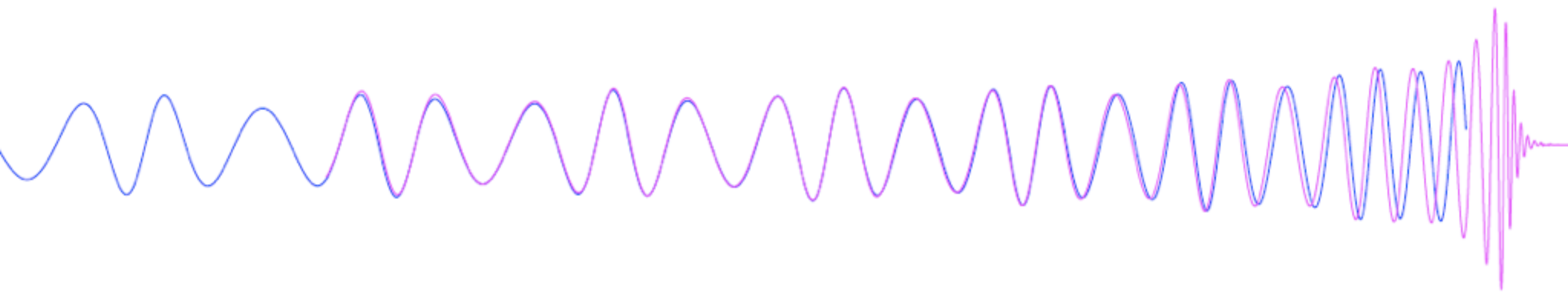
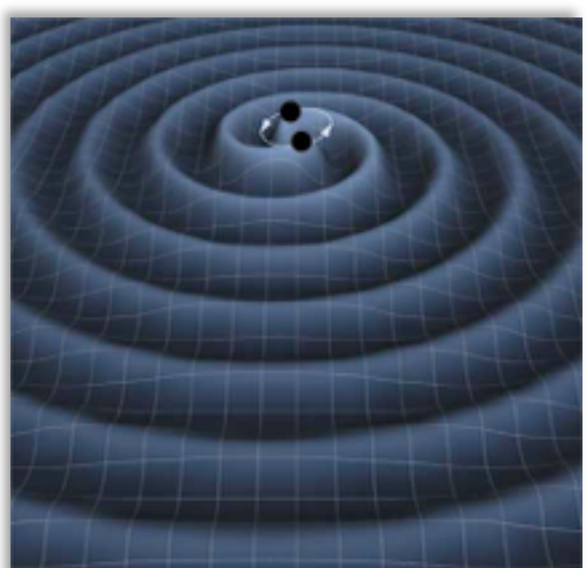
So, what do we do with this?

Deirdre Shoemaker
Center for Relativistic Astrophysics
Georgia Tech

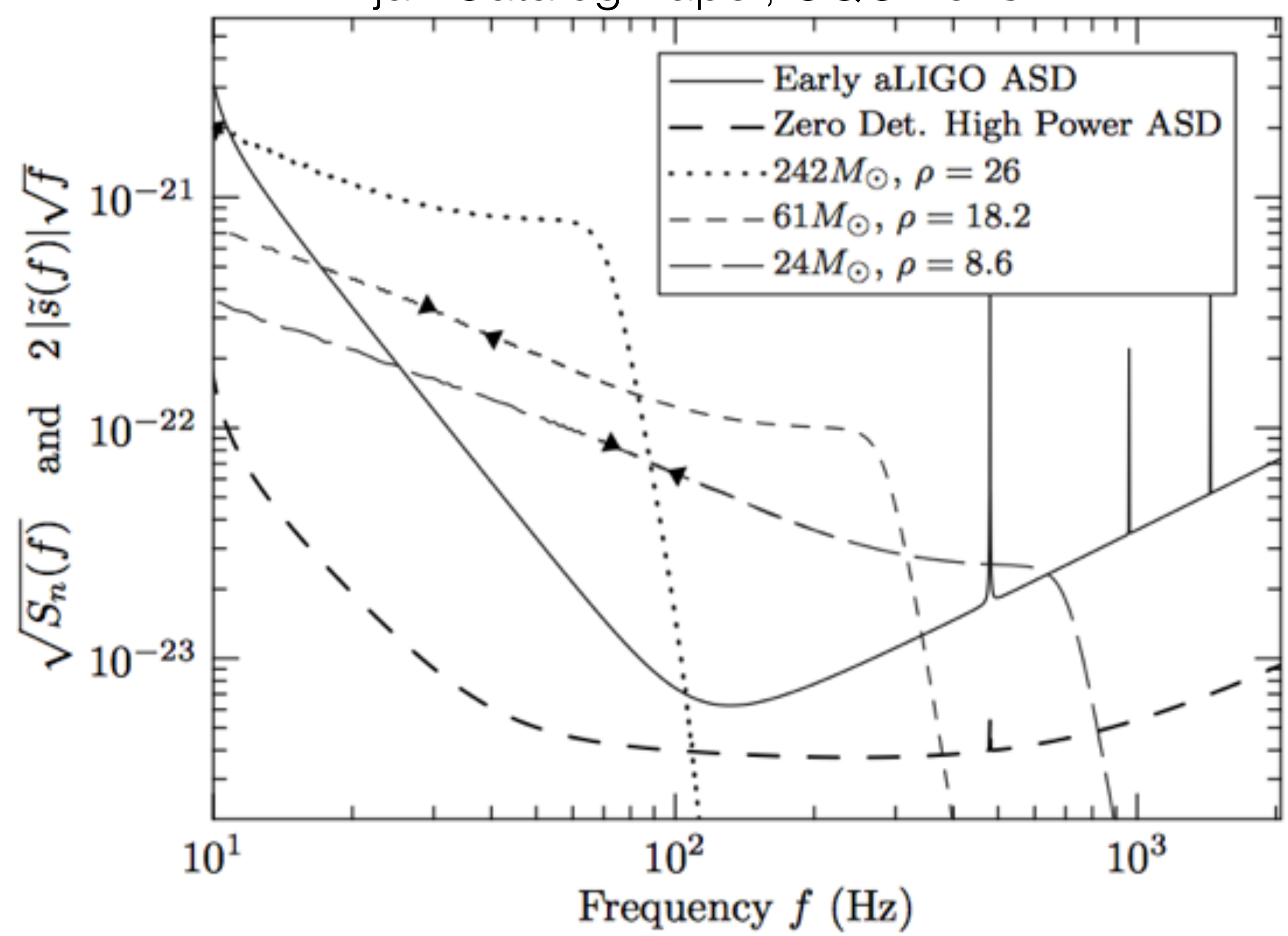


Testing GW Searches with NR …

- Use solutions of NR to detect and interpret gravitational waves from compact object coalescence (my focus BBH)
- Preparing NR output for DA input
- Length of waveforms
- Higher Modes
- Parameter coverage
- Is there any other path?



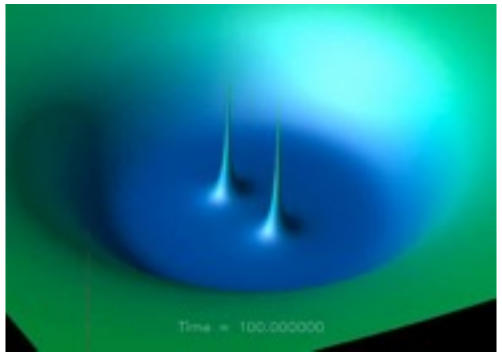
Ninja2 Catalog Paper, CQG 2013



Binary Black Hole Problem “Solved”

2005 Pretorius
Binary inspiral and merger

Phys.Rev.Lett. 95 (2005) 121101



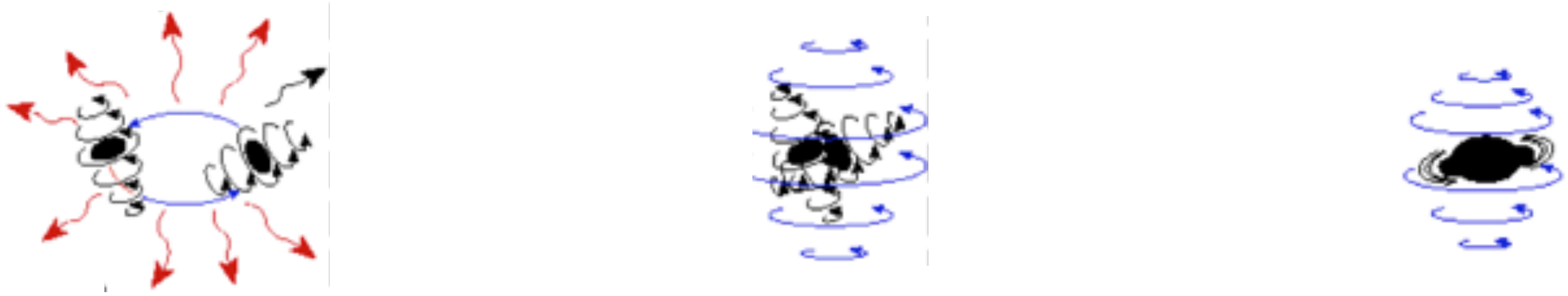
2006 RIT and NASA
Moving Punctures Method

Campanelli, Lousto, Zlochower
Phys.Rev.Lett. 96 (2006) 111101

Baker, Centrella, Choi, Koppitz, van Meter
Phys.Rev.Lett. 96 (2006) 111102

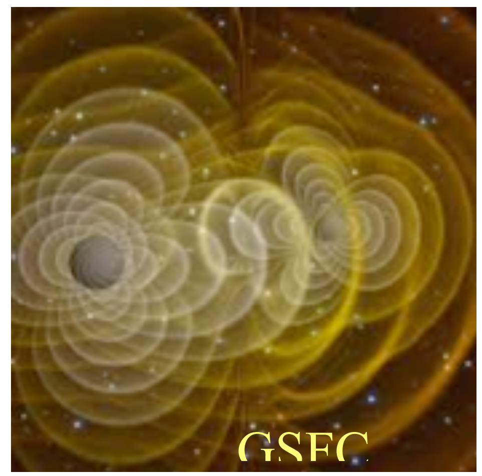
2008 NRDA Begins
Collaborations between NR, AR and GW
Samurai (PRD 2009)
NINJA (CQG 2009a, 2009b, CQG 2013, CQG 2014)
NRAR (CQG 2014)

Gravitational Waves Encode Physics



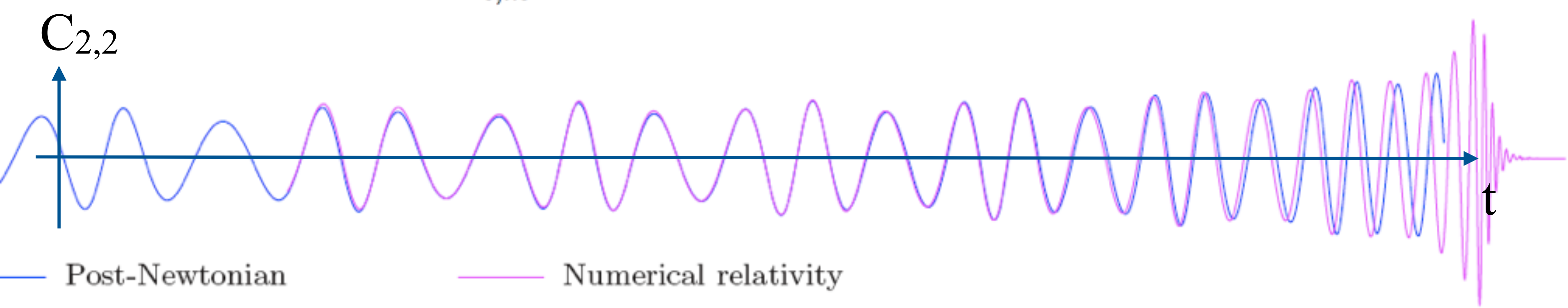
time

total mass, mass ratio, angular momentum, individual spins, eccentricity...



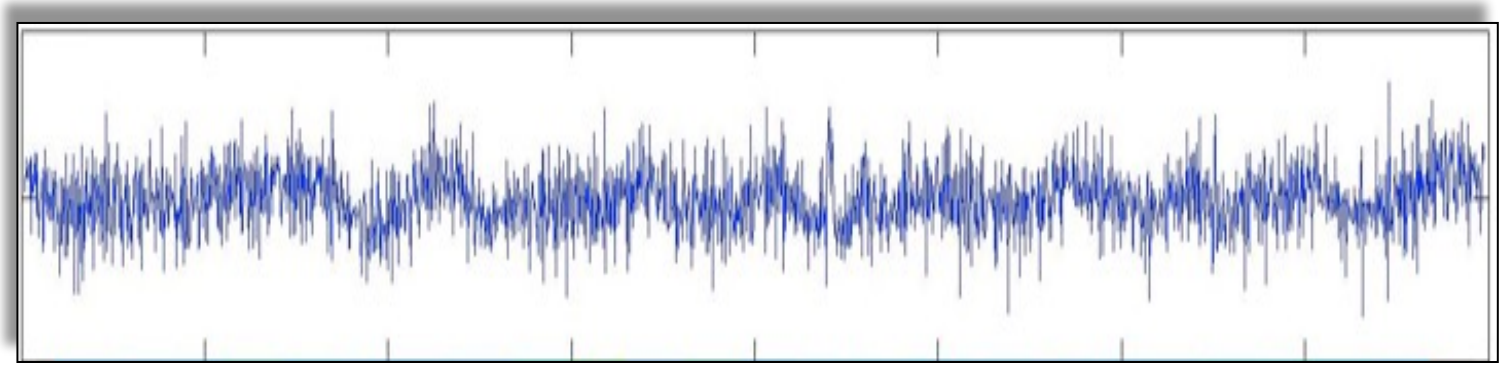
final mass and spin vector

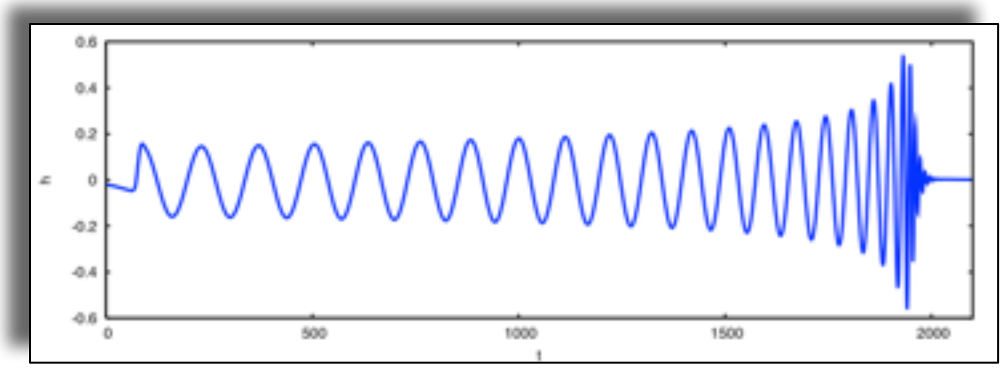
$$rM\Psi_4(\iota,\phi,t) = \sum_{l,m} {}_{-2}Y_{\ell m}(\iota,\phi)C_{\ell m}(t) \qquad \Psi_4 = \ddot{h}$$



We want to solve the complete parameter space, especially crucial as advanced detectors are preparing for science runs

Optimal Matched Filtering



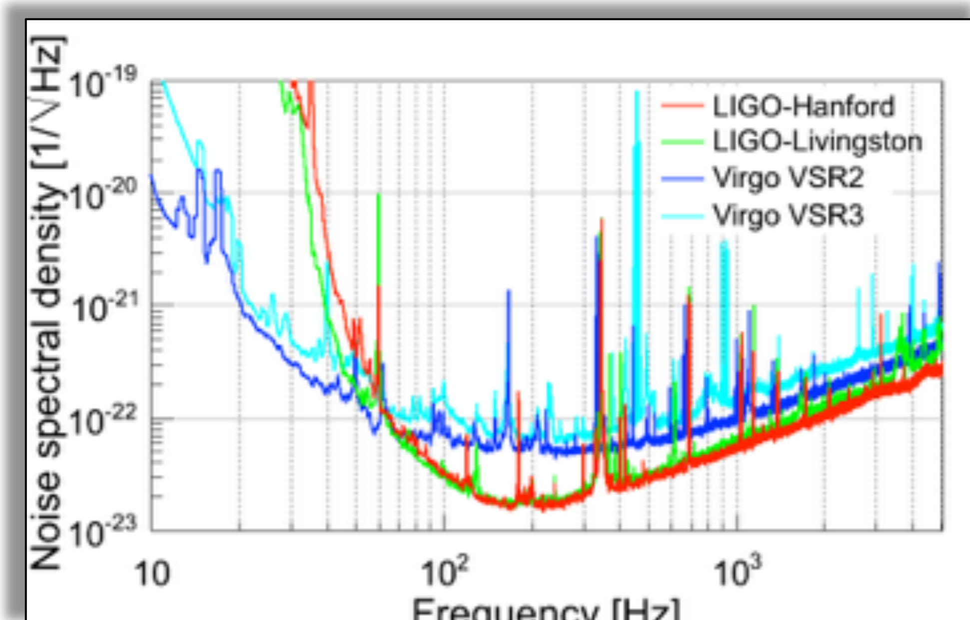


Data

Template

$$< s, h >= 4Re \int_0^\infty \frac{\tilde{s}(f)\tilde{h}^*(f)}{S_n(f)} df$$

Noise Power Spectral Density

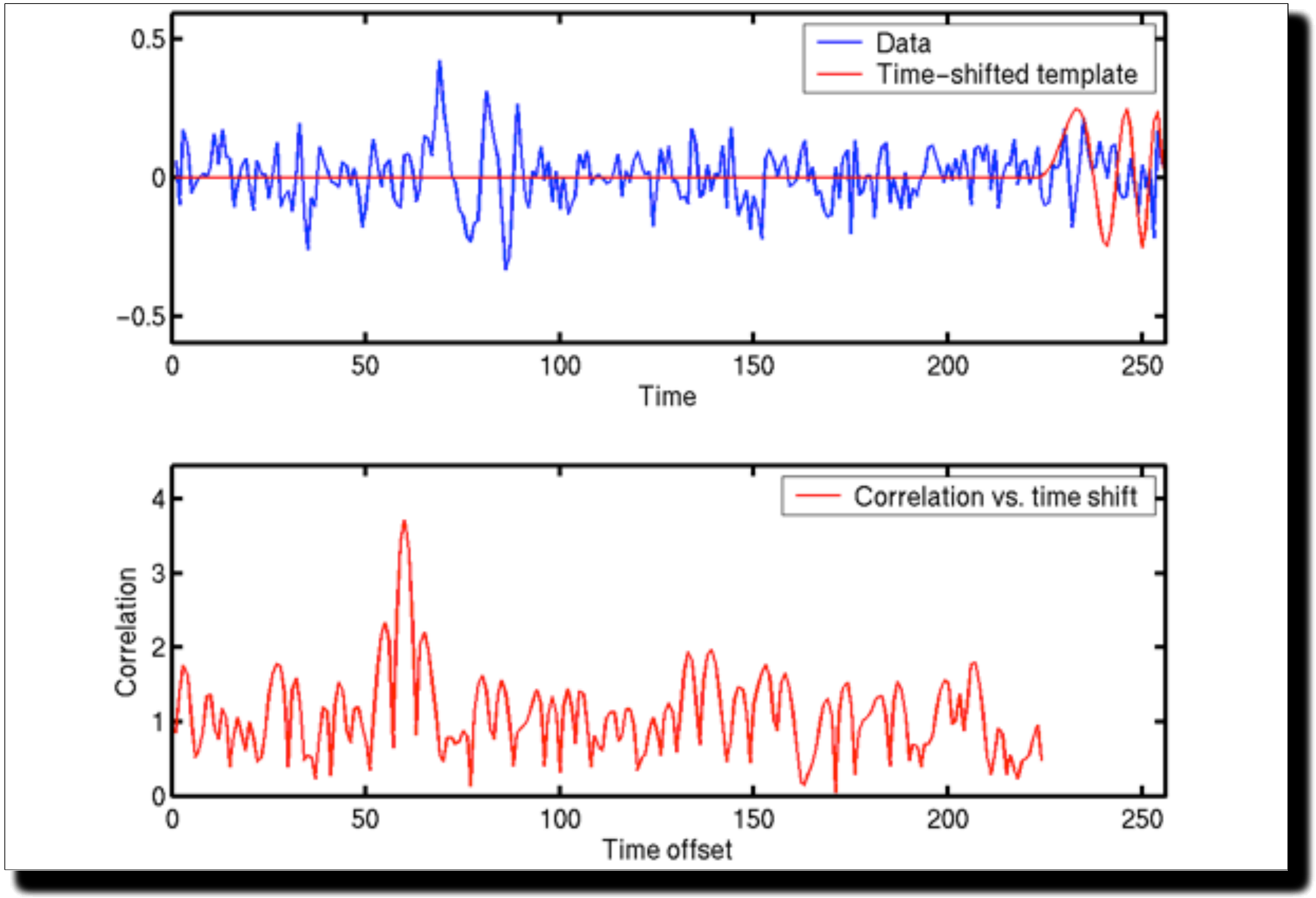


$$\mu(s,h) = \max_\lambda \frac{< s, h >}{\sqrt{< s, s >< h, h >}}$$

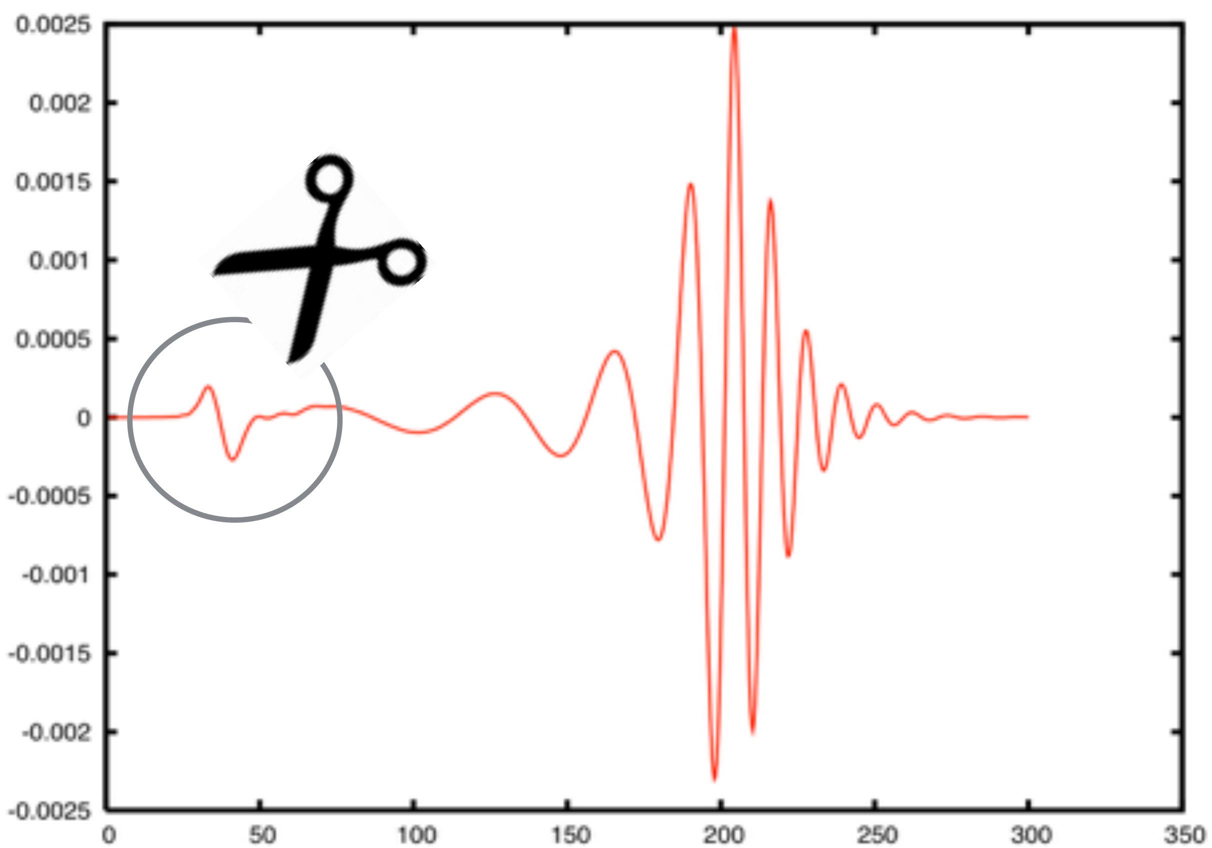
Look for maxima of $\mu(s, h)$ above some threshold

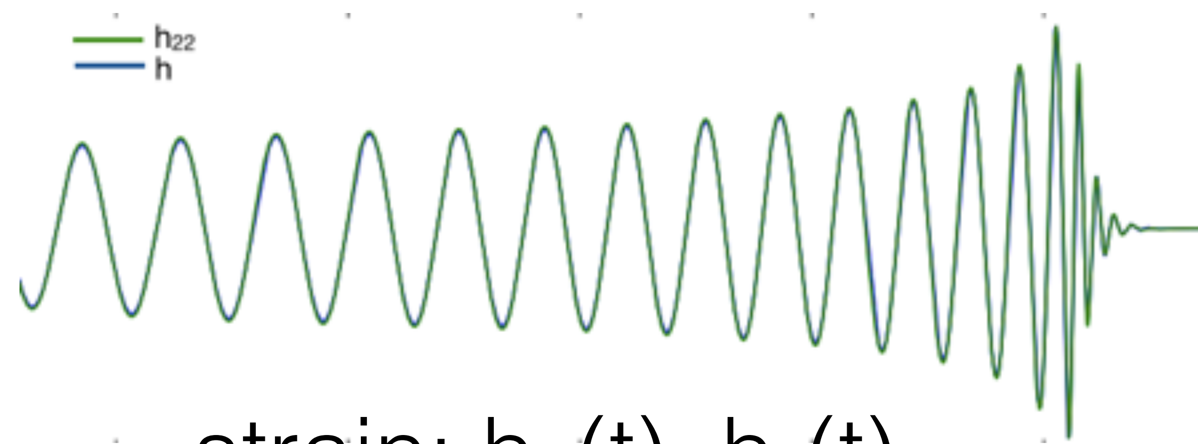
SNR: signal to noise ratio $\rho = \sqrt{\langle h \mid h \rangle}$

Matched Filter



Prepare NR output for DA input





strain: $h_+(t)$, $h_\times(t)$

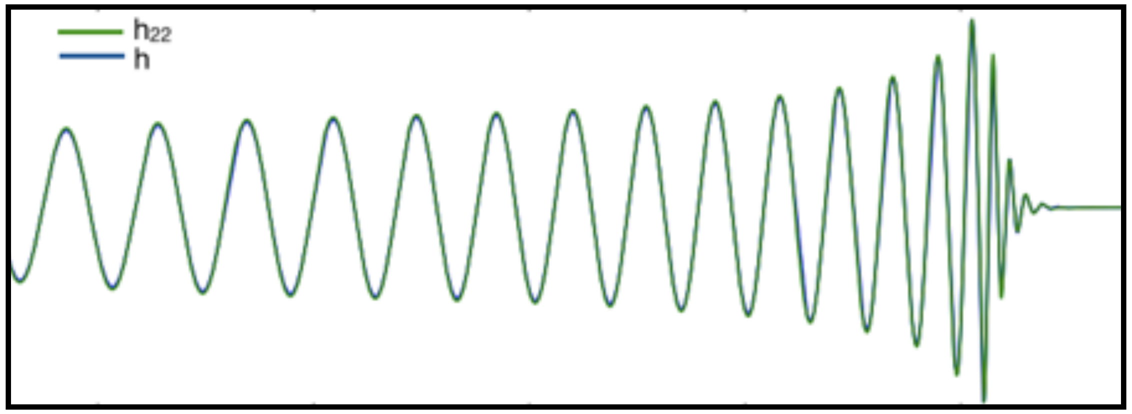
Extracting radiation
Reisswig & Pollney CQG 2011

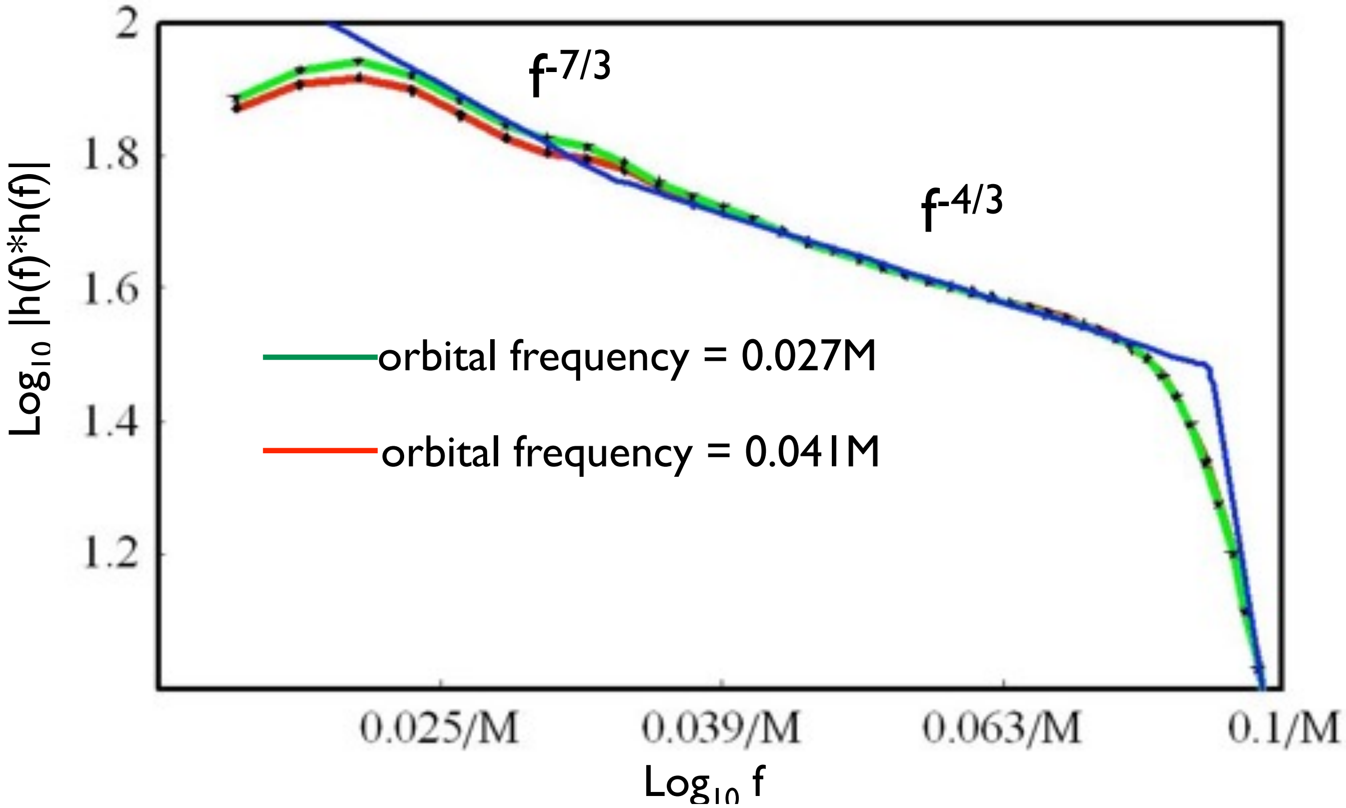
$$\Psi_4 = \ddot{h} \qquad rM\Psi_4(\iota,\phi,t) = \sum_{l,m} {}_{-2}Y_{\ell m}(\iota,\phi)C_{\ell m}(t)$$

NR meets DA

Take the time series, h(t) and take the Fourier transform to get

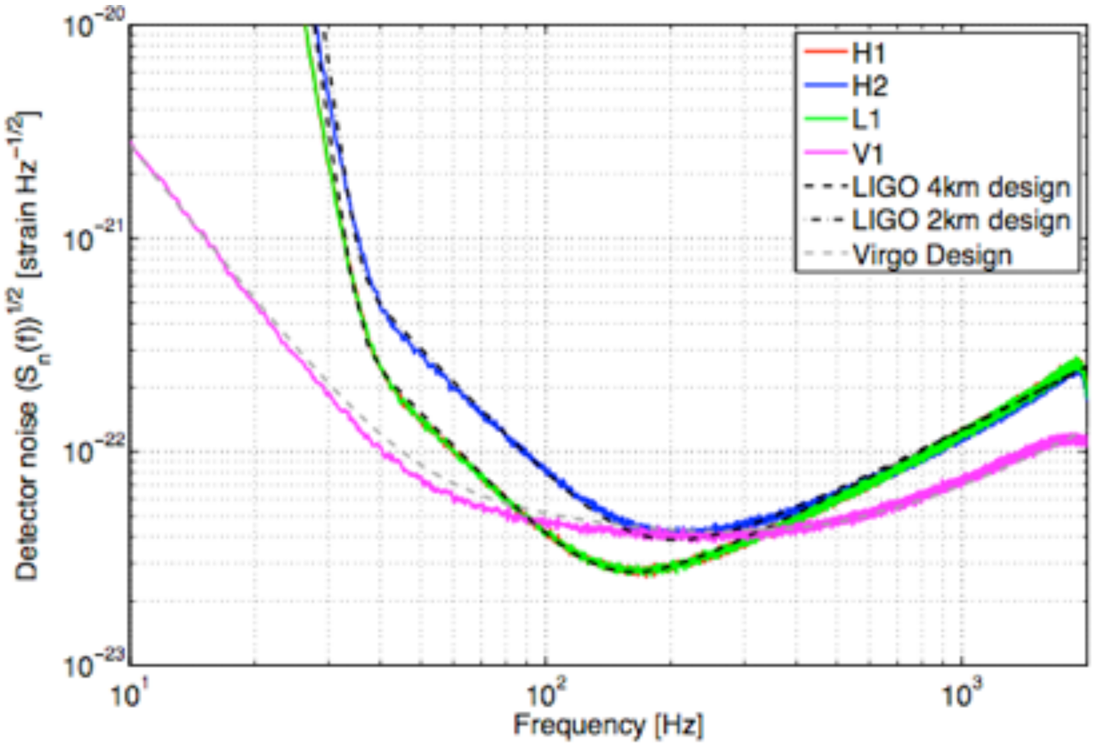
$$\tilde{h}(f) = \int_{-\infty}^{+\infty} e^{2\pi i f t} h(t) dt$$





compute physical units!
introduce a mass scale and distance

Detector spectral noise density is $S_n(f)$.



How are NR waveforms used in DA?

What are the requirements on the numerical waveforms that are needed in the detection of gravitational waves?

- Numerical accuracy (e.g. convergence, truncation errors)
- Astrophysical accuracy (e.g. initial data)

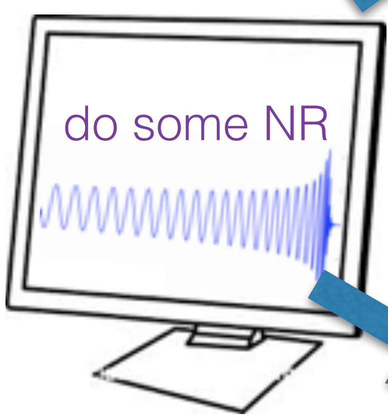
What are the requirements on the numerical waveforms that are needed in the characterization of the sources of gravitational waves?

- Source parameters (e.g. mass, spins, eccentricity, etc)
- Testing theories of gravity

NR waveforms are rarely used directly in searches, rather modeled first and then template banks are built out of the model.

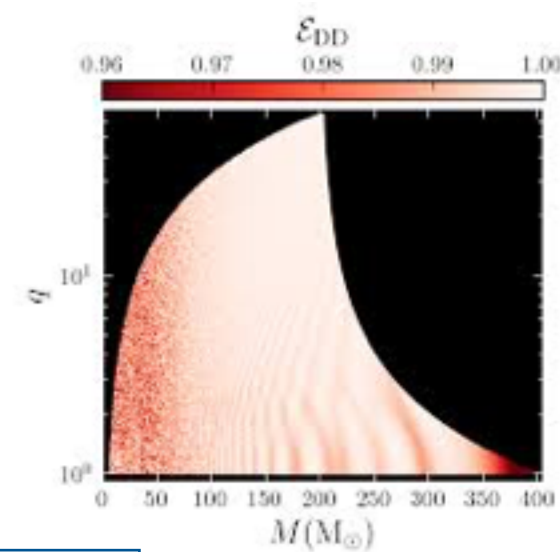
Roadmap

inject into the instrument (LIGO/VIRGO) to test pipelines



build model of IMR

create template banks



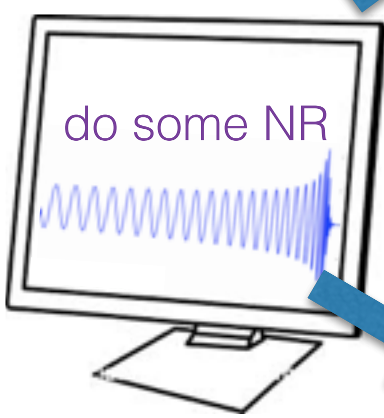
call from search pipeline

weeks for each run

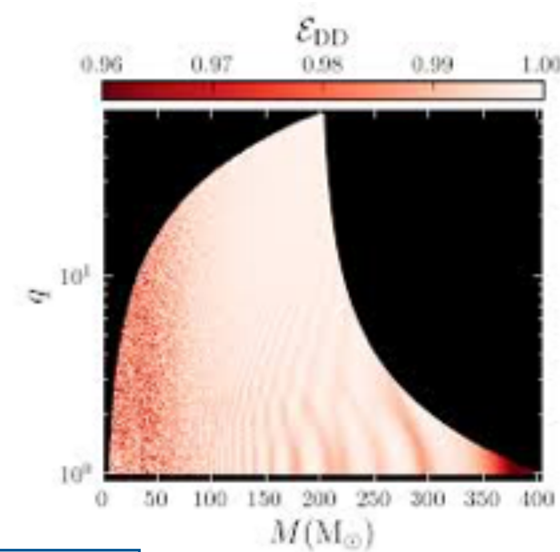
slow!

Roadmap

inject into the instrument (LIGO/ VIRGO) to test pipelines



build model of IMR



create template banks

surrogate models!

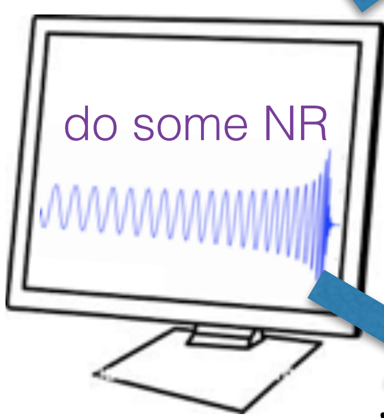
call from search pipeline

NR decisions to build better models

Impact of computational challenge

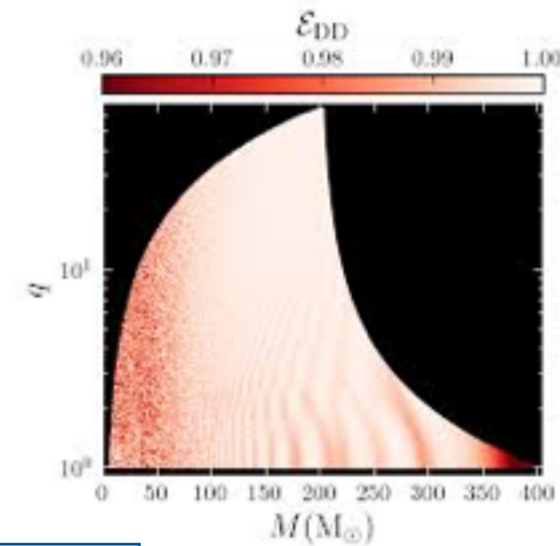
Roadmap

inject into the instrument (LIGO/ VIRGO) to test pipelines



build model of IMR

create template banks



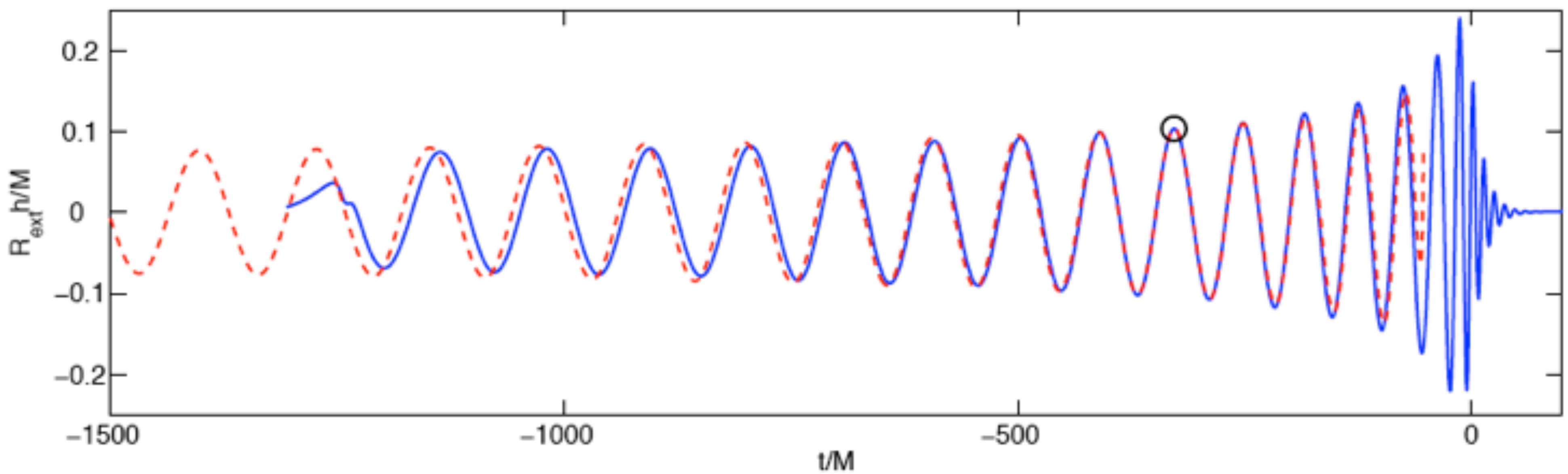
call from search pipeline

influence parameter choice for NR runs:
initial data

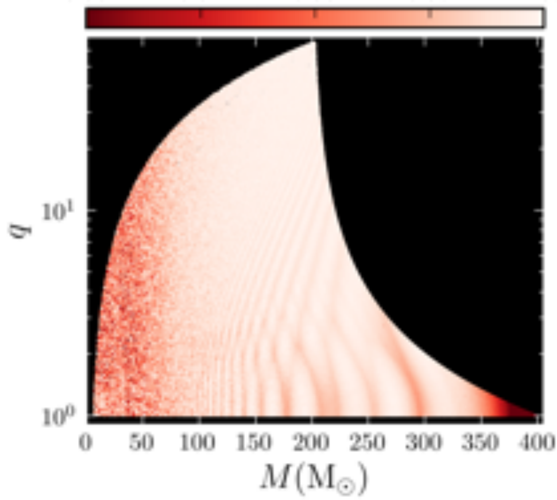
Inspiral-Merger-Ringdown (IMR) Models

1. Phenomenological - Phem Series
   - Ajith et al PRL 2011, Santamaria et al PRD 2010
   - fits to PN–NR hybrid waveforms

2. Effective One Body - EOBNR Series
   - Damour et al PRD 2013, Taracchini et al PRD 2014
   - combines PN expansion, re-summation techniques, and perturbation theory
   - model parameters calibrated against NR waveforms



State of the Art for IMR Models



- Parameter Coverage
  - EOBNR has a precessing (generic) series (Taracchini et al PRD 2014) when black-hole spins are aligned with the orbital angular momentum and calibrated to 2 precessing NR waveforms
  - PhemP Hannam et al PRL 2014 (no NR was used)
- Higher Modes - EOBNR has higher modes (Pan PRD 2010) for non-precessing
- Template banks as a function of mass
  Kumar et a PRD 89 (2014), Privitera et al PRD 89 (2014), Taracchini et al PRD 89 (2014)
- Placement Methods
  - Geometric methods (Brown et al …)
  - Placement methods fast for spinning (nonprecessing waveforms) see Capano talk Monday - Ajith et al PRD 2014
- Surrogate & Reduced Order Modeling (Blackman et al arXiv: 1502.07758, Smith et al PRD 87 2013, Caudill et al CQG 29 2012)

How long do NR waveforms need to be?

How long can we trust PN?

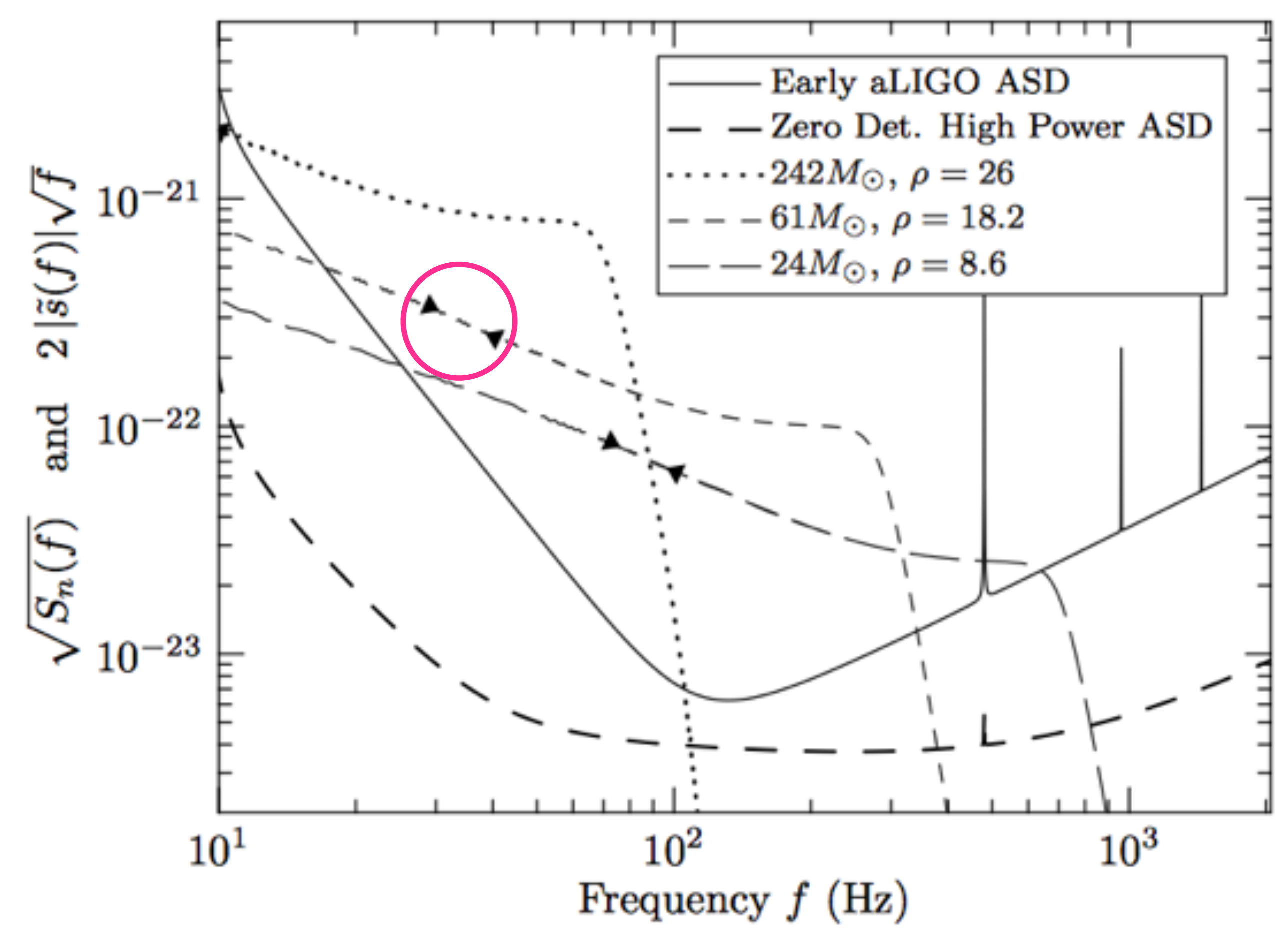
- Unequal mass binaries: current PN - potentially fail hundreds of orbits before merger (Damour et al PRD 2011, Ohme et al PRD 2011, MacDonald et al PRD 2013)
- Spinning: earlier (Nitz et al PRD 2013)
- NR simulations have been able to cover only tens of orbits (Buchman et al PRD 2012, Mroue et al PRL 2013, Hinder and NRAR CQG 2014)
- GAP!

$$f_{\mathrm{GW,\ in}} \sim 13\mathrm{Hz}\, \frac{M\Omega_{\mathrm{in}}}{0.02} \left(\frac{M}{100 M_\odot}\right)^{-1}$$

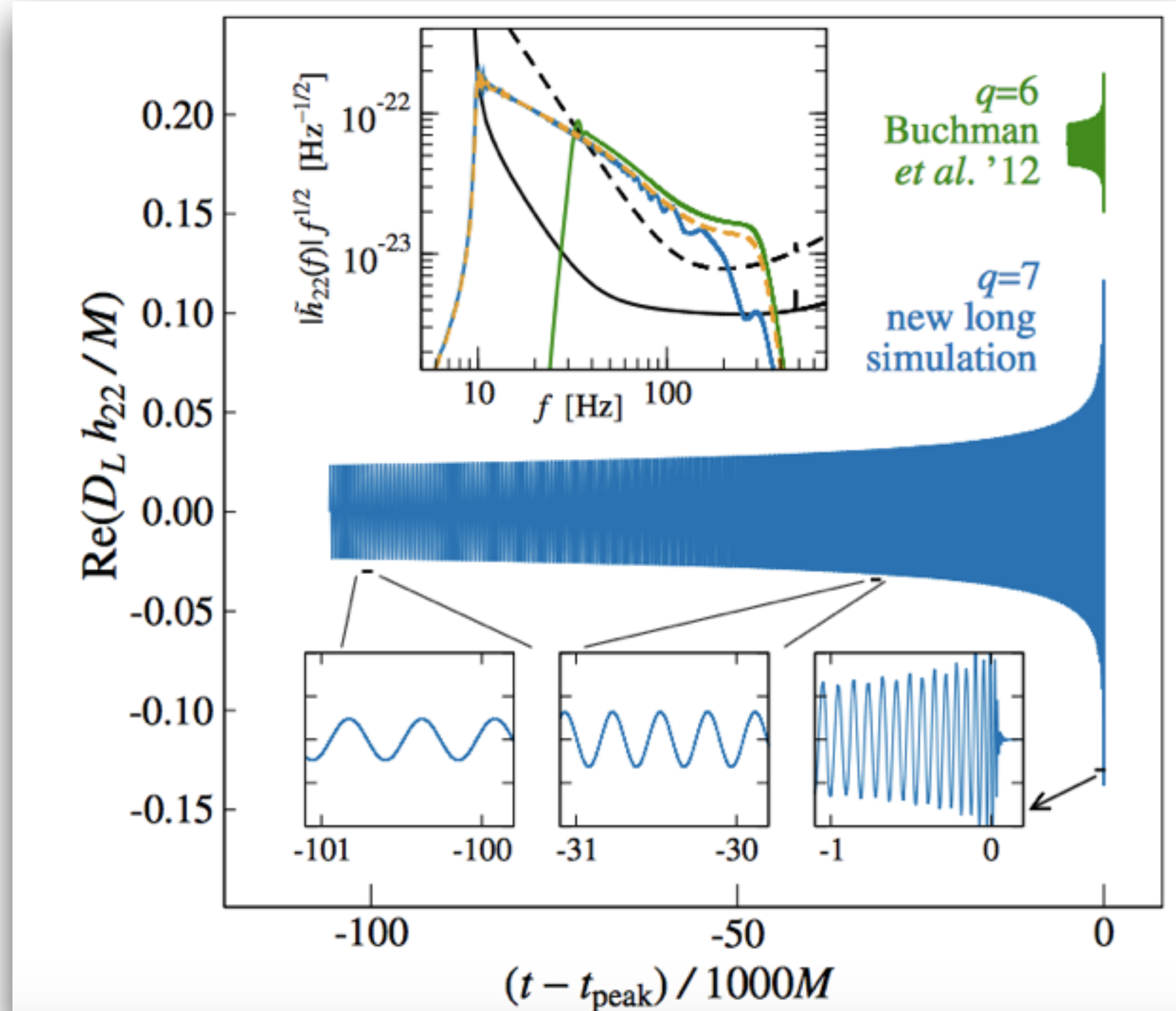
$$M\Omega_{\mathrm{in}} \sim 0.02$$

$$M \gtrsim 100 M_\odot$$

20-30 cycles



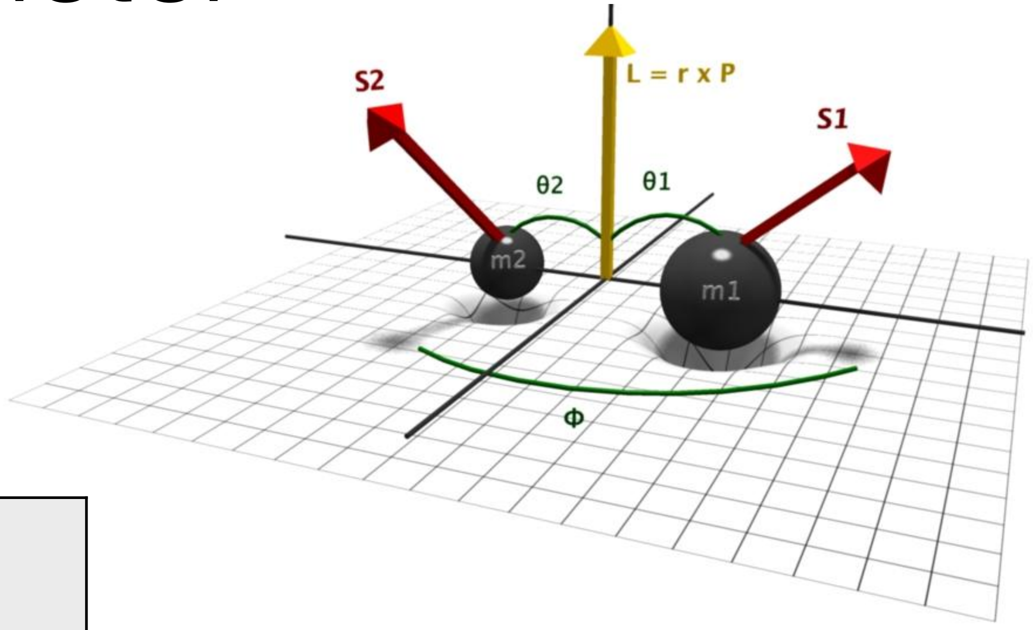
The case for/against Long NR Waveforms



350 NR GW cycles
45.5 M
q=7
arXiv:1502.04953
Szilagyi et al

EOB formalism accurately describes the inspiral dynamics 20 to 176 orbits before merger for this case (some caveats about the merger)

Where do we stand on parameter coverage?



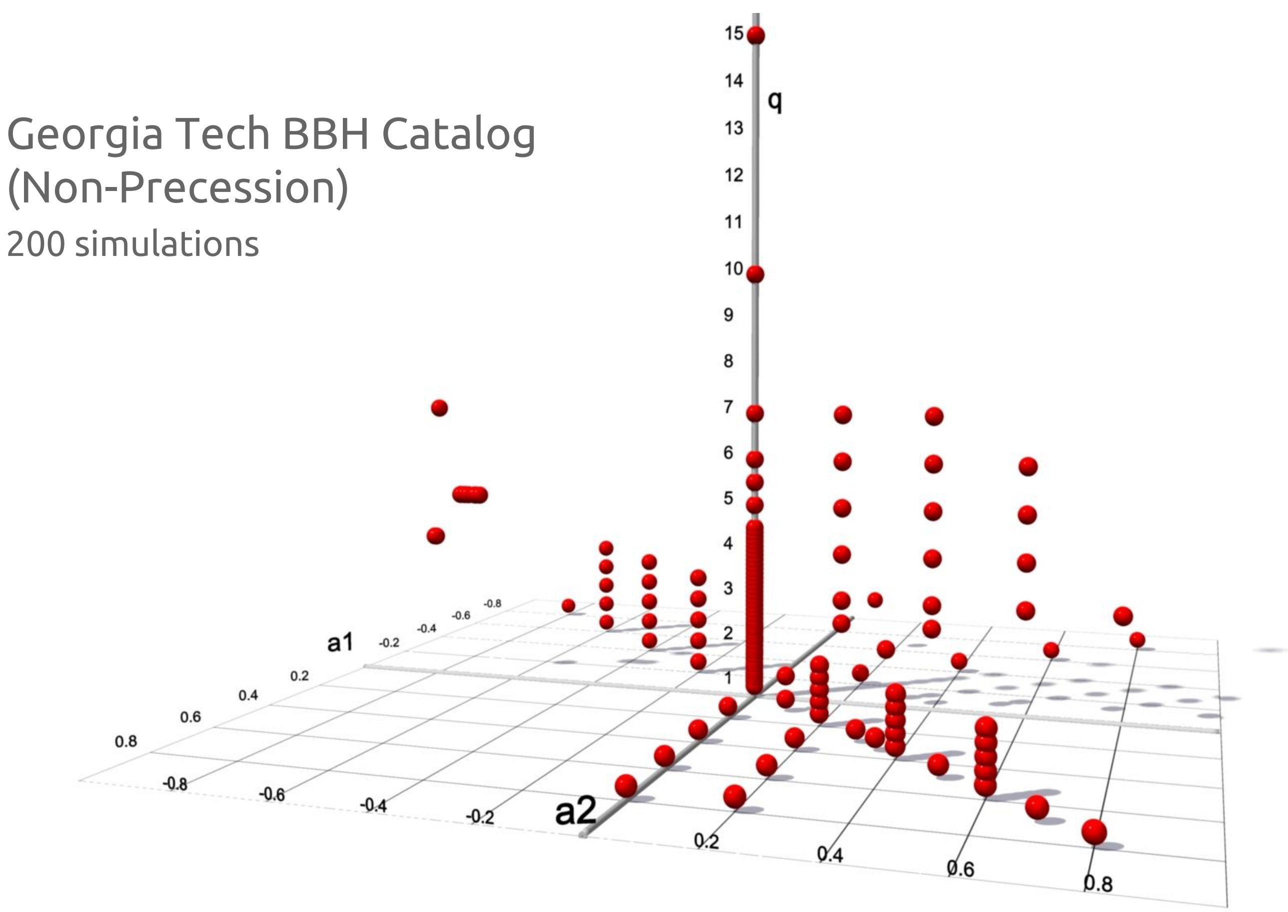
Parameter	Astrophysics	Gravitational Wave Detector	Numerical Relativity
total system mass in solar	1.5-40 40-100s?	noise/sensitivity sets a mass scale	BH mass scale invariant
BH spin magnitude	no strong constraints	sensitive to all spin magnitudes	struggling with close-to-maximal BH spin
BH spin direction	no strong constraints at birth*	preferential to aligned	good at any spin direction
mass ratio	“expect q of a few”	SNR decreases with decreasing mass-ratio	struggling with mass-ratios beyond 1:20
eccentricity	e>0? possible	sensitive	good at any eccentricity

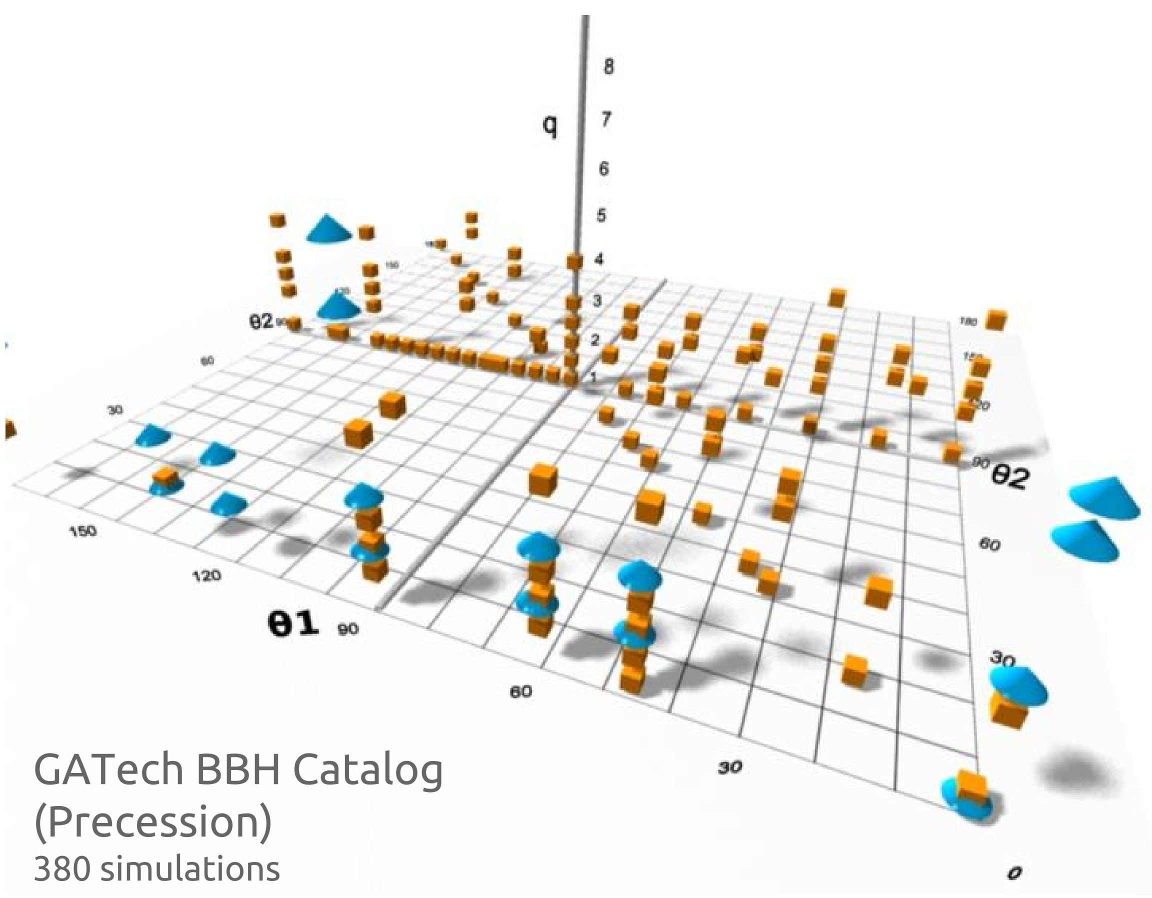
*see Gerosa et al PRD 2013; Schnittman PRD 2004

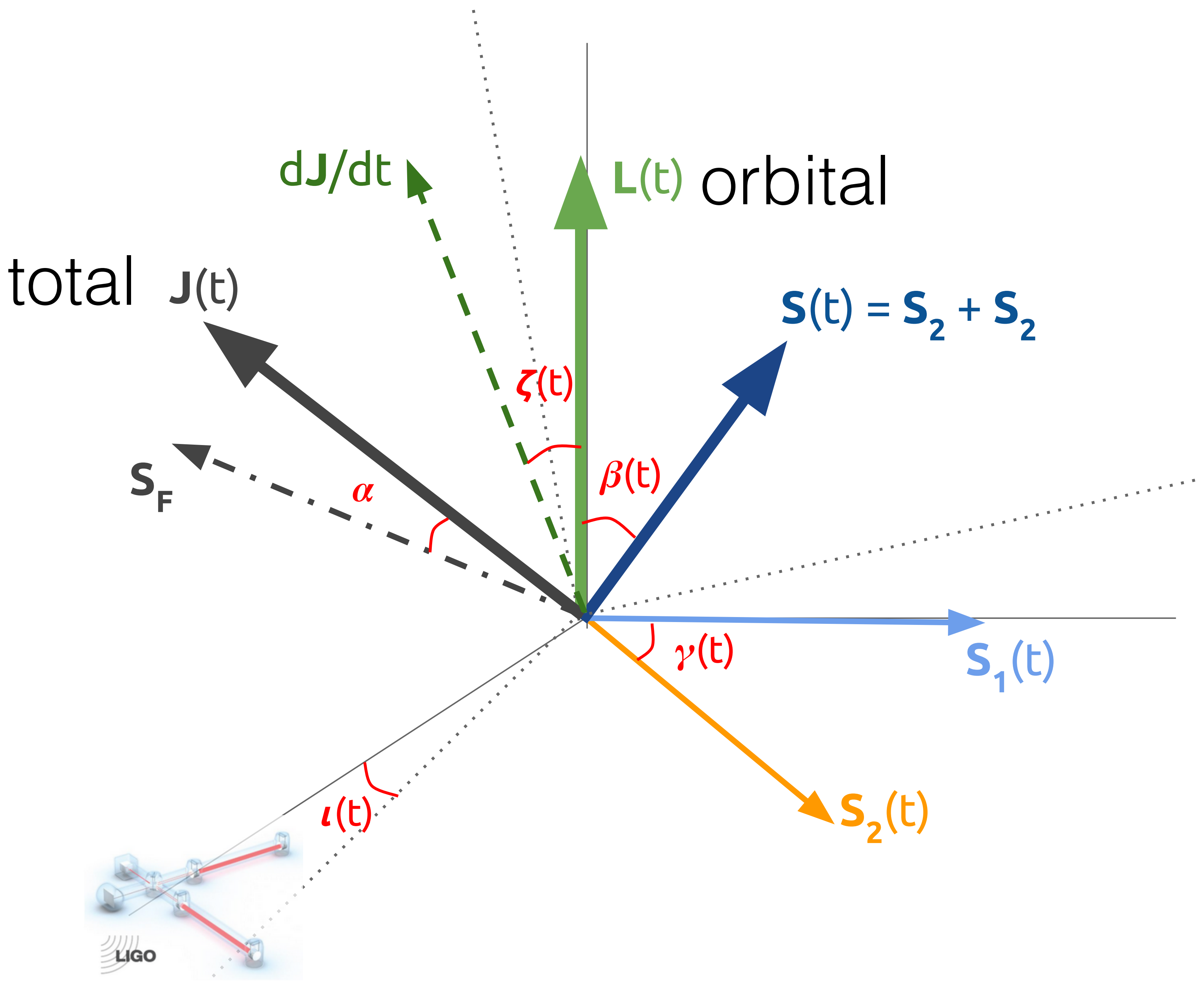
come up with parameters

Parameter Coverage in NR

- 171 generic runs Mroue et al PRL 2013 & More coming
- 600 generic runs GT catalog paper K. Jani et al in prep
- decent coverage of aligned spins, unequal masses q<15
- we have generic, precessing systems, but arbitrarily sampled

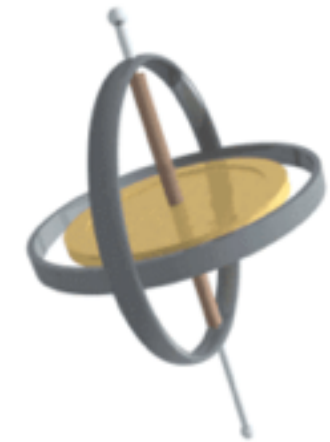


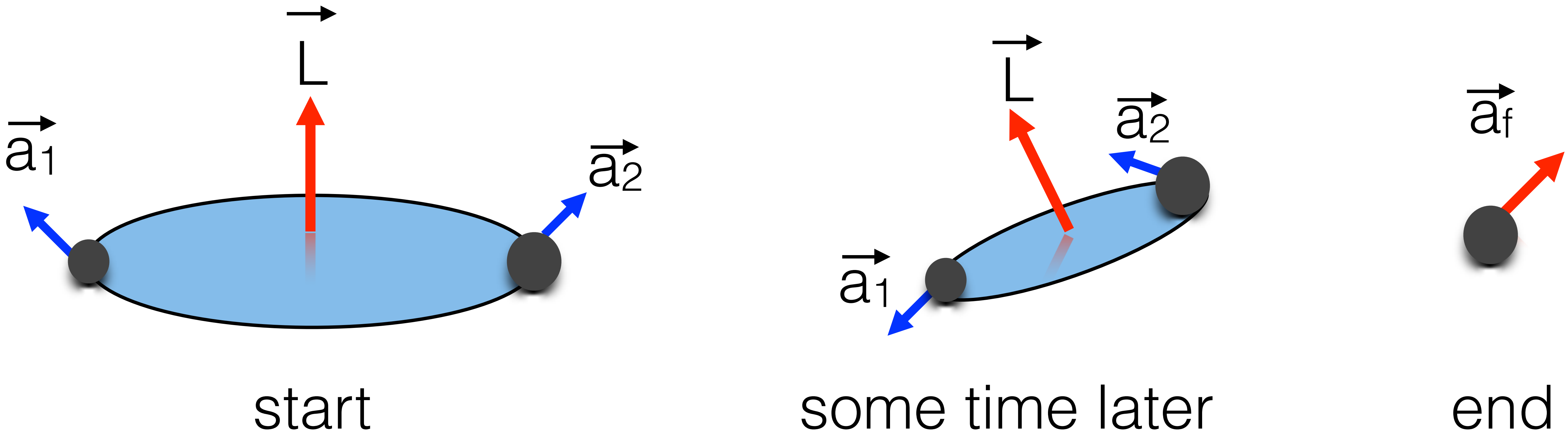




dJ/dt
L(t) orbital
total J(t)
S(t) = S2 + S2
ζ(t)
β(t)
S_F
α
γ(t)
S1(t)
S2(t)
ι(t)
LIGO

Cartoon of precession



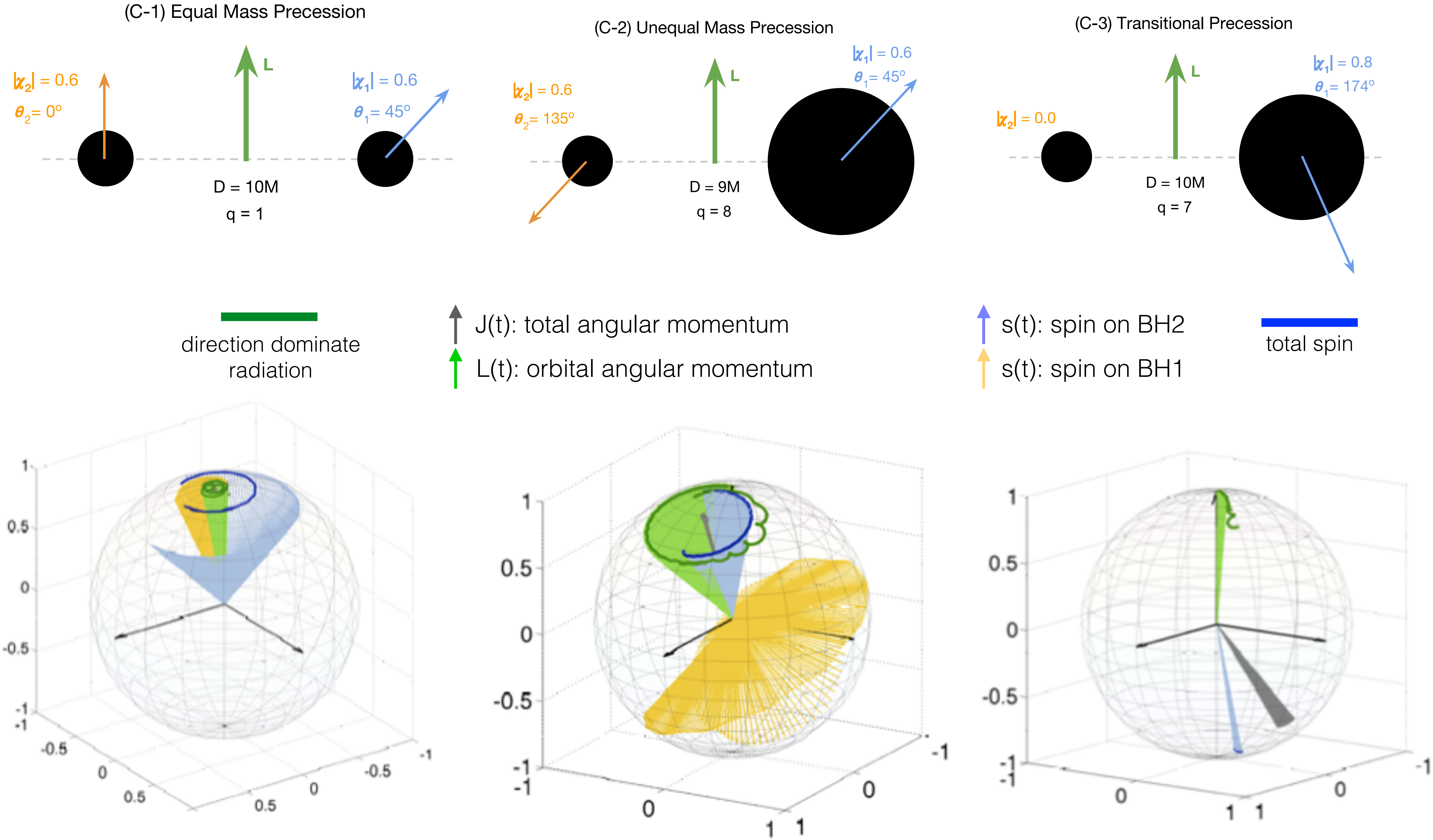


Precession adds a time dependence to an already large parameter space.

Examples of Precession

Jani in prep

related work O'Shaugnessy et al PRD 2012



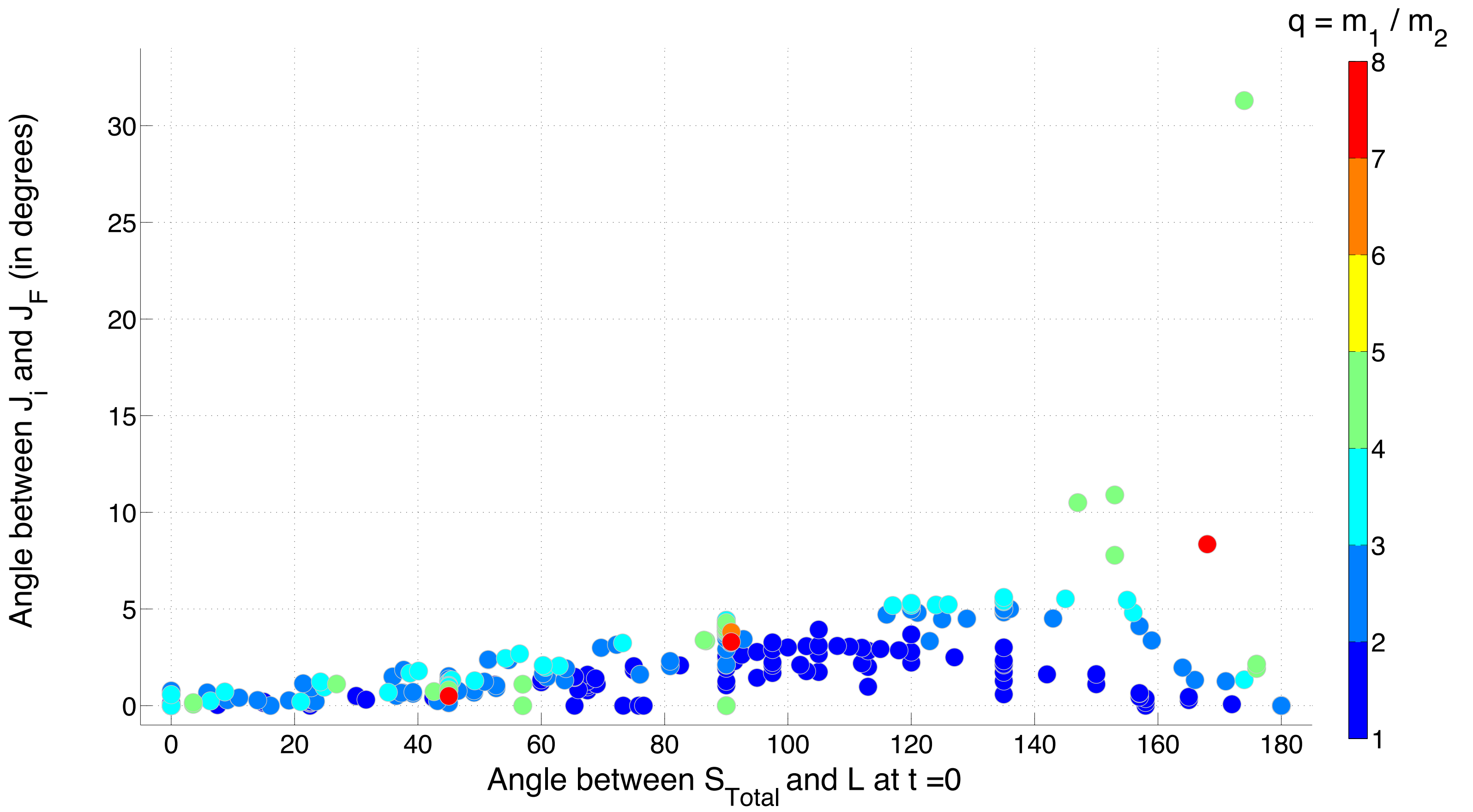
typically, dominate radiation follows, J (Apostolatos 1994) - there are exceptions - it does better around L (O'Shaughnessy et al PRD 2013)

Here be dragons

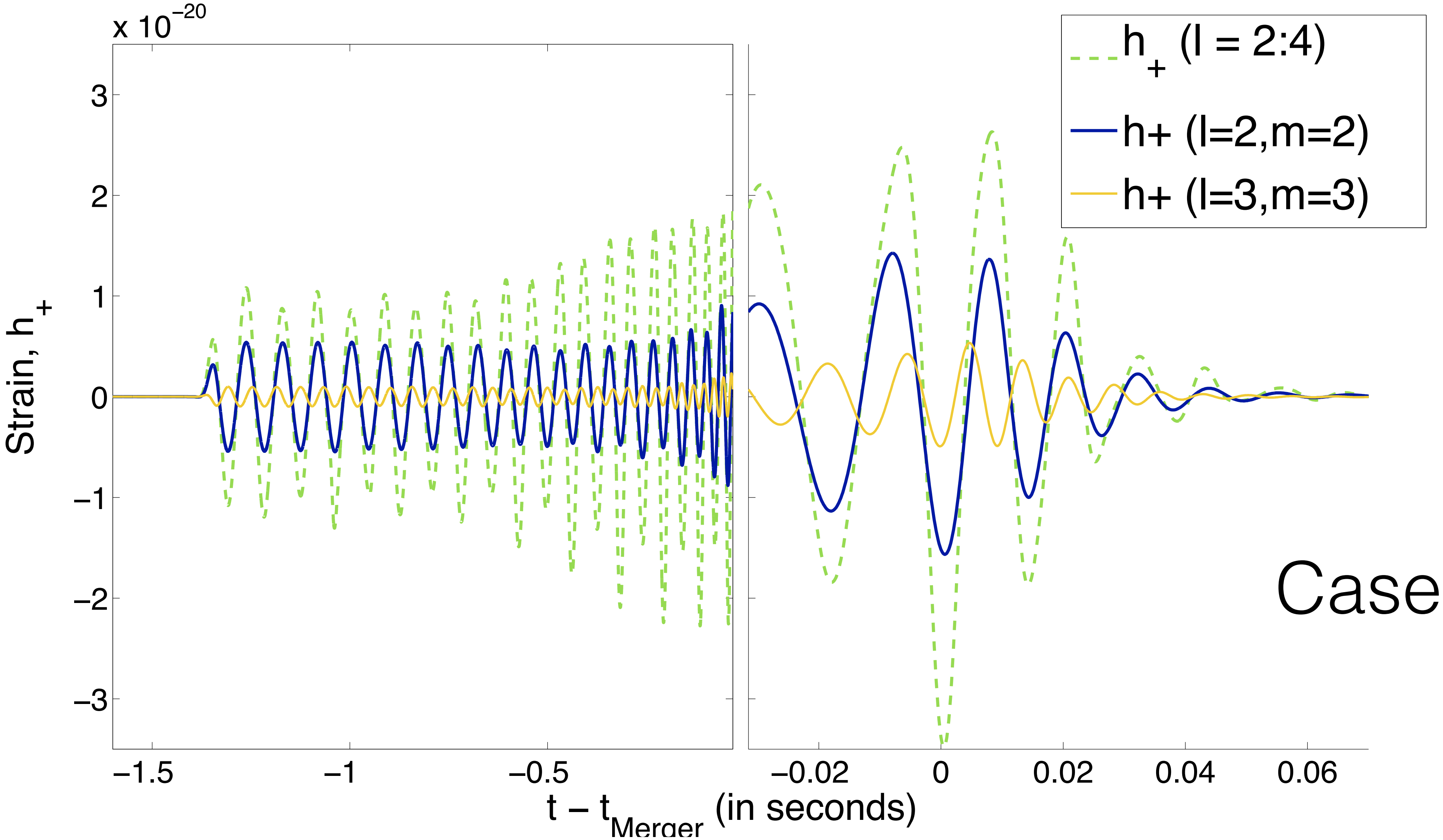
Case	C-1	C-2	C-3
energy radiated	7%	8%	1%
final spin magnitude	0.84	0.69	0.24
angle between initial and final total angular momentum*	0.4°	0.5°	9°

* maximum is 30°

- Different physics - Polarization and-preferential beaming of E and L (O'Shaughnessy et al PRD 2013, Boyle et al arXiv 1409.4431)
- But, can we model these signals as non-precessing? (Pekowsky et al PRD 2013, Schmidt et al PRD 2012 & Hannam PRL 2014)



Higher Modes



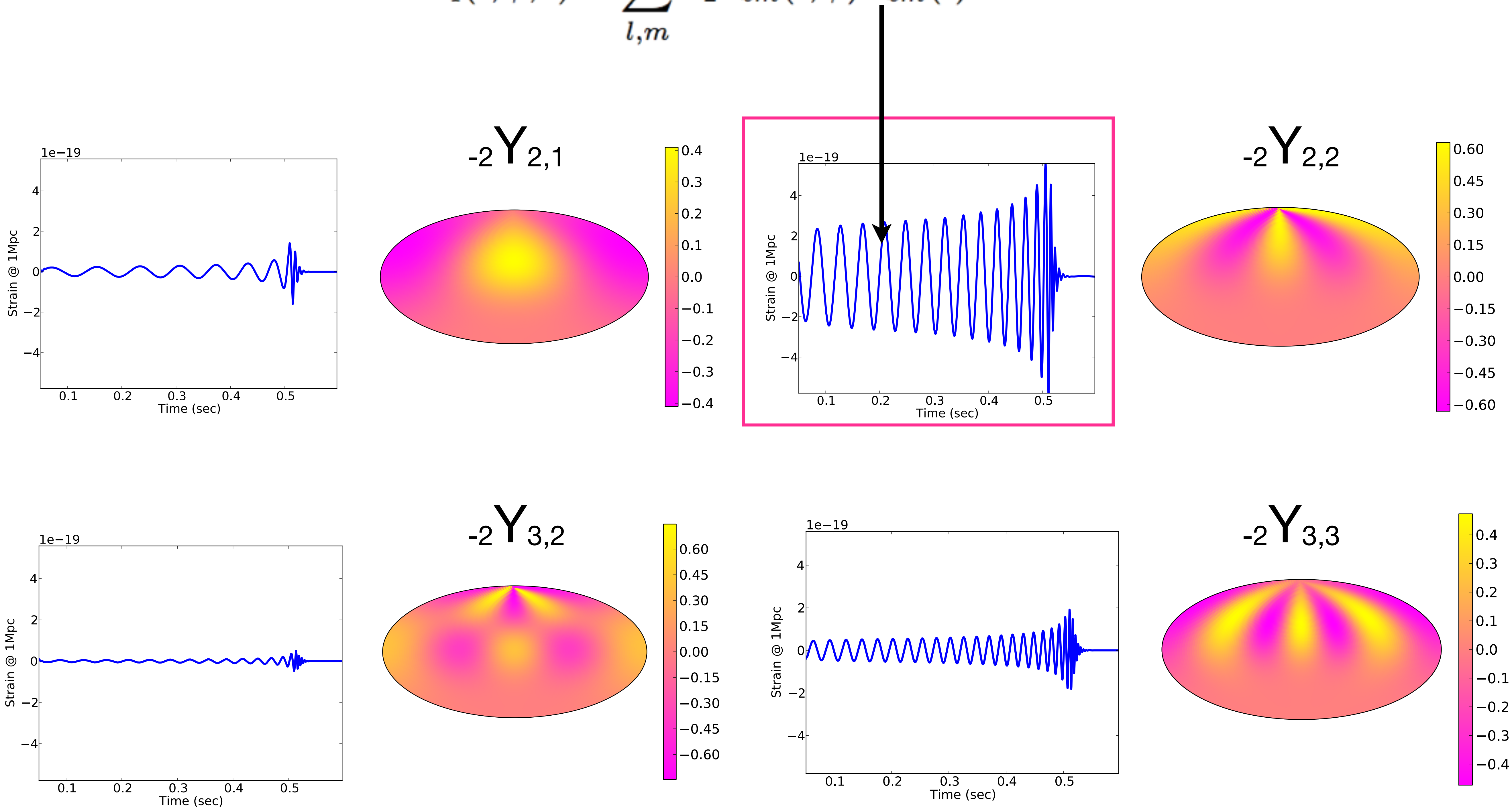
Case 2

$$rM\Psi_4(\iota,\phi,t) = \sum_{l,m} {}_{-2}Y_{\ell m}(\iota,\phi)C_{\ell m}(t)$$

Why not worry about this before? equal-mass, non-spinning or aligned spins radiate in 2,2 almost exclusively

Gravitational Radiation decomposed into spherical harmonics

$$rM\Psi_4(\iota, \phi, t) = \sum_{l,m} {}_{-2}Y_{\ell m}(\iota, \phi) C_{\ell m}(t)$$



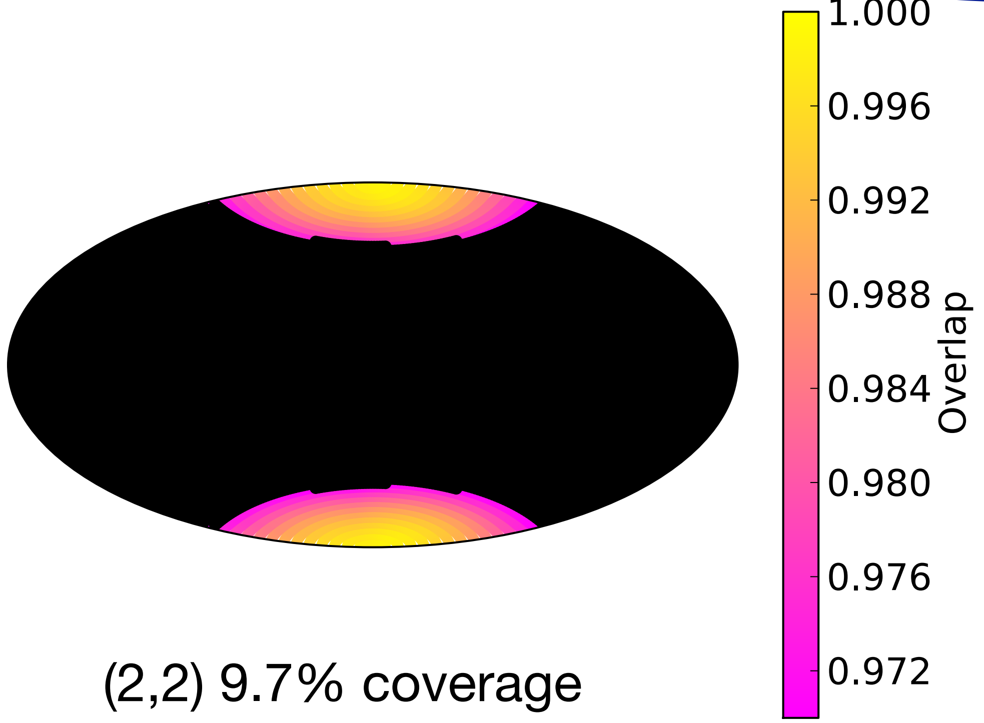
q=m_1/m_2=10, nonspinning

Painting the sky in radiation

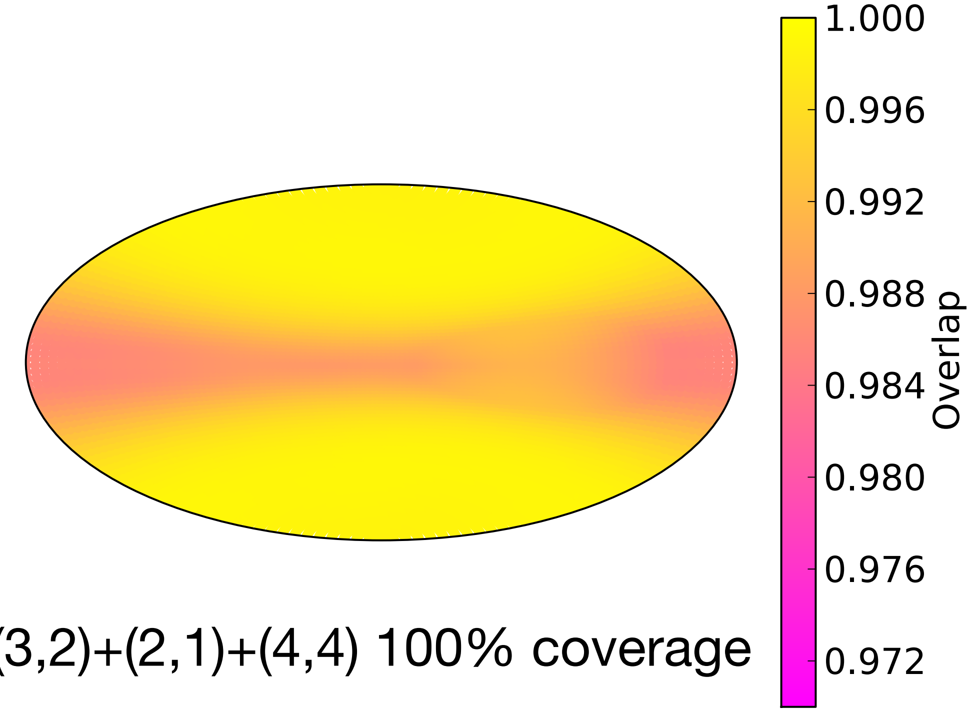
Match the (2,2) mode against a full mode signal as a function of orientation, requiring the match to exceed 0.97 (Healy et al PRD 2013 & Pekowsky et al PRD 2013)

q=10, nonspinning

detector is optimally oriented ... studying line of sight effects

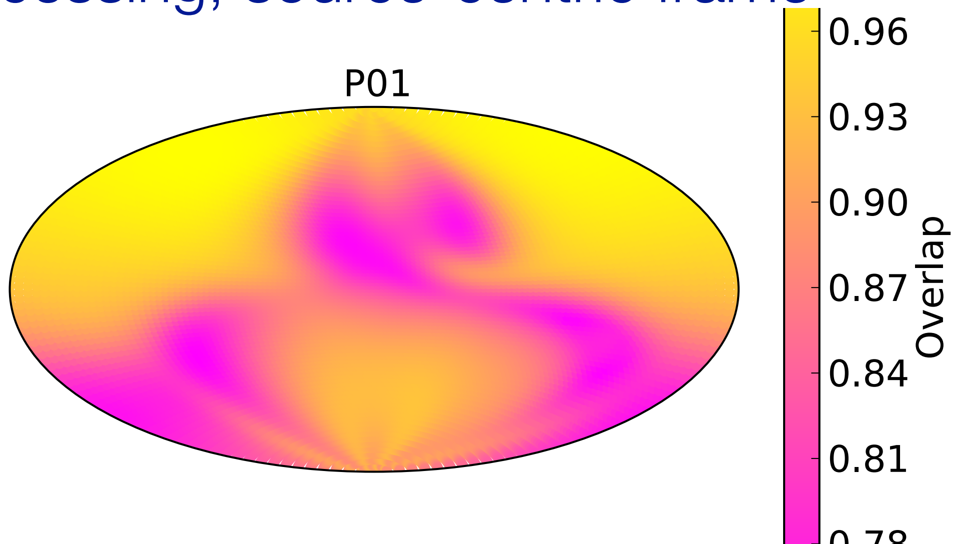


(2,2) 9.7% coverage



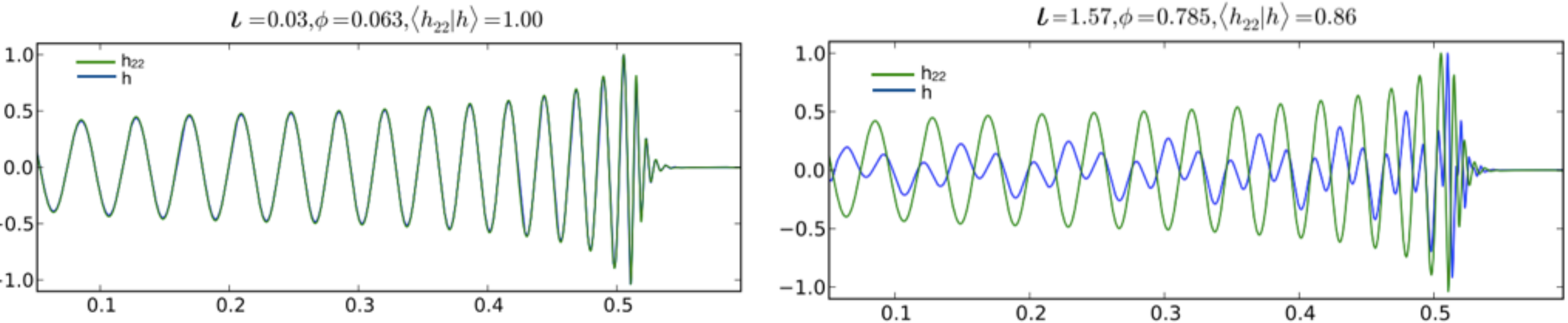
(2,2)+(3,2)+(2,1)+(4,4) 100% coverage

precessing, source-centric frame



(2,2) with full waveform

Higher Modes: To Be or Not to Be?



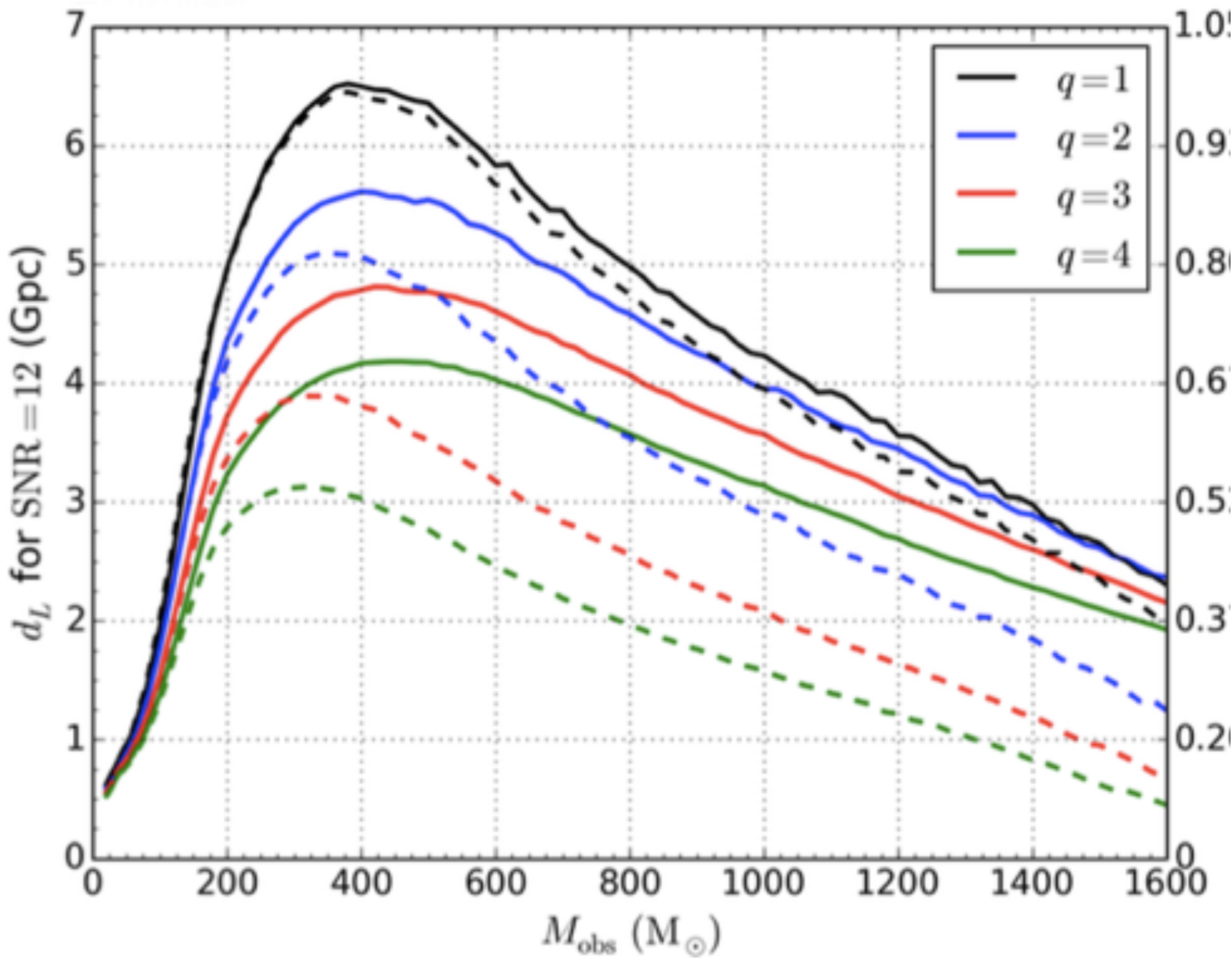
q=10, nonspinning

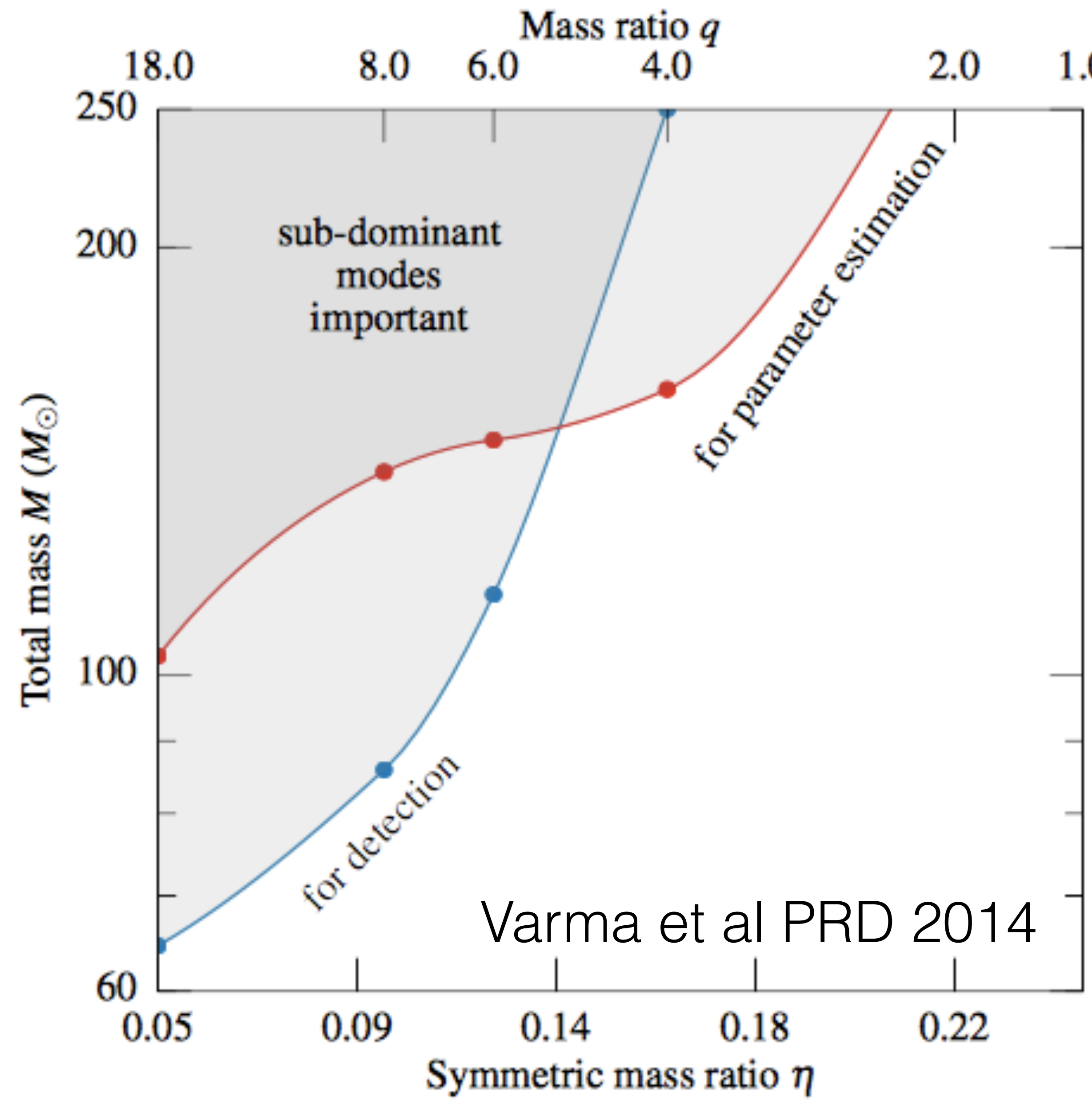
Healy et al PRD 2013

- modes contain angular dependence on the inclination, the orientation of the orbit in the plane of the sky (polarization), and the orbital phase of the binary
- present for (2, 2) mode
- but additional modes breaks degeneracies in the observed waveform as these angles vary

Intermediate, Unequal Mass

Graff et al arXiv:1504.04766



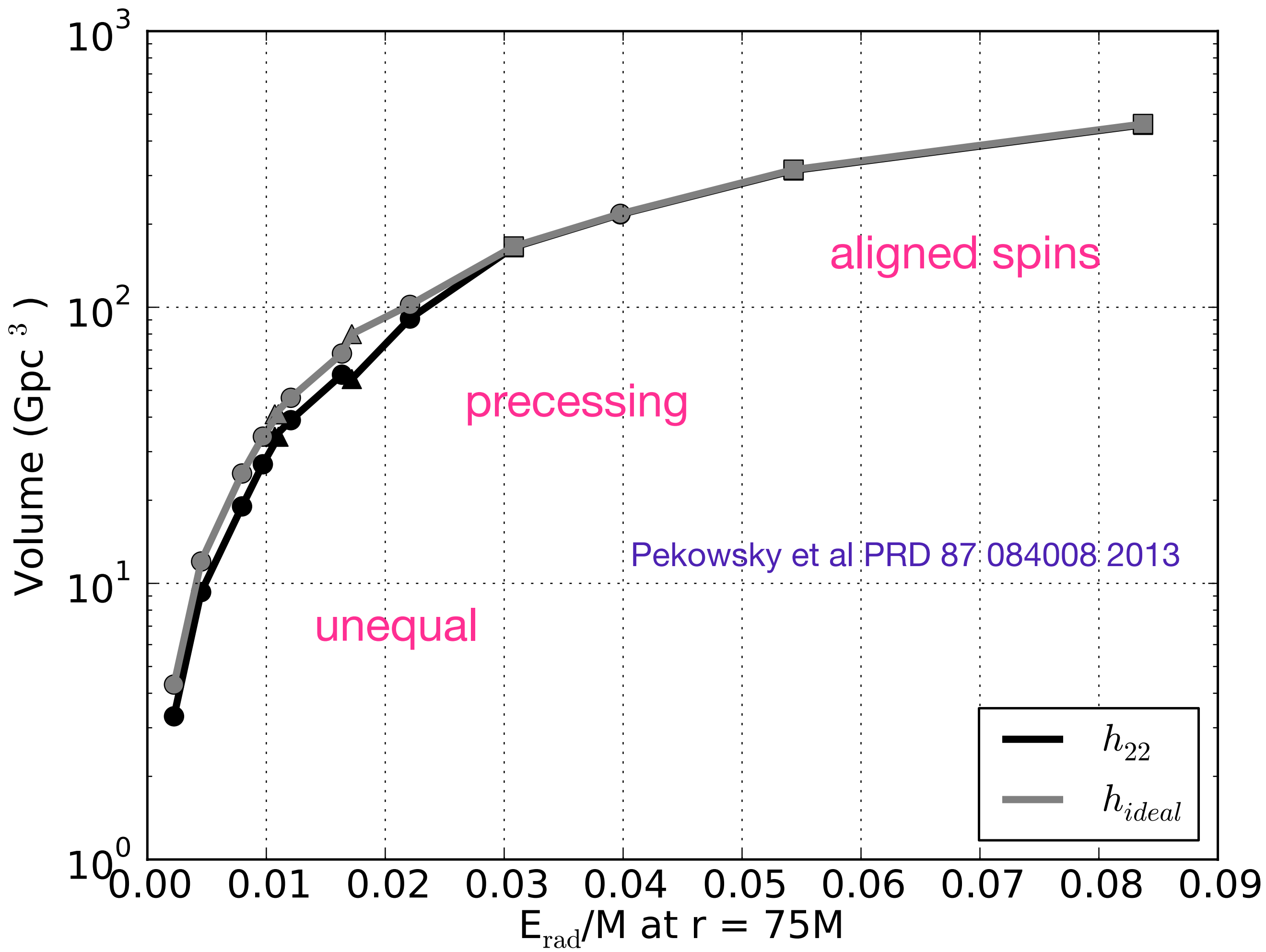


- inclusion of modes improves parameter estimation of the source mass, distance and orientation angles

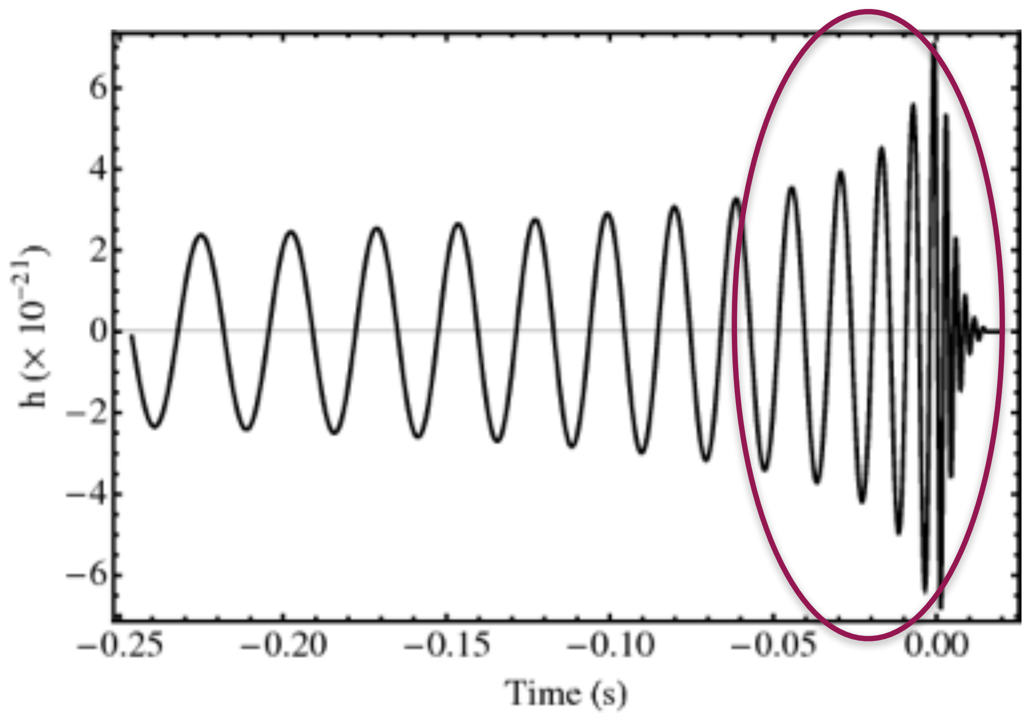
- region where contributions from modes important for detection and parameter estimation
- loss of detection rate due to neglecting modes > 10%
- and/or the systematic bias in the estimated parameters

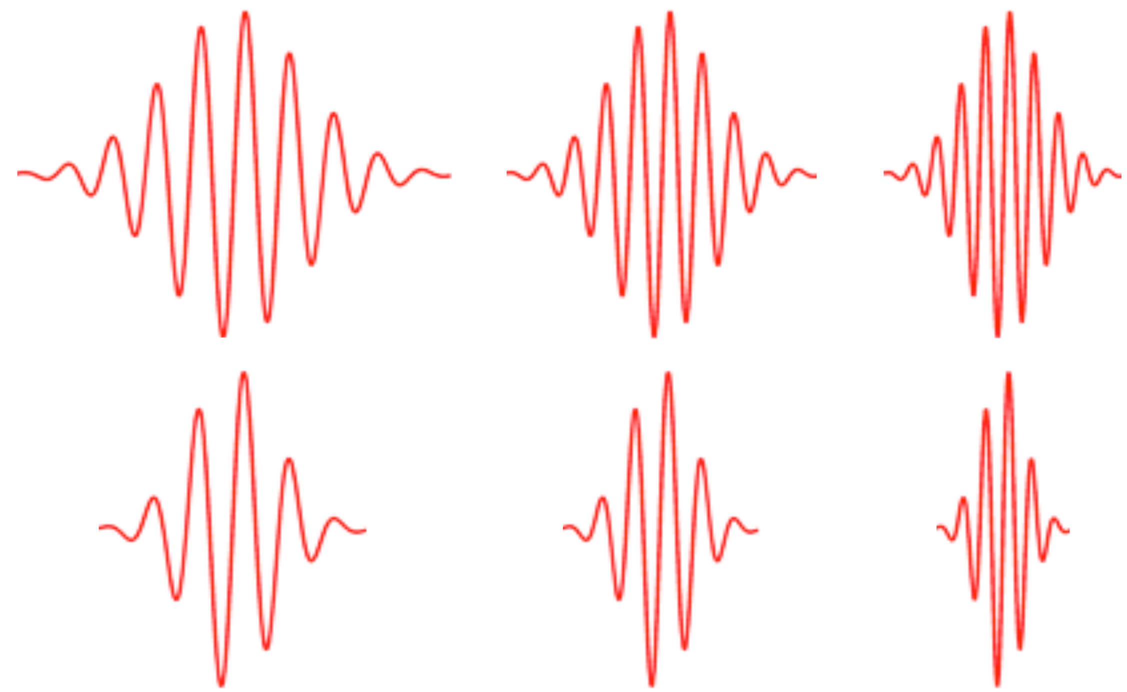
Status on Higher Modes

- More important for IMBH
- More important as q increases - but volume decreases
- Hybrids (Calderon et al arXiv 1501.00918) and EOBNR have included modes for non-precessing cases
- We saw importance for precessing cases - this will have to be thread through the models, template banks … to get to searches



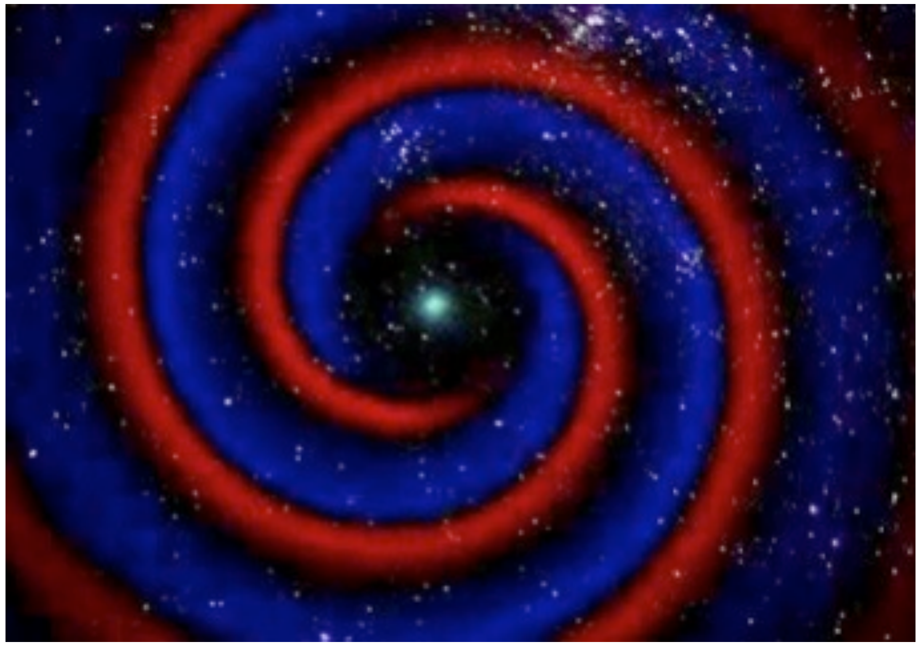
IMBBH Sources for both Bursts and CBC





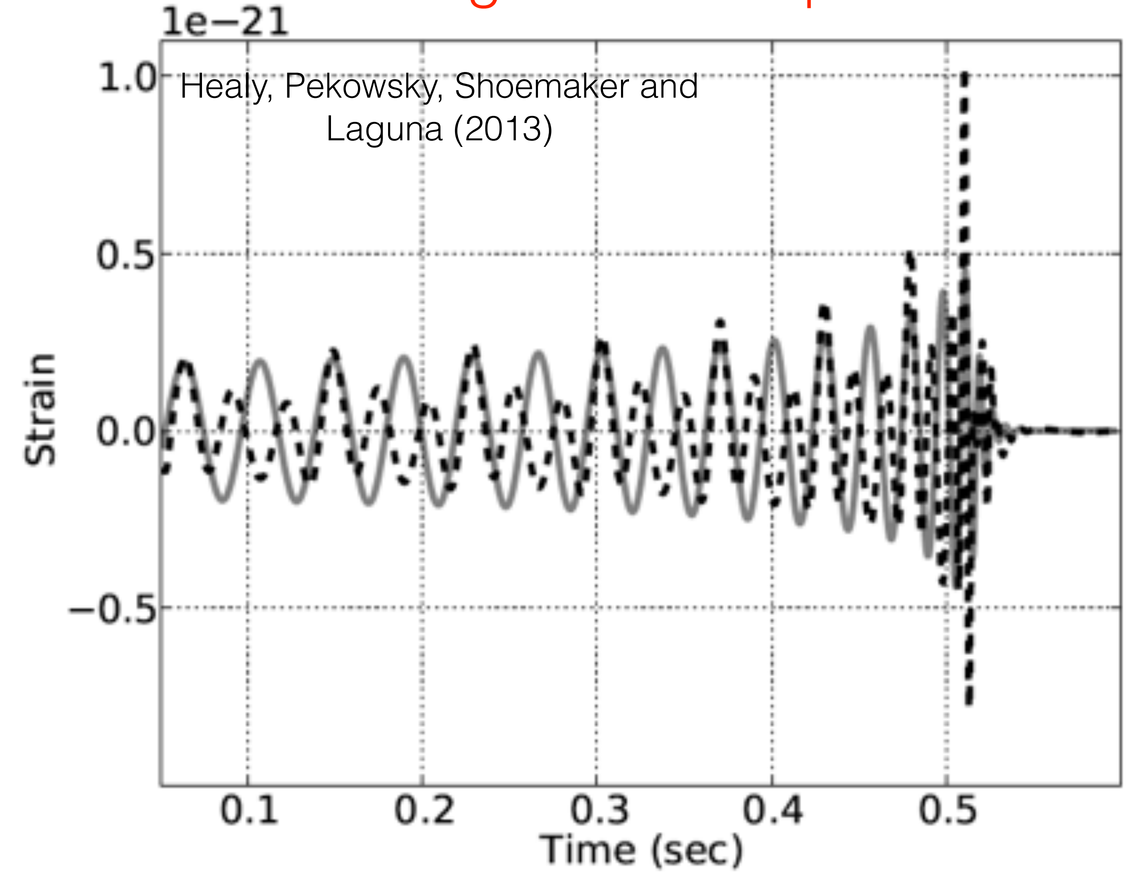
- The "best" method to detect BBHs uses exquisite details of BBH models
- Hard work, slow to get from NR to GW search (*but CRUCIAL)
- Is there any alternative?   IMBBH (100's of M) signals have few cycles in band, higher modes are more impactful and could be precessing
- Can we do coarse parameter estimation from a burst (unmodeled) search?

Sources of Gravitational Waves

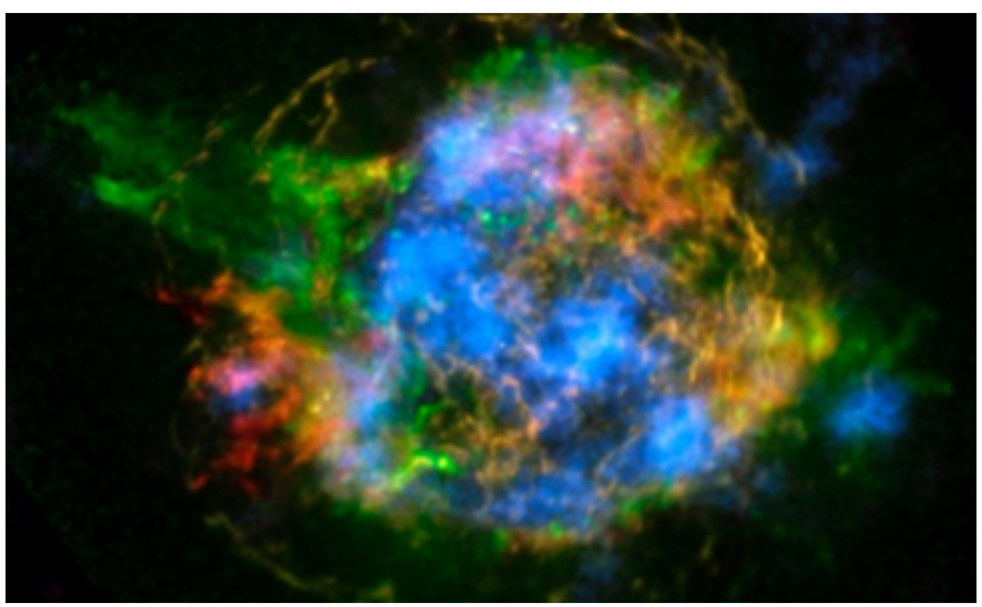


Gravitational Waves from Collision of 2 Black Holes: GT Simulation (Shoemaker, Laguna)

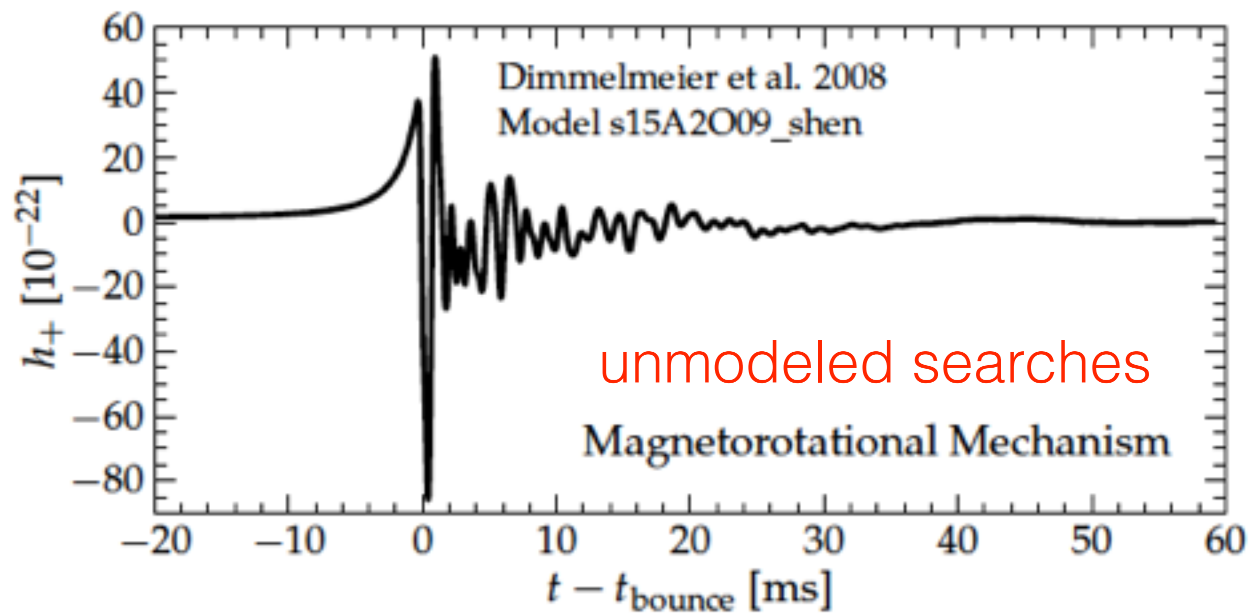
match to signal with exquisite detail



Prediction of Gravitational Waves



Electromagnetic Waves from Supernova: Observations

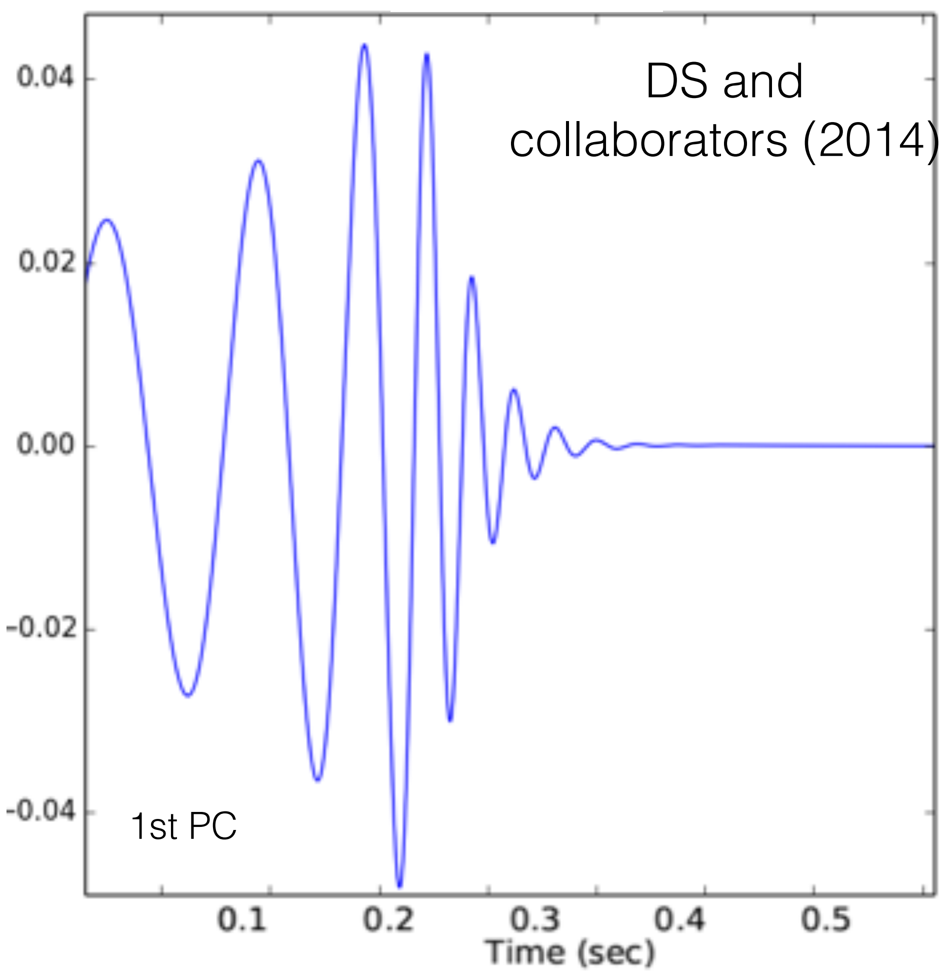


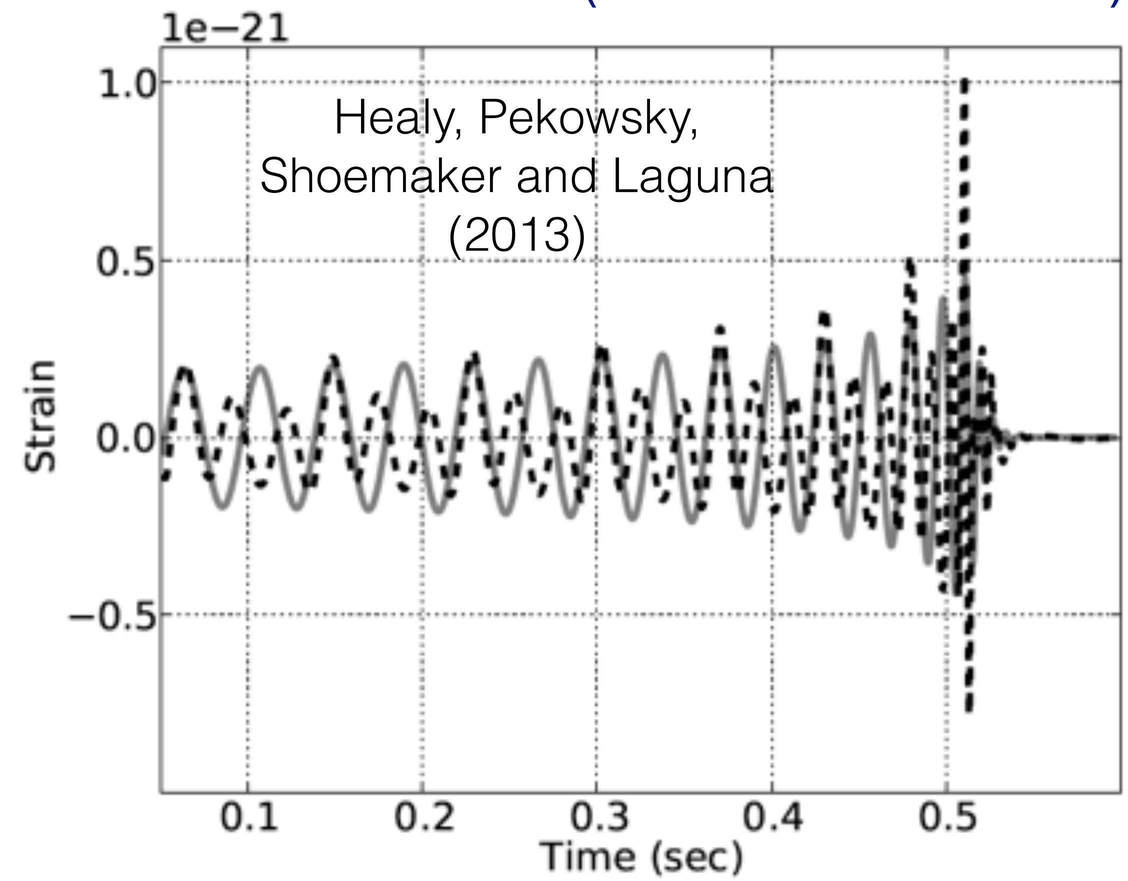
Prediction of Gravitational Waves

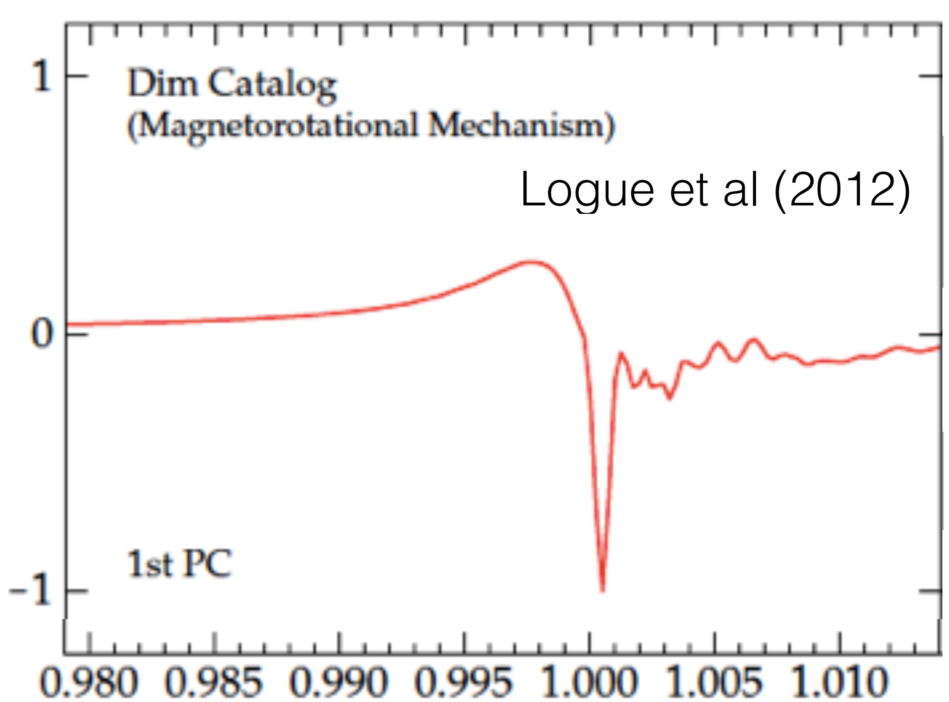
Can we identify bulk features?

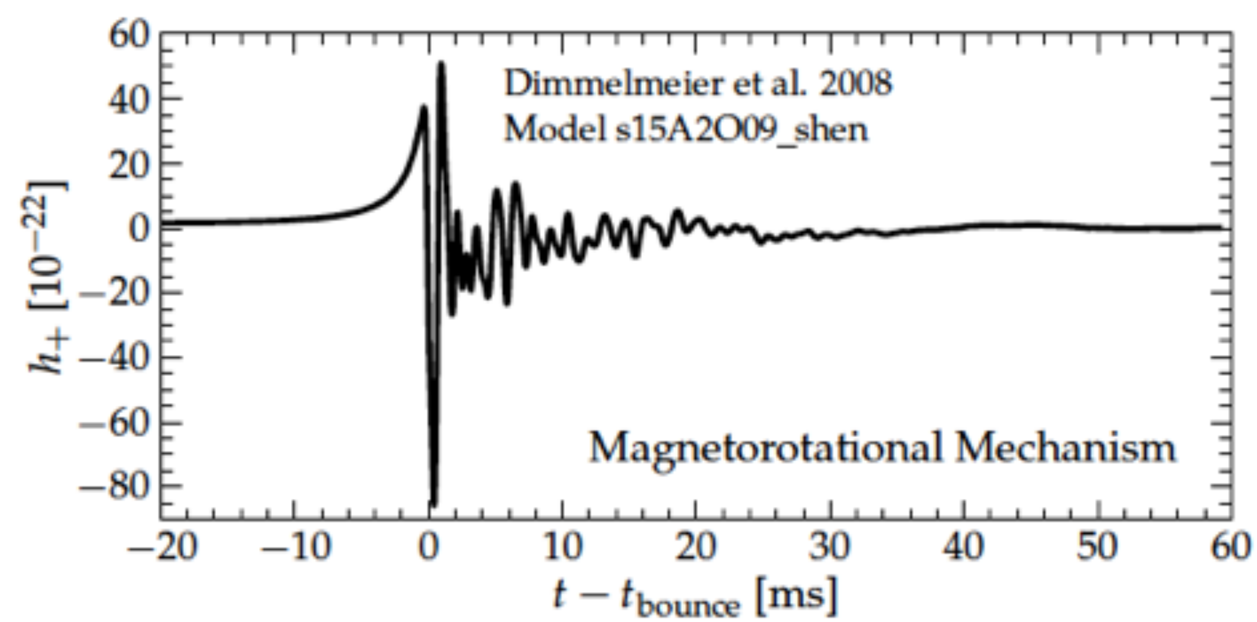
Principal Component Analysis

(NSF CAREER award)





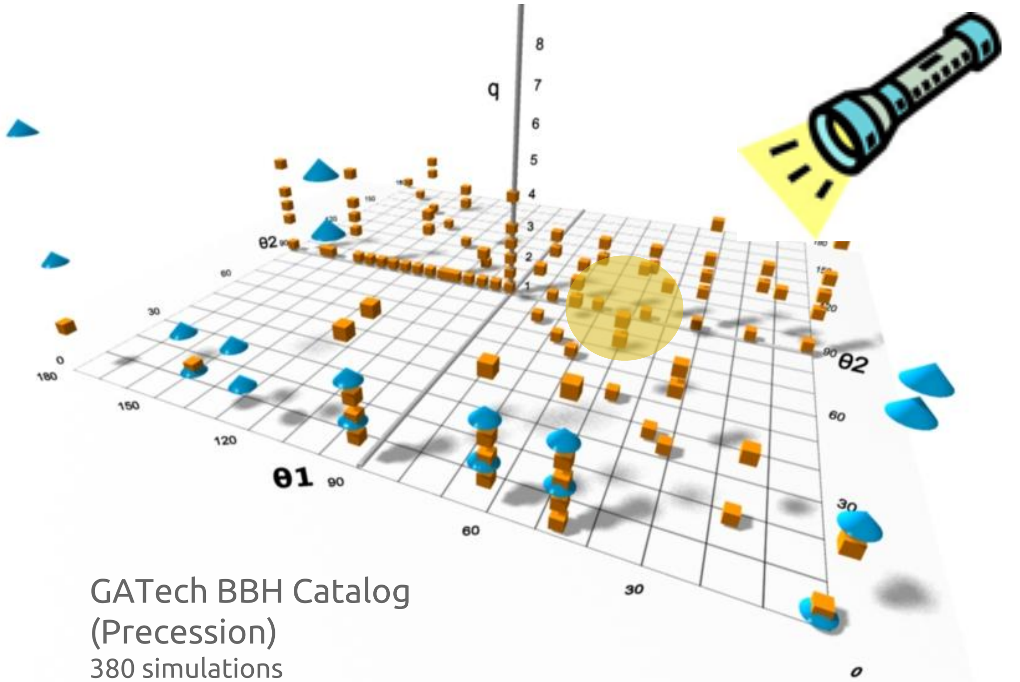




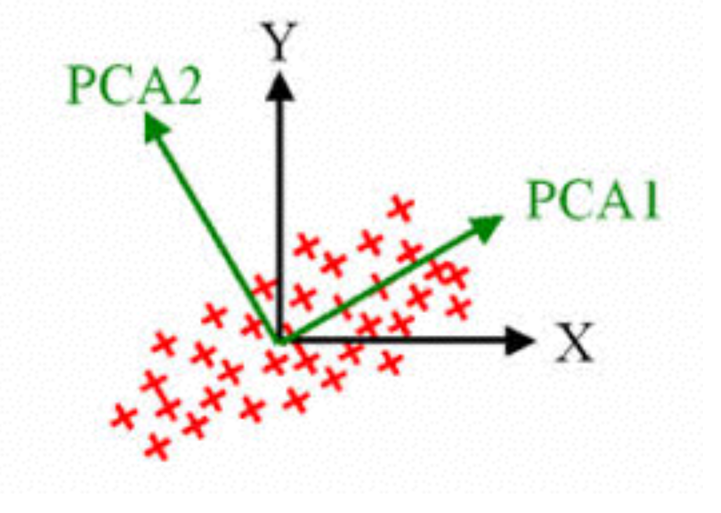
Identify Bulk Features in BBH Mergers

Can we distinguish BBH morphologies using PCA & and model selection “good enough” for astro?

- non-spinning, spinning & precession
- construct catalogs from NR BBH waveforms and apply PCA machinery
- Preliminary proof-of-concept to distinguish BBH signal morphologies using (Clark et al arXiv:1406.5426) with Glasgow (Siong Heng) and GT (Cadonati, Clark, Shoemaker) and students
- Method based on work by Logue et al (arXiv:1202.3256) and inspired by Engles et al PRD 90 2014

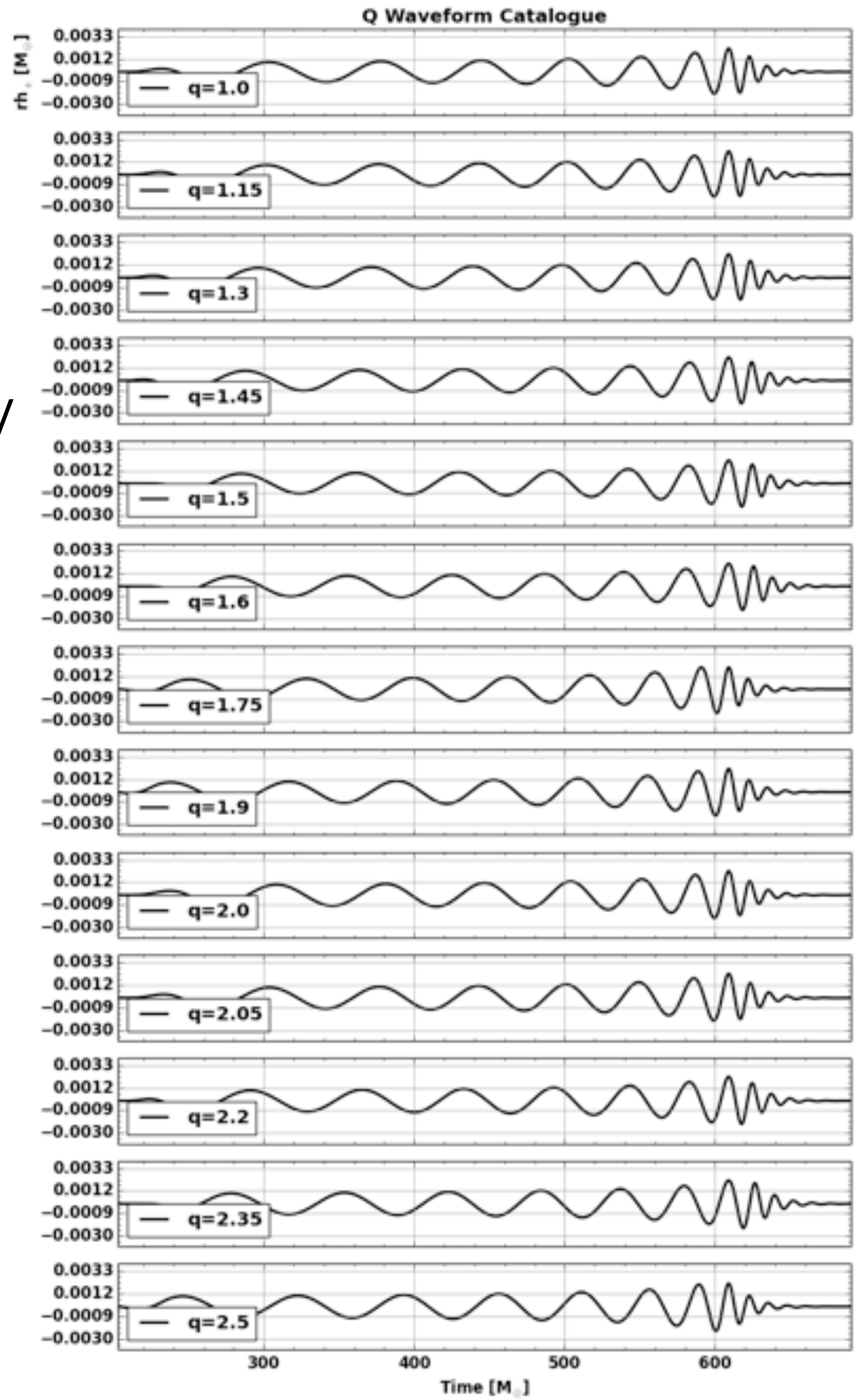


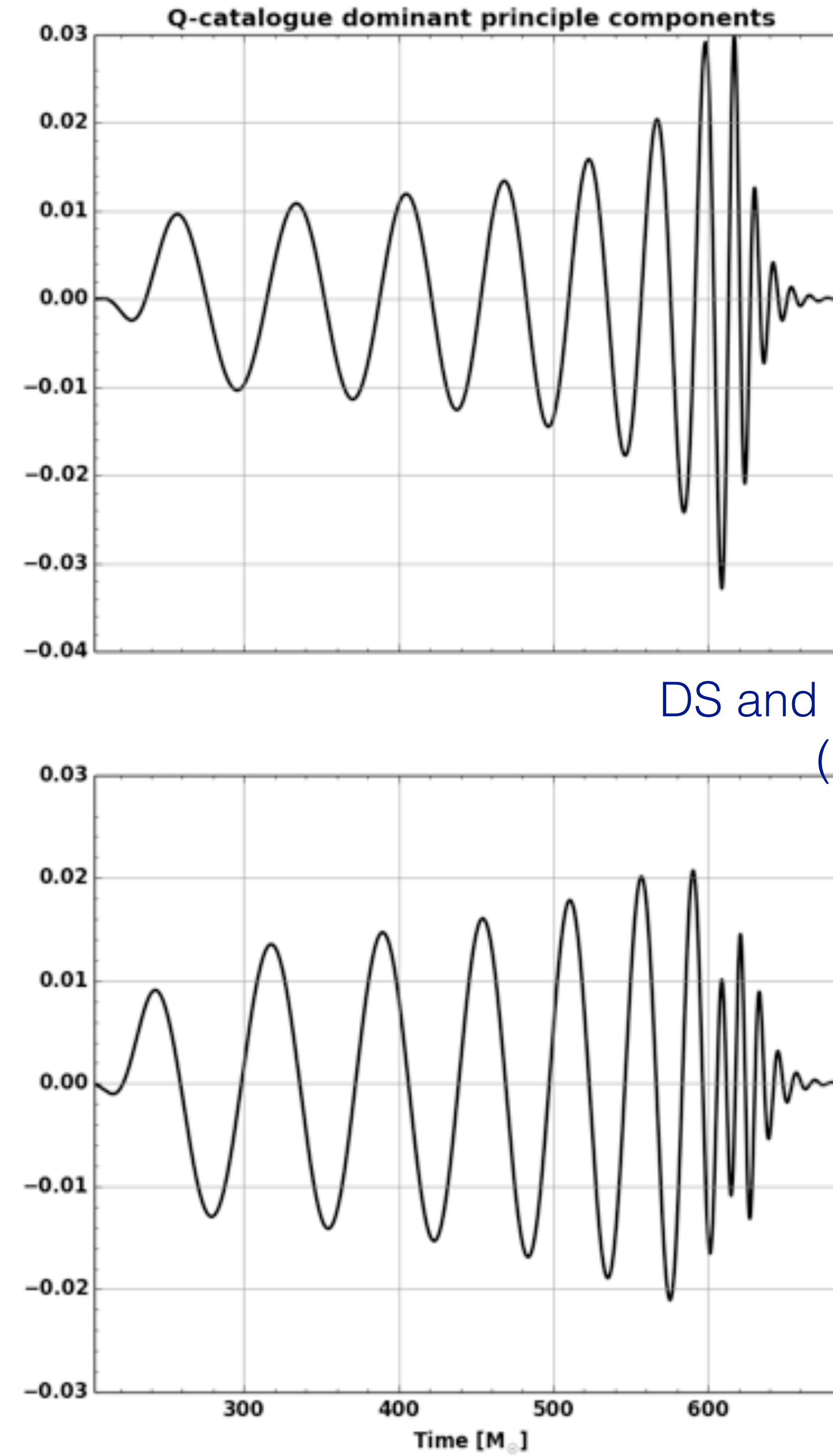
GATech BBH Catalog (Precession)
380 simulations



Two PCs capture features

black hole masses increasingly different

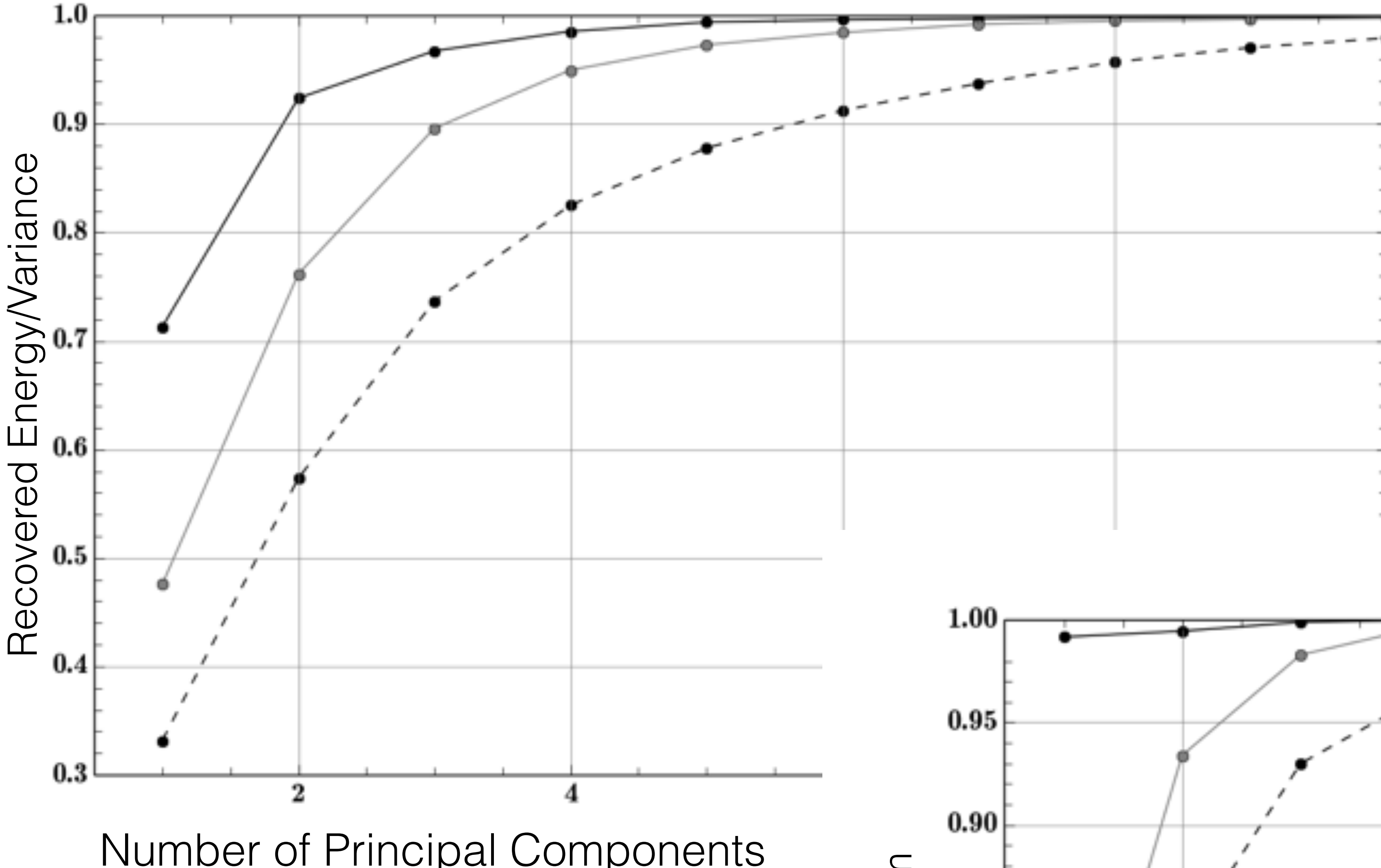


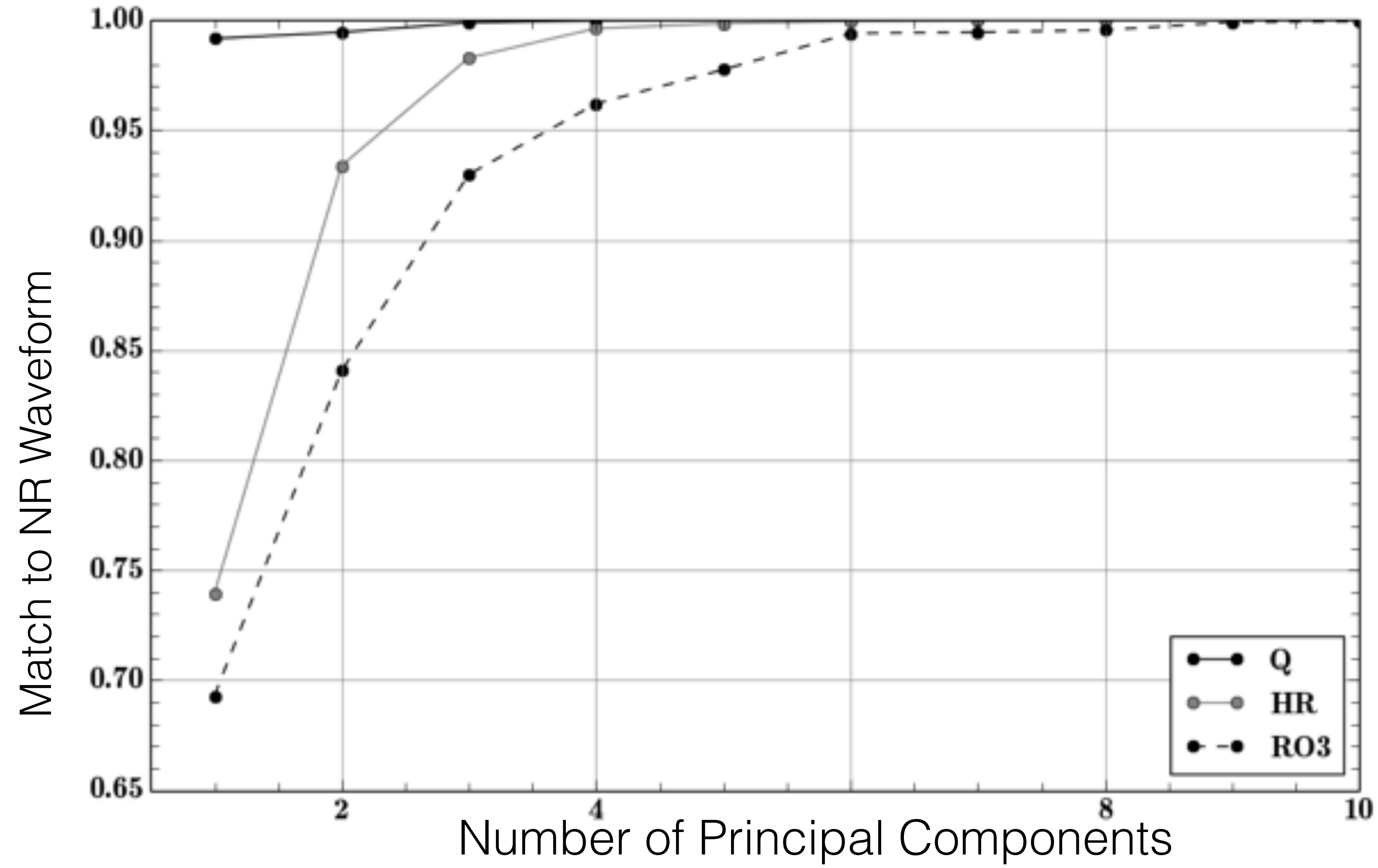


DS and collaborators (2014)

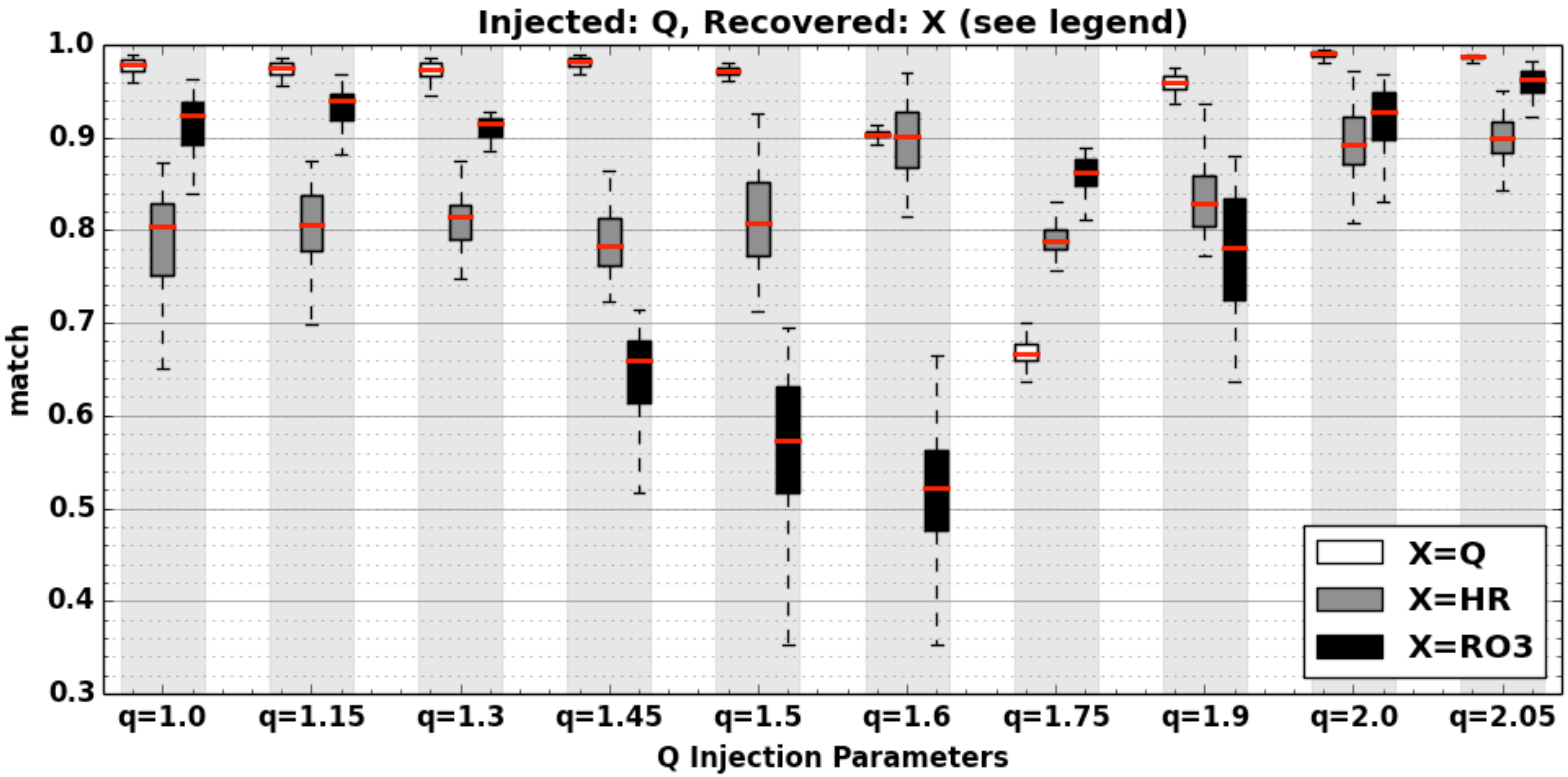
Develop a methodology that will recognize BH signals with as little information as possible

Results from our catalog





Model Selection is Possible



- Proof of concept that we can identify features of BBH mergers
- Could be useful with work to use in identifying mergers in the data and classifying them broadly

Future NR Code for DA

- fast
- on demand based on coarse parameter estimation
- opportunities to cut corners
- future detectors - may need more accuracy

Conclusions: Imagining the Future

Fundamental Physics, Engineering, Data, Computing, Astrophysics

- NR predict gravity's role in universe
- Better, longer, more parameters in NR
- Trends
  - precession is beginning to be modeled and templated
  - higher modes important for PE, increases importance with mass ratio, total mass and precession
- Future Innovations Needed
  - predicting next NR run and on demand simulation
  - speeding up template creation
  - IMBH opportunity to use less exquisitely modeled
- Yes, ready for GW data to confront theory