Atomic gas and galaxy evolution

Lourdes Verdes-Montenegro
(Instituto de Astrofísica de Andalucía-CSIC)
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HI Science with the SKA: surveys
HI Science in Spain: Resolved studies, Environment, Star formation beyond the optical disc and cold gas accretion
Additional studies: Our Galaxy, HI in Absorption, HI evolution with z
Advancing Astrophysics with the SKA, Giardini Naxos, 2014

- The Hydrogen Universe with the SKA. Staveley-Smith & Oosterloo
- Neutral Hydrogen and Galaxy Evolution. Blyth et al.
- The Intergalactic Medium and the Cosmic Web. Popping et al.
- The Neutral Interstellar Medium in Galaxies. de Blok et al.
- The Galaxy and Magellanic System. McClure-Griffiths et al.
- Cool Outflows and HI absorbers Morganti et al.
- Connecting the Baryons Meyer et al.
- Galaxy Formation & Dark Matter Modelling in the Era of the SKA. Power et al.
- SKA as Doorway to Angular Momentum Obreschkow et al.
- The Physics of the Cold Neutral Medium: Low-frequency Radio Recombination Lines with the SKA Oonk et al.

HI and Galaxy evolution Chapter: SKA White Book chapter

HI Galaxy Science with the SKA
Martin Meyer & Erwin de Blok on behalf of the HI SWG. (May 2017)
The Hydrogen Array was part of the initial concepts of the project. HI key in central processes of galaxy evolution and structure formation:

- the buildup of stellar mass in galaxies
- galaxy dynamics
- SF in and beyond the optical disc
- probing environmental influence.

**Internal evolution**
- Clouds of dust and gas
- Gas collapse
- Return to the ISM
- SF

**External: interactions**
- Processed gas
- Galactic Fountain (Fraternalli 2014)

**Cold gas accretion from the “Cosmic Web”**
- SNe, AGN extraplanar feedback
- Pristine gas

**Credits:**
- wikipedia.org
- pinterest.com

SKA will be the **first telescope** capable of directly mapping the full extent of the cosmic web that characterizes the large scale structure of the Universe (Wilcots 2004)
SKA1

Construction 2019 - 2024
Early science 2020

133+64 dishes

SKA1-mid = South Africa
350 MHz - 14GHz
Baselines 150 km
Band 1 (0.35–1.05GHz)
Band 2 (0.95–4.6GHz)

SKA2

2024 - 2030
Baselines up to 3500 km

Advanced Instrumentation Program

Phased array feeds (PAF)
**Key Science Projects**

**Notional package of Key Science Projects**

- Outcome of well-documented SKA1 science prioritization process
  - All objectives originated within the science community
  - Review and strong endorsement by advisory bodies (SRP, SEAC)
- Representative package of **high-impact science deliverables for 50 – 75% of the first 5 yrs** of science operations

<table>
<thead>
<tr>
<th>SWG</th>
<th>Objective</th>
</tr>
</thead>
<tbody>
<tr>
<td>CD/EoR</td>
<td>Physics of the early universe IGM - I. Imaging</td>
</tr>
<tr>
<td>CD/EoR</td>
<td>Physics of the early universe IGM - II. Power spectrum</td>
</tr>
<tr>
<td>Pulsars</td>
<td>Reveal pulsar population and MSPs for gravity tests and Gravitational Wave detection</td>
</tr>
<tr>
<td>Pulsars</td>
<td>High precision timing for testing gravity and GW detection</td>
</tr>
<tr>
<td>HI</td>
<td>Resolved HI kinematics and morphology of <del>10^{10} M_sol mass galaxies out to z</del>0.8</td>
</tr>
<tr>
<td>HI</td>
<td>High spatial resolution studies of the ISM in the nearby Universe.</td>
</tr>
<tr>
<td>HI</td>
<td>Multi-resolution mapping studies of the ISM in our Galaxy</td>
</tr>
<tr>
<td>Transients</td>
<td>Solve missing baryon problem at z~2 and determine the Dark Energy Equation of State</td>
</tr>
<tr>
<td>Cradle of Life</td>
<td>Map dust grain growth in the terrestrial planet forming zones at a distance of 100 pc</td>
</tr>
<tr>
<td>Magnetism</td>
<td>The resolved all-Sky characterisation of the interstellar and intergalactic magnetic fields</td>
</tr>
<tr>
<td>Cosmology</td>
<td>Constraints on primordial non-Gaussianity and tests of gravity on super-horizon scales.</td>
</tr>
<tr>
<td>Cosmology</td>
<td>Angular correlation functions to probe non-Gaussianity and the matter dipole</td>
</tr>
<tr>
<td>Continuum</td>
<td>Star formation history of the Universe (SFHU) – I+II. Non-thermal + Thermal processes</td>
</tr>
</tbody>
</table>

Braun et al, 2014, SKA1 Science Priority Outcomes
**HIGH PRIORITY HI SCIENCE OBJECTIVES**

- Resolved HI kinematics and morphology of $\sim 10^{10} M_\odot$ mass galaxies out to $z \sim 0.8$
- High spatial resolution (50 pc) studies of the ISM in the nearby Universe.
- Multi-resolution, multi-T mapping studies of the ISM in our Galaxy
- Cosmological evolution of cold HI (absorption) out to $z = 6$
- The gaseous interface and accretion physics between galaxies and the cosmic web
### Possible SKA1 HI Surveys

Meyer on behalf of HISWG (Town Hall meeting, 2017)

<table>
<thead>
<tr>
<th>Survey</th>
<th>Area (deg²)</th>
<th>Freq MHz</th>
<th>HI Resolution</th>
<th>&lt;z&gt; (zₗım)</th>
<th>T (hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium wide</td>
<td>400</td>
<td>950-1420</td>
<td>10'</td>
<td>0.1 (0.3)</td>
<td>2000</td>
</tr>
<tr>
<td>Medium deep</td>
<td>20</td>
<td>950-1420</td>
<td>5'</td>
<td>0.2 (0.5)</td>
<td>2000</td>
</tr>
<tr>
<td>Deep</td>
<td>1 pointing</td>
<td>600-1050</td>
<td>2'</td>
<td>0.5 (1)</td>
<td>3000</td>
</tr>
<tr>
<td>Targeted ISM</td>
<td>30 targets</td>
<td>1400-1420</td>
<td>3'-30''</td>
<td>0.002 (0.01)</td>
<td>3000</td>
</tr>
<tr>
<td>Targeted Accretion</td>
<td>30 targets</td>
<td>1400-1420</td>
<td>30'-1''</td>
<td>0.002 (0.01)</td>
<td>3000</td>
</tr>
<tr>
<td>Galaxy/MS</td>
<td>500</td>
<td>1418-1422</td>
<td>10'-1'</td>
<td>0 (0)</td>
<td>4500</td>
</tr>
<tr>
<td>Galaxy Abs</td>
<td>(5000)</td>
<td>1418-1422</td>
<td>2'</td>
<td>0 (0)</td>
<td>(10,000)</td>
</tr>
<tr>
<td>Absorption</td>
<td>1000+</td>
<td>350-1050</td>
<td>2'</td>
<td>1 (3)</td>
<td>1000+</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>200-350</td>
<td>10'</td>
<td>4 (6)</td>
<td>1000</td>
</tr>
</tbody>
</table>

Updated from Staveley-Smith & Oosterloo, 2015, PoS, AASKA14, 167

- Band 1 (0.35–1.05GHz)
- Band 2 (0.95–4.6GHz)
POSSIBLE SKA1 HI SURVEYS

Distribution with $z$ of HI masses of galaxies to be detected in the tiered set of 1000h surveys

$M^*(\text{HI})$ at $z = 0$
### Possible SKA1 HI Surveys

- 1-2 commensal programs possible

<table>
<thead>
<tr>
<th>Survey</th>
<th>Area (deg²)</th>
<th>Freq (MHz)</th>
<th>T (hrs)</th>
<th>Magnetism</th>
<th>Cosmology/ EoR</th>
<th>Continuum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium wide</td>
<td>400</td>
<td>950-1420</td>
<td>2000</td>
<td></td>
<td></td>
<td>1000 sq deg 5000 hours weak lensing</td>
</tr>
<tr>
<td>Medium deep</td>
<td>20</td>
<td>950-1420</td>
<td>2000</td>
<td></td>
<td></td>
<td>similar strategy</td>
</tr>
<tr>
<td>Deep</td>
<td>1 pointing</td>
<td>600-1050</td>
<td>3000</td>
<td></td>
<td></td>
<td>useful only if in band 1</td>
</tr>
<tr>
<td>Targeted</td>
<td>30 targets</td>
<td>1400-1420</td>
<td>3000</td>
<td></td>
<td></td>
<td>good match in sample, res and depth</td>
</tr>
<tr>
<td>Targeted (Accr)</td>
<td>(30 targets)</td>
<td>1400-1420</td>
<td>(3000)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Galaxy/MS</td>
<td>500</td>
<td>1418-1422</td>
<td>4500</td>
<td></td>
<td>commensal with Galaxy + Magn WG to get optimum 1200 deg2 and 11500 hours</td>
<td></td>
</tr>
<tr>
<td>Galaxy Abs</td>
<td>(5000)</td>
<td>1418-1422</td>
<td>(10000)</td>
<td></td>
<td>fully commensal with “Galaxy/MS”, continuum, magnetism</td>
<td></td>
</tr>
<tr>
<td>Absorption</td>
<td>1000+</td>
<td>350-1050</td>
<td>1,000+</td>
<td></td>
<td>fully commensal 5000 deg2 absorption survey</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>200-350</td>
<td>1,000</td>
<td></td>
<td>and commensal with medium-wide HI band 2</td>
<td></td>
</tr>
</tbody>
</table>

Update from Staveley-Smith & Oosterloo, 2015, PoS, AASKA14, 167

- Deep + highly resolved
  - HI in nearby galaxies
  - deep continuum + B
  - N(HI) < 10^18 at 1'
- Large area HI surveys
- Ultradeep
  - HI detection up to z ~2
  - Continuum SFR at high-z (Jarvis et al 2014)
HI science in Spain
Main areas of interest

- Synergies with nearby galaxy surveys
- Formation history of early type galaxies (ETGs)
- Environmental effects
- SF in the outskirts of disks and cold gas accretion
- Theoretical models (Domínguez-Tenreiro, Ascasibar; Quilis, Brook)
Main areas of interest

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Why SKA is needed

- Mapping feasible so far at only moderate redshifts \( (z < 0.25) \)
- Extensive HI-mapping of nearby spirals exists, but with angular resolutions one order of magnitude higher than standard optical observations.
- HI mapping of ETGs has been scarce till recently: ETGs are not any more red and quiescent
- HI stripping proposed to inhibit SF in extreme environments, although the removed gas is suspected to exist at \( N(\text{HI}) \) below current detection limits
- Cosmological cold gas accretion, predicted to occur at too low column densities to be detected by current interferometers
Role of gas in both sustaining and inhibiting SF: two ideal laboratories
- isolated galaxies (gas accretion from companions minimized)
- Hickson Compact Groups, high HI deficiency/stripping

Secular infall of HI to disc galaxies (involved in THINGS)
- Continuous line of research: kinematics of gas in the ISM out to ~ 20Mpc, $dv \sim 5$ km/sec @1” with GHaFaS FP @4.2m WHT (La Palma)
- Observations of matching HI kinematics to probe SF, SN needed

SF sustained by gas accretion
Sanchez Almeida et al 2014 (A&AAR)

Cold gas in the proto-cluster environments of high-z radio galaxies: evolution into giant Es
- HI in absorption against their (bright) radio continuum sources
- most massive systems in the Early Universe, ideal to search HI out to $z \sim 1-3$
- Now: CO emission + CO & HI absorption, proto-cluster radiogalaxies ($z \sim 2, VLA, ALMA, ATCA, GBT$)
Resolved studies of galaxies

Barrera-Ballesteros et al 2014. CALIFA interacting galaxies

Beckman, GHAFAS sample

Verdes-Montenegro Hickson group HCG 54. VLA HI map
SYNERGIES WITH NEARBY GALAXY SURVEYS

Interferometric HI studies of samples of nearby galaxies complement blind single dish studies as HIPASS and ALFALFA (HI-SF, morphology, mass, environment)

First steps to bridge the gap between star and galaxy scales

- **THINGS**: 34 galaxies, $3 < D < 15$ Mpc, VLA B+C+D, 6” (500pc)
- **LittleTHINGS** observed 21 dwarf irregular and blue compact galaxies
- **VLA-ANGST** LP, 35 gas-rich and actively star forming $(D < 4$ Mpc), selected from HST
- **FIGGS**, HI imaging at GMRT of extremely faint nearby dwarf irregular galaxies.
- **LVHIS**, deep HI observations with ATCA for all nearby, gas-rich galaxies $(D < 10$ Mpc, $< -30$) detected in HI PASS.
- **WHISP** HI-survey of spiral and irregular galaxies with WSRT
- **SHIELD** total halo masses of the extremely low-mass galaxies detected by ALFALFA with the VLA
- **HALOGAS** (Hydrogen Accretion in LOcal GAlaxieS), deep survey of edge-on nearby galaxies with the WSRT

(Walter+08, Begum+08, Hunter+12, Ott+12, van der Hulst+01, Koribalski08, Heald+11, Cannon+11, Heald+ 2014)
SYNERGIES WITH NEARBY GALAXY SURVEYS

Pathfinders:

- MeerKAT revealing the edge of M83 & interaction with IGM (Heald+ 2016)
- See later Hess et al mapping of compact group HCG 44

M83. Image credit: optical data from Palomar Observatory Sky Survey; radio data from SKA South Africa's MeerKAT
SYNERGIES WITH NEARBY GALAXY SURVEYS

Pathfinders:
ASKAP instantaneous field of view of 30 deg2, allowing to map a large number of galaxies together with their environments as part of WALLABY large program (Koribalski et al 2012)

30 square degrees. WALLABY = 1,200 of these fields. Each field = 500 galaxies detectable in HI
SYNERGIES WITH NEARBY GALAXY SURVEYS

- Few HI observations of nearby galaxies resolve individual HI complexes

<table>
<thead>
<tr>
<th>Table 1: 5σ H I column density limits (cm⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>beam size &amp; velocity resolution</td>
</tr>
<tr>
<td>size</td>
</tr>
<tr>
<td>t = 10ʰ</td>
</tr>
<tr>
<td>1''</td>
</tr>
<tr>
<td>3''</td>
</tr>
<tr>
<td>10''</td>
</tr>
<tr>
<td>30''</td>
</tr>
</tbody>
</table>

- Things:
  - N(HI) 5σ (5km/s, 6'' = 500 pc) = 2.7e20at/cm²

- HALOGAS:
  - 120h: 5σ over 4.2 km/s at 30'': 5 x 10⁻¹⁸ cm⁻²

THINGS:

- N(HI) 5σ (5km/s, 6'' = 500 pc) = 2.7e20at/cm²

HALOGAS:

- 120h: 5σ over 4.2 km/s at 30'': 5 x 10⁻¹⁸ cm⁻²

3'' = 150pc@10Mpc: Resolve individual HI clouds

Comparable to deep GBT single dish observations, but at ~20 times better resolution

3'' = 150pc@10Mpc: Resolve the thick disk and test accretion models

1'' would require 1000h to map most HI in a disk (3.9e20at/cm²) with SKA1
SYNERGIES WITH NEARBY GALAXY SURVEYS

Multiwavelength surveys of nearby galaxies with strong Spanish involvement with importante synergies with the SKA

‣ Spitzer Survey of Stellar Structure in Galaxies (S4G, IRAC@Spitzer, 3.6 and 4.5μ), volume-limited (D < 40 Mpc) Nearby spiral, dwarf star-forming galaxies, ellipticals
  ‣ Synergies with SKA HI studies: outer regions of galaxies with deep mid-IR/optical and imaging (Knapen+ 2014):
    ‣ radial HI profiles in relation with truncation/antitruncation studies (e.g. Martín-Navarro+ 2012, Muñoz-Mateos+ 2013), detection of tails, shells (e.g. Laine+ 2014, 2015), presence of tidal debris in ETGs (Kim+ 2012)

‣ NUGA (NUclei of GAlaxies ) IRAM key project: nuclear fueling, (few tens pc) later extended to the outer discs (HI-NUGA, 16 galaxies with VLA, few tens kpc):
  complementarity ALMA - SKA
    ‣ Mapping the various spatial scales of the different instabilities (HI: outer; CO: inner): non-axisymmetric potentials, tidal interactions.

‣ Sabater+ 2015 250,000 galaxies from the SDSS: level of nuclear activity depends primarily on the availability of cold gas in the nuclear regions of galaxies, while large-scale environment and galaxy interactions only affect AGN activity in an indirect manner, by influencing the central gas supply.
CALIFA: IFU data of 600 galaxies. Stellar and ionized gas kinematics and metallicities, as well as a spatial resolved derivation of the full SF history (0.005 ≤ z ≤ 0.03)

Combined with SKA data: gas duty cycle, since it will connect HI with the SF processes and the SF and chemical enrichment histories of galaxies

Spatial resolved derivation of the full SF history + properties of ionized gas mapped @ 2”

SKA I-MID: HI @ 3” in 10h
Galaxies and their environments
HI as a privileged tracer of galaxy interactions (nature vs nurture)

- Inventory of detailed HI observations of galaxies in *environmentally selected samples* is growing, ranging from isolated galaxies to groups or clusters.
- Large HI data set in and around many galaxies in different environments will be a prime goal for the SKA

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### Table: GALAXIES AND THEIR ENVIRONMENTS

<table>
<thead>
<tr>
<th>Survey</th>
<th>Area (deg²)</th>
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<th>HI Resolution</th>
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<td>2''</td>
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<td>3000</td>
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<tr>
<td><strong>Targeted ISM</strong></td>
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<td>3000</td>
</tr>
<tr>
<td><strong>Galaxy/MS</strong></td>
<td>500</td>
<td>1418-1422</td>
<td>10''-1''</td>
<td>0 (0)</td>
<td>4,500</td>
</tr>
<tr>
<td><strong>Galaxy Abs</strong></td>
<td>(5000)</td>
<td>1418-1422</td>
<td>2''</td>
<td>0 (0)</td>
<td>(10,000)</td>
</tr>
<tr>
<td><strong>Absorption</strong></td>
<td>1000+</td>
<td>350-1050</td>
<td>2''</td>
<td>1 (3)</td>
<td>1,000+</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>200-350</td>
<td>10''</td>
<td>4 (6)</td>
<td>1,000</td>
</tr>
</tbody>
</table>
ISOLATED GALAXIES

- AMIGA (Analysis of the interstellar Medium of Isolated GAlaxies) sample
- **Lowest values** relative to any other sample of most variables:
  - LFIR, molecular gas, MH2/MHI, SFE, asymmetries, bulge/total ratio, radiocontinuum, nuclear activity, and
  - HI asymmetry (Espada+11a, but still some level of HI asymmetry exists), generated recently (~1e8 yr) and with no tails/interactions with currently observed minor companions (Espada+11b, Portas+11, Sengupta+12; Scott+14, Ramírez-Moreta et al in prep)

In AMIGA sample the **gas captured from companion galaxies and galactic fountain processes (due to SF and Active Galactic Nuclei, AGN) are minimized**

**Privileged environment to study cold gas accretion**

See later
The HI scaling relations of isolated galaxies had not been updated since 1984.

These relations provide an up-to-date metric of HI-normalcy of isolated galaxies.

They are more self-consistent than previous relations and also include a complete treatment of non-detections and uncertainties.

Reference for the HI content of galaxies in other environments.
In the other extreme of galaxy environments, atomic gas is missing...

- Single dish study of 72 Hickson Compact Groups (Verdes-Montenegro et al 2001)
  HI deficiency of groups similar to Virgo or Coma clusters
- VLA study of 26 Hickson Compact Groups (Verdes-Montenegro et al 2001, 2007)

**Proposed evolutionary model:**

- Amount of detected HI decreases further with evolution, by continuous tidal stripping
- Low statistics to study correlation between tails and HI def.

**Phase 1:** Most gas in galaxies

**Phase 2:** Gas in tidal features

**Phase 3:** No HI in the galaxies

*VLA data (C+CnB+D) 5e19 cm$^{-2}$ at 20'' & 10 km/s*
Hickson Compact Groups

HI observations of 22 HCGs with GBT (1 pointing/group, Borthakur+ 2010, 2014)

- HI deficiency reduced but not completely eliminated
- **A diffuse HI component** missed by the VLA

- More consistent with tidal stripping than with ram-pressure
- Spread over > 1000 km/s
- Increasing with evolutionary stage
- HI excess mass bimodal: suggests rapid transition from HSB to LSB

- Most cases: filling factor << 100% == faint to be detected with VLA
- High filling factor cases == resolved extended structures

VLA data (C+CnB+D)
5e19 cm$^{-2}$ at 20$''$ & 10 km/s

SKA1-MID, 10h:
1.3e18 cm$^{-2}$ at 30$''$ and 5 km/s.
FOV 30$'$
Improve statistics to study correlation between mass in HI tidal structures (VLA cubes) and HI deficiency (GBT single dish).

Verdes-M, Yun, Borthakur, archive

**SKA1** expected to provide the needed $N(\text{HI})$ limit, UV coverage, FOV to map the diffuse gas ($6 \times 10^{18}$ cm$^{-2}$ @ 30” & 20 km/s, Blok et al 2014)

HCG 16

Hickson Compact Groups

Hess et al 2017

X3D pathway, Vogt et al 2015
Improve statistics to study correlation between mass in HI tidal structures (VLA cubes) and HI deficiency (GBT single dish).

SKA1 expected to provide the needed N(HI) limit, UV coverage, FOV to map the diffuse gas ($6 \times 10^{18}$ cm$^{-2}$ @ 30" & 20 km/s, Blok et al 2014).

HCG 44
Hess et al 2017
Star formation beyond the optical disc and cold gas accretion
SF BEYOND R25 AND COLD GAS ACCRETION

- 1/3 of galaxies show unusually extended HI distributions (e.g. Bosma 1981, Huchtmeier 1982).
- **GALEX** (Martin+ 2005) showed **SF far beyond the optical radius** of galaxies (Thilker+ 2005, Gil de Paz+ 2005, Erroz-Ferrer+ 2013), with good spatial correlation with the HI component (e.g Espada+ 2011).
- Comparing UV and HI: study of the Kennicutt- Schmidt law in the extreme low-density and often low-metallicity environments of the outskirts.
SF BEYOND R25 AND COLD GAS ACCRETION

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- Comparing UV and HI: study of the Kennicutt- Schmidt law in the extreme low-density and often low-metallicity environments of the outskirts.
- SKA:
  - It is possible to trigger SF in very low-density gaseous environments?
  - How galaxies acquire sufficient gas to sustain SFR: If gas accretion from the IGM is the dominant process by which galaxies acquire their gas, then it must happen below the current observational limit for the HI column density N(HI) \( \sim 10^{18} \text{ cm}^2 \).
  - Consistent with the study of cosmological hydrodynamic simulations by Popping+ (2009). In the filaments N(HI) decreases well below \( 10^{18} \text{ cm}^2 \), making them only accessible to SKA.

AMIGA sample the gas captured from companion galaxies and galactic fountain processes are minimized: Privileged environment to study cold gas accretion.
SF BEYOND R25 AND COLD GAS ACCRETION

› ASKAP: IMAGINE Imaging Galaxies Intergalactic and Nearby Environment
› PI: Attila Popping 28 spiral Galaxies and their direct environment
  ▶ 8 most compact ATCA configs Total time 2688 hours
  ▶ • NHI~2.5x10^{17} cm^{-2} over 20 km s^{-1} resolution 1’ to 2.5’ NGC2997

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de blok &oa 2016
Additional HI science

Multi-resolution mapping studies of the ISM in our Galaxy

HI absorption studies out to the highest redshifts

Farnes+16

Dutta+16

McClure-Griffiths et al, 2015, PoS, AASKA14, 130
HI EVOLUTION WITH REDSHIFT

- So far only few hundred galaxies detected in HI beyond the local Universe.
- Resolved HI kinematics + morphology of $\sim 10^{10} M_\odot$ galaxies out to $z \sim 0.8$:
  - Mass Assembly, baryon cycle; DM dependencies
  - HI mass function
- JVL A CHILES (PI. van Gorkom)
- 1000hr, $\sim 300$ galaxies at $0 < z < 0.5$
- Most distant detection of 21-cm line emission at $z = 0.376$
  - Large starbursting galaxy rich in HI & H2 gas ($M_{HI} = 3 \times 10^{10} M_\odot$)

What about HI???

CHILES
coSMOS HI Large Extragalactic Survey

Lookback time (Gyr)

Madau & Dickinson 2014
As nicely expressed by T.J. Cornwell and R.A. Perley in 1991, in order to motivate a km² Hydrogen Array:

“A volume of the ’Encyclopaedia of the Universe’ is written in 21 cm typescript. Unfortunately the printing is rather faint and we need a large ’lens’ to read the text!”