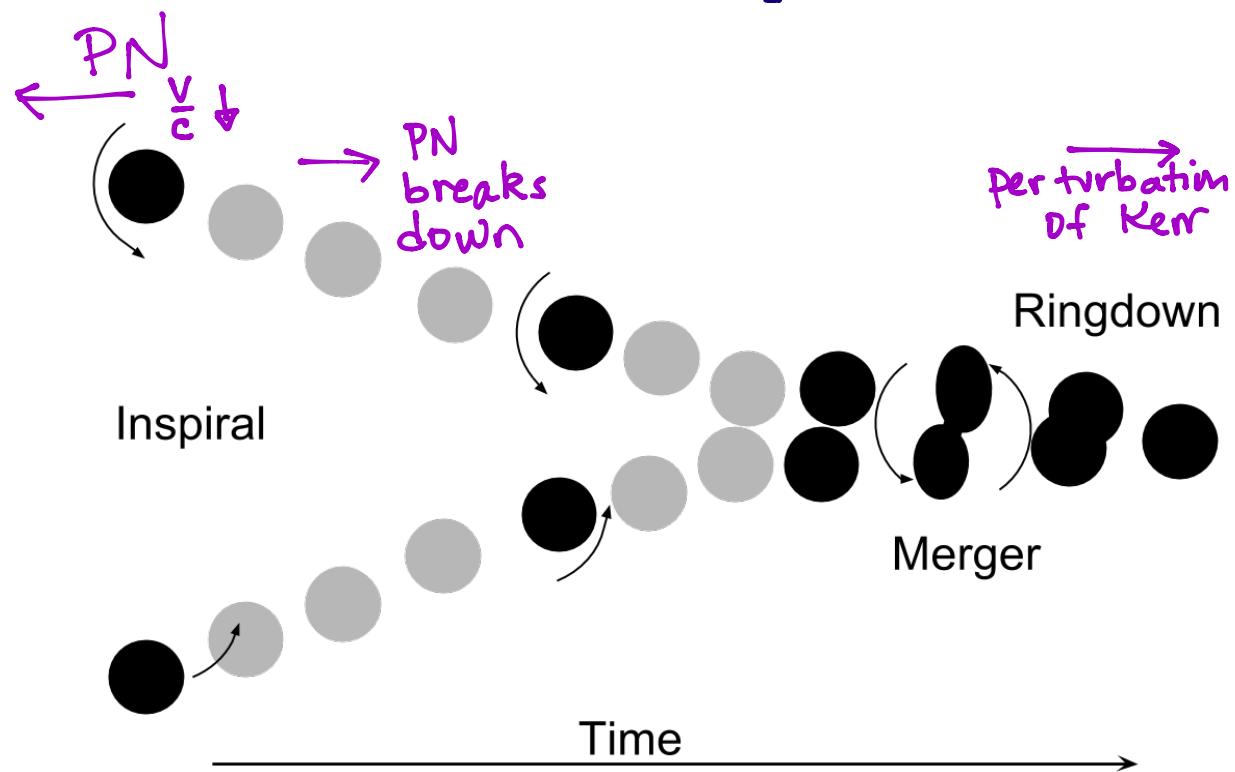
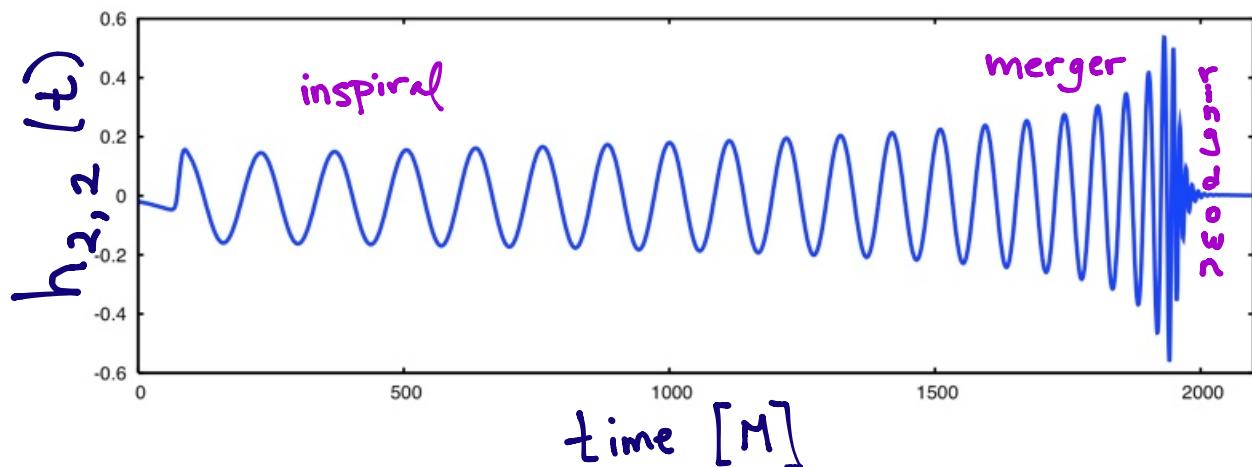


FROM NR to GWs for BBHs

D. Shoemaker, GT



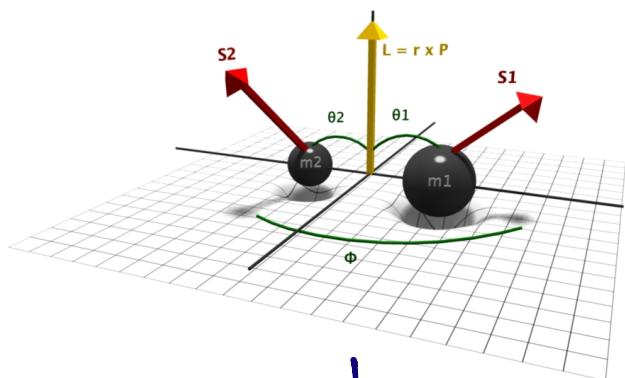
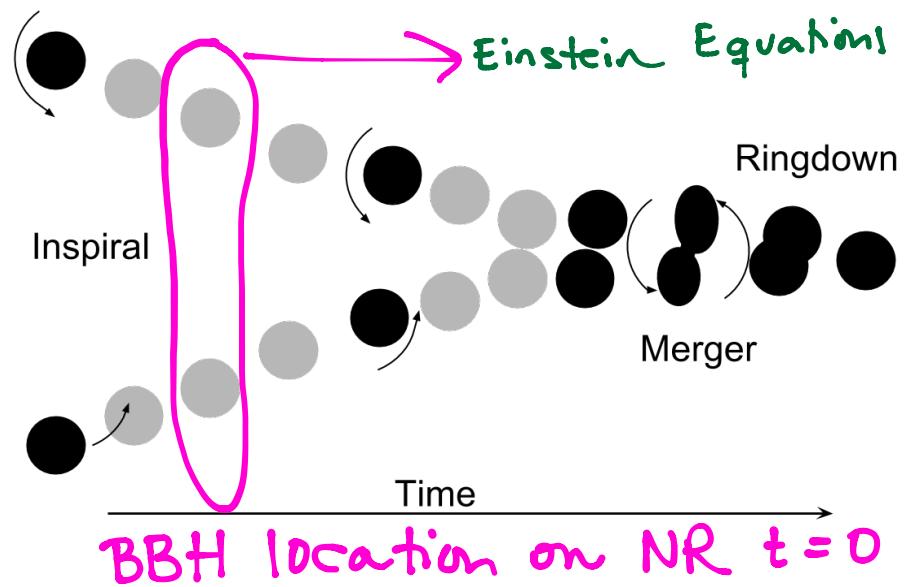
EINSTEIN EQN.

$$G_{\mu\nu} = 8\pi \bar{T}_{\mu\nu}$$
$$\equiv \circ$$

- NR solves full, non-linear Einstein eqn. (no approx)
 - errors arise from truncation error, initial data, GW extraction
 - typically solve 4d spacetime in 3d spatial chunks at each t
- $g_{ij}(x, y, z); \frac{\partial g_{ij}(x, y, z)}{\partial_t t}$
- main codes Einstein Toolkit (Loffler et al 2012)
SPEC (Szilagyi et al 2009)

* See L. Lehner CQG 2001 for a review of NR
& textbooks Alcubierre and Baumgarte-Shapiro

NR INITIAL DATA

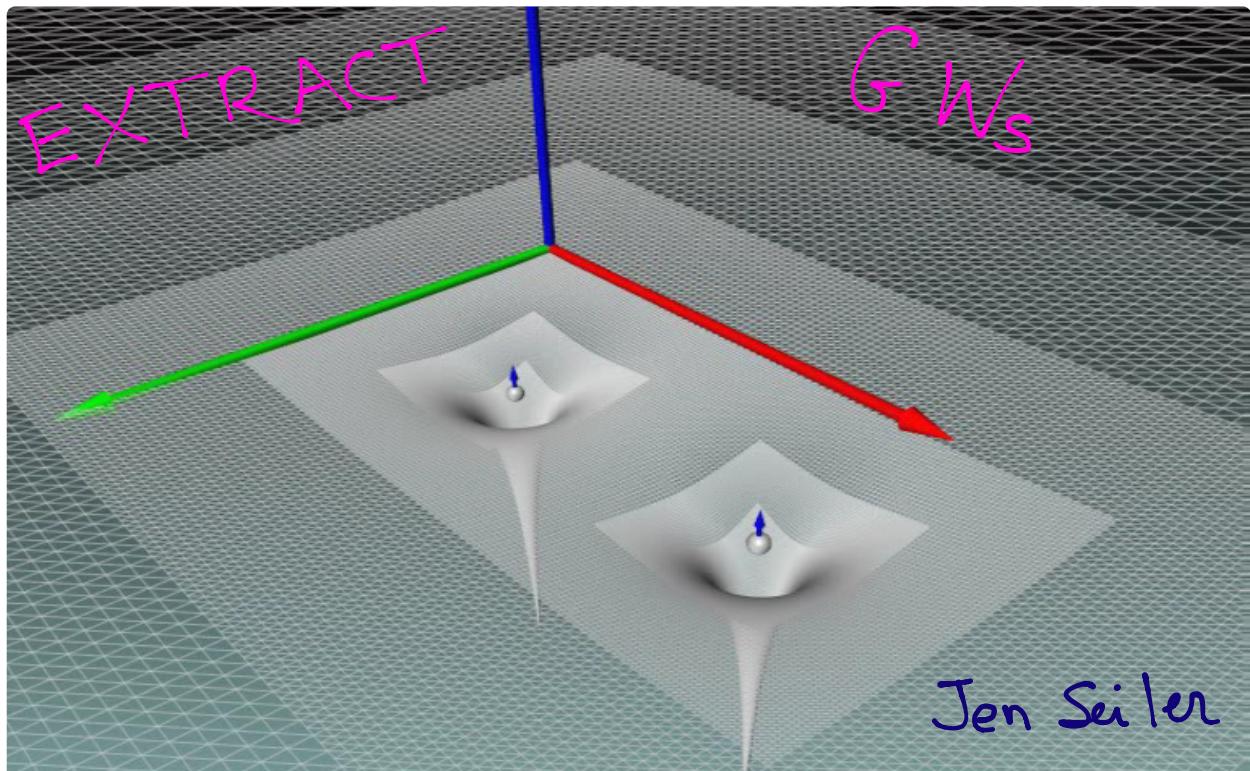


at $t=0$ SPECIFY
initial state of system
spacetime on 3d slice @ $t=0$

PN	NR
m_1, m_2	g_{ij}
\vec{s}_1, \vec{s}_2	$\partial_t g_{ij}$
a, ϵ	$\left. \begin{array}{l} g_{ij} \\ \partial_t g_{ij} \end{array} \right\}$ must satisfy 4 Einstein constraints

ONE solution takes WEEKS to months
on supercomputer

WHY SO SLOW?

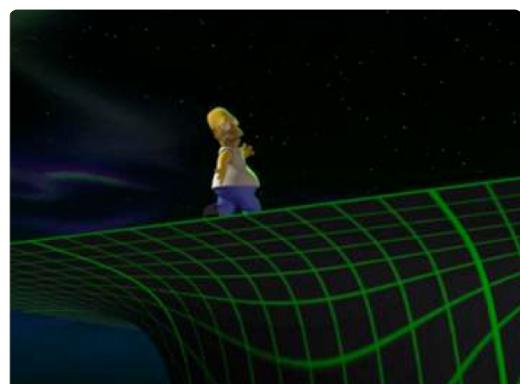


- 1) must resolve BH (#pts over horizon)
- 2) must resolve GWs far away

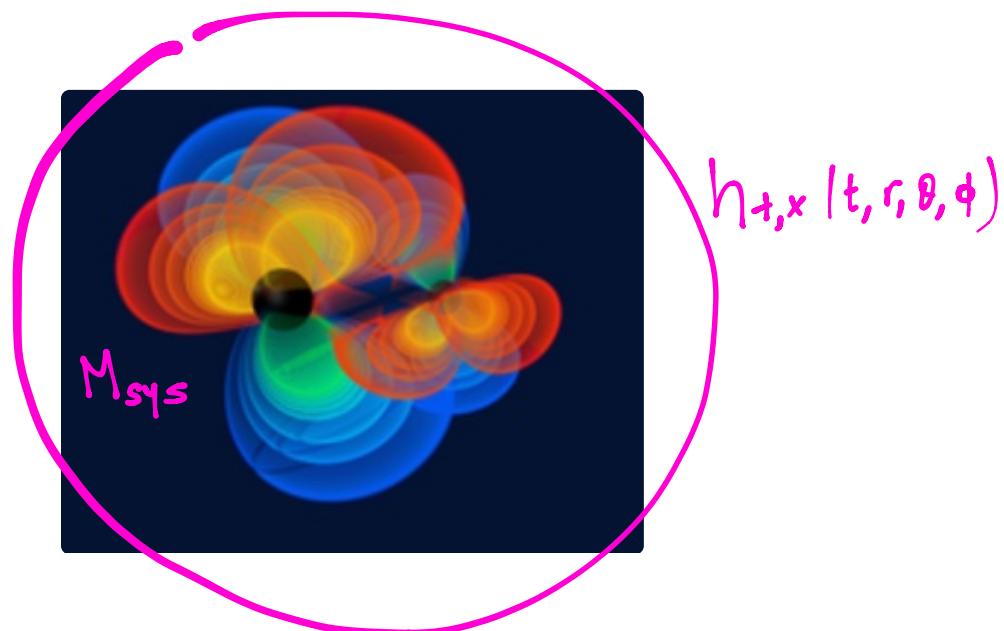
+ $q \uparrow$, more clock time pert

+ $|\vec{s}| \uparrow$,

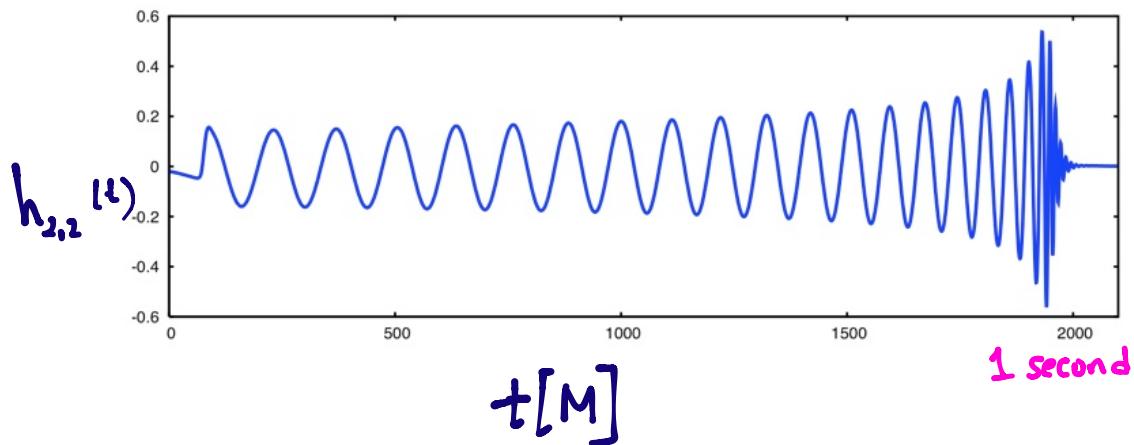
+ BH separation \uparrow , more t
and BH's move $v \downarrow$



NR OUTPUT: GWs



map $\theta, \phi \rightarrow l, m$



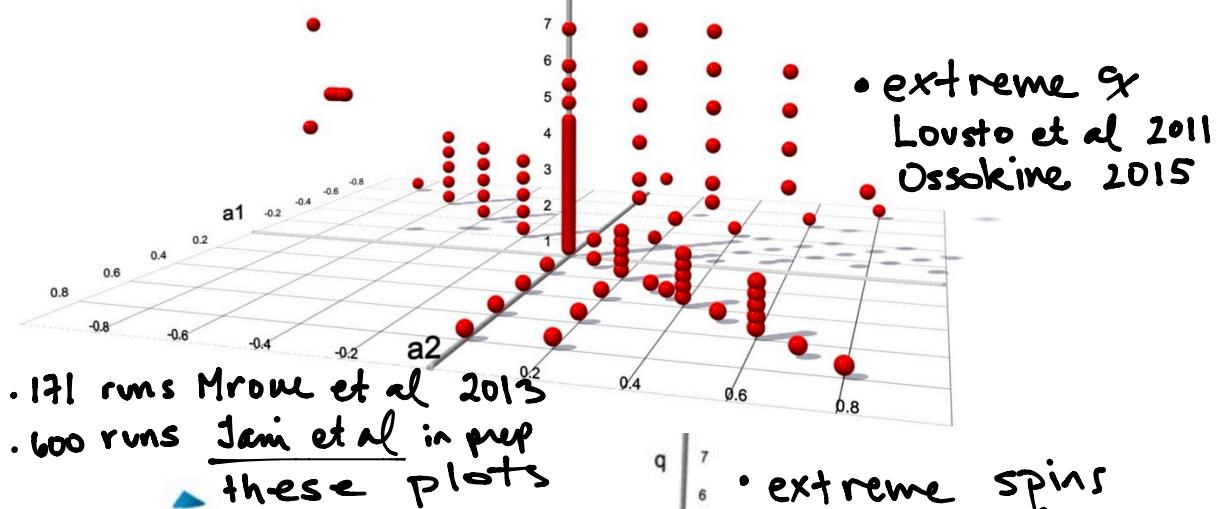
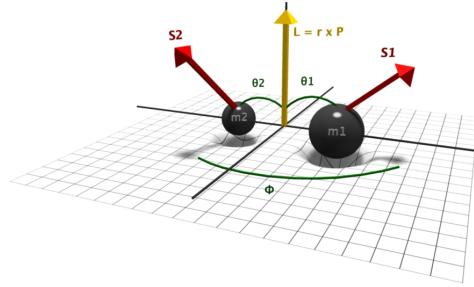
- solution scales with M
scale system to $100M_\odot$ ($1M_\odot \sim 5\mu\text{s}$)
 $\therefore 1 \text{ second}$

PARAMETER COVERAGE

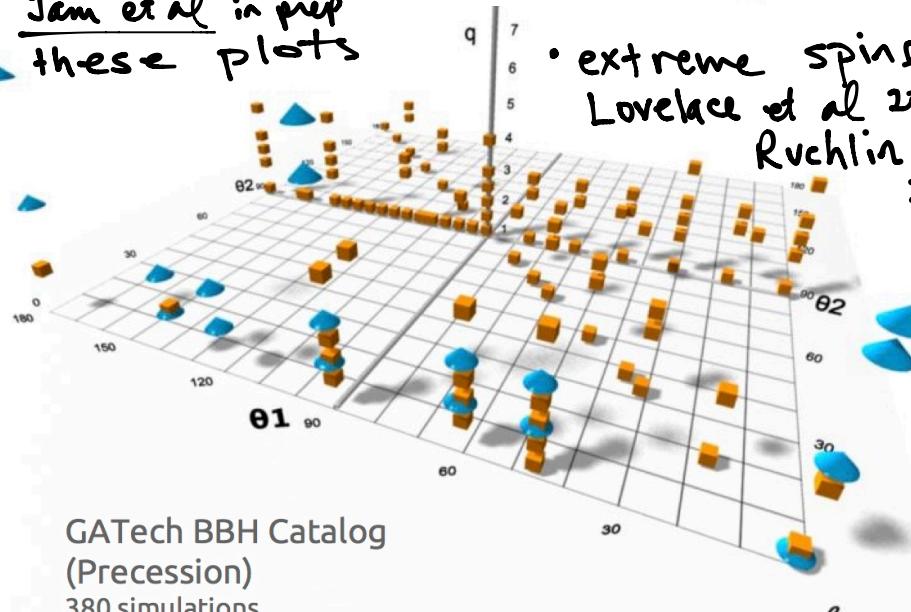
GaTech BBH Catalog
(Non-Precession)
220 simulations

$$q = 15$$

$$\frac{m_1}{m_2}$$

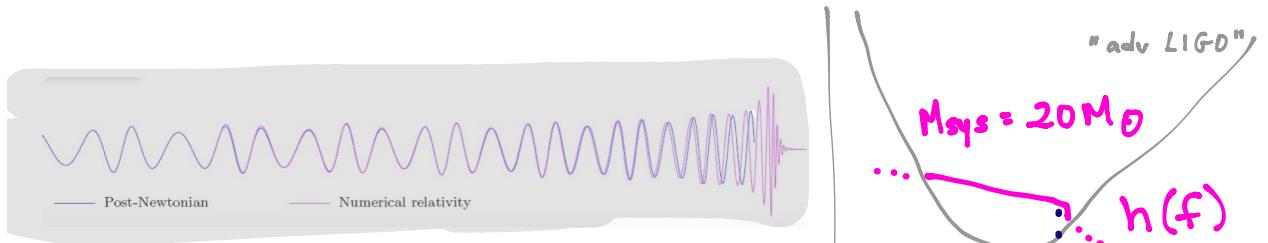


• extreme spins
Lovelace et al 2012
Ruchlin et al 2014

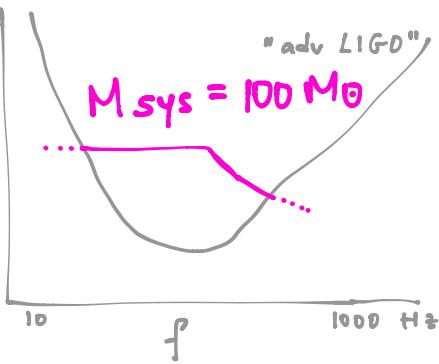


HOW can we SPEED UP NR waveform production?

GW Measurement

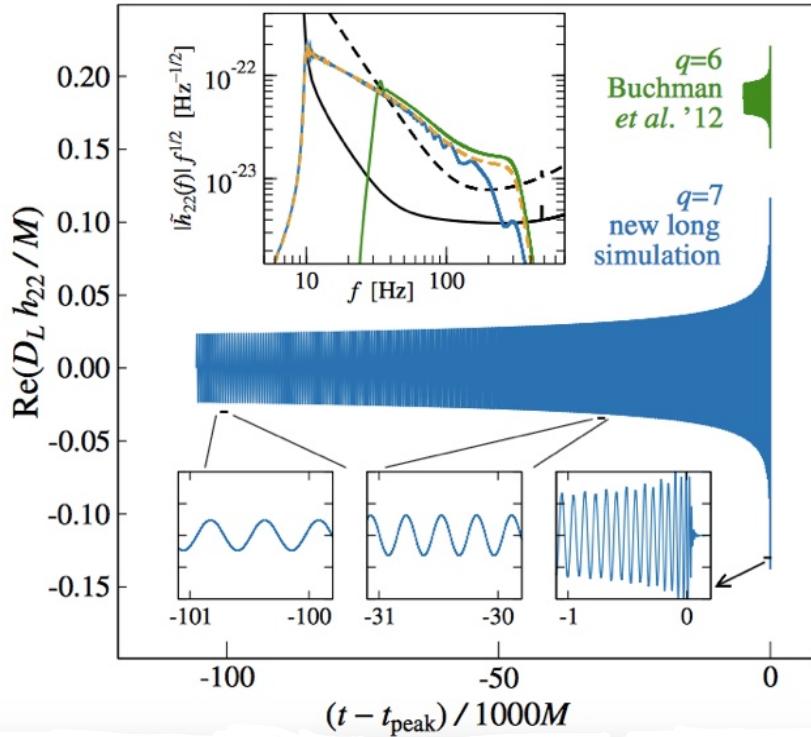


$M_{\text{sys}} \uparrow \Rightarrow \# \text{ GW cycles} \downarrow$
 $f_{\text{merger}} \downarrow$
 Distance reach \uparrow

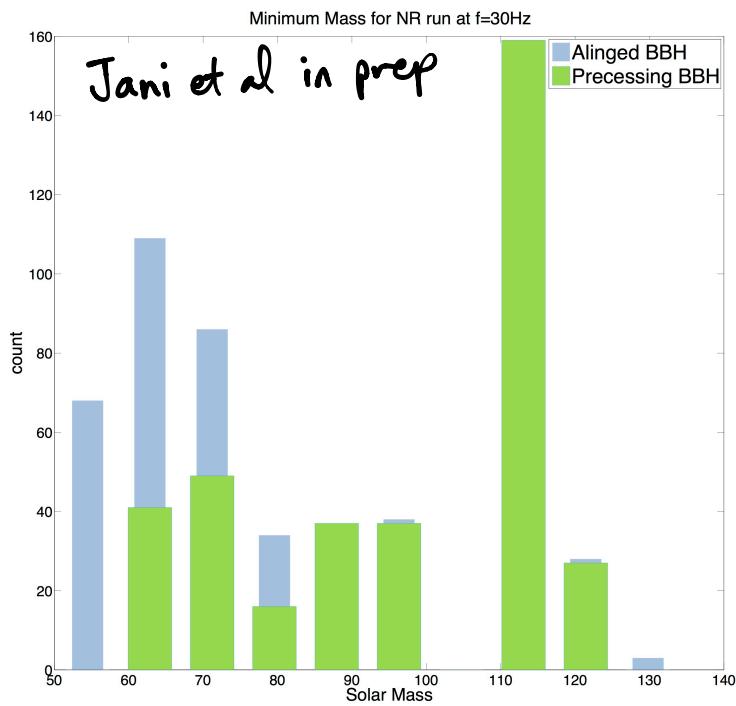


TENSION between PN + NR
 increase # cycles contributed by NR
 PN error \downarrow but NR takes LONG time

LENGTH of NR WFs



350 GW cycles
Szilagyi et al
1502.04953



NR Waveforms for LIGO/VIRGO

- NATURE : tests of search pipelines
- MODELS : NR waveforms do not provide $f(\vec{s}_1, \vec{s}_2, m_1, m_2, \dots)$ \therefore WF models built by fitting NR wfs

EDBNR Damour et al 2013

PHEM Ajith et al 2011

PCA Clark et al 2014 * preliminary, for model selection

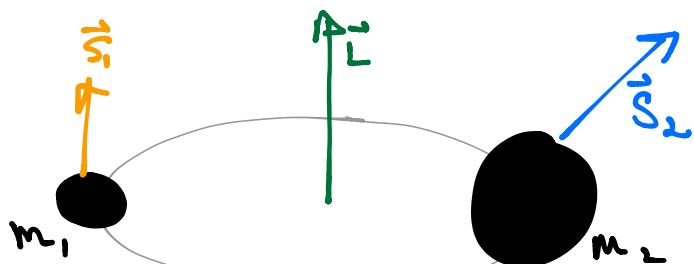
NR \rightarrow Model \rightarrow Template Bank \rightarrow Search
(Reduced order model, Blackman et al 2015
Smith et al 2013, Caudill 2012)

Models lag behind NR production \rightarrow as $N_{\text{sys}} \uparrow$
 \vec{s}_1, \vec{s}_2 become more important for sources
& higher modes

How do we speed up TIME between new NR WF and templates?

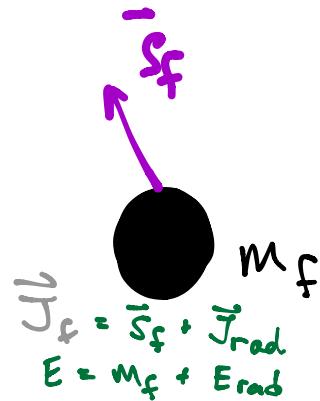
...SPIN... SPIN ... SPIN...

can be anything



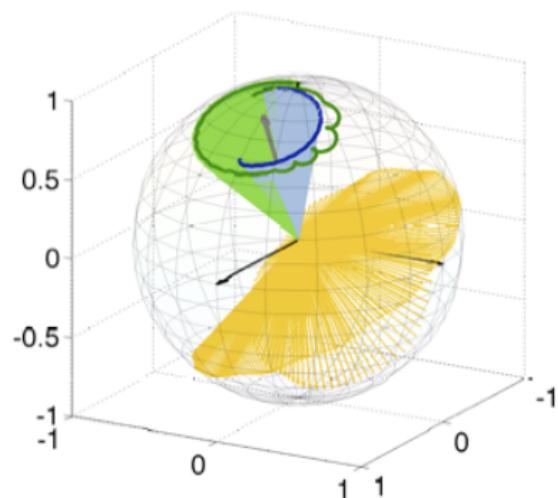
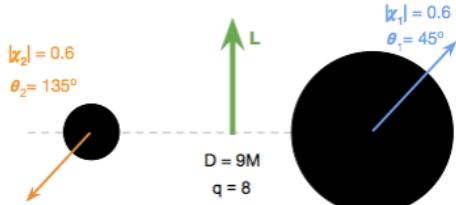
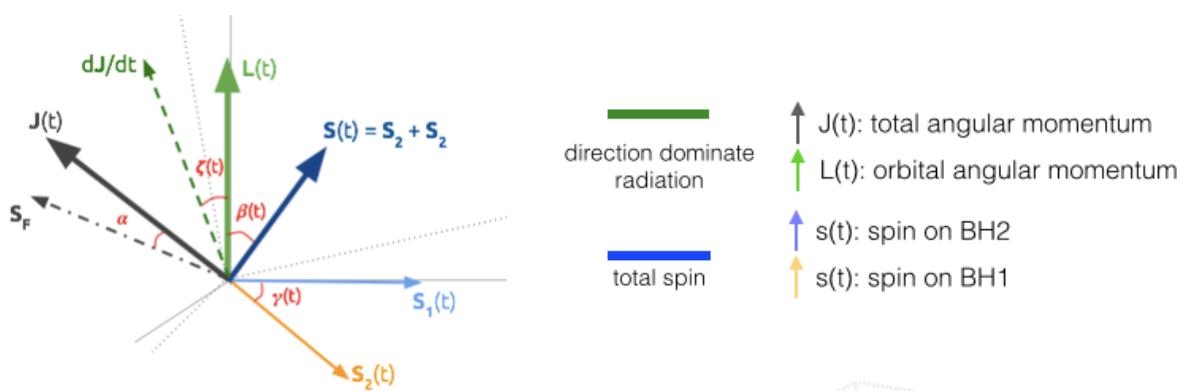
$$\vec{J}_i = \vec{L} + \vec{s}_1 + \vec{s}_2$$

$$E = m_1 + M_2$$



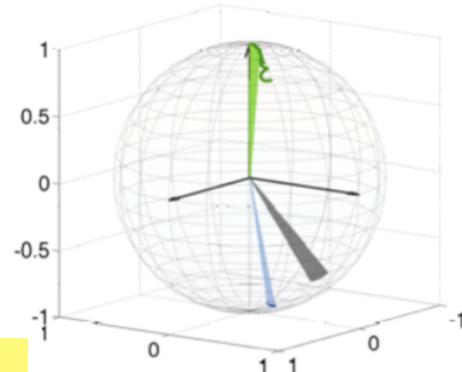
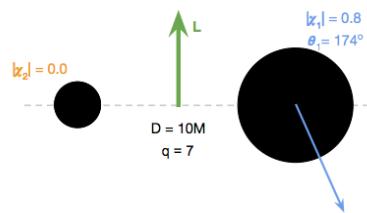
$$\vec{J}_f = \vec{s}_f + \vec{J}_{\text{rad}}$$

$$E = m_f + E_{\text{rad}}$$

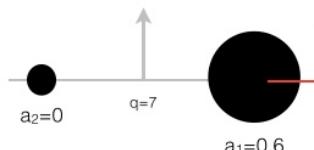
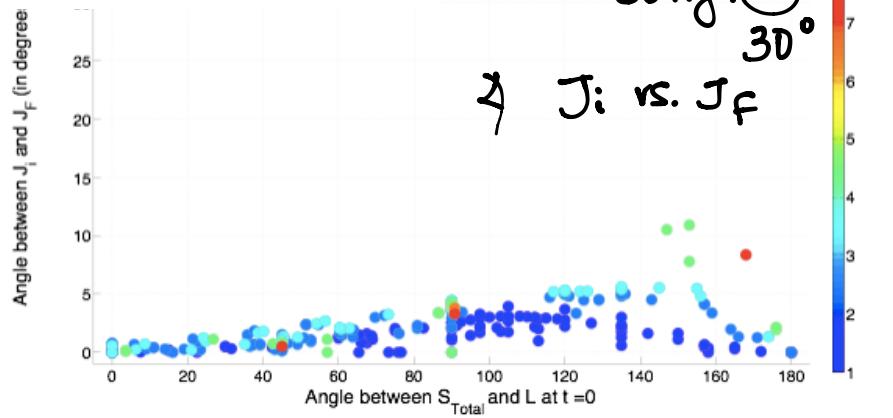


Jani et al 2 in prep

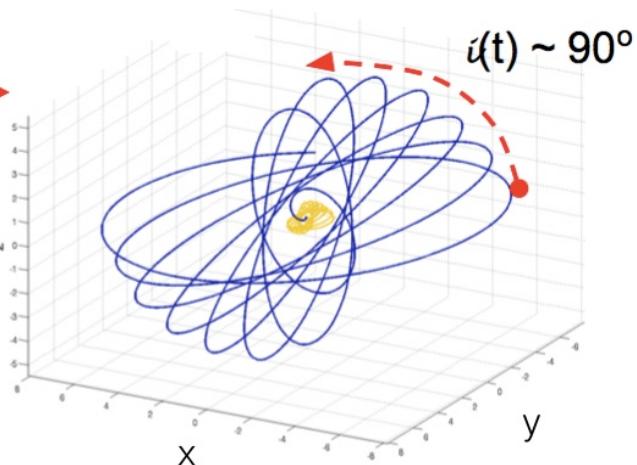
JOY OF PRECESSION



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

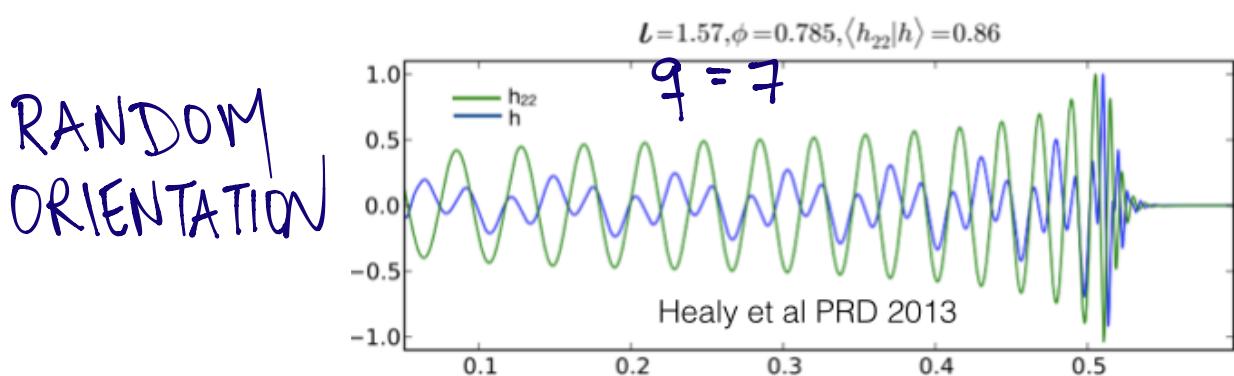
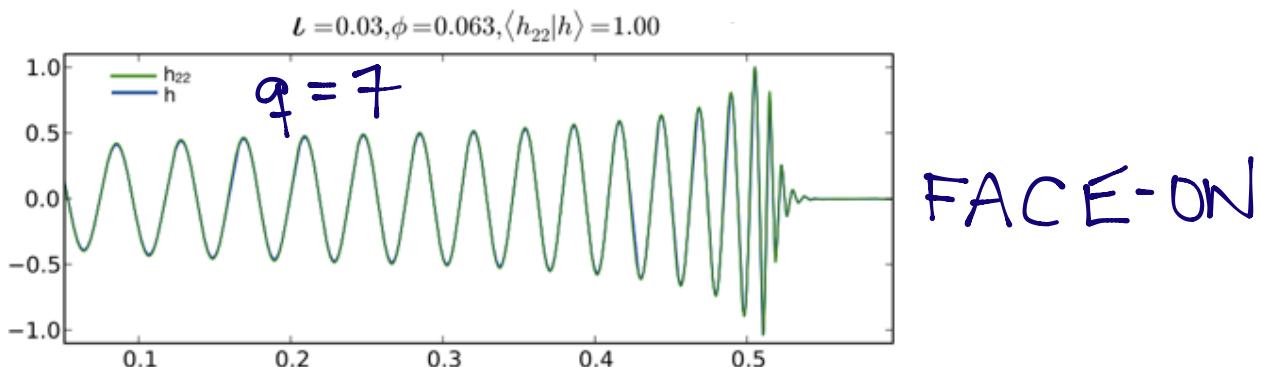
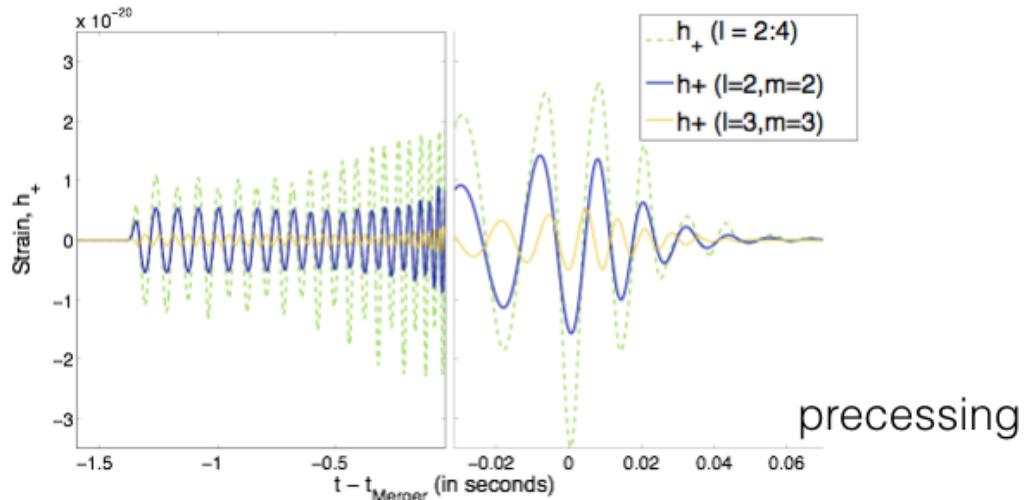


INCLINATION



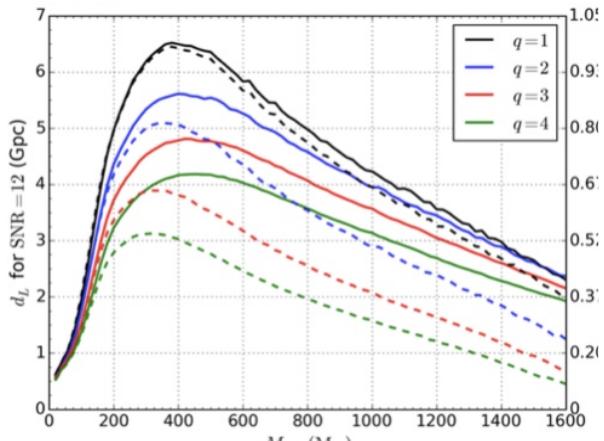
HIGHER MODES

a.k.a subdominant harmonics

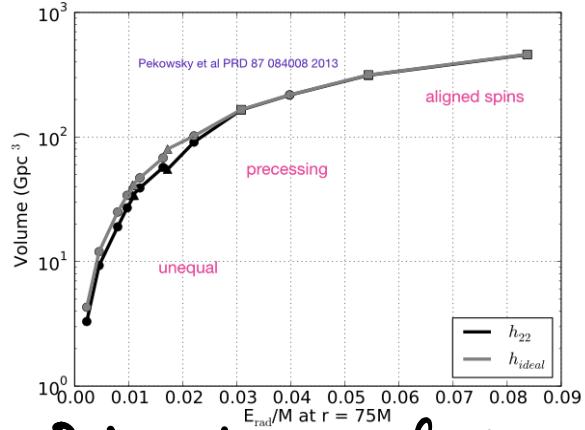


NR tells us...

- solution to BBH coalescence
- precession... including outlying cases unmodeled (models assume $\vec{J}_1 \parallel \vec{J}_2$)
- higher modes
- only when we combine with GW can we determine impact!



Graff et al 2015



Pekowsky et al 2013

see Varma et al 2014

QUESTIONS OF INTEREST to me

HOW can we SPEED UP NR waveform production?

- decrease accuracy of NR waveform
 - limit given by systematic errors in detectors
 - depends on what parameters we evolve
 - limit placed by astrophysical need
- find ways to reduce complexity of equations
 - this is hard & experimental
 - code for highly separated BHs
 - turn off terms that have little impact
- smart choice of next NR simulation
 - machine learning methods to pick regions of parameter space with impact
 - impact must be defined by GW data requirement

How do we speed up TIME between new NR WF and templates?

- use NR WFs with fewer cycles (PN errors)
- turn-the-crank fitting

INSTEAD of getting models more ACCURATE,
would we be better served by BROADER parameter coverage?

