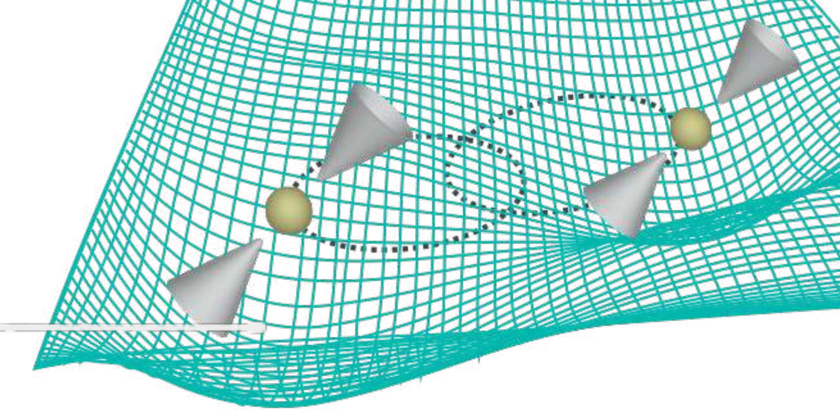
Marisa Geyer | 26 September

PULSAR TIMING THEORY

Department of Mathematics and Applied Mathematics

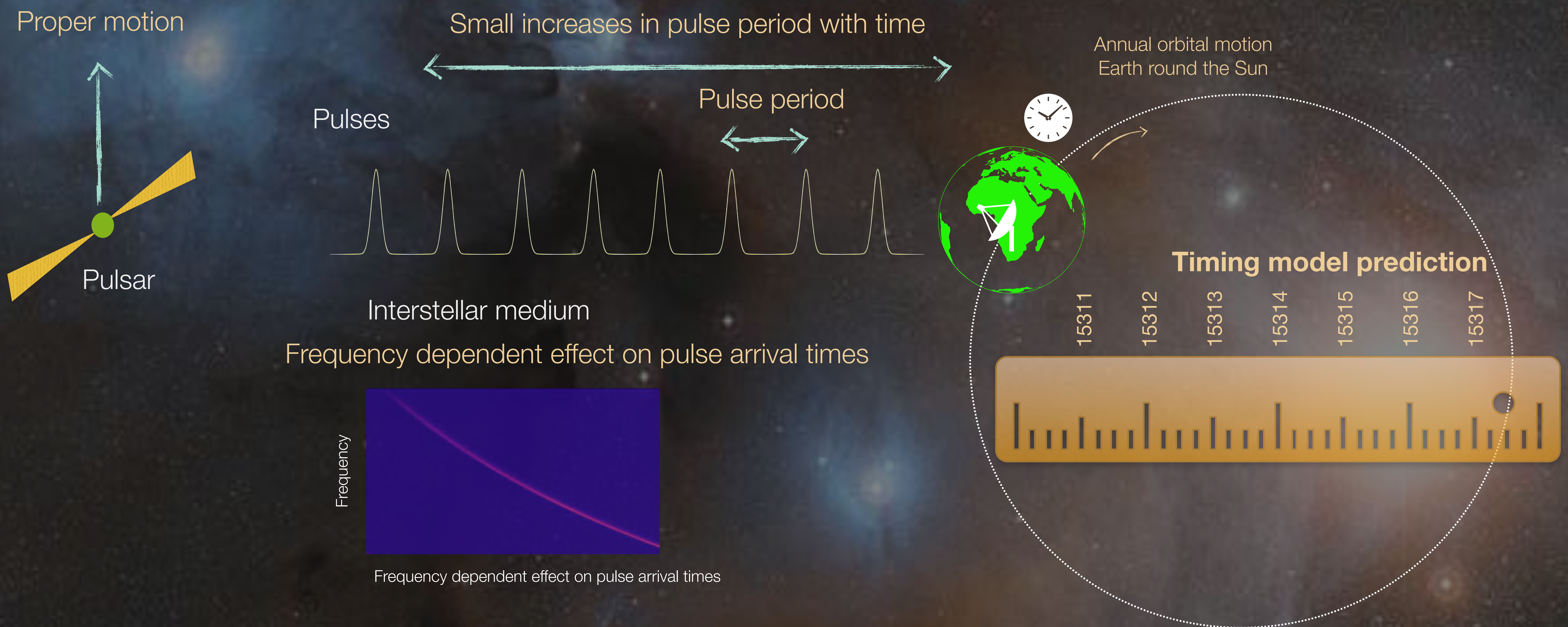
Schedule



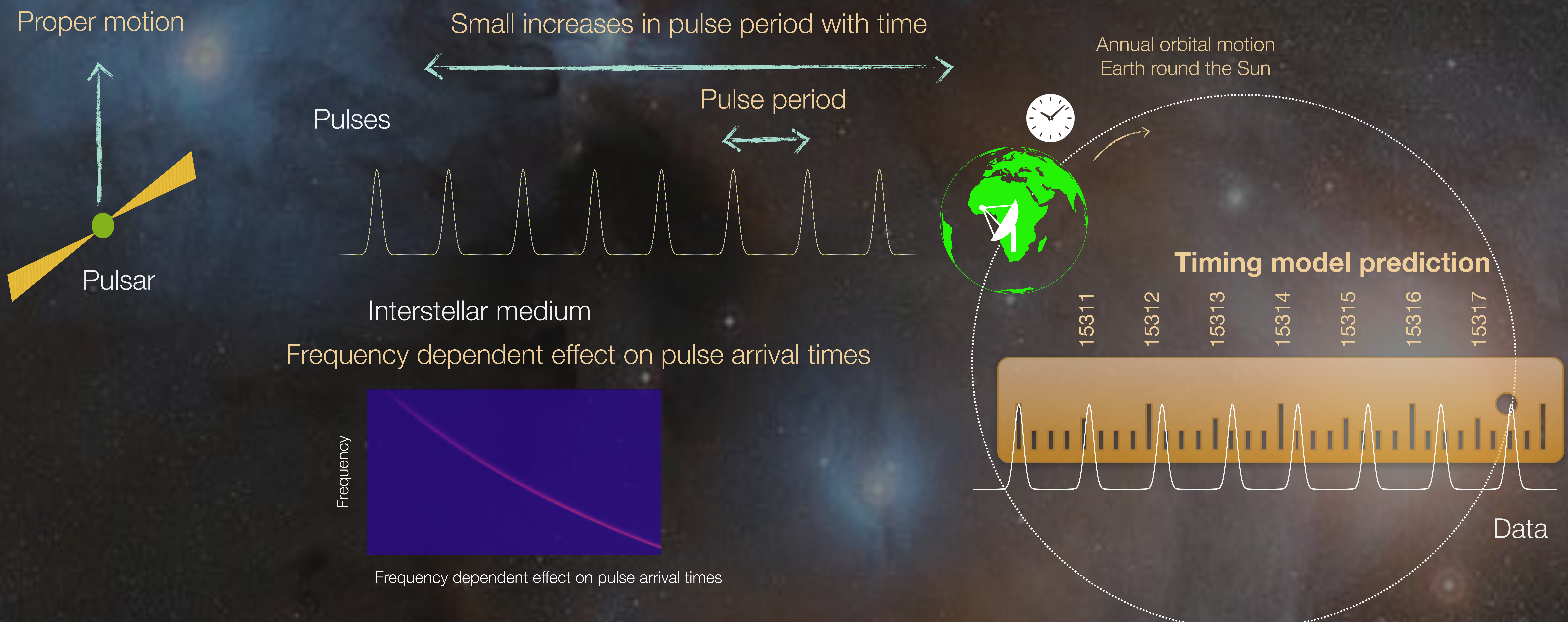
Pre-workshop	Pre-workshop survey

Time	Monday (25th)	Tuesday (26th)	Wednesday (27th)
09:00 - 10:00	No scheduled events	Interacting with Pulsar Data	Noise Modelling
10:00 - 10:30	Arrival, check in and registration	Morning Tea Break	Morning Tea Break
10:30 - 11:20	Software Debugging	Pulsar Timing Theory	Single Pulsar Noise Analysis with Enterprise
11:20 - 11:30	Short Break	Short Break	Short Break
11:30 - 12:30	Introduction to MeerKAT	Creating ToAs	Single Pulsar Noise Analysis with Enterprise
12:30 - 13:30	Lunch Break	Lunch Break	Lunch Break
13:30 - 14:20	Introduction to pulsars / searches	Timing with Tempo2	GW searches with enterprise
14:20 - 14:30	Short Break	Short Break	Short Break
14:30 - 15:30	Pulsar Data Theory	Bayesian Inference	Other
15:30 - 16:00	Afternoon Tea Break	Afternoon Tea Break	Afternoon Tea Break
16:00 - 17:30	GW Astrophysics	Other	SARAO Function

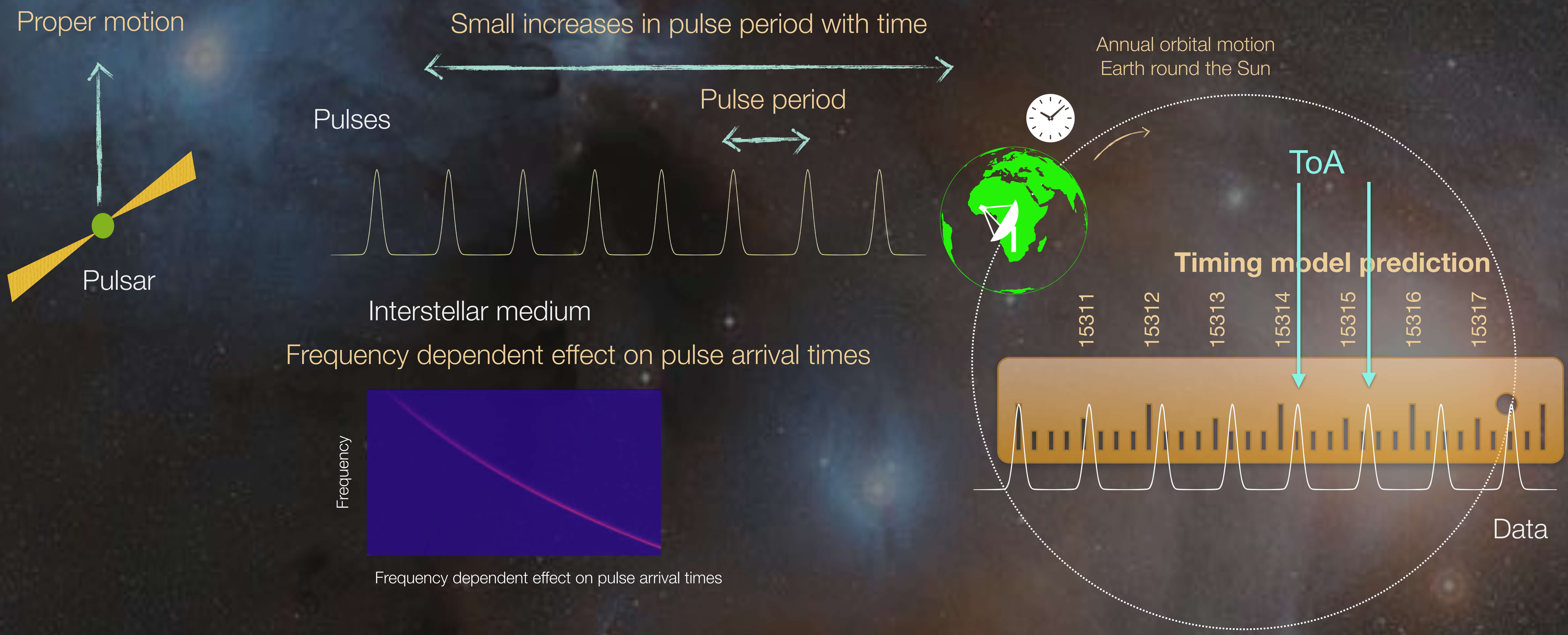
Pulsar timing principles



Pulsar timing principles



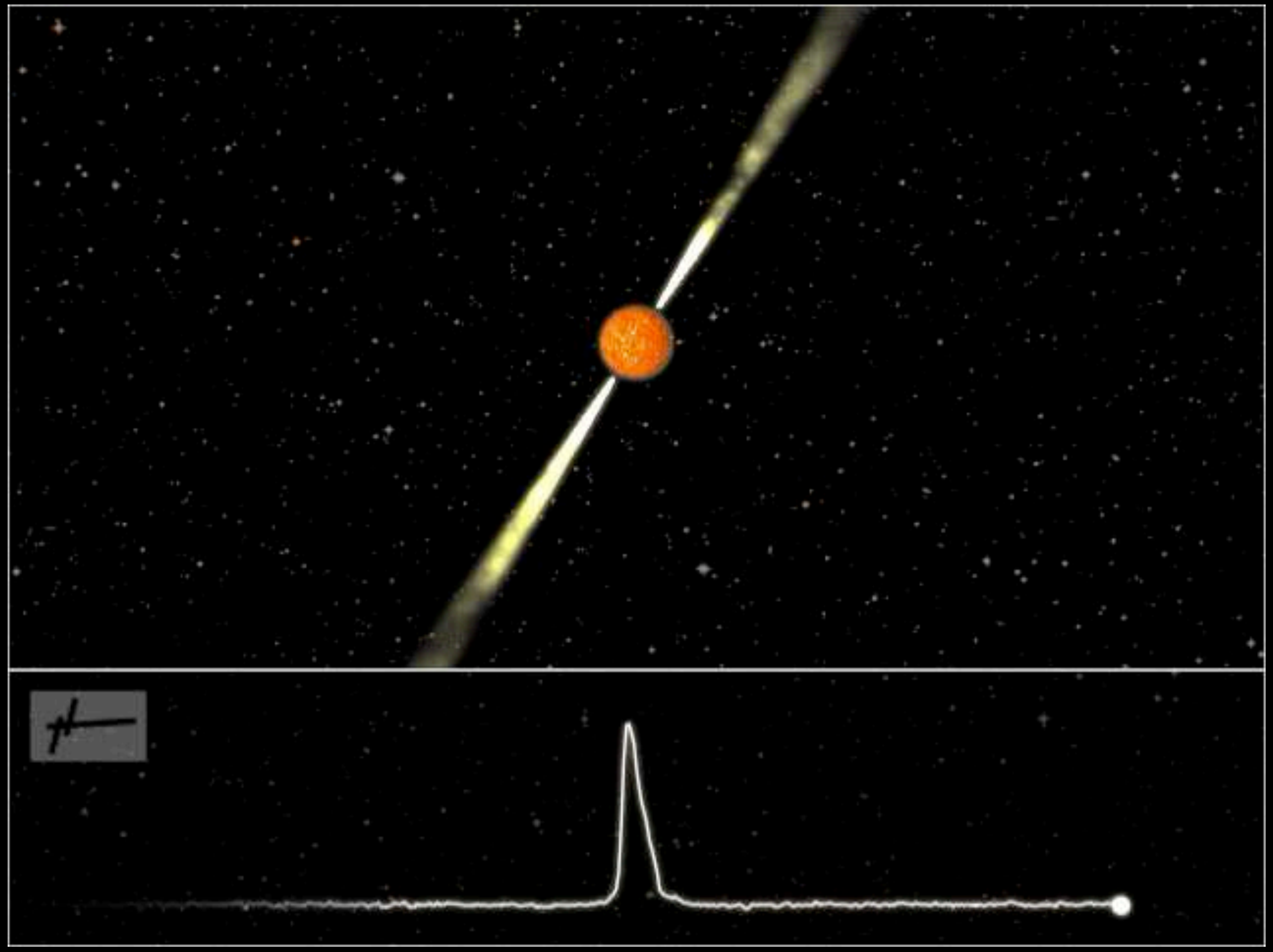
Pulsar timing principles



Side note:
Labelling rotations

The following are all different ways of describing that the pulsar has completed one rotation, and are therefore often used interchangeably

- One pulse period
- One rotation
- Pulse phase from 0 to 1
- Pulse longitude from 0 to 360 degrees
- Pulse longitude from 0 to 2π



0 ……….. pulse period …. P = 1.1sec

0 ……….. phase ……1

0 ……….. phase longitude …… 360^{o} / 2π

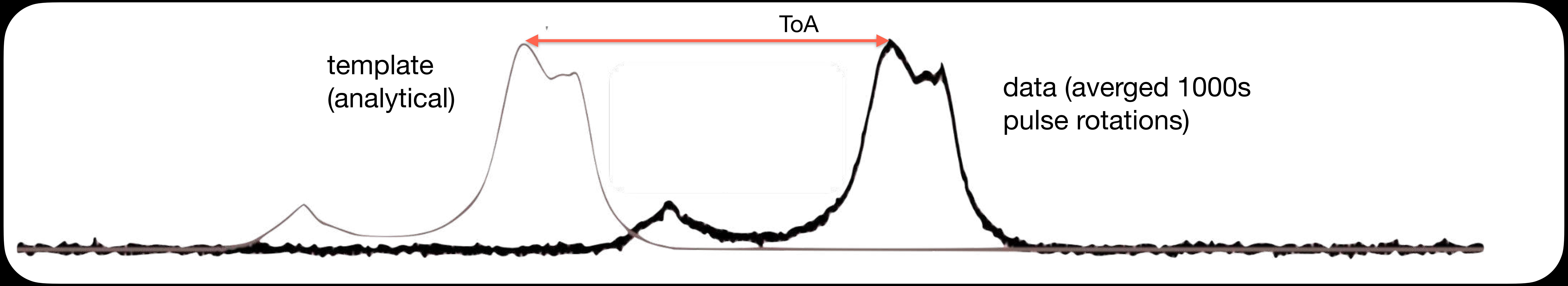
Pulsar timing - find Time of Arrival at Solar System Barycentre

Time of Arrival (ToA)

The ToAs are computed by correlating data with high S/N template

The timing model (phase evolution), for pulsar with spin-frequency ν at (corrected) time T, and ϕ_0 the pulsar phase at T_0

$$\phi(T) = \phi_0 + 2\pi\,(T - T_0)\,\nu + \frac{1}{2}\,2\pi\,(T - T_0)^2\,\dot{\nu} + \dots$$



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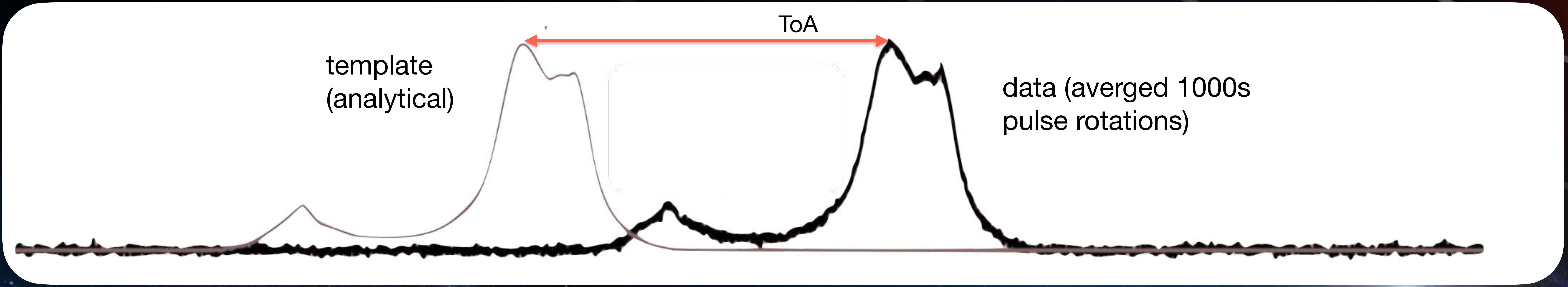

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Transform to SSB

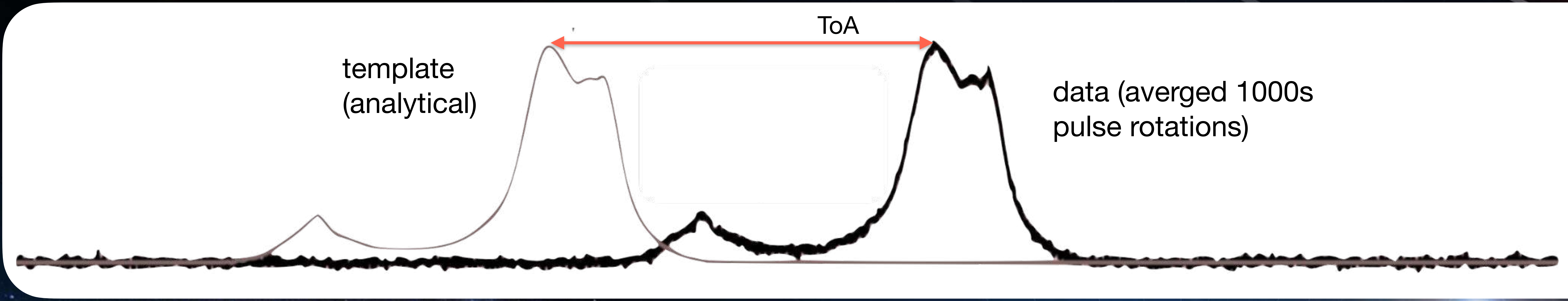
$$\Delta t = \Delta E_{\odot} + \Delta R_{\odot} + \Delta s_{\odot} - D/f^2 + \Delta_{\mathrm{PM}} + \Delta_{\mathrm{B}}$$

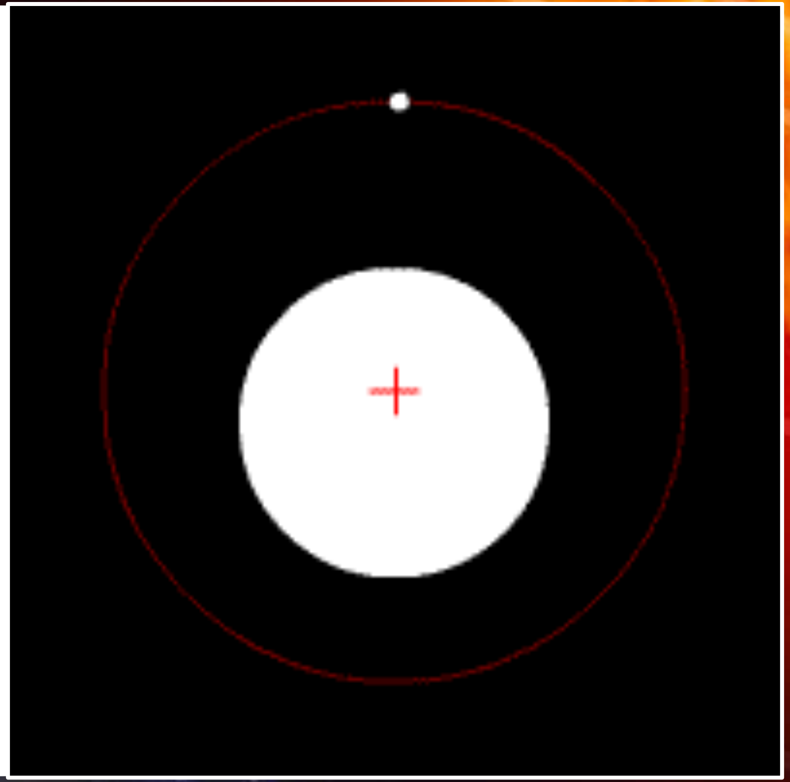
ToAs transferred to SSB (most intertial ref frame we have)
This includes adding corrections

(i) **Einstein delays**: gravitational redshift/time dilation due to the Sun

(ii) **Shapiro delays:** additional light travel time through gravitational potential well of the Sun (propagation through curved spacetime)

(iii) **Roemer delays**: classic light travel time from Earth to SSB





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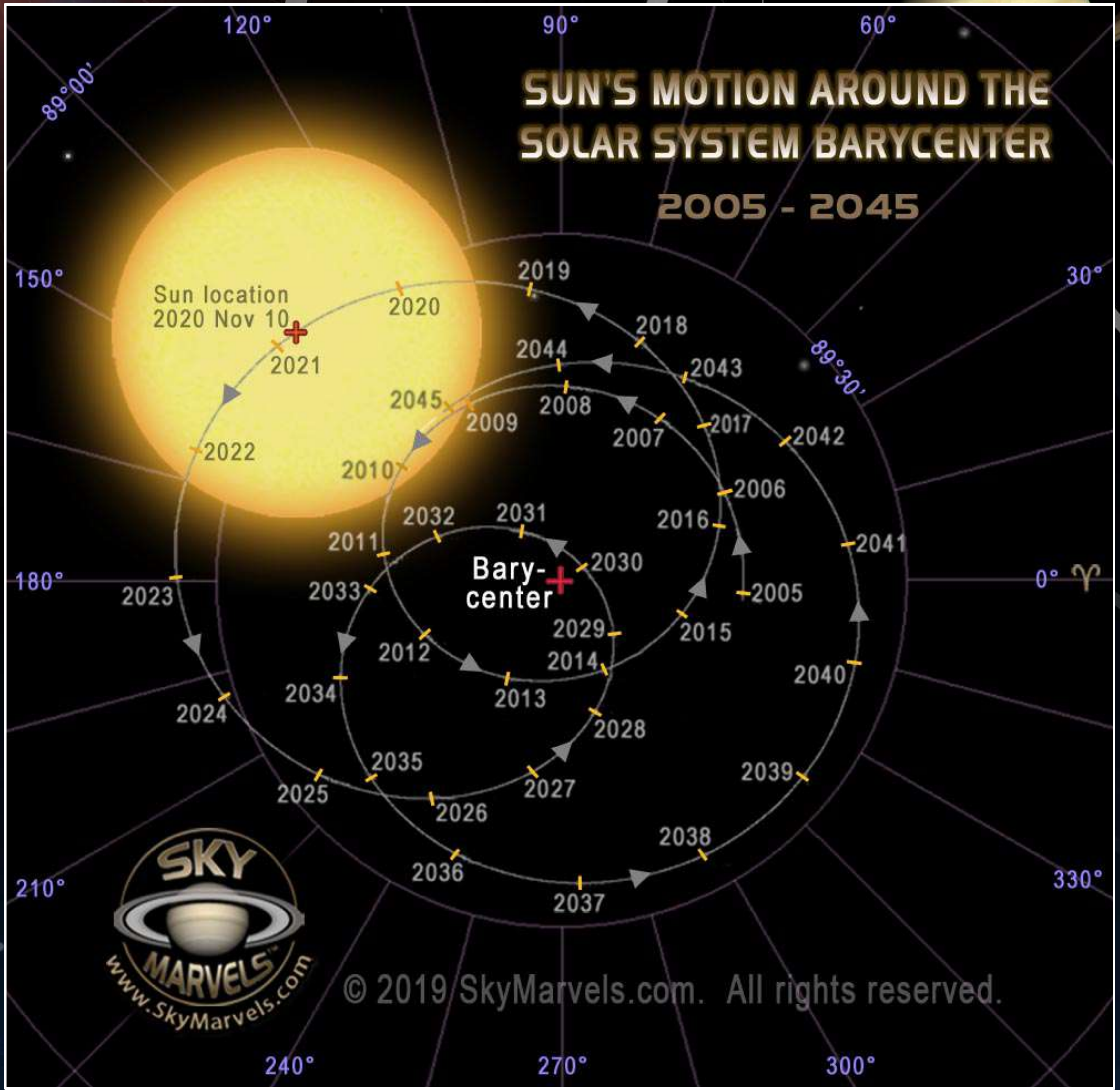

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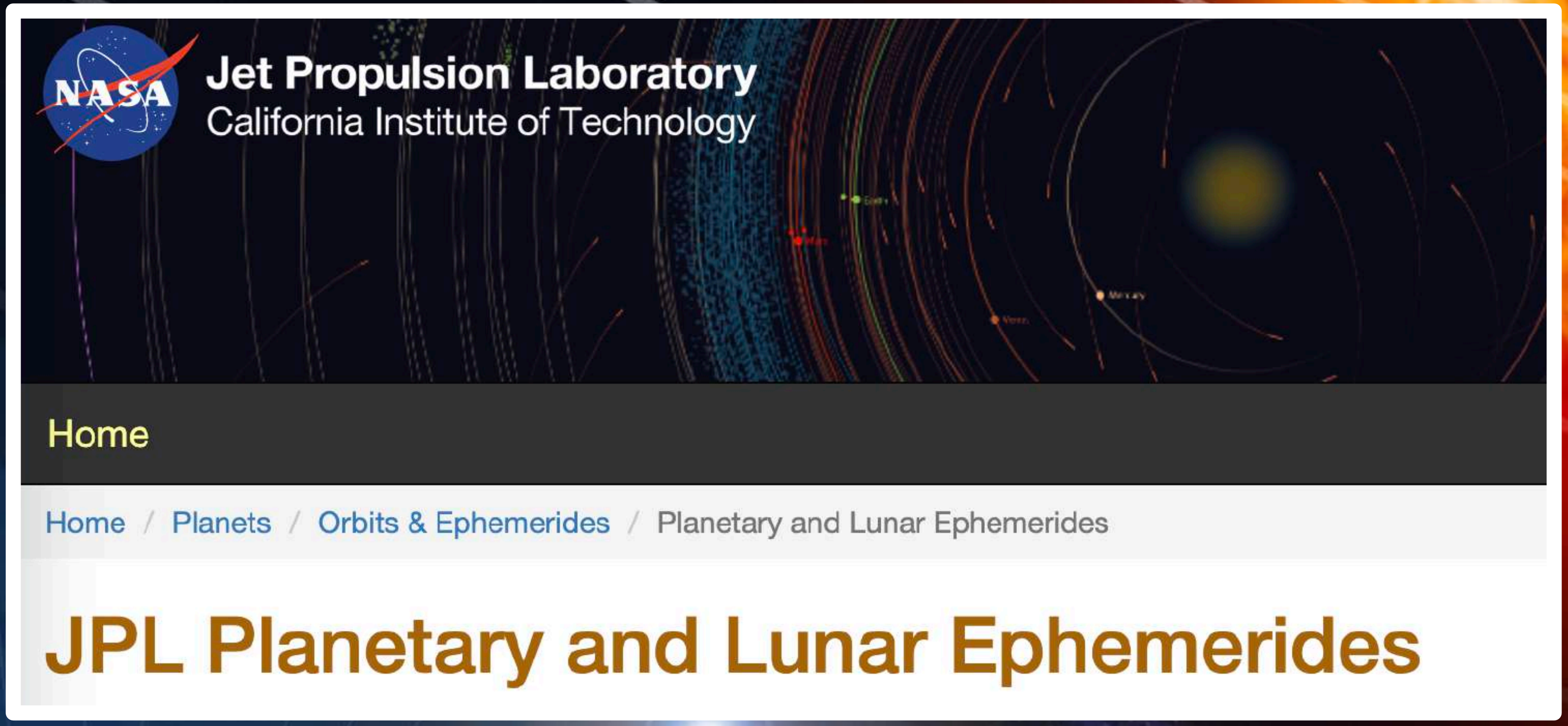
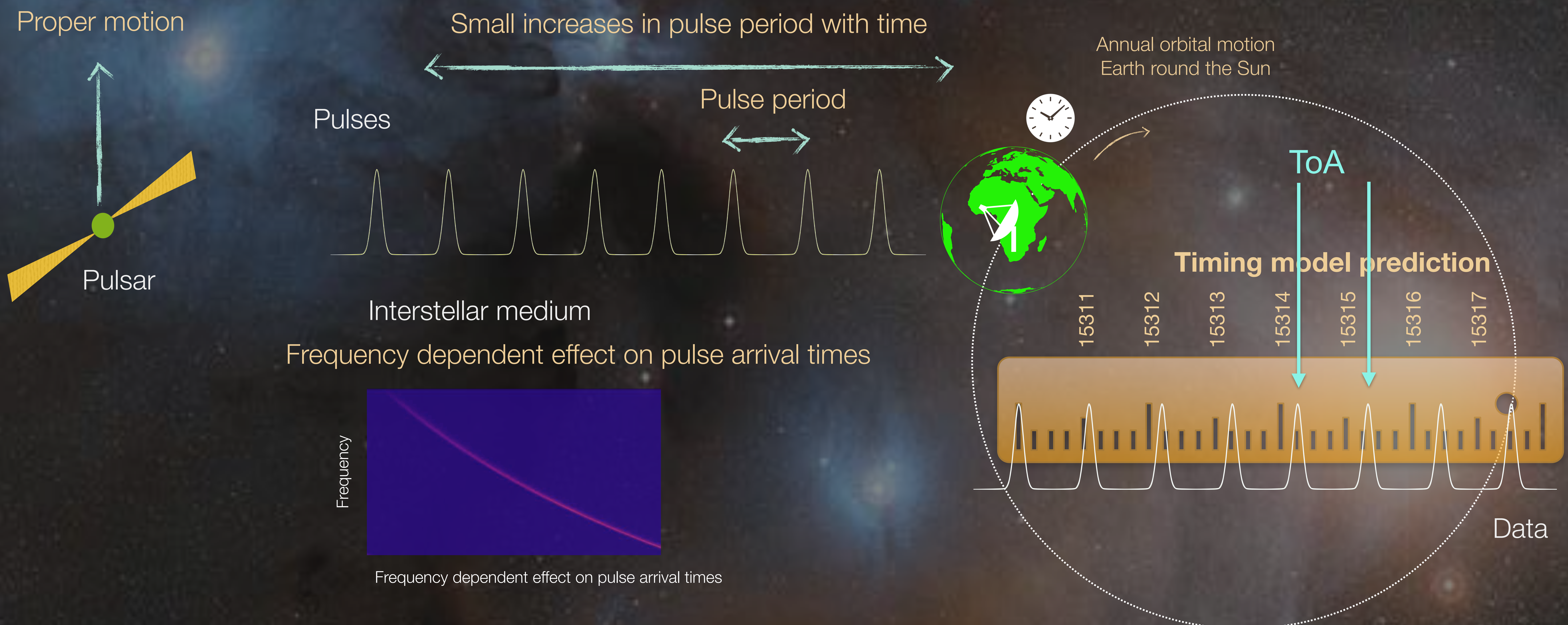
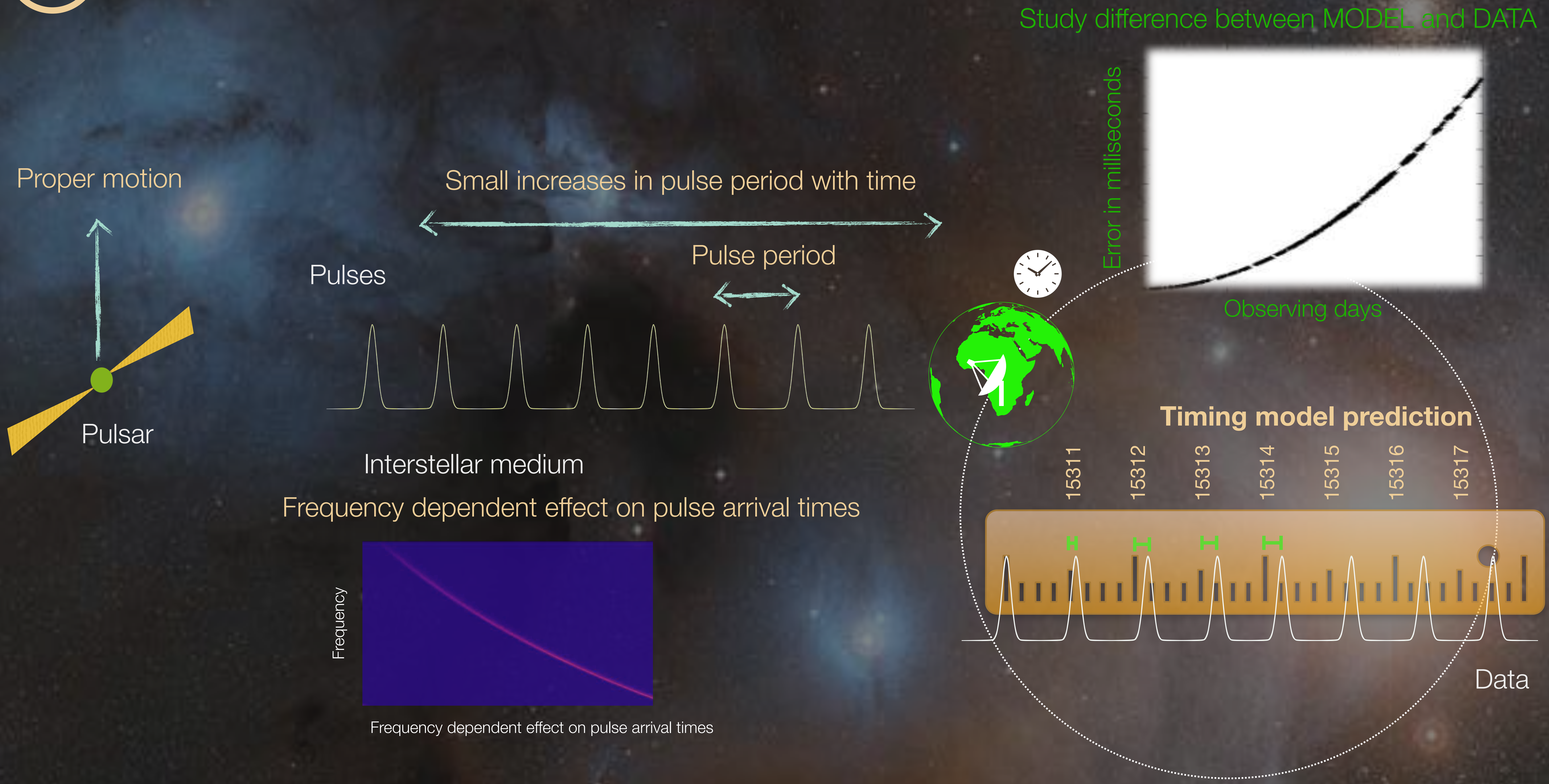


Pulsar timing principles

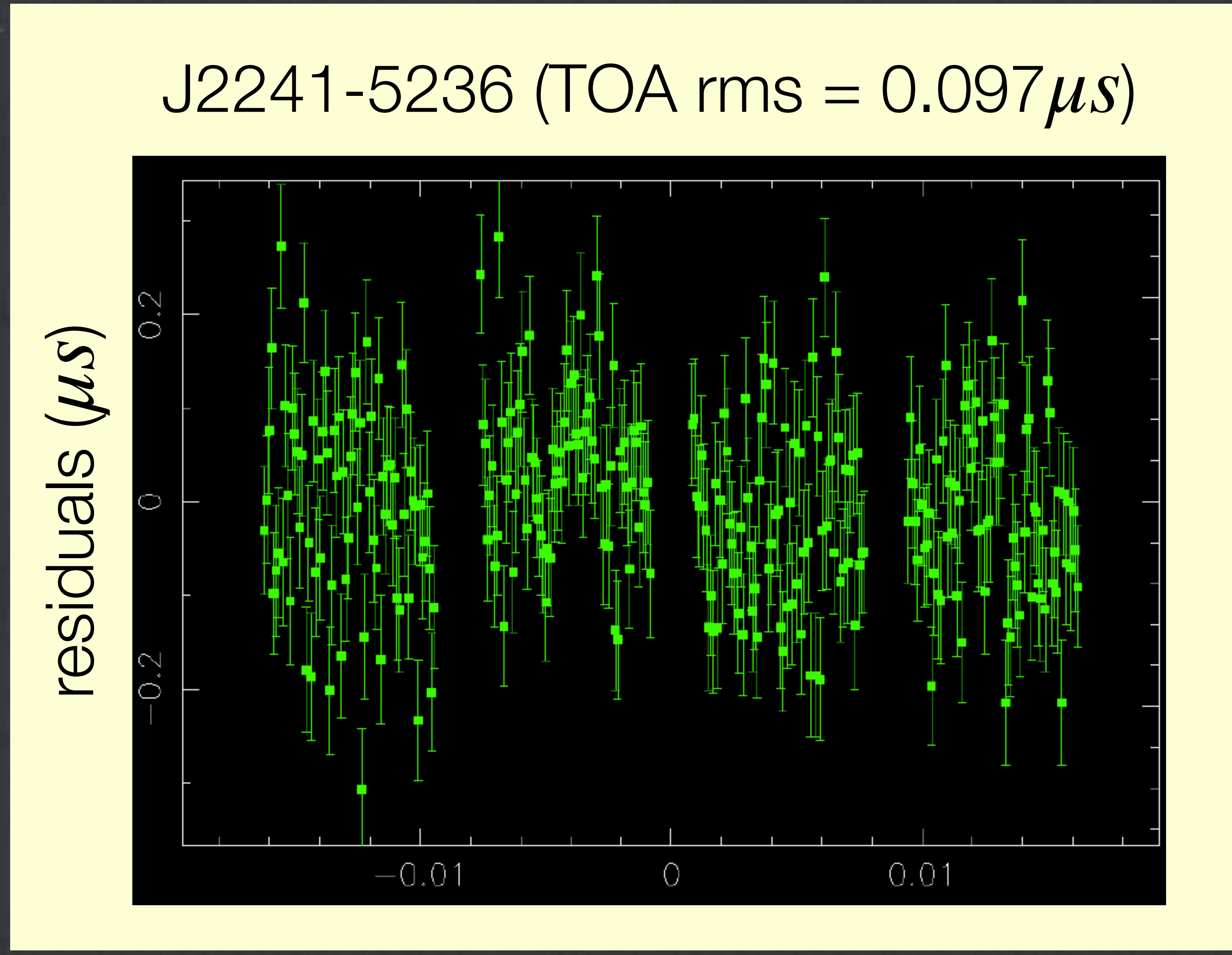


Pulsar timing principles

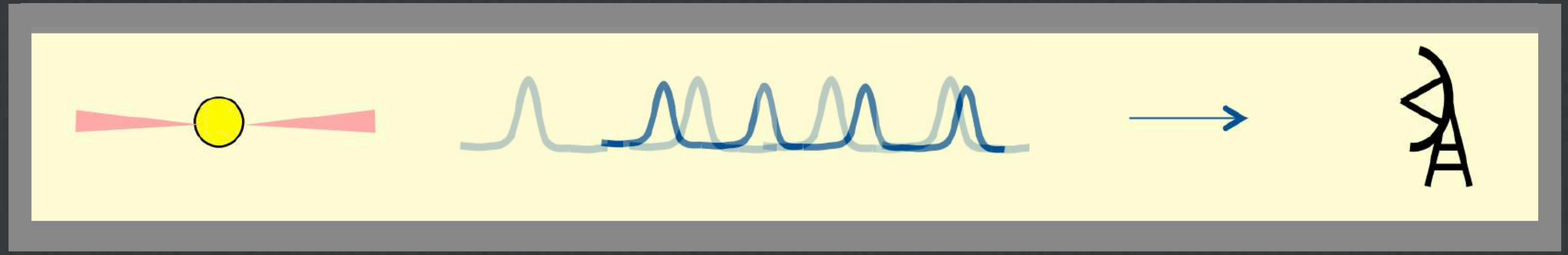


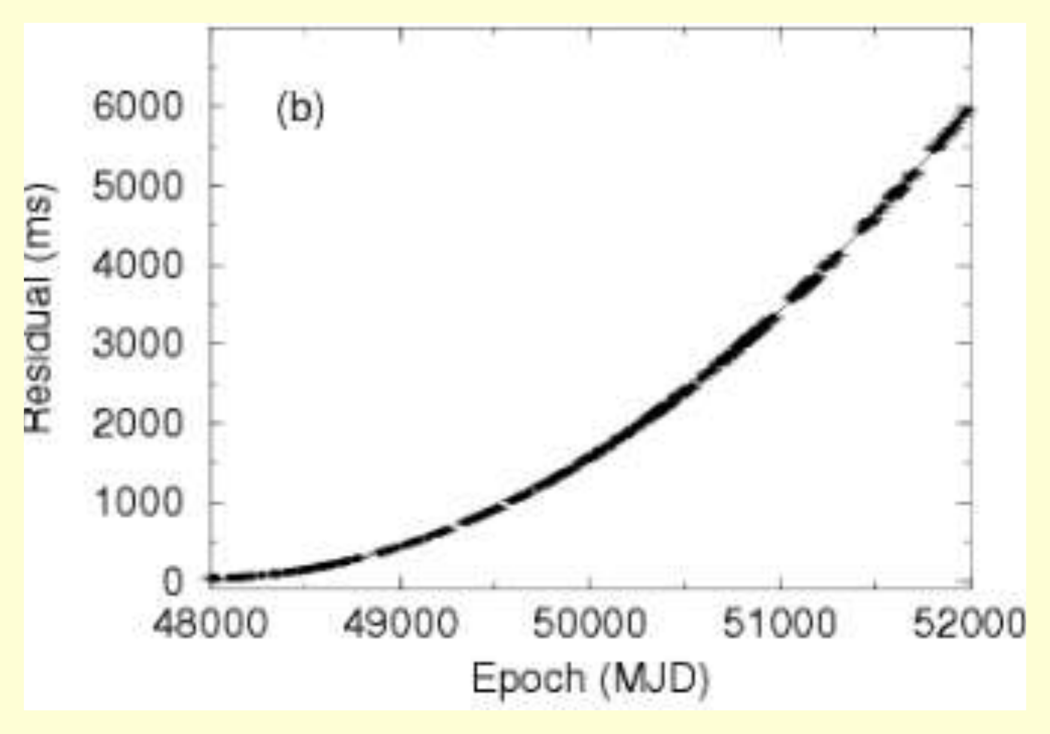

Pulsar timing principles
Study difference between MODEL and DATA
Error in microsec.
Observing days
Proper motion
Small increases in pulse period with time
Pulse period
Pulses
Pulsar
Interstellar medium
Frequency dependent effect on pulse arrival times
Timing model prediction
15311
15312
15313
15314
15315
15316
15317
Data
Frequency
Frequency dependent effect on pulse arrival times

Timing model errors



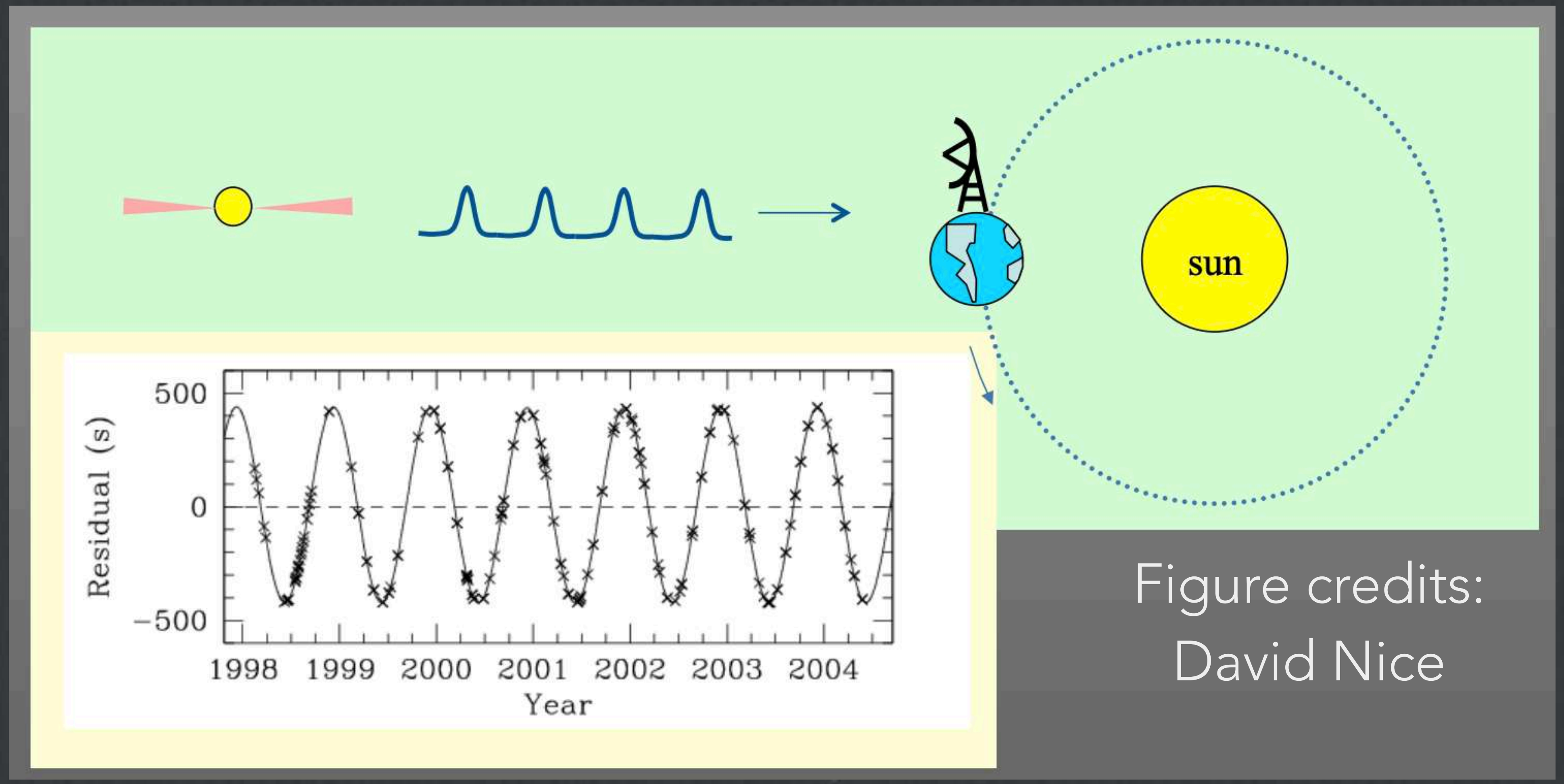
(a) Good timing model!



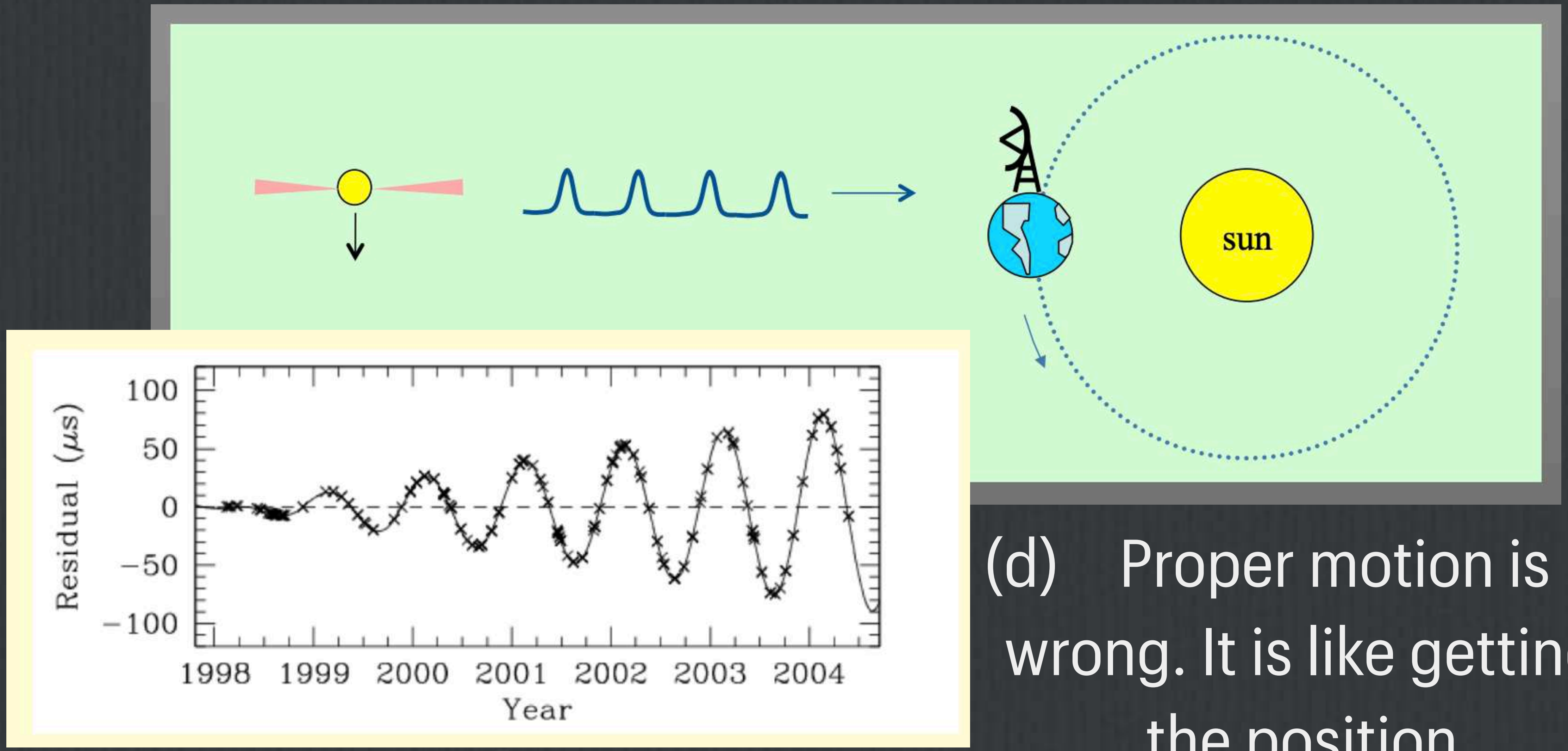


(b) Period derivative is wrong!

Pulses are delayed $\propto t^2$



(c) Wrong pulsar position. Delay in residuals due to travel time across Earth's orbit. Size of the delay depends on pulsar position!



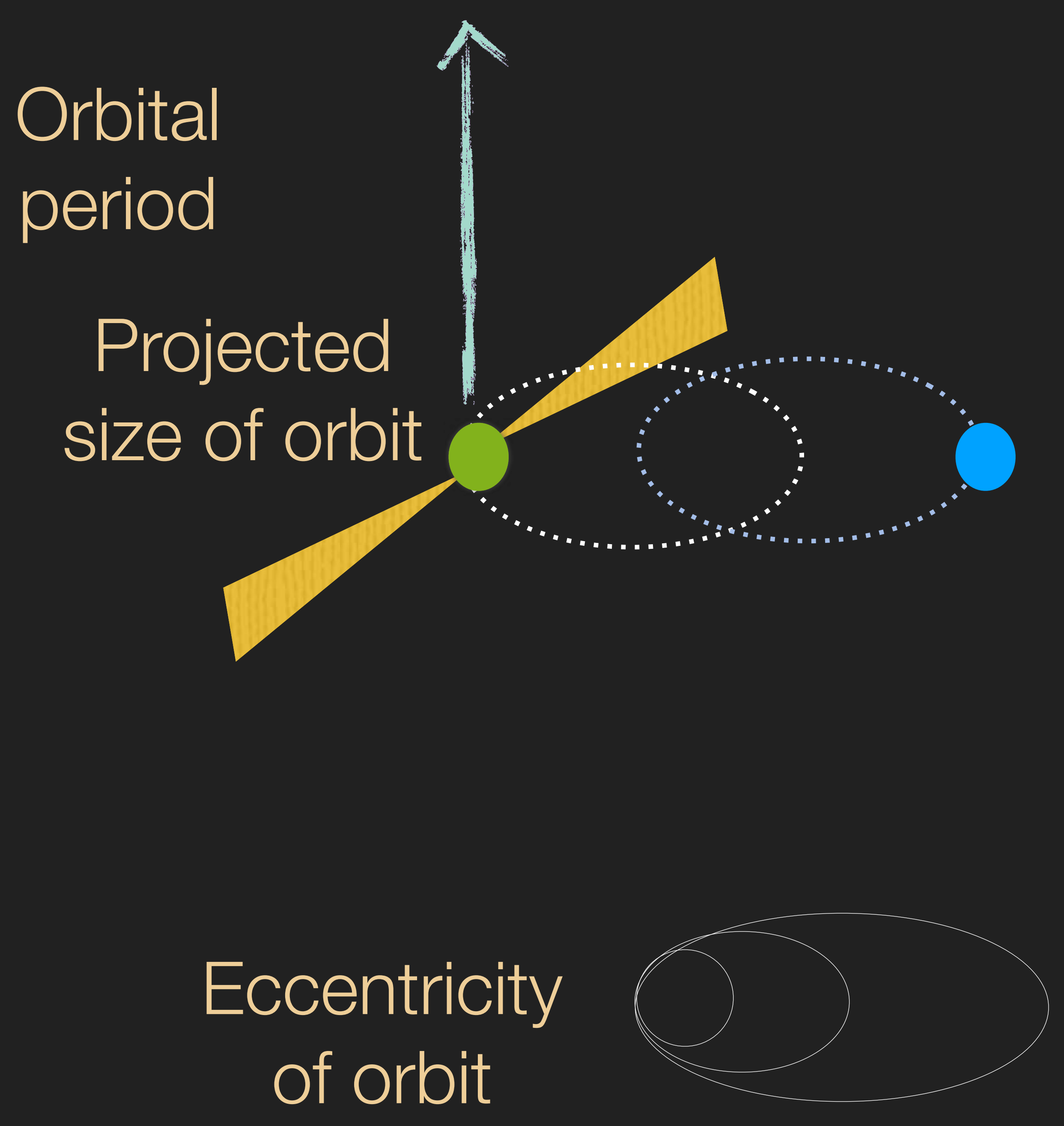
(d) Proper motion is wrong. It is like getting the position increasingly wrong!

Pulsar timing principles - for binaries

Full set of new binary parameters to compute from pulsar timing work!

Distance
Frequency dependent
effect on pulse arrival times

Analysing pulsars in relativistic binary orbits



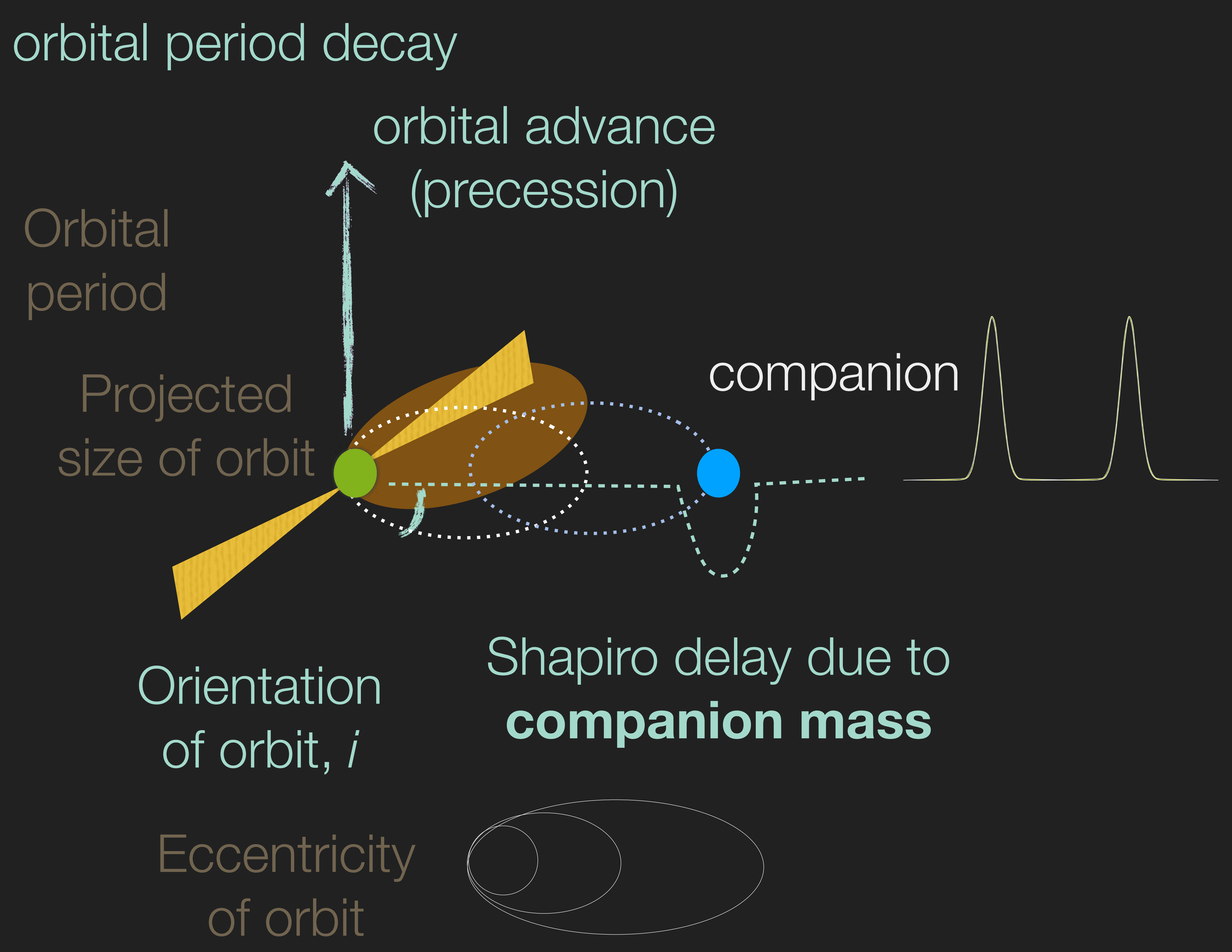
Measuring Keplerian parameters

- Orbital period (P_b)
- Projected semi-major axis of orbit (lt-s)
- Orbital eccentricity
- T_0 epoch of periastron (MJD)
- Longitude of periastron (deg)

Analysing pulsars in relativistic binary orbits

Measure relativistic corrections via **post-Keplerian parameters**

- advance of periastron $(\dot{\omega})$
- Shapiro delay (rate and shape, r and s)
- change in orbital period $(\dot{P}_b)$
- Einstein delay (γ)



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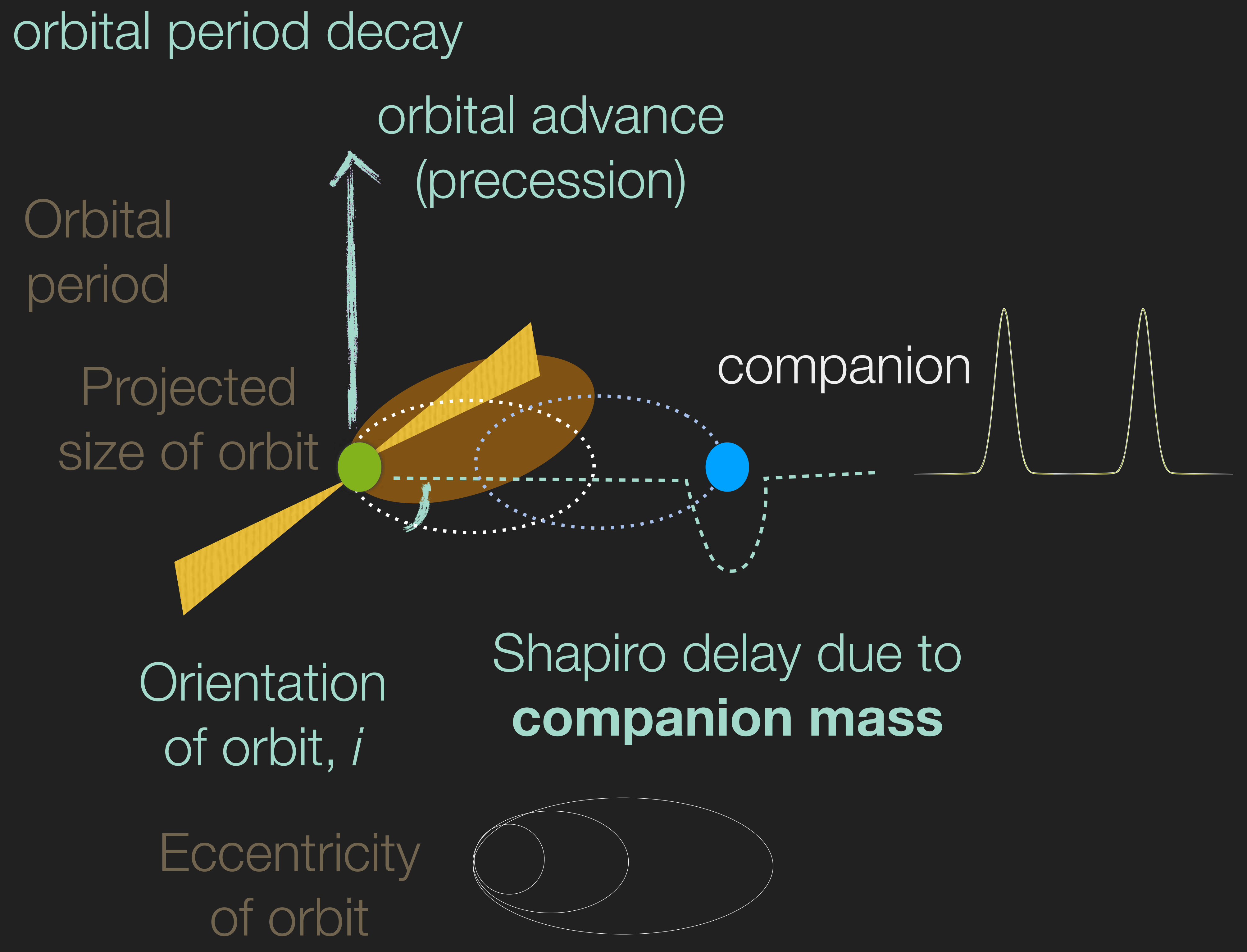
Measuring 2+ PK parameters allows for tests of GR



$$\dot{\omega} = 3T_\odot^{2/3}\left(\frac{P_b}{2\pi}\right)^{-5/3}\frac{1}{1-e^2}(m_p+m_c)^{2/3},$$

$$\gamma = T_\odot^{2/3}\left(\frac{P_b}{2\pi}\right)^{1/3} e\frac{m_c(m_p+2m_c)}{(m_p+m_c)^{4/3}},$$

$$r = T_\odot m_c,$$

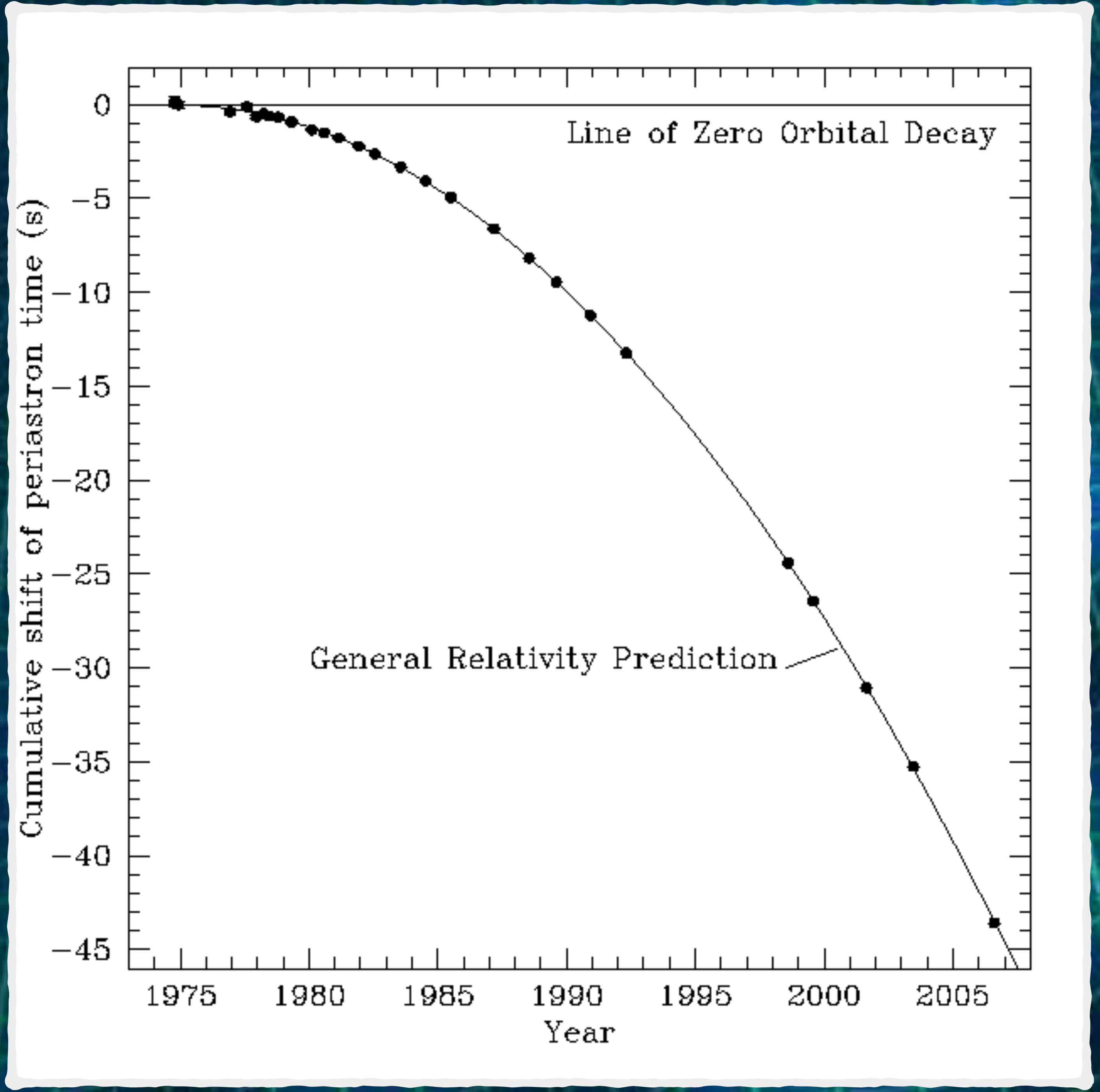
$$s = \sin i = T_\odot^{-1/3}\left(\frac{P_b}{2\pi}\right)^{-2/3} x\frac{(m_p+m_c)^{2/3}}{m_c},$$

$$\dot{P}_b = -\frac{192\pi}{5}T_\odot^{5/3}\left(\frac{P_b}{2\pi}\right)^{-5/3} f(e)\frac{m_p m_c}{(m_p+m_c)^{1/3}},$$

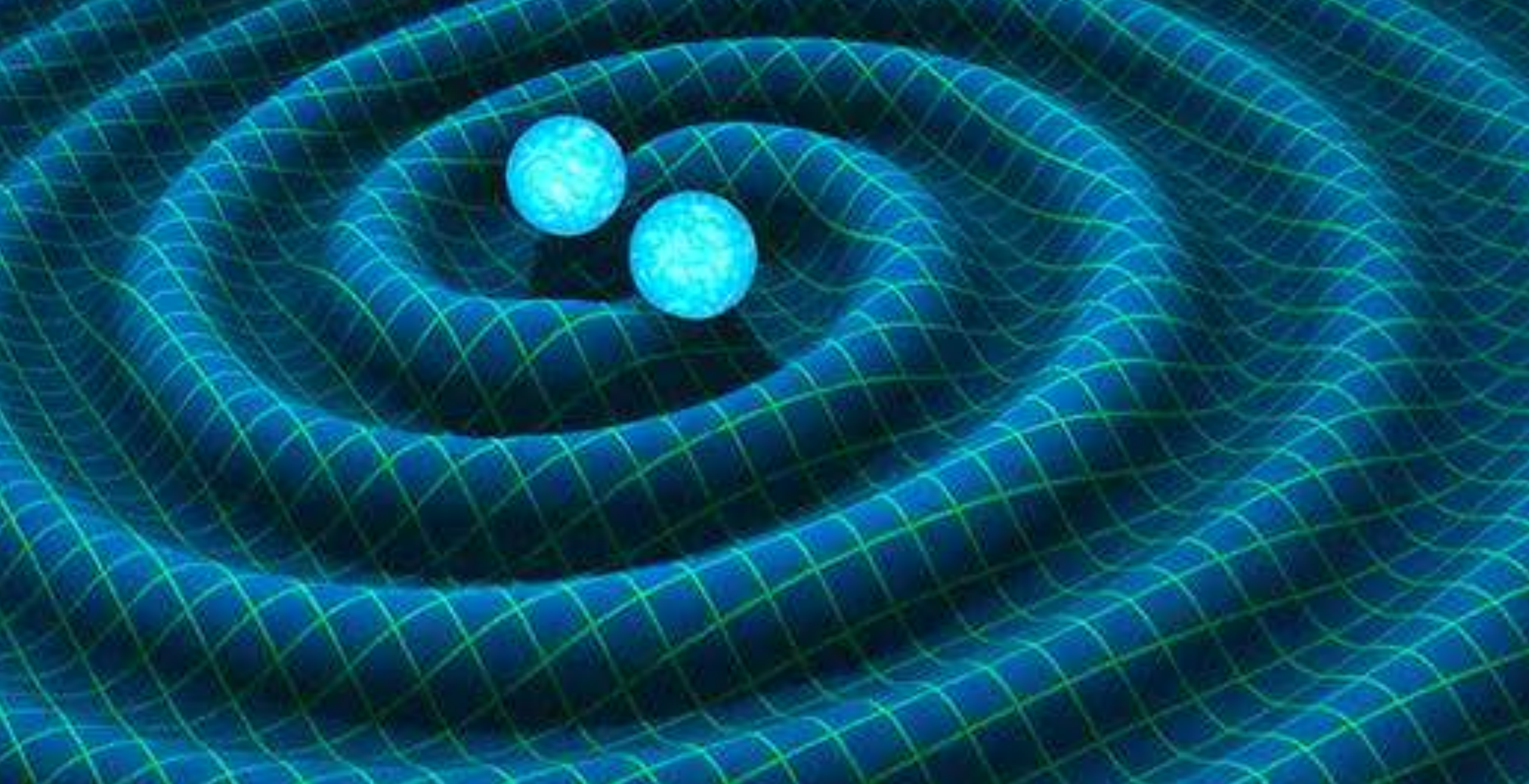
Damour & Deruelle 1986

Analysing pulsars in relativistic binaries: orbital decay

- First binary pulsar, discovered by Russell Hulse and Joseph Taylor in 1974
- Relativistic binary of NS and pulsar in orbit
- Pulsar: 59 ms pulse period
- Orbit: **7.75 hr** orbit
- Orbital precession: $d\omega/dt = 4.2°/yr$



Hulse-Taylor PSR B1913+16



- Orbital decay due to GW emission
- NSs are getting closer
- Semimajor axis decrease 3.5 m/yr
- Inspiral in 300 million yrs

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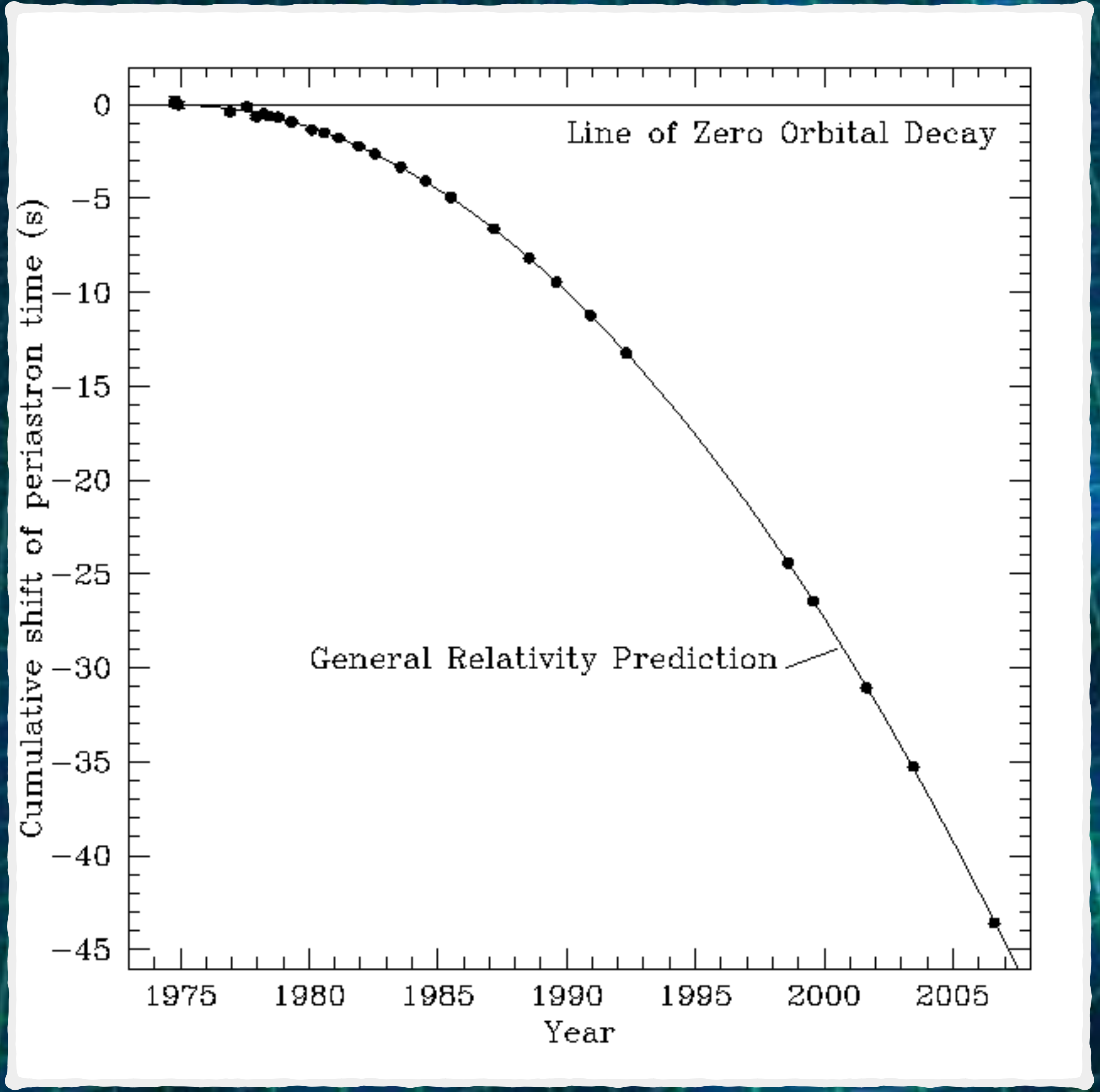
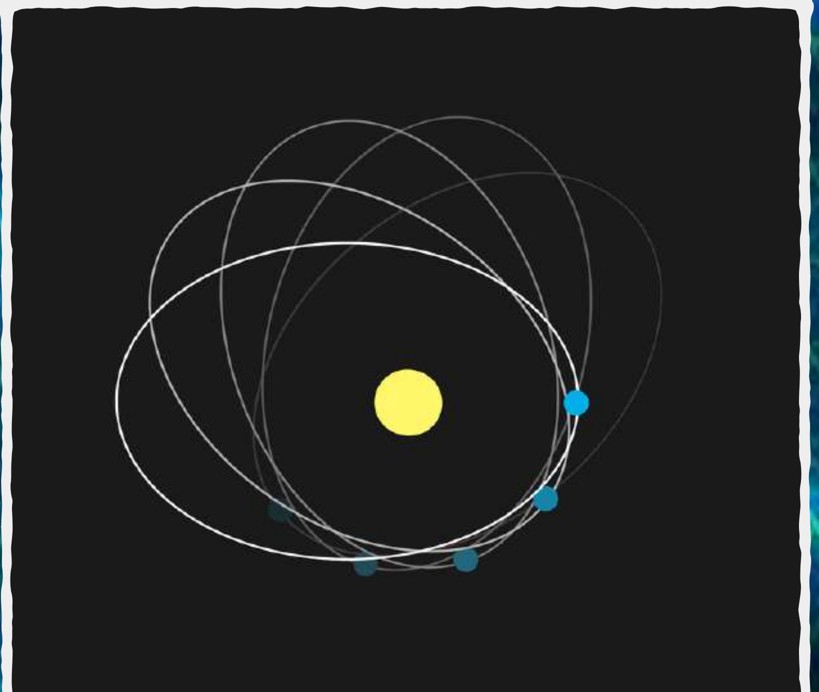


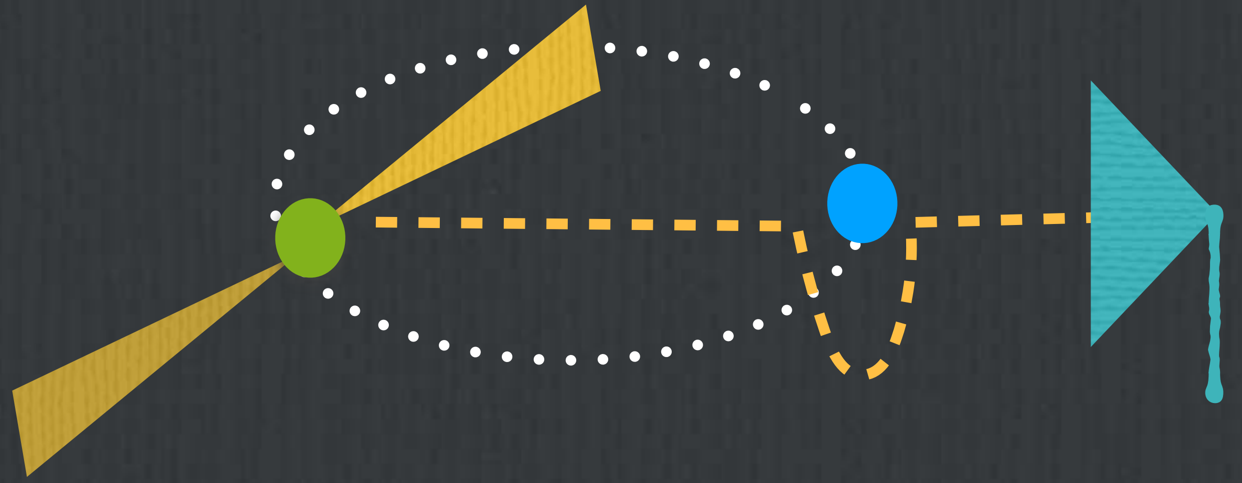


Mercury's dω/dt: 43"/century

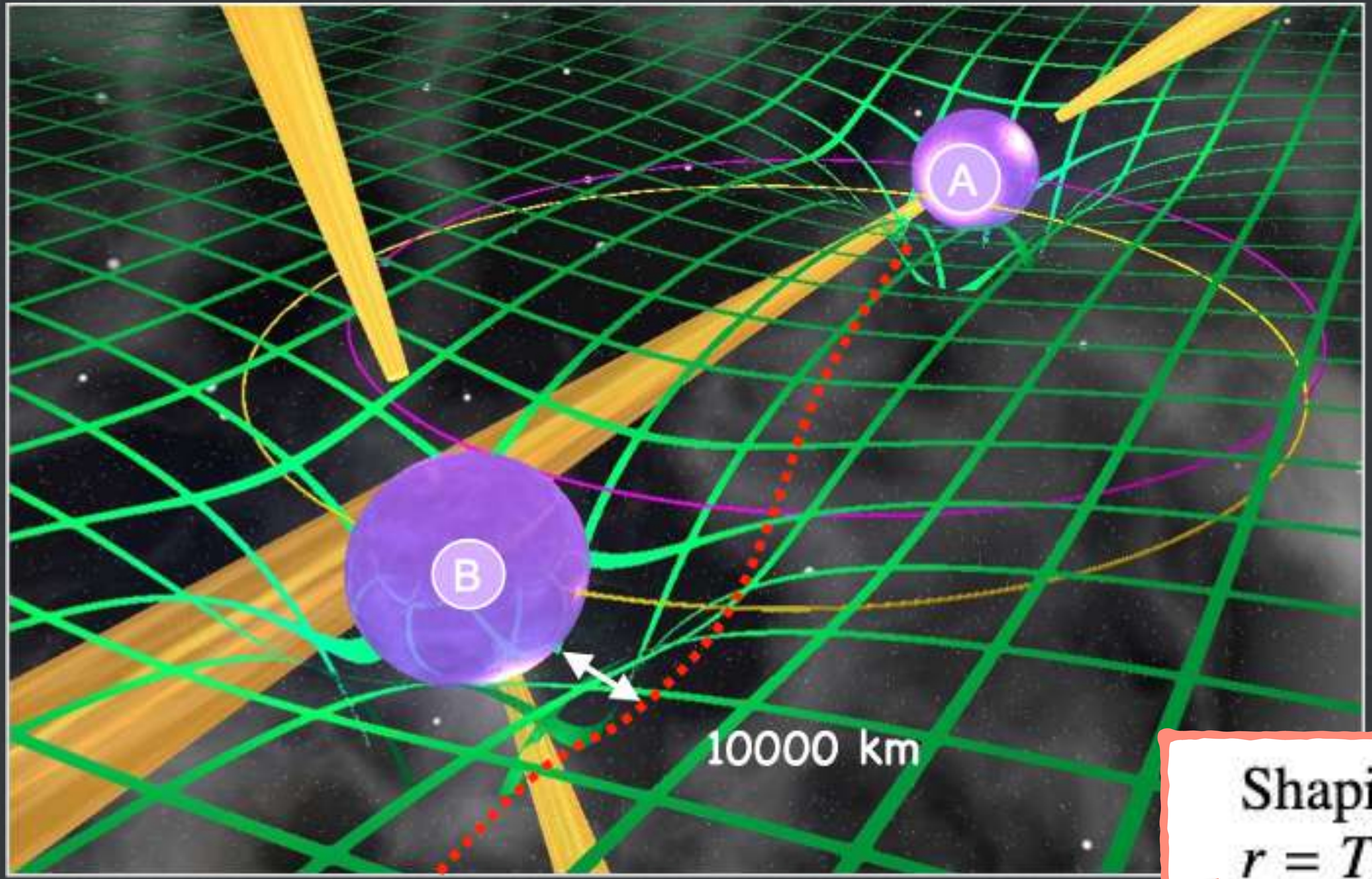
- Orbital decay due to GW emission
- NSs are getting closer
- Semimajor axis decrease 3.5 m/yr
- Inspiral in 300 million yrs

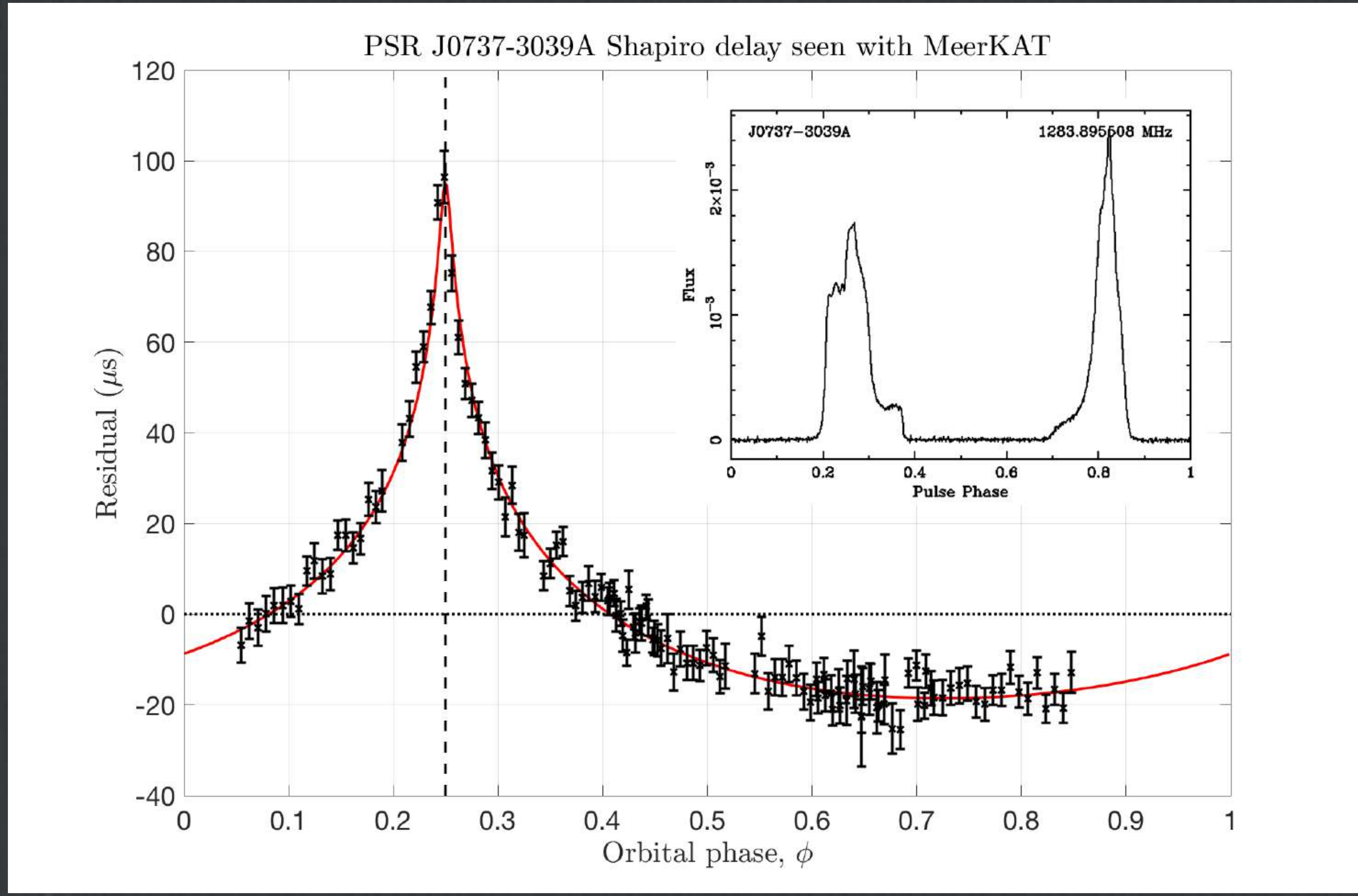
Analysing pulsars in relativistic binary orbits: Shapiro Delay

Shapiro delay — for nearly edge-on systems



Double Pulsar





ONE BINARY ORBIT (Pb)

Shapiro relations

$r = T_{\odot} m_c$

$s = \sin i$

Directly measure companion mass

and orbital inclination

Analysing pulsars in relativistic binary orbits: 2+PK == Tests of Theories of Gravity

Double pulsar: 2.5 hr orbit

- Discovered pulsar A at Parkes 2003, (Burgay et al, *Nature*)
- Found the orbit's orientation was changing rapidly: $d\omega/dt = 17°/yr$, suggesting a companion
- Companion turned out to be pulsar too!
- Great candidate for strong field tests of GR
- Orbit shrinks by 7mm per day
- GR prediction of orbital parameters agree to within 0.05% of measured orbital parameters

$$\dot\omega = 3T_\odot^{2/3}\left(\frac{P_b}{2\pi}\right)^{-5/3}\frac{1}{1-e^2}(m_p+m_c)^{2/3},$$

$$\gamma = T_\odot^{2/3}\left(\frac{P_b}{2\pi}\right)^{1/3} e\frac{m_c(m_p+2m_c)}{(m_p+m_c)^{4/3}},$$

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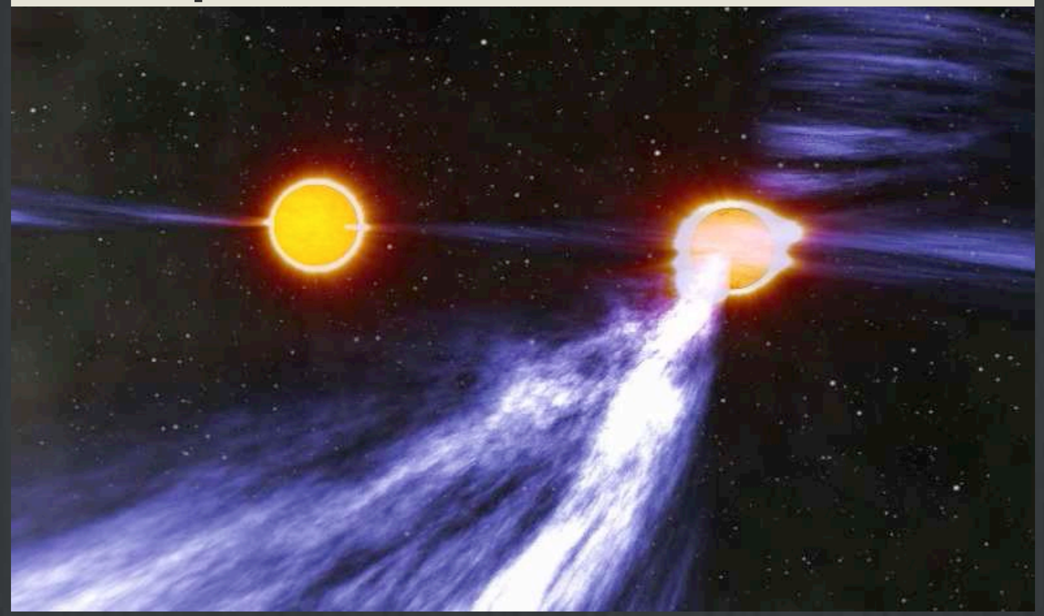
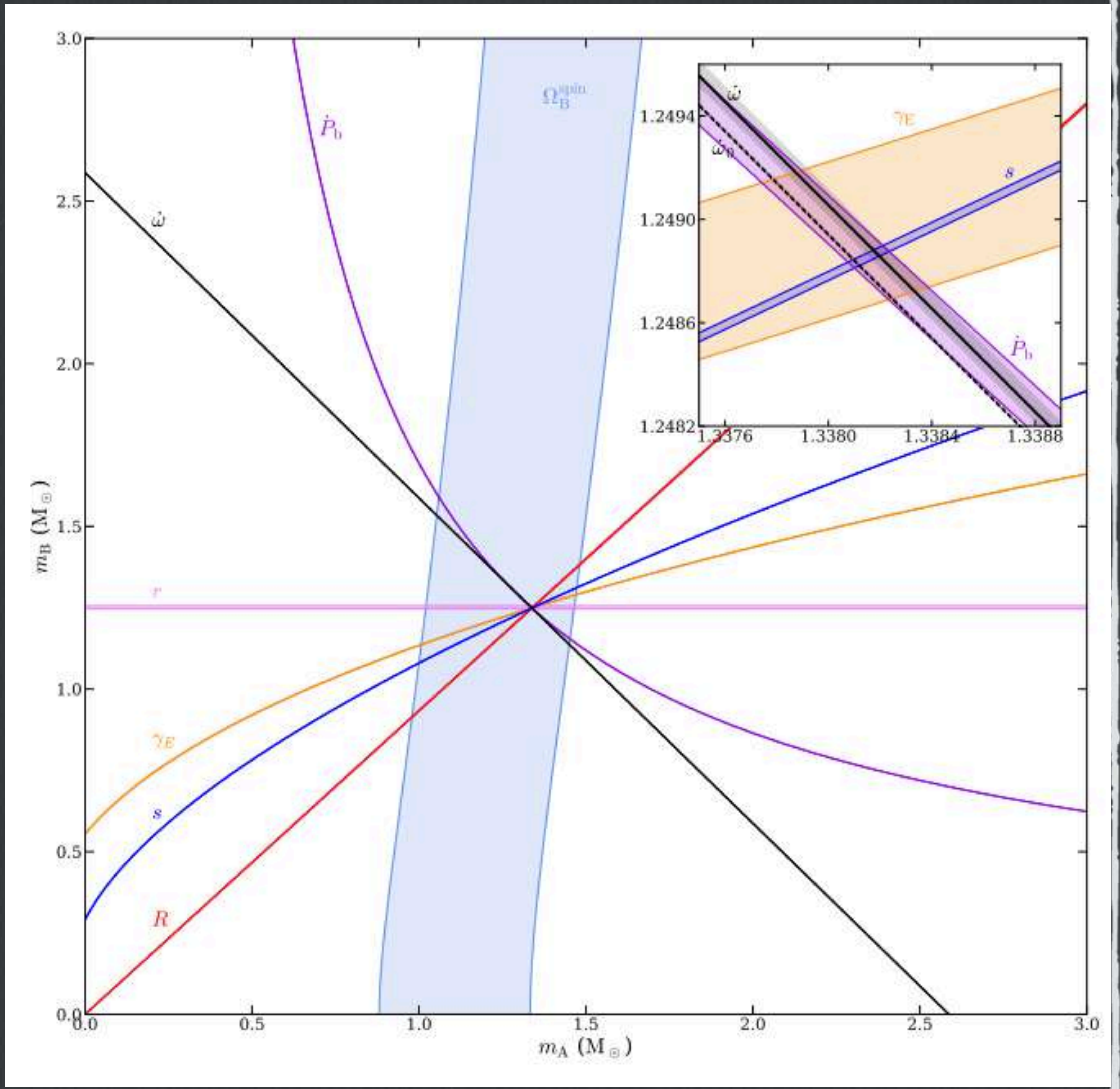
	Pulsar A	Pulsar B
Pulsar period	22 ms	2.7 s
Orbital period	2.4 hours	





Mass-mass diagramme of double pulsar | Kramer et al 2021

Analysing pulsars in relativistic binary orbits

PSR J0955-6150 — **highly eccentric** & relativistic binary
A&A March 2022

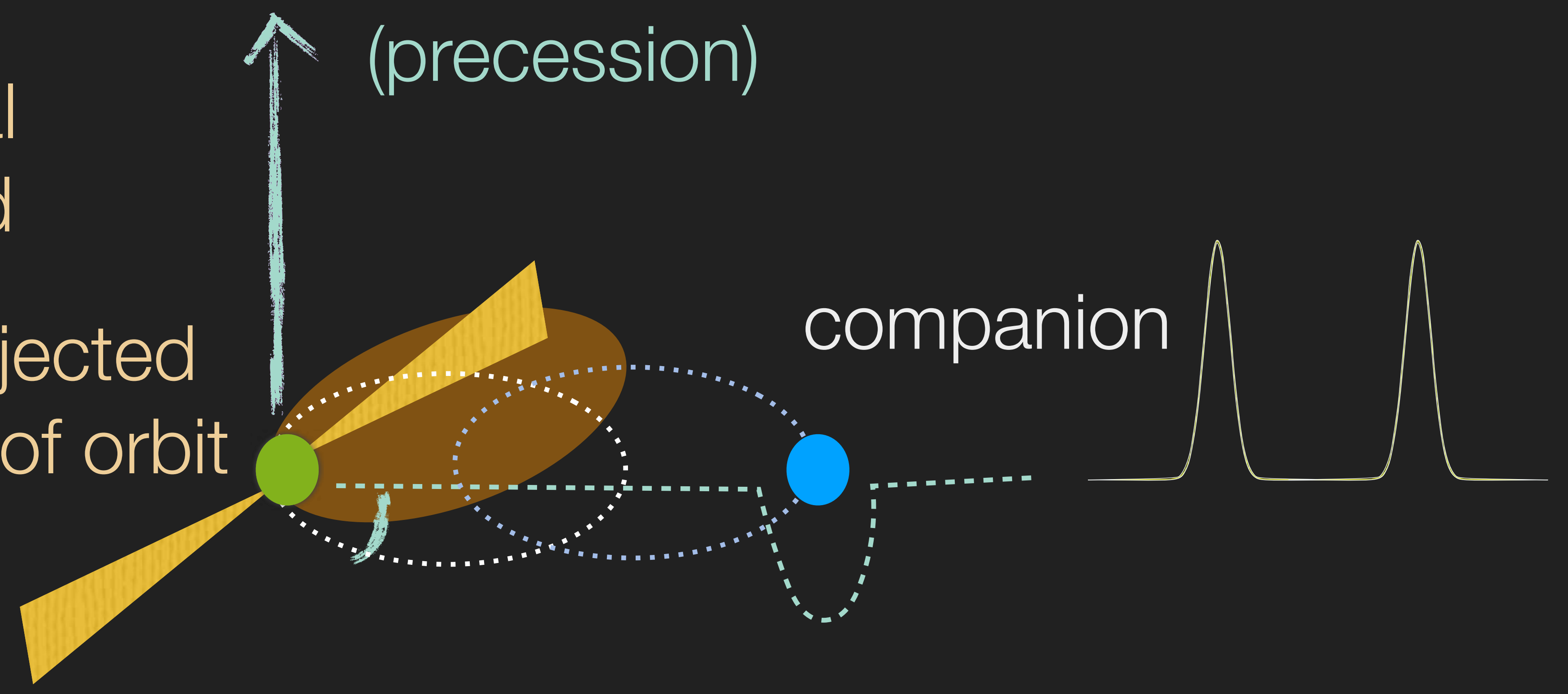
orbital period decay

orbital advance (precession)

Orbital period

Projected size of orbit

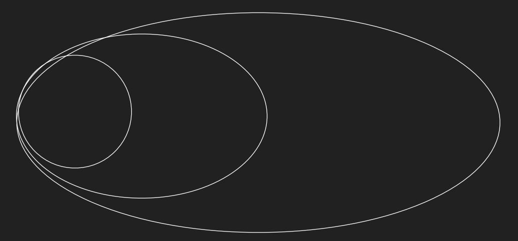
companion



Orientation of orbit, i

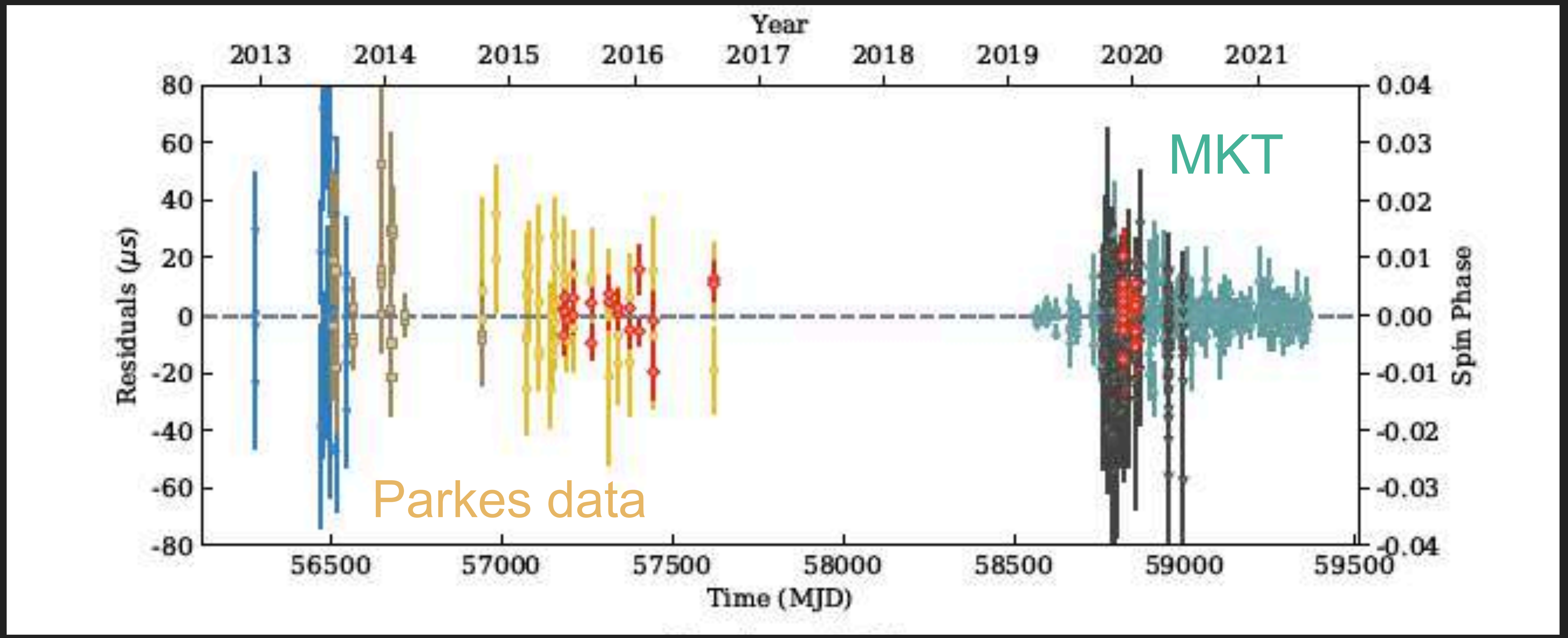
Shapiro delay due to **companion mass**

Eccentricity of orbit



~ 8 yr

microsec timing precision



Keplerian orbital parameters	
Orbital period, P_b (days)	24.57839502(6)
Projected semi-major axis of the pulsar orbit, x (lt-s)	13.282477(2)
Epoch of periastron, T_0 (MJD)	56287.604348(6)
Orbital eccentricity, e	0.11750575(1)
Longitude of periastron at T_0, ω (°)	202.92940(9)

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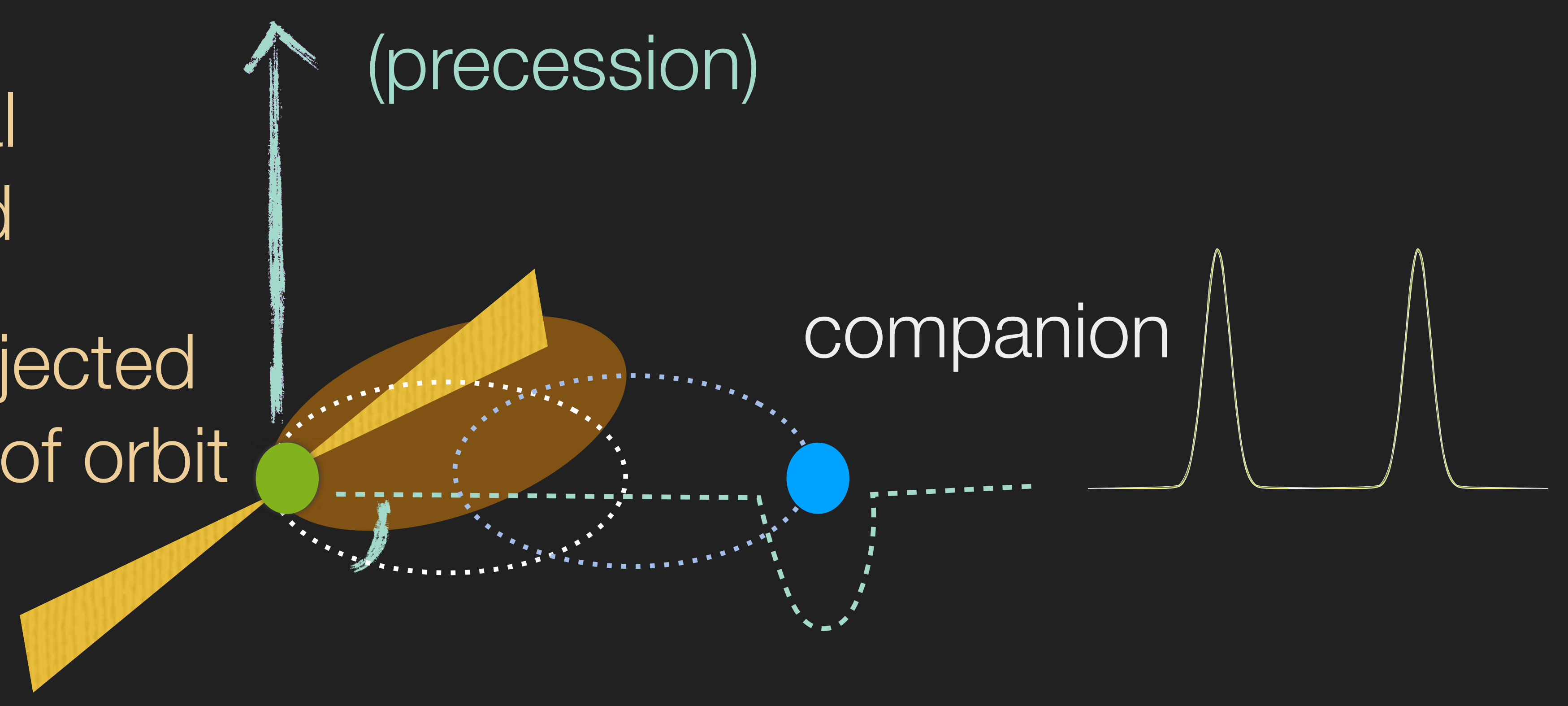
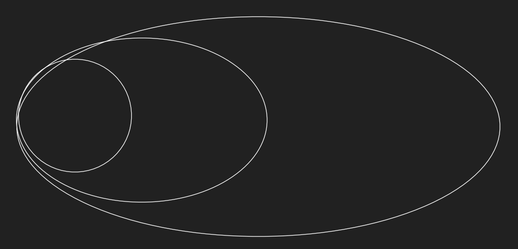
A&A March 2022

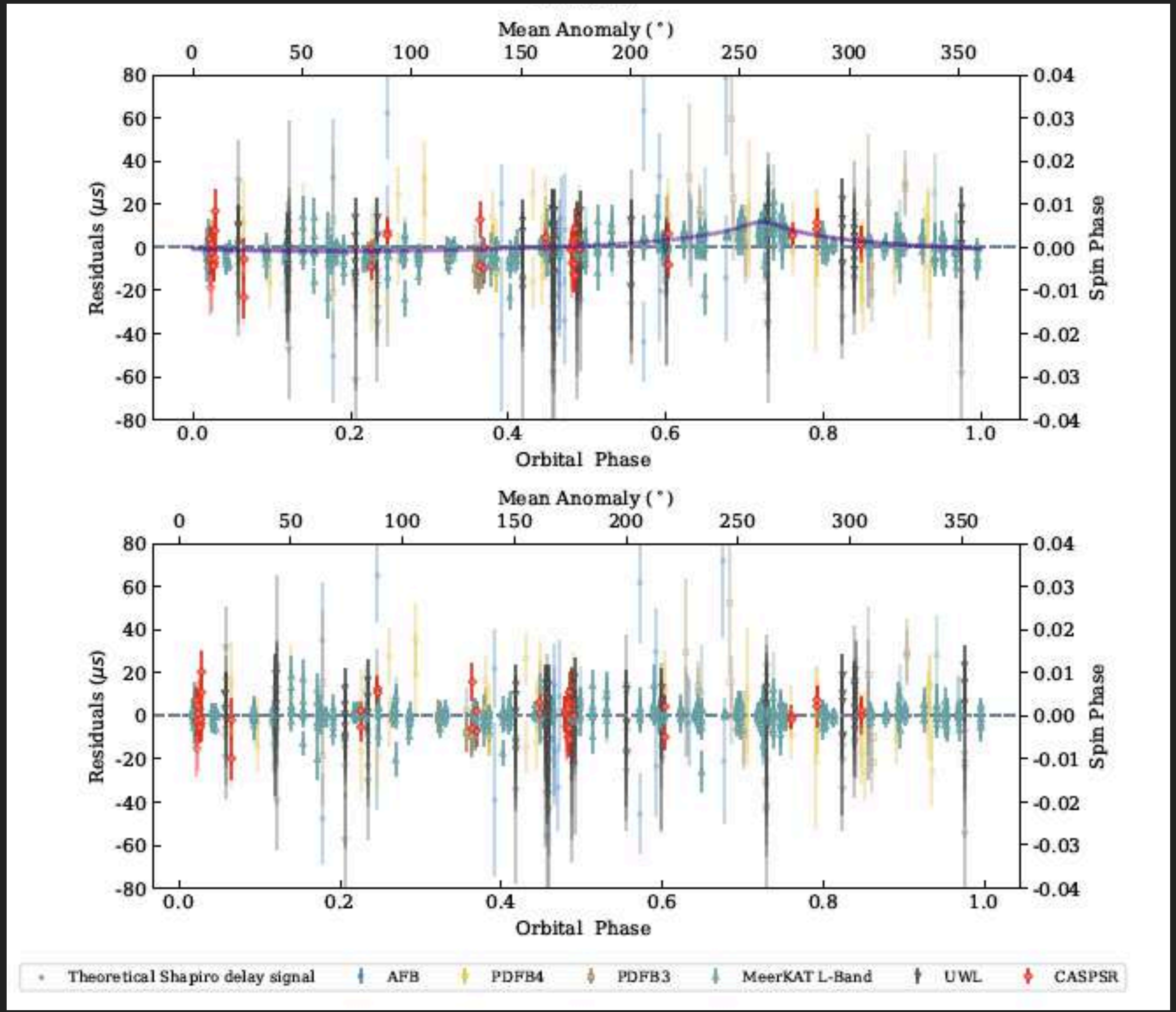


Eccentricity of orbit



Shapiro relations

$$r = T_{\odot} m_c$$
$$s = \sin i$$
$$\varsigma = \frac{\sin i}{1+|\cos i|}$$
$$h_3 = T_{\odot} m_c \varsigma^3$$



Analysing pulsars in relativistic binary orbits

$$\dot{\omega} = \frac{3\,(2\pi/P_b)^{5/3}}{1-e^2}(MT_\odot)^{2/3}$$

$\dot{\omega}$ = 0.00152(1) deg/yr

PSR J0955-6150 — **highly eccentric** & relativistic binary
A&A March 2022

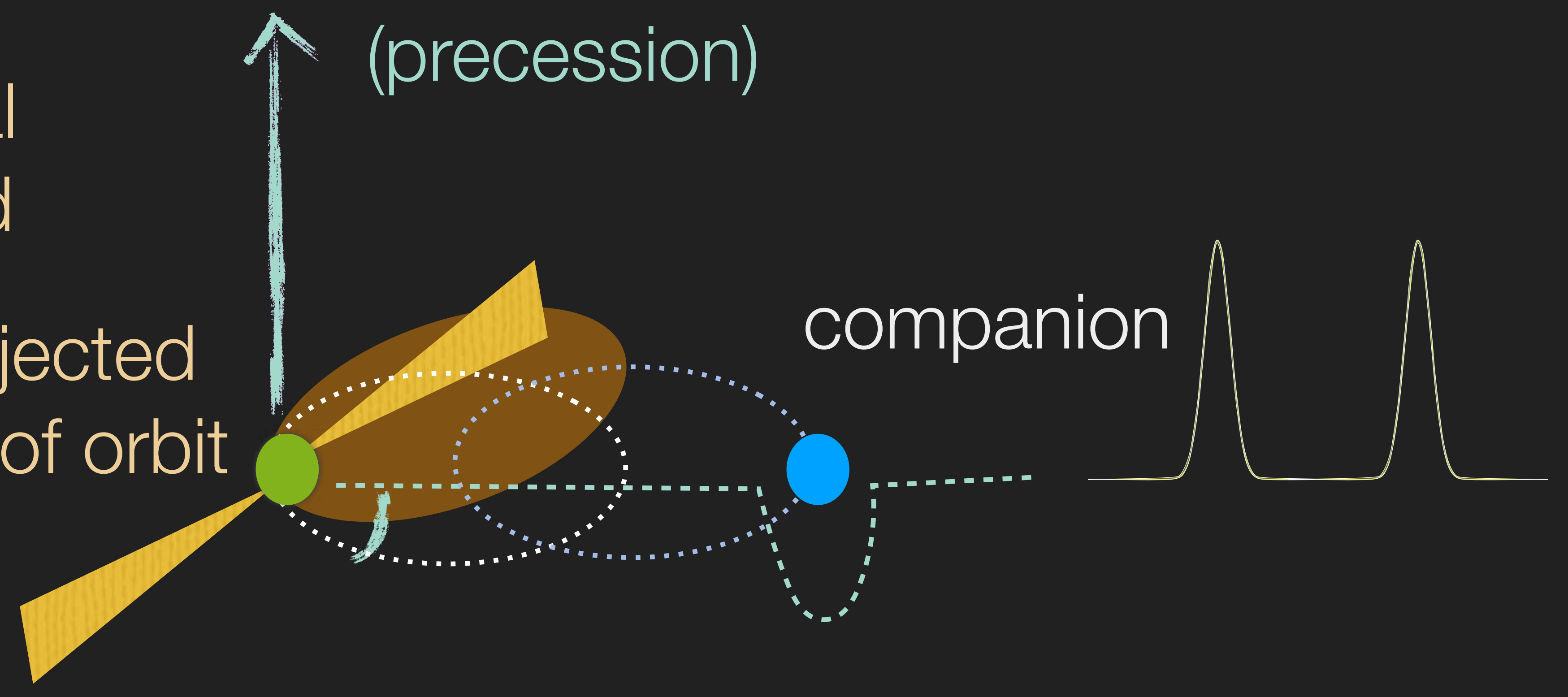
orbital period decay

orbital advance (precession)

Orbital period

Projected size of orbit

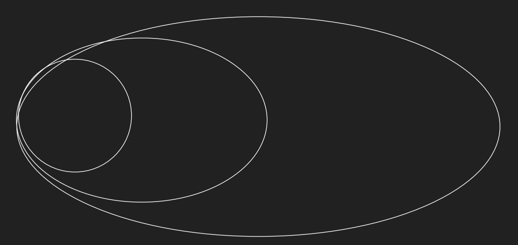
companion



Orientation of orbit, *i*

Shapiro delay due to **companion mass**

Eccentricity of orbit



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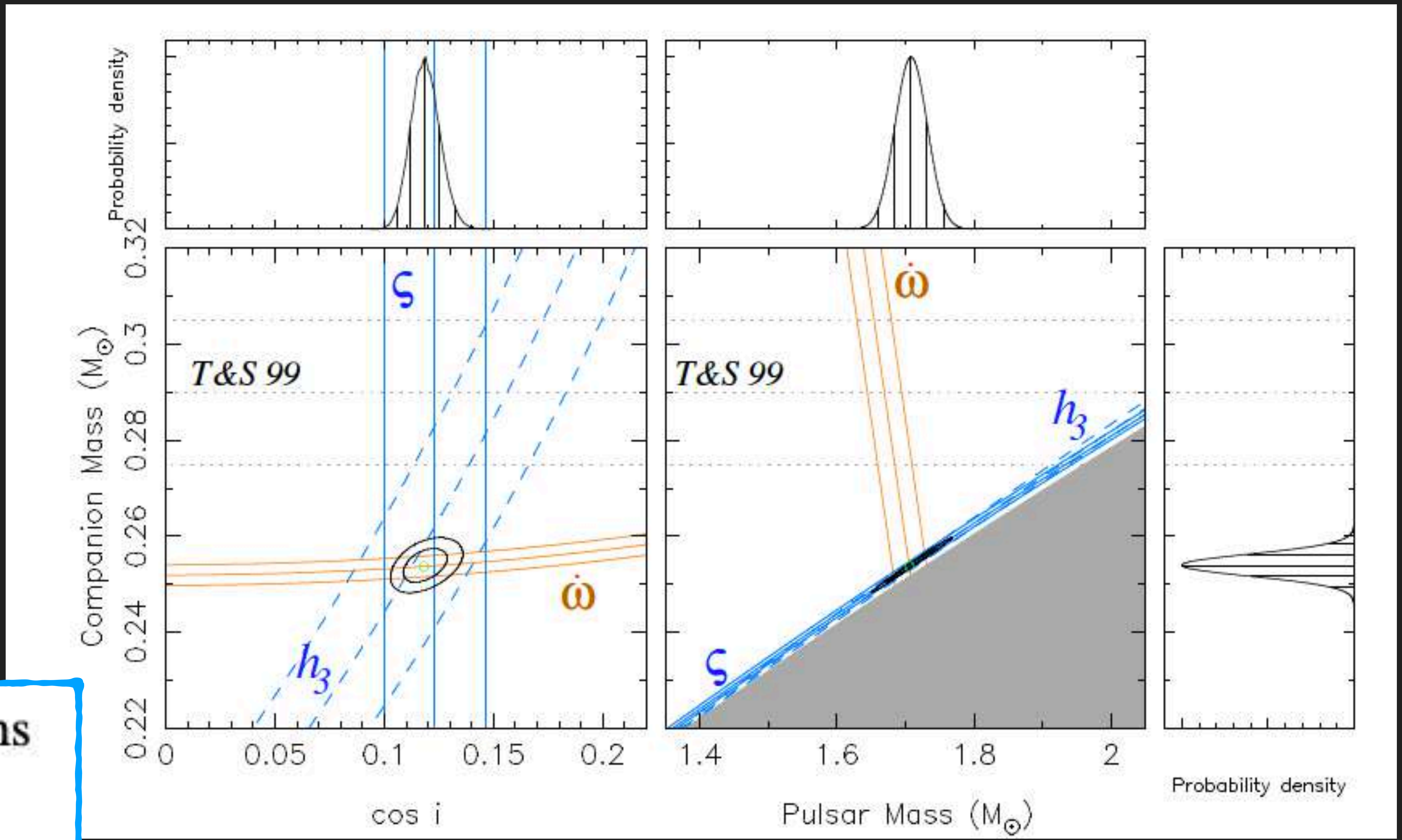


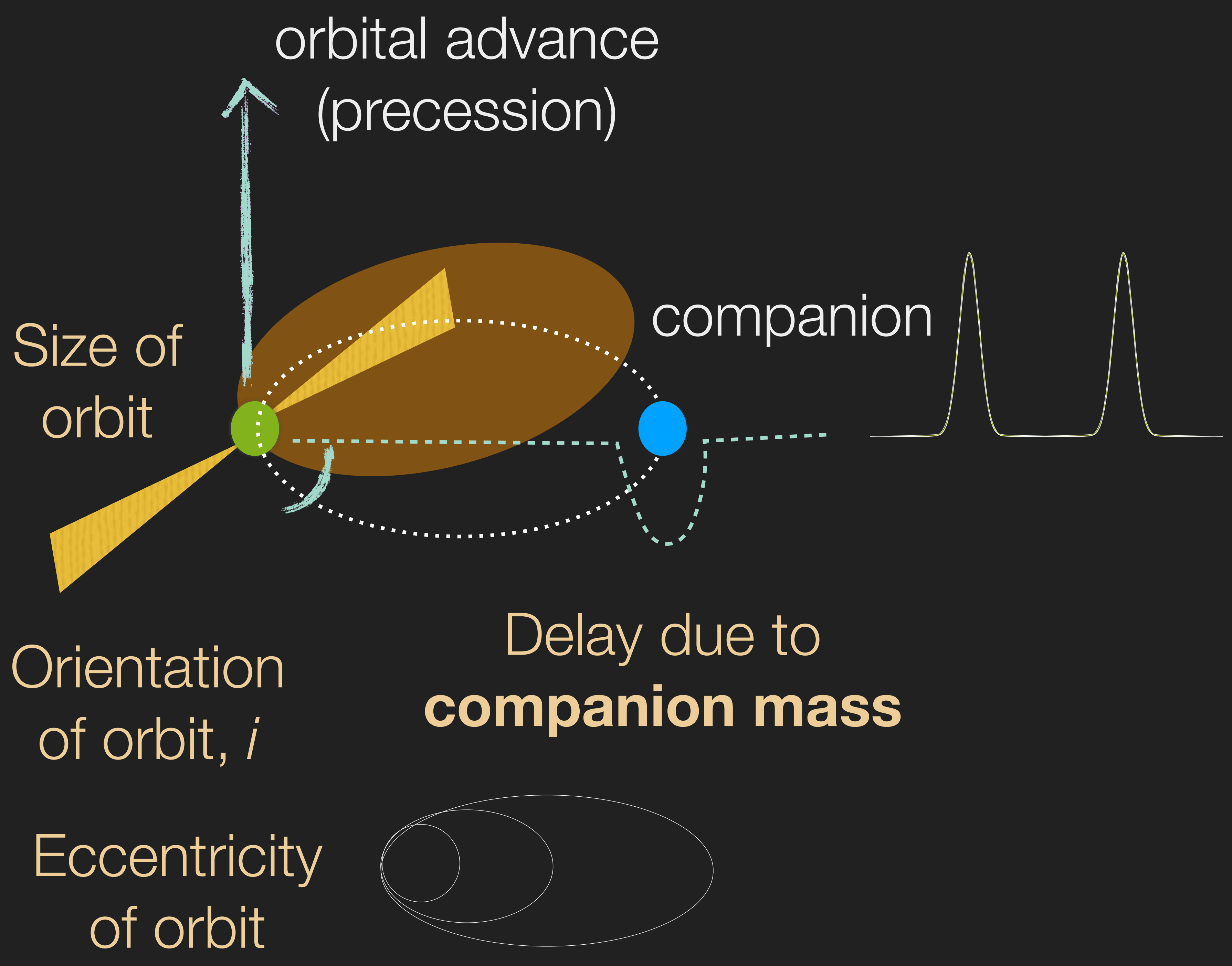
$i = 83.2(4)^\circ$

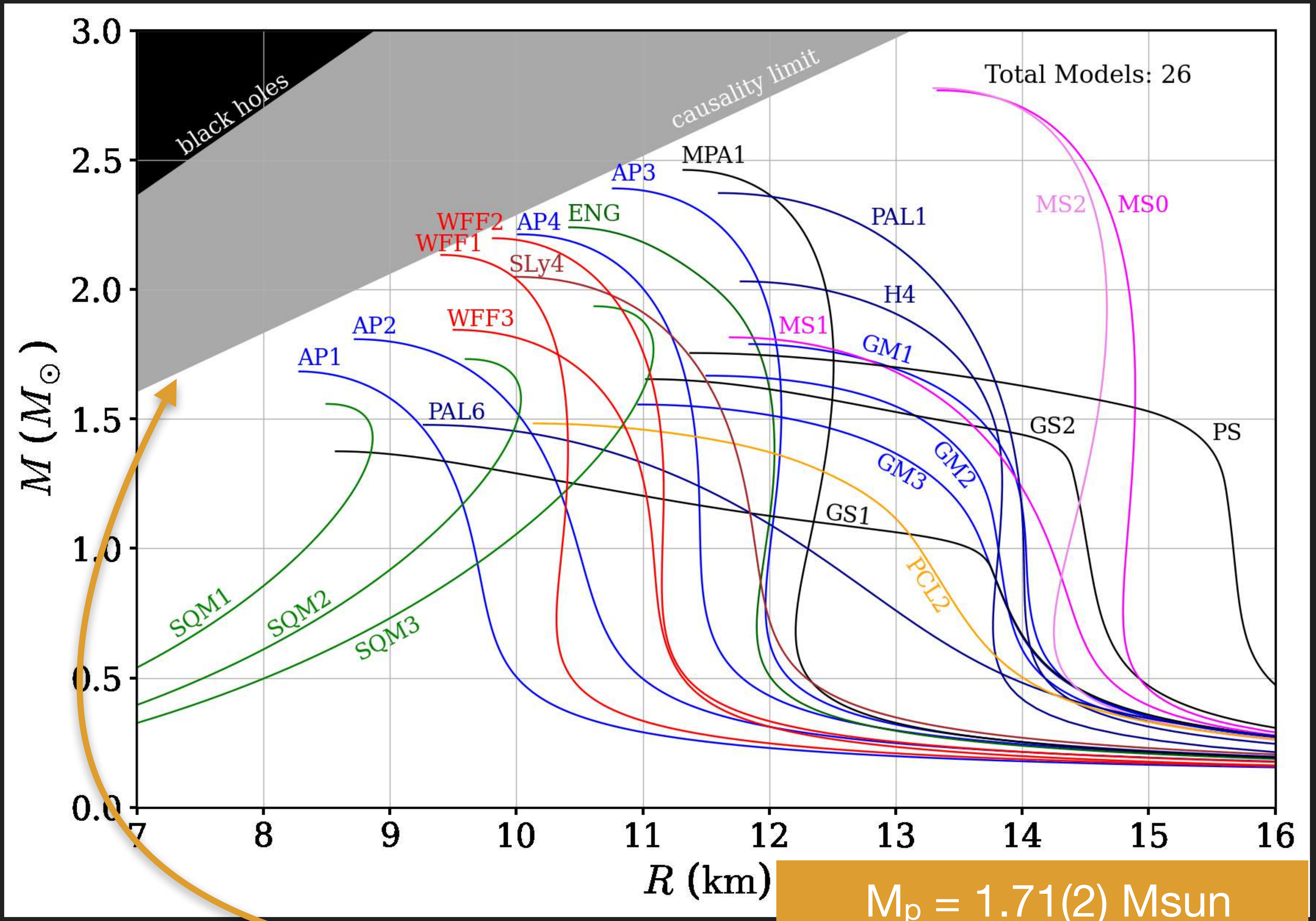
weighing masses

M_p = 1.71(2) Msun
M_c = 0.254(2) Msun

Probing nuclear matter using relativistic pulsar binaries

PSR J0955-6150 — **highly eccentric** & relativistic binary
A&A March 2022





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M_c = 0.254(2) Msun

Evidence for nanoHz Gravitational Waves in the news!

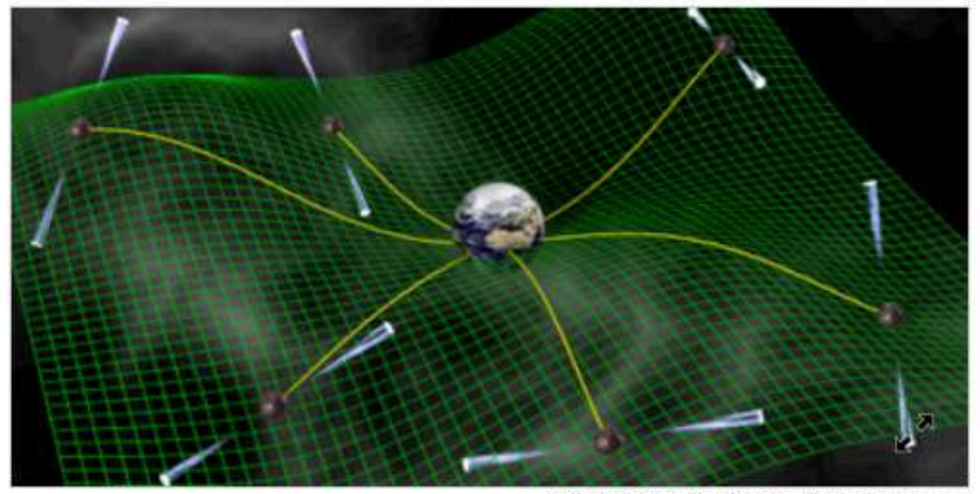
29 June 2023

RESEARCH NEWS

Researchers Capture Gravitational-Wave Background with Pulsar "Antennae"

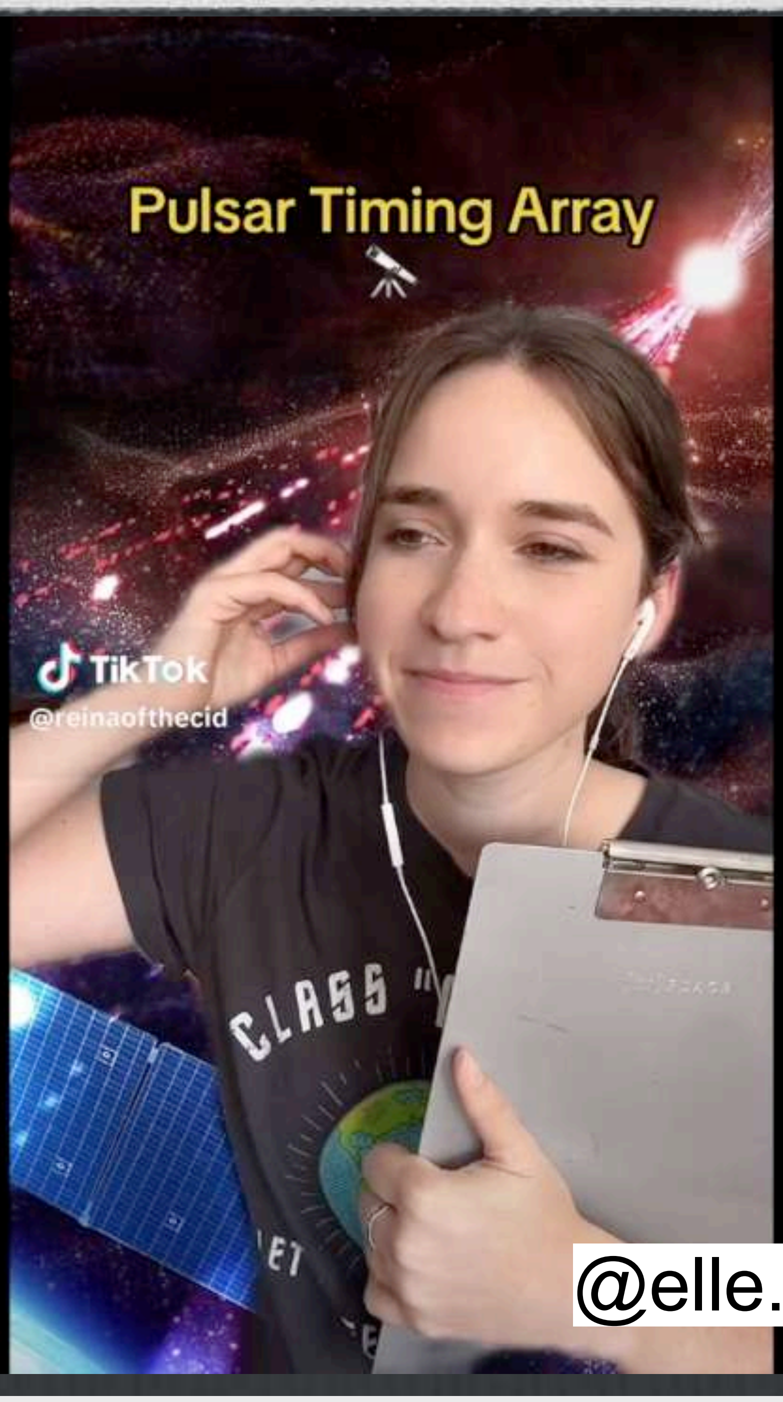
June 29, 2023 • *Physics* 16, 118

Four independent collaborations have spotted a background of gravitational waves that passes through our Galaxy, opening a new window on the astrophysical and cosmological processes that could produce such waves.



D. Champion/Max Planck Institute for Radio Astronomy

Pulsar timing arrays (PTAs) use a set of pulsars embedded in our Galaxy to probe the gravitational waves that modulate radio signals from the pulsars. Four PTA collabora… delivered evidence for a stochastic background of nanohertz gravitational waves.



@elle.cordova

The New York Times

The Cosmos Is Thrumming With Gravitational Waves, Astronomers Find

Radio telescopes around the world picked up a telltale hum reverberating across the cosmos, most likely from supermassive black holes merging in the early universe.

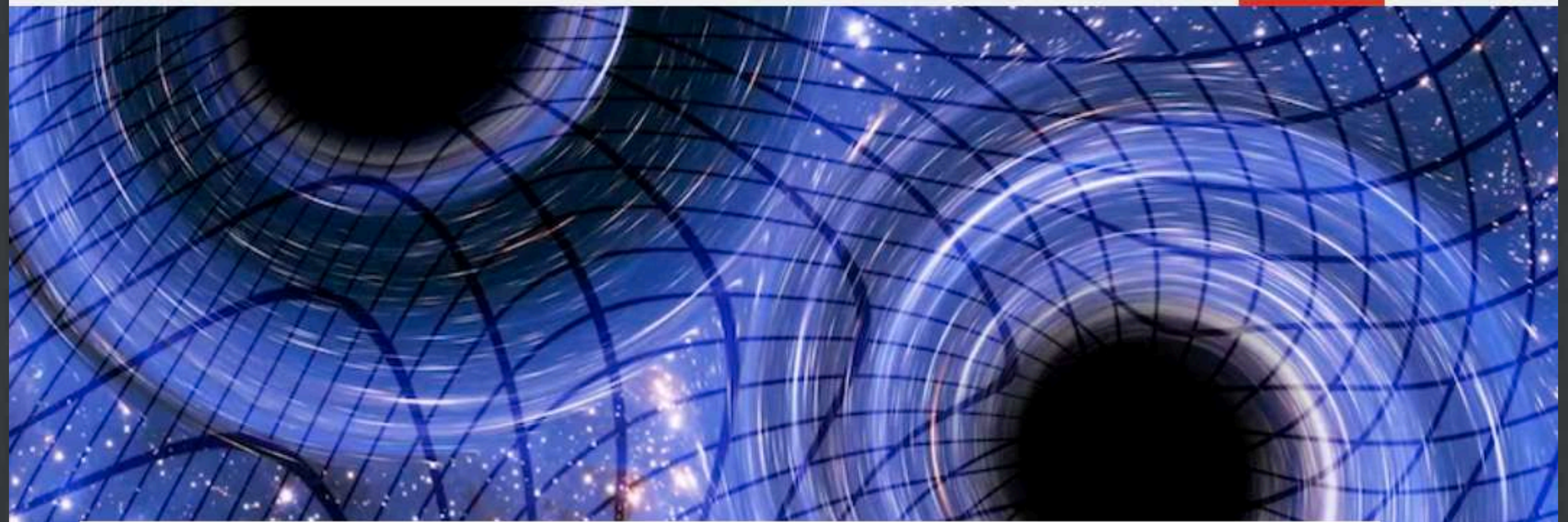
Share full article 362

The Very Large Array on the Plains of San Agustin, N.M., one of three radio telescopes that worked with a global consortium to detect the timing of pulsars. NRAO/AUI/NSF

THE CONVERSATION

Academic rigour, journalistic flair

COVID-19 Arts + Culture Business + Economy Education Environment + Energy Health + Medicine Politics Science + Tech



A subtle symphony of ripples in spacetime – astronomers use dead stars to measure gravitational waves produced by ancient black holes

Published: June 30, 2023 10.57pm SAST

Black holes and other massive objects create ripples in spacetime when they merge. Victor de Schwanburg/Science Photo Library via Getty Images

INVERSE

SPACE

Astronomers Capture Space-Squishing Echoes of Merging Supermassive Black Holes

Several teams of scientists from around the world all report detecting extremely low-frequency waves in spacetime, caused by merging supermassive black holes.

BY KIONA SMITH JUNE 29, 2023

There's a monster lurking at the center of every galaxy, millions of miles wide and millions of times more massive than our Sun: a supermassive black hole. When two of these cosmic leviathans meet, they fall into a million-year death spiral that ends in a dramatic merger.

Evidence for nanoHz Gravitational Wave in the news!

RESEARCH NEWS

Researchers Capture Gravitational-Wave Background with Pulsar "Antennae"

June 2

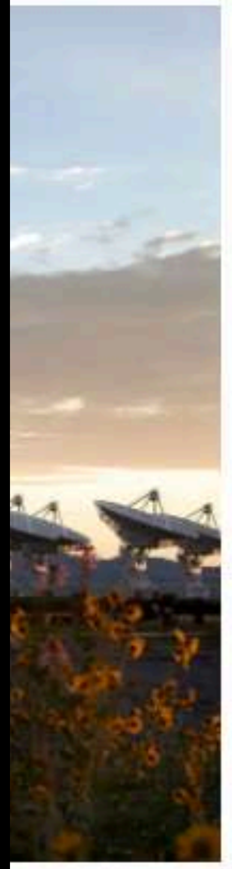
Four in

Galaxy

@elle.cordova

ers

num
rmassive



telescopes
/AUI/NSF

Summary 1

- **Creating ToAs (from data), and comparing these to parameter-based timing models, allow you to compute accurate timing parameters**

- **If pulsar is in a binary this includes computing Keplerian parameters (over time) and (over longer time) some post-Keplerian parameters (which depends on the system)**

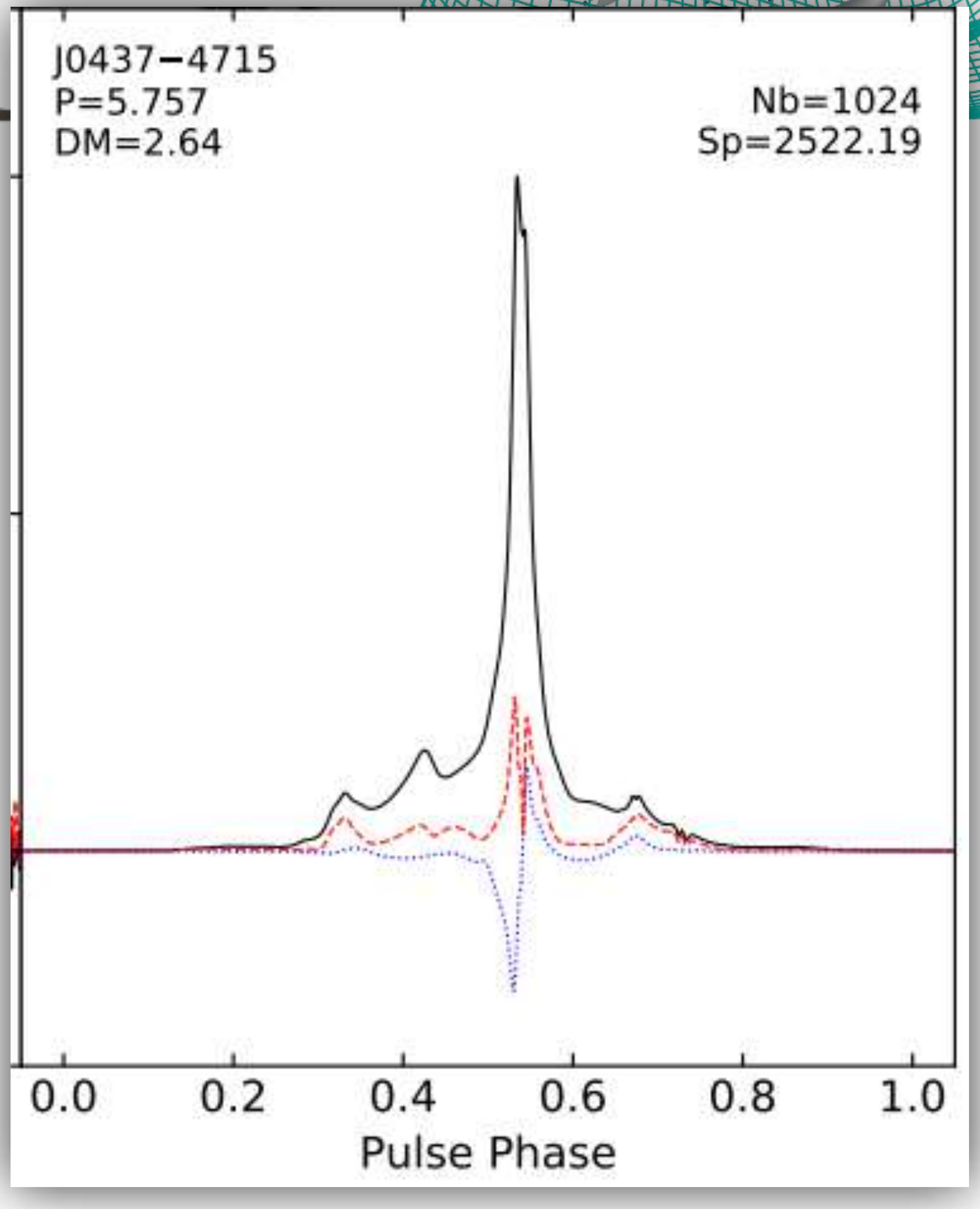
Timing parameters, especially Post-Keplerian tells us about all sorts of Fundamental Physics, including

- Pb-dot: evidence for GW emission via orbital decay
- Shapiro delay: allows you to weigh pulsars (EoS; — divide between BHs and NS?)
- PK parameters: 2PK+ tests of Gravity theories
- Whole array of precisely timed pulsars - nanoHz GW evidence

Precise timing models are phase connected

pulsar timing - *n.* the unambiguous accounting of each and every rotation of a neutron star

James McKee (IPTA 2019)

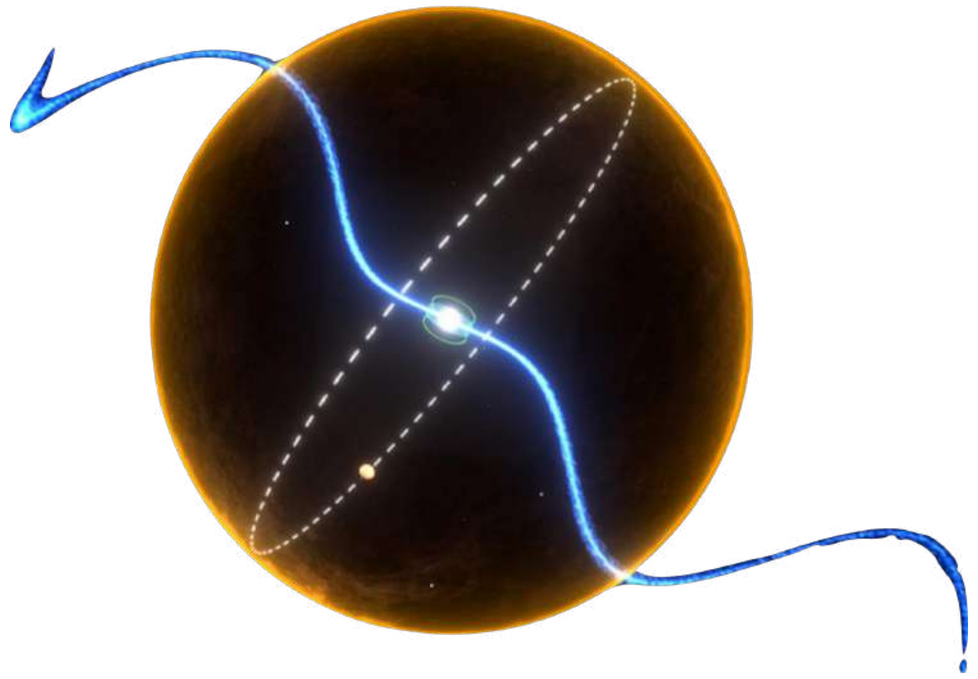


The Meertime programme started timing PSR J0437-4715 on 26 March 2019

pulse period ~5.757 ms

From noon 12:00:00:00000 on 26 March 2019, until

Until 15:00:00 - when you sign off for the day today,



MEERTIME

Precise timing models are phase connected

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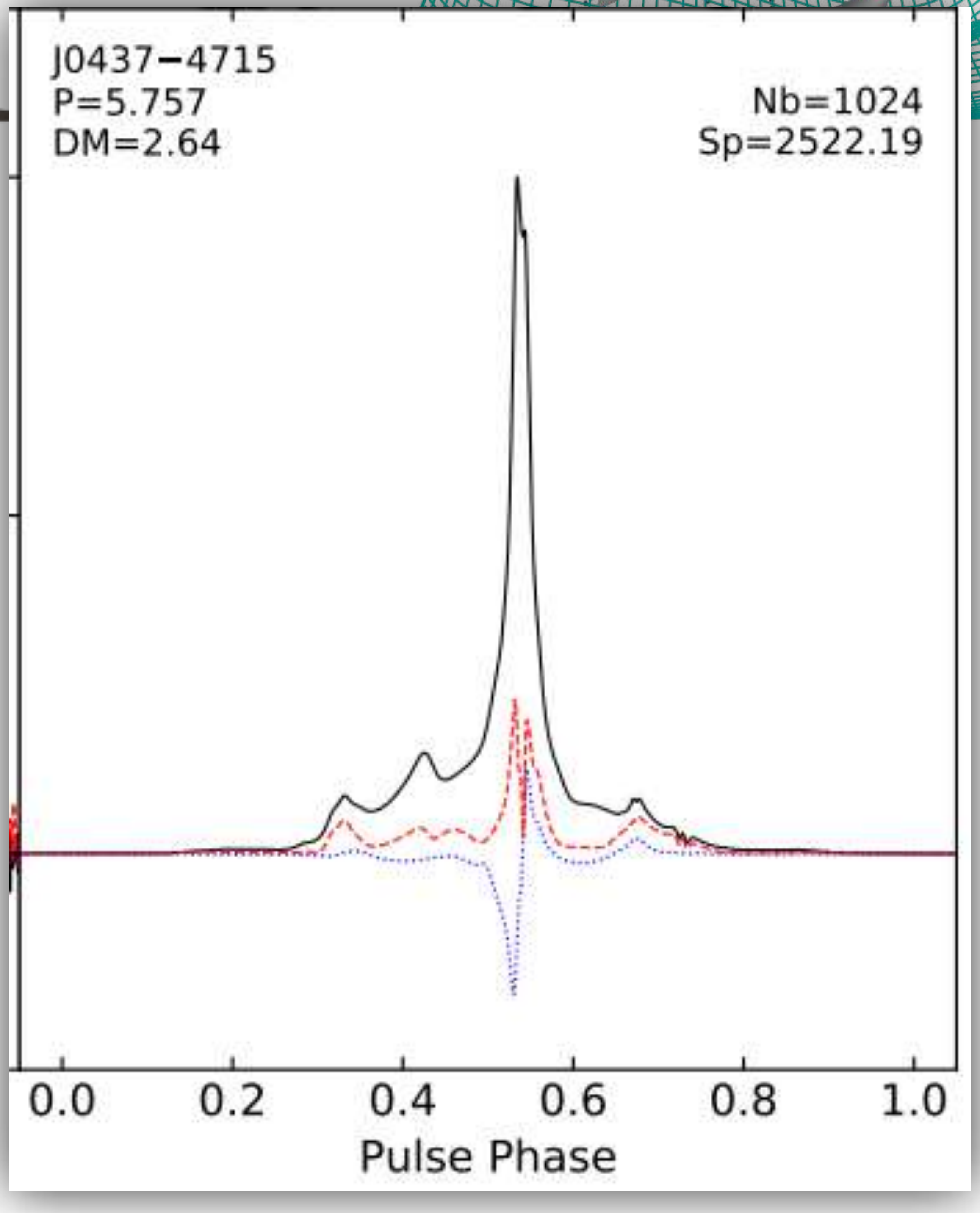

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we can show that the pulsar has made ***exactly 20 936 838 100 +/- 0*** *rotations*

MEERTIME

Precise timing models are phase connected

pulsar timing - *n.* the unambiguous accounting of each and every rotation of a neutron star

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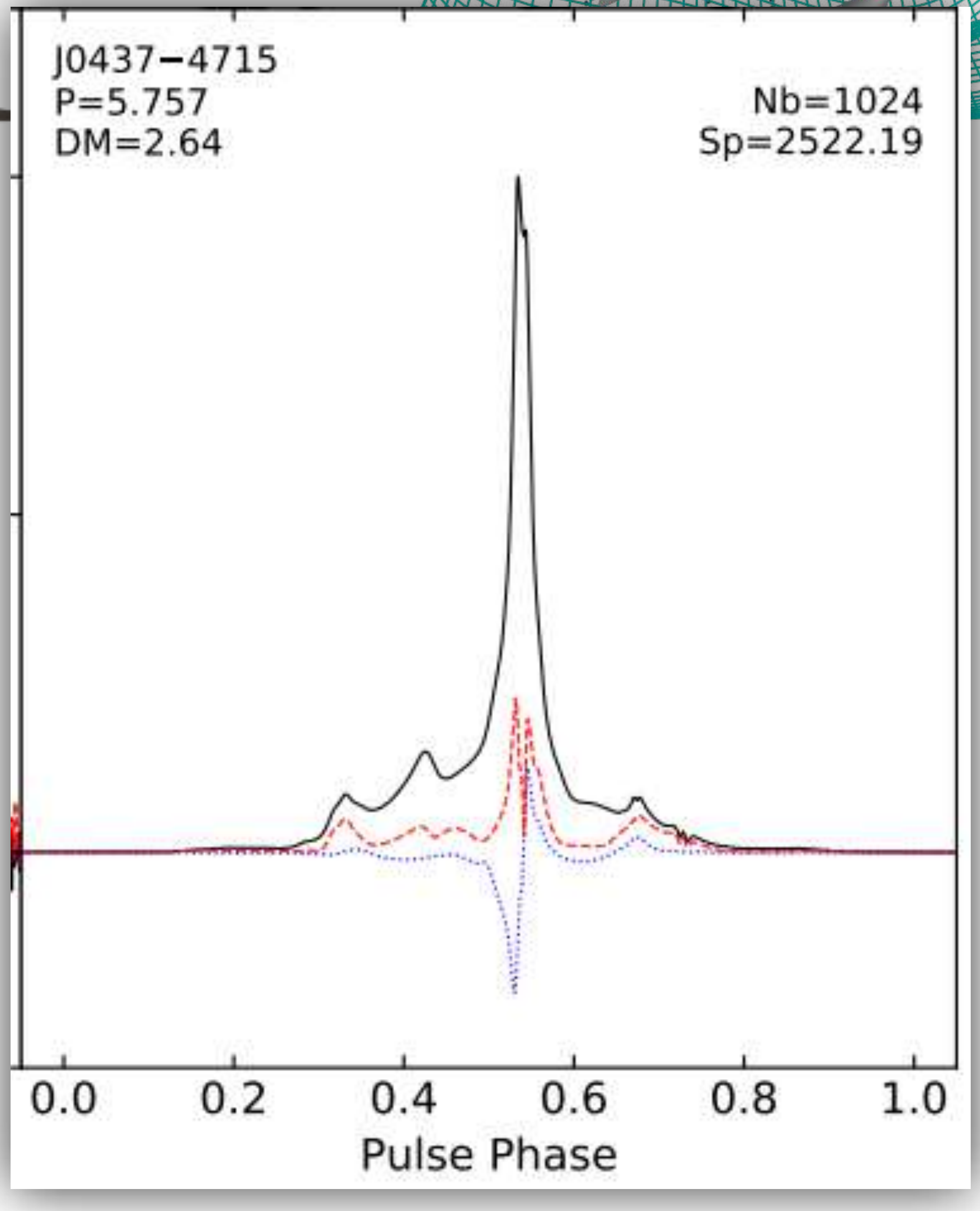

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Until 15:00:00 on 19 January 2023

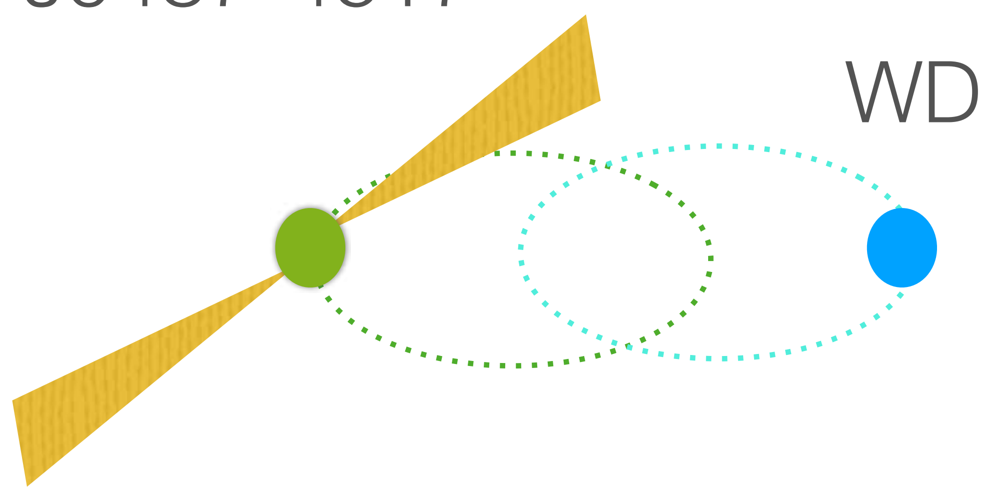
we can show that the pulsar has made ***exactly 20 936 838 100 +/- 0*** *rotations*

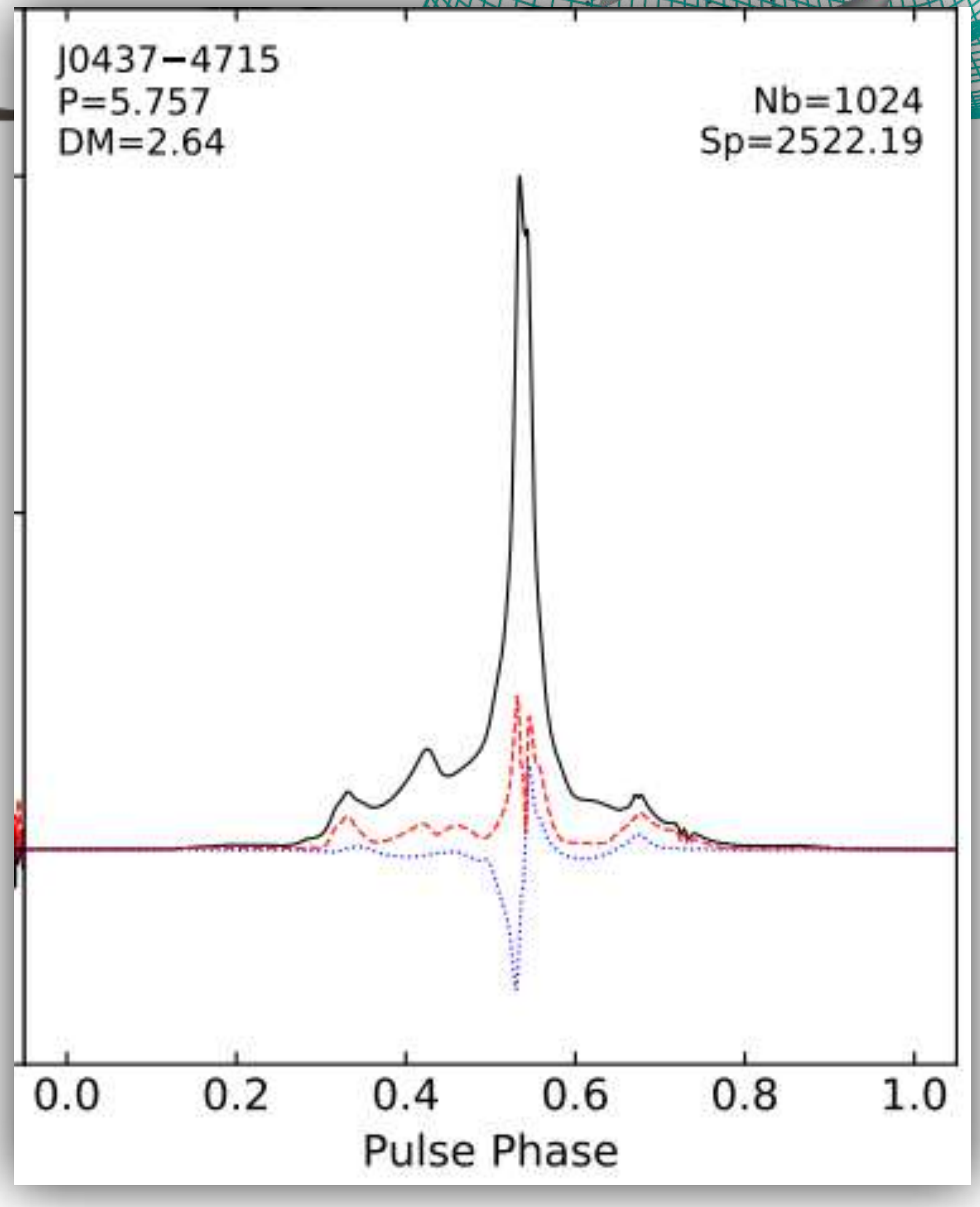
This is phase connection … we are 100% sure we haven't missed a single beat!

This is the process of obtaining an accurate timing model.
And it can only be done by monitoring the pulsar over longer time scales.

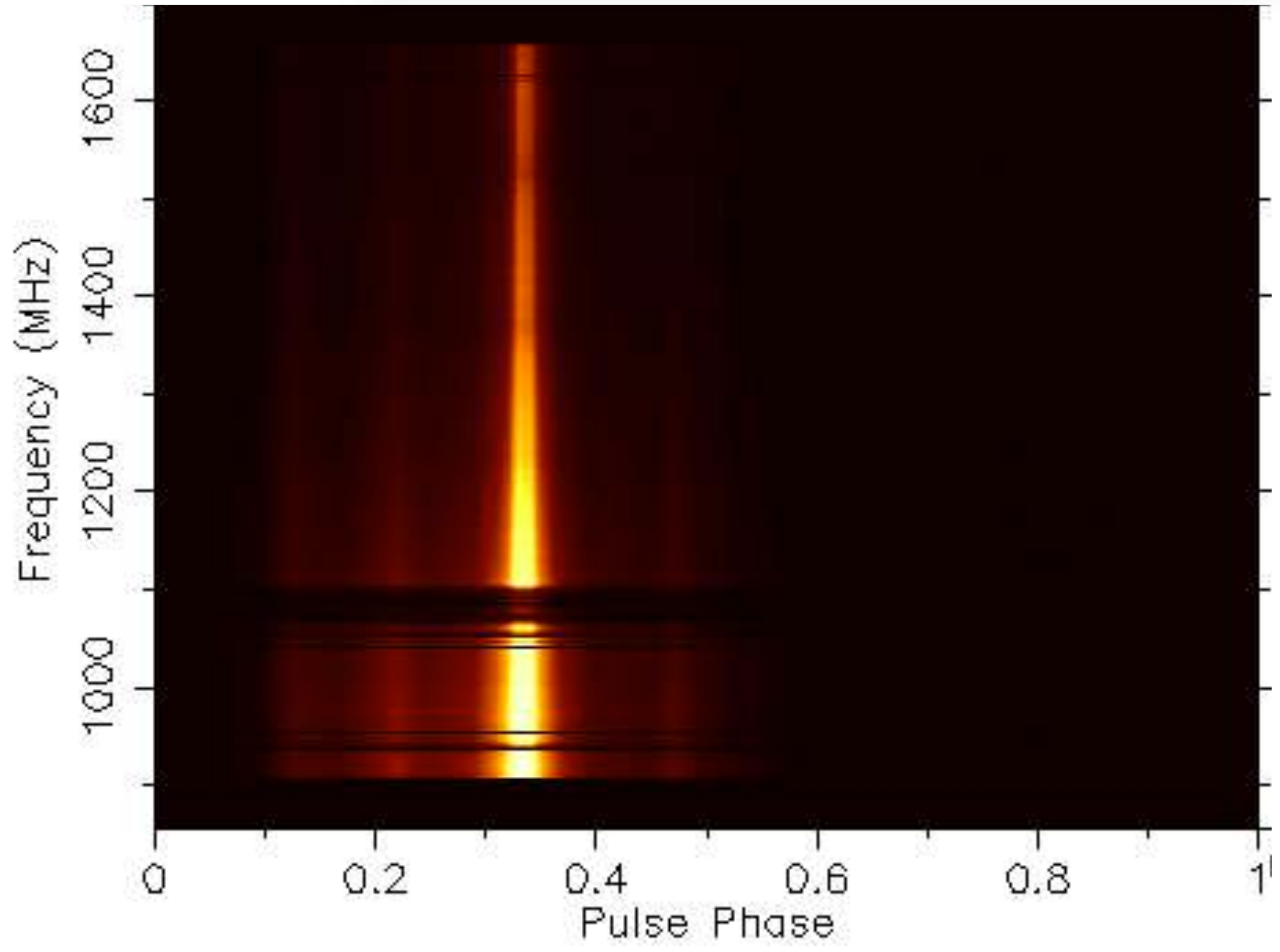
MEERTIME

Phase connected timing models can produce incredibly precise parameters!



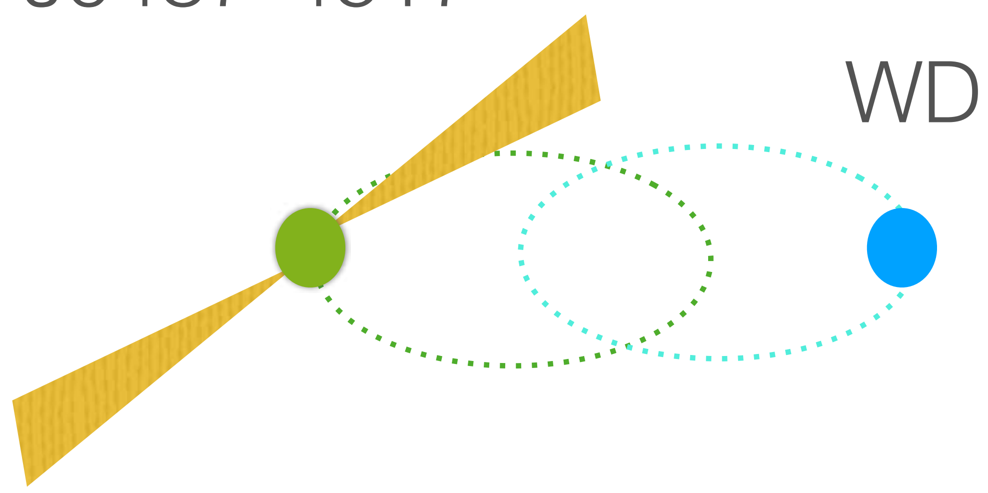


Verbiest et al. 2008,
Spiewak et al. 2022



J0437-4715 Pulse period: 5.75745192436213 ms

Phase connected timing models can produce incredibly precise parameters!



Verbiest et al. 2008,
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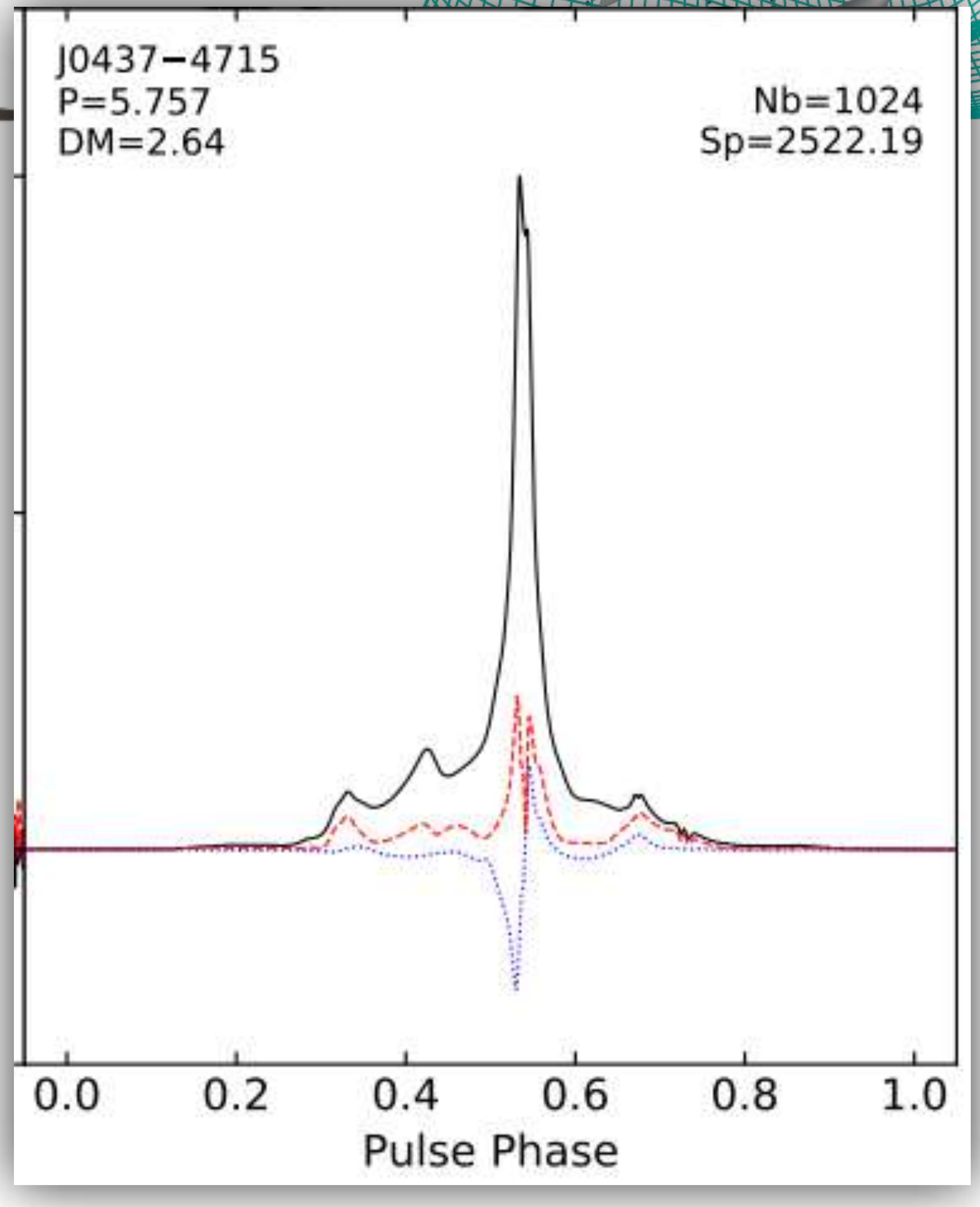
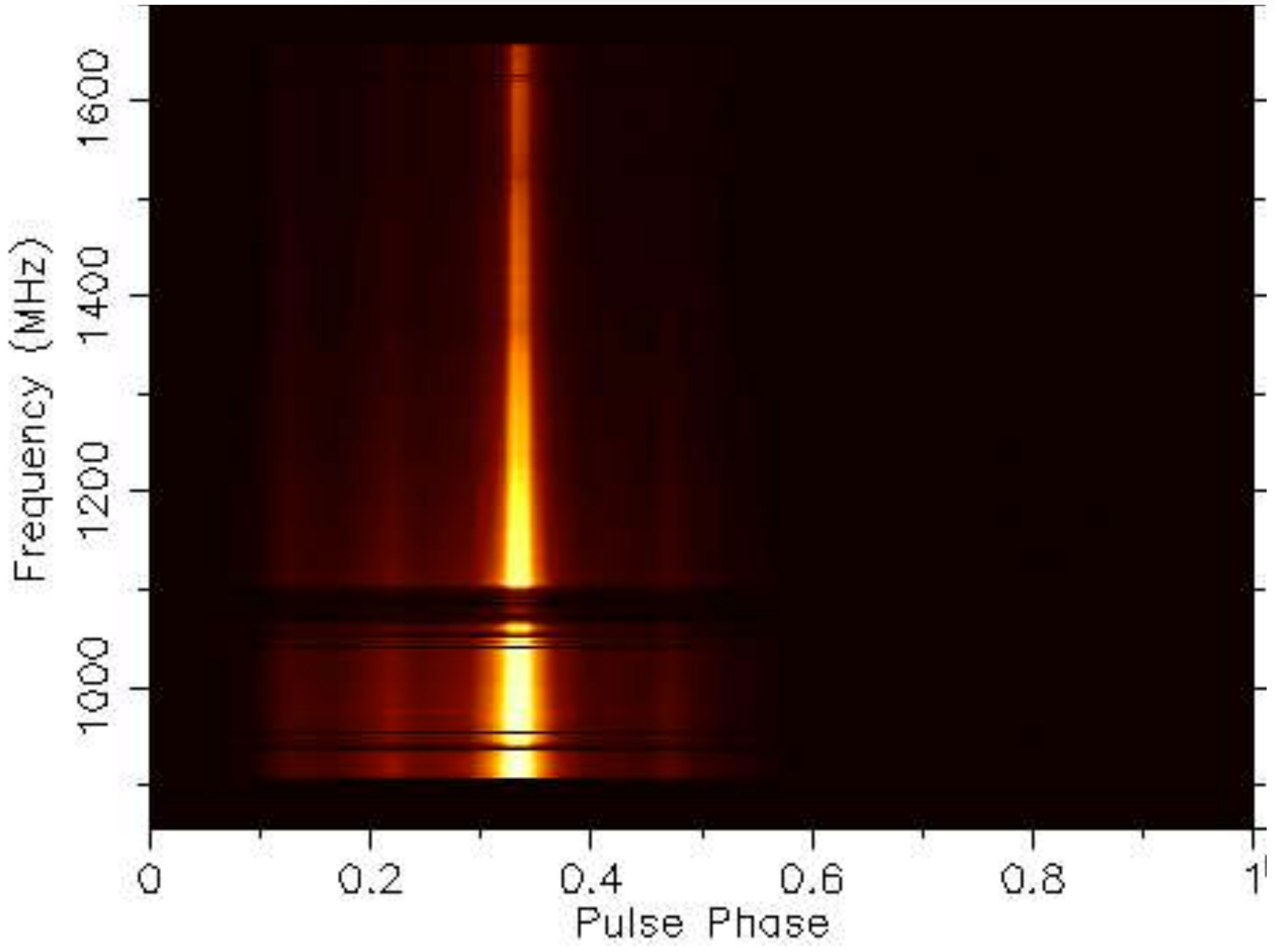
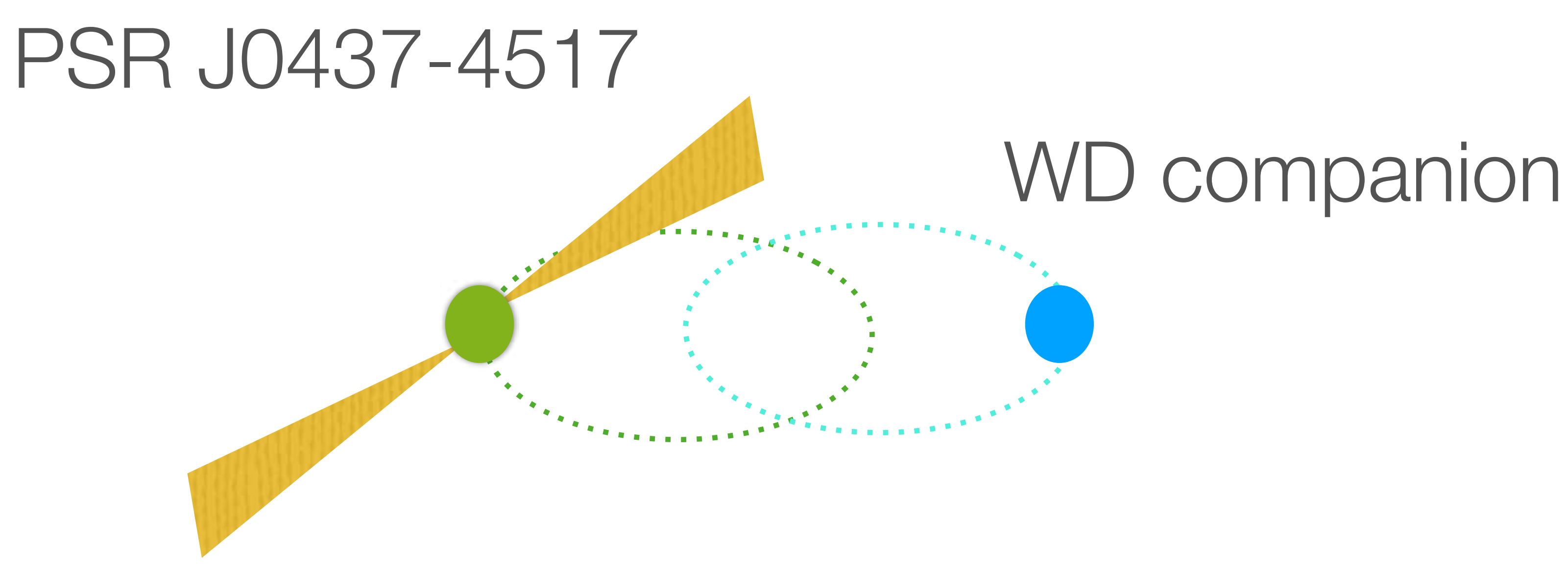


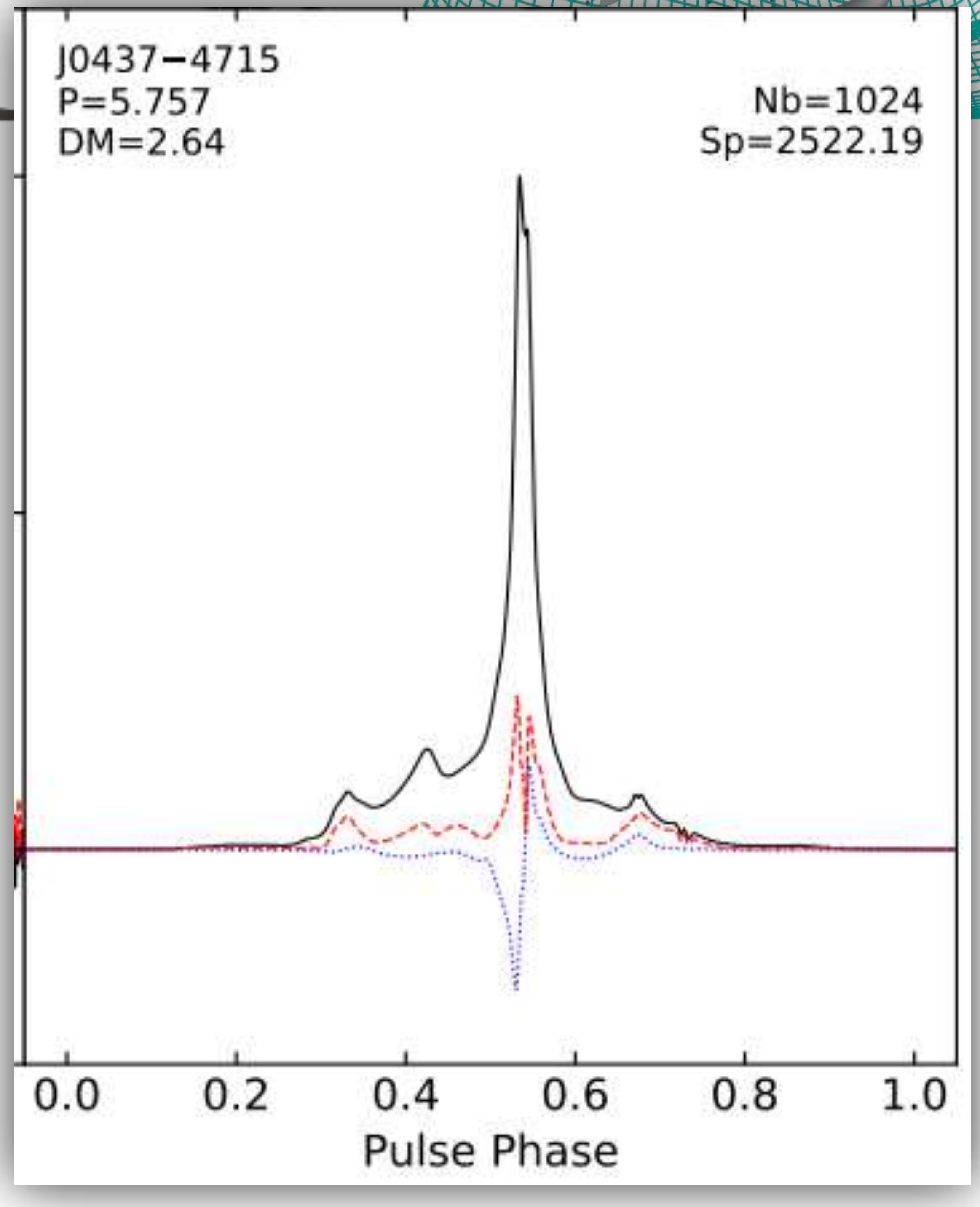


J0437-4715 Pulse period: 5.75745192436137(2) ms

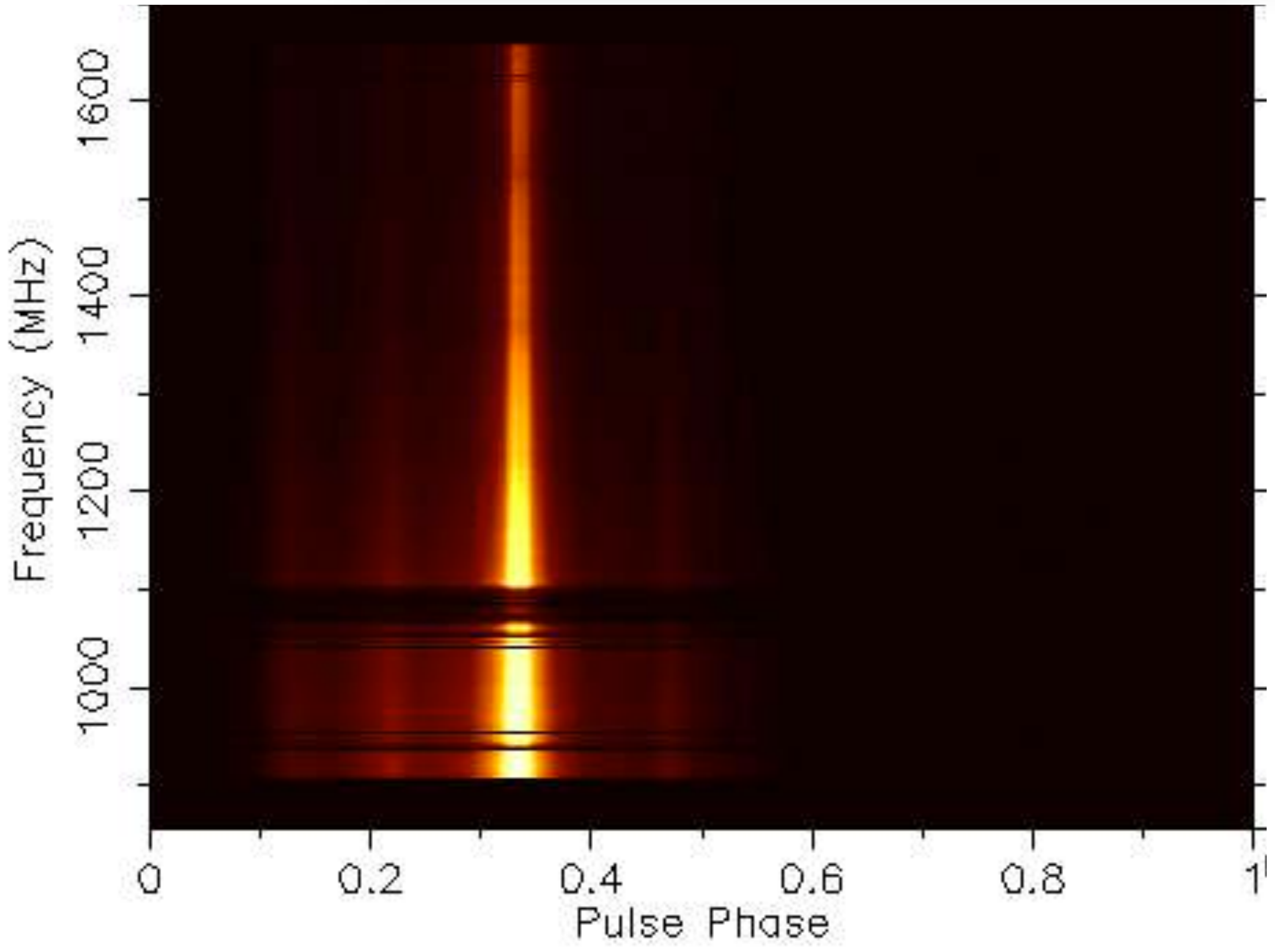
Phase connected timing models can produce incredibly precise parameters!



Right ascension, α . . . . $04^h37^m15^s.8147635(3)$
Declination, δ . . . . $-47°15'08''624170(3)$
Proper motion in α, μ_α (mas yr^{-1}) . . . 121.453(1)
Proper motion in δ, μ_δ (mas yr^{-1}) . . . −71.457(1)
Pulse period, P (ms) . . . . 5.757451924362137(2)
Pulse period derivative, $\dot{P}$ (10^{-20}) . . . . 5.729370(2)
Orbital period, Pb (days) . . . . 5.74104646(11)
Orbital period derivative, $\dot{P}_b$ (10^{-12}) . . . 3.73(2)
Parallax distance, D_π (pc) . . . . 127.6(11)
Projected semi-major axis, x (s) . . . . . 3.36669708(11)
Longitude of periastron, ω_0 (°) . . . . . 1.2224(36)
Orbital eccentricity, (10^{-5}) . . . . 1.9180(3)



Verbiest et al. 2008, Spiewak et al. 2022



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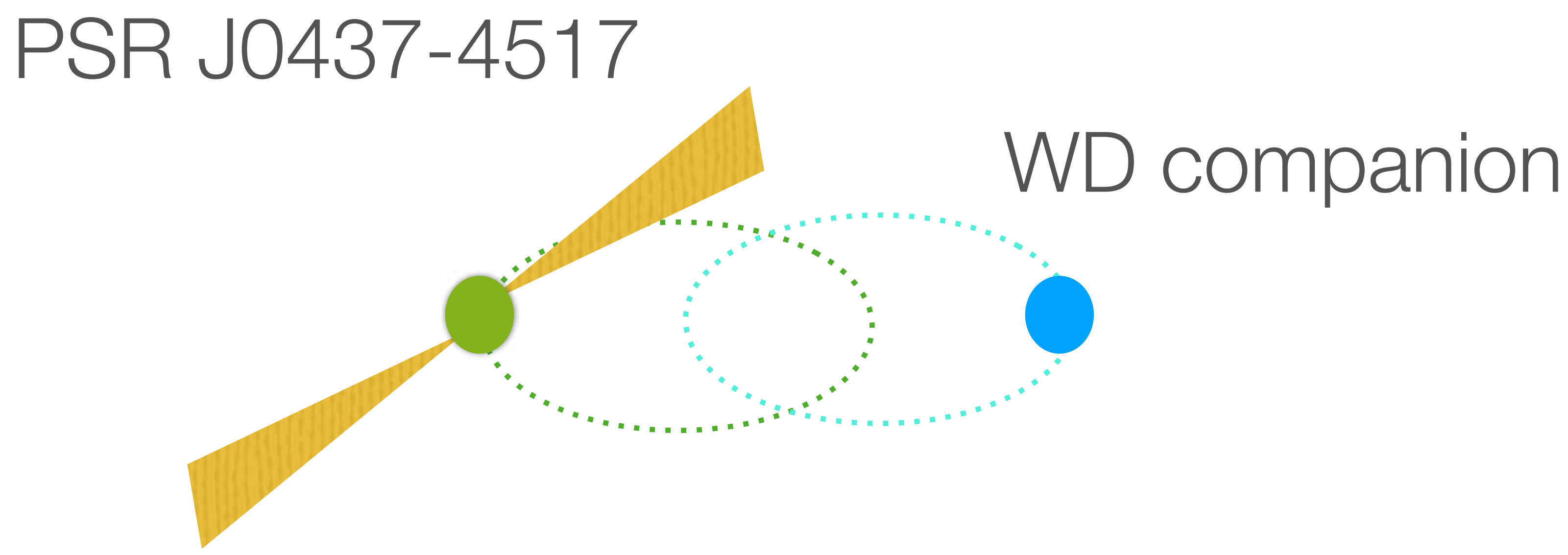
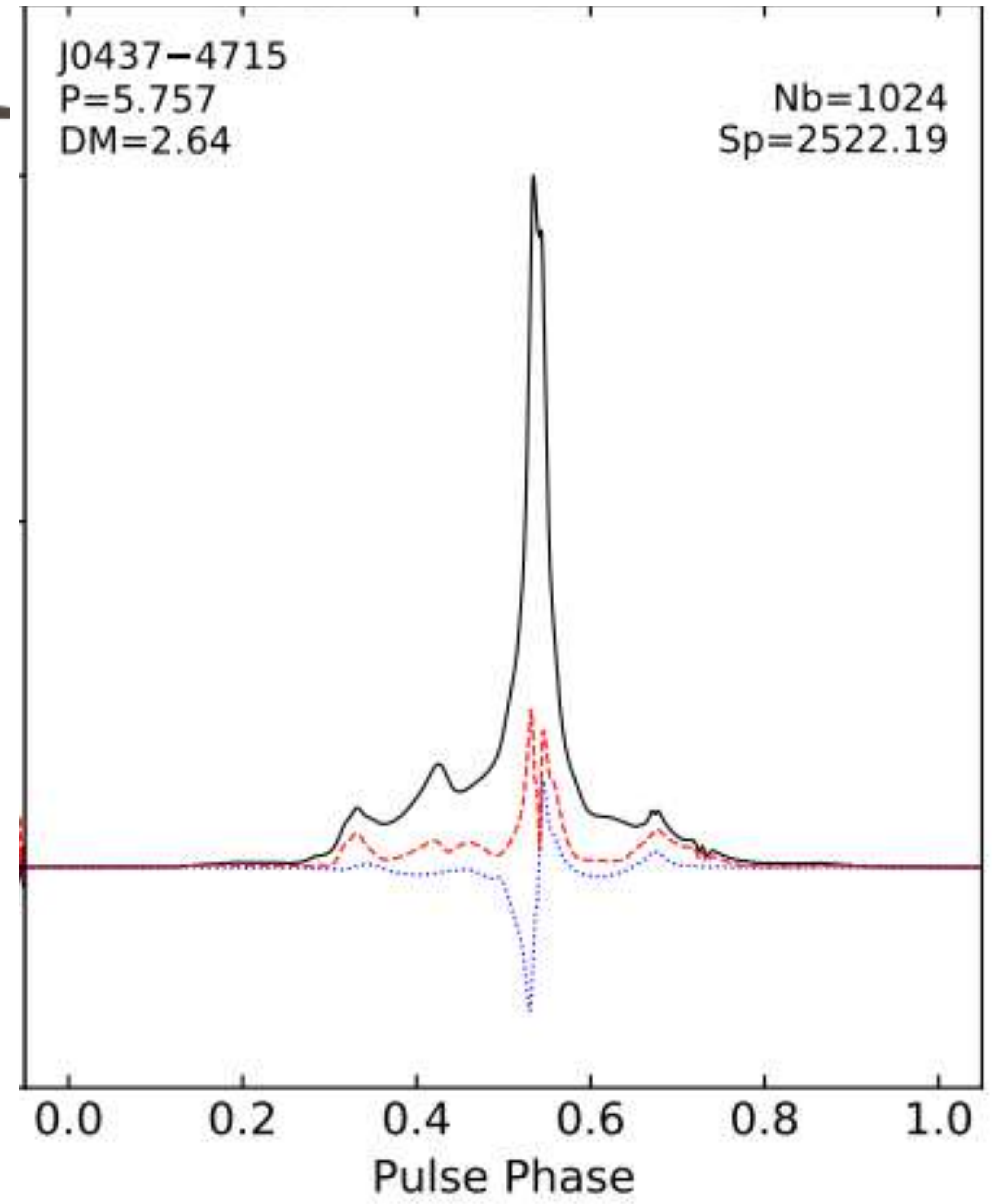
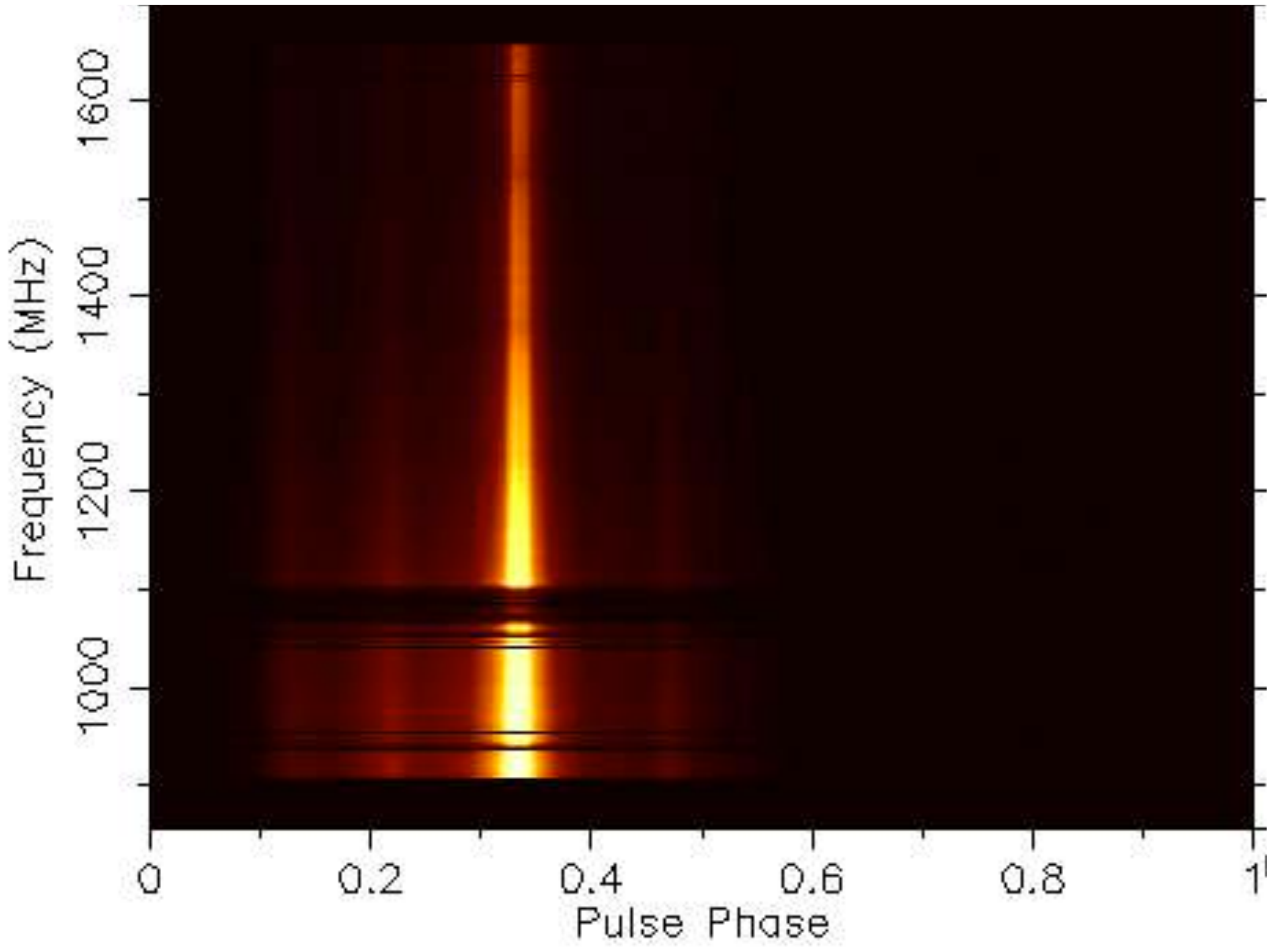


At ~ 4 x 10^{15} km away we are measuring orbital sizes with precision of ~ 30 meters!



Verbiest et al. 2008,
Spiewak et al. 2022



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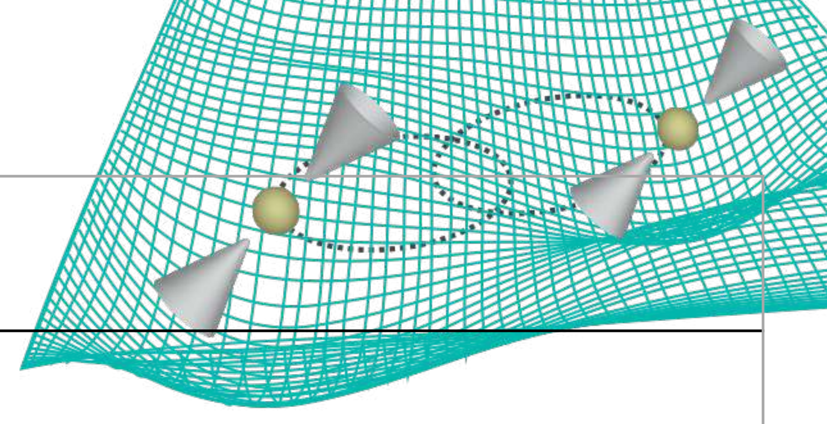

Time scale	Parameter	Requirements
Discovery	Position: ~ RA, DEC (to the size of the beam, ~few arcsec) Dispersion measure (DM) Pulse period (P0) at discovery (same as F0: spin frequency)	
Immediate follow-up (~weeks after discovery)	Binary confirmation (if you see P0 modulation) Orbital period (PB) up to order of magnitude (days/weeks/months)	
Few months regular observing	Isolated: Spin-down frequency (F1) or pulse period derivative (P1, Pdot) Binary: Solved binary orbit: PB, projected semi-major axis (A1 sin(i)), epoch of periastron (T0) Eccentricity (ecc, E) , Longitude of periastron (omega)	If the spin-down rate is high, as for a young pulsar Only if system is highly eccentric
One year	RA, DEC to < arcsec position Pdot/F1 for MSP binary	
One year+	Post-Keplerian parameters Orbital precession (OMDOT) Orbital decay (PBDOT) Orbital inclination (INC) — solving the geometry Mass of the companion (M2)	M2, INC: Requires orbital campaigns with high sensitivity across superior conjunction
Mutiple years	Parallax (PX) and therefore possible distance estimates	Provide pulsar is close (< 1kpc)
Mutiple years	Underlying noise processes: red-noise, DM-noise	

Step-by-Step timing

The softwares for the tasks

psrchive

- read metadata (psrstat)
- correct dispersion (pam -D)
- remove RFI (paz)
- reduce data resolutions (pam -f; pam -t, pam -b, pam -p)
- display data (psrplot)
- combine data (psradd)
- compute arrival times (pat)

tempo2

fitting and updating timing models
(aiming for phase connection and low residuals)

MEERTIME

PSRCHIVE

lives here:
`http://psrchive.sourceforge.net`

git:
`https://git.code.sf.net/p/psrchive/code`

maintainers: Willem van Straten, Stefan Osłowski, Aiden Hotan, Paul Demorest and others

Hotan et al. (2004); van Straten et al. (2012, 2011); van Straten (2013, 2006); van Straten et al. (2010)

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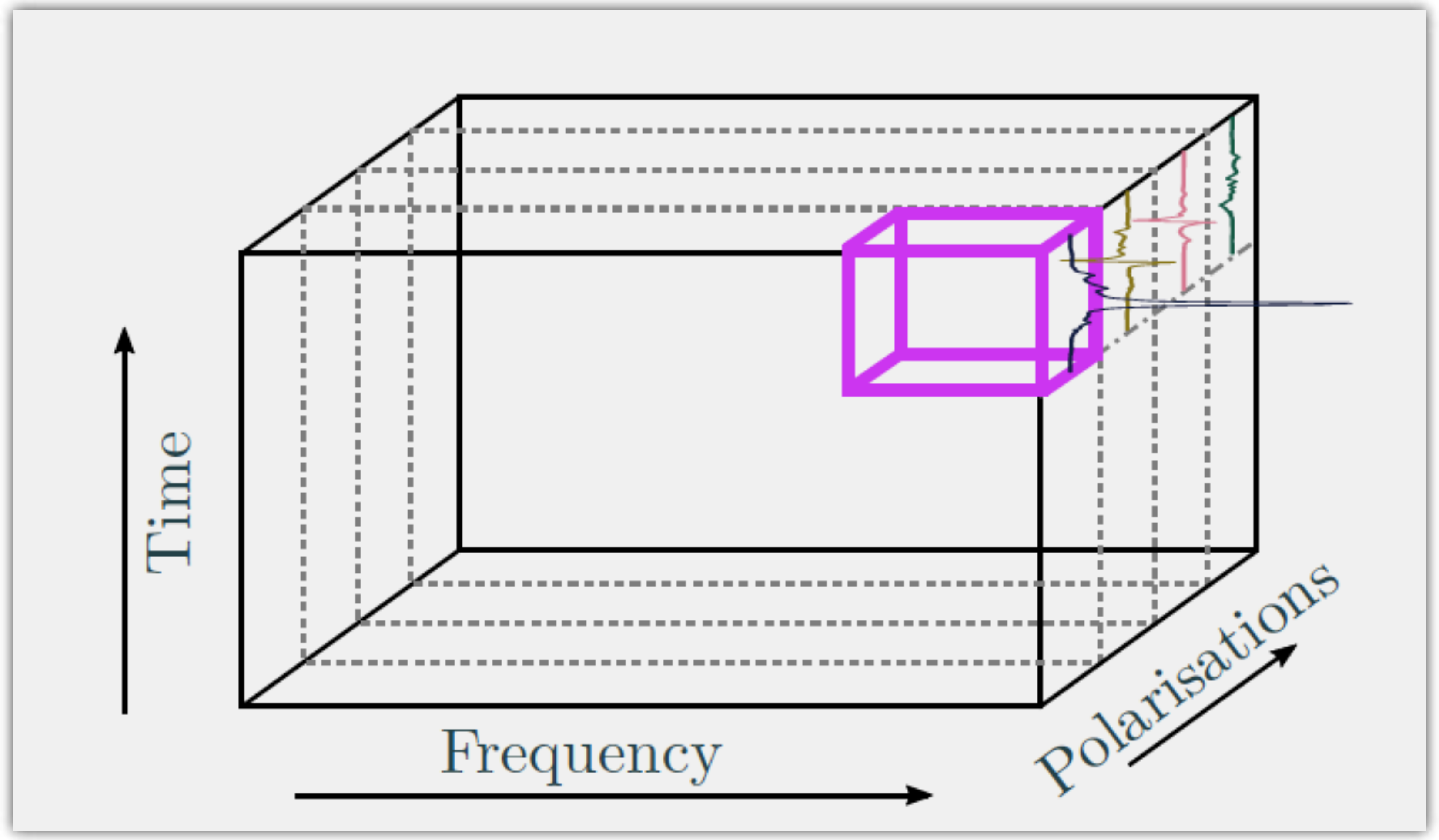
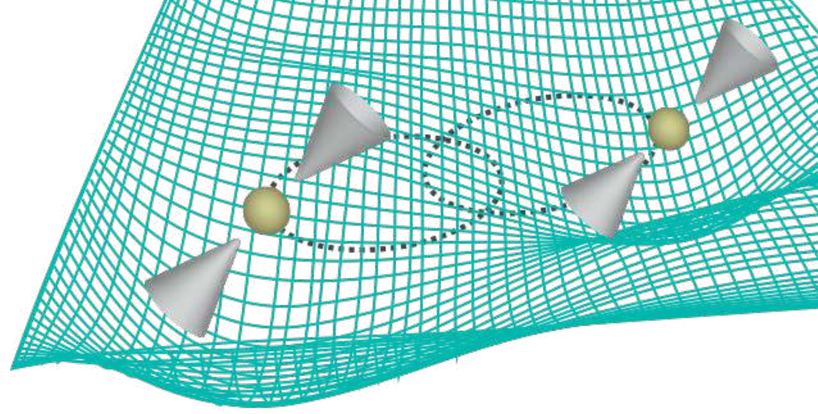
Hotan et al. (2004); van Straten et al. (2012, 2011); van Straten (2013, 2006); van Straten et al. (2010)

psrchive data cube (archive file; .ar)



credit: Golam Shaifullah



Step-by-Step timing

1. Create a Timing Template

Create high S/N standard – often with same frequency resolution (#channels) as data from which want to create Time of Arrival (ToA) values

Please add them → `psradd` | output filename: `-o J0955-6150.add` | `*.ar` → the pulsar data/ archive files (*.ar)

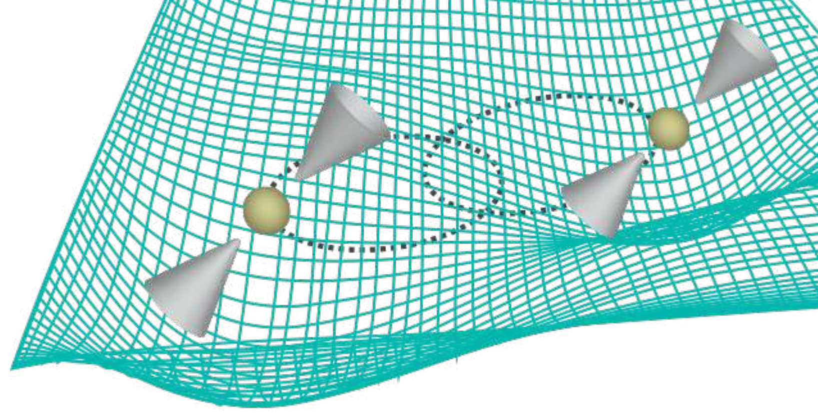
```
psradd -o J0955-6150.add *.ar
```

```
psrstat -c nchan -c nsubint -c npol -c nbin -c dmc J0955-6150.add
```

OUT: J0955-6150.add nchan=1024 nsubint=22 npol=1 nbin=1024 dmc=0

MEERTIME

Step-by-Step timing



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```

```
psrstat -c nchan -c nsubint -c npol -c nbin -c dmc J0955-6150.add
```

OUT: J0955-6150.add nchan=1024 nsubint=22 npol=1 nbin=1024 dmc=0

Choose e.g. 8 frequency channels for template (f: 1024/128 = 8)

```
pam -jDT -f 128 -e addch8 J0955-6150.add
```

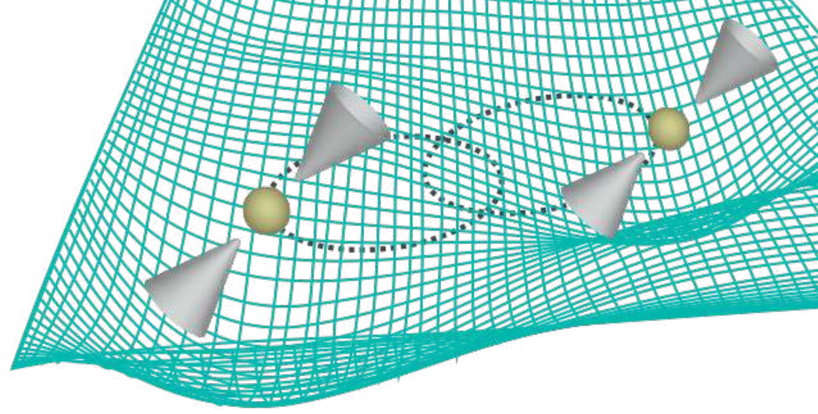
OUT: J0955-6150.add.ch8 written to disk, with

```
psredit -c nchan -c nsubint -c npol -c nbin -c dmc J0955-6150.addch8
```

OUT: J0955-6150.addch8 **nchan=8** nsubint=1 npol=1 nbin=1024 dmc=1

MEERTIME

Step-by-Step timing



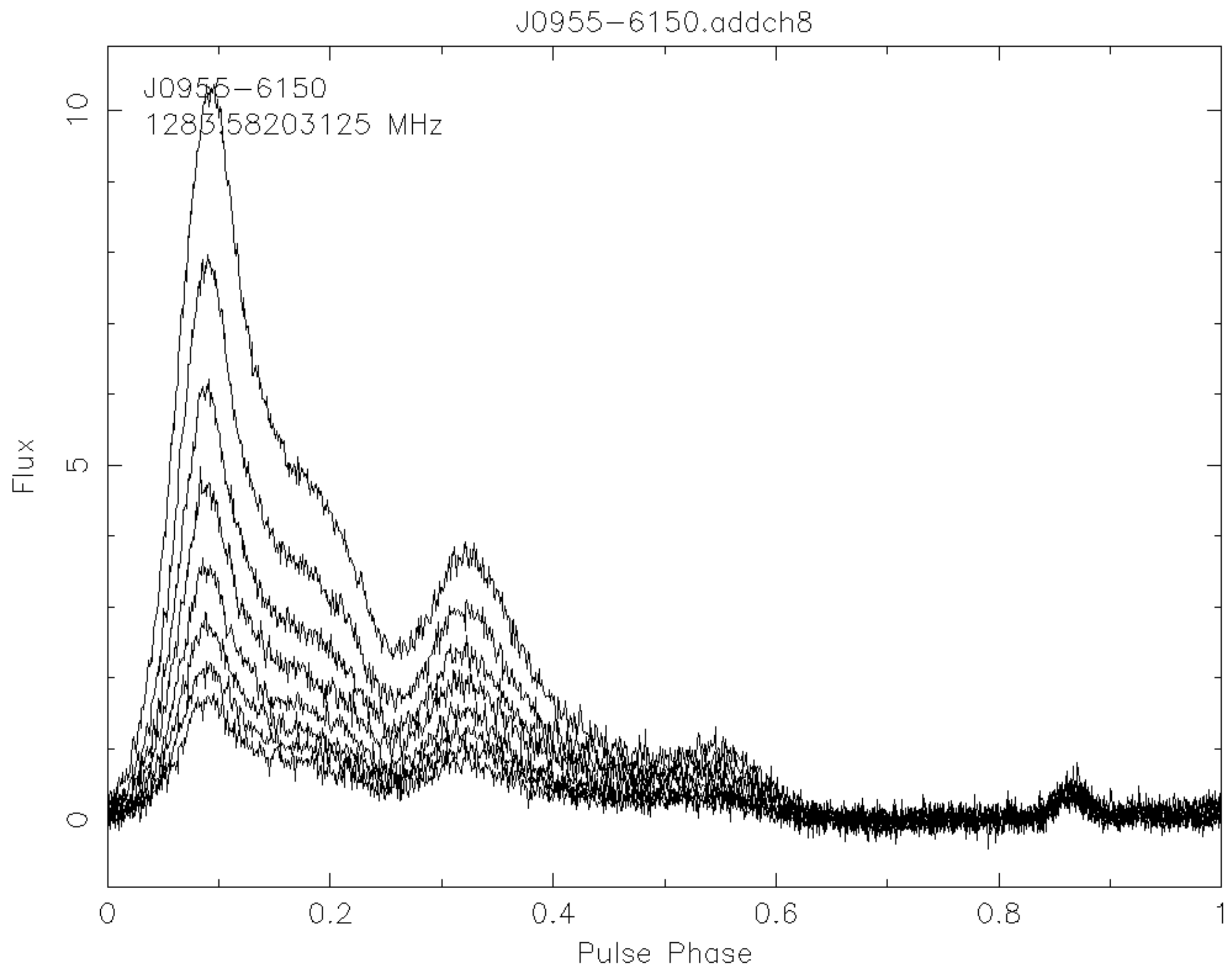
1. Create a Timing Template

Starting with 8-channel (one subint, DM-corrected) data,

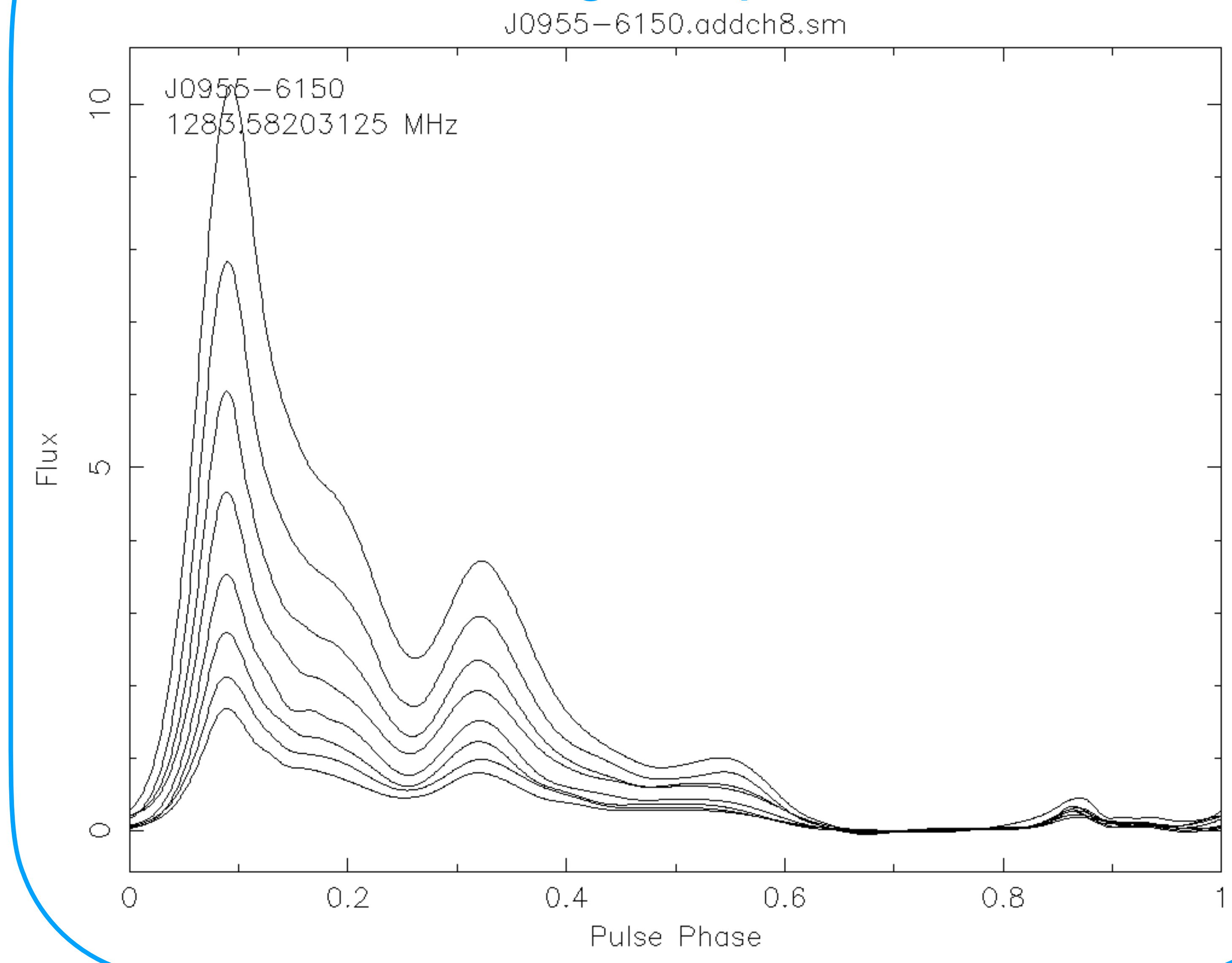
J0955-6150.addch8

we can change this into an analytical (noise-free) template by smoothing it

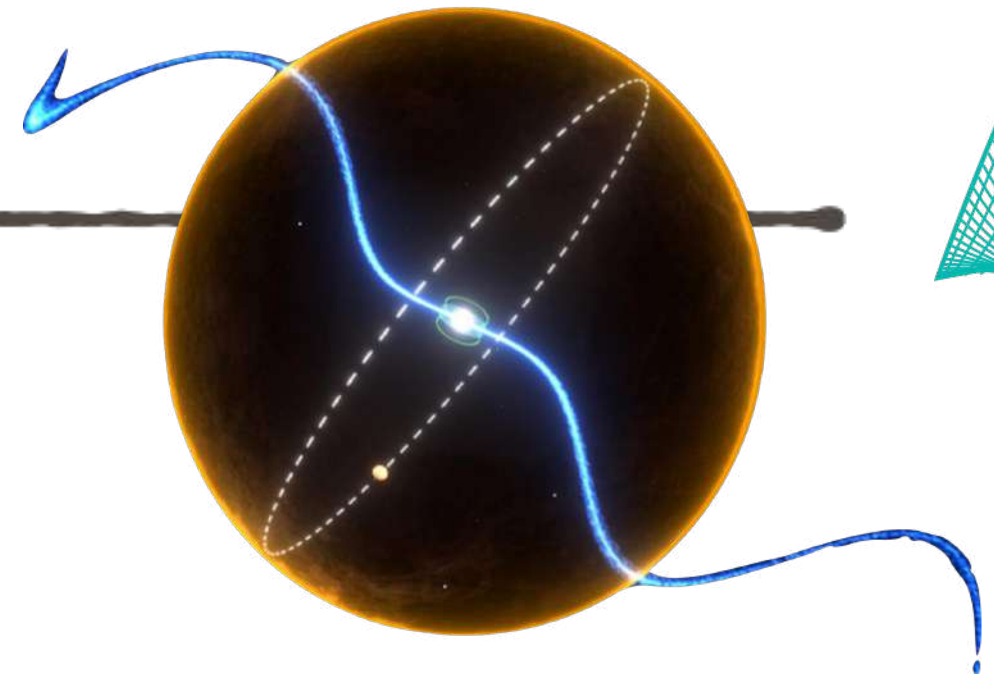
psrsmooth -W J0955-6150.addch8
OUT: J0955-6150.addch8.sm

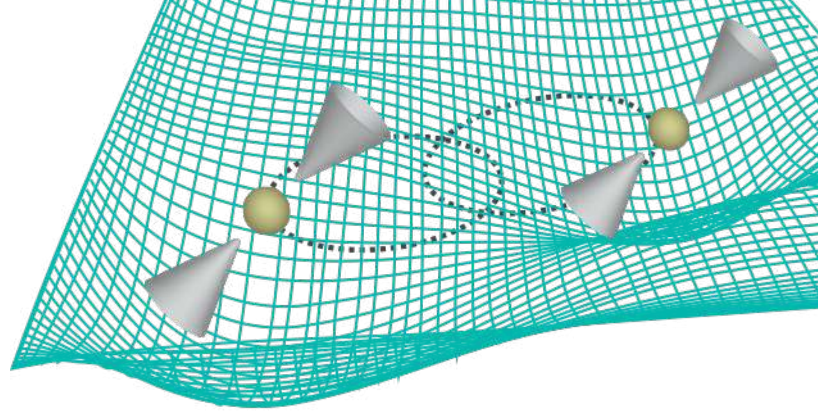


Smoothed timing template or standard



Step-by-Step timing





2. Finding Time of Arrival (ToA) values

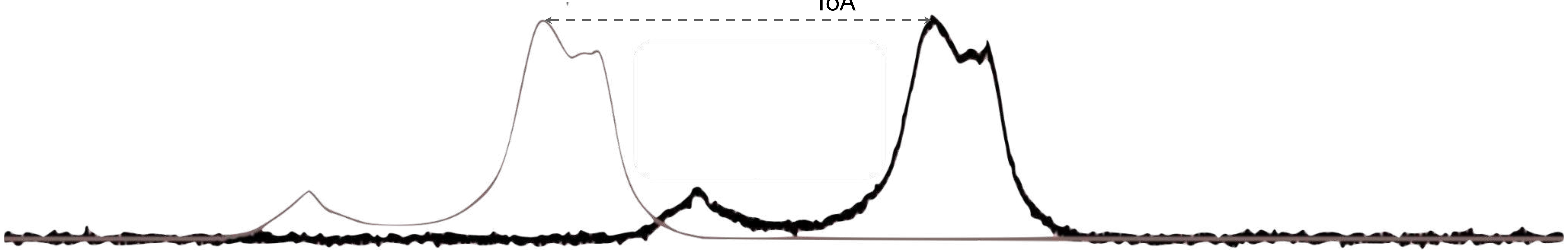
MEERTIME

Cross correlate our noise-free (8-channel) templates, with (8-channel) pulsar data archives, to obtain a ToA value per channel and time-block pair

ToAs are expressed in decimal MJD values

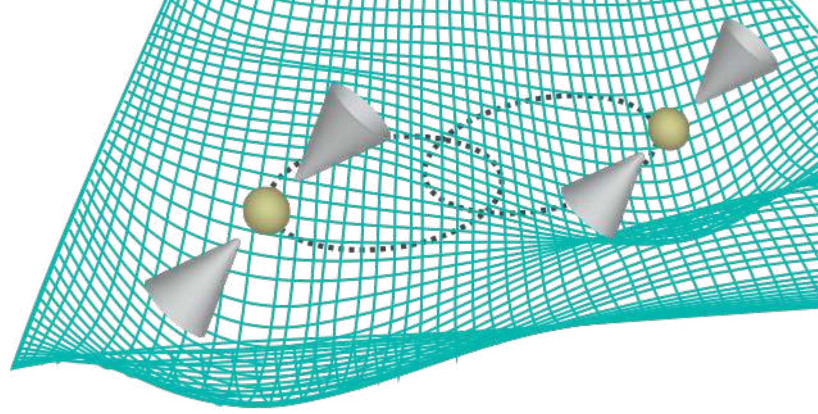
E.g. For a freq channel, and for an time-block (subintegration), do cross-correlation (template matching) to obtain a single ToA for that data

Repeat for other channels and epochs



ToA = P * ϕ
where ϕ is when template and data matches best

Step-by-Step timing



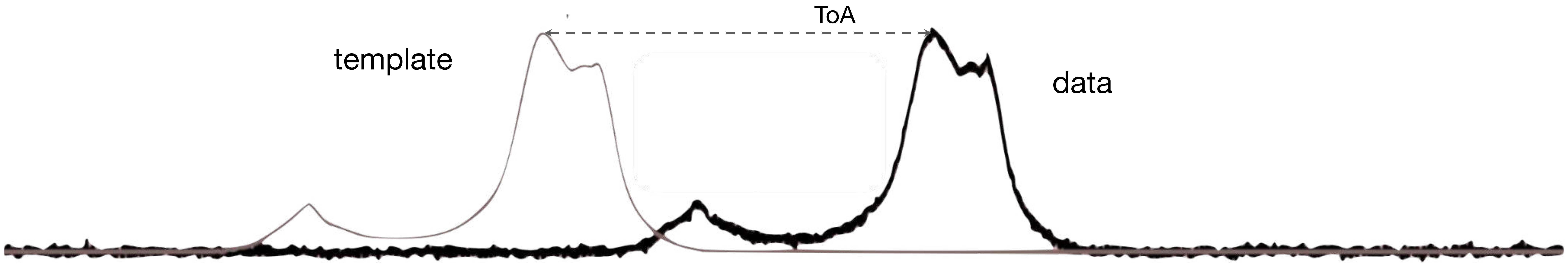
2. Computing Time of Arrival (ToA) values

MEERTIME

Software implemented to do so,

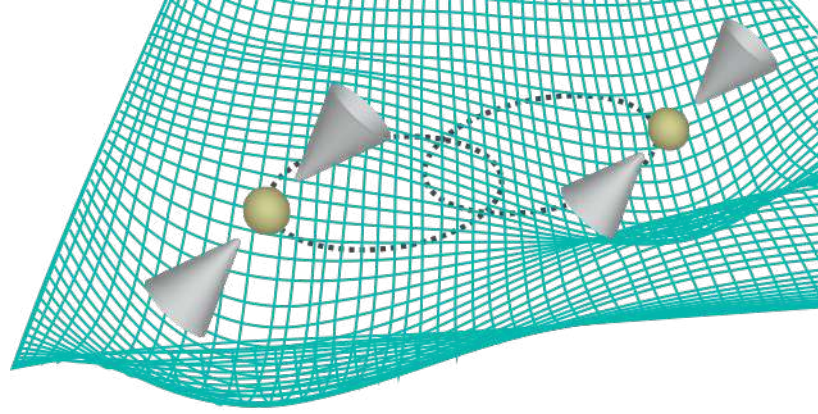
pat -s J0955-6150.addch8.sm *ch8.ar

the pulsar data/archive files (*.ar), RFI-cleaned, each with several time-blocks (subintegrations)



ToA = P * ϕ
where ϕ is when template and data matches best, relative to obs starting time

Step-by-Step timing



2. Computing Time of Arrival (ToA) values

Software implemented to do so,

pat -s J0955-6150.addch8.sm *ch8.ar > J0955-6150.tim

archive filename

frequency ToA (MJD) ToA_err << ------------------------------info flags------------------------------>>

```
ar   943.74347200  58623.68441813688988873 0.66300 meerkat -fe KAT -bk MKAT_L -be MKBF -f KAT_MKBF -bw 96.97 -tobs 1016 -tmplt J0955-6150_L_2D.stdD
ar  1039.99182800  58623.68441813263950735 0.72800 meerkat -fe KAT -bk MKAT_L -be MKBF -f KAT_MKBF -bw 96.97 -tobs 1016 -tmplt J0955-6150_L_2D.stdD
ar  1136.77198900  58623.68441812499021282 0.92300 meerkat -fe KAT -bk MKAT_L -be MKBF -f KAT_MKBF -bw 96.97 -tobs 1016 -tmplt J0955-6150_L_2D.stdD
ar  1233.27556000  58623.68441812824990222 1.18000 meerkat -fe KAT -bk MKAT_L -be MKBF -f KAT_MKBF -bw 96.97 -tobs 1016 -tmplt J0955-6150_L_2D.stdD
ar  1332.08500600  58623.68441811988757806 1.20400 meerkat -fe KAT -bk MKAT_L -be MKBF -f KAT_MKBF -bw 96.97 -tobs 1016 -tmplt J0955-6150_L_2D.stdD
ar  1429.10217800  58623.68441812721205153 1.64200 meerkat -fe KAT -bk MKAT_L -be MKBF -f KAT_MKBF -bw 96.97 -tobs 1016 -tmplt J0955-6150_L_2D.stdD
ar  1523.60311000  58623.68441813515844530 2.19100 meerkat -fe KAT -bk MKAT_L -be MKBF -f KAT_MKBF -bw 96.97 -tobs 1016 -tmplt J0955-6150_L_2D.stdD
ar  1624.53619800  58623.68441812787044043 2.74100 meerkat -fe KAT -bk MKAT_L -be MKBF -f KAT_MKBF -bw 96.97 -tobs 1016 -tmplt J0955-6150_L_2D.stdD
ar   943.83245800  58665.49118814866917759 2.00200 meerkat -fe KAT -bk MKAT_L -be MKBF -f KAT_MKBF -bw 96.97 -tobs 257.53 -tmplt J0955-6150_L_2D.stdD

ar  1040.02028200  58665.49118814572594260 2.38200 meerkat -fe KAT -bk MKAT_L -be MKBF -f KAT_MKBF -bw 96.97 -tobs 257.53 -tmplt J0955-6150_L_2D.stdD
ar  1135.64858100  58665.49118815039707542 3.14300 meerkat -fe KAT -bk MKAT_L -be MKBF -f KAT_MKBF -bw 96.97 -tobs 257.53 -tmplt J0955-6150_L_2D.stdD
ar  1233.99710500  58665.49118813595056210 4.57300 meerkat -fe KAT -bk MKAT_L -be MKBF -f KAT_MKBF -bw 96.97 -tobs 257.53 -tmplt J0955-6150_L_2D.stdD
ar  1332.13489600  58665.49118813309923581 4.68900 meerkat -fe KAT -bk MKAT_L -be MKBF -f KAT_MKBF -bw 96.97 -tobs 257.53 -tmplt J0955-6150_L_2D.stdD
ar  1429.09486100  58665.49118814083961837 6.33400 meerkat -fe KAT -bk MKAT_L -be MKBF -f KAT_MKBF -bw 96.97 -tobs 257.53 -tmplt J0955-6150_L_2D.stdD
ar  1523.24035200  58665.49118815036622365 8.81500 meerkat -fe KAT -bk MKAT_L -be MKBF -f KAT_MKBF -bw 96.97 -tobs 257.53 -tmplt J0955-6150_L_2D.stdD
ar  1624.64204800  58665.49118814107604081 8.90400 meerkat -fe KAT -bk MKAT_L -be MKBF -f KAT_MKBF -bw 96.97 -tobs 257.53 -tmplt J0955-6150_L_2D.stdD

ar   944.06110100  58683.66935835761604423 0.69700 meerkat -fe KAT -bk MKAT_L -be MKBF -f KAT_MKBF -bw 96.97 -tobs 2044 -tmplt J0955-6150_L_2D.stdD
ar  1040.58087200  58683.66935835124873577 0.84000 meerkat -fe KAT -bk MKAT_L -be MKBF -f KAT_MKBF -bw 96.97 -tobs 2044 -tmplt J0955-6150_L_2D.stdD
ar  1134.88975500  58683.66935834845932263 1.13100 meerkat -fe KAT -bk MKAT_L -be MKBF -f KAT_MKBF -bw 96.97 -tobs 2044 -tmplt J0955-6150_L_2D.stdD
ar  1232.42194200  58683.66935836216639544 1.44600 meerkat -fe KAT -bk MKAT_L -be MKBF -f KAT_MKBF -bw 96.97 -tobs 2044 -tmplt J0955-6150_L_2D.stdD
ar  1332.14735700  58683.66935834636886682 1.31200 meerkat -fe KAT -bk MKAT_L -be MKBF -f KAT_MKBF -bw 96.97 -tobs 2044 -tmplt J0955-6150_L_2D.stdD
… … … …
```

Step-by-Step timing

2. Computing Time of Arrival (ToA) values

Software implemented to do so,

pat -s J0955-6150.addch8.sm *ch8.ar > J0955-6150.tim

archive filename	frequency	ToA (MJD)	ToA_err	<< ---info flags--->>
ar	943.74347200	58623.684418136889888873	0.66300	meerkat -fe KAT -bk MKAT_L -be MKBF -f KAT_MKBF -bw 96.97 -tobs 1016 -tmplt J0955-6150_L_2D.stdD
ar	1039.99182800	58623.6844181326395073 5	0.72800	meerkat -fe KAT -bk MKAT_L -be MKBF -f KAT_MKBF -bw 96.97 -tobs 1016 -tmplt J0955-6150_L_2D.stdD
ar	1136.77198900	58623.6844181249902128 2	0.92300	meerkat -fe KAT -bk MKAT_L -be MKBF -f KAT_MKBF -bw 96.97 -tobs 1016 -tmplt J0955-6150_L_2D.stdD
ar	1233.27556000	58623.6844181282499022 2	1.18000	meerkat -fe KAT -bk MKAT_L -be MKBF -f KAT_MKBF -bw 96.97 -tobs 1016 -tmplt J0955-6150_L_2D.stdD
ar	1332.08500600	58623.6844181198875780 6	1.20400	meerkat -fe KAT -bk MKAT_L -be MKBF -f KAT_MKBF -bw 96.97 -tobs 1016 -tmplt J0955-6150_L_2D.stdD
ar	1429.10217800	58623.6844181272120515 3	1.64200	meerkat -fe KAT -bk MKAT_L -be MKBF -f KAT_MKBF -bw 96.97 -tobs 1016 -tmplt J0955-6150_L_2D.stdD
ar	1523.60311000	58623.6844181351584453 0	2.19100	meerkat -fe KAT -bk MKAT_L -be MKBF -f KAT_MKBF -bw 96.97 -tobs 1016 -tmplt J0955-6150_L_2D.stdD
ar	1624.53619800	58623.6844181278704404 3	2.74100	meerkat -fe KAT -bk MKAT_L -be MKBF -f KAT_MKBF -bw 96.97 -tobs 1016 -tmplt J0955-6150_L_2D.stdD
ar	943.83245800	58665.4911881486691775 9	2.00200	meerkat -fe KAT -bk MKAT_L -be MKBF -f KAT_MKBF -bw 96.97 -tobs 257.53 -tmplt J0955-6150_L_2D.stdD
ar	1040.02028200	58665.4911881457259426 0	2.38200	meerkat -fe KAT -bk MKAT_L -be MKBF -f KAT_MKBF -bw 96.97 -tobs 257.53 -tmplt J0955-6150_L_2D.stdD
ar	1135.64858100	58665.4911881503970754 2	3.14300	meerkat -fe KAT -bk MKAT_L -be MKBF -f KAT_MKBF -bw 96.97 -tobs 257.53 -tmplt J0955-6150_L_2D.stdD
ar	1233.99710500	58665.4911881359505621 0	4.57300	meerkat -fe KAT -bk MKAT_L -be MKBF -f KAT_MKBF -bw 96.97 -tobs 257.53 -tmplt J0955-6150_L_2D.stdD
ar	1332.13489600	58665.4911881330992358 1	4.68900	meerkat -fe KAT -bk MKAT_L -be MKBF -f KAT_MKBF -bw 96.97 -tobs 257.53 -tmplt J0955-6150_L_2D.stdD
ar	1429.09486100	58665.4911881408396183 7	6.33400	meerkat -fe KAT -bk MKAT_L -be MKBF -f KAT_MKBF -bw 96.97 -tobs 257.53 -tmplt J0955-6150_L_2D.stdD
ar	1523.24035200	58665.4911881503662236 5	8.81500	meerkat -fe KAT -bk MKAT_L -be MKBF -f KAT_MKBF -bw 96.97 -tobs 257.53 -tmplt J0955-6150_L_2D.stdD
ar	1624.64204800	58665.4911881410760408 1	8.90400	meerkat -fe KAT -bk MKAT_L -be MKBF -f KAT_MKBF -bw 96.97 -tobs 257.53 -tmplt J0955-6150_L_2D.stdD
ar	944.06110100	58683.6693583576160442 3	0.69700	meerkat -fe KAT -bk MKAT_L -be MKBF -f KAT_MKBF -bw 96.97 -tobs 2044 -tmplt J0955-6150_L_2D.stdD
ar	1040.58087200	58683.6693583512487357 7	0.84000	meerkat -fe KAT -bk MKAT_L -be MKBF -f KAT_MKBF -bw 96.97 -tobs 2044 -tmplt J0955-6150_L_2D.stdD
ar	1134.88975500	58683.6693583484593226 3	1.13100	meerkat -fe KAT -bk MKAT_L -be MKBF -f KAT_MKBF -bw 96.97 -tobs 2044 -tmplt J0955-6150_L_2D.stdD
ar	1232.42194200	58683.6693583621663954 4	1.44600	meerkat -fe KAT -bk MKAT_L -be MKBF -f KAT_MKBF -bw 96.97 -tobs 2044 -tmplt J0955-6150_L_2D.stdD
ar	1332.14735700	58683.6693583463688668 2	1.31200	meerkat -fe KAT -bk MKAT_L -be MKBF -f KAT_MKBF -bw 96.97 -tobs 2044 -tmplt J0955-6150_L_2D.stdD
…	…	…	…	

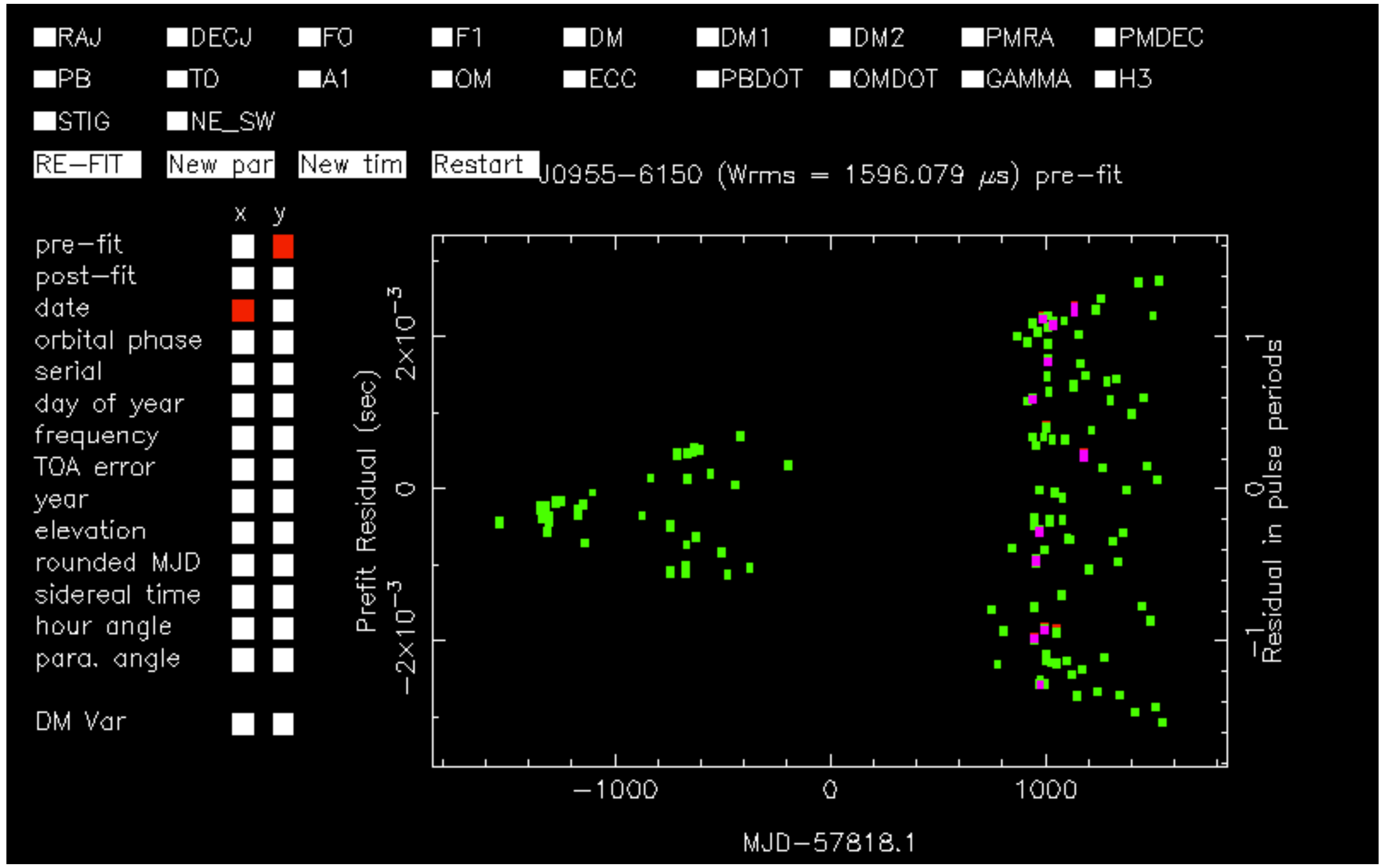
1 us ~ 1.16E-11 days
MJD decimals matter!

Step-by-Step timing

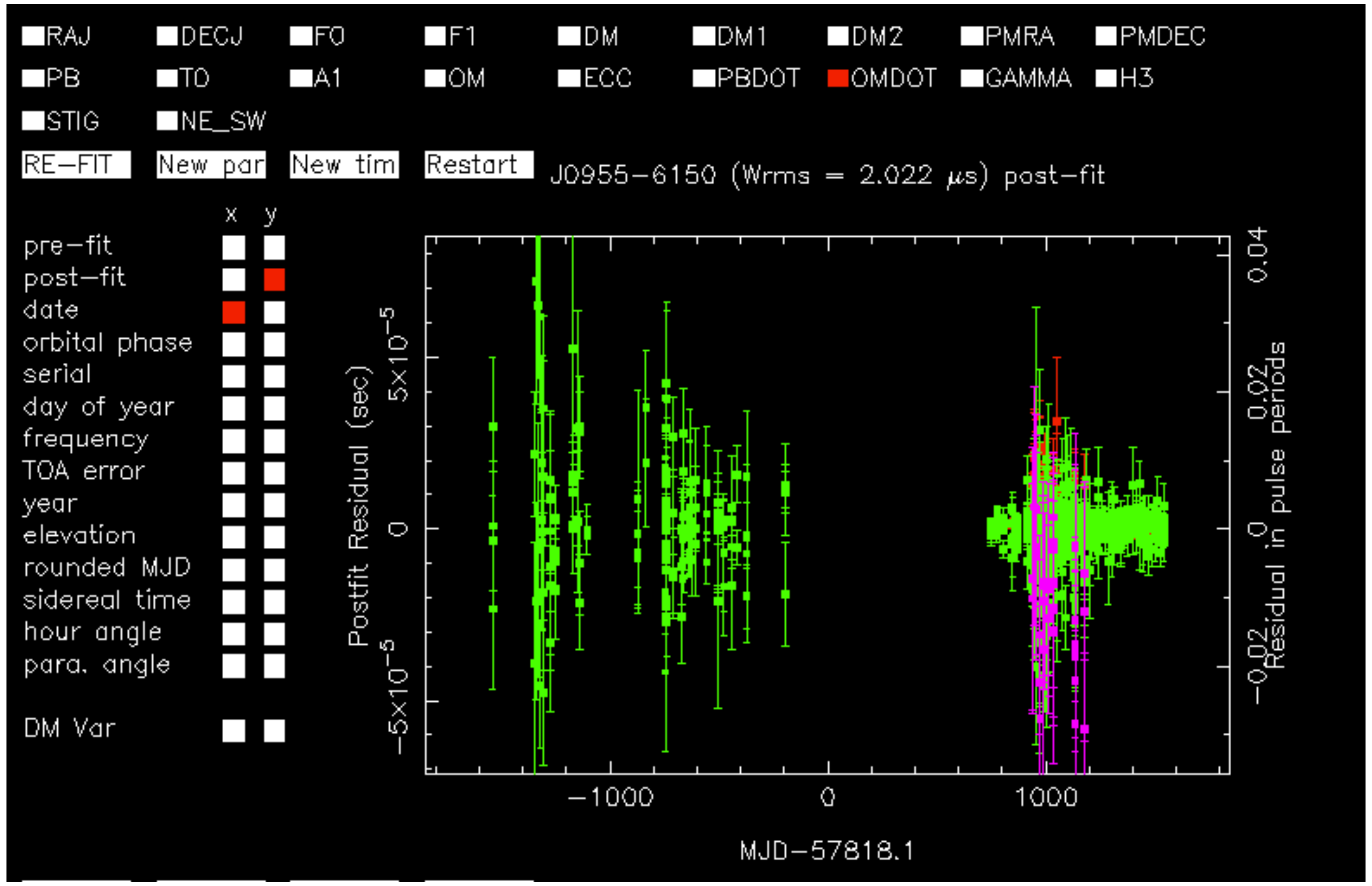
MEERTIME

3. Fitting (updating) the timing model

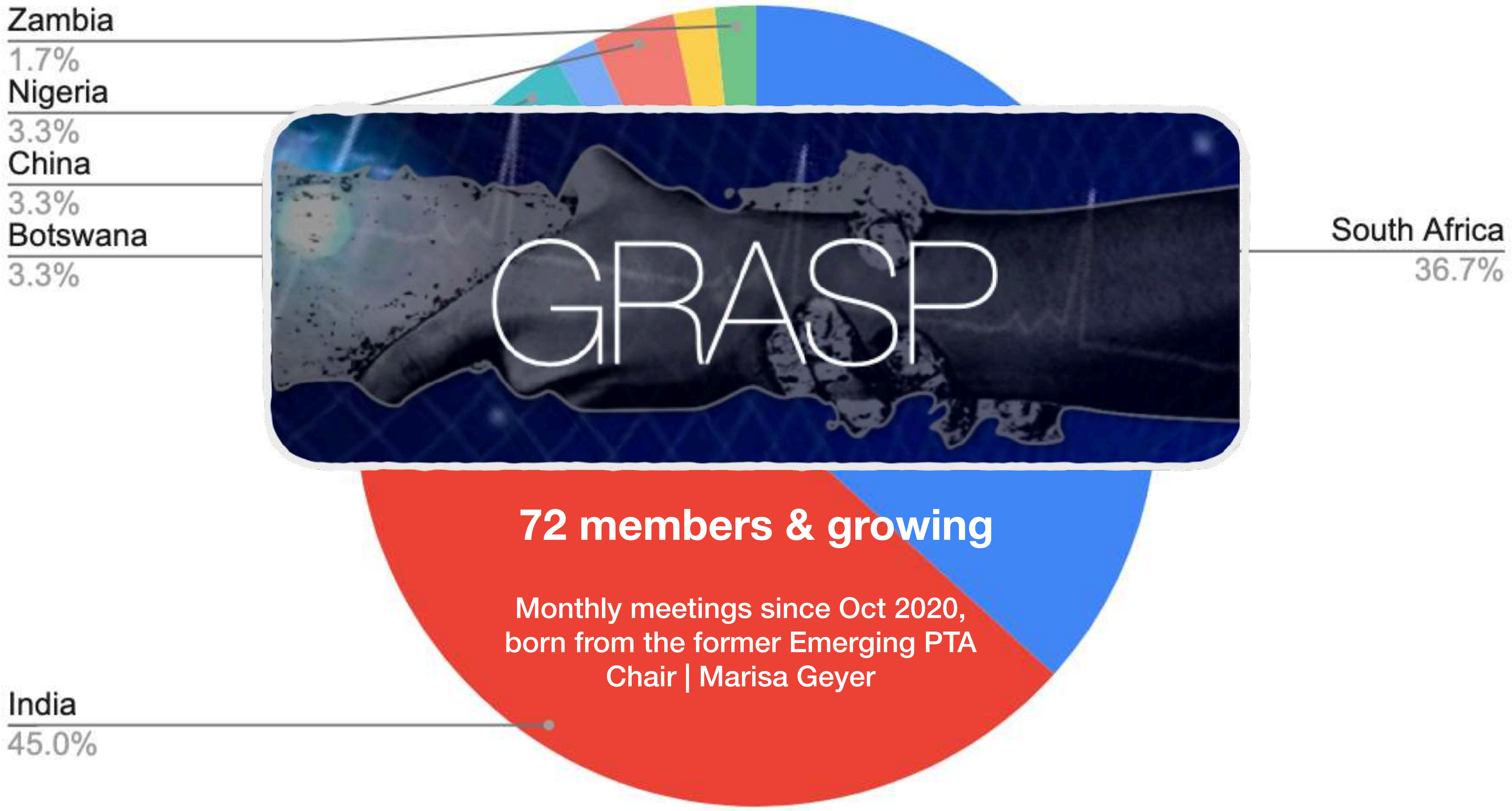
tempo2 -gr plk -f J0955-6150.par J0955-6150.tim



Before fitting for omdot (orbital precession)



After fitting for omdot (orbital precession)



Gravitational Radiation and Science with Pulsars

Monthly meetings between South African, Chinese and Indian pulsar researchers and students.

Since start (Oct 2020): India is now an official member of IPTA

InPTA
Indian Pulsar Timing Array

Please email: marisa.geyer@uct.ac.za if you want to join!

Jaikhomba Singha

Surajit Kalita

Amanda Weltman

Marisa Geyer

University of Cape Town · iYunivesithi yaseKapa · Universiteit van Kaapstad

MEERTIME node

University of Cape Town
Amanda Weltman (SARChI Cosmology, HIRAX, MeerTRAP)
Marisa Geyer (Lecturer, Meertime)
Venu Prayag (MSc/PhD, TRAPUM)
Senate Lekomola (MSc, Meertime)
Shruti Bhatporia (PhD, MeerTRAP, FRBs, HIRAX)
Surajit Kalita (Post-doc, NS theory, HIRAX)
Jaikhomba Singha (Post-doc to arrive Aug | InPTA member)

NRF National Research Foundation | SARAO South African Radio Astronomy Observatory

SARAO
Fernando Camilo (Meertime)
Sarah Buchner (Science Operations Lead, Meertime/TRAPUM)
Marcel Gouws (Engineer, PhD, Meertime)
Sam Andrianomena (Operations Scientist, ML, Meertime)
Vereese van Tonder (Engineering, noise analysis in pulsars)

Marcel Gouws

Sam Andrianomena

Vereese van Tonder

Sarah Buchner

InPTA

Shruti Bhatporia

Venu Prayag

Senate Lekomola

Christo Venter

Anu Kundu

NWU®

Tiaan Bezuidenhout

North West University
Christo Venter (pulsar theory, especially gamma rays)
Anu Kundu (post-doc, pulsar theory)
Tiaan Bezuidenhout (post-doc, MeerTRAP)
Heinrich Hurter (MSc, TRAPUM)

MPIfR
Denisha Pillay (MSc UKZN, PhD MPIfR, Meertime)
Isabella Rammala (PhD Rhodes, post-doc MPIfR)

RHODES UNIVERSITY *Where leaders learn*

Jacobus Diener

Botswana, Kenya, Nigeria and Zambia
Jacobus Diener (BUIST, Neutron star EoS)
Emmanuel Gosego (University Botswana)
Kennedy Konga (Meru University, Kenya)
Mukadi Chisabi (Copperbelt University, Zambia)
Ugochukwu Enwelum (University of Nigeria)

Jeandrew Brink

University of Free State
Jeandrew Brink (GWs, previous SA-PTA chair)
Corle van der Walt (MSc, BH imaging)
Judiet van der Mescht (MSc, GR tests)

UFS

Anslyn John

Stellenbosch University
Anslyn John (modified gravity)
Jacki Gilmore (signal processing)
Alex Faustmann (PhD student, noise in pulsars)

Isabella Rammala

Jacki Gilmore

Alex Faustmann

Stellenbosch UNIVERSITY IYUNIVESITHI UNIVERSITEIT

Timing and noise analysis of five millisecond pulsars observed with MeerKAT

M. Chisabi,[1]★ S. Andrianomena,[2,3]† U. Enwelum,[4] E. G. Gasennelwe,[5] A. Idris,[6] E. A. Idogbe,[7] S. Shilunga,[8] M. Geyer,[2,9]‡ D. J. Reardon,[10] C. F. Okany,[7,11] M. Shamohammadi,[10]

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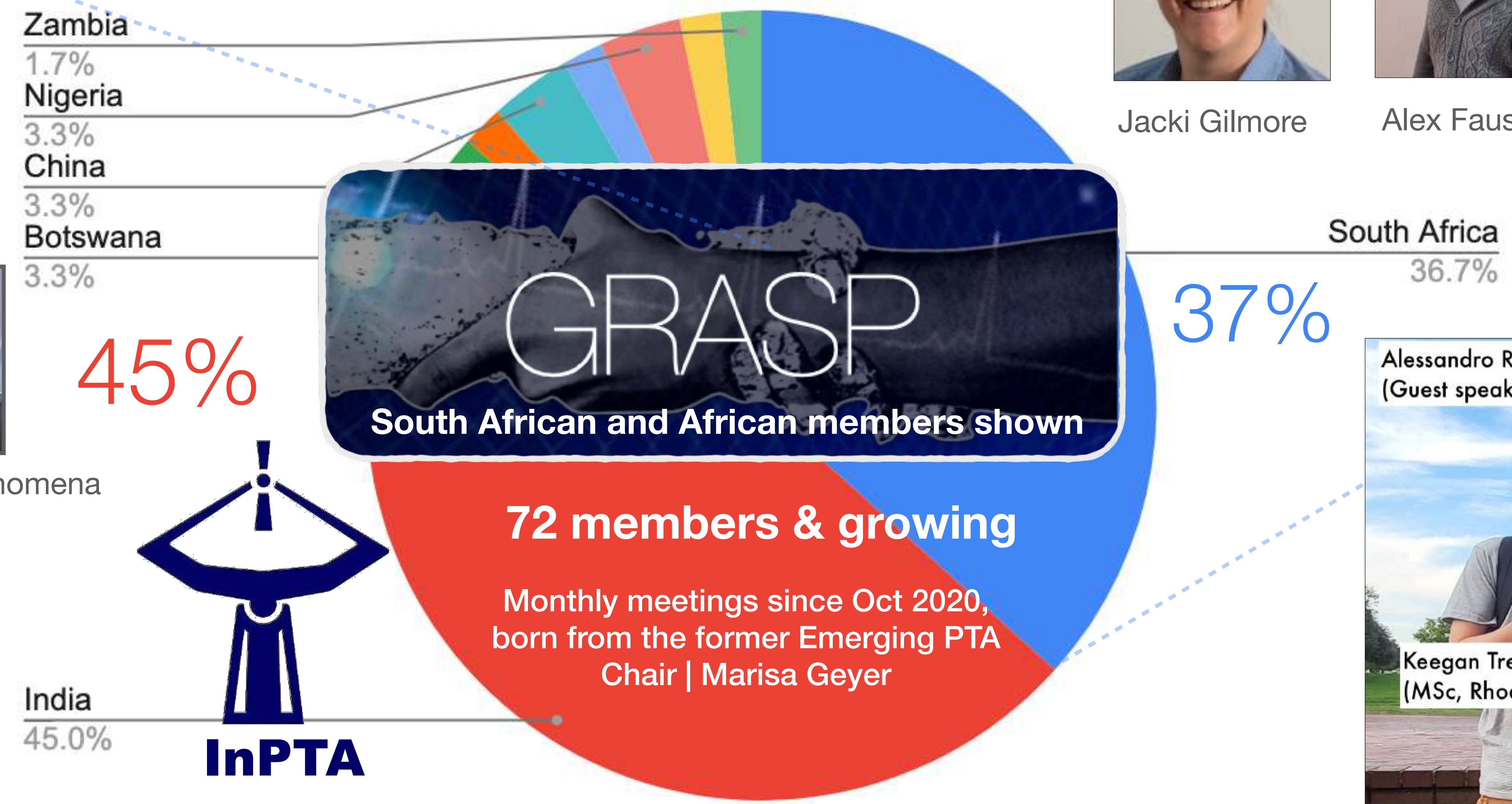
[10]Centre for Astrophysics and Supercomputing, Swinburne University of Technology, P.O. Box 218, Hawthorn, Victoria 3122, Australia
[11]Department of Physics & Astronomy, University of Nigeria, Nsukka, 410101, Nigeria

Mukadi Chisabi

Sam Andrianomena



InPTA

Gravitational Radiation and Science with Pulsars

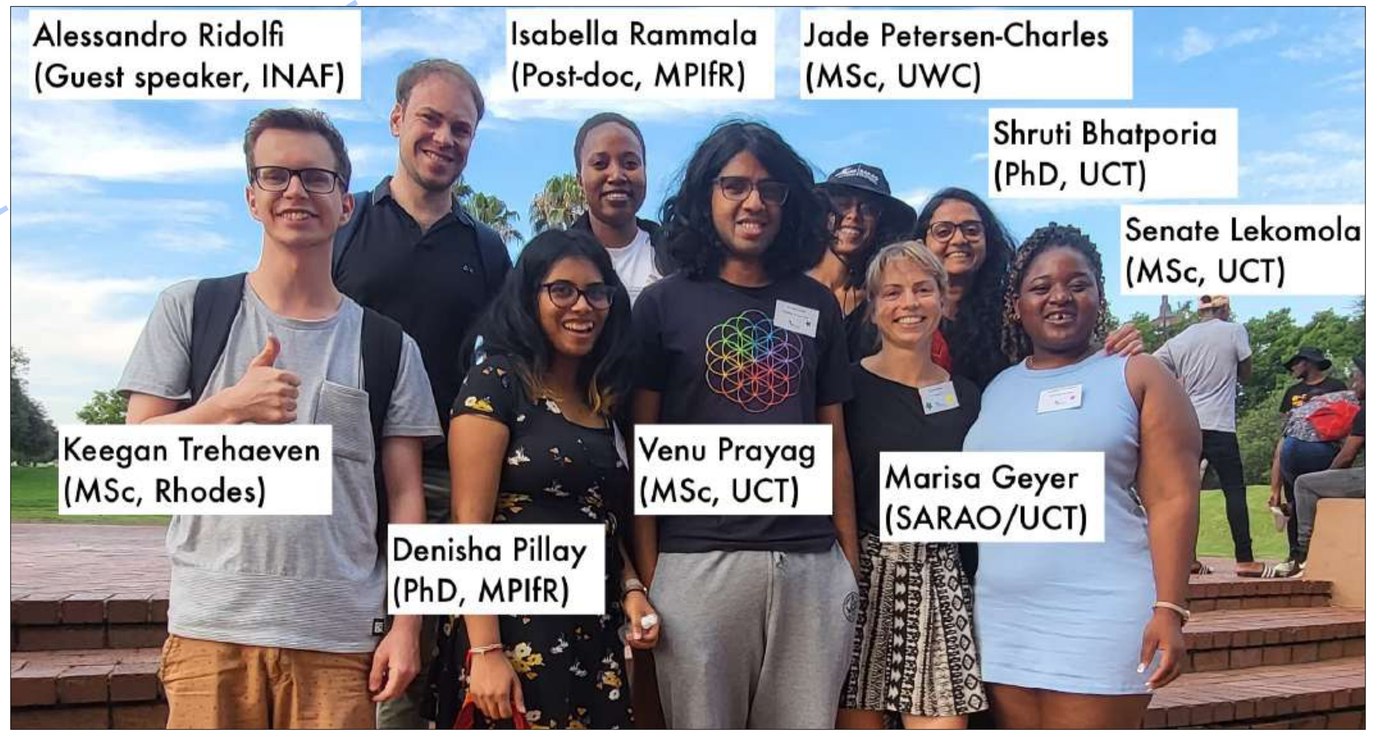
Growth through independent workshops and projects
- African Radio Interferometry Winter School
- MeerKAT pulsar timing workshop (Aditya, Ryan, Matthew, Reneé, Daniel, Federico, Marisa)
- RelBin research project (Daniel, Marisa, Mohsen, Sam)
- MKT Grand Tour (Vivek Krishnan-Venkatraman)

MEERTIME

[SARAO E-Learning Portal: https://www.sarao.ac.za/e-learning-portal/https://sauni.co.za/uct-registration-dates/](https://www.sarao.ac.za/e-learning-portal/https://sauni.co.za/uct-registration-dates/)

GRASP workshops and series
- Mayuresh Surnis pulsar searching
- Bhal Chandra Joshi lecture series on single pulses
- Thank you to many Meertime and PTA members participating as guest speakers!

SARAO bursary conference 2022



Call to join African Pulsar Timing group!

See your inboxes for email from interim committee
on Weds 20 September to saastronomers.

Needs fancy Logo!

Jeandrew Brink
Sarah Buchner
Fernando Camilo
Marisa Geyer
Christo Venter

Terms of Reference

Once membership is established, we will call for nominations
for chair and vice-chair

Call to join African Pulsar Timing group!

See your inboxes for email from interim committee
on Weds 20 September

APT

Needs fancy Logo!

Jeandrew Brink
Sarah Buchner
Fernando Camilo
Marisa Geyer
Christo Venter

Terms of Reference

2. The Purpose of the APT

APT aims at its core to be an enabling and learning environment for African researchers to gain experience in pulsar timing techniques and other pulsar-related science, ultimately allowing for research independence and organic research capacity growth.

The APT should provide an active research environment that encourages research development and growth through regular scientific meetings; by organizing pulsar timing and pulsar science workshops; and by encouraging research project collaborations.

The APT aims to provide easy access for students starting out in the field to obtain skills to master the data analysis, computational and conceptual skills needed for performing pulsar timing science. This includes providing an effective communal education repository that will help take the initial startup training load off individual supervisors and retaining a core base of technical knowledge.

A key goal of the APT is to have a significant number of African-based researchers publishing on pulsar science. This requires not only training in appropriate techniques, but also access to suitable tools and datasets. Relevant datasets can include existing Data Releases, as e.g. obtained from the MeerKAT telescope, as well as newly acquired datasets from both African-based instruments such as MeerKAT, HIRAX, and the upcoming SKA; as well as other world-class pulsar instruments.