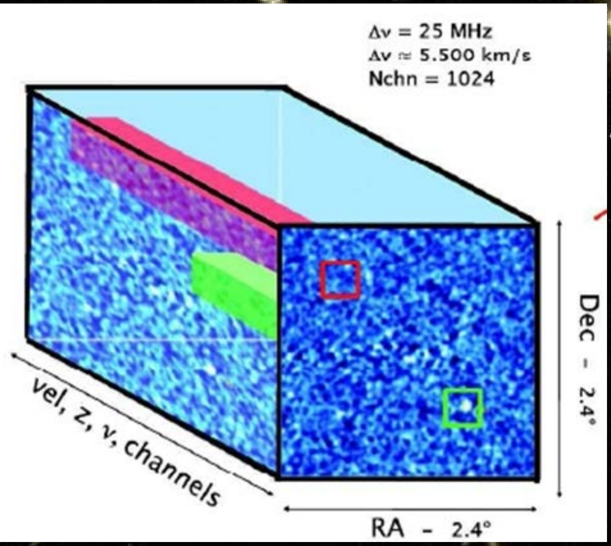
The Power and Promise of 21 cm HI line Surveys

Martha P. Haynes
Cornell University



Clues from the HI line

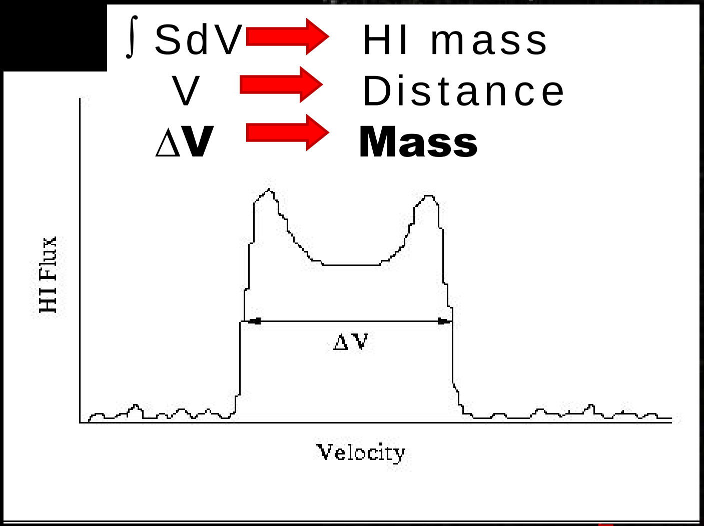
Easy to detect, **simple physics** ➔ cool gas mass

- Redshifts (=> distances via Hubble's Law)
  - BAO/Intensity mapping
- HI mass and distribution (extended objects)
  - Good index of star formation fertility
  - Can be dominant baryon form in low mass galaxies
  - Comparative HI content => HI deficiency
  - Tracer of interaction/tides/mergers
- Rotation velocities/curves
  - Tracer of host dynamics ➔ dark matter
  - Redshift independent distances ➔ (B)TF relation
- HI absorption: optical depth
  - Link to Ly-a absorbers
  - Fundamental constant evolution

- Comparison with stellar mass growth
- Large statistical samples… maps of resolved sources (future)

HI in M31

Credit: R. Braun



HI Radio Surveys: Considerations

HI survey "figure-of-merit" depends on:

- Collecting area
- Angular resolution
- Field-of-view
- Number of beams (pixels)
- Bandwidth (redshift coverage)
- System noise

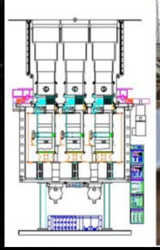
HI survey challenges:

- Radio frequency interference (RFI)
- Source confusion (Jones+ 2015a, 2015b)
- Computational requirements

Possibility of commensal surveys

- OIR: Count photons
- Radio: Detect waves (amplitude+phase)

Giovanelli & Haynes
2015 A&Arv 24, 1

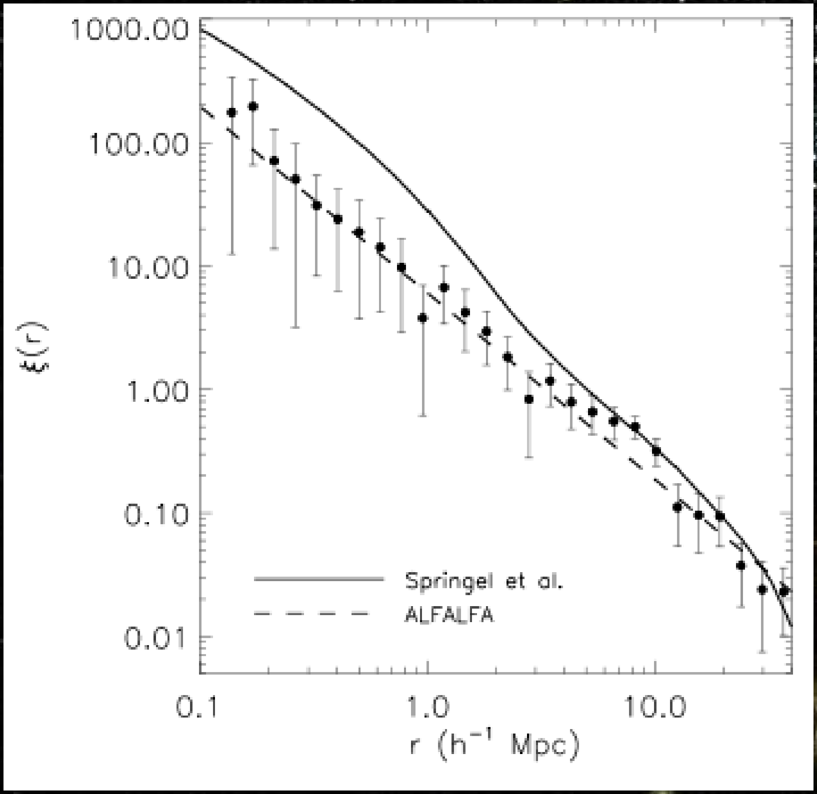


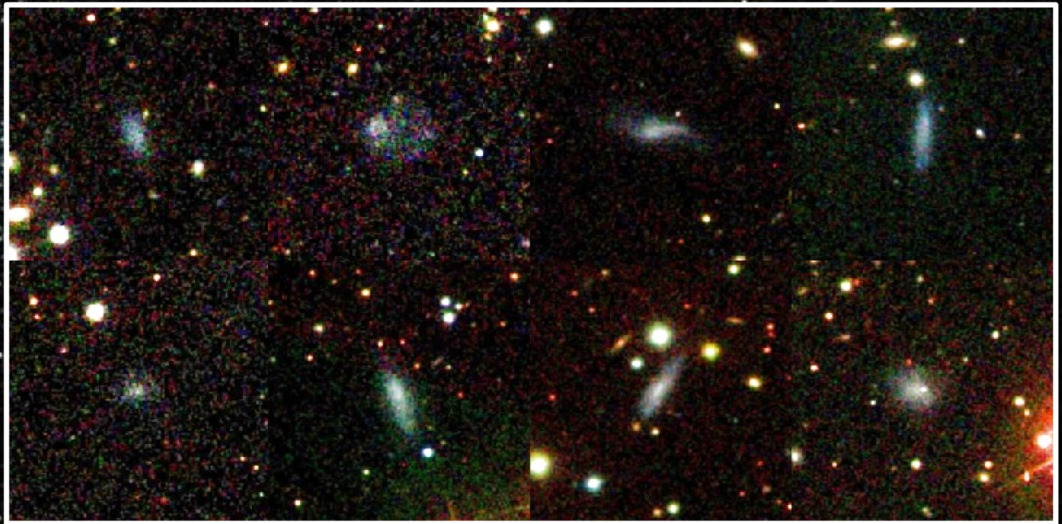

Arecibo Legacy Fast ALFA survey

- Designed specifically to determing the HI mass function, correlation function and velocity width function over a cosmologically significant volume.
- Covered 7000 sqd of high |b| sky out to z < 0.6 with 5.5 km/s resolution in 4400 hours of telescope time 2005-2011
- Final catalog contains 31,500 extragalactic HI sources (Haynes+ 2018 ApJ 861, 49) plus 2100 high velocity HI clouds (probably Galactic)
- Spectral stacking to dig deeper for selected populations.
- OHMs at z: (0.16-0.24)
- Strong educational component
    - 21 PhD dissertations, 10 from Cornell
    - >200 undergraduates working with the Undergraduate ALFALFA Team (consortium of 19 principally undergraduate institutions in US and Puerto Rico)

HI-selected ALFALFA population

The HI population is **much less clustered** on small scales, but follows the DM on large scales.





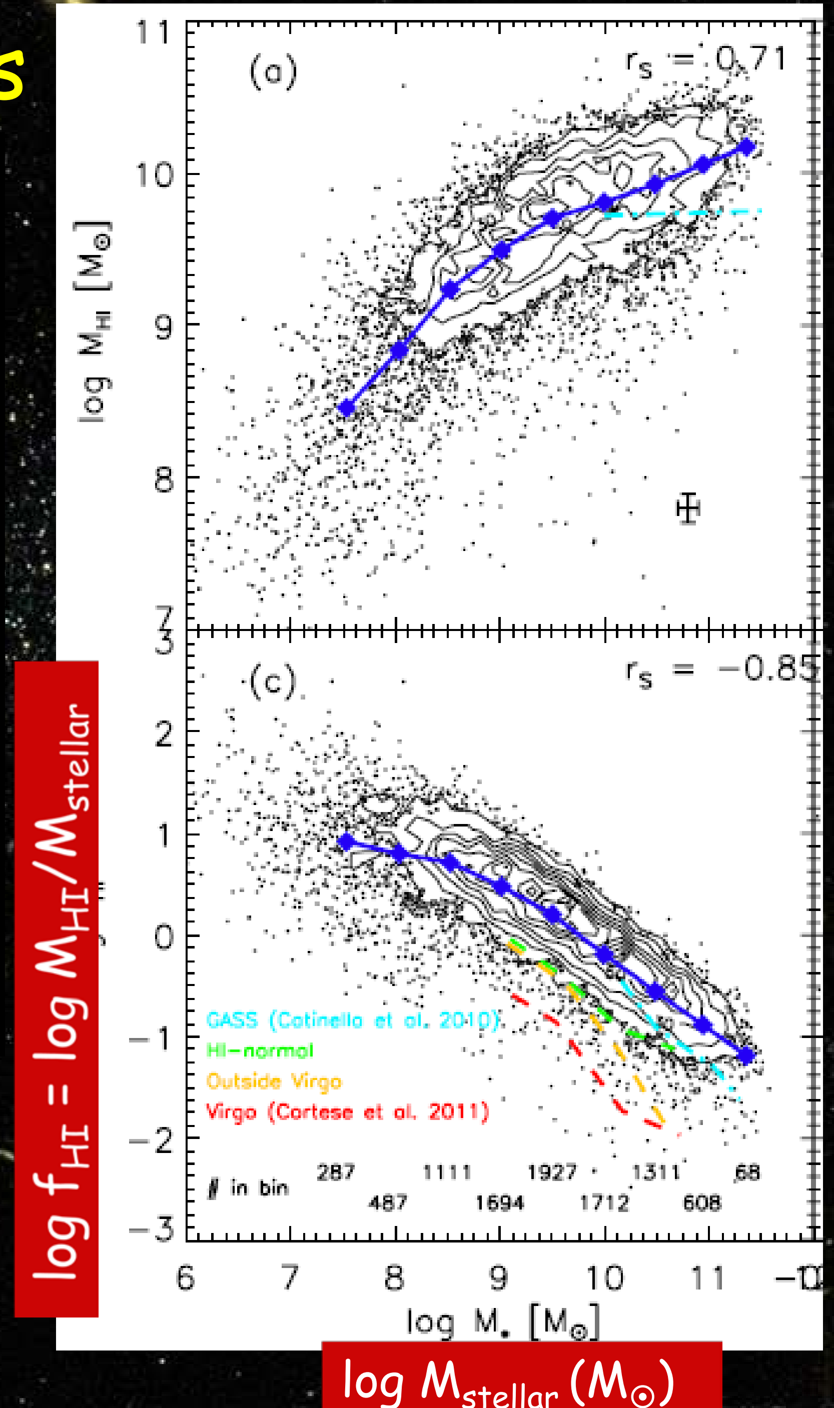
The HI population is **least clustered known =>** environmentally-driven processes are minimized.

Martin + (2012) Ap J 750, 38

HI-stellar scaling relations

Virtually all SF galaxies contain HI but the red sequence galaxies contain (none).

- HI fraction falls as the stellar luminosity/mass increases
- Low luminosity SF galaxies are HI-dominated (more mass in HI than in stars)
- Increased scatter and break in slope of M_{HI} versus $M_{stellar}$ relation (and also f_{HI}) below $M_{stellar} \sim 10^{9}\ M_{\odot}$
- HI represents the fuel reservoir for future star formation.

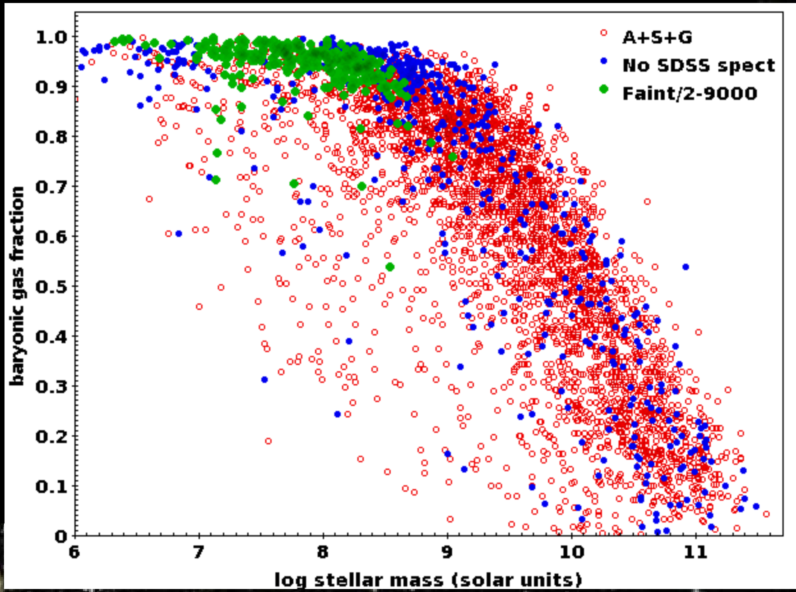


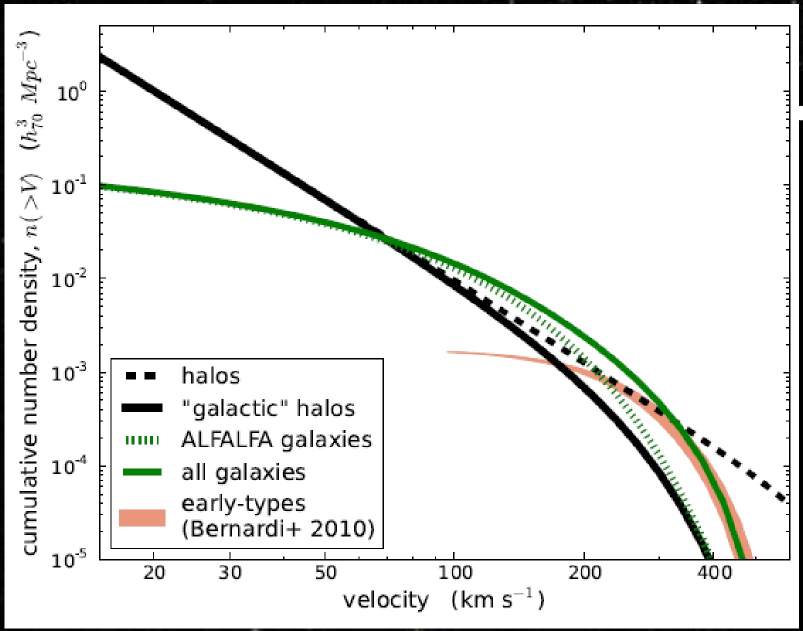
Huang+(2012b) ApJ 756, 113

IAU 2018

Low mass galaxies: Insights from ALFALFA

- At low M_{star}, the baryonic gas fraction $M_{HI} / (M_{HI} + M_{star})$ approaches 1.
- Many low HI mass dwarfs are LSB and patchy, so their stellar masses are uncertain.
- How does the V_{rot} measured by HI map to the V_{circ} of the DM halo?

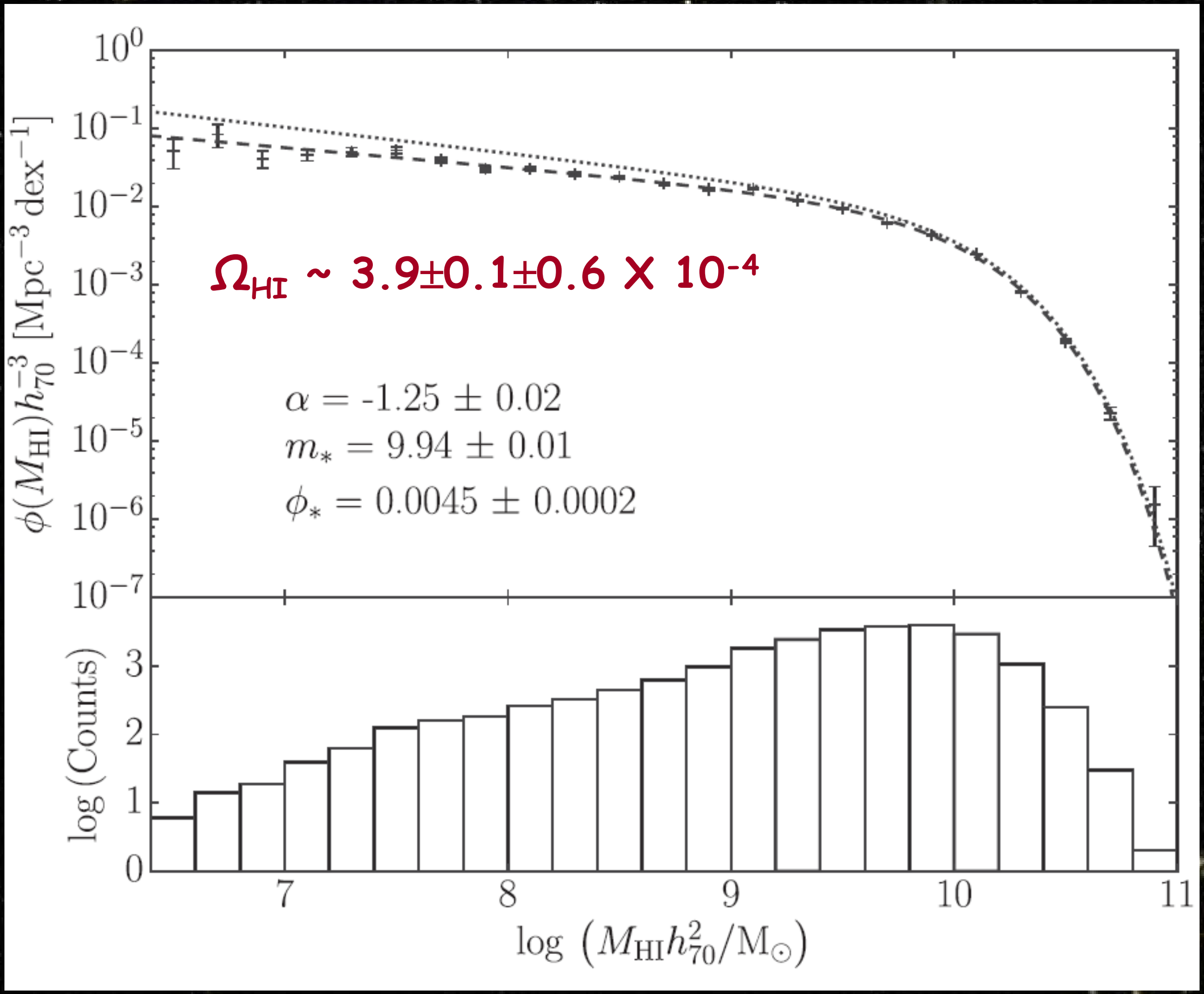




- The cumulative number density of ALFALFA galaxies at low velocities ("velocity function") does not match the predictions of numerical simulations of low mass halos => astrophysics?

Papastergis+ 2015, A&A 574, 113
Papastergis & Shankhar 2016 A&A 591, 58
Brooks+ 2017 ApJ 850, 97

HI Mass Function from ALFALFA



Martin+ 2010 ApJ 723, 1359

Hess & Wilcots, 2013 AJ 146, 124

Moorman+ 2014 MNRAS 444, 3559

Moorman+ 2016 ApJ 831, 118

Jones+ 2016, MNRAS 457, 4394

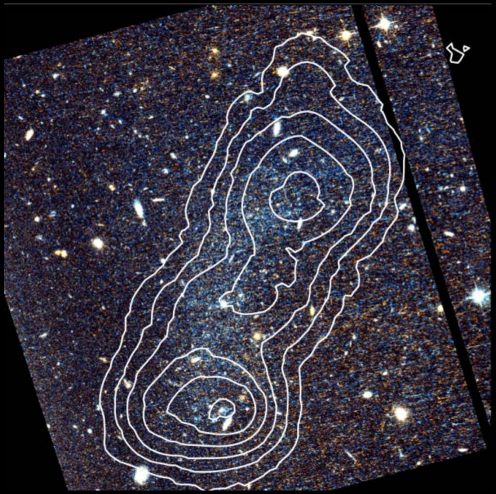
Jones+ 2018, MNRAS 477, 2

- Evidence that Local Volume may not be representative => need more surveys!

ALFALFA: Are there "dark galaxies"?

- In agreement with previous results, ALFALFA finds that fewer that 2% of (clearly extragalactic; not ALFALFA UCHVCs) HI sources cannot be identified with an optical counterpart.
- The majority of objects without OC's are found near to galaxies with similar redshifts.

Dark galaxies:
The burden is always on us to prove that
(1) the HI signal is real
(2) there is no OC even at LSB
(3) the HI is not tidal in origin
(4) not an OHM at z~0.2



Coma P Ball+ 2018 WSRT /VLA on HST

ALFALFA "(Almost) Dark" galaxies project
- Jones+ 2018 A&A 614, 21
- Ball+ 2018, AJ 155, 65
- Leisman+ 2017 ApJ 842, 133
- Janowiecki+ 2015, ApJ 801,96
- Cannon+ 2015, AJ 149, 72

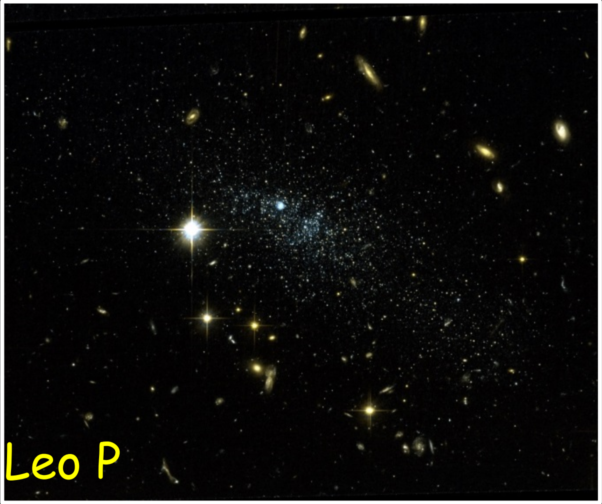
- Why has their gas not formed stars?
- What are the HI-bearing Ultra Diffuse Galaxies

Probing the Lowest HI Masses

- UCHVCs Giovanelli+ 2011; Adams+ 2013, 2015a,b; Janesh+ 2015
  - Overlap with Galactic velocities, no OC, do not violate astrophysical constraints (Sternberg + 2002)
  - Deep optical imaging to look for optical counterparts
- SHIELD Cannon+ 2011; McQuinn+ 2014, 2015a; McNichols 2016, Teich 2016
  - log M_{HI} < 7.2 (but with distance uncertainties)

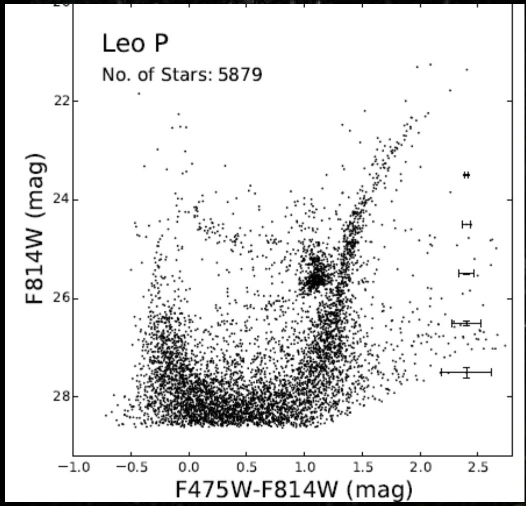
Leo P Giovanelli+ 2013; Rhode+ 2013; Skillman+ 2013; McQuinn+ 2013; Berstein-Cooper+ 2014; McQuinn+ 2015b; McQuinn+ 2015c

- Discovered as UCHVC with possible OC
- Reclassified as SHIELD galaxy when OC confirmed



- D = 1.62 Mpc; isolated
- M_V = -9.27; single HII region
- $M_{star} = 5.6 \times 10^5\ M_\odot$
- $M_{HI} = 8.1 \times 10^5\ M_\odot$
- SFR(Hα) = $4.3 \times 10^{-5}\ M_\odot$/yr
- 12+log(O/H) = 7.17 (3% solar)

What a dSph would look like in isolation (so retains gas)???



The z~0 HI population from ALFALFA

- HI blind surveys do not "see" the "red sequence" or the cores of rich clusters (HI deficiency)

- HI-selected galaxies are the least clustered population.
- The ALFALFA population is typically bluer, of lower metallicity and lower extinction, consistent with having extended disks and lower SFEs.
- Galaxies with higher HI fraction are hosted in halos with higher spin λ.
- HI dominates the (visible) baryons in low mass galaxies.
- Some of the dwarfs are nearly dormant : could there be a population of low mass dwarfs with stellar/gas contents so low that we don't see them except when they accrete a small amount of gas and form a few stars (Leo P)? =>
  "Vanishing Cheshire Cat" (Salpeter & Hoffman 1995 ApJ 441, 51; Kormendy & Freeman 2016, ApJ 817, 84)

Questions for future HI Surveys

- How does Ω_{HI} and the HIMF evolve with cosmic time and how does that variation reflect the buildup of stellar mass and consumption of molecular gas, especially at the peak of the SFR(t)?
- What is the slope α of the HIMF at the lowest masses? Does it depend on environment?
- What are the total masses of the DM halos which host the lowest mass HI-bearing galaxies?
- How do galaxies accrete HI? From where? How important is astrophysical feedback? How do galaxies of the lowest masses retain any baryons? How do stars form at very low gas density?
- Is there a missing population of "dormant galaxies" that are "Too Shy to Shine" most of the time?

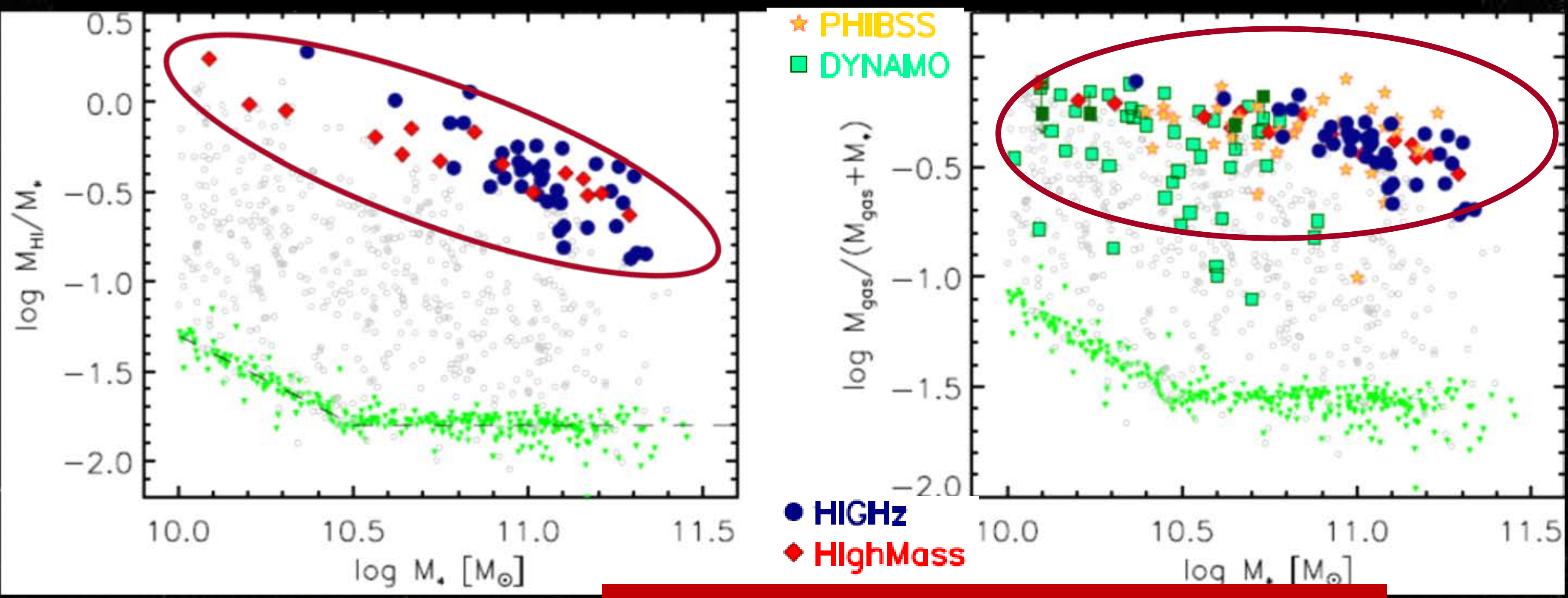
HI content at higher z: first results

BUDHIES/WSRT (Verheijen+ 2007; Jaffe+ 2015)
- Fields of clusters A963 and A2192 at z ~ 0.2

GMRT/A370 and COSMOS (Lah+ 2009, Rhee+ in prep)
- Fields of A370 and COSMOS at z ~ 0.35
- Stacking used to derive average properties

HIghZ (Catinella & Cortese 2015, MNRAS 446, 3526)
- Individual SDSS targets @ Arecibo, z = 0.1 to 0.26
- Similar to most massive, high gas fraction ALFALFA galaxies

Future surveys will trace HI over cosmic time

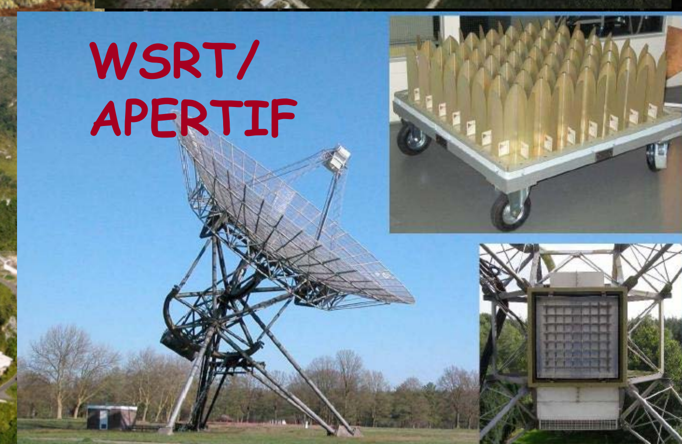


Huang+ 2014; Hallenbeck+ 2014 ALFALFA

The Promise of Future HI Surveys

Revolution in survey technology:

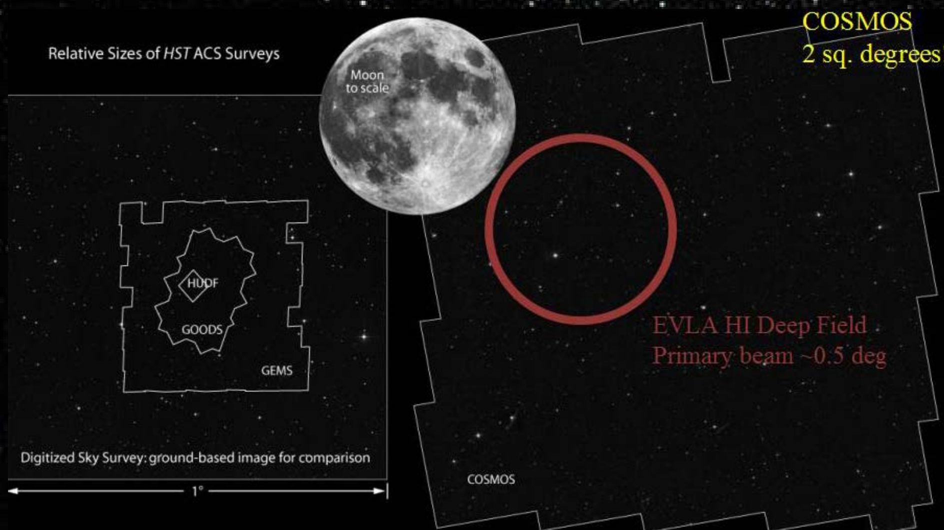
- New facilities: ASKAP, MeerKAT, FAST
- New technologies for existing facilities: VLA, WSRT, Arecibo, GBT
- Collecting area, bandwidth, field-of-view/simultaneous beams

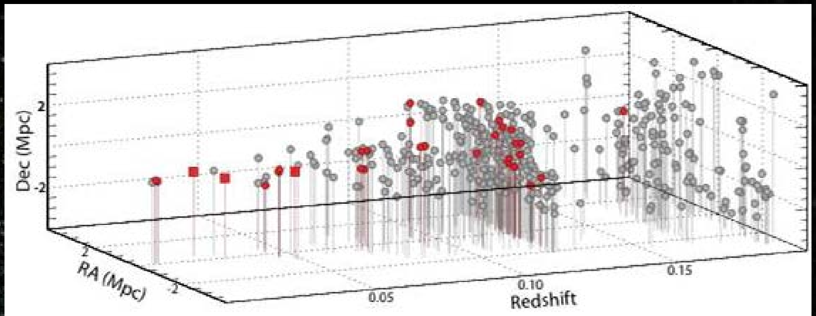


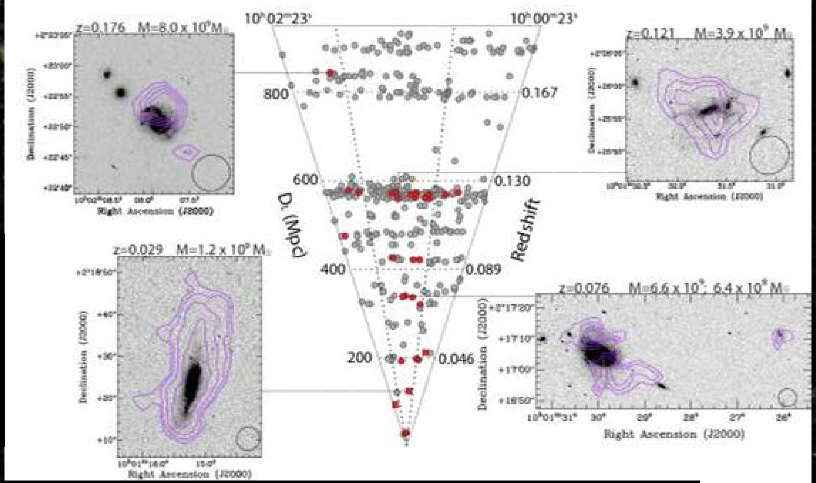
CHILES: (J. vanGorkom, PI)

On-going survey of COSMOS field with **VLA-B** (1000 hours)

- Deep survey to z ~ 0.45 with 5" resolution







Fernandez+ 2016ApJ...824L...1F

- HI and CO in massive starburst at z =0.35 => ***MUCH MORE TO COME!***

Fernandez+ 2013
2013ApJ...770L..29F

Commensal surveys:

- CHILES Verdes (L. Chomiuk, PI): transients
- CHILES Con Pol (C. Hales, PI): continuum/full polarization

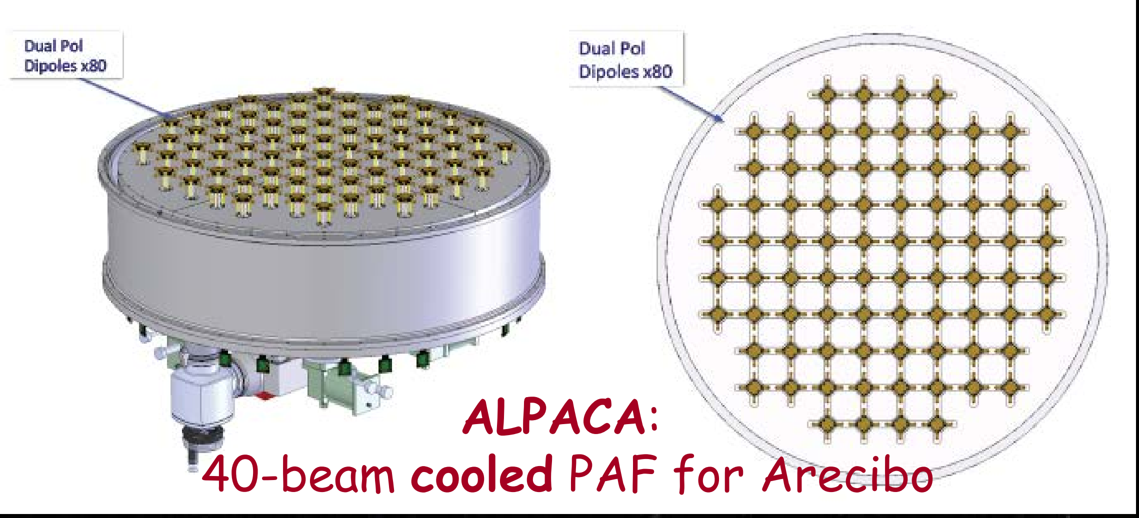
Revolution in Radio Arrays

Interferometer arrays

- Many dishes used
  - "Large N, small D"

Square Kilometre Array

- Pathfinders (2018-)
- Phase I (~2023)
- Full SKA (~2030)



ALPACA: 40-beam **cooled** PAF for Arecibo

Phased Array Feeds:

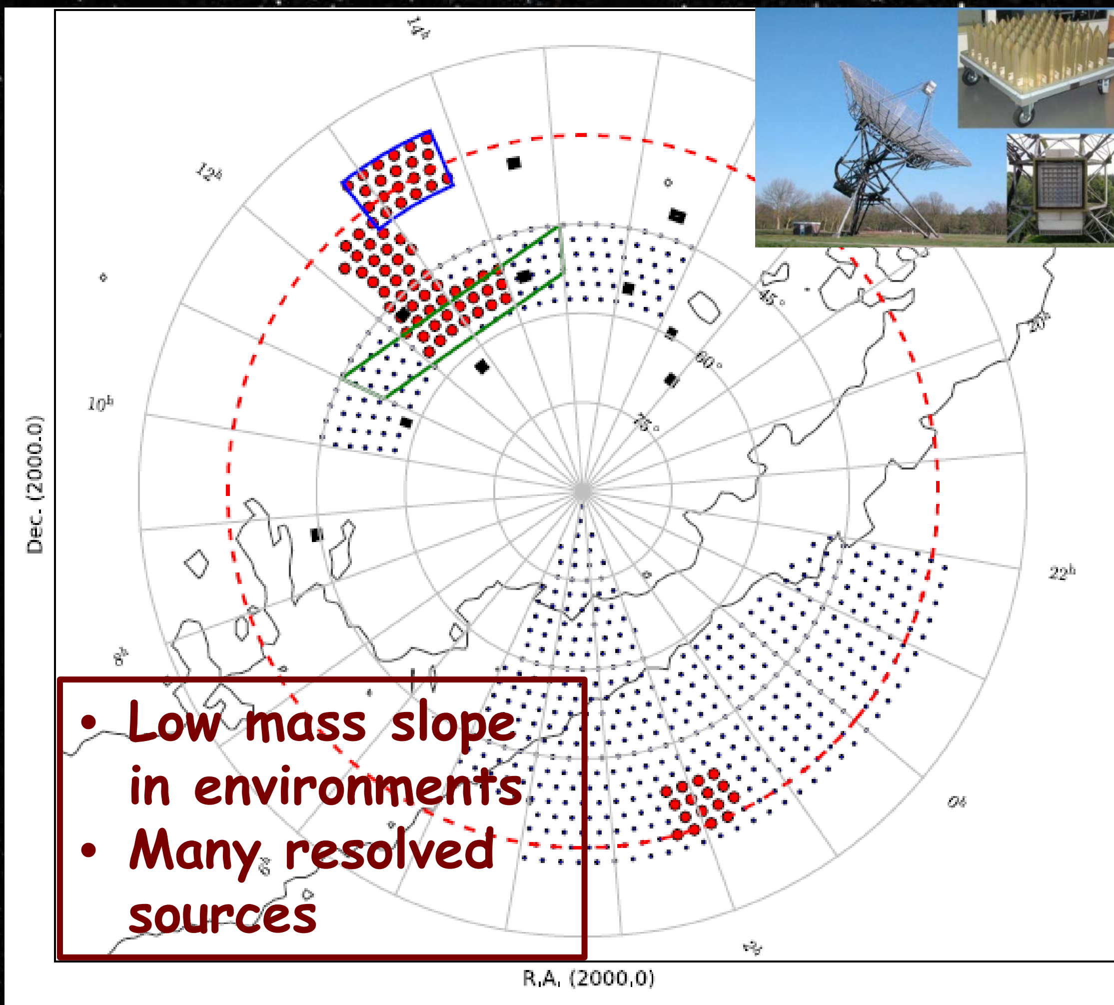
- Closely packed antenna elements sense EM field across the focal plane; outputs then combined coherently to synthesize many discrete beams => "beamformer "

Single dishes + multi-beam

- Collecting area for point-source sensitivity + sky coverage with multi-beam technology but relatively low angular resolution
  - Advantages:
    - Deep spectro-photometric (full-flux) source catalogs
  - Disadvantages:
    - Source confusion (increases with distance)
    - Susceptibility to radio frequency interference
- Deep surveys of local universe for low mass objects (e.g., Leo P analogs)
  - **Need** large solid angle to sample sufficient volume
- Local peculiar velocity surveys via BTFR
- Intensity mapping over redshift to trace evolution of large scale structure

WSRT/APERTIF

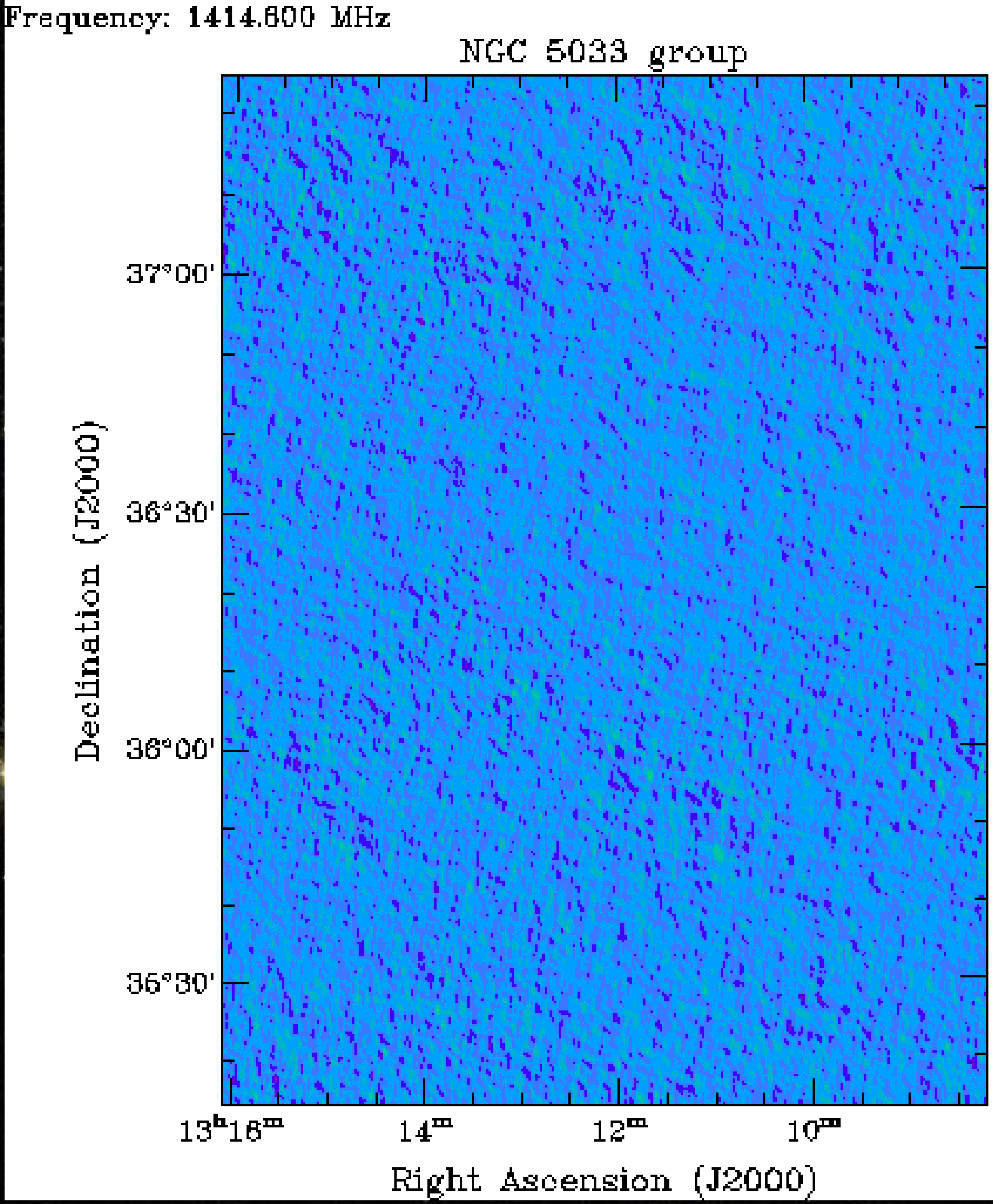
T. Oosterloo, M. Verheijen, E. deBlok PIs



- Low mass slope in environments
- Many resolved sources

- Existing WSRT array outfitted with PAFs:
- Resolution 15″ x 15″cos(Dec)
- Targeted regions (SDSS, MANGA targets, Het-Dex) to z=0.256
  - Shallow (black dots):
    - 3500 deg^2; 1 x 12^h
    - Complement to ASKAP/ WALLABY
  - Medium-deep (red dots)
    - 450 deg^2; 7 x 12^h
- Several LOFAR-selected fields of 10 deg^2; 4 x 12^h

APERTIF: First results



http://www.astron.nl/dailyimage/pictures/20171113/cube3.gif

Credit: Tom Oosterloo

ASKAP HI surveys

- 36 x 12m antennas + phased array feeds
  => Wide instantaneous FoV
- Angular resolution limited by computation

Strength: Wide Field-of-View

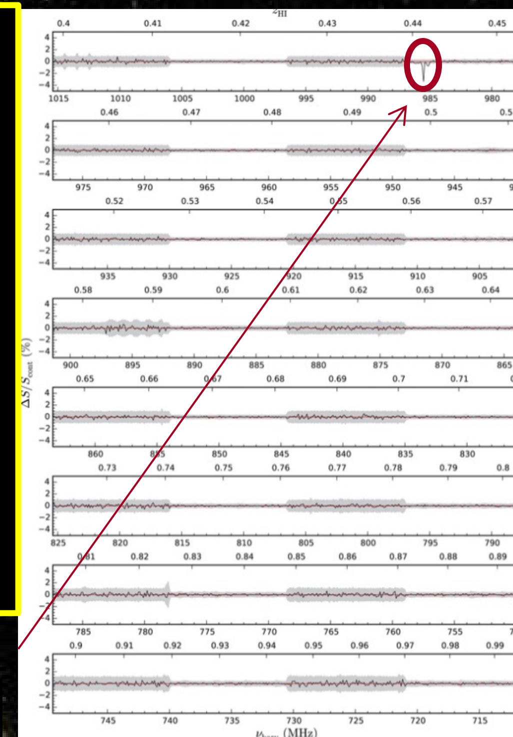
WALLABY
- 30000 deg^2 at 30″ resolution to z = 0.26

DINGO-DEEP
- 150 deg^2 at 10″ resolution to z = 0.26
- GAMA region

DINGO-UDEEP
- 60 deg^2 at 10″ resolution to z = 0.43
- GAMA region

FLASH
- HI absorption towards continuum sources over 0.5 < z < 1.

- Large catalog → HIMF
- Many resolved galaxies
- Stacking



The 711.5–1015.5MHz BETA spectrum towards PKS B1740-517, averaged over our three observing epochs. An absorption line is visible in the spectrum at a redshift of z = 0.4413. Credit: Allison, et al.

Allison+ 2015
Absorption line at z=0.44

MeerKAT HI surveys

- Broad bandwidth (more range in z)
- 64 x 13.5 m + single beam receivers
- Angular resolution of 12"

Strength: Deep surveys

MHONGHOOSE (de Blok, PI)

- 30 x 0.8 deg^2 at 12" resolution to z = 0.26
- Targeted fields of 30 nearby galaxies to very low HI column density: accretion/outflows

  (Carignan talk at IAU S344)

Fornax (Serra, PI)

- 11 deg^2 at 10" resolution to z = 1.4

LADUMA (Blyth, Hollewerda, Baker, PIs)

- 4 deg^2 at 10" resolution to z = 1.4
- ECDFS

MALS (Gupta, Srianand, PIs)

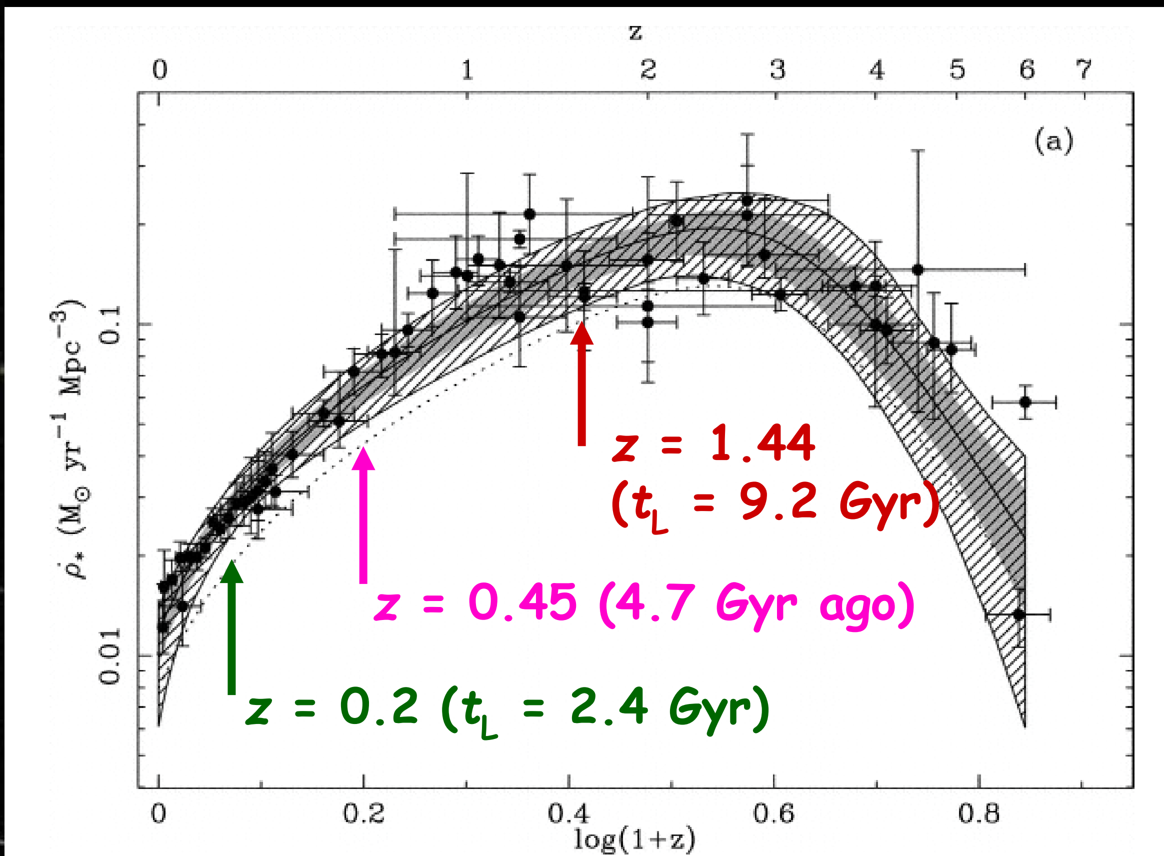
- HI absorption towards continuum sources to z < 1.8

Fornax
P. Serra

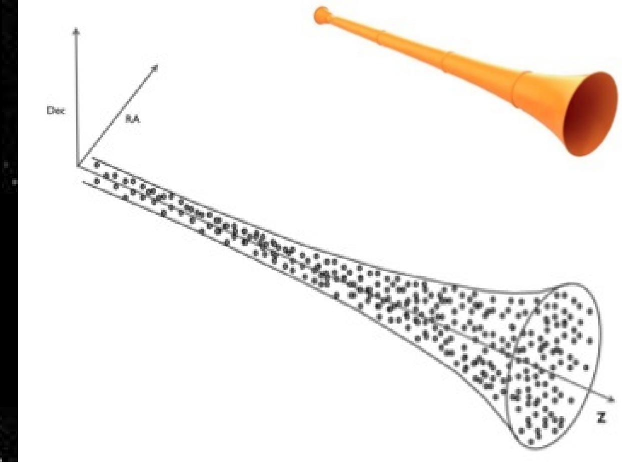
LADUMA

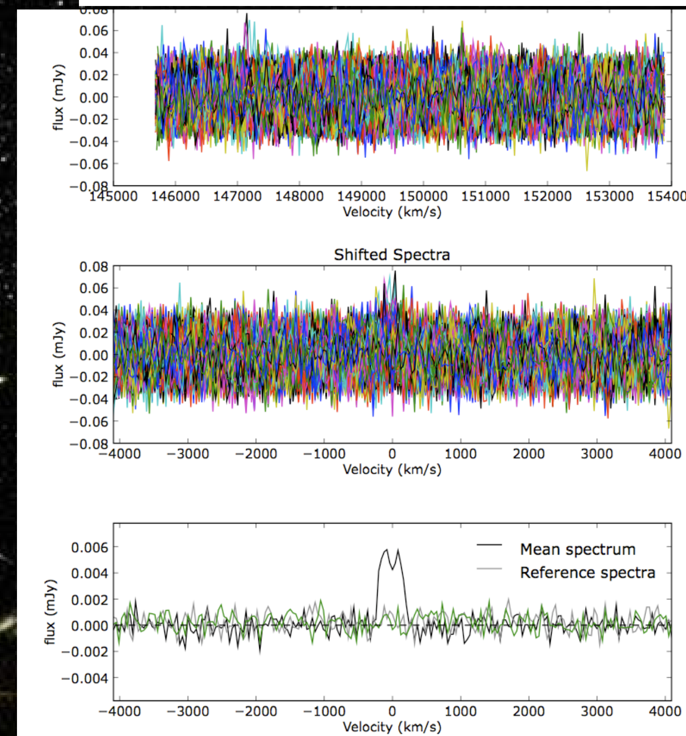
(S. Blyth, A. Baker, B.Holwerda PIs)

- Deep (3300 hours) on ECDFS field to z = 1.44
- 4 deg^2 at 12″ resolution
- Several thousand detections at 5σ



Hopkins & Beacom (2006)





Stacking of populations

HI surveys: Promising Prospectus

- HI is the fuel for future star formation => the availability of this fuel drives galaxy evolution
- For many/most scientific purposes, the HI must be understood in context along with the consumption of the molecular supply to build up the stellar content and with the dark matter.
- The HI-selected population is very biased. But so is ANY population selected by one constituent. We need to understand their interrelationships.
- We are on the verge of a new generation of HI surveys.
  - Deeper wide area spectro-photometric surveys of very local universe with big dishes for sheer sensitivity.
  - Surveys tracing evolution over cosmic time.
  - Interferometer arrays resolve galaxies => HI distribution, velocity fields for many 1000s of galaxies

A new era of HI surveys is upon us!