\[ \Omega_{\text{baryons}} = 0.045^{+/-0.004} \sim (1/6) \Omega_{\text{matter}} \]

Coronal & diffuse IG gas \sim 0.037
Cluster IGM \sim 0.002
Stars \sim 0.003
Cold Gas \sim 0.0008 (~2/3 atomic)

HI is a piffling fraction of cosmic matter, baryons

ALFALFA:
The Arecibo Legacy
Extragalactic HI Survey
HI: Why do we care?

- Optically thin $\Rightarrow$ cold gas mass
- Good index of SF fertility
- Excellent tracer of host dynamics
- Interaction/tidal/merger tracer
- Can be dominant baryon form in low mass galaxies
- HI Mass, Diameter Function, missing satellites
- Diagnostic tool of cluster dynamics/evolution
- Peculiar velocity, mass density field
- Low z link to DLAs
- LSS, cluster, group structure, void/metallicity problem
- BAO, EoR
Science goals and opportunity drive our choice of survey parameters...
High Velocity Clouds

Accreting Low-Metallicity Gas?

MILKY WAY
DDO 154

Arecibo map outer extent [Hoffman et al. 1993]

Extent of optical image

Carignan & Beaulieu 1989

VLA D-array HI column density contours
Haynes, Giovanelli & Roberts 1979
Arecibo data

Leo Triplet

NGC 3623
NGC 3627
NGC 3628

FIG. 1.—Neutral hydrogen contours of $\int T_dV$ superposed on an enlargement of the Palomar Sky Survey print of the Leo triplet. The northernmost galaxy is NGC 3628; the southermost is NGC 3627; the westernmost is NGC 3623. Crosses mark the sampling points of the Arecibo observations. The long appendage extending eastward from NGC 3628 is referred to as the plume; the extension in the region between the three galaxies is the bridge.

Haynes et al. (see page 84)
Figure 1. The Leo Ring System.

HI: Arecibo single dish map, 3.3' resolution, contours = 2 x 10^{16} cm^{-3} x 2'.
Optical: DSS, FOV = 70' x 100'.
Notes: Labeled galaxies have redshifts similar to the HI ring.
Reference: Schneider, S.E., Skrutskie, M.F., Hacking, P.B., Young, J.S.,
Dickman, R.L., Clemens, M.J., Salpeter, E.E., Houck, J.R., Terzian, Y.,

Schneider, Helou, Salpeter & Terzian 1983

Schneider et al 1989   VLA map
HI 1225+01

Optical galaxy

Chengalur, Giovanelli & Haynes 1991 VLA data
[first detected by Giovanelli, Williams & Haynes 1989 at Arecibo]
Dots: galaxies w/ measured HI
Contours: HI deficiency
Grey map: ROSAT 0.4-2.4 keV
Numerical simulations predict the existence of lots of low mass halos: Do they exist in the expected numbers? Klypin et al 1999

- Are baryons in small Dark Matter halos fried at the epoch of reionization?
- Are they blown away by the first generation of stars?
- Is gas accretion & cooling impeded in low M halos?
- Are baryons retained but unable to make stars?
- Is that more likely in cosmic voids?
The Void Problem

Scenario set by **Peebles 2001**: LCDM simulations show voids not being empty: they contain lower mass halos that "seem to be capable of developing into observable void objects"

- Observations, however, seem to indicate that the spatial distribution of dwarf galaxies is remarkably similar to that of brighter galaxies.
  - faint galaxies do not show a strong tendency to fill the voids.

The key assumption, in saying that there is a "Void Problem", is that \( \Lambda \)CDM predicts the existence of many more dwarf galaxies than observed.

with Snow White we ask

Where are the Dwarfs?

Disclaimer: this is NOT part of Jim Peebles’ paper
The HI Mass Function

- The HI mass function tells the number of galaxies per unit volume per unit decade of HI mass

\[ \Phi(x) = \frac{dn}{d(\log x)} = (\ln 10) \Phi^* x^{\alpha+1} e^{-x} \]

\[ x = \frac{M_{HI}}{M^*} \]

Figure from Zwaan et al. 2003
Springob et al.
Previous surveys have included few (if any) objects with HI masses less than $10^8 M_\odot$.

At lowest masses, differ by 10X:


Statistics
• Systematics

Parkes HIPASS survey: Zwaan et al. 2006
Schneider 2002

\[ \Phi \left( \text{Mpc}^{-3} \text{dex}^{-1} \right) \]

\[ \log_{10} \left( \frac{M_{\text{HI}}}{M_\odot} \right) \]

Schneider 2002
Beware of biases

... as for the impact of distance uncertainties...

(see Masters, Haynes & Giovanelli 2004)
Multiattractor models

- Infall onto one or more spherical attractors
- Tonry et al 2000 fit to ~300 SBF galaxies
Effect of distance uncertainties - BGC

Input $\alpha = -1.4$

Z03 fit ($\alpha = -1.3$)
Sensitivity requirements:
* detect $\sim 10^6 M_{\text{sun}}$ out to a few Mpc
* detect $\sim 10^7 M_{\text{sun}}$ out to the Virgo Cluster (16.7 Mpc)

Spectral resolution requirement:
* must resolve $W \sim 15$-20 km/s linewidth

Depth requirement:
* must sample fair cosmological volume at median $z$
Are\textit{c}ibo has provided excellent HI capability since the late 1970’s...

\textbf{ALFALFA : Why now ?}

- Multibeam receivers only possible after Gregorian Upgrade of 1990’s
- Field of View
- 7-beam receiver planned then (Kildal et al 1991), but plans not implemented until mid-2000’s
Blind X-gal HI surveys b.A. (before ALFALFA)

* AHISS and ADBS at Arecibo, using line feed receivers

* HIPASS (HI Parkes All Sky Survey; 1997-2002)
  Covered 71% of the sky (full coverage of S hemisphere), detected 5317 HI sources
  HICAT, the HIPASS catalog, contains 4315 sources in the Southern hemisphere and 1002 in the North
  cz range: -1280 to 12700 km/s
  Multibeam (13) receiver  ~14’ HPFW beam
  Telescope D=64m at lat=32:59:59.8S
Comparison of blind HI surveys

<table>
<thead>
<tr>
<th>Survey</th>
<th>Beam arcmin</th>
<th>Area sq. deg.</th>
<th>rms</th>
<th>min $M_{HI}$ @ 10 Mpc</th>
<th>$N_{det}$</th>
<th>$t_s$ sec</th>
<th>$N_{los}$</th>
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<td>25,000+</td>
<td>40</td>
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ALFALFA vs HIPASS

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
• ALFALFA detects ~5 sources per sq deg
• HIPASS detected 0.18 sources per sq deg
• HIPASS’ median cz is <3000 km/s
  • ALFALFA’s is 9000 km/s

Obviously, you have to do significantly better than any previous effort to justify your existence. But what does the improvement buy you?
HIPASS’ median $cz$ is $<3000$ km/s
ALFALFA’s is $\sim9000$ km/s

ALFALFA samples a “fair volume” of the Universe; HIPASS does not. The statistical properties derived from the survey are affected by the characteristics of our location, in the latter case.

Slice of the cosmic Density field along the Supergalactic Plane

You are here
1 order of magnitude more sensitive
1.6X total spectral bandwidth

That means that richer samples of the

• **most HI massive**: because this type of object is rare and thus large volumes need to be sampled to increase the catch, and the

• **least massive**: because, while abundant, these objects can only be detected if they are nearby

➔ In both cases, the increased survey volume made possible by the higher sensitivity and, for massive systems, also by the wider z-coverage, allows ALFALFA to largely outstrip the gains of the larger solid angle of the HIPASS survey
Source extraction and identification of counterparts at other wavelength regimes can be a painful experience...

...source centroiding as accurately as possible is thus highly desirable
Suppose HIPASS detects a source at S/N~6 near 3000 km/s in this field. The position error box will have a radius of ~2.5′.

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

ALFALFA will detect the same source with S/N~50 and the Arecibo beam is ¼ as wide as the Parkes one.

The same source will have an ALFALFA position error of ~ 0.1′

\[
\text{Centroiding accuracy goes roughly as} \quad \frac{\text{HPFW(PSF)}}{\text{S/N}}
\]
3X better spectral resolution...

HIPASS spectral resolution is 16 km/s

That means that the narrowest spectral line decently sampled is about 30 km/s. That excludes detection of (presumably) the most interesting dwarf systems, which often exhibit HP linewidths of less than 25 km/s

ALFALFA’s spectral resolution is 25 kHz, i.e. ~5.5 km/s for the HI line.
HIPASS production emphasizes the low sensitivity limit expressed in terms of column density:

\[ 6 \times 10^{17} \text{ cm}^{-2} \text{ per channel for gas that fills the beam} \]

\[ \Rightarrow \]

... a useless parameter since the number of objects that fill the Parkes beam are extremely few.
The HI mass of an optically thin HI source at distance $D_{Mpc}$, in solar units, is

$$M_{HI}/M_\odot = 2.356 \times 10^5 D_{Mpc}^2 \int S(V)dV;$$

(1)

where $S(V)$ is the HI line profile in Jy and $V$ is the Doppler velocity in km s$^{-1}$. To first order,

$$M_{HI}/M_\odot \approx 2.4 \times 10^5 D_{Mpc}^2 S_{peak} W_{kms};$$

(2)

where $S_{peak}$ is the line peak flux and $W_{kms}$ its velocity width in km s$^{-1}$. For detection, the signal-to-noise ratio $s = f_\beta S_{peak}/S_{noise}$ must exceed some threshold value; $f_\beta \leq 1$ quantifies the fraction of the source flux detected by the telescope’s beam. The parameter $f_\beta = 1$ for a point source, while for resolved sources, it decreases roughly like the ratio between the beam solid angle and the solid angle subtended by the source. An estimate of $S_{noise}$ can be obtained from the radiometer equation for the rms figure

$$S_{rms} = \frac{(T_{sys}/G)}{\sqrt{2 \times \Delta f_{ch} \times t_s \times f_t}},$$

(3)
Remember

\[ \frac{M_{HI}}{M_{sun}} = 2.36 \times 10^5 D_{Mpc}^2 \int S J_y dV \]

Approximated by

\[ \frac{M_{HI}}{M_{sun}} = 2.36 \times 10^5 D_{Mpc}^2 S_{peak} W_{kms} \]

Detection criterion:

\[ f_\beta S_{peak} / S_{noise} > (S / N)_{threshold} \]

where

\[ S_{noise} = \frac{(T_{sys} / G)}{\sqrt{2BW_{ch} t_s f_{smo} f_{sw} f_{other}}} \]

\( T_{sys} / G \approx 3 \) Jy (AO @ 21cm)

\( BW_{ch} = 25 \) kHz (~5 km/s)

\( f_{sw} \approx 1 \)

\( f_{smo} \propto W_{smo} \propto W_{kms} \)

for \( W_{kms} < 100 \) km/s, const for \( > 100 \) km/s

\[ \frac{f_\beta S_{peak}}{S_{noise}} \approx 1.4 \times 10^{-4} f_\beta (f_{smo} f_{other})^{1/2} W_{kms}^{-1} \frac{M_{HI}}{M_{sun}} D_{Mpc}^{-2} t_s^{1/2} > 5 \]

\( f_{other} \) takes into account mainly depression of \( S_{peak} \) due to smoothing
Calling a detection a feature that will yield a S/N~6 when spectrally sampled (by smoothing) at $\frac{1}{2}W_{\text{kms}}$, we can obtain the minimum integration time in sec, necessary to detect a mass $M_{\text{HI}}$ of width $W_{\text{kms}}$ at the distance $D_{\text{Mpc}}$:

$$t_s \approx 0.023 f_\beta^{-2} \left( \frac{T_{\text{sys}}}{G} \right)^{2} \left( \frac{M_{\text{HI}}}{10^6 M_{\text{sun}}} \right)^{-2} \left( D_{\text{Mpc}} \right)^{4} \left( \frac{W_{\text{kms}}}{200} \right)^{-2\gamma}$$

i.e. the depth of a survey increases only as $(t_s)^{1/4}$

This translates in rapidly diminishing returns: depressing. However, for equality of receiver performance, the time required to detect a given mass at given distance decreases as $G^{-2} \sim A^{-2}$, i.e. as the fourth power of the telescope diameter. Hence the tremendous advantage of Arecibo.
Alternatively, the minimum detectable HI mass at distance $D_{\text{Mpc}}$ is

$$
\left( \frac{M_{HI}}{10^6 M_\odot} \right)_{\text{min}} \simeq 0.5 f_\beta^{-1} t_s^{-1/2} (D_{\text{Mpc}})^2 \left( \frac{W_{\text{kms}}}{100} \right)^{-\gamma}
$$

[by comparison, HIPASS detects 1 million solar masses at 1 Mpc in 460 sec...]

On comparative advantages: in a survey, is aperture of a larger telescope offset by the larger solid angle which a smaller telescope can sweep per unit time?

- $A$ telescope collecting area
- $\Omega_b \propto A^{-1}$ telescope beam
- $G \propto A$ telescope gain
- $D_{\text{max}} \propto G^{1/2} \propto A^{1/2}$ max distance at which given HI mass is detectable
- $V_{\text{beam}} = \Omega_b D_{\text{max}}^3 / 3 \propto A^{1/2}$ volume sampled by beam out to $D_{\text{max}}$

i.e., at fixed total time and bandwidth,

the volume sampled by a survey scales like the telescope diameter.
Useful Relations

- The minimum $t_s$ to detect a source of $M_{HI}$, $W_{kms}$ at distance $D_{Mpc}$ is

$$t_s = \frac{1}{4} f_{\beta}^{-2} \left( \frac{M_{HI}}{10^6 M_\odot} \right)^{-2} (D_{Mpc})^4 \left( \frac{W_{kms}}{100} \right)^{-2\gamma}$$

- or, alternatively, the minimum HI mass detectable at distance $D_{Mpc}$ is

$$\left( \frac{M_{HI}}{10^6 M_\odot} \right)_{min} \simeq 0.5 f_{\beta}^{-1} t_s^{-1/2} (D_{Mpc})^2 \left( \frac{W_{kms}}{100} \right)^{-\gamma}$$

- The volume covered by the solid angle $\Omega$, out to distance $D_{Mpc}$, is

$$V = \Omega D_{Mpc}^3/3$$

- The maximum distance at which a given HI mass can be detected in time $t_s$ is

$$D_{Mpc,max}(M_{HI}) \propto t_s^{1/4}$$
OK, once you have decided on the minimum integration time needed to detect the statistically necessary number of sources of mass $M_{\text{HI}}$, how do you optimize the design of your survey?

- The time required to complete a survey covering a solid angle $\Omega$ is

$$t_{\text{survey}} \propto (\Omega/\Omega_b)t_s$$

- The survey volume sampled for a given HI mass is

$$V_{\text{survey}}(M_{\text{HI}}) \propto \Omega[D_{\text{Mpc, max}}(M_{\text{HI}})]^3 \propto \Omega t_s^{3/4}$$

- And

$$t_{\text{survey}} \propto V_{\text{survey}}(M_{\text{HI}}) D_{\text{Mpc, max}}(M_{\text{HI}}) \propto V_{\text{survey}}(M_{\text{HI}}) t_s^{1/4},$$

i.e. for a given $V_{\text{survey}}(M_{\text{HI}})$, which will yield a desired number of detections of clouds of mass $M_{\text{HI}}$, it’s better to maximize the sampled solid angle $\Omega$ than to increase the depth of the survey $D_{\text{Mpc, max}}(M_{\text{HI}})$. 
How do you optimize survey parameters?

→ Simulate
Slice of the cosmic Density field along The Supergalactic Plane

You are here
• Most of the mass is to be found in regions of density substantially higher than average

**Caveat:**
But, do low baryonic mass systems trace the cosmic density distribution?
\[ \Phi(x) = \frac{dn}{d(\log x)} = (\ln 10) \Phi^* x^{\alpha+1} e^{-x} \]

where

\[ x = \frac{M_{HI}}{M^*} \]

**Zwaan et al. 97:**

\[ \Phi^* = 0.0048 h^{3}_{70} \]

\[ \log M^*/M_{sun} = 9.86 - 2 \times \log h_{70} \]

\[ \alpha = -1.20 \]

**Rosenberg & Schneider 02:**

\[ \Phi^* = 0.0041 h^{3}_{70} \]

\[ \log M^*/M_{sun} = 9.94 - 2 \times \log h_{70} \]

\[ \alpha = -1.53 \]
log10 (M_\text{gal}) = [all]
M_\text{gal} < 6000 \ km/s
\tau = 1

1 second
3 seconds
7 seconds
300 sec

$|b| < 10$

AO limits
Virgo
11h-13h RA
0 to 27 Dec
60 sec
800 hours
ALFALFA, a Legacy HI Survey

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

- An extragalactic HI spectral line survey
- To cover 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)
- ~2 mJy rms [$M_{HI} \sim 10^5$ in LG, $\sim 10^7$ at Virgo distance]
- 4000 hrs of telescope time, spread over 6-7 years
- started Feb 2005; as of end of 2009, ~75% complete

http://egg.astro.cornell.edu/alfalfa
ALFALFA Sky Coverage

High galactic latitude sky visible from AO

Supergalactic plane
Observing Strategy: **Drift Mode, no Doppler tracking**

- **Minimum “intrusion”** (telescope does not move)
  - Standing Wave stability
  - Beam shape, sidelobe structure unchanged
  - Fixed gain, $T_{sys}$
  - Optimal bandpass correction
  - Minimal baseline distortion
  - 100 MHz (1335 to 1435 MHz) bandwidth, @ 25 kHz res

**2-pass strategy**
- Effective integration ~40 sec per beam
- Constant Dec tracks separated ~1' (HPBM~3.5')
Optimize use of the hardware...
Fig. 2.— Sketch of the geometry of the ALFA footprint, with the array located along the local meridian and rotated by an angle of 10° 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.
Fig. 3.— Beam pattern of beam 0. Contour lines and shading intervals are plotted at intervals of 3 dB below peak response (the highest contour is at half the peak power). The first sidelobe ring, with a diameter near 12′, is at approximately -15 dB.
WAPP

Beam 0
Beam 1
Beam 2
Beam 3
Beam 4
Beam 5
Beam 6

16 x 4096 ch,
100 MHz wide spectra
Comparison:
HIPASS vs ALFA
Beam layout on sky

Beam orientation for source on meridian south of AO zenith, for ALFA rotation angle of $+19^\circ$.

For this ALFA configuration, the tracks are spaced every 2.1 arcmin in Declination.
minimum intrusion approach

7 elliptical beams

\[ \text{Avg(HPBW)} = 3.5' \]
on elliptical pattern
of axial ratio \(~1.2\)
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 Sensitivity summary:

- A 1-second record of a drift scan, after accumulation of both polarizations, will yield a spectrum of $S_{\text{rms}} \sim 13(\text{res}/10)^{-1/2}$ mJy, where $\text{res}$ is the spectral resolution in km s$^{-1}$.

- A single drift, position–frequency map spatially smoothed to the spatial resolution of the telescope beam will yield $S_{\text{rms}} \sim 3.5(\text{res}/10)^{-1/2}$ mJy.

- A spatially two–dimensional map of two–pass ALFALFA data, smoothed with a kernel of 2’ at half power, will have $S_{\text{rms}} \sim 2.3(\text{res}/10)^{-1/2}$ mJy per pixel.

- The rms sensitivity per beam area, after a two–pass survey, will be $S_{\text{rms}} \sim 1.8(\text{res}/10)^{-1/2}$.

- The 6σ HI column density limit will be $N_{\text{HI,lim}} = 1.6 \times 10^{18}(W/10)(\text{res}/10)^{-1/2}$ atoms cm$^{-2}$, for a spectral line of width $W$ km s$^{-1}$, observed with a spectral resolution of $\text{res}$ km s$^{-1}$.

Can detect $10^6 \ M_{\text{sun}}$ to D$\sim$6 Mpc  
$10^7 \ M_{\text{sun}}$ to D$\sim$20 Mpc

with an effective integration time of $\sim$40 sec per beam solid angle
...make sure you have a well understood processing pipeline...
Processing the Data
- IDL environment
- Noise, bandpass, baseline calibration
- Flagging, visual inspection
- Continuum sources
- Gridding, data cubes
- Signal extraction
- Cataloging, x-referencing
- Public access
ALFALFA data products can be accessed through the web using robust, NVO-compatible software tools, developed by our students, thanks to an NSF/NVO development grant and the archival support of the Cornell Theory Center.

ALFALFA is already an integral part of the NVO footprint.

http://arecibo.tc.cornell.edu/hiarchive/alfalfa/
...test observing strategy and processing pipeline before wasting the first 100 hours of telescope time...
ALFALFA Precursor Run Detections

Completeness depends on Velocity Width

Units of Flux Integral: Jy km/s
Units of Width (full width): km/s
HIPASS Completeness Limit

HIPASS Detection Limit

Integrated Flux of 1 Jy km/s
...make sure there is a tough and efficient scheduler/organizer and caring boss...
ALFALFA schedule notation

- “Master list” of drift declinations preassigned, starting at 0° and moving northward
- Two passes: p1 and p2
  
  \[
  \begin{array}{|c|c|}
  \hline
  \text{pass} & \text{declination} \\
  \hline
  41p1 & +095118 \\
  42p1 & +100554 \\
  42p2 & +101312 \\
  \hline
  \end{array}
  \]

  14.6 arcmin

  7.3 arcmin

- Observing “block”: each session designated by local date at START as yy.mm.dd: 05.05.30
### Drift declination assignments

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<td>+121718</td>
<td>51p2</td>
<td>12.410009</td>
<td>+122436</td>
</tr>
</tbody>
</table>
Who is ALFALFA?

ALFALFA is an open collaboration: anybody with a valid scientific interest can join.

For participation guidelines, see: http://egg.astro.cornell.edu/alfalfa/joining.php

Recommended guidelines for authorship can be found at: http://egg.astro.cornell.edu/alfalfa/projects/authorshipguidelines.php


Projects (Team/PhD/undergrad): http://egg.astro.cornell.edu/alfalfa/projects/projects.php
Low mass systems are only visible in the very local Universe. Even if abundant, we only detect a few.
HIPASS Completeness Limit

HIPASS Limit

21238 HI sources cataloged so far

69% of ALFALFA detections are new (the conventional wisdom on which optical targets would turn out to be HI-rich appears to have been limited)

Unlike previous surveys, ALFALFA delivers a cosmologically fair sample
ALFALFA: 2 strips through Virgo

RA: 07:40h to 16:30h
Dec: 12deg to 16deg and 08deg to 12deg
Solid Angle: 1028 sq deg (15% of survey)
Over the ~1000 sq. deg. including the northern part of Virgo:

- **ALFALFA detects 5200 sources, HIPASS 178 (several unconfirmed)**
- While this region is perhaps the most intensively studied in the local Universe, at all wavelength bands (including HI, using optically selected samples), 
  - **69% of ALFALFA detections are new** (the conventional wisdom on which optical targets would turn out to be HI-rich appears to have been limited)
• “Minimum intrusion” approach on data taking (night time); “two-pass” strategy v important
• Data processing on fully home-grown software in IDL environment

**STATUS @ Sep’09**

• 75% of data acquired (585 observing runs)
• 60% of data processed to “level 2” (pre-grid)
• 30% of data fully processed, catalogs produced:
  - Spring (RA = 07:30 to 16:30):
    Dec strips +5 +7 +9 +11 +13 +15 +27
  - Fall (RA = 21:30 to 03:30):
    Dec strips +15 +25 +27 +29 +31
...as for future consideration...
AO FPA Sky Footprint Layout

Hexagonal 41 Beams

Rectangular 41 Beams

Credit: German Cortes, NAIC
### Survey Speed Figure of Merit

The Survey Speed Figure of Merit (FoM) is given by the equation:

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

### Parameters Used:

<table>
<thead>
<tr>
<th>Telescope</th>
<th>D (m)</th>
<th>Beam</th>
<th>Ntel*Nbm</th>
<th>Tsys</th>
<th>BW</th>
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</thead>
<tbody>
<tr>
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<td>225</td>
<td>3.5'</td>
<td>1x1</td>
<td>25K</td>
<td>100MHz</td>
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<tr>
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<td>3.5'</td>
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<td>30K</td>
<td>300</td>
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<tr>
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<td>3.5'</td>
<td>1x41</td>
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<td>300</td>
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<tr>
<td>APERTIF</td>
<td>25</td>
<td>30'</td>
<td>14x25</td>
<td>50K</td>
<td>300</td>
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<tr>
<td>ASKAP</td>
<td>12</td>
<td>60'</td>
<td>30x30</td>
<td>50K*</td>
<td>300</td>
</tr>
</tbody>
</table>

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

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

<table>
<thead>
<tr>
<th></th>
<th>((A_e)^2)</th>
<th>((T_{\text{sys}})^2)</th>
<th>FoV</th>
<th>BW</th>
<th>FoM</th>
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<tr>
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<td>1/4</td>
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<td>3</td>
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<td>1/4</td>
<td>8800</td>
<td>3</td>
<td>37</td>
</tr>
</tbody>
</table>
Instrumented with a ~40 beam FPPA, Arecibo would have a survey speed FoM comparable to ASKAP & APERTIF, with one important advantage: with a collecting area 10% of the SKA, the Arecibo telescope already exists.

One important disadvantage of AO: confusion limit will occur at much lower z than for distributed apertures like APERTIF and ASKAP.

→ Niche for AO41: large scale surveys of intrinsically weak sources at low z
http://egg.astro.cornell.edu/alfalfa/