# The WSRT HALOGAS Survey

Main Results and Public Data Release George Heald and the HALOGAS team

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# 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)



4 | George Heald | HALOGAS Results and Data Release

# **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<sub>25</sub> > 3'
  - $V_{sys}^{23} > 100 \text{ km/s}$
  - Inclination: moderate (50°  $\leq i \leq 75^{\circ}$ ) or edge-on (i  $\geq 85^{\circ}$ )
- This results in a broad range of galaxy morphology: one close pair, several massive spirals, wide span in SFR





### **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 ~ 1x10<sup>19</sup> cm<sup>-2</sup>
- Unresolved cloud mass sensitivity (at D=10 Mpc) ~  $2x10^5 M_{\odot}$





# **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 UBRHa 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

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	THE ASTROPHYSICAL &										
	© 2011. The American Astron			Г	Monthly Notices						
A&A 526, A118 (2			THE ASTROPHYSICAL JOURNA	A&A 554, A125 (2013)	ROYAL ASTRONOMICAL SOCIE	1					
DOI: 10.1051/000	HALOCAS, HA		© 2012. The American Astronomical S	DOI: 10.1051/0004-6361/2	MNRAS 434, 2069-2093 (201		1				
(c) ESO 2011	HALOGAS: HI			© ESO 2013	Advance Access publication		<b>G</b> 1 + + + + <b>P</b>				
	LAURA K 2	T	HALOCAS, HAODS			4.8:4.566.480 (2014)	Galaxies in 3D act Droosedings IAU S	THE ASTROPHYSICAL INTENAL \$39			
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				G. Gentile <sup>1,2</sup> , G. I.	P. Kamphuis, <sup>1,2*</sup>	HALOGAS				A GBT SURVEY OF THE HALOGAS GAI	LAXIES AND THEIR ENVIRONMENTS I:
					M T Patterson 6.	INALOGAO	1	Carlos J. Vargas <sup>1</sup> , George		REVEALING THE FOLL EXTENT OF HEARC	JUND NGC891, NGC925, NGC4414 & NGC4565
G. Heald <sup>1</sup>	We preser			1 Streen loop die Oberen	ICEBO Astronom & Same S		<sup>2</sup> Kaptown Ar			N. M. PINGEL <sup>1,2</sup> , D. J. PISANO <sup>1,2,3</sup> , G. HEALD <sup>4,5</sup> , T. H. J	ARRETT <sup>6</sup> , W. J. G. DE BLOK <sup>5,6,7</sup> , G. I. G. JÓZSA <sup>8,9,10</sup> , E.
	Our mode		We 21	e-mail: gi anfranco	<sup>2</sup> Astronomisches Institut Ruhr-		Rapicyn As	<sup>2</sup> C		JÜTTE <sup>12</sup> , R. J. RAND <sup>13</sup> , T. OOS	STERLOO <sup>5,7</sup> , AND B. WINKEL <sup>11</sup>
	extraplana		we present 21	2 Department of Physic	<sup>3</sup> Department of Physics and As	W. J. G. de Blok <sup>1,2,3</sup> ,		<sup>3</sup> ASTRON		Draft version .	August 8, 2018
1 Netherlands	Our mode		both the momb	<sup>3</sup> Netherlands Institute	<sup>4</sup> ASTRON, the Netherlands Ins		A hoters at 117 at	Kapteyn /		ABST	BACT
e-mail: heal	the line o	<sup>2</sup> I	and asymmetri	* Argelander-Institut fü	<sup>6</sup> Argelander-Institut für Astron		Abstract. we p	<sup>6</sup> D		We present initial results from a doop neutral hude	orem (H) summer of the HALOCAS solery comple
3 Astronomy 1	detect a la		see evidence fo	7700 Rondebosch, Re	7 Sterrenkundie Observatorium	1 Netherlands Institute for	res) Survey, which	Department of P	00	which includes the spiral galaxies NGC891, NGC9	25 NGC4414, and NGC4565, performed with the
<sup>4</sup> Kapteyn Ast	decreases		the disk, possib	<sup>6</sup> Astronomy Departme	<sup>8</sup> Department of Physics and As	<sup>2</sup> Astrophysics, Cosmolos	galaxies to date.	<sup>9</sup> Rhodes Centre for Radio Astronom	01	Robert C. Byrd Green Bank Telescope (GBT). T	he resulting observations cover at least four deg <sup>2</sup>
6 Astronomise	and reced		height above th	Kapteyn Astronomica	<sup>9</sup> Astrophysics, Cosmology and	7701 Rondebosch, Sout	actorize the low a		5	around these galaxies with an average $5\sigma$ detection	on limit of $1.2 \times 10^{18}$ cm <sup>-2</sup> over a velocity range of
7 Sterrenkund	mendung		receding naive	* Department of Astron		Kapteyn Astronomical I Department of Astronom	galaxies with exc	11 Depart	50	20 km s <sup>-1</sup> and angular scale of 9.1'. In addition t	to detecting the same total flux as the GBT data,
Received 15 C	Key word		several galaxie	Received 16 January 20		5 Sterrenkundig Observat	kinematic modeli	12	n	the spatial distribution of the GBT and original W	esterbork Synthesis Radio Telescope (WSRI) data
	dynamics		of high star for		Accepted 2013 June 21. Receiv	<sup>6</sup> Department of Physics a	dynamics in unpre	Receiv	$\triangleleft$	is on average 2%. We discuss the possible origins	of low column density HI of nearby spiral galaxies
			companion gal			<sup>8</sup> CSIRO Astronomy and	include new insig		5	The absence of a considerable amount of newly de	etected HI by the GBT indicates these galaxies do
We introduce		A	Key words: ga	We present the analysis		9 Department of Physics a	their extended gas		-	not have significant extended diffuse HI structures,	and suggests future surveys planned with the SKA
(WSRT). The		1)	spiral – galaxie	in LOcal GAlaxieS (H/		Received 21 August 2013	streams provides	We use new deep 21		and its precursors must go at least as deep as 10 <sup>1</sup>	<sup>7</sup> cm <sup>-2</sup> in column density to significantly increase
most sensitive nearby galaxie		in		extraplanar gas. We pres		10001100 211100201 2010	motivating some o	observations. We fin	A.	the probability of detecting HI associated with the	cosmic web and/or cold mode accretion.
phology, and k	Understanding t	In		rotation velocity as a fu			the modern gener	gradient in its rotatio	0	Keywords: galaxies: evolution: galaxies: forma NCC4414 NCC4565)	tion – galaxies: individual (NGC891, NGC925,
local Universe	extended gas in dis		1.1	for the first time in NG		We present deep H I imagi	Kammada ada	tilted ring models als	p.	NGC4414, NGC4000)	
data products o reveal a first el	fountain model pre	K	Understanding the or	traced by the Ha emissi		in LOcal GAlaxieS) surve	Keywords, galas	of ~10 km s <sup>-1</sup> . We a	4		
of spirals, and	by Bregman 1980,	14	is key to interpreting	studies, thanks to the im of modified Newtonian		more disturbed outer disk.		models and extraction	6	1. INTRODUCTION	vey (HALOGAS; Heald et al. 2011; hereby referred to as
but all show va their global ob	1989), interactions		their environments. Wh	galaxy, but the new oute		stage in the past. Modelin		extraplanar gas is sp	8	Resolved neutral hydrogen (HI) observations under-	H11) performed with the Very Large Array (VLA) and Westerbork Sunthesis Radio Telescope (WSPT) remove
then giobal en	accretion of prime		groups, or are relatively	Key words, anarias: h		of the disturbed nature of	1 Backgroup	r of a kinar	S	taken over the past decade have revealed many intricate	tively, provide high resolution maps of the environments
Key words. g	2008), and interact		between galaxy disks	Key Horda, galaxies, h		of NGC 4414 presented ne	r. Buckgrou	relationship to a near		details related to the morphology and dynamics of spi-	around nearby spiral galaxies.
	energization from	1	Is this gas ejected from			Key words, galaxies: hale	Spiral galaxies	from the center of N		vevs is to develop a deep understanding of how physi-	Accretion of diffuse gas onto the disks of galaxies from
1. Survey motiv	(e.g., Efstathiou 20		1976: Bregman 1980) a	1. Introduction		galaxies, sourceare	timescales and t	typical of H II region	5	cal processes within the disks of spiral galaxies, such as	the intergalactic medium (IGM) is a possible explana-
It is becoming inc	Galactic gaseou	0	models? Does some of				2008, and referen	Key words: galaxies		star formation and the subsequent stellar feedback, affect	tion for now the HI content of galaxies has remained rel- atively constant since $z \sim 2$ while the star formation rate
n is becoming me	Tüllmann et al. 200	0	sources (e.g., Kereš &	The last couple of decades		1. Introduction	ally established,	-	4	their local circumgalactic environments. Surveys such as	was up to 10 times higher at high redshifts (Noterdaeme
voked as a possibl	dust (e.g., Howk &	(1	galaxies or the IGM itse	galaxies (see Sancisi et al		The loss hards have a	(e.g., Kereš et a		0	2008) and Hydrogen Accretion in LOcal GAlaxies Sur-	et al. 2012; Madau & Dickinson 2014). The constant HI
trophysics. A typic	& Dettmar 2003), a	g	external components int	a review). This material in		of the resolved neutral hyd	clouds (HVCs) a	1. 100	0		content implies that galaxies have somehow replenished
necessary in order	Dahlem et al 200	(t	questions, a thorough st	Tüllmann et al. 2006; Li		galaxies. This is largely due	with low metalli	Substantial reservoirs of m	on i	<sup>1</sup> Department of Physics and Astronomy, West Virginia Uni-	themselves with enough gas to fuel continuous star for-
galaxies would use	Dettmar 2003), X-	w	Extraplanar compone	Rand 2001; Rossa & Det		as THINGS (Walter et al.	a small fraction	exist outside the plane of dis	õ	versity, White Hall, Box 6315, Morgantown, WV 26506; nipin-	mation. Hi is an intermediate phase towards molecular
ages (e.g., Larson	(Howk & Savage	fr	et al. 2006), relativistic	1999; Ménard et al. 2010), a		LITTLE THINGS (Hunter et 2012) FIGGS (Beggins at al	quired to be able	inis extraplanar material ha	00	<sup>2</sup> Center for Gravitational Waves and Cosmology, West Vir-	hydrogen, which is the raw ingredient of the star forma-
the solar neighbor	presence of these	a	(e.g., Howk & Savage 19	found to be often (but not		2012), FIGOS (Beguin et al. 2011). These surveys have a	not commonly d	(Tillmann et al. 2006) due		ginia University, Chestnut Ridge Research Building, Morgan- town WV 26505	tion fuel. If the star formation is to continue, external
gues that this infle	disk, both locally,		Rossa & Dettmar 2003).	associated with star format		the morphology and dynami	et al. 2012), and	(Rossa & Dettmar 2003) a	$\geq$	<sup>3</sup> Adjunct Astronomer at Green Bank Observatory, P.O. Box	gas has to be accreted and pass through the HI phase
to match the chem	as globally. This i	g	Swaters et al. 1997; Oos	The galactic fountain is		galaxies. An important scient	recognized as a	Oosterloo et al. 2007; Heald	1	<ol> <li>Green Bank, WV 24944, USA.</li> <li><sup>4</sup> CSIRO Astronomy and Space Science, PO Box 1130, Bent-</li> </ol>	at some stage in the accretion process. Observationally inferred accretion rates as traced by HL however, fall be-
1985; Schönrich &	origins	A	For all except H I there	tempts to explain the preser		to explore the physical proces	Putman et al. 2	wide range in temperatures a	1	ley WA 6102, Australia	tween 0.1 and 0.2 $M_{\odot}$ at low redshifts. This is a full order
also been invoked	Despite the like	0	and star formation in the	gas is expelled to large di	1 INTRODUCTION	to those of giant molecular c	I mass of their h	is likely an excellent probe o	a	<sup>o</sup> Netherlands Institute for Hadio Astronomy (ASTRON), Postbus 2, 7990 AA Dwingeloo, the Netherlands	of magnitude lower than what is needed for galaxies to
small number of b	nents and star forn	ne	aforementioned galactic	explosions and adiabatic er	In the last decade, it has	on maximizing spatial resolu	These slowly rot	their environments, and vice		<sup>6</sup> Department of Astronomy, University of Cape Town, Private	continually form stars at their current rates (Sancisi et al.
in galaxies, such a	traplanar H1 in ga	ec	origins. However, such	the galaxy disk due to radi	common in spiral galaxies	What happens to the gas	et al. 2010) and	It is possible that extraplanat		Bag X3, Rondebosch 7701, South Africa Kapteyn Astronomical Institute. University of Groningen.	2008; Kauffmann et al. 2010). This discrepancy presents
matical) and warp	formation are not w		and in fact there is evider	Bregman 1980). For the c	2008). Understanding the p	formation cycle is a question	Security and	the disk through various aper		PO Box 800, 9700 AV, Groningen, The Netherlands	two intriguing scenarios: the cycle of star formation will scenarios and the available fuel within a few
et al. 2005; Sanci	ples of HI shells at		an external origin in the	as "lag") with distance from	as well as the disc-halo con	from the disk due to star form	The HALOCAS	explosions or stellar winds f		South African Radio Astronomy Observatory (SARAO), SKA South Africa, The Park, Park Road, Pinelands, 7405, South	Gyr and star formation itself will gradually cease, or pro-
observational evid	of widespread H	st	1997) and nearby galaxi that motivates this	els of the interplay betwee		& Field 1976); how much ga	undertake to -	could then expand, and rain		Africa	cesses that refuel galaxies with the necessary gas have
galaxies of ≥0.2 M	established among		In addition to probin	gas (e.g. Fraternali & Bin	* E-mail: peter.kamphuis@csin	eventually falls back on the c	undertaken to pr	cooling. This process is refe		(RARG), PO Box 94, Grahamstown, 6140, South Africa	been missed by previous surveys. Numerical simulations
	halo components.		nents through their mor	additional mechanisms go	† Humboldt Fellow.	A Miching Astronom - Win	(HIGDER)	mechanism (Shapiro & Field 1		<sup>10</sup> Argelander-Institut f ür Astronomie, Auf dem H ügel 71,	have shown a likely mechanism for refueling star forma-
	greatly expanded o		through understanding	nar gas, because these sin	Visiting Astronomer, Kitt Pe     Astronomy Observatory which	Optical Astronomy Observatory	(WSRI) observe	material about the galactic ce		<sup>11</sup> Max-Planck-Institut für Radioastronomie (MPIfR). Auf	tary 'cold' mode (Kereš et al. 2005, 2009; Birnhoim &
			type models, gas is lau	shallow compared with ob-	ties for Research in Astronomy	of Universities for Research in A	served for 120 h	distance from the plane (Br		dem Hügel 69, 53121	Dekel 2003). Cold in the context of these numerical sim-
			moves to larger radii. In	ing hot gas, which would e	the National Science Foundation	agreement with the National Sci	is $N_{\rm HI} \lesssim 10^{19} { m cm}$	rotation velocity is generally		** Astronomiscnes institut Ruhr-Universität Bochum, Univer- sitätsstraße 150, 44780 Bochum, Germany	ulations refers to gas that has not been heated above the
			I I	ing not gas, which would the	© 2012 The Authors	I		extraplanar gas show log mon		13 Department of Physics and Astronomy, University of New	virial temperature of the galaxy's potential well ( $\sim 10^5$
			. 1		Published by Oxford University	I		be reproduced with ballistic		mexico, Atoiquerque, NM 8/131, USA	$\kappa_{j}$ , and not refers to gas that has virialized in a process
							Downloaded from https://www.cambri	······································			
							https://www.cambridge.org/core/term				

# **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**



- $R_1, R_2$  define the radial gas density distribution
- h gas density scale height
- dV/dz vertical gradient in rotational velocity
- $V_{r}, V_{R}$  vertical and radial velocities
- $\sigma$  velocity dispersion



 $R_1 = 0.89^{+0.13}_{-0.12}$ 

Marasco et al (in prep)

 $R_1 = 1.98^{+0.11}_{-0.10}$ 



# 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





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



Major axis position-velocity diagram

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



NGC 4258

#### KPNO images:

R = R + Ha

G = R

 $\mathsf{B}=B$ 



NGC 4258

**KPNO** images:

R = R + Ha

G = *R* 

B = *B* 

HALOGAS column density: Contours =  $2 \times 10^{19} * 2.5^{n}$ 



NGC 4258

#### R+Ha



#### Continuum + polarization from WSRT data - NGC 4258





# 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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