

# Extragalactic HI Surveys

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UAT Workshop at Green Bank  
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ALFALFA



# Extragalactic HI Surveys: Outline

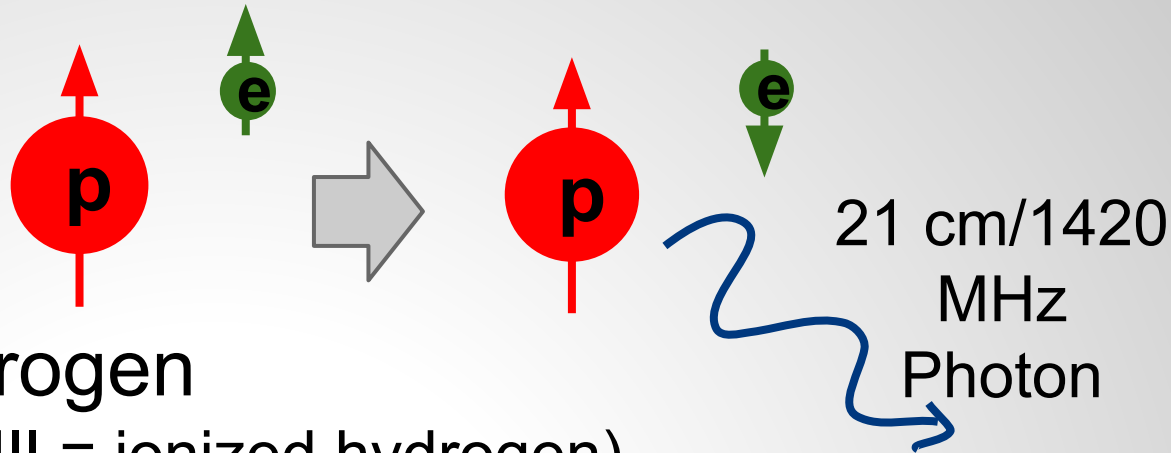
- Review: What is HI?
- Things to think about when designing a survey to look for HI in galaxies
  - The radiometer equation
  - Survey “Figure of Merit”
- Example HI surveys
  - What we do: ALFALFA
  - What we do: APPSS
- The Future of HI Surveys



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# What is HI?



- HI is atomic hydrogen
  - (as opposed to HII = ionized hydrogen)
- Why do we care about HI?
  - **Different biases than optical samples:**
    - Optical misses galaxies with few stars or diffuse objects, we still see them.
    - We see parts of galaxies we otherwise miss - gas traces a galaxy's rotation to large radii.
  - **Stars form from (molecular) gas:**
    - Atomic gas is a galaxy's reservoir of gas.
    - Gas rich galaxies are the galaxies forming stars.

# Survey Design: Blind vs Targeted

- Targeted Surveys:
  - Choose specific galaxies to observe
  - Good: Efficient
  - Bad: Selection bias
- Blind Surveys:
  - Choose where to look without prior knowledge
  - Good: No selection bias
  - Bad: Time consuming (requires sensitive telescopes)



# Survey Design: How Long to Look

- The radiometer equation for our observations

$$S_{\text{rms}} = \frac{(T_{\text{sys}}/G)}{\sqrt{2\Delta f_{\text{ch}} t_{\text{s}} f_t}}$$

For Arecibo LBW:

$$T_{\text{sys}} \sim 30\text{K}$$

$$G \sim 11 \text{ K/Jy}$$

For GBT L-band:

$$T_{\text{sys}} \sim 20\text{K}$$

$$G \sim 2 \text{ K/Jy}$$

- $\Delta f$  : is the bandwidth per channel
- $t_s$  : is the effective integration time, in secs
- $f_t$  : other losses (smoothing, bandpass subtraction, clipping, etc.)
- 2 from two independent polarizations.
- See Giovanelli + 2005, AJ 130, 2598

# How “fast” is your survey?

$$FoM \propto (A_{\text{eff}} / T_{\text{sys}})^2 \Omega_{\text{fov}} BW$$

- HI survey “figure-of-merit” depends on:
  - Sensitivity: Collecting area & system noise
  - field-of-view & number of beams (pixels)
  - Bandwidth (redshift coverage)

# Survey Design: Other Considerations

- Radio frequency interference (RFI)
- Angular Resolution:
  - Source confusion
  - Resolved sources; impact on sensitivity
- Computational requirements
- Telescope Scheduling
  - Possibility of commensal surveys
  - What part of the sky??
- Auxiliary data at other wavelengths?
- And more...



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# Which telescope do you choose?

Arecibo



$D=300\text{m}$

$T_{\text{sys}}=30\text{K}$

$\text{FOV}=7^{\circ}\times 3.5^{\circ}$

Low Confusion

Bad RFI

Limited sky area

GBT

$D=100\text{m}$

$T_{\text{sys}}=20\text{K}$

$\text{FOV}=1^{\circ}\times 9^{\circ}$

High Confusion

Good RFI

Large sky area

Parkes



$D=74\text{m}$

$T_{\text{sys}}=28\text{K}$

$\text{FOV}=13^{\circ}\times 15^{\circ}$

Very High Conf.

Good RFI

Large sky srea

ALFALFA





# Past and Current HI Surveys

Pre-1990s: Targeted Surveys

Mid-90s-present: Blind (and targeted) Surveys

**Table 1** Comparison of major blind HI surveys

Survey	Beam (')	Area (deg <sup>2</sup> )	$\delta_v$ (km s <sup>-1</sup> )	rms <sup>a</sup> (mJy)	$V_{\text{med}}$ (km s <sup>-1</sup> )	$N_{\text{det}}$
AHISS	3.3	13	16	0.7	4800	65
ADBS	3.3	430	34	3.3	3300	265
HIPASS	15.	30000	18	13	2800	5000
AGES	3.5	200	11	0.7	9500	2900
ALFALFA	3.5	6920	11	1.7	8200	31000

ALFALFA



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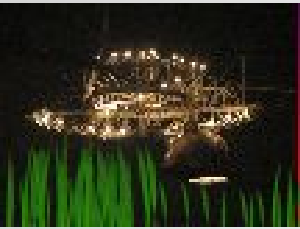
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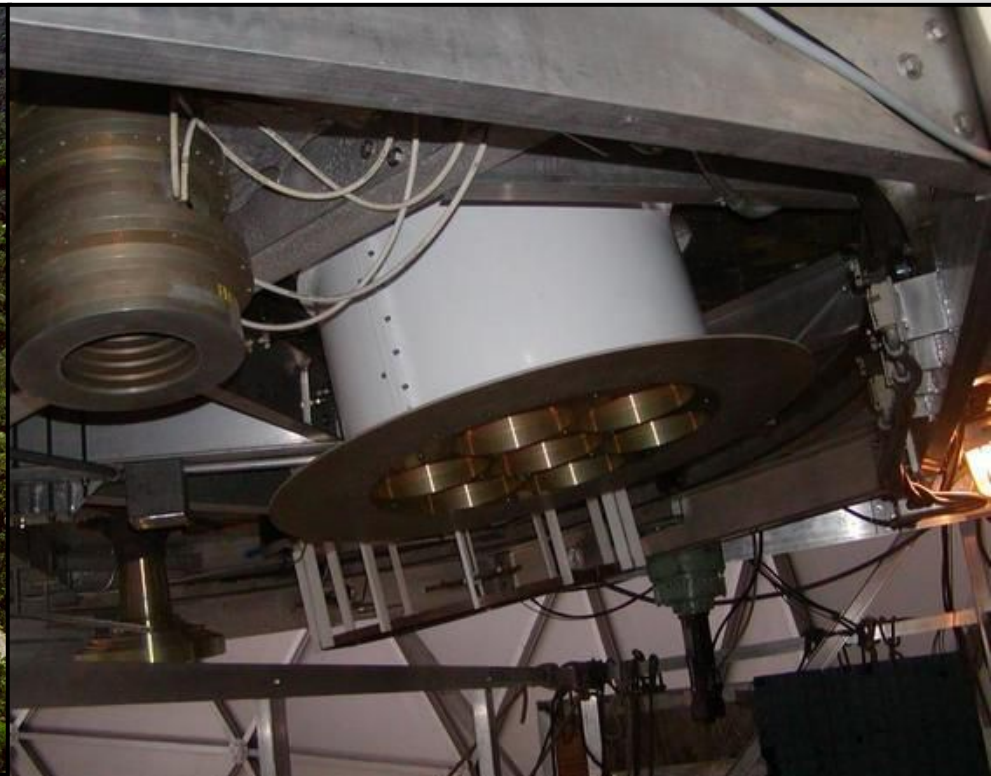


# Design to Practice: Introducing...

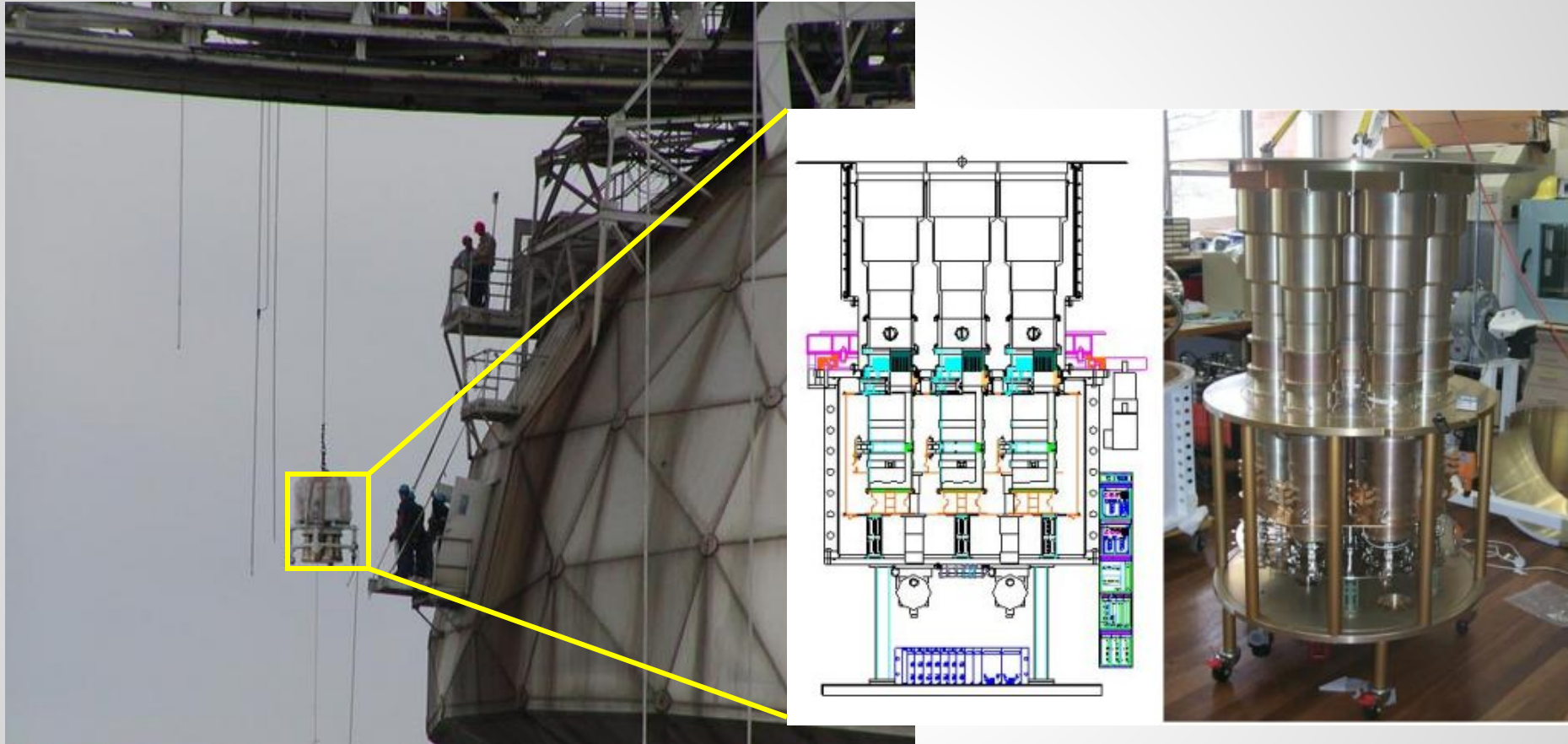


## The Arecibo Legacy Fast ALFA Survey

ALFA = Arecibo L-band Feed Array



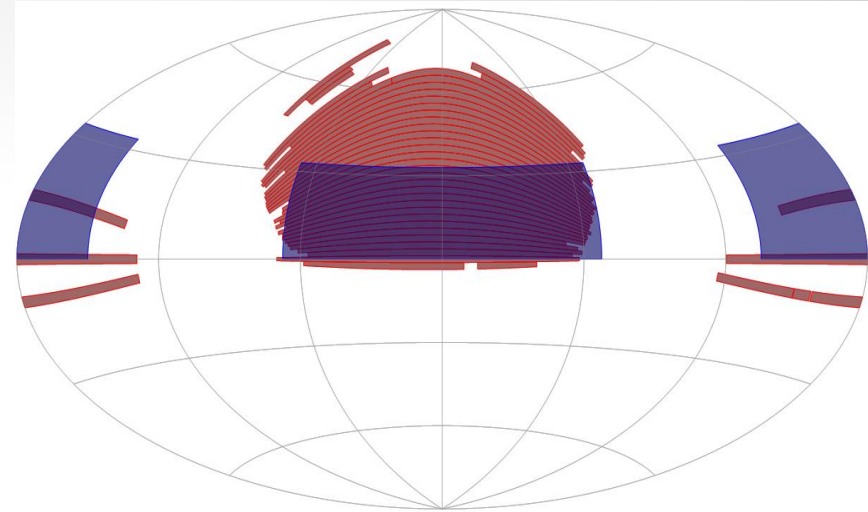
# ALFA: A “Radio Camera”



Arecibo L-band Feed Array (ALFA)

# So what is ALFALFA?

- A radio survey at 21cm
  - 4x better resolution and 10x better sensitivity than previous 21cm surveys
- Survey of local galaxies
  - $z \leq 0.06$ , ie distance  $\leq 250$  Mpc (local group  $\sim 1$  Mpc)
- “Blind” Survey of  $\sim 17\%$  of the sky
- A perennial flowering plant in the pea family; often feeds large farm animals

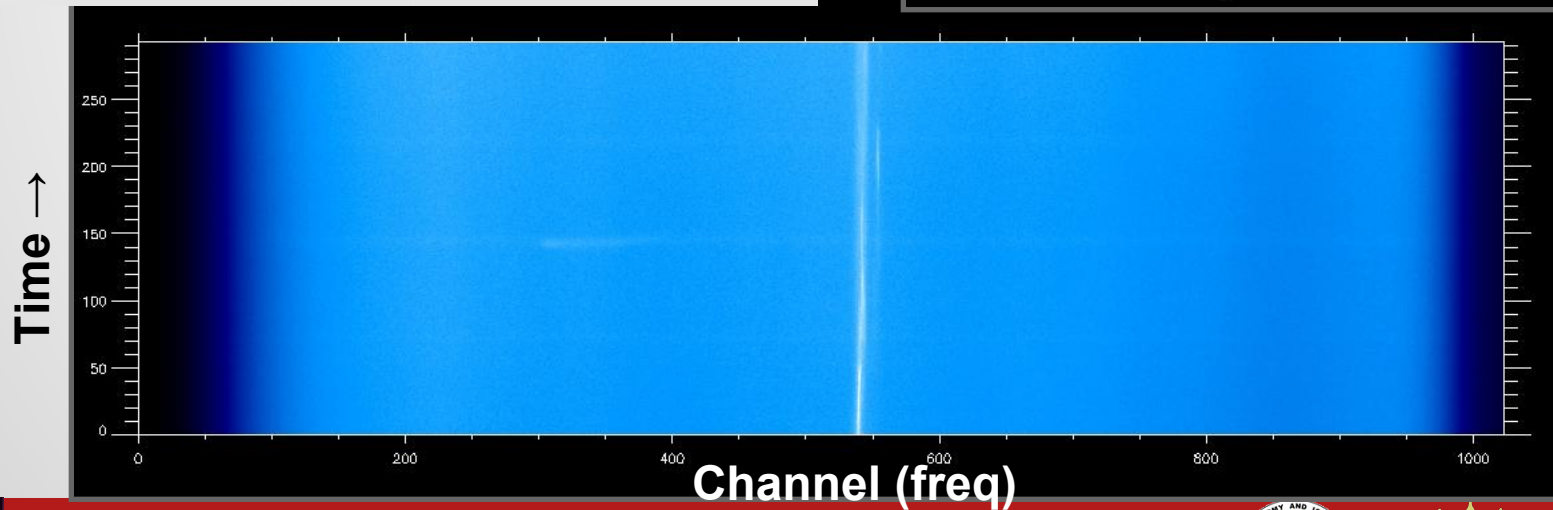
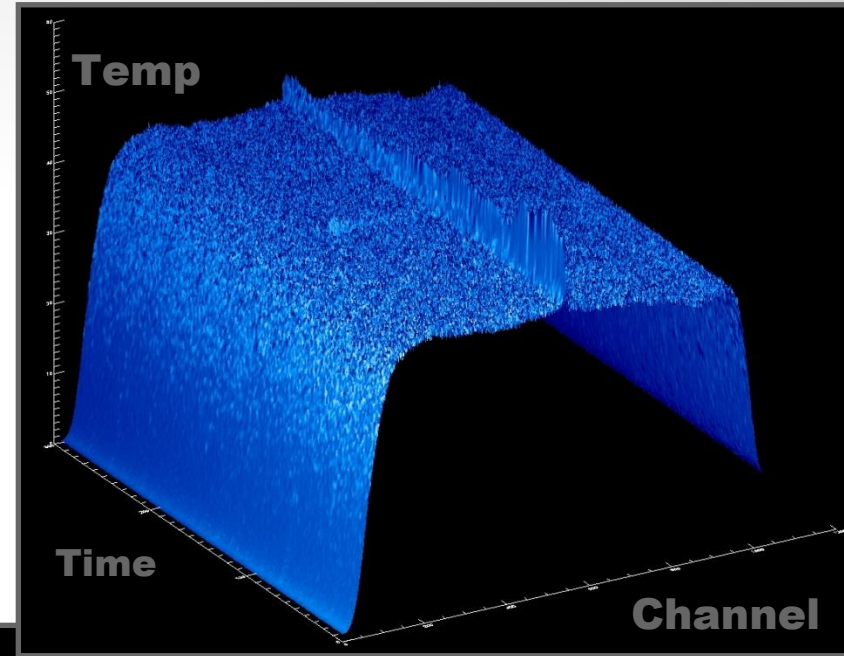


ALFALFA



# How does ALFALFA work?

- Observing: Drift scan

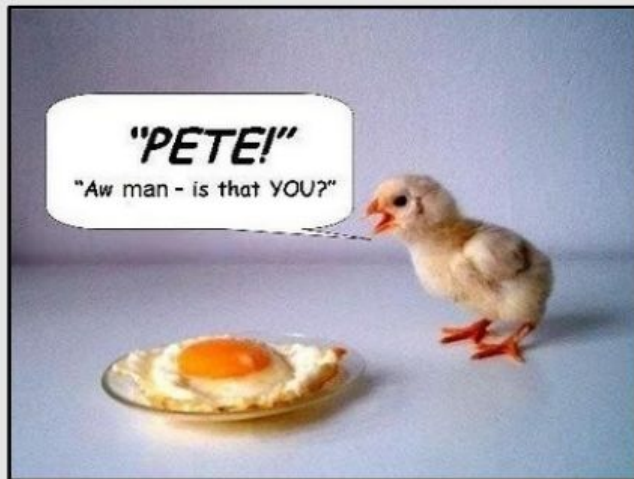


ALFALFA

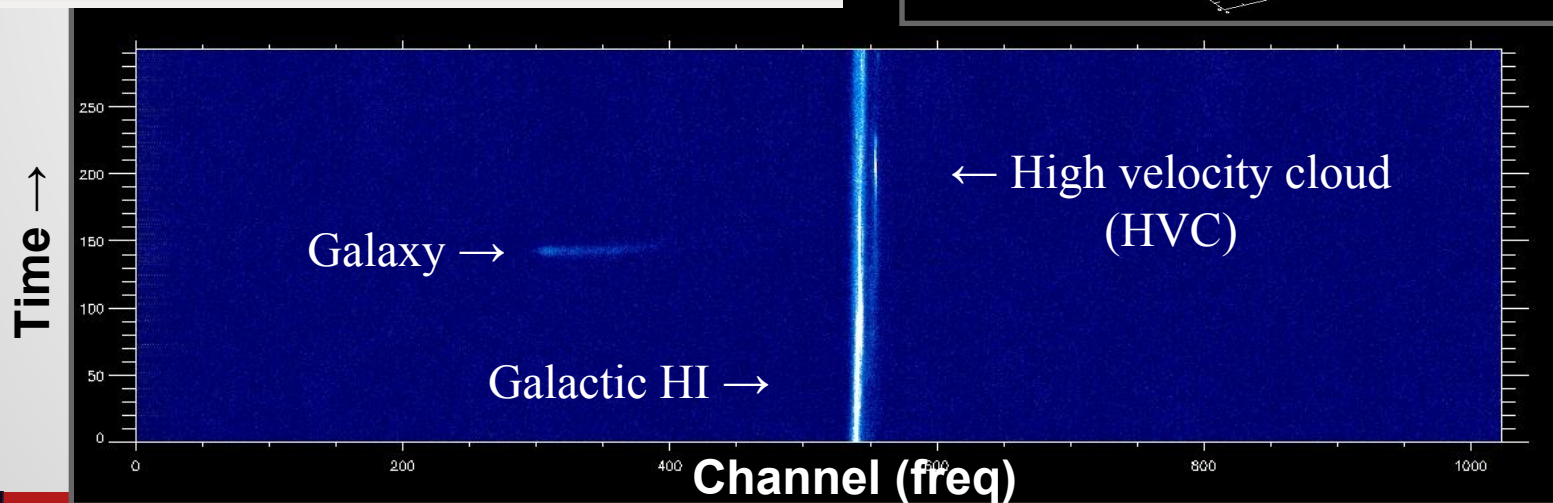
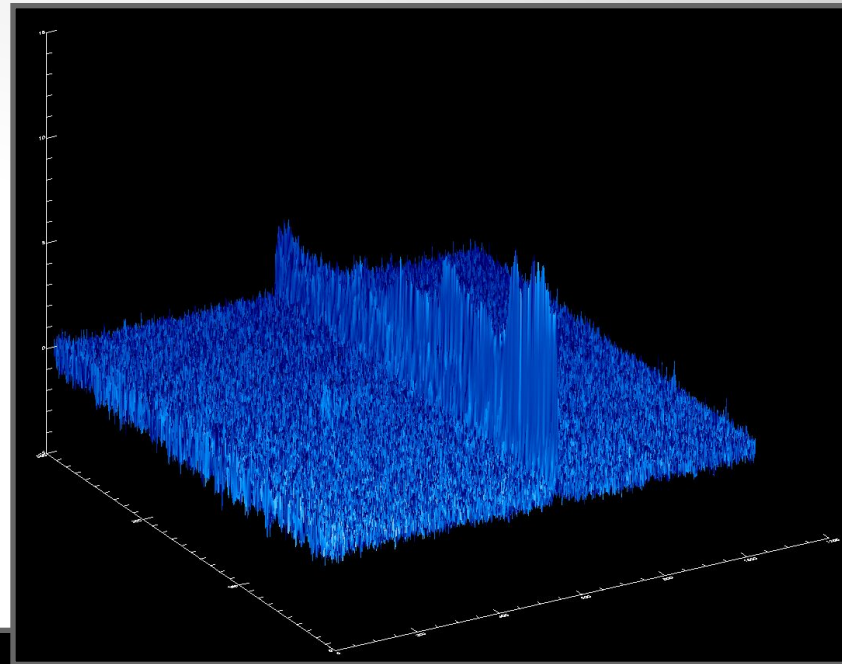


# How does ALFALFA work?

- Data reduction



"If you want to make omelettes you've got to break some eggs!"



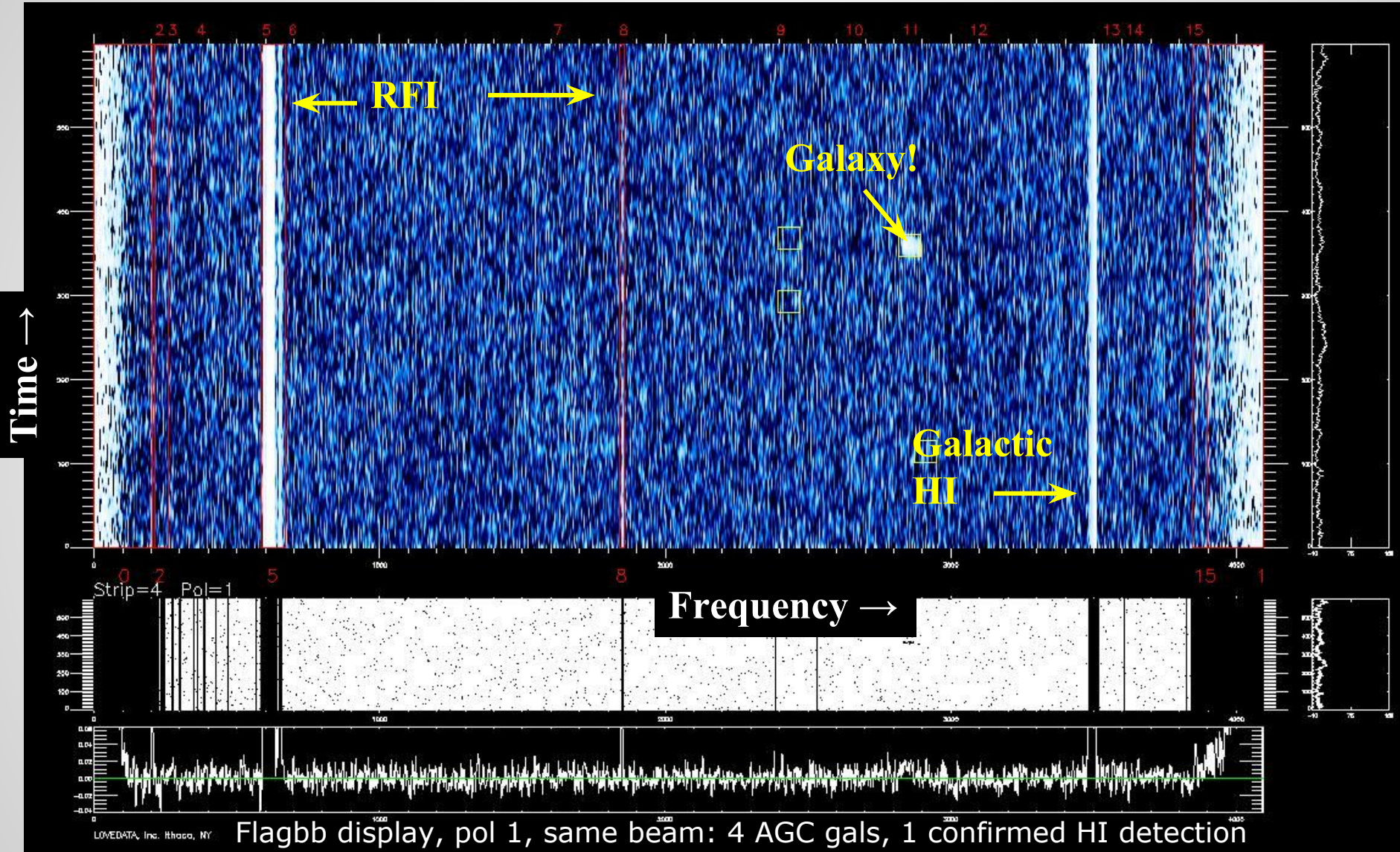
ALFALFA



15



# Dealing With RFI...



LOVEDATA, Inc. Ithaca, NY

Flagbb display, pol 1, same beam: 4 AGC gals, 1 confirmed HI detection

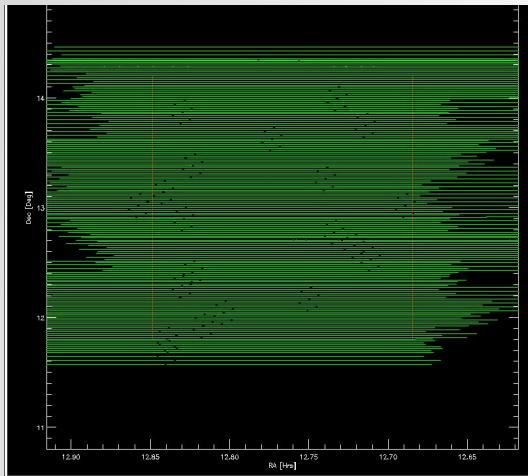
UAT 16.06

ALFALFA Channel

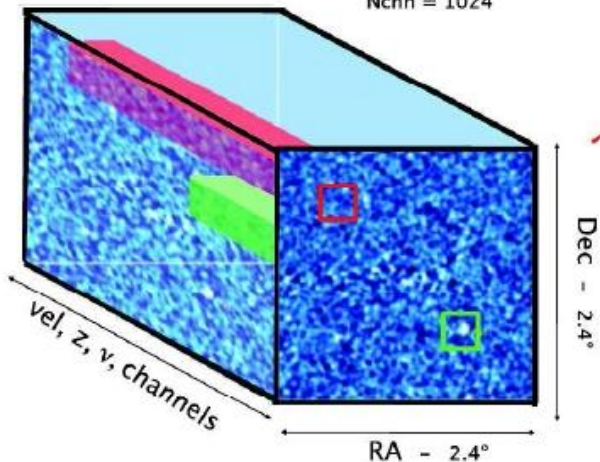




# From Drifts to Grids



$\Delta v = 25 \text{ MHz}$   
 $\Delta v \approx 5.500 \text{ km/s}$   
 $N_{\text{chn}} = 1024$



- Combine individual drift scans to produce a 3-D data cube, “grid”
- Standard ALFALFA grids are  $2.4^\circ \times 2.4^\circ$
- Each “grid” region of the sky is split into 4 frequency (cz), partially overlapping cubes, of 1024 freq/vel chans/each

# Source Extraction

ALFALFA Catalog creator

File Imaging

- (1) HI152947.8+260508\_1532+25a.src
- (2) HI152953.5+041105\_1532+05c.src
- (1) HI152956.8+072646\_1532+07d.src
- (1) HI153000.8+125922\_1532+13b.src
- (2) HI153003.0+261846\_1532+27d.src
- (4) HI153004.8+083711\_1532+09c.src
- (1) HI153009.3+252804\_1532+25c.src
- (4) HI153009.5+073415\_1532+07d.src
- (1) HI153011.6+055013\_1532+05b.src
- (5) HI153013.3+240023\_1532+25d.src
- (1) HI153020.8+074941\_1532+07c.src
- (3) HI153022.7+102807\_1532+11b.src
- (1) HI153023.9+271608\_1532+27a.src
- (1) HI153031.3+065630\_1532+07b.src
- (1) HI153031.9+144209\_1532+15b.src
- (1) HI153032.8+251550\_1532+25b.src
- (1) HI153034.0+050850\_1532+05c.src
- (1) HI153035.0+264447\_1532+27b.src
- (1) HI153037.2+272859\_1532+27c.src

STATUS

- ◇ (0) No status
- ◇ (1) Detection
- ◇ (2) Prior
- ◇ (3) Marginal
- ◇ (4) Low StN
- ◇ (5) Prior-
- ◇ (9) HVC

Mark \ Unmark

HI152947.8+260508  
 V50,W50: 2019.5 68.2+/- 5.5 km/s  
 V20,W20: 2019.8 107.4+/- 5.5 km/s  
 Vcen: 2016.2+/- 2.7 km/s  
 V,W Gauss: 0.0 0.0+/- 0.0 km/s  
 Stot(profile, P): 2.02+/- 0.07 Jy km/s  
 Stot(profile, G): 0.00+/- 0.00 Jy km/s  
 Map Stot: 1.92+/- 0.00 Jy km/s  
 meanS, peakS: 11.7 27.6 mJy  
 S/N P: 23.1 12.4 11.7 29.0  
 S/N G: 0.0 0.0 0.0 0.0  
 Cont: 13. mJy  
 Status Code: 1

(l,b) = ( 40.49, 54.74) degrees  
 Cen\_ell: 152949.3+260515 [2000]  
 Opt pos: 152948.2+260516 [2000]  
 dRA: -1.07685 sec  
 dDec: 1.33 arcsec  
 Ellipse: 4.0 x 3.5 PA= -18.  
 Isophote: 880. mJy km/s  
 Map Smax: 1759. mJy km/s  
 rms: 2.35 mJy  
 AGC727130

MODIFY PARAMETERS

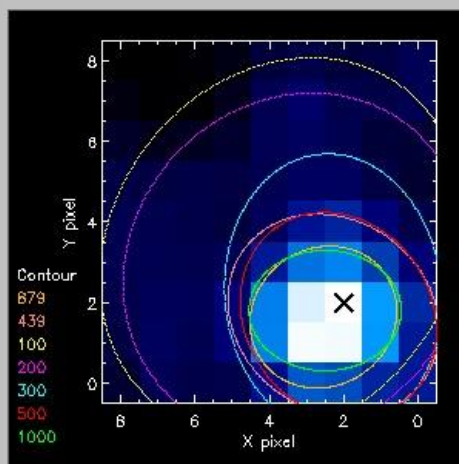
Optical Coordinates

Signal/Noise

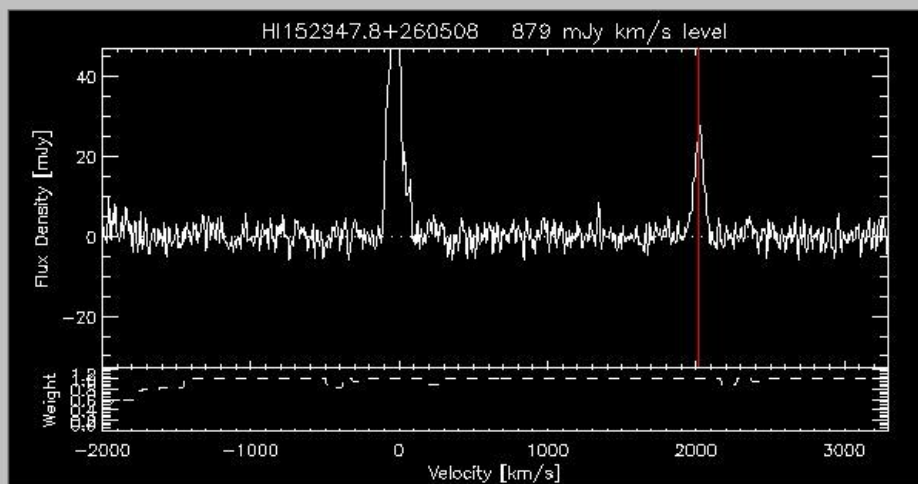
cz Err Stat/Sys  /

Width Err Stat/Sys  /

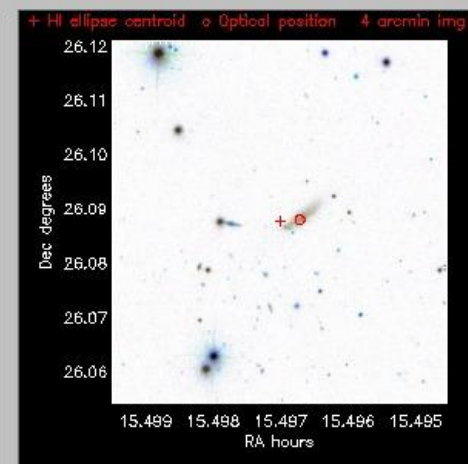
AGC Number  cz(opt)



Select Isophote:



SDSS ObjID: 587739382067167453 specObjID: 609061544193425408  
 petroMag(Err): u= 17.91( 0.09) g= 17.06( 0.02) r= 16.82( 0.01) i= 16.65( 0.04) z= 16.89( 0.11)  
 extinct: u= 0.27 g= 0.20 r= 0.14 i= 0.11 z= 0.08  
 petroR50\_r: 6.11 petroR90\_r: 13.46 expAB\_r: 0.33



SDSS Navigator  
 SkyView  
 NED

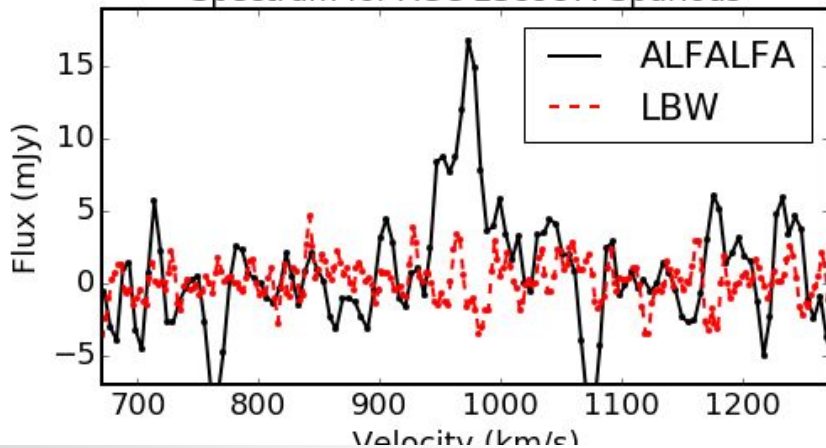
# ALFALFA



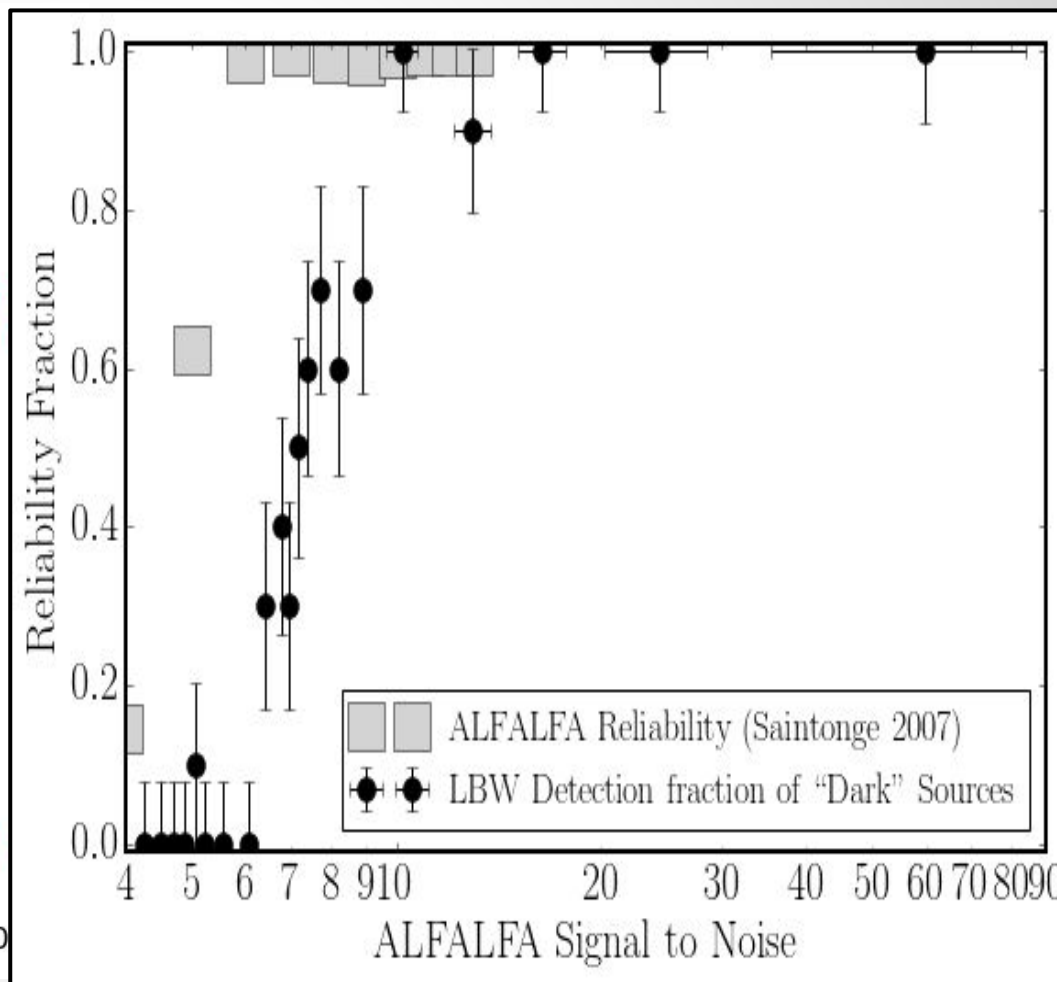
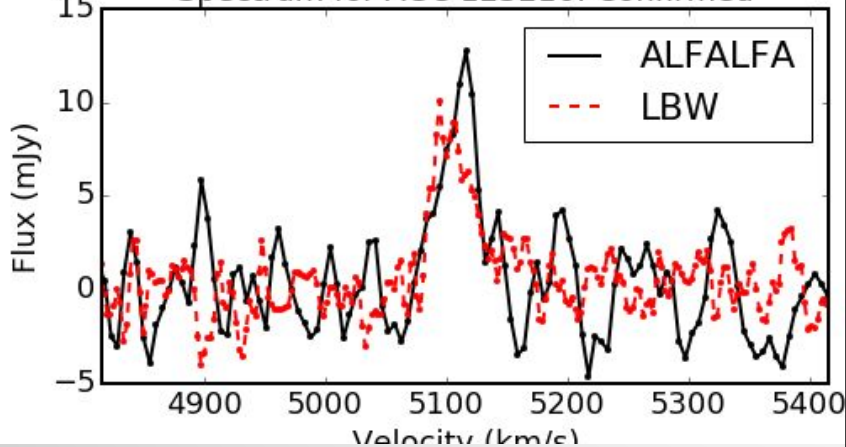
# Problem: are the detections real?

Solution: follow up with more Arecibo observations

Spectrum for AGC 238987: Spurious



Spectrum for AGC 123216: Confirmed

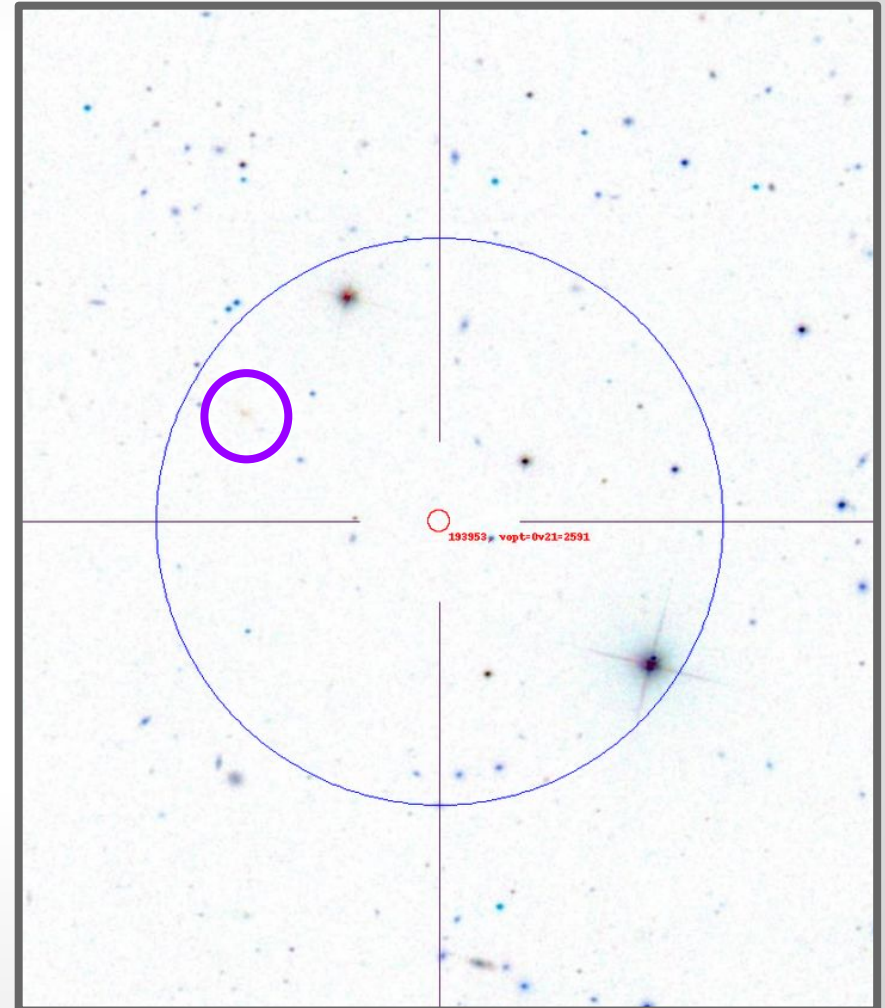


ALFALFA



# Identifying Optical Counterparts

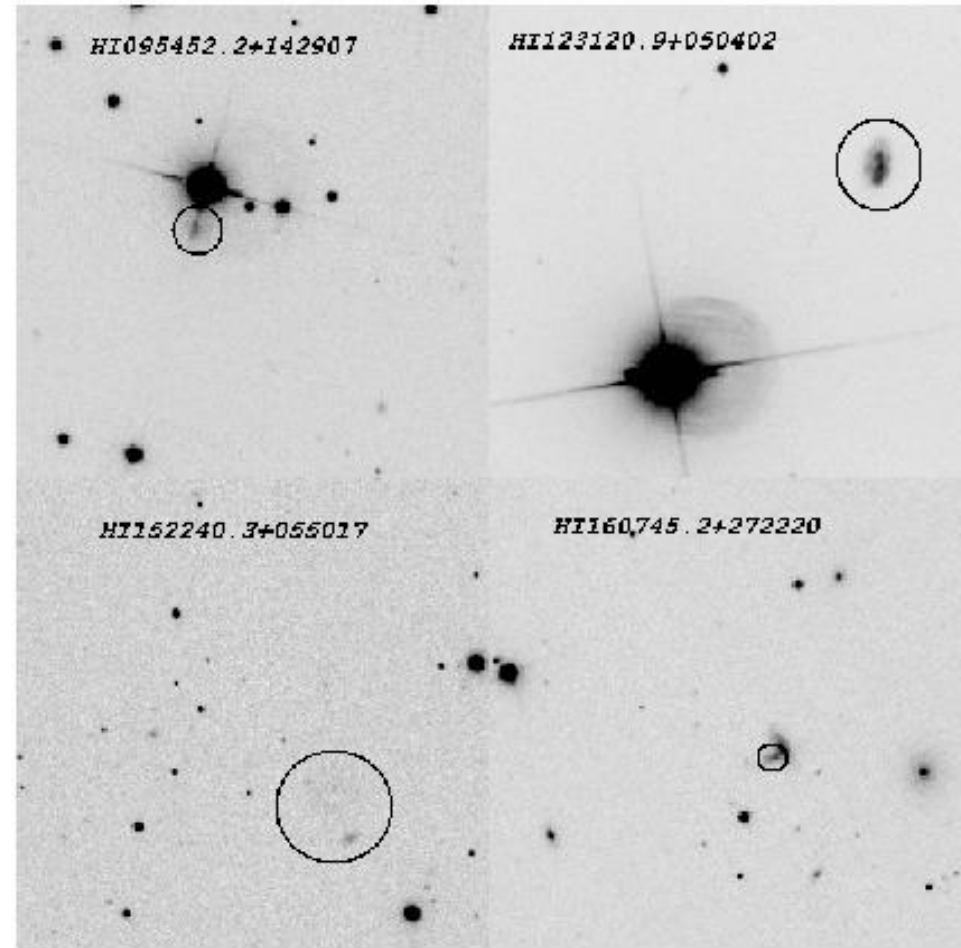
- ALFALFA does not resolve galaxies
- Beam (resolution)  $\sim 3.5'$  ( $\sim 200\times$  normal optical telescopes)
- Sources not in the center of the beam
- Sometimes stars in the way



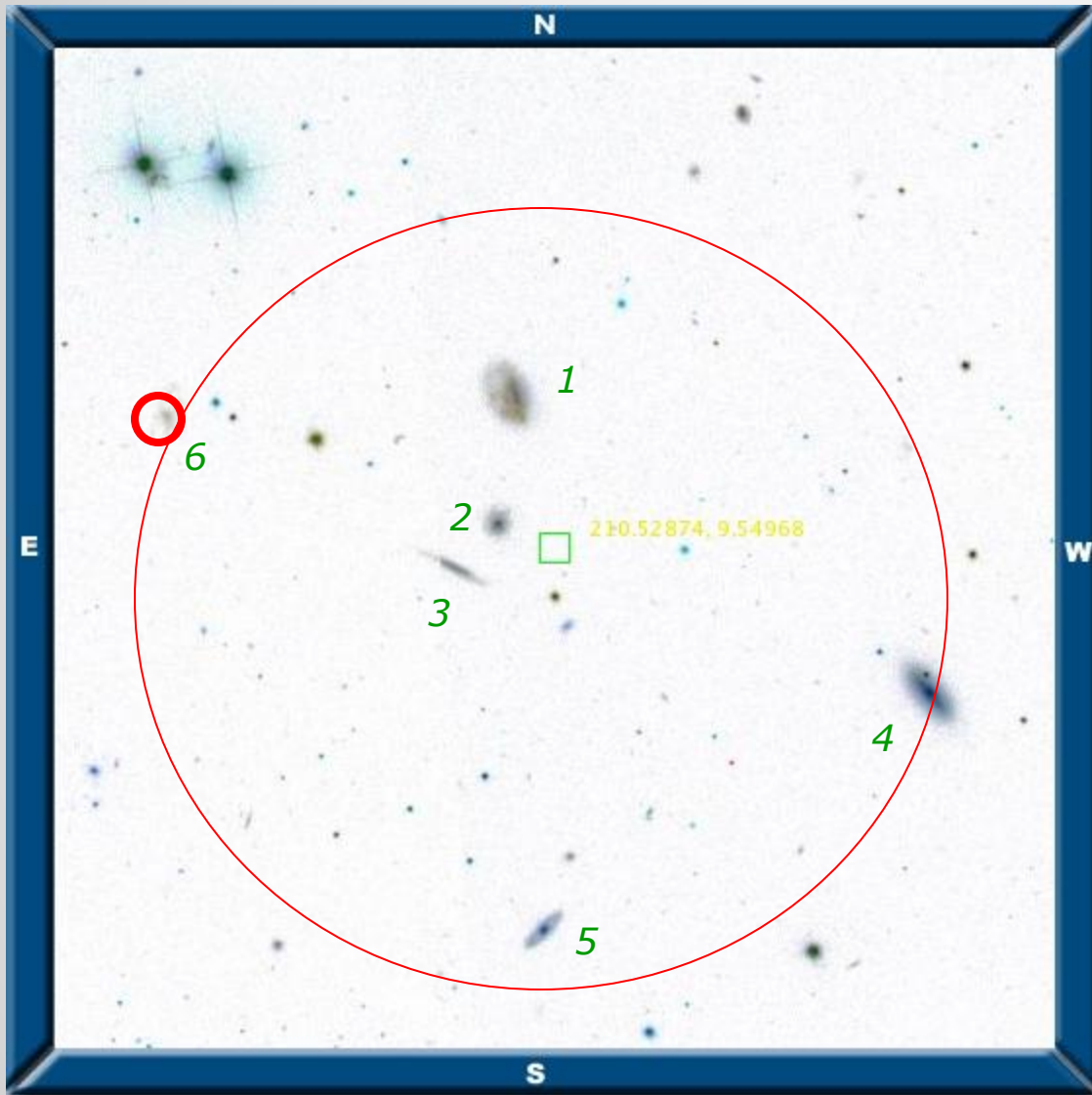
# Identifying Optical Counterparts

Of 15855 sources in  $\alpha.40$ :

- 1013 have no OC
- 844 are likely part of the MW
- 199 (<2%) extragalactic “darks”
- Of those, <50 are “isolated”



# ALFALFA advantage for finding the OC



Centroiding accuracy goes roughly as  $\text{HPFW}(\text{PSF})/(\text{S/N})$

Suppose HIPASS detects a source at  $\text{S/N} \sim 6$  near 3000 km/s in this field. The position error box will have a radius of  $\sim 2.5'$ .

The opt counterpart could be gal #1, 2, 3, 4, 5 or 6.

ALFALFA will detect the same source with  $\text{S/N} \sim 50!!$

and the Arecibo beam is  $\frac{1}{4}$  as wide as the Parkes one

→ The same source will have an ALFALFA position error of  $\sim 0.1'$

# The current state of ALFALFA

- Observing is done!
  - 4742 hours over almost 8 years
  - 808 observing runs
  - 99 observers
- All level 1 processing done
- Catalog >70% complete
- >25,000 extragalactic sources!



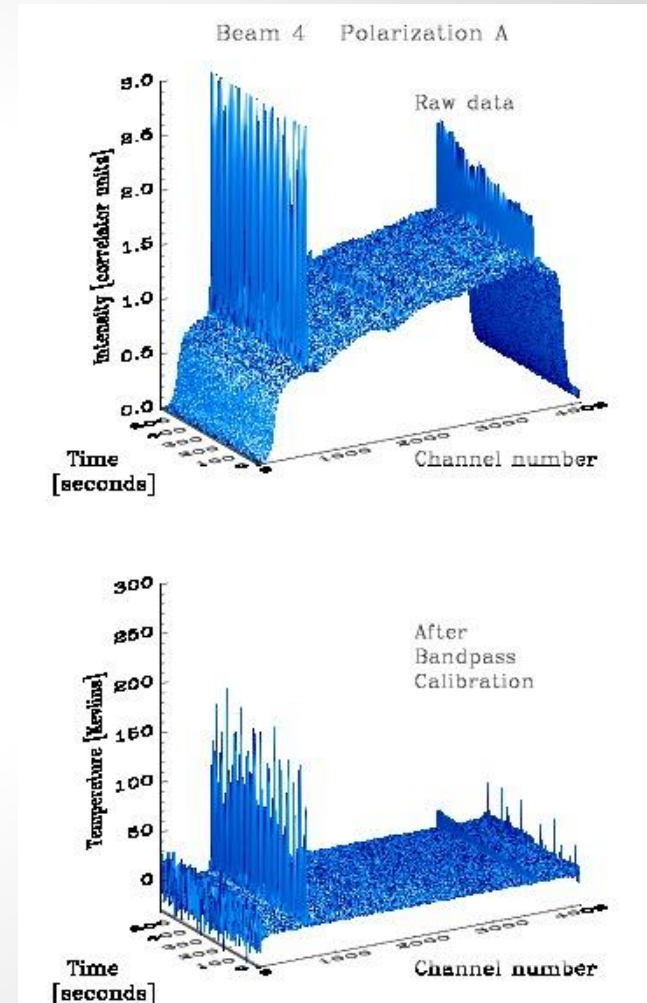
ALFALFA



# Aside:

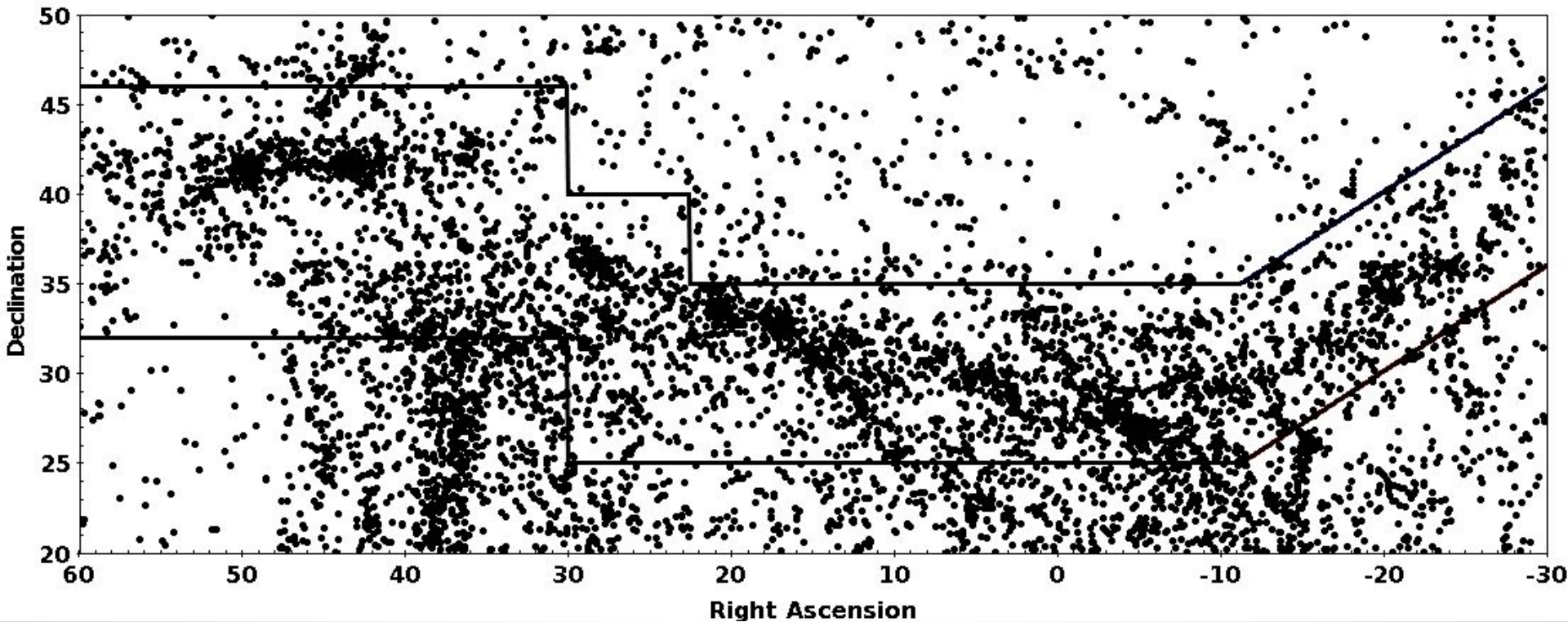
## Drift Scan vs Position Switching

- Sources much weaker than noise ( $T_{\text{sys}}$ )
- Need to subtract away known noise = blank sky
  
- Drift scan: lots of blank sky
- Pointed observing: Need to also point at blank sky (ON/ OFF pointings)





# APPSS



ALFALFA



# Future HI Surveys: Interferometers

## Upgraded Telescopes

The JVLA



WSRT



## New Telescopes

ASKAP



MeerKAT



ALFALFA



# Future HI Surveys

Survey	Res.# (")	Area (deg <sup>2</sup> )	$z$	$N_{\text{det}}^{\dagger}$	Ref	Note
VLA-B						
CHILES	5	0.8	<0.5	300	a	COSMOS deep field
WSRT/APERTIF						
WNSHS*	15	3500*	<0.26	50000*	b	Shallow, wide area
MediumDeep*	15	200*	<0.26	$1 \times 10^5$ *	c	Selected fields
ASKAP						
WALLABY	30	30000	<0.26	$>3 \times 10^5$	d	Shallow, wide area
DINGO-DEEP	10	150	0.1–0.26	50000	e	GAMA region
DINGO-UDEEP	10	60	0.1–0.43	50000	e	GAMA region
FLASH	30	Targeted	0.5-1.0	few 100s	f	HI absorption
MeerKAT						
MHONGOOSE <sup>&amp;</sup>	12	$30 \times 0.8$		$30^{\&}$	g	30 nearby galaxies
LADUMA	12	4	<1.4	10000	h	ECDF-S deep field

Giovanelli & Haynes 2016

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# Summary

- Lots to consider designing HI surveys
  - How long to look
  - How fast can you survey a volume of space
  - Lots of other things (RFI, confusion, etc.)
- ALFALFA is a state of the art blind HI Survey
  - Drift scan observing
  - Lots of reduction steps
  - Identifying OCs
- Lots of Exciting Future Science
  - APPSS
  - Surveys with upgraded and new telescopes



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