A Millisecond Pulsar Triple System (and Fermi MSP updates)

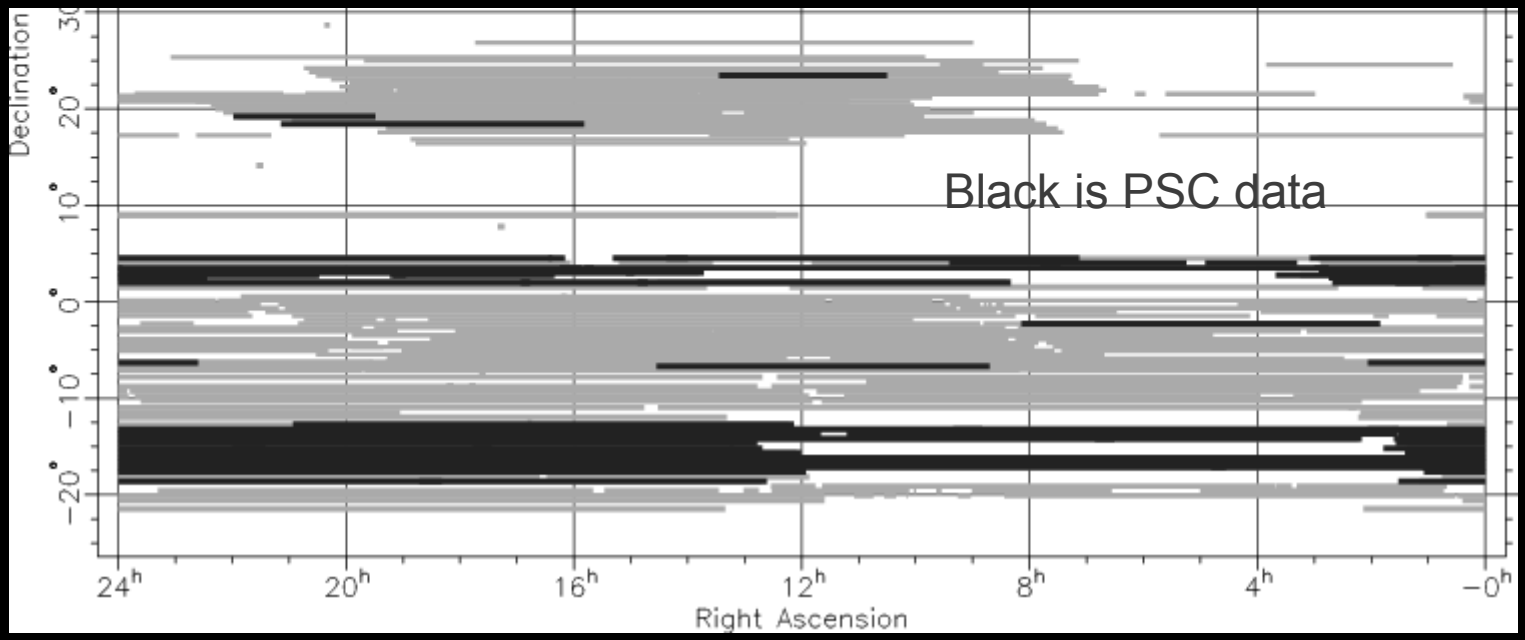
Scott Ransom
(NRAO / UVa)

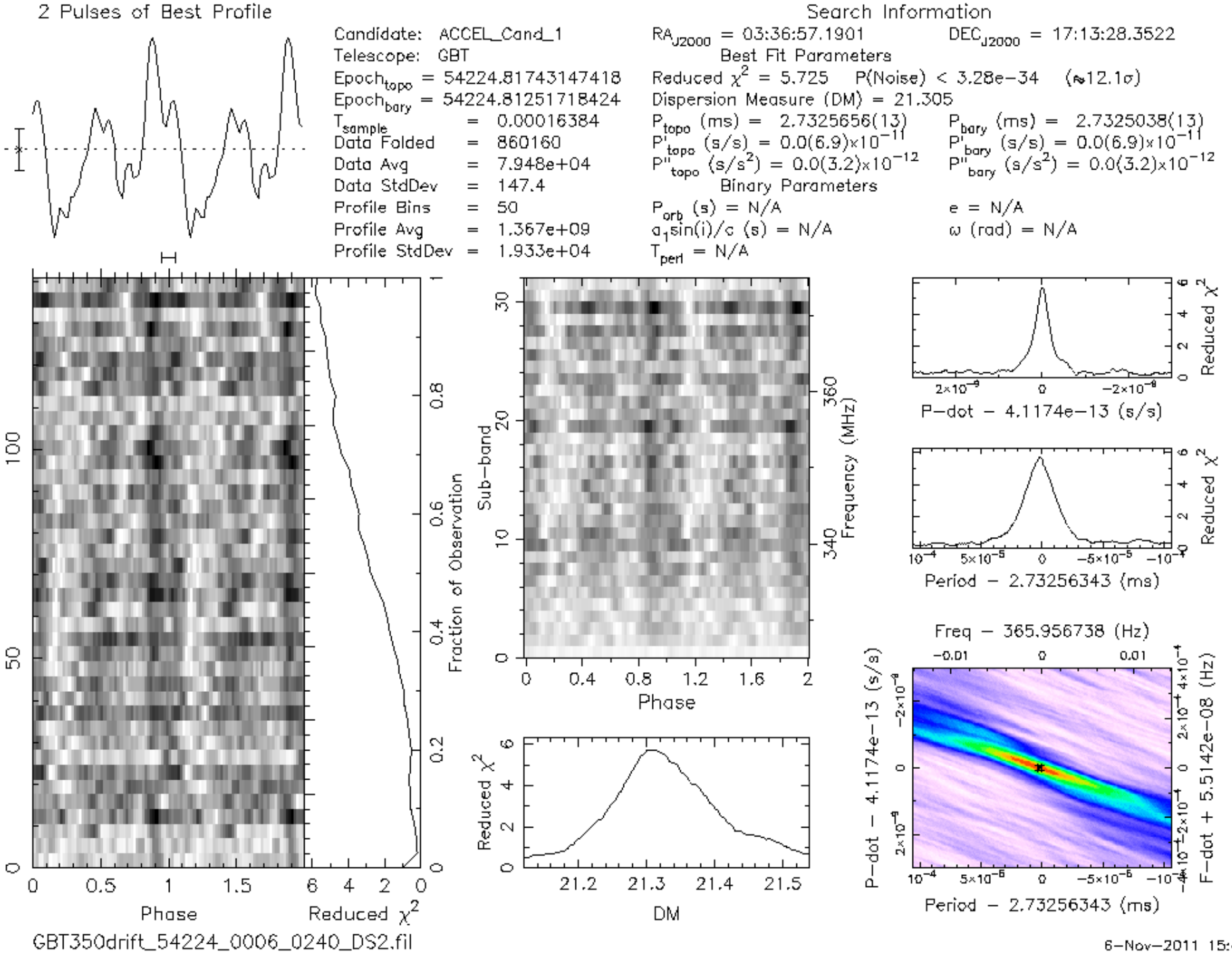
J0337+1715: Stairs, Lorimer, McLaughlin, Boyles, Lynch, Kaplan, Hessels, Deneva, Stovall, …

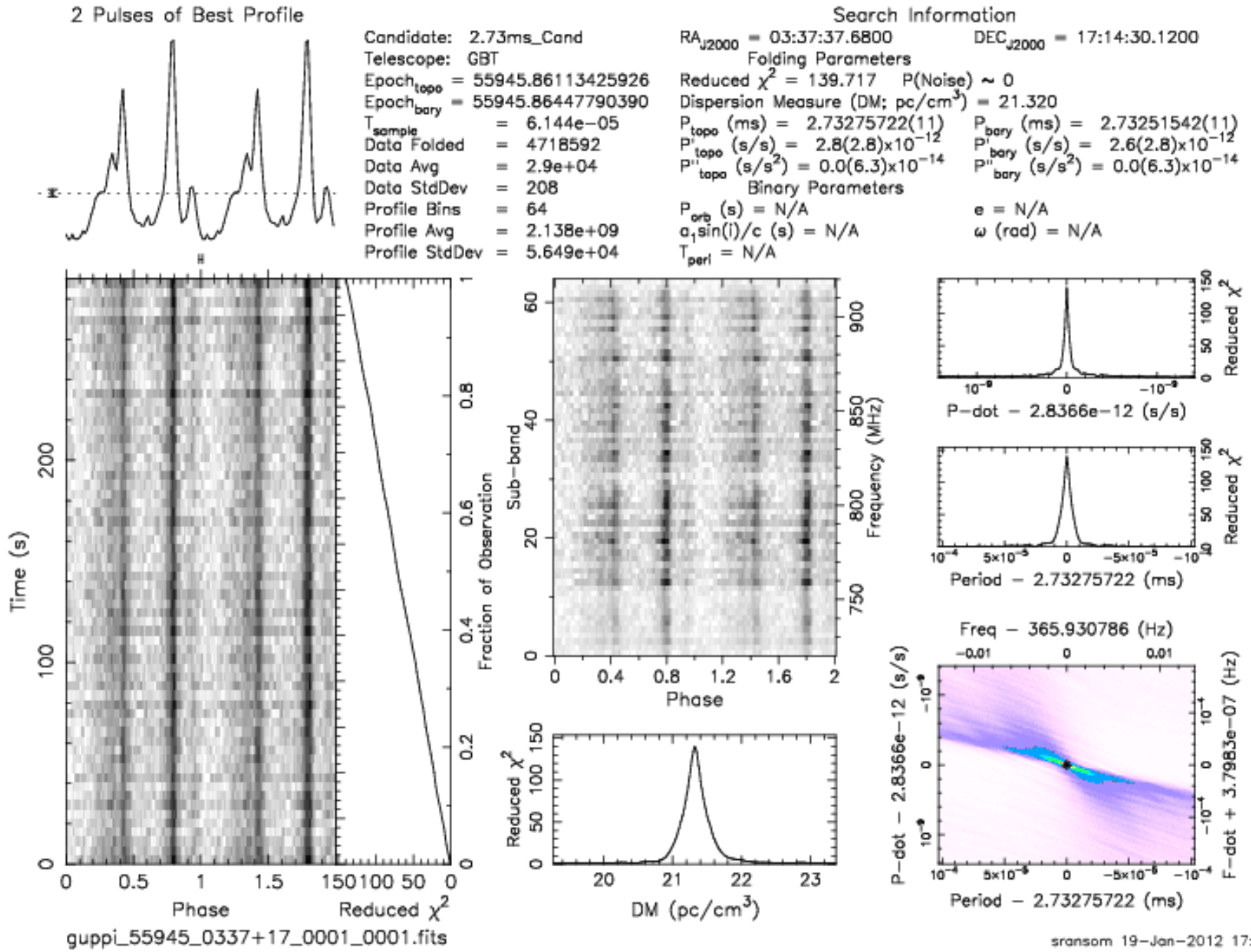
Fermi: Ray, Camilo, Kerr, McLaughlin, Hessels, Roberts, Decesar, ...

GBT Driftscan Survey

- Summer of 2007 during GBT azimjuth track repair
- ~1400 hrs, ~140 TB of data, ~30% of whole sky
- ~1/4 to Pulsar Search Collaboratory (also ARCC @ UTB)
- Processing nearly finished: >30PSRs, ~7 MSPs
- Boyles et al 2012 and Lynch et al 2012 coming soon




2 Pulses of Best Profile
Search Information
Candidate: ACCEL_Cand_1
Telescope: GBT
Epoch_topo = 54224.81743147418
Epoch_bary = 54224.81251718424
T_sample = 0.00016384
Data Folded = 860160
Data Avg = 7.948e+04
Data StdDev = 147.4
Profile Bins = 50
Profile Avg = 1.367e+09
Profile StdDev = 1.933e+04
RA_J2000 = 03:36:57.1901
DEC_J2000 = 17:13:28.3522
Best Fit Parameters
Reduced χ^2 = 5.725 P(Noise) < 3.28e-34 (≈12.1σ)
Dispersion Measure (DM) = 21.305
P_topo (ms) = 2.7325656(13)
P'_topo (s/s) = 0.0(6.9)×10^-11
P''_topo (s/s^2) = 0.0(3.2)×10^-12
P_bary (ms) = 2.7325038(13)
P'_bary (s/s) = 0.0(6.9)×10^-11
P''_bary (s/s^2) = 0.0(3.2)×10^-12
Binary Parameters
P_orb (s) = N/A
e = N/A
a_1sin(i)/c (s) = N/A
ω (rad) = N/A
T_perI = N/A
Time (s)
Phase
Reduced χ^2
Fraction of Observation
Sub-band
Frequency (MHz)
Phase
Reduced χ^2
DM
P-dot − 4.1174e-13 (s/s)
Reduced χ^2
Period − 2.73256343 (ms)
Reduced χ^2
Freq − 365.956738 (Hz)
P-dot − 4.1174e-13 (s/s)
F-dot + 5.5142e-08 (Hz)
Period − 2.73256343 (ms)
GBT350drift_54224_0006_0240_DS2.fil
6-Nov-2011 15:42

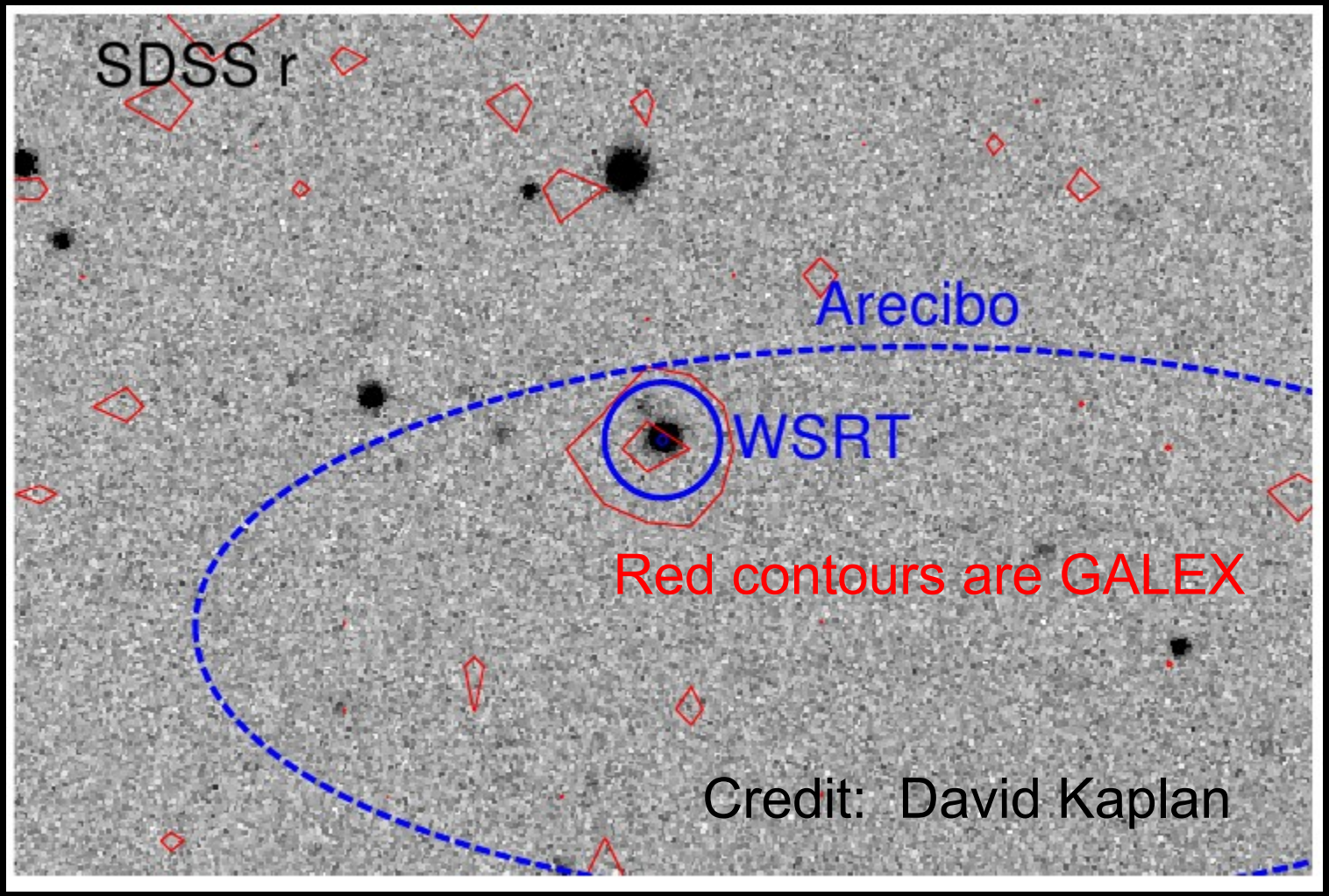

2 Pulses of Best Profile
Candidate: 2.73ms_Cand
Telescope: GBT
Epoch_topo = 55945.86113425926
Epoch_bary = 55945.86447790390
T_sample = 6.144e-05
Data Folded = 4718592
Data Avg = 2.9e+04
Data StdDev = 208
Profile Bins = 64
Profile Avg = 2.138e+09
Profile StdDev = 5.649e+04
Search Information
RA_J2000 = 03:37:37.6800
DEC_J2000 = 17:14:30.1200
Folding Parameters
Reduced χ² = 139.717 P(Noise) ~ 0
Dispersion Measure (DM; pc/cm³) = 21.320
P_topo (ms) = 2.73275722(11)
P_bary (ms) = 2.73251542(11)
P'_topo (s/s) = 2.8(2.8)x10⁻¹²
P'_bary (s/s) = 2.6(2.8)x10⁻¹²
P''_topo (s/s²) = 0.0(6.3)x10⁻¹⁴
P''_bary (s/s²) = 0.0(6.3)x10⁻¹⁴
Binary Parameters
P_orb (s) = N/A
e = N/A
a₁sin(i)/c (s) = N/A
ω (rad) = N/A
T_perI = N/A
Time (s)
Phase
Reduced χ²
Fraction of Observation
Sub-band
Frequency (MHz)
DM (pc/cm³)
P-dot − 2.8366e-12 (s/s)
Period − 2.73275722 (ms)
Freq − 365.930786 (Hz)
P-dot − 2.8366e-12 (s/s)
F-dot + 3.7983e-07 (Hz)
guppi_55945_0337+17_0001_0001.fits
sransom 19-Jan-2012 17:45

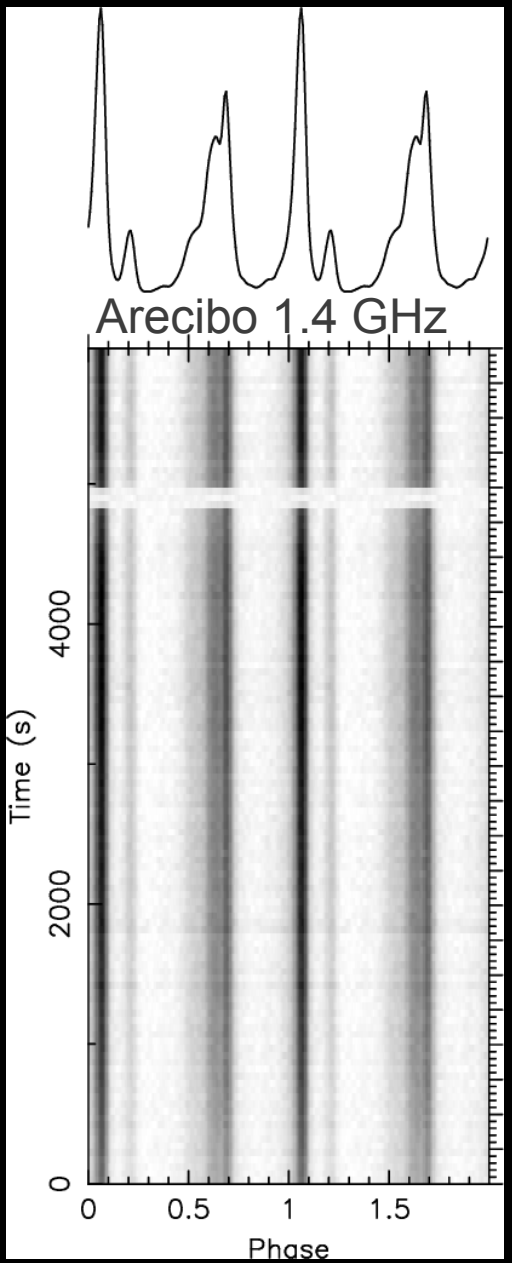
PSR J0337+17

- Basic characteristics:
  - Relatively bright (~2 mJy) binary MSP @ 2.73 ms
  - In Arecibo declination range
  - Dispersion Measure indicates a distance of <1 kpc
  - Orbit was slightly tricky to solve...
    - 1.63 day orbit with WD companion >0.12 Msun
    - Could not phase-connect the timing data... pulsar seemed to have a huge frequency derivative

Improved position...

- Multi-frequency observations with GBT, Arecibo and Westerbork strongly constrained position...
- Optical/UV counterpart (SDSS / GALEX)

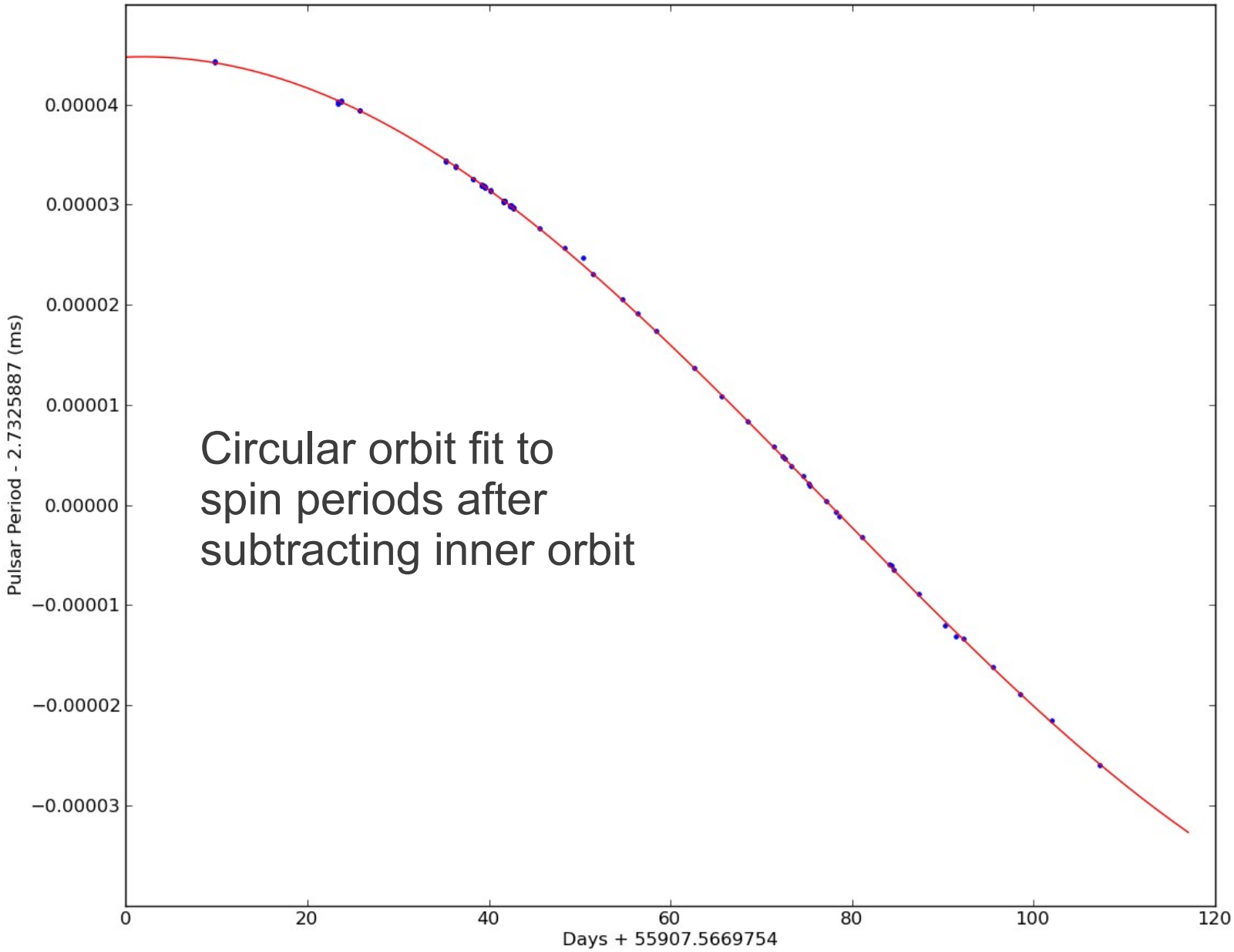


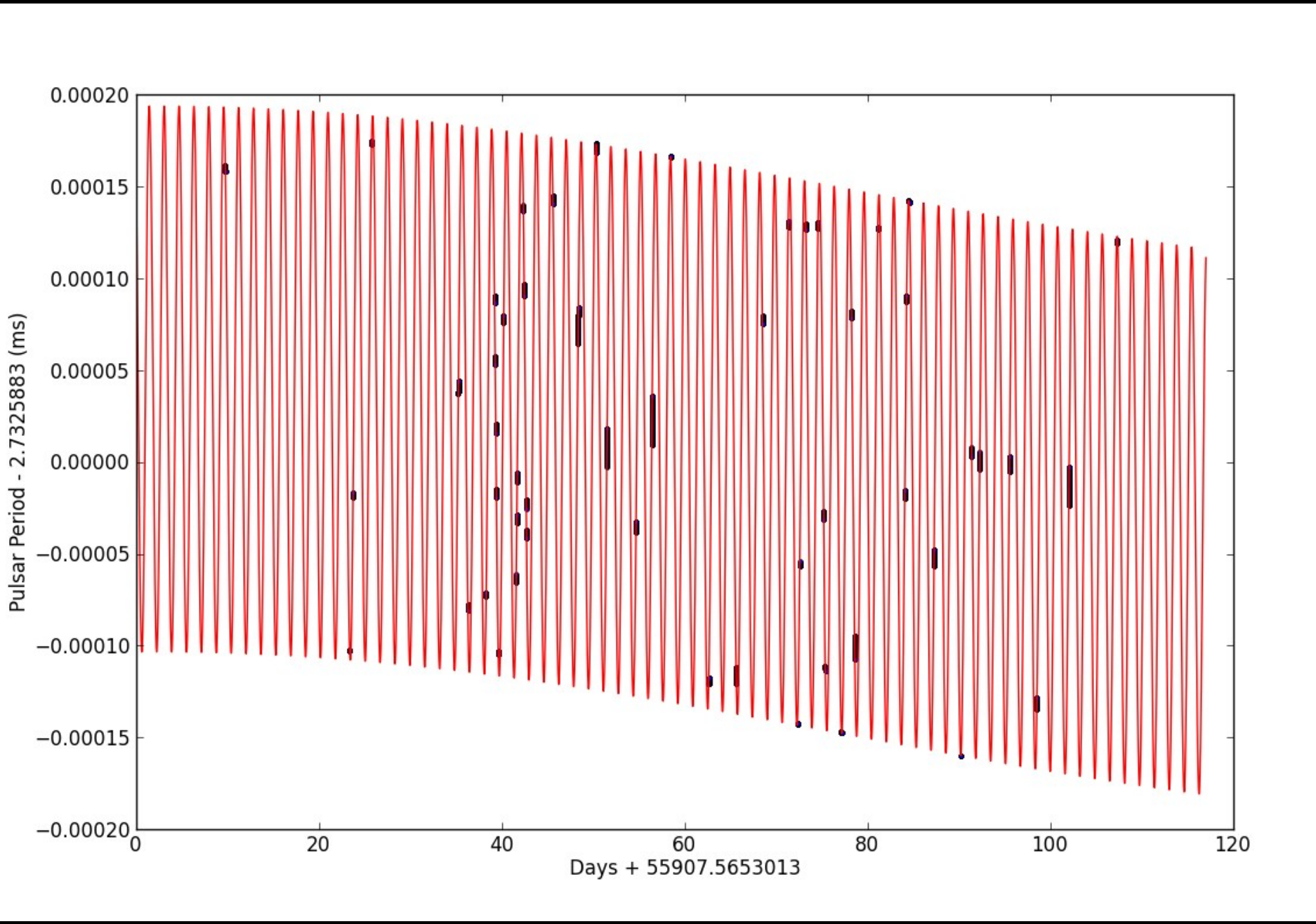


...and **lots** of timing data

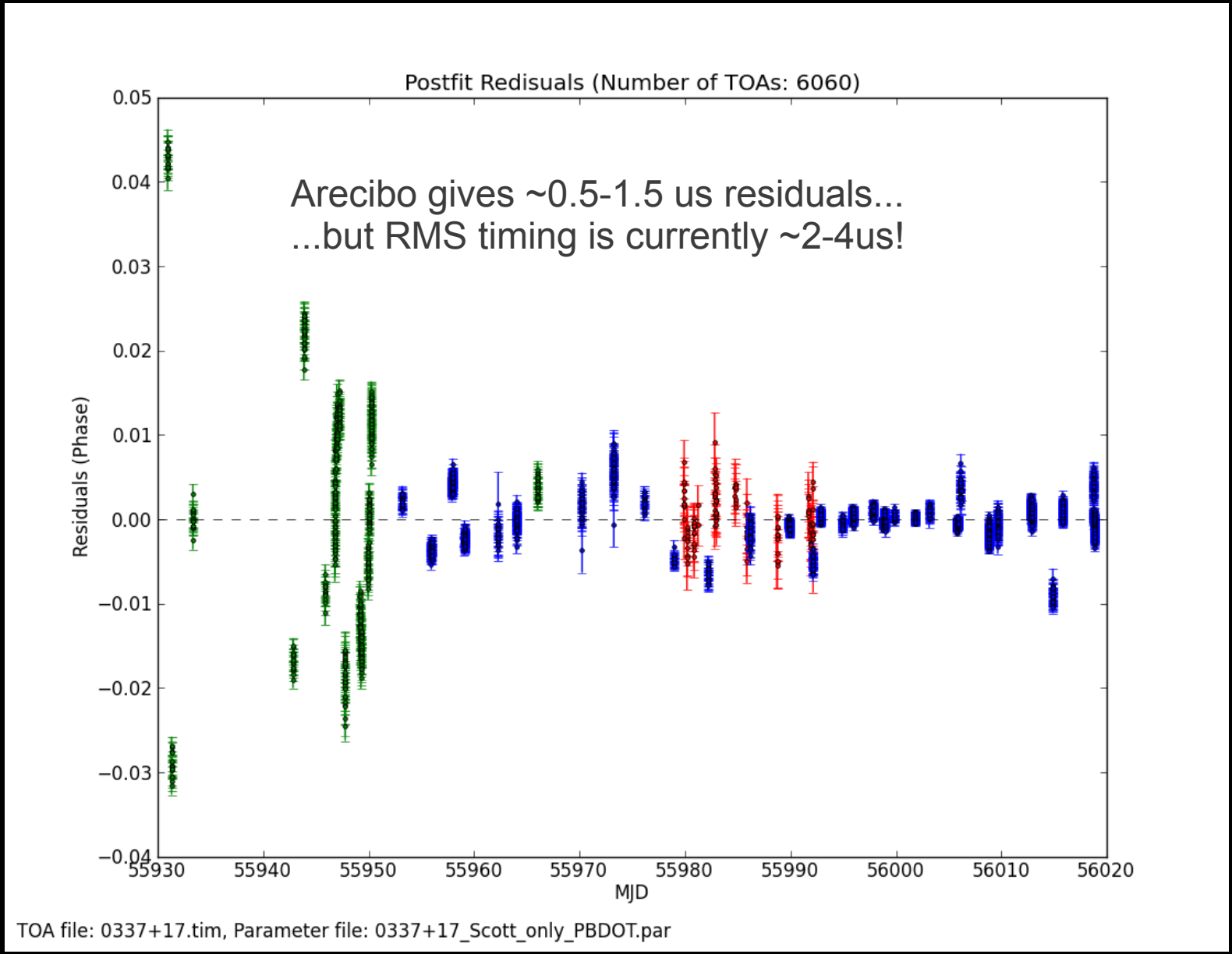
PSR J0337+1715 is in a triple system!

- Inner orbit has “high” eccentricity
  - Should be <1×10^{-5} (from fluctuation dissipation theory; Phinney 1993), but it is 6.5×10^{-4} (~2 orders of mag higher)
- Outer orbit is ~327 days
  - nearly circular (e ~ 0.03)
  - Minimum companion mass ~0.25 Msun
- Periastrons seem to be aligned (on average) to <1 deg
- Extremely strong measurement of decrease in orbital period of inner orbit already (P / Pdot ~ 10000 years!)

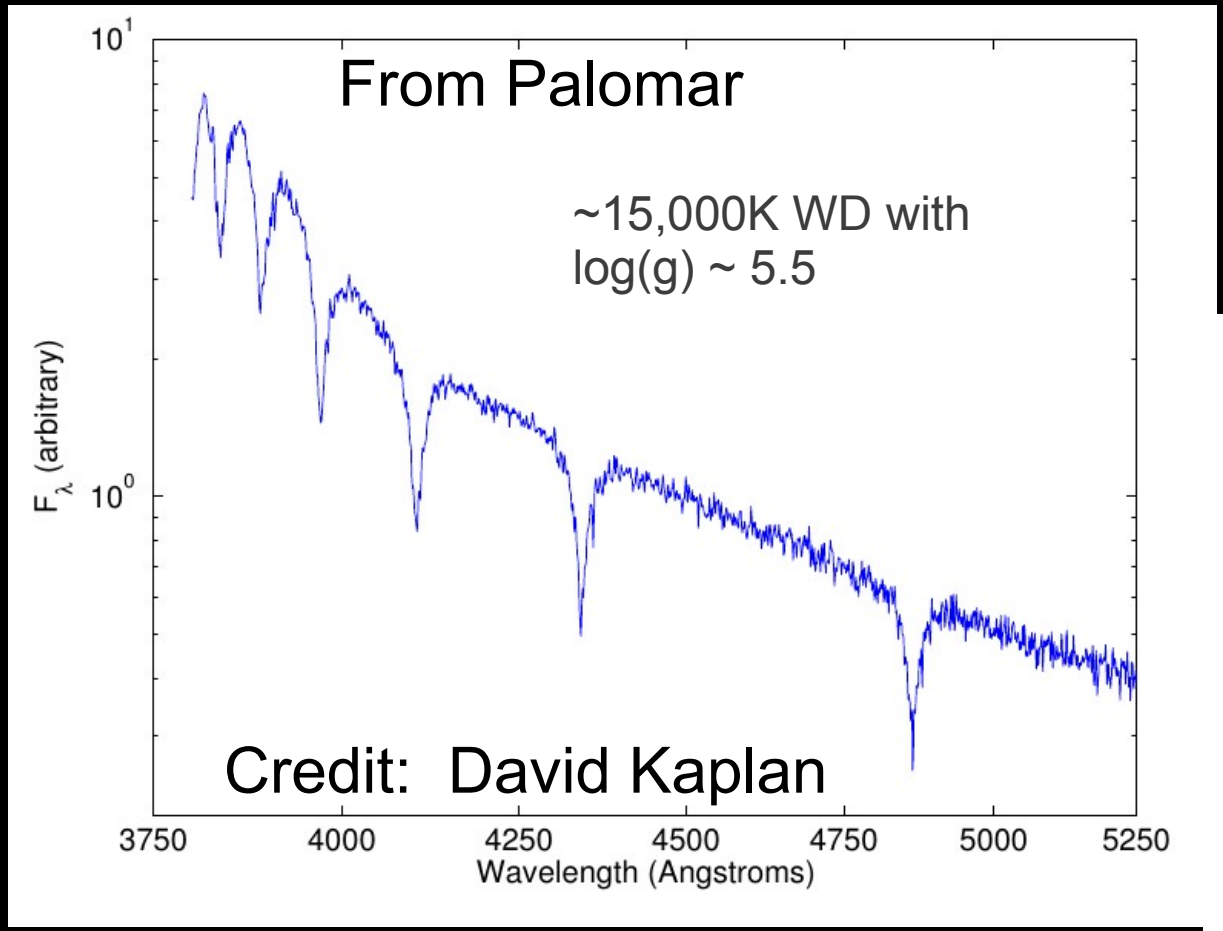

Circular orbit fit to
spin periods after
subtracting inner orbit
Pulsar Period - 2.7325887 (ms)
0.00004
0.00003
0.00002
0.00001
0.00000
−0.00001
−0.00002
−0.00003
0
20
40
60
80
100
120
Days + 55907.5669754

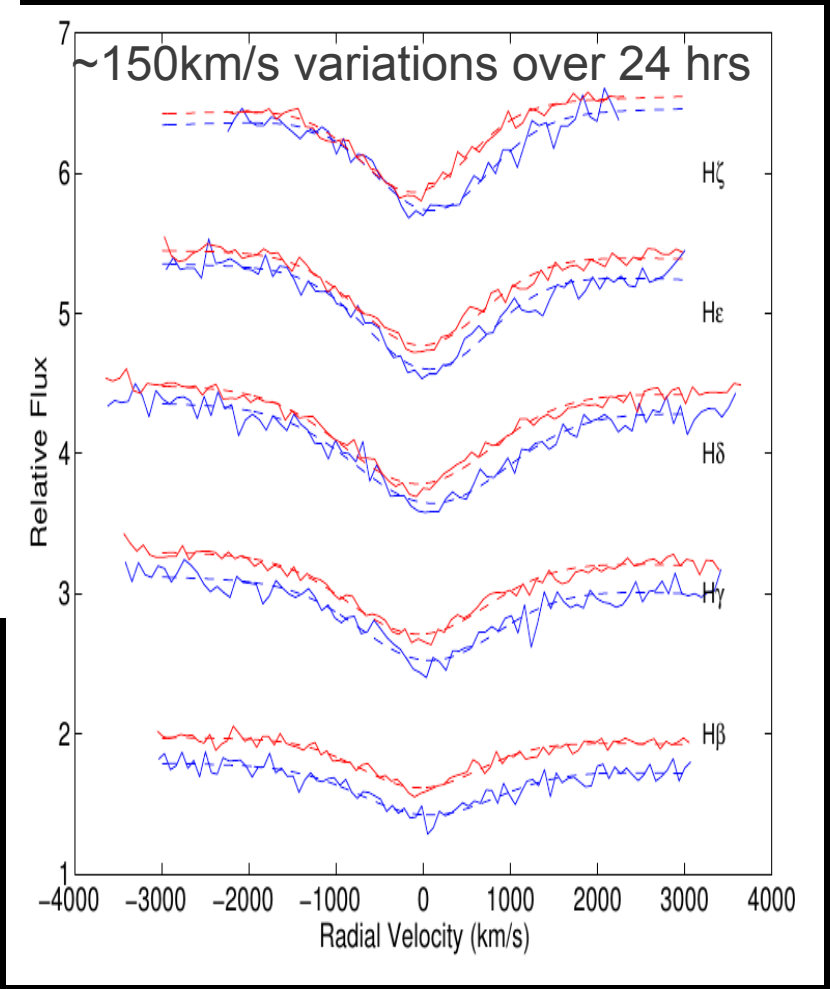

0.00020
0.00015
0.00010
0.00005
0.00000
−0.00005
−0.00010
−0.00015
−0.00020
Pulsar Period - 2.7325883 (ms)
0
20
40
60
80
100
120
Days + 55907.5653013

Lots of timing systematics...

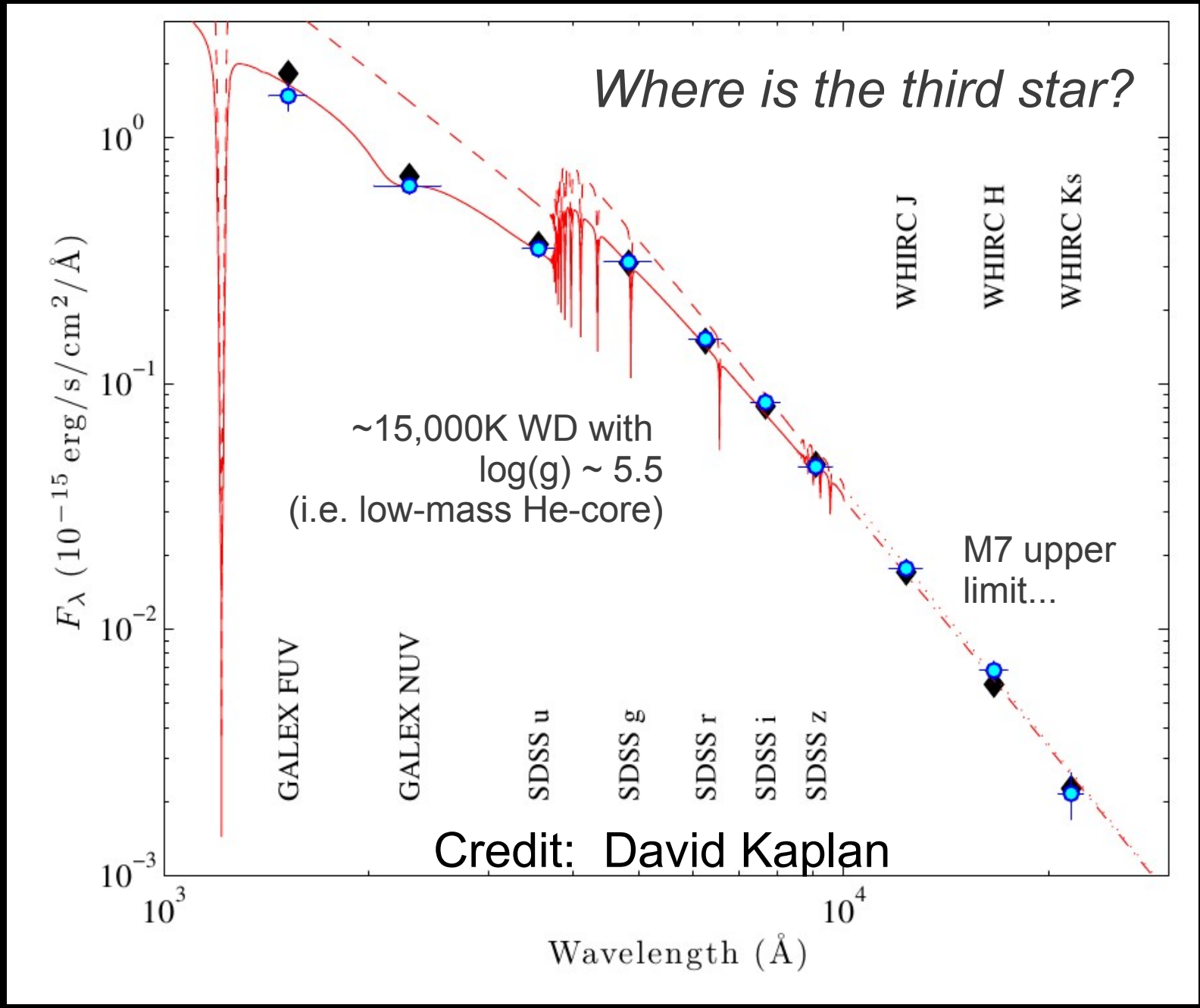


Optical spectroscopy on the WD...





UV/Optical/NIR photometry...



Similar to B1620-26 (MSP+WD+Planet)

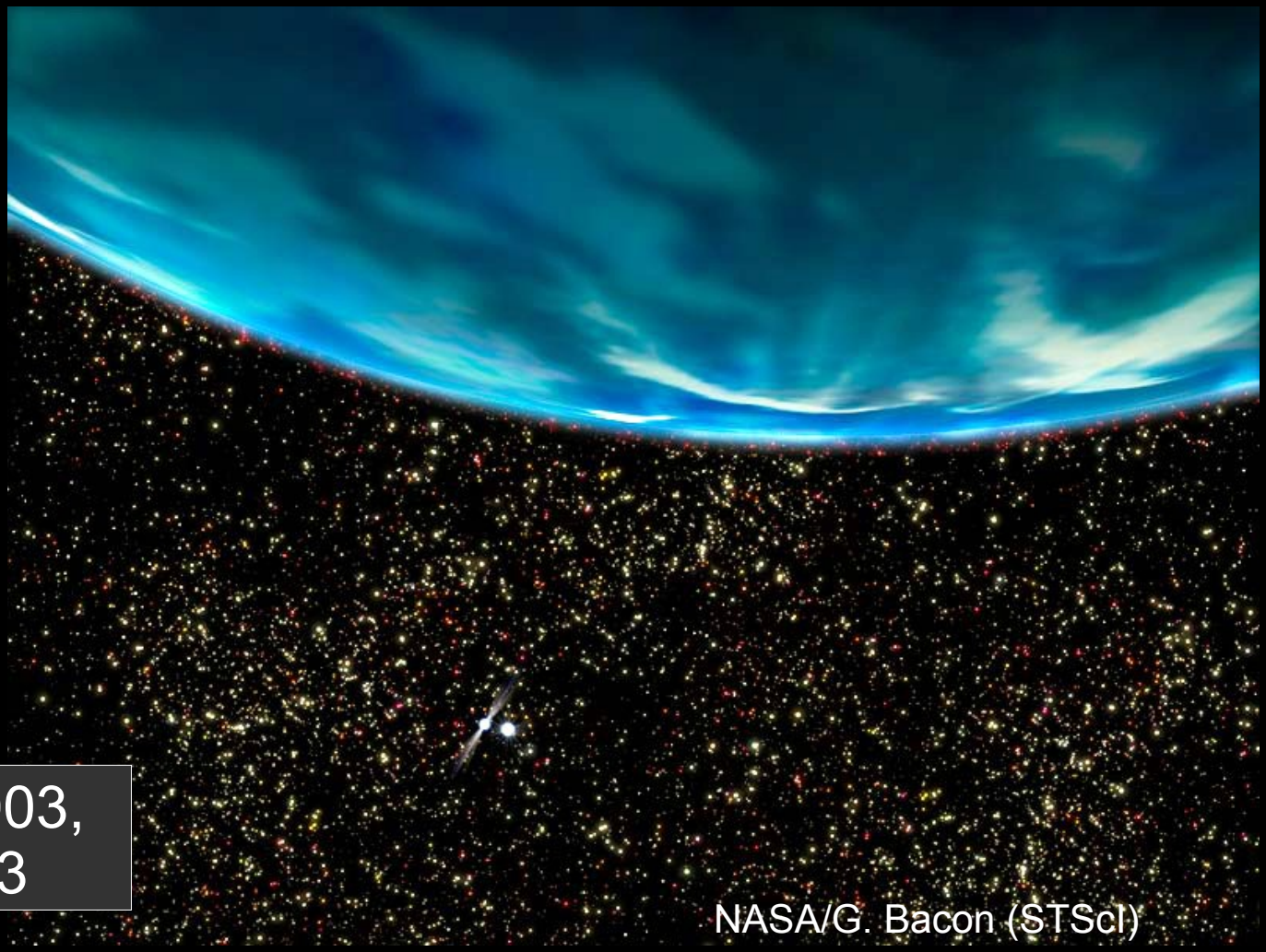
In glubular cluster M4

~0.3 Msun WD
191 day orbit

~1Mjup planet in
~100 yr orbit

Nasty long-term
Timing effects
(ask Ingrid)

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



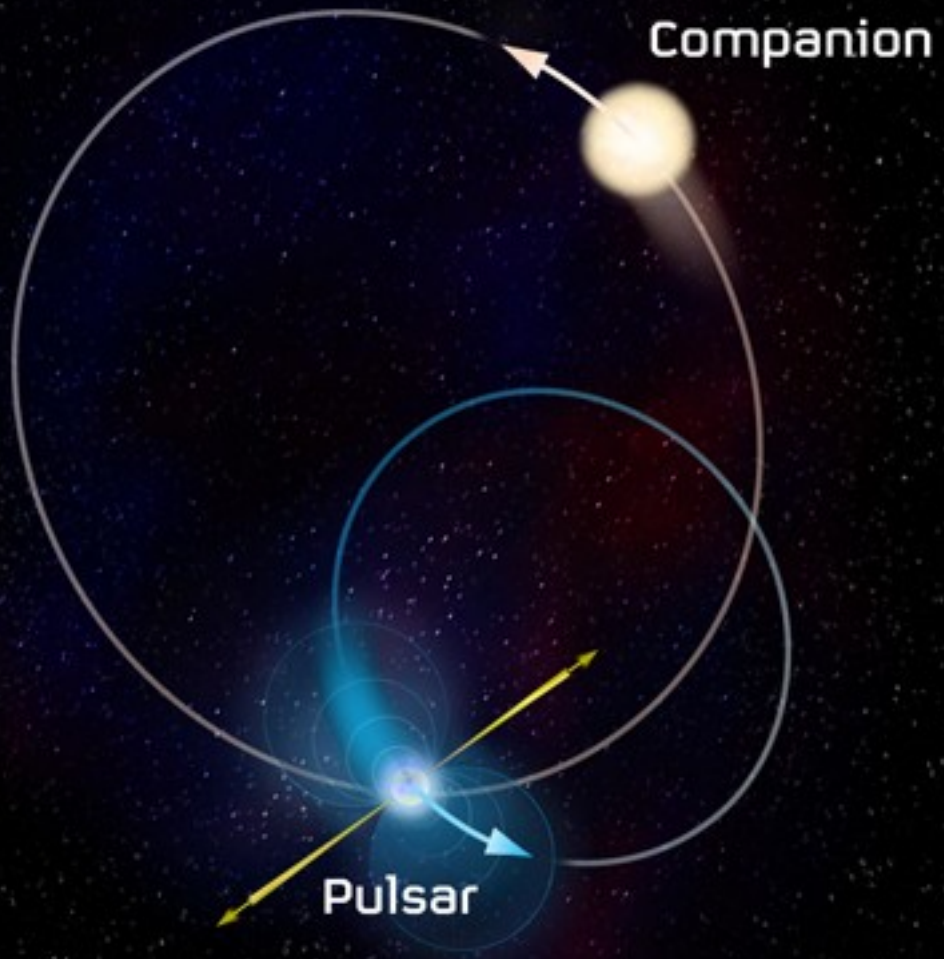
Sigurdsson et al. 2003, *Science*, 301, 193

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



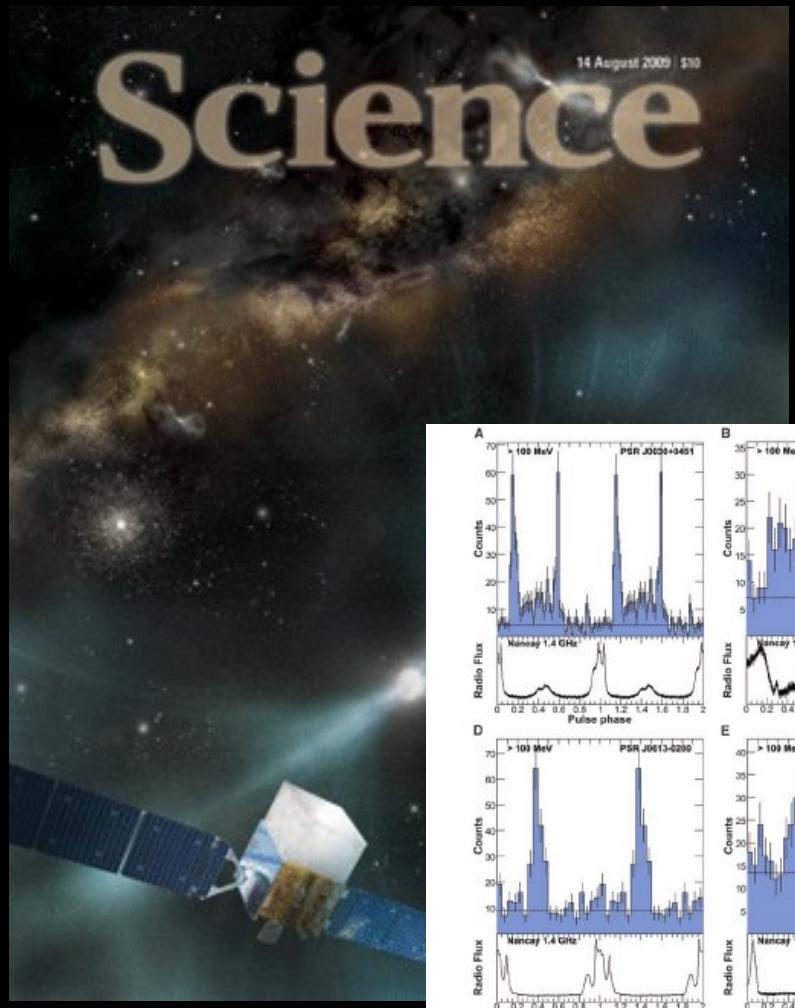
Bill Saxton, NRAO/AUI/NSF

Thoughts on J0337+1715 for future...

- Should show classical secular three-body effects over short timescales (e.g. Ford et al 2000 and many others)
  - Maybe we are already seeing them (Pb-dot)?
  - Precision tests of the theory?
- Optical work will “fully-solve” the inner binary, including masses and inclinations
- Dynamics modeling may fully solve the outer binary
- Deeper optical/IR spectroscopy could lead to radial velocities of the outer star as well
- What is the nature of the outer star? M8 or M9? Or is it a smaller/cooler/older CO WD?
- Why is the outer orbit so circular?

Fermi MSP Primer

- After only a few months, confirmed EGRET detection of MSP J0218+4232 and had detected 8 other millisecond PSRs
- Power-law spectra with exponential cut-off between 1-5 GeV
- Indicates emission from outer magnetosphere



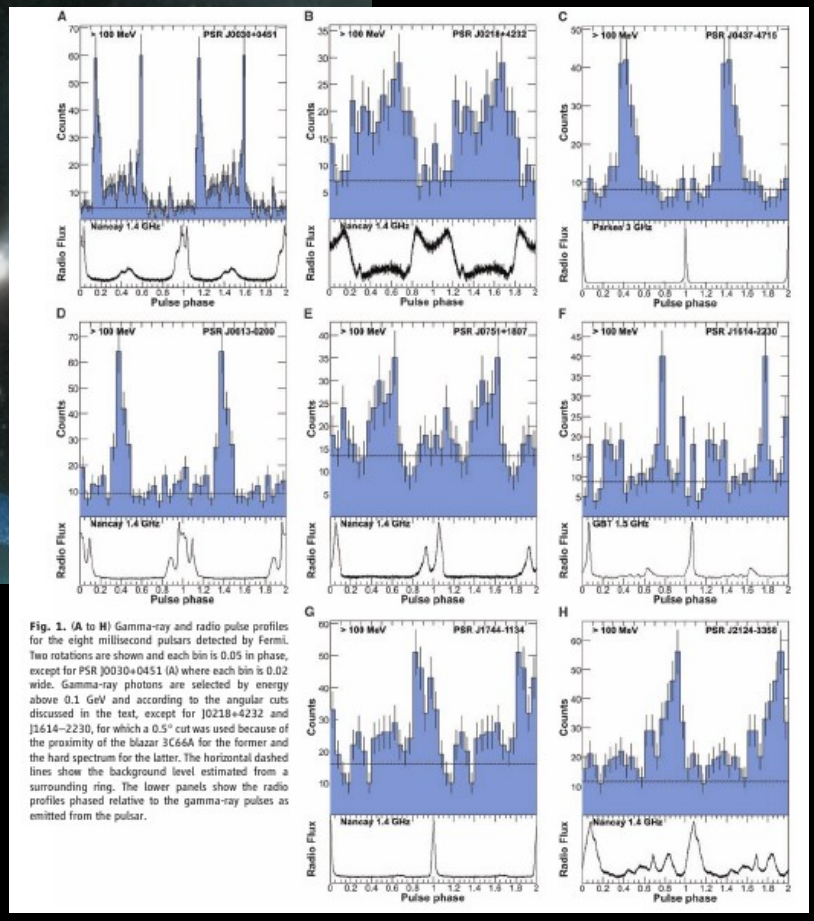
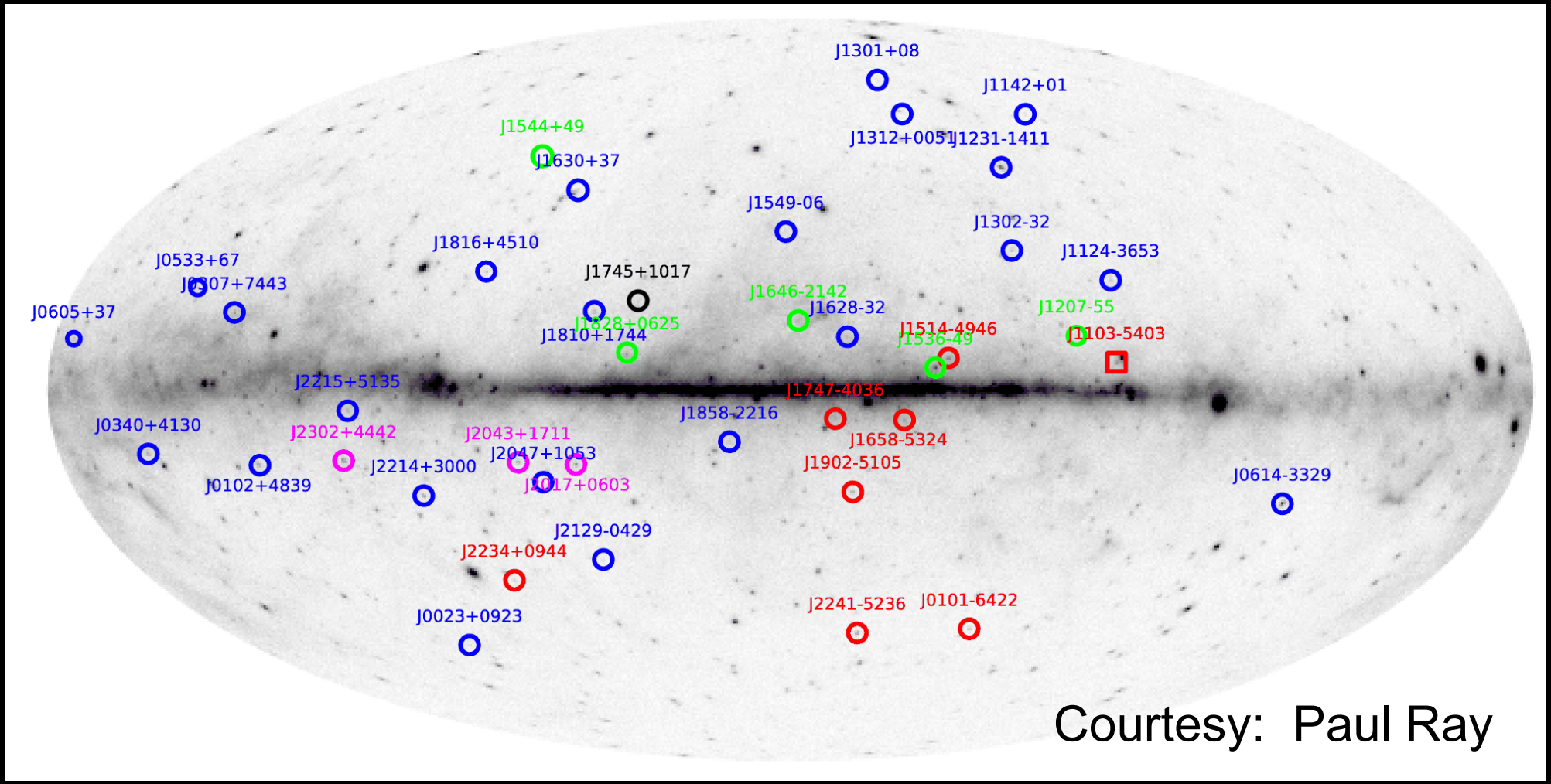


Fig. 1. (A to H) Gamma-ray and radio pulse profiles for the eight millisecond pulsars detected by Fermi. Two rotations are shown and each bin is 0.05 in phase, except for PSR J0030+0451 (A) where each bin is 0.02 wide. Gamma-ray photons are selected by energy above 0.1 GeV and according to the angular cuts discussed in the text, except for J0218+4232 and J1614−2230, for which a 0.5° cut was used because of the proximity of the blazar 3C66A for the former and the hard spectrum for the latter. The horizontal dashed lines show the background level estimated from a surrounding ring. The lower panels show the radio profiles phased relative to the gamma-ray pulses as emitted from the pulsar.

Abdo et al, 2009, Science, 325, 845

Currently 42 new Radio/gamma-ray MSPs because of *Fermi*!

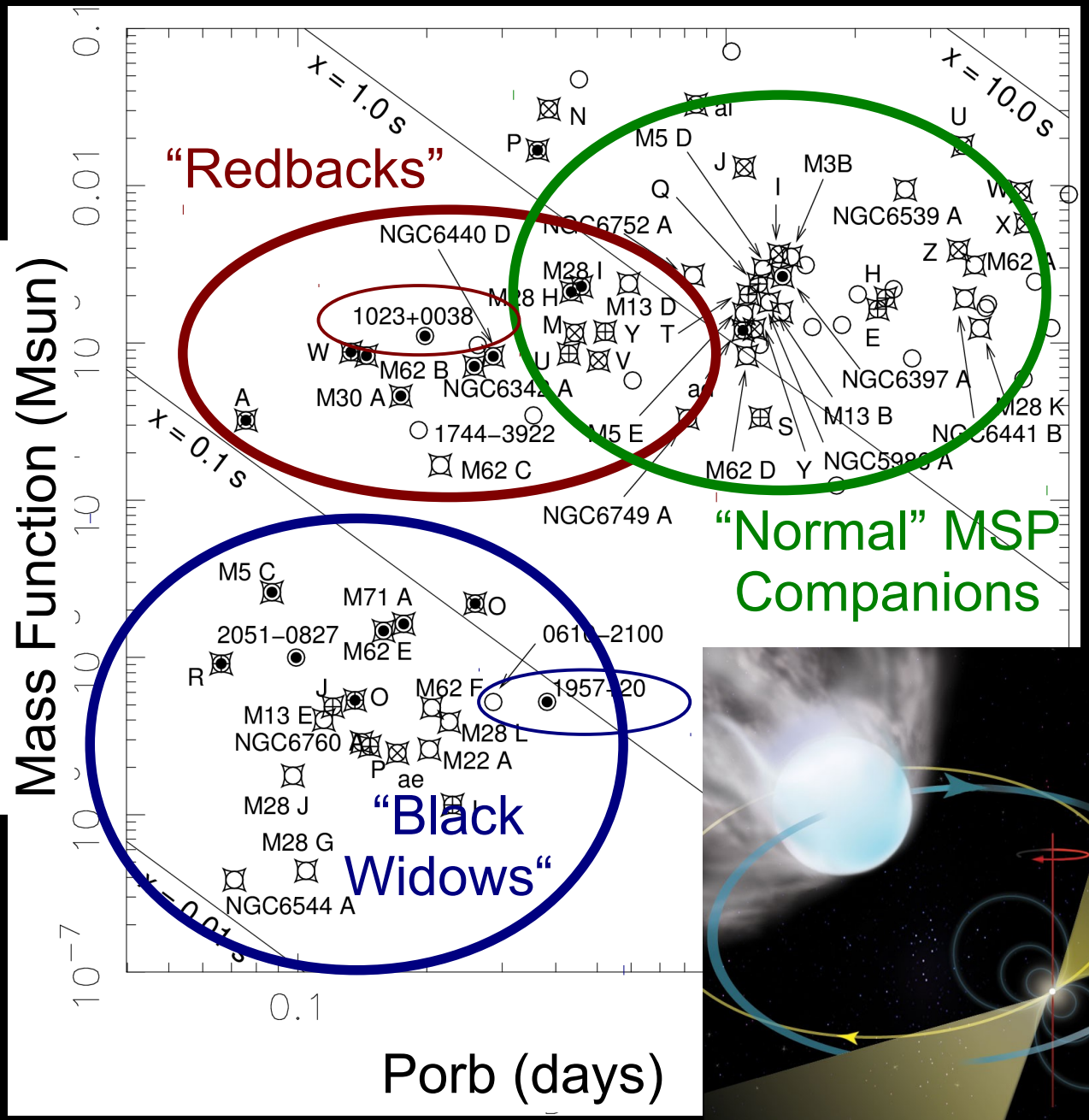
From radio searches of Fermi Unassociated Sources



Radio Fermi MSP Summary

- 42 new radio MSPs from searching Fermi UnIDs
- “Typical” MSPs
  - ~2-4 ms, 85% binary, Edot ~10^{34} ergs/s, 0.5-3 kpc
  - Implies “all” MSPs emit gamma-rays?
- ~10-15% of the new pulsars may be usable for high-precision timing (i.e. NANOGrav)
- Radio flux not (strongly) correlated with G-ray flux
- Many (most?) are weak x-ray sources
- Most (25+) do not (yet) have gamma-ray pulsations (requires a full year of radio timing for position etc)
- Ridiculous number of previously rare eclipsing systems

Strange Eclipsing Binaries (spiders?)



"Normal" MSP companion: He WDs (0.1-0.3 Msun), ~1-100 day orbits

"Black Widows": 10-80 Jupiter mass companions, <1 day orbits, many eclipse

"Redbacks": 0.1-0.4 Msun "main-seq" companions, <1 day orbits, eclipses

Both black-widows and redbacks have become "common" in globular clusters over the last decade. But not in Galactic disk.

Courtesy: Paulo Freire

Black Widows and Redbacks in Galactic Field

	Pulsar	P_s (ms)	$E/10^{34}$ (erg/s)	d_{NE2001} (kpc)	P_B (hrs)	M_C (min. solar)
Old BWs	B1957+20 F	1.61	1.1	2.5	9.2	0.021
	J0610-2100 F	3.86	0.23	3.5	6.9	0.025
	J2051-0827	4.51	0.5	1.0	2.4	0.027
New BWs	J2241-5236[P] F	2.19	2.5	0.5	3.4	0.012
	J2214+3000[G8] F	3.12	1.9	3.6	10.0	0.014
	J1745+1017[N] F	2.65	1.3	1.3	17.5	0.014
	J2234+09[P] F	3.63	??	??	10	0.015
	J0023+09[G3] F	3.05	3.4	0.7	3.3	0.016
	J1301+08[G8] F	1.84	??	0.7	6.5	0.024
	J1124-36[G3] F	2.41	??	??	5.4	0.027
	J2256-1024[3] F	2.29	5.2	0.6	5.1	0.034
	J2047+10[G8] F	4.29	??	2.0	3.0	0.035
	J1731-1847[1]	2.3	7.6	2.5	7.5	0.04
	J1810+17[G3] F	1.66	4.0	2.0	3.6	0.044
New RBs	J1628-32[G8] F	3.21	??	1.2	5.0	0.16
	J1816+45[4] F	3.19	??	??	8.7	0.16
	J1023+0038[3] F	1.69	5	0.6 (1.3)	4.8	0.2
	J2215+51[G3] F	2.61	1.3	3.0	4.2	0.22
	J1723-28[2]	1.86	??	0.75	14.8	0.24
	J2129-04[G3] F	7.61	??	0.9	15.2	0.37

3 Black Widows over past 25 years

9/11 new Black Widows in past 3 yrs from Fermi!

4/6 “Redbacks” in past 3 yrs from Fermi!

F=Fermi detected; 1. HTRUPS Keith et al. 2010 2. PMB pulsar, Crawford et al. 2010 3. GBT Drift Scan 4. GBNCC
Fermi targeted discoveries: G8=GBT 820 MHz, G3=GBT 350 MHz, N=Nancay, P=Parkes

Table from Mallory Roberts

Black Widows and Redbacks in Galactic Field

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	J1023+0038[3] F	1.69	~5	0.6 (1.3)	4.8	0.2
	J2215+51[G3] F	2.61	13	3.0	4.2	0.22
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	J2129-04[G3] F	7.61	??	0.9	15.2	0.37

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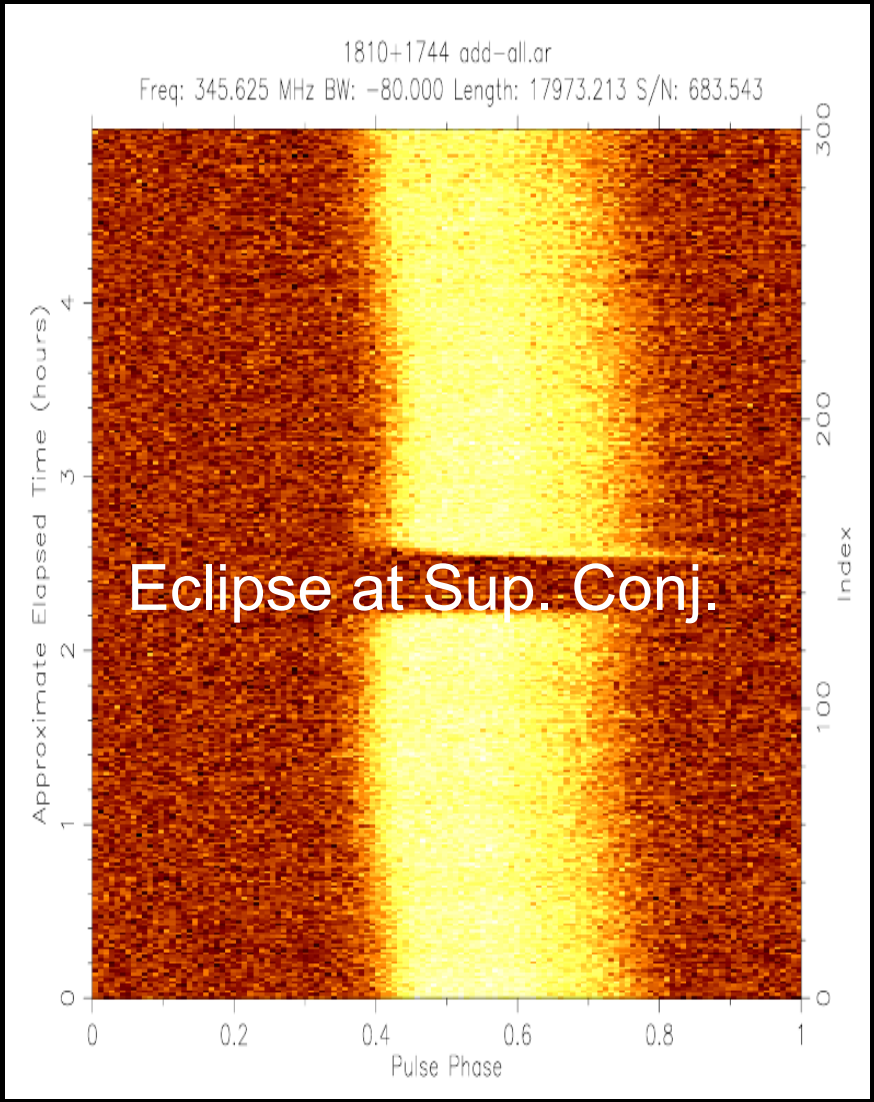
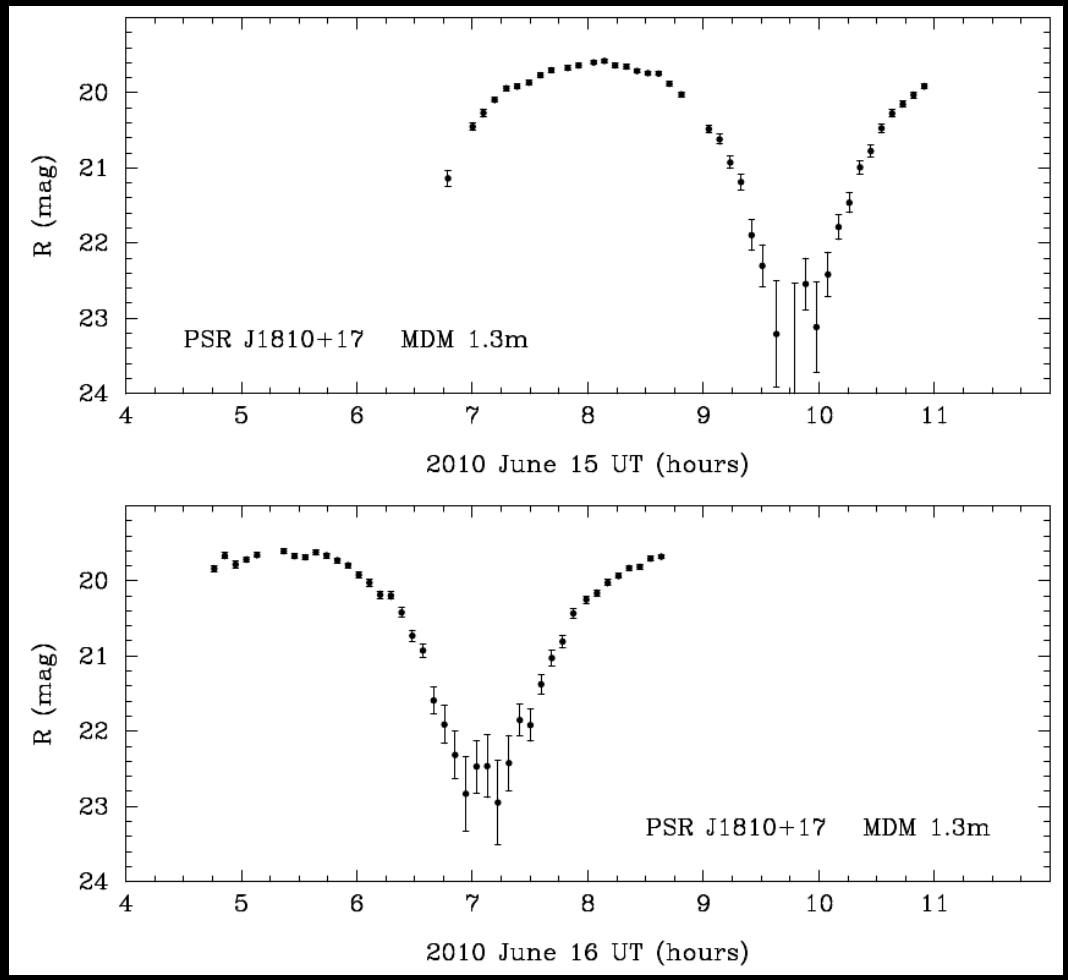
Table from Mallory Roberts

New Black Widow: J1810-197



350MHz full-orbit
WSRT observation
(Jason Hessels)



Optical lightcurve
of companion
(Jules Halpern)

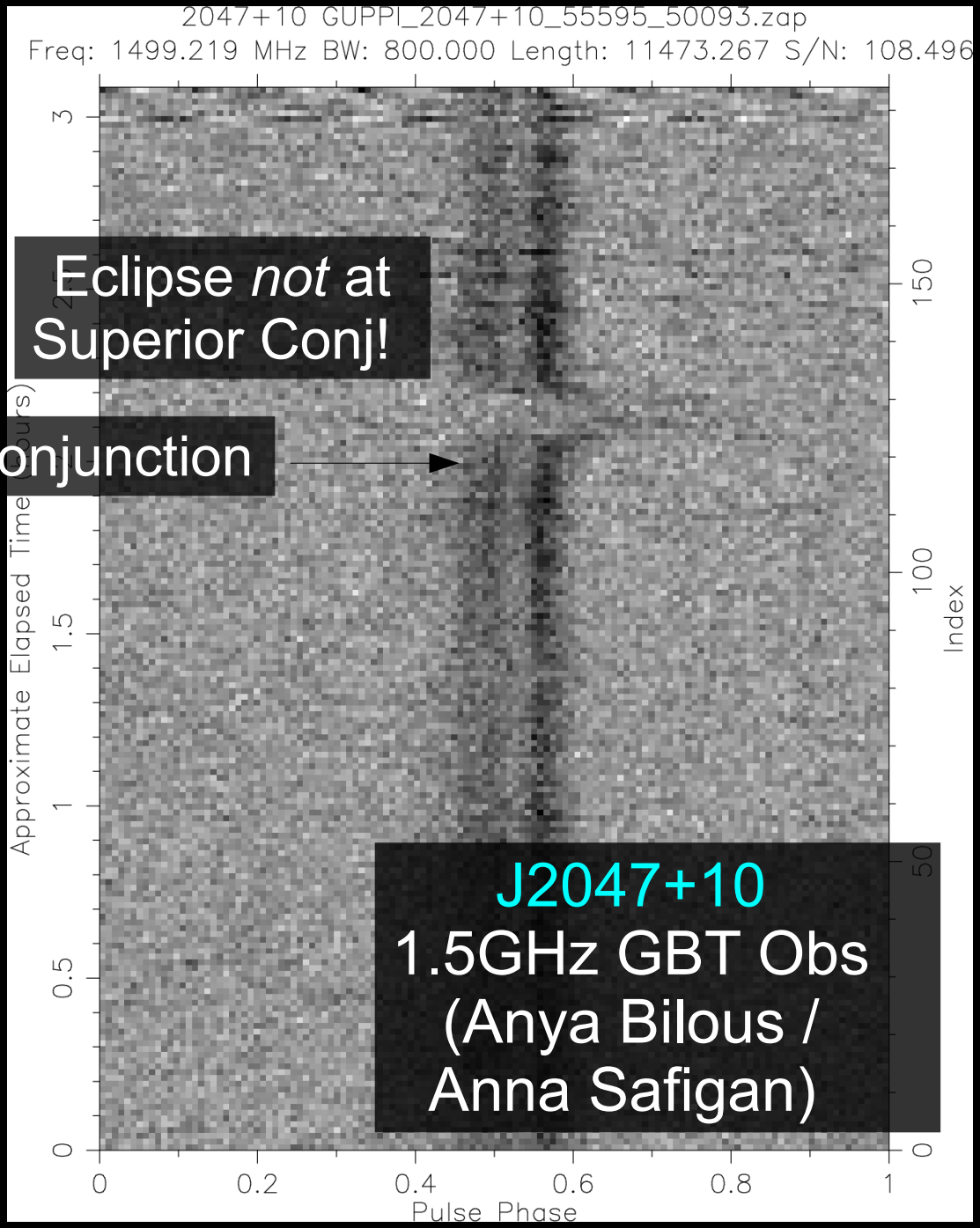
Other New Black Widows

Some have strange eclipse properties

2-3 have no or very minor eclipses (inclination effect?)

Many will be amenable to optical / x-ray follow-up

Seem to pulse in gamma-rays, so why are they selected preferentially by Fermi?



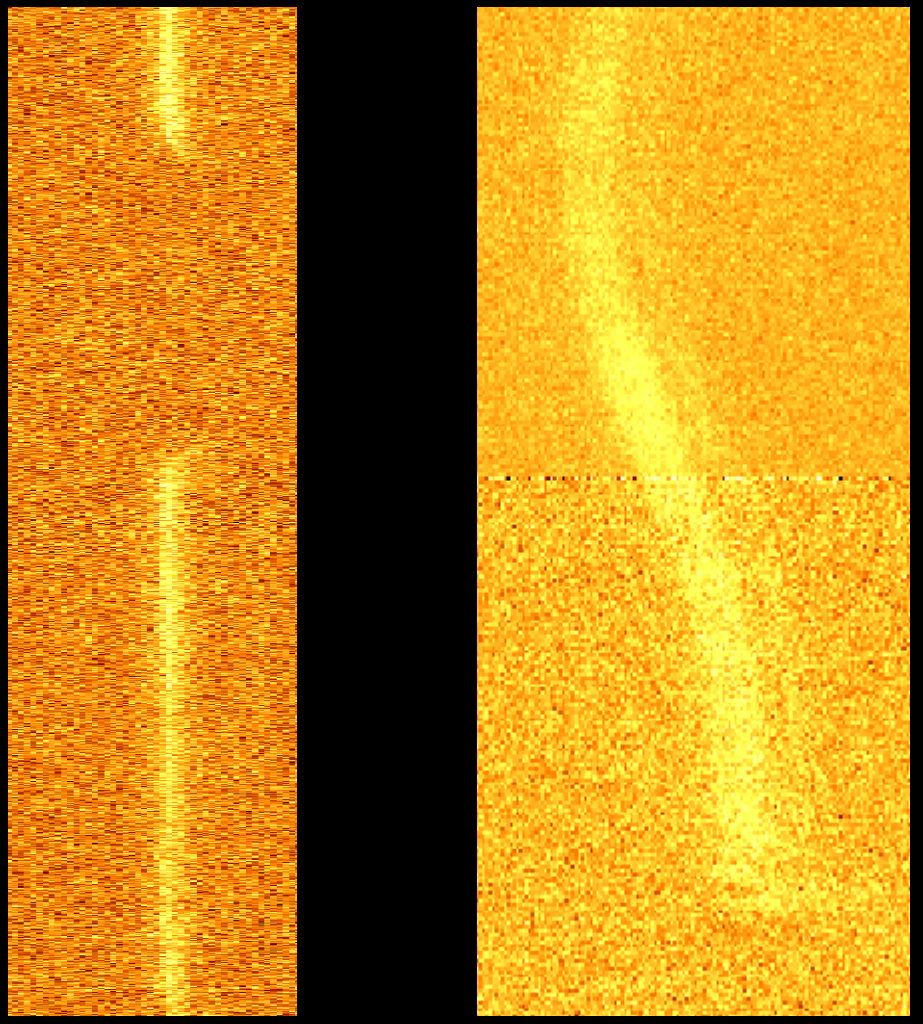
Four New Fermi “Redbacks”

Prototype system only discovered 3 yrs ago: J1023+0038

(Archibald et al. 2009, Science, 324, 1411)

Very prominent eclipses and timing “noise” due to gas and tidal effects

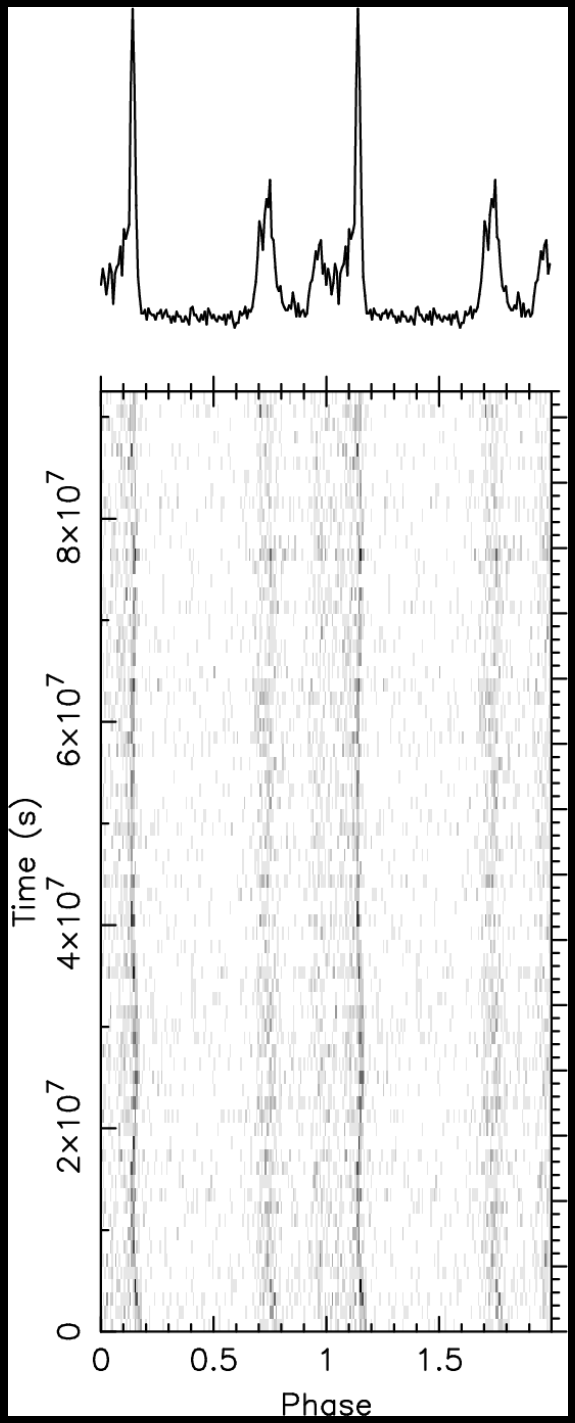
Many will be amenable to optical / x-ray follow-up



J2215+51 and J1628-32
2.0 GHz Full-orbit GBT Obs

Radio timing is required

- Unambiguously account for every rotation of the pulsar
- Gives milli-arcsec positions and spin-down information
- Allows for multi-wavelength follow-up
- Requires ~1yr for a “solution”



PSR J1231-1411

~3yrs of Fermi data

~3000 photons (~3/day)

~560 binary orbits

~24 billion rotations of MSP

Summary

- There are tons of interesting MSPs out there still
  - Both All-sky and Fermi-directed surveys are useful
- J0337+1715 will be a precision test-case for classical, secular, three-body effects on “human” timescales
- Fermi-directed MSPs are still appearing (2 within last 2 weeks) and we will likely get ~20 more before the mission ends
  - Lots of interesting eclipsing systems
  - 10-15% will end up being high-precision for NANOGrav