Gravitational Wave Astronomy and Astrophysics

Will M. Farr
CIERA Fellow

The Future of Astronomy: Fellows at the Frontiers of Science
Northwestern University, Aug 31 – Sept 3, 2011

LIGO-G1100912

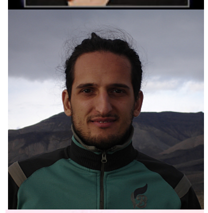
Some CIERA Projects

- Secular Dynamics of Hot Jupiters: Naoz, WMF, et al (2011a,b)
- Supernova spin production: WMF, Kremer, Lyutikov, Kalogera (2011)
- Black Hole Mass Distribution: WMF, *et al* (2010)
- X-Ray Binary Evolution: Valsecchi, Glebbeek, WMF, *et al* (2010)
- Tides in WD binaries: Valsecchi, WMF, *et al* (2011)
- Gravitational Wave Parameter Estimation….

NU LIGO Group

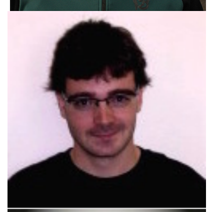
Vicky Kalogera (PI)

Diego Fazi



Marc van der Sluys

Vivien Raymond



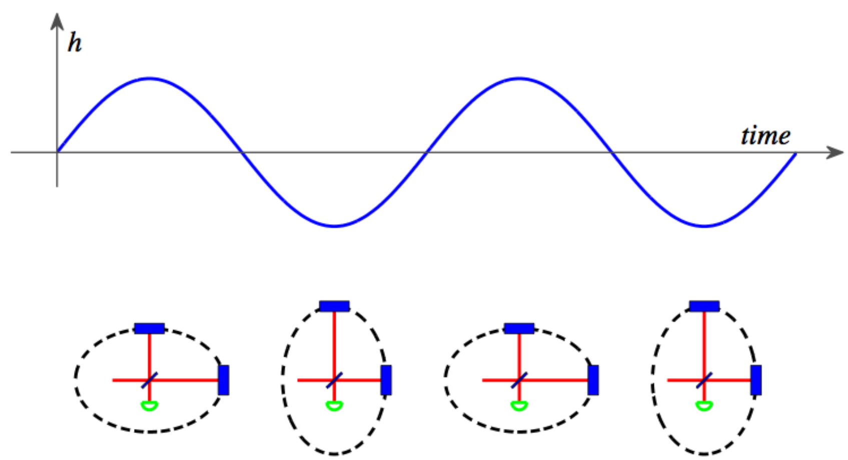
Ben Farr

Ilya Mandel

Carl Rodriguez

Gravitational Waves

- Accelerating masses produce disturbances in spacetime.
- Propagate at speed of light, interact weakly => good observational tool.
- Produce changes in separation between test masses.
- Two polarizations: "+" (shown) and "x".

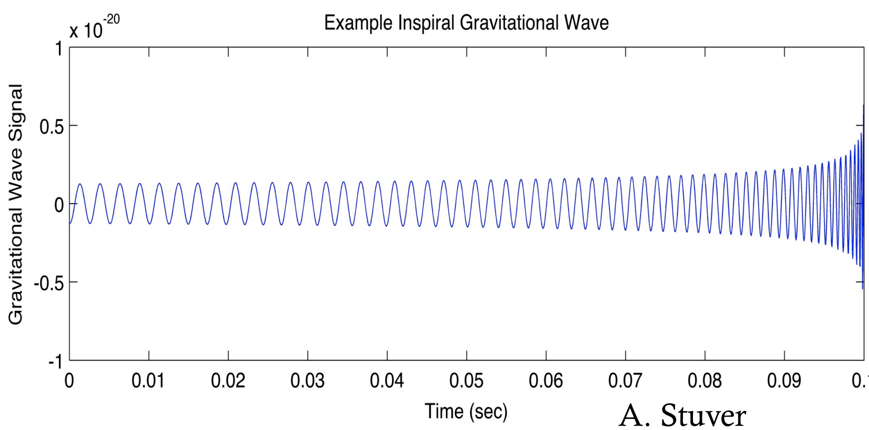


Abbott, *et al* (2009)

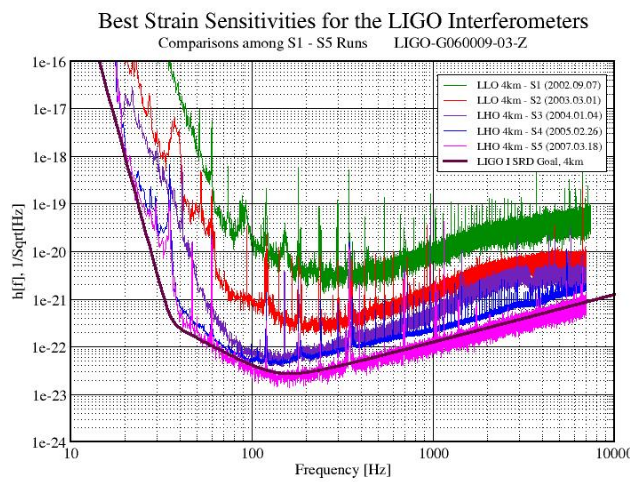
Compact Binary Coalescence

- NS-NS, NS-BH, or BH-BH binary inspiral, merger, and ringdown

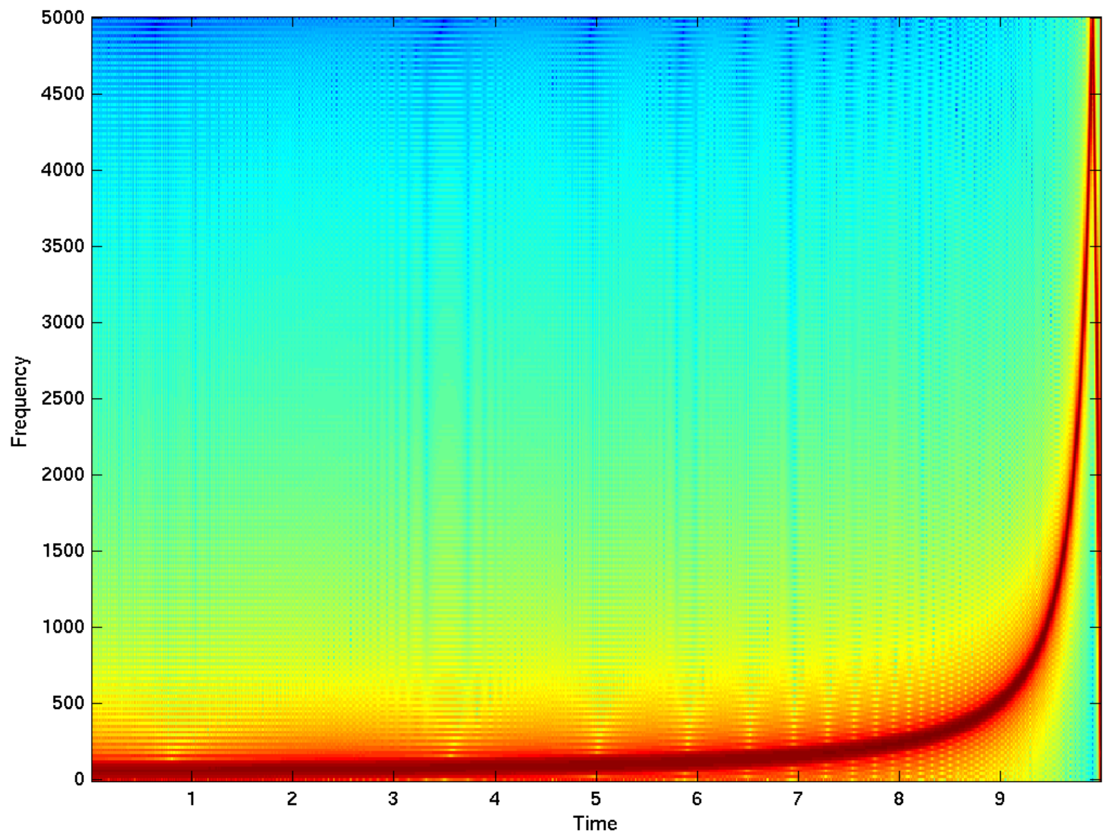
$$f_{\max} \sim 1500\,\mathrm{Hz}\left(\frac{1.4\,M_\odot}{M}\right)$$



A. Stuver



Spectrogram



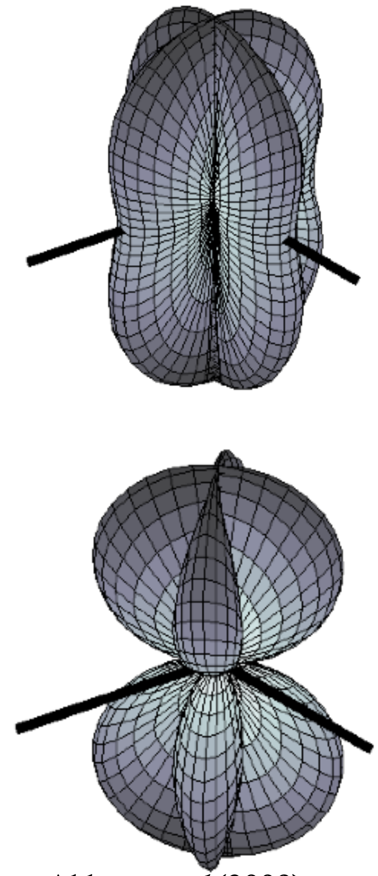
K. Riles/LIGO Lab

LIGO/Virgo Detectors

4 km arms => $\Delta L = 10^{-21} L \sim 4 \times 10^{-18}$ m

Sensitive to CBC up to ~100 Mpc.

LIGO Lab



Abbott, *et al* (2009)

Rates of CBCs

- See Abadie, *et al*, Class. Quant. Grav., **27**, 173001 (2010), arXiv:1003.2480.

Objects	per Myr per MWEG	LIGO (per yr)	AdLIGO (per yr)
NS-NS	1 – 4000	2×10^{-4} – 0.6	0.4 – 1000
NS-BH	0.05 – 100	7×10^{-5} – 0.1	0.2 – 300
BH-BH	0.01 – 30	2×10^{-4} – 0.5	0.4 – 1000

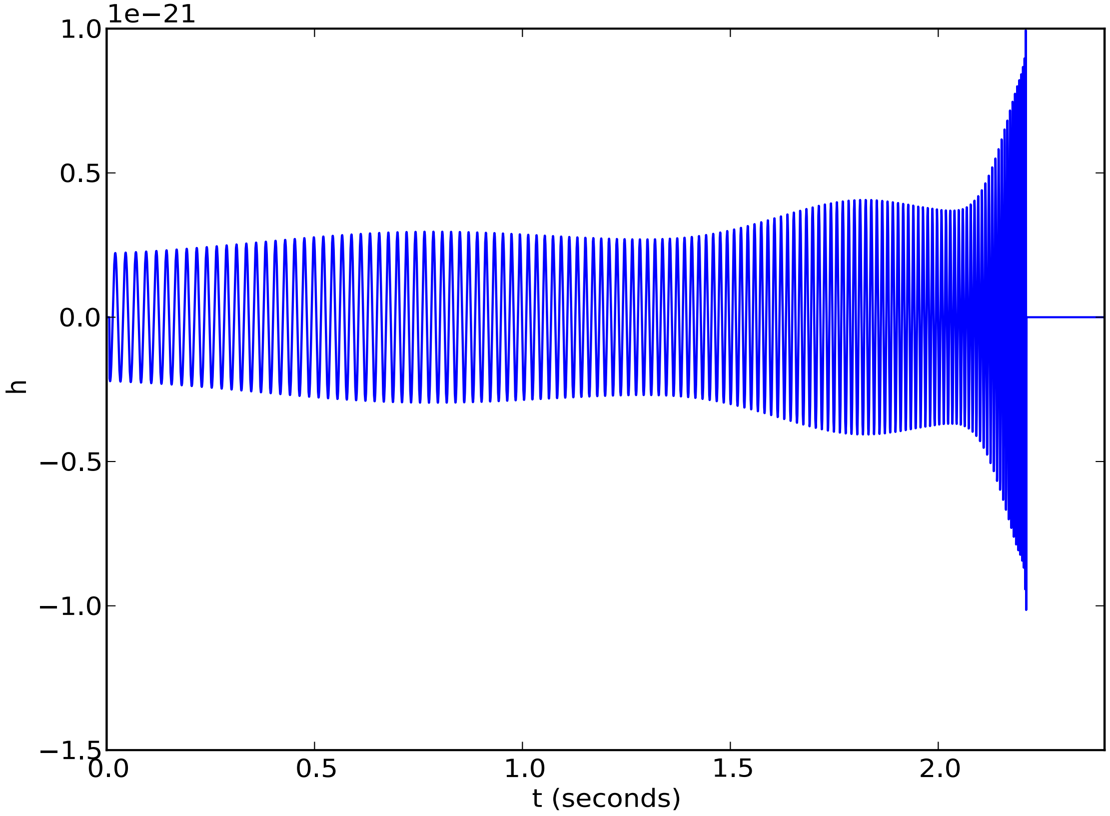
Astrophysical Questions

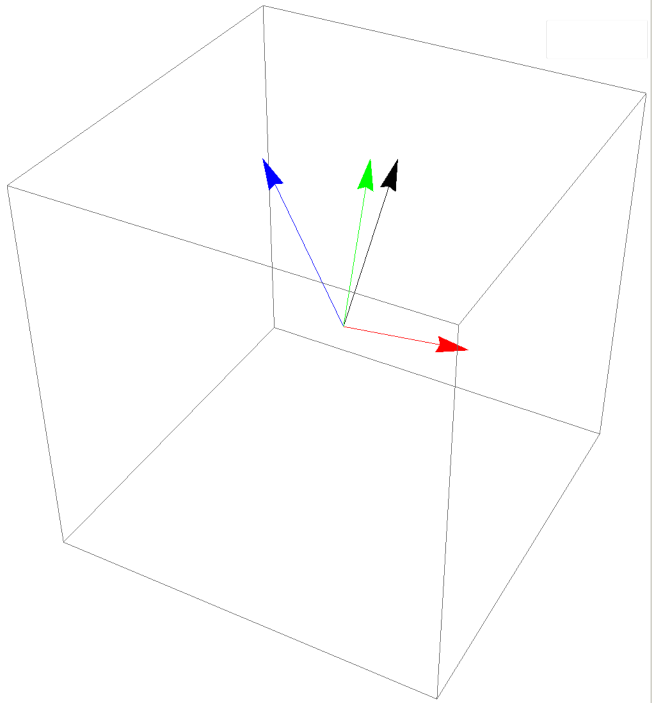
- What are the mass distributions of coalescing compact objects?
- Are CBCs associated with an EM signal?
- **How are compact binaries that coalesce formed?**
- **What is the accretion history of these objects?**
- **When matter is involved in the coalescence, what is its equation of state?**

Waveform Parameters

Intrinsic	M_1, M_2 or Mc, q	Controls length, strength, f_{max}.
Spin	a_1, a_2, angles	Modulates waveform, can accelerate or delay coalescence.
Extrinsic	RA, dec, distance, inclination, time	Strength, polarization, sky location.
Extrinsic, Nuisance	Waveform phase, polarization angle.	

Effects of Spin





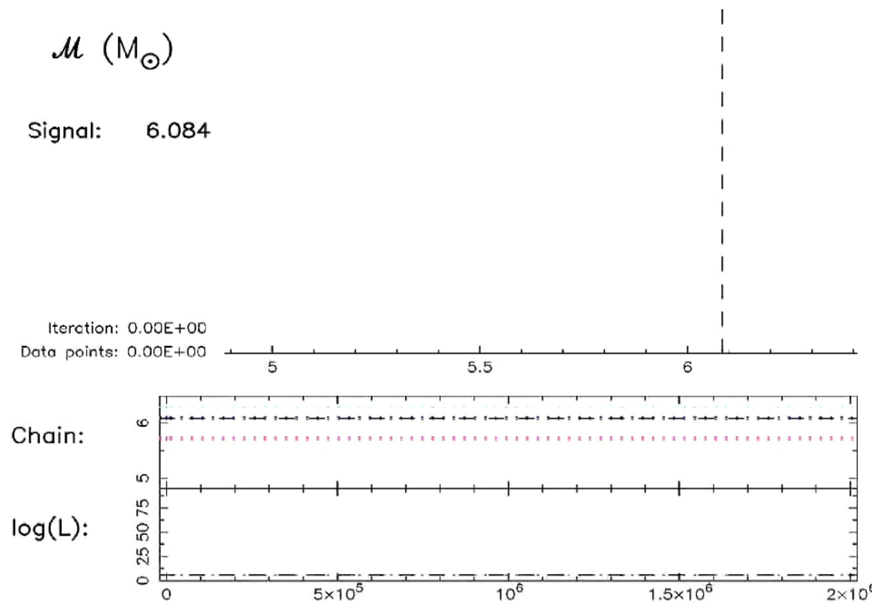
Parameter Estimation

- Given a stretch of data that contain both signal and random noise: d = n + s.
- Propose a signal (i.e. pick 15 parameters).
- Subtract: $n = d - h_{proposed}$. Compute $p(d|\text{params})$ from knowledge of noise properties.
- Repeat, constructing probability distribution of parameters from Bayes' rule:

$$p(\text{params}|d) \propto p(d|\text{params})p(\text{params})$$

MCMC

- Efficient sampling method (15-D!)
- Propose a change to current parameters, accept if better, or if worse with finite probability.

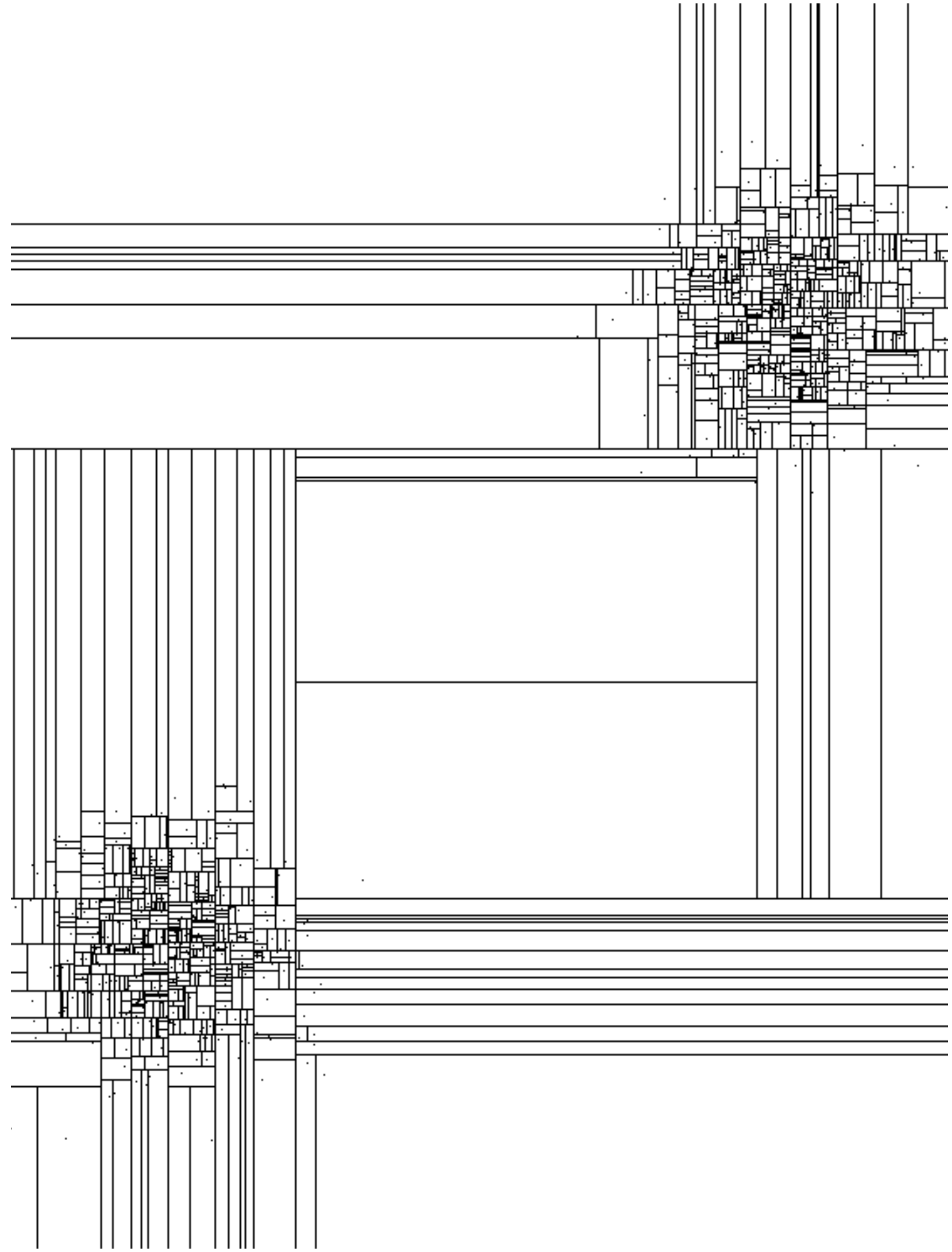


MCMC Efficiency

- Want **rapid** and **accurate** parameter estimation, in highly-correlated, multi-modal parameter spaces. The key is to not waste jumps.
- Working on a code, `LALInferenceMCMC`, part of the LIGO Algorithms Library.
- Buzzwords: parallelized, parallel-tempered MCMC, capable of differential-evolution and correlated jumps.

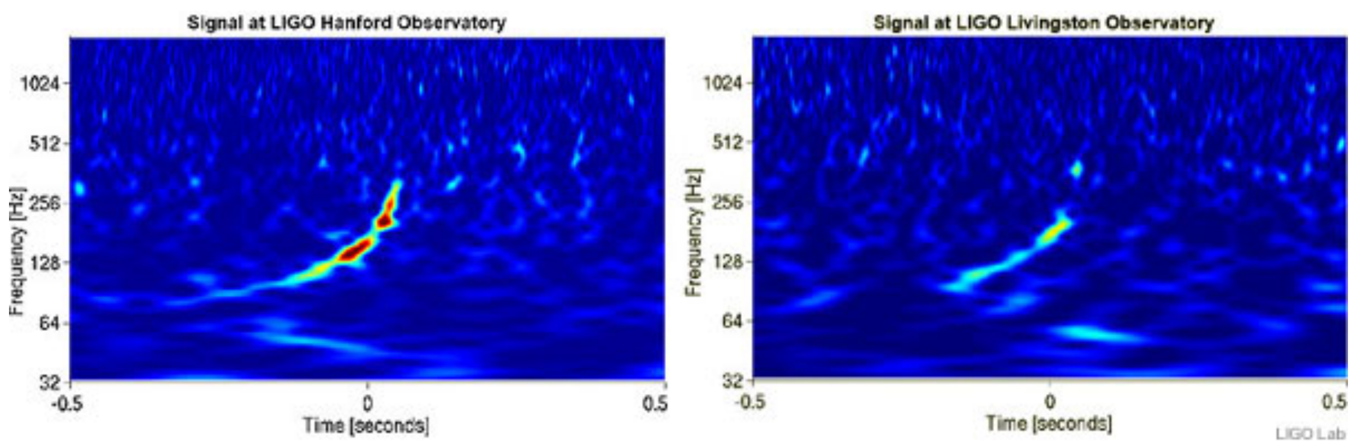
Better Multi-Modal Proposals

- Farr & Mandel (2011).
- Interpolates within a cloud of points in n-D to propose a new jump.
- Allows for easy transitions between separate modes, or even models (spinning vs. non-spinning).
- To appear soon in `LALInferenceMCMC`



Blind Injection

- See http://www.ligo.org/science/GW100916/ .
- On Sept 16, 2010, a GW signal was injected into the HLV network (blind to the collaboration).



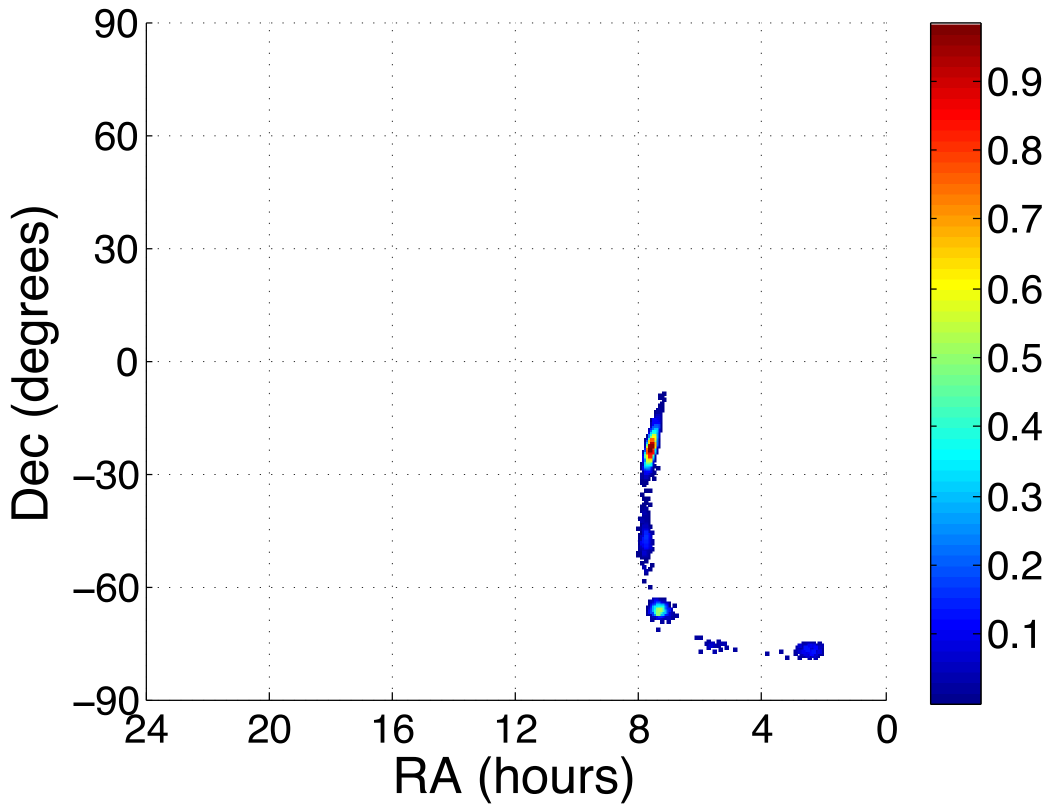
Blind Parameter Estimation

- Quickly detected; alerts to ROTSE, TAROT, Skymapper, Zadko, and Swift for EM follow-up.
- Subsequent parameter analysis:

M_1	5.4 – 10.5 MSun
M_2	2.7 – 5.5 MSun
a_1	> 0.67
d	7 – 60 Mpc

- Uncertainties dominated by model differences (systematic).

Sky Location



Challenges in the Advanced Detector Era

- PE on detector data that is sensitive to much longer waveforms.
- Eliminating/understanding systematic uncertainties from waveform models.
- Improving efficiency/automating PE on spinning waveforms.
- Keeping up with the potential large numbers of detections to answer astrophysical questions!