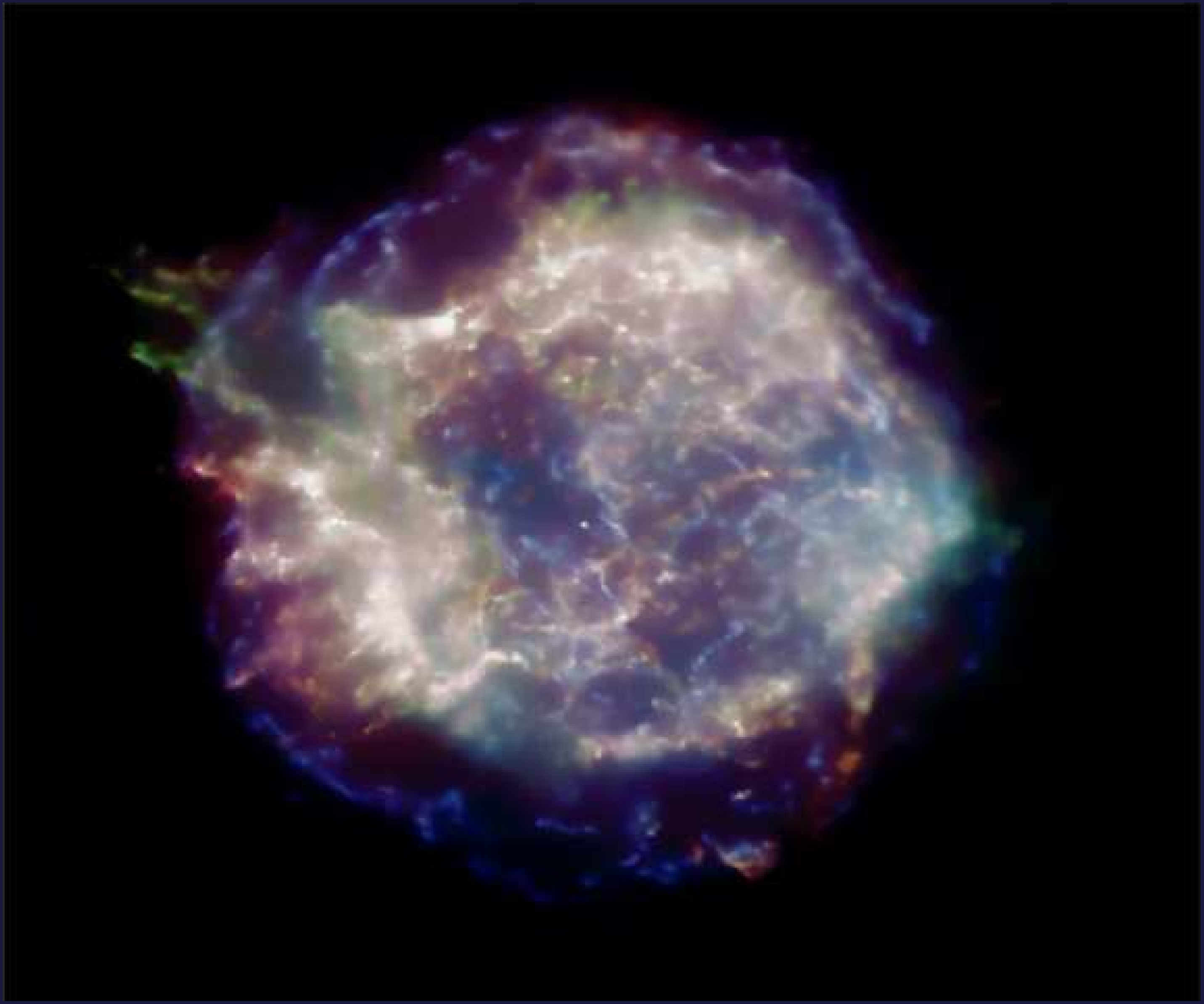
Astrometric Observations of Neutron Stars

Shami Chatterjee

21 July 2009

- Neutron Stars are laboratories for extreme physics.



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- Attaining high precision.
- Results and future directions.

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  $\longrightarrow$ Reference frame and calibrator stability?
- Positions from different points in Earth's orbit: Parallax π.
  $\longrightarrow$ Frequent sampling over the orbit helps measurement.

Neutron Star Astrometry

→ Optical / IR.
(e.g., HST π to RX J0720.4$-$3125, Kaplan et al.)

→ X-ray.
(e.g., CXO μ of NS in Puppis A, Winkler & Petre.)

→ Radio pulse timing of recycled pulsars.
(e.g., J0437$-$4715; van Stratten, Bailes, et al.)

→ Radio interferometry.
The majority of NS parallaxes are from VLBI.

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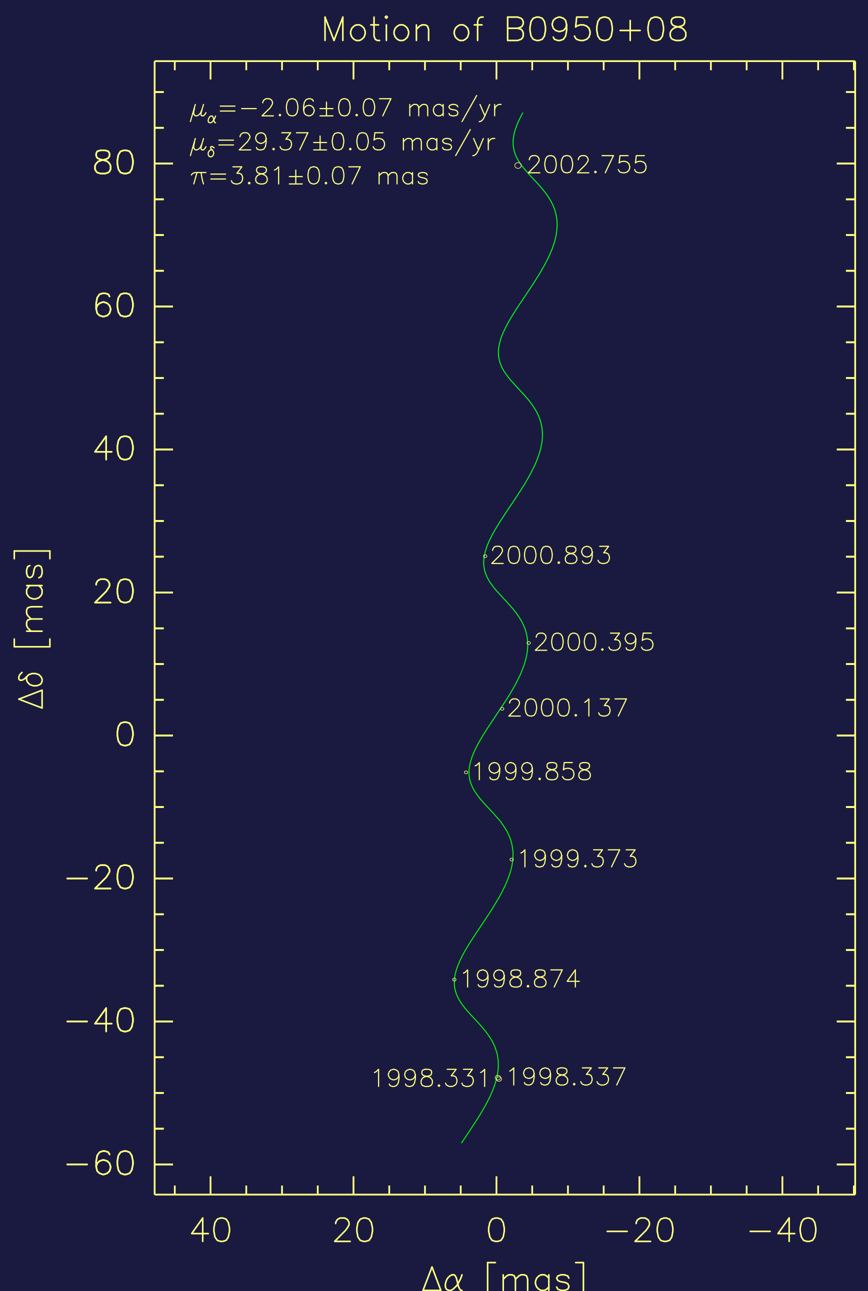
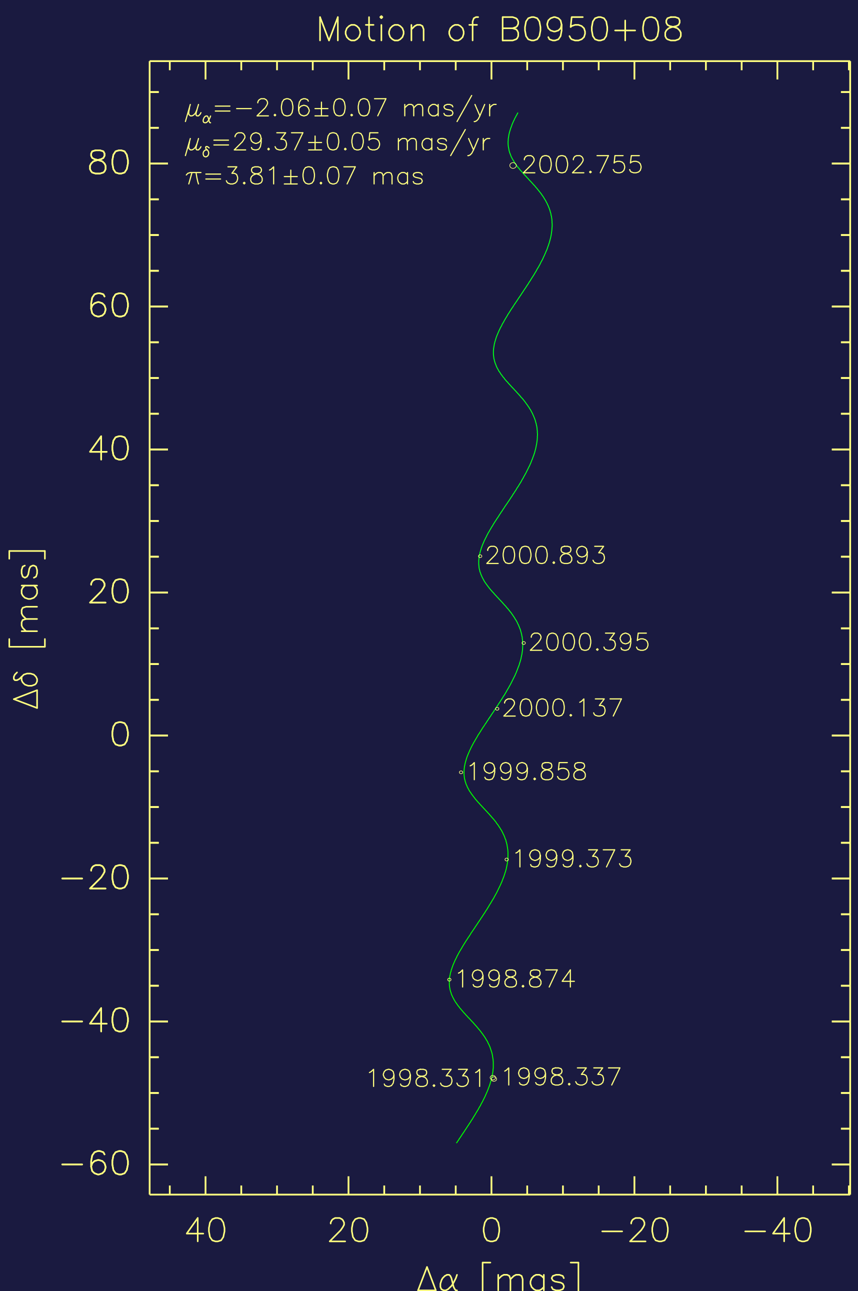


(Brisken et al. 2000 ++)



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$\{\mu, \pi\} \Rightarrow$
Model-independent distances and velocities.

Why do it?
(What's in it for me?)

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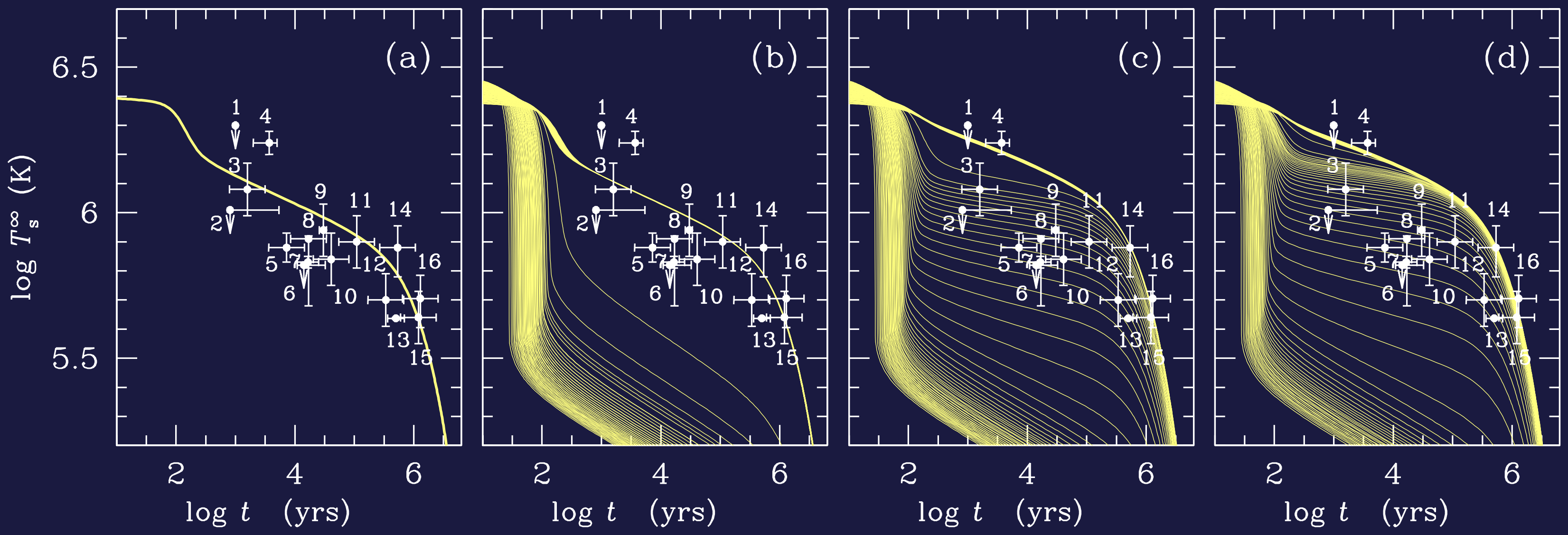
(e.g., Lattimer & Prakash 2006, Yakolev et al. 2007)



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- Environment: Model the local ISM with ISS, bow shocks.

(e.g., Taylor & Cordes 1993, Cordes & Lazio 2001, etc.)

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- Verify solar system–extragalactic reference frame ties.

(e.g., Bartel et al. 1996; also Fomalont & Reid 2007)

Case study: PSR B1508+55

How large are the kicks that NS receive at birth?

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B1508+55 is a very “ordinary” pulsar:

- Rotation period is 0.74 seconds.
- Inferred magnetic field is 2×10^{12} Gauss.
- Characteristic age is 2.3 million years.
- Located well outside Galactic plane ($b = 52.3°$).

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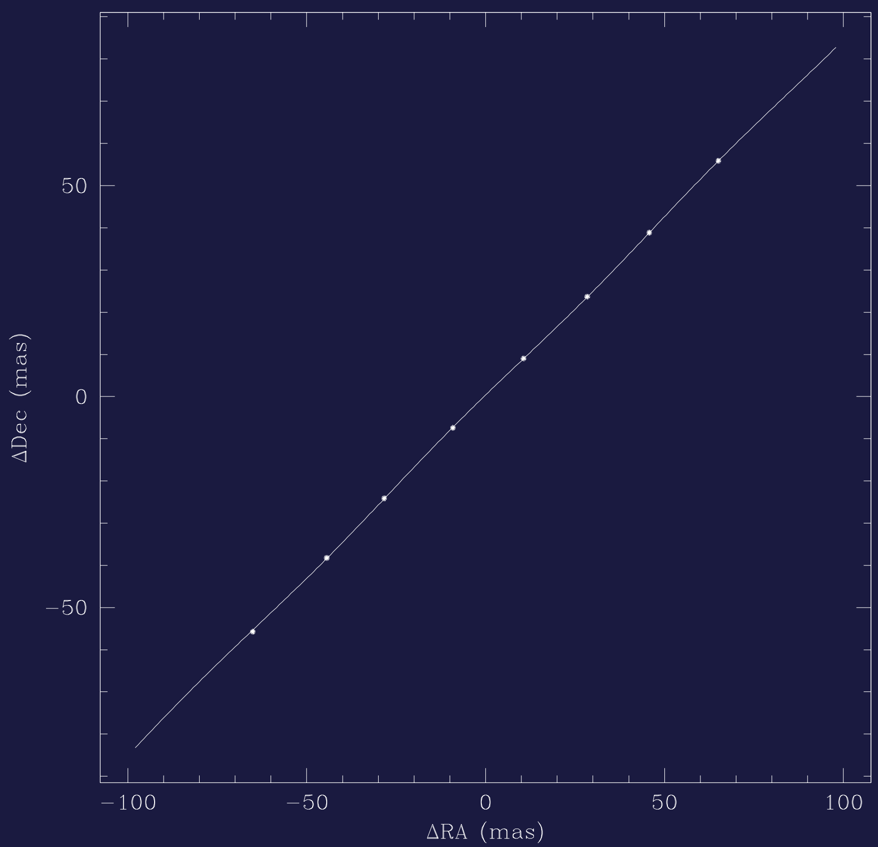
Observe 8 times over 2 years with the VLBA...

Astrometric Results for B1508+55



μ_a = -73.61 ± 0.04 mas yr^{-1}

μ_d = -62.62 ± 0.09 mas yr^{-1}

π = 0.42 ± 0.04 mas

(with Vlemmings, Brisken, Lazio, Cordes,

Goss, Thorsett, Fomalont, Lyne, Kramer)

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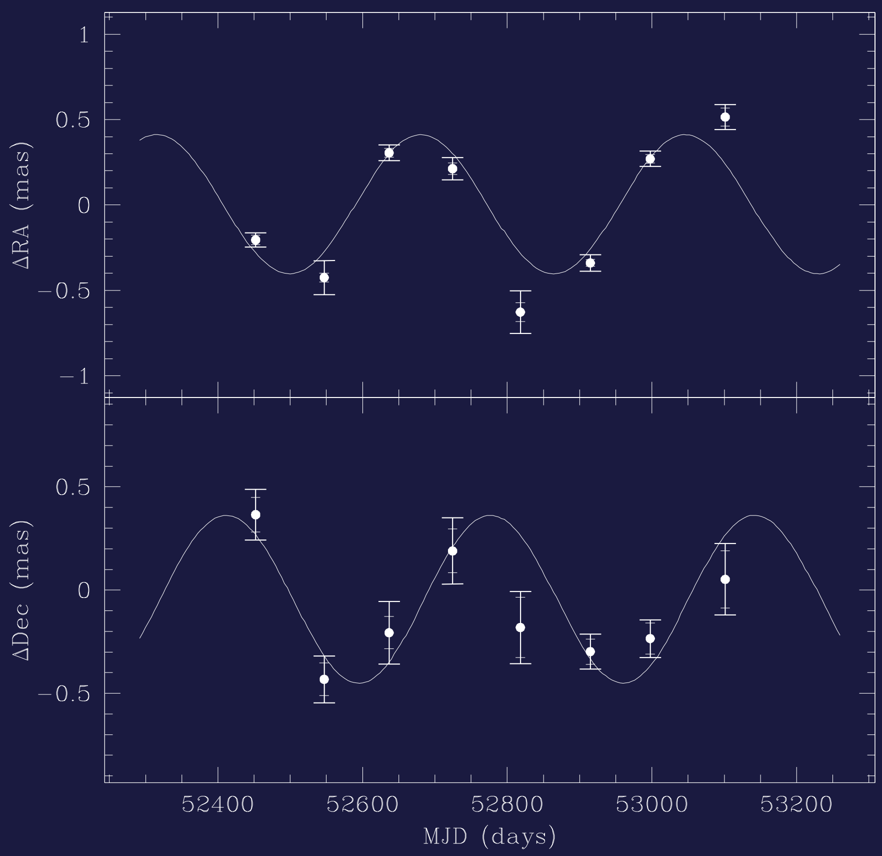

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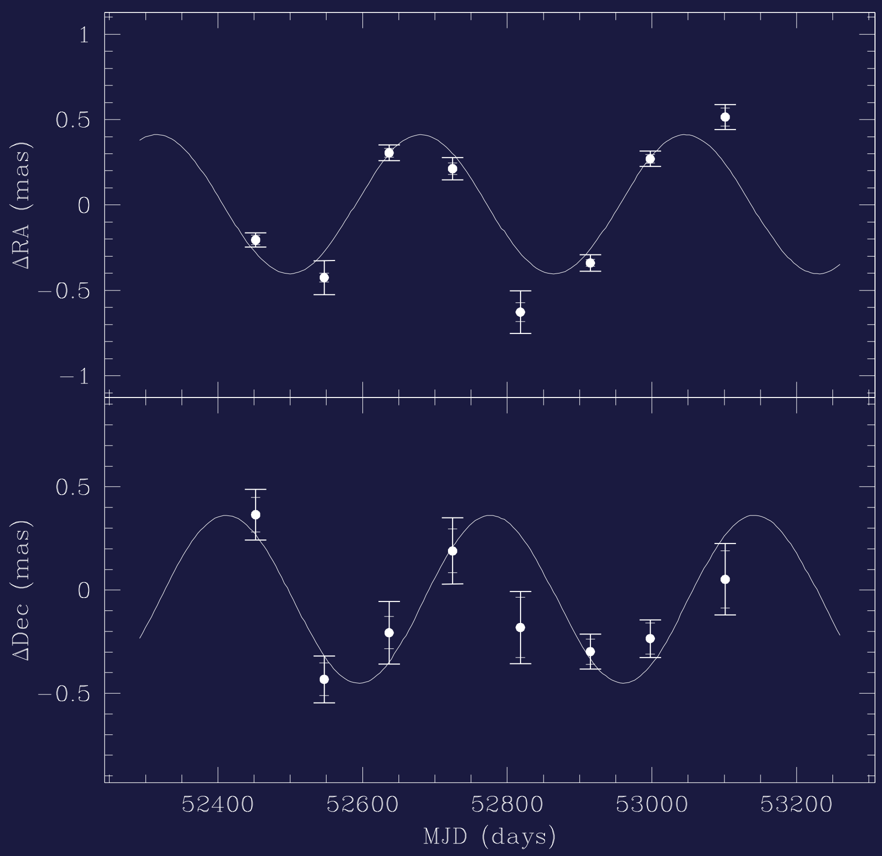

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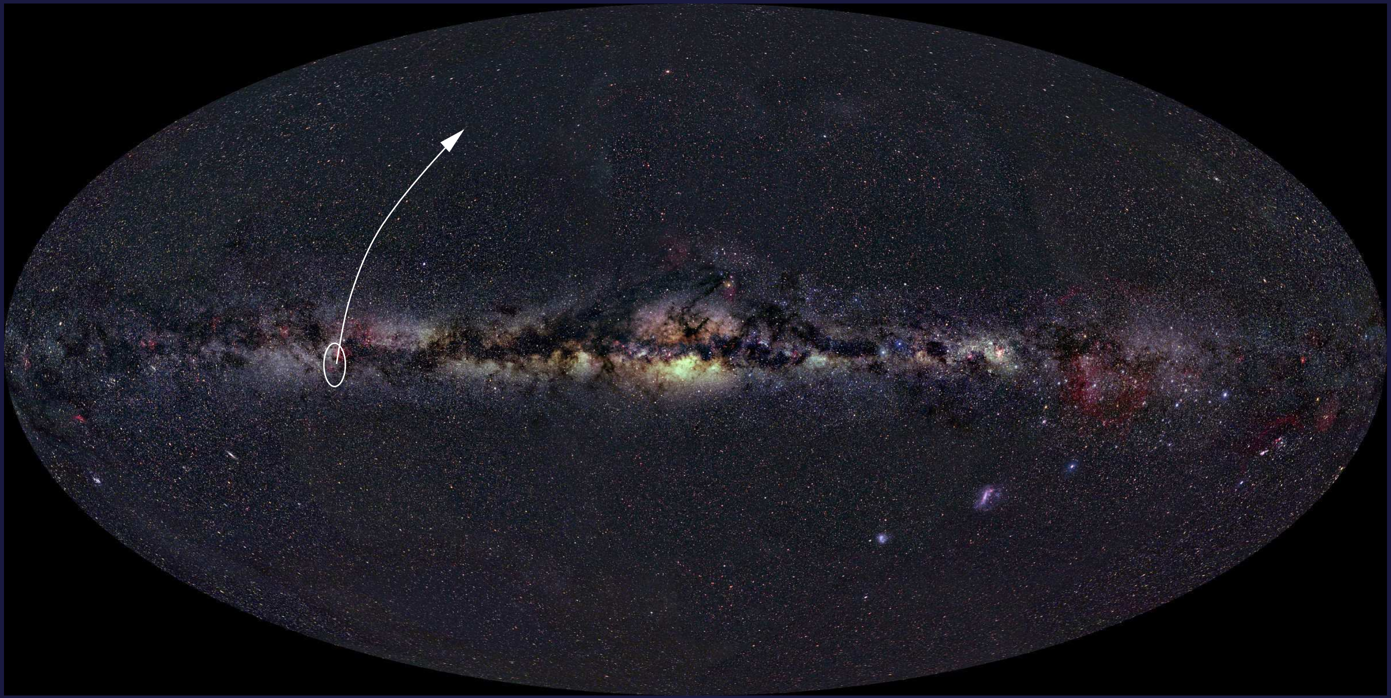
The highest measured model-independent velocity yet!

(Chatterjee et al. 2005)

The Birth Site of B1508+55



Orbit of B1508+55 overlaid on Axel Mellinger's image of the Galaxy.

- Current Galactic latitude = 52.3°.
- Trace back orbit in Galaxy: born in Galactic plane.
- Birth in or near Cygnus OB associations.

B1508+55: Getting its Kicks

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- Work ongoing: better simulations, SASI, acoustic modes.

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$\Rightarrow$ High velocities impose severe constraints on core collapse and kick velocity scenarios.

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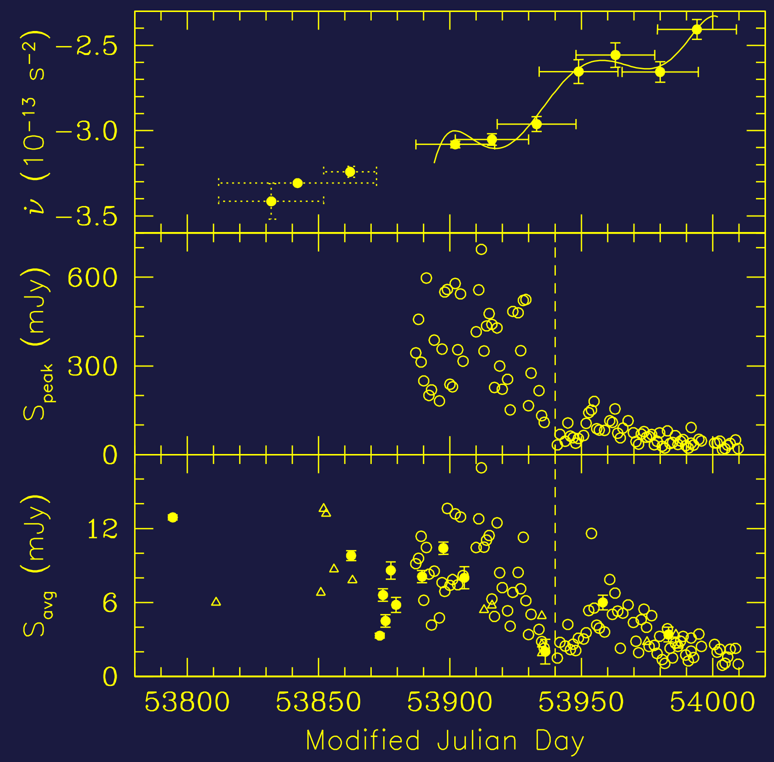
- Need X-ray or adaptive optics IR obs over many years.

$\longrightarrow$ Interesting preliminary results.
(e.g., two-epoch *Chandra* obs; Kaplan et al. 2009),
But we need longer time baselines.

Magnetar XTE J1810–197

- Camilo et al. (2006): Transient pulsed radio emission!
- Rapidly fading...



(from Camilo et al. 2006)

Magnetar XTE J1810–197

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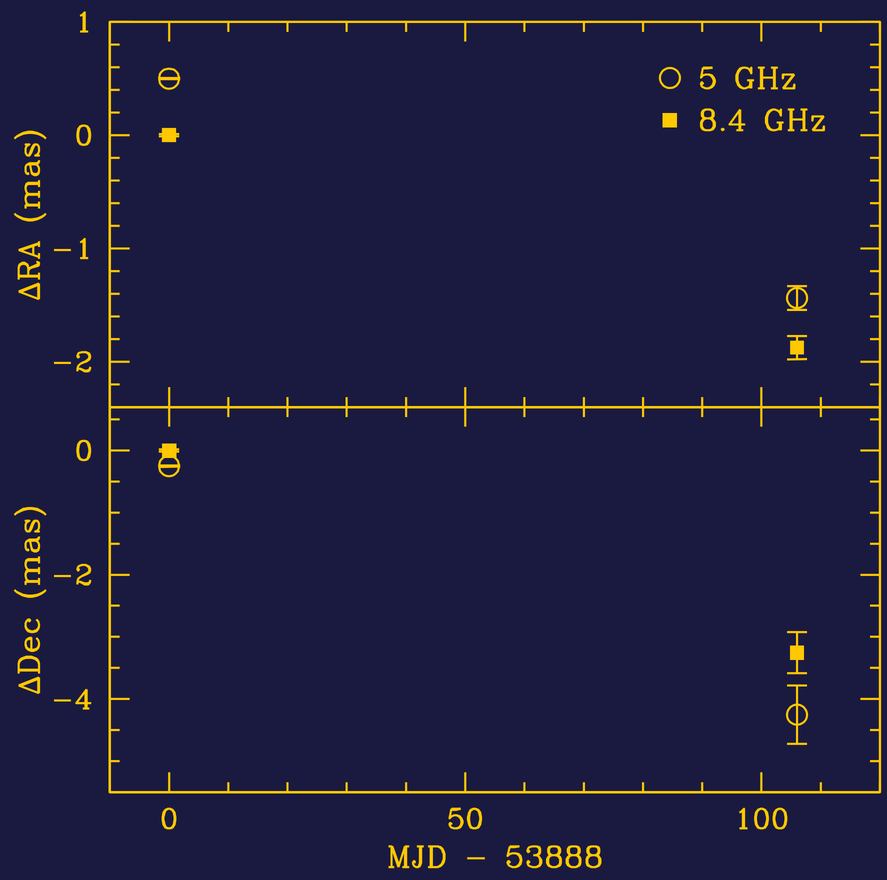
- But bright enough for VLBA obs at 5, 8.4 GHz over 106 days.

A Magnetar Proper Motion



$\mu_\alpha = -6.60 \pm 0.06$ mas yr^{-1}
$\mu_\delta = -11.7 \pm 1.0$ mas yr^{-1}

$\Rightarrow$
For $D = 3.5 \pm 0.5$ kpc,
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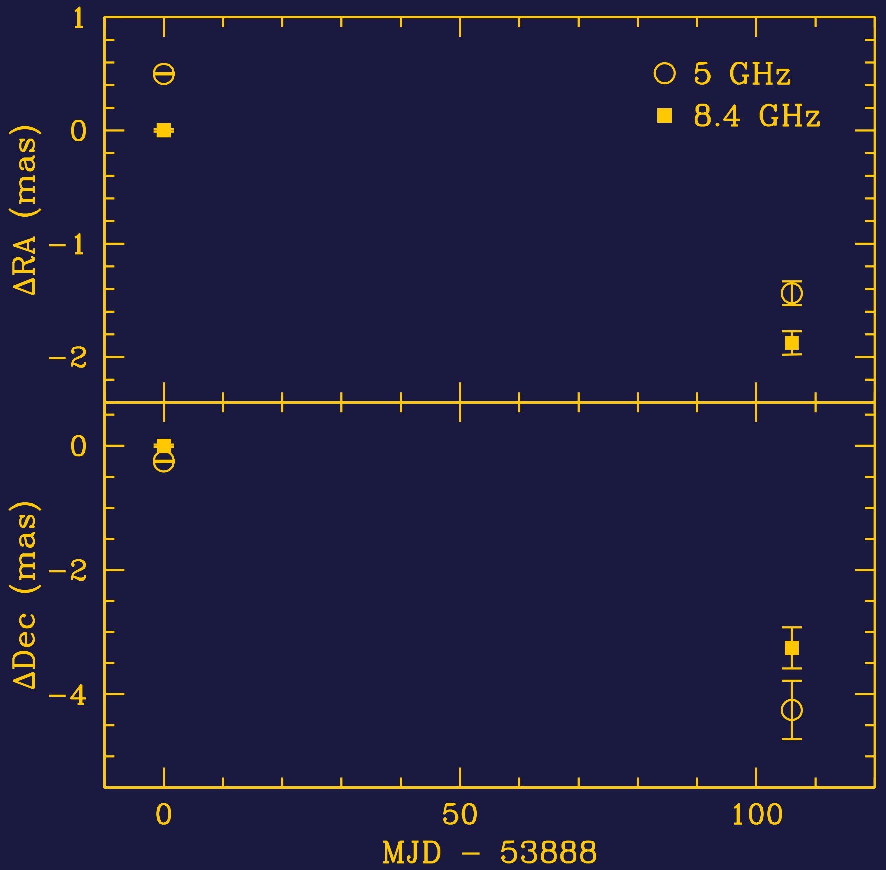

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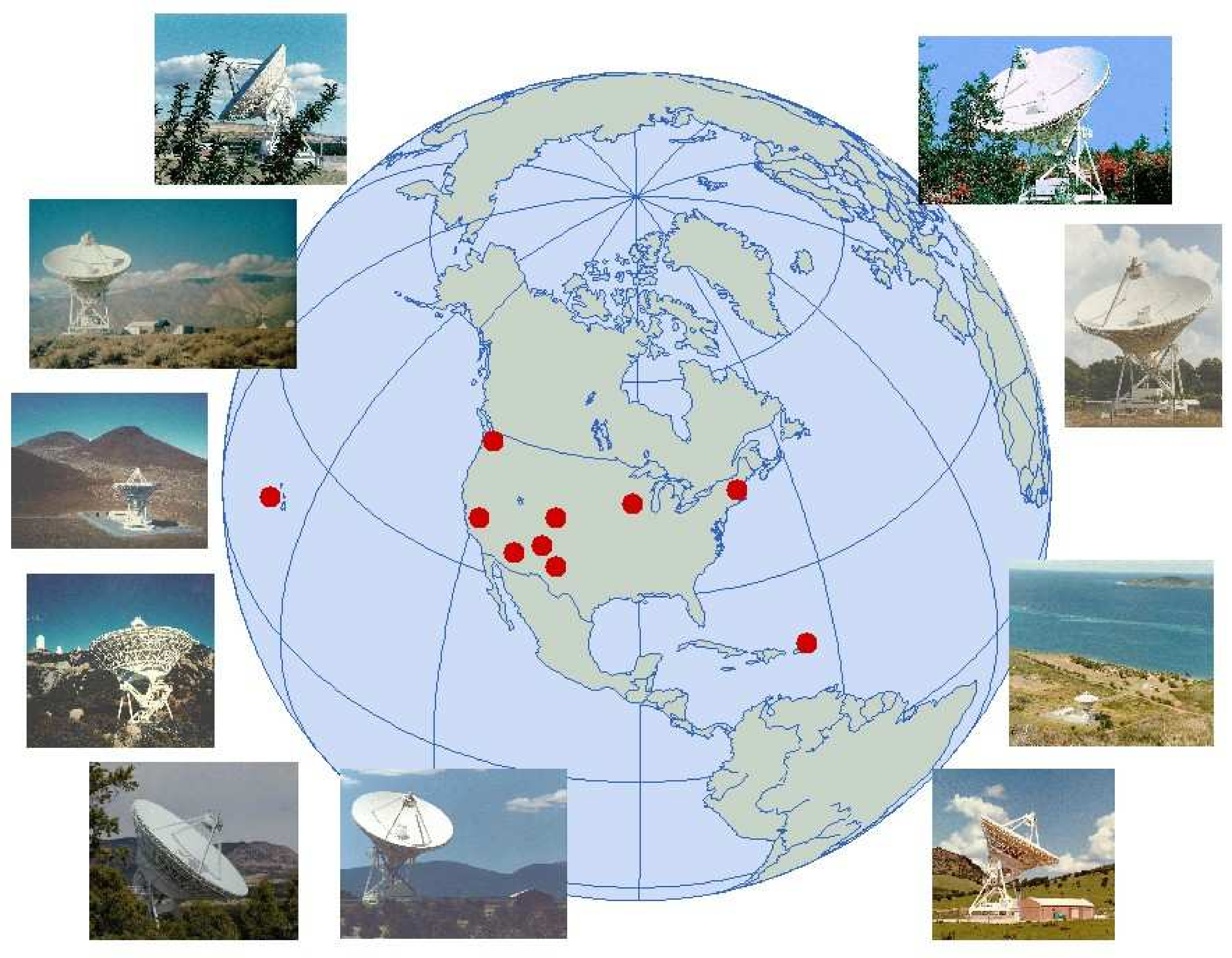
$\Rightarrow$ For this one magnetar V$_\perp$, no exotic kicks are required.

How do we do it?



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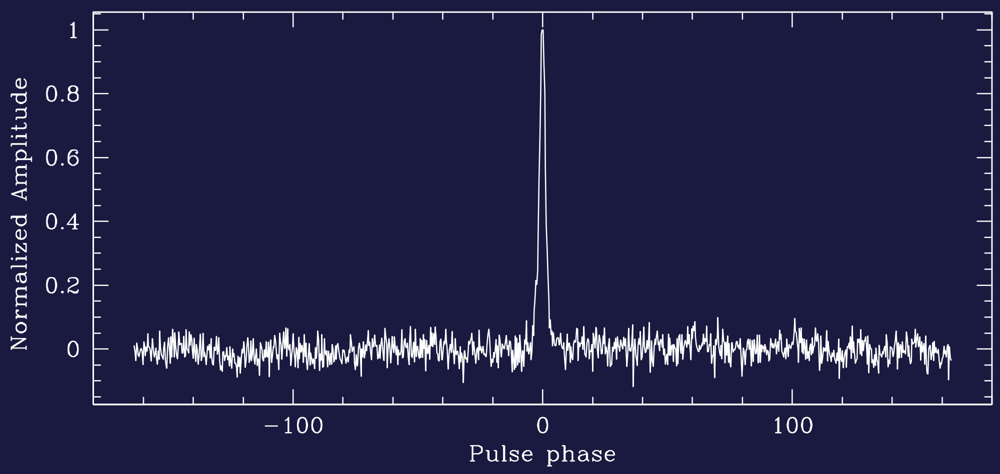

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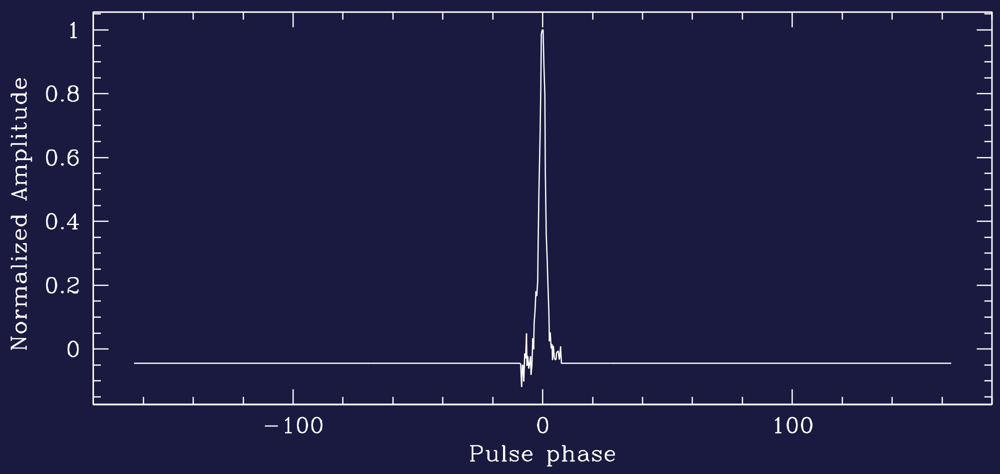

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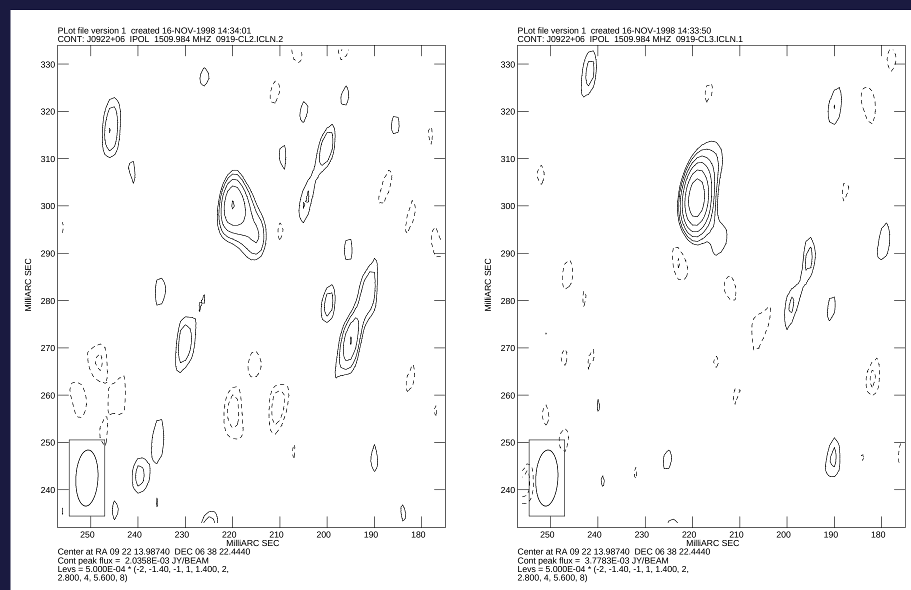

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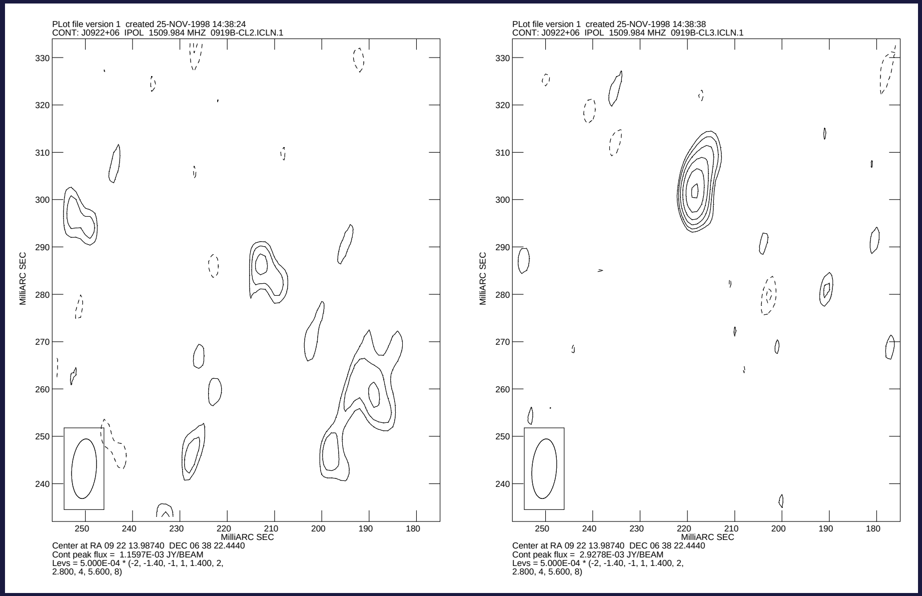

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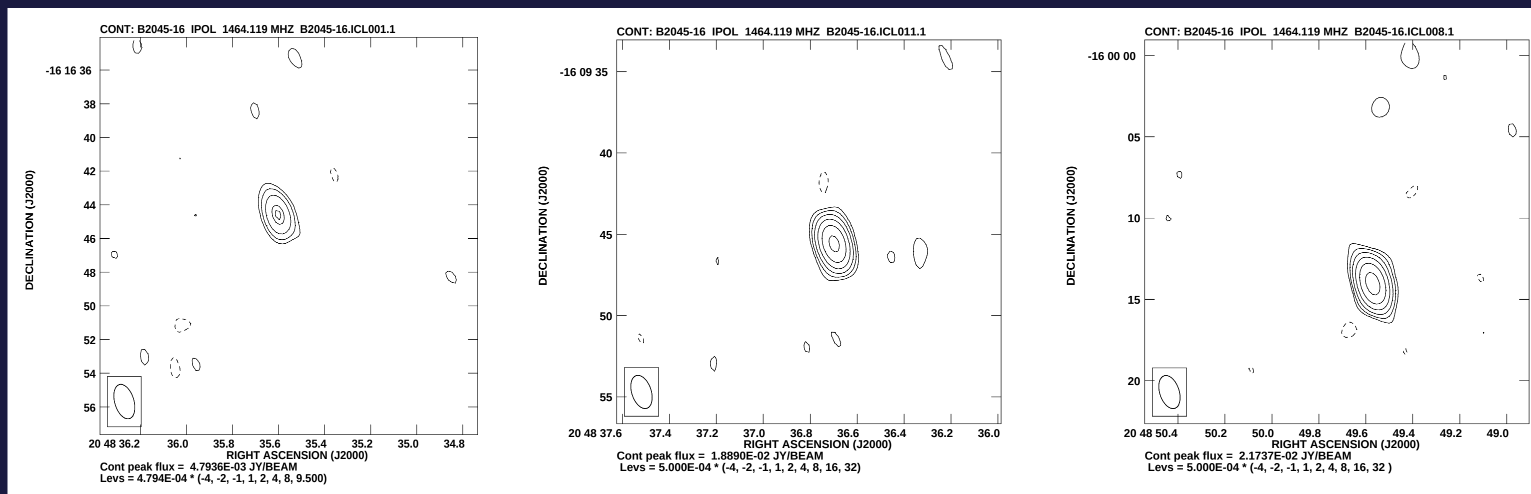
A systematic approach to In-beam Calibration

- Image the VLA 1.4 GHz primary beam (25′);
  Identify compact sources.



63 target fields = 1060 sources detected (∼16 / field).

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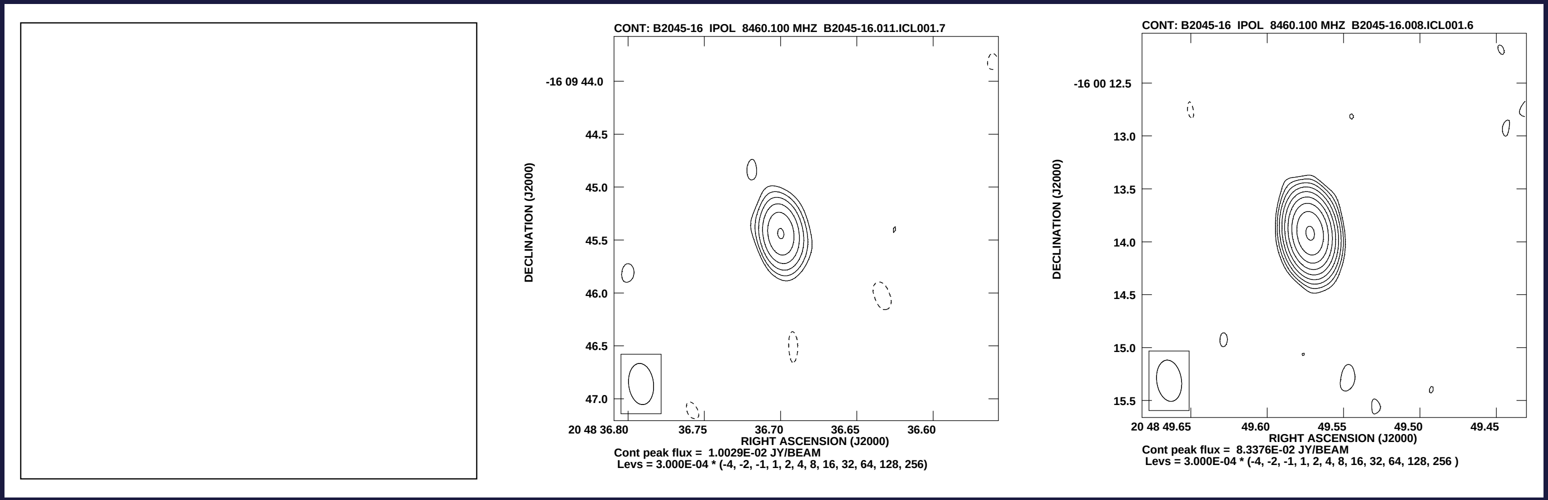

269 apparently compact sources imaged ($\sim$4 / field).

A systematic approach to In-beam Calibration

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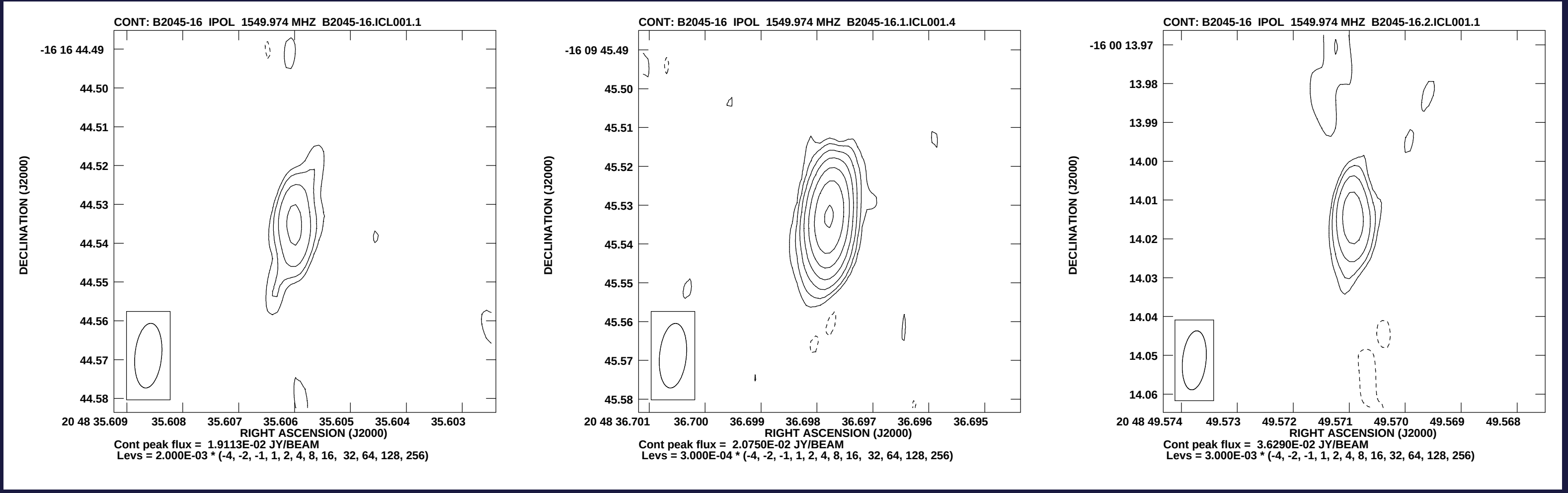
- Verify compactness at higher frequencies with VLA.
- Image with the VLBA.



55 out 63 targets had 1 or more in-beam calibrator.

A systematic approach to In-beam Calibration

- Image the VLA 1.4 GHz primary beam (25′);
  Identify compact sources.
- Verify compactness at higher frequencies with VLA.
- Image with the VLBA.

- Observe over 2 years:

$\longrightarrow$ 8 epochs: $\{\pi_{\max},\ \pi_{\min}\}$.
$\longrightarrow$ 4 frequency bands, dual polarization, 256 Mb/s.

$\Rightarrow$ High quality astrometry.

A systematic approach to Systematic Errors

- Bootstrap: infer uncertainties from the data itself.

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$\rightarrow$ Choose values *with replacement*.

$\Rightarrow 32^{32}$ combinations possible (but some are degenerate).

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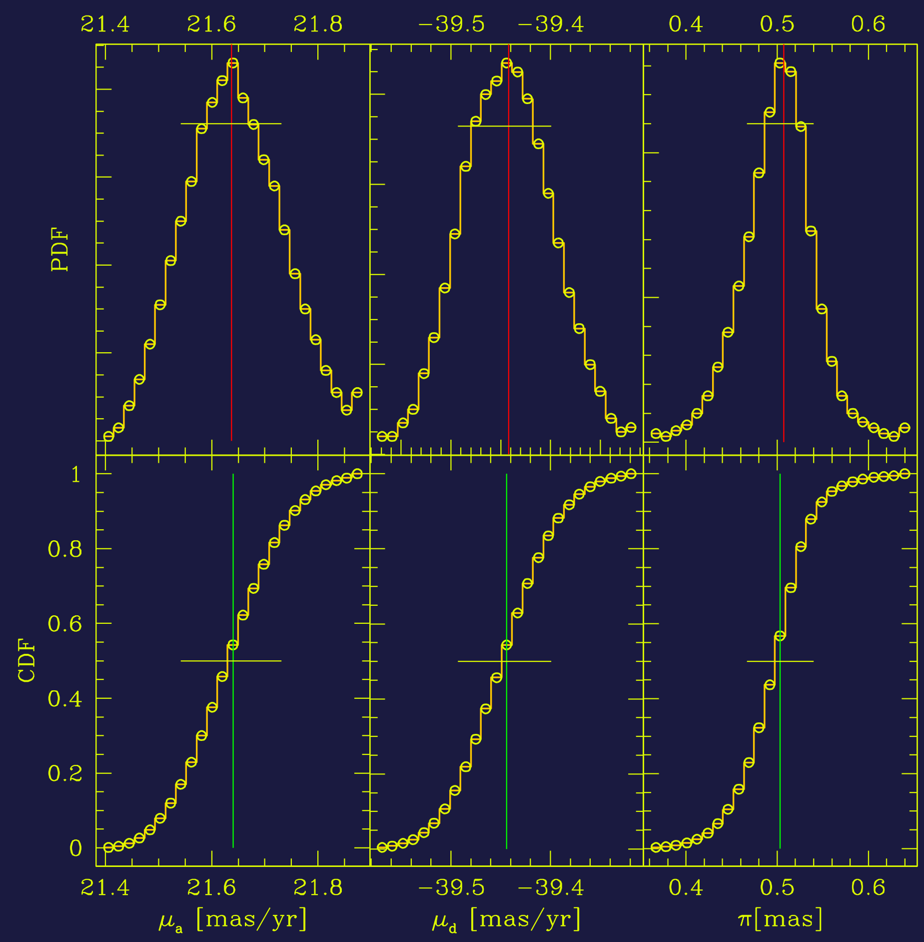
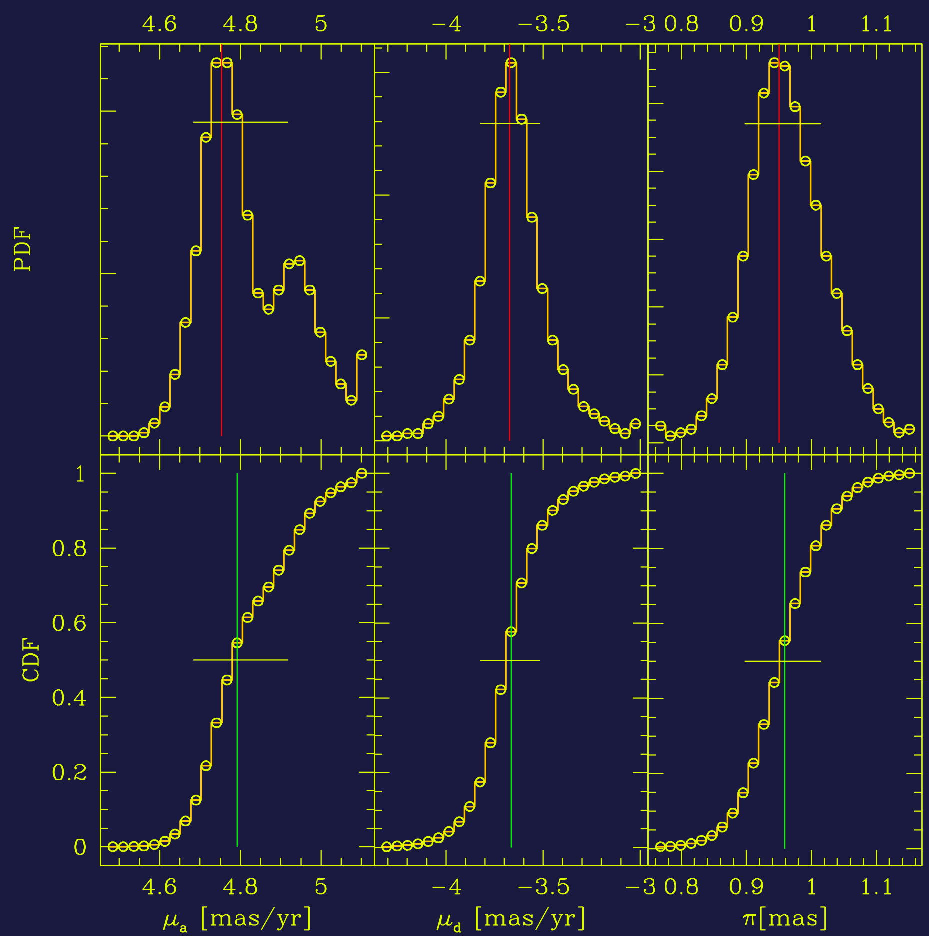
$\rightarrow$ Explore $\sim 10,000$ fits...

A systematic approach to Systematic Errors



Normal case: Bootstrap results for B0818−03

A systematic approach to Systematic Errors



Worst case: Bootstrap results for J1713+0747

Southern hemisphere

- Long Baseline Array
  (Parkes, ATCA, Mopra, Tidbinbilla; +Hobart? +Ceduna?)

$\Rightarrow$ Shorter baselines, poorer UV coverage, tougher calibration.

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→ Note ASKAP under construction in Western Australia.

Southern hemisphere

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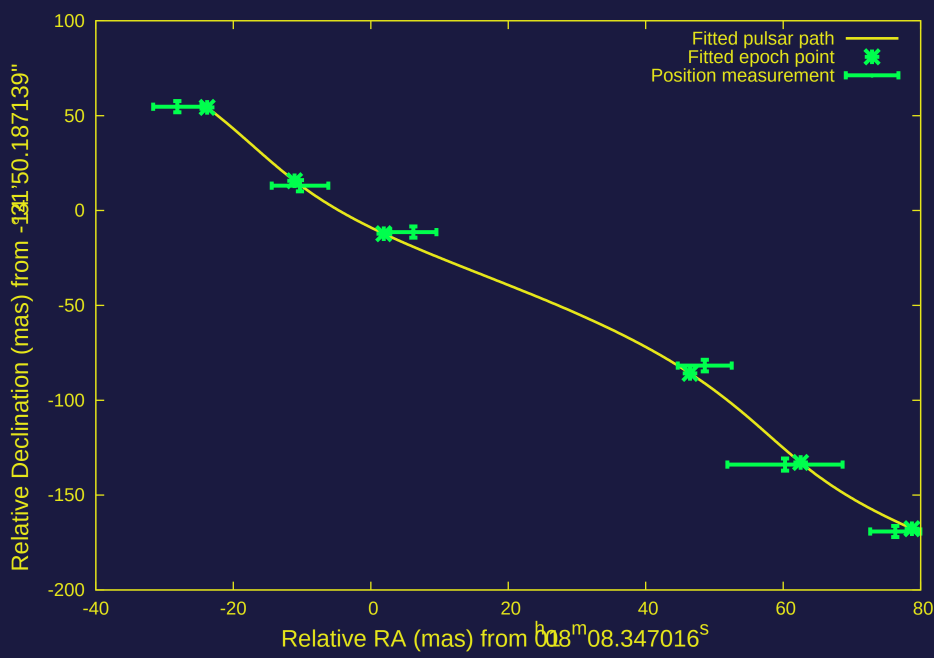
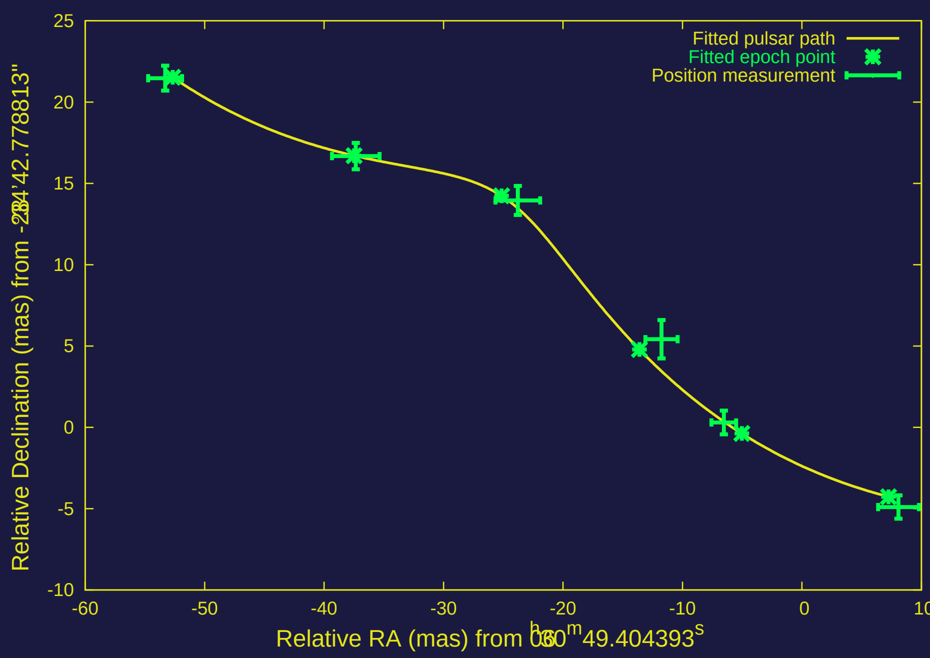
- Fantastic parallax measurements by Deller et al. (2008, 2009).



PSR J0108−1431



PSR J0630−2834

Where do we stand?
And what next?

Both quantity and quality

- Individual measurements can be extremely valuable.
  $\rightarrow$ e.g., Astrometry on binary pulsars $\Rightarrow$ GR.
  $\rightarrow$ e.g., Case studies outlined in this talk.

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- A large ensemble of measurements enables deeper insights.
  $\longrightarrow$ e.g., Velocities $\Rightarrow$ supernova core collapse.
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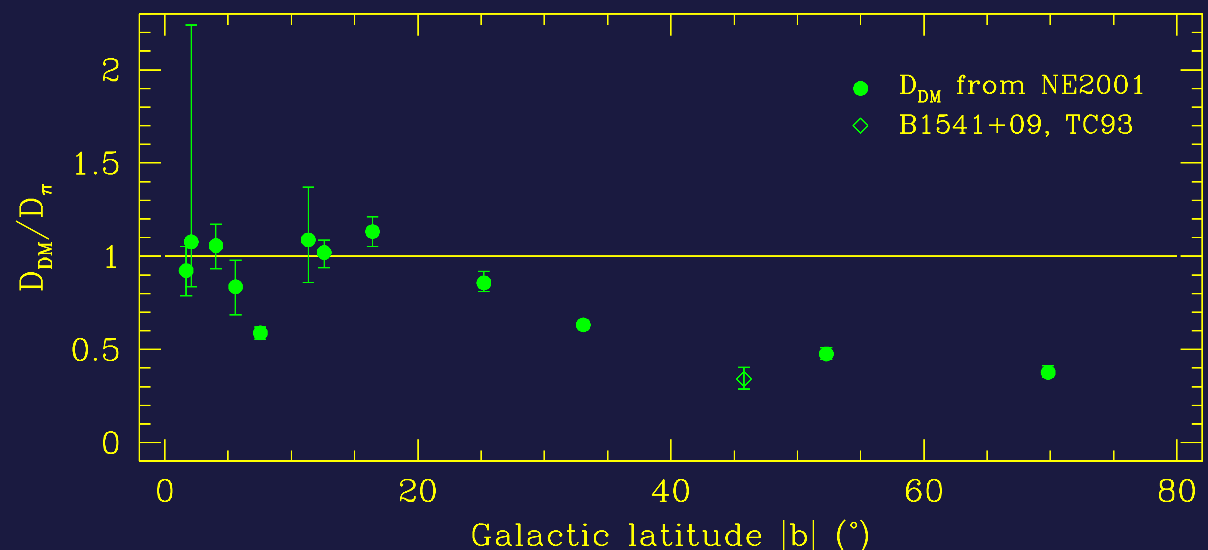

Large samples test models, enable refinements (Chatterjee et al. 2009)

High Sensitivity VLBI

- Larger samples require higher sensitivities, better techniques.
  $\longrightarrow$ VLBA bandwidth expansion.
  $\longrightarrow$ High sensitivity arrays.

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... but larger telescopes
$\Rightarrow$ smaller FoV;
$\Rightarrow$ harder calibration;
$\Rightarrow$ trickier phase referencing.

Technical Progress

- GPS Ionospheric calibration: capabilities improving.

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- Focal plane arrays:
  eliminate need to slew for phase referencing?

Parkes testbed FPA; CSIRO July 2008

Final Thoughts and Future Directions

- Precision astrometry enables unique science.

$\longrightarrow$ The origins, evolution, astrophysics, environments of NS.

$\longrightarrow$ e.g., Constraints on supernova core collapse, NS kicks.

Final Thoughts and Future Directions

- Precision astrometry enables unique science.

$\longrightarrow$ The origins, evolution, astrophysics, environments of NS.

- The importance of a consistent, systematic approach.

$\longrightarrow$ Control of systematic errors essential.
$\longrightarrow$ Larger field of view $\Rightarrow$ more inbeam sources.
$\longrightarrow$ More sensitivity $\Rightarrow$ higher ν_{obs} as well.

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- Precision astrometry enables unique science.

$\longrightarrow$ The origins, evolution, astrophysics, environments of NS.

- The importance of a consistent, systematic approach.

- Future instruments, technology, techniques:

$\longrightarrow$ Ionospheric calibration: GPS.

$\longrightarrow$ Focal plane arrays: vastly larger FOVs.

$\longrightarrow$ SKA: mas resolution required for the μJy sky

$\Rightarrow$ High precision radio astrometry.

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A long but incomplete list:

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Stephen Thorsett (UCSC), Don Backer (UC Berkeley),
Ed Fomalont, John Benson, Mark McKinnon (NRAO),
David Kaplan (UCSB), David Helfand, Fernando Camilo (Columbia),
and many others ...

Pulsar Astrometry: http://www.astro.cornell.edu/~shami/psrvlb/