Getting the most out of gravitational-wave observations: kicks and spin precession

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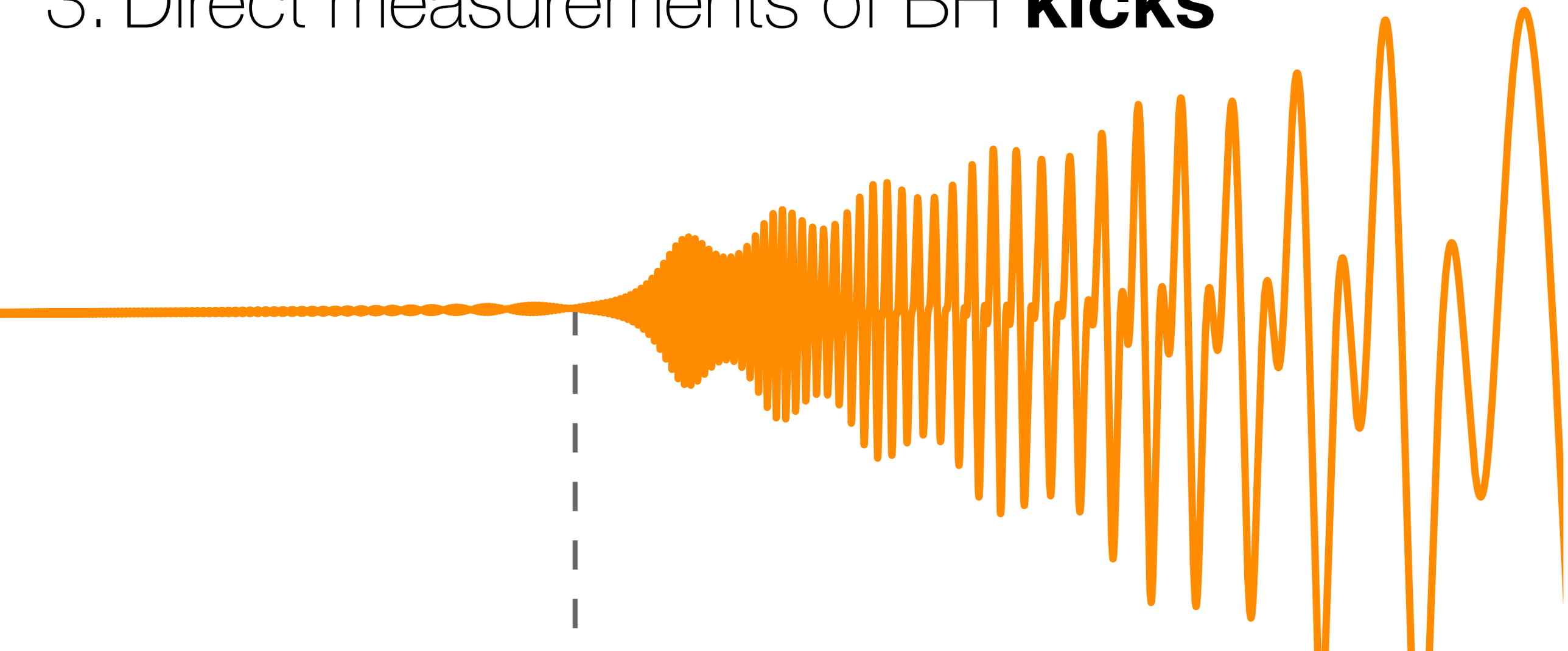
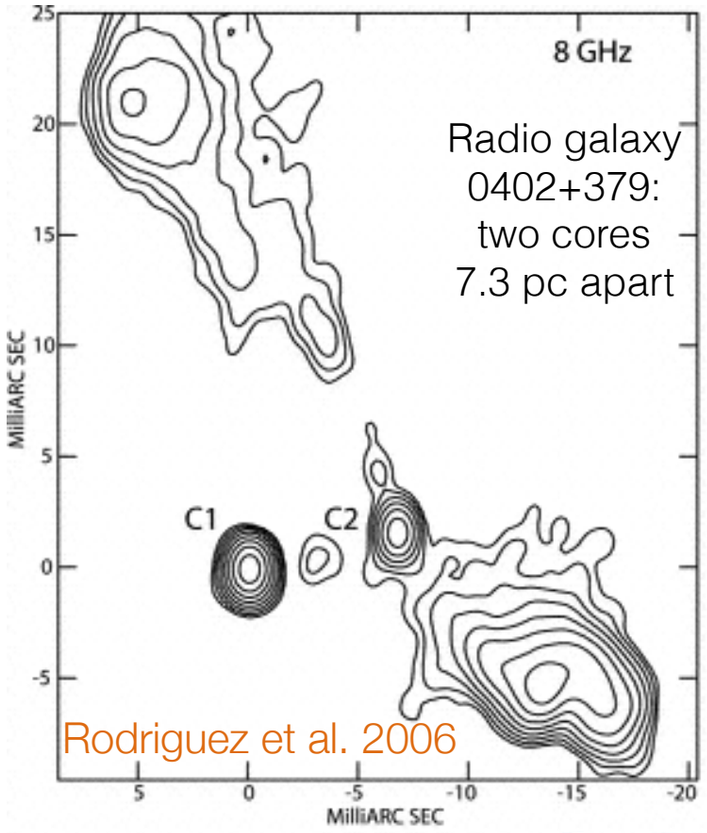
Outline

1. Spinning BH binaires
2. Astrophysics with BH **spin precession**
3. Direct measurements of BH **kicks**



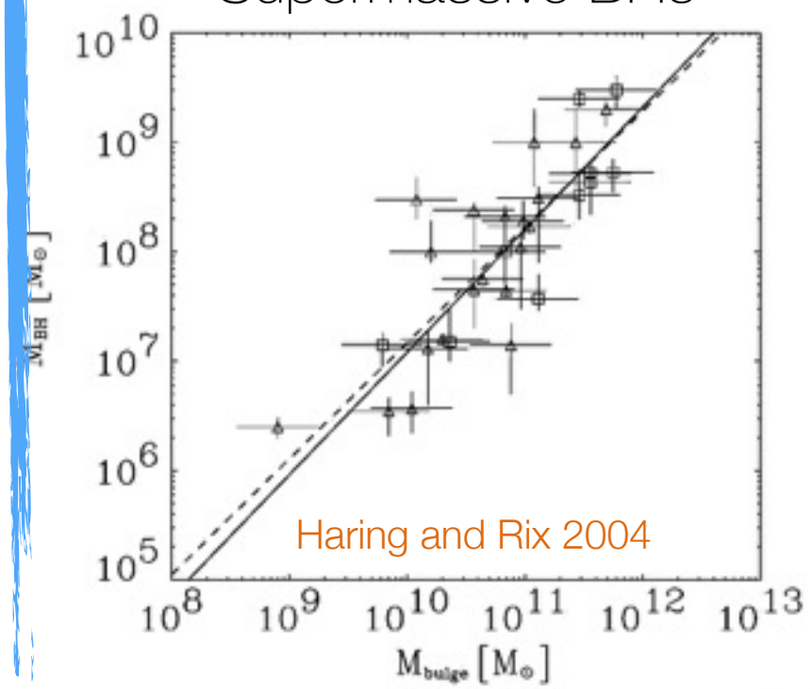
Merging BH binaries?

Most convincing BH-binary candidate

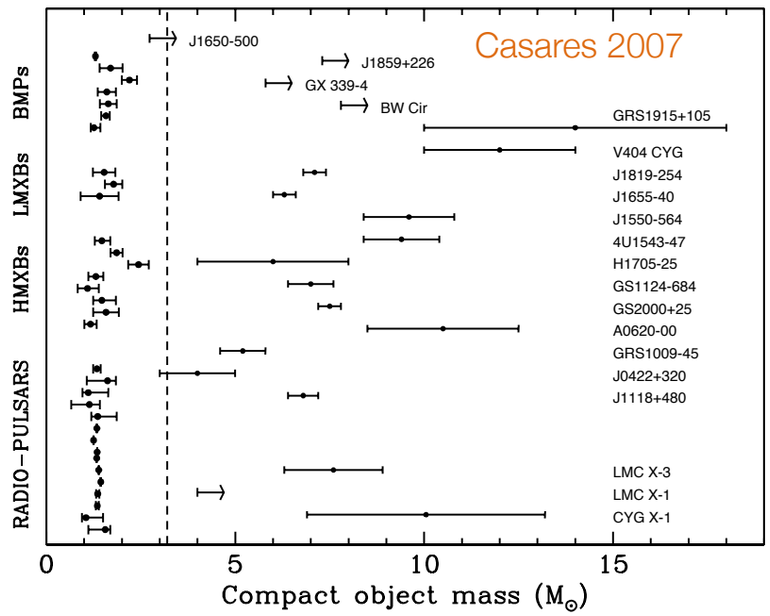


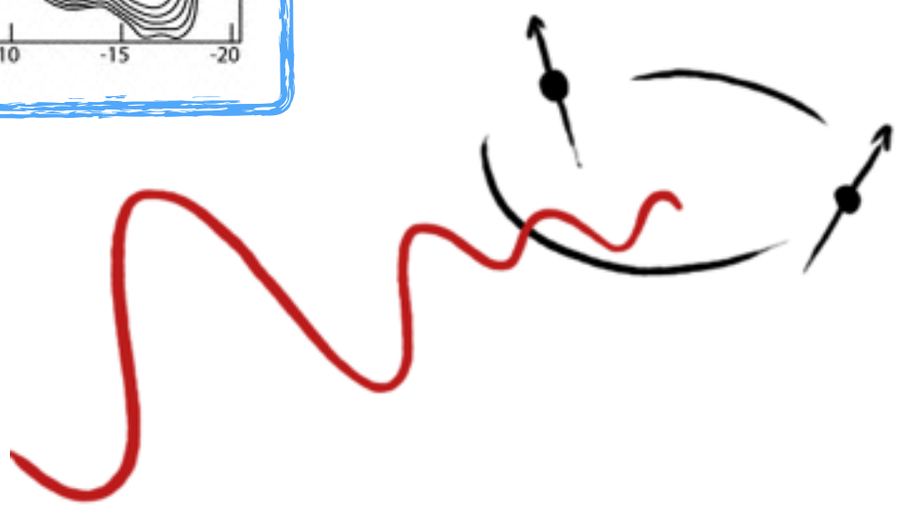
Mass measurements

Supermassive BHs

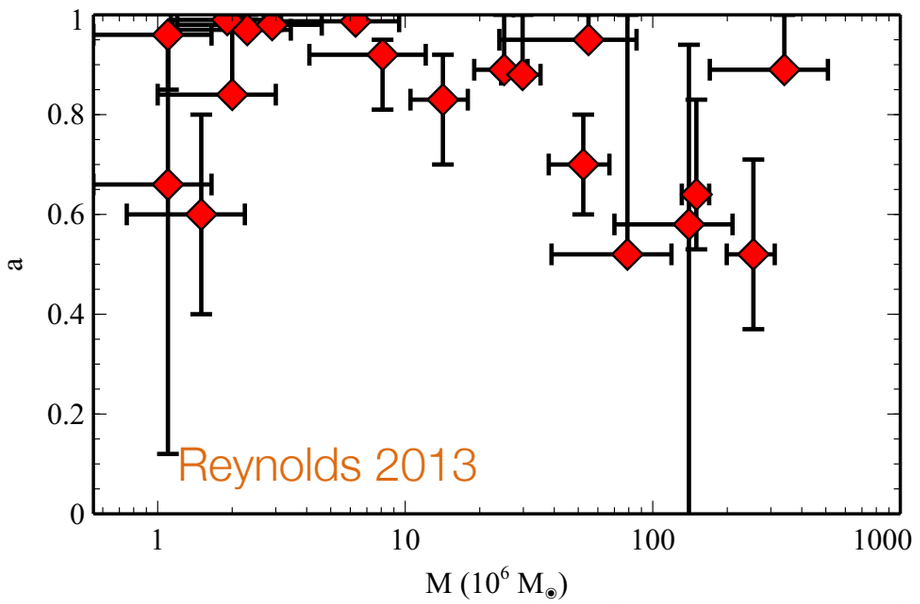


Stellar-mass BHs

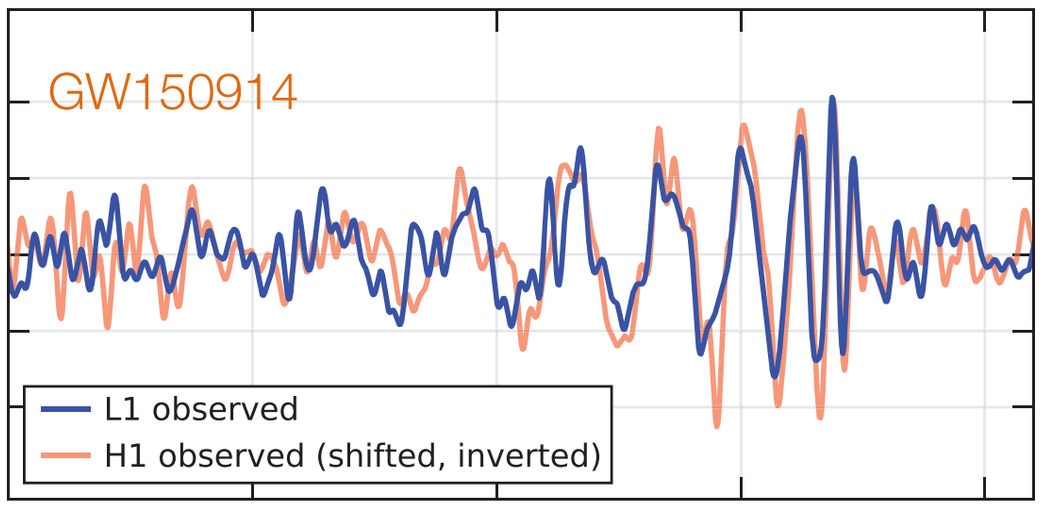


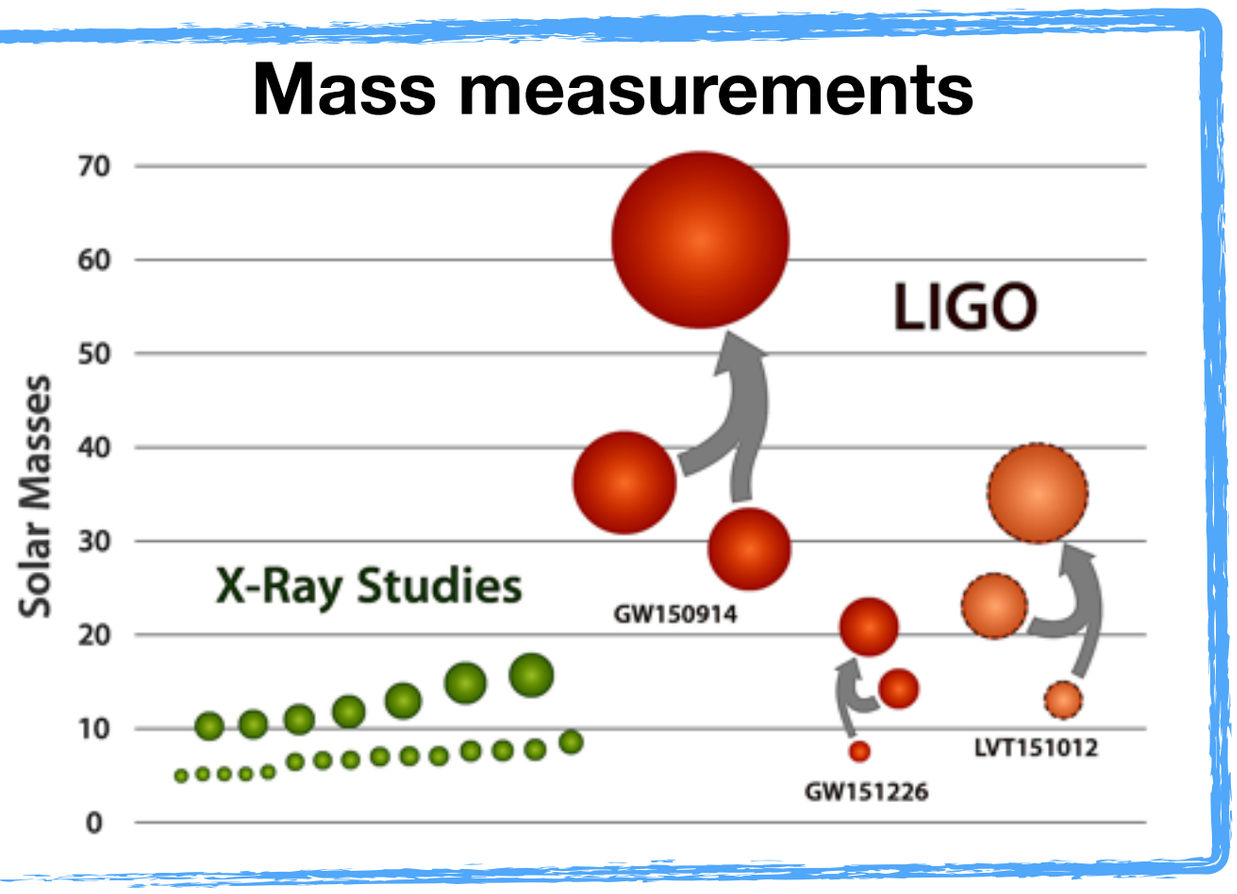


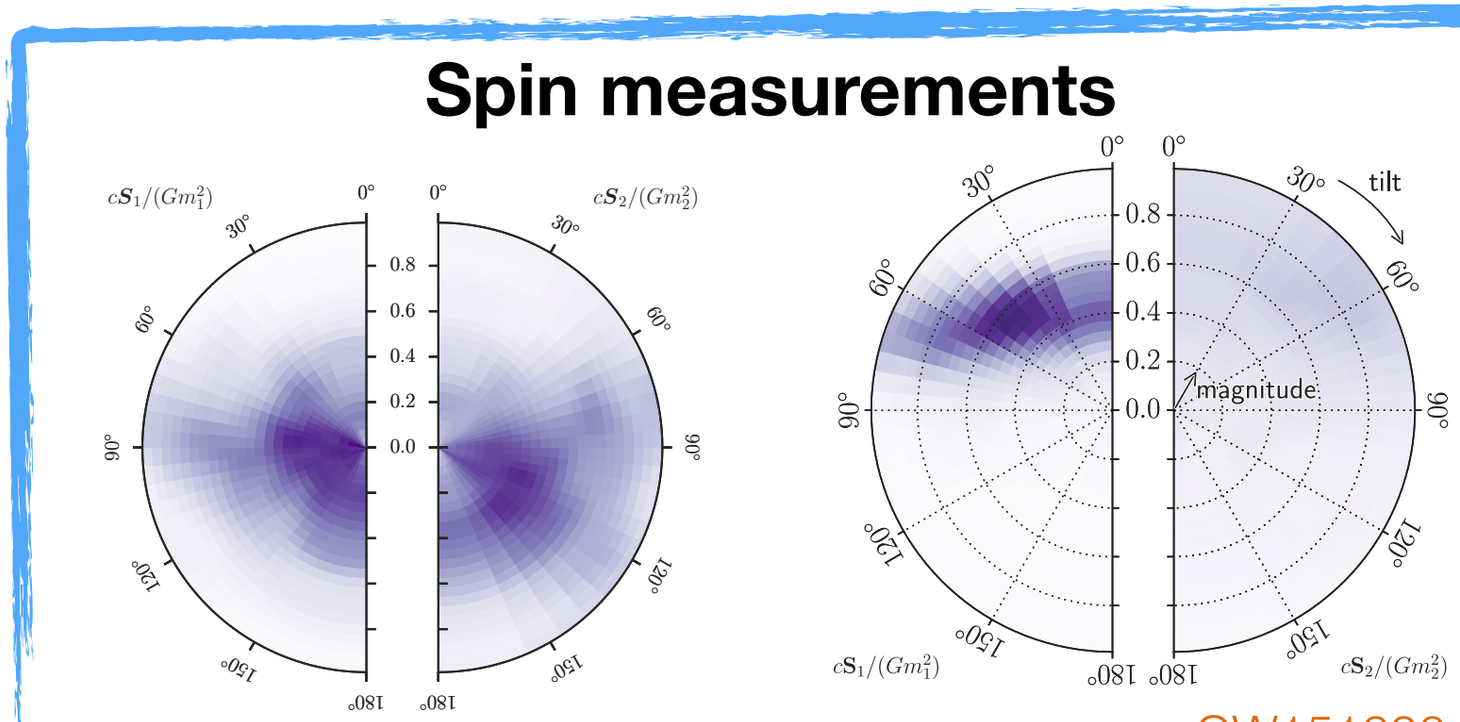
Spin measurements



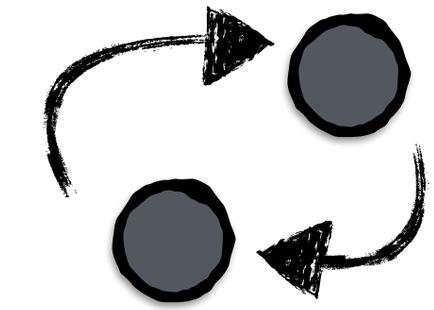
Merging BH binaries!



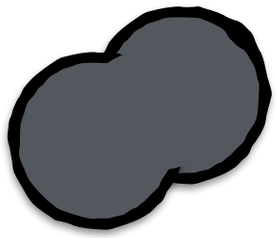




GW signals from BH mergers

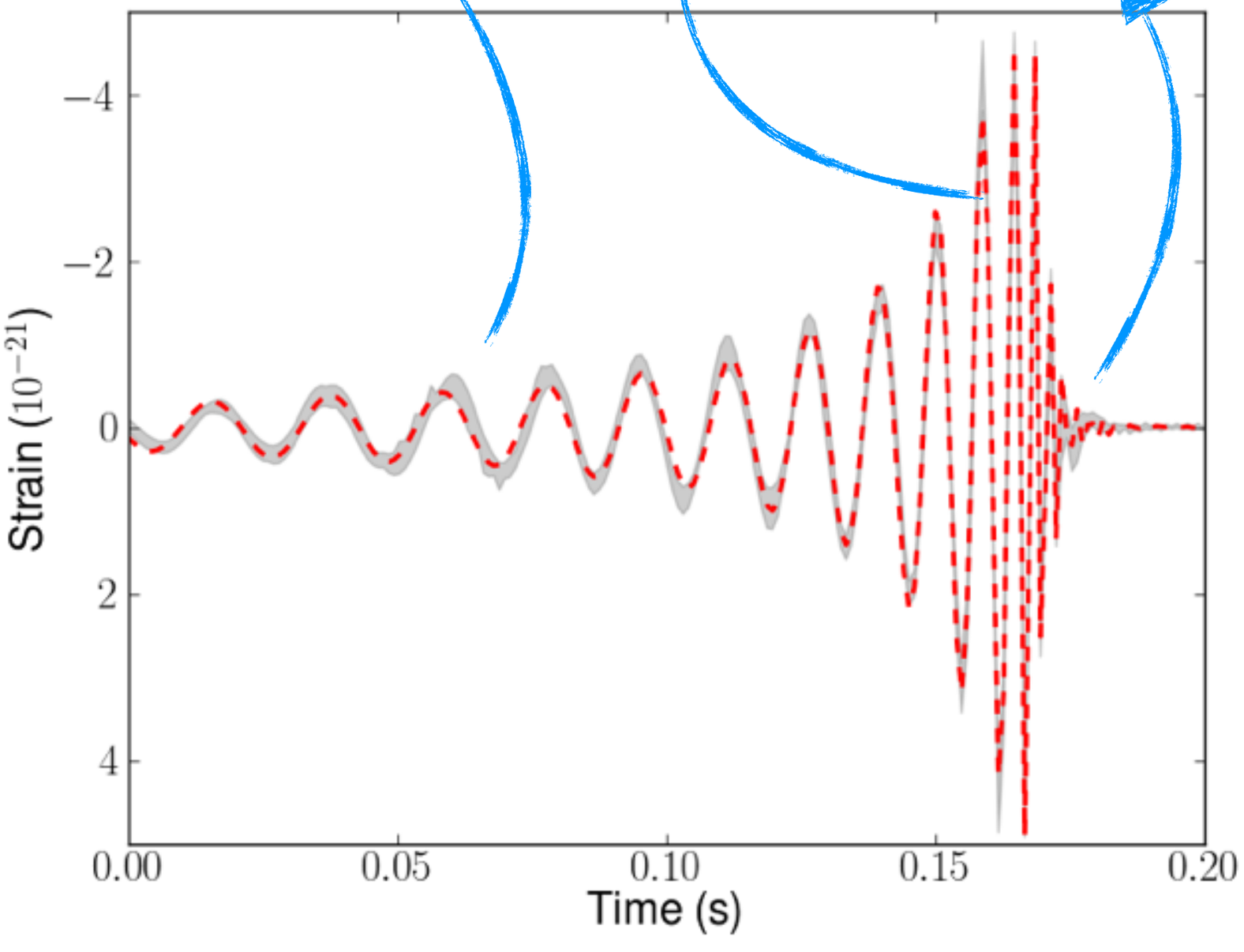


Inspiral
post-Newtonian



Merger
numerical relativity

Ringdown
BH perturbations



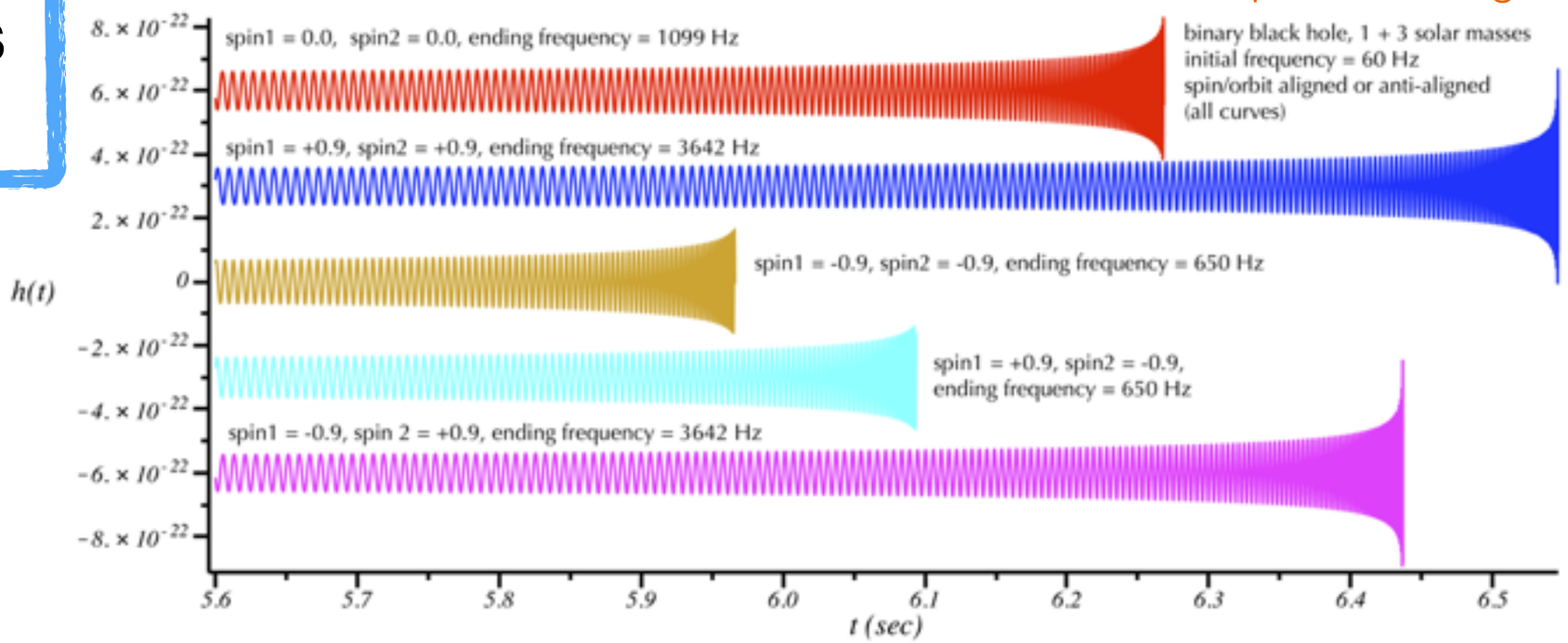
- Frequency gradually increases during the **inspiral**
- **Merger** of two BHs is one of the most energetic events in the Universe
- *BHs have no hair*: final remnant has to dissipate all properties but mass and spin (**ringdown**)

How about the spin?

Aligned components of the spins

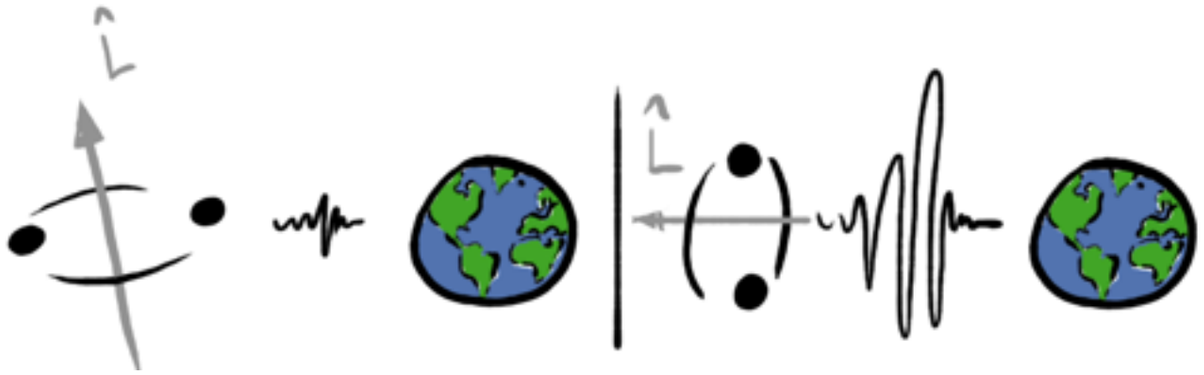
- Different merger frequency (analog of the ISCO)
- Aligned spins take longer to merge

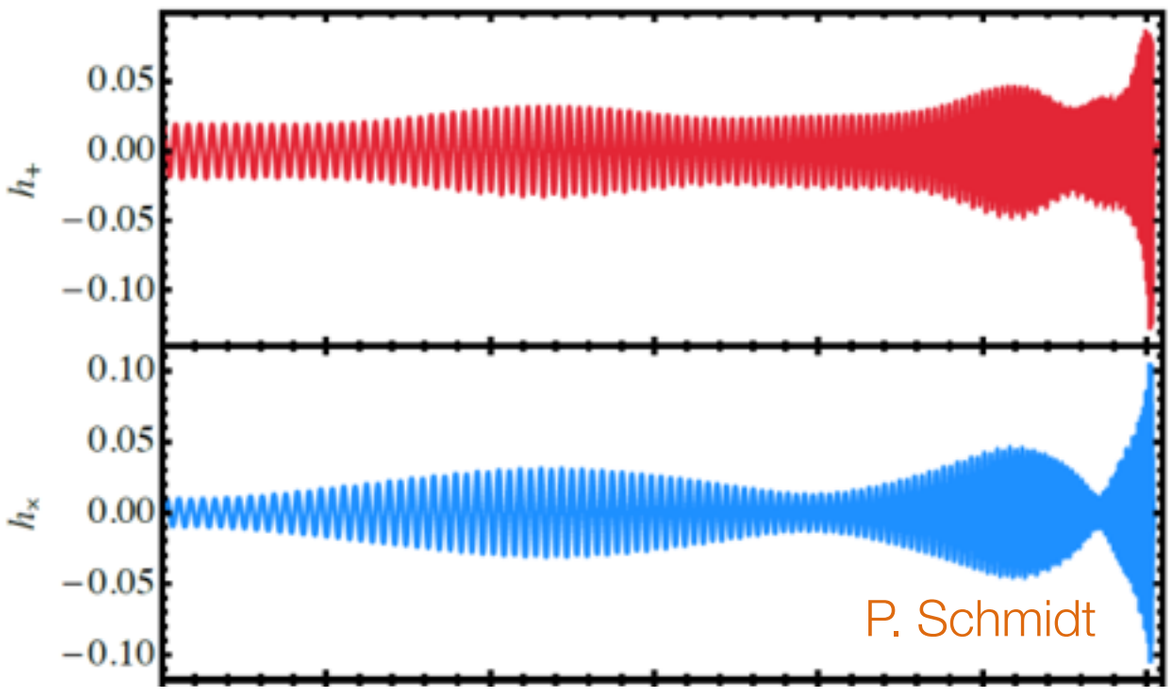
M. Favata, soundofspacetime.org



Orbital-plane components of the spins

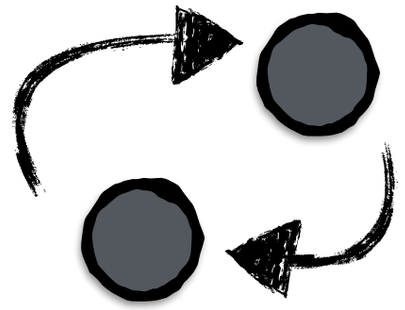
- spin precession; orbital plane precession
- Peculiar waveform modulations





P. Schmidt

A tale of three timescales



1. **Orbital** motion → $t_{\rm orb} \propto (r/r_g)^{3/2}$ Kepler's third law
2. Spin & orbital-plane **precession** → $t_{\rm pre} \propto (r/r_g)^{5/2}$ Apostolatos et al 1994
3. GW emission and **inspiral** → $t_{\rm RR} \propto (r/r_g)^{4}$ Quadrupole formula Peters & Matthews 1963

if **(Post-)Newtonian** $r \gg r_g = GM/c^2$: timescale hierarchy

Orbit << Precession << Inspiral

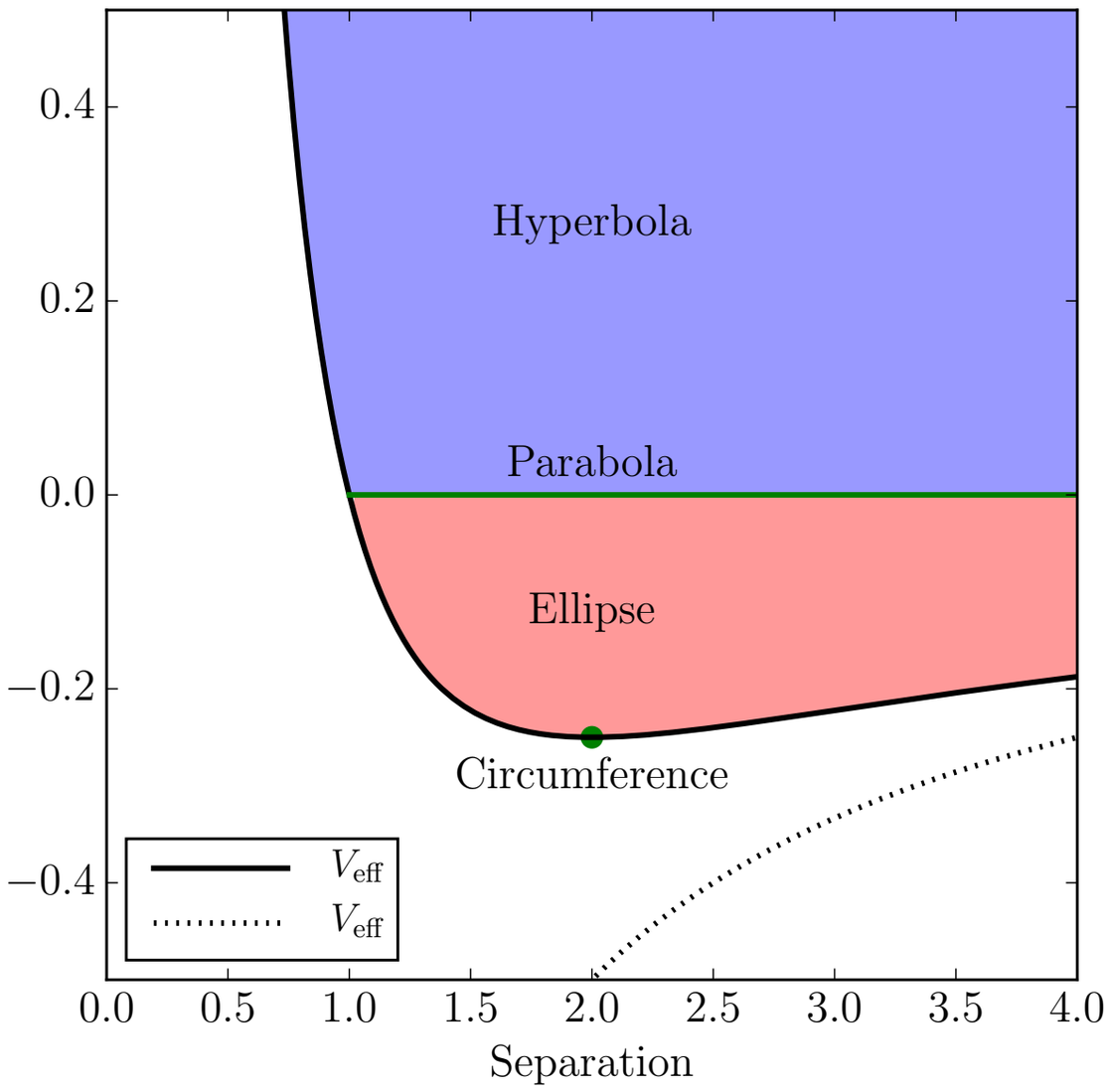
BH binary **multi-timescale** analysis:

1. Solve the dynamics (hopefully analytically) on the shorter time
2. Quasi-adiabatic evolution ("average") on the longer time

Common practice in binary dynamics

- periastron precession
- osculating orbital elements
- variation of constants

On the shoulders of giants



Kepler's two-body problem

What you do:

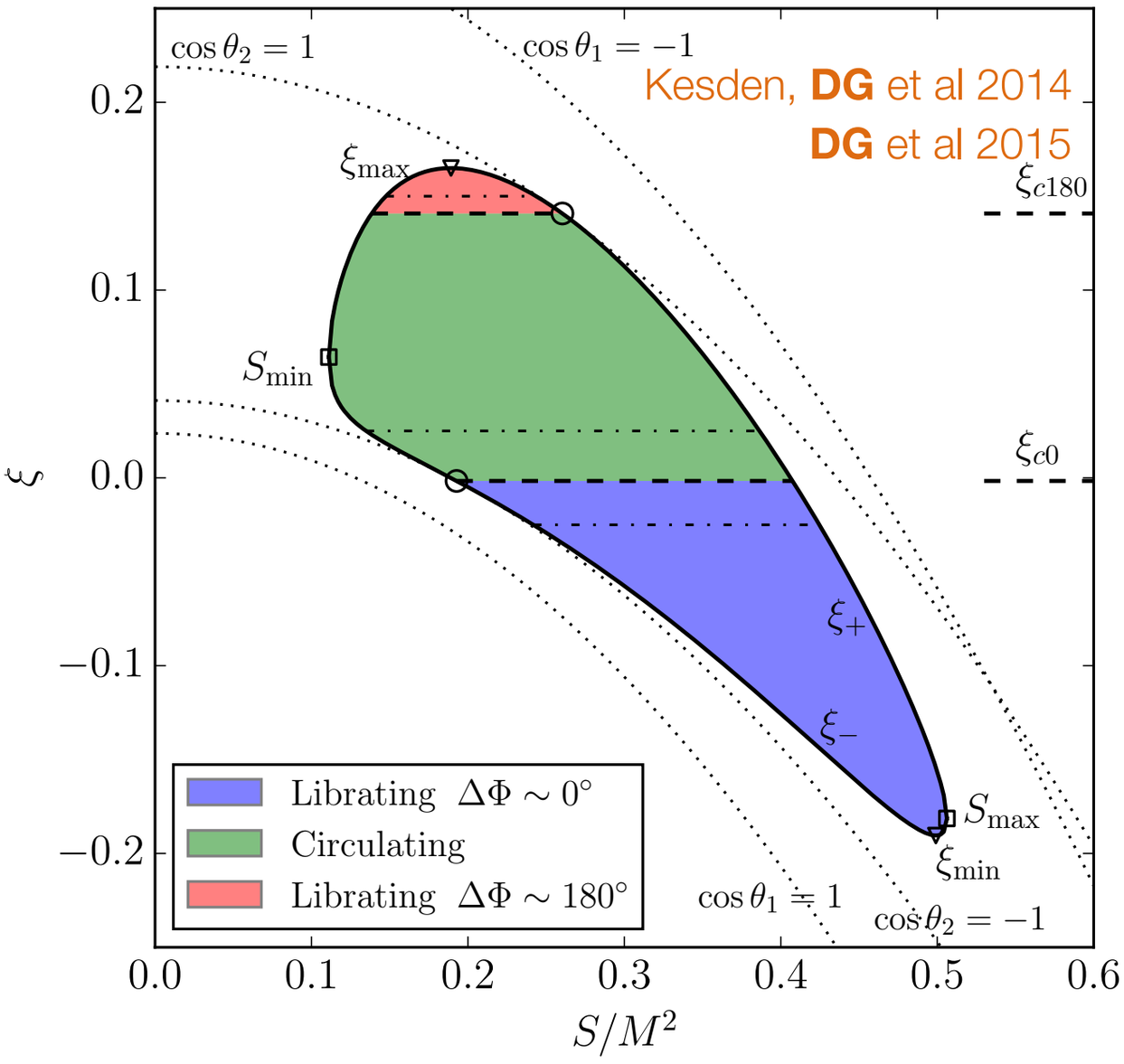
- One effective particle: 3D
- 3D to 2D problem:
  L is a **constant** of motion!
- Energy is **constant:** 2D to 1D?
- Effective potential

What you get:

- A lot of understanding
- Solutions are Kepler's orbits
- **Phases**: bound, unbound

Integrating GMm/r^2 to get a bunch of points along an orbit or…
knowing that that curve is an ellipse!

Effective potentials for spin precession



What you do:

- Start from three angles and r
- 4D to 2D problem: GW are frozen, r and J are **constant**,
- Further constant of motion, **effective spin:** 2D to 1D
- Effective potentials for BH binary spin precession

What you get:

- Analytical solutions
- **Phases**: circulating, librating
- A lot of understanding

Integrating the PN eq. to get a bunch of points on a precession cone or…
knowing the shape of that cone!

Spin morphologies

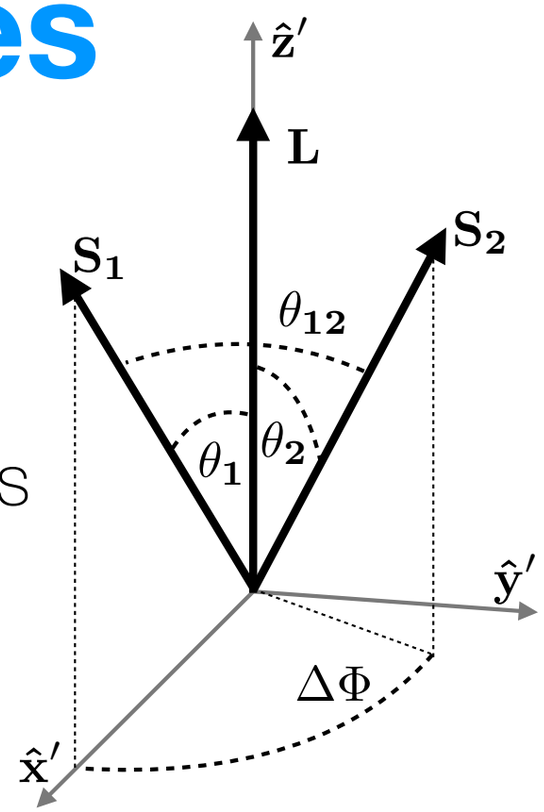
How do **solutions** look like?

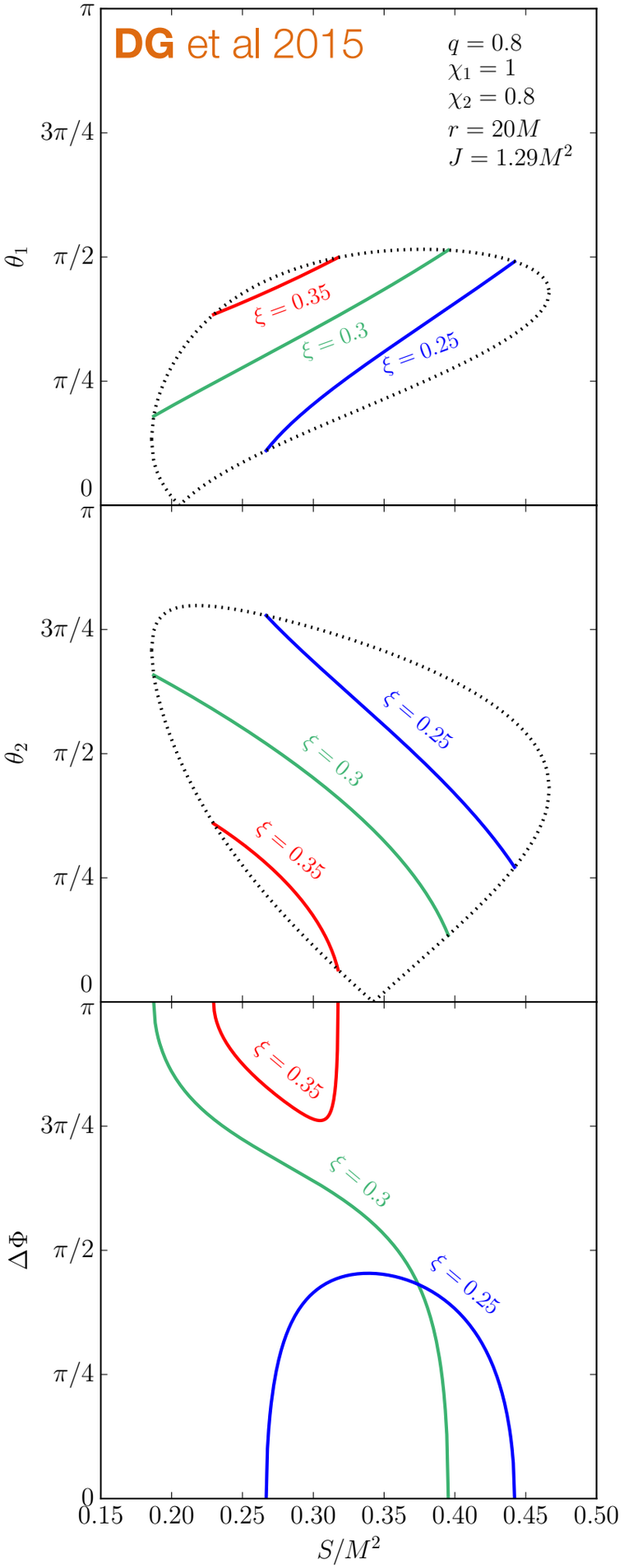
Spin tilts $\theta_1,\ \theta_2$

- **Bounded** by the effective potentials
- Monotonic

Azimuthal projections $\Delta\Phi$

- Three different **morphologies**
- Boundaries if aligned
- **Morphological transitions** during the inspiral

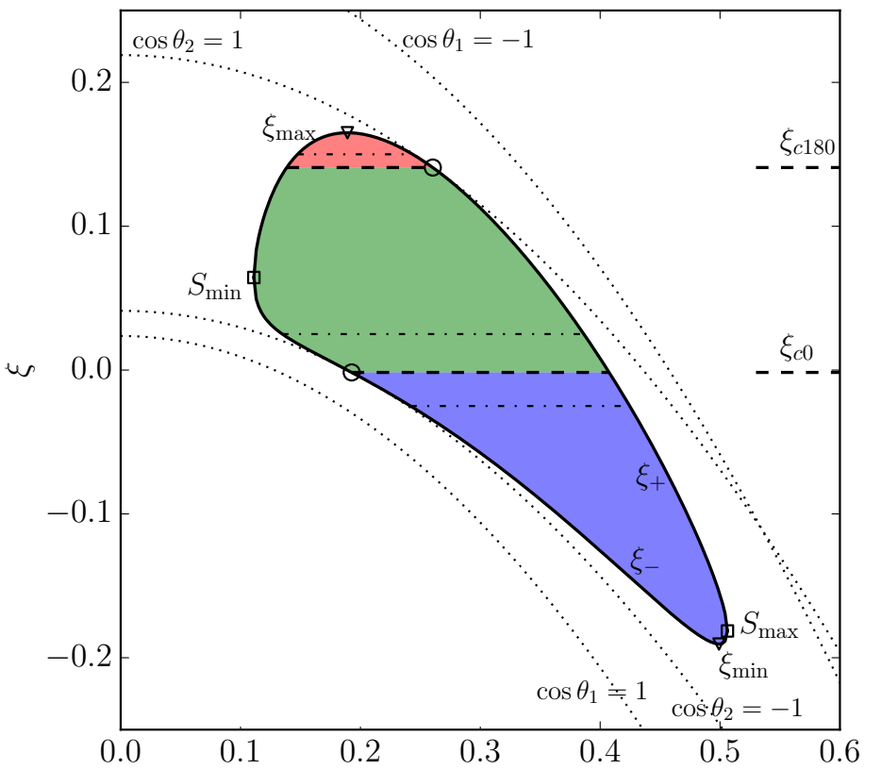




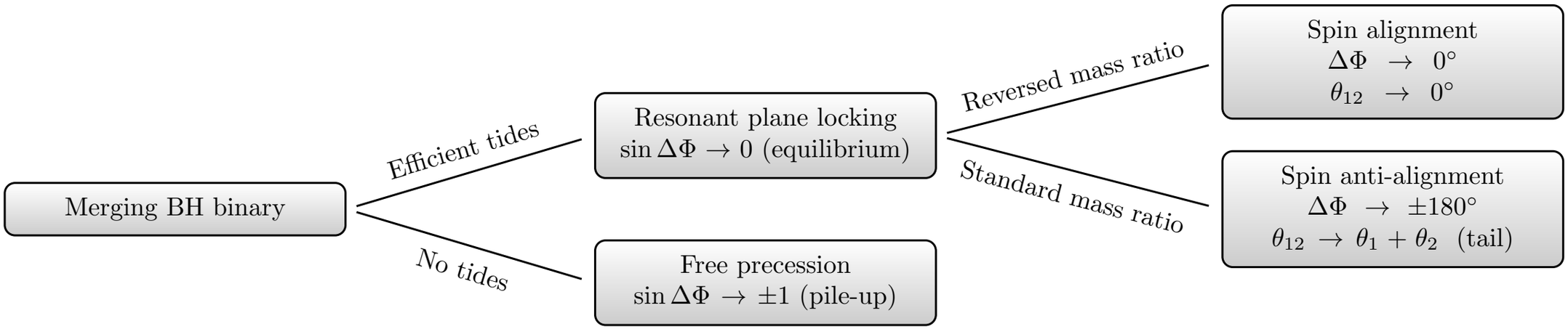
Librating $\Delta\Phi \sim 0$

Circulating

Librating $\Delta\Phi \sim \pi$



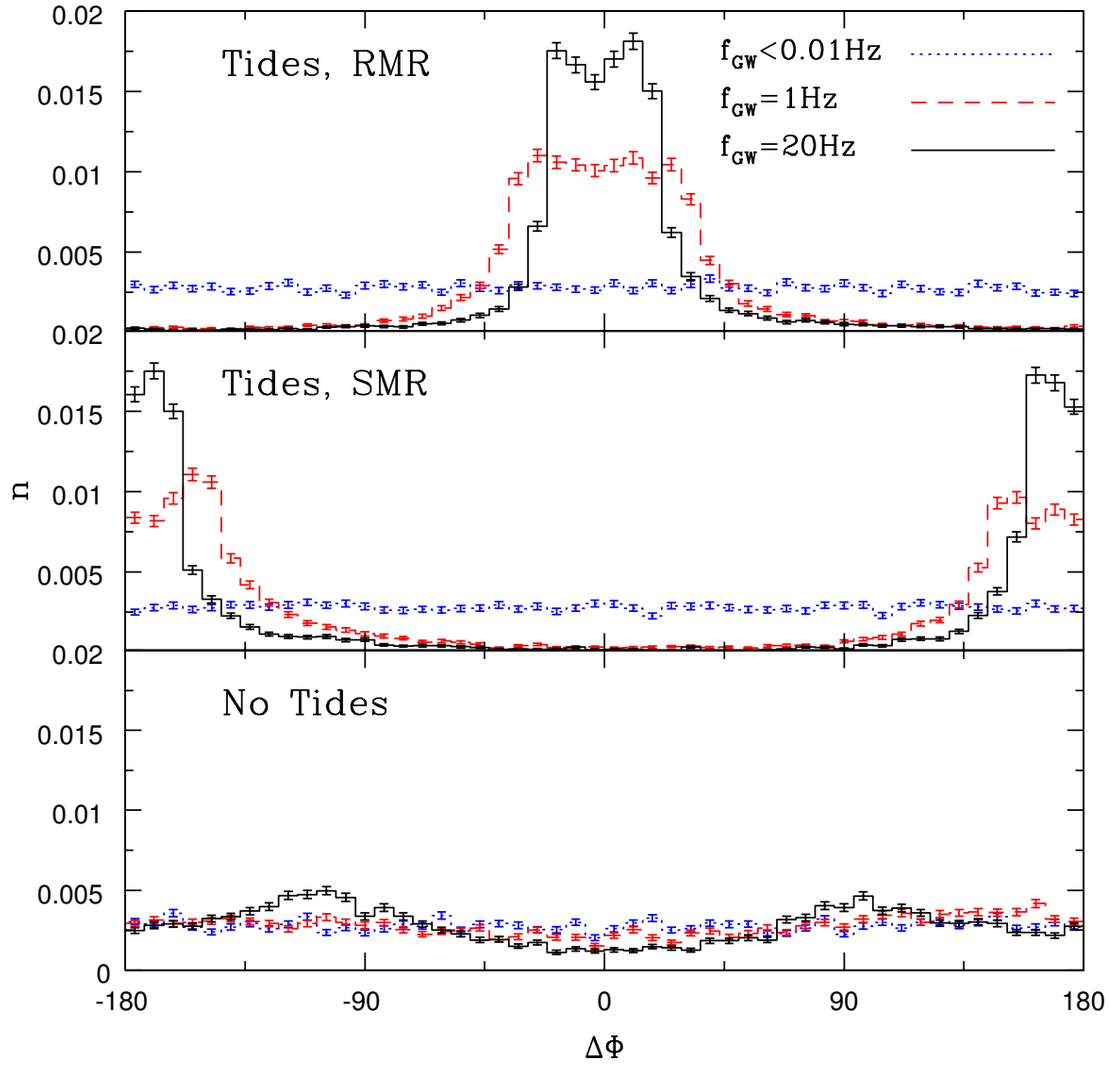
Astrophysics with BH binary spins



- **Morphology**: feature of spin precession that does not vary on the precessional time!
- Spin morphology tracks precise **formation mechanisms**
- Tidal interactions, mass transfer events

Spin morphology is a new channel to BH astrophysics

DG et al 2013



Try this at home

precession: new open-source python module

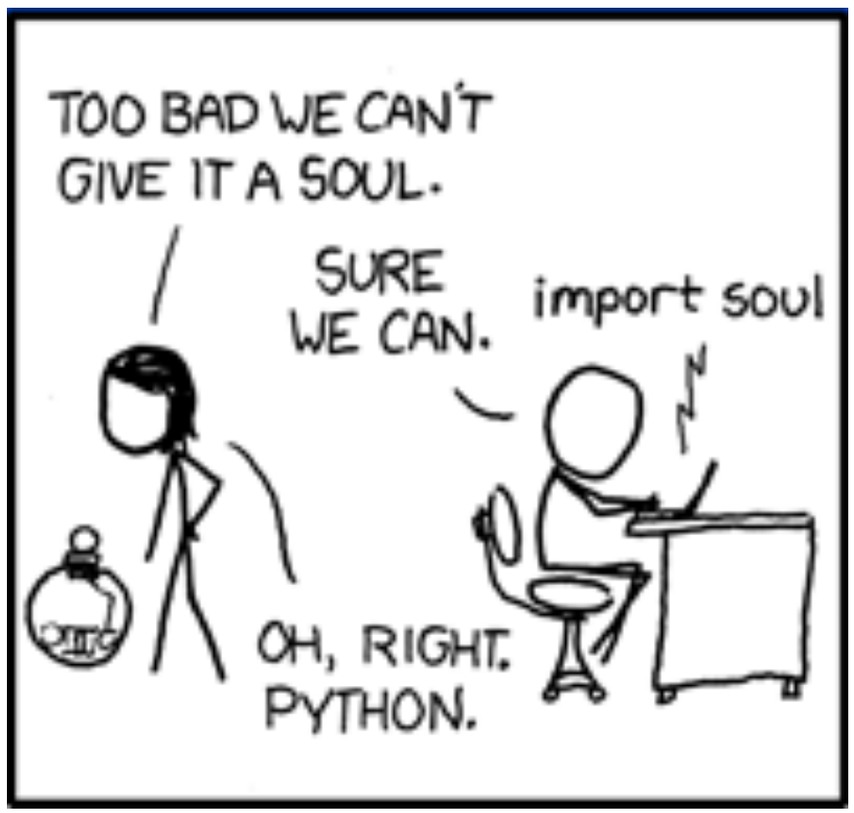
Distributed on **GitHub,** uploaded on the Python package index (**pip**)

I'm easy...

```
pip install precession
>>> import precession
```

Features

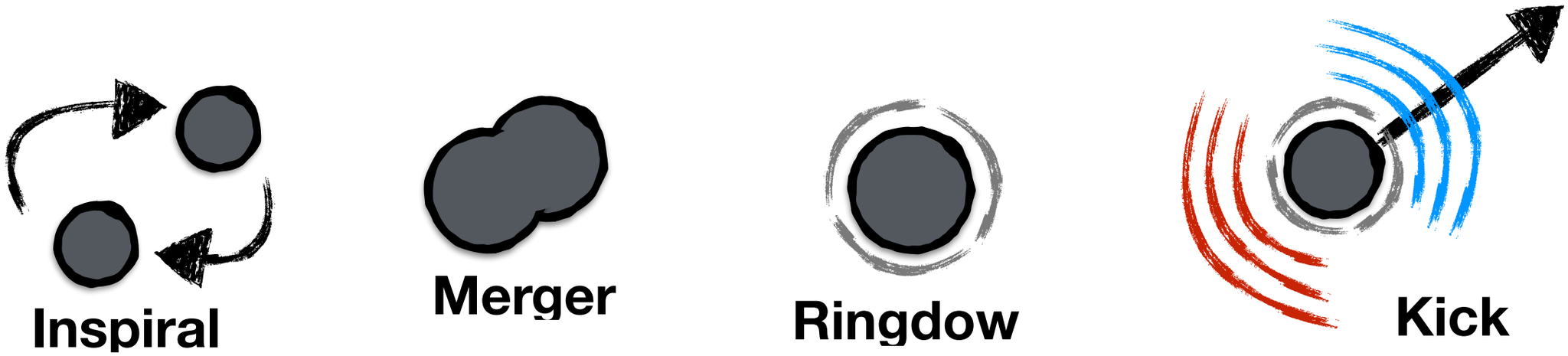
1. Precessional dynamics
2. Orbit-averaged inspirals
3. Precession-averaged inspirals
4. Superkick predictions
5. API documentation
6. Tests and tutorial



... check me out!

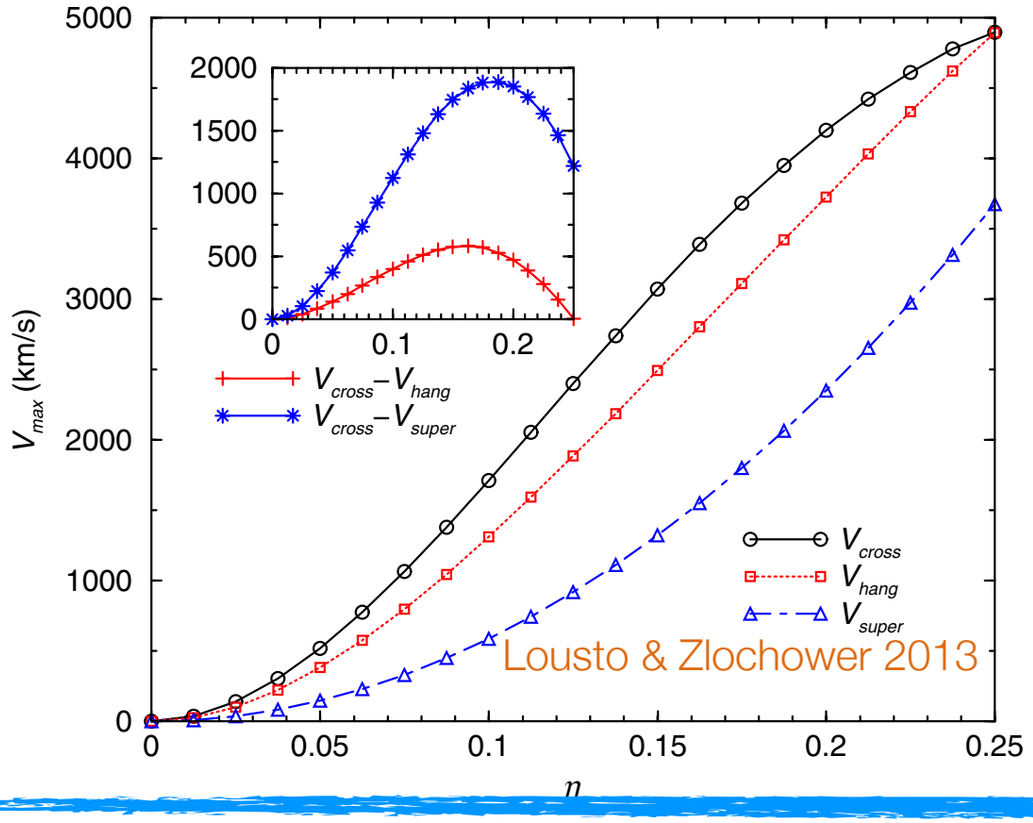
davidegerosa.com/precession

Black-hole kicks

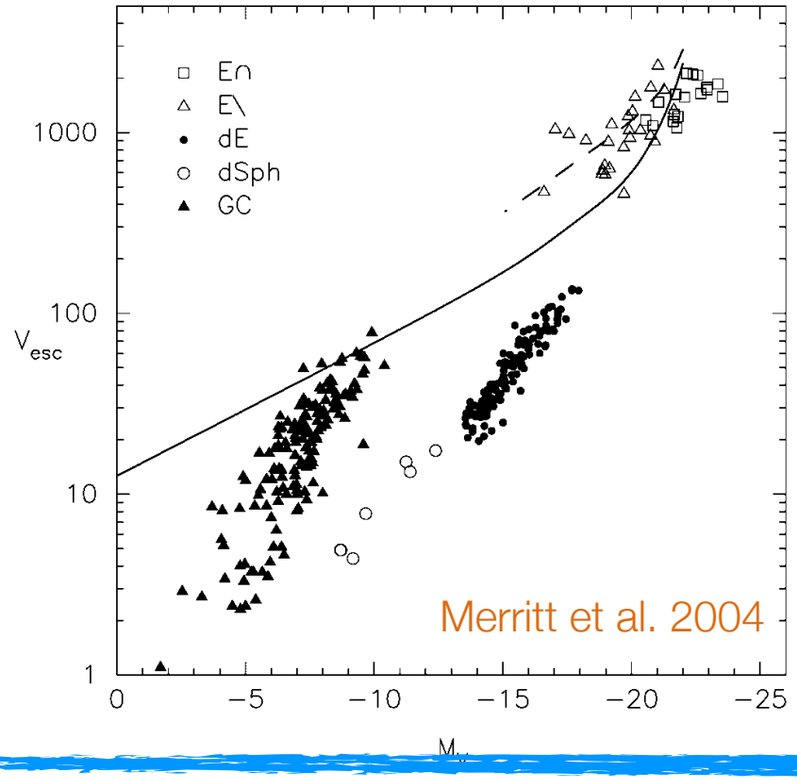


- **Asymmetry** in the GW emission in the late inspiral and merger
- Remnant must **recoil** in the other direction

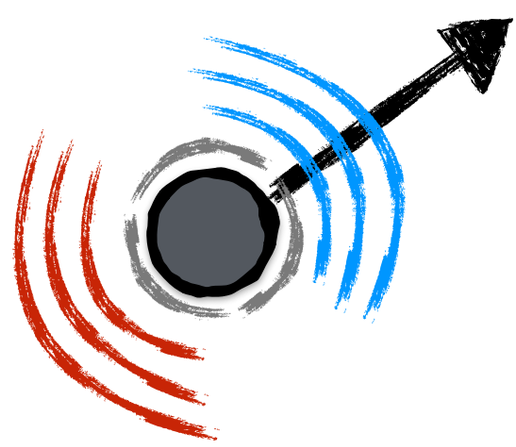
Kicks up to 5000 km/s!



Larger than galaxy escape speeds!



Kicked waveforms



- In GW measurements, **total mass** and **redshift** are degenerate
- Kicks in the waveform shows up as a red/blueshift!

Cosmology:

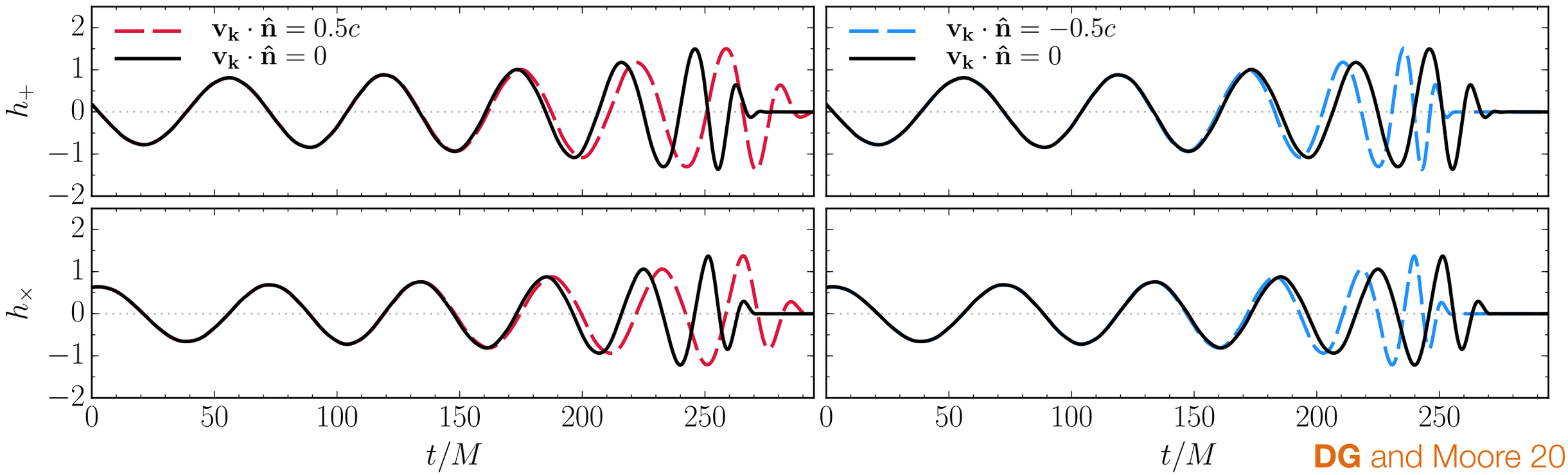
entire waveforms is shifted

$$M \to M(1+z)$$

Kicks:

differential Doppler shift

$$M \to M\left(1 + \frac{\mathbf{v_k}(t)}{c} \cdot \hat{\mathbf{n}}\right)$$



DG and Moore 2016

Can kick shifts be detected?

Signal-to-noise ratio

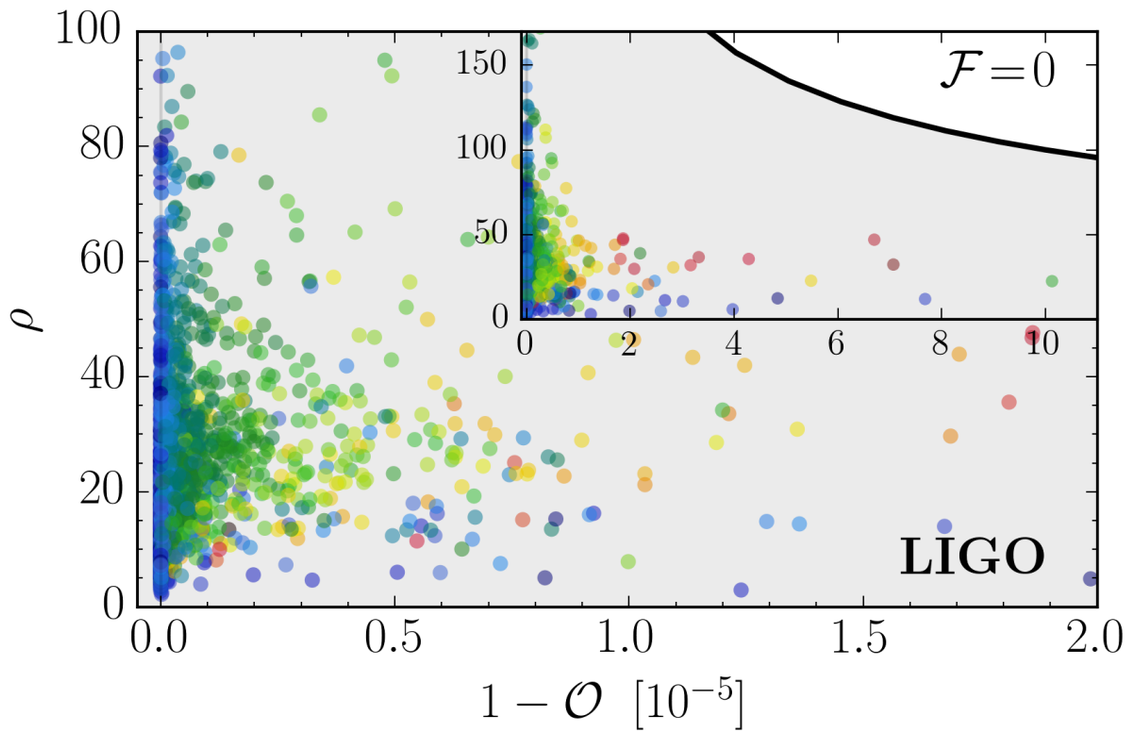
$$\rho = \sqrt{< h_0 | h_0 >}$$

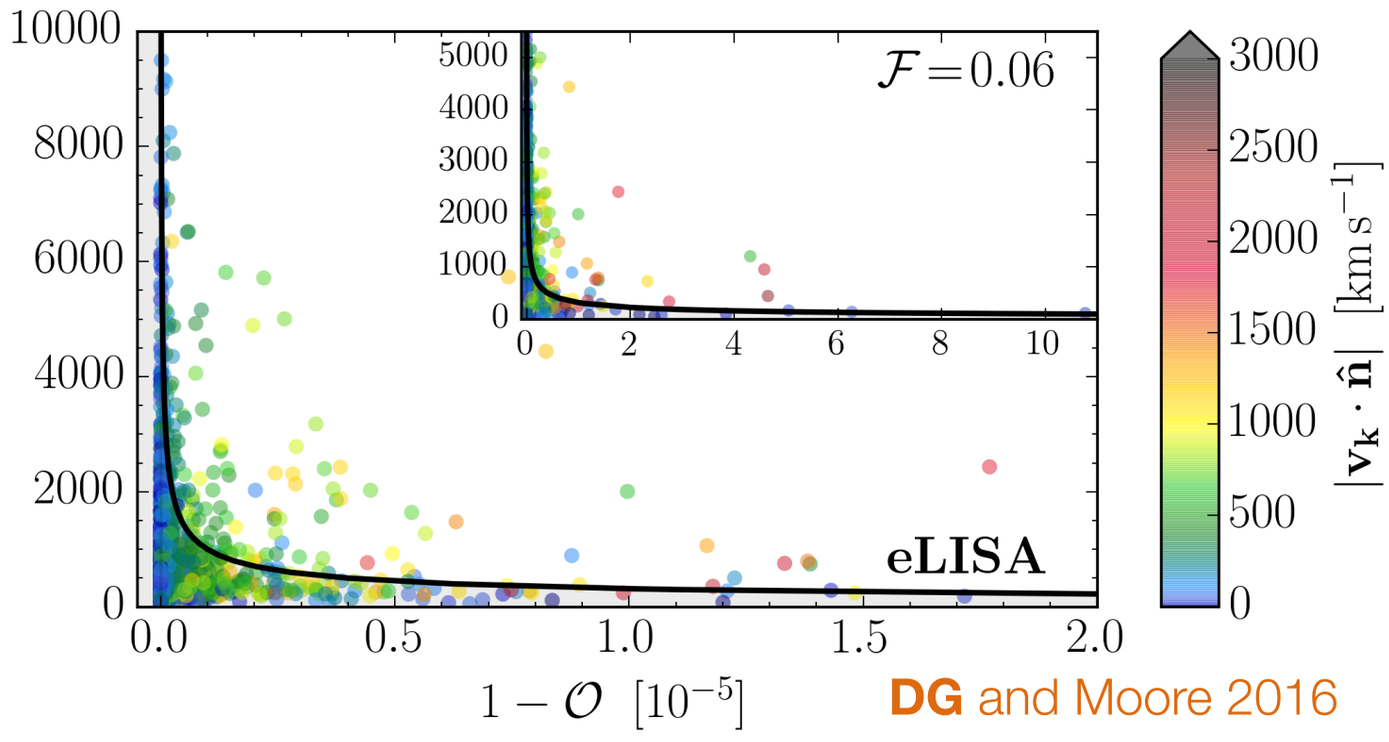
Overlap

$$\mathcal{O} = \max_{t_c, \phi_c} \frac{(h_0|h_k)}{\sqrt{(h_0|h_0)(h_k|h_k)}}$$

Distinguishable if

$$\mathcal{O} < 1 - \frac{1}{\rho^2}$$





DG and Moore 2016

eLISA can!

- Hulse-Taylor pulsar: first evidence GWs carry **energy**
- GW150914: first evidence of **GWs** themselves
- Kicks: first evidence GWs carry **linear momentum**

Outline

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arXiv: 1606.04226

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3. Direct measurements of BH **kicks**