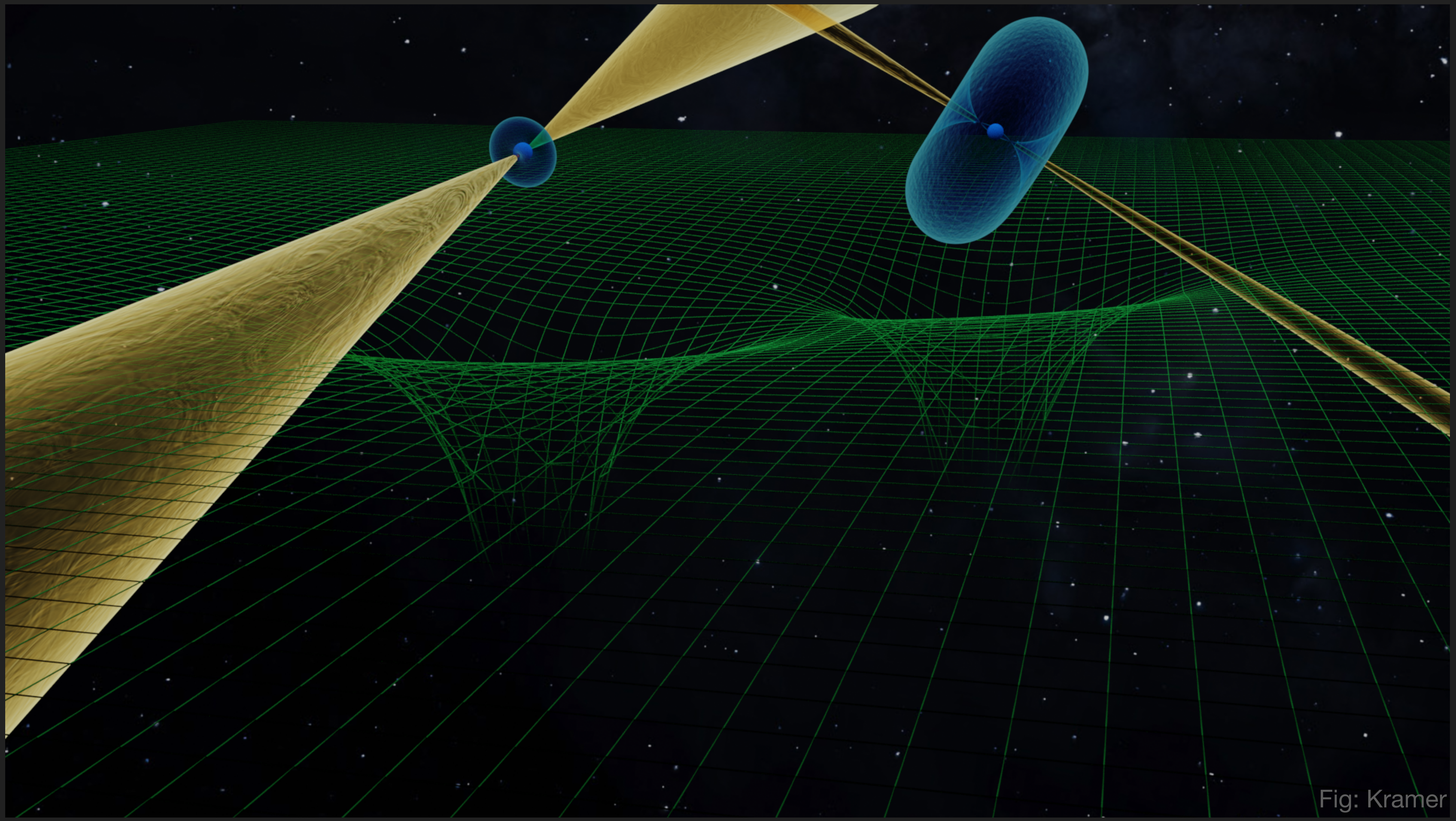
Radio pulsars and relativistic gravity

MAX-PLANCK-GESELLSCHAFT

Max-Planck-Institut
für Radioastronomie



Dr. Vivek Venkatraman Krishnan
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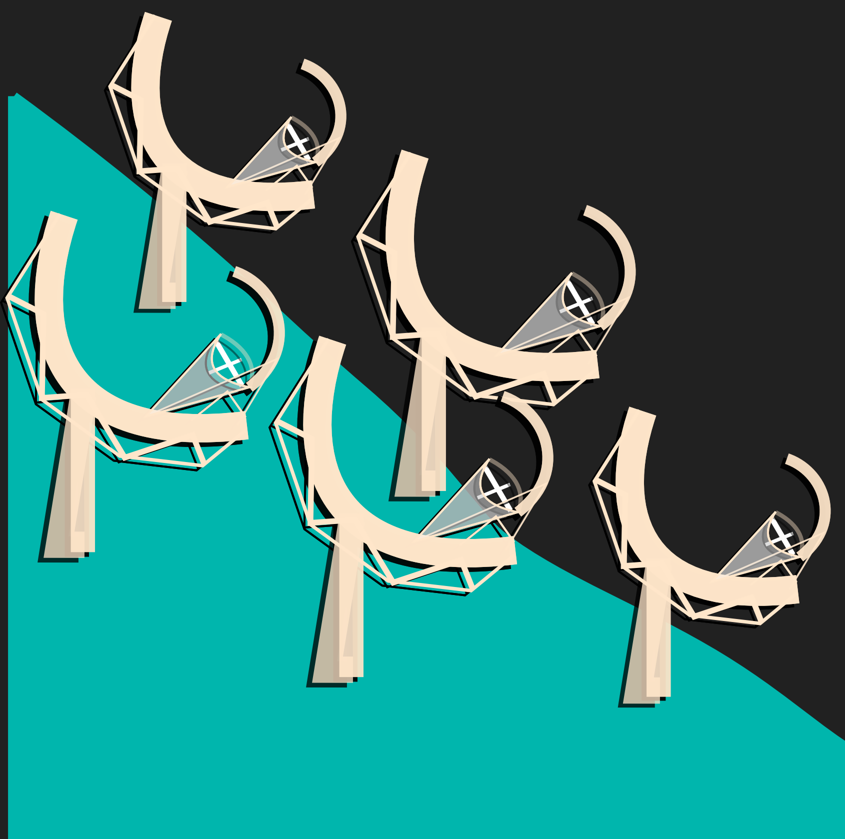
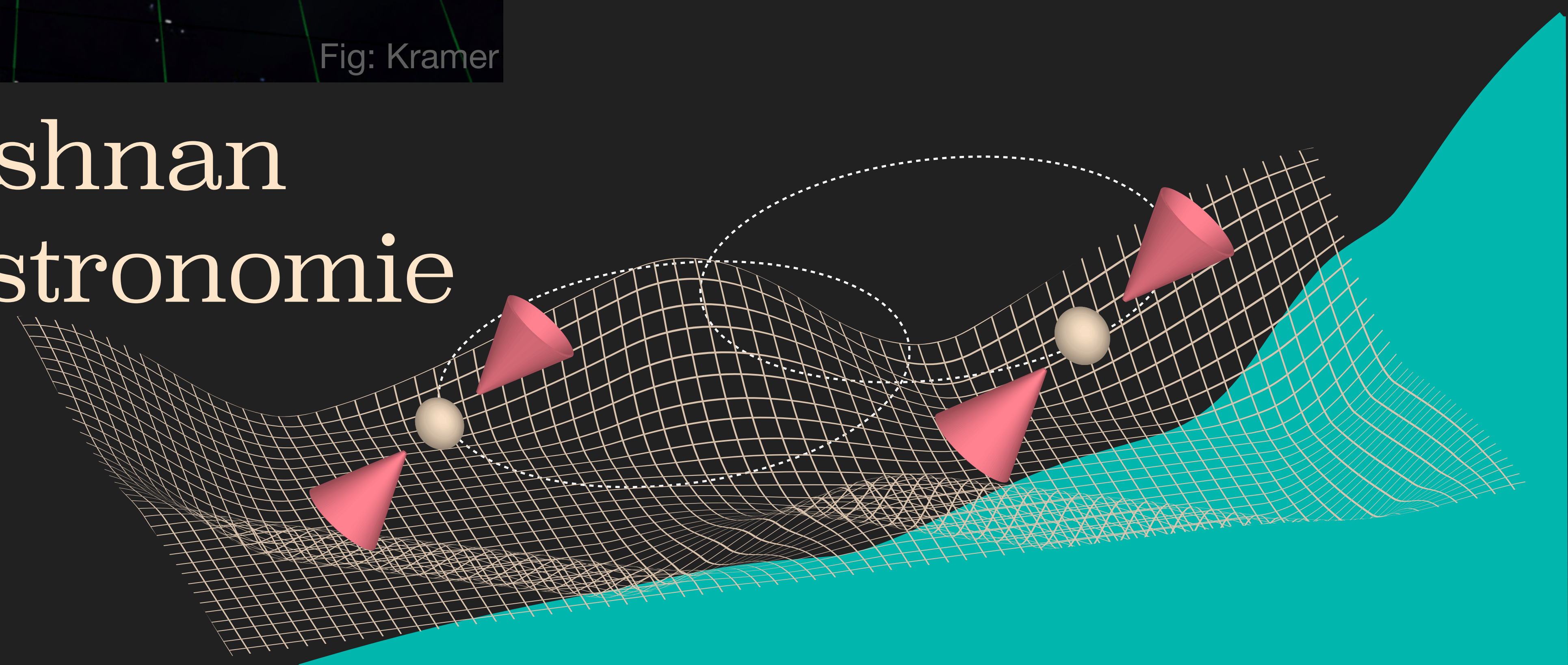
Bonn, Germany

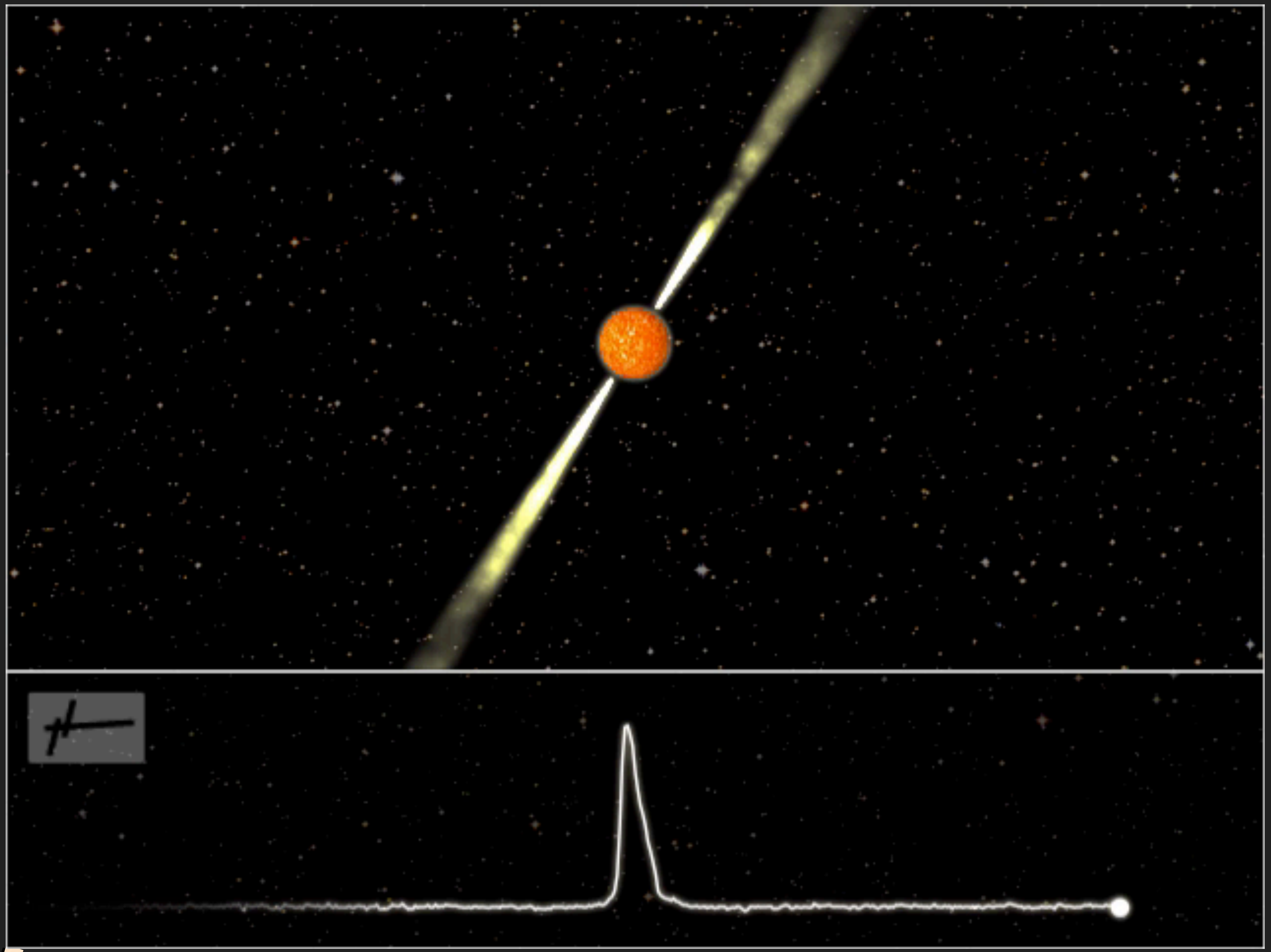




Gravity regimes and experiments

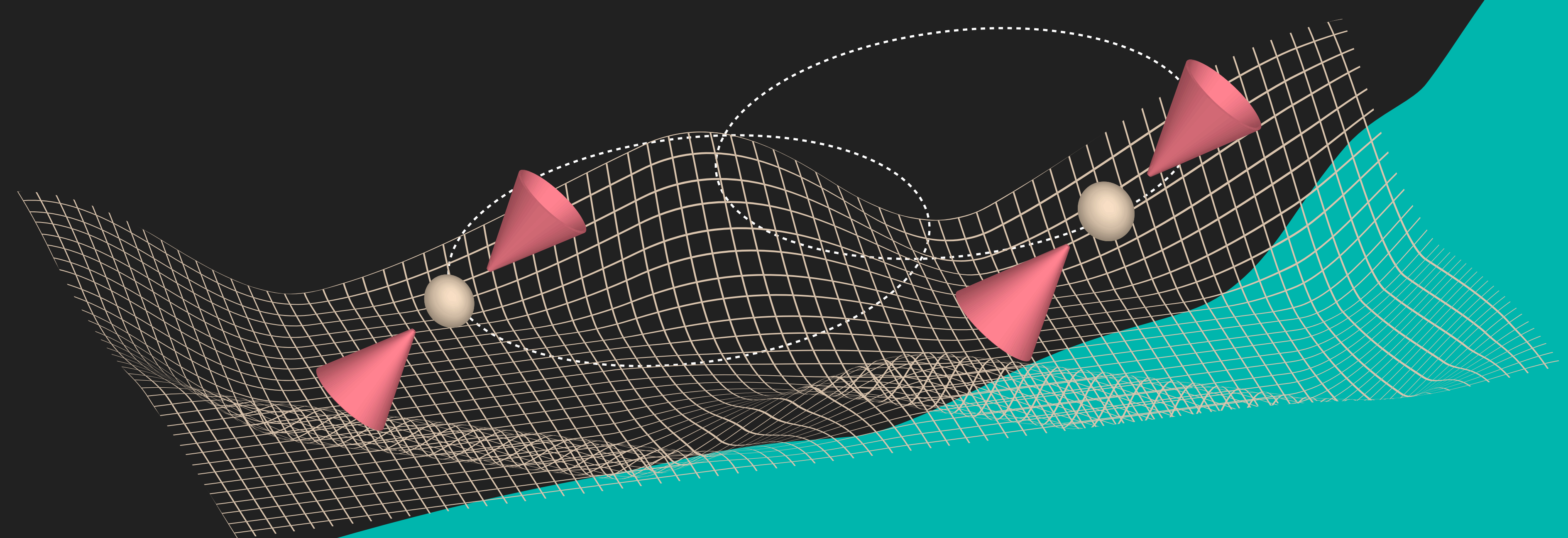
* terms and conditions apply

Pulsars

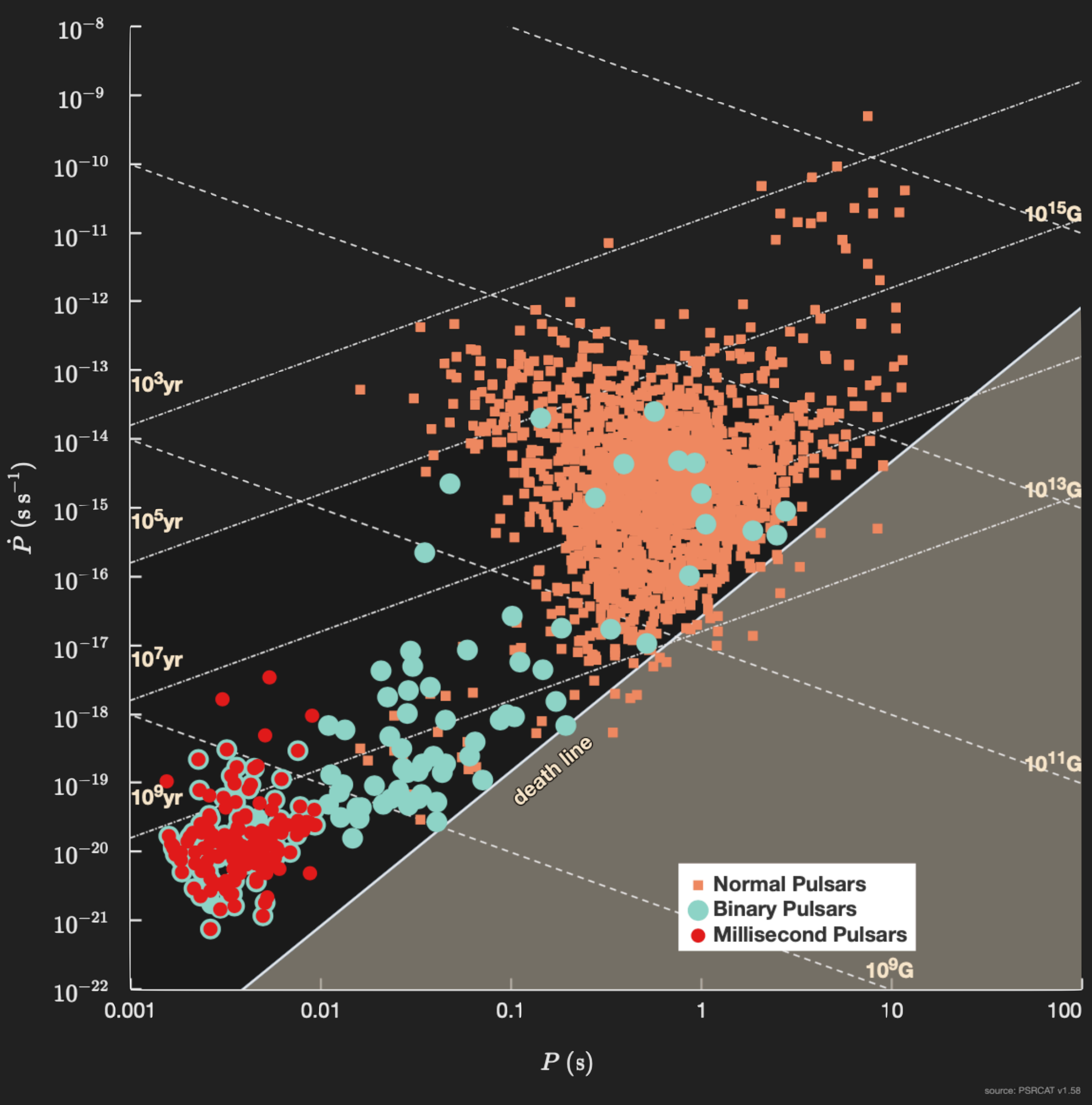


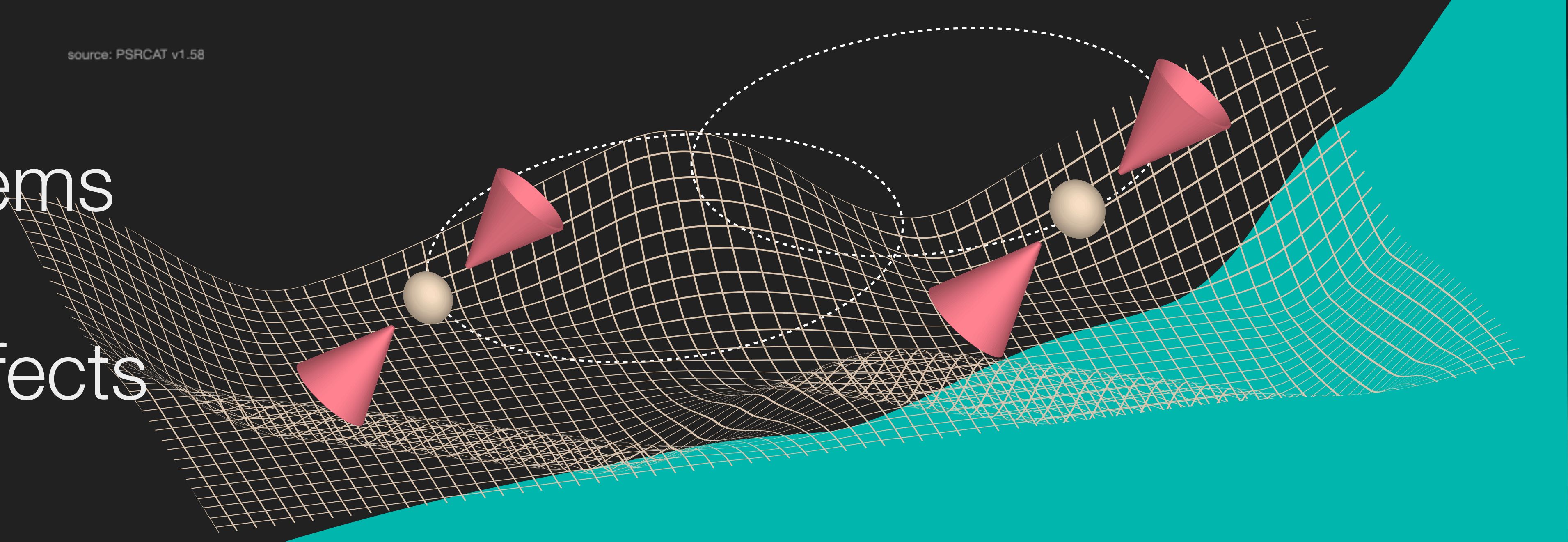
(Credit: Prof. Joeri van Leeuwen)

- ☐ Neutron stars that emit coherent magnetic dipole radiation
- ☐ High rotational stability
- ☐ arrival times of "pulses" are highly regular and can be "timed" to unparalleled precision*



The $P - \dot{P}$ diagram

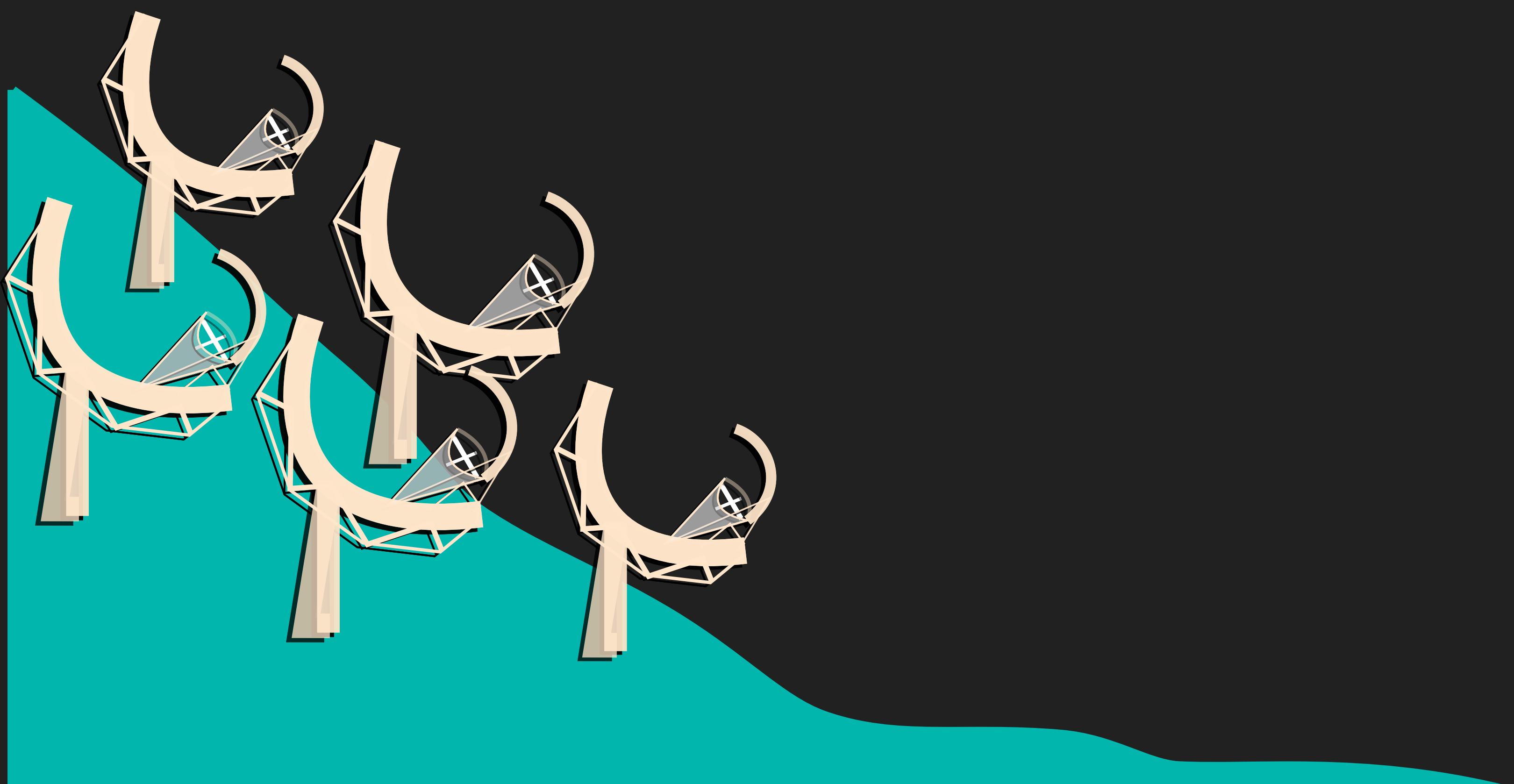


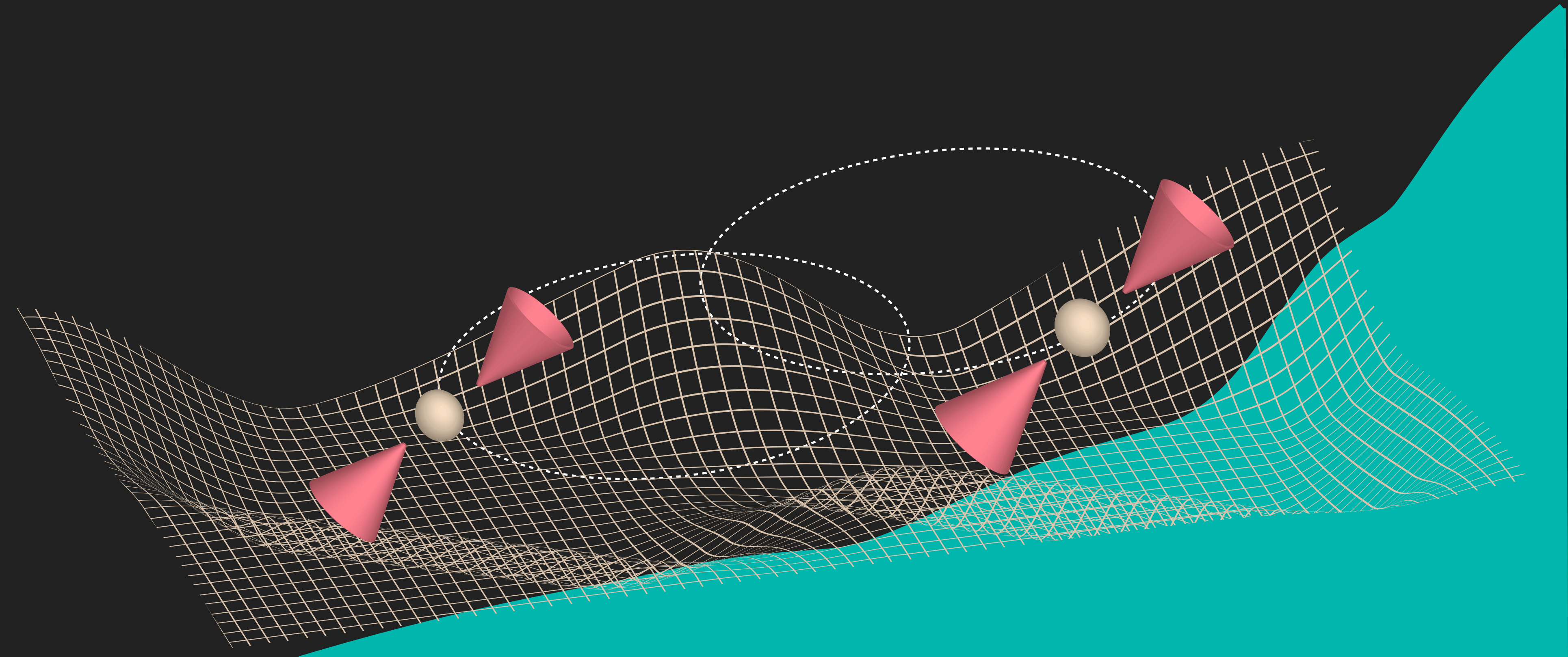


- ☐ 10% of known pulsars in binary systems
- ☐ 10% of binaries exhibits relativistic effects

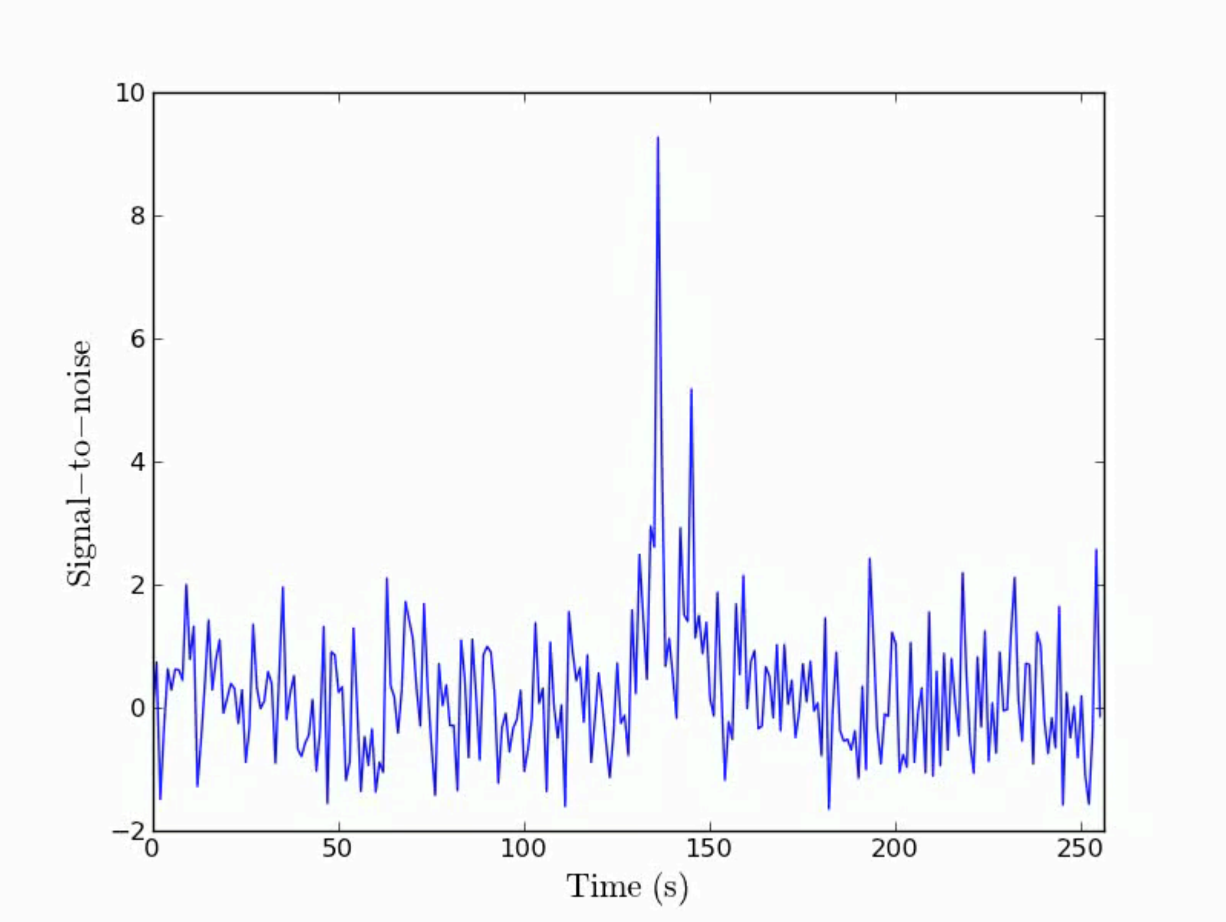
How do we measure it?

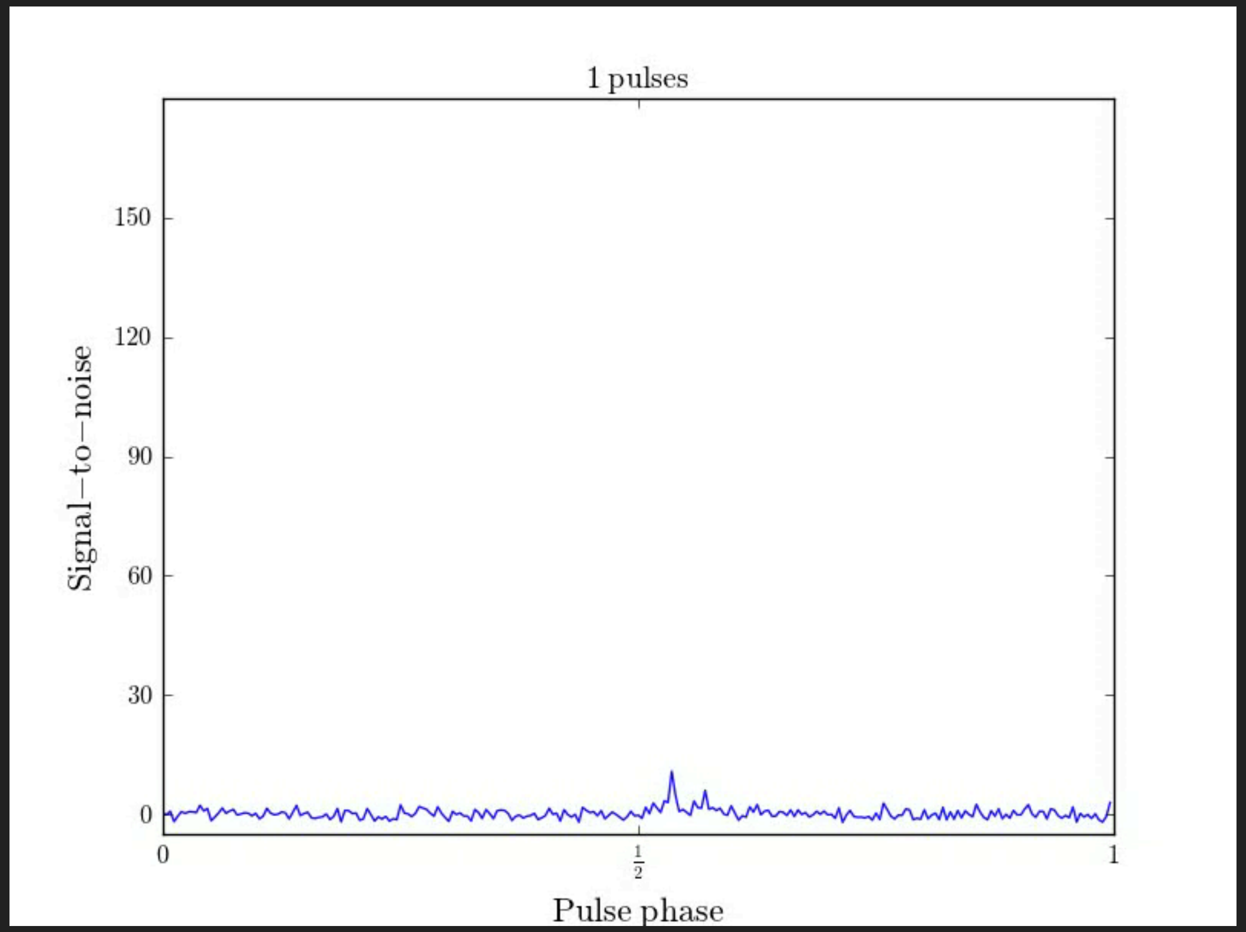
The art of pulsar timing!

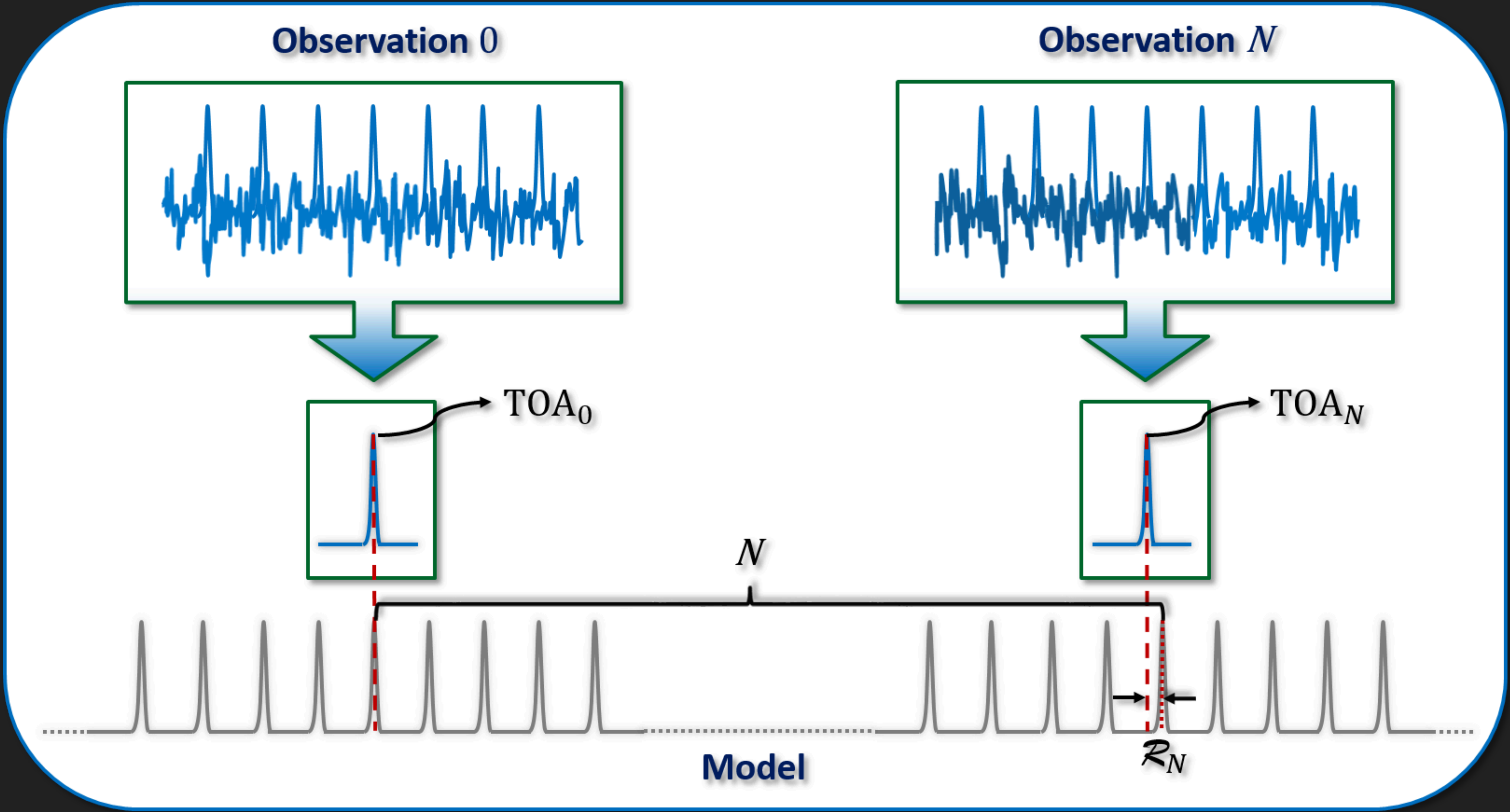


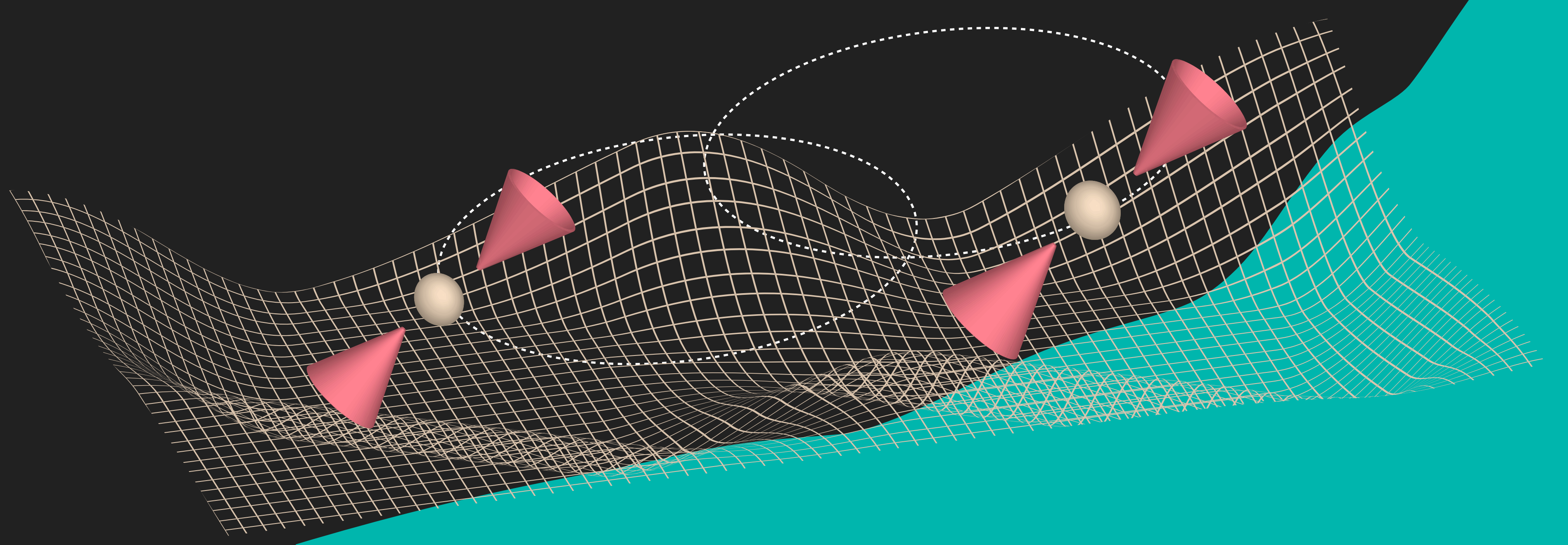


Pulsar timing, ToA and the residual





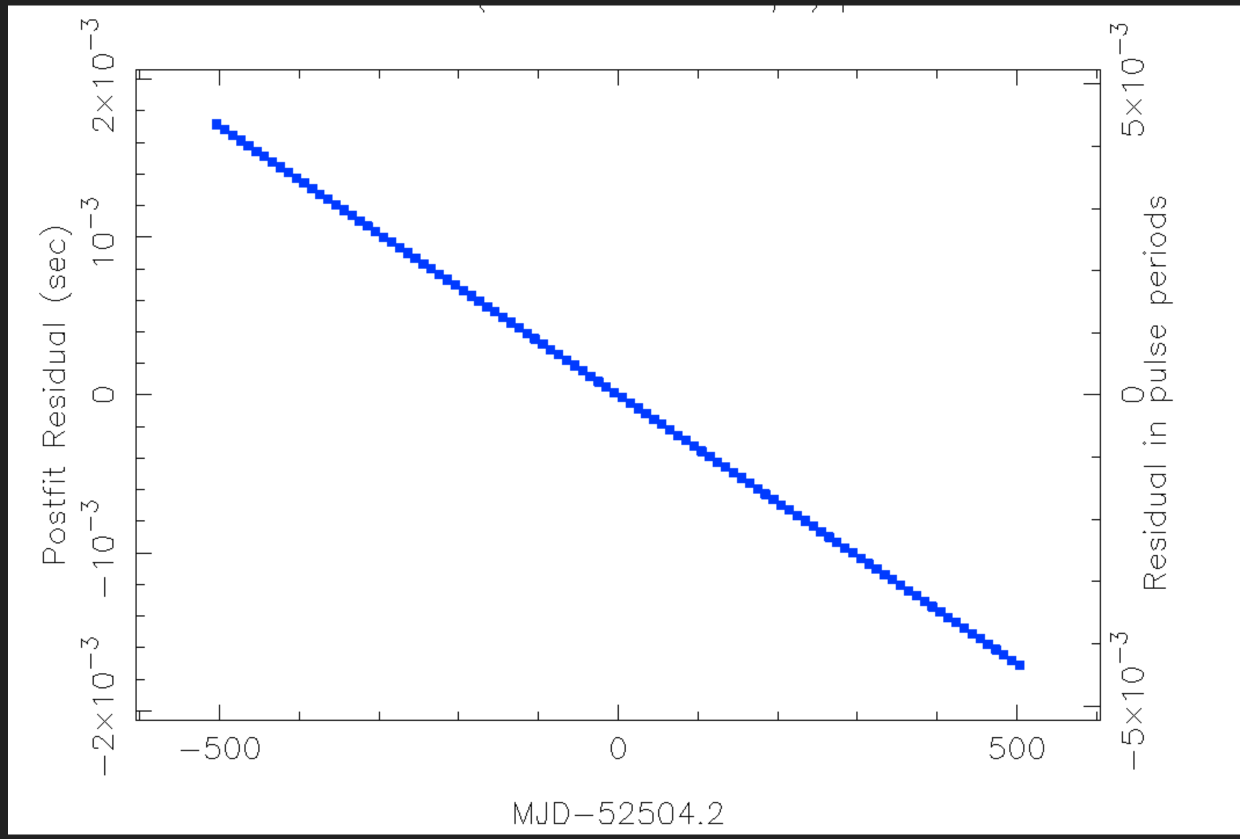




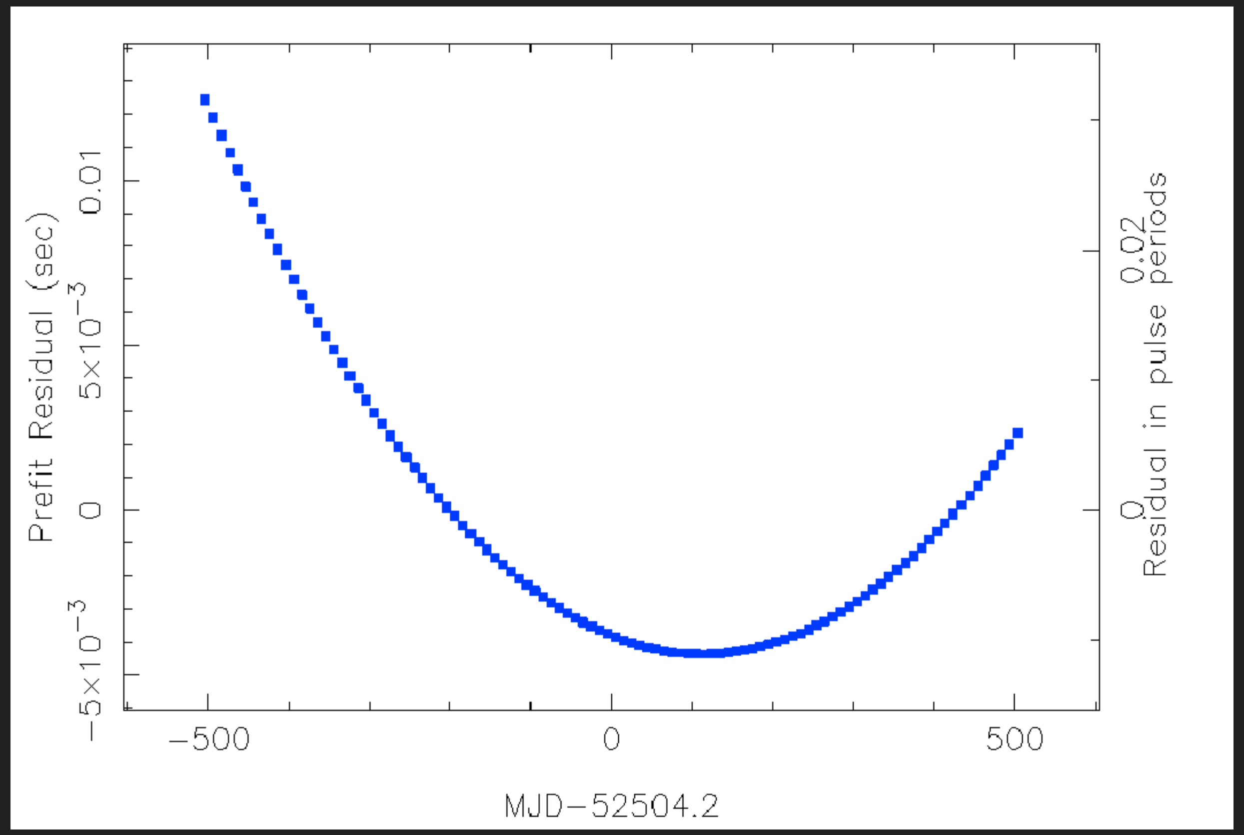
But how do you know what is wrong?

- ☐ Un-modelled/ inaccurate models of spin, orbital, astrometric & relativistic dynamics in the system create short to long term drifts in the timing residuals.

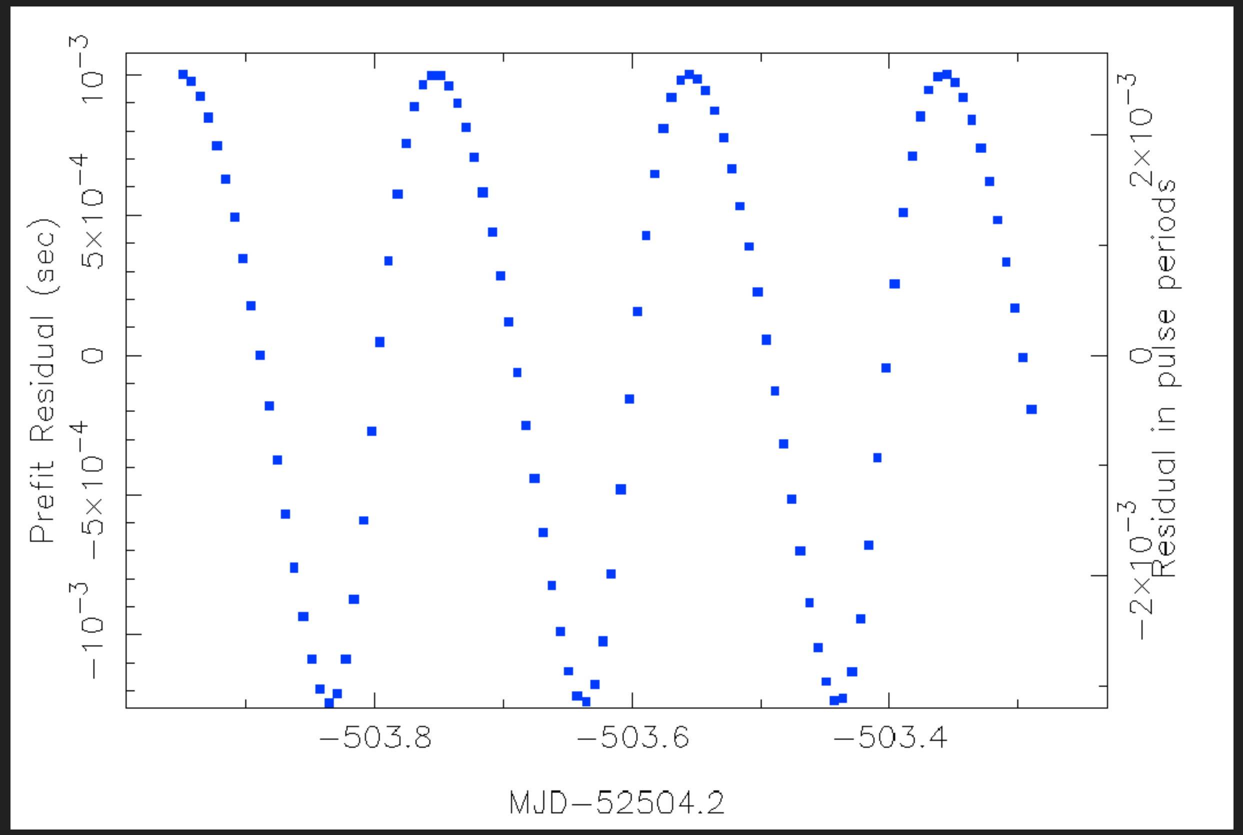
- ☐ One can fit for such offsets and develop a better pulsar “model”



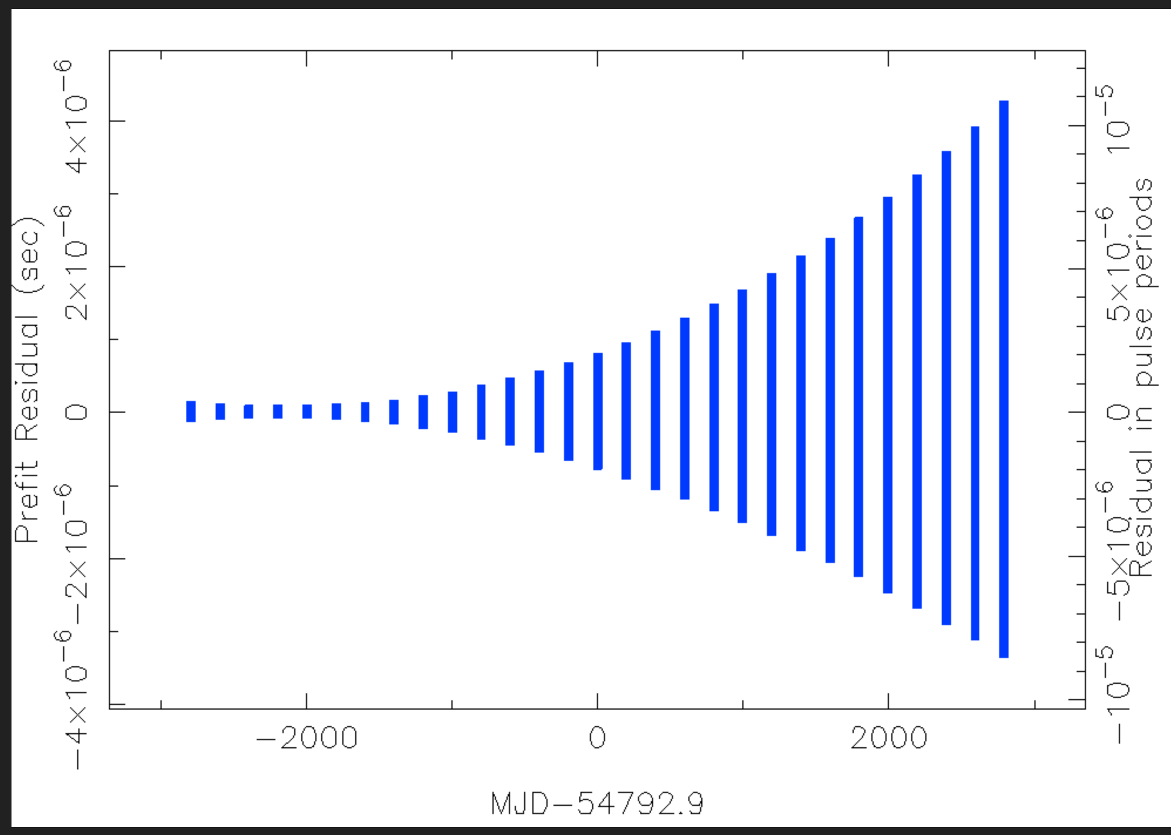
Incorrect spin



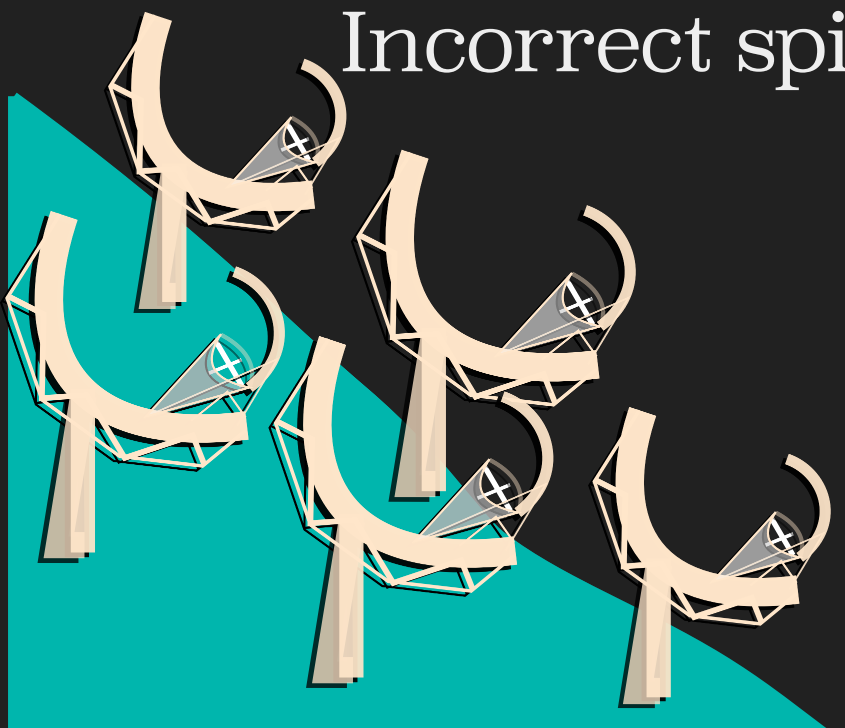
Incorrect spin-down

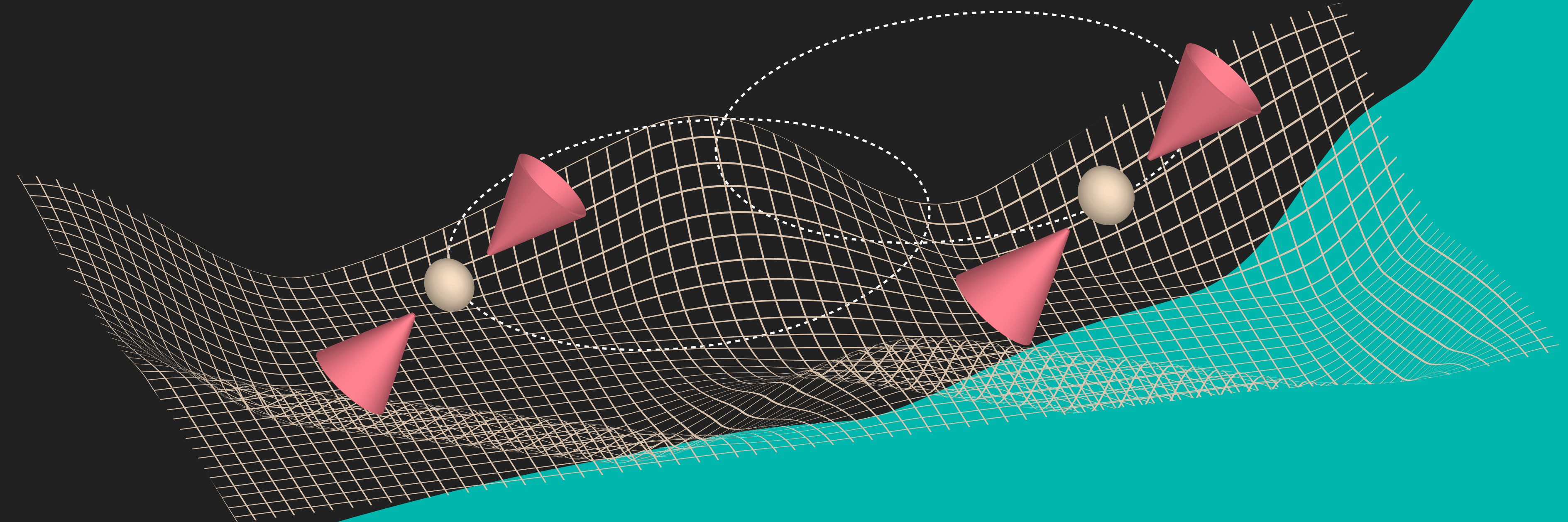


Un-modelled orbit

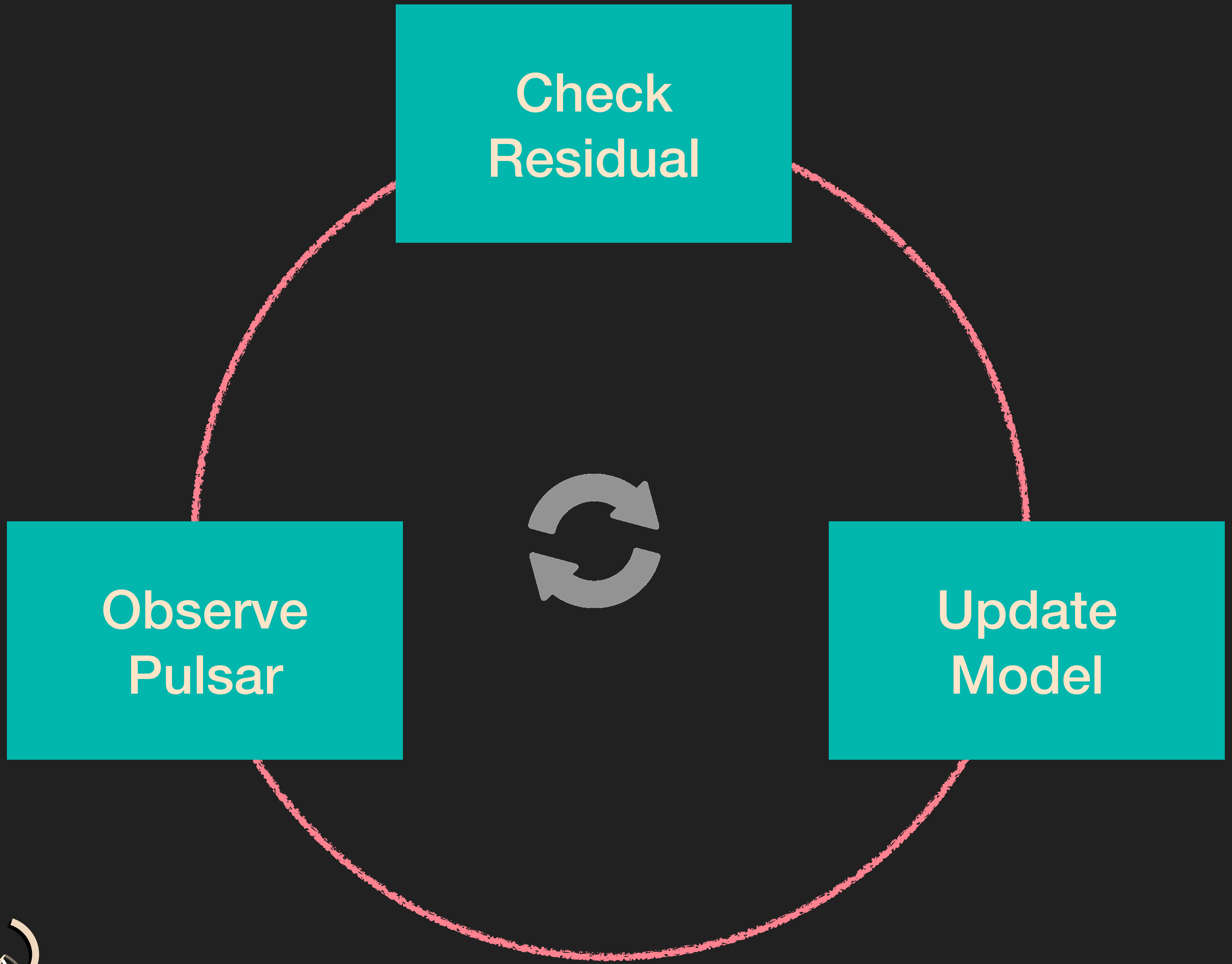


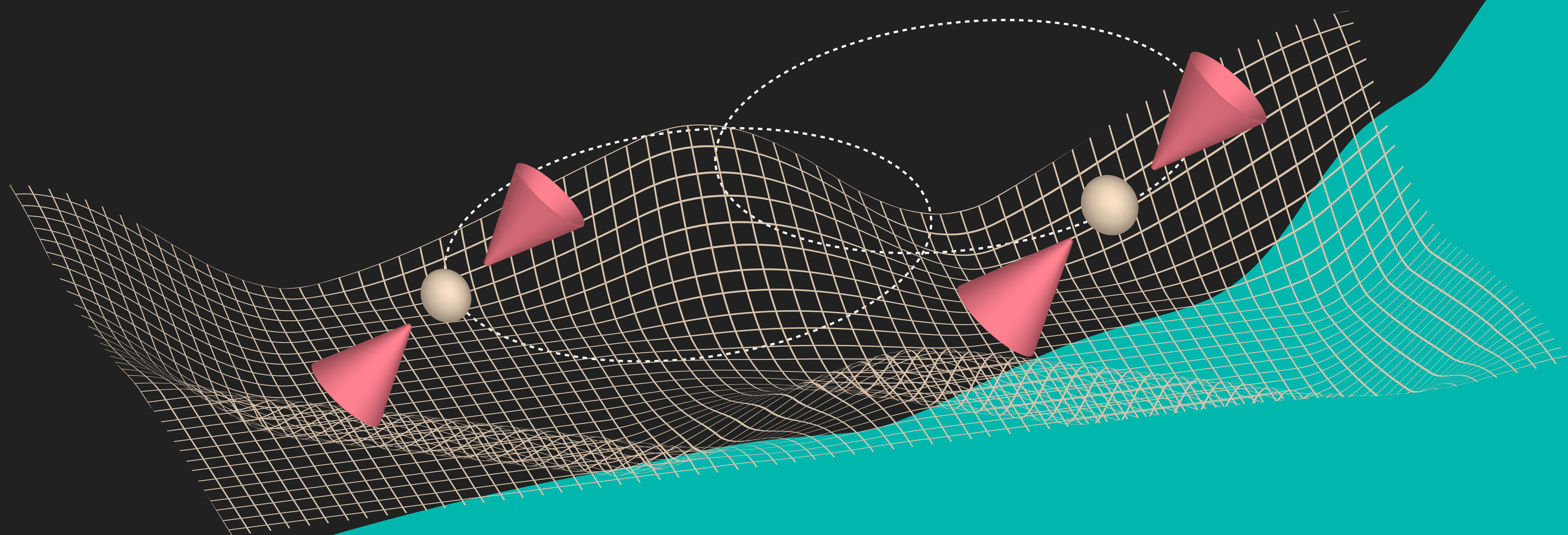
Un-modelled relativistic effect



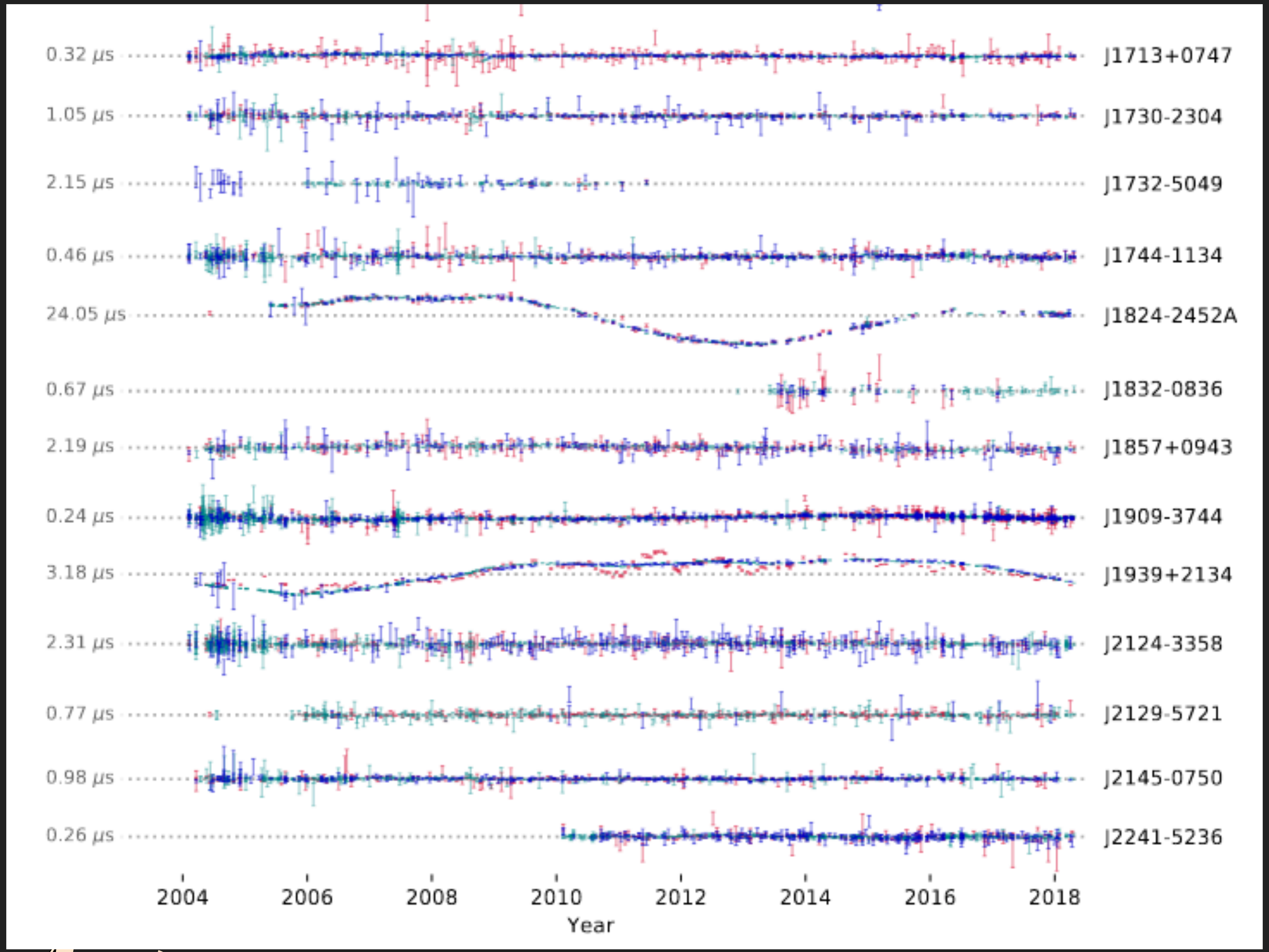


For the next few years…..





The power of pulsar timing



[Kerr et al. 2020]

Spin parameters:

Period:	2.947108069160717(3) ms	(Reardon et al. 2015)

3 atto seconds uncertainty!

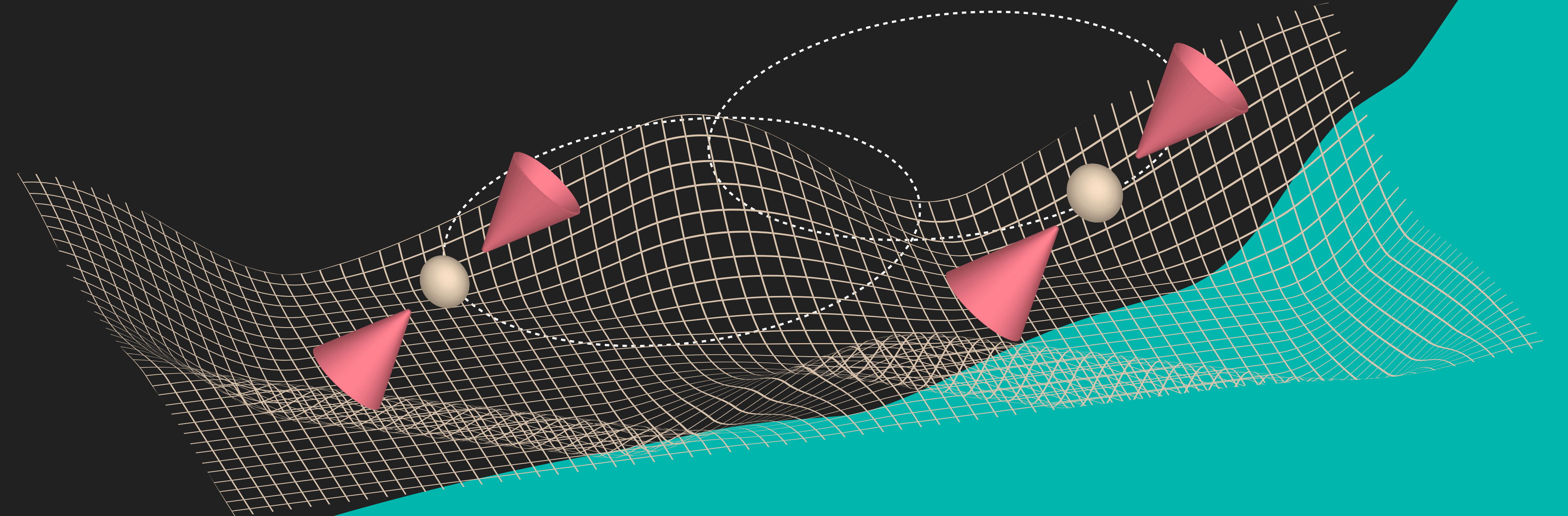
Astrometry:

Position in the sky:	0.6 μas	(Reardon et al. 2015)
Proper motion:	140.911(3) mas/yr	(Reardon et al. 2015)
Distance:	156.79 ± 0.25 pc	(Reardon et al. 2015)

Orbital parameters:

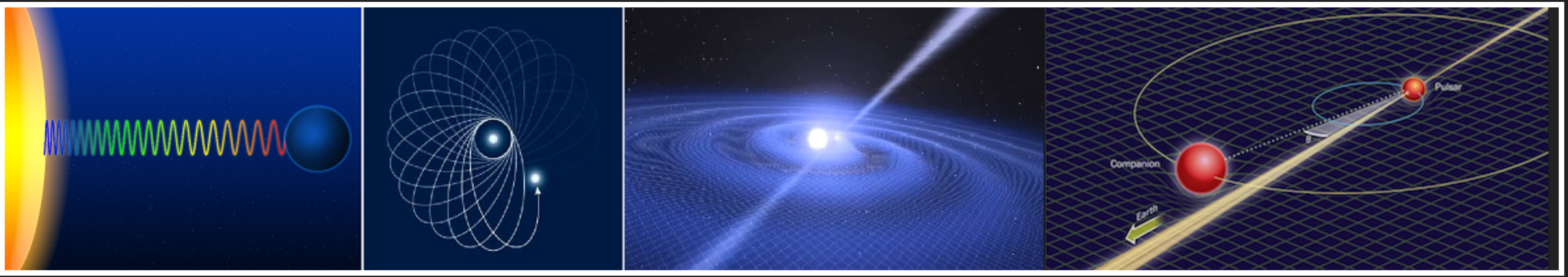
0.1 μs uncertainty!

Orbital period:	0.102251559297(1) days	(Kramer et al., submitted)
Projected semi-major axis	31 659 820.5(2) km	(Heusgen et al., in prep.)
Eccentricity:	0.436678414(5)	(Heusgen et al., in prep.)



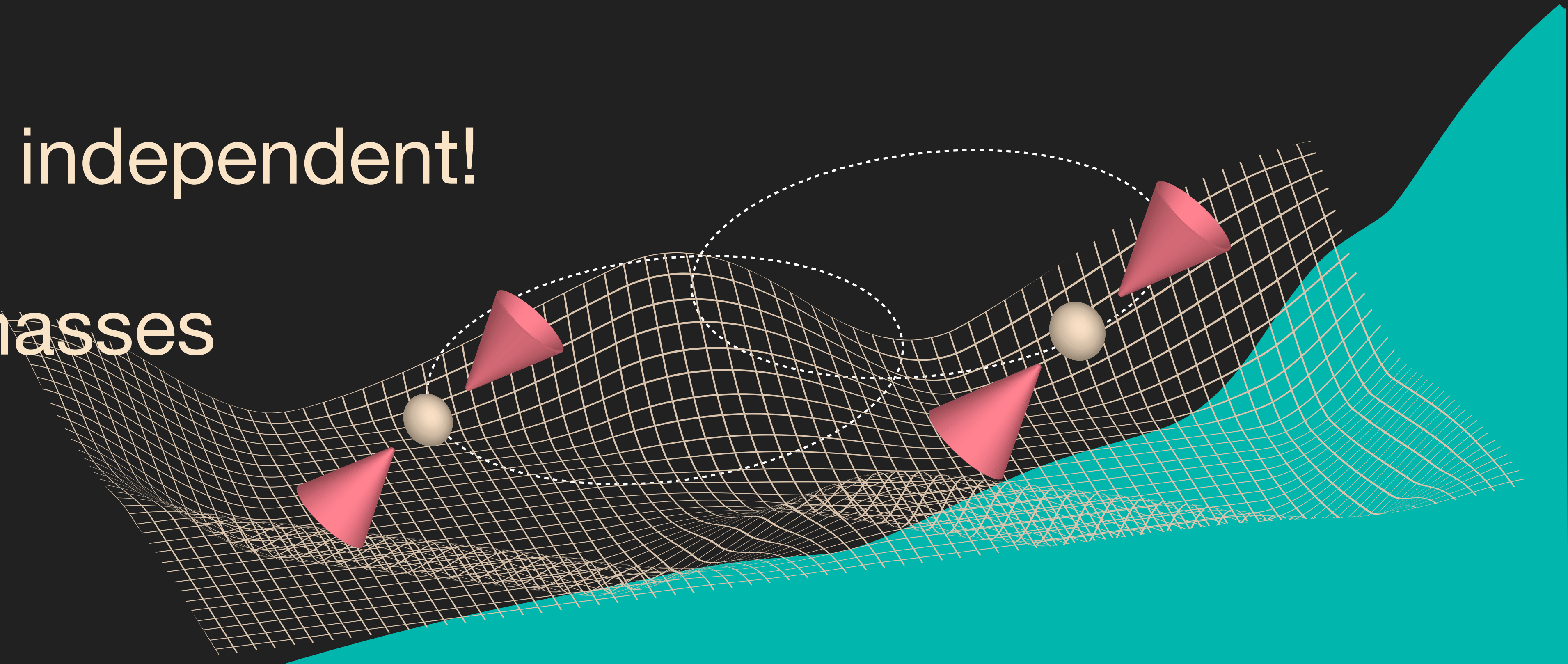
Relativistic effects: The PK formalism

- ☐ Periastron advance ($\dot{\omega}$)
- ☐ Gravitational wave damping ($\dot{P}_{\rm b}$)
- ☐ Shapiro delay (r, s)
- ☐ Gravitational redshift and transverse Doppler effect (γ)



Measurements from Geometry & Algebra. Hence theory independent!

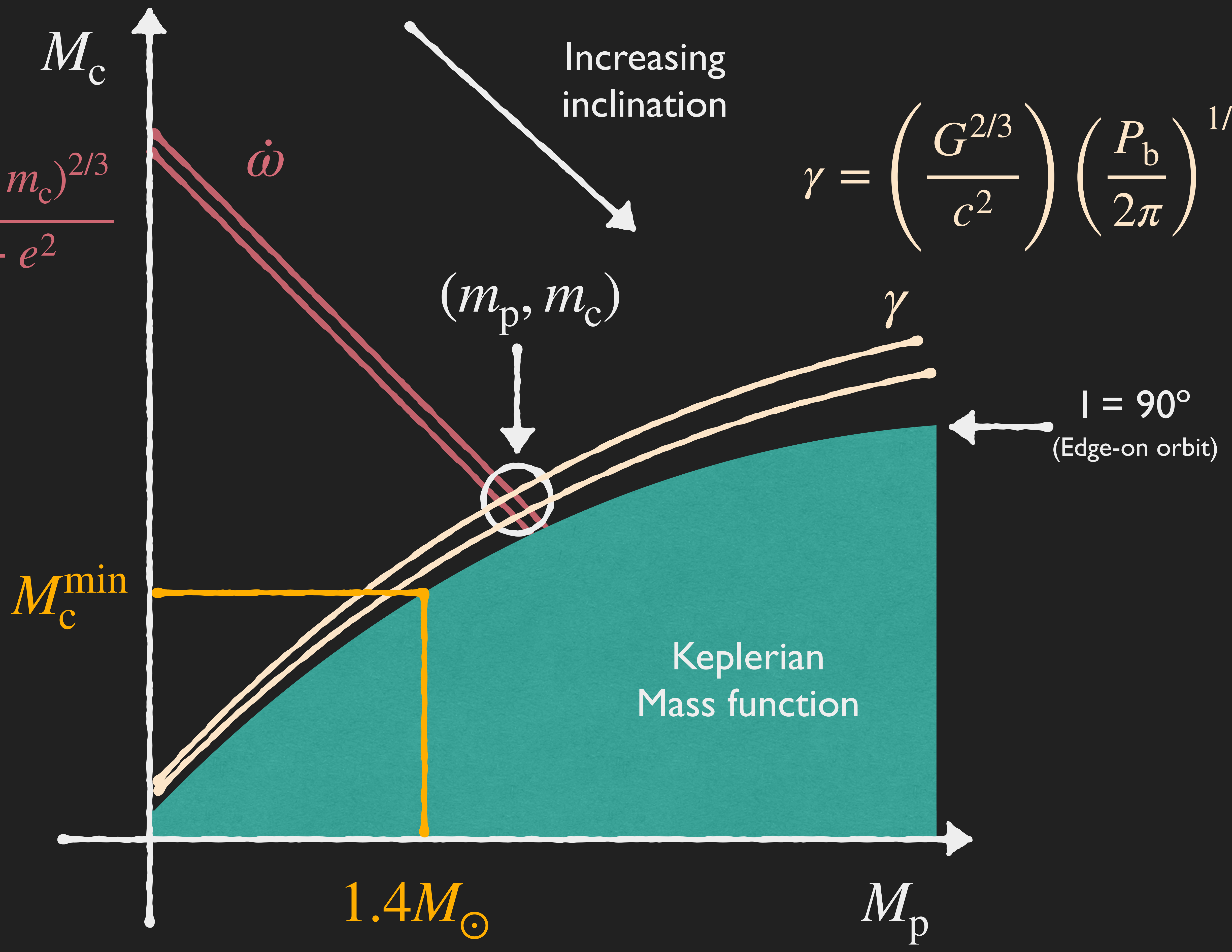
Theories of gravity relate PK parameters to masses

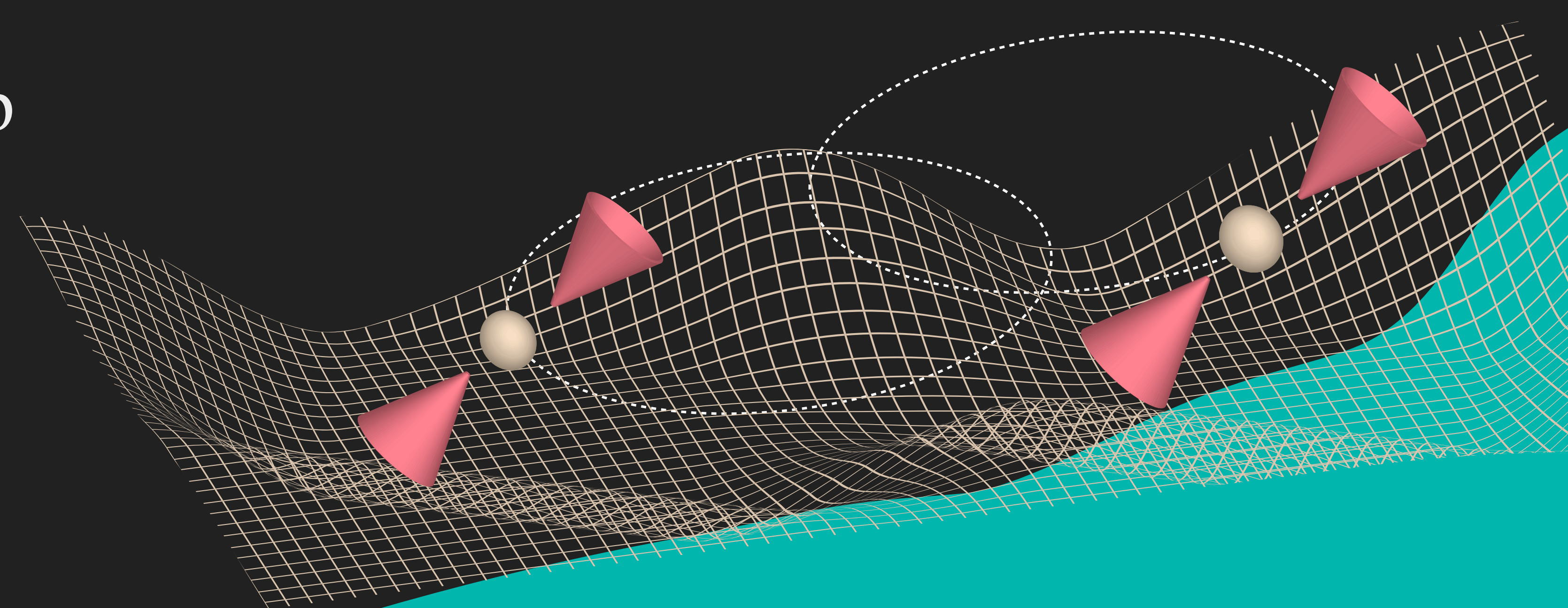


The mass-mass diagram

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

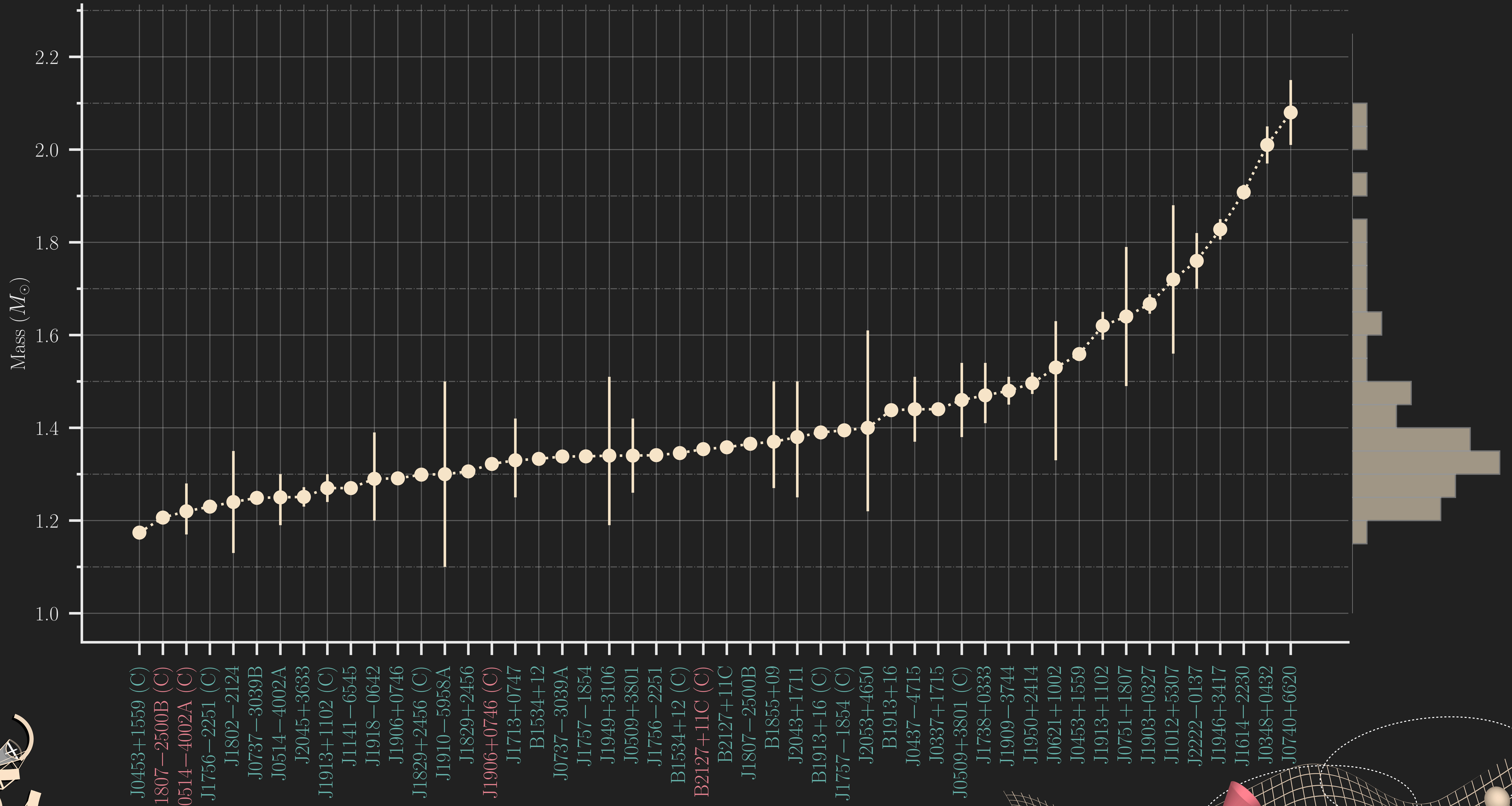
$$\gamma = \left(\frac{G^{2/3}}{c^2}\right)\left(\frac{P_b}{2\pi}\right)^{1/3} e\, m_p(m_p + 2m_c)\,(m_p + 2m_c)^{-4/3}$$

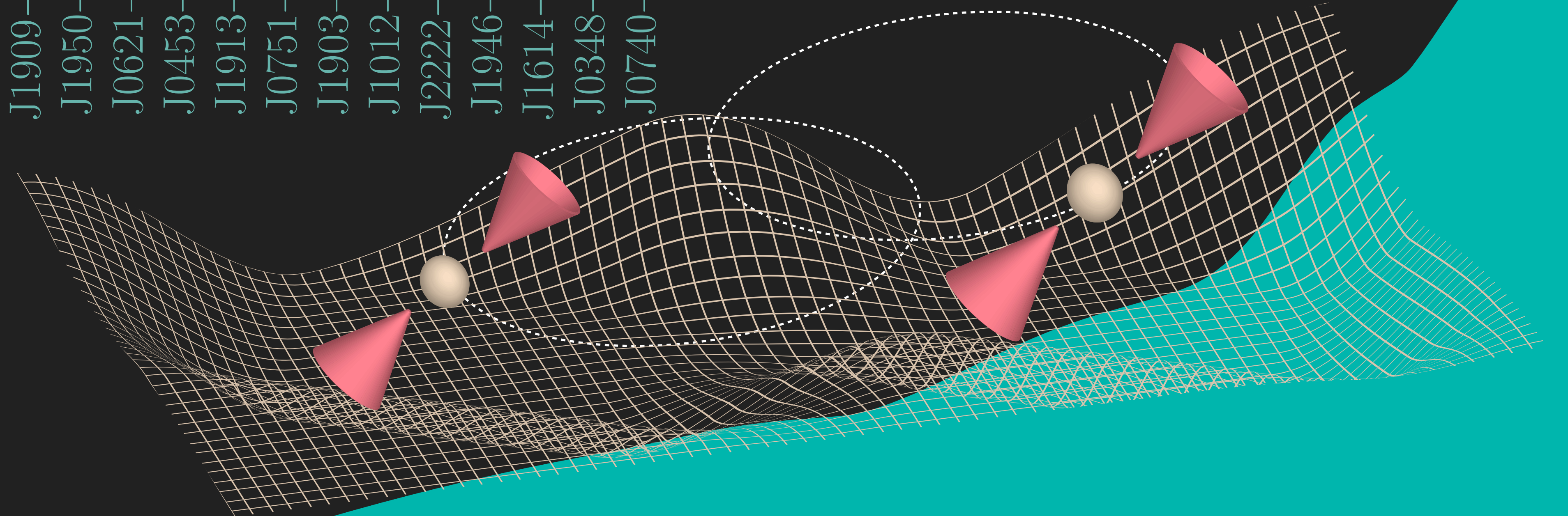




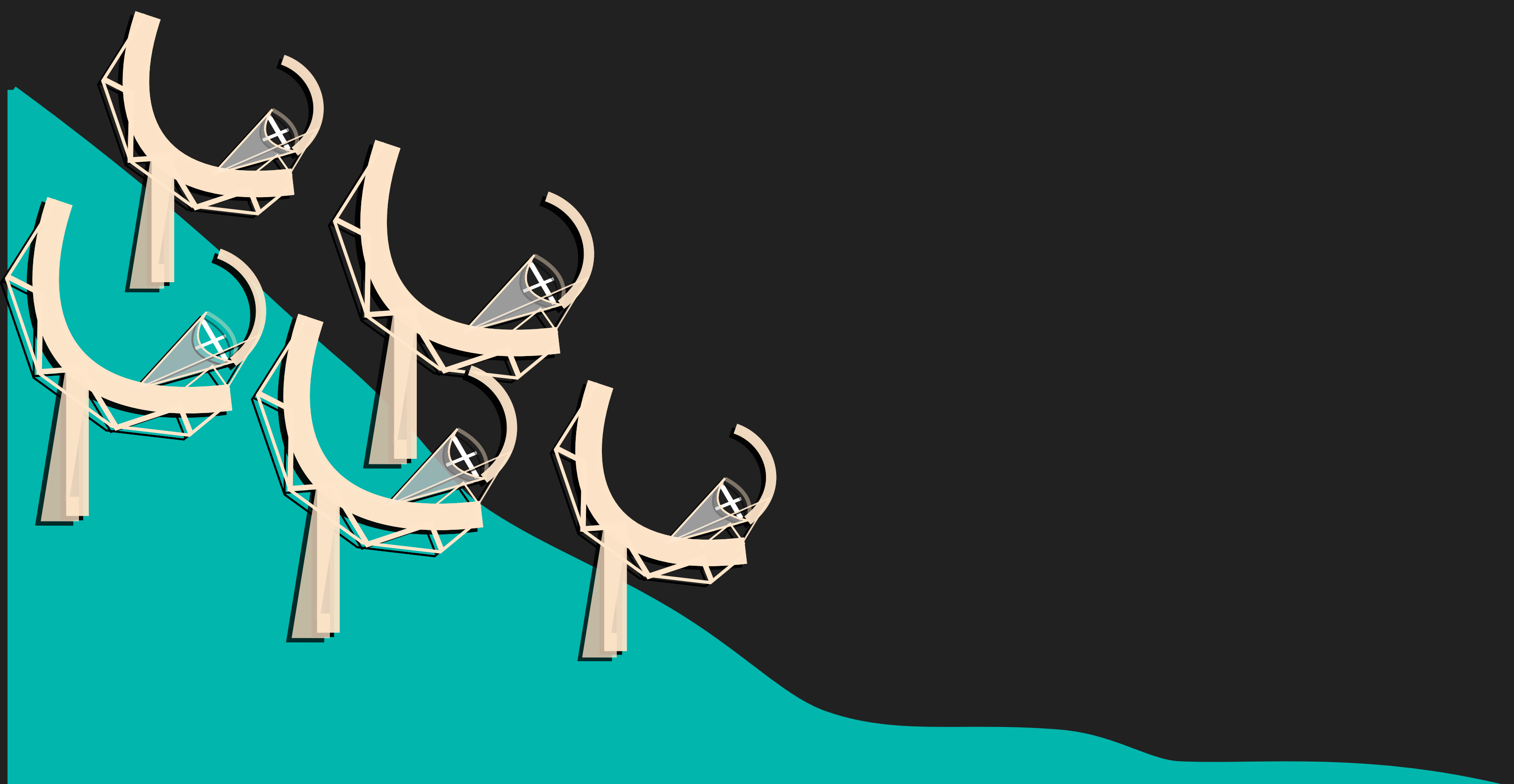
Using Kepler's laws
Assuming General Relativity

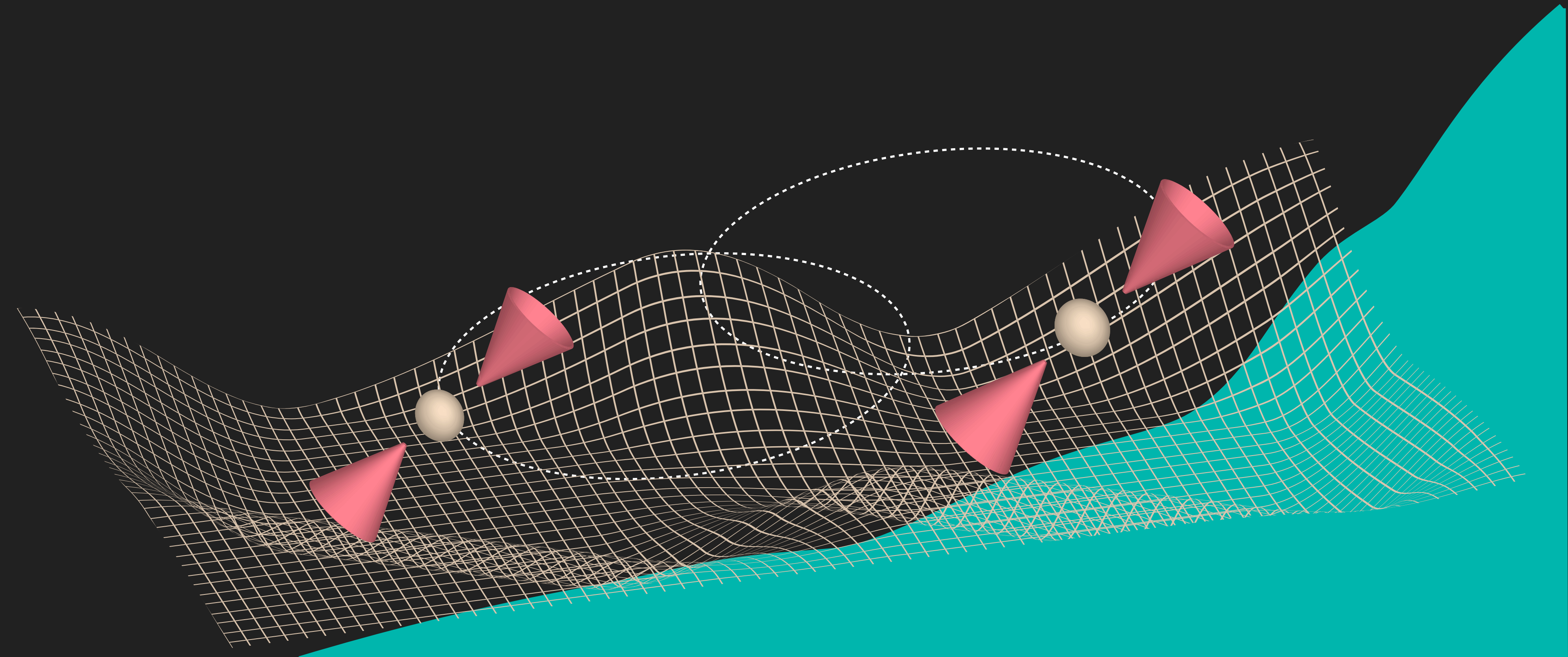
Mass measurements of binary pulsar systems



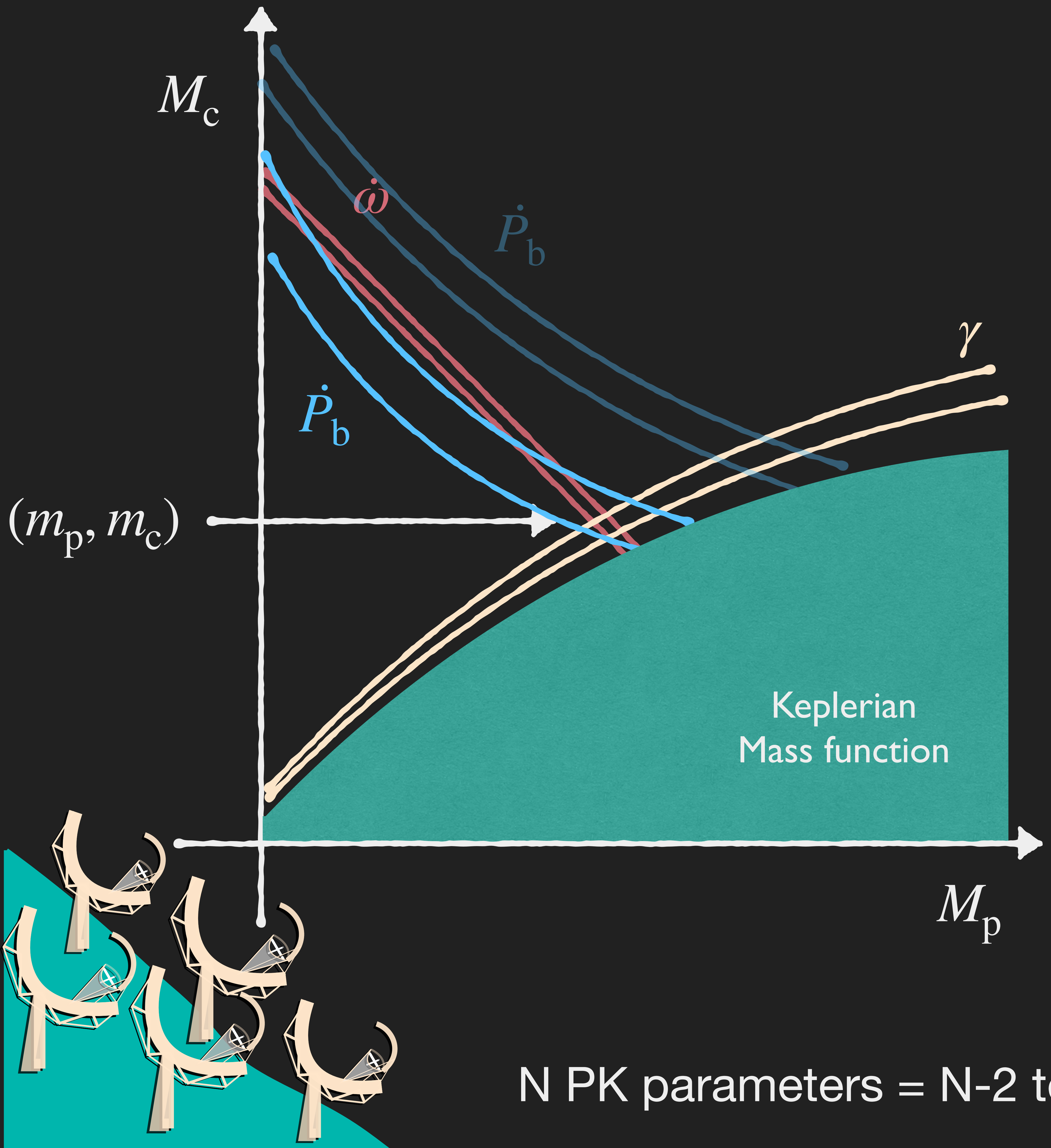


What if you can measure more?





Testing gravity

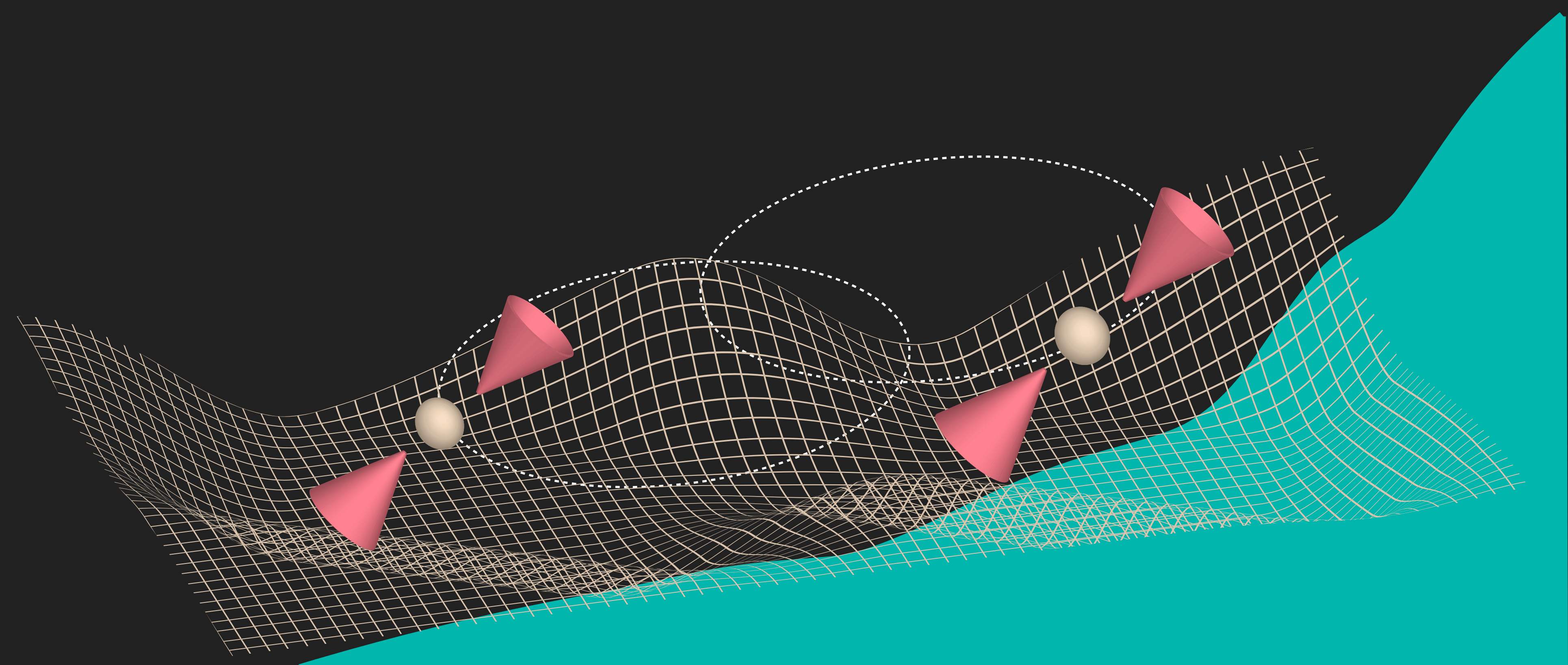


$$\dot{\omega} = 3\left(\frac{G^{2/3}}{c^2}\right)\left(\frac{P_b}{2\pi}\right)^{-5/3}\frac{(m_p + m_c)^{2/3}}{1 - e^2}$$

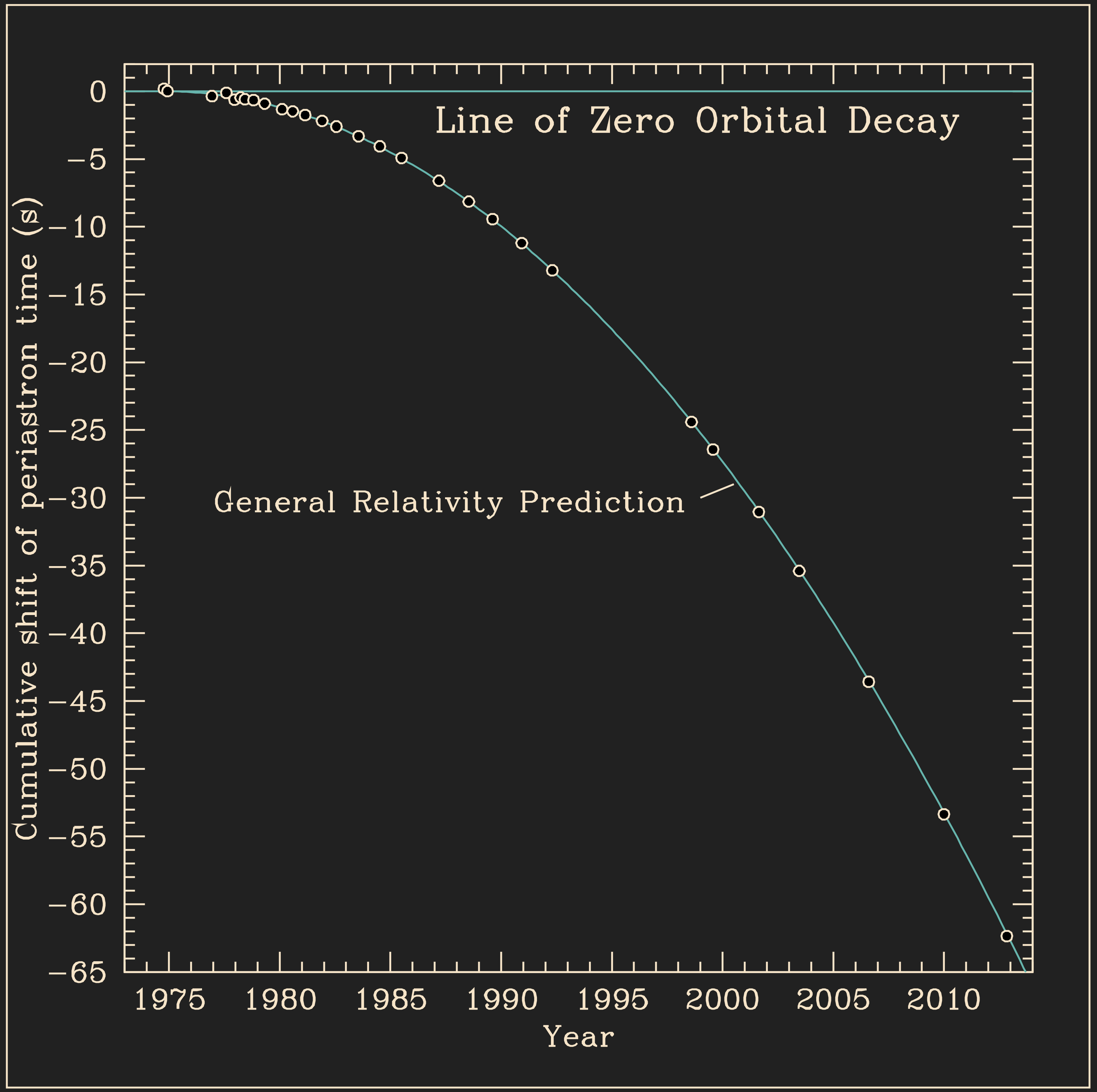
$$\gamma = \left(\frac{G^{2/3}}{c^2}\right)\left(\frac{P_b}{2\pi}\right)^{1/3} e\, m_p(m_p + 2m_c)\,(m_p + 2m_c)^{-4/3}$$

$$\dot{P}_b = -\frac{192\pi G^{5/3}}{5c^5}\left(\frac{P_b}{2\pi}\right)^{5/3}\frac{(1 + 73e^2/24 + 37e^4/96)}{(1 - e^2)^{7/2}} m_p m_c (m_p + m_c)^{-1/3}$$

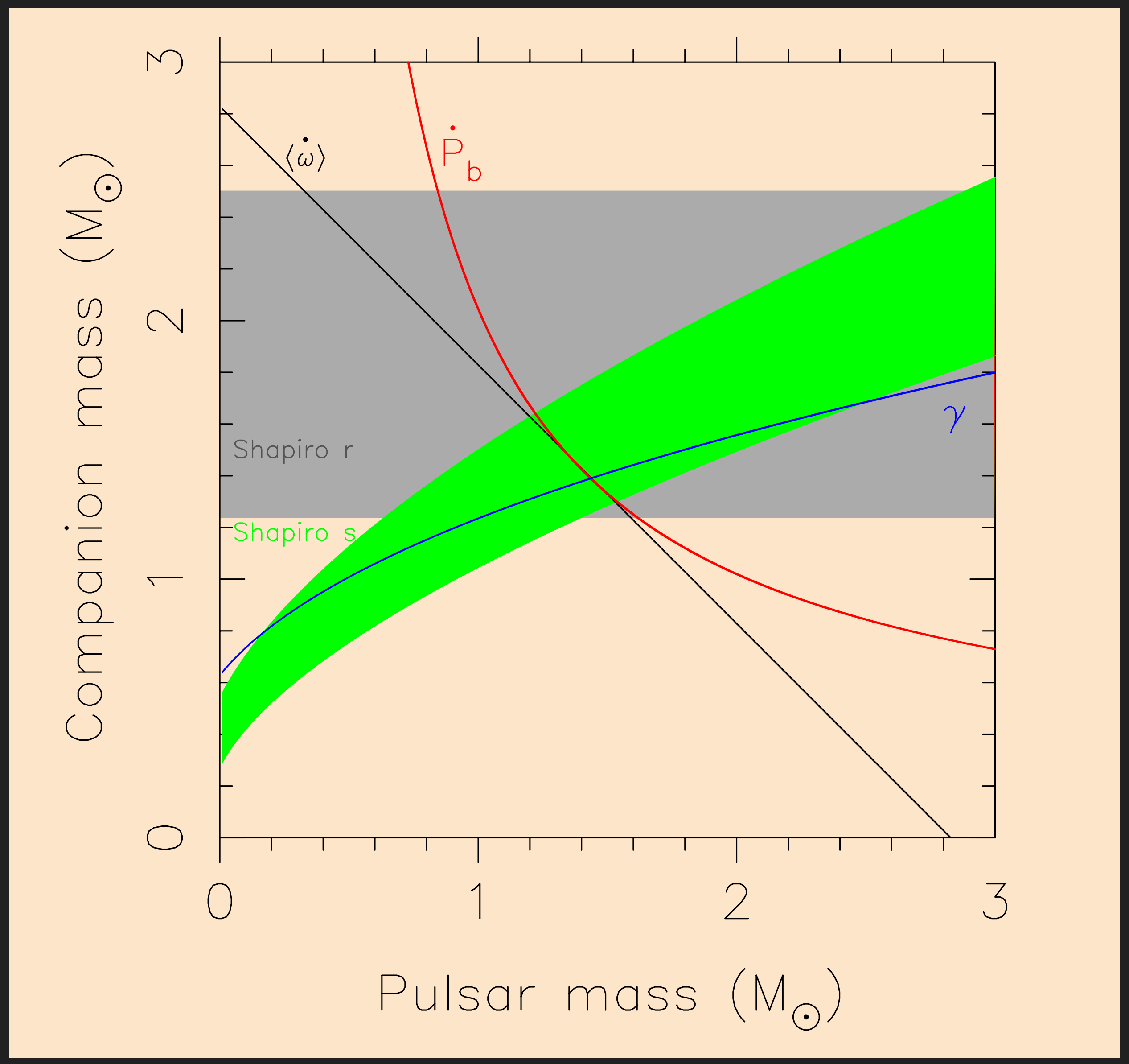
N PK parameters = N-2 tests of the theory



The Hulse-Taylor pulsar: PSR B1913+16

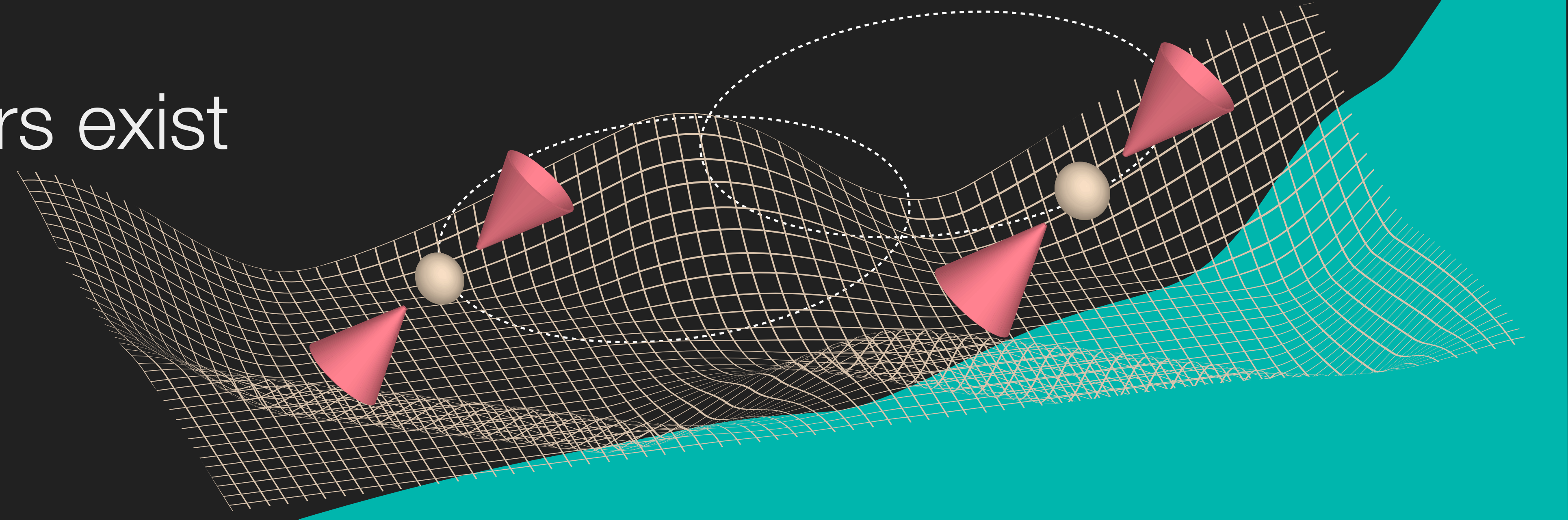


[Weisberg & Huang 2016]

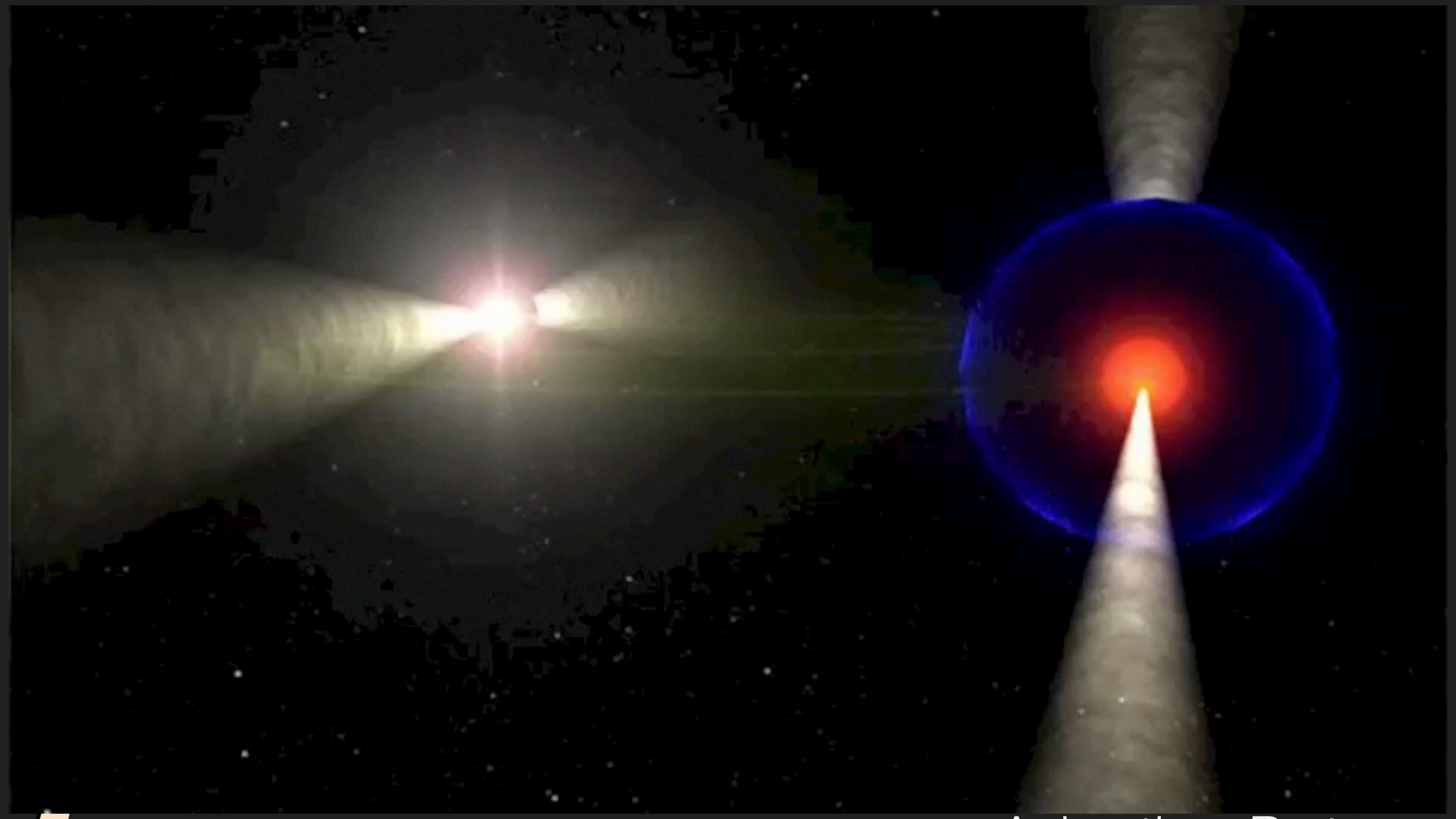


[Weisberg & Huang 2016]

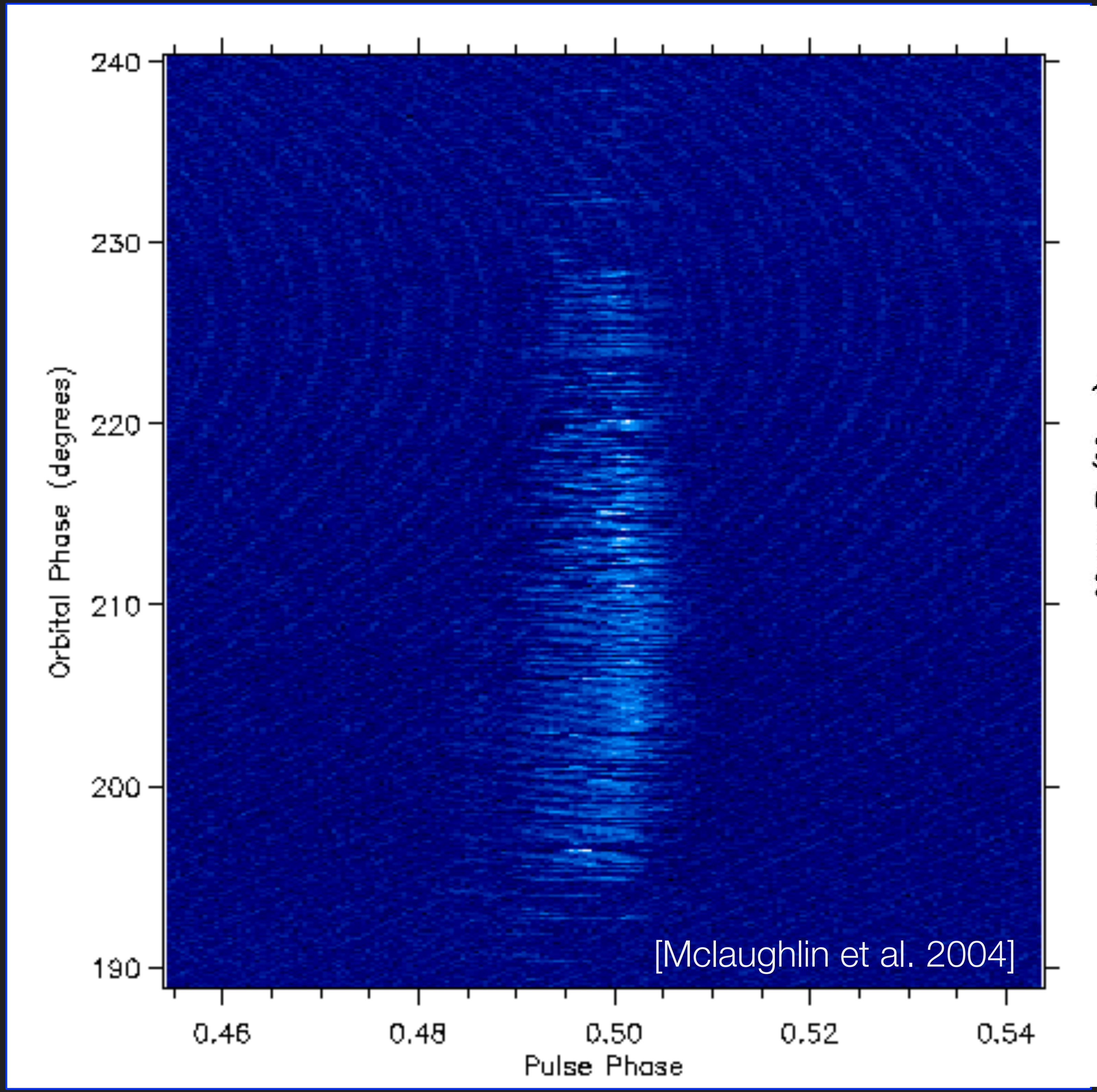
- ☐ Gravitational waves exist with energy loss predicted by GR
- ☐ GR holds in strongly curved spacetime
- ☐ DNS mergers exist

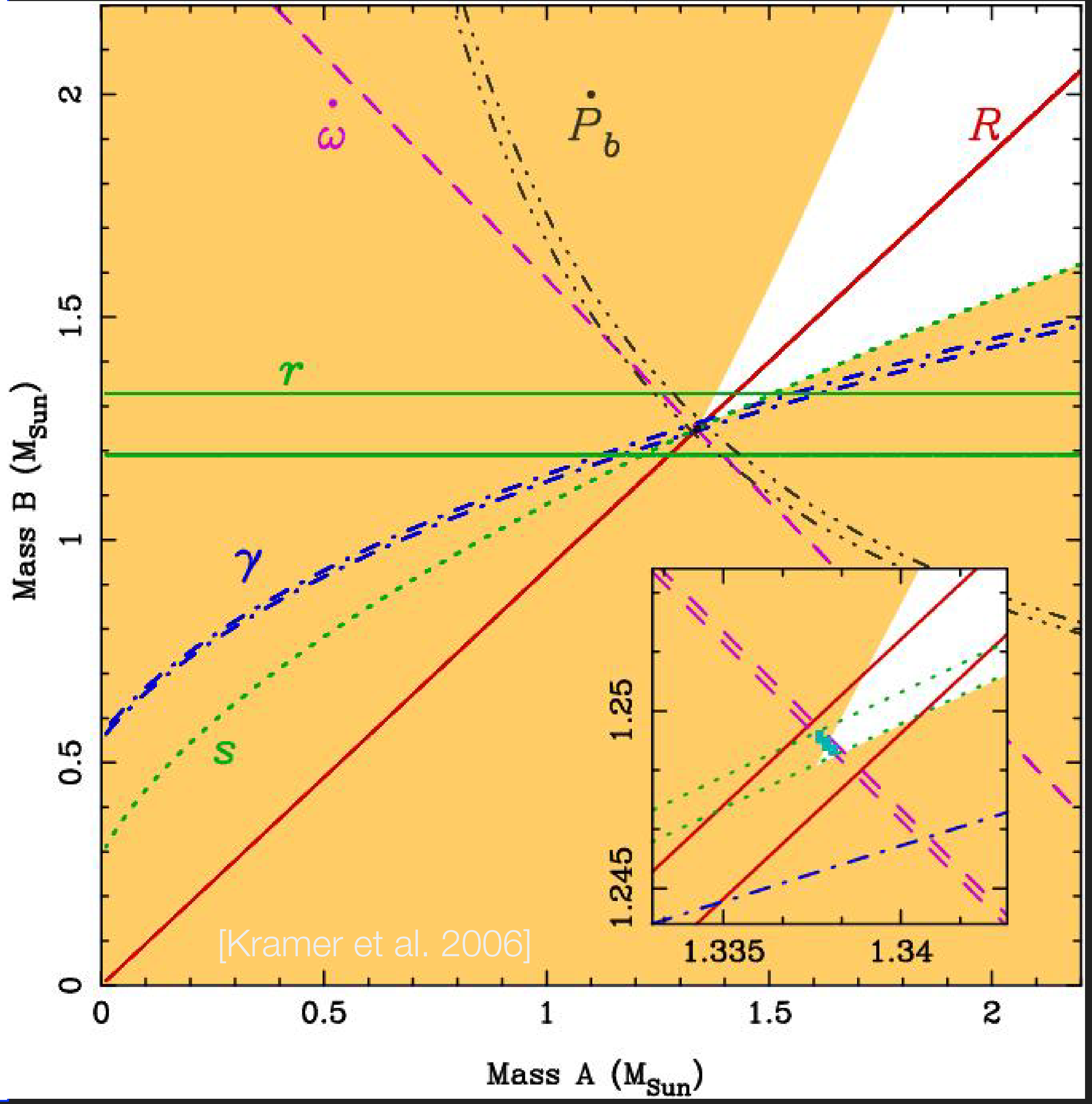


The double pulsar



Animation: Breton

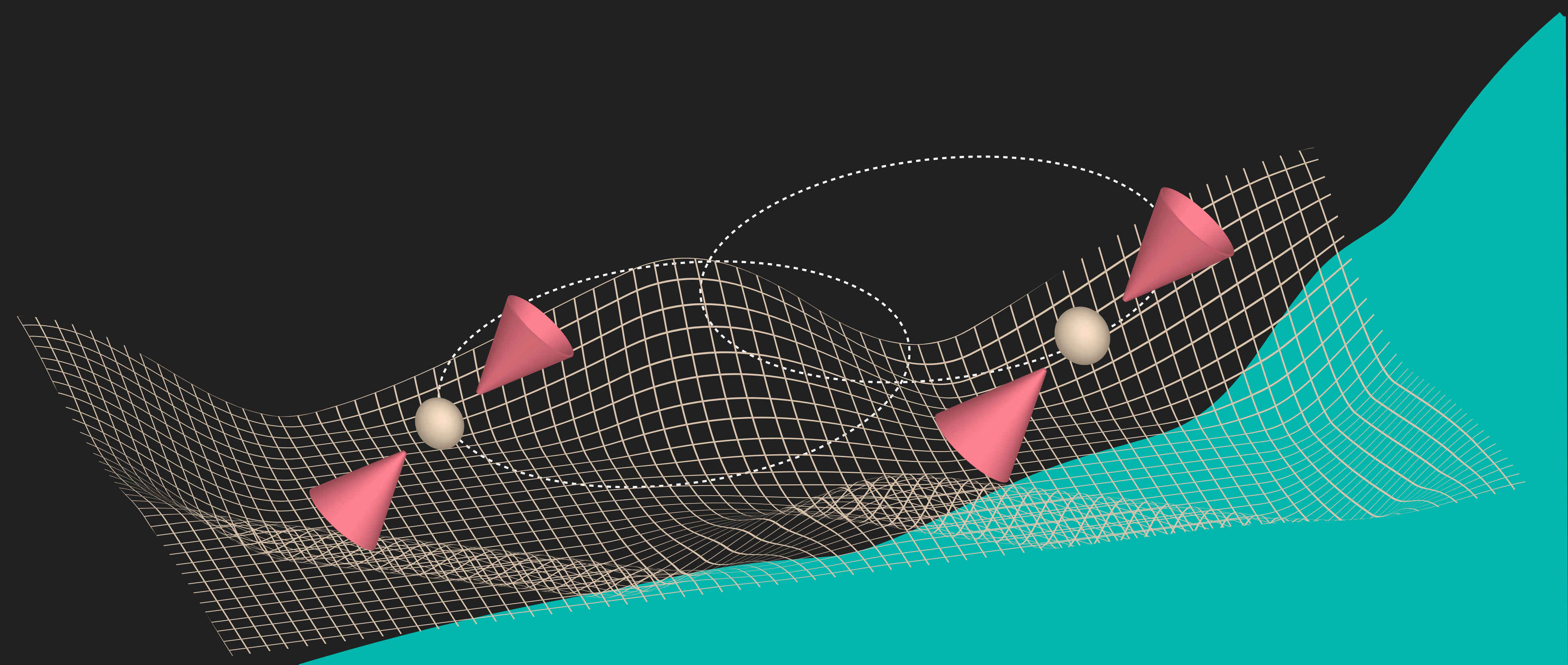




Spin periods: 23 ms / 2.8 s

Orbital period: 2.45 h

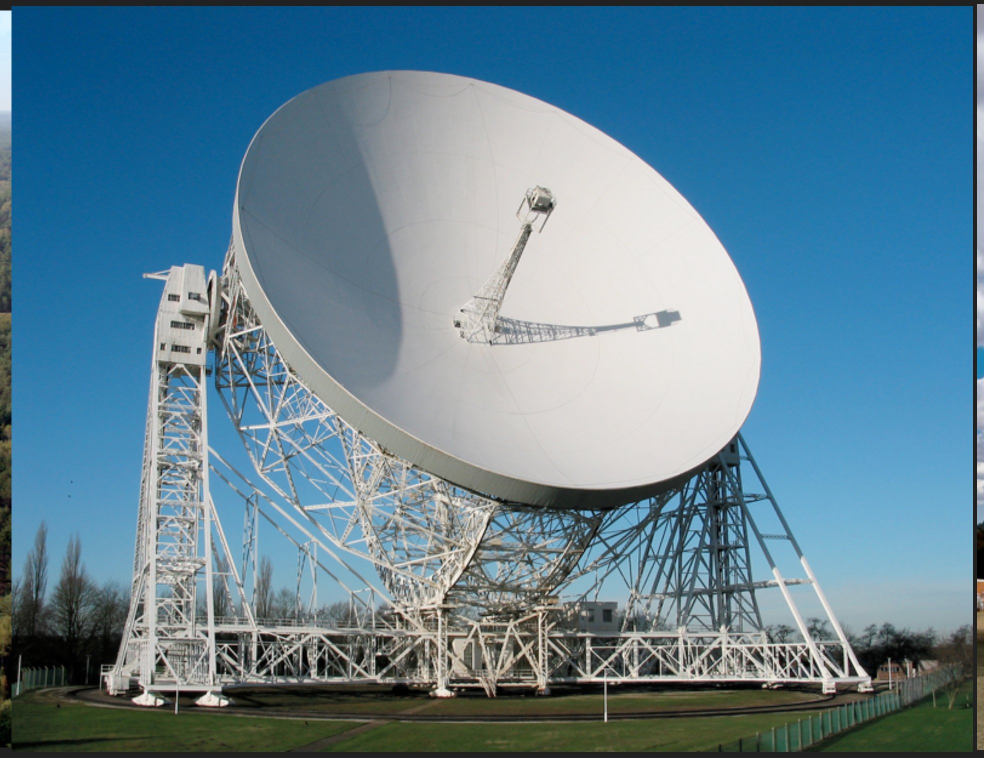
Eccentricity: 0.088



The double pulsar: until now

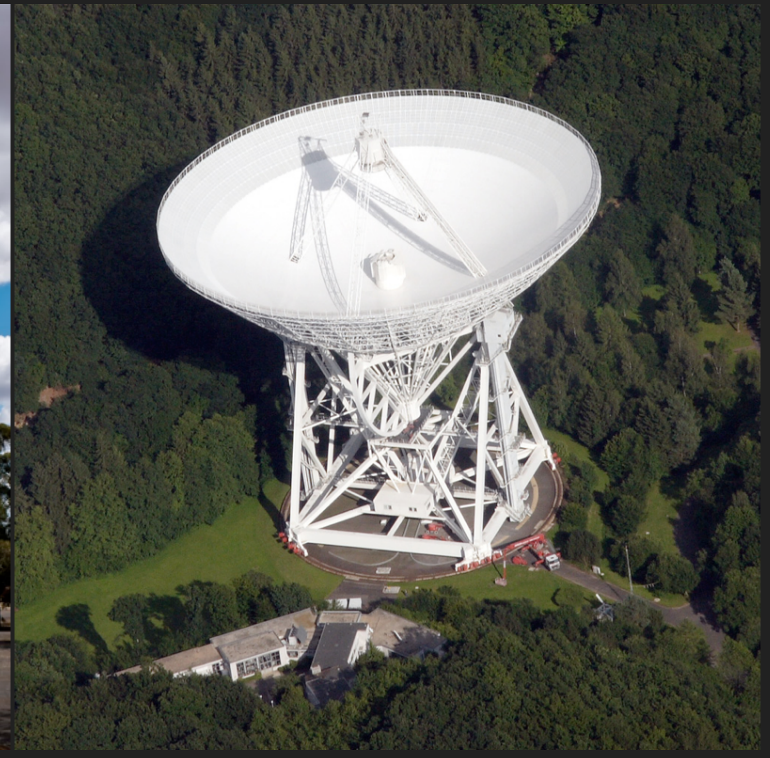
Green Bank
Telescope, USA

Nancay Radio
Telescope, France



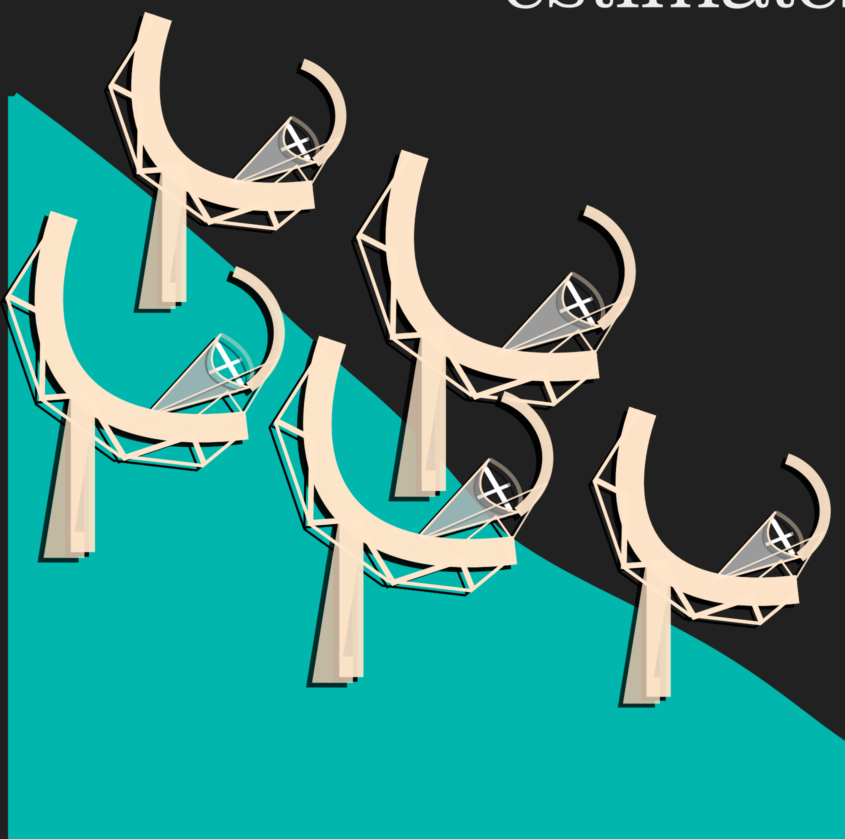
Lovell telescope, UK

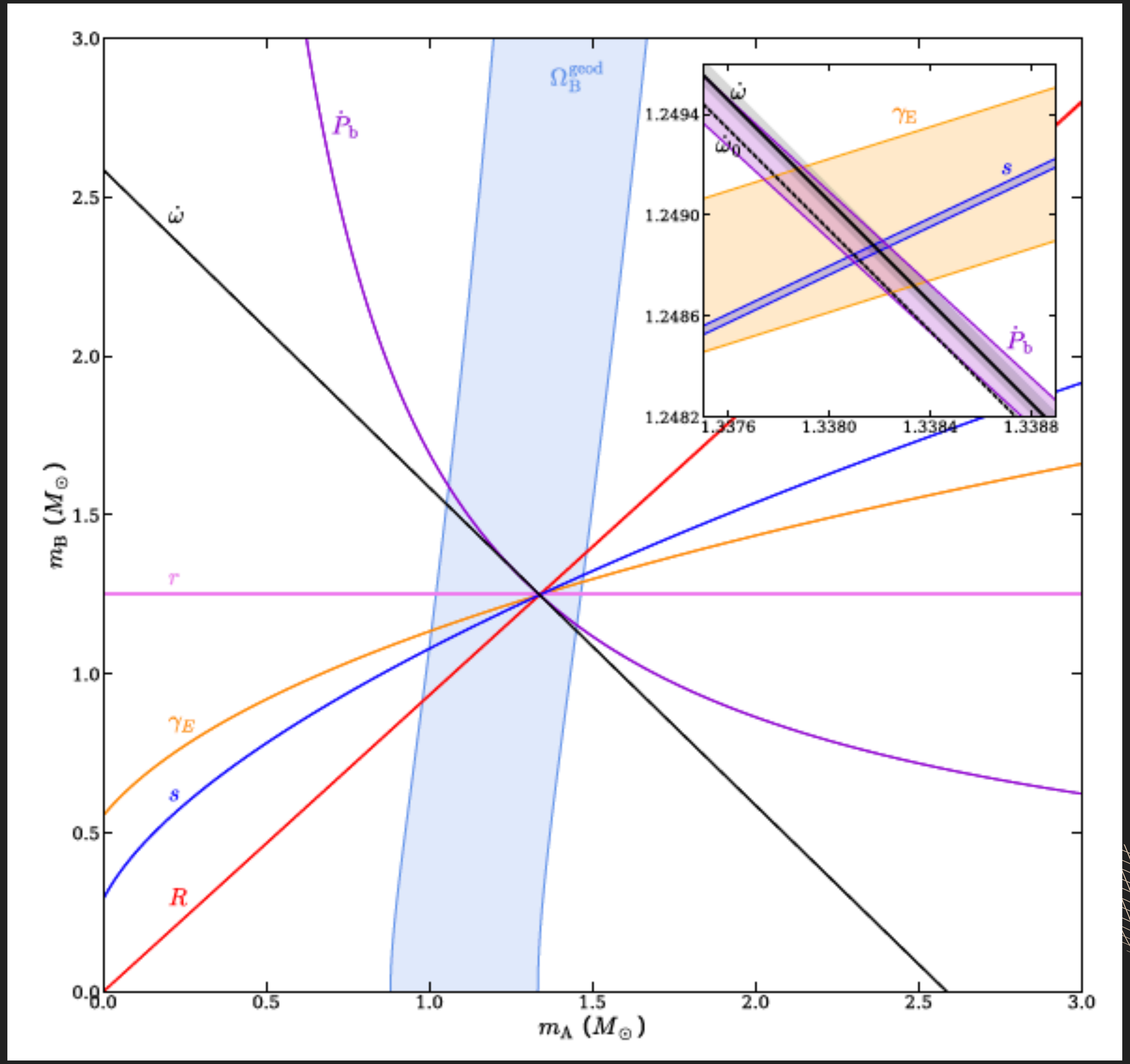
Parkes Radio Telescope,
Australia



100-m Effelsberg telescope,
Germany

1 million arrival time
estimates over 16 years



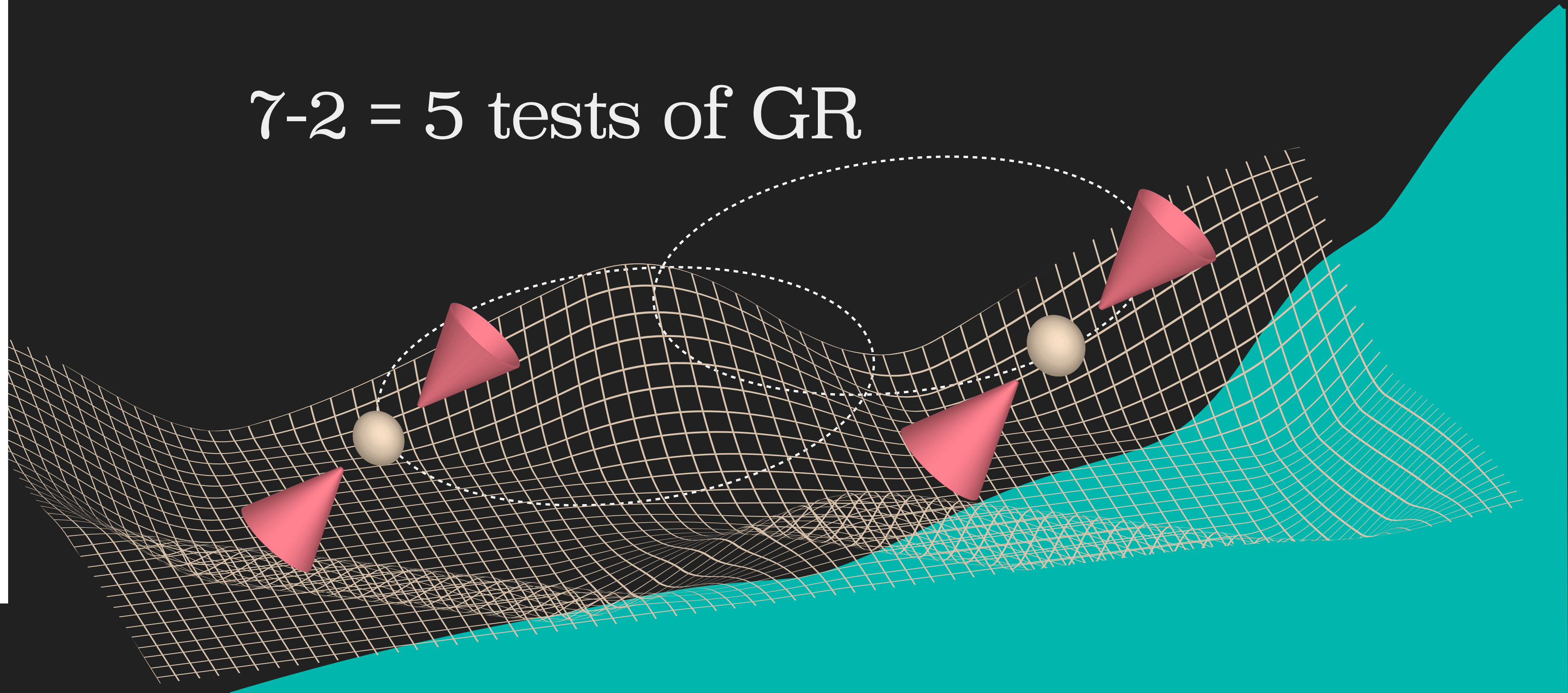


Kramer et al. (submitted)

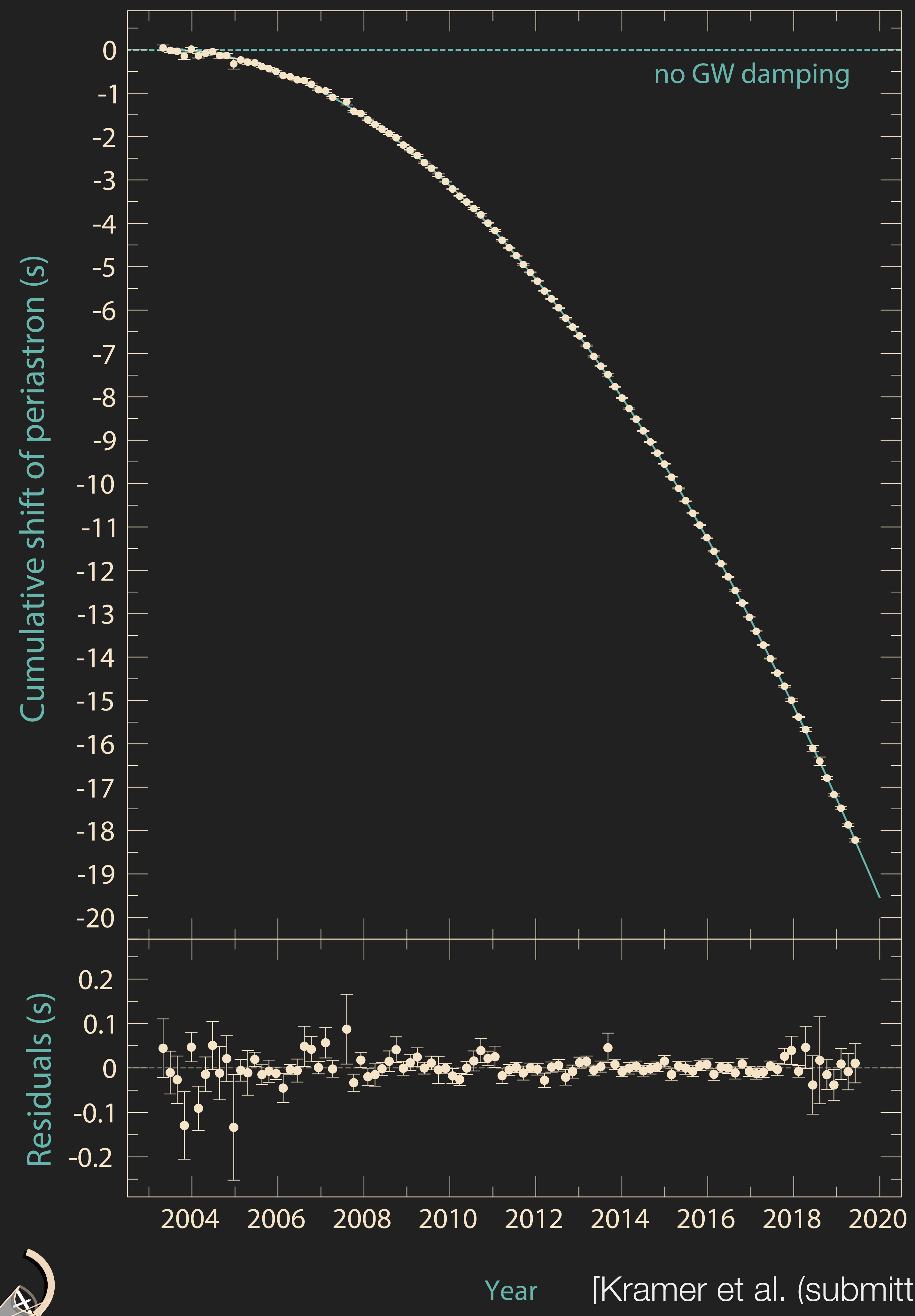
$m_p = 1.33818(1)M_\odot$

$m_c = 1.24886(1)M_\odot$

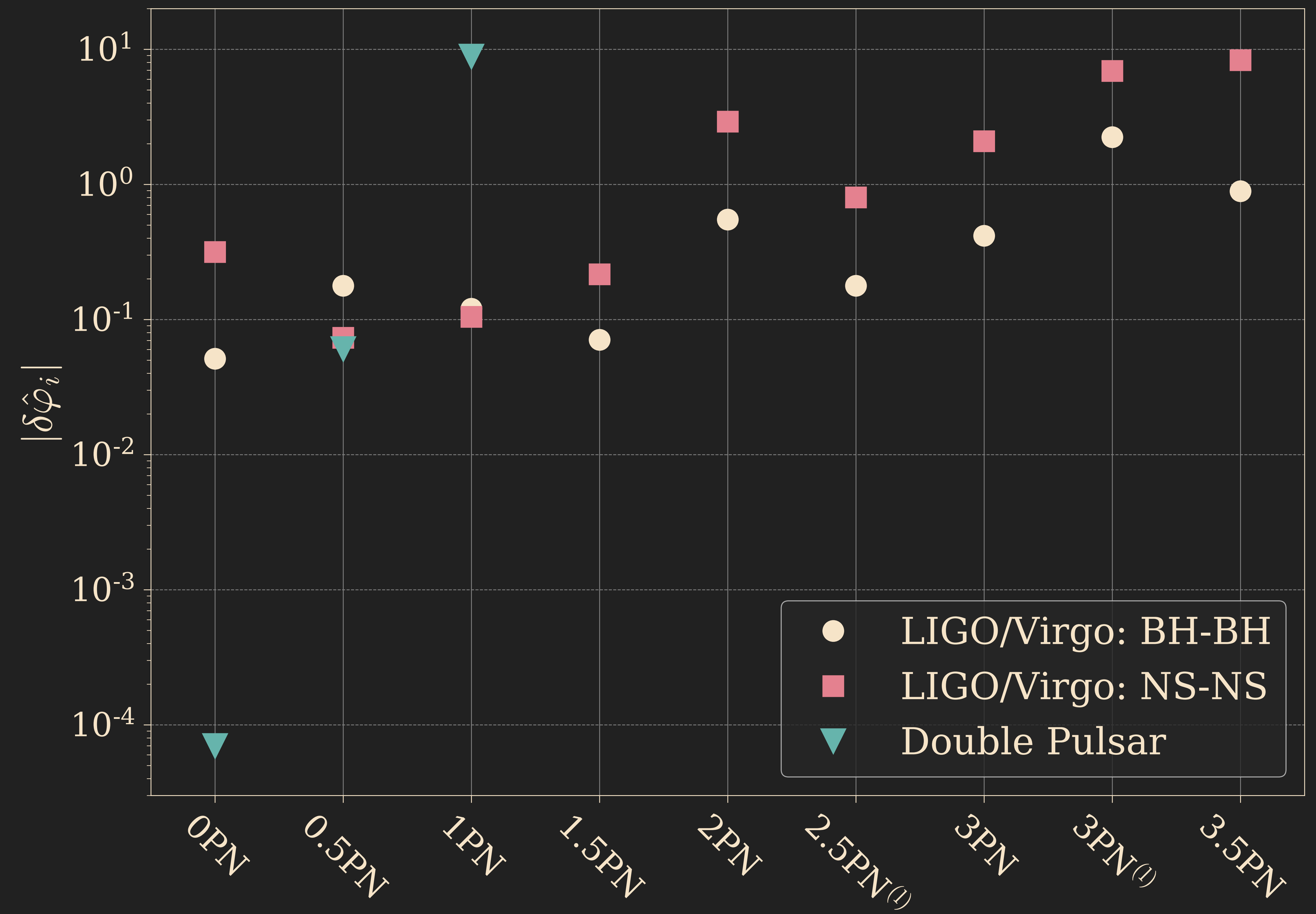
7-2 = 5 tests of GR



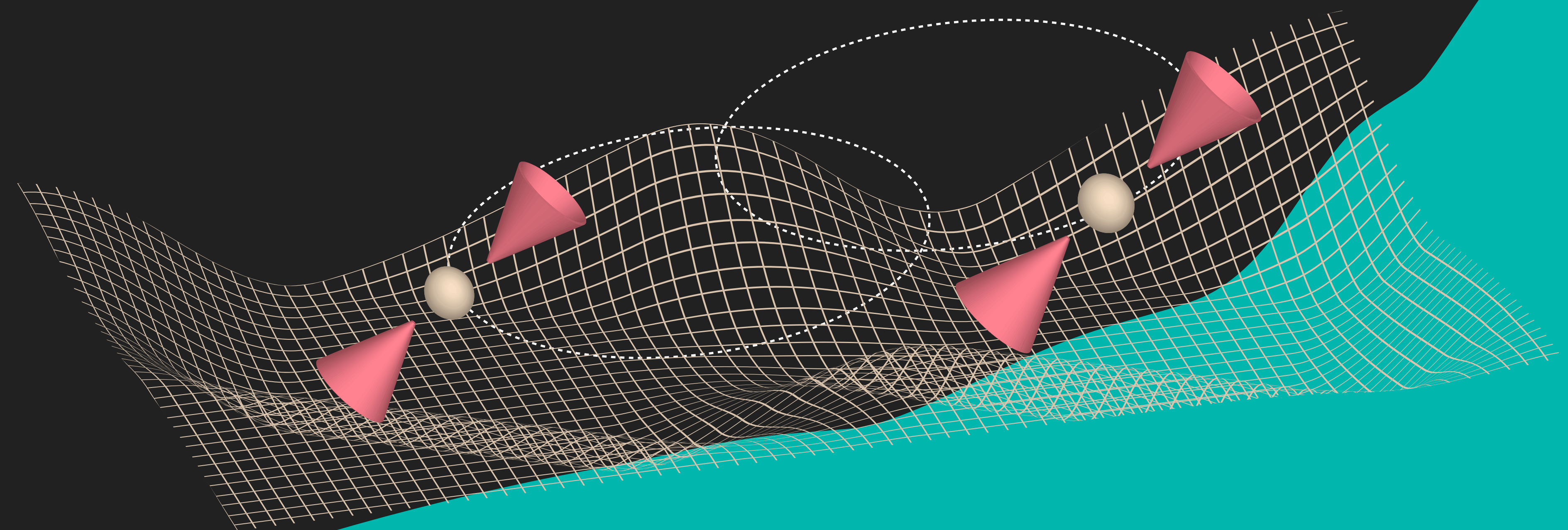
The double pulsar: gravitational wave damping



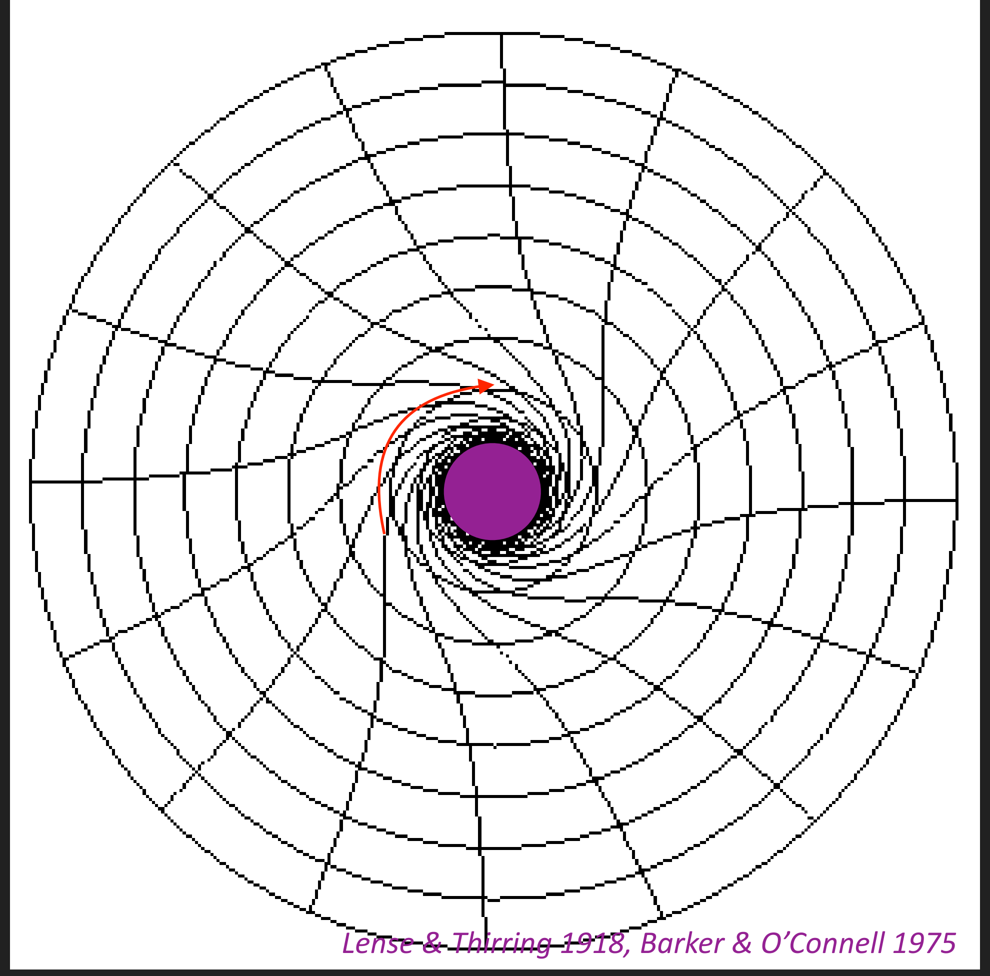
[Kramer et al. (submitted)]

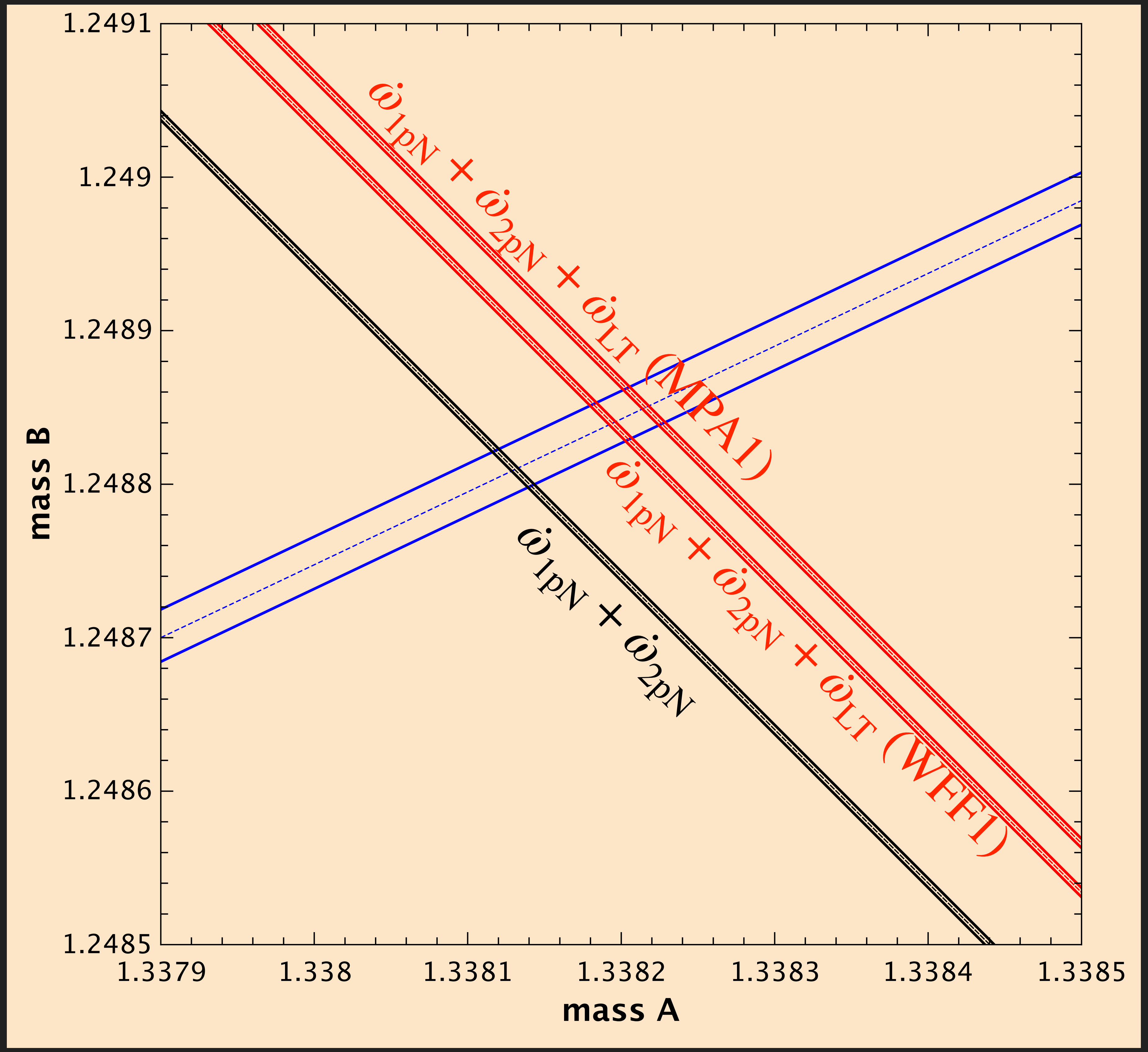


[LSC 2016,2018,2019, Kramer et al. (submitted)]



The double pulsar: LT precession?



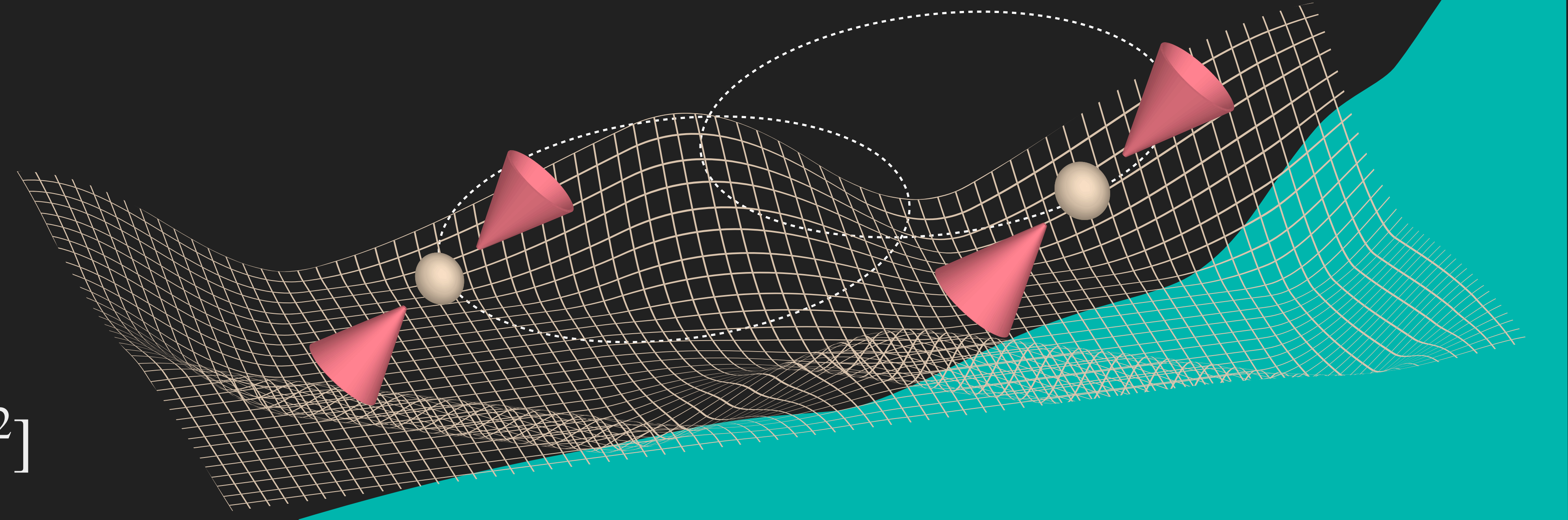


[Kramer et al. (submitted)]

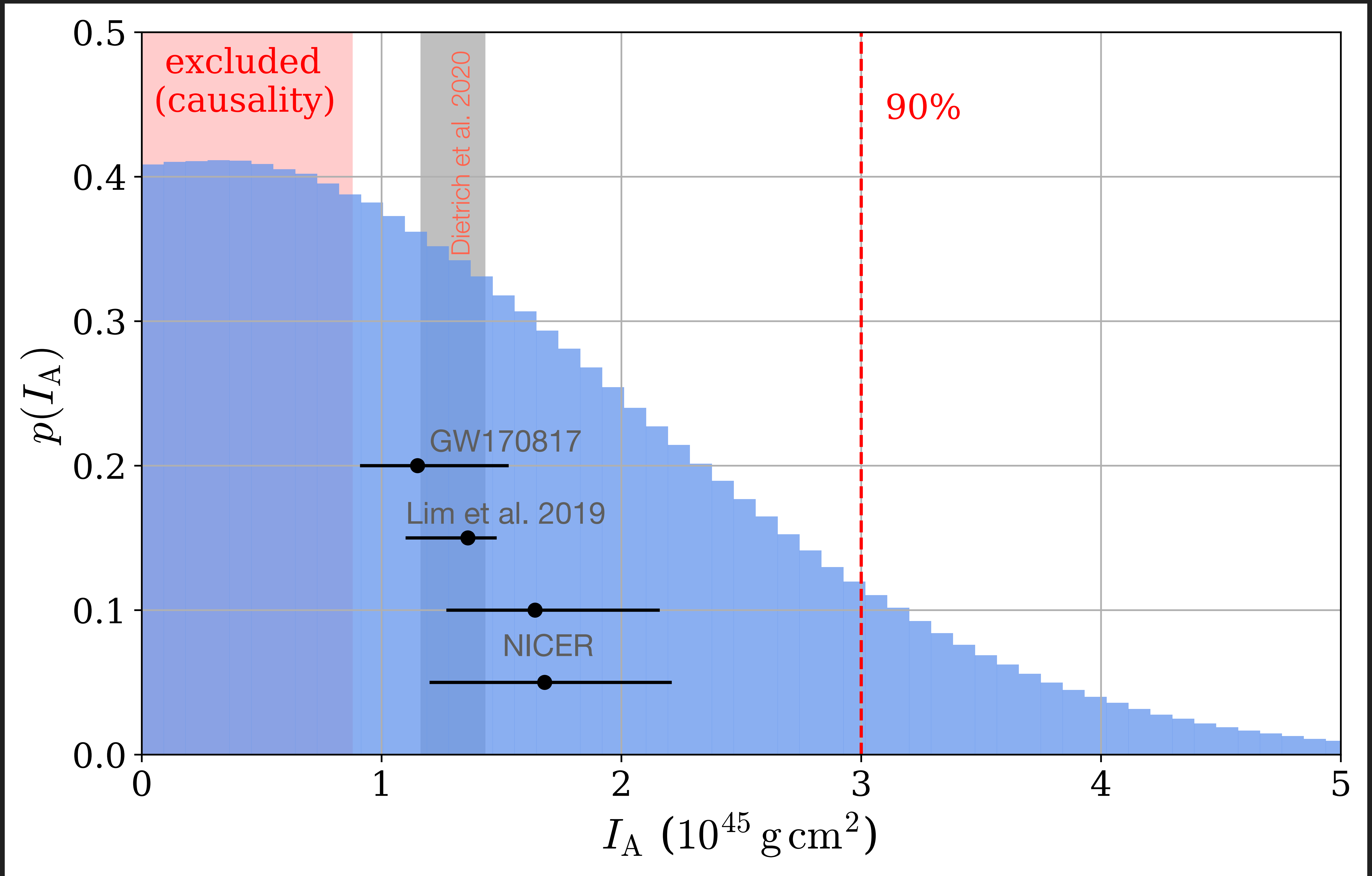
$$\dot\omega_{\rm obs} = \dot\omega_{\rm 1PN} + \dot\omega_{\rm 2PN} + \dot\omega_{\rm LT}$$

$$\dot\omega_{\rm LT} = -T_\odot \left(\frac{P_b}{2\pi}\right)^{-2} \frac{1}{(1-e^2)^{3/2}} \frac{4m_p + 3m_c}{m_p + m_c} \frac{c}{G} S_p$$

$$\dot\omega_{\rm obs}[\rm deg/yr] = 16.899317(13)$$
$$\dot\omega_{\rm 2pN}[\rm deg/yr] = 0.000439$$
$$\dot\omega_{\rm LT}[\rm deg/yr] = -0.000377 \times I_A\,[10^{45}\,\rm g\,cm^2]$$



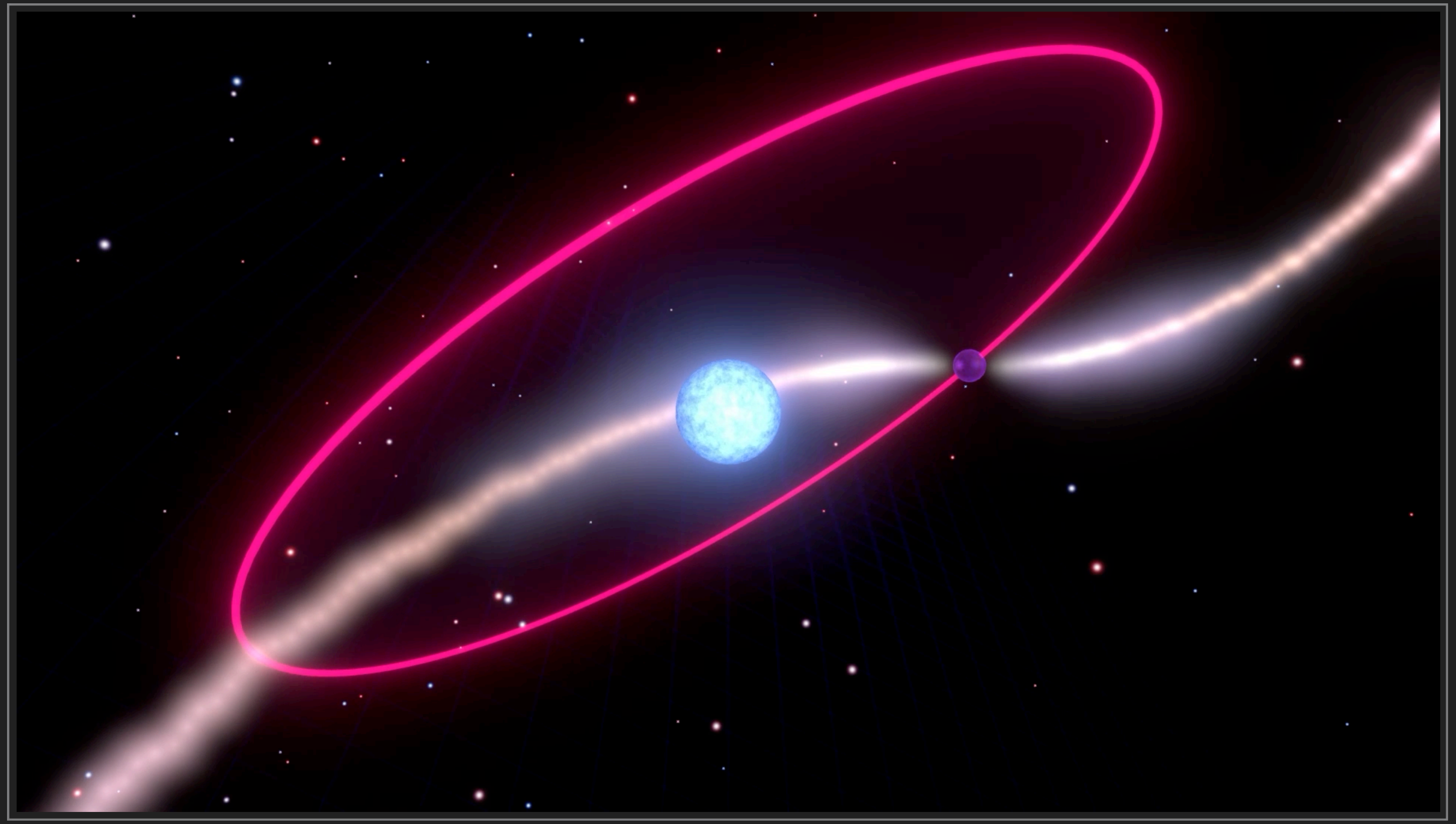
Constraints on MoI



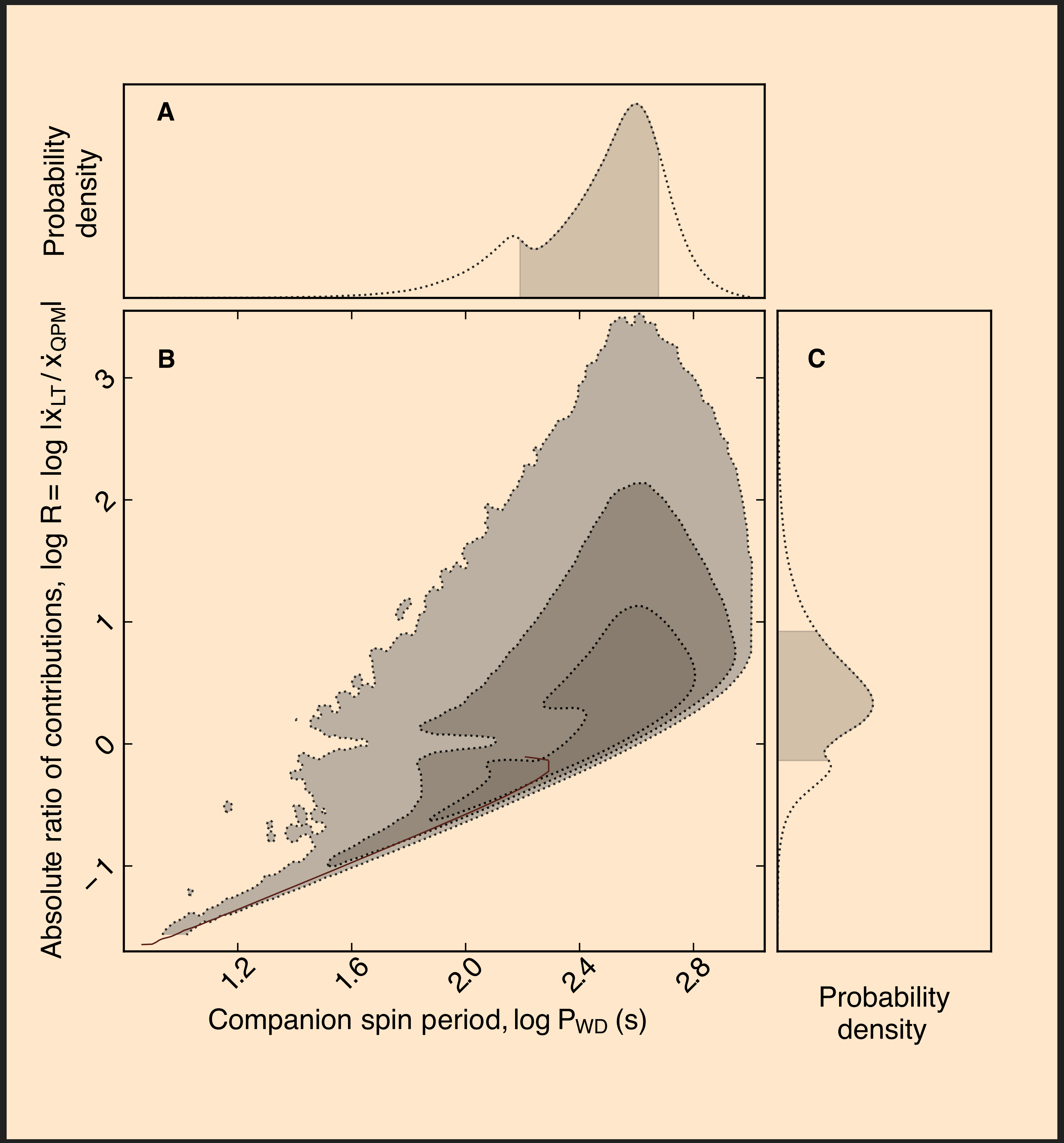
[Kramer et al. (submitted)]

Check Hu et al. 2020 for predictions

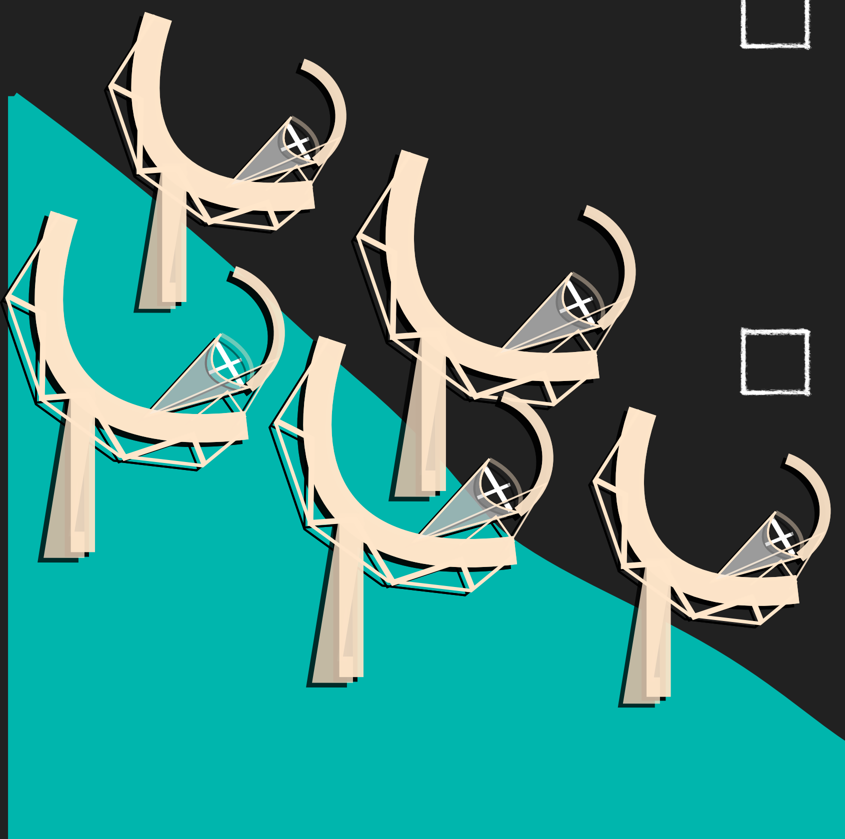
J1141-6545

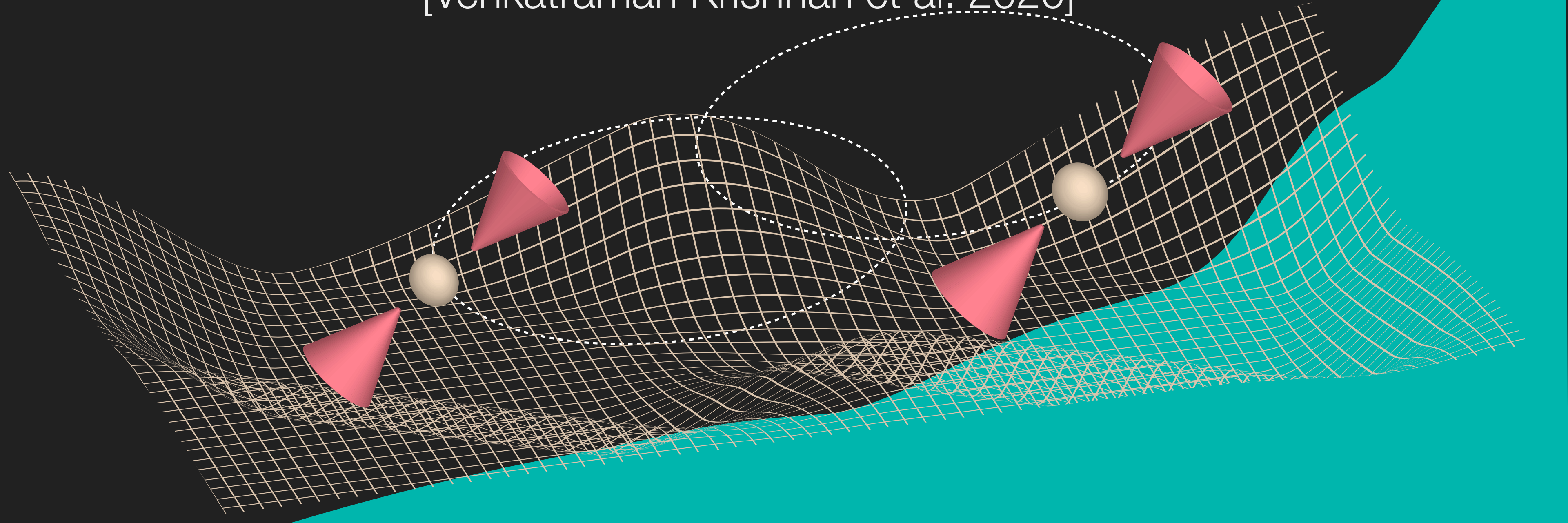


- ☐ Pulsar-WD system with a young pulsar - 394ms spin period in a 4.74-hr orbit
- ☐ Peculiar binary evolution
- ☐ LT precession makes the orbit tumble: 1.7” per year
- ☐ Use LT precession as a tool to infer the spin-period of the WD



[Venkatraman Krishnan et al. 2020]

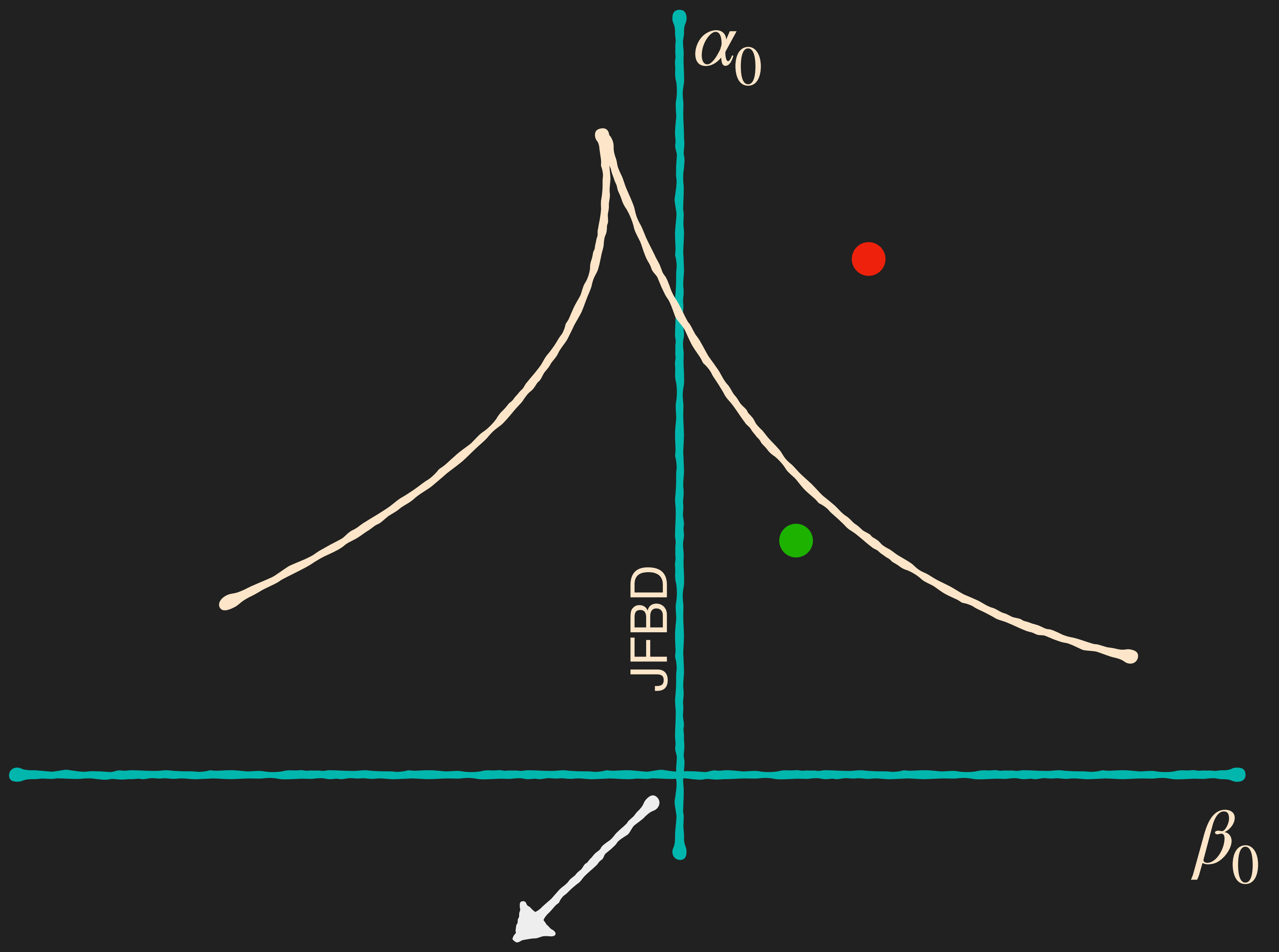




Tests of alternative theories of gravity: DEF gravity

[Damour & Esposito Farésé 1992,1993,1996,1998]

- DEF gravity:
  - Scalar-tensor theory of gravity
  - Gravity is mediated by a scalar φ in addition to the Einstein metric $g_{\mu\nu}$
  - Natural extension of GR, generalisation of JFBD theory

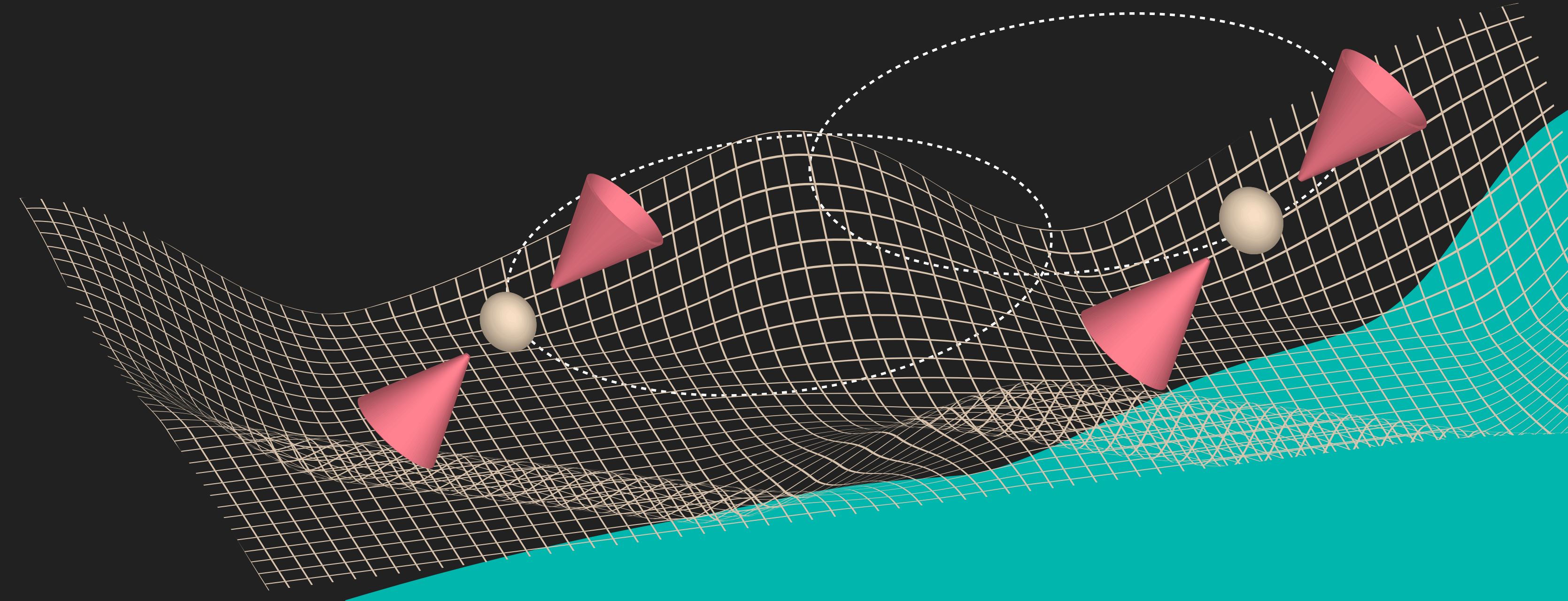


$\alpha_0 = \beta_0 = 0 = GR$

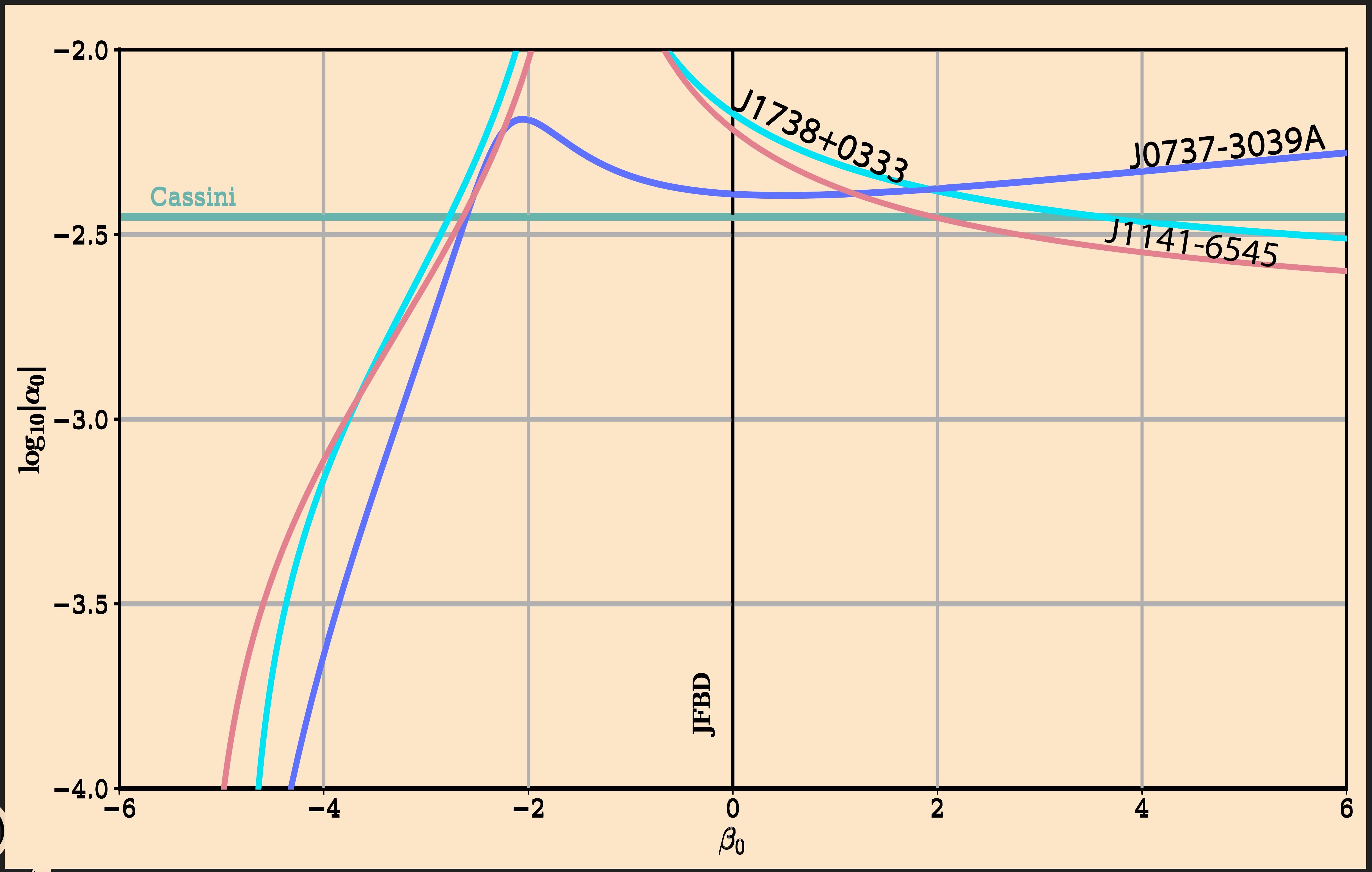
$$\tilde{g}_{\mu\nu} \equiv A(\varphi)^2 g_{\mu\nu}; \quad A(\varphi) \equiv \exp\left(\frac{1}{2}\beta\varphi^2\right)$$

$$\alpha(\varphi) \equiv \frac{\partial \ln(A(\varphi))}{\partial\varphi} = \beta\varphi; \quad \beta(\varphi) \equiv \frac{\partial^2 \ln(A(\varphi))}{\partial\varphi^2} = \frac{\partial\alpha(\varphi)}{\partial\varphi}.$$

At infinity, $\varphi = \varphi_0; \implies \alpha = \alpha_0; \beta = \beta_0$.



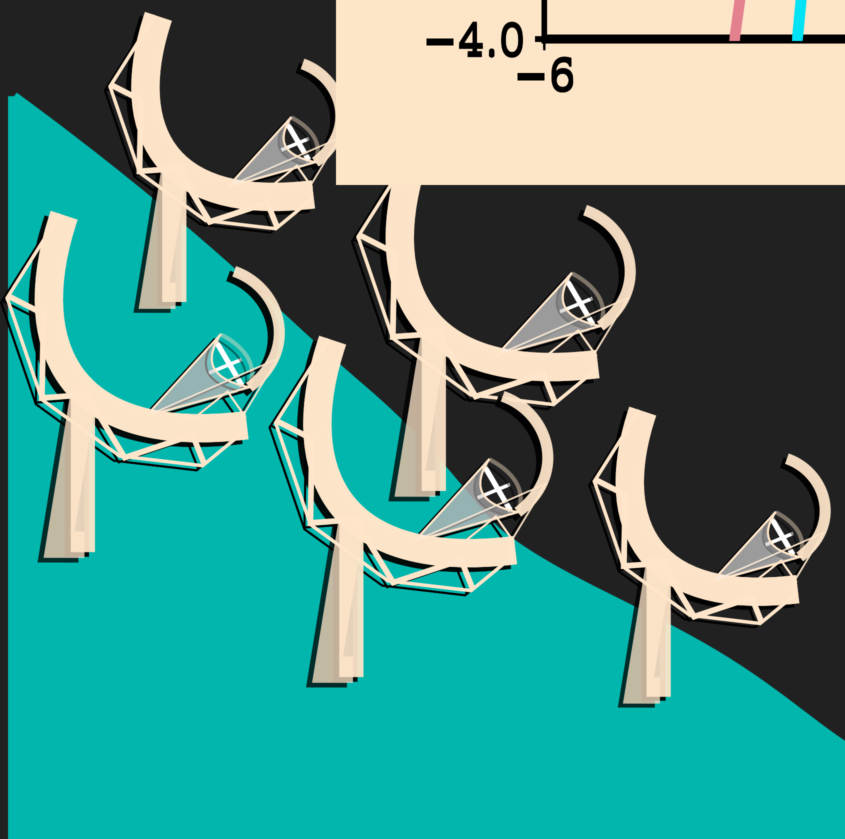
DEF gravity vs Pulsars

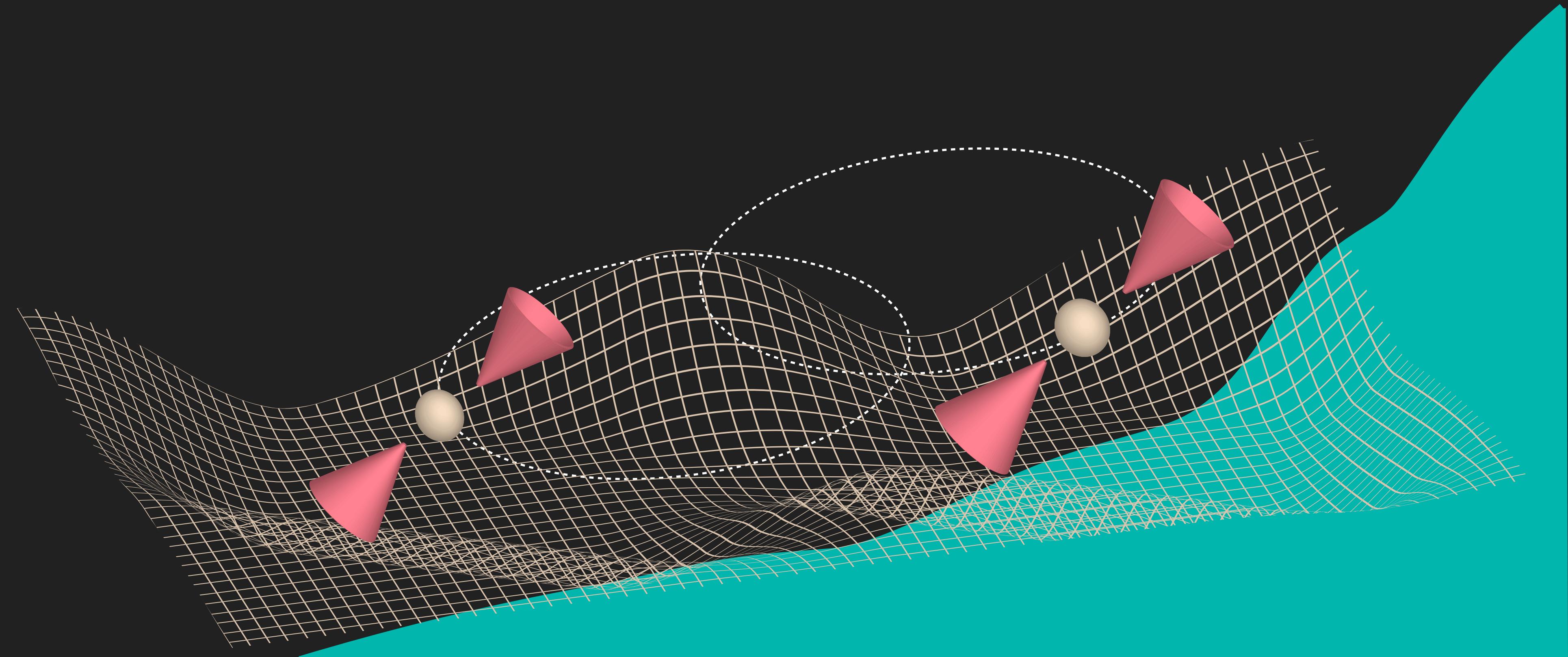


J1738+0333 - Freire et al. (2012)

J0737-3039A - Kramer et al. (submitted)

J1141-6545 - Batrakov et al. (in prep.)





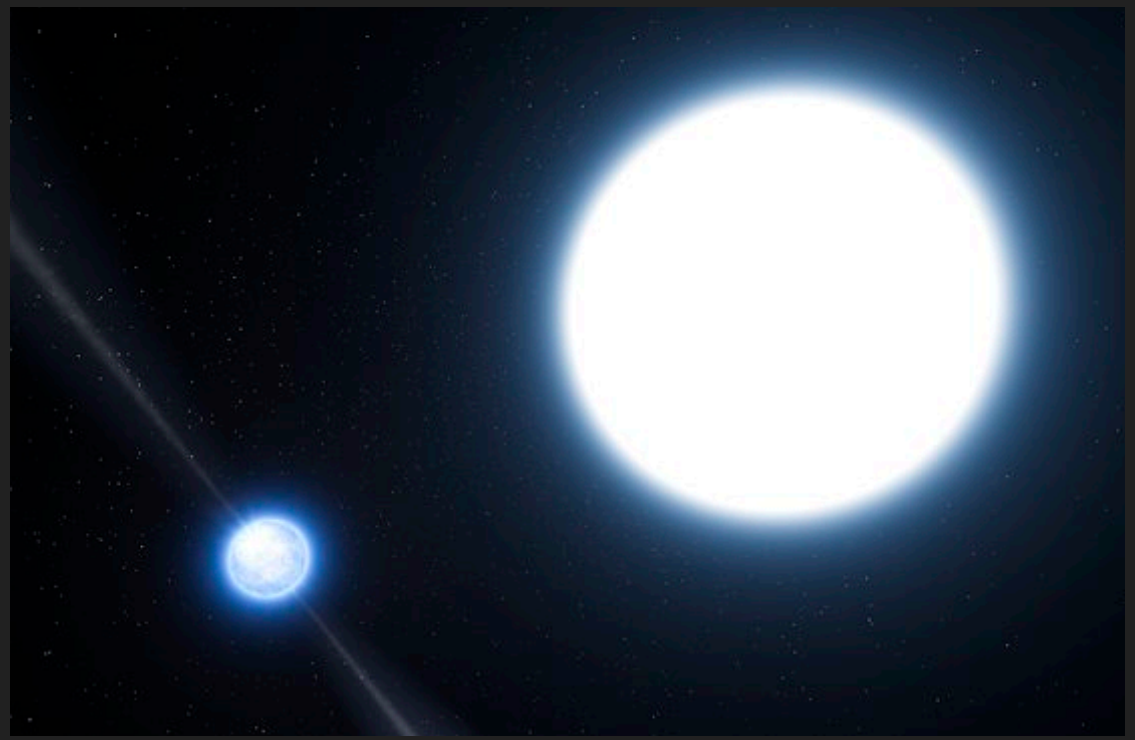
Tests of universality of free fall

Weak equivalence principle

Strong equivalence principle

Weak field

Strong field



$E_{grav} = 0$

$\epsilon \equiv \frac{E_{grav}}{mc^2} \simeq -5 \times 10^{-10}$

$\epsilon \equiv \frac{E_{grav}}{mc^2} \simeq -0.2$

MICROSCOPE

Lunar Laser Ranging

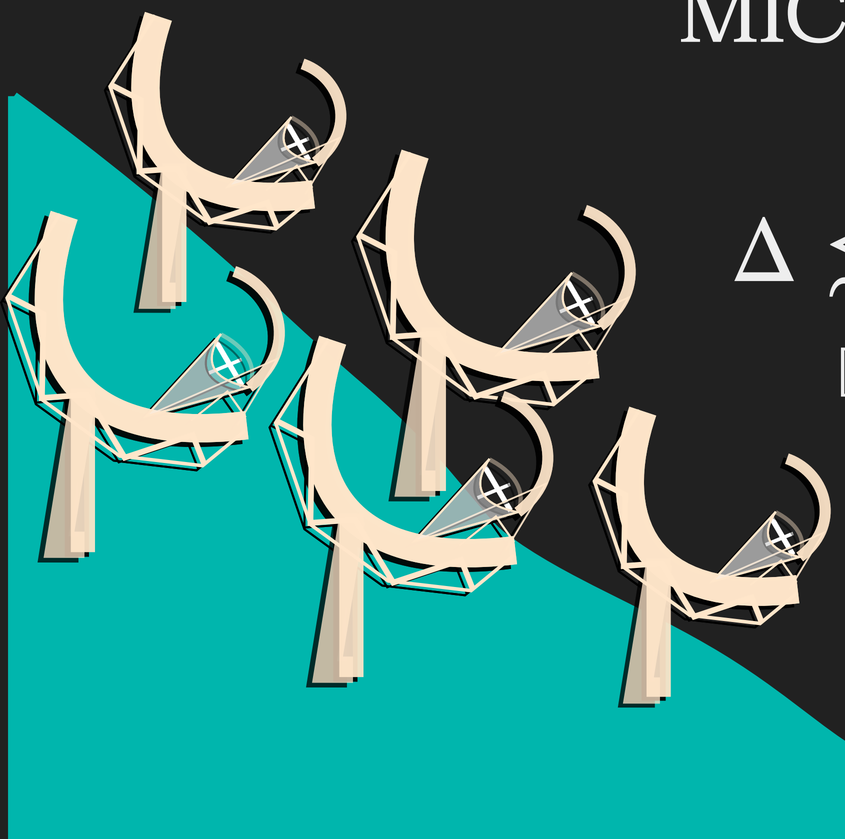
$\Delta \lesssim 10^{-14}$

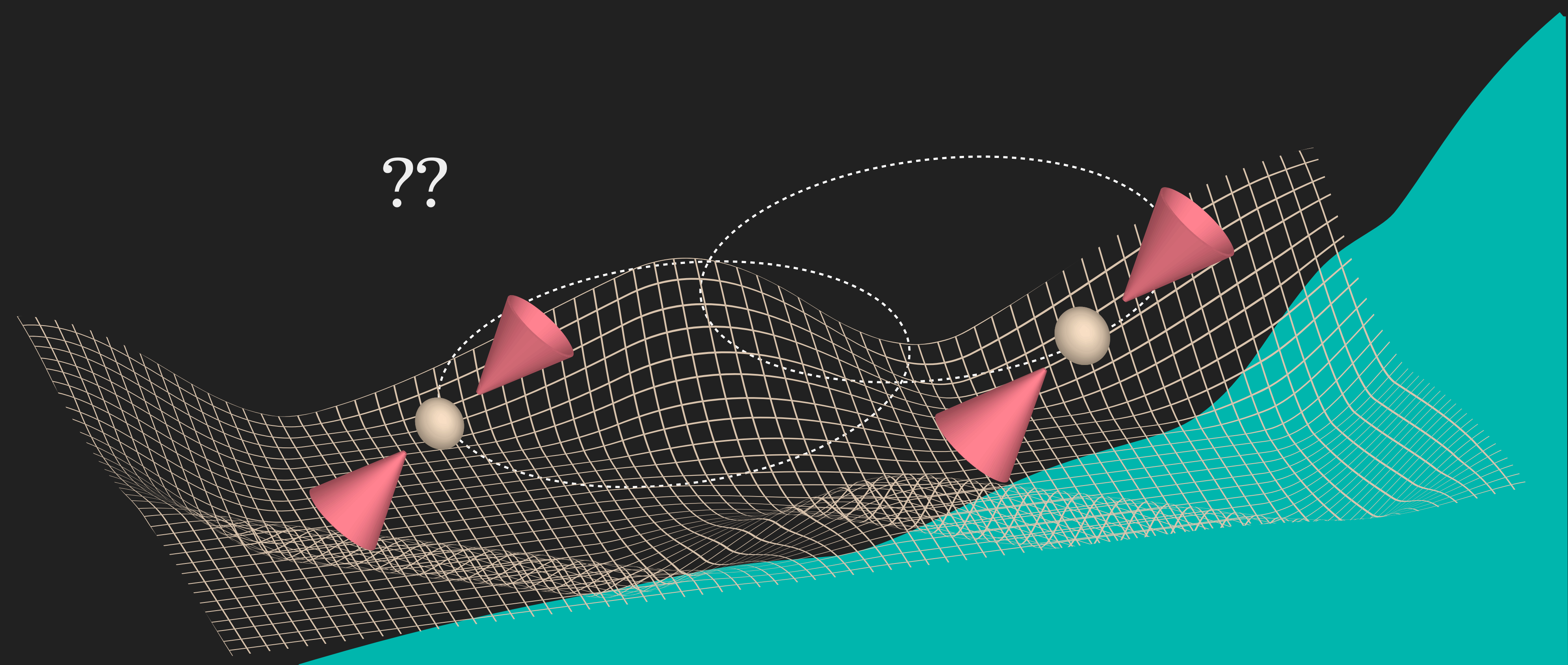
[Touboul et al. 2017]

$\Delta \lesssim 4 \times 10^{-4} |\epsilon|$

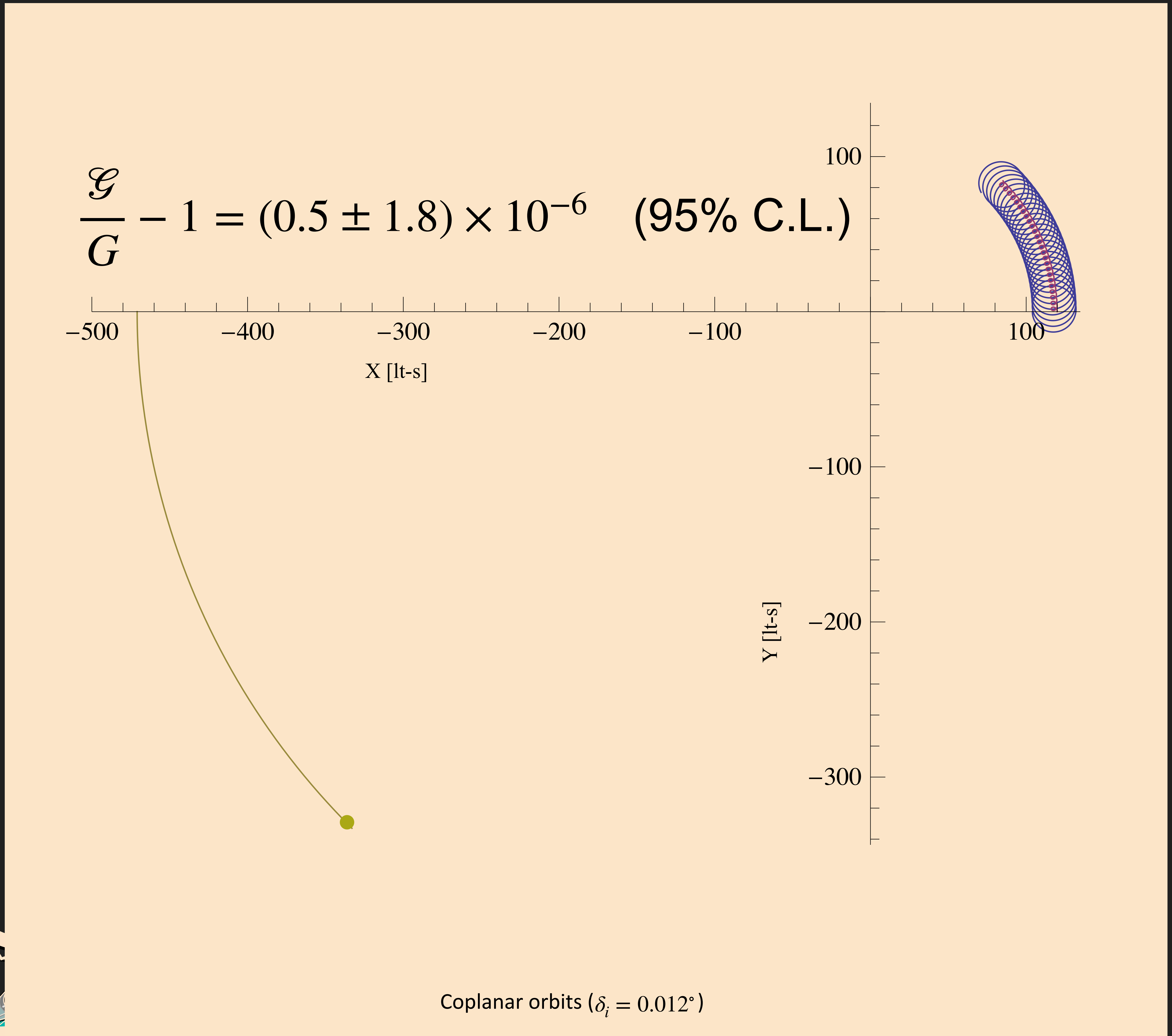
[Hofmann & Müller 2018]

??

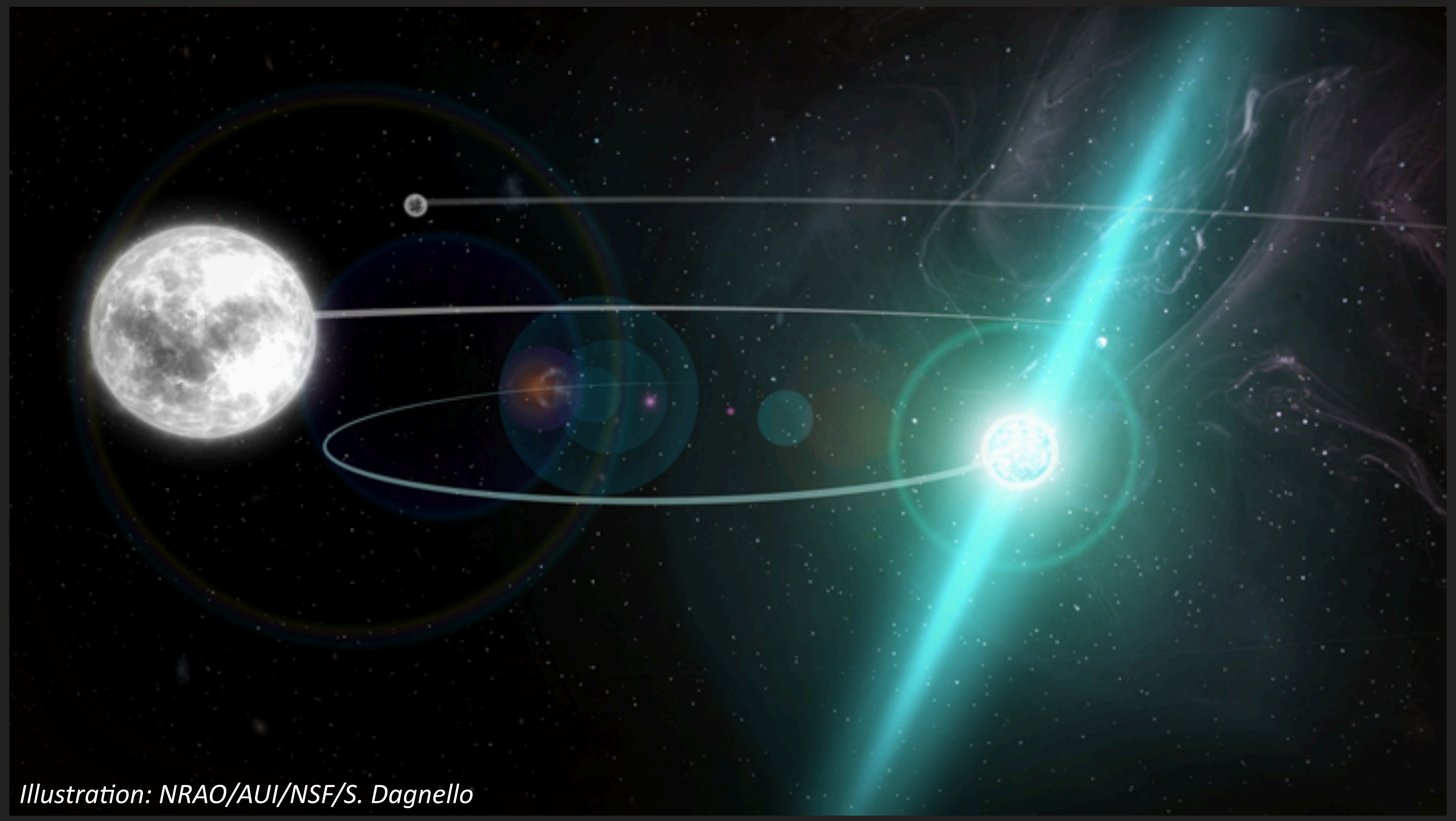




A stellar triple system

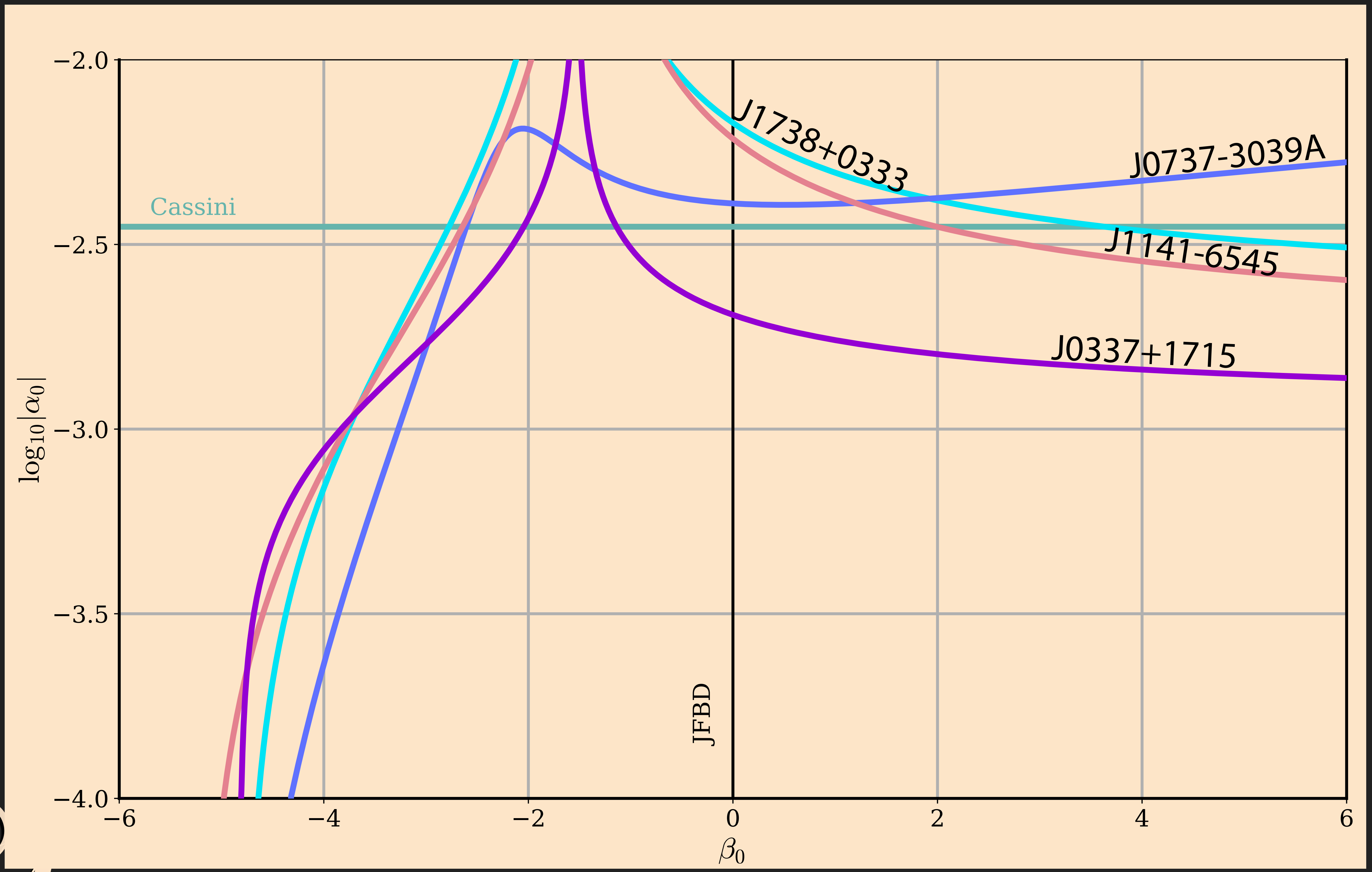


[Voison et al. 2018]



PSR J0337+1715: P = 2.7 ms, M_{PSR} = 1.436 $M_\odot$
Inner orbit: 1.63 d, M_{WD} = 0.197 $M_\odot$
Outer orbit: 327 d, M_{WD} = 0.410 $M_\odot$

Tests of scalar-tensor gravity: triple system



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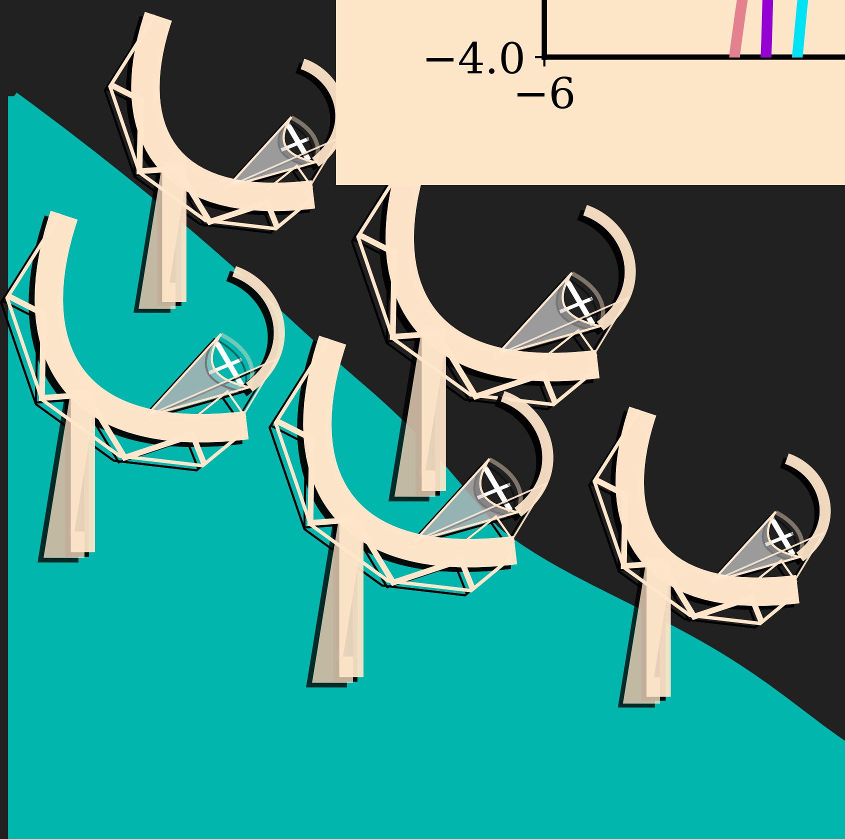
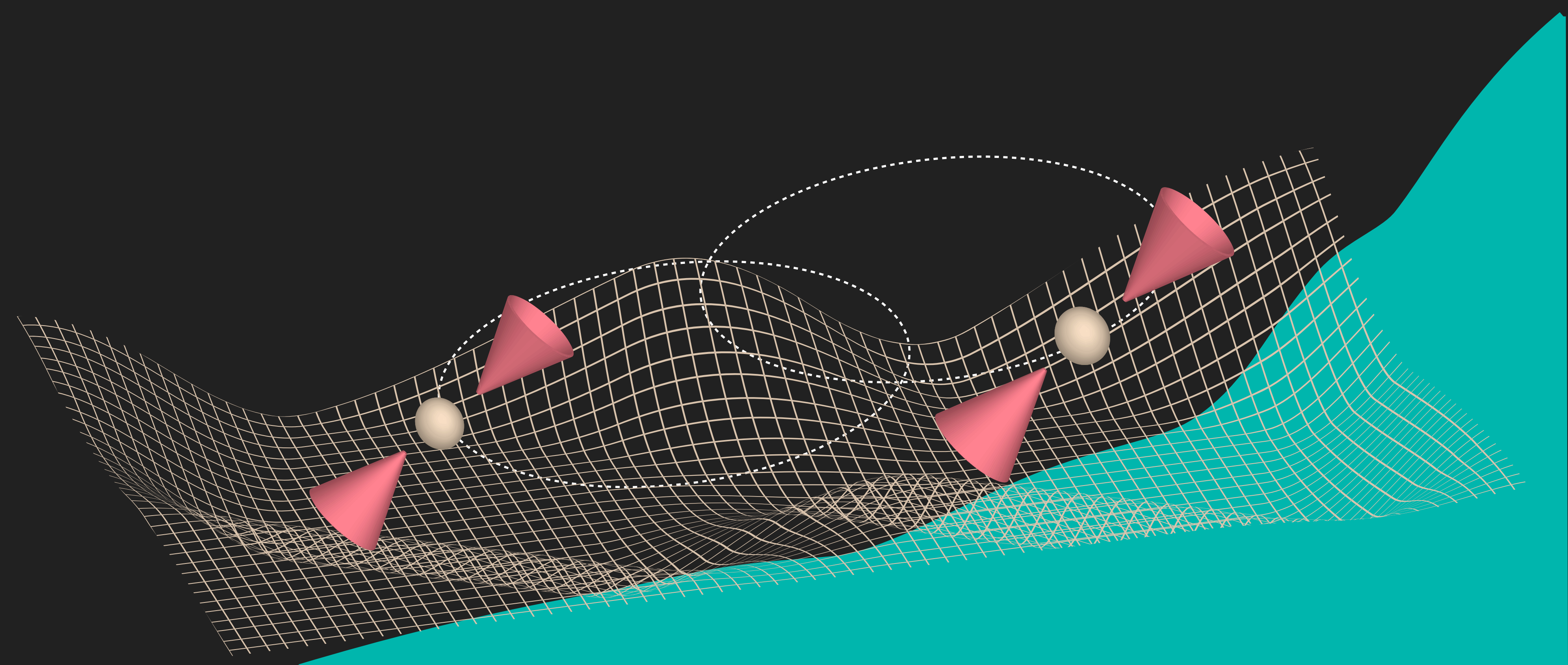
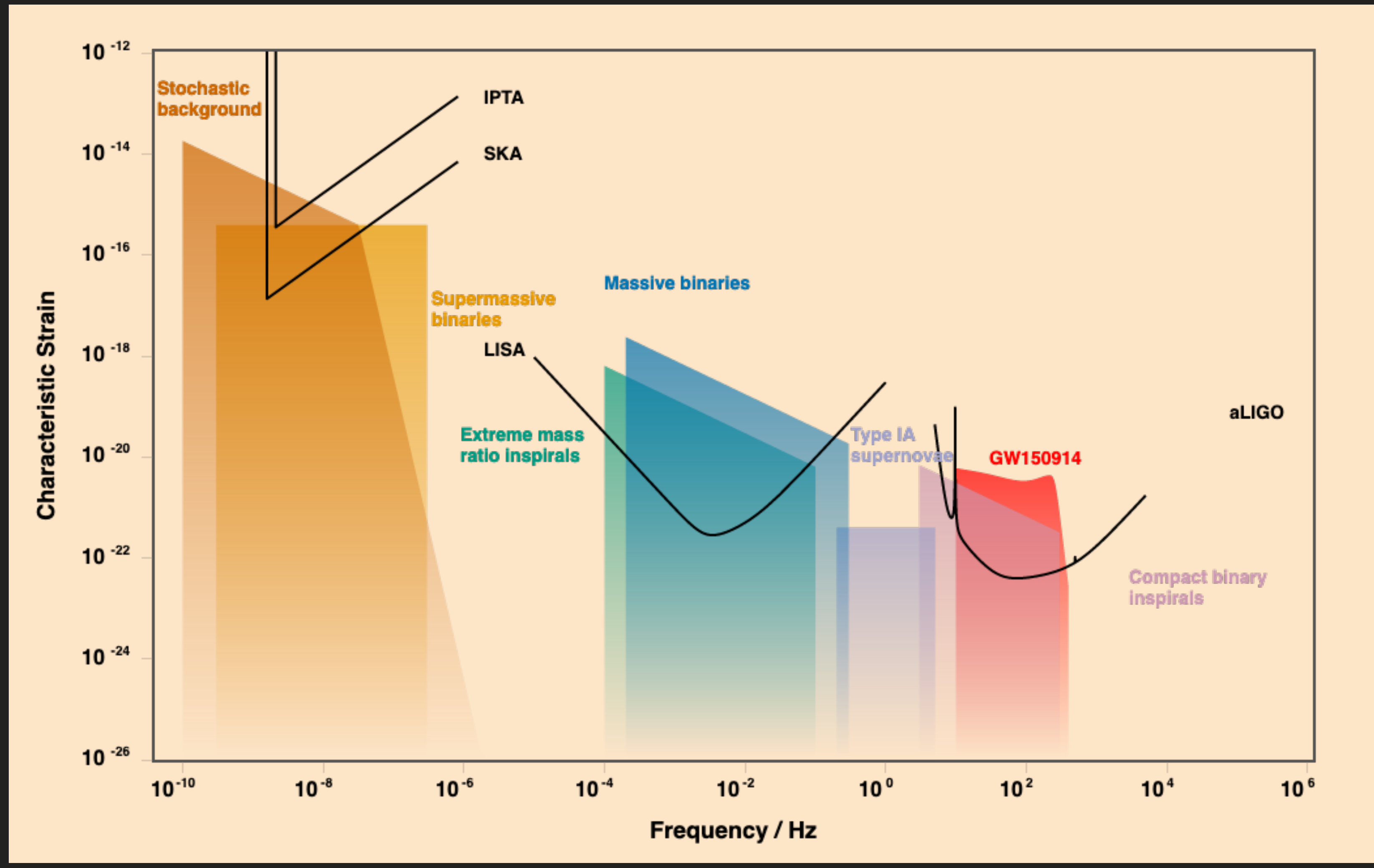
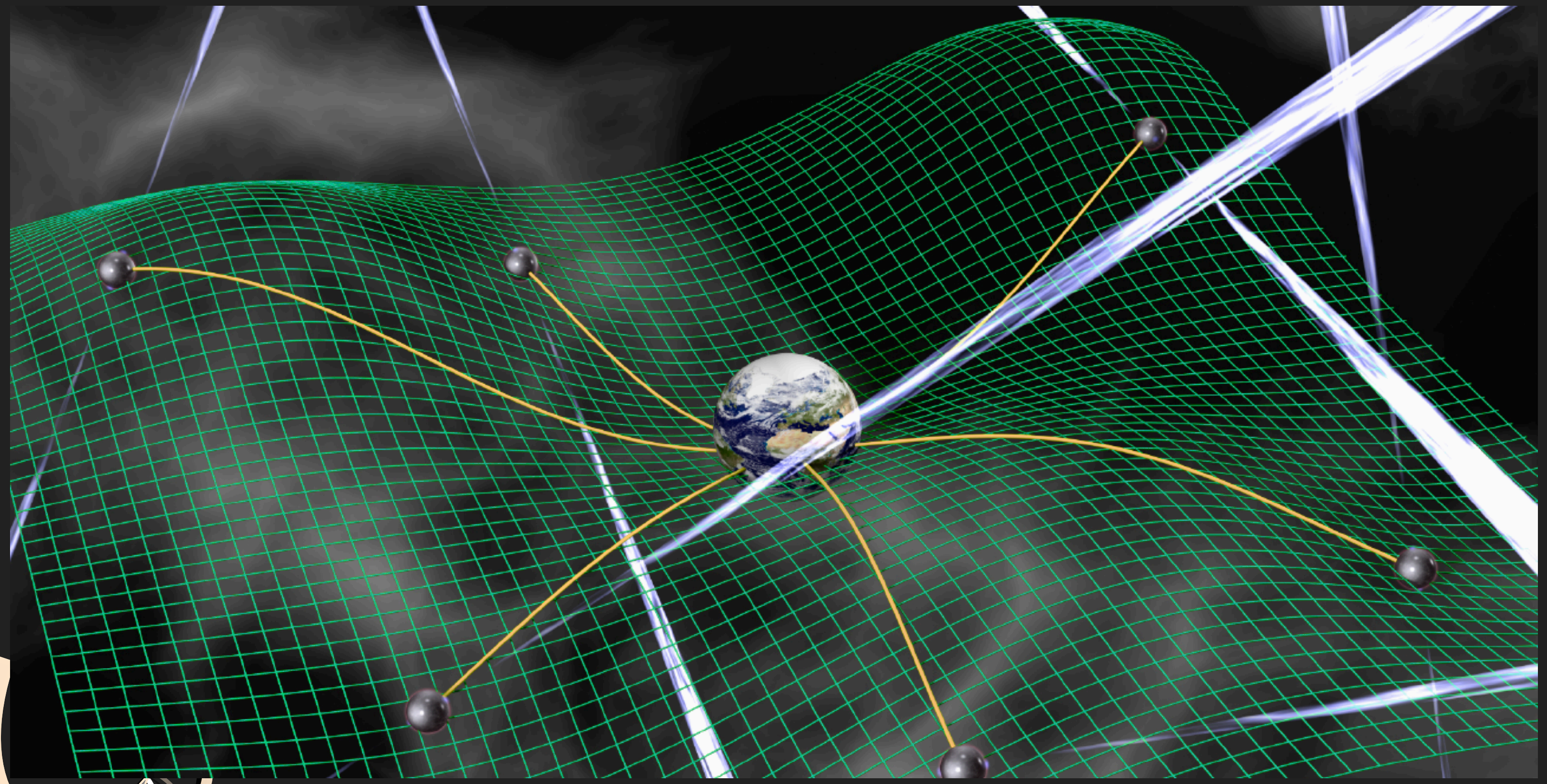
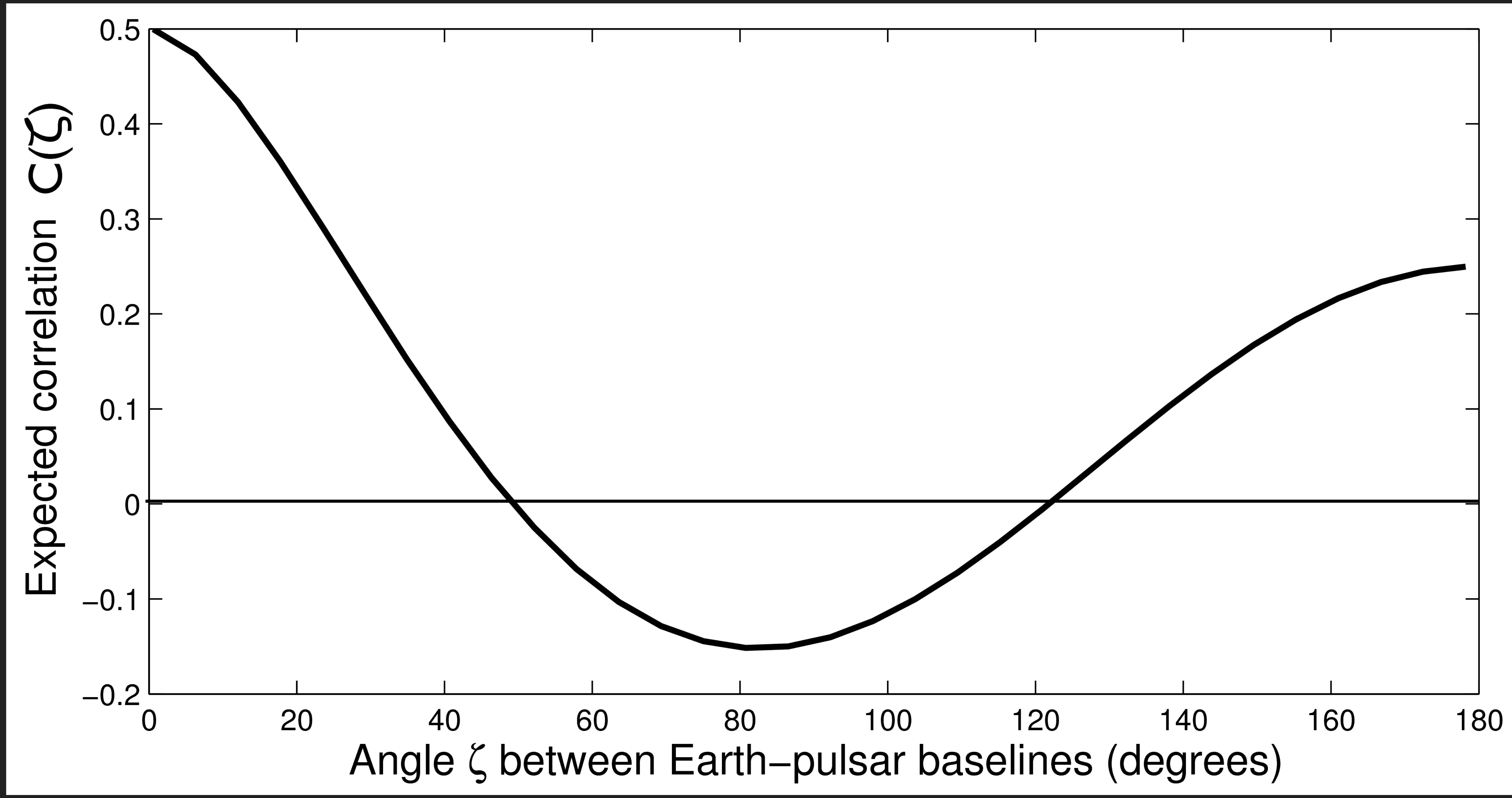




Pulsars as gravitational wave detectors

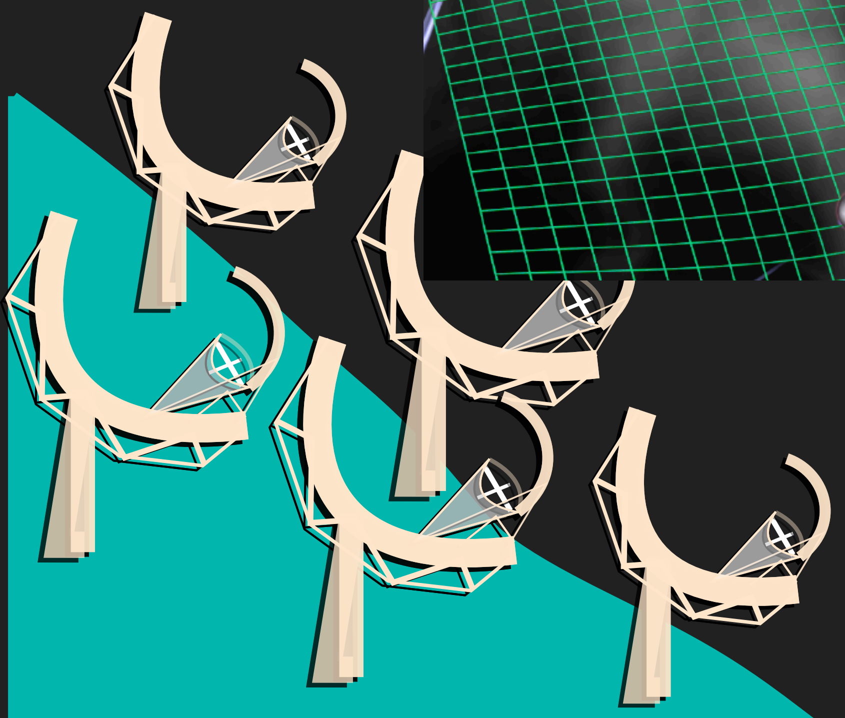


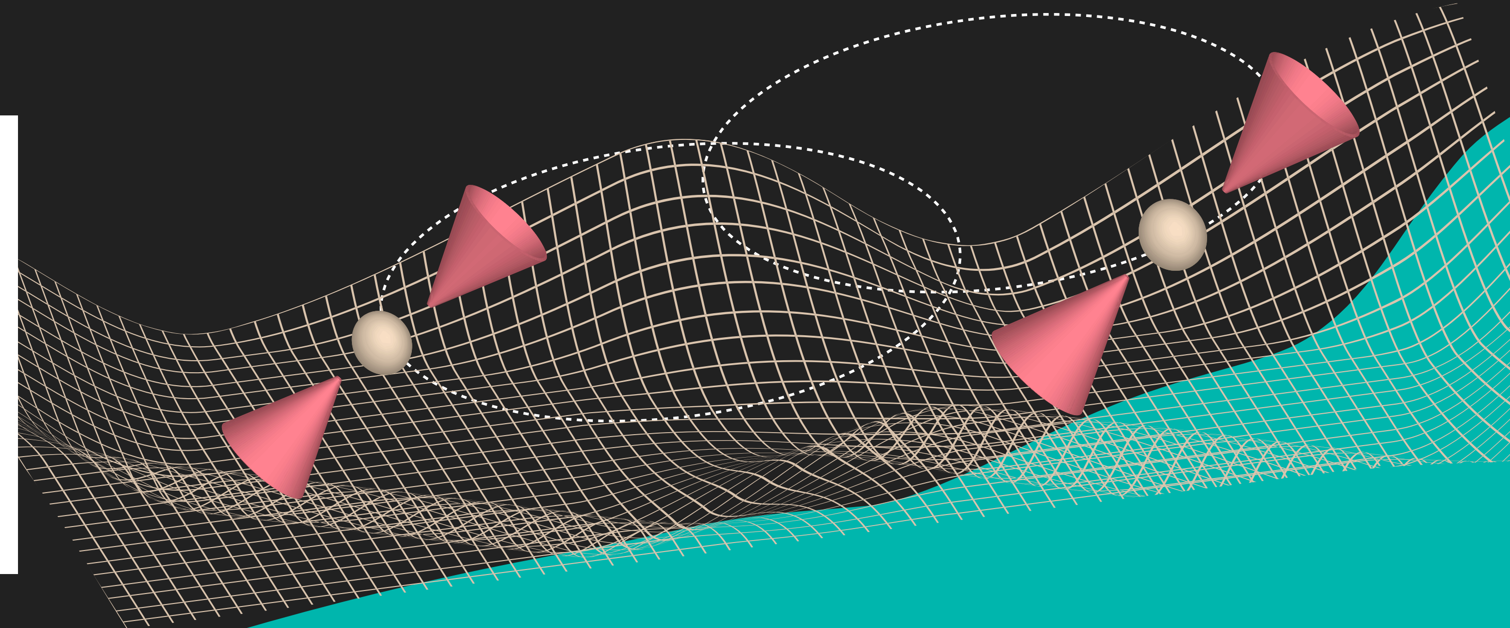




[Hellings & Downs 1983]

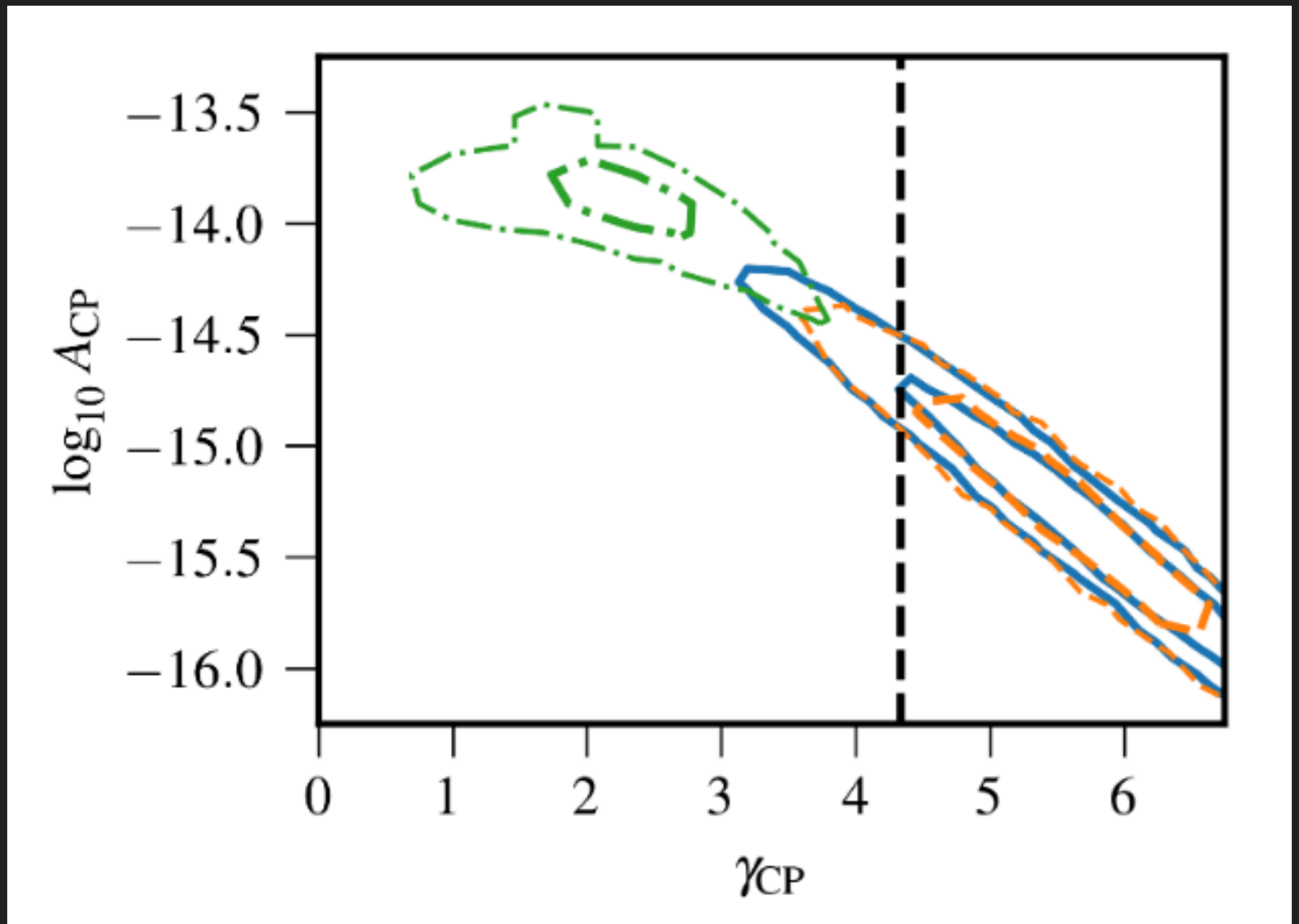
$$h(f) = A_{\rm gwb}\left(\frac{f}{\rm Yr^{-1}}\right)^{\alpha=-2/3} \implies P(f) = \frac{A_{\rm gwb}^2}{12\pi^2}\left(\frac{f}{\rm Yr^{-1}}\right)^{\alpha^2-3=-13/3}$$



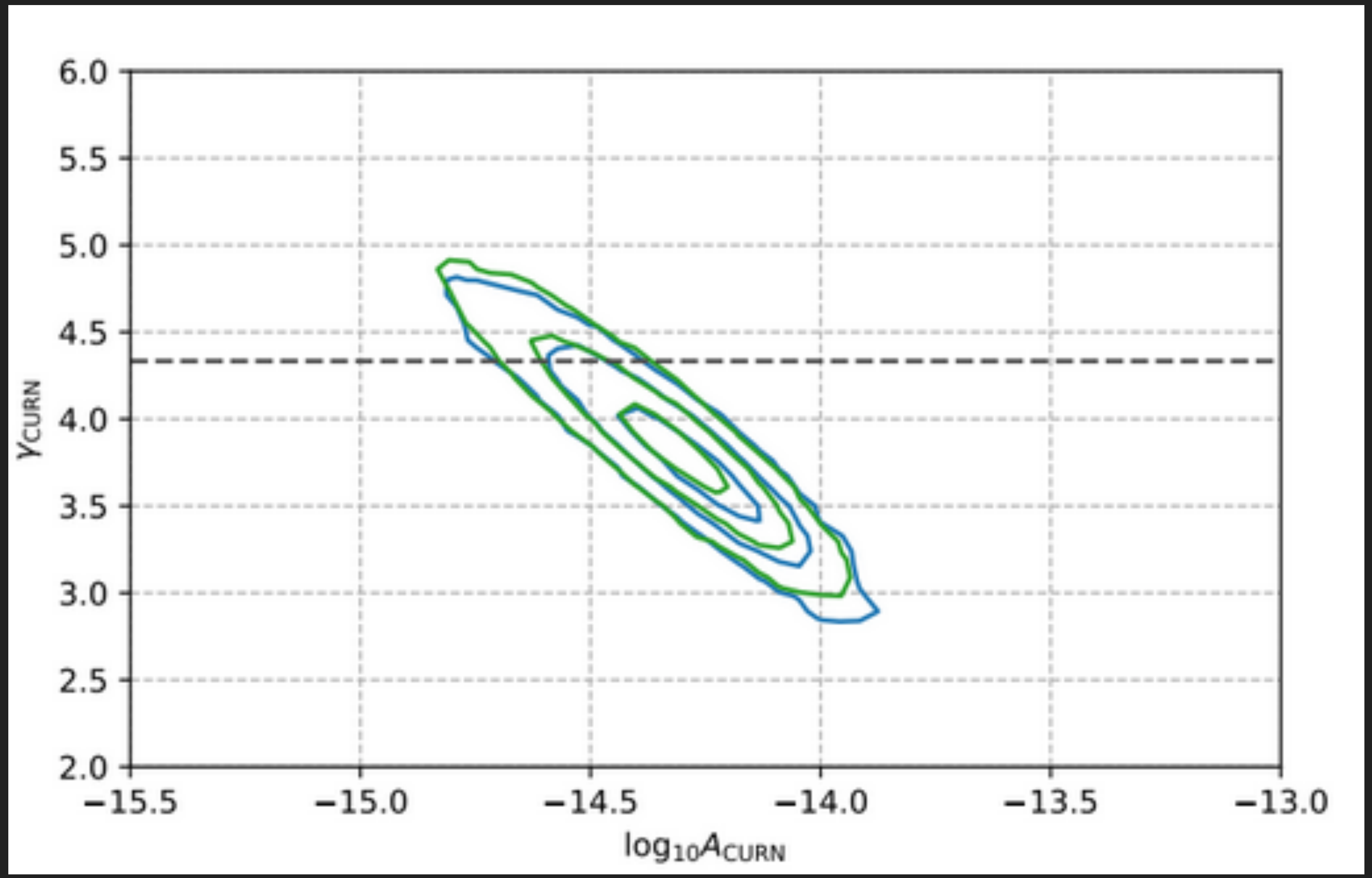


EPTA NANOGrav PPTA INTERNATIONAL PULSAR TIMING ARRAY IPTA

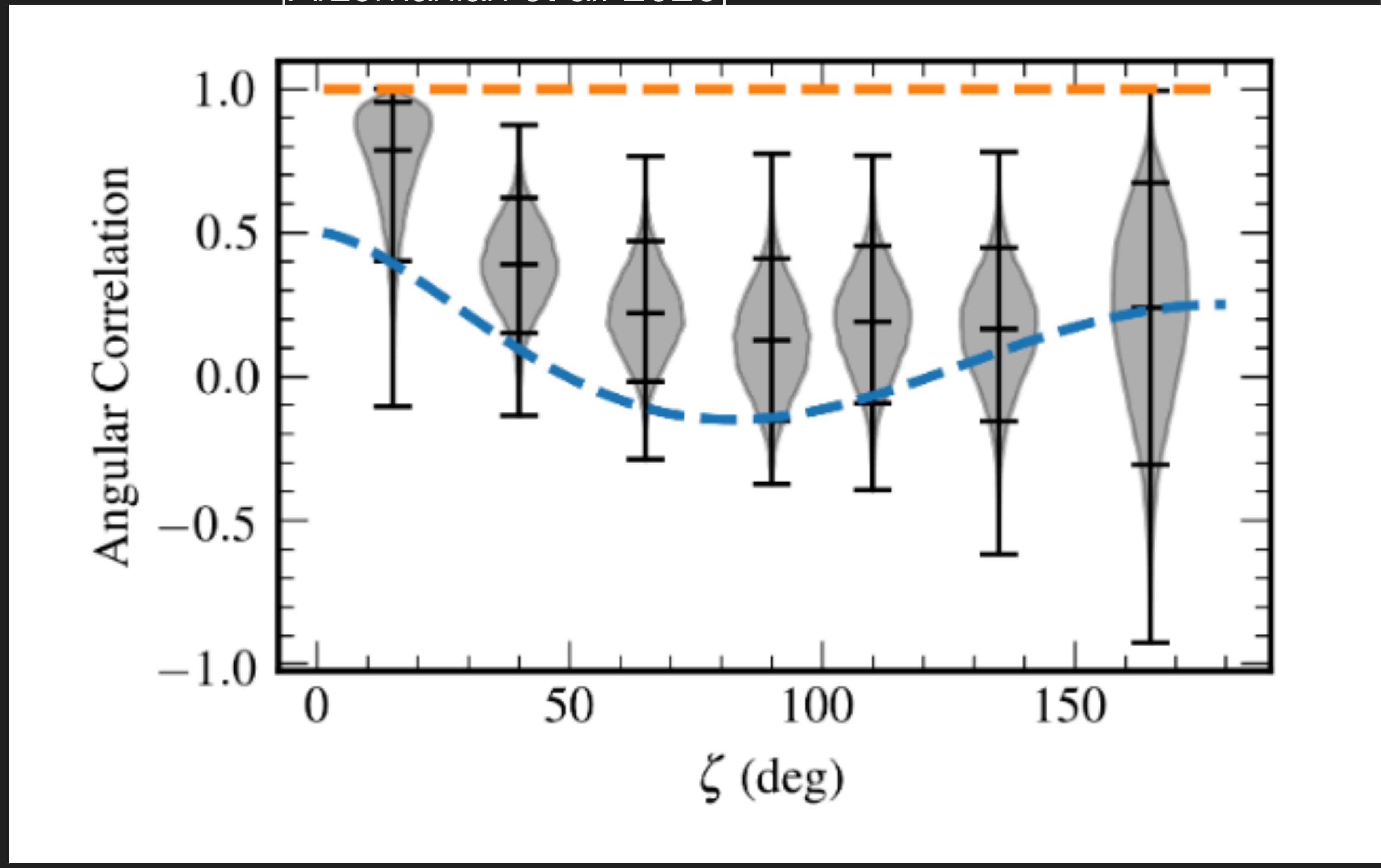
There is something, is this gravitational waves?



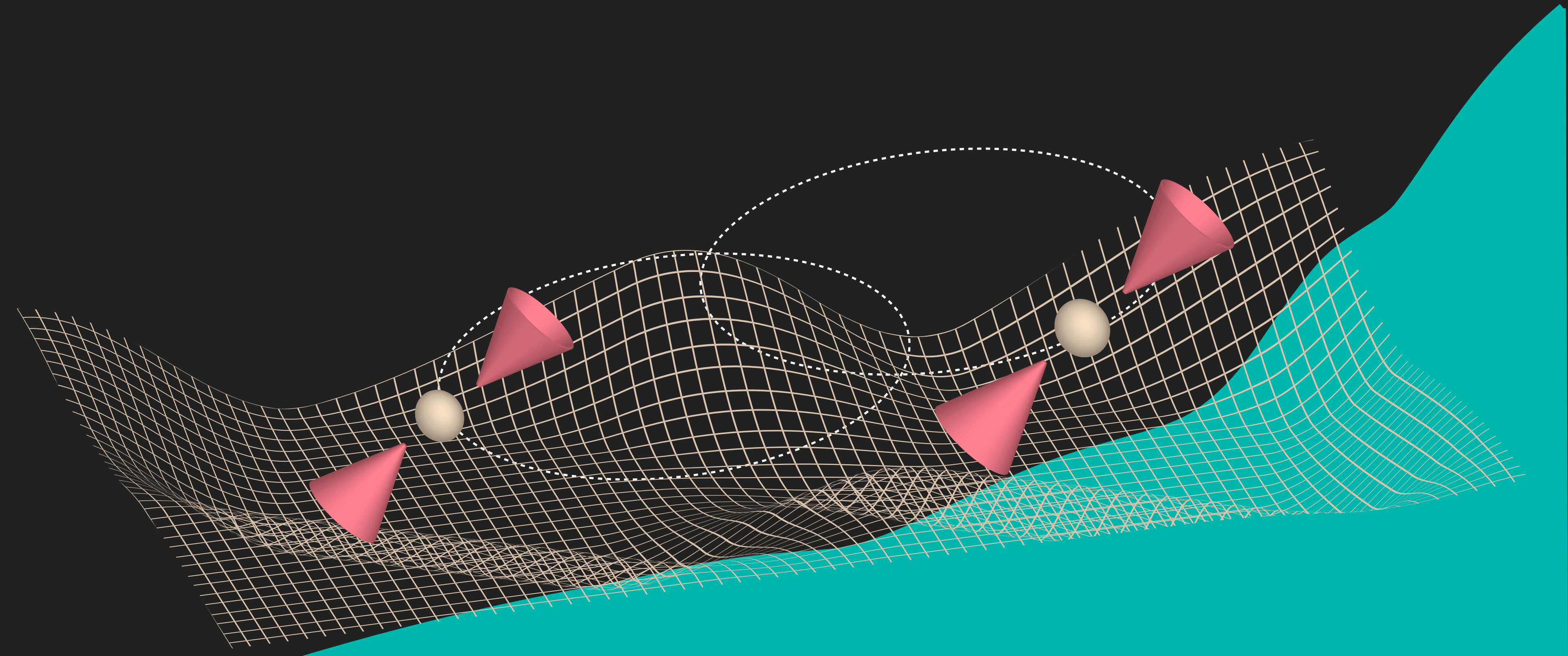
[Arzomanian et al. 2020]



[EPTA collaboration, in prep.; PRELIMINARY RESULT]



[Arzomanian et al. 2020]

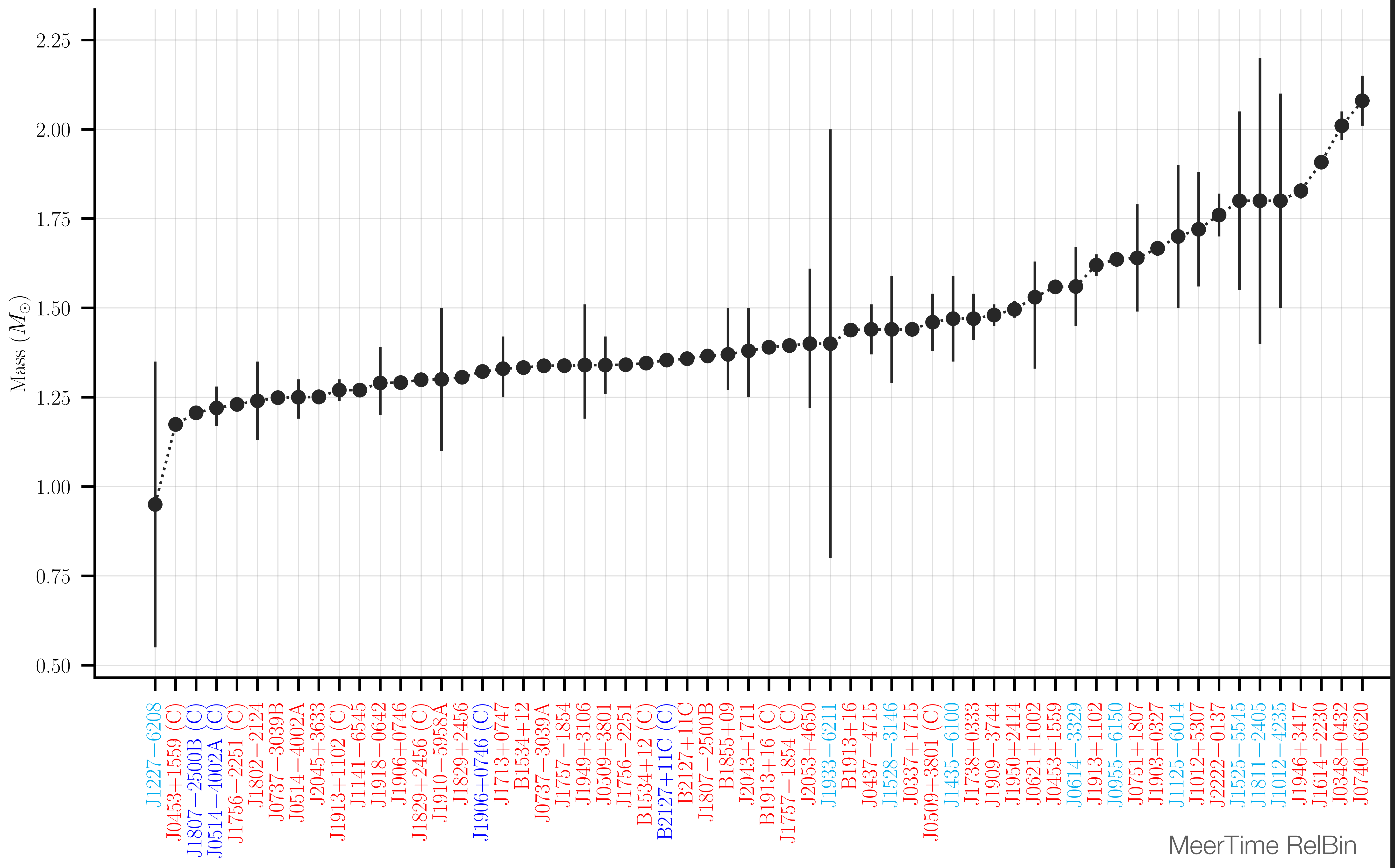


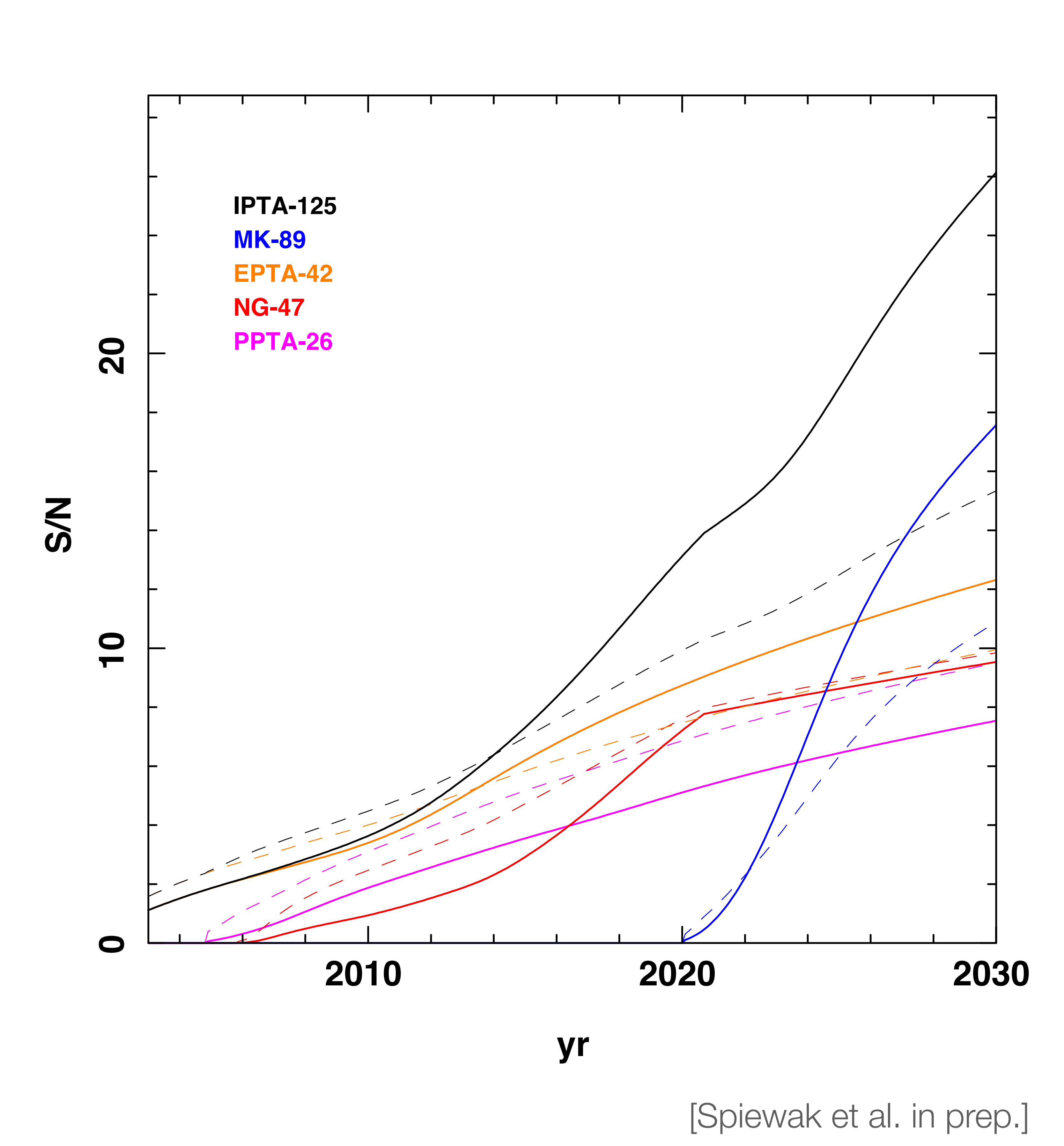
Pulsar timing: Near future

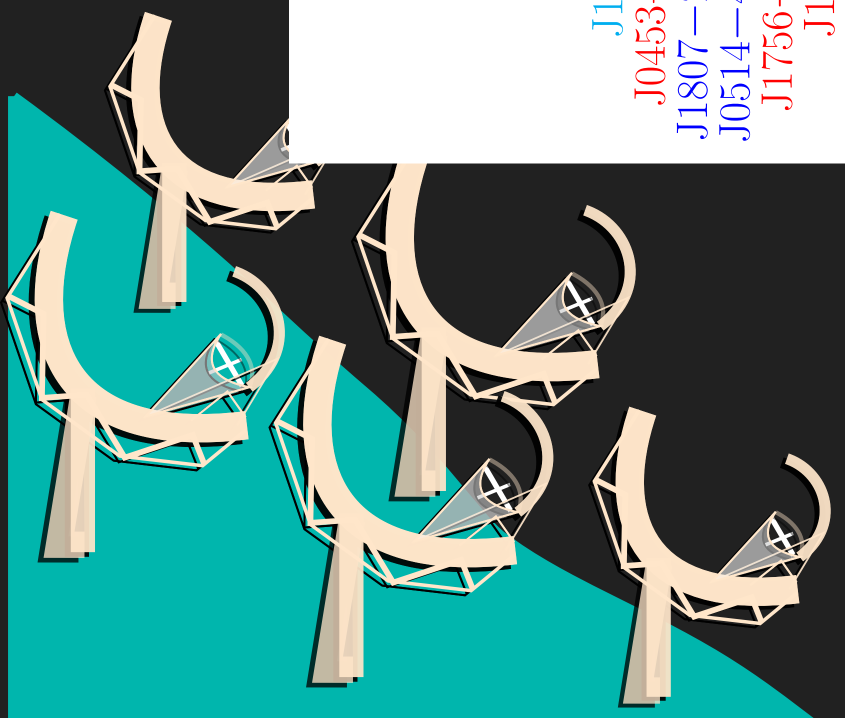
FAST Telescope, China

MeerKAT telescope, SA

MeerKAT as a pulsar timing instrument







Thank you for listening!