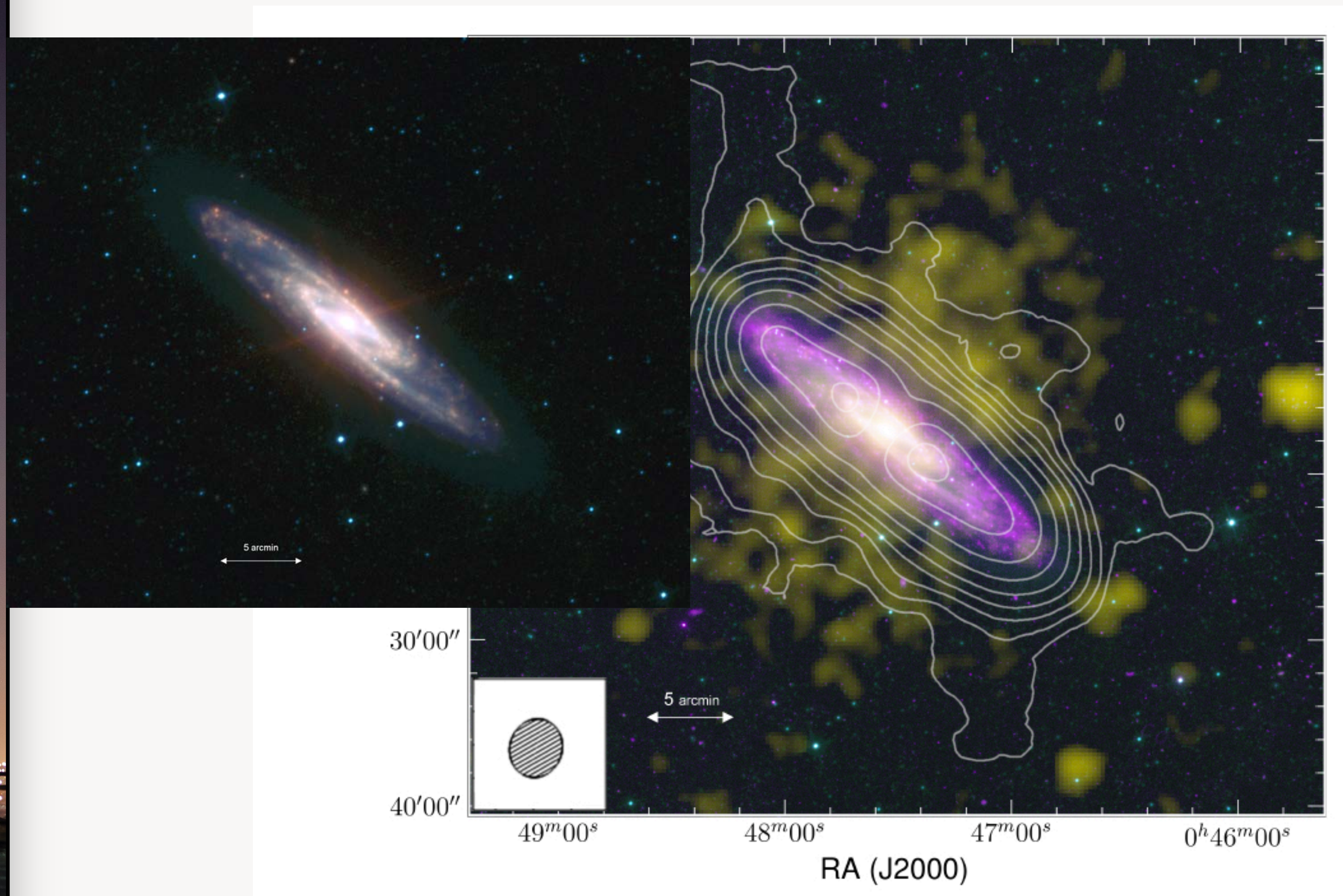
Radio Astronomy at UCT



PROFESSOR CLAUDE CARIGNAN

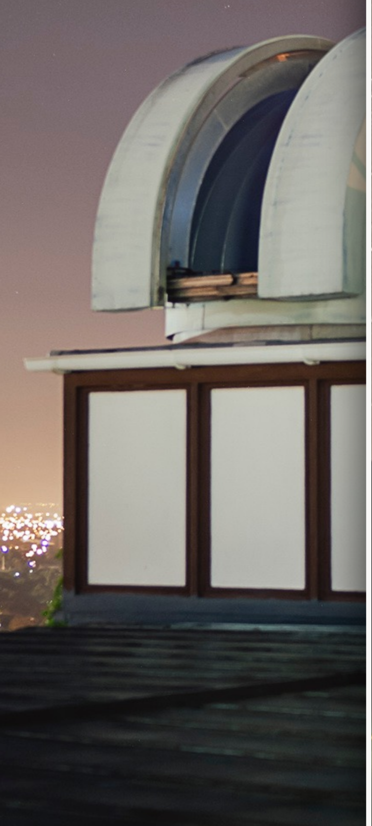
South African SKA Research Chair in Extragalactic Multi-Wavelength Astronomy
Department of Astronomy, University of Cape Town

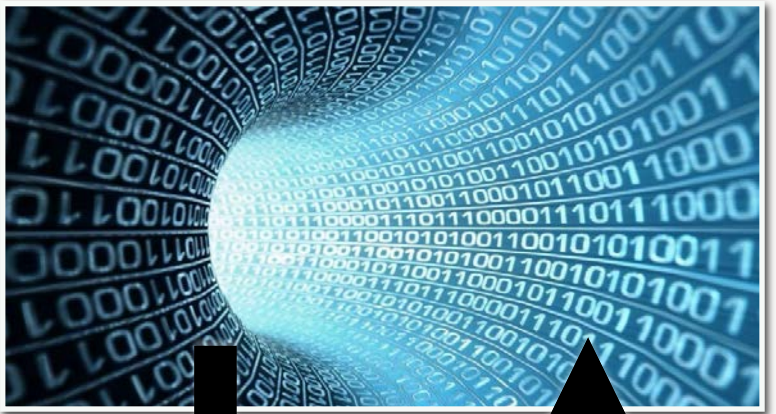
MONDAY 27 MARCH 2017 – DARA MEETING

University of Cape Town • iYunivesithi yaseKapa • Universiteit van Kaapstad

SPES BONA

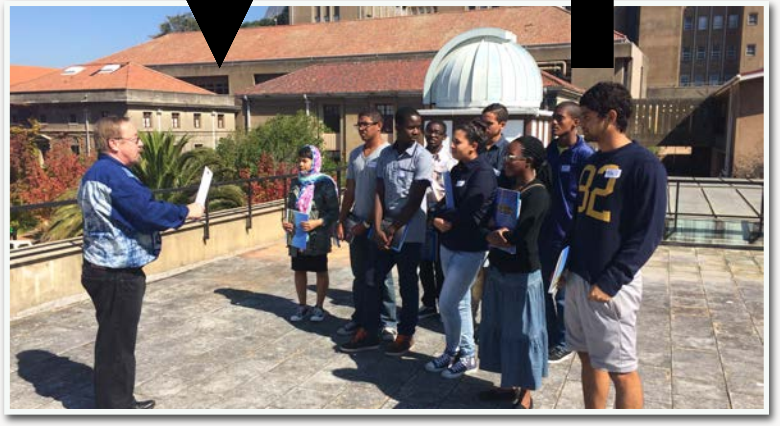
Science & Education





ASTRONOMY,
STATISTICS
COMPUTER SCIENCE
PHYSICS,
MATHEMATICS

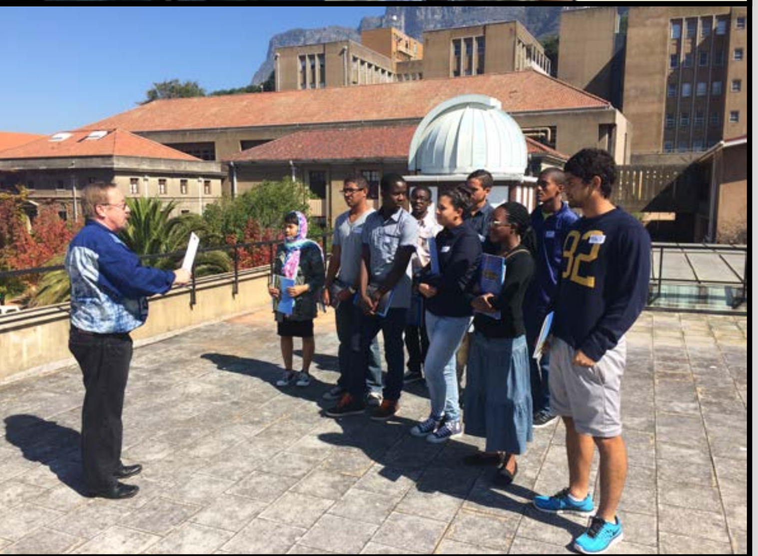
MACHINE LEARNING
ENGINEERING



ASTRONOMY, PHYSICS, MATHEMATICS
ENGINEERING

ASTROATUCT

ASTRONOMYUCT



ASTROATUCT

ASTRONOMYUCT

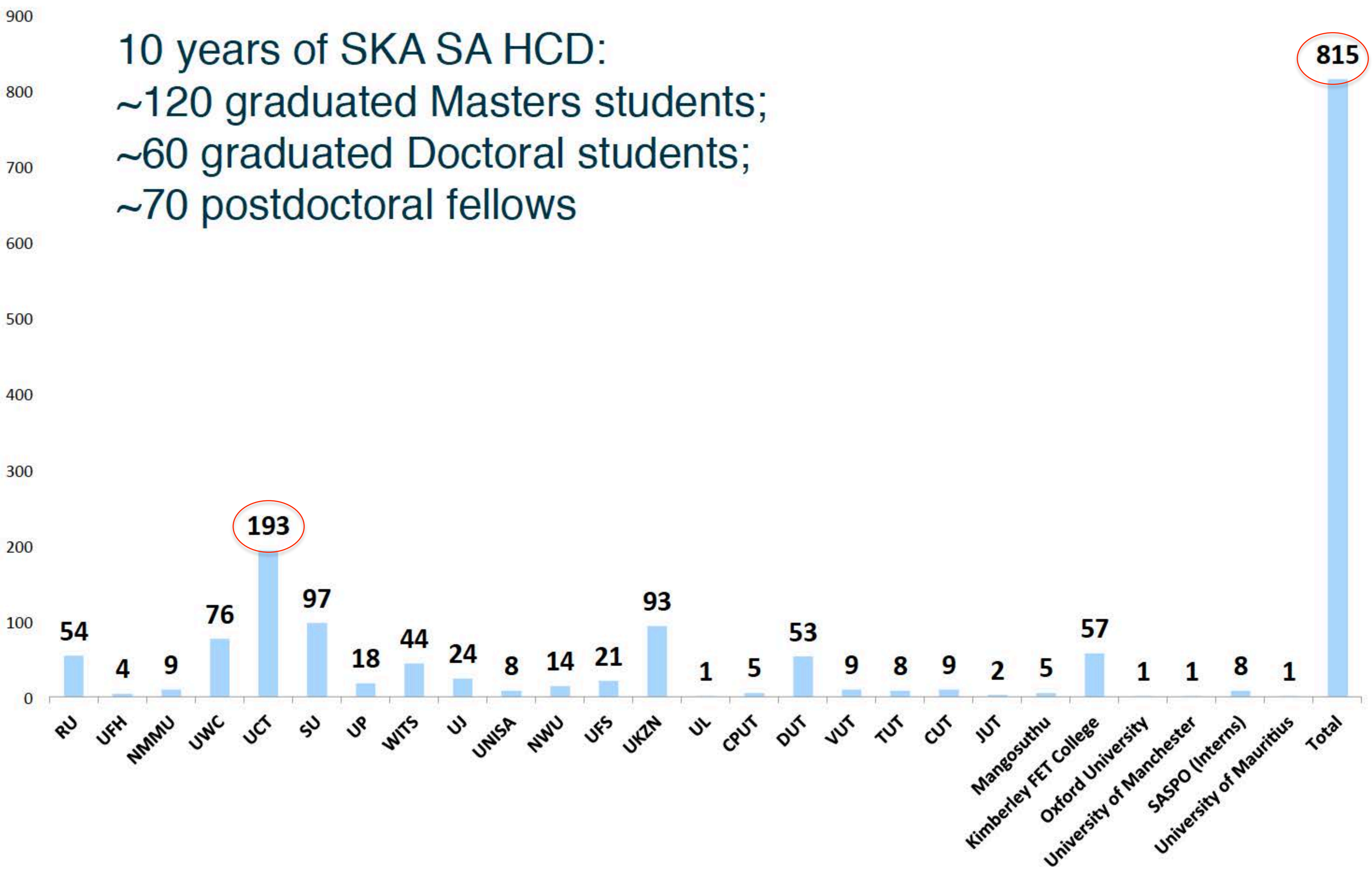
Science & Education

ASTRONOMY AT UCT:

- LARGEST UNIVERSITY-BASED ASTRONOMY GROUP IN SOUTH AFRICA
- 10 YEARS OF UNDERGRADUATE MAJOR IN ASTROPHYSICS (SINCE 2006)
- 2 ANNUAL OPEN DAYS AND TEACHING TELESCOPES ON CAMPUS
- HOST OF THE NATIONAL ASTROPHYSICS AND SPACE SCIENCE PROGRAM
- CURRENTLY 34 POSTGRADUATE STUDENTS (MSC AND PHD)
- LEADING 40% OF THE MEERKAT LEGACY SURVEYS (2018-2023)
- INTER-UNIVERSITY INSTITUTE FOR DATA INTENSIVE ASTRONOMY (IDIA)
- LARGE INTERNATIONAL PARTNERSHIPS (UK, NL, USA, AUS)

Number of Grants Awarded to Education Institutions

10 years of SKA SA HCD:
~120 graduated Masters students;
~60 graduated Doctoral students;
~70 postdoctoral fellows



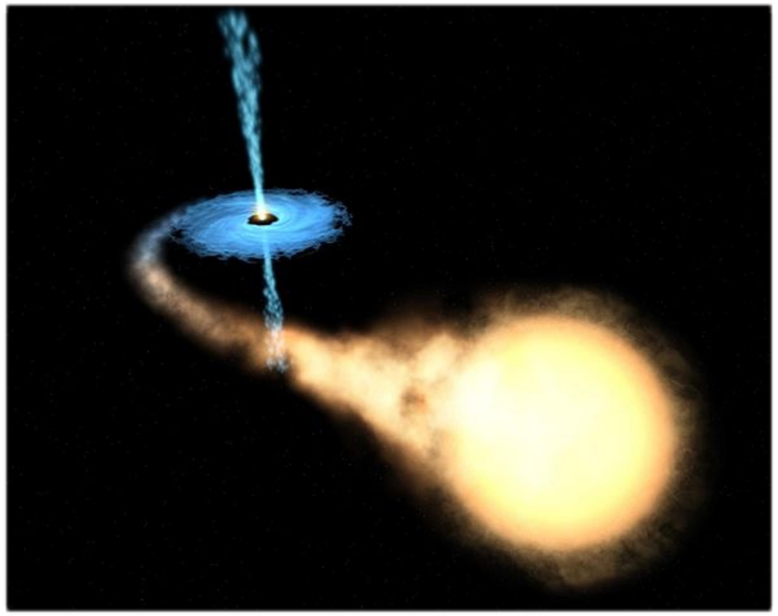
MeerKAT and the Large Survey Projects

MEERKAT LARGE SURVEY PROJECTS (70% of all available time in the first 5 years)		
Radio Pulsar Timing	Bailes (AU)	7860 h
Testing Einstein's theory of gravity and gravitational radiation - Investigating the physics of enigmatic neutron stars through observations of pulsars		
LADUMA	Blyth, Holwerda, Baker (**UCT**,NL,US)	5000 h
An ultra-deep survey of neutral hydrogen gas in the early universe		
MESMER	Heywood (UK)	6500 h
Searching for CO at high red-shift (z>7) to investigate the role of molecular hydrogen in the early universe		
MeerKAT Absorption Line Survey	Gupta, Srianand (NL, IN)	4000 h
Survey for H and OH lines in absorption against distant continuum sources; OH line ratios may give clues about changes in the fundamental constants in the early universe).		
MHONGOOSE	de Blok (NL,**UCT**)	6000 h
Investigations of different types of galaxies; dark matter and the cosmic web		
MeerKAT HI Survey of Fornax	Serra (NL)	2450 h
Galaxy formation and evolution in the cluster environment		
MeerGAL	Thompson, Goedhart (UK,SA)	3300 h
Galactic structure and dynamics, distribution of ionised gas, recombination lines, interstellar molecular gas and masers		
MIGHTEE	Jarvis, van der Heyden (UK,**UCT**)	1950 h
Deep continuum observations of the earliest radio galaxies		
TRAPUM	Stappers, Kramer (UK, DE)	3080 h
Searching for, and investigating new and exotic pulsars		
ThunderKAT	Woudt, Fender (**UCT**,UK)	3000 h
Study of explosive radio transients with MeerKAT; accretion-induced outflow from compact stellar remnants, e.g. relativistic jets and (super)novae		

MeerKAT Large Survey Programs (LSPs with SA (UCT) PIs)

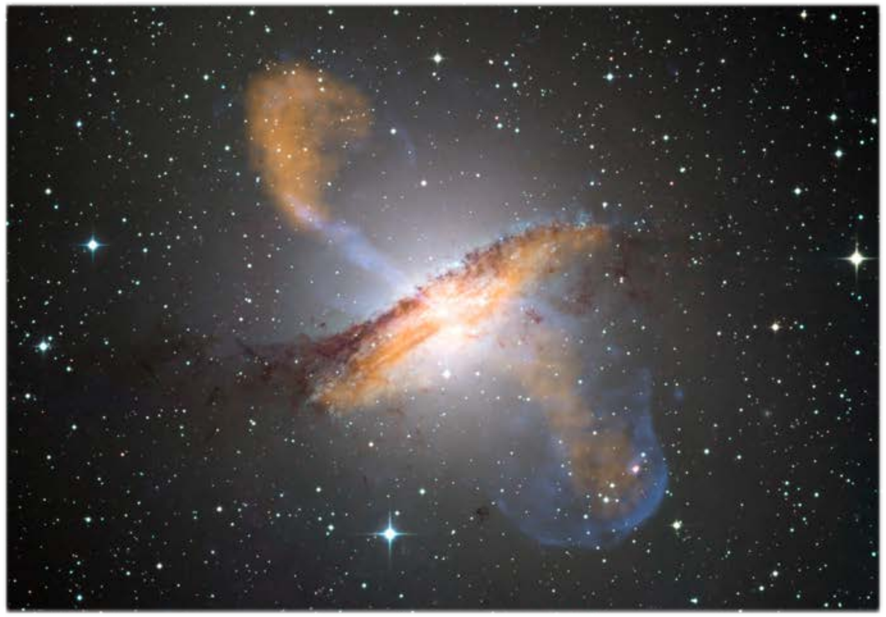
MHONGOOSE:

GALAXY EVOLUTION IN THE NEARBY UNIVERSE & DARK MATTER



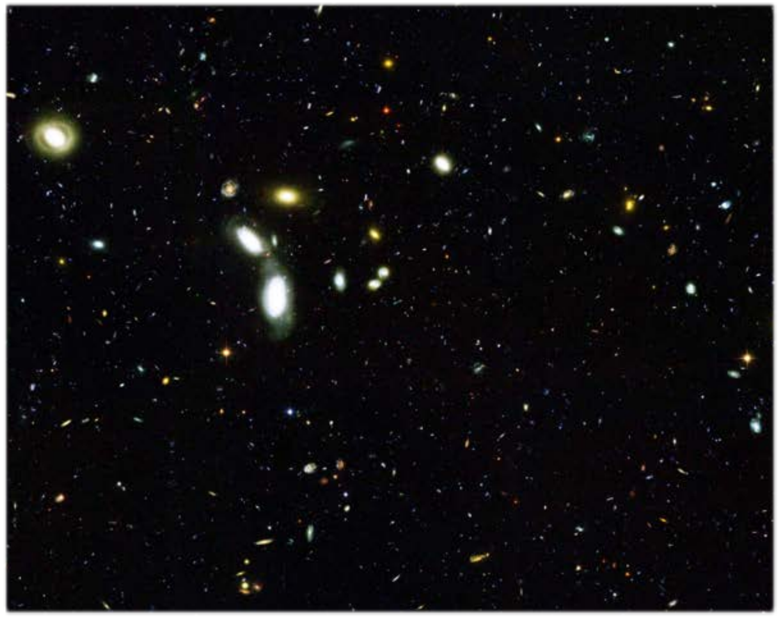
THUNDERKAT:

EXPLOSIVE TRANSIENTS, RELATIVISTIC JETS & UNKNOWN PHENOMENA



MIGHTEE:

GALAXY EVOLUTION, STAR FORMATION & SUPERMASSIVE BLACK HOLES



LADUMA:

DEEPEST VIEW OF THE RADIO UNIVERSE: GALAXY EVOLUTION OVER COSMIC TIME

MHONGOOSE

MeerKAT HI Observations of Nearby Galactic Objects: Observing Southern Emitters

PI: W.J.G. de Blok (ASTRON/UCT/Kapteyn)

- Galaxies do not have enough has to keep forming stars - this gas has to come from outside galaxies
- Simulations predict the gas must fall in from the surroundings of these galaxies, but is extremely faint
- MeerKAT is the first and (until SKA) only telescope worldwide with the sensitivity to detect this gas *and* to make detailed maps
- MHONGOOSE will survey this gas and map it around 30 nearby galaxies over a large range of total mass

Tentative detection of infalling gas (red blob) around galaxy NGC 2403 (blue) observed with the GBT single dish telescope. The resolution of the GBT is low (about the size of the blob) so it cannot resolve the structure of the gas. MeerKAT will increase the resolution by a factor of 10 or more.

MHONGOOSE

MeerKAT HI Observations of Nearby Galactic Objects: Observing Southern Emitters

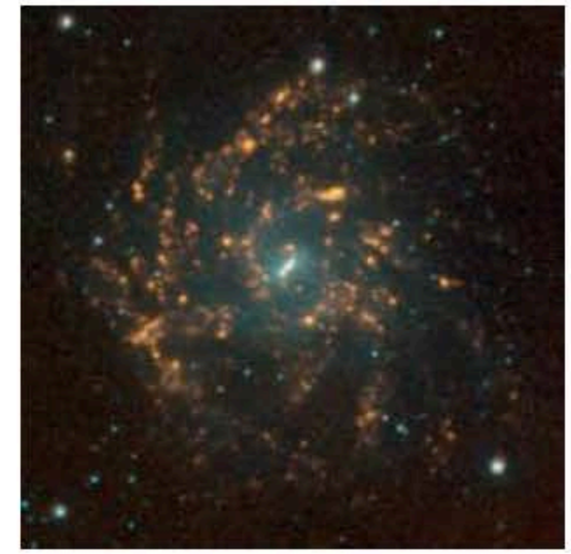
PI: W.J.G. de Blok (ASTRON/UCT/Kapteyn)

- MHONGOOSE will also investigate how gas in galaxies turns into stars: for our 30 galaxies we are collecting data in many parts of the spectrum to map all phases of star formation

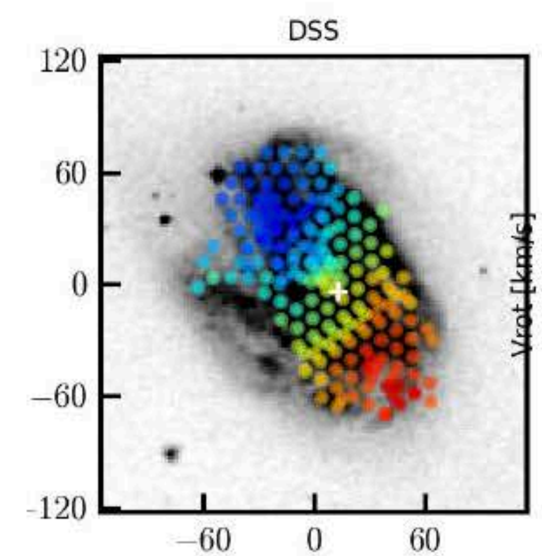
- We also measure kinematics of the gas from which stars form using optical telescopes (PhD Thesis Moses Mogotsi, UCT)

- Moses is one of ~10 South African PhD and Masters students that have so far worked within MHONGOOSE, in addition to ~5 postdocs

- MHONGOOSE's largest nationality is South African (26%) and South African MHONGOOSE team members played a large role in the commissioning of KAT-7



Picture of H alpha emission of star forming regions in one of the sample galaxies. This is an example of one of the many multi wavelength images already available.



Example optical velocity field of one of the MHONGOOSE galaxies from the thesis of Moses Mogotsi (UCT)

KAT-7 HI Science Verification Projects Completed

- **NGC 3109** (C. Carignan, B. Frank, K. Hess, D. Lucero, T. Randriamampandry, S. Goedhart, S. Passmoor 2013, AJ, 146, 48)
- **NGC 253** (D. Lucero, C. Carignan, E. C. Elson, T. Randriamampandry, T. H. Jarrett, T. A. Oosterloo, G. H. Heald 2015, MNRAS, 450, 3935)
- **Antlia Cluster** (K. M. Hess, T. H. Jarrett, C. Carignan, S. Passmoor, S. Goedhart 2015, MNRAS, 452, 1617)
- **Pisces A & B** (C. Carignan, Y. Libert, D. Lucero, T. Randriamampandry, T. H. Jarrett, T. A. Oosterloo, Tollerud, E. J. 2016, A&A, 587, L3)
- **M 83** (G. Heald, E. de Blok, D. Lucero, N., C. Carignan, T. Jarrett, E. Elson, N. Oozeer, T. Randriamampandry, L. van Zee 2016, MNRAS, 462, 1238)
- **Virgo Cluster HI** (A. Sorgho, K. Hess, C. Carignan, T. A. Oosterloo 2017, MNRAS, 464, 530)
- **HCG44** (K. Hess, M.E. Cluver, S. Yahya, L. Leisman, P. Serra, D. Lucero, S. Passmoor, C. Carignan 2017, MNRAS, 464, 957)
- **Engineering and Science Highlights of the KAT-7 Radio Telescope** (Foley, A. R. et al 2016, MNRAS, 460, 1664)

Understanding the Galactic gas cycle with MHONGOOSE

MHONGOOSE:

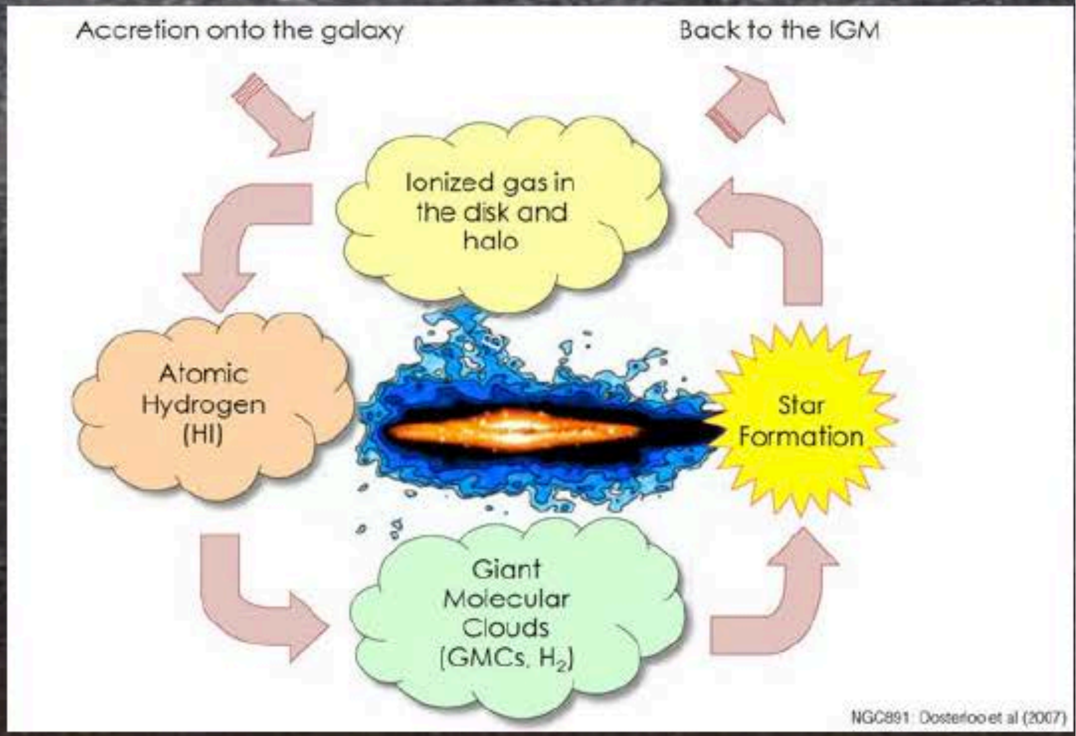
- Deep observations of 30 nearby galaxies
- 200 hours per galaxy; 6000 hours total
- 25 times longer than THINGS
- twice as deep as HALOGAS

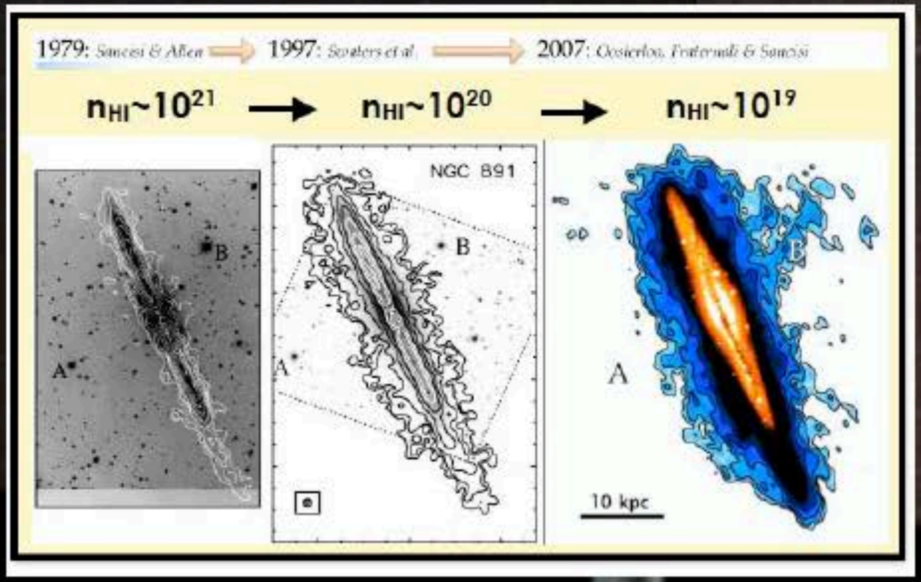
High resolution:

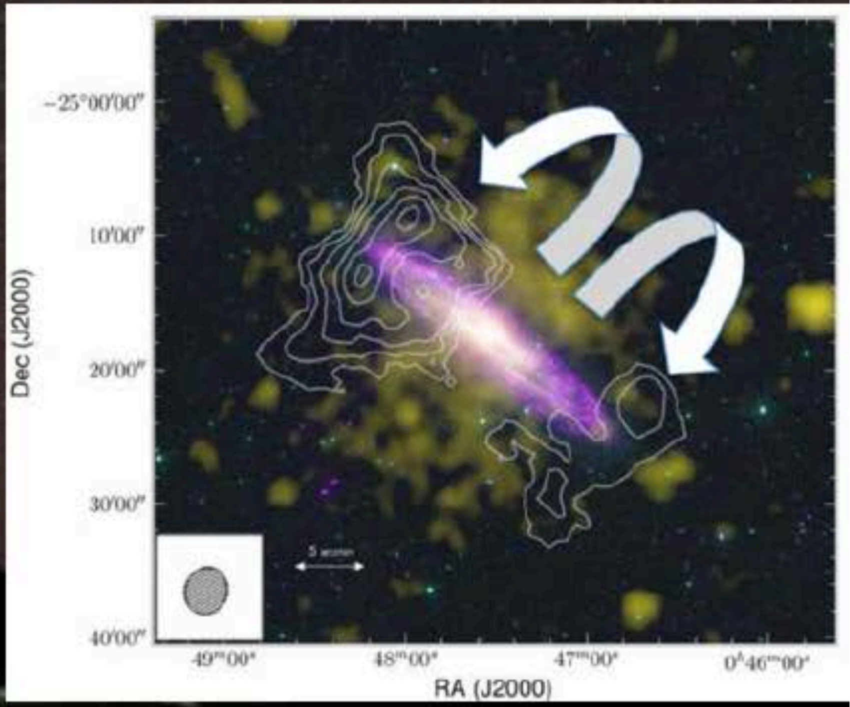
- star formation
- dynamics
- structure of the ISM

High sensitivity:

- cosmic web
- accretion







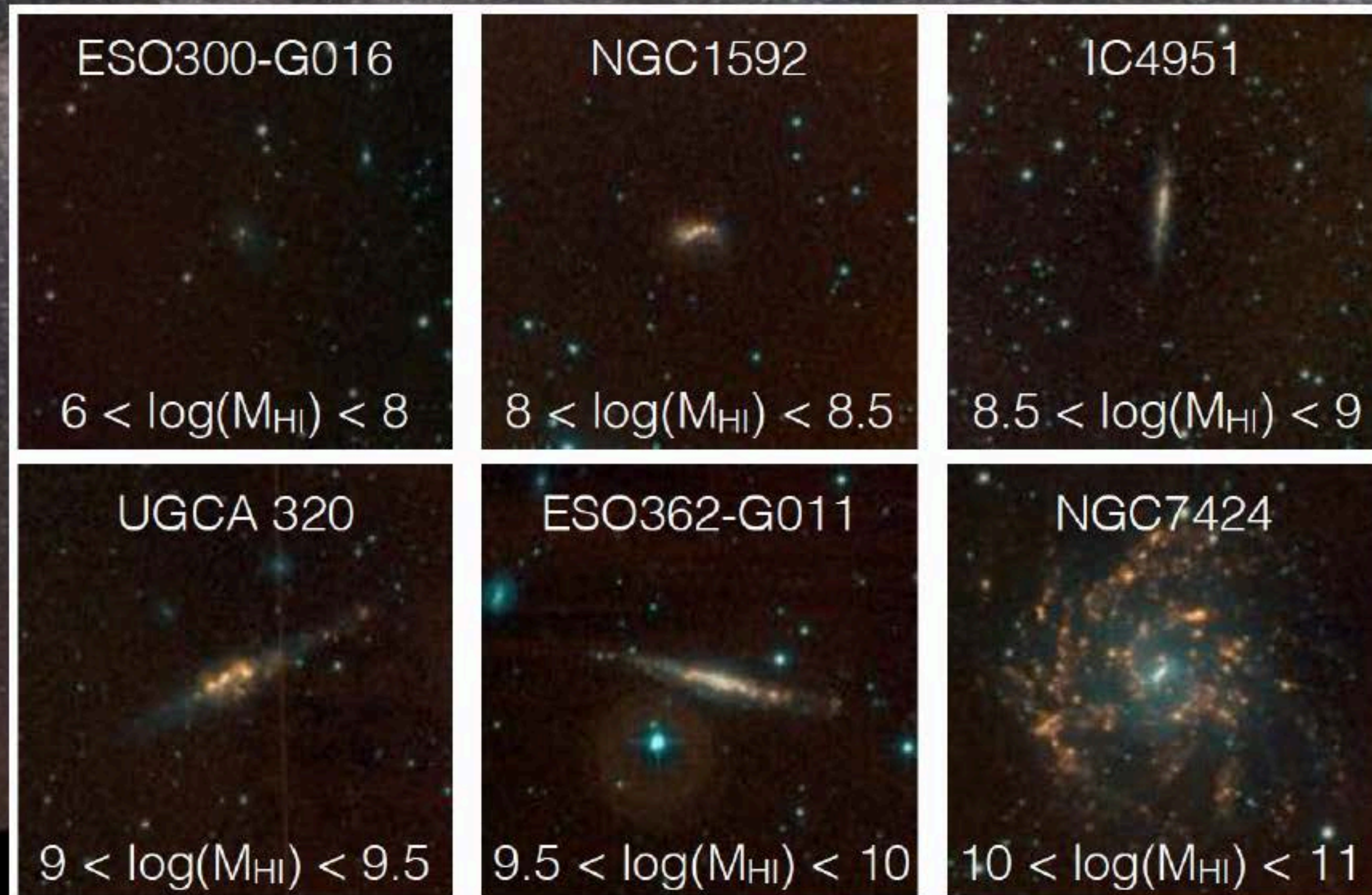
KAT7 - NGC 253: Lucero et al. 2015

MHONGOOSE 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
	30 gal.s

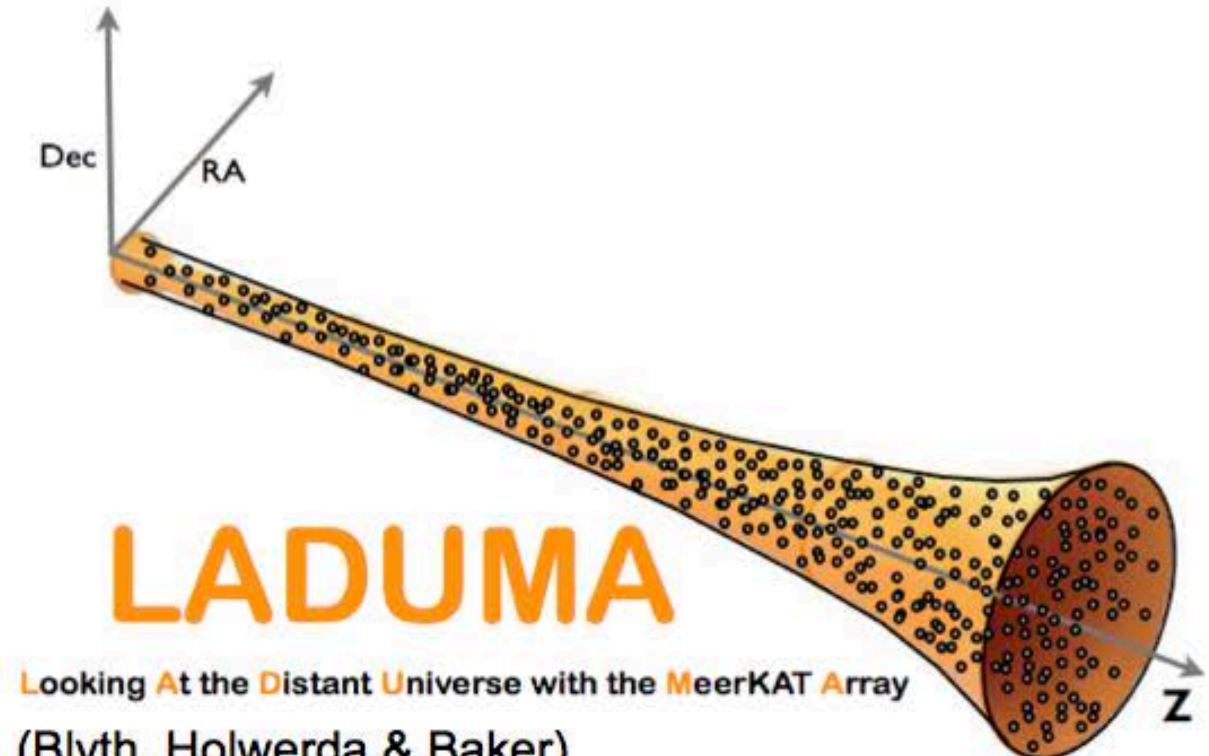
- 5 galaxies per bin
- All i from face-on to edge-on



The LADUMA Survey

The **L**ooking **A**t the **D**istant **U**niverse with the **M**eerKAT **A**rray is one of 2 Priority 1 surveys to be done with MeerKAT

- Plan to observe single pointing (ECDF-S) for ~3300h to make the deepest observations of neutral hydrogen (HI) in galaxies to date
- Will probe the gas content of galaxies back in cosmic time over half the age of the universe.



(Blyth, Holwerda & Baker)

Headline science goals:

To investigate as a function of cosmic time:

- How HI is distributed in galaxies in different environments
- How the neutral gas density of the Universe evolves
- how galaxies' HI masses depend on stellar/halo mass
- evolution of the baryonic Tully-Fisher relation

LADUMA

Observing plan:

- single pointing encompassing ECDF-S field (δ = -27°)
- proposed 333h with L-band (z<0.58), 3091h with UHF band (0.42 < z < 1.4)

The LADUMA science case benefits from the wealth of multi-λ data available in the field:

Imaging	optical, multiband (*HST*, VST ~26 AB)	central region + larger region
	near+mid IR (VISTA + *Spitzer*)	full region
	UV (*GALEX*)	central region
	X-ray	central
Photometric redshifts	COMBO-17, SWIRE, MUSYC	various coverage
Spectroscopic redshifts	~4000 publicly available ~3000 LADUMA	more to come as surveys complete

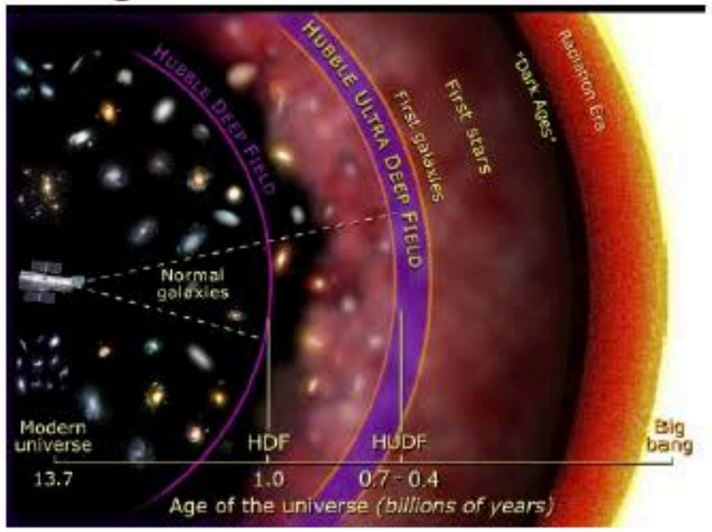
SA participation:

- 1/3 PIs (Blyth)
- 1/3 working group leads
- ~1/3 of CoIs (22.5/69)

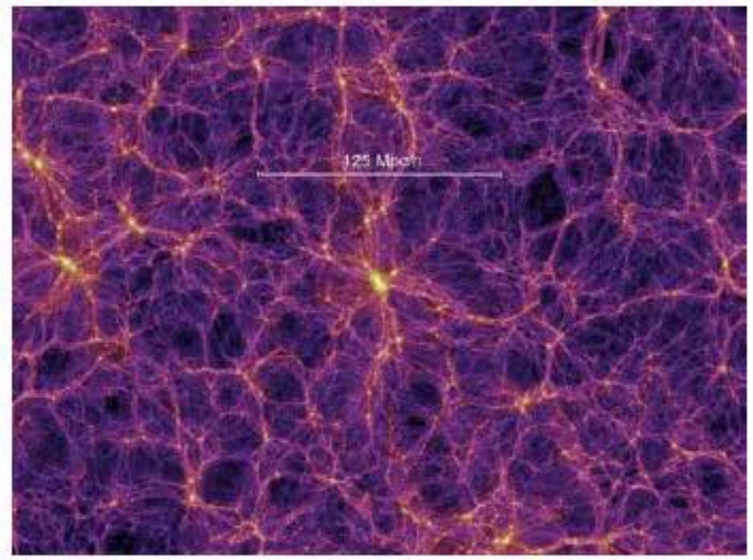
MIGHTEE: Galaxy Formation, Cosmology and Cosmic Magnetism

M. Jarvis (Oxford) & R. Taylor (UCT/UWC)

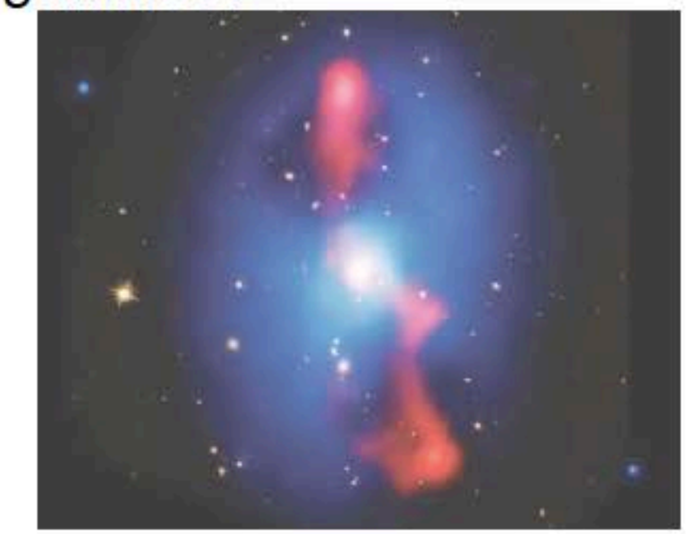
How and when were the first galaxies formed?

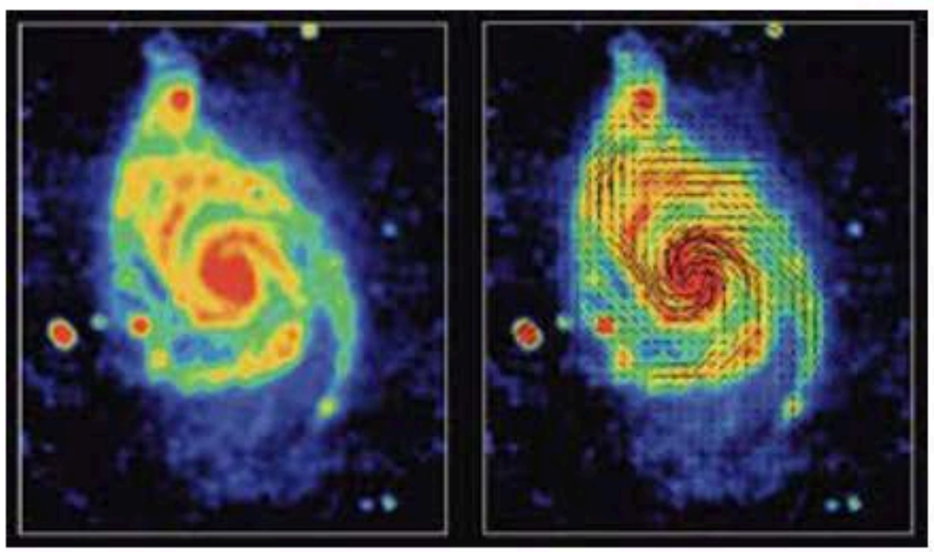


How do Baryons trace and affect the Dark Matter distribution?

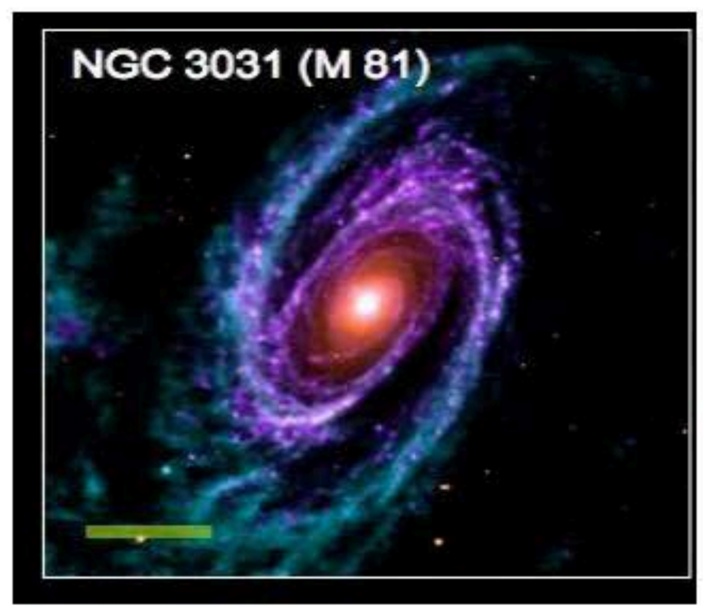


How are BHs fueled and how does BH accretion affect the evolution of galaxies?





What is the origin of cosmic magnetism, and how do magnetic fields influence global galaxy evolution?



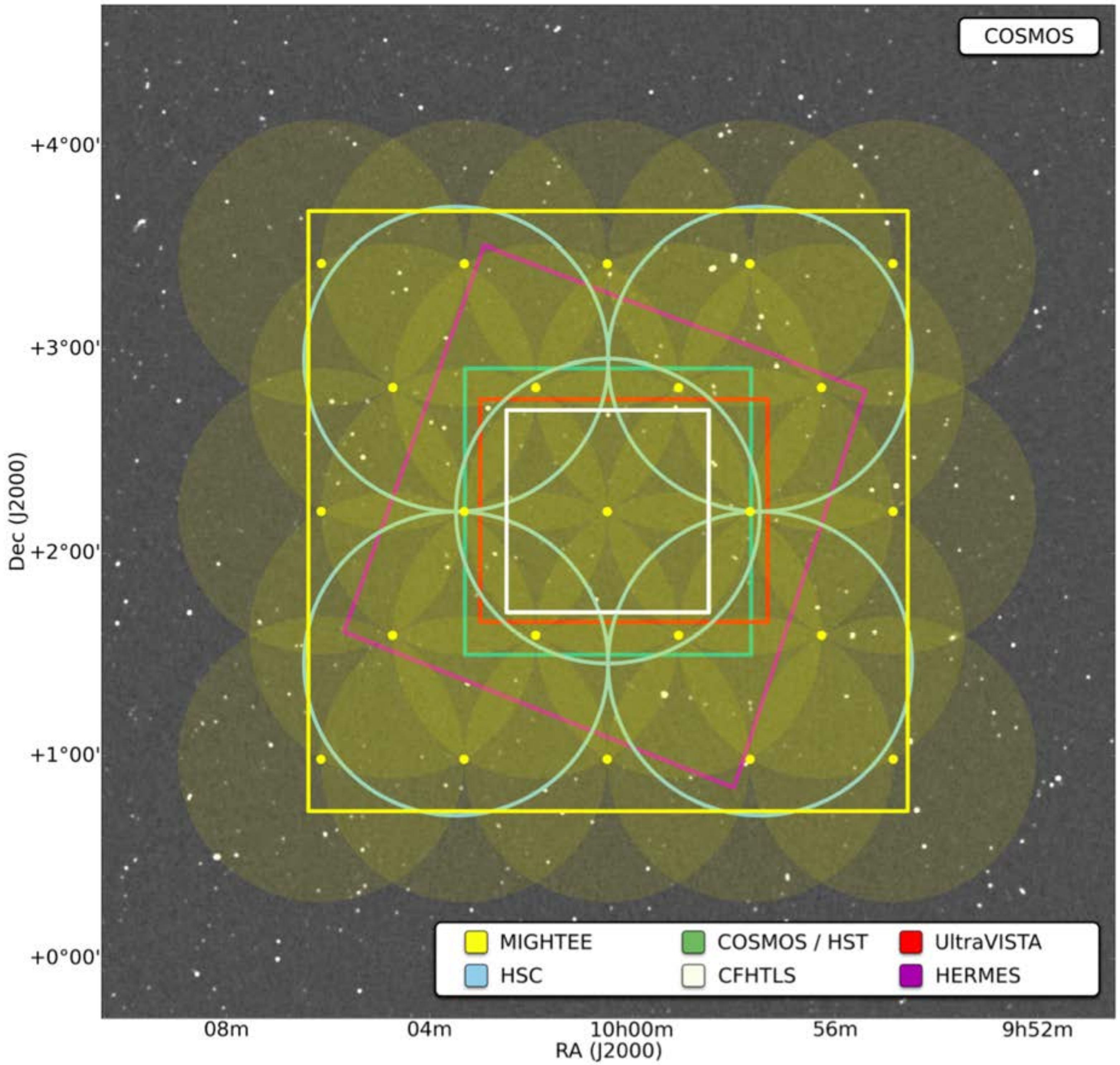
How do we go from gas to stars in galaxies?

What is the environmental influence?

Multi-wavelength data critical to MIGHTEE Science

- MIGHTEE consortium members involved in multi-wavelength surveys over MIGHTEE fields
- key involvement in VISTA, *Herschel*, *Spitzer*, *XMM* surveys
- In the future, team members are playing leading roles in ESO-MOONs and ESO-4MOST multi-object spectroscopic surveys that will target the MIGHTEE fields.
- The MIGHTEE fields are also the LSST Deep Drilling Fields – key fields for SA researchers

Typical MIGHTEE Footprint: COSMOS Field



Ian Heywood

MIGHTEE

- MeerKAT International GigaHertz Tuned Extragalactic Exploration (Jarvis & Taylor).
  - L-band
    - Broad Band, Full Polarisation.
    - High Spectral Line Resolution (HI).
  - Survey Area: ~20 sq. deg., over ~4 fields.
  - ~1500 hrs.
  - Radio Continuum — SF and AGN activity.
  - MIGHTEE-HI (Frank & Maddox)— comprehensive study of HI in a variety environments.

LADUMA

- Looking At the Distant Universe with the MeerKAT Array
- Deep HI survey with MeerKAT
- 5000 hours of a single pointing
- HI detections to z<=0.6, stacked detections to z>1

MIGHTEE

- MeerKAT International Giga-Hertz Tiered Extragalactic Exploration
- *Continuum* (imaging) survey
- 35 deg^2, 50 hours per pointing
- ➡ *Data taken in spectral line (HI) mod*

LADUMA

- Looking At the Distant Universe with the MeerKAT Array
- Deep HI survey with MeerKAT
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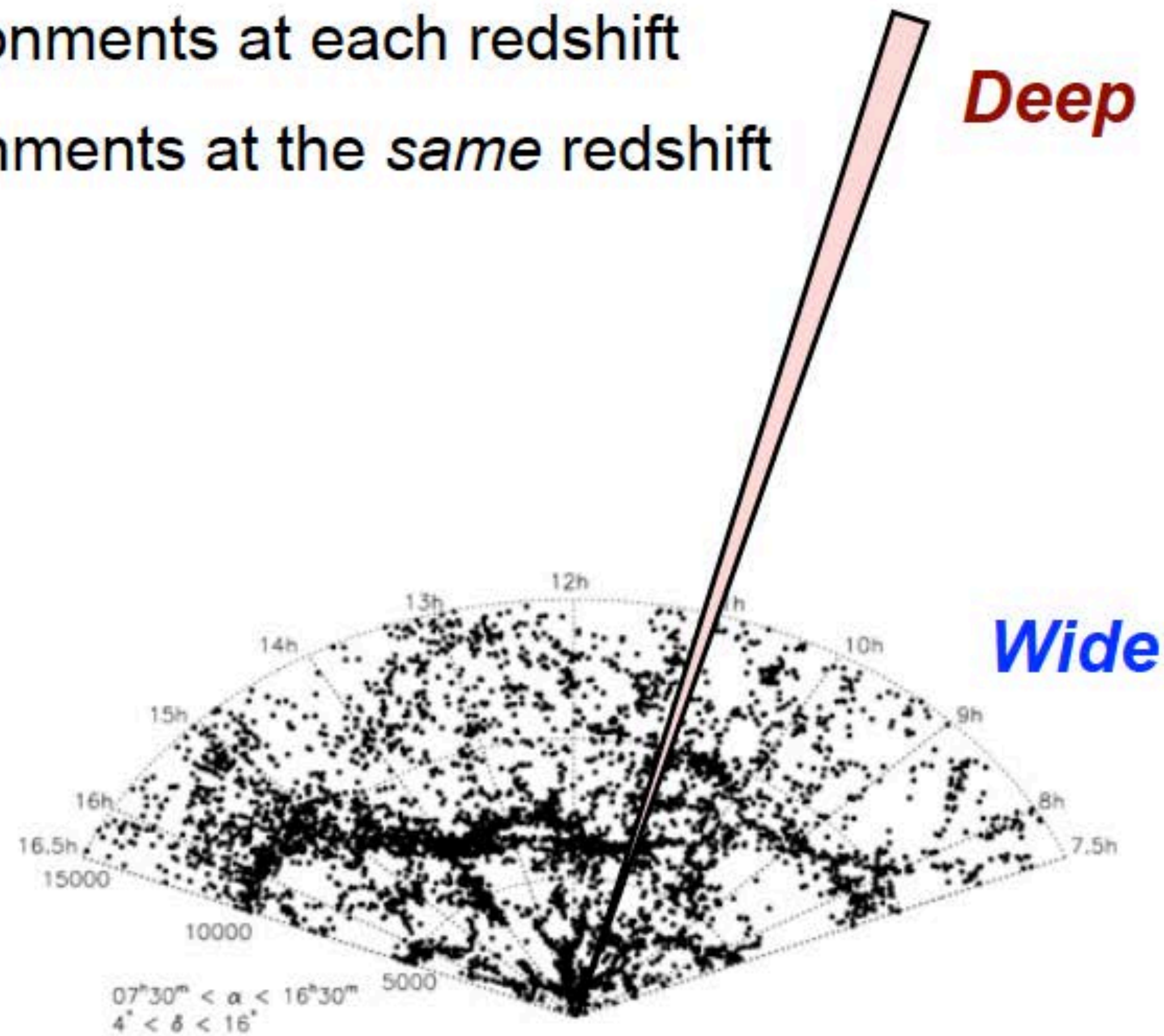
- MeerKAT International Giga-Hertz Tiered Extragalactic Exploration
- ~~*Continuum* (imaging)~~ *HI* survey
- 35 deg^2, 50 hours per pointing
- ➡ *Data taken in spectral line (HI) mode*

What use is a (relatively) shallow HI survey?

- Explore the high mass end of the HI mass function
- Predicted to have many more detections, improved population statistics
- Explore a wider variety of environments than available in the deep fields (clusters, groups, filaments, voids, field)

Deep: Different environments at each redshift

Wide: Various environments at the *same* redshift



***not to scale*

HI and MIGHTEE

- Hundreds of resolved galaxies out to z~0.1
- Expect to see a few $M_{HI} \sim 1x10^8 M_\odot$ galaxies
- MIGHTEE/LADUMA Commensality: MIGHTEE explores the high mass end of the HI distribution
- Large census of HI properties as a function of environment:
  - HI vs SF/AGN-activity in voids, groups and clusters

MIGHTEE HI: MIGHTEE+LADUMA

- LADUMA + MIGHTEE are very complementary
- MIGHTEE explores the high mass end of the HI distribution
- Further commensalities are investigated in Maddox, Jarvis & Oosterloo, 2016

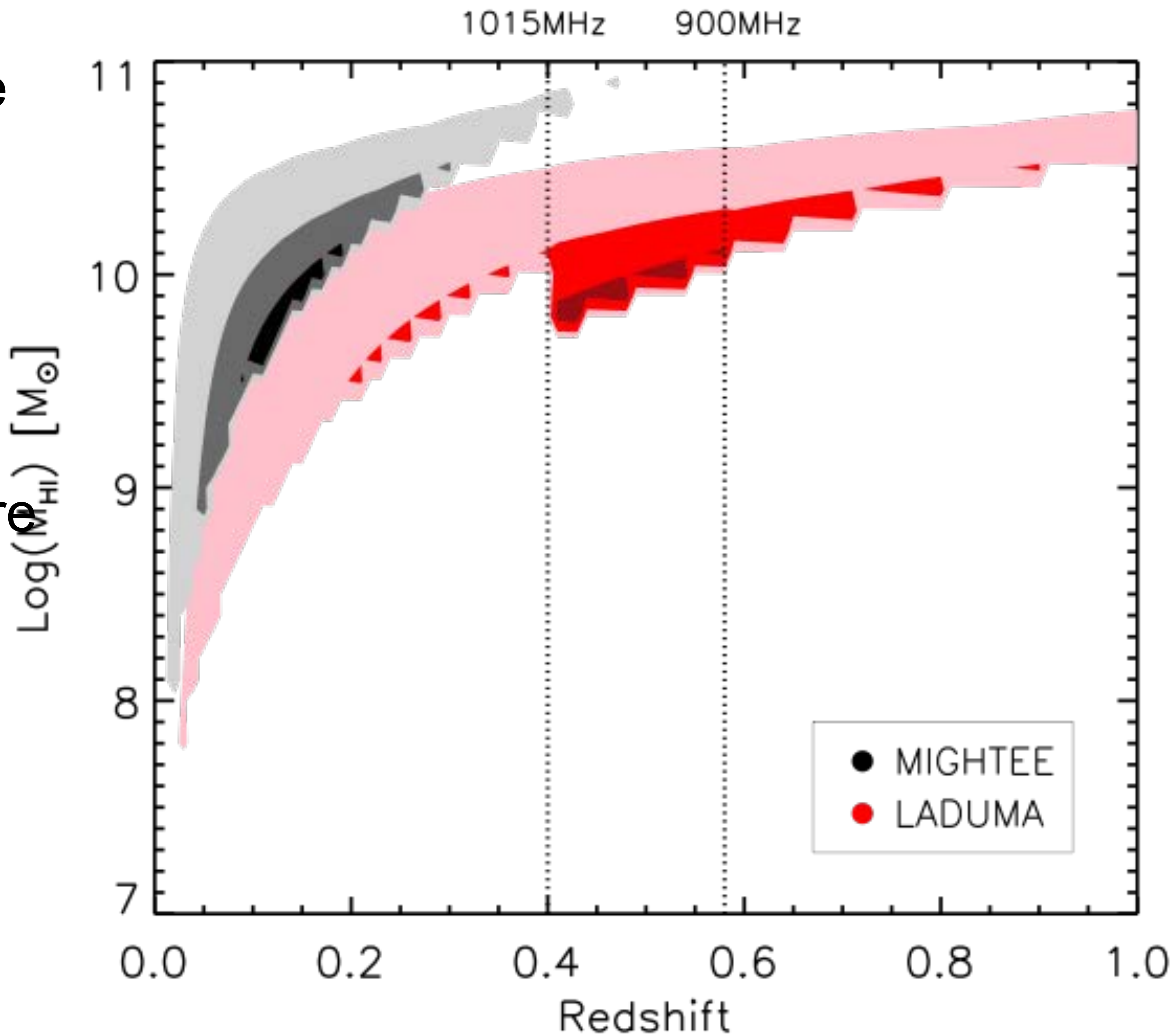


Figure from Natasha Maddox

What use is a (relatively) shallow HI survey?

- Explore the high mass end of the HI mass function
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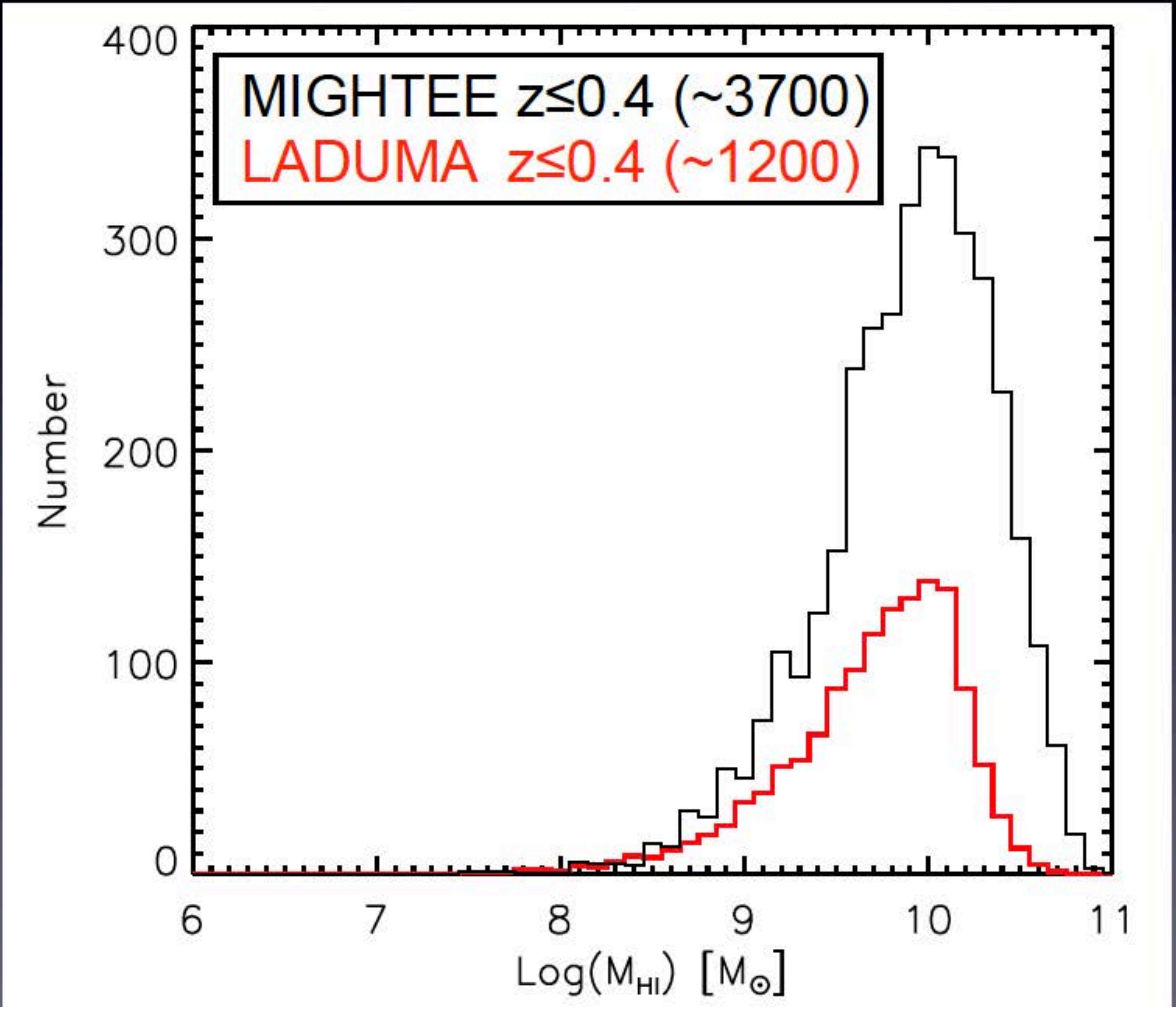


ThunderKAT 2016

Synopsis

ThunderKAT PIs: Patrick Woudt (UCT) & Rob Fender (Oxford)
ThunderKAT membership (open): 60 co-investigators from 10 countries (32% ZA)

ThunderKAT is the image-plane transients programme for MeerKAT. The goal is to find, identify and understand high-energy astrophysical processes via their radio emission (often in concert with observations at other wavelengths).

> *"Through a comprehensive and complementary programme of surveying and monitoring Galactic synchrotron transients (across a range of compact accretors and a range of other explosive phenomena) and exploring distinct populations of extragalactic synchrotron transients (microquasars, supernovae (SNe) and possibly yet unknown transient phenomena) – both from direct surveys and commensal observations – we will revolutionise our understanding of the dynamic and explosive transient radio sky." (ThunderKAT 2010 Science Case)*

As well as proposing for targeted programmes of their own, ThunderKAT has made agreements with the other LSPs to search their data for transients. This **commensal** use of the other surveys, which remains one of the key ThunderKAT programme goals in 2016, means that the combined MeerKAT LSPs will produce by far the largest GHz-frequency radio transient programme to date. ThunderKAT will focus on Target-of-Opportunity (ToO) and monitoring programmes of a set of well-defined transients.

ThunderKAT 2016

Science Themes

Relativistic Accretion

- Black holes and neutron stars in X-ray binaries, Tidal Disruption Events, Ultra-luminous X-ray sources

White Dwarf Accretion

- Outflows from accretion-power outbursts of white dwarfs, outflows from thermonuclear eruptions on white dwarfs

Cosmic Explosions

- Gamma-ray bursts; Core-collapse supernovae; Type Ia supernovae

Fast and Coherent Transients

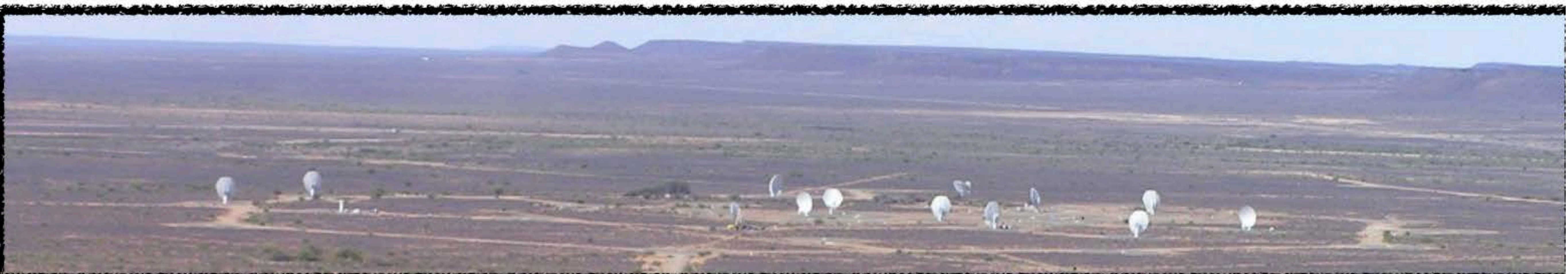
- Fast radio bursts (imaging)

Gravitational Wave Sources

- Gravitational wave events and electro-magnetic counterparts

Innovations: MeerLICHT

MeerLICHT PIs: Patrick Woudt (UCT), Paul Groot (Radboud) & Rob Fender (Oxford)
MeerLICHT membership (institutional, closed): UCT, Radboud, Oxford, SAAO, Manchester



Whatever MeerKAT observes, MeerLICHT observes [at the same time]

Innovations: MeerLICHT

MeerLICHT PIs: Patrick Woudt (UCT), Paul Groot (Radboud) & Rob Fender (Oxford)
MeerLICHT membership (institutional, closed): UCT, Radboud, Oxford, SAAO, Manchester

The MeerLICHT project is currently in its final phase of construction, and soon moves into the ‘installation and commissioning’ phase. The telescope is expected to arrive at the Sutherland station of the South African Astronomical Observatory in 2017 March for installation and engineering/science commissioning.

Pre-construction: 2012 – 2015
Construction: 2016 – 2017 (Jan-February)
Installation and commissioning: 2017 (March-June)
Early science: 2017 (July-December)
Science operations: 2018 – 2022Time Lines

Whatever MeerKAT observes, MeerLICHT observes [at the same time]

Towards a Full Census of the Obscure(d) Vela Supercluster

A MeerKAT M32 Early Science survey to map the fully obscured part of the Vela SCL

Background: *Recent spectroscopic observations of ~4500 galaxies (SALT, AAOmega, +)*

- revealed a potential massive supercluster at 18000 km/s (possibly Shapley-like)
- straddling the Milk Way in Vela (l ~ 275° ± 20°, |b| ~ 5°-10°)
- close to where cosmic flow fields suggest significant mass excess
- due to foreground contamination (|b| < 5°) ***major part of supercluster can not be charted at any wavelength,*** **except through the 21cm line of HI**

MeerKAT survey: *map all galaxies with log $M_{HI} > 9.5\ M_{\odot}$ within 16-24000km/s across ZOA over minimal suspected supercluster extent (l x b ~ 20° x 12° = 240°)*

- MeerKAT sensitivity, survey speed, and resolution ideal for mapping supercluster
- Simulations show: primary goals can be achieved on reasonable time scales
- Nyquist sampling: 960 pointings → **240 hrs for**

Why M32?

- Testing & preparation of data pipelines for MeerKAT HI-LSP's (Fornax, Laduma)
- While aiming for potential high-impact early-science results

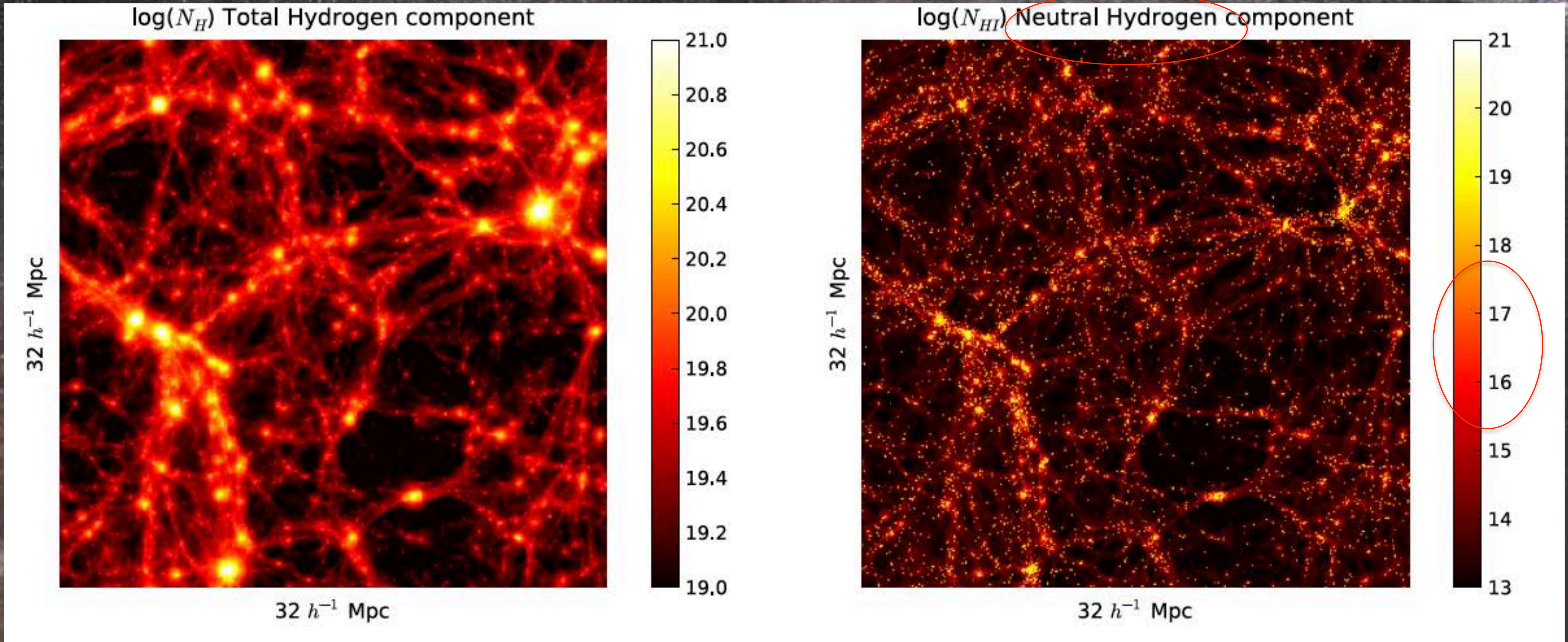
Collaboration:

Renée Kraan-Korteweg (PI), Sarah Blyth (co-PI Laduma), Claude Carignan, Ed Elson, Brad Frank, Tom Jarrett @UCT; Michelle Cluver @UWC; Gyula Jozsa @SKA;Paolo Serra (PI Fornax) @INAF

Reaching the Cosmic Web
with MeerKAT + FAST

FAST: “Five-hundred-meter Aperture Spherical Telescope
In China’s Guizhou province

Galaxy – IGM Connection



Popping et al, 2015, PoS, AASKA14, 132

See also sim.s by Powers & Davé)

To reach the Cosmic web, need to go down to 10

Sensitivities prospects in the SKA era

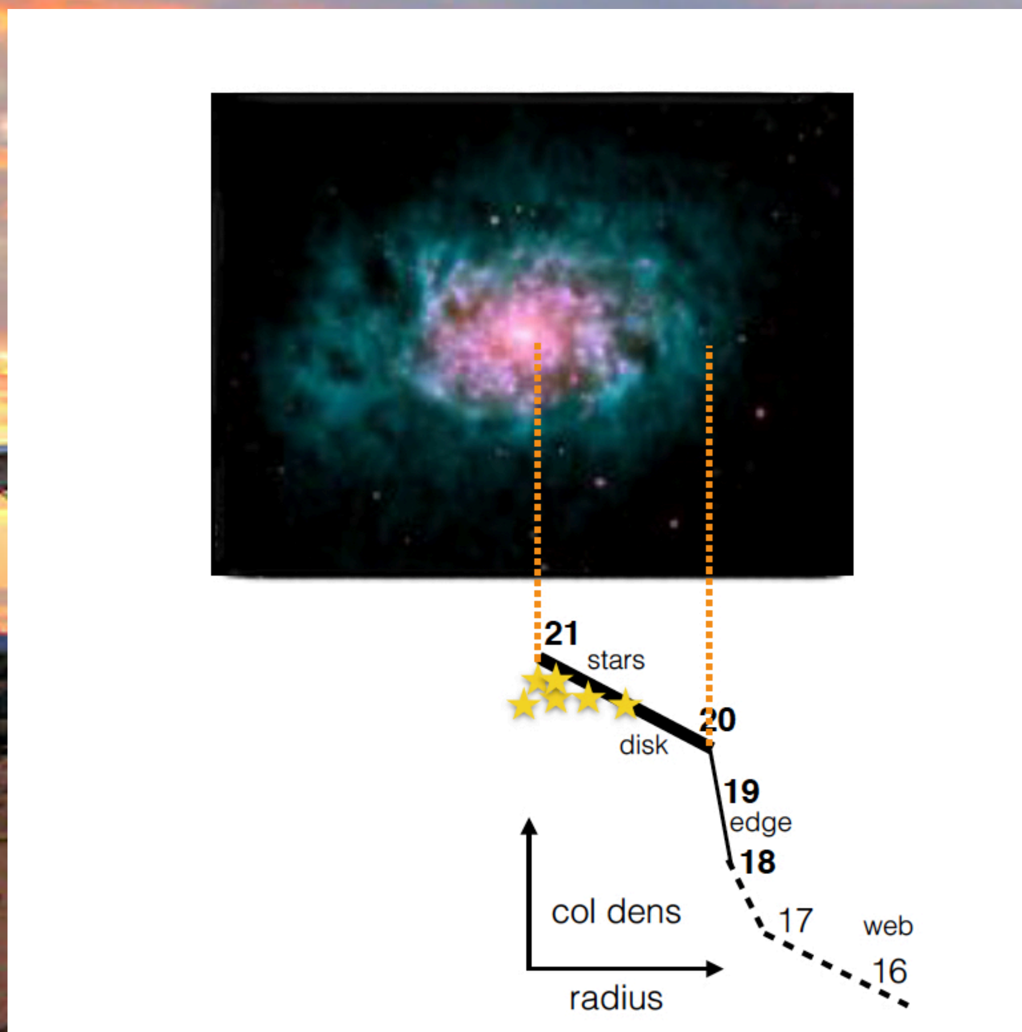
Table 1. Expected sensitivities of different telescopes at 5σ.

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

~2018: MeerKAT + FAST

Reaching the Cosmic Web with MeerKAT + FAST



$3.1\cdot 10^{17}\ SdV/\theta^2$ atoms/cm²

where θ is beam size (arcmin)

dV km/s

S mJy/beam

- THINGS (VLA): 10h 5σ over 5 km/s @30": $5\text{x}10^{19}$ cm^{-2}
- KAT-7 : 100h 5σ over 5 km/s @3': $5\text{x}10^{18}$ cm^{-2}
- HALOGAS (WSRT): 120h 5σ over 5 km/s @30": $5\text{x}10^{18}$ cm^{-2}
- KAT-7 + WSRT 100h 5σ over 16 km/s @3': $1\text{x}10^{18}$ cm^{-2}
- MeerKAT: 200h 5σ over 16 km/s @90": $5.0\text{x}10^{17}$ cm^{-2}
- **MeerKAT + FAST** s **@30"** < $5.0\text{x}10^{17}$ **cm^{-2}**

2018-19

- SKA_1-mid: 100h 5σ over 5 km/s @30": $7.5\text{x}10^{17}$ cm^{-2} **2023**
- SKA_2: 10h 5σ over 5 km/s @30": $2.5\text{x}10^{17}$ cm^{-2} **2030**
- SKA_2: 100h 5σ over 5 km/s @30": $9.0\text{x}10^{16}$ cm^{-22} **2030**