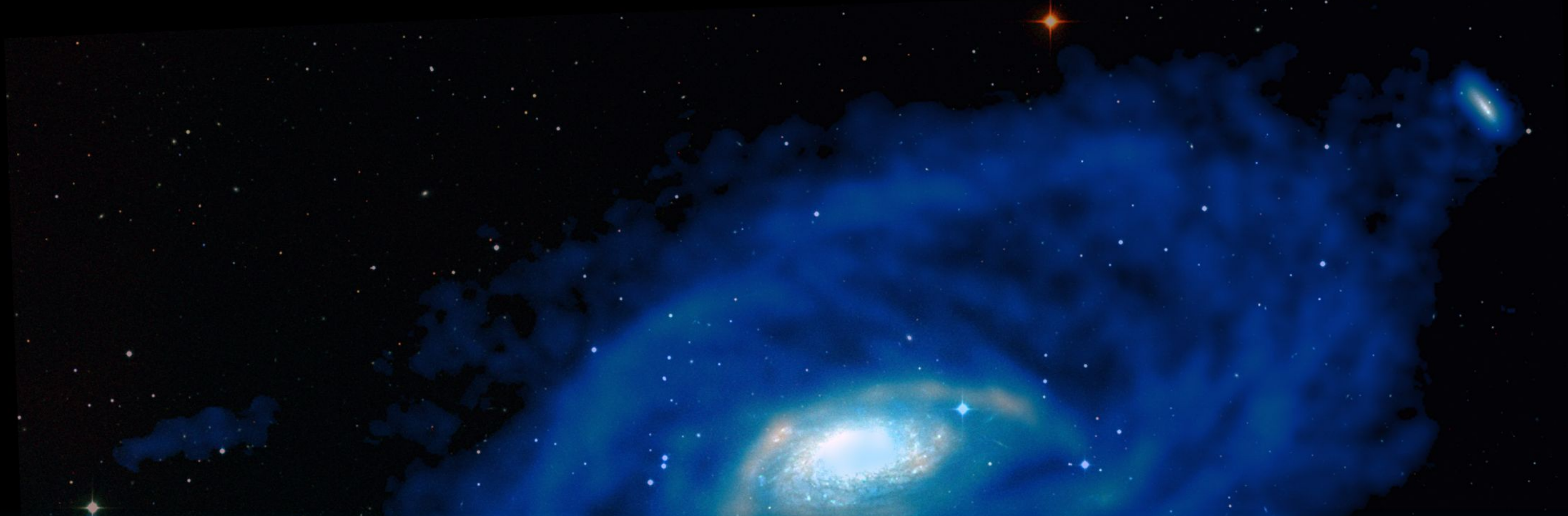


The WSRT HALOGAS Survey

Main Results and Public Data Release

George Heald and the HALOGAS team

Outline

- Recap of science case and galaxy sample
- HALOGAS observations and ancillary data
- Results and publications
- Main outcomes
- Public data releases
  - DR1 (12 February 2019) - WSRT HI cubes and moment maps
  - DR2 (31 May 2019) - Ancillary data
- Timeline for final publications, and moving forward ...

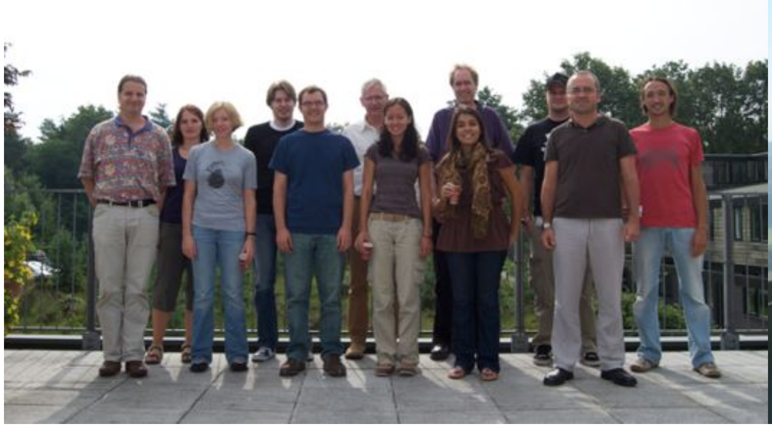
Motivation

Motivation for HALOGAS project was similar to the MHONGOOSE science case

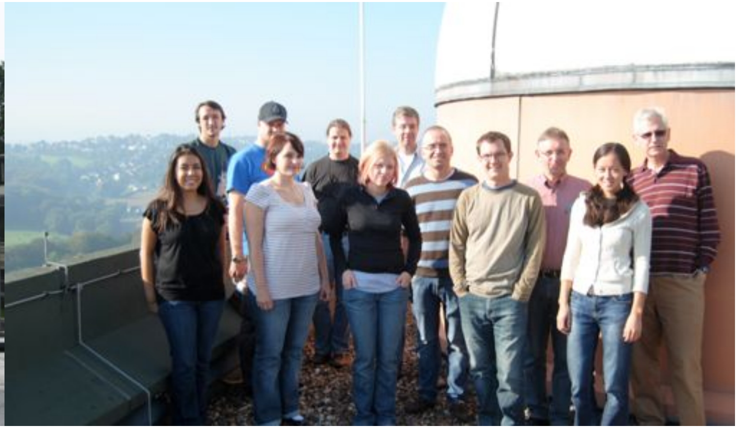
- How common are thick HI disks and what are their properties?
- What is the origin of thick disks, and how are they related to star formation and/or the gas accretion process?
- How much cool neutral hydrogen surrounds spiral galaxies, in what form is it typically found, and what is its contribution to the gas accretion process?
- Is accreting neutral hydrogen a substantial contributor to the gas mass budget in the star formation process?

HALOGAS team past & present

George Heald, Björn Adebahr, Nadya Ben Bekhti, Bob Benjamin, **Erwin de Blok**, Ralf-Jürgen Dettmar, Lars Flöer, Filippo Fraternali, Gianfranco Gentile, Mark Gorski, Noelia Herrera-Ruiz, Gyula Jozsa, Eva Jütte, Peter Kamphuis, Antonino Marasco, Tom Oosterloo, Maria Patterson, **Nick Pingel**, Rich Rand, Renzo Sancisi, **Paolo Serra**, Carlos Vargas, Rene Walterbos, Benjamin Winkel, Cat Wu, Laura Zschaechner



2010 (Dwingeloo, The Netherlands)



2011 (Bochum, Germany)

HALOGAS sample

- 24 nearby galaxies, selected on properties not related to HI content:
  - Hubble type Sa-Sd (barred and unbarred)
  - Declination > +25°
  - Distance (Tully 1988) < 11 Mpc
  - $D_{25} > 3'$
  - $V_{sys} > 100$ km/s
  - Inclination: moderate (50° ≤ i ≤ 75°) or edge-on (i ≥ 85°)
- This results in a broad range of galaxy morphology: one close pair, several massive spirals, wide span in SFR

THE HALOGAS SAMPLE

NGC 672	NGC 4258
NGC 891	NGC 4274
NGC 925	NGC 4414
NGC 949	NGC 4448
UGC 2082	NGC 4559
NGC 1003	NGC 4565
NGC 2403	UGC 7774
UGC 4278	NGC 4631
NGC 2541	NGC 5023
NGC 3198	NGC 5055
NGC 4062	NGC 5229
NGC 4244	NGC 5585

WSRT observations

- Primary observations: 10x12hr in WSRT Maxishort configuration
- 10 MHz line bandwidth, 1024 channels (velocity resolution 4.12 km/s after Hanning smoothing)
- Second half of survey: line band supplemented (“for free”) with 4x20 MHz full-polarization continuum bands
- Typical noise level ~ 0.2 mJy/beam per 4.12 km/s channel
- Column density sensitivity ~ 1×10^{19} cm^{-2}
- Unresolved cloud mass sensitivity (at D=10 Mpc) ~ 2×10^{5} $M_{\odot}$


Halogas

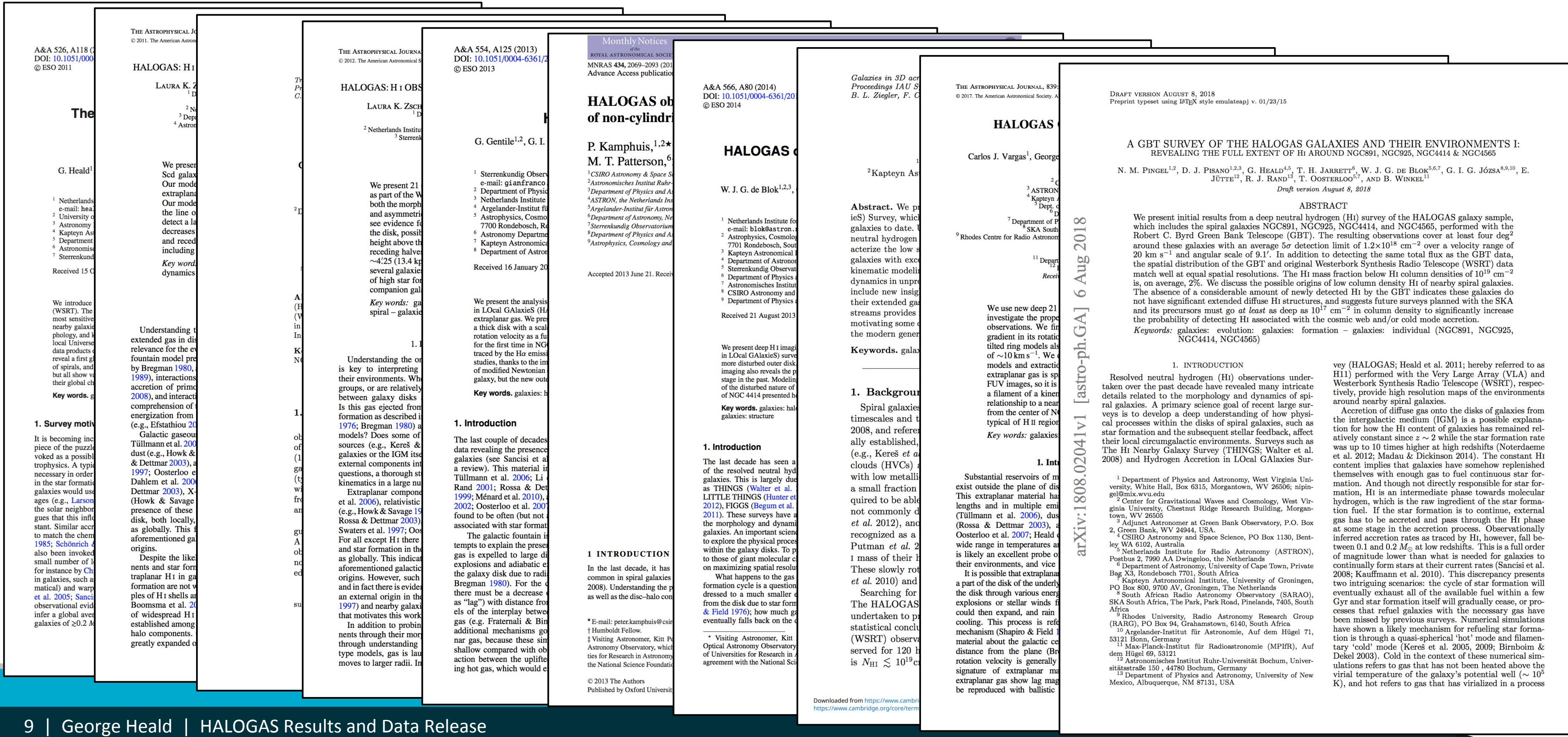
Ancillary data

Several other datasets have been collected to supplement the main HI data

- Search for stellar counterparts to outer-disk gas and probe disk star formation
  - Deep, widefield R-band imaging on INT (“HALOSTARS” project, PI Jozsa)
  - Deep, widefield UBRHα imaging at KPNO (PI Patterson)
- Probe extended, low column density gas in outer parts and fill short spacings
  - Single-dish HI data from GBT (PIs Pingel, Pisano)
  - Single-dish HI data from Effelsberg (PIs Heald, Winkel)

Release of these data is planned for HALOGAS-DR2 (more about this later)

HALOGAS publications



Draft version August 8, 2018
Preprint typeset using LaTeX style emulateapj v. 01/23/15

A GBT SURVEY OF THE HALOGAS GALAXIES AND THEIR ENVIRONMENTS I: REVEALING THE FULL EXTENT OF HI AROUND NGC891, NGC925, NGC4414 & NGC4565

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Draft version August 8, 2018

arXiv:1808.02041v1 [astro-ph.GA] 6 Aug 2018

ABSTRACT

We present initial results from a deep neutral hydrogen (HI) survey of the HALOGAS galaxy sample, which includes the spiral galaxies NGC891, NGC925, NGC4414, and NGC4565, performed with the Robert C. Byrd Green Bank Telescope (GBT). The resulting observations cover at least four deg^2 around these galaxies with an average 5σ detection limit of 1.2×10^{18} cm^{-2} over a velocity range of 20 km s^{-1} and angular scale of 9.1′. In addition to detecting the same total flux as the GBT data, the spatial distribution of the GBT and original Westerbork Synthesis Radio Telescope (WSRT) data match well at equal spatial resolutions. The HI mass fraction below HI column densities of 10^{19} cm^{-2} is, on average, 2%. We discuss the possible origins of low column density HI of nearby spiral galaxies. The absence of a considerable amount of newly detected HI by the GBT indicates these galaxies do not have significant extended diffuse HI structures, and suggests future surveys planned with the SKA and its precursors must go *at least* as deep as 10^{17} cm^{-2} in column density to significantly increase the probability of detecting HI associated with the cosmic web and/or cold mode accretion.

Keywords: galaxies: evolution: galaxies: formation – galaxies: individual (NGC891, NGC925, NGC4414, NGC4565)

1. INTRODUCTION

Resolved neutral hydrogen (HI) observations undertaken over the past decade have revealed many intricate details related to the morphology and dynamics of spiral galaxies. A primary science goal of recent large surveys is to develop a deep understanding of how physical processes within the disks of spiral galaxies, such as star formation and the subsequent stellar feedback, affect their local circumgalactic environments. Surveys such as The HI Nearby Galaxy Survey (THINGS; Walter et al. 2008) and Hydrogen Accretion in LOcal GAlaxies Survey (HALOGAS; Heald et al. 2011; hereby referred to as H11) performed with the Very Large Array (VLA) and Westerbork Synthesis Radio Telescope (WSRT), respectively, provide high resolution maps of the environments around nearby spiral galaxies.

Accretion of diffuse gas onto the disks of galaxies from the intergalactic medium (IGM) is a possible explanation for how the HI content of galaxies has remained relatively constant since $z \sim 2$ while the star formation rate was up to 10 times higher at high redshifts (Noterdaeme et al. 2012; Madau & Dickinson 2014). The constant HI content implies that galaxies have somehow replenished themselves with enough gas to fuel continuous star formation. And though not directly responsible for star formation, HI is an intermediate phase towards molecular hydrogen, which is the raw ingredient of the star formation fuel. If the star formation is to continue, external gas has to be accreted and pass through the HI phase at some stage in the accretion process. Observationally inferred accretion rates as traced by HI, however, fall between 0.1 and 0.2 $M_\odot$ at low redshifts. This is a full order of magnitude lower than what is needed for galaxies to continually form stars at their current rates (Sancisi et al. 2008; Kauffmann et al. 2010). This discrepancy presents two intriguing scenarios: the cycle of star formation will eventually exhaust all of the available fuel within a few Gyr and star formation itself will gradually cease, or processes that refuel galaxies with the necessary gas have been missed by previous surveys. Numerical simulations have shown a likely mechanism for efficient star formation is through a quasi-spherical 'hot' mode and filamentary 'cold' mode (Kereš et al. 2005, 2009; Birnboim & Dekel 2003). Cold in the context of these numerical simulations refers to gas that has not been heated above the virial temperature of the galaxy's potential well ($\sim 10^5$ K), and hot refers to gas that has virialized in a process

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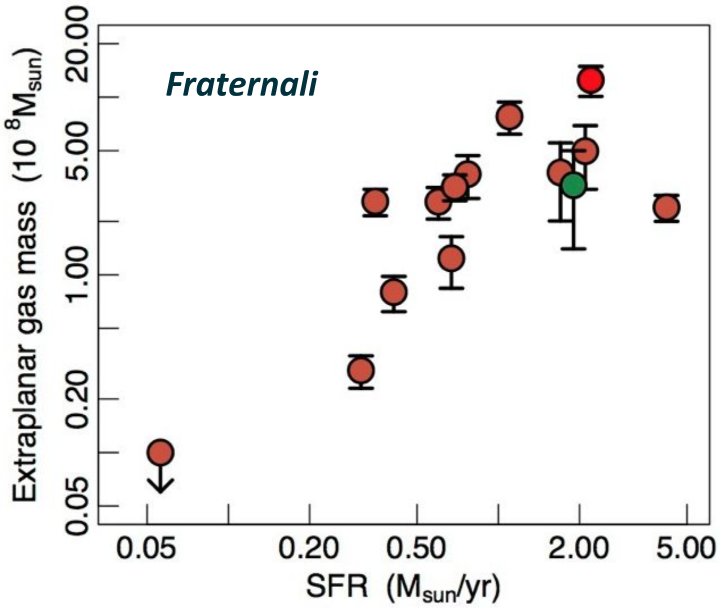
HALOGAS primary outcomes: I

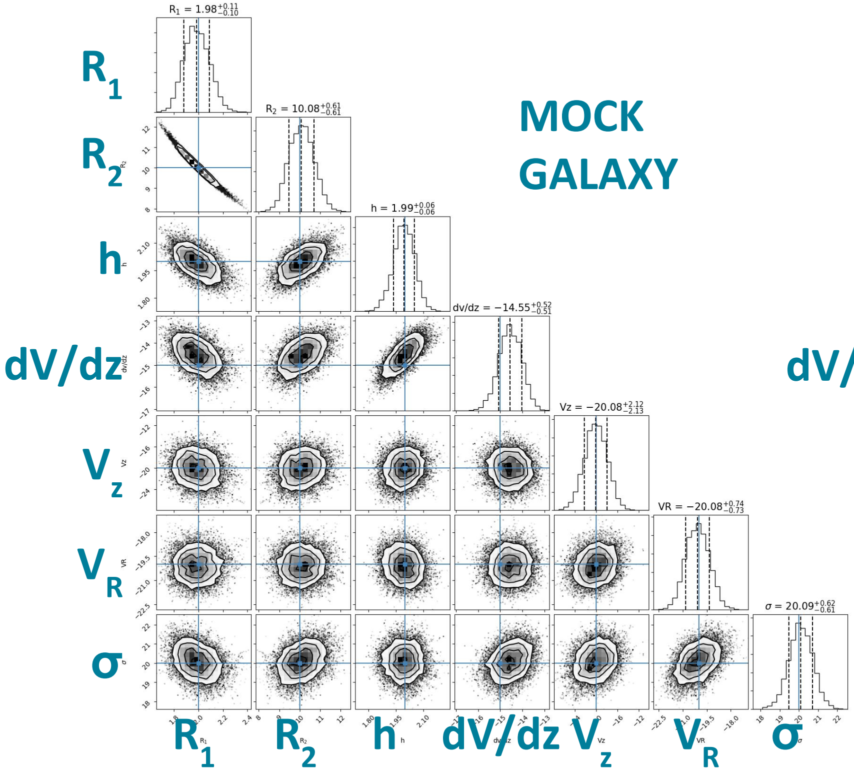
Properties of thick HI disks and their connection to star formation activity in the thin disk

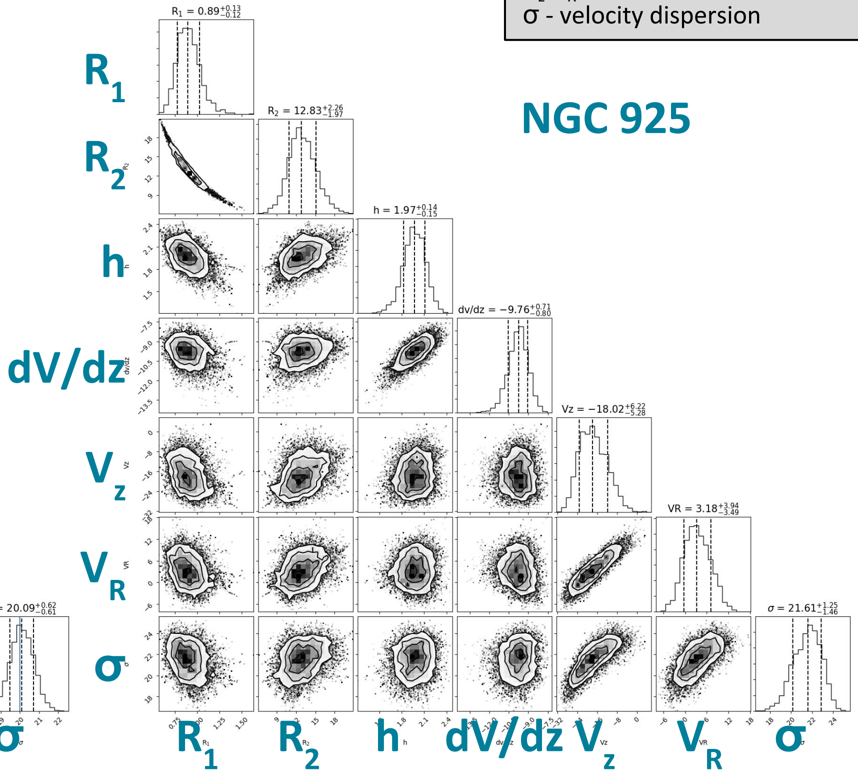
- Preliminary: ***mass*** and ***extent*** of extraplanar HI layers correlate with SFR
- Now using consistent MCMC-based fitting algorithm to constrain model parameters for thick disk gas (Marasco et al, in prep)
- All modeled galaxies show a rotational gradient with height, and most also show inflow



HALOGAS primary outcomes: I

<u>Model parameter index</u>
R_1, R_2 - define the radial gas density distribution
h - gas density scale height
dV/dz - vertical gradient in rotational velocity
V_z, V_R - vertical and radial velocities
σ - velocity dispersion



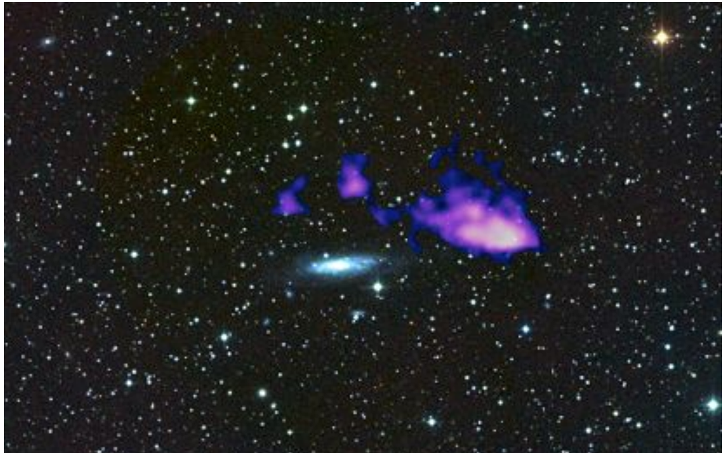


Marasco et al (in prep)

HALOGAS primary outcomes: II

Very few (but not zero!) HI clouds detected around HALOGAS galaxies

- What is the implied maximum admitted accretion rate?
- Detailed source finding effort underway, searching for mock injected clouds
- Preliminary results suggest that at most ~10% of SFR can typically be accommodated given the HALOGAS detection limits
- Final outcome to be presented by Herrera-Ruiz et al (in prep)
- Forthcoming survey efforts (IMAGINE, MHONGOOSE) crucially search larger areas



NGC 1003: DSS + HVC analogs

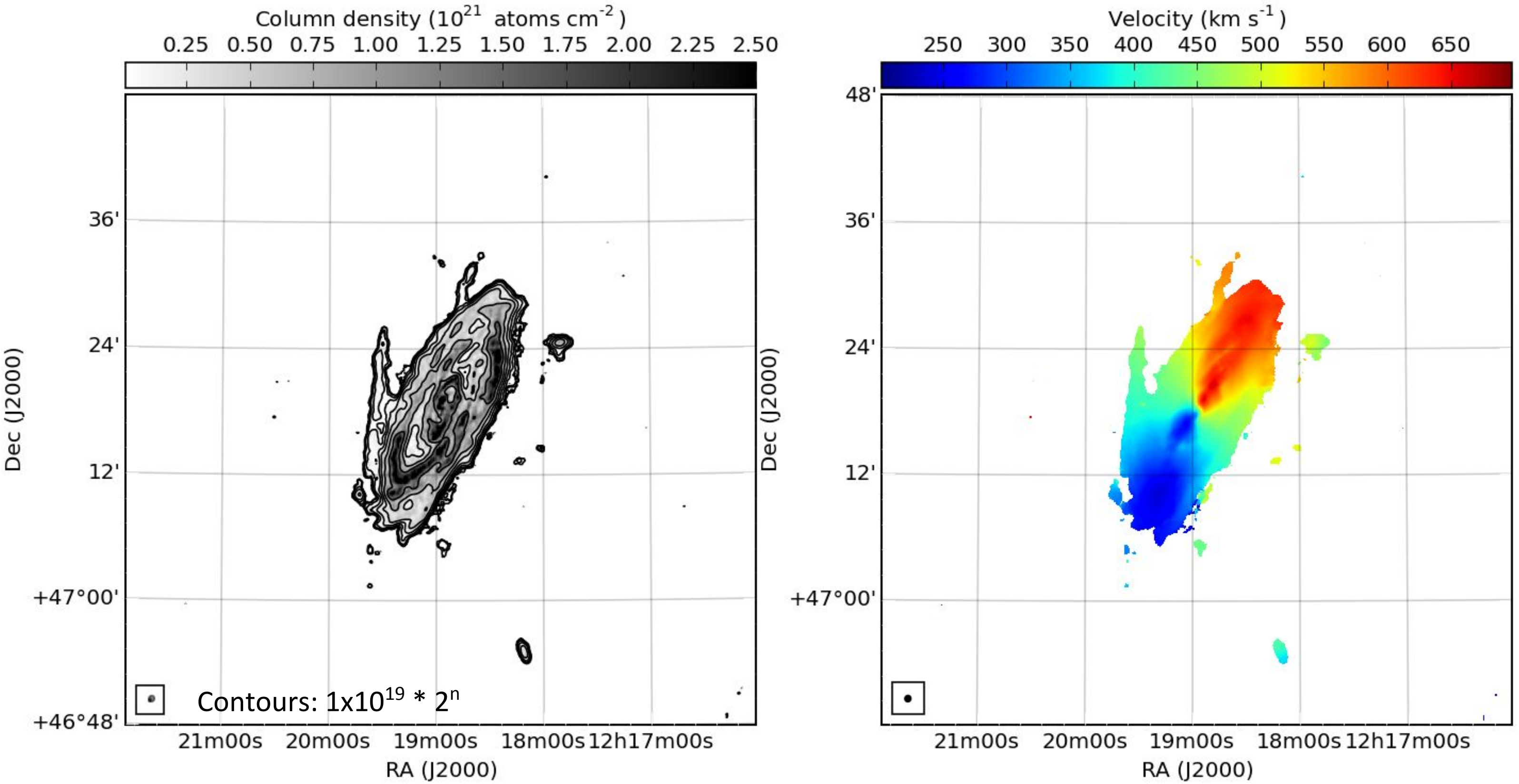
HALOGAS DR1

Data release comprises the following products (for all 24 galaxies):

- Low resolution (~30” or typically ~1.5 kpc)
    - Data cube
    - Moment-0 and column density images
    - Moment-1 (average velocity) image
- High resolution (~15” or typically ~0.7 kpc)
    - Data cube
    - Moment-0 and column density images
    - Moment-1 (average velocity) image

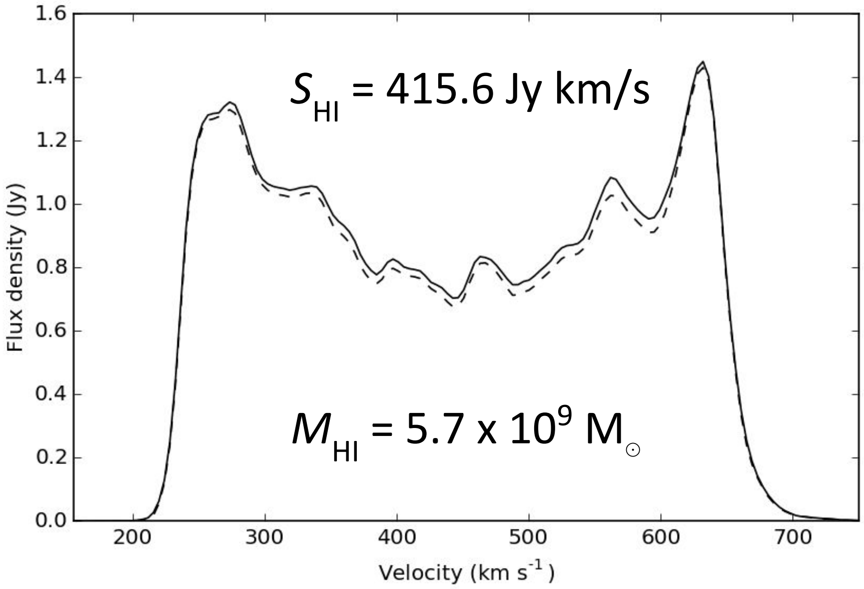
Data for NGC 891 from Oosterloo+ (2007); NGC 2403 from Fraternali+ (2002)

HALOGAS DR1: NGC 4258

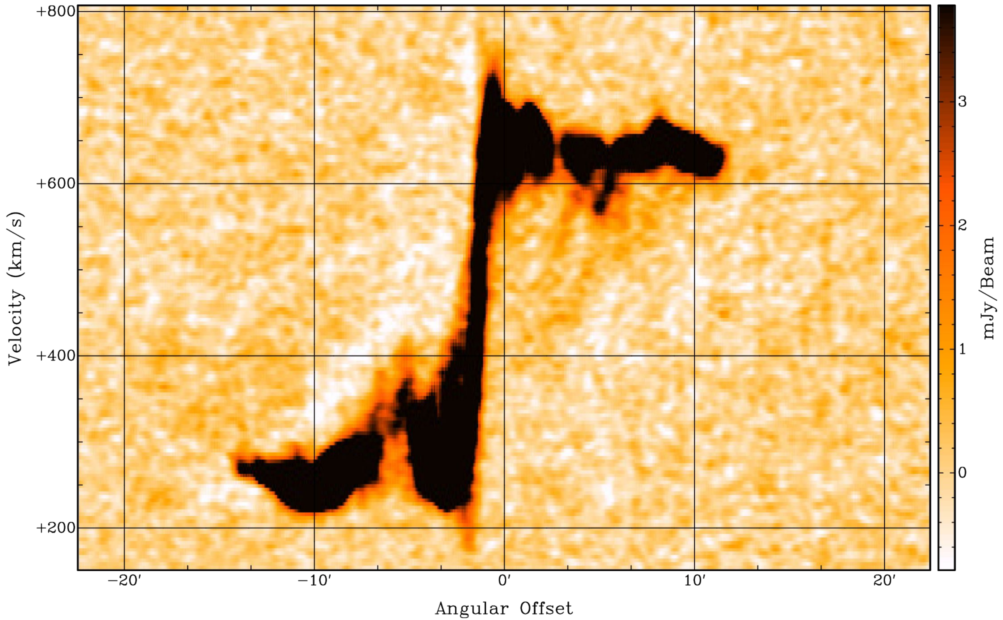


HALOGAS DR1: NGC 4258

Global velocity profile



Major axis position-velocity diagram



HALOGAS DR2

HALOGAS Data Release 2 (DR2) will include ancillary data for all galaxies including:

- Single-dish cubes from GBT and Effelsberg
- Deep imaging from INT and KPNO
- Continuum images (total intensity)
- Linear polarization images (polarized intensity, RM, pol angle)

HALOGAS DR2 will be made public on 31 May 2019

HALOGAS DR2

NGC 4258

KPNO images:

R = *R*+Hα

G = *R*

B = *B*

HALOGAS DR2

NGC 4258

KPNO images:

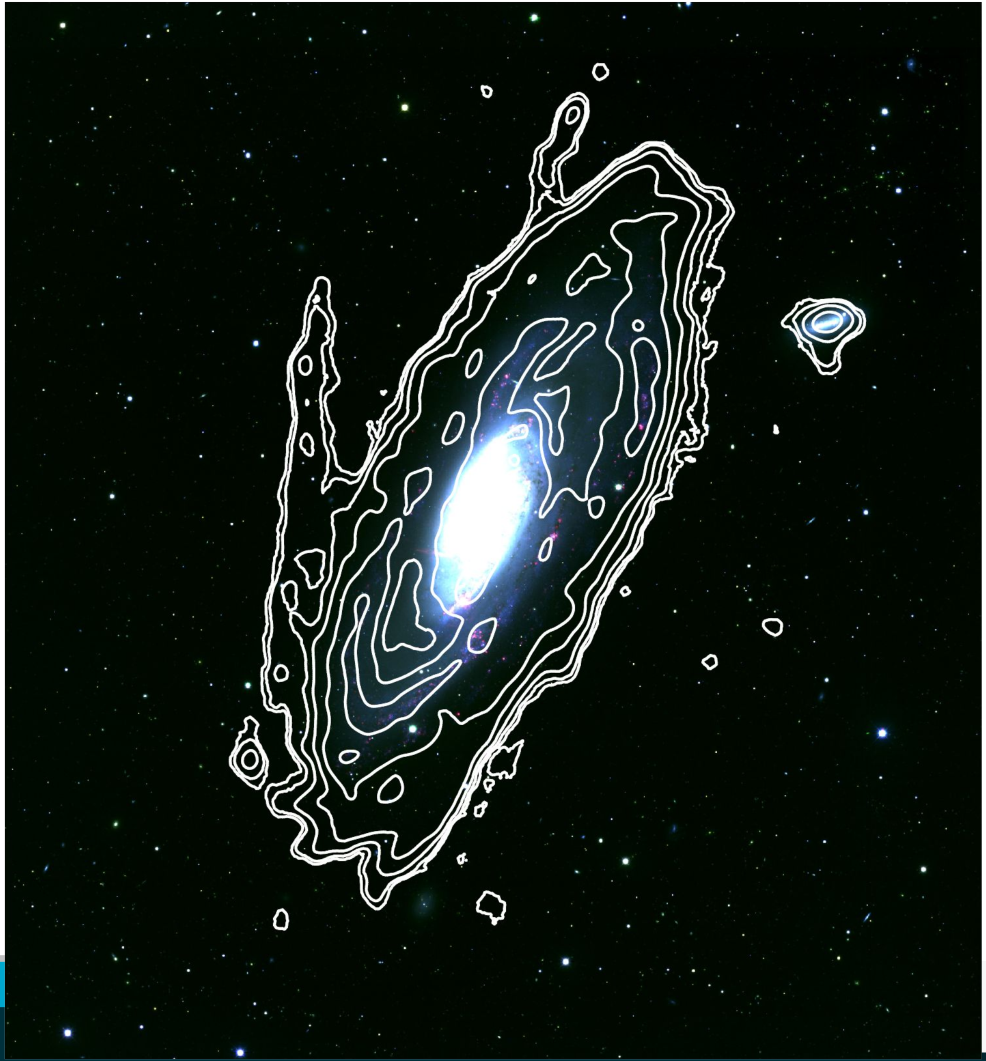
R = *R*+Hα

G = *R*

B = *B*

HALOGAS column density:

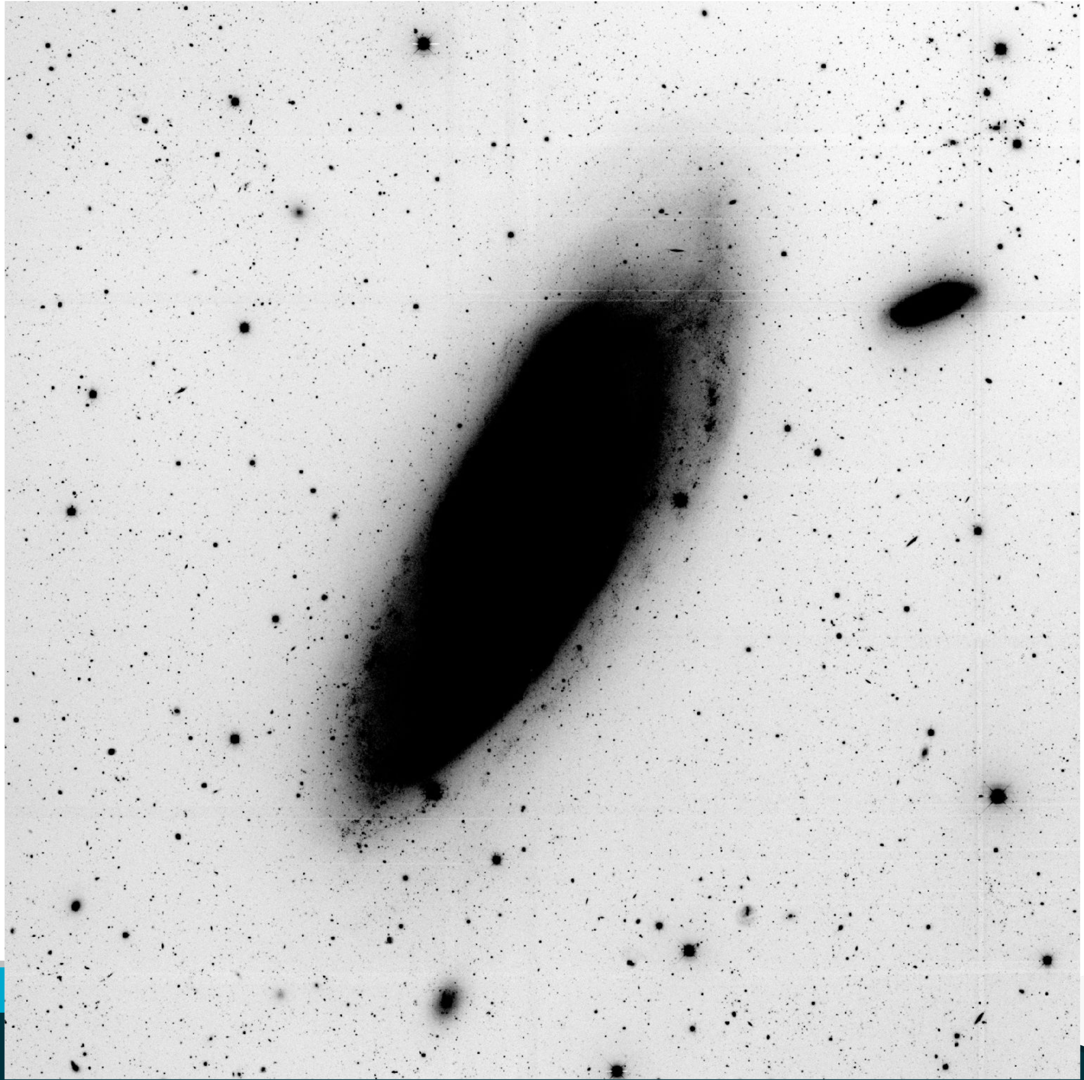
Contours = $2 \times 10^{19} * 2.5^{n}$



HALOGAS DR2

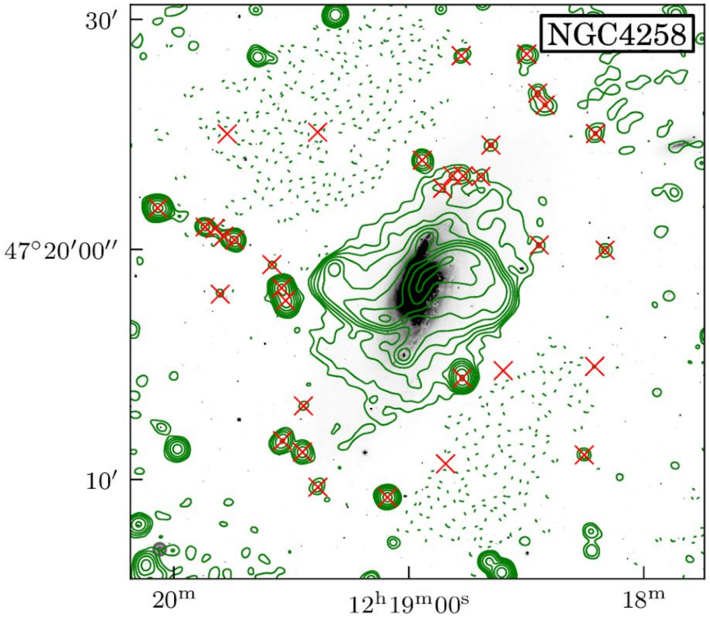
NGC 4258

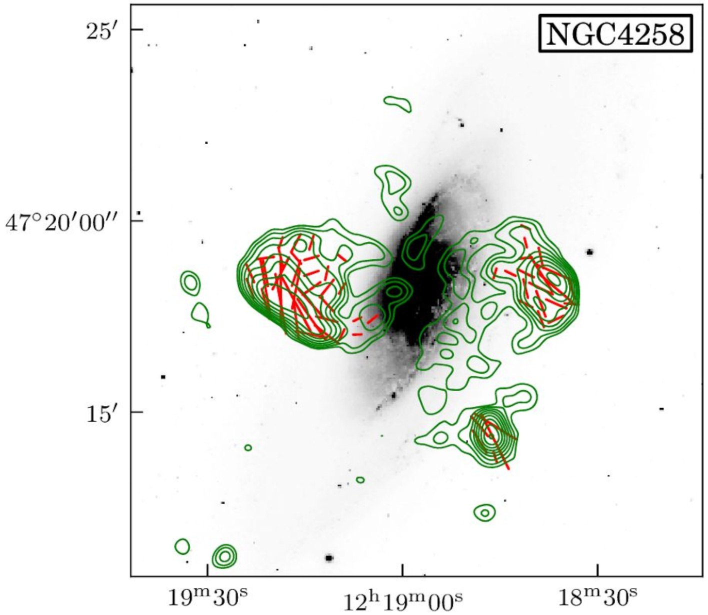
R+Hα



HALOGAS DR2

Continuum + polarization from WSRT data - NGC 4258





Adebahr

Summary publications and the future

Batch of summary publications are planned to coincide with HALOGAS-DR2

- HALOGAS Atlas and Data Release paper (Heald et al)
- Connection between star formation and thick HI disks (Marasco et al)
- Census of HI clouds and limits on cold gas accretion rate (Herrera-Ruiz et al)

HALOGAS results lead directly toward the new nearby galaxy surveys

- Deep imaging with FAST (+ MeerKAT)
- IMAGINE: ATCA Legacy Survey, see talk by Attila Popping
- MHONGOOSE: MeerKAT Large Survey Project, see talk by Erwin de Blok

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

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