Pulsar timing in Extreme Mass Ratio Binaries

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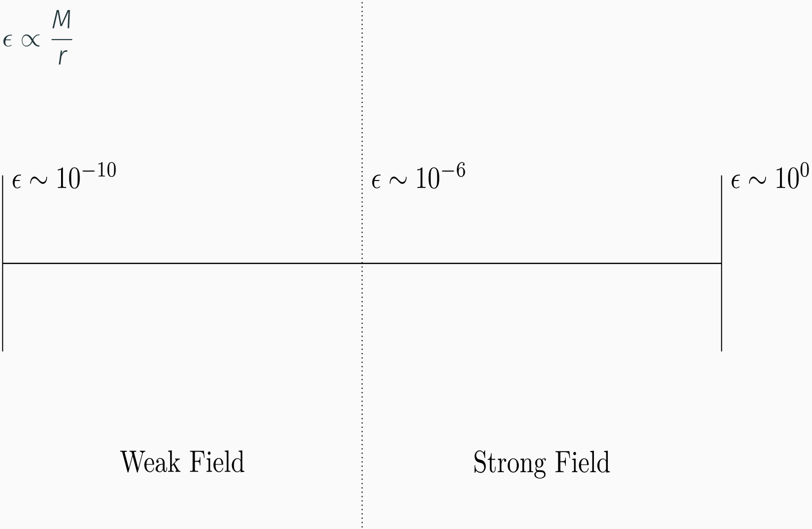
A Problem

GR is incomplete

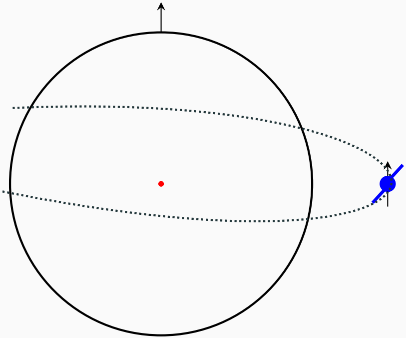
- Field equations = Non-unique
- Breaks down: Singularities + Quantum Gravity

Strong vs. Weak fields

$\epsilon \propto \frac{M}{r}$

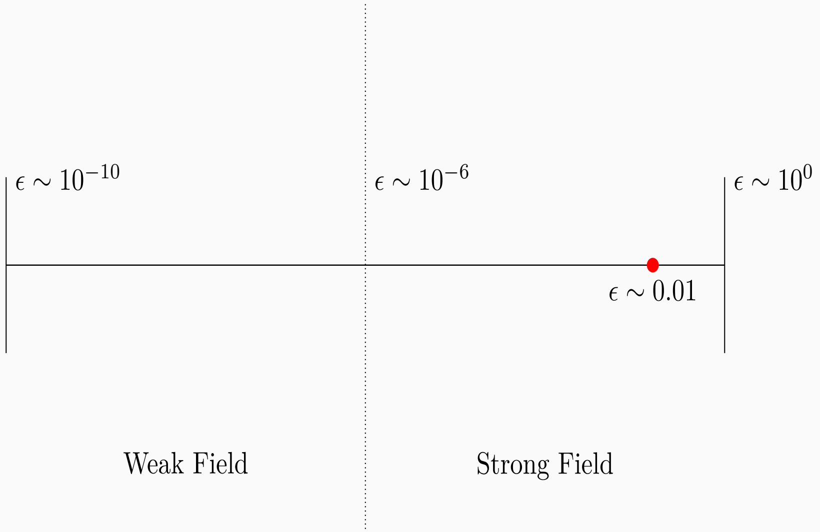


How can we probe strong fields?



- Extreme Mass Ratio Binary (EMRB)
- Event Horizon Clock

Strong-field probe



Scientific prospects

3 important parameters:

$$M, \chi, Q$$

Fundamental Physics

- No Hair Theorem ($Q = -\chi^2$)
- Cosmic Censorship Conjecture ($\chi \leq M^2$)

Astrophysics

- Astrophysical BH = Kerr solution?
- Constrain low end of $M - \sigma$ relation / Existence of IMBH

Hunting Grounds

- Galactic Centre
- Globular Clusters

Detection Prospects

- $\lesssim 10^4$ PSR at < 1 pc (*Wharton et al. 2012, ApJ 753:108, Rajwade et al. 2017, MNRAS 471:730*)
- Closest semi-major axis $\lesssim 100$ AU
- Closest pericentre distance ~ 2 AU (*Zhang et al. 2014, ApJ 784:106*)

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No such PSR-EMRB yet detected!

This Work

Goal: Use the next-generation radio telescopes to time a pulsar in orbit around a massive central black hole.

Require theoretical basis for PSR Timing Signal

This Work: Why?

- Detection. *e.g. Are our algorithms good enough?*
- Modelling. *i.e. GR predictions vs. observation*

This Work: How?

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Behaviour of light + Orbital Dynamics = Timing signal

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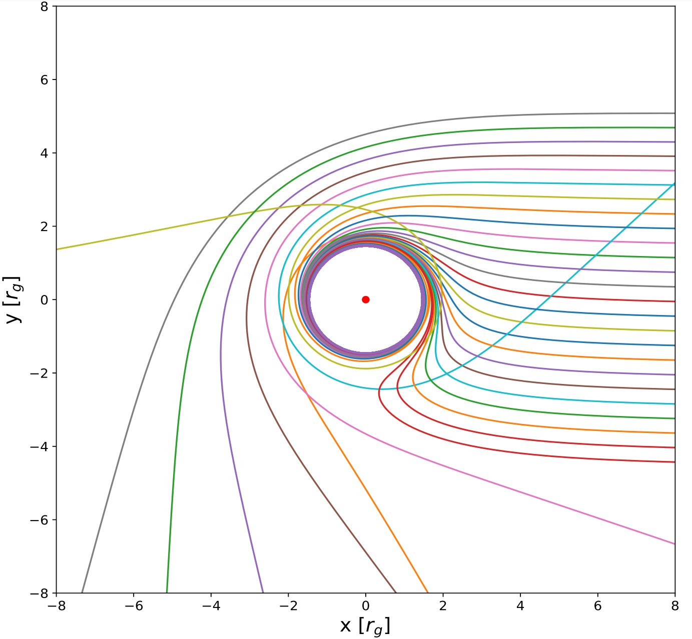
Ray Tracing



This Work: How?

Require theoretical basis for PSR Timing Signal

Behaviour of light + Orbital Dynamics = Timing signal

PSR Orbital Dynamics

- Textbook GR: point particles.
- Real pulsars $\neq$ point particles!

Creating the skeleton

$$T^{\mu\nu}{}_{;\nu} = 0$$

Multipole expansion to dipole order:

$$\frac{Dp^{\mu}}{d\tau} = -\frac{1}{2} R^{\mu}_{\nu\alpha\beta} u^{\nu} s^{\alpha\beta}$$

$$\frac{Ds^{\mu\nu}}{d\tau} = p^{\mu} u^{\nu} - p^{\nu} u^{\mu}$$

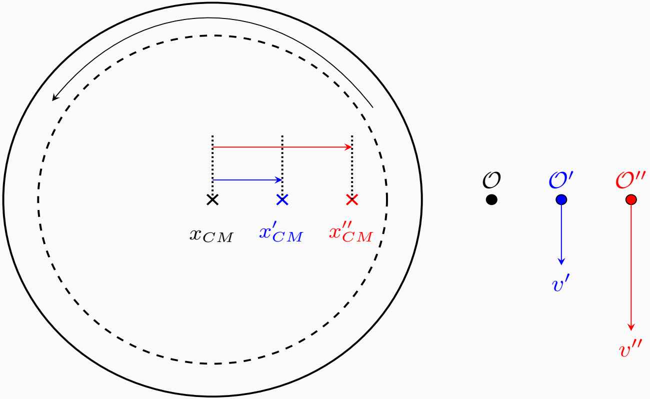
(*Mathisson 1937, Papetrou 1951, Dixon 1974*)

Equations are indeterminate

Choosing a centre of mass

Multipole expansion defined w.r.t some reference worldline $z^\alpha(\tau)$.

Centre of mass is observer dependent.



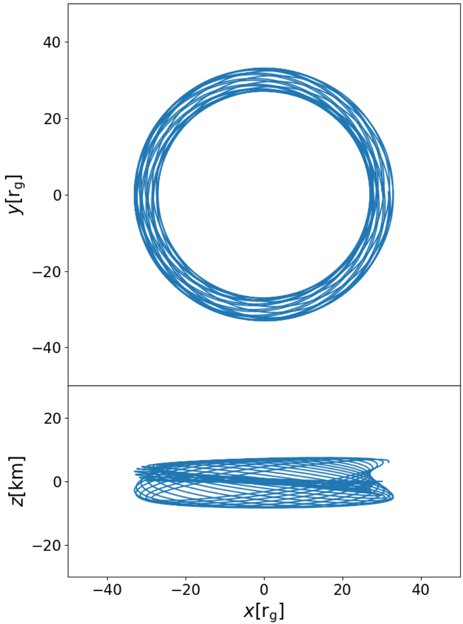
How to choose a reference worldline?

(*Costa & José 2014, arXiv:1410.6443*)

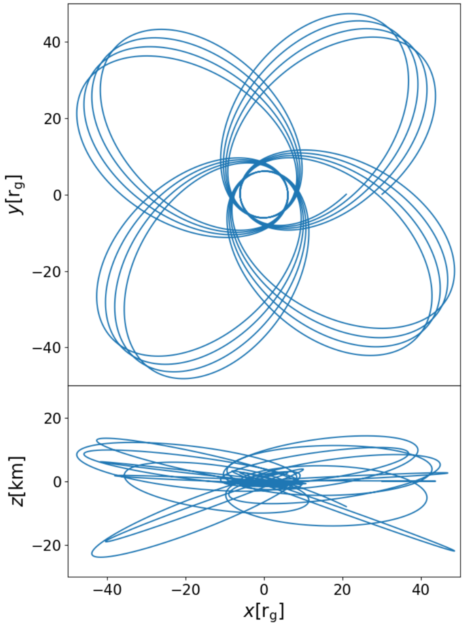
Spin Couplings

- Spin-spin
- Spin-orbit
- Spin-curvature

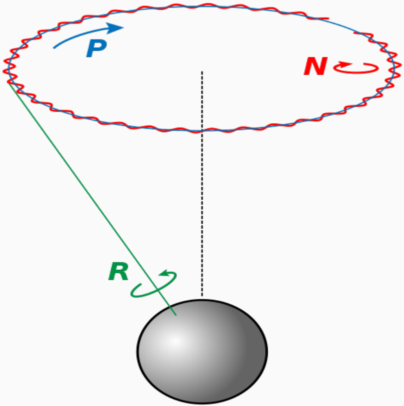
Orbital Dynamics: circular

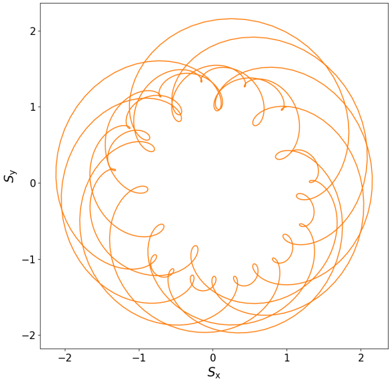


Orbital Dynamics: eccentric

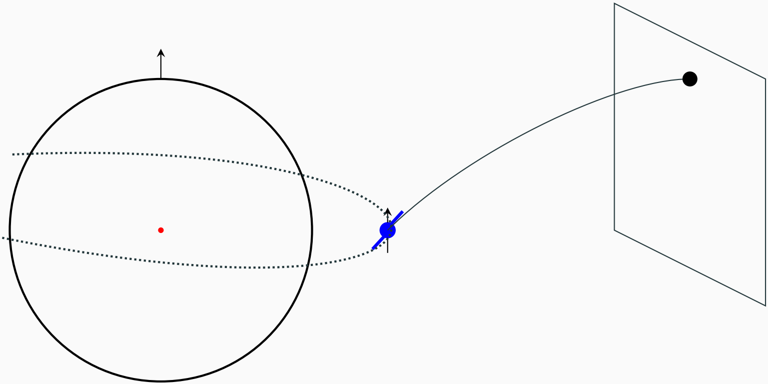


Spin Precession





Putting it all together...



Behaviour of light + Orbital Dynamics = Timing signal

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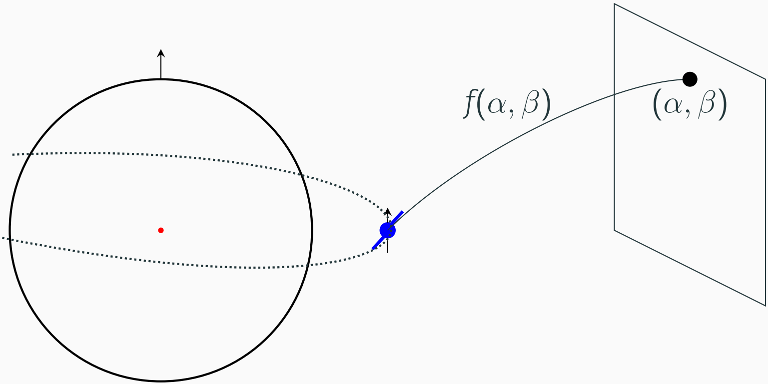

Behaviour of light + Orbital Dynamics = Timing signal

Optimization problem

$$f(\alpha, \beta)$$

Effects to consider

- Gravitational lensing
- Primary/Secondary rays
- Influence of plasma: temporal/spatial dispersion
- Gravitational/Relativistic time dilation
- Orbital Dynamics
- Spin-curvature coupling (+spin-spin, spin-orbit)
- Spin precession
- Relativistic aberration

Photon ToA, pulse profile, intensity, observability

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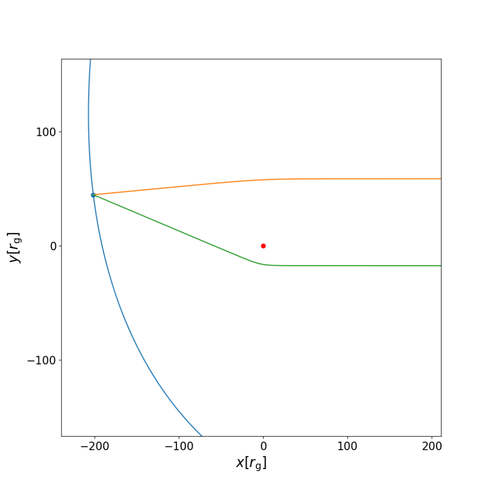
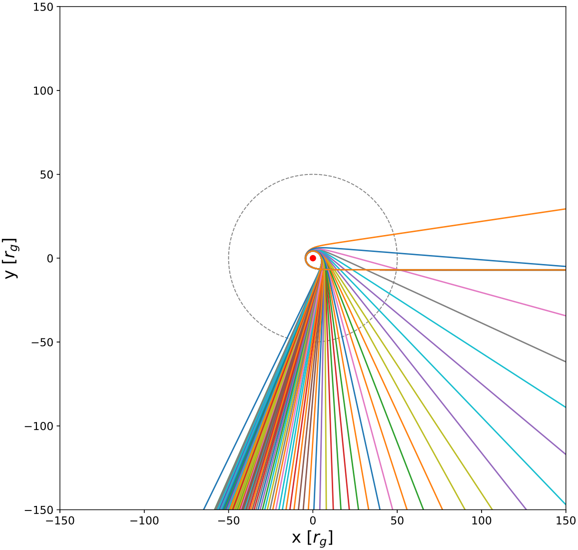
Gravitational Bending



- Deviation from straight lines
- Primary/Secondary Rays

Plasma: spatial dispersion



Summary

- PSR-EMRB = precision strong-gravity probes
- Require fully relativistic $t - \nu$ model
- Open question: How good are current methods?

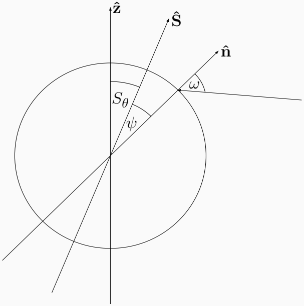
References:

Kimpson et al. 2019, doi:10.1093/mnras/stz138
Kimpson et al. 2019, doi:10.1093/mnras/stz845

Questions?

Putting it all together...

- Pulsar emission $\neq$ isotropic
- Find intersection with radiation point $x^i_{\mathrm{rad}} = R_{\mathrm{PSR}}\hat{\mathsf{n}} + x^i_{\mathrm{pulsar}}$
- $\hat{\mathsf{n}} = \hat{\mathsf{n}}(S_\theta(\tau), \psi)$



Aberration

- ‘Seen’ if $\omega < \omega_c$
- Global $\omega \neq$ Local ω
- Transform to coming frame