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# Toward early-warning detection of gravitational waves from compact binary coalescence

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## Motivation

AS A COMPACT BINARY SYSTEM loses energy to gravitational waves (GWs), its orbital separation decays, leading to a runaway inspiral with the GW amplitude and frequency increasing until the system eventually merges.

If a neutron star (NS) is involved, it may become tidally disrupted near merger and fuel an electromagnetic (EM) counterpart (Shibata & Taniguchi, 2008). Effort from both the GW and astronomy communities may make it possible to use GW observations as an early warning trigger for EM followup.

In principal, the GW signal is detectable even before tidal disruption. One may have the ambition of reporting GW candidates not minutes after merger, but seconds before. We explore one essential ingredient of this problem, a computationally inexpensive low-latency filtering algorithm.

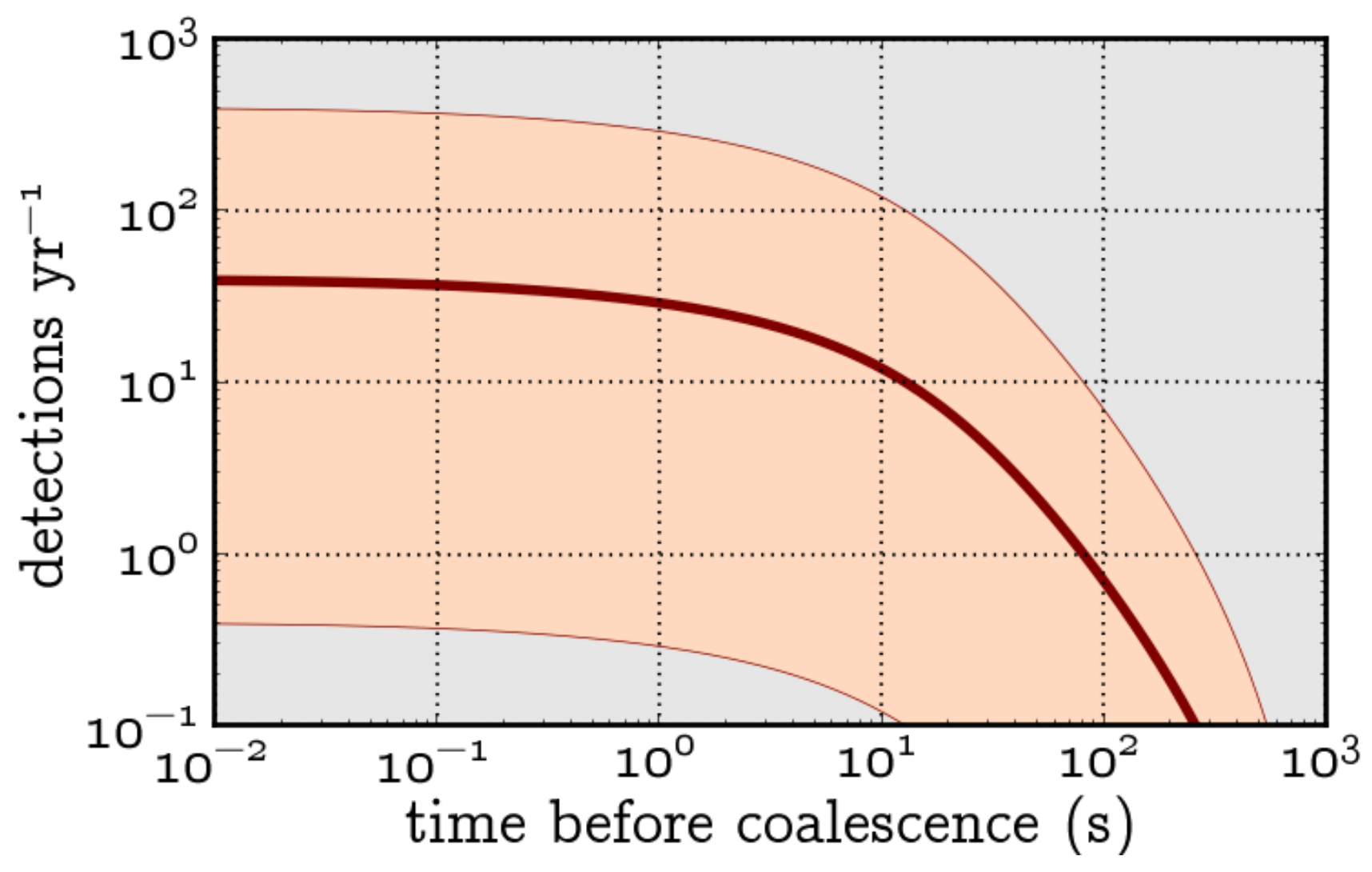

FIGURE 1: *Expected number of NS–NS sources detectable by Advanced LIGO a given number of seconds before coalescence. The heavy solid line is the most realistic yearly rate estimate. The shaded region represents the 5 to 95% confidence interval arising from uncertainty in predicted event rates (Abadie et al., 2010).*

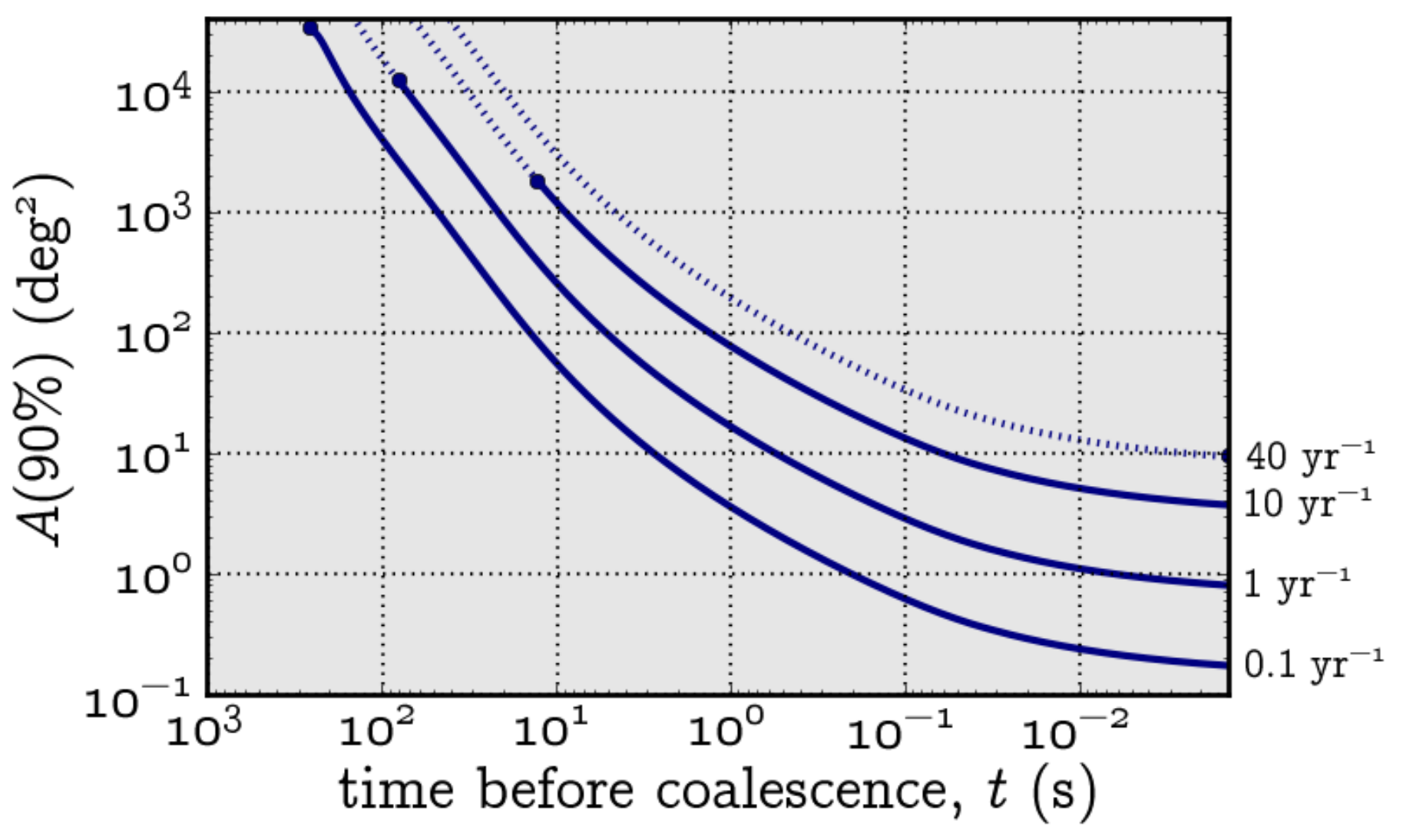

FIGURE 2: *Area of the 90% confidence region (Fairhurst, 2009) without a galaxy catalog prior as a function of time before coalescence for sources with anticipated detectability rates of 40, 10, 1, and 0.1 yr$^{-1}$. The heavy dot indicates the time at which the accumulated SNR exceeds a threshold of 8.*

There were a number of sources of latency associated with the search for CBC signals in the joint LIGO/Virgo data-taking run S6/VSR3 (Hughey, 2011):

- Data acquisition and aggregation ($\gtrsim$100 ms)
- Data conditioning (~1 min)
- Trigger generation (2–5 min)
- Alert generation (2–3 min)
- Human validation (10–20 min)

## The LLOID algorithm

SEARCHES FOR INSPIRAL SIGNALS employ matched filter banks. Our algorithm, called LLOID (Low Latency Online Inspiral Detection), consists of a network of orthogonal filters that closely approximates the matched filters, but with greatly reduced computational cost and with nearly zero latency. Similar to the multi-band approach of Buskulic et al. (2010), we chop the templates into disjoint *time slices* that are processed at reduced sample rates. Then, we reduce the number of filters using the singular value decomposition (SVD) to factor the time-sliced templates into orthogonal FIR filters and a reconstruction matrix (Cannon et al., 2010).

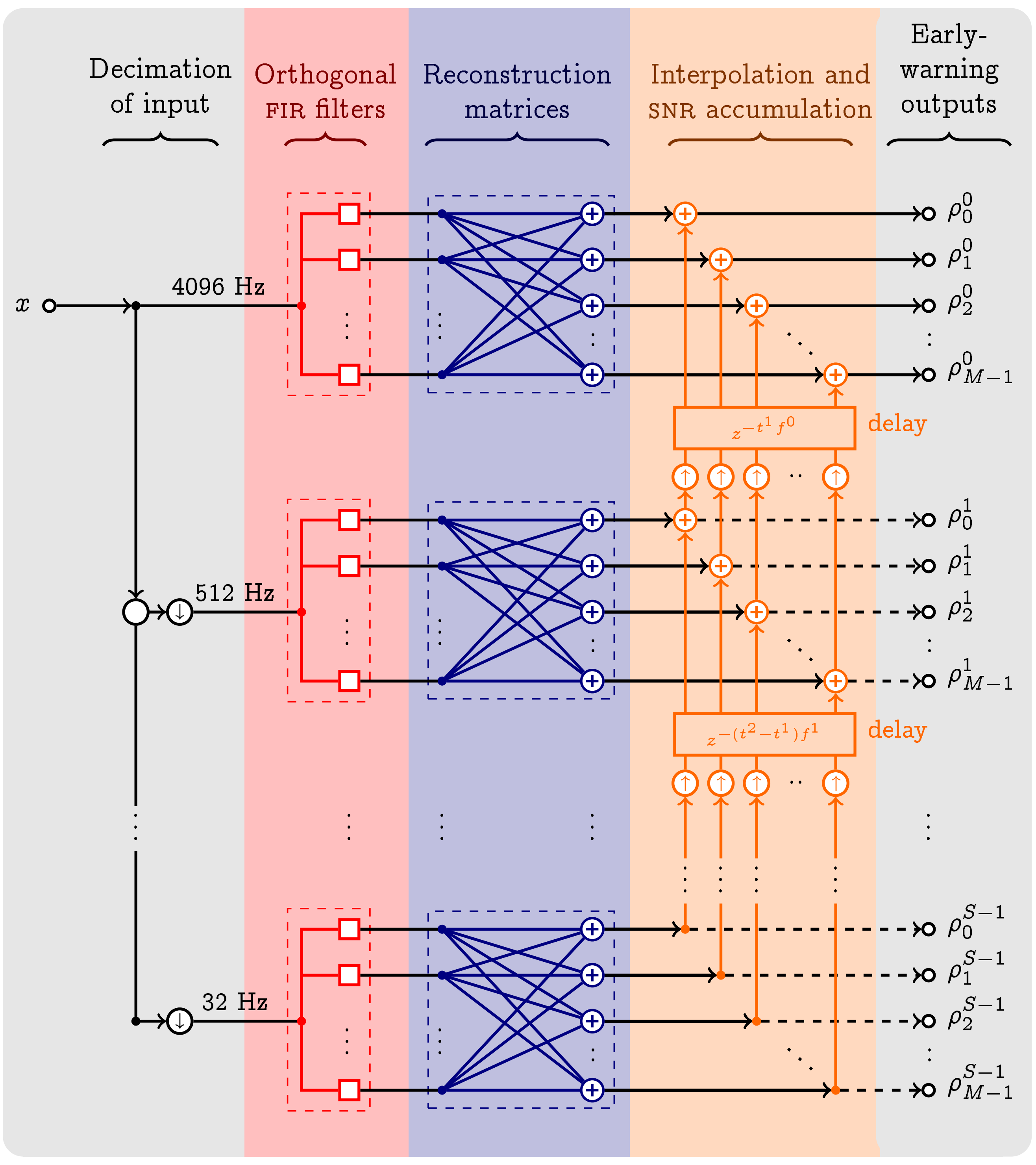

FIGURE 3: *Schematic of LLOID algorithm. Circles with arrows represent interpolation ⊙ or decimation ⊙. Circles with plus signs represent summing junctions ⊕. Squares □ stand for FIR filters.*

$$\underbrace{\rho_i^s\,[k]}_{\text{early-warning output}} = \overbrace{\left(H^{\uparrow}\rho_i^{s+1}\right)[k]}^{\text{SNR from previous time slices}} + \underbrace{\sum_{l=0}^{L^s-1} v_{il}^s \sigma_l^s}_{\text{reconstruction}} \overbrace{\sum_{n=0}^{N^s-1} u_l^s[n]\, \underbrace{x^s[k-n]}_{\text{decimated } h(t)}}^{\text{orthogonal FIR filters}}$$

## Results and conclusion

TABLE 1: *Cost and latency of the TD method, the FD method, and LLOID.*

| method | flop/s (sub-bank) | latency (s) | flop/s (NS–NS) | number of machines |
|---|---|---|---|---|
| time domain | $4.9 \times 10^{13}$ | 0 | $3.8 \times 10^{15}$ | ~$3.8 \times 10^{5}$ |
| frequency domain | $5.2 \times 10^{8}$ | $2 \times 10^{3}$ | $5.9 \times 10^{10}$ | ~5.9 |
| LLOID (theory) | $6.6 \times 10^{8}$ | 0 | $1.1 \times 10^{11}$ | ~11 |
| LLOID (prototype) | (0.9 cores) | 0.5 | ——— | $\gtrsim$10 |

WE HAVE SHOWN a computationally feasible filtering algorithm for rapid and even early-warning detection of GWs from compact binary inspirals. It is one part of a complicated analysis and observation strategy with other latency sources. We hope it will motivate work to reduce technical latency, leading to even faster EM followup to catch prompt emission in the advanced detector era.

## Implementation in GStreamer

WE TESTED THE ACCURACY OF LLOID using a sub-bank of 1314 (real-valued) templates with an Advanced LIGO (high-power, zero detuning) noise spectrum down to 10 Hz.

Figures 4 and 5 depict the masses used for the test and the resulting time-slice design, respectively. The SVD tolerance is set to 0.9999, which guarantees a fractional SNR loss less than 0.003. Table 1 in Results summarizes measurements of latency for a fixed accuracy based on a GStreamer-based prototype of the LLOID algorithm.

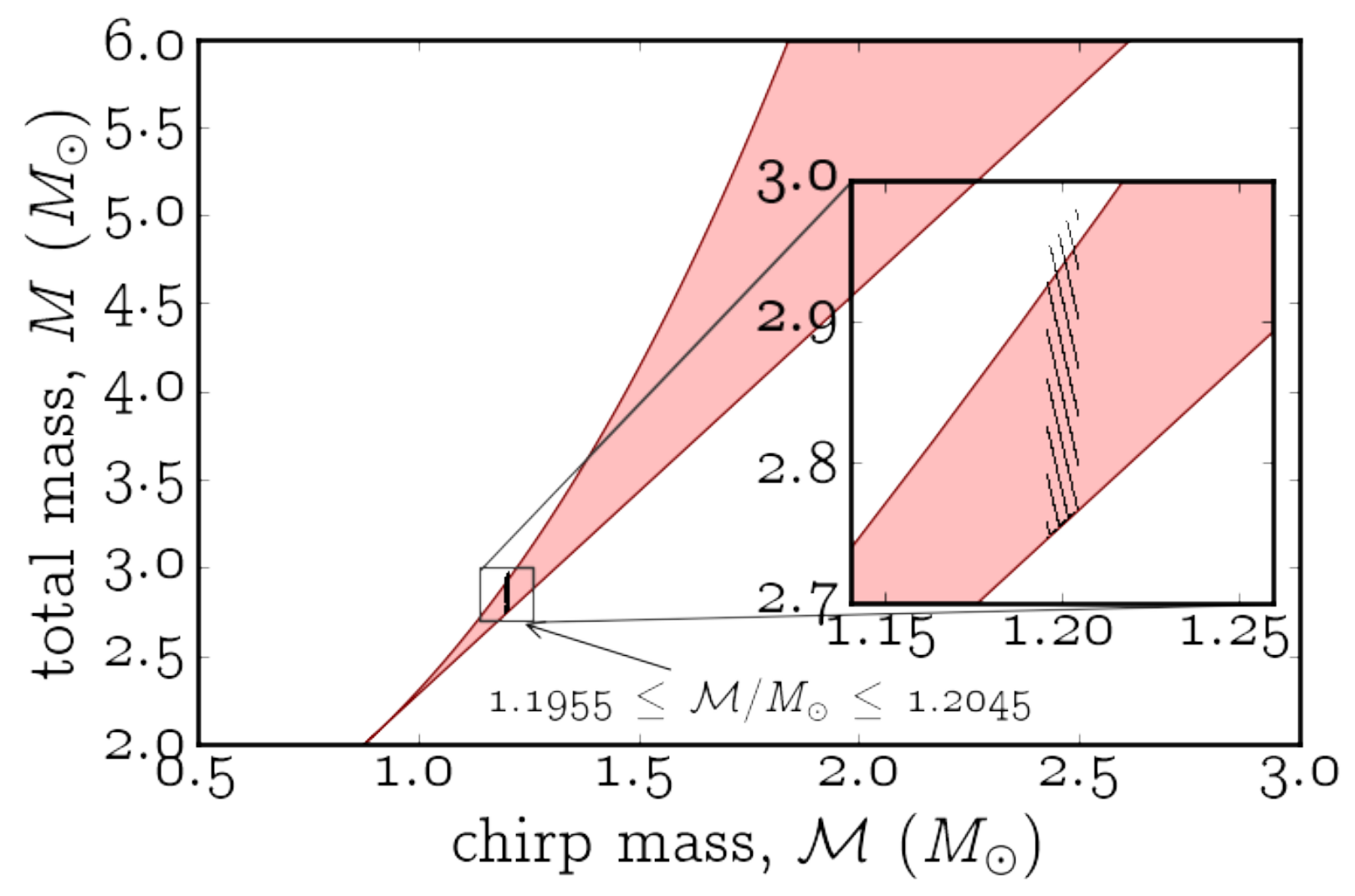

FIGURE 4: *Source parameters for benchmark. Waveforms enter the Advanced LIGO band ~17.5 minutes before merger.*

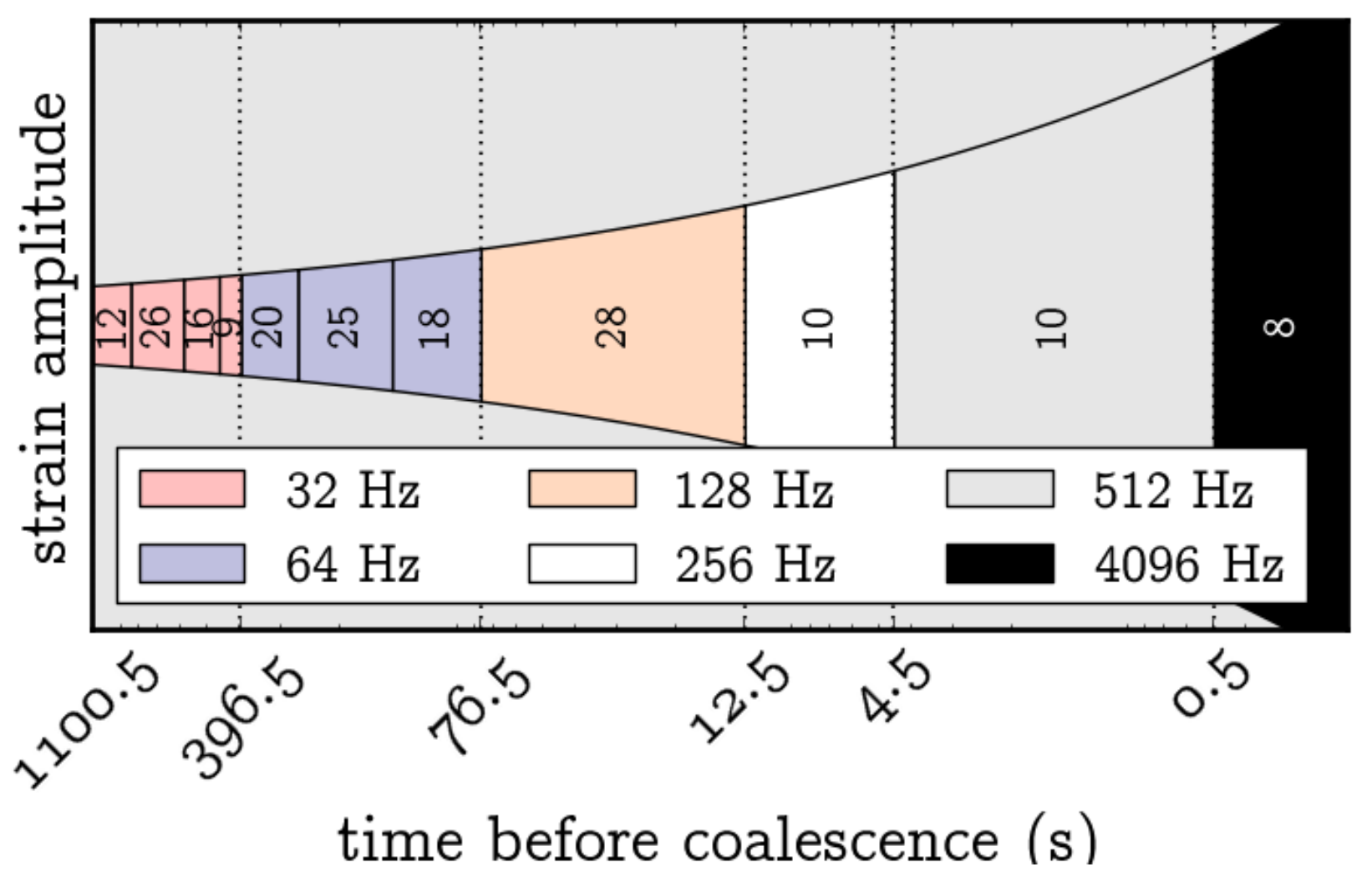

FIGURE 5: *Representative waveform amplitude envelope with time slices color-coded by sample rate and annotated with the number of orthogonal templates.*

GStreamer is an open-source framework used for Linux desktop and mobile multimedia players. As ground-based interferometric detectors are sensitive to GWs at audio frequencies, GStreamer happens to be an excellent fit for low-latency LIGO data analysis.

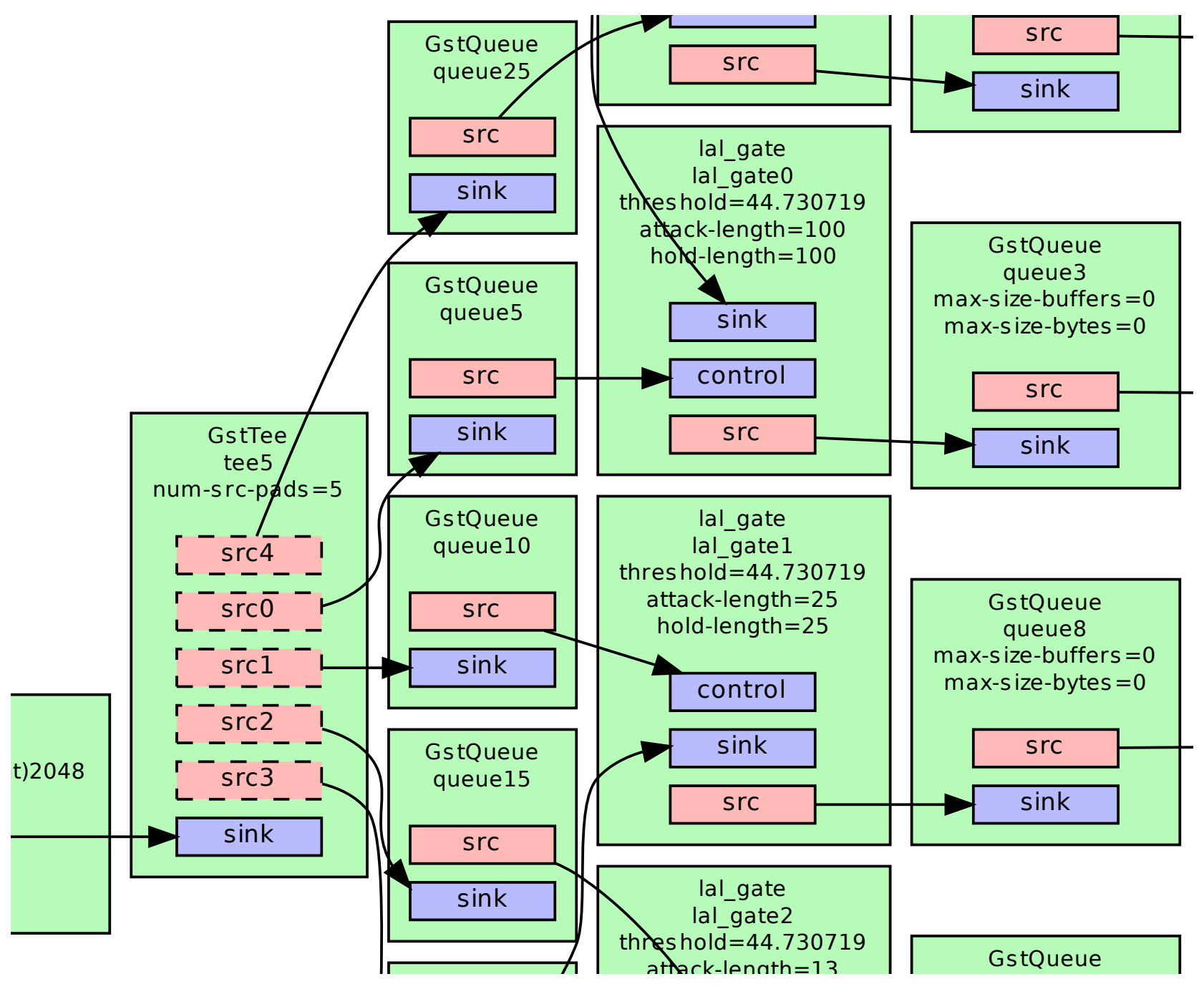

FIGURE 6: *Visualization of part of a typical GStreamer pipeline.*

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