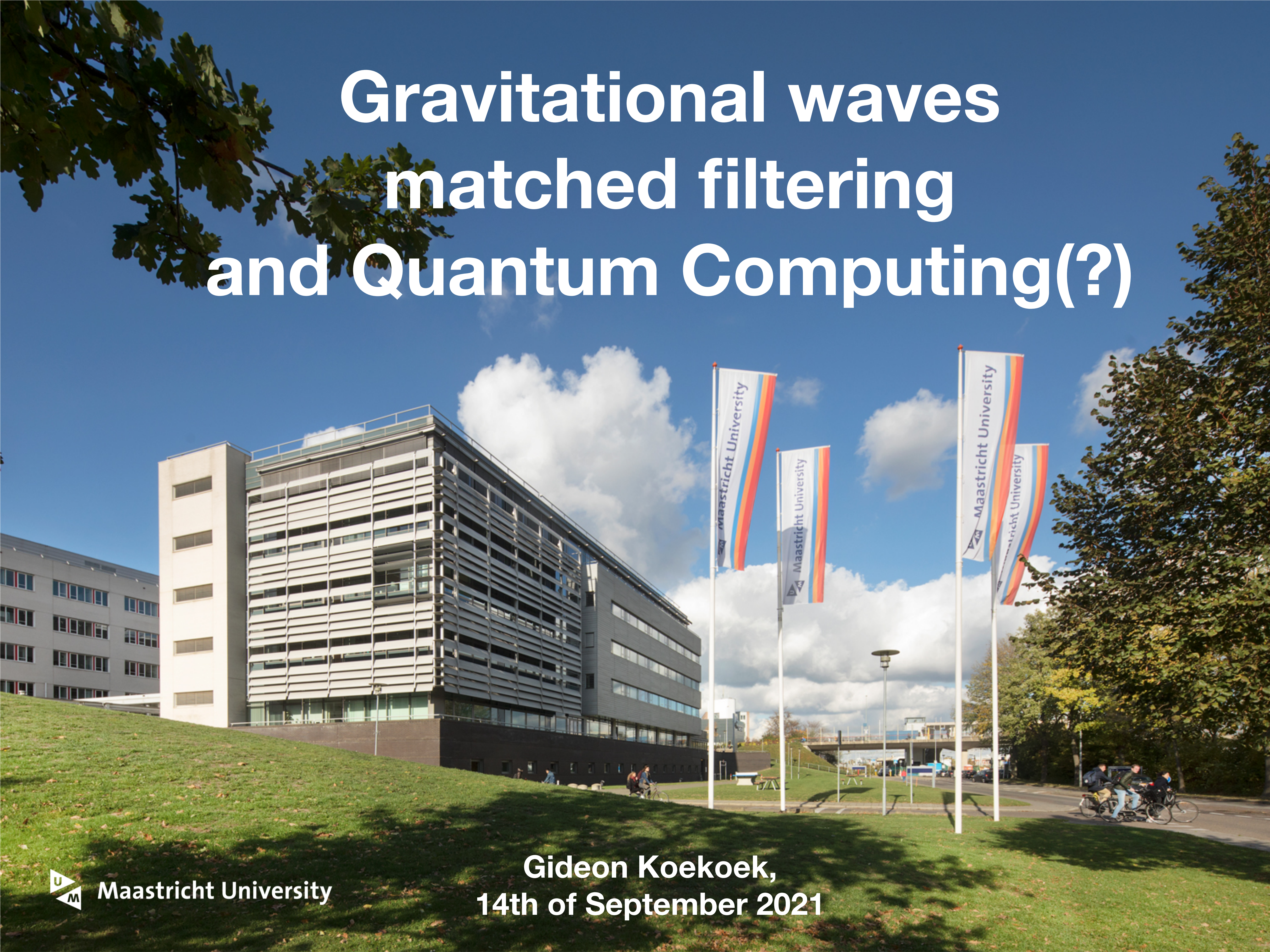
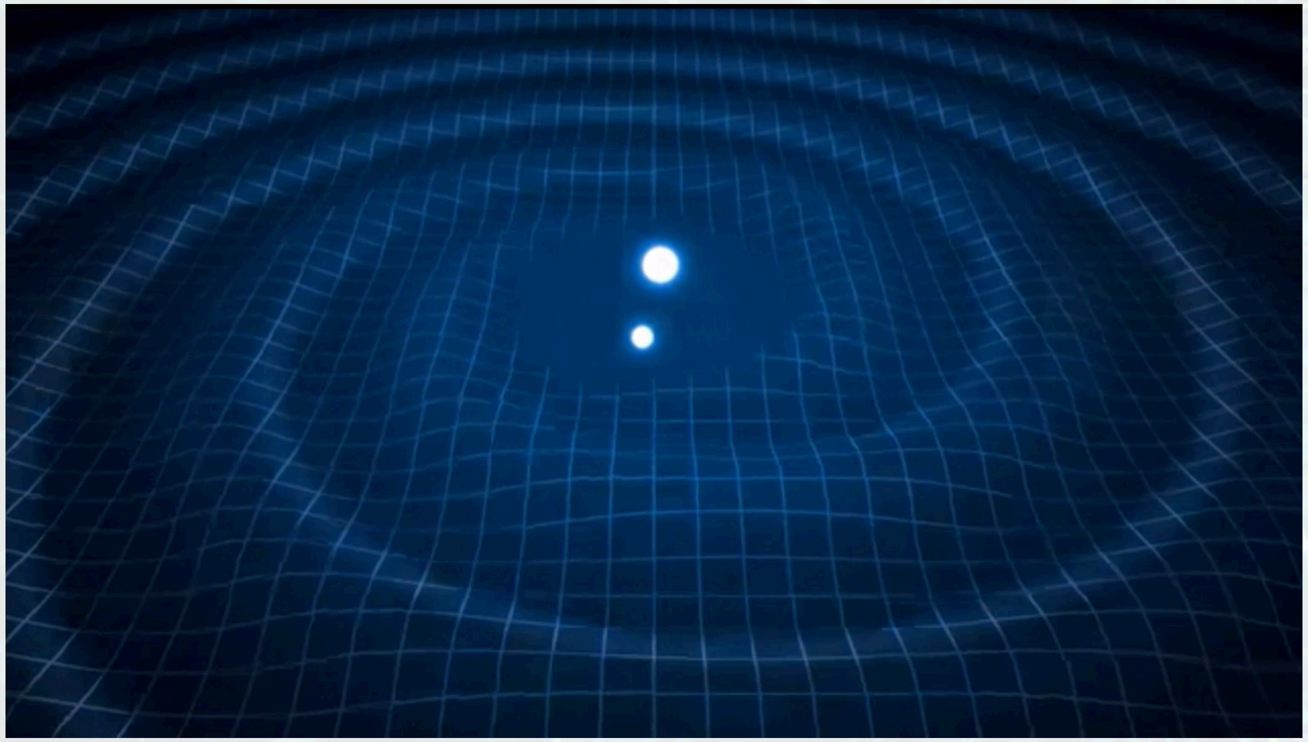
Gravitational waves matched filtering and Quantum Computing(?)

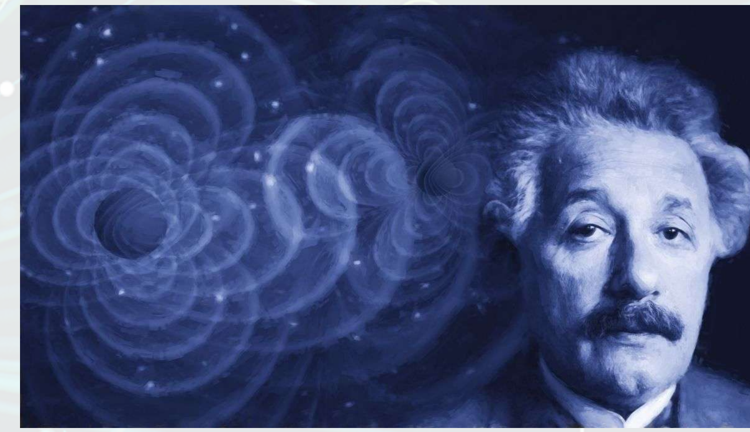


Maastricht University

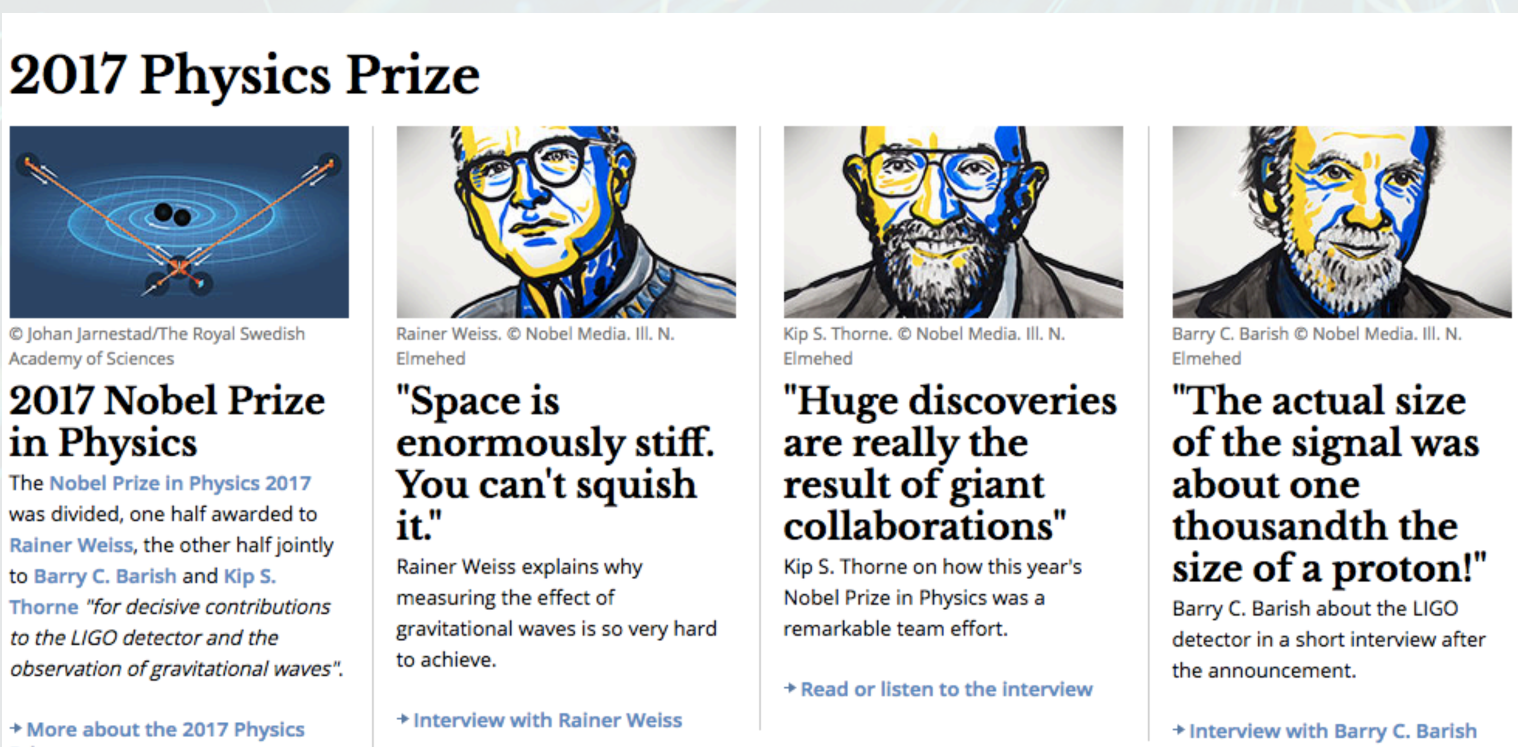
Gideon Koekoek,
14th of September 2021

Gravitational Waves: solving the biggest mysteries of the universe





- Predicted by Einstein in 1916
- Result of time changing quadrupole moment (prime example: binary system)
- Amplitudes are of order of magnitude O(10^{-21}) meters.



2017 Physics Prize

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2017 Nobel Prize in Physics

The Nobel Prize in Physics 2017 was divided, one half awarded to Rainer Weiss, the other half jointly to Barry C. Barish and Kip S. Thorne *"for decisive contributions to the LIGO detector and the observation of gravitational waves"*.

→ More about the 2017 Physics Prize

Rainer Weiss. © Nobel Media. Ill. N. Elmehed

"Space is enormously stiff. You can't squish it."

Rainer Weiss explains why measuring the effect of gravitational waves is so very hard to achieve.

→ Interview with Rainer Weiss

Kip S. Thorne. © Nobel Media. Ill. N. Elmehed

"Huge discoveries are really the result of giant collaborations"

Kip S. Thorne on how this year's Nobel Prize in Physics was a remarkable team effort.

→ Read or listen to the interview

Barry C. Barish © Nobel Media. Ill. N. Elmehed

"The actual size of the signal was about one thousandth the size of a proton!"

Barry C. Barish about the LIGO detector in a short interview after the announcement.

→ Interview with Barry C. Barish

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Gravitational Waves:
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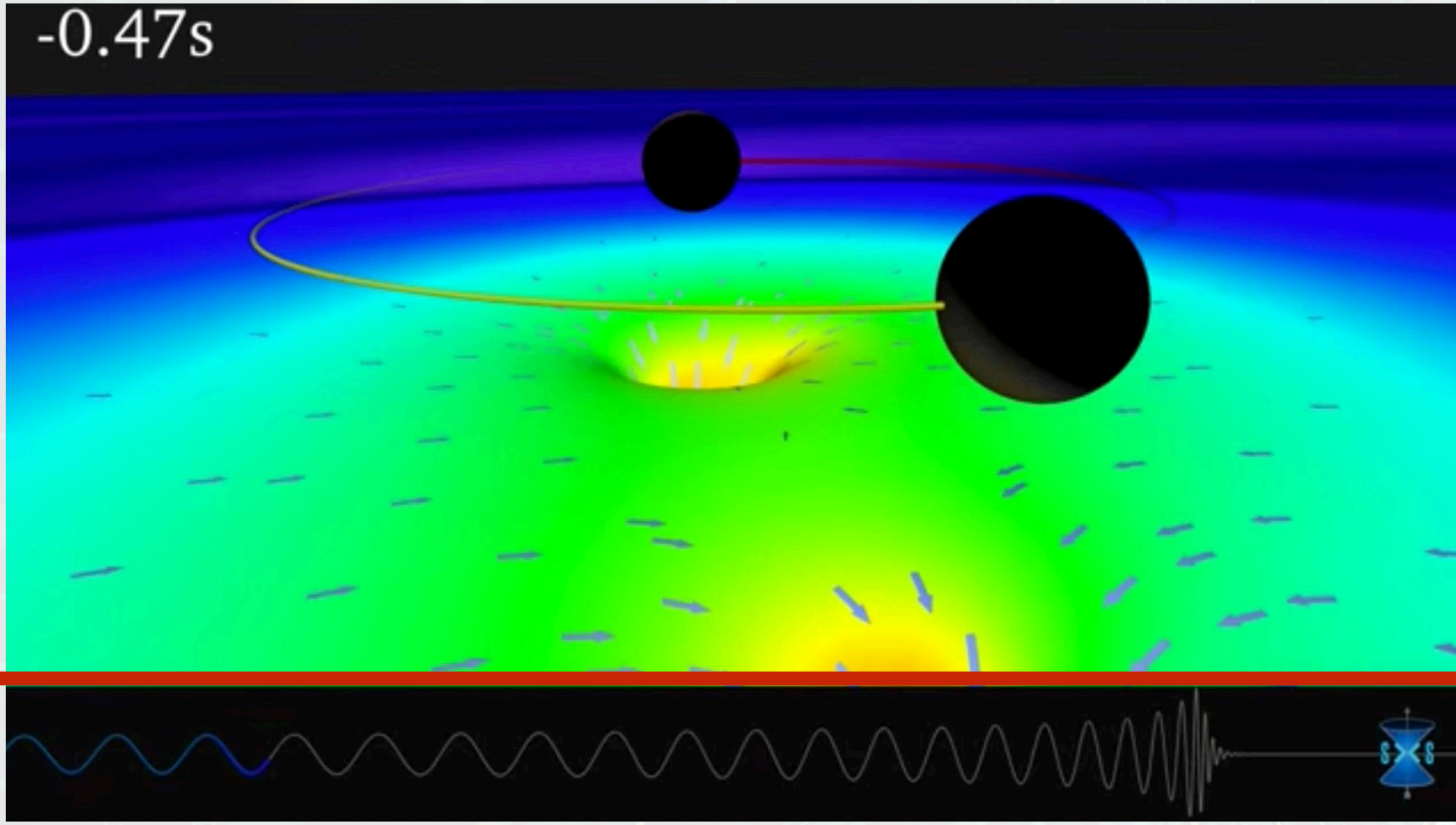
Q: What makes spacetime curve? A: mass and energy!

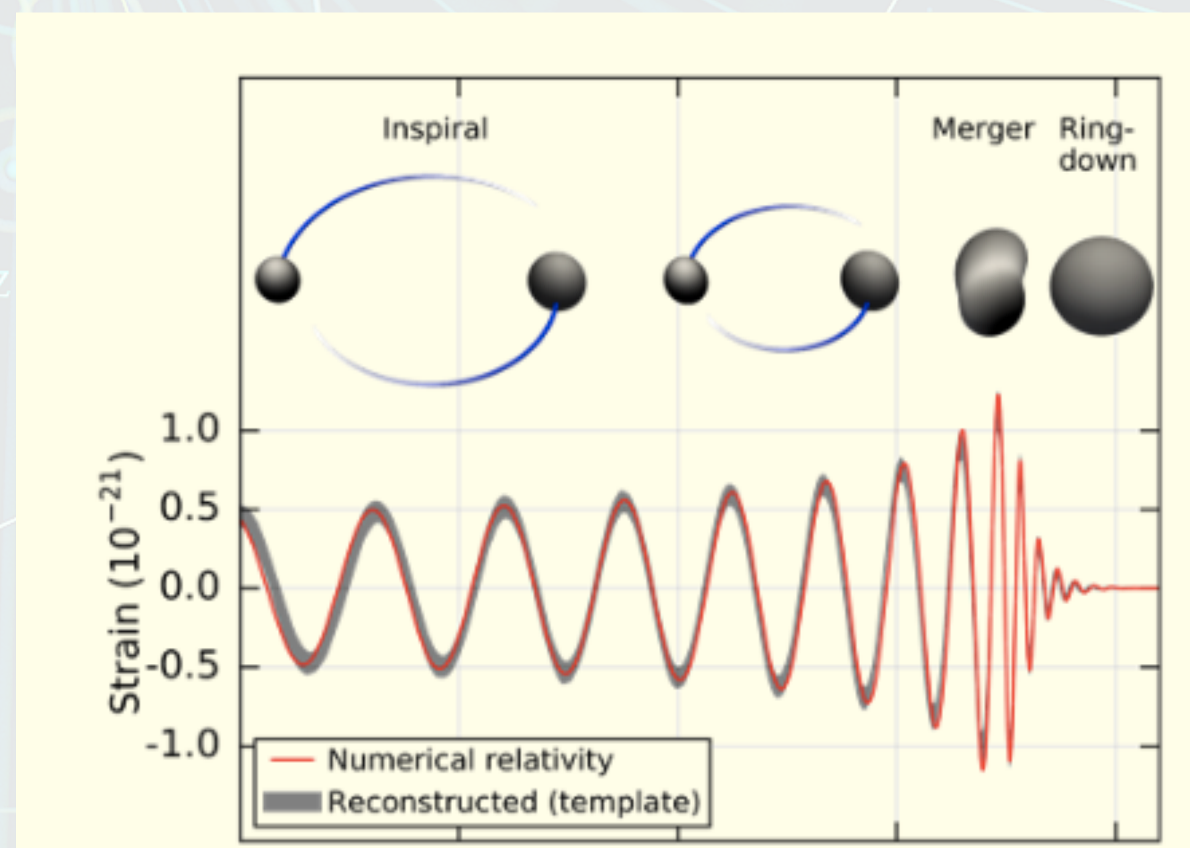
$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = -\frac{8\pi G}{c^4} T_{\mu\nu}$$

This is a very small value ~ 10^{-45} (!!)

$\Rightarrow$ It takes a lot of mass and energy to curve spacetime: Gravity is very weak!

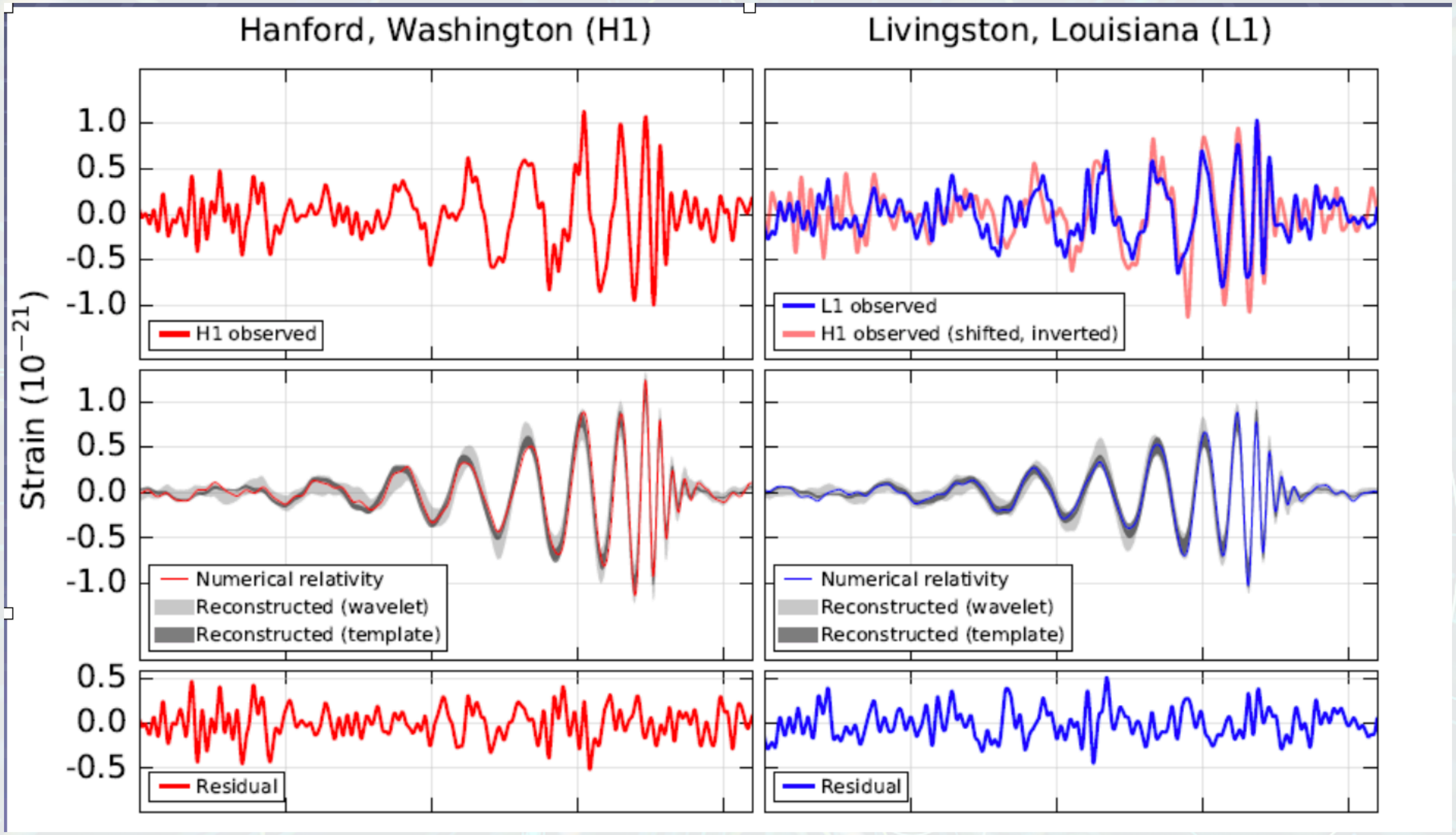


Characteristic shape of a gravitational ave

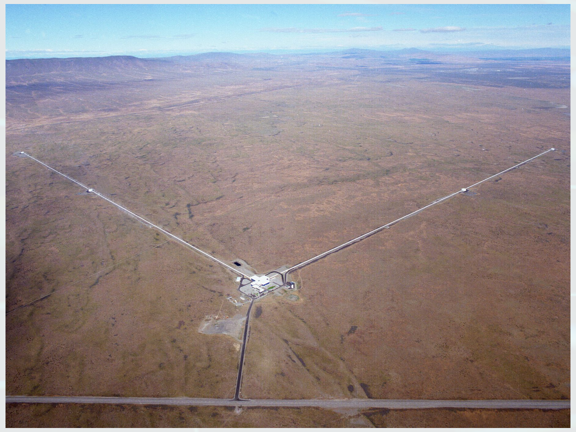


Video by LIGO:

https://www.youtube.com/watch?v=1agm33iEAuo

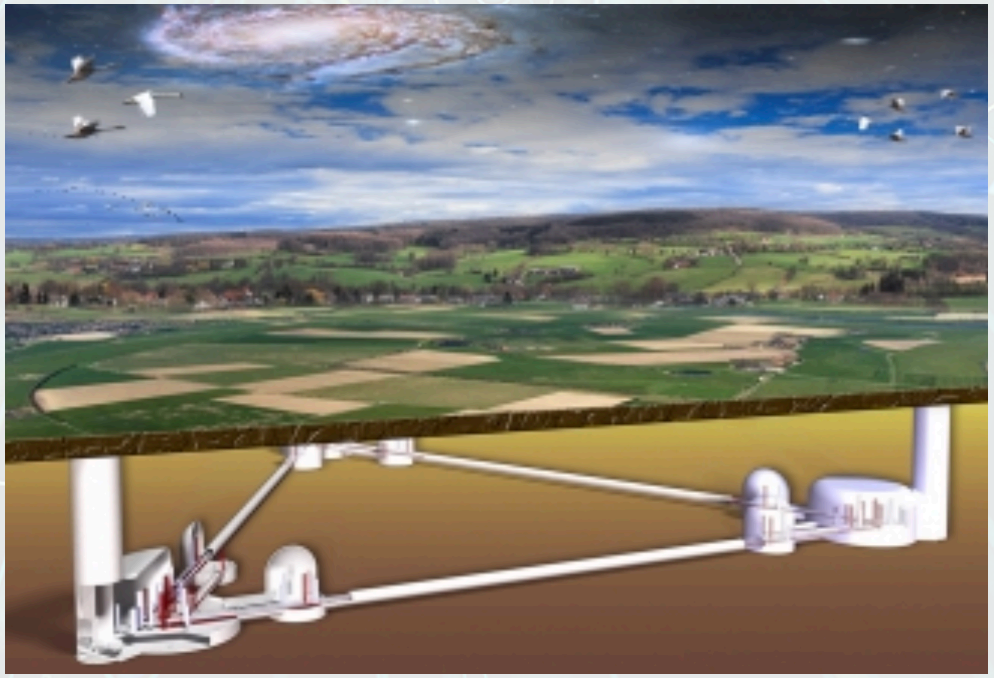

Hanford, Washington (H1)
Livingston, Louisiana (L1)
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
H1 observed
L1 observed
H1 observed (shifted, inverted)
Numerical relativity
Reconstructed (wavelet)
Reconstructed (template)
Residual

Gravitational Waves:
solving the biggest mysteries of the universe



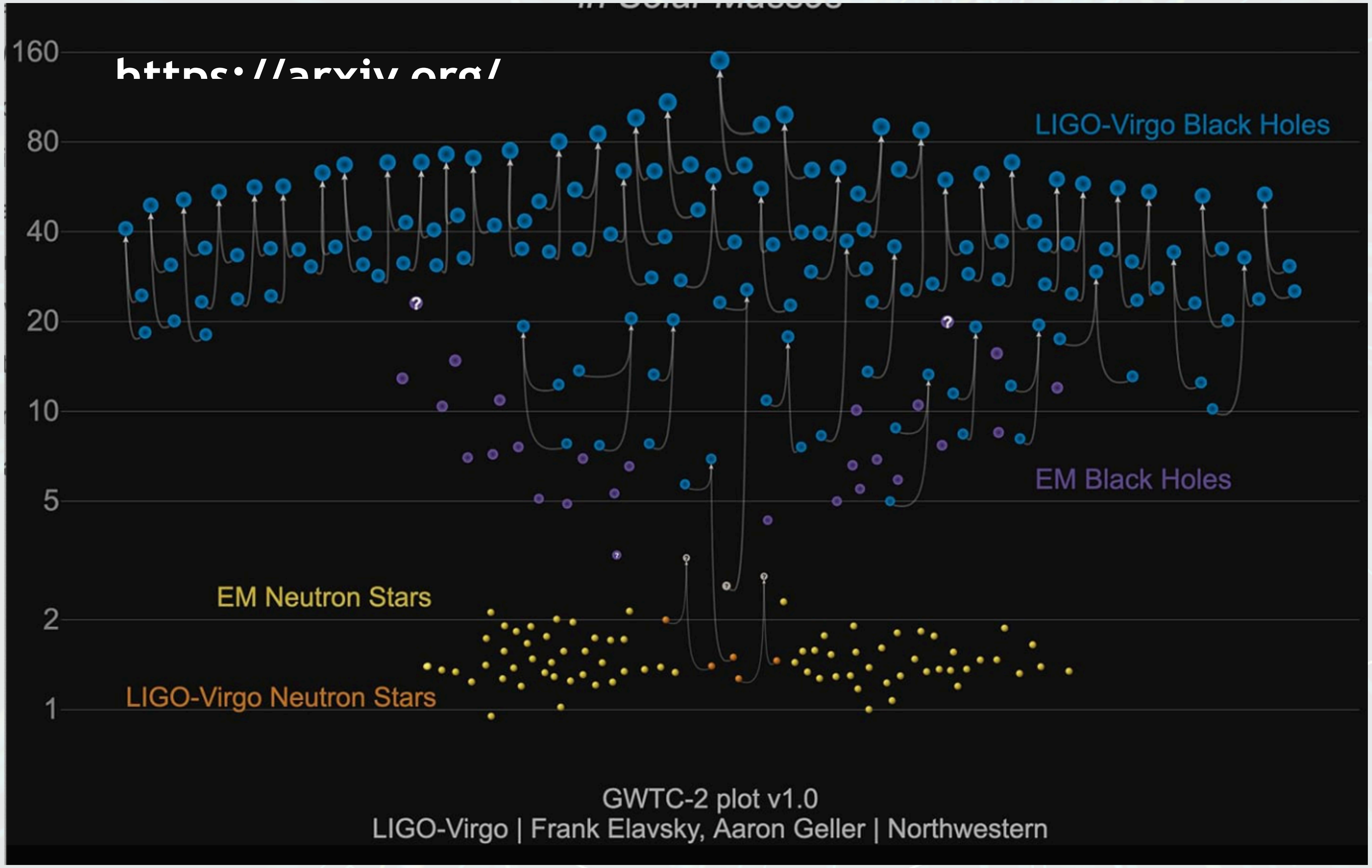
LIGO/Virgo collaboration

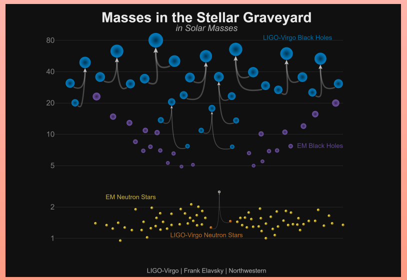
- Three-detector network (two detectors in US, one in Italy)
- O(1000) scientists from all over the world
- Nikhef has been a member for 10+ years
- Maastricht University has been member since 2017
- UM has own fundamental physics group, that works on instrumentation of gravitational waves detection.



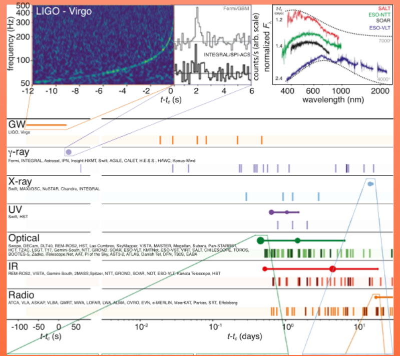
Gravitational Waves:
solving the biggest mysteries of the universe

From 2015 until now (Observation runs 1, 2, 3): ~60 confirmed detections.

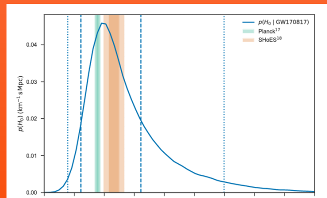




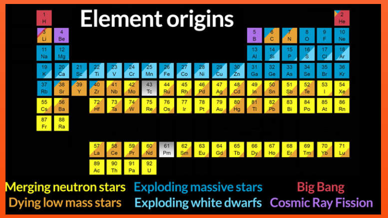
Found new class of heavy stellar mass BBH



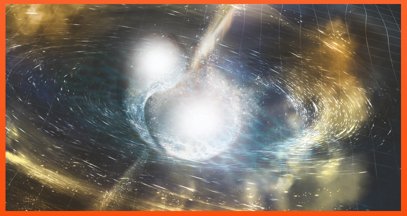
Start of GW multi-messenger astronomy


Cosmology independent of distance ladder

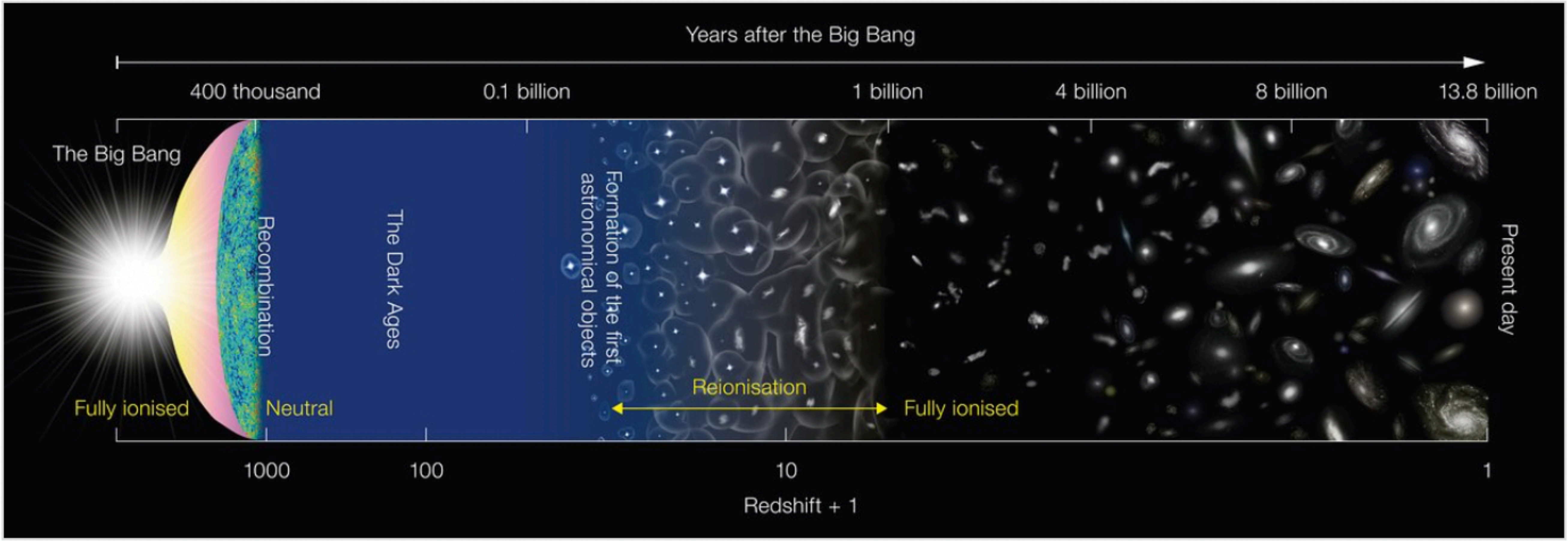

Ruled out some proposed EOS of neutron stars



Confirmed Kilonova and R-process

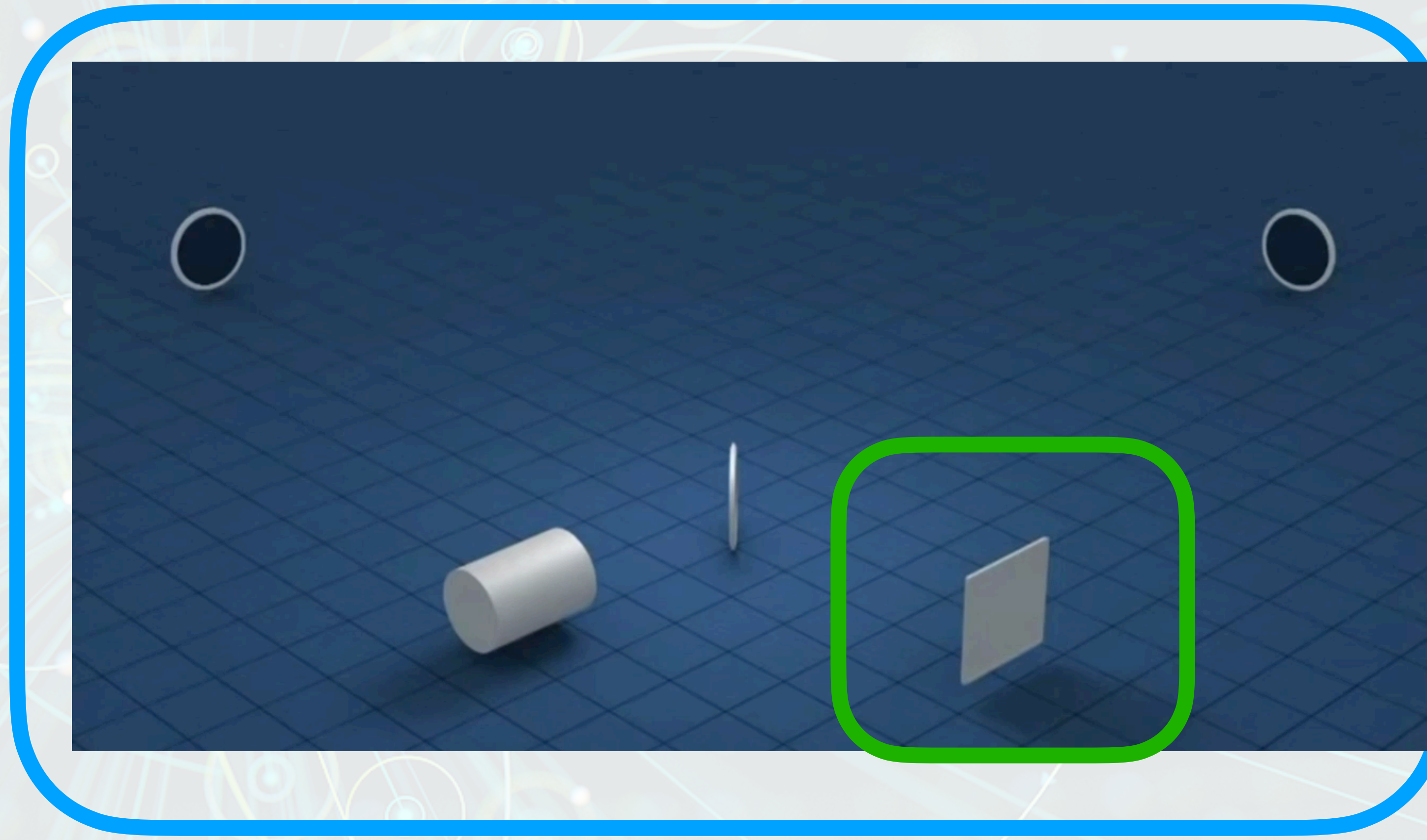

Confirmed BNS as origin for some GRBs

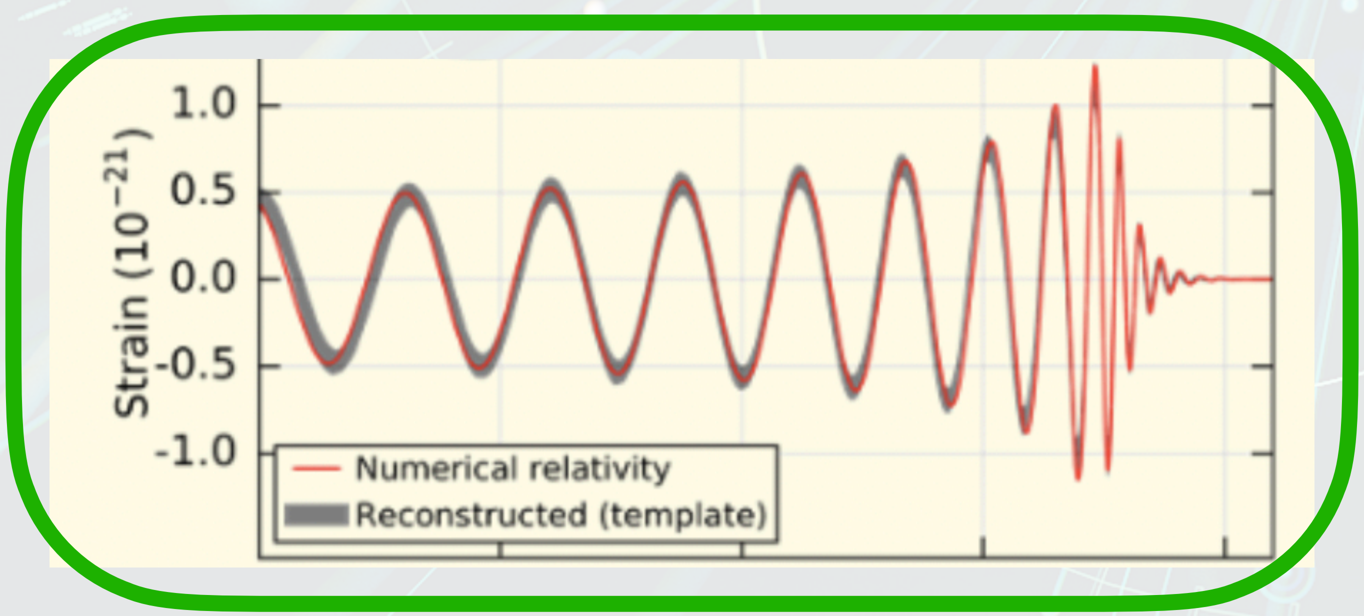
Gravitational Waves:
solving the biggest mysteries of the universe

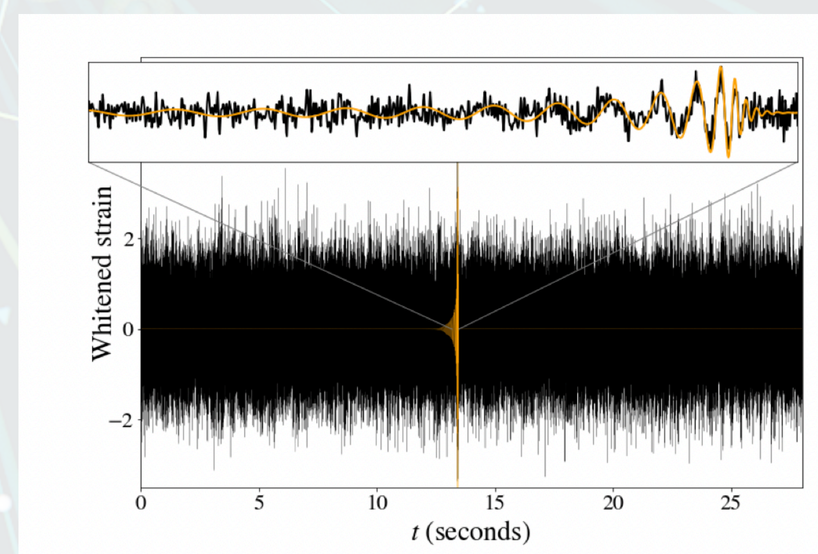


Gravitational waves offer us:

- new data on black holes (and therefore stellar formation)
- precision tests of General Relativity (and therefore future+past of Universe)
- particle physics processes at energy scales >> earth measurements
- cosmological data (Dark Matter/Dark Energy/..)
- snapshot of Big Bang itself







Pre-processing + matched filtering

Data analysis: Matched filtering

Goal: find template that best matches the signal *s* measured

$$s(t) = h(t) + n(t)$$

- by maximising the signal-to-noise ratio SNR, in which

$$\mathrm{SNR} = \frac{S}{N}$$

S → $S = < \tilde{s} > |_{h\neq 0}$ (average filtered signal if GW present)

N → $N = \sqrt{< \tilde{n}^2 > - < \tilde{n} >^2}$ (average standard deviation of filtered noise)

The signal is filtered by *K*(*t*)

$$\tilde{s} \equiv \int_{\infty}^{\infty} K(t) s(t)\, dt$$

and one can show that the highest SNR is obtained (*Wiener filter*) as follows:

$$\frac{S}{N} = \sqrt{4 \int_0^{\infty} \frac{|\tilde{h}(f)|^2}{S_n(f)}\, df}$$

in which the *power spectral density* S_n is defined via: $S_n(f)\delta(f - f') = 2 < \tilde{n}^*(f)\tilde{n}(f') >$

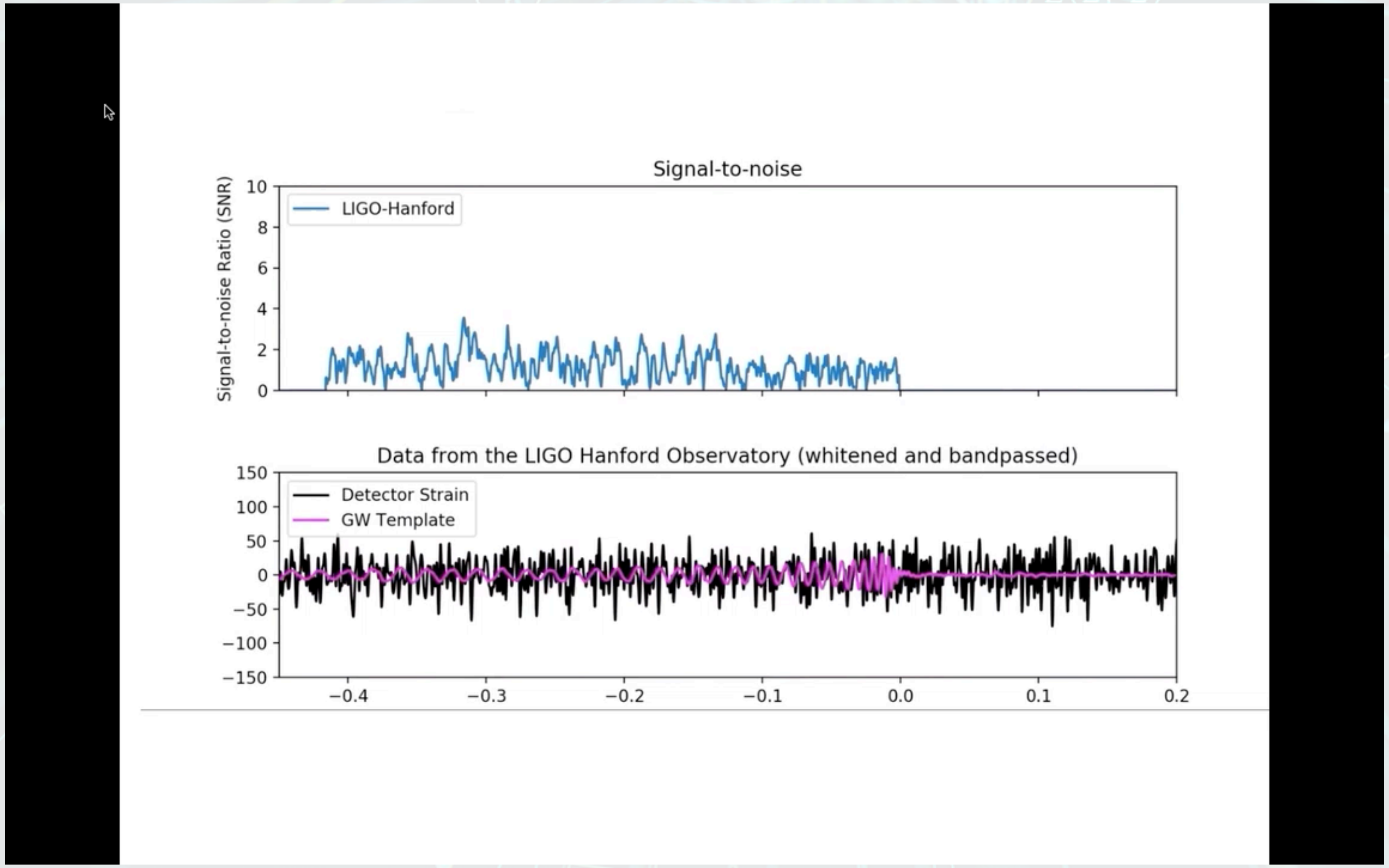
Data analysis: Matched filtering

$$\frac{S}{N} = \sqrt{4 \int_0^\infty \frac{|\tilde{h}(f)|^2}{S_n(f)}\, df}$$

→ $h(f)$ = what one looks for

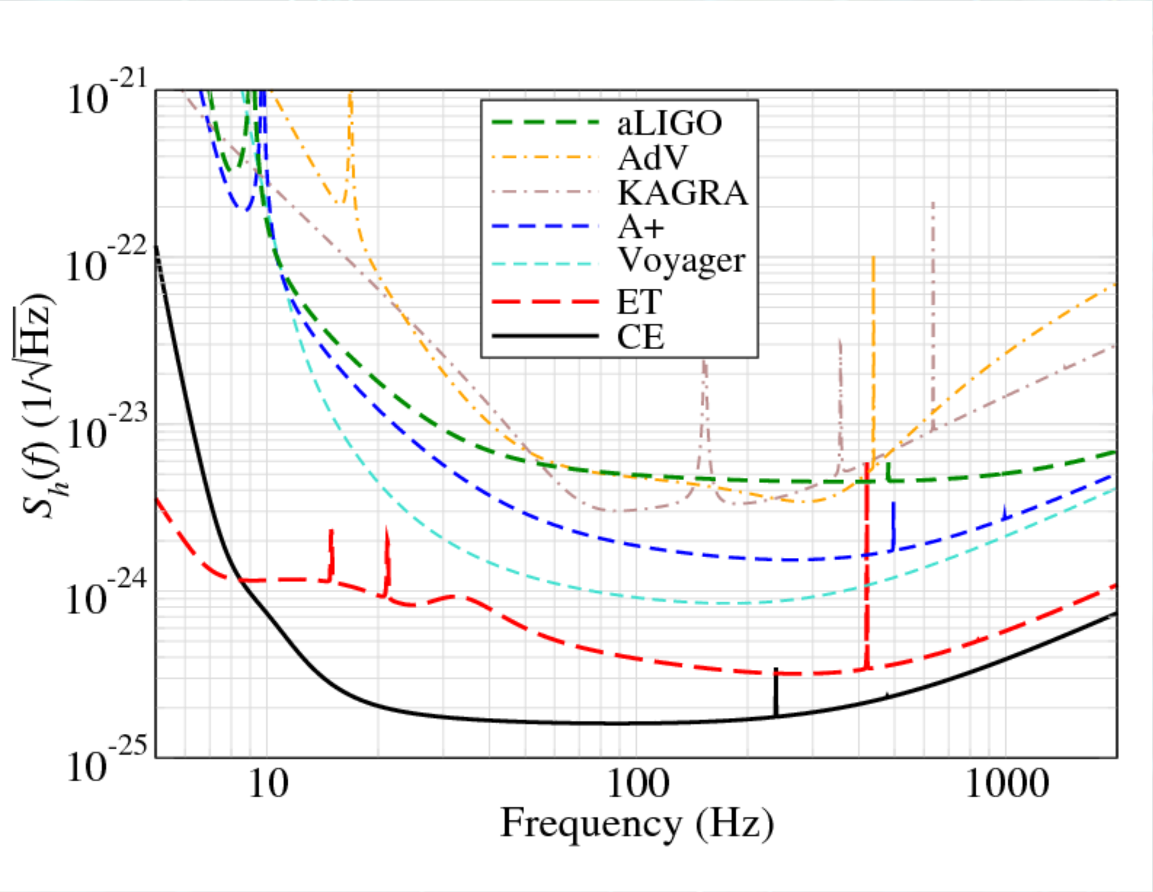
→ $S_n(f)$ = how one is thwarted by the detector

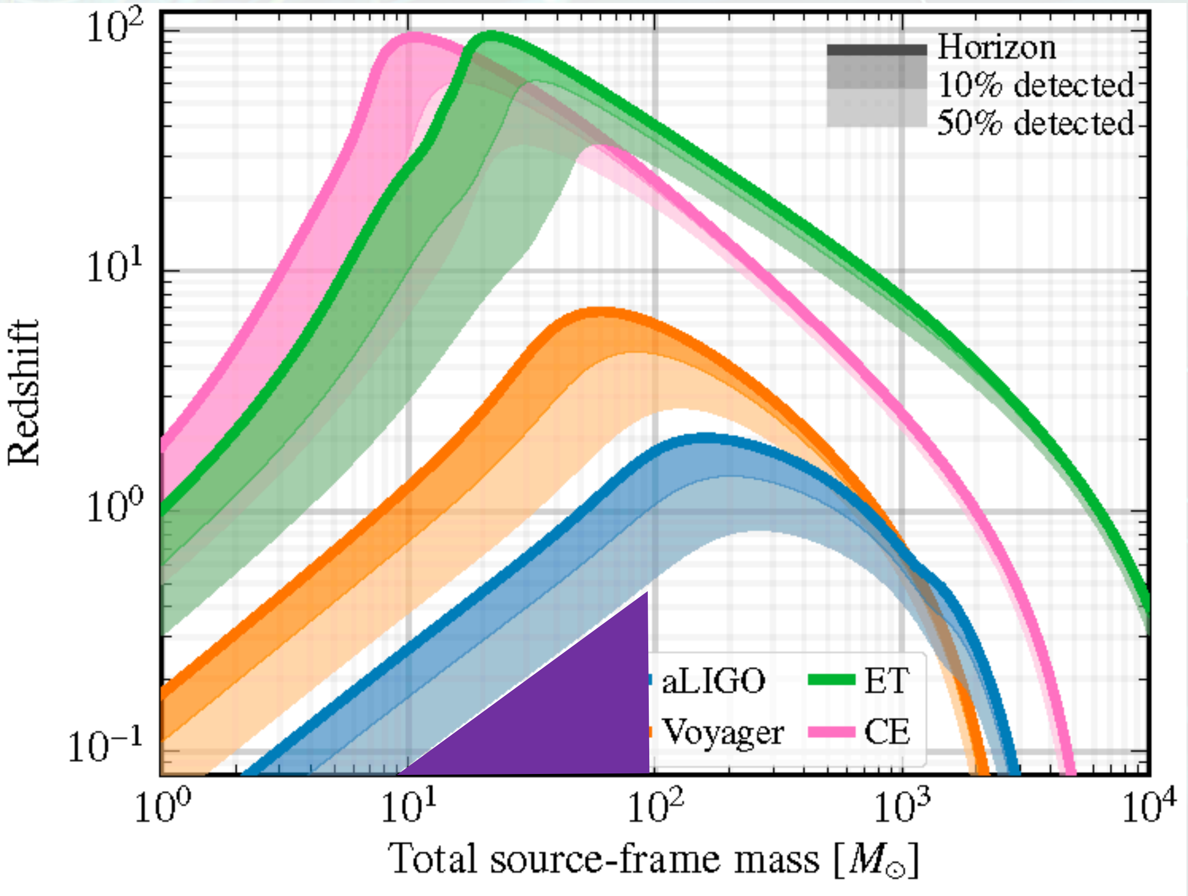
Approach: Try out gravitational waveform *h(f)* for different values of the parameter space, look for parameters that have highest SNR.



Data analysis: Matched filtering

Next generation detectors (e.g. Einstein Telescope) will have increased sensitivity due to novel techniques in quantum squeezing of light, low temperature operation, new mirror materials and suspension techniques, and seismic damping due to underground operation.

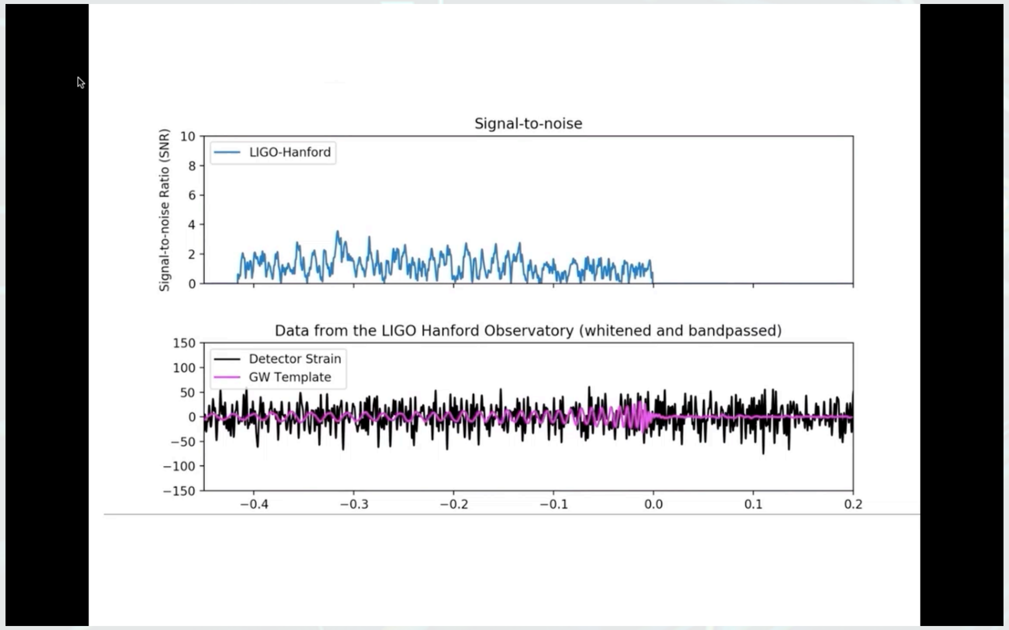




O(10^5) increase in gravitational wave detections.

Challenges

More data gives us three challenges in the realm of data analysis.



- Increase in sample size:
  wider lower frequency range increases the length of each gravitational wave signal; signals lengths of O(1) seconds to O(minutes-hours) become the norm.
- Increase in detail:
  wider higher frequency range include more (nucleonic) detail, increasing the parameter space; parameter space increases to ~15 dimensions.
- Increase in volume:
  gravitational wave signals will overlap continuously and might require novel data-analysis techniques.

Matched filtering will become unfeasible.

Challenges

("Gravitational-Wave Data Analysis Computing Challenges in the 3G Era",
I. Bird, P. Couvares, E. Porter, J. Willis, on behalf of LVC, 30th of July 2019)

Conclusion and Summary Recommendations

The GW community must make smart data analysis computing investments well in advance of, as well as during, the 3G era. Without major innovation, 3G data analysis (search and PE) naively requiring a 1000x increase in computing demand may need to be implemented on 10-100x faster hardware. Current algorithms will not scale; new techniques have not yet been developed and **there is not yet a broad consensus on how difficult it may be**. Data analysis innovations, and expert code optimization effort for the most expensive search and PE codes will be needed to bridge this gap.

We need to plan for increased investment in data analysis software development and computing infrastructure effort compared to the 2G era, or or potentially sacrifice important science opportunities.

Usage of Quantum computing

Grover's algorithm:

A quantum search procedure that picks out *r* desired entries from a list of *N* elements. This takes O($N^{1/2}$) attempts. https://arxiv.org/abs/quant-ph/9605043

linear combination of all entries i

$$|s>=\frac{1}{\sqrt{N}}\sum|i>$$

split up in two subspaces for desired entries w and undesired entries w±

$$|s>=\sqrt{\frac{r}{N}}|w>+\sqrt{\frac{N-r}{N}}|w_\perp>$$

probability of successful search

probability of unsuccessful search

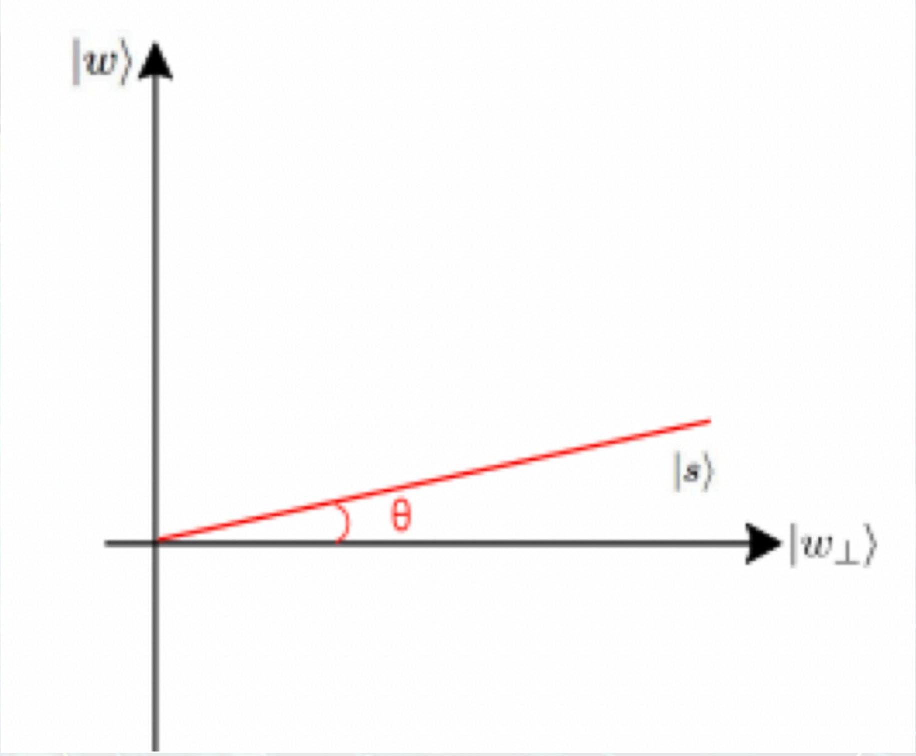
Grover's operator G maximises the probability for successful search:

$$G=\Big(2|s><s|-I\Big)U_f$$

flips sign of subspace |*w*>. It contains the search criterion (the oracle)

Usage of Quantum computing

Grover's algorithm enhances the probability for successful match and decreases probability for failed match. Graphically:



$$G = \begin{pmatrix} \cos(2\theta) & -\sin(2\theta) \\ \sin(2\theta) & \cos(2\theta) \end{pmatrix}$$

which after repeated (k) application yields the state:

$$G^k|s> = \sin\left((2k+1)\theta\right)|w> + \cos\left((2k+1)\theta\right)|w_\perp>$$

This is maximised after $o\left(\frac{\pi}{4}\sqrt{\frac{N}{r}}\right)$ applications of *G*.

Grover's algorithm & matched filtering

$$|s>=\frac{1}{\sqrt{N}}\sum|i>$$ → templates of a gravitational wave signal

Oracle *G*: SNR calculation and checking whether it is above a user-defined threshold ρ_{th}

A quantum algorithm for gravitational wave matched filtering

Sijia Gao [1,*], Fergus Hayes [1,†], Sarah Croke [1], Chris Messenger [1], and John Veitch [1]

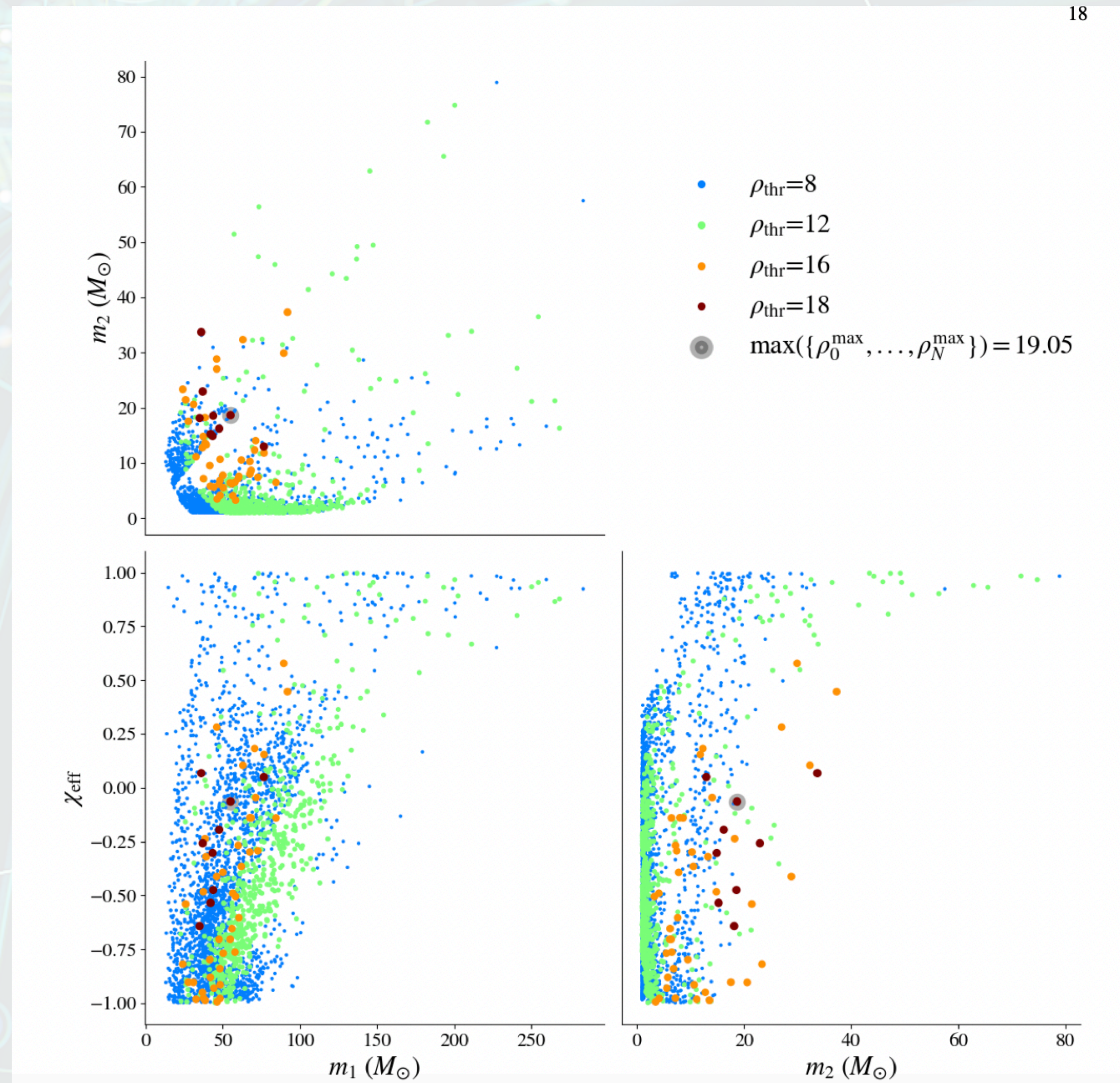
[1] *SUPA, School of Physics and Astronomy, University of Glasgow, Glasgow G12 8QQ, United Kingdom*

(Dated: September 6, 2021)

Quantum computational devices, currently under development, have the potential to accelerate data analysis techniques beyond the ability of any classical algorithm. We propose the application of a quantum algorithm for the detection of unknown signals in noisy data. We apply Grover's algorithm to matched-filtering, a signal processing technique that compares data to a number of candidate signal templates. In comparison to the classical method, this provides a speed-up proportional to the square-root of the number of templates, which would make possible otherwise intractable searches. We demonstrate both a proof-of-principle quantum circuit implementation, and a simulation of the algorithm's application to the detection of the first gravitational wave signal GW150914. We discuss the time complexity and space requirements of our algorithm as well as its implications for the currently computationally-limited searches for continuous gravitational waves.

PACS numbers: 03.67.Ac; 04.30.-w; 07.05.Kf
Keywords: Quantum algorithm, matched filtering, Grover's algorithm, gravitational waves, continuous waves, data analysis

Gao et al.
https://arxiv.org/abs/2109.01535



What we are interested in:

- Can this proof of principle be scaled up to fuller template banks?

  collaboration with Chris van den Broeck, Sarah Caudill (UU) and UM

- Can the oracle calls be made into a quantum computing step?

- (Related) is there an efficient (non-linear) PDE q-solving algorithm?

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = -\frac{8\pi G}{c^4} T_{\mu\nu}$$

- Are there novel ways to do data-analysis, *i.e.* not a quantum version of classical pipelines?

  collaboration with Pietro Bonizzi (Data Knowledge and Engineering, UM) and TU/e

..and we QC invite experts to help us with.


Maastricht University