IT TAKES TWO (SPINS) TO TANGO:

Interpreting gravitational-wave data with an generalized effective precession parameter

Davide Gerosa, Matthew Mould, Daria Gangardt, Patricia Schmidt, Geraint Pratten, Lucy Thomas

UNIVERSITY OF BIRMINGHAM

mmould@star.sr.bham.ac.uk

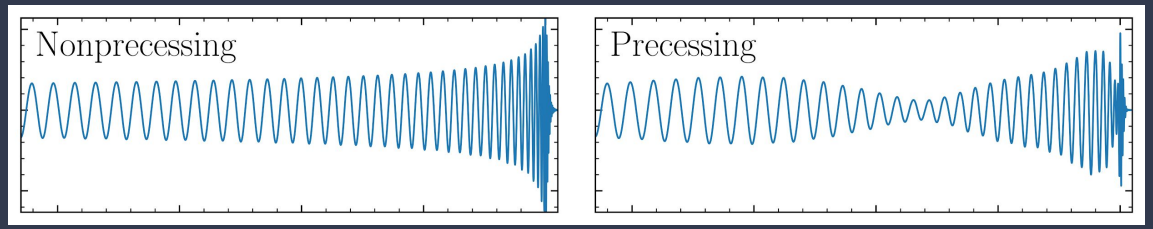
PRD **103** 064067
arXiv:2011.11948

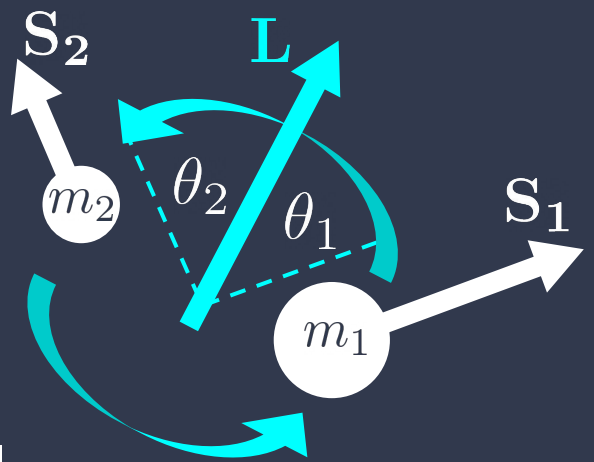
Meeting of the National Research Group on Gravitational Waves

30 March 2021

Introduction - spins and precession

- Astrophysical formation ⇒ spin misalignments
- Spin misalignments ⇒ spin precession
- Spin precession ⇒ modulated gravitational waves
- Modulated GWs ⇒ detectable effect (if modeled)
- Use effective spin parameters ⇒ $\chi_{\rm eff}$ $\chi_{\rm p}$





$$q = m_2/m_1$$
$$\chi_{\rm i} = S_{\rm i}/m_{\rm i}^2$$
$$S = |\mathbf{S_1} + \mathbf{S_2}|$$

Rederiving χ_p - the effective precessing spin

- Measure precession with orbital plane changes:

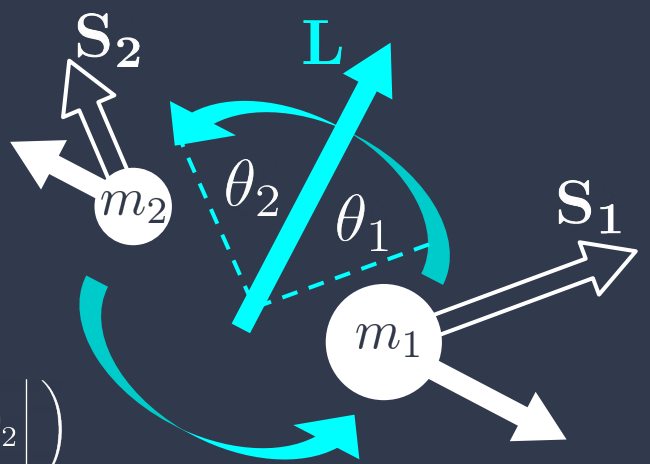
$$\frac{d\hat{\mathbf{L}}}{dt} = \left(\Omega_1\chi_1\hat{\mathbf{S}}_1 + \Omega_2\chi_2\hat{\mathbf{S}}_2\right) \times \hat{\mathbf{L}}$$

- Average extremal cases and normalize:

$$\chi_\mathrm{p} \equiv \frac{1}{2}\left(\chi_1 \sin\theta_1 + \chi_2\frac{\Omega_2}{\Omega_1}\sin\theta_2 + \left|\chi_1\sin\theta_1 - \chi_2\frac{\Omega_2}{\Omega_1}\sin\theta_2\right|\right)$$

$$= \max\left(\chi_1\sin\theta_1\,,\ \chi_2\frac{\Omega_2}{\Omega_1}\sin\theta_2\right)$$

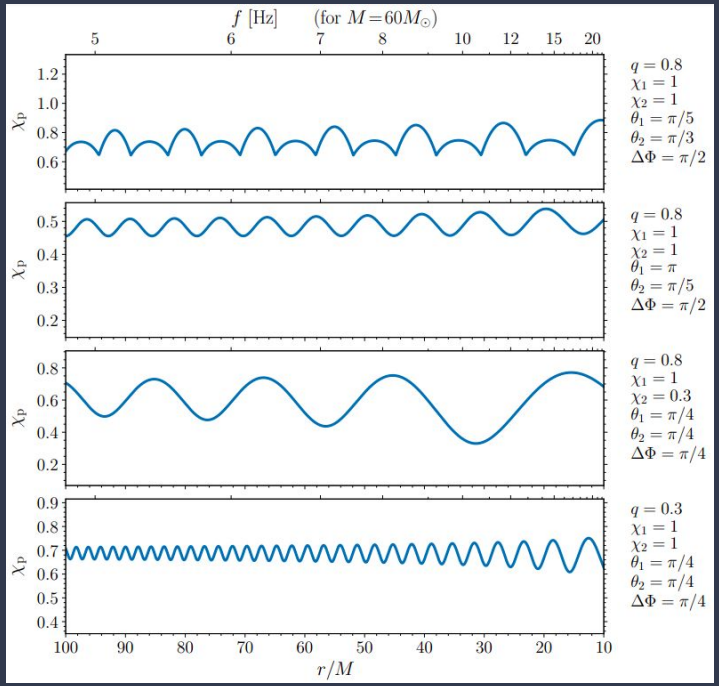
P Schmidt+ 2014



Rederiving χ_p - inconsistencies

$$\chi_{\rm p} = \max\left(\chi_1 \sin\theta_1\,,\ \chi_2 \frac{\Omega_2}{\Omega_1} \sin\theta_2\right)$$

- It does not properly account for two spins
- It inconsistently averages over spin parameters
- It is not a conserved quantity on ANY of the binary timescales



A new generalized χ_p - back to the start

$$\frac{d\hat{\mathbf{L}}}{dt} = \left(\Omega_1\chi_1\hat{\mathbf{S}}_1 + \Omega_2\chi_2\hat{\mathbf{S}}_2\right) \times \hat{\mathbf{L}}$$

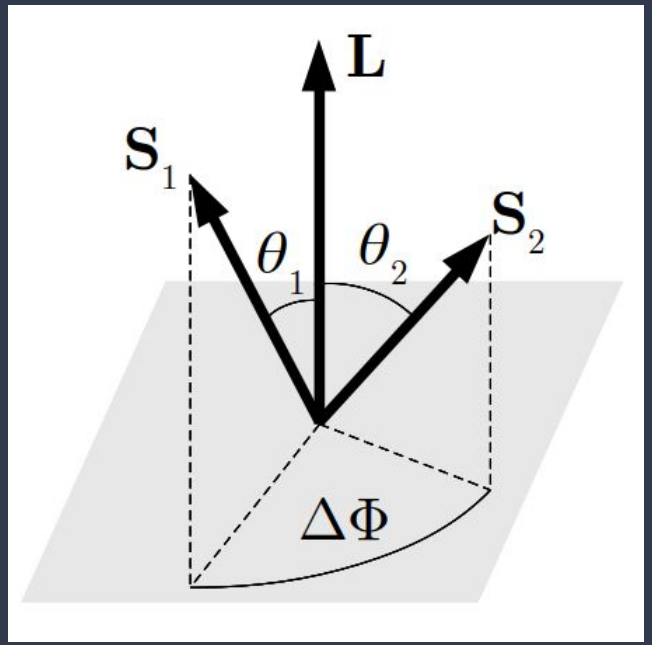
- Look at the magnitude of the entire expression

$$\left|\frac{d\hat{\mathbf{L}}}{dt}\right|^2 = (\Omega_1\chi_1 \sin\theta_1)^2 + (\Omega_2\chi_2 \sin\theta_2)^2 + 2\Omega_1\Omega_2\chi_1\chi_2 \sin\theta_1 \sin\theta_2 \cos\Delta\Phi$$

- Keep the same normalization

$$\chi_p \equiv \frac{1}{\Omega_1}\left|\frac{d\hat{\mathbf{L}}}{dt}\right|$$

Generalized, but retains variations on all timescales



A new generalized χ_p - consistent spin averaging

- Functions can be averaged over a precession cycle:

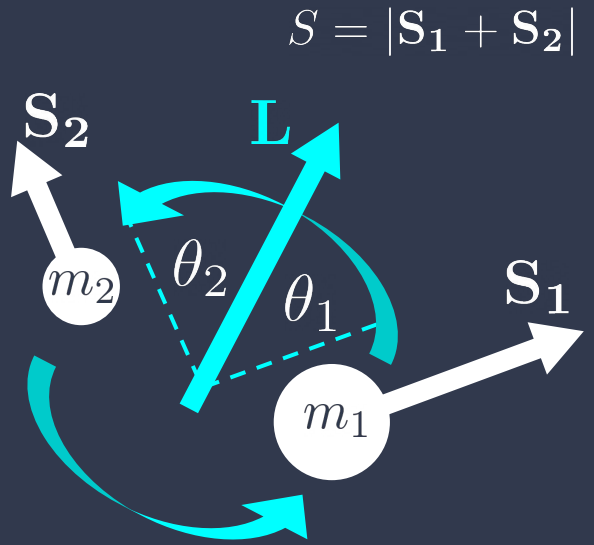
$$\langle f \rangle \equiv \frac{1}{\tau}\int_0^\tau f\,dt = \frac{2}{\tau}\int_{S_-}^{S_+}\frac{f}{|dS/dt|}dS$$

M Kesden+ 2014
D Gerosa+ 2015

- Averaging the previous definition removes precession-timescale variations

$$\chi_{\rm p} \equiv \left\langle \frac{1}{\Omega_1}\left|\frac{d\hat{\mathbf{L}}}{dt}\right|\right\rangle$$

- But this still contains radiation-reaction variations



A new generalized χ_p - how does it look?

- 'Heuristic'

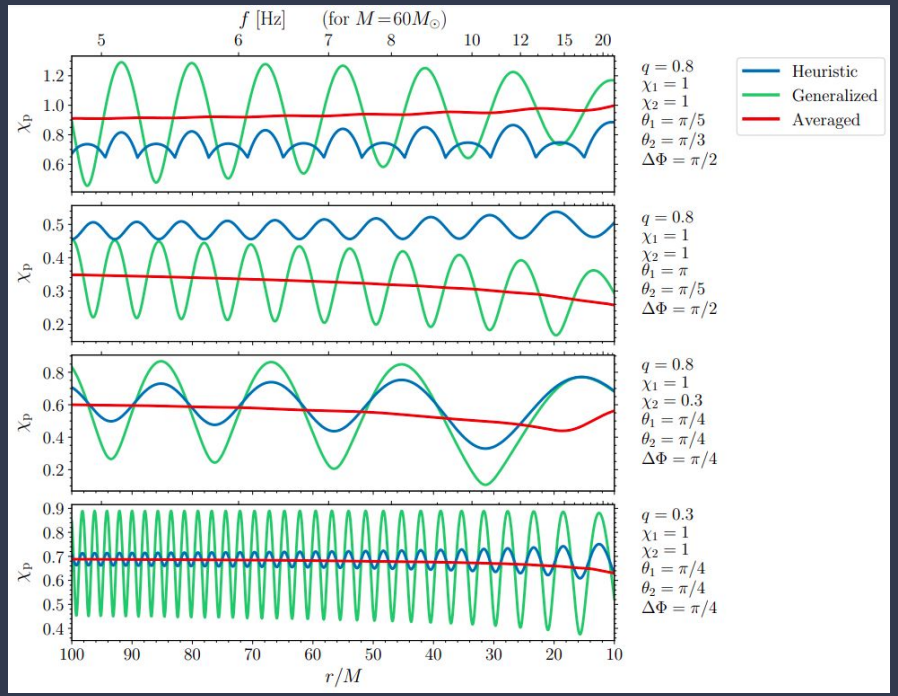
$$\chi_p \equiv \max\left(\chi_1 \sin\theta_1\,,\ \chi_2 \frac{\Omega_2}{\Omega_1}\sin\theta_2\right)$$

- 'Generalized'

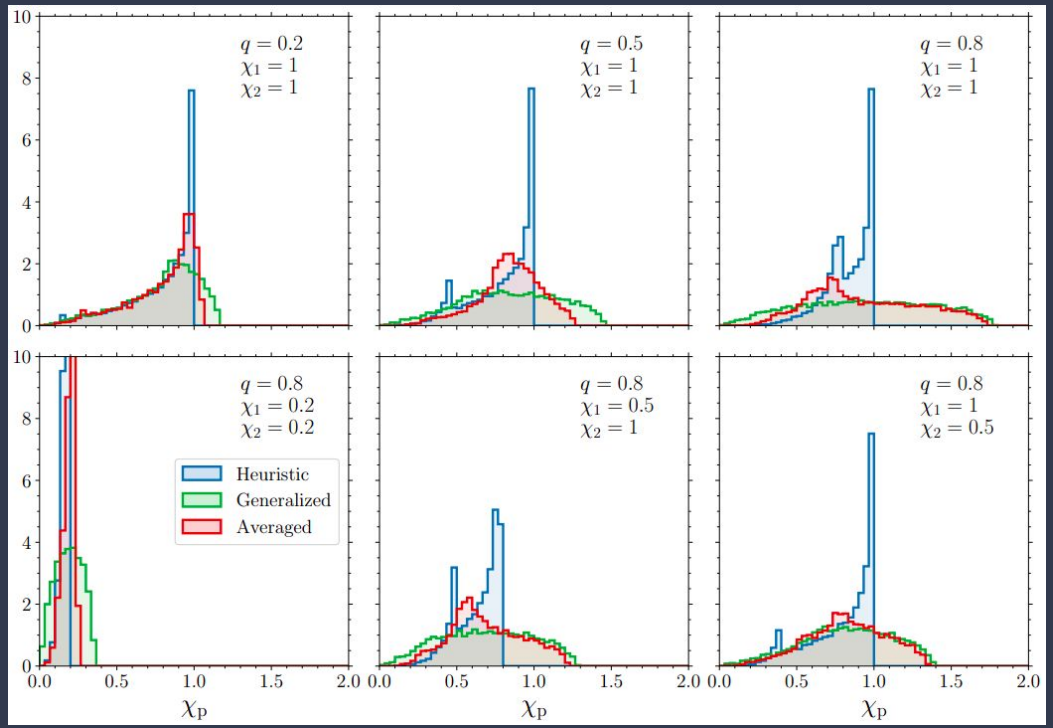
$$\chi_p \equiv \frac{1}{\Omega_1}\left|\frac{d\hat{\mathbf{L}}}{dt}\right|$$

- 'Averaged'

$$\chi_p \equiv \left\langle \frac{1}{\Omega_1}\left|\frac{d\hat{\mathbf{L}}}{dt}\right| \right\rangle$$



What's the difference? - parameter space exploration

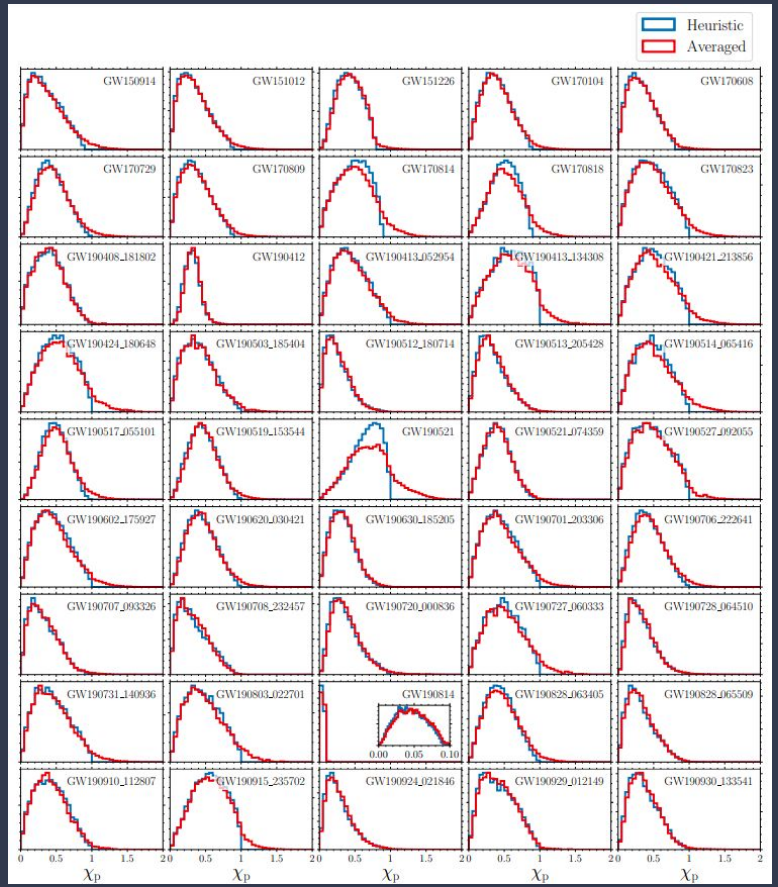


- Limiting cases:
  - Zero spin limit (both spins are low)
  - Single spin limit (one low spin, or low mass ratio)
  - Two large spins
- Inconsistent averaging gives 'heuristic' two artificial peaks
- 'Averaged' accounts for both spins

What's the difference? - a look at GWTC-2

The new 'averaged' definition:

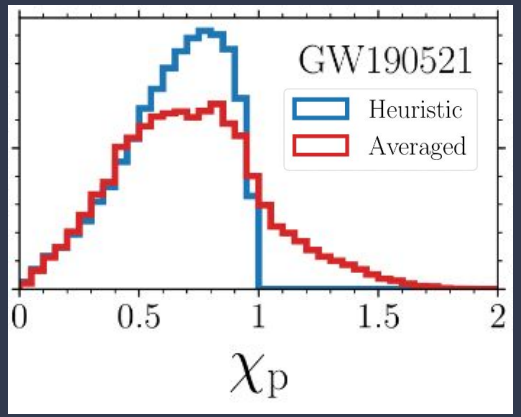
- agrees with the previous definition in low-precession limit (due to normalization)
- prevents posterior railing at boundary
- presents a previously inaccessible region between 1 and 2
- this region can ONLY be populated by binaries with two precessing spins

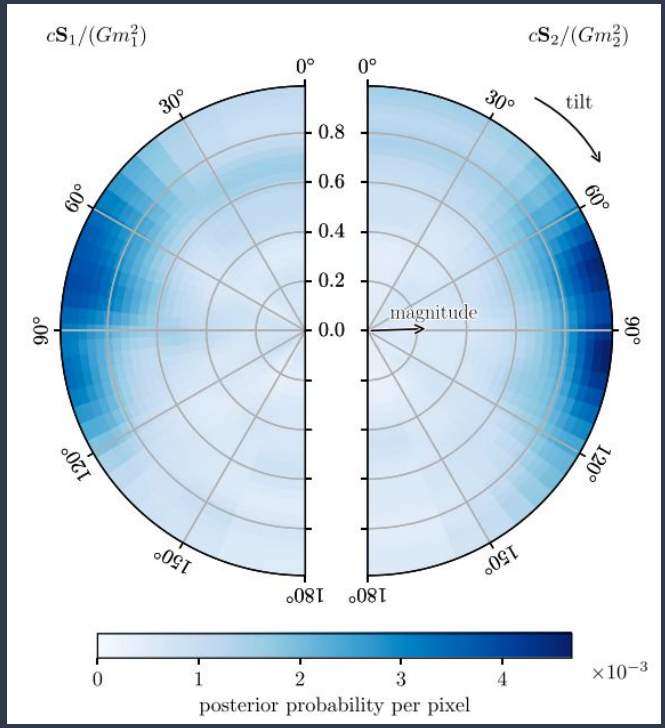


What's the difference? - GW190521

LVC+ 2020

- GW190521 shows the strongest deviations
- 'Averaged' definition indicates GW190521 may contained two precessing spins
- LVC analysis is in agreement, showing that GW190521 may contain highly tilted spins





Conclusions

- Effective precessing spin was originally designed for waveform modelling
- Several heuristic choices make it unsuitable for its current use in data analysis:
  - Not conserved on any timescale (**pop-synth distributions ≠ LIGO posteriors**)
  - An effective single-spin approximant
  - Does not consistently average over spin parameters
- Our proposed redefinition:
  - Consistently accounts for all (PN) spin information
  - Is approximately conserved on the precession timescale (but not over an inspiral)
- Applied to GWTC-2, we see stronger evidence for two precessing spins

Links

Paper: arXiv:2011.11948

GitHub: github.com/dgerosa/generalizedchip