Searching for binaries with spin with Advanced LIGO and Advanced Virgo

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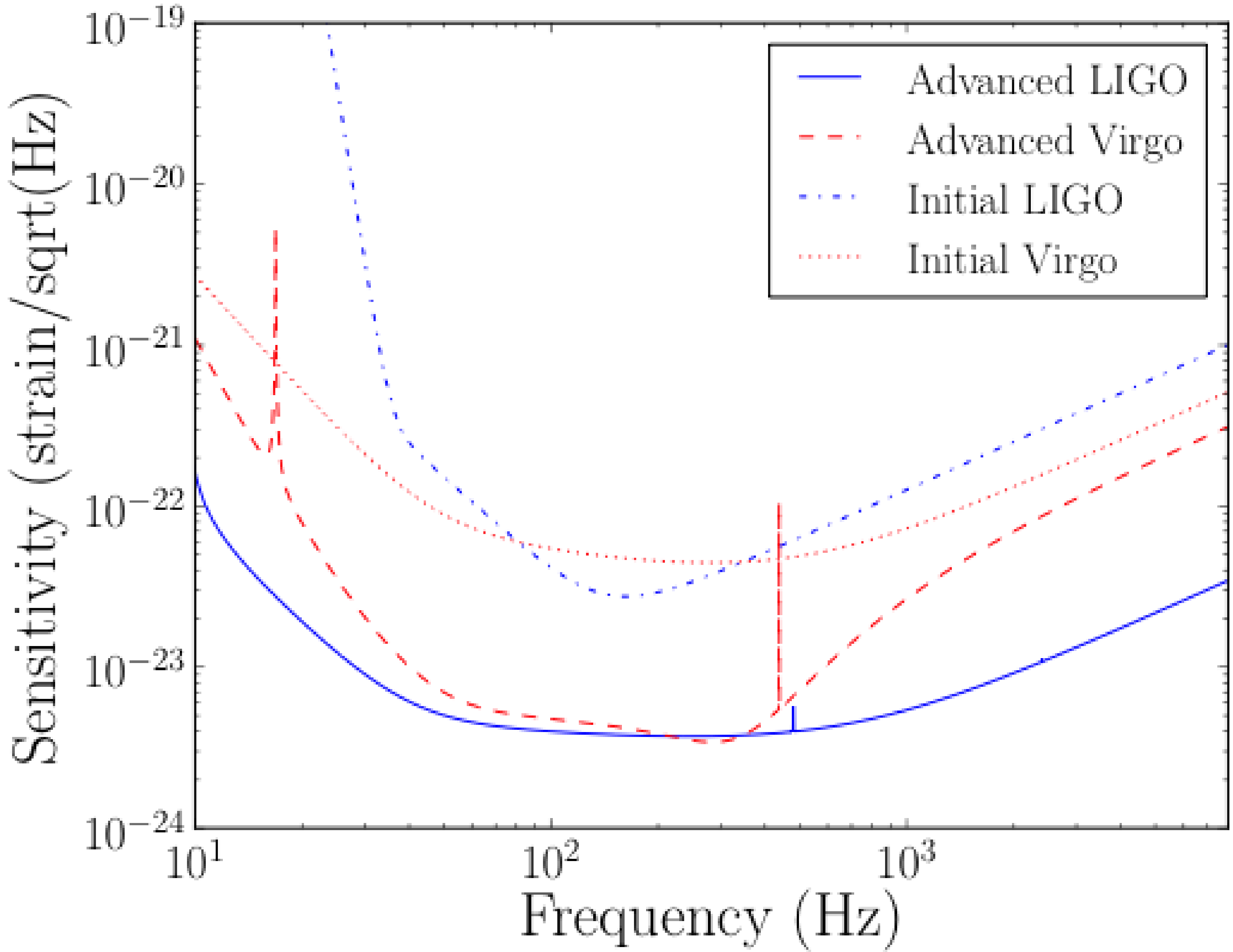
Motivation

- We have a well established method for searching for systems that do not have spin.
  - Matched filtering with non-spinning waveforms
  - Good for binary neutron stars
- Also has some sensitivity to spinning systems
  - NSBH, BBH
- We don't want to miss binaries where spin matters!
  - Need to quantify the effects of spin and improve search

Motivation



Advanced LIGO
Advanced Virgo
Initial LIGO
Initial Virgo
Sensitivity (strain/sqrt(Hz))
Frequency (Hz)
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{1}
10^{2}
10^{3}

Talk Overview

- What changes when the components of the binary have spin?
- Why is it a challenge to search for objects with spin?
- Searching for aligned-spin waveforms?
- Searching for precessing waveforms?
- What about other effects?
  - Sub-dominant modes, matter effects, eccentricity ….

What changes with spin?

- The coupling between the spinning bodies and the orbital angular momentum cause:
  - Changes in the frequency evolution of the system (and thus frequency of emitted GWs)
  - Changes in the energy lost to GWs (and thus amplitude of emitted GWs)
  - Precession

Apostolatos et al, Phys. Rev. D 49, 6274
Kidder et al, Phys Rev D 47, 4183
Kidder, Phys Rev D 52, 821
Buonnano et al, Phys Rev D 67, 104025

Frequency evolution

- Spin affects the frequency evolution of a CBC

No spin: -

$$\frac{\dot{\omega}}{\omega^2} = \frac{96}{5}\left(\mathcal{M}\omega\right)^{5/3}\left\{1+A(\mathcal{M},\eta)\left(\mathcal{M}\omega\right)^{2/3}+B(\mathcal{M},\eta)\left(\mathcal{M}\omega\right)^{3/3}+\left(C(\mathcal{M},\eta)\right)\left(\mathcal{M}\omega\right)^{4/3} + \left(D(\mathcal{M},\eta)\right)\left(\mathcal{M}\omega\right)^{5/3}+\ldots\right\}$$

Chirp mass: $\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}$

Symmetric mass ratio: $\eta = \frac{(m_1 m_2)}{(m_1+m_2)^2}$

Poisson and Will, Phys Rev D 52, 848
Buonnano et al, Phys Rev D 80, 084043

Frequency evolution

- Spin affects the frequency evolution of a CBC

With spin:

$$\frac{\dot{\omega}}{\omega^2} = \frac{96}{5}(\mathcal{M}\omega)^{5/3}\left\{1 + A(\mathcal{M},\eta)(\mathcal{M}\omega)^{2/3} + B(\mathcal{M},\eta)(\mathcal{M}\omega)^{3/3} + (C(\mathcal{M},\eta) + \mathrm{SO})(\mathcal{M}\omega)^{4/3} + (D(\mathcal{M},\eta) + \mathrm{SS})(\mathcal{M}\omega)^{5/3} + \ldots\right\}$$

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What changes with spin?

- The interactions of the spinning bodies with the orbital angular momentum, each other and themselves cause:
  - Changes in the frequency evolution of the system (and thus frequency of emitted GWs)
  - ~~Changes in the energy lost to GWs (and thus amplitude of emitted GWs)~~
  - Precession

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Kidder et al, Phys Rev D 47, 4183
Kidder, Phys Rev D 52, 821
Buonnano et al, Phys Rev D 67, 104025

Simple Precession

- Most precessing binaries undergo "simple precession"
  - **L** and $\mathbf{S}_{1,2}$ precess around **J**
  - **L**: orbital angular momentum'
  - $\mathbf{S}_i$: Spin (component's angular momentum)
  - **J**: Total angular momentum

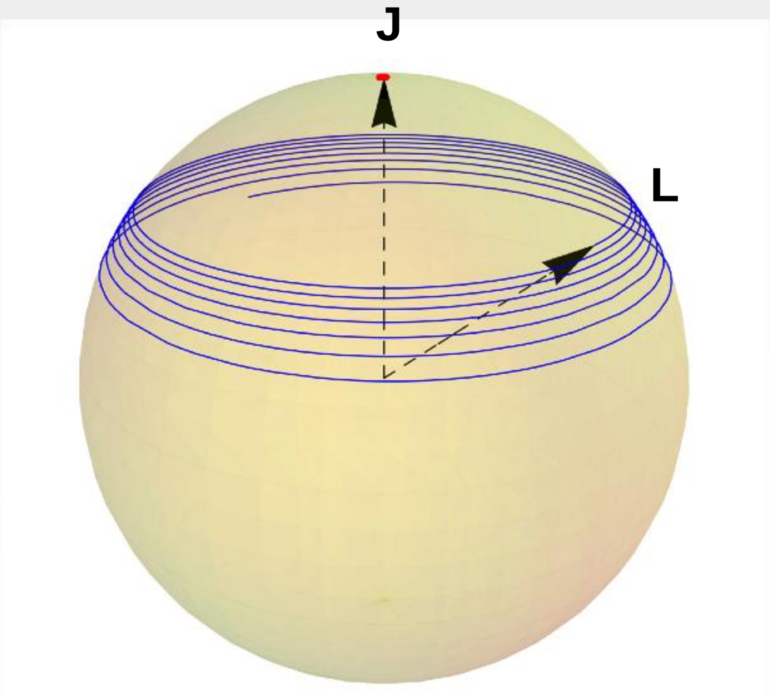
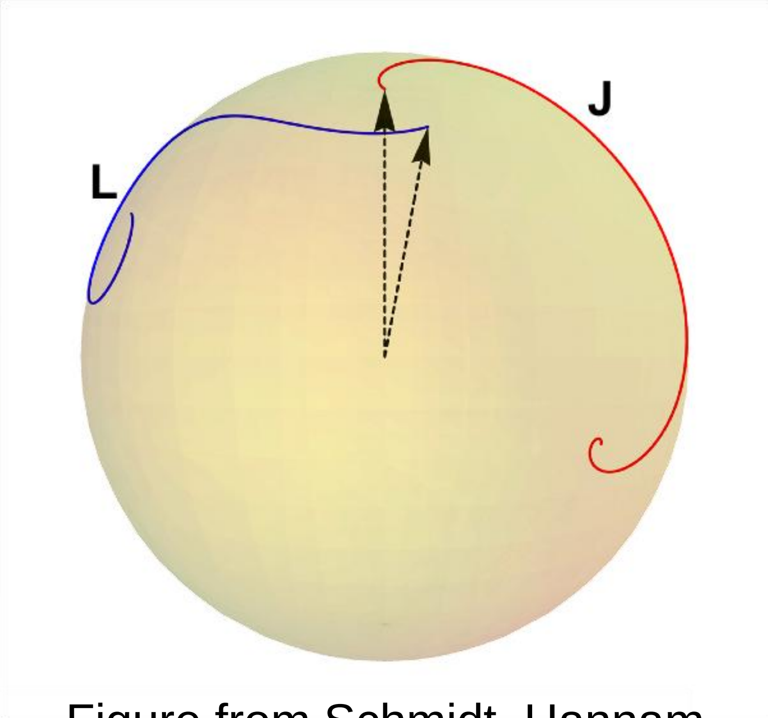


Figure from Schmidt, Hannam and Husa. arXiv:1207.3088

Apostolatos et al, Phys. Rev. D 49, 6274
Brown et al, arXiv:1203.6060

Transitional Precession

- When **J** becomes very small "transitional precession" can occur
- **S** and **L** "tumble" during the transition
- Simple precession resumes once **J** becomes larger
- Very rarely occurs



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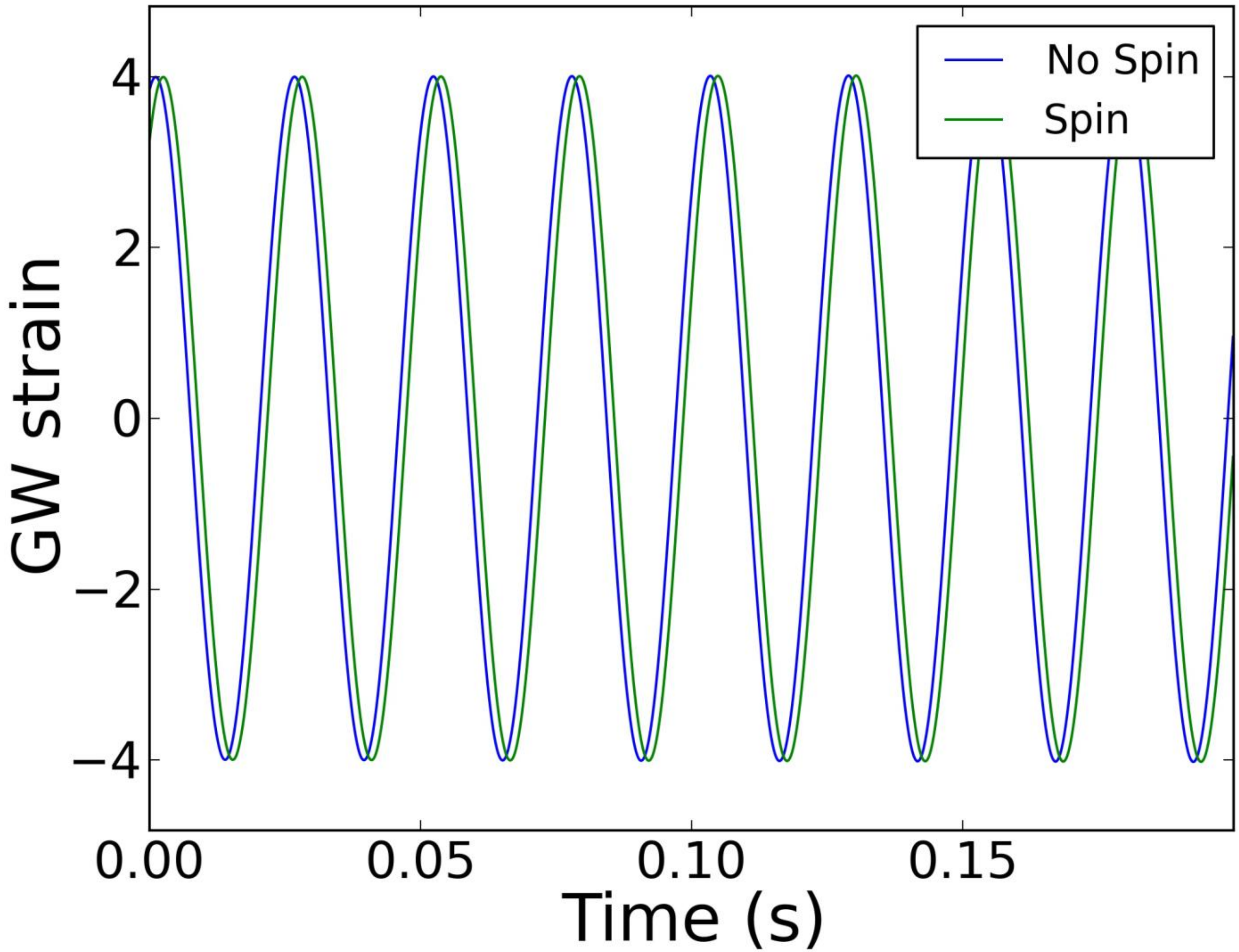
Apostolatos et al, Phys. Rev. D 49, 6274

Phase changes



$m_1 = m_2 = 3M_\odot$

For spin:

$\chi_1 = \chi_2 = 1$

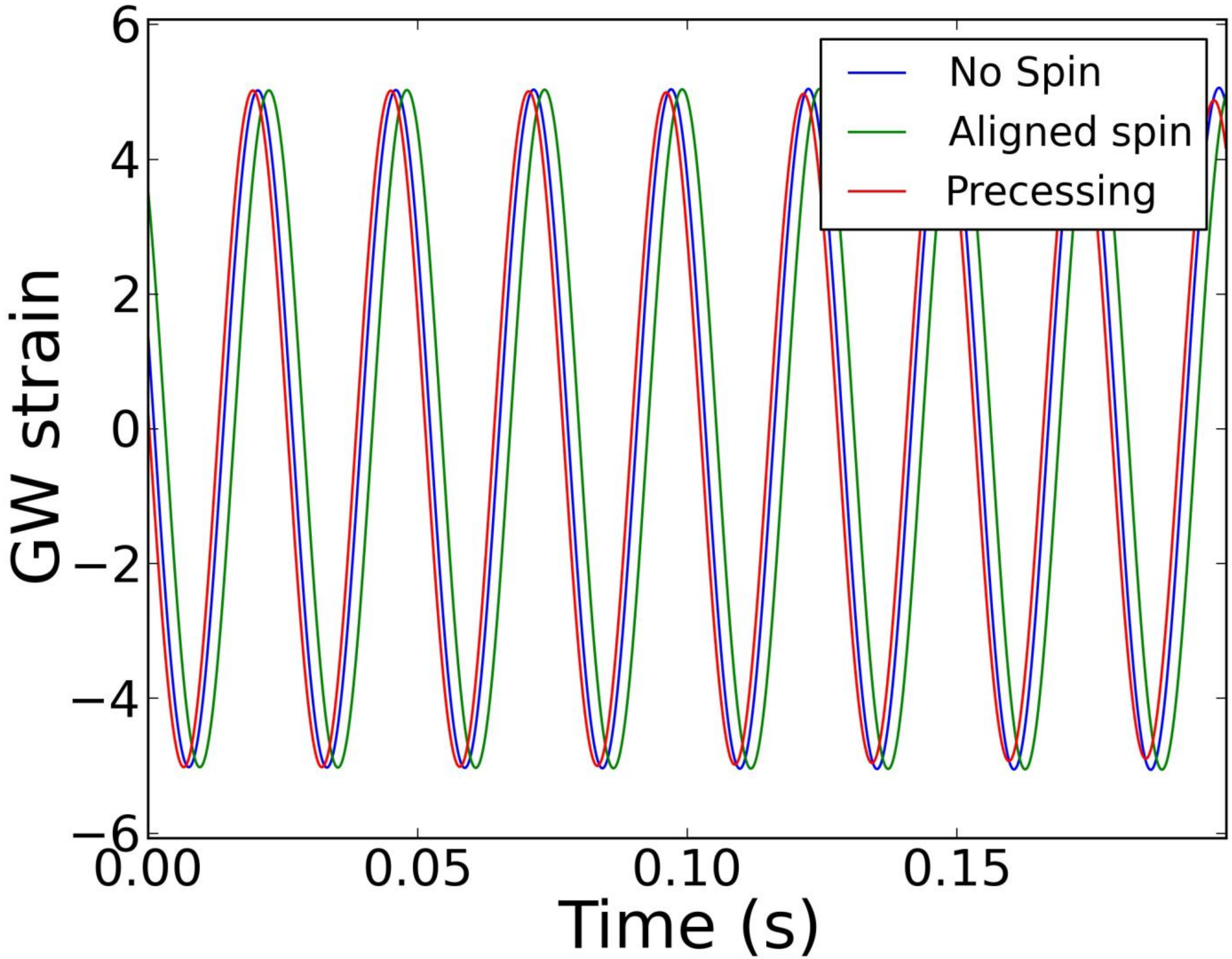
$\chi_{1,2} = \mathbf{S}_{1,2}/m_{1,2}^2$

$\mathbf{S}_1 \cdot \mathbf{L} = \mathbf{S}_2 \cdot \mathbf{L} = 1$

At t=0, frequency of GWs for both traces is 40Hz

Precession

$m_1 = 1.4 M_\odot, \quad m_2 = 10 M_\odot$



For aligned spin:

$$\chi_1 = \chi_2 = 1$$

$$\chi_{1,2} = \mathbf{S}_{1,2}/m_{1,2}^2$$

$$\mathbf{S}_1 \cdot \mathbf{L} = \mathbf{S}_2 \cdot \mathbf{L} = 1$$

For precessing:

$$\chi_1 = \chi_2 = 1$$

$$\mathbf{S}_1 \cdot \mathbf{L} = \mathbf{S}_2 \cdot \mathbf{L} = 0$$

$$\mathbf{S}_1 \cdot \mathbf{S}_2 = 0$$

At t=0, frequency of GWs for all traces is 40Hz

Spin effects

- Spin will also affect the merger, ringdown etc.
- See talks by:
  - Yi Pan (Analytical modeling of spinning systems)
  - Geoffrey Lovelace (Numerical modeling of spin systems)

How do we search for non-spinning systems?

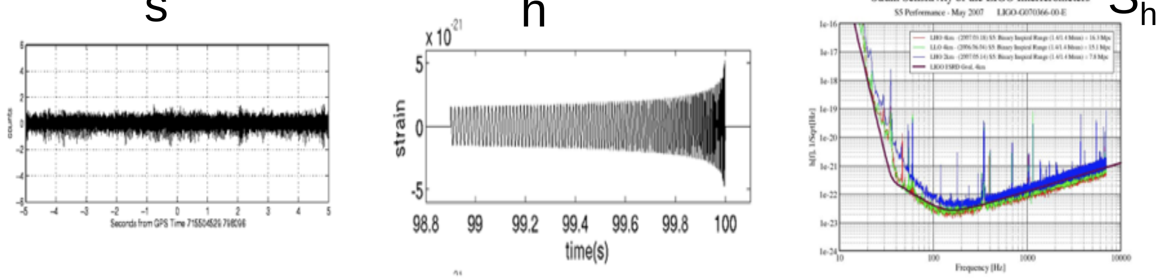
How does this non-spinning search do with spinning signals?

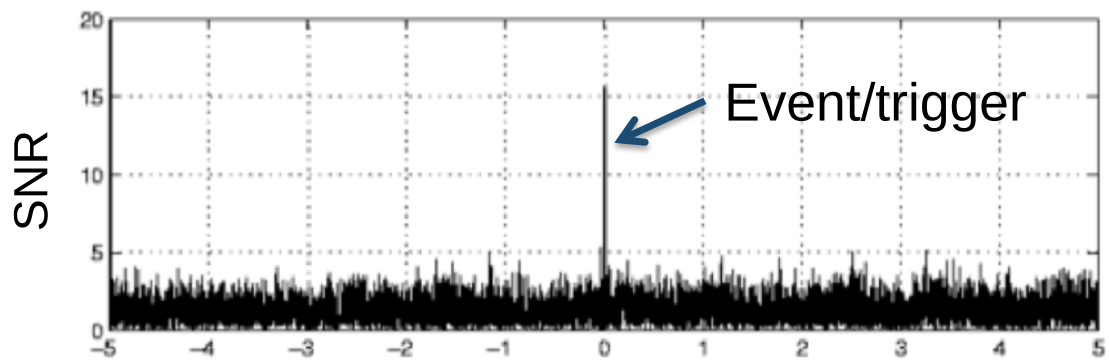
Matched-filtering

$$(s|h) = 4\,\mathrm{Re}\int_0^\infty \frac{\tilde{s}(f)\tilde{h}^\star(f))}{S_h(f)}$$

DATA X TEMPLATE / POWER SPECTRUM

s h S_h





Matched-filtering

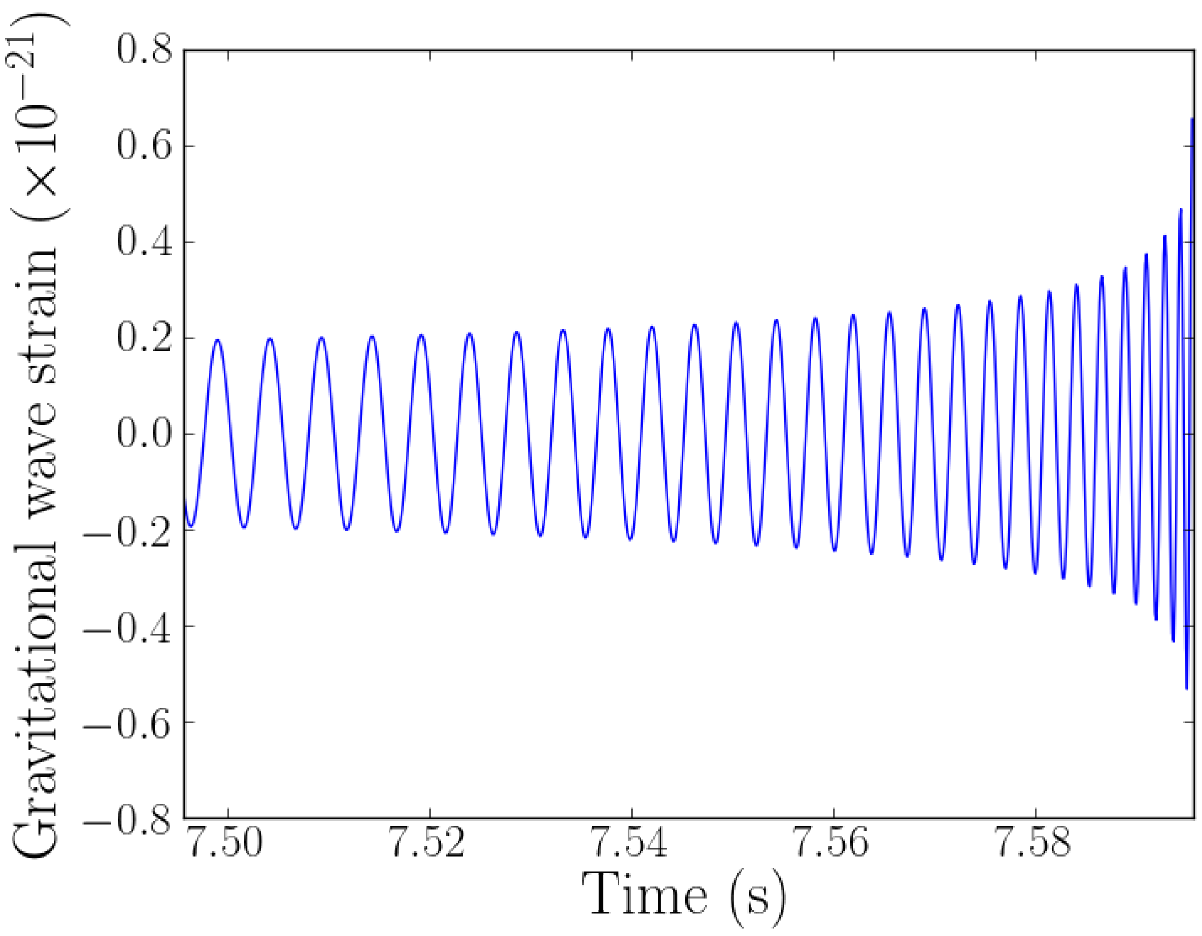
- Restricting to dominant mode:

$$\tilde{h}(f) = \tilde{A}(D, \iota, \theta, \psi, \phi)\mathcal{M}^{5/6} f^{-7/6} \exp\left[i\left(\Phi(\mathcal{M}, \eta, f) + \tilde{\Phi}_0(\iota, \varphi, \theta, \psi, \phi)\right)\right]$$

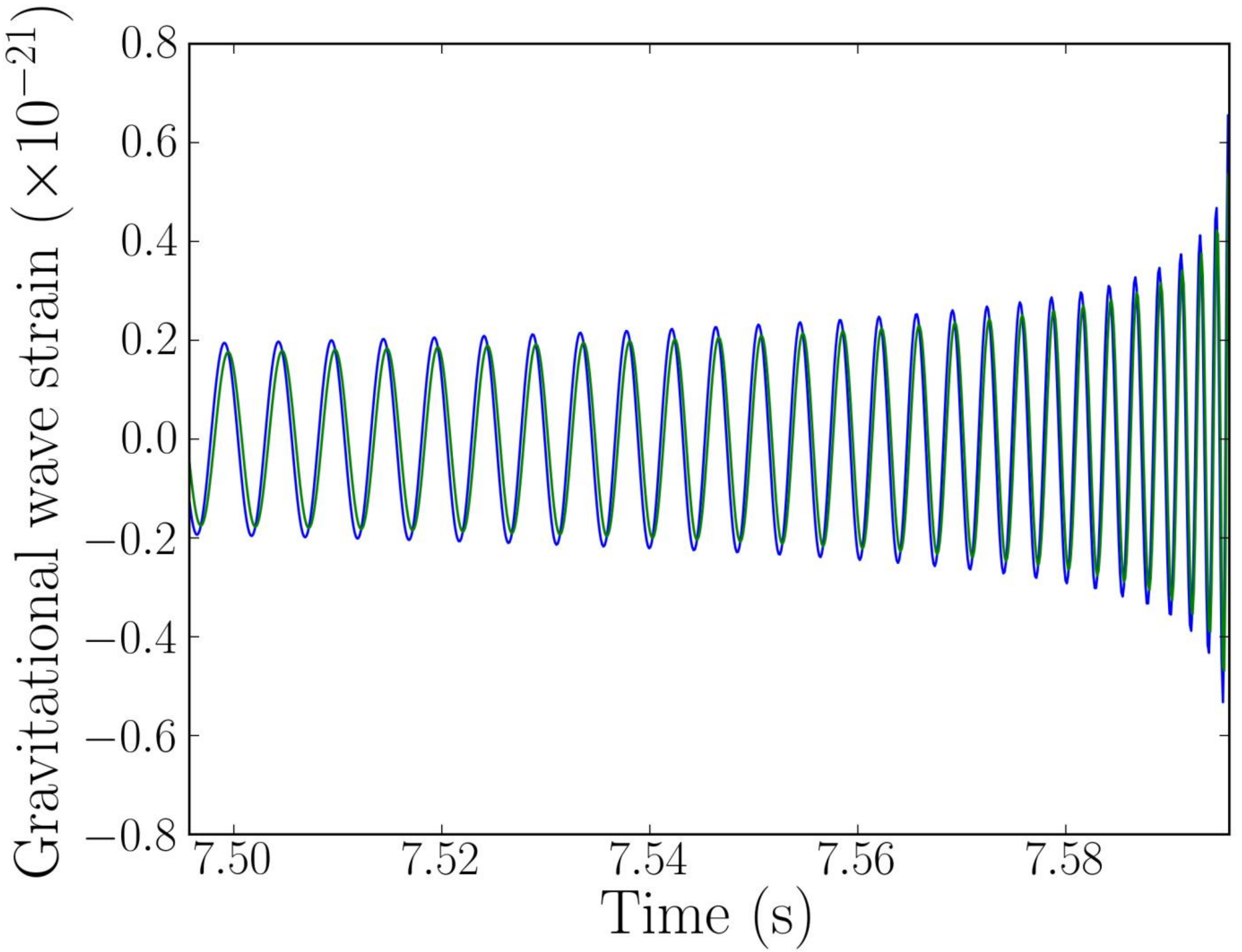
Orientation and location parameters

- Orientation and location parameters enter only as amplitude or phase shifts

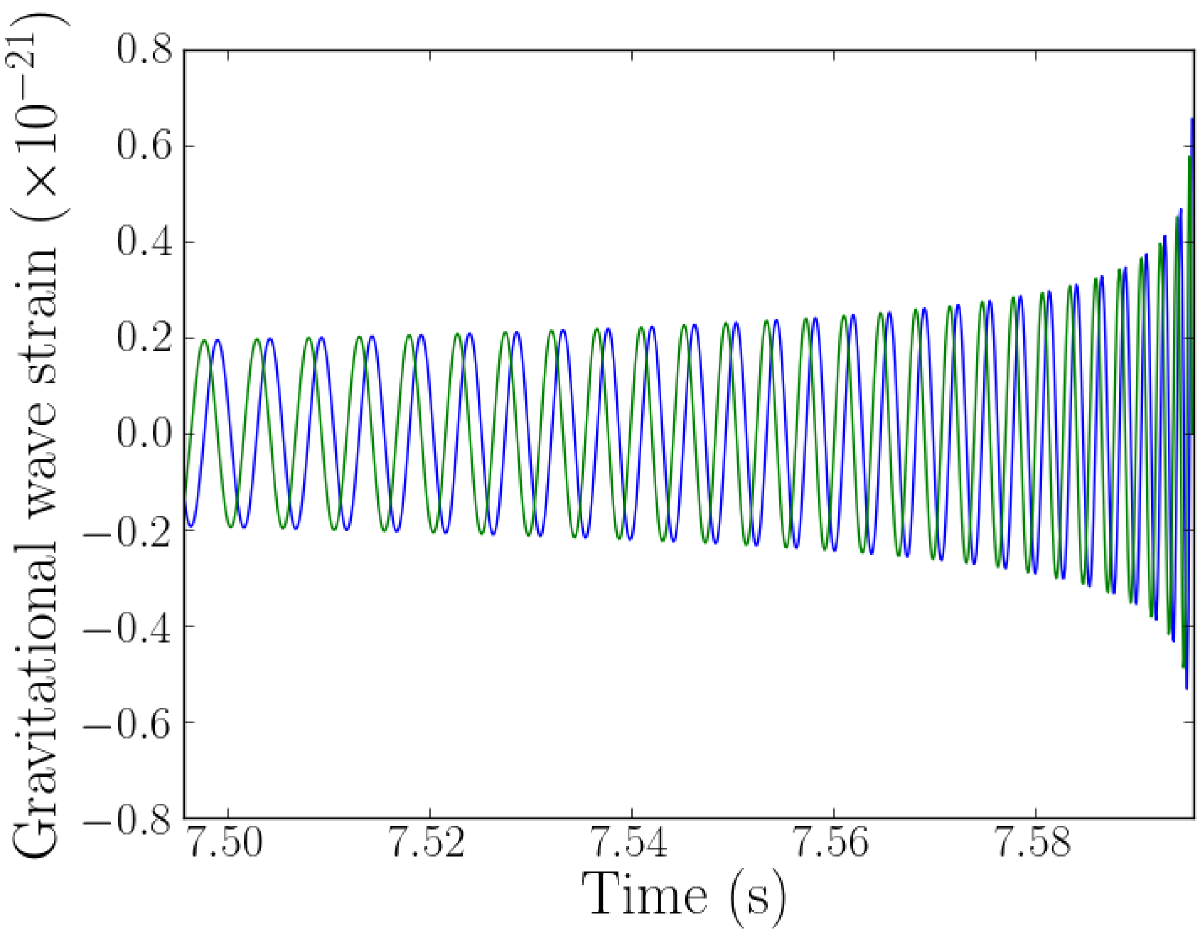
Non-spin search



Non-spin search



Non-spin search



Maximised SNR

$$(s|h) = 4\,\mathrm{Re}\left(\int_0^\infty \frac{\tilde{s}(f))\tilde{h}^*(f))}{S_h(f))} df\right)$$

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Maximise over orientation and location parameters

$$(s|h)_{\mathrm{maximised}} = 4\left|\int_0^\infty \frac{\tilde{s}(f))\tilde{h}^*(f))}{S_h(f))} df\right|$$

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$$(s|h)_{\mathrm{maximised}} = 4\left|\int_0^\infty \frac{\tilde{s}(f))\tilde{h}^*(f))}{S_h(f))}df\right|$$

As a function of the coalescence time

$$(s|h)_{\mathrm{maximised}}(t_c) = 4\left|\int_0^\infty \frac{\tilde{s}(f)\tilde{h}^*(f)}{S_h(f)}e^{-2\pi i f t_c}df\right|$$

Masses

- No trick to deal with the mass range – use a bank of filters

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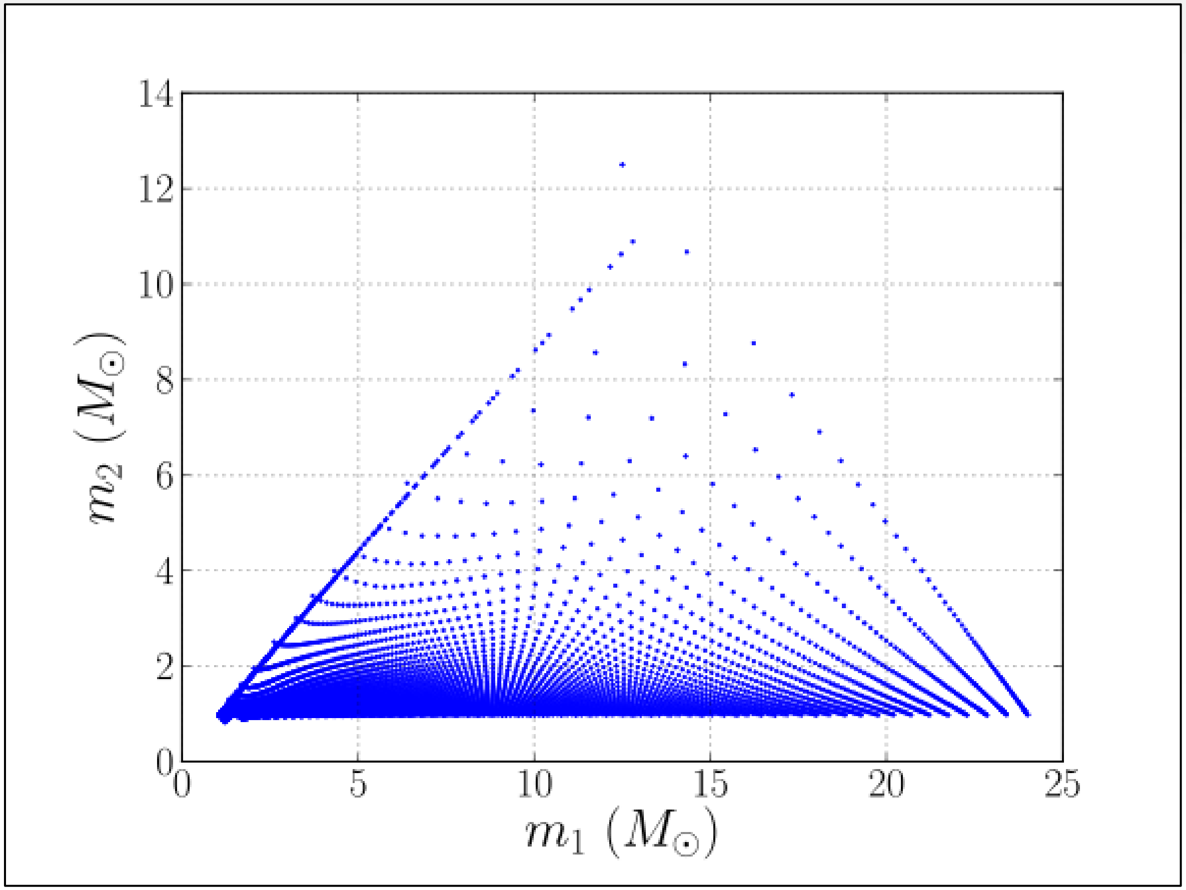
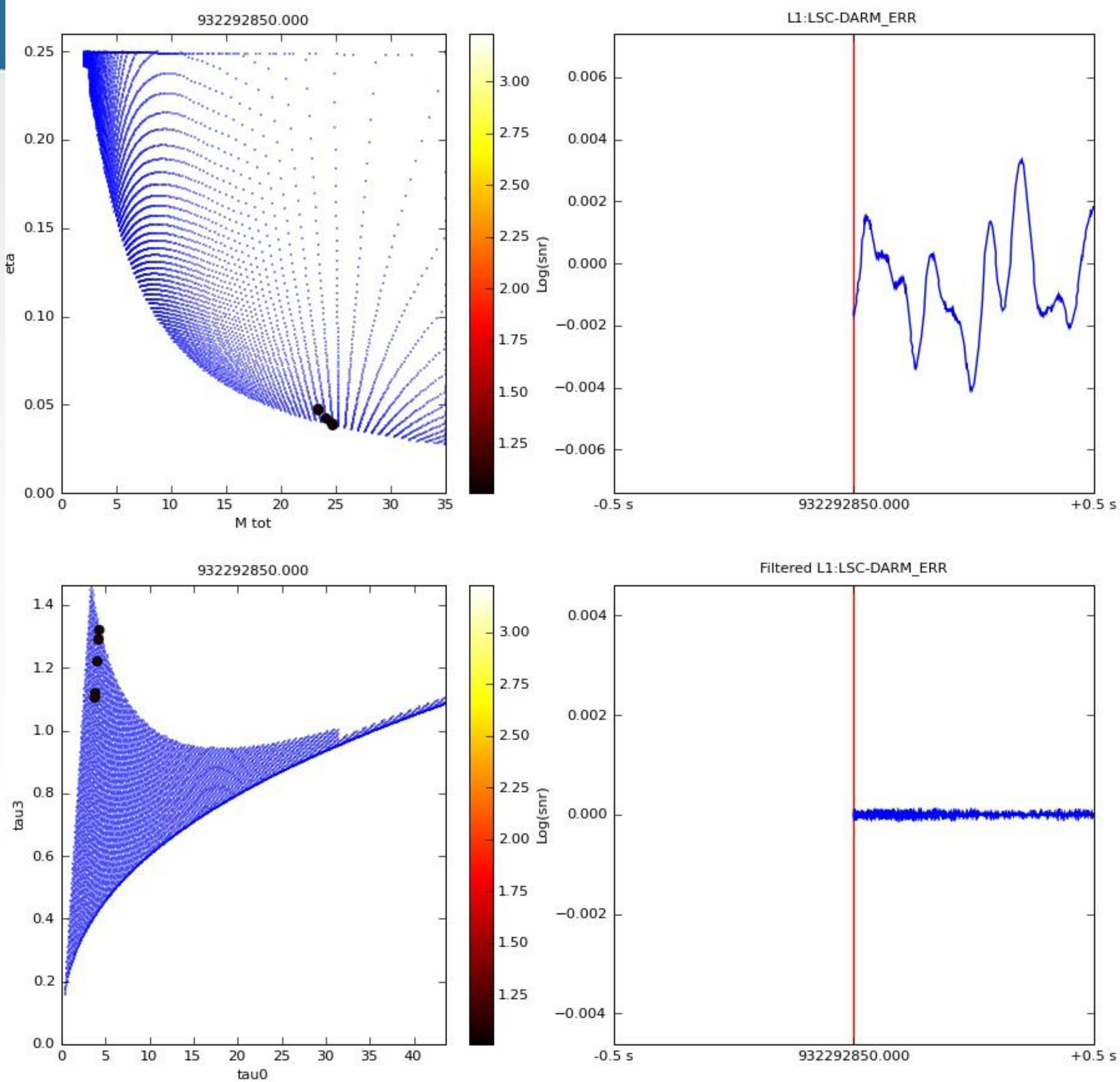


Mitigating non-Gaussianity

- Non-Gaussian background will cause loud SNR events
- The effect of this is mitigated by:
  - Coincidence test
  - Removing times of poor data quality
  - A set of signal based vetoes, such as chi-squared tests

Data Analysis – A movie

Bank templates



Raw data

High-pass filtered data

THANKS to Larne Pekowsky for making this movie

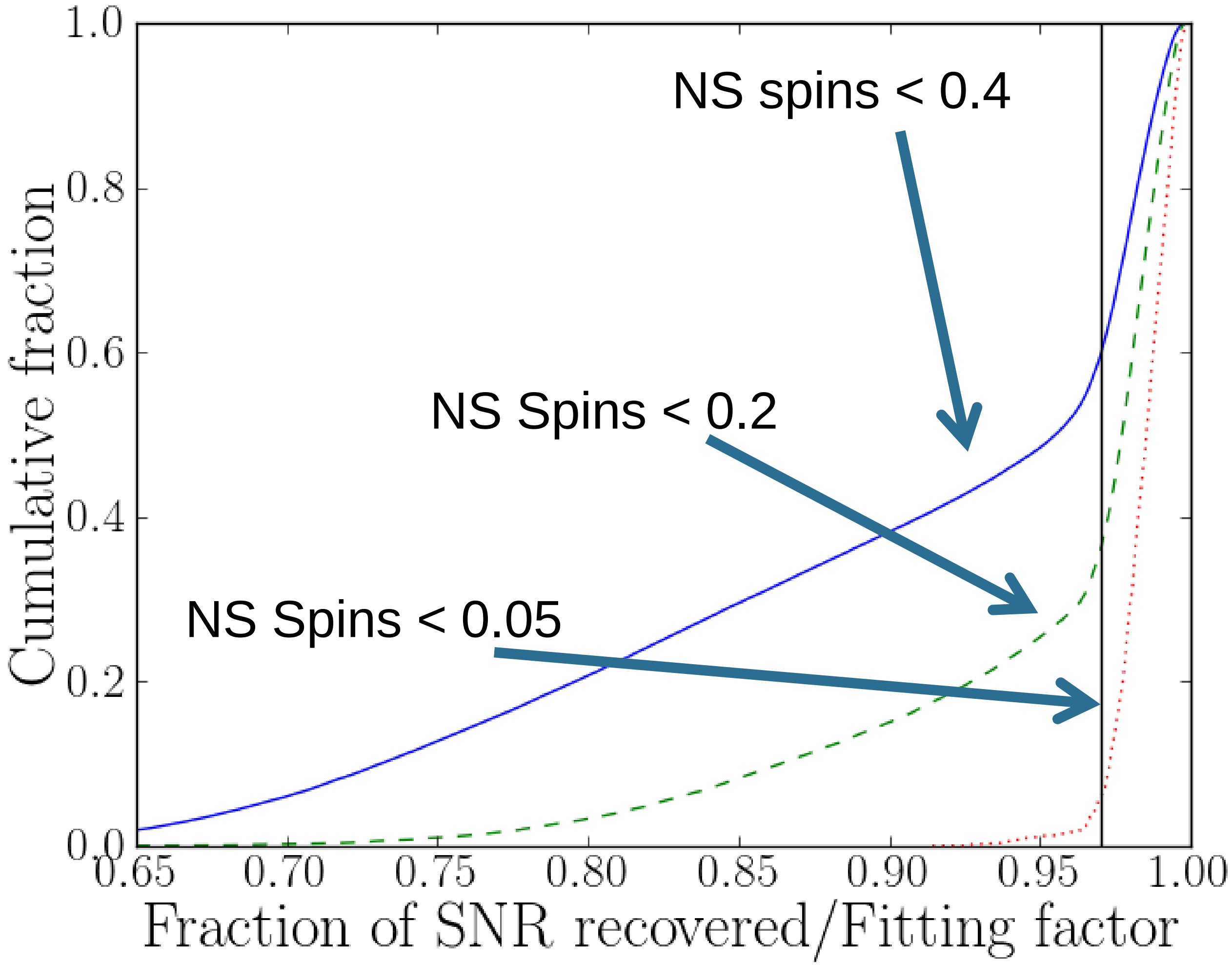
Is a spinning search needed?

- How well would we do if we used the non-spinning search to search for generic systems?
  - Some SNR would be lost, but how much?
- We can measure this:
  - Create generic waveforms
  - Search for them using the non-spinning bank
  - Determine largest SNR
  - Compare to SNR obtained using exact waveform
  - Known as Fitting Factor

BNS signal distribution

- Uniform in component masses:
  - Both NSs between 1 and 3 solar masses
- Uniform in component spin magnitudes:
  - Both NSs spin from 0 – 0.05 or 0 – 0.4
- Isotropic in all orientation/location angles
- Analytical inspiral only waveforms (“TaylorT4”)
- Use aLIGO zero-detuned, high-power sensitivity curve

BNS non-spinning search



Plot from Brown,IH,Lundgren and Nitz (arXiv:1207.6406)

NSBH signal distribution

- Uniform in component masses:
  - NSs between 1 and 3 solar masses
  - BHs between 3 and 25 solar masses
- Uniform in component spin magnitudes:
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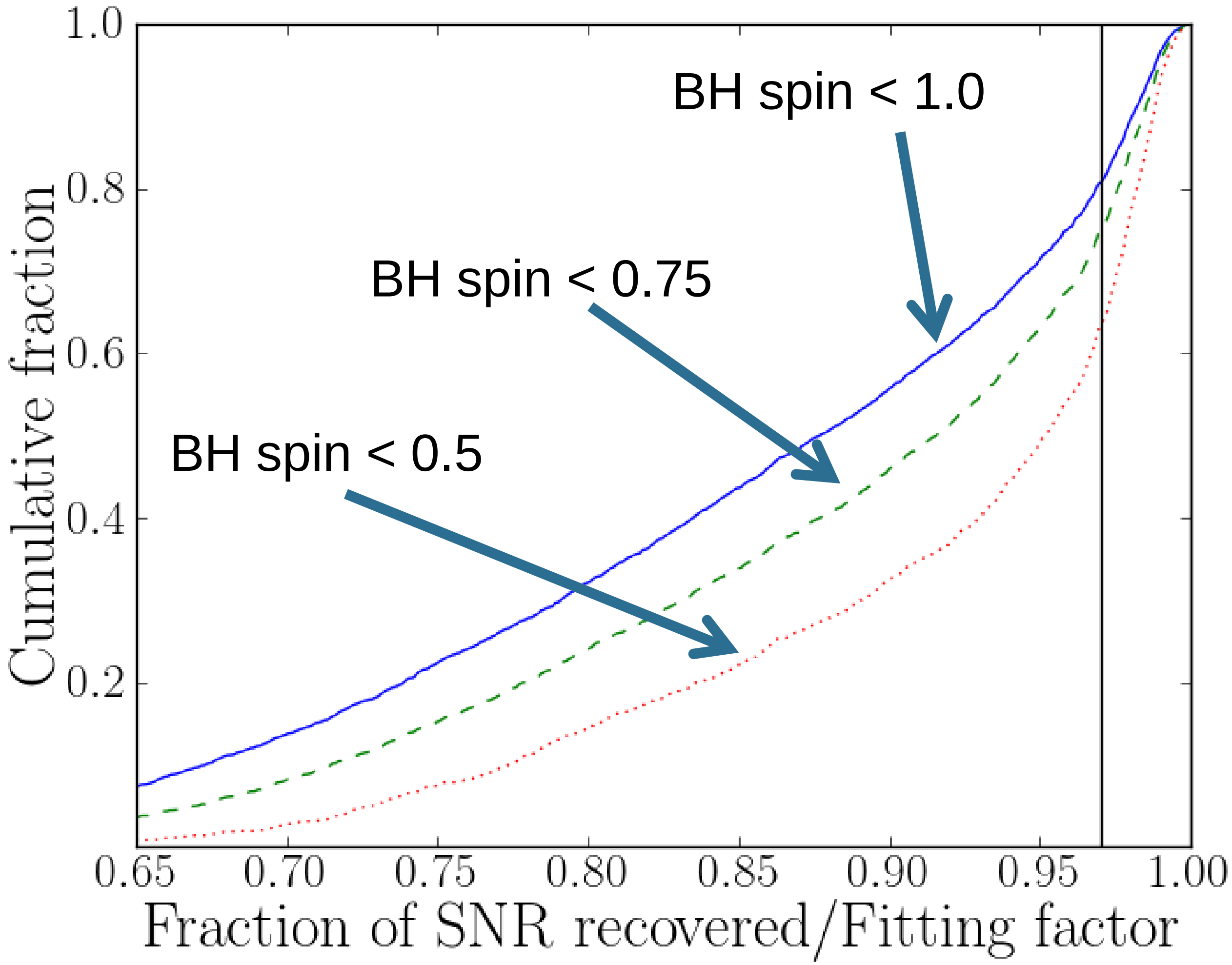

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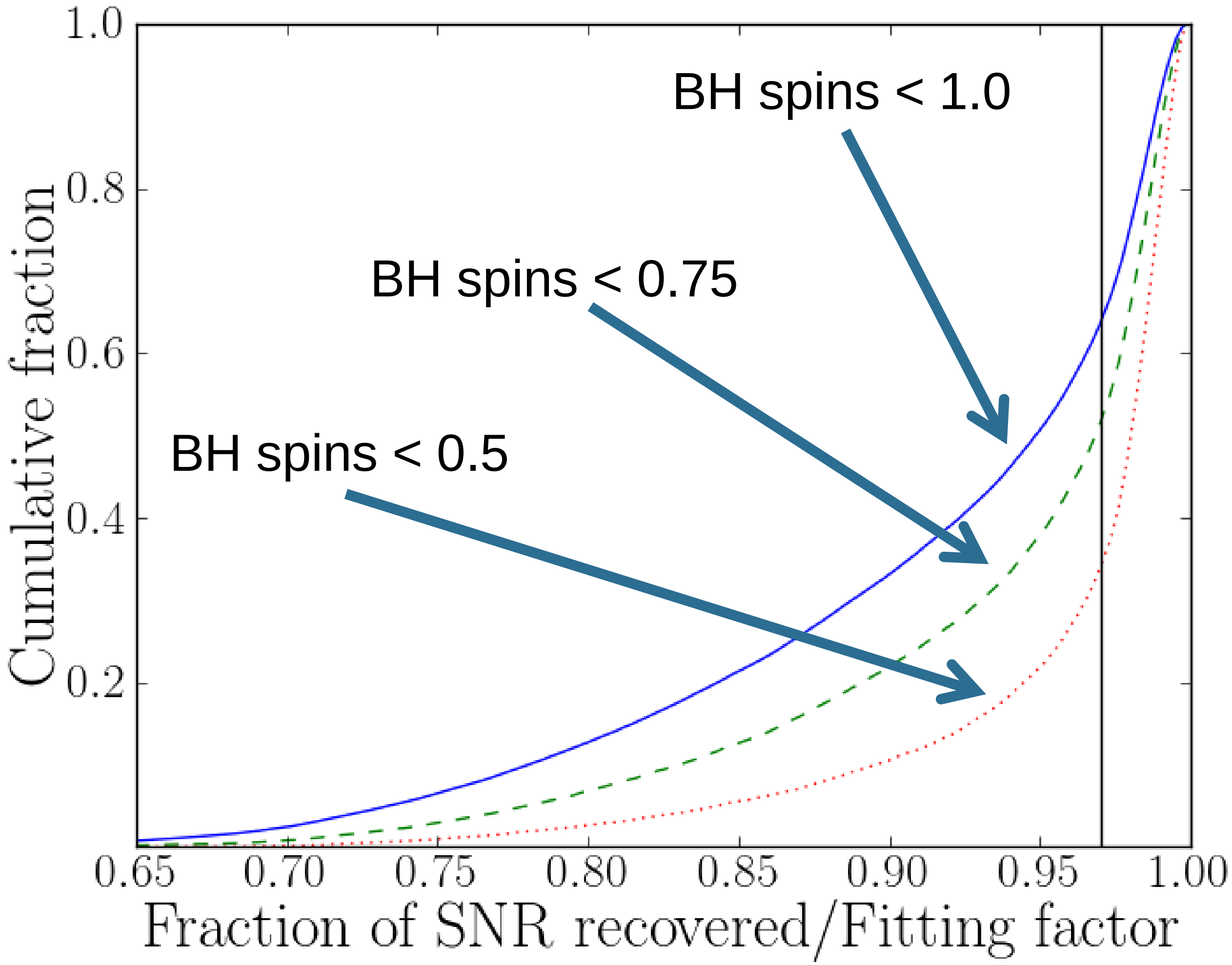

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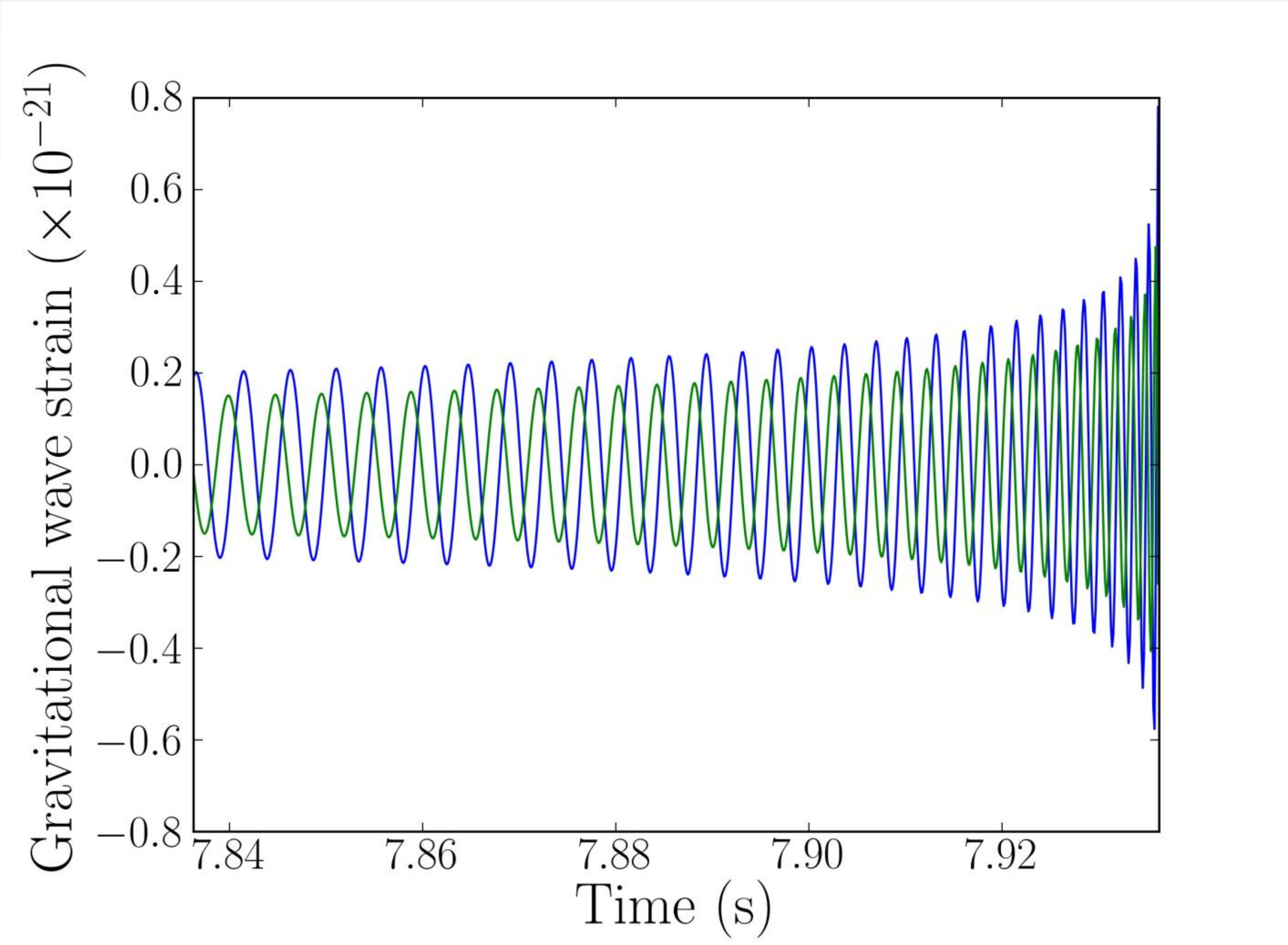
Summary and caveats

- Employing the non-spinning search in the advanced detector era will result in regions of parameter space where spin will reduce our detection ability
- Results are only as good as the waveforms we have
  - To evaluate BBH performance we really need precessing waveforms with merger and ringdown
  - We did not include any mismatch between the template waveforms and the “signals”
- Results depend on the chosen distribution of signals
  - Restricting the parameter space will help us

How can we search with aligned-spinning waveforms?

How does an aligned-spinning search do with generic signals?

Aligned spin



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Aligned spin challenges

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  - Bank of waveforms must be 4 dimensional
    - Geometric placement
      - Brown,IH,Lundgren and Nitz (arXiv:1207.6406)
      - See poster by Alex Nitz
    - Stochastic placement
      - See poster by Stephen Privitera
      - See also: IH, Allen and Sathyaprakash (Phys Rev D 80, 104014)
        Babak (Class.Quant.Grav. 25,195011)

Aligned spin challenges

- Now have 4 intrinsic parameters (masses **and** spins)
  - Determining multi-detector coincidence
    - Demand that the same waveform is significant in >1 observatories
    - Cannon et al (Astrophys.J. 748,136)
    - West et al (In progress)

Aligned spin challenges

- Now have 4 intrinsic parameters (masses **and** spins)
  - More templates = more background events
  - More templates = more computational cost

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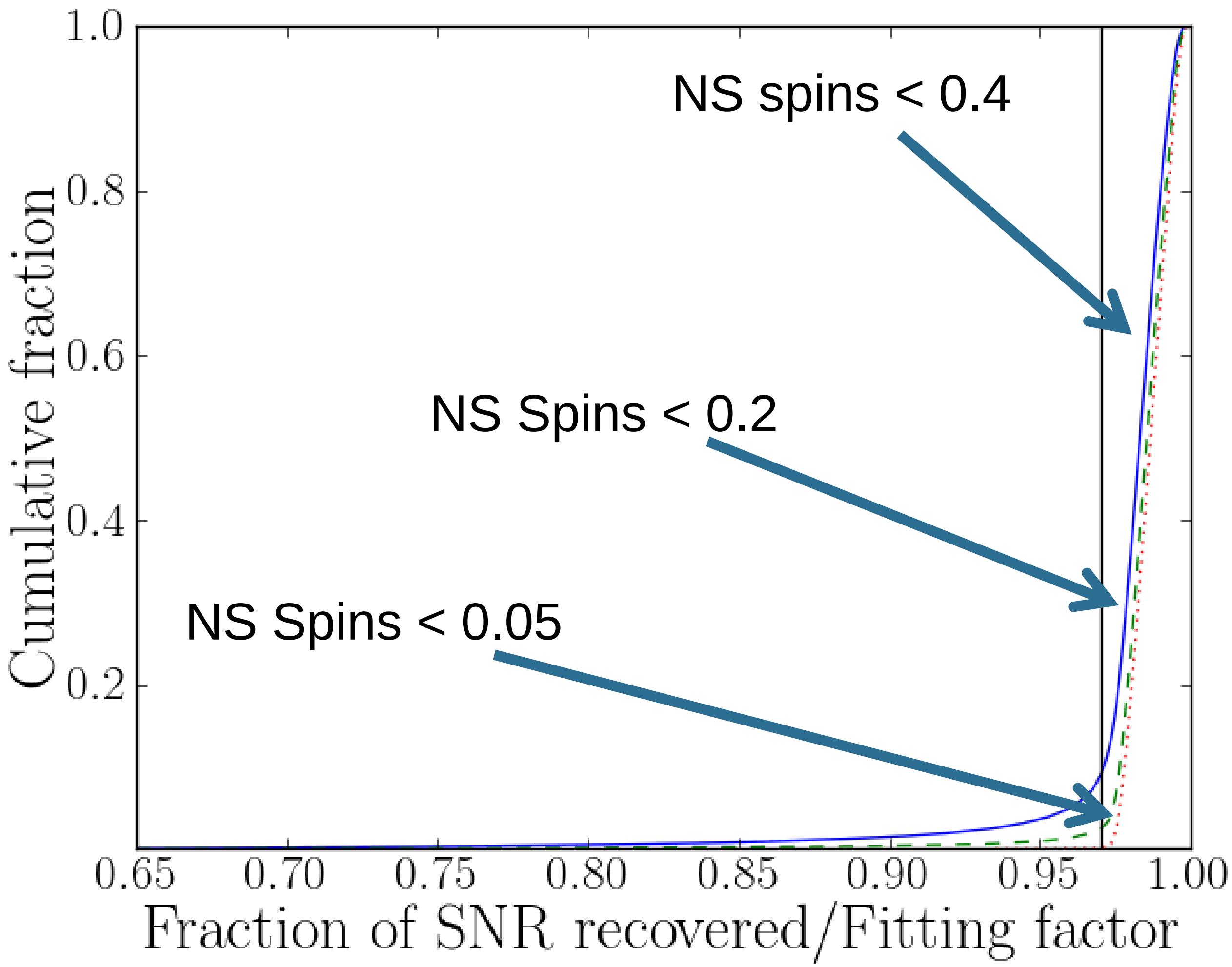
BNS aligned-spinning search



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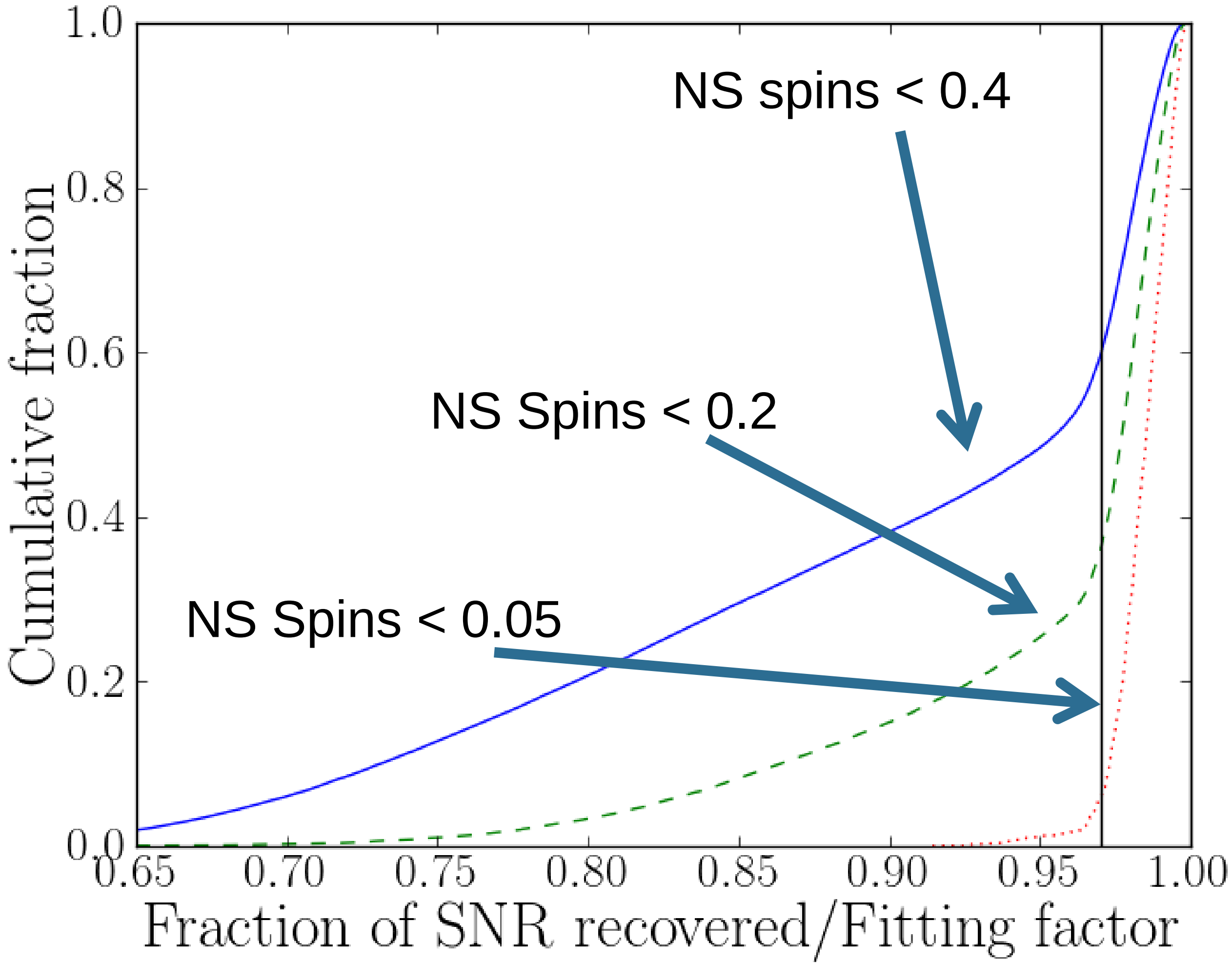

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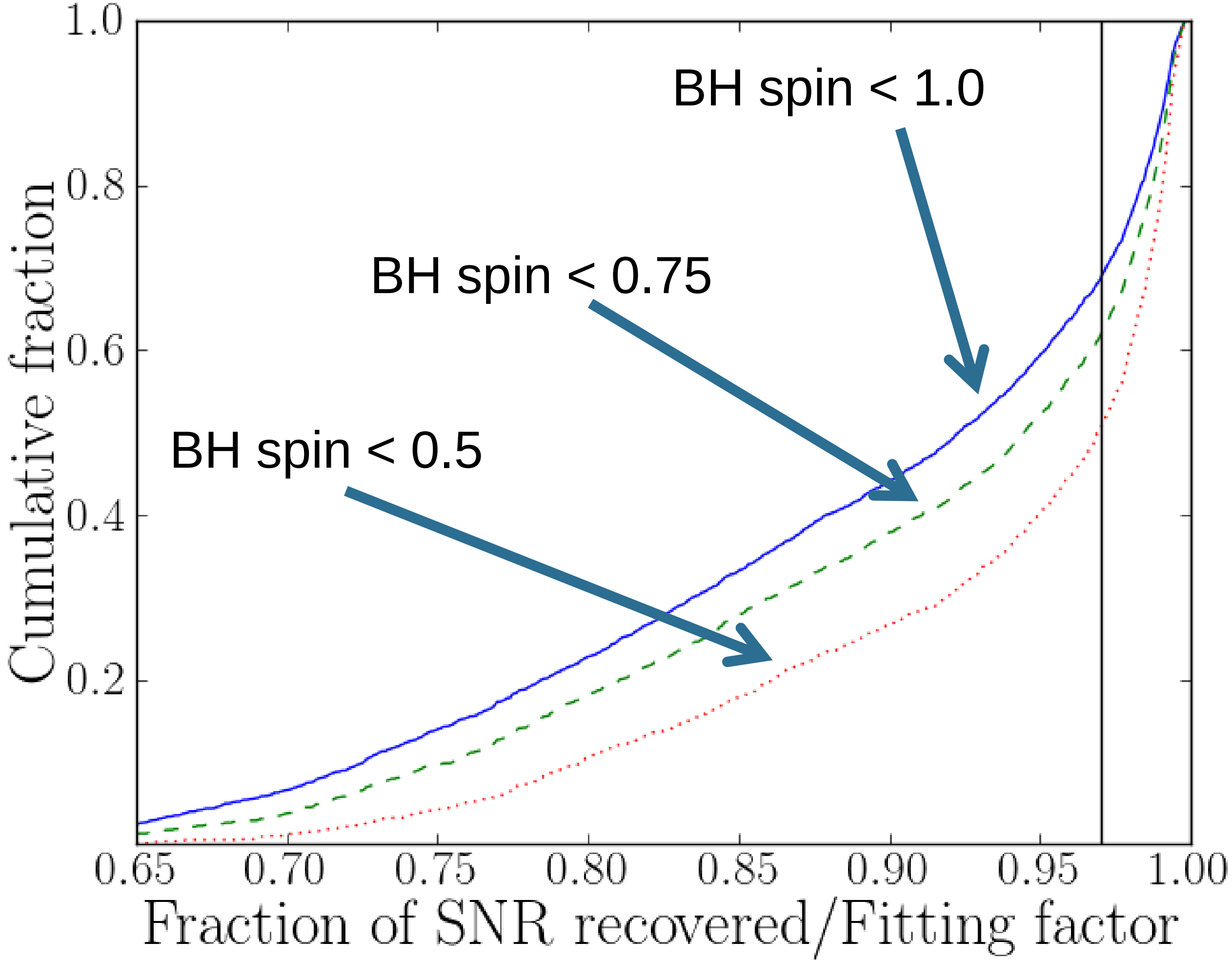
NSBH aligned-spinning search



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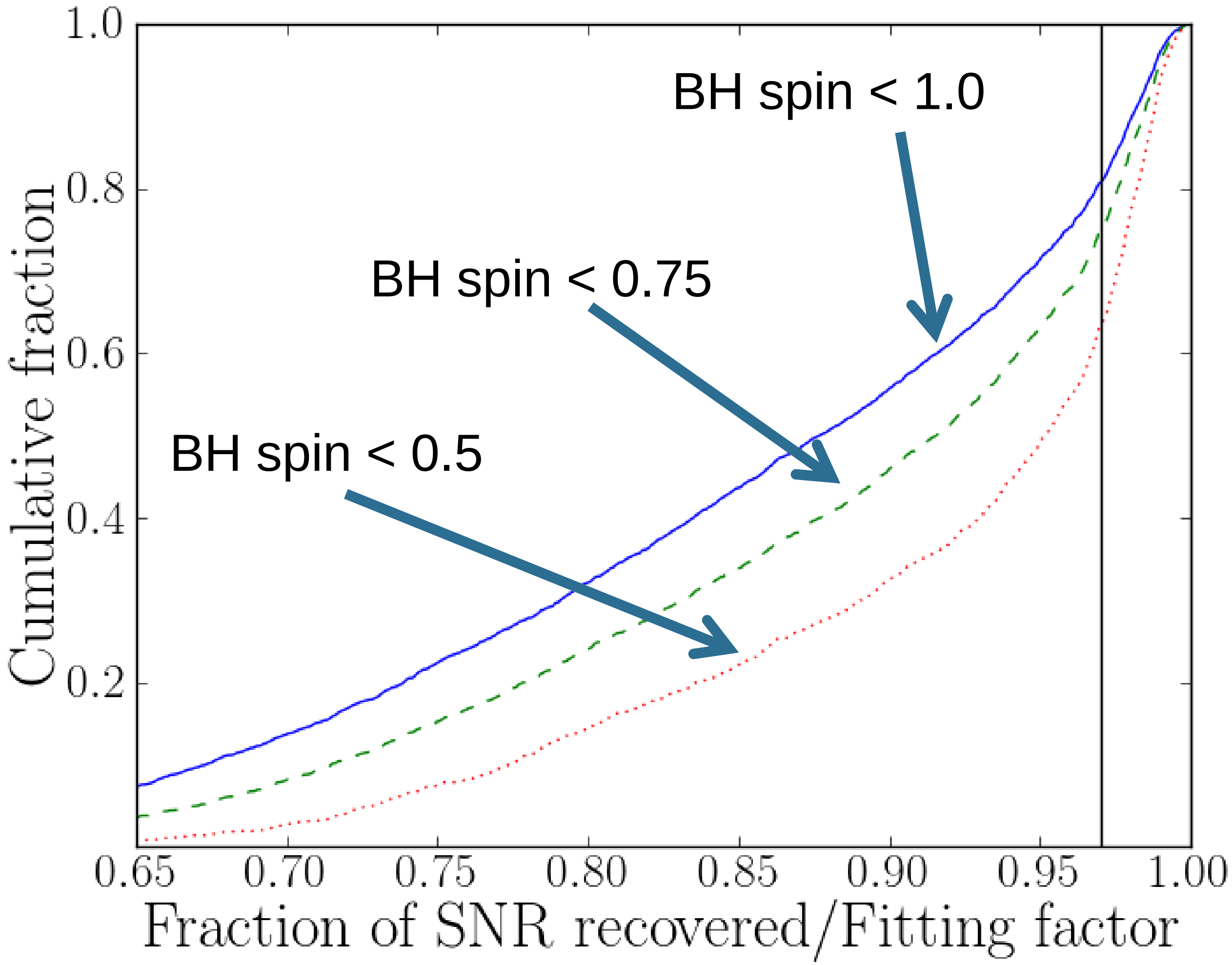
NSBH non-spinning search



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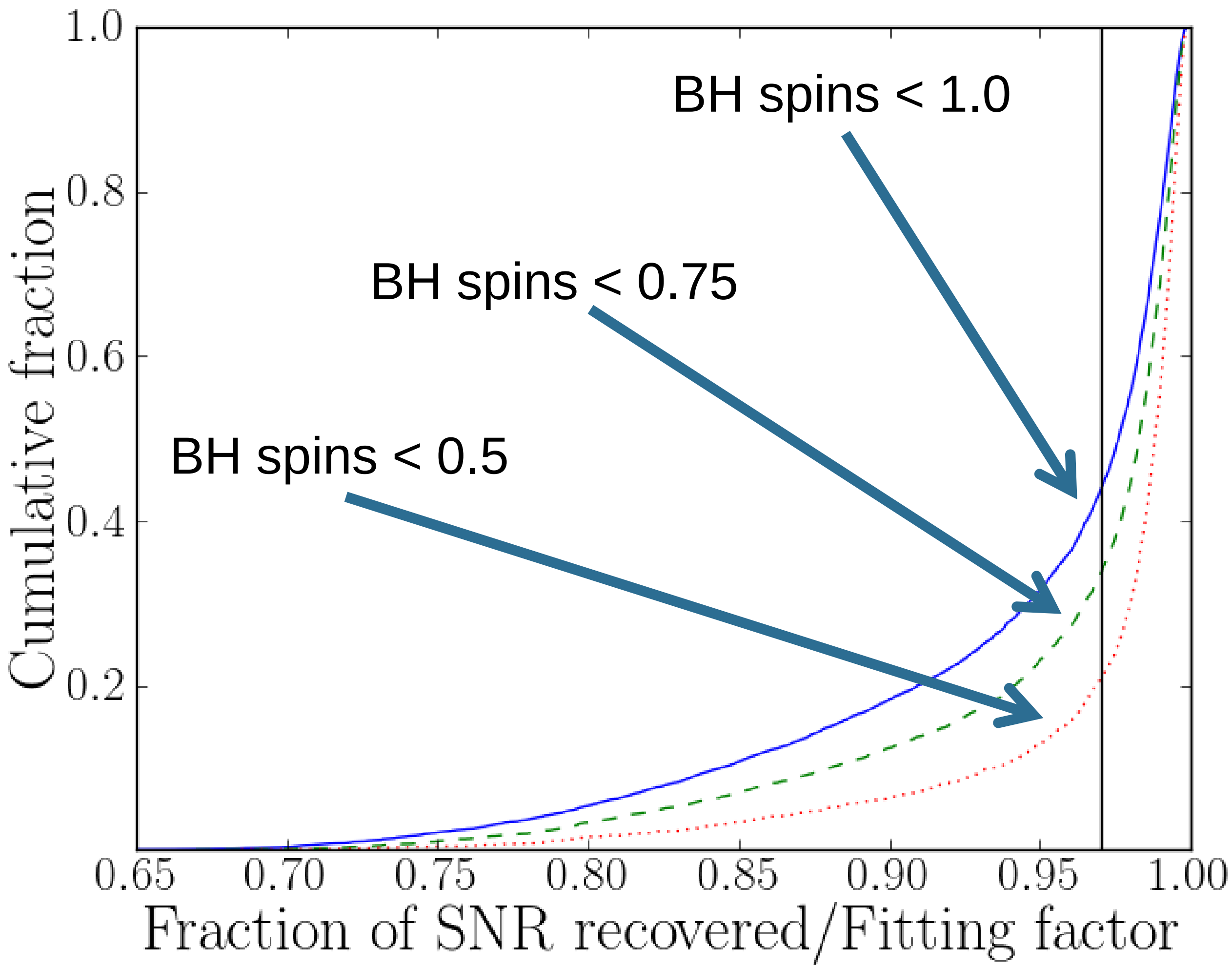

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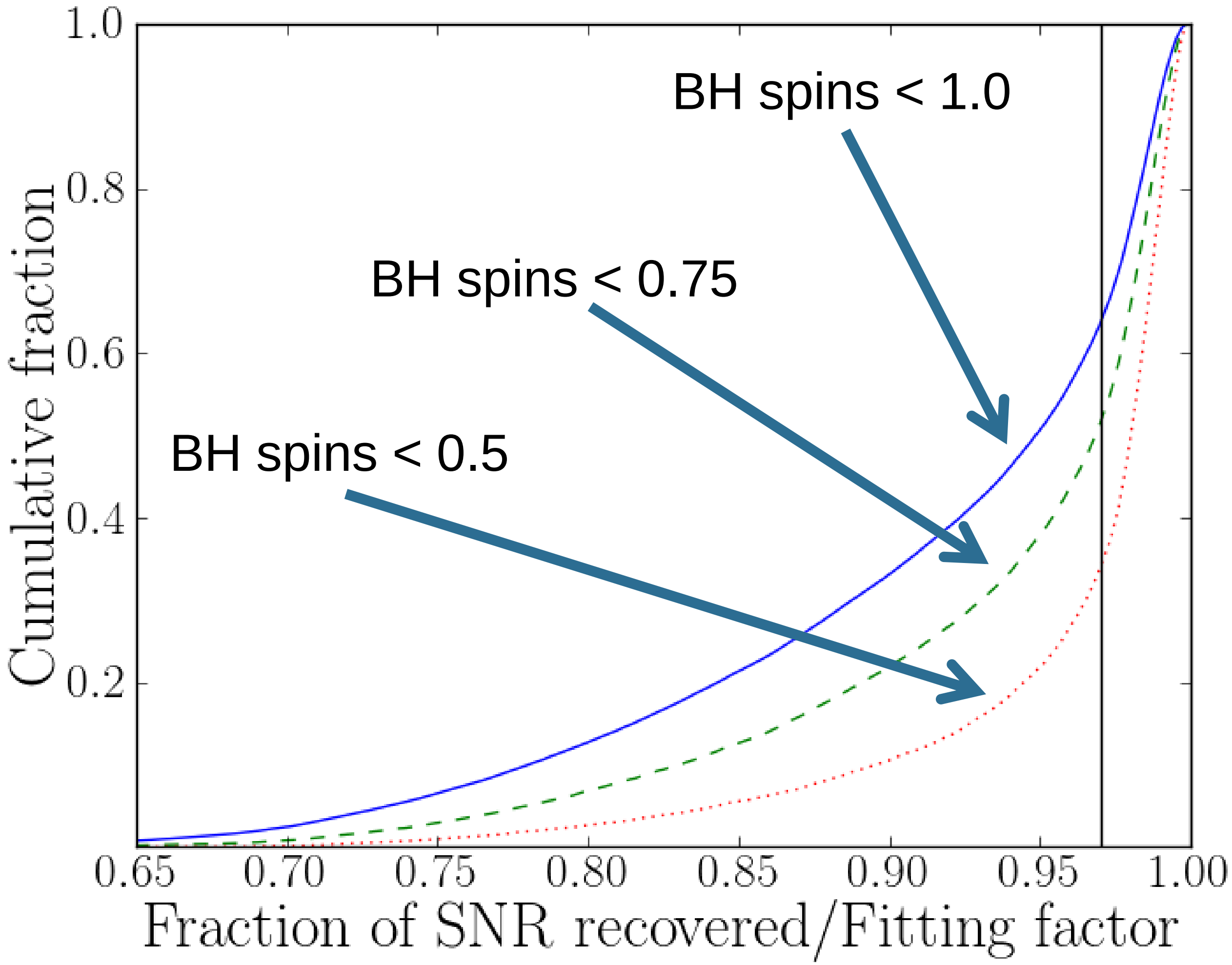


Plot from Brown,IH,Lundgren and Nitz (In preparation)

Aligned spin summary

- With an aligned spin search, signals are picked up with larger SNR.
- BUT precession matters in a significant region of the NSBH and BBH parameter space
- More templates = more background events
- More templates = more computational cost

How can we search with precessing waveforms?

Dealing with precession?

- If we ignore precession, we will miss systems with certain spin configurations
- To date, no search for precessing systems has been run and published using data from our observatories and has increased detection efficiency relative to a non-spinning search
- Ideas have been proposed and tested!

Naïve approach

- Why is a precessing search not simply an extension of an aligned spin search?

	Intrinsic Parameters	Number of templates
Non-spin search	Masses (2)	$\sim 10^5$
Aligned-spin search	Masses, Spin amplitudes (4)	$\sim 10^6$
Precessing search	Masses, Spin amplitudes and orientations, inclination, polarization (>8)	????

Phenomenological templates

- Idea: Use unphysical templates that match well with real, precessing templates
- Reality: Tried in searches in S4 and S5, efficiency less than that of a non-spinning search
- Why?
  - Increased freedom meant background triggers were louder
  - No adequate glitch-rejection technique was available

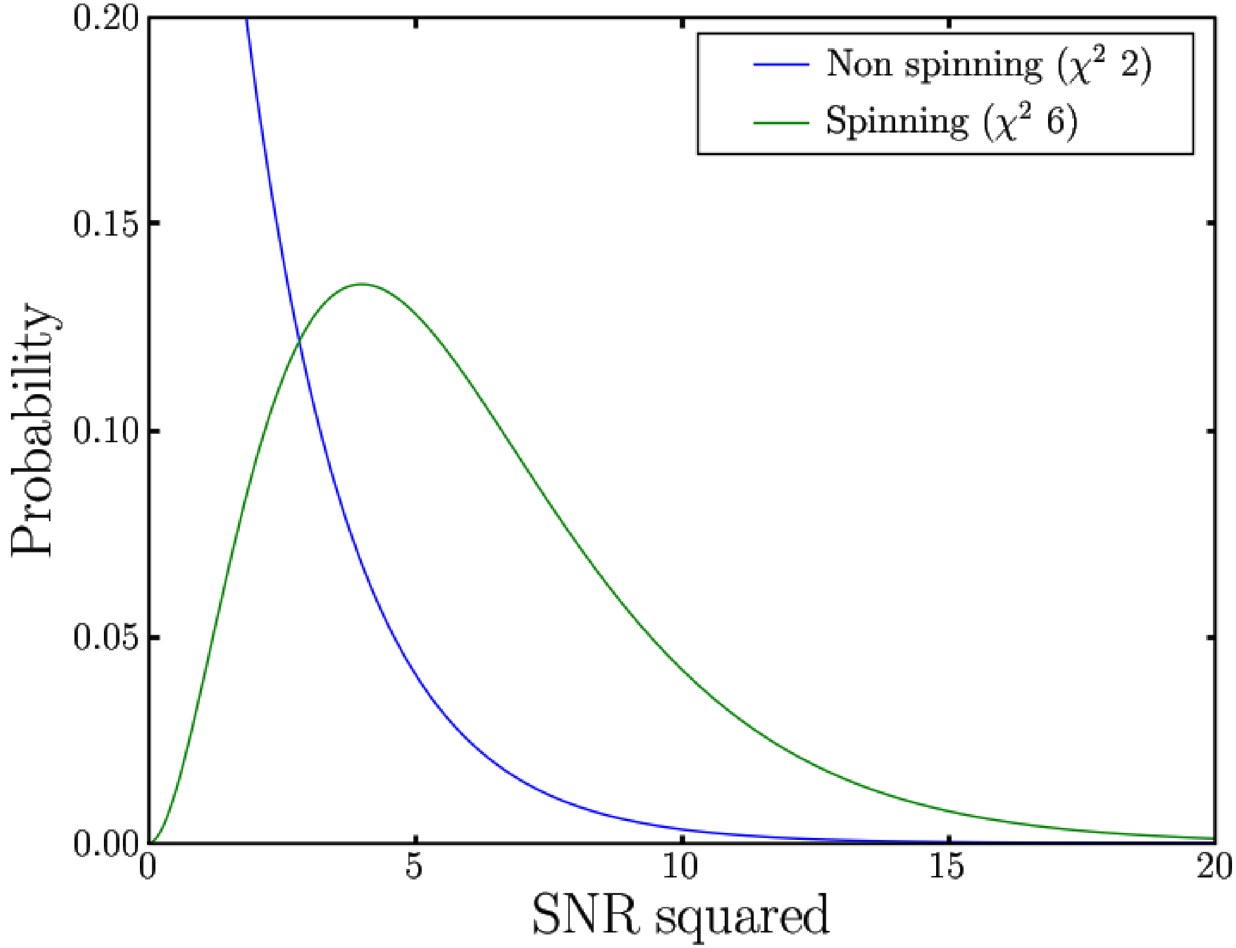
Buonnano et al, Phys. Rev. D 67, 104025
Van Den Broeck, IH et al, Phys.Rev. D 80, 024009
Abbott et al, Phys. Rev. D 78, 042002

Physical template family

- Idea:
  - Restrict to single spin systems; good for NSBH
  - Decompose waveform into 5 basis vectors to reduce to 4 intrinsic parameters:
    - masses, |**S**| and **S**.**L**
  - Different combinations of the 5 basis vectors correspond to different values of extrinsic parameters

Buonnano et al, Phys.Rev. D 69, 104017
Fazi, PhD Thesis
IH and Fairhurst, Class.Quant.Grav. 28, 134008

Physical template family



- Background events will be louder
- Only useful if aligned-spin search recovers < 88% of SNR

Other effects

- What about sub-dominant amplitude modes?
- What about eccentricity?
- What about matter effects?
- Are our waveform models accurate in all regimes?
- What if the signal is not quite what we expect

Conclusions

- We have a lot of experience with non-spinning searches
- We know how to conduct aligned spinning searches
- There are ideas for how to conduct a precessing search, but so far nothing that increases efficiency
- Detecting all possible systems is vital if we want to do astrophysics in the coming years

END

Phase changes

- Spin affects the frequency evolution of a CBC

$$
\begin{aligned}
\frac{\dot{\omega}}{\omega^2} = \frac{96}{5}\,\eta\,(M\omega)^{5/3}\Bigg\{ & 1 - \frac{743 + 924\,\eta}{336}\,(M\omega)^{2/3} - \left(\frac{1}{12}\sum_{i=1,2}\left[\chi_i\left(\hat{\mathbf{L}}_N\cdot\hat{\mathbf{S}}_i\right)\left(113\frac{m_i^2}{M^2} + 75\eta\right)\right] - 4\pi\right)(M\omega) \\
& + \left\{\left(\frac{34\,103}{18\,144} + \frac{13\,661}{2\,016}\,\eta + \frac{59}{18}\,\eta^2\right) - \frac{1}{48}\,\eta\,\chi_1\chi_2\left[247\,(\hat{\mathbf{S}}_1\cdot\hat{\mathbf{S}}_2) - 721\,(\hat{\mathbf{L}}_N\cdot\hat{\mathbf{S}}_1)(\hat{\mathbf{L}}_N\cdot\hat{\mathbf{S}}_2)\right]\right\}(M\omega)^{4/3} \\
& - \frac{1}{672}\,(4\,159 + 15\,876\,\eta)\,\pi\,(M\omega)^{5/3} + \Bigg[\left(\frac{16\,447\,322\,263}{139\,708\,800} - \frac{1\,712}{105}\gamma_E + \frac{16}{3}\pi^2\right) + \left(-\frac{273\,811\,877}{1\,088\,640} + \frac{451}{48}\pi^2 - \frac{88}{3}\hat{\theta}\right)\eta \\
& + \frac{541}{896}\eta^2 - \frac{5\,605}{2\,592}\eta^3 - \frac{856}{105}\log\left[16(M\omega)^{2/3}\right]\Bigg](M\omega)^2 + \left(-\frac{4\,415}{4\,032} + \frac{358\,675}{6\,048}\,\eta + \frac{91\,495}{1\,512}\,\eta^2\right)\pi\,(M\omega)^{7/3}\Bigg\},
\end{aligned}
$$

Extra terms due to spin of system

Precession

- If spins and orbital angular not aligned the system will precess

$$\dot{\mathbf{S}}_1 = \alpha\,(m_1, m_2, \mathbf{S}_2)\,\mathbf{S}_1 \times \mathbf{L}_N + \beta\,(m_1, m_2)\,\mathbf{S}_1 \times \mathbf{S}_2$$

$$\dot{\mathbf{S}}_2 = \alpha\,(m_2, m_1, \mathbf{S}_1)\,\mathbf{S}_2 \times \mathbf{L}_N + \beta\,(m_2, m_1)\,\mathbf{S}_2 \times \mathbf{S}_1$$

$$\dot{\mathbf{L}}_N = \gamma\,(m_1, m_2, \mathbf{S}_2)\,\mathbf{S}_1 \times \mathbf{L}_N + \gamma\,(m_2, m_1, \mathbf{S}_1)\,\mathbf{S}_2 \times \mathbf{L}_N$$

$\dot{\mathbf{L}}_N$ -> orbital angular momentum (to dominant order)