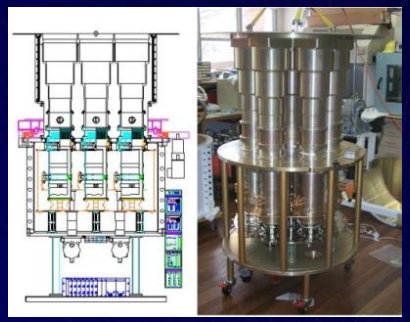
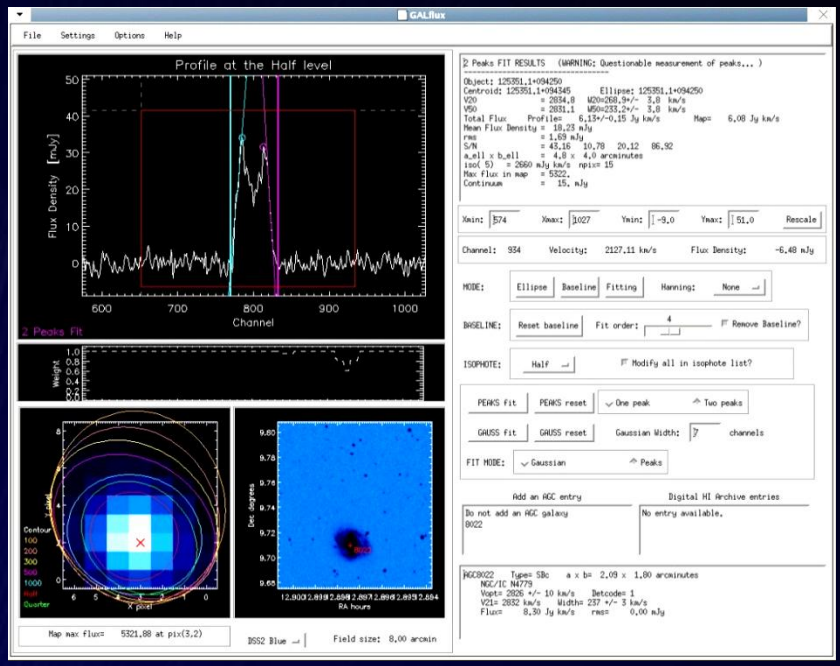
The ALFALFA Census of Gas-Bearing Galaxies at z=0

The Arecibo Legacy Fast ALFA (ALFALFA) Survey





Martha Haynes

Cornell University

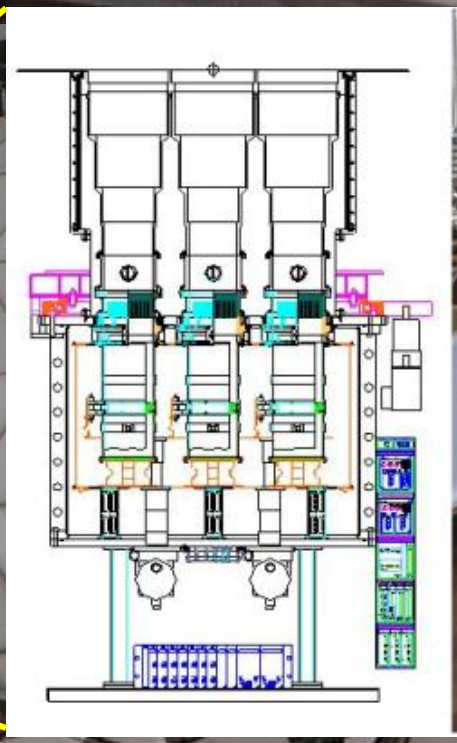
For the ALFALFA team

Green Bank

April 1, 2012

ALFALFA

It is a radio "camera"



Arecibo L-band Feed Array (ALFA)

ALFALFA

ALFALFA, a Legacy Survey

The Arecibo Legacy Fast ALFA Survey

Main People Science Schedule Data Documentation Links Publications Undergrads
Non-experts News/Events Observing/Data Team

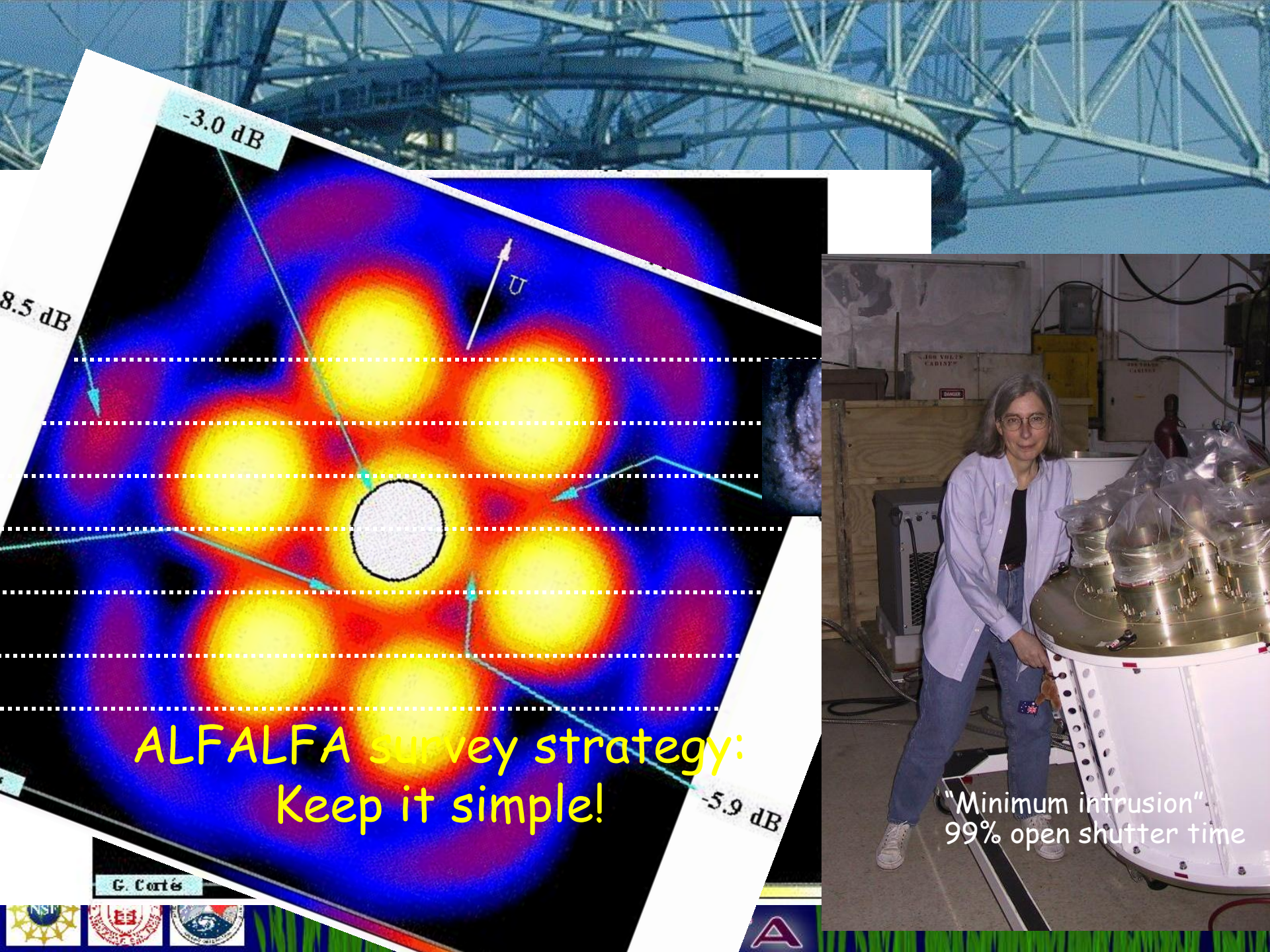
Overview

Check out the ALFALFA blog!

Arecibo is the world's most sensitive radio telescope at L-band. In addition to that all-important sensitivity advantage, Arecibo equipped with ALFA offers important and significant improvements in angular and spectral resolution over the available major wide area extragalactic HI line surveys such as HIPASS and HIJASS. To break ground into new science areas, extragalactic HI surveys with ALFA must exploit those capabilities to explore larger volumes with greater sensitivity than have the previous surveys. The lowest mass objects will only be detected nearby; wide areal coverage is the most efficient means of increasing the volume sampled locally. An extragalactic survey covering the high galactic latitude sky visible from Arecibo will produce an extensive database of HI spectra that will be of use to a broad community of investigators, including many interested in the correlative mining of

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

ALFALFA



ALFALFA survey strategy: Keep it simple!

"Minimum intrusion"
99% open shutter time

The ALFALFA team: An open collaboration

Heavy student involvement:

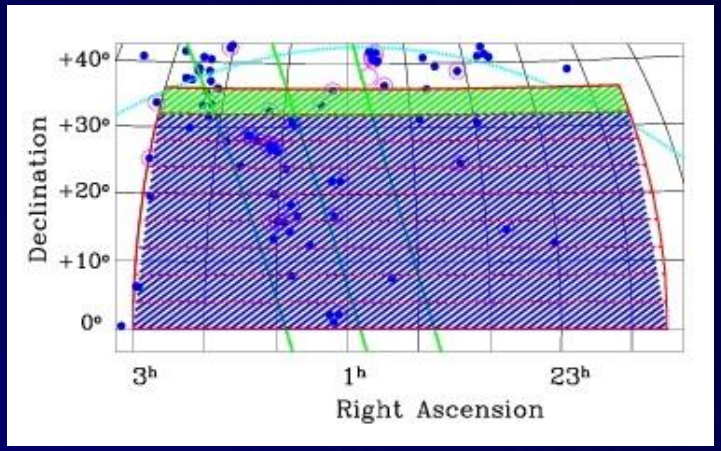
- 7 PhDs to date
- 10 PhDs underway
- 145 undergrads (so far!)

45 papers in refereed literature (appeared or submitted) with lots more on the way!

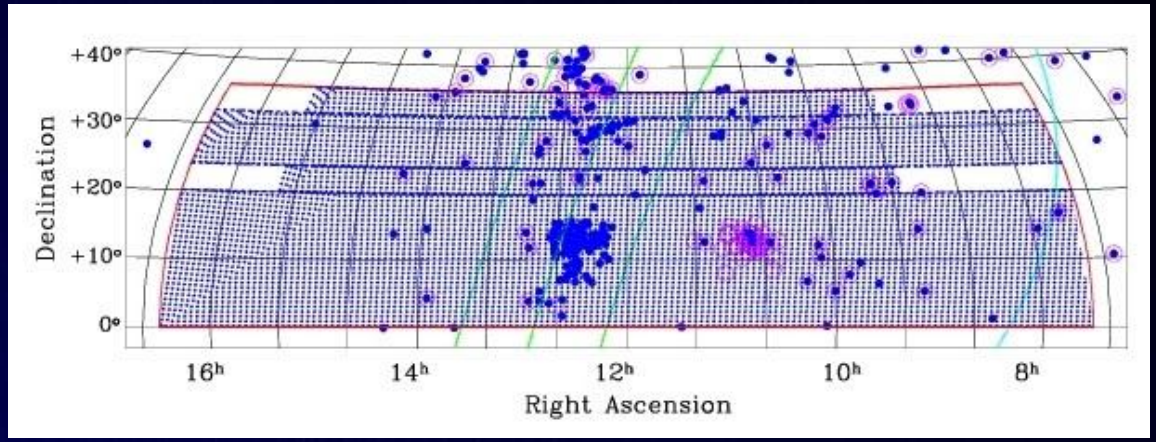
ALFALFA

ALFALFA observing status Mar 2012

- 779 observing runs, 4300 hours, most remotely
- 20,000 "good" detections in 50% of final area



"fall"



"spring"

We hope to complete the legacy survey observations in Fall 2012.

ALFALFA also bears full responsibility for the observing for the commensal galactic HI program "TOGS" (Mary Putman, PI)

Followup "pointed" observations with LBW target most enigmatic objects (dark galaxies, OHM candidates, etc).

ALFALFA

ALFALFA: A 2nd generation HI survey

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

- To date, determinations of HIMF have:
  - been based only only few thousand objects
  - been strongly impacted by local large scale structure
  - included few objects with log $M_{HI}/M_{\odot} < 8$
  - included few objects with log $M_{HI}/M_{\odot} > 10$

- Nearly all star-forming galaxies contain HI
- At mid-low stellar masses, the gas fraction M_{HI}/M_{stars} can be > 1.

ALFALFA:
- Designed to explore the HI mass function over a cosmologically significant volume with adequate statistics and dynamic range.

Comparison of blind HI surveys

Survey	Beam arcmin	Area sq. deg.	rms (mJy @ 18 km/s)	min M_{HI} @ 10 Mpc	N_{det}	t_s sec	N_{los}
AHISS	3.3	13	0.7	2.0×10^6	65	var	17,000
ADBS	3.3	430	3.3	9.6×10^6	265	12	500,000
HIPASS	15.	30,000	13	3.6×10^7	4315	460	1.9×10^6
HIDEEP	15	32	3.2	8.8×10^6	129	9000	2000
AGES	3.5	200	0.5	3×10^6		300	
ALFALFA	3.5	7,000	2.0	6.0×10^6	30,000+	40	7×10^6

ALFALFA is ~ 1 order of magnitude more sensitive than HIPASS with 4X better angular resolution, 3X better spectral resolution, and 1.6X total spectral bandwidth

=> 29X source density (5.3 gals/sqd vs 0.18 gals/sqd)

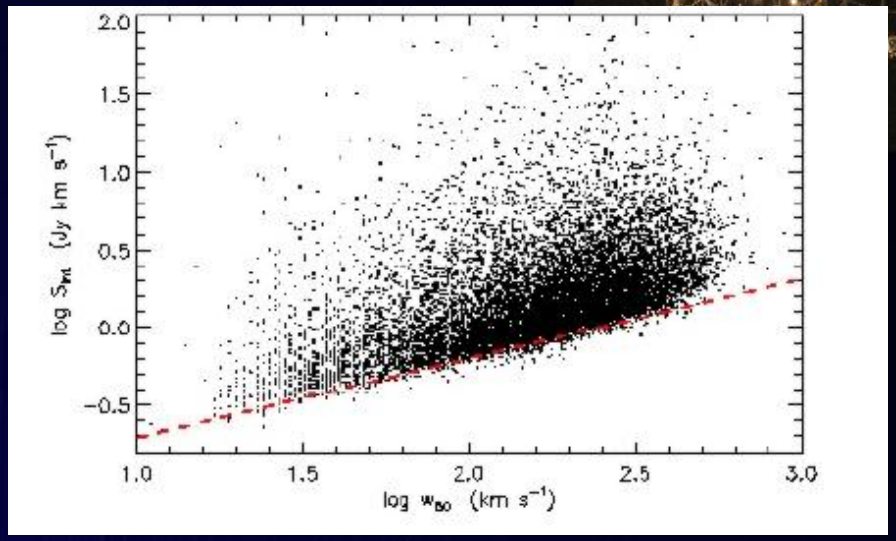
ALFALFA

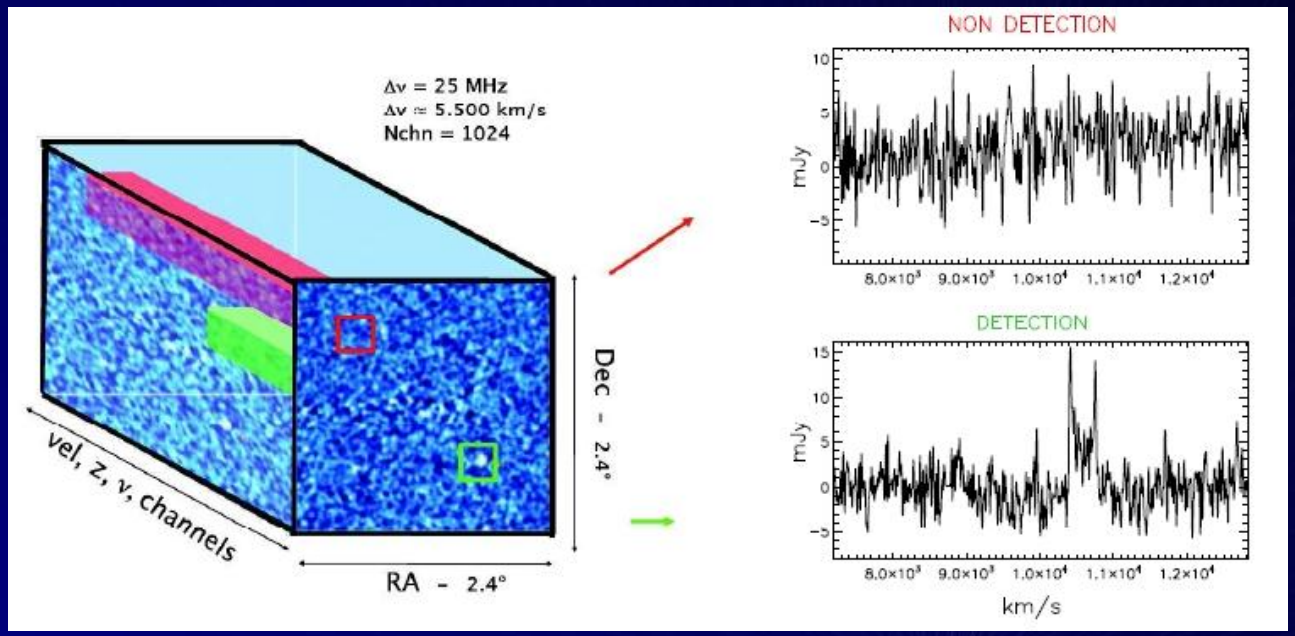
Mining ALFALFA

Signal extraction done in Fourier domain using matched filter algorithm (Saintonge 2007, AJ, 133, 2087)

HI flux density sensitivity depends on HI line width => but well-behaved

Amélie Saintonge (Cornell)
PhD thesis





Fabello+ 2010 MNRAS 411, 993

ALFALFA pipeline tracks RFI/continuum
=> Spectral stacking to dig deeper.

Silvia Fabello (MPA)
PhD thesis

ALFALFA

Identifying Optical Counterparts

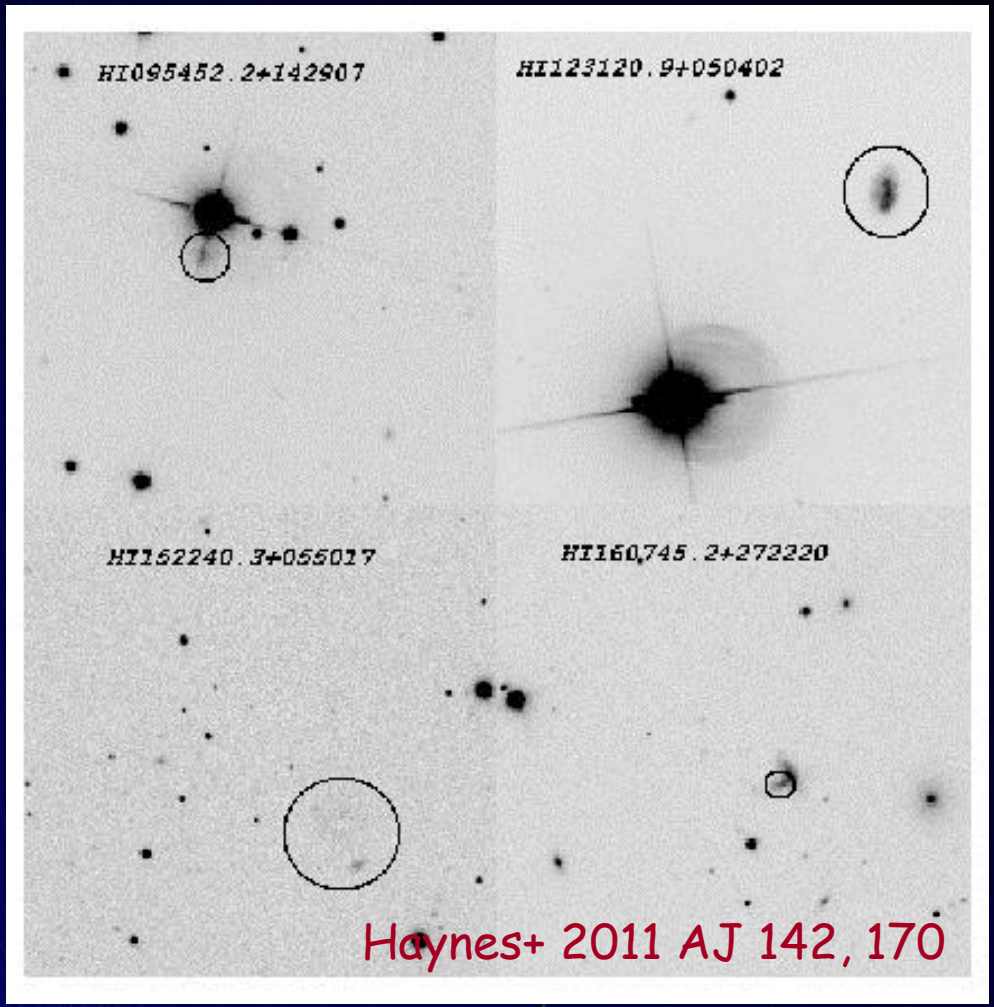
ALFALFA source centroids good to ~18" (depends on S/N)

ALFALFA catalogs include:

- the HI centroid position
- the position of the most probable OC
- OC's SDSS PhotoObjID and SpecObjID (where applicable)

Of 15855 sources in α.40:

- 1013 have no OC
- 844 of those could be HVCs (or LG minihalos)
- 199 (<2%) extragalactic
- Of those, <50 are "isolated"



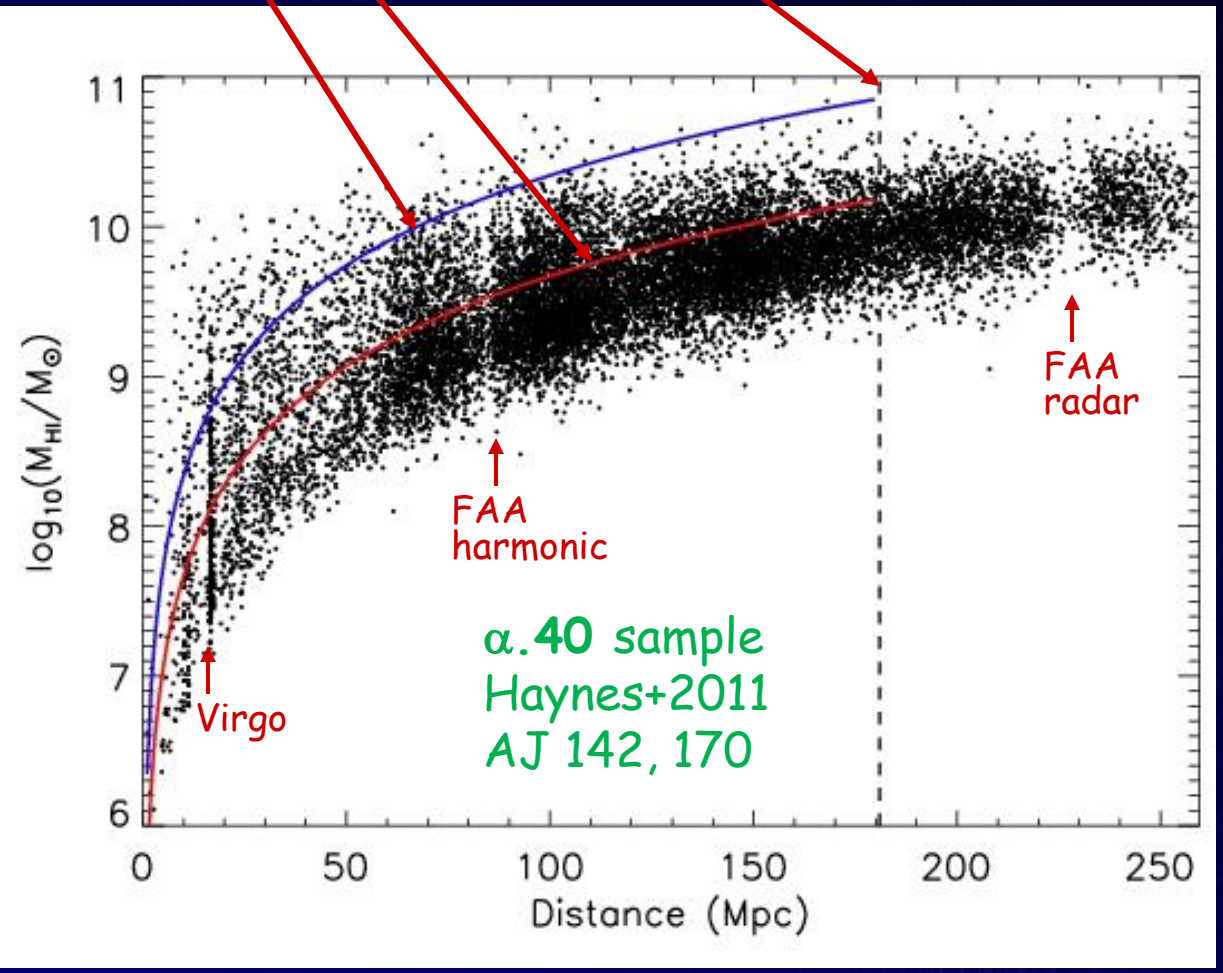
Haynes+ 2011 AJ 142, 170

ALFALFA

ALFALFA Science Goals

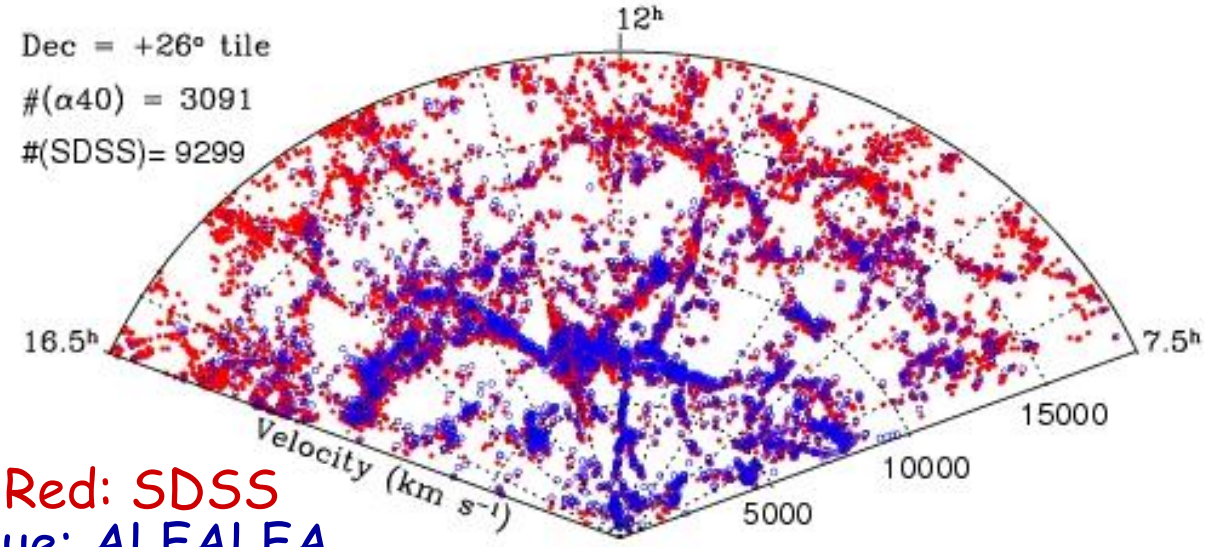
1. Census of HI in the Local Universe over cosmologically significant volume
2. Determination of the faint end of the HI Mass Function and the abundance of low mass gas rich halos
3. Environmental variation in the HI Mass Function
4. Blind survey for HI tidal remnants
5. Determination of the HI Diameter 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 $0.16 < z < 0.25$

ALFALFA 40% catalog

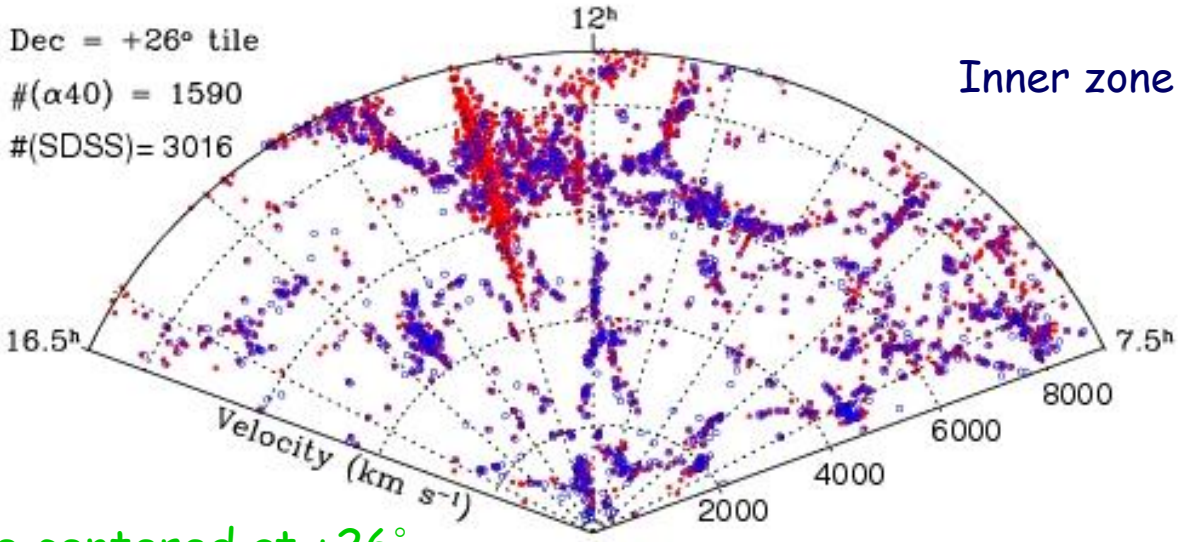


- ALFALFA covers adequate volume with adequate sensitivity
  - 15000+ detections in 40% of final area
  - 70% are "new" !!!
- In addition to sensitivity, bandwidth and velocity resolution, ALFALFA yields positions to < 20"
  ⇒Identification of most probable optical counterpart (OC)
- Continuum/RFI tracked
  ⇒Allows stacking at arbitrary positions

ALFALFA



Red: SDSS
Blue: ALFALFA



Inner zone

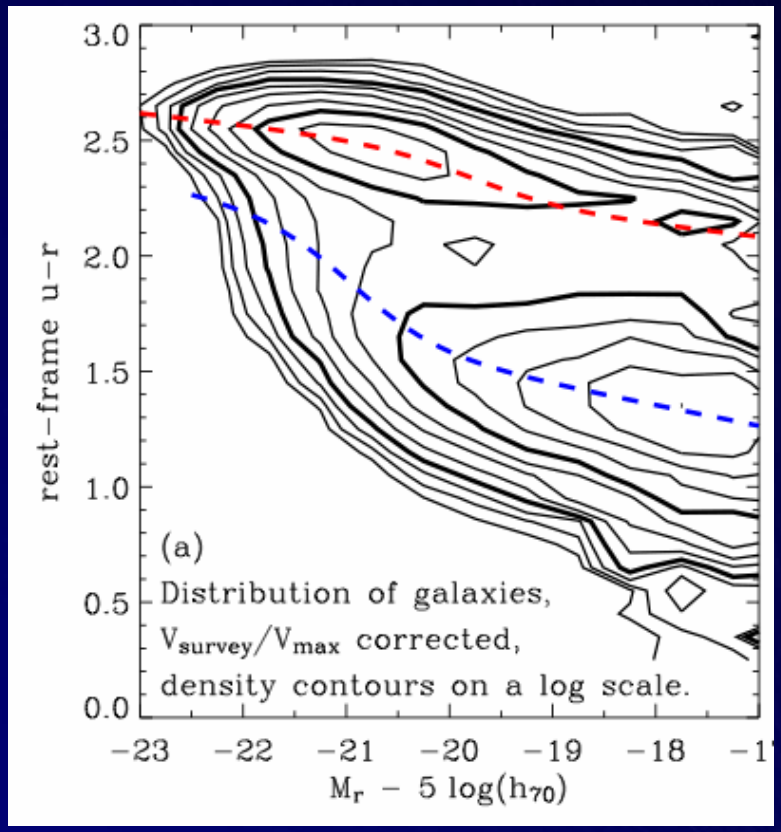
4° tile centered at +26°

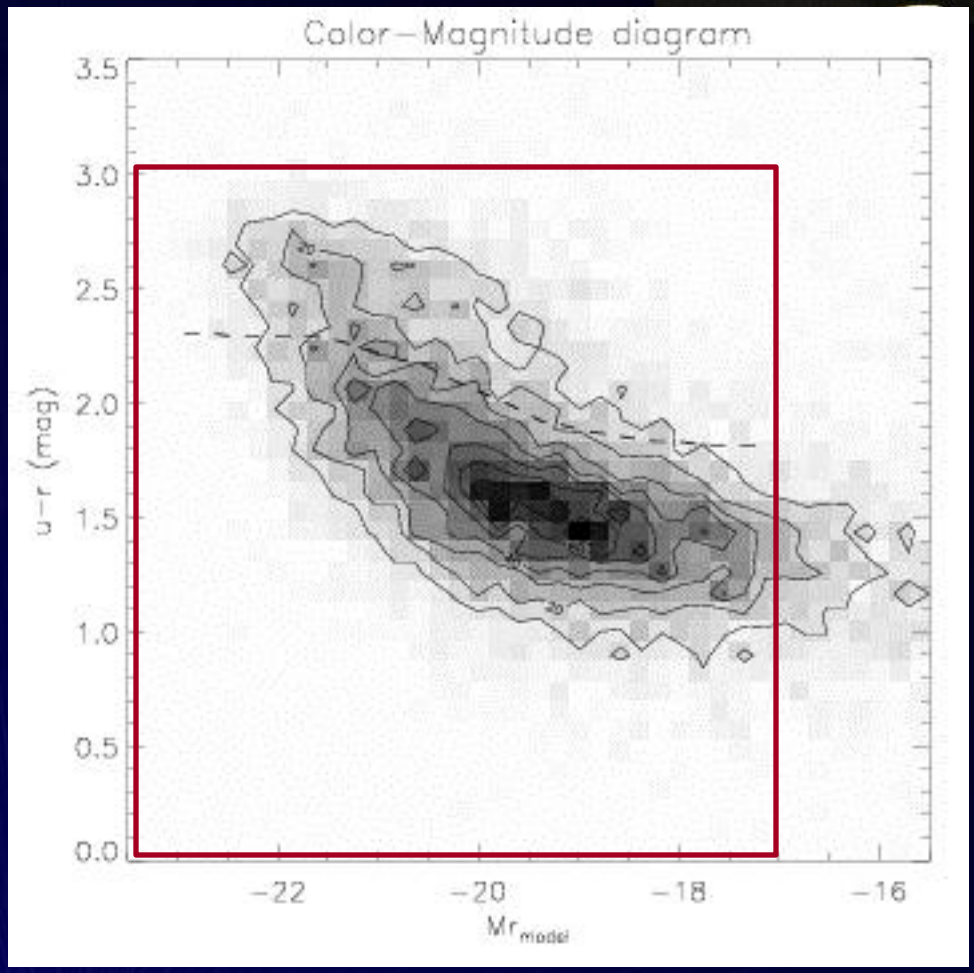
- 7000 sqd of high galactic latitude sky with median cz ~8800 km/s
- Undersamples clusters but traces well the lower density regions
- Large overlapping areas with SDSS and GALEX
- Adds constraints on the gas to models of galaxy evolution

ALFALFA

The ALFALFA population

- Star-forming galaxies but not the red sequence

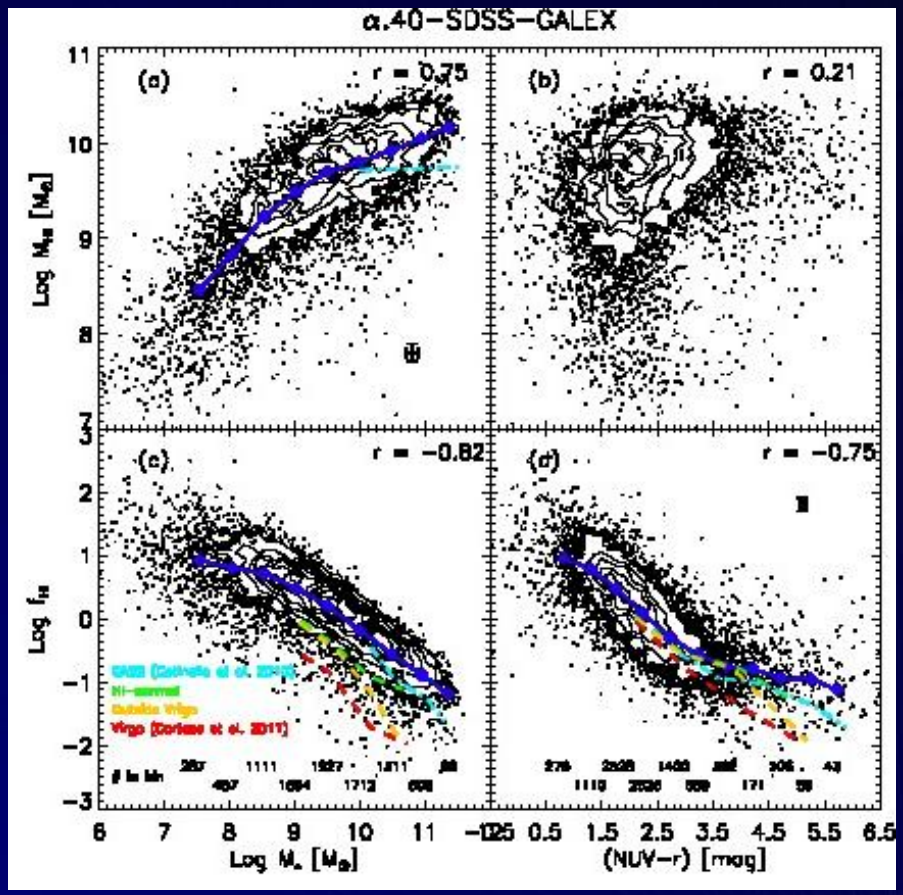




Shan Huang (Cornell) PhD thesis
Huang et al (2012b) to be submitted soon!

ALFALFA

The ALFALFA population



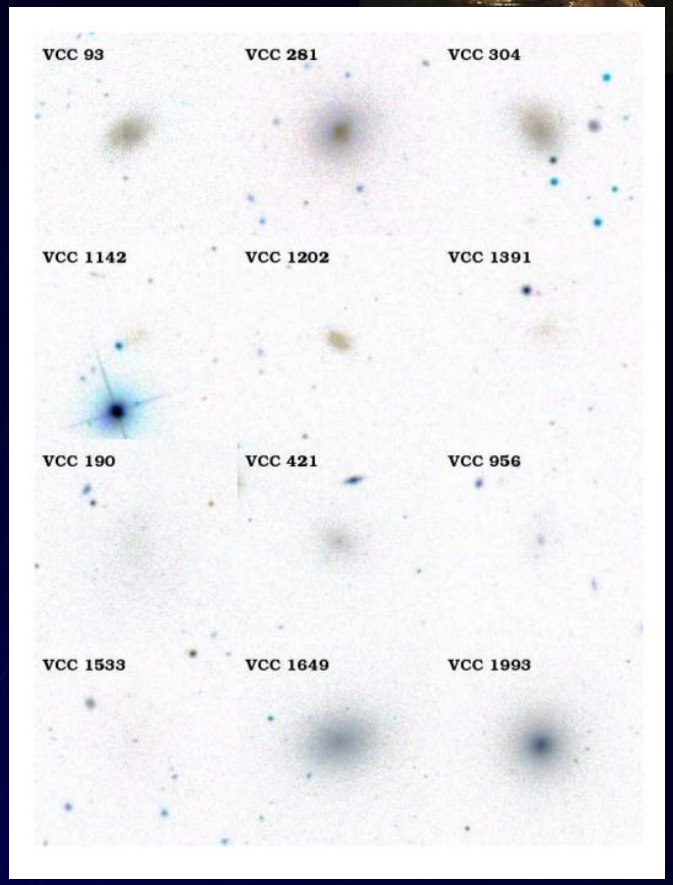
Shan Huang (Cornell) PhD thesis
Huang et al (2012a) AJ (in press)
Huang et al (2012b) to be submitted

- Although extinction is lower in HI selected galaxies, it is not negligible.
- HI selected galaxies are gas-rich, bluer, and have higher SFR and SSFRs but lower SFEs and metallicities than optically selected ones. Their gas depletion times (Roberts' times) are longer.
  - Consistent with HI population having more extended disks.
- Nearly all star forming galaxies have HI.
  - There are low f_{gas} dwarfs

ALFALFA

Gas-bearing dE's in Virgo: recent accretion?

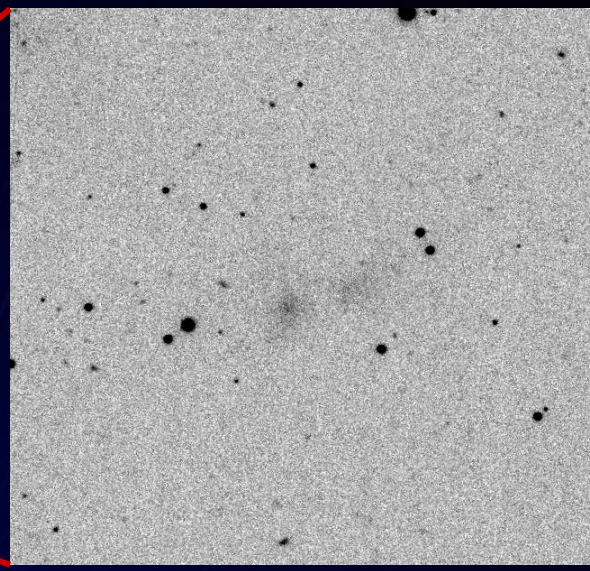
- ALFALFA's "blind" coverage allows a statistically complete view of Virgo dwarfs
- Of 365 confirmed, low L ($M_B > -16$) VCC dwarfs, 80 are detected by ALFALFA.
- 12 of the 80 are classified as dE/dSph (early type dwarfs: ETD).
- Half of the ETDs are blue; half are red.
- Stacking shows the rest contain no gas (at 10X better sensitivity)
- The gas fraction (M_{HI}/M_*) of the ETDs is comparable to that of the LTDs, but the Roberts' times are relatively long, especially among the red population.
- Why do the red ETDs have gas but still look red and early?



Greg Hallenbeck (Cornell) PhD thesis
Huang et al. (2012a) in press
Hallenbeck et al (2012) submitted

ALFALFA

ALFALFA: tidal dwarfs



A tidal dwarf galaxy in NGC 3166/9? 7

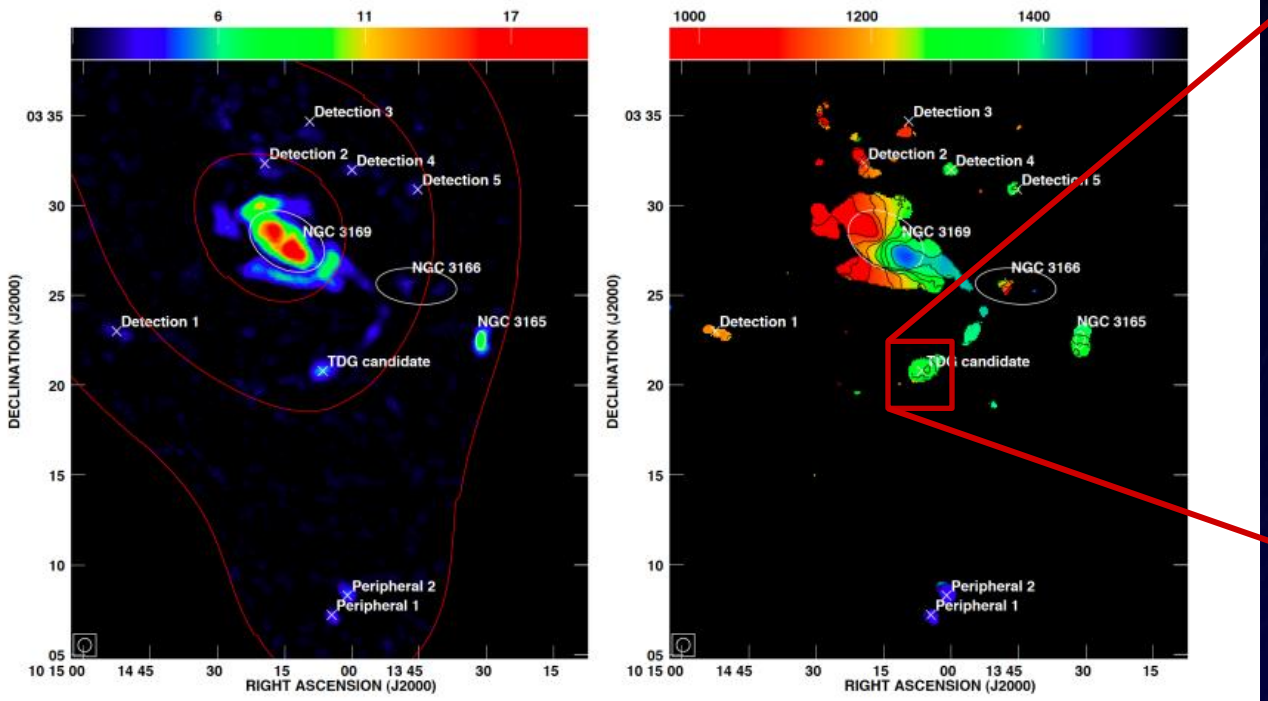


Figure 5. *Left:* GMRT total intensity map of the H I in NGC 3166/9 at 45″ resolution. The red contours show the regions in the map with $\sigma = (1.7, 2, 2.8)$ mJy beam^{-1} and the colour scale ranges linearly from 3 to 19 $\times 10^{20}$ atoms cm^{-2}. *Right:* GMRT intensity-weighted velocity map of the H I in NGC 3166/9 at 45″ resolution. Velocity contours are at (1000, 1050, 1100, 1150, 1200, 1250, 1300, 1350, 1400, 1450, 1500) km s^{-1}. In both maps, the synthesized beam is shown in the bottom left corner and the locations of the H I detections and the main group of galaxies are labelled. Ellipses on the NGC galaxies represent the sizes of their optical counterparts. To remove spurious signals, regions in each datacube channel where the map noise $\sigma > 2.8$ mJy beam^{-1} or where the signal-to-noise S/N < 3 were blanked before the moments were computed. In addition, the velocity map is blanked at locations where $N_{H_I} \leqslant 1.1 \times 10^{20}$ atoms cm^{-2}.

- 8 low mass objects identified
- One appears to be a tidal dwarf $M_{dyn}/M_{HI} \sim 1.4$

Karen Lee-Waddell (RMCC/Queen's) Master's thesis
Lee-Waddell et al (2012) to be submitted soon!

ALFALFA

HI114310.1+141330
J114310.3+141328.9

HI121850.1+123621
J121851.3+123549.9

HI122022.6+121136
J122022.9+121108.9

HI122710.8+155407
J122711.8+155349.9

HI123506.6+123100
J123507.99+123020

HI12440
J124409

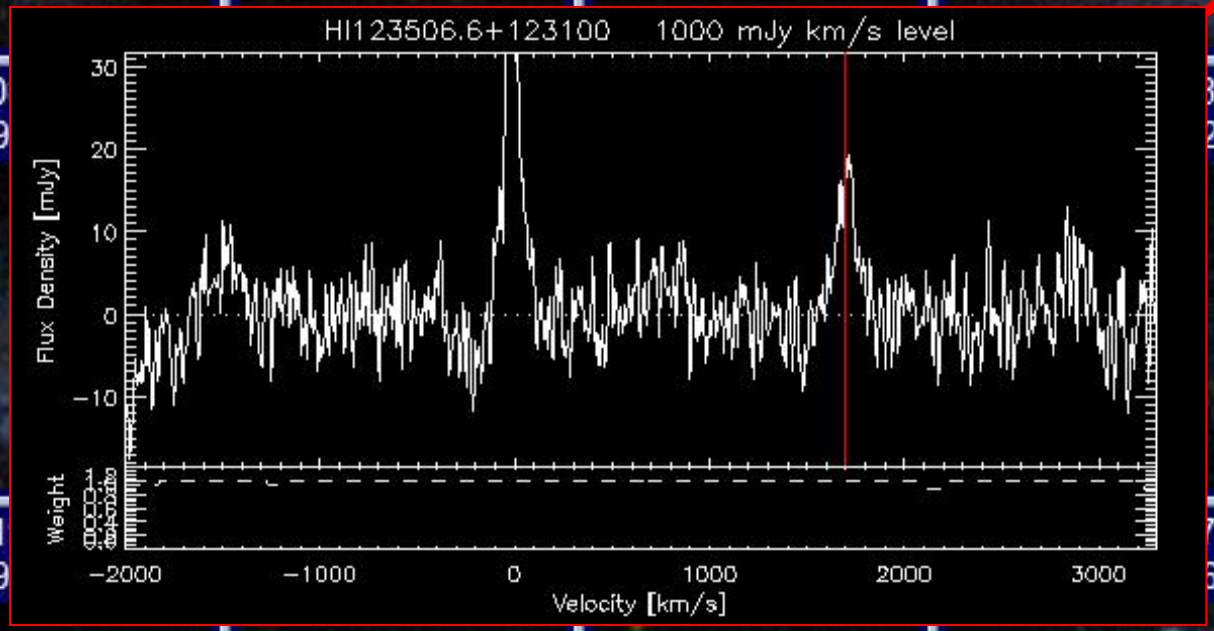
330
29.9

HI122942.6+094202
J122942.96+094152

HI12301
J123019

707
655

HI125401.5+092700
J125402.09+092648.9



Stay tuned for Riccardo's talk

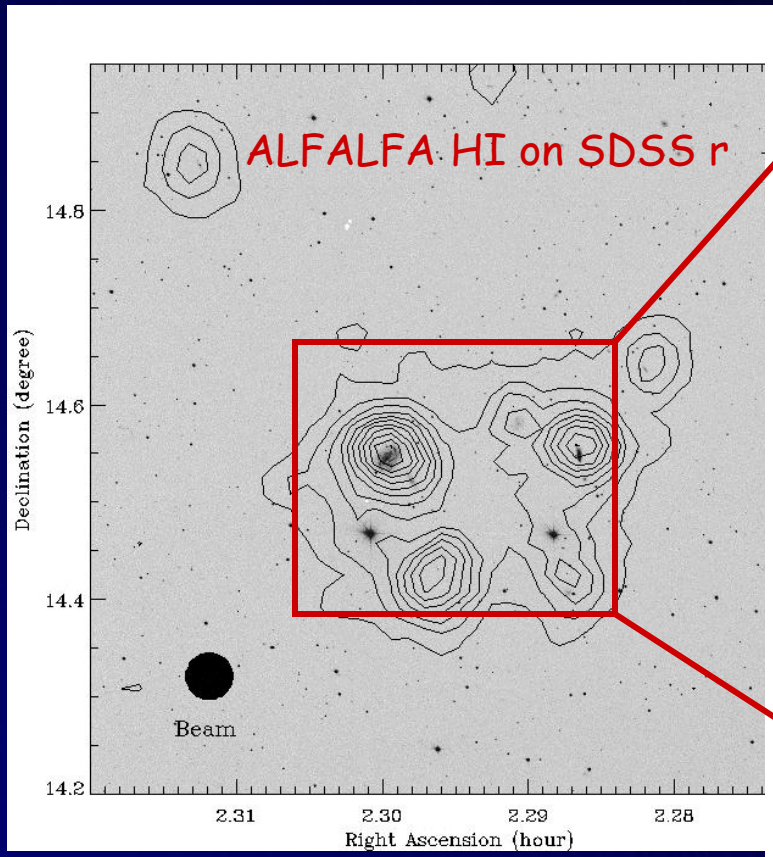
ALFALFA

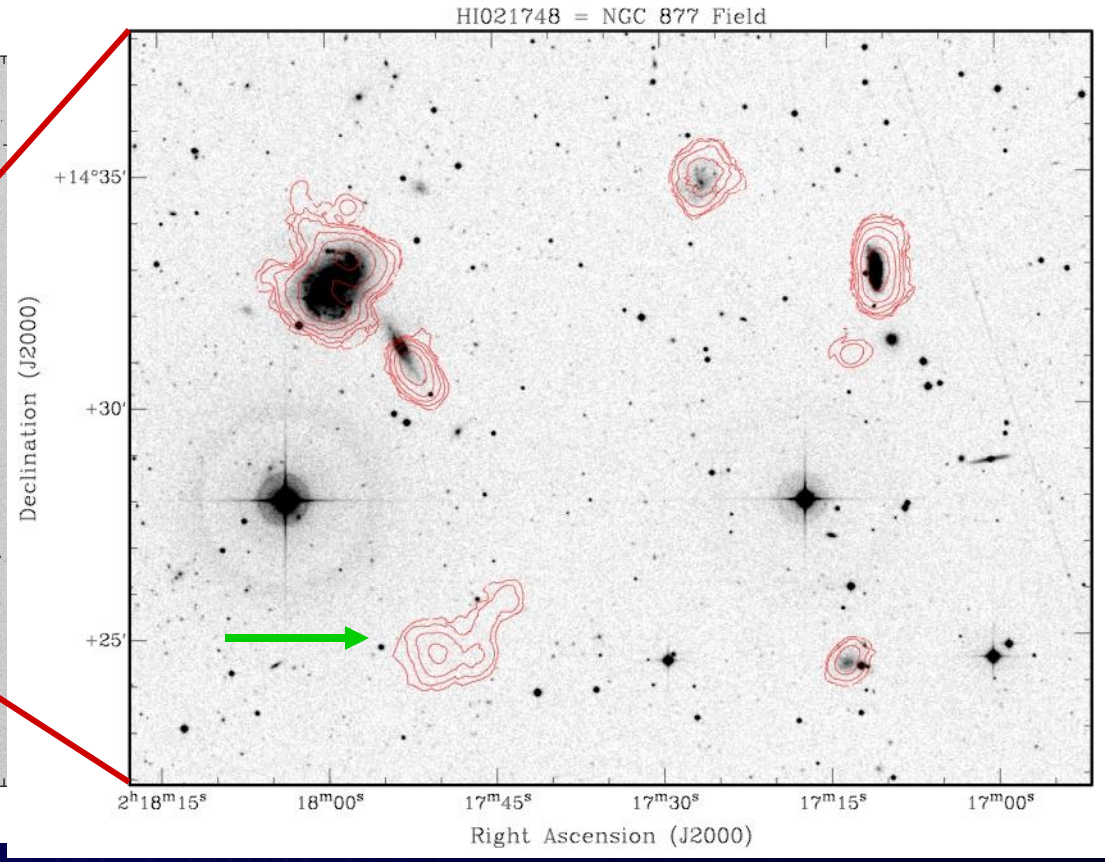
ALFALFA: a wide area blind HI survey

- In agreement with previous results, ALFALFA finds that fewer that 2% of (clearly extragalactic) HI sources cannot be identified with an optical counterpart.
- The majority of objects without OC's are found near to galaxies with similar redshifts.
- There are few interesting cases to be confirmed (work in progress):
  - LSB or dark galaxies
  - OHMs with $0.16 < z < 0.25$
  - Mystery lines?

The burden is always on us to prove that
(1) the signal is real and
(2) there is no OC even at low surface brightness

"Dark" object in a group



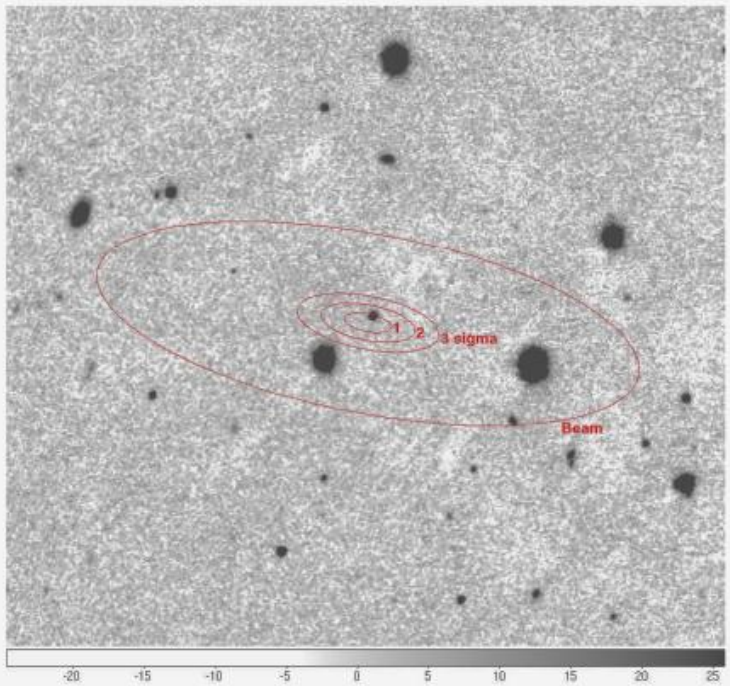


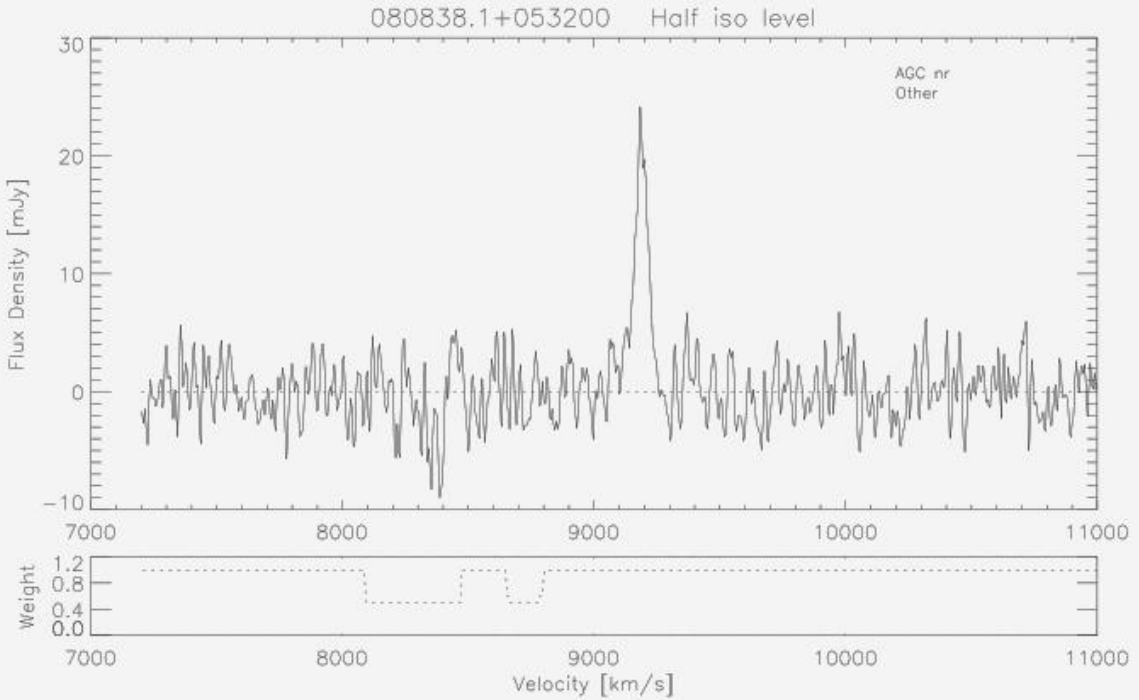
HI peak with no optical/marginal UV: almost dark?

Karen Lee-Waddell, Kristine Spekkens (RMCC/Canada), MH, RG (CU), Cannon (Macalester), Salzer (Indiana)

ALFALFA

HI0808+05: what is it?





Left: K_s (2.2μm) image with 45" EVLA-D beam and centroid confidence intervals (red). The obvious IR/opt OC is a K or M star.

Right: Original ALFALFA spectrum. The HI source at 1378.2 MHz has been confirmed with AO/LBW, GBT and EVLA.

Lead: Jeremy Darling (Colorado)

ALFALFA

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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 $0.16 < z < 0.25$

HI cosmology

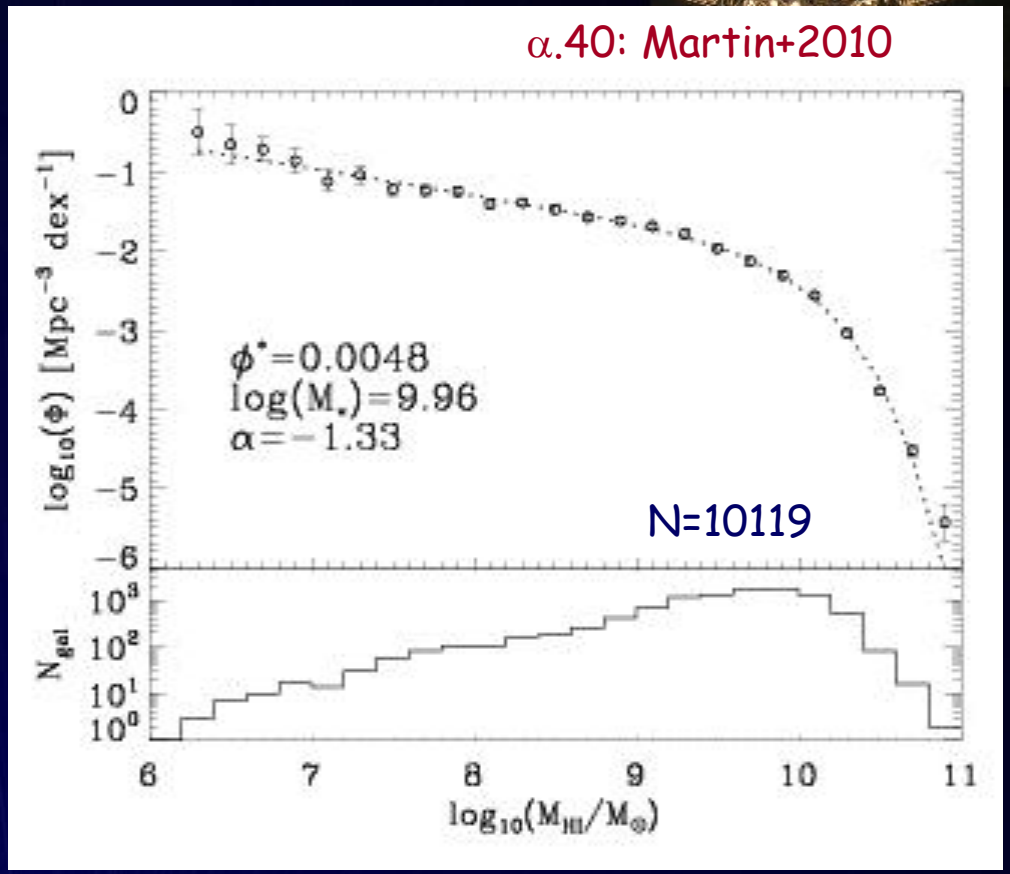
- The HI Mass Function: # galaxies per interval of HI mass per unit volume (analogous to a luminosity function)
- The HI correlation function: how do HI galaxies cluster?
- The HI velocity width function: a perspective on the halo mass function. (Manolis' talk)

All of these yield insight into the distribution of dark matter halos, in this case ones which are gas-bearing, regardless of their stellar content.

HIMF from ALFALFA:

Martin+ 2010 ApJ 723, 1359

- Based on contiguous regions in Virgo vs anti-Virgo directions (35% of total)
- 10,119 Code 1 ("best"); cz < 15,000 km/s
- $\Omega_{HI} = 4.3 \pm 0.3 \times 10^{-4}$ (16% higher than HIPASS)



Good news for the SKA!

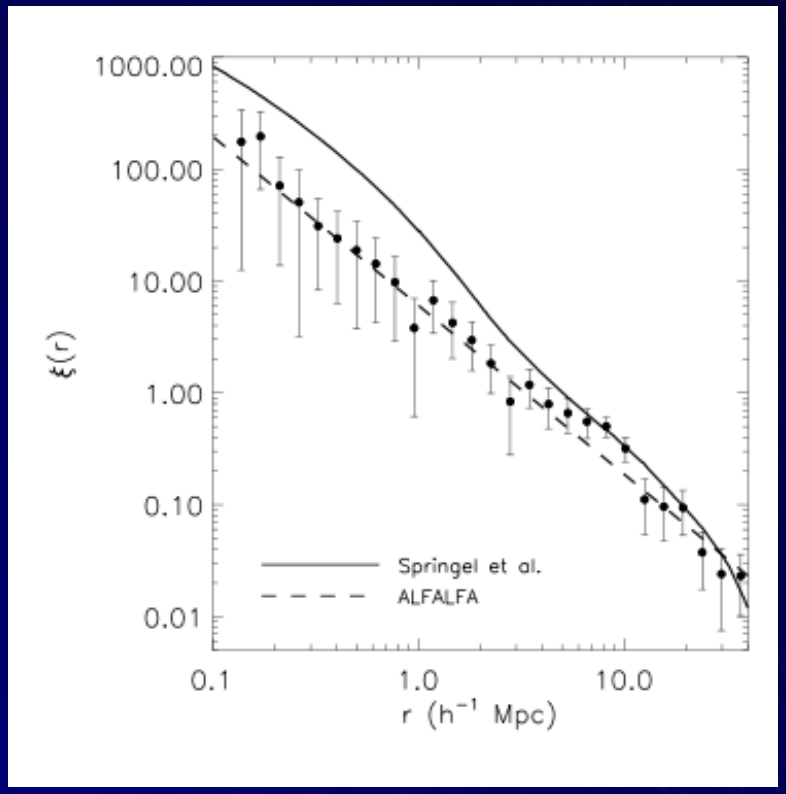
ALFALFA is the first blind HI survey to cover adequate volume at both the low and high HI mass ends

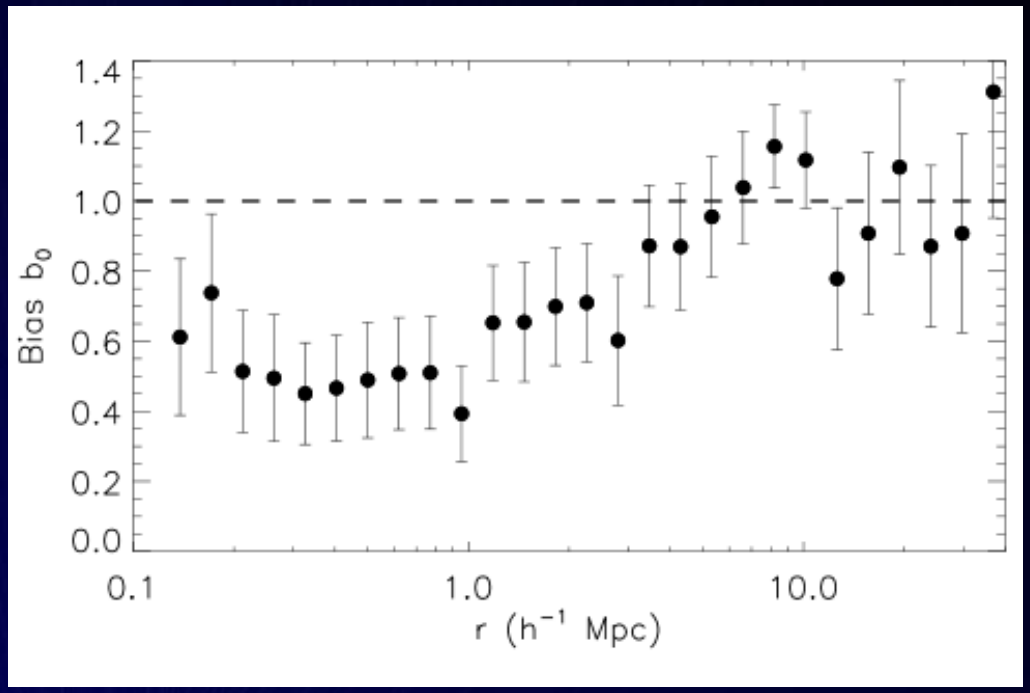
Ann Martin (Cornell)
PhD thesis

ALFALFA

The HI correlation function at z=0

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 in press

ALFALFA

ALFALFA sprouts!

Sheila K.

SHIELD

John C.

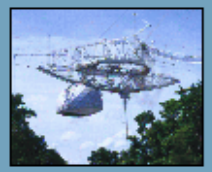
The Survey of HI in Extremely Low-mass Dwarfs

using the
Expanded Very Large Array (EVLA)

EVLA OSRO Program 10B-187

John M. Cannon (PI, Macalester College)
Betsey Adams, Riccardo Giovanelli, Martha Haynes (Cornell University)
Kristy McQuinn (University of Minnesota)
Jürgen Ott (National Radio Astronomy Observatory)
Amélie Saintonge (Max-Planck-Institute for Extraterrestrial Physics)
John J. Salzer (Indiana University)
Evan D. Skillman (University of Minnesota)

Plus numerous others



THE GALEX ARECIBO SDSS SURVEY
(GASS)

Barbara C.

SDSS

COLD GASS
CO LEGACY DATABASE FOR GASS

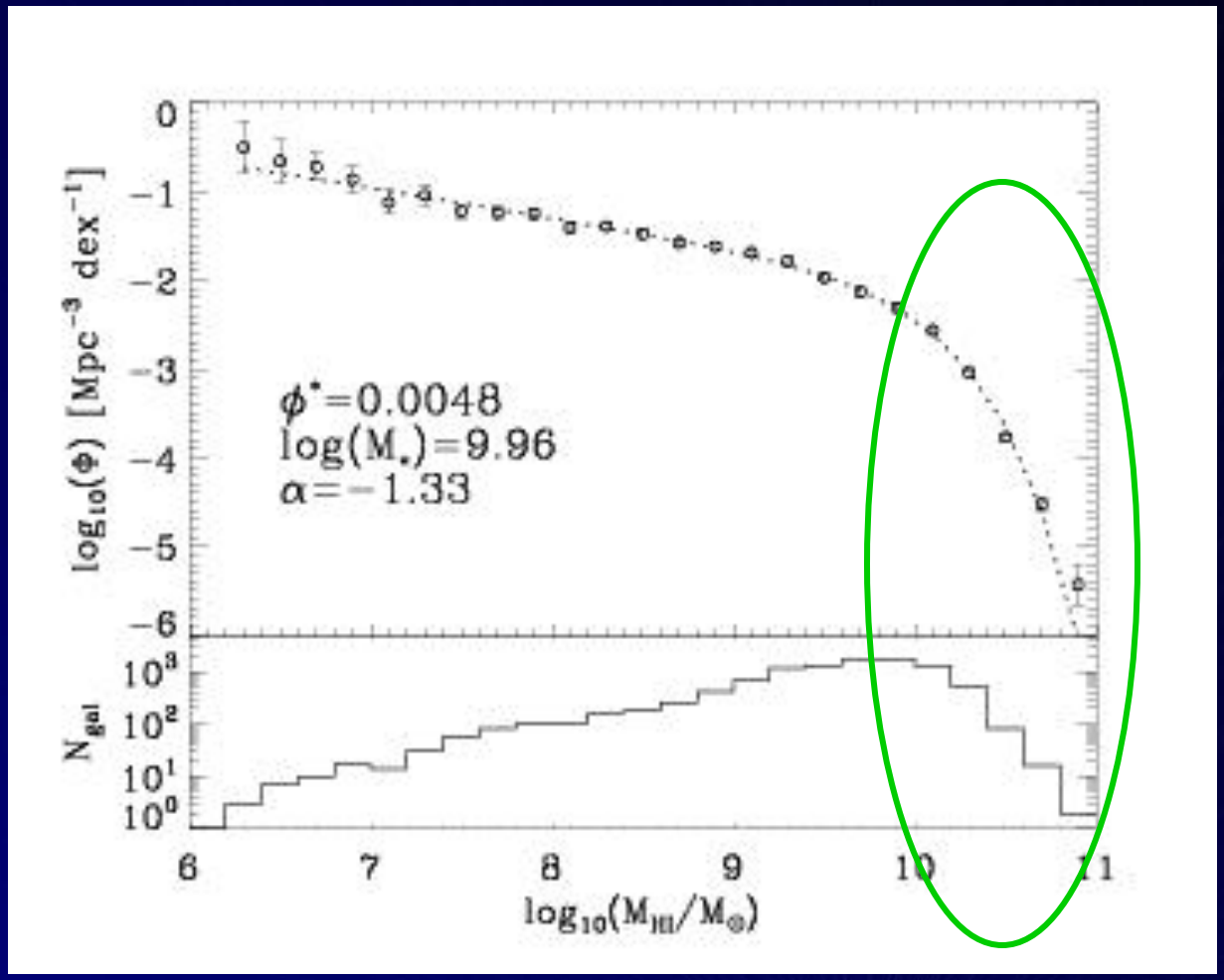
AN IRAM LARGE PROGRAM

iram

NSF

ALFALFA

HIMF from ALFALFA



Martin et al. 2010
ApJ 723, 1359

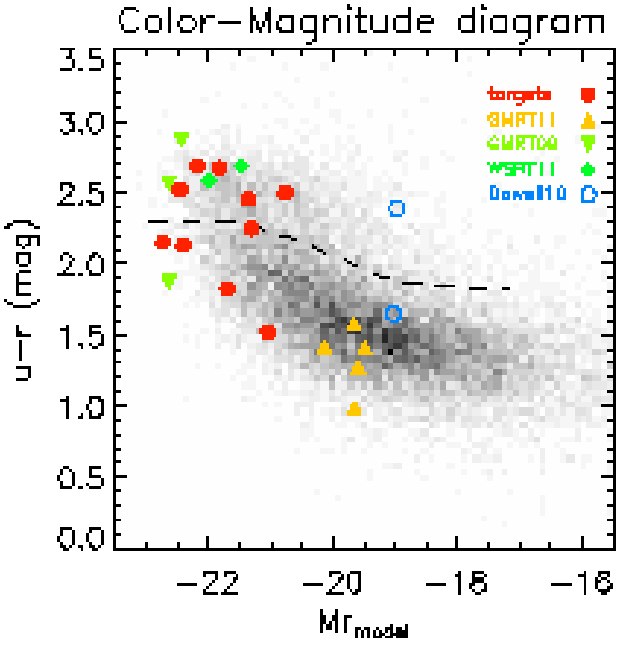
- Perhaps the most surprising result is the richness of the high HI mass population.
- At highest HI mass, we predict 10X more than HIPASS

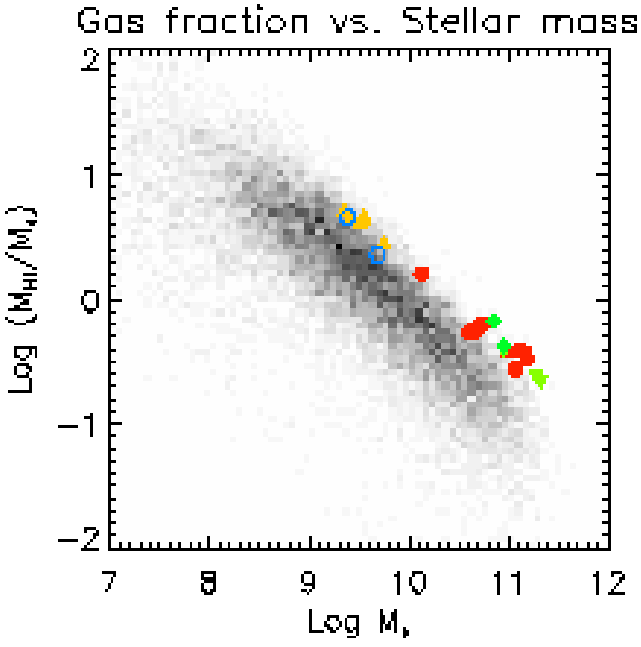
Ann Martin
PhD thesis

ALFALFA

HIghMass: HI-rich massive galaxies

Some of the high HI mass galaxies are exceptionally gas-rich; in some, the HI makes up the dominant form of baryons. How/why?





For the SKA, we need to understand the HI population itself

- M_* calculated from NUV-opt SED fitting
- Account for internal extinction!

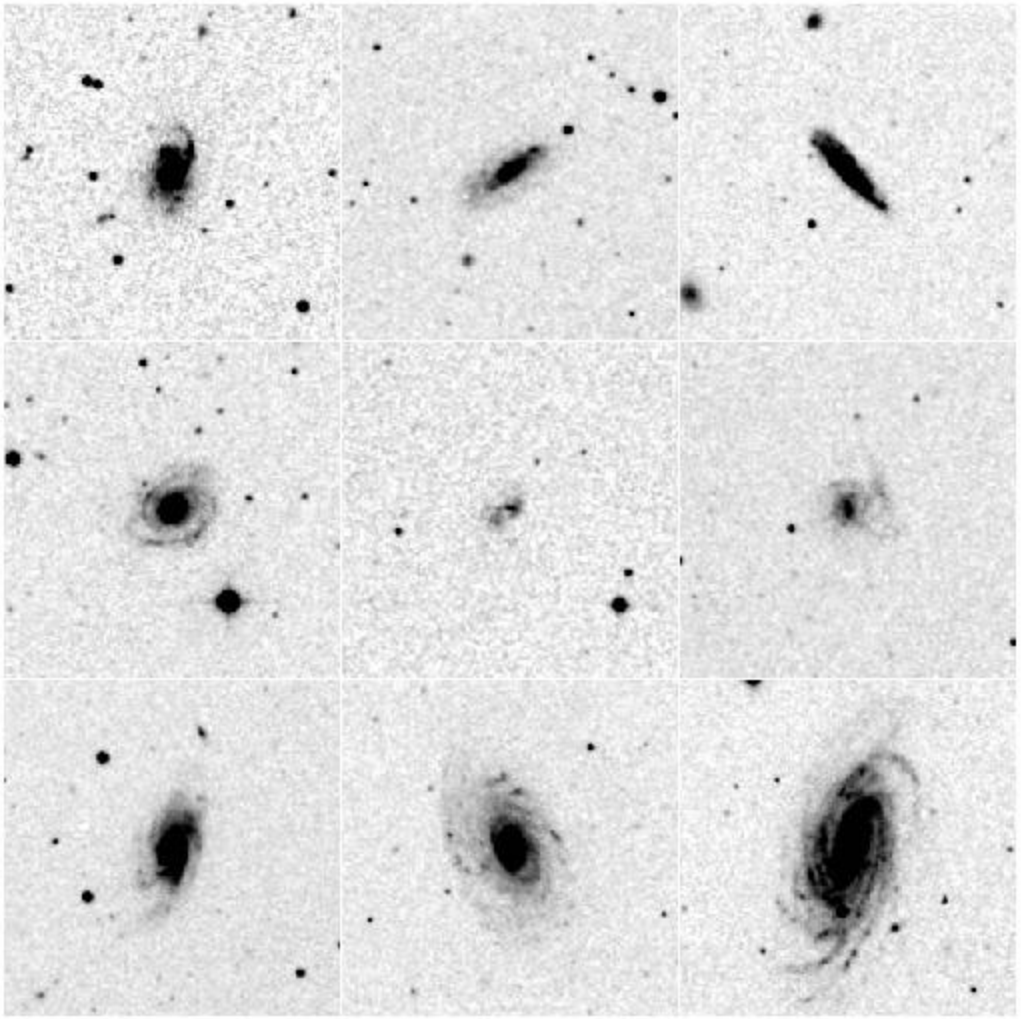
Shan Huang PhD
(In collab w J. Brinchmann)

ALFALFA

HIghMass:
High HI mass, gas-rich galaxies at z~0

ALFALFA detects a rich population with log M_{HI} > 10.

- Candidates to migrate from BC to RS but not yet reached phase of significant SF?
- Alternative mode of (late) accretion?
- => higher than average spin parameter?



ALFALFA

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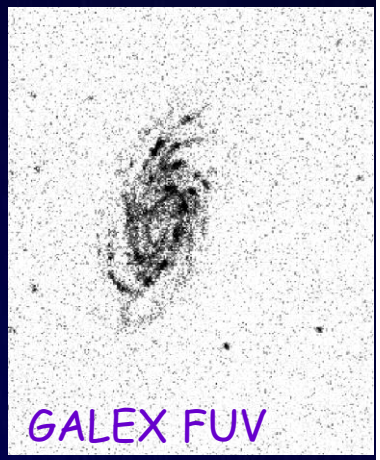
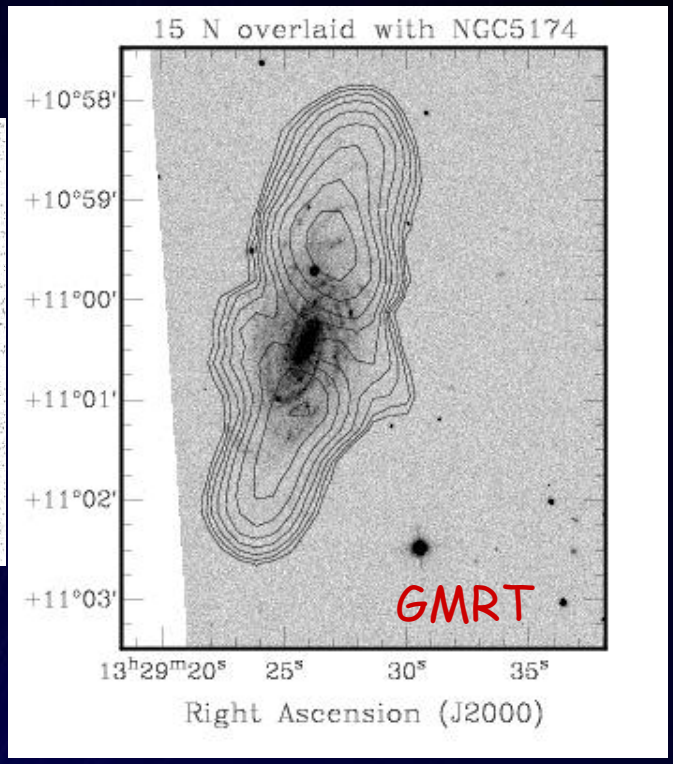
- => higher than average spin parameter?

HI velocity field





Preliminary; Chengalur+

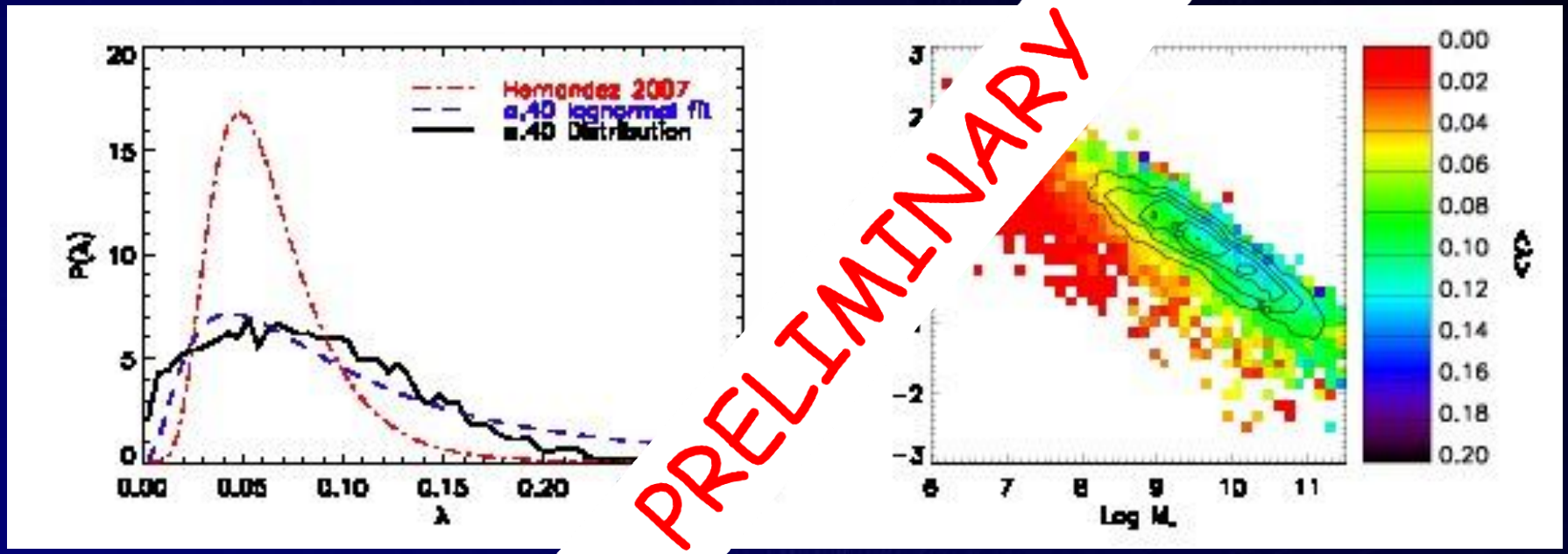
Huang (PhD: GALEX, Herschel, Hα, SED-fitting)
Adams (PhD: GMRT/WSRT)
Hallenbeck (PhD: EVLA, CARMA)

ALFALFA

What is the ALFALFA population?

The spin parameter: $\lambda = J|E|^{1/2}G^{-1}M^{-5/2}$

ALFALFA population is characterized by high spin parameter.



Shan Huang+ (2012b) to be submitted

ALFALFA

ALFALFA: Volume + Sensitivity

- ALFALFA is the first blind HI survey to sample a cosmologically significant volume at z=0
  - Robust determination of HIMF and VF at z=0
  - HI-selected galaxies are weakly clustered on small scales but trace the large scale structure
  - Work on environmental variations continues as ALFALFA completes
- There are **no** "dark" HI galaxies with HI masses > 10^9 $M_\odot$
- ALFALFA sources provide the means to determine the baryon fraction as fn. of halo mass and test models of dropoff at $M_{halo} \sim 10^9$ $M_\odot$ (Manolis' and Riccardo's talks)
- ALFALFA identifies a set of gas-rich Local Group "minihalo" candidates; evidence which will refute or confirm that hypothesis is being sought. (Riccardo's talk... maybe we have found one!)
- ALFALFA detects a previously-unrecognized population of very high HI mass galaxies with HI masses > 10^{10} $M_\odot$; in some, cool gas contributes the dominant form of baryons. => Good news for SKA!
  - There is more ALFALFA to be harvested!

ALFALFA