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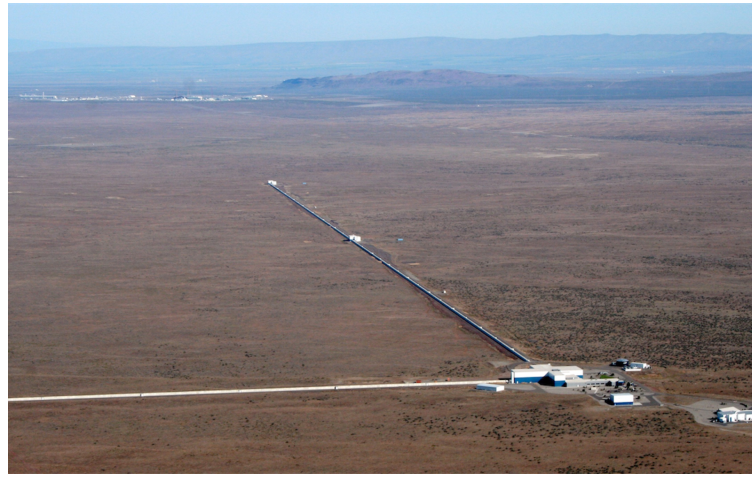

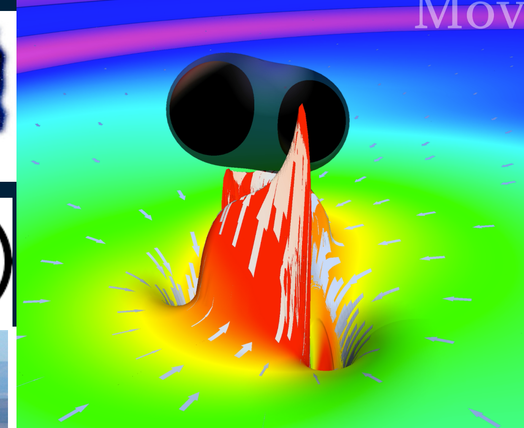

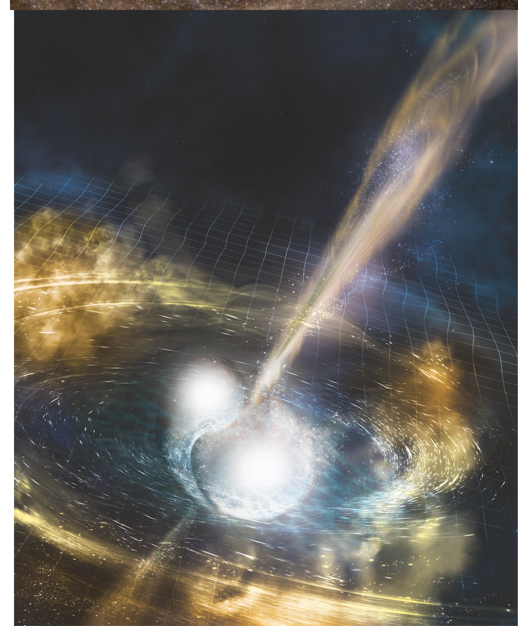

Sensing the space-time

The dawn of Gravitational wave astronomy

Borja Sorazu

Institute for gravitational research, University of Glasgow

on behalf of the LIGO scientific collaboration and Virgo

LSC – a World town

The LIGO Scientific collaboration (LSC) is made out of 1000+ scientist of more than 90 institutions in 16 countries. **www.ligo.org**

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LSC - Institutions

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American University
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PennState
Southern University and Agricultural & Mechanical College
Massachusetts Institute of Technology
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University of Washington
Università degli Studi del Sannio
LSU Louisiana State University
Colorado State University
Charles Sturt University
Marshall Space Flight Center
CMI Chennai Mathematical Institute
The University of Tokyo
ACIGA
ICTS International Centre for Theoretical Sciences, Tata Institute of Fundamental Research
University of Birmingham
Georgia Institute of Technology
Korean Gravitational-Wave Group
Universität Hamburg, Der Forschung | Der Lehre | Der Bildung
University of Szeged
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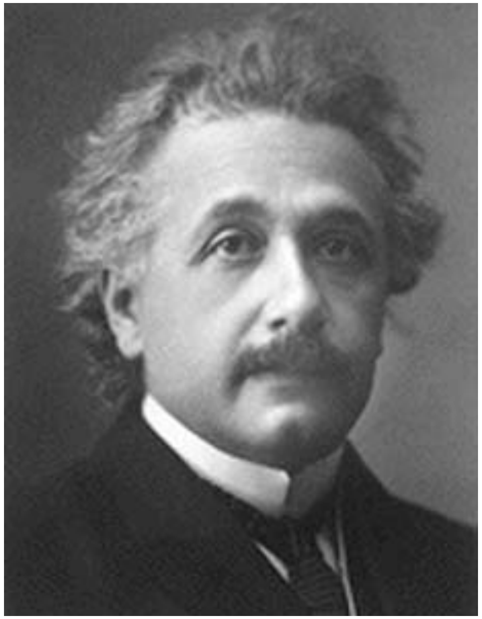
IISER Kolkata
NASA Goddard Space Flight Center

Introduction

- What are gravitational waves?
- Gravitational wave detections
- GW170817 – the dawn of multi-messenger astronomy
- Scientific implications
- Gravitational wave detectors
- What do we expect for the future?

What are gravitational waves?

The Theory of General Relativity



"Reality is not a space that evolves in time but it is a mathematical structure of 4D (space and time unified) which does not evolve." H. Minkowski

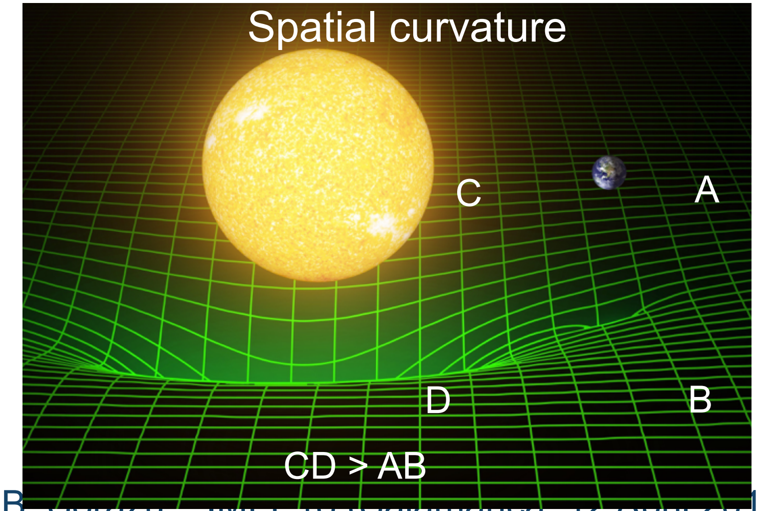
Informs matter how to move in a curved space-time →

$$T_{\mu\nu} = \frac{c^4}{8\pi G} G_{\mu\nu}$$

← Informs matter how to curve space-time

"Mass tells space-time how to curve, and space-time tells mass how to move." John Wheeler

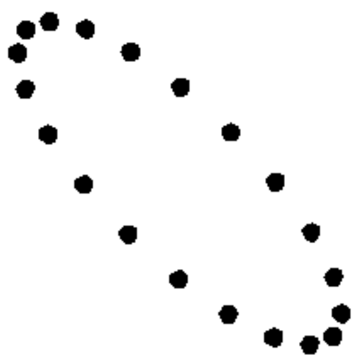
Gravity →movement of matter in this curved geometry.

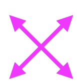


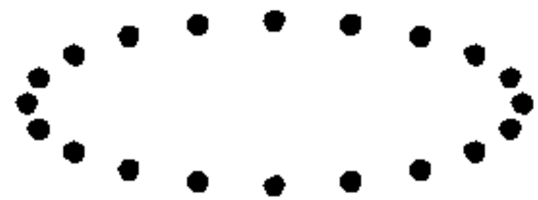
What are gravitational waves?

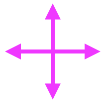
- Moving matter changes the curvature of the space-time as waves.
- **Gravity** is the way in which matters perceives space-time distortion → **Waves of gravity**.
- They are vibration **of (not in)** the space-time.
- Propagate at speed *c*, very weak interaction with matter→ they do not distort or disperse.

The effect of GWs on a fixed place in space is to stretch it and shrink it alternatively and orthogonally.



“Cross” polarisation 



“Plus” polarisation 

Gravitational waves are very faint

To detect a gravitational wave → measure the change it makes in the distance between two free particles.

This change is very small because space-time is very stiff:

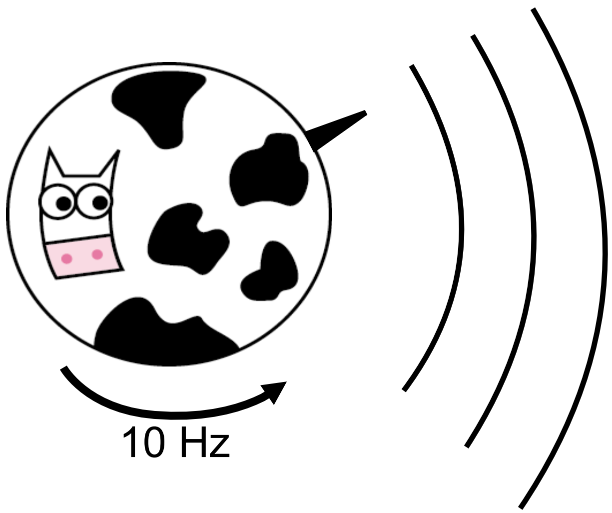
Stiffness of space-time

$$T_{\mu\nu} = 5 \cdot 10^{42} G_{\mu\nu}$$

Similar to Hooke's law:

$$(\vec{F} = k\vec{x})$$

1000 kg
2 m



$$h = \frac{\Delta l}{L} \approx 10^{-49}$$

Amplitude of GW (strain, deformation per unit length).

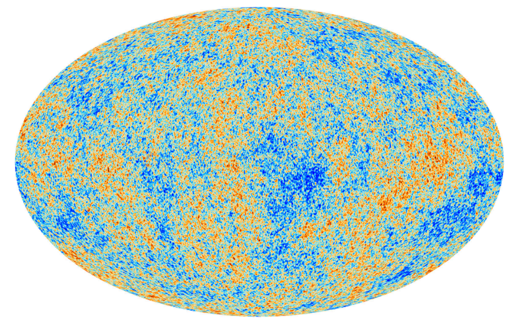
For a person 1.8m tall, it would stretch and shrink by:
0.0000000000000000000000000000000000
000000000000018 mm = 1.8×10^{-46} mm.
(proton radius= 0.85×10^{-12} mm)

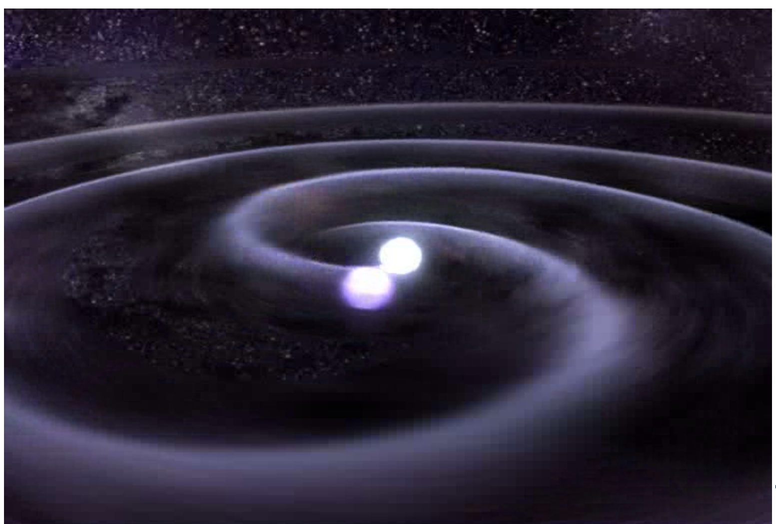
What type of sources can we detect?

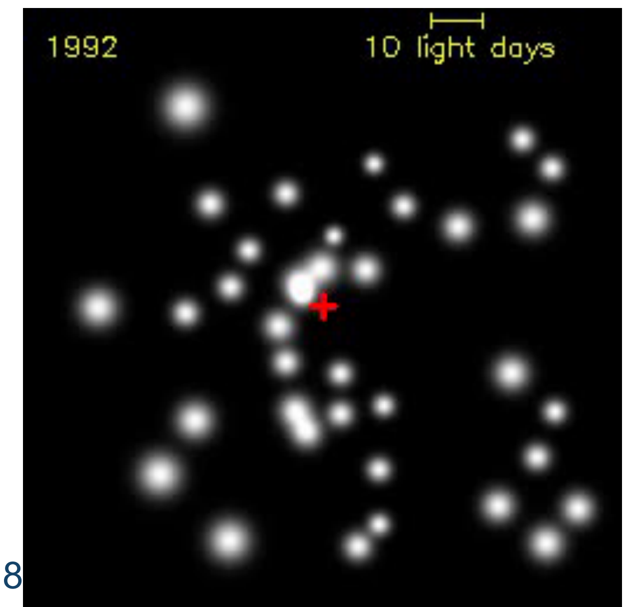
$$h \approx \frac{G}{c^2}\frac{M}{d}\left(\frac{v}{c}\right)^2$$

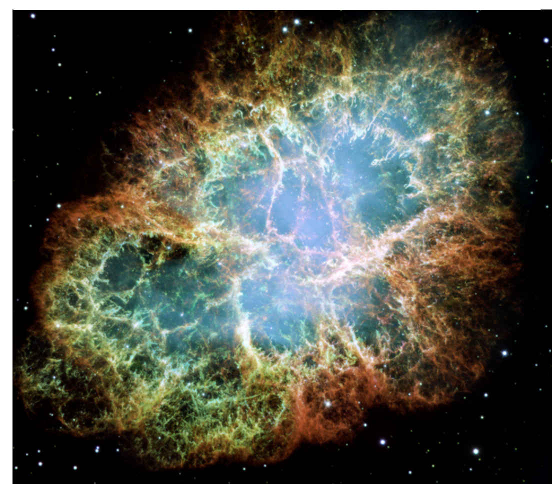
→ Sources of big mass, accelerated and moving at relativistic speeds:

- Supermassive black holes at galaxy centres.
- Compact binary coalescent systems; NS-NS, NS-BH, BH-BH.
- Collapse of massive stars (supernovas).
- Inflation of the universe after the Big Bang.
- Pulsars y Gamma ray sources (asymmetric).


Credit: Planck Collaboration







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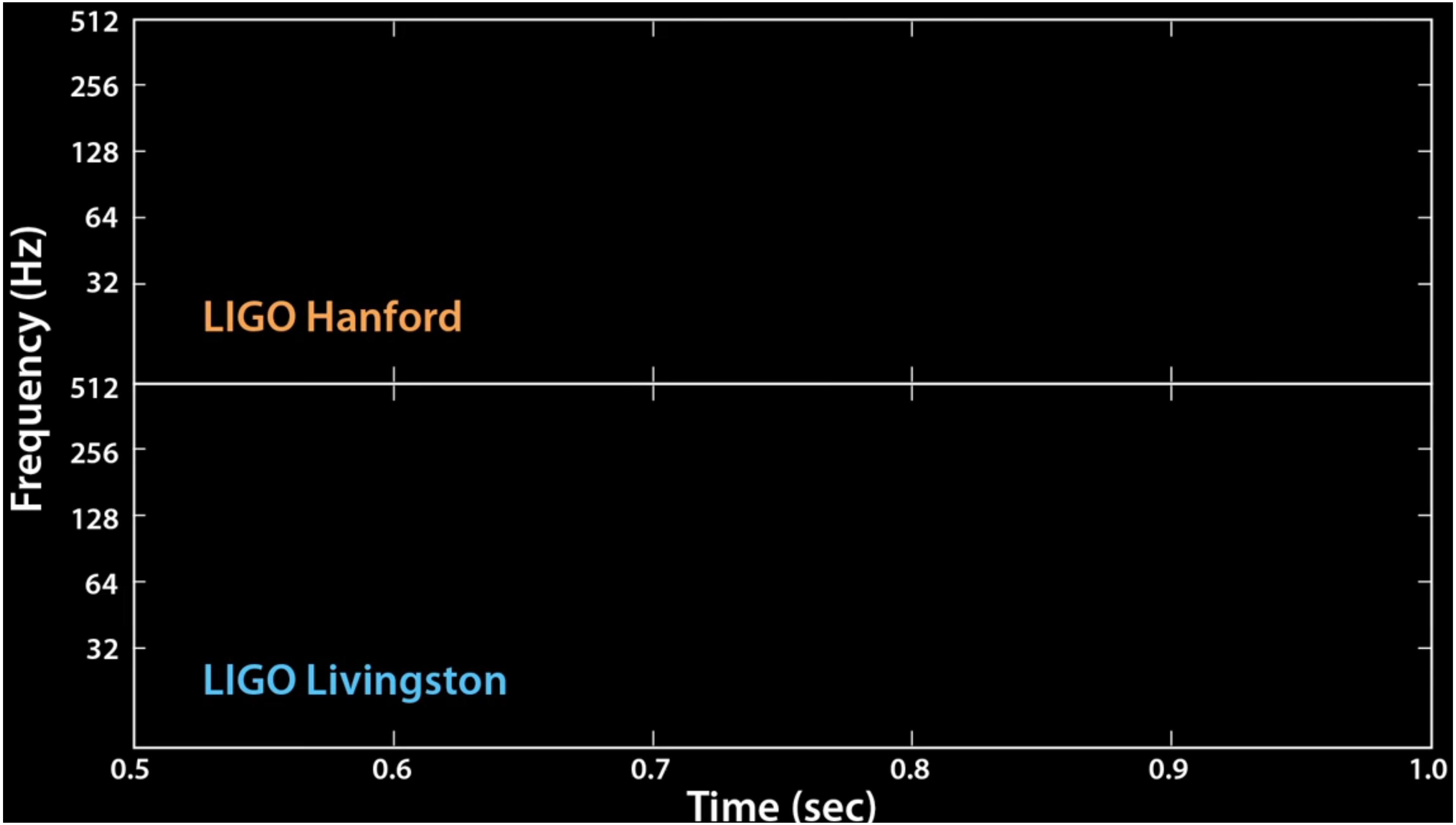
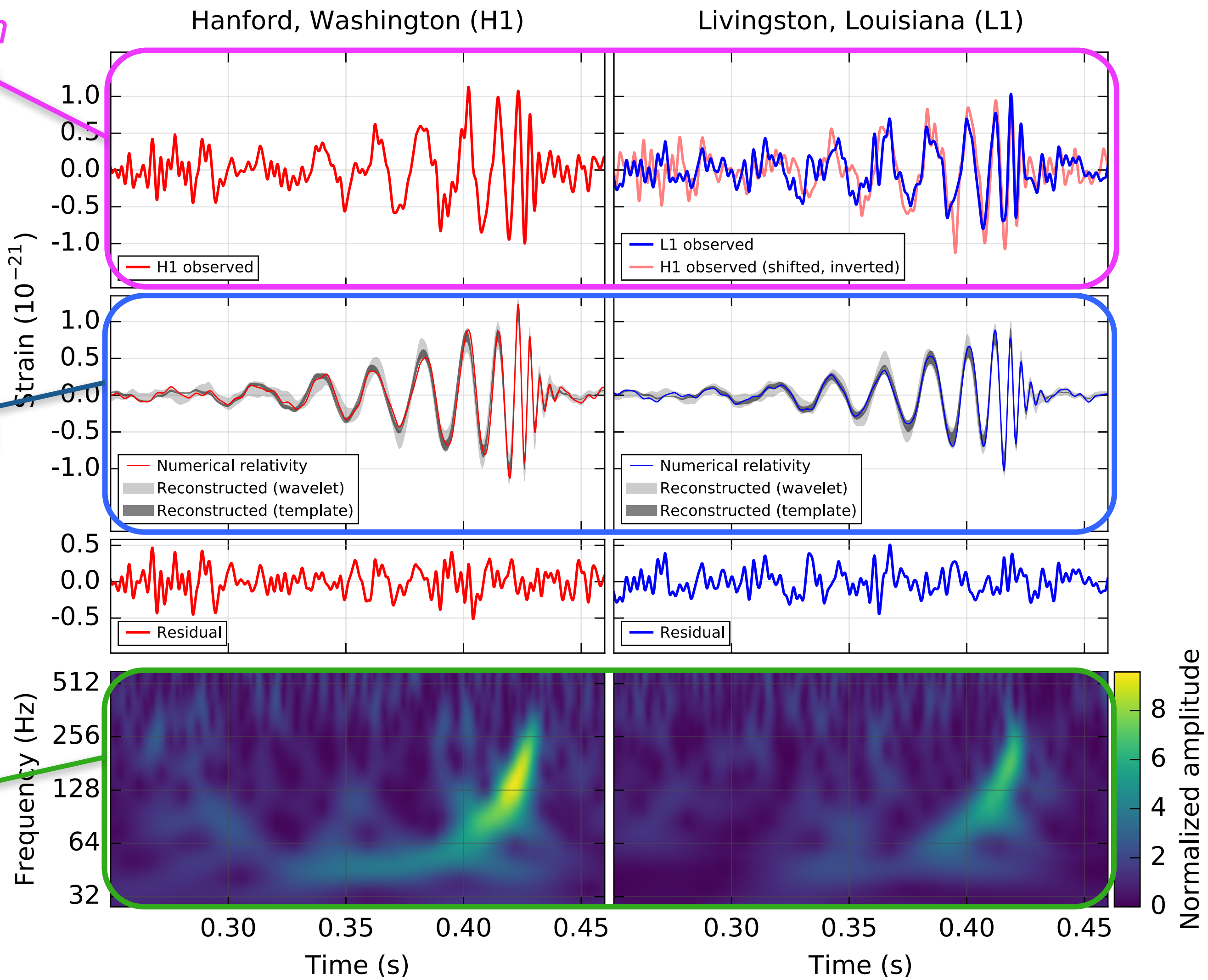
Gravitational wave detections

Listen the symphony of GW150914



GW150914 signal in both LIGO detectors

- Arrives to Livingston 7ms before Hanford, *triangulation*
- Reconstructed signal using 2 models:
  - •Resolves GR assuming CBC source, huge range of parameters→*match filtering*
  - •Generic search→looks for coincident excess energy on detectors' spectrogam'. Then fit chirp's curve to GR to extract source parameters.
- *Spectrogram*: Typical chirp of CBC sources as energy is emitted in GWs the inspiral orbit reduces collapsing faster with higher amplitude GWs.



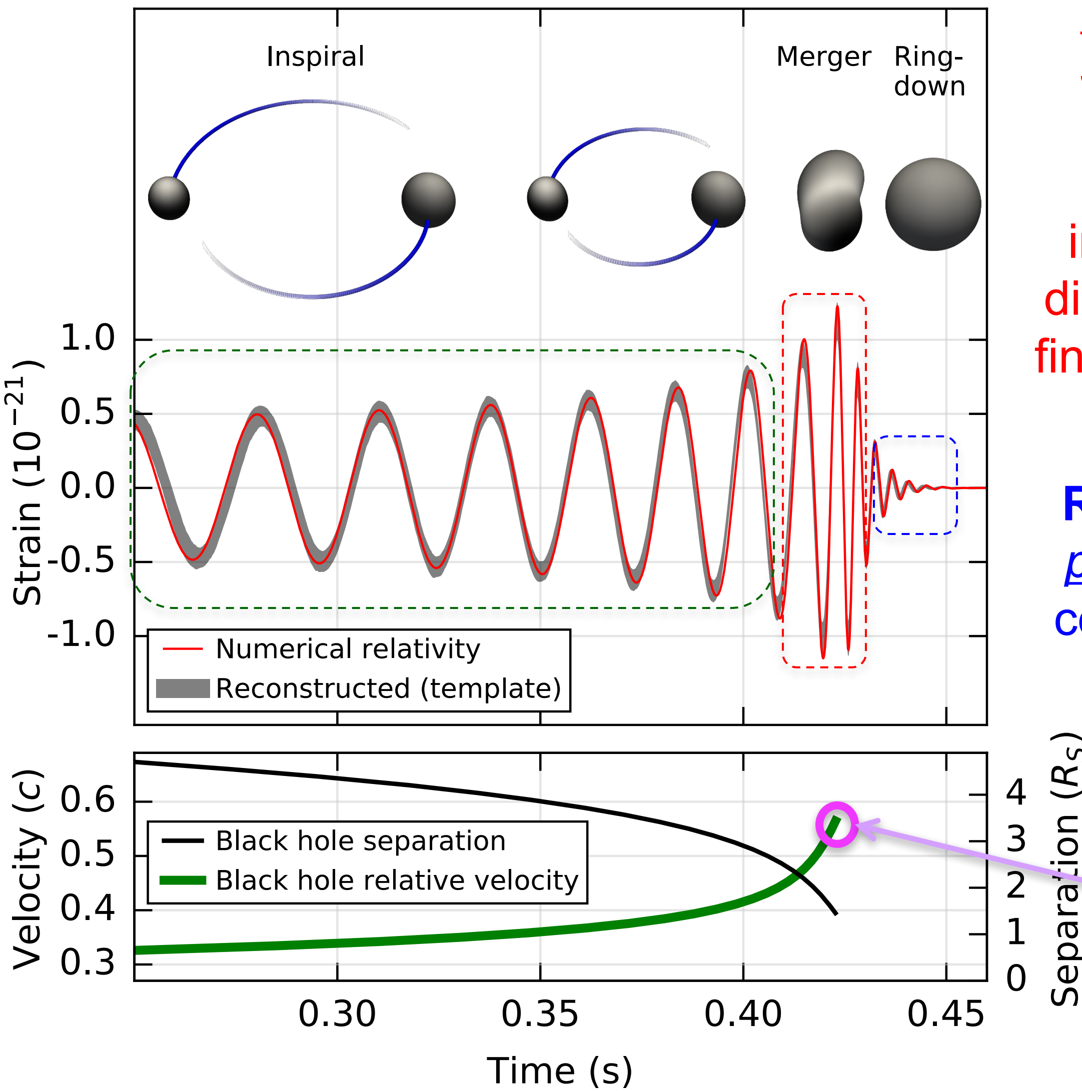
GW150914 – characterisation of the source

First observation of space-time dynamic under a strong field.

BH are characterised by: mass and spin (space-time swirls).

Signal divided in 3 regions. For each region we use different extraction methods.

Inspiral (*post-Newtoniana theory*): informs of chirp mass of BHs and limits their spins.



Merger (*Numerical Relativity, complete simulation of GR → possible for last 10 years*): amplitude informs of luminosity distance. Partial info of final BH mass and spin.

Ringdown (*theory of perturbation of BHs*): completes info of final BH mass and spin.

In the collision, two BHs moving at *0.5c!!!!*

Summary of parameters for GW150914

- SNR: 24
- Max. strain (h): 10^{-21} (like changing distance between Sun and closest star by the thickness of a hair).
- Duration: 200ms (between 30 and 350 Hz)

Mass of primary BH: $36^{+5}_{-4} M_\odot$

Mass of secondary BH: $29^{+4}_{-4} M_\odot$

Mass final BH: $62^{+4}_{-4} M_\odot$

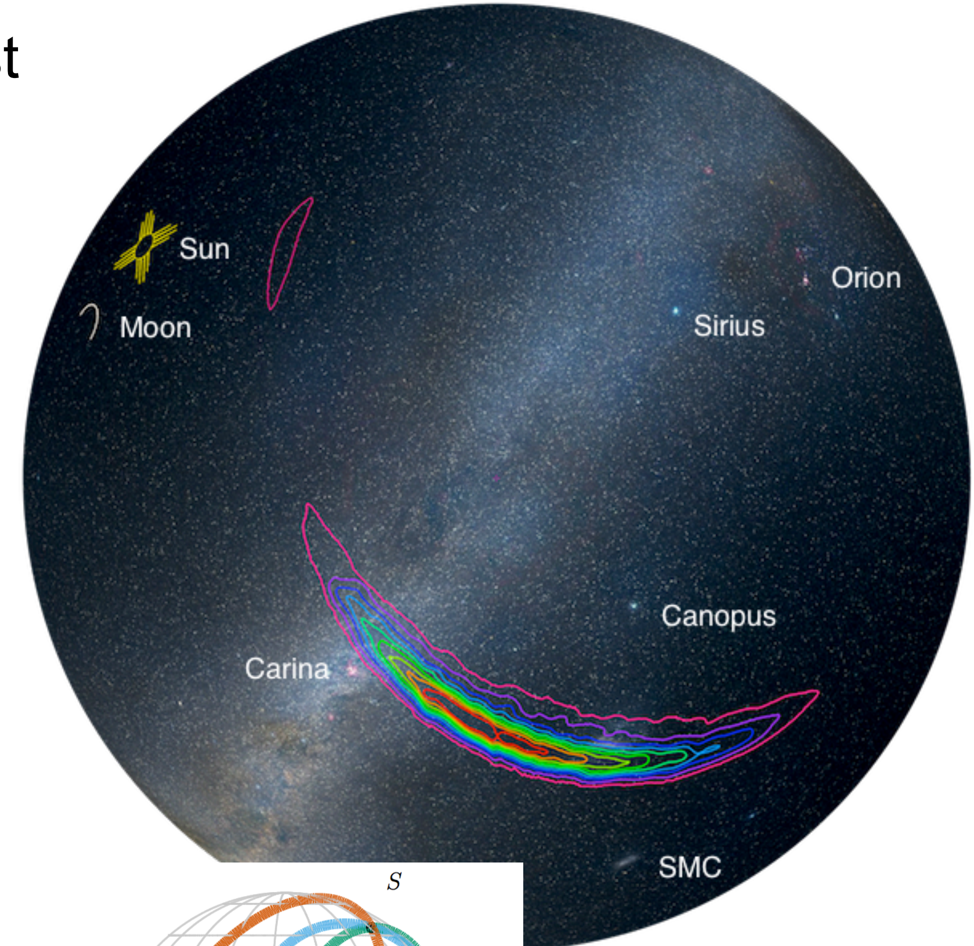
→ 3 $M_\odot$ emitted as GWs

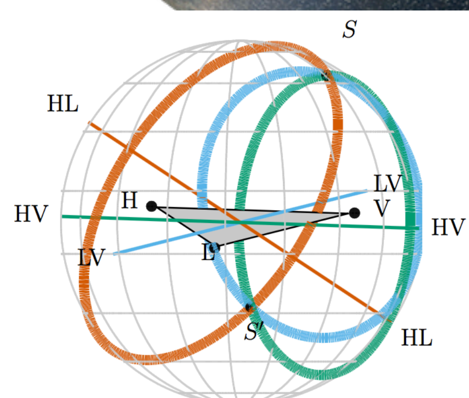
Max. Speed of BHs: ~ 0.6 c

Luminosity distance: 410^{+160}_{-180} Mpc → 1330 million light years

Source location for GW150914

- Detectors sensitive to all sky. Highest sensitivity vertical to detector plane.
- Triangulation by difference in arrival time to detectors…
- ... And consistency of signal's amplitude and phase (affected by calibration uncertainty).
- <u>2 detectors</u>; localization in long bands (triangulation circle):
  - **South hemisphere**.
  - **600 degrees^2** (90% confidence)
  - Volume includes 10^9 Milky Ways
- <u>3 detectors</u>; better location (intersection of 3 circles).





Source location for GW150914

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  sensitivity vertical to det
- Triangulation by differen
  time to detectors…
- ... And consistency of si
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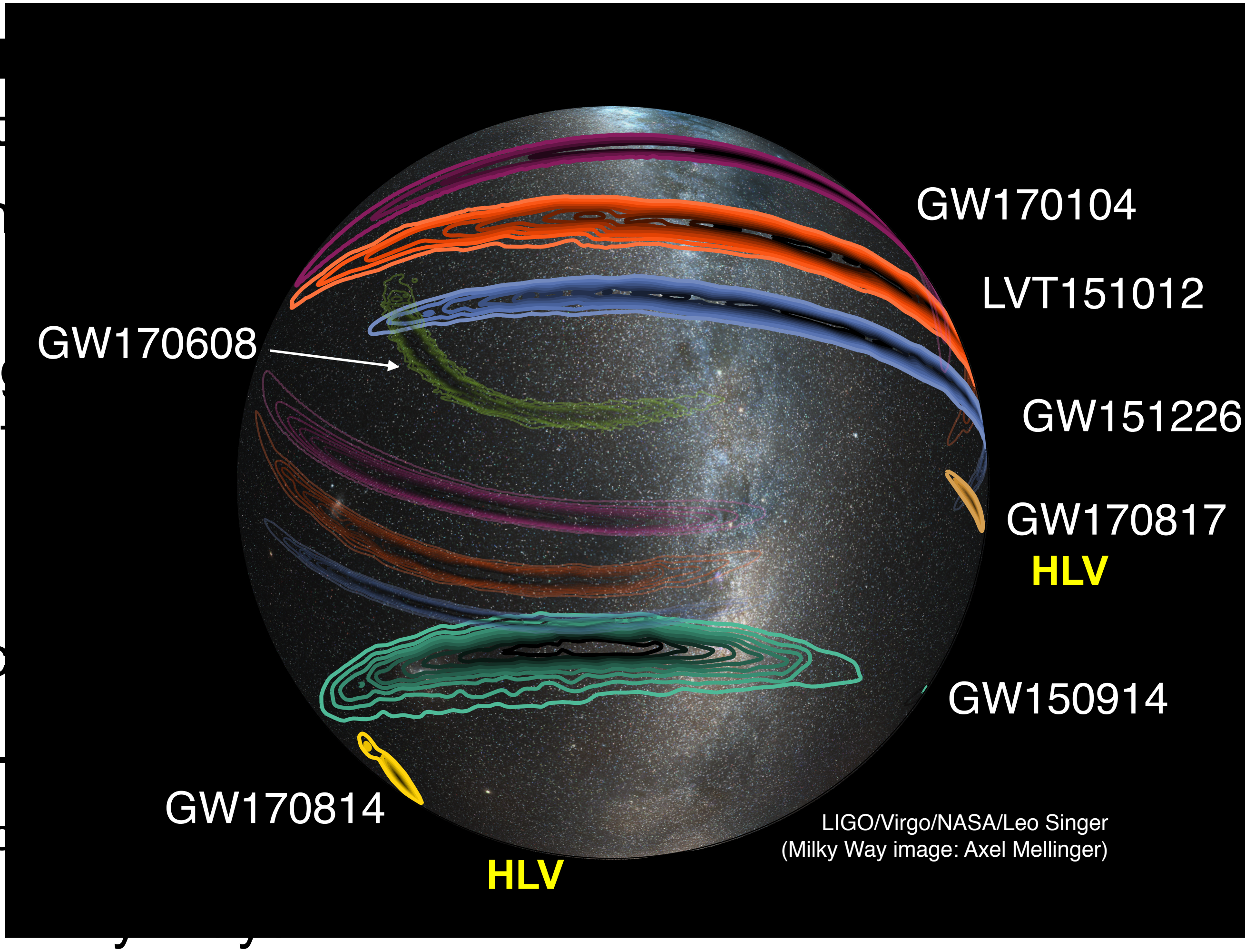
  calibration uncertainty).
- 2 detectors; localization
  bands (triangulation circ
  - **South hemisphere.**
  - **600 degrees²** (90% c
  - Volume includes10⁹

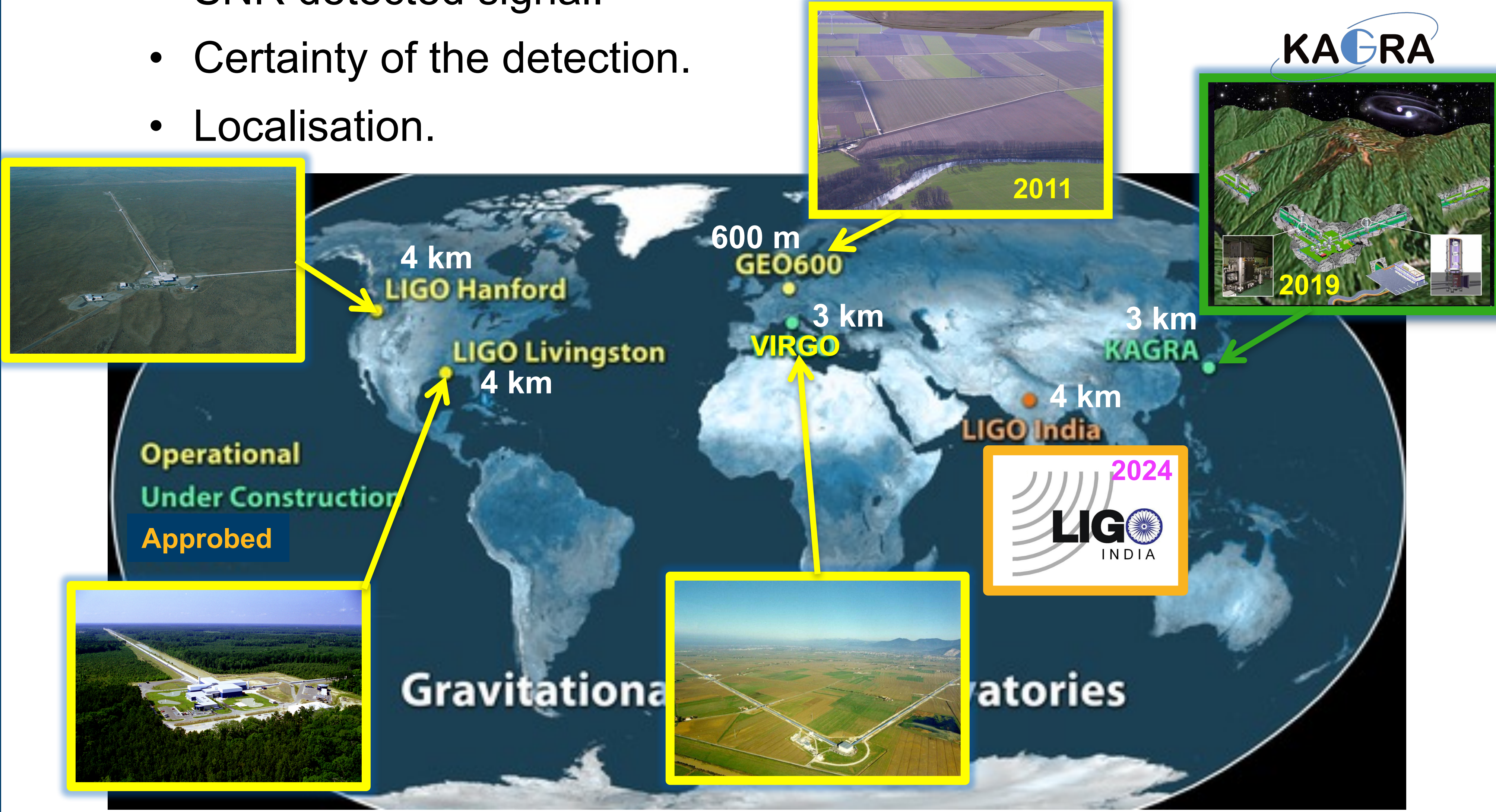


- 3 detectors; better location
  (intersection of 3 circles).

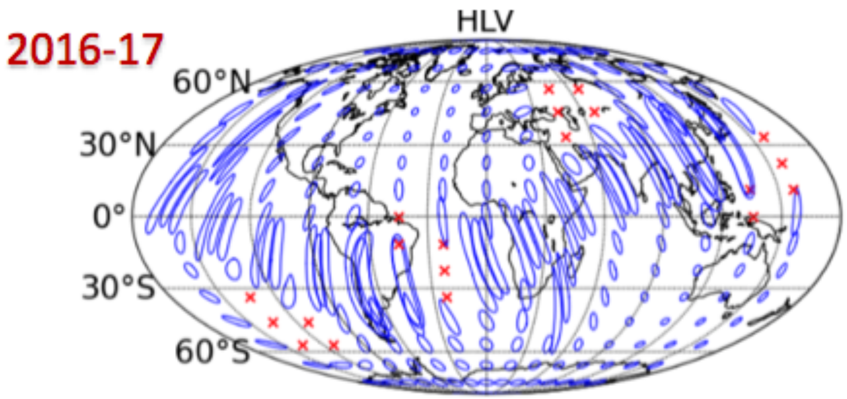
Global network of detectors

A global network of detectors improves:

- SNR detected signal.
- Certainty of the detection.
- Localisation.



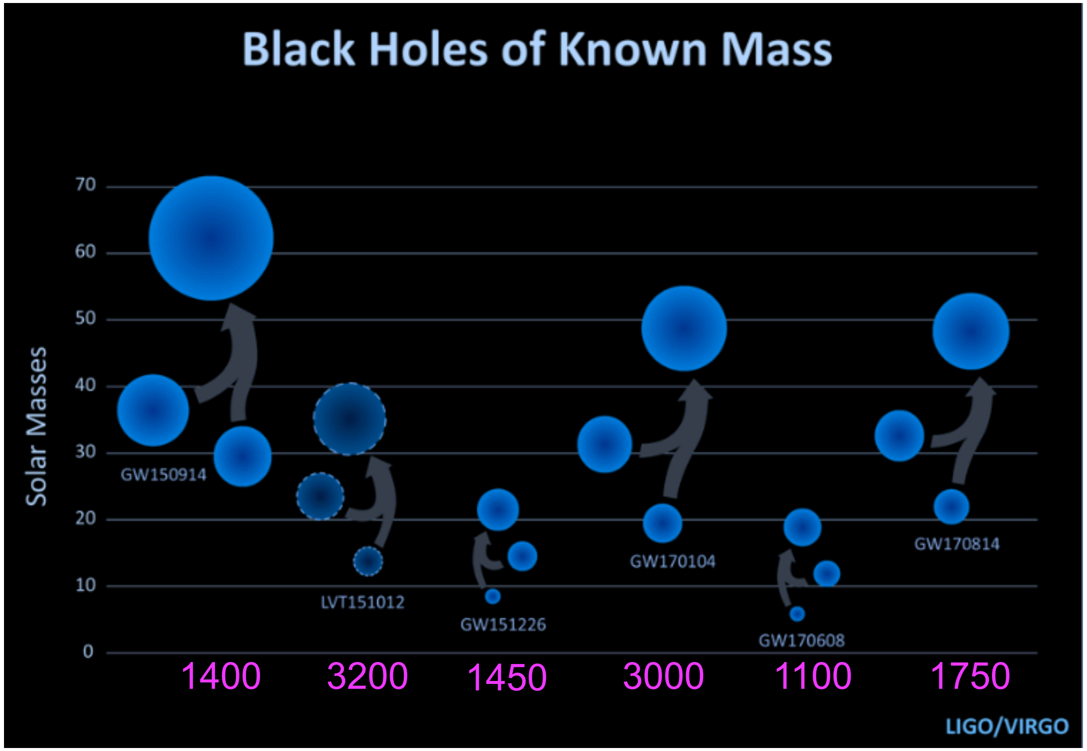
Global network of detectors- ‘Localization’



- Adding Virgo (August 2017) → breaks annular uncertainty. From hundreds to tens of degrees^2
- ↑ detectors’ sensitivity → ↓ source location error.
- With LIGO-India → great new improvement → few degrees^2

Other BBH detections

- During O1 (18 Sept 2015 – 12 Jan 2016): 2, GW150914 and GW151226.
- During O2 (30 Nov 2016 – 25 August 2017): 3 announced, GW170104, GW170608 and **GW170814**
- No EM → BHs dimension imply no accretion disc.



Distance to source in million light years

Other BBH detections

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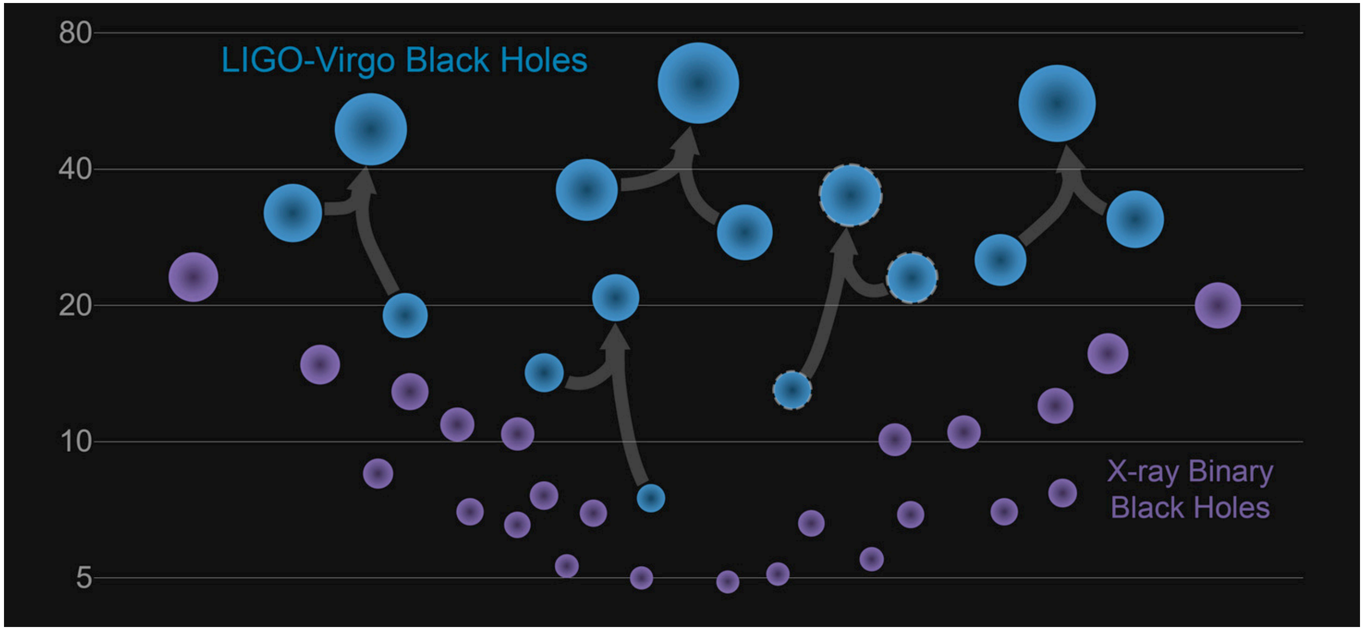
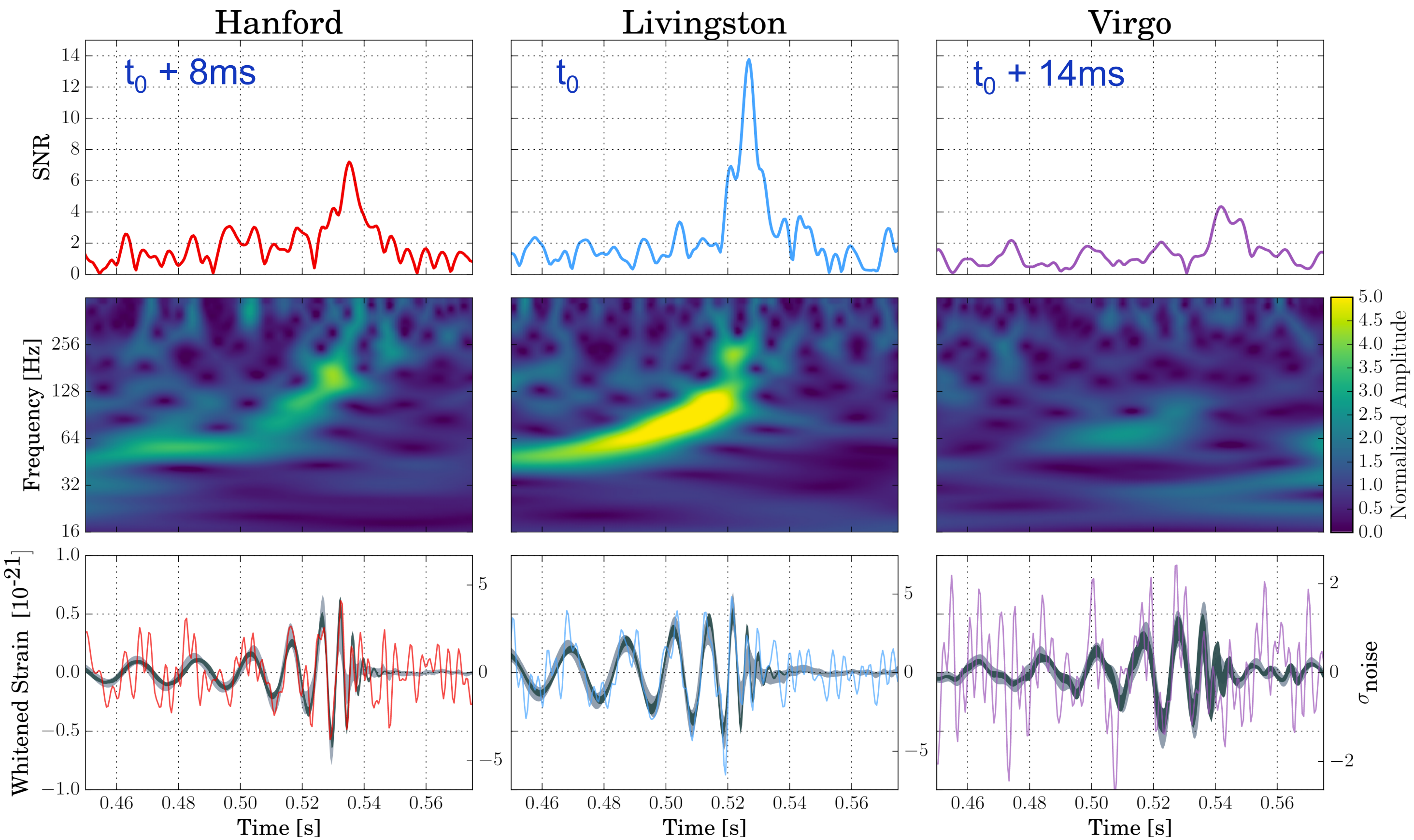


First triple detection GW170814: LIGO+Virgo

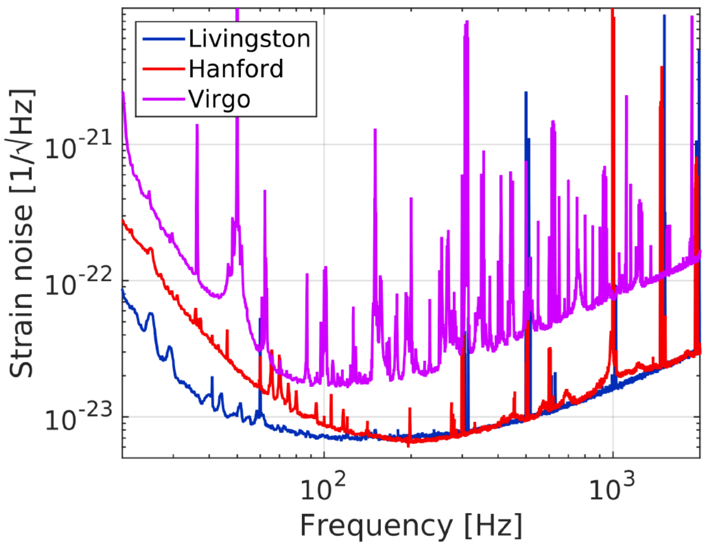
- **GW170814** first detection with 3 detectors (LLO, LHO and Virgo joining O2 on 1 August 2017).



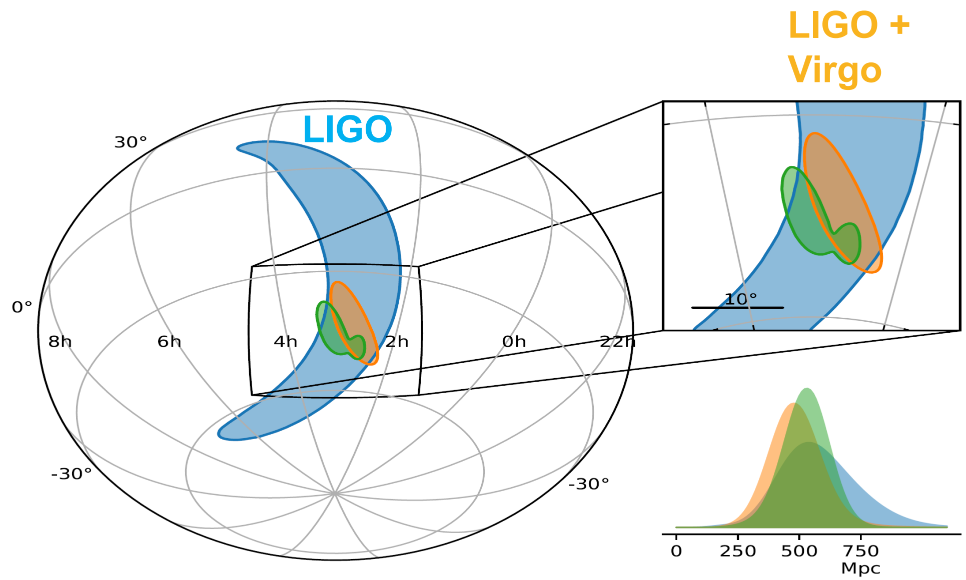
- Signal is observed at different time in the 3 detectors due to the finite propagation speed of GWs → source location.

First triple detection GW170814: LIGO+Virgo

- 3 detectors → Great localization improvement :
  - 90% credibility region: 1160 degrees^2 (LIGO), 60 degrees^2 (LIGO+Virgo).
  - Also improved luminosity distance uncertainty by 50%



Sensitivity of the 3 detectors during GW170814



Source location of GW170814 inc. distance

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GW170817

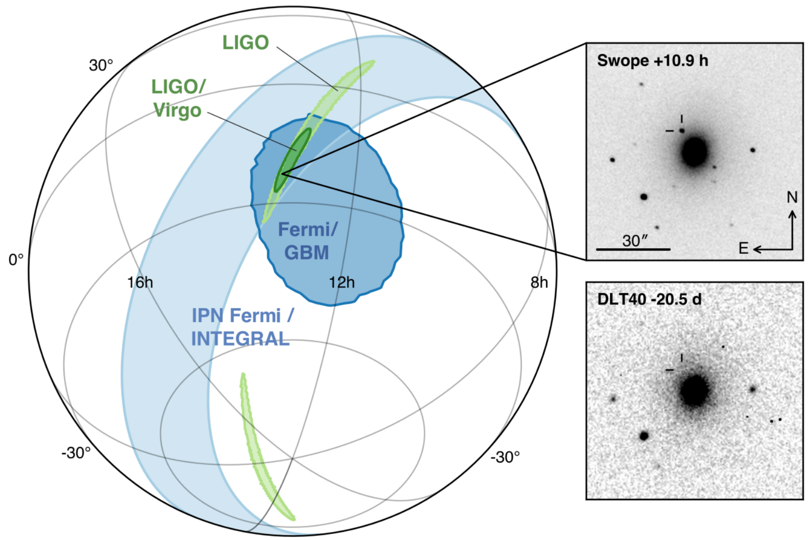
The dawn of multi-messenger astronomy

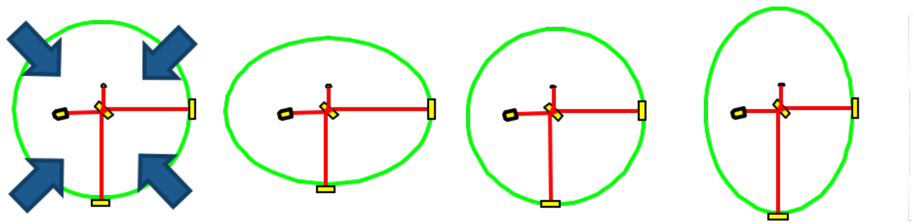
GW170817 – first GW signal of a BNS

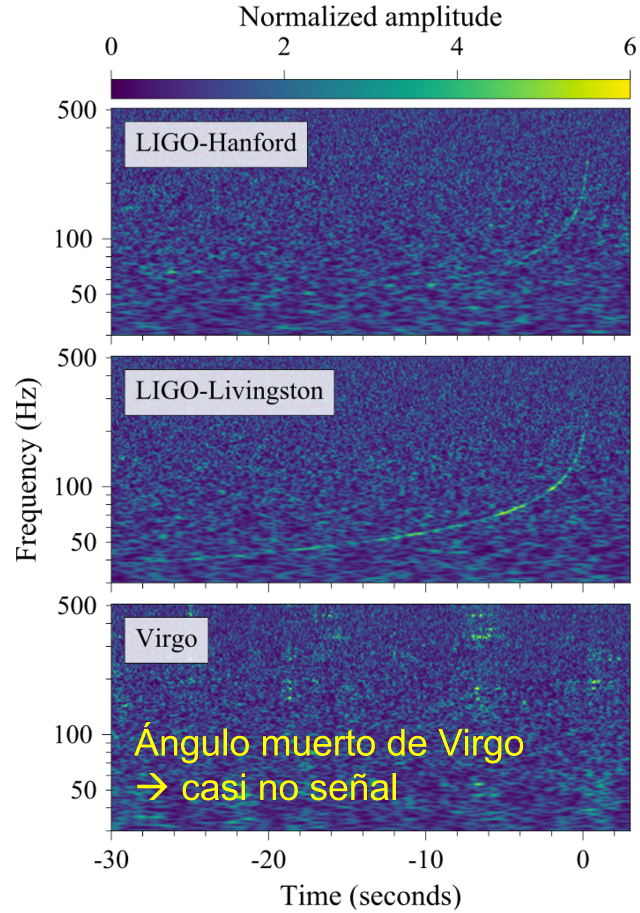
On 17 August 2017, the 2 aLIGO detectors and Virgo observed the GW signal emitted during the 100s before the merger of two neutron stars. **This time there was an EM counterpart!!!**

Astronomia multi-mensajeros → Evento observado con OGs y EMs.

GW170817 – dawn of multi-messenger astronomy



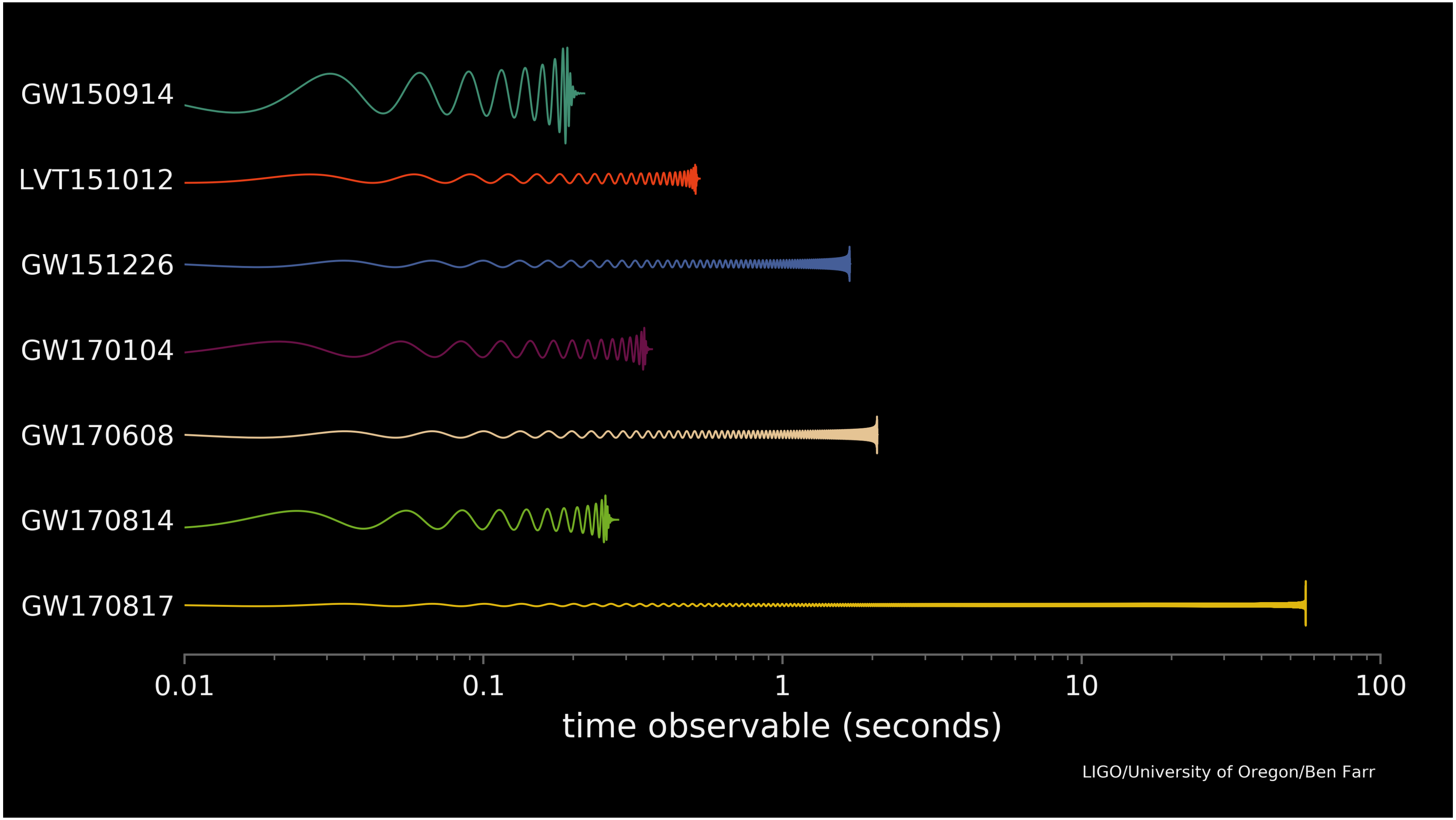




- The high precision on localization allowed for an exhaustive follow up after the merger, through the whole EM spectrum → Confirm that **kilonova** are associated to BNS mergers.
- Closest source of GW detected, only 100 M light years. The highest SNR signal and of longest time duration.

Temporal comparison of GW detections

In logarithmic scale!!

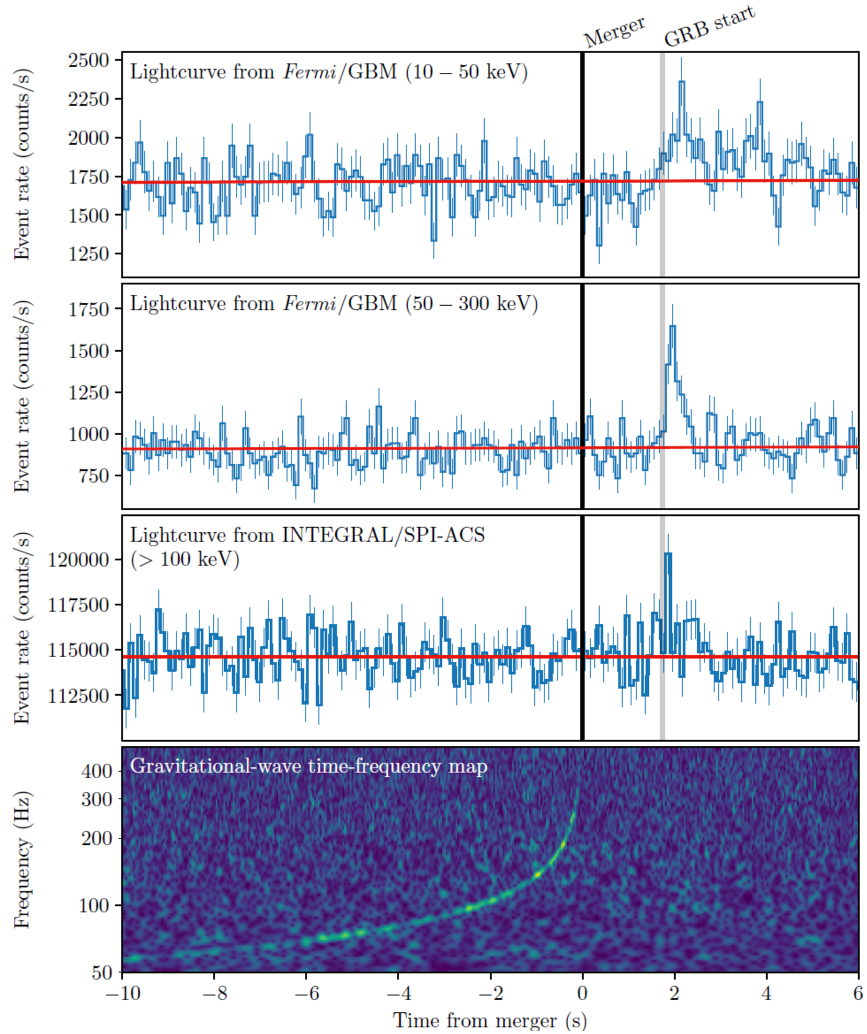


Scientific implications of GW170817

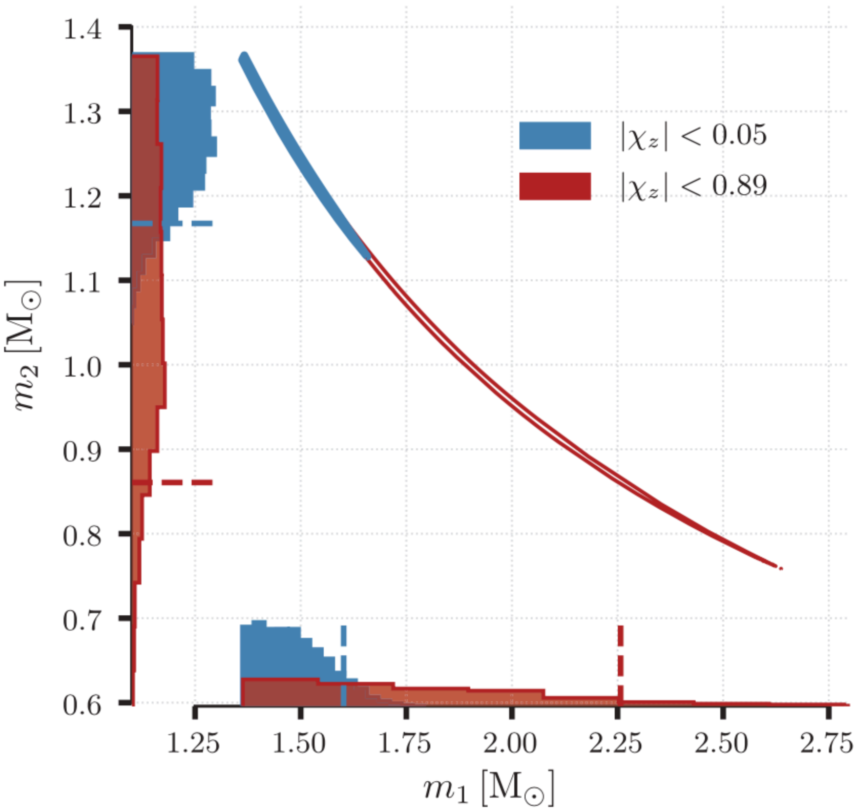
Constrain speed of gravity

- Time delay of (+1.74 ± 0.05) s between GRB and GW170817.
- Distance travelled ~130 M light years.
- Constrain difference between the speed of gravity and the speed of light to be between -3×10^{-15} and $+7 \times 10^{-16}$.

GRB only 1.7s after GW



Information in Gravitational Waves



	Low-spin priors ($|\chi| \leq 0.05$)
Primary mass m_1	1.36–1.60 $M_\odot$
Secondary mass m_2	1.17–1.36 $M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.7–1.0
Total mass $m_{\rm tot}$	$2.74^{+0.04}_{-0.01} M_\odot$
Radiated energy $E_{\rm rad}$	$> 0.025 M_\odot c^2$
Luminosity distance D_L	40^{+8}_{-14} Mpc
Viewing angle Θ	$\leq 55°$
Using NGC 4993 location	$\leq 28°$

$$R = 1540^{+3200}_{-1220}\ \mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$$

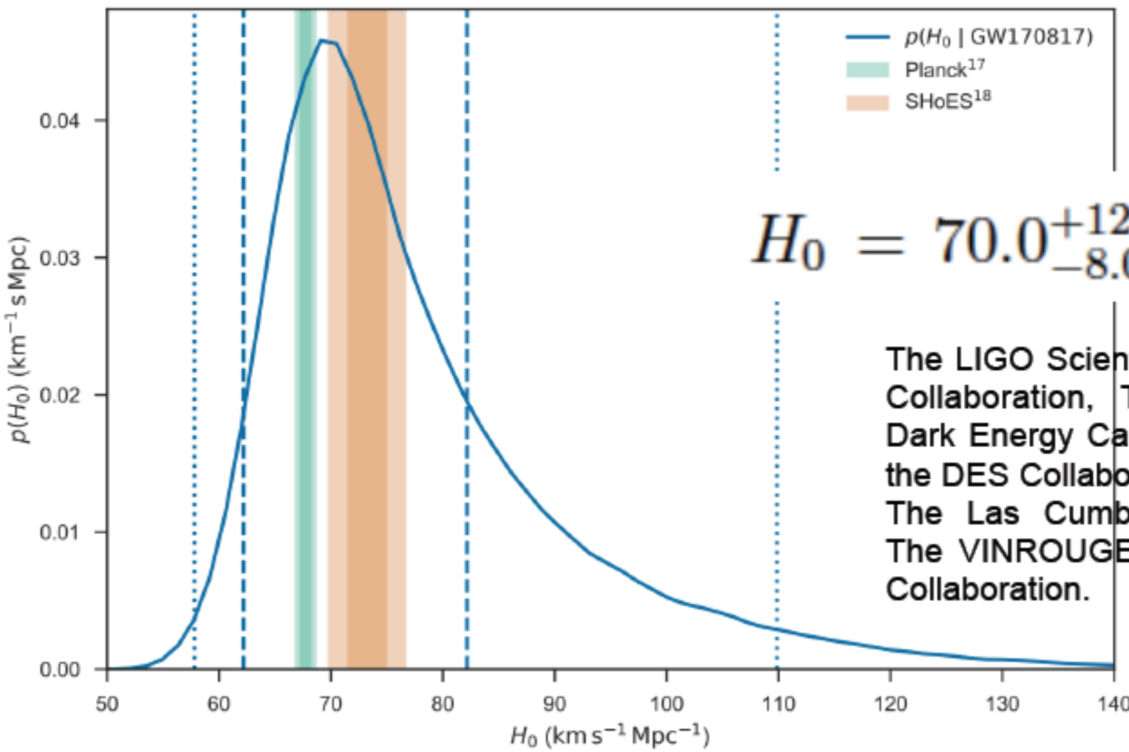
- More common than we expected
- Consistent with galactic BNS observations
- Tidal effects are not taken into account
- Neutron star maximum mass: ~2.2 Msun

LIGO+Virgo *PRL* 119, 161101 (2017)

From Imre Bartos, G1702357

Standard sirens – Hubble constant

- From amplitude of GW signal → absolute distance to source ~40Mpc
  - Independent from ‘cosmic distance ladder’
  - Calibrated by general relativity
- From the EM afterglow we measure redshift (v_H)
- Hubble constant (H_0) = expansion rate of the Universe = v_H / d



$$H_0 = 70.0^{+12.0}_{-8.0}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

The LIGO Scientific Collaboration and The Virgo Collaboration, The 1M2H Collaboration, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration, The DLT40 Collaboration, The Las Cumbres Observatory Collaboration, The VINROUGE Collaboration & The MASTER Collaboration.

Nature (2017)

...also

- First evidence that short-GRBs are associated to BNS
- The high precision on the localisation of the source allowed an exhaustive follow-up in all EM spectrum after collision→ confirms that **kilonova** are associated to BNS mergers.
- Limits the possible equations of state for neutron stars and their structure.
- **Mass of graviton** $m_g < \text{(few)} \cdot 10^{-23}\ eV/c^2$ (consistent with 0)
- No neutrino emissions were associated to this event.

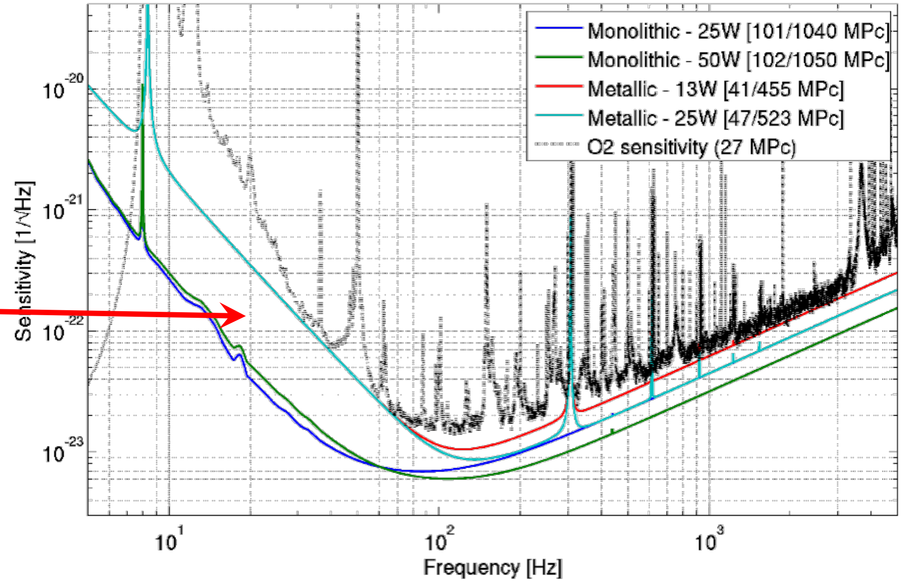
~12 months commissioning

Progress of detectors towards O3

Main Virgo upgrades

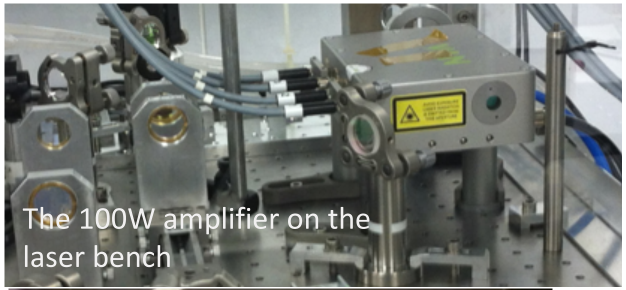
- All test masses suspended with **fused silica fibers**

Will boost the low frequency sensitivity.



- Installation of GEO squeezer. On-site measured **squeezing**: around 10 dB;

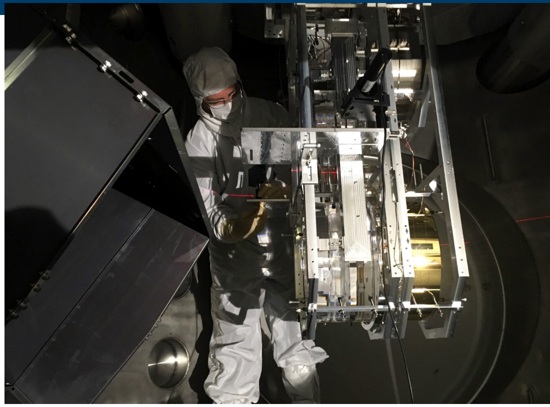
Improves high frequency sensitivity.



- New high power laser amplifier: delivers up to 60W to interferometer.
- New monolithic pre-mode-cleaner, for high power.

from Brian O'Reilly and Alessio Rocchi, G1800395

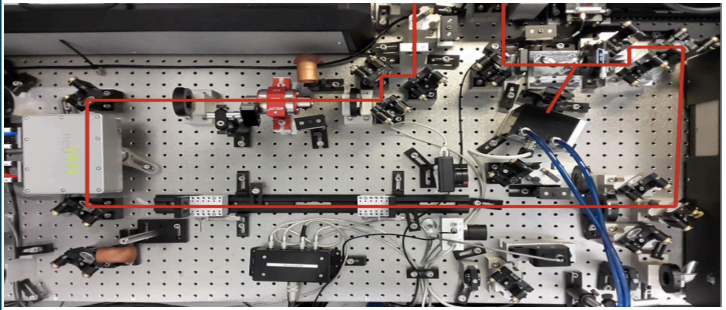
Main aLIGO upgrades



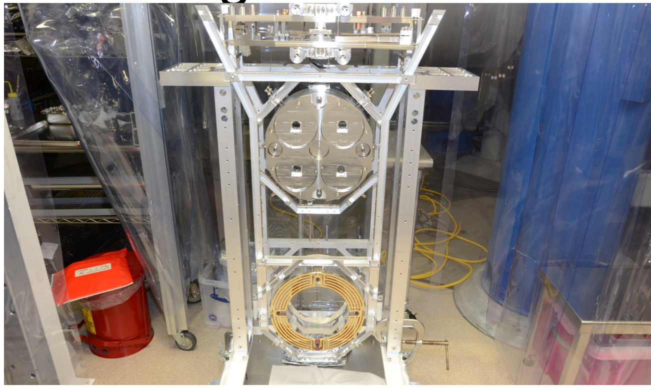
- ITM replacement, a point absorber was found on the HR side of H1 ITMX.

Affected ability of H1 to operate at higher power.

- Also replace ETMs at both detectors.

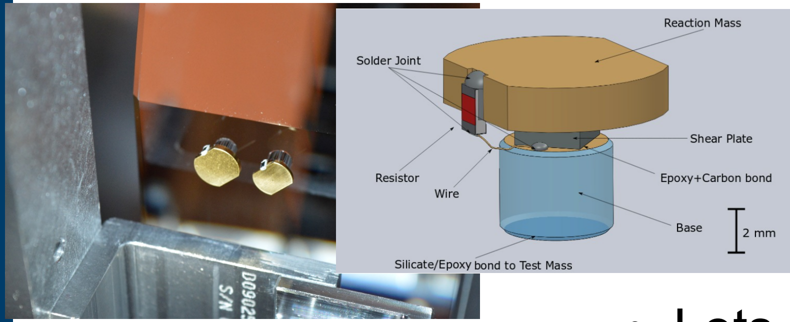


- Installation of a 70W laser amplifier at both LLO and LHO → delivering 50W to interferometer.



- Replace End Reaction Masses by annular version

Hope to reduce residual gas damping noise by a factor of 2.5 (an issue below 60Hz)



- Installing acoustic mode dampers to the test masses.

Mitigate parametric instabilities at high power

- Lots of new baffles installed to absorb scattered light.

from Brian O'Reilly and Alessio Rocchi, G1800395

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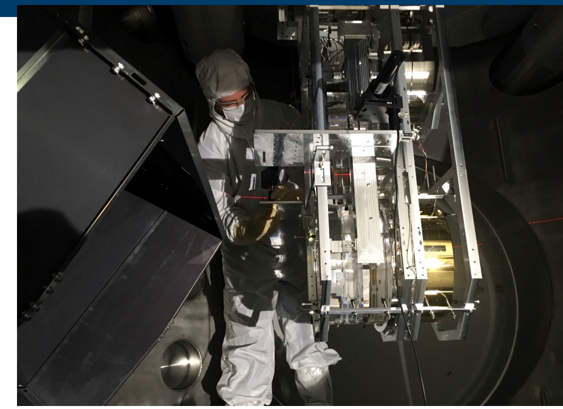
Main aLIGO upgrades



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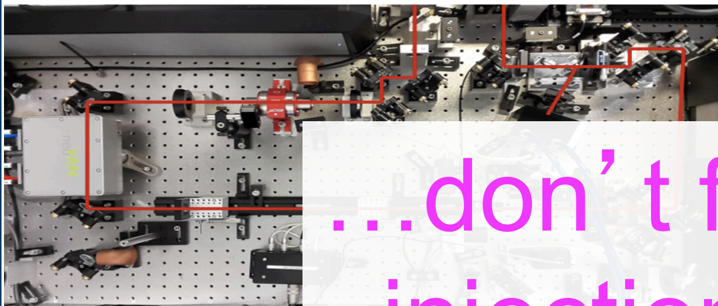
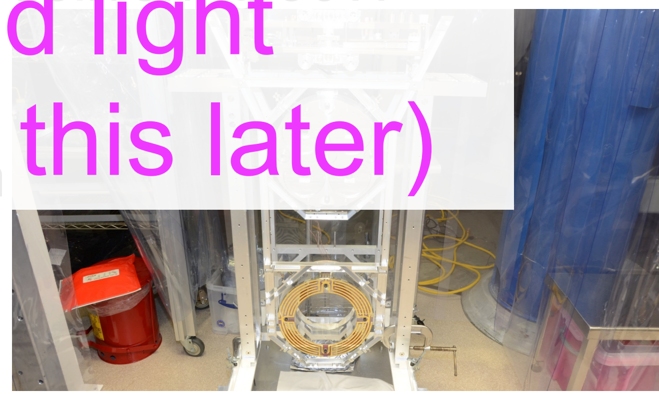
Affected ability of H1 to operate at higher power.

- Also replace ETMs at both detectors.



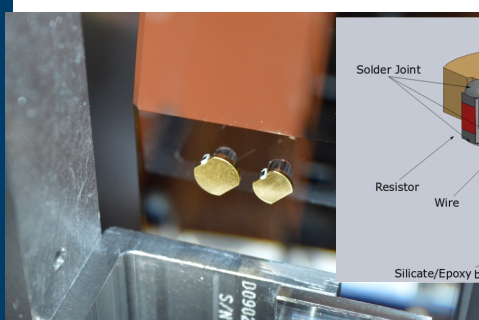
- Installation of a 70W laser amplifier at both LLO and LHO → delivering 50W to interferometer.

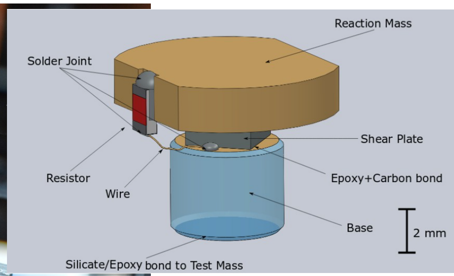
…don't forget squeezed light injection! (more about this later)



- Replace End Reaction Masses by annular version

Hope to reduce residual gas damping noise by a factor of 2.5 (an issue below 60Hz)





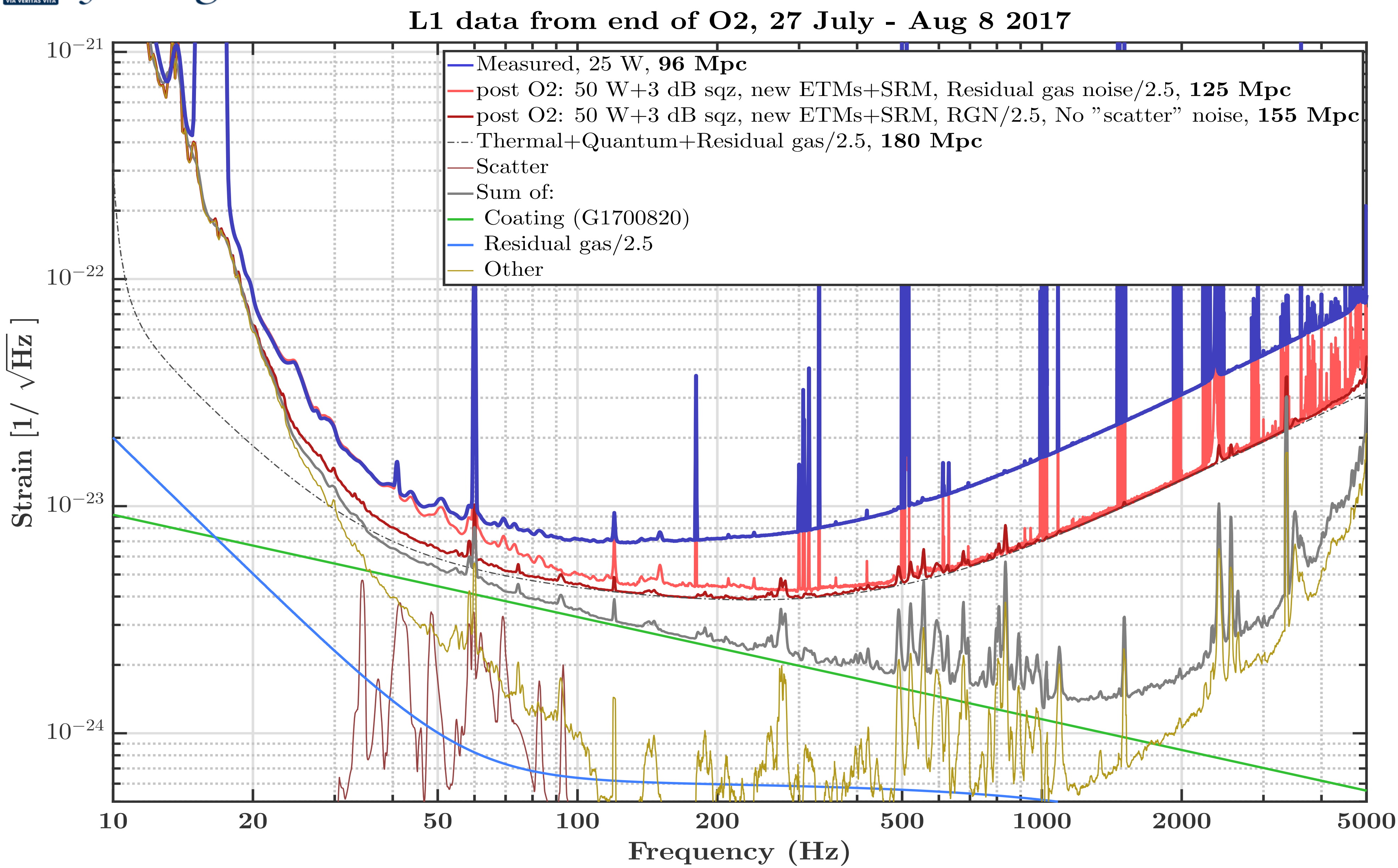
- Installing acoustic mode dampers to the test masses.

Mitigate parametric instabilities at high power

- Lots of new baffles installed to absorb scattered light.

from Brian O'Reilly and Alessio Rocchi, G1800395

Possible aLIGO noise projection after upgrades



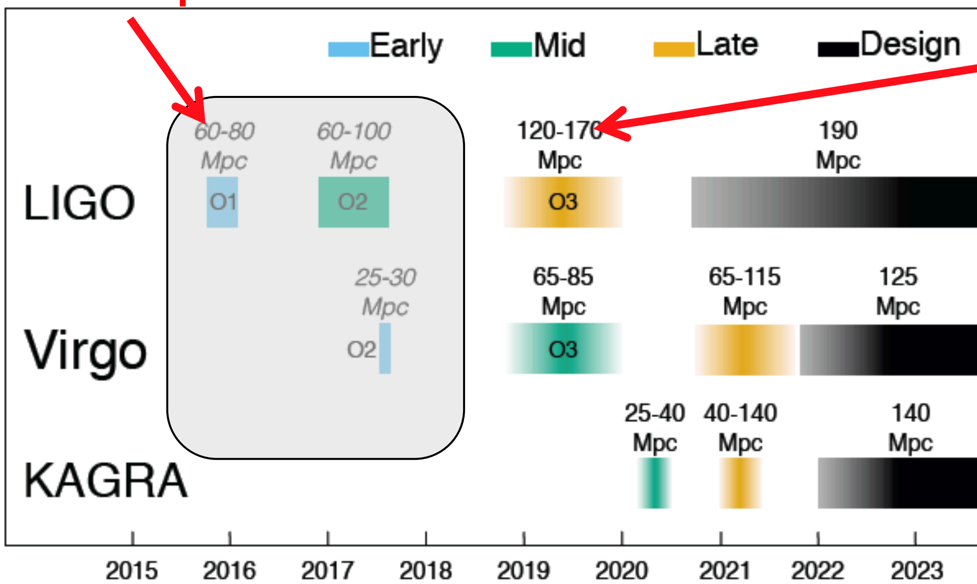
from Brian O'Reilly and Alessio Rocchi, G1800395

Sensitivity timeline and coalescent rates

Living Rev Relativ (2016) 19: 1

Prospects for Observing and Localizing GW Transients with aLIGO, AdV and KAGRA 7

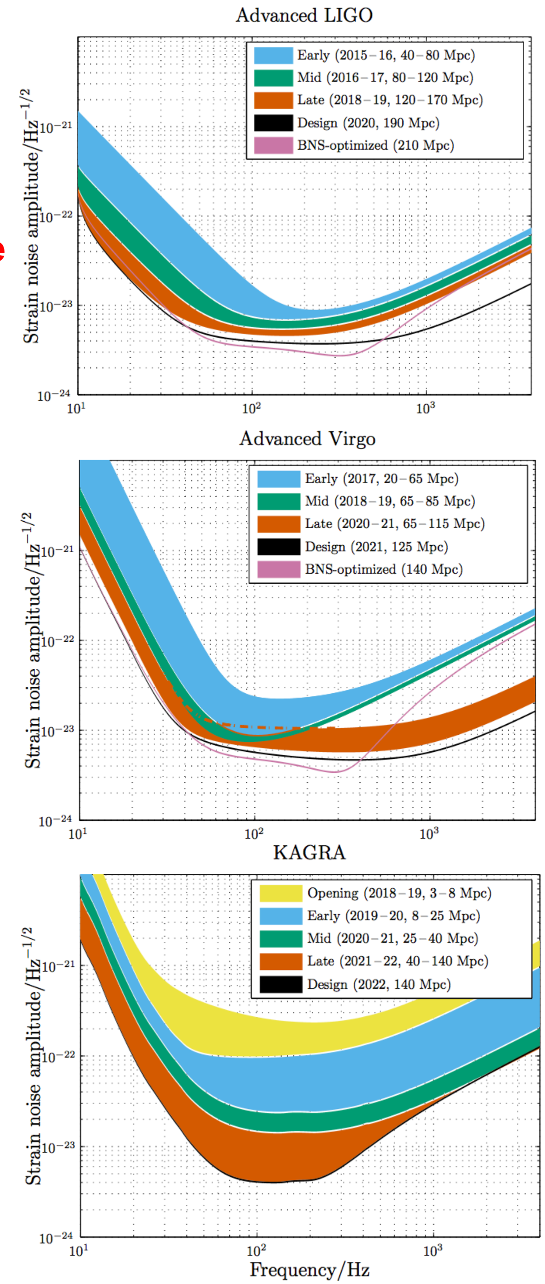
O1 data is public



O3: GW candidates with high confidence public to full astronomical community.

Numbers are BNS range sensitivity

	LIGO		Virgo		KAGRA	
	BNS range/Mpc	BBH range/Mpc	BNS range/Mpc	BBH range/Mpc	BNS range/Mpc	BBH range/Mpc
Early	40 – 80	415 – 775	20 – 65	220 – 615	8 – 25	80 – 250
Mid	80 – 120	775 – 1110	65 – 85	615 – 790	25 – 40	250 – 405
Late	120 – 170	1110 – 1490	65 – 115	610 – 1030	40 – 140	405 – 1270
Design	190	1640	125	1130	140	1270



Coalescent rates based on observations:

- BNS: post-GW170817 (O1 as prior): R_{BNS}=0.3 – 4.5 $Mpc^{-3}Myr^{-1}$
- BBH: post-GW170104: R_{BBH}=0.01-0.2 $Mpc^{-3}Myr^{-1}$

Sensitivity timeline and coalescent rates

Living Rev Relativ (2016) 19: 1

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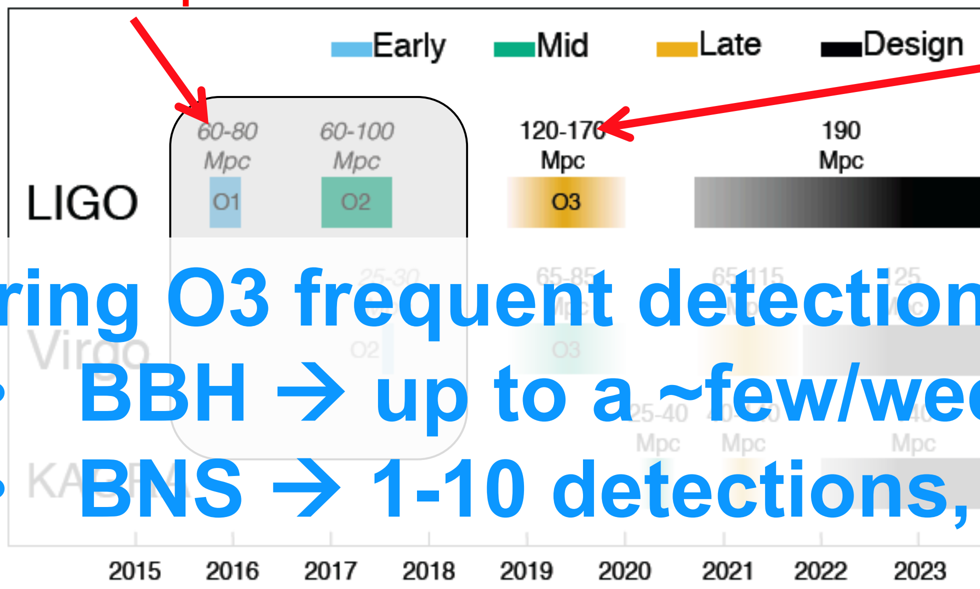
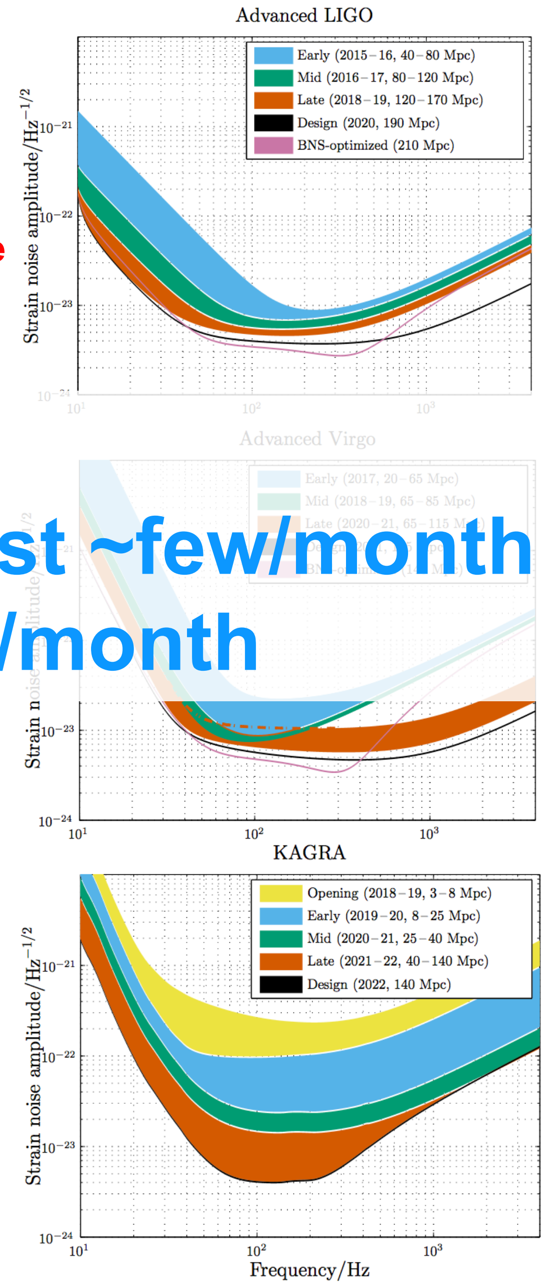


O3: GW candidates with high confidence public to full astronomical community.

Numbers are BNS range sensitivity

During O3 frequent detections:

- BBH → up to a ~few/week, at least ~few/month
- BNS → 1-10 detections, up to ~1/month



	LIGO		Virgo		KAGRA	
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Early	40 – 80	415 – 775	20 – 65	220 – 615	8 – 25	80 – 250
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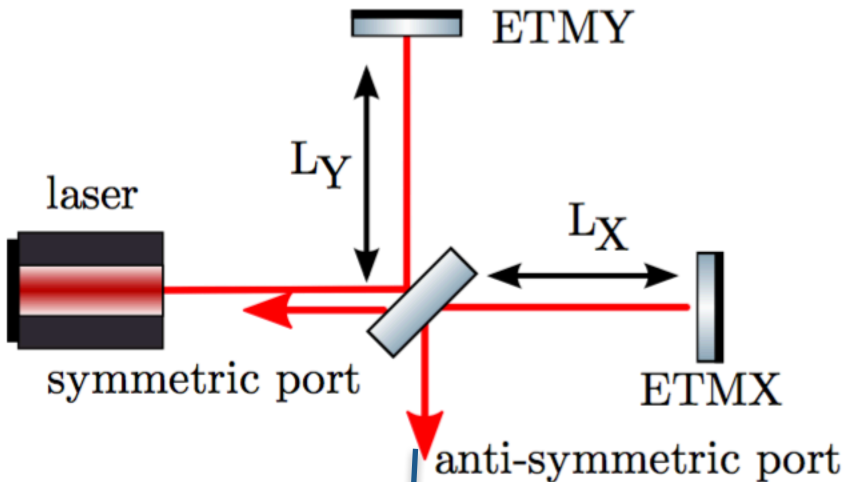
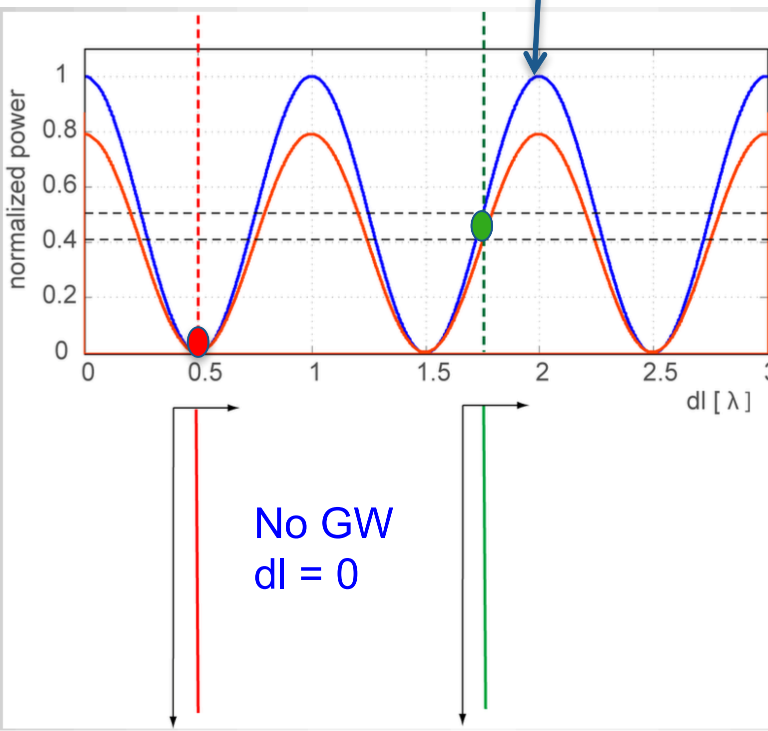
University of Glasgow

Gravitational wave detectors

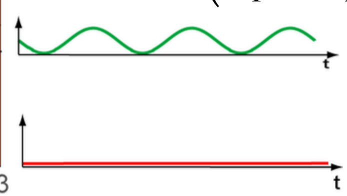
Operation of a Michelson interferometer





$$\frac{P_D}{P_0} = \frac{1}{2}\left[1+\cos\left(\frac{2\pi}{\lambda}dL\right)\right]$$

$$dL = 2\left(L_Y - L_X\right)$$

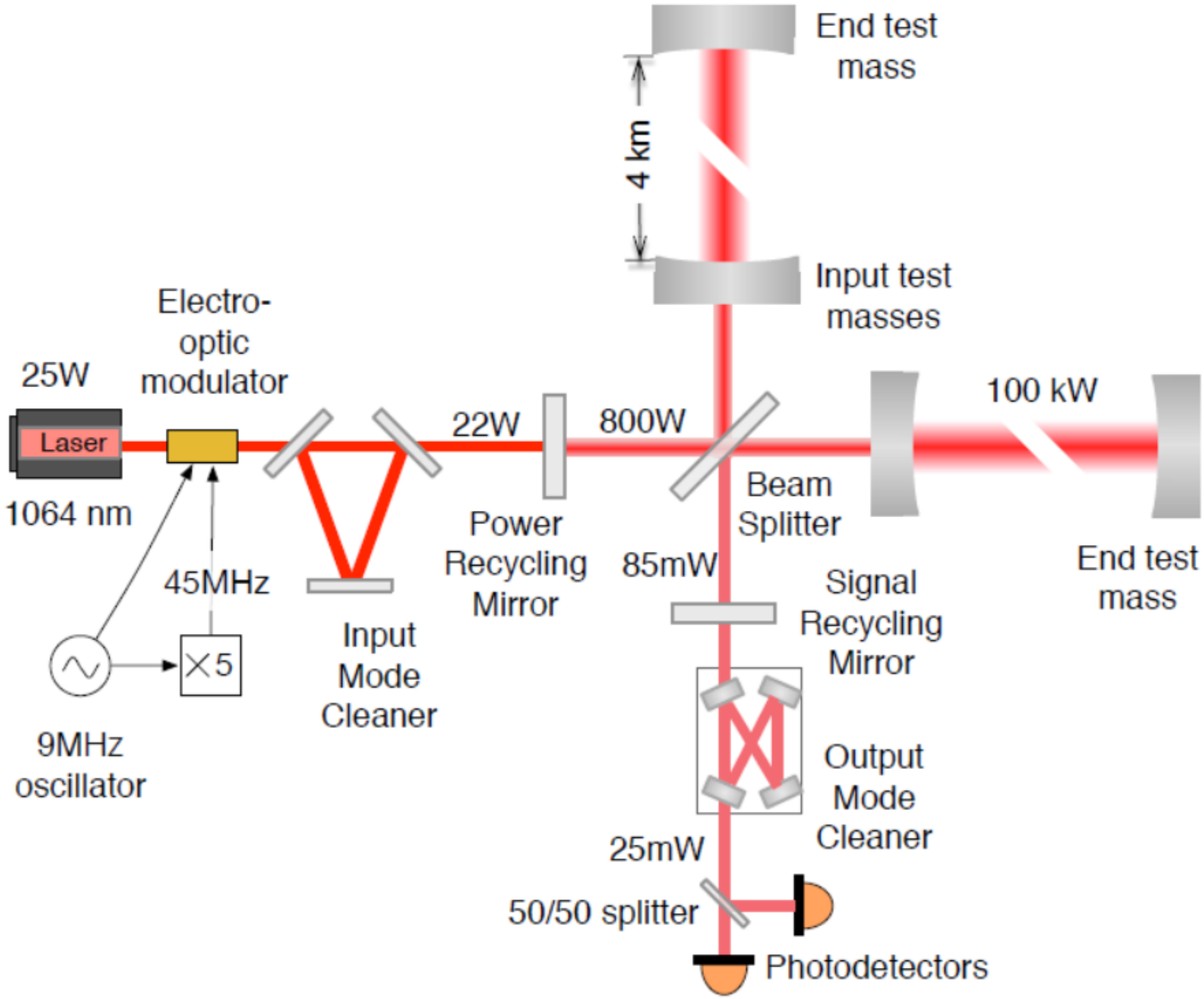


With operation point (green dot): We see power changes in output due to fluctuations of circulating power.

Not the case with OP (red dot)

- Signal on PD proportional to:
  - P_0 laser power
  - dl α h × L
  - 1/λ
- We want: longer arms, high circulating power and small λ.
- Operation point on dark fringe (red dot) → light back to laser → can be recycled

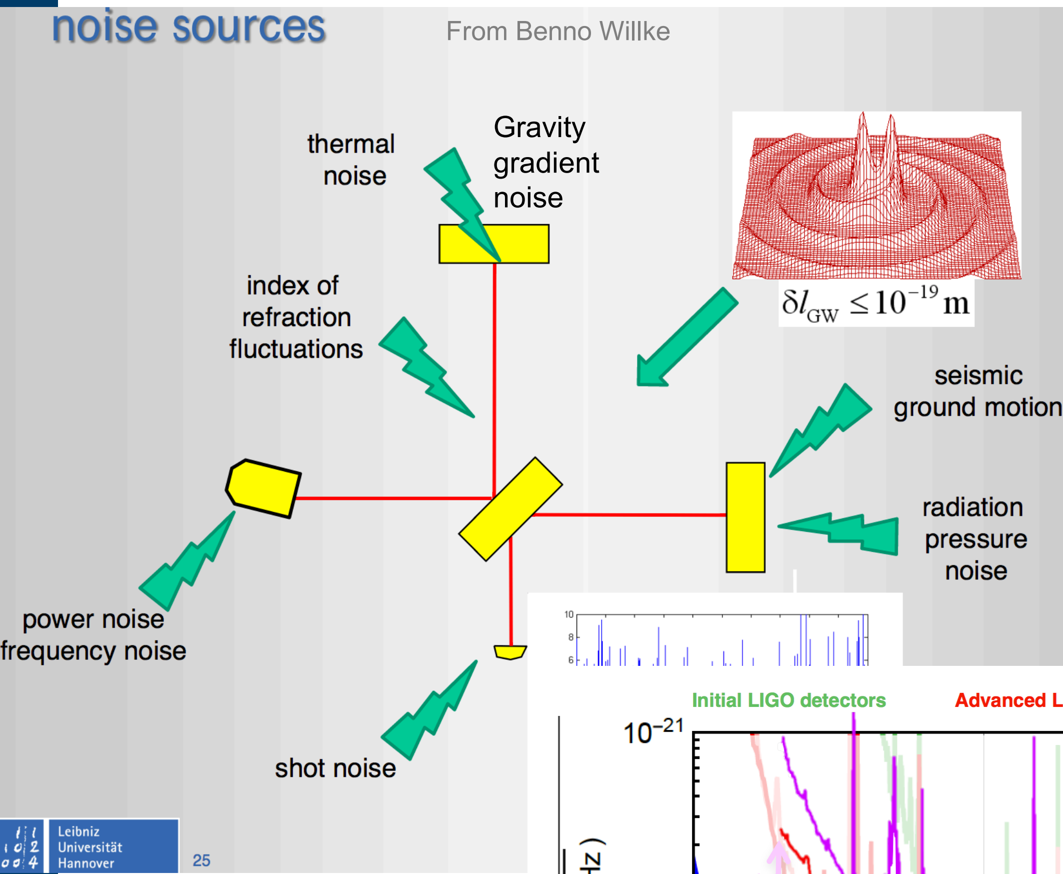
GW detectors are more complex

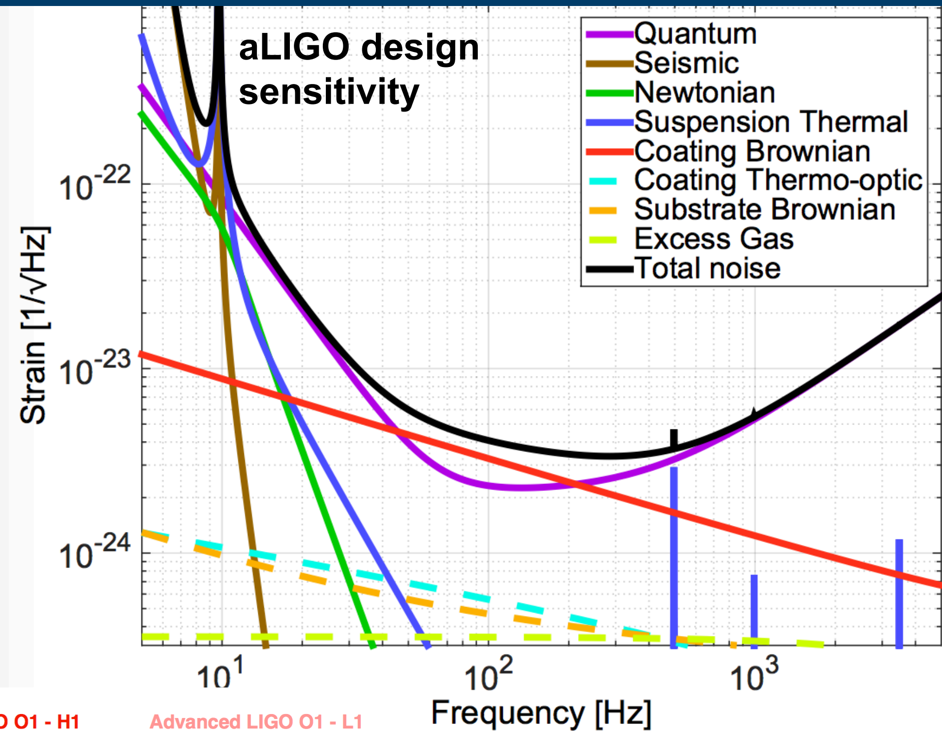


- Optical cavities on the arms to increase the circulating power and the effective arm length.
- PRM = Recycles the light coming back to laser (OP dark fringe)
- SRM = Recycles the GW signal back to the interferometer. It allows adjustment of the maximum sensitivity band.

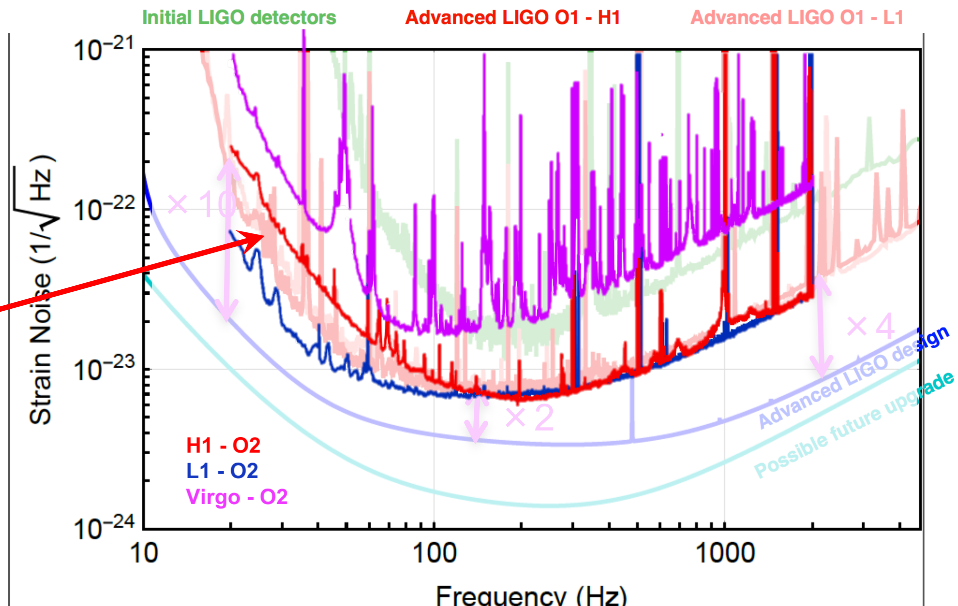
From Steve Detweiler

Fundamental noises on GW detectors





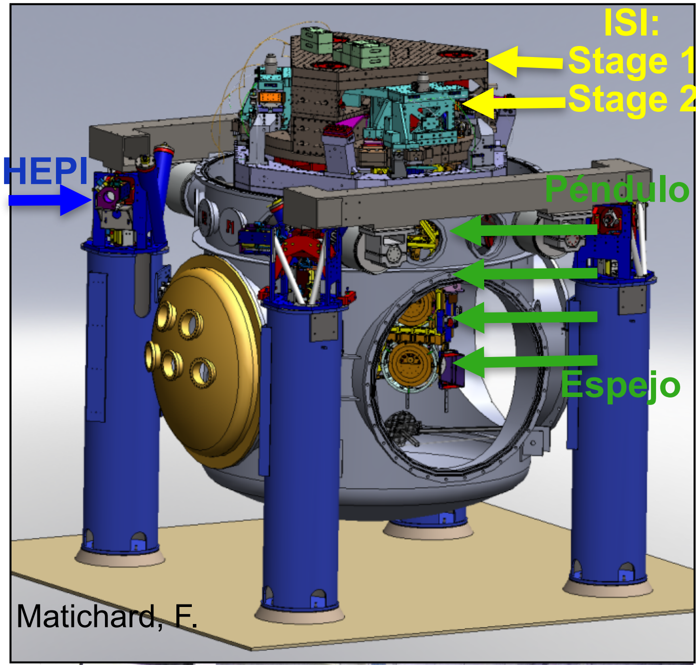
‘Technical’ noise, worsen during pre O2 commissioning at LHO

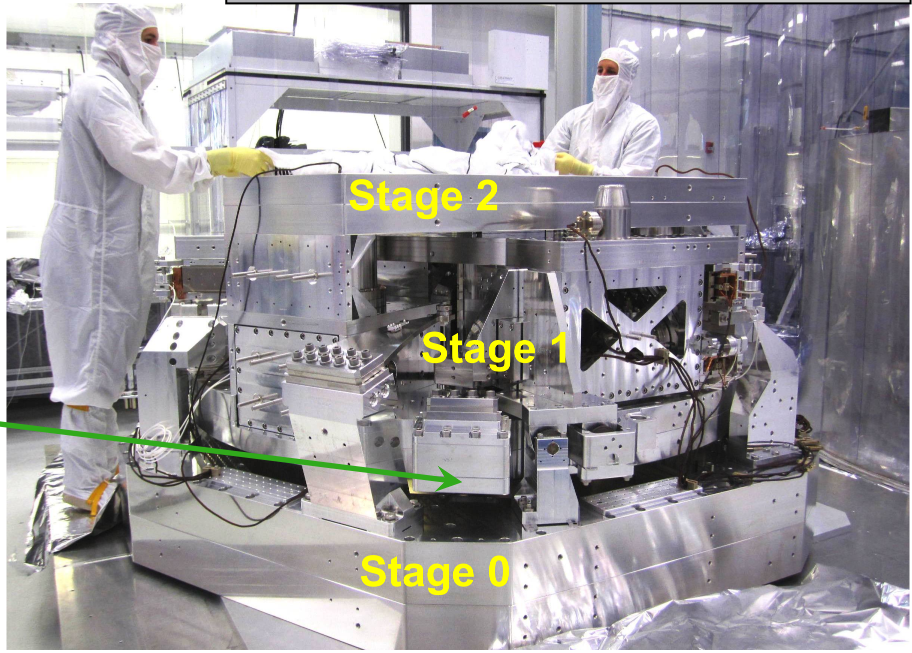


Seismic noise – active

- 7 stages seismic isolation of test masses :
  - 3 active stages (HEPI y ISI)
  - 4 passive stages as a pendulum with the test masses on the bottom stage.
- 3 active stages with 6 degrees of freedom each:
  - Hydraulic external Pre-isolation (HEPI).
  - 2 internal stages (ISI).
- Active stages isolate the suspension pendulum through many sensors of position, acceleration and velocity on all degrees of freedom.

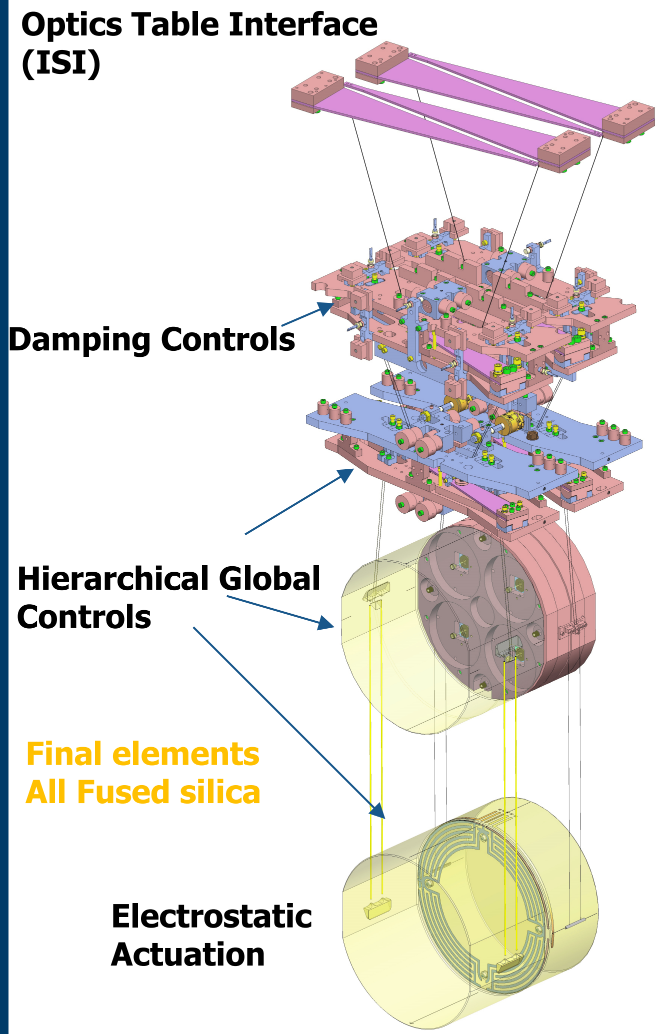
  The top stage of the pendulum is attached to the bottom plate of the ISI 2nd stage.



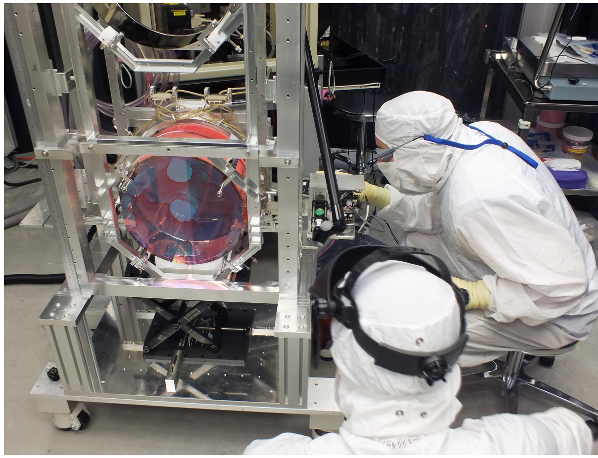


Seismic noise – passive

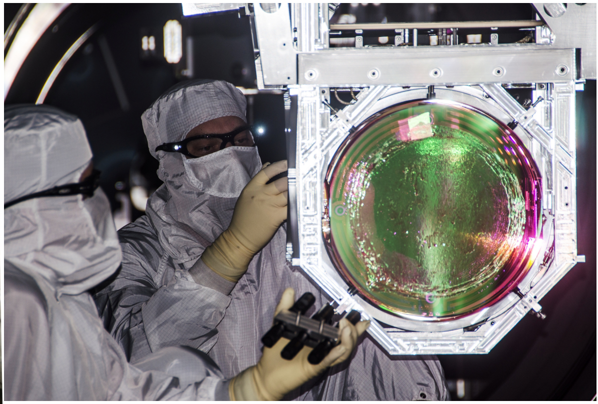
- Test masses suspended on a 4 stage pendulum:



Inspecting last stage of the pendulum suspension. Monolithic of fused silica.

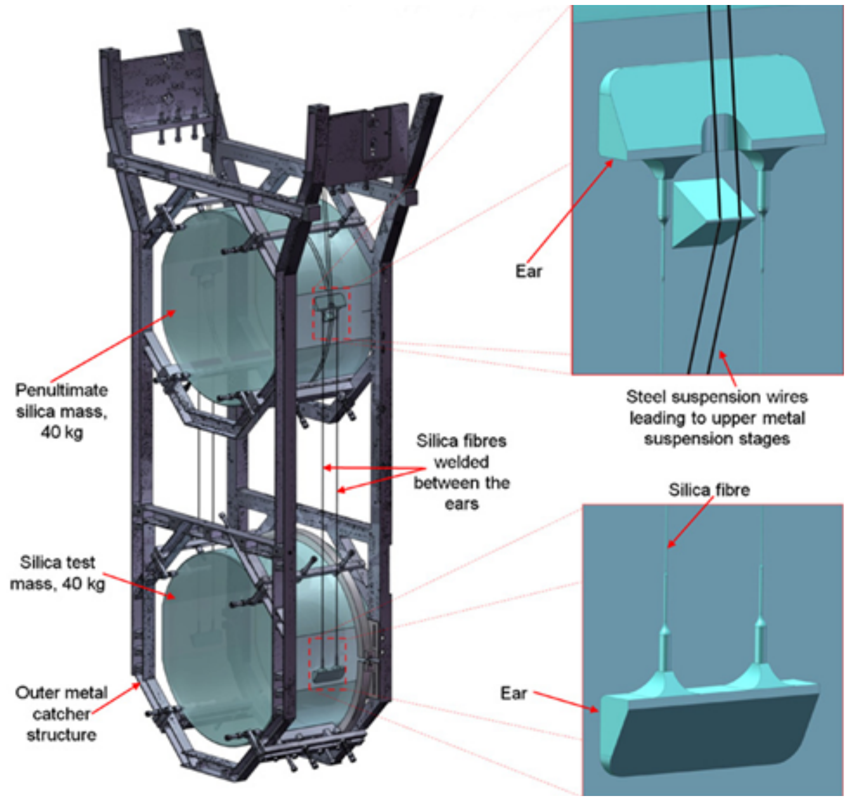


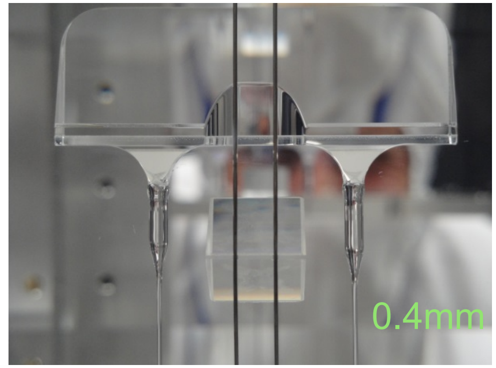
Welding silica fibres to test masses.



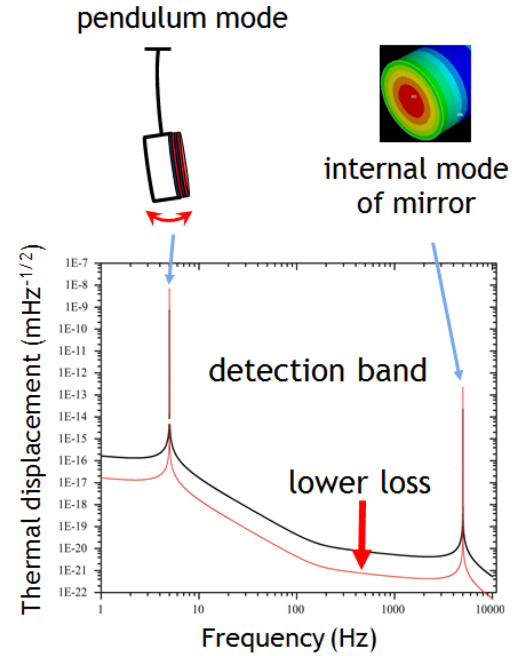
Inspecting reaction mass with the ESD. Protected with *First Contact*

Suspension thermal noise





Fused silica 'ears' joined to the sides of the test masses by a silicate joint (thickness of joint 60nm)



- The last stage of the suspension pendulum is monolithic → mirror test mass, upper mass and suspension fibres are all of fused silica.
- Fused silica has very low mechanical dissipation → Q = 10^9 (vacuum) → pendulum oscillations would take 17 years to attenuate, violin modes → 7 days.
- Concentrate thermal energy at resonances

- Thermal noise (Brownian motion) on the metallic wires and the fused silica fibres cause movement on the test masses.

Quantum noise

- Heisenberg uncertainty → Energy fluctuations of vacuum → $\Delta E \Delta t \geq \frac{\hbar}{2}$
- Distributed over amplitude and phase quadratures of EM field:

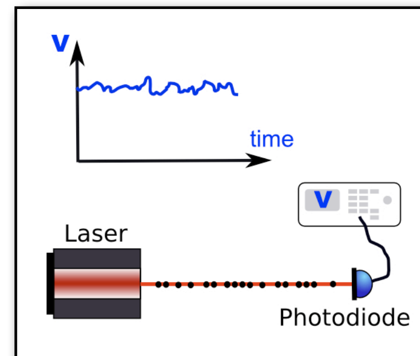
$$\Delta E = \Delta n \hbar \omega \qquad \Delta t = \frac{\phi}{\omega} \;\Rightarrow\; \Delta n \Delta \phi = \frac{1}{2} \;\Rightarrow\; \Delta n = \sqrt{N} \qquad \Delta \phi = \frac{1}{2\sqrt{N}}$$

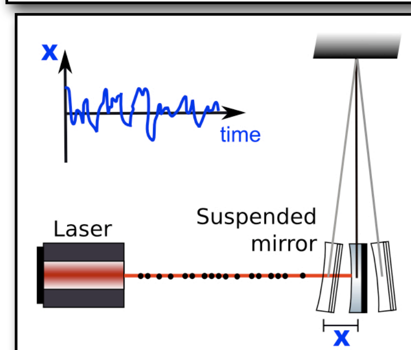
Photons follow Poisson stats

- Fluctuations enters interferometer's dark port, adds to arms' light and reach PD combining with GW signal field.

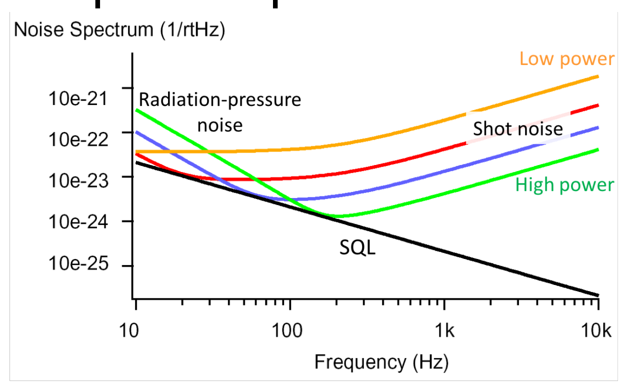
Quantum noise two forms:

- **shot noise**, intensity noise on PD current (photon count fluctuations)→limits precision arm displacement→Δt→Δϕ $\propto \frac{1}{\sqrt{P}}$
- **radiation pressure noise**, fluctuations of arms' light power→fluctuating radiation pressure moves mirrors → amplitude fluctuation Δn coupled to phase quadrature. $\propto \frac{\sqrt{P}}{m}$





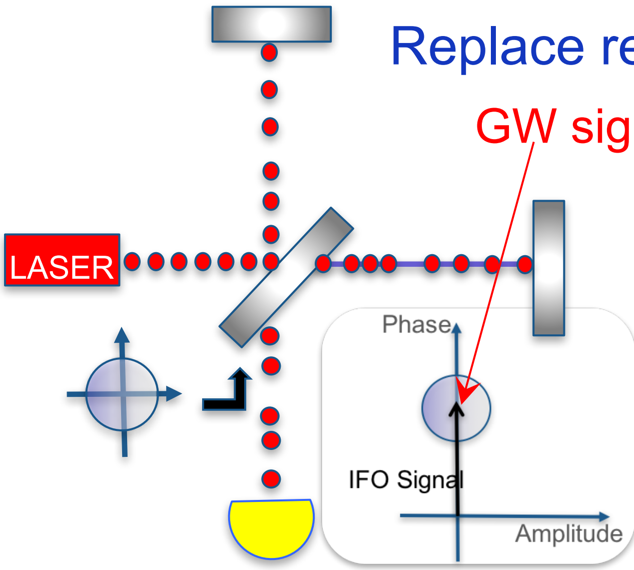
- Trade-off is called SQL



Quantum noise reduction – Squeezed light

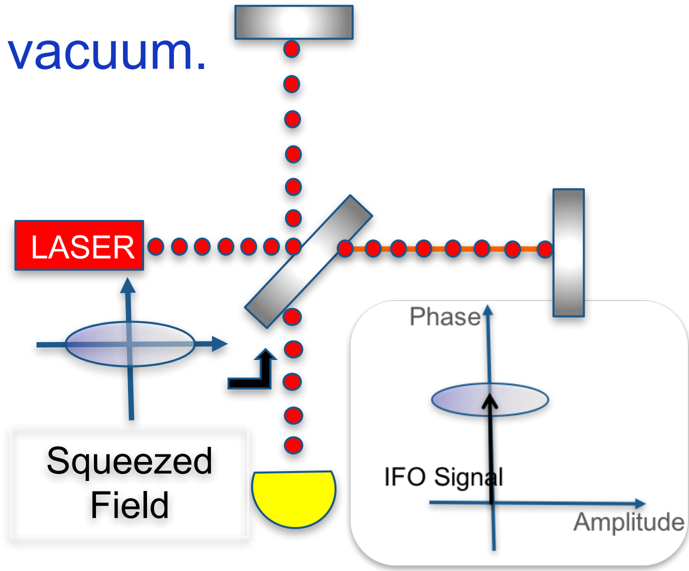
Replace regular vacuum with squeezed vacuum.

GW signal shows on Phase quadrature.

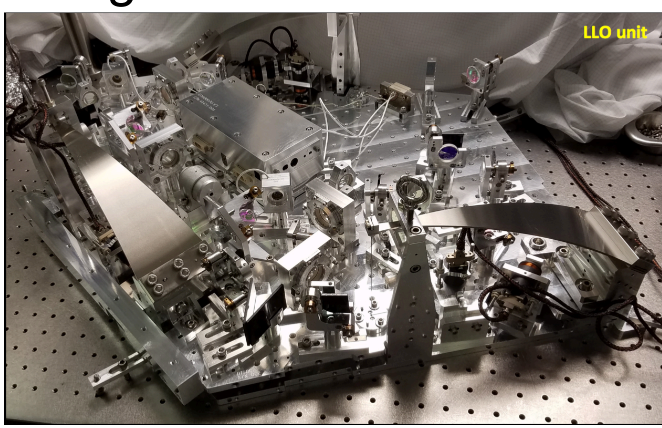


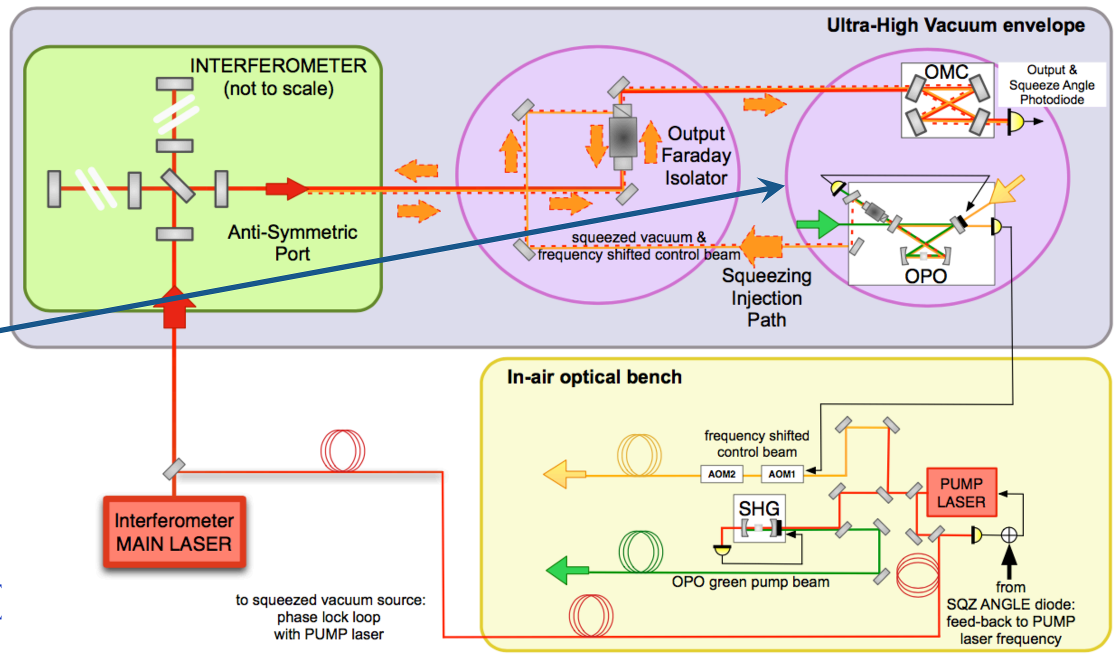
HUP → uncertainty area fixed →reducing uncertainty in one quadrature increases the other.

Squeezed phase quadrature reduces shot noise but increases rad. pressure noise due to increased amp. quadrat.



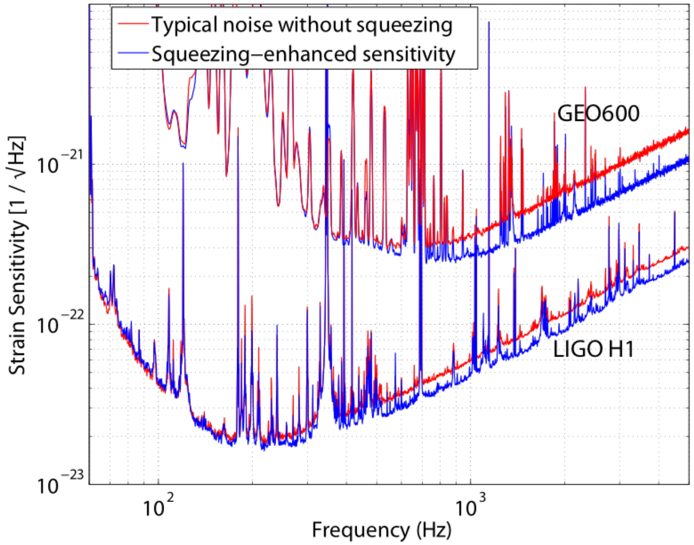
- Done using non-linear crystals acting as OPOs.





diagrams from Lisa Barsotti (G1800598 G1602253)

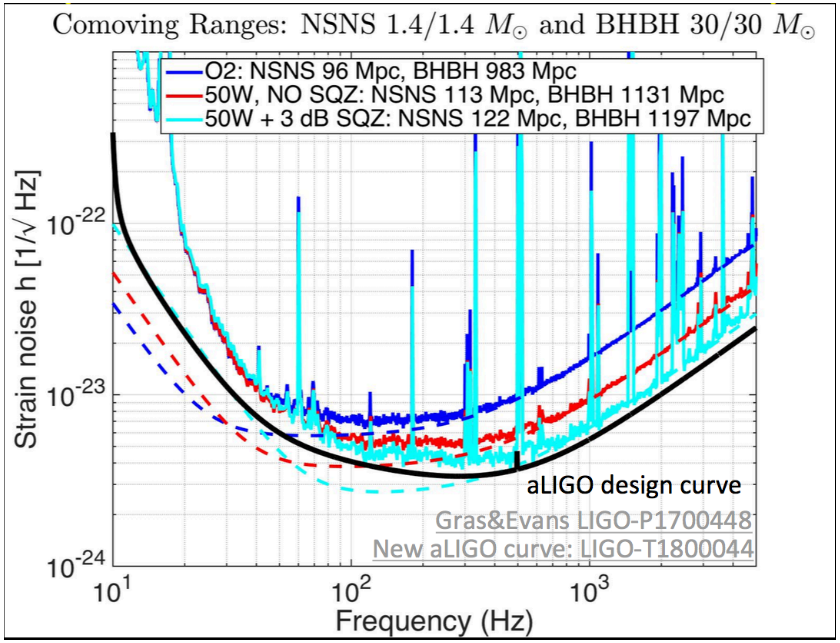
Squeezed light on detectors – and aLIGO O3



Nature Physics 7, 62–965 (2011), Nature Photonics 7, 613–619 (2013)

- GEO600 has used squeezed light since 2009
- eLIGO demonstrated it in 2011 (pre-aLIGO)
- Squeezed light not part of original aLIGO design.
- Progress on squeezed light technology motivated built of 2 squeezers and installation is ongoing ready for O3.

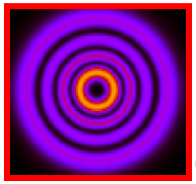
- Targeting 3dB squeezing for O3 (40% shot-noise reduction) → **Equivalent to doubling the laser power!**



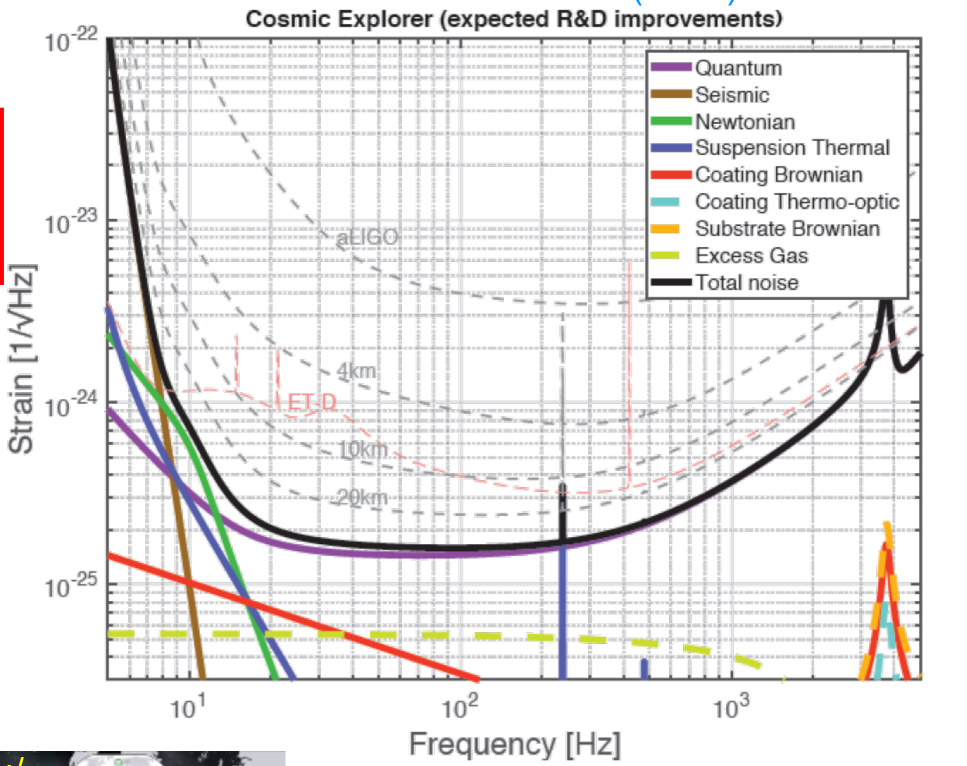
plots from Lisa Barsotti (G1800598)

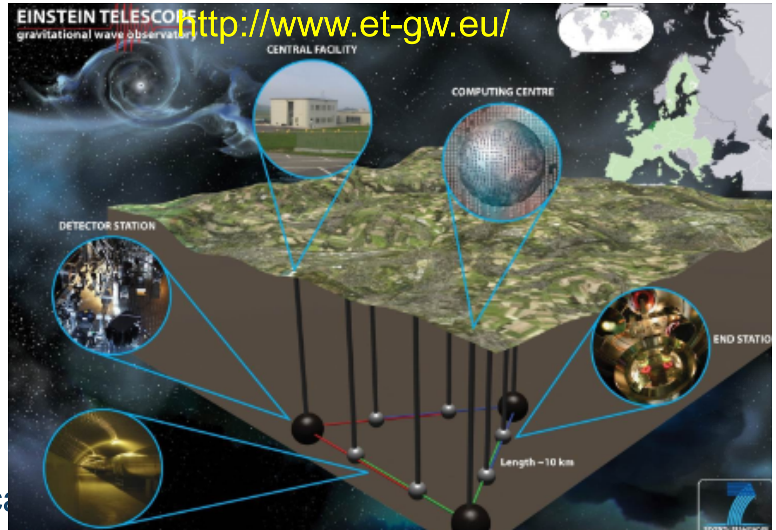
3rd generation of detectors – increase sensitivity to reach further

- Bigger and heavier test masses.
- Longer test mass suspensions
- Cryogenics (cooling down test masses and their suspensions).
- Lower coating thermal noise with new materials and exotic beam profiles.
- Improve quantum noise in the whole frequency band: Frequency dependent 'Squeezing' → filter cavities.
- Even more powerful Lasers.
- Go underground.
- Longer arms (10-40 km)
- …

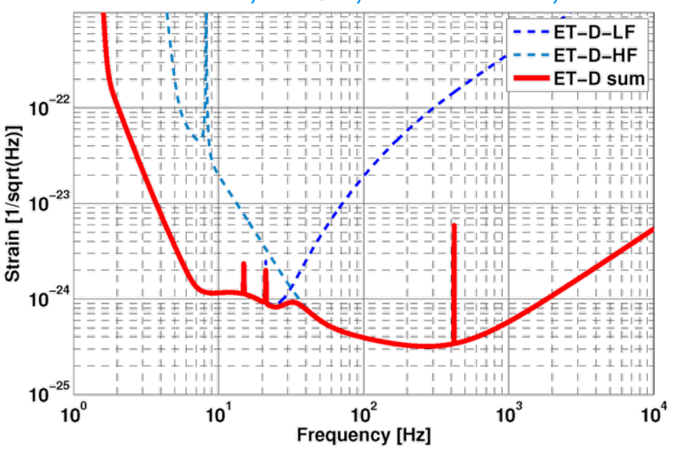


Class. Quantum Grav. 34 (2017) 044001





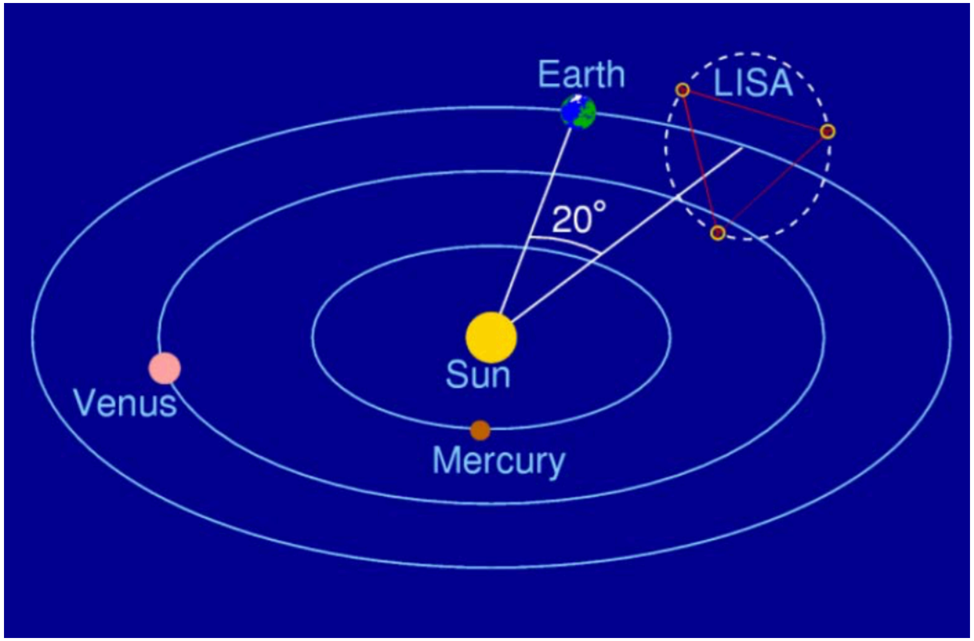
S.Hild et al., CQG, 28 094013, 2011

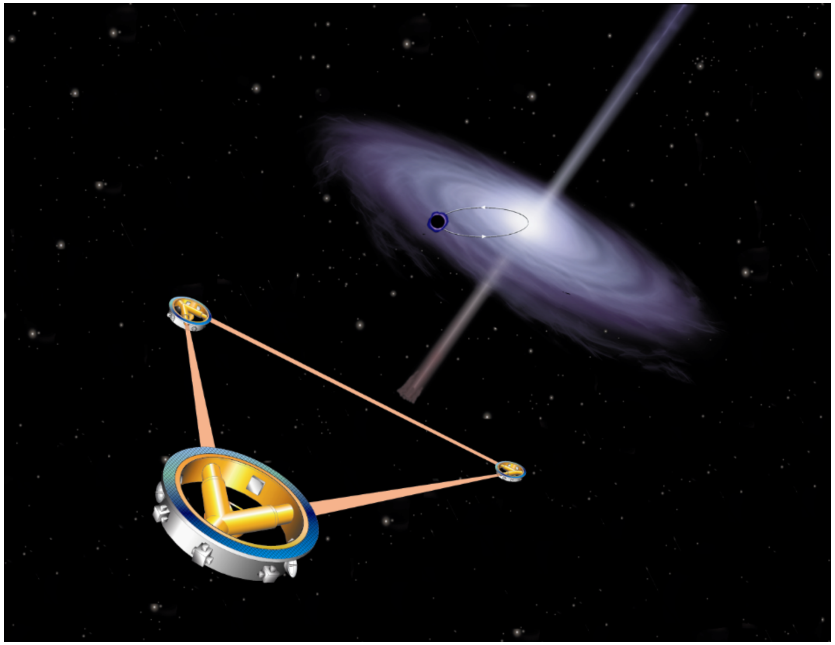


Future – Space → LISA

- 3 satellites separated 2.5 millon kms on a triangular formation.
- Following Earth on its orbit round the Sun.
- Laser interferometry to measure their relative distances.
- ESA approved mission on June 2017→Launch expected on 2034.

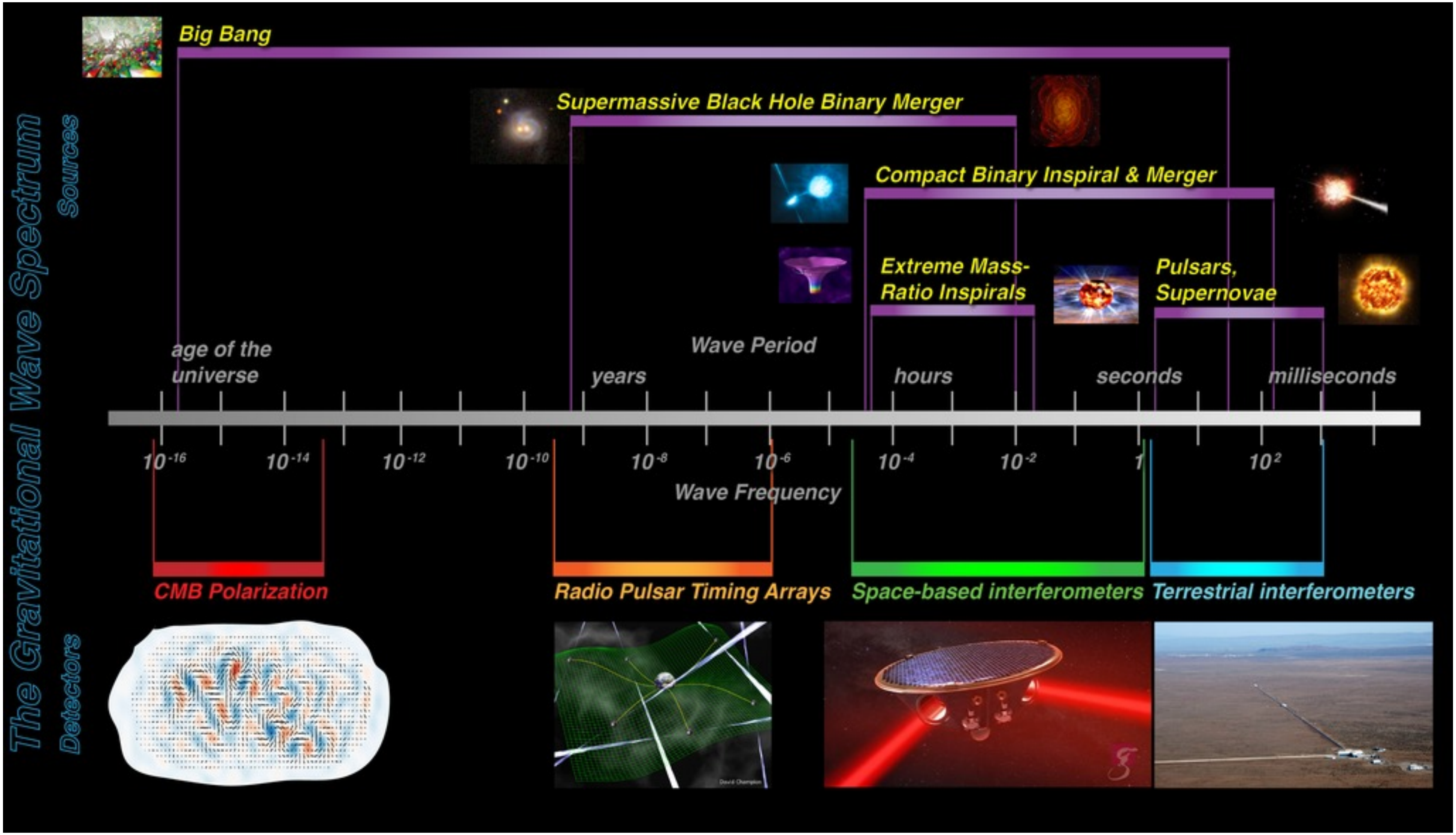
www.elisascience.org





From Steve Detweiler

GWs frequency spectrum



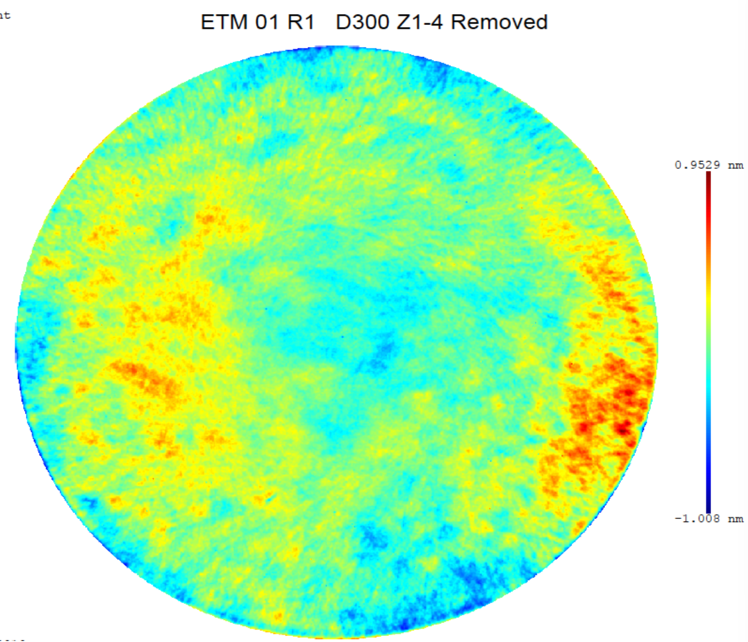
University of Glasgow

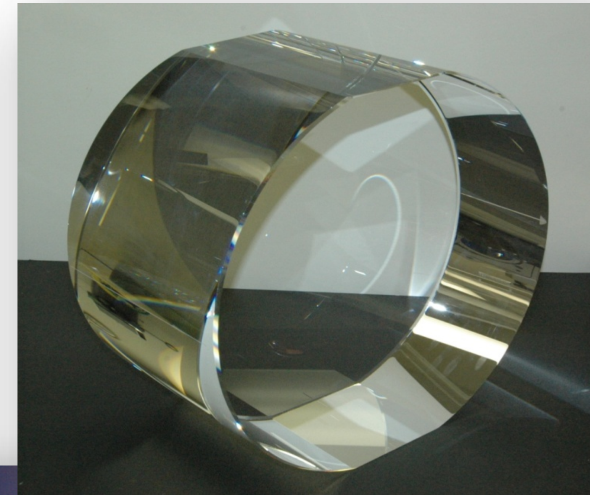
Thank you for your attention

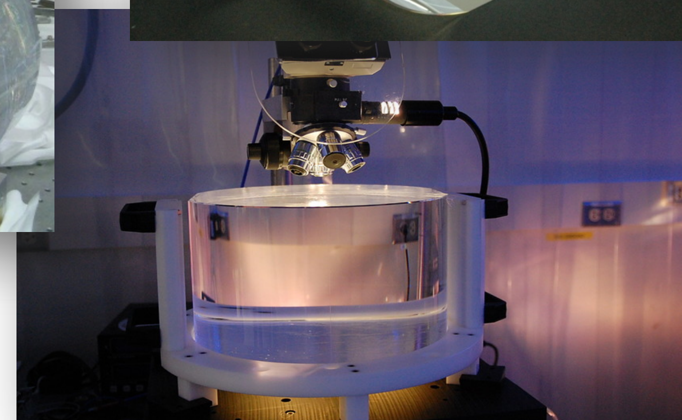
Questions?

Other slides

Coating thermal noise







- Test mass mirror coatings designed to have high very low mechanical dissipation, low absorption and very high reflectivity.
- Dimensions: diameter 35 cm, thickness 20 cm
- Weight: 40 kgs
- Absorption: coating< 0.5 ppm, substrate=4ppm
- Transmission: ETM<6ppm, ITM=1.4%
- Extreme flatness: 1nm rms over 30cm (equivalent to the highest mountain on Earth being 4cm)

- Brownian motion on the substrate and coating of the test masses.
- state of the art in substrates and polishing
- Pushes the art for coating

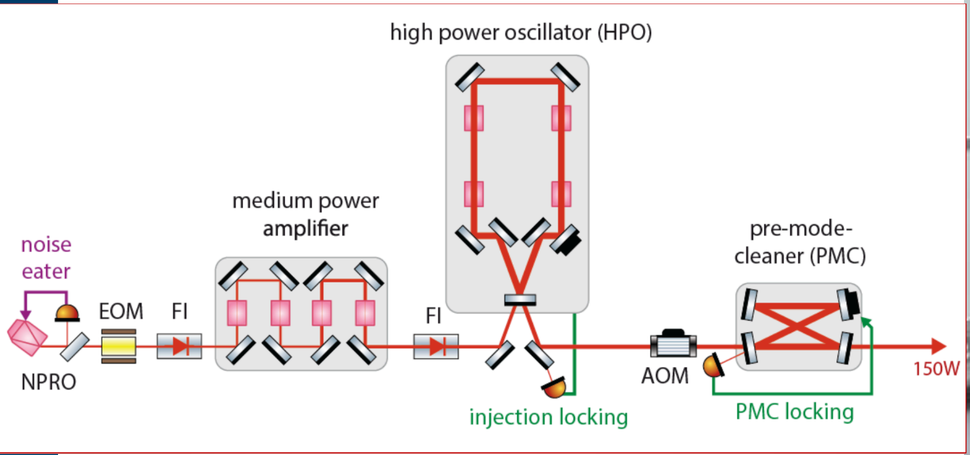
Interferometer arms- 4kms long vacuum tubes

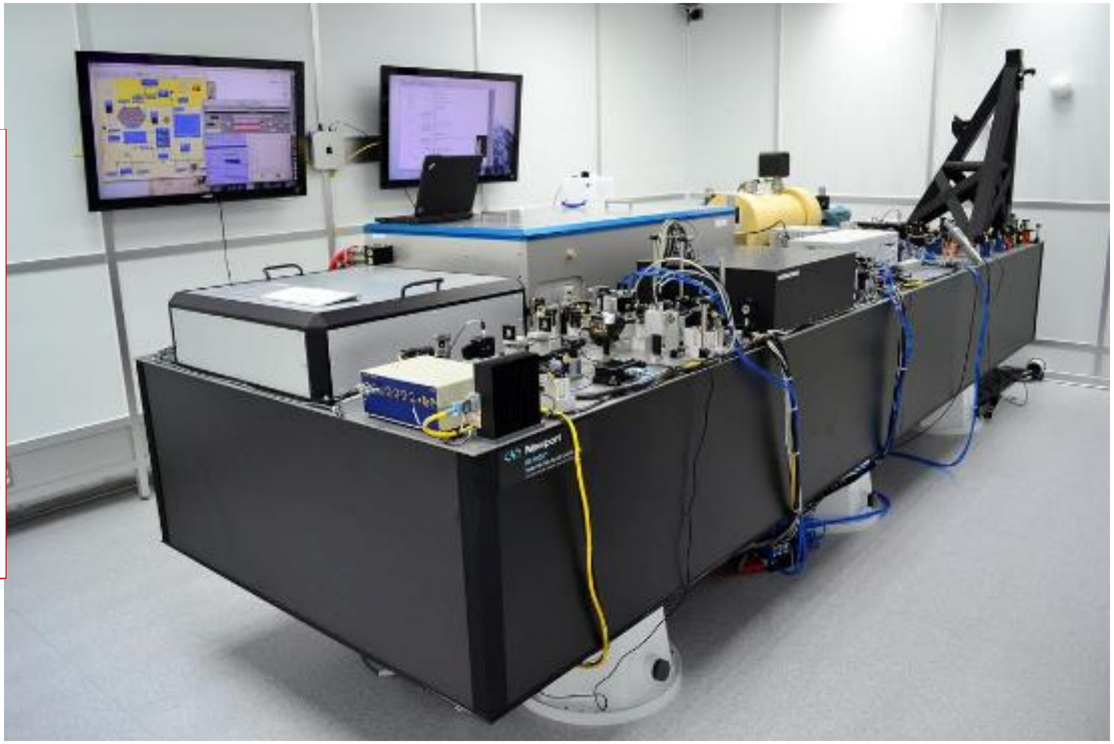
Concrete cover

- Path of the interf. arms
- Diameter: 1.2m
- Tube is divided in sections that were welded on portable clean rooms (in-situ).
- 50 kms of welds!
- Internal vacuum: 10^{-11}atm!
- Biggest volume of vacuum on Earth.
- This is needed to reduce:
  - Acoustic noise coupling
  - Rayleigh dispersion

From Steve Detweiler

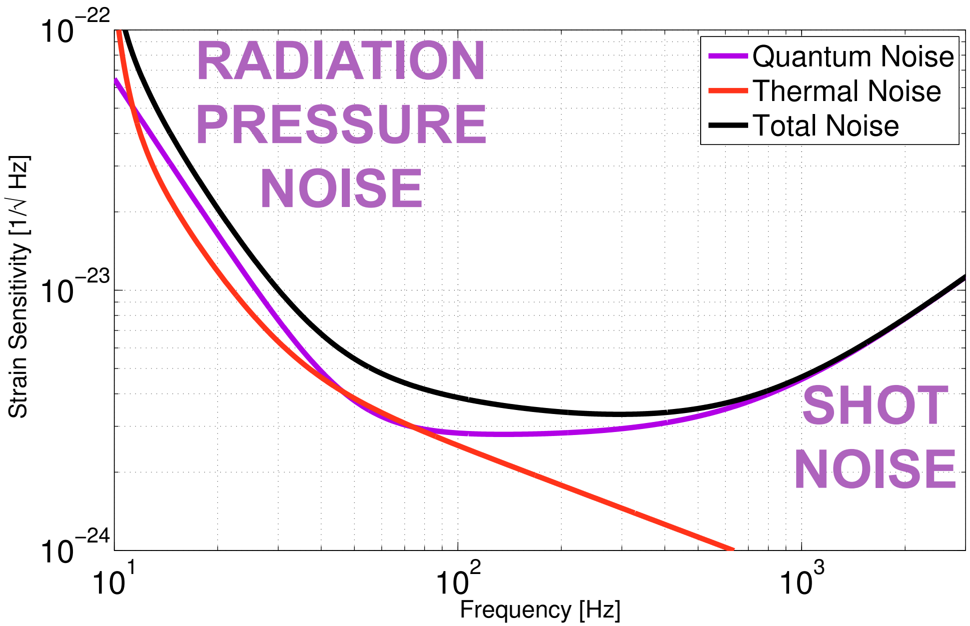
Laser aLIGO - 200 W Nd:YAG

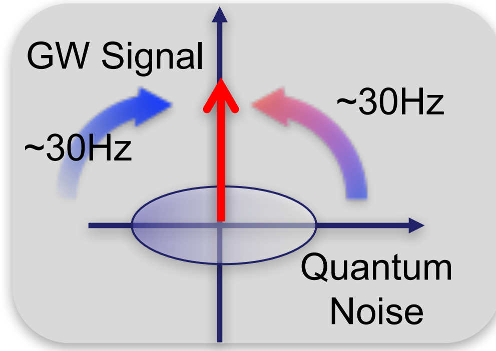


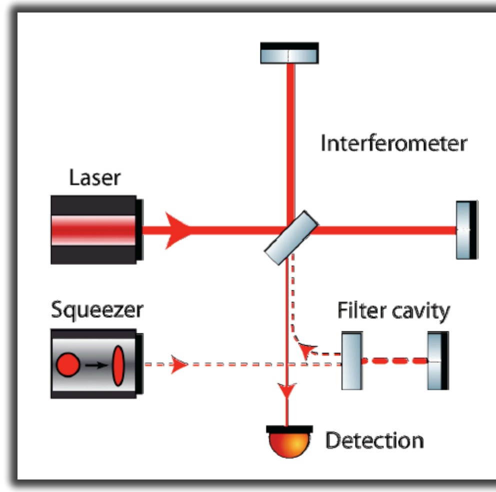


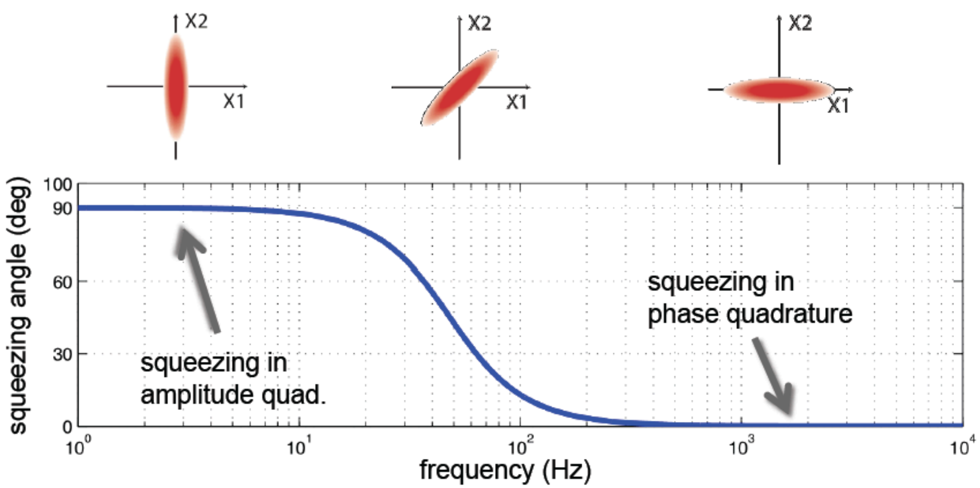
- λ = 1.064 μm (infrared)
- Stored on a clean box free from acoustic noise coupling and dust.
- Power and frequency stabilisation:
  - RIN < 10^{-8} [1/√Hz]
  - Relative frequency noise Δf/f < 10^{-17} [1/√Hz] (detection band)
  - HOM < 0.1% (relative intensity on higher order spatial modes)

Frequency dependent squeezing for aLIGO full sensitivity – improves both radiation pressure and shot noise







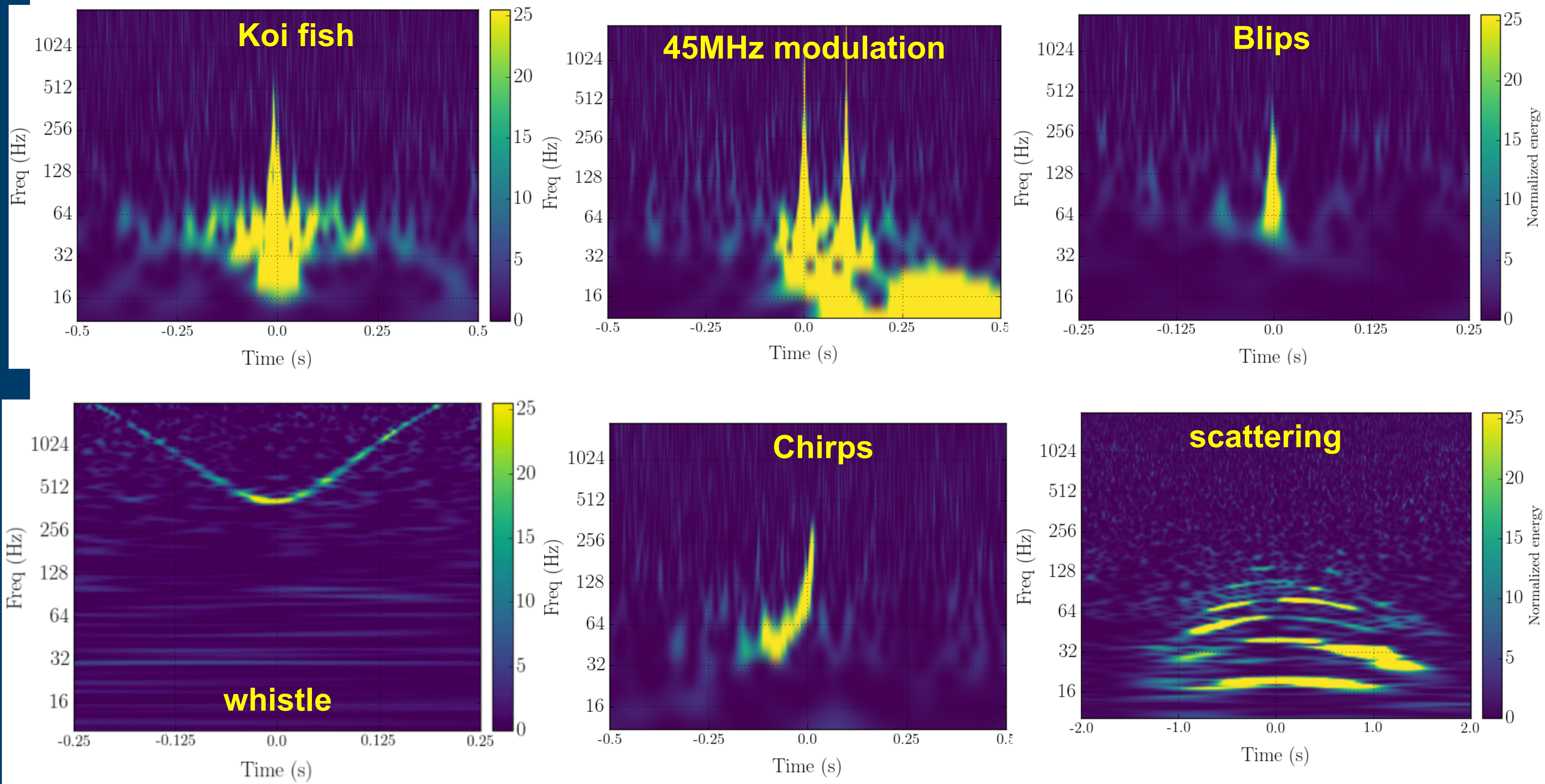


High finesse detuned **"filter cavity"** which rotates the squeezing angle as function of frequency

Kimble et al., Phys. Rev. D 65**(2) 022002** 2001

Glitch noise classification

- Classify transient noise of same time-freq characteristics may help to identify the source and correct the issue:



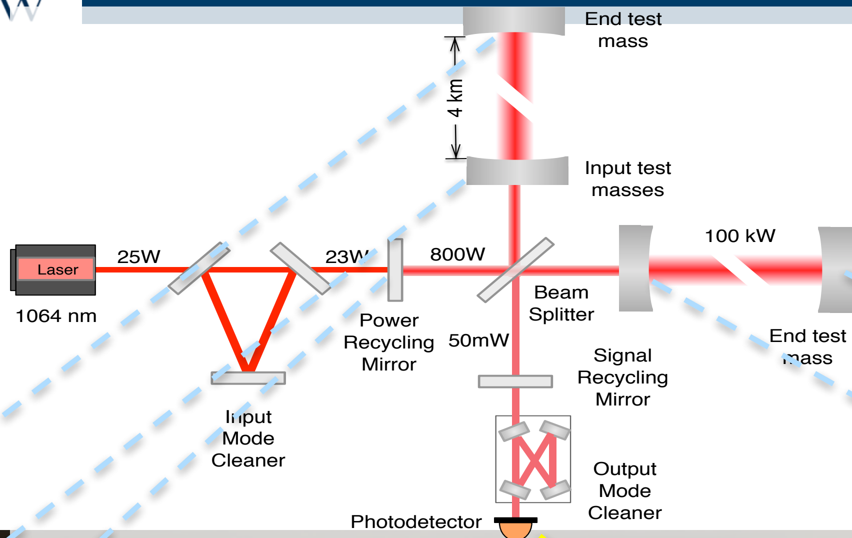
Search for GW signals – computational requirements

Atlas Computer Cluster (Hanover, Alemania)

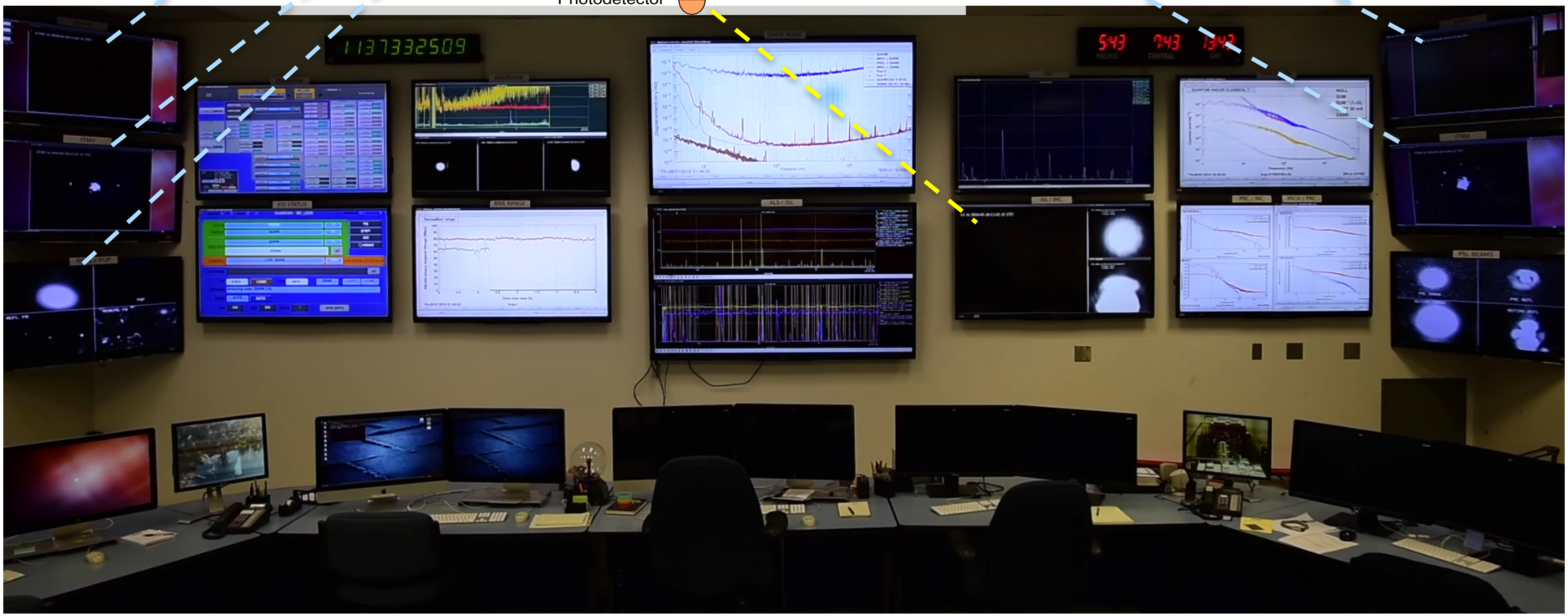
- GW data analysis requires computer cluster
- Atlas cluster (operated by the AEI) is the most powerful LSC cluster
  - 3330 compute nodes (each with at least 4 CPU cores)
  - 850 GPUs
  - 5 Petabyte hard disks (data storage + 4.5PB magnetic tape)
  - 400 TeraFLOP/s (computational power)

From Benno Willke

Lock acquisition in aLIGO

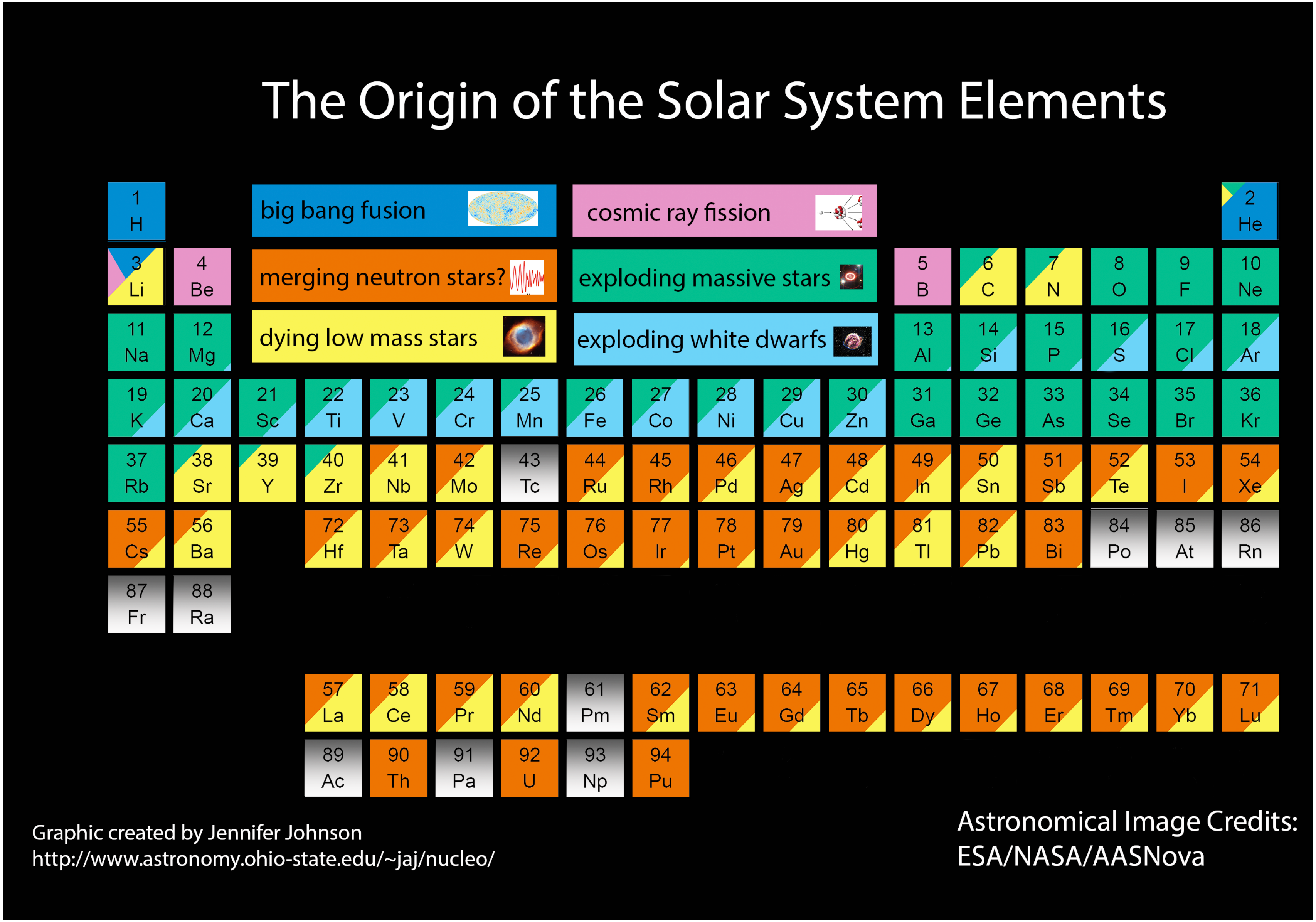


- Optical power aLIGO (**O1**).
- 8 less power than their capacity.

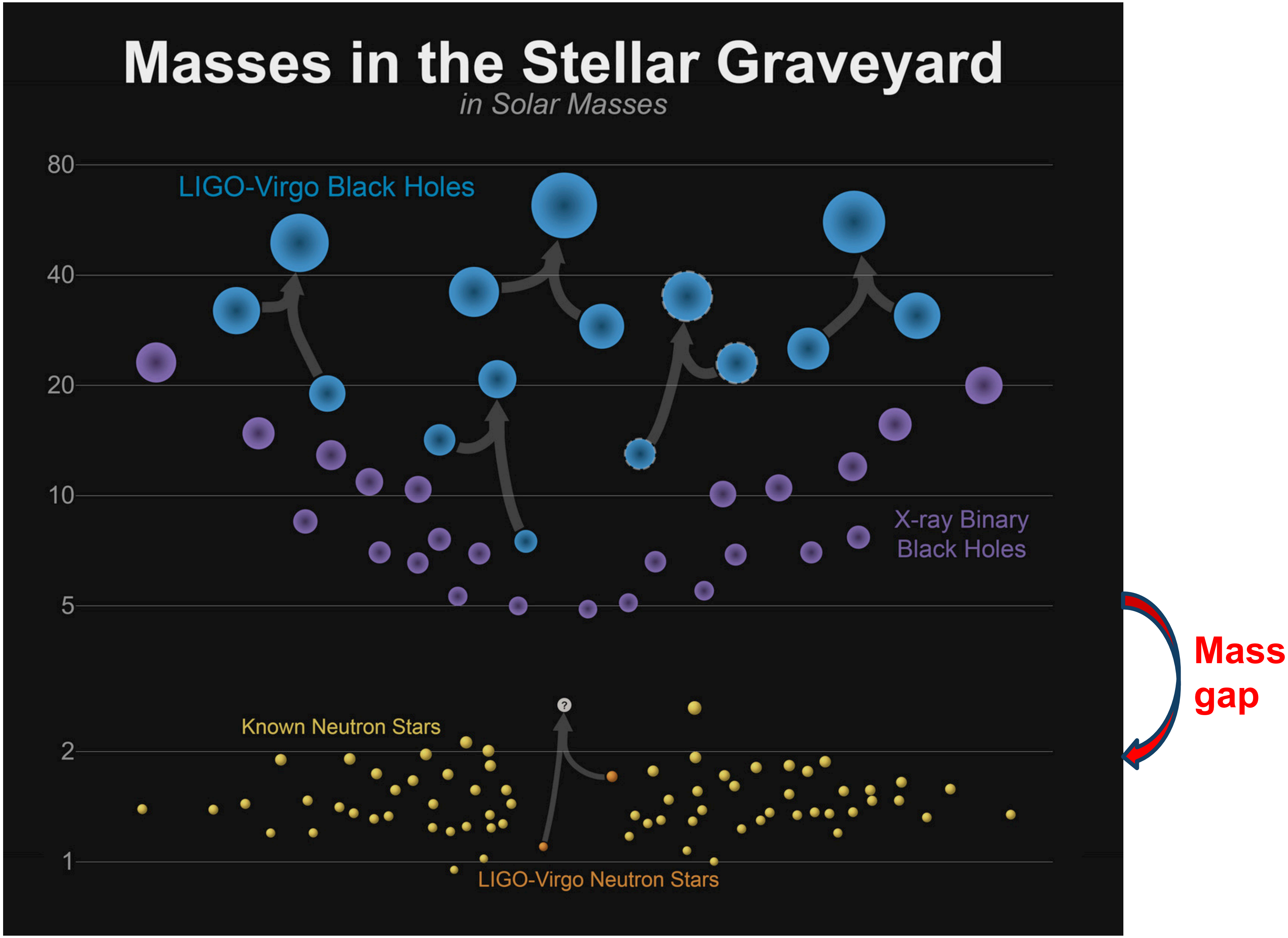


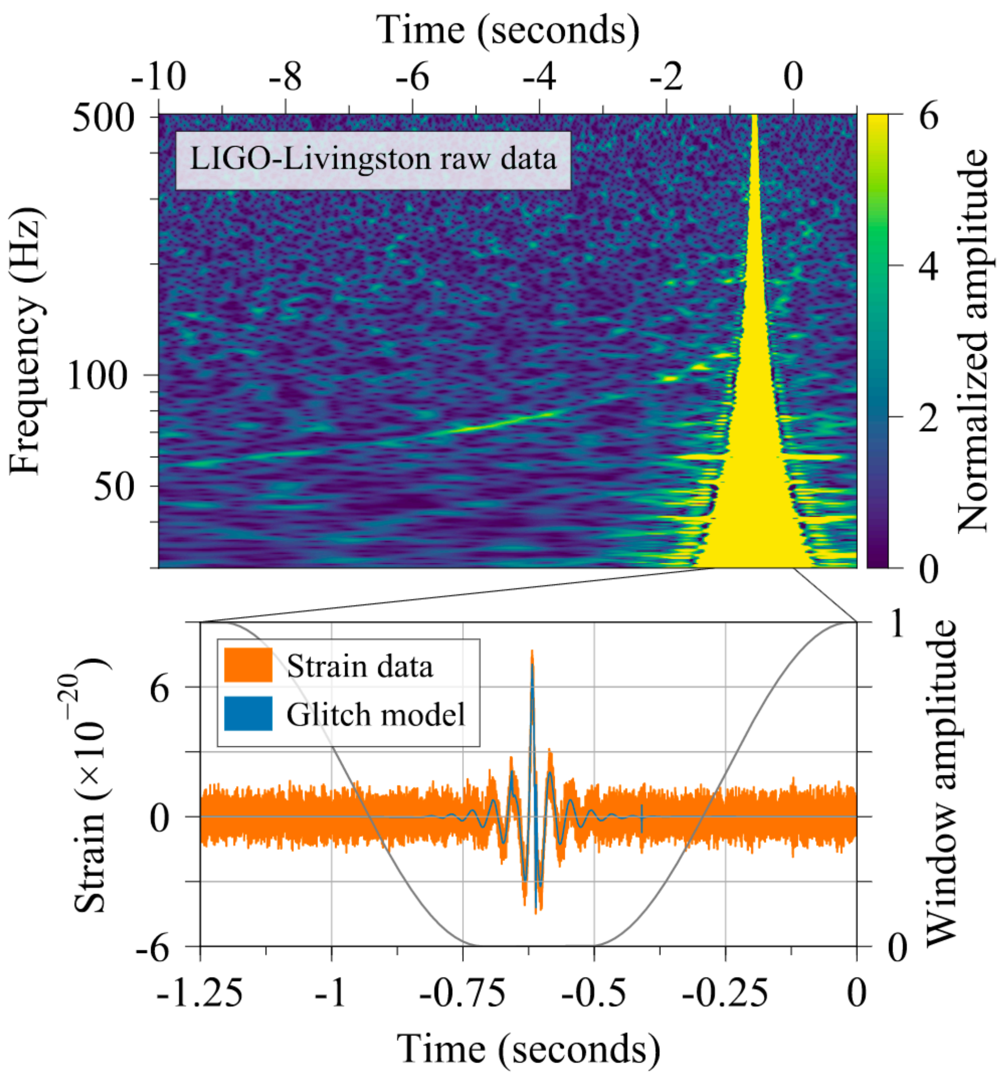
From M. Fyffe

GW170817 – Kilonova



Mass gap between known NS and BH





- Instrumental Glitch, due to breve (5ms) saturations of DAC that provides control signal to the position of the test masses.
- Easy to remove after identifying and characterising type of glitch:
  - Fast analysis, detection: remove the time interval of the glitch (Tukey window).
  - Full analysis, paramater estimation: Glitch model and subtraction.

GW151226 – Match filtering in action

LVC , Physical Review Letters 116, 241103 (2016)

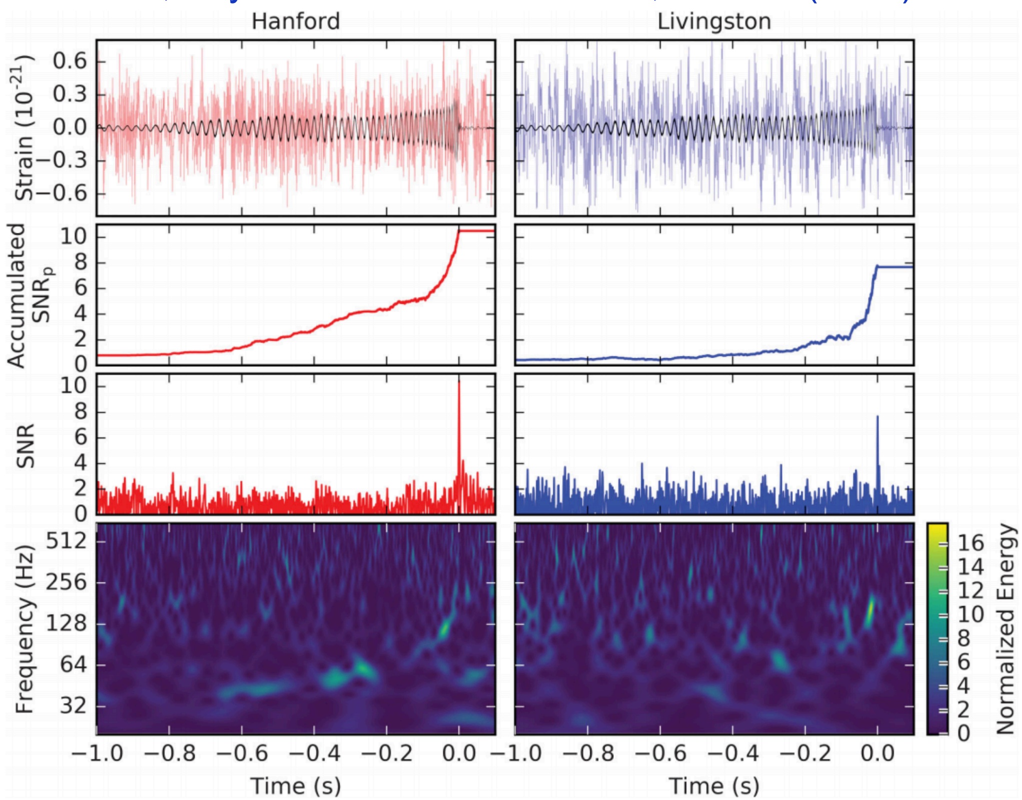


FIG. 1. GW151226 observed by the LIGO Hanford (left column) and Livingston (right column) detectors, where times are relative to December 26, 2015 at 03:38:53.648 UTC. *First row:* Strain data from the two detectors, where the data are filtered with a 30–600-Hz bandpass filter to suppress large fluctuations outside this range and band-reject filters to remove strong instrumental spectral lines [46]. Also shown (black) is the best-match template from a nonprecessing spin waveform model reconstructed using a Bayesian analysis [21] with the same filtering applied. As a result, modulations in the waveform are present due to this conditioning and not due to precession effects. The thickness of the line indicates the 90% credible region. See Fig. 5 for a reconstruction of the best-match template with no filtering applied. *Second row:* The accumulated peak signal-to-noise ratio (SNR_p) as a function of time when integrating from the start of the best-match template, corresponding to a gravitational-wave frequency of 30 Hz, up to its merger time. The total accumulated SNR_p corresponds to the peak in the next row. *Third row:* Signal-to-noise ratio (SNR) time series produced by time shifting the best-match template waveform and computing the integrated SNR at each point in time. The peak of the SNR time series gives the merger time of the best-match template for which the highest overlap with the data is achieved. The single-detector SNRs in LIGO Hanford and Livingston are 10.5 and 7.9, respectively, primarily because of the detectors' differing sensitivities. *Fourth row:* Time-frequency representation [47] of the strain data around the time of GW151226. In contrast to GW150914 [4], the signal is not easily visible.

GW151226:
at 03:38:53 UTC

$14M_\odot + 8M_\odot = 21\ M_\odot$

SNR = 13, > 5 sigmas

$E_{radiated} = 1M_\odot c^2$
in 1 second

440 Mpc, z=0.09

~1.4 billion light years