Sub-Solar Mass CBC Search in S5 Initial LIGO Data

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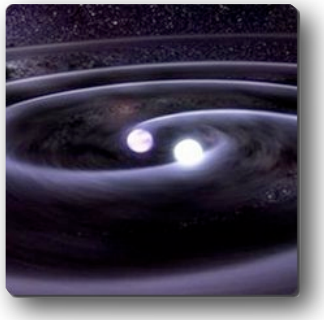
Outline

- Introduction to compact binary coalescence GW searches
- Overview of optimal detection statistic and matched filtering
- Sub-solar mass search motivation and details
- Sub-solar mass search tools and pipeline
- Status and future work

Compact Binary Coalescence



- A compact binary coalescence (CBC) event is composed of three phases: *inspiral*, *merger*, and *ringdown*

- Gravitational-wave strain of *inspiral* with phase given in post-Newtonian expansion using the stationary phase approximation:

$$\tilde{h}(f) = \mathcal{A} f^{-7/6} e^{i\psi(f;\theta_i)}$$
$$\text{where } \theta_i = \{m_1, m_2, \ldots\}$$

- Generally, a "search" refers to the calculation of the probability that a gravitational wave signal is in our data

- For a CBC inspiral search, we use the above analytic approximation as a template for what a signal in our data would look like

What statistic should be computed to characterize a detection?

Optimal Detection Statistic

- The likelihood ratio is:

$$\Lambda(\mathcal{H}_1|s) = \frac{p(s|\mathcal{H}_1)}{p(s|\mathcal{H}_0)}$$

- Where the null hypothesis and the alternative hypothesis are

$$\begin{aligned} \mathcal{H}_0 : \ n(t) &= s(t) \\ \mathcal{H}_1 : \ n(t) &= s(t) - h(t) \end{aligned}$$

- For Gaussian noise, the likelihood ratio is:

$$\Lambda(\mathcal{H}_1|s) = e^{(s|h)} e^{-(h|h)/2}$$

Jolien D.E. Creighton and Warren G. Anderson. *Gravitational-Wave Physics and Astronomy.*

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optimal detection statistic

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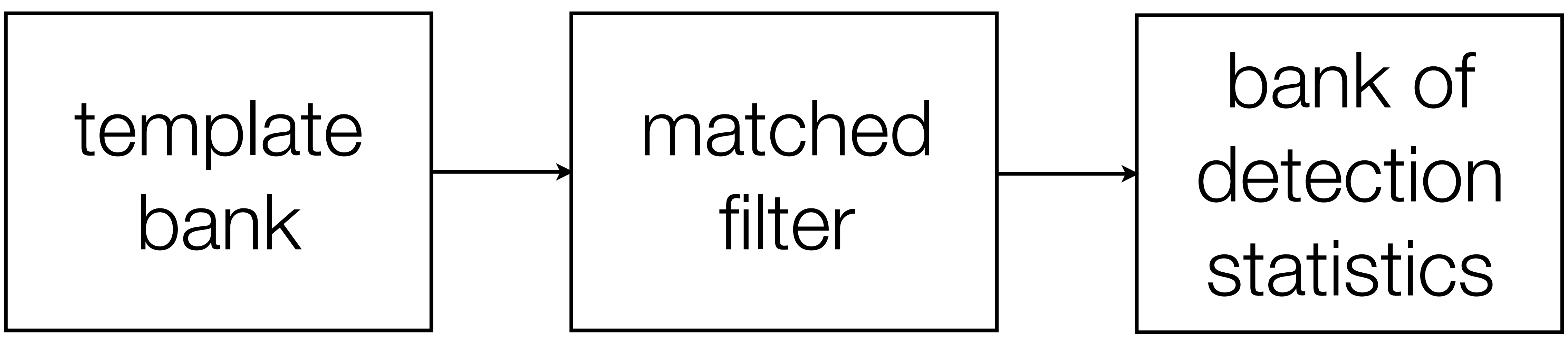
Matched Filtering Search

- The "matched filter" is the inner product of the anticipated signal with the data

$$(s, h) = 4\Re \int_0^\infty \frac{\tilde{s}(f)\tilde{h}^*(f)}{S_n(f)} df$$



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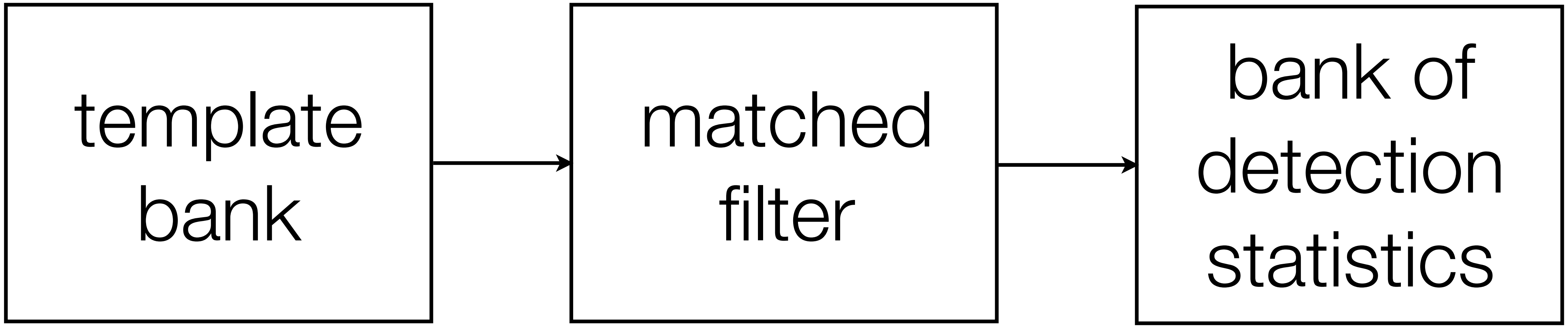


Note: Cannot search entire parameter space at once

Sub-Solar Mass Search Motivation

- The sub-solar mass region of parameter space is un-searched for a CBC inspiral event in S5 iLIGO data
- Why hasn't it been searched?
  - Unlikely sources (such as primordial black holes)
  - Long signals (what if the detector data becomes very noisy in the middle of a signal?)
  - Many templates
  - Computationally costly with unlikely yield of detection

Sub-Solar Mass Search Motivation

- Why bother with the search?
  - Excellent test of aLIGO technologies

	iLIGO SSM search	aLIGO BNS search
# of templates	~100,000	~200,000
template duration	~10 minutes	~10 minutes

  - Possibility of a detection while testing technologies for a low latency search

Sub-Solar Mass Search Details

- Component mass range: $0.2 - 1.0 M_{\odot}$
- Total mass range: $0.4 - 2.0 M_{\odot}$
- Low frequency cutoff: $40\ \mathrm{Hz}$

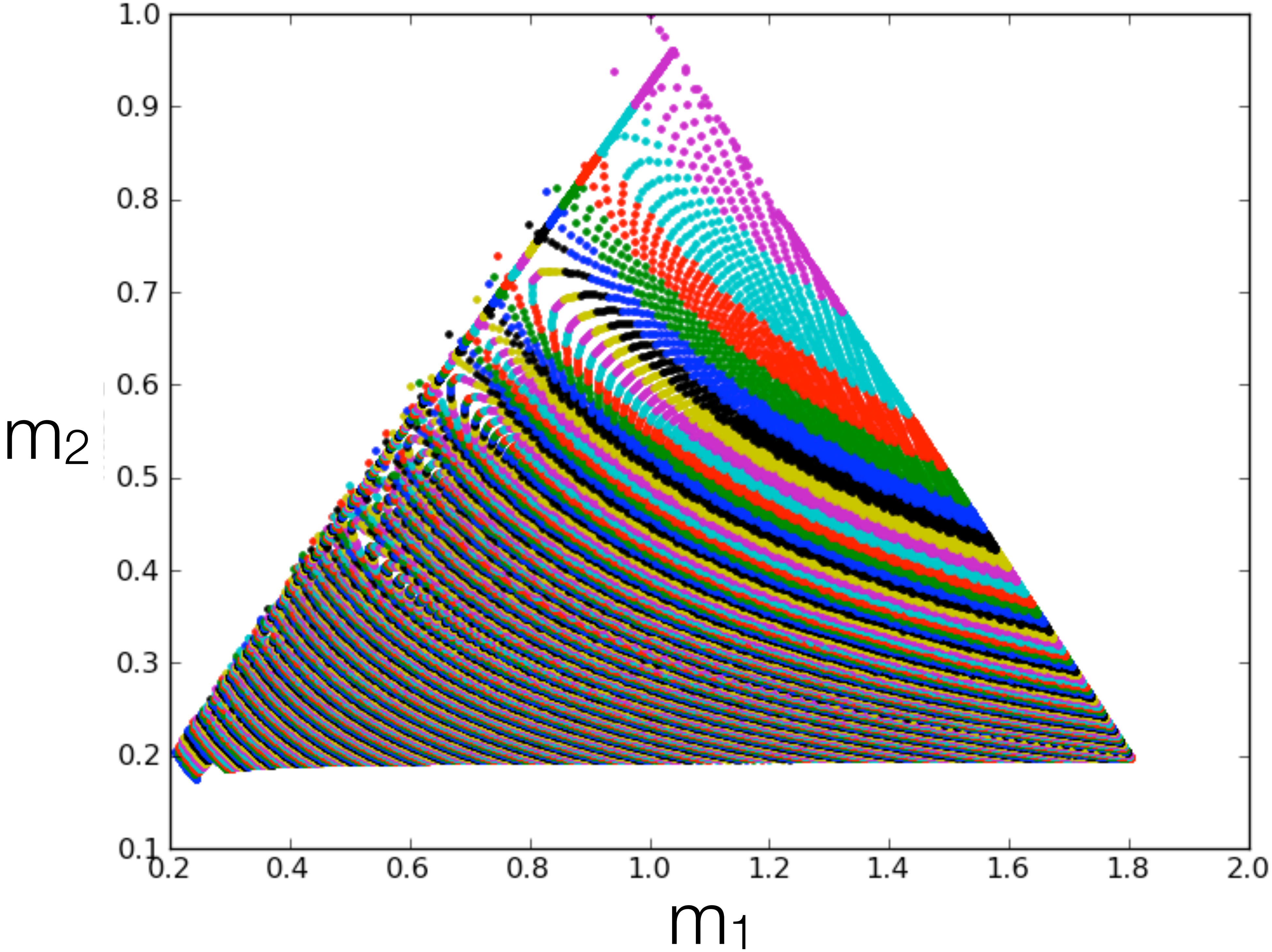
Methods used for this search can be translated to an aLIGO search with component masses in the range $1.0 - 35.0 M_{\odot}$ (a promising mass range for sources) and a low frequency cutoff of 10 Hz

Note: The low frequency cutoff will be different for aLIGO than it was for iLIGO

Sub-Solar Mass Search Details

- How large template banks are handled:
  - Template banks are split into sub-banks by chirp mass
  - Sub-banks are time sliced
  - SVD method is used to reduce size of template bank[1]
- How long signals are handled:
  - Stream-based matched filtering (gstlal)
  - Filtering across gaps in data
  - Accumulated detection statistic (SNR) across gaps

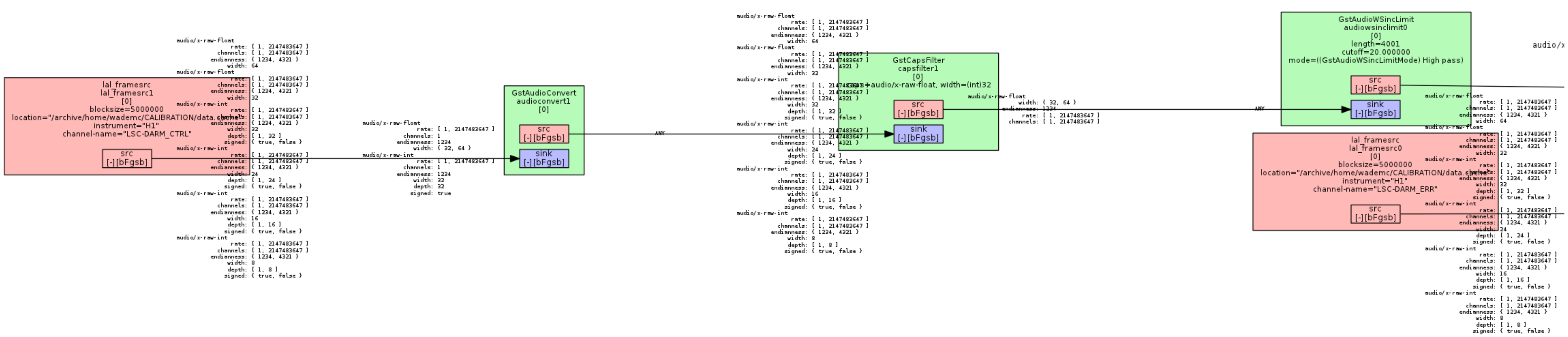
[1] K. Cannon, A. Chapman, C. Hanna, D. Keppel, A. Searle, A. Weintsein. arXiv:1005.0012



107281 templates; 215 sub-banks split by chirp mass

gstlal Overview

- The search pipeline `gstlal_inspiral`[1] has been developed using gstlal
- gstlal is a gstreamer based set of library functions for low latency gravitational-wave data analysis
- gstlal wraps LAL functions with gstreamer elements



[1]Developed by Kipp Cannon, Chad Hanna, Drew Keppel

iLIGO S5 detectors

H1H2 Coherent and Null Data Streams

- Can take advantage of the two co-located Hanford detectors

- Coherent stream: improved sensitivity

$$\tilde{s}_{1+2}(f) = \frac{\tilde{s}_1(f)/S_1(f) + \tilde{s}_2(f)/S_2(f)}{1/S_1(f) + 1/S_2(f)}$$

- Null stream: no gravitational wave signal is present

$$\begin{aligned}\tilde{s}_{1-2}(t) &= s_1(t) - s_2(t) \\ &= [h(t) + n_1(t)] - [h(t) + n_2(t)] \\ &= n_1(t) - n_2(t)\end{aligned}$$

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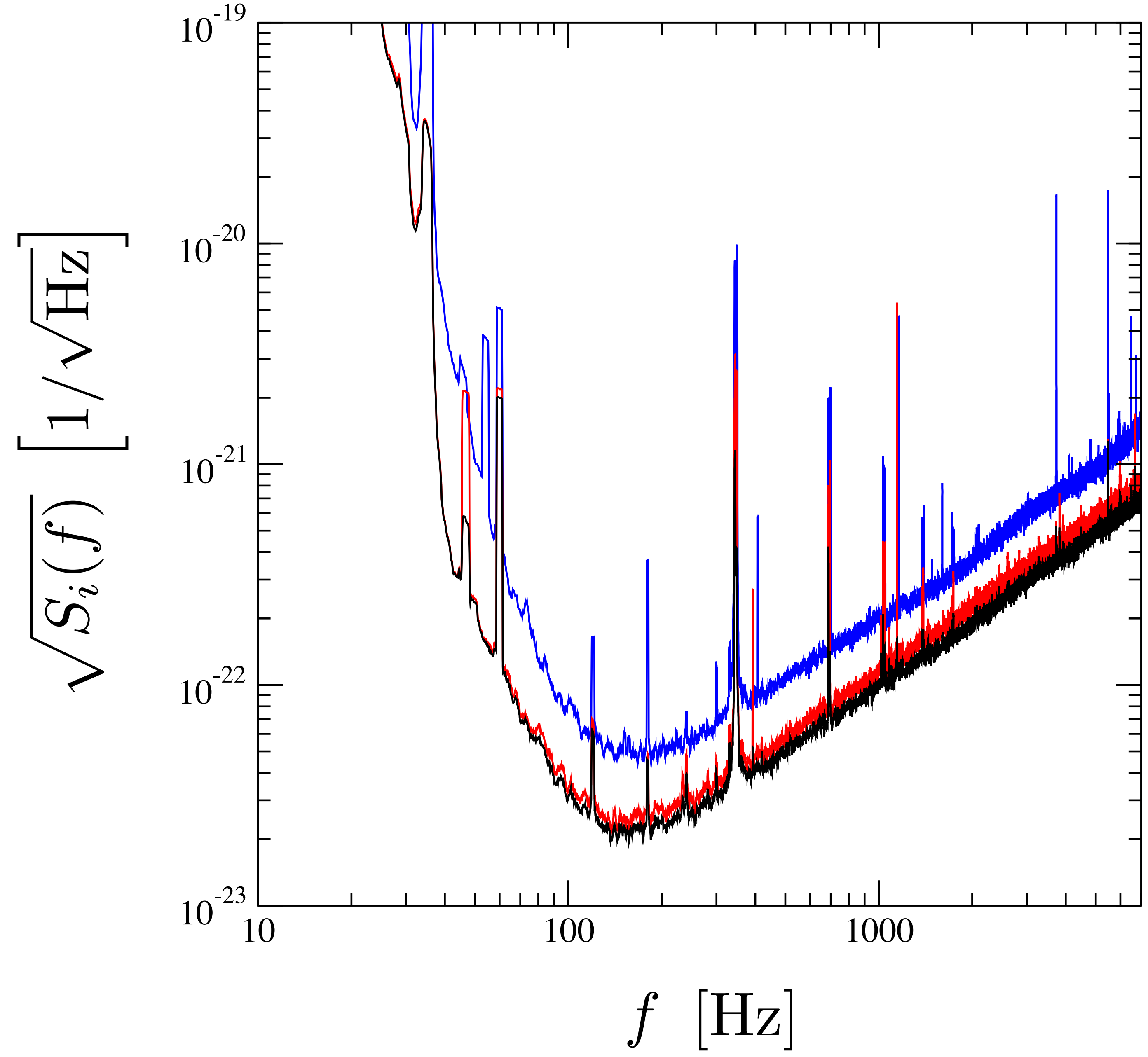


Red - H1

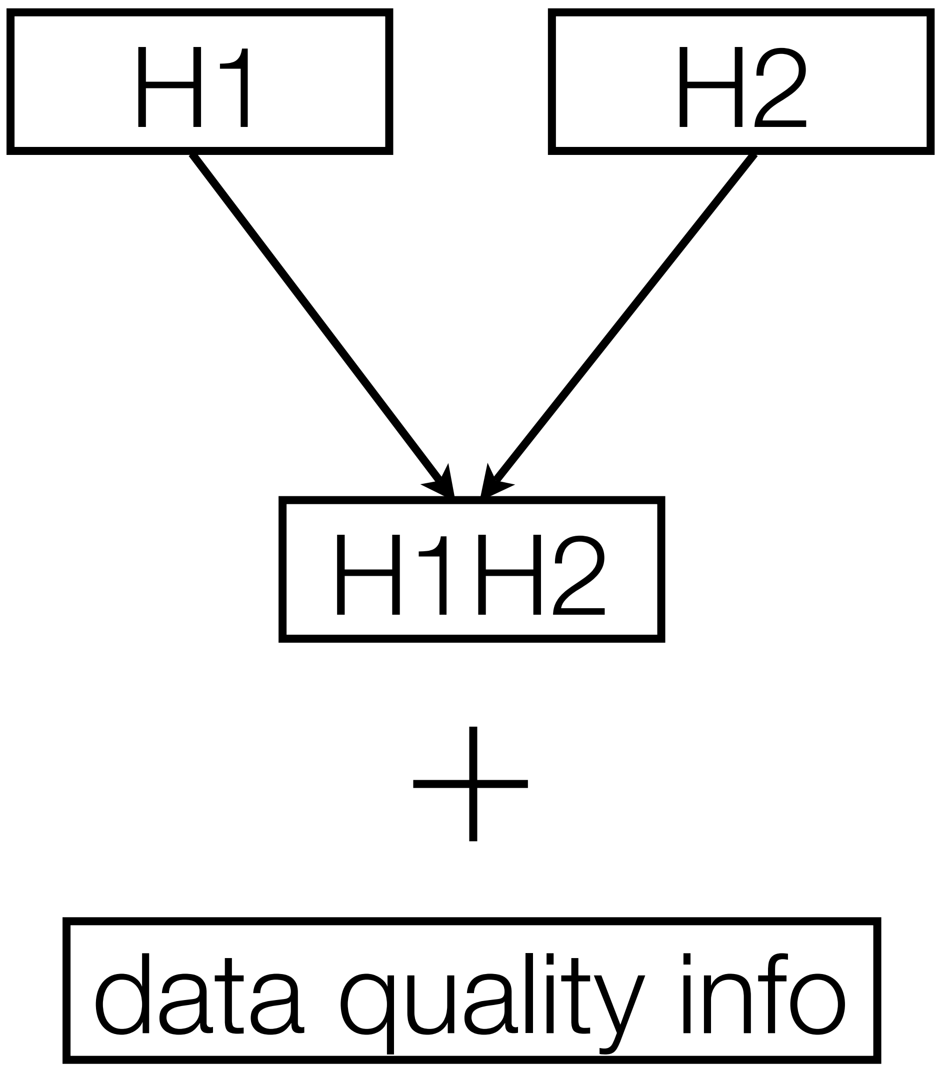
Blue - H2

Black - H1H2

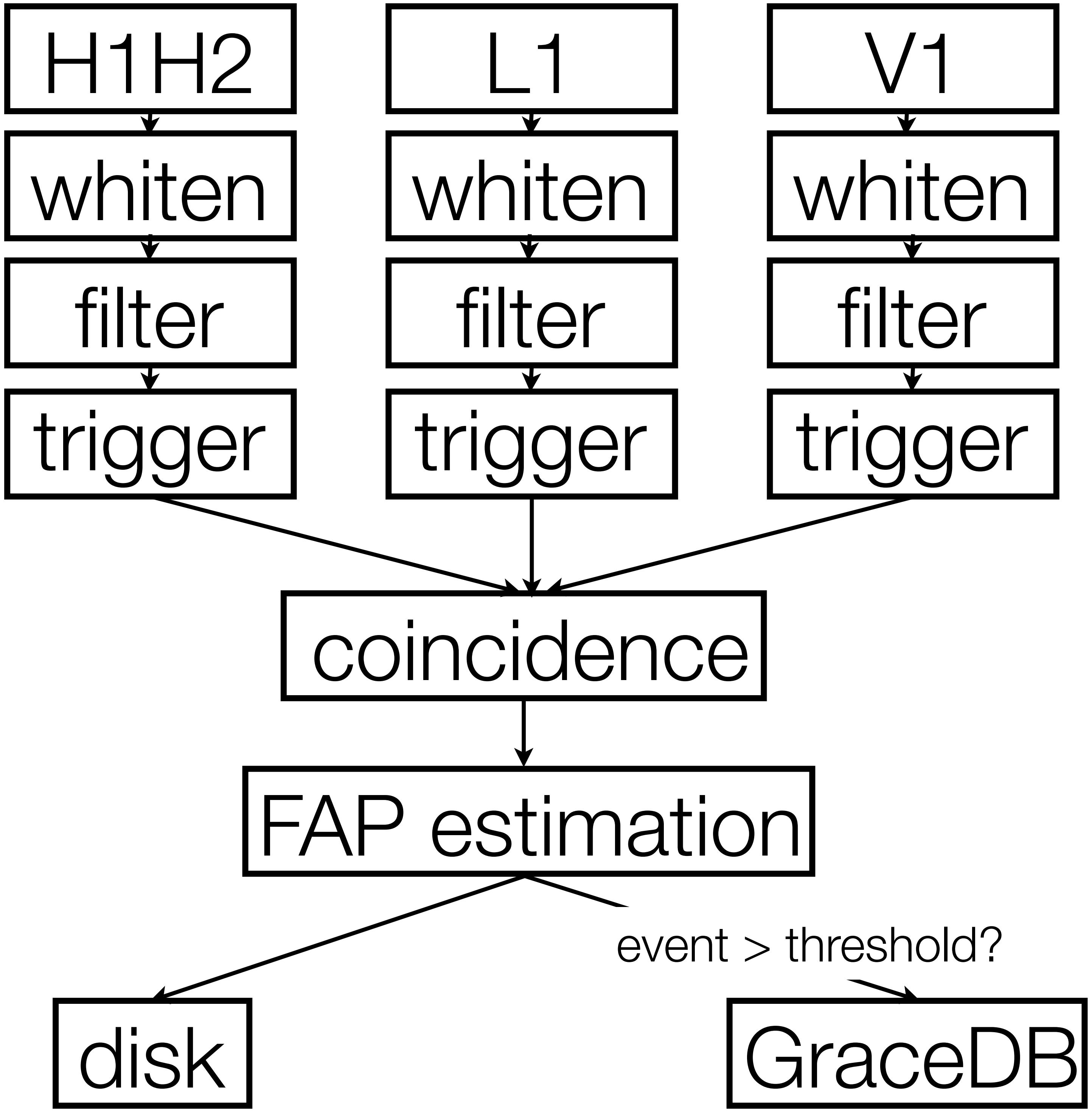
~10% improvement in sensitivity

H1H2 Coherent and Null in SSM Search

- Separate H1 and H2 instruments are replaced by virtual “H1H2” (coherent stream)
- Null stream is used as glitch veto, since the null stream contains no gravitational wave signals
- A glitch is a short duration noise transient



Pipeline Outline



Status and Future Work

- `gstlal_inspiral` is a mature code (has been tested in aLIGO software engineering runs)
- H1H2 coherent and null code is developed and we are currently working on connecting this code to `gstlal_inspiral`
- Within a few months, we hope to have analyzed a month of S5 data and begin a code review
- After the review, we will analyze the remainder of the S5 data