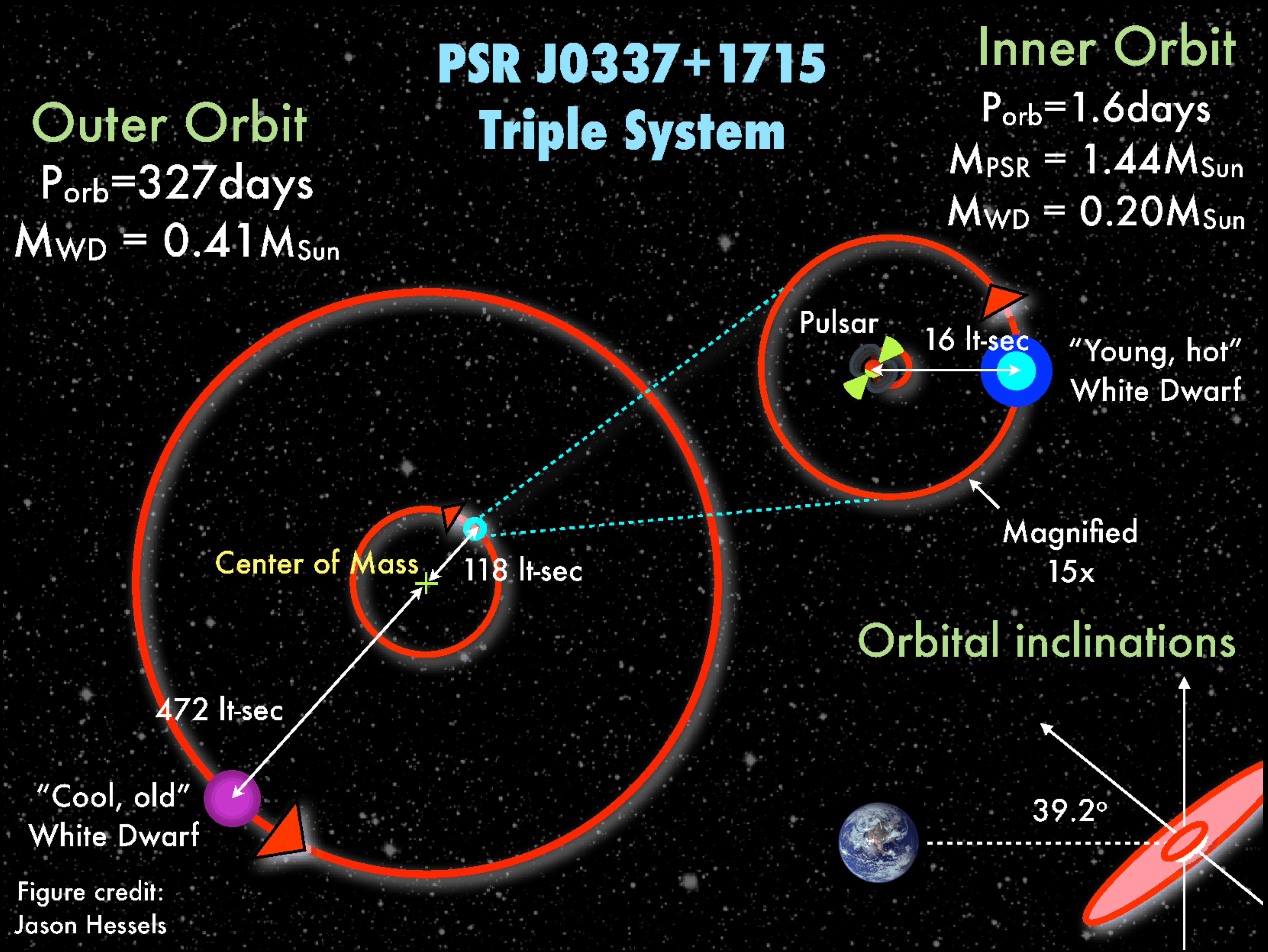
A Millisecond Pulsar in a Stellar Triple System

Scott Ransom

With Ingrid Stairs, Anne Archibald, Jason Hessels, David Kaplan, Marten van Kerkwijk, Jason Boyles, Adam Deller, Shami Chatterjee, Ryan Lynch, Duncan Lorimer and other members of the GBT Drift-scan collaboration (including Vicky Kaspi!)

Ransom et al. Nature, in press (Due 8 Jan 2014)

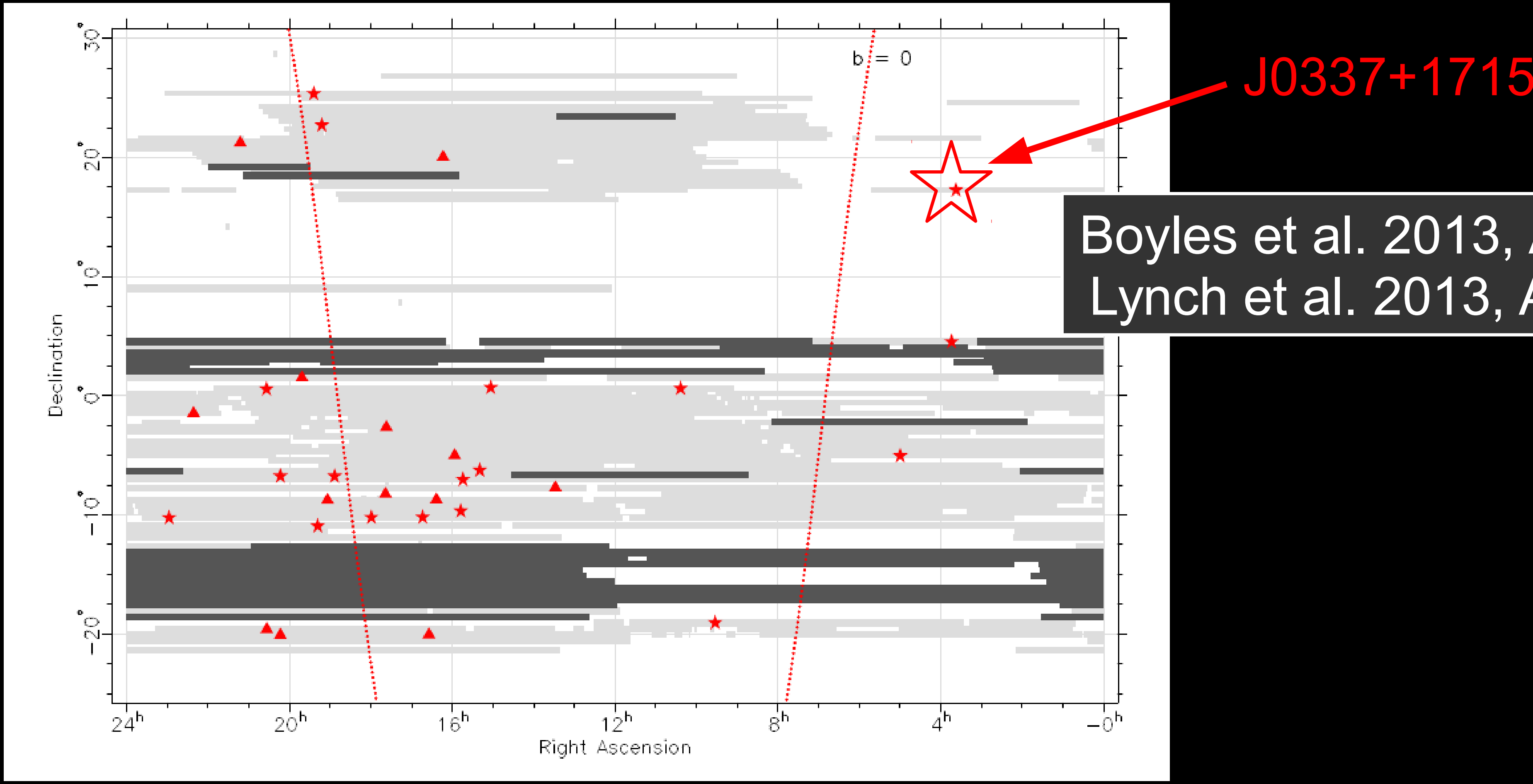

PSR J0337+1715
Triple System
Outer Orbit
P_orb=327days
M_WD = 0.41M_Sun
Inner Orbit
P_orb=1.6days
M_PSR = 1.44M_Sun
M_WD = 0.20M_Sun
Pulsar
16 lt-sec
"Young, hot" White Dwarf
Magnified 15x
Center of Mass
118 lt-sec
472 lt-sec
"Cool, old" White Dwarf
Orbital inclinations
39.2°
Figure credit: Jason Hessels

350MHz Drift Scan Survey during Track Repair

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

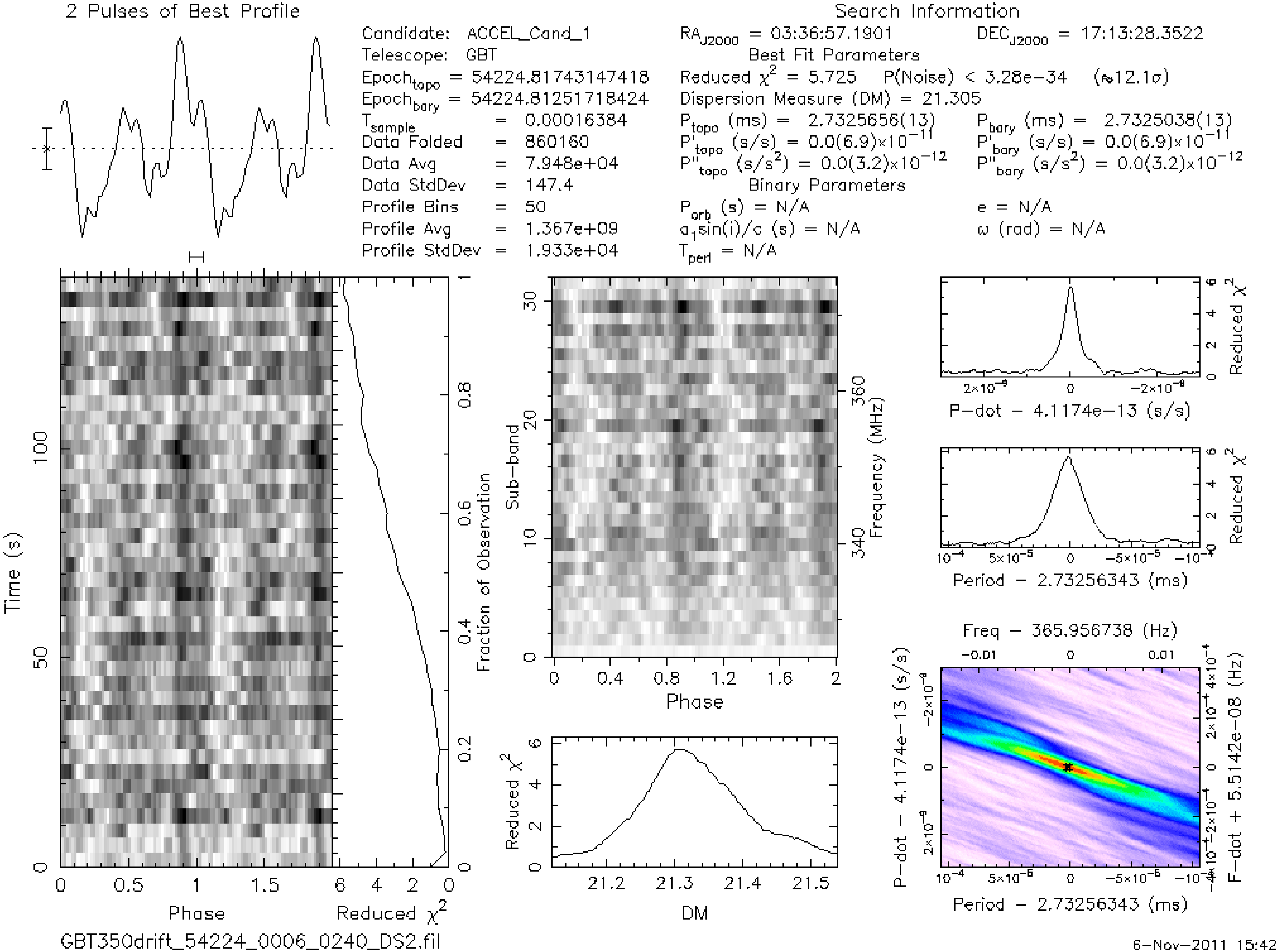
~1350 hrs of obs @25 MB/s ~ 135 TB (~25% of the full sky!)

35 new pulsars, including 7 MSPs plus dozens(?) of RRATs



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

GBT Driftscan discovery by Jason Boyles



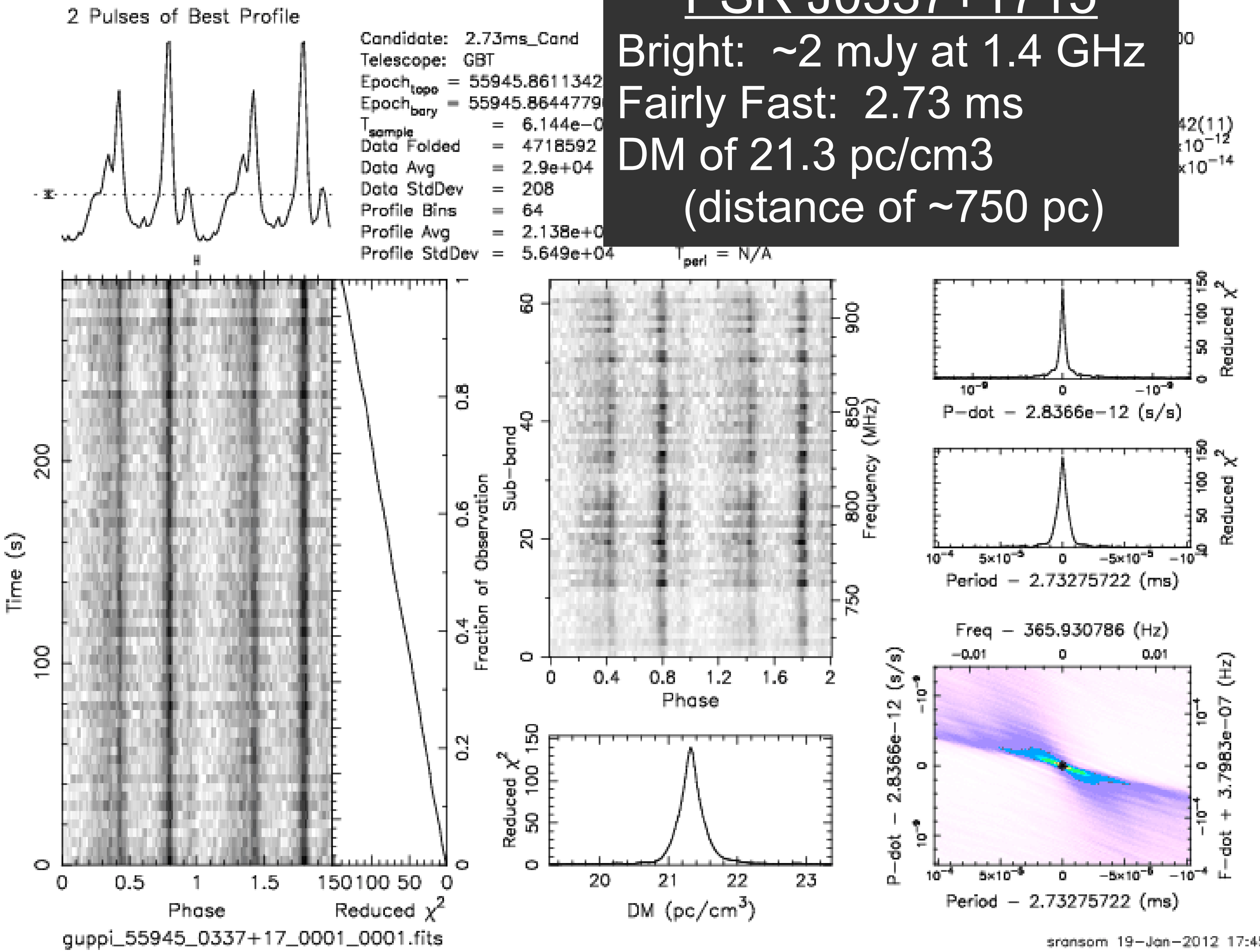
PSR J0337+1715

Bright: ~2 mJy at 1.4 GHz

Fairly Fast: 2.73 ms

DM of 21.3 pc/cm3

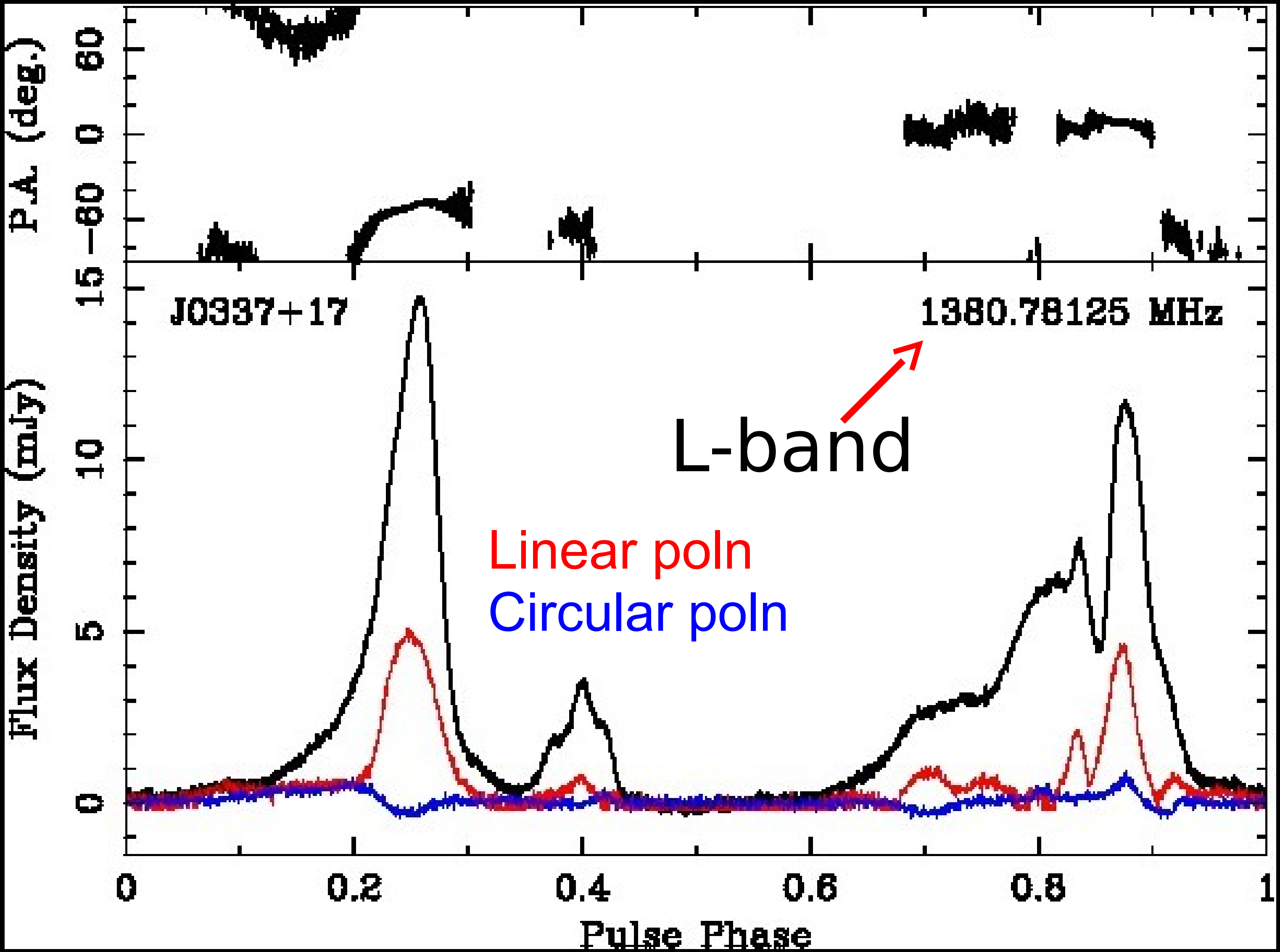
(distance of ~750 pc)



Arecibo PUPPI observations:

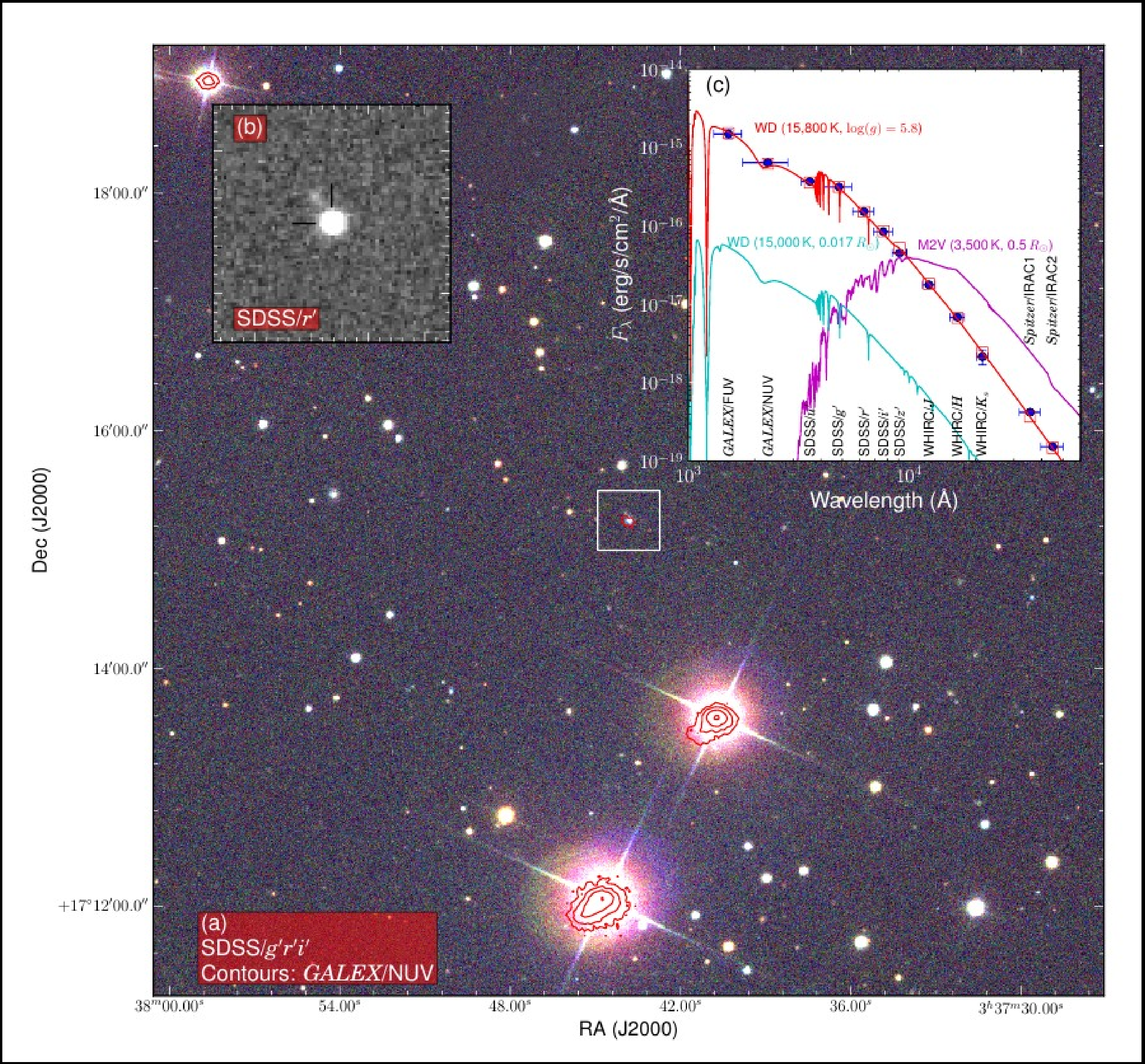
~0.8μs TOAs in 10 seconds (from ~13,000 TOAs)!

Likely a ~100ns MSP or better!



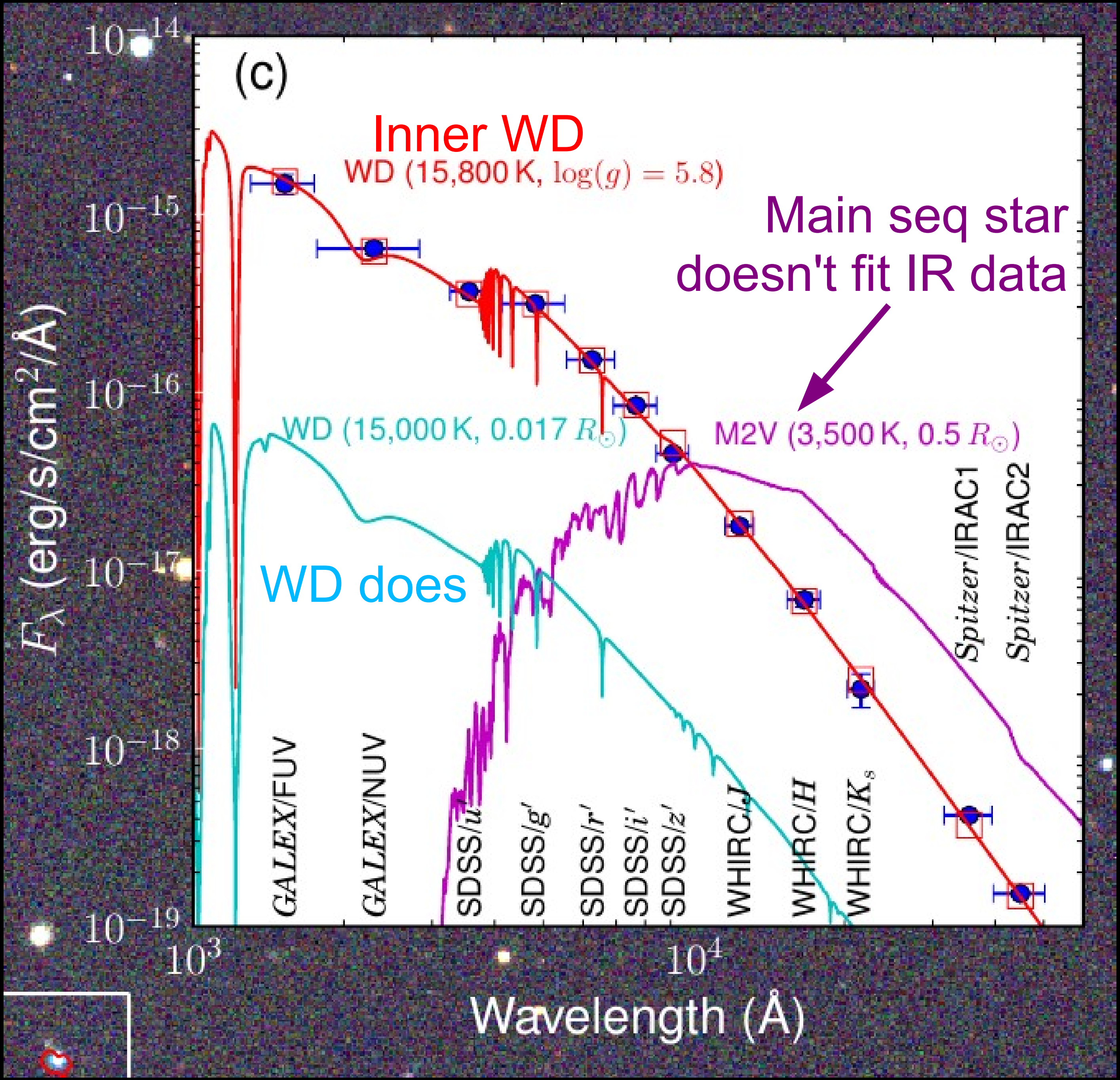
Optical Counterpart in SDSS etc...

18-19 mag
GALEX source

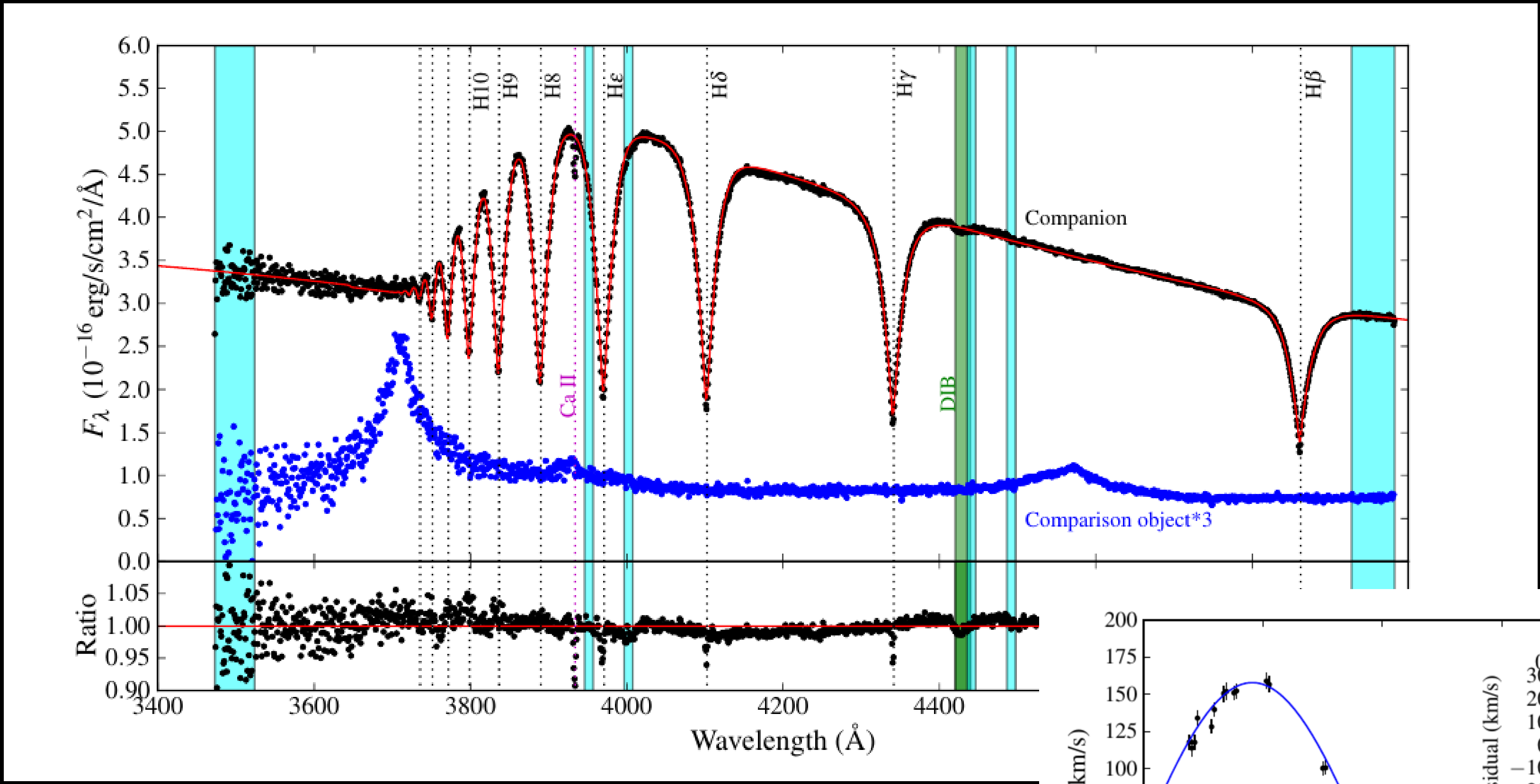


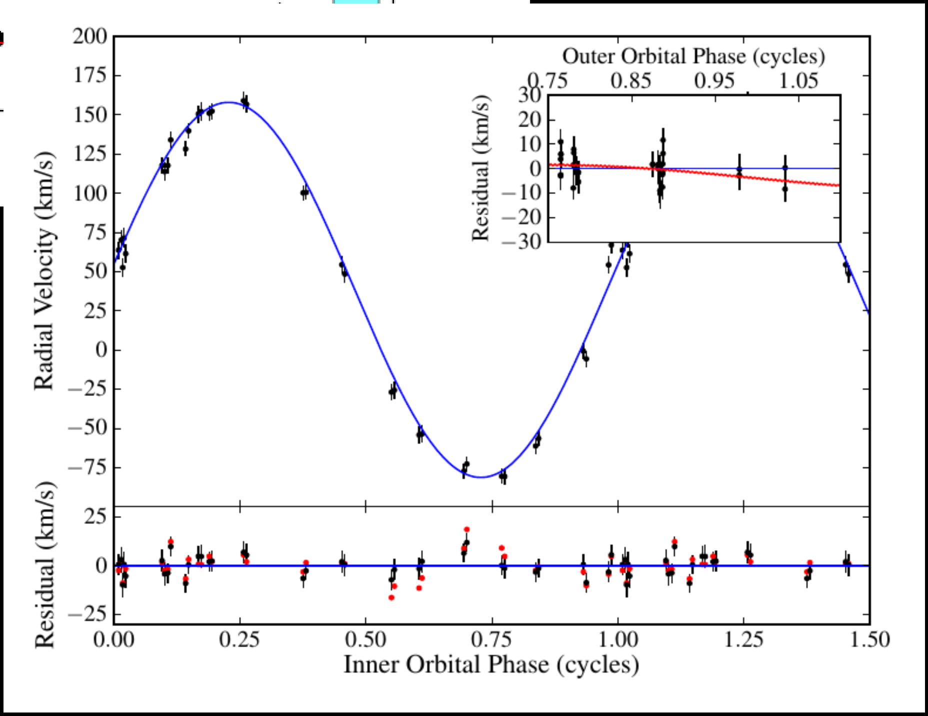
Optical Counterpart in SDSS etc...

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:

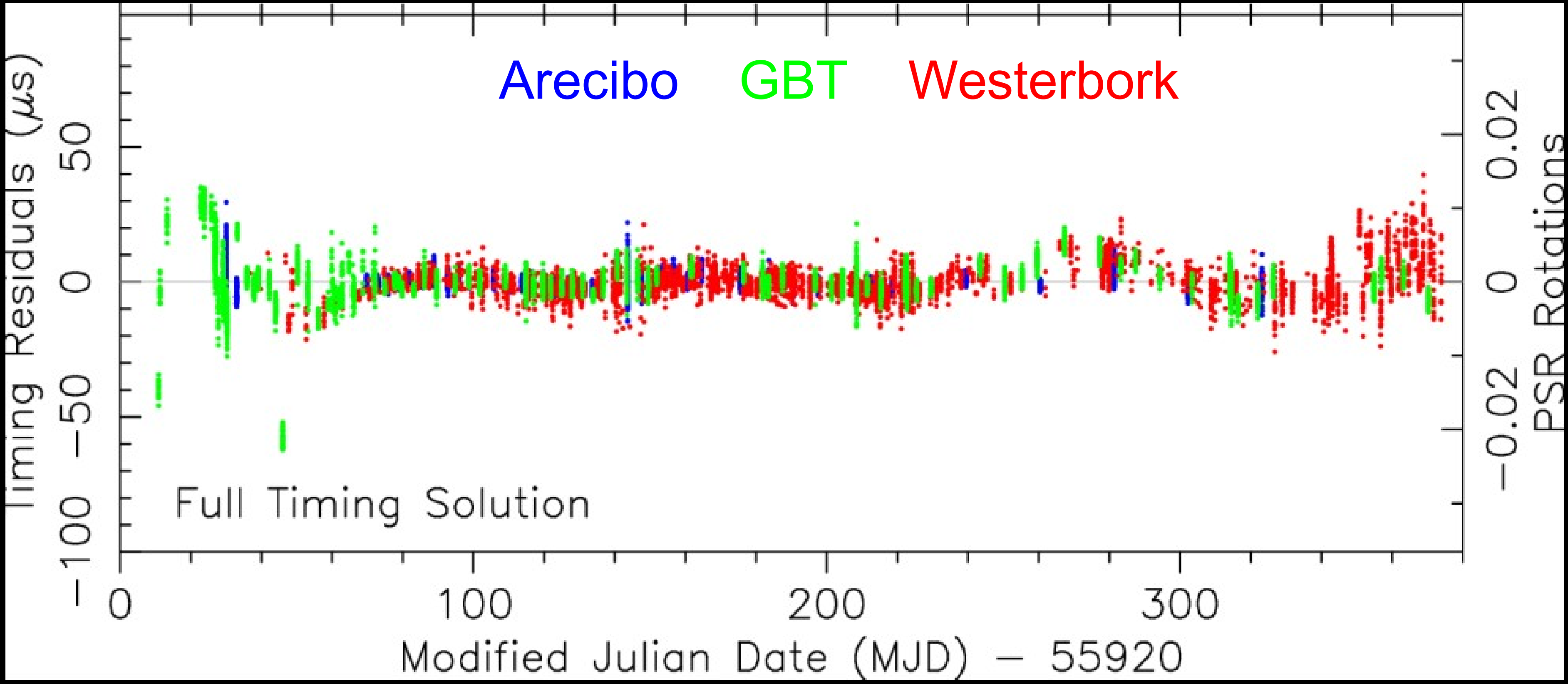
D = 1,300+/-80 pc

Kaplan, van Kerkwijk et al in prep.

Pulsar timing over past 1.5 years...

26,000+ arrival times now cover more than 1 outer orbit

WSRT near daily, GBT weekly, Arecibo every other week



Pu… …ver past 1.5 years...

29,000… …cover more than 1 outer orbit

WSRT… …kly, Arecibo every other week

```
PSR              J0337+17
RAJ         03:37:43.82589000
DECJ          17:15:14.8281000
POSEPOCH           56337.0000
F0       365.9533436144258189  0  0.0000000000656904
F1         7.8335396316700D-15  0  1.490959143049D-17
PEPOCH           56100.000000
START               55930.923
FINISH              56293.906
DM                  21.313000
SOLARN0                 10.00
EPHEM                   DE405
CLK                 UTC(NIST)
NTOA                    25173
TRES                     2.58
TZRMJD   56100.13622674904492
TZRFRQ               1379.999
TZRSITE                     j
NITS                        9
BINARY                    BTX
PLAN   1
A1              1.217519002  0           0.000000028
E               0.0006930546  0          0.0000000360
T0           56100.069980812  0           0.000017193
OM           94.223914360778  0         0.003798095338
OMDOT              5.0402353  0              0.0411788
FB0      7.102810302497D-06  0  3.624766695763D-12
FB1     -2.678657572018D-16  0  1.604430406730D-18
FB2      2.040510792551D-23  0  8.684852611298D-25
FB3      2.107991635896D-29  0  2.924232988033D-31
FB4     -3.647825395913D-36  0  1.899824658464D-37
FB5     -1.901910353912D-42  0  3.524512908951D-44
FB6      6.806285773018D-49  0  2.499637441639D-50
FB7      8.287744673248D-58  0  7.925156422829D-60
XDOT                0.848172  0              0.008998
XDOT2    6.094600874182D-19  0  4.408287558814D-21
XDOT3    4.041033710308D-25  0  2.363736605124D-27
XDOT4    4.115933106721D-32  0  7.928065027946D-34
XDOT5   -8.780341227322D-38  0  5.313279069544D-40
XDOT6   -8.155333445717D-45  0  9.551706225208D-47
XDOT7    9.566677953347D-51  0  7.018937288810D-53
EDOT                3.605679  0              0.014736
EDOT2   -9.267816214308D-19  0  5.701507711604D-21
EDOT3   -2.513015302987D-25  0  2.901568228531D-27
EDOT4    1.011182036574D-31  0  1.119425793782D-33
EDOT5    2.390268070244D-38  0  5.738080634124D-40
EDOT6   -7.689510947189D-45  0  1.432883466762D-46
EDOT7   -1.997419251915D-51  0  7.600536242990D-53
OMDOT2   1.584870327986D-15  0  1.008073928136D-17
OMDOT3  -1.542392073552D-22  0  5.456721771192D-24
OMDOT4  -1.273776352049D-28  0  1.837357300767D-30
OMDOT5   2.374972921499D-35  0  1.193660403351D-36
OMDOT6   1.170599443867D-41  0  2.214679319489D-43
OMDOT7  -4.274713914263D-48  0  1.570497580968D-49
A1_2          74.669547637  0           0.000002110
E_2            0.035345260  0           0.000000005
T0_2       55990.016090114  0           0.000003972
PB_2        327.221472217949  0        0.000003699414
OM_2         95.728375319373  0        0.000004990797
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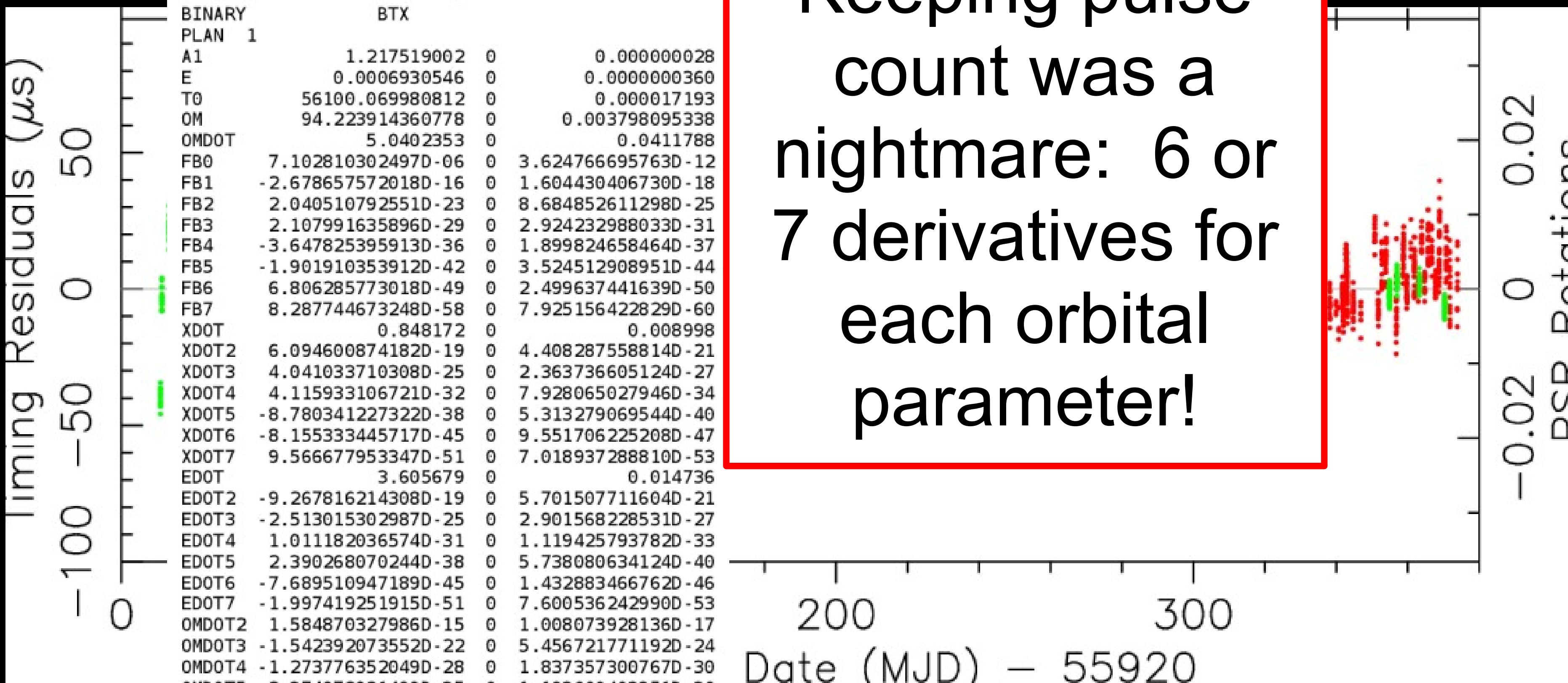
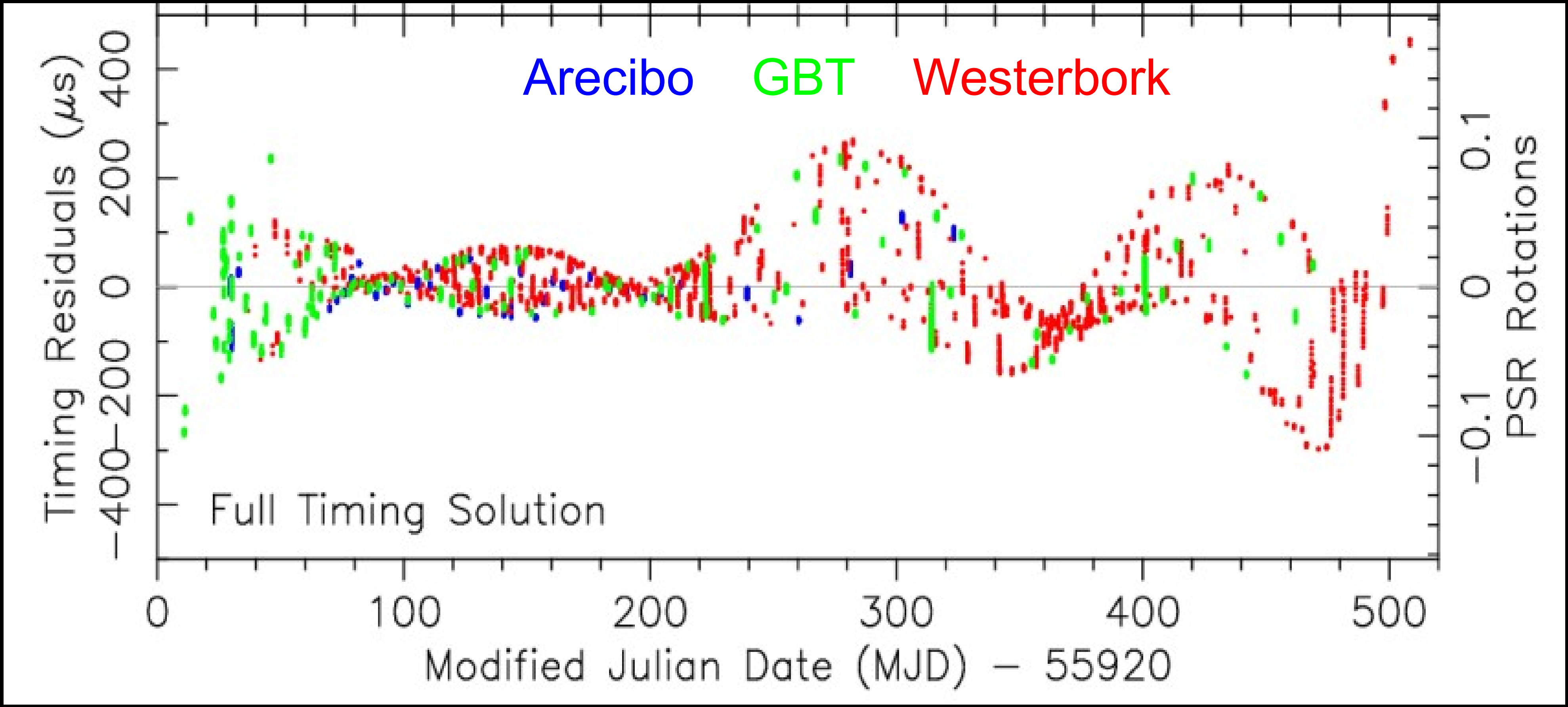
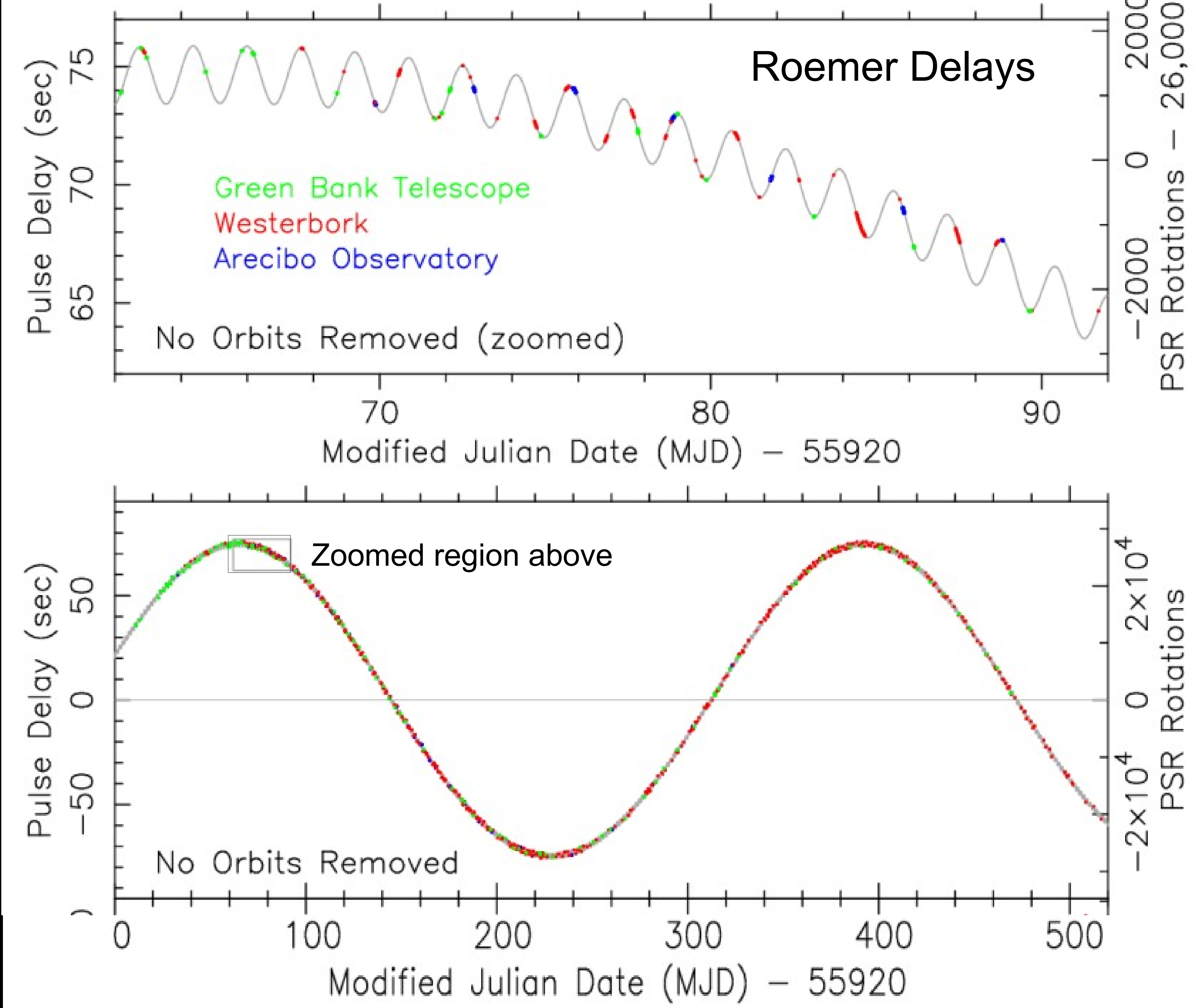


Keeping pulse count was a nightmare: 6 or 7 derivatives for each orbital parameter!

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



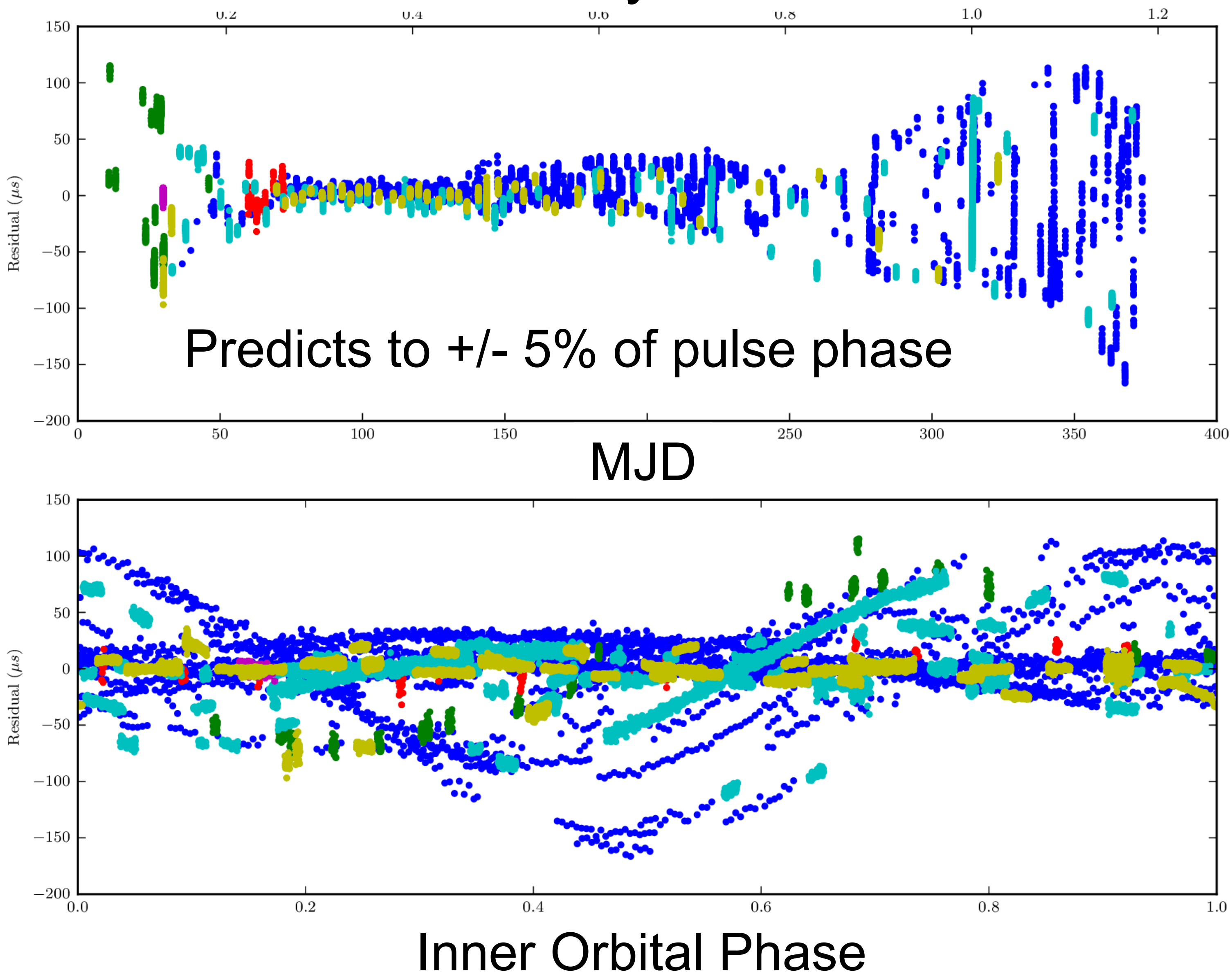

Roemer Delays
Green Bank Telescope
Westerbork
Arecibo Observatory
No Orbits Removed (zoomed)
Pulse Delay (sec)
PSR Rotations − 26,000
Modified Julian Date (MJD) − 55920
Zoomed region above
No Orbits Removed
Pulse Delay (sec)
PSR Rotations
Modified Julian Date (MJD) − 55920

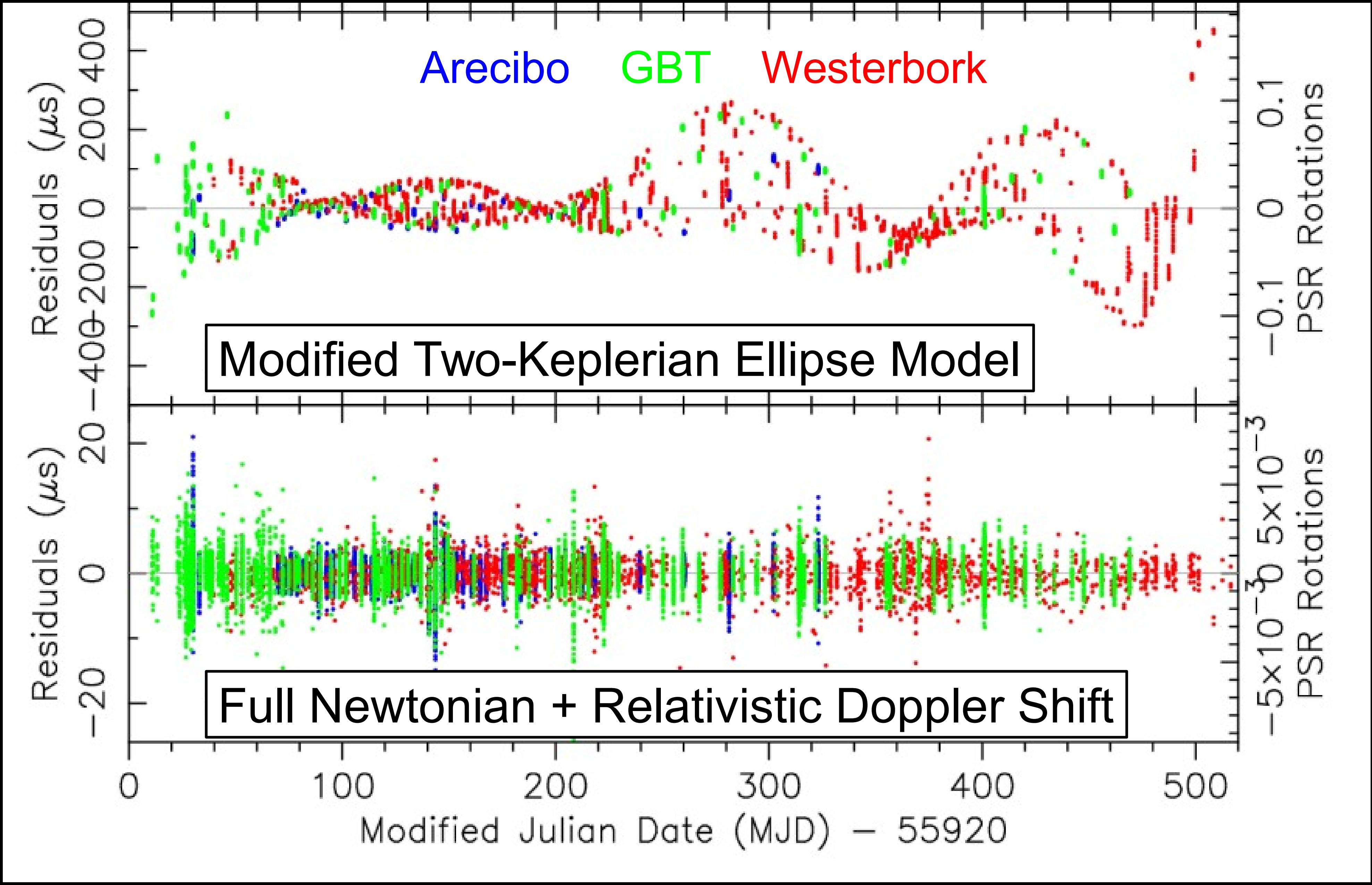
Major timing breakthrough!

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

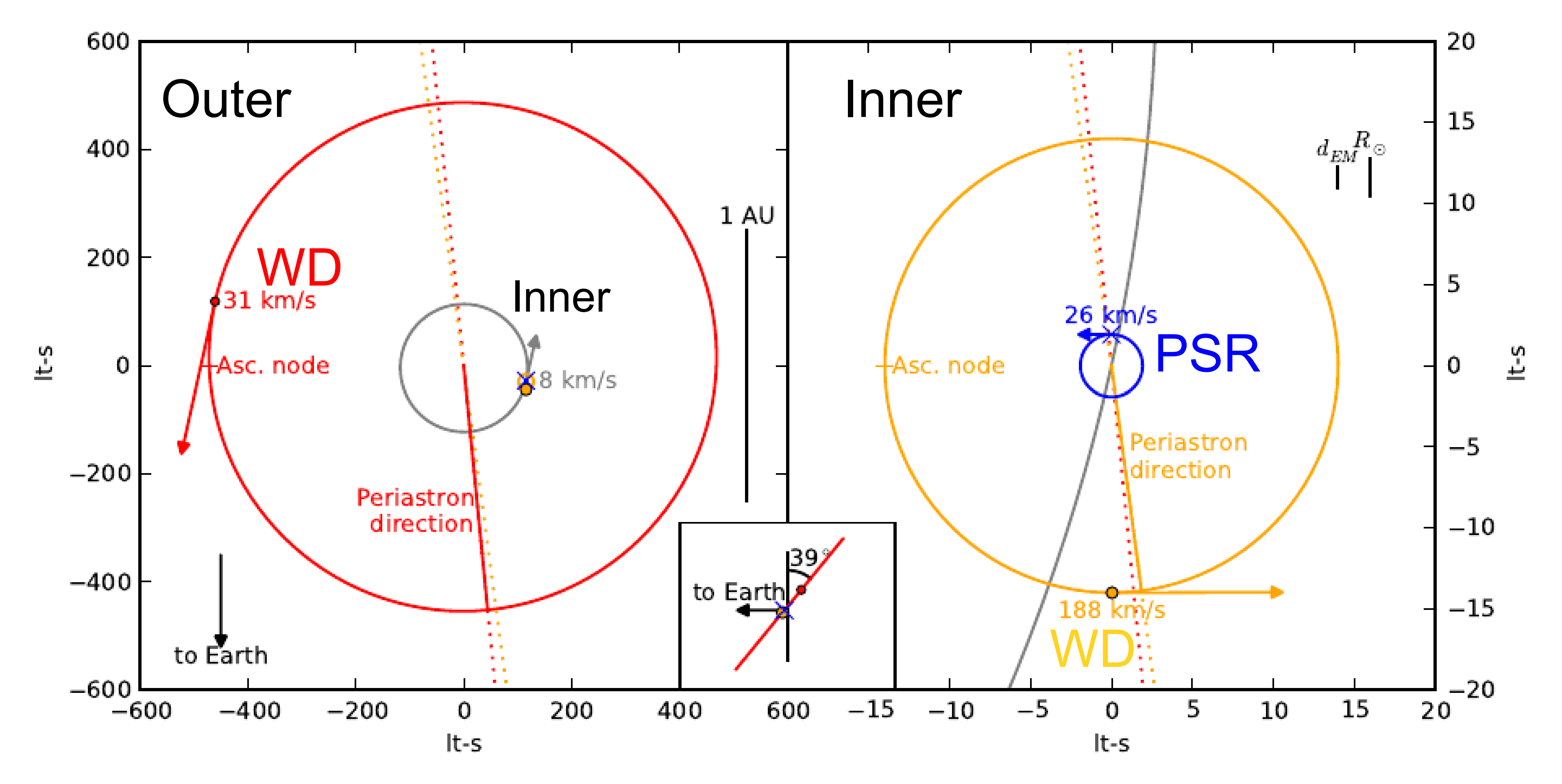




~1.34us weighted RMS for 26,260 TOAs!

PSR J0337+1715: fully solved!

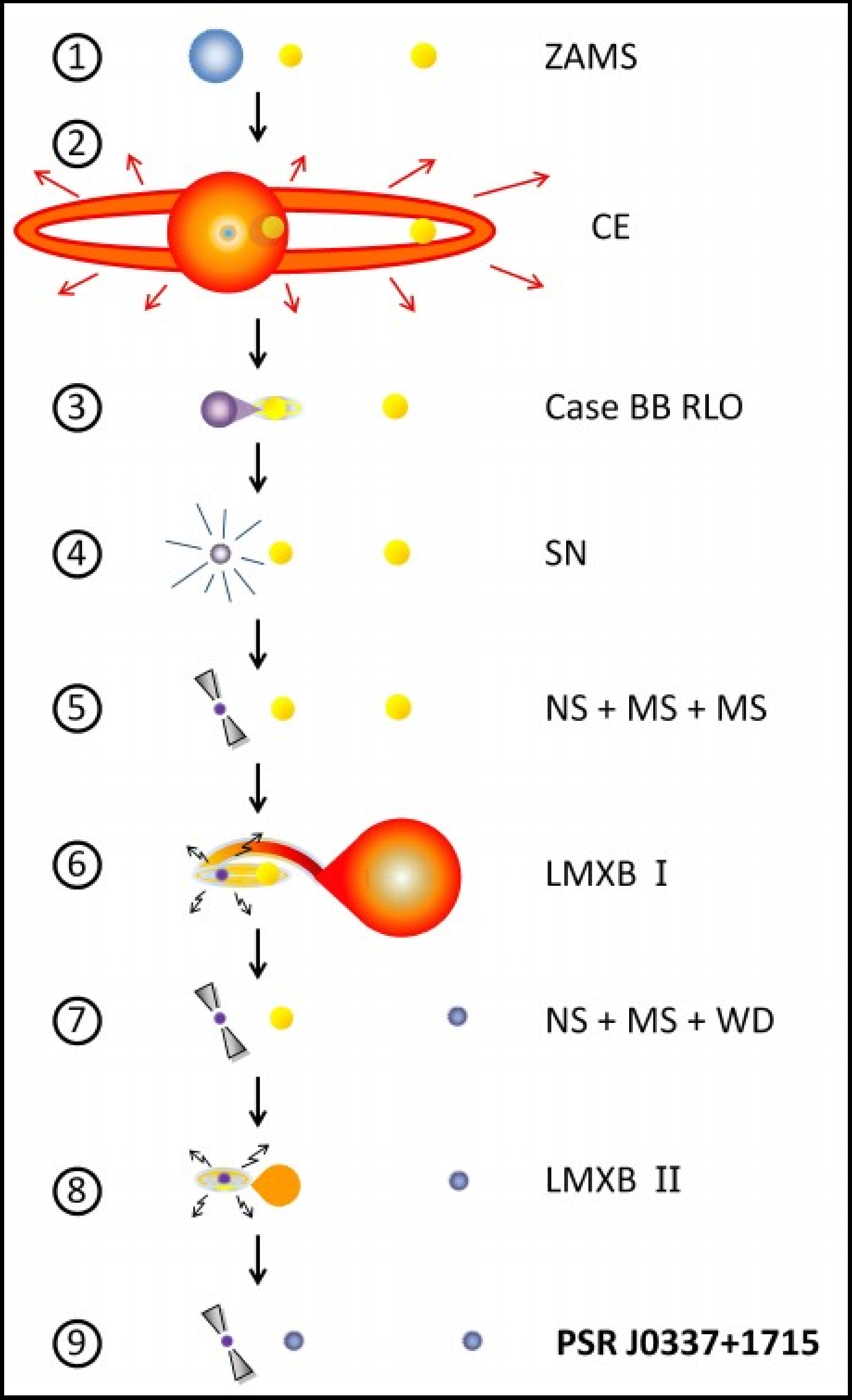
- High precision masses: Mpsr = 1.4378(13) Msun
  Mwd_i = 0.19751(15) Msun   Mwd_o = 0.4101(3) Msun
- Orbits are co-planar to < 0.02 deg! (*i* = 39.24 deg)
- Apsides aligned (despite e_i ~ 7×10^{-4} and e_o ~ 0.035!)



System Evolution?

- 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, 2014, ApJ, in press



Unique Tests of General Relativity

- Strong Equivalence Principle states:
  - Weak Equivalence Principle (i.e. $M_{grav} = M_{inertial}$) holds for self-gravitating bodies as well as test bodies
  - And local Lorentz and position invariance
- GR is the only viable metric theory that embodies the SEP

Unique Tests of General Relativity

- Strong Equivalence Principle states:
  - Weak Equivalence Principle (i.e. $M_{grav} = M_{inertial}$) holds for self-gravitating bodies as well as test bodies
  - And local Lorentz and position invariance
- GR is the only viable metric theory that embodies the SEP
- Pulsar + white dwarf binaries can make interesting tests
  - Orbits “polarized” due to different accelerations in Galactic gravitational field due to different self-gravities
  - See Cliff Will, 2006, Living Reviews of Relativity and Freire, Kramer & Wex, 2012, CQG, 29, 18

Unique Tests of General Relativity

- Gravitational binding energies:
  - NS ~ $3GM/5Rc^2 \sim 0.1$
  - WDs ~ 10^{-6}
  - For planets/moons ~10^{-11} to 10^{-9} (i.e. Solar System tests)

- J0337+1715: the NS and inner WD fall in strong grav. field of outer WD rather than Galaxy: field is 6-7 orders-of-mag larger
  - "G" effectively different for NS and inner WD if SEP invalid
  - Tests with this triple should be many *orders-of-magnitude* better than any previous others – and very soon!

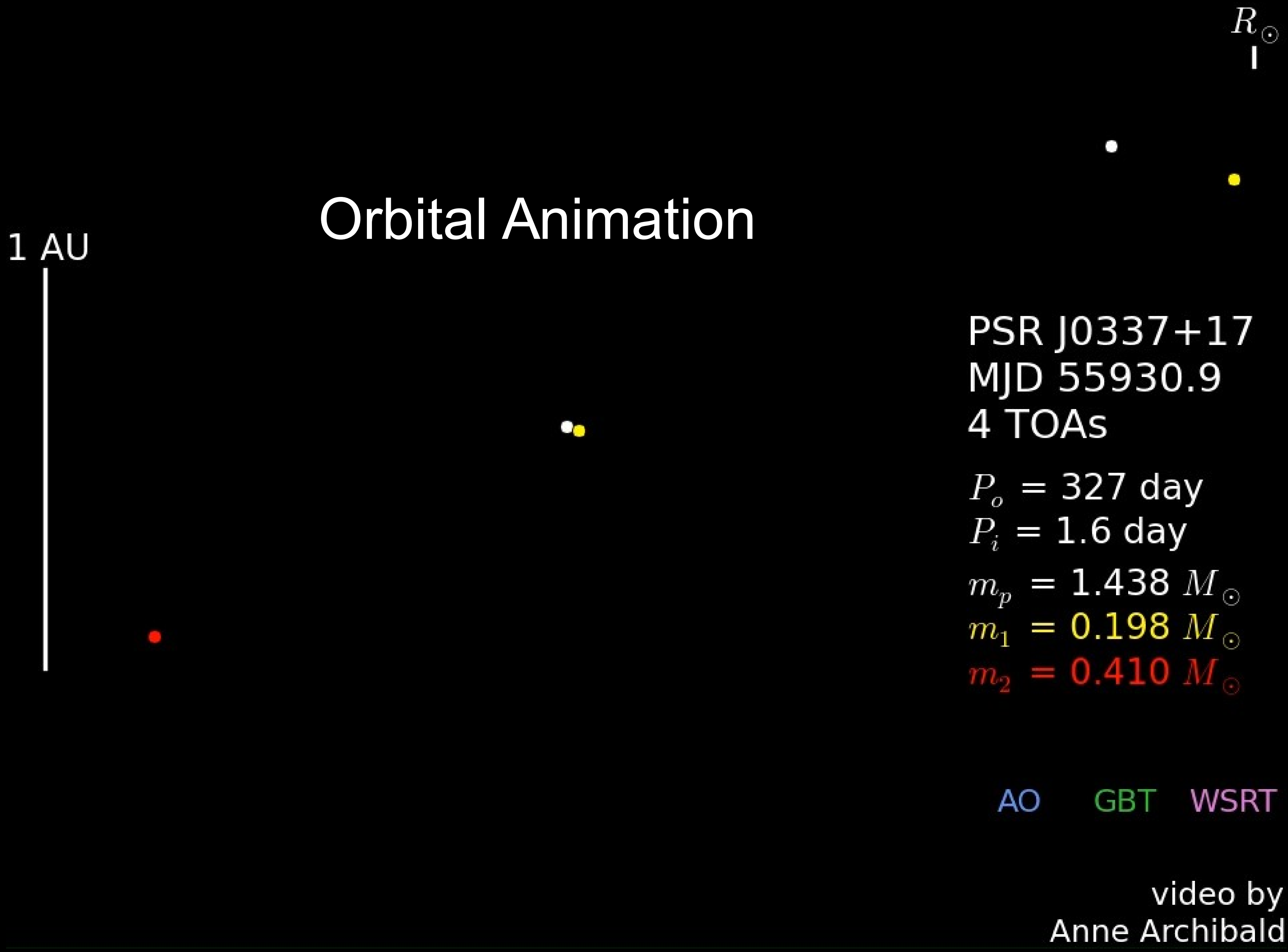
Archibald et al. in prep

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 tests of the Strong Equivalence Principle
  - High precision, clean examples of 3-body perturbations
  - 1-2% VLBA distance will calibrate low-mass WD models
  - Much fodder for binary / stellar evolution models
  - Potentially one of the best timing pulsars in NANOGrav

Ransom et al. Nature, in press (Due 8 Jan 2014)

Orbital Animation



Shorter time-scales + stronger effects

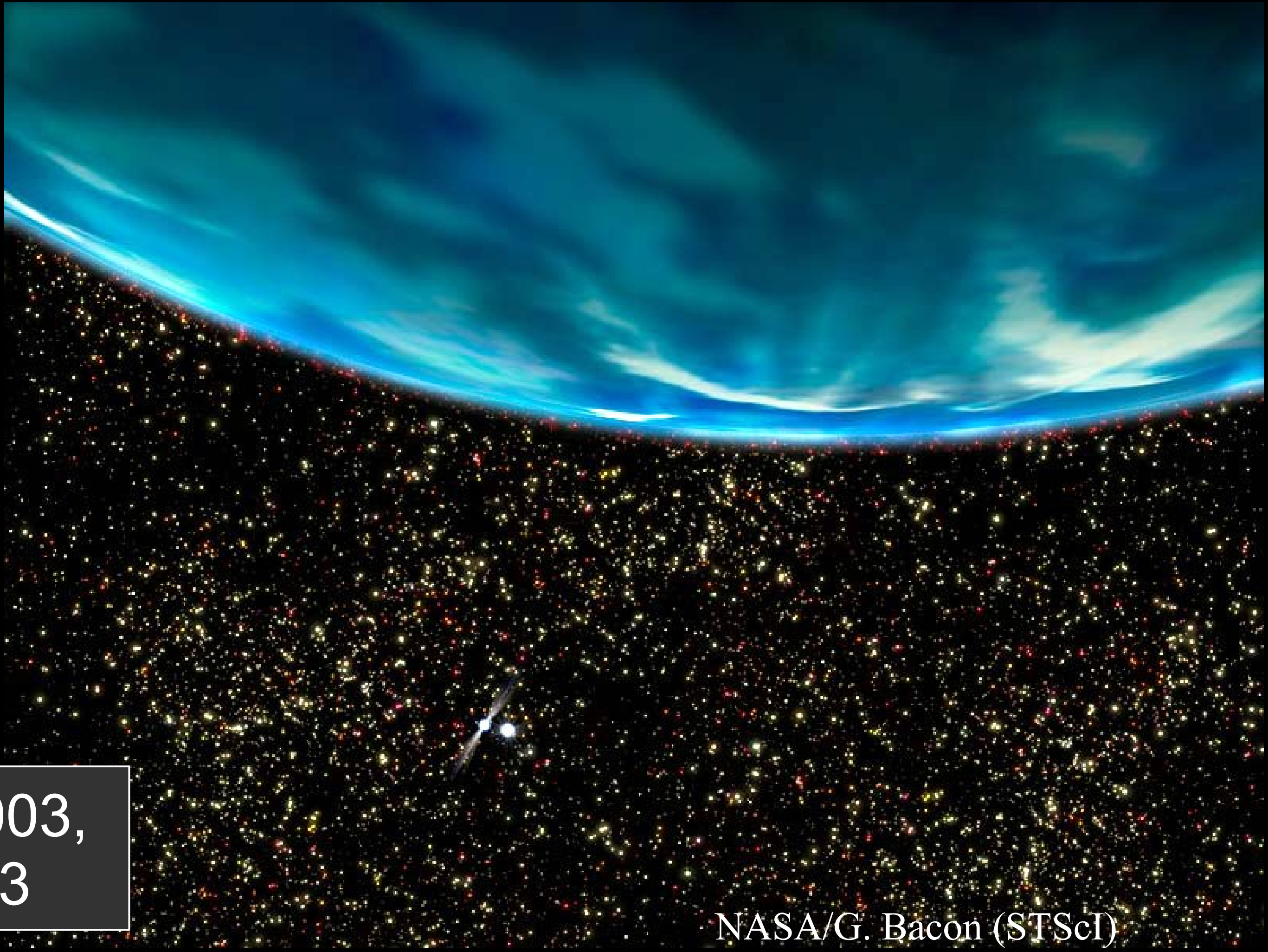
PSR B1620-26
in globular cluster M4
(MSP+WD+Planet)

~0.3 $M_\odot$ WD
191 day orbit

~1M_{Jup} planet in
~100 yr orbit

Nasty long-term
timing effects

e.g Thorsett, Arzoumanian, & Taylor. 1993, ApJ, 412, L33

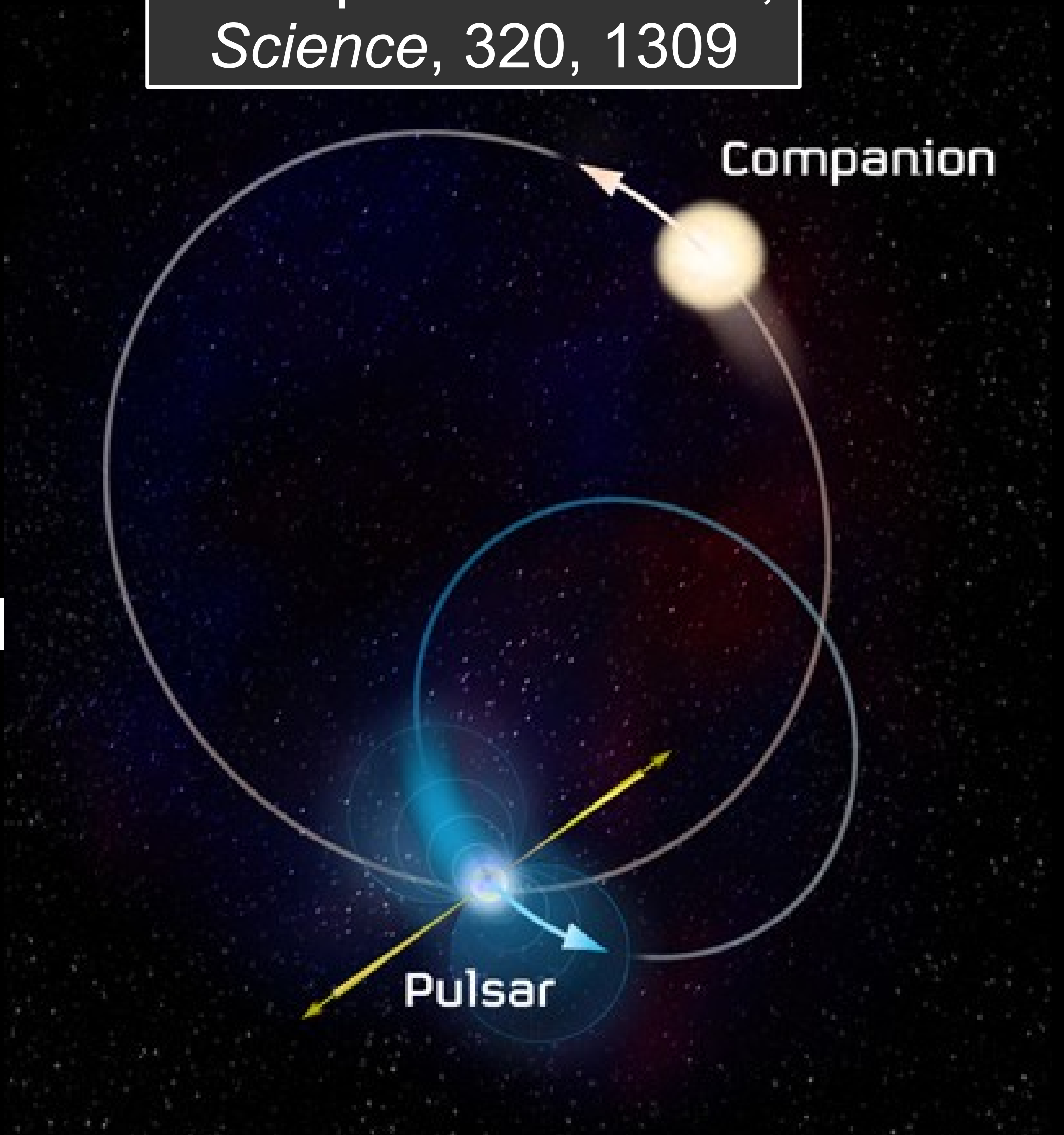


Sigurdsson et al. 2003, *Science*, 301, 193

Similar evolution to J1903+0327?

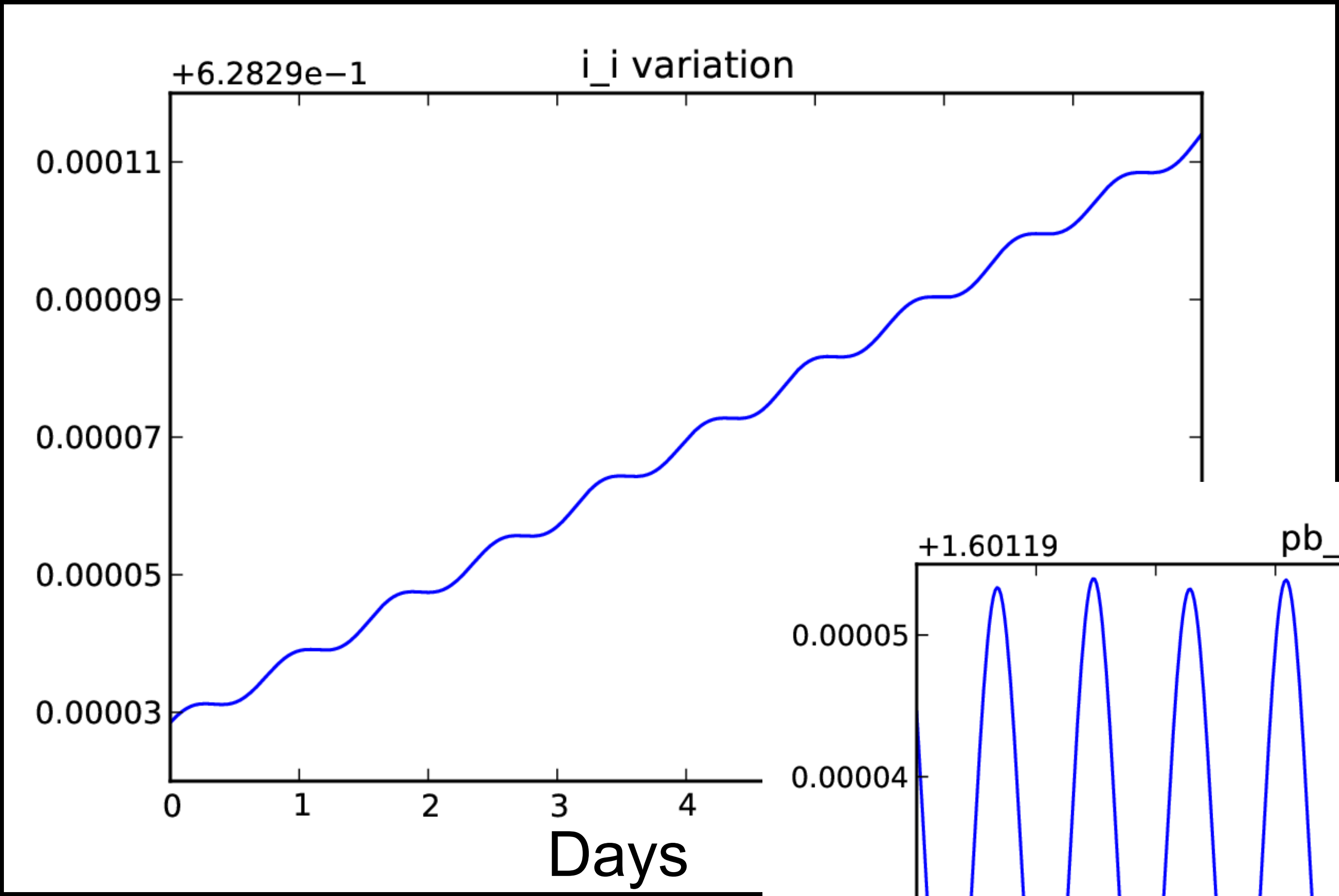
- Fully recycled MSP
- 95 day, eccentric orbit (e = 0.44)
- Massive MS companion
- Massive (1.67 $M_{\odot}$) NS
- Previously a triple system?
  - Ejected WD in dynamical Instability?

Champion et al. 2008, *Science*, 320, 1309

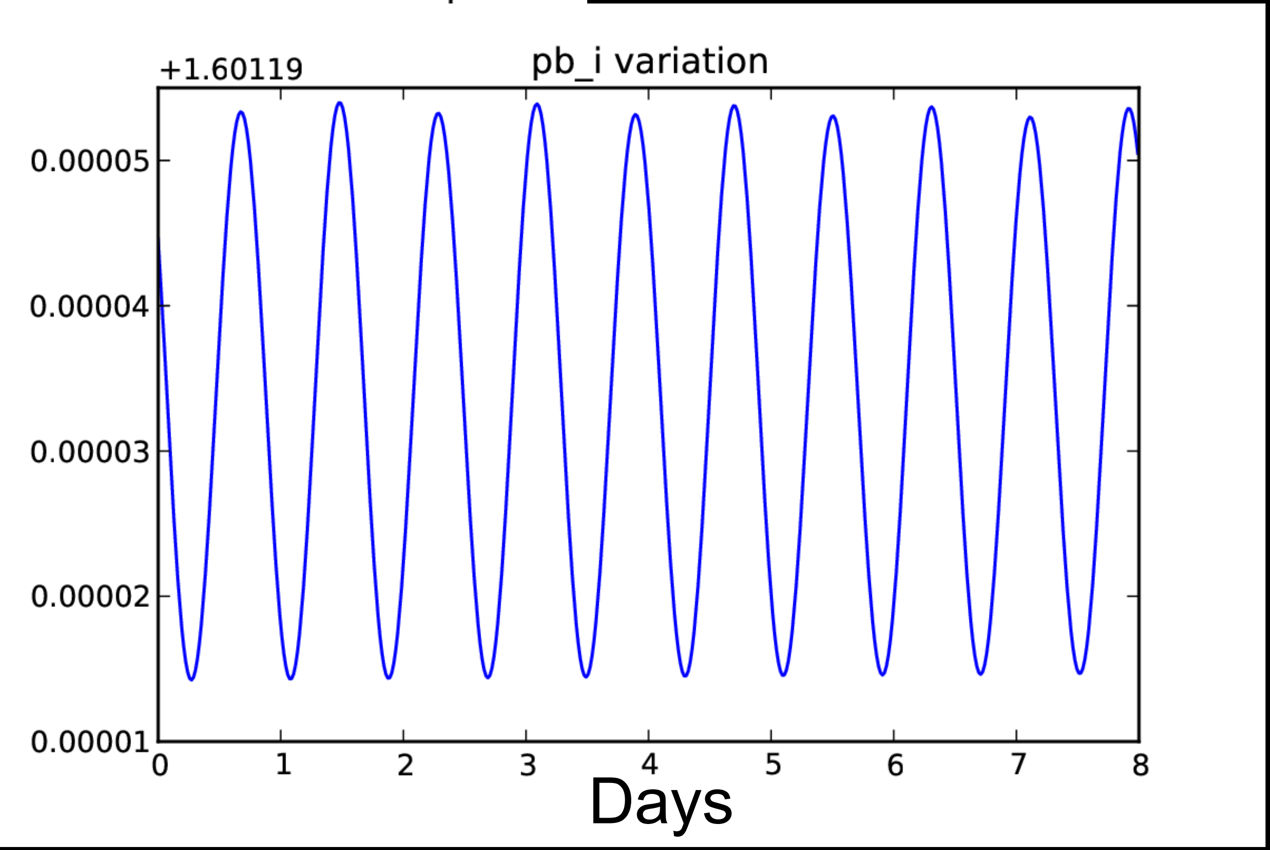


Portegies Zwart et al. 2011, ApJ, 734, 55

Changing inner inclination and period



Osculating orbital elements easily visible



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 ~237/D_{kpc} μas, easily measurable with VLBA

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