Searching for Gravitational Waves From Compact Binaries

Duncan Brown
California Institute of Technology
and
LIGO Scientific Collaboration

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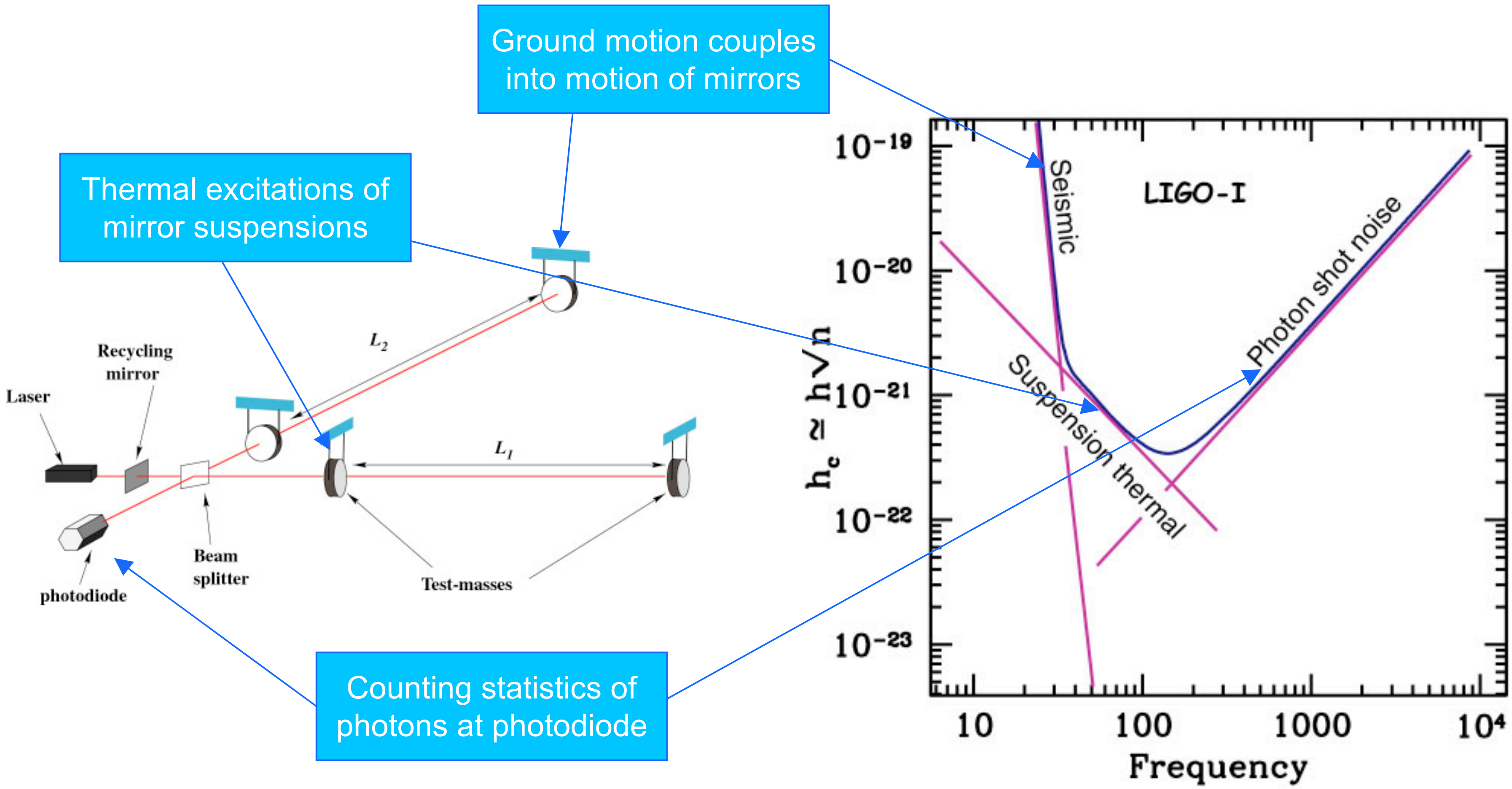
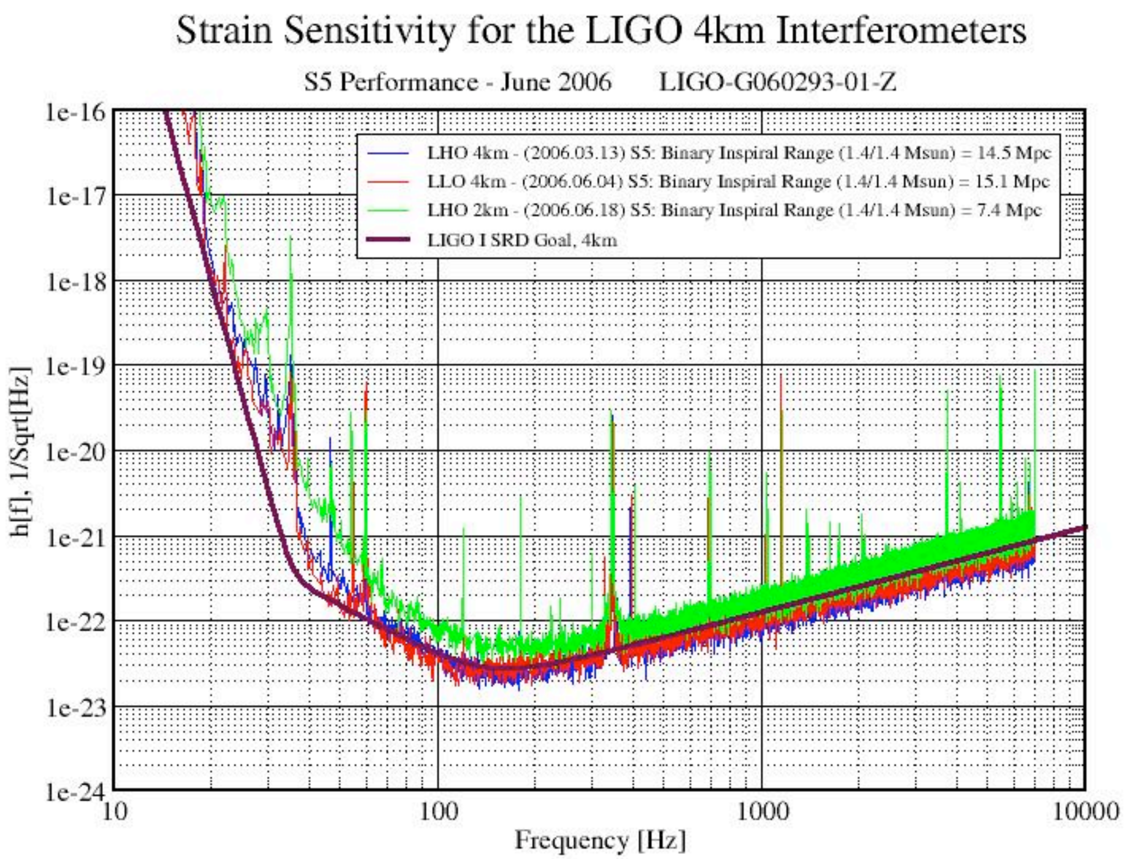
Overview

- What sources are we currently searching for?
- What are the tools we currently use to perform the searches?
- What problems do we encounter in practice?
- How might numerical relativity help in current and future searches?

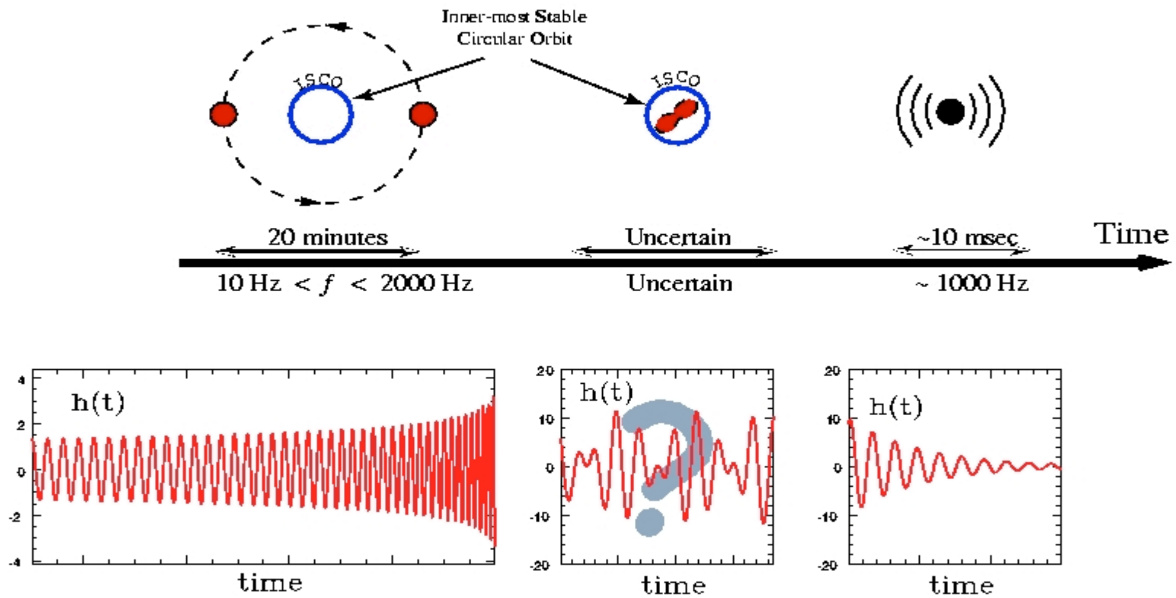
The LIGO Interferometers



Current LIGO Sensitivity



Evolution of Binary System



- LIGO is sensitive to inspirals containing neutron stars and black holes

$$M_{\rm total} \lesssim 100 M_\odot$$

Astrophysical Rate Estimates

- Binary neutron star (BNS) systems known to exist from radio observations
  - » Hulse-Taylor pulsar
  - » J0737-3039 (both neutron stars are visible as pulsars)

- Rate estimates give NS/NS upper bound of ~ 1/3 years at LIGO S5 sensitivity

- Rates for black hole binaries much more uncertain
  - » Population synthesis gives upper limit of 1/yr at LIGO S5 sensitivity

Binary Coalescence Waveforms

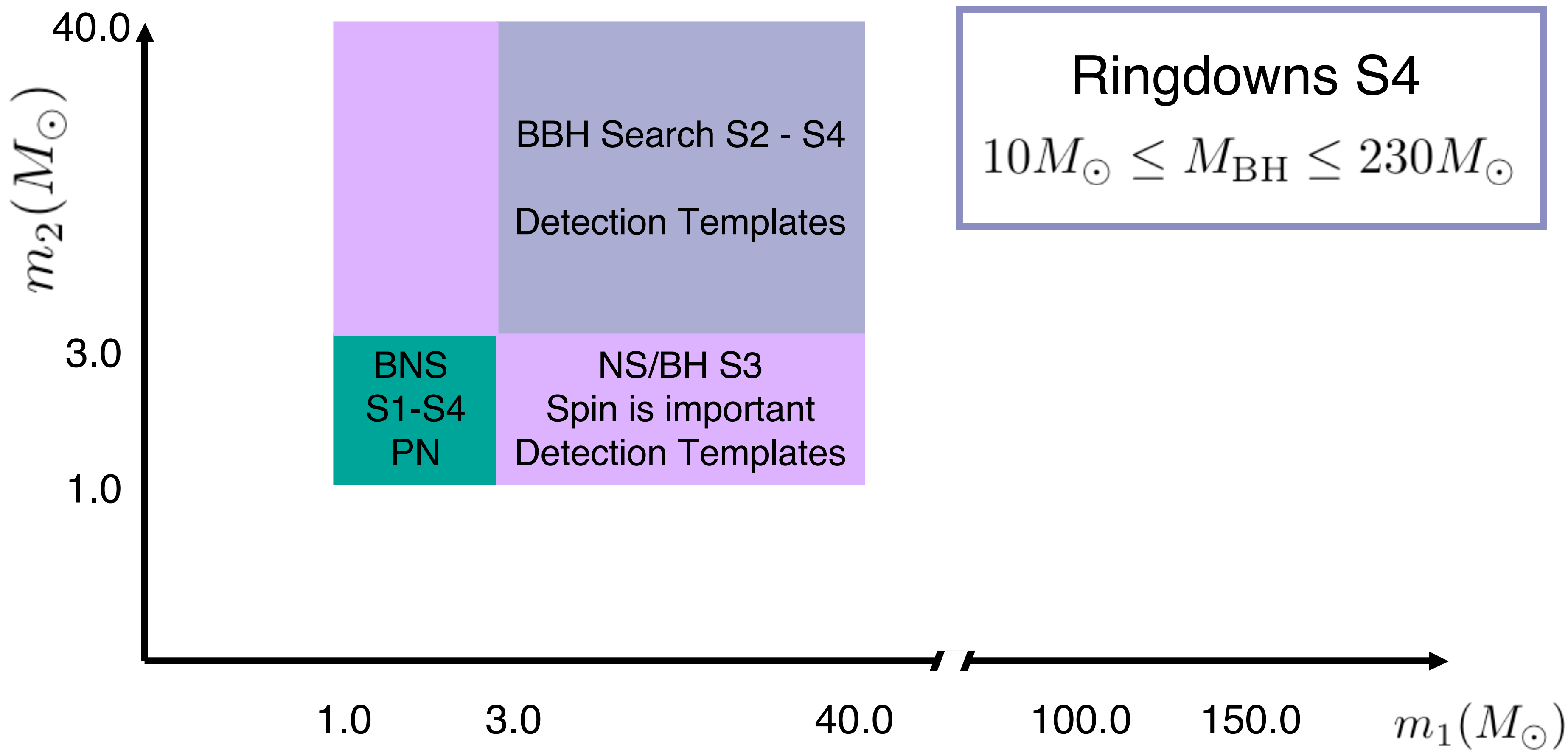
- Assume inspiral signals are (reasonably) well modeled
  - We use matched filtering to perform inspiral waveforms

- Post-Newtonian templates accurate for low mass systems in LIGO band

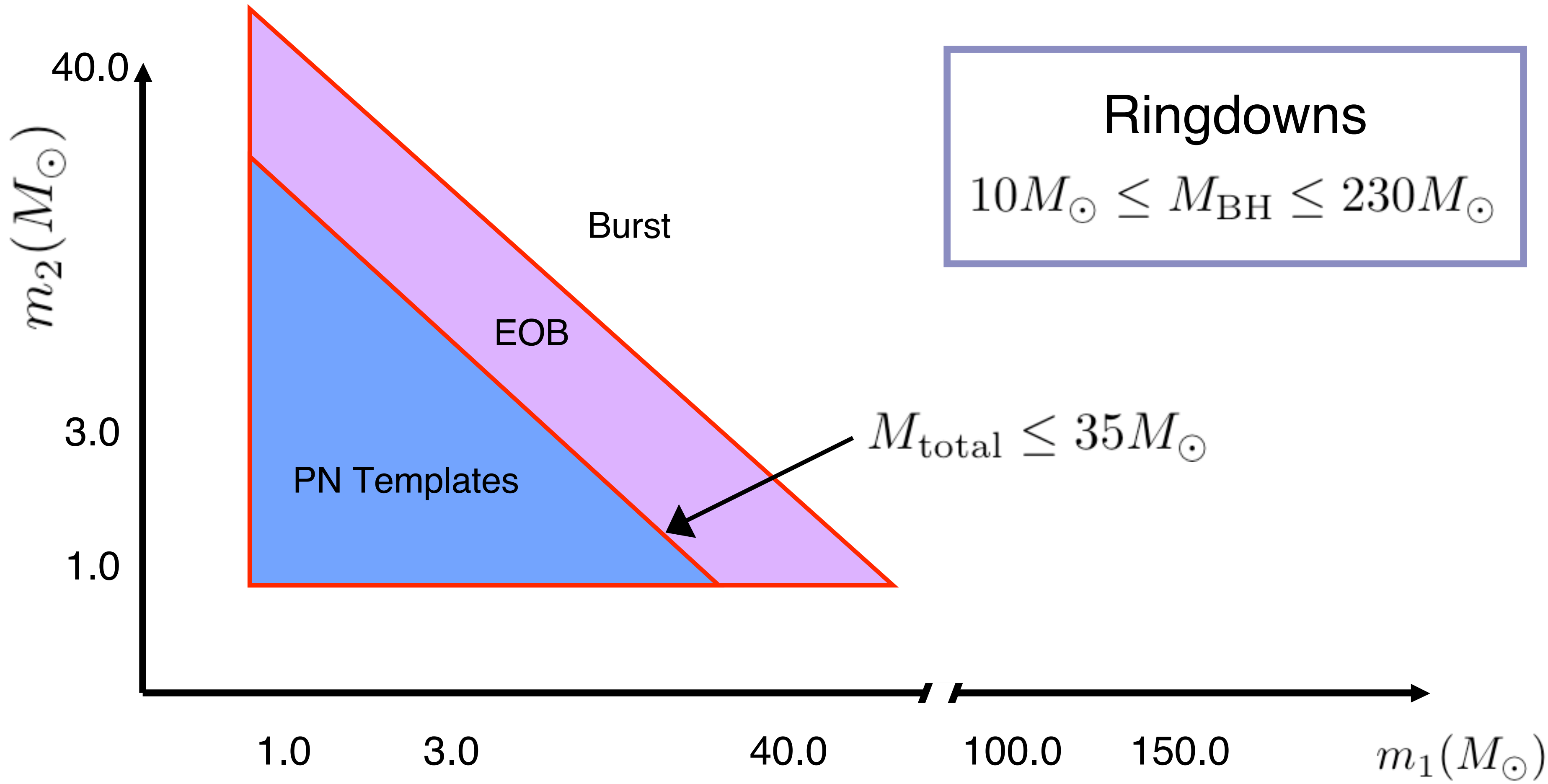
- At higher masses post-Newtonian approximation breaks down, but do the templates?

- At still higher masses, inspiral searches transition into burst searches

Overview of S1 - S4 Searches



Overview of S5 Searches



Matched Filtering

- Assume the signal we are searching for is known, up to unknown arrival time, constant phase and amplitude

$$h(t) = A_0 A(t) \cos(\phi(t) + \phi_0)$$

- Construct matched filter statistic for this signal

$$\rho^2(t) = \rho_c^2(t) + \rho_s^2(t)$$

$$\rho_c^2(t) = \frac{1}{\sigma} \int_{f_{\rm low}}^{f_{\rm max}} \frac{\tilde{s}(f)\tilde{h}_c^*(f)}{S_n(f)} e^{2\pi i f t}\, dt$$

Matched Filtering

- Choose templates to be normalized to strain at 1 Mpc

$$\sigma = \int_{f_{\rm low}}^{f_{\rm max}} \frac{\tilde{h}_c(f)\tilde{h}_c^*(f)}{S_n(f)}\, df$$

- Cutoff f_{low} is determined by detector, f_{max} by template
- Effective distance to signal is given by

$$D = \frac{\sigma}{\rho}\,{\rm Mpc}$$

Mismatch

- What if the template is incorrect?
- Loss in signal to noise ratio is given by the mismatch

$$\text{mismatch} = 1 - \text{match}$$

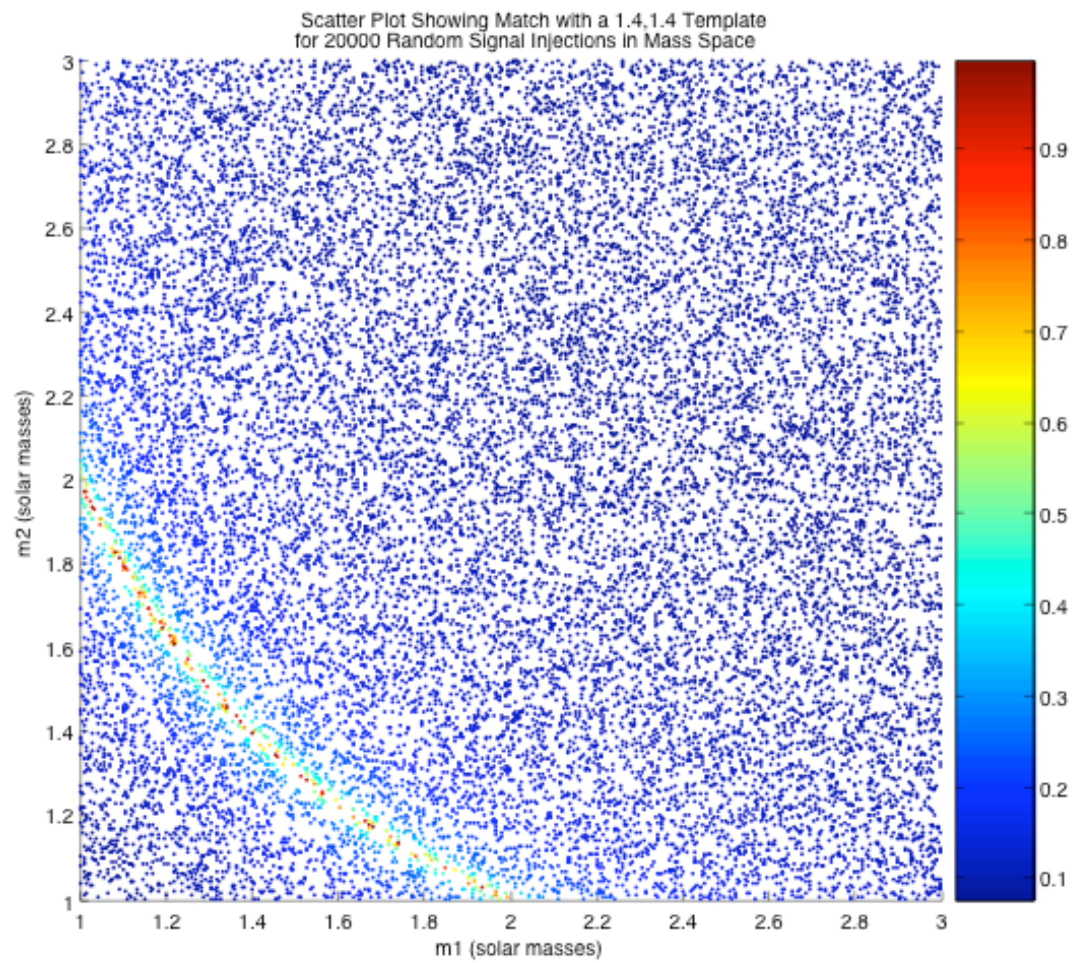
$$\text{match} = \max_{t_0, \phi_0, \mathcal{M}, \eta, \ldots} \frac{\langle h | h_{\text{true}} \rangle}{\sqrt{\langle h | h \rangle \langle h_{\text{true}} | h_{\text{true}} \rangle}}$$

$$\langle a | b \rangle = \int_{f_{\text{low}}}^{f_{\text{max}}} \frac{\tilde{a}(f) \tilde{b}^*(f)}{S_n(f)} \, df$$

Mismatch and Event Rate

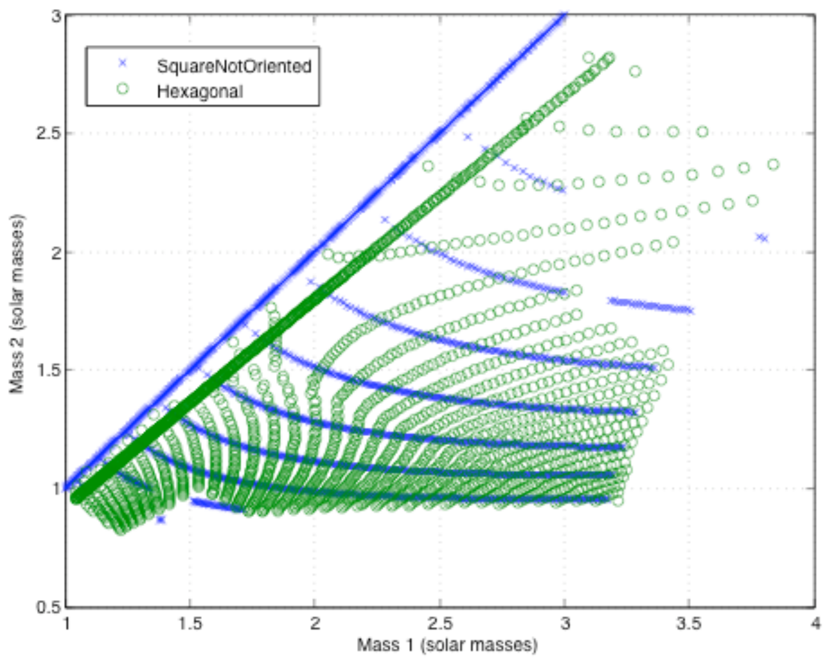
- Any mismatch between signal and template reduces the distance to which we can detect inspiral signals
- Loss in signal-to-noise ratio is loss in detector range
- Loss in event rate = $(\text{Loss in range})^3$
- We must be careful that the mismatch between the signal and our templates does not unacceptably reduce our rate

Mismatch for Low Mass Signals

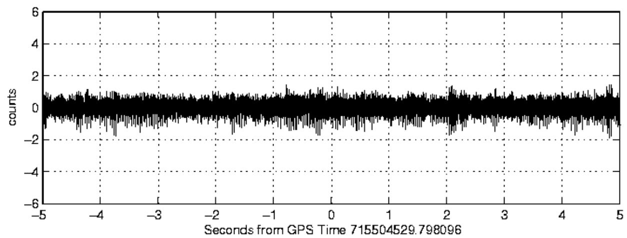


Inspiral Template Banks

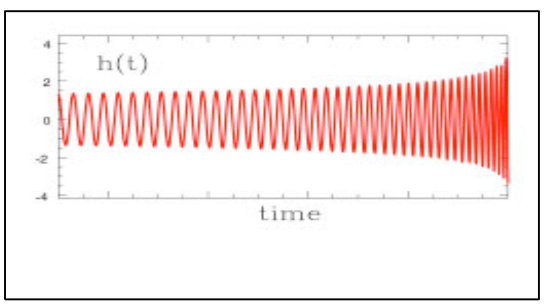
- To search for signals in the mass region of interest, we must construct a template bank
- Lay down grid of templates so that loss in SNR between signal in space and nearest template is no greater than ~ 3%



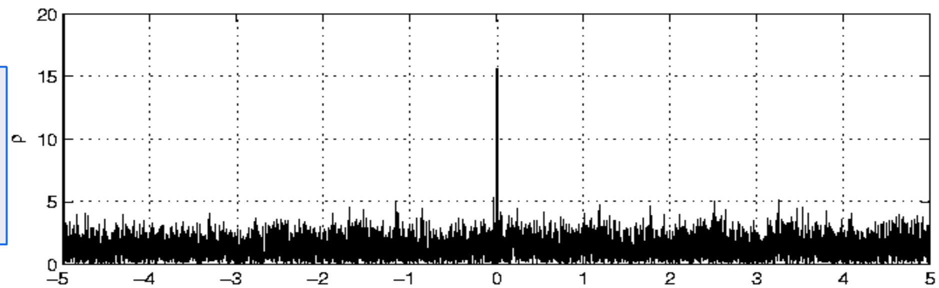
Is that it…?



Filter to suppress high/low freq



SNR



Coalescence Time

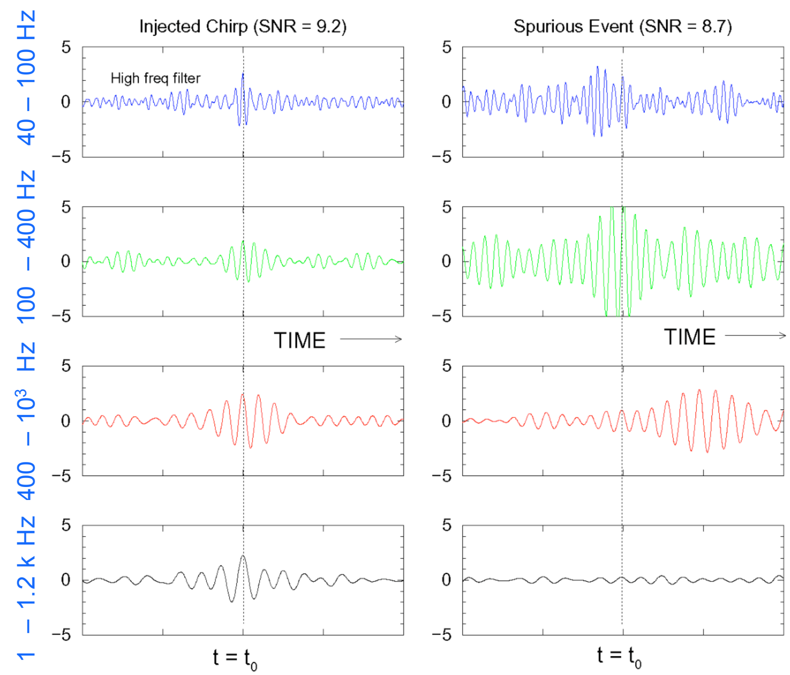
Signal Based Vetoes

- Unfortunately not… any large transient (glitch) in the data can cause the matched filter to have a large SNR output

- We use signal based vetoes to check that the matched filter output is consistent with a signal
- If we have enough cycles, one of the strongest vetoes is the χ^2 veto

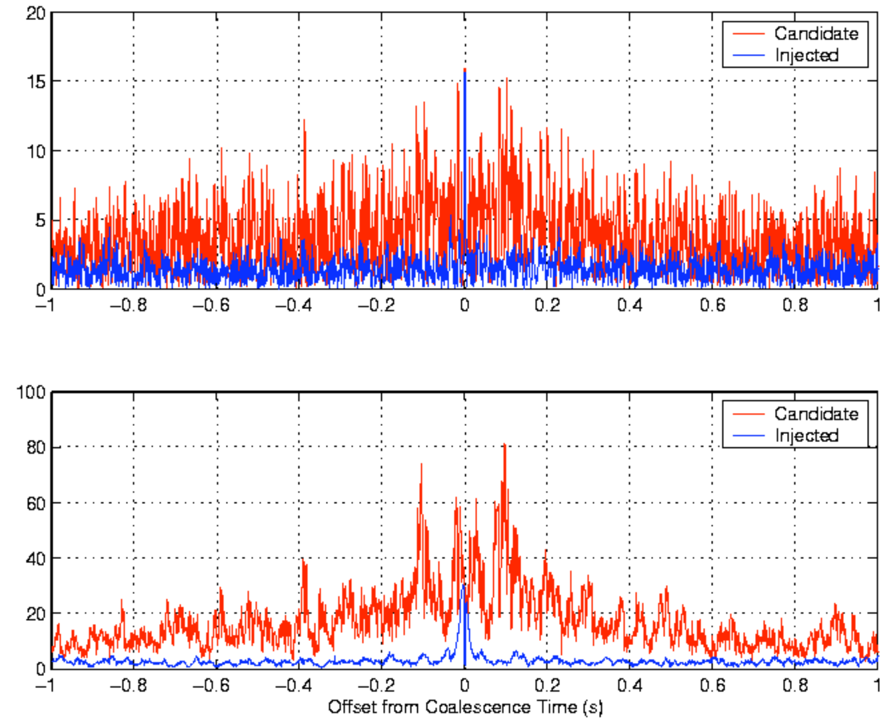
$$\chi^2 = p \sum_{i=1}^{p} \left(\rho_{c,l} - \frac{\rho_c}{p} \right)^2 + \left(\rho_{s,l} - \frac{\rho_s}{p} \right)^2$$

$$\frac{\chi^2}{p + \delta^2 \rho^2} < \text{threshold}$$



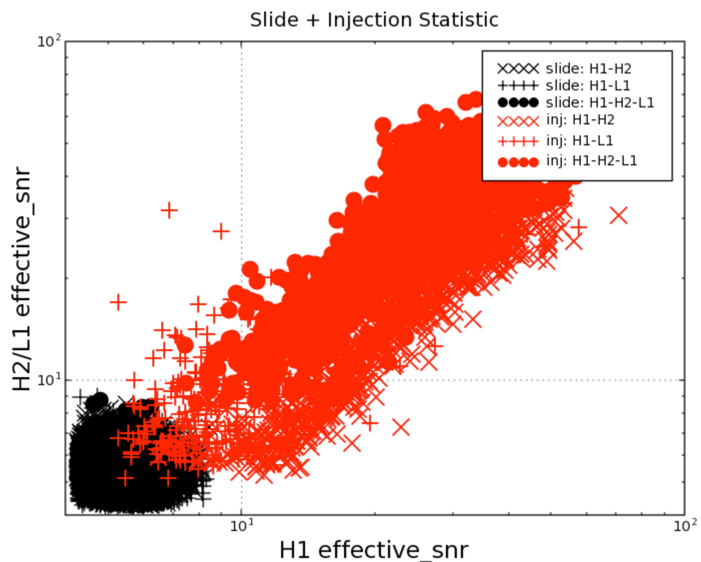
Glitches in the Data

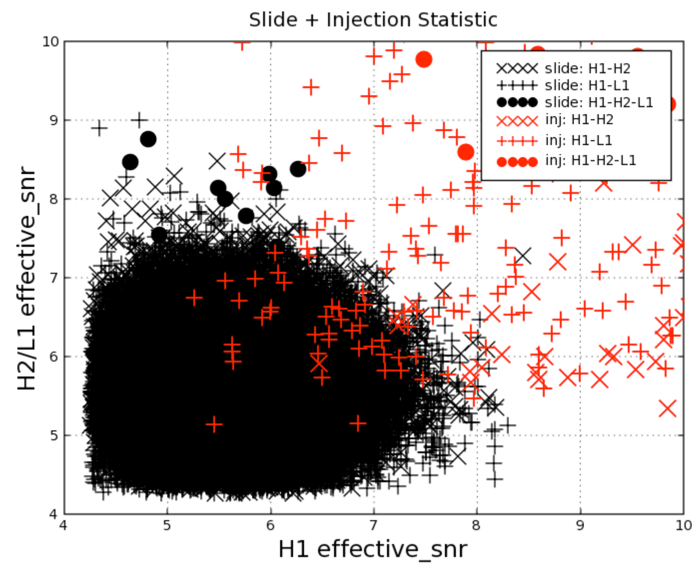
- Glitches can still be a problem, even with signal based vetoes (particularly in higher mass searches)
- A lot of work in the LSC is devoted to finding, identifying and eliminating glitches
- Loud glitches reduce our range (and hence rate) by hiding signals
- Even if a template has excellent overlap with signals, if it picks up lots of glitches we have a problem



Tuning a Search

- Our main tools are software injections and background estimation using time slides





$$\rho^2_{\mathrm{effective}} = \rho^2 \Bigg/ \sqrt{\left(\frac{\chi^2}{2p-2}\right)\left(1+\frac{\rho^2}{250}\right)}$$

How Could Numerical Relativity Help?

- Provide “signals” which which we can test our current black hole searches
  - » Inject numerical relativity waveforms into LIGO data and see how our searches perform

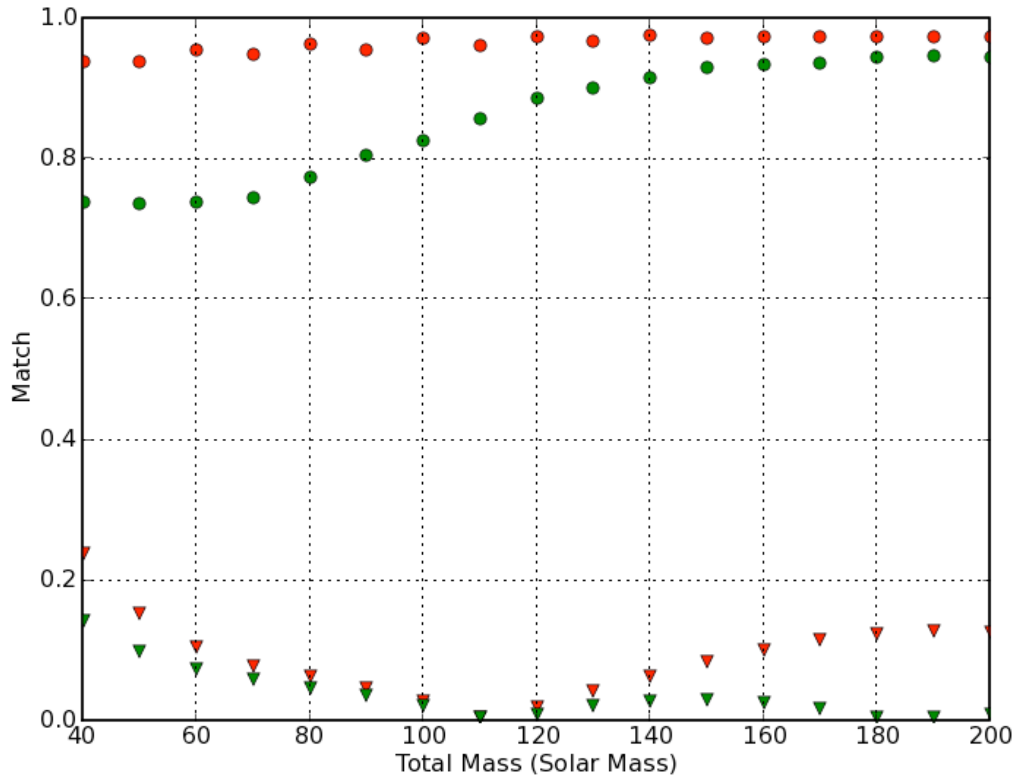
- Help extend current physical templates into regions where they are uncertain
  - » Modify phase evolution of pN templates, but without introducing too much freedom

- Develop template banks of numerical waveforms
  - » Long enough templates to perform a χ^2 veto would be nice

Waveform Accuracy

- How accurate do we need numerical waveforms?
- What is the match between higher and higher resolutions?
- What effects are due to the initial data? (e.g. effect of eccentricity in initial data)
- What is the effect of the waveform extraction radius?
- Data analysis expresses accuracy in terms of the match… Is the match convergent?

Testing Accuracy with Match



Maximized over time

Finest vs next finest

Finest vs coarsest

No time maximization

Baumgarte, Brady, Creighton, Lehner, Pretorius

Talking to each other…

- When NR waveforms are scaled to physical units, they may be the complete waveform, or just part of it
- Current results are very encouraging and already of great interest to data analysis
- Can we agree on what data to exchange and how to exchange it?
- The LIGO detectors measure time in seconds…
- G in Hanford and Livingston is 6.67259×10^{-11}

Conclusions

- Numerical relativity is producing waveforms that are of great interest to data analysis *right now*
- Compact binary inspiral searches are underway now for signals for which NR already has the complete waveform
- Let's inject numerical relativity waveforms into LIGO data and see how our current searches perform
- What happens when we make a detection?
  - » Steve will talk in more detail parameter estimation and systematic effects

Ringdown Waveforms

- If final product of inspiral is perturbed black hole, it will settle down to a Kerr black hole by quasinormal ringdown
- Waveforms well modeled by black hole perturbation theory
- All compact binary searches use matched filtering