Tests of GR using Neutron Star – White Dwarf Binaries

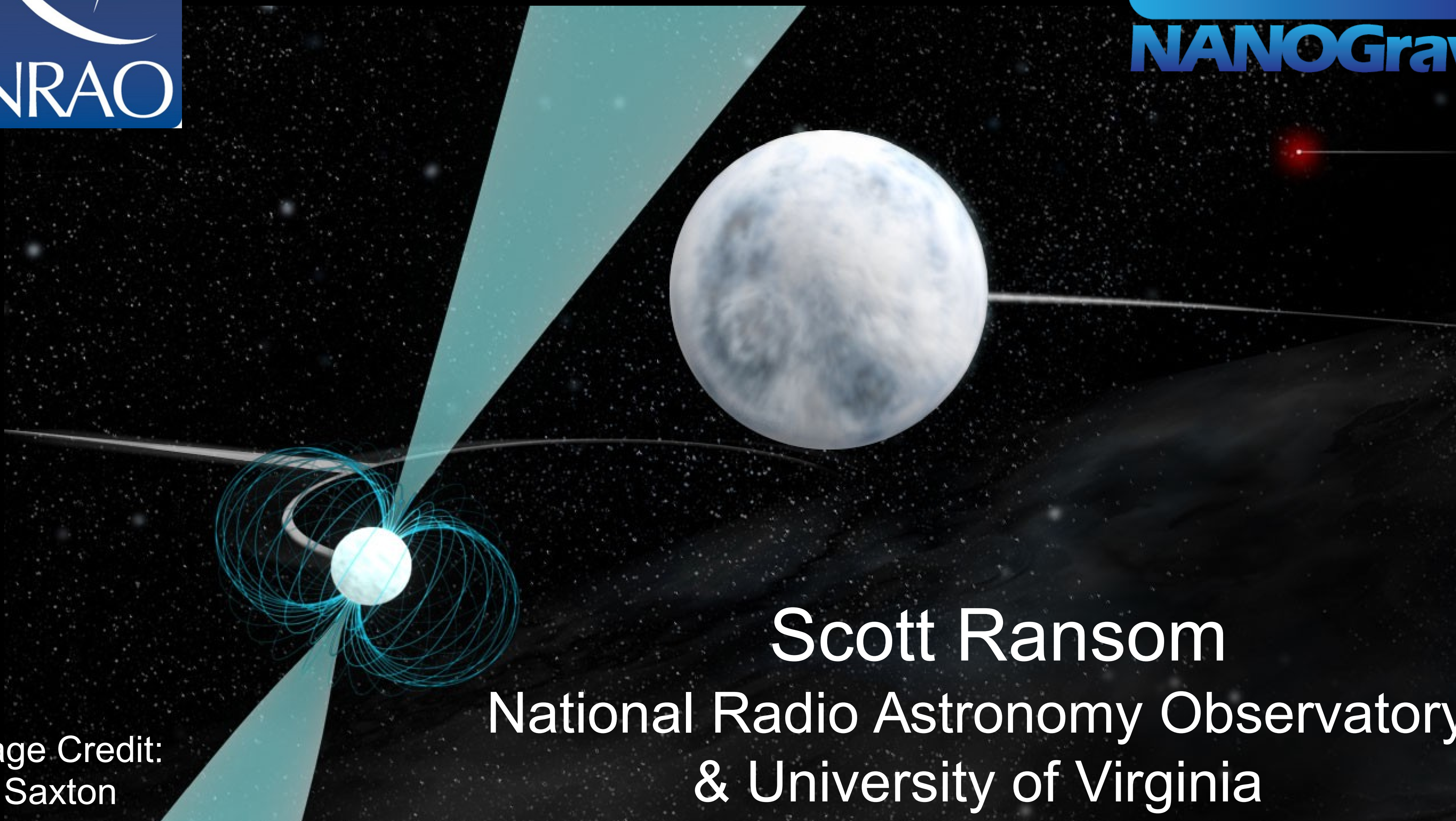


Image Credit:
Bill Saxton

Scott Ransom
National Radio Astronomy Observatory
& University of Virginia

Pulsar Population of the Galaxy

~2300 pulsars known, but the Galaxy has ~30000 (and ~10000 MSPs)

Only 2-3% of known pulsars are "interesting" for basic/astro physics individually

In Galaxy, we know:

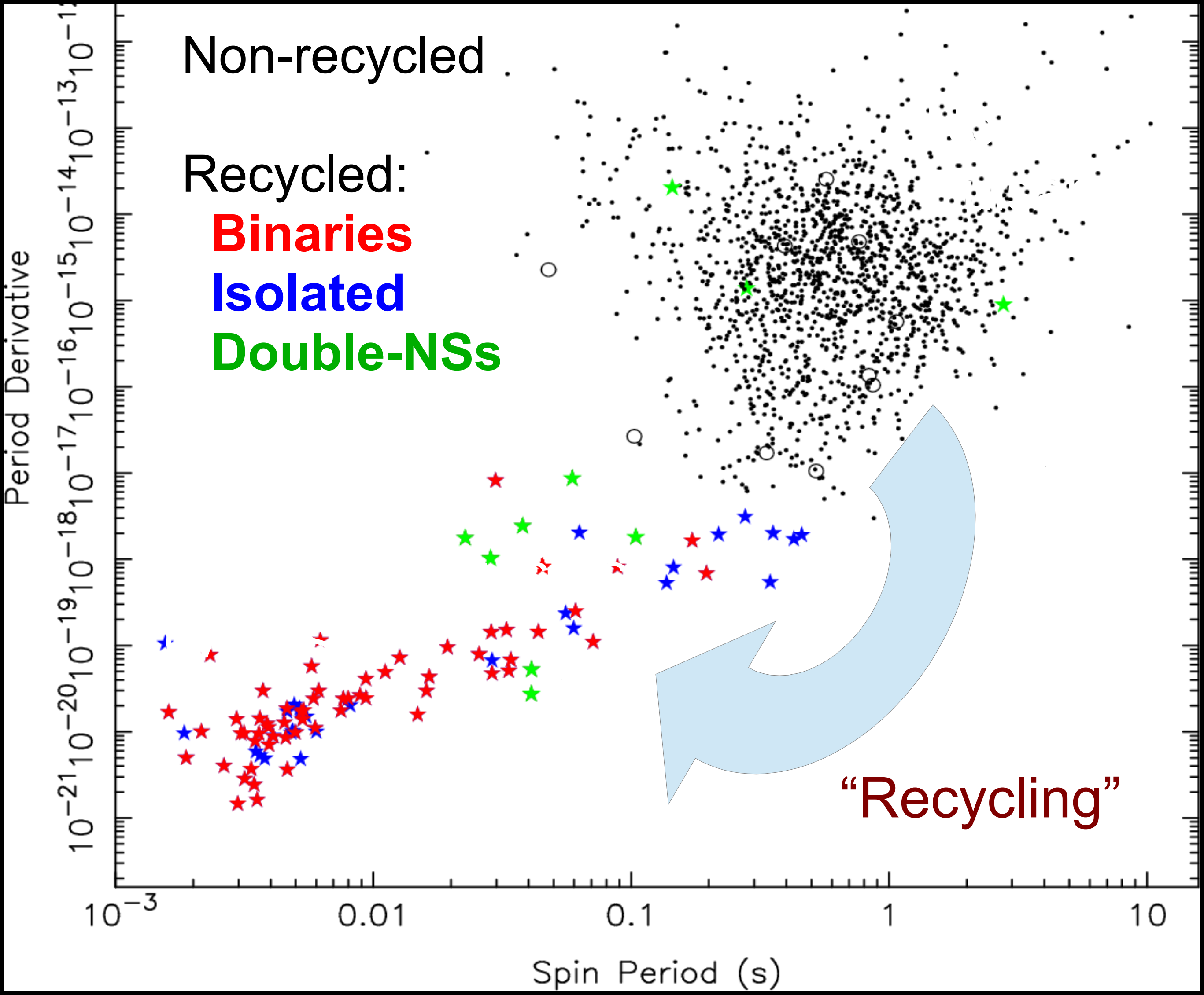
~160 binary MSPs
~40 isolated MSPs

~40 binary part-recyc
~20 isolated part-recyc

Definitions:

Part-recycled:
P > 20 ms, B < 3×10^{10} G

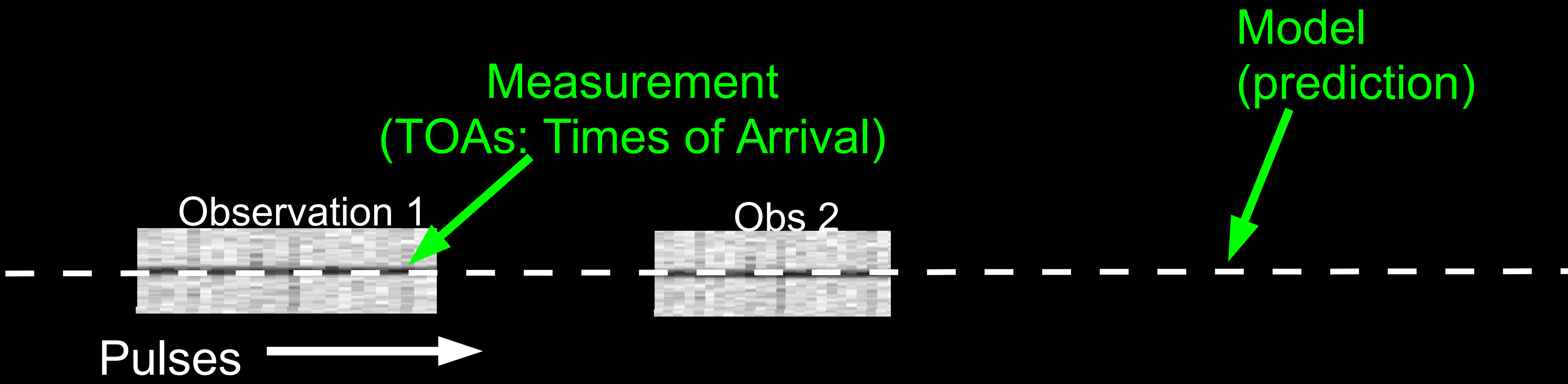
MSP:
P < 20 ms, B < 10^{9} G



Pulsar Timing:

Pulse Phase Tracking

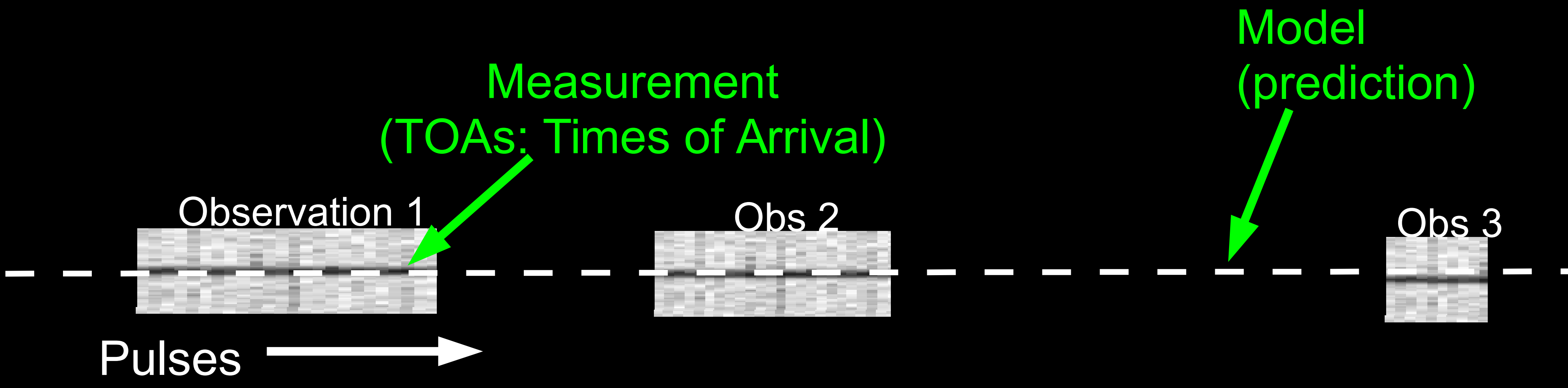
Unambiguously account for every rotation of a pulsar over years



Pulsar Timing:

Pulse Phase Tracking

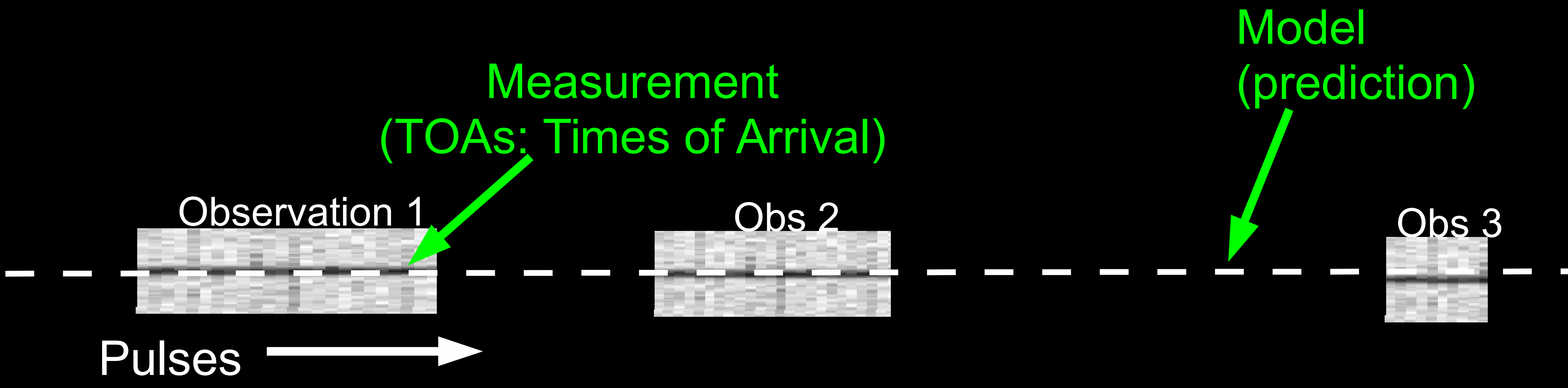
Unambiguously account for every rotation of a pulsar over years



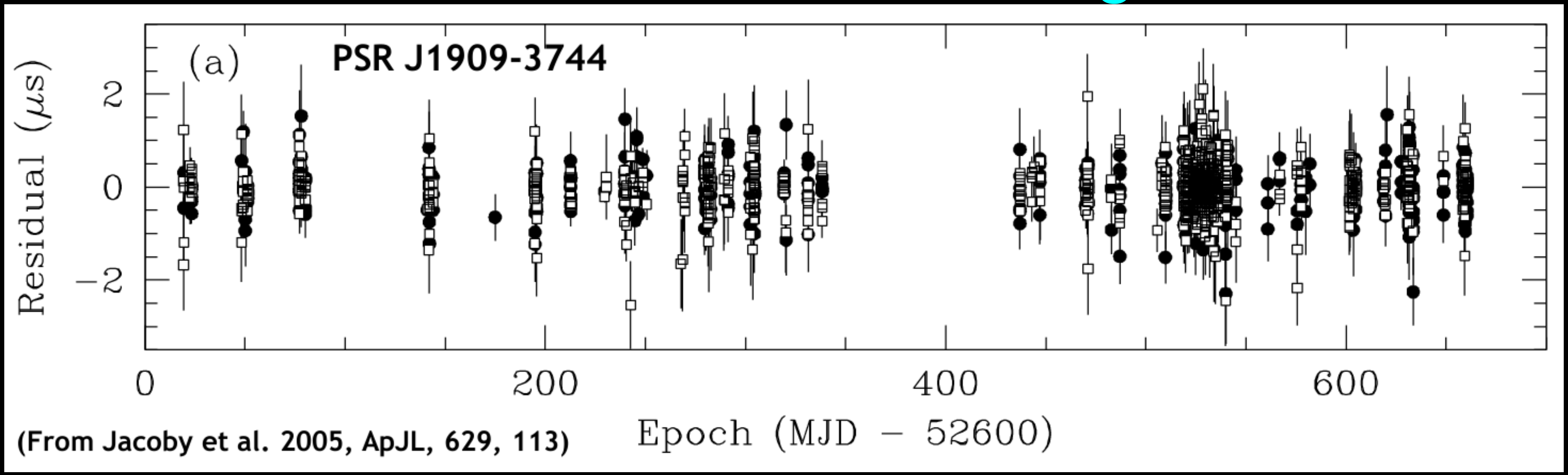
Pulsar Timing:

Pulse Phase Tracking

Unambiguously account for every rotation of a pulsar over years



Measurement - Model = Timing Residuals



(From Jacoby et al. 2005, ApJL, 629, 113)

200ns RMS over 2 yrs

Post-Keplerian Orbital Parameters

Besides the normal 5 "Keplerian" parameters (P_{orb}, e, *asin*(*i*)/c, T_0, ω), General Relativity gives:

$$\dot{\omega} = 3\left(\frac{P_b}{2\pi}\right)^{-5/3}(T_\odot M)^{2/3}(1-e^2)^{-1}$$ (Orbital Precession)

$$\gamma = e\left(\frac{P_b}{2\pi}\right)^{1/3} T_\odot^{2/3} M^{-4/3} m_2 (m_1 + 2m_2)$$ (Grav redshift + time dilation)

$$\dot{P}_b = -\frac{192\pi}{5}\left(\frac{P_b}{2\pi}\right)^{-5/3}\left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right)(1-e^2)^{-7/2} T_\odot^{5/3} m_1 m_2 M^{-1/3}$$

$$r = T_\odot m_2$$

$$s = x\left(\frac{P_b}{2\pi}\right)^{-2/3} T_\odot^{-1/3} M^{2/3} m_2^{-1}$$

(Shapiro delay: "range" and "shape")

where: $T_\odot \equiv GM_\odot/c^3$ = 4.925490947 μs, $M = m_1 + m_2$, and $s \equiv \sin(i)$

These are only functions of:

- the (precisely!) known Keplerian orbital parameters P_b, e, asin(i)
- the mass of the pulsar m_1 and the mass of the companion m_2

Post-Keplerian Orbital Parameters

Besides the normal 5 “Keplerian” parameters (P_{orb}, e, *asin*(*i*)/c, T_0, ω), General Relativity gives:

$\dot{\omega} =$	Need eccentric orbit and time for precession	(Orbital Precession)
$\gamma =$		(Grav redshift + time dilation)
$\dot{P}_b =$	Need compact orbit and a lot of patience	
$r =$	Need high precision, Inclination, and m_2	(Shapiro delay: “range” and “shape”)
$s =$		

where: $T_\odot \equiv GM_\odot/c^3$ = 4.925490947 μs, $M = m_1 + m_2$, and $s \equiv \sin(i)$

These are only functions of:

- the (precisely!) known Keplerian orbital parameters P_b, e, asin(i)
- the mass of the pulsar m_1 and the mass of the companion m_2

The Binary Pulsar: B1913+16

First binary pulsar discovered at Arecibo Observatory by Hulse and Taylor in 1974

NS-NS Binary

P_{psr} = 59.03 ms

P_{orb} = 7.752 hrs

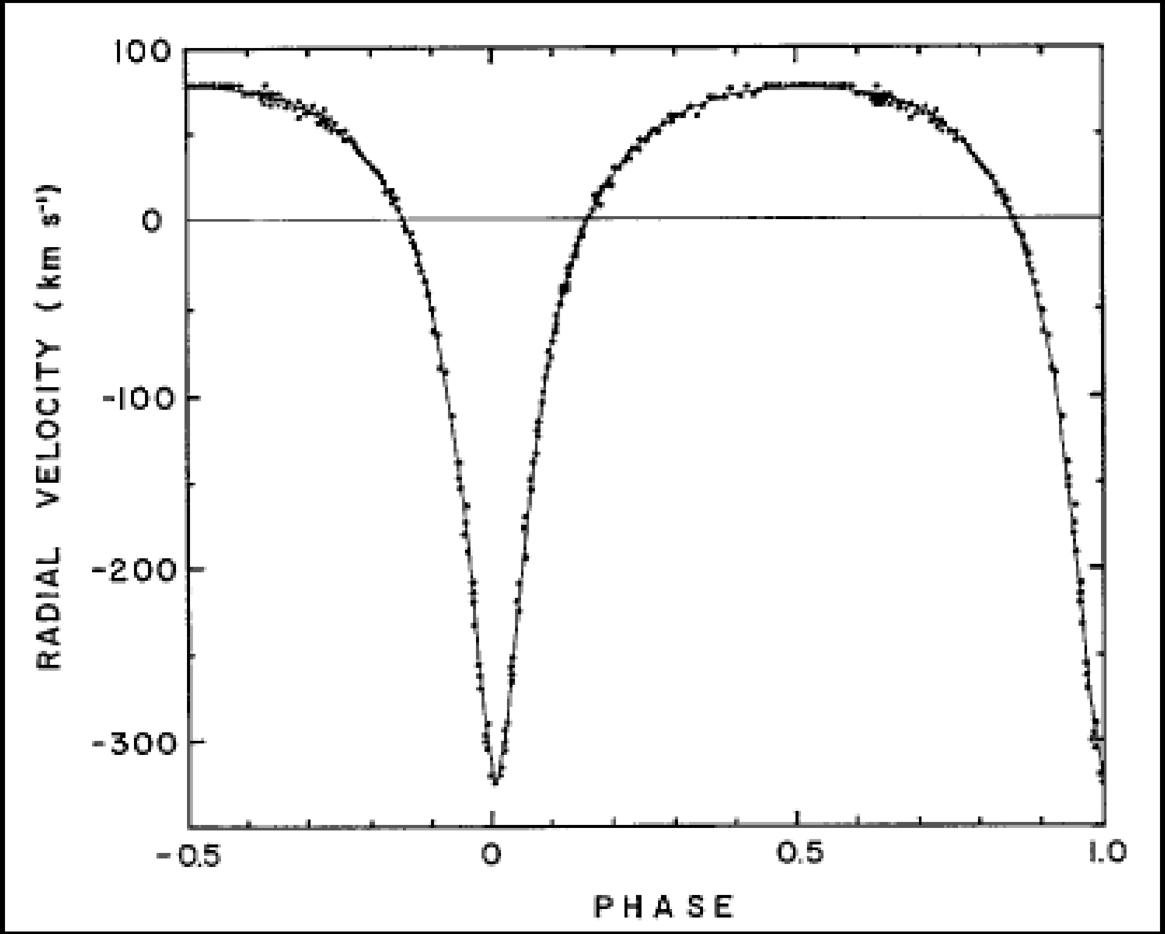
a sin(i)/c = 2.342 lt-s

e = 0.6171

$\dot{\omega}$ = 4.2 deg/yr

M_c = 1.3874(7) $M_\odot$

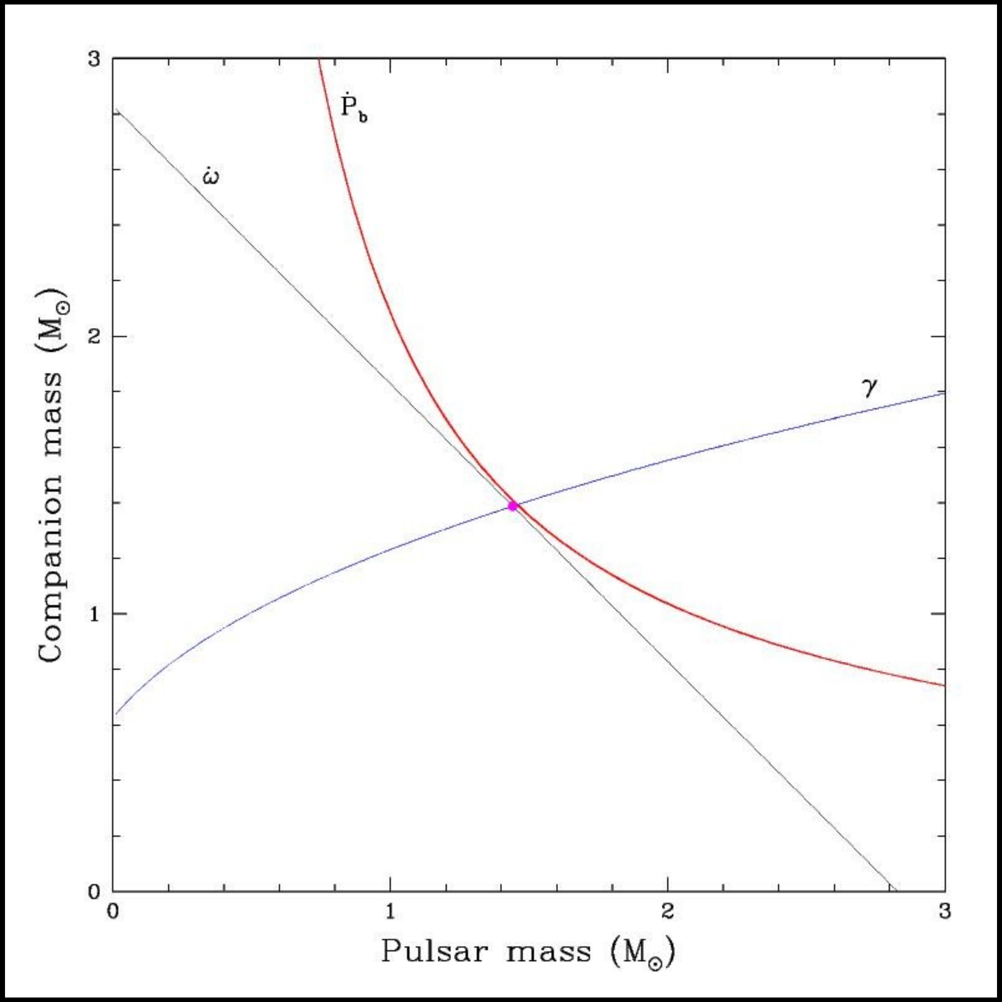
M_p = 1.4411(7) $M_\odot$

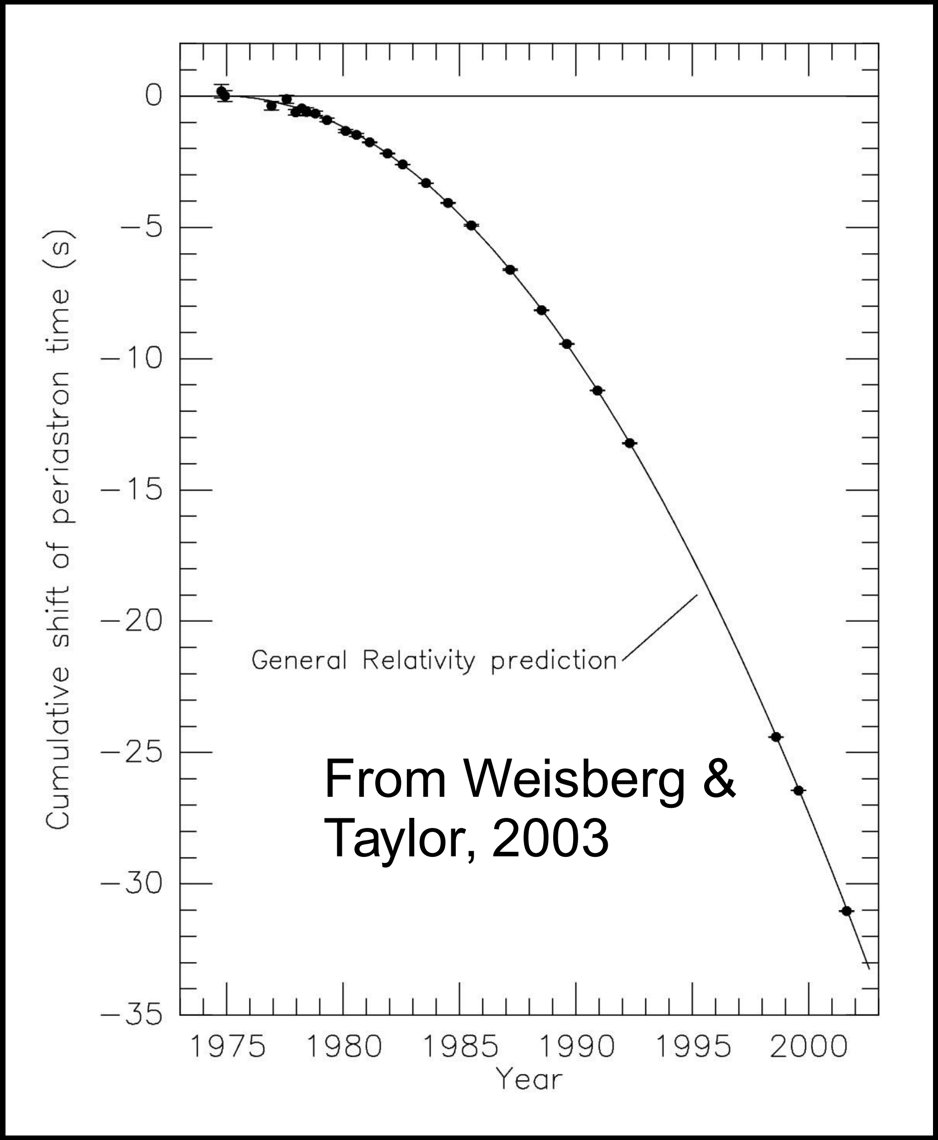


The Binary Pulsar: B1913+16

Three Relativistic Observables: $\dot{\omega}$, γ, $\dot{P}_{orb}$

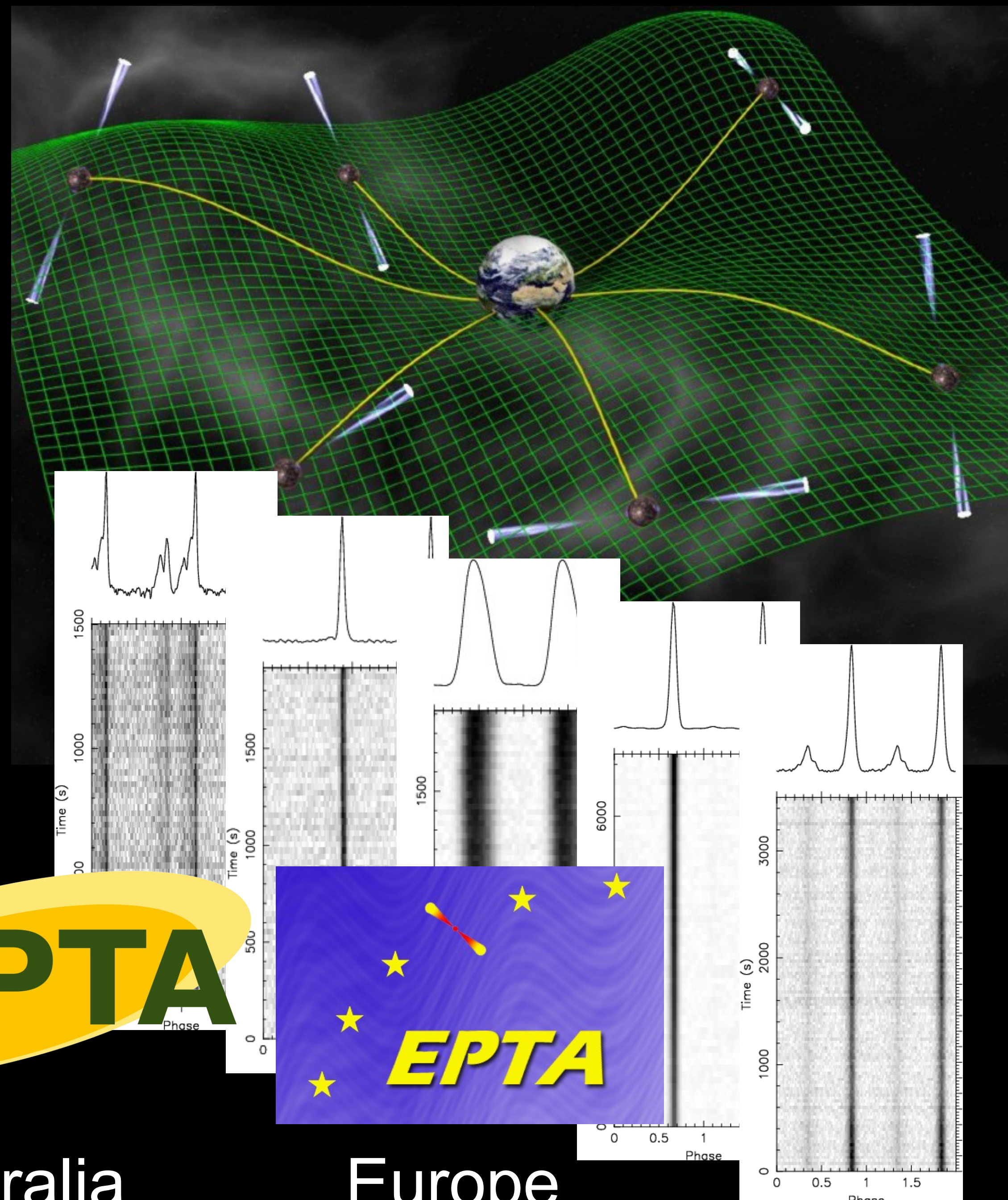
Indirect detection of Gravitational Radiation





Gravitational Wave Detection with a Pulsar Timing Array

- Need good MSPs
- **Significance scales directly with the number of MSPs being timed.** Lack of good MSPs is currently the biggest limitation
- Must time the pulsars for 5-10 years at a precision of ~100 nano-seconds!



N. America

Australia

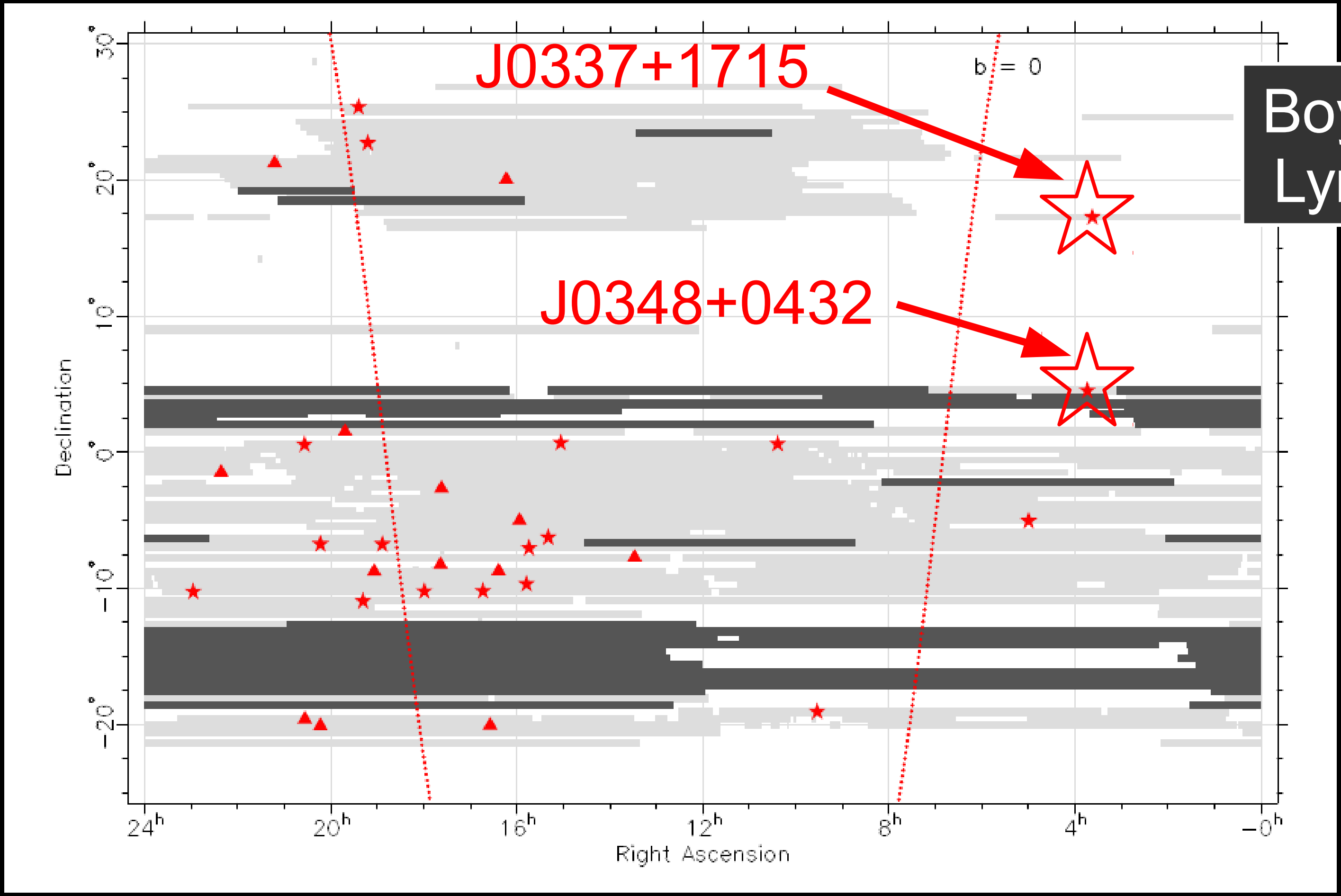
Europe

GBT 350MHz Drift Scan Survey in 2007

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!)

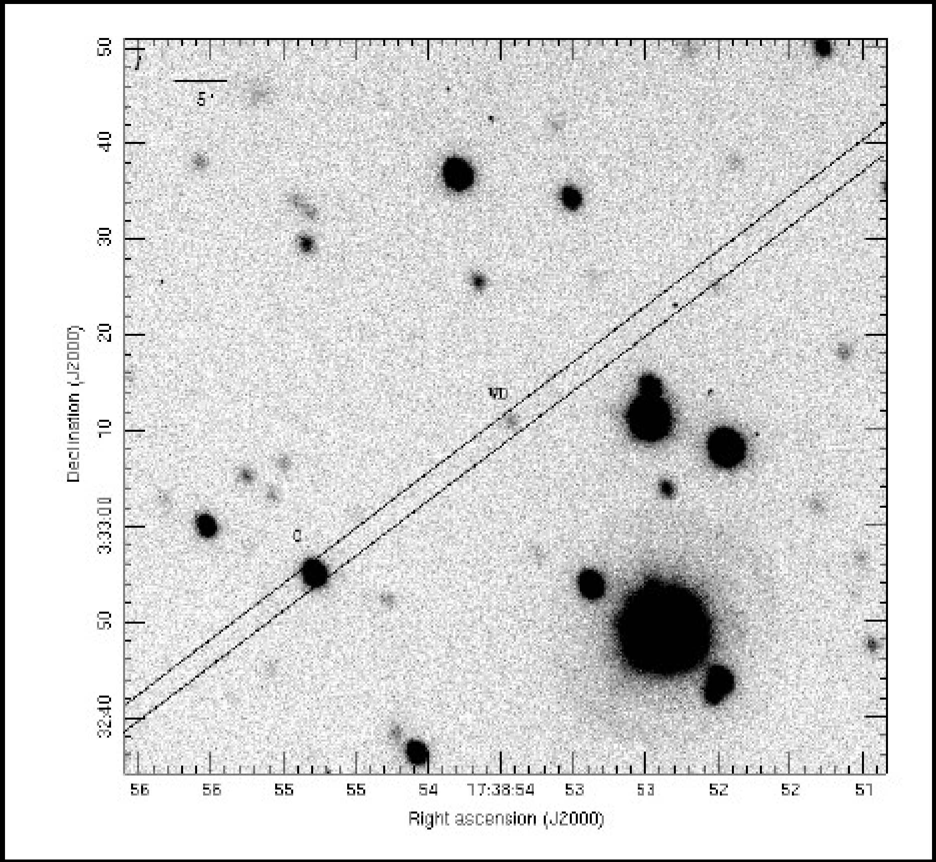
So far 2 fantastic pulsar – white dwarf systems....

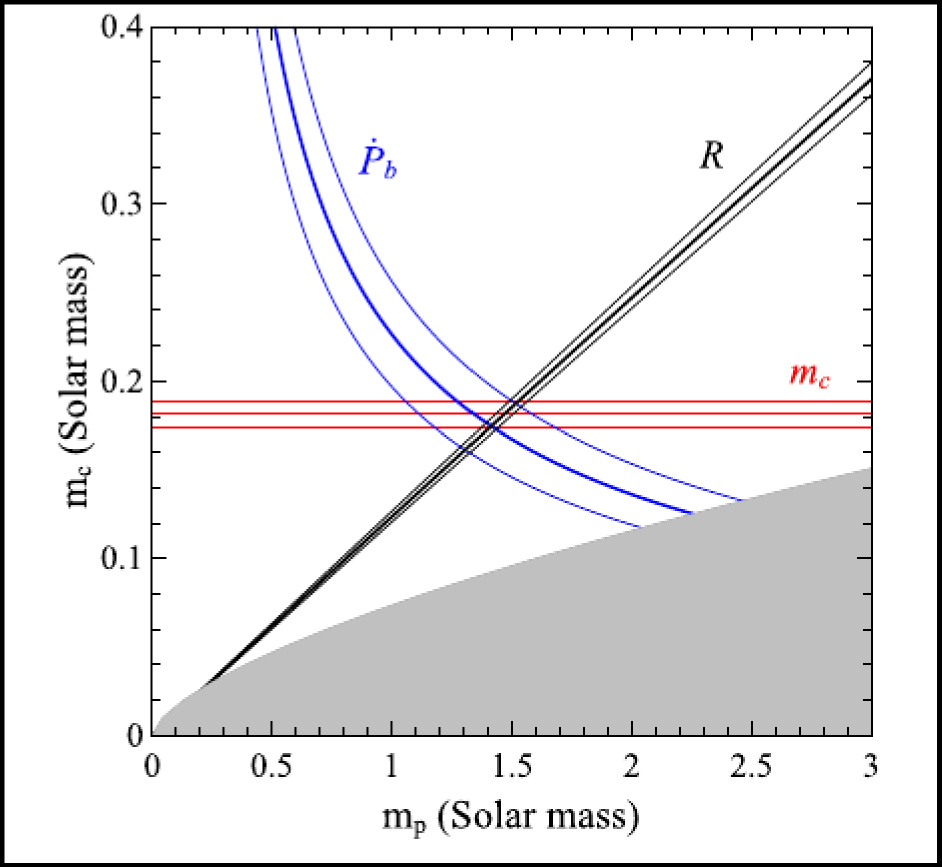


Boyles et al. 2013, ApJ
Lynch et al. 2013, ApJ

PSR J1738+0333

- 5.85 ms pulsar from 2001
- 8.5 hr, highly circular, orbit with WD
- Excellent long-term timing: Pb-dot, π
- Optical obs: mass ratio (8.1±0.2) and WD model gives M_{wd} = 0.181(7) $M_{\odot}$





This is an excellent test of scalar-tensor gravity!

Antoniadis et al. 2012
Freire et al. 2012

NS-WD radiative test of GR

Wex 2014
arXiv: 1402.5594

In mono-scalar-tensor theories, there can be dipolar gravitational radiation:

$$\dot{P}_b = -2\pi \frac{m_p m_c}{M^2} \frac{1 + e^2/2}{(1 - e^2)^{5/2}} \frac{\mathcal{V}_b^3}{c^3} \frac{(\alpha_p - \alpha_c)^2}{1 + \alpha_p \alpha_c} + \mathcal{O}(\mathcal{V}_b^5/c^5)$$

α_p and α_c are the effective scalar coupling of PSR & companion

To first order: $(\alpha_p - \alpha_c) \propto (\epsilon_p - \epsilon_c) + \mathcal{O}(\epsilon^2)$

Where $\epsilon \sim GM/Rc^2$ is the gravitational binding energy:

ϵ ~0.1 for NSs ~10^{-6} for WDs ~10^{-10} for planets

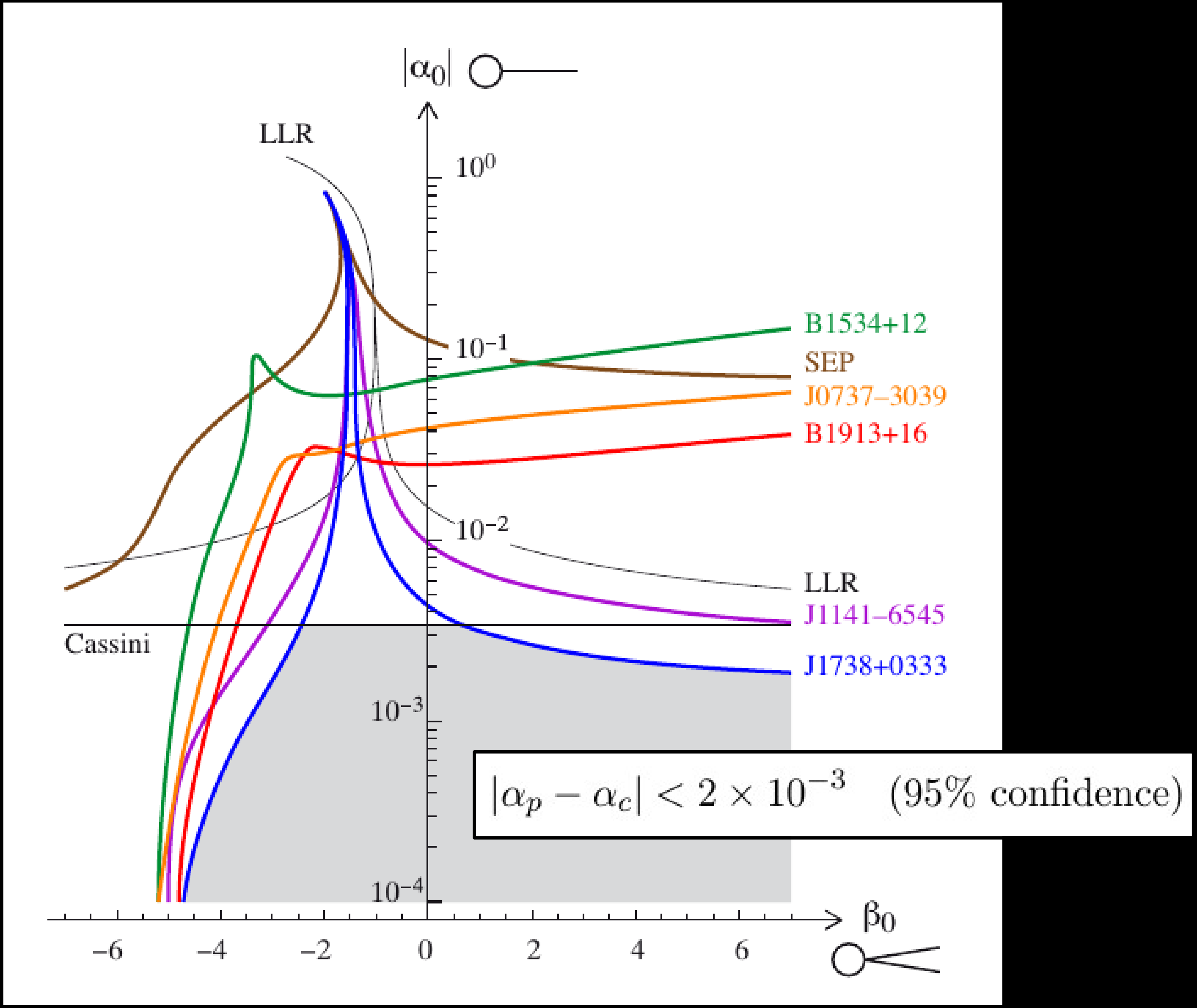
NS-NS systems have: $(\epsilon_p - \epsilon_c)^2 \sim 10^{-5}$ to 10^{-4}

J1738+0333 (i.e. NS-WD) has: $(\epsilon_p - \epsilon_c)^2 \sim 0.012$

PSR-WD orbital decays can be dominated by dipolar radiation, despite "good" NS-NS quadrupolar tests

Constraints on scalar-tensor theories

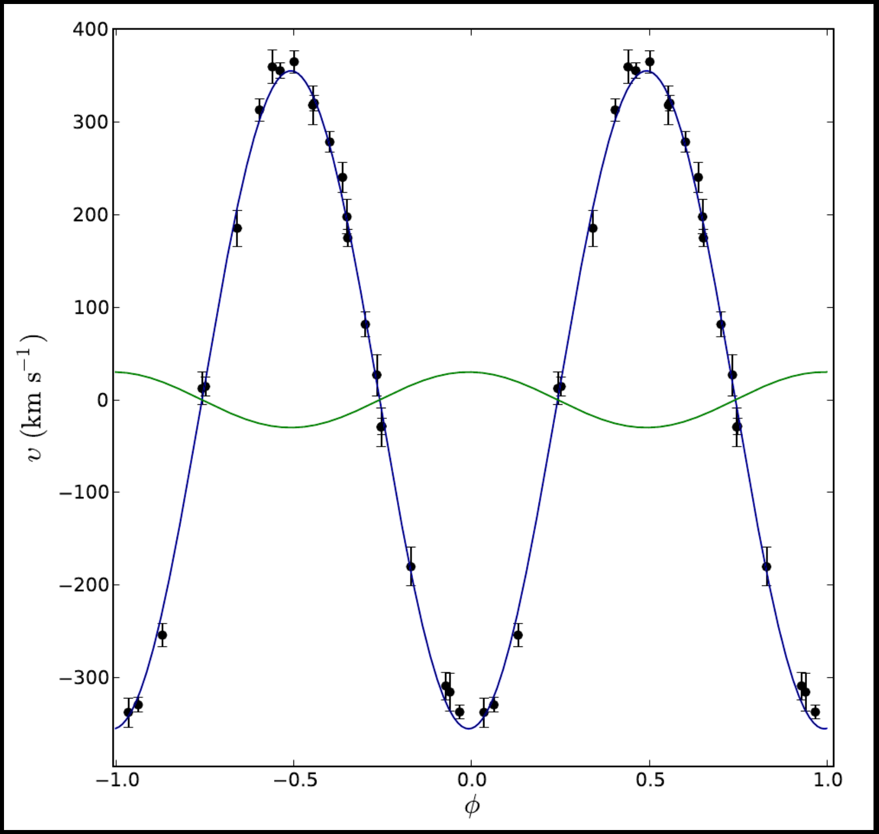
- $T_1(\alpha_0,\beta_0)$ theories
- GR has $\alpha_0=\beta_0=0$
- Jordan – Fierz – Brans – Dicke theory has $\beta_0=0$
- This is a form of Strong Equivalence Principle violation test

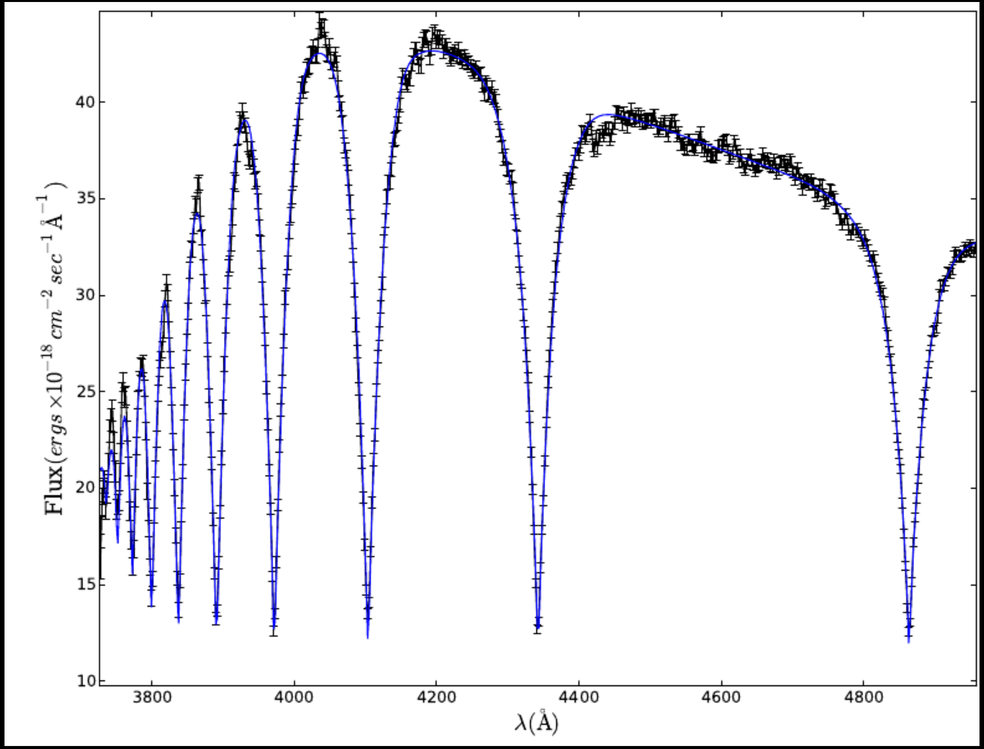


Wex 2014, arXiv: 1402.5594

PSR J0348+0432

- 39.1 ms GBT Driftscan pulsar
- 2.4hr relativistic orbit with WD
- He WD is ~10,120K, log(g) ~6.0
- Mass ratio of 11.70 +/- 0.13!
- Orbital period decay coming...





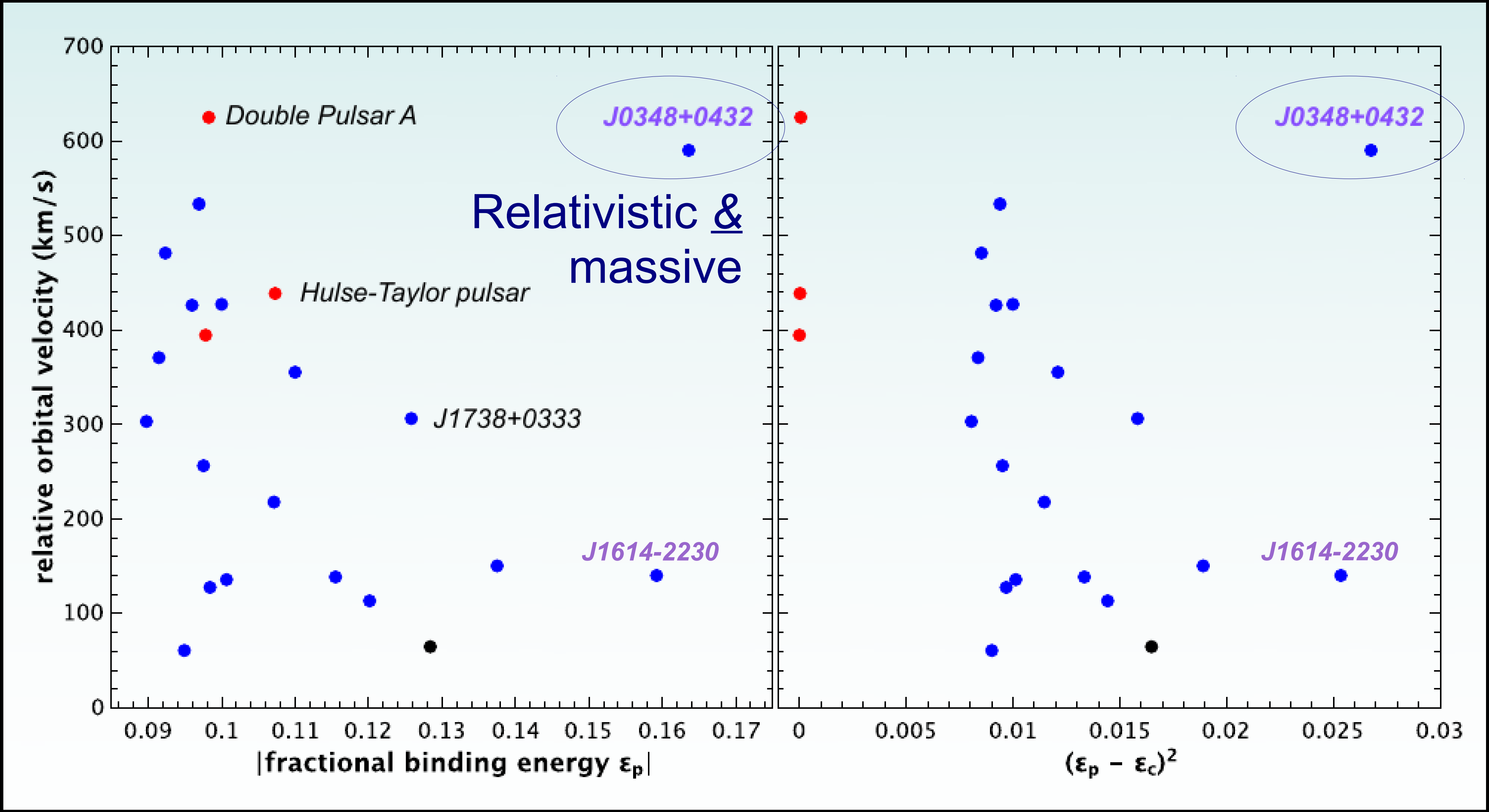
NS mass ~ 2.01(4) Msun!

(interesting tests of GR)

Antoniadis et al *Science*, 2013, 340, 448

Gravitational Binding Energy

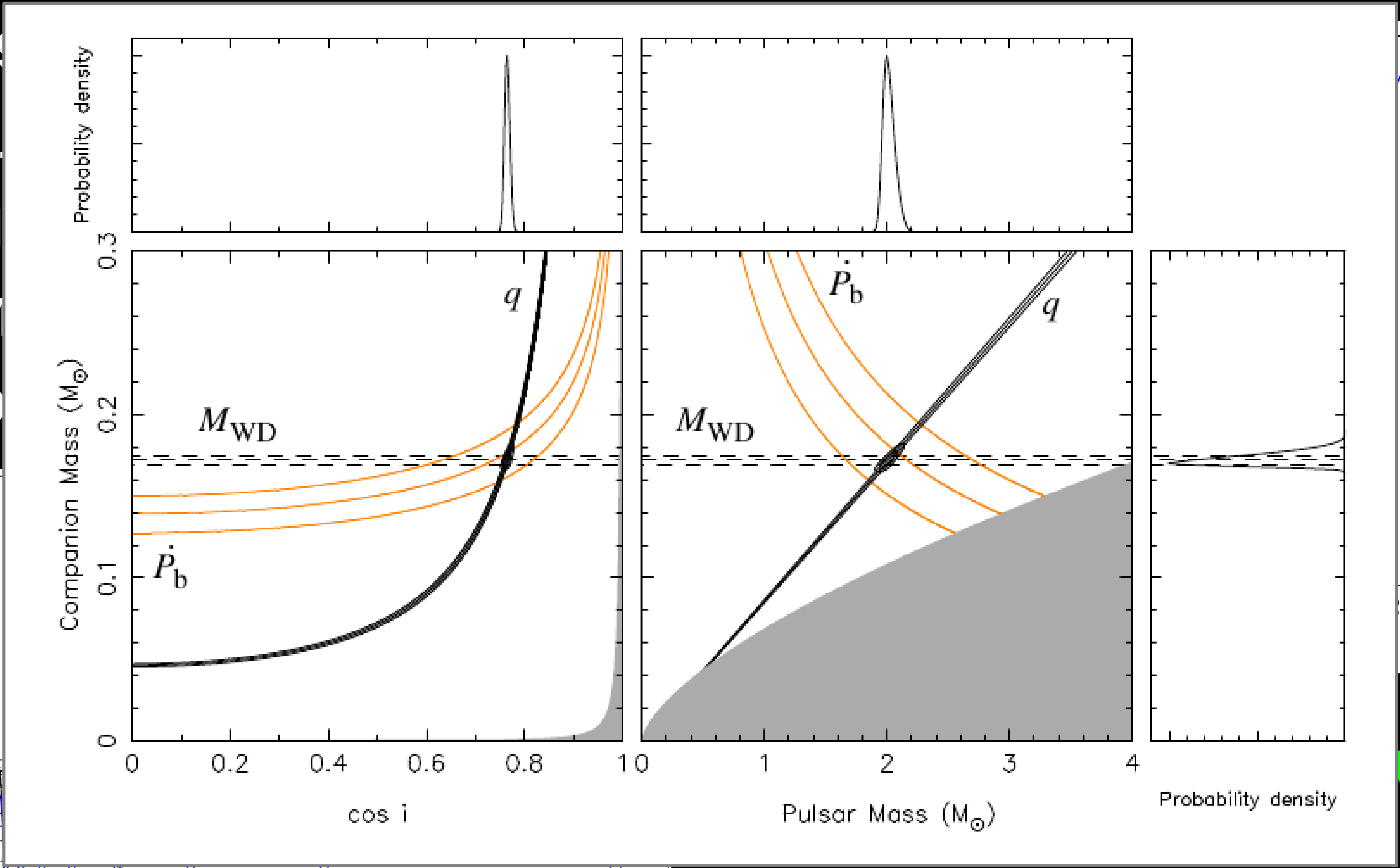
Massive NS gives qualitatively different tests than previously

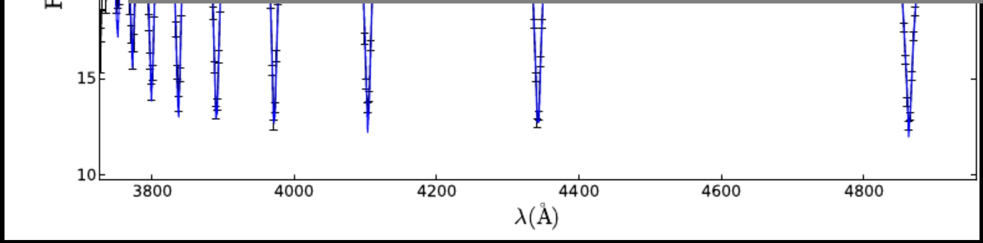


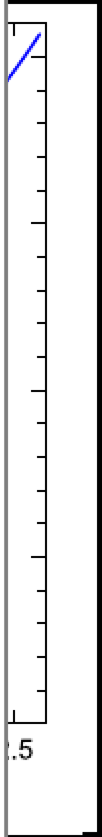
N. Wex

PSR J0348+0432

- 39
- 2.
- H
- M
- O





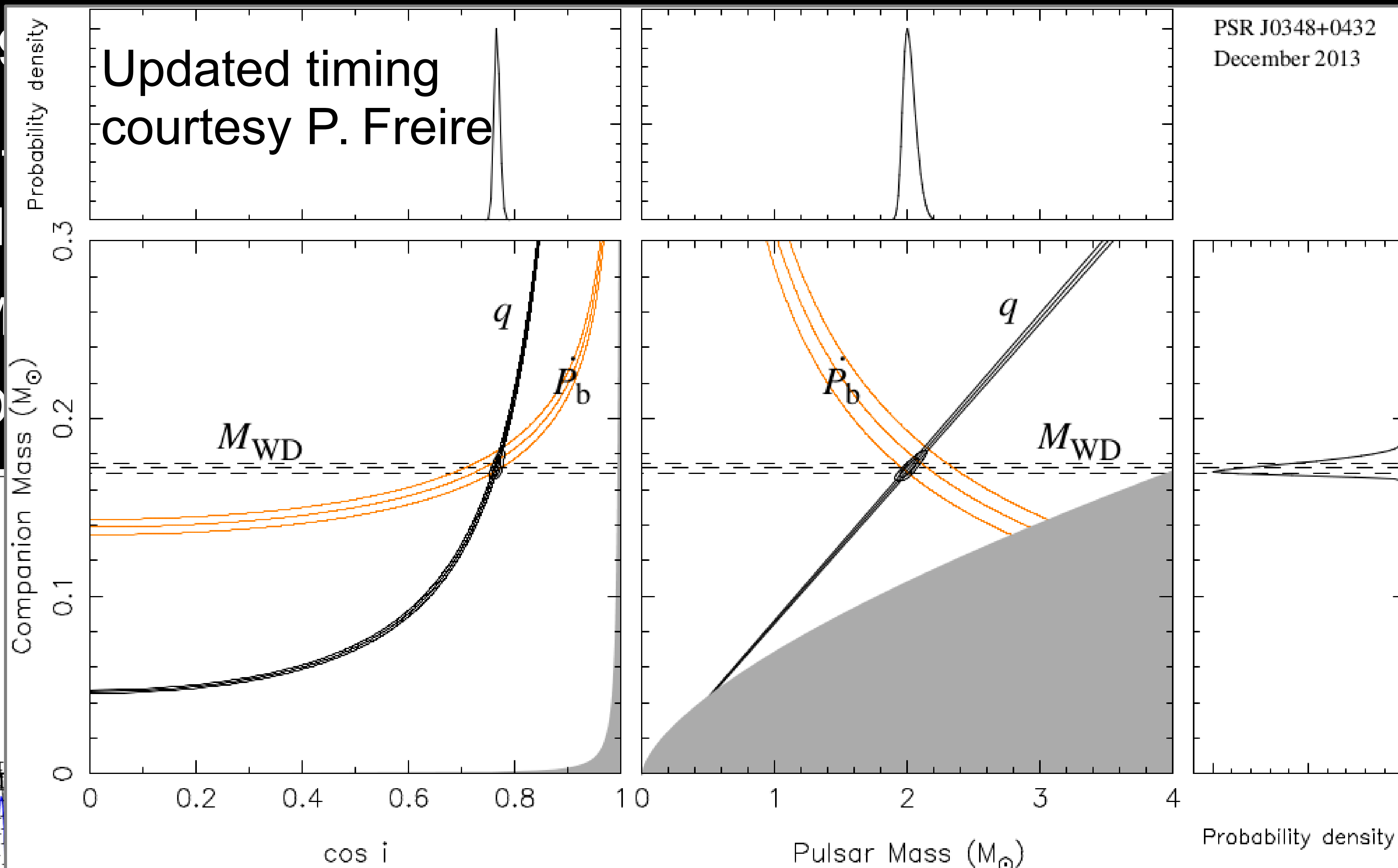


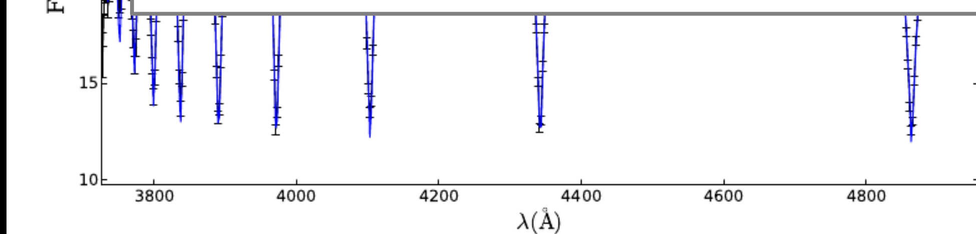
un!

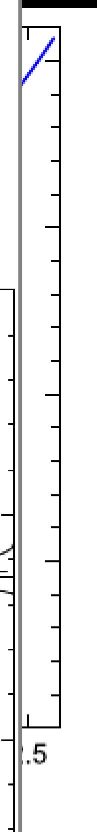
Antoniadis et al *Science*, 2013, 340, 448

PSR J0348+0432

- 39
- 2.
- H
- M
- O





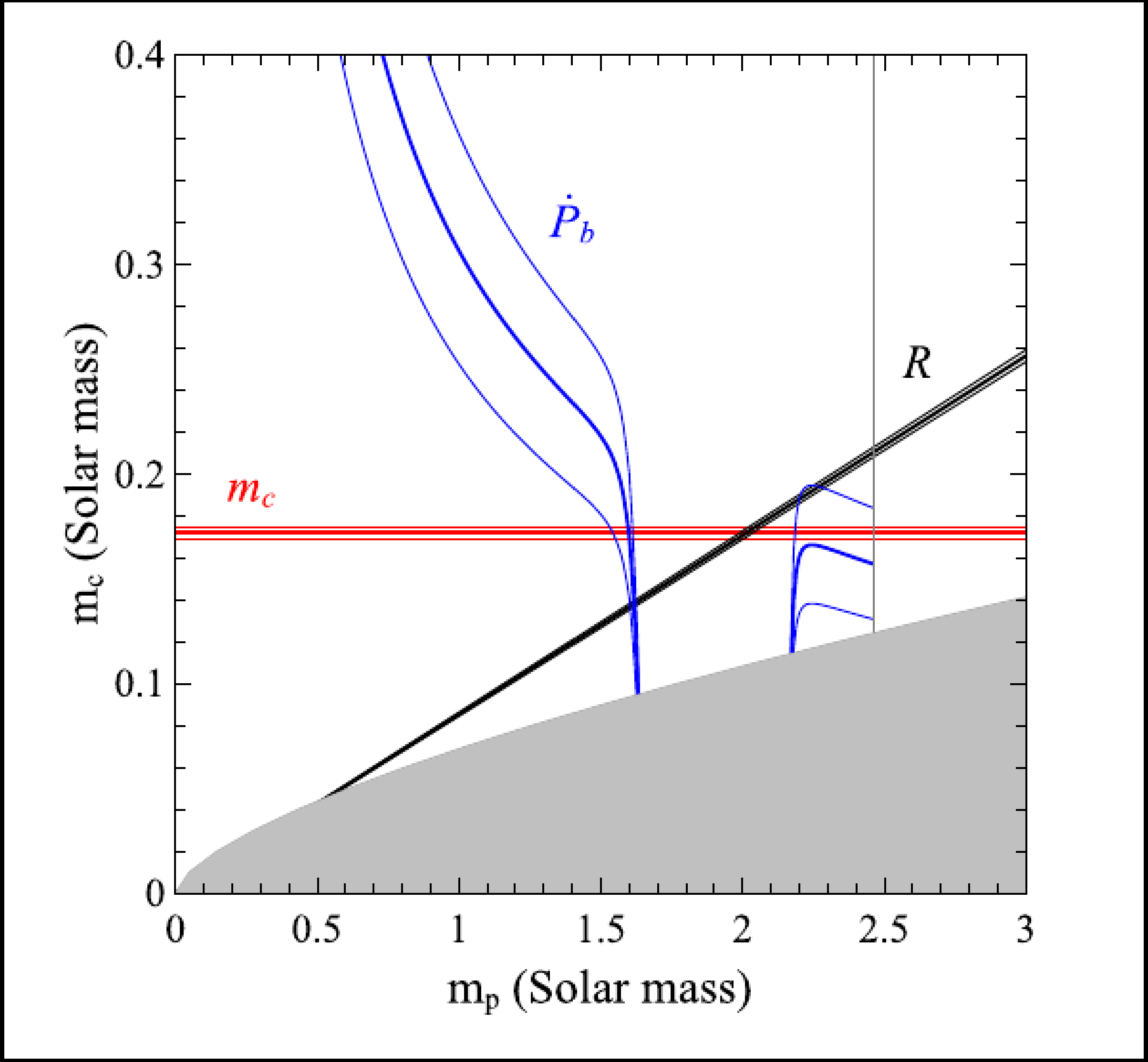


un!

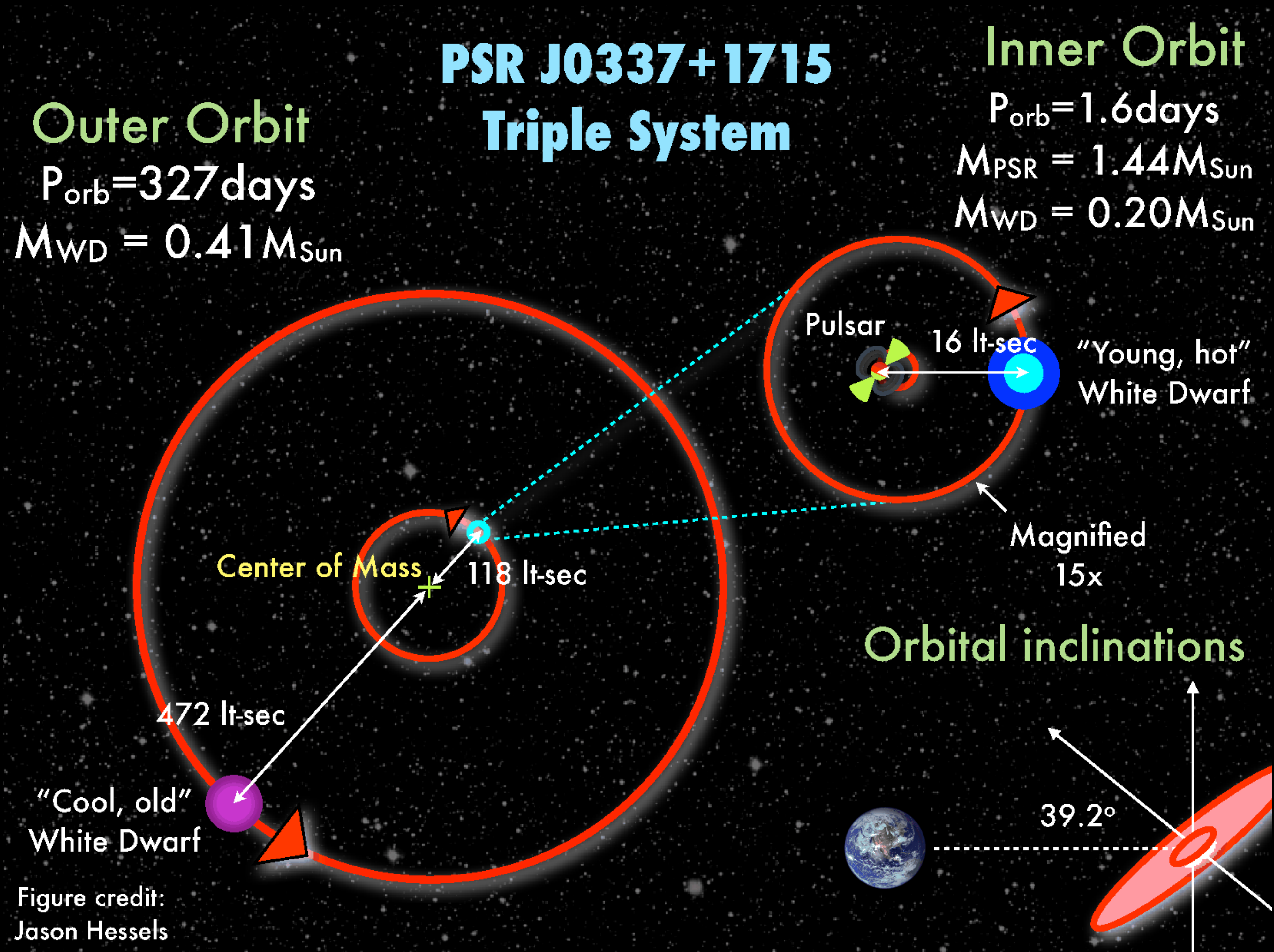
Antoniadis et al *Science*, 2013, 340, 448

J0348 rules out new parameter space

An example of a scalar-tensor theory $T_1(10^{-4}, -4.5)$ which passes J1738+0333 tests, but which fails for J0348+0432

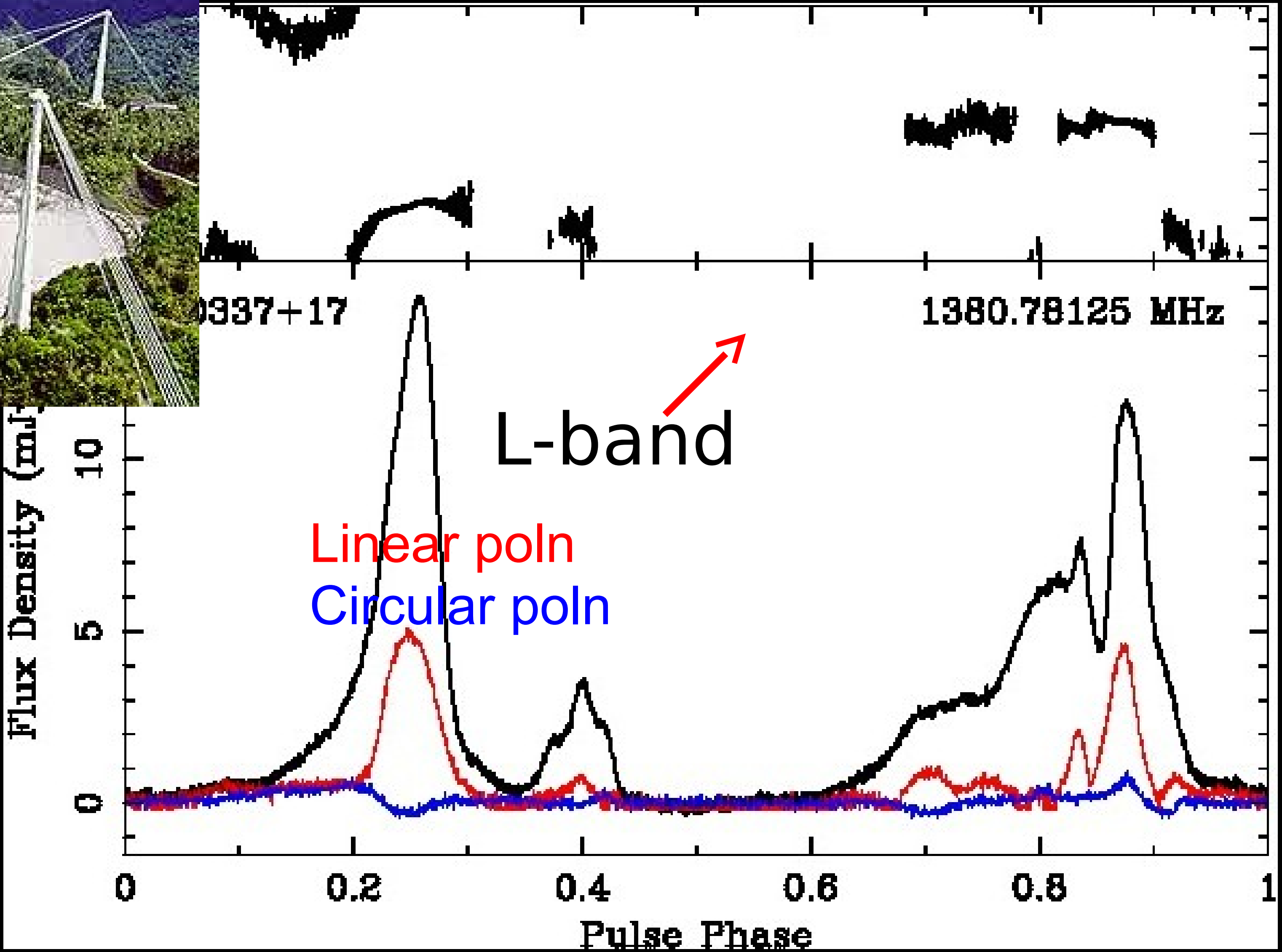


Wex 2014, arXiv: 1402.5594


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

Relatively bright 2.7ms pulsar! 366 Hz!
Arecibo can see it!

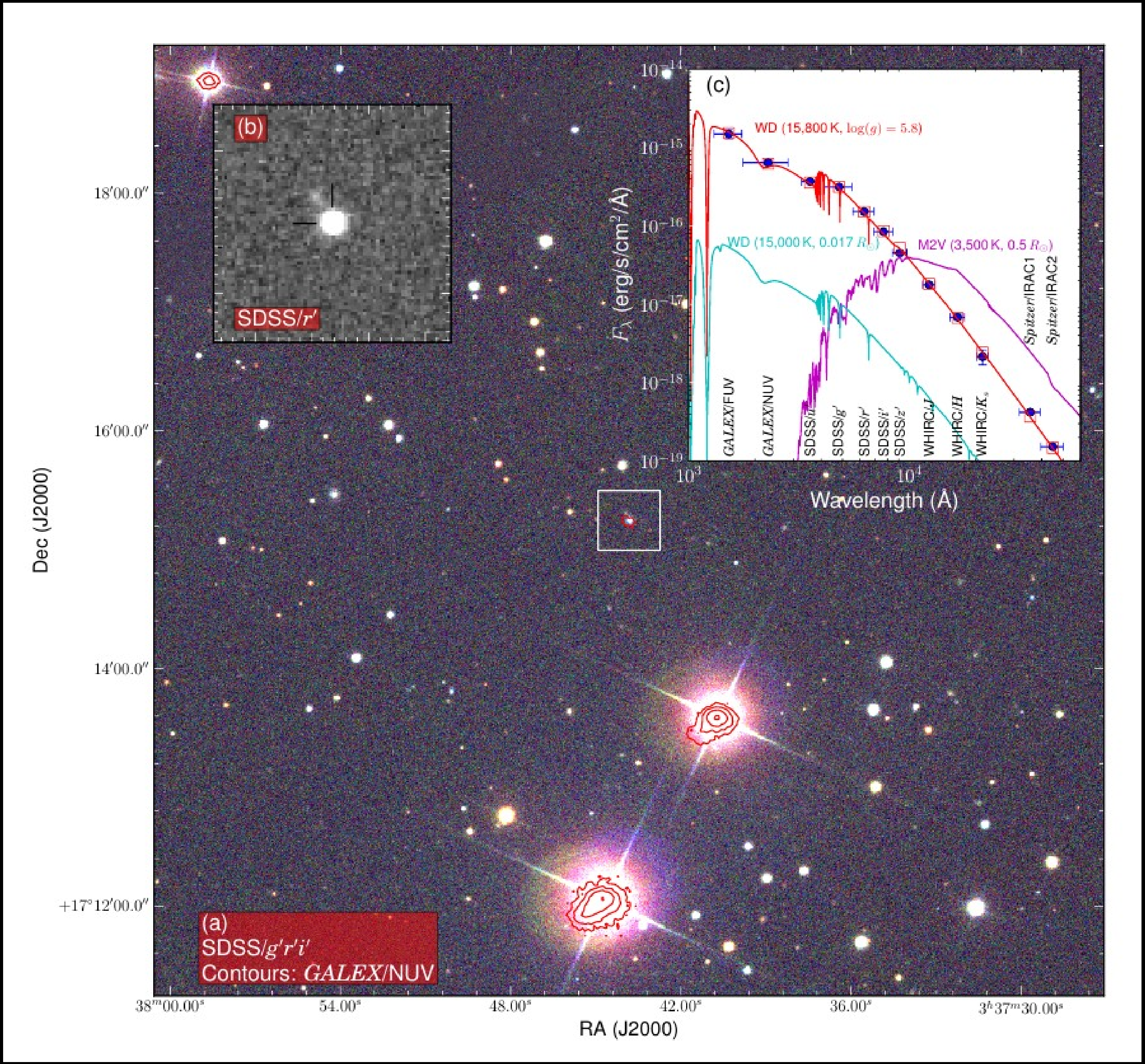
~0.8μs arrival times in 10 seconds (~13,000 of them)!



UV/Optical/IR Counterpart

<u>Inner White Dwarf</u>

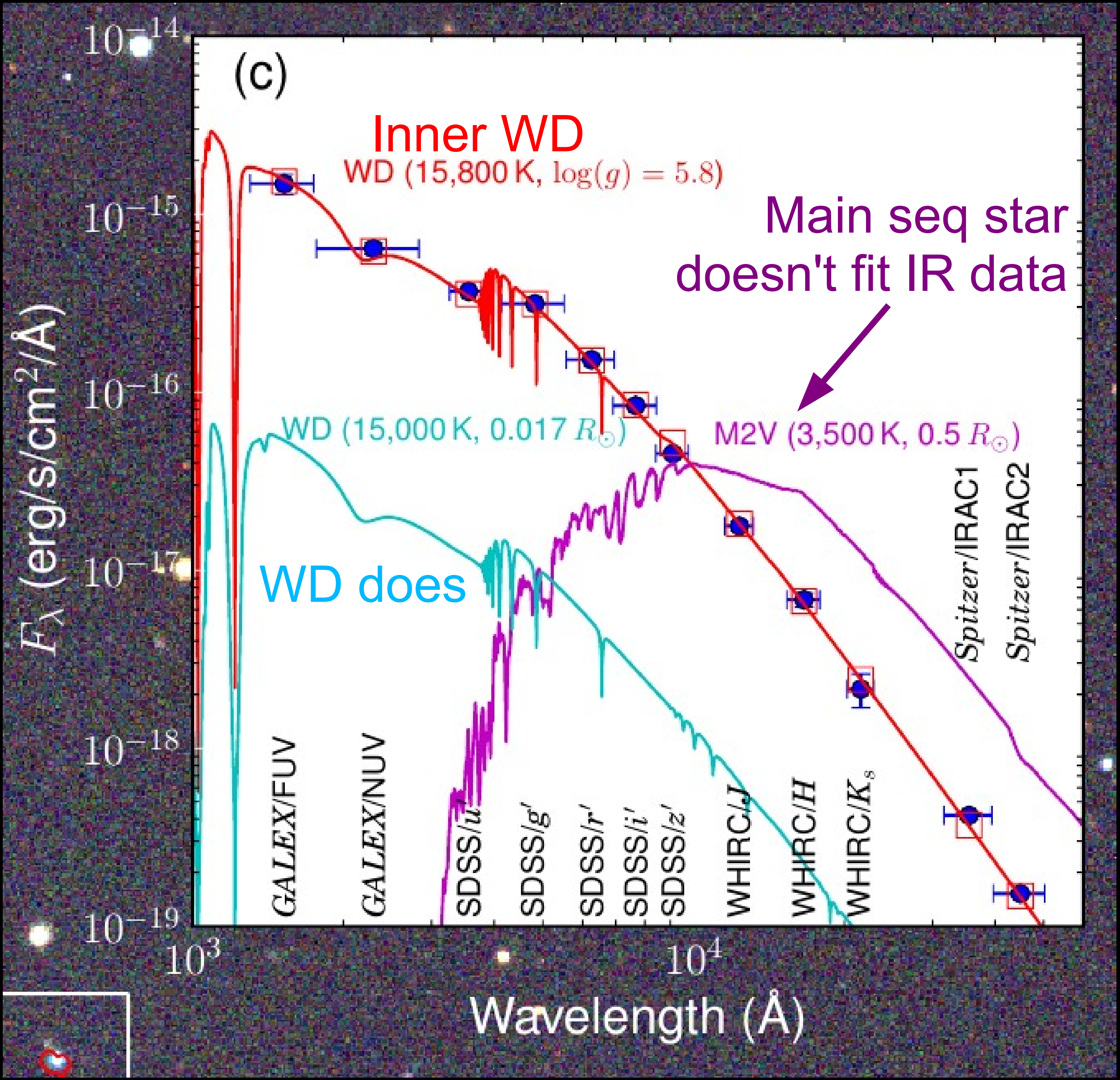
~18-19 mag
GALEX (UV)
SDSS (Opt)
WIYN (IR)
Spitzer (IR)



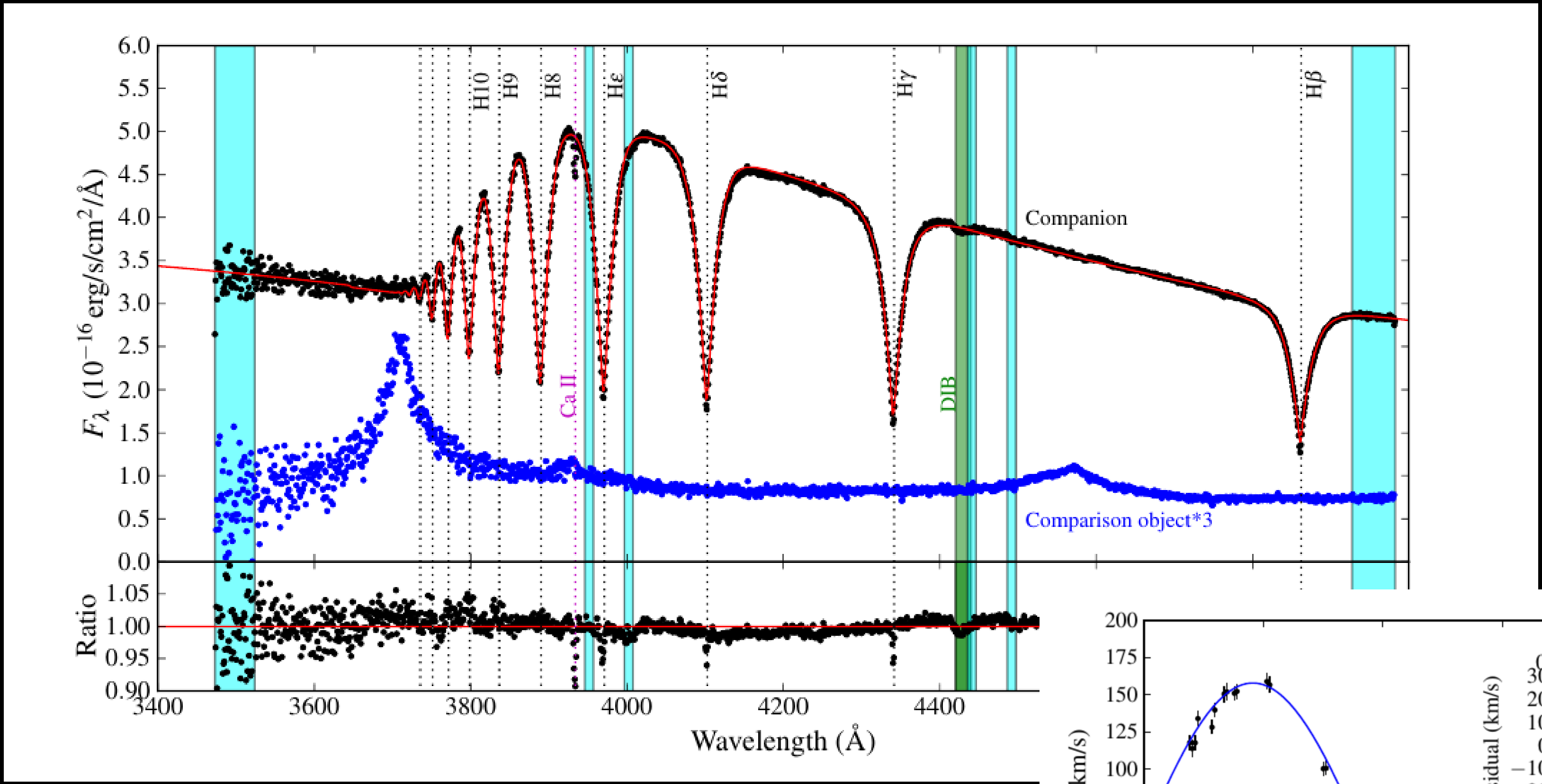
UV/Optical/IR Counterpart

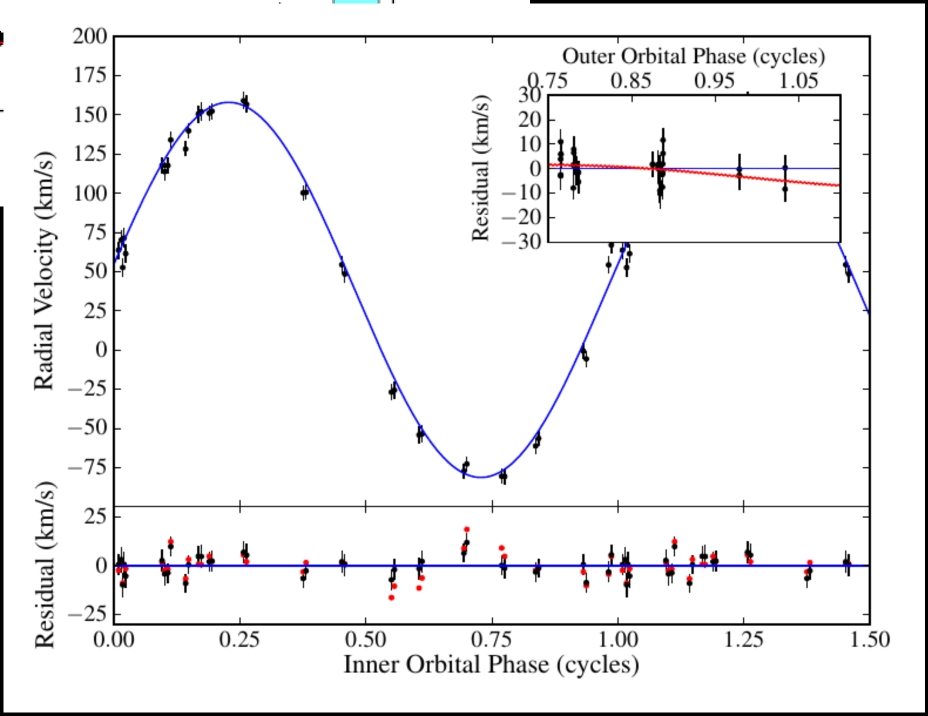
<u>Inner White Dwarf</u>
~18-19 mag
GALEX (UV)
SDSS (Opt)
WIYN (IR)
Spitzer (IR)

Outer star is therefore a cooler WD!



Optical spectroscopy on inner WD...





Teff = 15,800K log(g) = 5.82

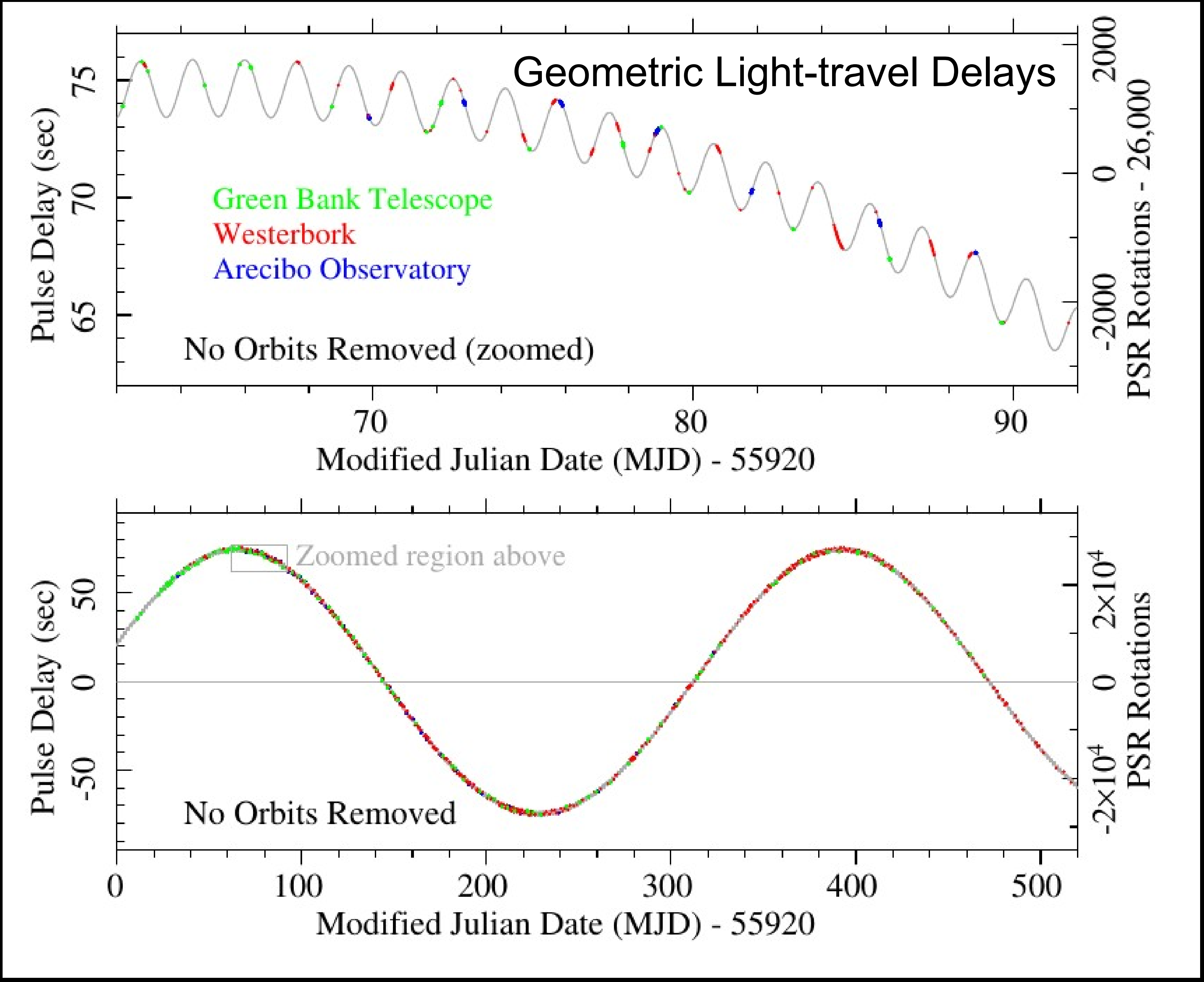
Therefore He WD of 0.15-0.2 Msun

RVs give mass ratio of 7.32+/-0.08

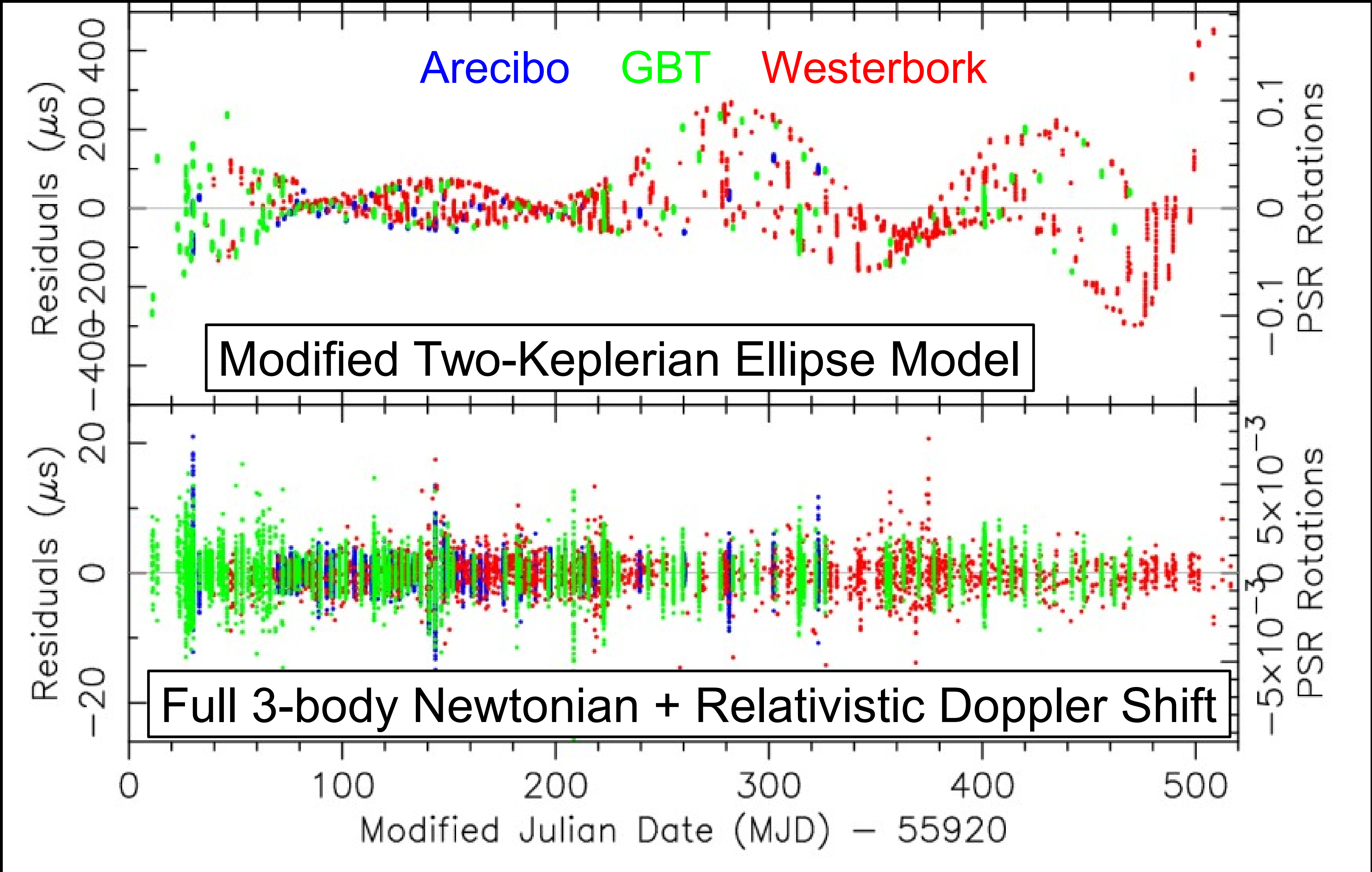
W/ timing masses, gives ~6% radius:

D = 1,300+/-80 pc

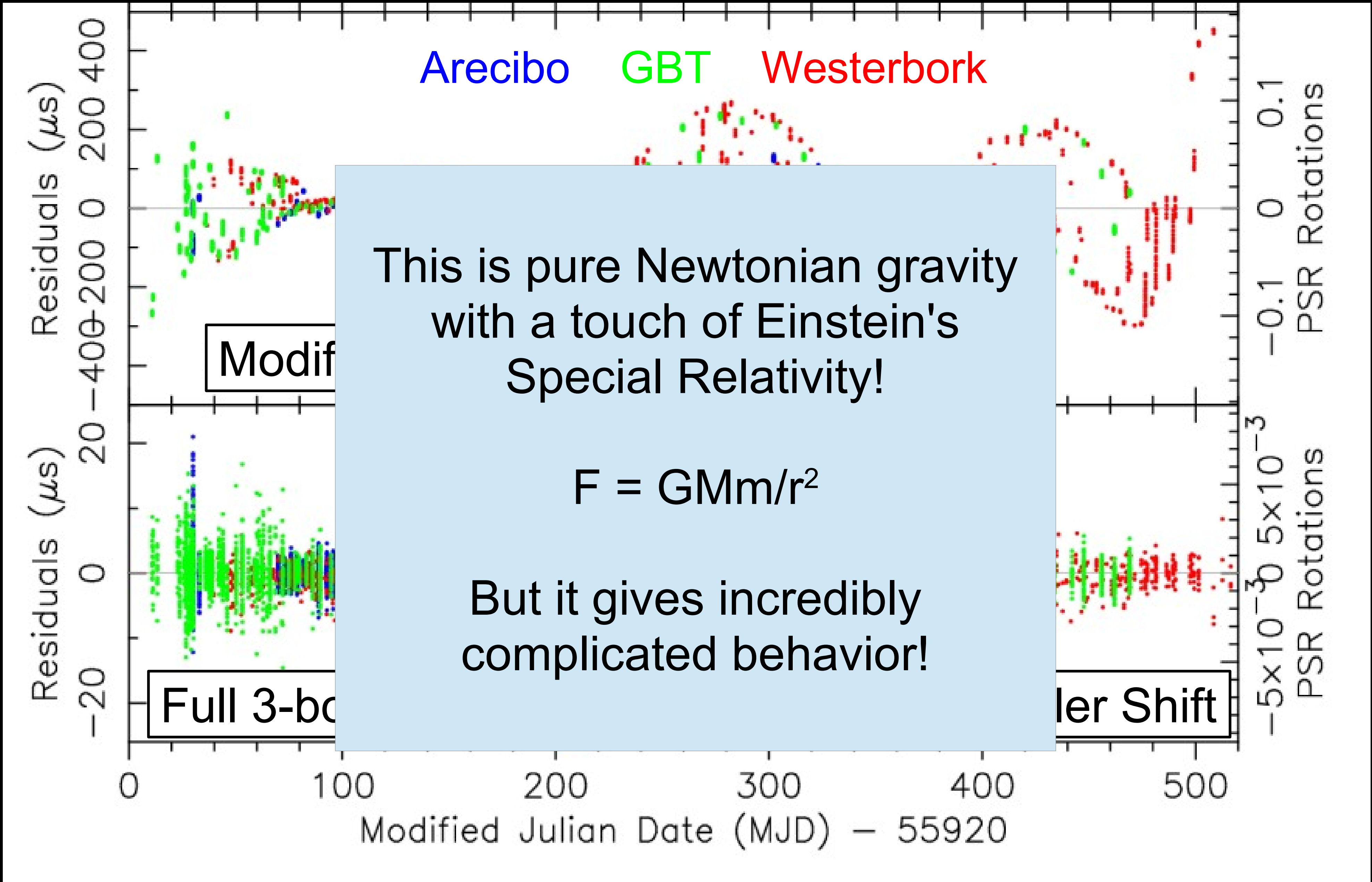
Kaplan, van Kerkwijk et al 2014, ApJ



Geometric Light-travel 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



~1.34 us weighted RMS for 26,260 TOAs!



This is pure Newtonian gravity with a touch of Einstein's Special Relativity!

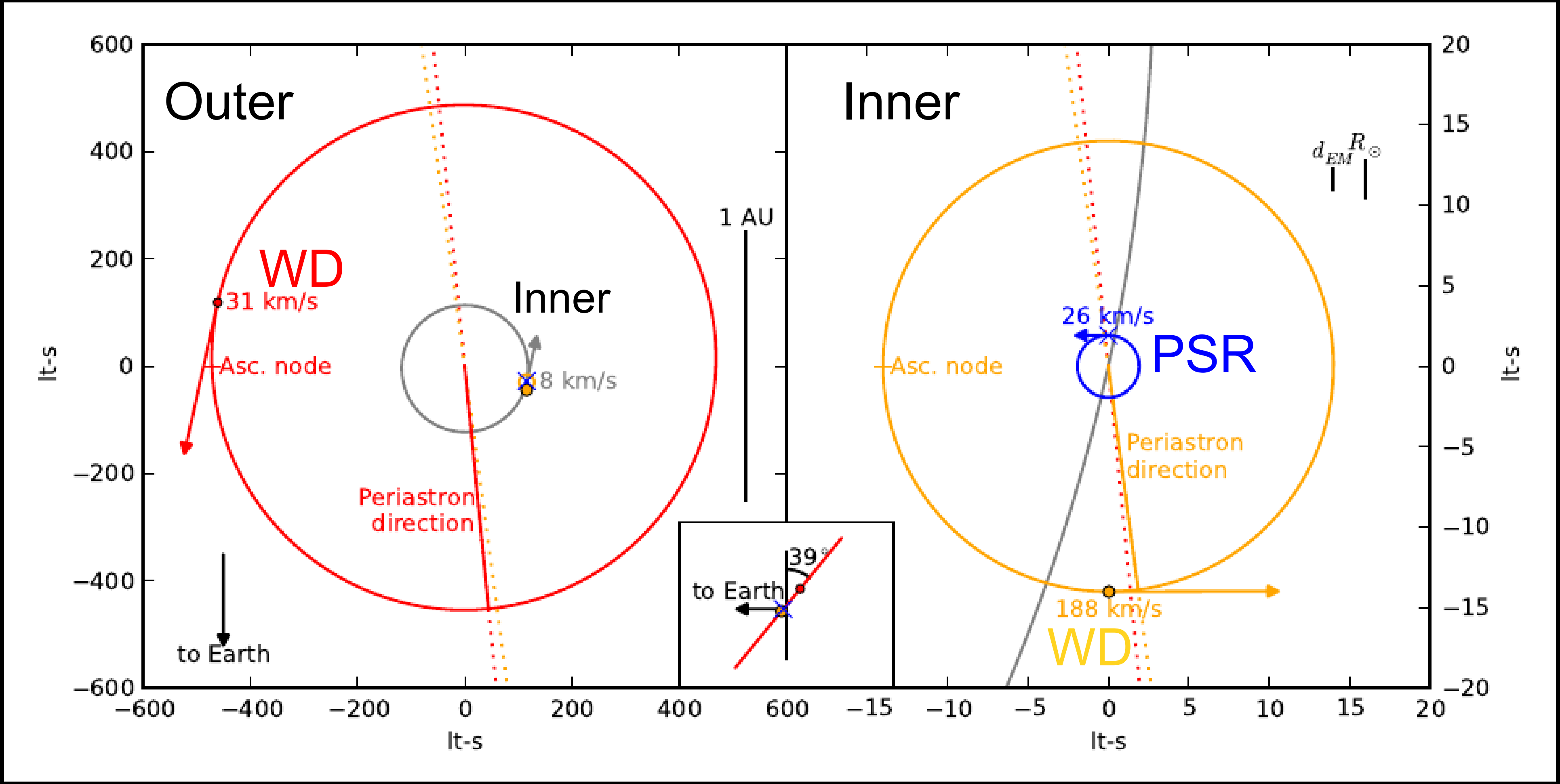
$$F = GMm/r^2$$

But it gives incredibly complicated behavior!

~1.34 us 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 $e_i \sim 7\times10^{-4}$ and $e_o \sim 0.035$!)



Strong Equivalence Principle

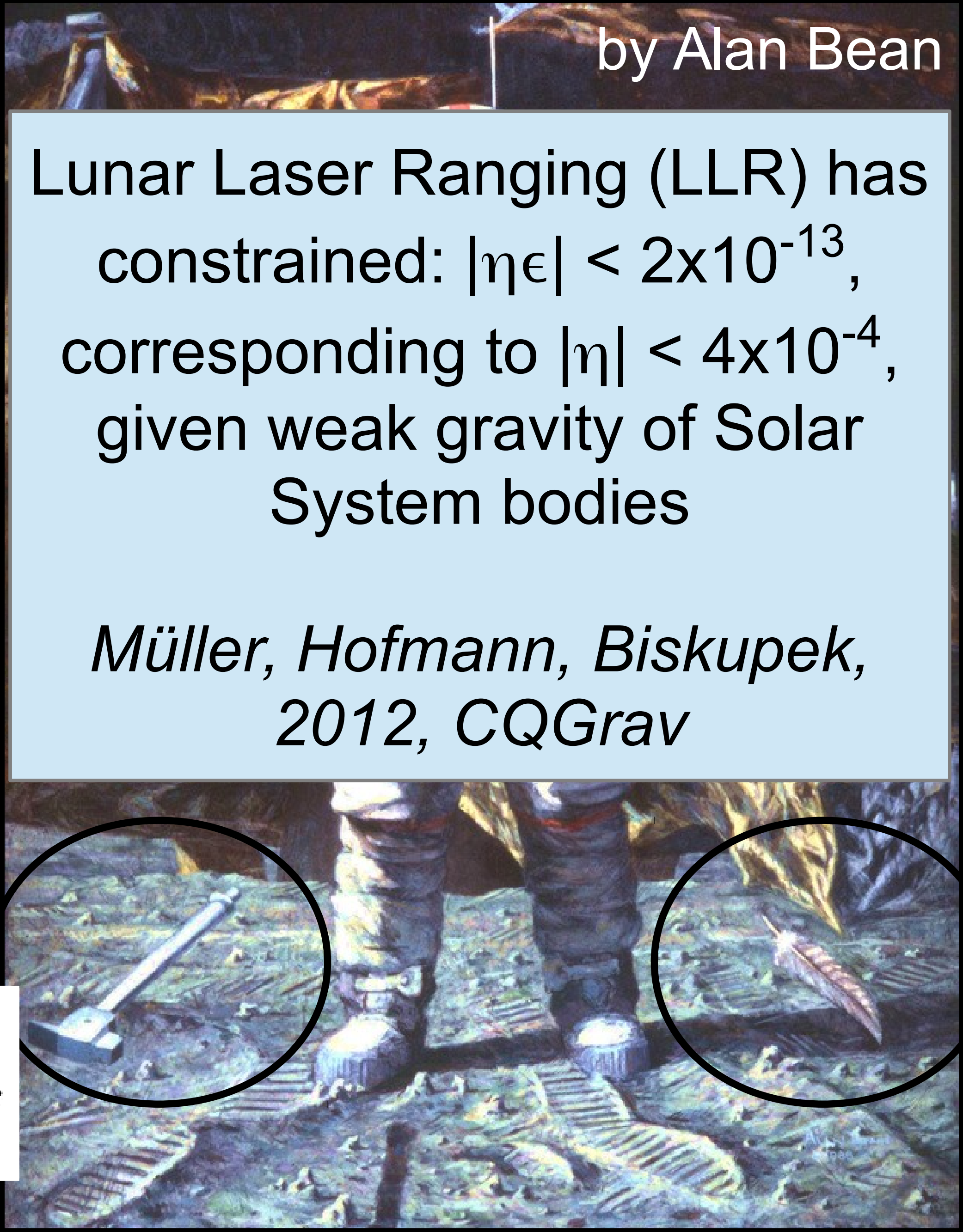
- Gravitational and inertial masses are equal
- Composition, shape, mass, location etc doesn't matter
- This applies to objects with strong self-gravity as well:
  - Gravitational binding energy gravitates!
  - Only GR embodies this
- Tested via the Nordtvedt parameter, η:

$$\left(\frac{m_{\rm grav}}{m_{\rm inertial}}\right) = 1 + \Delta = 1 + \eta\epsilon + \mathcal{O}(\epsilon^2).$$

Strong Equivalence Principle

- Gravitational and inertial masses are equal
- Composition, shape, mass, location etc doesn't matter
- This applies to objects with strong self-gravity as well:
  - Gravitational binding energy gravitates!
  - Only GR embodies this
- Tested via the Nordtvedt paramater, η:

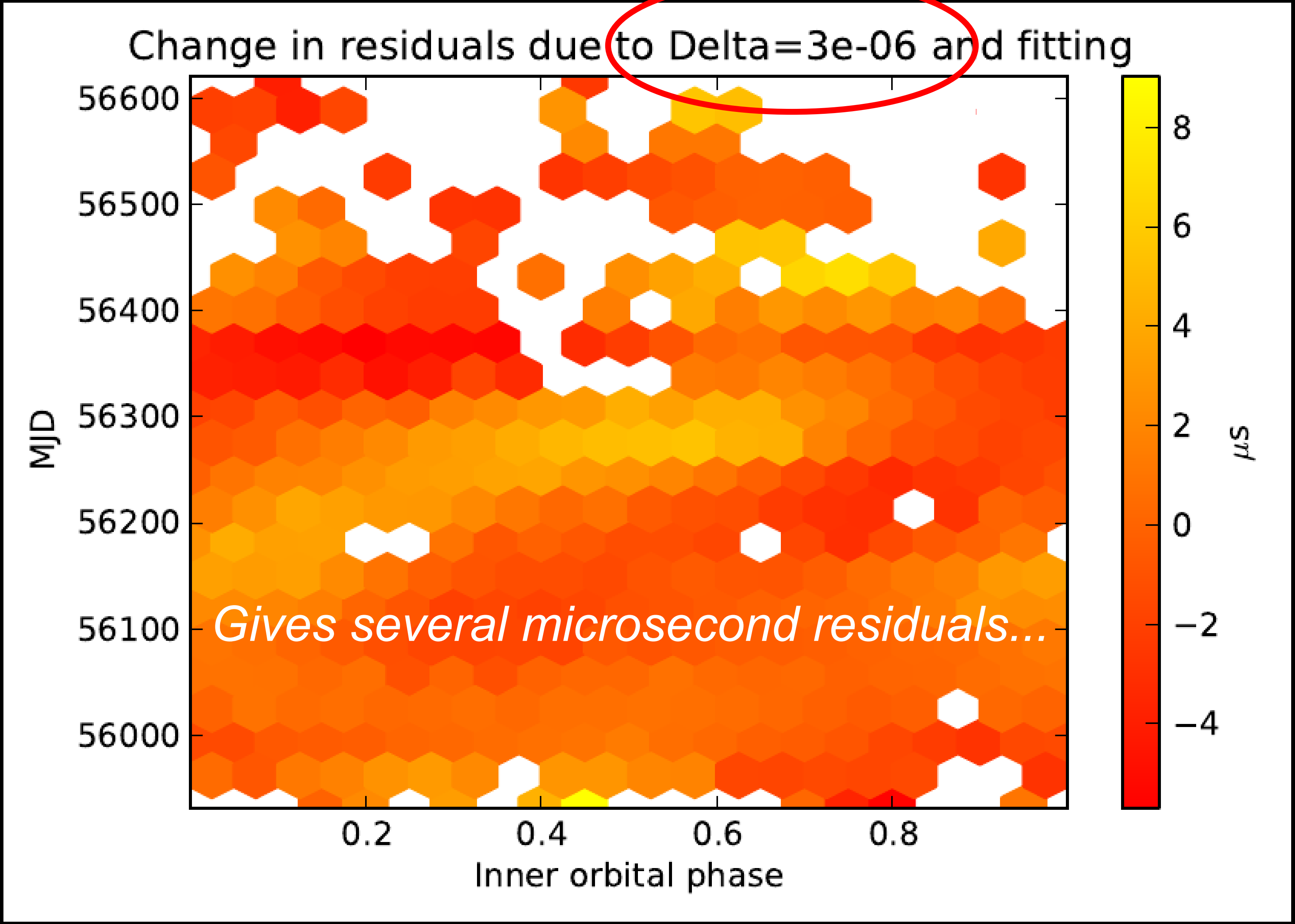
$$\left(\frac{m_{\rm grav}}{m_{\rm inertial}}\right) = 1 + \Delta = 1 + \eta\epsilon + \mathcal{O}(\epsilon^2).$$



Lunar Laser Ranging (LLR) has constrained: $|\eta\epsilon| < 2\text{x}10^{-13}$, corresponding to $|\eta| < 4\text{x}10^{-4}$, given weak gravity of Solar System bodies

Müller, Hofmann, Biskupek, 2012, CQGrav

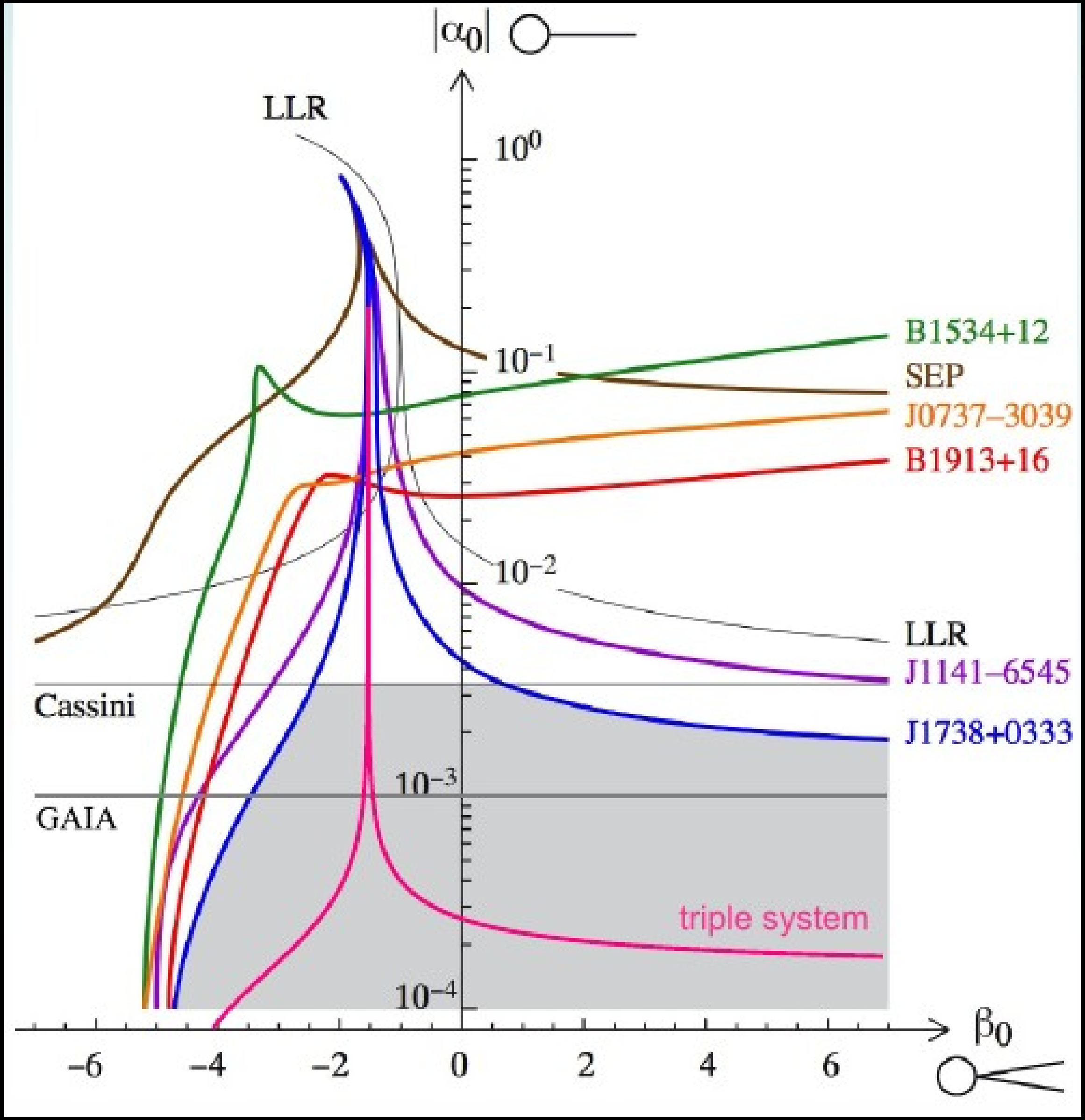
Example of initial testing...



Plot by Anne Archibald

J0337+1715 scalar-tensor constraints

- "G" effectively different for NS and WD. They fall in relatively "strong" grav field of outer WD.
- Prediction is ~1-2 orders of mag better than other current or future tests (including Lunar Laser Ranging!), and soon! (Archibald et al in prep).
- $T_1(\alpha_0,\beta_0)$ theories
- GR has $\alpha_0=\beta_0=0$
- Jordan–Fierz–Brans–Dicke theory has $\beta_0=0$

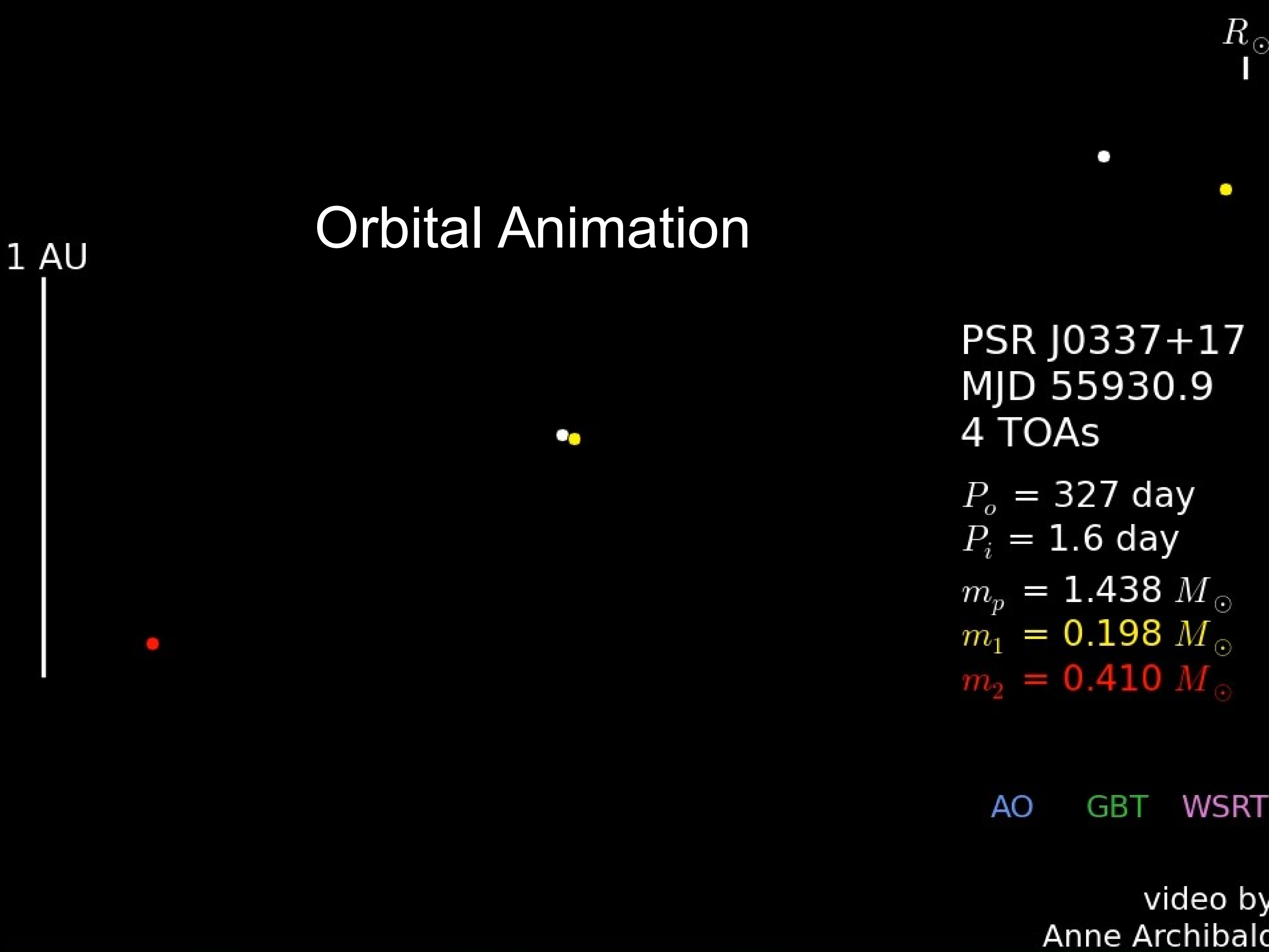


N. Wex, private communication

Summary: PSR-WD tests of GR

- All-sky pulsar surveys provide amazing (and surprising) systems to test GR in interesting ways
- The survey yield will increase in the next decade
- There are 10^4 - 10^5 pulsars to find in the Galaxy, and a few percent of them will be interesting
- High-precision timing makes many PSR systems interesting now that were uninteresting yesterday
- New tests of the Strong Equivalence Principle will be out very soon (especially J0337+1715)

Orbital Animation



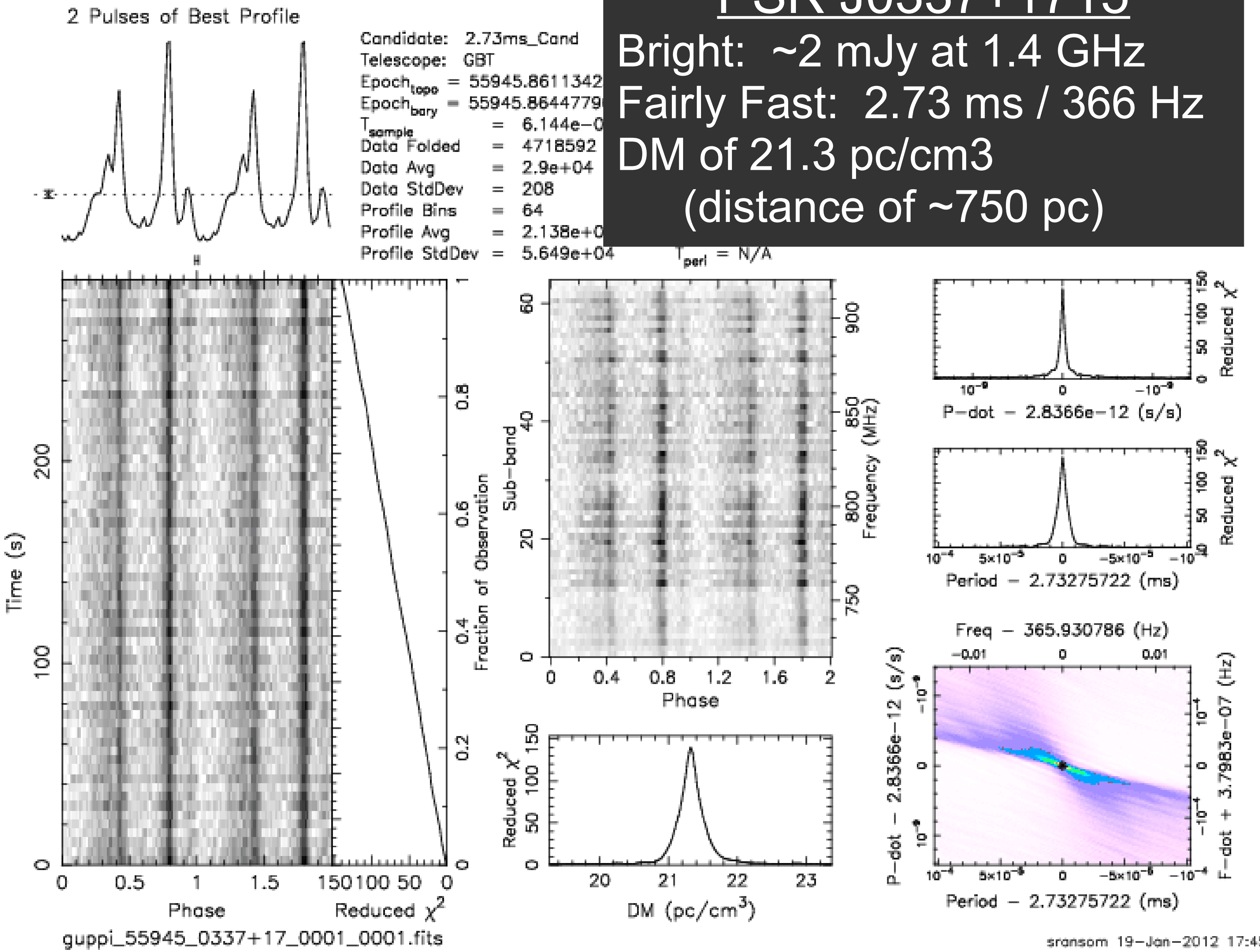
PSR J0337+1715

Bright: ~2 mJy at 1.4 GHz

Fairly Fast: 2.73 ms / 366 Hz

DM of 21.3 pc/cm3

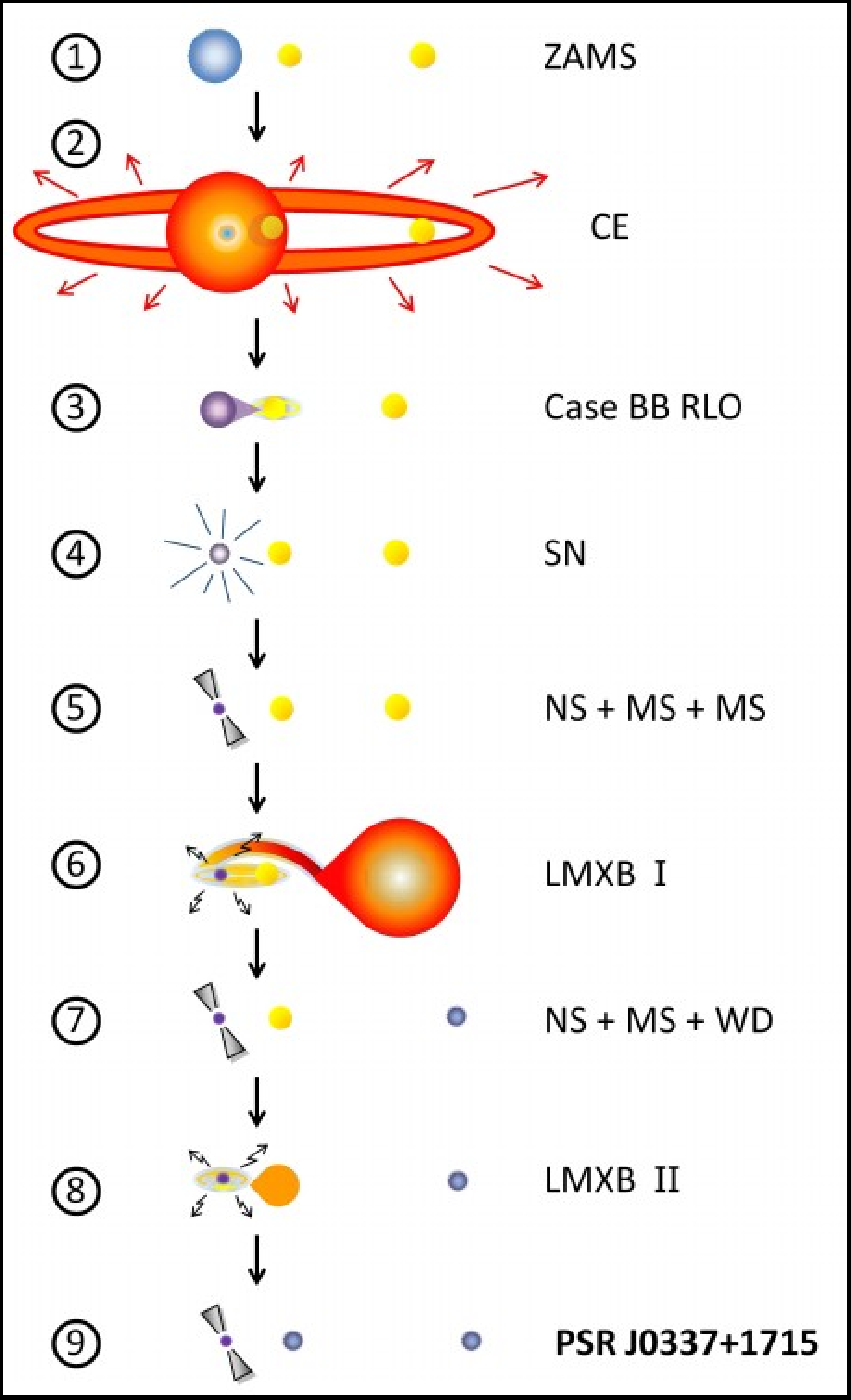
(distance of ~750 pc)



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

Tauris and van den Heuvel, 2014, ApJ



VLBA Distance Soon

- Already have 3 epochs 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