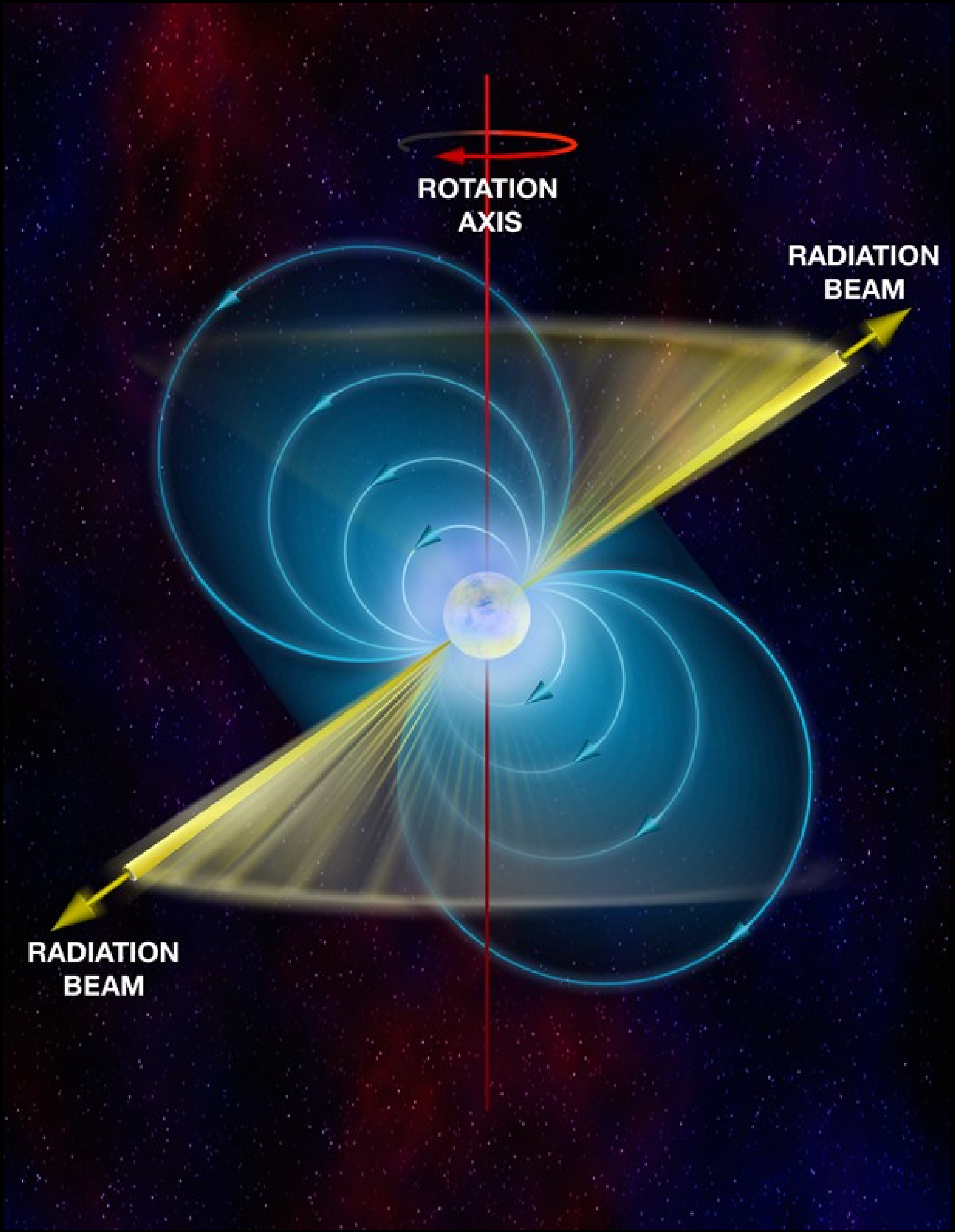
The GBT 350 MHz Surveys

Scott Ransom

NRAO Charlottesville



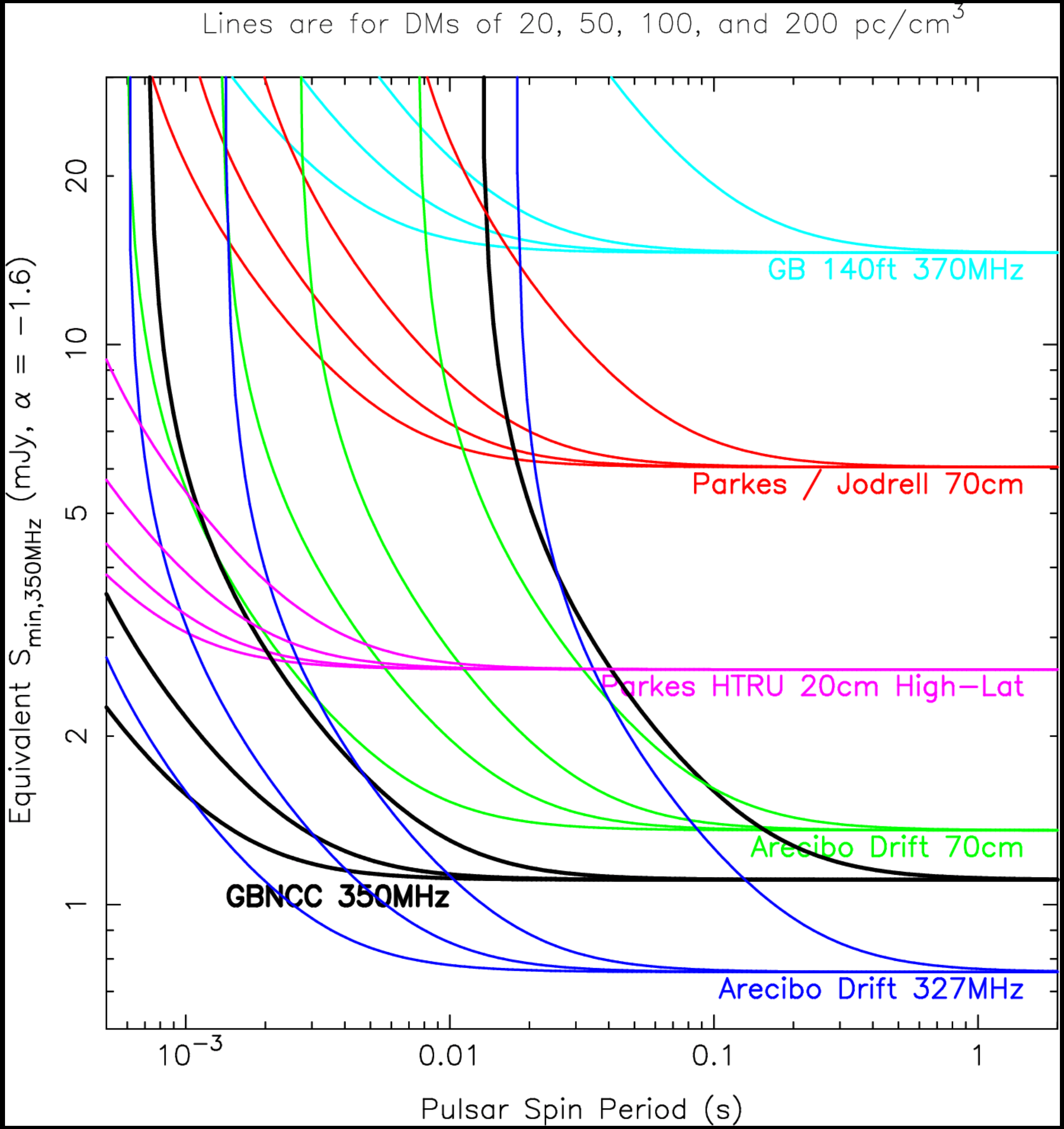
GBT 350 MHz System

- Prime Focus 1 (i.e. PF1) receiver
  - 4 feeds: 350/430/600/820 MHz, G = 2 K/Jy
  - Trcvr ~ 25 K (i.e. cooled) + Tsky ~ 30K - hundreds of K
  - At 350 MHz, GBT FWHM beam is 0.58°
- 80+ MHz of clean bandwidth (~20K DMs required)
- Spigot: 50 MHz BW, 82 us, 1024 or 2048 chan
- GUPPI: (2008+) ~90 MHz BW, 82 us, 4096 chan
- Approximately 0.5 PB of search data so far:
- ~105 normal PSRs, ~30 recycled PSRs, 16 RRATs

350 MHz Survey Sensitivity

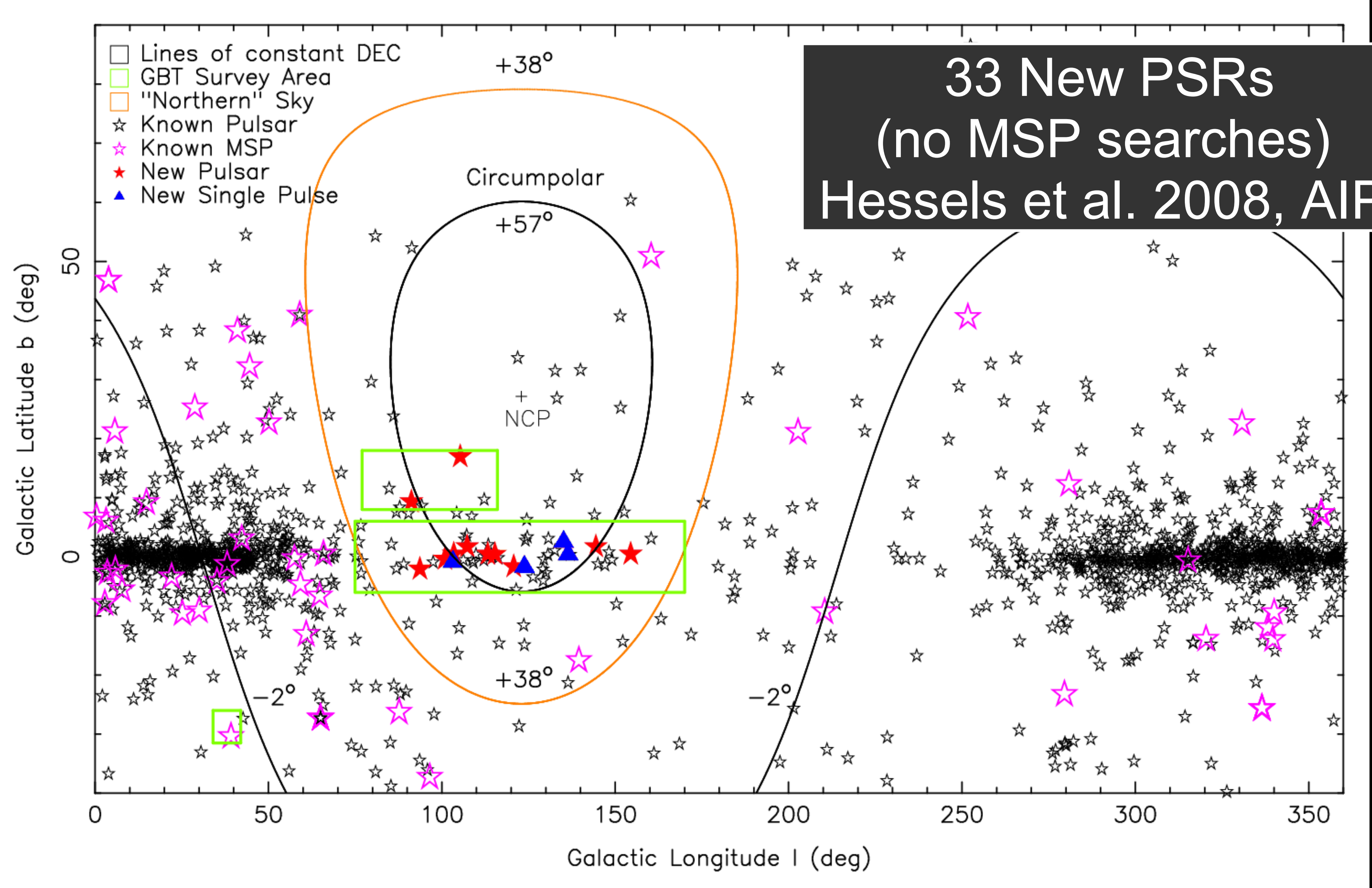
2-minute integrations
Tsys ~ 90K

DMs of
20, 50,100 and 200 pc/cm^3



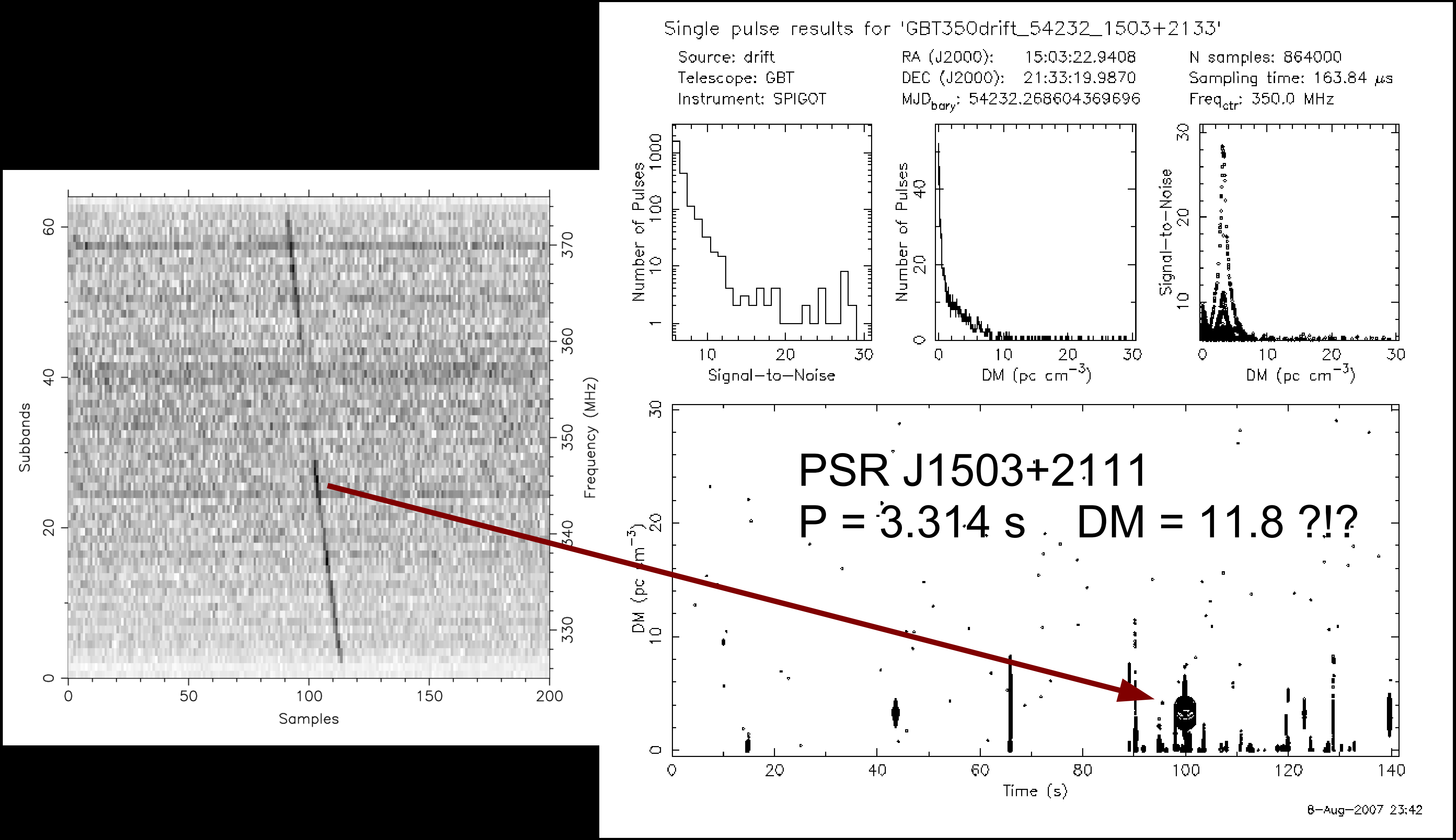
2005-6: 350MHz N. Galactic Plane Survey

150+ hrs Hessels, Ransom, Kaspi, Roberts, Champion, Stappers



33 New PSRs
(no MSP searches)
Hessels et al. 2008, AIP

Low DM and slow pulsars are easy



2007: GBT Track Repairs

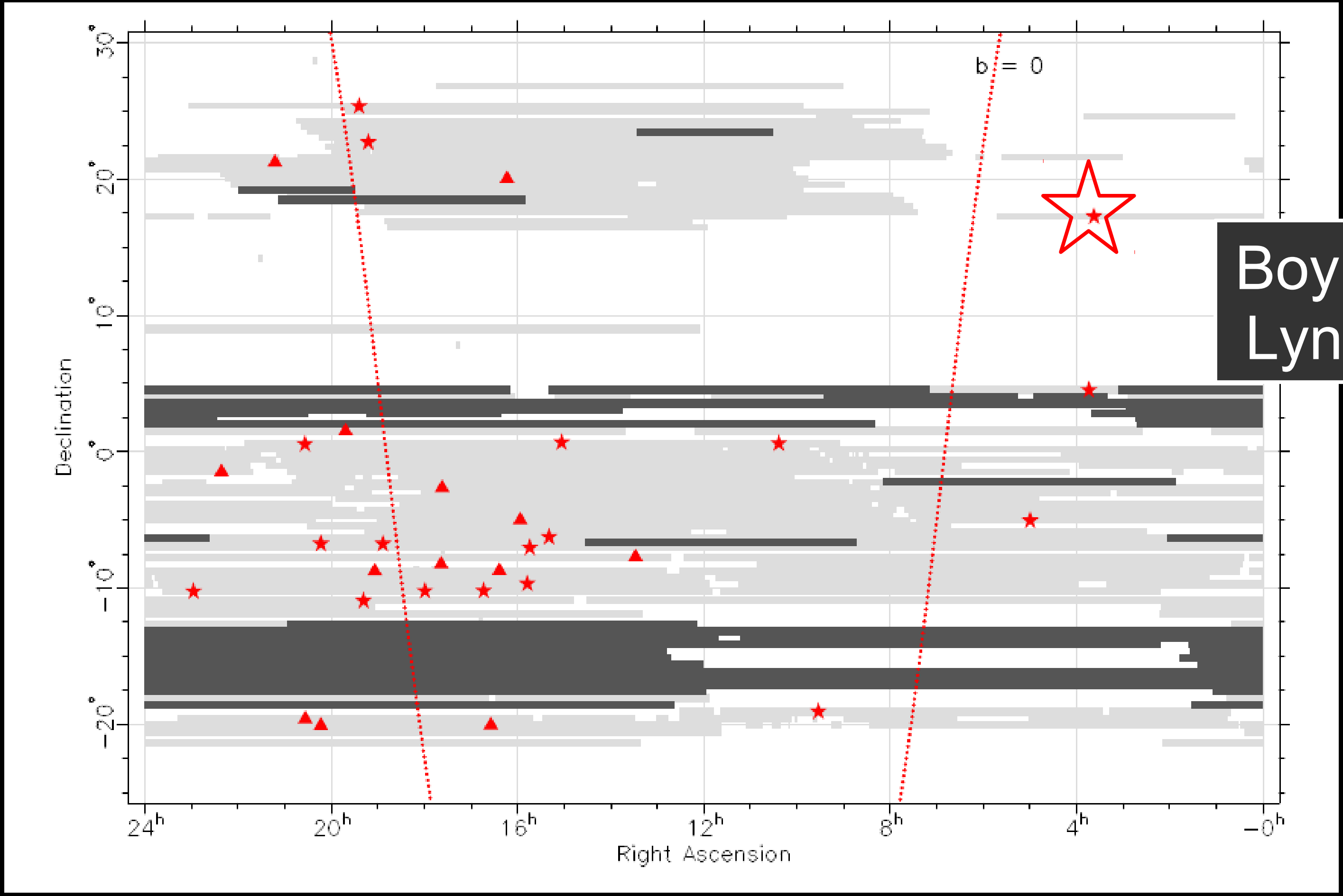
GBT closed for track repairs in summer for 4.5 months

350MHz Drift Scan Survey during Track Repair

Lorimer, McLaughlin, Ransom, Boyles, Lynch, Hessels, Kondratiev, Stairs, van Leeuwen, Archibald, Kaspi, Roberts, Stovall, Karako-Argaman, + several undergraduate students...

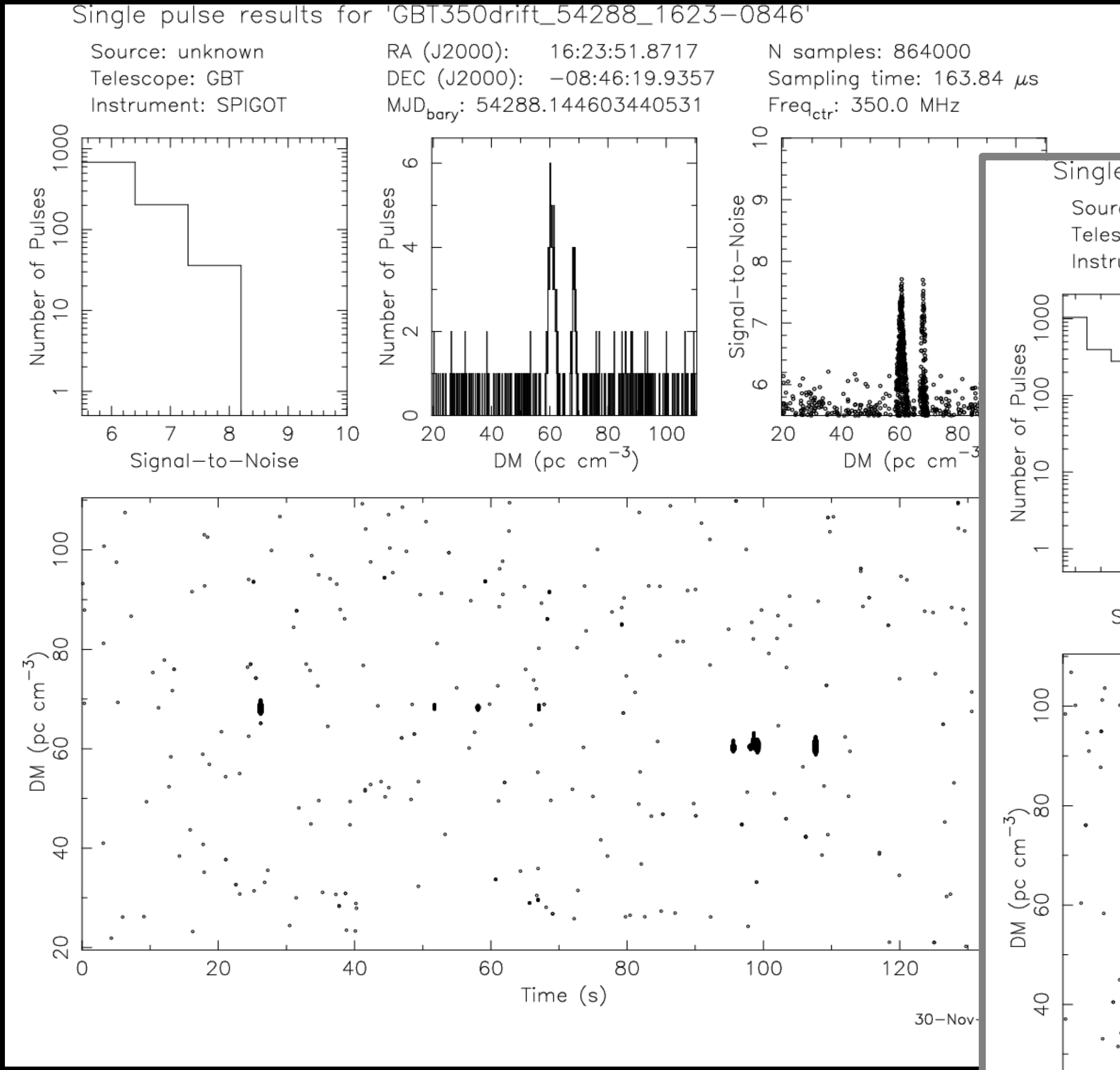
~1350 hrs of obs @ 25 MB/s ~135 TB (~25% of the full sky!)

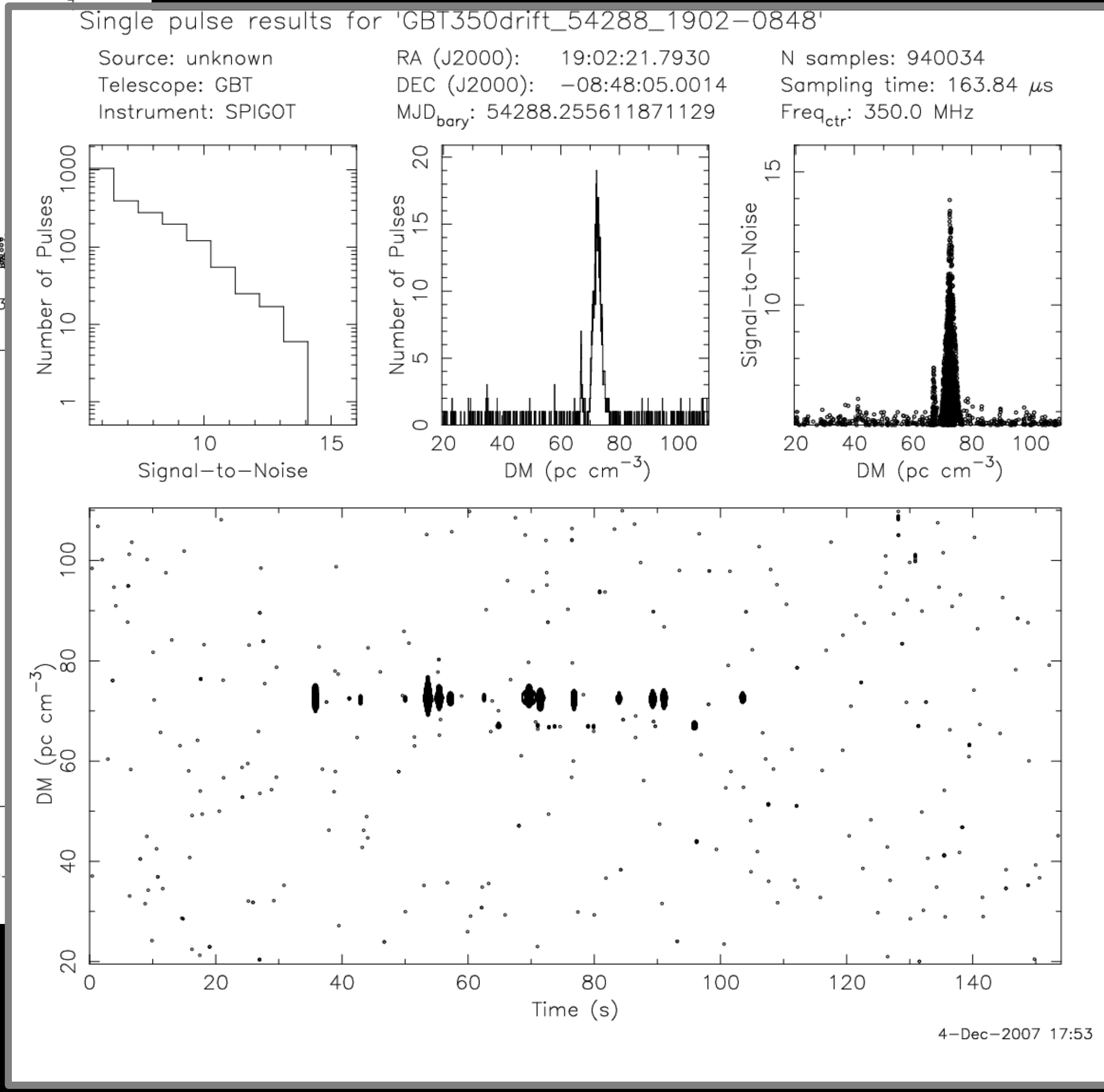
40+ new pulsars, including 8 MSPs plus 9 RRATs



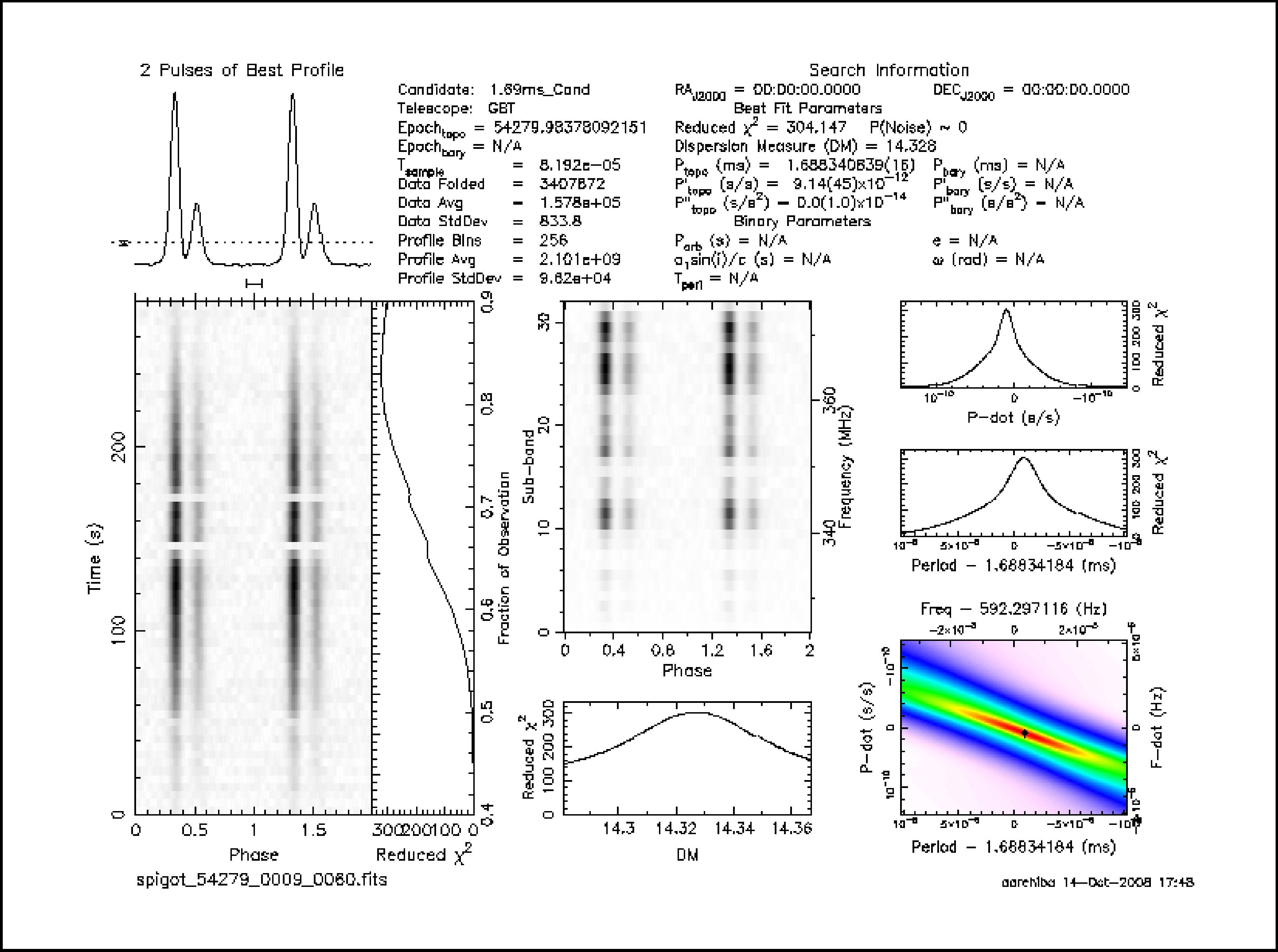
Boyles et al. 2013, ApJ
Lynch et al. 2013, ApJ

Multiple pulsars in a beam





One of the MSPs was very bright....

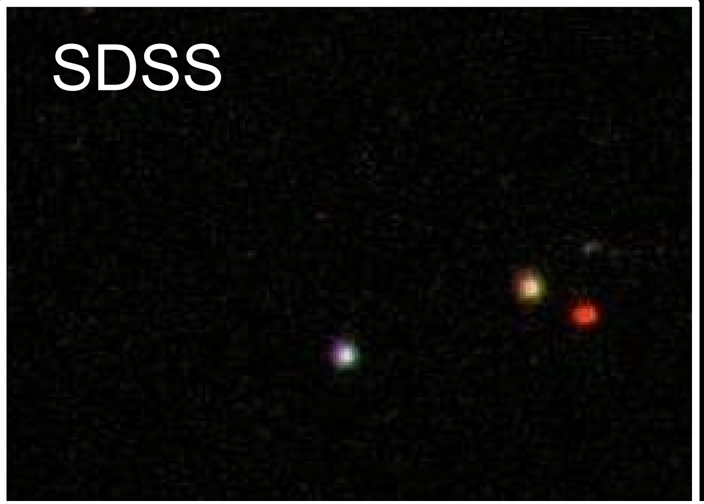


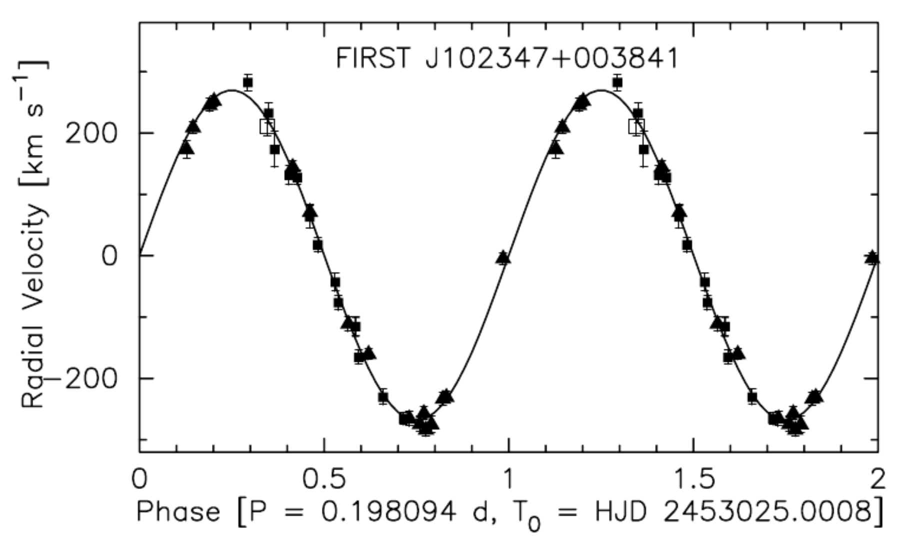
PSR J1023 follow-up observations...

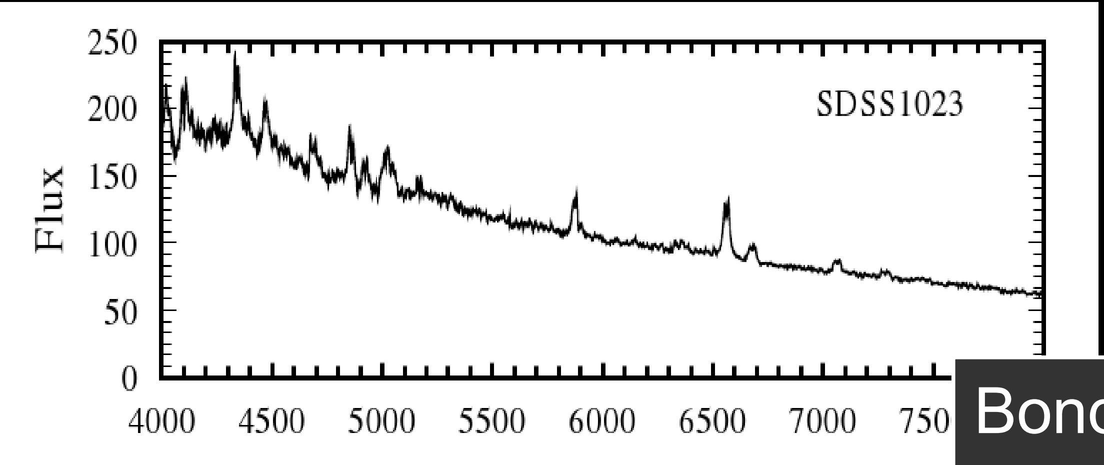
Previously (over last 10 yrs) detected in FIRST, optical images/spectra, and X-rays and identified as a strange CV or a quiescent LMXB!

4.75 hr binary!

Evidence for accretion!

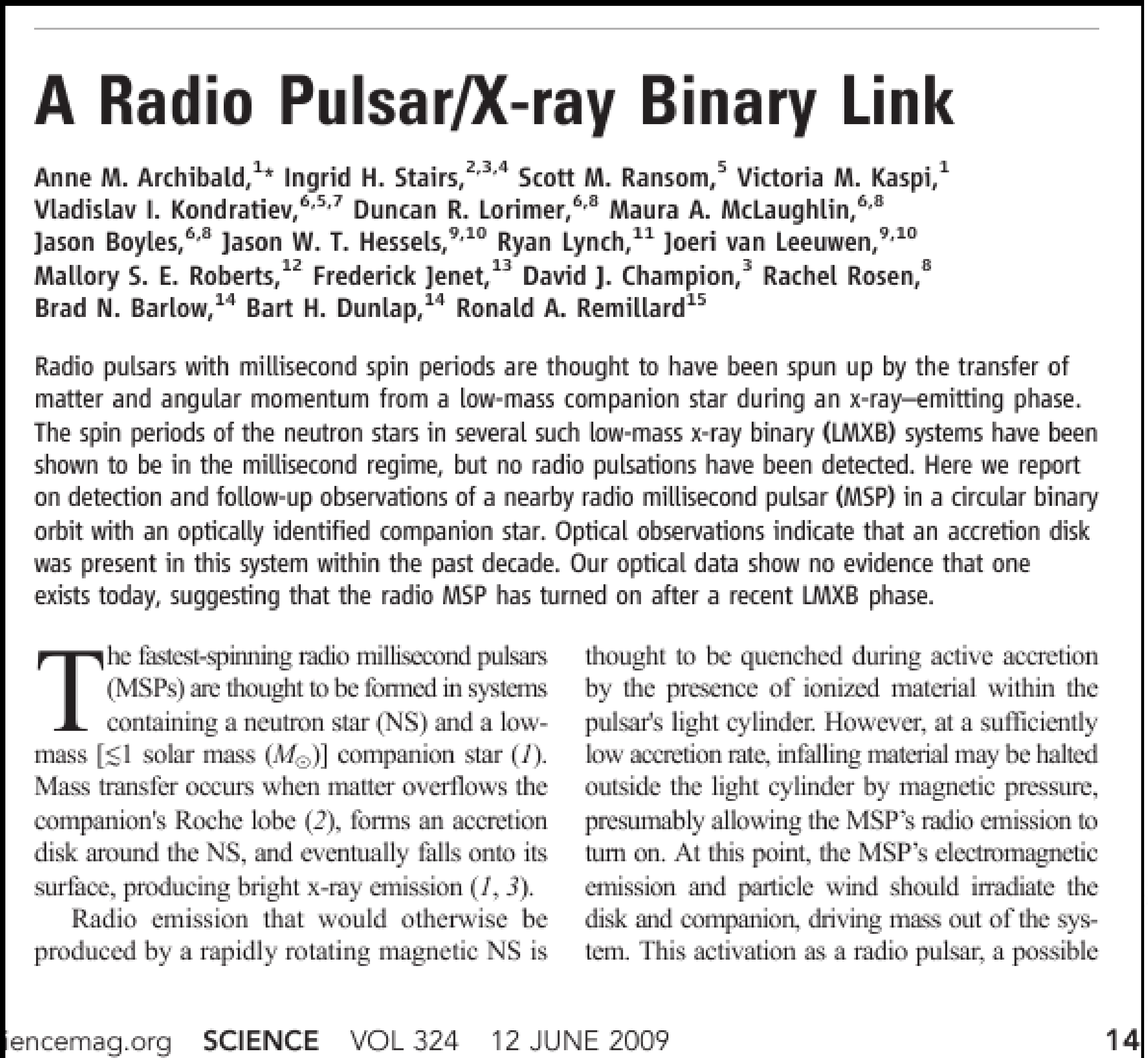






Bond et al. 2002, Szkody et al. 2003, Homer et al. 2006,
Thorstensen & Armstrong 2005

J1023-0038: "Missing Link" System



A Radio Pulsar/X-ray Binary Link

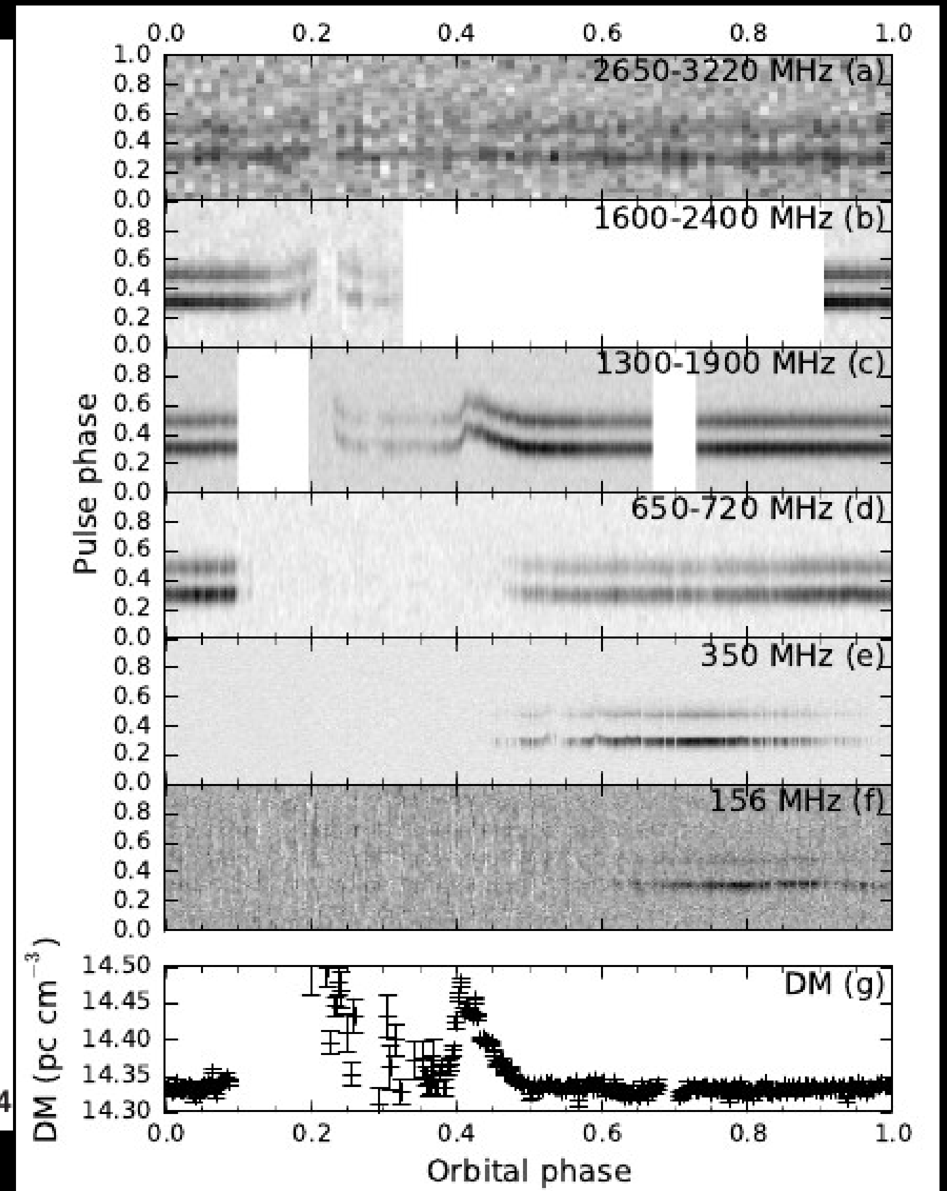
Anne M. Archibald,[1]* Ingrid H. Stairs,[2,3,4] Scott M. Ransom,[5] Victoria M. Kaspi,[1] Vladislav I. Kondratiev,[6,5,7] Duncan R. Lorimer,[6,8] Maura A. McLaughlin,[6,8] Jason Boyles,[6,8] Jason W. T. Hessels,[9,10] Ryan Lynch,[11] Joeri van Leeuwen,[9,10] Mallory S. E. Roberts,[12] Frederick Jenet,[13] David J. Champion,[3] Rachel Rosen,[8] Brad N. Barlow,[14] Bart H. Dunlap,[14] Ronald A. Remillard[15]

Radio pulsars with millisecond spin periods are thought to have been spun up by the transfer of matter and angular momentum from a low-mass companion star during an x-ray–emitting phase. The spin periods of the neutron stars in several such low-mass x-ray binary (LMXB) systems have been shown to be in the millisecond regime, but no radio pulsations have been detected. Here we report on detection and follow-up observations of a nearby radio millisecond pulsar (MSP) in a circular binary orbit with an optically identified companion star. Optical observations indicate that an accretion disk was present in this system within the past decade. Our optical data show no evidence that one exists today, suggesting that the radio MSP has turned on after a recent LMXB phase.

The fastest-spinning radio millisecond pulsars (MSPs) are thought to be formed in systems containing a neutron star (NS) and a low-mass [≲1 solar mass ($M_\odot$)] companion star (*1*). Mass transfer occurs when matter overflows the companion's Roche lobe (*2*), forms an accretion disk around the NS, and eventually falls onto its surface, producing bright x-ray emission (*1*, *3*).

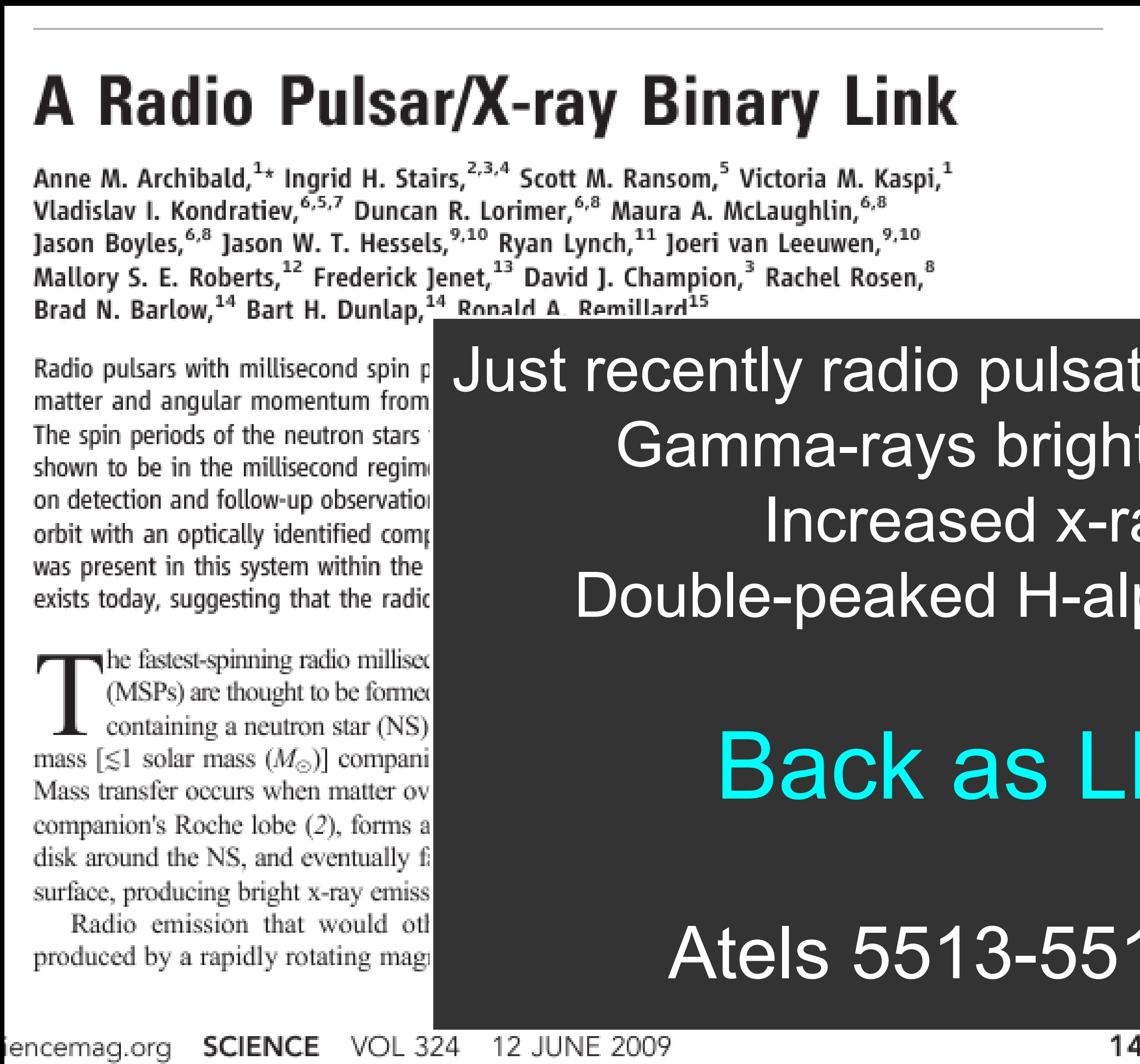
Radio emission that would otherwise be produced by a rapidly rotating magnetic NS is thought to be quenched during active accretion by the presence of ionized material within the pulsar's light cylinder. However, at a sufficiently low accretion rate, infalling material may be halted outside the light cylinder by magnetic pressure, presumably allowing the MSP's radio emission to turn on. At this point, the MSP's electromagnetic emission and particle wind should irradiate the disk and companion, driving mass out of the system. This activation as a radio pulsar, a possible

iencemag.org SCIENCE VOL 324 12 JUNE 2009 14



Archibald et al, 2009, *Science*, 324, 1411

J1023-0038: “Missing Link” System



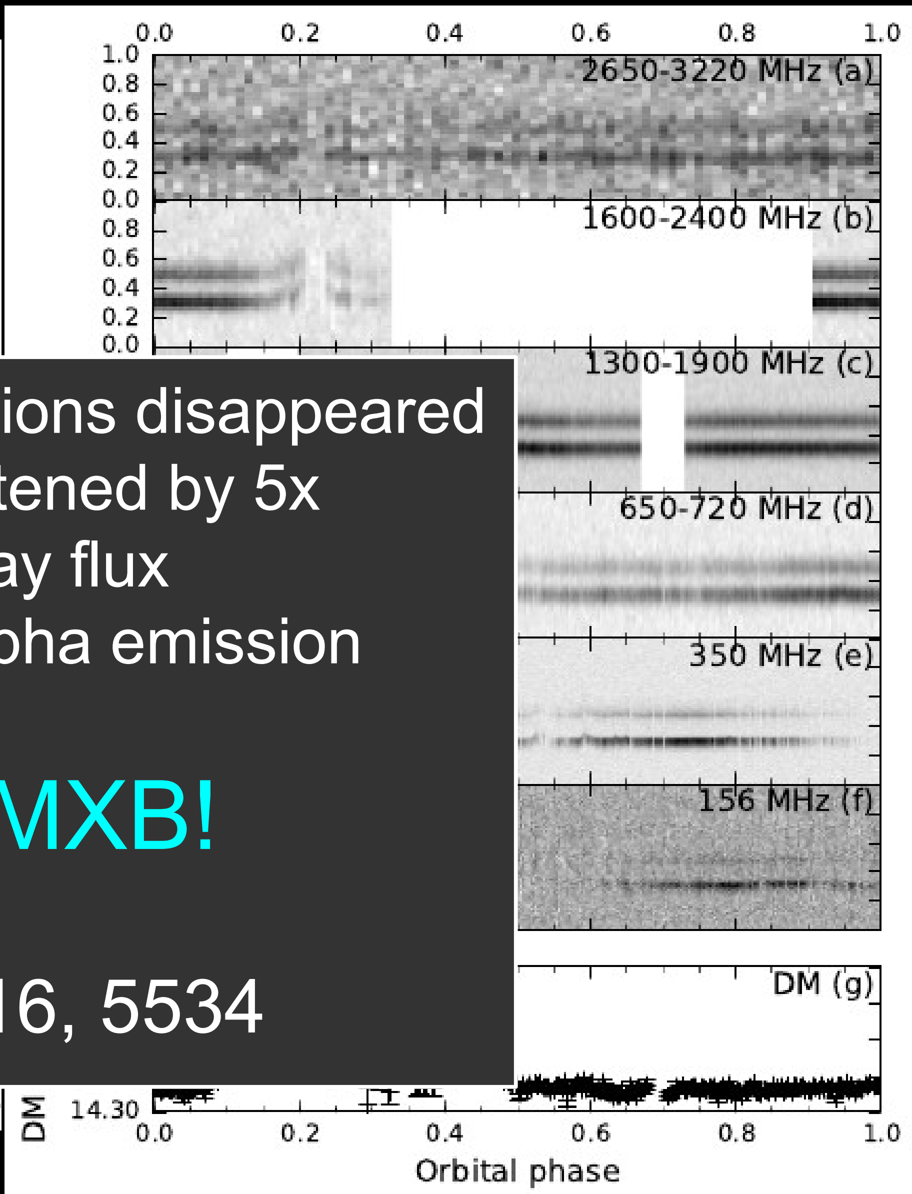
A Radio Pulsar/X-ray Binary Link

Anne M. Archibald,[1*] Ingrid H. Stairs,[2,3,4] Scott M. Ransom,[5] Victoria M. Kaspi,[1]
Vladislav I. Kondratiev,[6,5,7] Duncan R. Lorimer,[6,8] Maura A. McLaughlin,[6,8]
Jason Boyles,[6,8] Jason W. T. Hessels,[9,10] Ryan Lynch,[11] Joeri van Leeuwen,[9,10]
Mallory S. E. Roberts,[12] Frederick Jenet,[13] David J. Champion,[3] Rachel Rosen,[8]
Brad N. Barlow,[14] Bart H. Dunlap,[14] Ronald A. Remillard[15]

Radio pulsars with millisecond spin p
matter and angular momentum from
The spin periods of the neutron stars
shown to be in the millisecond regim
on detection and follow-up observatio
orbit with an optically identified comp
was present in this system within the
exists today, suggesting that the radi

The fastest-spinning radio millisec
(MSPs) are thought to be forme
containing a neutron star (NS)
mass [≲1 solar mass ($M_\odot$)] compani
Mass transfer occurs when matter ov
companion's Roche lobe (2), forms a
disk around the NS, and eventually f
surface, producing bright x-ray emiss
Radio emission that would ot
produced by a rapidly rotating mag

iencemag.org SCIENCE VOL 324 12 JUNE 2009 14



Just recently radio pulsations disappeared
Gamma-rays brightened by 5x
Increased x-ray flux
Double-peaked H-alpha emission

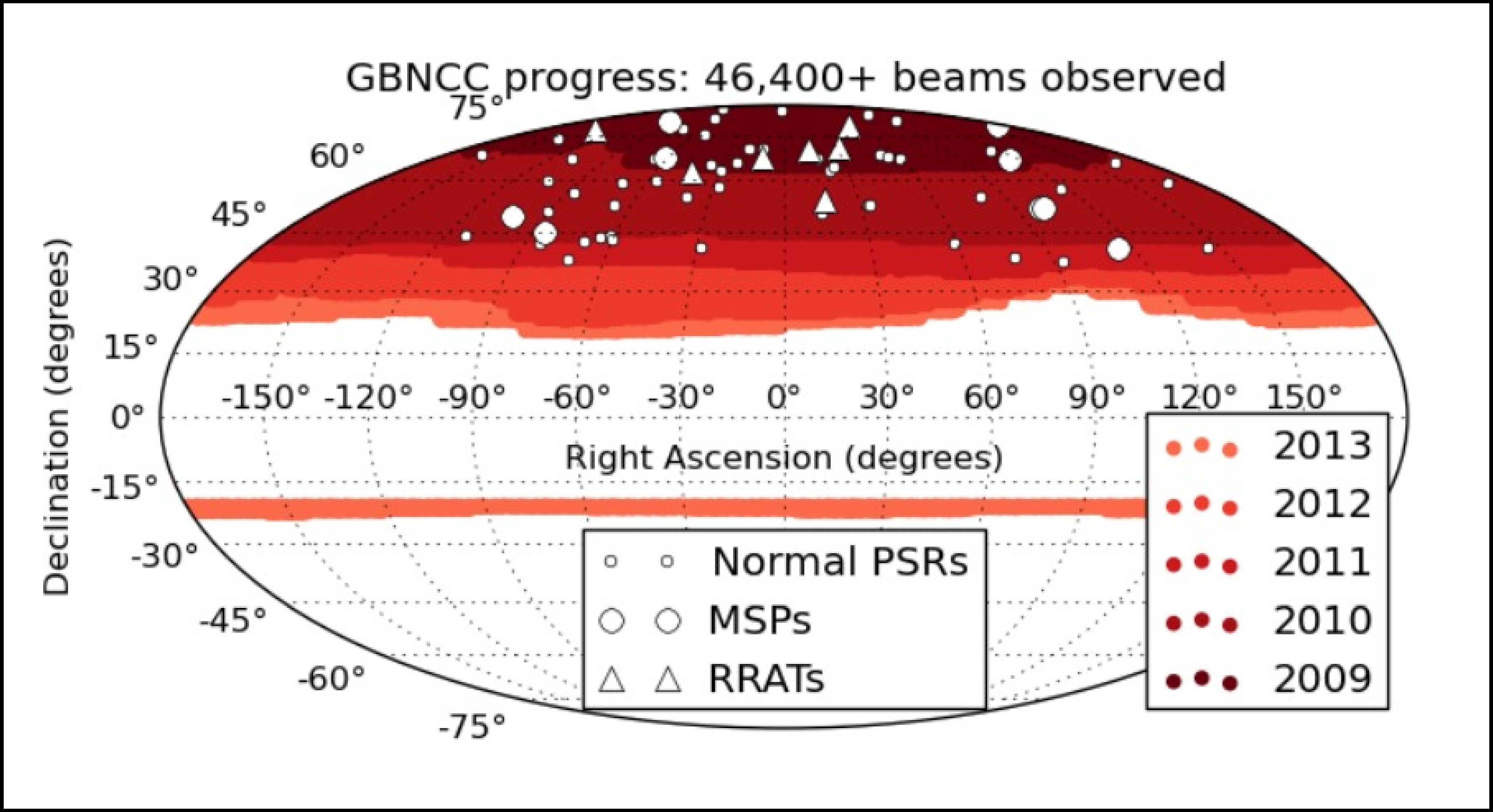
Back as LMXB!

Atels 5513-5516, 5534

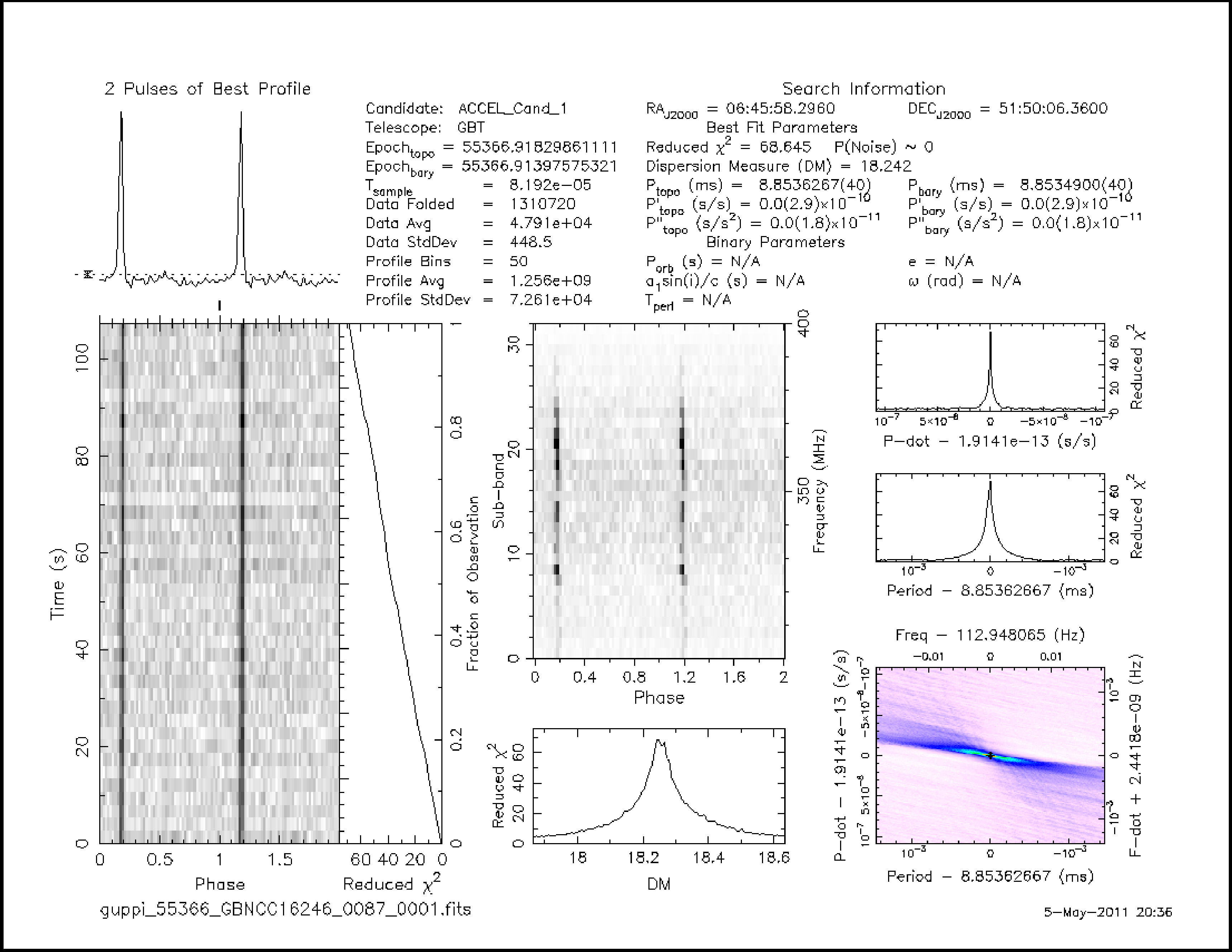
Archibald et al, 2009, *Science*, 324, 1411

GBNCC:
Green Bank North Celestial Cap Survey

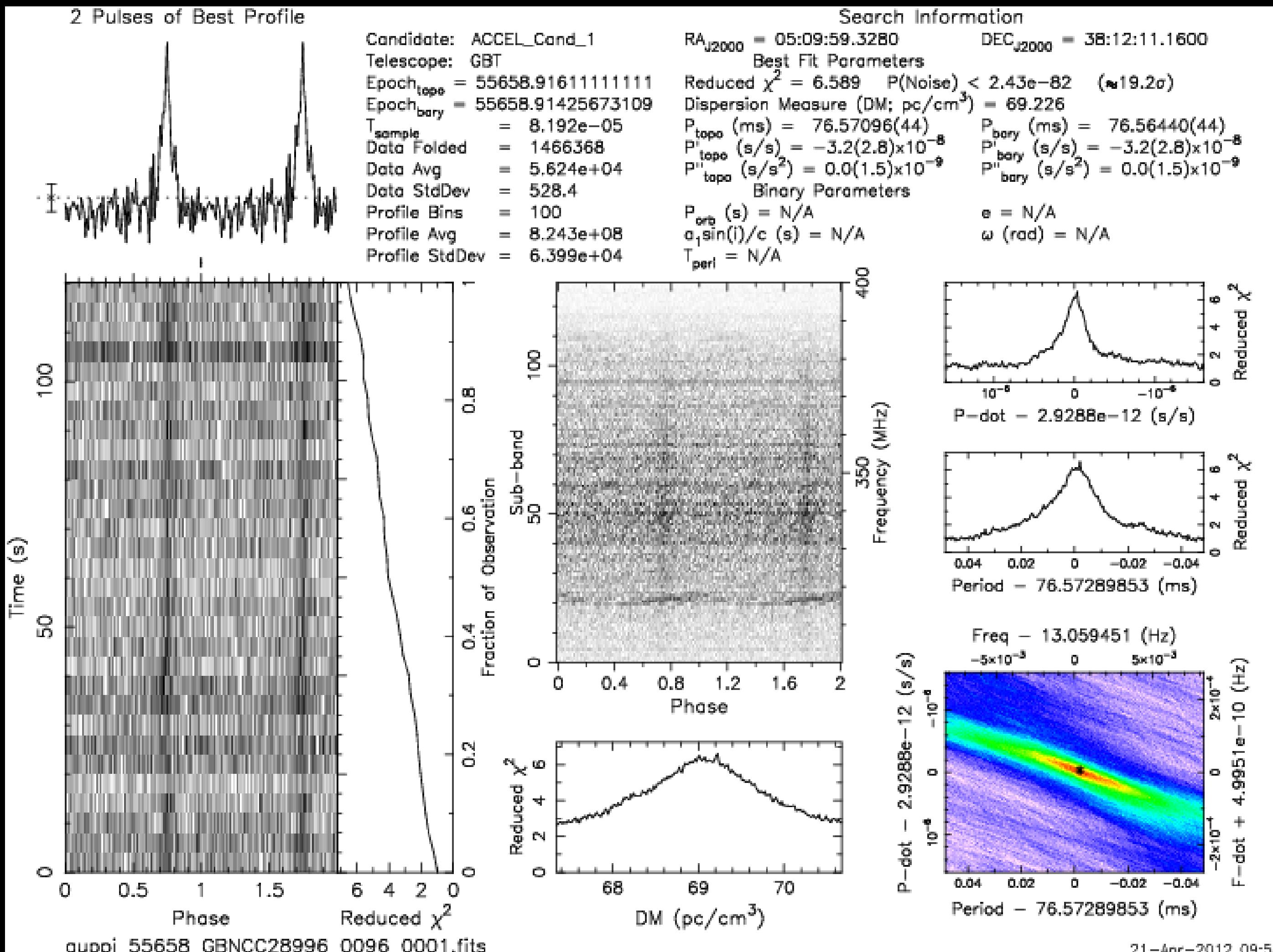
- ~Same crew as driftscan (PI Ransom), uses GUPPI
- 280 TB so far, 62 normal PSRs, 9 MSPs, 6(?) RRATs



Couple new likely PTA PSRs...



New Double-NS System: J0509+3801



76.5ms

DM = 69

Porb = 9.1 hr

e = 0.59

Mtot ~ 2.85 Msun

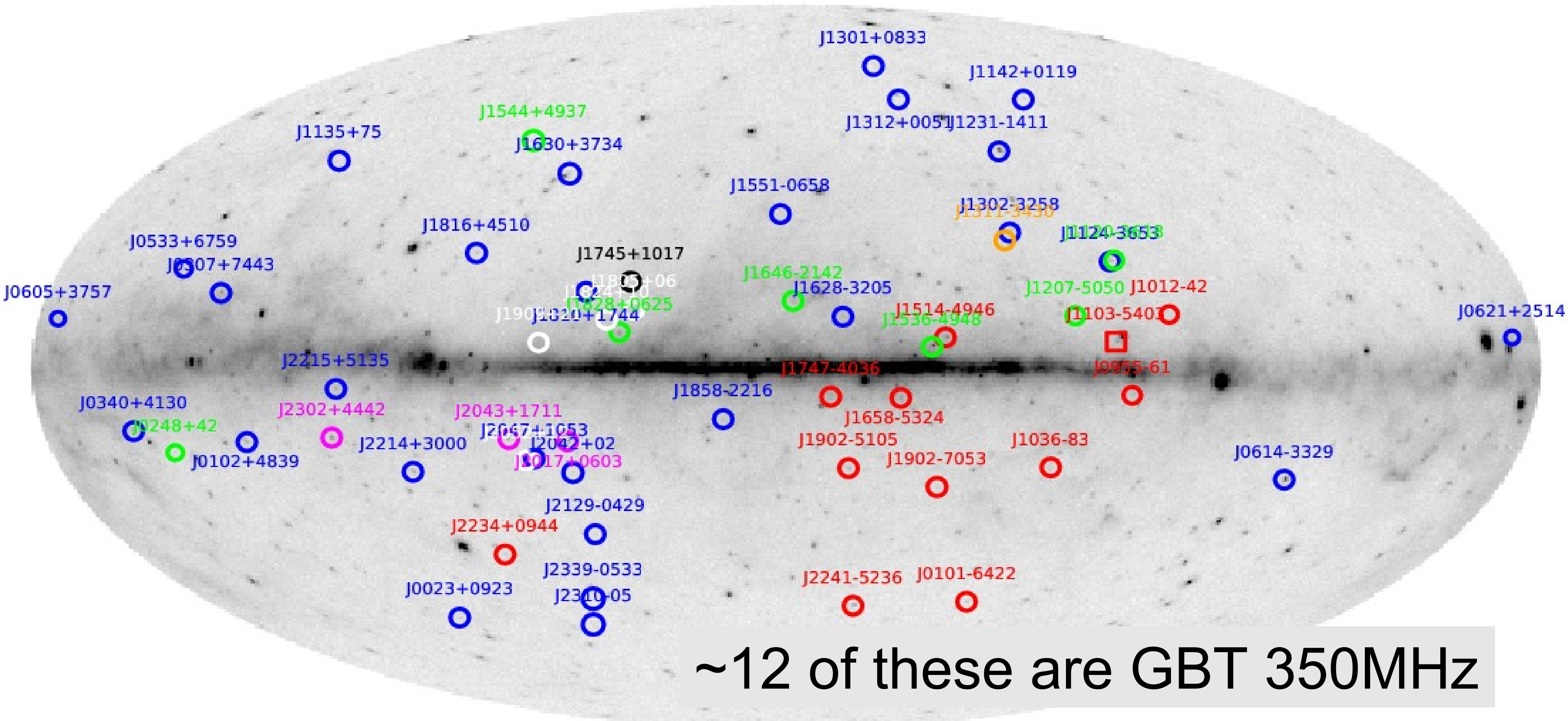
Coalesce < 1Gyr

Where are the FRBs?

- So far nothing....
- Driftscan was processed to DM ~ 1100 pc/cm^3
- GBNCC original pipeline only processed to DM ~ 550 pc/cm^3
- Dispersive delay across band is 20-sec for DM = 1000 pc/cm^3
- Will re-process GBNCC observations using GPU pipeline this year

Currently ~55 new Radio/gamma-ray MSPs because of *Fermi*!

~10% of them look like they will be "good timers"

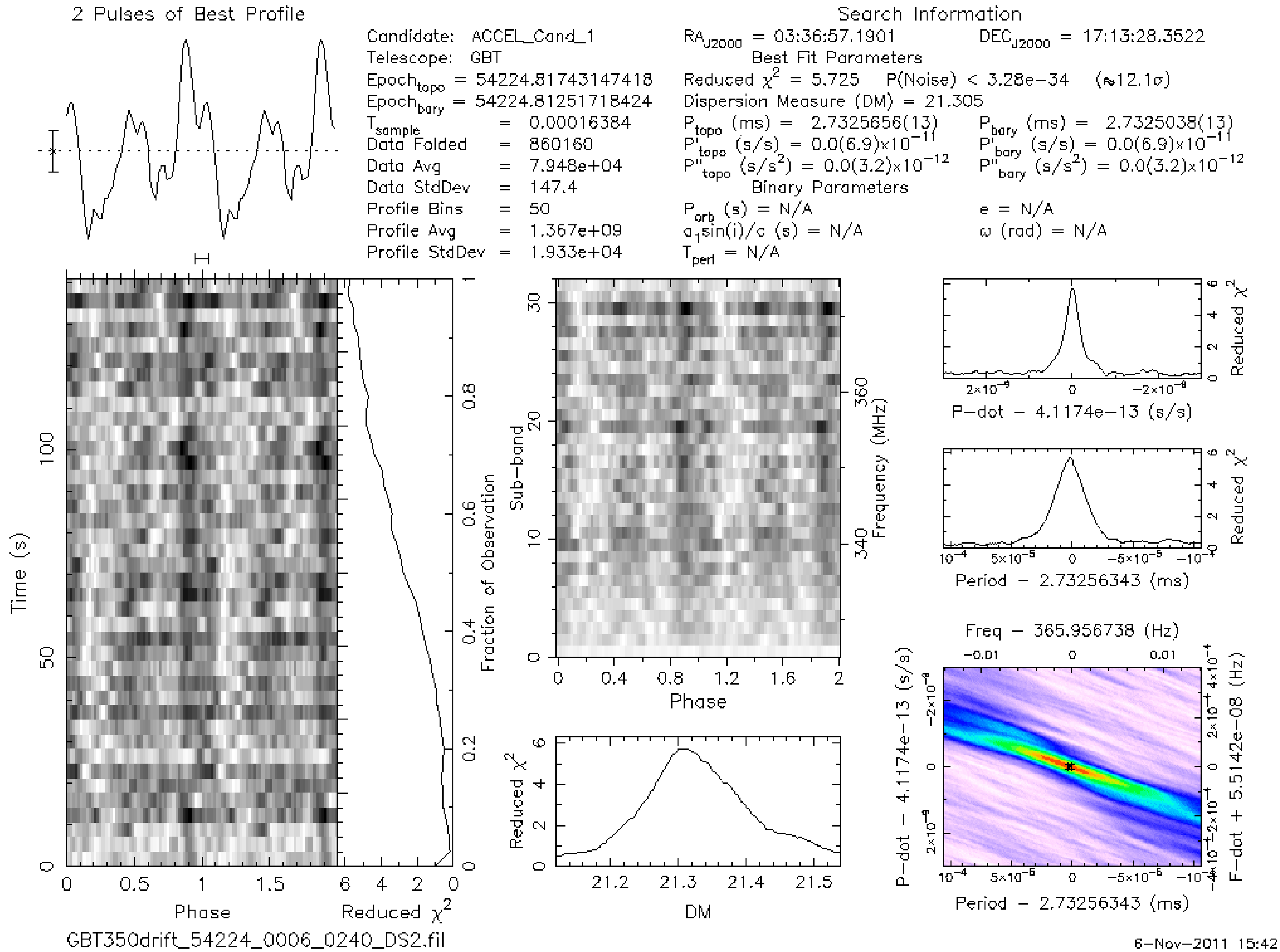


Courtesy: Paul Ray

GBT 350MHz Surveys

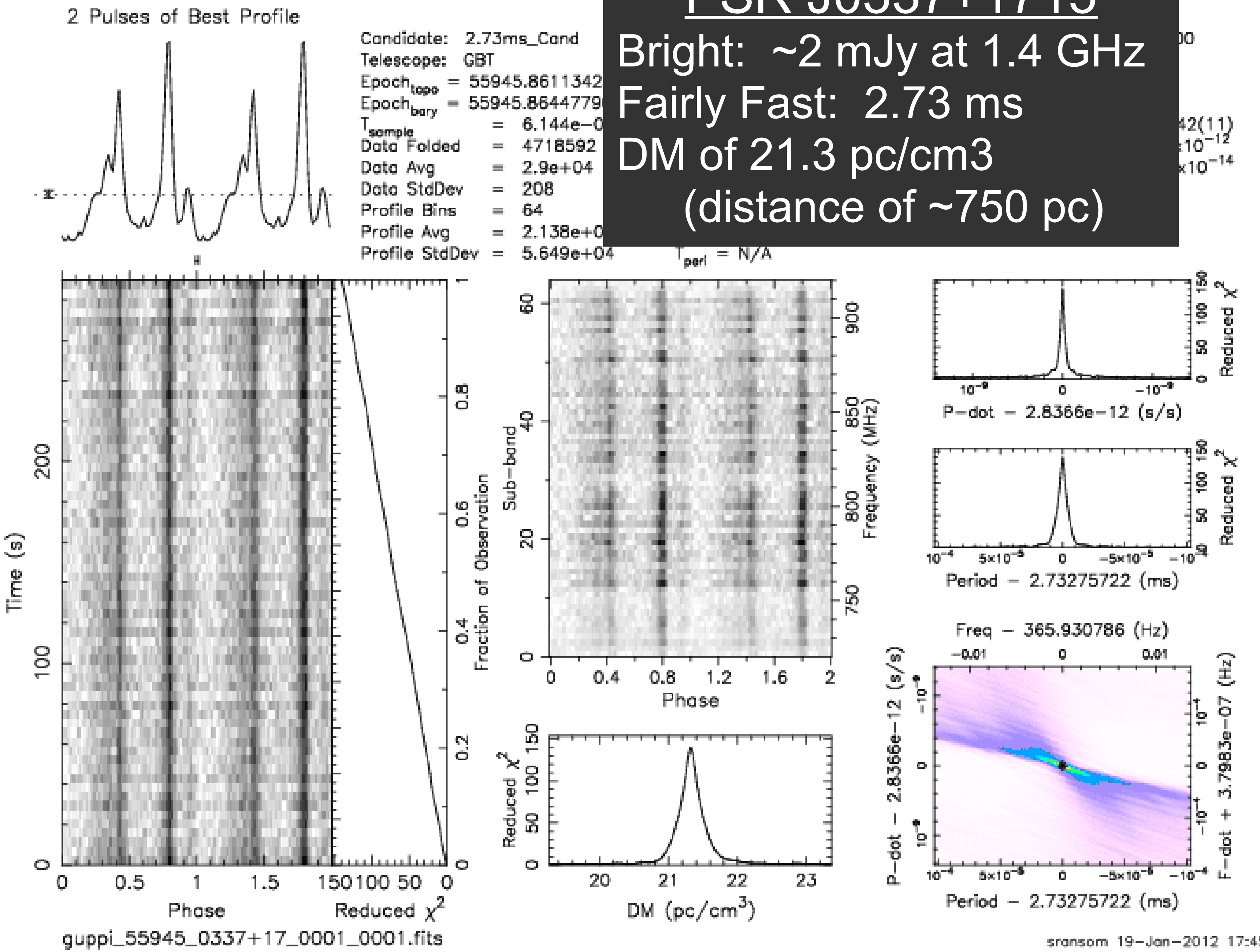
- GBNCC is ongoing... eventual goal to cover the full GBT sky (5000+ hrs: ~37% complete)
- Improved pipeline in place, and cand viewer
- More Fermi searches with 350MHz as well
- Should end up with 40-50 new MSPs in total
- This is an excellent band to search in.
- L-band survey with FLAG in future... (25K!?)
- Still finding cool stuff....

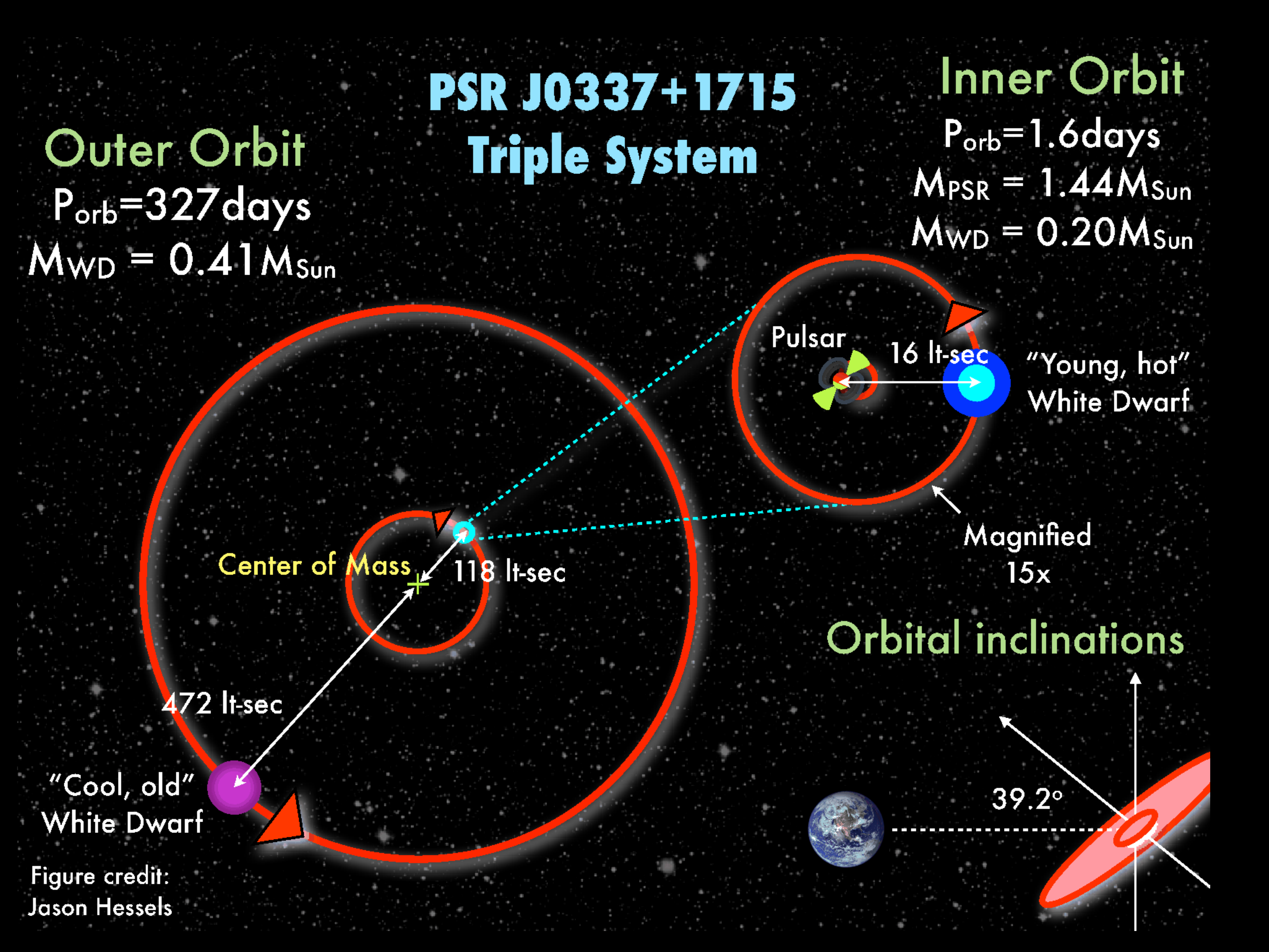
GBT Driftscan discovery by Jason Boyles



PSR J0337+1715

Bright: ~2 mJy at 1.4 GHz
Fairly Fast: 2.73 ms
DM of 21.3 pc/cm3
(distance of ~750 pc)

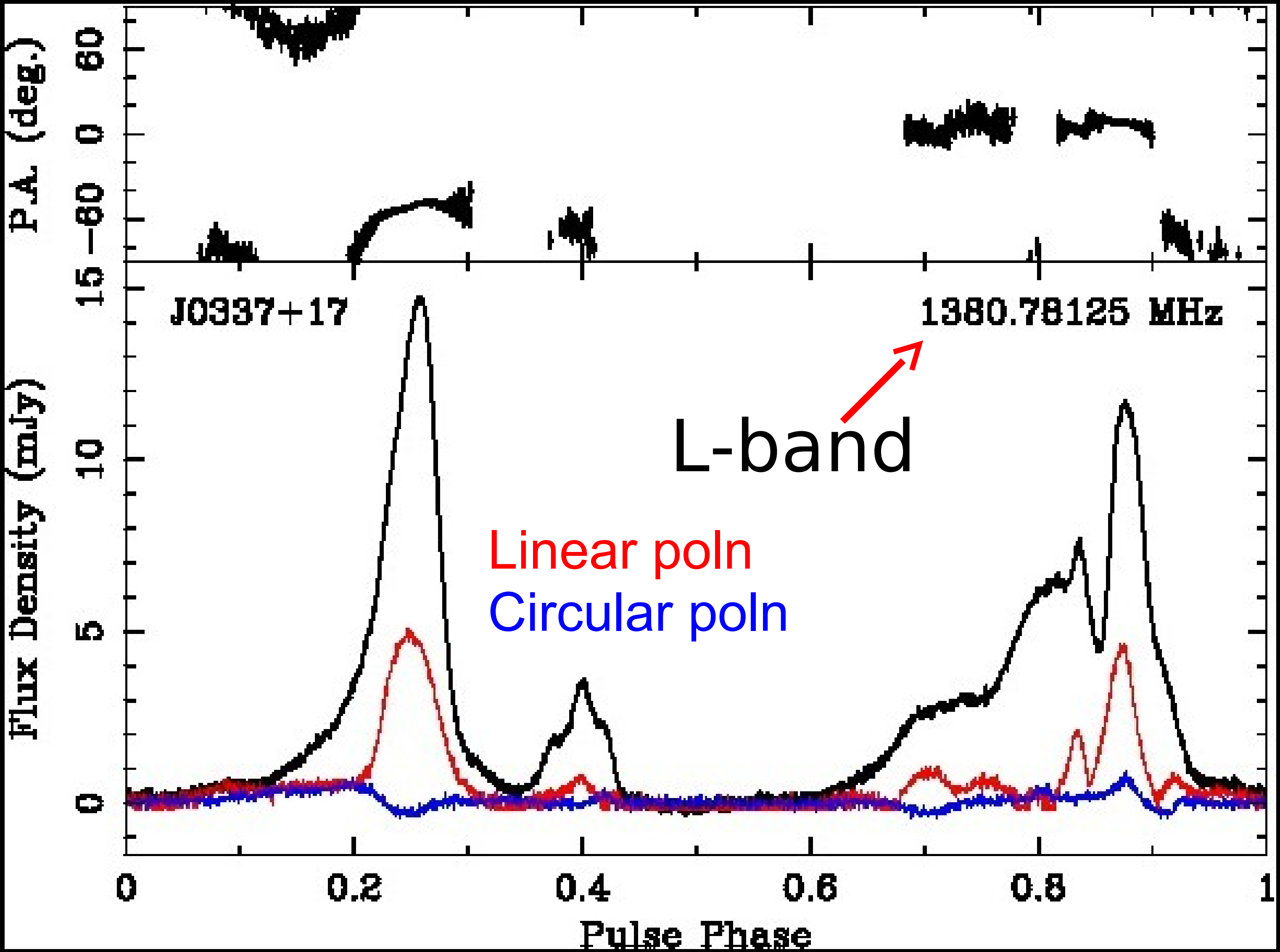



PSR J0337+1715
Triple System
Outer Orbit
P_{orb}=327days
M_{WD} = 0.41M_{Sun}
Inner Orbit
P_{orb}=1.6days
M_{PSR} = 1.44M_{Sun}
M_{WD} = 0.20M_{Sun}
Pulsar
16 lt-sec
"Young, hot" White Dwarf
Magnified 15x
Center of Mass
118 lt-sec
472 lt-sec
"Cool, old" White Dwarf
Orbital inclinations
39.2°
Figure credit: Jason Hessels

Arecibo PUPPI observations:

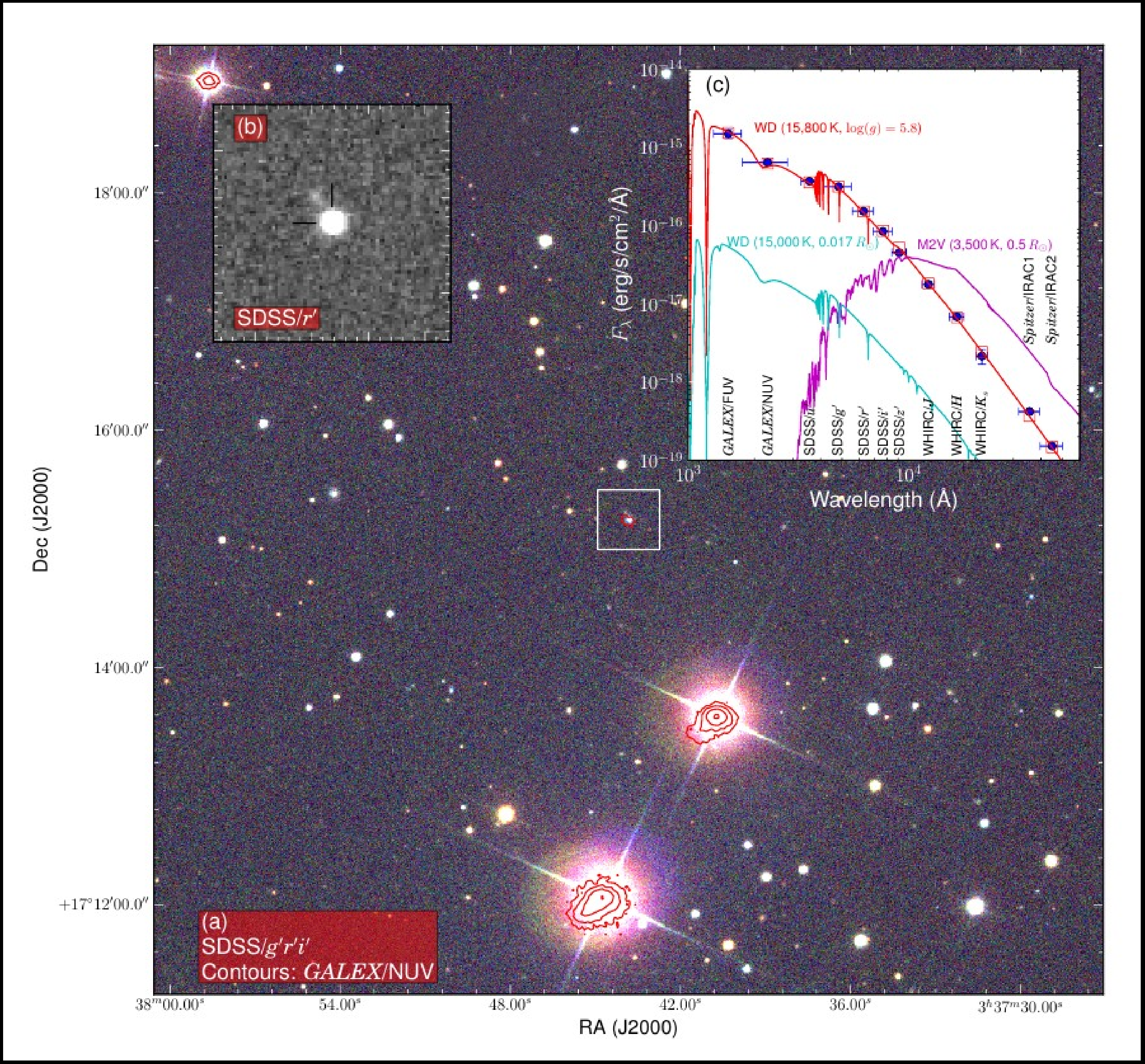
~0.8μs TOAs in 10 seconds (from ~13,000 TOAs)!

Likely a ~100ns MSP or better!



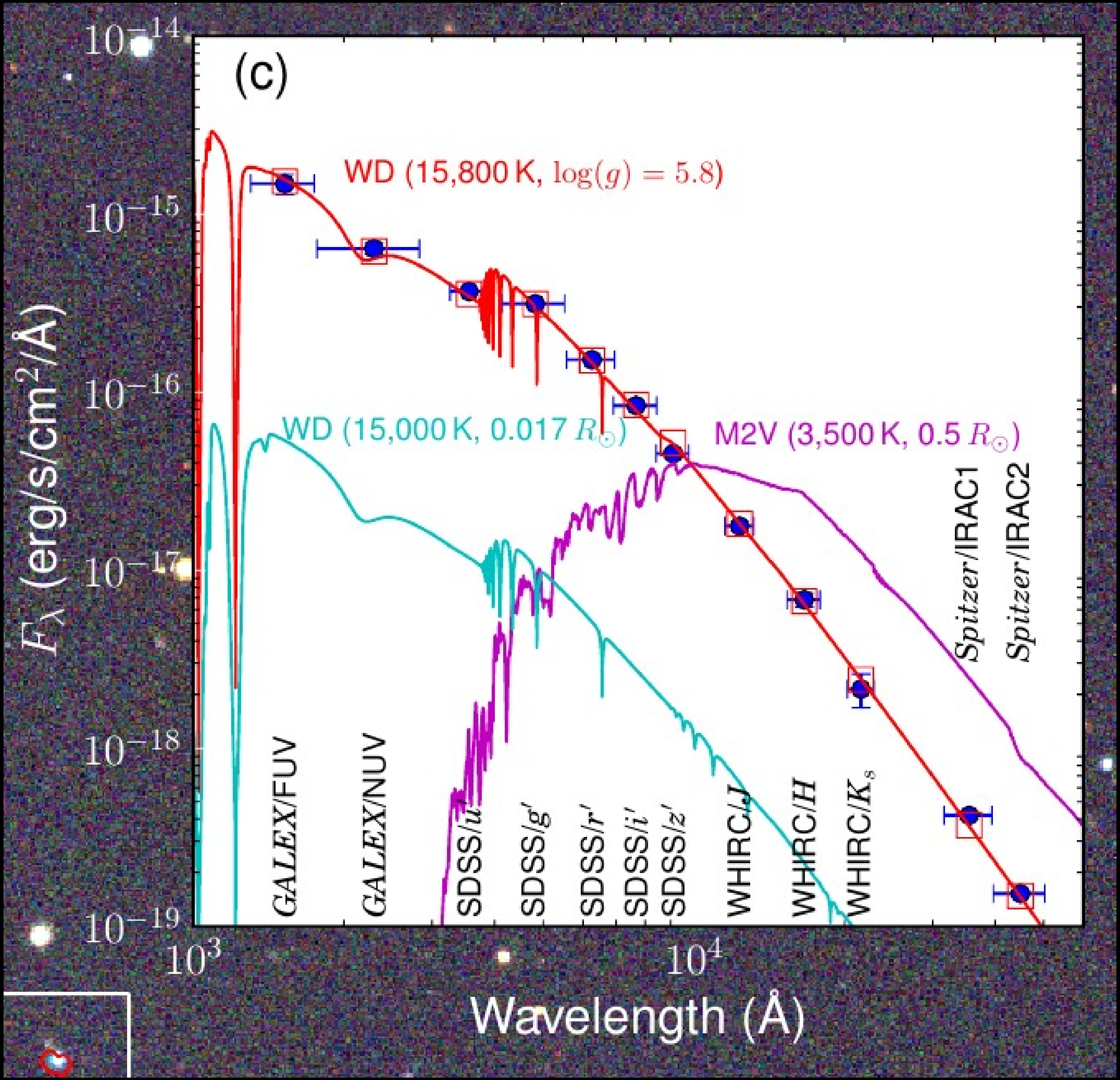
Optical Counterpart in SDSS etc...

18-19 mag
GALEX source

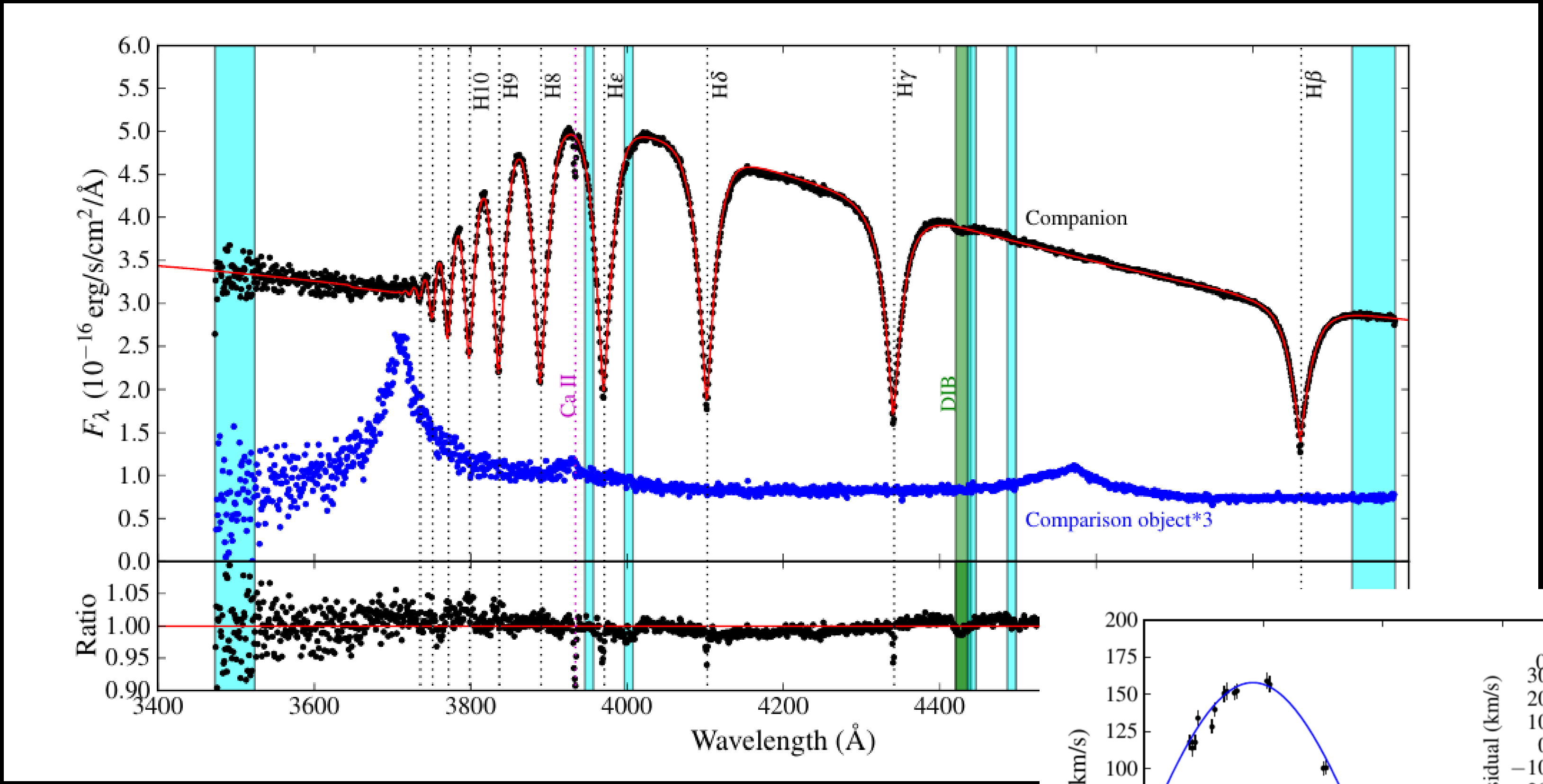


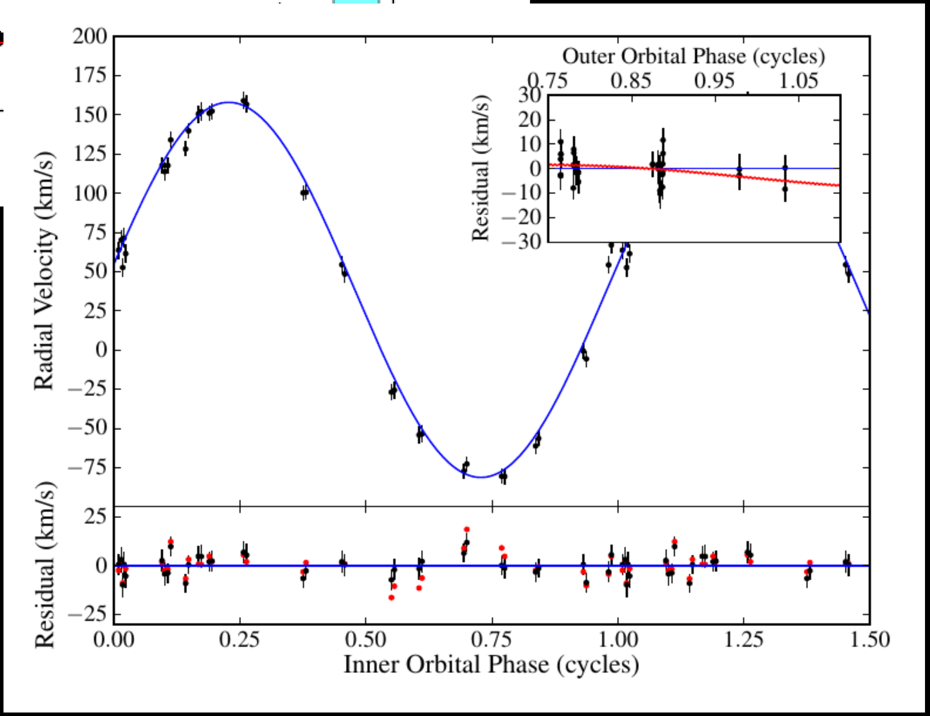
Optical Counterpart in SDSS etc...

18-19 mag
GALEX source
Outer star is WD



Optical spectroscopy on inner WD...





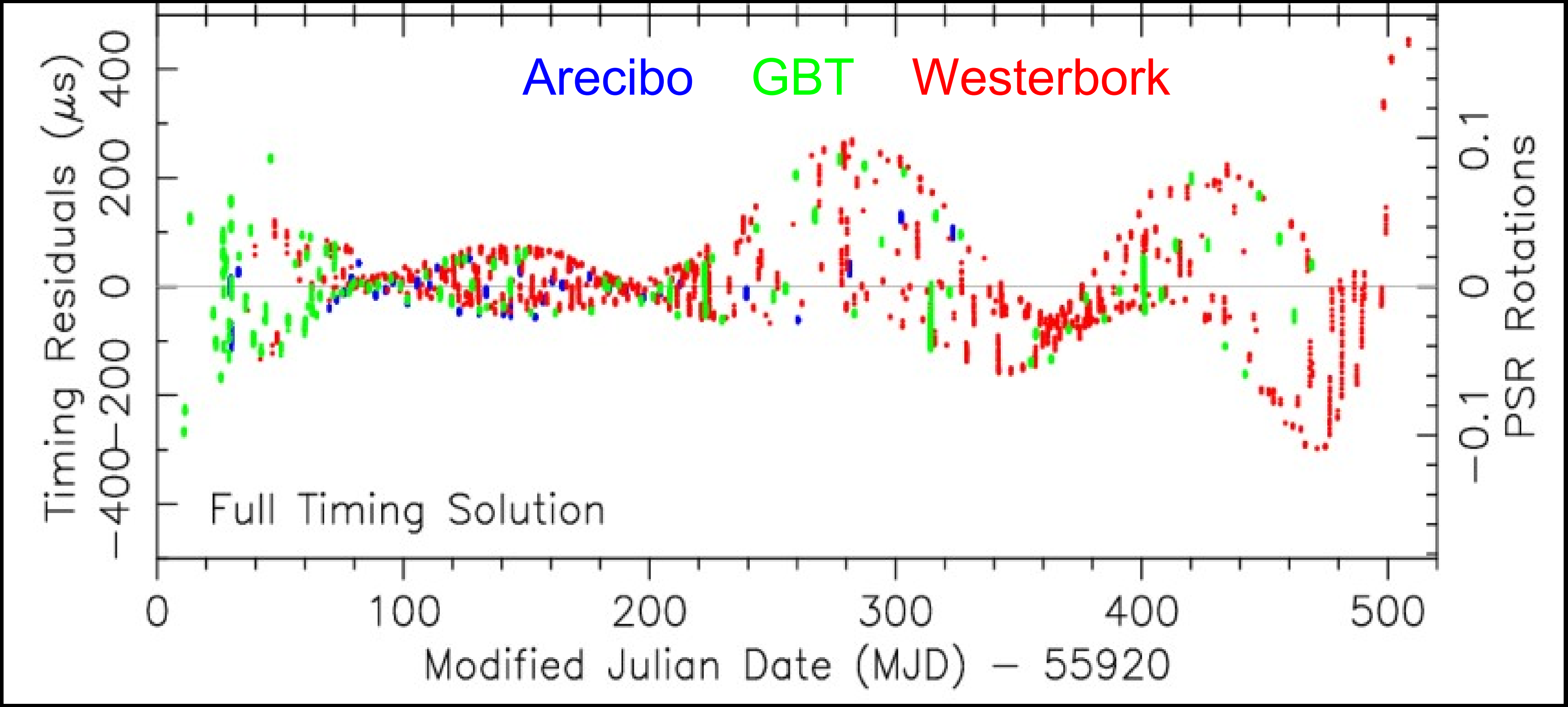
Teff = 15,800K log(g) = 5.82
Therefore He WD of 0.15-0.2 Msun
RVs give mass ratio of 7.32+/-0.08
W/ timing masses, gives ~6% radius:

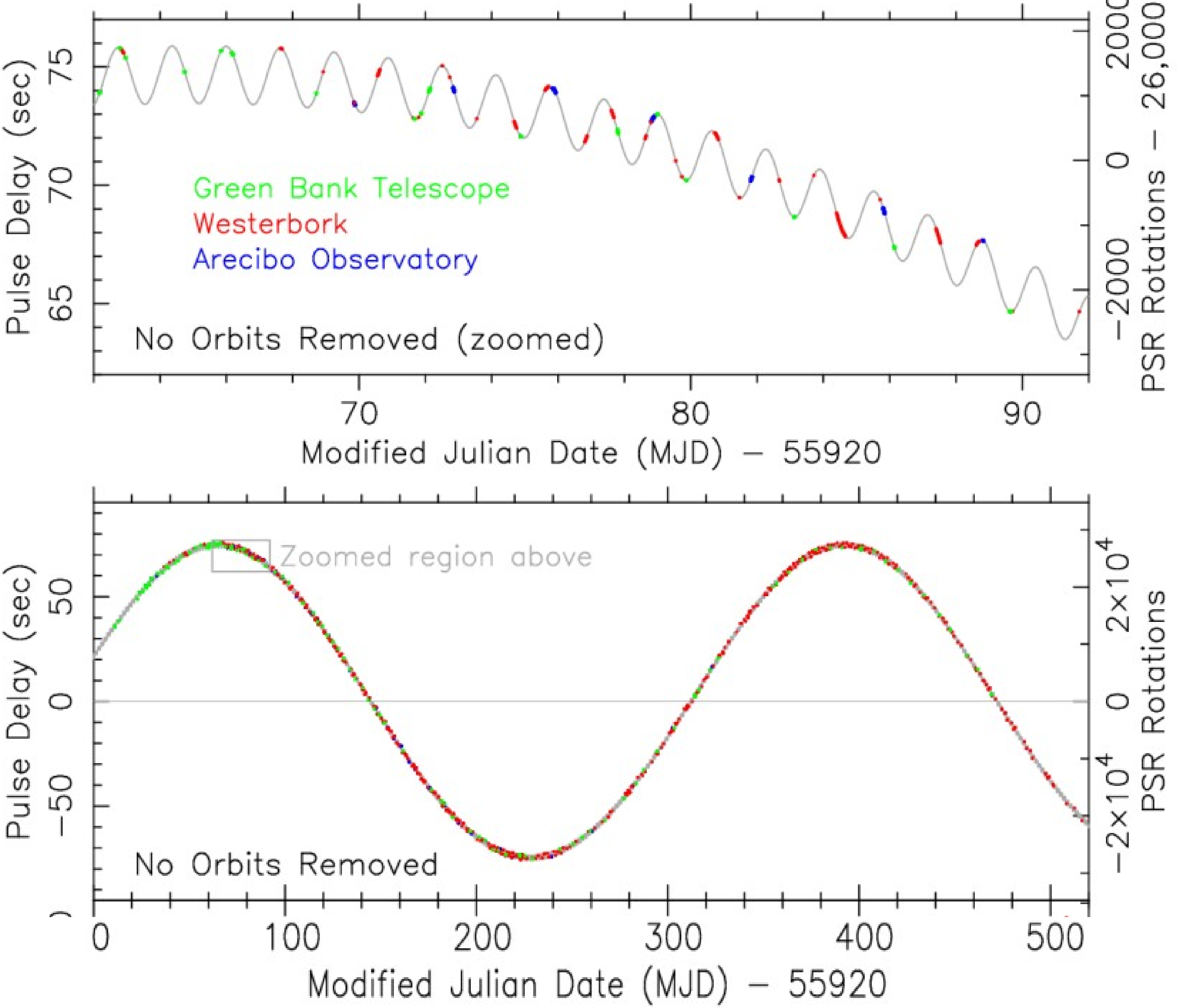
D = 1,300+/-80 pc

Kaplan, van Kerkwijk et al in prep.

Marten van Kerkwijk made a modified 2 Keplerian orbit model

- The inner orbit's T0 is perturbed by outer orbit
- Keeps phase to within 10% of pulse phase
- Allows real-time folding at observatories



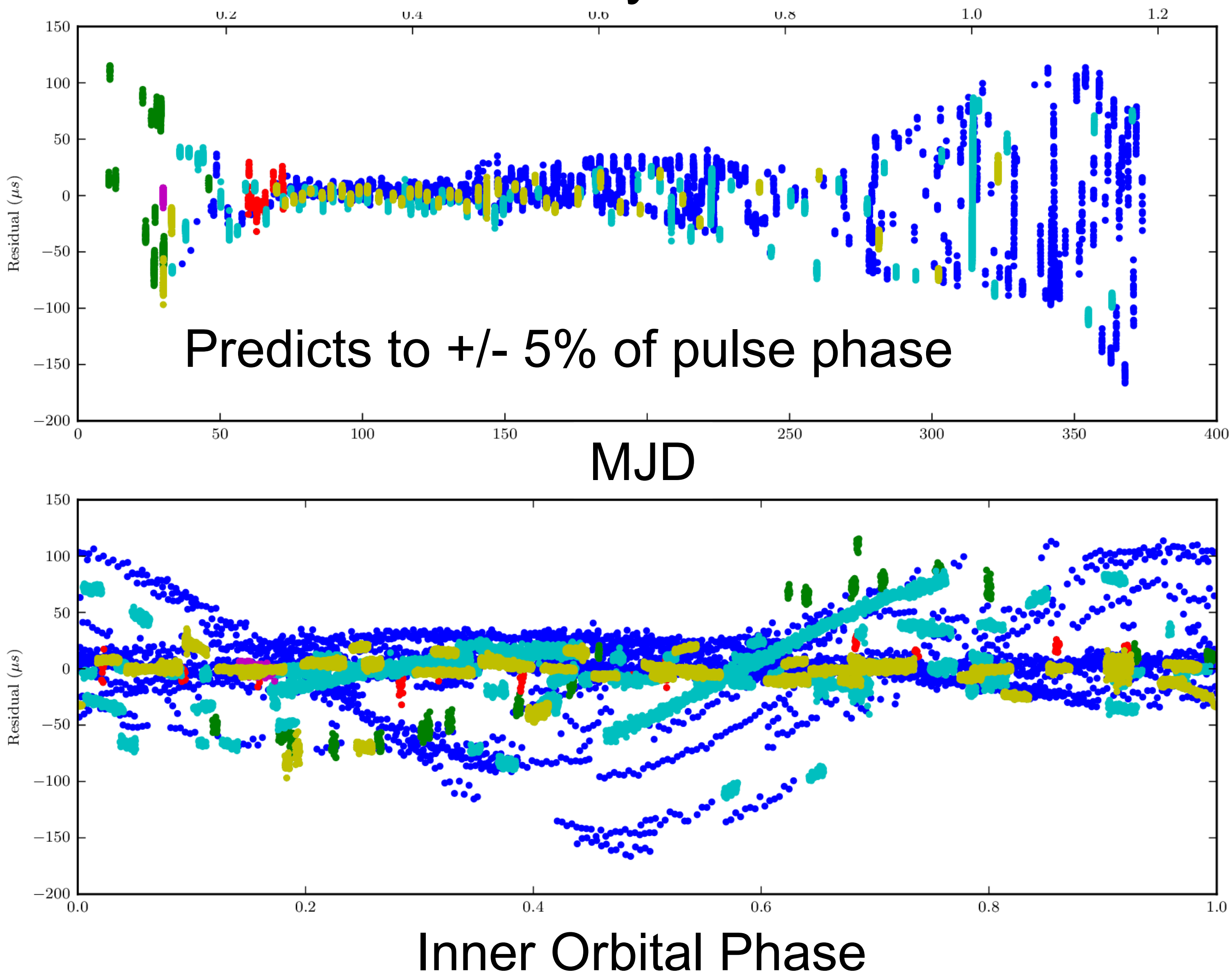


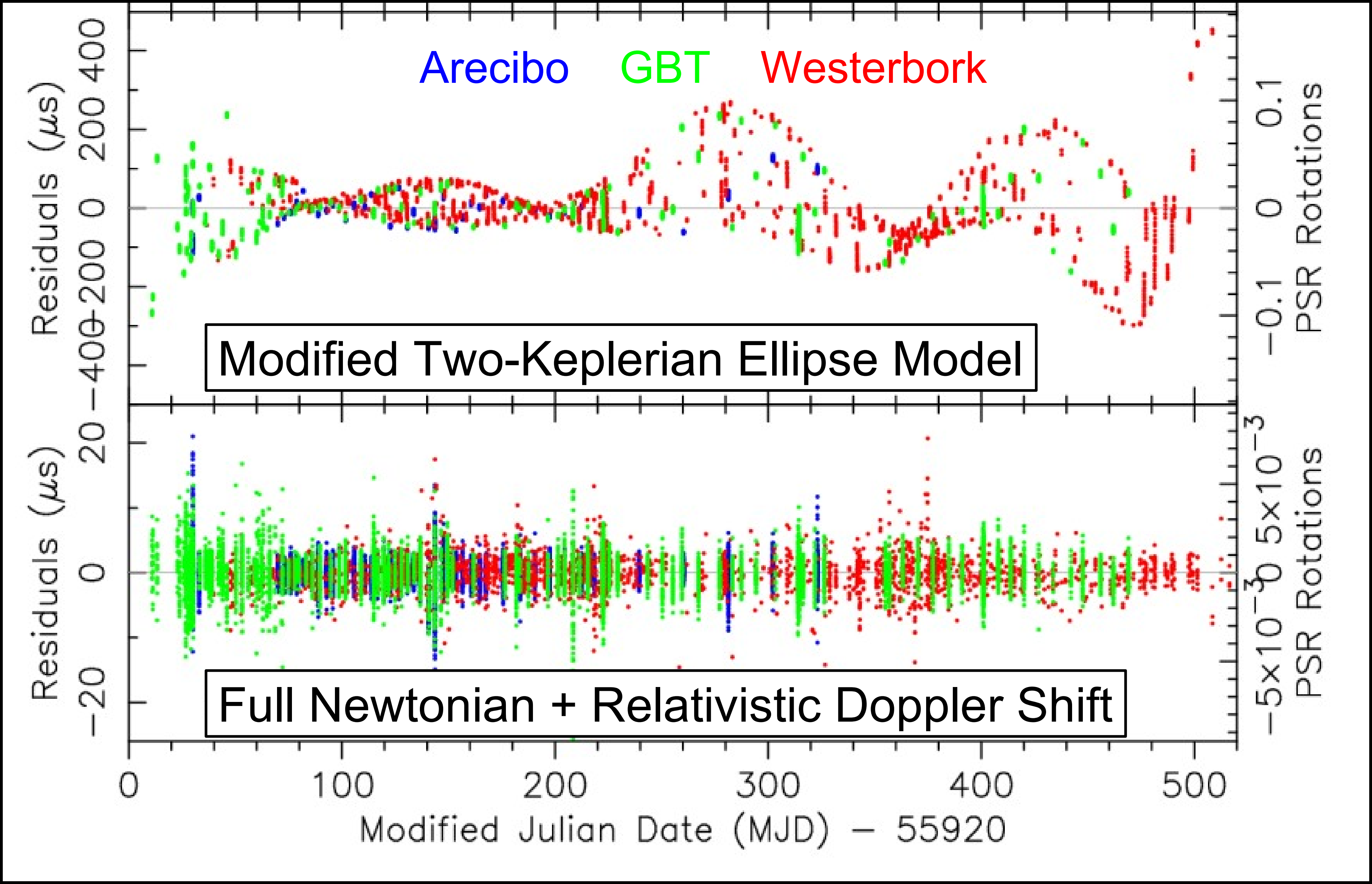
Pulse Delay (sec)
PSR Rotations − 26,000
Green Bank Telescope
Westerbork
Arecibo Observatory
No Orbits Removed (zoomed)
Modified Julian Date (MJD) − 55920
Pulse Delay (sec)
PSR Rotations
Zoomed region above
No Orbits Removed
Modified Julian Date (MJD) − 55920

Major timing breakthrough!
by Anne Archibald

- We can't get “normal” pulsar timing solution
- Full three-body Newtonian dynamics integrations (using long double), fit to phase-connected timing data
- Huge dynamic range: microsecond arrival times over more than 1 year (10^{13})
- Was able to get a good fit....

Pure Newtonian 3-body solution

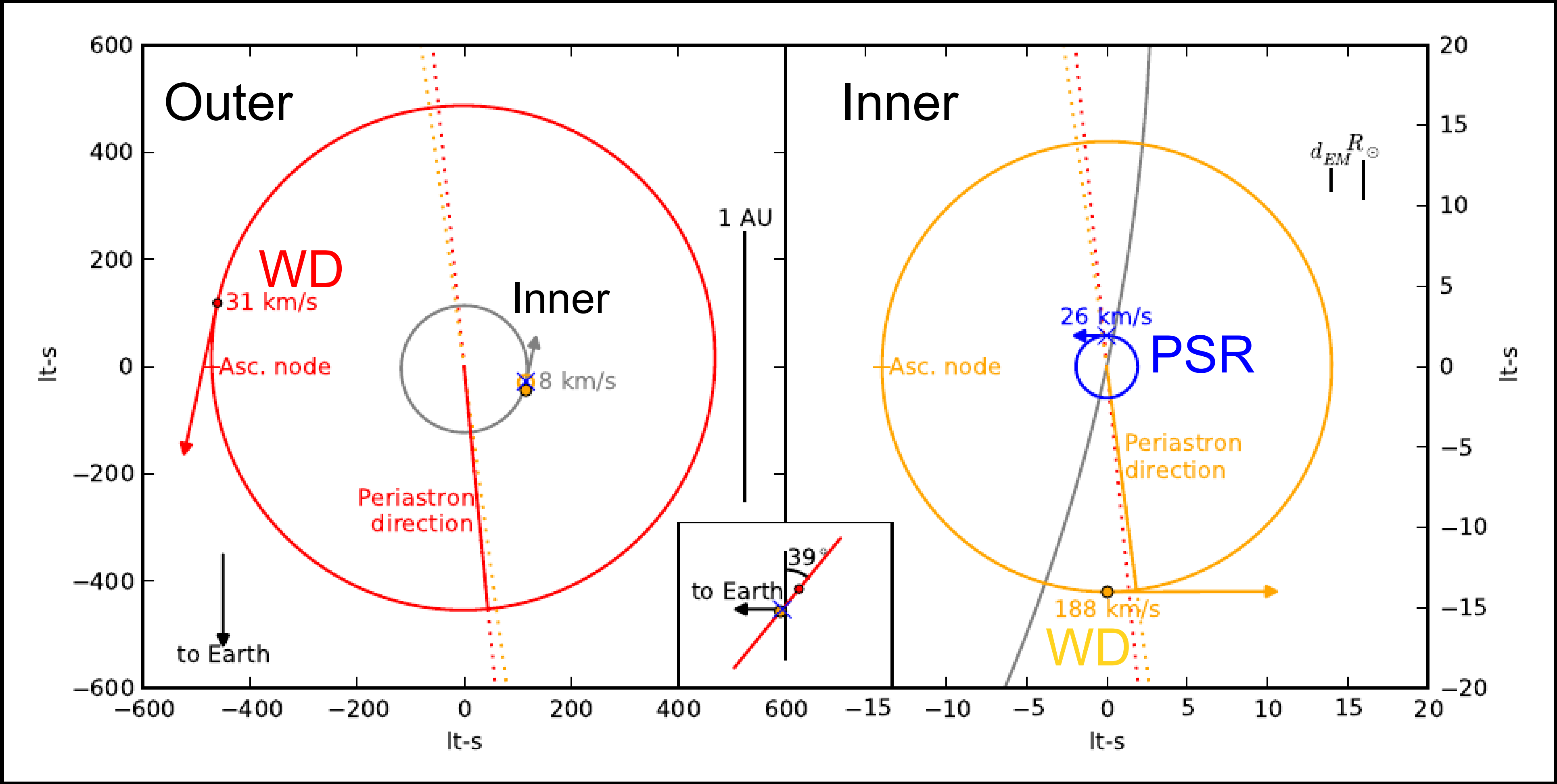




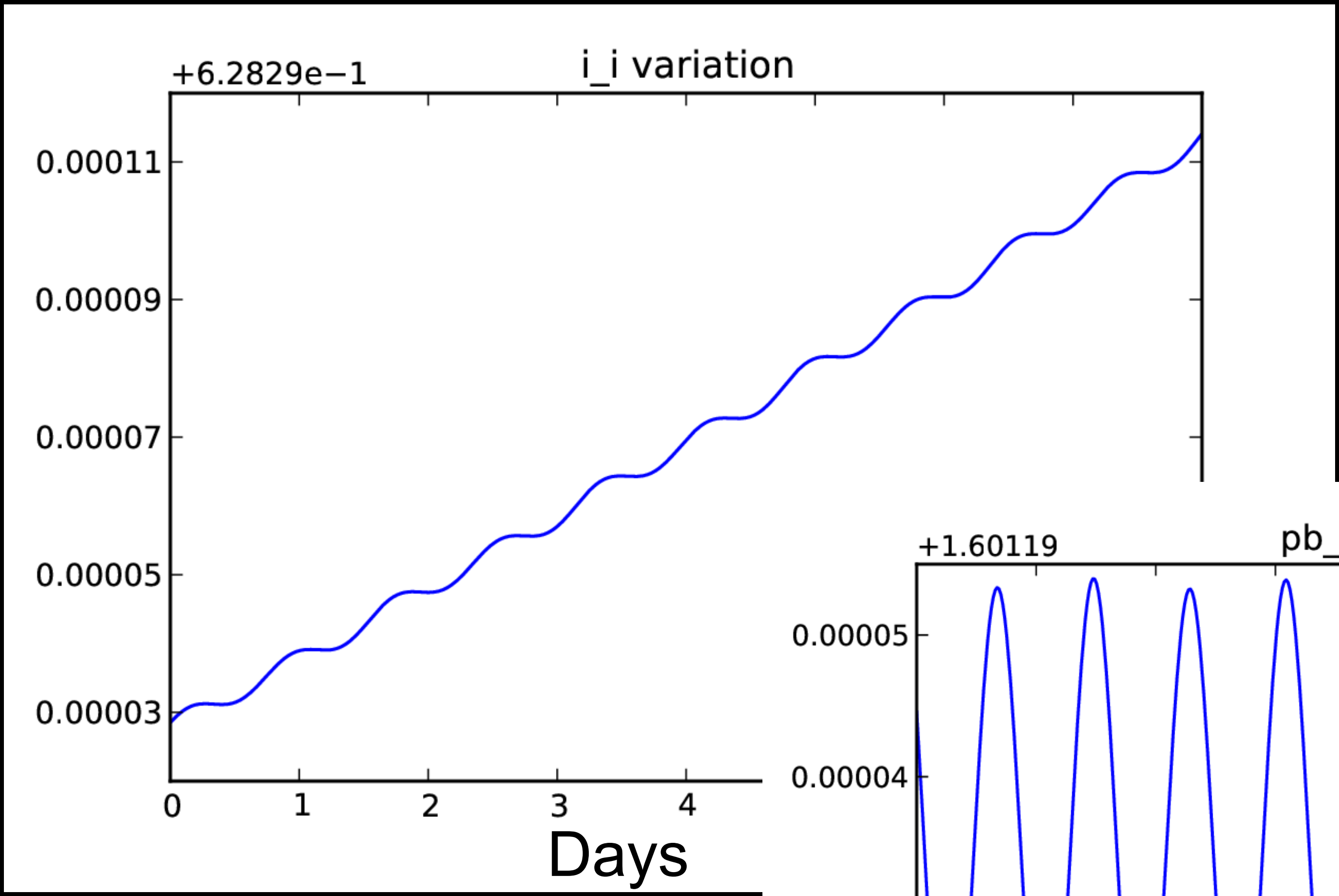
~1.34us weighted RMS for 26,260 TOAs!

PSR J0337+1715: fully solved!

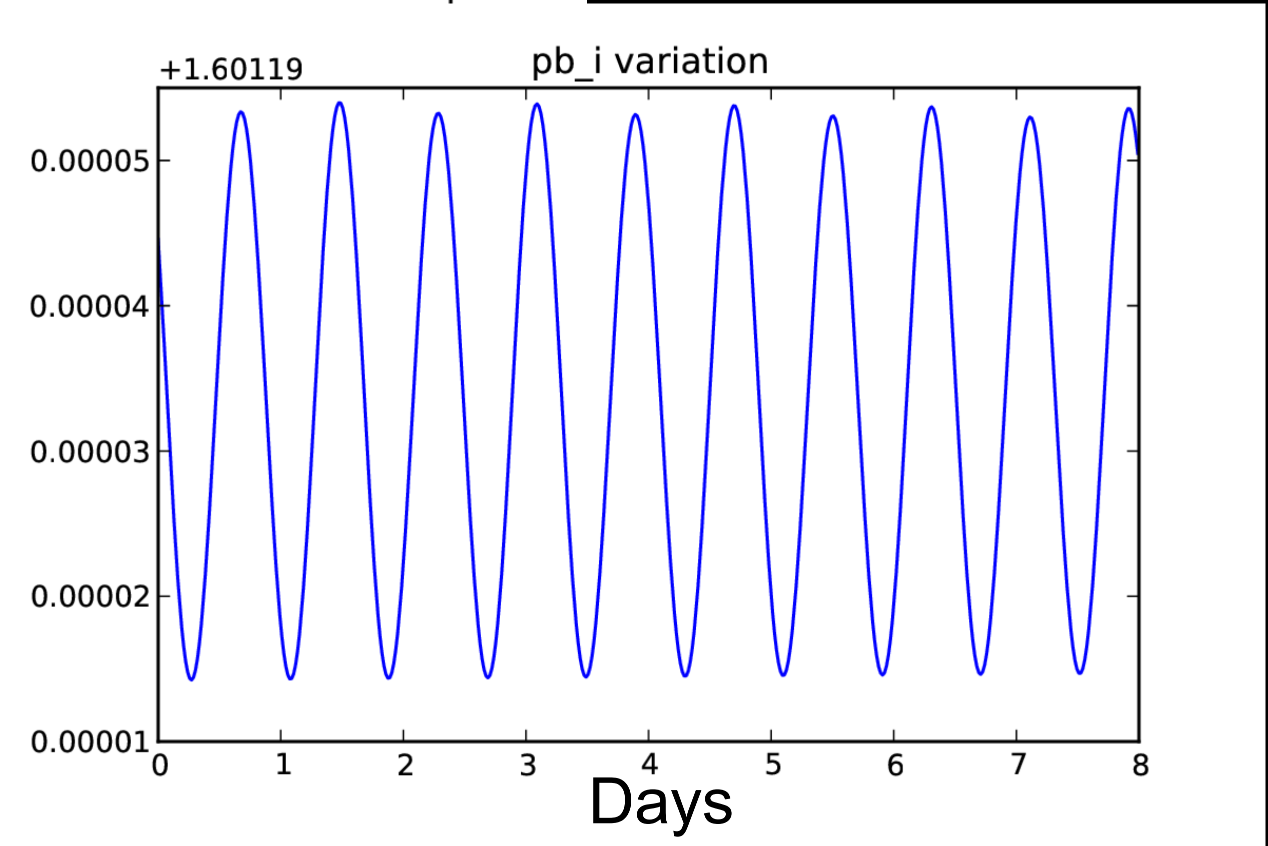
- High precision masses: Mpsr = 1.4378(13) Msun
  Mwd_i = 0.19751(15) Msun   Mwd_o = 0.4101(3) Msun
- Orbits are co-planar to < 0.02 deg! (*i* = 39.24 deg)
- Apsides aligned (despite e_i ~ 7x10^{-4} and e_o ~ 0.035!)



Changing inner inclination and period



Osculating orbital elements



Variations at ½ orbital periods of both inner and outer orbits, as well as secular effects

VLBA Distance Soon

- Already have 1st epoch of approved VLBA campaign... 1-2% distance on the way (Adam Deller and co)

  - Will be a perfect "calibration" source for low-mass He WD models

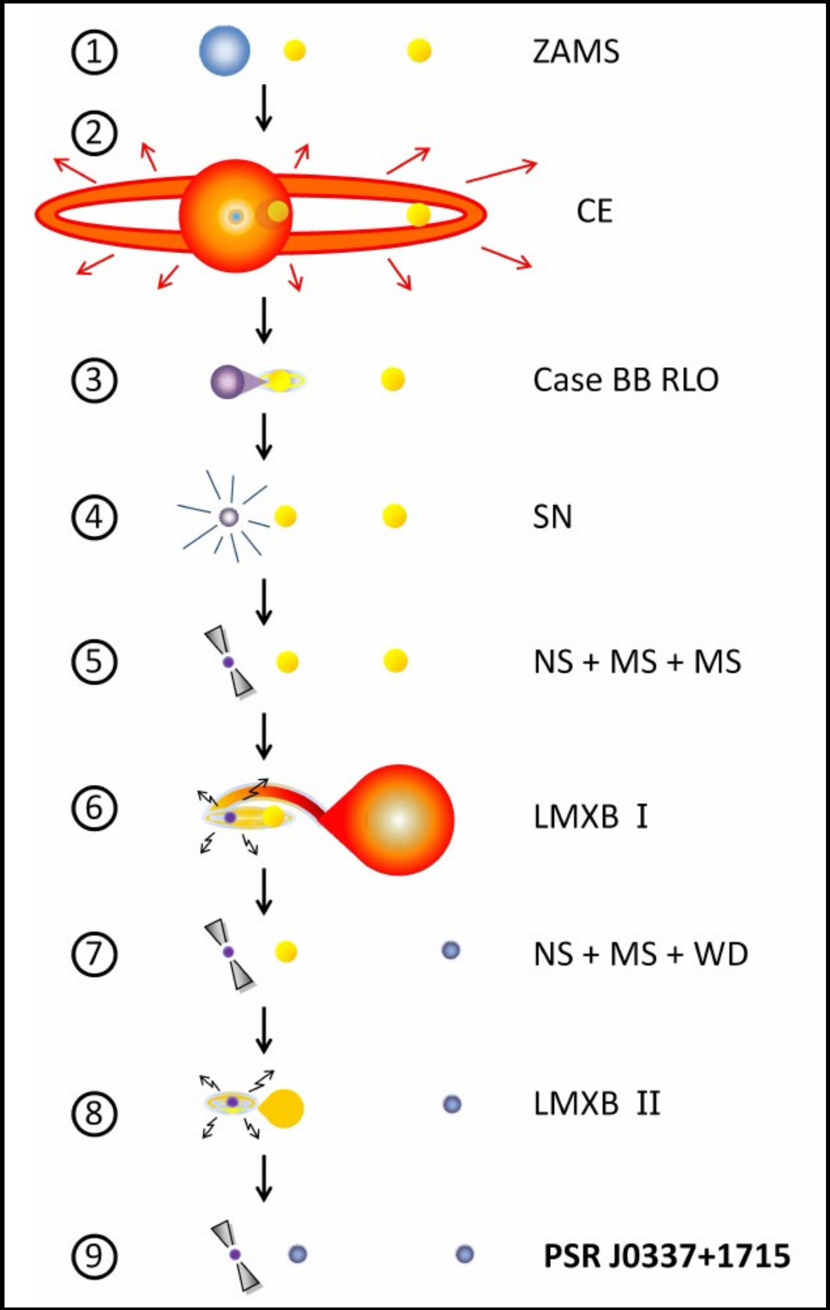
  - Astrometric reflex motion from outer orbit is $\sim 237/D_{kpc}$ μas, easily measurable with VLBA

  - Since size of orbit is known from timing, will also give independent geometric distance

Evolution of system?

- Questions:
  - Why so co-planar?
  - Why so circular?
  - Multiple mass xfers?
- Possible Answers:
  - Common envelope(s?)
  - Mass xfer-ed 3 times!
  - Multiple LMXB phases
  - WDs fall on predicted mass/Porb relation

Tauris and van den Heuvel, 2013, ApJ, submitted



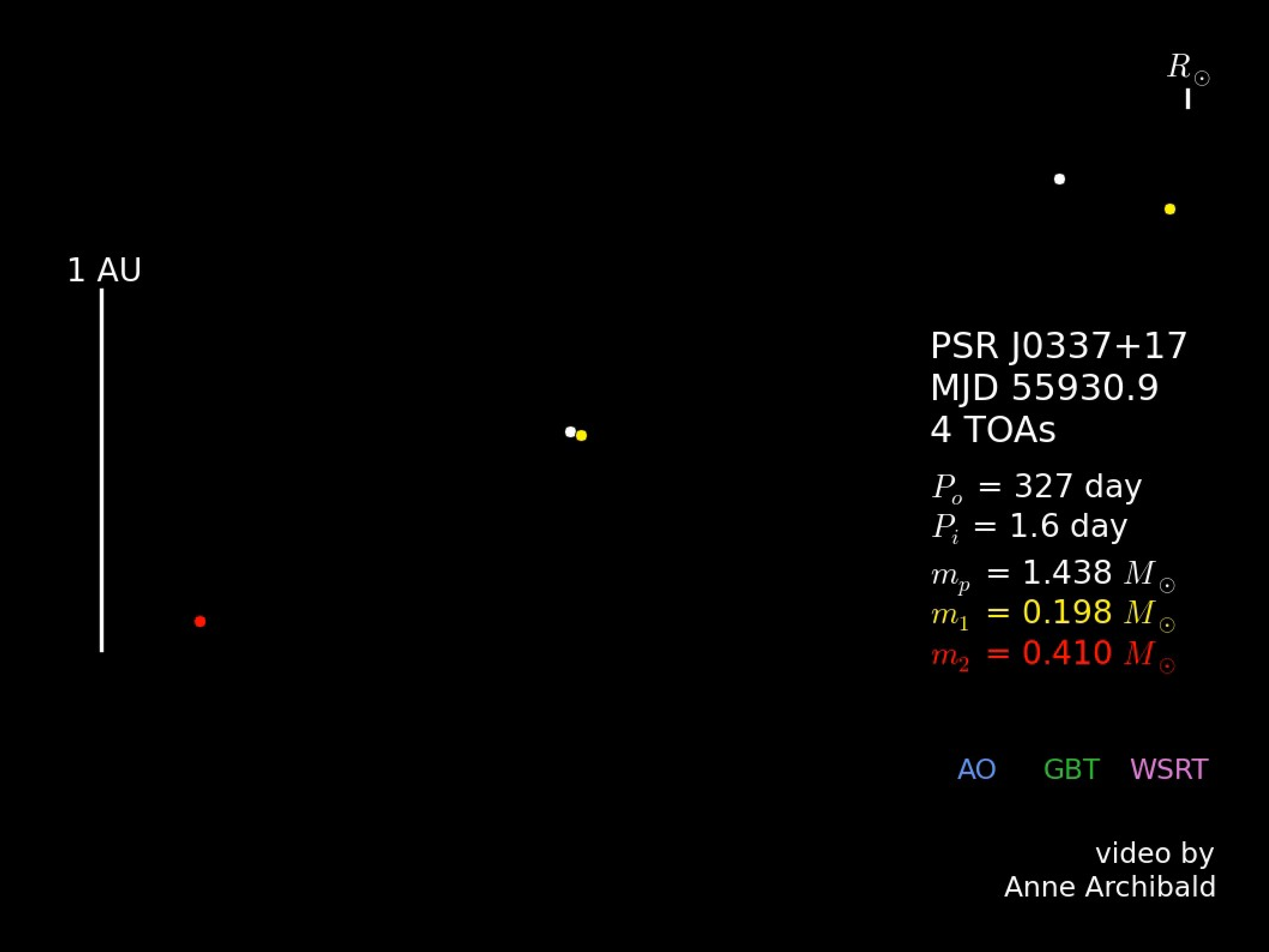
Unique Tests of General Relativity

- Complicated stuff: See C. Will, 2006, LRR
- Strong Equivalence Principle
  - Weak Equivalence Principle ($M_{grav} = M_{inertial}$) holds for self-gravitating bodies as well as test bodies
  - Also local Lorentz and position invariance
- GR is the only viable metric theory that embodies the SEP
- Gravitational binding energy: NS ~ $3GM/5Rc^2 \sim 0.1$
  - For WD ~ 10^{-6}. For planets/moons ~10^{-11} to 10^{-9}.
- NS and inner WD are falling in strong grav field of outer WD
  - G for NS and inner WD should be different if SEP invalid
  - Our tests should be *orders of magnitude* better than others

PSR J0337+1715: Summary

- A unique, clean, and beautiful 3-body system
- Has already provided extremely precise masses and inclinations via model-independent gravitational effects
- Will provide:
  - High precision, clean examples of 3-body perturbations
  - Excellent calibration of low-mass WD models
  - Much fodder for binary / stellar evolution models
  - High-precision tests of the Strong Equivalence Principle
  - Potentially one of the best timing pulsars in NANOGrav

Ransom et al. Nature, submitted


$R_\odot$
1 AU
PSR J0337+17
MJD 55930.9
4 TOAs
P_o = 327 day
P_i = 1.6 day
m_p = 1.438 $M_\odot$
m_1 = 0.198 $M_\odot$
m_2 = 0.410 $M_\odot$
AO
GBT
WSRT
video by
Anne Archibald