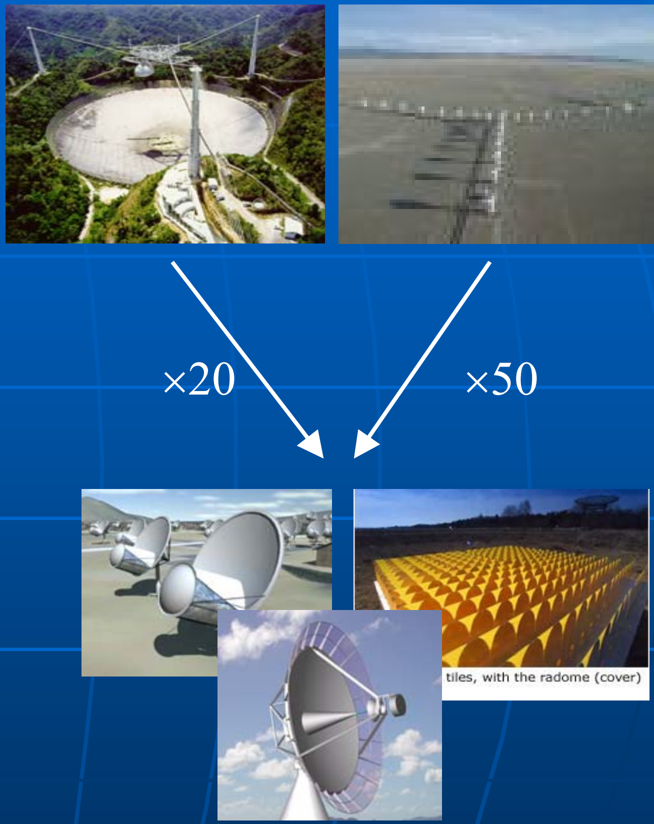
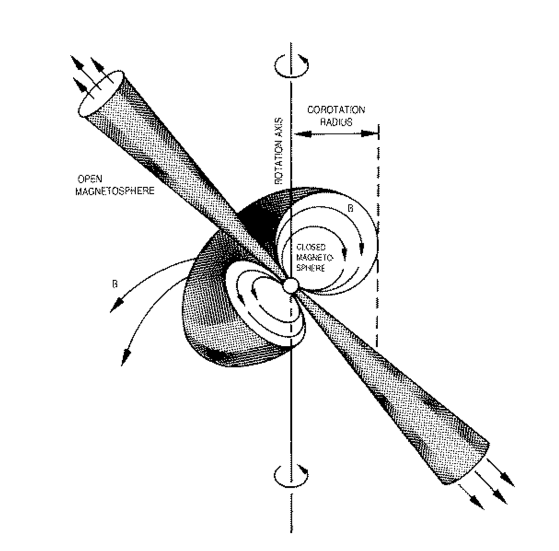
Legacy Pulsar Surveys

- Why more pulsars?
  - Science frontiers
- New prospects:
  - Known pulsars are periodic transients
  - Aperiodic pulsar transients (RRATs, bursters, etc.)
- Massive surveys:
  - Recent past, present and future
  - Follow up: time them, locate them (VLBI)
  - Cross-λ: especially gamma-rays (GLAST)
- Data management:
  - Analysis and archival of massive data sets
  - Mining of intermediate data products



Pulsar Science

- Extreme matter physics
  - 10x nuclear density: teaspoon ~ 10^8 tons
  - High-temperature superfluid & superconductor
  - $B \sim B_q = 4.4 \times 10^{13}$ Gauss
  - Voltage drops ~ 10^{12} volts
  - $F_{EM} = 10^9 F_g = 10^9 \times 10^{11} F_{gEarth}$
- Relativistic plasma physics
  - Magnetospheres
  - Radiation mechanisms
- Tests of theories of gravity
- Gravitational wave detectors
- Probes of turbulent and magnetized ISM (& IGM)
- End states of stellar evolution
  - Massive stars ⇒ neutron stars or black holes



A Double-Pulsar System: A Rare Laboratory for Relativistic Gravity and Plasma Physics

A. G. Lyne,[1*] M. Burgay,[2] M. Kramer,[1] A. Possenti,[3,4] R.N. Manchester,[5] F. Camilo,[6] M. A. McLaughlin,[1] D. R. Lorimer,[1] N. D'Amico,[3,7] B. C. Joshi,[8] J. Reynolds,[9] P. C. C. Freire[10]

The clocklike properties of pulsars moving in the gravitational fields of their unseen neutron-star companions have allowed unique tests of general relativity and provided evidence for gravitational radiation. We report here the detection of the 2.8-second pulsar J0737−3039B as the companion to the 23-millisecond pulsar J0737−3039A in a highly relativistic double neutron star system, allowing unprecedented tests of fundamental gravitational physics. We observed a short eclipse of J0737−3039A by J0737−3039B and orbital modulation of the flux density and the pulse shape of J0737−3039B, probably because of the influence of J0737−3039A's energy flux on its magnetosphere. These effects will allow us to probe magneto-ionic properties of a pulsar magnetosphere.

www.sciencemag.org SCIENCE VOL 303 20 FEBRUARY 2004

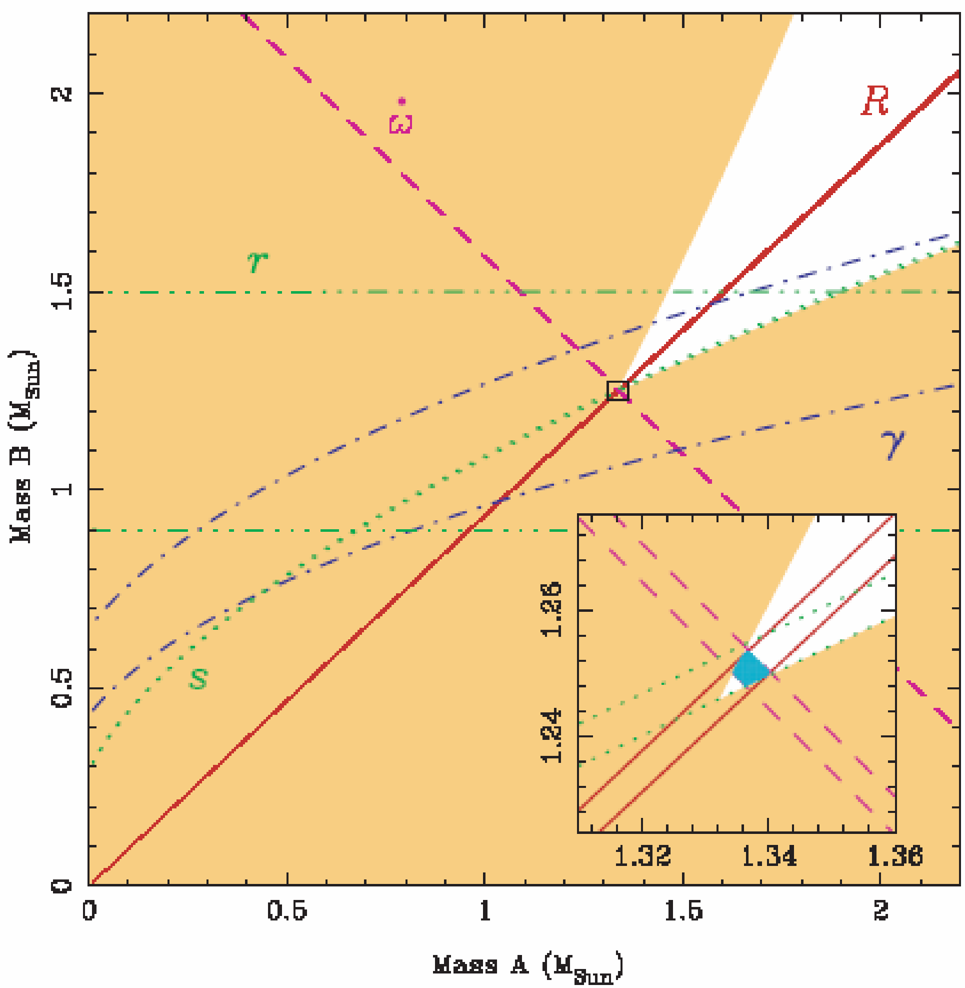
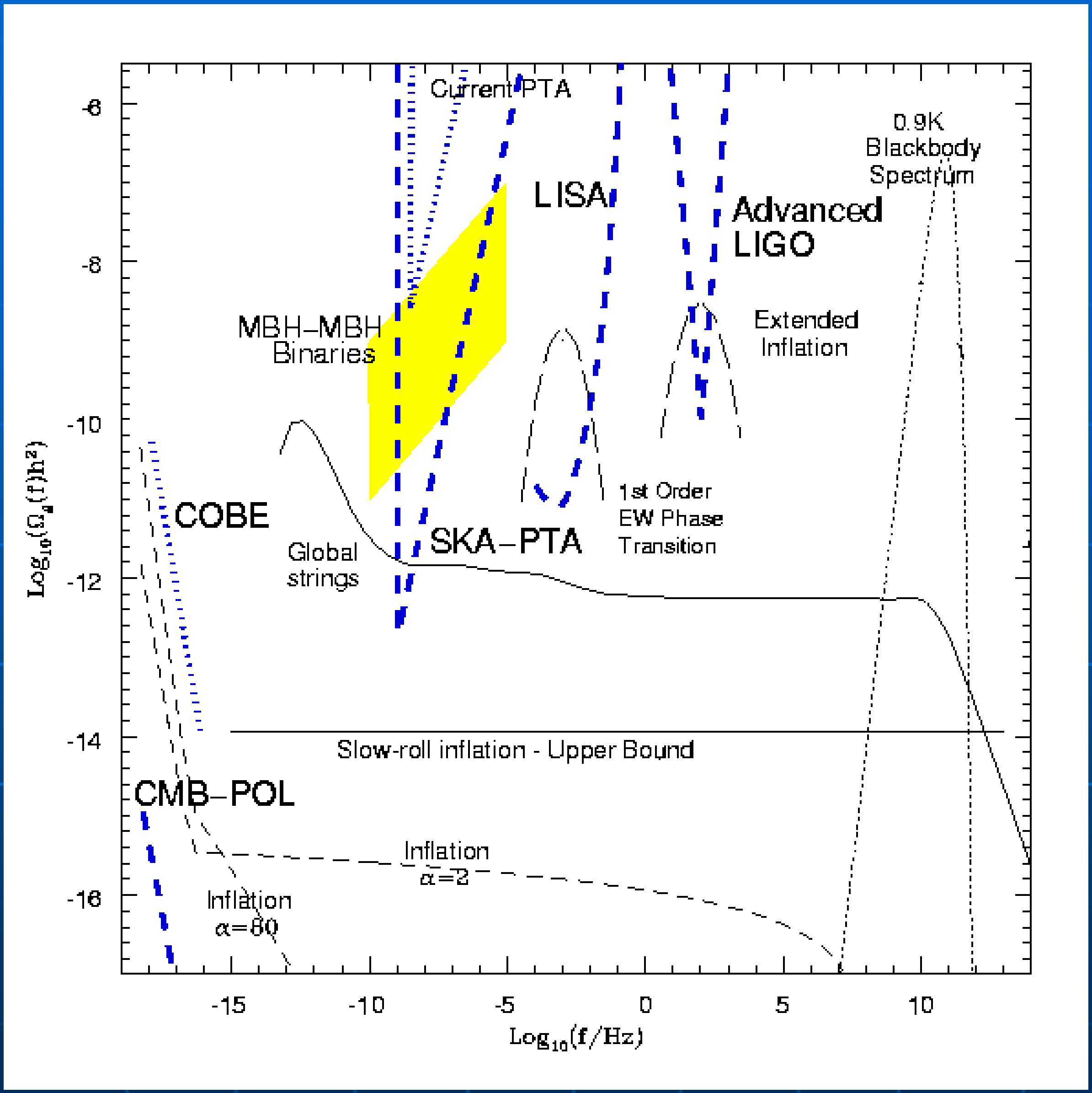


Fig. 3. The observational constraints on the masses m_A and m_B. The colored regions are those that are excluded by the Keplerian mass functions of the two pulsars. Further constraints are shown as pairs of lines enclosing permitted regions as predicted by general relativity: (i) the measurement of the advance of periastron $\dot{\omega}$, giving the total mass $m_A + m_B = 2.588 \pm 0.003\ M_\odot$ (dashed line); (ii) the measurement of $R \equiv m_A/m_B = x_B/x_A = 1.069 \pm 0.006$ (solid line); (iii) the measurement of the gravitational redshift and time dilation parameter γ (dot-dash line); (iv) the measurement of Shapiro parameter r giving $m_B = 1.2 \pm 0.3\ M_\odot$ (dot-dot-dot-dash line); and (v) Shapiro parameter s (dotted line). **Inset**) An enlarged view of the small square that encompasses the intersection of the three tightest constraints, with the scales increased by a factor of 16. The permitted regions are those between the pairs of parallel lines, and we see that an area exists which is compatible with all constraints, delineated by the solid blue region.



Pulsars as gravitational wave detectors:

Earth and pulsar = test masses

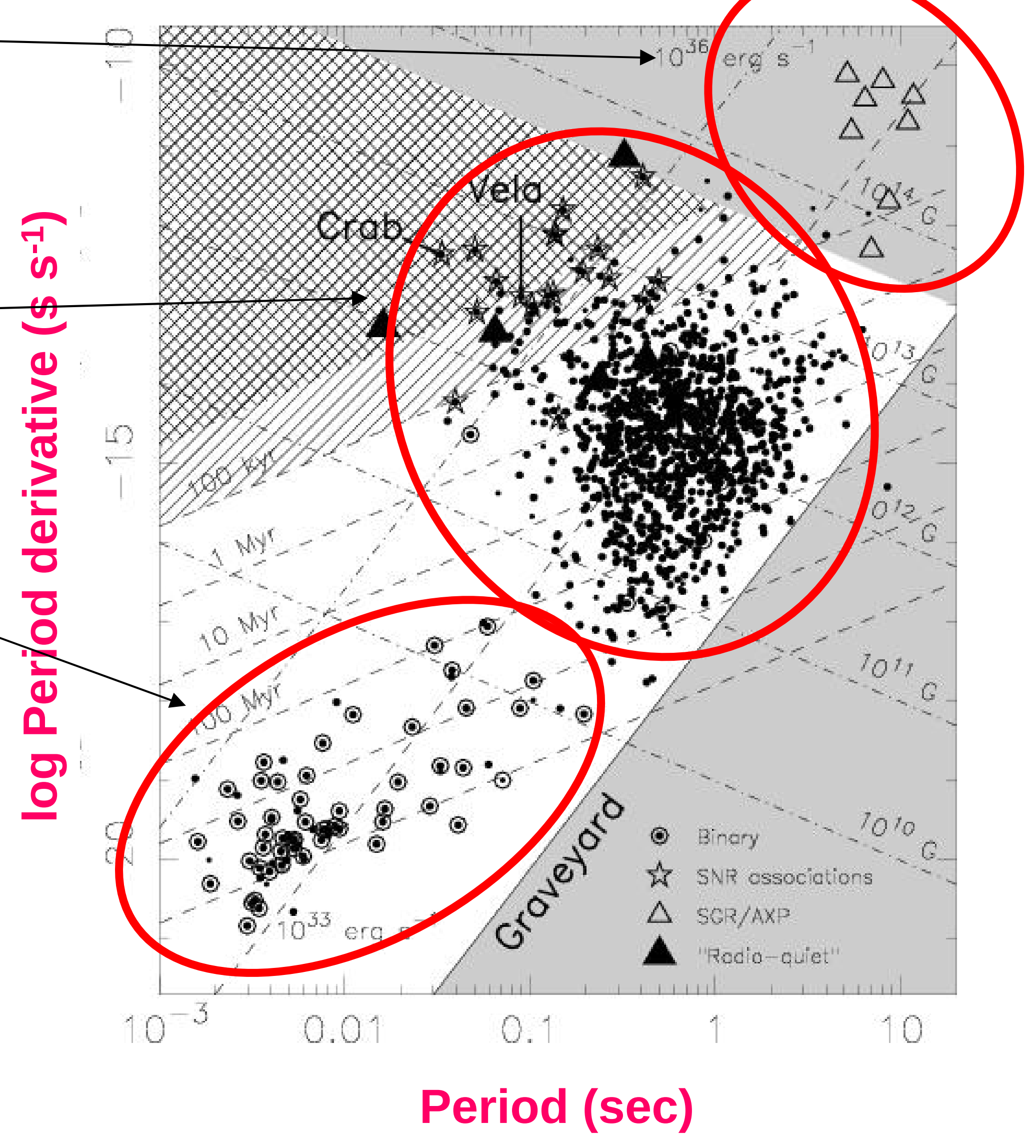
Requires sub-μs TOAs

~ 10^{-9} Hz gravitational waves

Complementary to LIGO II and LISA

Pulsar Populations: P - $\dot{P}$ Diagram

- **Magnetars+high-field pulsars**
  - P ~ 5-12 s
  - B ~ 10^{14} – 10^{15} G
- **Canonical pulsars**
  - P~ 20ms – 5s
  - B ~ $10^{12\pm1}$ G
- **Recycled/Millisecond pulsars (MSPs)**
  - P ~ 1.5 – 20ms
  - B ~ 10^{8} – 10^{9} ms
- **Braking index n:**
  - Pdot $\propto P^{2-n}$, n=3 magnetic dipole radiation
- **Death line**
- **Strong selection effects**

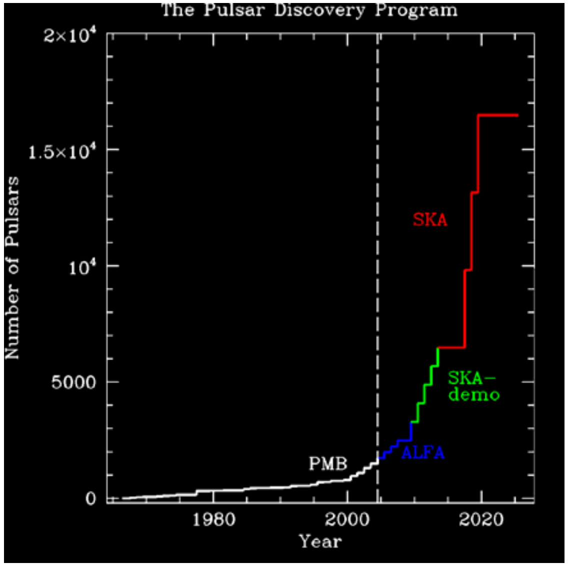


Birth Rates and Population Numbers

$$N_{\text{detectable}} = f_b \times R \times T_{\text{radio}}$$

The SKA has high detection probabilities for most of these objects

⇒ "full Galactic census" of these NS sub- populations



The SKA as a Pulsar/Gravity Machine

- Relativistic binaries (NS-NS, NS-BH) for probing strong-field gravity
- Orbit evolution of pulsars around Sgr A*
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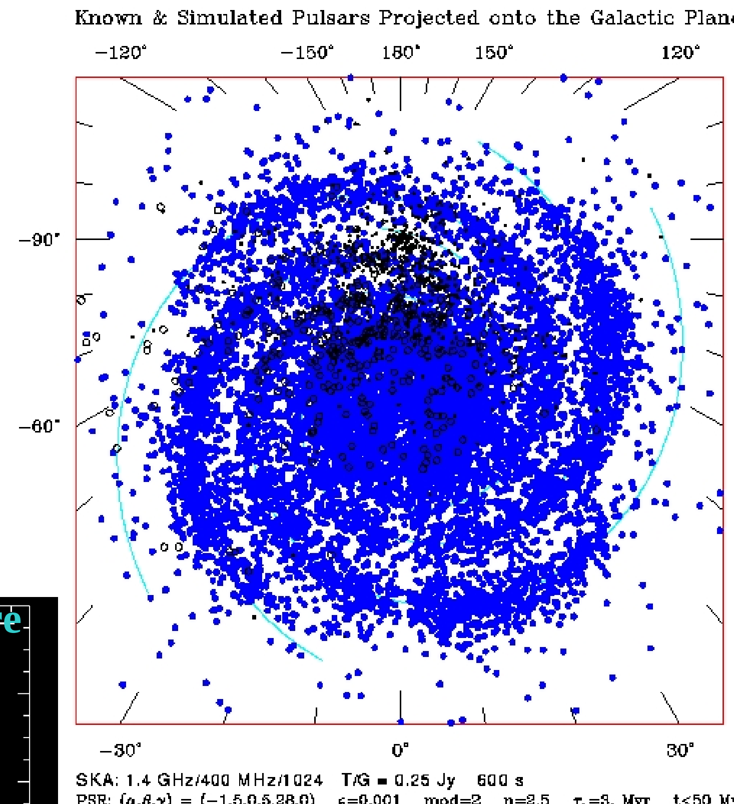
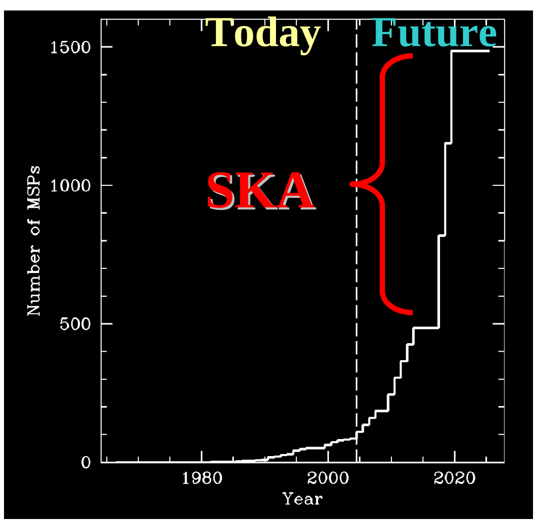
- MSPs suitable for gravitational wave detection
- 100s of NS masses (vs. evolutionary path, EOS, etc)
- Galactic tomography of electron density and magnetic field; definition of Milky Way's spiral structure
- Target classes for multiwavelength and non-EM studies (future gamma-ray missions, gravitational wave detectors)



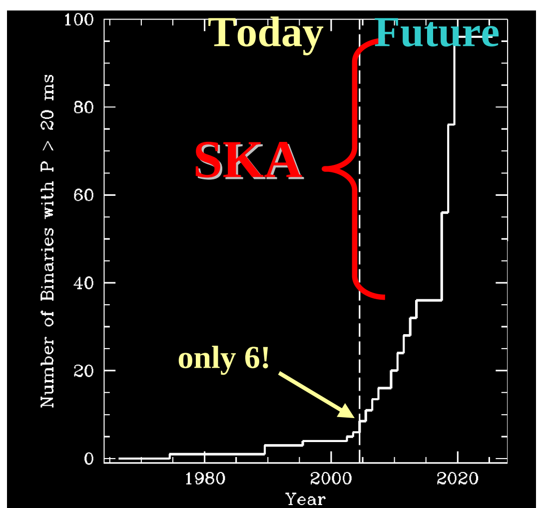
Blue points: SKA simulation
Black points: known pulsars

~10^4 pulsar detections

Millisecond Pulsars



Relativistic Binaries



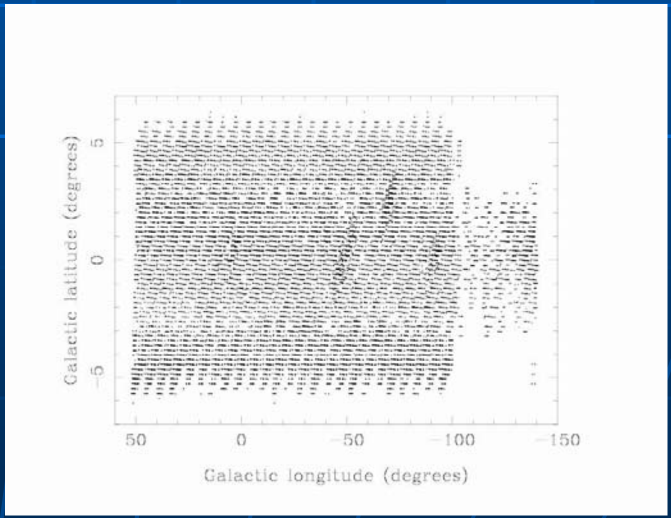
Pulsar Search Domains

Region/Direction	Kind of Pulsar	Telescopes
Galactic Plane	Young pulsars (< 1 Myr)	Arecibo, Effelsberg, GBT, Jodrell, Parkes, WSRT, SKA
Galactic Center	Young, recycled, binary, circum-SgrA*	GBT, EVLA, Parkes, SKA
Moderate Galactic latitudes	MSPs, binary, runaway	Arecibo, GBT, Parkes, SKA
Globular clusters	MSPs, binary	Arecibo, GBT, Parkes, SKA
Local Group Galaxies	Young (probably) Giant pulses	Arecibo, GBT, SKA

Parkes Multibeam Galactic Plane Pulsar Survey

- Most successful survey to date:
  - 800 new pulsars
- Gain ~ 0.7 K Jy^{-1}
- 1.4 $\pm$ 0.144 GHz
- $-100° < l < 50°$ and $|b| < 5°$
- 13 $\times$ 14 arcmin beams
- δt = 250 μs, $\delta\nu$ = 3 MHz, T = 2100 s
- Data sets ~ 96 channels x 8.4×10^6 s $\times$ 1 bit /beam
- ~ 3100 total pointings
- Raw data (mostly) saved ~ 4 TB

Also, high-latitude survey for MSPs, binaries



Globular Cluster Pulsars

Disproportionate ratio of MSPs/binaries to canonical pulsars due to exchange reactions in dense clusters

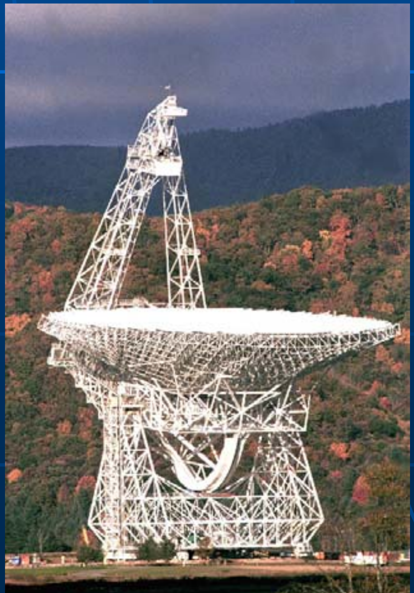
Terzan 5:

33 pulsars, mostly MSPs

Ransom et al. 2005, Science, 307, 892

PSR J1748-2446ad fastest spin (716 Hz)

(Hessels et al. 2006)



PALFA Survey Goals

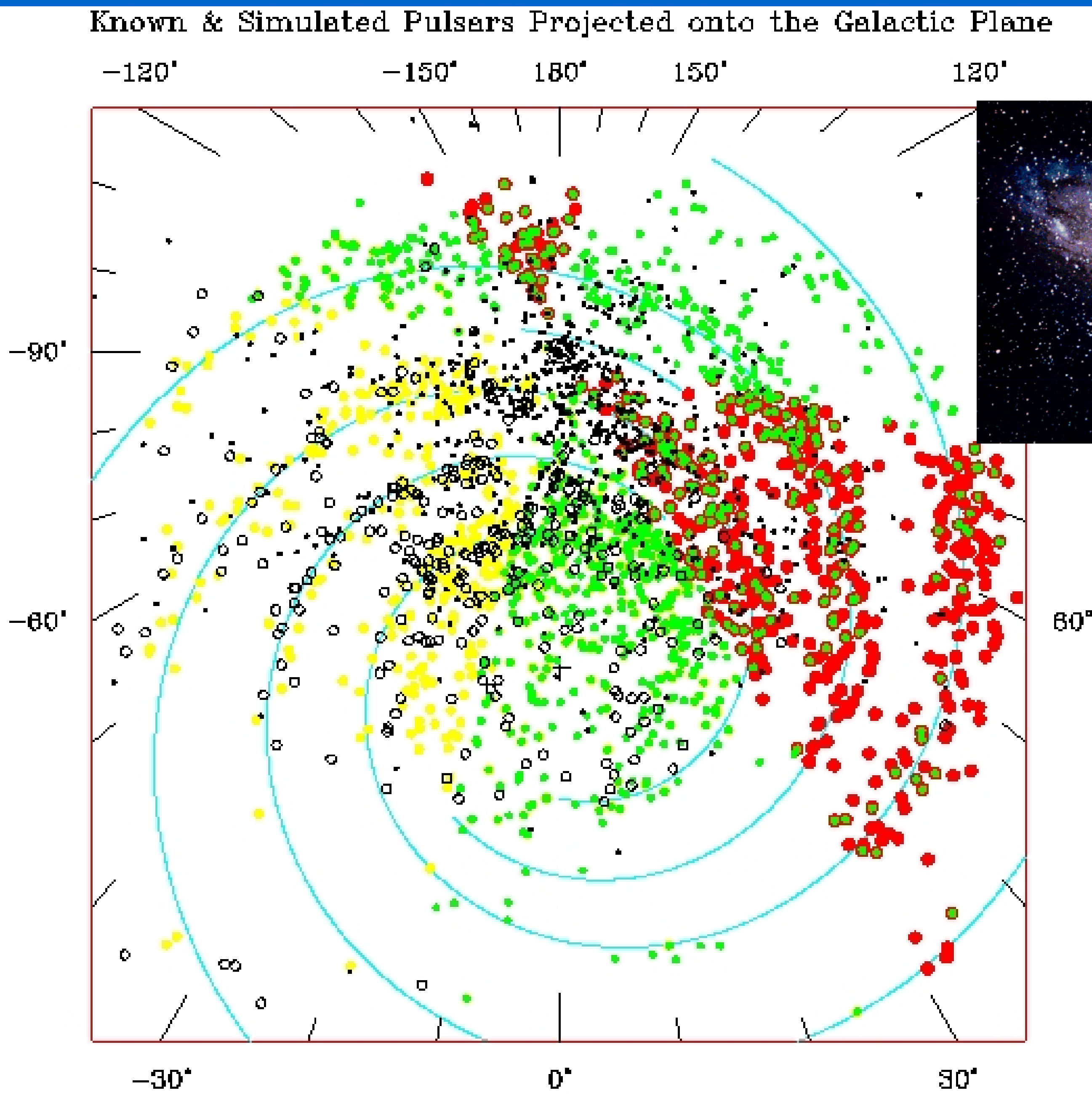
10^3 new pulsars

- Galactic plane survey: $|b|<5°$, $32° < l < 77°$, 400s dwell times
- Intermediate latitude survey: $5° < |b| < 15°$ for MSPs, NS-NS
- Reach edge of Galactic population for much of luminosity function
- High sensitivity to millisecond pulsars (dedispersion)
- D_{max} = 2 to 3 times greater than for Parkes MB

Sensitivity to transient sources (algorithms)

Data management:

- Keep all raw data (~ 1 Petabyte after 5 years) at the Cornell Theory Center (CISE grant: $1.8M)
- Database of raw data, data products, end products
- Web based tools for Linux-Windows interface (mySQL ↔ ServerSQL)
- VO linkage (in future)



Simulated & actual

Yield ~ 1000 pulsars.

First Results

ARECIBO PULSAR SURVEY USING ALFA. I. SURVEY STRATEGY AND FIRST DISCOVERIES

J. M. CORDES,[1] P. C. C. FREIRE,[2] D. R. LORIMER,[3] F. CAMILO,[4] D. J. CHAMPION,[3] D. J. NICE,[5] R. RAMACHANDRAN,[6]
J. W. T. HESSELS,[7] W. VLEMMINGS,[1] J. VAN LEEUWEN,[8] S. M. RANSOM,[9] N. D. R. BHAT,[10] Z. ARZOUMANIAN,[11]
M. A. MCLAUGHLIN,[3] V. M. KASPI,[7] L. KASIAN,[8] J. S. DENEVA,[1] B. REID,[5] S. CHATTERJEE,[12] J. L. HAN,[13] D. C. BACKER,[6]
I. H. STAIRS,[8] A. A. DESHPANDE[2] AND C.-A. FAUCHER-GIGUÈRE[7]

Draft version December 27, 2005

ApJ, 637, 446, 2006

11 new pulsars: 1 binary, 1 w/ gamma-ray counterpart, 1 transient source

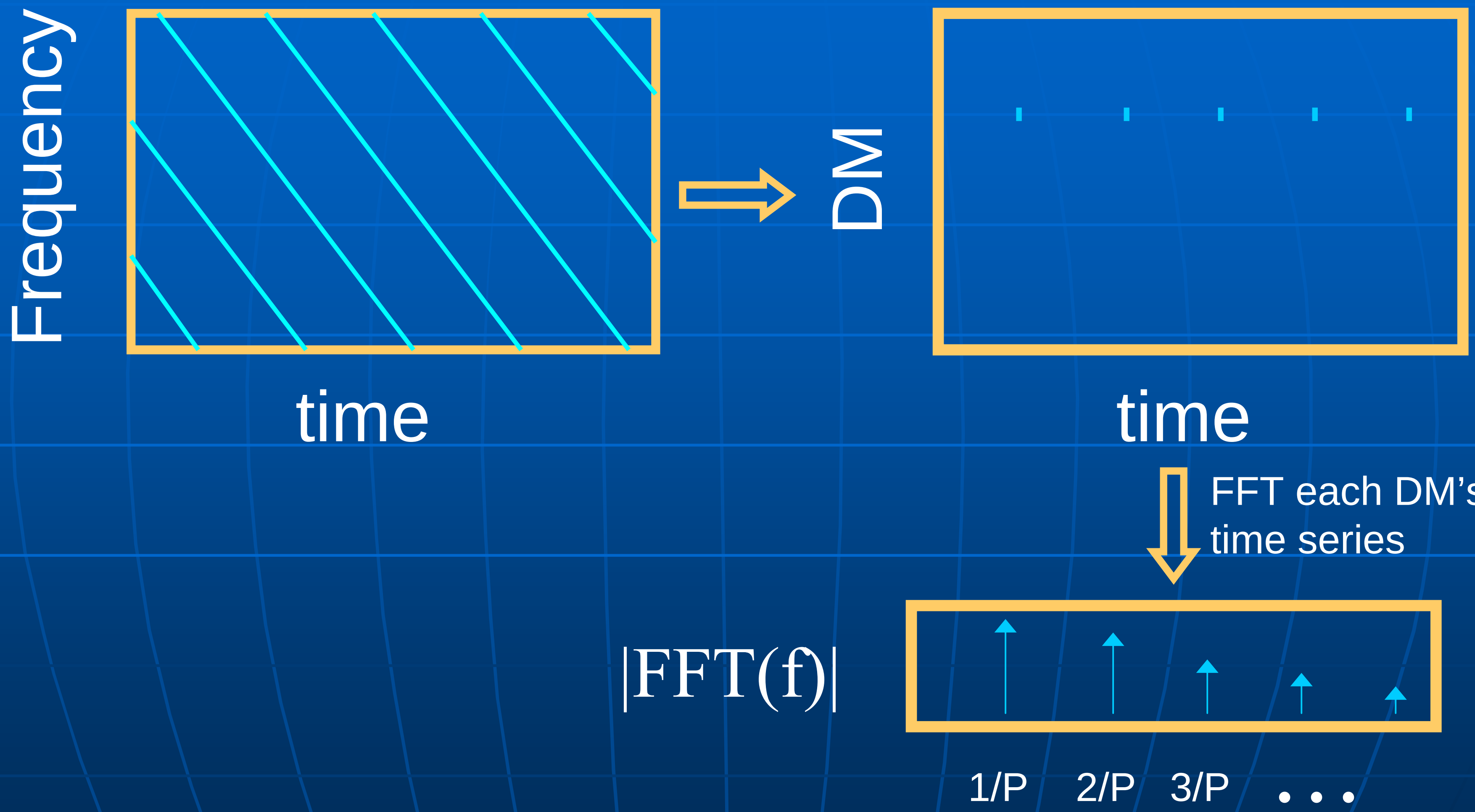
Arecibo Pulsar Survey Using ALFA. II. The young, highly relativistic binary pulsar J1906+0746

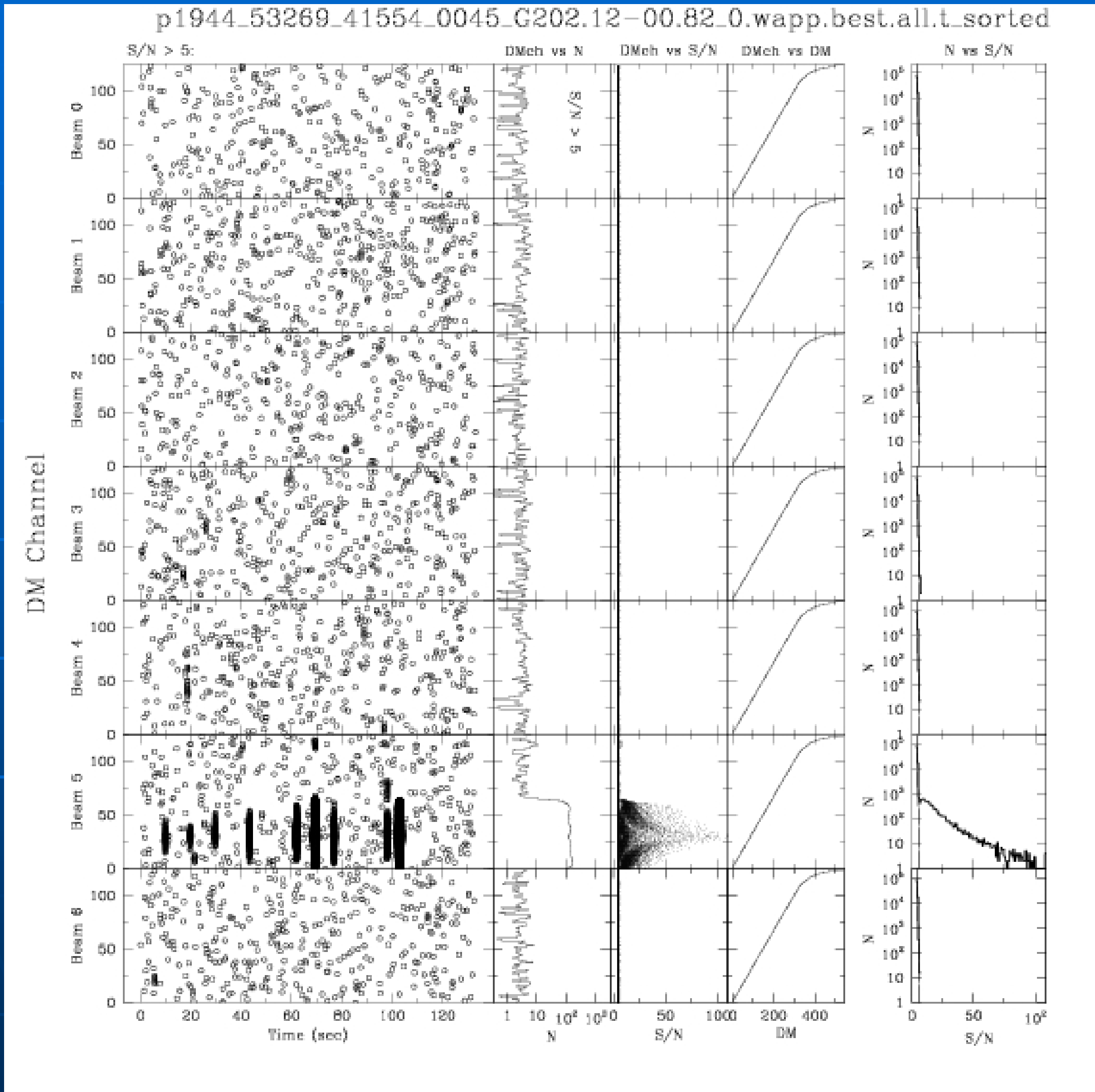
D. R. Lorimer,[1] I. H. Stairs,[2] P. C. C. Freire,[3] J. M. Cordes,[4] F. Camilo,[5] A. J. Faulkner,[1]
A. G. Lyne,[1] D. J. Nice,[6] S. M. Ransom,[7] Z. Arzoumanian,[8] R. N. Manchester,[9]
D. J. Champion,[1] J. van Leeuwen,[2] M. A. McLaughlin,[1] R. Ramachandran,[10]
J. W. T. Hessels,[11] W. Vlemmings,[1] A. A. Deshpande,[3] N. D. R. Bhat,[12] S. Chatterjee,[7,13]
J. L. Han,[14] B. M. Gaensler,[13] L. Kasian, [2] J. S. Deneva,[4] B. Reid,[15] T. J. W. Lazio,[16]
V. M. Kaspi,[11] F. Crawford,[17] A. N. Lommen,[18] D. C. Backer,[10] M. Kramer,[1]
B. W. Stappers, [19,20] G. B. Hobbs,[9] A. Possenti,[21] N. D'Amico,[21] and M. Burgay[21]

ApJ, 640, 428, 2006

Exploited database of Parkes Multibeam survey + multiobservatory followup

Pulsar Periodicity Search





A pulsar found through its single-pulse emission, not its periodicity (c.f. Crab giant pulses).

Algorithm: matched filtering in the DM-t plane.

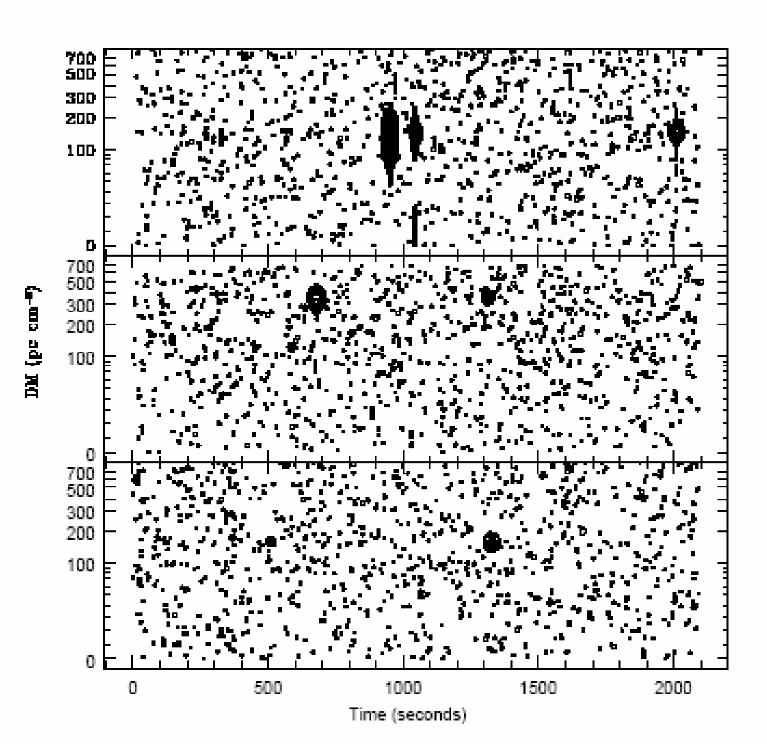
ALFA's 7 beams provide powerful discrimination between celestial and RFI transients

Transient radio bursts from rotating neutron stars

M. A. McLaughlin *, A. G. Lyne*, D. R. Lorimer*, M. Kramer*, A. J. Faulkner*, R. N. Manchester †, J. M. Cordes ‡, F. Camilo §, A. Possenti ¶, I. H. Stairs ‖, G. Hobbs†, N. D'Amico **¶, M. Burgay¶ & J. T. O'Brien*

Nature, 439, 837, 2006

- 11 sources found in reanalysis of Parkes MB survey
  - missed in periodicity search
- Pulse rates ~ 0.3 to 20 pulses hr^{-1}
- Extreme cases of pulse nulling?
- Implied Galactic population ~ "normal" pulsar population (i.e. ~ 2×10^5 objects)



Processing Basic Data Units

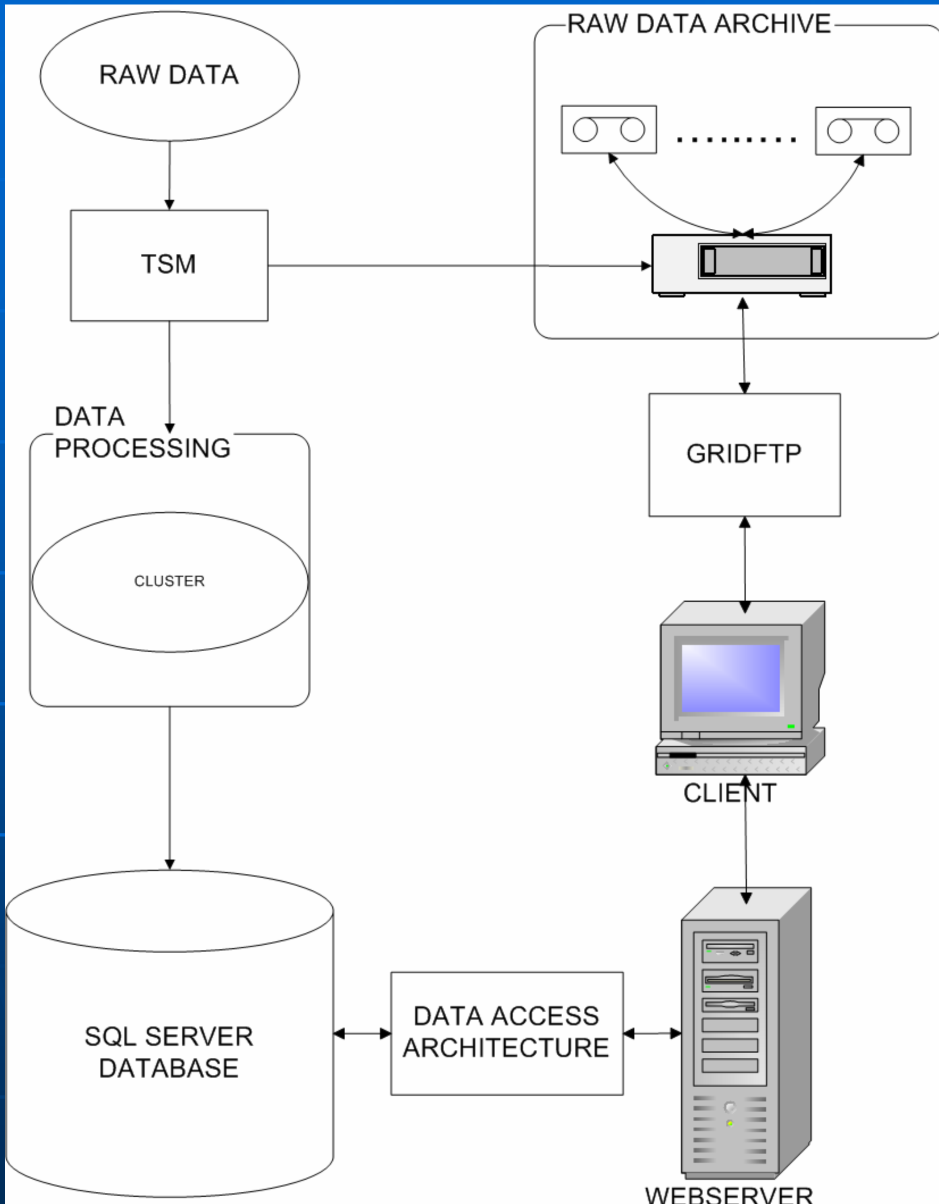
- Traditional:
    - a narrow search for periodic, dispersed signals
    - blunt instrument approach to RFI: discard data
- Our approach:
    - seek a wide range of signal types
    - classify <u>all</u> non-noise events and signals, whether celestial or terrestrial, whether natural or artificial
- Enabling infrastructure:
    - access to large volumes of raw data
    - high throughput processing
    - global analyses of data products through custom database

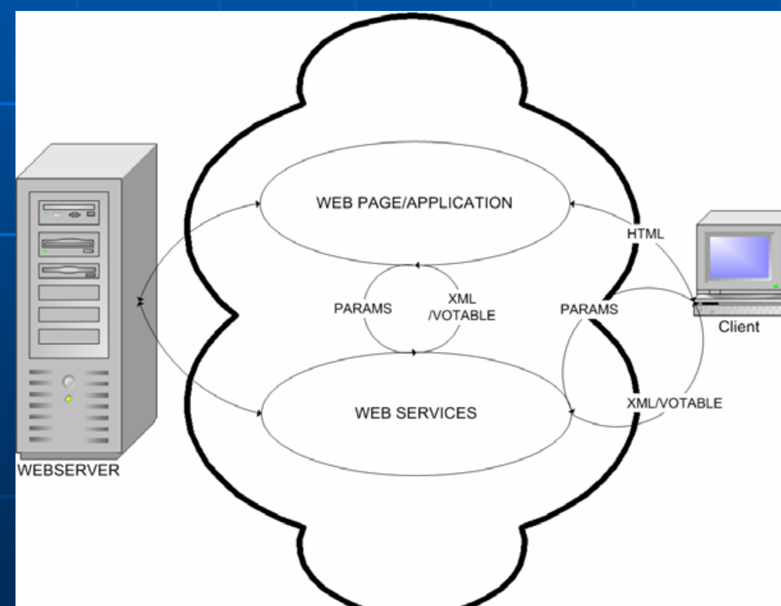
Data management at the Cornell Theory Center

- raw data
- data products
- algorithms, tools
- networking (NLR)

Issues:

- evolution of media (disk/tape)
- network charges
- data integrity/security





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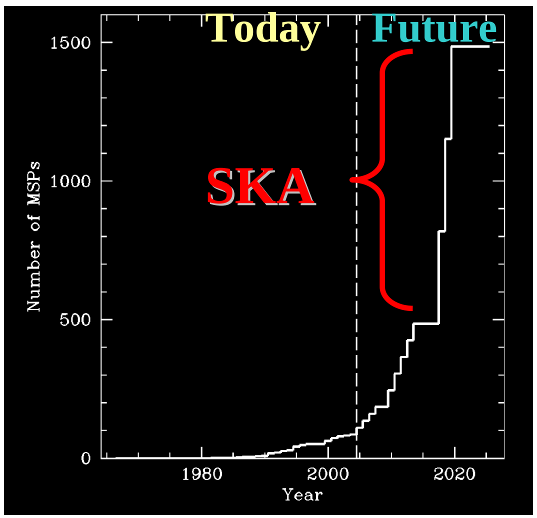
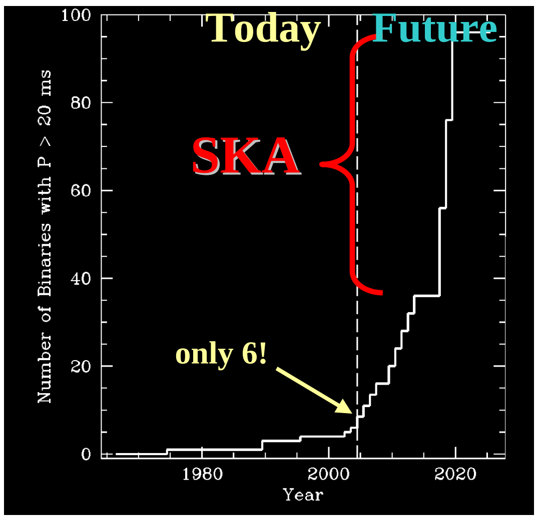
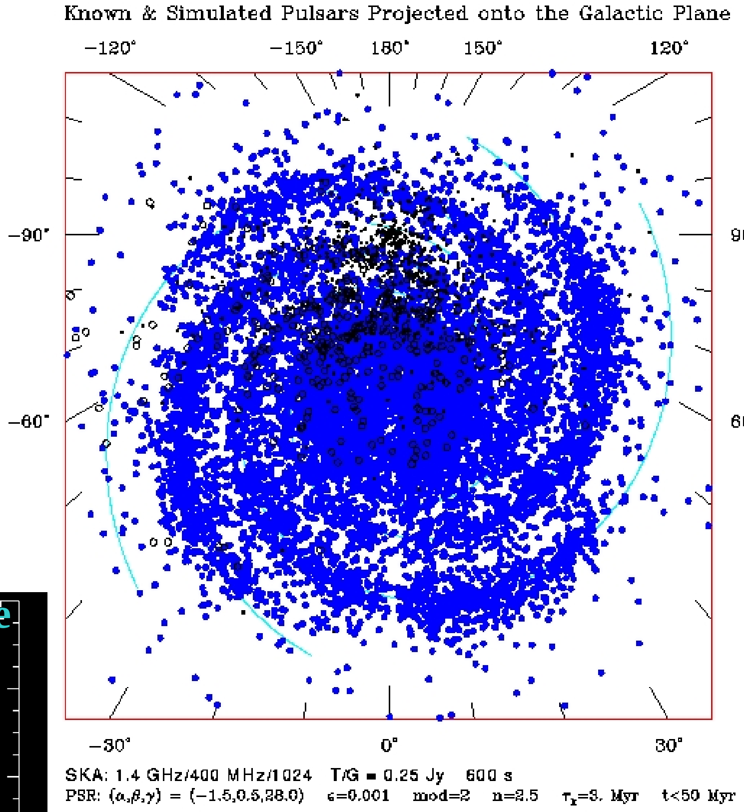
- Target classes for multiwavelength and non-EM studies (future gamma-ray missions, gravitational wave detectors)

Millisecond Pulsars



Relativistic Binaries





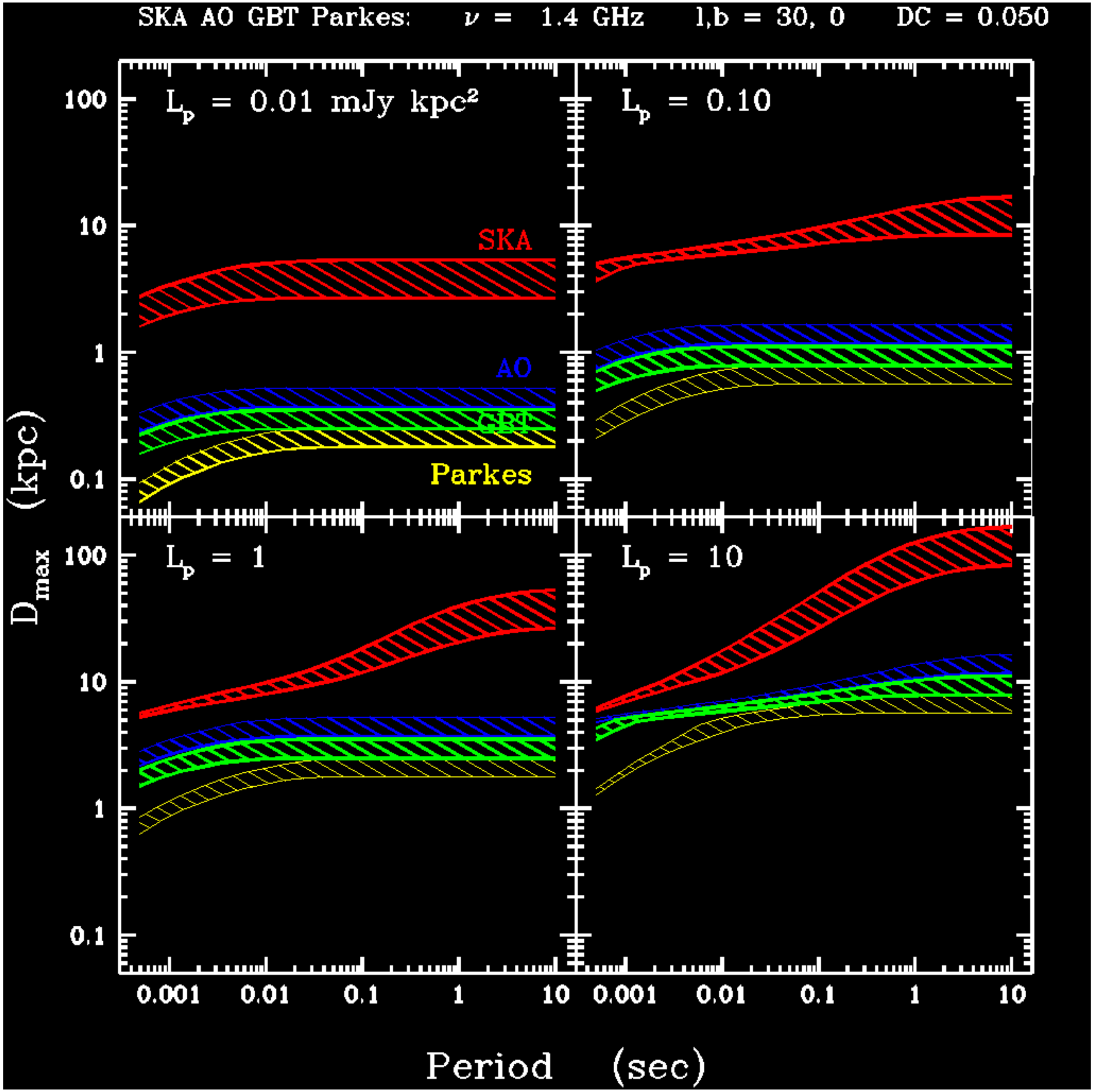
Blue points: SKA simulation
Black points: known pulsars

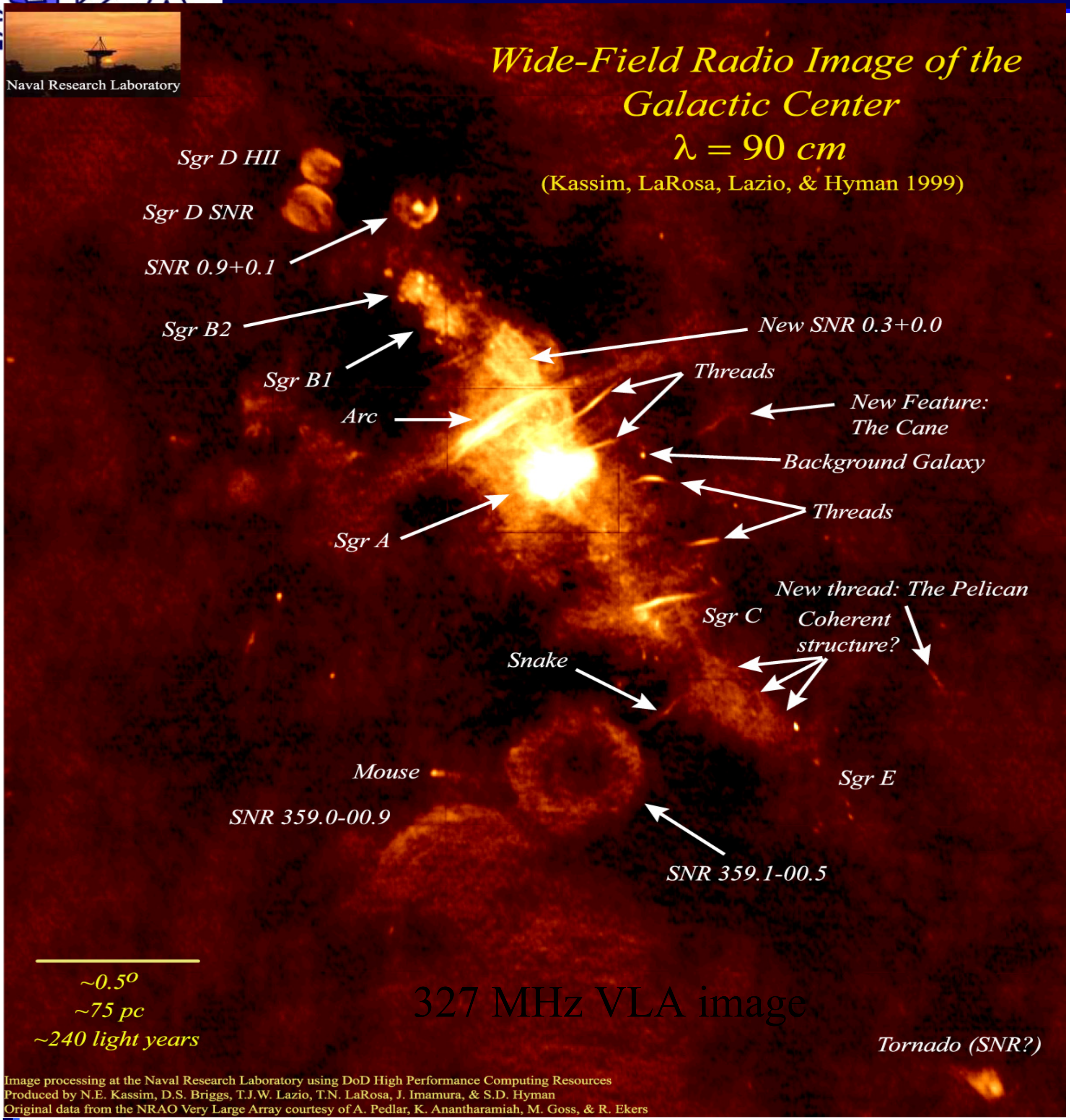
~10^4 pulsar detections

D_{max} vs P

D_{max} = maximum detectable distance for period P given luminosity L_p

Detection curves take into account interstellar scattering (NE2001 model) instrumental effects, additive noise





Galactic Center Region

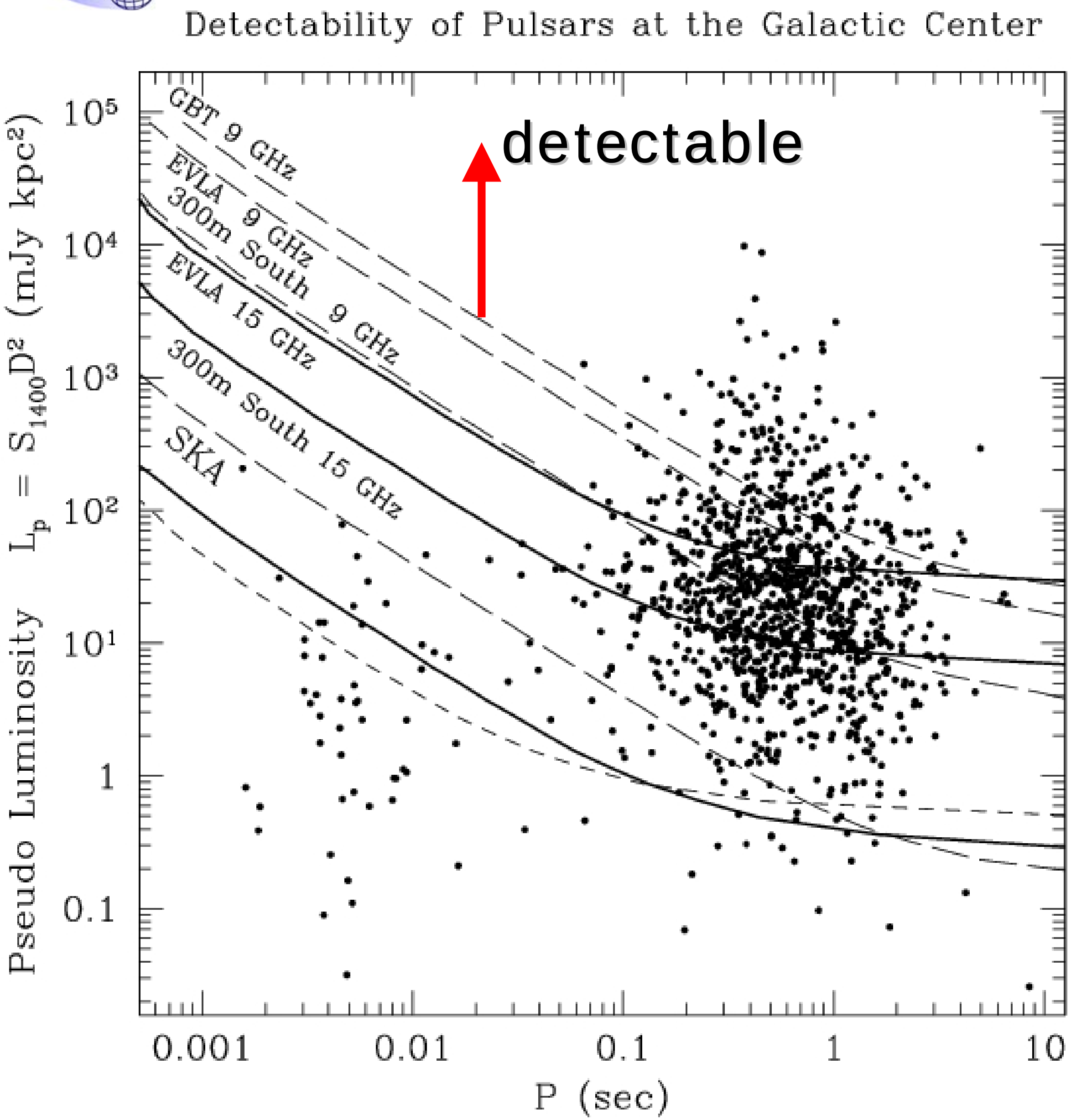
Sgr A* = 3×10^6 black hole with a surrounding star cluster with ~ 10^8 stars. Many of these are neutron stars.

Detecting pulsars in Sgr A* is difficult because of the intense scattering screen in front of Sgr A*.

Multipath differential arrival times

$\tau_d \sim 2000\ \nu^{-4}$ sec

Solution: high sensitivity at high frequency



Sampling of pulsar L-P distribution with different instruments

EVLA can sample a good fraction of the luminosity function

A southern-hemisphere Arecibo-like aperture samples even more

SKA may be necessary to realize timing precision required for physics payoff (black hole spin, GR tests)

GBT Surveys

- Complete the Galactic plane (Parkes, Arecibo)
  - Draft white paper written ~ 2001
- Best telescope in northern sky
- Larger throughput than Parkes MB survey
- Galactic plane, NS-X binaries, MSPs
- Several × 1000 hr
- Focal plane array needed
  - Horn cluster
  - Phased array

Summary/Conclusions

Pulsar surveys + follow up will provide much greater returns than achieved so far:

- Binaries deeper into the strong-field regime to test gravity
- Extreme spin states (sub-ms?)
- Extreme B (radio magnetars?)
- 100s of NS masses, 10^3s of WD masses, BH masses?
- Aperiodic pulsars
  - RRATs
  - Bursters (B1931+24)
  - Giant pulses (Crab-like, several MSPs) with large B_{LC}
  - GC radio transients?

Digital requirements are increasing per discovery

- Sampling of f-t plane (wider bandwidths, faster spectrometers)
- Dedispersion and periodicity searches
- Single pulse searches
- Acceleration searches
- More sophisticated binary searches (smaller P_{orb}, eccentric binaries)
- Greater f-t complexity than interstellar dispersion

Summary/Conclusions

Digital costs dropping dramatically

- Larger data sets
- More ambitious survey goals

Data archival and management

- Important to save raw data
  - Reprocessing with new algorithms (c.f. Parkes MB)
  - Cross-λ studies and (re) discoveries (e.g. radio/GLAST)
  - Back estimation of arrival times after later discovery
- invest a/m costs proportionately to total survey cost
- Modern database systems needed to achieve virtual observatory functionality and discovery potential

Future radio telescopes: frequency coverage, wide FoV

- SKA and its forerunners (0.1–- to 25++) GHz
- Data management a bigger enterprise than data acquisition

QuickTime™ and a
Cinepak decompressor
are needed to see this picture.

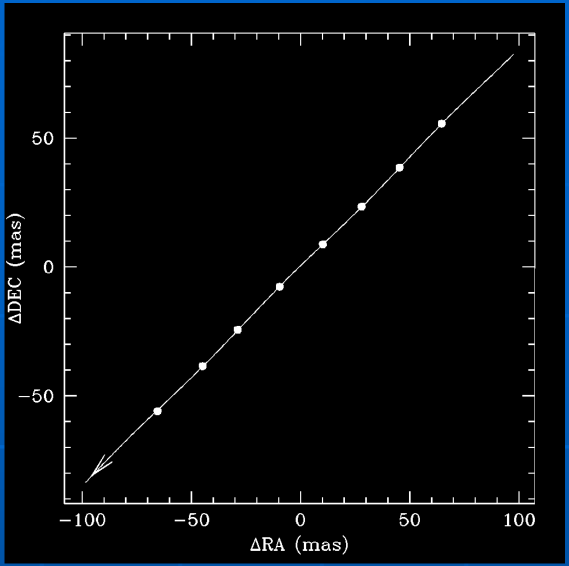
Kramer et al.

Extra Slides

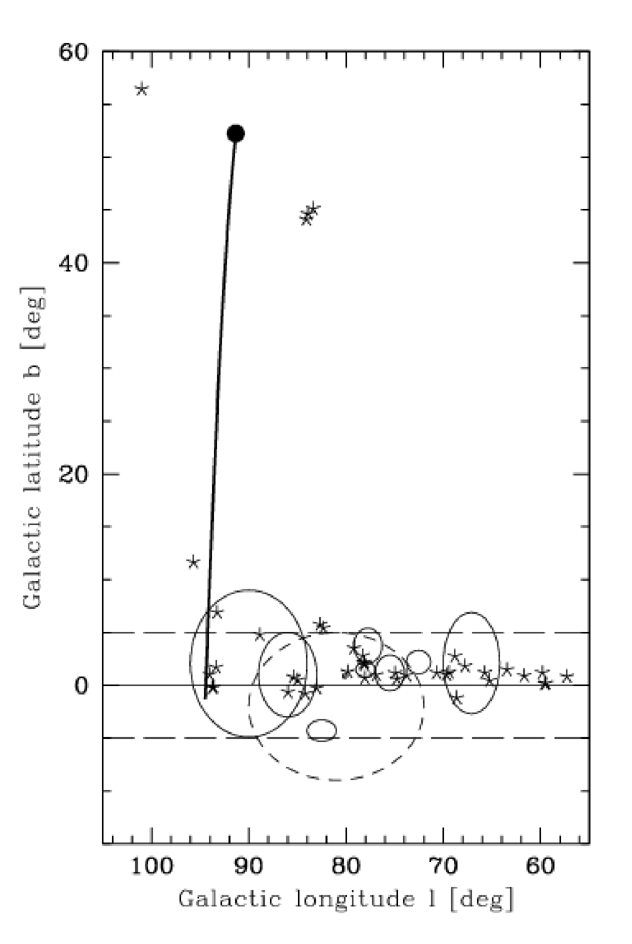
B1508+55

Chatterjee et al. 2005

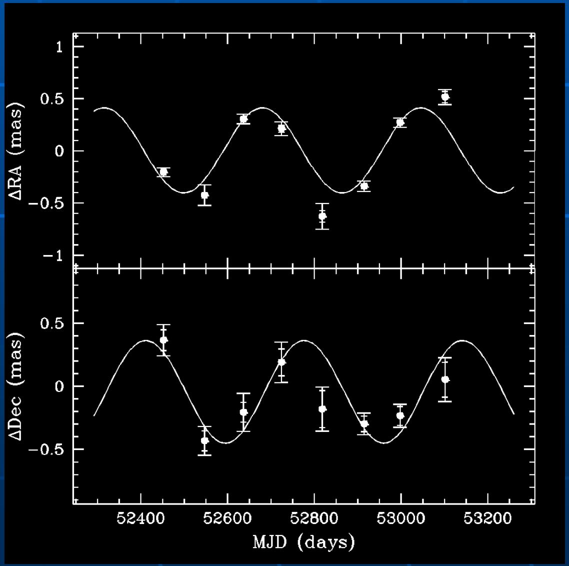
VLBA



- l,b = 91.3°, 52.3°
- D = 2.45±0.25 kpc
- $V_{\perp} = 1114_{-94}^{+132}$ km s^{-1}
- P = 0.74 s
- B = 2x10^{12} G
- τ = P/2Pdot = 2.36 Myr



The highest measured velocity using direct distance measurement



2.5x further than electron density model based distance estimate (NE2001)

Possibly born in Cyg OB 7

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, GBT, SKA) can dramatically increase the volume searched (galactic & extragalactic)

PULSAR SEARCHING