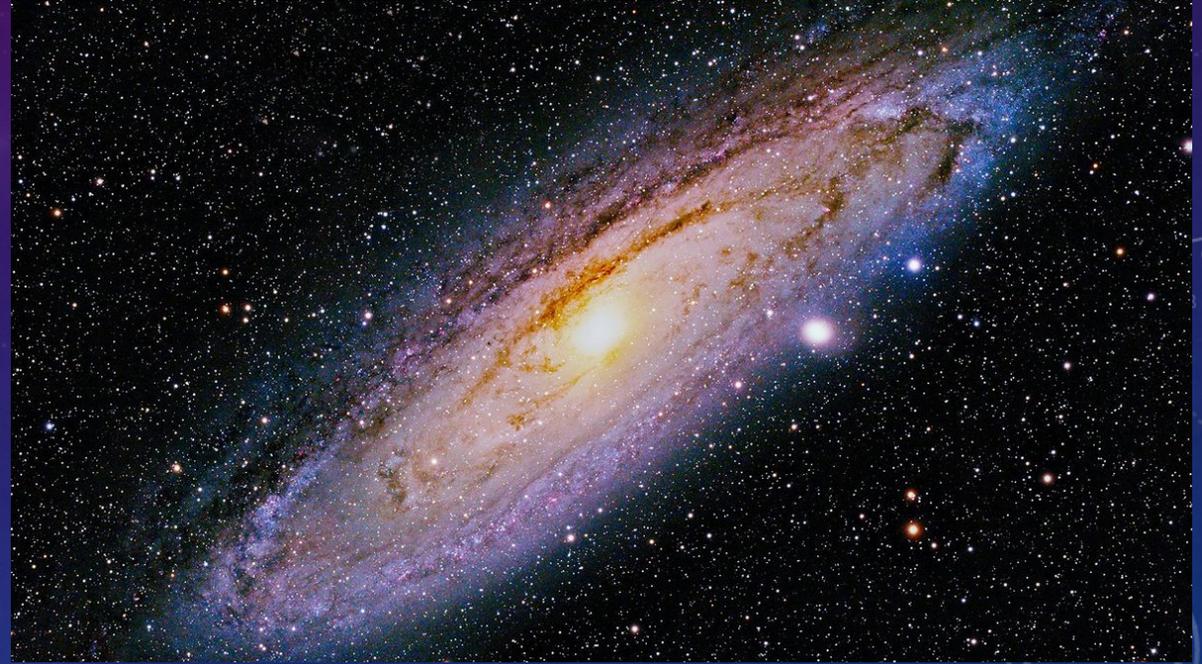
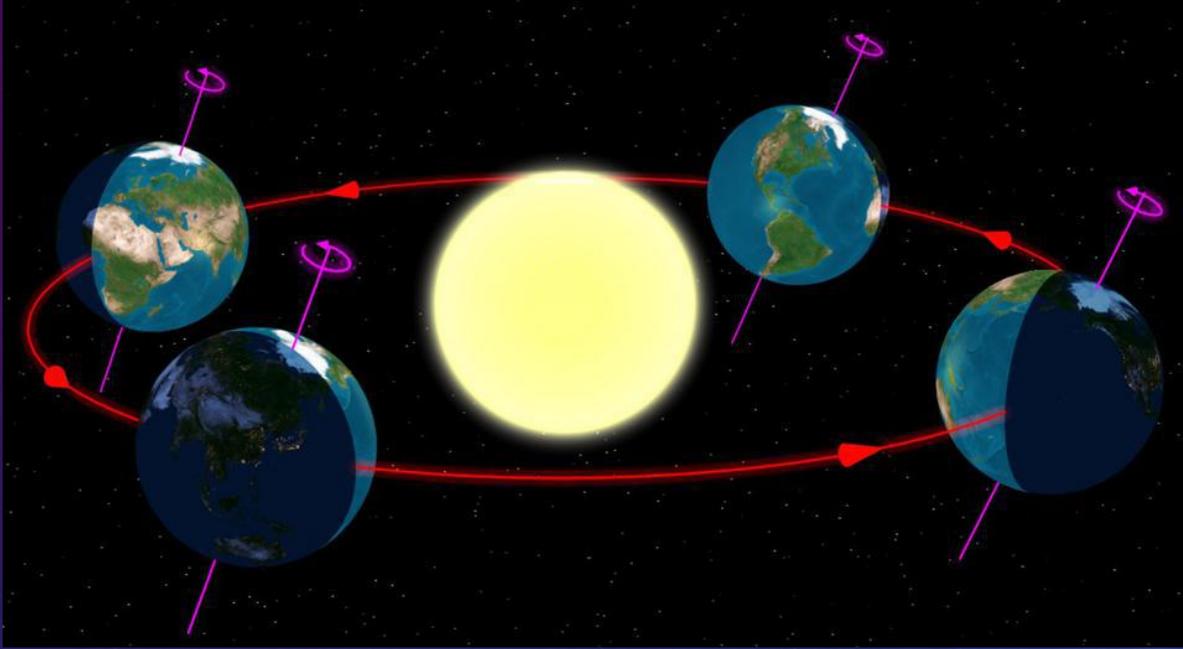


SPACE, SPINS AND VERY DENSE THINGS

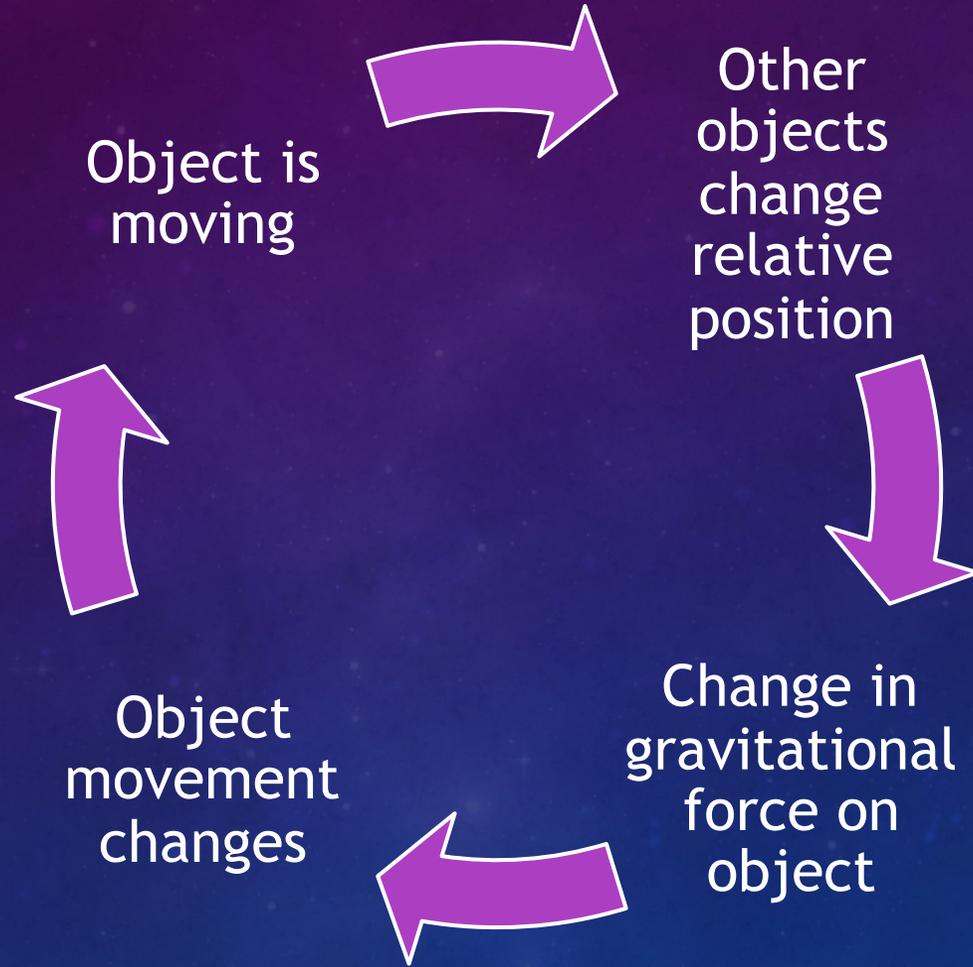
THE WHIRLING WOBBLINESS OF PRECESSING GRAVITATIONAL WAVES

EVERYTHING IS ROTATING...

2



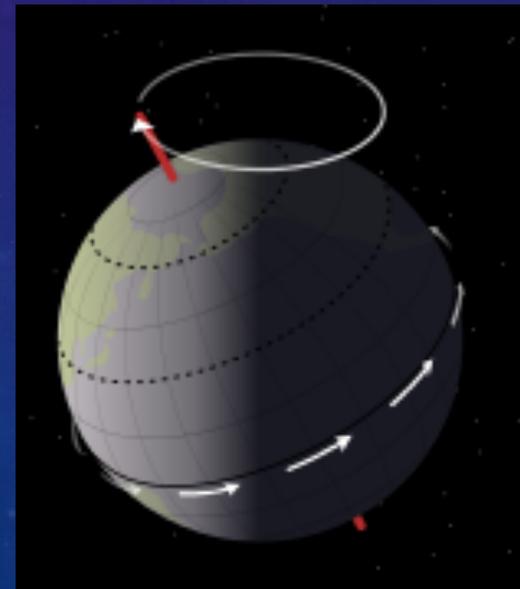
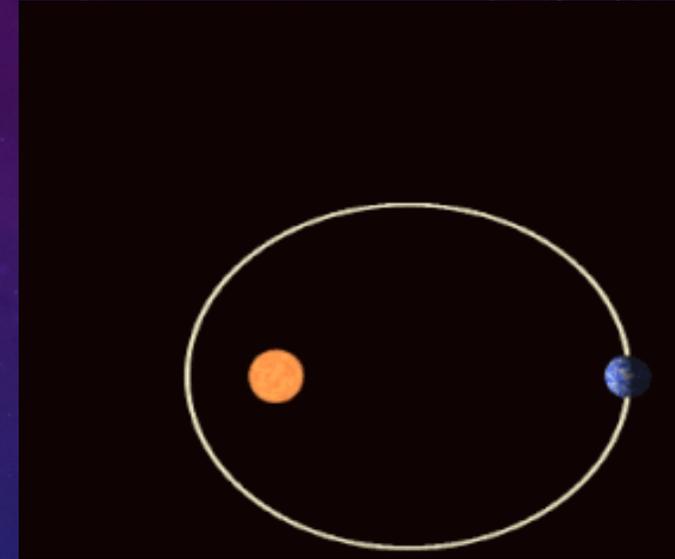
ROTATIONS ARE CHANGING...



Precession: Slow changes in the rotation of a spinning body.

CLASSICAL PRECESSION

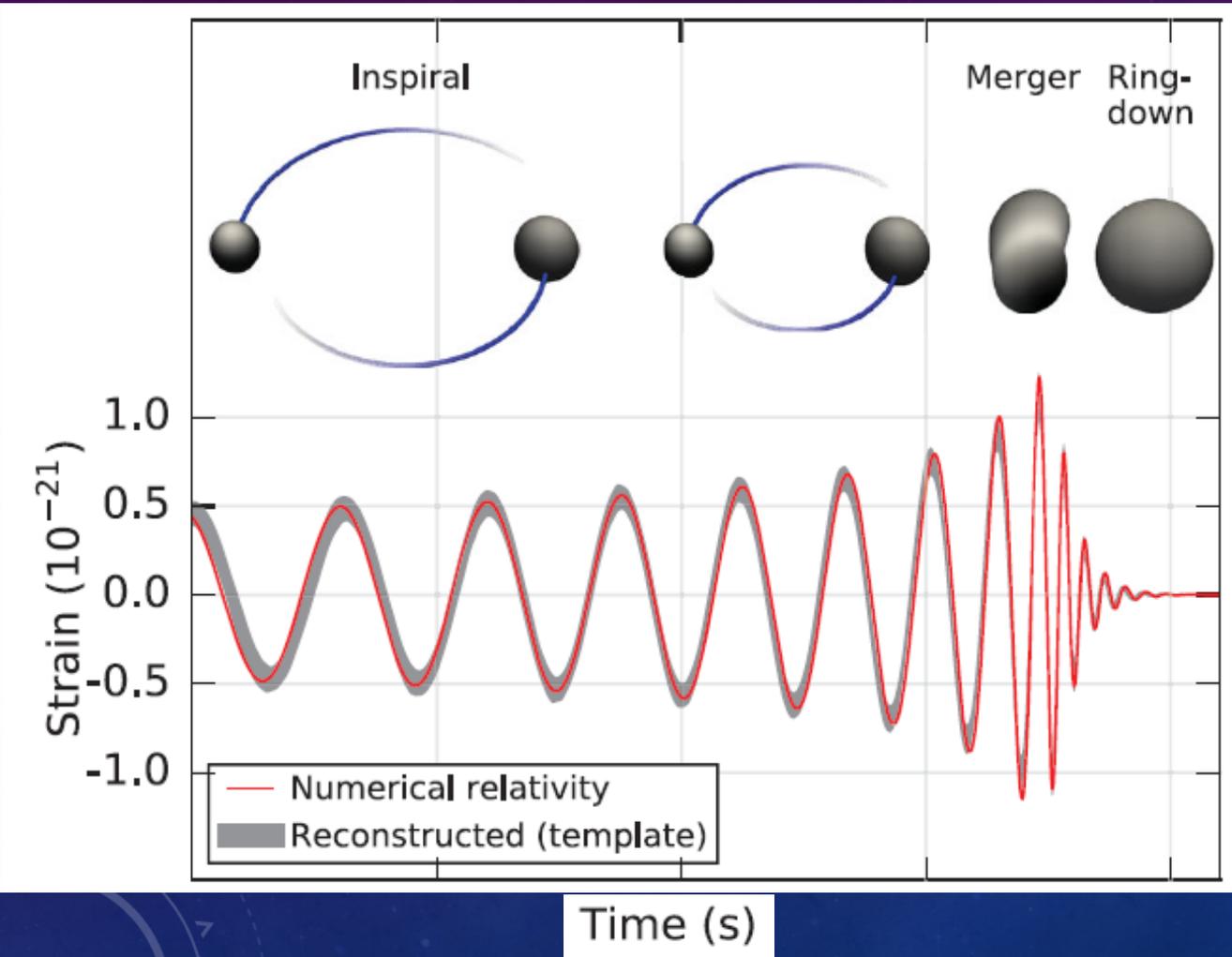
- **Perihelion precession**
 - Due to gravitational forces from other planets
- **Axial precession**
 - Due to tidal forces from moon/sun pulling on bulging equator



Wikipedia
Commons

GRAVITATIONAL WAVES FROM BINARY BLACK HOLE MERGERS

5



- Provide a new window onto previously unseen phenomena
- Key source for ground-based detectors is merger of binary black holes (and neutron stars)
- More complicated system = more modes

PARAMETERS



- Mass
- Spin
- Charge
- Location

$$(m, \vec{\chi}, d, \alpha, \delta)$$

THE SHAPE OF GRAVITATIONAL WAVES

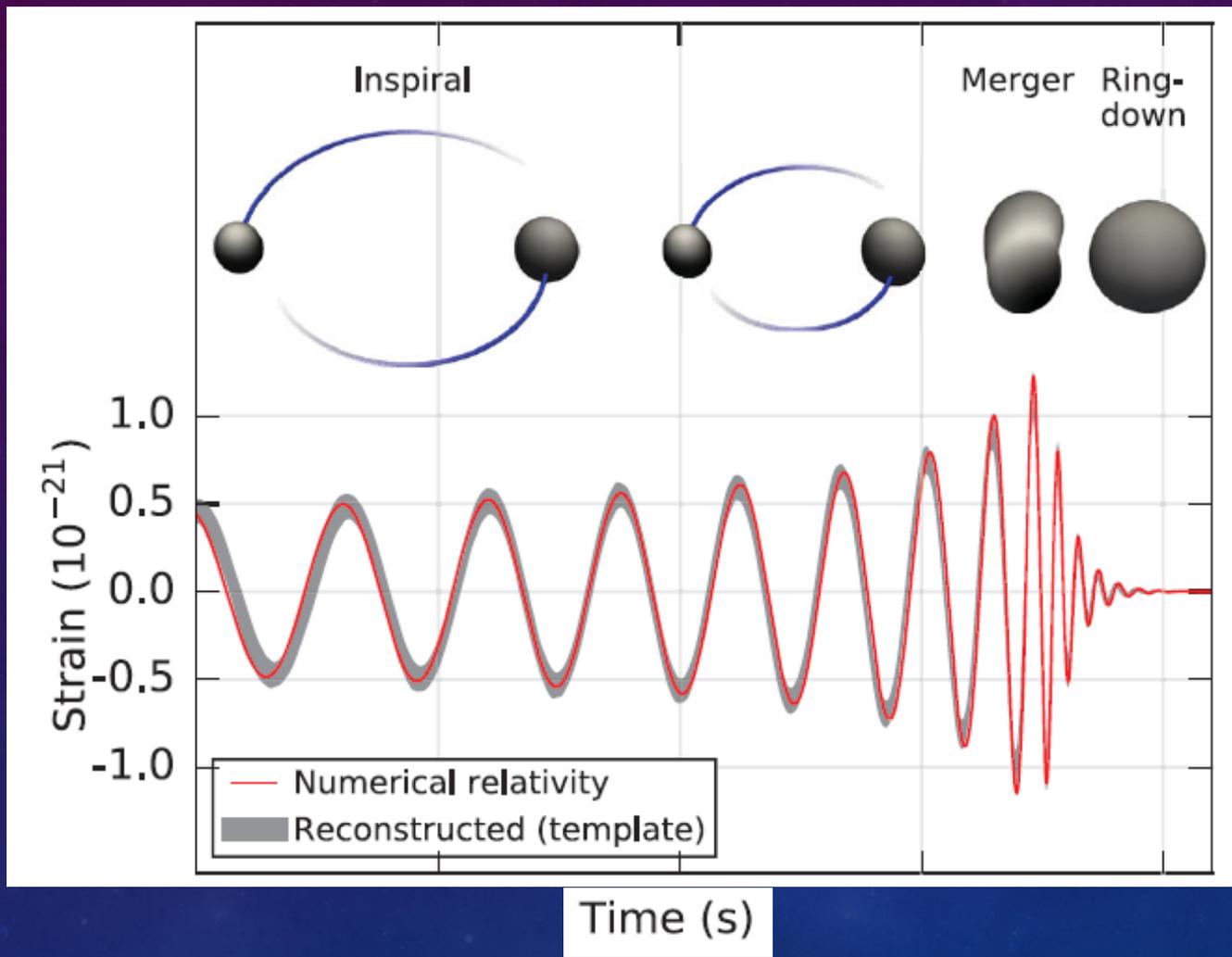
7

- Source parameters encoded GW signal
- To estimate these parameters from a signal, we need waveform models
 - Accurate
 - Computationally efficient
 - Complete (include relevant physical phenomena)



THE SHAPE OF GRAVITATIONAL WAVES

8



Distance

Total mass M

PARAMETERS

9

Intrinsic parameters

Extrinsic parameters

$$h = h(M, q, \vec{\chi}_1, \vec{\chi}_2, e, d_L, \alpha, \delta, l, \psi, t_c, \phi_c)$$

$$M = m_1 + m_2$$

Total mass can be factored out

Waveform models depend on mass ratio and spins,

Assume $e = 0$

Binary location

Binary orientation

Coalescence time and phase

HOW DOES THIS RELATE TO PRECESSION?

10

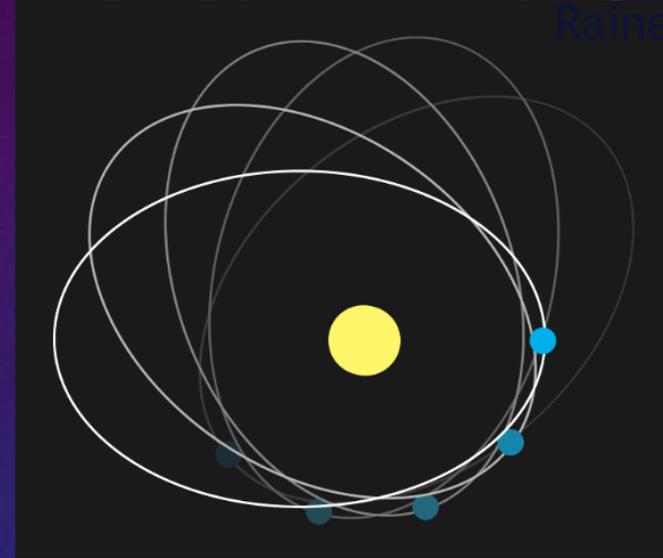
Binary black
holes spin around
each other



Binary black holes
can precess

GENERAL-RELATIVISTIC PRECESSION

- **Geodetic (de Sitter) precession**
 - Due to curvature of spacetime near large masses
 - Correction to Mercury's perihelion precession
- **Lense-Thirring (spin) precession**
 - Due to frame-dragging of spacetime near large rotating bodies
 - More important effect for spinning binary black holes



Rainer Zenz

11

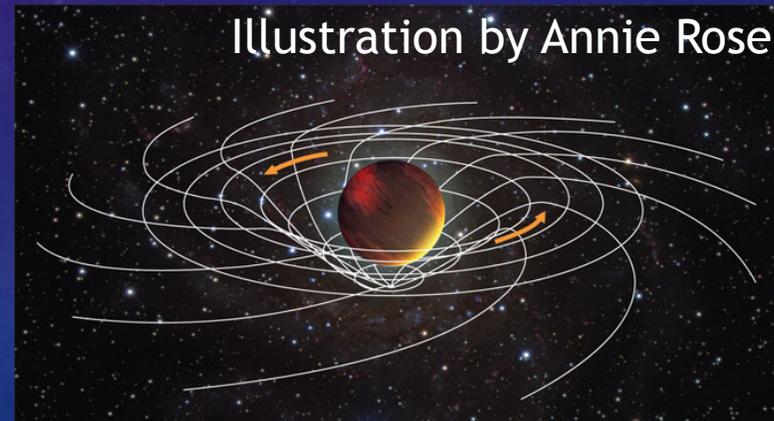
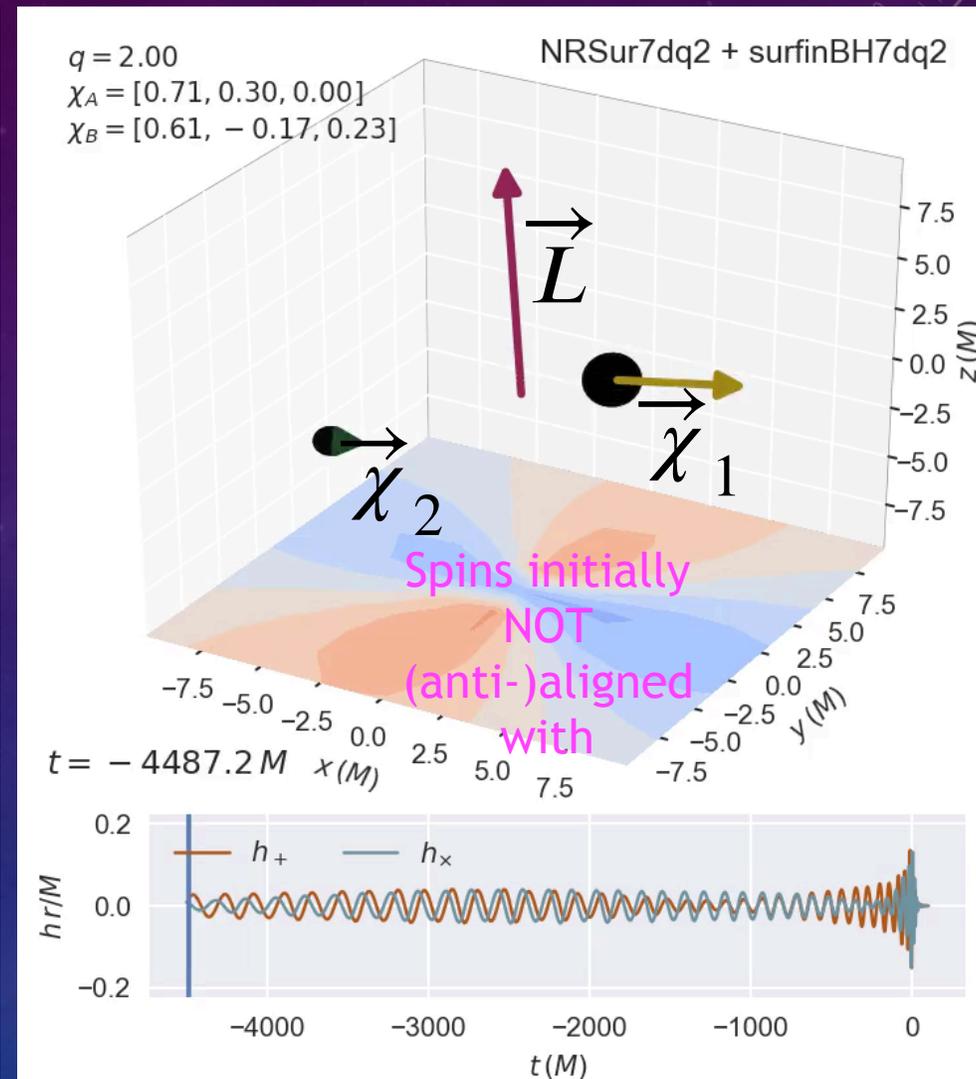
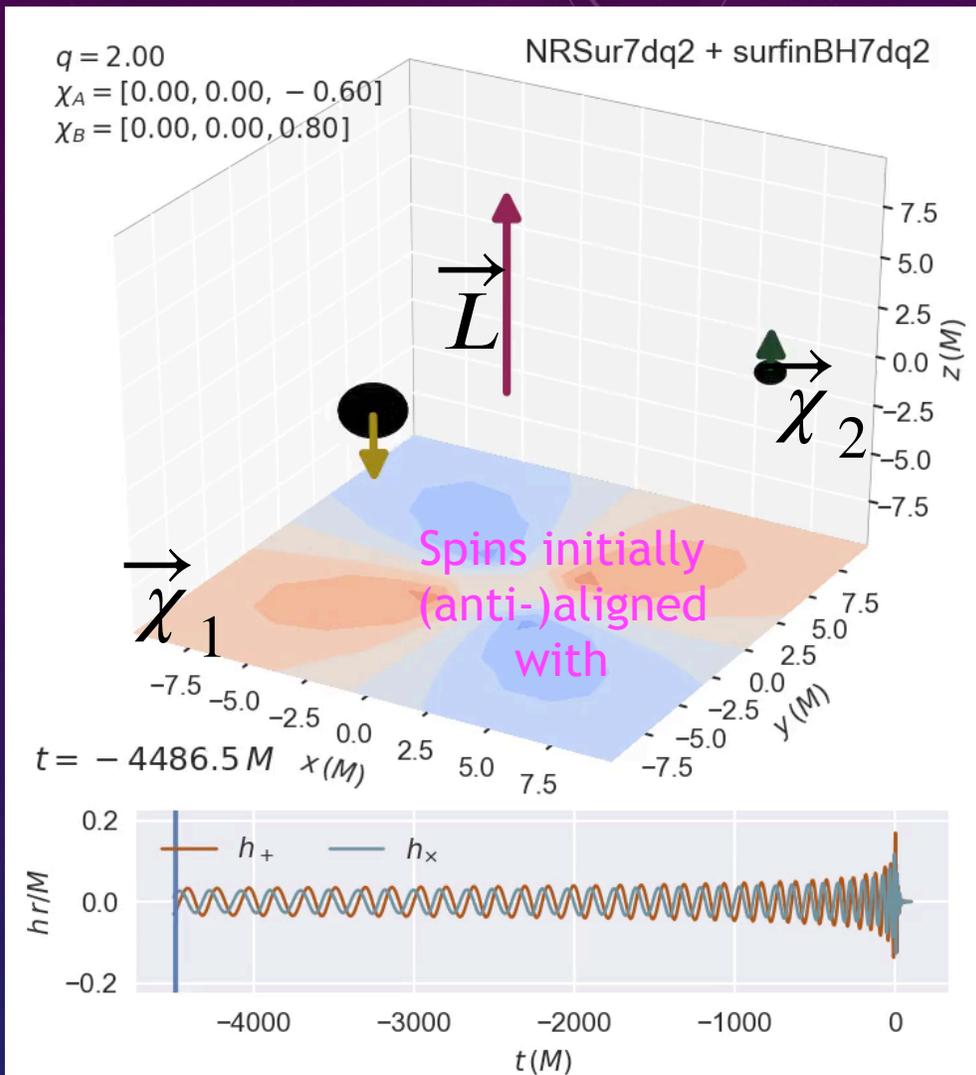
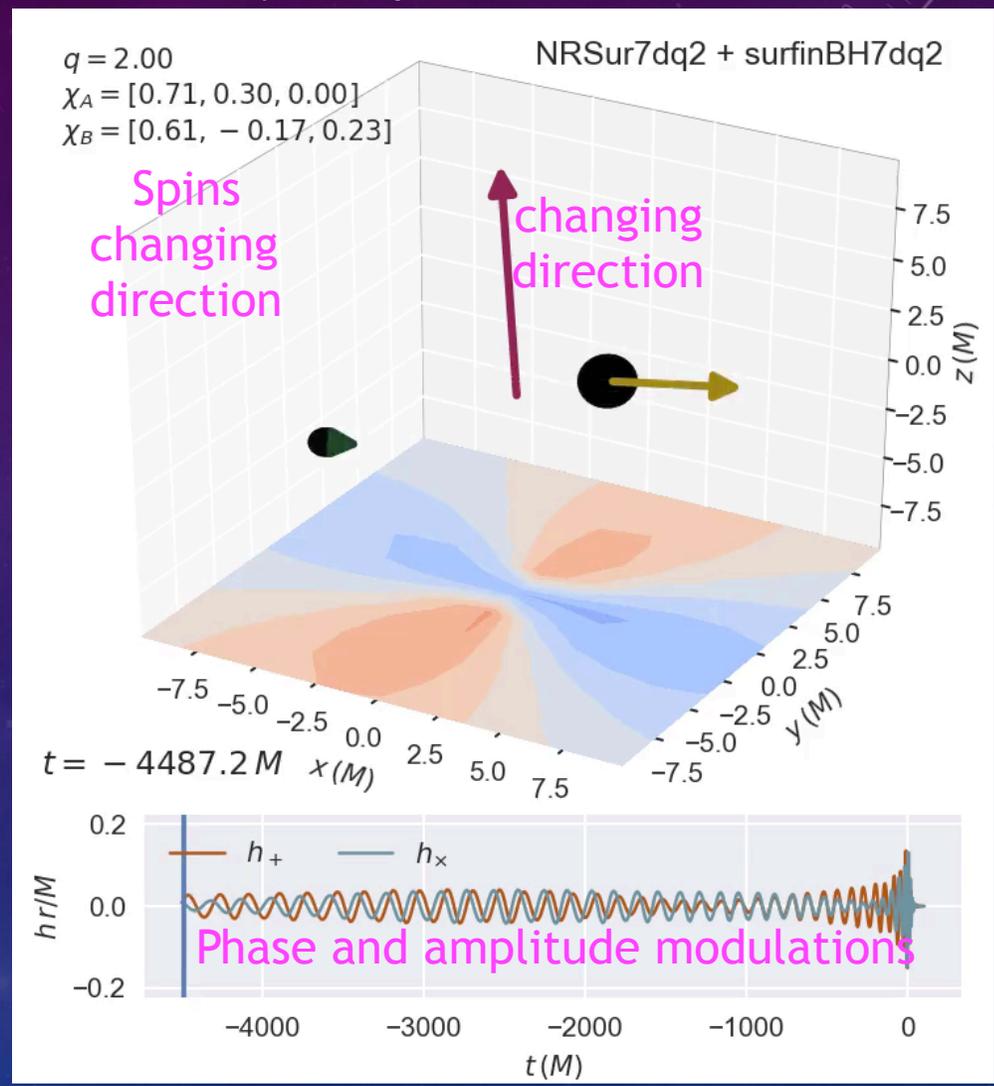
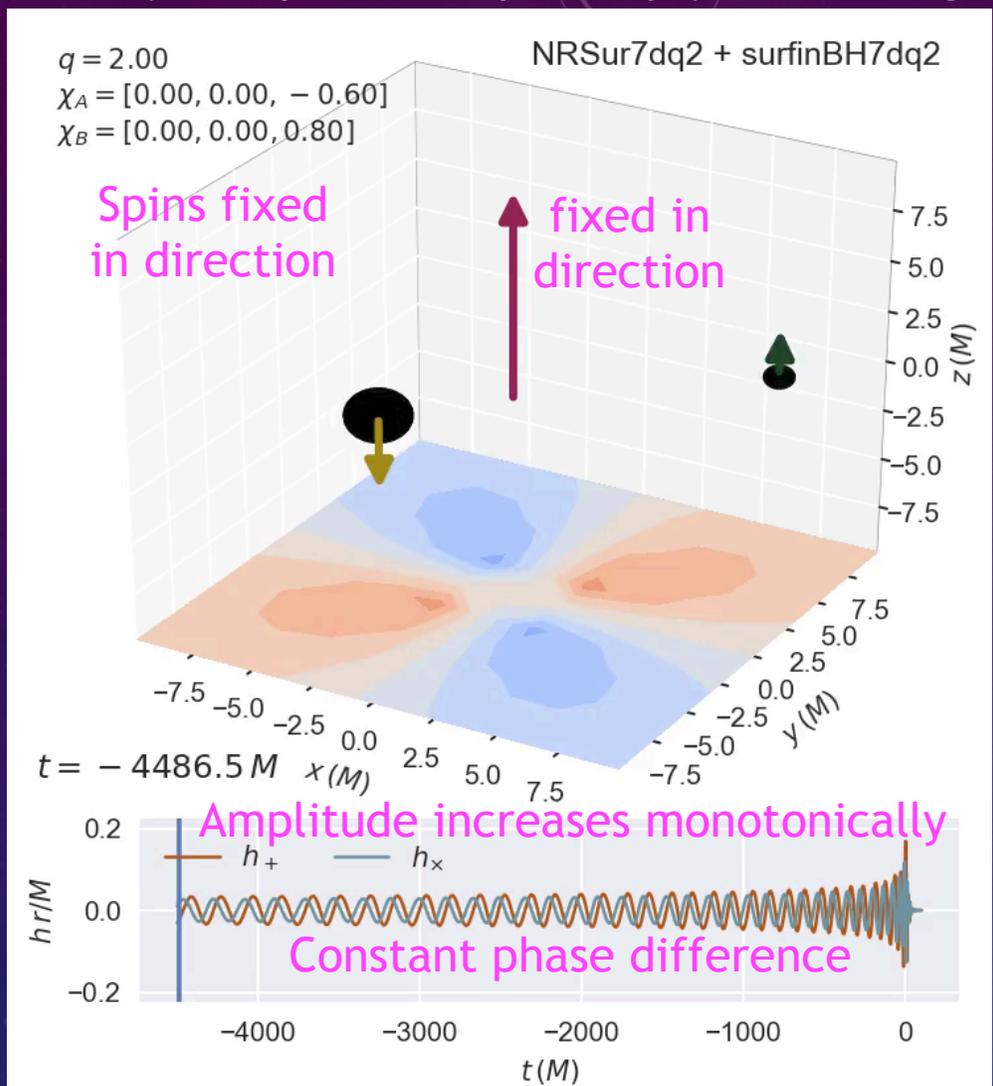


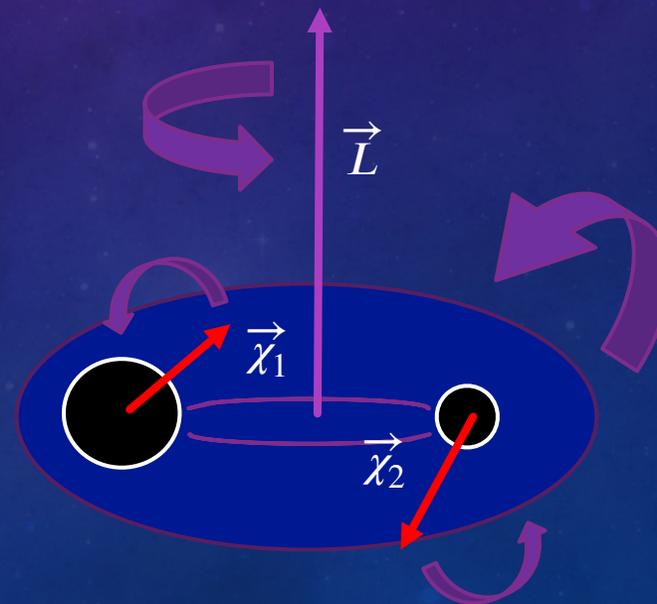
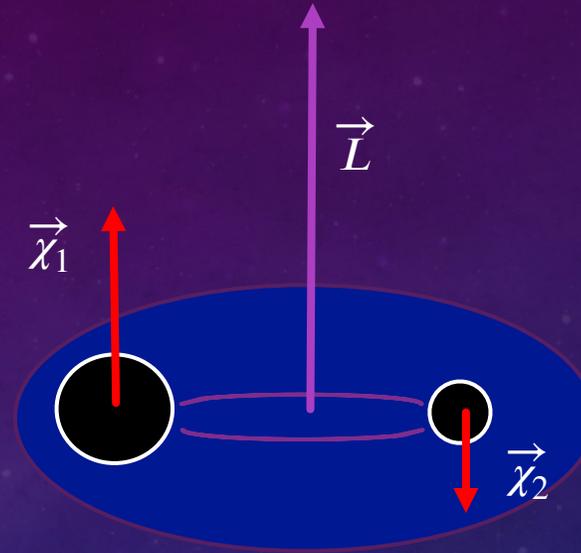
Illustration by Annie Rosen



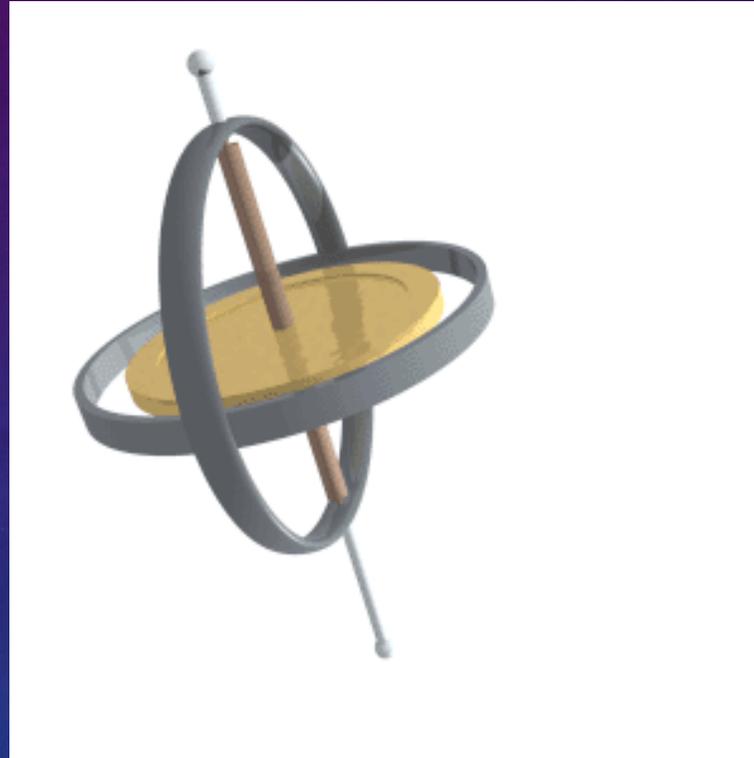


WHAT IS PRECESSION?

- Precession occurs when one, or both, of the spin vectors is misaligned with
- In a spin-aligned system, orbital plane remains fixed
- In a precessing system:
(t), (t), (t)



WHAT DOES IT LOOK LIKE?



WHAT IS PRECESSION?

- Can decouple components of spins in and out of the orbital plane
- 4 in-plane components source precession

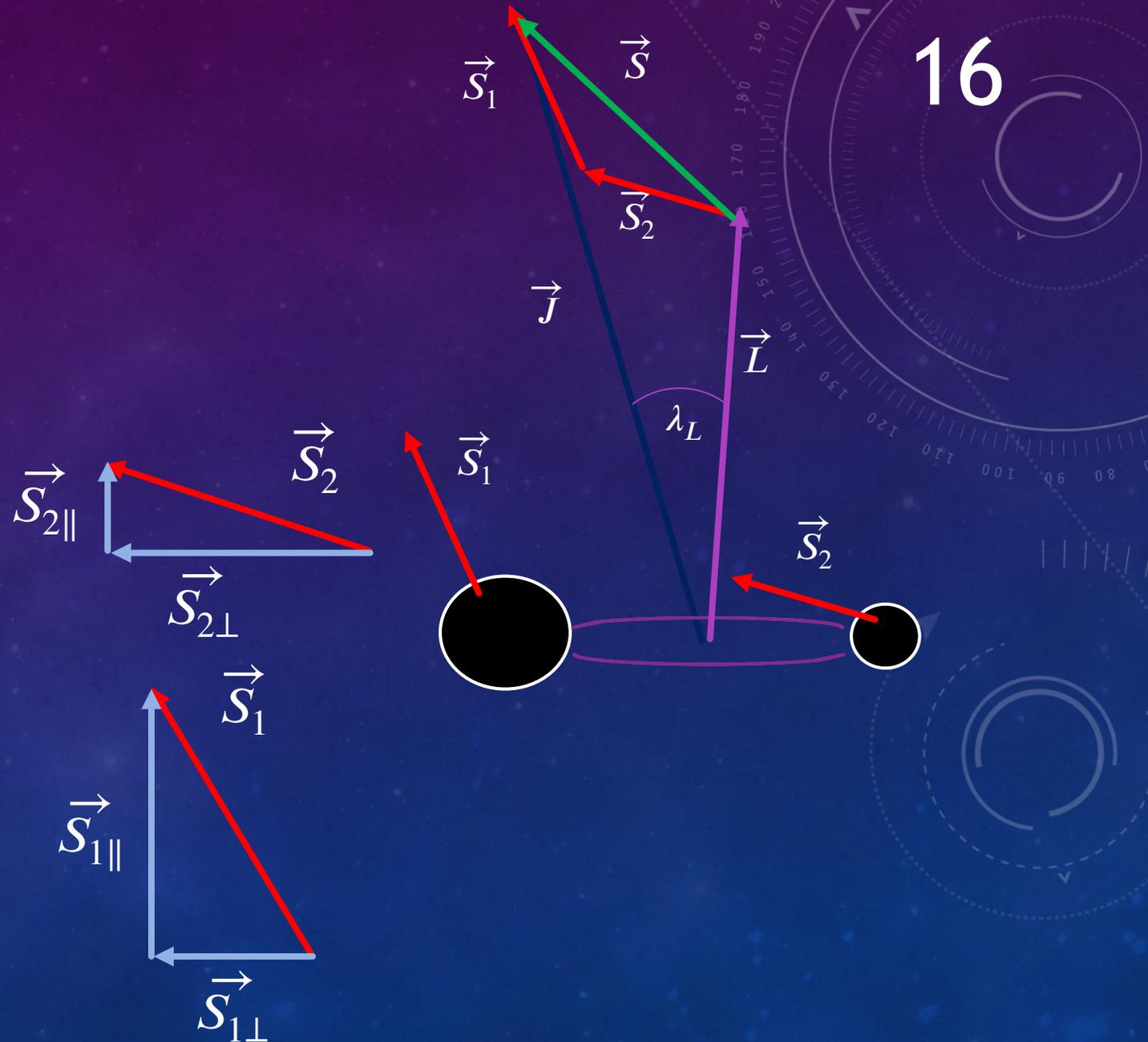
$$h^{prec}(q, \vec{\chi}_{1\perp}, \vec{\chi}_{2\perp}, \chi_{1\parallel}, \chi_{2\parallel})$$

7 dimensions

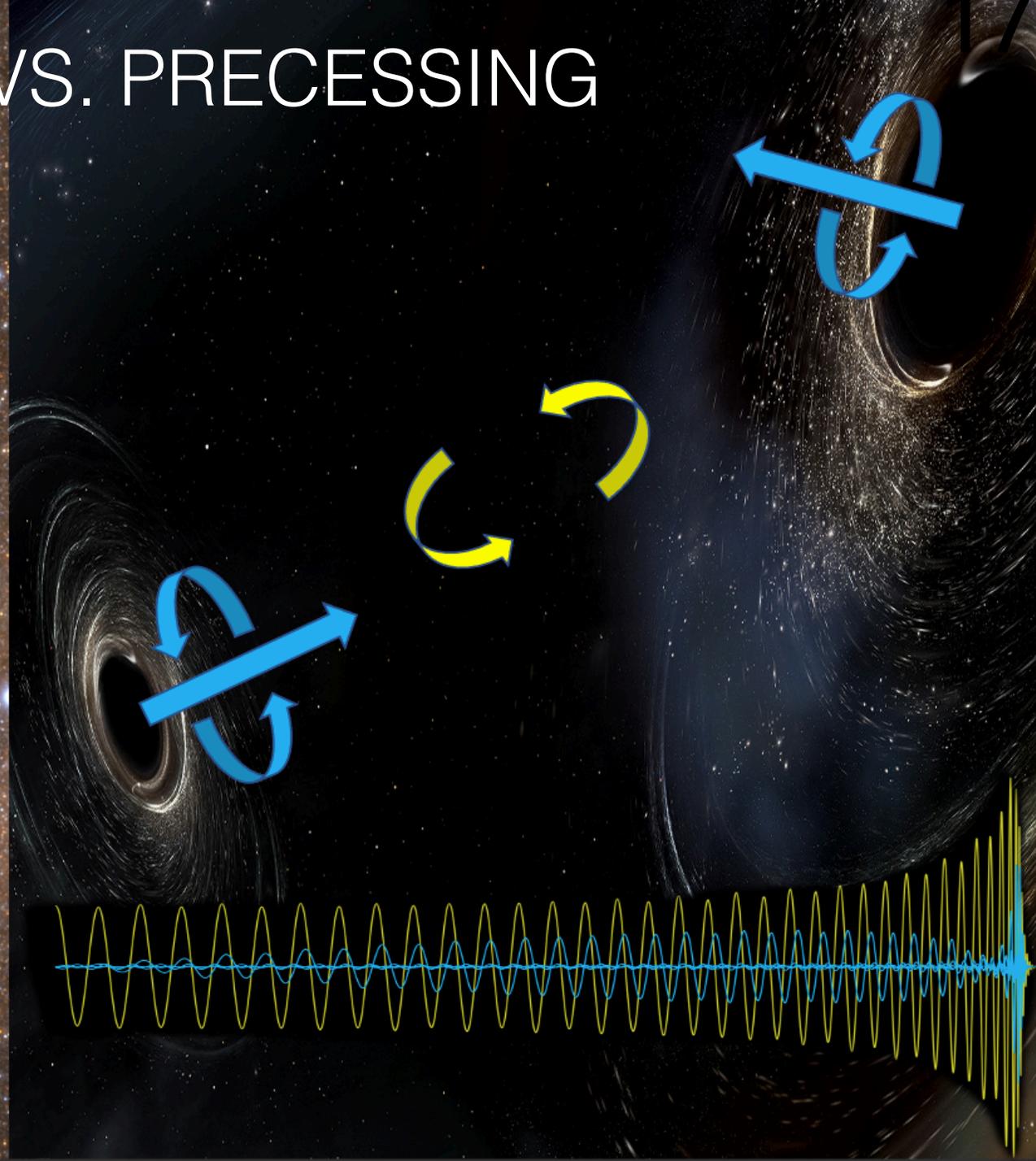
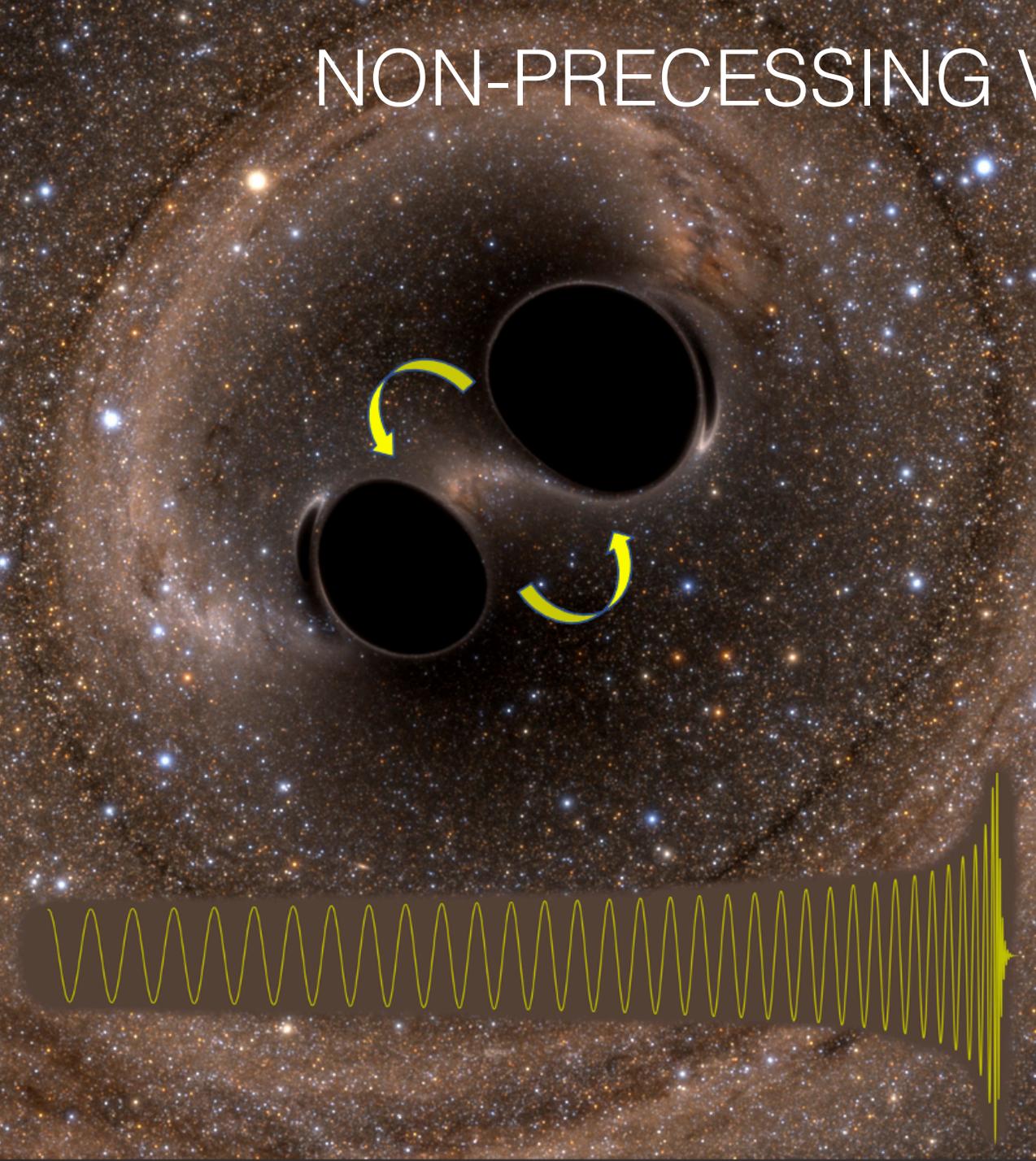
$$h^{AS}(q, \chi_{1\parallel}, \chi_{2\parallel})$$

3 dimensions

- approximately fixed
- traces out a gradually widening cone around



NON-PRECESSING VS. PRECESSING



WHY IS PRECESSION COMPLICATED?

18

- Precession introduces complications and breaks symmetries:
 - Amplitude and phase modulations
 - Need all 6 spin components
 - Higher-order modes
- **BUT PRECESSION GIVES US MORE INFORMATION**

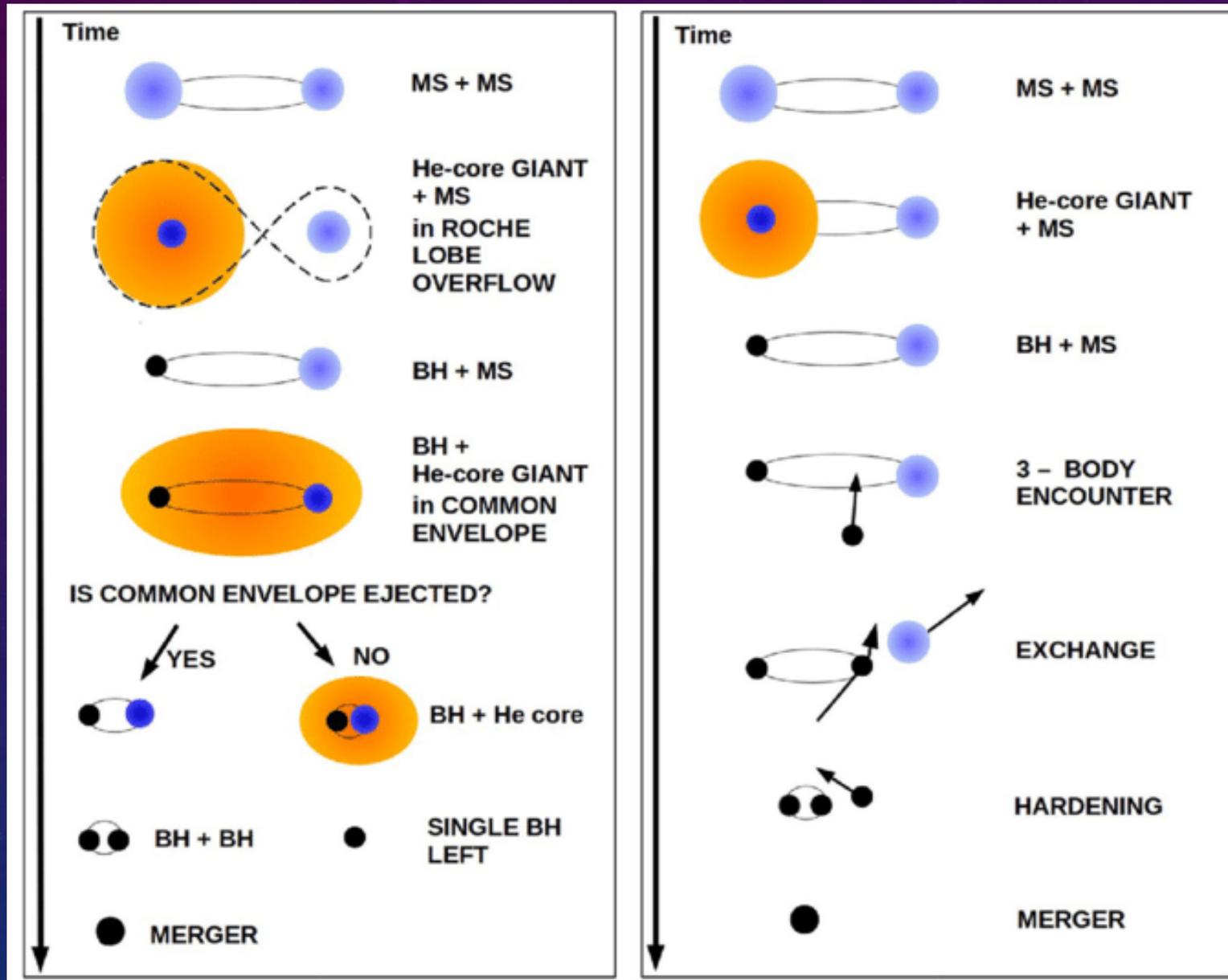
HOW DID THE BINARY FORM?

Mapelli

19

Isolated

Dynamical

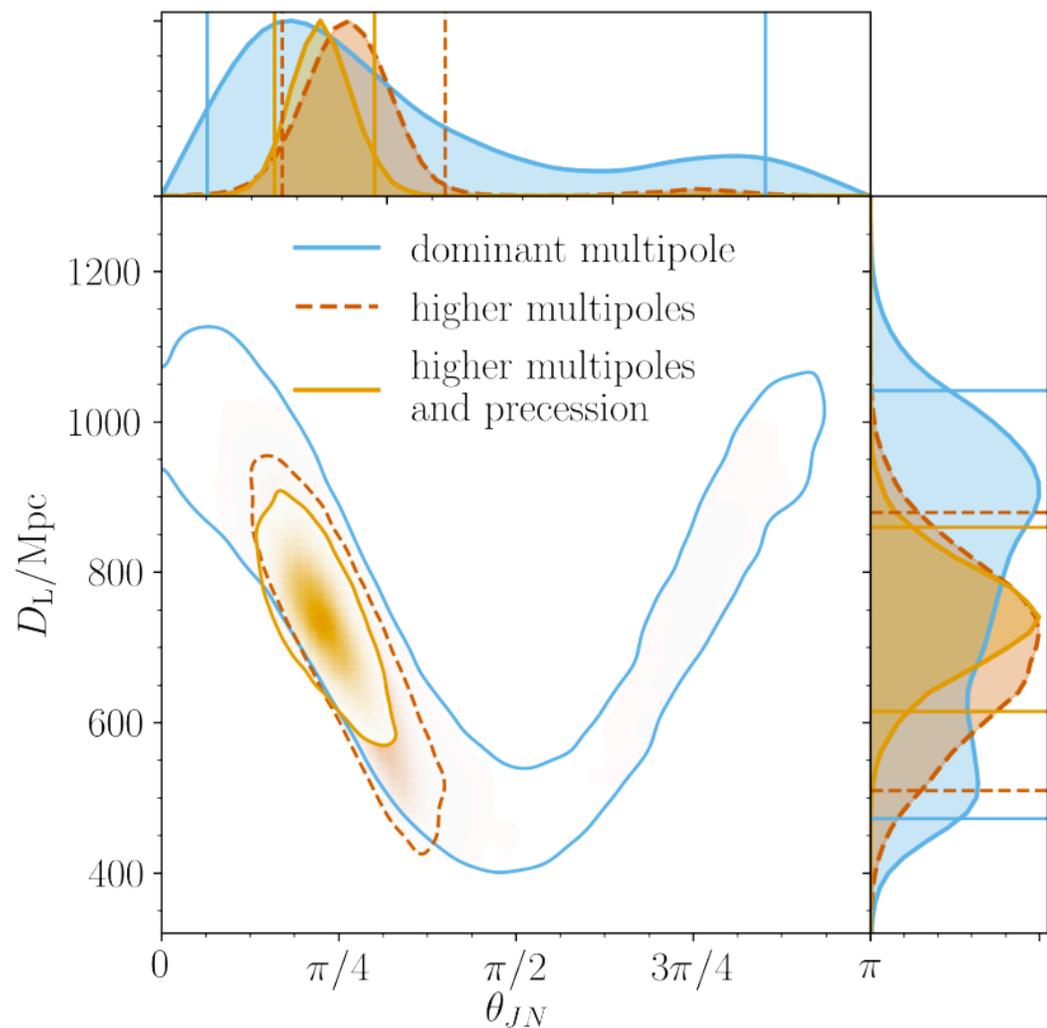


CRACKING THE PARAMETER CODE

$$h(M, q, \vec{\chi}_1, \vec{\chi}_2, e, d_L, \alpha, \delta, i, \psi, t_c, \phi_c)$$

20



CRACKING THE
PARAMETER CODE

SUMMARY

- Precession: slow changes in the rotation of a spinning body
- Source parameters encoded into GW signal: need models
- Precession greatly complicates GWs
- Precession gives us more information to codebreak

