Searching for Compact Binary Coalescence Signals in Gravitational-Wave Data

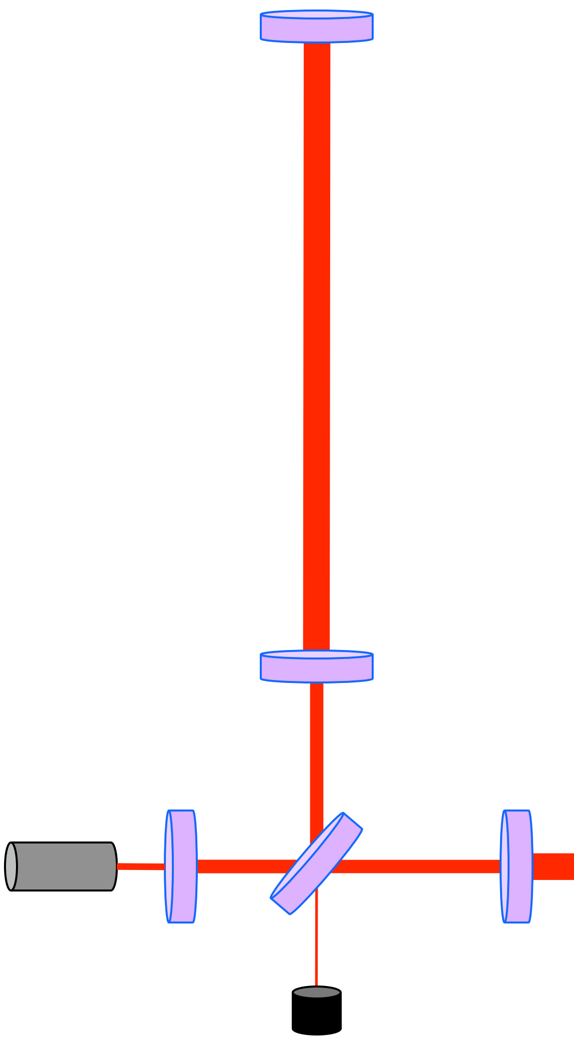
Drew Keppel
for the LIGO Scientific Collaboration and Virgo Collaboration

LIGO Laboratory
California Institute of Technology

University of Texas – Brownsville, 5 March 2010

LIGO-G1000145-v2

The Detectors



Credit: LIGO Lab

Credit: LIGO Lab

© Eurelios 2000

- Michelson Interferometers at their core
  - » Sensitive to differential displacements
- Gravitational-waves cause stretching and squeezing detectable by interferometers
- Kilometer scale detectors now have strain sensitivities below 10^{-22} $Hz^{-1/2}$

Gravitational-Wave Generation

Electromagnetism

$$\Box^2 A^\mu = 0$$

I. Electric-charge monopoles

II. Electric-charge dipoles

III. Electric-current dipoles

IV. Electric-charge quadrupoles

General Relativity

$$\Box^2 h^{\mu\nu} = 0$$

I. Mass monopoles — **Energy Conservation**

II. Mass dipoles — **Linear Momentum Conservation**

III. Mass current dipoles — **Angular Momentum Conservation**

IV. Mass quadrupoles

Types of
Gravitational-Wave Sources

Astrophysical Sources

- Stochastic Background
  - » Primordial background
  - » Phase Transitions
  - » Cosmic strings
- Continuous Waves
  - » Mountains in rotating pulsar
  - » Quadrupole-producing oscillation modes of pulsars
- Unmodeled Gravitational-Wave Transients
  - » Supernova
  - » ???
- Modeled Gravitational-Wave Transients
  - » Binary combinations of neutron stars and/or black holes
  - » Travelling cusps on cosmic strings
  - » Ringdowns of neutron stars or black holes

LIGO

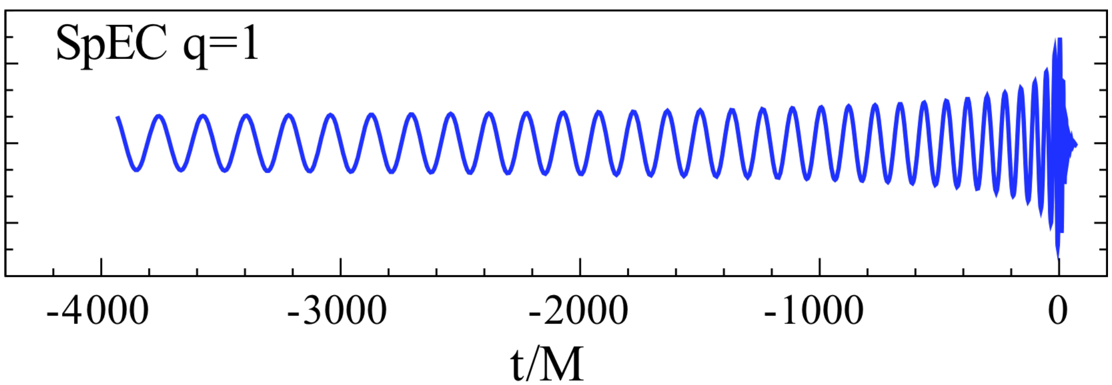
LSC LIGO Scientific Collaboration

VIRGO

Compact Binary Coalescence Waveforms

Waveforms from Coalescing Binaries

- Complete CBC waveforms consist of three phases
  - » Inspiral
  - » Merger
  - » Ringdown



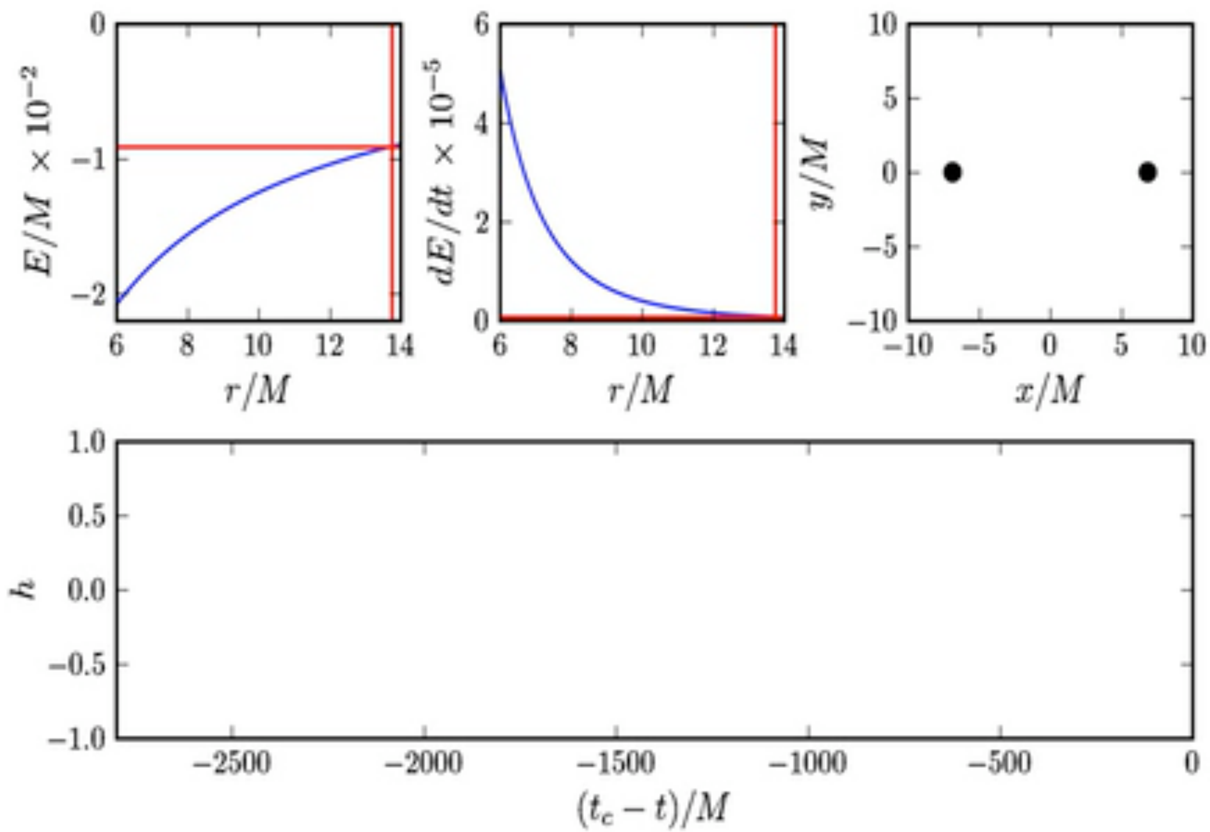
M. Scheel et al, PRD **79** 024003 (2009)
The First NINJA Project, arXiv:0901.4399v1 [gr-qc]

Waveforms from Coalescing Binaries

- Inspiral phase governed by post-Newtonian theory
  - » Binaries inspiral through energy loss due to GW emission

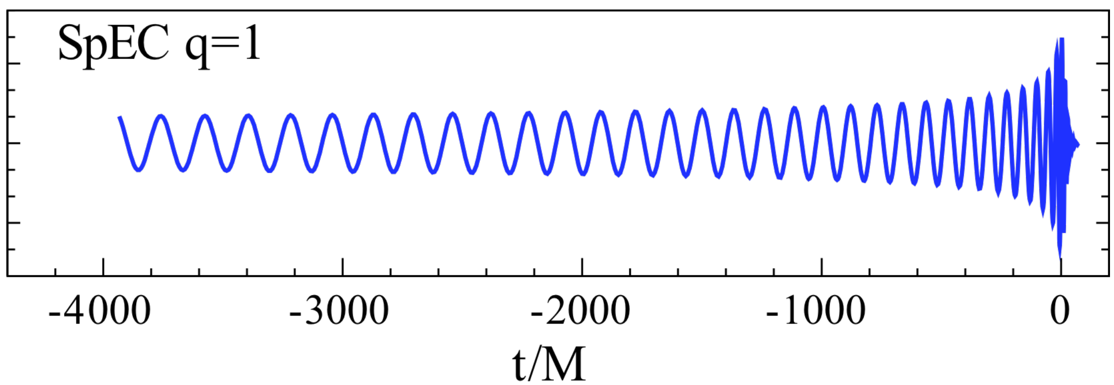
$$E = -\frac{1}{2}\frac{\mu M}{r}$$

$$\frac{dE}{dt} = \frac{32\mu^2 M^3}{5r^5}$$



Waveforms from Coalescing Binaries

- Inspiral phase governed by post-Newtonian theory
  - » Binaries inspiral through energy loss due to GW emission
- Ringdown phase governed by black-hole perturbation theory
- Merger phase explored with numerical relativity



M. Scheel et al, PRD **79** 024003 (2009)
The First NINJA Project, arXiv:0901.4399v1 [gr-qc]

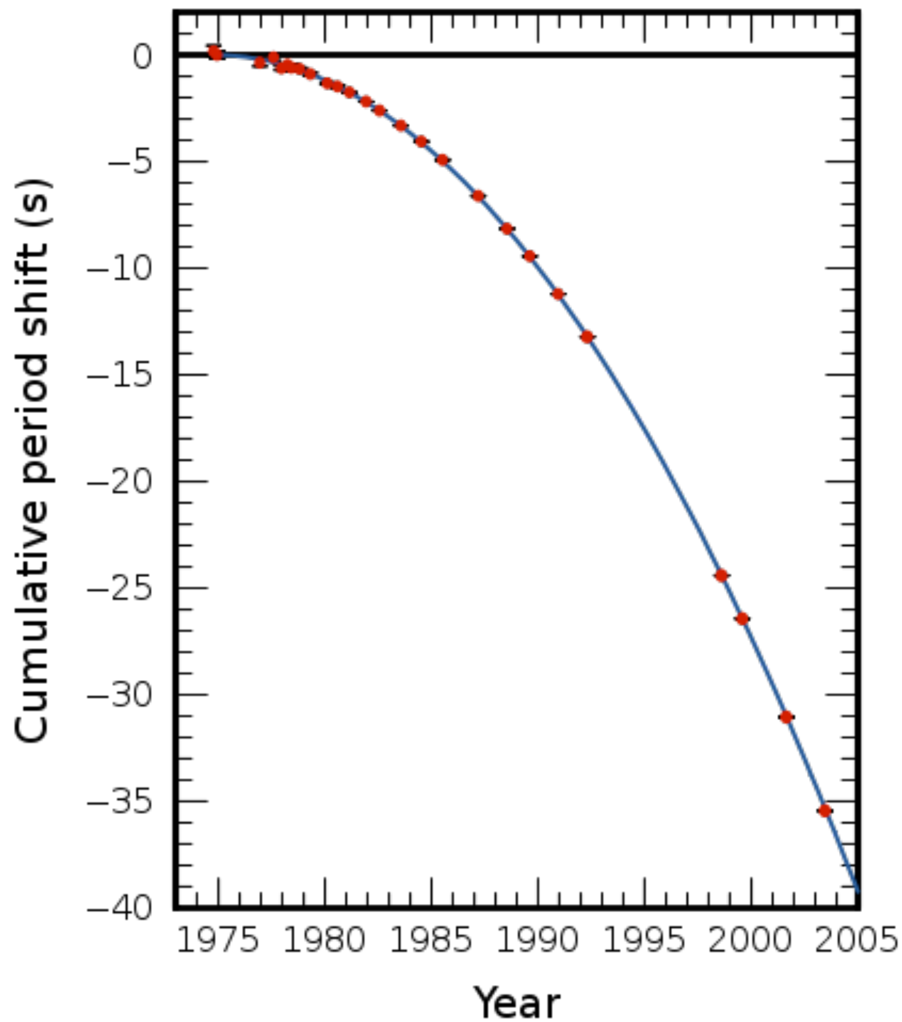
Inferring Coalescence Rates

How do we know sources exist?

- Hulse-Taylor Pulsar, 1974
  - » Binary pulsar 1913+16
  - » Two similarly sized objects
  - » Separation of less than Earth-Moon distance
  - » Orbital period of ~8 hours…

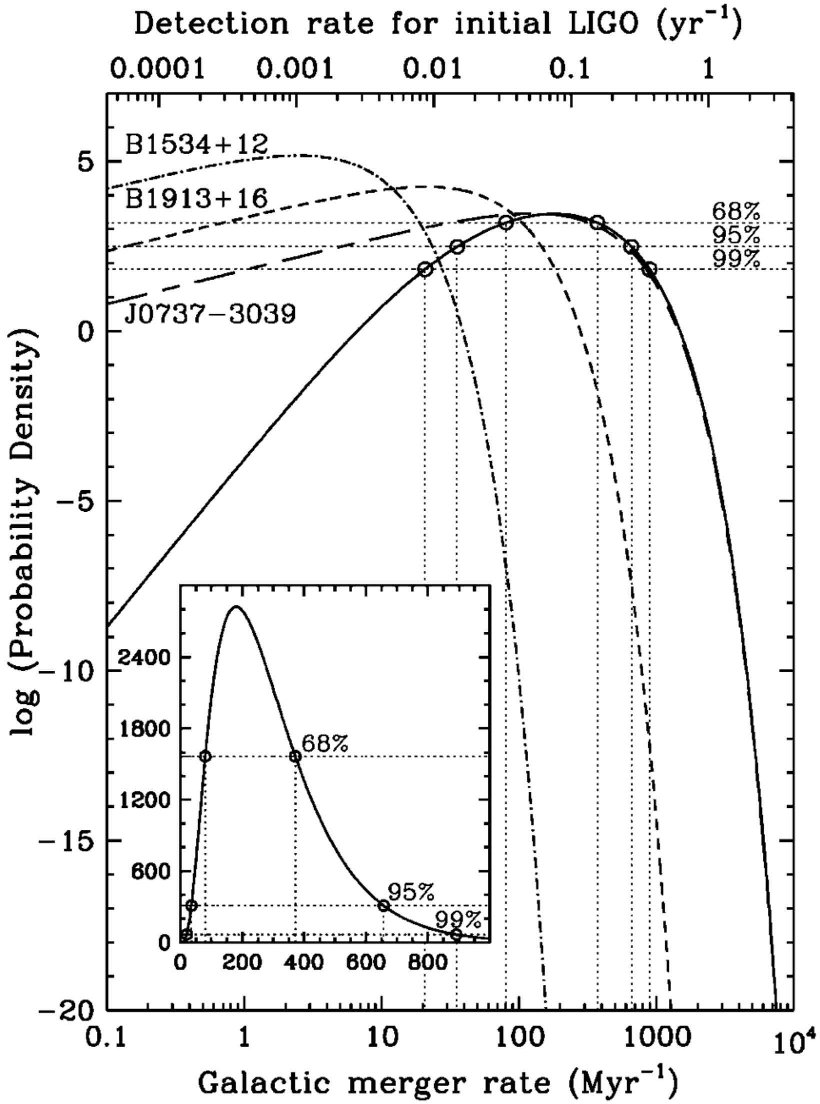
  …and shrinking!

- Orbital energy loss consistent with GR to ~0.2%
- Will be a signal for LIGO in 300 Myr



J. M. Weisberg and J. H. Taylor, *Relativistic Binary Pulsar B1913+16: Thirty Years of Observations and Analysis*, July 2004

Expected Merger Rates

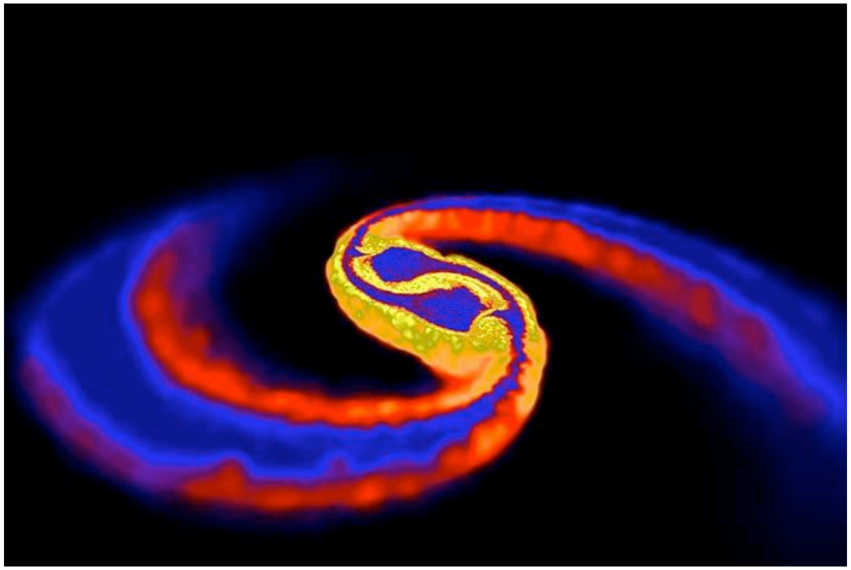


- Compact binary pulsar observations
  - » We have seen some systems which will merge soon
  - » Haven't seen them all
  - » Estimate how many we haven't seen

Kalogera *et al.*, ApJ Lett, **601** (2) L179 (2004)

Expected Merger Rates

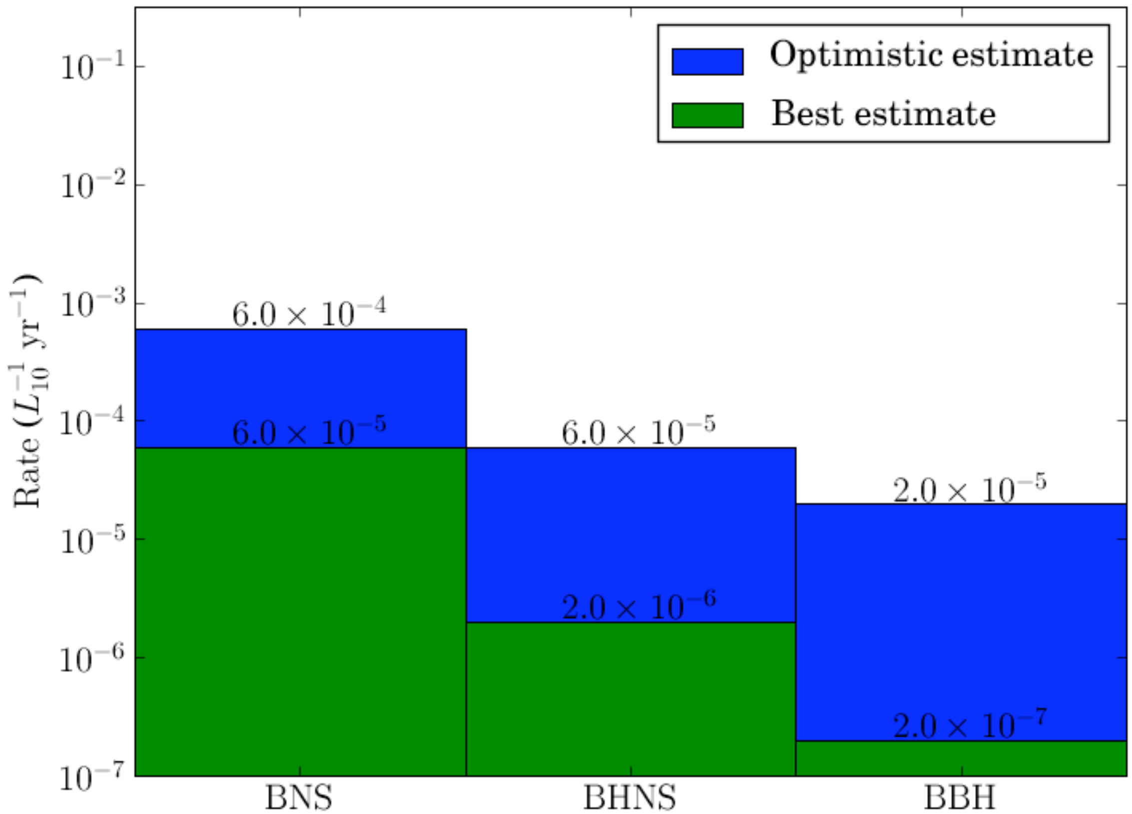
- Short gamma-ray bursts
  - » assumed to be associated with binary coalescences involving neutron stars
- Estimate coalescence rate based on observed short GRB rate
- Predicted rates can vary based on beaming angle of GRB sources



NS-NS Simulation
Credit: Price and Roswog

Expected Merger Rates

- Produce rate estimates for different mass systems
- Rates vary depending on method of estimation
- Summarize optimistic and best estimates



Rate Estimate Summaries from LIGO-P0900125

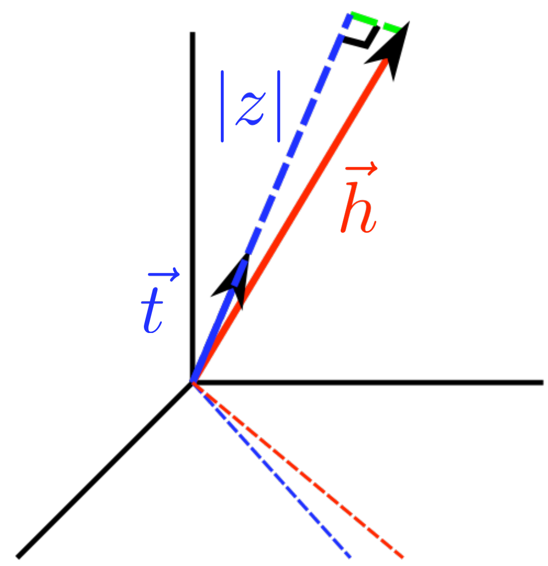
Search Techniques

How to search for a known signal

- Matched Filtering is the optimal way of searching for a known signal

$$z(t) = 4\Re \int_0^\infty \frac{\tilde{t}^*(f)\tilde{h}(f)}{S_n(f)} e^{2\pi i f t} df$$

- Can be seen as projecting the data onto the direction of a unit template waveform

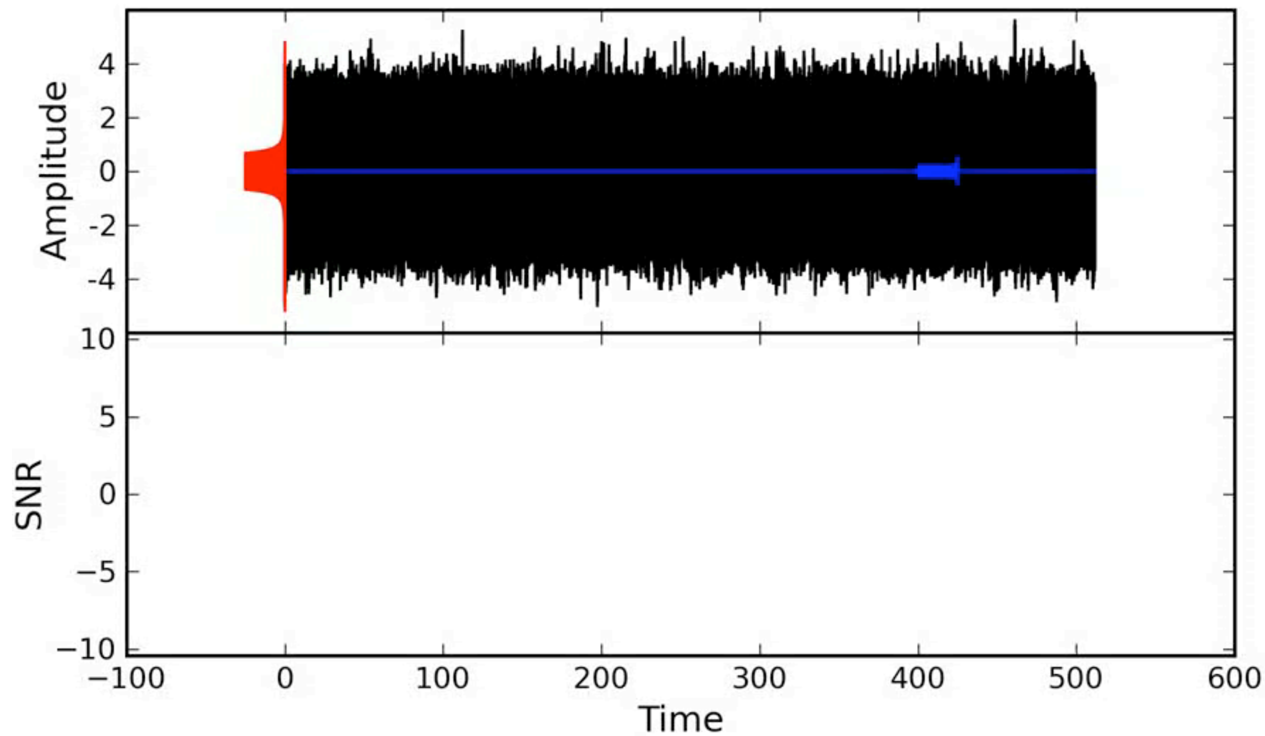


- Produce “triggers” from peaks in the SNR

How to search for a known signal

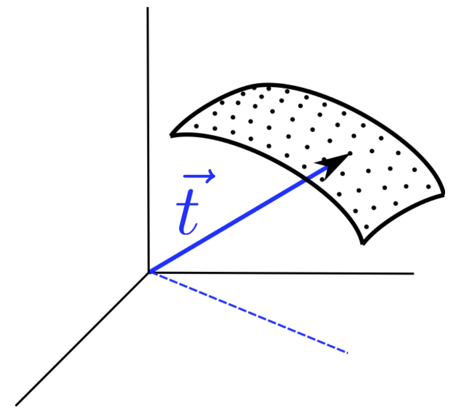
- Matched Filtering is the optimal way of searching for a known signal

$$z(t) = 4\Re \int_0^\infty \frac{\tilde{t}^*(f)\tilde{h}(f)}{S_n(f)} e^{2\pi i f t} df$$

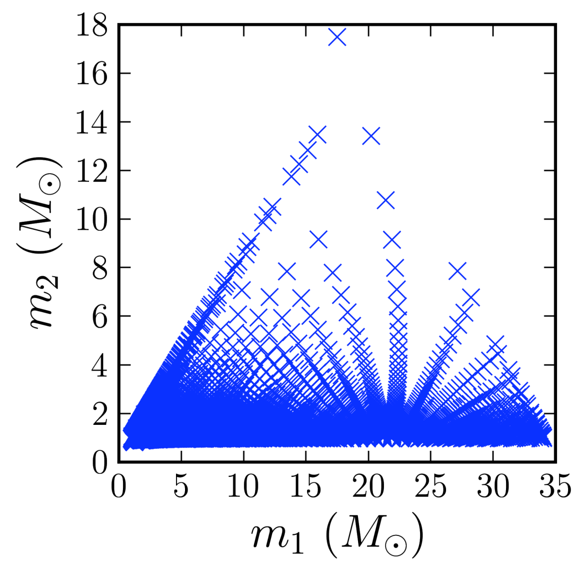


Template Banks

- For a given region of parameter space, matched filter data against many template waveforms

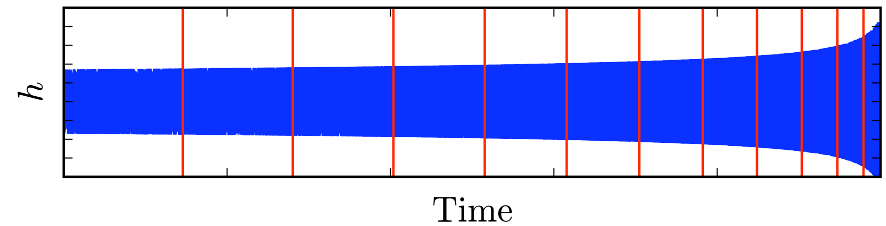


- Density of templates determined by fraction of signal power we are willing to miss
  - » the "mismatch" between the signal and any template

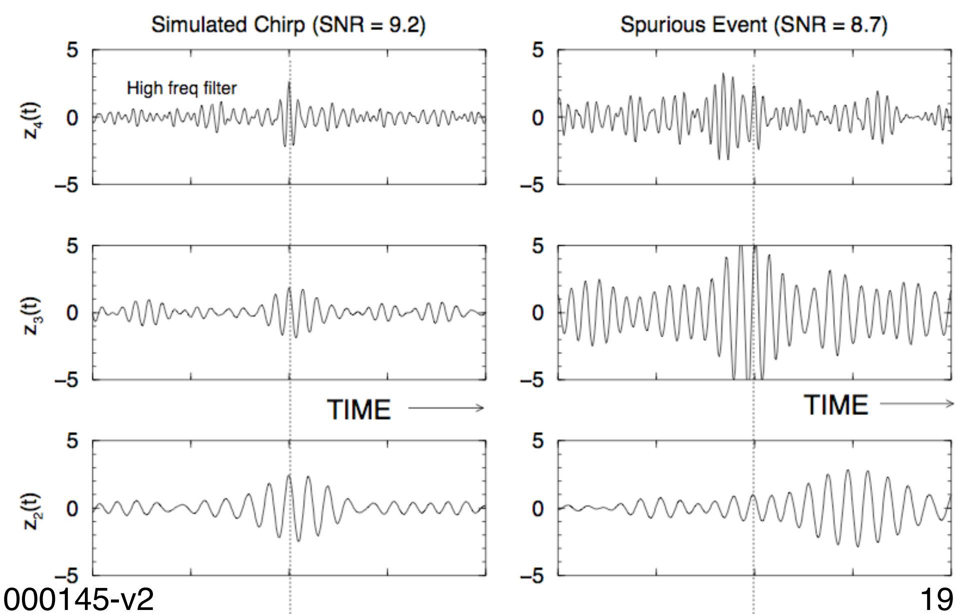


Signal-Based Vetoes

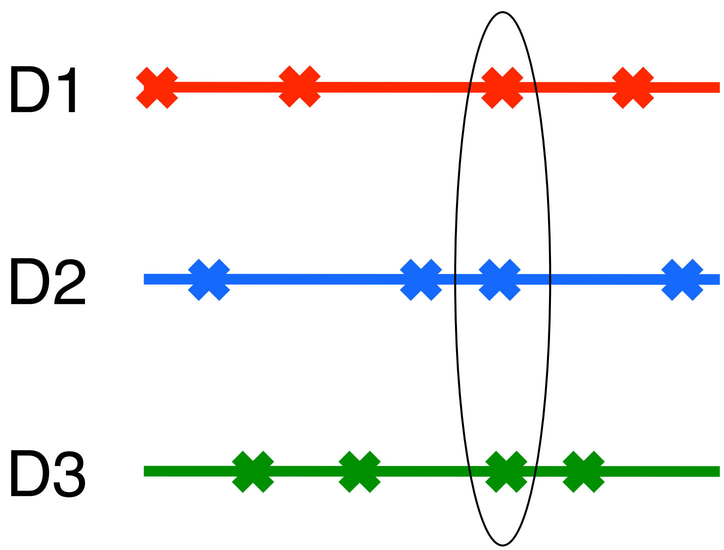
- SNR is optimal statistic in Gaussian noise
- Real detector data contains non-Gaussian glitches
- Use signal-based vetoes to separate signals from glitches



$$\chi^2 = \sum_{i=1}^{p} \left(|z_i| - \frac{|z|}{p} \right)^2$$



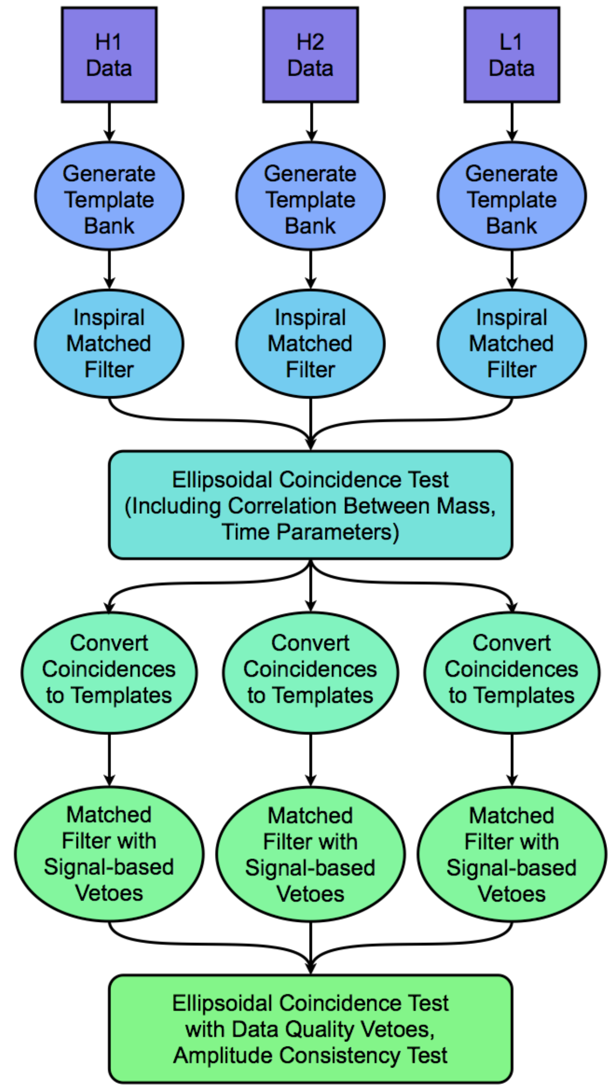
Coincidence



- Require coincidence between multiple detectors
  - » Time consistency
  - » Mass consistency
- Reduces false alarm rate

Putting it all together

- Hierarchical two-stage pipeline
- Reduces computational cost
  - » Coincidence lowers number of number of times we compute the signal-based vetoes

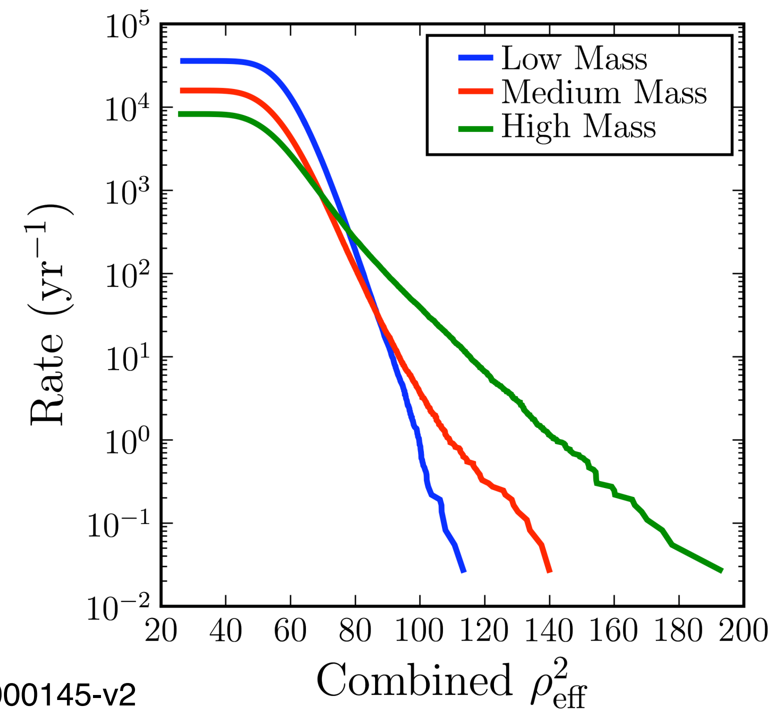


Detection Statistics

- Rank triggers using detection statistic
  - » Efficiently separates signal from background
  - » Example: effective SNR

$$\rho_{\mathrm{eff}}^2 = \frac{\rho^2}{\sqrt{\left(\frac{\chi^2}{\mathrm{D.o.F.}}\right)\left(1+\frac{\rho^2}{250}\right)}}$$

- Use likelihood information to rank triggers from different portions of parameter space
  - » Example: high mass templates more affected by non-Gaussian glitches

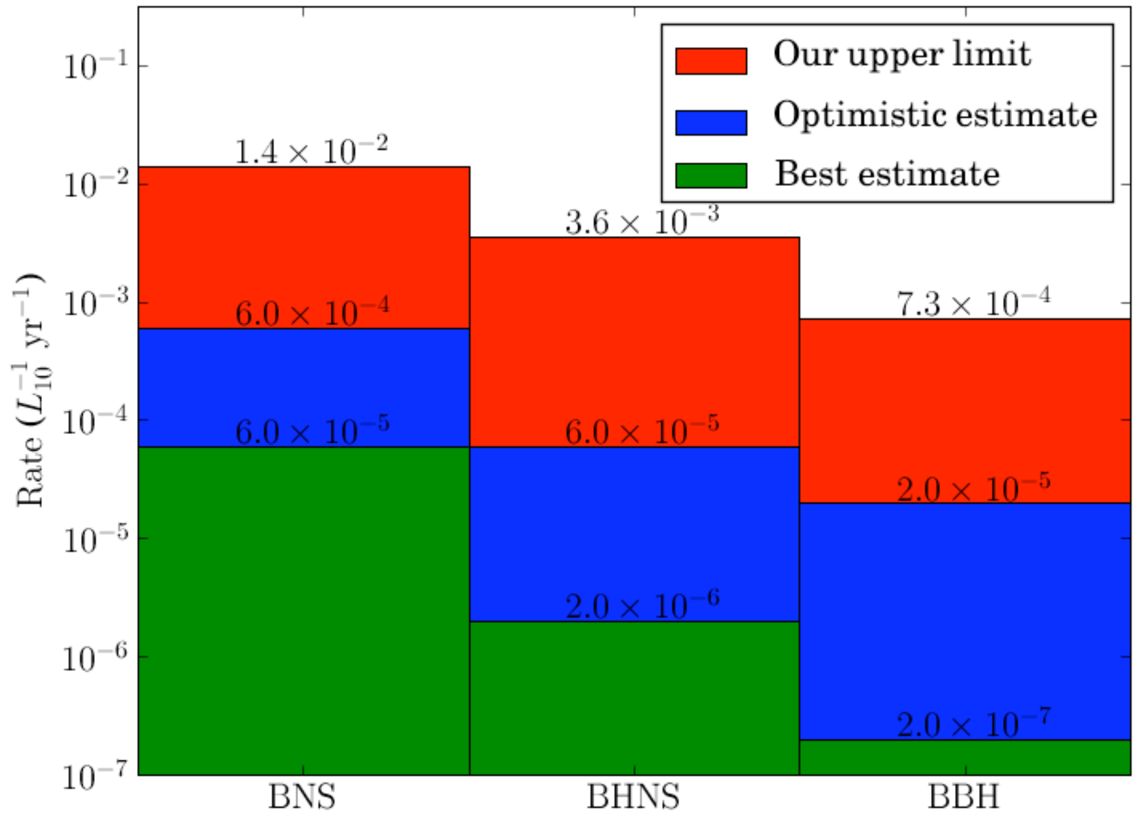


Types of Searches

- All-sky searches
  - » Search for signals coming at any time and from any direction
  - » Examples include the low mass and high mass CBC searches

All-Sky Low Mass CBC Search Results

- Use inspiral-only templates
  - » Component Masses > 1 $M_\odot$
  - » Total mass up to 35 $M_\odot$
- Results combined from S3, S4, and S5*
- Less than two orders-of-magnitude away from the optimistic estimates

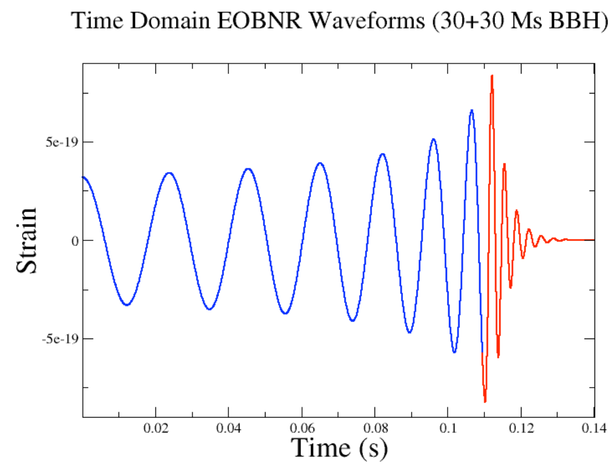


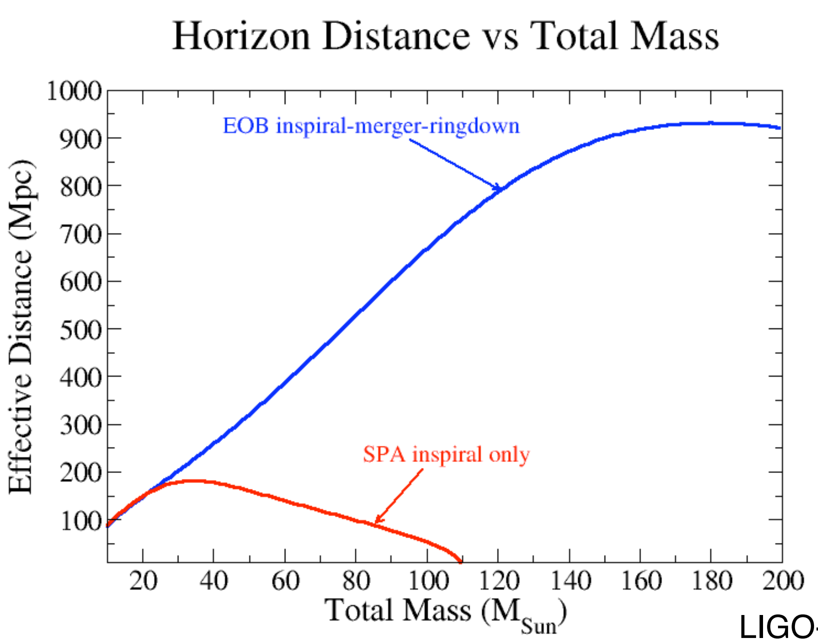
Upper Limits
Phys. Rev. D, **80** 047101 (2009)

*Joint S5 / VSR1 analysis complete and under internal review

All-Sky High Mass CBC Search

- Use Effective-One-Body templates tuned to numerical relativity
  - » Includes inspiral, merger, and ringdown phases of the waveform





- Larger reach for higher masses
- S5 search parameters
  - » Component masses > 1 $M_\odot$
  - » Total mass 25 to 100 $M_\odot$
- Search complete, review ongoing

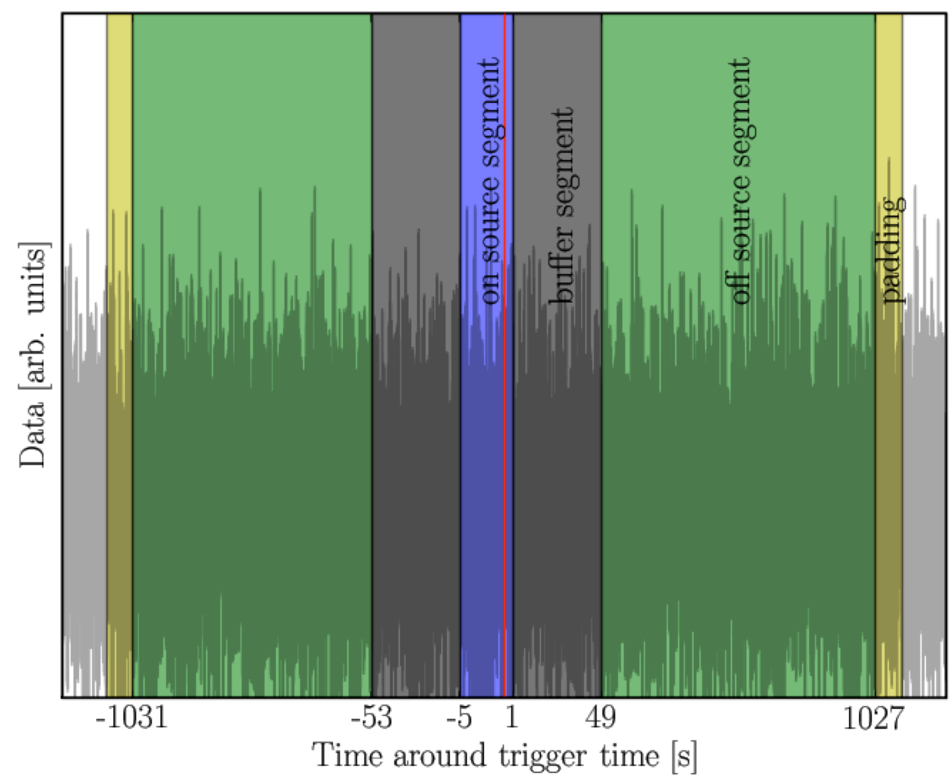
Types of Searches

- All-sky searches
  - » Search for signals coming at any time and from any direction
  - » Examples include the low mass and high mass CBC searches
- Trigger searches
  - » Search data from a particular time and sky-position, digging down into the noise
  - » Examples are the searches associated with short GRBs

Triggered Searches

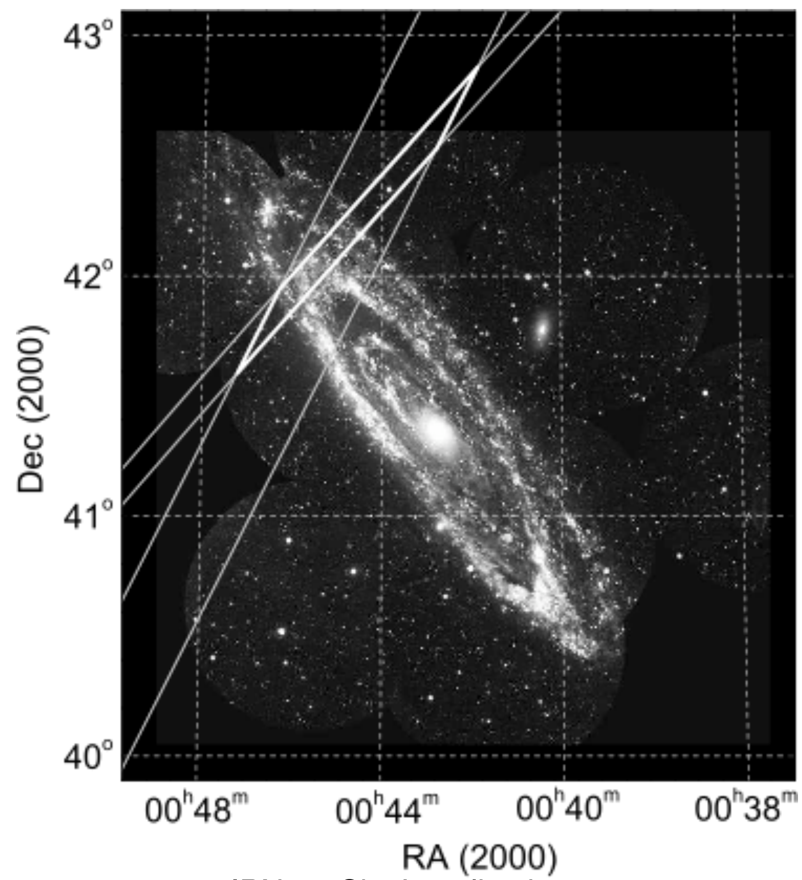
- Searches for CBC signals associated with short GRBs analyze less data

- Use off source segments to estimate background and sensitivity of the on source region



Connecting to Astronomy: GRB070201

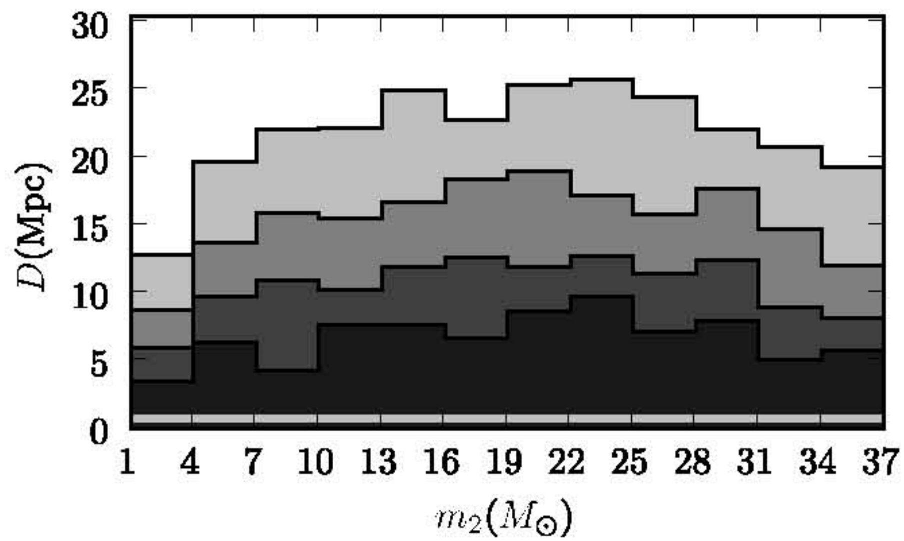
- Error box for sky localization intersected the arms of M31, D < 1 Mpc
- 2 Hanford LIGO detectors operating at this time
- LIGO in the perfect position to make a statement on this event



IPN 3σ Sky Localization
Mazets et al, ApJ 680, 545 (2008)

Connecting to Astronomy: GRB070201

- LIGO able to rule out that there was a CBC signal associated with this GRB from M31 with >99% confidence
- If this were a BNS merger, LIGO could exclude D < 3.5 Mpc at 90% confidence
- Higher mass progenitors excluded to higher distances



Ap.J. **681**(2):1419–1430 (2008); arXiv:0711.1163

What can we learn?

- Observation of CBC signals will affect our knowledge in a number of ways

- BNS / BHNS observations out to 100 Mpc ➔ NS equation of state
  - » Observations of high frequency components are essential
  - » NSs distinguishable from point-particles
  - » NS pressure could be constrained
  - » NS radius measurement accuracy >1km

Read et al, Phys. Rev. D, **79** 124033 2009

- Multiple detections can be used to infer underlying event population

I. Mandel, arXiv:0912.5531v1

Current Data Analysis Issues: Reducing Latency

Template Banks

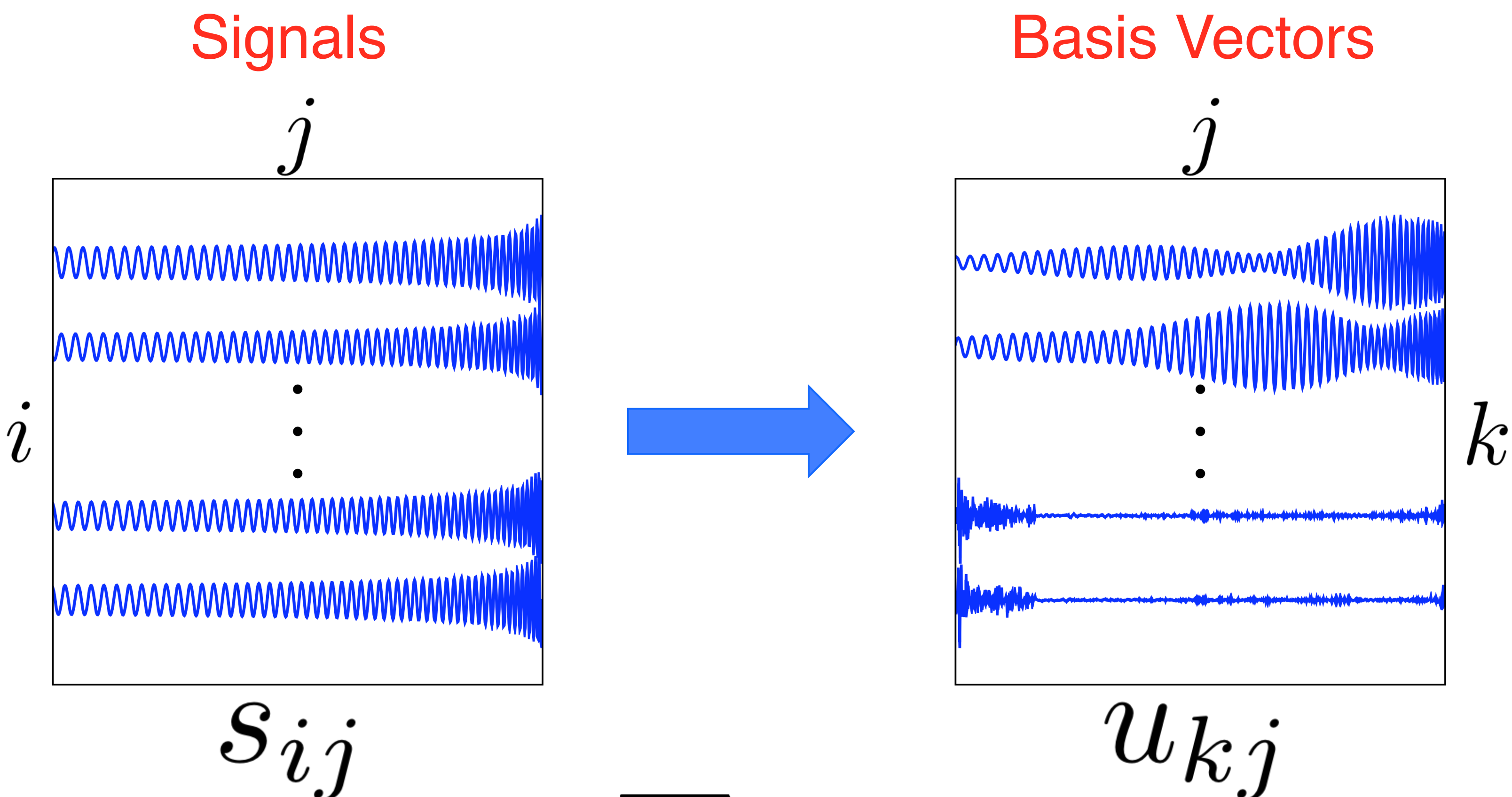
- Neighboring templates highly overlapping
  - » Standard is to tolerate 3% SNR loss
- Decomposing templates into a set of orthonormal vectors using Singular Value Decomposition
- Ranks basis vectors by their singular values
- Identifies low singular-valued basis vectors, which can be discarded without losing much reconstruction accuracy

$$s_{ij} = \sum_k \sigma_k v_{ik} u_{kj}$$

$$\sum_i u_{ji} u_{ki} = \delta_{jk} \, , \, \sum_i v_{ij} v_{ik} = \delta_{jk}$$

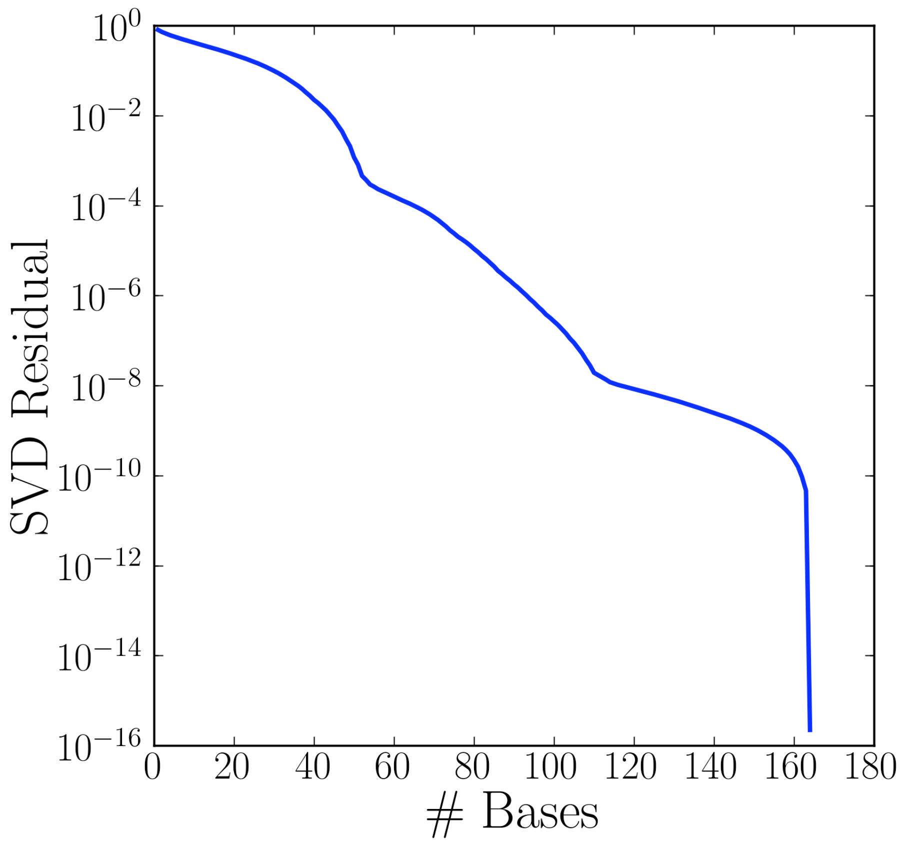
$$\tilde{s}_{ij} = \sum_{k=0}^{r} \sigma_k v_{ik} u_{kj}$$

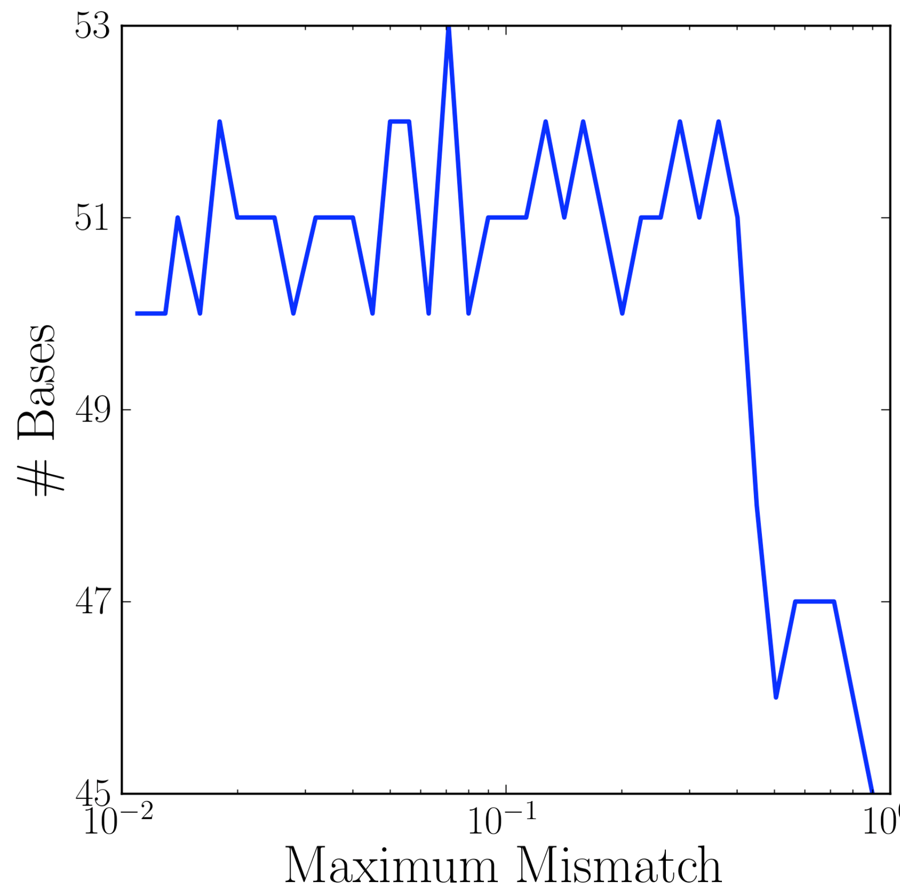
Singular Value Decomposition: CBC Waveforms



$$s_{ij} = \sum_k \sigma_k v_{ik} u_{kj}$$

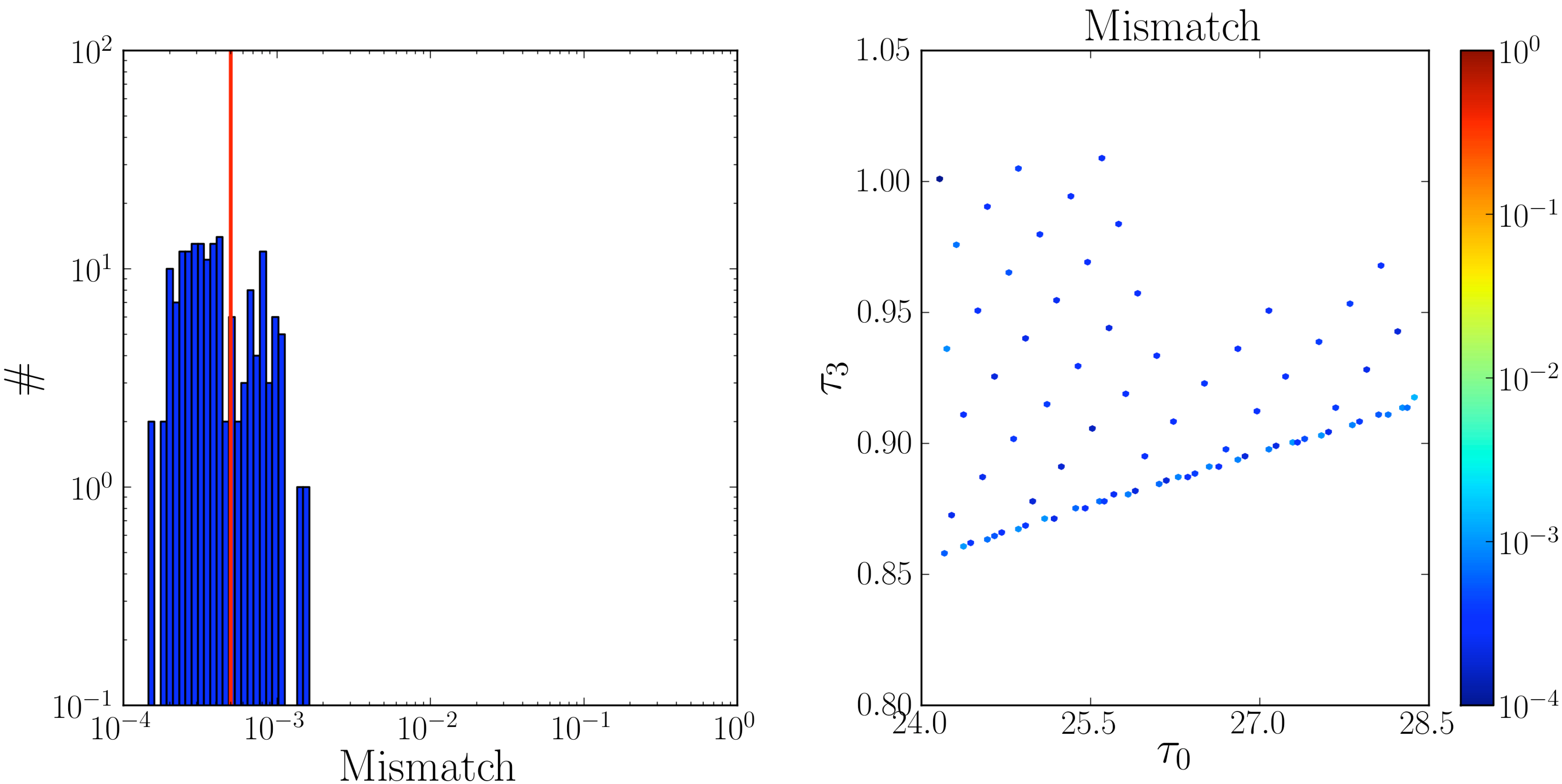
SVD Residual





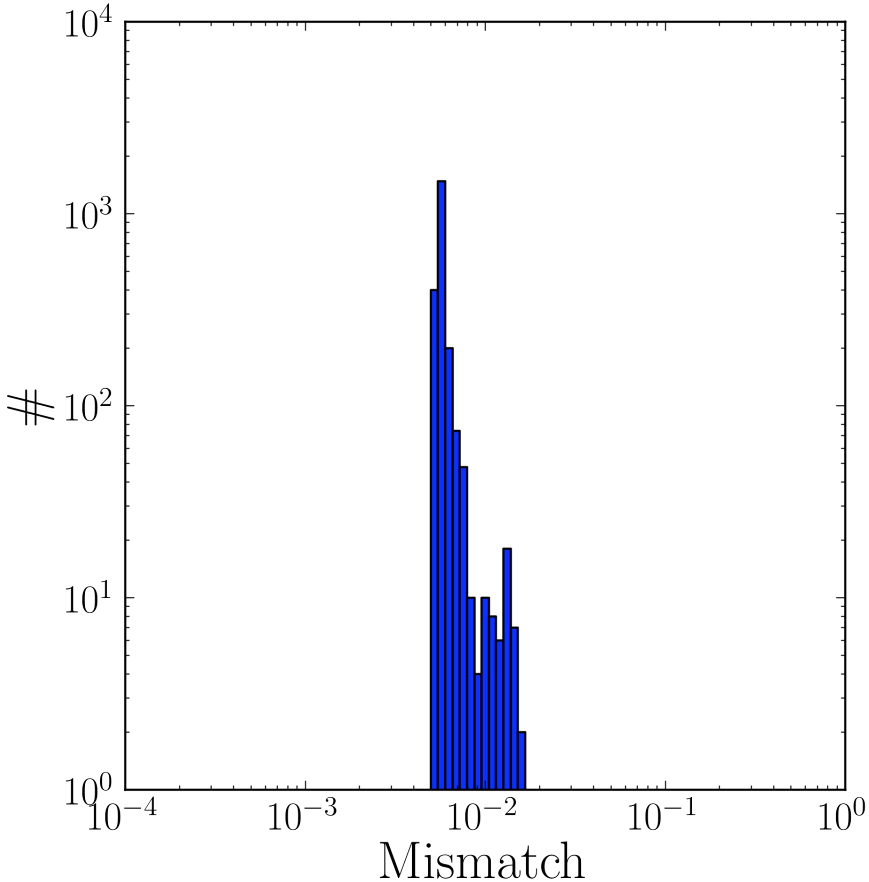
- Fraction of singular values discarded gives the SVD residual
- For a given residual and parameter space, the number of basis vectors is independent of template bank density

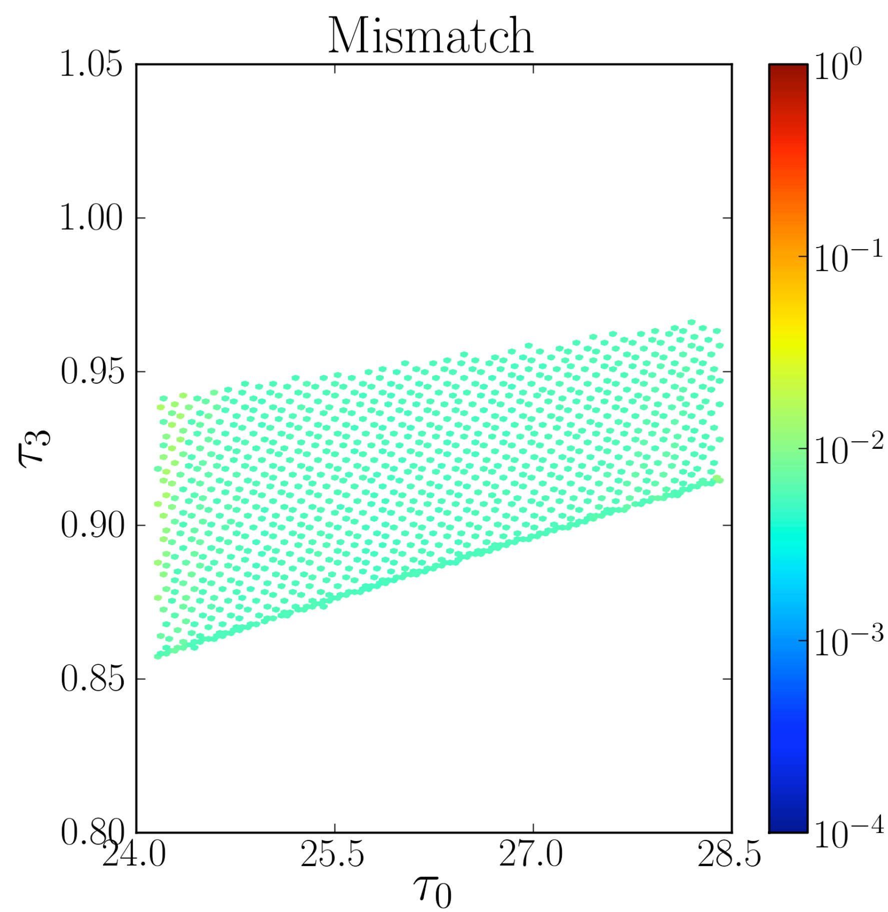
Reconstruction Accuracy of Template Bank



- SVD residual identifies rough amount of SNR loss
- Worst reconstruction occurs at edges of parameter space

Reconstruction Accuracy of Signal Manifold



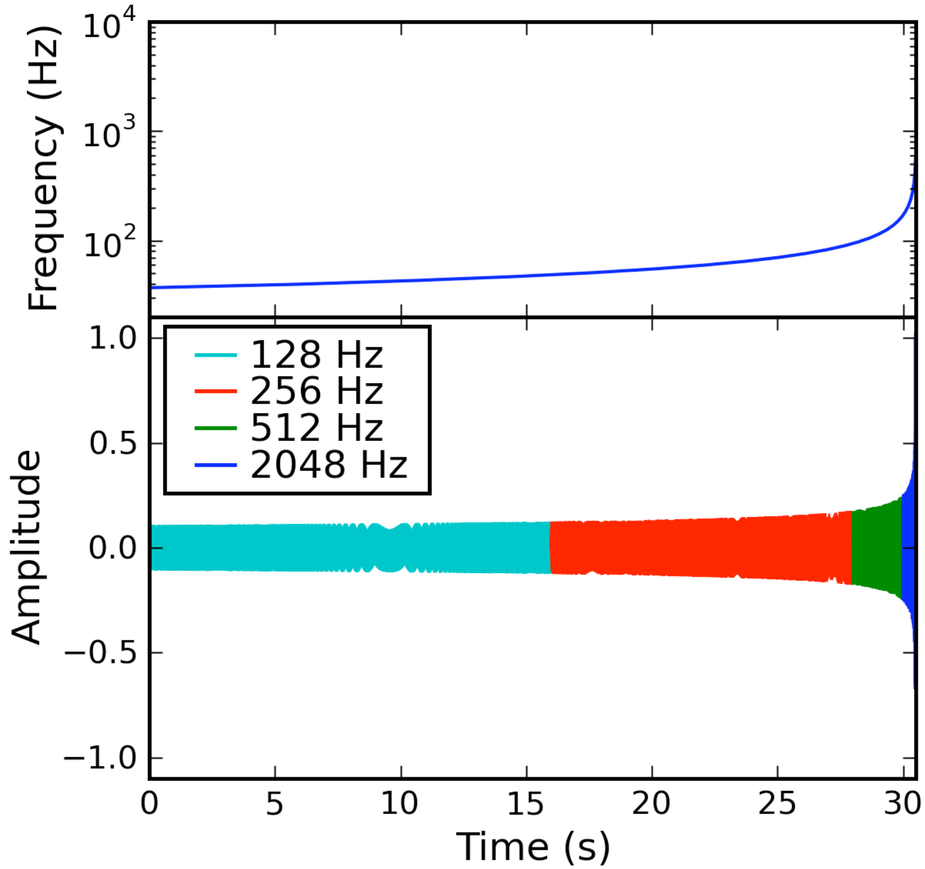


- Same basis vectors can be used to reconstruct other waveforms in within the parameter space

$$v'_{ik} = \sum_j s_{ij} u_{kj}$$

Multi-Band Analysis

- Standard CBC waveforms are quasimonochromatic with monotonically increasing frequency
- Filter earlier parts of waveforms using lower sample rates
  - » Example lowers filter cost by factor of >8
- Introduced to GW community in Virgo's MBTA pipeline*



*F. Marion, Proceeding of XXXVIIIth Recontres de Moriond, 2004

Advanced Detector Pipeline

- Employ latency saving techniques
- Change data analysis strategy to process data in streaming mode
- Based on open source, multimedia software “Gstreamer”
  - » Provides stock data analysis “elements”
  - » Links elements together seamlessly