HI Science in the Local Universe

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HI Science in the Local Universe

The connection, over time, between **star formation**, **HI**, **dynamics** and **accretion**, is one of the issues that will be addressed in the coming years through large, deep surveys of the HI in the *local* and *distant* Universe

- How do galaxies assemble and evolve ?
- How is star formation regulated ?
- How are the outer disks and cosmic web linked ?

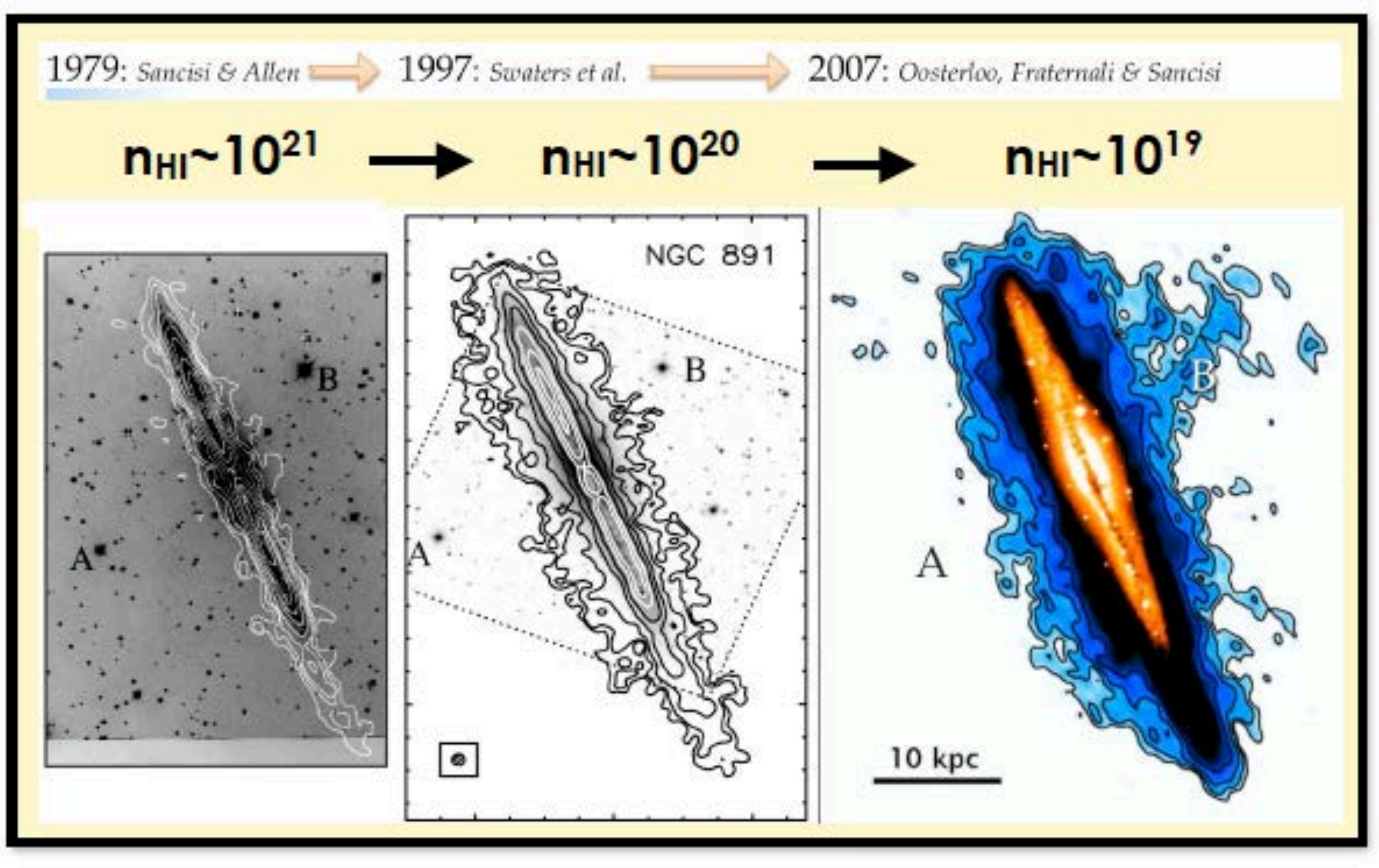
HI Science in the Local Universe

- In the context of this meeting, one might think that MeerKAT and SKA1-MID should answer most of the questions we want to answer on HI in the Local Universe.

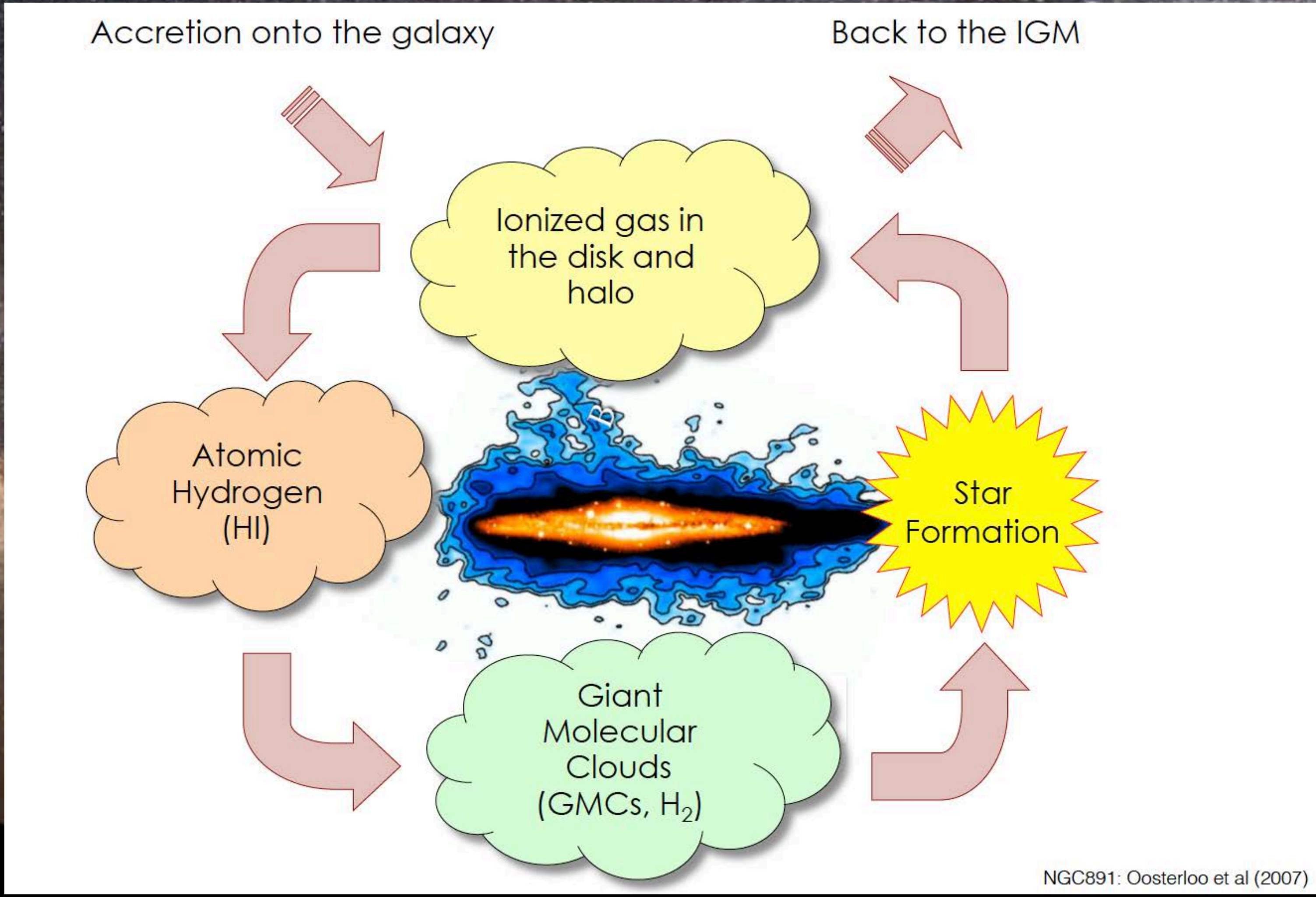
- While this is partly true, we will see at the end that one of the important science case for HI studies in the Local Universe is left out and will have to wait for the full SKA

- This science case should be considered in the final design, would it be AA or not.

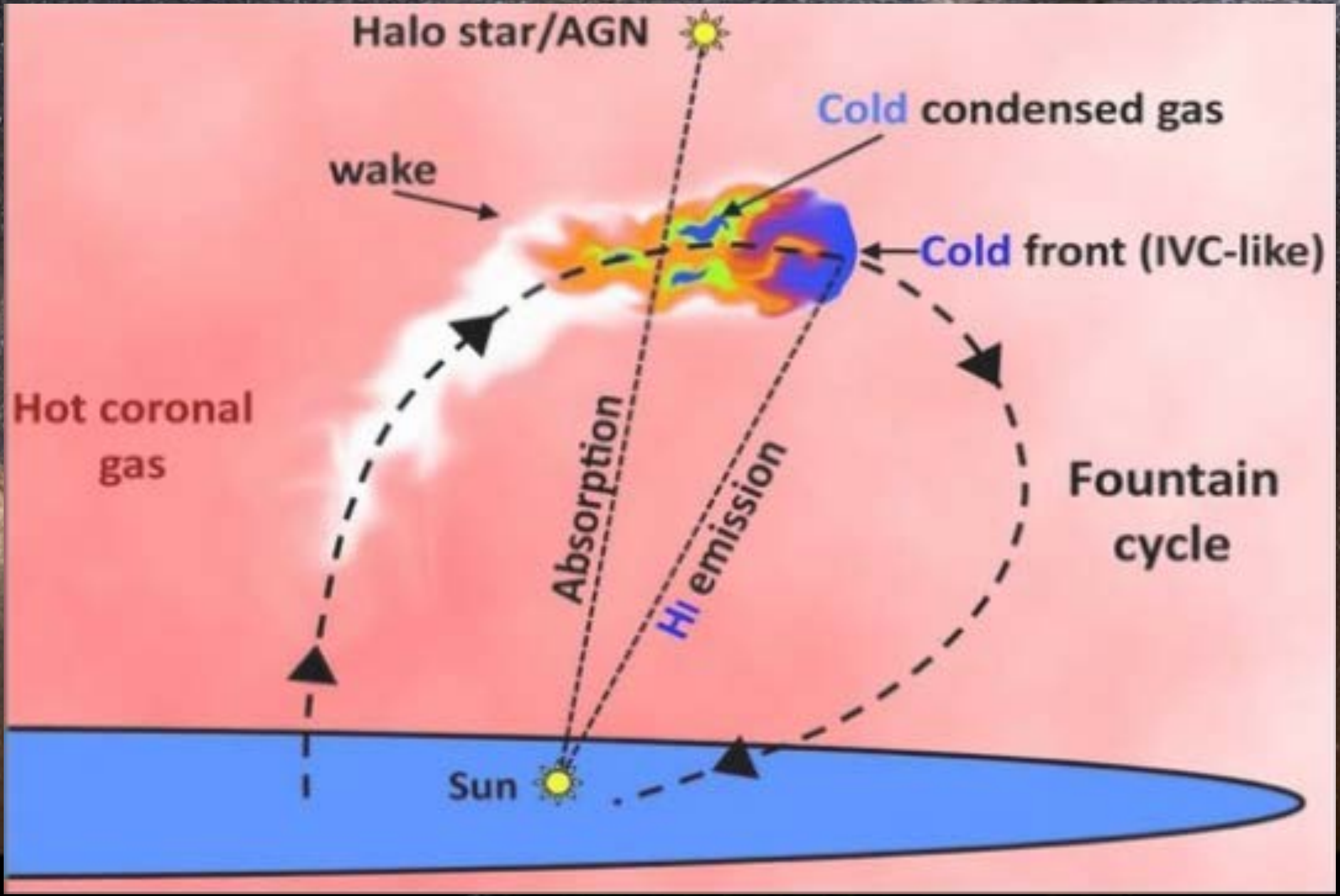
Galactic gas cycle



Galactic gas cycle



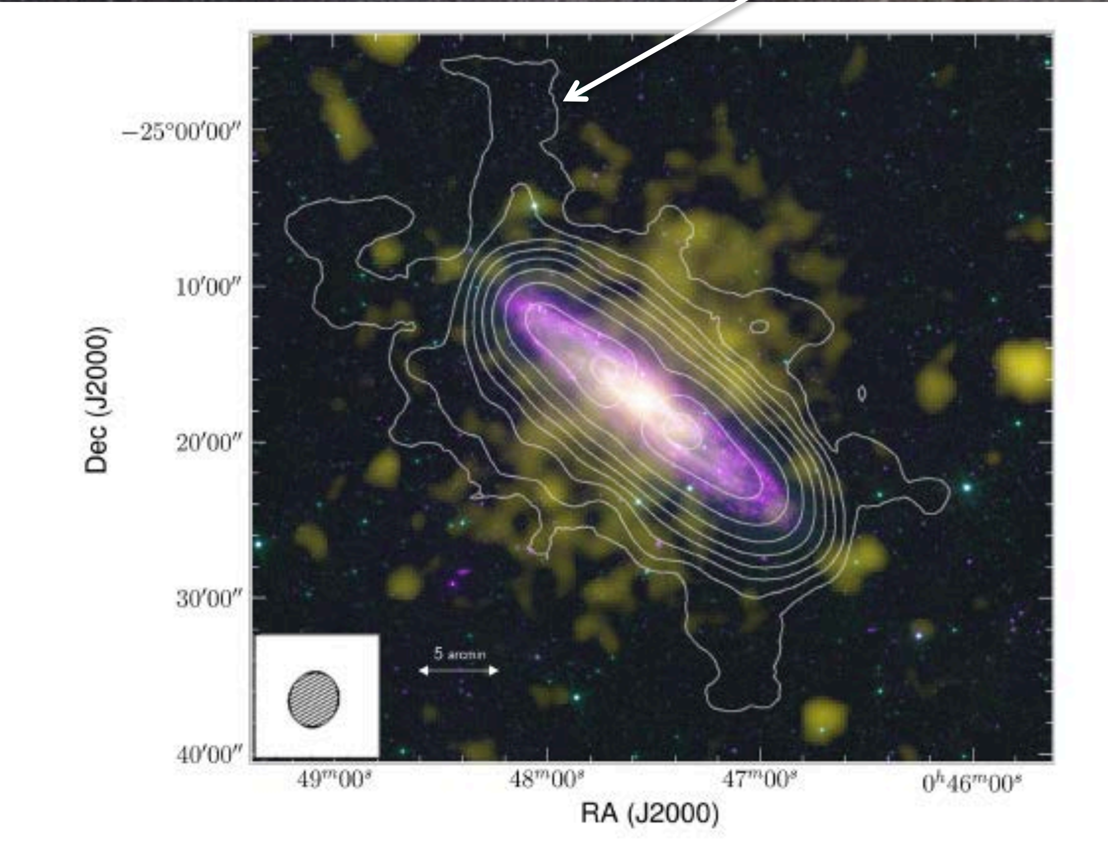
Galactic gas cycle



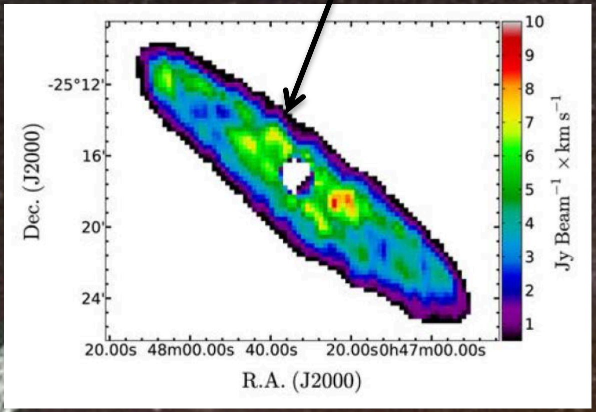
Fraternali 2013

Galactic gas cycle

$N_{HI} \sim 1 \times 10^{19}$ cm^{-2}



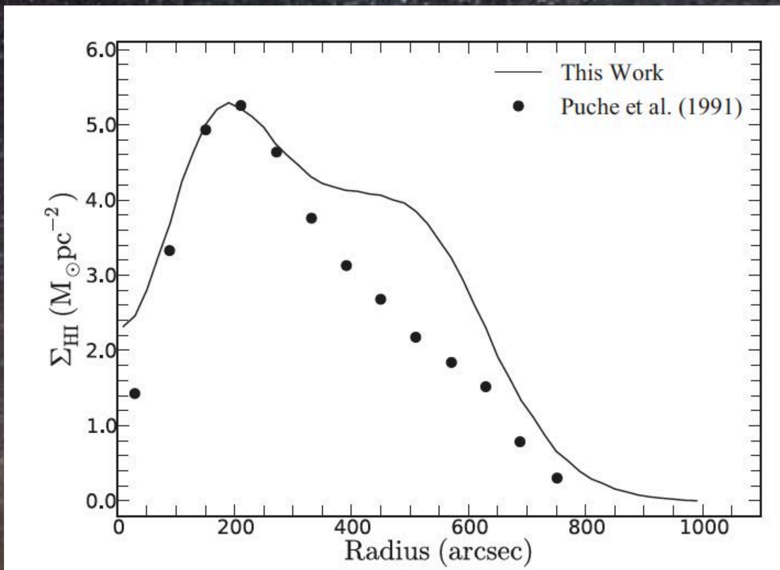
$n_{HI} \sim 2 \times 10^{20}$ cm^{-2}

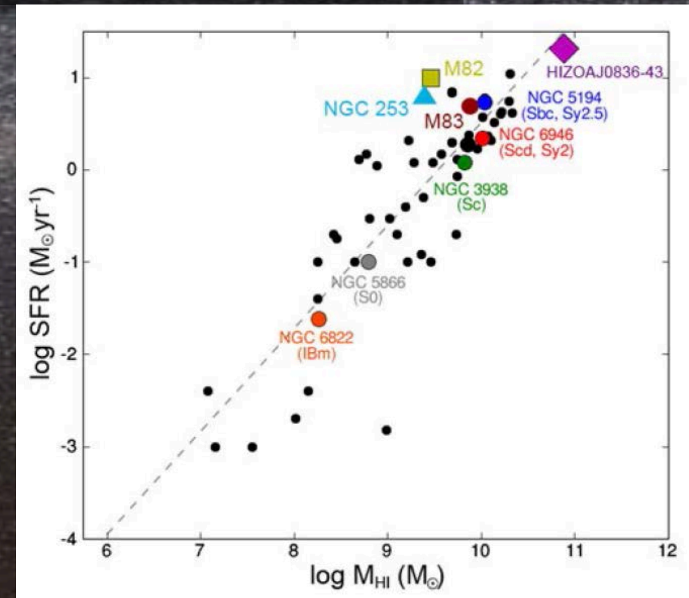


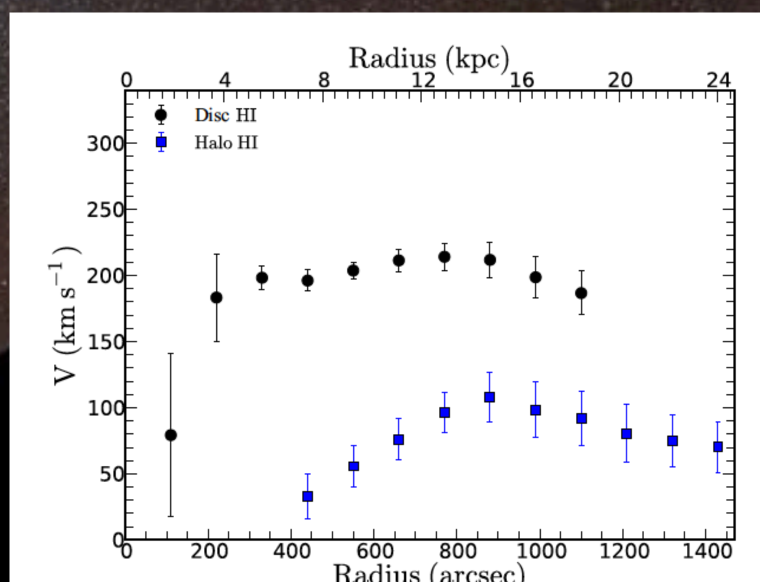
NGC 253 with VLA: Puche et al. 1991

NGC 253 with KAT-7: Lucero et al. 2015 (~100 hours)

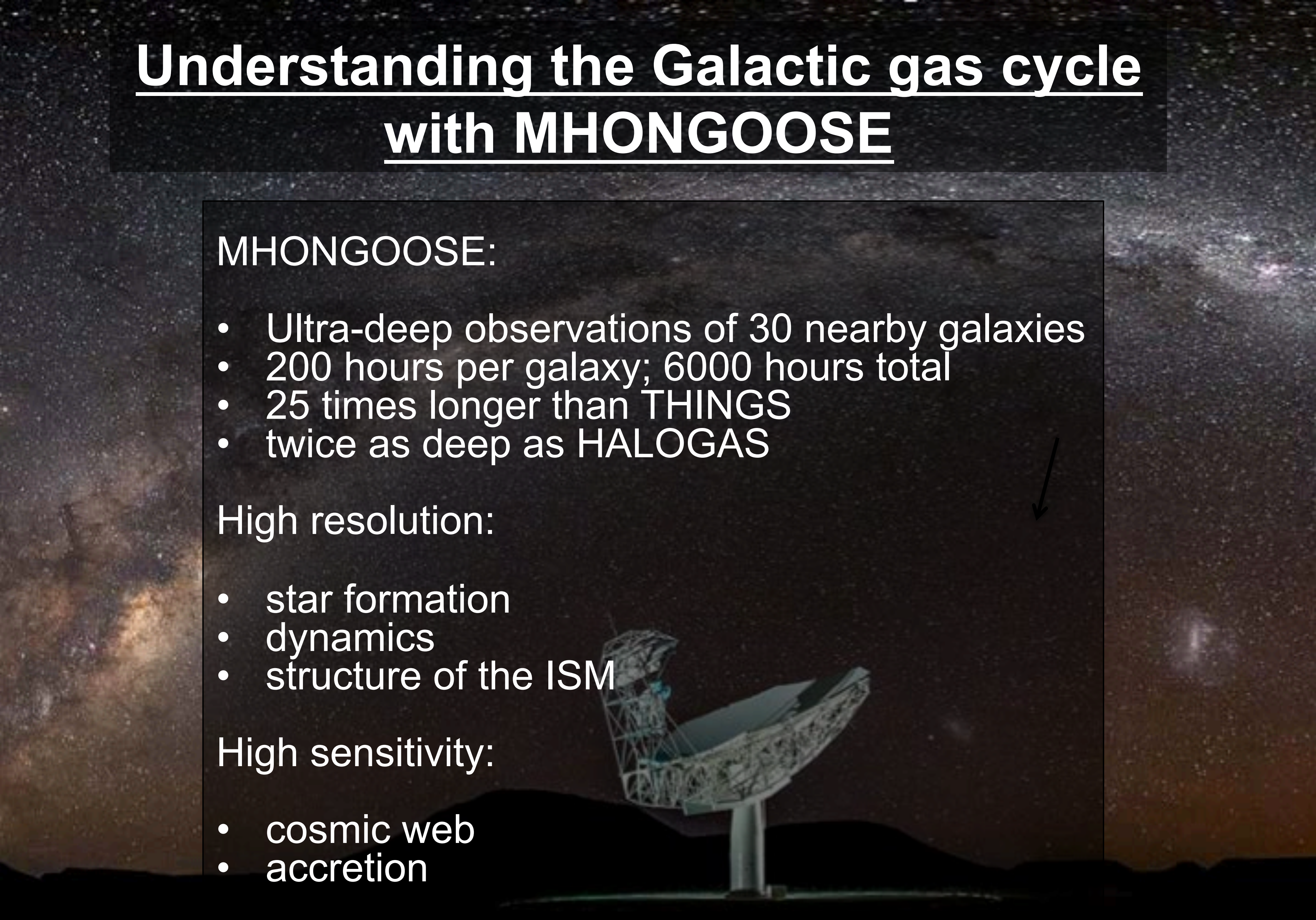
Galactic gas cycle







NGC 253: Lucero et al. 2015



Understanding the Galactic gas cycle with MHONGOOSE

MHONGOOSE:

- Ultra-deep observations of 30 nearby galaxies
- 200 hours per galaxy; 6000 hours total
- 25 times longer than THINGS
- twice as deep as HALOGAS

High resolution:

- star formation
- dynamics
- structure of the ISM

High sensitivity:

- cosmic web
- accretion

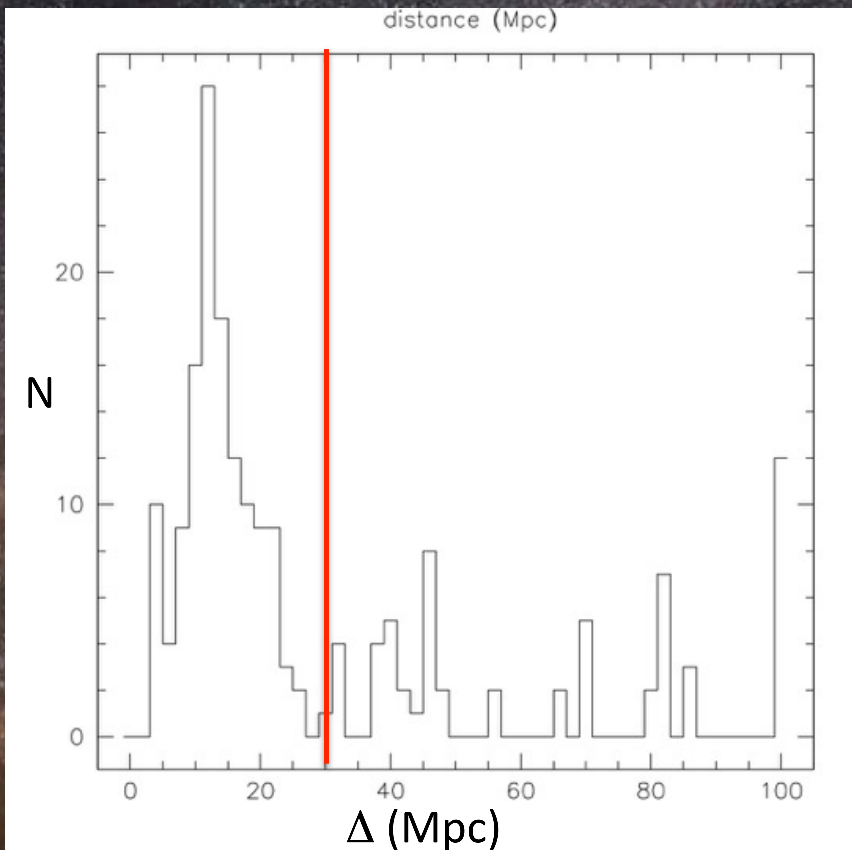
MHONGOOSE
Selection of the sample

- ➢ HI detected:
- HIPASS-based sample
- Galactic latitude |b| > 30°, Galactic standard of rest velocity > 200 km s^{-1}
- Projected distance from the LMC > 10°

- ➢ Detected in SINGG (Survey for Ionization in Neutral Gas Galaxies) and SUNGG (Survey for Ultraviolet emission in Neutral Gas Galaxies) (P.I. Meurer)

- ➢ Hα, optical, WISE and GALEX are available: 151 galaxies.

MHONGOOSE
precursor sample



- Cut at 30 Mpc (MeerKAT beam 1 kpc)
- Galaxies with dec < -10^{o}
- Exclude galaxies in the Fornax survey region
- 88 galaxies

MHONGOOSE
precursor sample

- representative number of galaxies as uniformly as possible over $\log(M_{HI})$

$6 < \log M_{HI} < 8$	5
$8 < \log M_{HI} < 8.5$	16
$8.5 < \log M_{HI} < 9$	18
$9 < \log M_{HI} < 9.5$	26
$9.5 < \log M_{HI} < 10$	15
$10 < \log M_{HI} < 11$	7

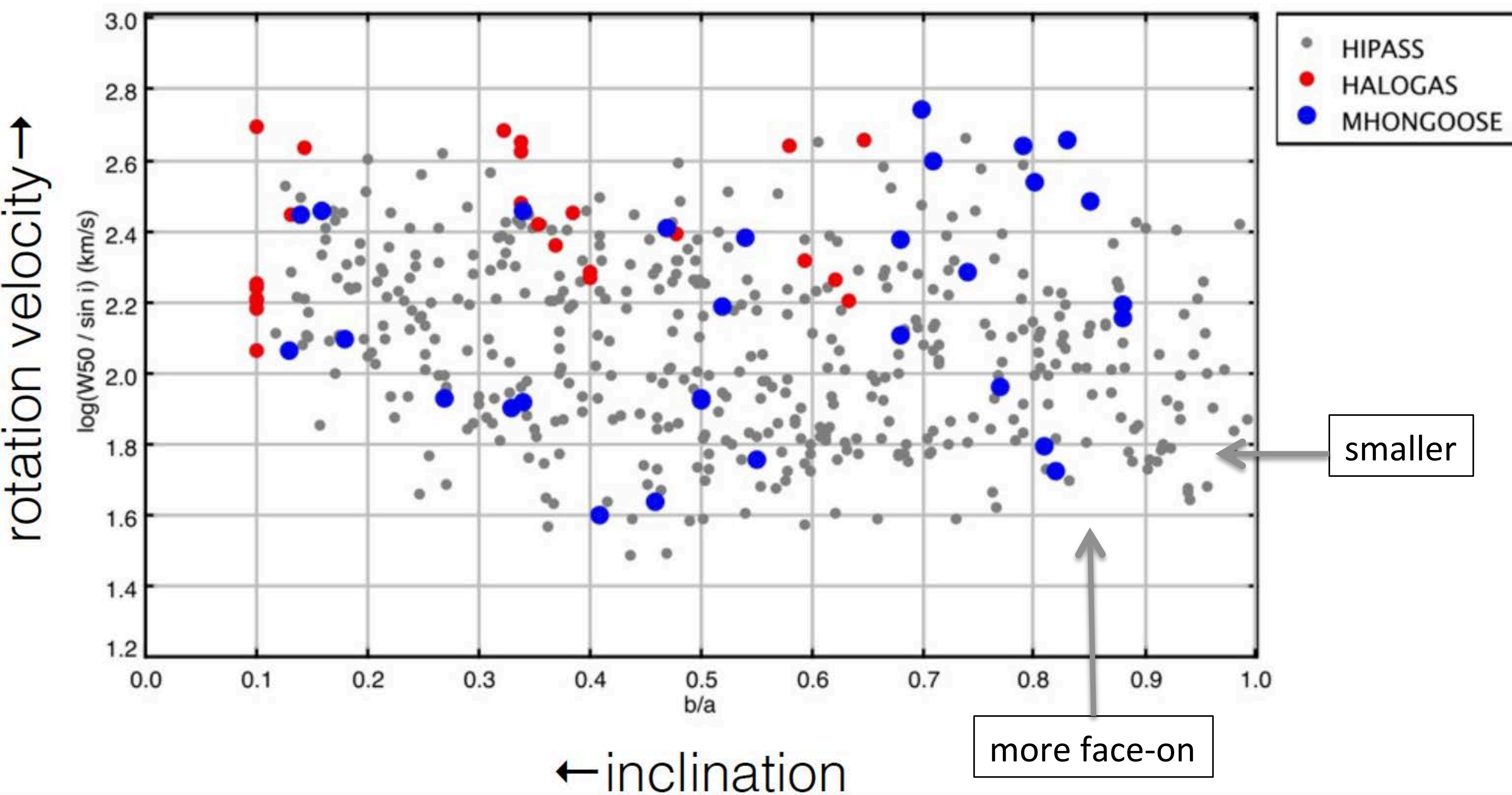
- 5 galaxies per bin → 30 galaxies

MHONGOOSE
Selection of the sample

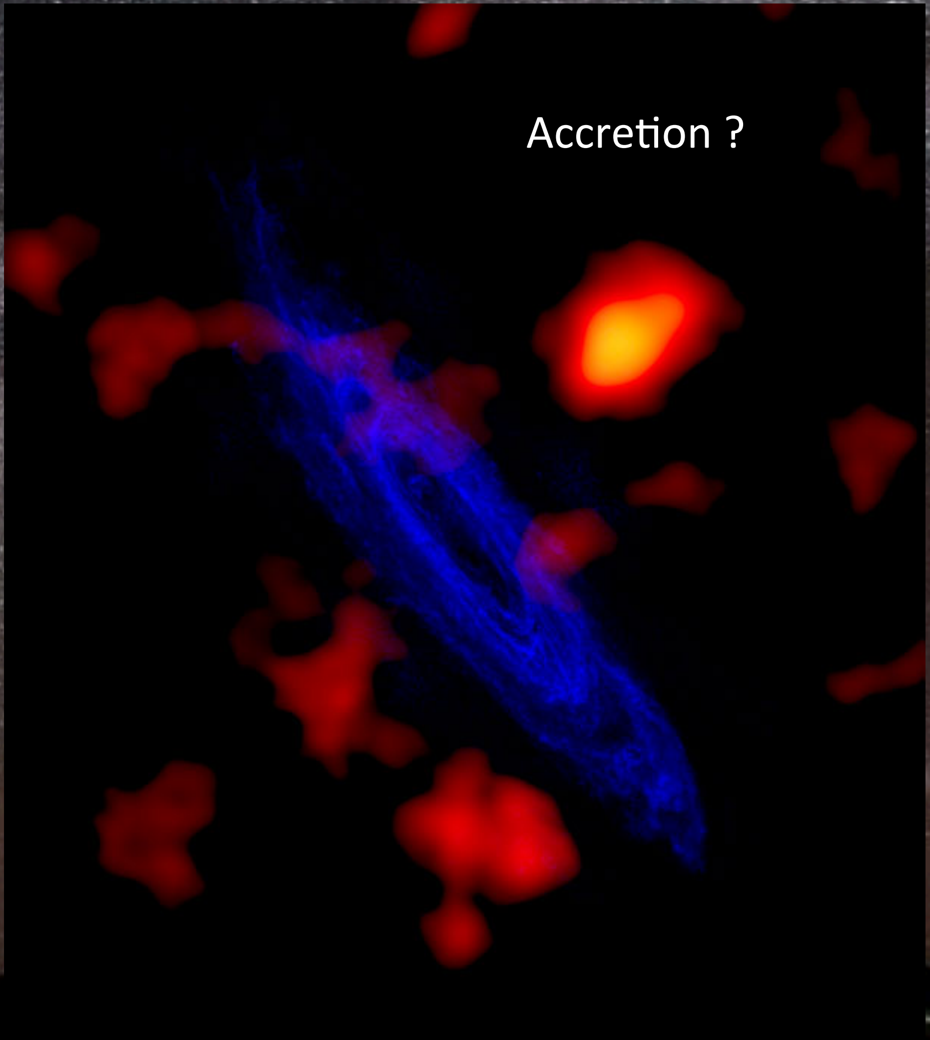
Criteria for the MHONGOOSE final sample

- Exclude galaxies with obvious quality issues
- Exclude interacting galaxies
- Must fit in one MeerKAT field (no mosaic)
- Best edge-on (extra-planar), face-on (dispersion) and ~60 deg inclination (kinematics)
- With these, large range in surface brightness and SFR

MHONGOOSE
Selection of the sample



Faint HI in the Local Group



Thilker et al. 2004

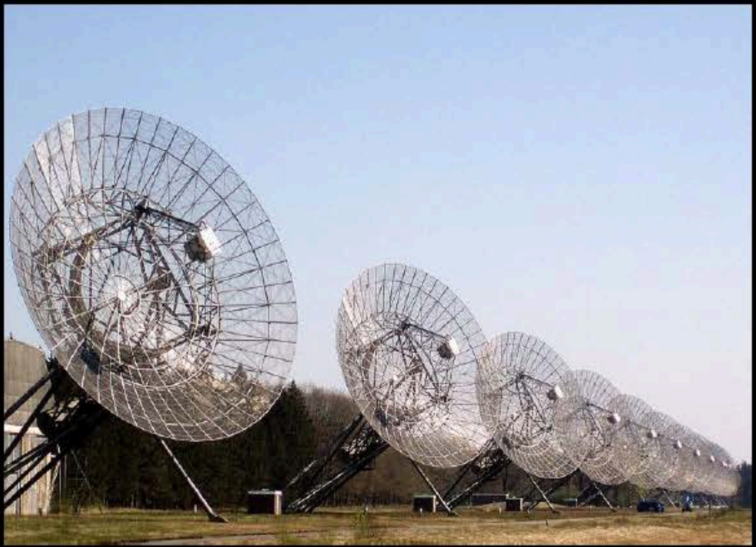
Faint HI in the Local Group

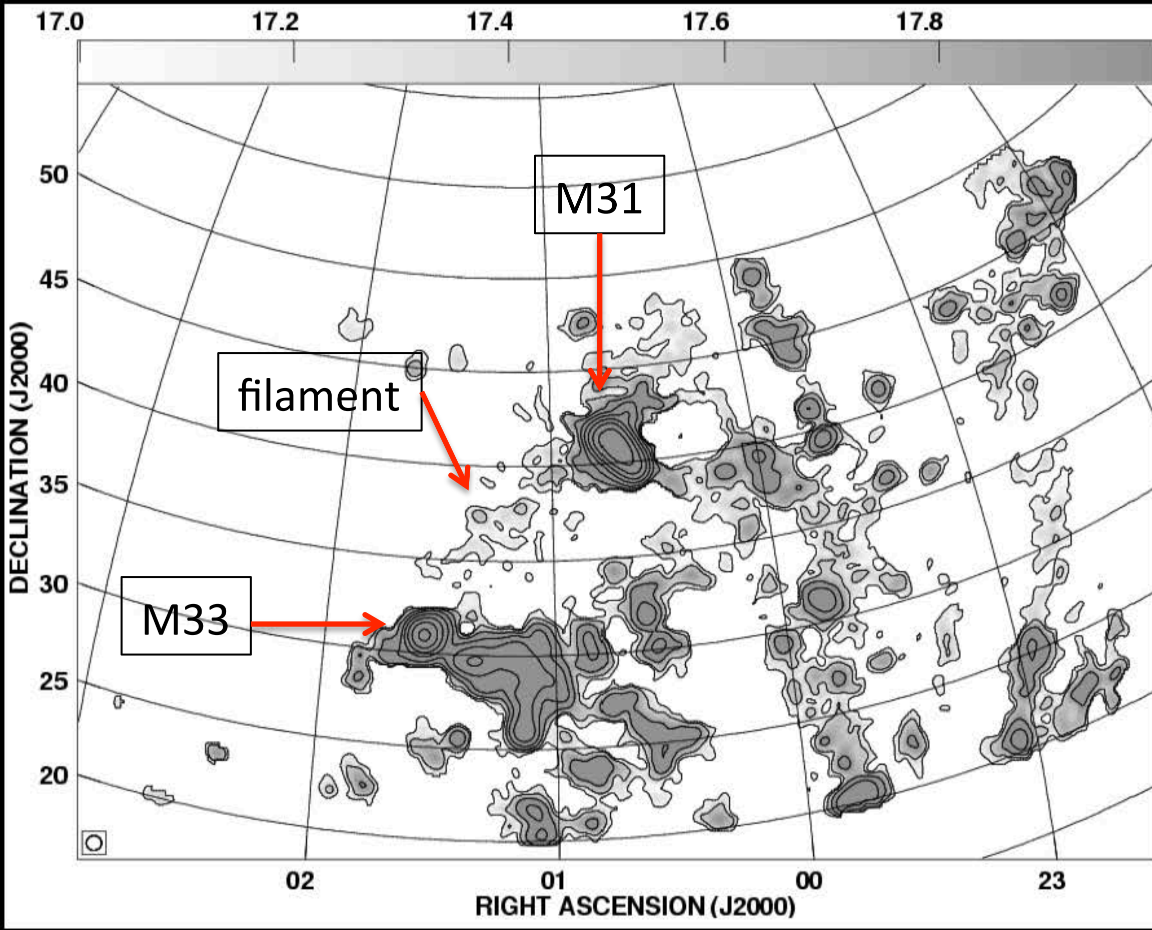
Braun & Thilker (2004, BT04)

Westerbork Synthesis Radio Telescope – each dish as a separate antenna

Survey of HI in the Local Group

$\log(N_{HI}) = 17.0\ \mathrm{cm}^{-2}$ (2-3σ)

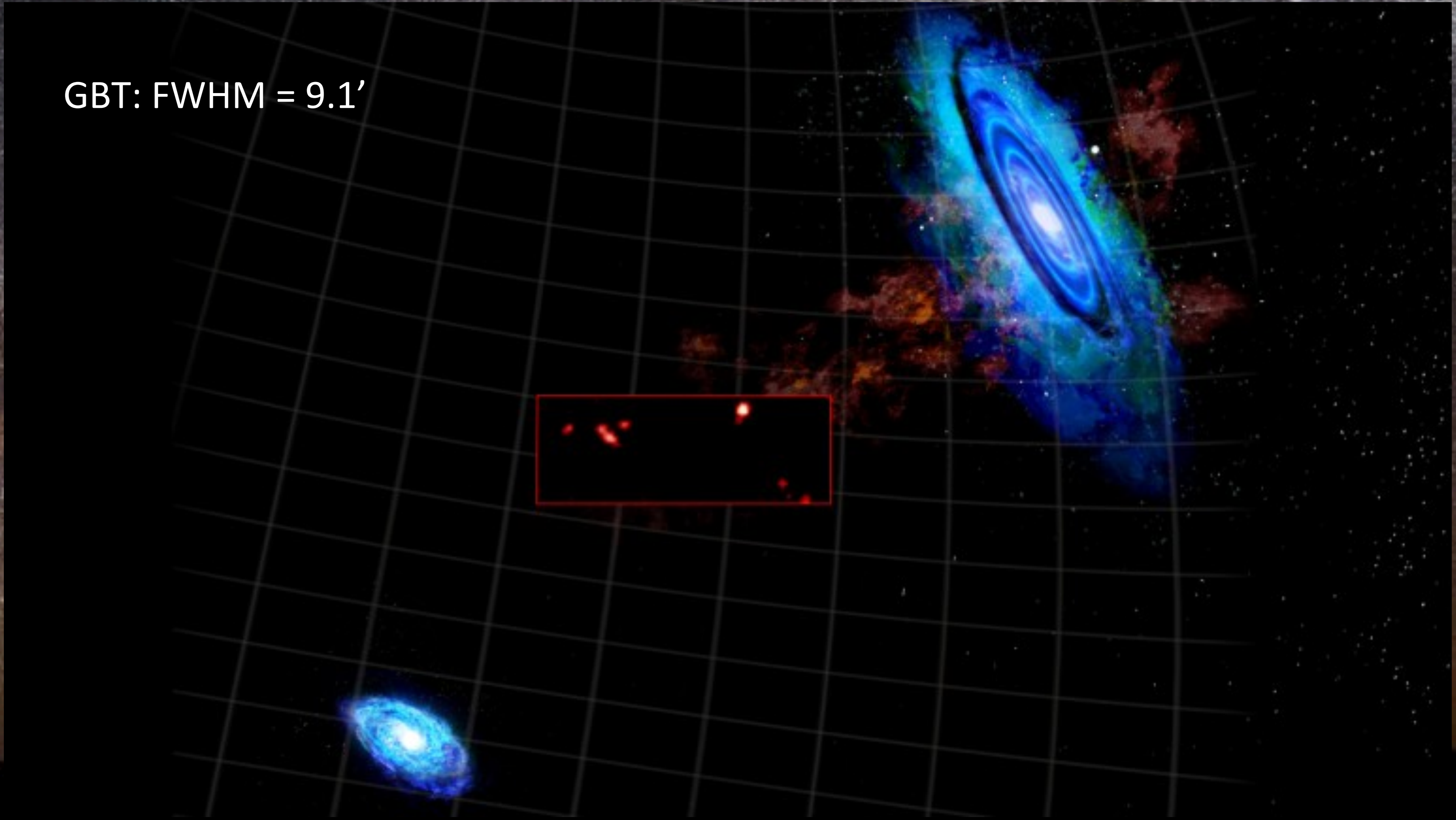




Braun & Thilker (2004), A&A, 417, 421-435

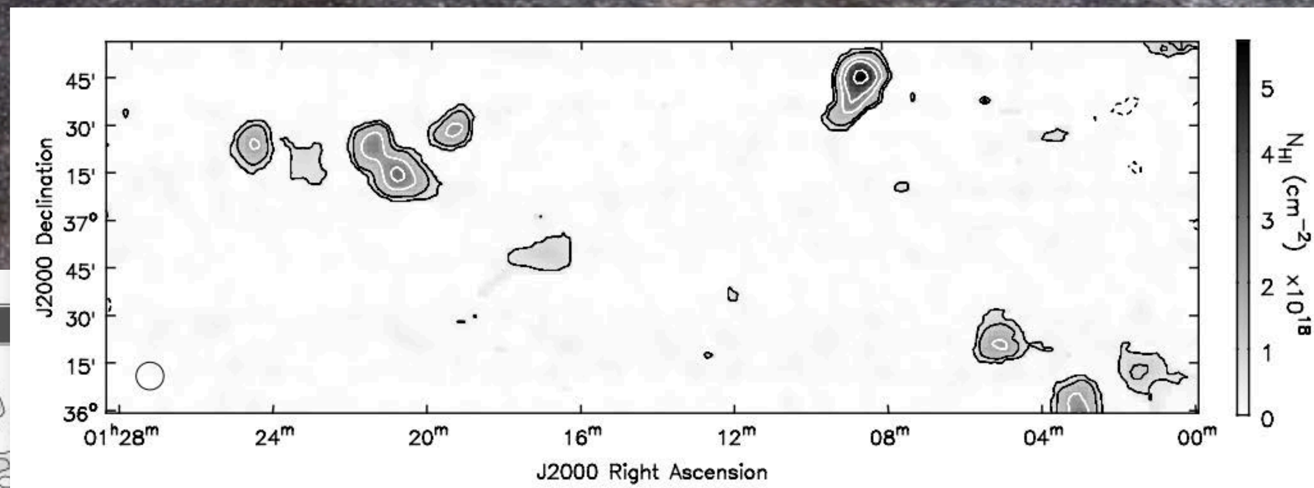
Resolution = single dish ~ 49'

Faint HI in the Local Group

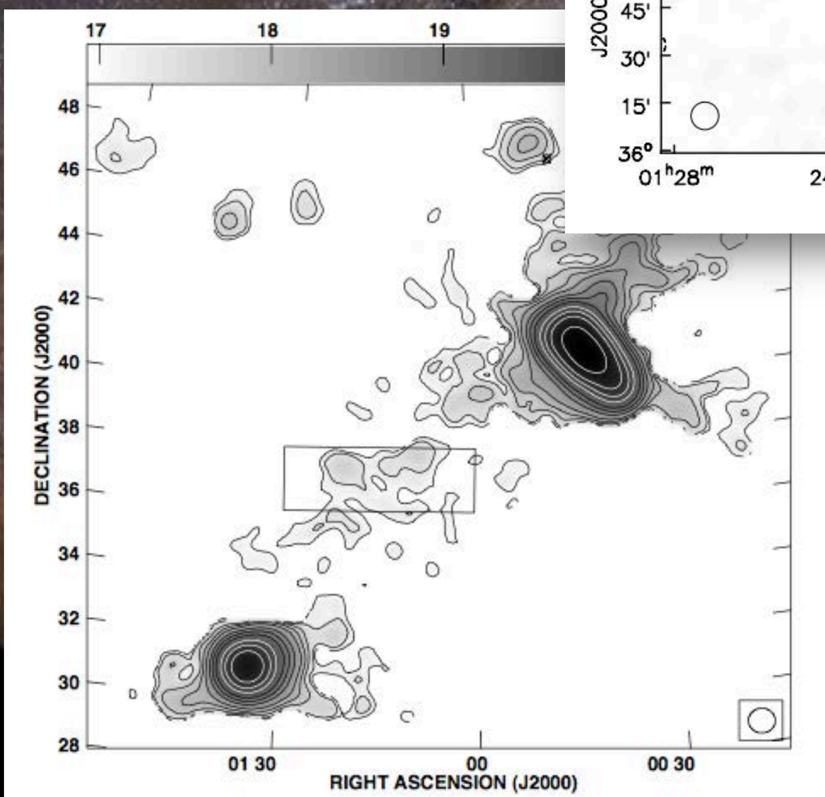


Wolfe et al. 2013, Nature, 497, 224

Faint HI in the Local Group

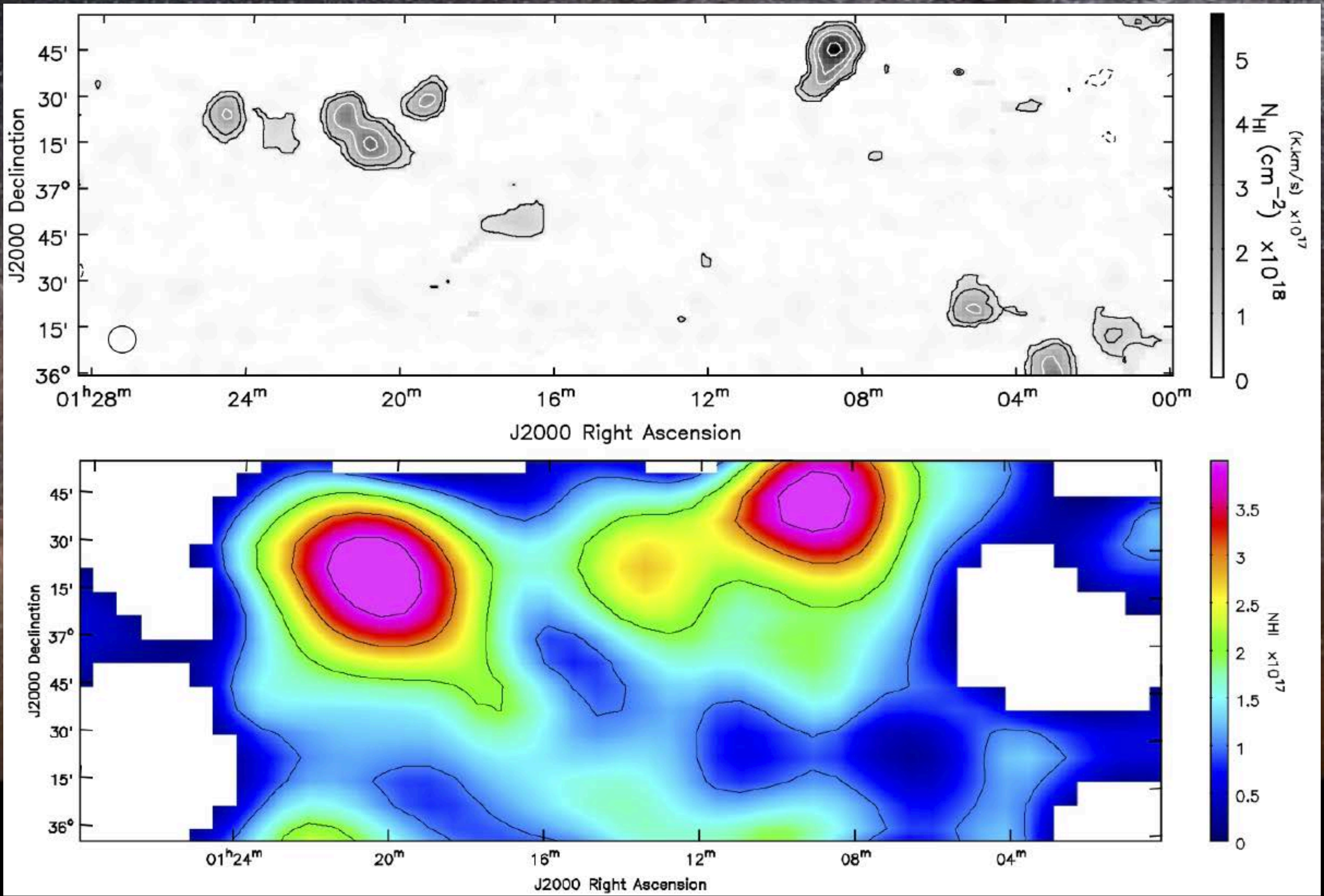


Wolfe et al. 2016 / res ~ 9'

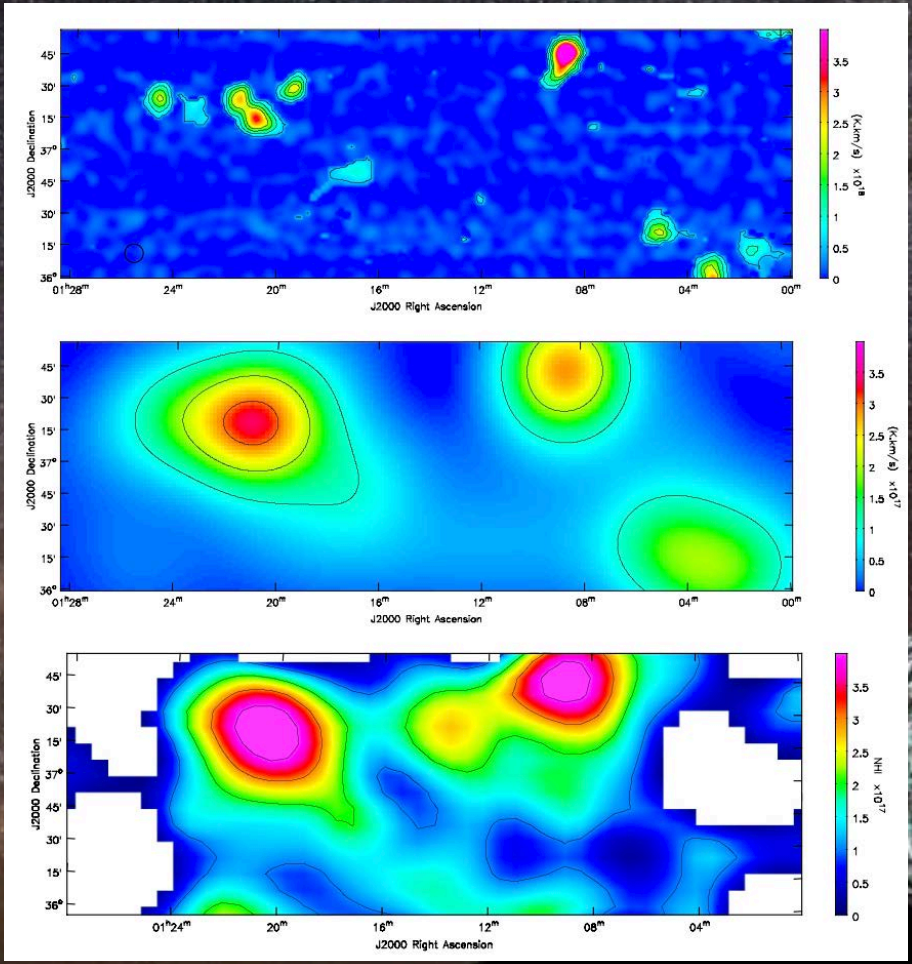


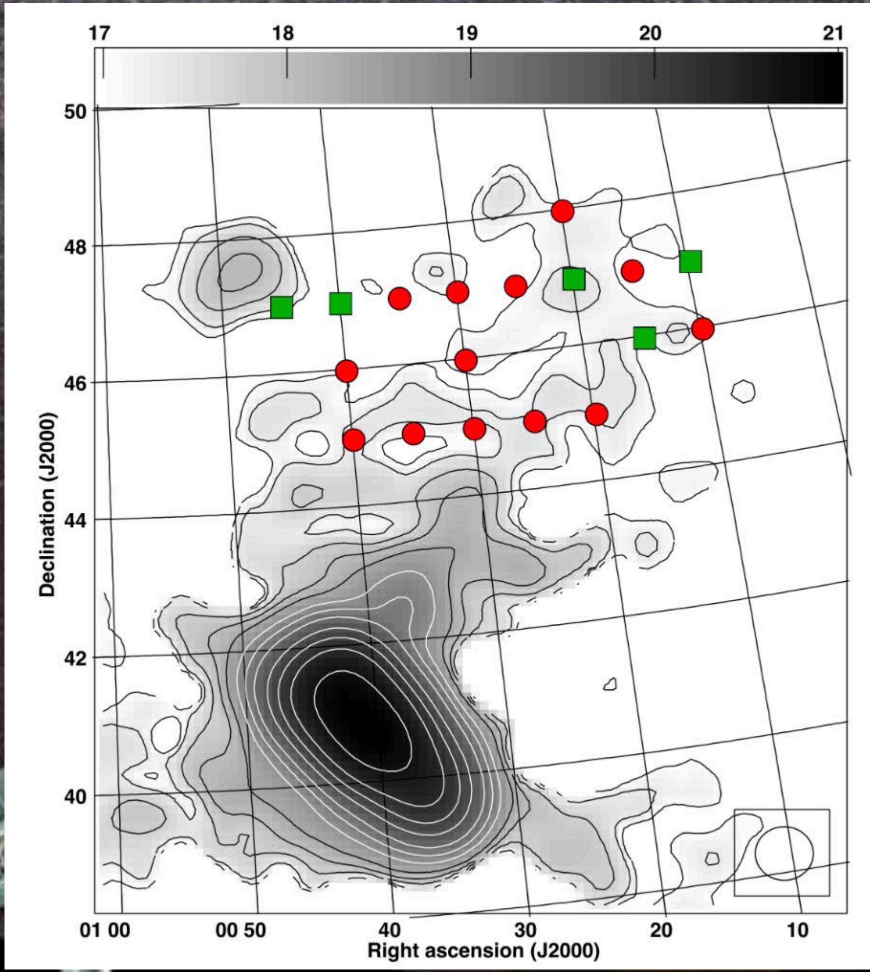
Braun & Thilker 2004 / res ~ 49'

Faint HI in the Local Group



Faint HI in the Local Group





Wolfe et al. 2016

Faint HI in the Local Group

Table 1
Clouds Detected Between M31 and M33

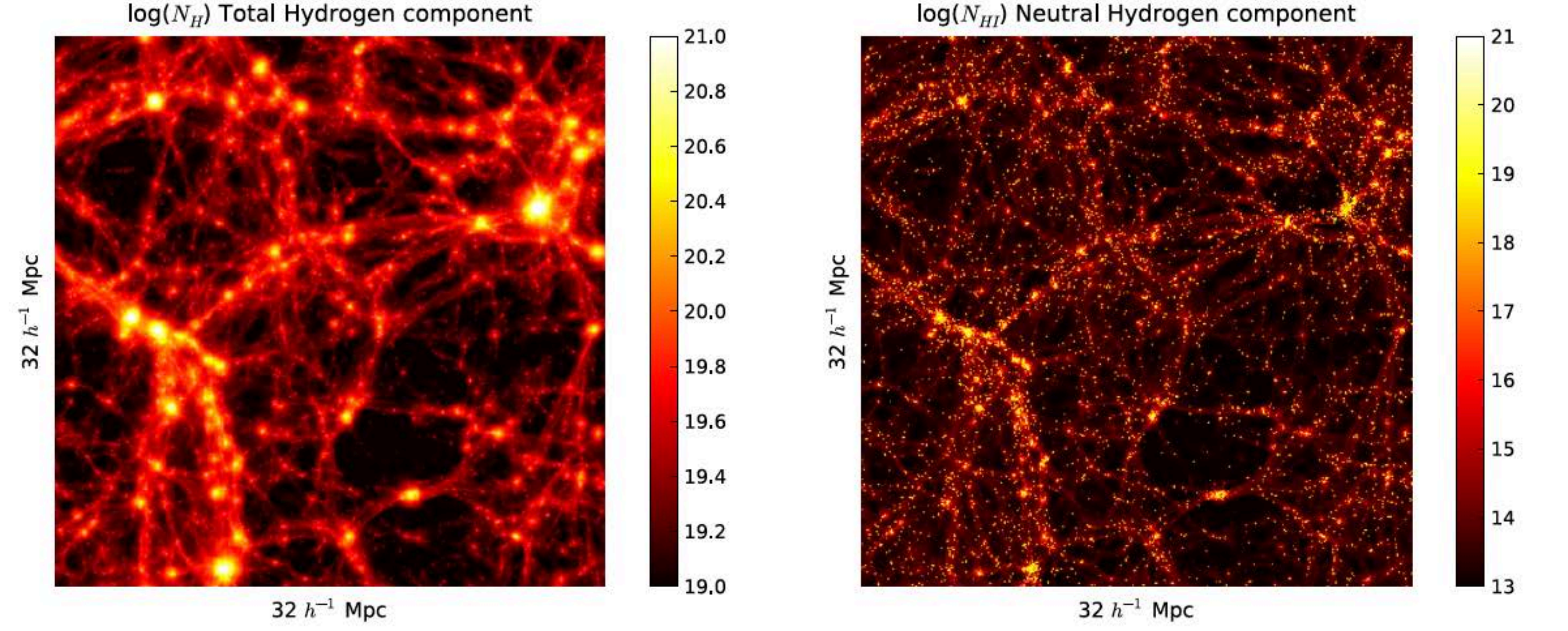
Cloud (1)	J2000 (hh:mm:ss dd:mm:ss) (2)	T_L (mK) (3)	FWHM (km s^{-1}) (4)	V_{LSR} (km s^{-1}) (5)	N_{HI} (10^{18} cm^{-2}) (6)
1	01:24:41.6 +37:24:00	44.0±2.4	25.5±1.6	−297.8 ± 0.7	2.2 ± 0.1
2	01:23:21.7 +37:18:45	10.9±2.2	39.3±9.3	−223.0 ± 4.0	0.8 ± 0.1
3	01:20:51.8 +37:15:15	63.2±1.8	27.2±0.9	−237.3 ± 0.4	3.3 ± 0.1
4	01:19:15.8 +37:29:15	28.5±2.1	38.1±3.3	−228.2 ± 1.4	2.2 ± 0.1
5	01:16:53.7 +36:49:00	18.3±1.7	26.2±3.0	−308.7 ± 1.2	0.9 ± 0.1
6	01:08:29.6 +37:45:00	81.3±3.6	32.0±1.9	−278.6 ± 0.6	5.0 ± 0.1
7	01:05:00.3 +36:21:00	34.7±3.0	31.4±3.5	−210.2 ± 1.2	2.1 ± 0.2
8	01:03:01.8 +36:00:00	35.0±2.6	36.8±3.4	−281.4 ± 1.3	2.5 ± 0.2
9	01:01:24.6 +36:12:15	25.4±3.2	19.2±2.9	−341.0 ± 1.2	0.9 ± 0.1

Table 2
Derived Cloud Properties[a]

Cloud (1)	V_{LGSR} (km s^{-1}) (2)	Diam[b] (kpc) (3)	⟨Diam⟩[c] (kpc) (4)	⟨FWHM⟩[d] (km s^{-1}) (5)	$r_{1/2}$[e] (kpc) (6)	M_{HI} (10^4 $M_\odot$) (7)	M_{dyn}[f] (10^8 $M_\odot$) (8)	ρ[g] (kpc) (9)
1	−61	4.4	3.2	22.2 ± 0.6	0.38:	12.7 ± 0.2	0.5:	126
2	+14	4.4	2.8	28.0 ± 3.5	0.75	4.5 ± 0.2	1.5	123
3	+1	7.2	5.3	27.6 ± 0.8		33.0 ± 0.3		118
3a				28.0 ± 1.0	0.82	22.7 ± 0.2	1.6	
3b				27.1 ± 1.3	0.34:	10.2 ± 0.2	0.6:	
4	+12	3.7	3.1	26.5 ± 1.5	0.41:	8.6 ± 0.2	0.7:	112
5	−69	7.0	3.8	21.8 ± 2.5	1.13	7.8 ± 0.2	1.3	109
6	−32	7.2	4.6	33.6 ± 1.3	0.78	39.2 ± 0.3	2.2	87
7	+36	4.9	3.9	27.4 ± 2.1	0.71	12.6 ± 0.4	1.3	92
8	−35	> 3.5	> 3.2	29.6 ± 2.1		> 11.6		91
9	−94	3.5	3.2	20.5 ± 2.3	0.96	8.7 ± 0.2	1.0	88

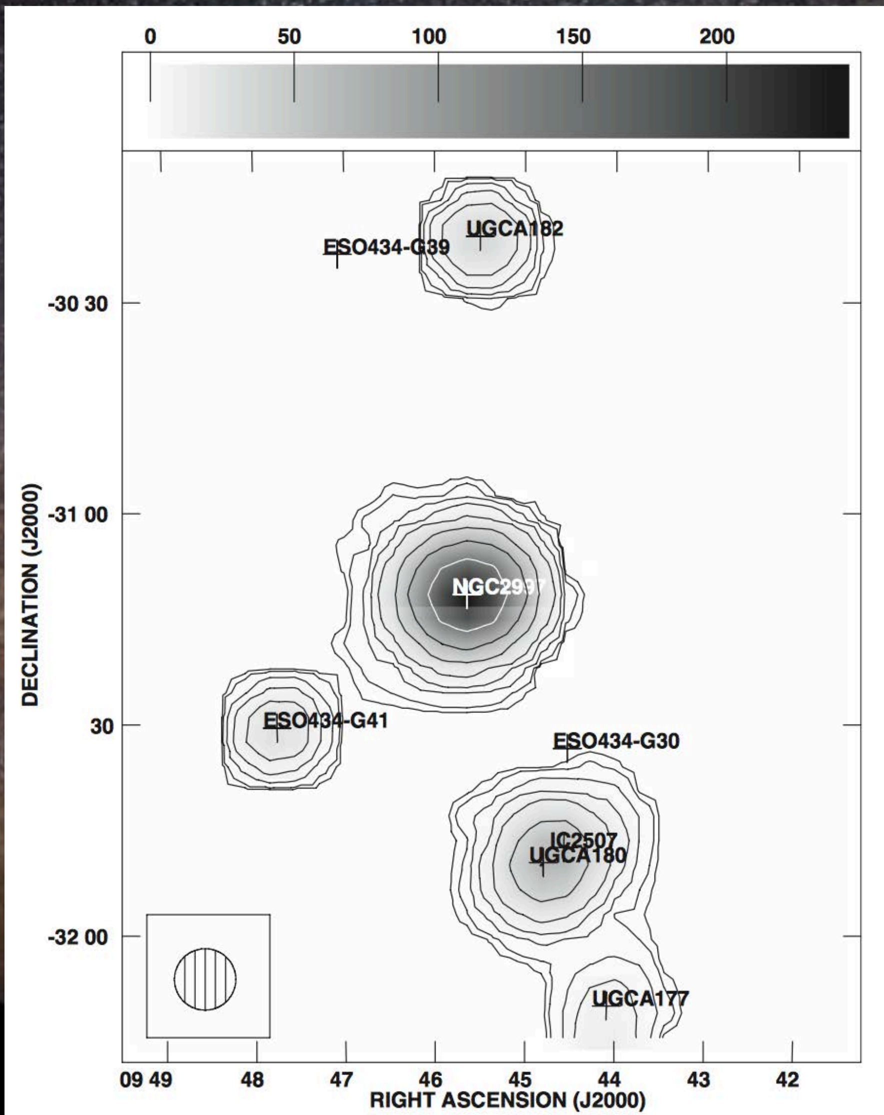
Wolfe et al. 2016 (Δ_{M31} ~ 800 kpc / 1' = 233 pc / $HPBW_{GBT}$ ~ 2 kpc)

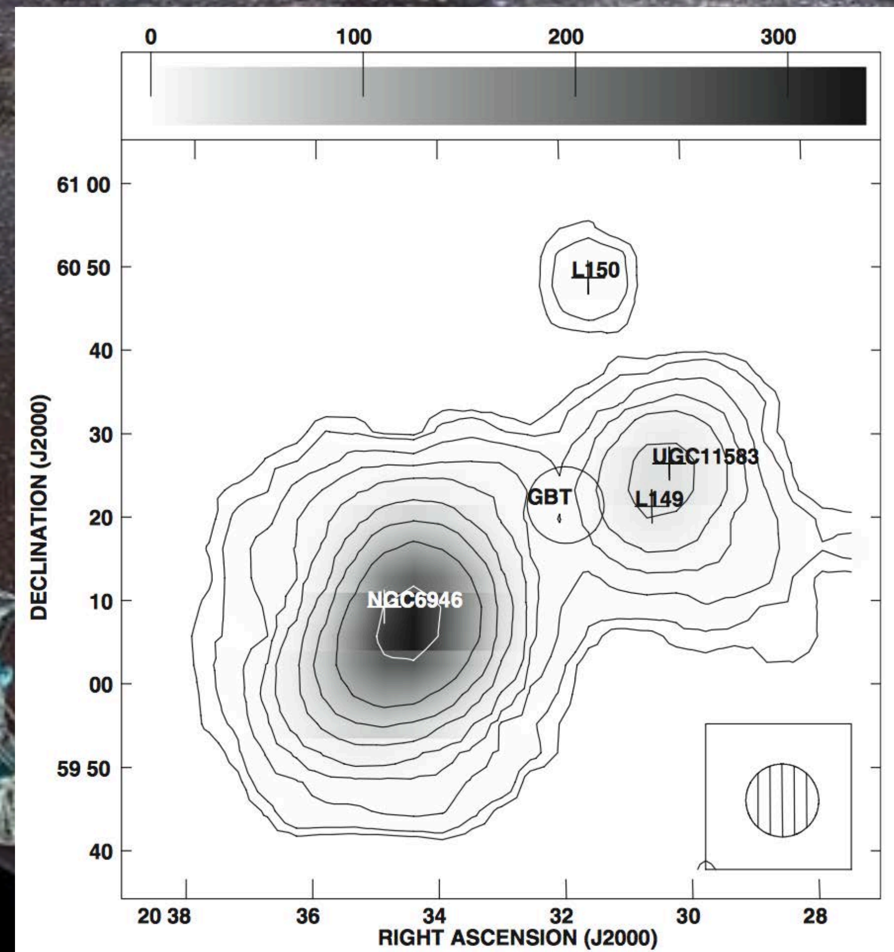
Galaxy – IGM Connection



Popping et al, 2015, PoS, AASKA14, 132

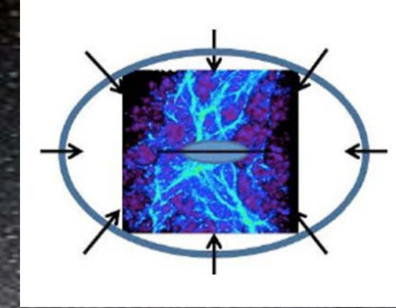
Galaxy – IGM Connection
Need sensitivity & resolution





Pisano 2014 / GBT / 1 x 10^{18} cm^{-2}

Fuelling of Galaxies

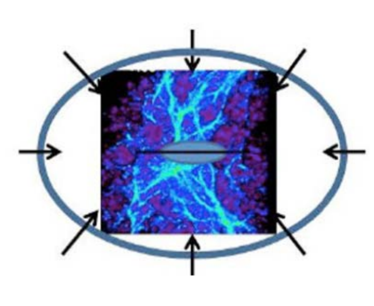


HI key to unlocking galaxy evolution

- Galaxy evolution studies dominated by optical/NIR (stars)
- Need to understand how galaxies fuelled (gas)
- HI is the fundamental baryonic building block

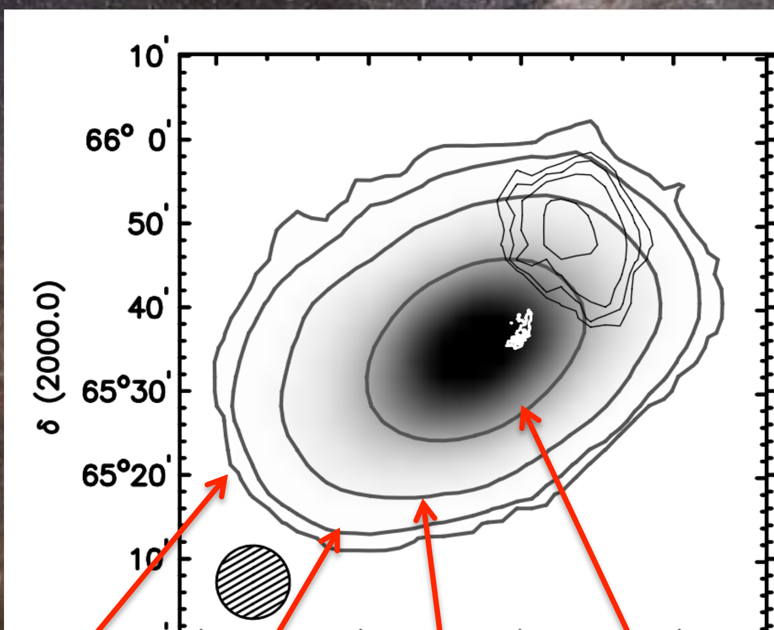
- How are galaxies re-fuelled from the IGM ?
- What is the nature of diffuse intergalactic gas ?
- Requires column densities $n_{HI} < 10^{18}\ \mathrm{cm}^{-2}$
  & resolution of a few kpc

Fuelling of Galaxies

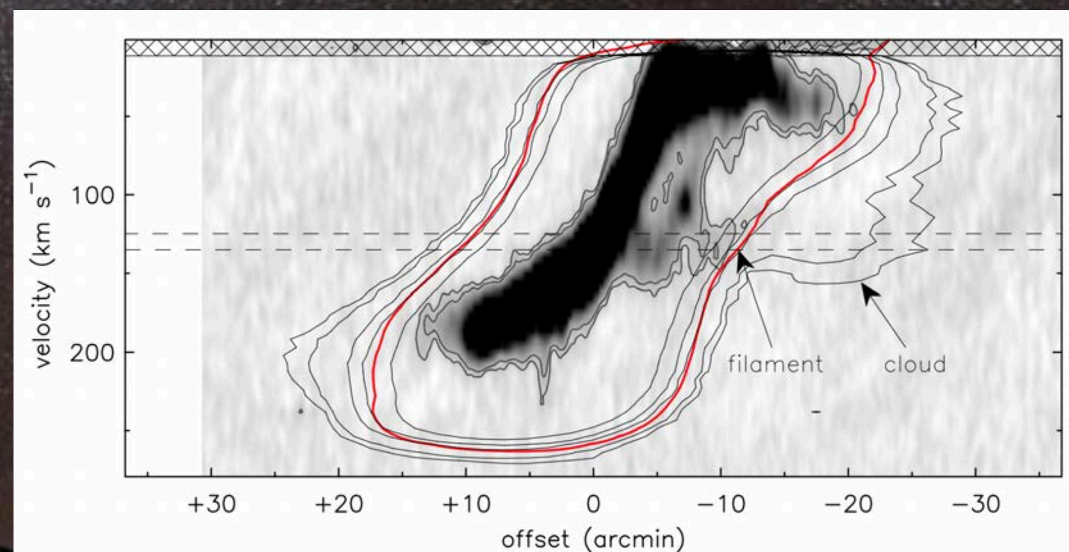


A low H I column density filament in NGC 2403: signature of interaction or accretion

W.J.G. de Blok[1,2,3], Katie M. Keating[4], D.J. Pisano[5,6], F. Fraternali[7,3], F. Walter[8], T. Oosterloo[1,3], E. Brinks[9], F. Bigiel[10], A. Leroy[11]

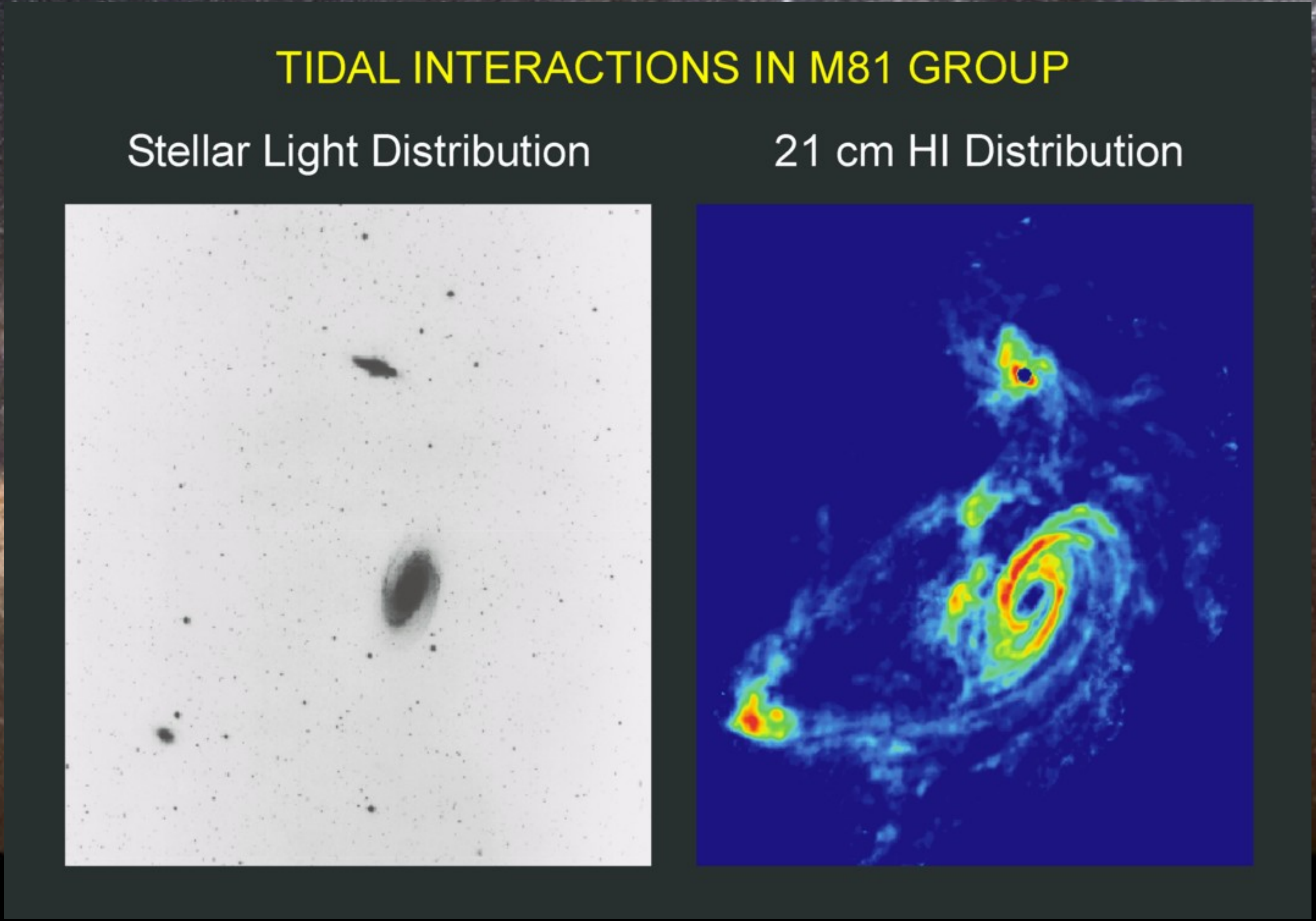


5×10^{17} / 5×10^{18} / 5×10^{19} / 5×10^{20} cm^{-2}



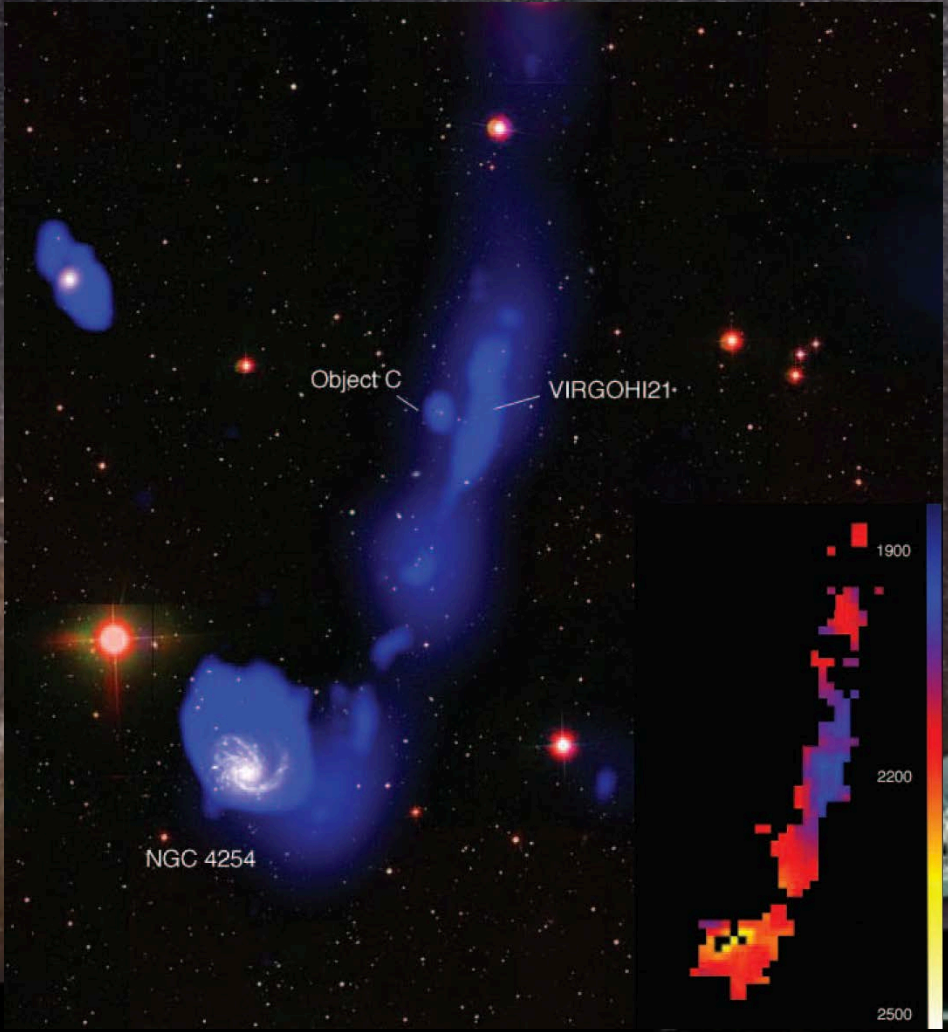
de Blok et al. 2014 (GBT & VLA)

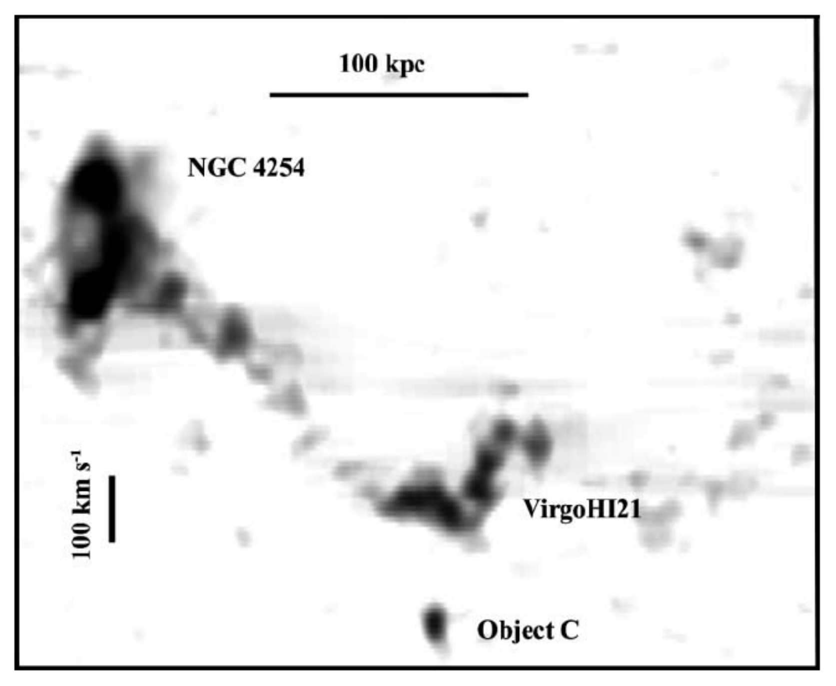
Tidal interactions



Yun et al. 1994

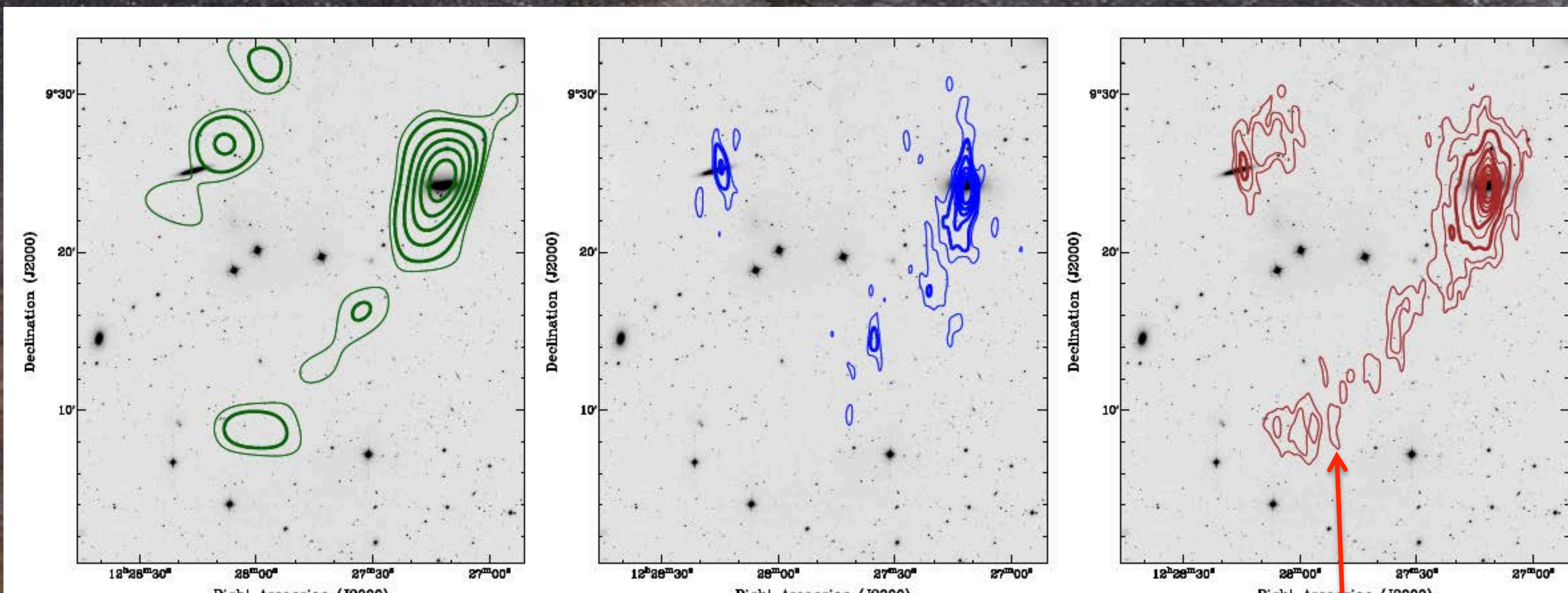
Tidal interactions





Duc & Bournaud 2008

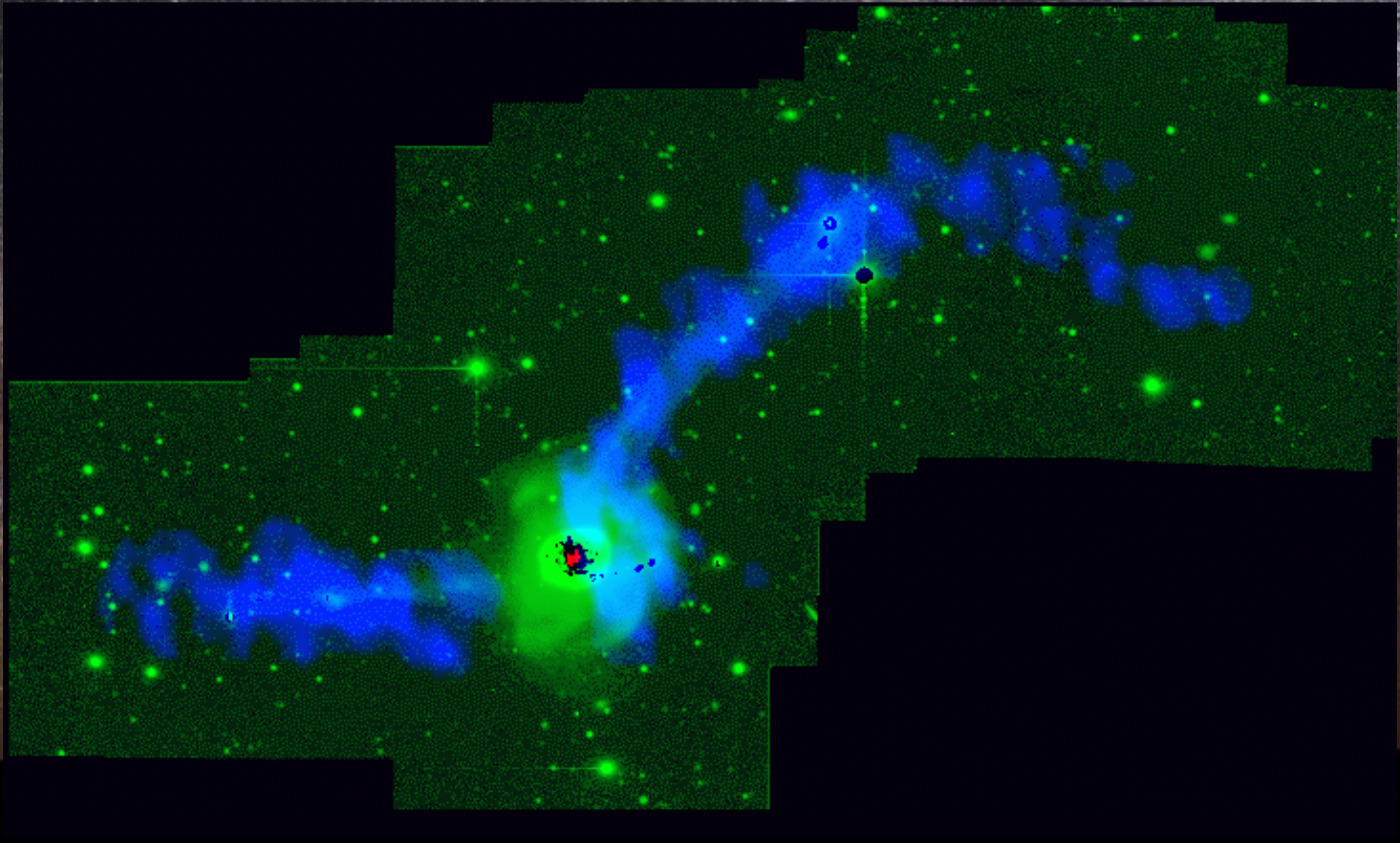
Tidal interactions



$N_{HI} \sim 5 \times 10^{18}$ cm^{-2}

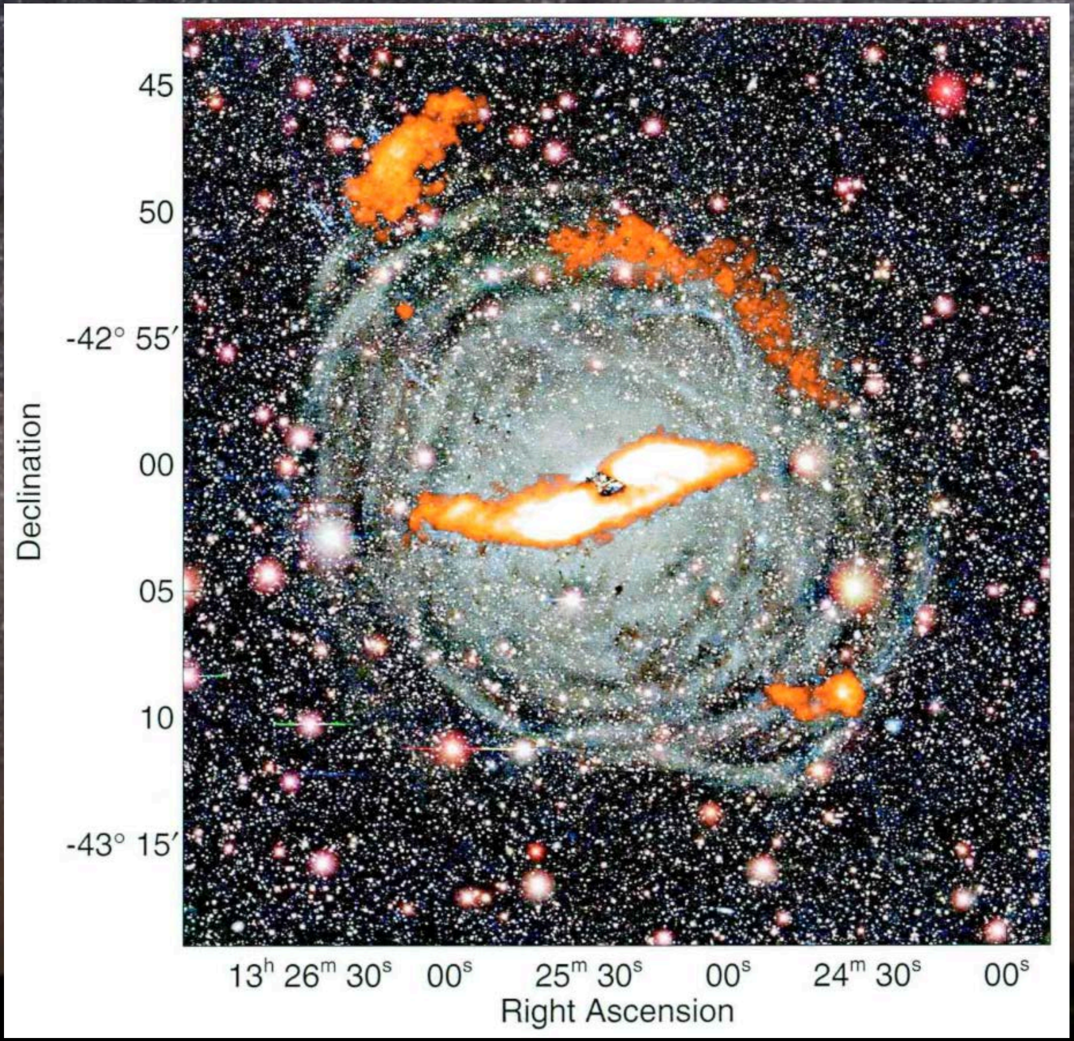
Sorgho et al. 2016

Mergers: NGC 7252



Hibbard et al. 1994

Mergers: Cen A

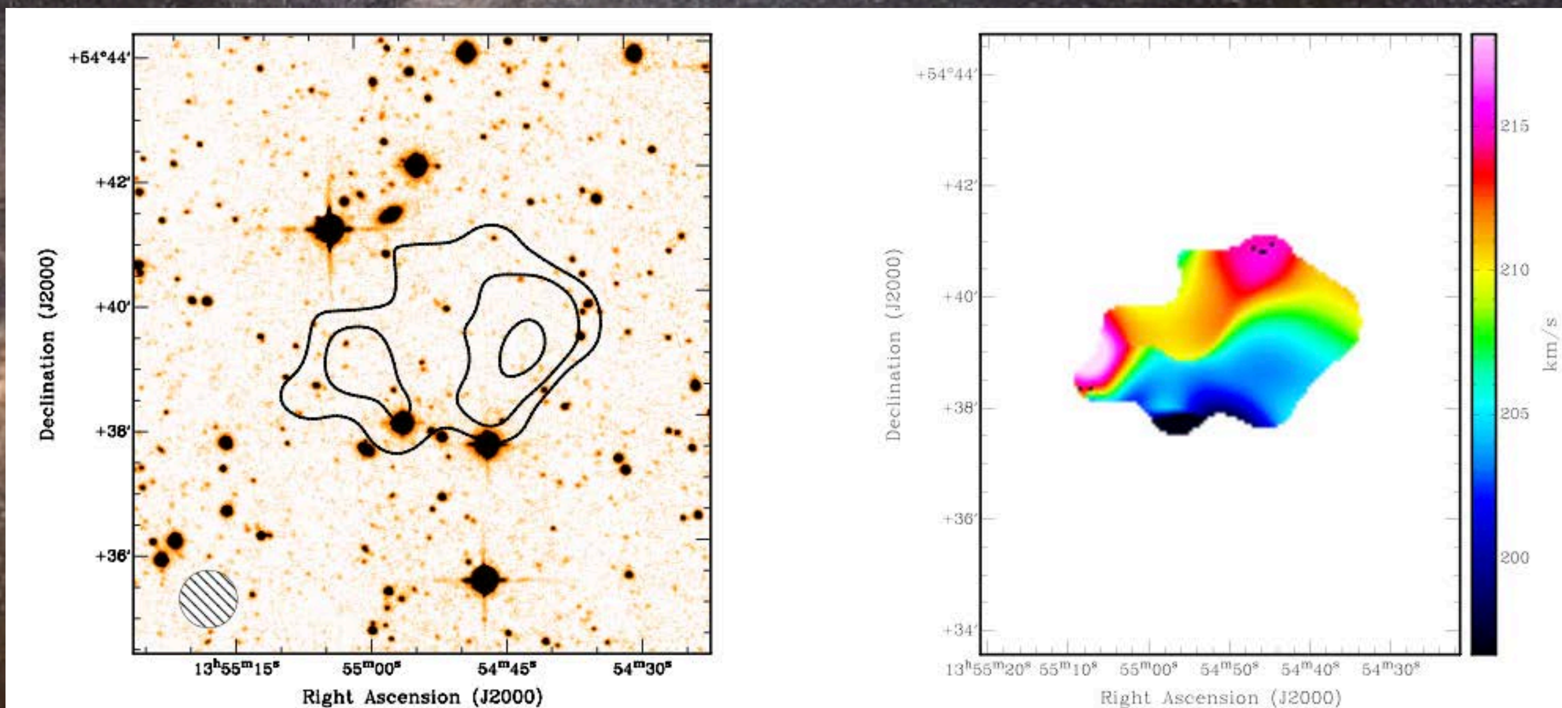


Struve et al. 2010

Dark Galaxies ?

Is GBT 1355+5439 a dark galaxy?

T. A. Oosterloo[1,2], G. H. Heald[1], and W. J. G. de Blok[1,3]



M_{HI} ~ few x 10^5 M_{sol} / size ~ 1 kpc

Oosterloo, Heald & de Blok 2013

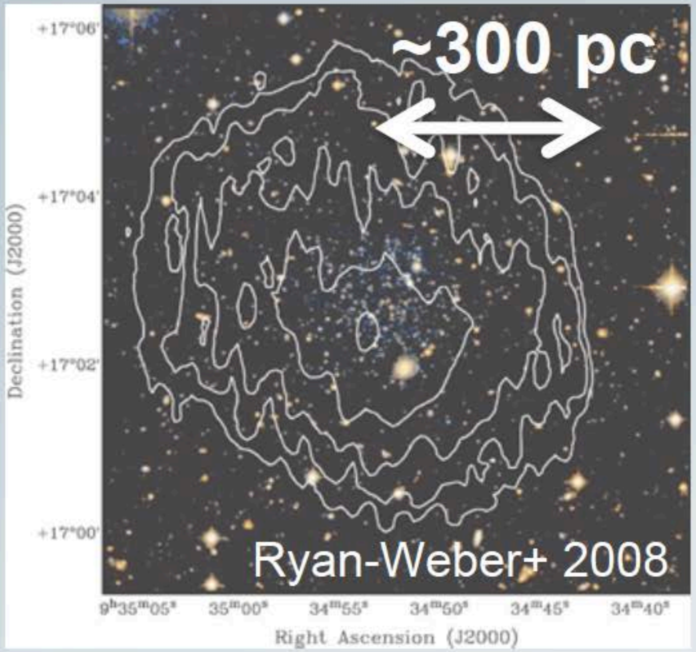
Nearly Dark Galaxies

Leo T:

D~0.42 Mpc

$M_{HI} \sim 3 \times 10^5 M_{sun}$

$M_{star} = 1 \times 10^5 M_{sun}$

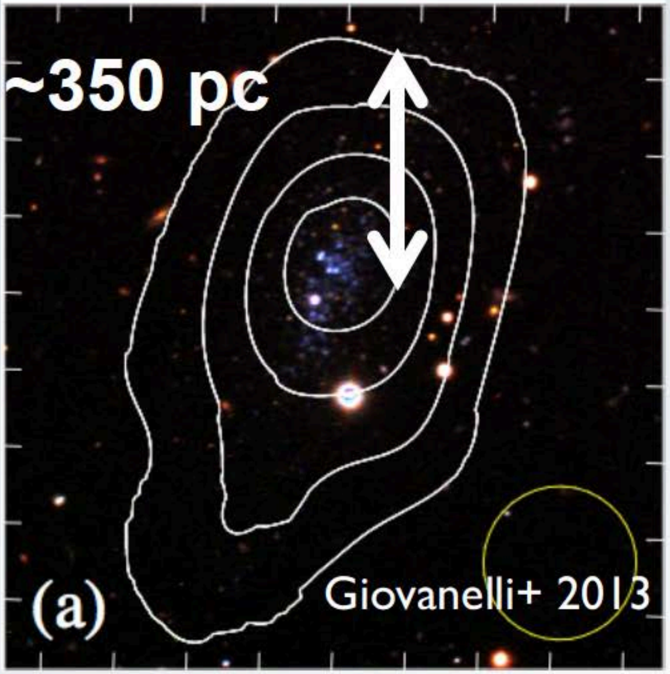


Leo P:

D~1.6 Mpc

$M_{HI} \sim 8 \times 10^5 M_{sun}$

$M_{star} \sim 6 \times 10^5 M_{sun}$



Nearly Dark Galaxies

H I observations of two new dwarf galaxies: Pisces A and B with the SKA Pathfinder KAT-7*

C. Carignan[1,2], Y. Libert[1], D. M. Lucero[1,4], T. H. Randriamampandry[1], T. H. Jarrett[1],
T. A. Oosterloo[3,4], and E. J. Tollerud[5]

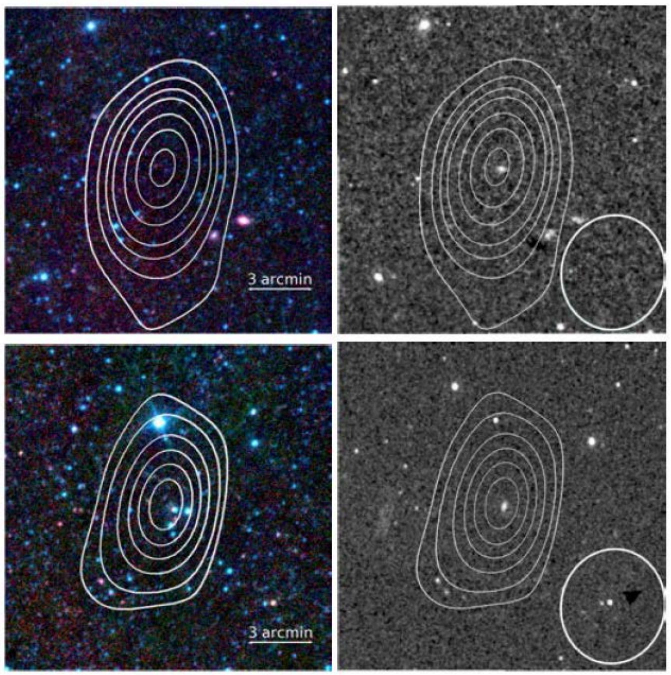
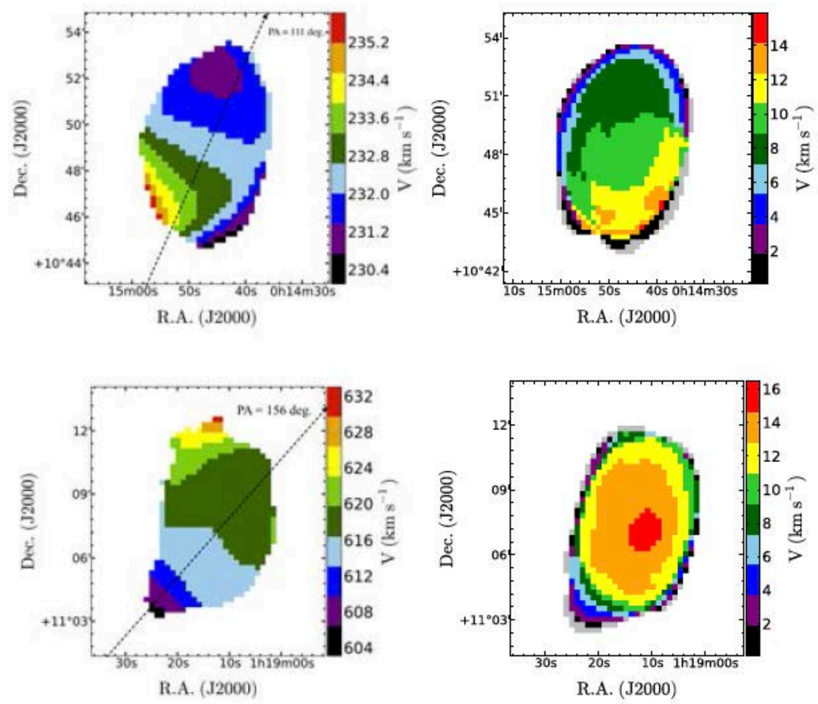


Fig. 2. HI distributions in Pisces A (*top*) and Pisces B (*bottom*), superposed on the 3-color WISE w1+w2+w3 composite (*left*) and Galex NUV (*right*) images from the natural weighted cubes. Contours are at 0.3 (3σ), 0.6, 1.2, 1.8, 2.4, and 3.0 × 10^{19} cm^{-2}.

A&A 587, L3 (2016)



Carignan et al. 2016

SKA1 HI Science Priorities

- Resolved HI kinematics and morphology of ~10^{10} $M_\odot$ mass **galaxies out to z~0.8**
- High spatial resolution studies of the **ISM in the nearby Universe**.
- Multi-resolution mapping studies of the **ISM in our Galaxy**
- **HI absorption studies** out to the highest redshifts.
- The gaseous interface and accretion physics between **galaxies and the IGM**

SKA1 science goals

Science Goal	SWG	Objective	SWG Rank
1	*CD/EoR*	Physics of the early universe IGM - I. Imaging	1/3
2	*CD/EoR*	Physics of the early universe IGM - II. Power spectrum	2/3
3	*CD/EoR*	Physics of the early universe IGM - III. HI absorption line spectra (21cm forest)	3/3
4	*Pulsars*	Reveal pulsar population and MSPs for gravity tests and Gravitational Wave detection	1/3
5	*Pulsars*	High precision timing for testing gravity and GW detection	1/3
6	*Pulsars*	Characterising the pulsar population	2/3
7	*Pulsars*	Finding and using (Millisecond) Pulsars in Globular Clusters and External Galaxies	2/3
8	*Pulsars*	Finding pulsars in the Galactic Centre	2/3
9	*Pulsars*	Astrometric measurements of pulsars to enable improved tests of GR	2/3
10	*Pulsars*	Mapping the pulsar beam	3/3
11	*Pulsars*	Understanding pulsars and their environments through their interactions	3/3
12	*Pulsars*	Mapping the Galactic Structure	3/3
13	*HI*	Resolved HI kinematics and morphology of ~10^10 M_sol mass galaxies out to z~0.8	1/5
14	*HI*	High spatial resolution studies of the ISM in the nearby Universe.	2/5
15	*HI*	Multi-resolution mapping studies of the ISM in our Galaxy	3/5
16	*HI*	HI absorption studies out to the highest redshifts.	4/5
17	*HI*	The gaseous interface and accretion physics between galaxies and the IGM	5/5
18	*Transients*	Solve missing baryon problem at z~2 and determine the Dark Energy Equation of State	=1/4
19	*Transients*	Accessing New Physics using Ultra-Luminous Cosmic Explosions	=1/4
20	*Transients*	Galaxy growth through measurements of Black Hole accretion, growth and feedback	3/4
21	*Transients*	Detect the Electromagnetic Counterparts to Gravitational Wave Events	4/4
22	*Cradle of Life*	Map dust grain growth in the terrestrial planet forming zones at a distance of 100 pc	1/5
23	*Cradle of Life*	Characterise exo-planet magnetic fields and rotational periods	2/5
24	*Cradle of Life*	Survey all nearby (~100 pc) stars for radio emission from technological civilizations.	3/5
25	*Cradle of Life*	The detection of pre-biotic molecules in pre-stellar cores at distance of 100 pc.	4/5
26	*Cradle of Life*	Mapping of the sub-structure and dynamics of nearby clusters using maser emission.	5/5
27	*Magnetism*	The resolved all-Sky characterisation of the interstellar and intergalactic magnetic fields	1/5
28	*Magnetism*	Determine origin, maintenance and amplification of magnetic fields at high redshifts - I.	2/5
29	*Magnetism*	Detection of polarised emission in Cosmic Web filaments	3/5
30	*Magnetism*	Determine origin, maintenance and amplification of magnetic fields at high redshifts - II.	4/5
31	*Magnetism*	Intrinsic properties of polarised sources	5/5
32	*Cosmology*	Constraints on primordial non-Gaussianity and tests of gravity on super-horizon scales.	1/5
33	*Cosmology*	Angular correlation functions to probe non-Gaussianity and the matter dipole	2/5
34	*Cosmology*	Map the dark Universe with a completely new kind of weak lensing survey - in the radio.	3/5
35	*Cosmology*	Dark energy & GR via power spectrum, BAO, redshift-space distortions and topology.	4/5
36	*Cosmology*	Test dark energy & general relativity with fore-runner of the 'billion galaxy' survey.	5/5
37	*Continuum*	Measure the Star formation history of the Universe (SFHU) - I. Non-thermal processes	1/8
38	*Continuum*	Measure the Star formation history of the Universe (SFHU) - II. Thermal processes	2/8
39	*Continuum*	Probe the role of black holes in galaxy evolution - I.	3/8
40	*Continuum*	Probe the role of black holes in galaxy evolution - II.	4/8
41	*Continuum*	Probe cosmic rays and magnetic fields in ICM and cosmic filaments.	5/8
42	*Continuum*	Study the detailed astrophysics of star-formation and accretion processes - I.	6/8
43	*Continuum*	Probing dark matter and the high redshift Universe with strong gravitational lensing.	7/8
44	*Continuum*	Legacy/Serendipity/Rare.	8/8

Table 1. Collated list of science goals. Within each science area, the entries are ordered in the rank provided by the SWG Chairs. The eight different groups of SWG contributions are listed in the Table in an arbitrary sequence.

Braun et al, 2014, SKA1 Science Priority Outcomes

SKA1 HI Science Priorities

- Resolved HI kinematics and morphology of ~10^{10} $M_\odot$ mass **galaxies out to z~0.8**
- High spatial resolution studies of the **ISM in the nearby Universe**.
- Multi-resolution mapping studies of the **ISM in our Galaxy**
- **HI absorption studies** out to the highest redshifts.
- The gaseous interface and accretion physics between **galaxies and the IGM**

priority SKA1 science goals

Science Goal	SWG	Objective	SWG Rank
1	*CD/EoR*	Physics of the early universe IGM - I. Imaging	1/3
2	*CD/EoR*	Physics of the early universe IGM - II. Power spectrum	2/3
4	*Pulsars*	Reveal pulsar population and MSPs for gravity tests and Gravitational Wave detection	1/3
5	*Pulsars*	High precision timing for testing gravity and GW detection	1/3
13	*HI*	Resolved HI kinematics and morphology of ~10^10 M_sol mass galaxies out to z~0.8	1/5
14	*HI*	High spatial resolution studies of the ISM in the nearby Universe.	2/5
15	*HI*	Multi-resolution mapping studies of the ISM in our Galaxy	3/5
18	*Transients*	Solve missing baryon problem at z~2 and determine the Dark Energy Equation of State	=1/4
22	*Cradle of Life*	Map dust grain growth in the terrestrial planet forming zones at a distance of 100 pc	1/5
27	*Magnetism*	The resolved all-Sky characterisation of the interstellar and intergalactic magnetic fields	1/5
32	*Cosmology*	Constraints on primordial non-Gaussianity and tests of gravity on super-horizon scales.	1/5
33	*Cosmology*	Angular correlation functions to probe non-Gaussianity and the matter dipole	2/5
37 + 38	*Continuum*	Star formation history of the Universe (SFHU) – I+II. Non-thermal & Thermal processes	1+2/8

Design should have this science goal in mind

SKA2

Conclusions
Galaxy – IGM Connection

- The interaction of galaxies with their environment, the Intergalactic Medium (IGM), is a very important aspect of galaxy formation.

- One of the most fundamental, but unanswered questions in the evolution of galaxies is how gas circulates in and around galaxies and how it enters the galaxies to support star formation.

- We have several lines of evidence that the observed evolution of star formation requires gas accretion from the IGM at all times and on all cosmic scales.

Conclusions
Galaxy – IGM Connection

- To truly make significant progress in understanding the distribution of neutral hydrogen in the IGM, column densities of $N_{HI} \sim 10^{18}$ cm^{-2} and below have to be probed over large areas on the sky at sub-arcminute resolution.

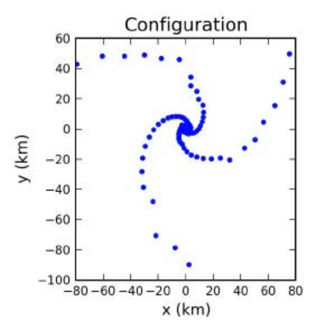
- These are the densities of the faintest structures known today around nearby galaxies, though mostly found with single dish telescopes which do not have the resolution to resolve these structures and investigate any kinematics.

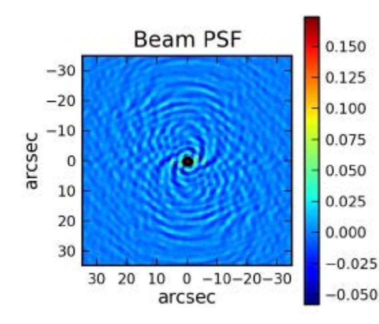
- Existing interferometers lack the collecting power or short baselines to achieve brightness sensitivities typically below N_{HI} 10^{19} cm^{-2} .

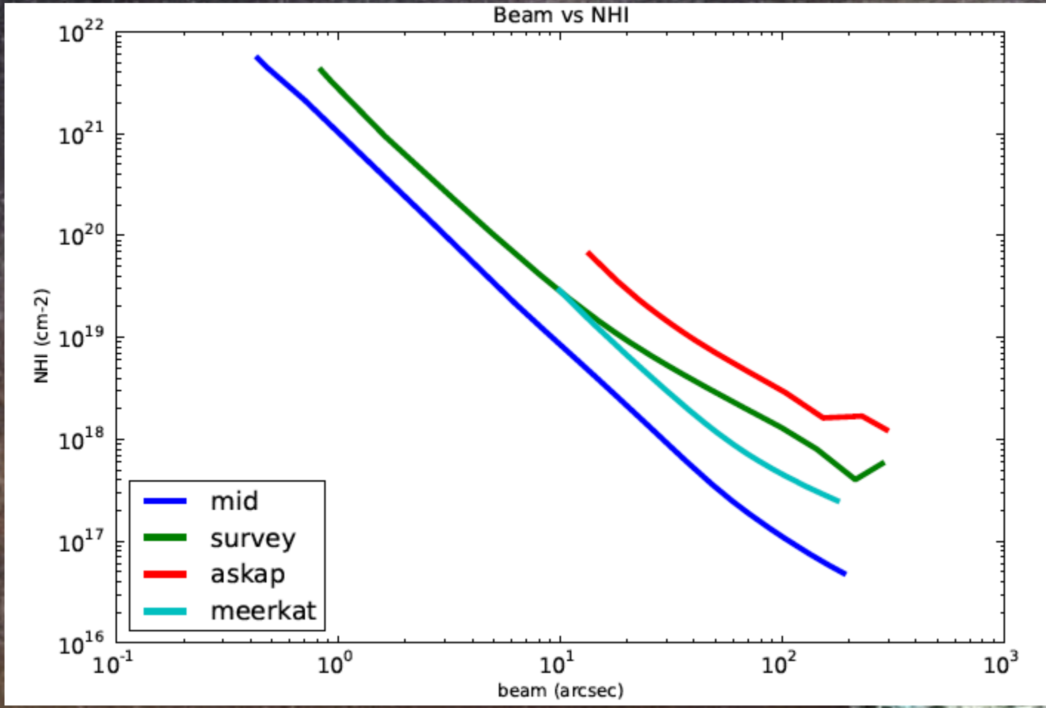
Conclusions
Galaxy – IGM Connection

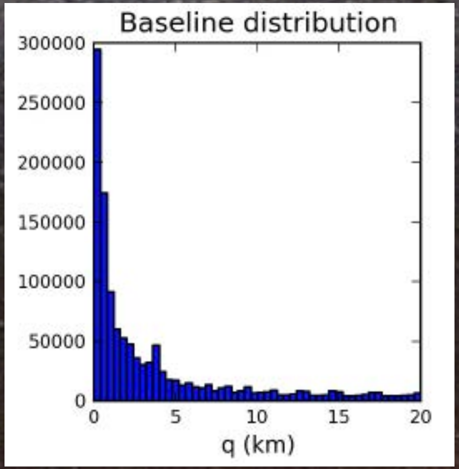
- The interplay of gas between galaxies and the surrounding IGM is a key aspect in galaxy formation.
- The cosmic web holds the large reservoir of gas that eventually accretes into galaxies and supports the formation of stars.
- For the imaging of the diffuse gas filaments in the cosmic web, HI column densities are required in the range N_{HI} 10^{15} - 10^{18} cm^{-2} which is mostly the realm of the full SKA.
- Observations with the SKA1 will be able to start detecting low column density gas over very large areas much deeper than before, but also resolve this gas at sub-arcmin resolution.

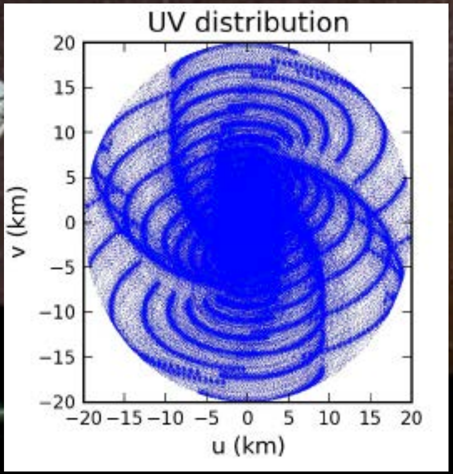
Prospects of SKA1-MID











Popping et al. 2015, AASKA14, 132

Sensitivities prospects in the SKA era

Table 1. Expected sensitivities of different telescopes at 5σ.

Telescope Array(s)	Integration hours	resolution km s^{-1}	beam arcsecs	sensitivity cm^{-2}	Expected date
VLA (THINGS)	10	5	30	5.0×10^{19}	
KAT-7	100	5	210	5.0×10^{18}	
WSRT (HALOGAS)	120	5	30	5.0×10^{18}	
KAT-7 + WSRT	100	16	210	1.0×10^{18}	
MeerKAT	200	16	90	5.0×10^{17}	2017
SKA_1-MID	100	5	30	7.5×10^{17}	2023
SKA_2	10	5	30	2.5×10^{17}	2030
SKA_2	100	5	30	7.5×10^{16}	2030

Carignan 2016

MeerKAT + FAST

- In the near future (2018), the best combination to study low column density HI with a good spatial resolution will be to combine the sensitivity of FAST with the spatial resolution of MeerKAT.

- The combination of the data from those two telescopes will allow, 5 years before SKA1-MID, to do "cosmic web" research to levels < 5×10^{17} cm^{-2}, close to 10^{16} cm^{-2}, densities that would normally only be accessible to the full SKA around 2030.

- It is at those densities that we expect the galaxies to connect with the surrounding cosmic web.