Large-Scale Surveys with the ARECIBO L-BAND FEED ARRAY (ALFA): Scientific Potential and Link to the Next Generation of Radio Telescopes

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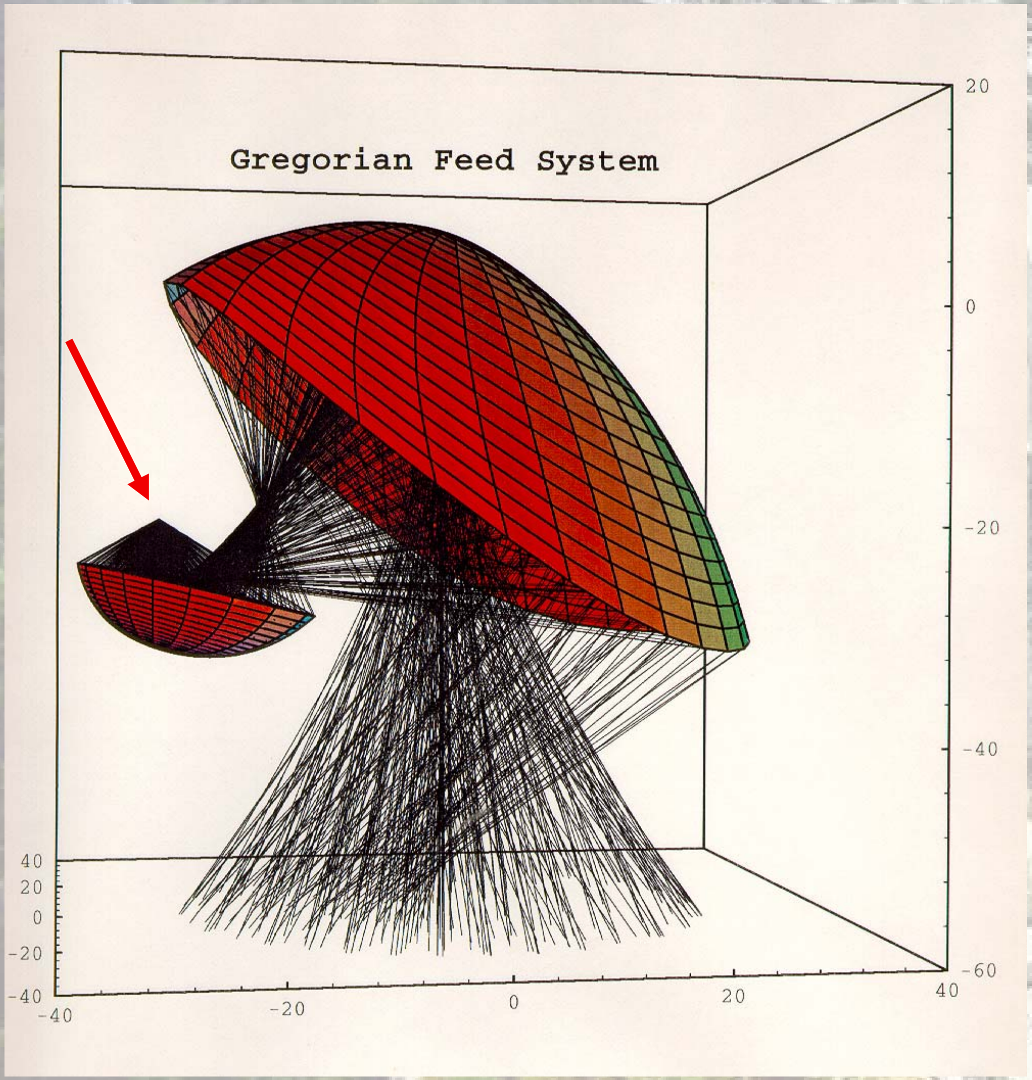
Gregorian Upgrade



Transforms the Arecibo line-focus to a point-focus

Allows use of focal plane receivers, including a focal plane array receiver

Radio Camera

Arecibo L-Band Feed Array

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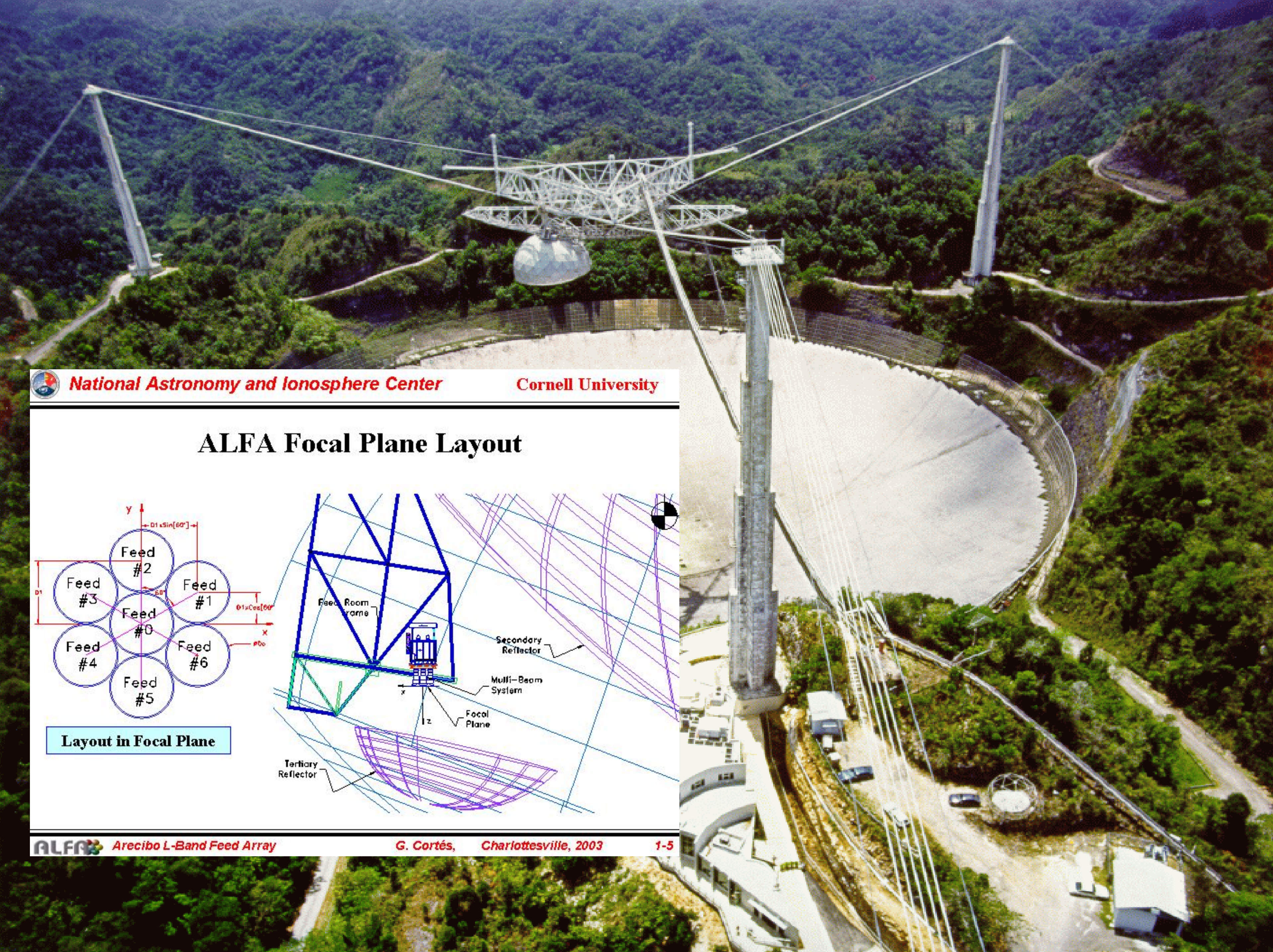
National Astronomy and Ionosphere Center
Cornell University
ALFA Focal Plane Layout
Feed #2
Feed #3
Feed #1
Feed #0
Feed #4
Feed #6
Feed #5
Layout in Focal Plane
Secondary Reflector
Multi-Beam System
Focal Plane
Tertiary Reflector
ALFA
Arecibo L-Band Feed Array
G. Cortés,
Charlottesville, 2003
1-5

ALFA is a 7 pixel spectroscopic radio camera

No. of Horns	7
Polarization	Dual linear
Polarization Isolation	> 20dB
Bandwidth	~300MHz
Frequency range	1225 - 1525MHz
Gain variation over band	+1/-2 dB
Dewar flange input noise temperature	6 – 8 K average
Calibration noise source	Correlated between polarizations
Dewar rotation	+/- 110 °
weight	~900kg (2000 lbs)
horns	Stepped TE_{11} horns, ∅25cm
Backend processors	Direct FFT, and correlators

7 times faster mapping!

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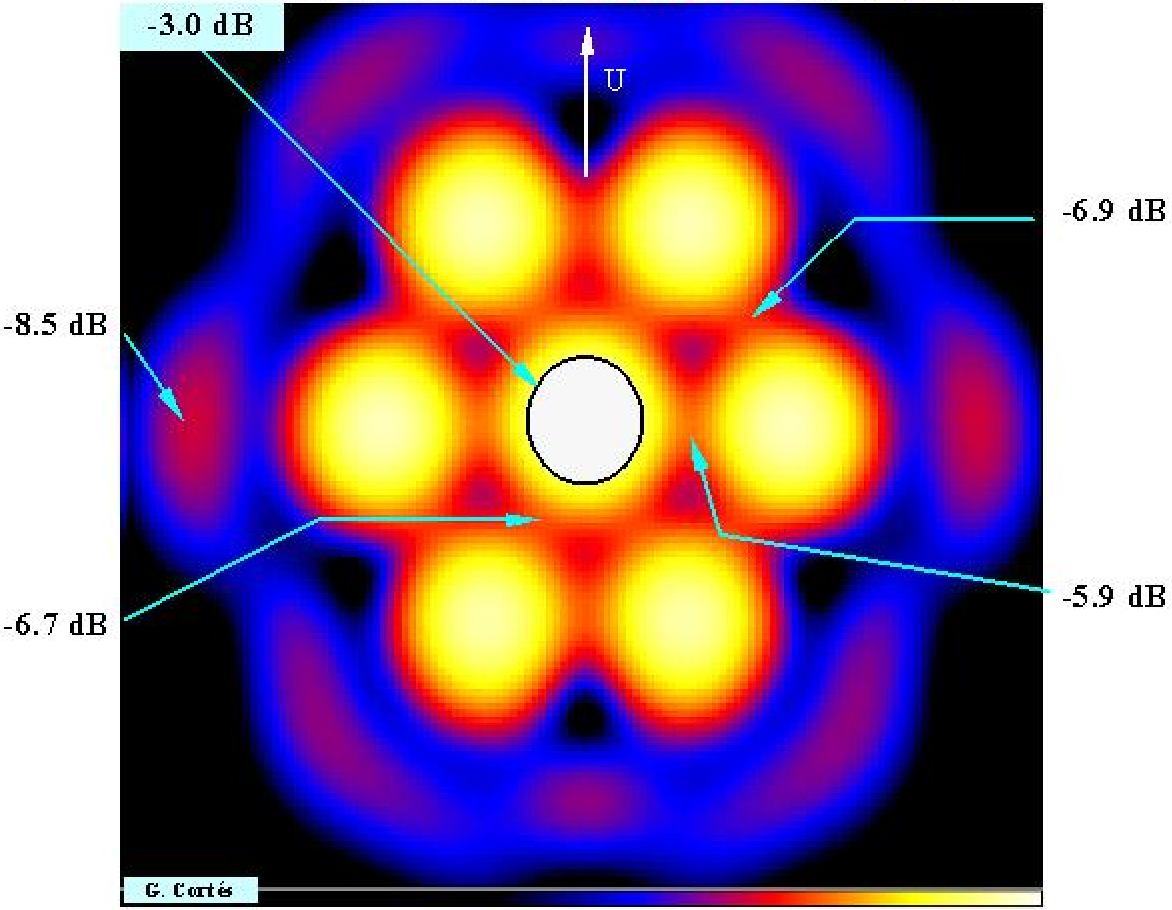
Total Incoherent Multi Beam Pattern

TE11 Mode Horn 25.0 cm x 26.0 cm



Sky Area 25’x25’ at 1.375 GHz

SCIENTIFIC FOCUS OF ALFA

- **Galactic Astronomy**
  - ***21cm Line of Atomic Hydrogen***
  - ***Radio Recombination Lines***
  - ***Continuum***
- **Pulsar Astronomy**
- **Extragalactic Astronomy**
  - ***HI***
  - ***OH Megamasers***

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Multiple Backends for Different Scientific Tasks

	Bandwidth	Channels per polarization	Input Levels	Output Levels	Dump Time	Misc.
P-ALFA	300 MHz	1000 (res. 300 kHz)	8 bits min	4 bits max (flexible)	64 usec	output after long-term mean removed in SW
E-ALFA	200 MHz min	8192 (res. 25 kHz)	8 bits min (12 desired)	16 bits min @ 1 sec dumps	1 sec (or less for rfi)	flexible blanking in hardware
G-ALFA HI	1415-1425 MHz	10k, 20k desired (res. 1 kHz min)	10 desired (few ok if little rfi)	10 bits	1 sec	blanking not needed*
G-ALFA recombination lines	One 6 MHz band + eleven 3 MHz bands (all fixed)	~40k channels (res. 0.5 kHz, 1kHz min)	8 bits min	10 bits	<1 sec	blanking not needed*
G-ALFA continuum	300 MHz	1000 (res. 300 kHz)	8 bits min	16 bits	0.1 sec	blanking not needed* full Stokes required

*rfi excised in software

CURRENT STATUS OF ALFA

- Front end installed on telescope April 2004
- 7 x 100 MHz bandwidth WAPP systems available for spectroscopy & pulsar search
- Downconverter & fiber optics IF system installed and tested
- Test observations underway May 2004
- 2 additional processors (300 MHz BW & High Resolution) under construction – 2004/5
- Software under development by NAIC & scientific consortia

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GALFA-HI

Galactic Astronomy Using the 21cm Line of Atomic Hydrogen

GALFA HI SUB-CONSORTIUM

THE MAJOR THEMES

- **What are the critical physical processes that determine the structure and evolution of the interstellar medium?**
- **What are the CONNECTIONS -- between atomic and molecular ISM, between the “cold” and “normal” neutral medium, and between the Disk and the Halo?**
- **What are high latitude clouds and clouds in the Galactic Halo?**

Galactic HI

- Neutral Hydrogen as Probe of the Origin & Evolution of Molecular Clouds
- Interstellar Turbulence (low & high – b)
- Cold Neutral Medium
- The Disk-Halo Connection
- HI Clouds in the Galactic Halo
- High-Latitude Line Wings & Turbulence
- High-Latitude Clouds
- HI Self-Absorption & Kinematics
- Line Wings at Forbidden Velocities

GALFA HI – High Latitude Surveys: Interstellar Turbulence

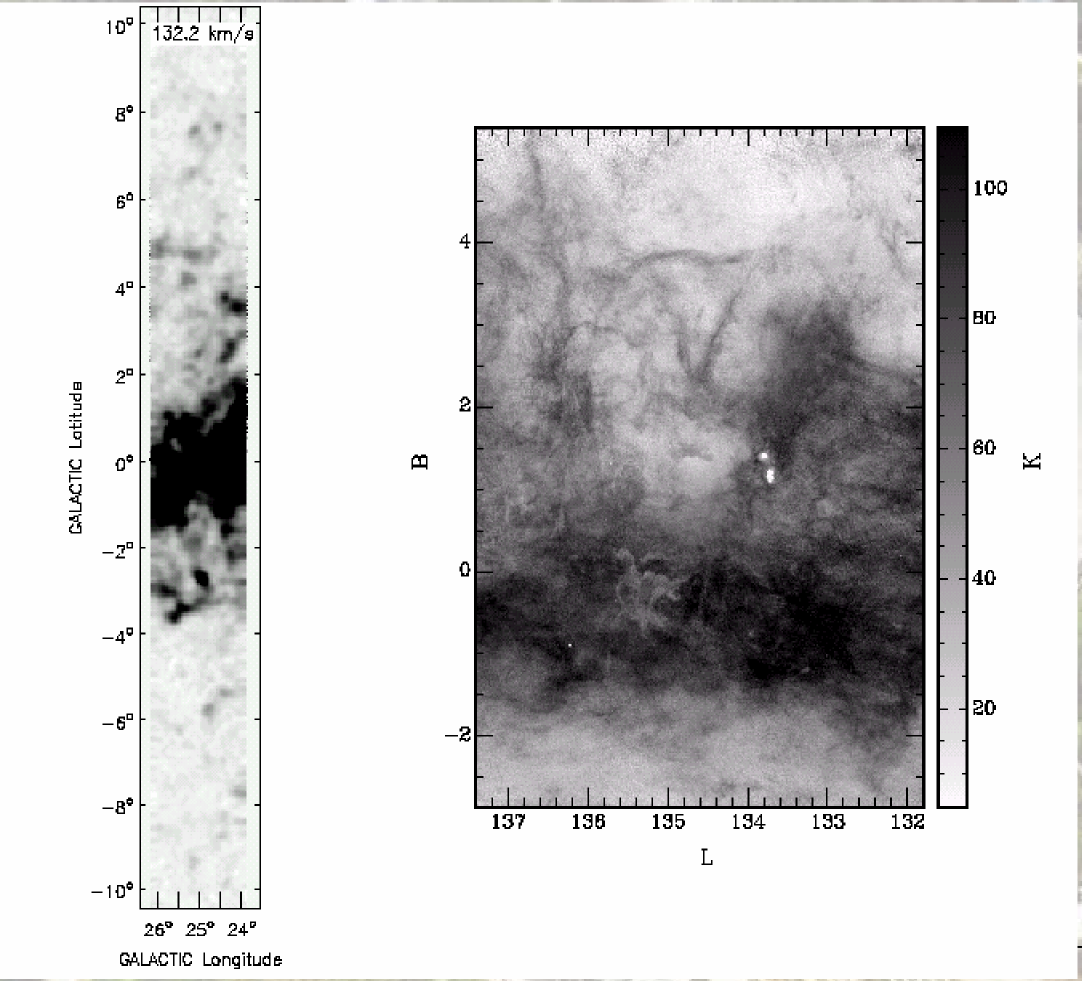
Critical mechanism for determining structure of ISM

- **Intermittency**
- **Energy Injection**
- **Relationship with Theory**

Require l-b-v cubes for which you can calculate velocity-density correlations

The Disk-Halo Connection

"Spurs" & "Chimneys" imply energy input from Plane

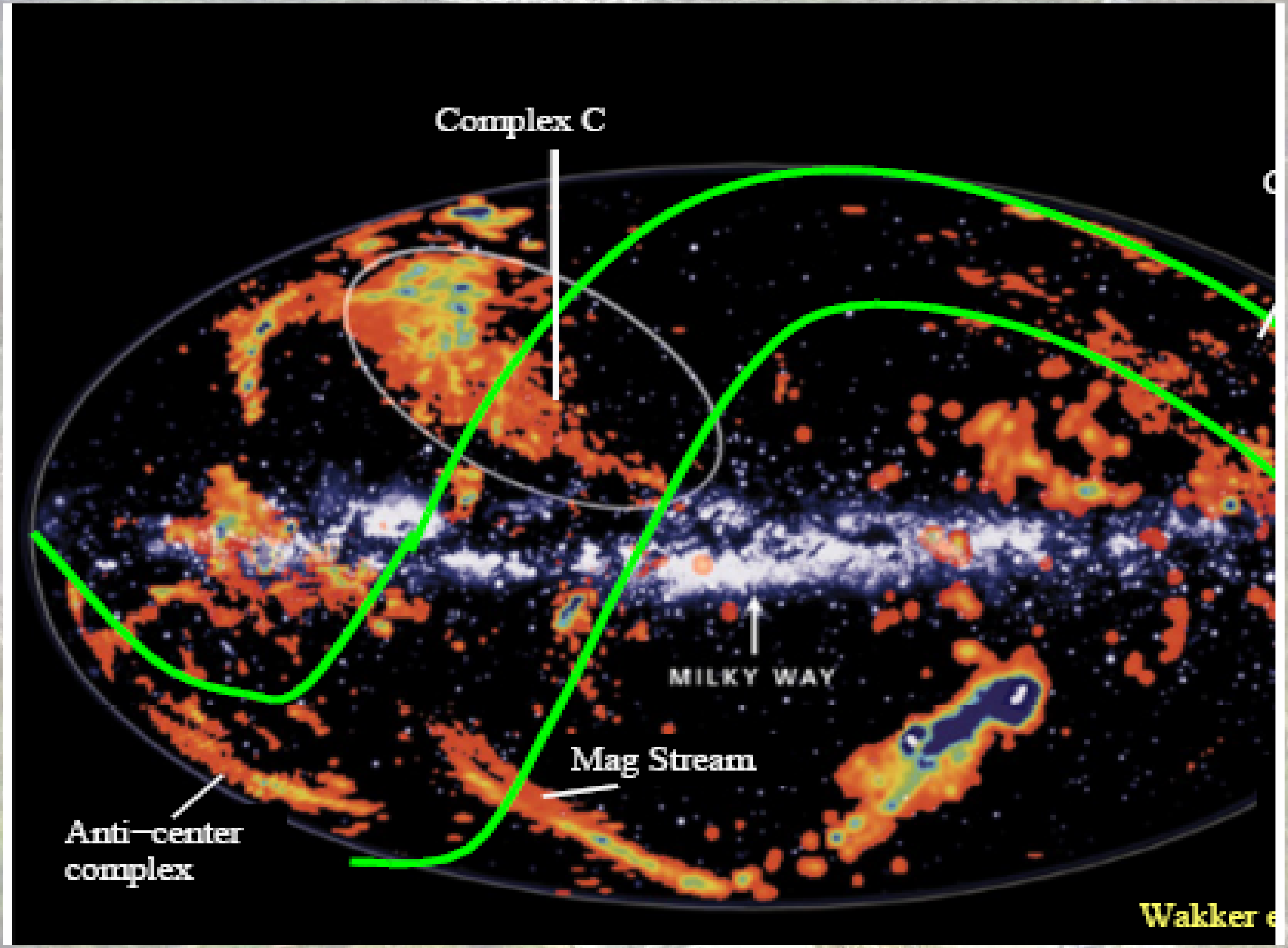


GALFA HI – High Latitude Surveys: HI Clouds in the Galactic Halo

Gas at high latitudes not consistent with Galactic rotation models – clouds are clearly outside the Galactic disk

- –Intermediate Velocity Clouds (IVCs): distances few hundred pc - 2 kpc; solar metallicities; final stage of a Galactic fountain (?)
- –High Velocity Clouds (HVCs): deviate by > 50 km from Galactic rotation; metallicity = 0.1 solar; two-phase structure with cold cores embedded in warm envelope; DISTANCE UNCERTAIN
- –Magellanic Stream: only HVC complex with known origin, namely that they are tidal debris of Magellanic Clouds; HI mass almost 5×10^8 solar masses;
- –Compact High Velocity Clouds (CHVCs): separate class spatially and kinematically; visible counterparts of Dark Matter Halos (?)

HI Clouds in the Galactic Halo (cont'd.)



GALFA HI – Low Latitude Surveys:
Survey of the Galactic Plane at |b| < 5 deg

SCIENTIFIC OBJECTIVES:

(2) Use HI sef-absorption to map spiral arms in first quadrant (resolve distance ambiguities)

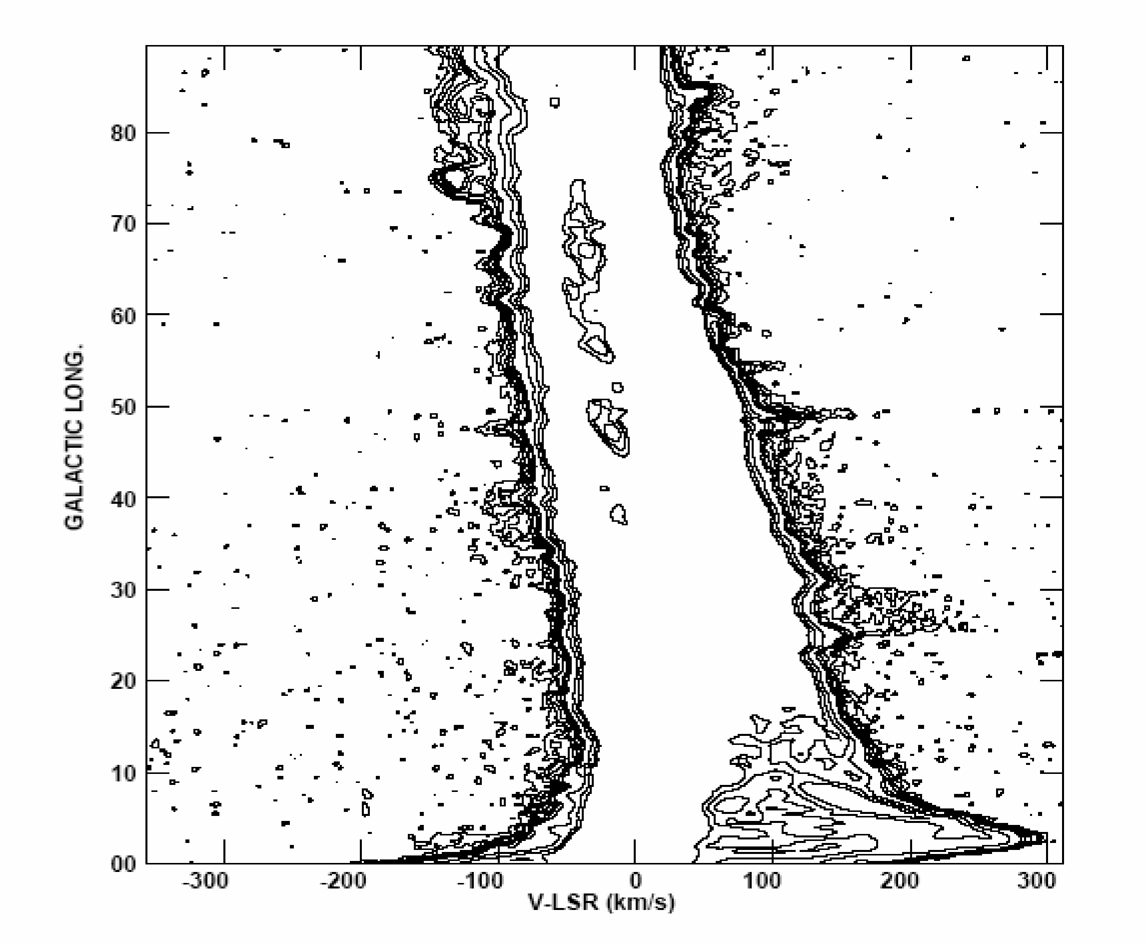
(3) Study atomic and molecular gas in Giant Molecular Clouds (sites of formation of massive stars)

(4) Infrared Luminosity Function of the Inner Galaxy – correlations with MSX and other surveys

Area to be mapped is approximately 800 deg^2

GALFA HI – Low Latitude Surveys:

FV Line Wings –undiscovered supernovae?



ALFA PULSAR SURVEYS - Pulsar Science Highlights

– Neutron star physics
– Magnetospheric physics (emission mechanisms)
– Probing the interstellar medium
– Orbital elements of binary pulsars and tests of gravitation theories
– Pulsars as gravitational wave detectors

Why more pulsars?

- Extreme Pulsars:
  - $P < 1$ ms — $P > 5$ sec
  - $P_{orb} <$ hours — $B > 10^{13}$ G (link to magnetars?)
  - $V > 1000$ km s^{-1}
- Population & Stellar Evolution Issues
- NS-NS & NS-BH binaries
- The high-energy connection (e.g. GLAST)
- Physics payoff (GR, LIGO, GRBs…)
- Serendipity (strange stars, transient sources)
- Mapping the Galactic magnetoionic medium

New instruments (AO-ALFA, GBT, SKA) can dramatically increase the volume searched (galactic & extragalactic)

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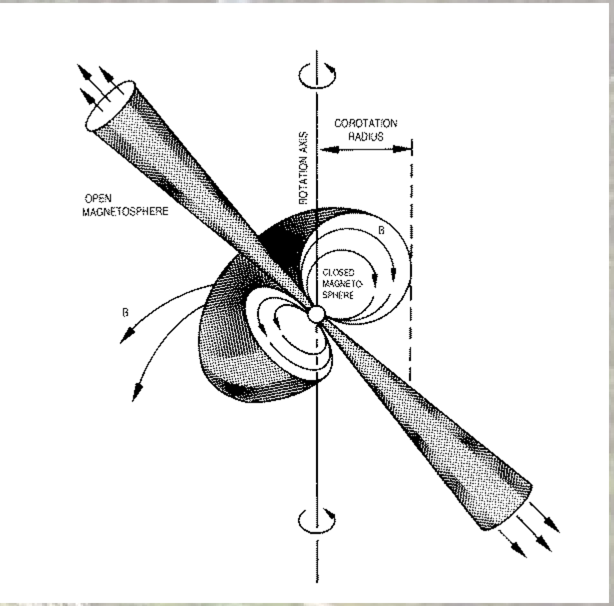
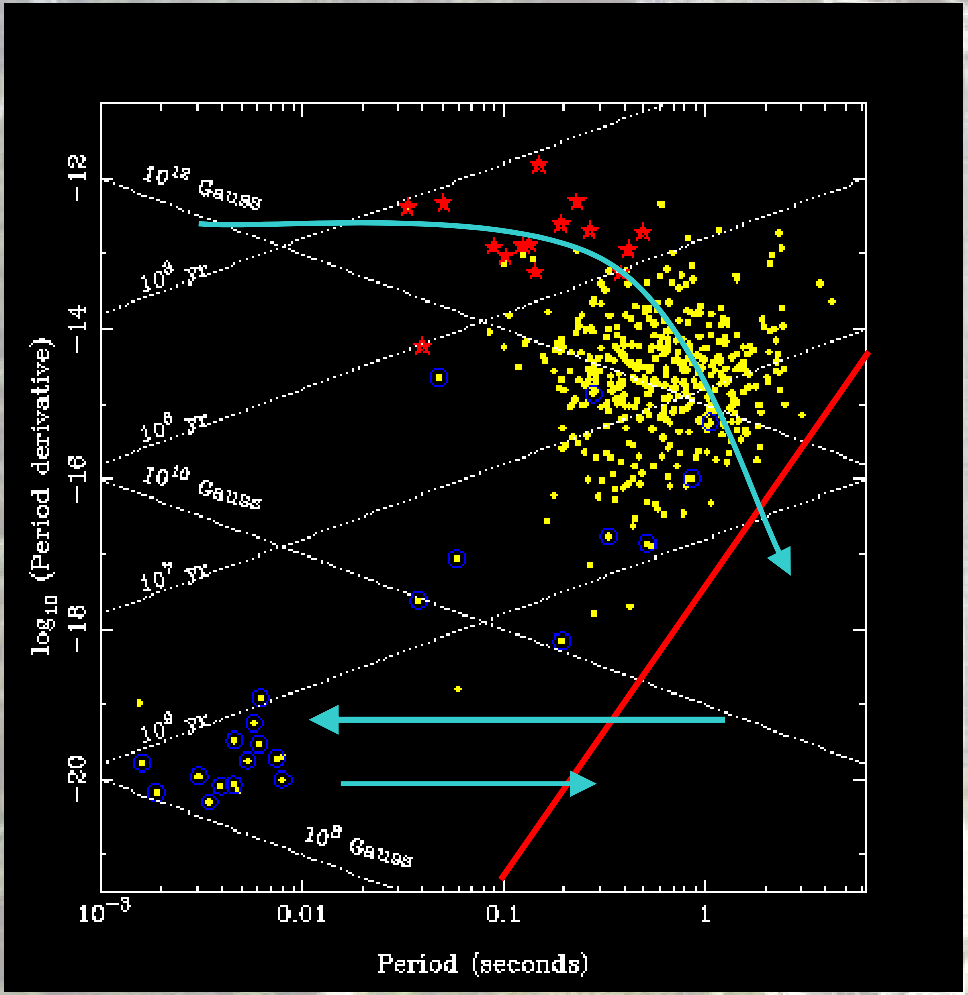
Pulsars are Extreme -

– 10x nuclear density
– High-temperature superfluid & superconductor
– $B \sim B_q = 4.4 \times 10^{13}$ Gauss
– Voltage drops ~ 10^{12} volts
– $F_{EM} = 10^9 F_g = 10^9 \times 10^{11} F_{gEarth}$



Pulsar Populations



- Canonical (1700+):
  - P ~ 0.01 - 1.5s
  - dP/dt ~ 10^{-14} s/s
  - B ~ 10^{12} - 10^{13} G
  - 1% of known have companions
  - Age ~ 10^{5} - 10^{8} yr
- Millisecond (~80):
  - P ~ 1.5 - 30ms
  - dP/dt ~ 10^{-20} s/s
  - 80% of known have companions
  - B ~ 10^{8} - 10^{9} G
  - Age ~ 10^{9} - 10^{10} yr

www.livingreviews.org/Articles/Volume4/2001-5lorimer/

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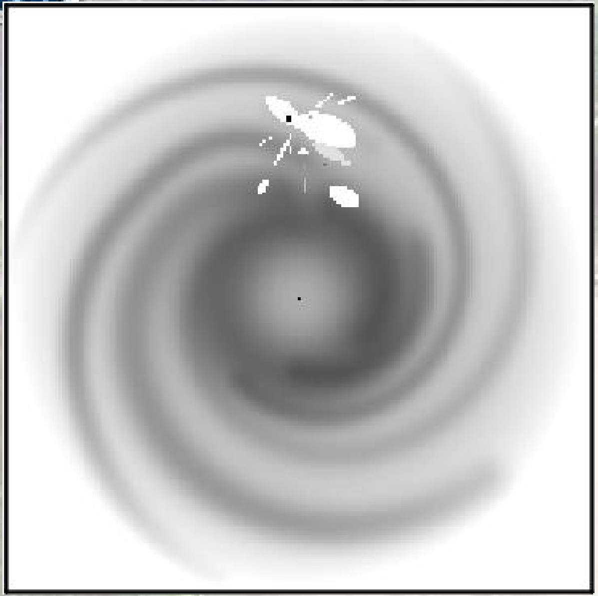
Fast and Faster Pulsars

- Recently recycled: PSR J1740-5340, with P = 3.6 ms
- “Black Widow” PSR 1957+20, with P = 1.6 ms — companion will evaporate in about 10^9 yr
- Fastest known rotator: PSR 1937+21, with P = 1.5578 ms
- Sub-millisecond pulsars — ?

Motivation for Sub-MSP Searches

- Limits on pulsar periods and masses
- Equation of state of exotic matter
- Phase transitions in neutron stars
- Ground state of matter in the Universe
  - Hadronic (no strangeness)?
  - Hyperonic (strangeness)?
  - Quark deconfined?
  - Strange deconfined?

Pulsars as Probes of the Galaxy



Electron density projected onto the Galactic plane:

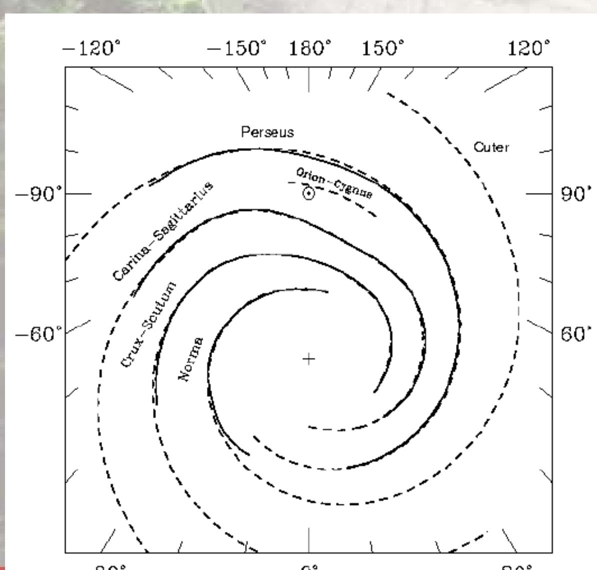
Two disk components, spiral arms, Galactic center, clumps and voids

Paper I = the model (astro-ph/0207156)

Paper II = methodology & particular lines of sight (astro-ph/0301598)

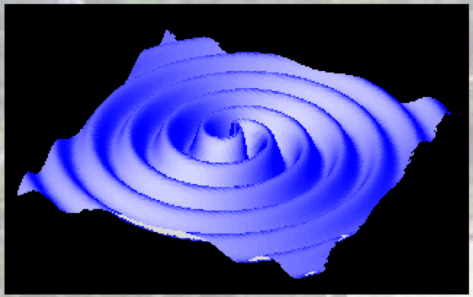
Code + driver files + papers:

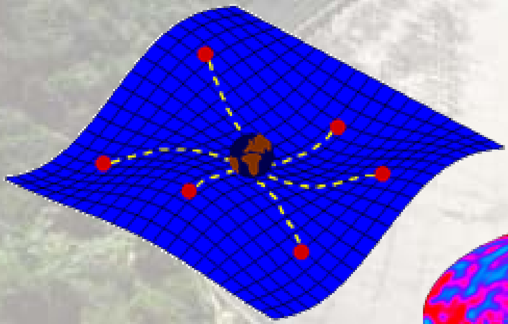
www.astro.cornell.edu/~cordes/NE2001

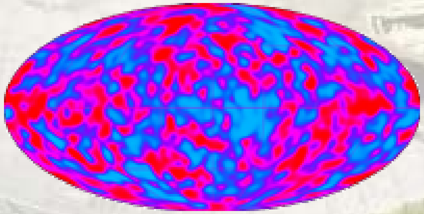


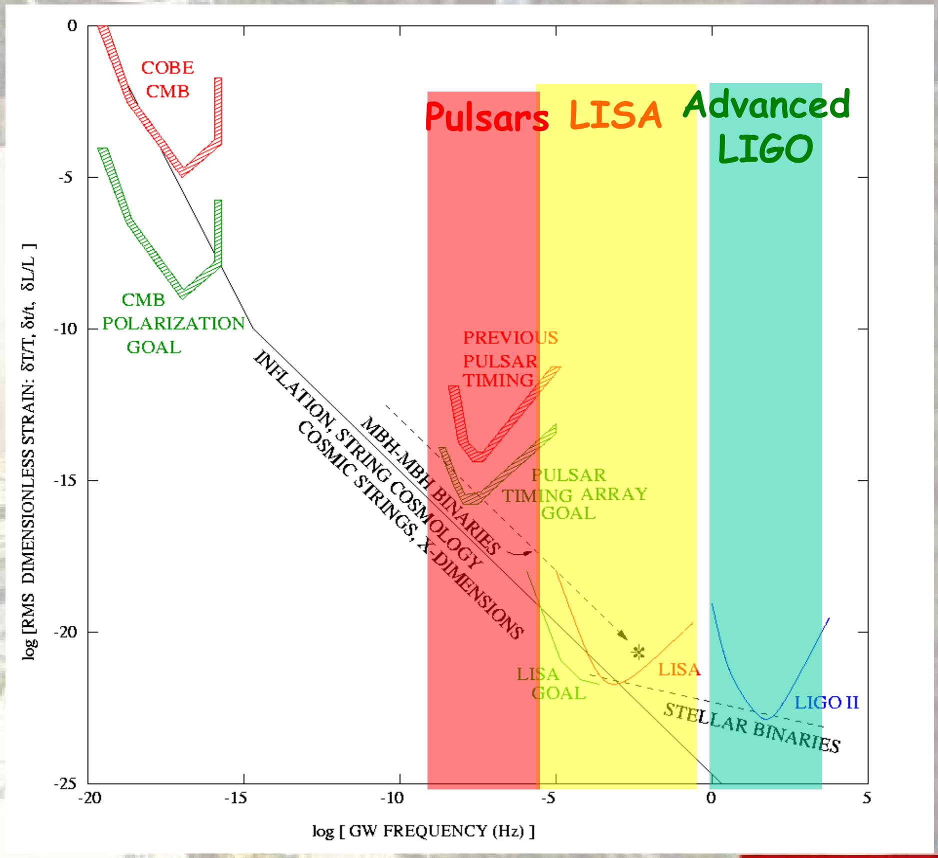
Cosmological Gravitational Wave Background

Millisecond pulsars act as arms of huge detector:









Pulsar Timing Array:

Look for global spatial pattern in timing residuals

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P-ALFA Science Goals Require Massive Surveys

– Drift scan surveys

(14 sec across 3.5 arcmin)

– Deep Galactic plane survey (GPS)

(5-10min, |b| < 5 deg, 30 < l < 80 + anticenter)

– Medium latitude surveys

(5 < |b| < 25 deg)

– Targeted searches: globular clusters, high EM/DM HII regions, SNRs, Galactic chimneys, M33, X/γ -ray selected objects

(long dwell times, up to 2.5 hr)

1 PETABYTE TOTAL DATA VOLUME

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ALFA Galactic Plane Survey

- $|b| < 5$ deg, 32 deg $< l < 80$ deg + anticenter?
- 1.225-1.525 GHz bandwidth = 300 MHz
- digital backends (<0.3 MHz channels)
  - FPGA-FFT or Polyphase filter approach (300 MHz)
- ~300 s integrations, **2000-3000 hours total**
- Can see 2.5 to 5 times further than Parkes MB
  - period dependent
  - from AO sensitivity + narrower channels (larger DM)
- Expect ~1000 new pulsars (modulo pulsar scale height ⇔ velocity distribution, birth sites, etc.)

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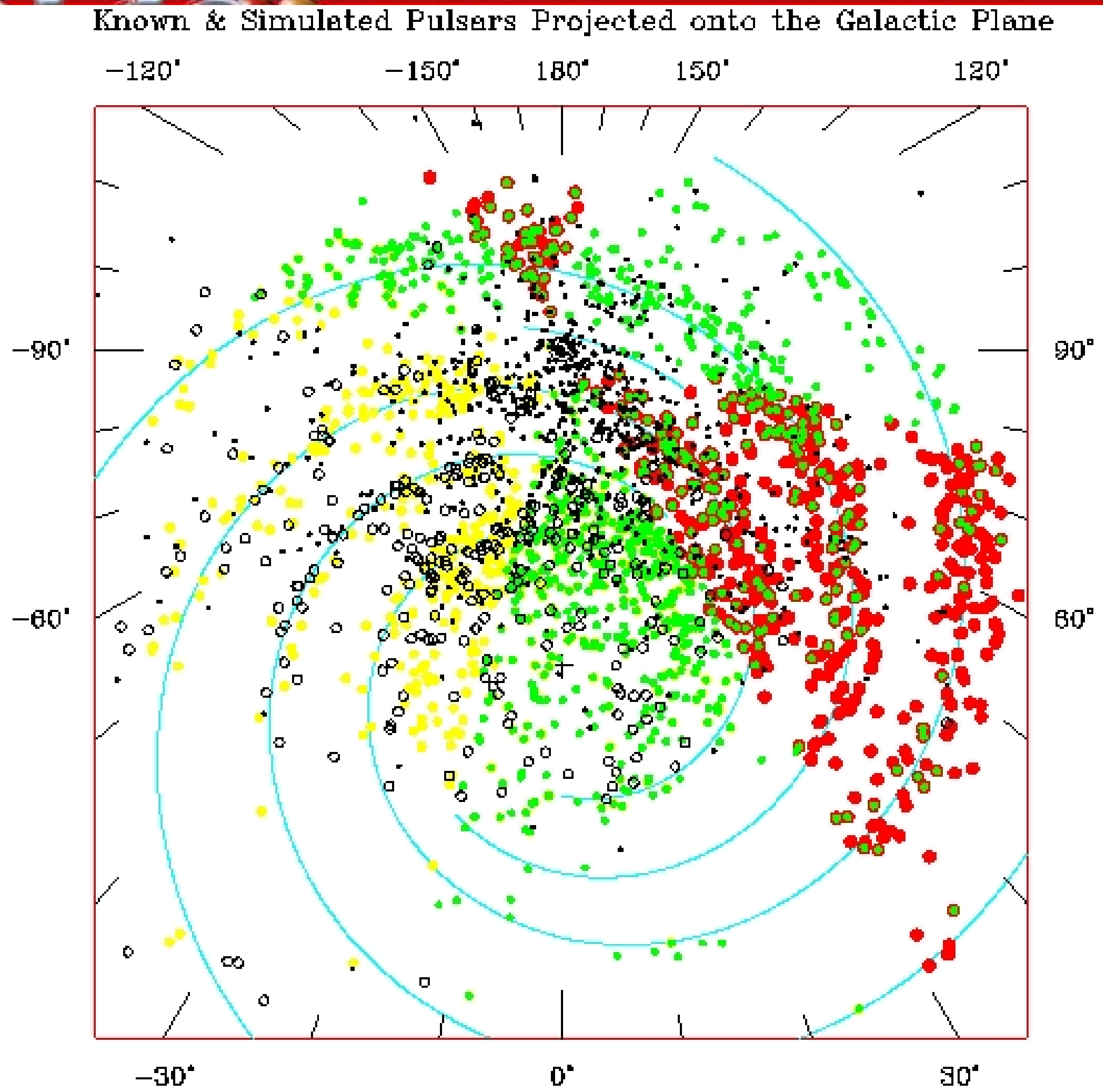

Surveys with Parkes, Arecibo & GBT

Simulated & actual

Yield ~ 1000 pulsars

ONLY A HINT OF PROBABLE RESULTS FROM SKA

E-ALFA: Extragalactic HI Surveys using ALFA at Arecibo

Scientific Goals of E-ALFA Surveys:

- Determine the local density dependence of the HIMF
- Map the distribution of luminous and dark matter
- Investigate the faint end of the HI mass function (HIMF) in the local (z < 0.1) Universe
- Determine the gas-rich membership of nearby groups
- of galaxies
- Determine the population of gas-rich systems in the Local Group and the periphery of the MW (HVCs)
- Investigate connection w/Ly a absorbers via 21cm absorption
- Find (rare) OH Megamasers near z=0.25
- Be surprised !!

A STEP TOWARDS SURVEYS POSSIBLE WITH SKA

Planned Major E-ALFA Surveys

All-Arecibo sky Fast ALFA Survey (ALFALFA)
~ 2000 hours, 12,000 square degrees, one-pass (?)
in drift mode, 50-100 MHz coverage

Very Deep Survey
~ 1100 hours, 0.4 square degrees, 200 MHz coverage,
50-100 hours integration per beam

Medium-Deep (Virgo and other groups) Survey
Virgo-anti Virgo (VAVA) will require ~900 hours,
drift mode, 5 passes (60 sec per beam)

ZOA survey – probably piggyback on Pulsar galactic
plane survey: ~300 sec per beam, stare mode,
+/- 5 deg gal latitude of plane visible from AO

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Survey	Beam arcmin	Area sq. deg.	rms(mJy) (@ 13 km/s)	min M_{HI} @ 1 Mpc	N_{det}	t_s sec	N_{los}
ALFALFA	3.5	12,000	3.0	4.0×10^5	12,000?	12	5×10^6
VAVA	3.5	900	1.0	1.3×10^5	3,000?	60	300,000
ZOA	3.5	1000	0.5	0.7×10^5	8,000?	300	330,000
AO-DEEP	3.5	0.4	0.05	0.7×10^4	40?	252,000	105

ALFALFA and VAVA' will be run in drift mode

ALFALFA in one or perhaps two passes,
VAVA' probably in 5 passes

ZOA will dwell 3-5 minutes per beam

DEEP will dwell ~70 hrs per beam

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