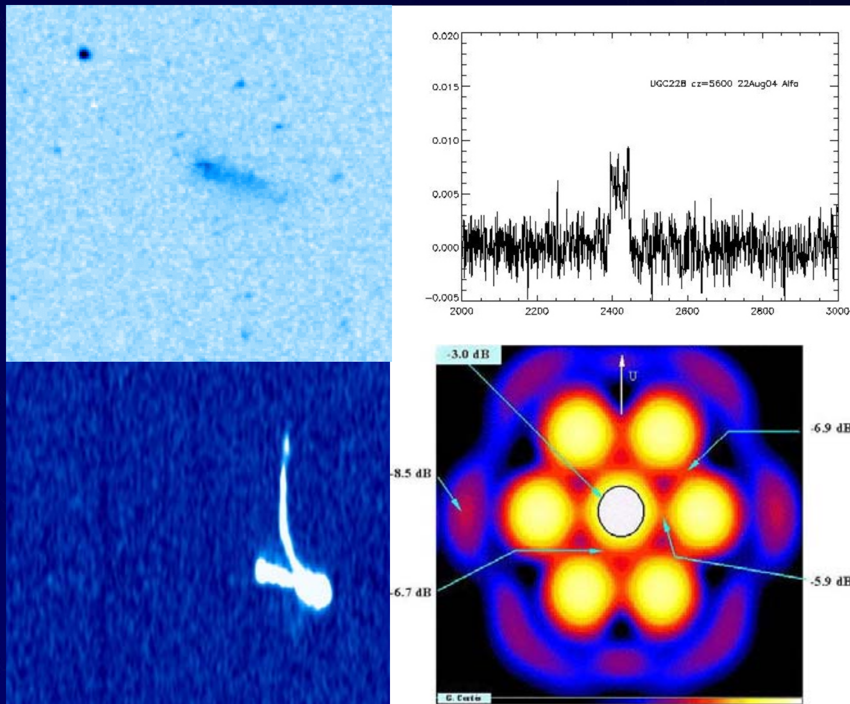


Introduction to ALFA and ALFALFA

Martha Haynes

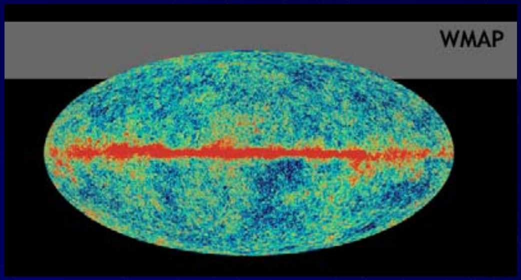
UAT09 09.01.12

ALFALFA

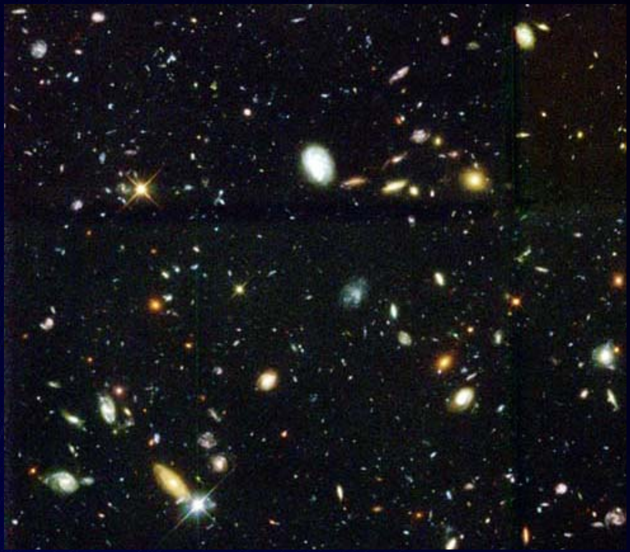
ALFALFA: A Census of Gas-bearing Galaxies

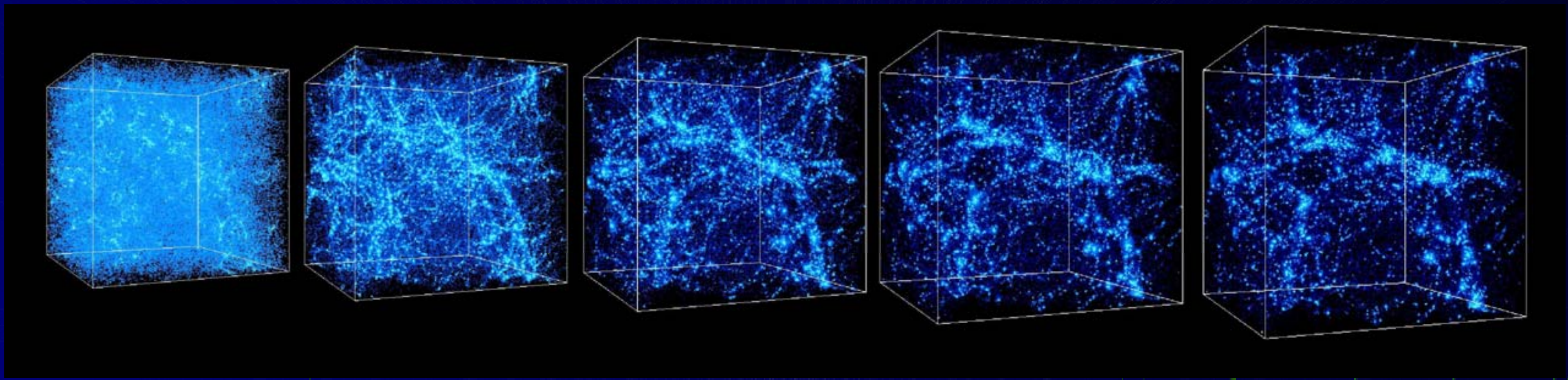
- A galaxy is a gravitationally bound object that consists of billions (and billions) of stars, gas clouds (of varying temperature and density = interstellar medium), dust clouds (mixed with the gas), and (so it seems), 90% dark matter.
- Optical surveys, like the Sloan Digital Sky Survey, detect the 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).

How and when do galaxies form?

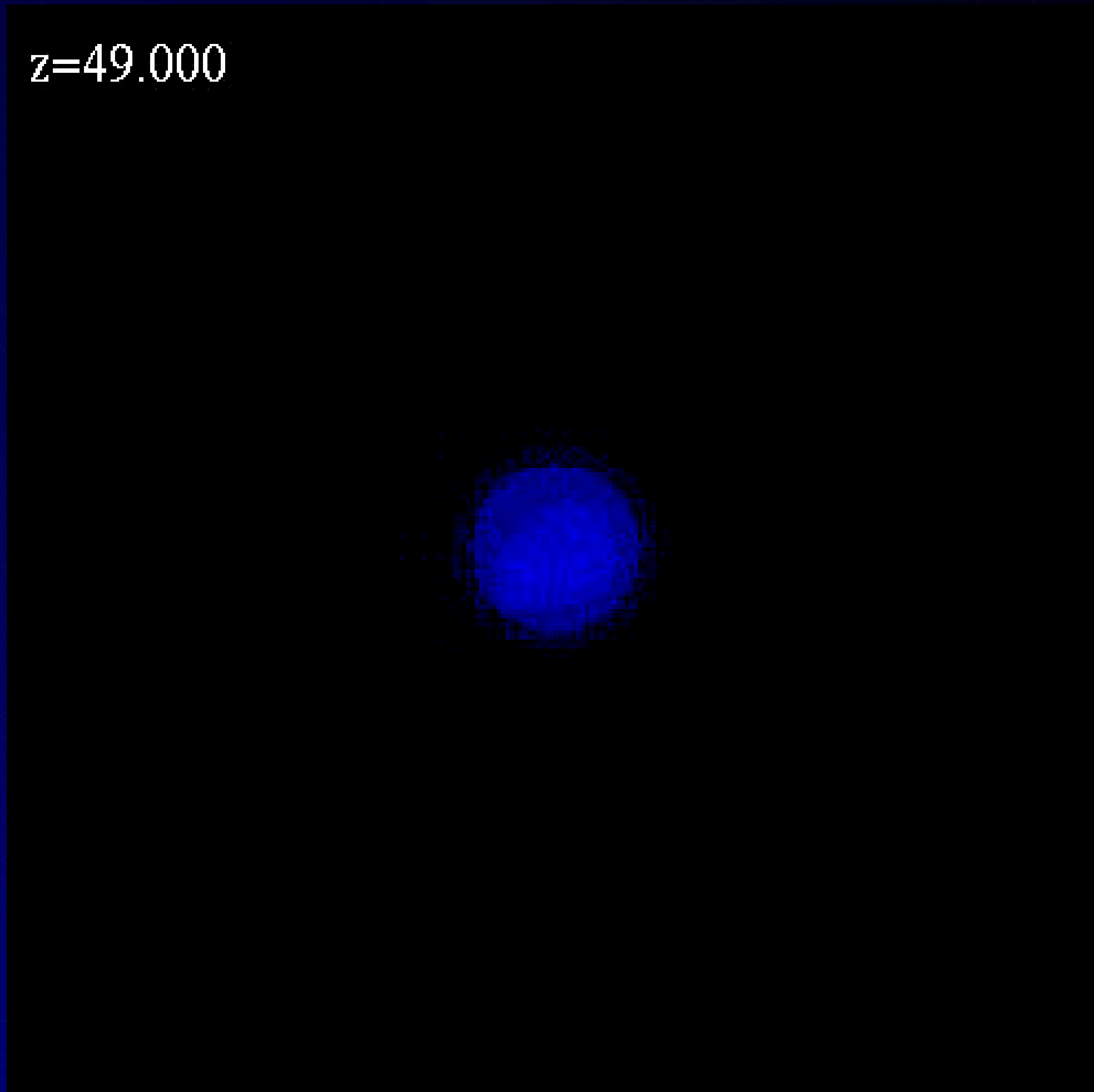


Numerical simulations are used to trace the gravitational collapse of matter (dark+luminous) across cosmic time

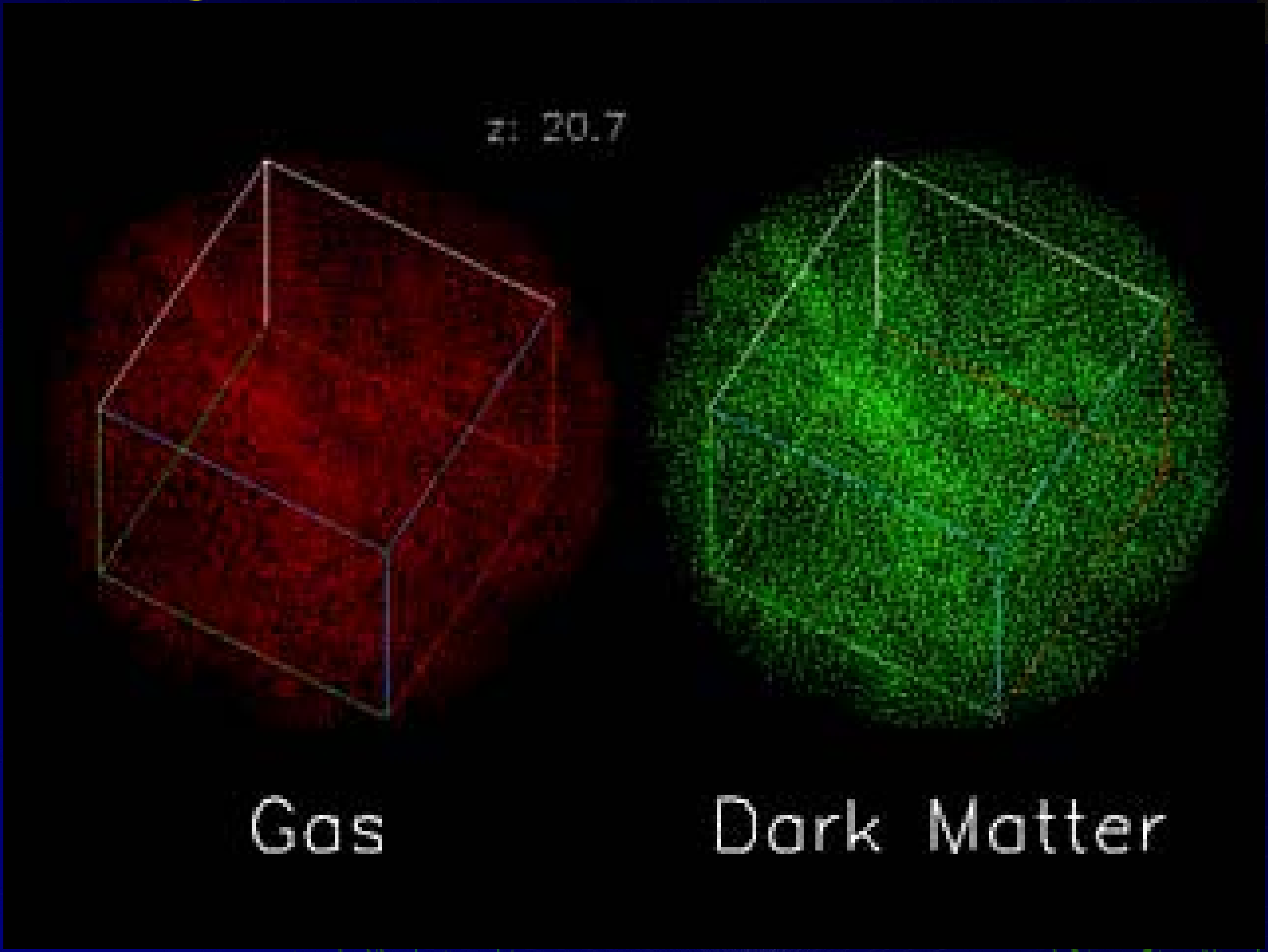




Virgo cluster movie from Ben Moore



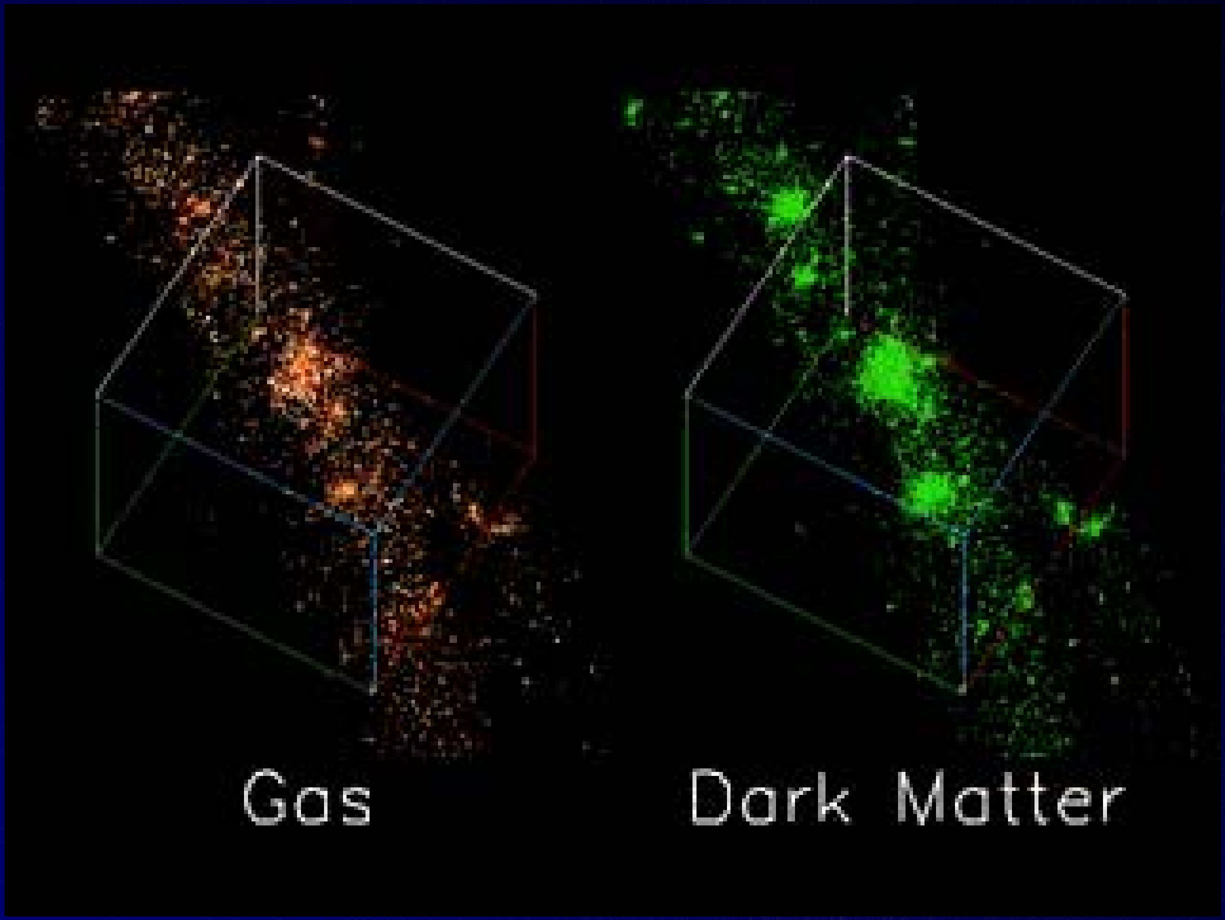
Large scale structure formation



Simulation by Matthias Steinmetz

ALFALFA

Evolution of a galaxy



Simulation by
Matthias Steinmetz

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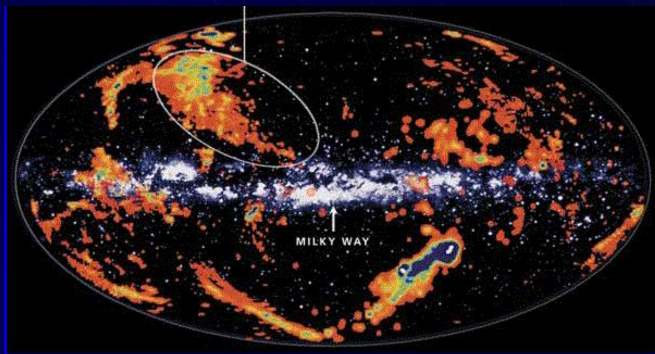
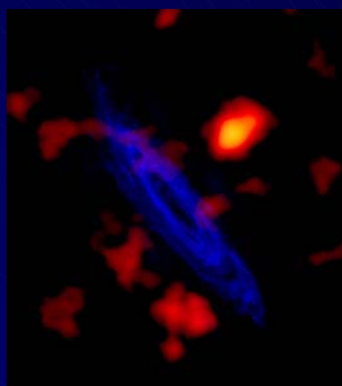
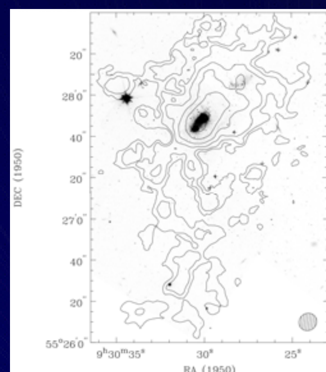
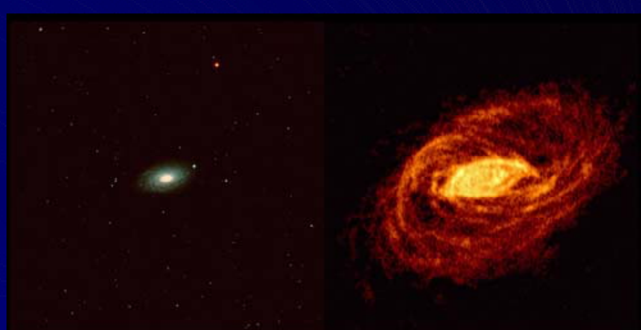
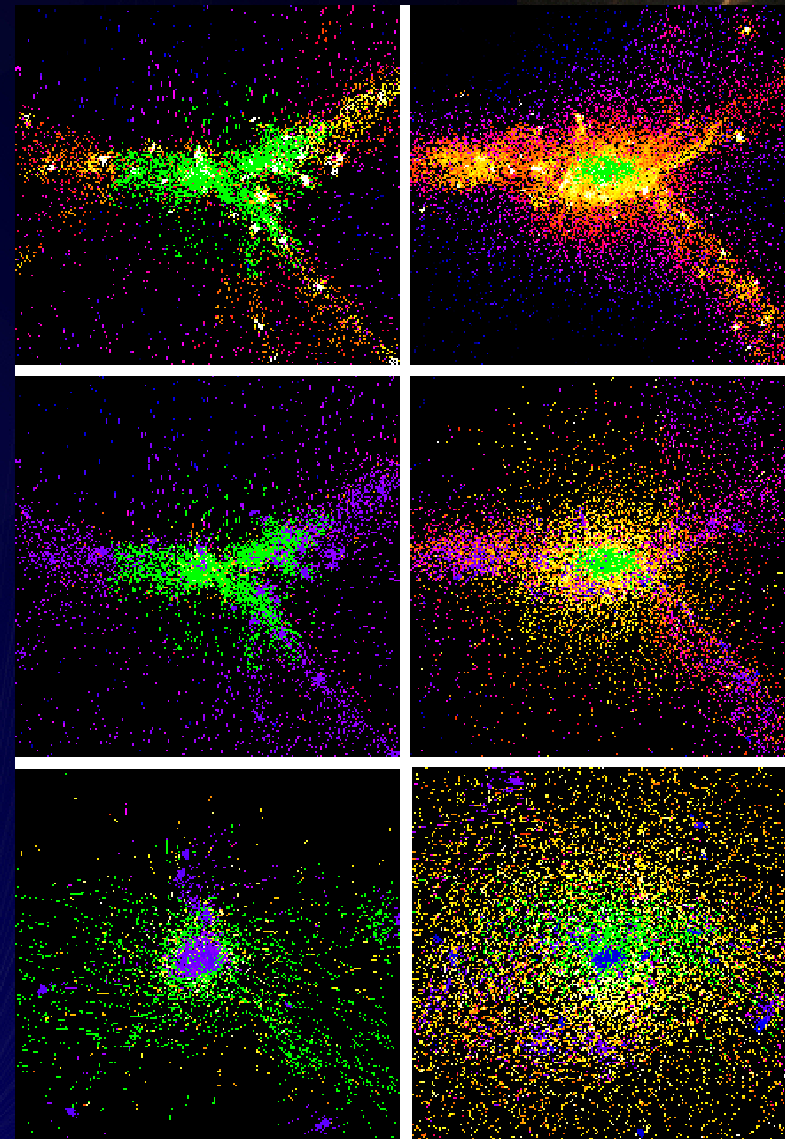
How and when do galaxies acquire their gas?











Kereš *et al.* (2005)

Components of Interstellar Medium

The interstellar medium is composed of gas in different phases (temperatures, densities, species)

Molecular clouds: T ~ 3 -50 K, densest, mostly H_2

CNM = Cold Neutral Medium: T ~ 80 K, dense, mostly HI (=H^0)

WNM = Warm Neutral Medium: T < 8000 K, surrounding or between CNM, HI still an important part

WIM = Warm Ionized Medium: T ~ 10000 K (HII = H^+)

HIM = Hot Ionized Medium: T ~ 10^6 K highly ionized (H^+) diffuse $H\alpha$ emission (allowed transition in H)

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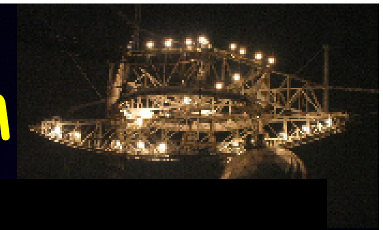
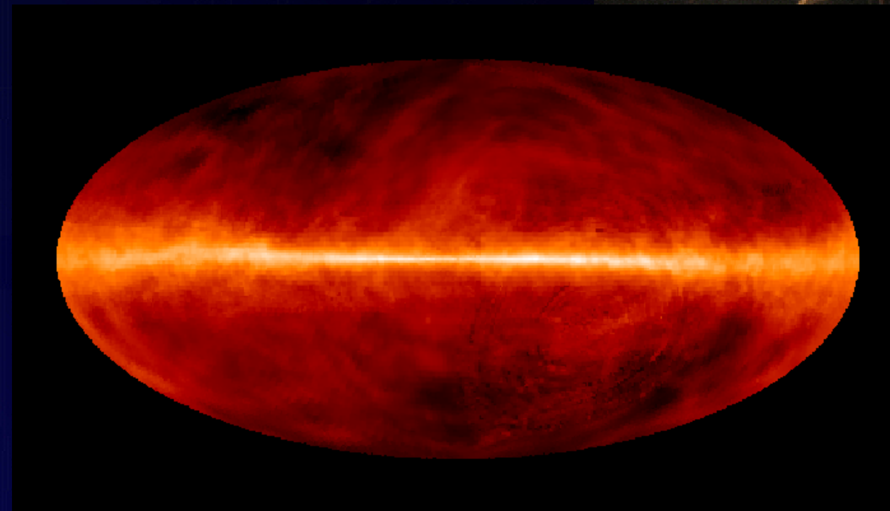
Hydrogen in the Interstellar Medium



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.

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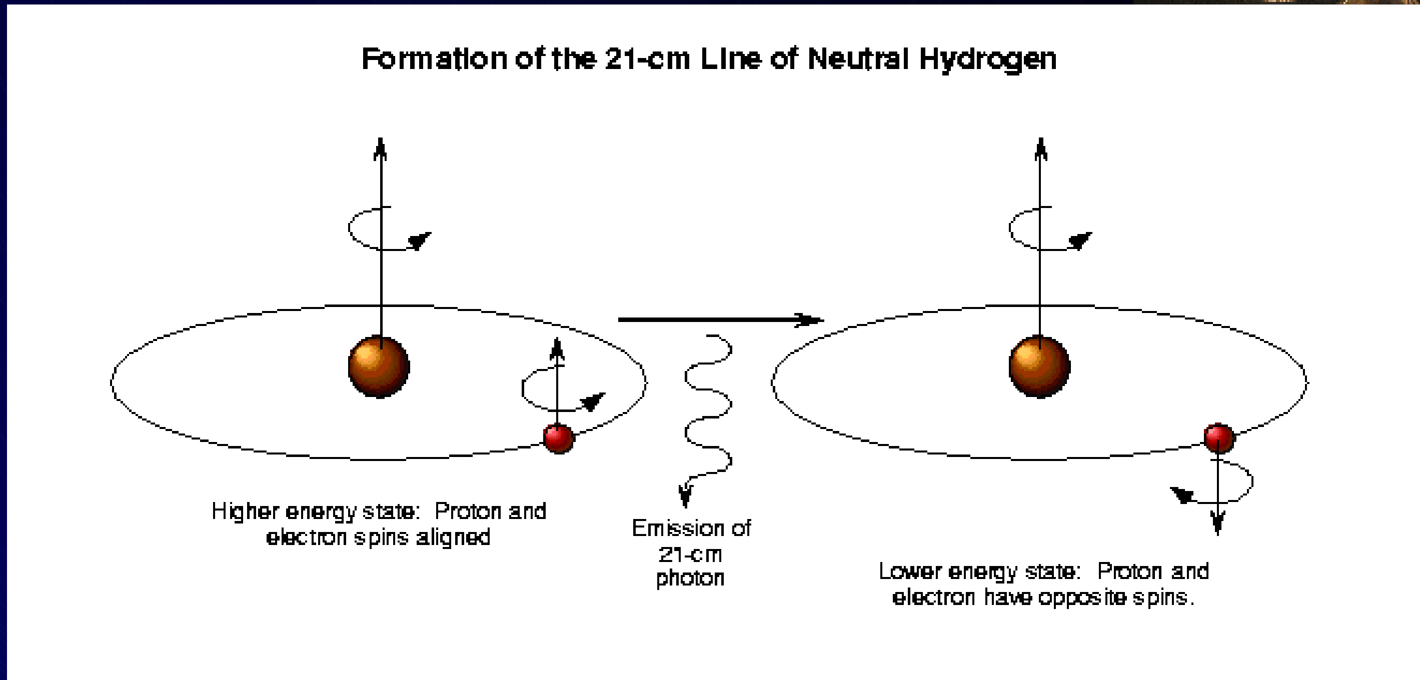
HI 21 cm line

- Neutral hydrogen (H I) spin-flip transition



ΔE 1 0

The transition probability for spontaneous emission 1 → 0 is

$$A_{10} = 2.85 \times 10^{-15}\, s^{-1} \cong \left(11 \times 10^{6}\, yr\right)^{-1}$$

The smallness of the spontaneous transition probability is due to

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

The "natural" halfwidth of the transition is 5×10^{-16} Hz

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21-cm Line of Atomic HI

Through Hydrogen maser measurements the frequency is:
1,420,405,751.7667 ± 0.0010 Hz
Energy $hc/\lambda \sim 5 \times 10^{-6}$ 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-a 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.

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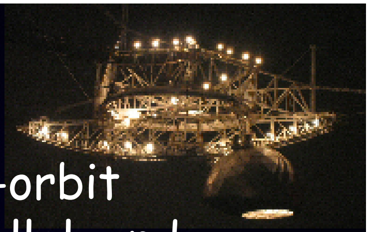
HI Gas in Galaxies



- Atomic hydrogen has two states in its ground level, split by spin-orbit coupling. Parallel spins give a slightly higher energy than antiparallel, and decays by emission of a photon at 1420.406 MHz.

- The upper level is populated by collisions, and has a decay half-life of about 3.5 x 10^{14} seconds = 1.1 x 10^{7} years; this is detectable only because there are lots of H atoms. 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.

- 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)

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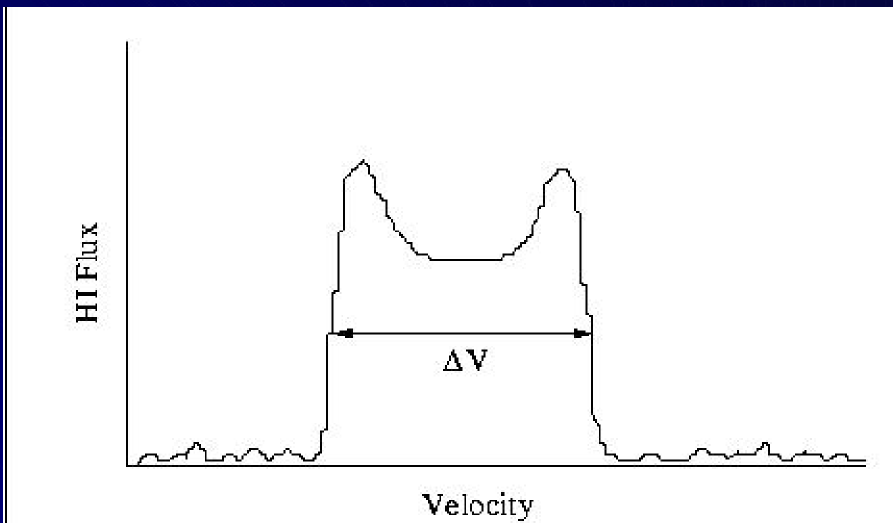
HI emission from galaxies

- 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)



Rest frequency 1420.4058 MHz

$\int F dV$ ➡ HI mass
V ➡ Distance
ΔV ➡ Mass

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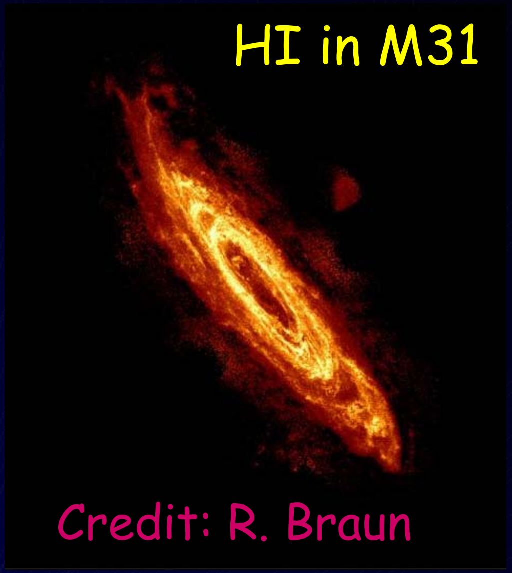
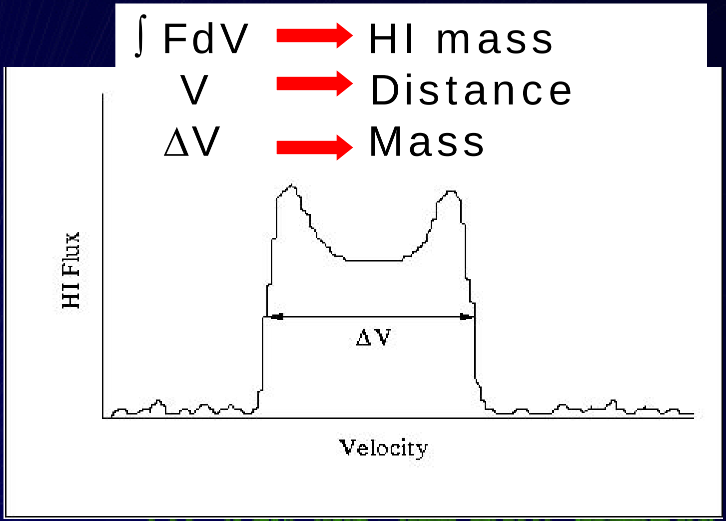
Clues from the HI line

- 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
- Redshifts
- Rotational velocities
  - Dark matter
  - Redshift-independent distances via Tully-Fisher relation
- HI absorption: optical depth
  - Link to Ly-a absorbers
  - Fundamental constant evolution





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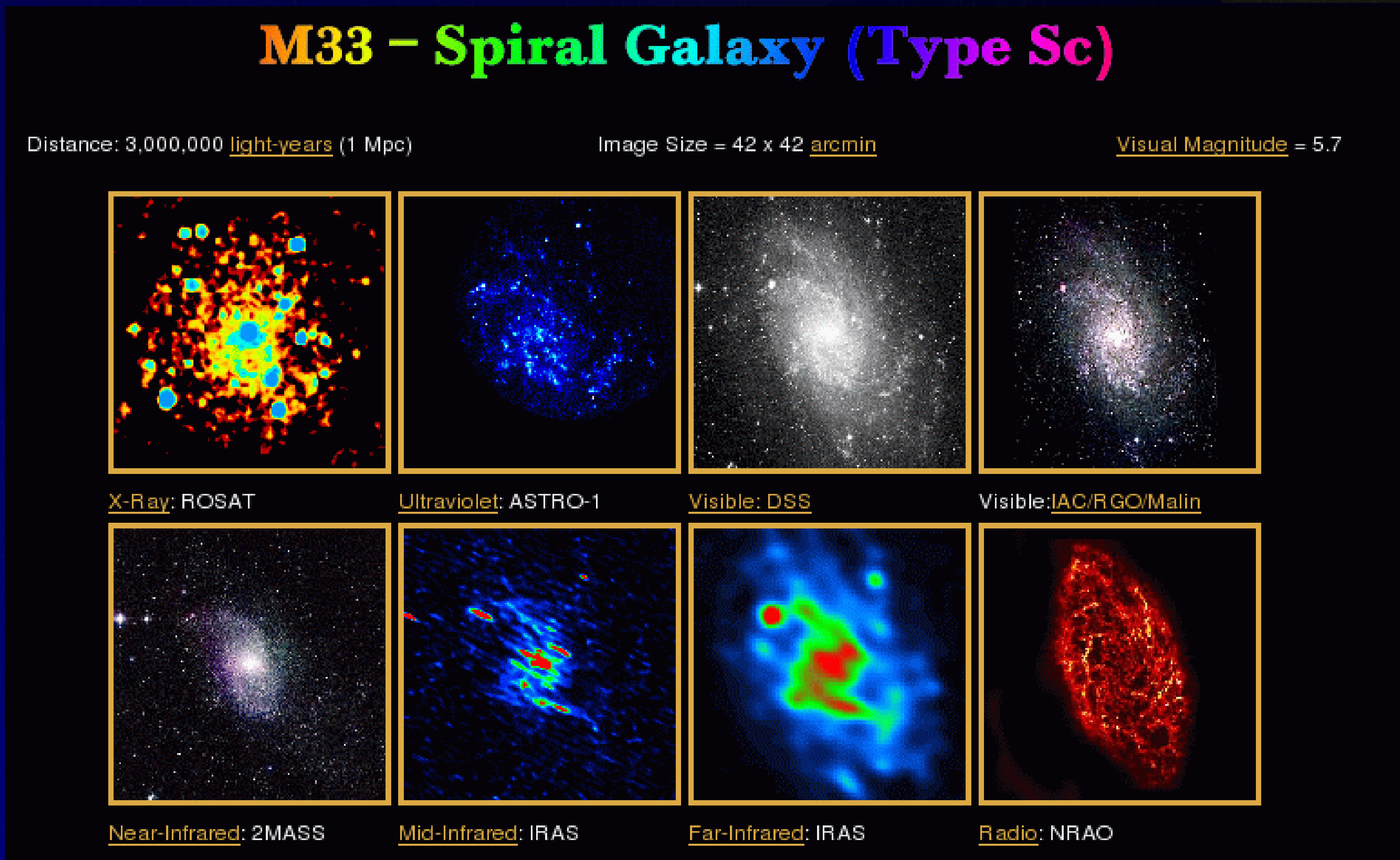
HI: The Fuel for Star Formation



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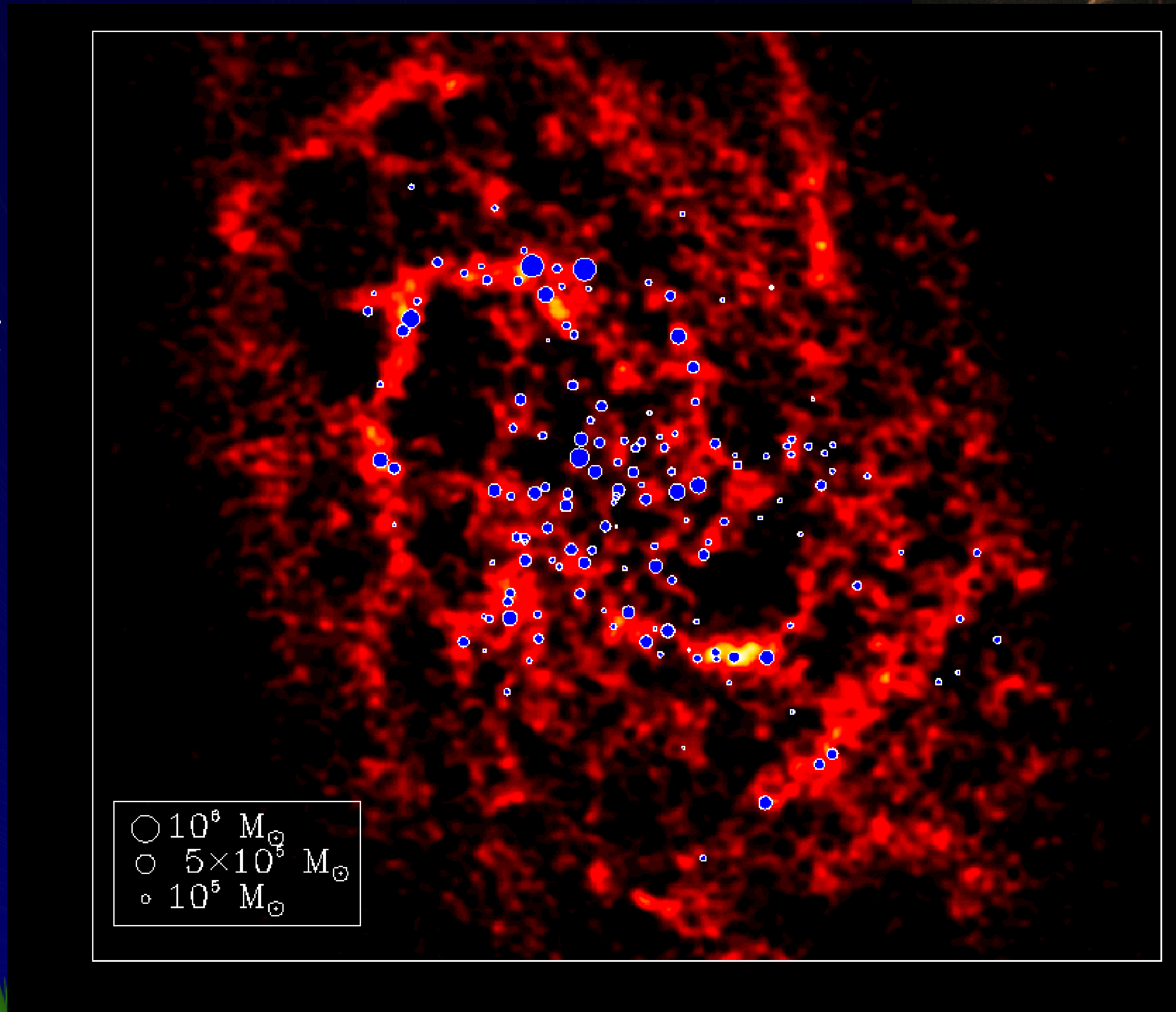
HI and H_2

M33

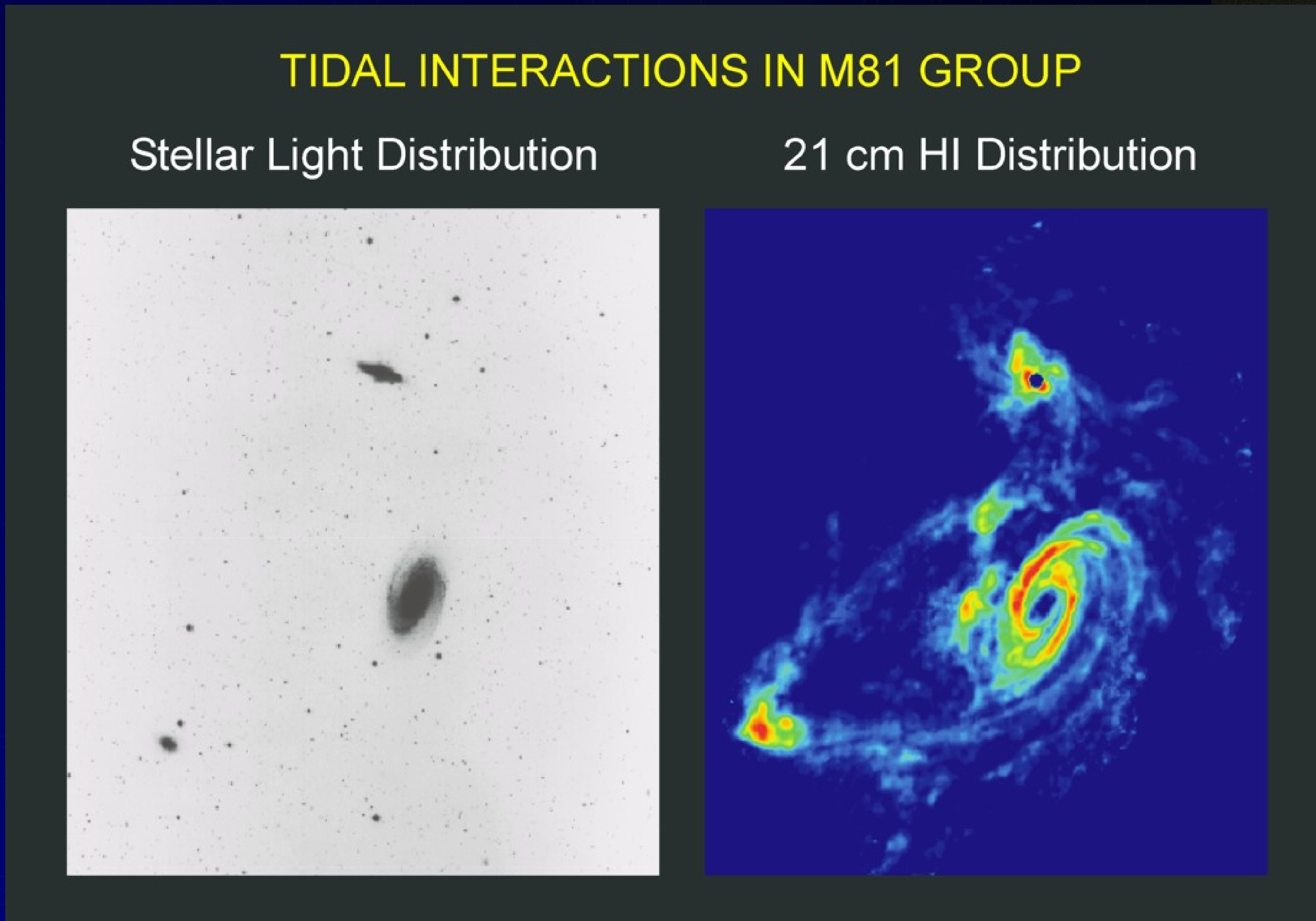
CO GMC's (Engargiola et al. 2004)

superposed on HI

(Deul & van der Hulst 1987)



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



Credit: NRAO, Yun et al.

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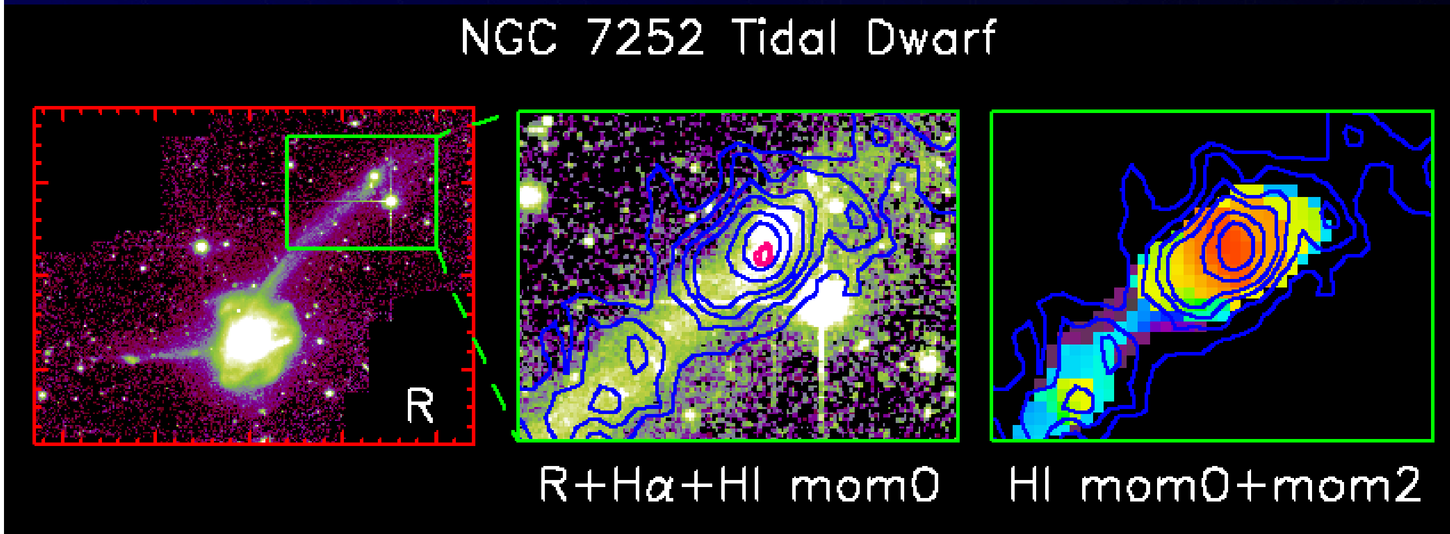
Tidal Dwarf Galaxies



Hibbard *et al.* 1994

- Expected to form in dynamically cool, gas-rich tidal tails
- Should be a mix of pre-existing stars from tidally disrupted material and a "new generation" of young stars produced as HI gas condenses => fall off the metallicity-luminosity relation
- Should contain little dark matter (assuming no DM in galaxy disks)
- Although young TDGs may be prominent due to the burst of star formation, their long-term fate remains unclear

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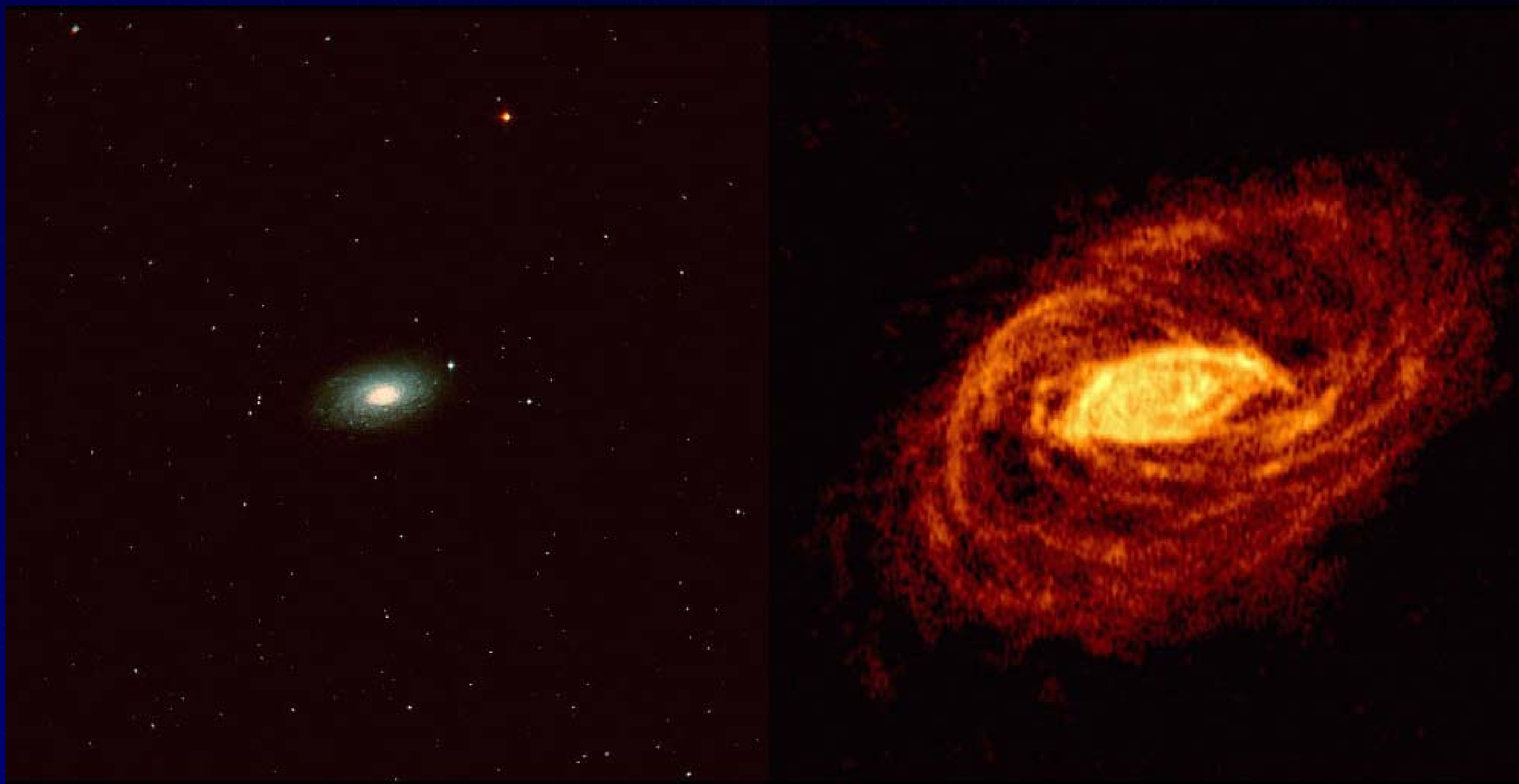
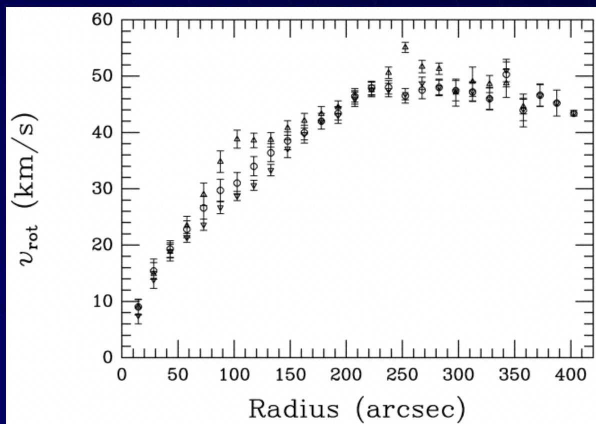
HI: Probing Dark Matter

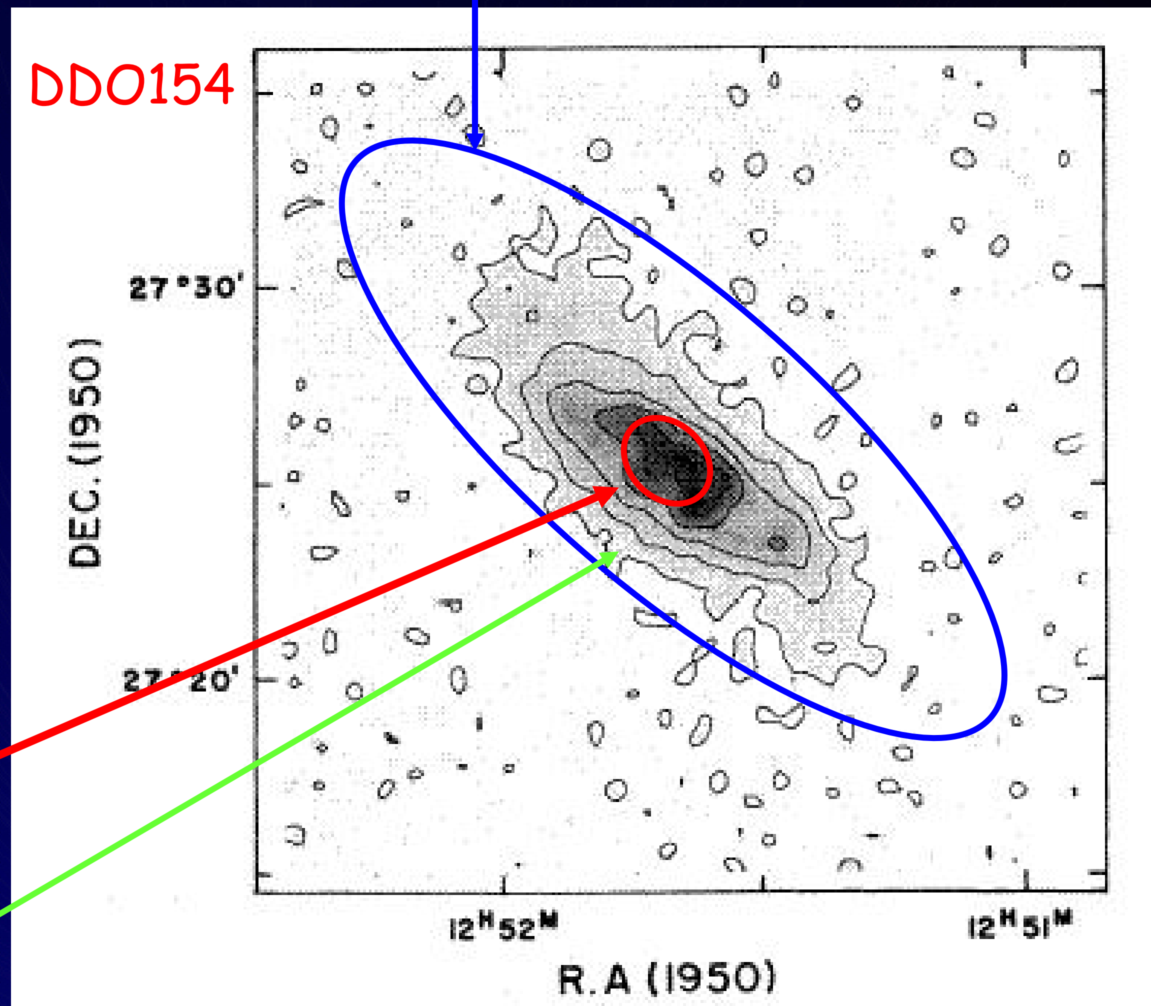


NGC 5055 Optical (left); HI (right)
Tom Osterloo

Are there totally "dark" galaxies?

Arecibo map outer extent [Hoffman et al. 1993]





$M_H = 2.5 \times 10^8 M_\odot$

$M_{stars} = 5.0 \times 10^7 M_\odot$

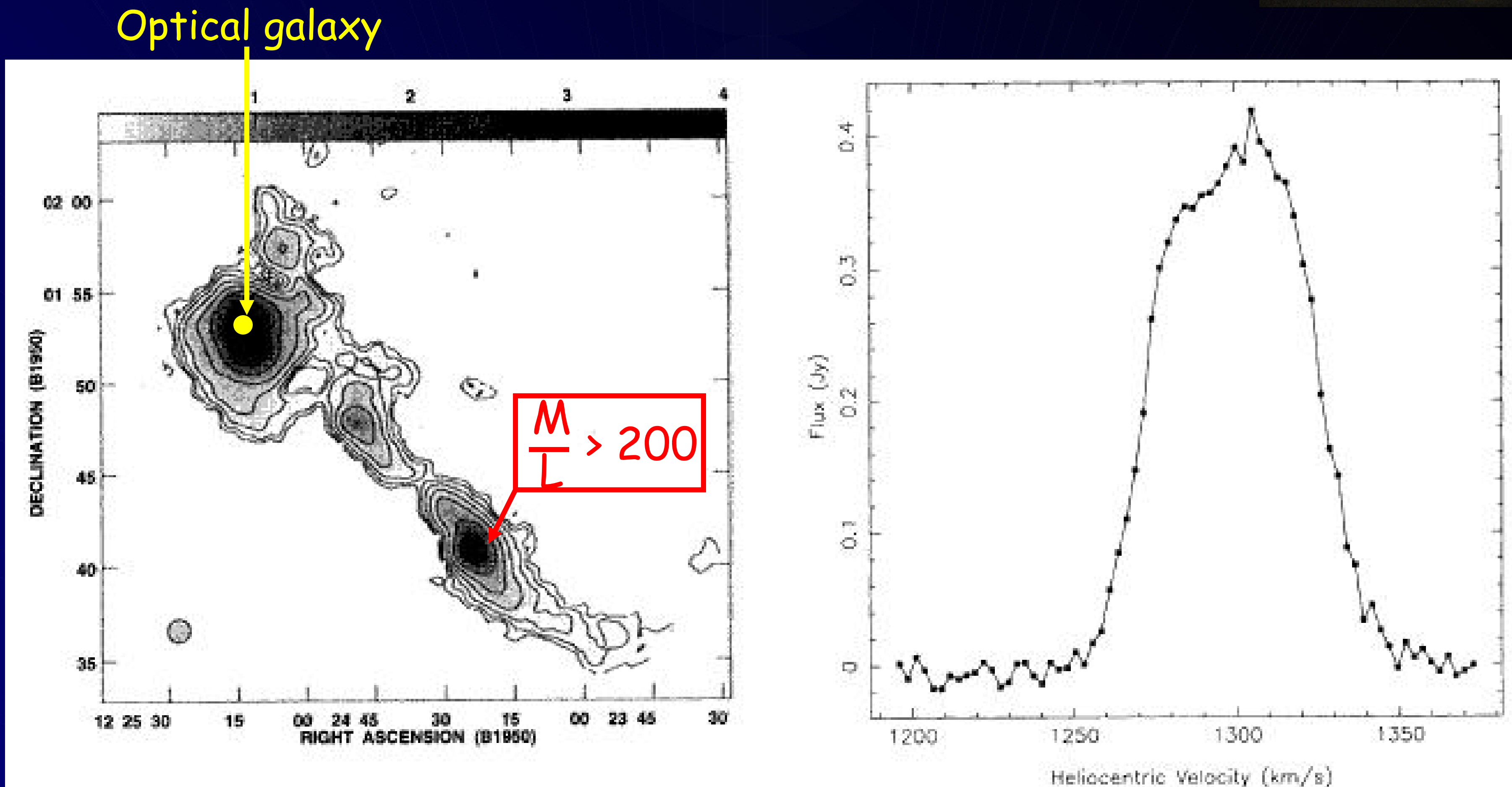
$M_{Dyn} = 3.0 \times 10^9 M_\odot$

Extent of
Optical image

Carignan & Beaulieu 1989
VLA D HI

ALFALFA

HI 1225+01



Giovanelli, Williams & Haynes 1989

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The HI 21 cm line @ 1.42 GHz

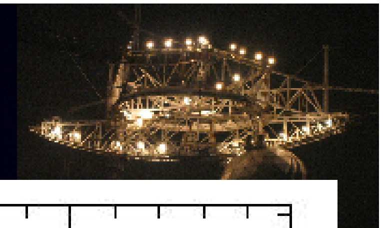
HI : Why do we care ?

- Easy to detect, simply 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

The HI Mass Function

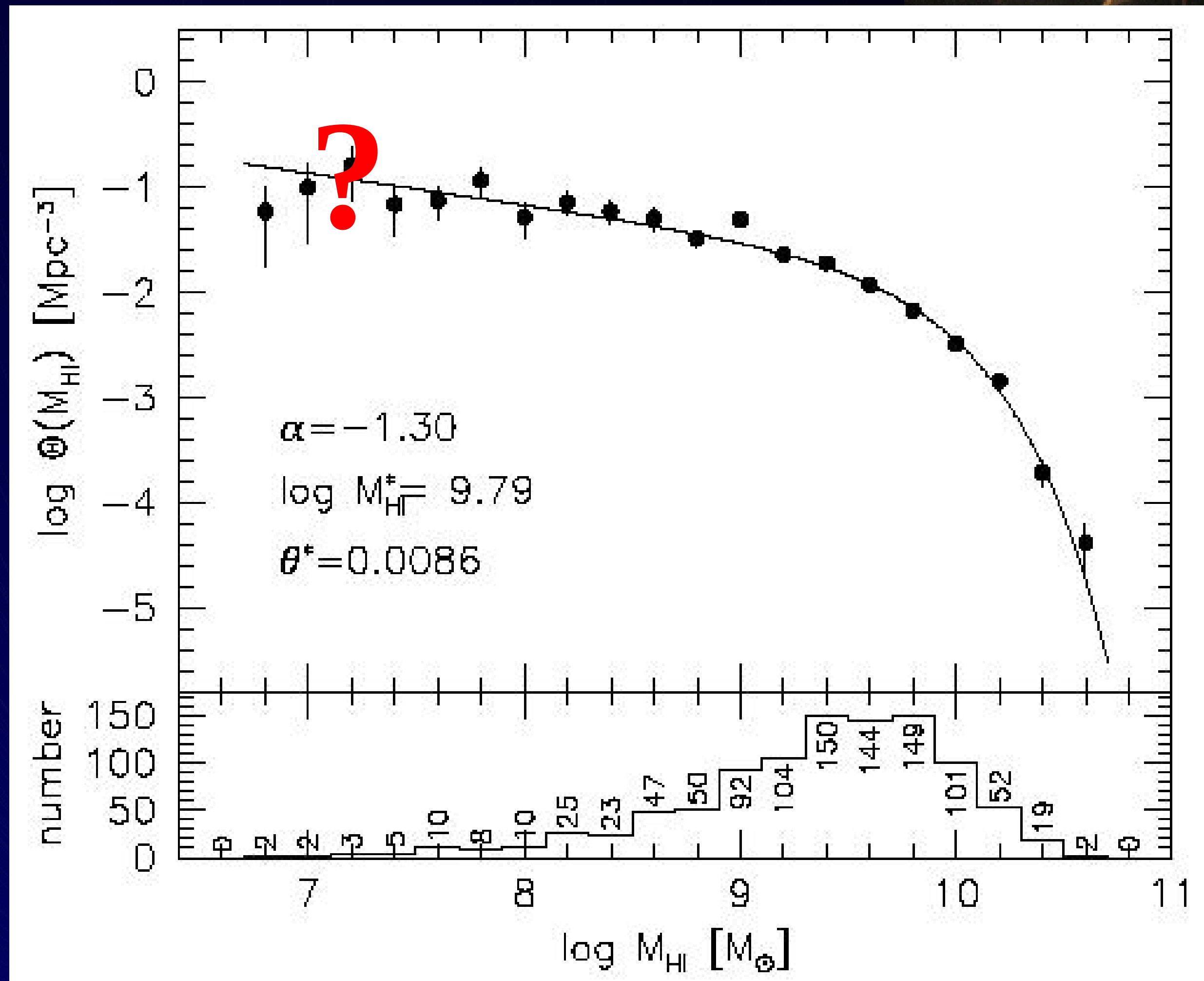


- How many HI sources are there?
- Previous surveys have included few (if any) objects with HI masses less than 10^8 $M_\odot$.
- At lowest masses, differ by 10X:

  Rosenberg & Schneider (2000)

  versus

  Zwaan et al. (1997)



Parkes HIPASS survey: Zwaan et al. 2003

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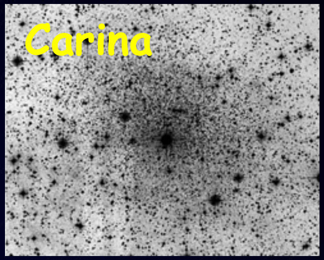
Dwarf galaxies

- dE, dSph, dIrr
- Low mass: detected only nearby
- Dark matter dominated
- Low abundances
- Stellar mass: 10^6-10^8 $M_\odot$
- Blue Luminosity: 10^6-10^8 $L_\odot$ ($M_B > -15$)
- Dynamical mass: 10^7-10^9 $M_\odot$

Where they are gas-rich:

- HI mass: 10^6-10^8 $M_\odot$
    - Sometimes, extensive HI
    - Evidence for dark matter



"Dwarf galaxies of the Local Group" Mateo 1998 ARAA

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Where are the low HI mass galaxies?

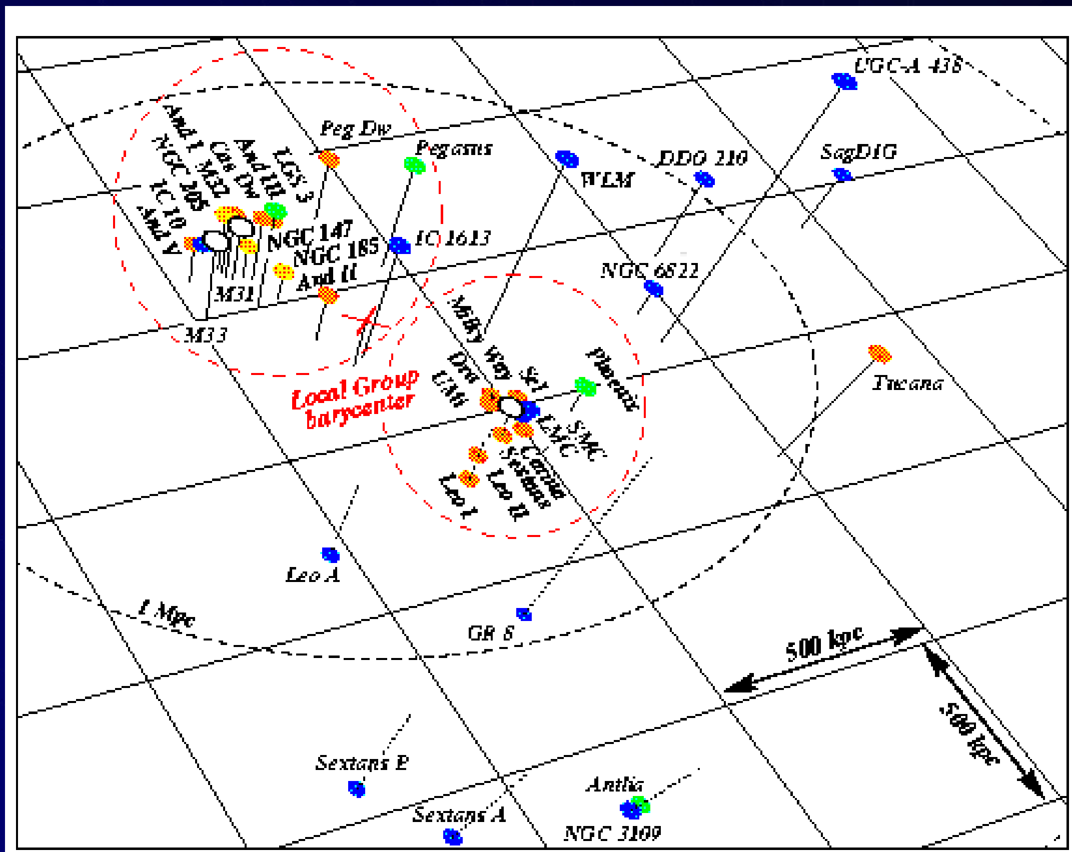

Diagram from Grebel 1999

- Galaxies mainly clustered around the two principal galaxies MW & M31
- Morphological segregation evident
  - dE/dSph near large galaxies
  - dI at larger distances

- Giant spirals
- dSph (+dEll)
- dIrr
- dIrr/dSph

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The Search for Low Mass Halos

- Do large numbers of low mass "halos" exist?
- If so, do they contain baryons?
- If so, could they be "starless" but *gas-rich*?
- If so, could they be found preferentially in some environments but not in others?

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ALFALFA: A 2nd 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_{HI}

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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 $0.16 < z < 0.25$

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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	5300	460	1.9×10^6
HIJASS	12.	(TBD)	13	3.6×10^7	(?)	3500	(TBD)
J-Virgo	12	32	4	1.1×10^7	31	3500	3200
HIDEEP	15	32	3.2	8.8×10^6	129	9000	2000
ALFALFA	3.5	7,000	1.7	4.4×10^6	25,000+	40	7×10^6

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

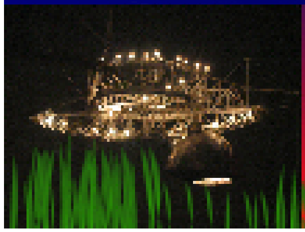
Median cz for HIPASS ~ 2800 km/s
For ALFALFA ~ 7500 km/s

Arecibo Legacy Fast ALFA Survey

- One of several major surveys currently ongoing at Arecibo, exploiting its new multibeam capability

- An extragalactic spectral line survey
- Covers 7000 sq deg of high galactic latitude sky
- 1345-1435 MHz (-2000 to +17500 km/s for HI line)
- 5 km/s resolution
- 2-pass, drift mode (total int. time per beam ~ 40 sec)
- 1.5-2 mJy rms
- 4400 hrs of telescope time, 5 (6,7…) years
- started Feb 4, 2005; ~3000 hrs to date

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



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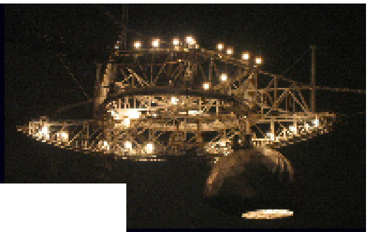
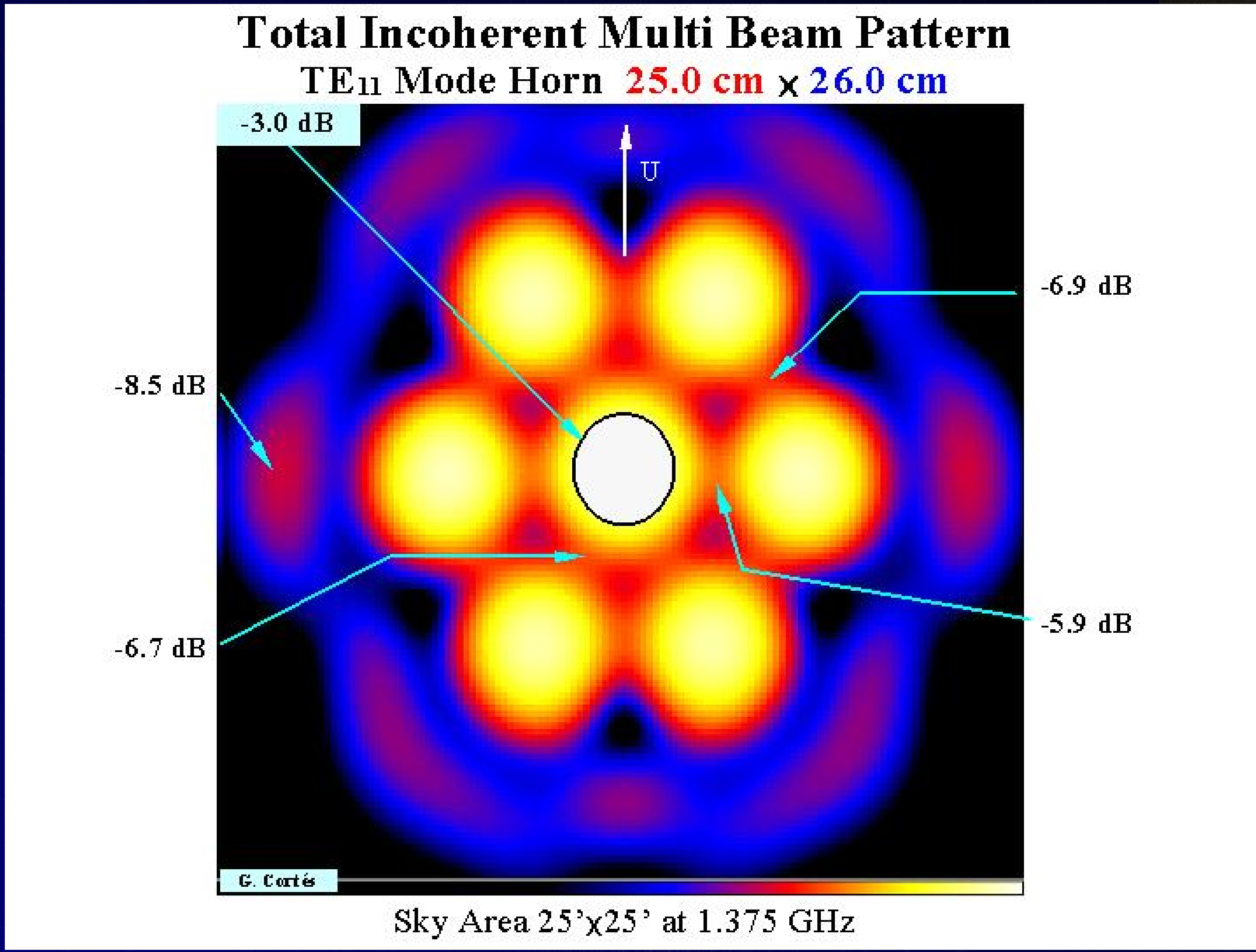
ALFA: Arecibo L-band Feed Array





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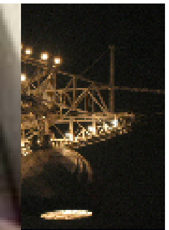
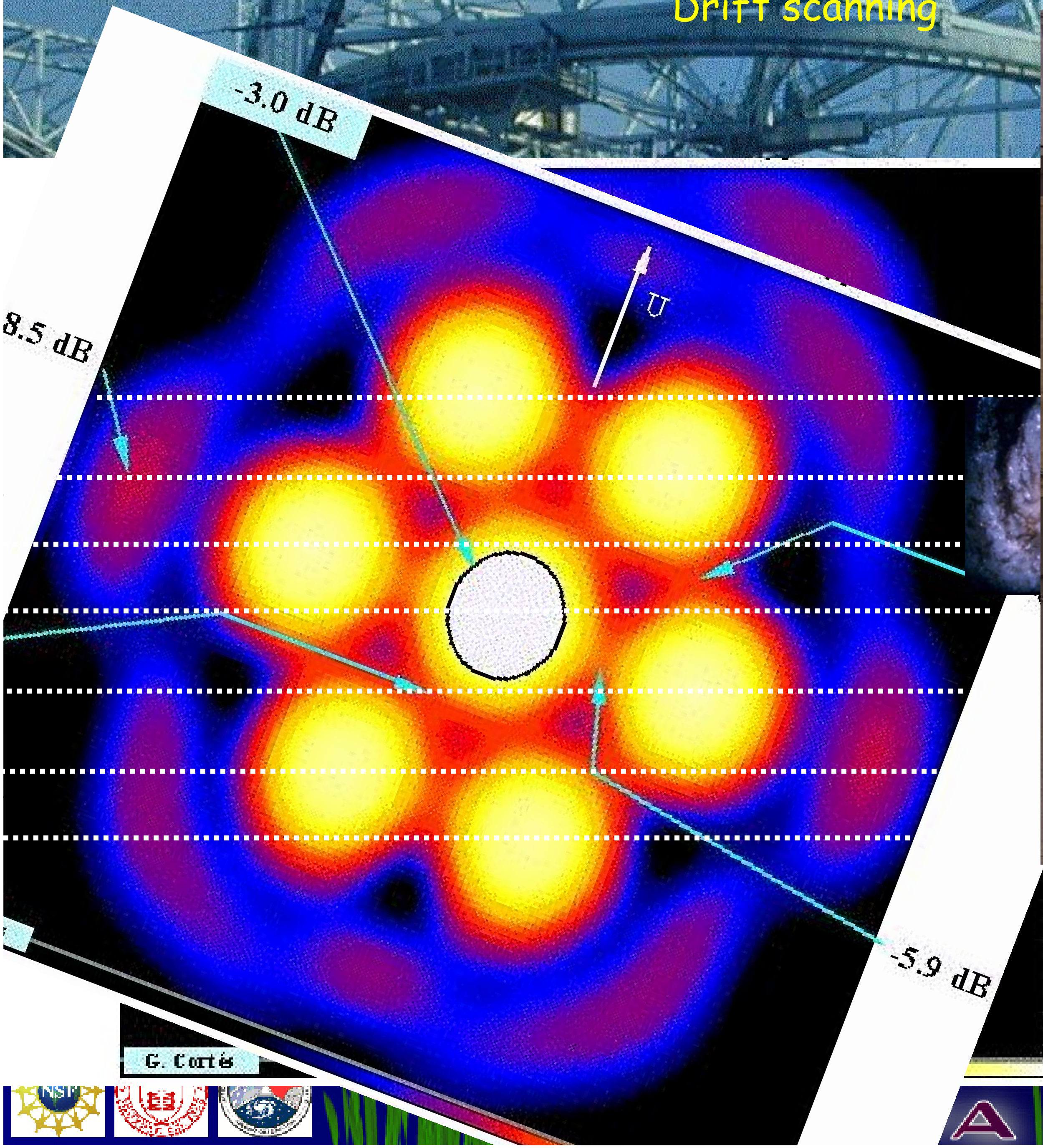
It is a radio "camera"



Arecibo L-band Feed Array

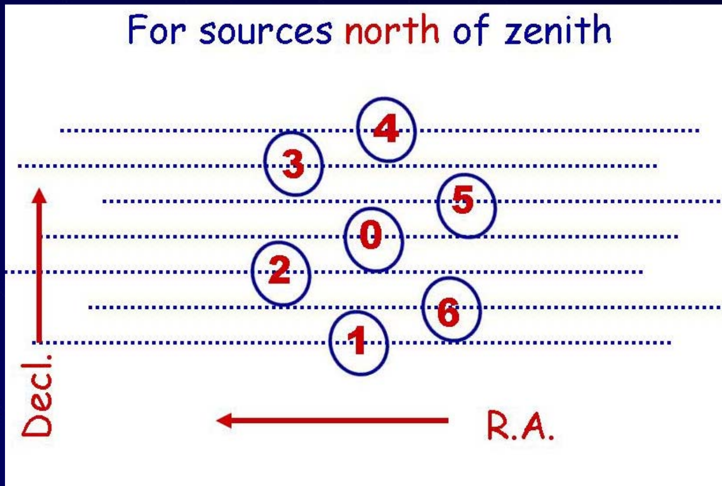
Drift scanning



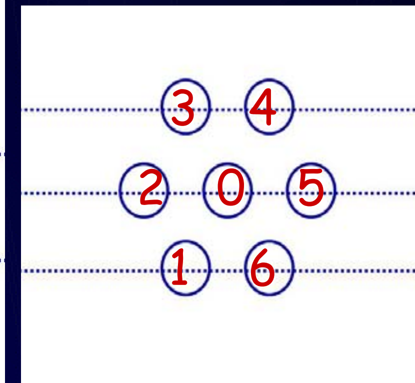
7 elliptical beams
Avg(HPBW)=3.5′
on elliptical pattern
of axial ratio ~1.2

Array rotation

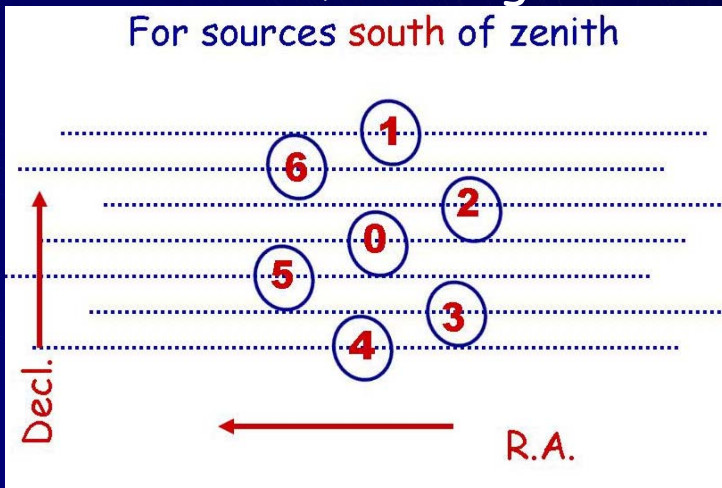
Dec > +18, RotAng=19



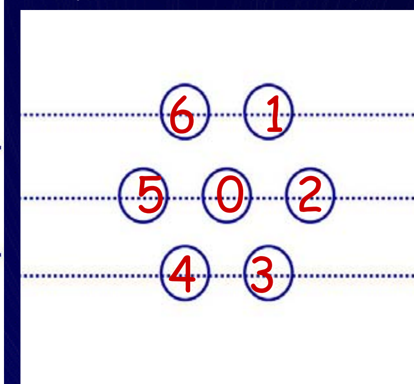
Dec > +18
No rotation



Dec < +18, RotAng=19



Dec < +18
No rotation



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

Note: The beams are actually elliptical, NOT circular.

ALFA at 19°

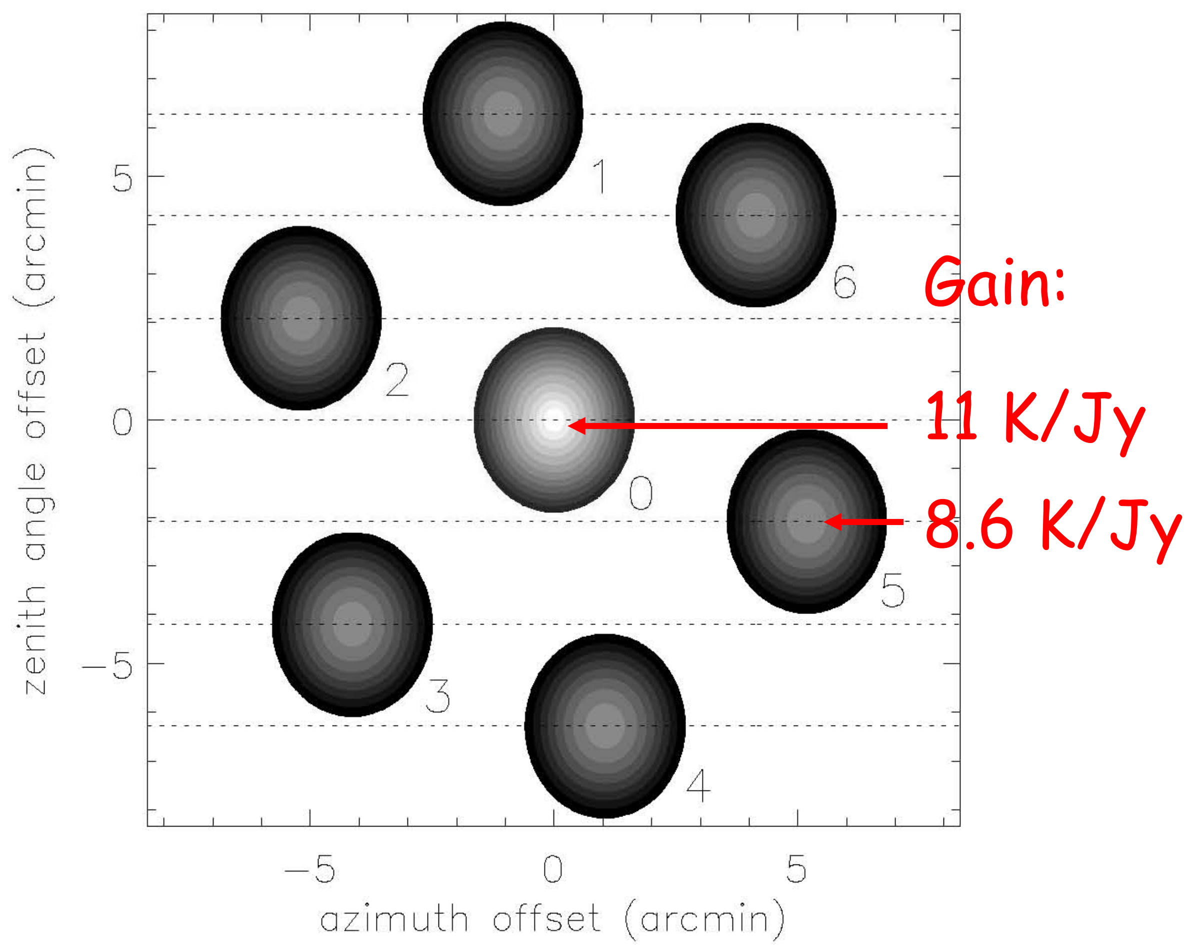


Fig. 2.— Sketch of the geometry of the ALFA footprint, with the array located along the local meridian and rotated by an angle of 19° about its axis. The outer boundary of each beam corresponds to the -3 dB level. The dashed horizontal lines represent the tracks at constant Declination of the seven ALFA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

ALFALFA

ALFALFA schedule notation

- "Master list" of drift declinations preassigned, starting at 0° and moving northward to +36° => DriftN, N = 1, 148
- Two passes: p1 and p2

107p1	+255454
107p2	+260212
108p2	+261648

7.3 arcmin

14.6 arcmin

ALFALFA

ALFALFA drift mode

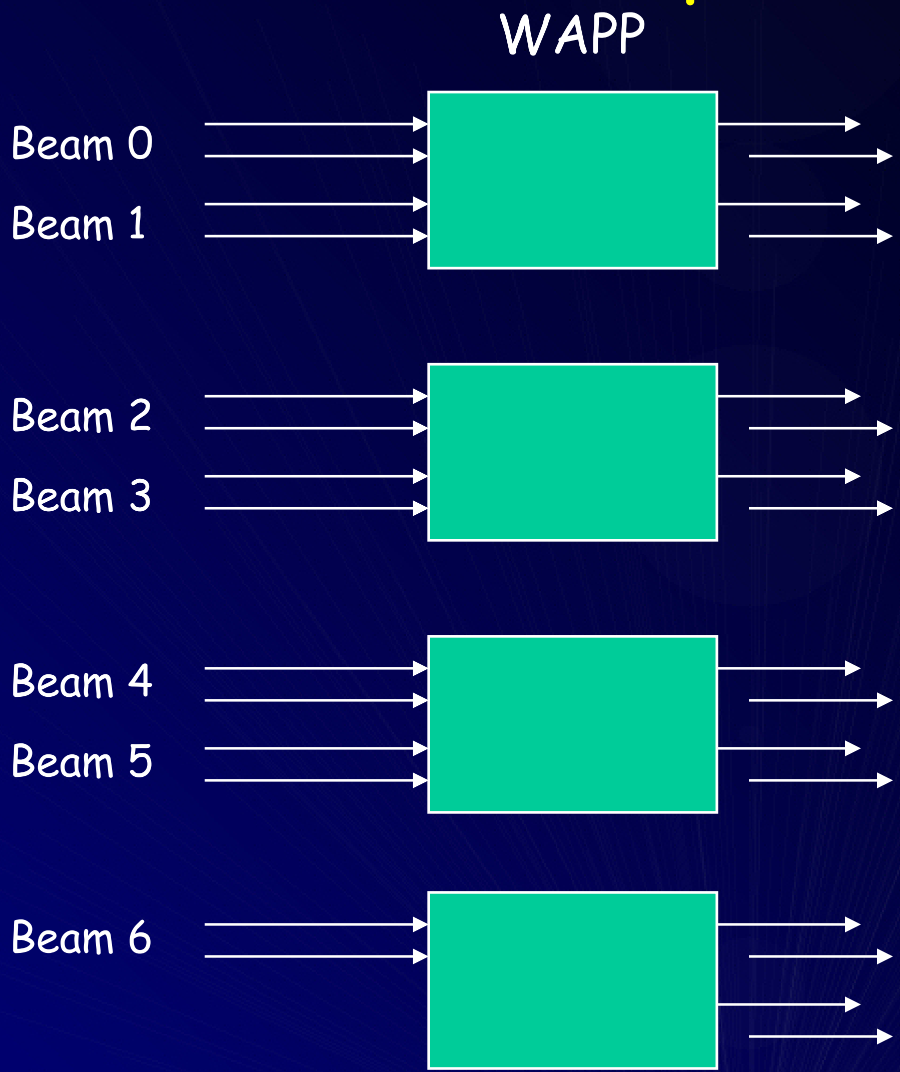
- "Almost" fixed azimuth drifts
  - Track in J2000 Declination
  - Declination of all survey drifts specified, except for +16° < DecJ < +20° (zenith "Zone of Avoidance")
- Specify observing "block" according to date/time at start, specified as yy.mm.dd

  09.01.12a: This (early) morning's block

  09.01.12p : This afternoon's block

Block	Date	AST	LST	#	DecJ
09.01.12p	M 12Jan	16h00-17h00	23h02-00h02	14p2	+032424
09.01.13a	T 13Jan	00h15-07h15	07h04-14h05	14p2	+032424
09.01.13p	T 13Jan	18h30-20h15	01h37-03h22	49p2	+115524
09.01.14	W 14Jan	18h15-20h15	01h41-03h26	41p1	+095118

Spectrometer setup for ALFALFA



ALFA spectra:

16 x 4096 frequency channels (2 not used)

7 beams X 2 polarizations/beam

100 MHz wide

Centered at 1385 MHz

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.

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

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RFI List

Mozilla Firefox

File Edit View Go Bookmarks Tools Help

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

User Record Viewer

1241.75 1244.6 1256.5 1261.25	1.67	jan97	active Radar	**Aerostat** radar ballon in lajas. dual freq or quad freq modes. 160 usec per pulse, chirped. Rotation rate 11.59 secs. Blanks toward AO. (see radar info)
1270/1290	.2	feb02	active Radar	**Remy Radar** 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 radar info)
1287.5/1299.84 1300,1399.83 1400 1411.52 1412.5	<.025	jan01 apr02		**Distomat** birdies. Occur every 2 minutes for a few seconds. Az dependent.Distomats have a 27 Mhz clock. Data was measured in jan01 (before shielding work) Data was remeasured in apr02 (after some shielding work). The window was changed
1330/1350	.2	jan97	active Radar	**FAA airport radar**.12 sec rotation, 5 ipps about 2.5 ms,5 usec pulse, 1350 then 1330 pulse sent each ipp. (radar info)
1366.2/1382.66 1324/1340 1387.3/1371.0		feb01	Radar	**Radars with 1.94 sec rotation** rates. (more info). 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	**GPS L3** downlink. (more info)
1388.55	.024	98		**beeper** harmonic (3rd of 462.85)
1388.6	.024	93		**beeper** harmonic (3rd of 462.875) (borinquen beepers)
1388.858 1417.495	<190 (hz)	may02		**dome camera** birides. part of a comb of 14.3185 Mhz. (more info).
1390.8	.024	feb93		**beeper** harmonic (3rd of 463.6 (mr. beeper)
1407	.3	apr01	fixed	**tvChan20** arecibo. Drifted around with time. They were having trouble with their transmitter. (more info)
1422.5				**tvChan54** 2nd harmonic
1525-1545		aug03		**Inmarsat stdBC** ship,portable earch downlinks **Inmarsat stdM** ship downlinks

Done

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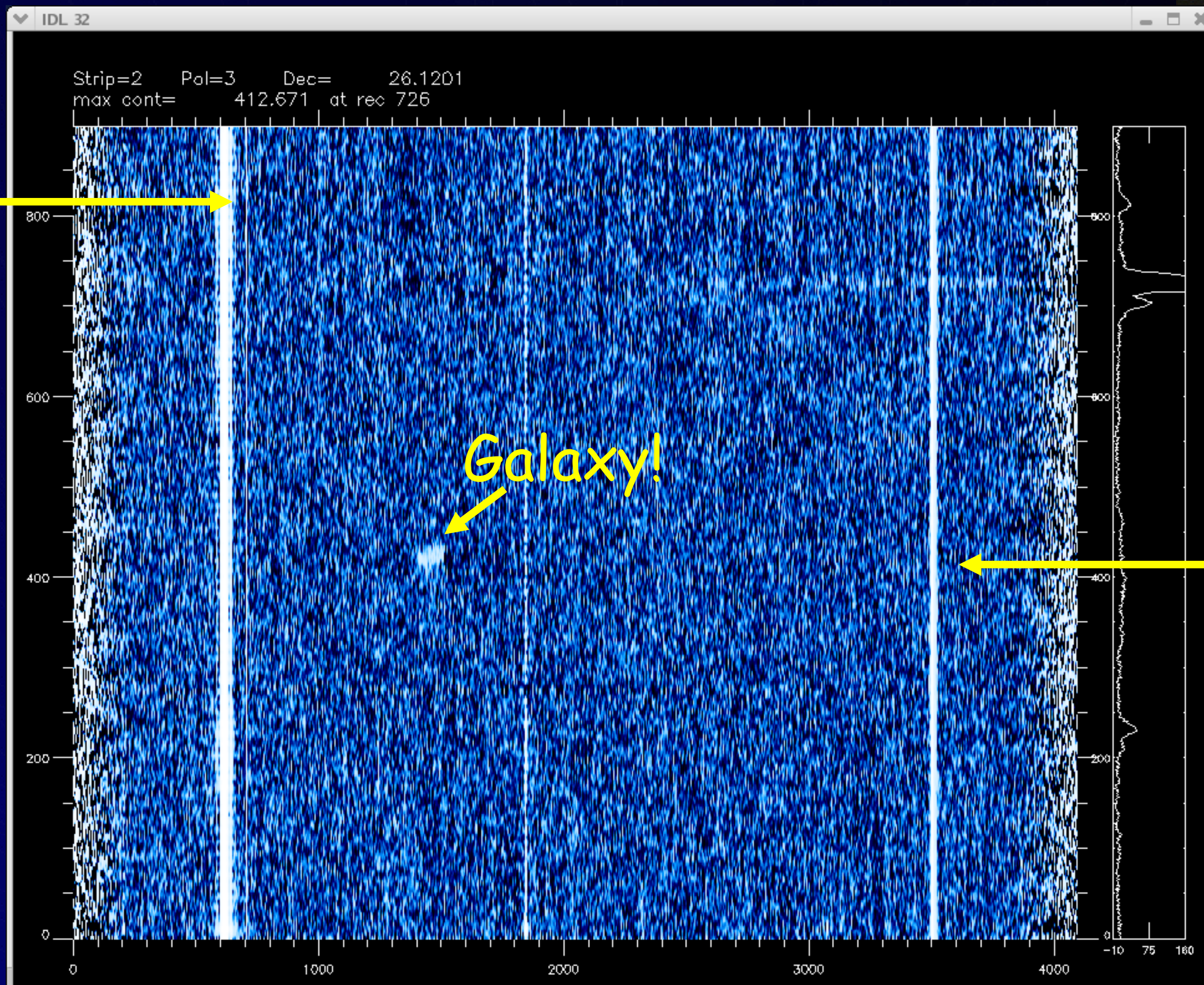
RFI is ugly



IDL 32
Strip=2 Pol=3 Dec= 26.1201
max cont= 412.671 at rec 726
FAA radar
Galaxy!
Galactic hydrogen
Record/time/R.A. →
Channel number/frequency →
0
1000
2000
3000
4000
200
400
600
800

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 2nd drift by half of the beam spacing.

- Helps with position centroiding
- Evens out the gain scalloping

We conduct the 2nd 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.

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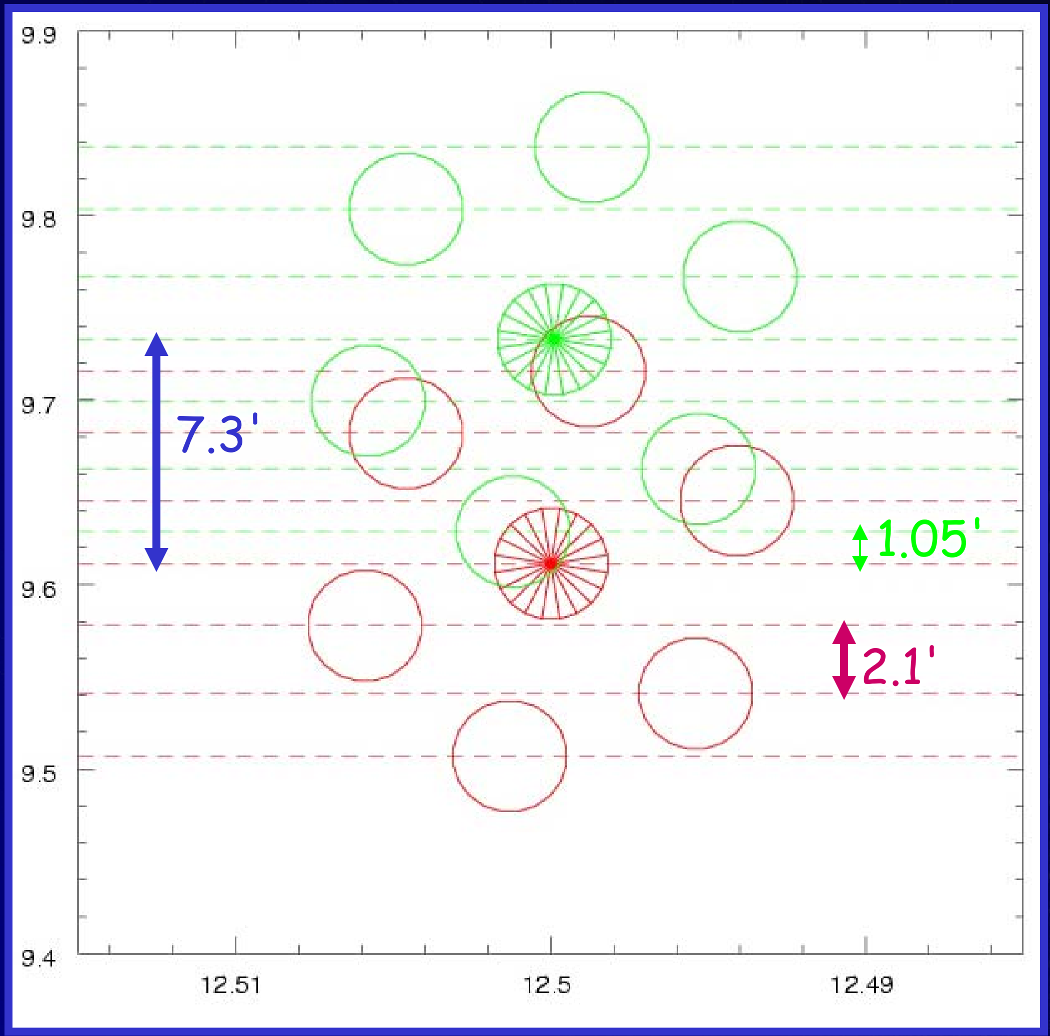
2-pass beam layout



Final coverage for 2 pass strategy

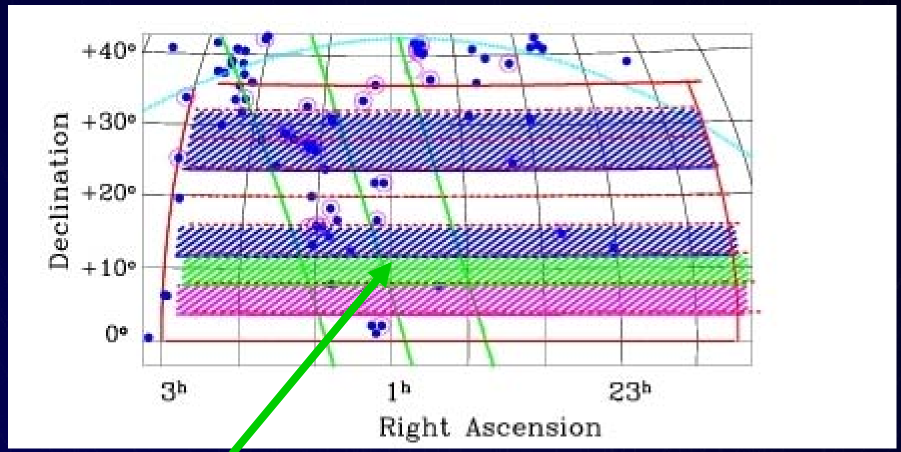
- For the 2nd pass, Beam 0, which has higher gain than the others, is offset by 7.3 arcmin from its 1st pass position.
- Some smoothing of gain scalloping.
- 2-pass sampling thus at 1.05 arcmin
- 2nd pass occurs 3-9 months after the 1st pass (vs. RFI)

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 1st pass (to aid RFI identification and signal confirmation).

ALFALFA Survey 2005-8

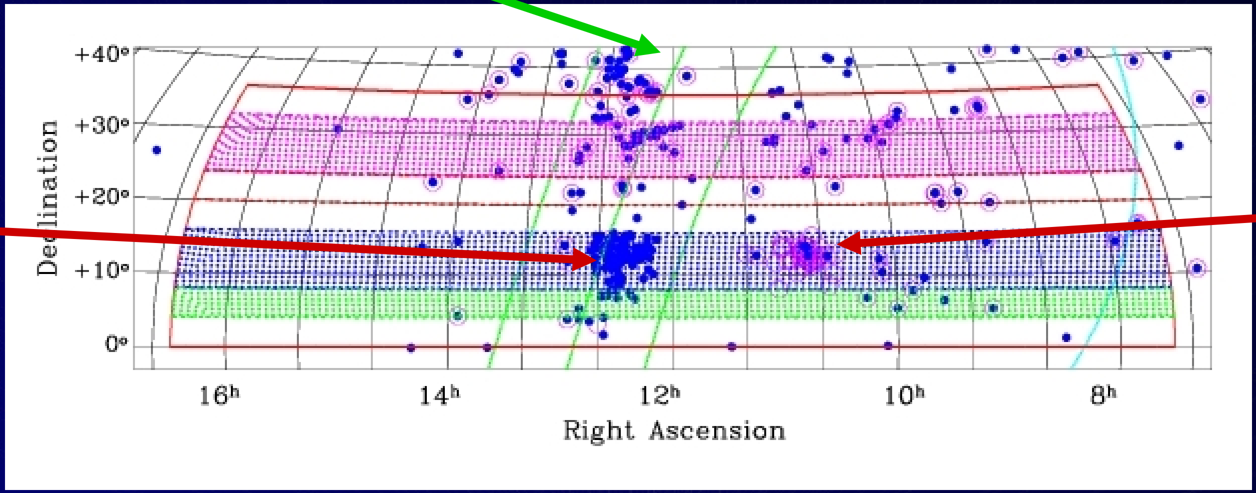
High galactic latitude sky visible from AO



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

Supergalactic plane

Virgo cluster



Leo Group

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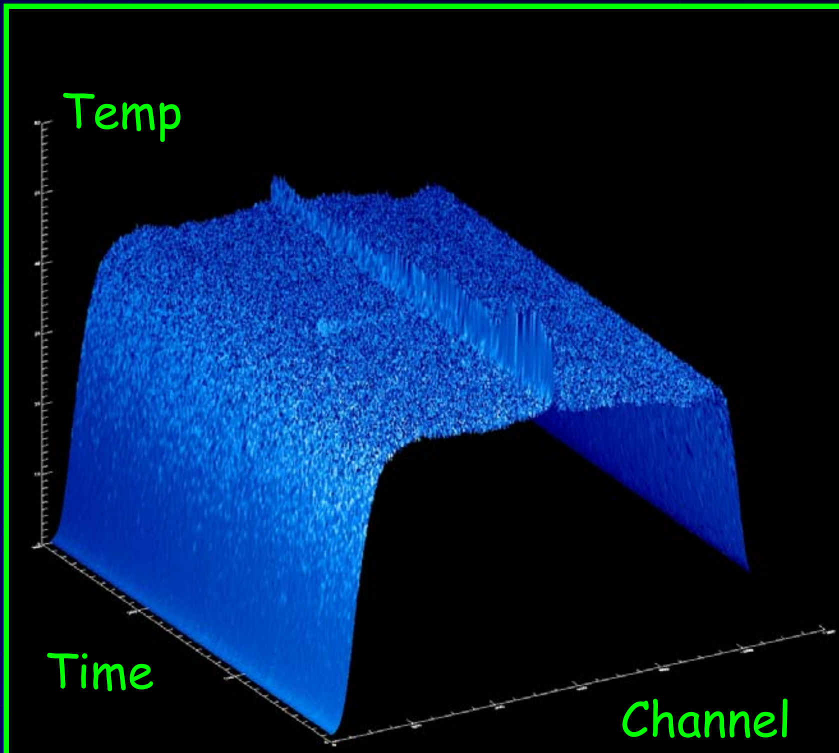
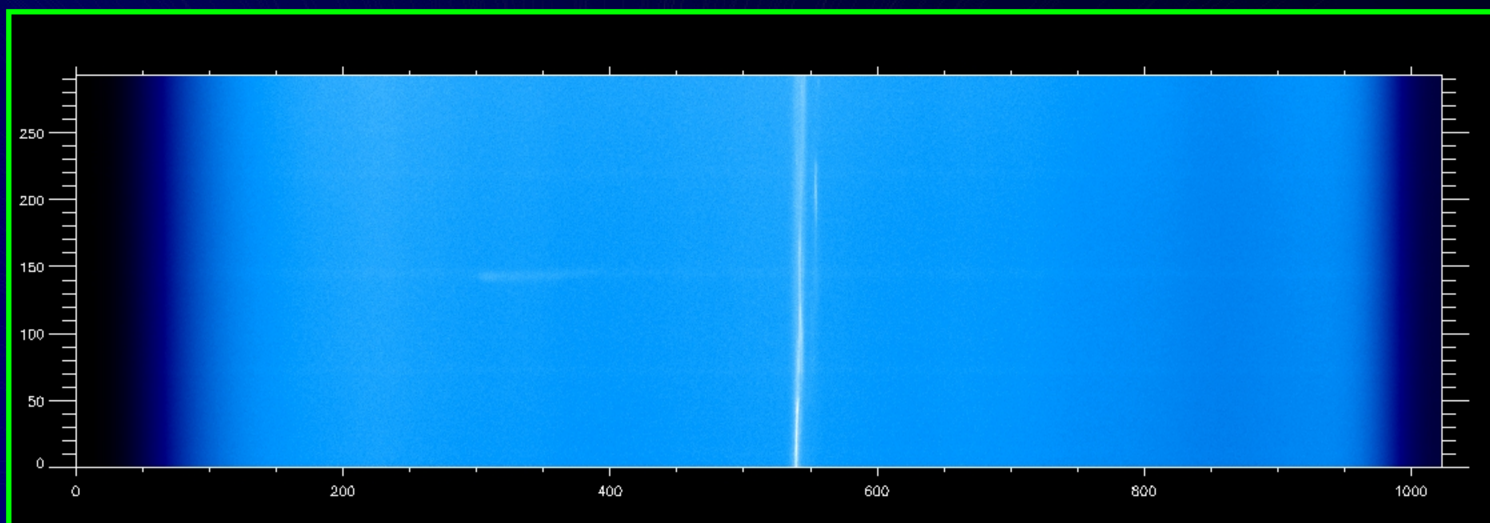
Raw data



← *A Drift scan, before bandpass correction (bpd)*

Time



Channel

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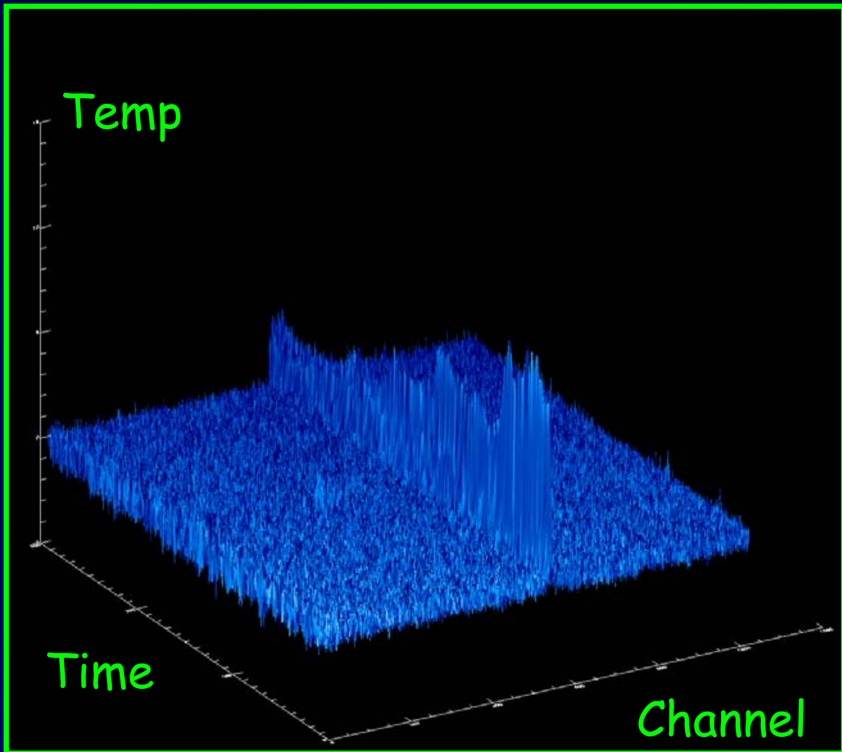
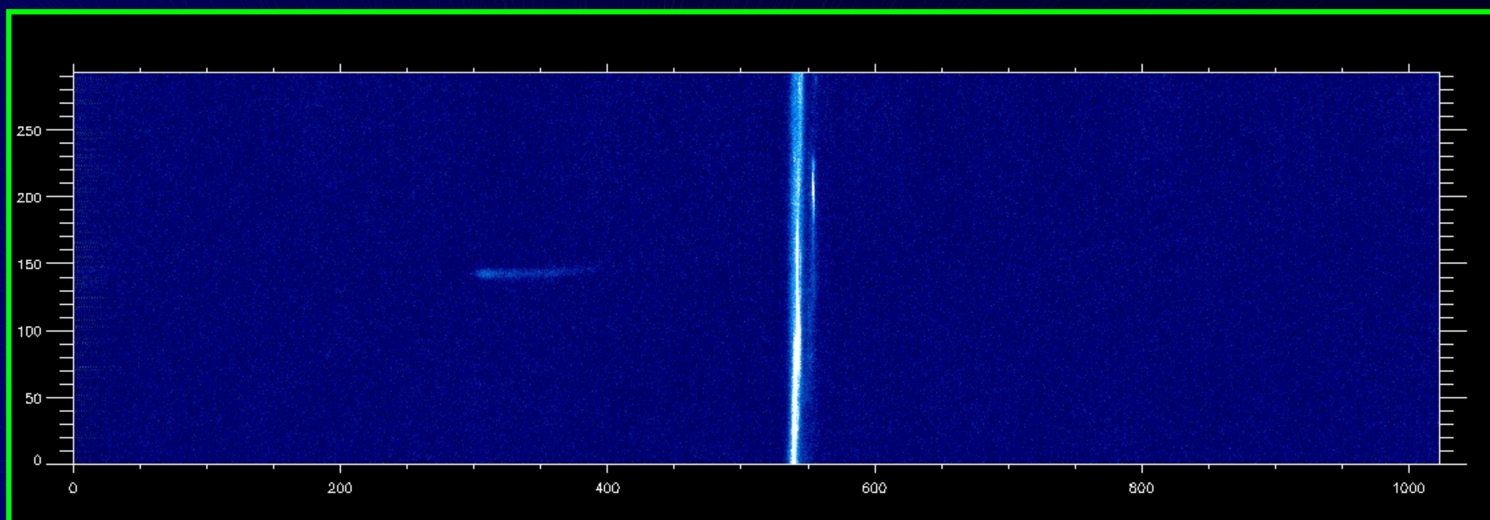
After BPD



← A Drift scan, after bandpass correction (bpd)

Time



Channel

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.
  - We got an A+ last year.

ALFALFA observing sequence

- Set dome at transit (360° or 180°)
- Rotate ALFA to 19°
- 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

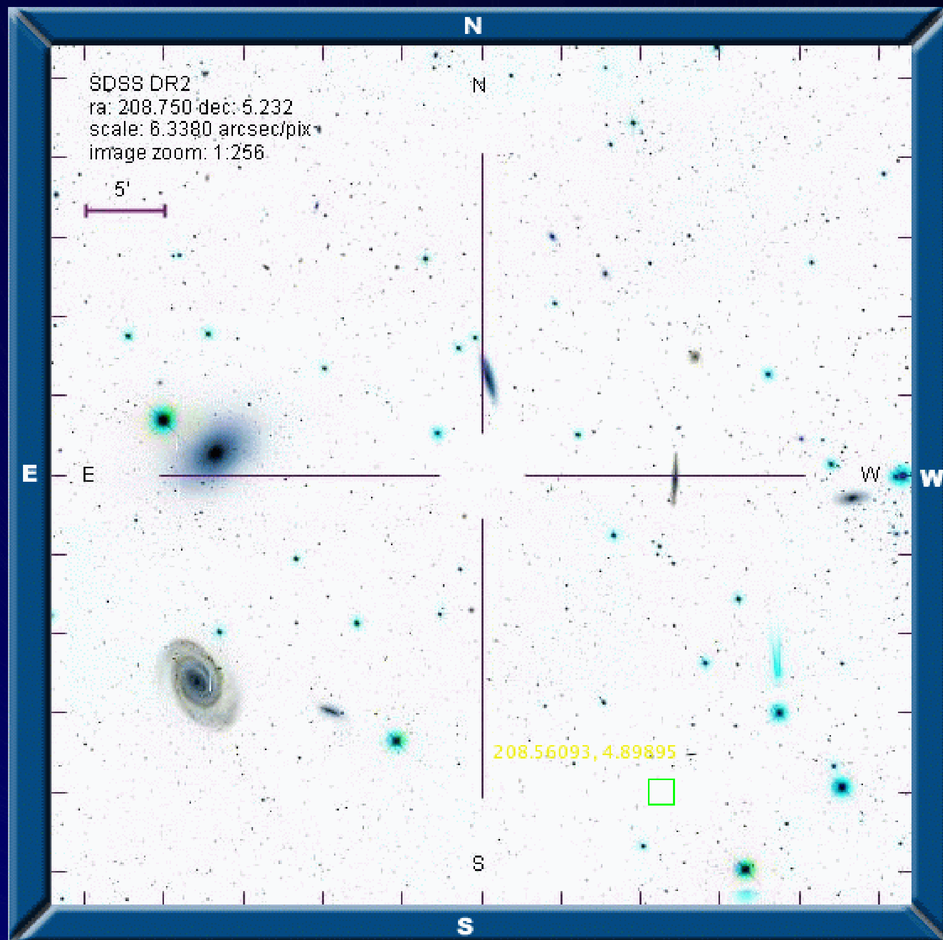
Scavenger Hunt #1

http://egg.astro.cornell.edu/alfalfa/ugradteam/hunt09/hunt2_09.htm

- Think about using ALFA for ALFALFA
- Start thinking about what we can learn about galaxies

ALFALFA

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



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