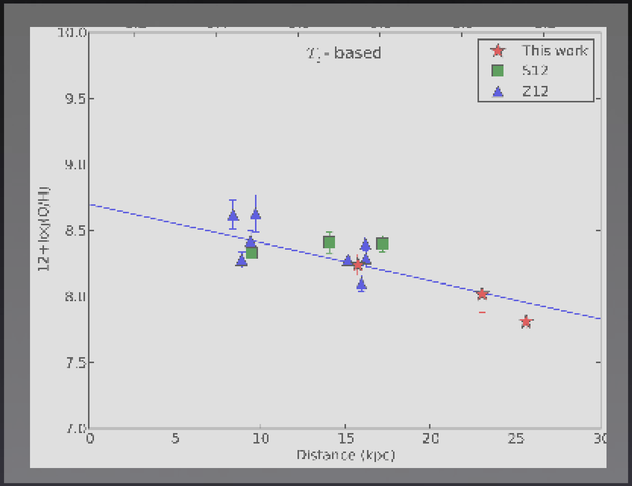






Cloud has mass of few times 10^6 solar masses. More than expected, but not very high.

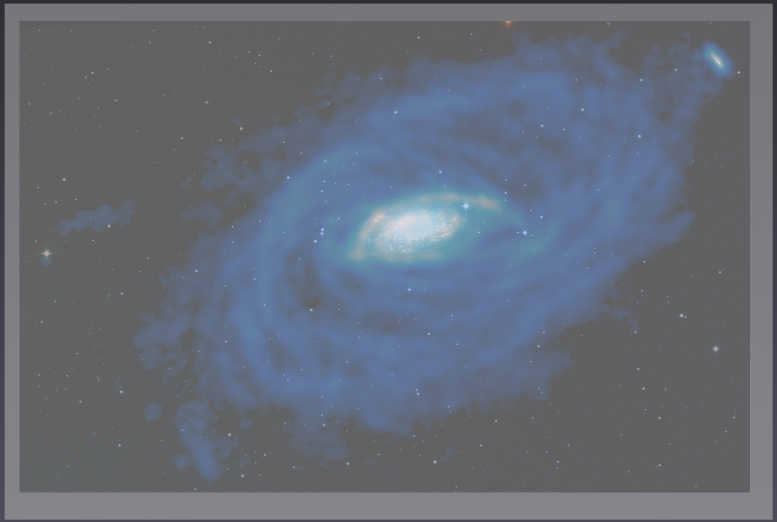
Thesis Projects



Extended metallicity gradients

of HII regions in the outer discs

of M81 and M31.



Tilted-ring modeling

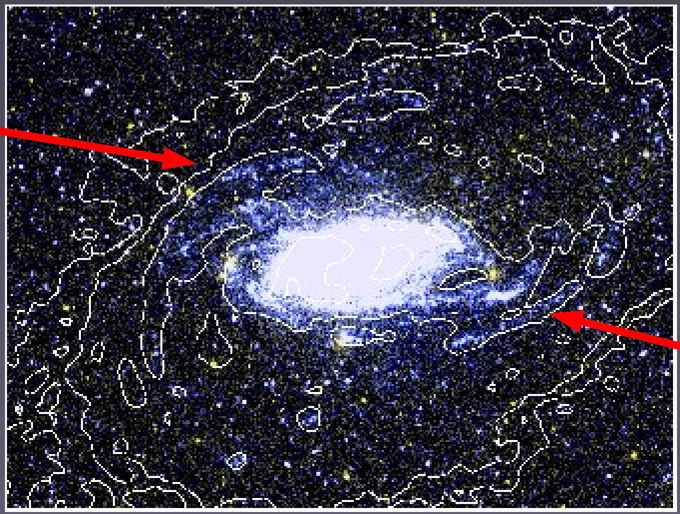
of the gaseous halo of NGC 5055

from the HALOGAS survey.

Outer disc star formation

from Halpha and GALEX UV imaging

of galaxies in the HALOGAS sample.



Kitt Peak Observations

4-meter MOSAIC 1.1

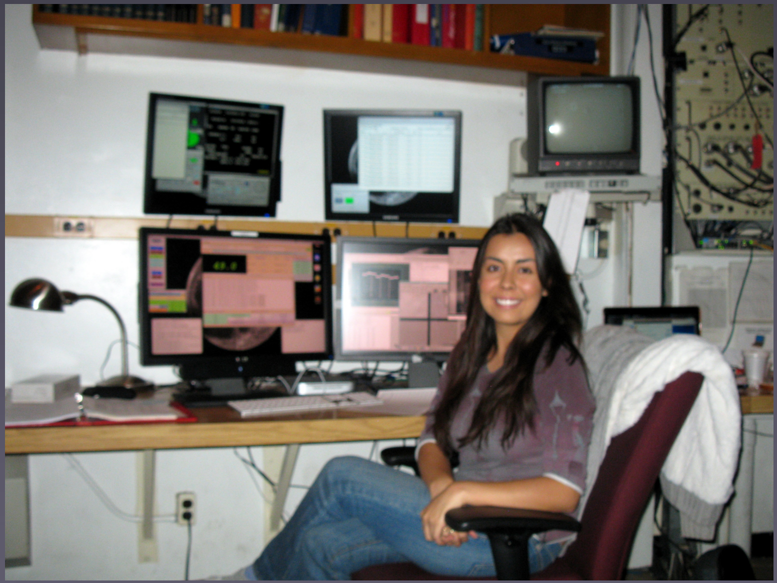
FOV= 36 arcmin

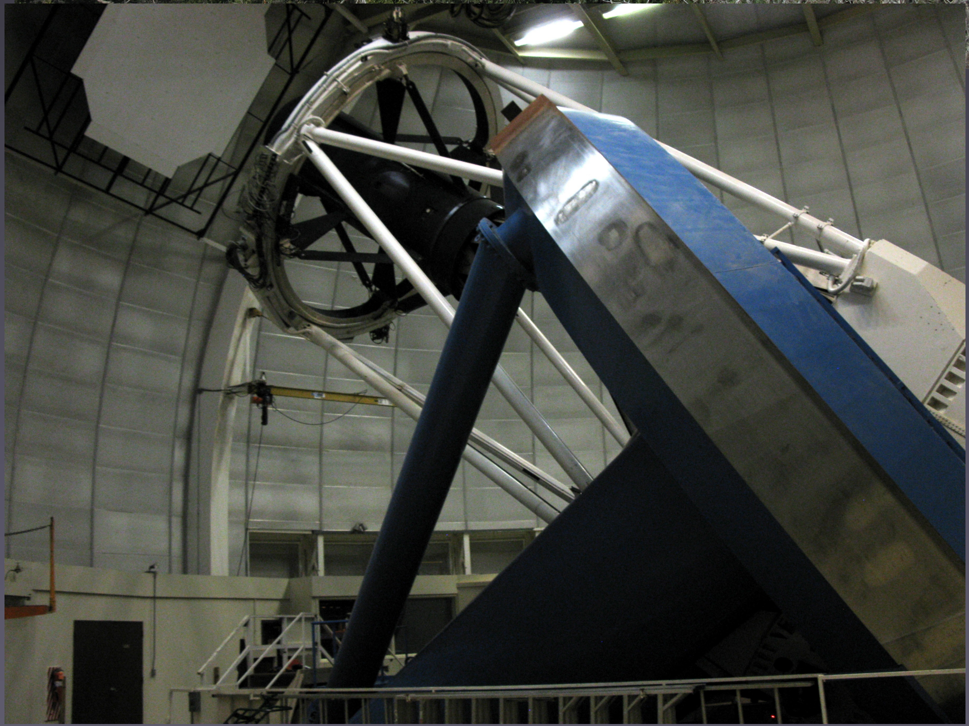
U B Ha R imaging

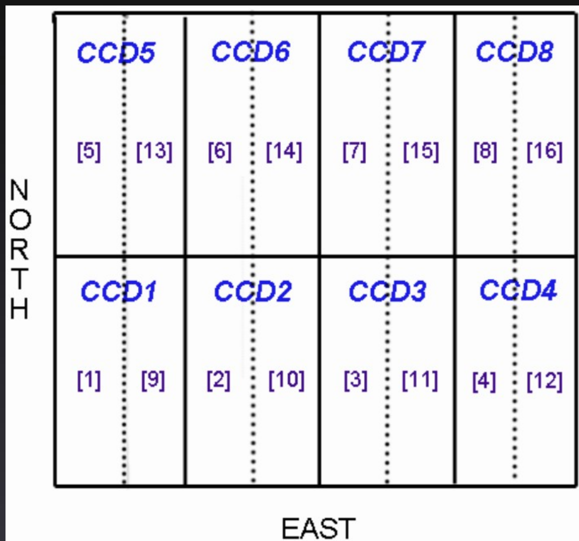
- 30 minutes UBHa
- (2 hours in B for some)
- 10 minutes R

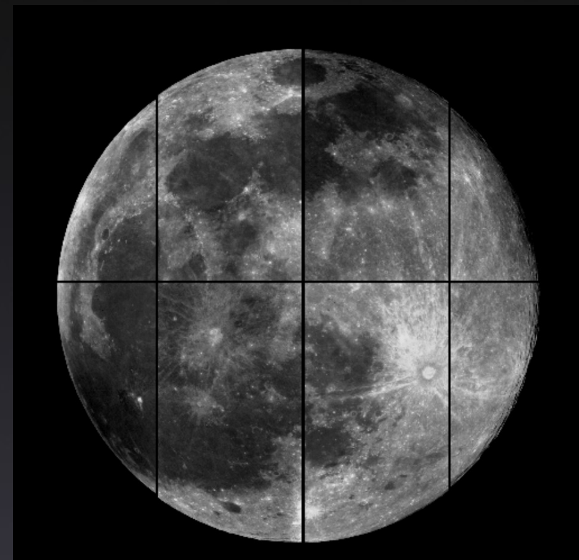
4 nights in Jan 2012 (3 good)

4 nights in Mar 2012 (4 good)









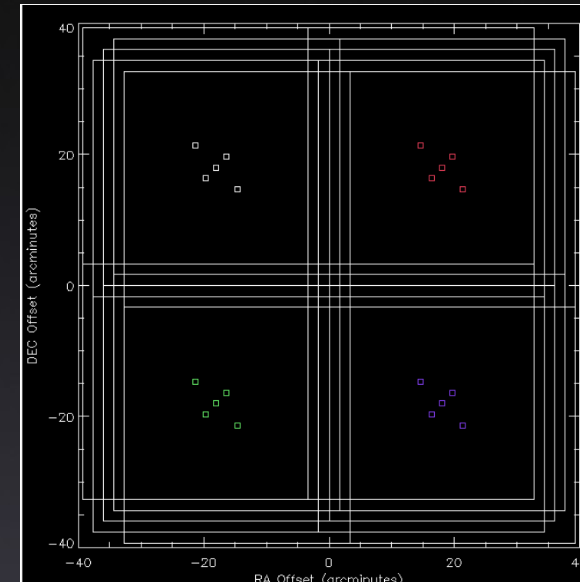
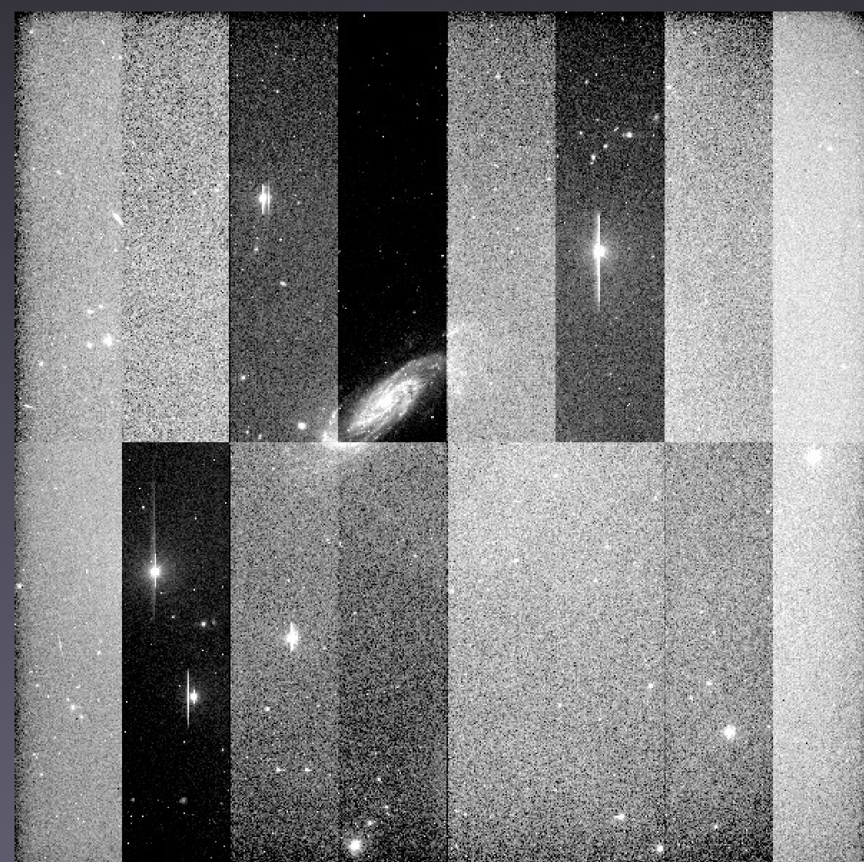


Image size: 8192 x 8192 pixels

282 Mbytes per image

FOV = 36 arcmin

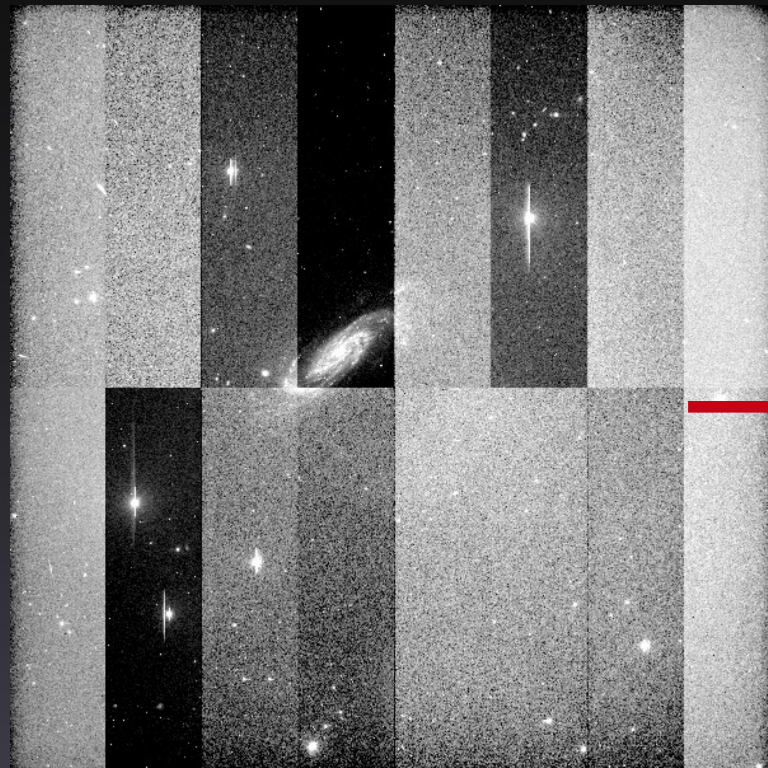
0.26” per pixel



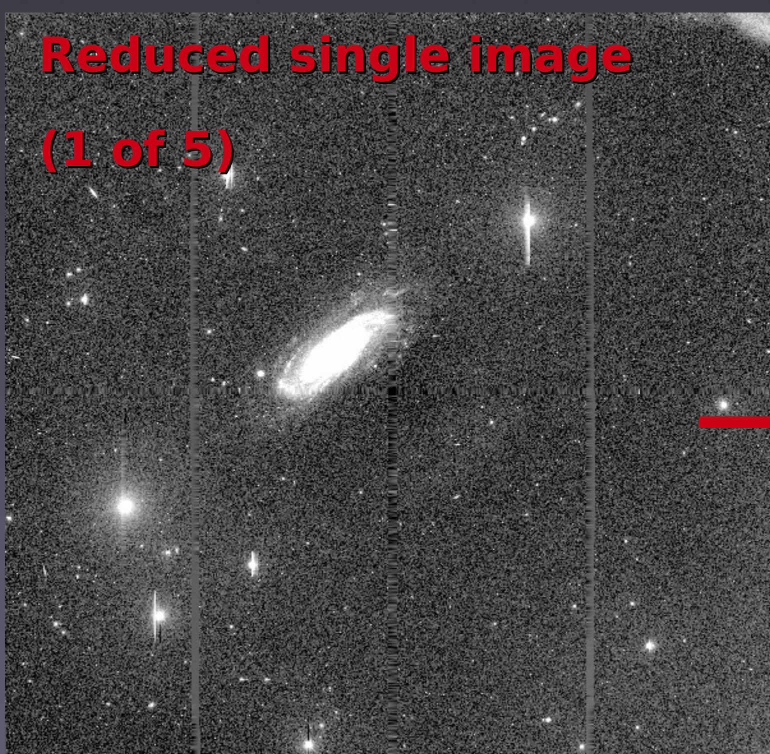
Raw image

(1 of 5)

- Image Reduction Analysis Facility (IRAF)
- MSCRED package



- Bias subtracted
- Bleed trails and cross talk removed
- Dome flat fielded
- Ghost pupil subtracted
- Super sky flat fielded



- WCS registered
- Satellite trails removed
- Dithered images stacked
- Sky gradient removed
- Flux calibration applied

Star formation in outer discs

Seven XUV discs (Thilker+, 2007)

Type I – knots of emission

Type 2 – diffuse halo

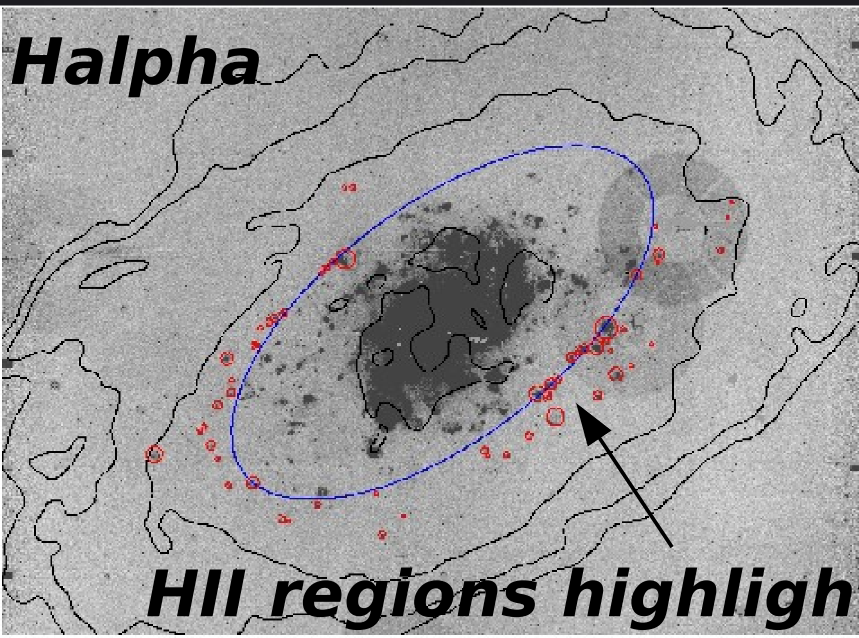
→ *Relationship between Halpha, UV, HI*

→ *Properties of stars in outer disc HII regions*

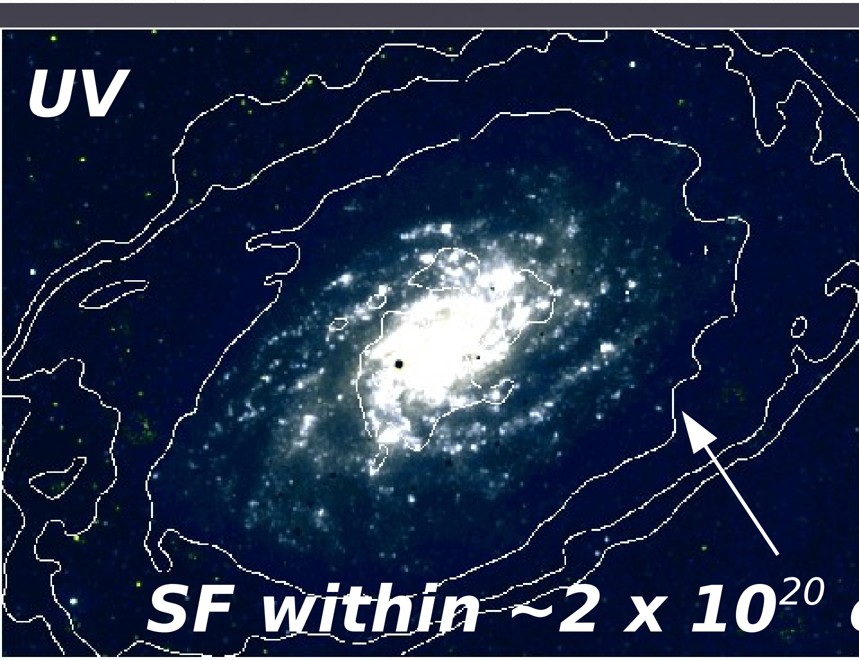
Table 5.1. Sample properties

Galaxy	Type	XUV	Dist (Mpc)	R_{25} (arcmin)	v_{sys} (km s^{-1})	i (deg)	PA (deg)	SFR ($M_\odot$ yr^{-1})
NGC 2403	SAcd	mixed	3.2	10.9	132	62	127	0.9
NGC 2541	SAcd	2	12.0	3.2	553	67	165	0.3
NGC 3198	SBc	1	14.5	4.3	660	71	35	1.0
NGC 4258	SABbc	1	7.6	9.3	449	71	150	3.1
NGC 4414	SAc	1	17.8	1.8	720	50	155	4.2
NGC 4559	SABcd	1	7.9	5.4	816	69	150	0.4
NGC 5055	SAbc	1	8.5	6.3	499	55	105	2.6

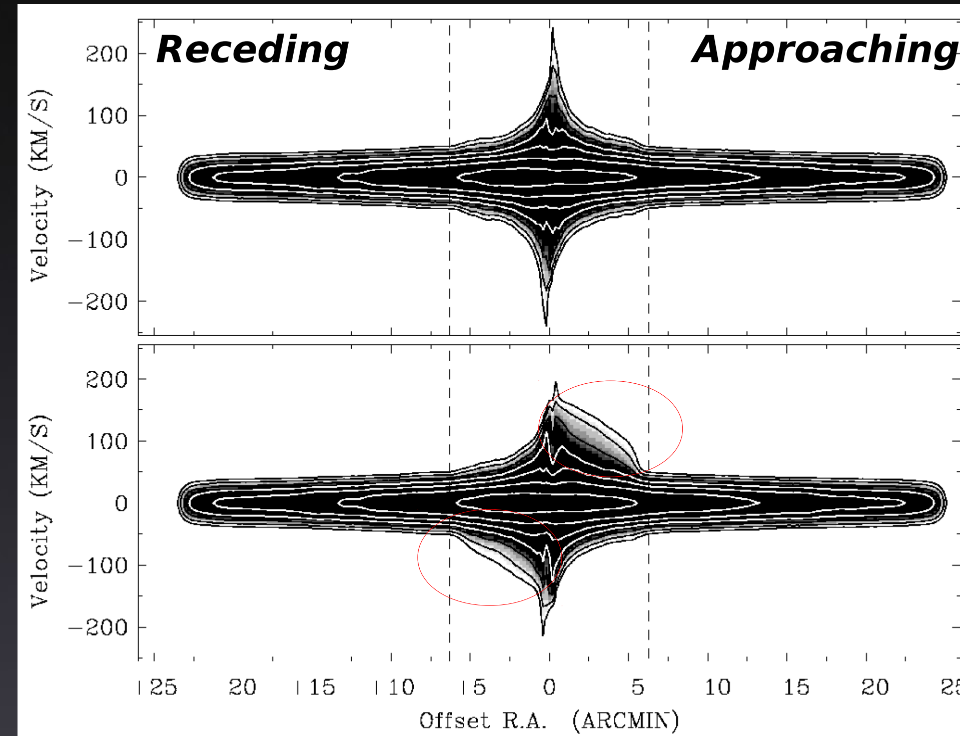
Relationship between Halpha, UV, HI

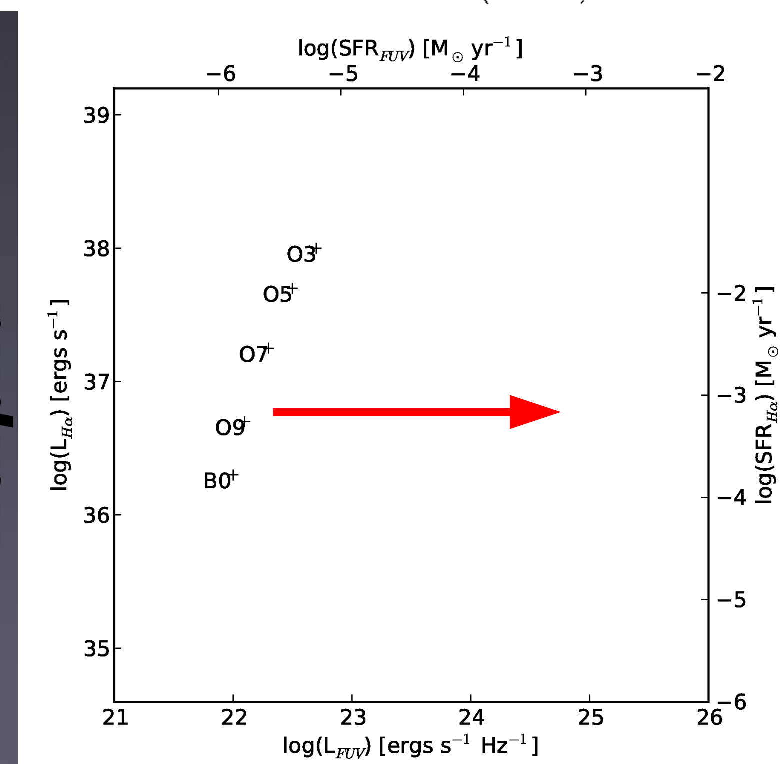


HII regions highlighted



SF within ~2 x 10^{20} cm^{-2}

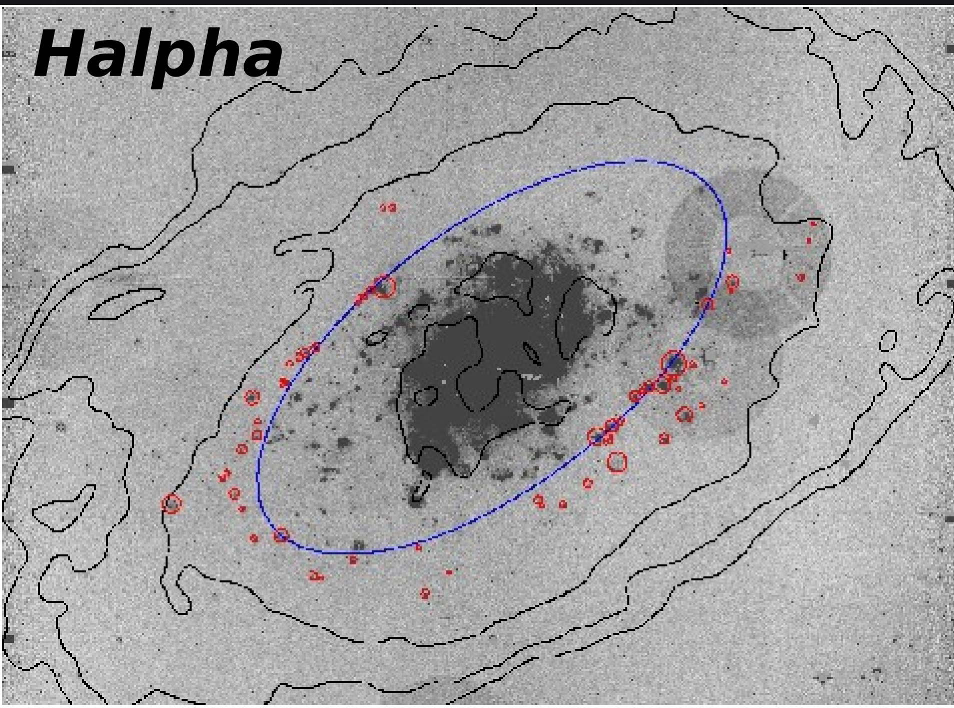


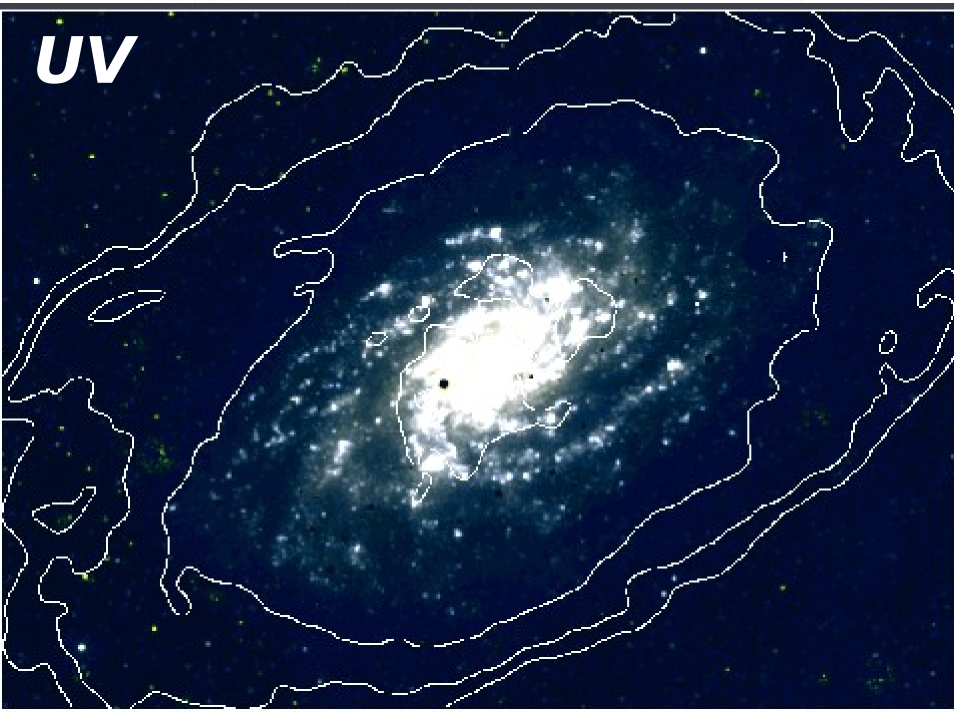


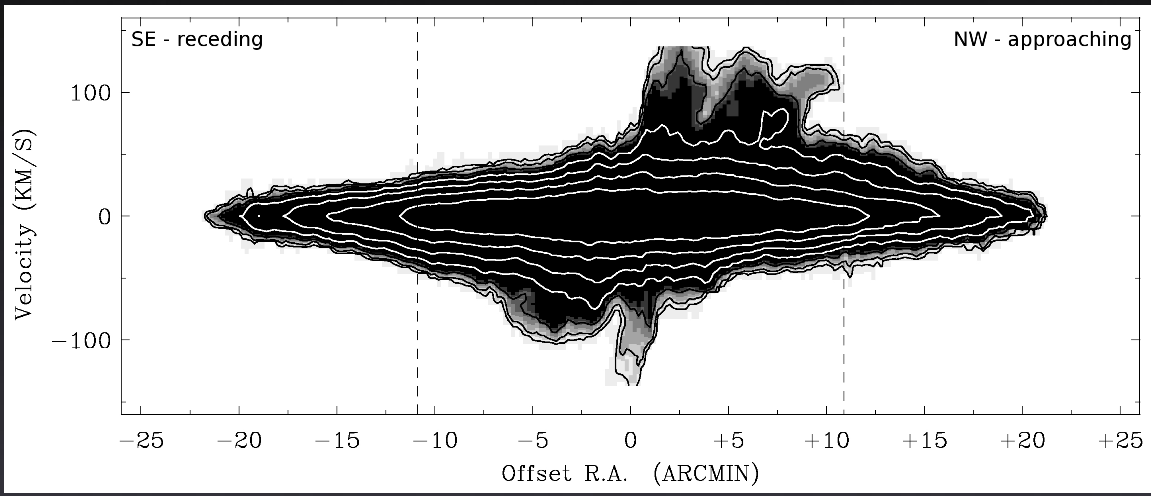
Halpha

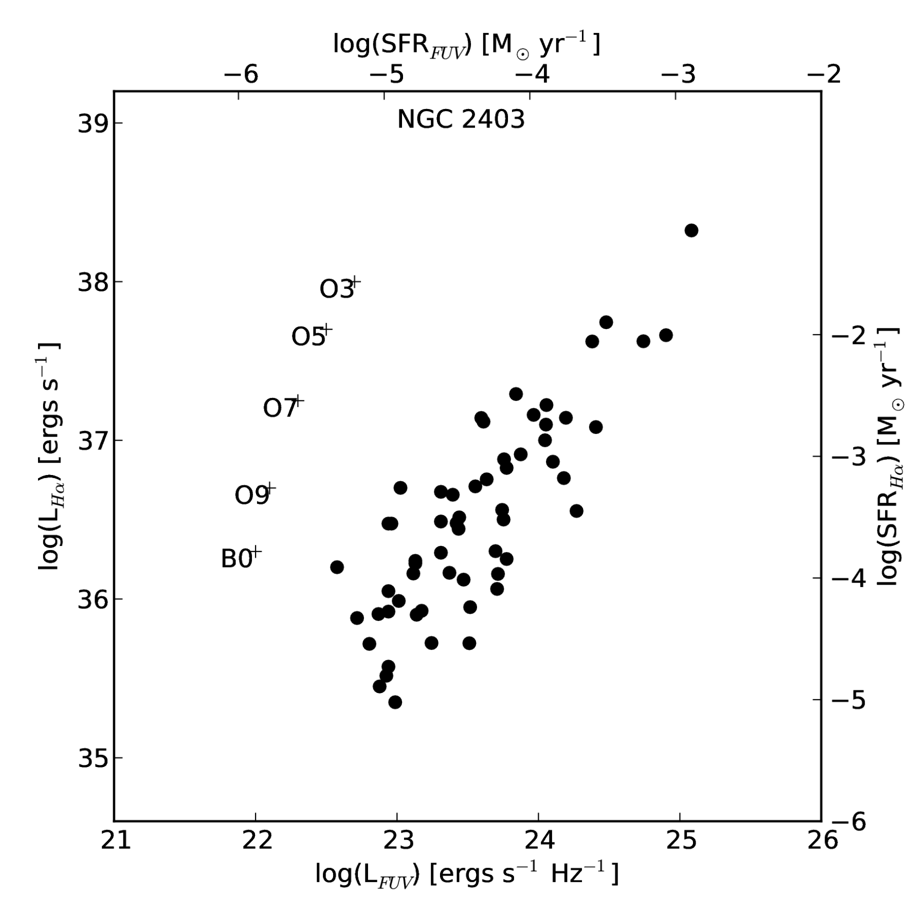
FUV

Star formation and HI: NGC 2403

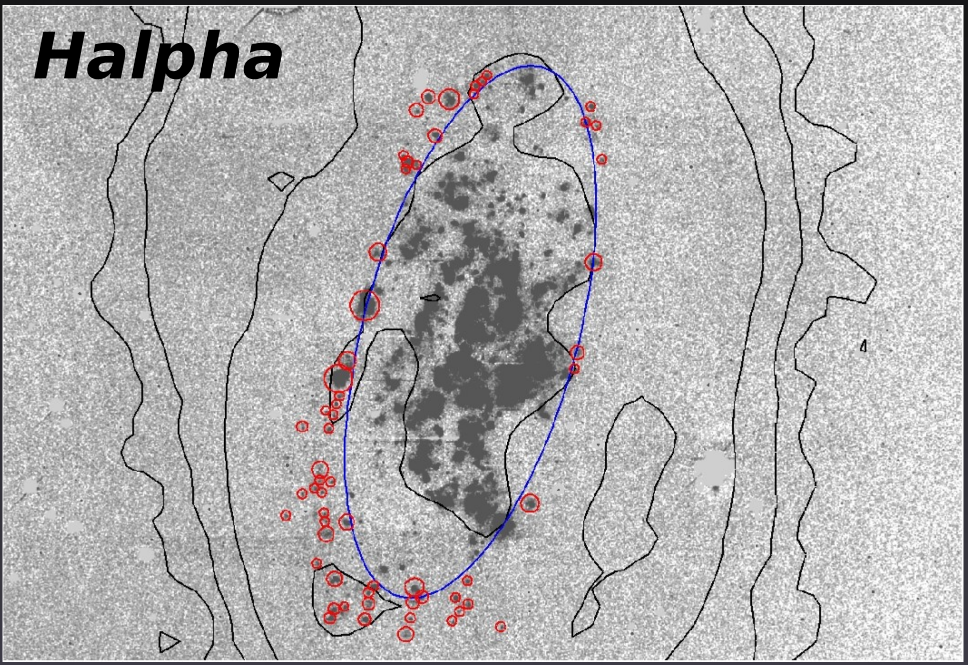


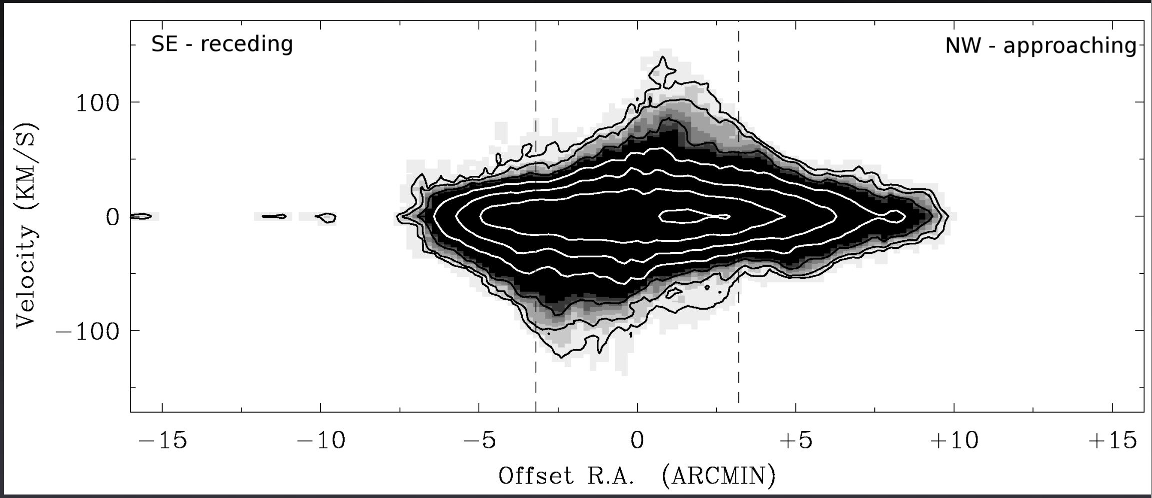


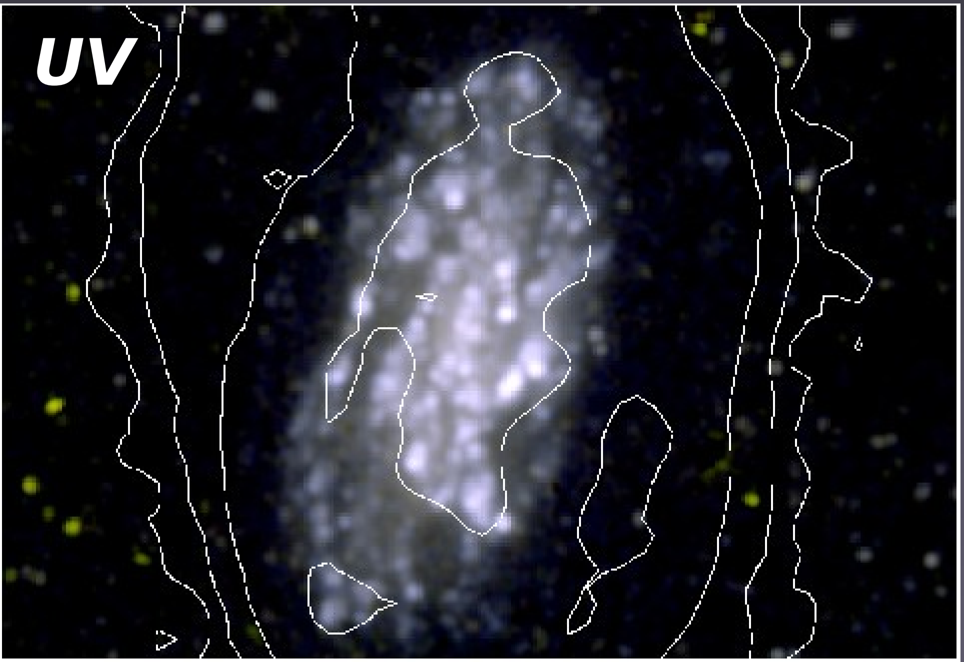


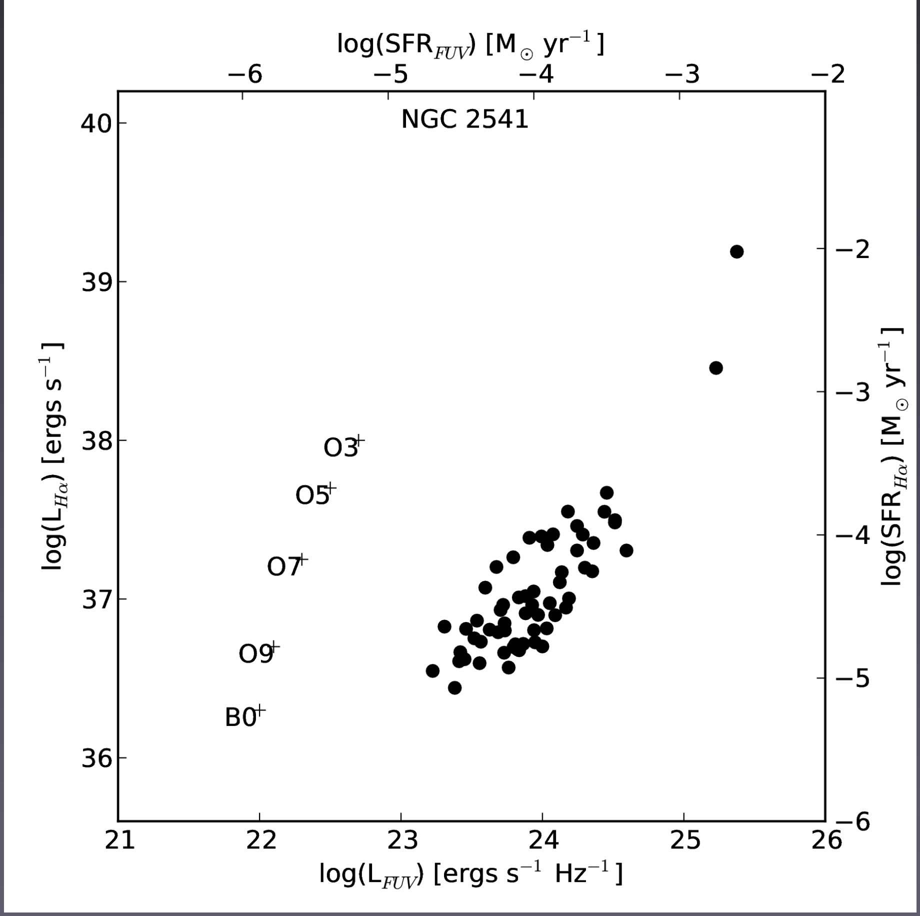


Star formation and HI: NGC 2541

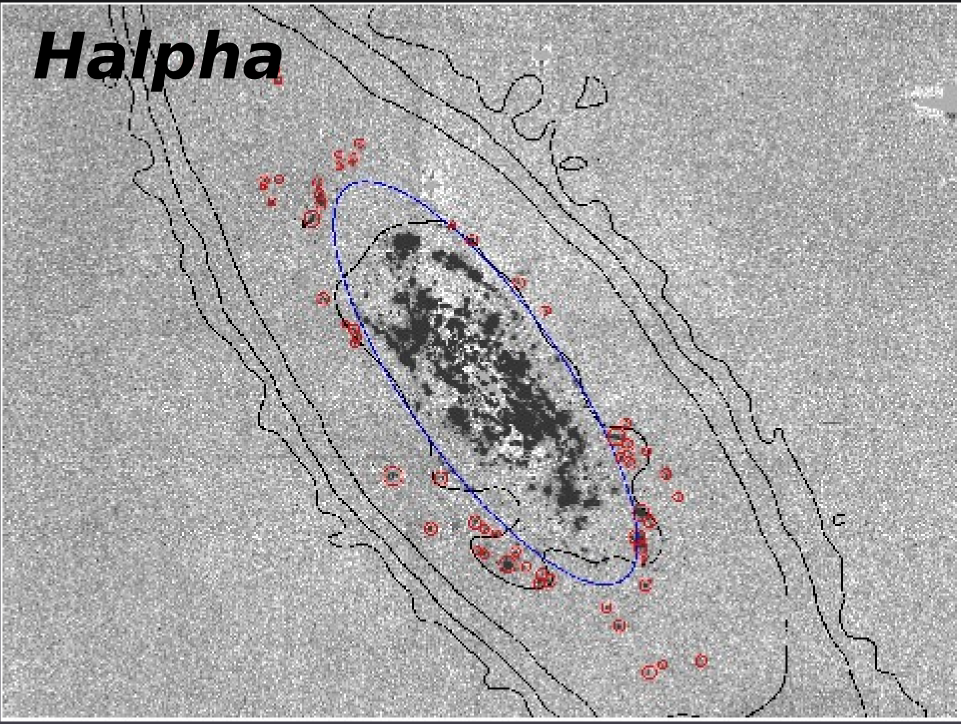


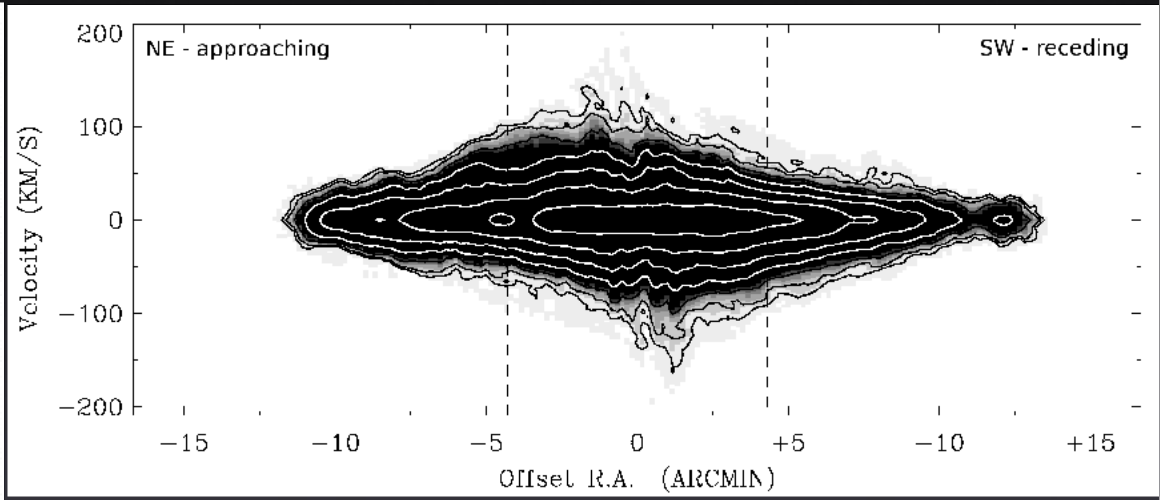


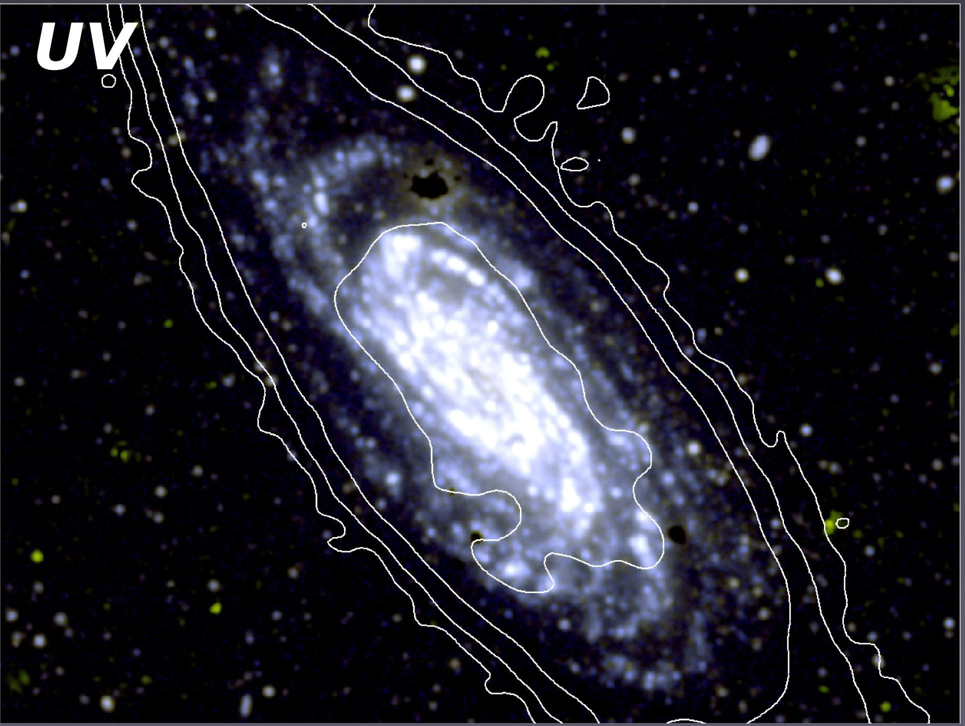


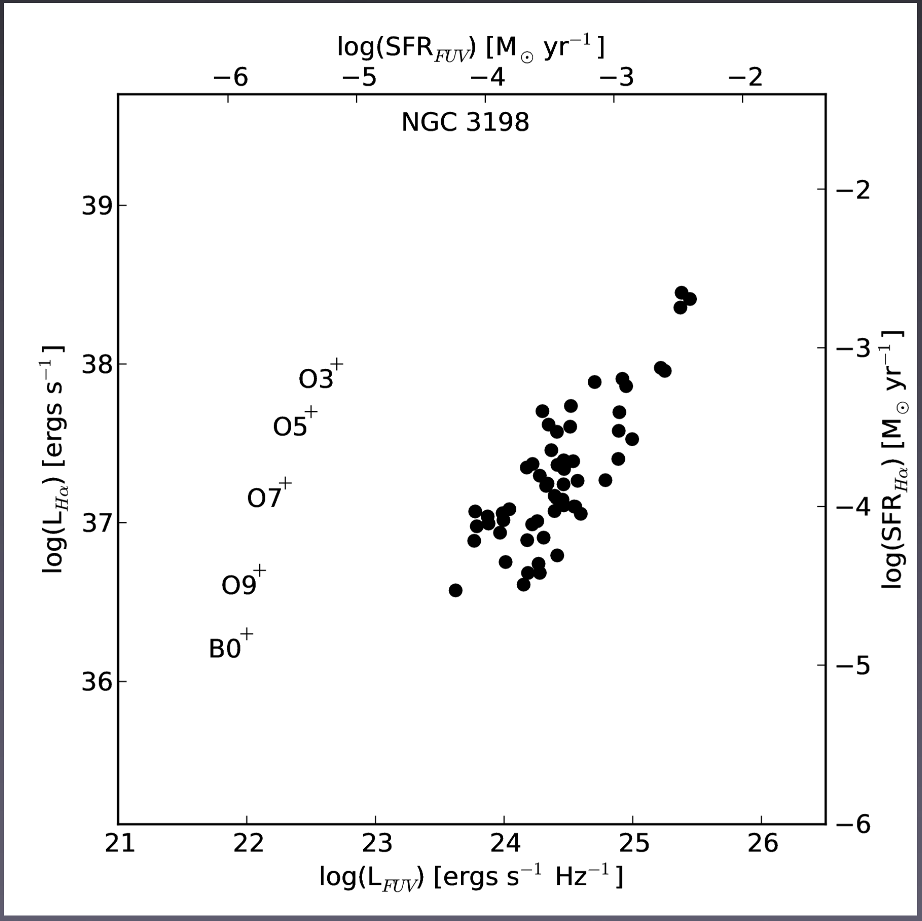


Star formation and HI: NGC 3198

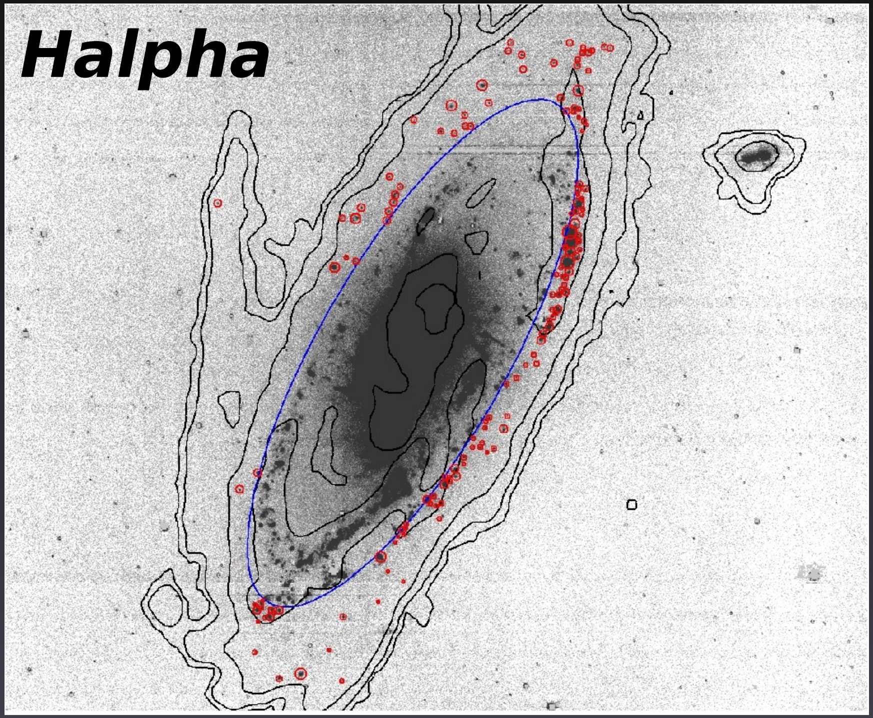


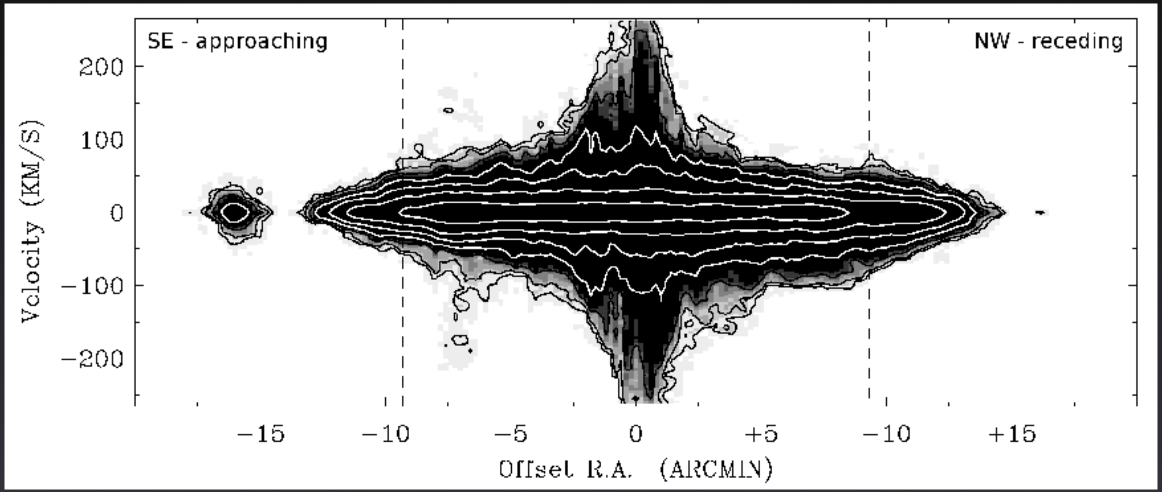


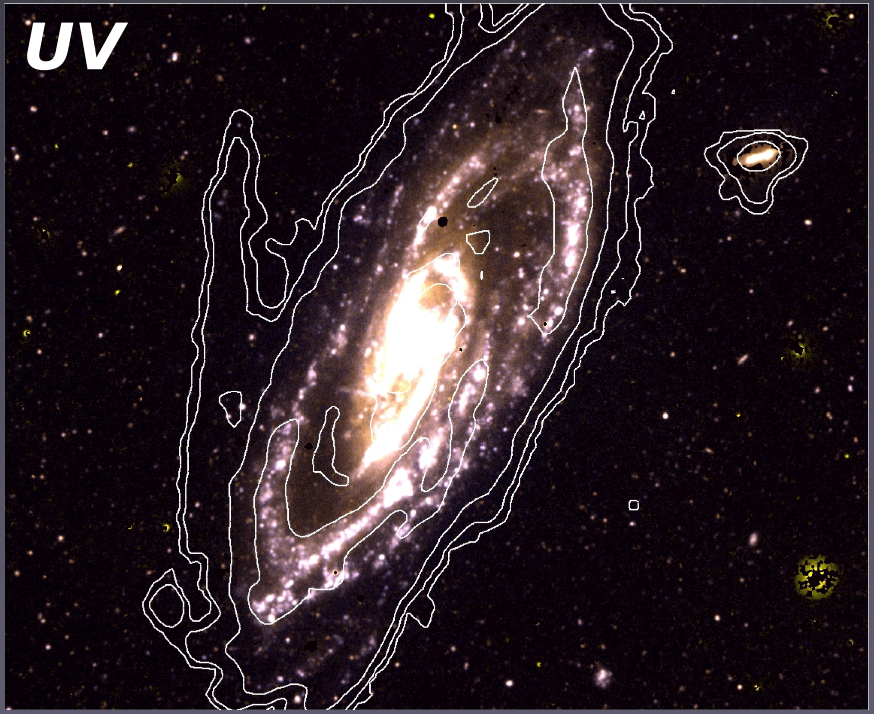


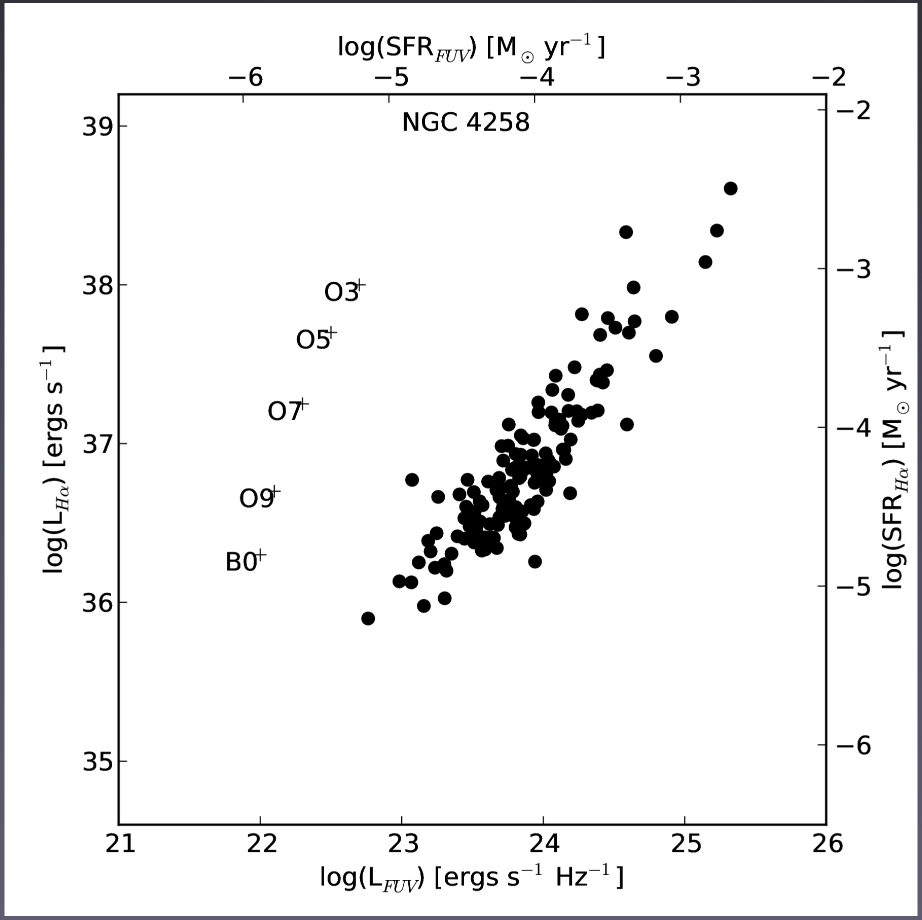


Star formation and HI: NGC 4258

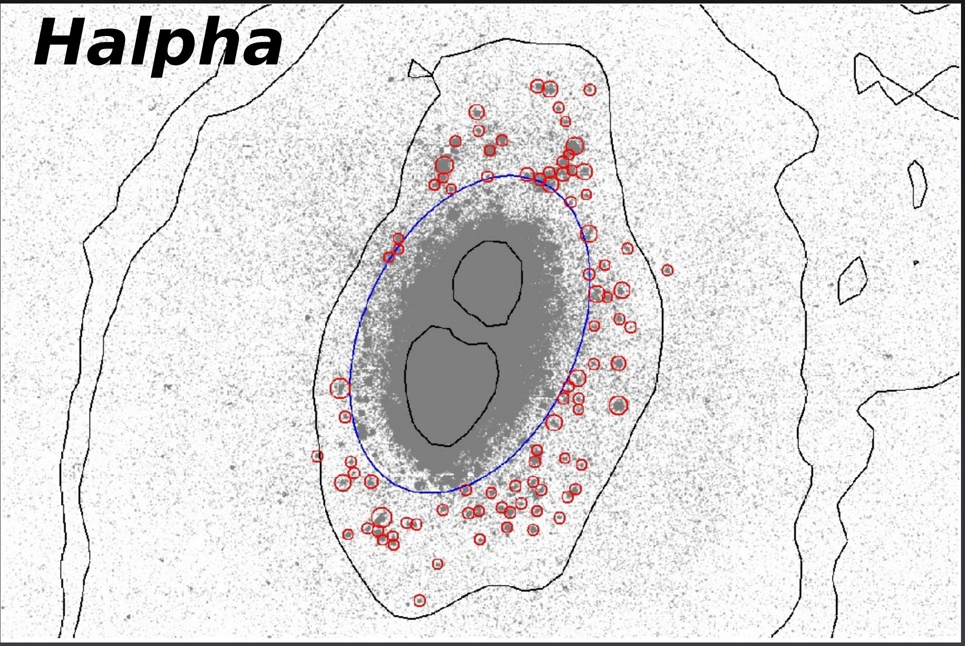


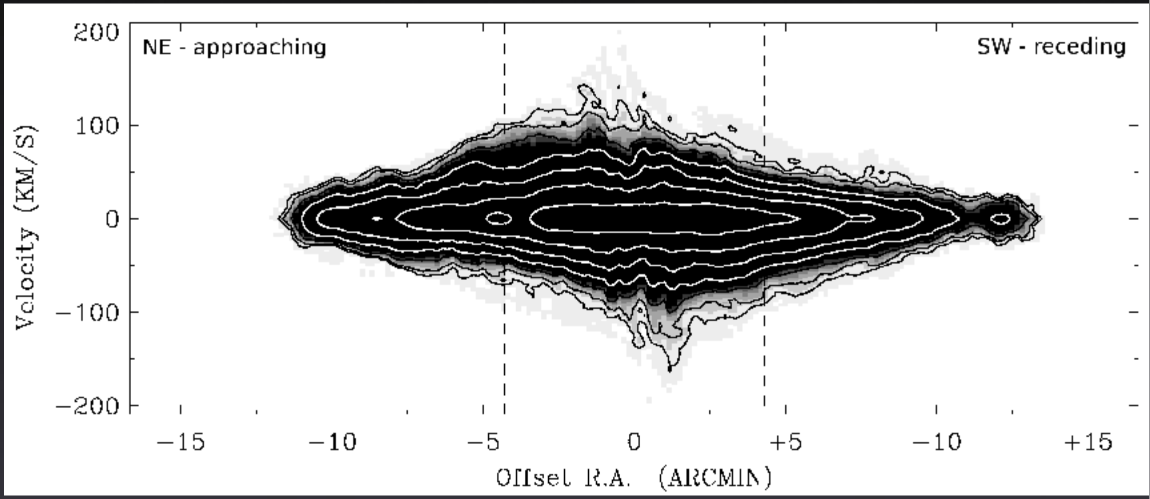


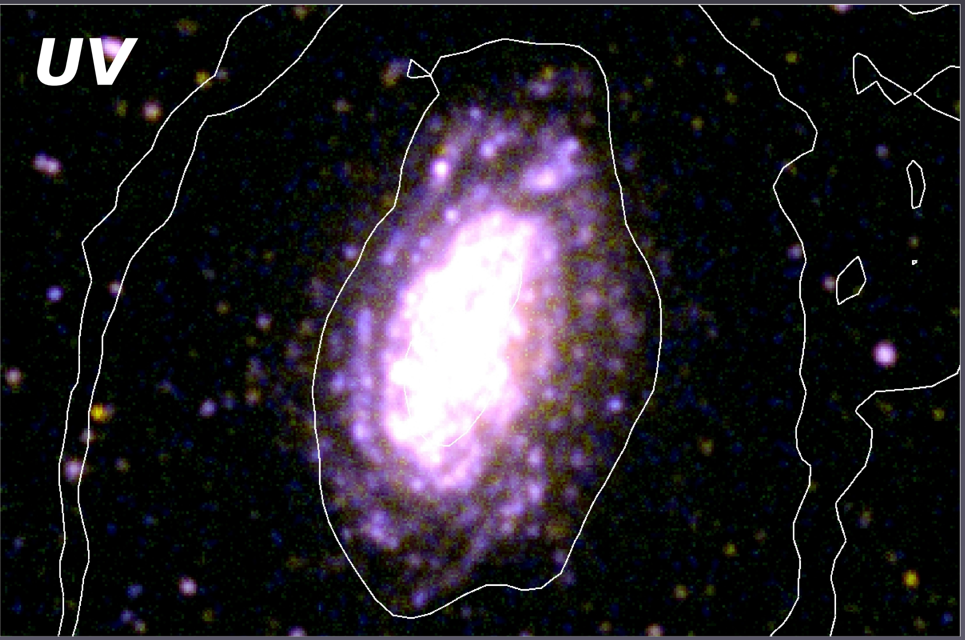


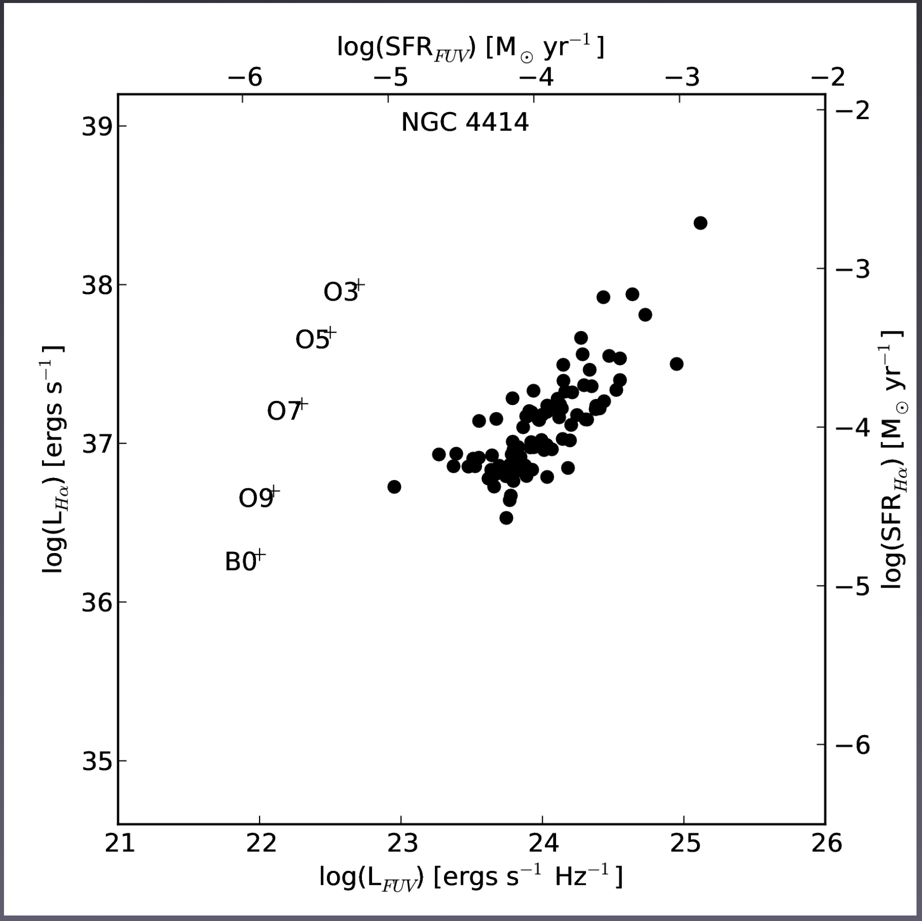


Star formation and HI: NGC 4414

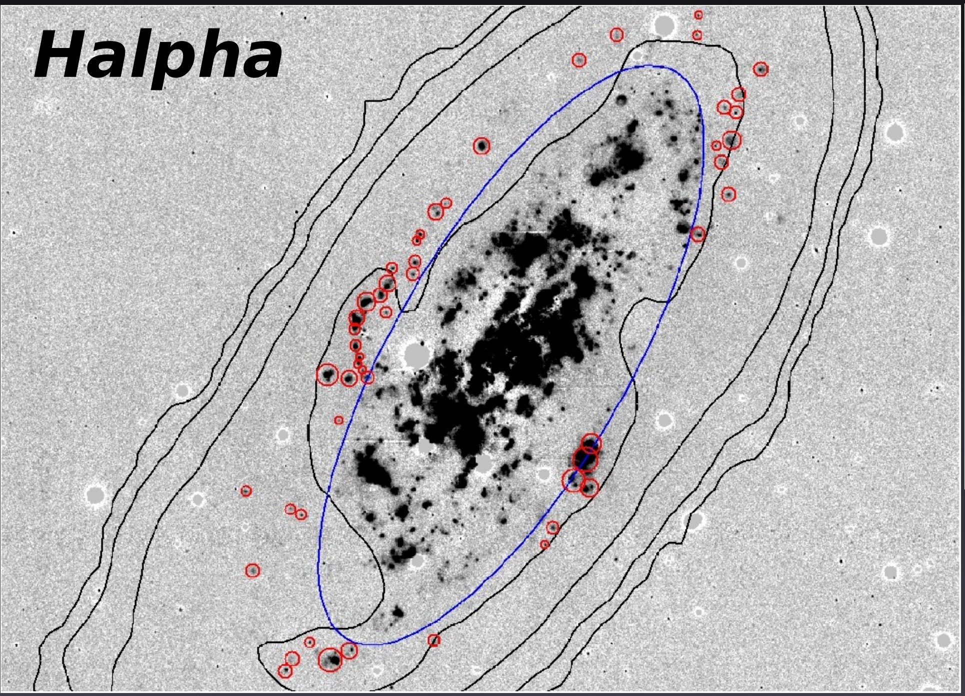


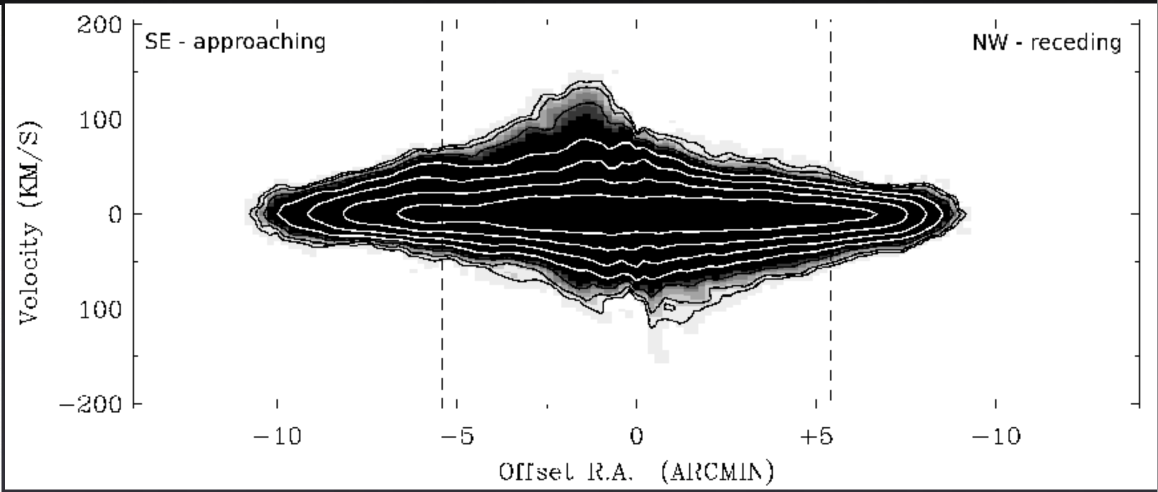


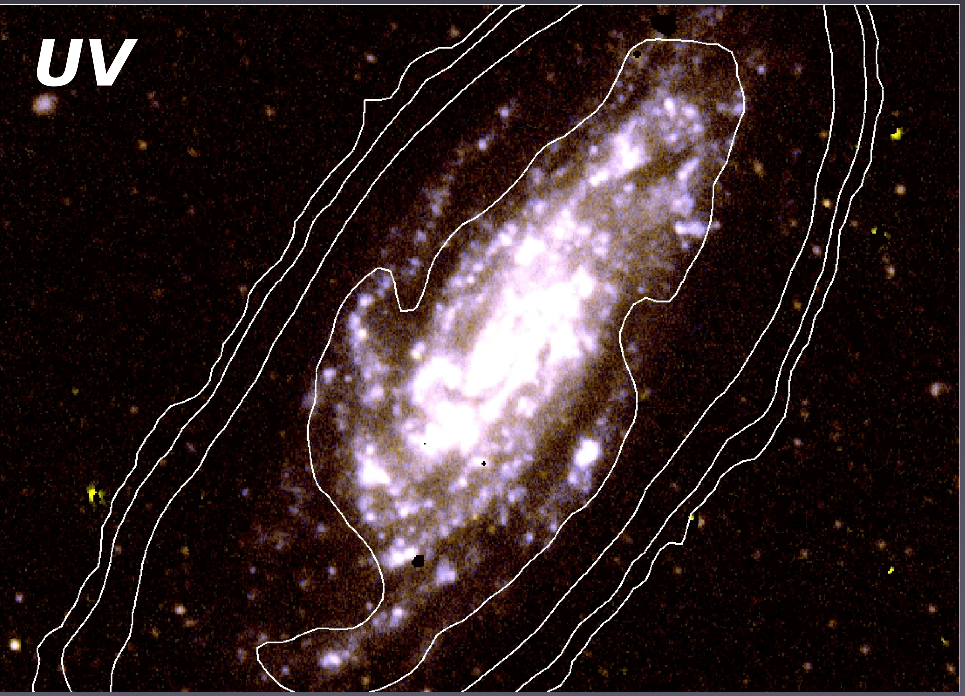


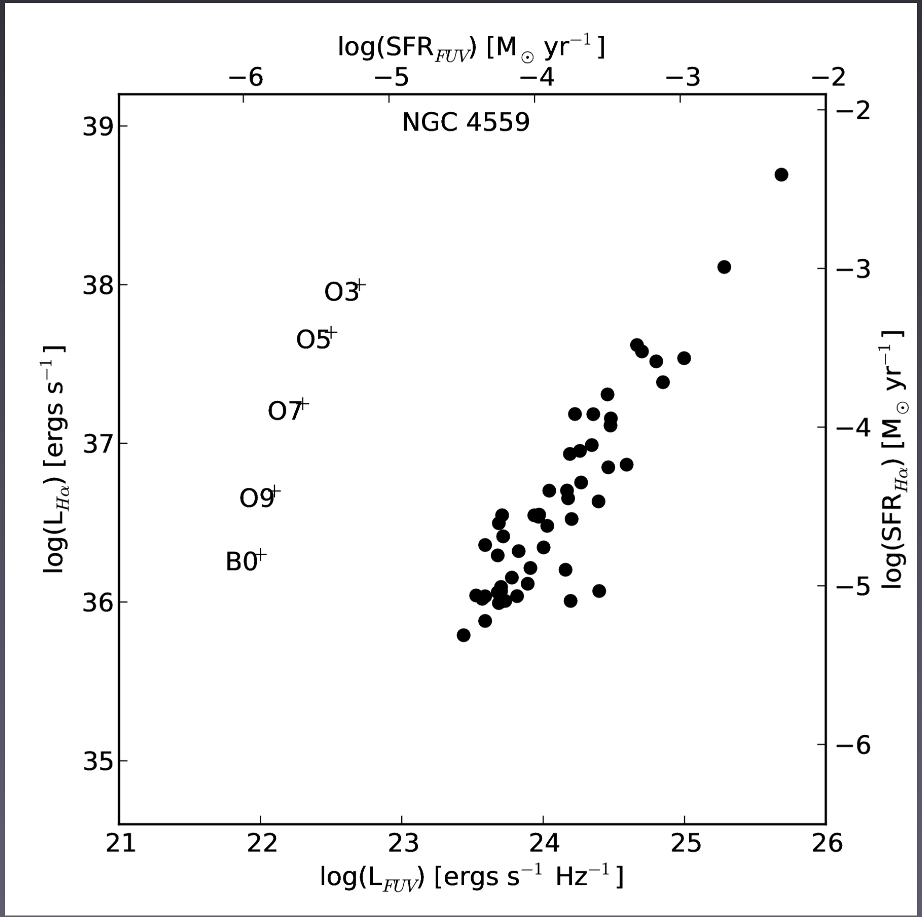


Star formation and HI: NGC 4559

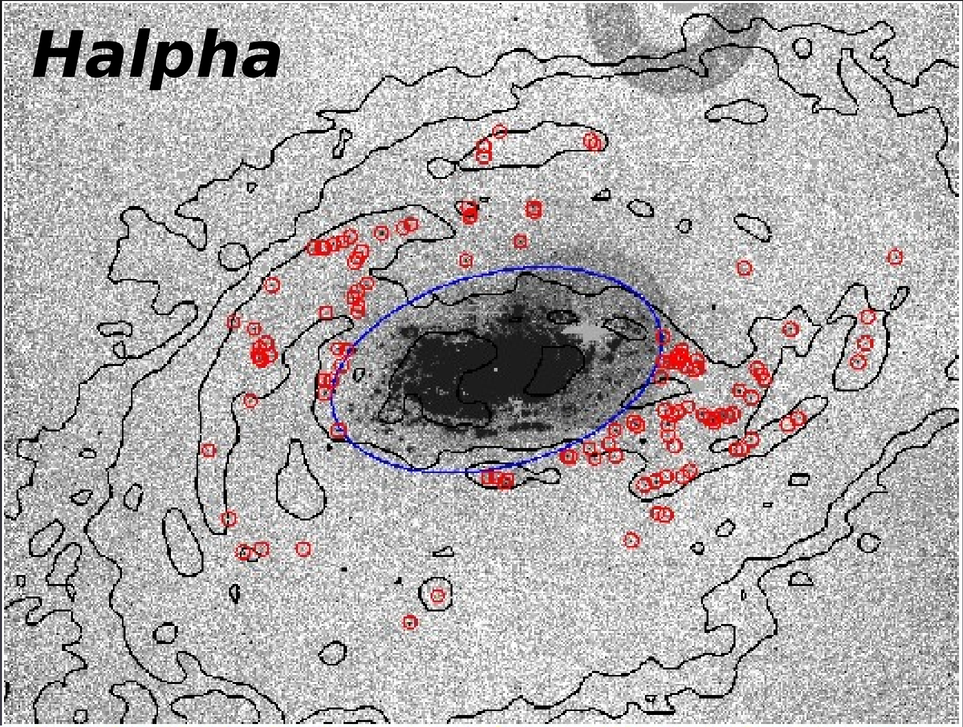


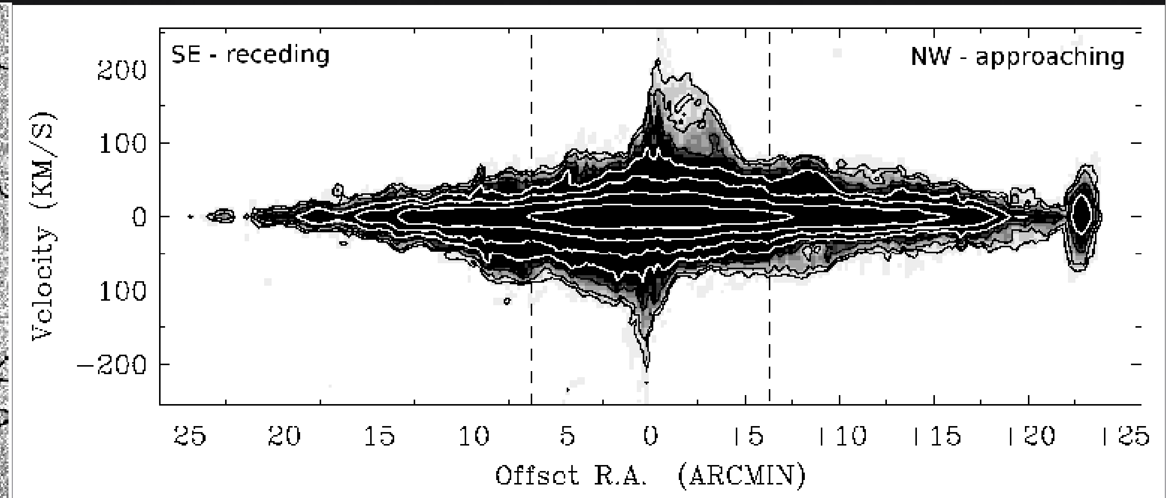


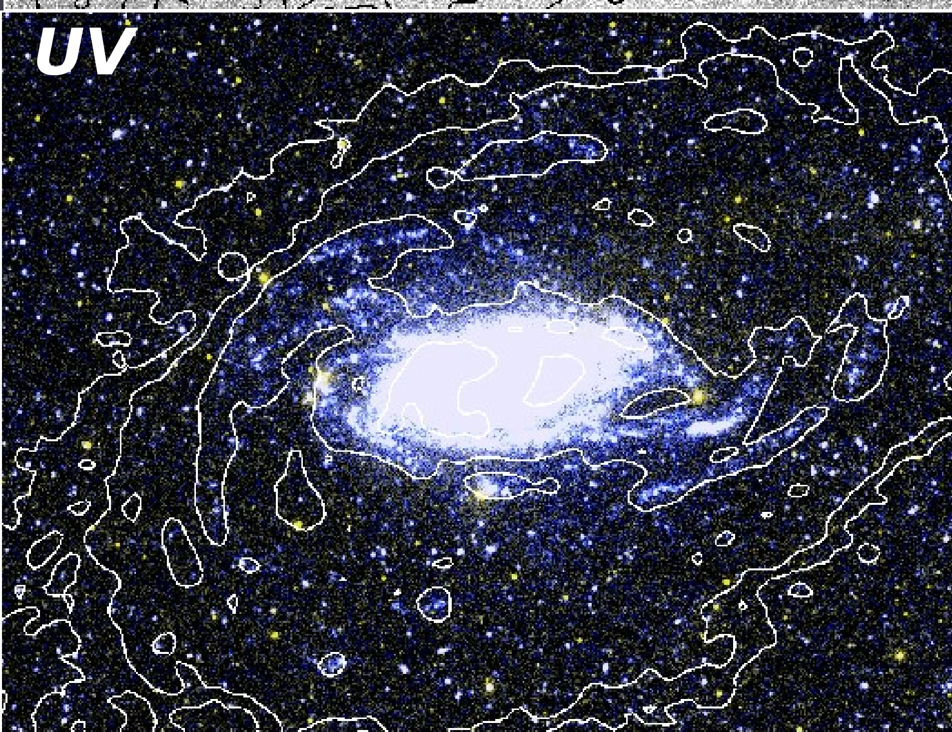


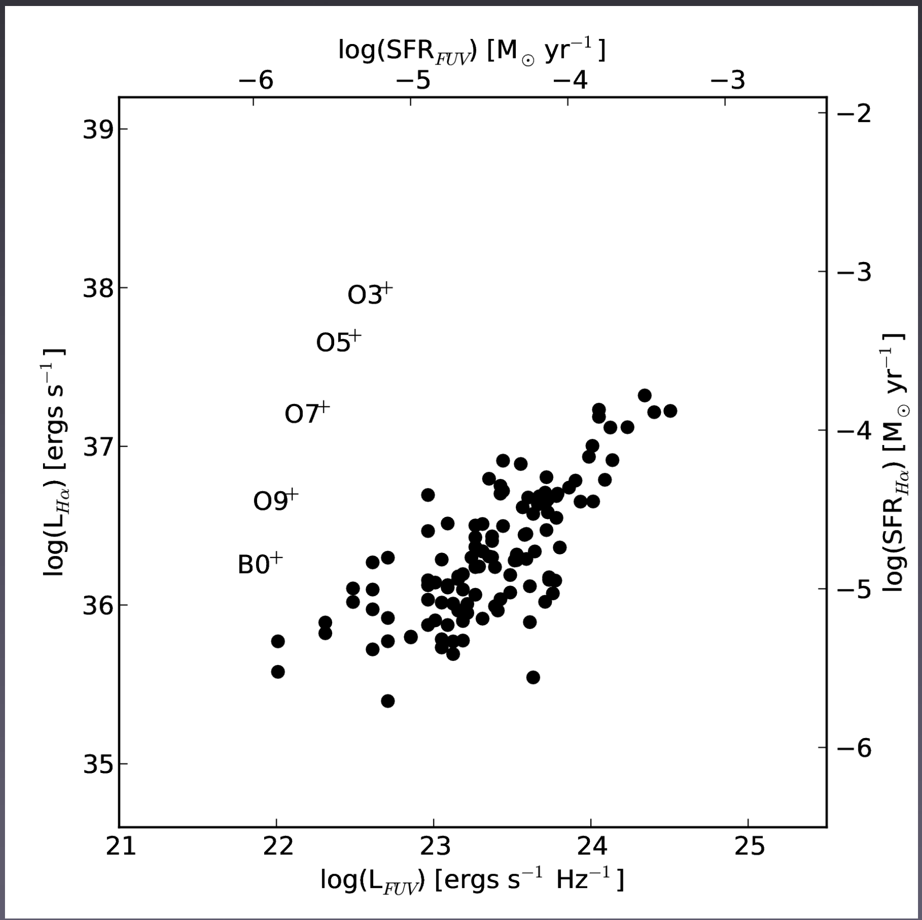


Star formation and HI: NGC 5055





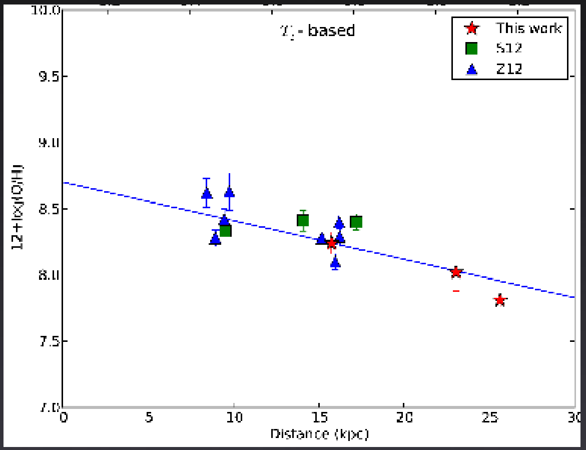




Theses (Dutch style): Properties of gas, star formation, and life

Metallicity gradients

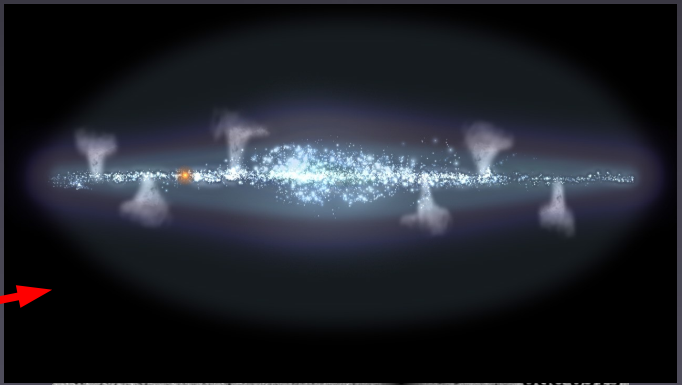
- HII region gradient of M81 is
  ~ -0.013 dex/kpc (strong line)
  ~ -0.020 dex/kpc (temp) *(Ch 2)*.



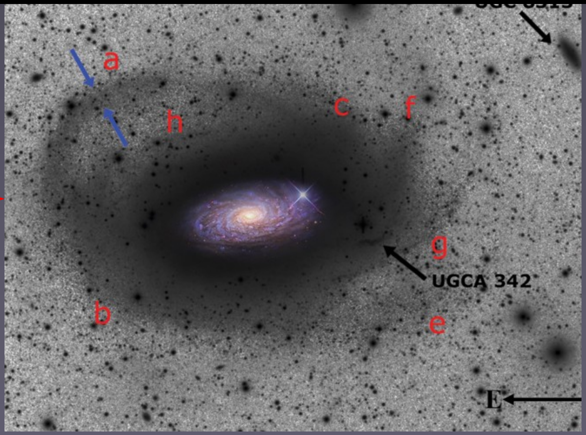
- HII region gradient of M31 is
  ~ -0.018 dex/kpc (strong line)
  ~ -0.028 dex/kpc (temp) *(Ch 3)*.

- Slopes of strong line gradients are relatively consistent but not good for absolute abundances *(Ch 2 & 3)*.

Gaseous halos



- Evidence for 'lagging halo' gas likely blown out of the disc by star formation *(Ch 4 & 5)*.

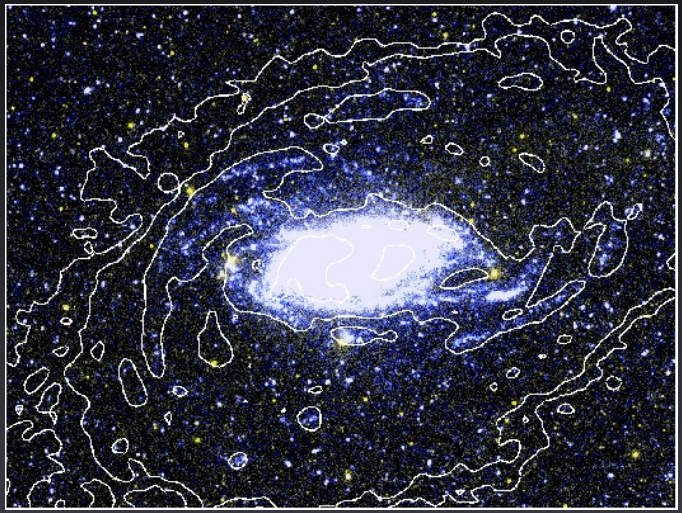


- NGC 5055 shows anomalous velocity gas cloud that may have been accreted during a recent merger *(Ch 4)*.

Theses (Dutch style):
Properties of gas, star formation, and life

Outer disc star forming conditions:

- Requires column density of HI few times 10^{20} cm^{-2} *(Ch 4 & 5)*.
- HII regions consist of single ionizing massive stars and many lower mass non-ionizing stars *(Ch 4 & 5)*.



Other observations:

- It is *clearly* possible to have doubly ionized hydrogen...if the hydrogen is in the form of H- *(inferred from Chris's class)*.
- Timeline for any thesis is always 2 years and has no basis in reality *(any proposal)*.
- Gas : stars :: Diet Dr Pepper : my thesis, ie., fuel, requires relatively high density *(office 108 recycling bin)*.
- $$Stress(\text{grad office}) \equiv C_1 \sum_i \left(\frac{X_{grad,i}}{(t_{D\text{-}day,i} - t)^2} \right) - C_2 N_{dachshunds}$$

  (see, e.g, office 108).

Future Work

Metallicity gradients:

- More HII regions with electron temperature abundances.
- Different strong line calibrations.

Gaseous halos:

- Finish analysis of entire HALOGAS sample.
- Deep optical data for stellar streams.

Outer disc star formation:

- Select by UV emission.
- Look at non-XUV disc galaxies.