Precession during merger

R. O'Shaughnessy (UWM)
J. Healy, L. London, D. Shoemaker (Georgia Tech)

Chirps and Mergers, KITP/UCSB
2012-08-03

Key concepts of talk

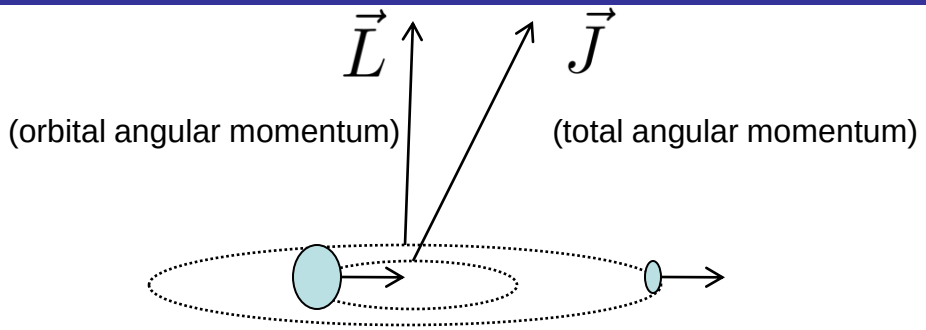
Title

"Precession during merger: Strong polarization changes are observationally accessible features of strong-field gravity during binary black hole merger"

Translation

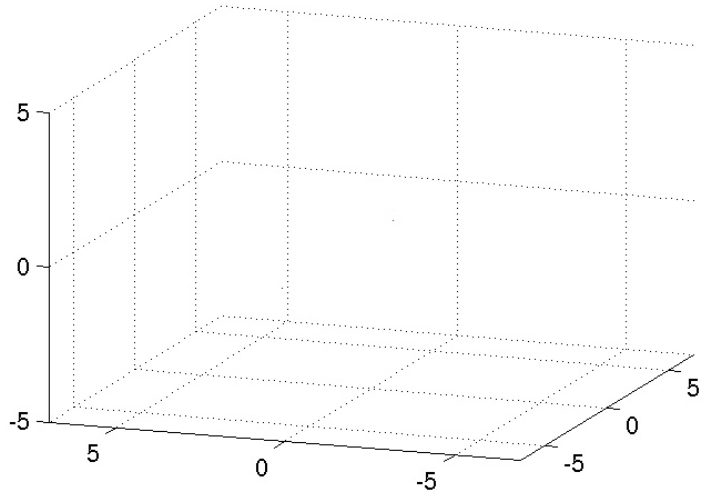
- A: (GW) Polarization changes during, after merger
- B: Tracks a **direction** (and line of sight)
- C: It is detectable
- D: Simple interpretation (precession)
  Encodes astrophysics (transverse spins) in merger, ringdown

Fiducial example



$$m_1/m_2 = 4$$
$$a_1 = a_2 = 0.6$$

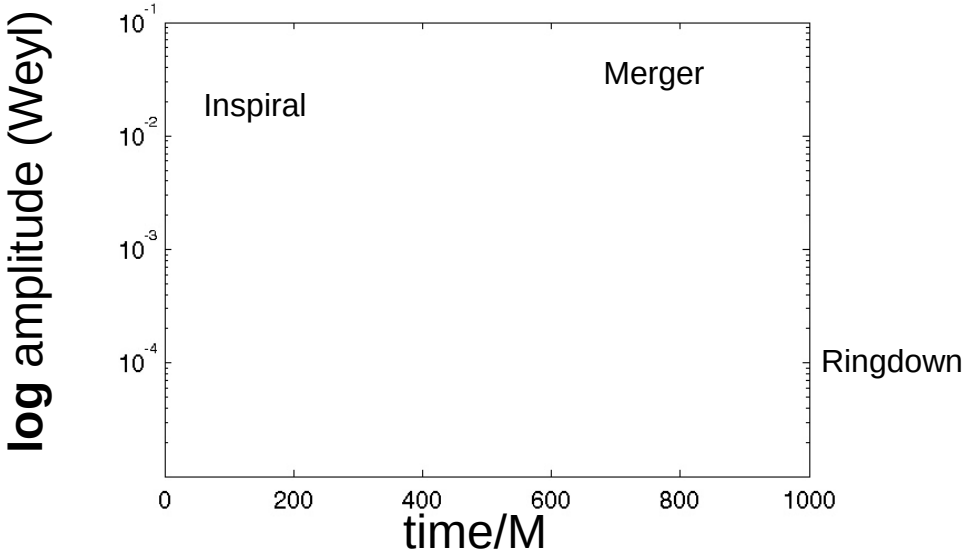
Locations



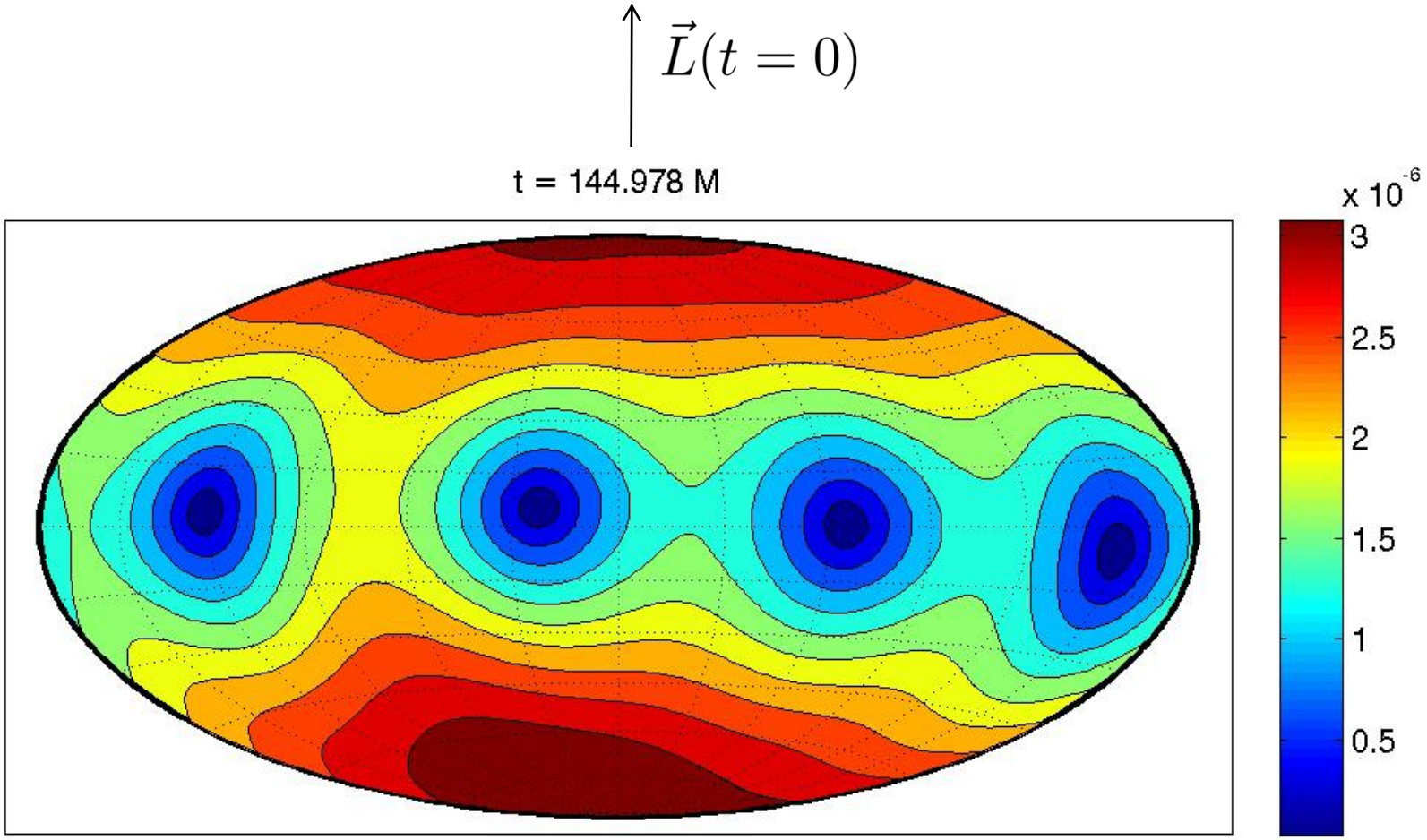
One of ~ 100 distinct **precessing** simulations

[Maya; Cactus+carpet+Einstein toolkit]

Waveform (one direction)

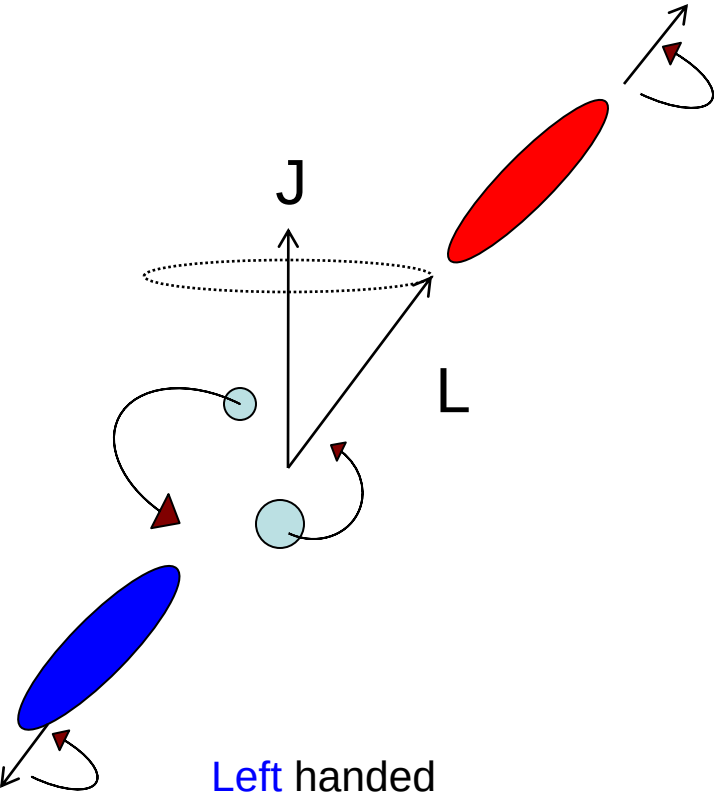


Fiducial example



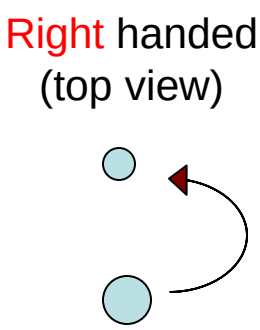
Precession modulates GW

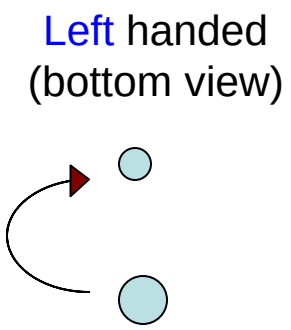
Analogy: Single-spin precession, early inspiral



Features

- L precessing around J
- GW signal along ±L**, right** or **left** handed



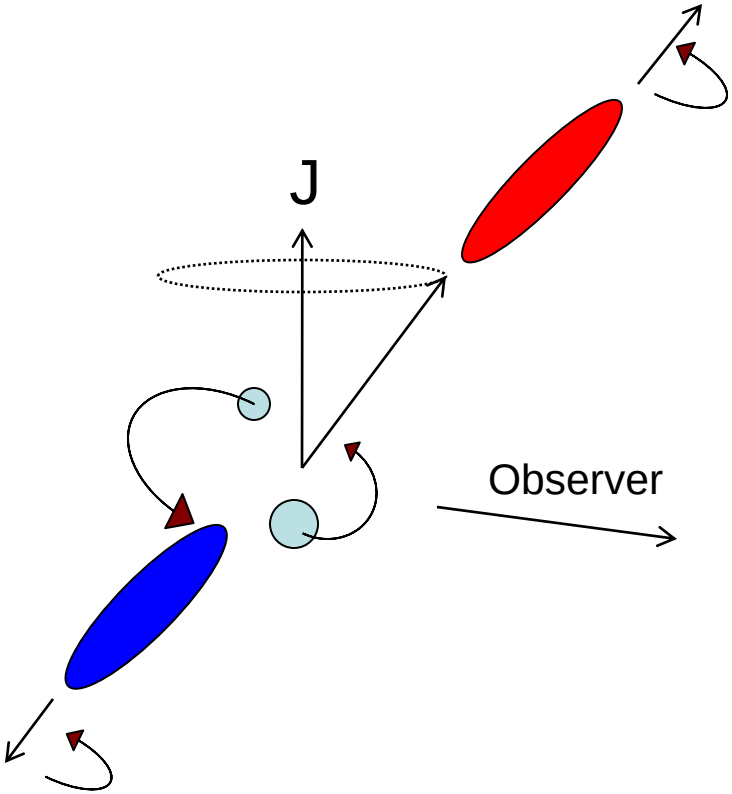


Polarization changes during merger

- Experiments see one line of sight

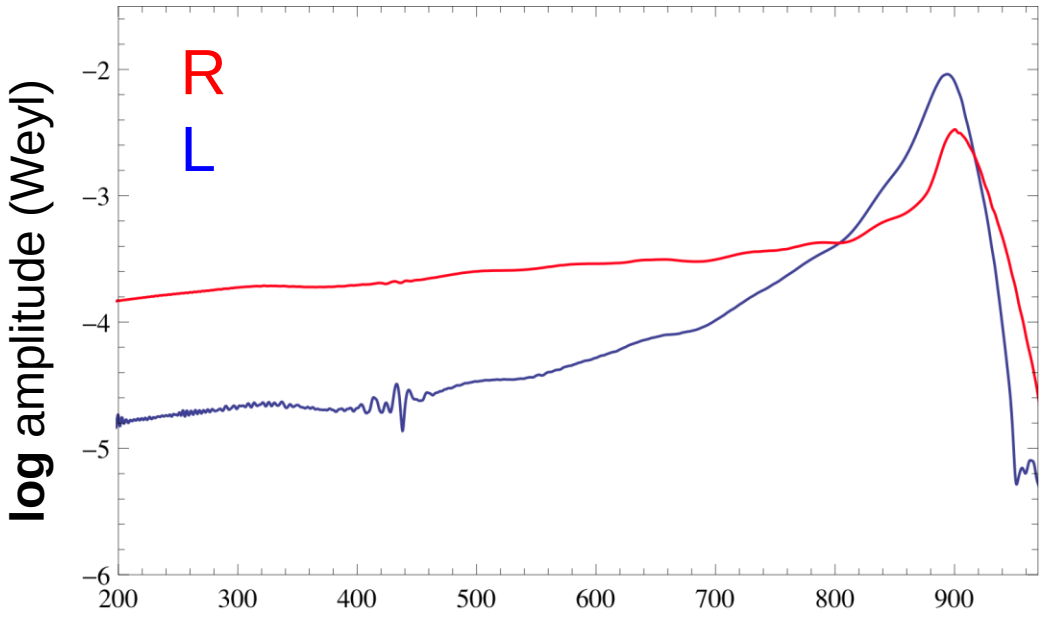
  Measure R,L

  …if sensitive to both linear polarizations
- Polarization changes during merger



Right handed

Left handed



Polarization follows “peak”

A: Polarization changes

B: **Traces path of “L”**

… **each line of sight**

… works after merger

To include merger:

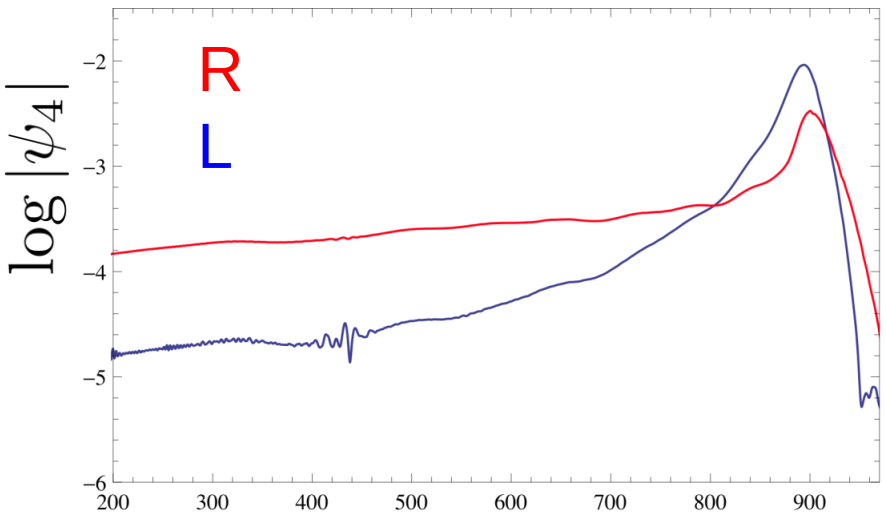
‘Peak’ or “L” -> ‘preferred location’

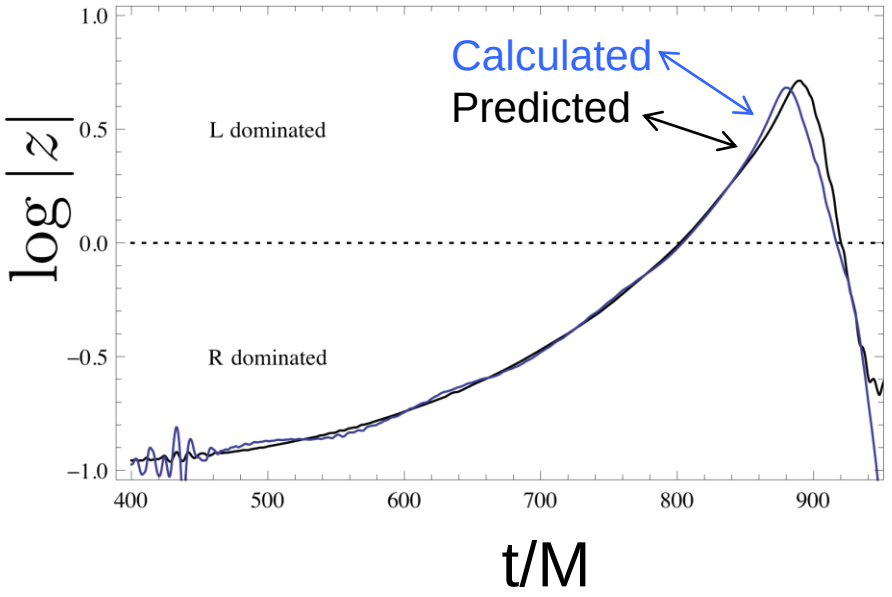
Schmidt et al 2011

ROS et al 2011 [arxiv: 1109.5224]

Boyle et al 2012

$$z(t) \equiv \frac{\psi^*_{4,L}(t)}{\psi_{4,R}(t)}$$





Detectable

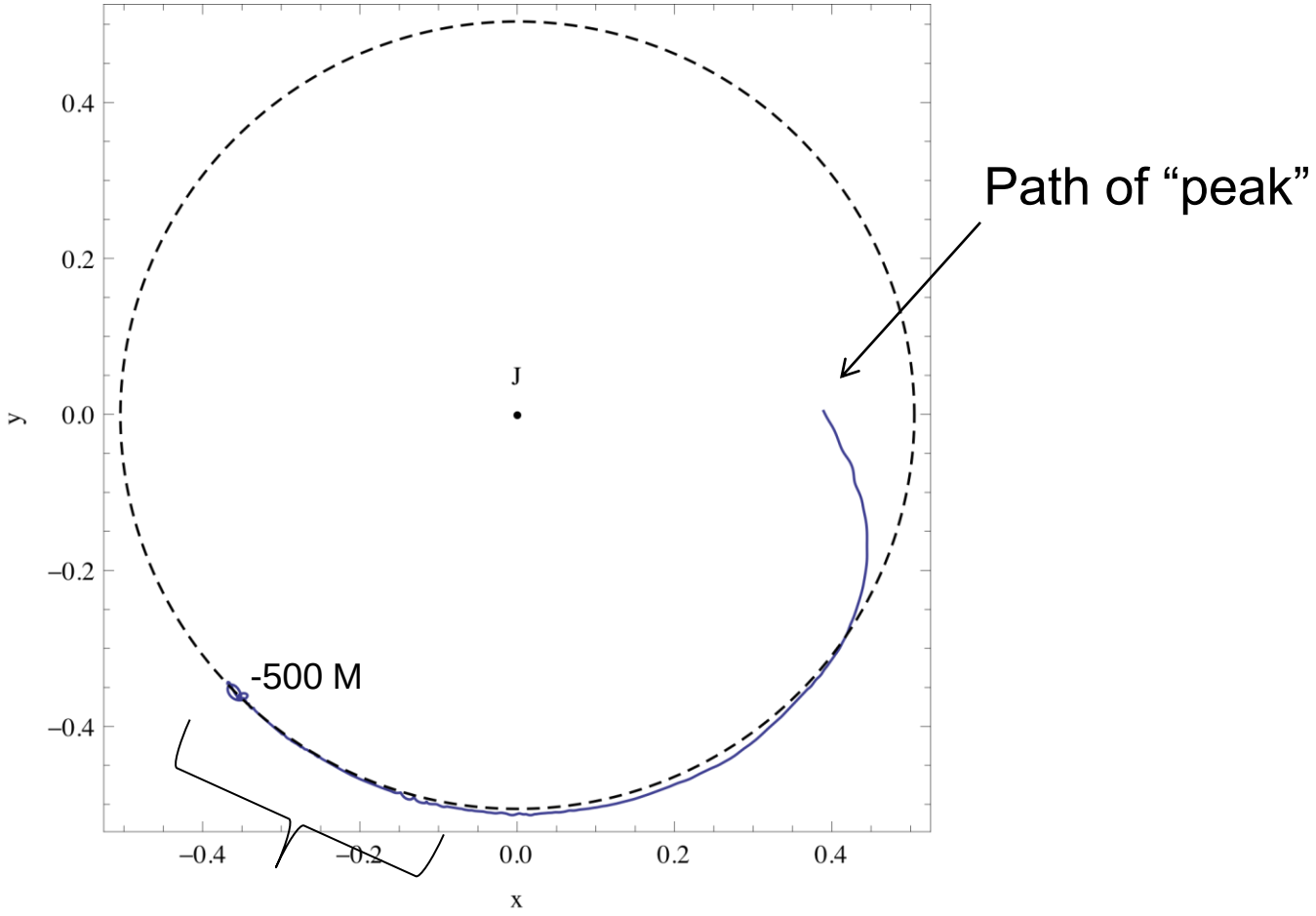
- A: Polarization changes during, after merger
- B: Tracks a **direction** (and line of sight)

- C: It is detectable
  - Argument 1: Direction changes significantly “in band”
  - Argument 2: Waveform modulated (“clearly not like nonprecessing”)

Large, fast direction changes

View from “above” final J

Before [0 M]

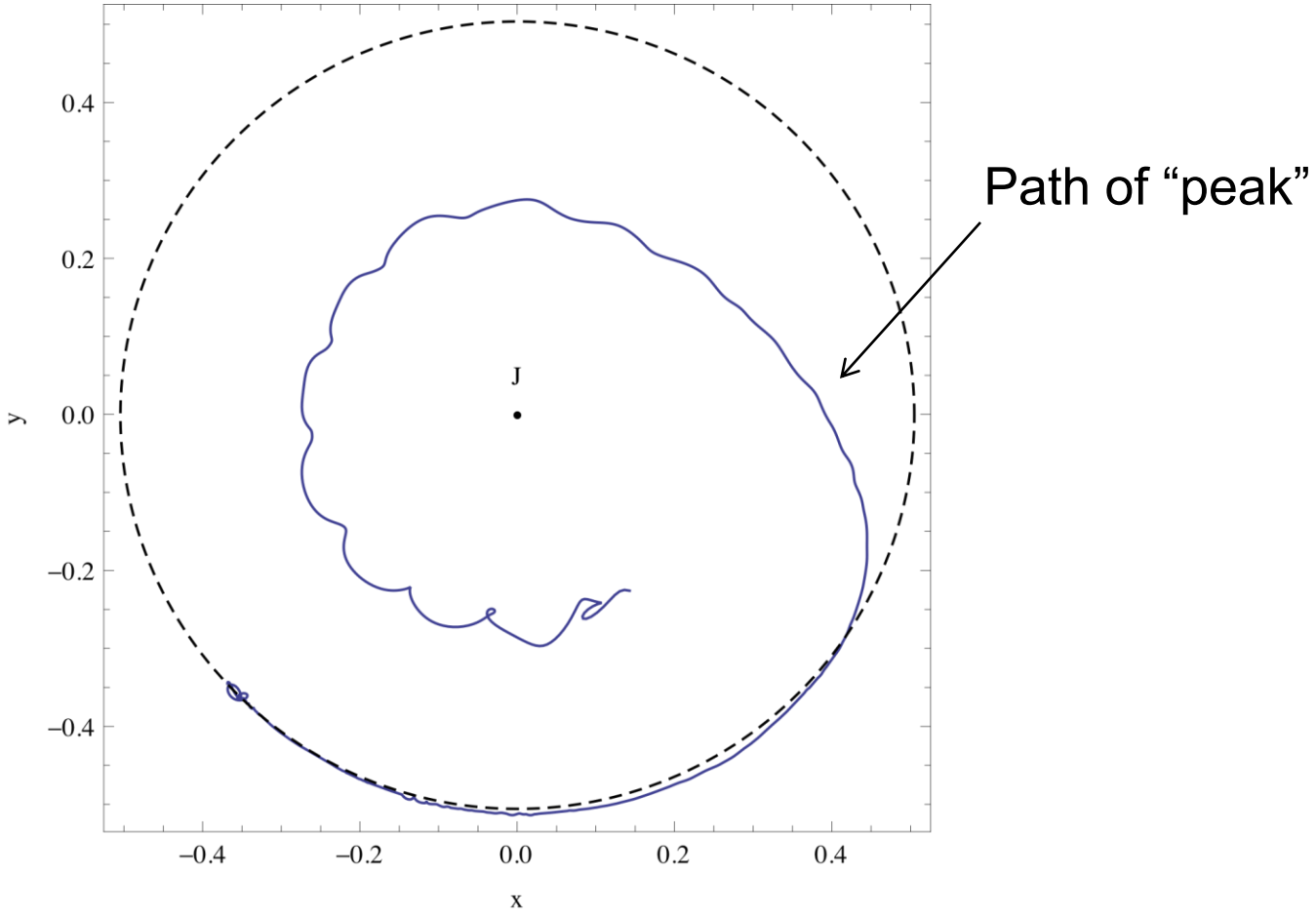


Little change over a few orbits

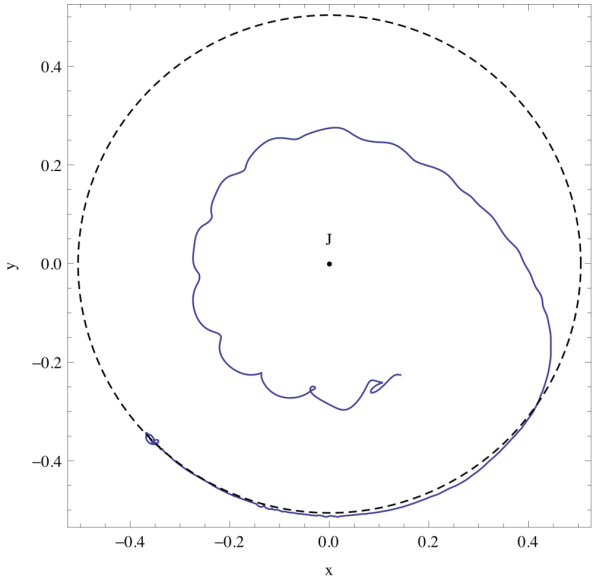
Large, fast direction changes

View from “above” final J

After [90 M]



What is going on?



"Precession" after merger

$$\partial_t \hat{V} = \underbrace{\Omega \hat{J}}_{\text{"precession rate"}} \times \hat{V}$$

BH perturbation view:

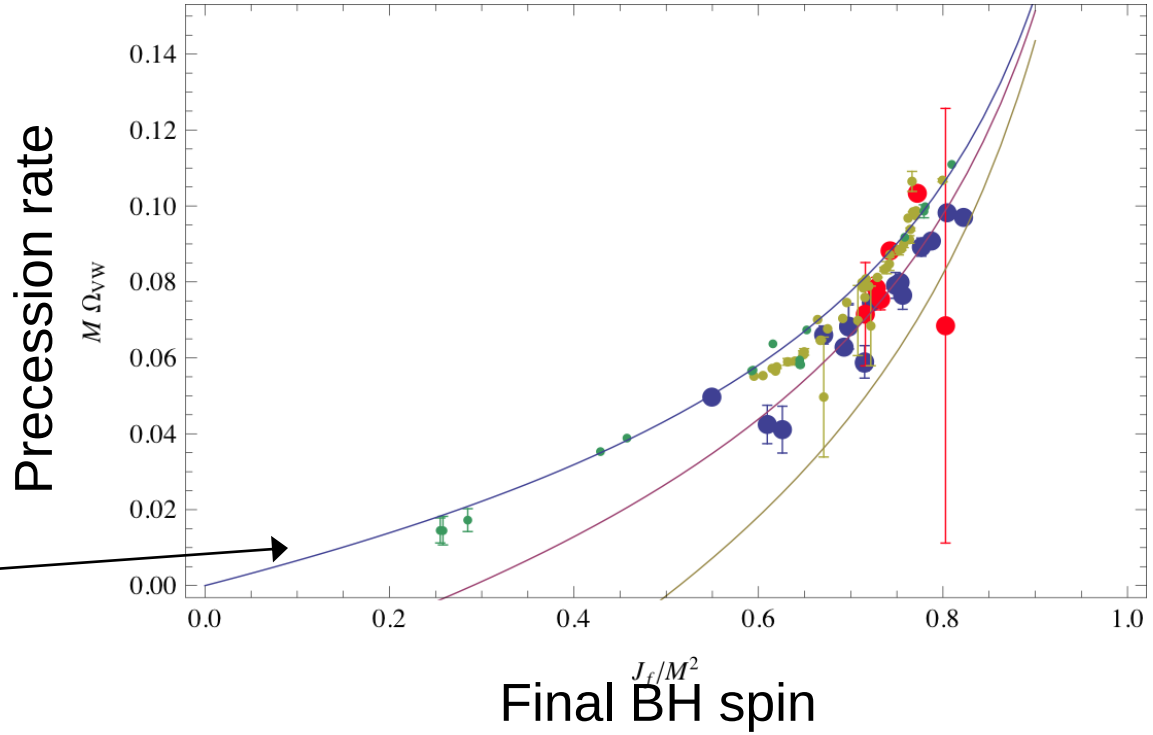
Multimodal (m=2,1,…),
quasi-coherent

- "Precession rate" [points]

QNM frequency **differences**

$\omega_{22,0} - \omega_{21,0}$

$\omega_{22,1} - \omega_{21,1}$



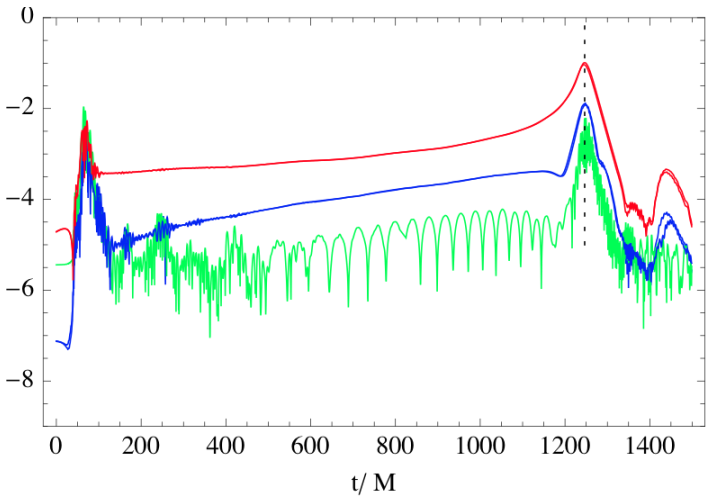
Significant modulations

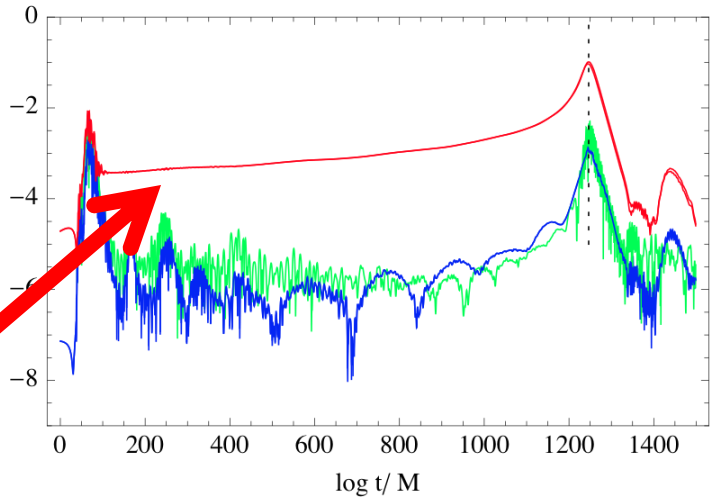
- **How significant?**
  - Fraction of amplitude lost
    vs **nonprecessing reference**

$$\frac{|\langle\psi|\psi_{ref}\rangle|}{\sqrt{\langle\psi|\psi\rangle\langle\psi_{ref}|\psi_{ref}\rangle}}$$

  - Compare with nonprecessing
    [BH-NS : Brown et al arXiv:1203.6060]

    Lose amplitude **in direct proportion**
    to precession–induced modulations



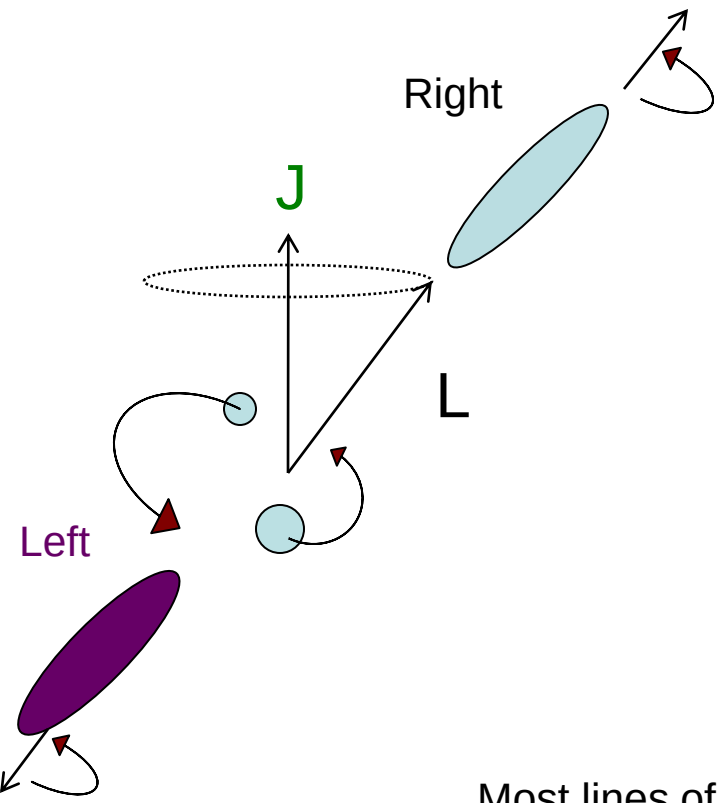


- **What reference? Itself!**
  - Go to corotating frame
  - Use (l,m) = (2,2) mode **in corotating frame**

$$\psi = U(R)\psi_{\rm corot}$$

Schmidt et al 2011
ROS et al 2011 [arxiv: 1109.5224]
Boyle et al 2012

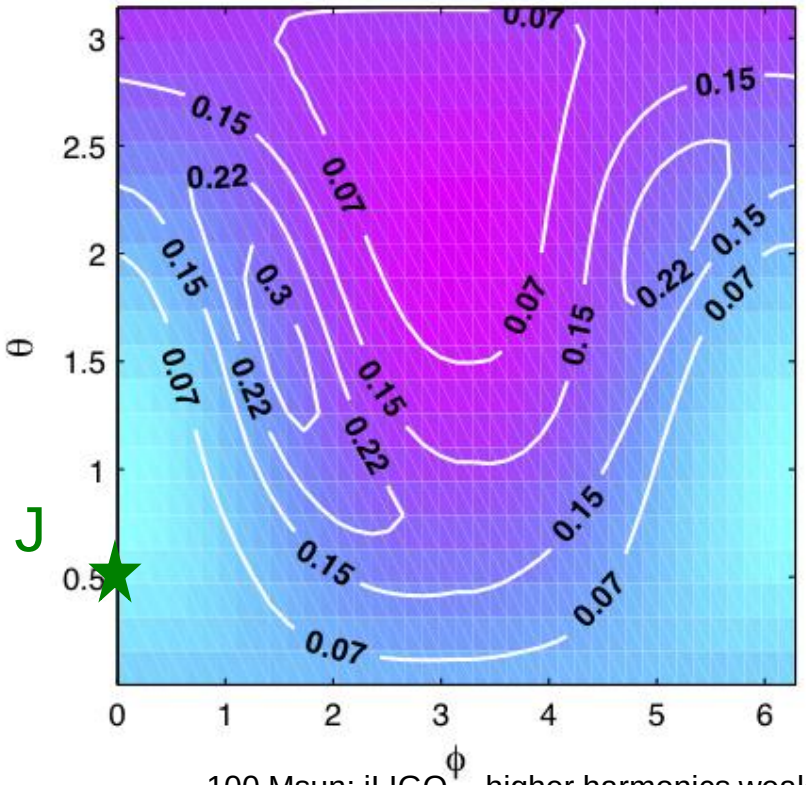
Significant modulations



Most lines of sight
- a nonprecessing search loses power
- if detectable, enough lost to measure some precessing parameters

Figure key

- J
- Gradient: “orbital plane” [estimate]
- Contours: Fraction of power “lost”
  - Comparison: > ~2% = detectable effect [SNR 10]



100 Msun; iLIGO - higher harmonics weak

Summary

- A: Polarization changes during, after merger
- B: Tracks a **direction** (and line of sight)
- C: It is detectable
- D: Simple interpretation (precession)
  Encodes astrophysics in merger, ringdown
  (spin-orbit misalignment, …)

Conclusions

- Short precessing merger signals modulated
  - **Measurable**
  - Precession = “natural” coordinate/parameter

- Implications
  - Simulation placement
  - Searches and parameter estimation
    - Phenomenological precession fitting
  - Astrophysics
    - Spin-orbit misalignment from merger, ringdown?
  - Testing GR
    - Strong field dynamics …even with short merger signal alone

Equation support

- Complex overlap
  - Maximize over time and **polarization**

$$(\Psi_A|\Psi_B) \equiv \int_{-\infty}^{\infty} \frac{2df}{(2\pi f)^4 S_h} \Psi_A^*(f)\Psi_B(f)$$

- Preferred orientation

Rotation group generators

$$\left\langle L_{(a}L_{b)} \right\rangle = \frac{\left\langle \psi_4^*(\hat{n},t)\mathcal{L}_{(a}\mathcal{L}_{b)}\psi_4(\hat{n},t) \right\rangle_{\text{angles}}}{\left\langle |\psi_4|^2 \right\rangle_{\text{angles}}}$$

- Polarization projection: Frequency domain

$$\tilde{\psi}_{4,R}(f) \equiv \begin{cases} \tilde{\psi}_4(f) & f > 0 \\ 0 & f < 0 \end{cases}$$

- (Complex) polarization amplitude

$$z(t) \equiv \frac{\psi_{4,L}^*(t)}{\psi_{4,R}(t)}$$

- An estimate of the peak location O, from line of sight frame (n,x,y)

$$z_O(t) = \frac{[\hat{O}\cdot(\hat{x}_n + i\hat{y}_n)]^4}{(1+\hat{O}\cdot\hat{n})^4}$$

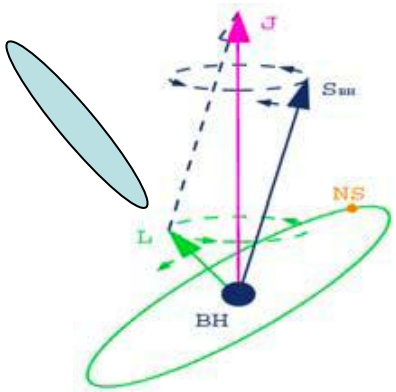
Spin and waveforms

Generic precession:

Misaligned binaries precess [ACST]

$$\partial_t X = \Omega_X \times X \qquad X = S_{1,2}, L$$

…often around nearly-constant **J** direction



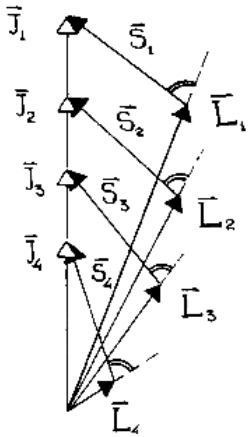
(Leading order): Propagation of L modulates waveform

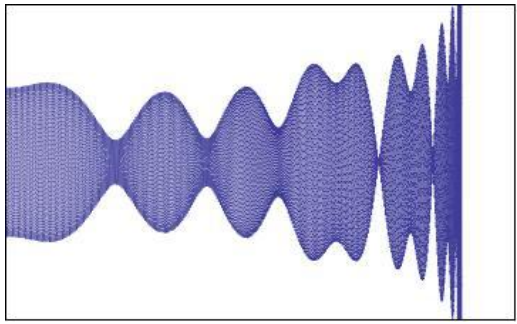
J loss decreases L:

More spin-dominated

More “freedom” for L at late times…

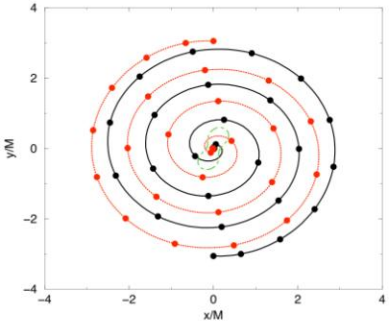
less freedom early or

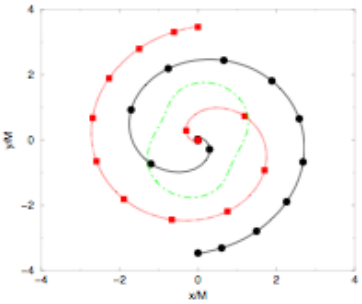




Other spin effect: Duration (=SNR,amplitud

Angular momentum “barrier”, more emission





Precession: modulated wave

Secular part:

- phase:
  - chirps, but at different rate
  - **depends on line of sight**
    - (somewhat)

Modulating part:

- magnitude depends on **opening cone only,**
  - not mass, spin (once cone known)
    - good approx: **precession cone opens slowly**
    - model:
      - **complex** (fourier) **amplitude** z

- usually several cycles in band
  - number depends on mass, spin, NOT geometry

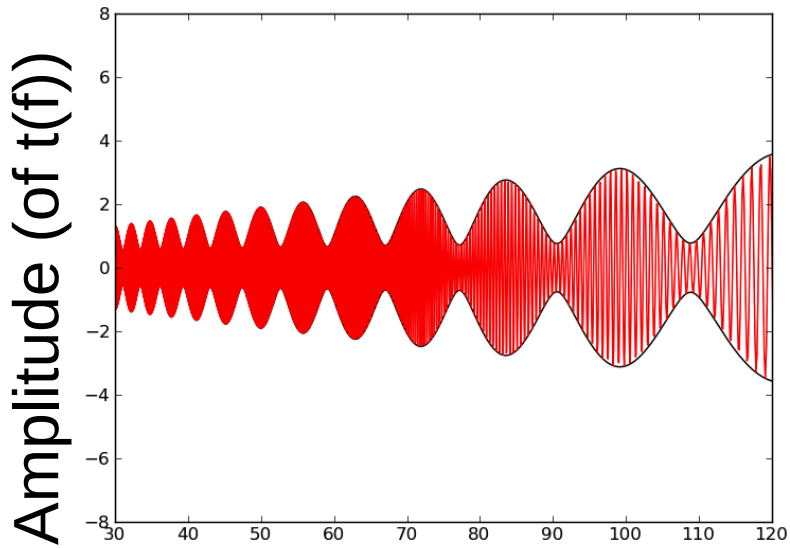
Separation of timescales:

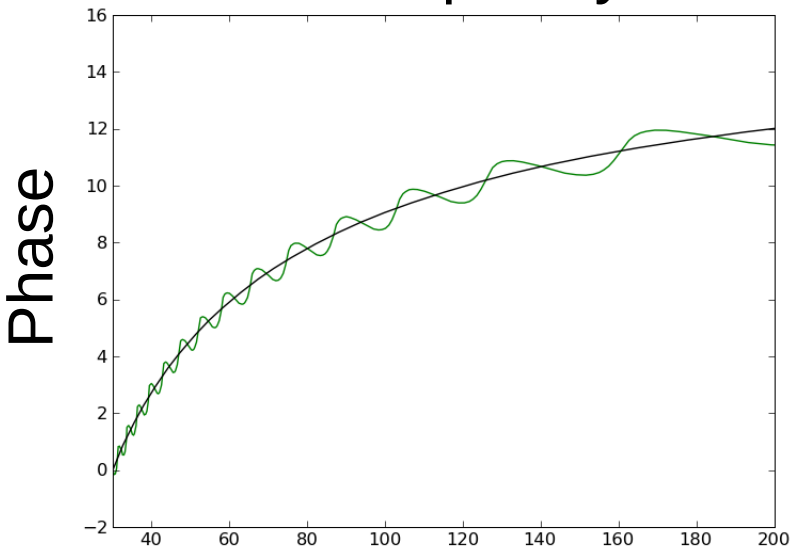
…+ use LIGO-like detectors (relatively) narrowband

-> a) ignore increasing opening angle (usually suppressed below radiation time)

b) average SNR across the lighthouse

c) factor overlap: masses, geometry





e.g., Brown et al arXiv:1203.6060

Measurable effects

- Each path (& modulation) distinct
  …**if** you precess (in band), measurable
  …need **one loud** or **many faint**

- **Different regimes**:
  - BH-NS : [Brown et al arXiv:1203.6060]
    Many L cycles, each **faint**.
    Can be **strongly** modulated
    Measurable: ~ “mean” precession path of L
  - BH-BH (>100 Msun) :
    Any at cycles at all? Too short?
    Merger epoch, so no precession?