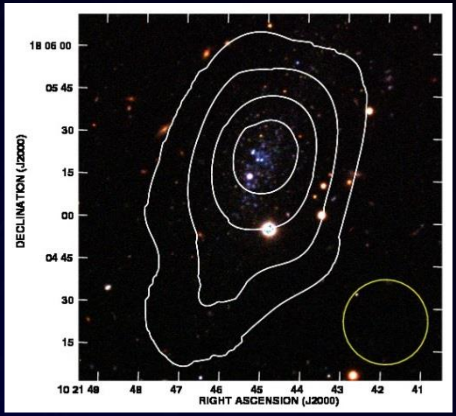
Prospects for Extragalactic HI Line Studies with Large Single Dishes

… and a few lessons from the *Arecibo Legacy Fast ALFA* (ALFALFA) Survey



Martha Haynes
Cornell University

3rd U.S.-China Workshop
Green Bank
May 20, 2014

Surveys: A "golden age" for HI science

Single dish:

2000's : HIPASS (Parkes)
2005- : ALFALFA (Arecibo), EBHIS (Effelsberg), GASS (Arecibo; targeted, not blind)

Synthesis:

THINGS, LittleTHINGS, VLA-ANGST, VIVA, SHIELD
ATLAS-3D (WSRT; ETGs also observed optically)
CHILES (VLA pilot higher redshift)

And even more to come..!

ALFALFA

Arecibo Legacy Fast ALFA Survey

- One of several major surveys undertaken at Arecibo, exploiting its ALFA multibeam capability
- An extragalactic spectral line survey (mainly HI)
- Covers ~7000 sq deg of high galactic latitude sky
- 1345-1435 MHz (-2000 to +17500 km/s for HI line)
- 5 km/s resolution (100 MHz/4096 channels)
- 2-pass, drift mode (total int. time per beam ~ 40 sec)
- ~2 mJy rms (per spectral resolution element)
- 4400 hrs of telescope time; 99% "open shutter" time
- Started Feb 4, 2005; completed Oct 26, 2012
- 59 (published) + 5 (submitted) refereed papers to date
- 11 PhDs completed; 9+ underway; + Undergrad ALFALFA Team
- An "open collaboration": let's do science!

http://egg.astro.cornell.edu/alfalfa

ALFALFA

ALFALFA: A 2nd generation HI survey

- In comparison with opt/IR, the HI view is largely immature

ALFALFA:

- Designed to explore the HI mass function over a cosmologically significant volume
  - Higher sensitivity than previous surveys
  - Higher spectral resolution => low mass halos
  - Higher angular resolution => most probable optical (stellar) counterparts
  - Deeper: 3X HIPASS median redshift => volume
  - Wider area than surveys (other than HIPASS) => nearby volumes for lowest M_{HI} => cosmologically significant volume

We're here to talk about the 3rd generation!!!!!!!!!!!

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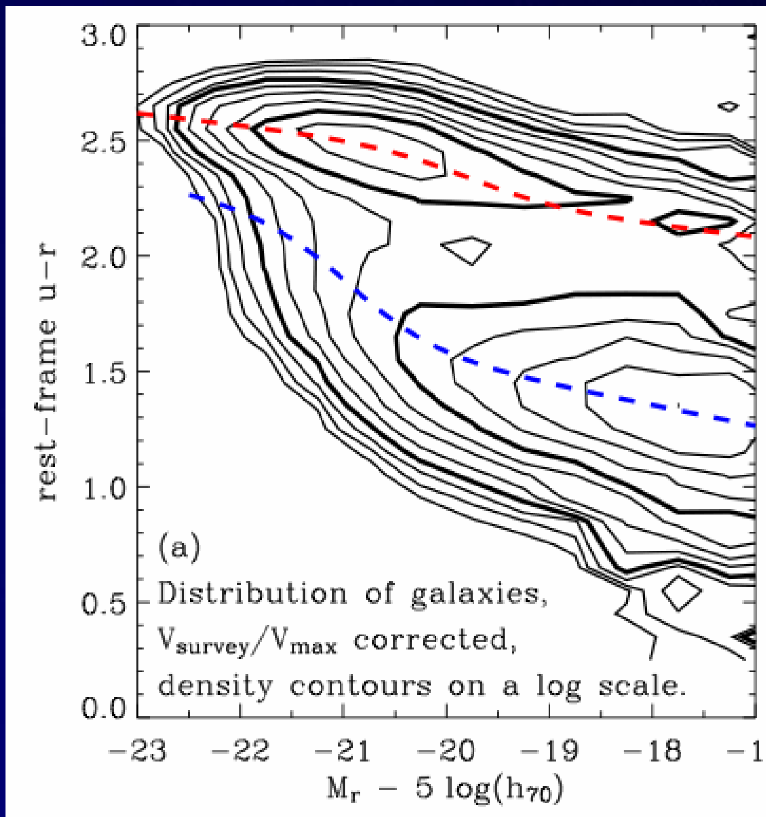
3rd generation

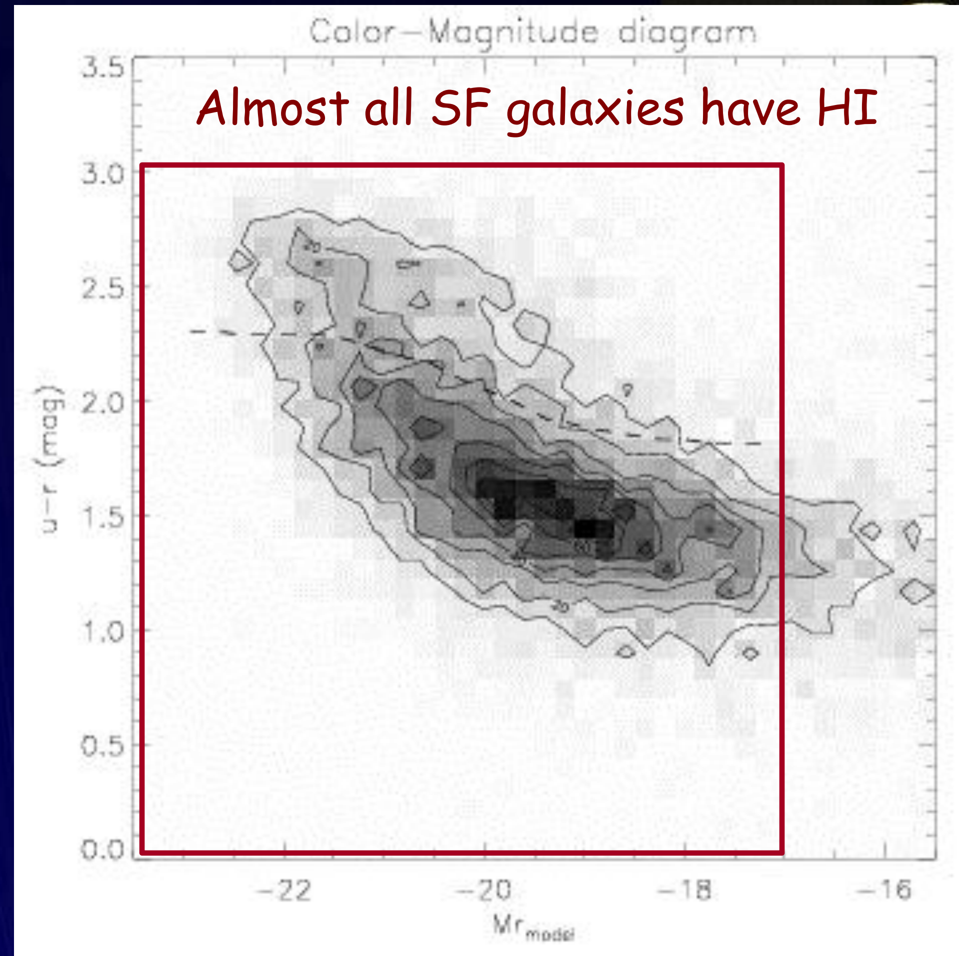
MUCH MORE DEMANDING THAN ALFALFA

The ALFALFA galaxy population

- Star-forming galaxies but **not** the red sequence



Optical (SDSS) galaxies
Baldry+ 2004

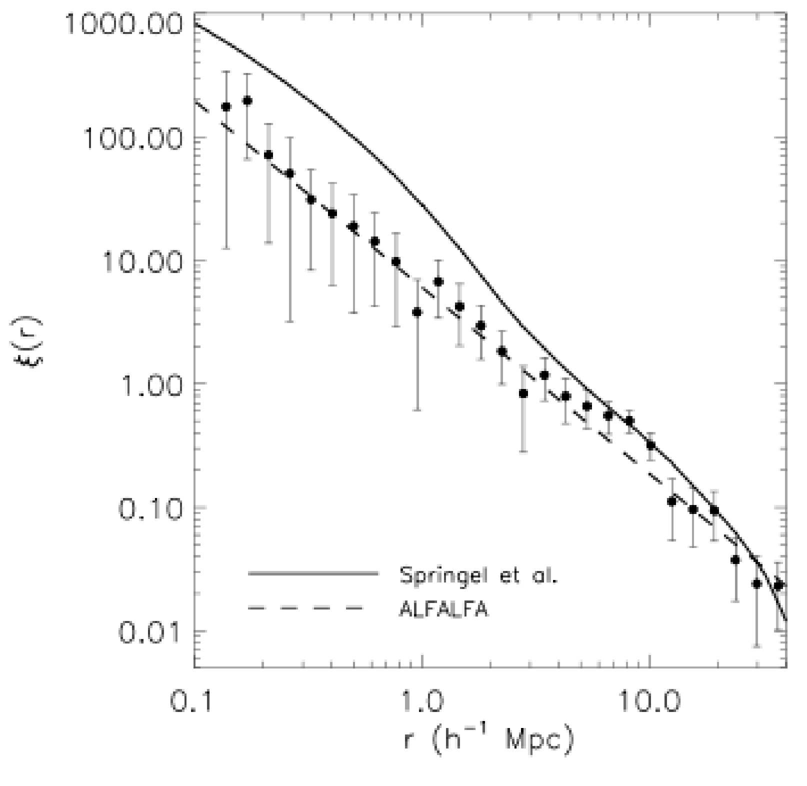


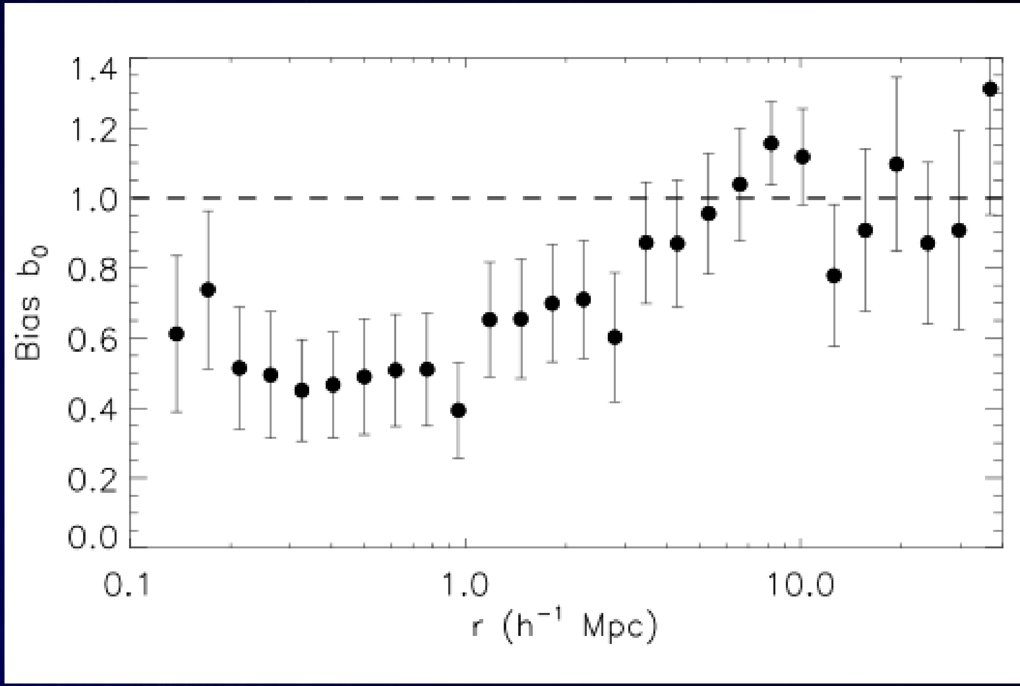
Shan Huang (Cornell) PhD thesis
Huang+(2012b) ApJ 756, 113

ALFALFA

HI-selected ALFALFA population

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

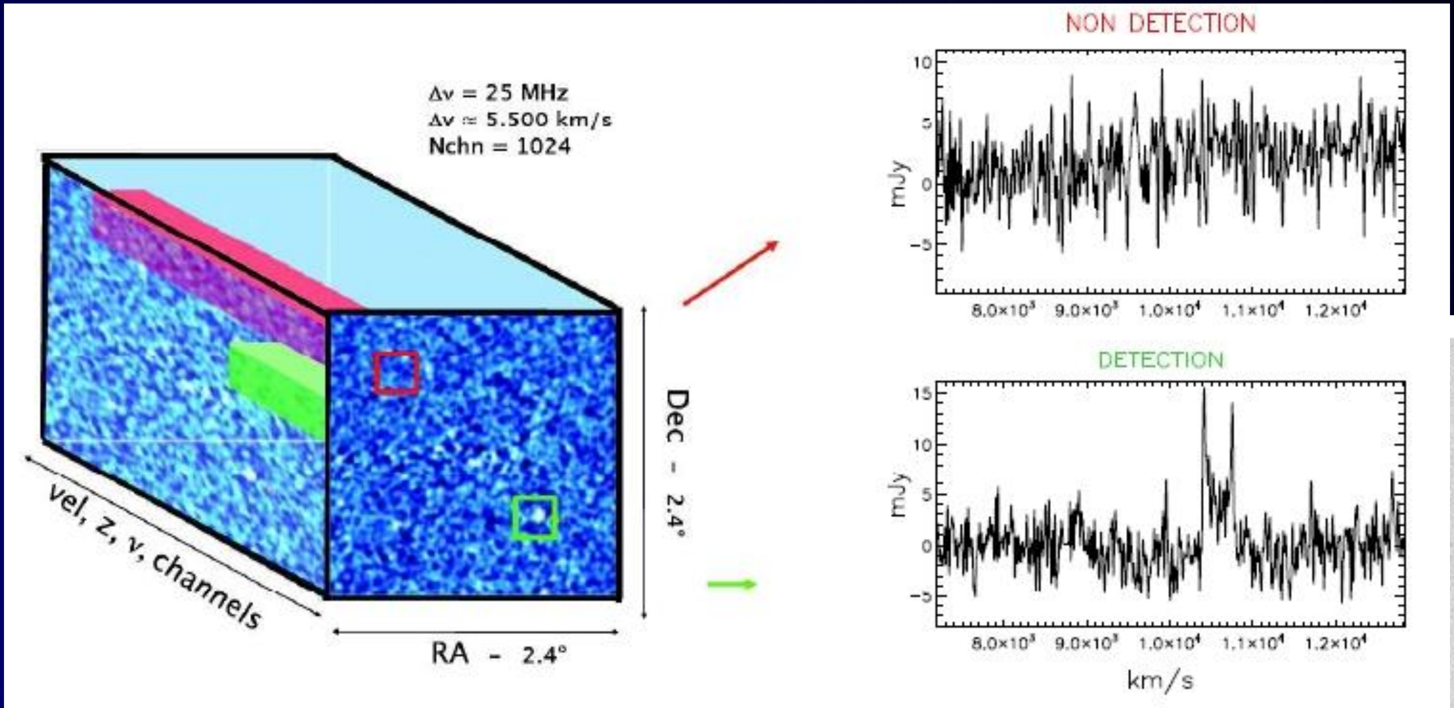


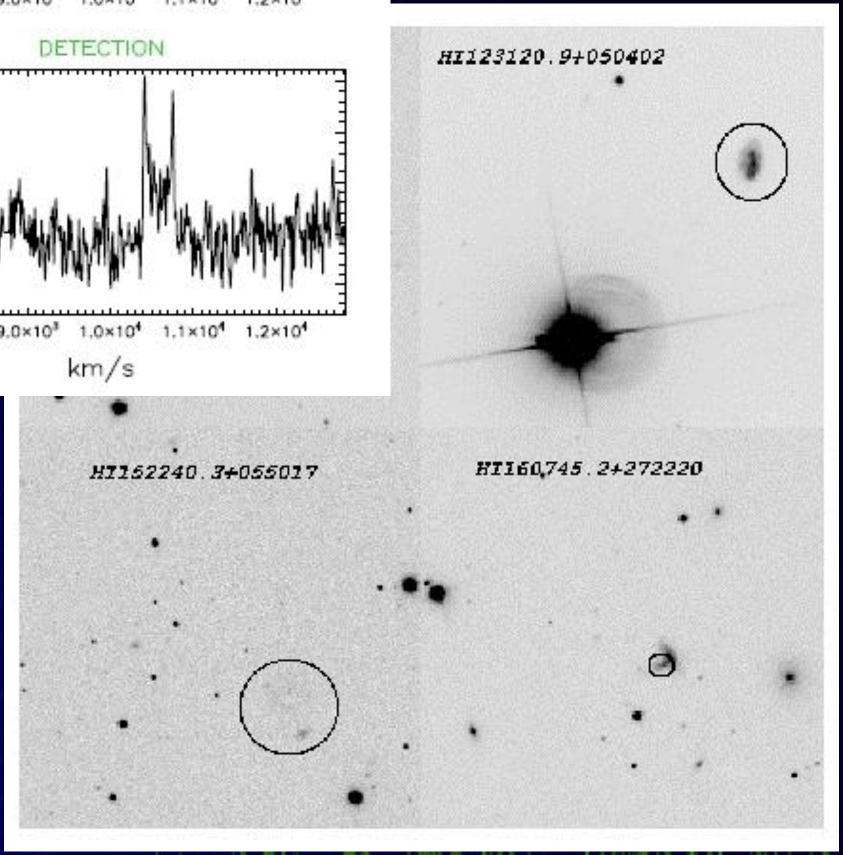


Important for intepretation of future evolution and intensity mapping experiments

Ann Martin (Cornell) PhD thesis, 2011
Martin + (2012) Ap J 750, 38

ALFALFA+Future ExGal HI surveys





- Automated signal extraction
  - Saintonge, 2007 AJ
- Spectral stacking
  - Fabello+ 2010
- Optical counterpart identification
  - Haynes+ 2011

Surveys: A "golden age" for HI science

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GBT nearby groups (M81/2; NGC2403 etc)

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CHILES (higher redshift)

And… coming soon….

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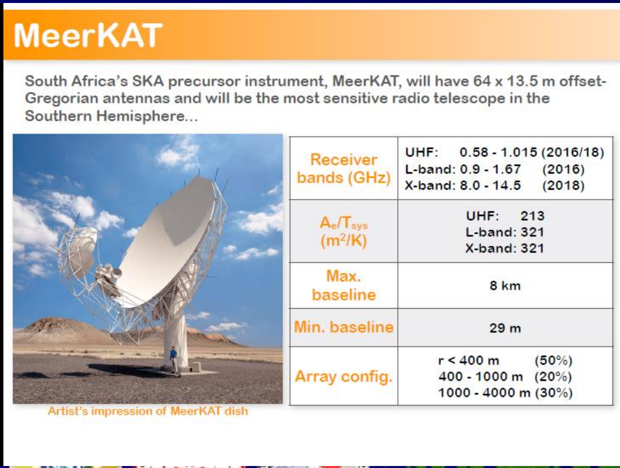
SKA pathfinder arrays

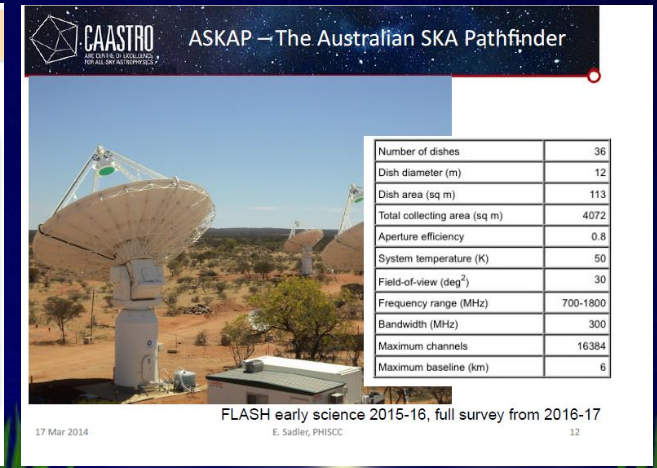
APERTIF
ASKAP-12, -36
MeerKAT
SKA I/ Survey

Examples:

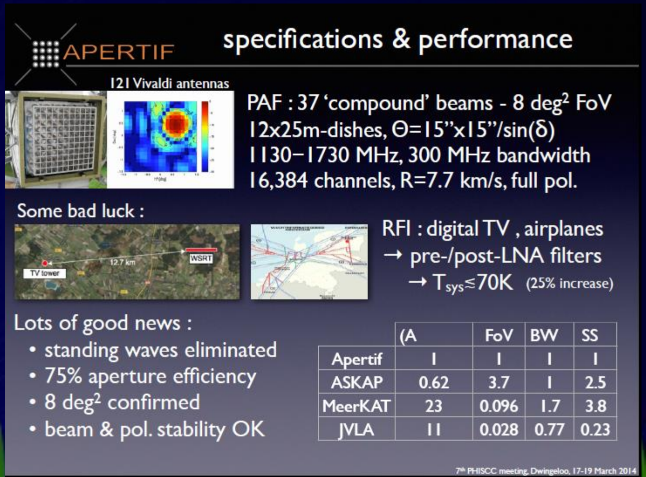
- WALLABY (ASKAP): "all sky", 0.0 < z < 0.26; 1.6 mJy/beam, 30"
- LADUMA (MeerKAT): 5000 hours on ECDF-S; stacking!
- MediumDeep (APERTIF): 500 sqd over several fields
- FLASH (AKSAP): HI in absorption
- DINGO (ASKAP): deep survey on GAMA fields
- MONGHOOSE (MeerKAT): deep survey centered on selected galaxies to look at low column density HI
- SKA-I survey…. TBD



Receiver bands (GHz)	UHF: 0.58 - 1.015 (2016/18) L-band: 0.9 - 1.67 (2016) X-band: 8.0 - 14.5 (2018)
A_e/T_{sys} (m^2/K)	UHF: 213 L-band: 321 X-band: 321
Max. baseline	8 km
Min. baseline	29 m
Array config.	r < 400 m (50%) 400 - 1000 m (20%) 1000 - 4000 m (30%)



Number of dishes	36
Dish diameter (m)	12
Dish area (sq m)	113
Total collecting area (sq m)	4072
Aperture efficiency	0.8
System temperature (K)	50
Field-of-view (deg^2)	30
Frequency range (MHz)	700-1800
Bandwidth (MHz)	300
Maximum channels	16384
Maximum baseline (km)	6



	(A	FoV	BW	SS
Apertif	1	1	1	1
ASKAP	0.62	3.7	1	2.5
MeerKAT	23	0.096	1.7	3.8
JVLA	11	0.028	0.77	0.23

Single Dishes vs Arrays

Following on the discussion in Jay Lockman's talk

- Collecting area!
- Surface brightness sensitivity (see Jay's talk)
- Number/complexity of subsystems (e.g. receivers/PAFs)
    - Cooled front ends so lower Tsys
    - More spectral channels
    - More bandwidth
- Angular resolution
- - for single dishes: susceptibility to RFI (ground/air/space)

- + for GBT: clear aperture, NRQZ

What science is optimized by any particular telescope?

sensitivity

The minimun integration time in sec , to detect an HI mass M_{HI} at the distance D_{Mpc} with a $T_{sys}/G = 3$ Jy telescope (e.g. Arecibo), is

$$t_s \approx 0.25 \left(\frac{M_{HI}}{10^6 M_{sun}} \right)^{-2} D_{Mpc}^4 \left(\frac{W_{kms}}{100} \right)^{\gamma}$$

Where $\gamma=1$ for $W<300$ km/s and increases to $\gamma\sim2$ at larger widths.

i.e. the Depth of the survey increases only as

$$D_{Mpc} \propto t_s^{1/4}$$

- While a galaxy with 1% the HI mass of the MW at Virgo distance can be detected in less than 1 min with ALFA,
- A MW HI mass at even moderate z (e.g. z~0.25, D~ 1Gpc) will require many hours of integration

➔ Only the most massive HI sources are detectable at even moderate z

Giovanelli (2008)

Survey Speed Figure of Merit

$$FoM \propto \left(\frac{A_{eff}}{T_{sys}} \right)^2 \Omega_{fov} BW$$

Parameters Used:

	D (m)	Beam	Ntel*Nbm	Tsys	BW
AO1	225	3.5'	1x1	25K	100MHz
ALFA	225	3.5'	1x7	30K	300*
AO40	225	3.5'	1x40	50K	300
APERTIF	25	30'	14x25	70K	300
ASKAP	12	60'	30x30	35K*	300

(*) The actual performance that FPPAs will deliver is still very uncertain; Tsys values of 35K or 50K are rough expectations. It would be fair to use the same Tsys values for all telescopes → a value of 50K for ASKAP would then apply.

Adapted from Giovanelli (2008)

Big single dishes+multibeams ARE competitive!

Survey Speed
Figure of Merit

$$FoM \propto \left(\frac{A_{eff}}{T_{sys}}\right)^2 \Omega_{fov} BW$$

	$(A_e)^2$	$(Tsys)^2$	FoV	BW	FoM
AO1	1	1	1	1	1
ALFA	1	1/1.4	7	3**	14**
AO40	1	1/4	40	3	30
APERTIF	1/41	1/6	1800	3	22
ASKAP	1/170	1/2*	8800	3	74*

(*) For Tsys=50K, the FoM of ASKAP is 37, comparable w/AO40 & APERTIF

Adapted from Giovanelli (2008)

ALFALFA Science Goals

1. Census of HI in the Local Universe over cosmologically significant volume
2. Determination of the faint end of the HI Mass Function and the abundance of low mass gas rich halos
3. Environmental variation in the HI Mass Function
4. Blind survey for HI tidal remnants
5. Determination of the HI Diameter Function
6. The low HI column density environment of galaxies
7. The nature of HVC's around the MW (and beyond?)
8. HI absorbers and the link to Ly α absorbers
9. OH Megamasers at intermediate redshift $0.16 < z < 0.25$

Importantly: a $z\sim0$ survey

ALFALFA

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Science goals => principal driver
- Unique and compelling

Dictate requirements for instrument/telescope:
- Sky coverage (how much?)
- Bandwidth AND velocity resolution
- Sensitivity (volume sensitivity)

These in turn dictate observing strategy

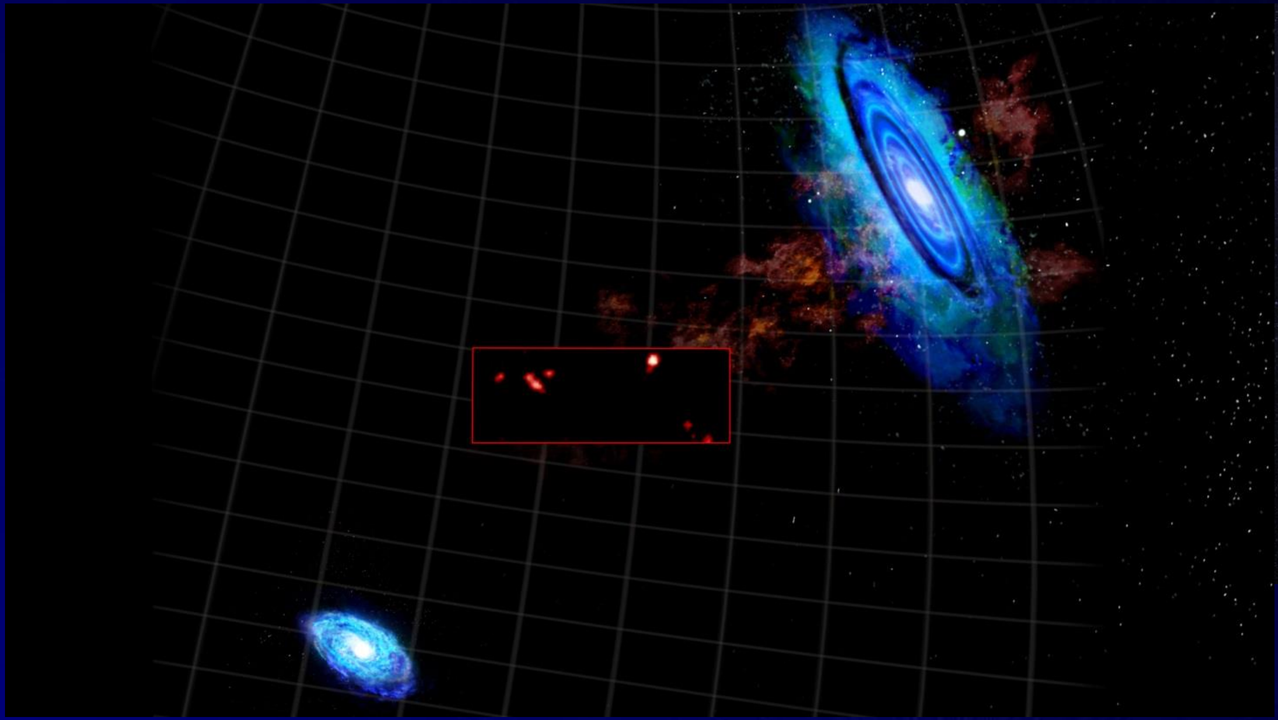
@ Arecibo: **Drift** scan, 2-pass, "minimum-intrusion" strategy

ALFALFA

When low column density counts

Diffuse/cosmic web gas => low column density

- As discussed in Jay Lockman's talk
- Does cold accretion fuel star formation?



When discovery is the driver

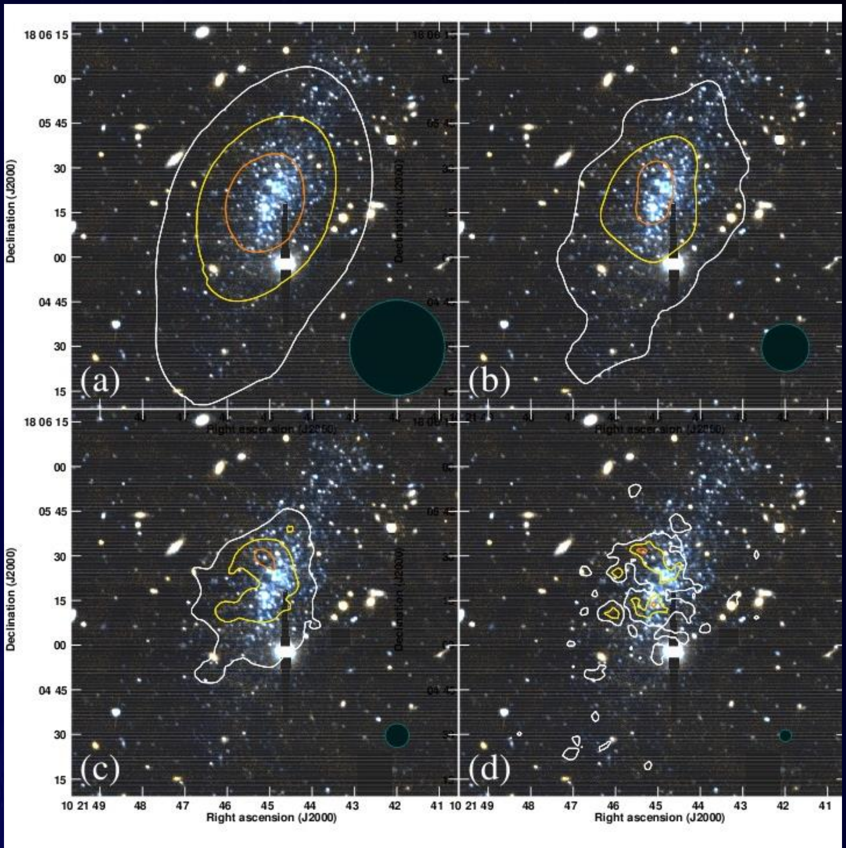
Counting low mass halos: the faint end of the HIMF

- Missing satellite problem
- Void problem
- Field galaxy problem

Leo P: A new nearby dwarf discovered as an UltraCompact High Velocity Cloud in ALFALFA

- Need large solid angle
- Distance ambiguities
- Need resolution of few km/s
- Need high sensitivity (to small HI masses) at significant distances

Deeper than ALFALFA, sensitive to HI masses of few x 10^5 $M_\odot$ over significant nearby volume



Discovered by ALFALFA
VLA+GMRT: Bernstein-Cooper et al. (2014)

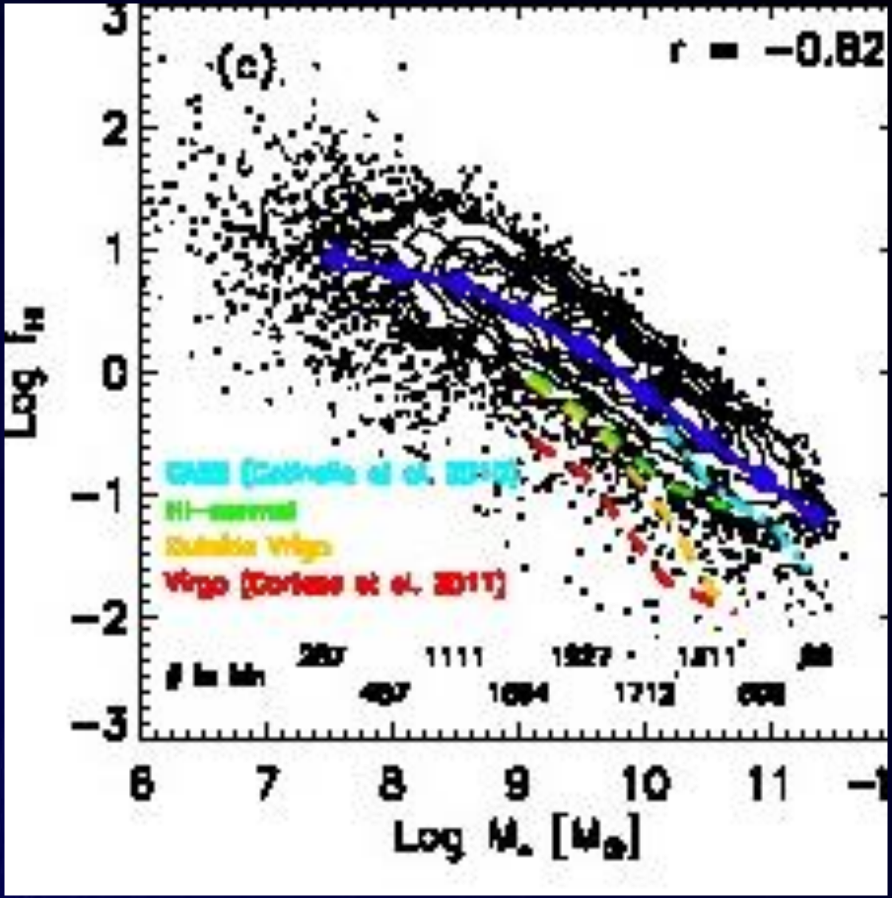
ALFALFA

When a census is the driver

Intermediate mass, star forming galaxies: How, why, where?

- Moderate mass SF galaxies have more HI than stars
- Virtually all HI detections with log $M_H > 8$ have optical counterparts
- But, they may not be included in flux-limited UV/OIR surveys
  - Shredding of pipeline photometry

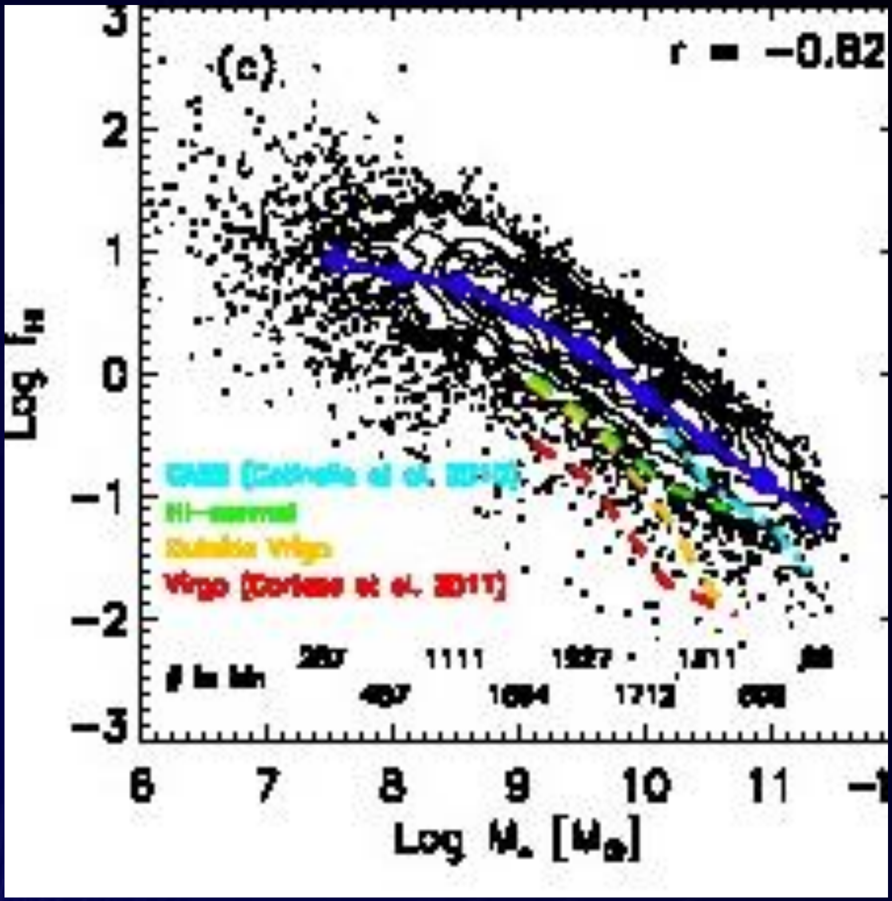
Deeper surveys needed over 1000s of square degrees to catch up with SDSS/PanSTARRS



When detection is the driver

"Typical" star forming galaxies: How, why, where, when?

- At redshift z~0.1 (comparable depth to SDSS), the Arecibo beam (4.') subtends about 400 kpc => $R_{200}(MW)$ ~ 400 kpc.
- *A survey which retains sensitivity at this distance to MW-mass galaxies.*
- Need to have complementary multiwavelength data
- Need to plan best strategy (targeted vs blind?)



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When sensitivity is the driver

***The processes responsible for making galaxies HI poor*.**

- Majority of galaxies in rich clusters are HI deficient, many by a factor of 10 (or more)
- Very high mass galaxies in general have low gas fractions; many have very low gas fractions, according to how red they are.

- HI-deficient galaxies are **not detected** by blind HI surveys
  - Need to push to constant gas fraction
  - Targeted observations better strategy

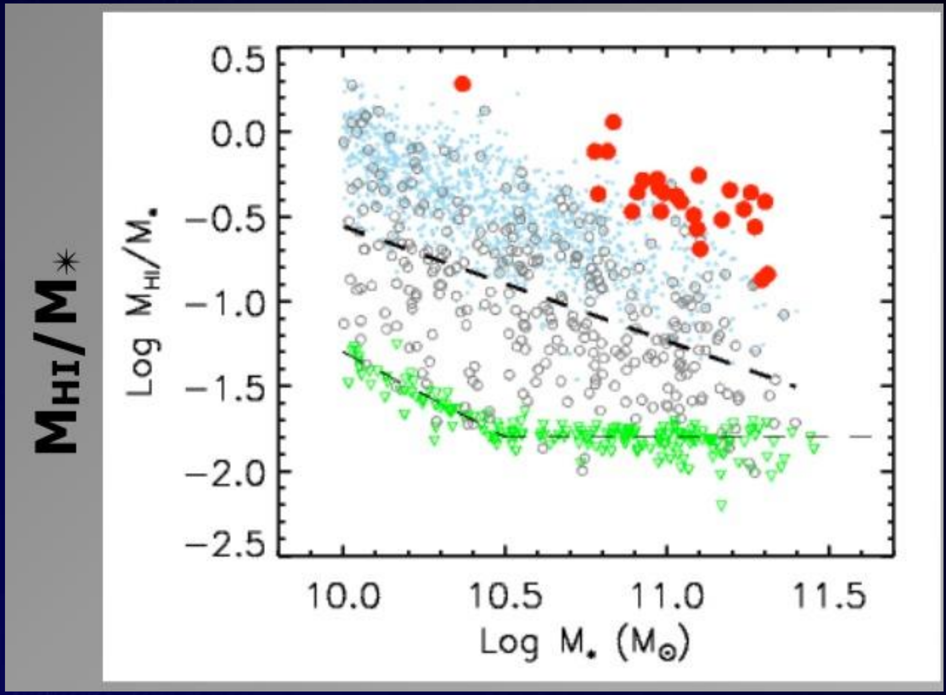
e.g. GASS (Schiminovich et al.), HI deficiency in clusters

ALFALFA

When detection is the driver

Targeting intermediate redshift galaxies

- Observations tough: requires hours per target
- RFI environment is critical



Red points: z ~ 0.2 HI detections
Catinella & Cortese 2014 in prep

- Pre-select targets based on optical spectroscopy to study selected populations
  - It is possible!
- Test stacking bias (required for higher z surveys).
- Evolution of T-F relation (rotational velocity as predictor of luminosity)

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When a census is the driver

Targeting intermediate redshift groups

- At z=0.5 (950 MHz), Arecibo beam (5.25′) subtends 2.0 Mpc => R_{200}(Coma) ~ 2.0 Mpc
- Measure integrated HI emission of clusters/groups discovered in OIR surveys as function of redshift/richness/SFR

ALFALFA

When resolution isn't the driver

<u>Application of the T-F relation in the infall regions in the local universe:</u>

-- The next talk, by Li Xiao, on an example of a possible future survey to measure and characterize the flow around the Pisces-Perseus supercluster.

ALFALFA

The Future of Big Dish ExGal-HI

- There is fundamental/transformational extragalactic HI science that is best/uniquely done with large single dishes with/out multiple beam devices.
- Lots of overlap in software/hardware/need for multiwavelength plus complementarity of different telescope designs/circumstances.
- In order to maximize scientific productivity and efficiency, it would be advantageous to construct a coordinated program of surveys/multiwavelength observations with the large single dish telescopes in the northern hemisphere
  - e.g. a coordinating committee for single dish surveys?