Abnormal correlations in the LIGO data

Hao Liu & the Danish team

Based on:

Journal of Cosmology and Astroparticle Physics

On the time lags of the LIGO signals

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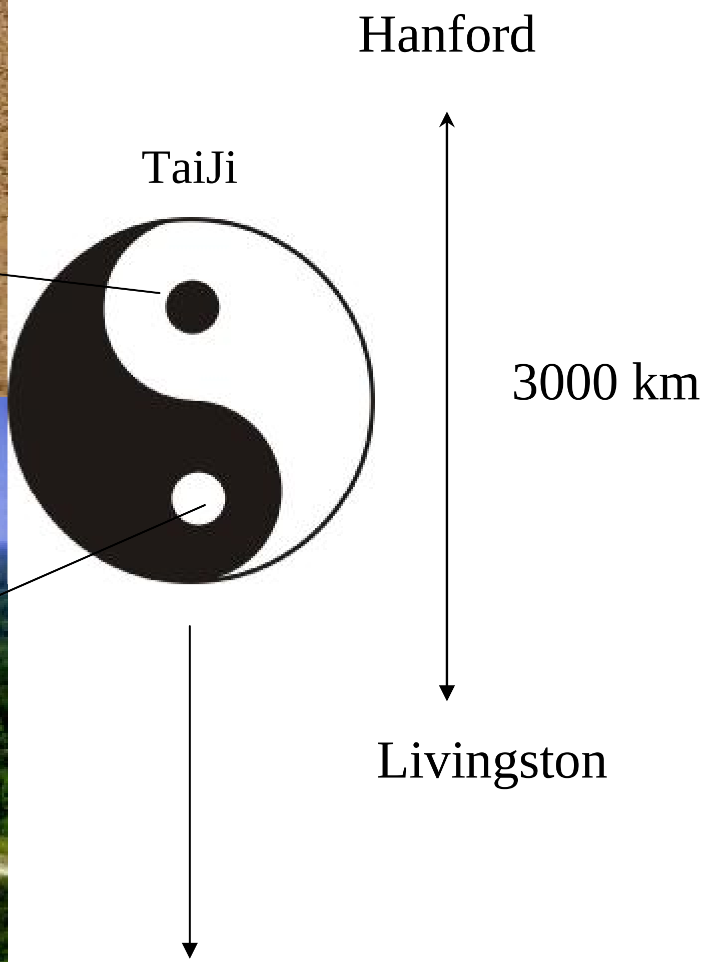


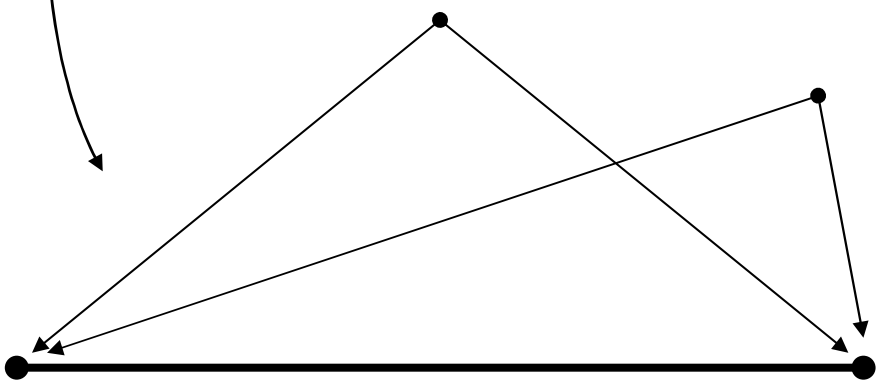
“TaiJi” is also the name
of the Chinese project
for space GW detection

H/L time lag

- Detection of a GW event needs at least two detectors.
  - Time lag
    - Light speed à distance (3000 Km) à -10~10 ms
    - Line-of-sight
  - Similarity
    - Strong correlation with a proper time lag
  - Both are reasonably good à candidate
- For residual, none of the above is expected

Detector - detector

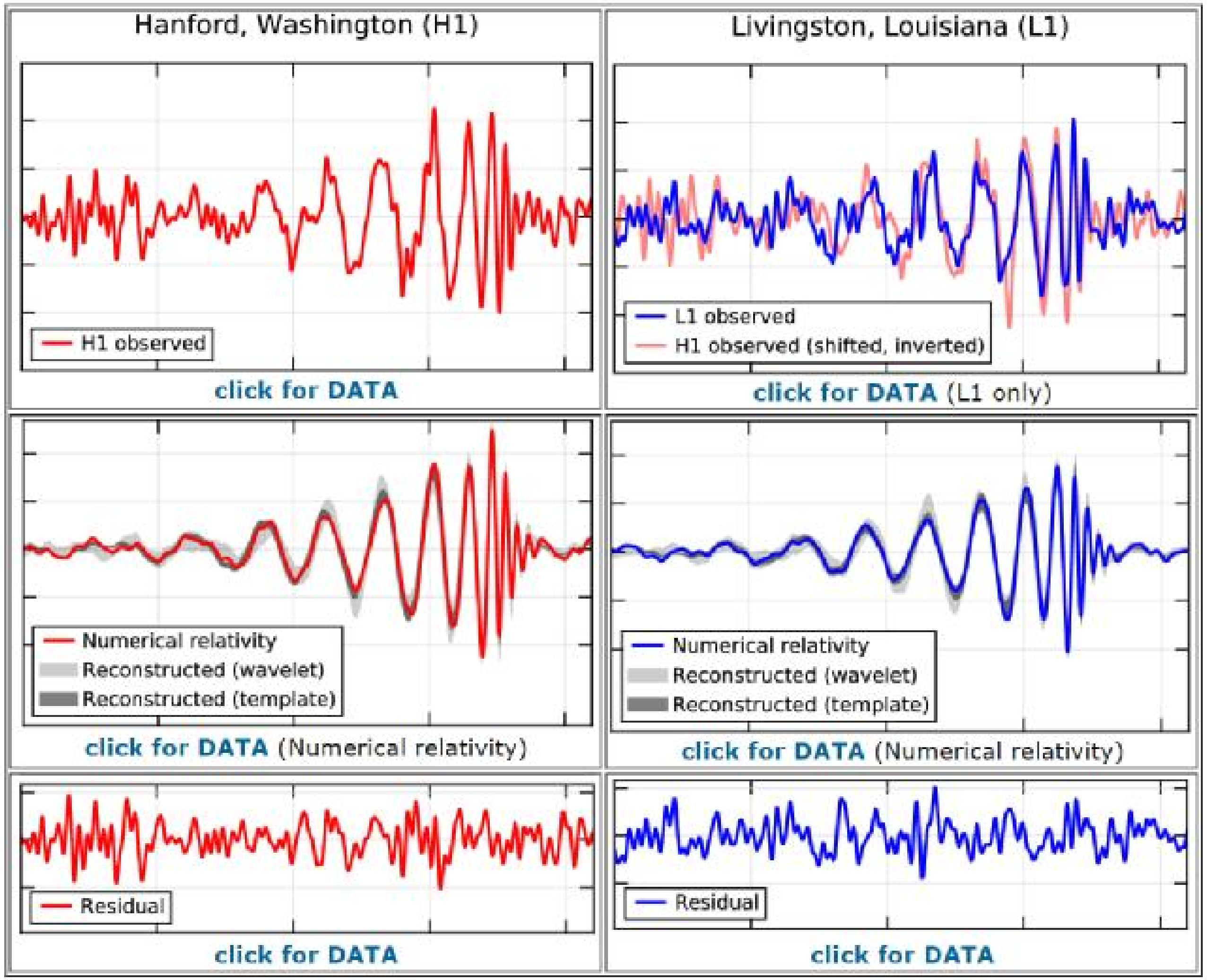
Detector - GR

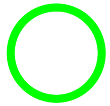


The Pearson correlation coefficient:

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}}$$

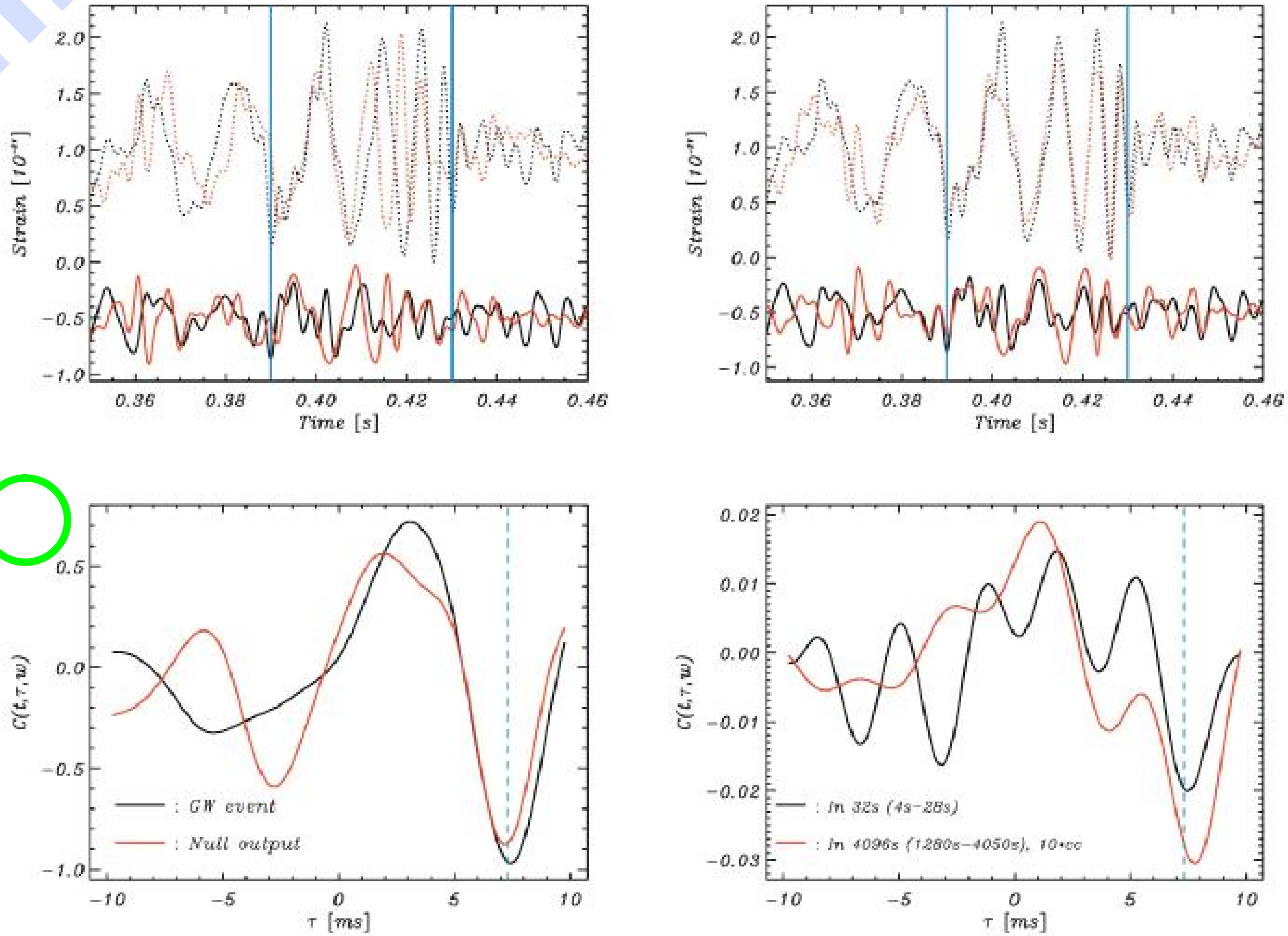
GW150914 and the residual (Fig. 1, Phys. Rev. Lett. 116, 061102)





Abnormal correlation of the residual

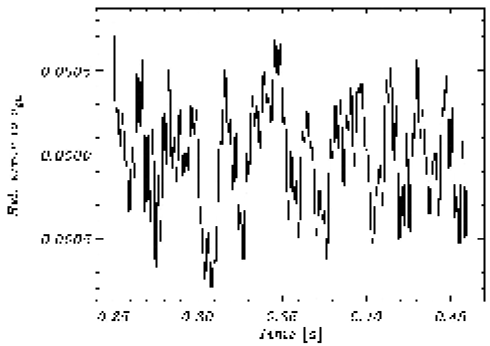
Both = ○



See also: http://www.nbi.ku.dk/gravitational-waves/

The first idea that comes to our mind

- Is something wrong with the GW-template?
  - There are two templates published:
  - Fig. 1, Phys. Rev. Lett. 116, 061102
  - https://losc.ligo.org/s/events/LOSC_Event_tutorial.zip
- Our work has been:
  - Tested for both.
  - Intensively inspected by both us and LIGO
  - Only minor amplitude changes



- Nothing we can do with the unpublished templates.
- However, we can and should do something without templates.

Where are the abnormal correlations?

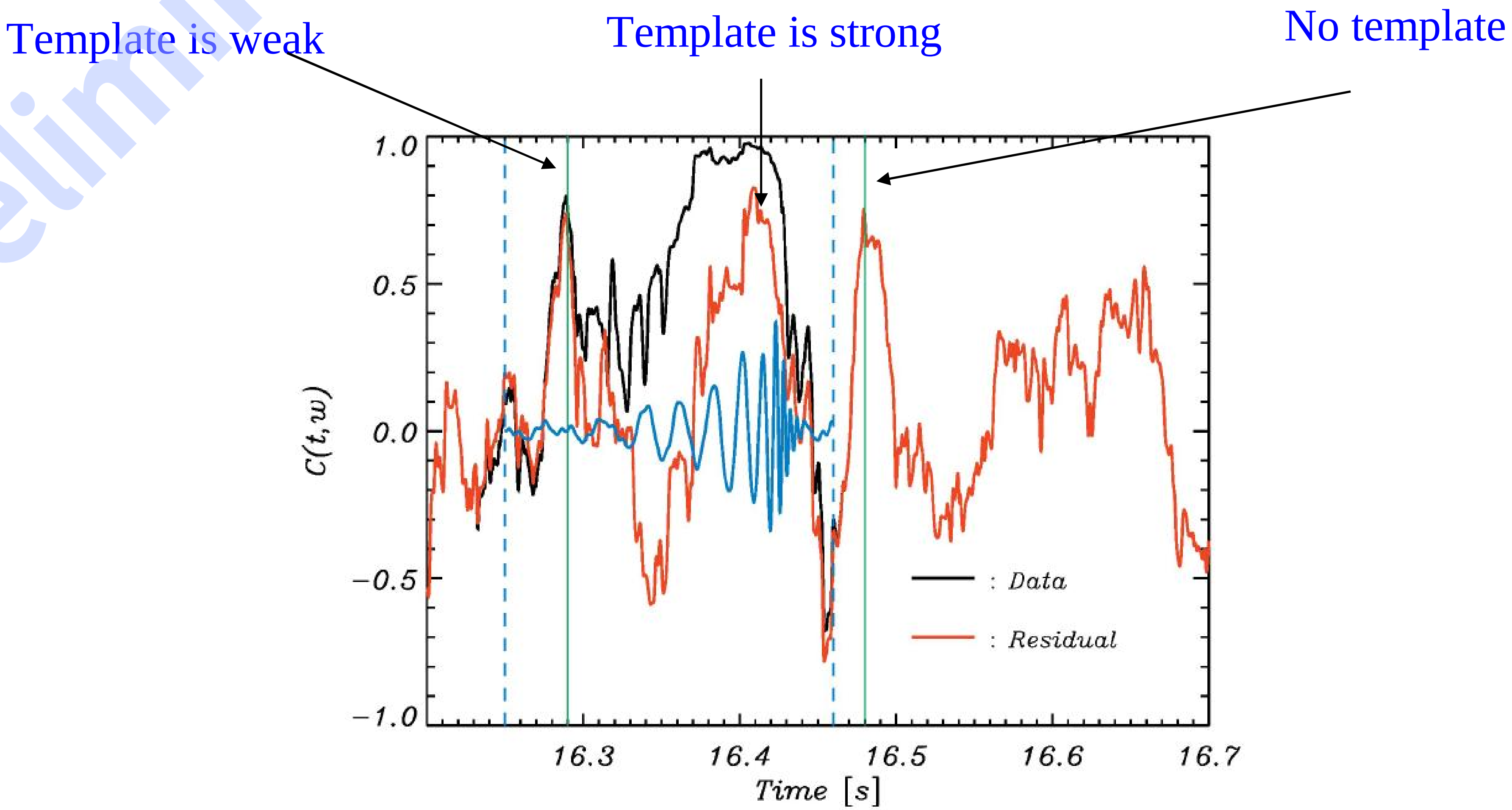
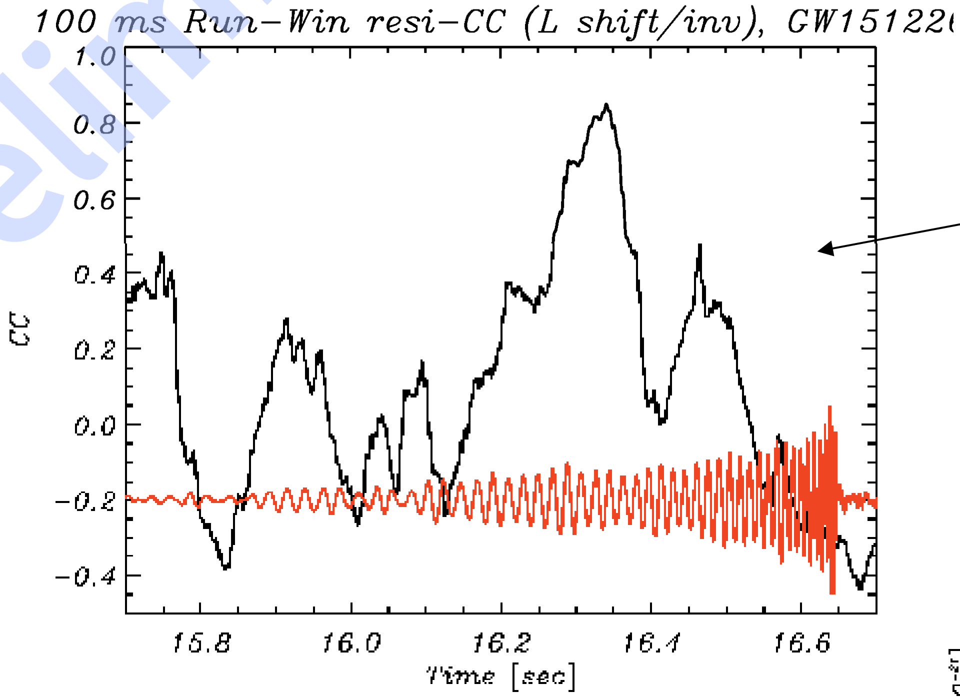


Figure 25. The running window correlation $C(t, w)$ (Eq. (G.1)) with Livingston inverted and shifted by 7 ms. Black for the clean strain data, and red for the residual (data minus template). The precursor and echo peaks are marked by the green vertical lines.

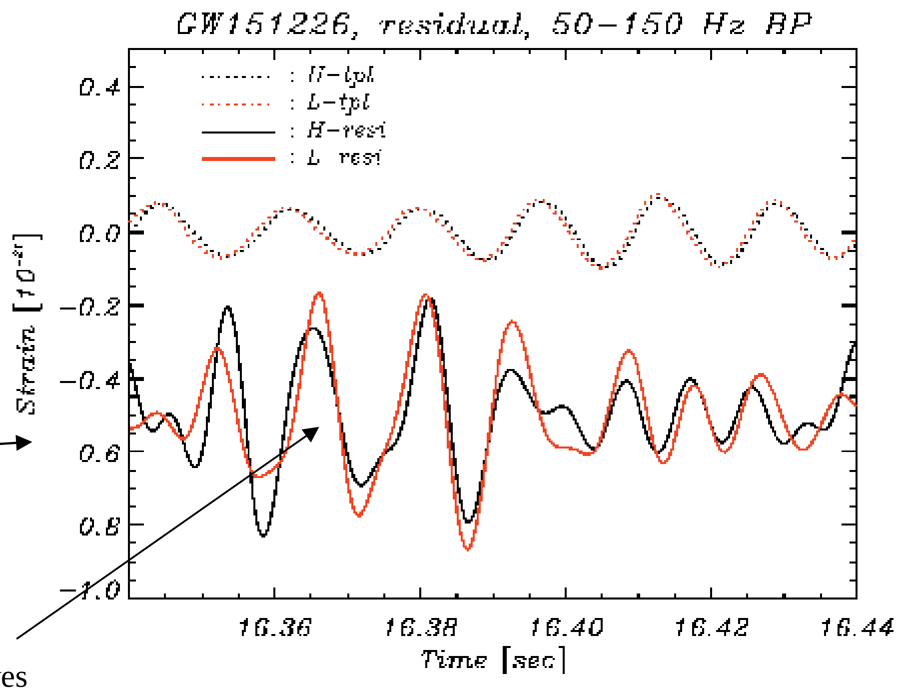
For GW151226 (where GW is very weak)



Similar to the previous page, but for GW151226

https://losc.ligo.org/events/GW151226/

The corresponding time-domain signal



Strong correlation between the residuals can be seen by naked eyes

Blind estimation of the common signal

- Description of the method: estimation of the common signal without a template
  - A: denotes the common signal
  - X, Y: denote the Hanford and Livingston data
  - Corr(A, X), Corr(A, Y): They should be high
  - Corr(A-X, A-Y): This should be low
- Why do we want to estimate the common signal?
  - To check if the LIGO template is consistent with a blind estimation
  - To try to reduce the level of residual-CC with a reasonable common signal estimation.

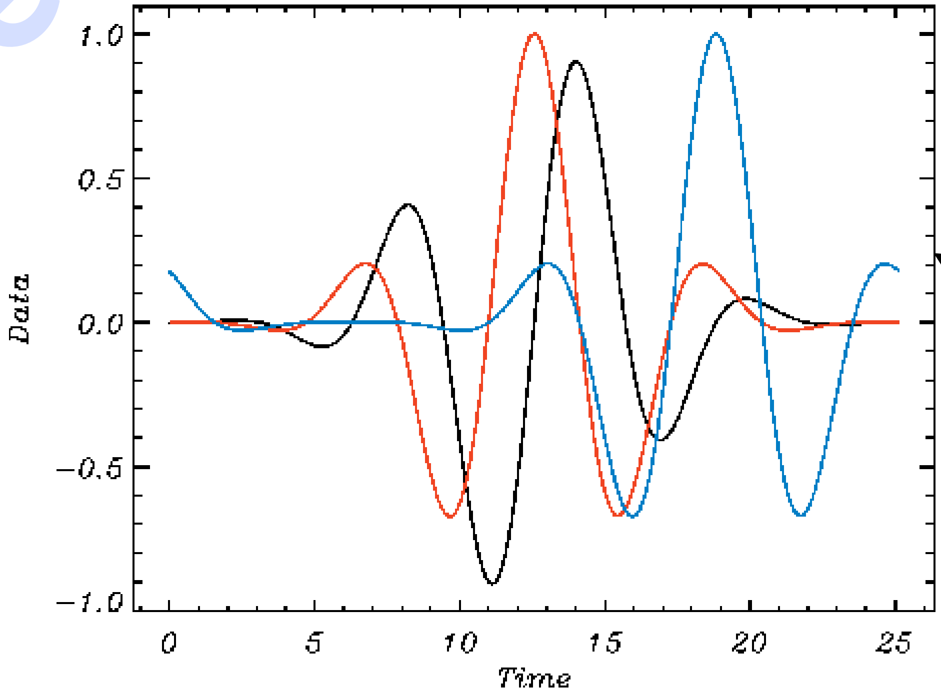
$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}}$$

Before estimation, we should match H/L

$$H(\omega) = \alpha L(\omega) e^{i(\Delta + \omega \cdot \tau)},$$

Close to π

"Matching" means optimization of these three **constant** parameters.



Before matching, they look different.

After matching, they will be exactly same (for this example).

- https://losc.ligo.org/s/events/GW150914/LOSC_Event_tutorial_GW150914.html

Likelihood for this estimation

Estimation → Data

Corr(A, X) —Fisher transform→ $Z_{XY} = \frac{1}{2}\log(\frac{1+C_{XY}}{1-C_{XY}}),$ For enhanced Gaussianity

https://en.wikipedia.org/wiki/Fisher_transformation

expectation — Probability density function

Null hypothesis: $E(Z_{AX}) = 0$ → $PDF(Z_{AX}) \sim e^{-k_1 (Z_{AX})^2}$

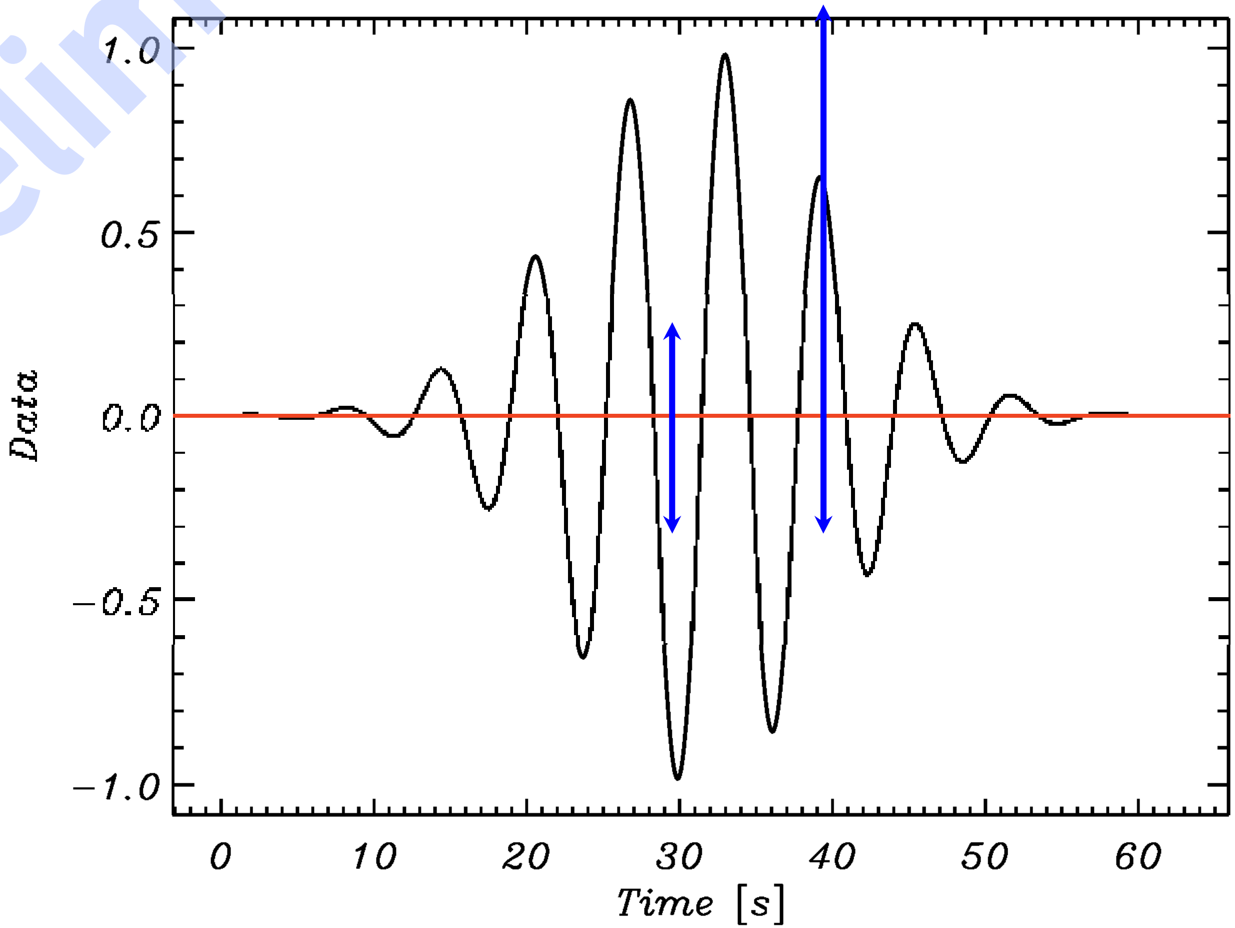
Null hypothesis: $E(Z_{R_xR_y}) = 0$ → $PDF(Z_{R_xR_y}) \sim e^{-k_2 (Z_{R_xR_y})^2}$

Assume H/L independence (Not 100% sure in reality, but good as a null hypothesis)

Three-parameter likelihood (take log for simplification)

$$\log(L) \propto Z_{AX}^2 + Z_{AY}^2 - Z_{R_xR_y}^2 \bullet k'$$

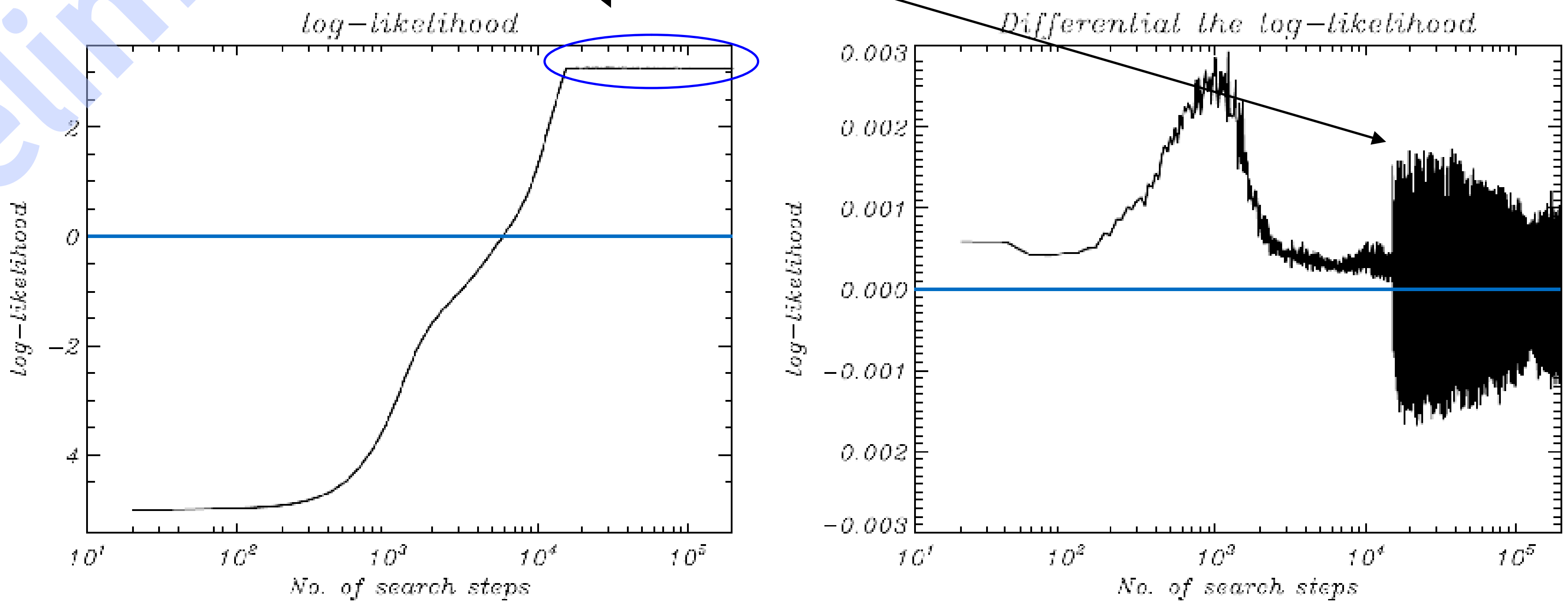
Random walk



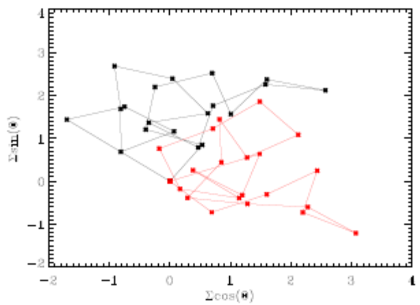
1) Determine a direction that gives higher likelihood
2) A small walk with random size along this direction

Oscillation of the likelihood

In this region, Higher likelihood ≠ better solution



M Hansen et al, 2011, arxiv:1103.6135



We know that the Best Common Signal lies in the oscillatory region.

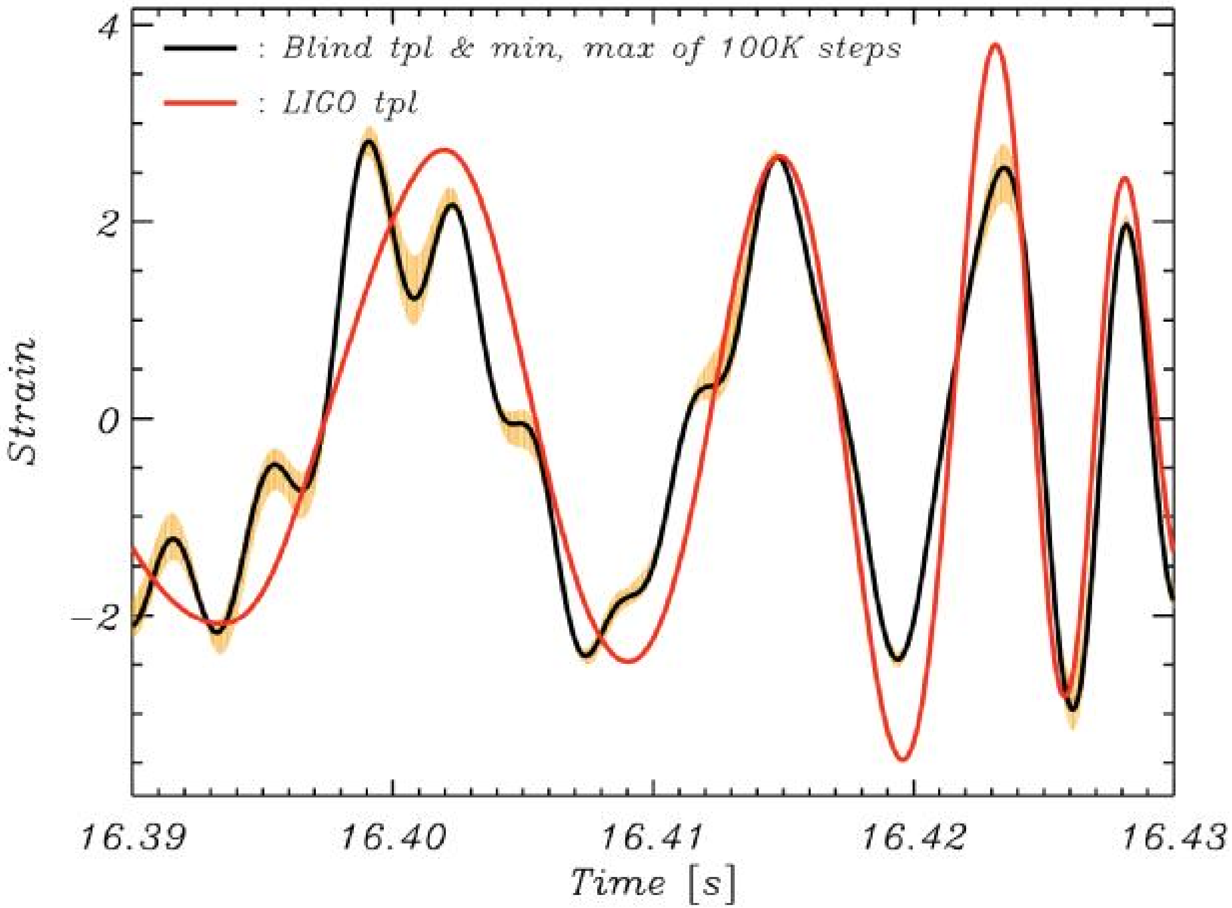
But it cannot be determined precisely.

The oscillatory region determines the mean and the uncertainty range of the Best Common Signal.

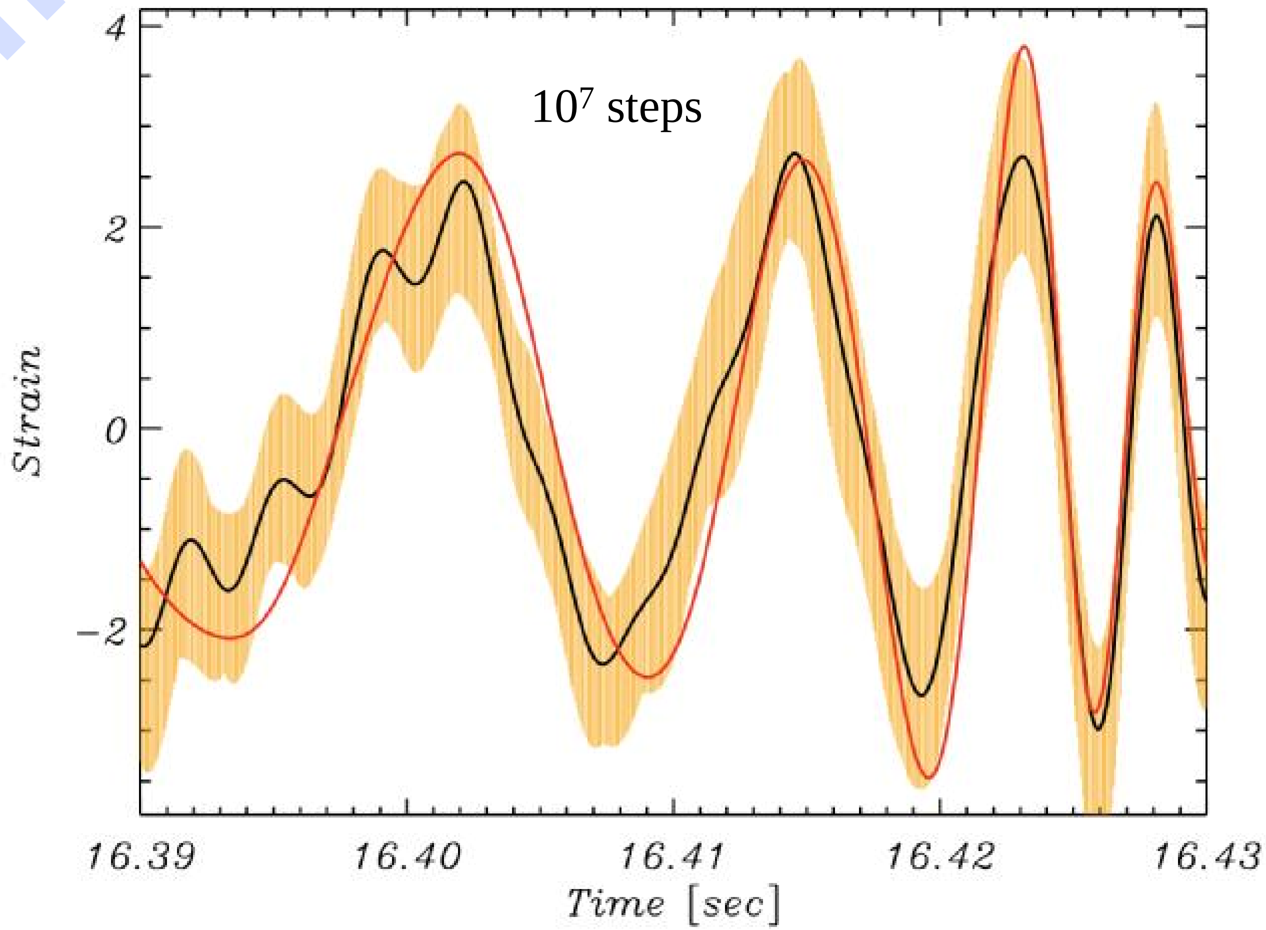
In the oscillation region:

Mean à Solution (black line)

Min-max range à Range of uncertainty (yellow)



Run the same procedure for 100 times each time with a new random initial guess

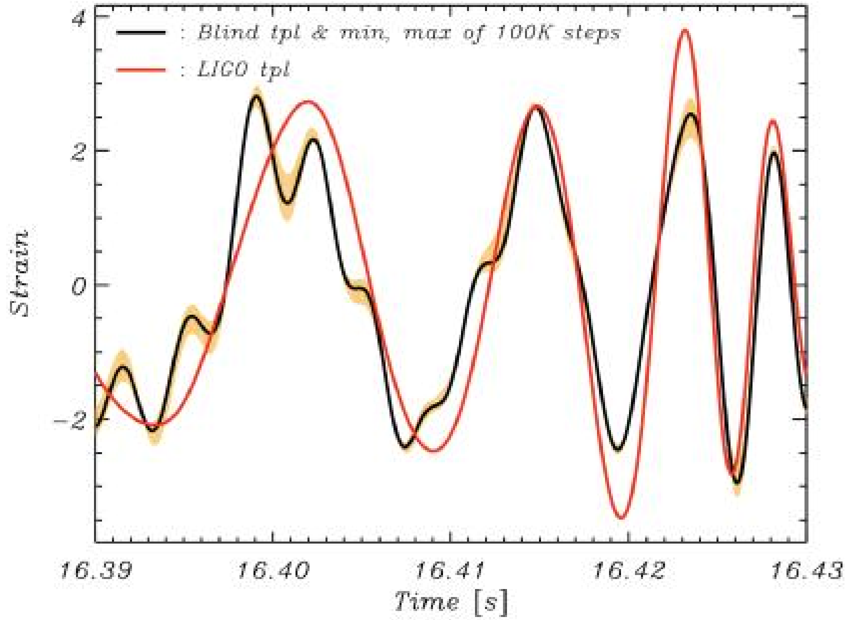


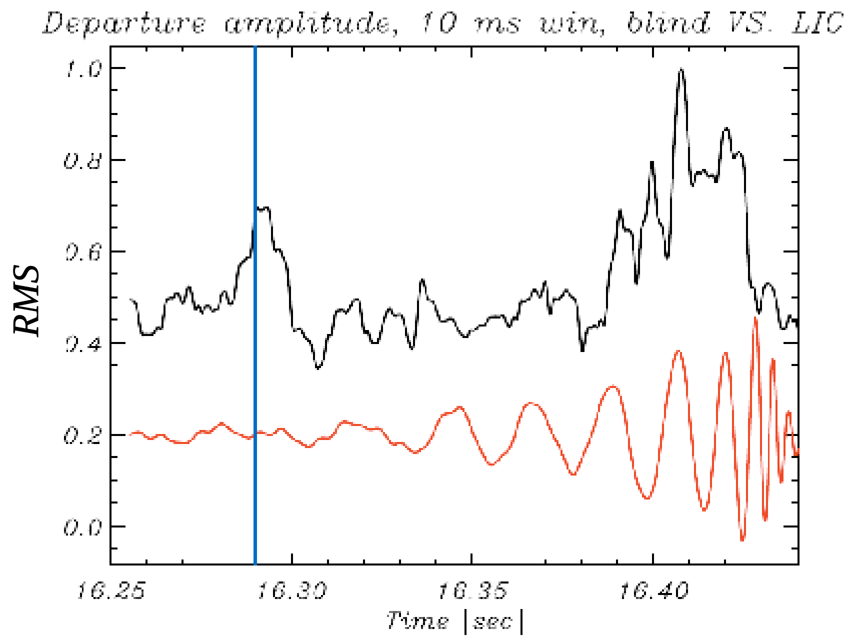
1) Range of uncertainty
2) Stability of the solution

Where do we find discrepancies?

RMS in small time-window for:
LIGO minus each solution

Average over the 100 run





Regions with large discrepancies are identical with regions with a high residual CC.

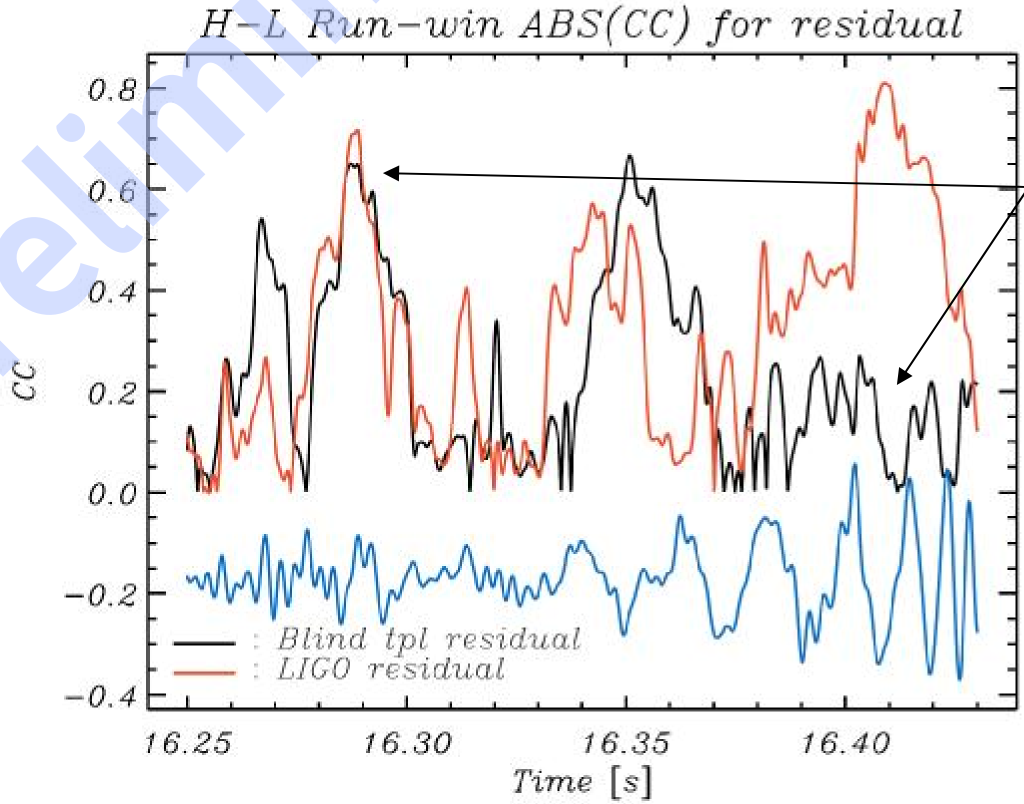
Beginning of the talk: resi-CC **à** extra common signal

Here: common signal **à** resi-CC

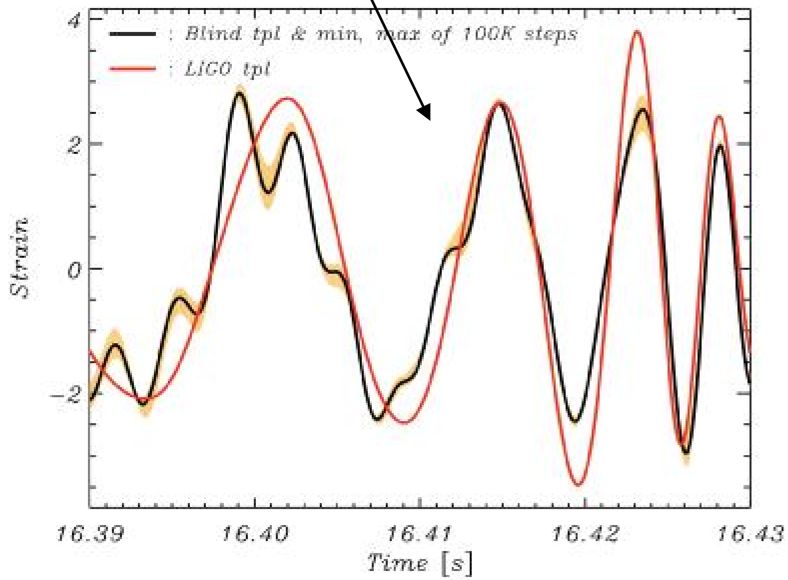
Self-consistent

The LIGO GW15014 template is not an optimal estimator for the common signal

How about the residual-correlation?



1. Can reduce the resi-CC
2. But only part of it
3. The price is huge: big difference to GW150914

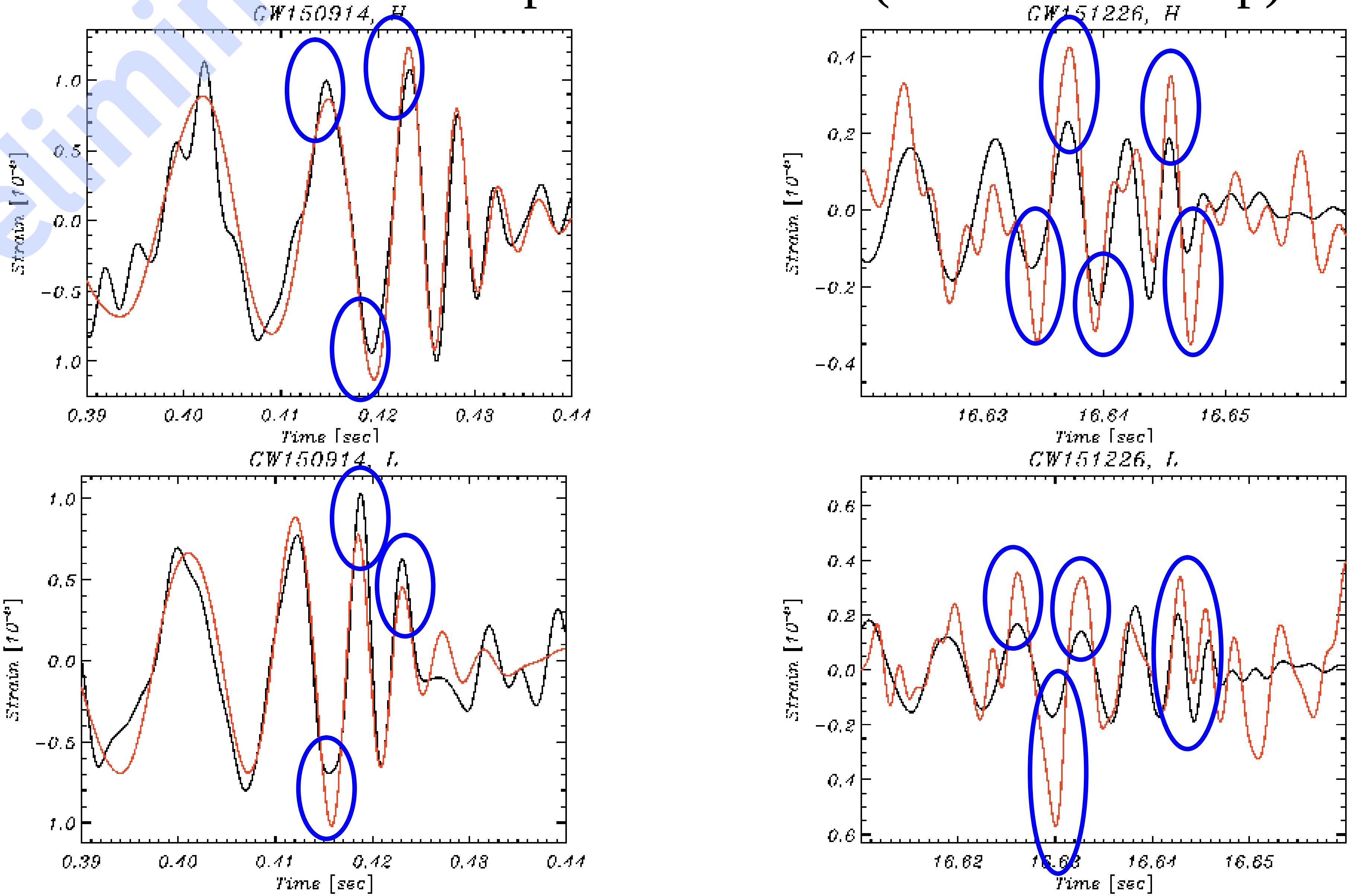


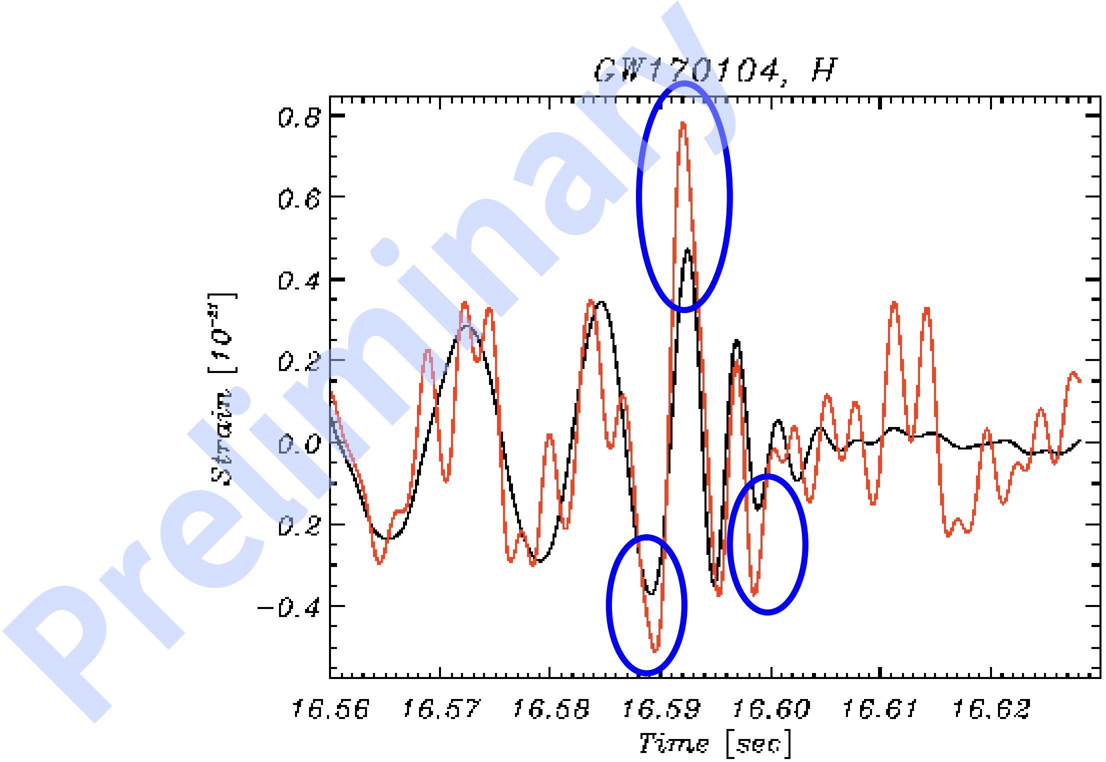
- Can we really treat the data as GW + noise?

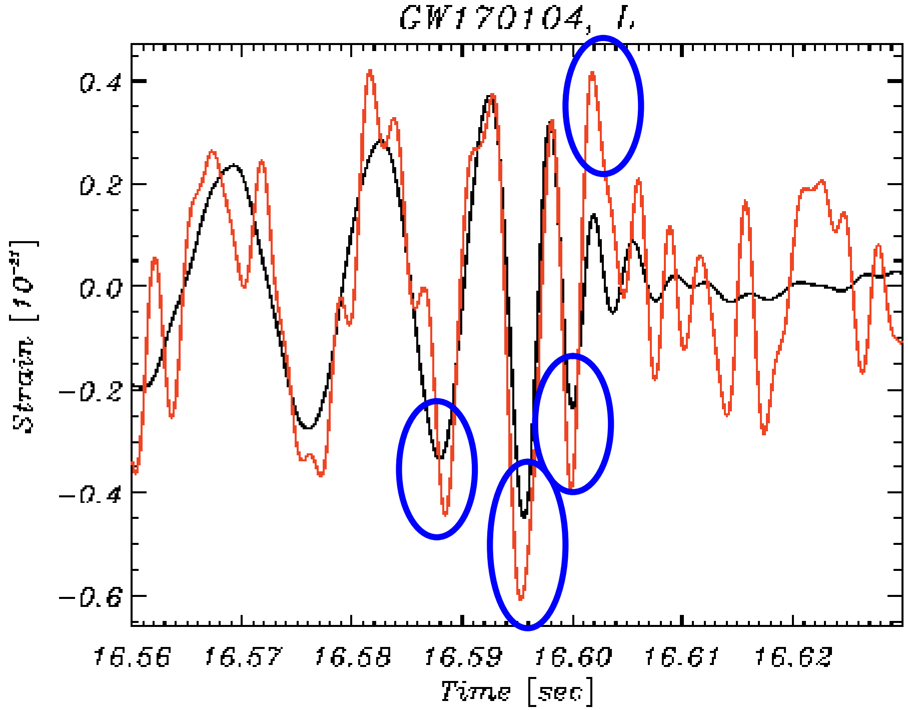
  common Different

- A dilemma:
  - GW à resi-CC
  - Common signal à Big change to GW

Is GW+noise enough?
Direct observation: peak mismatch (all near the chirp)



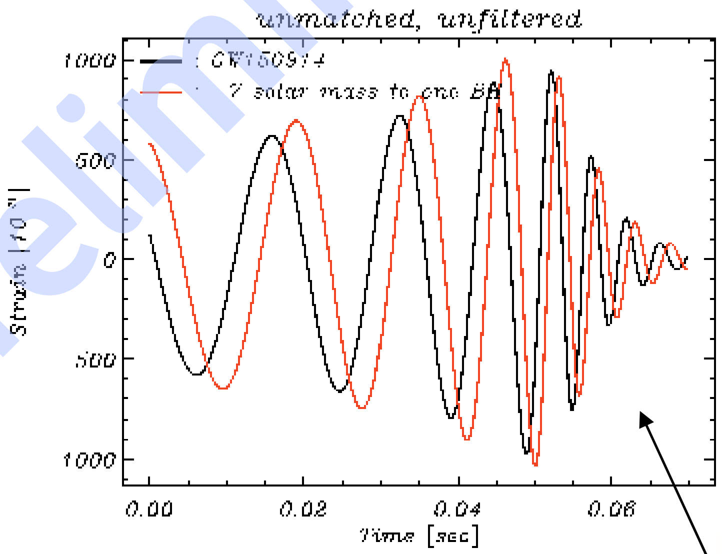


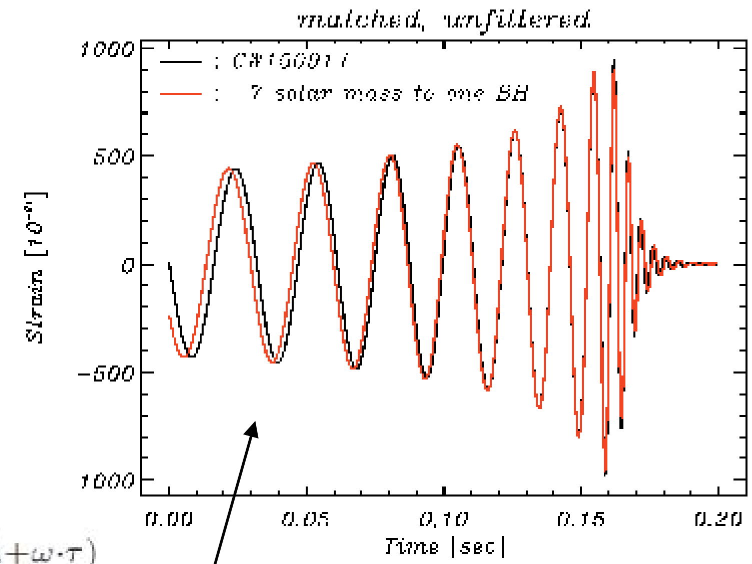


Such peak-mismatch is very common for all current GW events, and it really indicates that “GW+noise” assumption is insufficient.

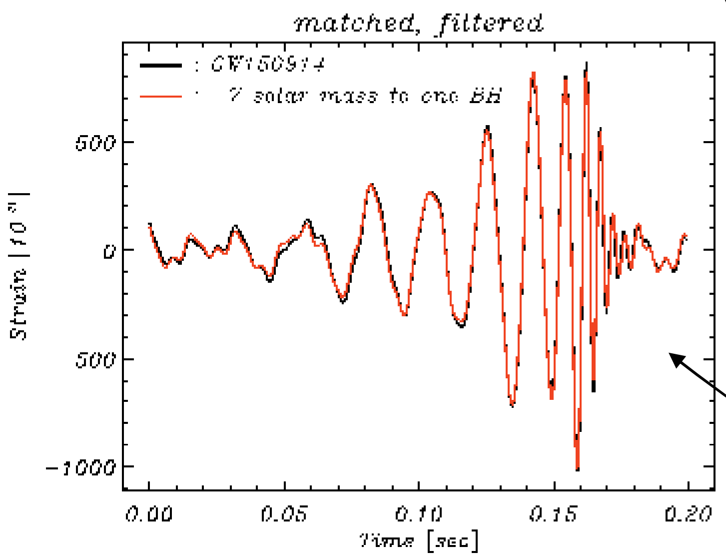
How about the GW-part (degeneracy?)

Raw product of pyCBC (the LIGO program)





$$H(\omega) = \alpha L(\omega) e^{i(\Delta+\omega\cdot\tau)},$$



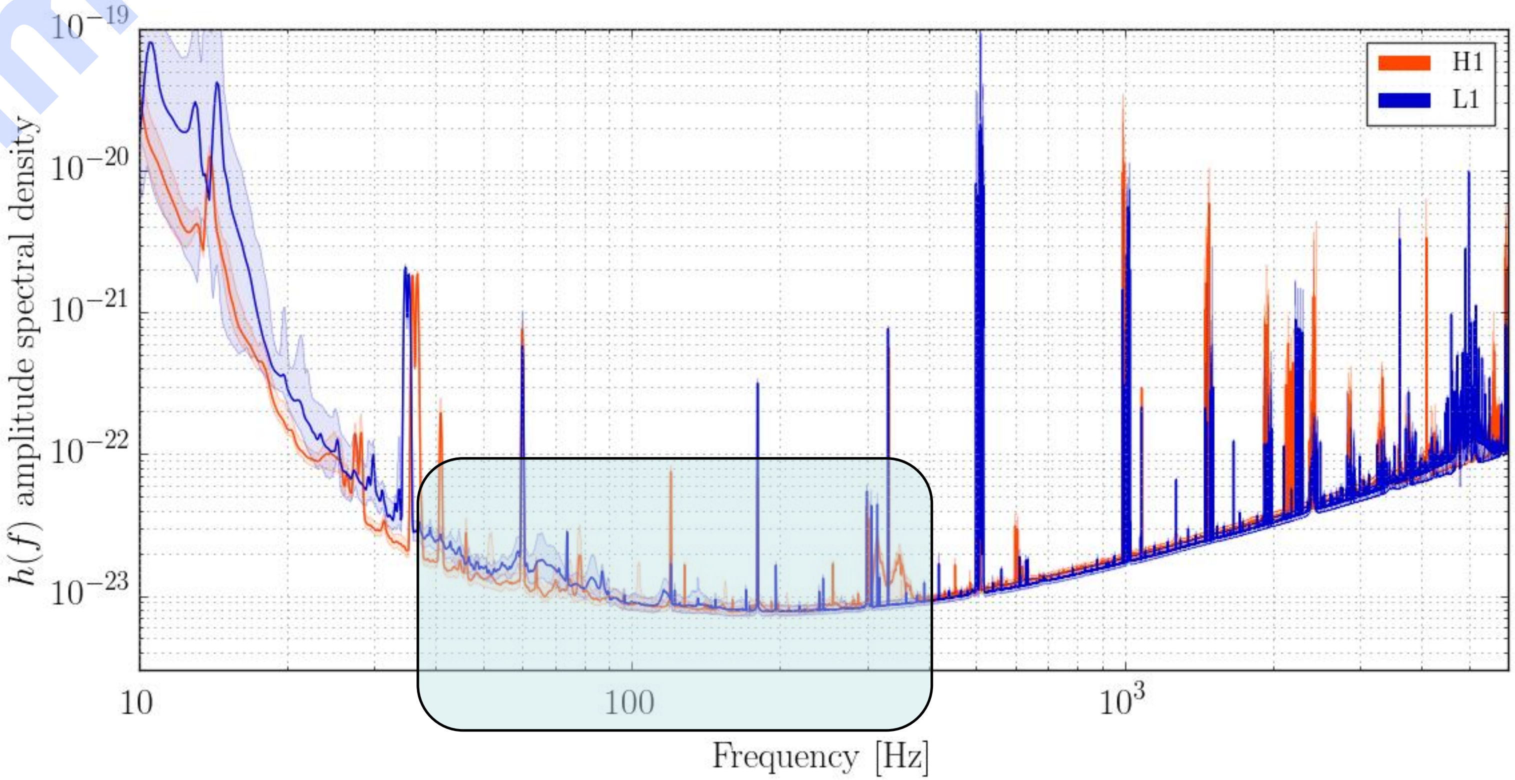
Comparison of two GW-templates with 7-solar-mass diff to one BH (use pyCBC, but not real LIGO templates)

LIGO claim 4~5 solar-mass as 1-sigma error

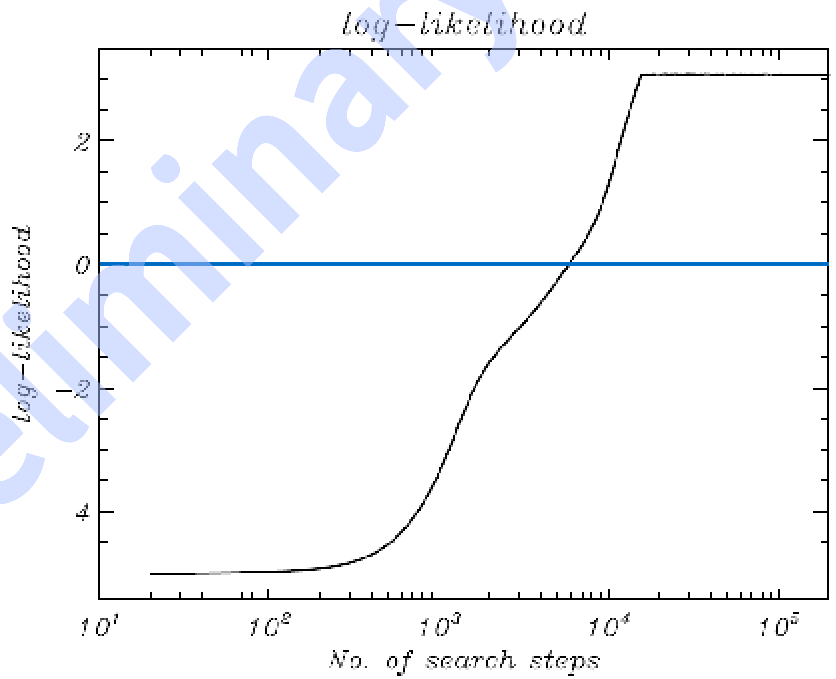
TPL0 —match→ TPL1 —bandpass→ TPL2

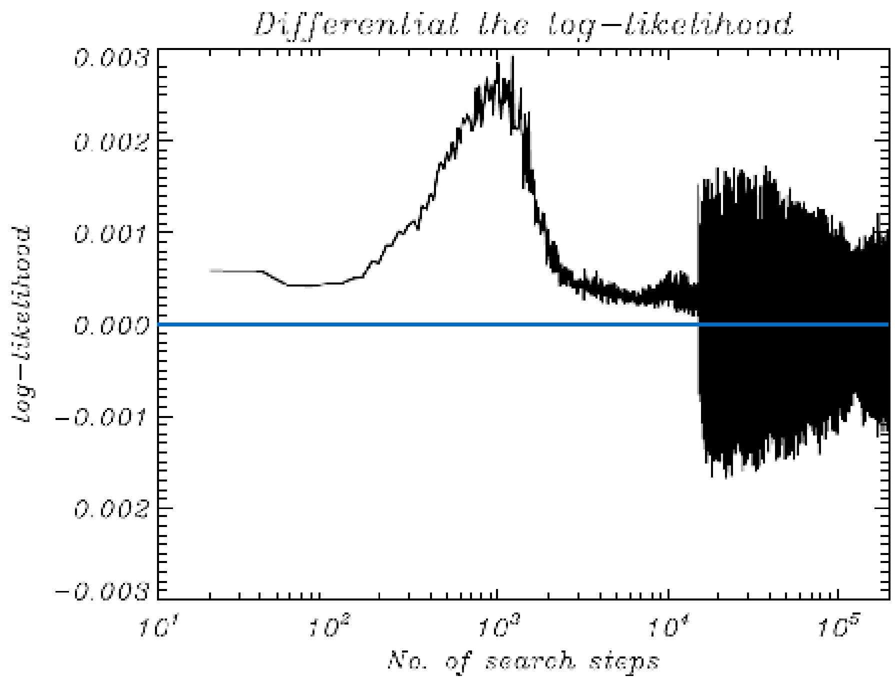
Can we skip band pass and use a longer time range?

The band pass is inevitable à Use of longer time range for discrimination is impossible

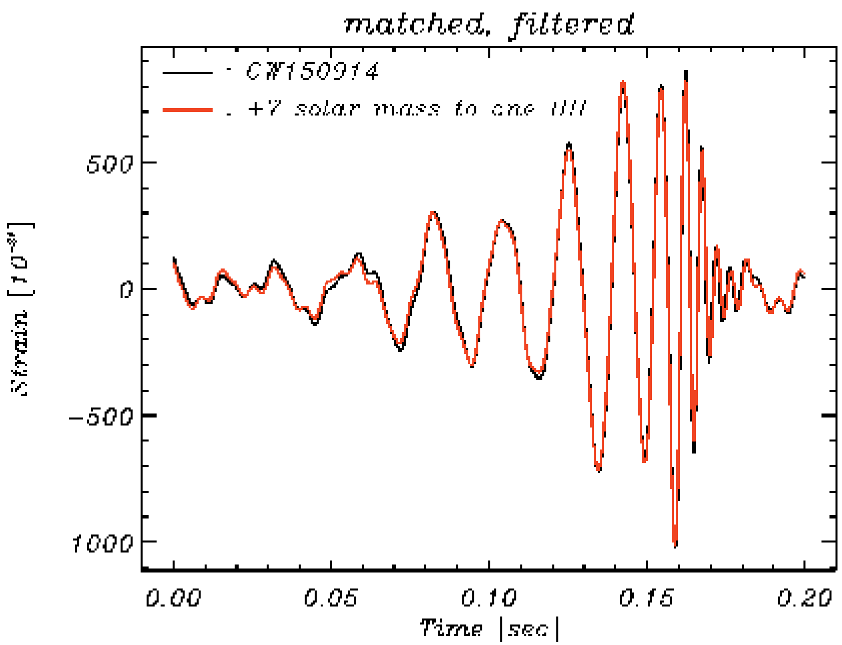


1) Noise level
2) GW-event frequency range





In this region, Higher likelihood ≠ better solution

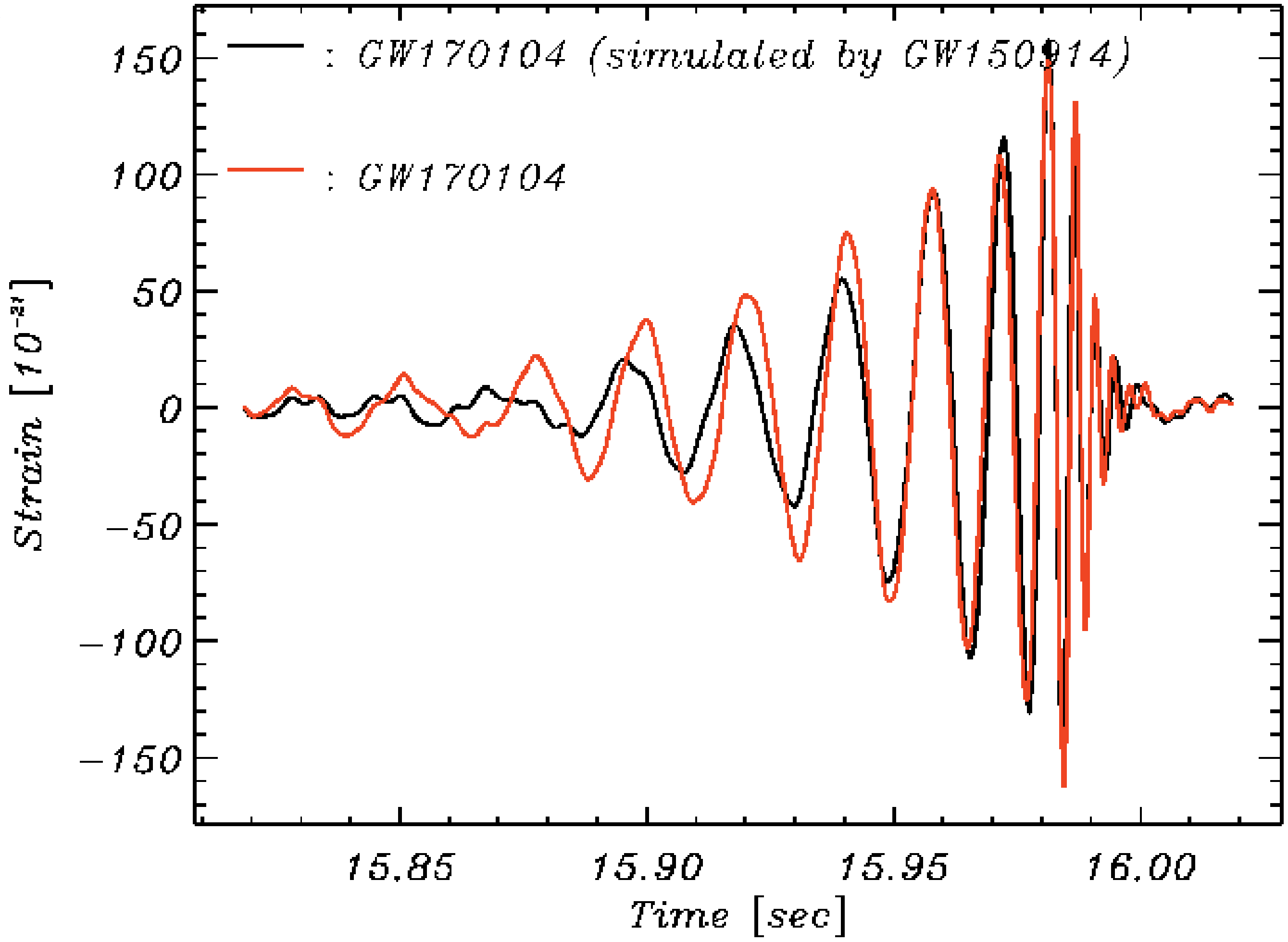


Guess:

A +7 solar mass template is well within the "oscillation region" (only an analogy, the actual procedure is certainly different)

LIGO GW150914 template may give higher likelihood, but is not 100% "better"

What happens if we try to match GW170104 with GW150914?



What will happen if we try to match GW170104 with GW150914?

- No change to the program, only replace the template file to “cheat” the program.
- By the LIGO program (whitening, 43-800 Hz)
  - For both H/L, the SNR decrease by ~10%
- By our program (linear filtering, 43-430 Hz)
  - For Hanford, the SNR decrease by ~10%
  - For Livingston, the SNR increase by ~1%

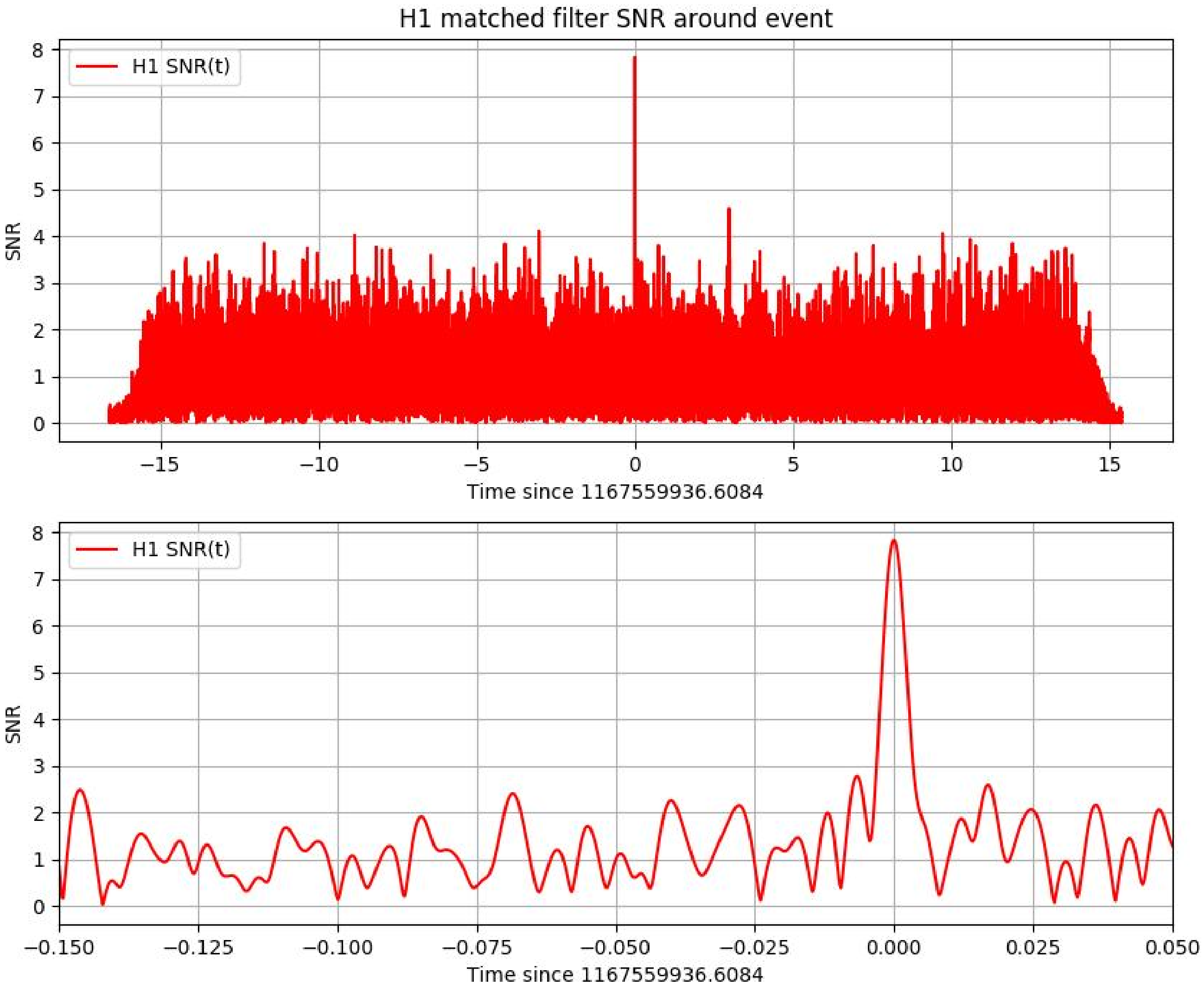
The LIGO SNR: Brief description:

Comparison of the covariances, Template-data VS. template-noise

Exact definition:

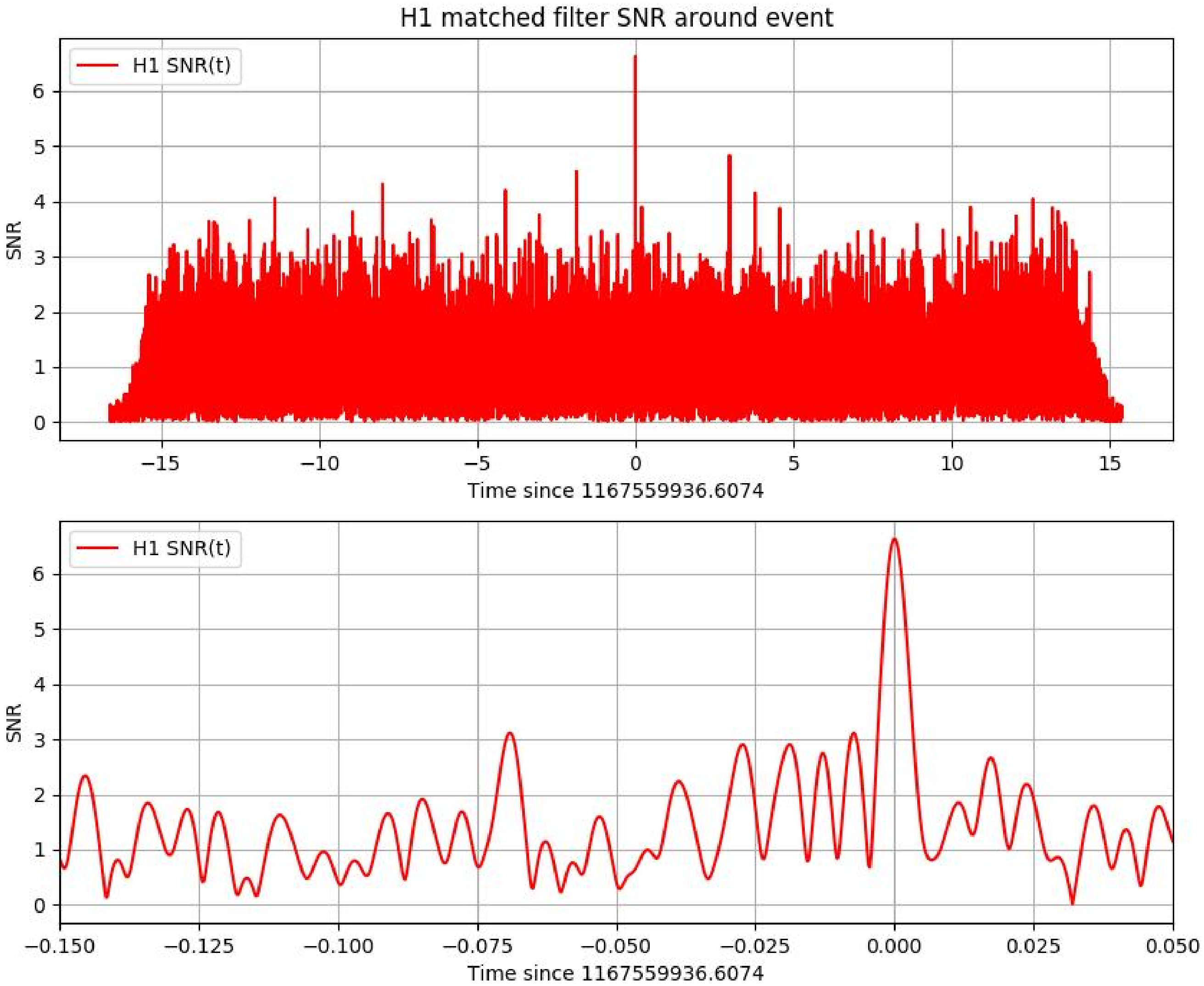
https://arxiv.org/pdf/1508.02357.pdf

True result (LIGO program)



False result

- Therefore, by using GW150914 template for GW170104, the result is not much different



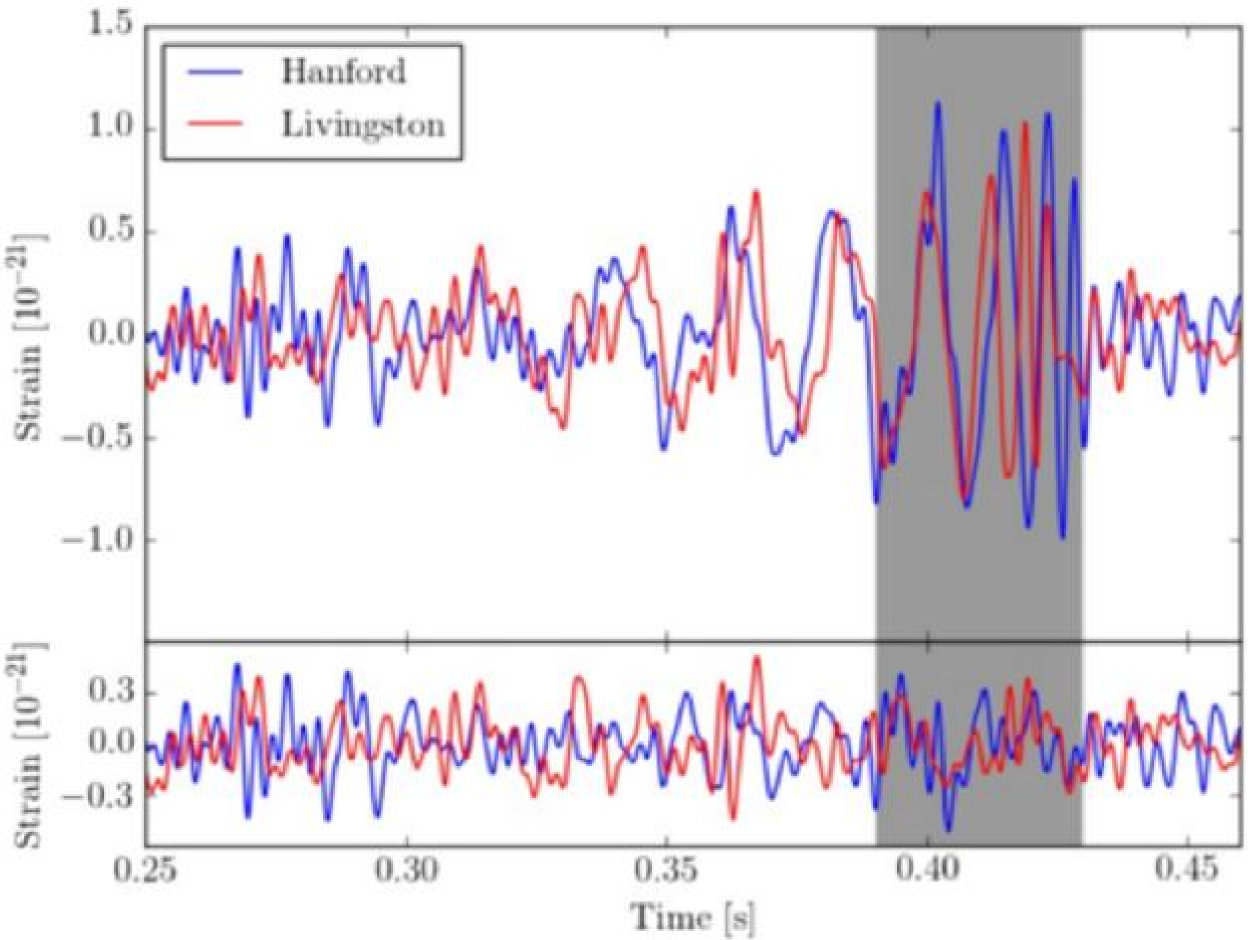
Could we find out more events like GW150914 ?

- With a full constraint, the answer is "No"
  - Hanford and Livingston
  - Full frequency band of the event (35-350 Hz)
  - Full time range (~0.2 sec)
  - The LIGO significance estimation gives a very low false alert rate (1 event per 203,000 years)
- Let's try a partial constraint for **illustration.**

Could we find out more events like GW150914 ?

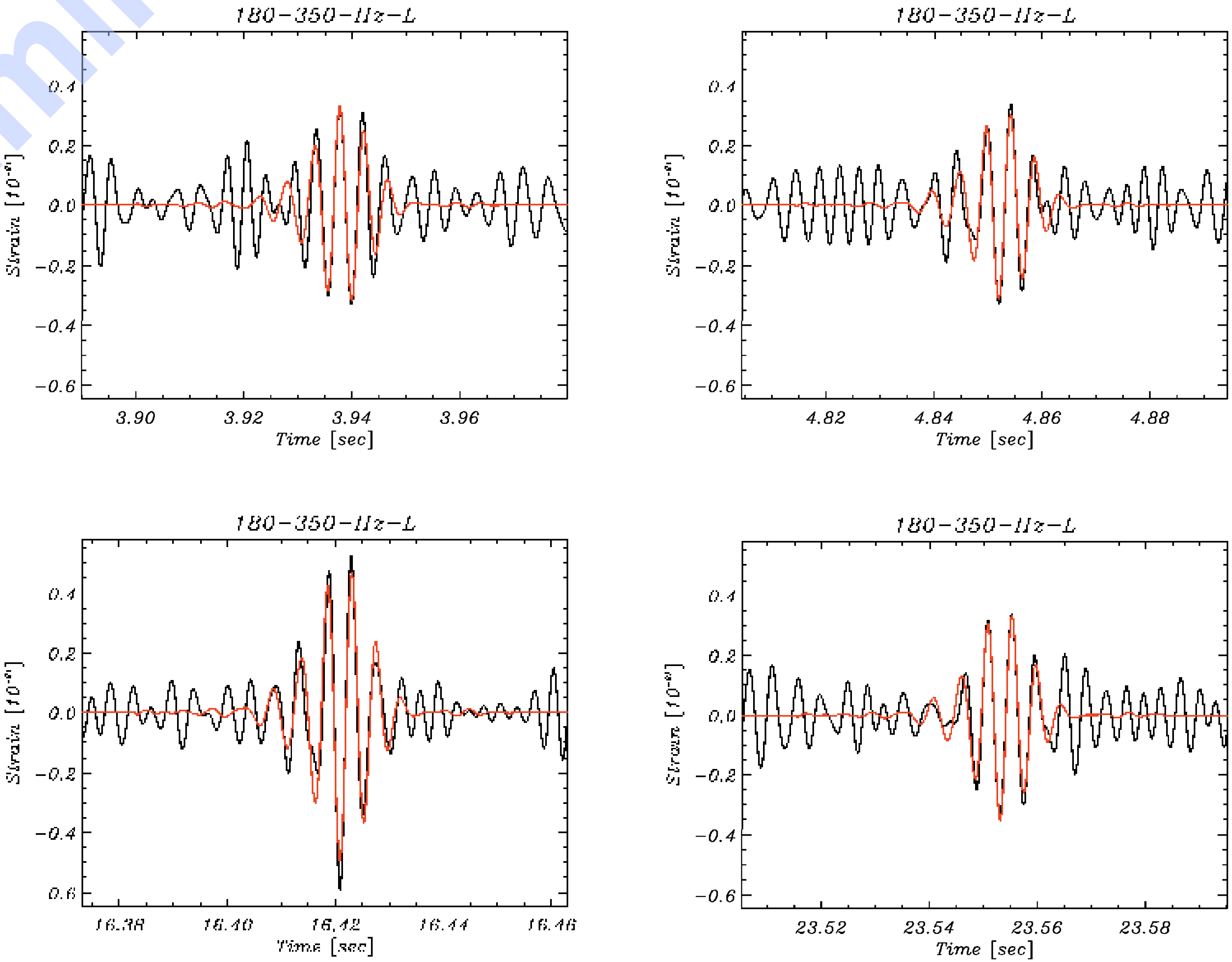
What if we look at the BPF at 180-350 Hz?

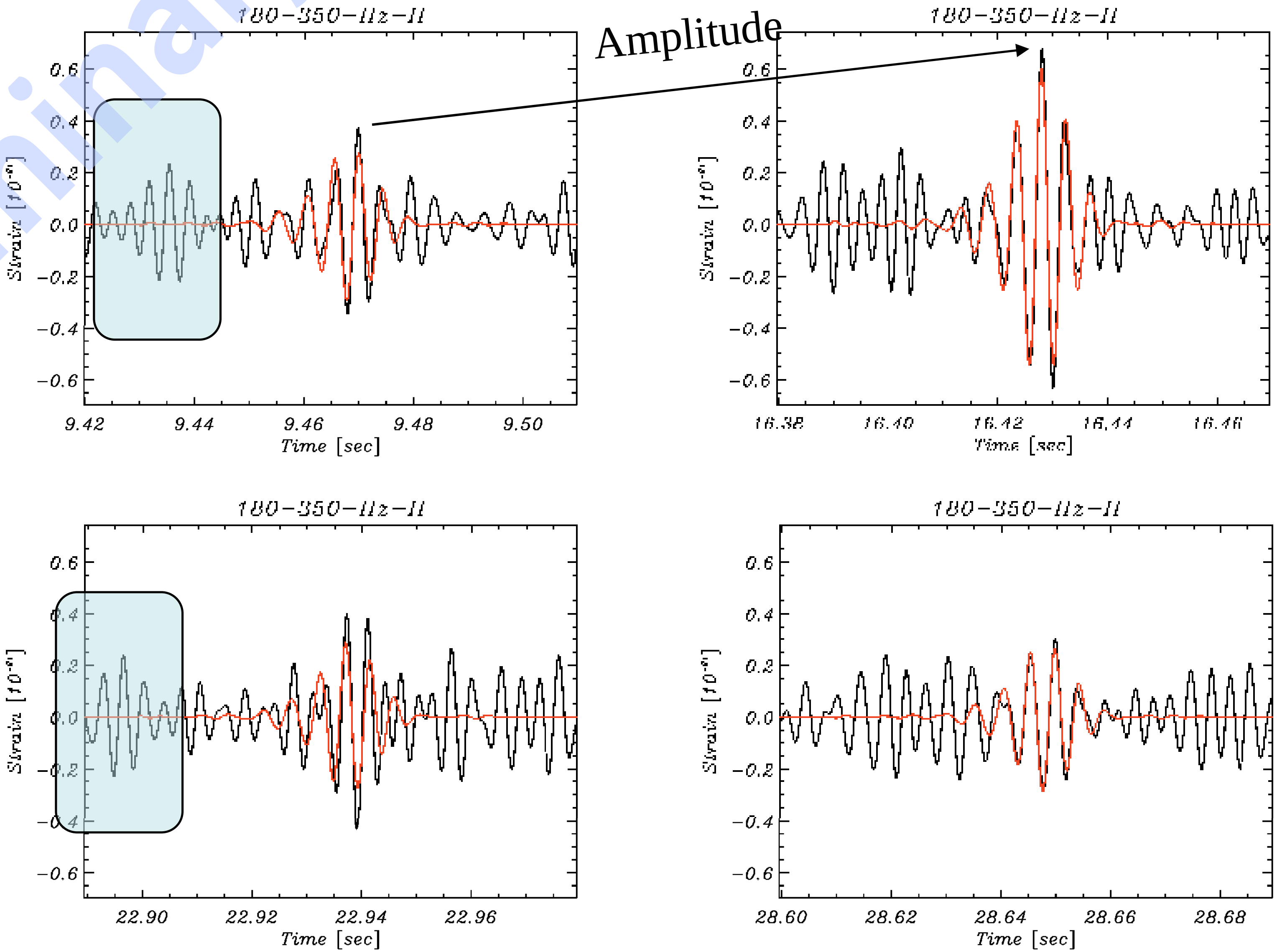
We are still inside 35-350 Hz recommended by LIGO



With this BPF we are in the domain, discussed in our JCAP paper .

We can easily find many chirp instances





180–350–Hz–H
Amplitude
Strain [10⁻²¹]
Time [sec]
9.42
9.44
9.46
9.48
9.50
16.38
16.40
16.42
16.44
16.46
22.90
22.92
22.94
22.96
28.60
28.62
28.64
28.66
28.68
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6

Could we find out more events like GW150914 ?

- With a full constraint, the answer is “No”
  - Hanford and Livingston
  - Full frequency band of the event (35-350 Hz)
  - Full time range (~0.2 sec)
  - The LIGO significance estimation gives a very low false alert rate (1 event per 203,000 years)
- How about a partial constraint for illustration?
- It’s important to study the origin of the chirp-like structure
  - Purely random à the LIGO significance estimation will be OK
  - Has physical origin à one should be more careful about the significance estimation.

Conclusion

- Did we see chirps in the LIGO detectors?
  - Yes, no doubt about that.
- Is the chirp due to GW-signal?
  - We really like this conclusion, but we also need to be careful about reasonable questions (abnormal CC, blind estimation).
- Are the BH parameters accurate?
  - We didn't test the central value claimed by LIGO, but the error bars seem to be bigger than one thought.
  - A 7-solar mass difference is almost indistinguishable
- Is everything as perfect as GW + random noise?
  - I don't think so