Title: Tackling the Challenges of Gravitational-Wave Astronomy

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Abstract: Gravitational radiation promises to teach us many new things about the universe and the world around us, but all attempts to observe gravitational waves have so far been unsuccessful. I will discuss some of the challenges we need to overcome in our quest to detect this elusive form of energy, and how tackling these challenges is opening new windows on fundamental physics. I will show, specifically, how novel data analysis strategies have been used to combat detector noise in searches for gravitational waves from cosmic strings, and how the search for the signatures of neutron star collisions has created new techniques for modelling the mergers of compact objects.

Tackling the Challenges of Gravitational-Wave Astronomy

Kipp Cannon

Perimeter Institute, Waterloo, May 15th 2013

What is This?

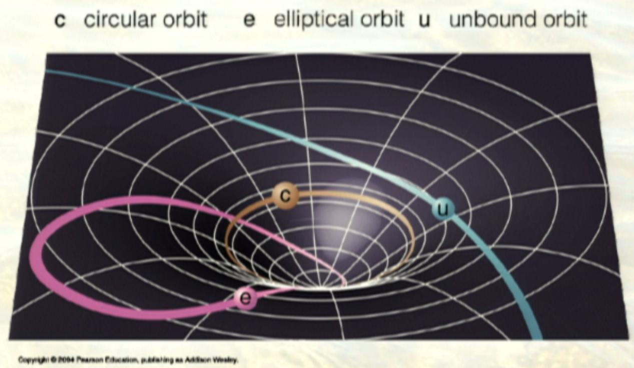
- I'm a senior research associate at the Canadian Institute for Theoretical Astrophysics.
- For the past 8 years I have been a member of the LIGO Scientific Collaboration (LSC) engaged in the search for gravitational waves using the LIGO, GEO600, and Virgo gravitational-wave antennas.

What is This?

- I'm going to talk about
  - what gravitational waves are and what gravitational-wave astronomy is,
  - the challenges in searching for gravitational waves from cosmic strings and the collisions of compact objects,
  - some of the fun fall-out from the work I've done to address those challenges.
- Collaborators: Chad Hanna (Perimeter Institute), Drew Keppel (AEI, Hannover), Florent Robinet (LAL, Orsay), and many undergraduate and graduate students over the years.

What is Gravity?

- 1916 & 1918, Einstein published the general theory of relativity (GR).
- In GR, space and time are unified into a four-dimensional structure called spacetime.
- In GR, spacetime can be curved.
- Gravity is the observed consequence of the curvature of spacetime.

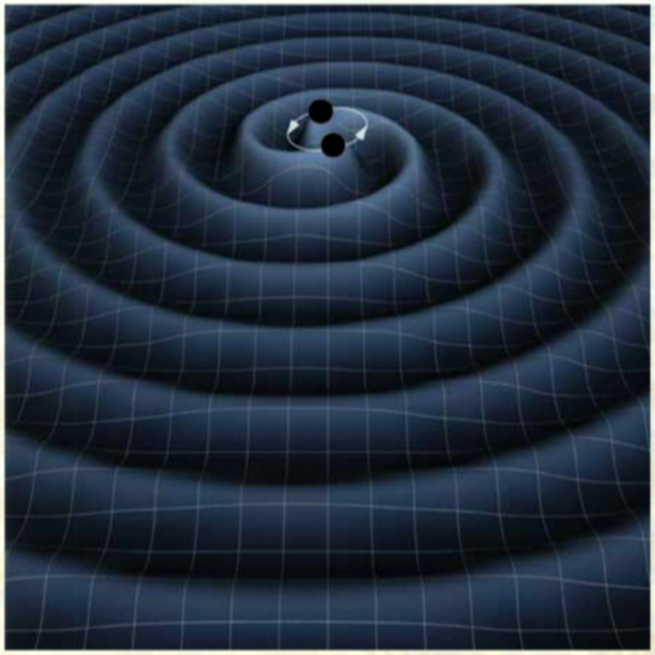


- Einstein's equation for the dynamics of spacetime,

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

makes a similar prediction,

$$\Box h_{\mu\nu} = 0.$$



- Says that accelerating a mass (a.k.a. gravitational charge) will result in it emitting a wave of spacetime curvature.
- A gravitational wave is a travelling warp in space and time.

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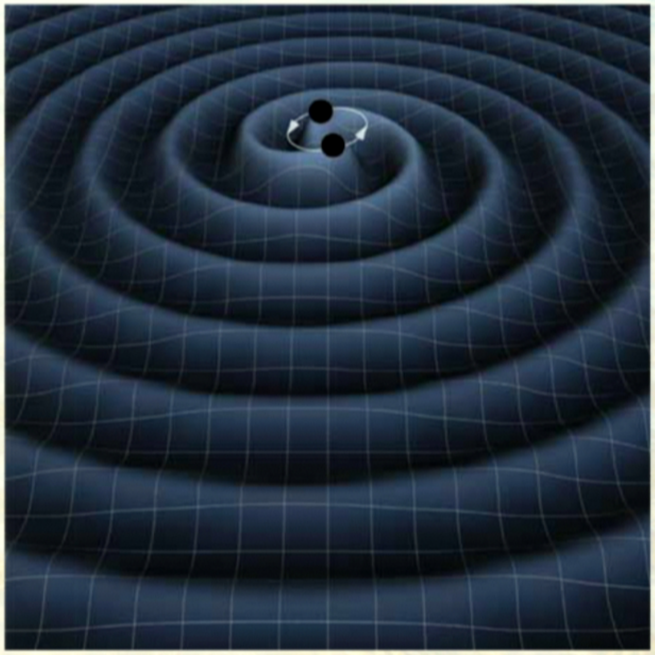

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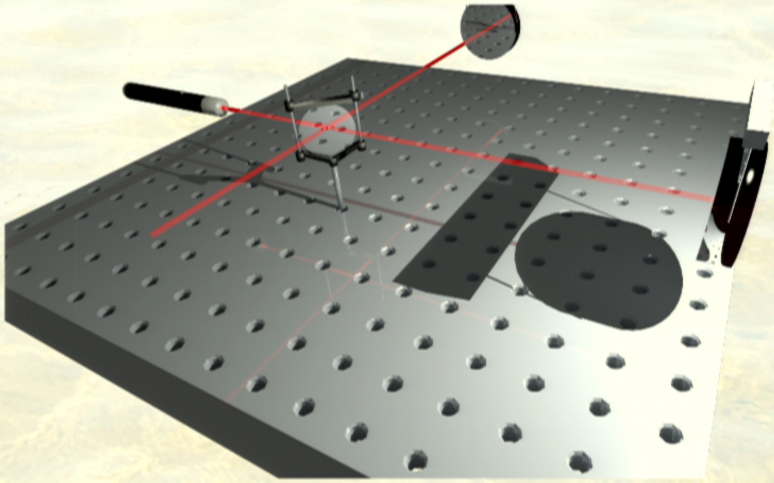
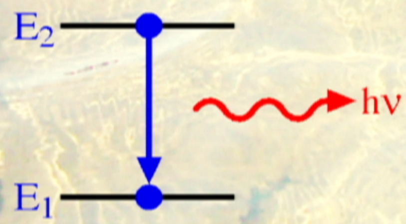
- Gravitational waves should be detectable using devices that respond to changes in the distance between things
  - Tuning forks
  - Laser interferometers



(image of Joseph Weber courtesy of LSU)

So What is Gravitational-Wave Astronomy?

- Instead of looking for light or radio waves from stars and other astronomical objects, we look for gravitational waves.
- Electromagnetic astronomy tells us about the movement of electric charges and currents in the objects that create the electromagnetic waves.
- Combining the observations with other knowledge (like atomic spectra measured here on Earth) we can infer many things:
  - the atomic and molecular composition of the material
  - how quickly the material is approaching or receding from us
  - how far away it is
  - its temperature



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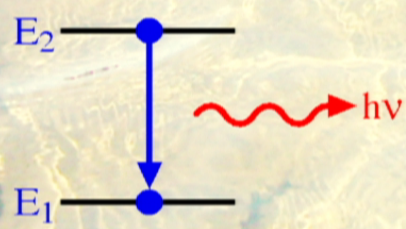


- Gravitational wave astronomy will tell us about the movement of the gravitational charges and currents — masses and momentum density — in the objects that create the gravitational waves.

- The brightest sources of gravitational waves will be objects with strong gravitational fields undergoing large accelerations.
- Colliding black holes.
- Colliding neutron stars (stars that have exhausted their fuel and collapsed to nuclear density material).
- Cosmic strings.

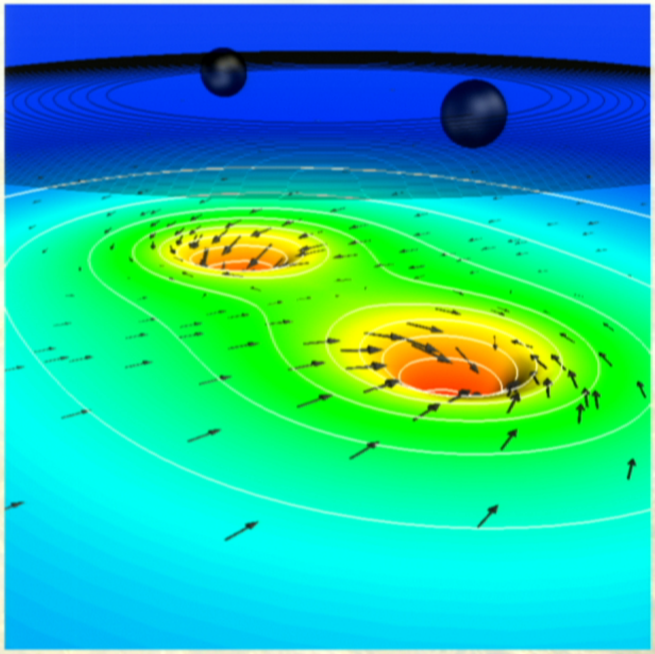
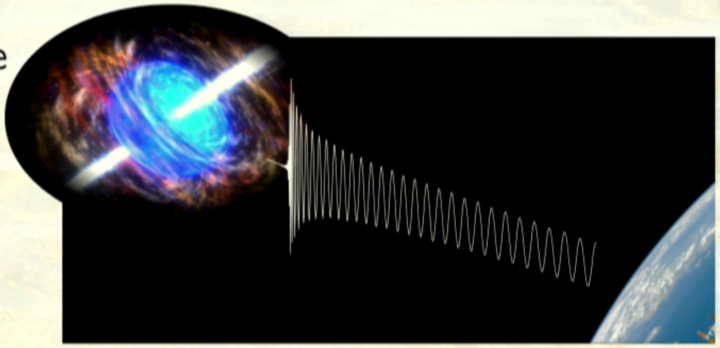


Image: Harald Pfeiffer

What do we hope to learn?

- Comparing observations with computer simulations of black hole and neutron star collisions can tell us:
  - if general relativity is the correct theory of gravity
  - the properties of the objects that collided (mass, rotation rate, equation of state, ...)
  - how far away they are



- Measuring the rate of collisions will teach us about the evolution of stars.
- Identifying bursts from cosmic strings can teach us about phase transitions in the early universe.

What are the challenges?

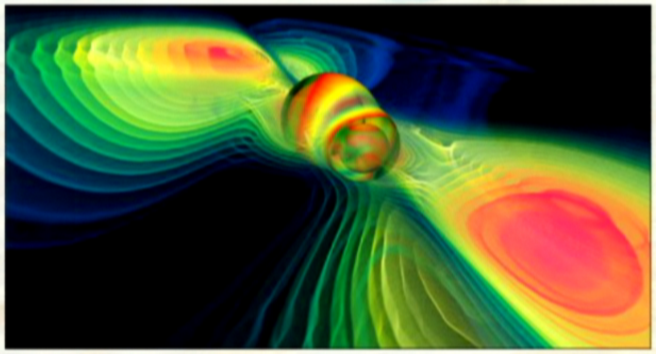


Image: MPI for Gravitational Physics/W.Benger-ZIB

- There's really only one: **gravitational waves are extremely weak.**
- $1.4M_\odot + 1.4M_\odot$ NS pair orbiting at $D = 50\,\mathrm{km}$ has orbital frequency of $f = 275\,\mathrm{Hz}$, $\dot{E} \sim 10^{46}\,\mathrm{W}$;
- $\odot = 10^{26.5}\,\mathrm{W}$;
- if located in Virgo cluster at $R = 17\,\mathrm{Mpc}$, then $\Phi \sim 200\,\mathrm{mW/m^2}$ at Earth;
- gravity is a very *very* stiff "trampoline": strain at Earth for same source $h \sim 10^{-21}$.

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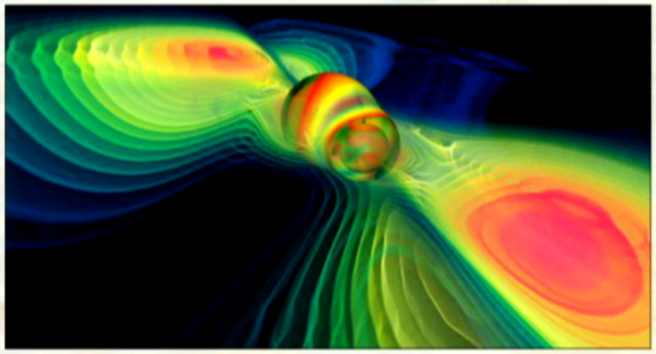

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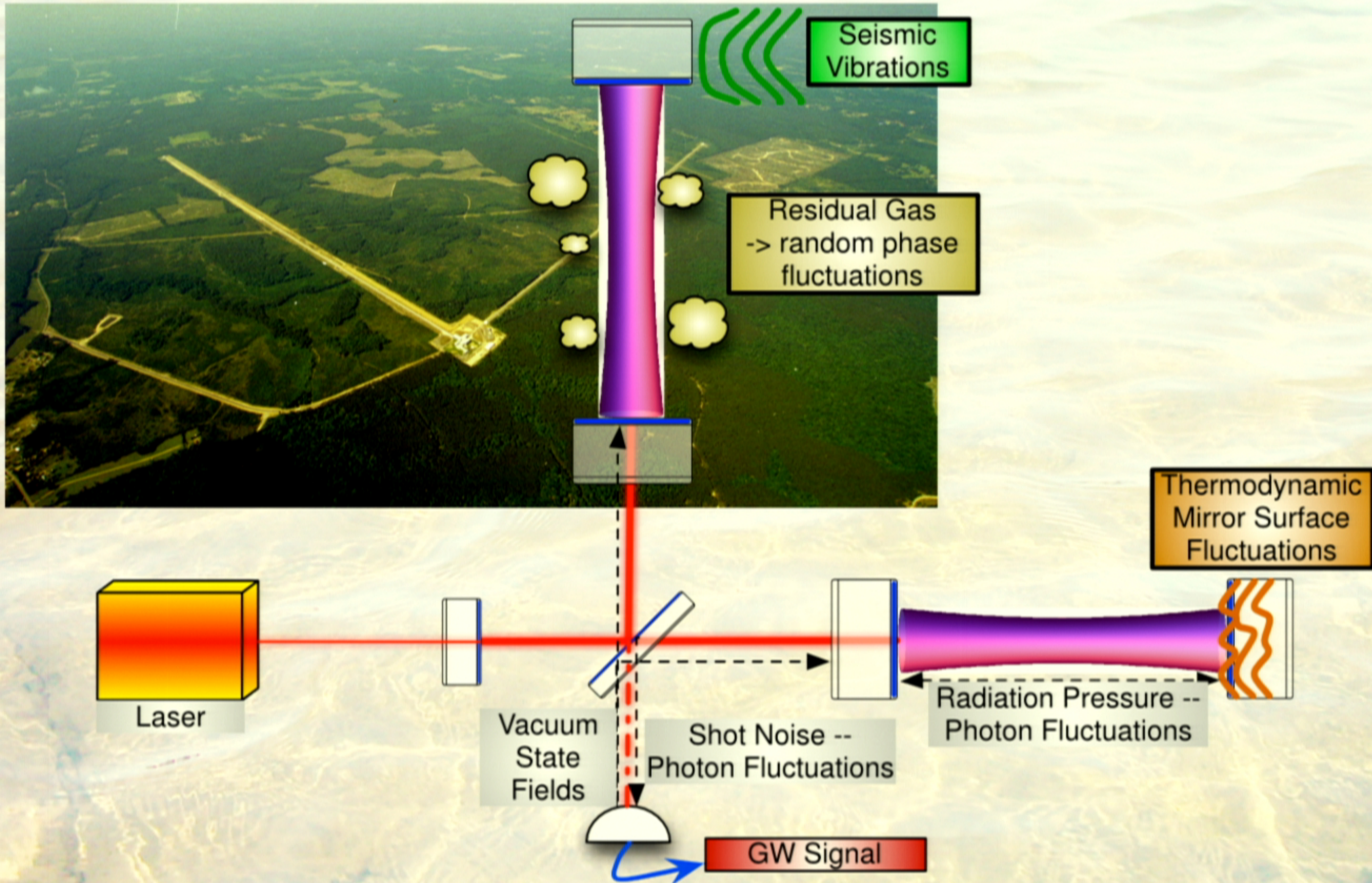
What is LIGO?

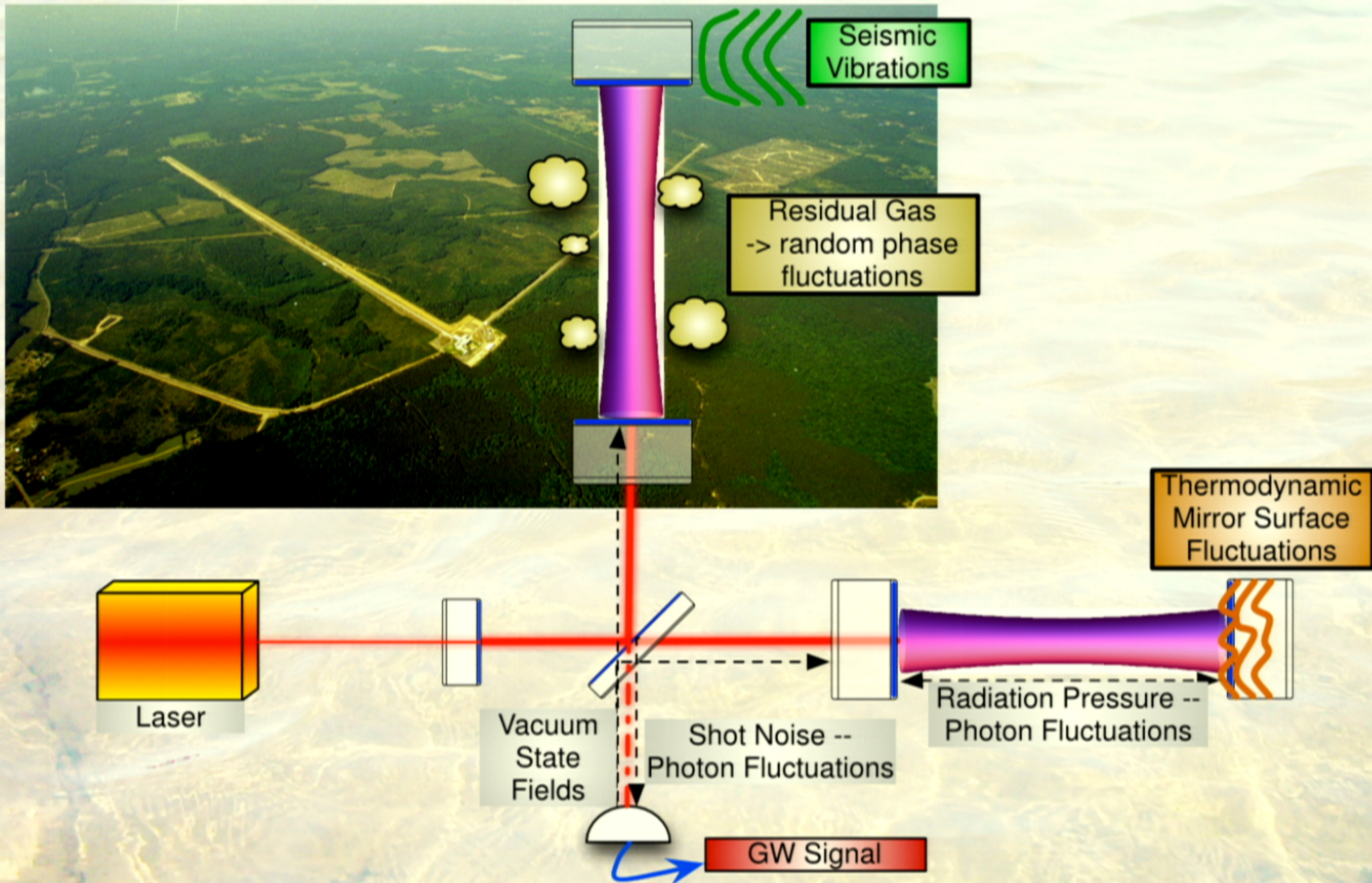
- NSF-funded project operated jointly by CIT and MIT.
- Two laser interferometers at two observatories:
  - One $4\,\mathrm{km}$ laser interferometer in Hanford, WA
  - One $4\,\mathrm{km}$ laser interferometer in Livingston, LA
- A 3rd $4\,\mathrm{km}$ laser interferometer to be built in India (LIGO-India or IndiGO).

Noise Sources



(graphic courtesy Rana Adhikari)

Noise Sources



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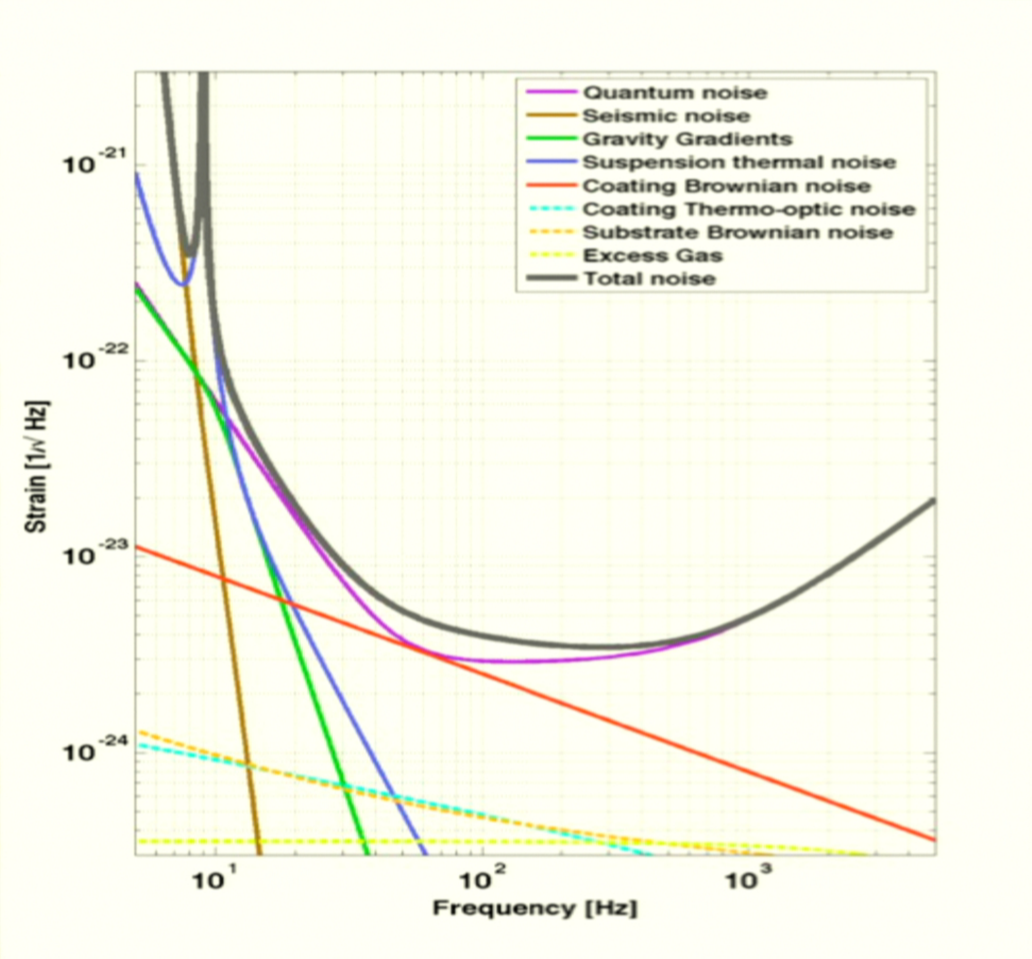
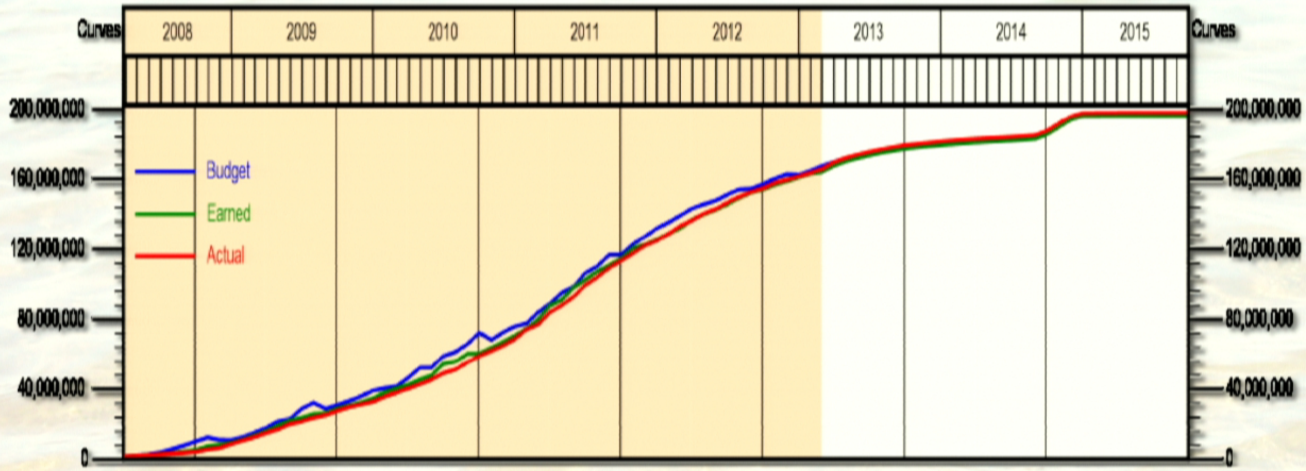


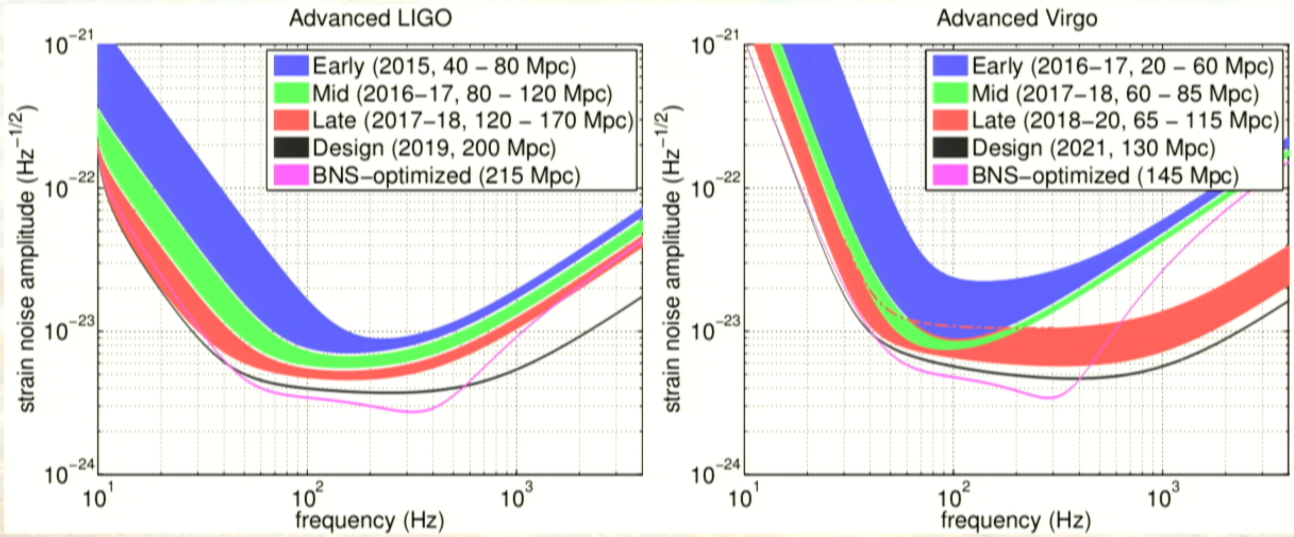
Current Status of aLIGO



(plot courtesy David Shoemaker)

- Budget reductions due to sequester being absorbed without science impact, e.g., by scale-back of LIGO Open Science Centre, and consumption of contingency funds.
- First "strain data" from L1 expected this month (dual-recycled inner Michelson cavity to become operational, no arm cavities).

Sensitivity Scenarios



(plots taken from arXiv:1304.0670)

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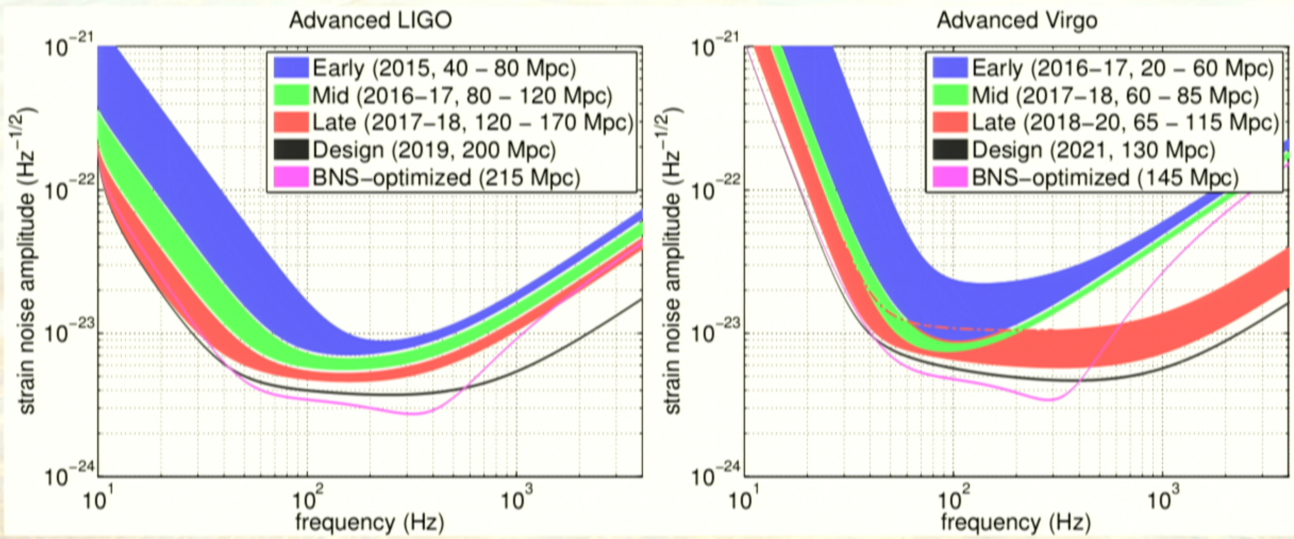
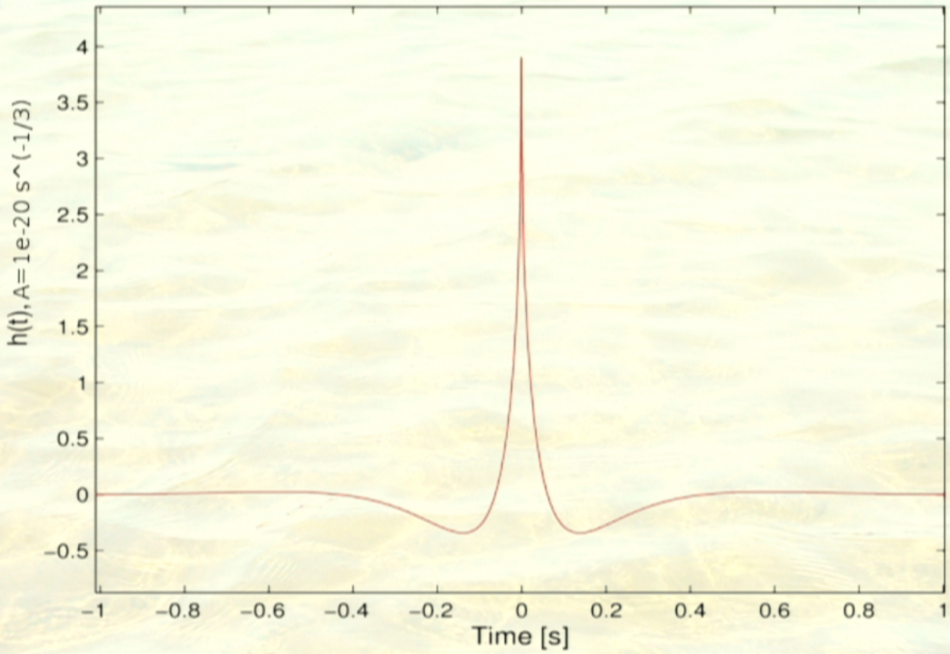


(plots taken from arXiv:1304.0670)

Search for Cosmic Strings

- Cosmic strings are hypothetical, thin, line-like concentrations of energy.
- They are a generic prediction of field theories, the result of phase transitions settling into different ground states in different regions of the universe.
- Strings are long — reach from one side of the universe to another.
- Once a contender for the source of the anisotropy that initiated galaxy condensation; CMB observations now reject this hypothesis and constrain string properties if they exist.

Waveform



GW strain of a string cusp. A low-frequency cut-off has been placed at $1\,\mathrm{Hz}$ for convenience, and a high-frequency cut-off at $500\,\mathrm{Hz}$. The high-frequency cut-off varies, being set by the angle between the string cusp direction of travel and the observer.

Finding Them

- Bayes theorem:

$$P(\text{event is GW}|\text{properties}) = \frac{P(\text{properties}|\text{GW})P(\text{GW})}{P(\text{properties})}$$

- Cannot evaluate this.
- Requires things we don't know, like how many GWs we have detected.
- For example, knowing $P(\text{GW}) \neq 0$ is equivalent to discovering GWs.

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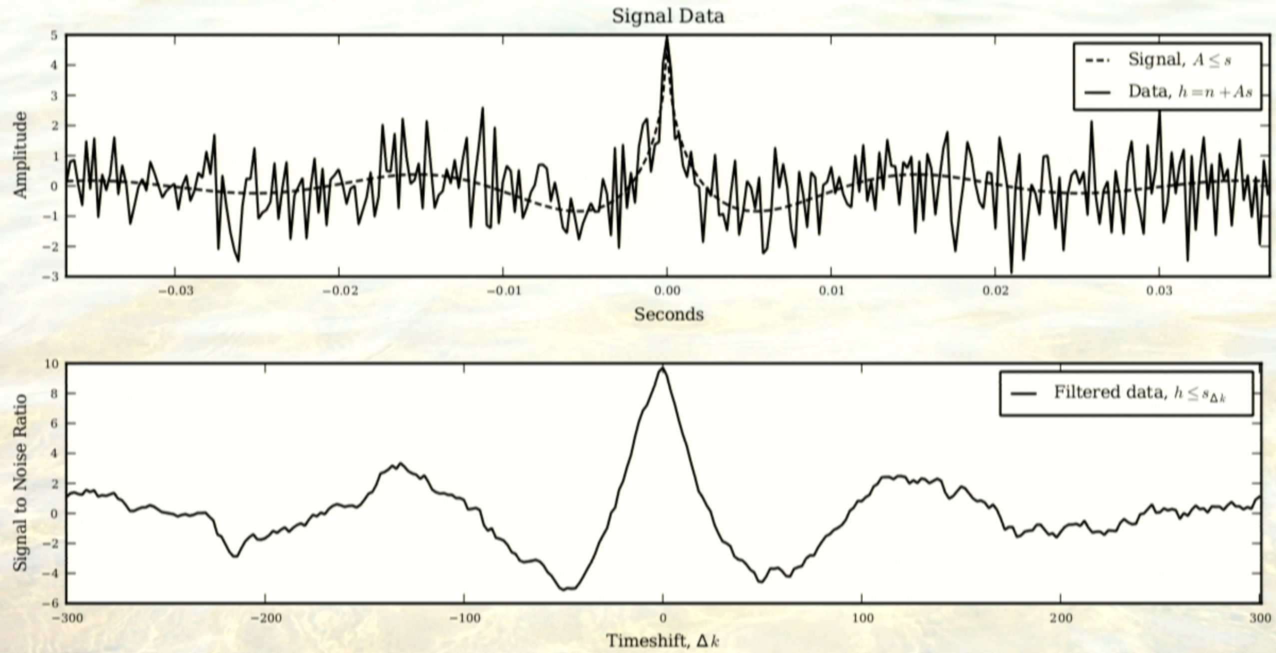
Likelihood Ratio

- Know $P(\text{event is GW}) = 1 - P(\text{event is not GW})$
- Can use to show that

$$P(\text{event is GW}|\text{properties}) = \frac{P(\text{properties}|\text{GW})P(\text{GW})}{P(\text{properties})}$$

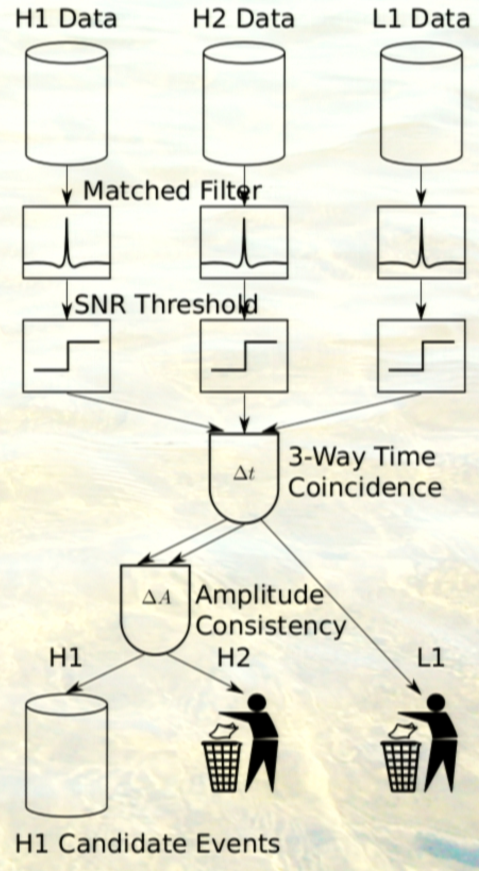
is a monotonically increasing function of

$$\Lambda(\text{event}) = \frac{P(\text{properties}|\text{event is GW})}{P(\text{properties}|\text{event is not GW})}$$

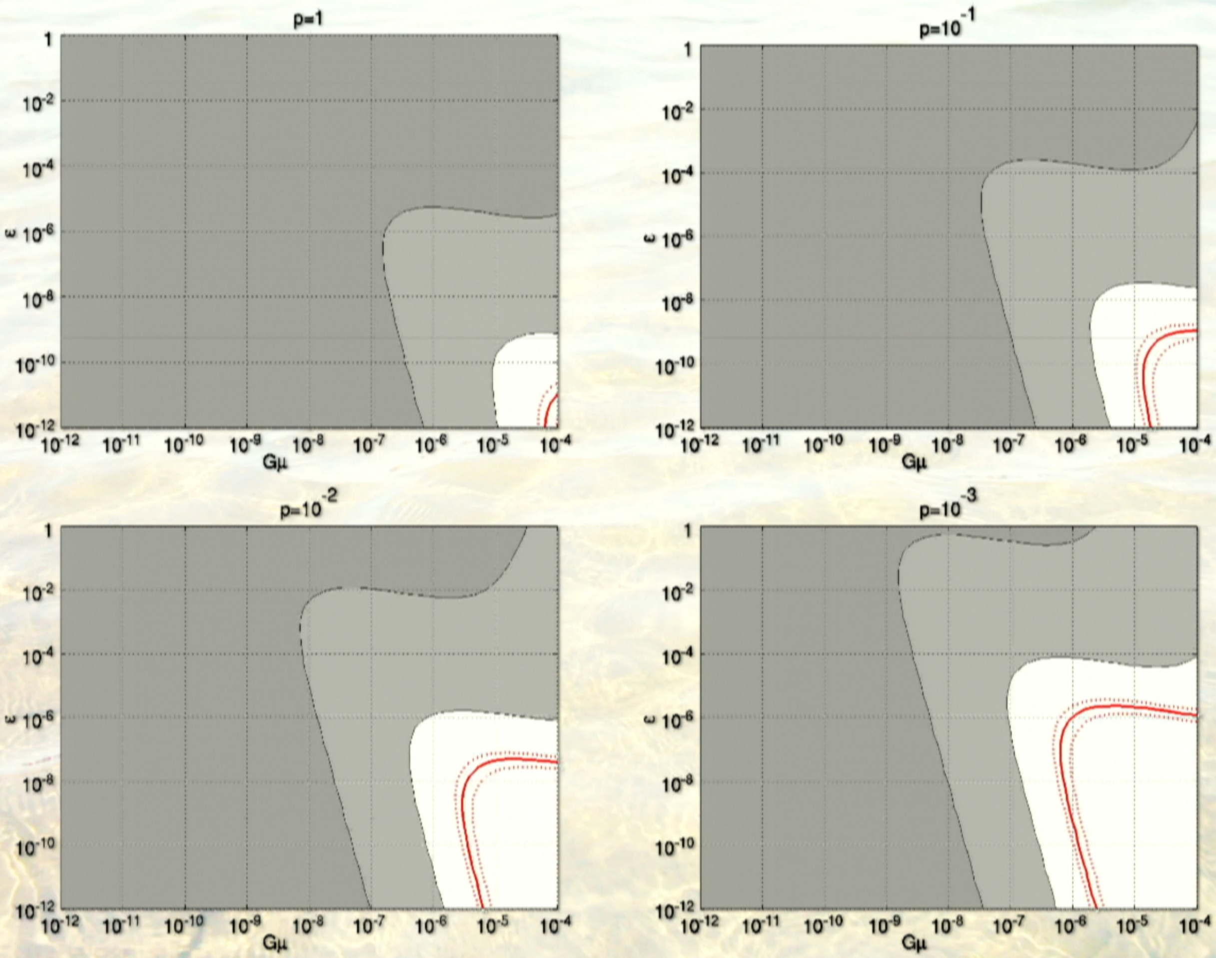

Signal Data
Signal, $A \leq s$
Data, $h = n + As$
Amplitude
Seconds
Filtered data, $h \leq s_{\Delta k}$
Signal to Noise Ratio
Timeshift, Δk

Old Pipeline

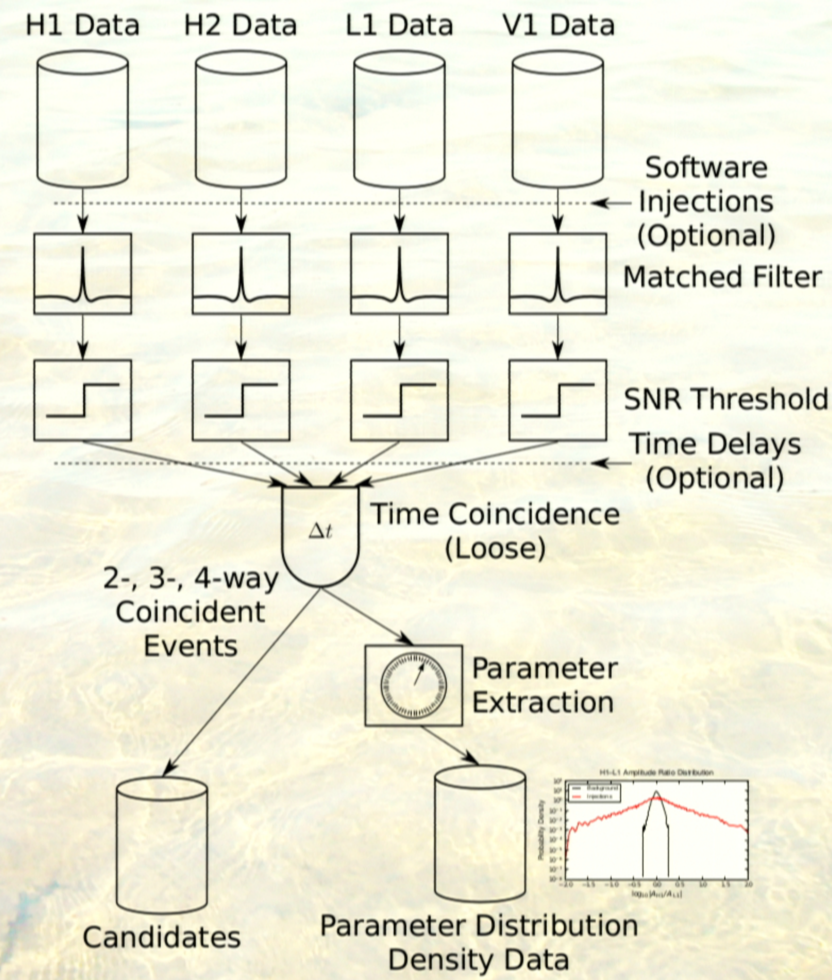
- Time-series strain data read from disk.
- Data conditioned, passed through matched filter for string cusp waveforms, result is signal-to-noise ratio (SNR) time series.
- Threshold on SNR time series, producing a list of candidate events for each instrument.
- Δt window identifies times when all instruments see an event.
- Amplitude consistency cut applied to the co-located Hanford instruments.
- H1 events surviving cuts constitute final candidate list.



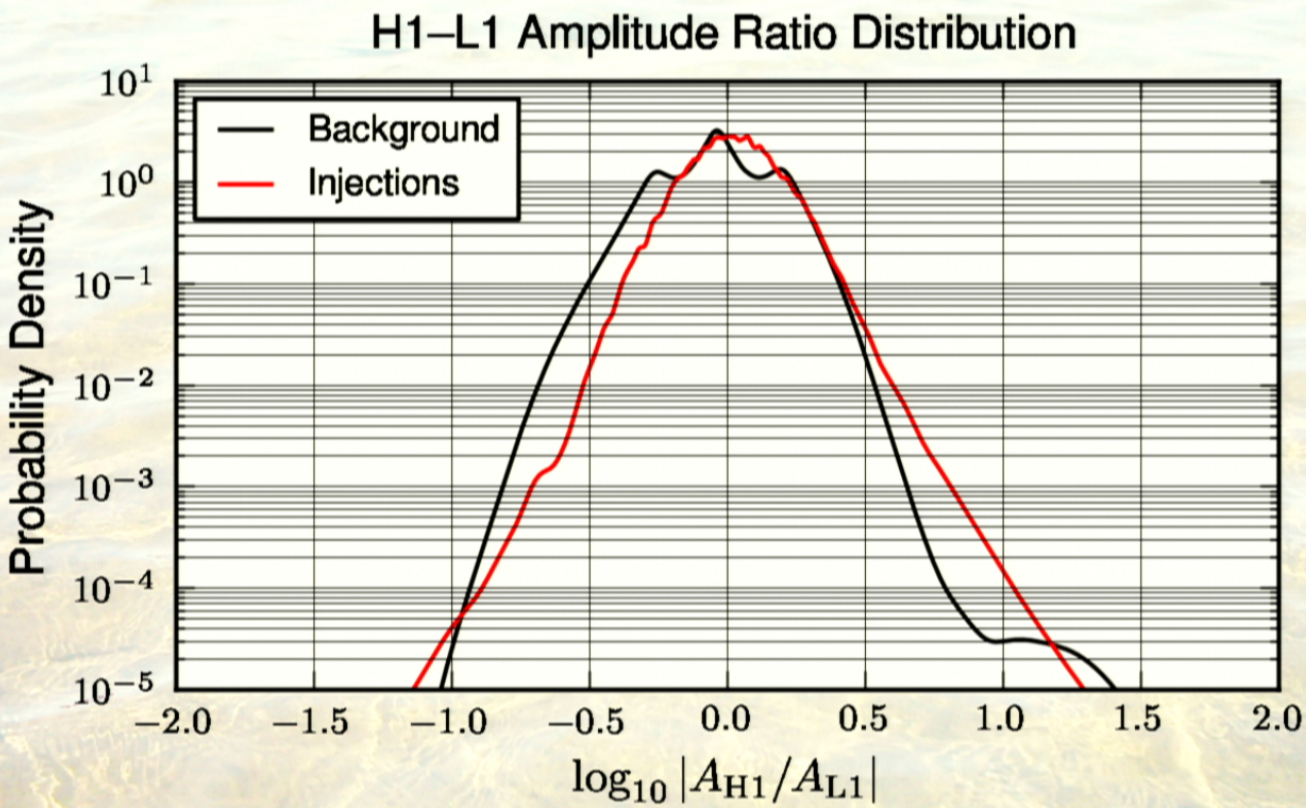
Old Results (LIGO's 4th Science Run)



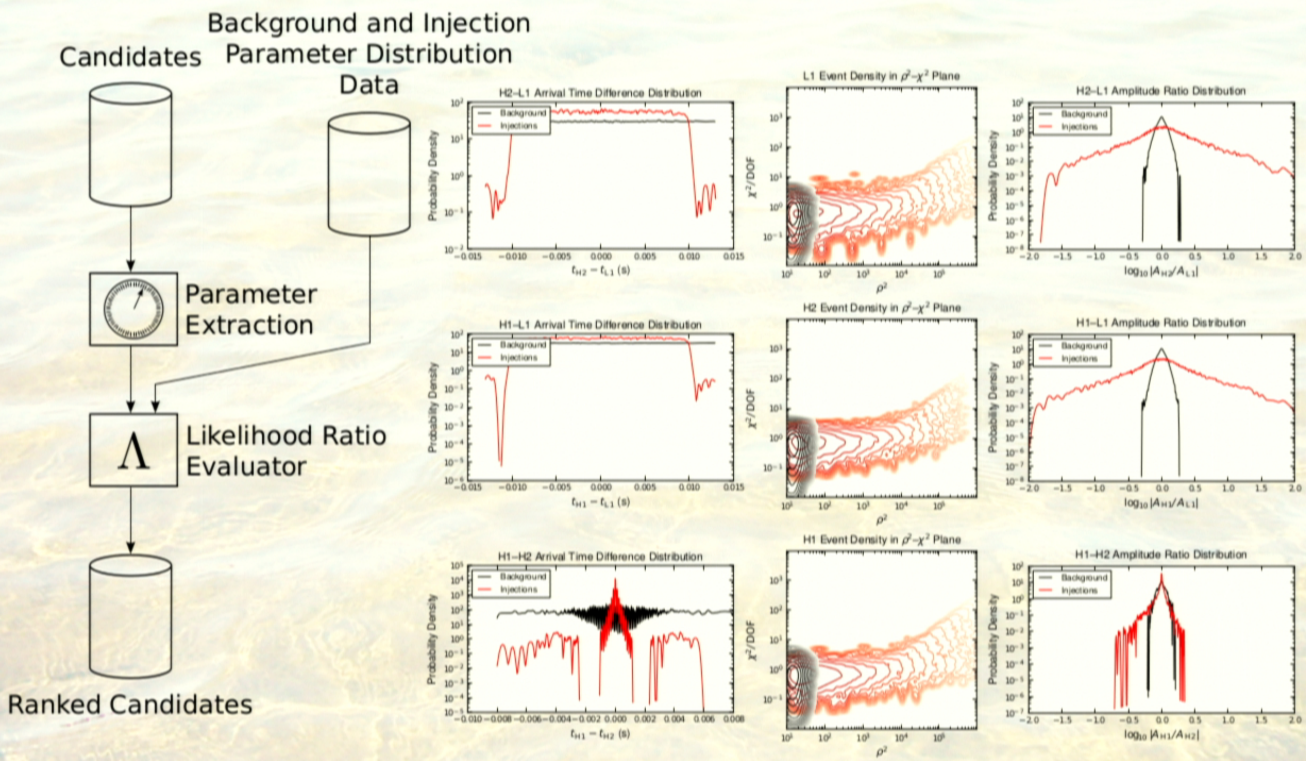
New Pipeline — Phase 1



New Pipeline — Phase 1 (continued)



New Pipeline — Phase 2

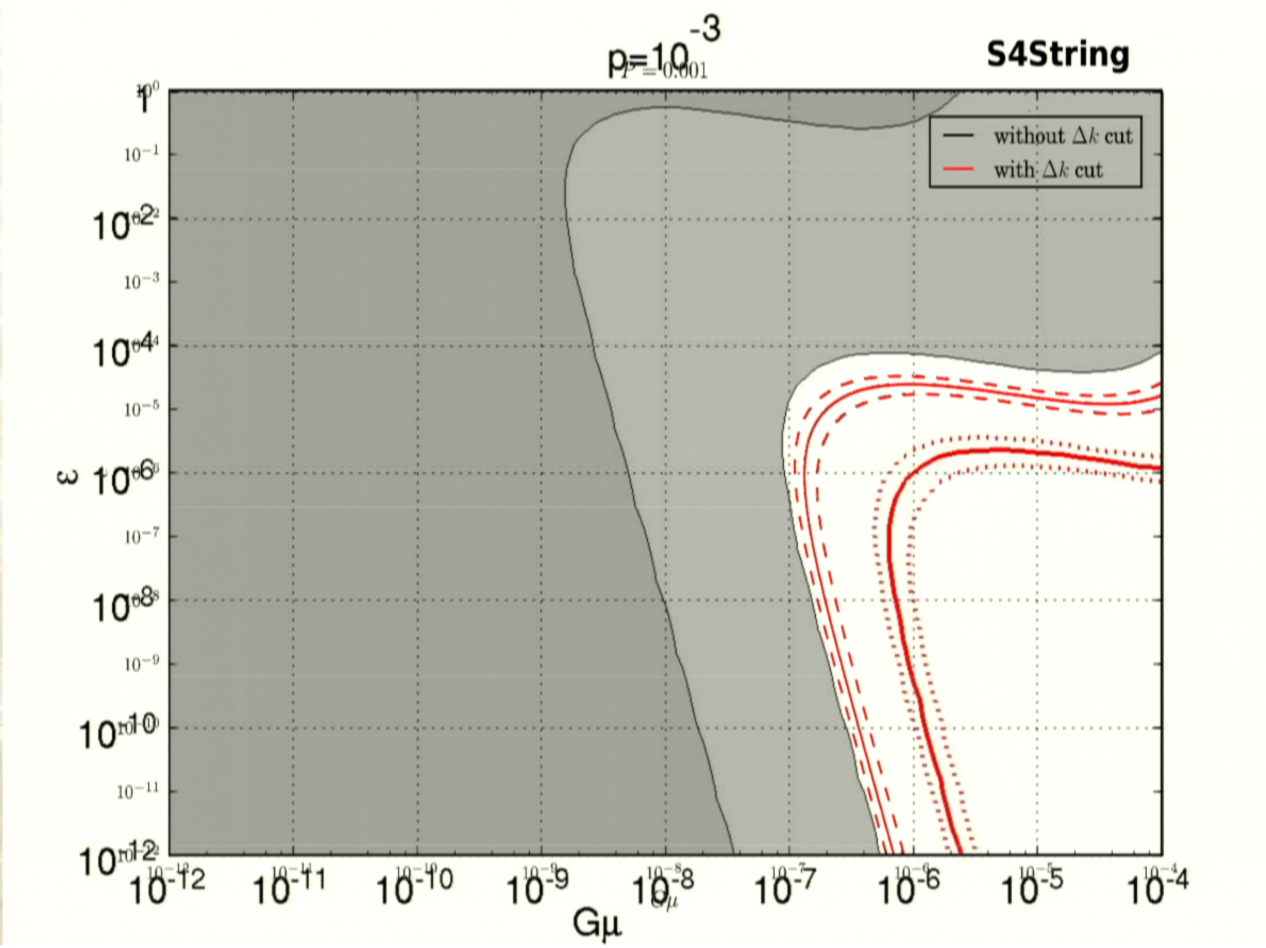


see Class. Quant. Grav. 25(10):105024, May 2008.

New Pipeline Summary

- Add χ^2 waveform consistency test to improve glitch rejection.
- Replace Δt and ΔA cuts with multi-variate likelihood ratio based ranking statistic
- Incorporate other physical event parameters in ranking statistic such as high-frequency cut-off, etc..
- Allow flexible network configurations (do not require full n-way coincidence) to increase observation time, sky coverage.
- Add Virgo as fourth instrument to increase observation time, sky coverage, and glitch rejection.
- Incorporate cosmological and string population models into ranking statistic.

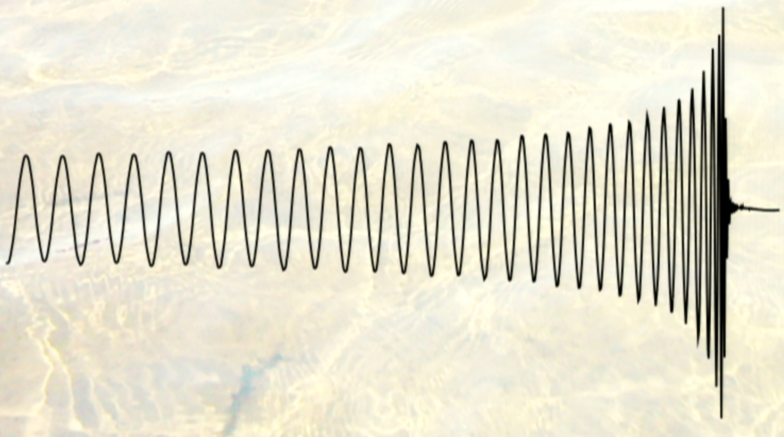
Re-Analyze LIGO's 4th Science Run (Preliminary Sensitivity)

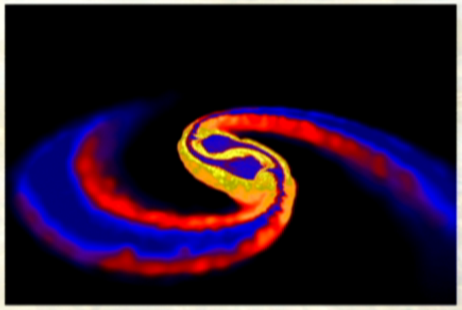


Searches for compact object mergers

What the searches are targeting

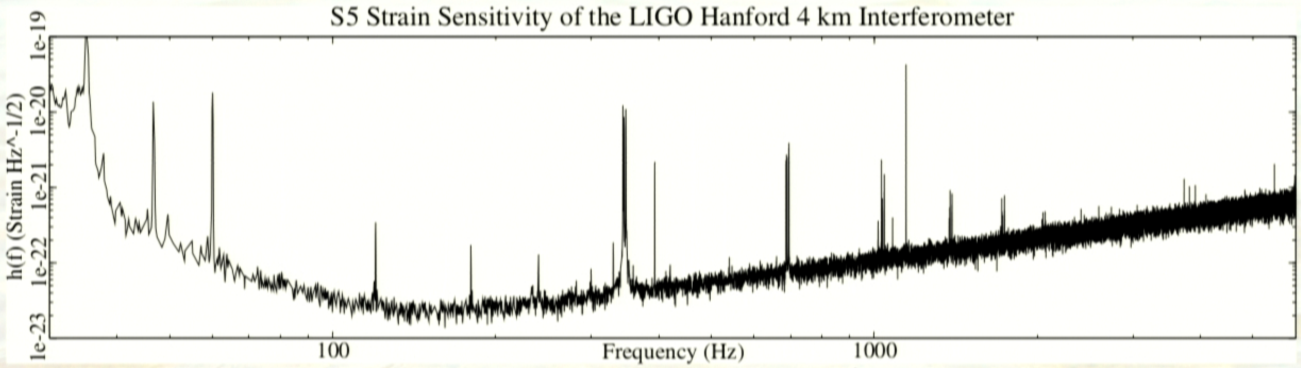
- Binary systems of massive compact objects in close orbits: neutron stars (NS), black holes (BH), primordial black holes (PBH).
- Orbits decay by radiating energy as gravitational waves.
- Component objects eventually collide and merge.

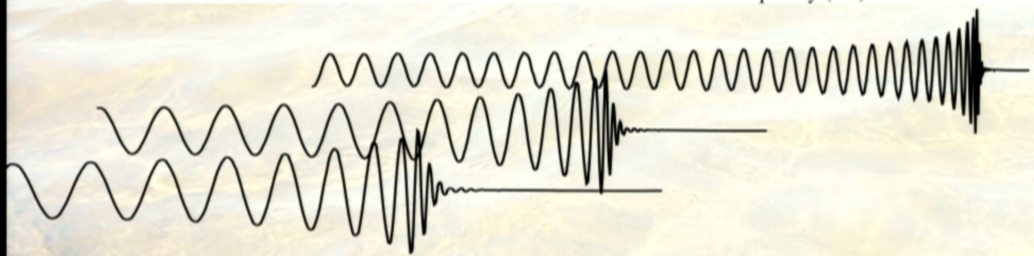




NS–NS merger. Credit: Daniel Price and Stephan Rosswog

Waveform anatomy (no eccentricity, no spin)



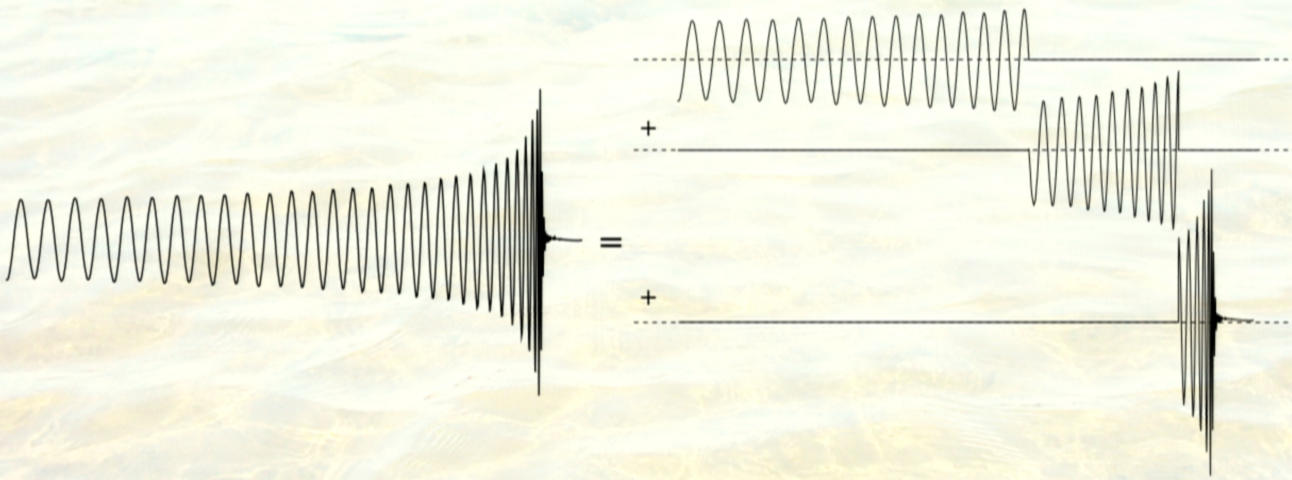


- "low mass": $M_{\rm total} <\sim 30\,{\rm M}_\odot \rightarrow$ merger is hidden in the shot noise.
- "high mass": $M_{\rm total} >\sim 30\,{\rm M}_\odot \rightarrow$ merger occurs in or below the "bucket" of the LIGO band.

Advanced LIGO vs. Initial LIGO

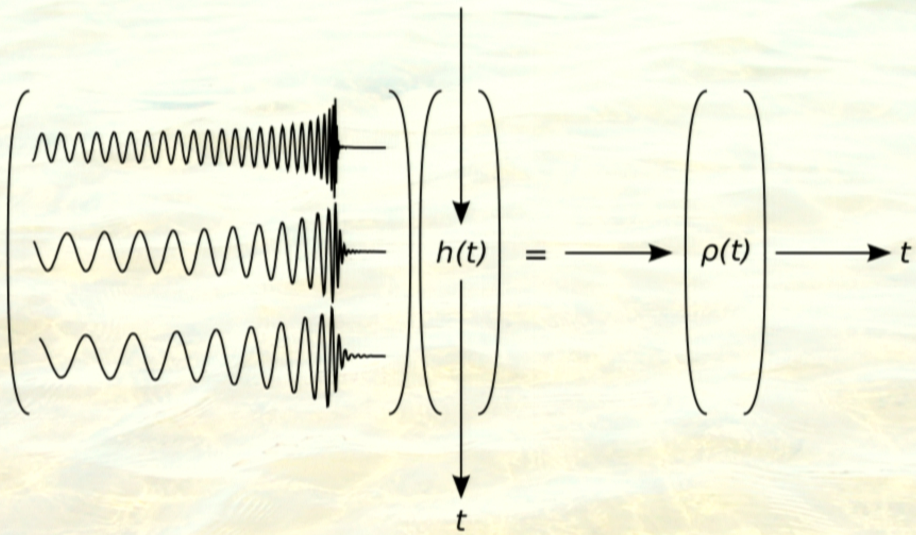
- Initial LIGO's low-frequency cut-off was about $40\,\mathrm{Hz}$
  - $1M_\odot, 1M_\odot$ waveform spends $45\,\mathrm{s}$ above $40\,\mathrm{Hz}$.
- Advanced LIGO's low-frequency cut-off target is $10\,\mathrm{Hz}$
  - $1M_\odot, 1M_\odot$ waveform spends $1800\,\mathrm{s}$ above $10\,\mathrm{Hz}$.
- Longer observations mean higher frequency resolution.
  - Number of templates required for "low-mass" increases from $\mathrm{O(10k)}$ to $\mathrm{O(1M)}$.

Solution 1: Down Sampling



- Write template as a sum of several slices, each stored at a different sample rate.
- Longest pieces are also lowest-frequency pieces: RAM savings are significant.

Solution 2: Orthonormal Basis



- By construction each template has a high overlap with its immediate neighbours.
- Singular-Value Decomposition (SVD) allows templates to be expressed as linear combinations of a smaller number of orthonormal functions.
- arXiv:1005:0012v2

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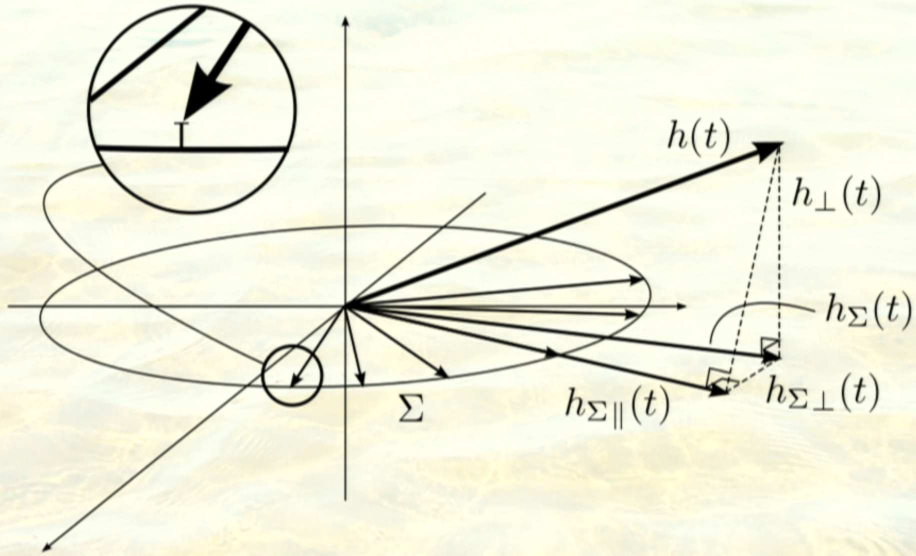

- Orthonormal basis allows several new statistics to be computed easily.
- arXiv:1101.0584v1, arXiv:1101.4939v1.

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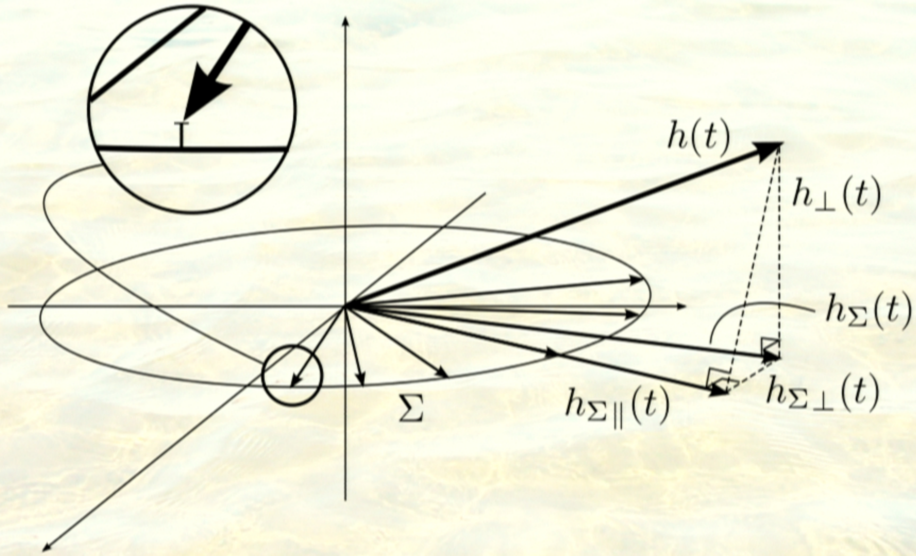

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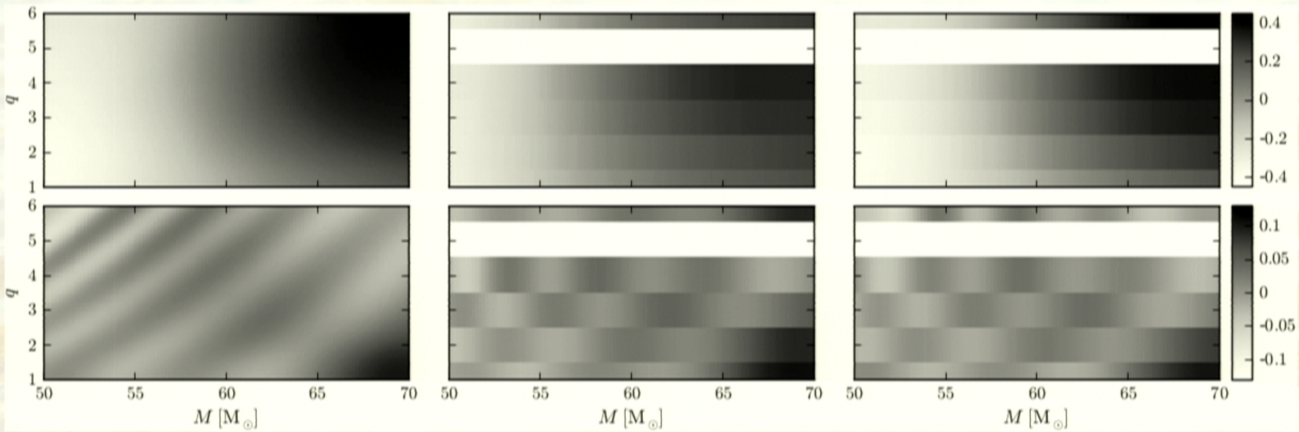
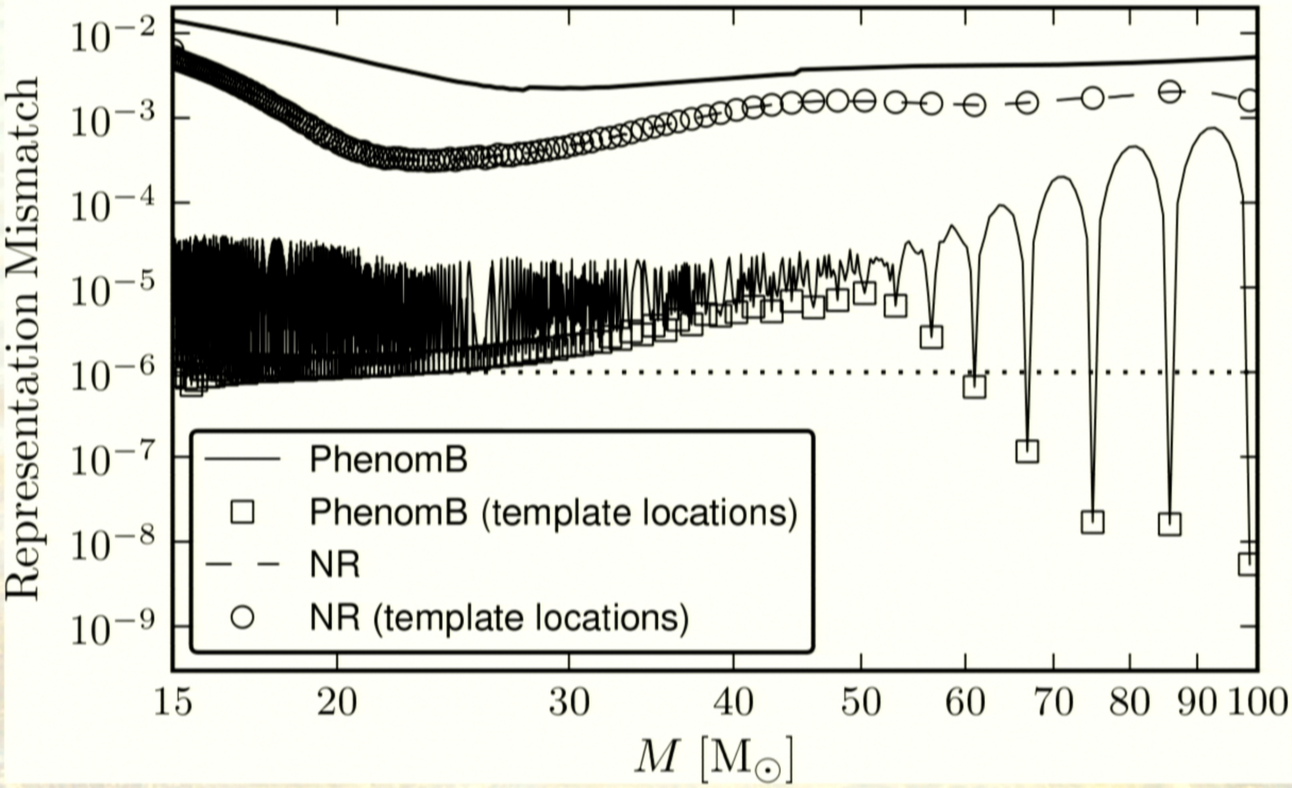
What do the Projections Look Like?



- arXiv:1211.7095

Fun Fall-out: NR waveform interpolation



- arXiv:1211.7095

The Future

- Technology for detections seems to be in hand, but is it?
  - Spin? Precession? Eccentricity? Higher-order modes?
- Undiscovered country is astrophysical interpretation.
- What hypotheses can be constrained? How?
  - Barausse et al., Neutron-star mergers in scalar-tensor theories of gravity, arXiv:1212.5053 — constrain alternative theories of gravity?
  - Poisson et al., Black holes in tidal environments — infer presence of event horizon?
- No discoveries without data.