

HI Galaxies: science results from centimetre wavelength SKA precursors

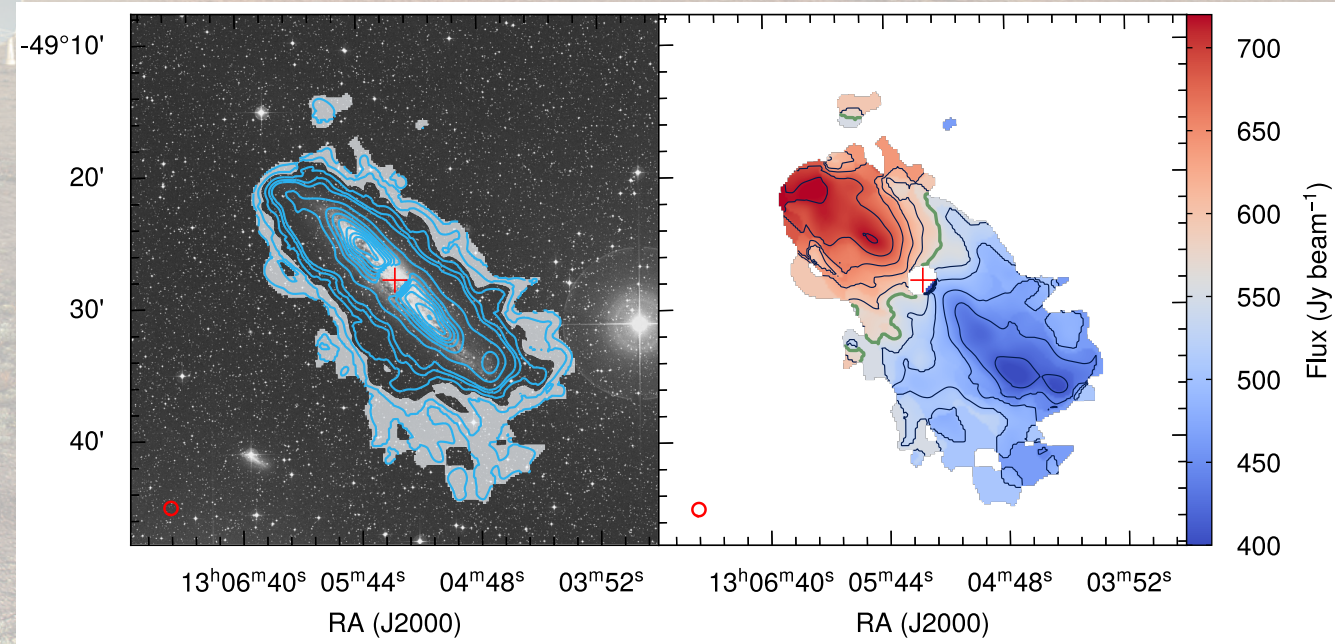
Kelley M. Hess

National SKA Science Day Sweden

2 February 2023

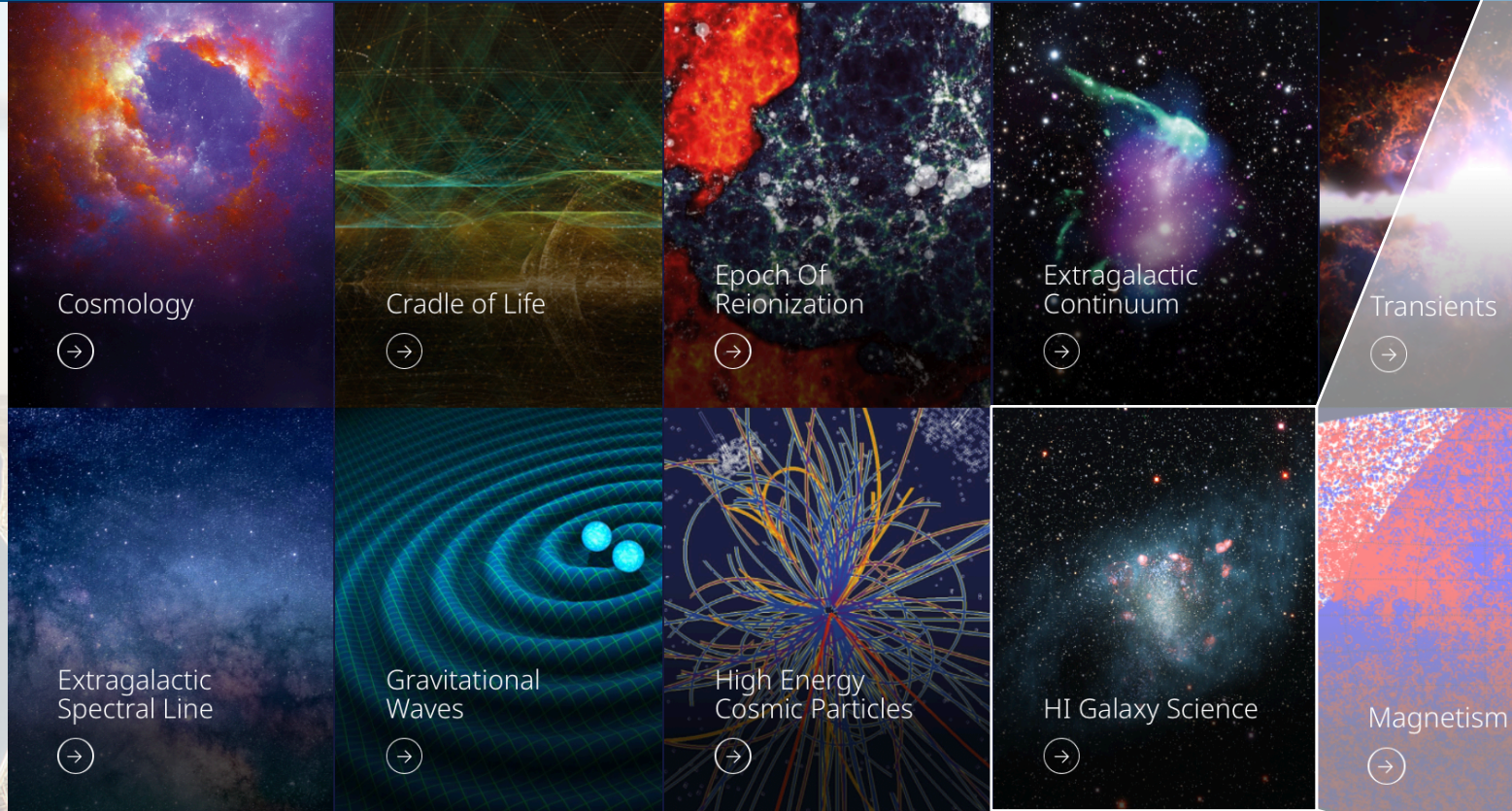
Why study HI?

- Neutral atomic hydrogen (HI) is the fundamental fuel for star formation in galaxies
- Sensitive probe of the dark matter halo in a galaxy
- Traces a history of past interactions
- Scaling relations provide insight into baryonic cycle in galaxies: HI mass vs HI size, stellar mass, SFR, sSFR, etc
- How is HI linked to star formation galaxy disks & related to kinematics
- How does accretion fuel star formation
- What is the fate of HI in environmental
- How do HI scaling relations vary with



NGC 4945; Ianjamasimanana et al (2019)

SKA Science Community



HI Galaxy Science Science Working Group

The Square Kilometer Array (SKA) is a global observatory to build the largest radio telescope on Earth, both in physical scale and in terms of the volume of data it will generate. Consisting of two telescope arrays located respectively in Australia and South Africa and incorporating the Murchison Widefield Array (MWA) in Australia, the SKA will revolutionize our understanding of the universe. The science cases for the SKA have been categorized into several broad areas, including a wide range of areas of physics, cosmology, and astrophysics. Science Working Groups (SWGs) and Focus Groups (FGs) covering all these areas have been set up to coordinate the SKA science cases, providing a context for coordination between the SKA Observer Science Team and the international community. This banner provides a summary of the HI Galaxy Science Working Group.

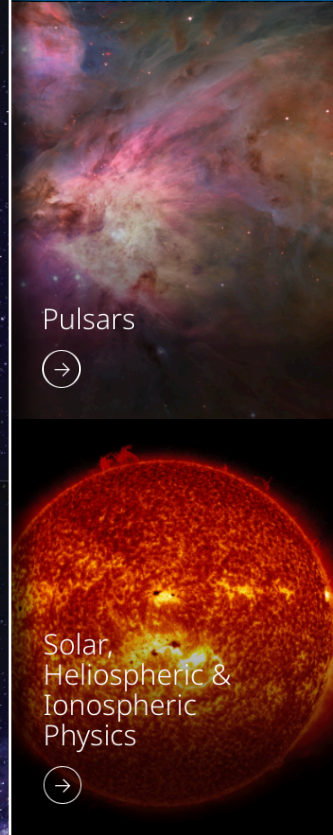
The HI Science Working Group is focused on studying the formation and evolution of galaxies by mapping the 21-cm spectral line of neutral atomic hydrogen (HI) in absorption and emission, over cosmic time. Using SKA we will conduct deep HI observations of millions of galaxies out to redshift $z=1$. Our primary goals are to investigate the structure and dynamics of cold gas in and around galaxies, explore the gas-phase interface between galaxy formation and intergalactic gas as well as map large-scale galaxy structures and their peculiar motions. Our key questions regarding galaxy formation and evolution are:

How do galaxies replenish their gas?
Current models of galaxy evolution predict that galaxies are embedded in an extended Cosmic Web of gaseous filaments. For galaxies to continue forming stars over a trillion years, they must continue to acquire new gas to form stars. With its high sensitivity and resolution, the SKA will enable us for the first time the study of this very low density gas to allow us to detect and map the gaseous structure between galaxies and the surrounding intergalactic medium.

How are gas accretion, star formation & feedback related?
The gas phase of galaxies traces the formation of gas, star formation and gas outflows (feedback). We are interested in understanding the interplay between the molecular gas surface density, very little is known about the processes contributing to star formation at sub-galactic scales. Similar regulatory processes such as interstellar shock gas from galaxy disks back into the halo creating holes and bubbles in galaxy disks. The resolution of the SKA will enable us to study the DM structure and kinematics in nearby galaxies with unprecedented precision to better understand these fundamental processes.

How is the HI in galaxies linked to AGN activity?
Associated HI absorption around a radio source from galaxy can tell us about the structure of the central regions and feedback of AGN. The SKA will enable us to measure HI absorption in AGN out to $z=1$ and to trace related gas outflows from remote zones to investigate the role of AGN feedback in galaxy evolution.

How is HI affected by galaxy interactions, environment & redshift?
We will HI surveys to go with the SKA will provide statistical samples for emission and absorption to study the role of environment on the gas content of galaxies and to investigate the processes leading to the building of stellar mass (including galaxy mergers and interactions) and the quenching of star formation over cosmic time. High precision observations will also take on the 2D structure of galaxy disks, their interface with the intergalactic medium, the dark matter content and the galaxy halo problem, and the formation of star dwarf galaxies.

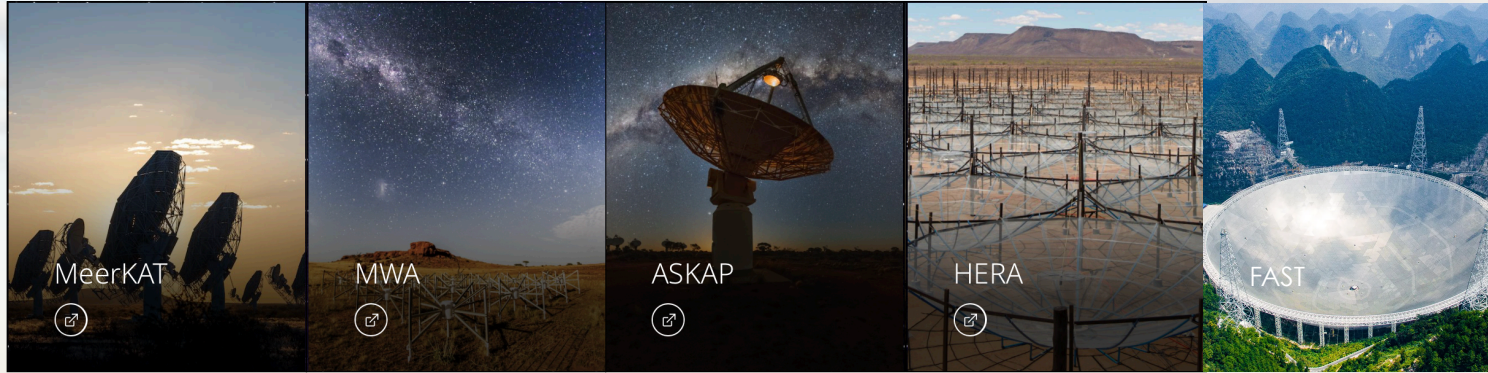


- ▶ How do galaxies replenish their gas?
- ▶ How are gas accretion, star formation, and feedback related?
- ▶ How is the HI in galaxies linked to AGN activity?
- ▶ How is HI affected by galaxy interactions, environment, & redshift?

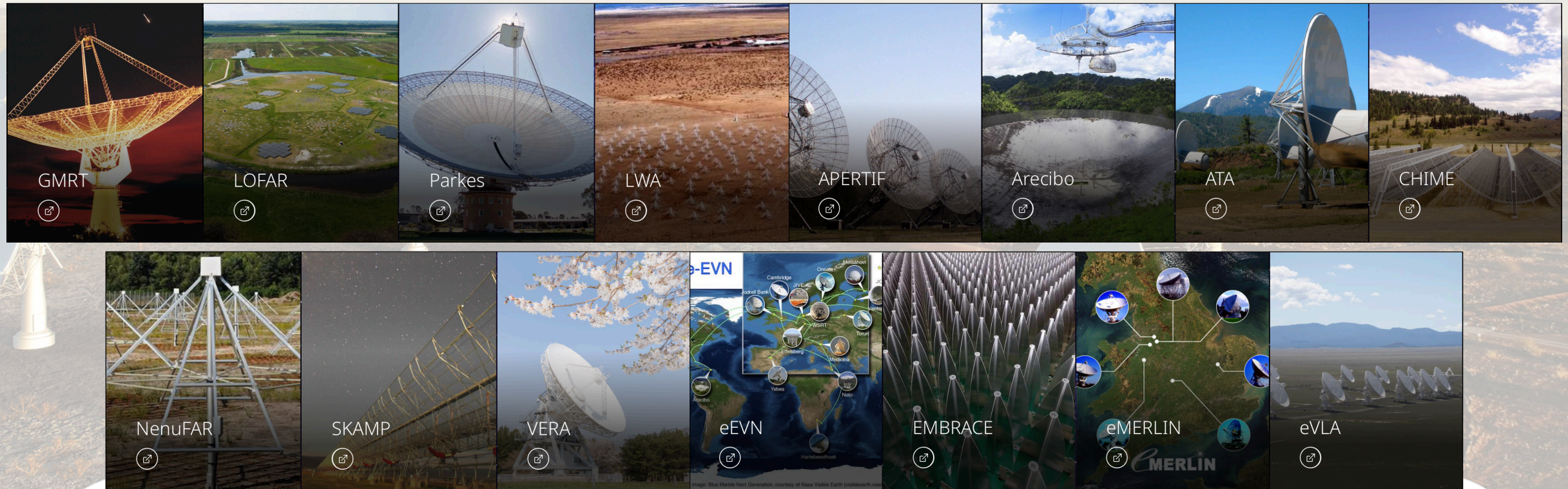


A global family of precursor and pathfinder facilities

Precursors:

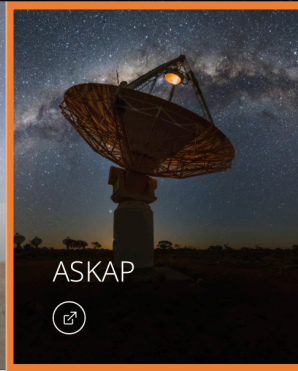
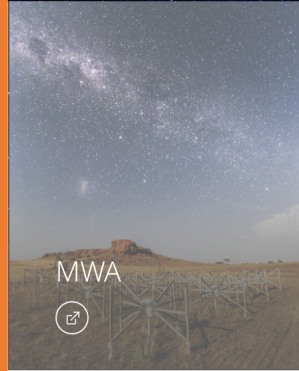
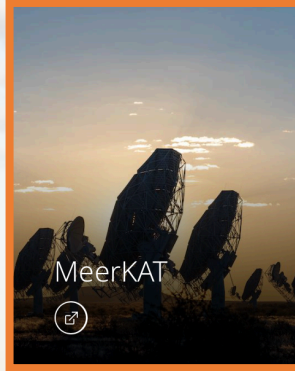


Pathfinders:

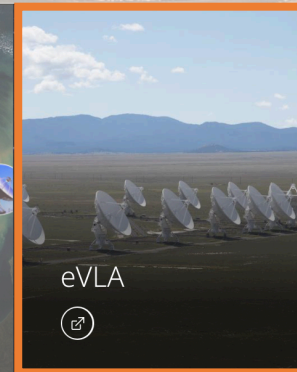
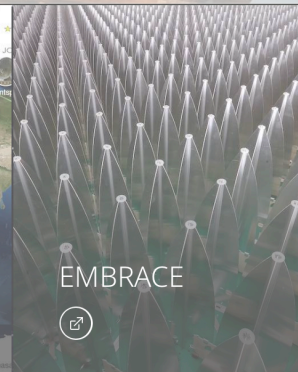
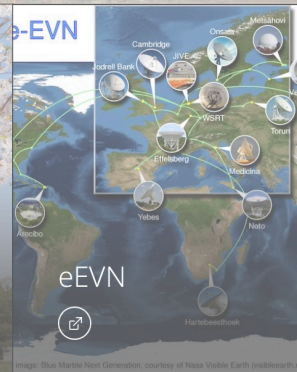
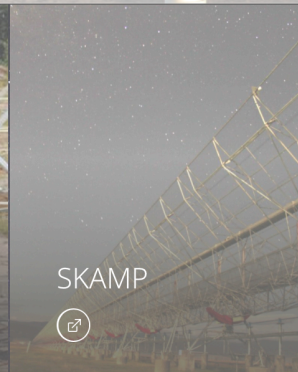
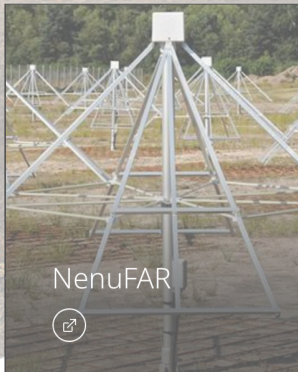
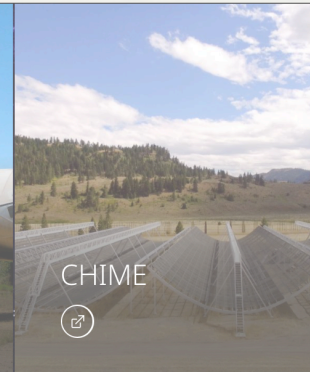
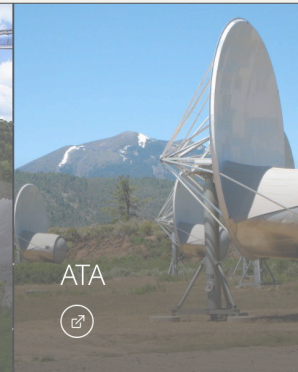
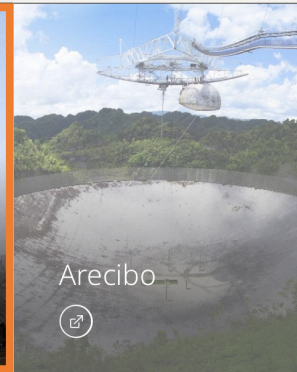
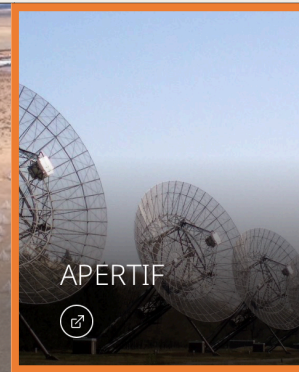
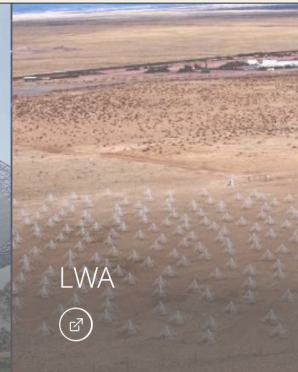
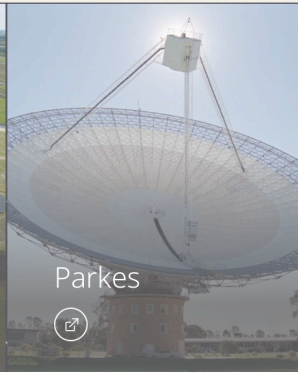
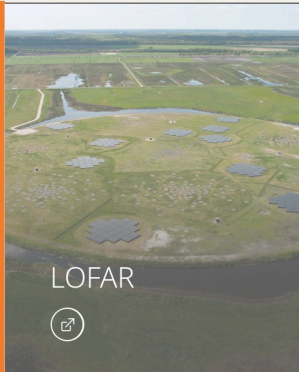
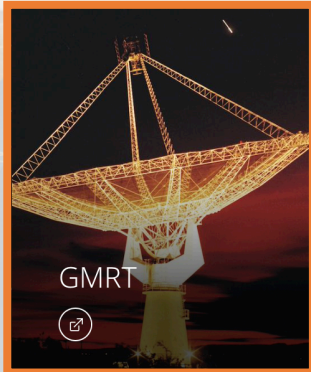


A global family of precursor and pathfinder facilities

Precursors:

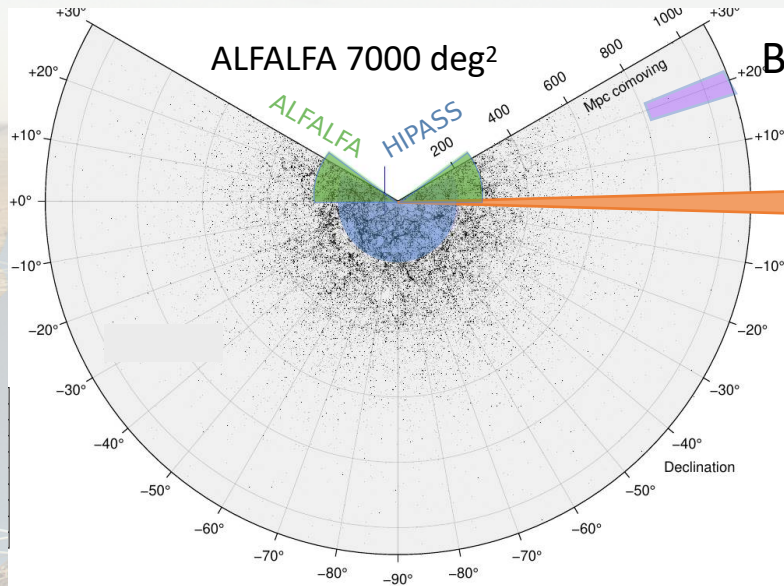


Pathfinders:



HI surveys with SKA pathfinders: pushing instrumentation limits

- Untargeted HI surveys

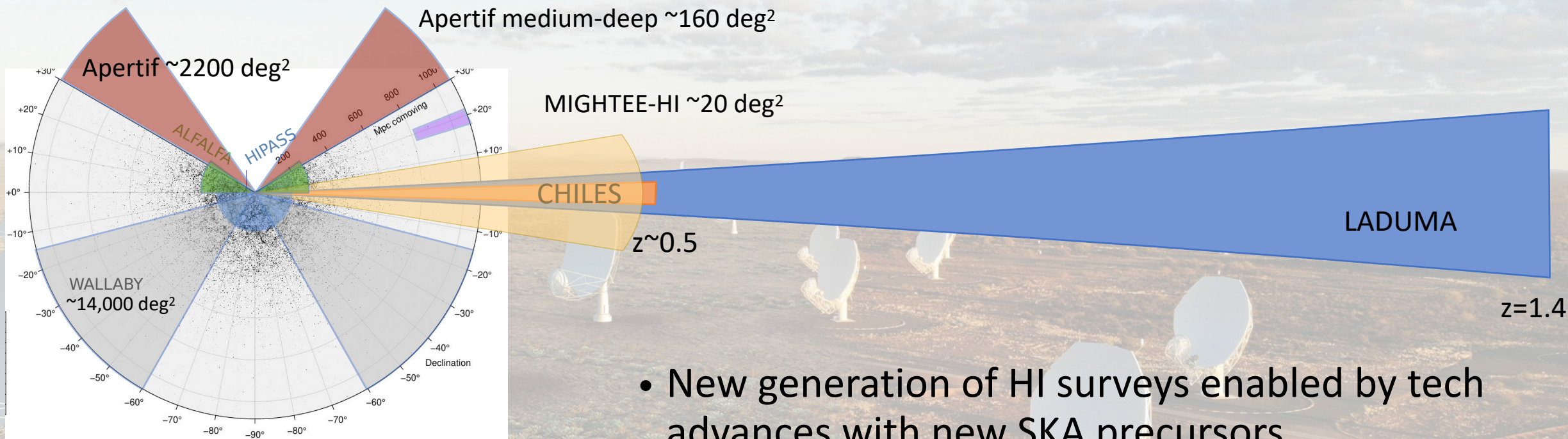


- Previous generation of HI studies

- Pointed HI observations
- Wide-area unresolved HI surveys
- CHILES: upgraded EVLA

HI surveys with SKA precursors: a tiered approach

- Untargeted HI surveys



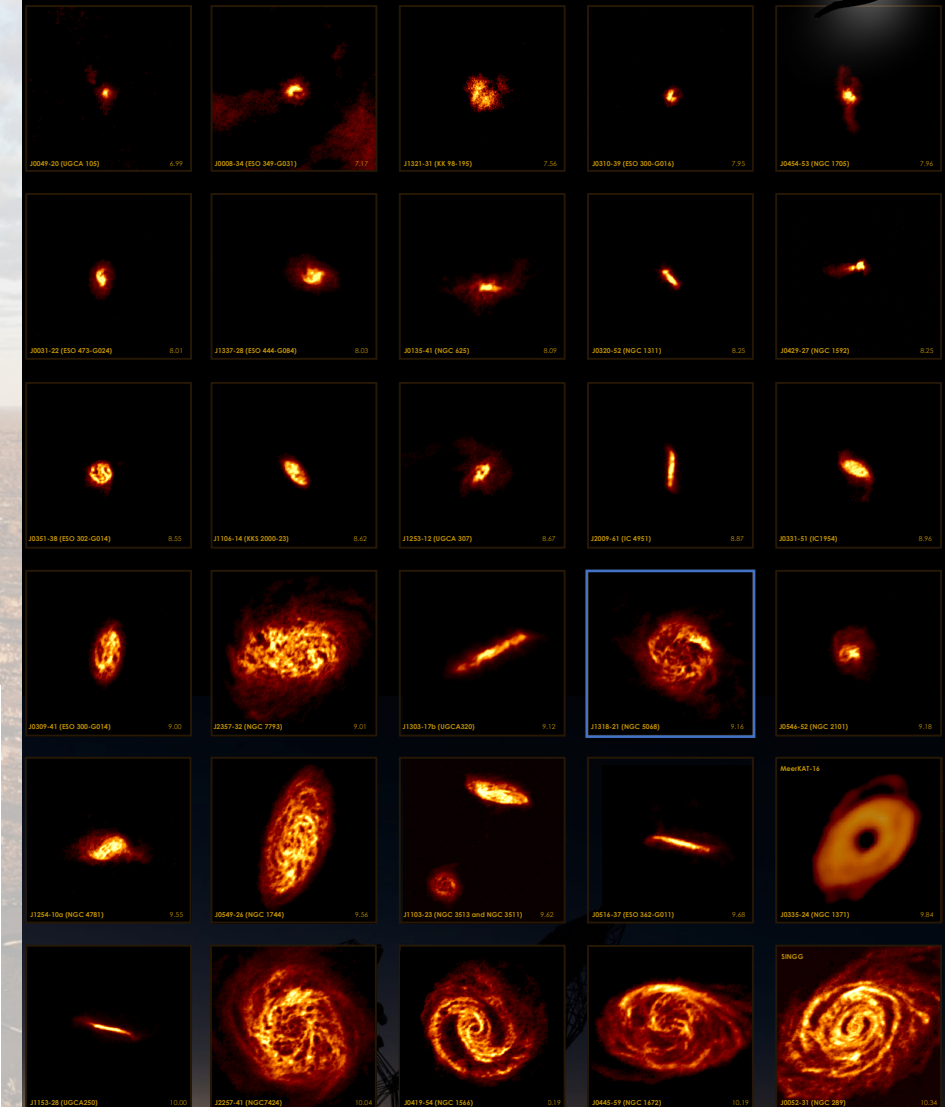
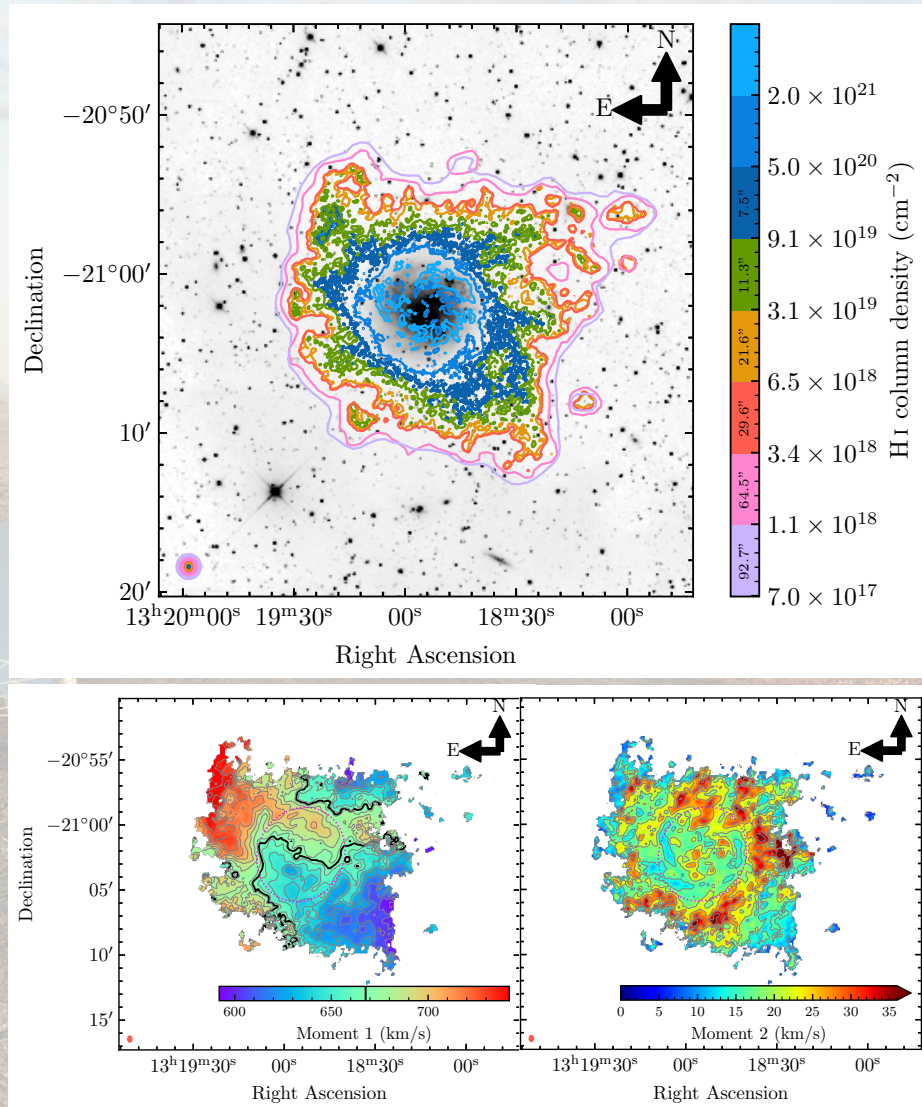
- New generation of HI surveys enabled by tech advances with new SKA precursors
- Improved surface brightness & resolution
- Wide-area; medium-deep; deep



MHONGOOSE: Single dish sensitivity but at interferometric resolution

MeerKAT:

- Study HI accretion & link with star formation
- 30 nearby field disk & dwarf galaxies
- HIPASS detected/SINGG
- $M_{\text{HI}} \sim 10^7\text{-}10^{11}$
- Each 55h
- HI column density limit of $\sim 5 \times 10^{17} \text{ cm}^{-2}$ ($3\sigma/16 \text{ km/s}$)



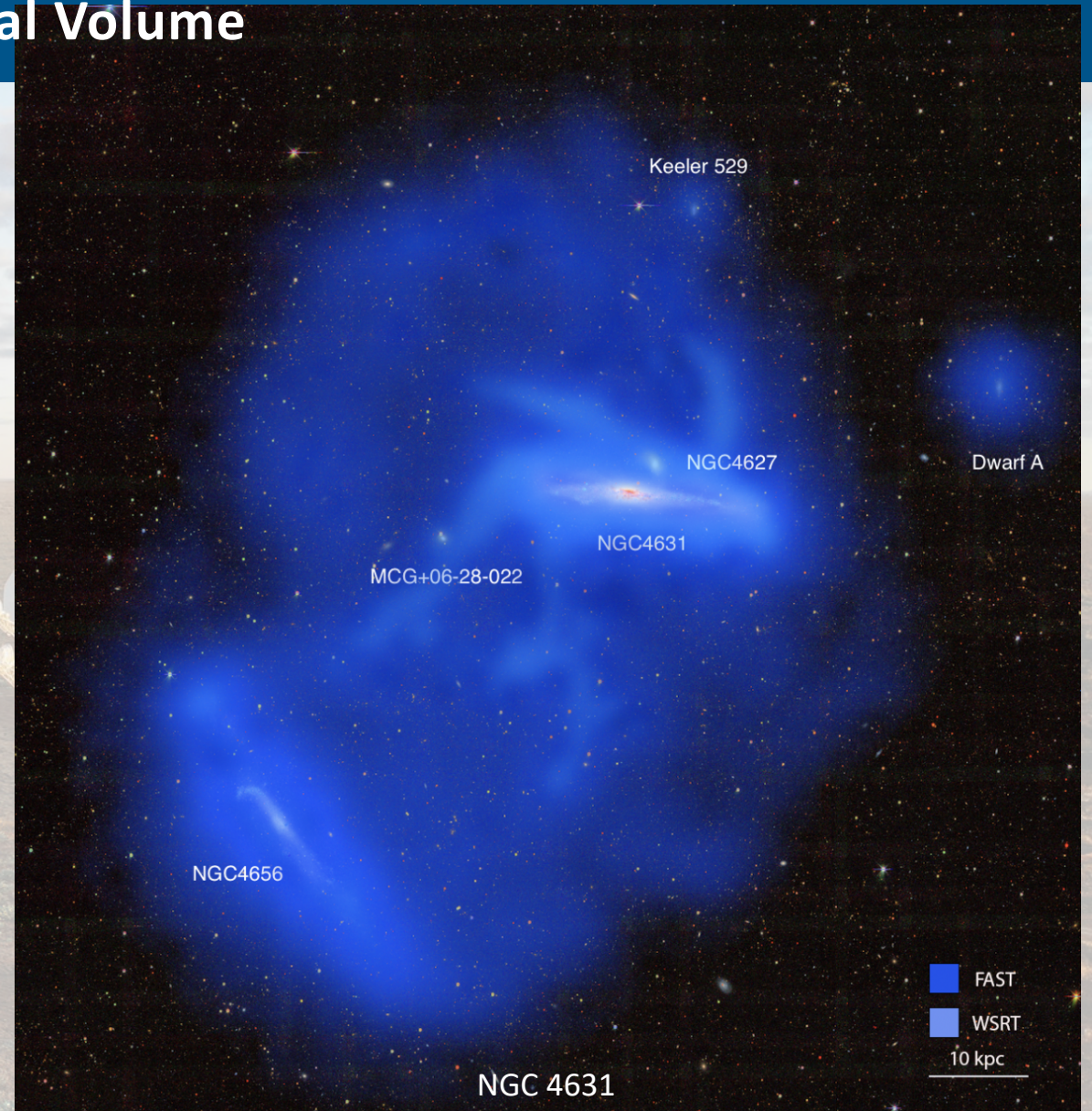
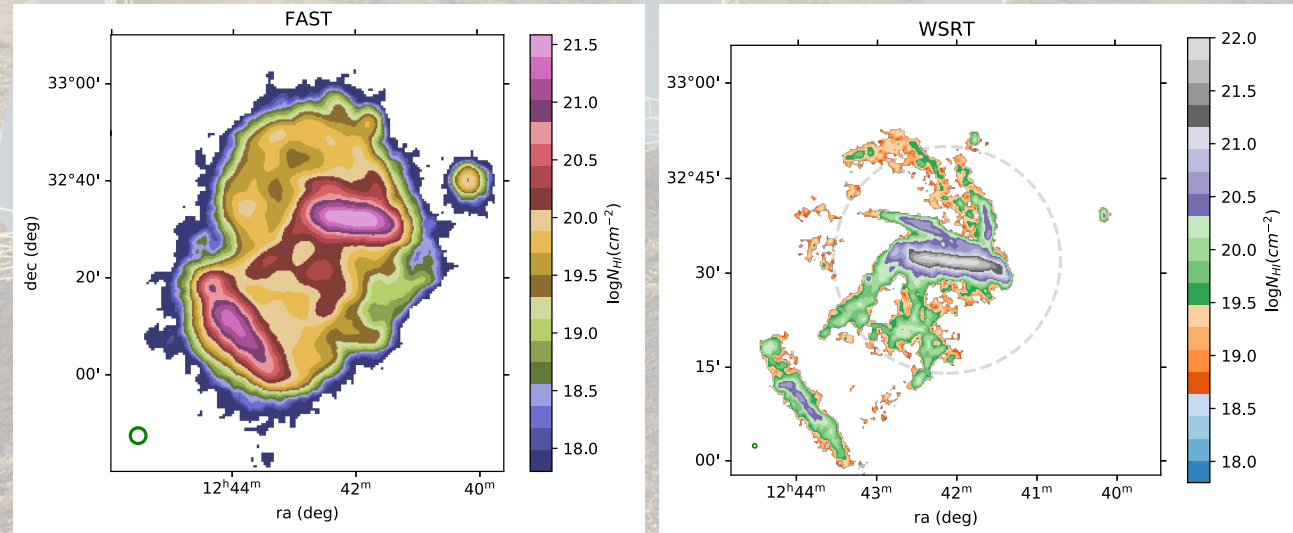
Healy et al, in prep

Instituto de Astrofísica de Andalucía, IAA-CSIC



FEASTS: HI in/surrounding galaxies in the Local Volume

- FAST: 2.4 deg² in 4.47 hours
- Combine single dish & interferometric data
- Low surf brightness gas >25% of total mass
- Separate warm and cool HI; argue that the HI is cooling out of the intragroup medium

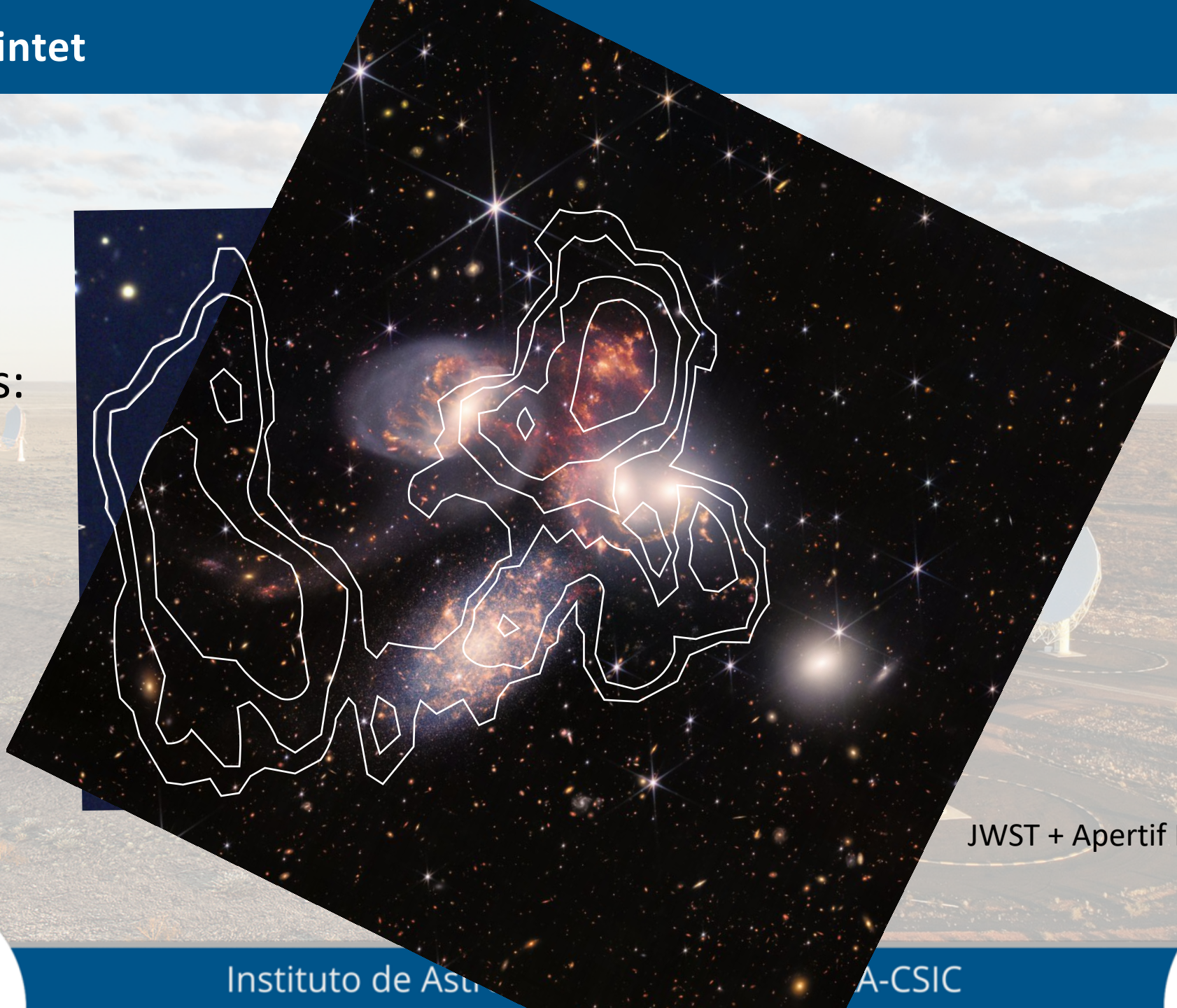


Wang et al (2022)

Stephan's Quintet

VLA

Group observations:
quantify the amount of
intragroup HI; tidal
debris; gas processing



JWST + Apertif HI contours

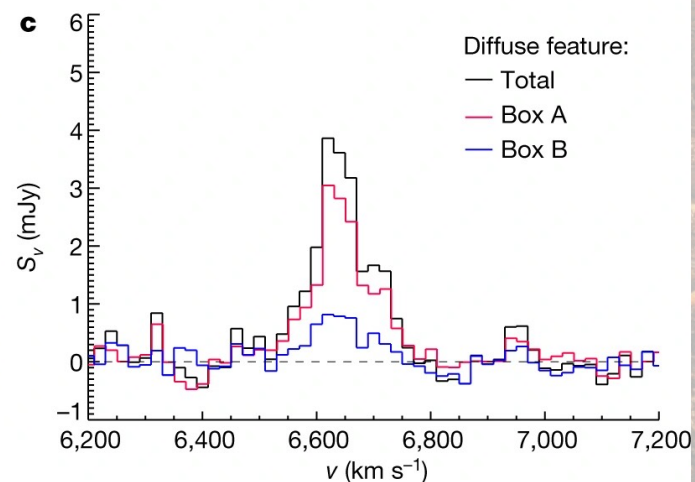
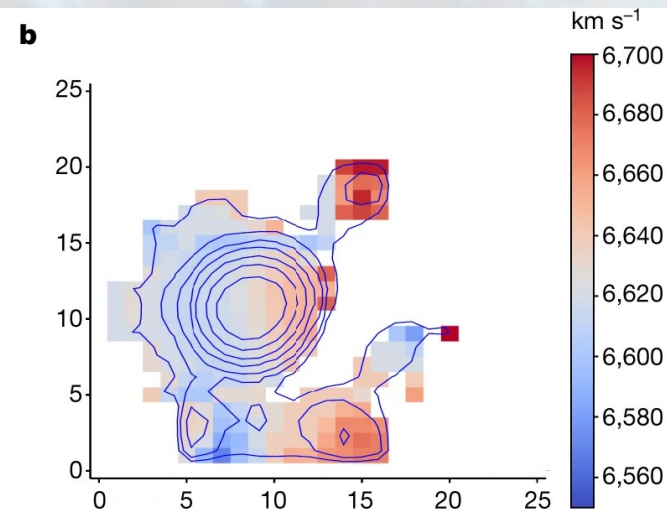
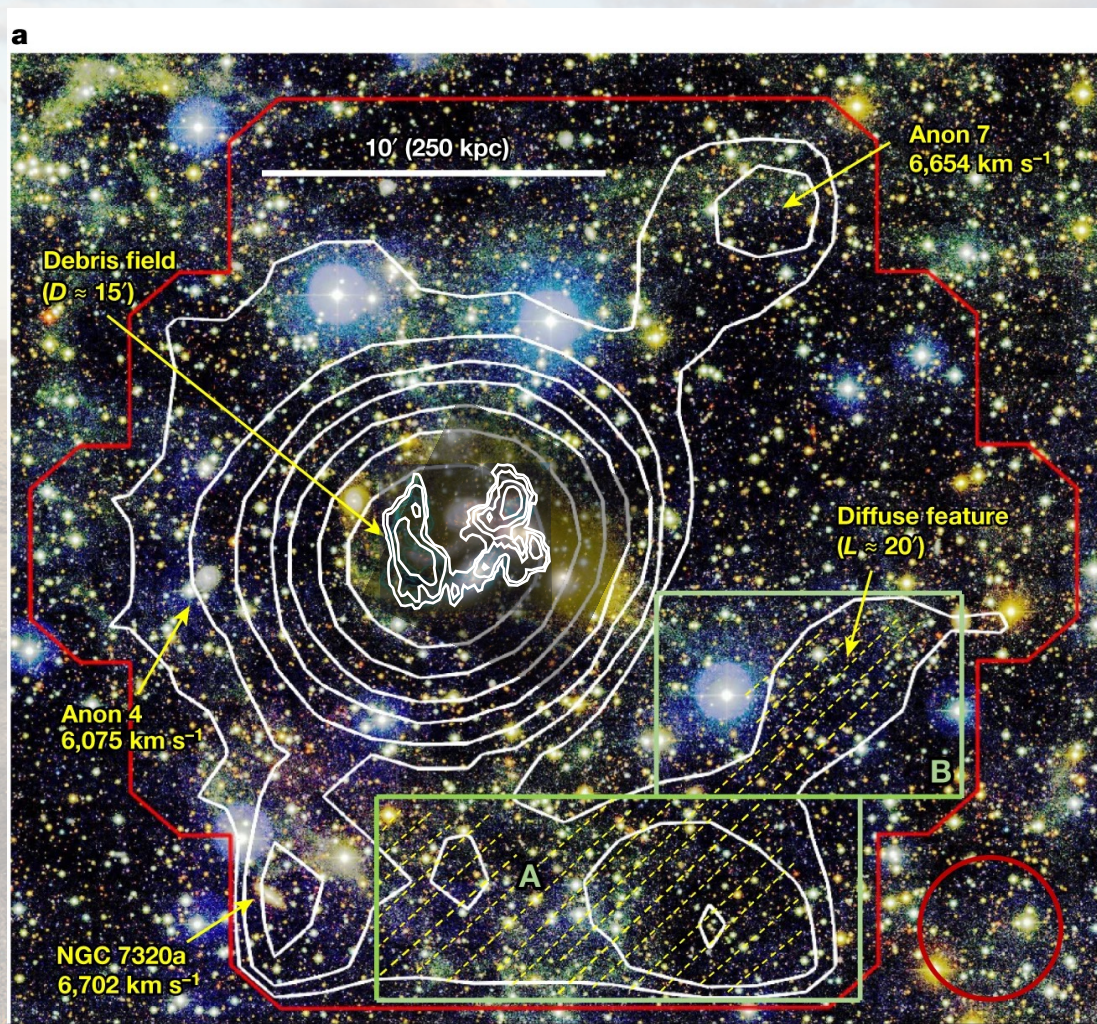
Stephan's Quintet

FAST

Nature
Xu et al (2022)

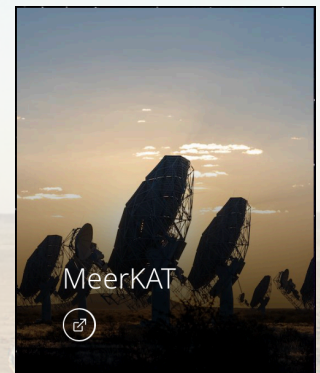
0.6 Mpc
HI debris field

$N_{\text{HI}} =$
 $7.4 \times 10^{17} \text{ cm}^{-2}$
(at 5.5σ level)

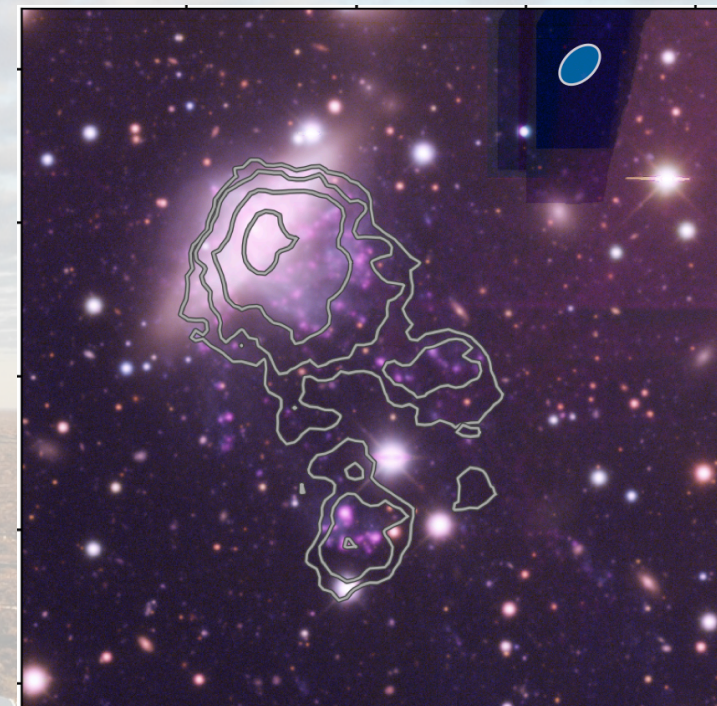
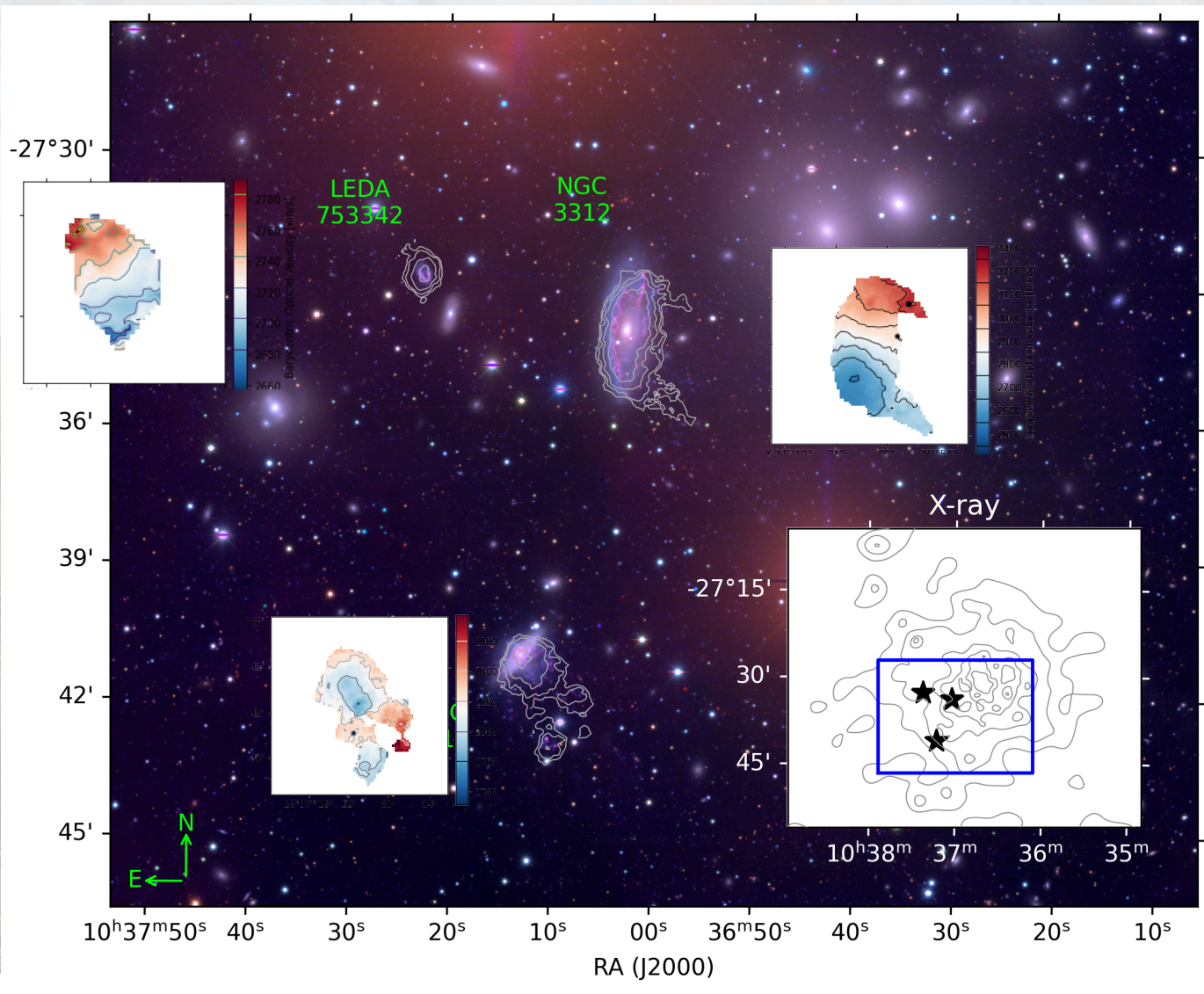


More FAST
results see also:
Zhu et al (2022)
Wang et al (2022)

Galaxy Clusters with MeerKAT: prevalence of ram pressure stripping & jellyfish galaxies



Hess et al (2022)

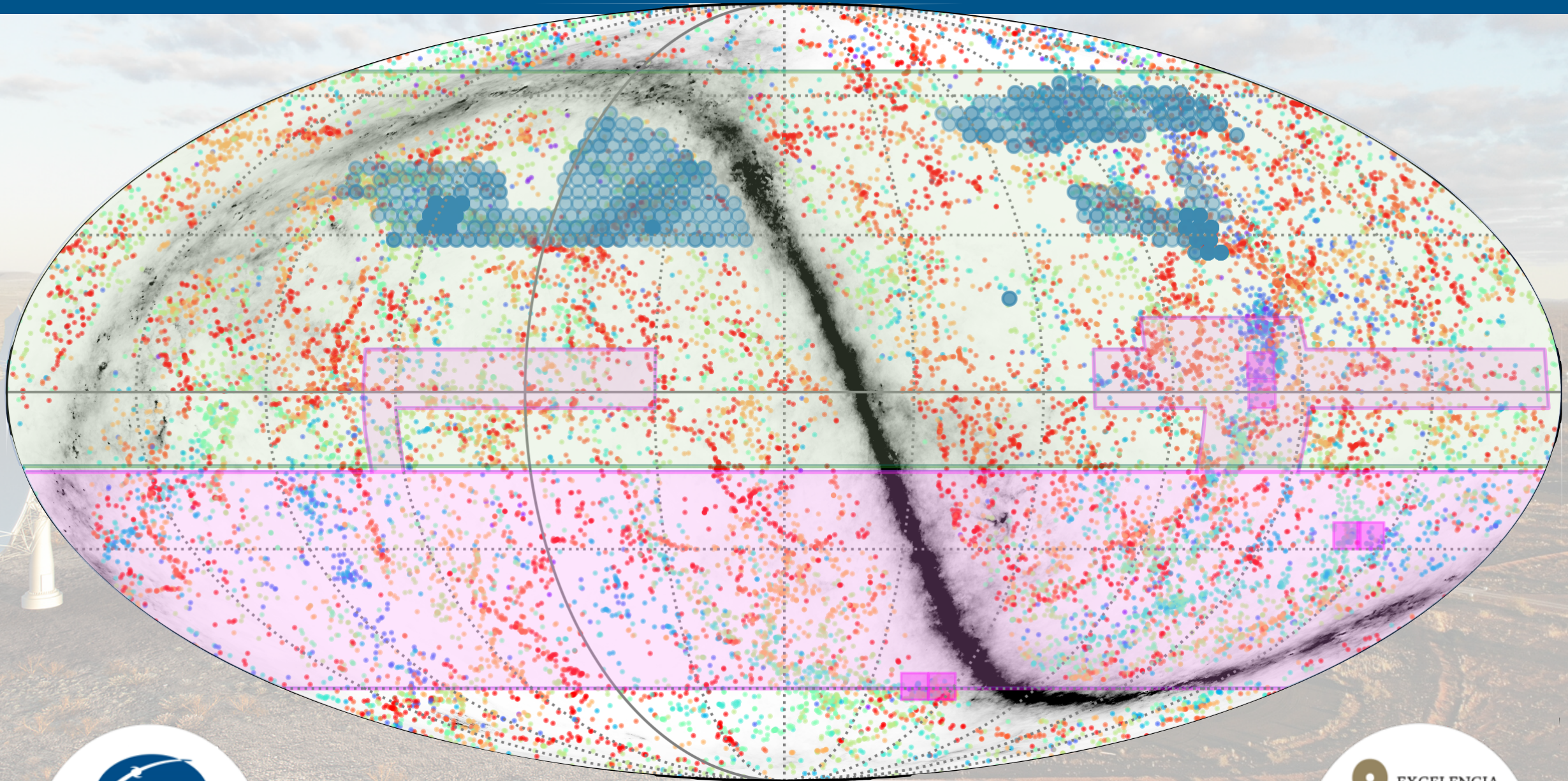


MeerKAT HI + DECam Halpha:

- HI and star forming tails
- NGC 3314a/b: 2 galaxies in projection
- Drag: galaxies have past cluster pericenter



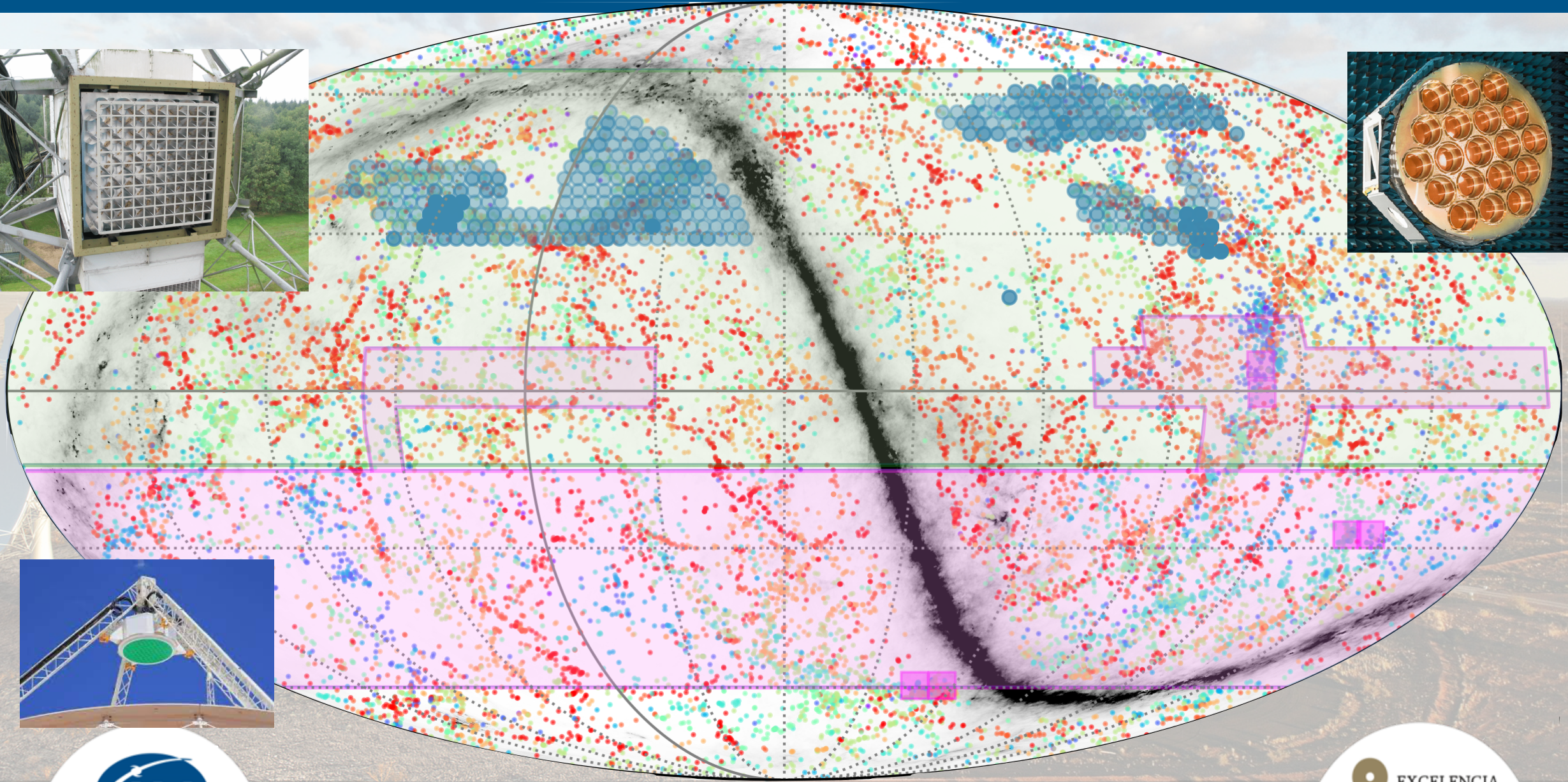
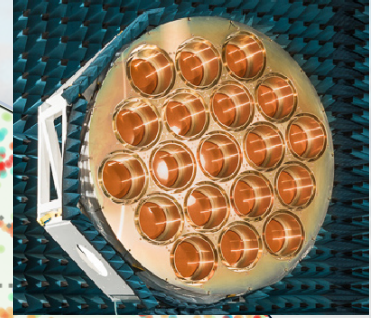
WIDE AREA SURVEYS: Apertif, WALLABY, CRAFTS



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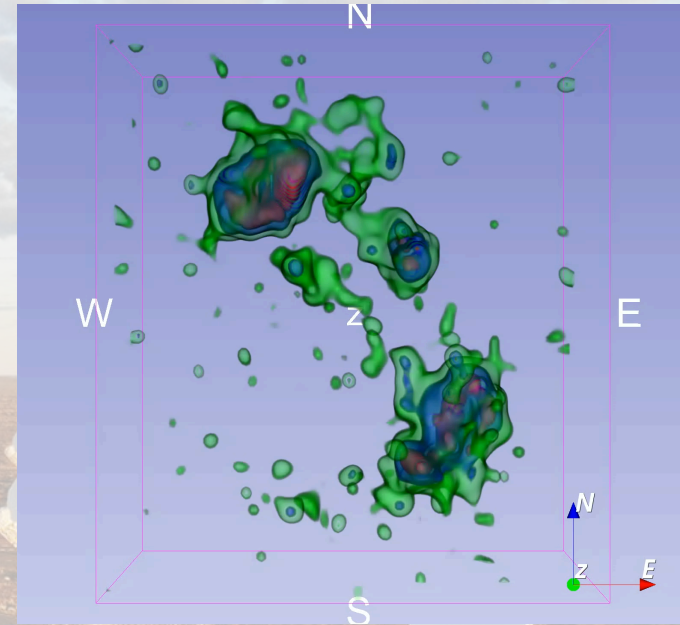
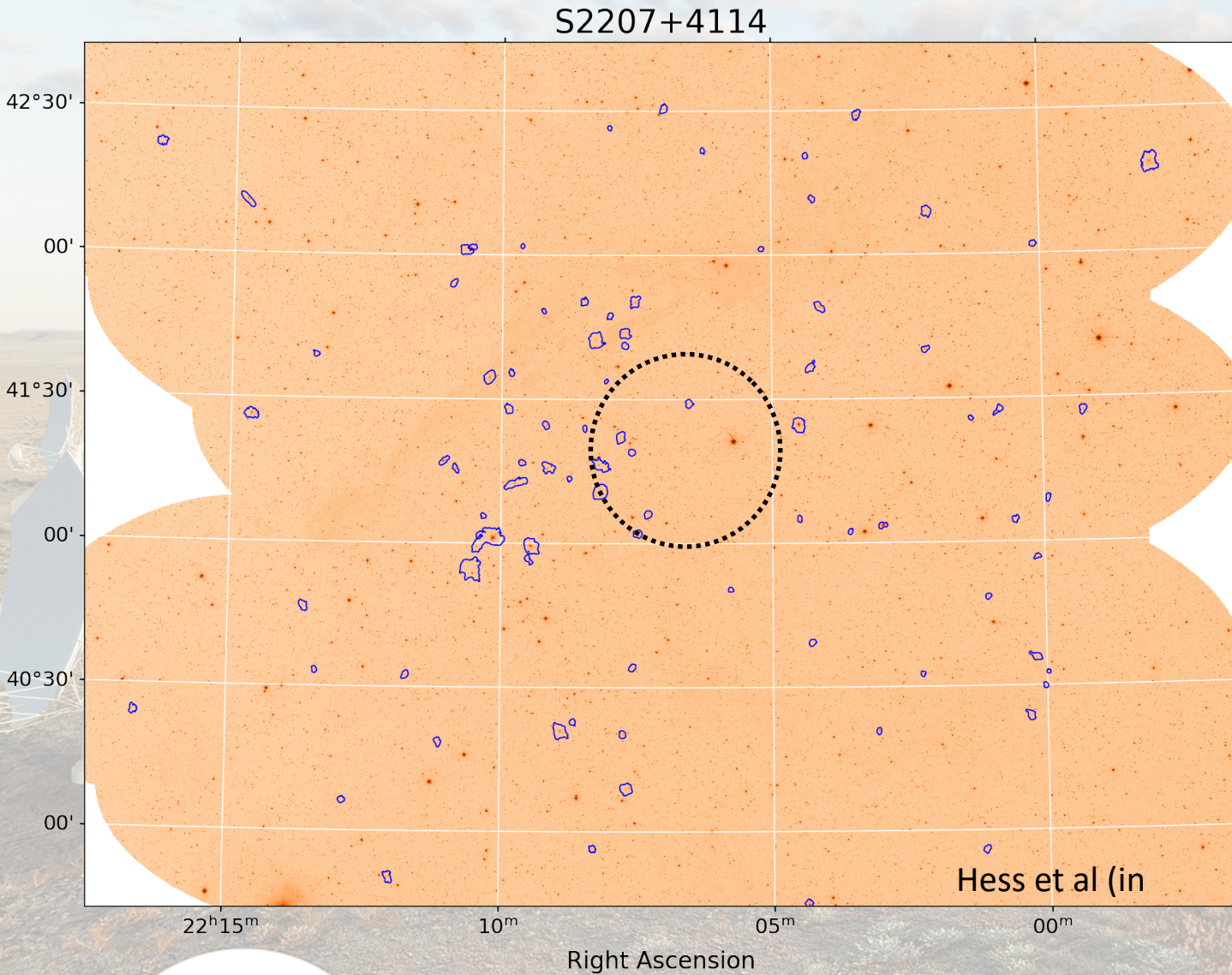
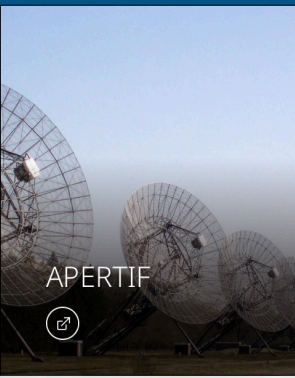


WIDE AREA SURVEYS: Apertif, WALLABY, CRAFTS

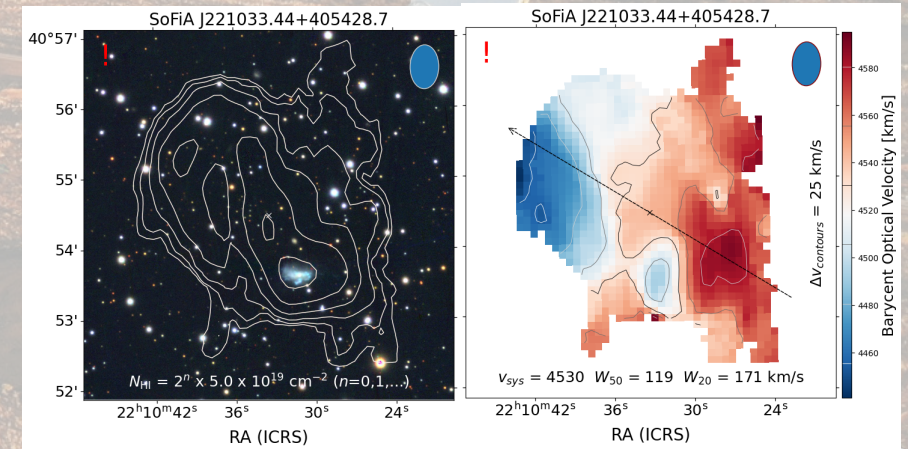


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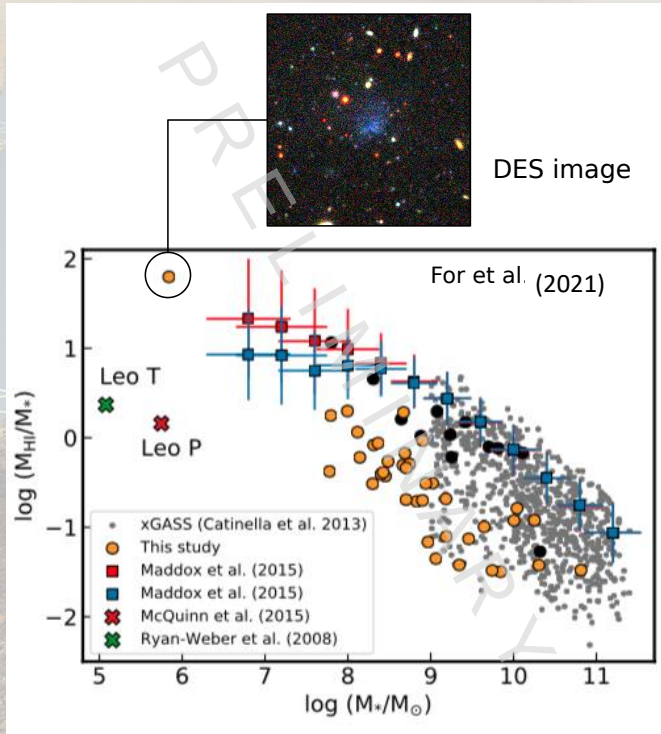




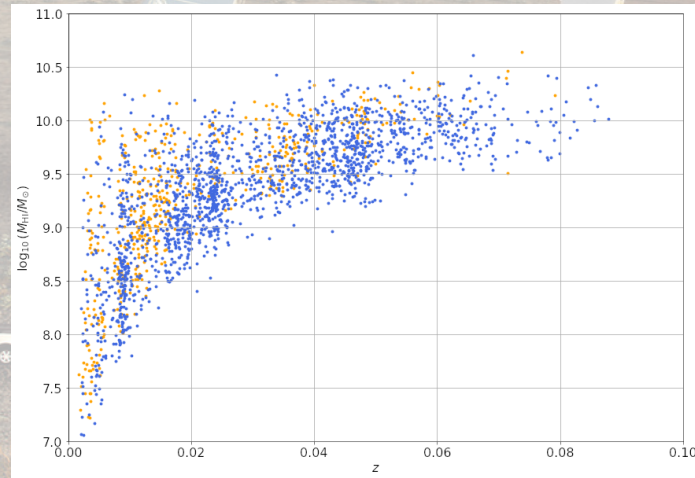
- DR1: Adams et al (2022)
- van Cappellen et al (2022)
- Denes et al (2022)
- Kutkin et al (2022)



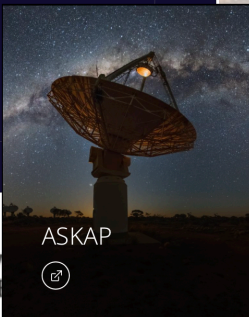
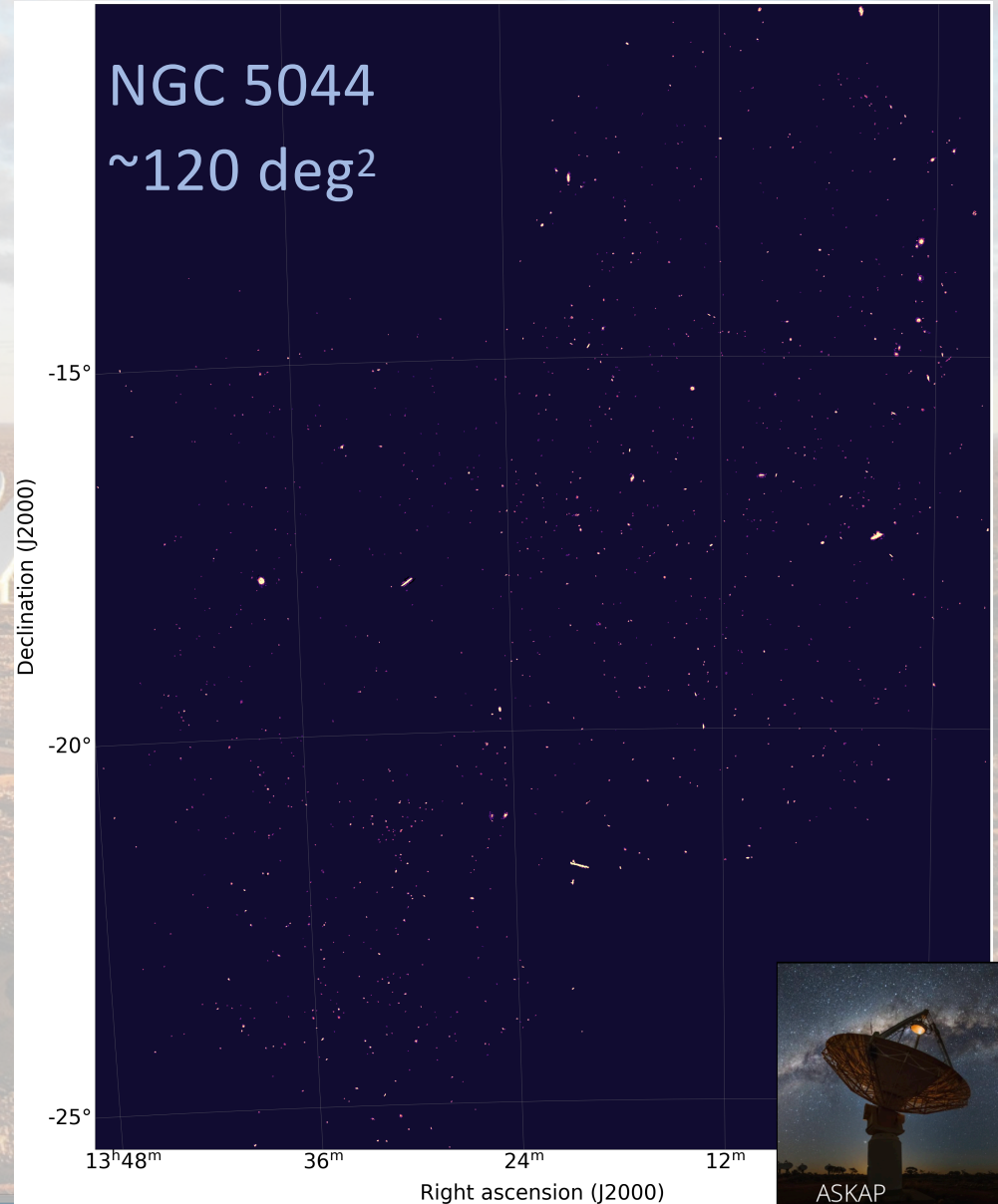
- Unbiased view of HI in galaxies with environment
- Dwarf galaxies: dark matter halo mass/distribution
- Galaxy kinematics: quantifying frequency of warps; how bars funnel gas in center of galaxies



25+ papers and counting on from Early Science + Phase 1 + Phase 2...



DR1; Westmeier et al (2022)



Medium-deep HI surveys: Apertif MDS & MIGHTEE-HI

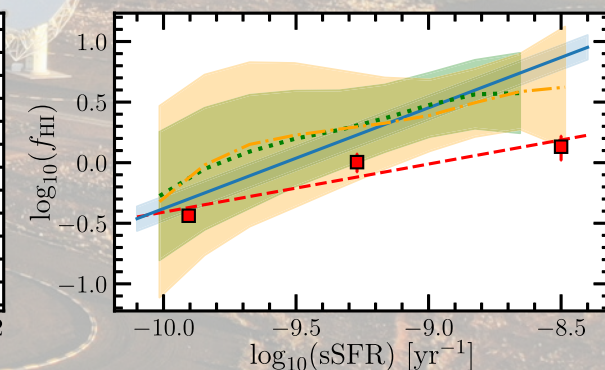
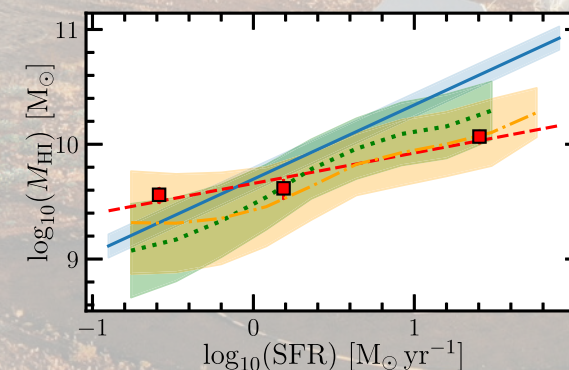
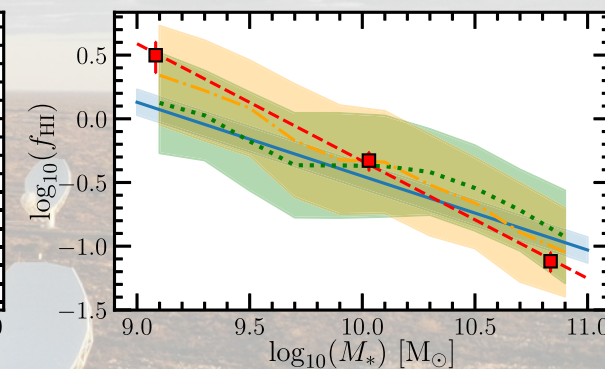
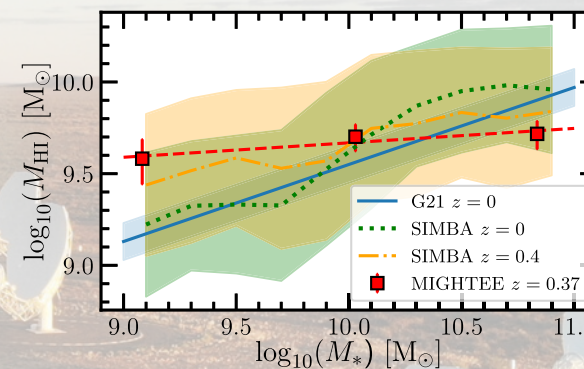
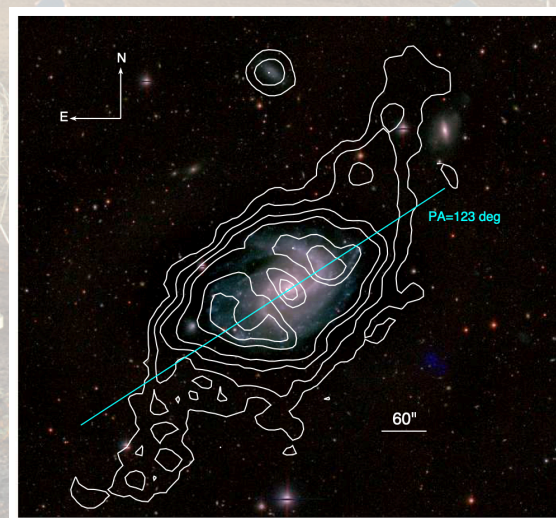
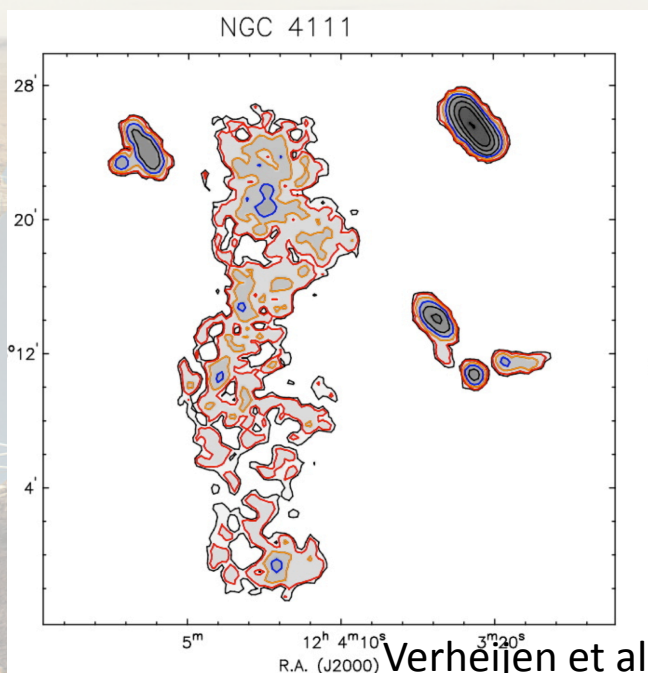
- Tens to hundreds of deg²
- Fills the niche between wide and deep surveys
- Good depth; good area; good resolution; great ancillary data

See also:

Ranchod et al (2021)

Ponomareva et al (2021, in prep)

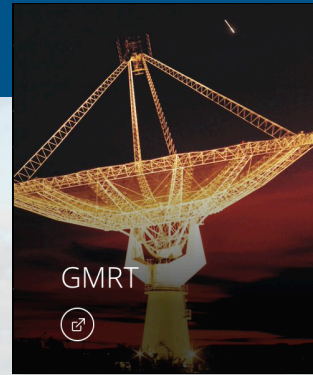
Rajohnson et al (2022)



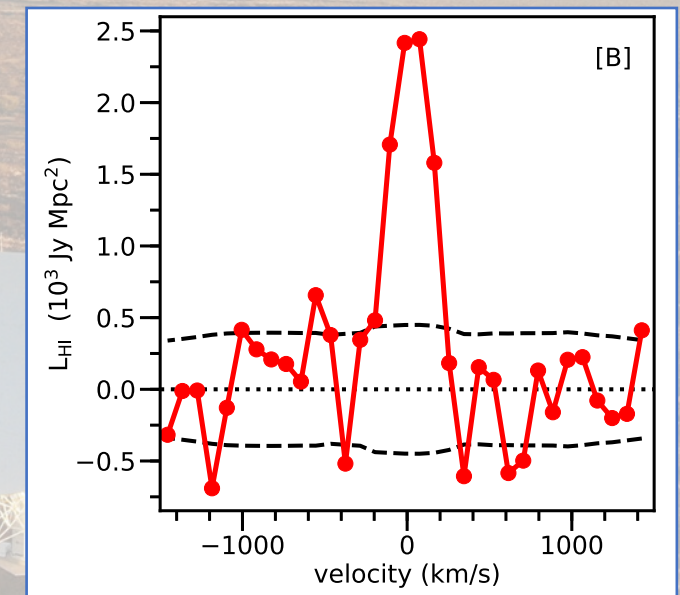
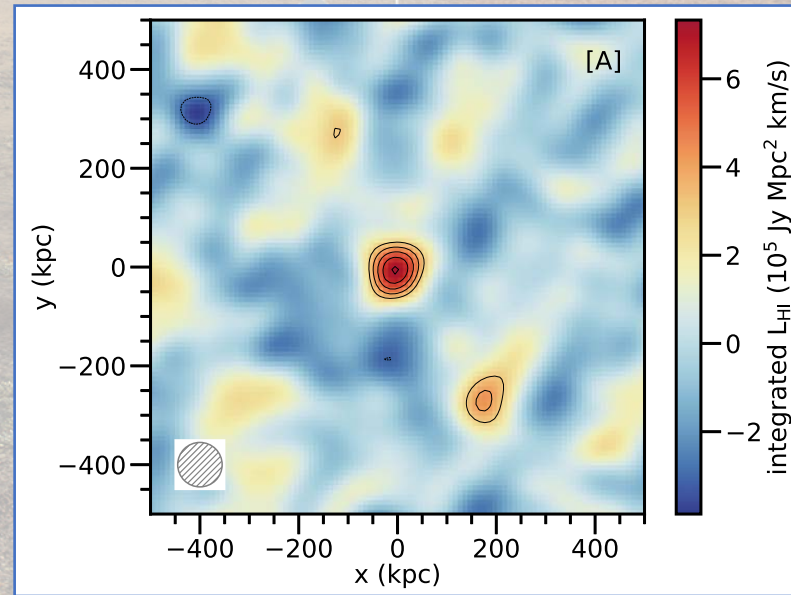
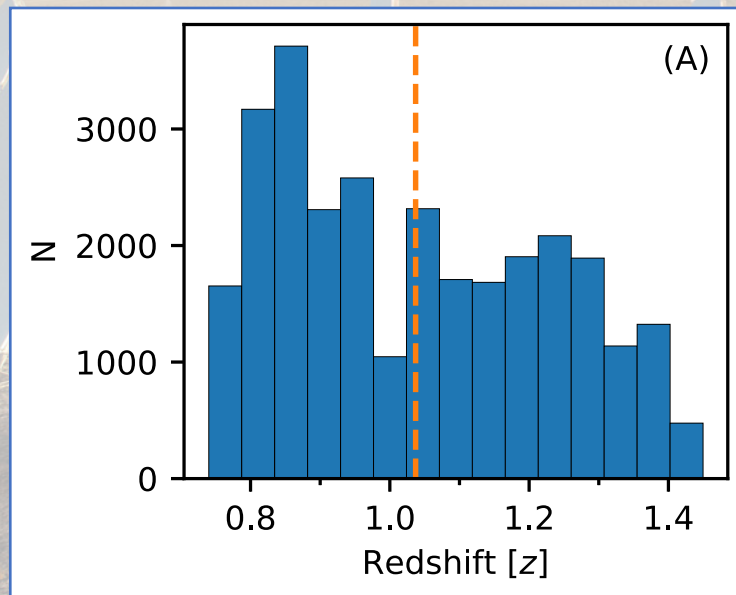
Sinigaglia et al (2022)



GMRT DEEP2 stacking: HI detection at $z=1$!



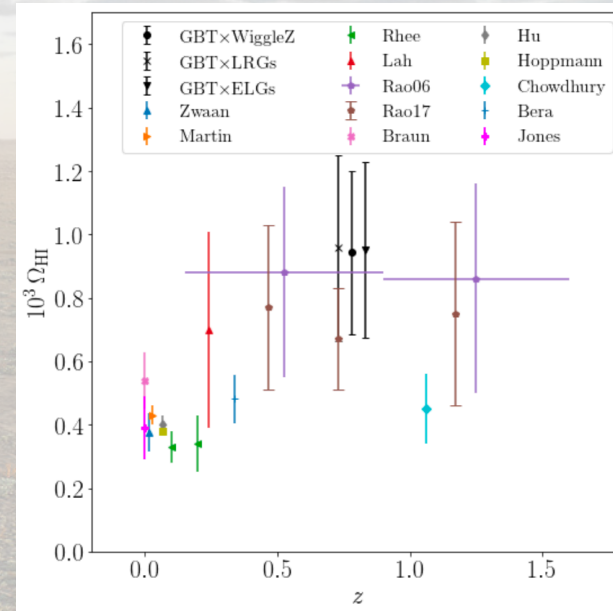
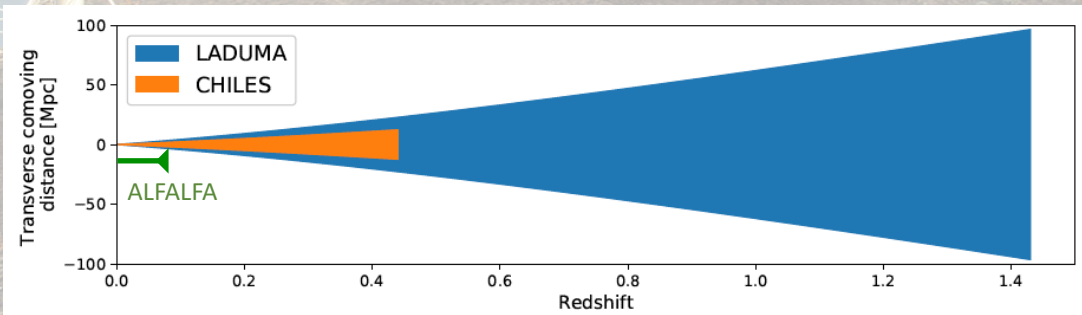
- Stacking 11,419 galaxies with spectroscopic redshifts $\langle M_* \rangle = 10^{10} M_\odot$
- 510 hours between 7 pointings
- $\langle M_{\text{HI}} \rangle = 1.3 \times 10^{10} M_\odot$ at $\langle z \rangle = 1$; significantly more than $\langle M_{\text{HI}} \rangle = 3.9 \times 10^9 M_\odot$ at $\langle z \rangle = 0$



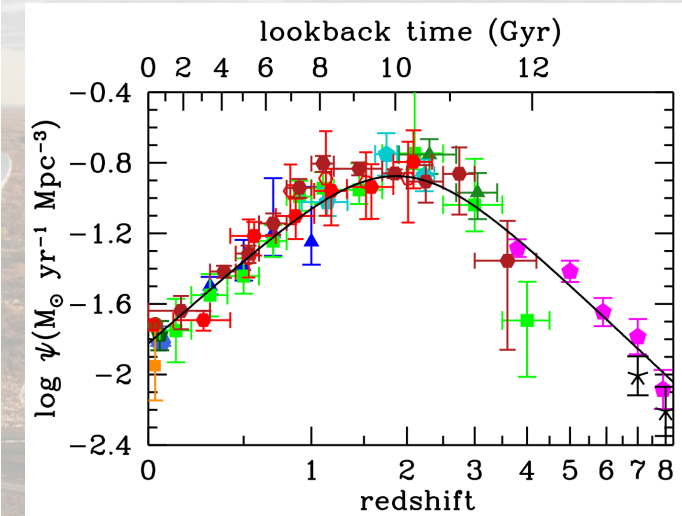
Chowdhury et al (2022, 2020)

DEEP HI SURVEYS: CHILES, LADUMA, DINGO

- Single pointing surveys >1000 hours on JVLA, MeerKAT, ASKAP
- Science goals
 - Cosmic evolution in Ω_{HI} ;
HI mass function, HI scaling relations, Tully-Fisher, HI with environment



Wolz et al (2021)

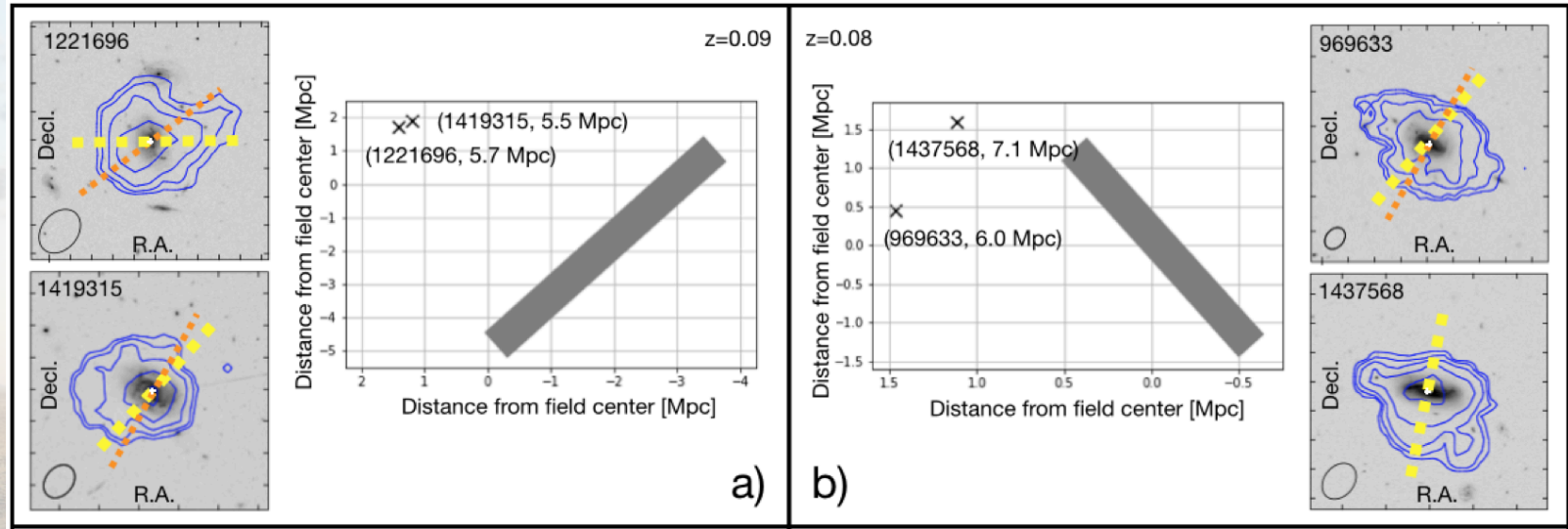


Madau & Dickinson (2014)



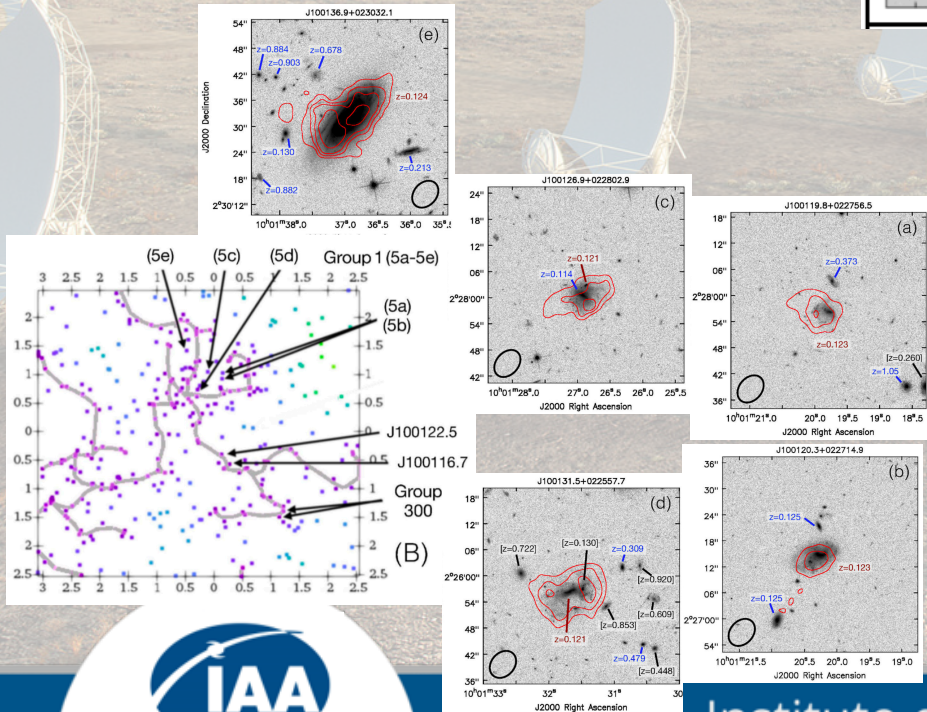
CHILES: Resolved galaxies in different environments

- Low HI mass: aligned with filaments $10^{9.5} M_{\odot}$
- High HI mass: anti-aligned with filaments

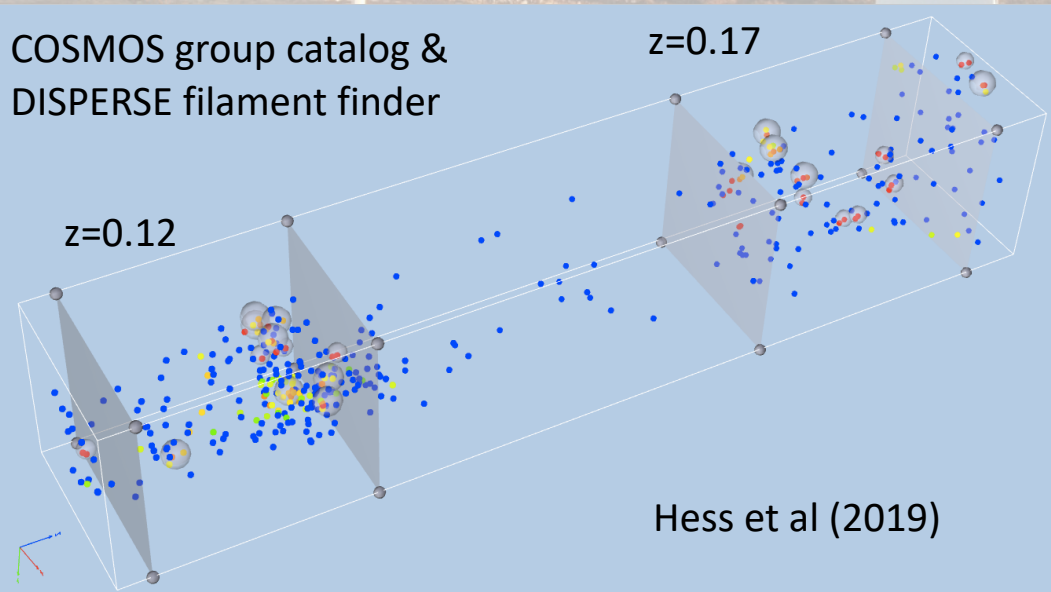


Blue Bird et al (2019)

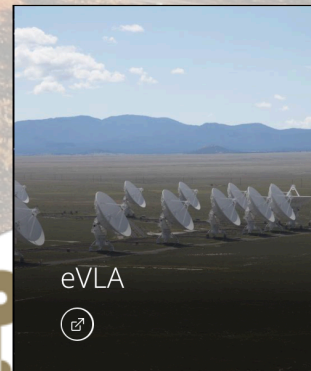
See also
MIGHTEE-HI
Tudorache et al
(2022)



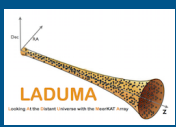
COSMOS group catalog &
DISPERSE filament finder



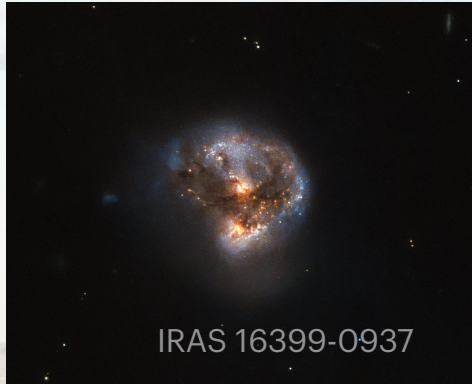
Hess et al (2019)



eVLA



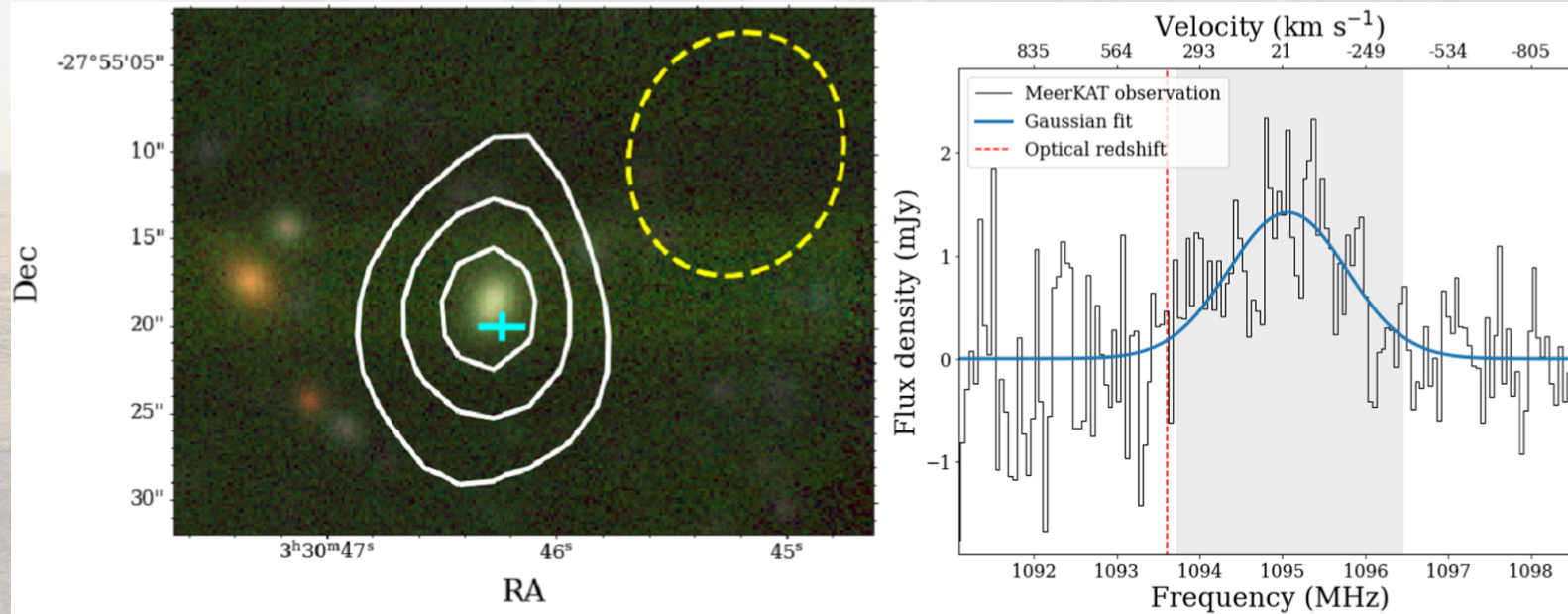
LADUMA: Highest redshift untargeted detection of OH megamaser at $z=0.526$



IRAS 16399-0937

Glowacki et al (2022)

- 1667 MHz line redshifted into L-band ($z > 0.12$)

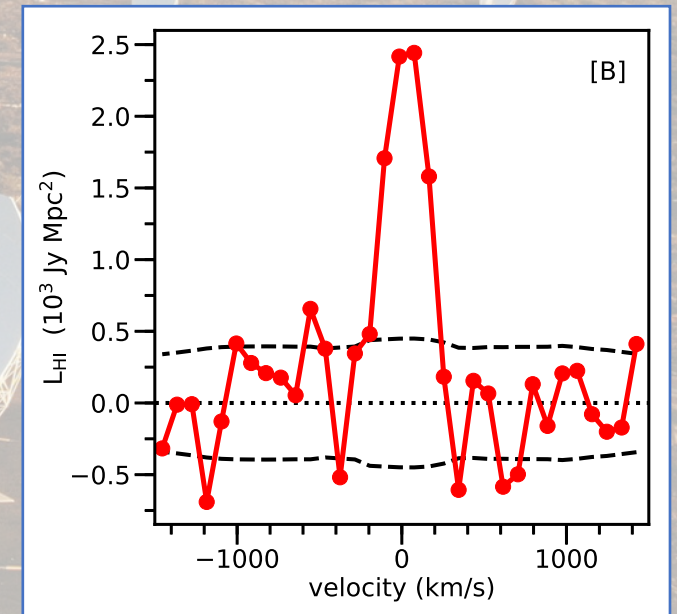
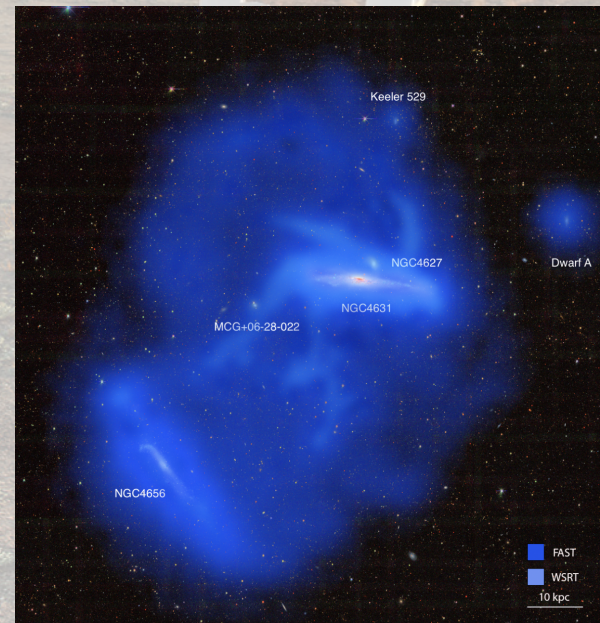
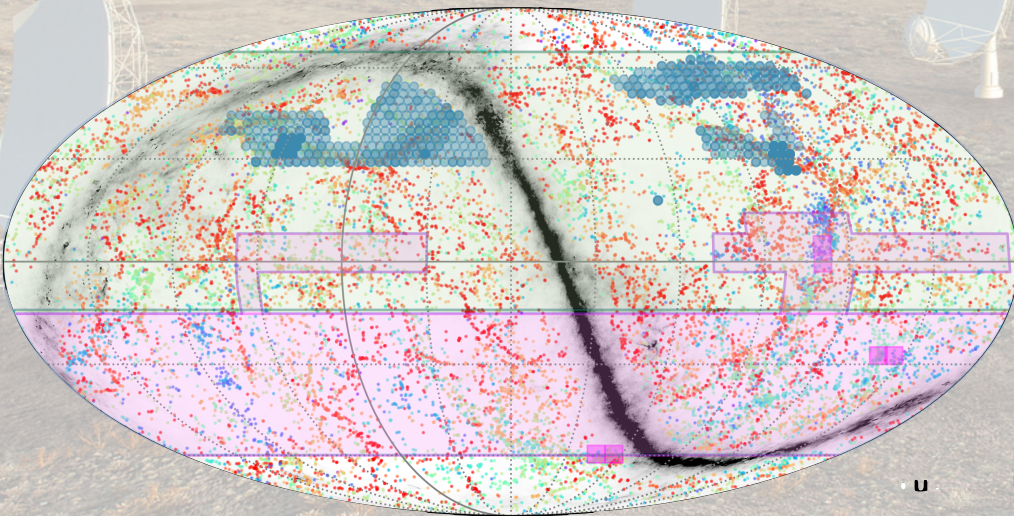


See also OHM discovered by Hess et al (2021) with Apertif

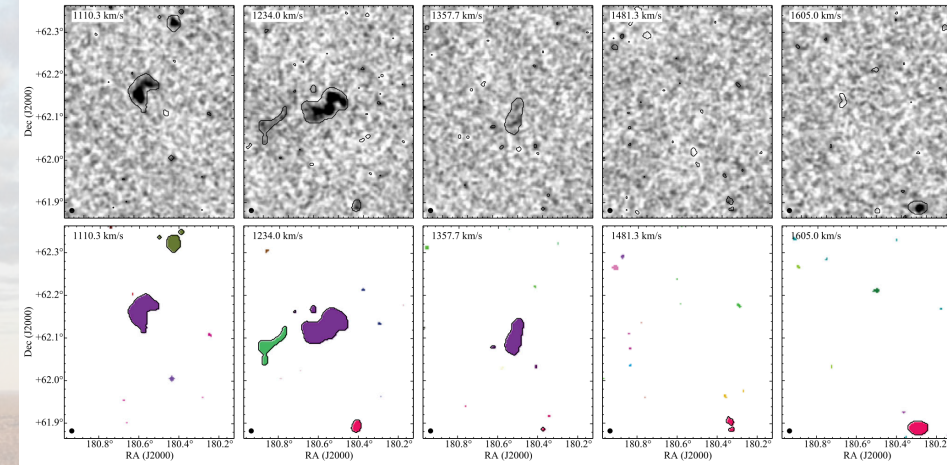
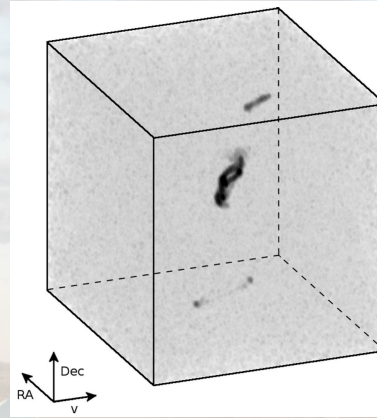
- First untargeted OH maser detection beyond $z=0.5$
- Host galaxy is ULIRG with $L_{\text{FIR}} \sim 1.6 \times 10^{12} L_{\odot}$
- OHMs are tracers of the cosmic merger rate

Science highlights

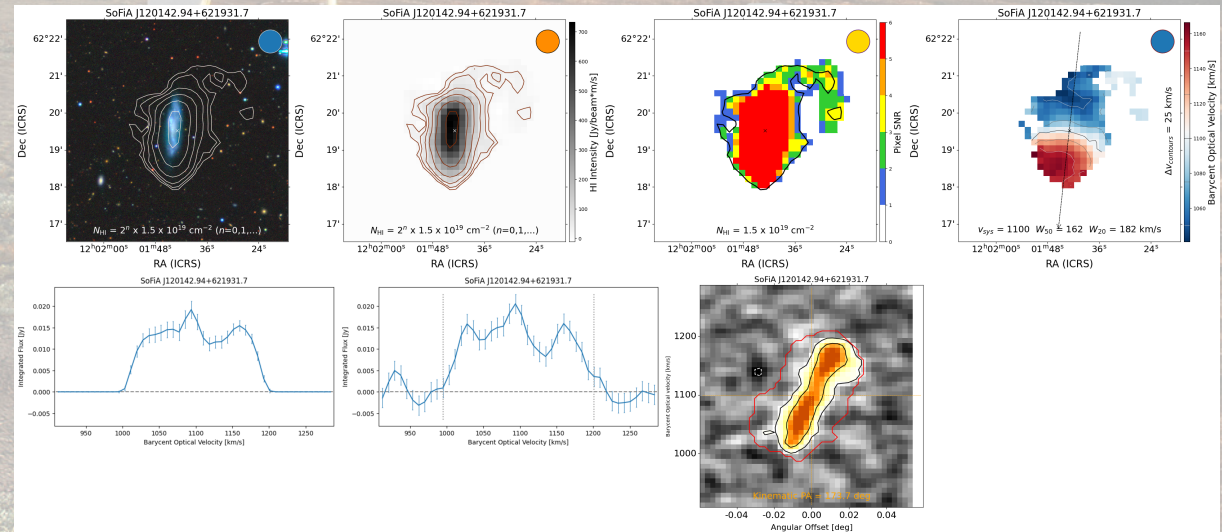
- Combining high surface brightness sensitivity (single dish or interferometers with lots of short baselines) with high resolution imaging
- Untargeted wide-area observations present an unbiased view of HI in a range of environments; what types of galaxies contain HI
- Pushing well beyond the local Universe



- Source Finding Application (SoFiA)
 - Identify, catalog, parametrize sources in a noise dominated cube
 - Well vetted in SKA SDC2
- SoFiA Image Pipeline:
 - Convert SoFiA output catalogs and FITS files to publication quality images



Serra et al (2015); Westmeier et al (2021)

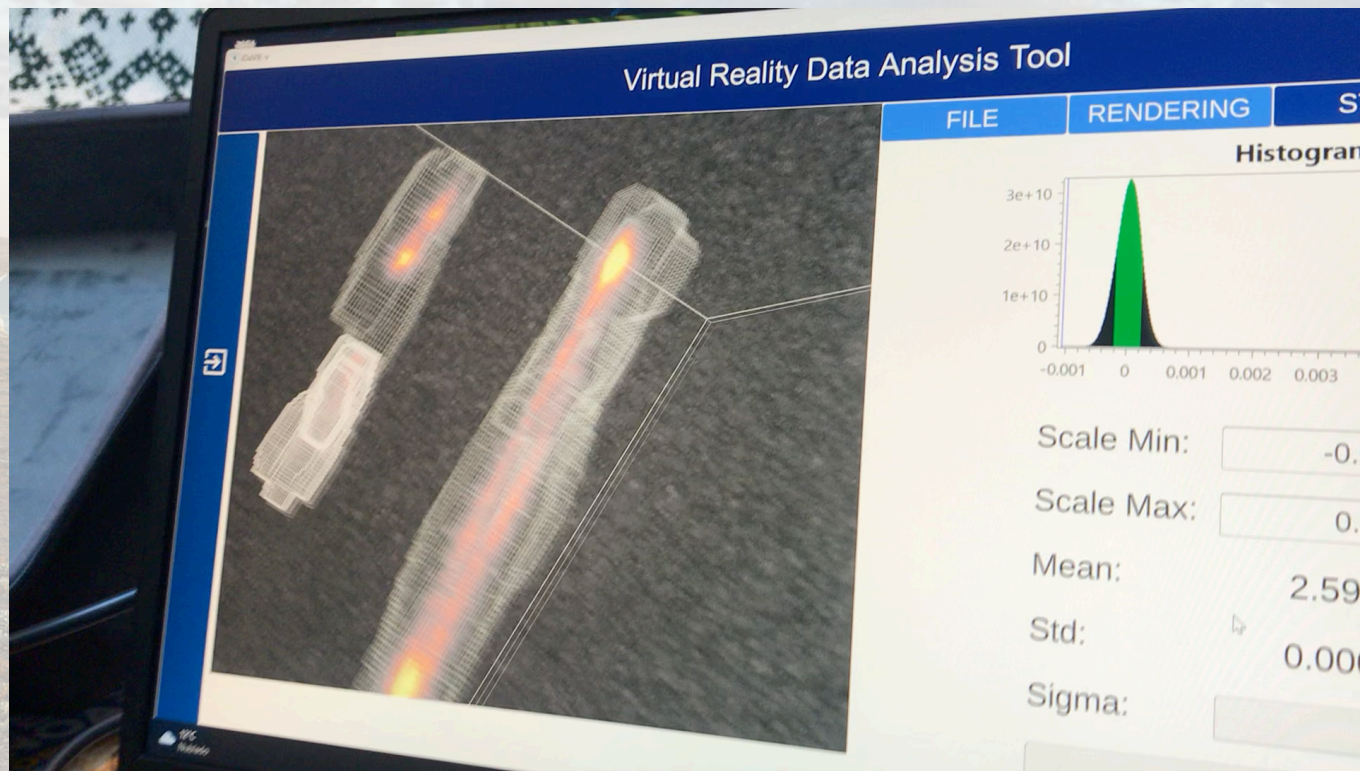
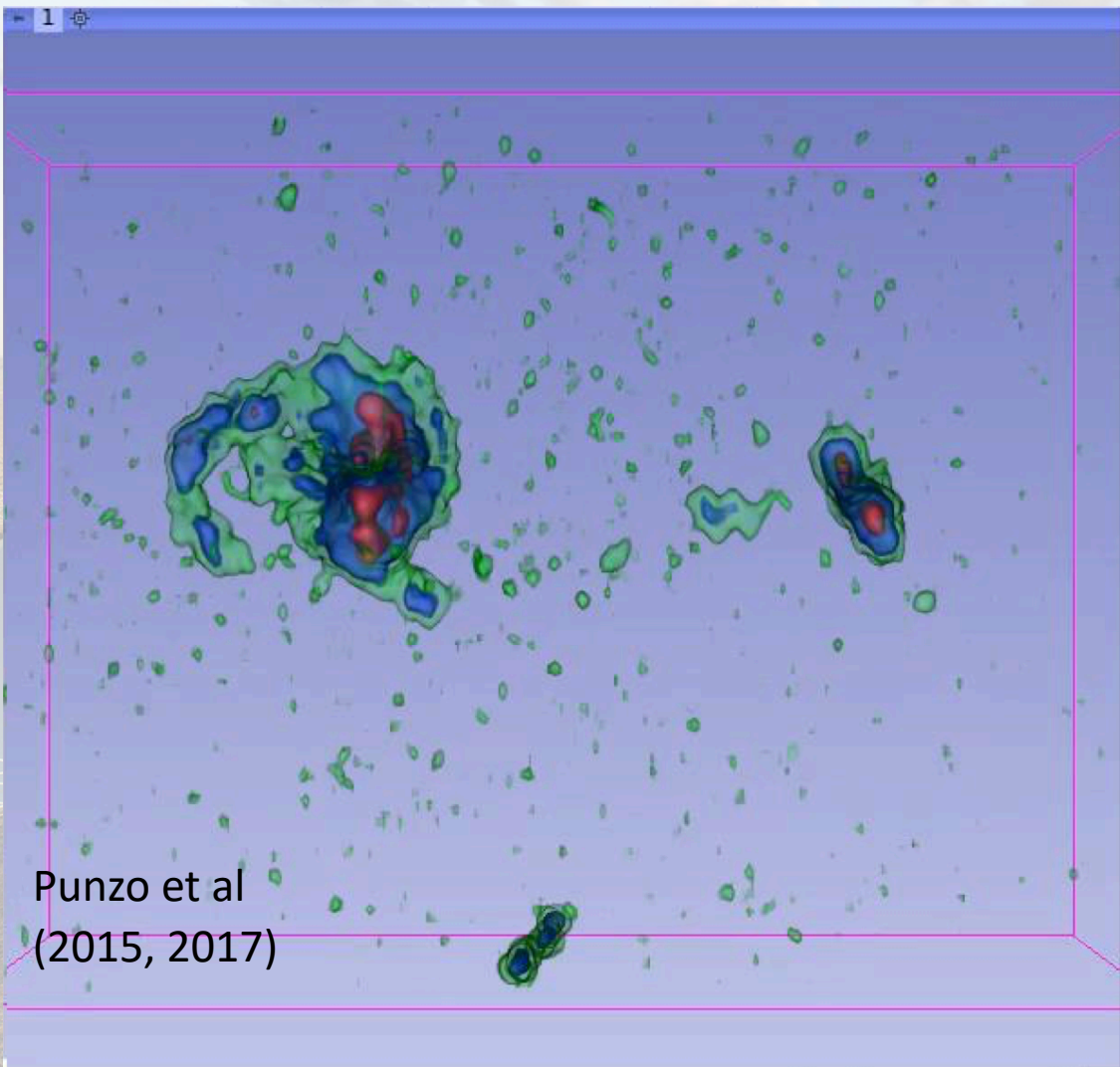


Hess et al (2022)

<https://github.com/kmhess/SoFiA-image-pipeline>



HI TOOLS: Source finding, source characterization, and data visualization

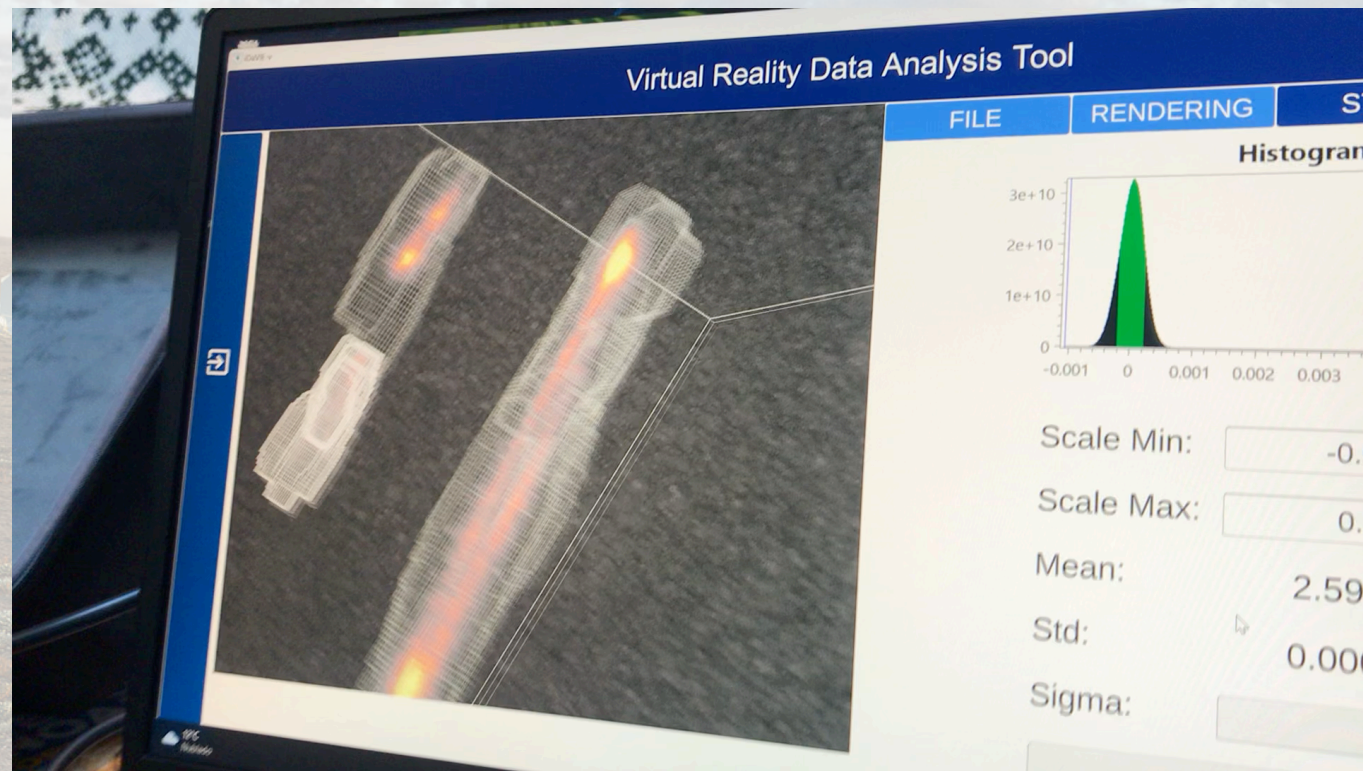


iDAVIE: Jarrett et al (2021)
<https://idavie.readthedocs.io/en/latest/>





HI TOOLS: Source finding, source characterization, and data visualization



iDAVIE: Jarrett et al (2021)
<https://idavie.readthedocs.io/en/latest/>



Conclusions

- Surveys with precursors are combining high surface brightness sensitivity (single dish or interferometers with lots of short baselines) with high spatial resolution
- Untargeted wide-area observations present an unbiased view of HI in a range of environments; what types of galaxies contain HI
- Pushing well beyond the local Universe
- Tools for HI surveys; maximizing science from large data volumes are being developed and tested now -- demonstrating success with current surveys