

# Introduction to ALFA and ALFALFA

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UAT11 11.01.17



ALFALFA

# ALFALFA: A Census of Gas-bearing Galaxies



- A galaxy is a gravitationally bound object that consists of billions (and billions) of stars, gas clouds (of varying temperature and density = interstellar medium), dust clouds (mixed with the gas), and (so it seems), 90% dark matter.
- Optical surveys, like the Sloan Digital Sky Survey, detect the stellar component of galaxies.
- ALFALFA is designed to detect the cool (not hot; not cold) atomic gas in and near galaxies.
- ALFALFA is a blind survey; we observe the whole area of sky, whether or not we think/know there is an optical galaxy there.
- ALFALFA is a spectroscopic survey; not only do we detect the HI line flux, we also measure its frequency (velocity) and the width of the HI line (a measure of rotational velocity).

2



ALFALFA

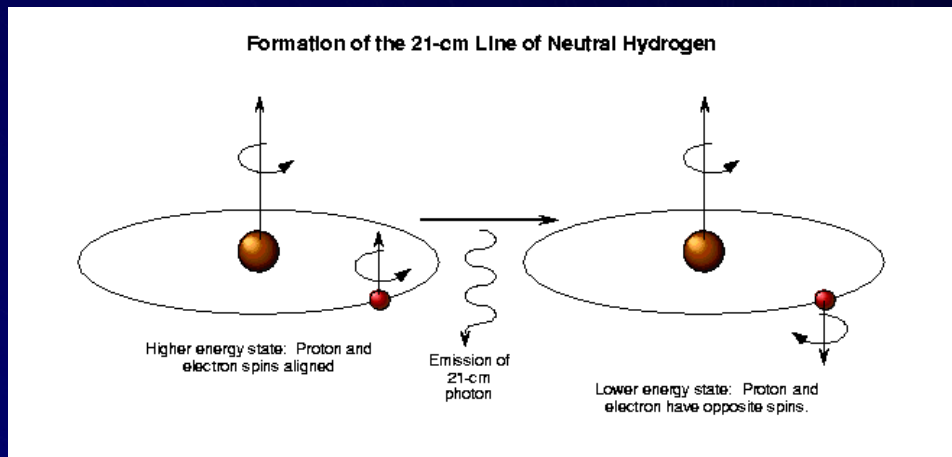
# 21-cm Line of Atomic HI



Through Hydrogen maser measurements the frequency is:  
 $1,420,405,751.7667 \pm 0.0010$  Hz

$$\text{Energy } hc/\lambda \sim 5 \times 10^{-6} \text{ eV}$$

Compared to energy of a visible light photon which is about 2 eV.



About 4.4% of the visible matter in our galaxy is HI  
 $\Rightarrow 4.8 \times 10^9 M_{\odot}$ .

The fraction of interstellar space filled with HI clouds is 20% to 90%.

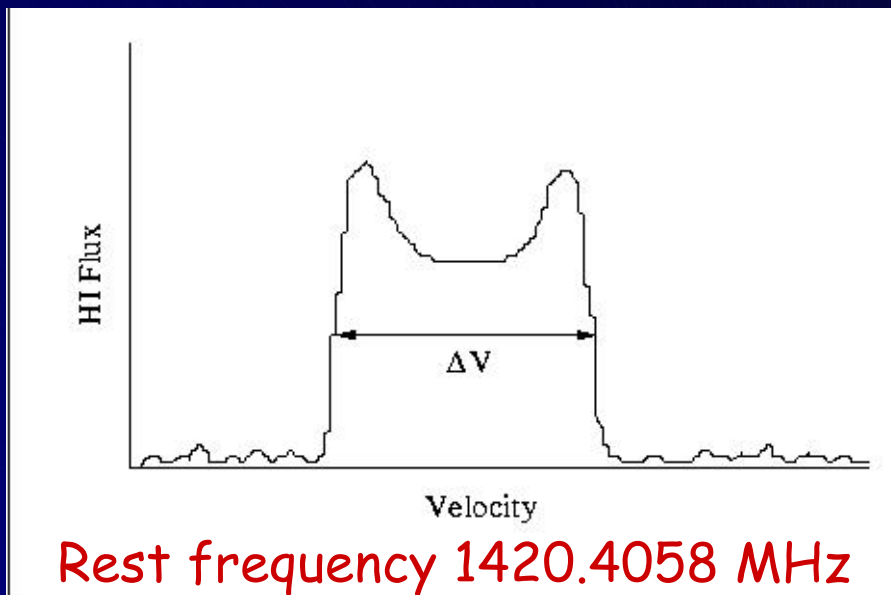
- In the MW there are some  $10^{66.5}$  HI atoms;
- At the rate  $A_{10}$ , about  $10^{52}$  atoms per sec would emit a photon.
- In reality, the transition probability is  $10^5$  times larger than  $A_{10}$
- Hence the galactic HI emission is very easily detectable.



# HI emission from galaxies



- Under most circumstances, the total H I mass can be derived from the integrated line profile; that is, **the flux** (integrated over all frequencies where there is signal) is **proportional to the number** of hydrogen atoms.
- The frequency (velocity) spread of the line reflects the velocities of the gas atoms, not quantum mechanics => hence the **width of the line** tells about the **motions of the gas** (rotation within the galaxy or turbulence, expansion, etc)



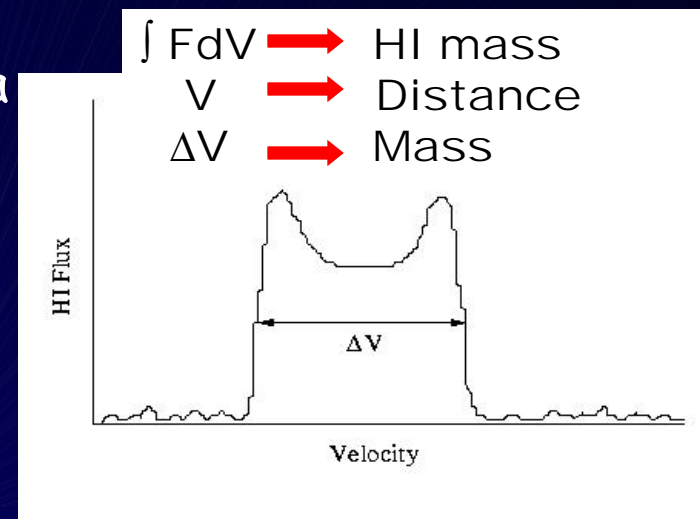
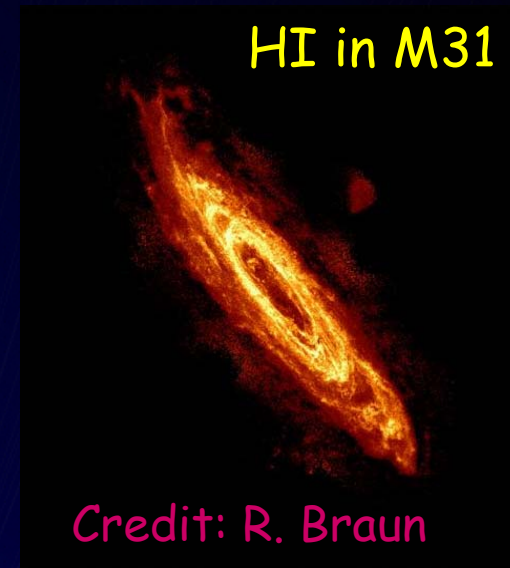
$$\int F dV \longrightarrow \text{HI mass}$$
$$V \longrightarrow \text{Distance}$$
$$\Delta V \longrightarrow \text{Mass}$$



# Clues from the HI line



- **Redshifts** ( $\Rightarrow$  distances via Hubble's Law)
- **HI mass and distribution** (for extended objects)
  - Normal, star-forming disks
  - Low mass, LSB dwarfs
  - Potential for future star formation (HI content)
  - HI deficiency in clusters
  - History of tidal events
- **Rotational velocities**
  - Dark matter
  - Redshift-independent distances via Tully-Fisher relation
- **HI absorption**: optical depth
  - Link to Ly- $\alpha$  absorbers
  - Fundamental constant evolution



# HI: The fuel for star formation

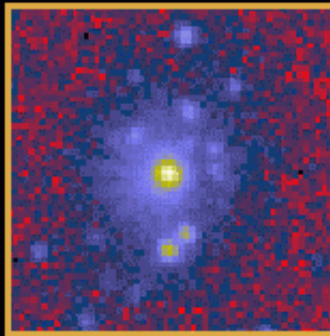


## M81 – Spiral Galaxy (Type Sb)

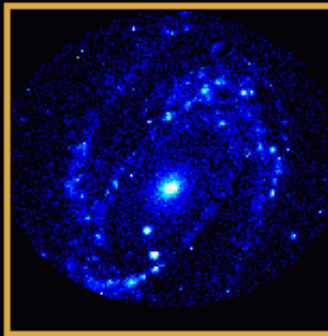
Distance: 12,000,000 light-years (3.7 Mpc)

Image Size = 14 x 14 arcmin

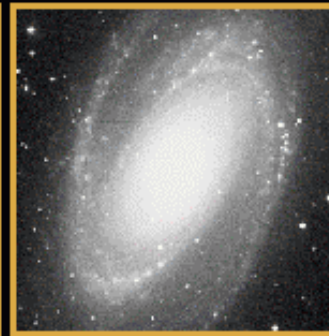
Visual Magnitude = 6.9



X-Ray: ROSAT



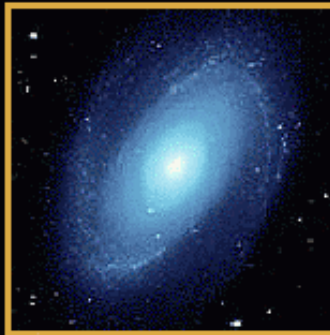
Ultraviolet: ASTRO-1



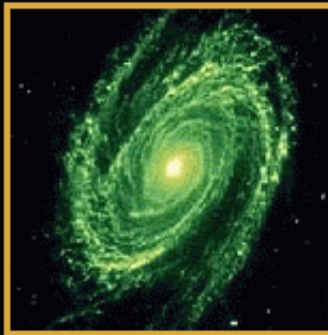
Visible: DSS



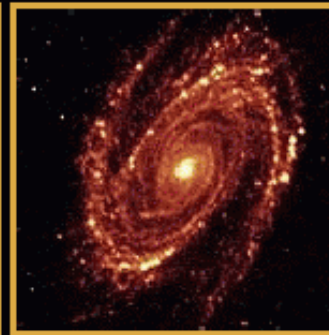
Visible: R. Gendler



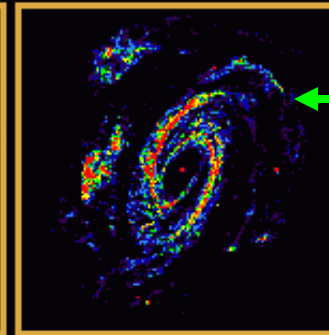
Near-Infrared: Spitzer



Mid-Infrared: Spitzer



Far-Infrared: Spitzer



Radio: VLA

HI  
21 cm  
line

[http://coolcosmos.ipac.caltech.edu/cosmic\\_classroom/multiwavelength\\_astronomy/multiwavelength\\_museum/m81.html](http://coolcosmos.ipac.caltech.edu/cosmic_classroom/multiwavelength_astronomy/multiwavelength_museum/m81.html)



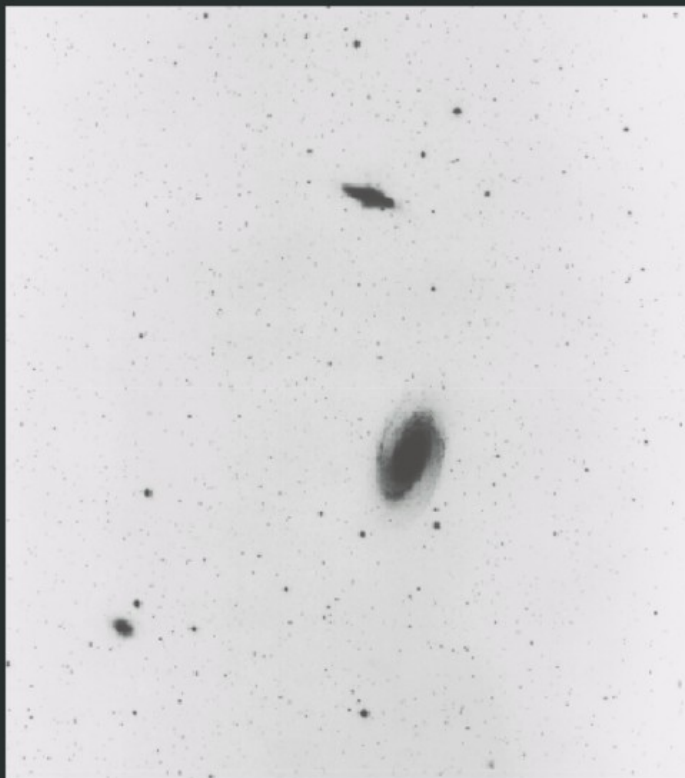
ALFALFA

In some cases, the HI reveals interaction where the optical does not: M81/M82 system

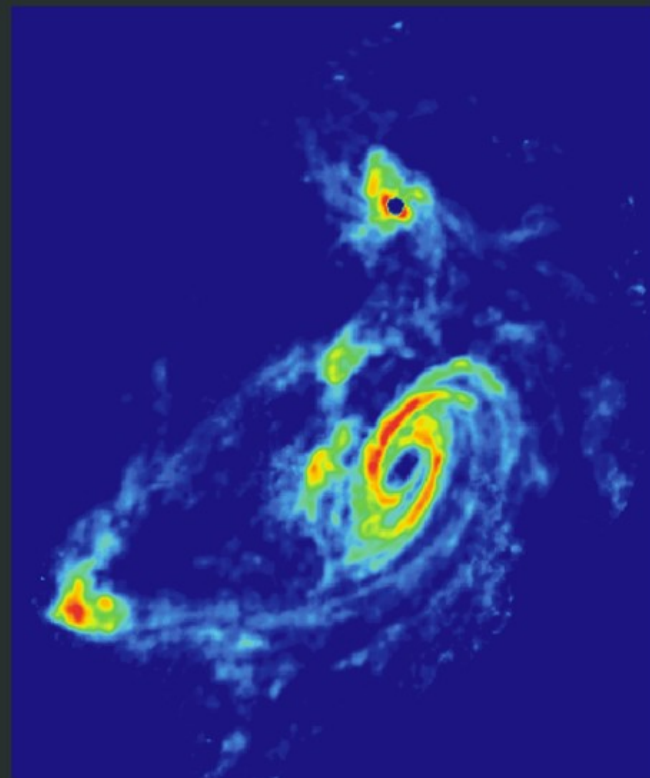


## TIDAL INTERACTIONS IN M81 GROUP

Stellar Light Distribution



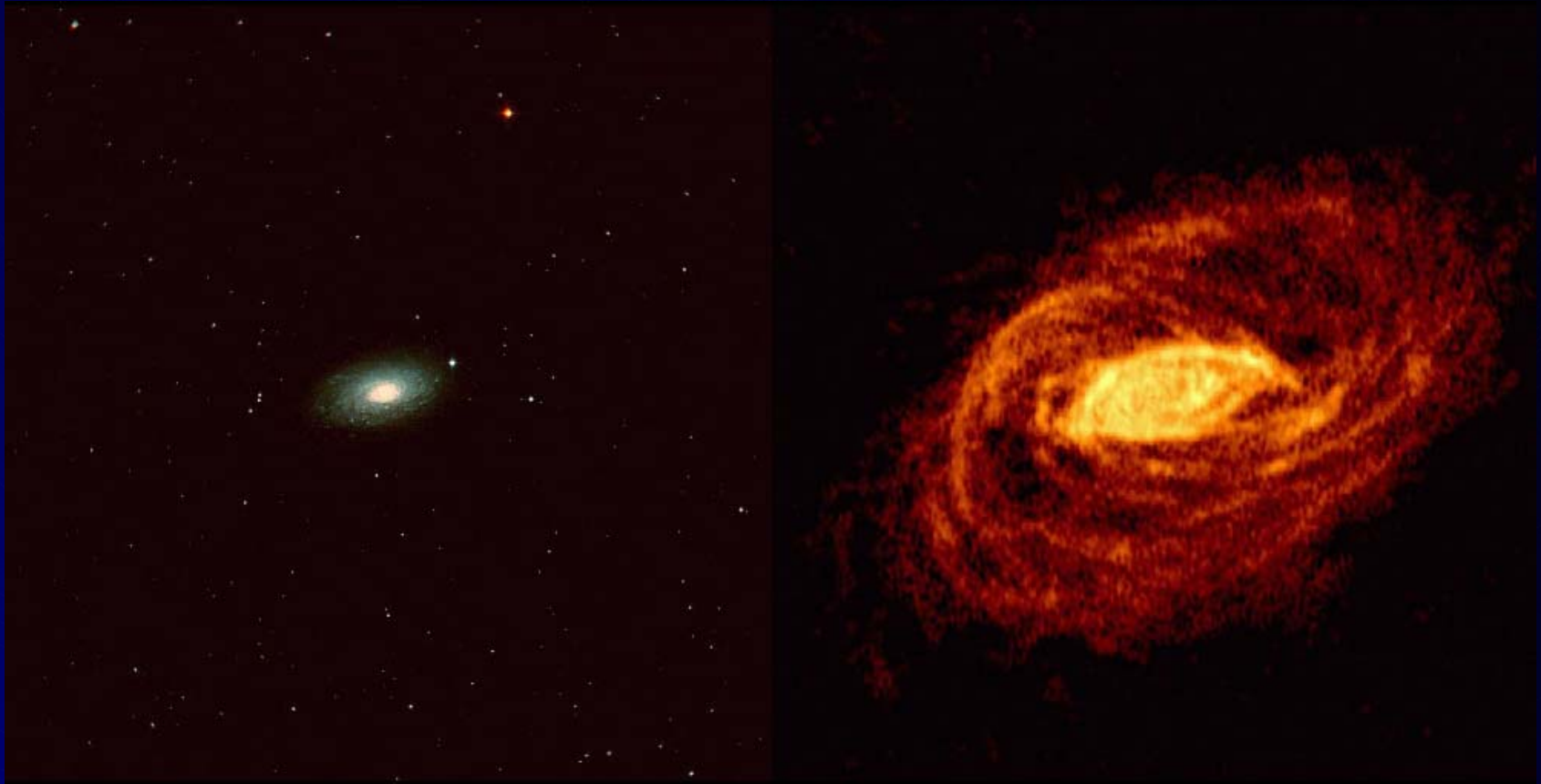
21 cm HI Distribution



Credit: NRAO, Yun et al.

ALFALFA

# HI: Probing Dark Matter



NGC 5055 Optical (left); HI (right)  
Tom Osterloo





# The HI 21 cm line @ 1.42 GHz



*HI : Why do we care ?*

- Easy to detect, simple physics → cold gas mass
- Good index of SF fertility → future SF
- Comparative HI content ⇒ HI deficiency
- Excellent tracer of host dynamics → dark matter
- Useful Cosmology tool → TF relation, HIMF, BAO
- Interaction/tidal/merger tracer
- Can be **dominant baryon form** in low mass galaxies
- **ALFALFA**: A census of HI in the local universe



# 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  $\alpha$  absorbers
9. **OH Megamasers** at intermediate redshift  $0.16 < z < 0.25$



# Comparison of blind HI surveys



Survey	Beam arcmin	Area sq. deg.	rms (mJy @ 18 km/s)	min $M_{\text{HI}}$ @ 10 Mpc	$N_{\text{det}}$	$t_s$ sec	$N_{\text{los}}$
AHISS	3.3	13	0.7	$2.0 \times 10^6$	65	var	17,000
ADBS	3.3	430	3.3	$9.6 \times 10^6$	265	12	500,000
HIPASS	15.	30,000	13	$3.6 \times 10^7$	5300	460	$1.9 \times 10^6$
HIJASS	12.	(TBD)	13	$3.6 \times 10^7$	(?)	3500	(TBD)
J-Virgo	12	32	4	$1.1 \times 10^7$	31	3500	3200
HIDEEP	15	32	3.2	$8.8 \times 10^6$	129	9000	2000
ALFALFA	3.5	7,000	1.7	$4.4 \times 10^6$	25,000+	40	$7 \times 10^6$

ALFALFA will be ~ 1 order of magnitude more sensitive than HIPASS with 4X better angular resolution.

Median cz for HIPASS ~ 2800 km/s

For ALFALFA ~ 7500 km/s



# ALFALFA: A 2<sup>nd</sup> generation HI survey



- In comparison with opt/IR, the HI view is largely immature
- HIMF based on only few thousand objects (HIPASS)

## 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  $M_{\text{HI}}$  => cosmologically significant volume

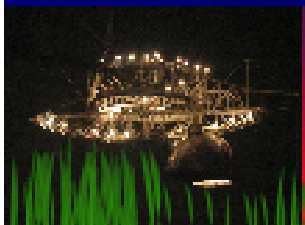


# Arecibo Legacy Fast ALFA Survey

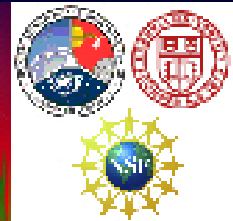


- One of several major surveys currently ongoing at Arecibo, exploiting its new multibeam capability
- An extragalactic spectral line survey (mainly HI)
- Covers 7000 sq deg of high galactic latitude sky
- 1345-1435 MHz (-2000 to +17500 km/s for HI line)
- 5 km/s resolution (100 MHz/4096 channels)
- 2-pass, drift mode (total int. time per beam ~ 40 sec)
- 1.5-2 mJy rms (per spectral resolution element)
- 4400 hrs of telescope time; complete in 2012?!
- started Feb 4, 2005; ~4100 hrs to date
- 35 refereed papers to date
- An "open collaboration": let's do science!

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



# ALFALFA

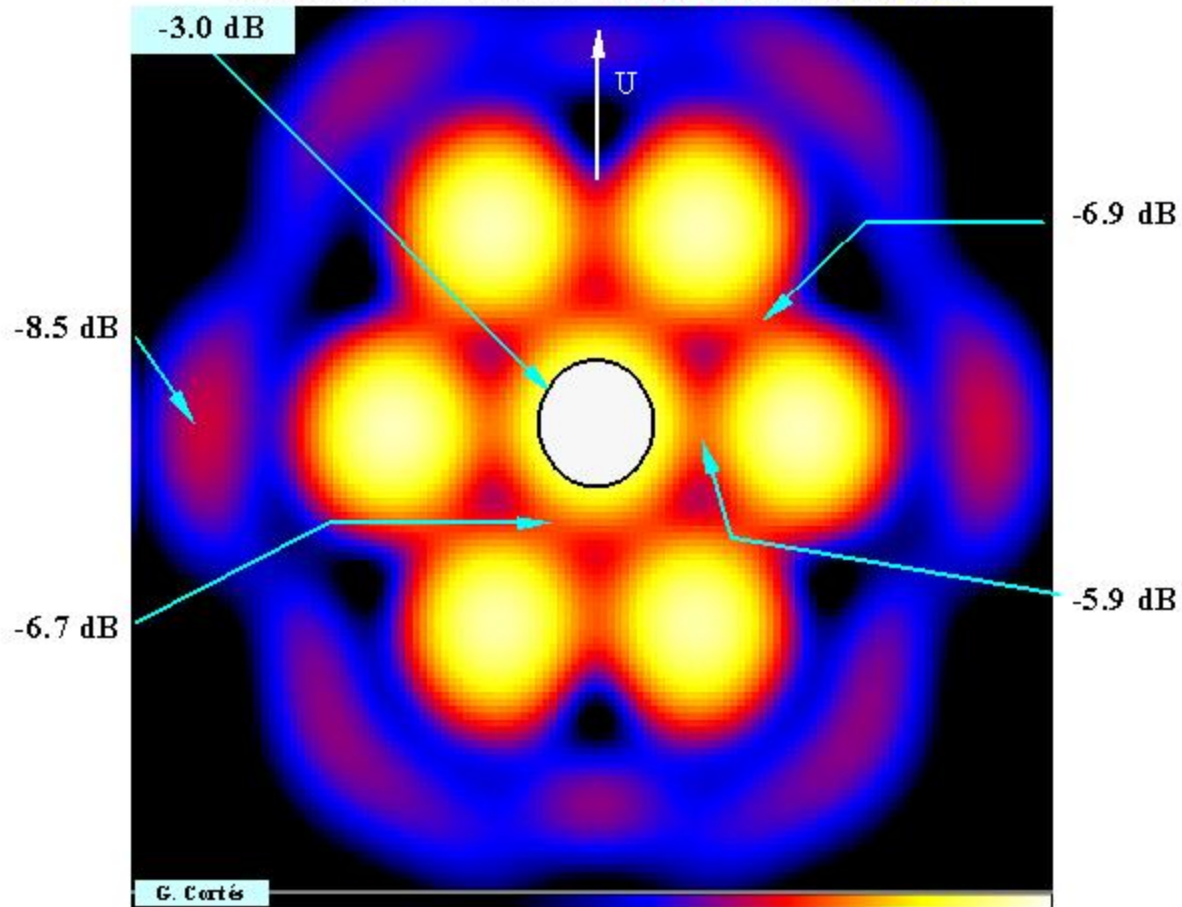


# ALFA: Arecibo L-band Feed Array



## Total Incoherent Multi Beam Pattern

TE<sub>11</sub> Mode Horn 25.0 cm x 26.0 cm



Sky Area 25' x 25' at 1.375 GHz



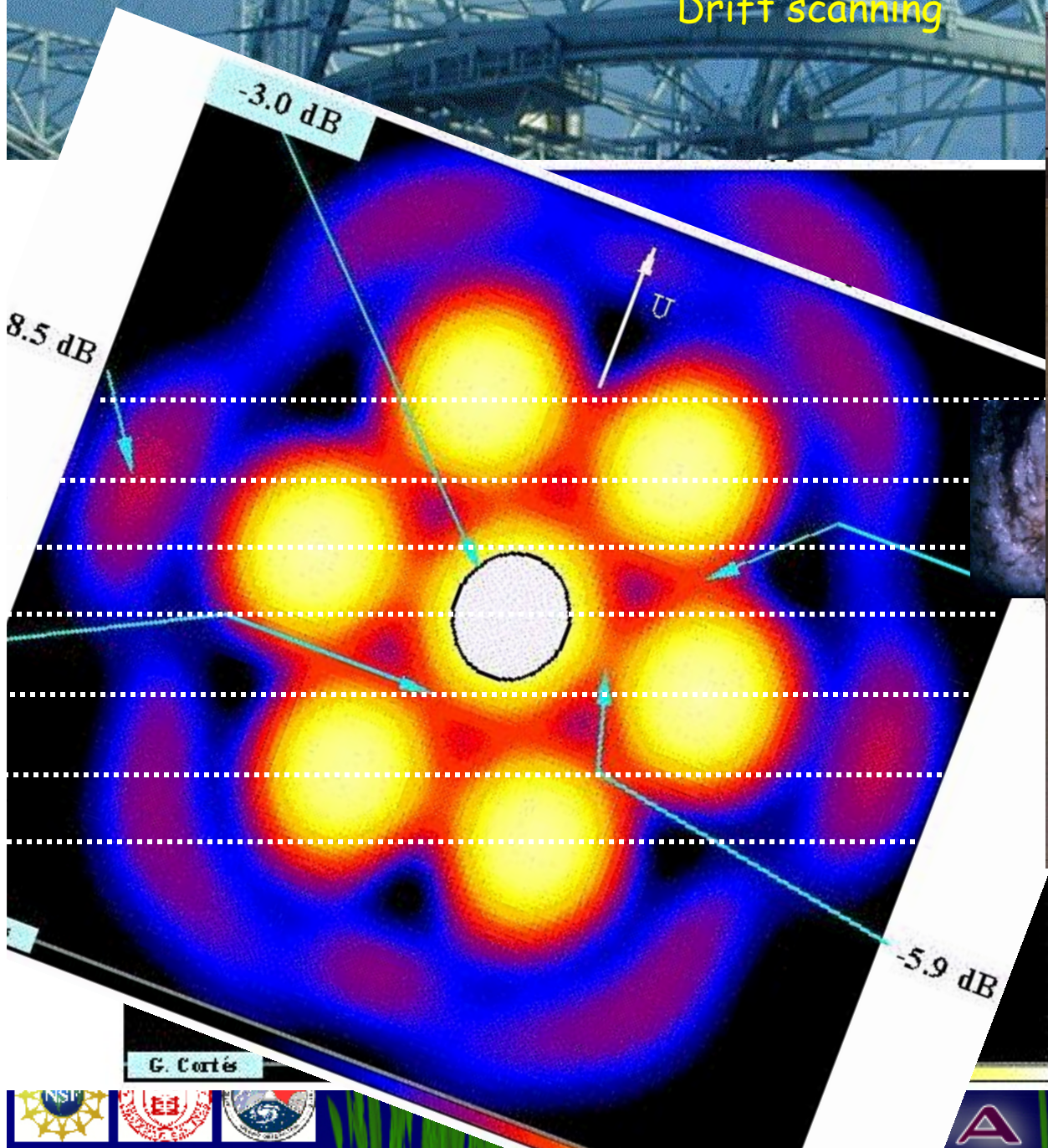
It is a radio "camera"

Arecibo L-band Feed Array



ALFALFA

# Drift scanning



7 elliptical beams 16  
Avg(HPBW)=3.5'  
on elliptical pattern  
of axial ratio ~1.2

G. Cortés

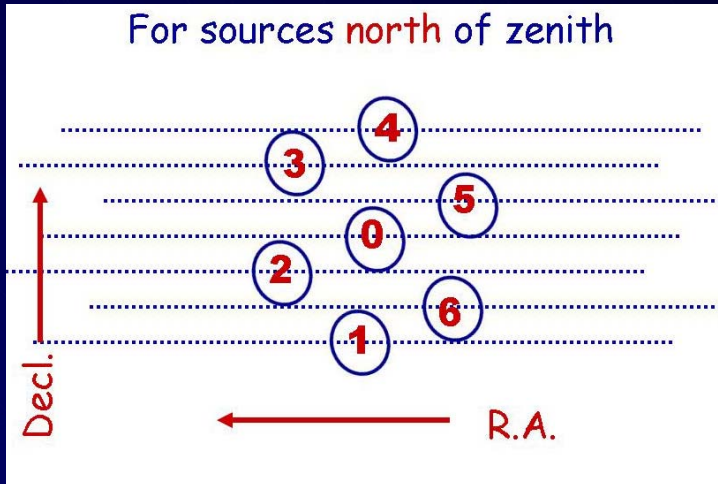






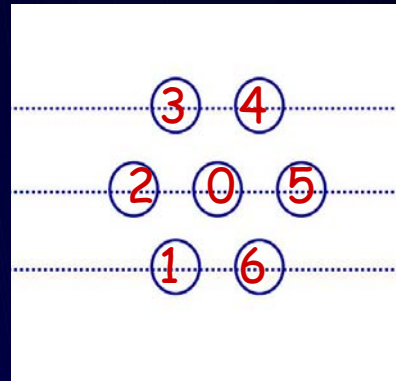
Dec > +18, RotAng=19

For sources north of zenith



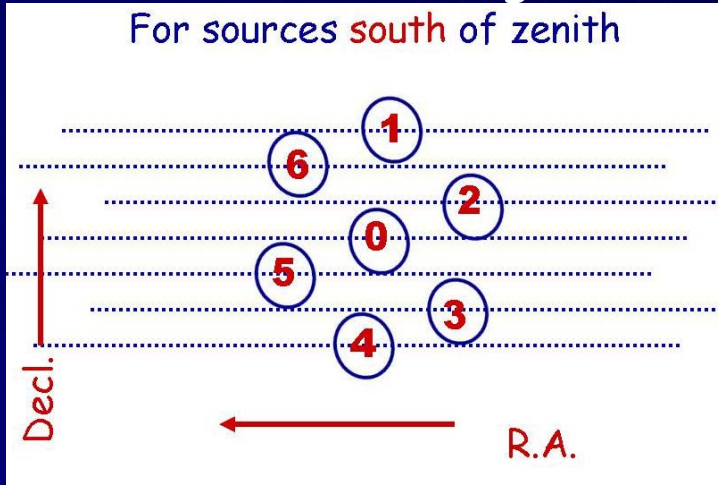
Dec > +18

No rotation



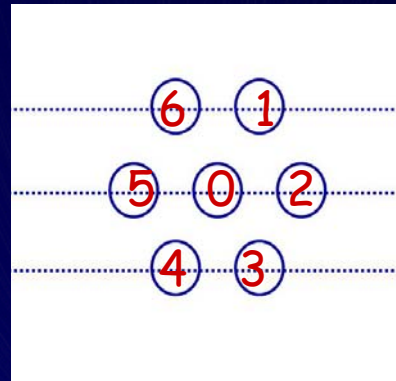
Dec < +18, RotAng=19

For sources south of zenith



Dec < +18

No rotation



## Array rotation

The individual feed horns move along an elliptical ring oriented in Az, ZA.

Note: The beams are actually elliptical, NOT circular.



ALFAFA

# ALFA at 19°

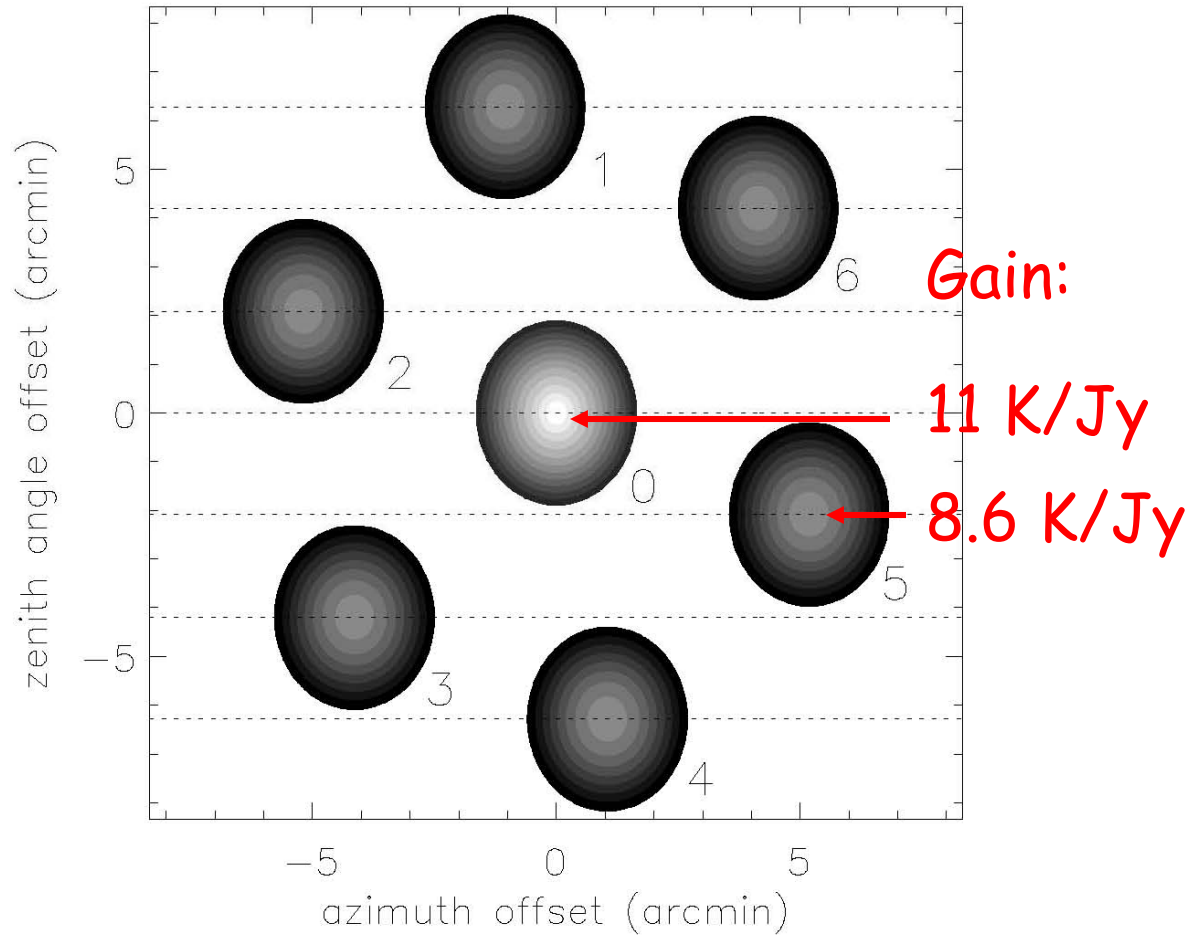


Fig. 2.— Sketch of the geometry of the ALFA footprint, with the array located along the local meridian and rotated by an angle of  $19^\circ$  about its axis. The outer boundary of each beam corresponds to the -3 dB level. The dashed horizontal lines represent the tracks at constant Declination of the seven ALFA beams, as data is acquired in drift mode.



# ALFALFA schedule notation



- “Master list” of drift declinations preassigned, starting at  $0^\circ$  and moving northward to  $+36^\circ \Rightarrow$  DriftN,  $N = 1, 148$
- Two passes: p1 and p2

134p1	+322906
134p2	+323624
135p2	+325100

7.3 arcmin

14.6 arcmin



# ALFALFA drift mode



- “Almost” fixed azimuth drifts
  - Track in J2000 Declination
  - Declination of all survey drifts specified, except for  $+16^\circ < \text{DecJ} < +20^\circ$  (zenith “Zone of Avoidance”)
- Specify observing “block” according to date/time at start, specified as yy.mm.dd

11.01.17: This (early) morning's block

11.01.18 : Tonight's (tomorrow morning) block

Block	Date	AST	LST	#	DecJ
11.01.17	M 17Jan	01h45-06h30	09h03-13h48	134p1	+322906
11.01.18	T 18Jan	01h30-06h15	08h52-13h37	138p1	+332730
11.01.19	W 19Jan	01h30-06h15	08h56-13h41	136p1	+325818

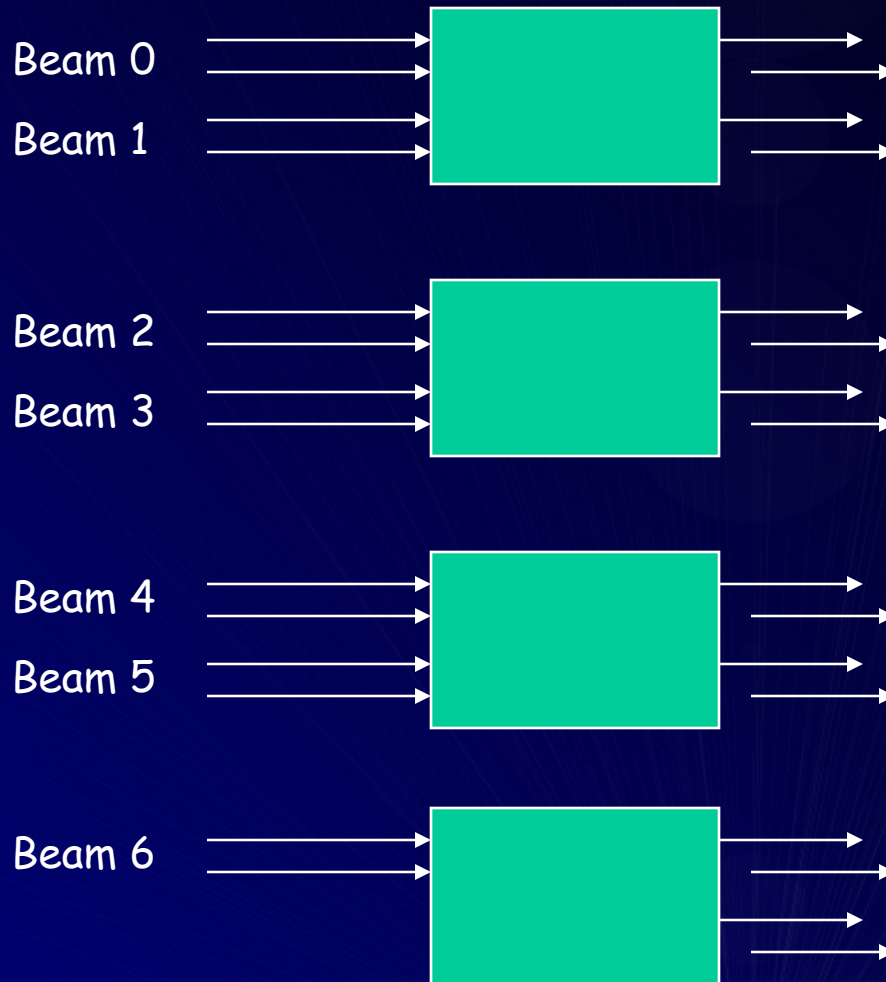
But: we actually run 15 minutes later to run calibration for TOGS



# Spectrometer setup for ALFALFA



WAPP



ALFA spectra:

16 x 4096 frequency channels (2 not used)

7 beams X 2 polarizations/beam

100 MHz wide

Centered at 1385 MHz

So resolution is  
100 MHz/4096  
channels



# Radio Frequency Interference



- Man-made signals are much stronger than cosmic ones!
- Some are always present; others come and go.
- Radars (e.g. FAA at San Juan airport) occur with some regular period (e.g. 12 sec)
- Some RFI is so strong that it "saturates" the front end.
- Some RFI can be avoided through coordination (Puntas Salinas)

We have to live with it (but we don't have to like it!).

See: [http://www.naic.edu/~a2010/rfi\\_common.htm](http://www.naic.edu/~a2010/rfi_common.htm)



# RFI List

Mozilla Firefox

File Edit View Go Bookmarks Tools Help

http://www.naic.edu/%7Ephil/rfi/rfilist.html#band%20birdies

User Record Viewer

1241.75 1244.6 1256.5 1261.25	1.67	jan97	active Radar	<b>Aerostat</b> radar balloon in lajas. dual freq or quad freq modes. 160 usec per pulse, chirped. Rotation rate 11.59 secs. Blanks toward A.O. (see <a href="#">radar info</a> )
1270/1290	.2	feb02	active Radar	<b>Remy Radar</b> at the end of the runway .(fps20-93a). 12 sec rotation rate, single ipp of 2781. Runs in 1270 or 1290 mode (not simultaneously). (see <a href="#">radar info</a> )
1287.5/1299.84 1300,1399.83 1400 1411.52 1412.5	<.025	jan01 apr02		<b>Distomat</b> birdies. Occur every 2 minutes for a few seconds. Az dependent.Distomats have a 27 Mhz clock. Data was measured in jan01 ( <a href="#">before shielding work</a> ) Data was remeasured in apr02 ( <a href="#">after some shielding work</a> ). The window was changed
1330/1350	.2	jan97	active Radar	<b>FAA airport radar.</b> 12 sec rotation, 5 ipp's about 2.5 ms,5 usec pulse, 1350 then 1330 pulse sent each ipp. ( <a href="#">radar info</a> )
1366.2/1382.66 1324/1340 1387.3/1371.0		feb01	Radar	<b>Radars with 1.94 sec rotation</b> rates. ( <a href="#">more info</a> ). These radar were probably associated with military ship practices. Fast rotating radars are needed when objects move far within 1 rotation (planes near aircraft carriers,etc..)
1381.05	1	sep91	active	<b>GPS L3</b> downlink. ( <a href="#">more info</a> )
1388.55	.024	98		<b>beeper</b> harmonic (3rd of 462.85)
1388.6	.024	93		<b>beeper</b> harmonic (3rd of 462.875) (borinquen beepers)
1388.858 1417.495	<190 (hz)	may02		<b>dome camera</b> birides. part of a comb of 14.3185 Mhz. ( <a href="#">more info</a> ).
1390.8	.024	feb93		<b>beeper</b> harmonic (3rd of 463.6 (mr. beeper)
1407	.3	apr01	fixed	<b>tvChan20</b> arecibo. Drifted around with time. They were having trouble with their transmitter. ( <a href="#">more info</a> )
1422.5				<b>tvChan54</b> 2nd harmonic
1525-1545		aug03		<b>Inmarsat stdBC</b> ship,portable earch downlinks <b>Inmarsat stdM</b> ship downlinks

Done

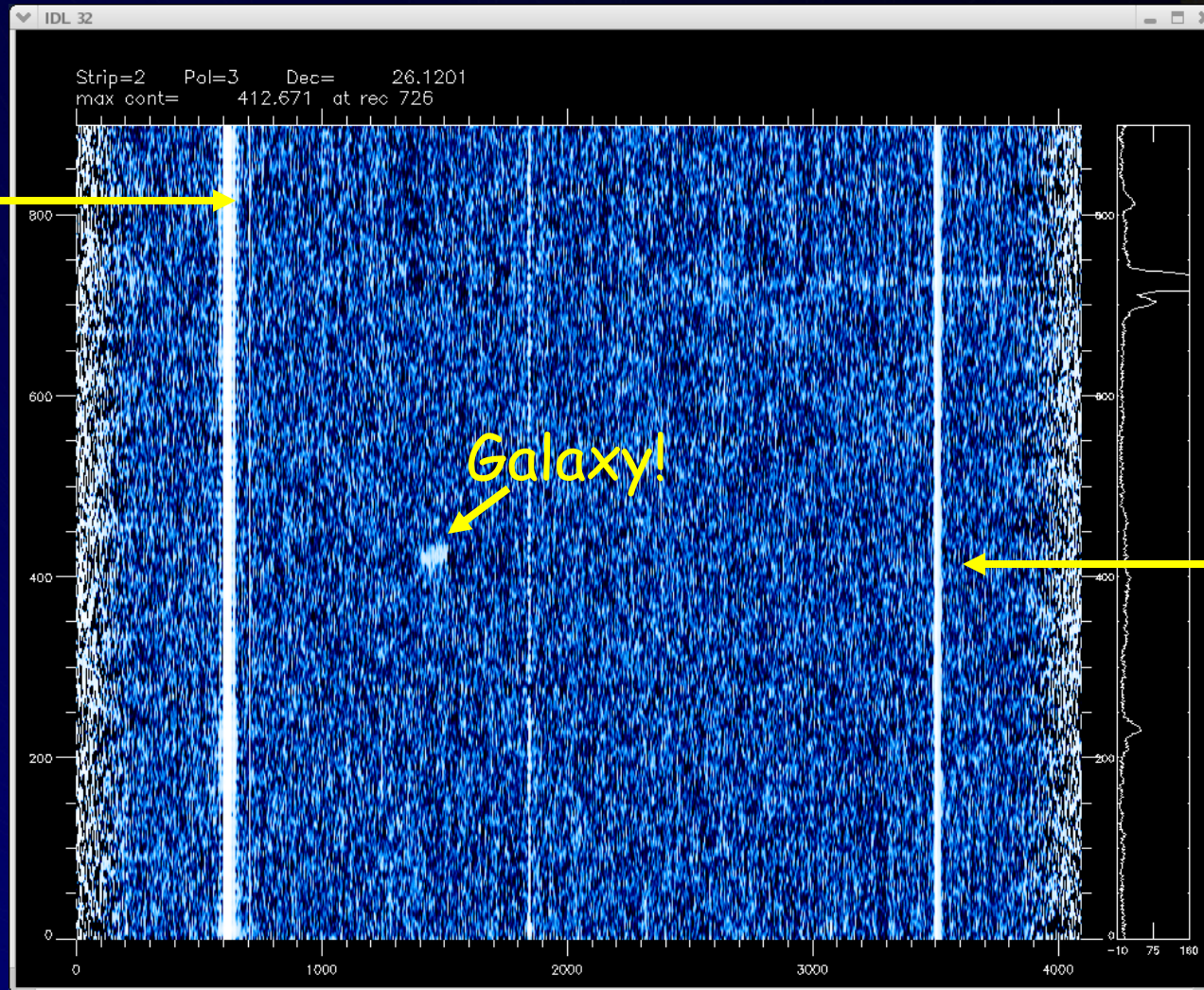


# RFI is ugly



FAA  
radar

Record/time/R.A. →



Galactic  
hydrogen

Channel number/frequency →





# Two-pass strategy



We want to drift across each stop on the sky TWICE

- Double integration time
- Helps to discriminate cosmic sources from
  1. Noise
  2. RFI

We offset the 2<sup>nd</sup> drift by half of the beam spacing.

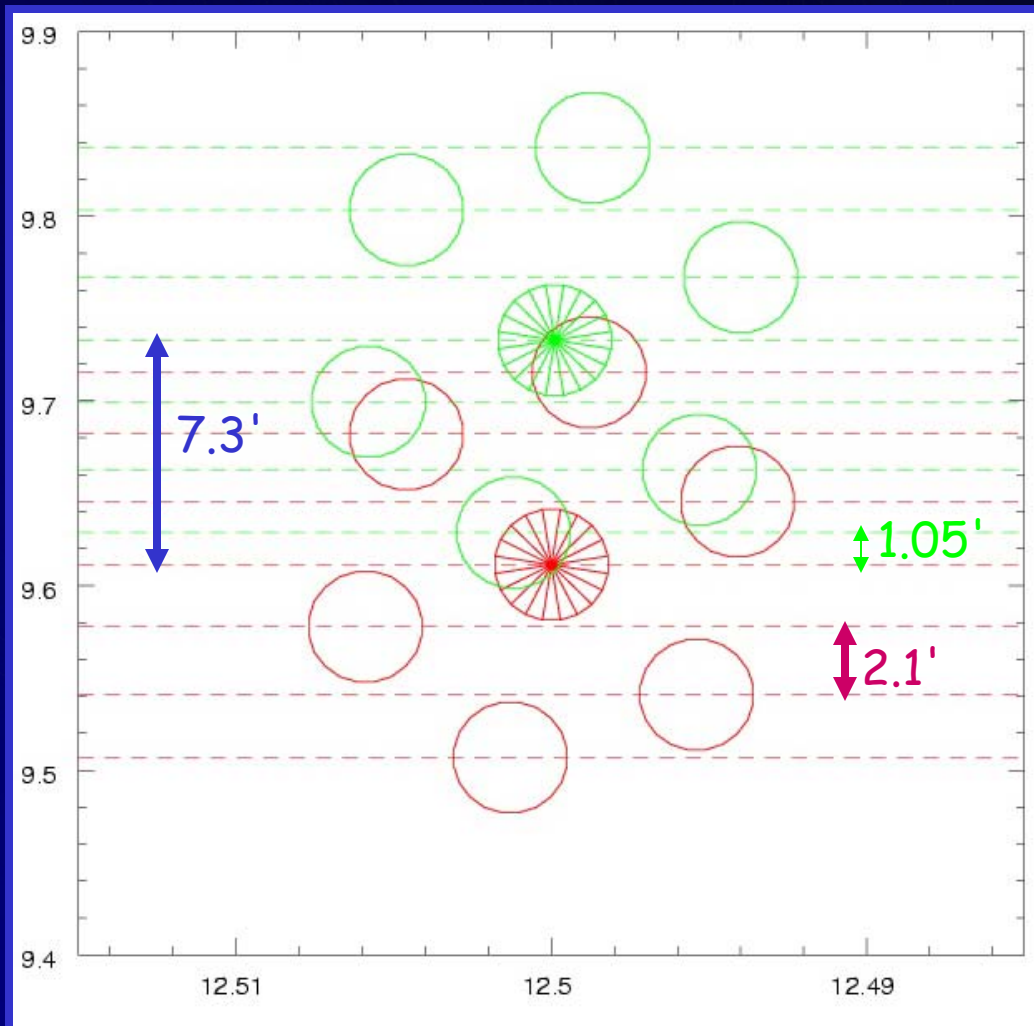
- Helps with position centroiding
- Evens out the gain scalloping

We conduct the 2<sup>nd</sup> pass 3-9 months after the first.

- Cosmic sources will have shifted in frequency due to the Earth's motion around the Sun, but terrestrial ones won't have.
- Some interference comes and goes.



# 2-pass beam layout



## Final coverage for 2 pass strategy

- For the 2<sup>nd</sup> pass, Beam 0, which has higher gain than the others, is offset by 7.3 arcmin from its 1<sup>st</sup> pass position.
- Some smoothing of gain scalloping.
- 2-pass sampling thus at 1.05 arcmin
- 2<sup>nd</sup> pass occurs 3-9 months after the 1<sup>st</sup> pass (vs. RFI)



# ALFALFA Scheduling Strategy



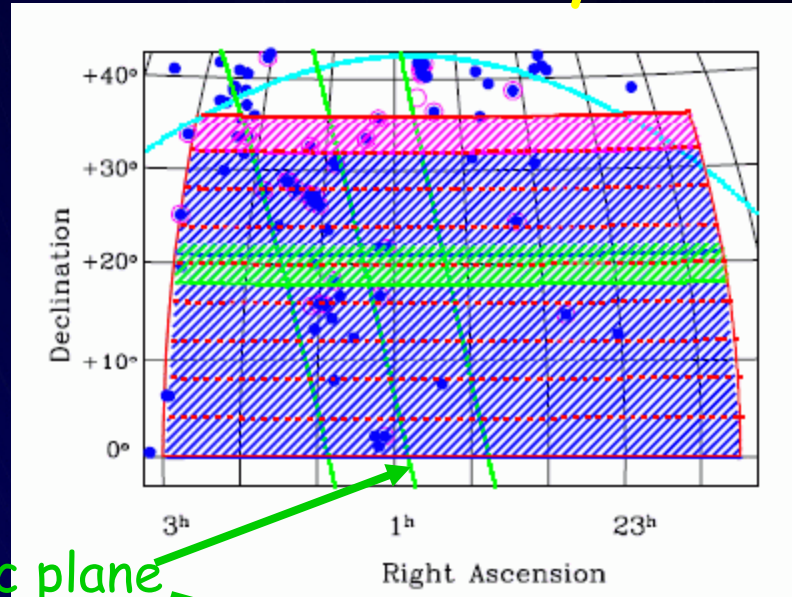
- ALFALFA aims to survey 7000 square degrees of high galactic latitude sky.
- “Fixed azimuth drift” mode: the telescope moves only slightly, to maintain constant Dec (J2000); Drifts offset by 14.6 arcmin.
- A “tile” of data will contain all beam positions within a box of 20 min in RA by 4 degrees in Dec.
- Within a single observing block, the data taking sequence consists of a series of 600 second (10 min) drifts at constant Dec J.
- Over a season, we try to “complete” sets of drifts within a tile: 16 drifts/tile/pass.
- The second pass occurs 3-9 months after the 1<sup>st</sup> pass (to aid RFI identification and signal confirmation).



# ALFALFA Survey 2005-10



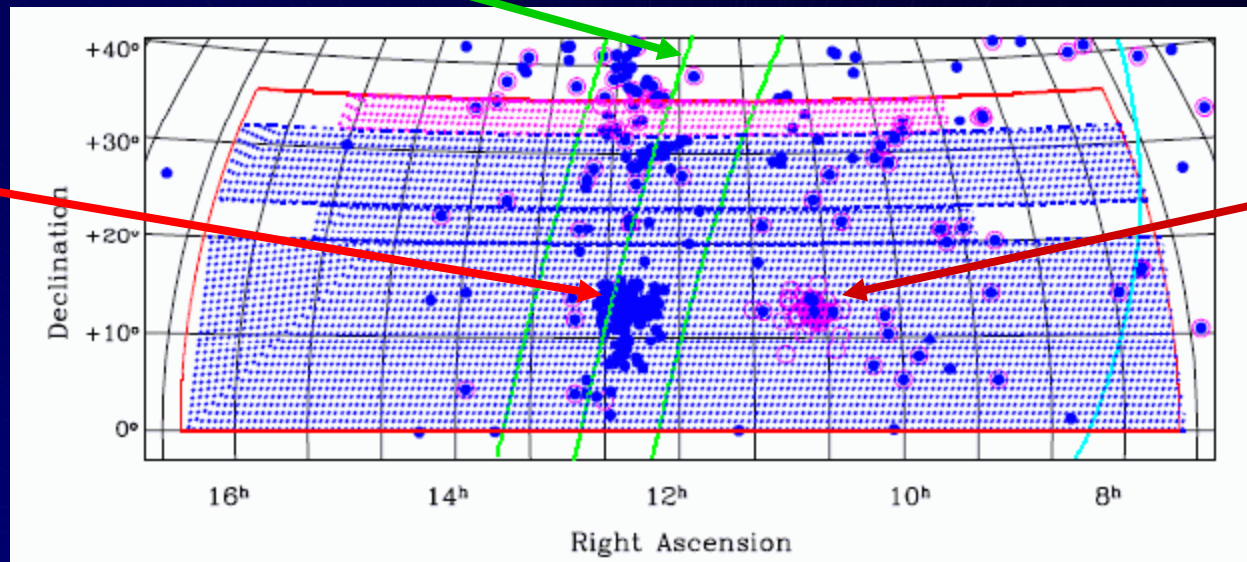
High galactic latitude sky visible from AO



- Commensal with TOGS HI
- Does not compete with galactic plane surveys

Supergalactic plane

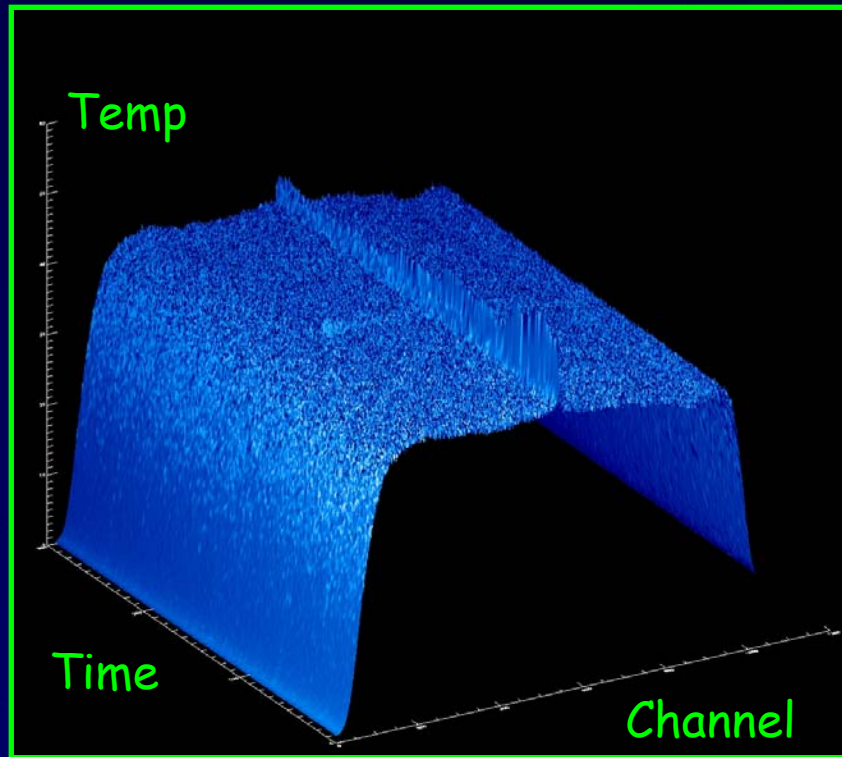
Virgo cluster



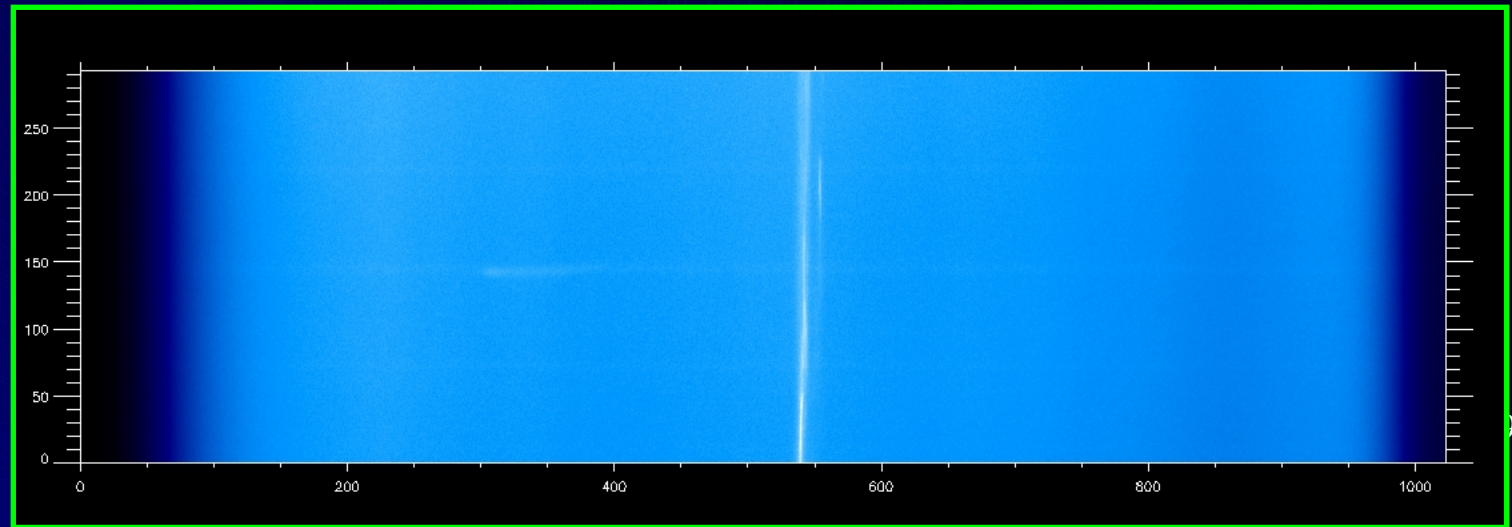
Leo Group



# Raw data



← A Drift scan, before bandpass correction (bpd)

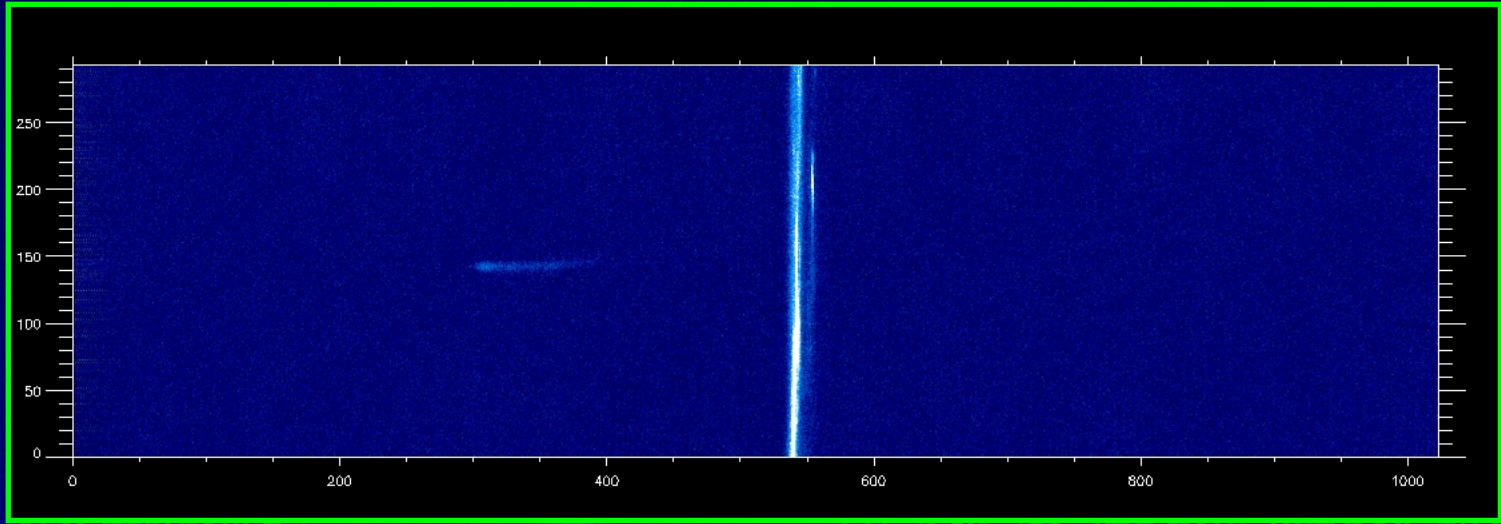
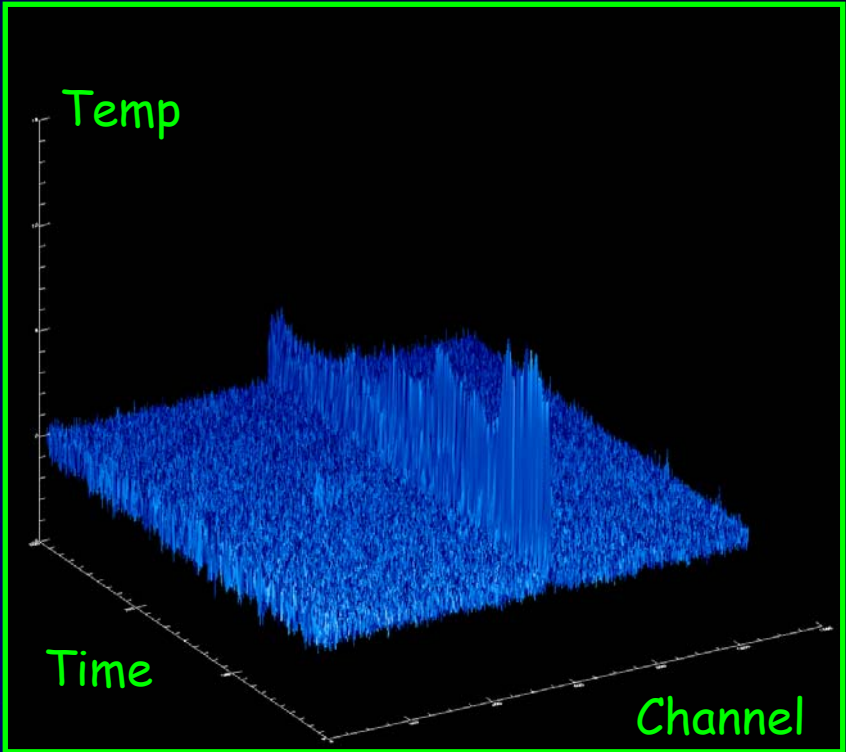


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After BPD

← A Drift scan, after bandpass correction (bpd)



ALFAFA

# Maximizing Observing Efficiency



- Telescope time is precious and competition is stiff.
- Our science goals demand high quality data.
- The legacy nature of ALFALFA raises the standards for data product generation and delivery.
- Arecibo and ALFA are complex instruments to use.
- RFI is nasty and inevitable.
- ALFALFA uses a lot of telescope time and generates a lot of data!
- The A2010 proposal was approved pending periodic reviews of our ability to perform the survey.

The ALFALFA technique delivers >99% "open shutter" time



# ALFALFA observing sequence



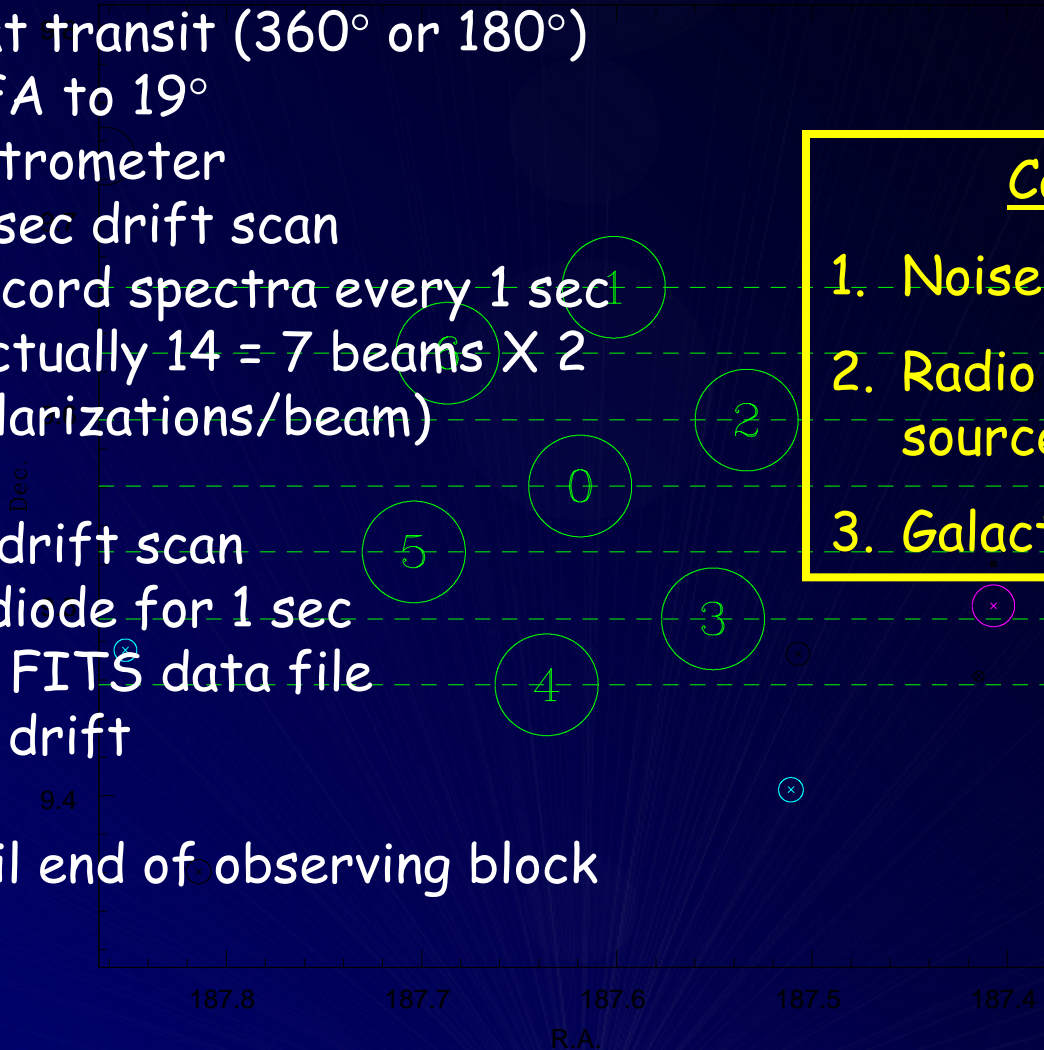
- Set dome at transit ( $360^\circ$  or  $180^\circ$ )
- Rotate ALFA to  $19^\circ$
- Setup spectrometer
- Start 600 sec drift scan
  - Record spectra every 1 sec (actually 14 = 7 beams X 2 polarizations/beam)

- .....
- Terminate drift scan
  - Fire noise diode for 1 sec
  - Close/open FITS data file
  - Start next drift

.....  
Repeat until end of observing block

## Calibration:

1. Noise diode
2. Radio continuum sources of known flux
3. Galactic Hydrogen



ALFALFA



# Scavenger Hunt #1



[http://egg.astro.cornell.edu/alfalfa/ugradteam/hunt10/hunt1\\_10.htm](http://egg.astro.cornell.edu/alfalfa/ugradteam/hunt10/hunt1_10.htm)

- Think about using ALFA for ALFALFA
- Start thinking about what we can learn about galaxies
- Please: **no cheating by return attendees!**

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

[http://www.naic.edu/~a2010/galaxy\\_a2010.html](http://www.naic.edu/~a2010/galaxy_a2010.html)

Team website: A2010 + coolHI



# Scavenger Hunt #1



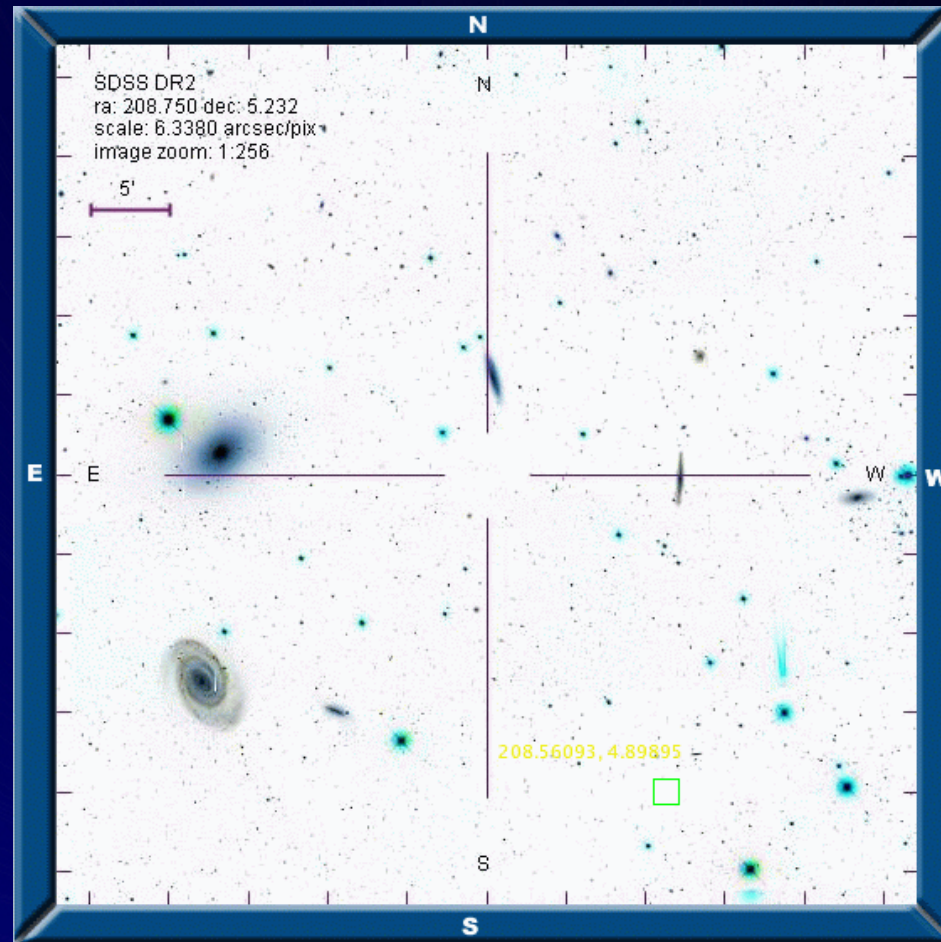
[http://egg.astro.cornell.edu/alfalfa/ugradteam/hunt11/hunt1\\_11.htm](http://egg.astro.cornell.edu/alfalfa/ugradteam/hunt11/hunt1_11.htm)

To run IDL here at the workshop

- `ssh -X alfalfa@fusion01.naic.edu`
- `zw1400+09` (ask Tom where this comes from!)
- `cd /share/alfalfa/team`
- `idl`
- `@wasinit2`
- `@alfinit`



So, enough talk;  
let's eat...!





**ALFALFA**



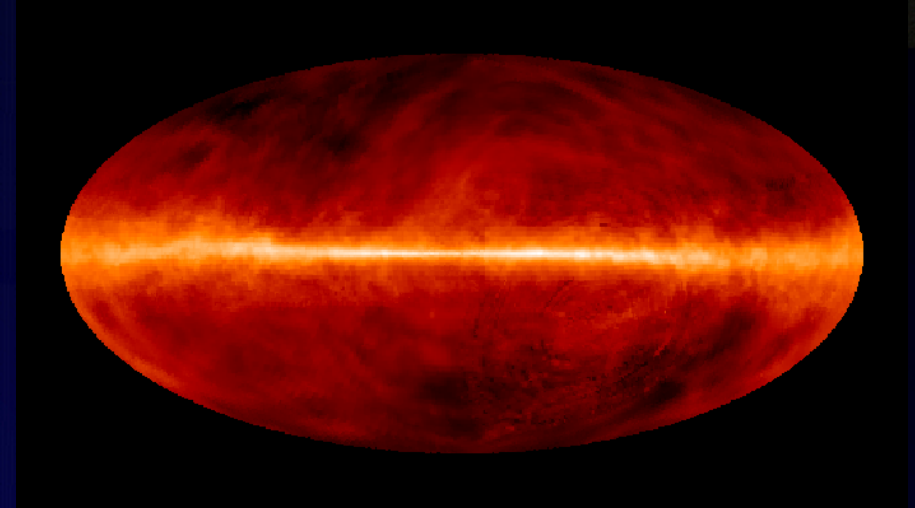
# Hydrogen in the Interstellar Medium



HI is the designation often used for neutral hydrogen atoms in space.

It is estimated that 4.4% of the visible matter in our galaxy is HI.  
That is  $4.8 \times 10^9 M_{\odot}$ .

The fraction of interstellar space filled with HI clouds is 20% to 90%.



Full-Sky Map at 1420 MHz  
Shows distribution of HI

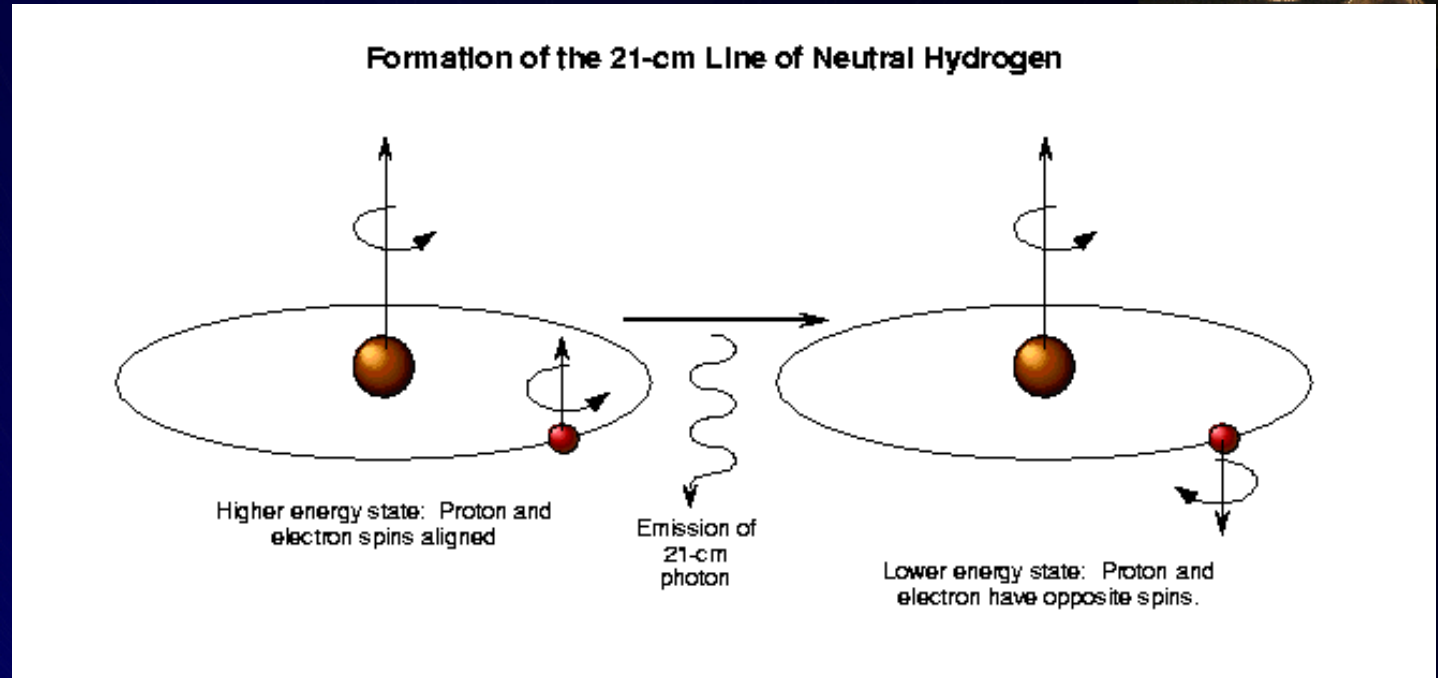
Estimates for hydrogen molecules,  $H_2$ , vary -  $1.2$  to  $3.5 \times 10^9 M_{\odot}$ .  
 $H_2$  tends to concentrate in a small number of giant gas clouds.



# HI 21 cm line



- Neutral hydrogen (HI) spin-flip transition



$\Delta E$   $\frac{1}{0}$  The transition probability for spontaneous emission  $1 \rightarrow 0$  is  $A_{10} = 2.85 \times 10^{-15} \text{ s}^{-1} \cong (11 \times 10^6 \text{ yr})^{-1}$

The smallness of the spontaneous transition probability is due to

- the fact that the transition is "forbidden"
- the dependence of  $A_{10}$  on  $\text{freq}^3$

The "natural" halfwidth of the transition is  $5 \times 10^{-16} \text{ Hz}$



# 21-cm Line of Atomic HI



Through Hydrogen maser measurements the frequency is:  
 $1,420,405,751.7667 \pm 0.0010$  Hz

$$\text{Energy } hc/\lambda \sim 5 \times 10^{-6} \text{ eV}$$

Compared to energy of a visible light photon which is about 2 eV.

- Predicted 1944 by van der Hulst
- First observed 1951 by Ewen and Purcell
- Observed regularly with Arecibo telescope by ALFALFA team members

The transition is mainly excited by other mechanisms, which make it orders of magnitude more frequent, e.g., the upper level is populated by:

- Collisions
  - Excitation by stellar radiation field or Lyman- $\alpha$  photons
- 
- In the MW there are some  $10^{66.5}$  HI atoms;
  - At the rate  $A_{10}$ , about  $10^{52}$  atoms per sec would emit a photon.
  - In reality, the transition probability is  $10^5$  times larger than  $A_{10}$
  - Hence the galactic HI emission is very easily detectable.

