Neutron Stars, Radio Transients, and Precision Astrometry

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Cornell University

19 May 2011

Discovery, Precision Measurements, and Theoretical Progress

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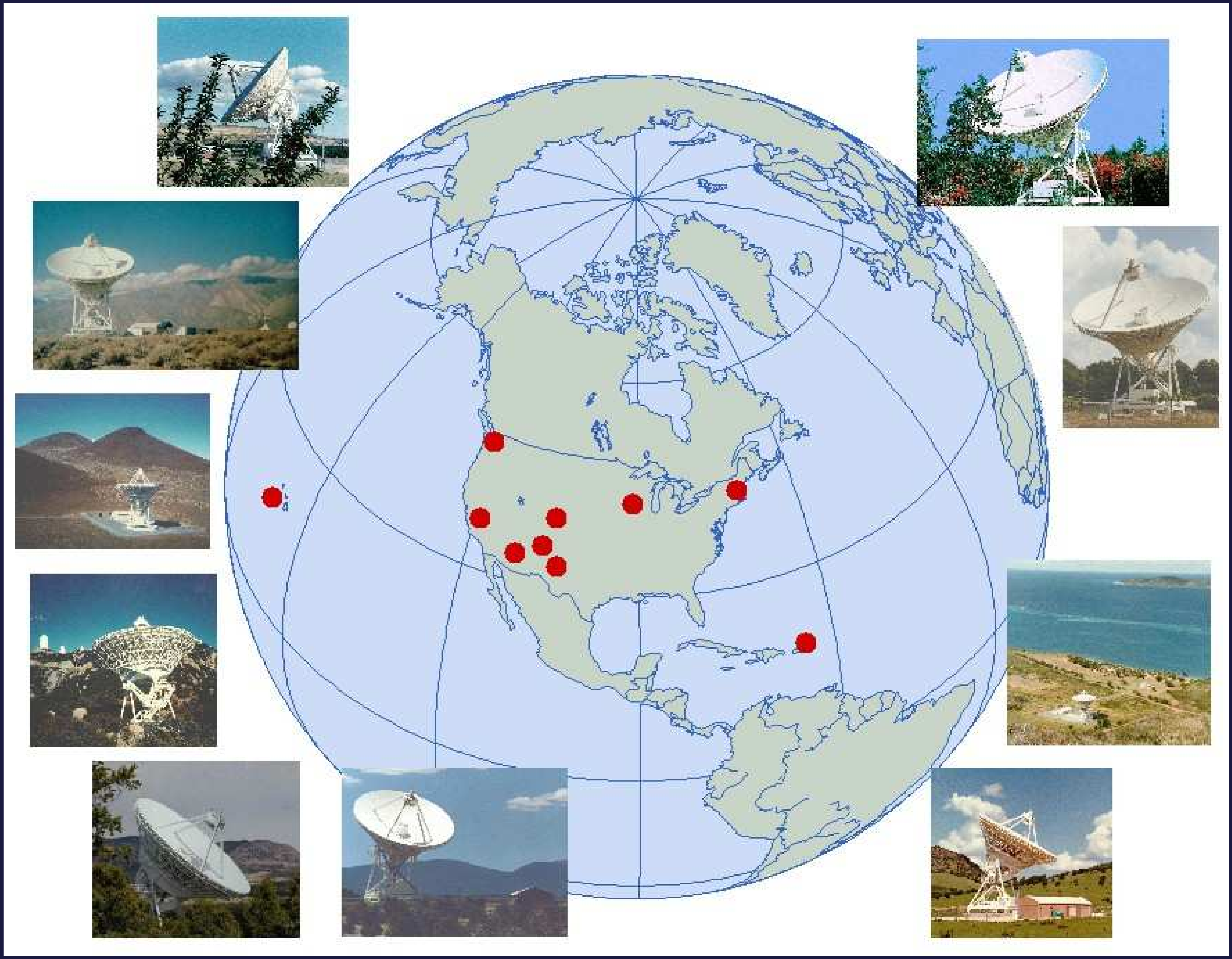
In this talk:

- Precision astrometry of neutron stars:
  $\longrightarrow$ Supernova core collapse.
  $\longrightarrow$ Gamma ray emission energetics.
- Radio transients:
  $\longrightarrow$ VAST, an ASKAP Survey Science program.

Measuring Pulsar Proper Motions and Parallaxes



Case study: PSR B1508+55

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 ($b = 52.3^\circ$).

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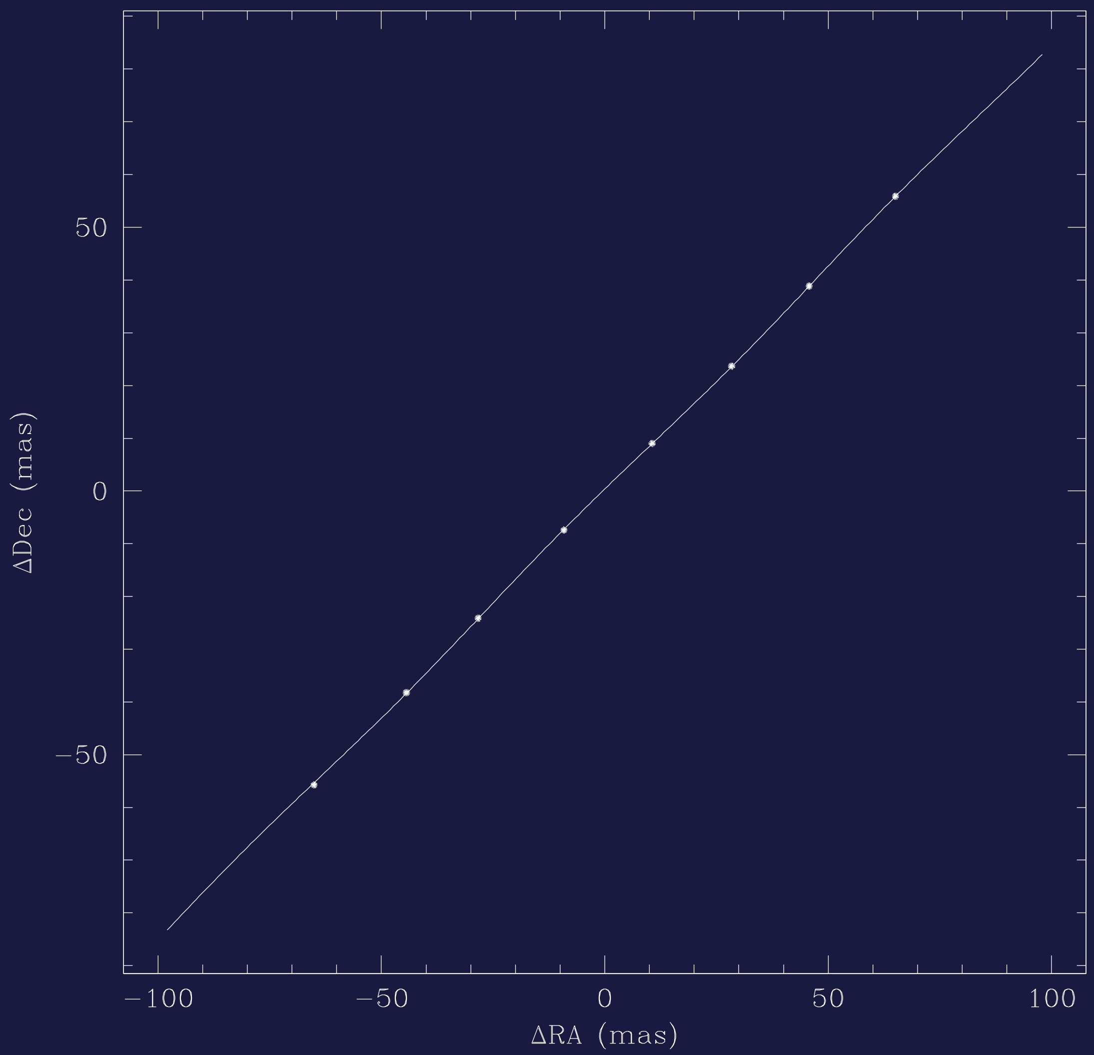
Observe 8 times over 2 years with the VLBA...

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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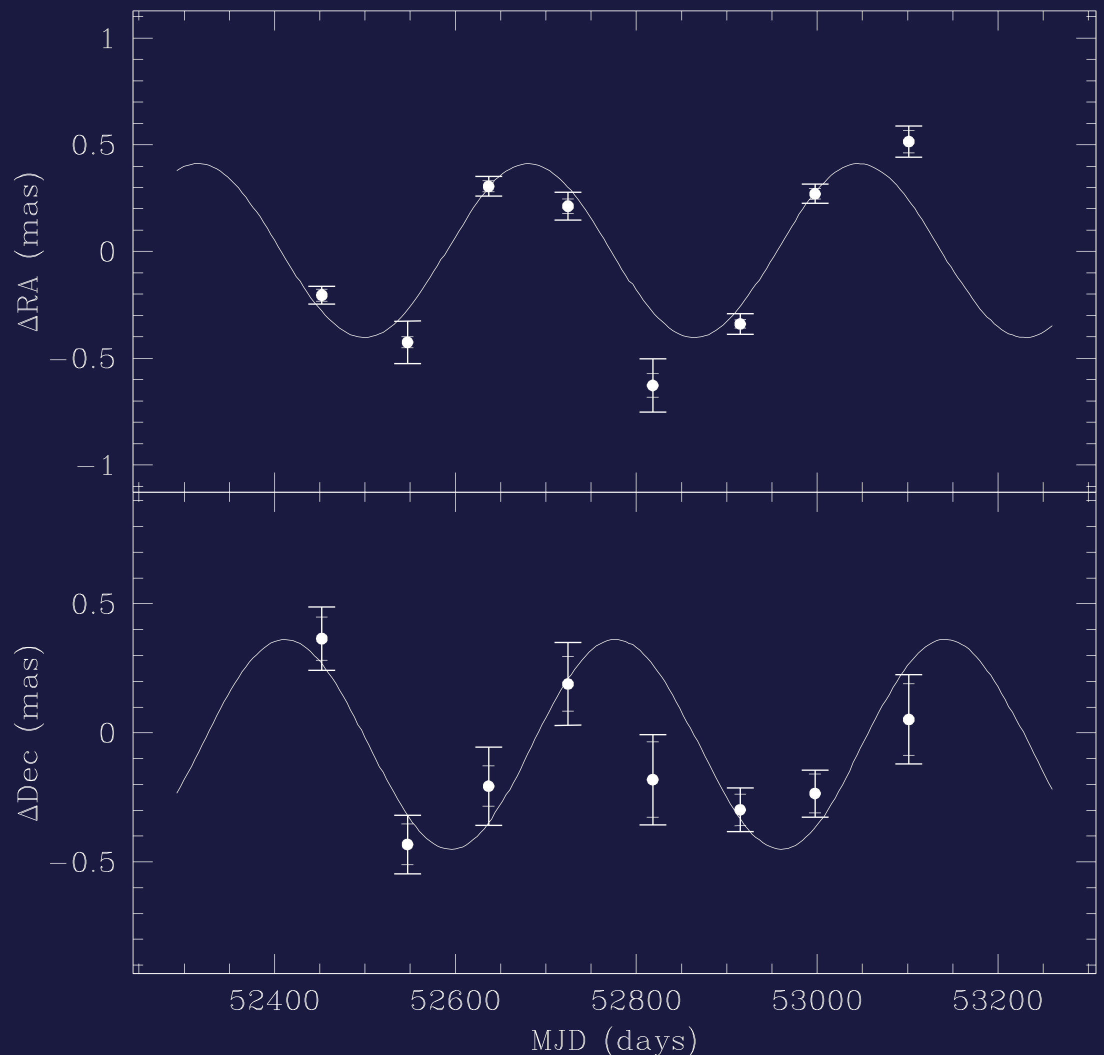

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$V_\perp$ = 1083^{+103}_{-90} km s^{-1}

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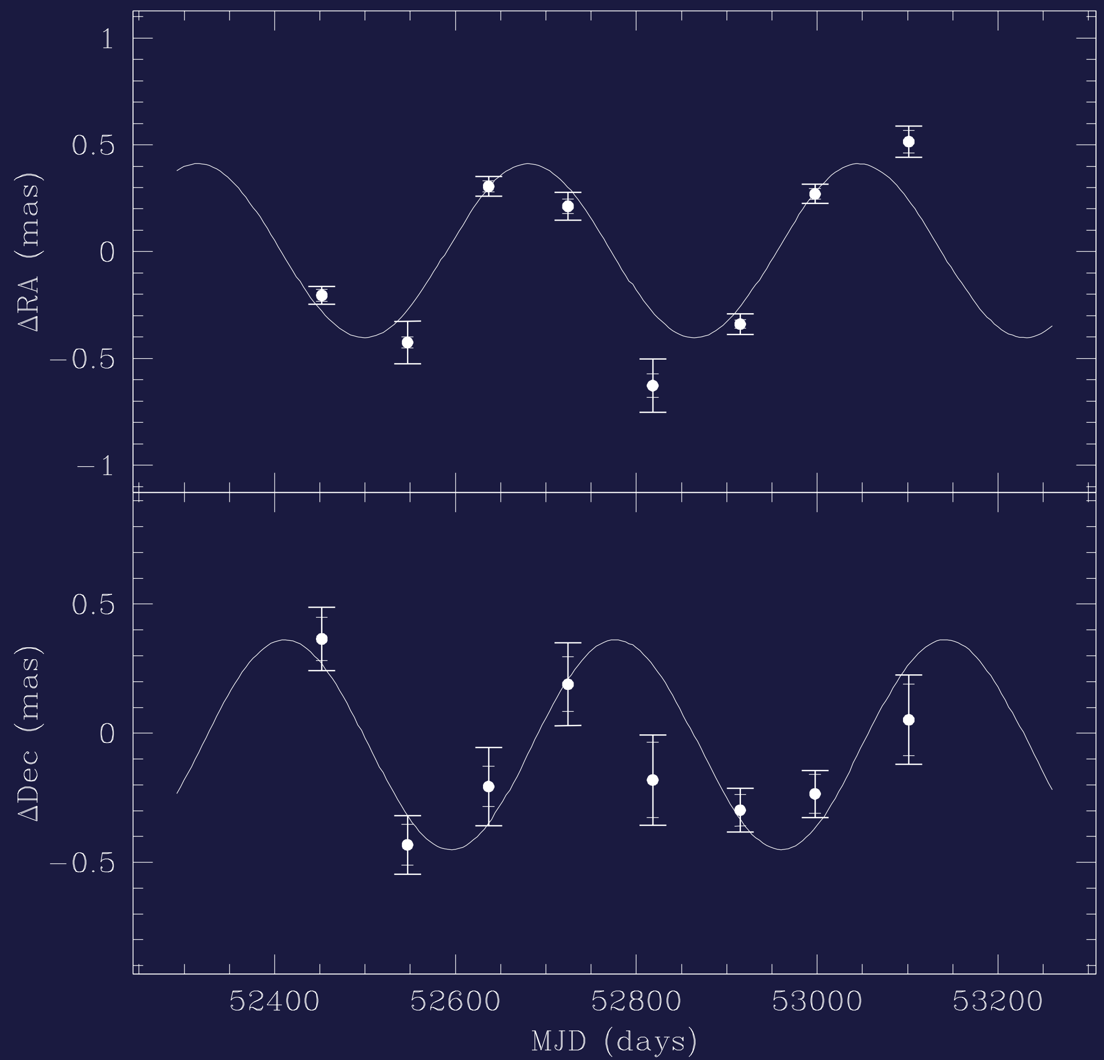

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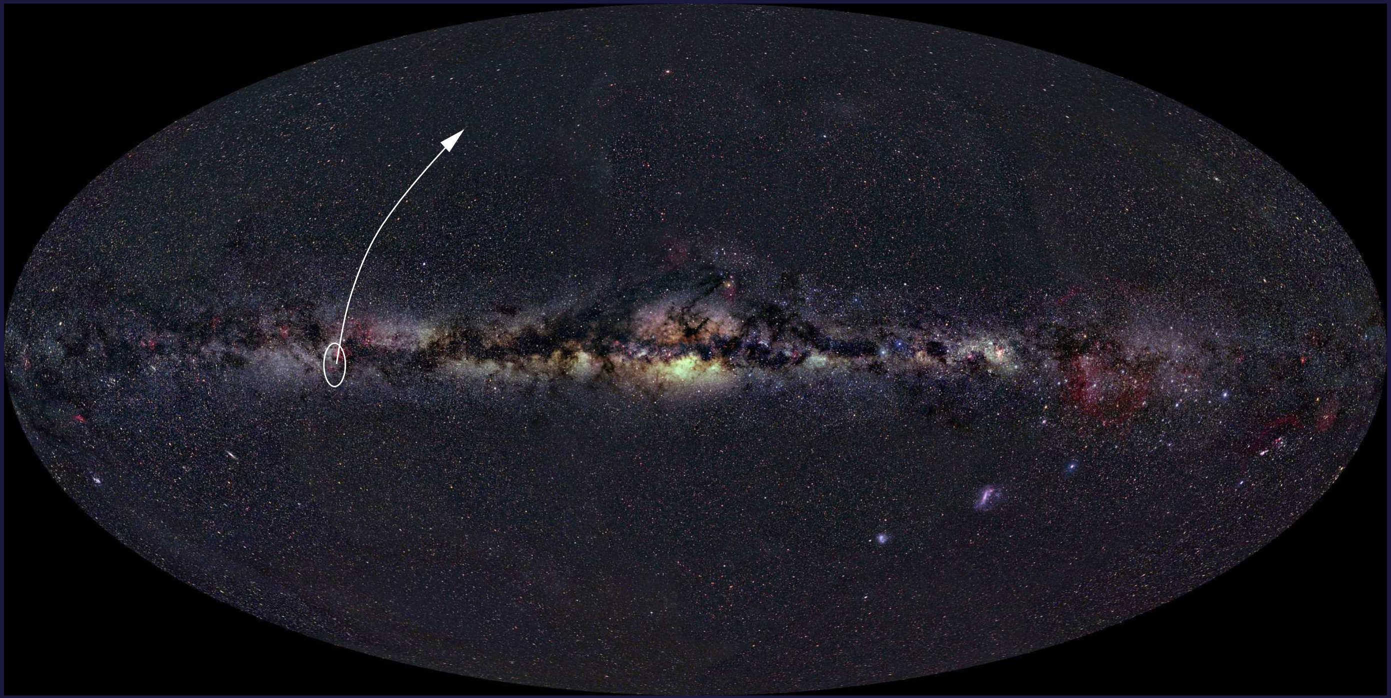
The highest measured model-independent velocity yet!

The Birth Site of B1508+55

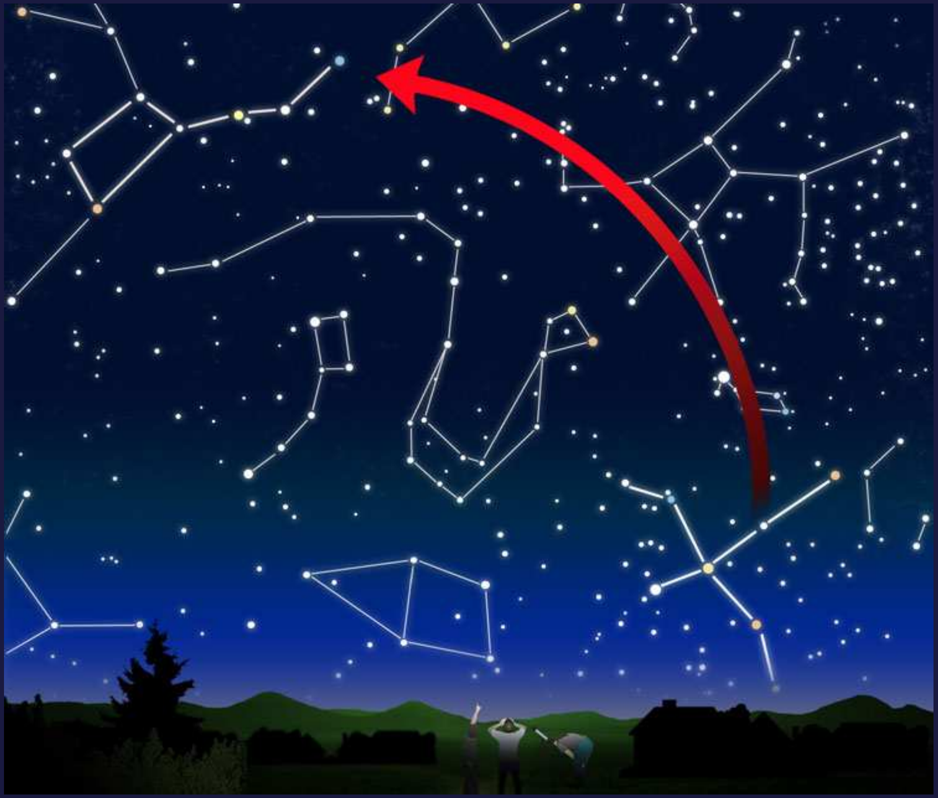


Orbit of B1508+55 overlaid on Axel Mellinger's image of the Galaxy.

- 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

- B1508+55: implied birth velocity ≈ 1100 km s^{-1}.
- Binary disruption is unlikely to impart such a high velocity; a kick is required.



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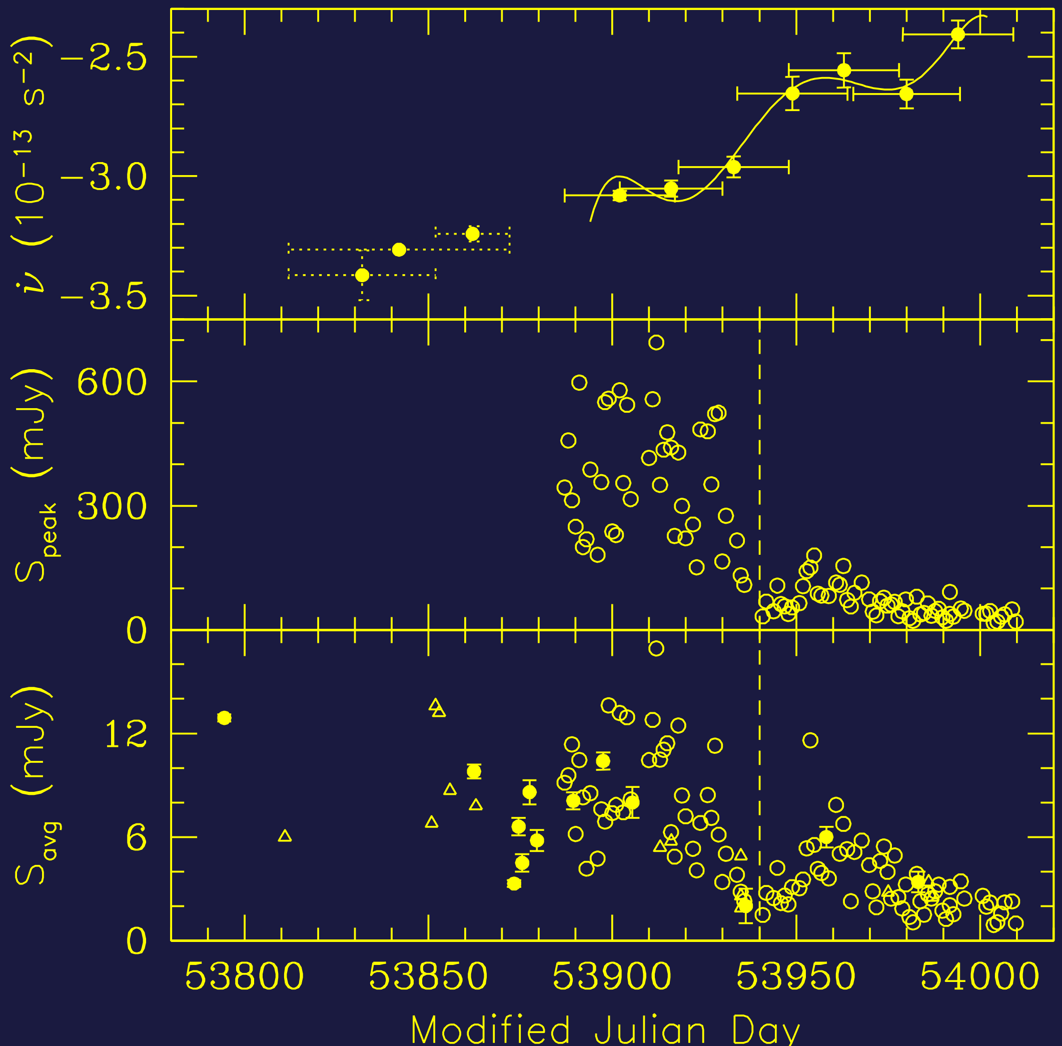
$\rightarrow$ We can also do this for other compact radio sources, of course...

Magnetar XTE J1810–197

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



(from Camilo et al. 2006)

Magnetar XTE J1810–197

- Camilo et al. (2006): Transient pulsed radio emission!
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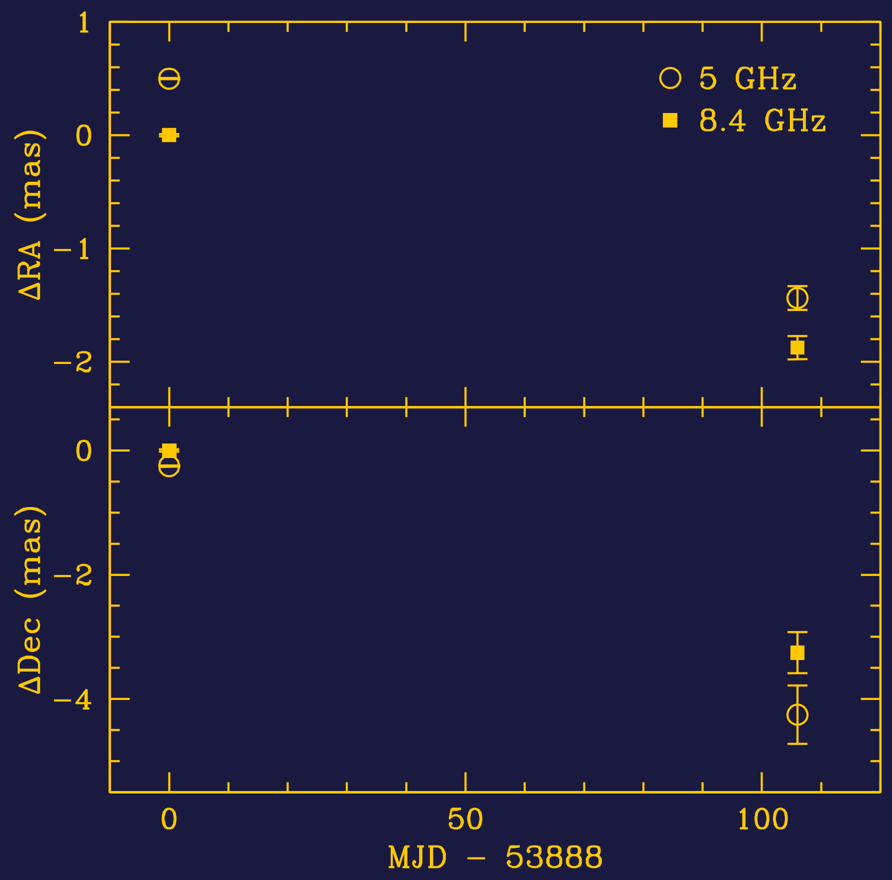
- But bright enough for VLBA obs at 5, 8.4 GHz over 106 days.

A Magnetar Proper Motion



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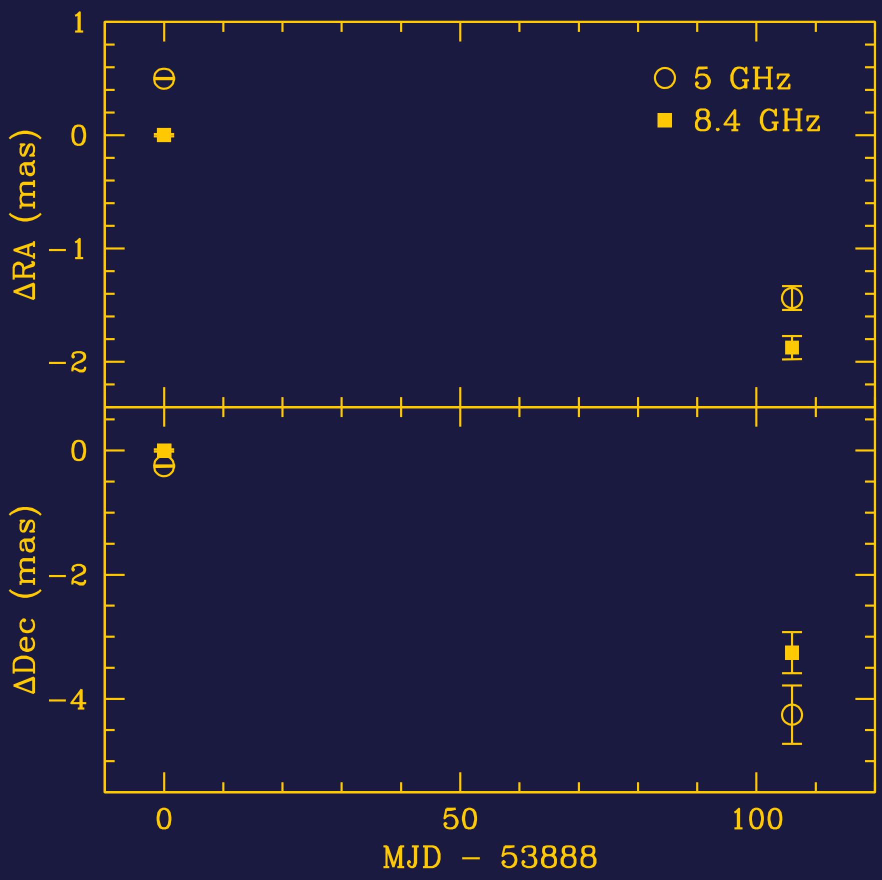

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For $D = 3.5 \pm 0.5$ kpc,

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(Helfand, Chatterjee, et al. 2007)

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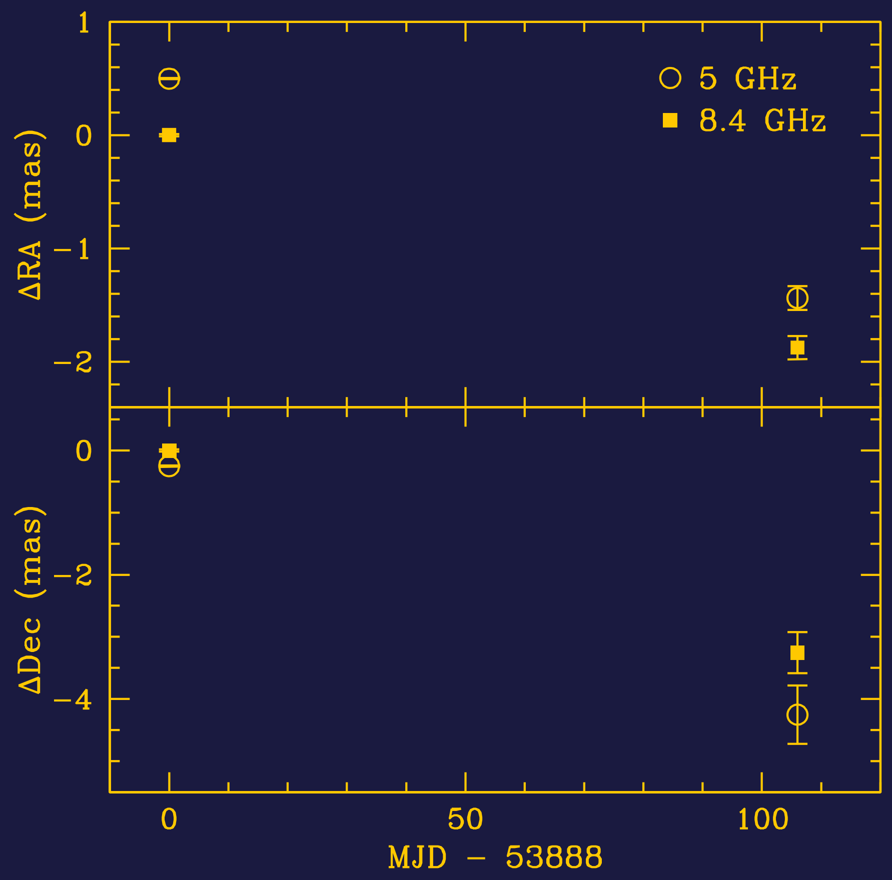

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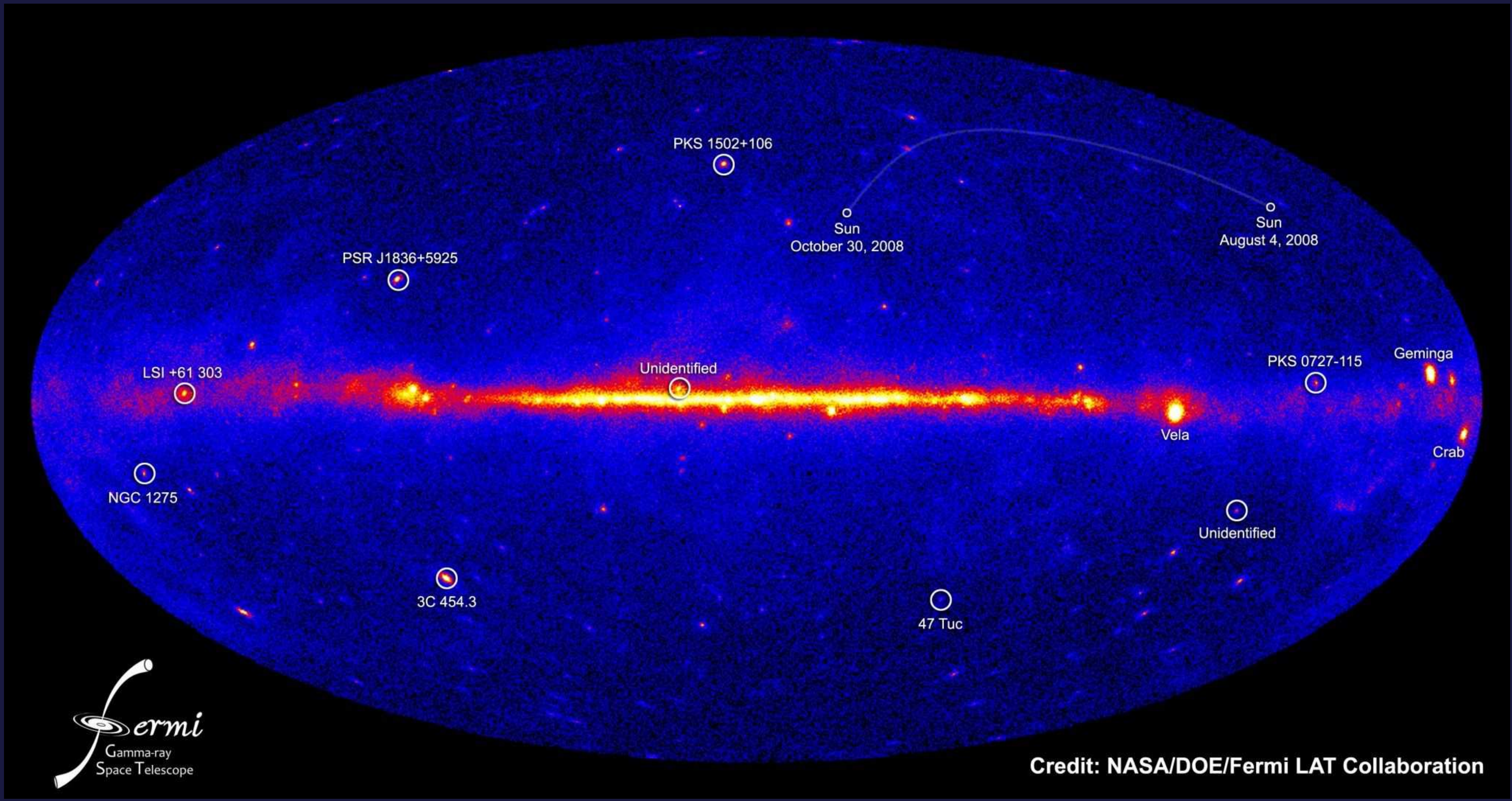
$\Rightarrow$ For this one magnetar $V_\perp$, no exotic kicks are required.

The *Fermi* gamma-ray space telescope

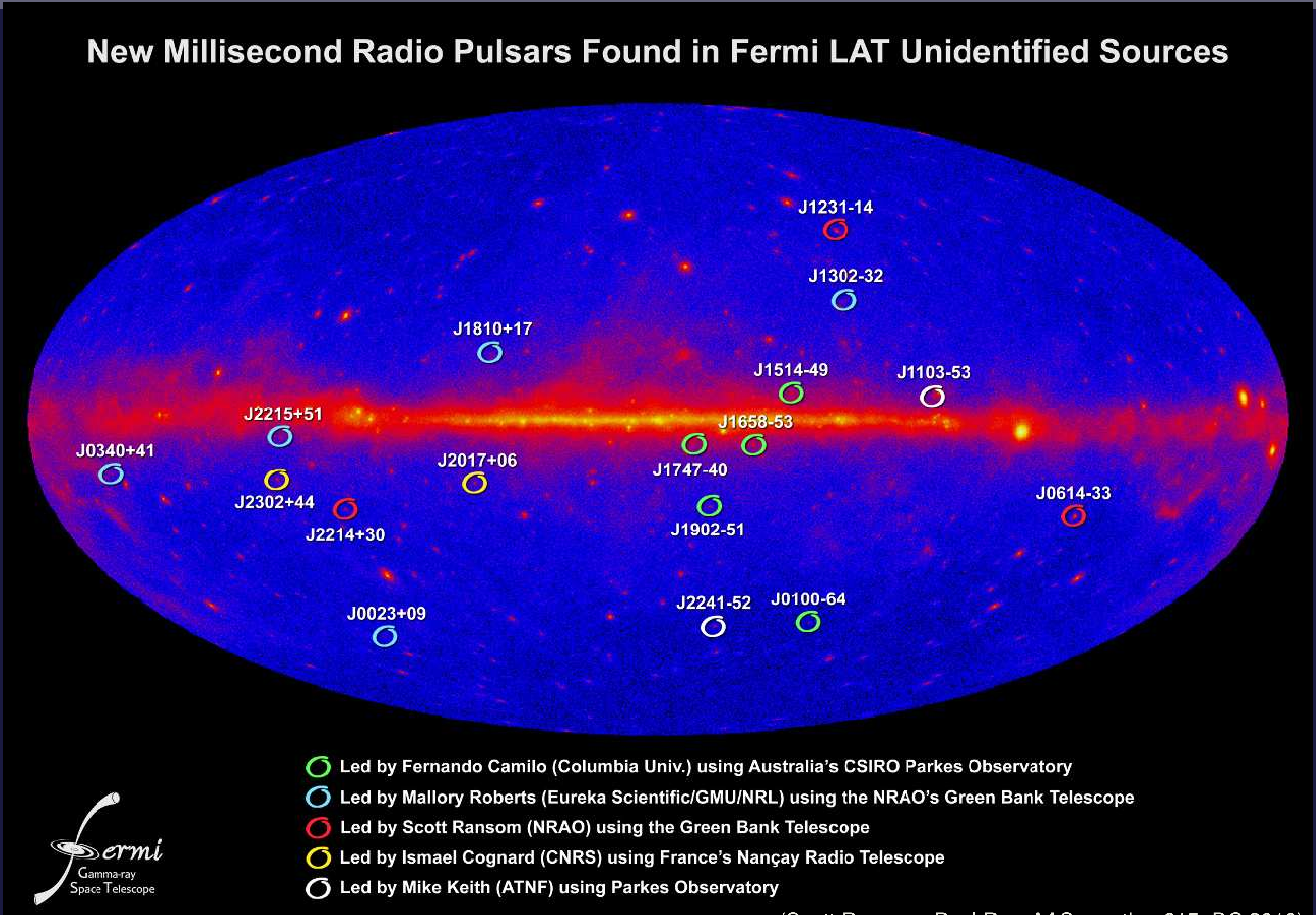
- LAT: Imaging high-energy gamma-ray telescope.
- 20 MeV—300 GeV; FoV covers 20% of the sky.
- Continous scanning: whole sky imaged every 3 hours.

Fermi 3-month all-sky image



Note: Crab, Vela, Geminga, J1836+5925, and "Unidentified"...

A neutron star discovery machine!



(Scott Ransom, Paul Ray, AAS meeting 215, DC 2010)

Pulsar science with *Fermi*

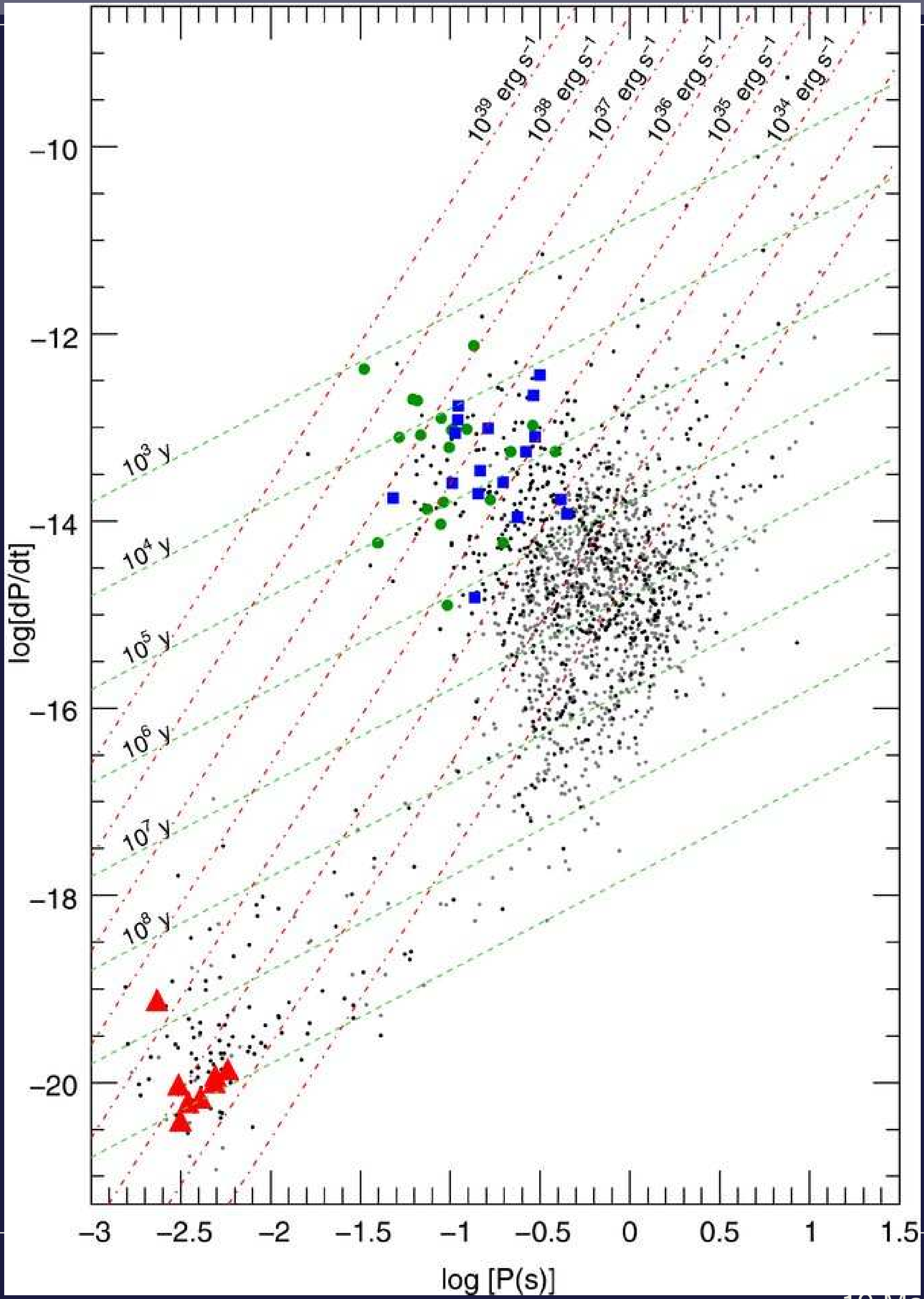
First *Fermi* PSR catalog: 46 gamma-ray pulsars!

→ 16 new pulsars from γ-ray blind searches.

→ Many more from radio follow-up of unidentified point sources.

→ More discoveries on a regular basis.

→ Young + recycled.



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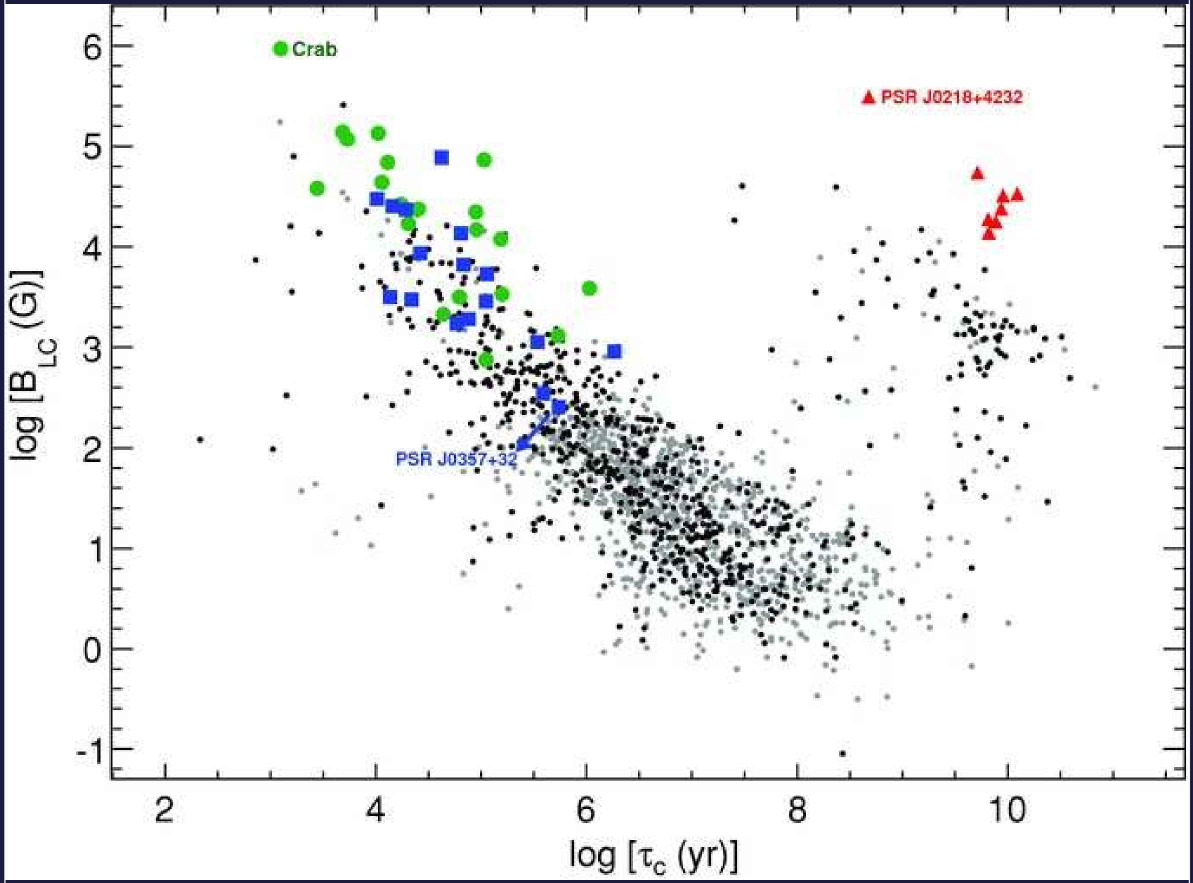
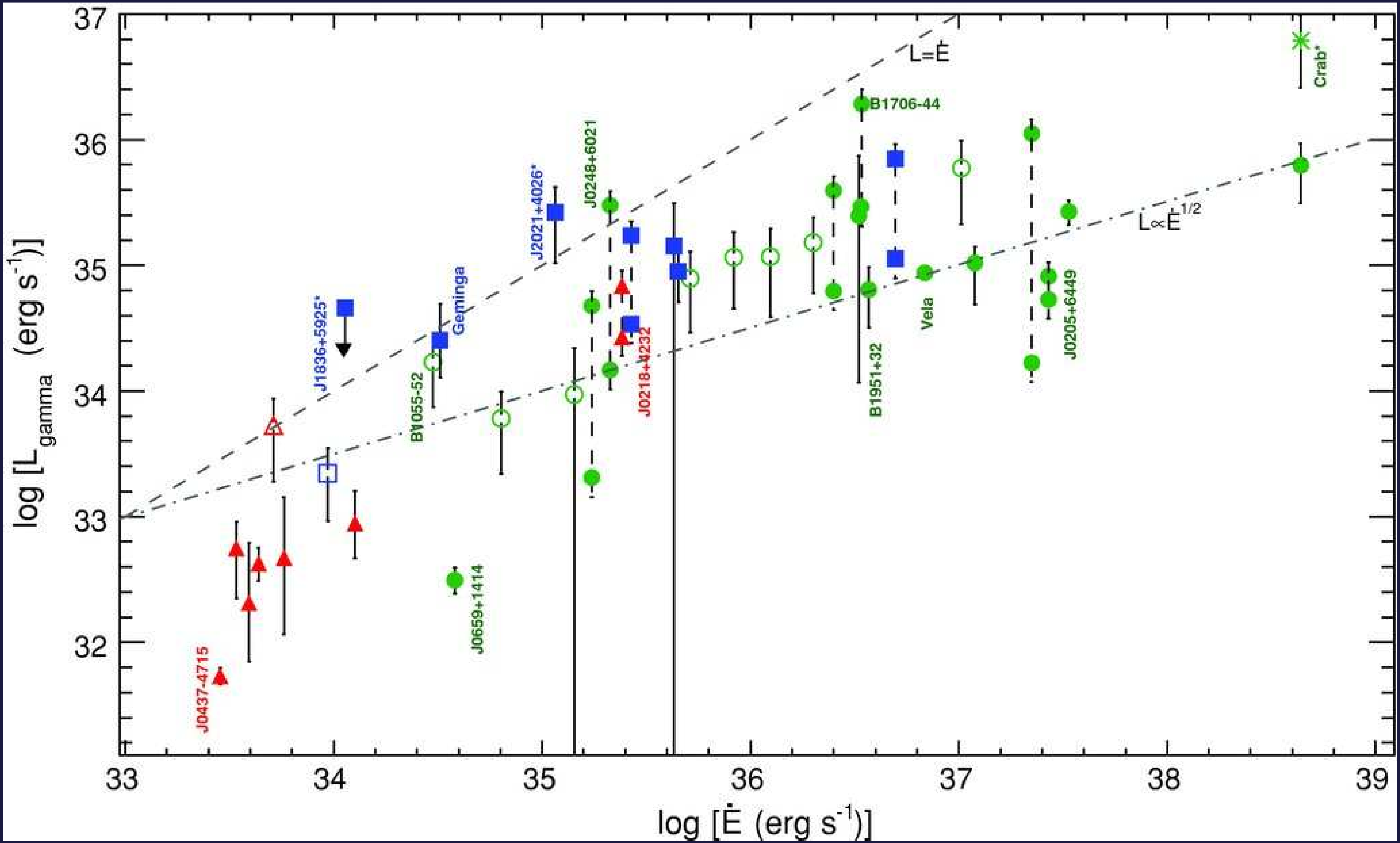


- High B$_{LC}$ $\Leftrightarrow$ γ-ray emission?
- Interesting physics to be sorted out.

Gamma ray luminosity vs Spindown $\dot{E}$



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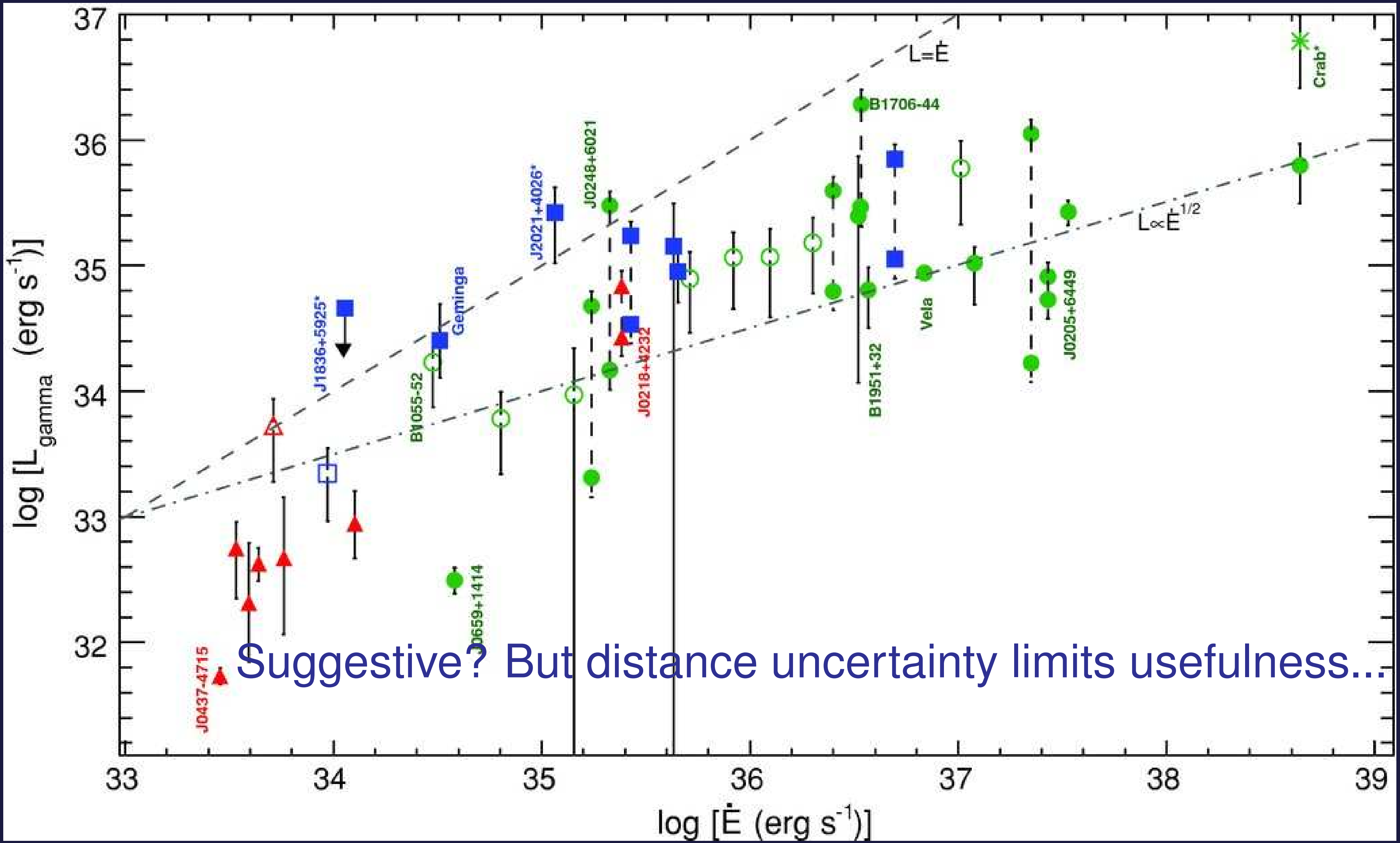
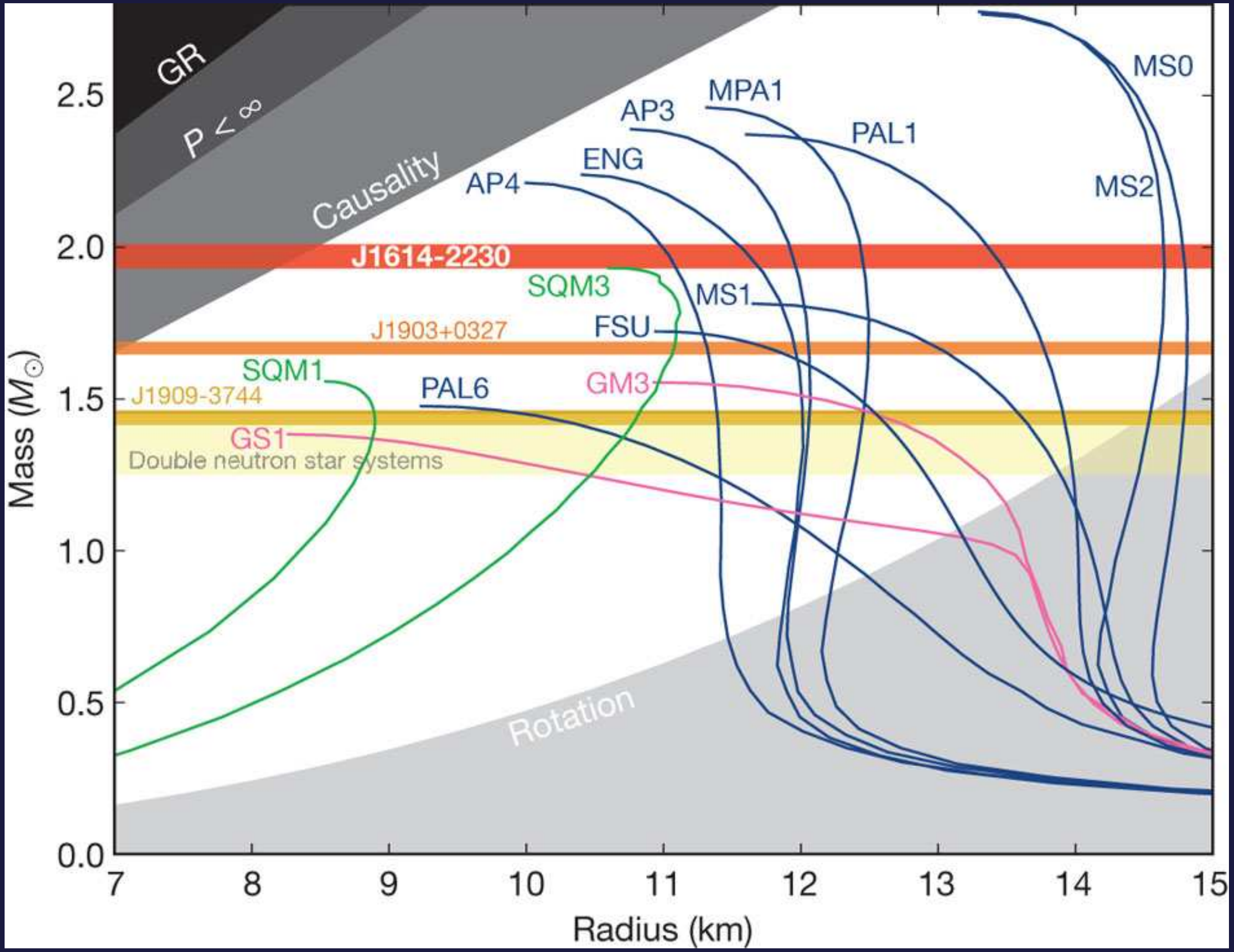


Case study: PSR J1614–2230

- Mass from Shapiro delay = 1.97(4) $M_\odot$ (Demorest et al. 2010).



⇒ Rules out most exotic quark matter equations of state.

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... Happenstance? Coincidence?

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$\Rightarrow$ A precise distance may constrain the NS moment of inertia.

Neutron Stars and Astrometry

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- Astrophysics: NS kicks constrain models of suernova core collapse – hydrodynamic, magnetic field-driven, or hybrids.
- Astrophysics: Compare apparent L_γ with absolute $\dot{E} = I\omega\dot{\omega}$. $\rightarrow$ Emission geometry, luminosity evolution.

Neutron Stars and Astrometry

Astrometry is a force multiplier: precise astrometry improves the science return from new discoveries.

- Origins: Use μ and τ to trace path back to birth sites and associations with massive star clusters, SNRs.
- Relativistic winds: Calibrate energetics of PWNe, probe interaction with ISM and bulk flows.

Neutron Stars and Astrometry

Astrometry is a force multiplier: precise astrometry improves the science return from new discoveries.

• Gravitational physics: Astrometric parameters for stable recycled pulsars independent of pulse timing.
$\longrightarrow$ Shklovskii effect corrections, break timing degeneracies.

• Galactic electron density modeling: improve DM-based distance estimates for entire population.

Neutron Stars and Astrometry

Astrometry is a force multiplier: precise astrometry improves the science return from new discoveries.

- Astrophysics: SN core collapse, L_γ vs. $\dot{E}$.
- Origins: Birth sites, associations.
- Relativistic winds and the ISM.
- Gravitational physics.
- Galactic modeling: N_e distribution.

VLBA observations in progress

Two parallel efforts in progress:

- Targeted astrometry on a subset of *Fermi*-detected radio pulsars: 18 targets, 12 being observed (epochs 1–3).

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VLBA astrometry collaboration:
Adam Deller, Walter Brisken, Miller Goss,
Jim Cordes, Joseph Lazio, Wouter Vlemmings, et al.

Goal: A distance measuring service

Is <u>YOUR</u> Neutron Star:

★ A radio emitter?

★ Brighter than ~1 mJy?

★ Closer than ~8 kpc?

★ North of -25 in Dec?

**Measure a parallax*
with the VLBA!**

*Certain conditions, exclusions, and limitations apply. Please talk to the presenter or consult your friendly local expert about why the VLBA may be right for YOU!

VAST and the Dynamic Radio Sky

- The dynamic radio sky is a discovery frontier.

  Why? Trade-off between sky coverage and sensitivity.
  (There are no all-sky monitors at $\sim$GHz frequencies.)

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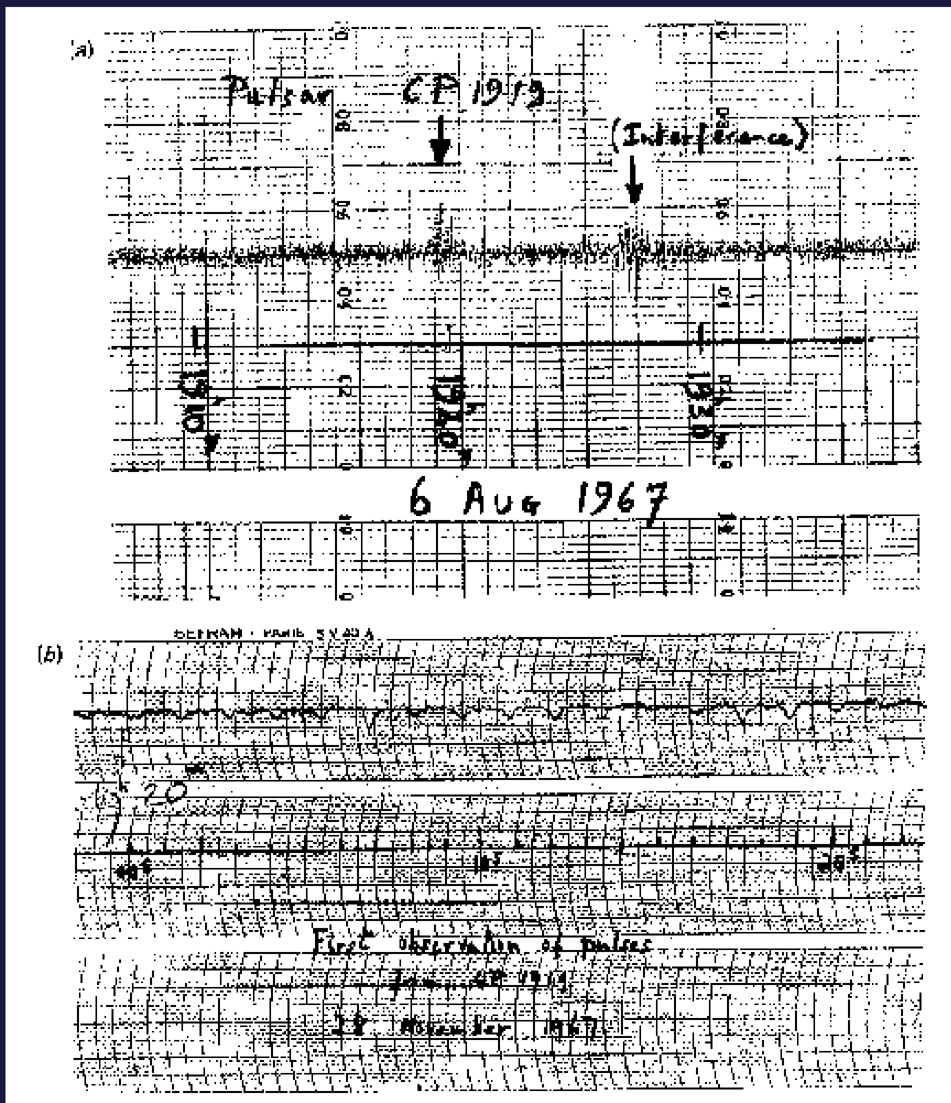
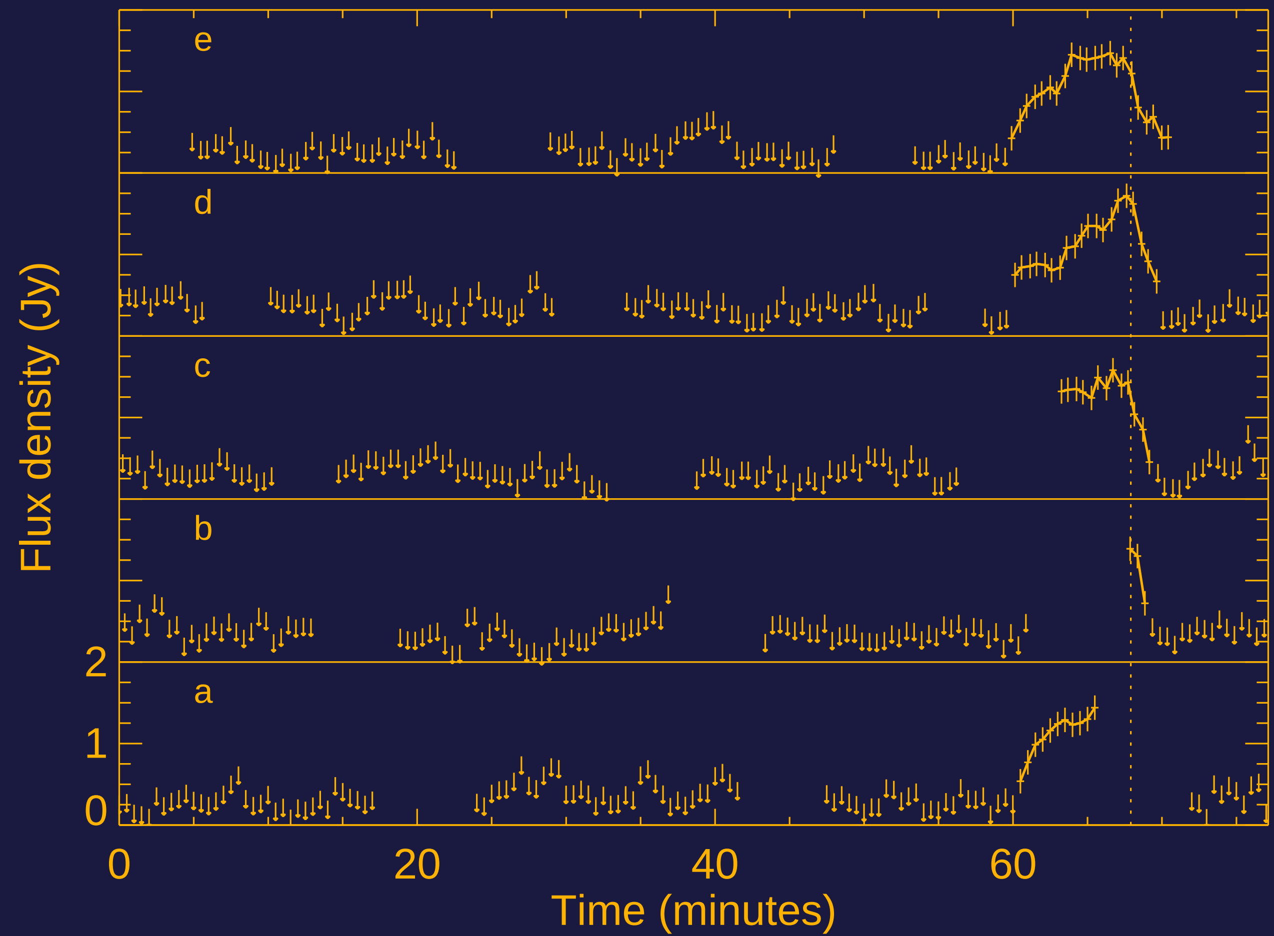


VAST and the Dynamic Radio Sky

- The dynamic radio sky is a discovery frontier.
- VAST $\rightarrow$ "Slow" transients, no dispersion searching.
- Ultimately, we want to go from discovery $\rightarrow$ science.
  - Explosive events.
  - Accretion-powered.
  - Magnetic field driven.
  - Propagation effects.

The Dynamic Radio Sky



GCRT 1745–3009: Periodic 1 Jy bursts at 330 MHz.
77 min intervals, 10 min bursts... coherent, unexplained.

(Hyman et al. 2005, Nature, 434, 50)

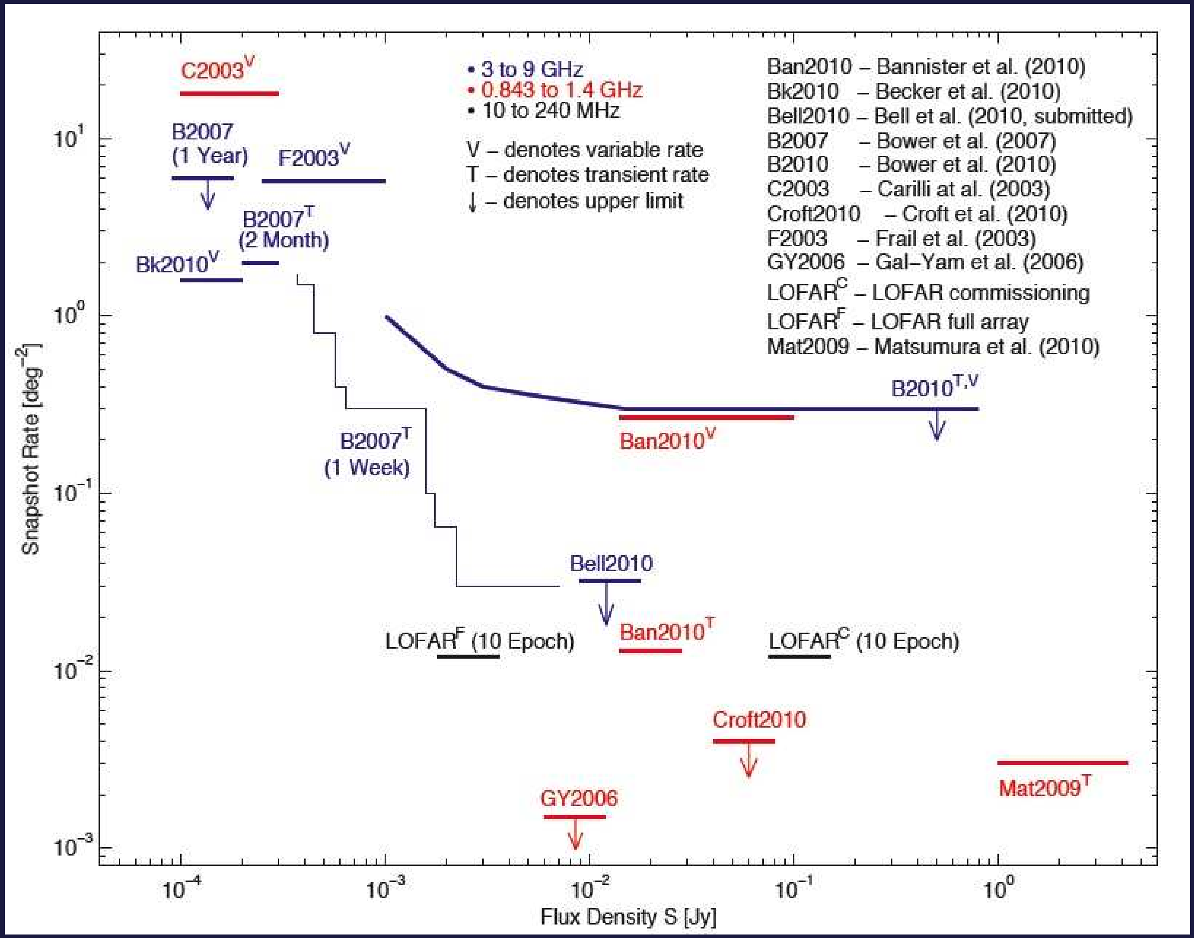
The Dynamic Radio Sky

The dynamic radio sky is a discovery frontier.

As we know,
There are known knowns.
There are things we know we know.
We also know
There are known unknowns.
That is to say
We know there are some things
We do not know.
But there are also unknown unknowns,
The ones we don't know
We don't know.

— US Sec Def. Donald Rumsfeld
DoD briefing, 12 Feb 2002

Radio Transients: Observational constraints



Log N—log S distribution of transient and variable sources from different surveys: different ν_{obs}, cadences, sky coverage, etc.

(Plot from Bell et al. 2011)

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- 36 dishes, 12-m diameter, 2 km core, up to 6 km baselines.
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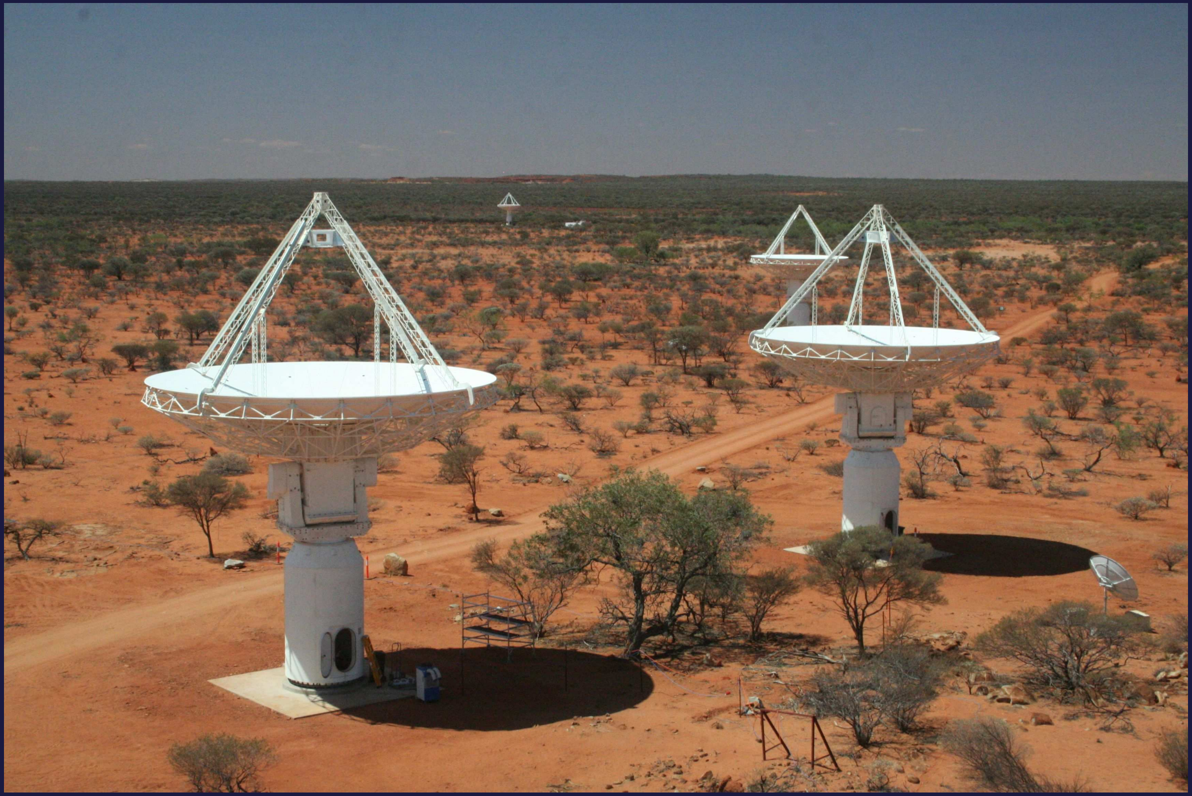

(Oct 2010, with thanks to Ant Schinckel, CSIRO)

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Parkes testbed FPA; CSIRO July 2008

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Wide field of view ($\gtrsim$30 sq deg):
$\Rightarrow$ ASKAP is well-suited for surveys for radio transients.

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- Wide range of science goals, but the same technical challenges:
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  - Identification and classification.
  - Triggered follow-up observations.

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- Open collaboration:
  We welcome interested and active new members!

Happy 70th Birthday, Miller!

- A whole generation of students, postdocs, and young radio astronomers owes you a debt of thanks!
- Your unflagging enthusiasm has helped drag many a paper across the finish line.
- We will look forward to many more marked up paper drafts.

Radio astronomy and transients: we live in interesting times.

Extras

Goal: A distance measuring service

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- Also possible:
  - Regular monitoring of specific sources;
  - Triggered observations;
  - Archival searches for longer timescales;
  - ... etc.

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- VAST-Deep: 30 sq deg observed daily.
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- VAST-GP: 750 sq deg observed 64 times.
  $\longrightarrow$ 16 min per field; 0.1 mJy/beam; 600 hrs.

VAST Strawman Surveys

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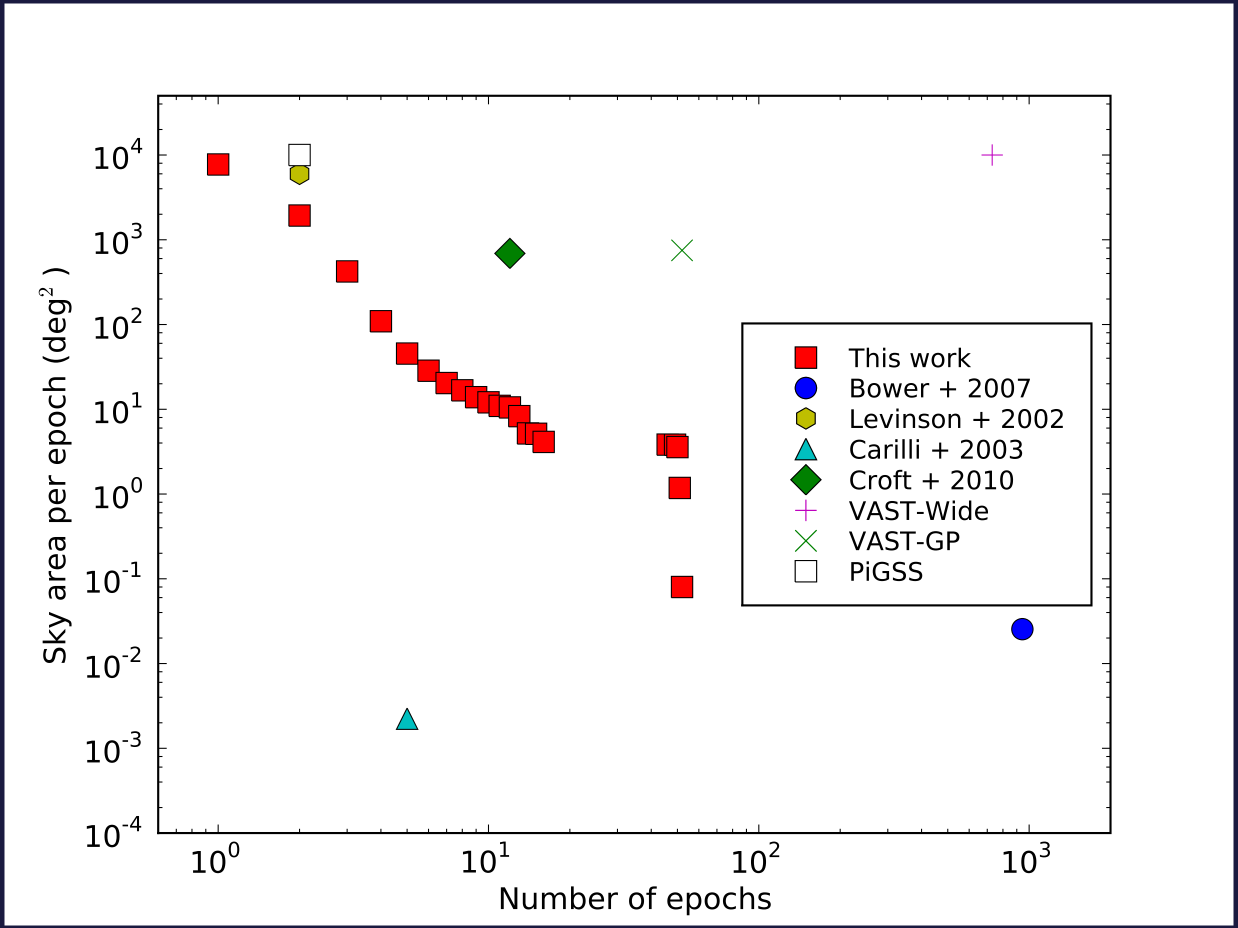
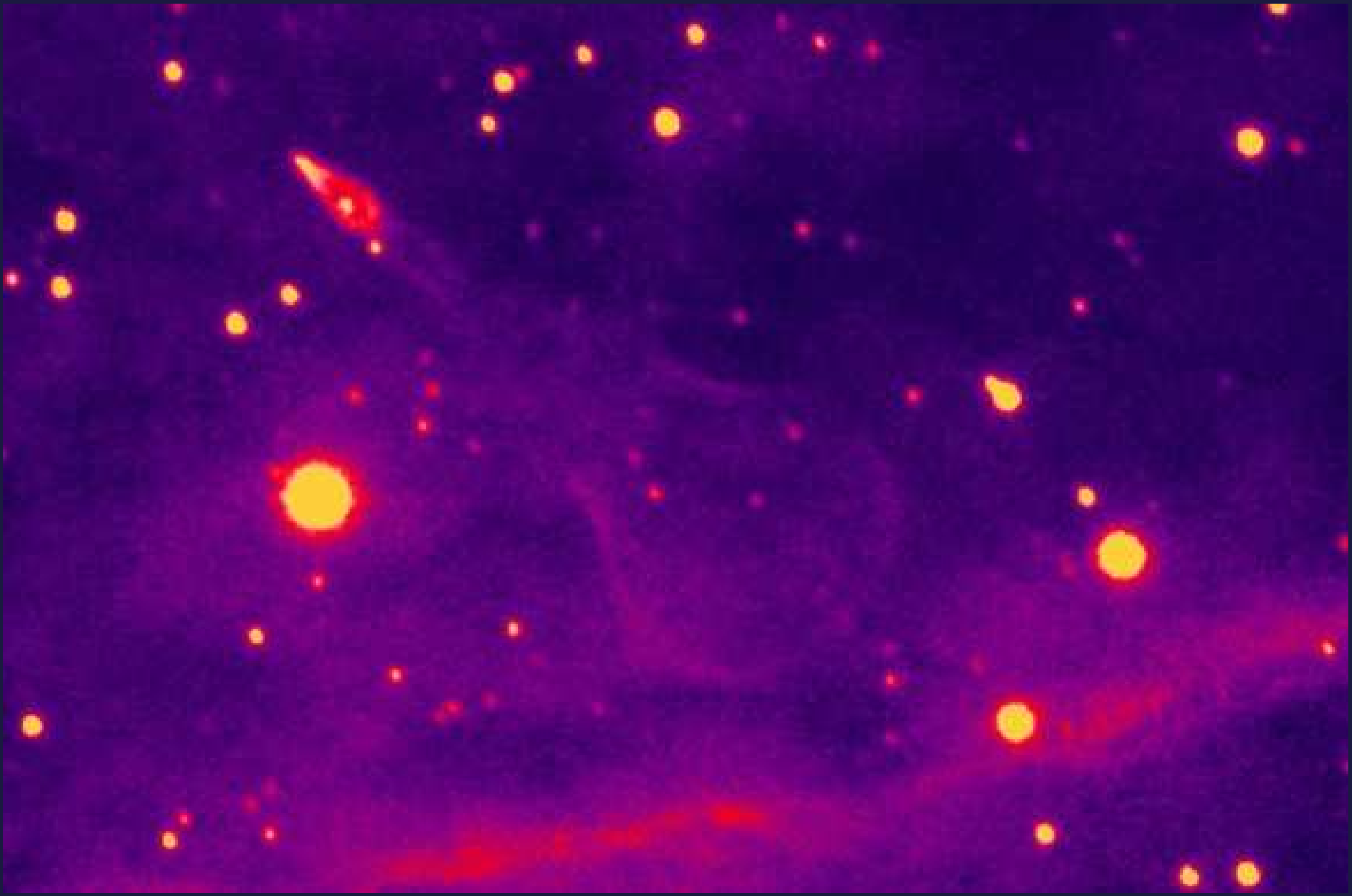


(Analysis of 30-yr Molonglo archive, Bannister et al. 2011)

VAST Strawman Surveys

- ASKAP is optimized for survey speed: VAST will *far exceed* existing surveys on that metric.
- Major challenges ahead: what do we do with the data?
  - Massive data volume: real-time detection pipeline.
  - Reliable automated source finding.
  - Multi-wavelength follow-up, source ID, classification.
  - Database handling, algorithm development, etc.

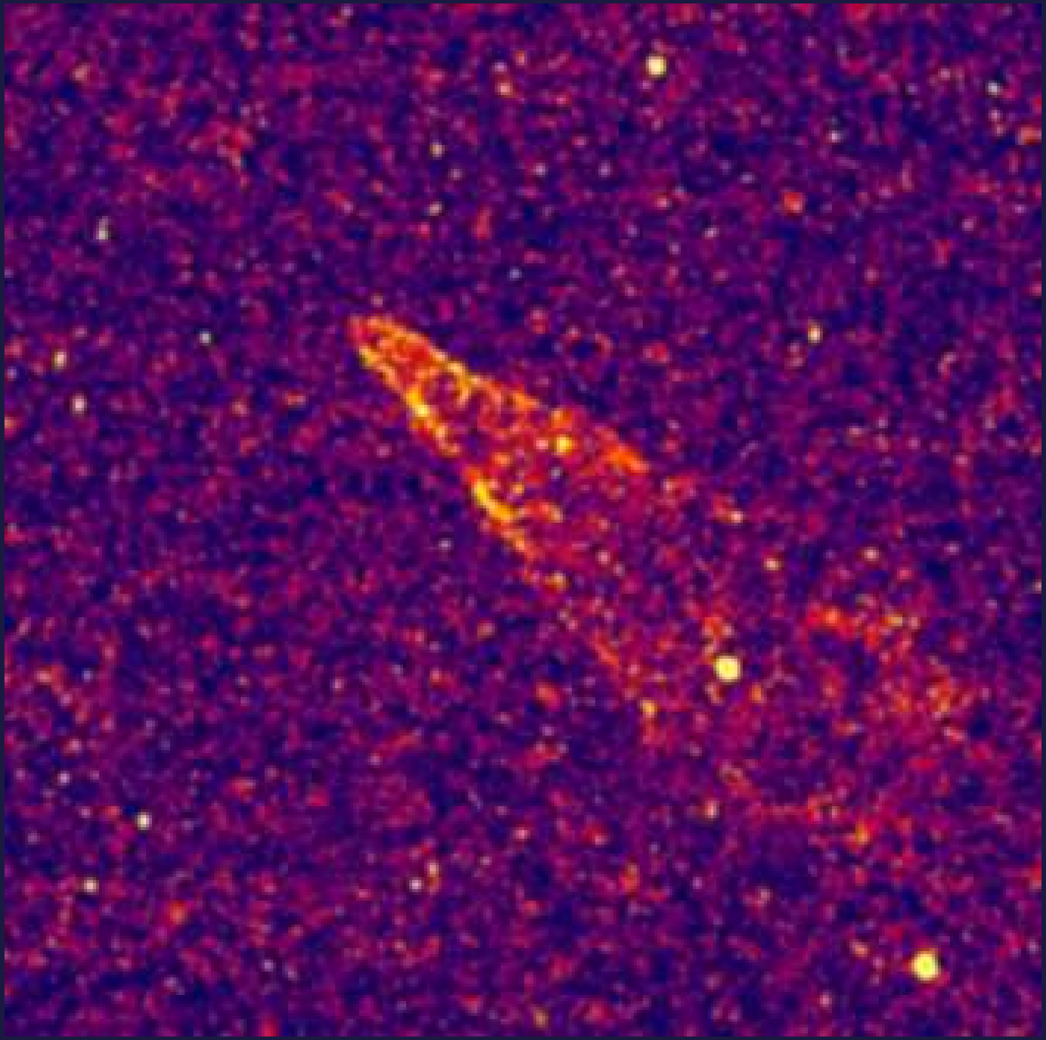
Probing Structure in the ISM: the Guitar nebula



Guitar Nebula: $V_{\perp} = 1640$ km/s at 1.9 kpc

Cordes, Romani, & Lundgren 1993; Chatterjee & Cordes 2002

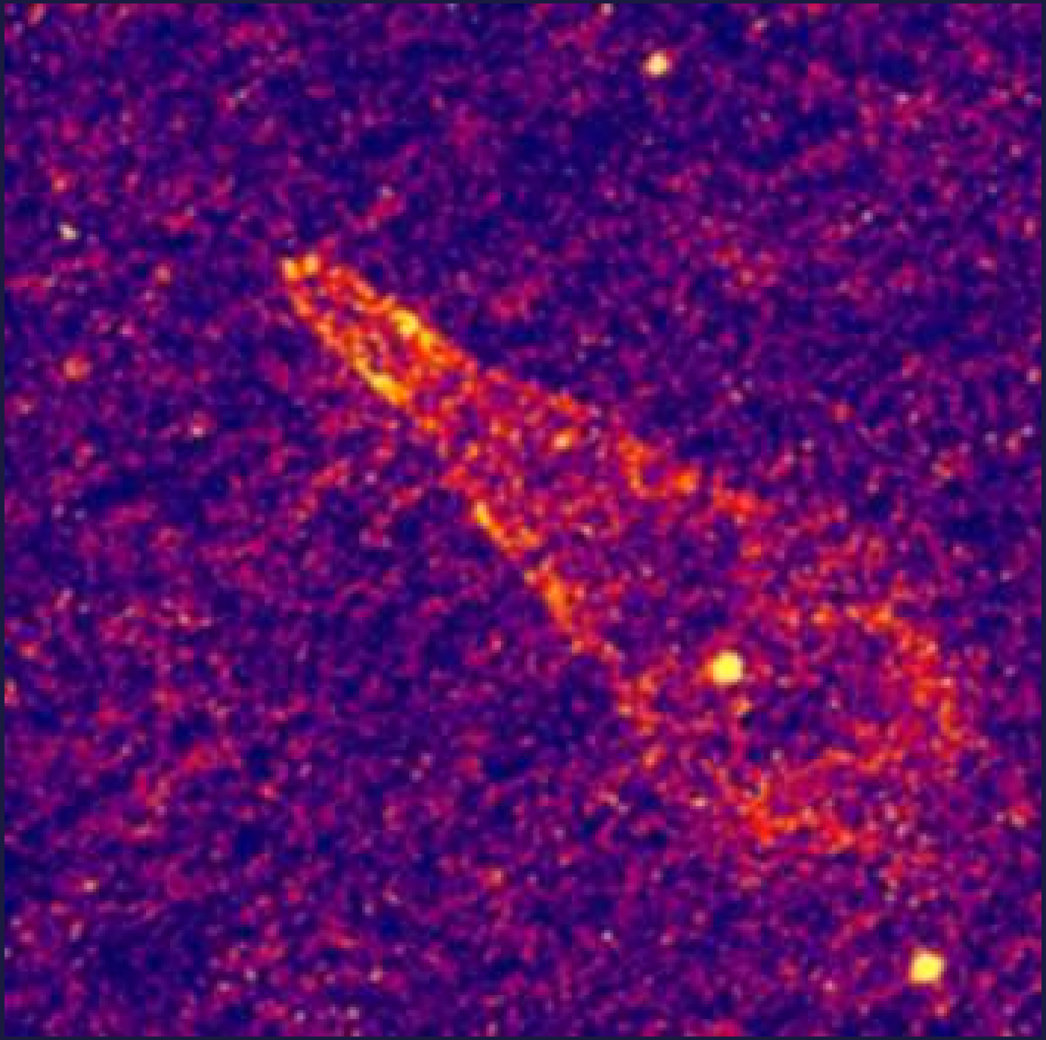
An Evolving Bow Shock



1994 December: Narrow-band Hα; $T_{int} = 7200$ s; Drizzled.

Chatterjee & Cordes 2002, 2004

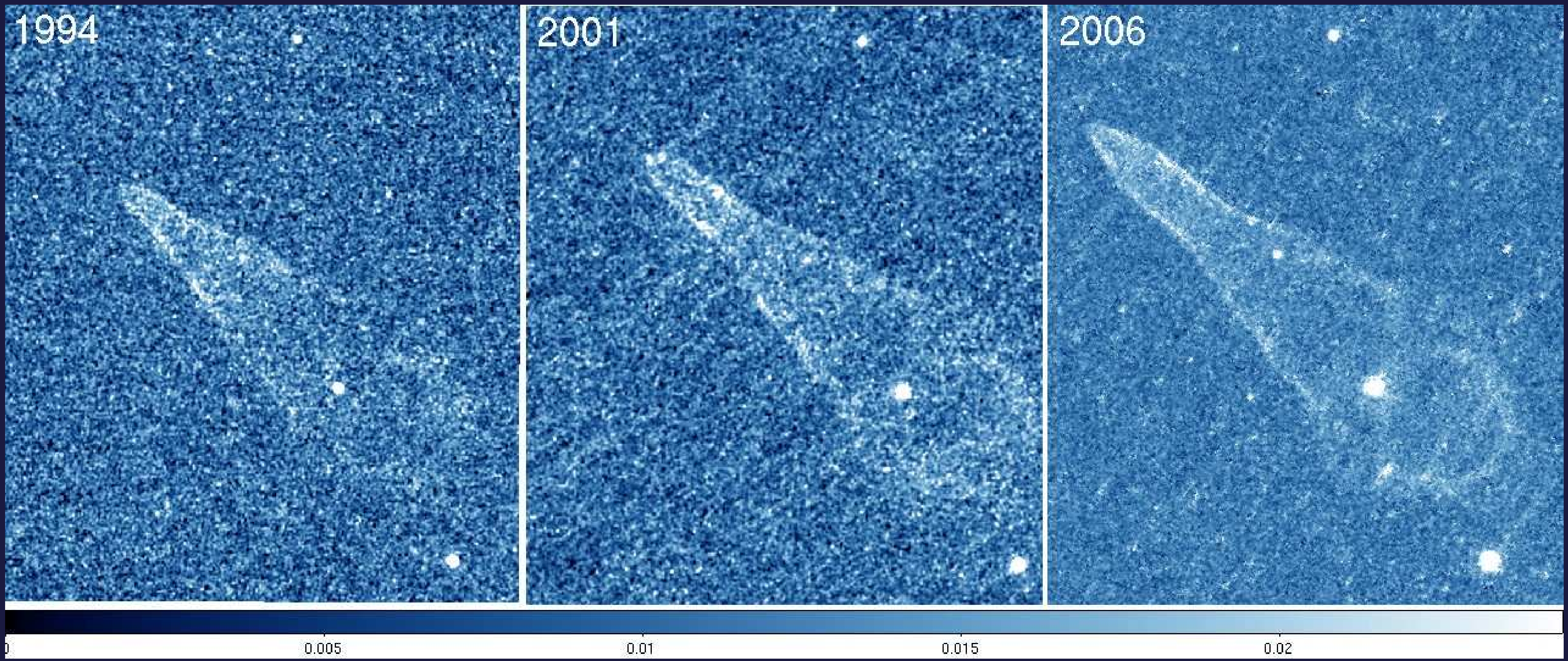
An Evolving Bow Shock



2001 December: Narrow-band Hα; $\mathrm{T_{int}} = 17600$ s; Drizzled.

Chatterjee & Cordes 2002, 2004

An Evolving Bow Shock



- Images from 1994 (WFPC2), 2001 (WFPC2), 2006 (ACS).
- Changing shape, stand-off distance trace changes in ISM.