Coherent burst searches for gravitational waves from compact binary objects

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in collaboration with

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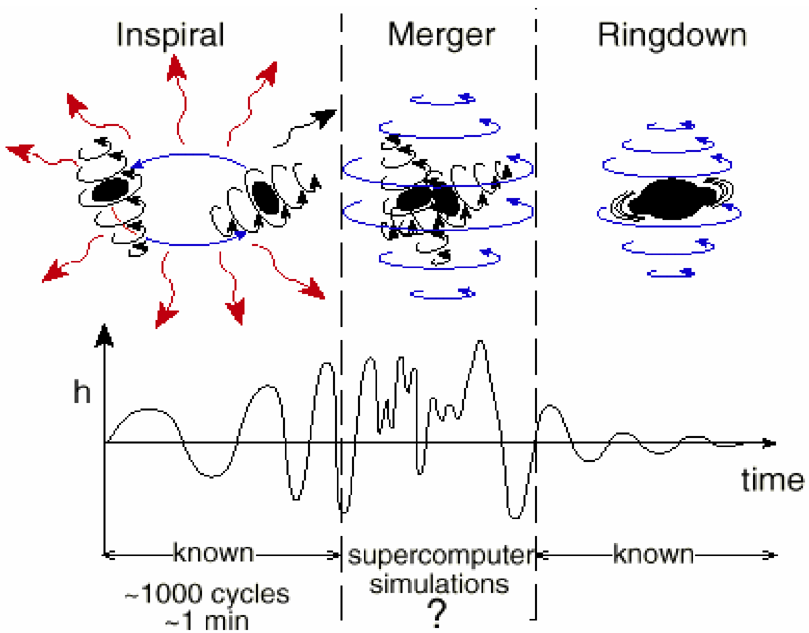
Outline

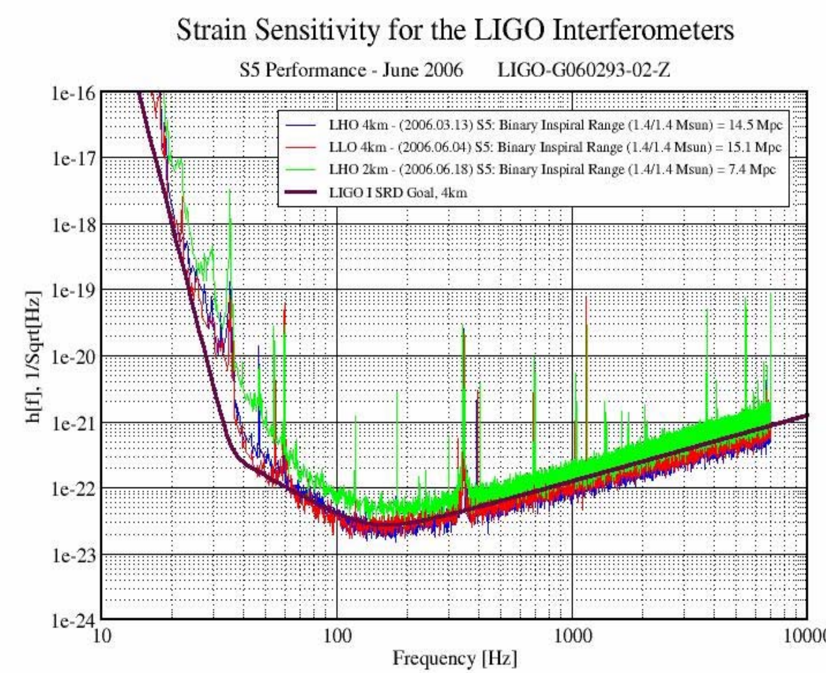
- Compact Binary Coalescence
- Template searches
- CBC Modeling
  - hybrid waveforms
- Coherent Burst Searches
  - constrained likelihood analysis
  - survey of full CBC parameter space
- Summary

How do we survey the full CBC parameter space?

CBC: NS-NS, NS-BH, BH-BH

Compact binary mergers





$$f_{lso} \approx 205 Hz \cdot \left(\frac{20 M_o}{M}\right) \qquad f_{qnr} \approx 1300 Hz \cdot \left(\frac{20 M_o}{M}\right)$$

E.Flanagan and S.Hughes, PRD57, 4535 (1998)

- **CBC sources are well understood theoretically, particularly binary BH**
- **Massive binary BH objects can be detected via merger and ring-down**
- **One of the most promising sources to be detected with LIGO**

CBC Template Searches

- By using theoretical predictions generate a bank of templates covering some parameter space Ω of expected GW signals

$$\Omega \equiv \{m_1, m_2, \vec{s}_1, \vec{s}_2, \theta, \varphi, \psi, i, \ldots\}$$

- matched filters
  - max correlation <xξ(Ω)>: x – data, ξ(Ω) – calculated detector response
  - coherent searches

$$L(x\,|\,\Omega) = -\ln\left(\max_{templates}\left(\frac{P(x\,|\,\Omega)}{P(x\,|\,0)}\right)\right)$$

See poster by Sukanta Bose et al.

- advantages:
  - optimal detection sensitivity for selected class of sources
  - possible estimation of source parameters Ω
- disadvantages:
  - need large number of templates to cover full CBC parameter space
  - complete templates (with all CBC phases) are not readily available, particularly for NS-BH sources

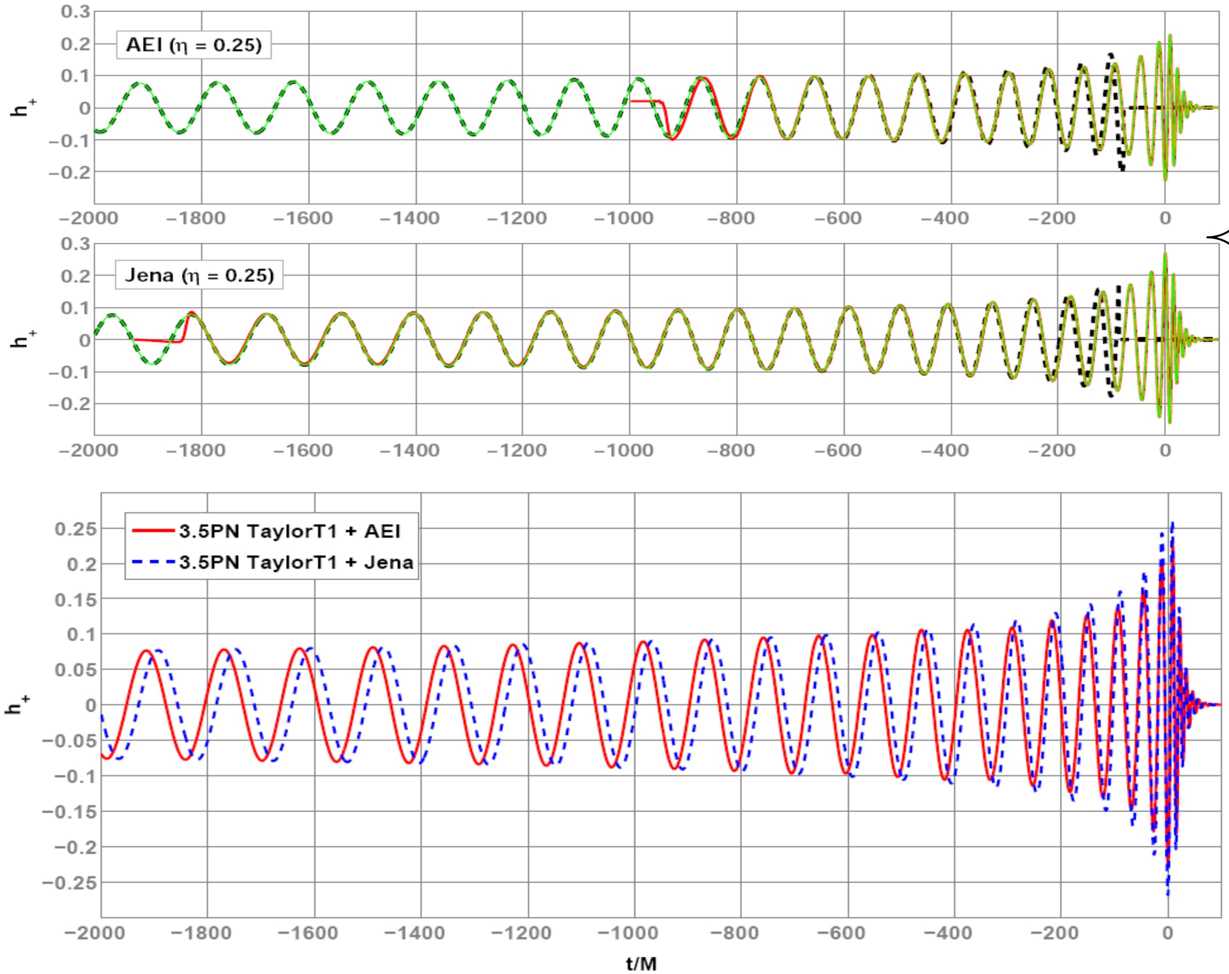
modelling of binary black holes

- **Inspiral stage** modelled by post-Newtonian approximation to GR.
  - Blanchet et al (2004), Arun et al (2004), Kidder(2007).
- **Merger stage** modelled by numerical-relativity simulations.
  - Pretorius (2005), Baker et al (2006, 2007), Campanelli et al (2006, 2007), Gonzalez et al (2006, 2007), Koppitz et al (2007), Pollney et al (2007), Rezzolla et al (2007), Boyle et al (2007), Hannam et al (2007).
- **Ring-down stage** modelled by black-hole perturbation theory.
  - Teukolsky & Press (1974), Echeverria (1989)
  - Numerical-relativity waveforms also contain the ring-down

Hybrid BBH waveforms

- **Great progress in analytical and numerical relativity in solving the binary BH problem.**
- **Gravitational waveforms from all the three (inspiral, merger and ring-down) stages can be computed**
- **But, it is still too expensive to compute NR waveforms**
- **Possible solution: Post-Newtonian (PN) theory is known to work very well at the (early) inspiral stage. PN inspiral waveforms can be matched with NR (merger + ring down) waveforms in a region where both calculations are valid thus constructing "hybrid waveforms.**
  (Buonanno et al (2007), Pan et al (2007), Ajith et al (2007a, 2007b))

Constructing hybrid waveforms



- **Red** NR waveforms from AEI and Jena
- **Black** 3.5PN TaylorT1 waveforms
- **Green** Hybrid waveforms

$$\eta = \frac{m_1 m_2}{(m_1+m_2)^2}$$

P. Ajith et al, arXiv:0710.2335 [grqc]

See also talk by Lucia Santamaria et al.

Status of constructing hybrid waveforms

- Hybrid waveforms (leading harmonic) from non-spinning binaries in the range $1 \le m_1/m_2 \le 4$ are already available.
- Hybrid waveforms that may be available in the near future
  - Non-spinning BBH with $m_1/m_2 > 4$
  - Non-spinning BBH including higher harmonics
  - Spinning hybrid BBH with certain spin configuration (e.g, spins orthogonal to the orbital plane)
- However, due to computational cost of the NR waveforms, the construction of large template banks to survey the full BBH parameter space may still be in a distant future

Coherent Burst Searches

- **Likelihood ratio for Gaussian noise with variance σ^2_k and GW waveforms h_+, h_x : $x_k[i]$ – detector output, F_k – antenna patterns**

$$L = \sum_i \sum_k \frac{1}{\sigma_k^2}\left[x_k^2[i] - \left(x_k[i] - \xi_k[i]\right)^2\right]$$

detector response - $\xi_k = h_+ F_{+k} + h_\times F_{\times k}$

- **Find solutions by variation of *L* over un-known functions h_+, h_x (Flanagan & Hughes, PRD 57 4577 (1998))**

- **search in the "full" parameter space**
  - **good for un-modeled burst searches, but…**
  - **number of free parameters is comparable to the number of data samples**
  - **need to reduce the parameter space → constraints & regulators (Klimenko et al , PRD 72, 122002, 2005)**

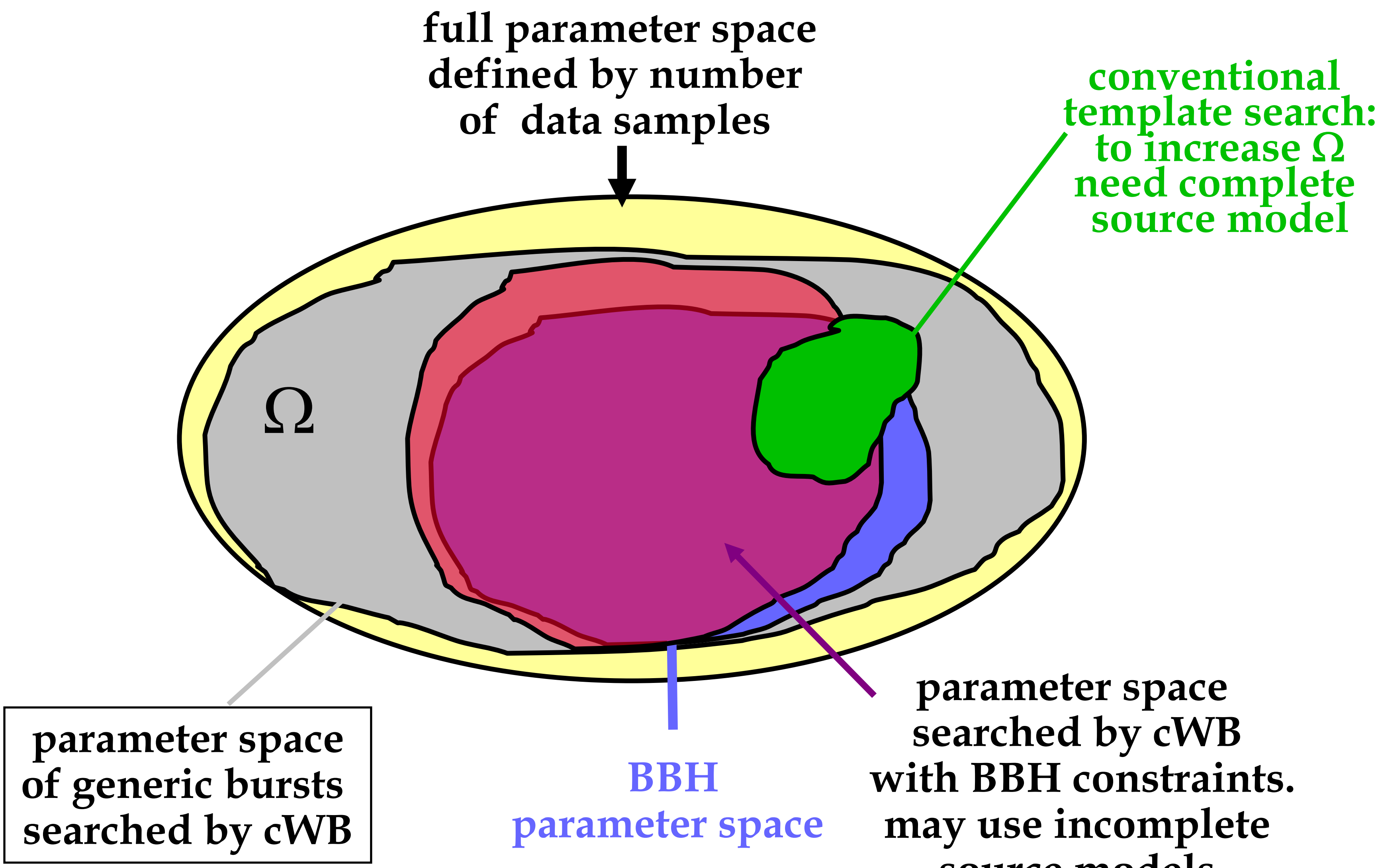
Likelihood constraints

- Goal: reduce parameter space searched by the pipeline and thus increase the detection efficiency
- Model independent constraints
  - e.g. require that responses ξ_k and detector noise are orthogonal

$$L = L_o(x, h_+, h_\times) + \sum \lambda_k \left(\langle x_k \xi_k \rangle - \langle \xi_k^2 \rangle \right)$$

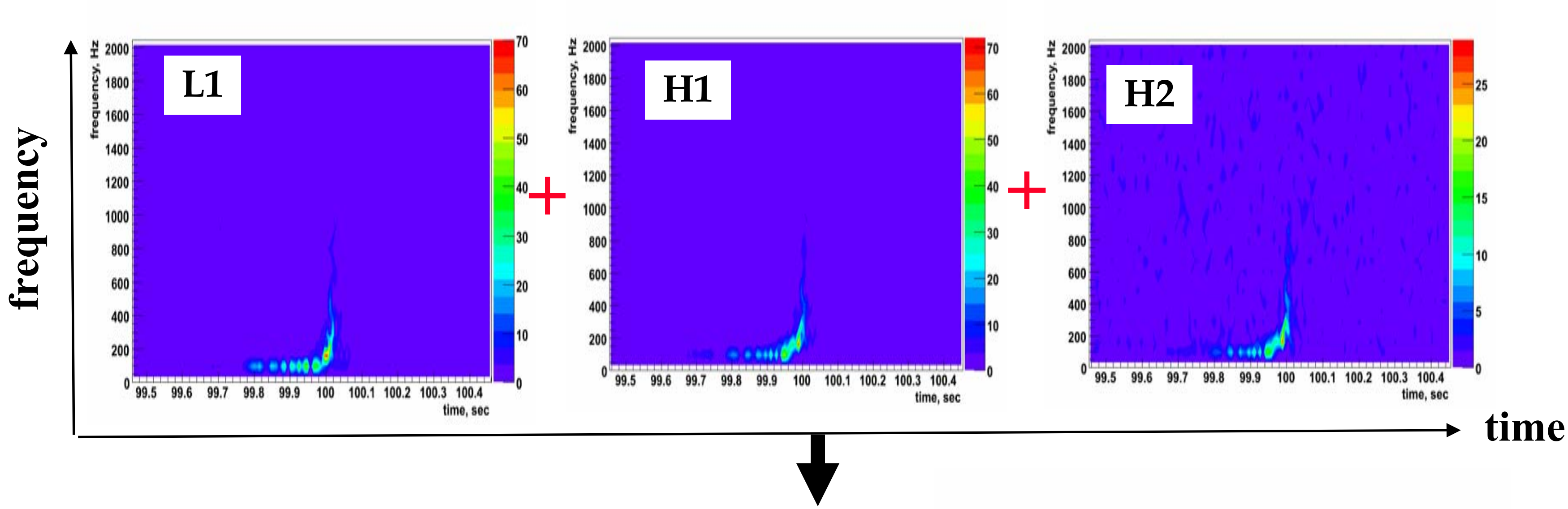
  - such constraints remove some unphysical solutions for h+ and hx
- Model dependent constraints
  - Unlike for template searches, incomplete source models can be used
  - there are several options how the BBH constraints can be introduced either constraining the likelihood functional or at the trigger selection stage
  - hybrid waveforms are used to test the implemented constraints and estimate the sensitivity of the search

Survey of the full BBH space



Coherent WaveBurst

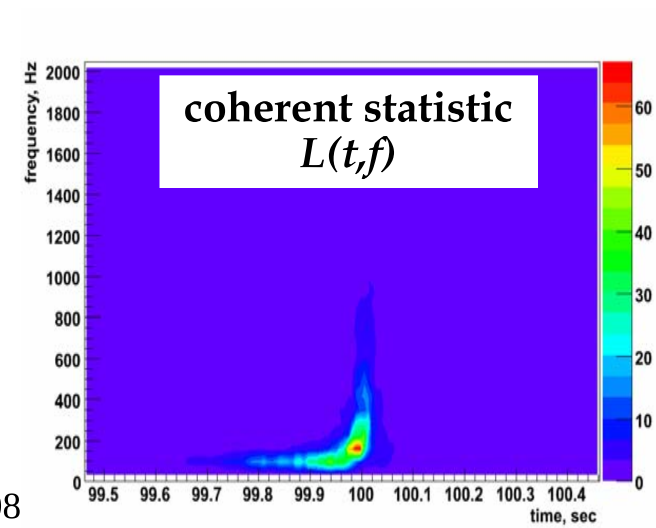
- **End-to-end multi-detector coherent pipeline**
  - construct coherent statistics for detection and rejection of artifacts
  - performs search over the entire sky
  - estimates background with time shifts



$$\xi_k = h_+ F_{+k} + h_x F_{xk}$$

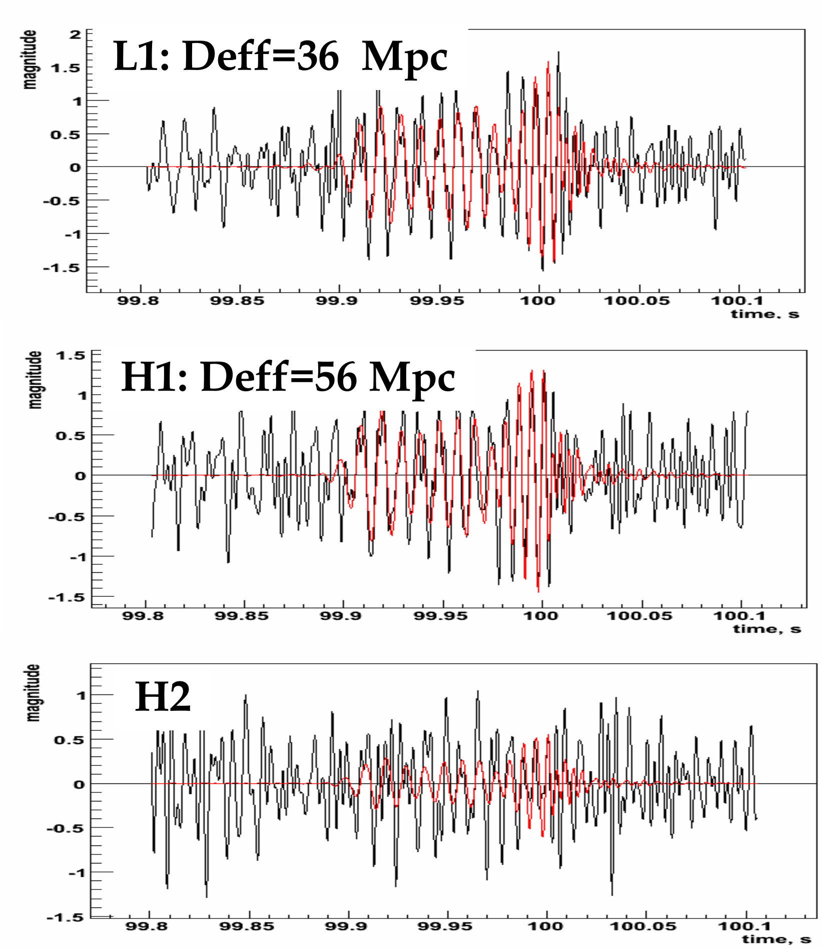
$$L(t,f) = \max_{h_+ h_\times \theta \varphi} \sum_k \frac{x_k^2[t,f] - \left(x_k[t,f] - \xi_k[t,f]\right)^2}{\sigma_k^2(f)}$$

Hybrid BH-BH: 18 Mo, 2 Mpc

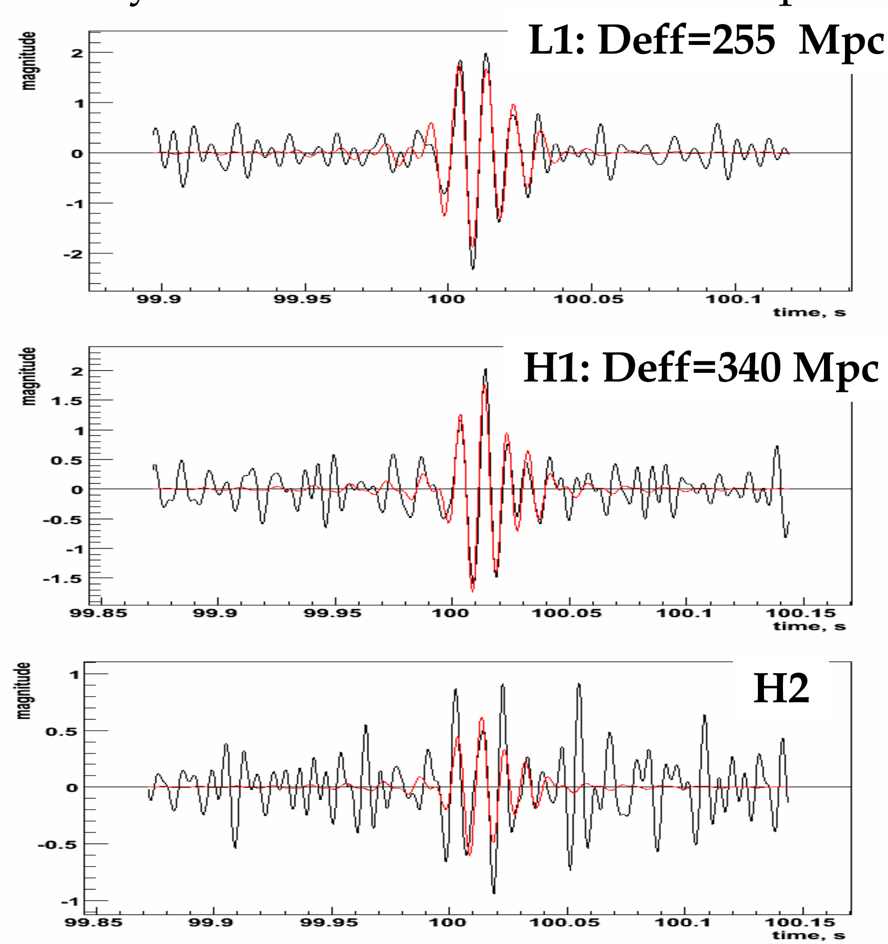


Hybrid injections

Hybrid BBH 1.2: 18 Mo, D=25 Mpc



Hybrid BBH 1: 150 Mo, D=65 Mpc



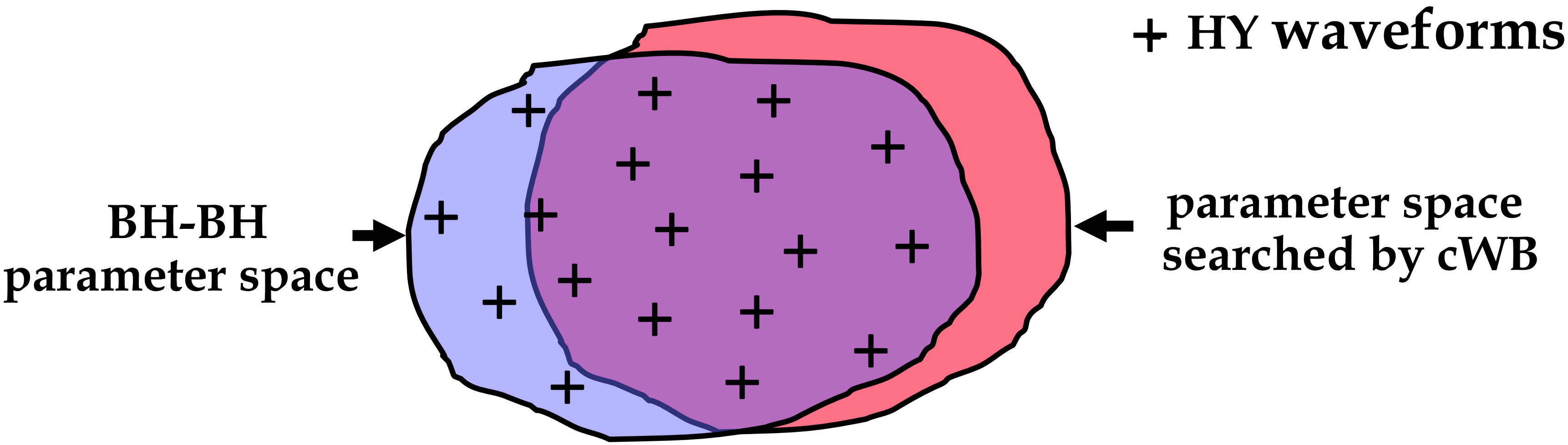
11 average SNR per detector 10

$$D_{eff} = \frac{D}{\sqrt{F_+^2(1+\cos^2(i))^2/4 + F_\times^2\cos^2(i)}}$$

See details of signal reconstruction in A.Mercer's poster "Coherent event display"

Use of hybrid waveforms

- Use small number of representative hybrid waveforms for sparse tiling of the parameter space
  - used for cWB tuning and estimation of the BBH efficiency



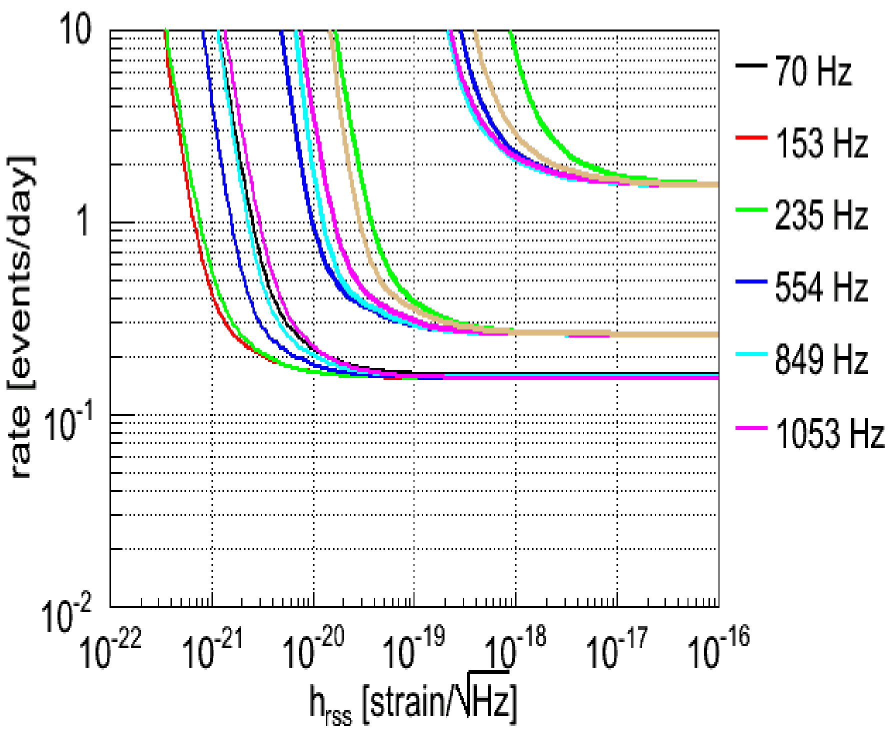
- How many waveforms?
  - Initial search – total 28 waveforms

Mass ratio:	1	1:2	1:5	1:10			
Spin parameter:	0	0.5⇊	0.5⇈	0.5⇅	0.9⇊	0.9⇈	0.9⇅

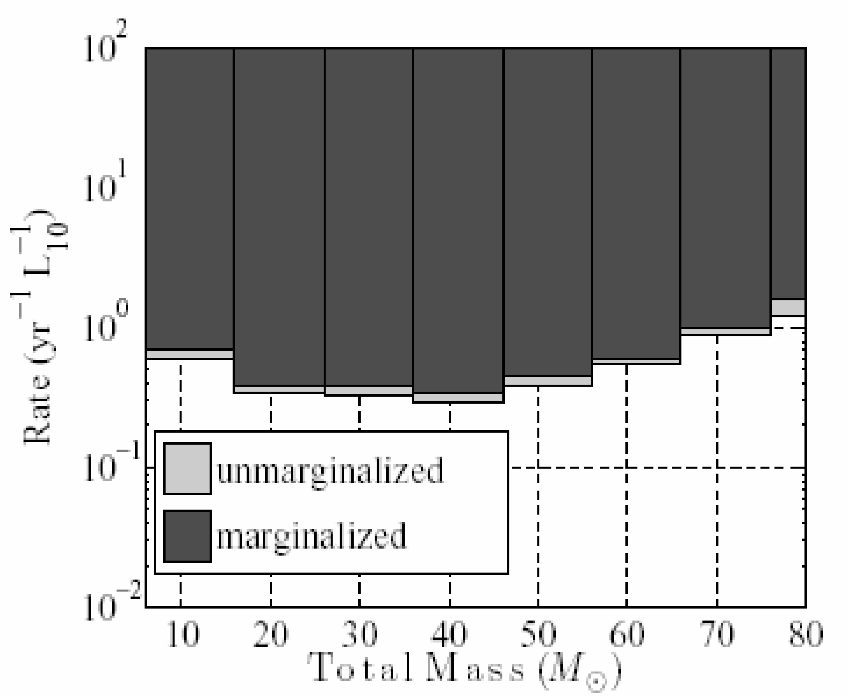
  - advanced search – may add more waveforms

Interpretation of search results

LIGO burst searches
arXiv:0704.0943v3 [gr-qc]



S4 LIGO BBH search
arXiv:0704.3368v2 [gr-qc]



- **dedicated BBH coherent WaveBurst search**
  - **more direct astrophysical interpretation of the results**
  - **complementary to traditional inspiral searches**
  - **expect better detection for massive BBH (M>50Mo)**

Summary

- **Compact binary coalescence, particularly binary BH, are the most promising GW sources for detection.**
- **Progress in NR makes possible calculation of complete waveforms for binary BH. However, creation of large template banks to survey the full BBH parameter presents a significant computational challenge.**
- **Such survey is possible with the coherent burst algorithms which require only a small number of representative BBH waveforms used for estimation of the sensitivity of the search**
- **We plan to customize the existing coherent WaveBurst algorithm by introducing BBH constraints and conduct the BBH search with the LIGO data**