Catching gravitational waves: a new discovery and a new astronomy

Prof Sheila Rowan
For the LIGO Scientific Collaboration
Institute for Gravitational Research
University of Glasgow
UK

DESY Zeuthen
15th June 2016

Latest news:
Upcoming webcast – this evening …

Wednesday, 15 June, 10:15 am PDT

Latest News from the LIGO Scientific Collaboration

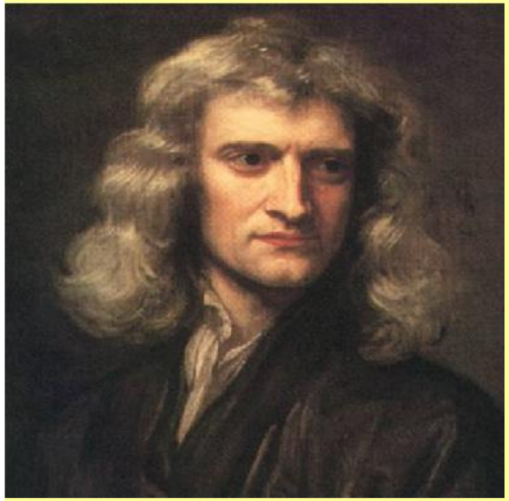
Webcast link: https://aas.org/aas-briefing-webcast

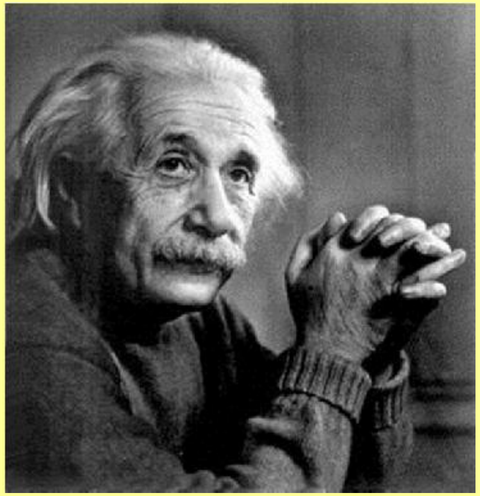
Gabriela González
LIGO Scientific Collaboration Spokesperson
(Louisiana State University)

Fulvio Ricci
Virgo Spokesperson
(University of Rome Sapienza & INFN Rome)

Dave Reitze
Executive Director of LIGO
(Caltech)

Gravitation





The Einstein field equations of GR have wave solutions

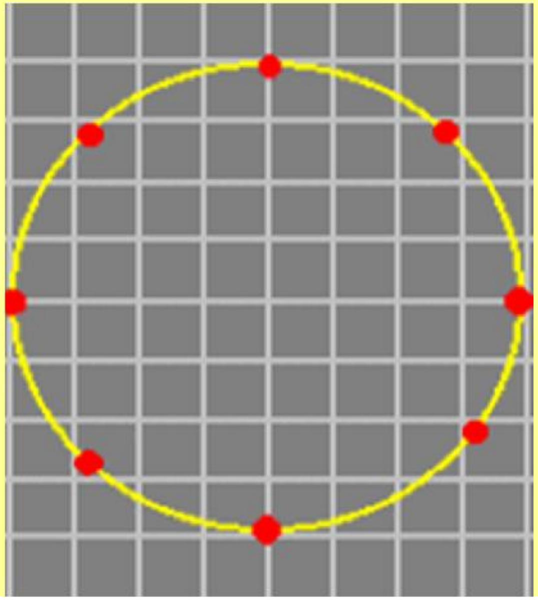
- Emitted by a rapidly changing configuration of mass
- Travel away from the source at the speed of light
- Change the effective distance between inertial points — i.e. the spacetime metric — transverse to the direction of travel

Newton's Theory

"instantaneous action at a distance"

Einstein's Theory

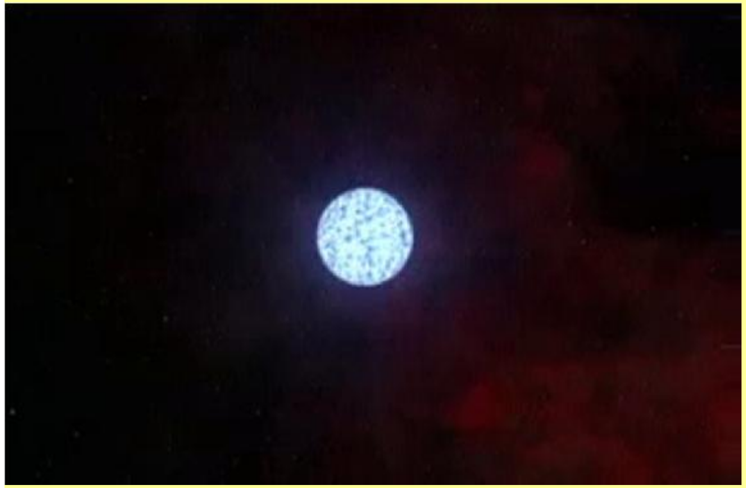
information cannot be carried faster than speed of light – there must be gravitational radiation



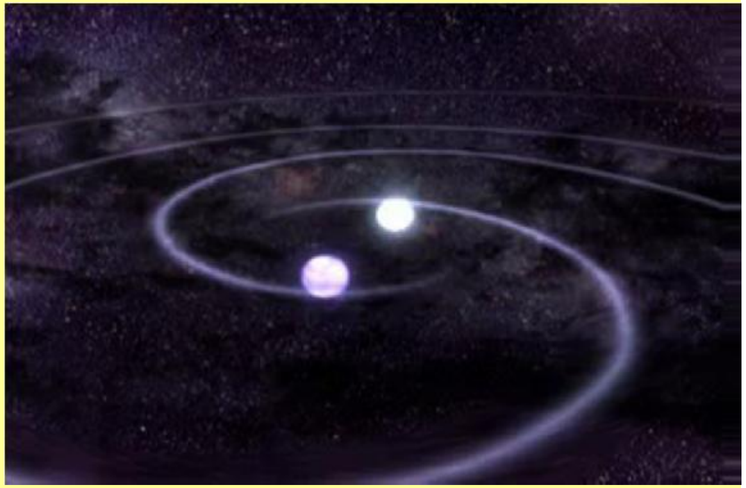
Looking at a fixed place in space while time moves forward, the waves alternately *stretch* and *shrink* the space

Gravitational wave sources in ground-based detectors

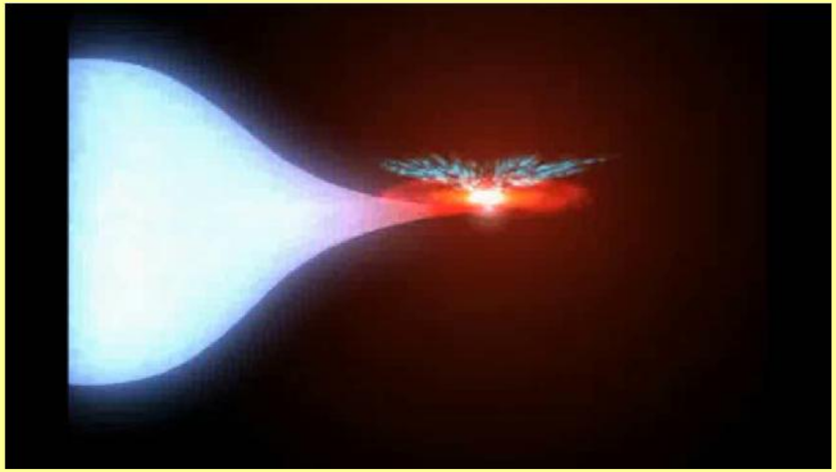
Supernovae and black hole formation



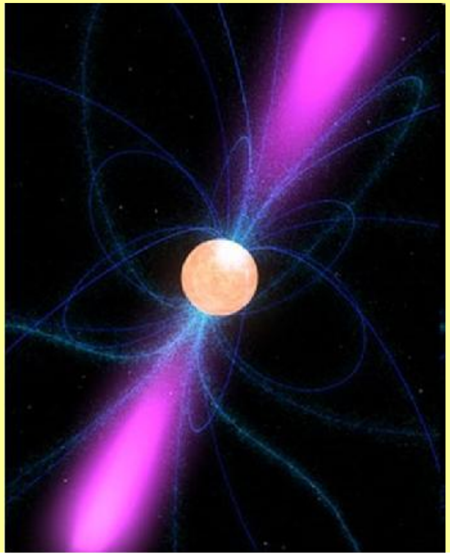
Binaries of black holes and neutron stars



Pulsars; modes and instabilities of neutron stars



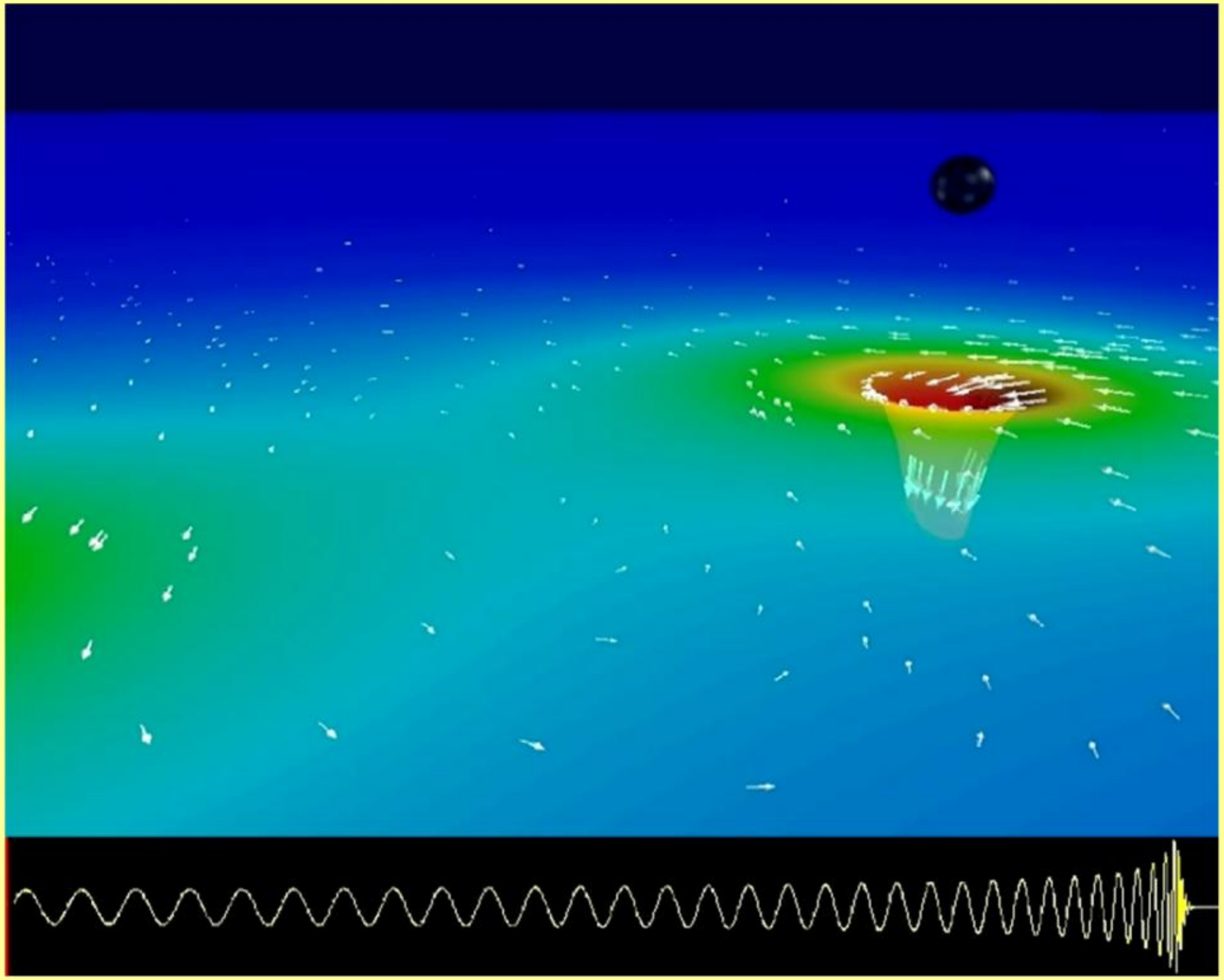
Spinning neutron stars in X-ray binaries



- GWs trace the bulk motion of their source
- Non-imaging
- Very weakly scattered / absorbed.
- Complementary to properties of photons

Listening for Merging Binary Black Holes

Caltech/Cornell
“Simulating
Extreme Spacetime”
(SXS)
Collaboration

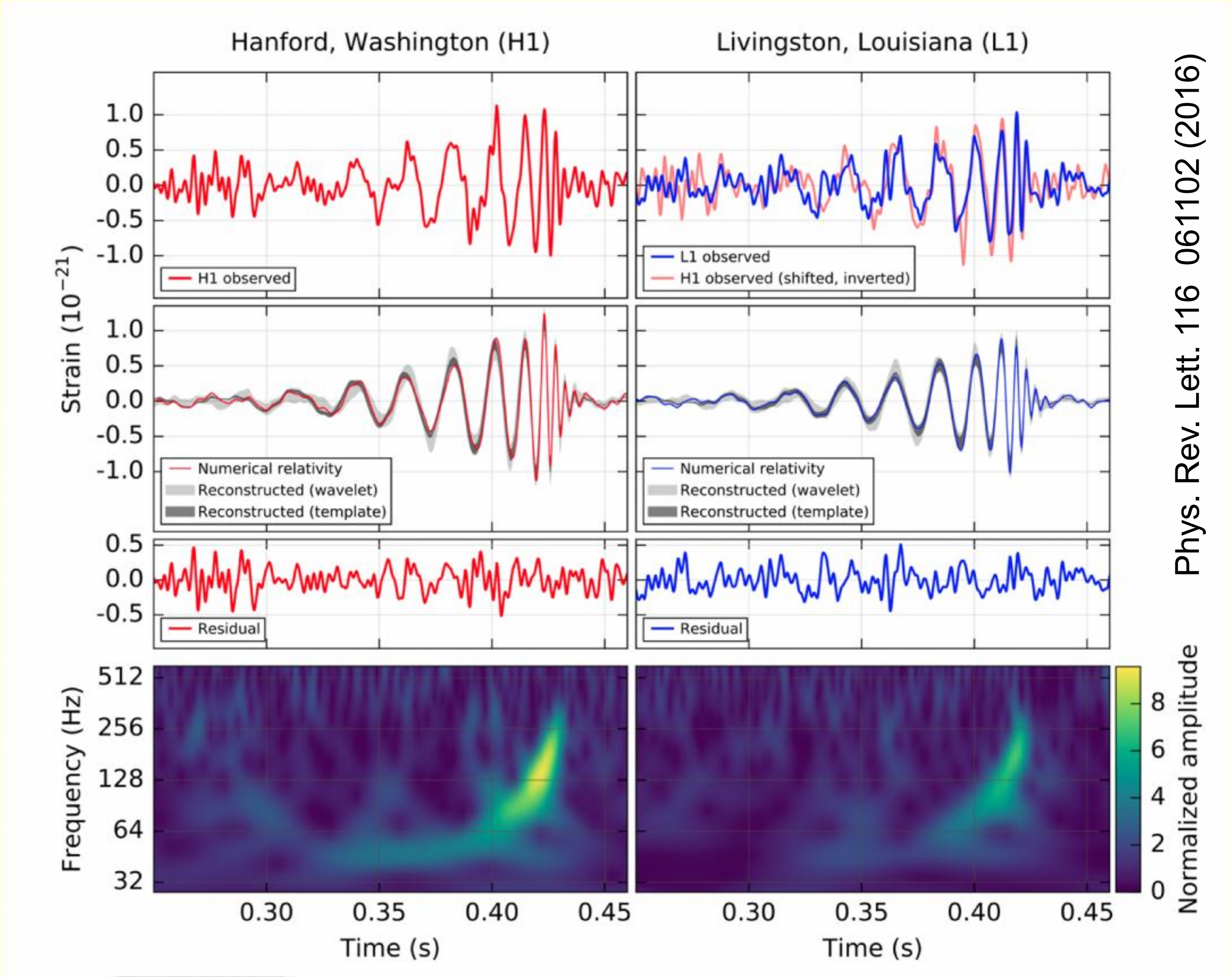


Movie simulation
credit:
Harald Pfeiffer
(CITA)

LIGO-G1501277-v2

http://www.black-holes.org/explore/movies

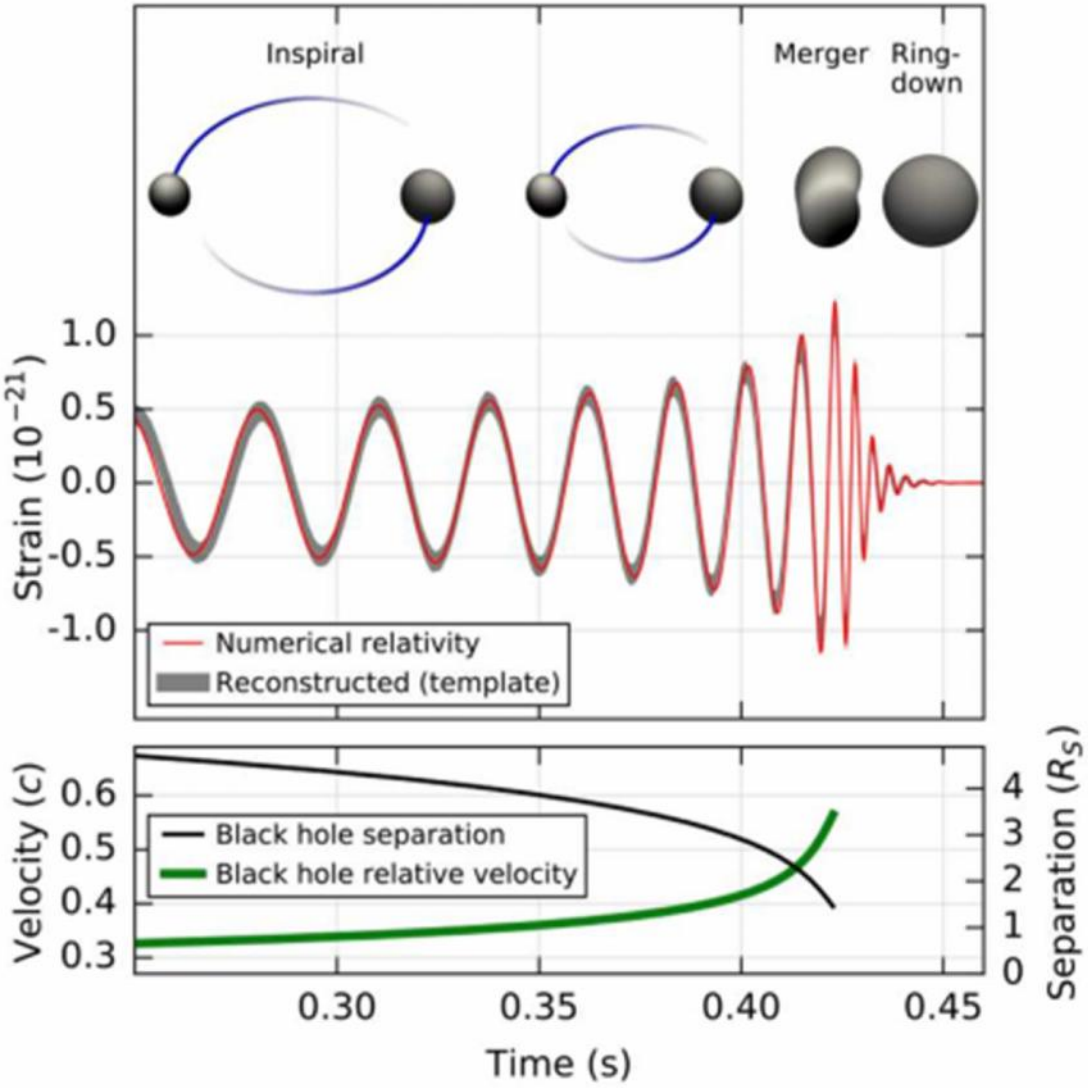
With two ‘detectors’ the LIGO (includes GEO) and Virgo collaborations found such a signal – reported in Feb this year



Phys. Rev. Lett. 116 061102 (2016)

PhysRevLett.116.061102

What was it we saw ?



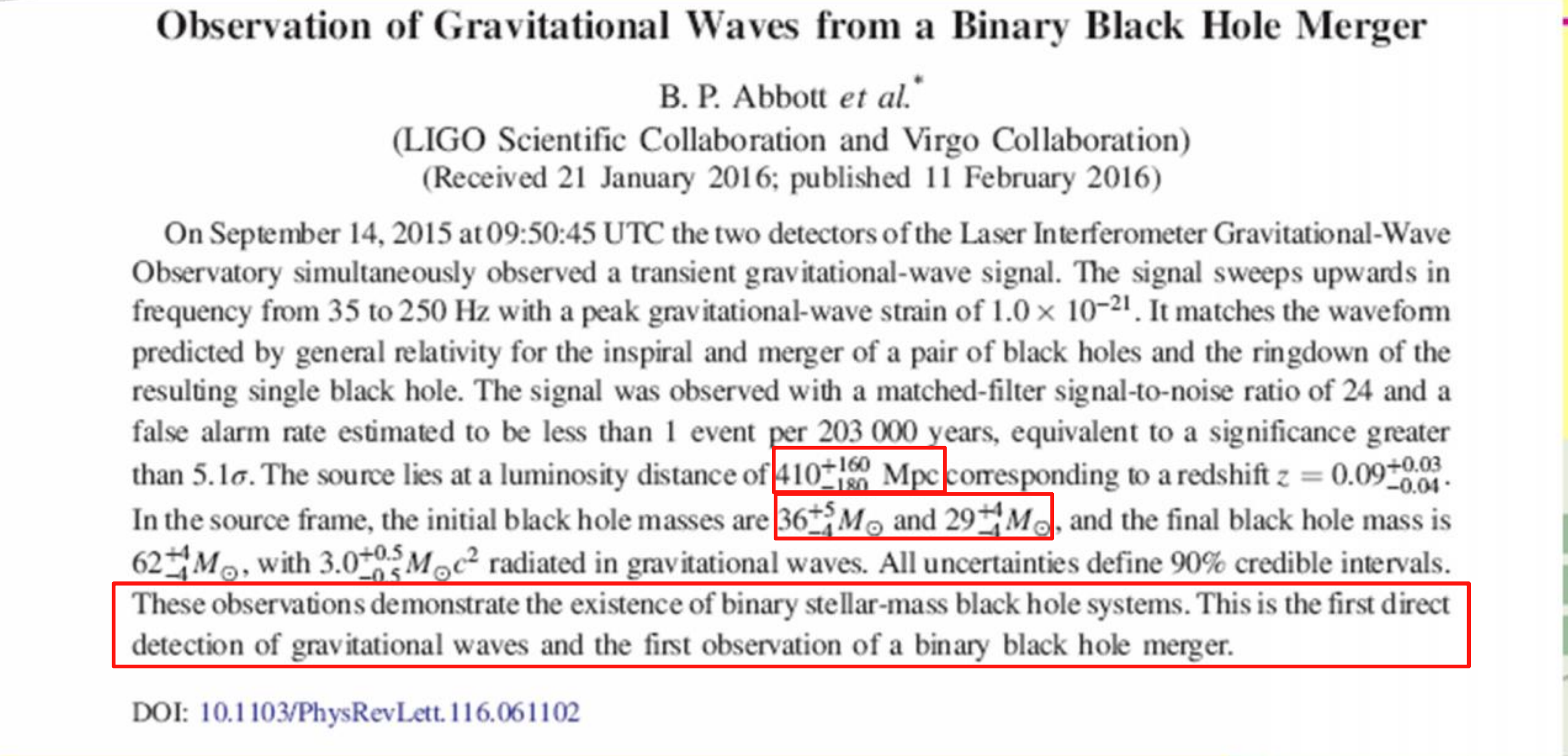
PhysRevLett.116.061102

Verifies Einstein, Schwarzschild by making first true gravitational observation of **two black holes coalescing**

Detected in the 100th anniversary year of General Relativity

Announced in the 100th anniversary year of the prediction of the existence of gravitational waves

The paper - published Thursday Feb 11th in Physical Review Letters



Observation of Gravitational Waves from a Binary Black Hole Merger

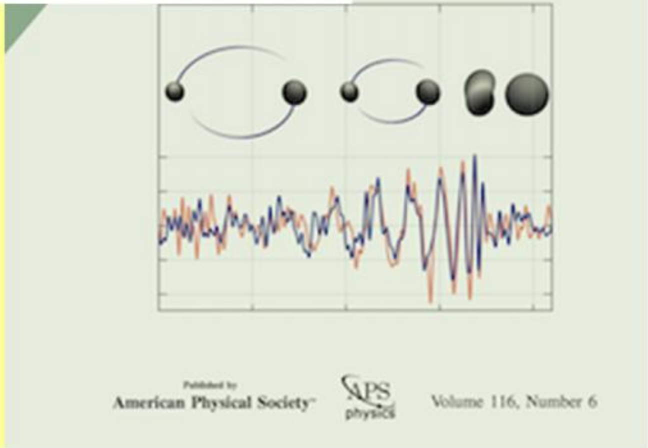
B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, and the final black hole mass is $62^{+4}_{-4} M_\odot$, with $3.0^{+0.5}_{-0.5} M_\odot c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

DOI: 10.1103/PhysRevLett.116.061102

PHYSICAL
REVIEW
LETTERS

12 FEBRUARY 2016



Published by American Physical Society
APS physics
Volume 116, Number 6

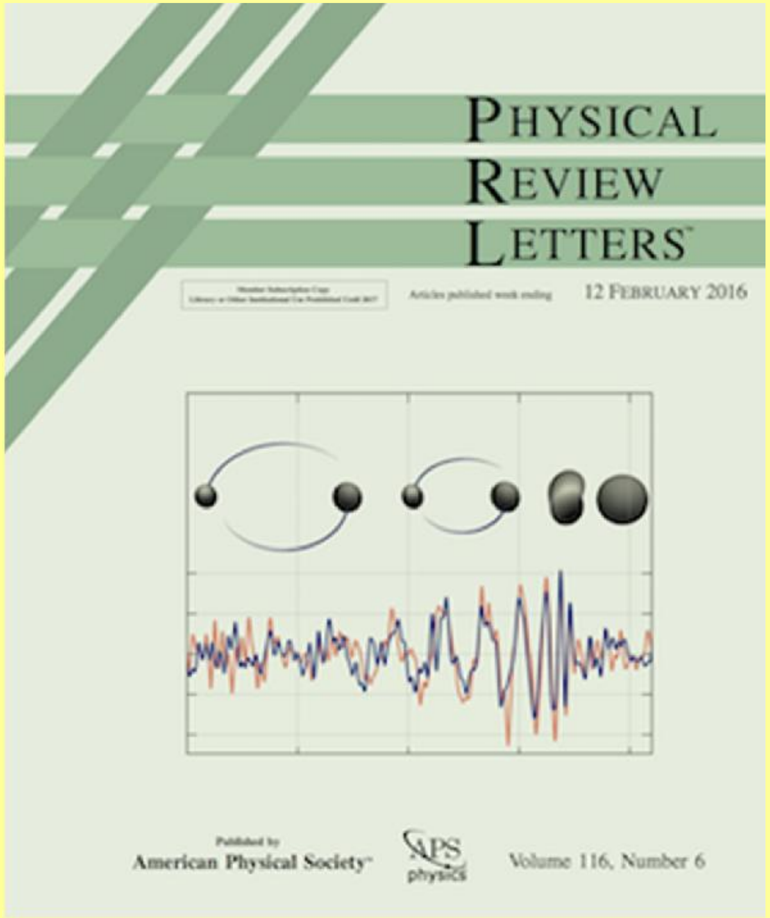
From exact signal shape we get masses of the individual black holes

From the signal size we get the distance to the coalescence :
~ 1.3 Billion Light Years

From precise evolution of the frequency of the signal we get the black hole spins

Properties of the final black hole

- Mass: 62 times the mass of the sun (~ 20 million Earths)
- Event horizon: Schwarzschild radius: ~183 km (diameter ~366 km, so about the size of Iceland)
- Spin frequency: ~100 Hz
- Horizon equatorial velocity: ~0.4c



PHYSICAL REVIEW LETTERS

Articles published week ending 12 FEBRUARY 2016

Published by American Physical Society

APS physics

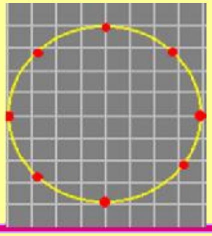
Volume 116, Number 6

Related publications

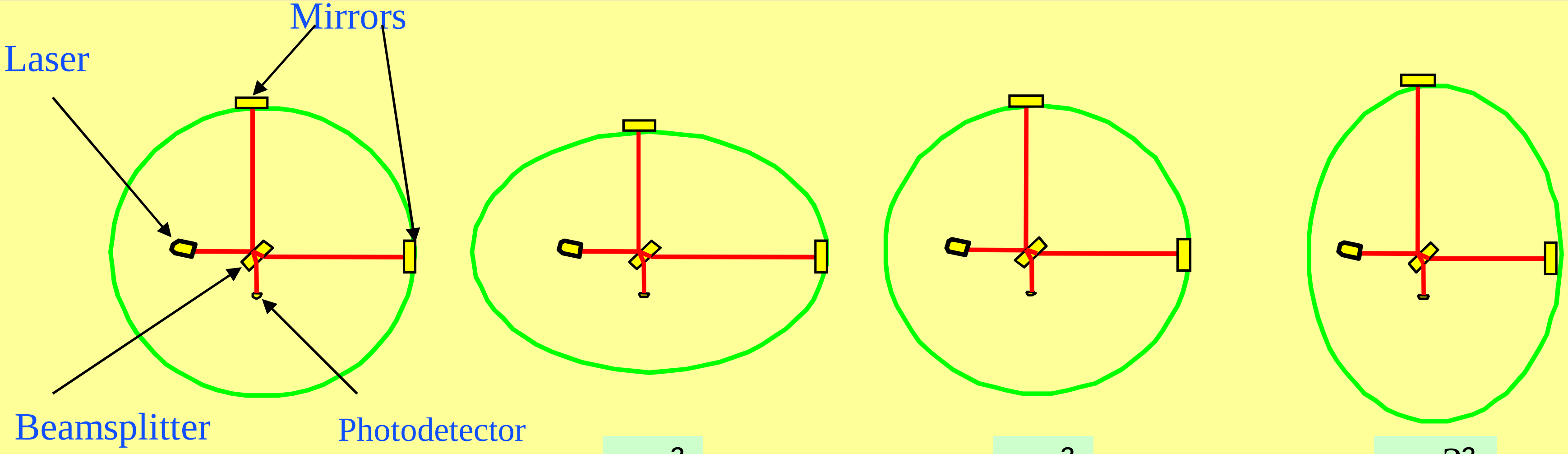
Related Papers: see https://papers.ligo.org/

LIGO-P1500229: Observing gravitational-wave transient GW150914 with minimal assumptions

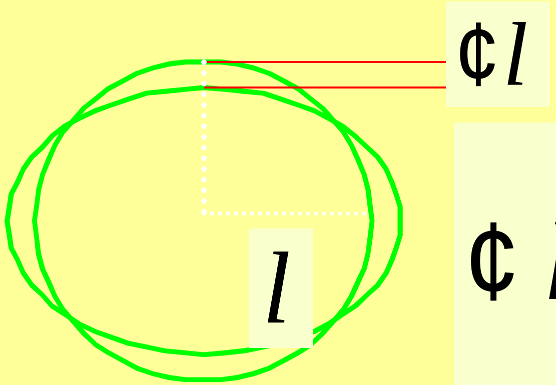
- LIGO-P1500269: GW150914: First results from the search for binary black hole
- coalescence with Advanced LIGO
- LIGO-P1500218: Properties of the binary black hole merger GW150914
- LIGO-P1500217: The Rate of Binary Black Hole Mergers Inferred from Advanced
- LIGO Observations Surrounding GW150914
- LIGO-P1500262: Astrophysical Implications of the Binary Black-Hole Merger
- GW150914
- LIGO-P1500213: Tests of general relativity with GW150914
- LIGO-P1500222: GW150914: Implications for the stochastic gravitational-wave
- background from binary black holes
- LIGO-P1500248: Calibration of the Advanced LIGO detectors for the discovery of
- the binary black-hole merger GW150914
- LIGO-P1500238: Characterization of transient noise in Advanced LIGO relevant
- to gravitational wave signal GW150914
- LIGO-P1500227: Localization and broadband follow-up of the gravitational-wave
- transient GW150914
- LIGO-P1500271: High-energy Neutrino follow-up search of Gravitational Wave Event GW150914 with IceCube and ANTARES
- LIGO-P1500237: GW150914: The Advanced LIGO Detectors in the Era of First Discoveries



Operation of Interferometric Gravitational Wave Detectors



$t = 0$ $t = \frac{2}{4}$ $t = \frac{2}{2}$ $t = \frac{3^2}{4}$



$$\text{¢}\, l = \frac{h}{2} l$$

Gravitational wave amplitude

$$h = \frac{2\text{¢}\, l}{l} \leq 10^{-22}$$

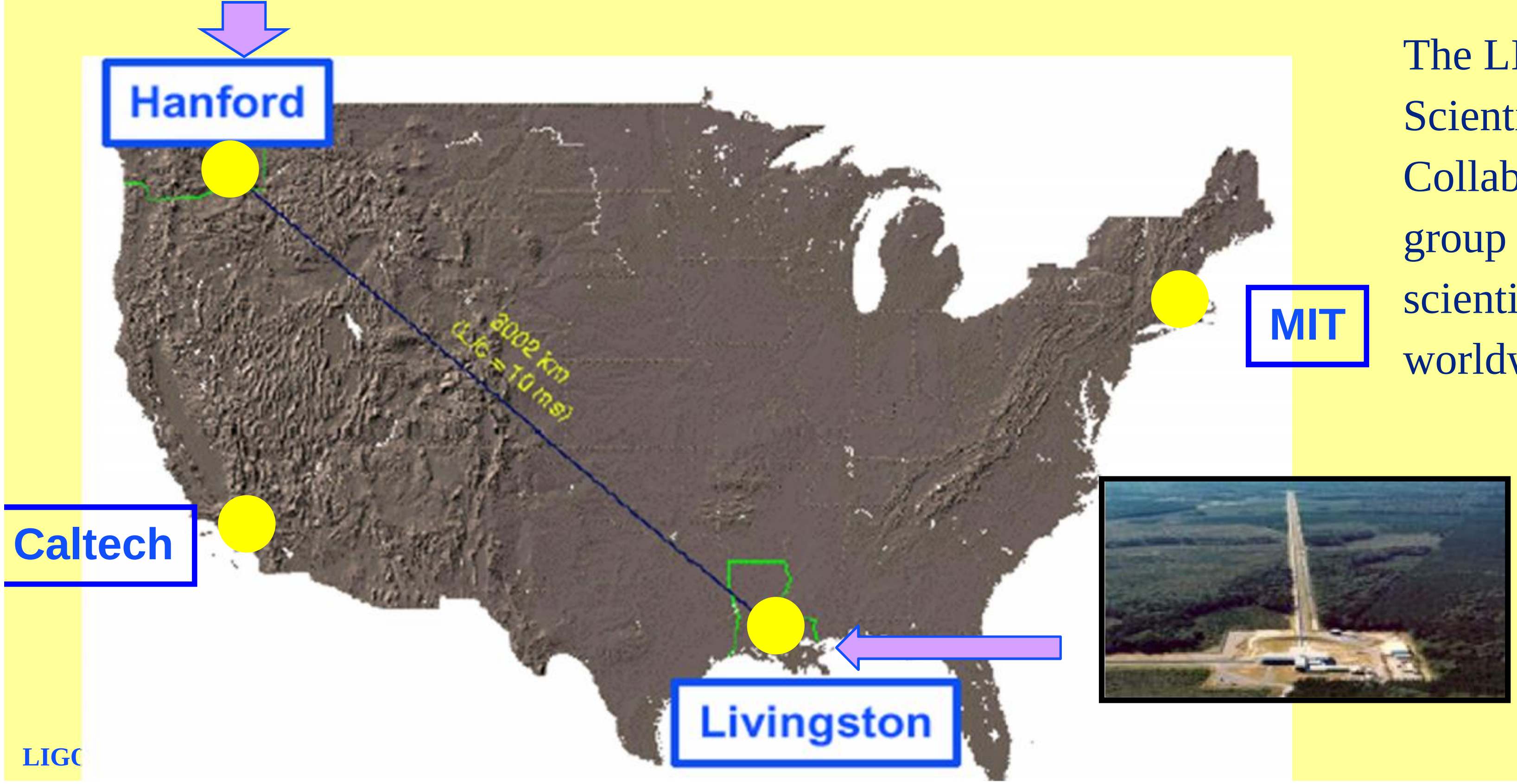
For Typical Astronomical sources

For best performance want arm length ~ λ/4
i.e. for 1kHz signals, length = 75 km

Such lengths not really possible on earth, but optical path can be folded – reduce arm lengths to ~few km

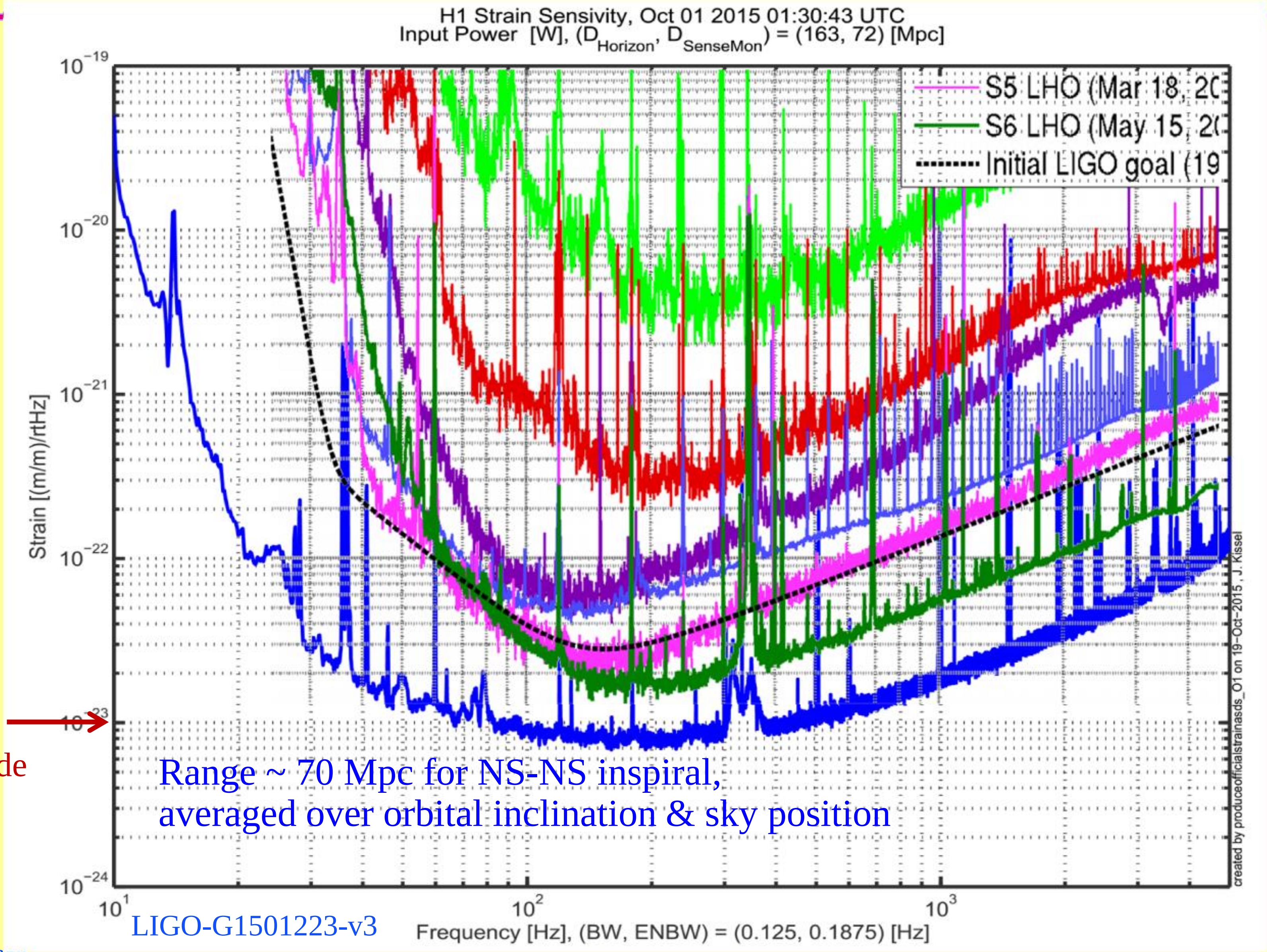
LIGO Observatories

- Mission: to develop gravitational-wave detectors, and to operate them as astrophysical observatories
- Jointly managed by Caltech and MIT; responsible for operating LIGO Hanford and Livingston Observatories
- Requires instrument science at the frontiers of physics fundamental limits



The LIGO Scientific Collaboration: a group of 900+ scientists worldwide

Advanced LIGO sensitivity in Observing run 1



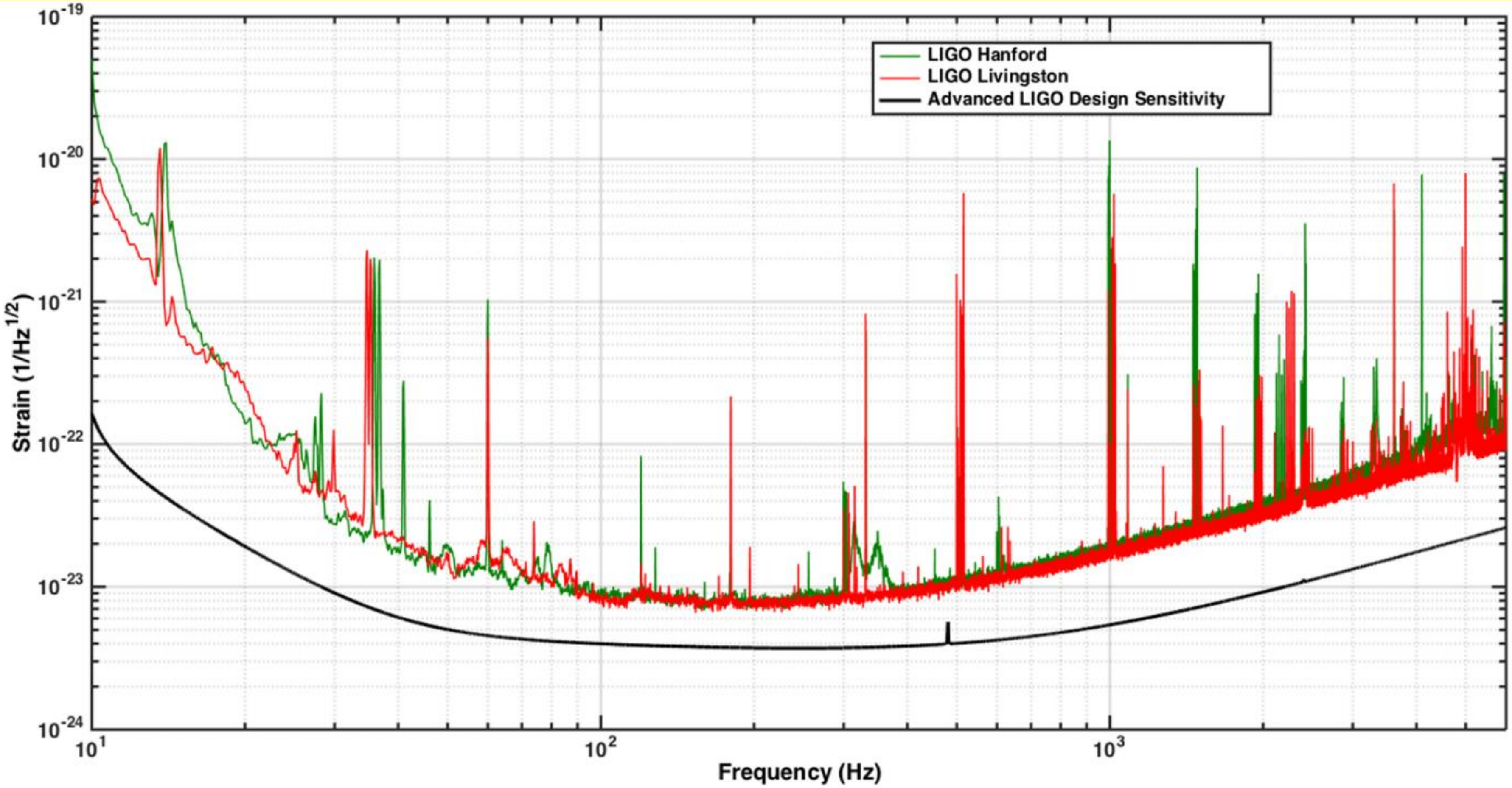
Range ~ 70 Mpc for NS-NS inspiral, averaged over orbital inclination & sky position

LIGO-G1501223-v3

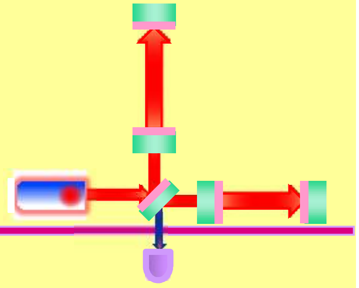
10 amplitude spectral density

Advanced LIGO Sensitivity: Observing Run 1 vs design sensitivity

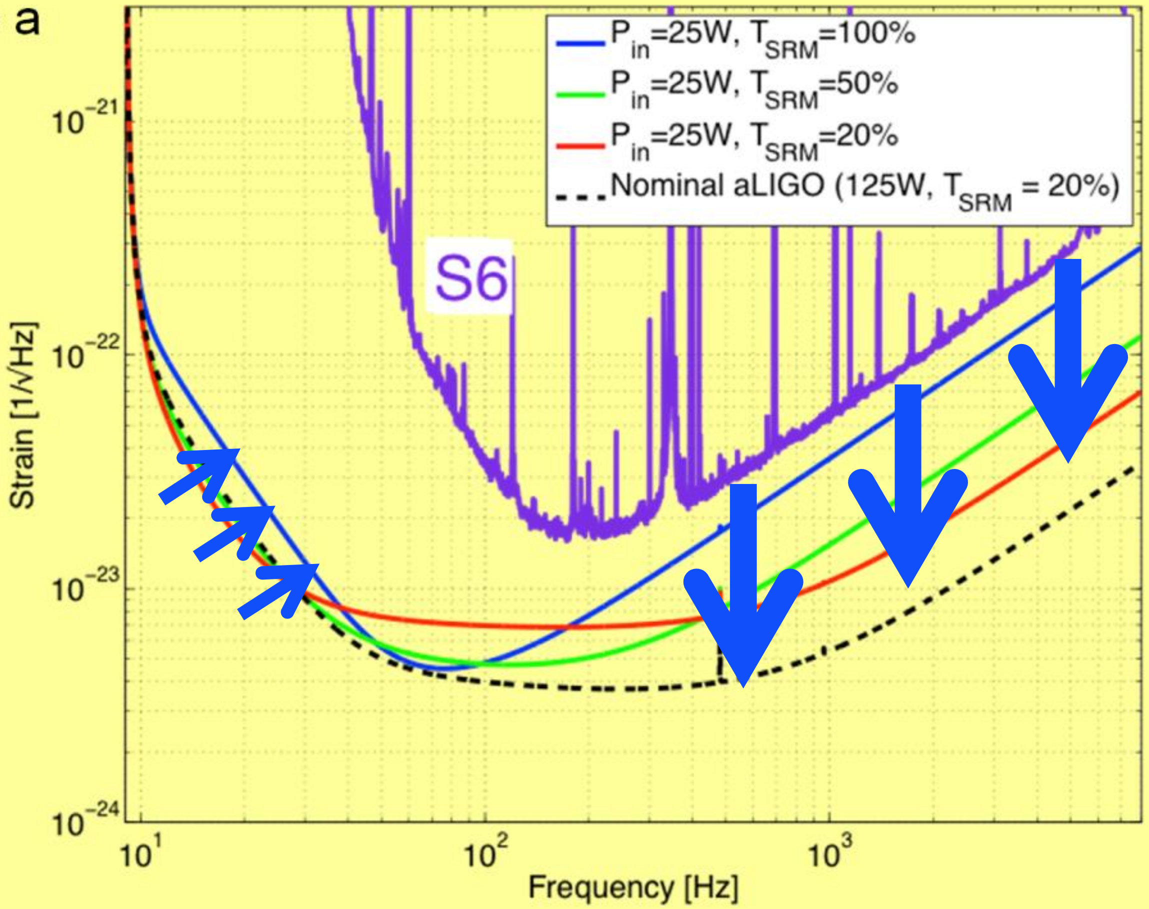
Advanced LIGO Observing Run 1 Began in September 2015



How to get from LIGO to Advanced LIGO: Addressing limits to performance

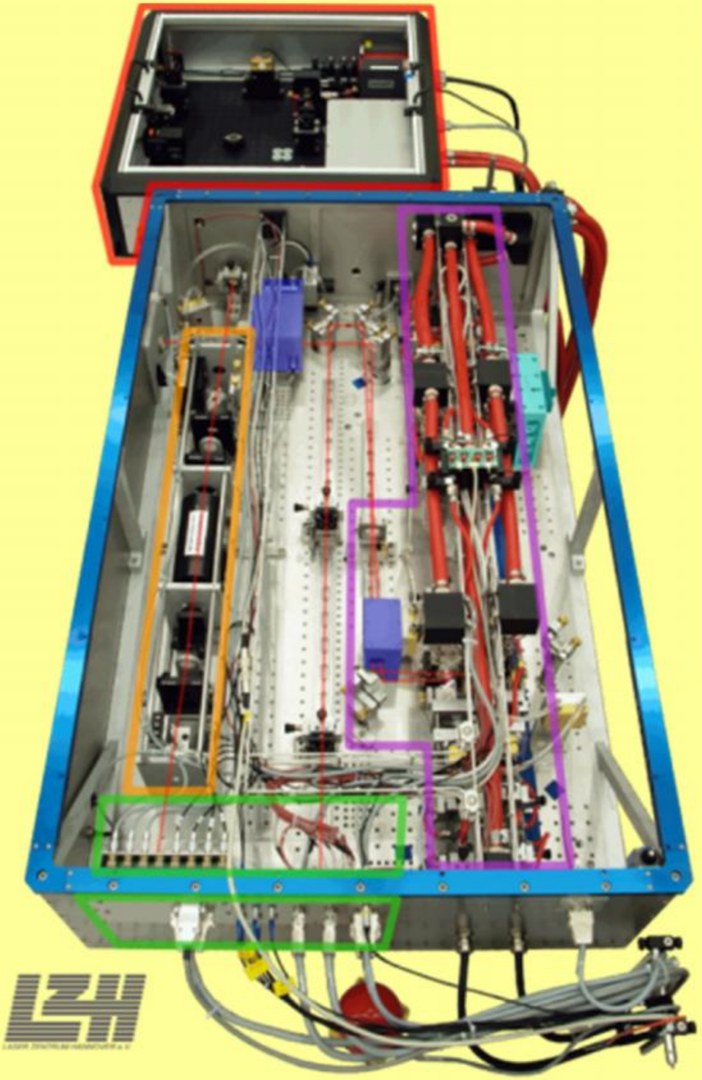


- **Shot noise** – ability to resolve a fringe shift due to a GW (counting statistics)
- Fringe Resolution at high frequencies improves as (laser power)$^{1/2}$
- Point of diminishing returns when buffeting of test mass by photons increases low-frequency noise – use heavy test masses
- ‘Standard Quantum Limit’
- Advanced LIGO reaches this limit with its **200W laser, 40 kg test masses**



200W Nd:YAG laser

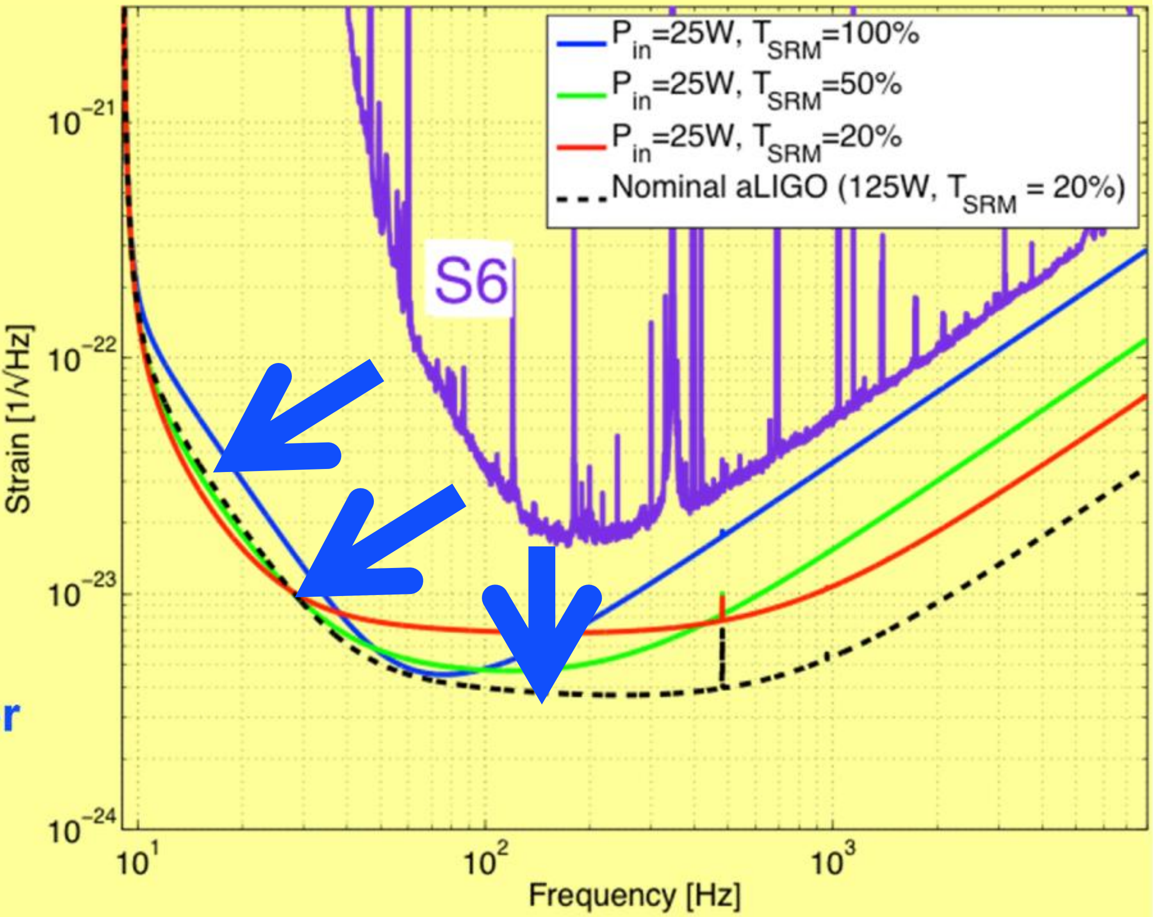
Designed and contributed by
Max Planck Albert Einstein Institute



- Stabilized in power and frequency
- Uses a monolithic master oscillator followed by injection-locked rod amplifier

Addressing limits to performance

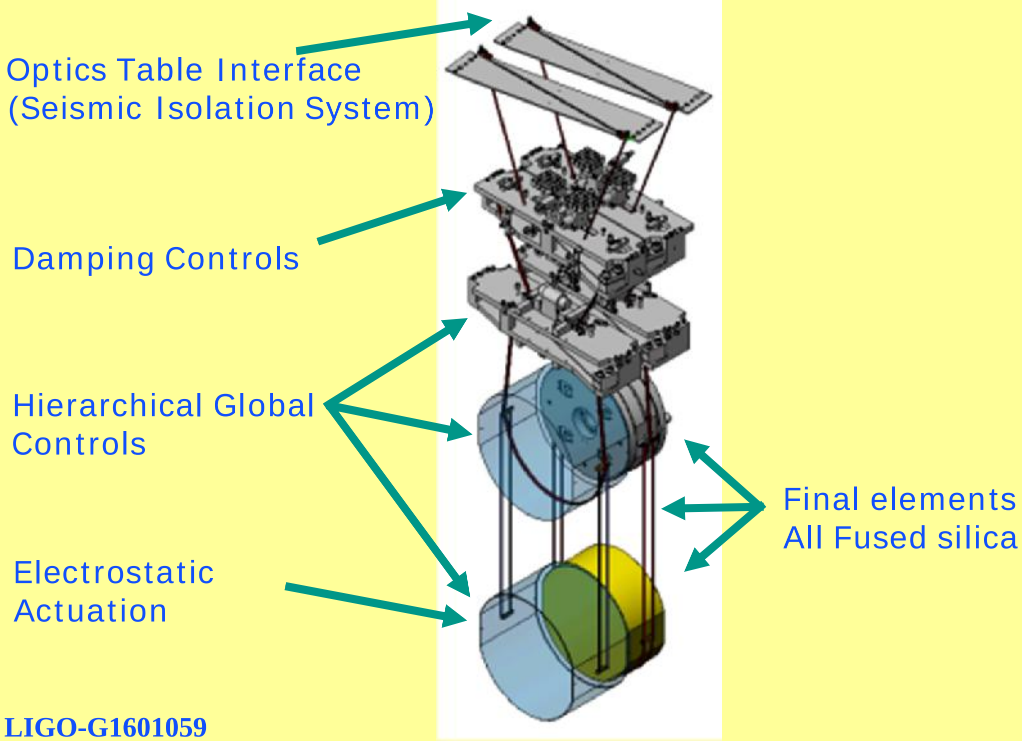
- **Thermal noise** – kT of energy per mechanical mode
- Wish to keep the motion of components due to thermal energy below the level which masks GW
- Low mechanical loss materials
- Realized in aLIGO with an all **fused-silica test mass suspension**
- **Test mass internal modes, Mirror coatings engineered for low mechanical loss**



Test Mass Quadruple Pendulum suspension UK hardware contribution:

designed jointly by the UK and LIGO lab,

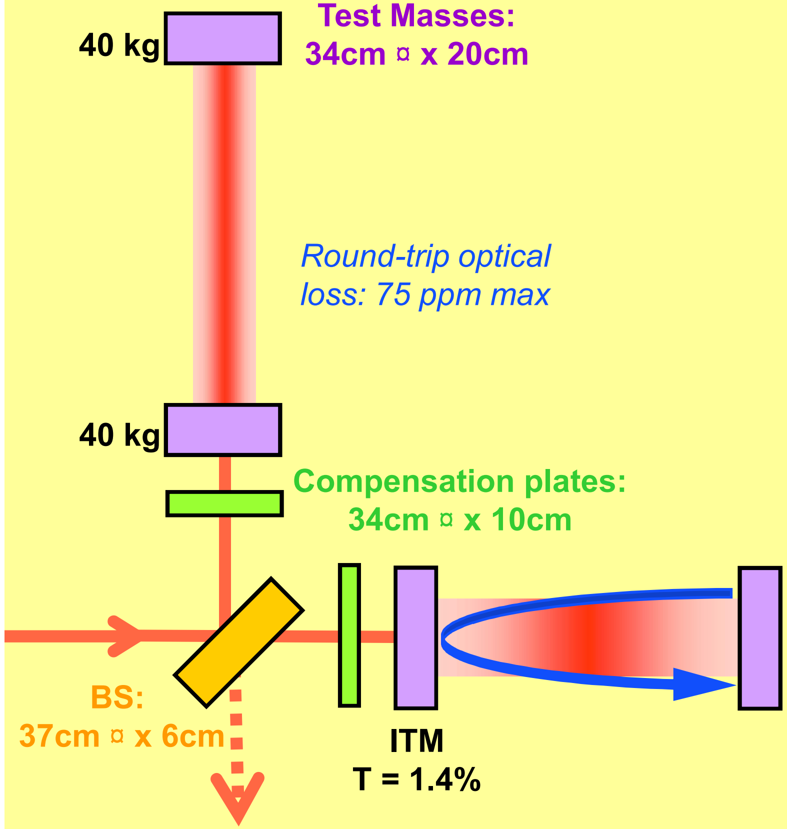
- Quadruple pendulum suspensions for the main optics; second 'reaction' mass to give quiet point from which to push
- Create quasi-monolithic pendulums using fused silica fibers to suspend 40 kg test mass
  - Very low thermal noise



LIGO-G1301277

Test Masses

- Requires the state of the art in substrates and polishing
- Pushes the art for coating
- Sum-nm flatness over 300mm



40 kg

Test Masses:
34cm ¤ x 20cm

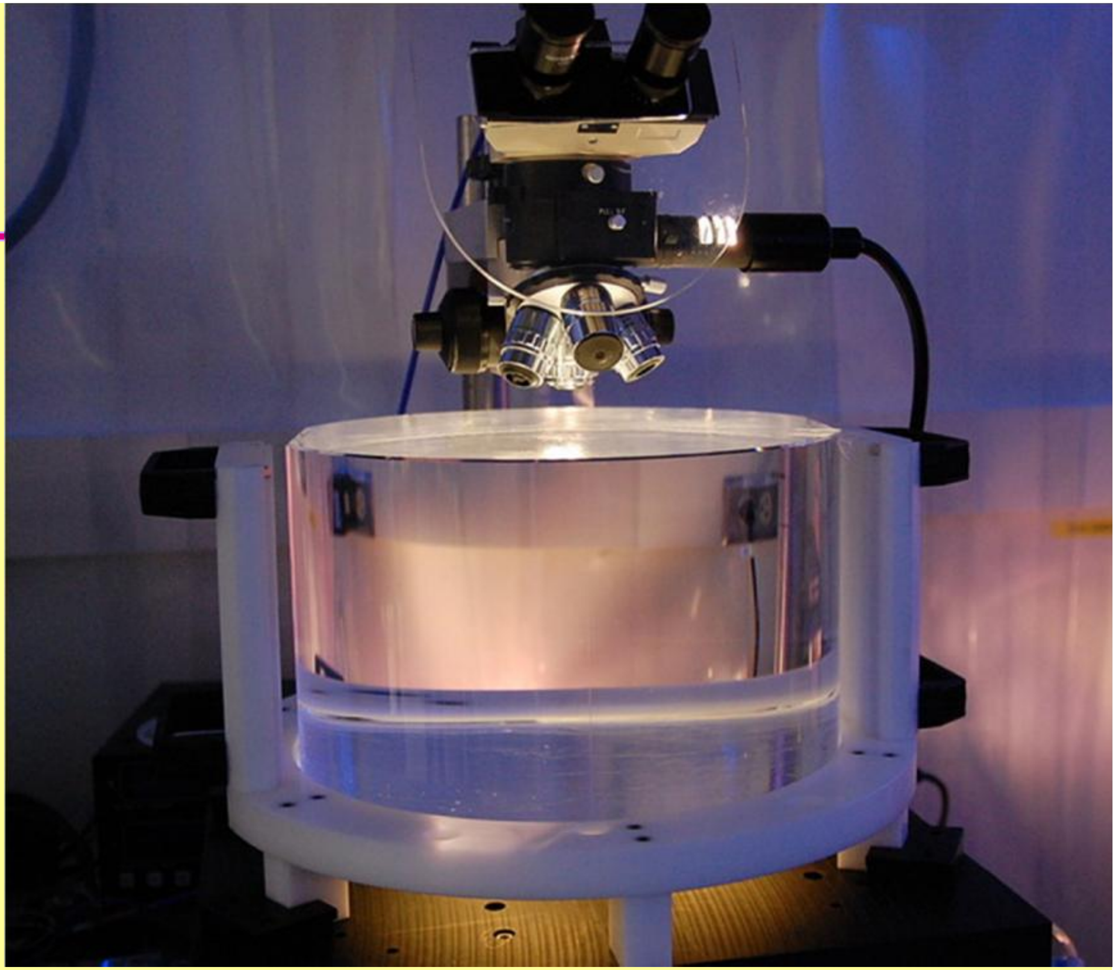
Round-trip optical loss: 75 ppm max

40 kg

Compensation plates:
34cm ¤ x 10cm

BS:
37cm ¤ x 6cm

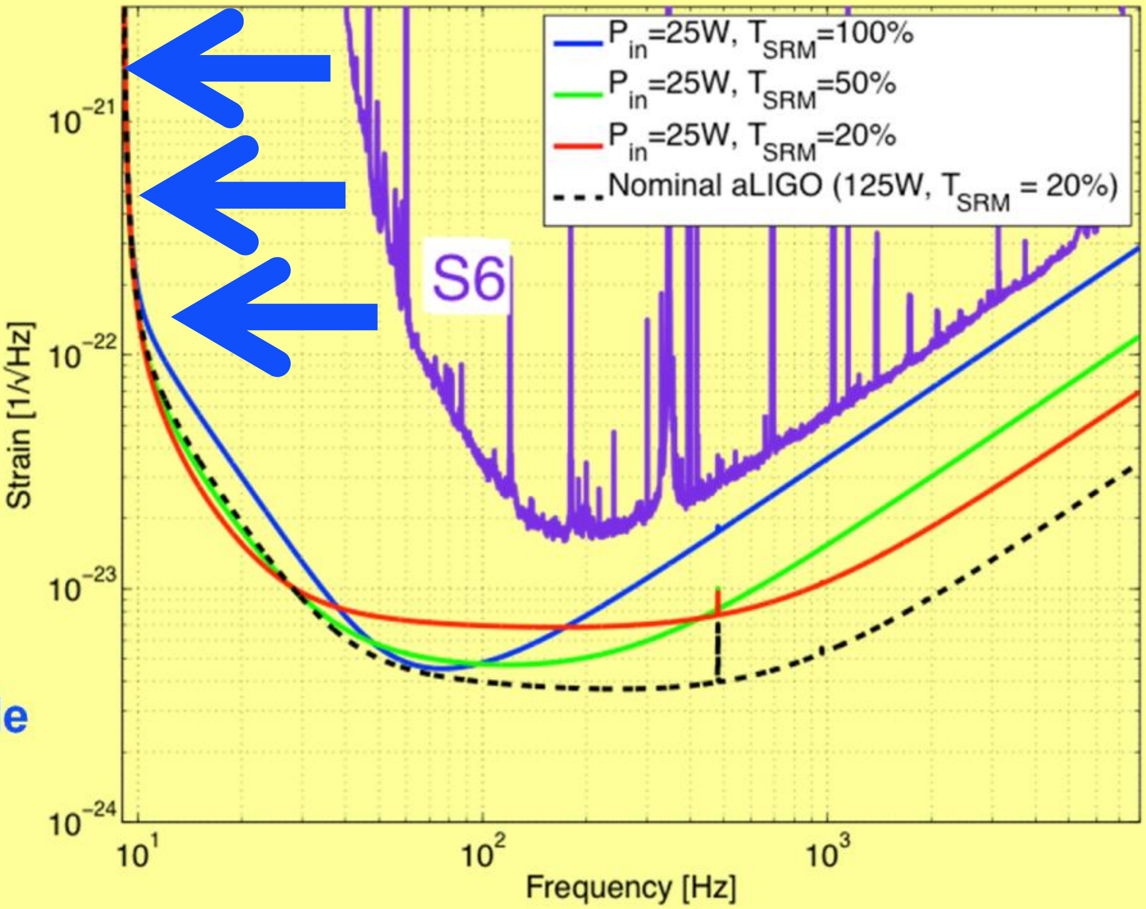
ITM
T = 1.4%



- Both the physical test mass – a free point in space-time – and a crucial optical element
- Mechanical requirements: bulk and coating thermal noise, high resonant frequency
- Optical requirements: figure, scatter, homogeneity, bulk and coating absorption

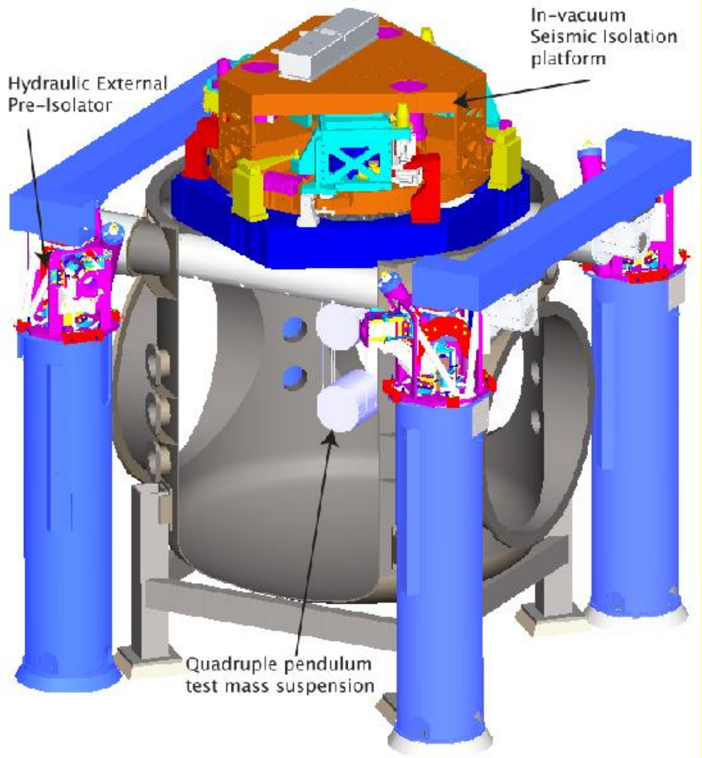
Addressing limits to performance

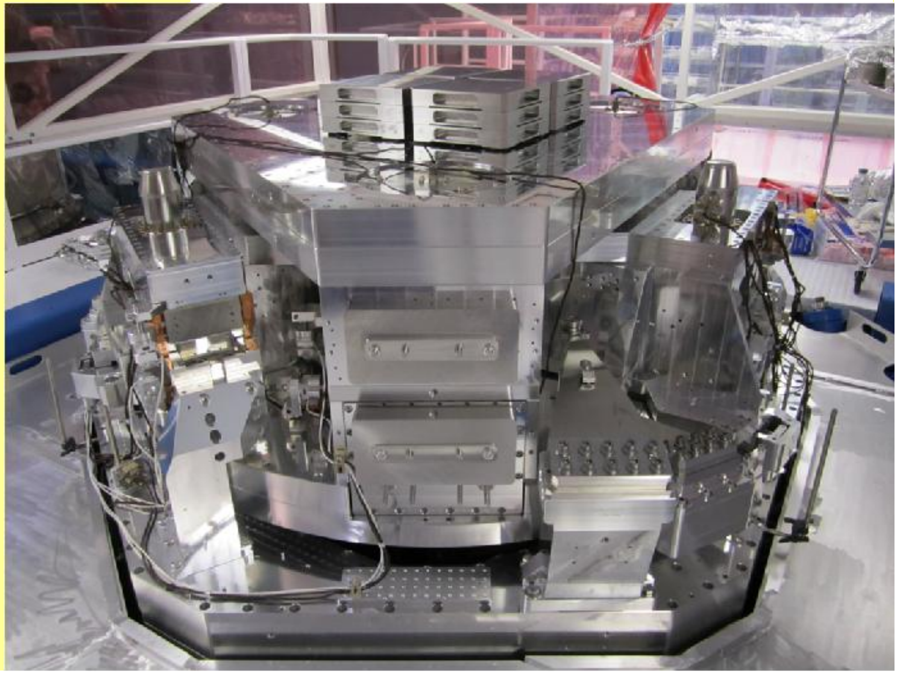
- **Seismic noise** – must prevent masking of GWs, enable practical control systems
- Motion from waves on coasts…and people moving around
- GW band: 10 Hz and above – direct effect of masking
- Control Band: below 10 Hz – forces needed to hold optics on resonance and aligned
- aLIGO uses **active servo-controlled platforms, multiple pendulums**
- Limit on the ground: Newtownian background – wandering net gravity vector; a limit in the 10-20 Hz band

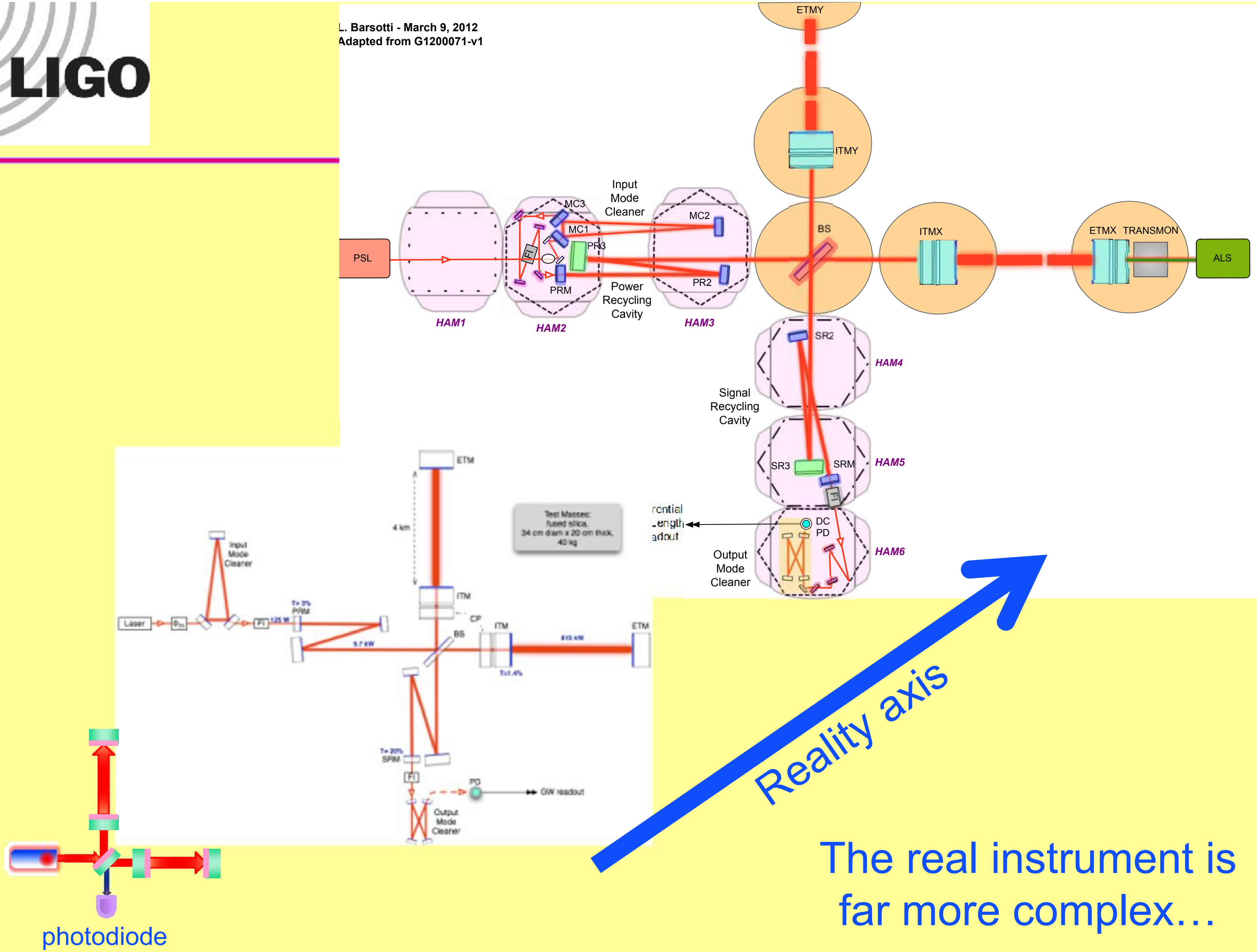


Seismic Isolation: Multi-Stage Solution

- Objectives:
  - Render seismic noise a negligible limitation to GW searches
  - Reduce actuation forces on test masses
- Both suspension and seismic isolation systems contribute to attenuation
- Choose an active isolation approach, 3 stages of 6 degrees-of-freedom :
  - 1) Hydraulic External Pre-Isolation
  - 2) Two Active Stages of Internal Seismic Isolation
- Low noise sensors (position, velocity, acceleration) are combined, passed through a servo amplifier, and delivered to the optimal actuator as a function of frequency to hold platform still in inertial space







The real instrument is far more complex…

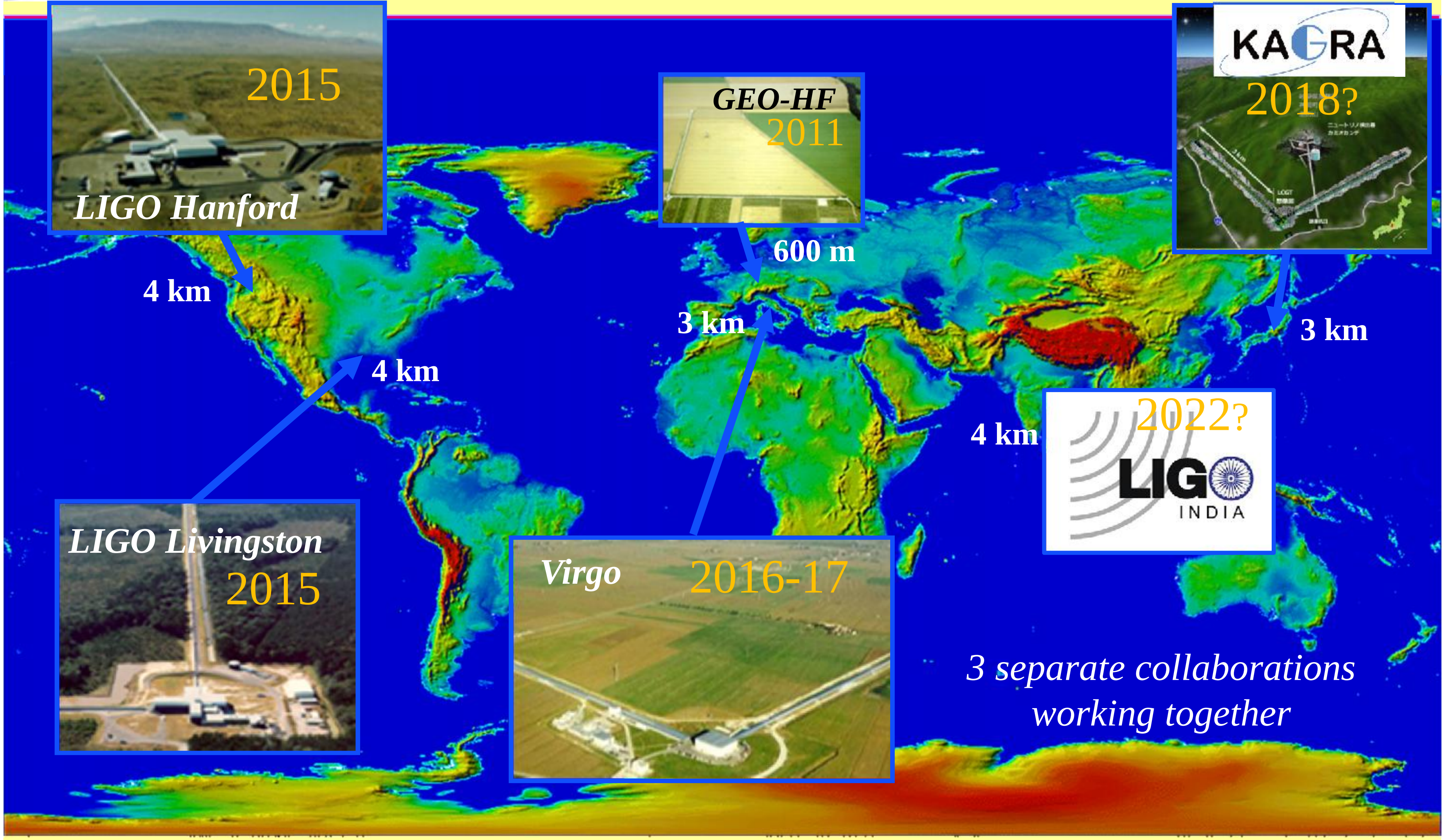
Additional challenges…

LIGO-G070024-01-W

Raab: Status of GW Searches in US with LIGO

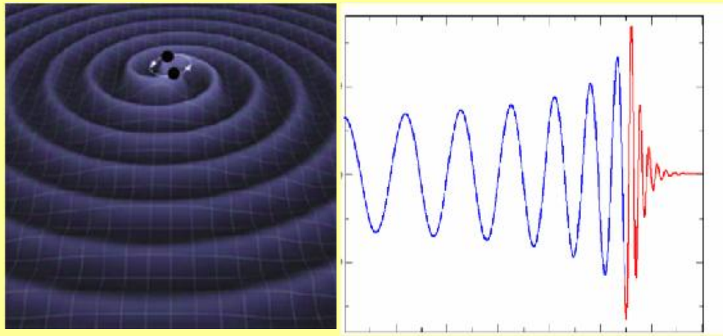
34

Advanced GW Detector Network: Under Construction → Operating



3 separate collaborations working together

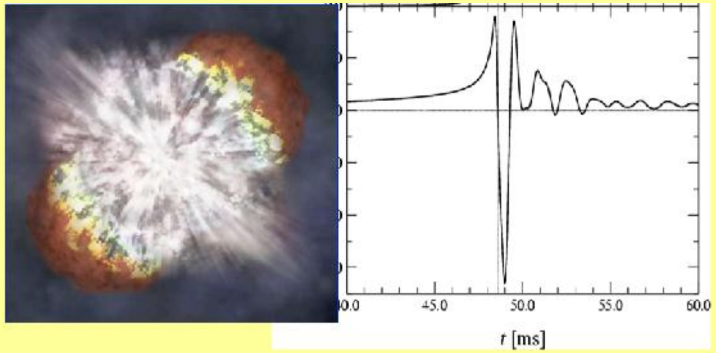
Searches for GW transient sources



Compact Binary Coalescence (CBC)

Known waveform ➔ Matched filtering

Templates for a range of component masses (spin affects waveforms too, but not so important for initial detection)



Unmodelled GW Burst (< few secs duration)

e.g. from stellar core collapse

Arbitrary waveform ➔ Excess power

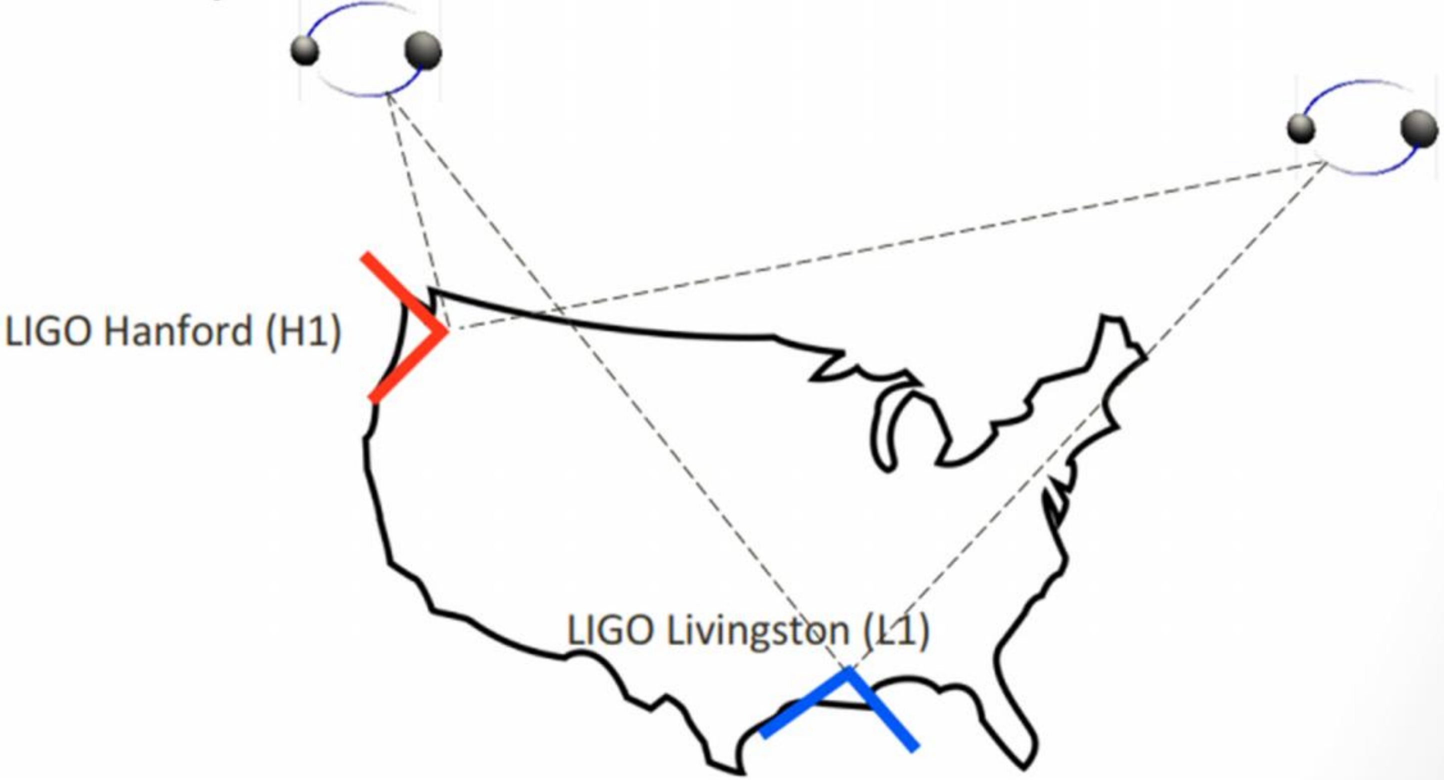
Require coherent signals in detectors,
using direction-dependent antenna response

Low-latency searches run continuously as data is collected

- Whenever two or more detectors are operating normally
- With coherent analysis, identify event candidates and generate preliminary sky position probability maps within a few minutes

Rapid Source sky-localisation

- The sky location of the gravitational wave source can be estimated through the event arrival time at each detector
  - gravitational waves travel at the speed of light
- Rapid sky localisation allows search for counterpart transient signals by optical, X-ray, GRB, ... observatories



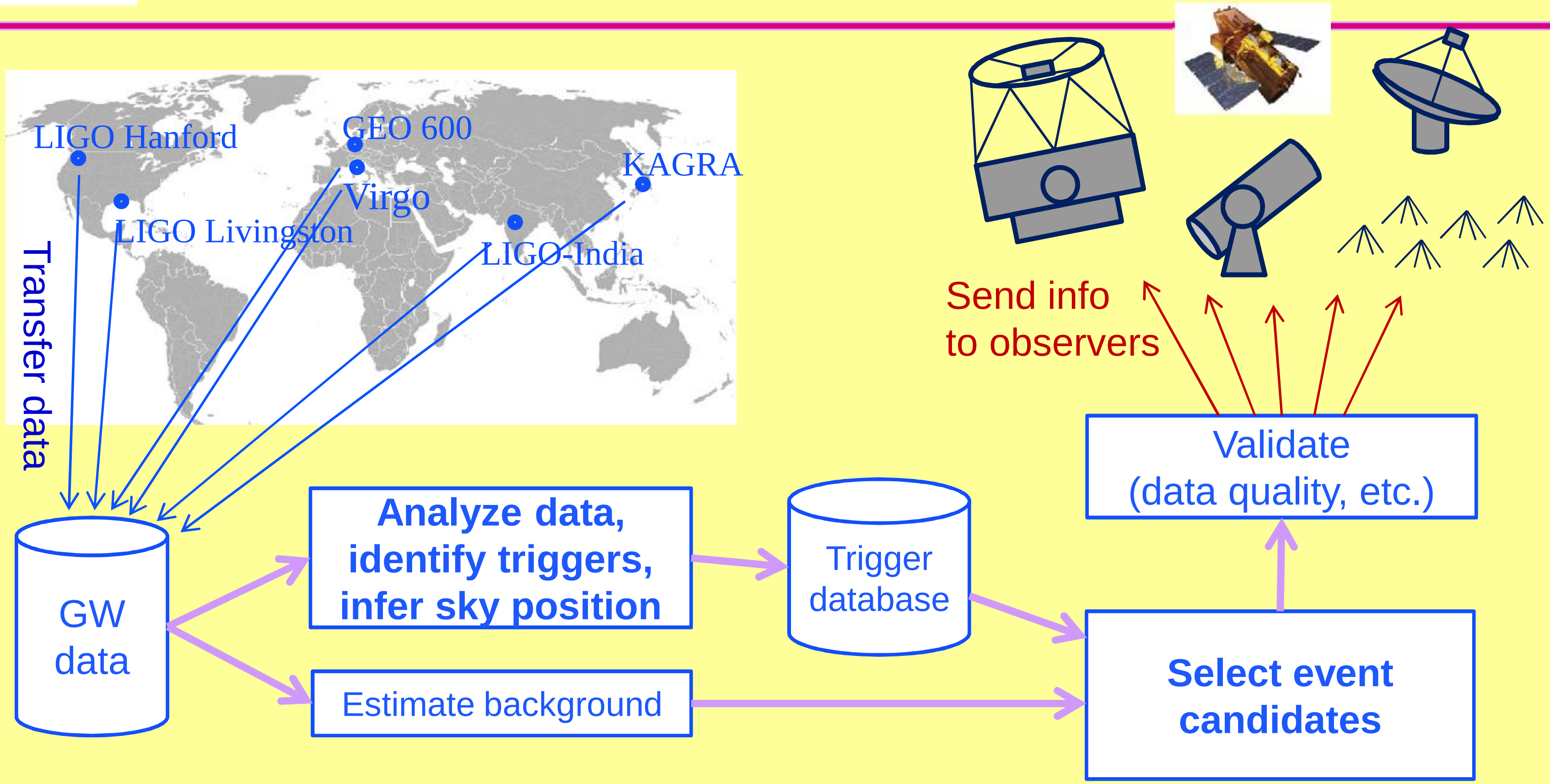
Goals for Multi-Messenger Science

- Identify GW event candidates as quickly as possible
  - With basic event parameters and an estimate of confidence
- Provide rapid alerts to other observers
  - Allow correlation with other transient survey events or candidates *
  - Trigger follow-up observations (prompt and/or delayed)

- What this can enable:
  - Pick out interesting (initially marginal) events from GW and other surveys
  - Prioritize follow-up observing resources
  - Maybe catch a counterpart that would have been missed, or detected only later
  - Identify host galaxy ➔ provide astronomical context
  - Obtain multi-wavelength (and multi-messenger) data for remarkable events

** LIGO/Virgo also monitor GCN (Gamma Ray Co-ordinates Network) and consider other significant transient events, and do deeper GW analysis for notable reported events*

Generating and Distributing Prompt Alerts



GW data

Analyze data, identify triggers, infer sky position

Estimate background

Trigger database

Select event candidates

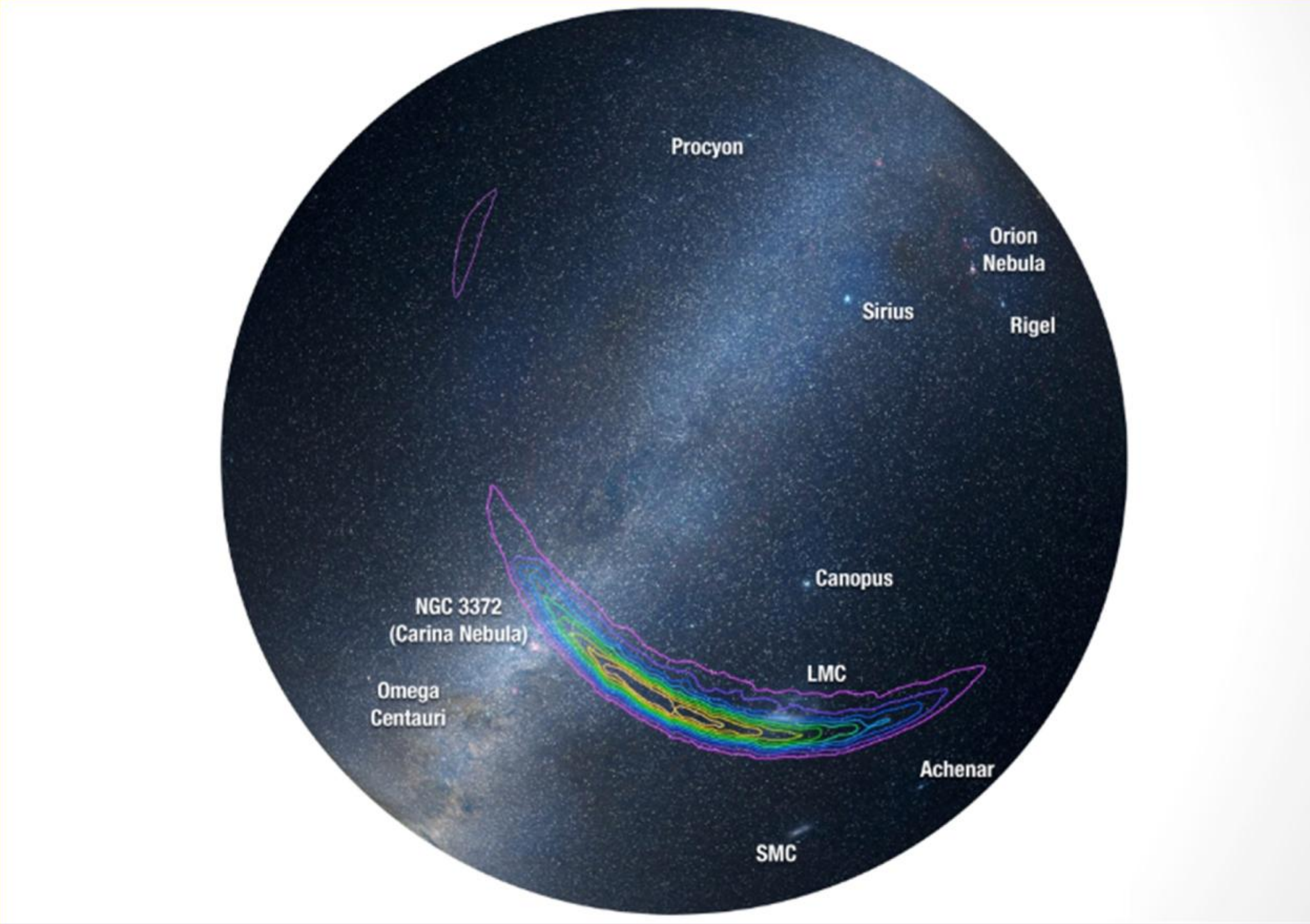
Validate (data quality, etc.)

Send info to observers

- Challenge: GW reconstructed sky regions are large
- With just the two LIGO detectors: typically a few hundred square degrees
- LIGO+Virgo: typically several tens of square degrees
- Will improve with KAGRA and LIGO-India

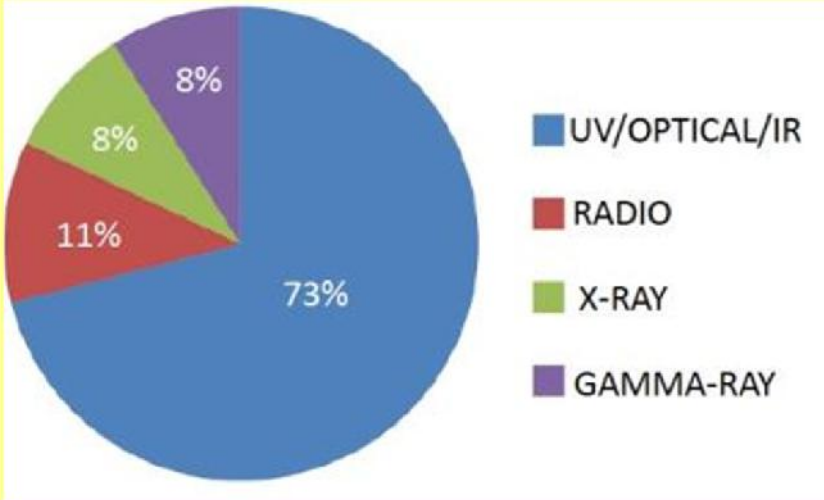
Swift: NASA E/PO, Sonoma State U., Aurore Simonnet

GW150914 Sky Location estimate



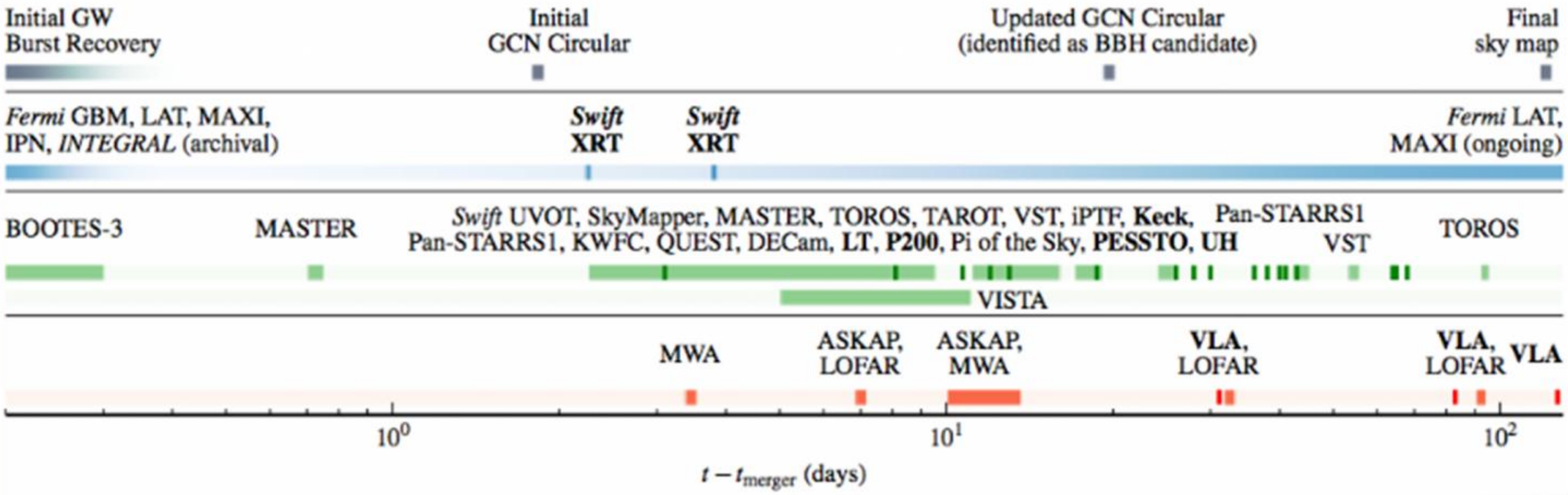
Partnerships for Follow-up Observing

- There’s a lot to be gained from finding counterparts
- Established a standard MOU framework to share information promptly while maintaining confidentiality for event candidates
  - LIGO/Virgo will need to carefully validate the first few detections, at least
  - Once GW detections become routine (≥ 4 published), there will be prompt public alerts of *high-confidence* detections
- Currently LIGO & Virgo have signed MOUs with ~75 groups so far Broad spectrum of transient astronomy researchers and instruments
  - Optical, Radio, X-ray, gamma-ray, VHE
  - Special LVC GCN Notices and Circulars with distribution limited to partners
- Encourage free communication among all “inside the bubble” for multiwavelength follow-up



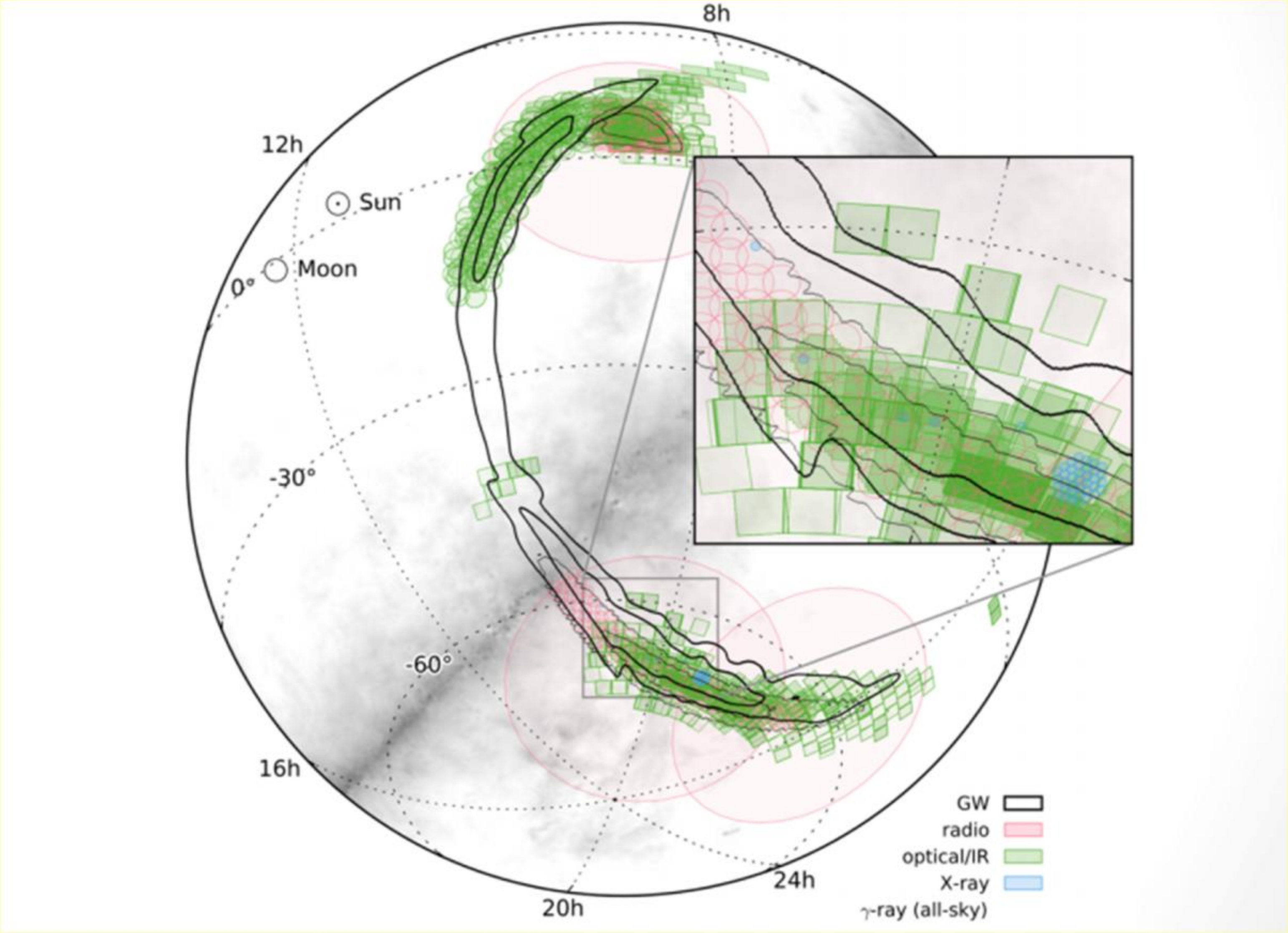
Electro-magnetic Follow-ups

- Timeline



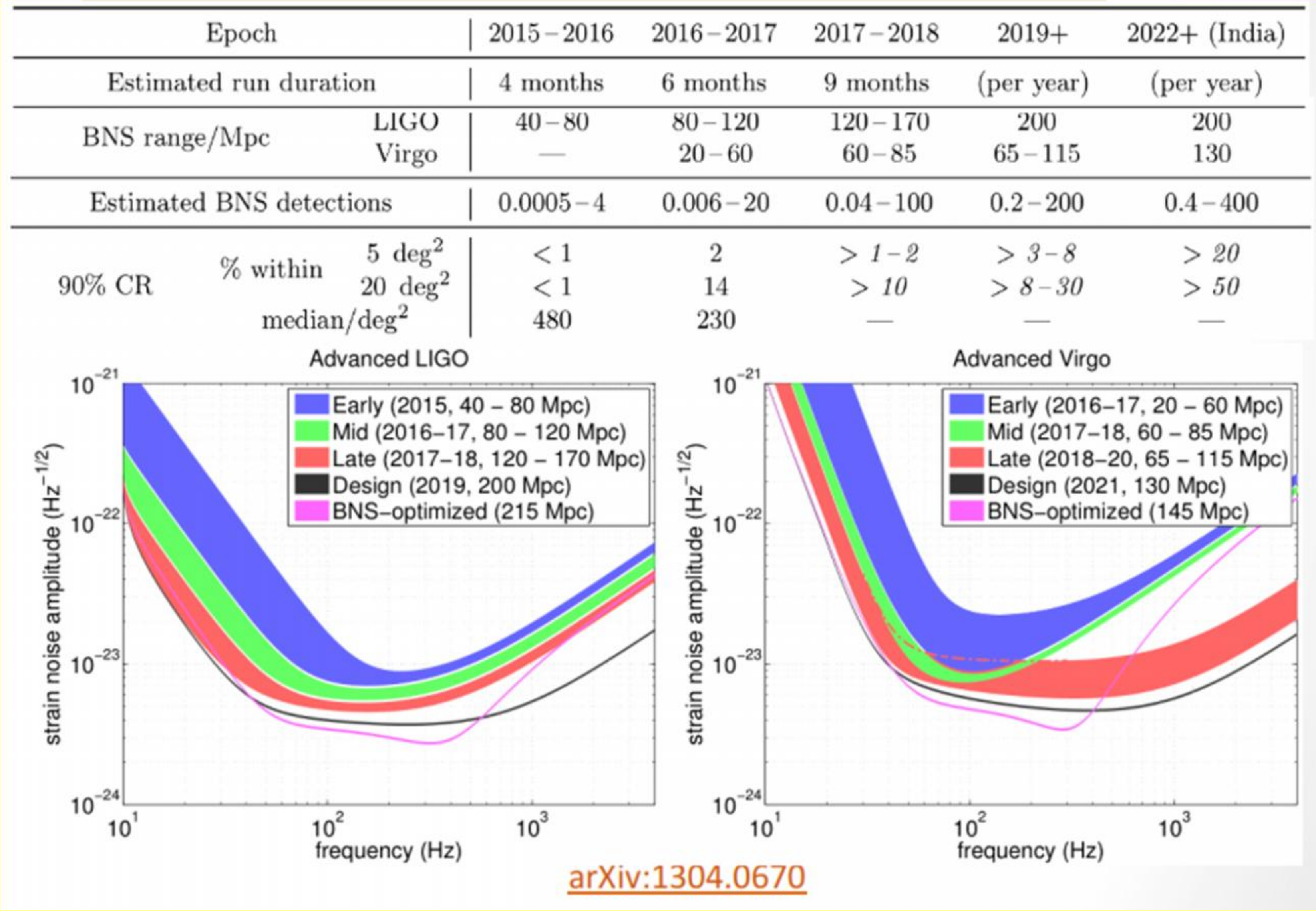
http://arxiv.org/abs/1602.08492

Electro-magnetic Follow-ups



arXiv:1602.08492v2 [astro-ph.HE]

Upcoming Observing Runs

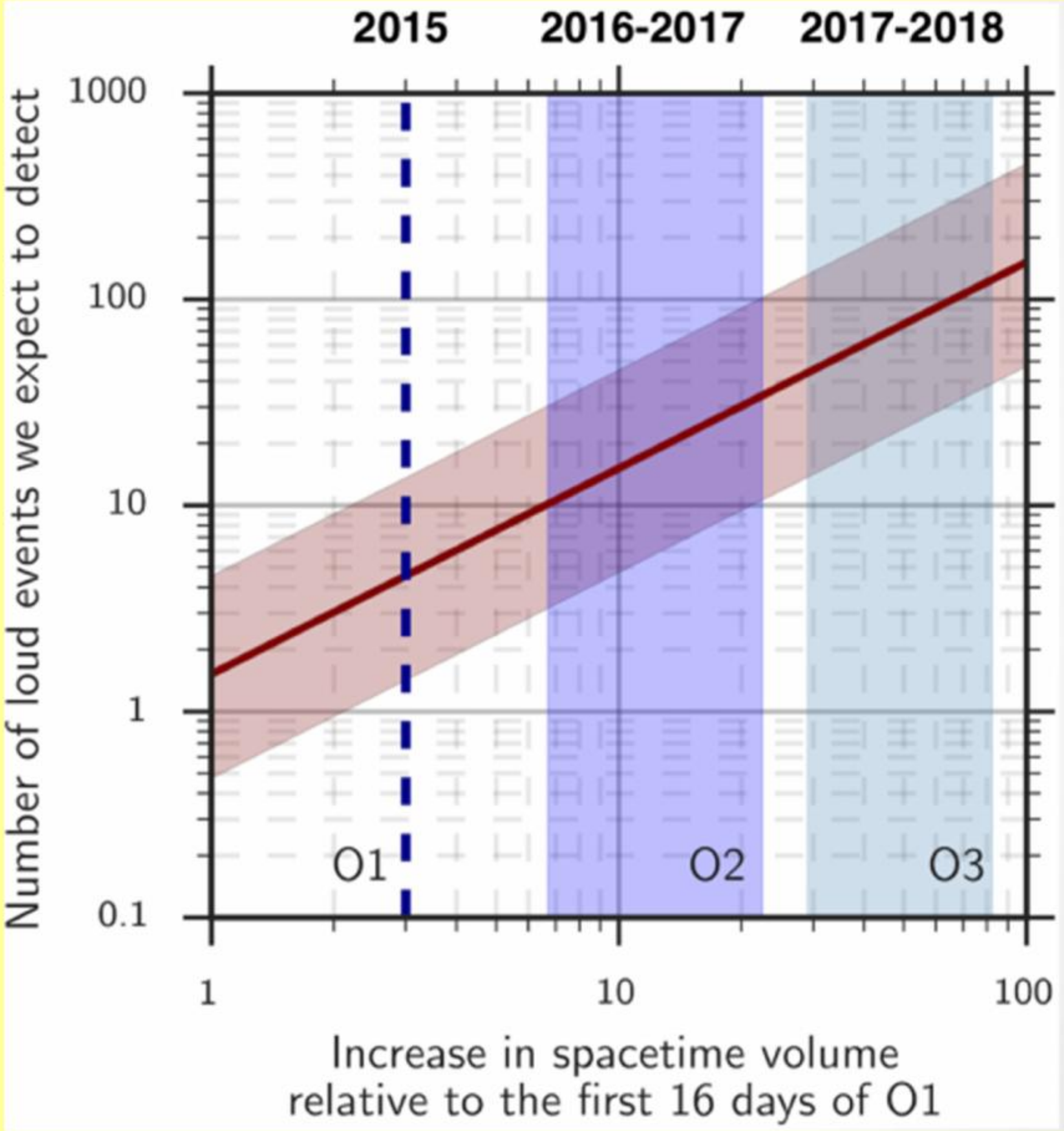


Epoch		2015 – 2016	2016 – 2017	2017 – 2018	2019+	2022+ (India)
Estimated run duration		4 months	6 months	9 months	(per year)	(per year)
BNS range/Mpc	LIGO	40 – 80	80 – 120	120 – 170	200	200
	Virgo	—	20 – 60	60 – 85	65 – 115	130
Estimated BNS detections		0.0005 – 4	0.006 – 20	0.04 – 100	0.2 – 200	0.4 – 400
90% CR	% within 5 deg^2	< 1	2	*> 1 – 2*	*> 3 – 8*	*> 20*
	% within 20 deg^2	< 1	14	*> 10*	*> 8 – 30*	*> 50*
	median/deg^2	480	230	—	—	—

arXiv:1304.0670

Prospects for next observing runs

- The next observing runs target improved sensitivities and longer runs
- Further BBH systems clearly represent a key observing target
- We will also be searching for signals from binary neutron stars, unmodelled transients, stochastic background, rotating neutron stars...



http://arxiv.org/pdf/1602.03842v1.pdf

Beyond black holes

Detect gravitational waves from binary NS and BH-NS systems

- neutron star equation of state
- EM follow-up: multi-messenger astronomy
- observe kilonova signal + joint observations of GRB central engine

Detect and identify gravitational waves from new sources

- generic transients
- continuous emissions from neutron stars

Detect population of gravitational wave signals

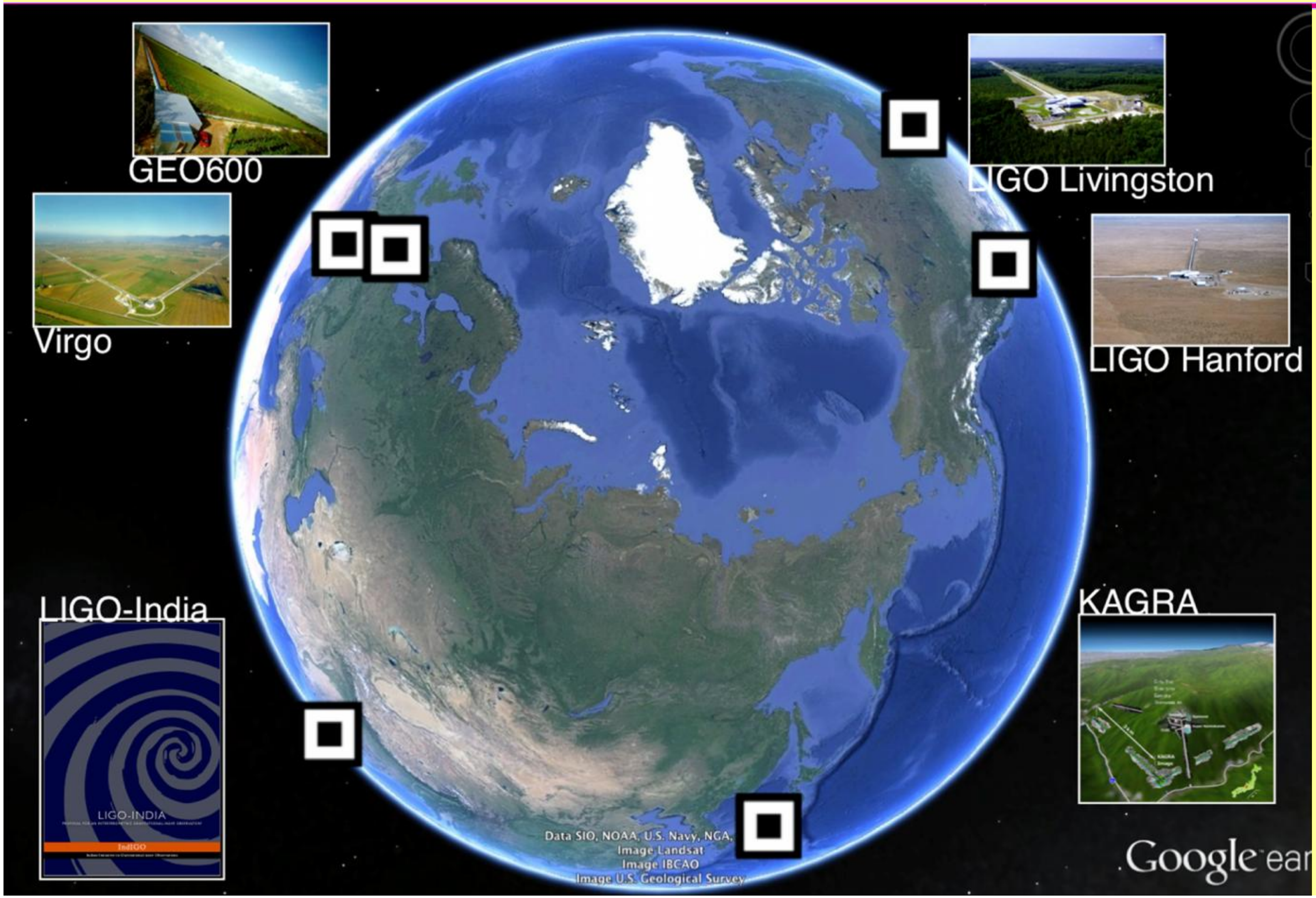
- a population starts to enable an understanding of formation routes

Learn about astrophysical environment of gravitational wave sources

- host galaxies!

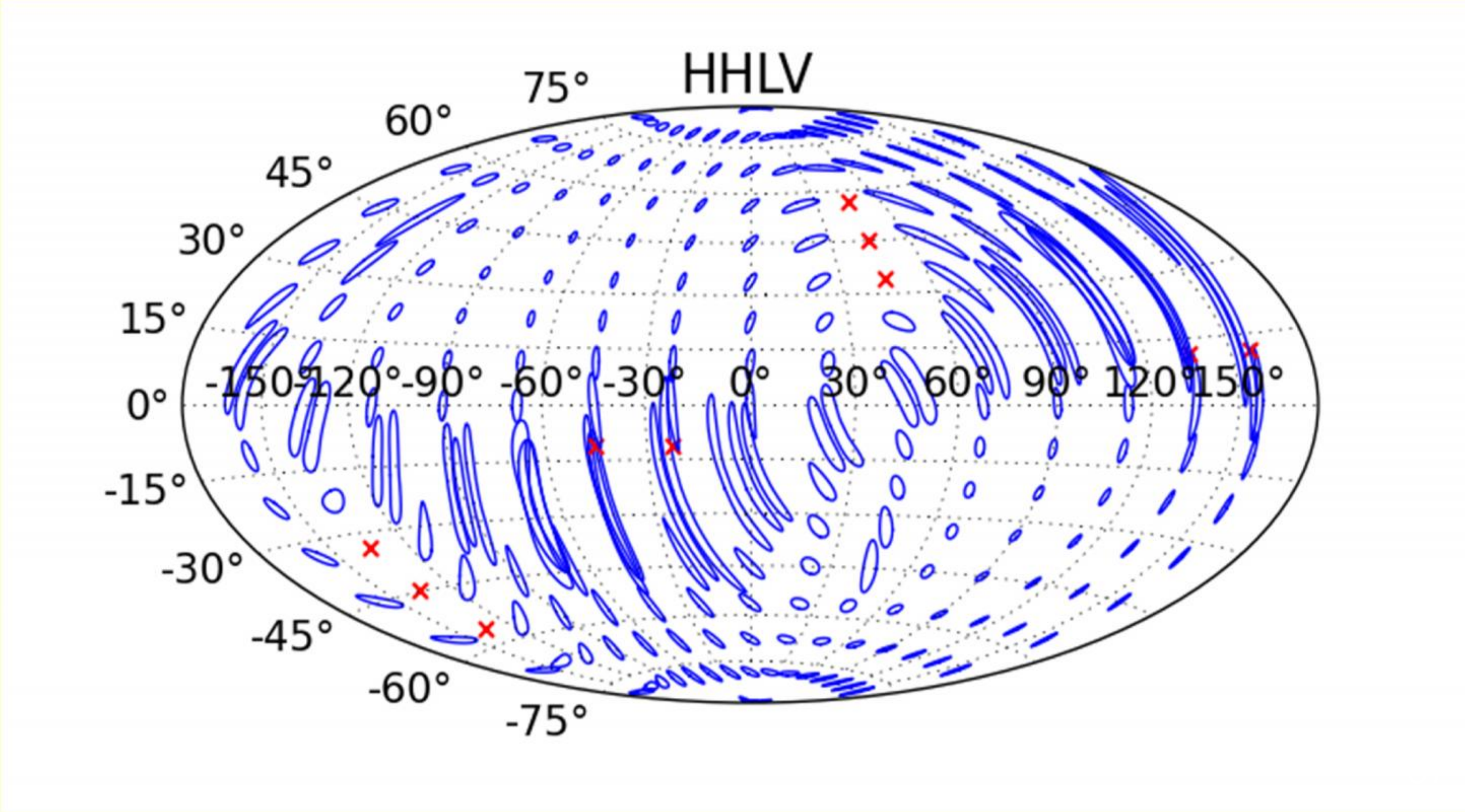
Others?

Gravitational wave detector network ~2020



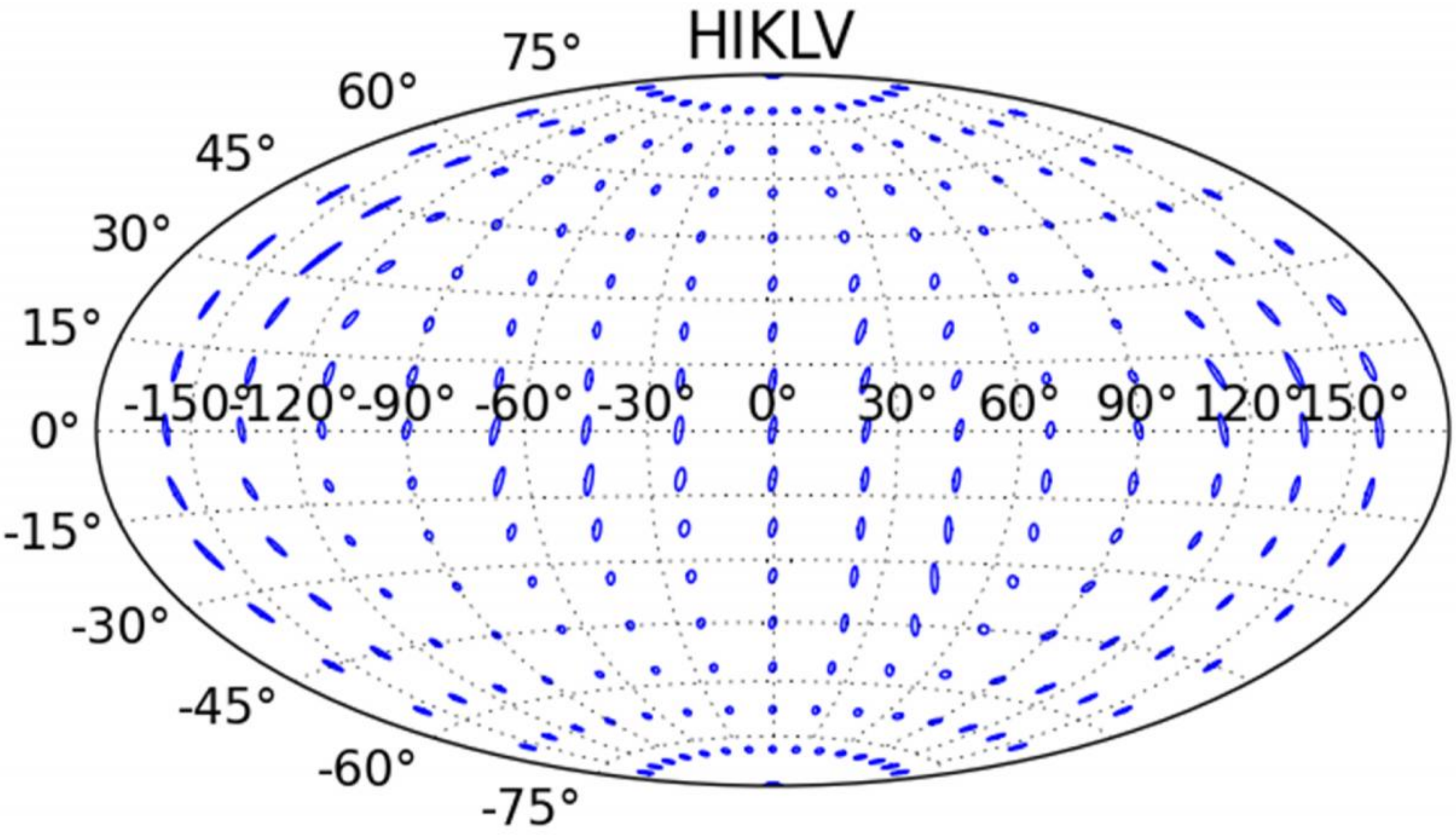
Data SIO, NOAA, U.S. Navy, NGA,
Image Landsat
Image IBCAO
Image U.S. Geological Survey

Sky localisation with 3 detector sites



S. Fairhurst, "*Improved source localization with LIGO India*", arXiv:1205.6611v1

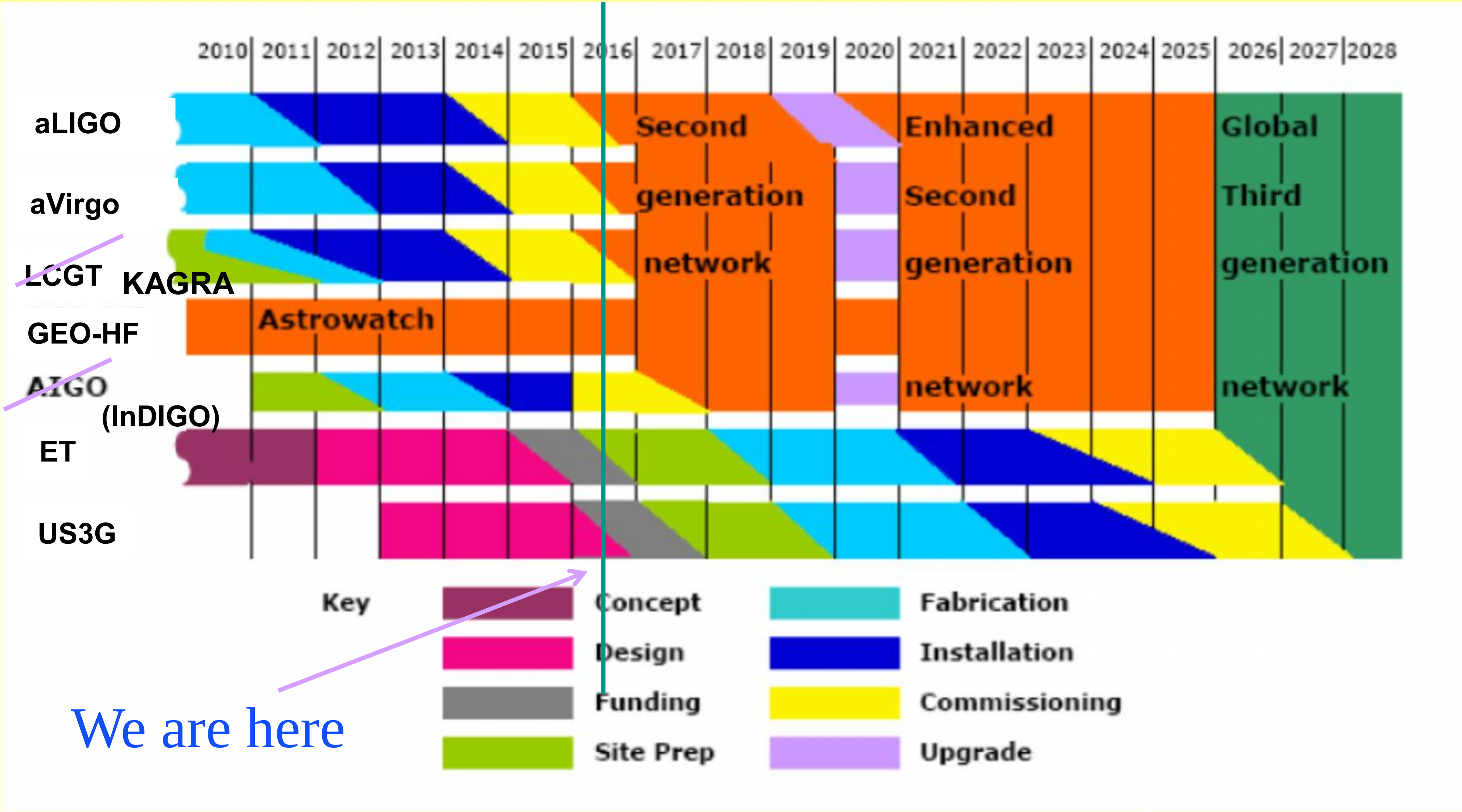
Sky localisation with 5 detector sites



S. Fairhurst, "*Improved source localization with LIGO India*", arXiv:1205.6611v1

The global Gravitational Waves roadmap

GWIC
Gravitational Wave International Committee

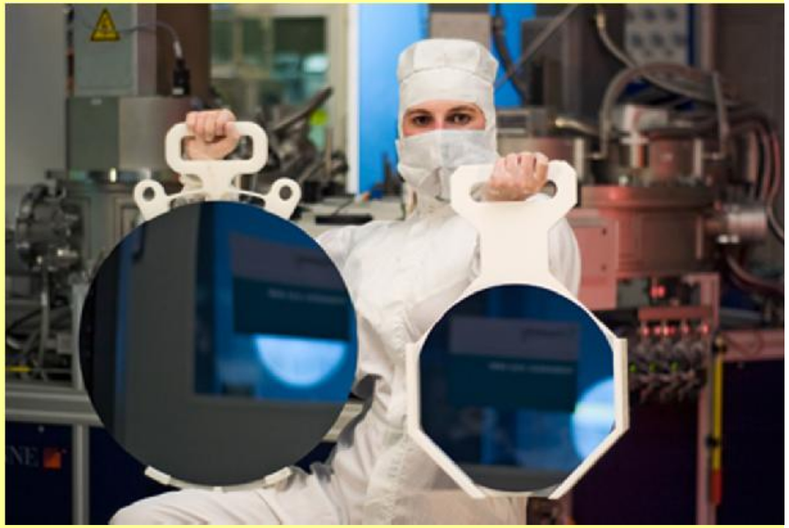


From the Gravitational Wave International Committee (GWIC roadmap - available at: http://gwic.ligo.org/roadmap/)

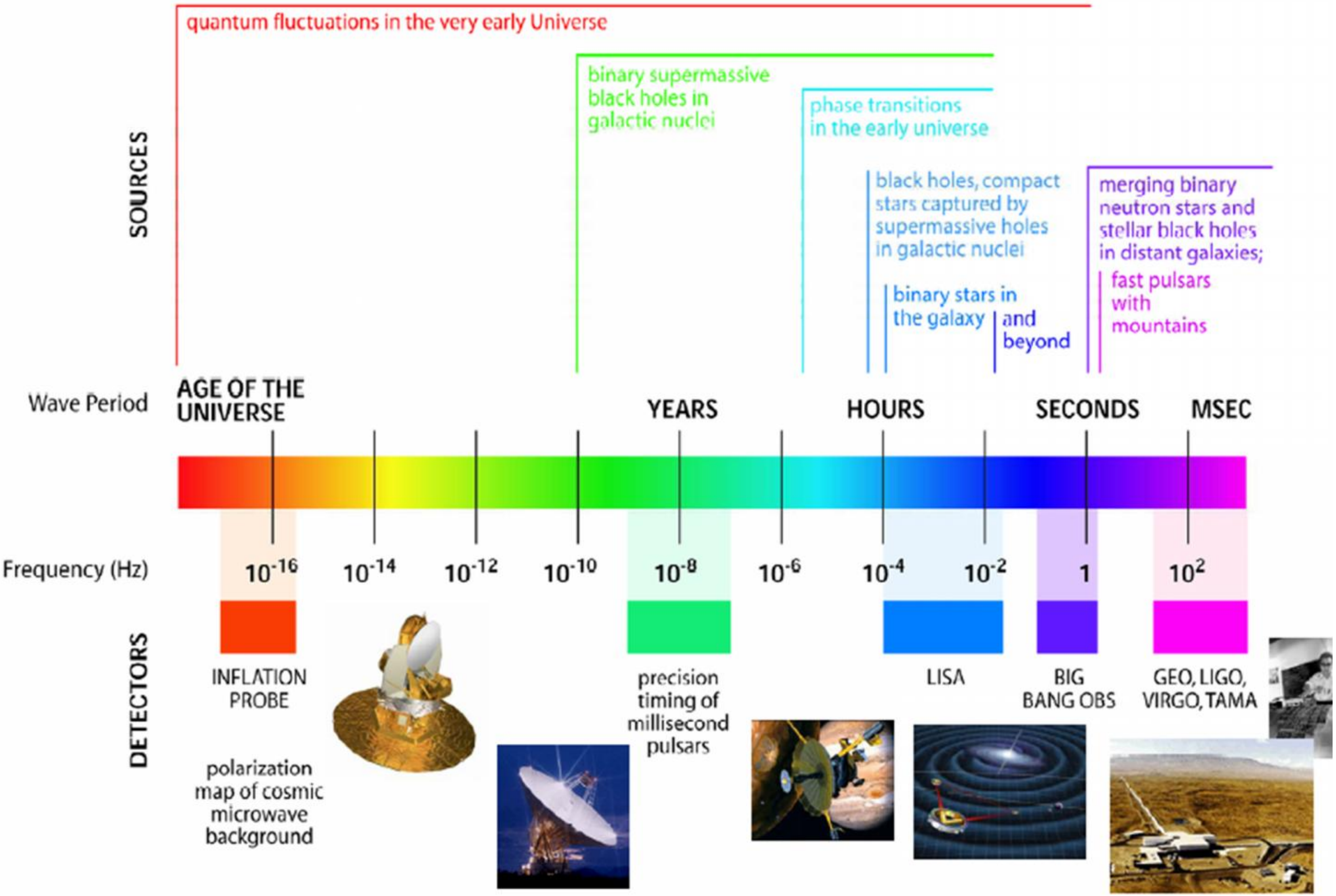
Beyond Advanced detectors

What new technologies are needed?

- Longer arms & underground site
- Higher power than advanced detectors (3 MW)
- Cryogenic optics for low thermal noise
  - Split into two (Xylophone) to make Cryogenic operation and high laser powers compatible
- Larger, heavier optics; non-Gaussian laser beams;
- Laser wavelength (Silicon:1550nm; fused Silica: 1064nm)
- Frequency dependent 10 dB ‚squeezing‘



THE GRAVITATIONAL WAVE SPECTRUM



SOURCES

quantum fluctuations in the very early Universe

binary supermassive black holes in galactic nuclei

phase transitions in the early universe

black holes, compact stars captured by supermassive holes in galactic nuclei

binary stars in the galaxy

and beyond

merging binary neutron stars and stellar black holes in distant galaxies;

fast pulsars with mountains

Wave Period

AGE OF THE UNIVERSE

YEARS

HOURS

SECONDS

MSEC

Frequency (Hz)

10^{-16} 10^{-14} 10^{-12} 10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2} 1 10^{2}

DETECTORS

INFLATION PROBE

polarization map of cosmic microwave background

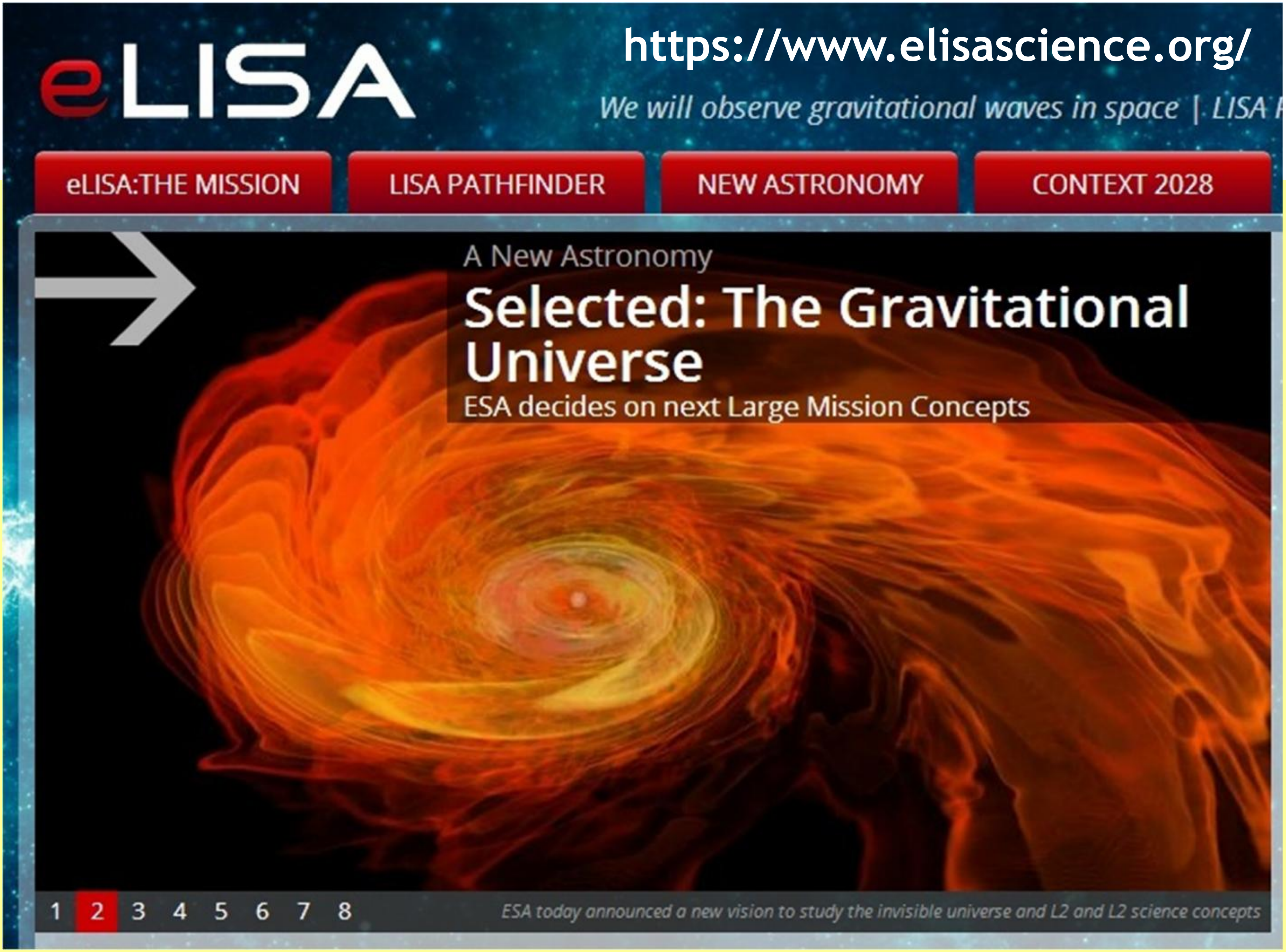
precision timing of millisecond pulsars

LISA

BIG BANG OBS

GEO, LIGO, VIRGO, TAMA

https://www.elisascience.org/



We will observe gravitational waves in space | LISA

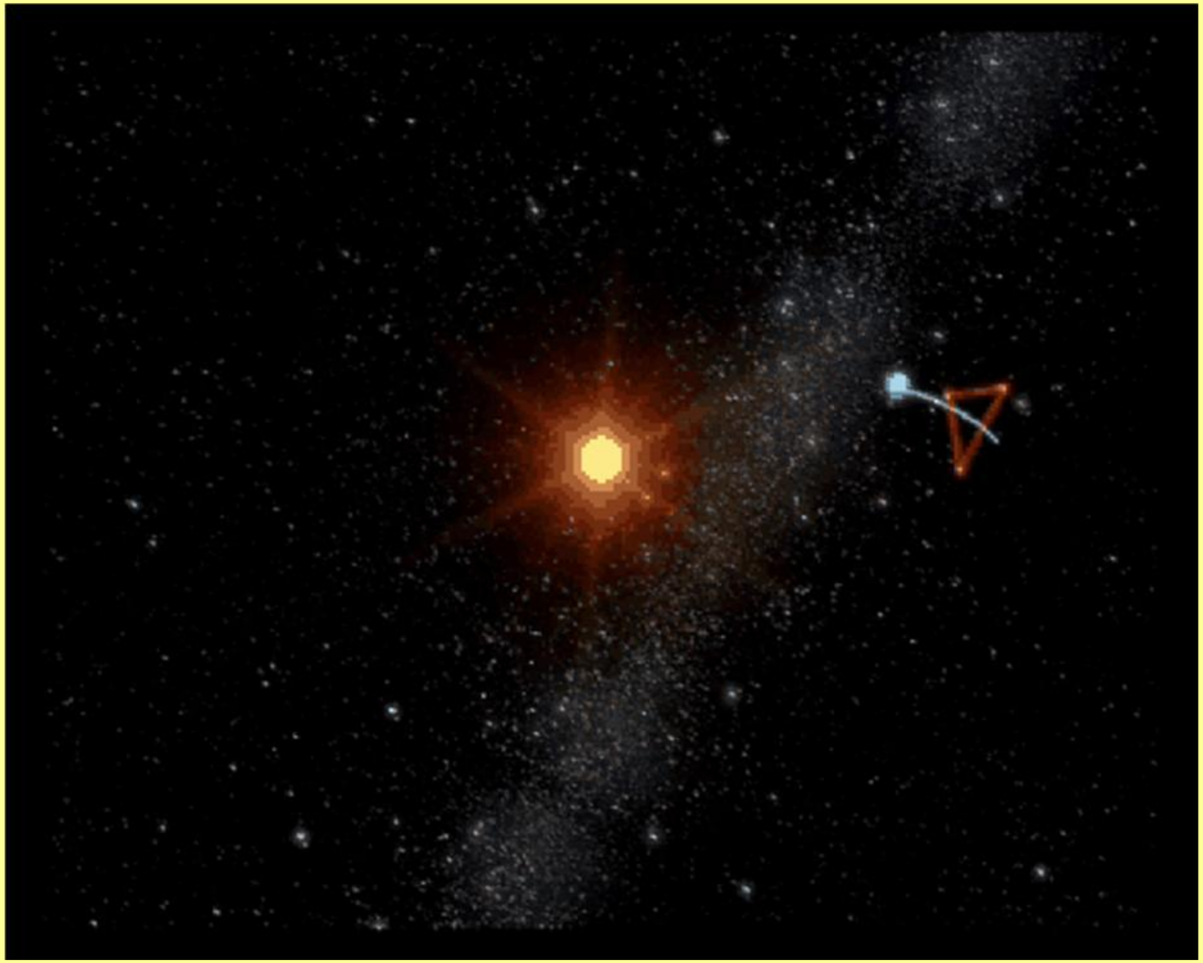
A New Astronomy

Selected: The Gravitational Universe

ESA decides on next Large Mission Concepts

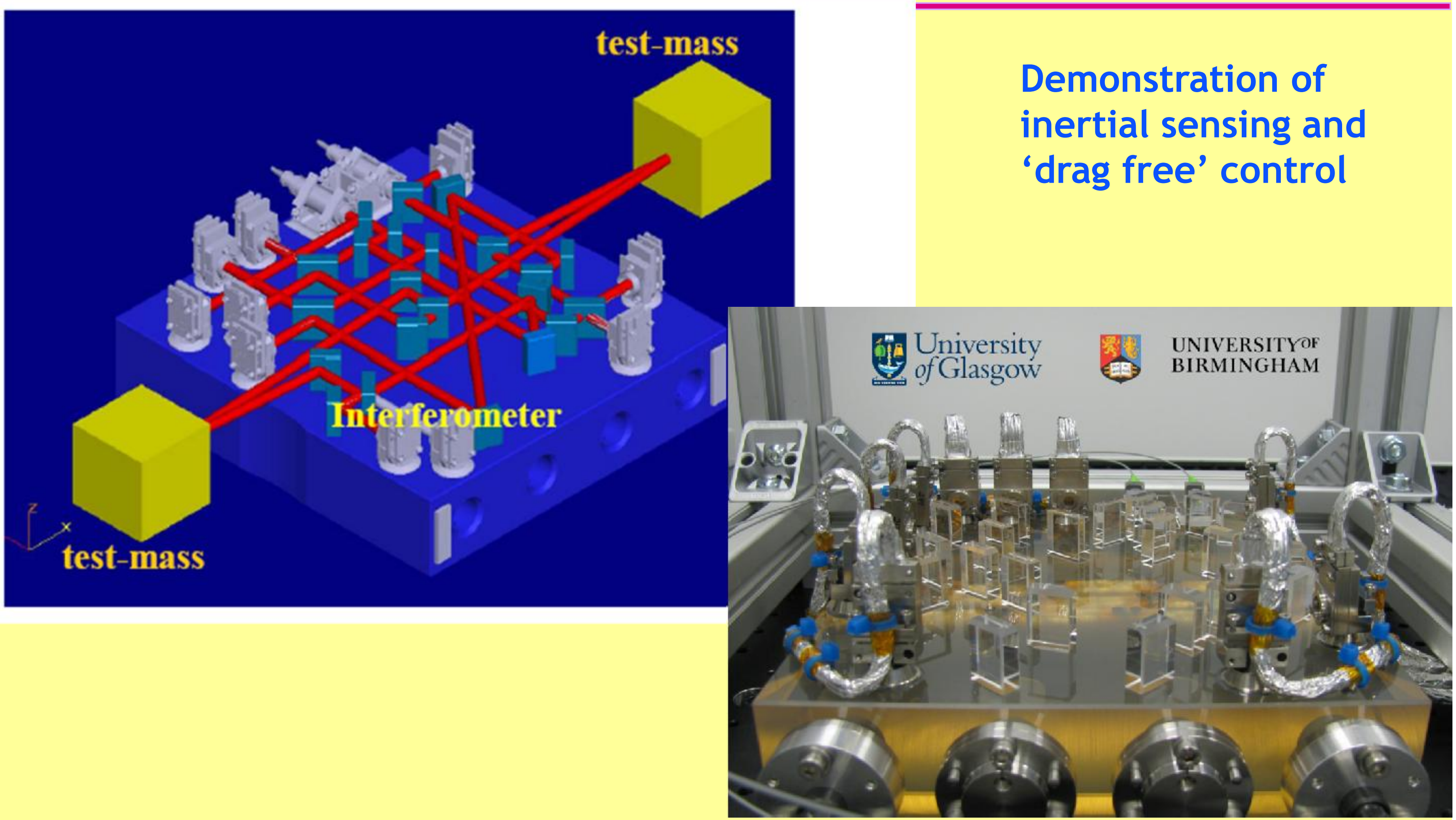
ESA today announced a new vision to study the invisible universe and L2 and L2 science concepts

Space-based detector : ORBIT



Technology demonstrator launched in 2015 (‘LISA Pathfinder’ Concept)

Demonstration of inertial sensing and ‘drag free’ control



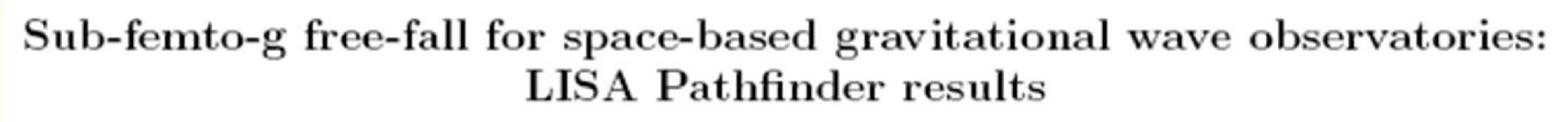
Technology demonstrator launched in 2015 (‘LISA Pathfinder’ Concept)

LISA Pathfinder was shipped to the spaceport in Kourou on Sept 3rd 2015

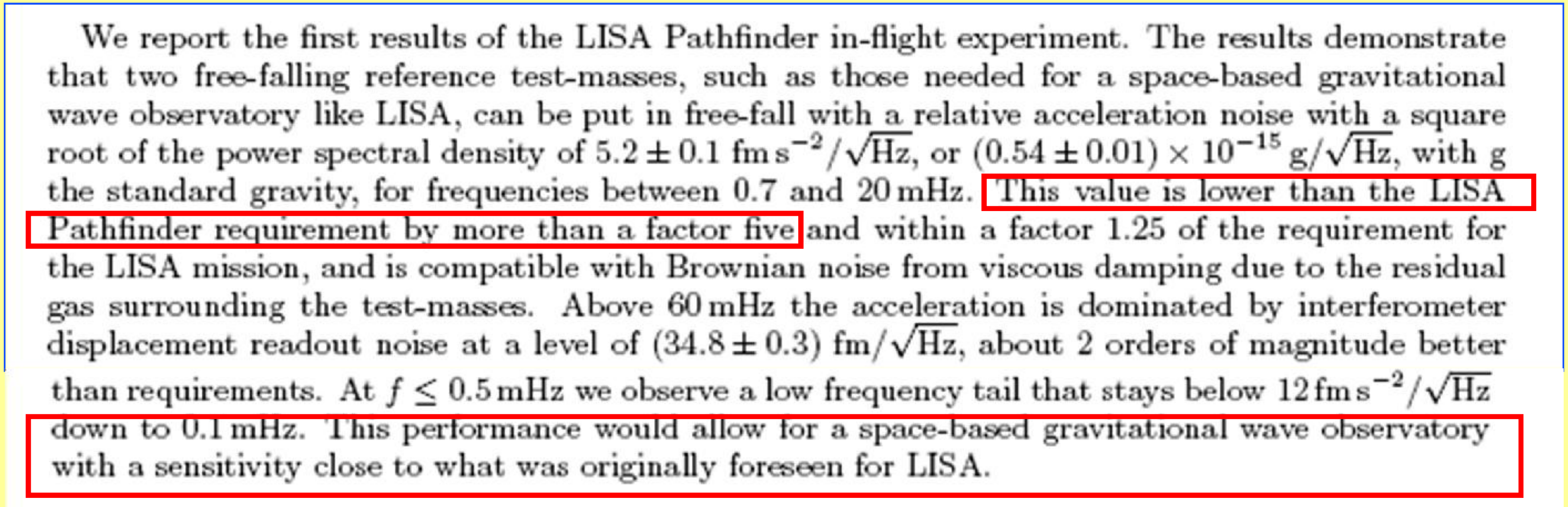
Liftoff of Vega VV06 carrying LISA Pathfinder

- …3 December 2015 from Europe's Spaceport, French Guyana.
- The satellite was placed in a low-earth transfer orbit. From there, LISA Pathfinder used it's own propulsion module in a series of low-earth orbital maneuvers ("slingshot maneuvers") to reach the velocity necessary to reach operational orbit around **Lagrange point L1**.

Published this week in PRL

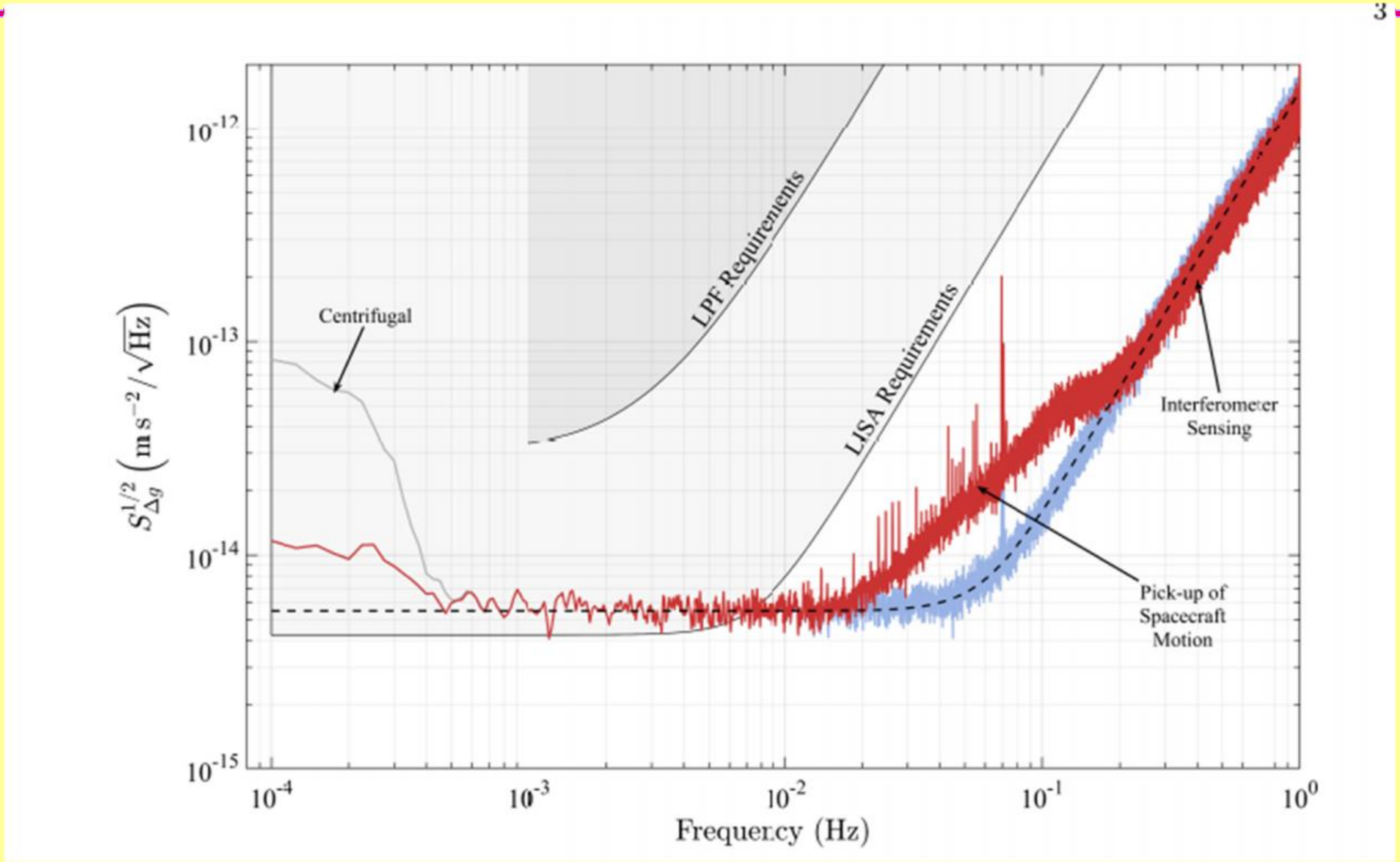


Sub-femto-g free-fall for space-based gravitational wave observatories: LISA Pathfinder results



We report the first results of the LISA Pathfinder in-flight experiment. The results demonstrate that two free-falling reference test-masses, such as those needed for a space-based gravitational wave observatory like LISA, can be put in free-fall with a relative acceleration noise with a square root of the power spectral density of $5.2 \pm 0.1\ \mathrm{fm\,s^{-2}}/\sqrt{\mathrm{Hz}}$, or $(0.54 \pm 0.01) \times 10^{-15}\ \mathrm{g}/\sqrt{\mathrm{Hz}}$, with g the standard gravity, for frequencies between 0.7 and 20 mHz. This value is lower than the LISA Pathfinder requirement by more than a factor five and within a factor 1.25 of the requirement for the LISA mission, and is compatible with Brownian noise from viscous damping due to the residual gas surrounding the test-masses. Above 60 mHz the acceleration is dominated by interferometer displacement readout noise at a level of $(34.8 \pm 0.3)\ \mathrm{fm}/\sqrt{\mathrm{Hz}}$, about 2 orders of magnitude better than requirements. At $f \leq 0.5\,\mathrm{mHz}$ we observe a low frequency tail that stays below $12\ \mathrm{fm\,s^{-2}}/\sqrt{\mathrm{Hz}}$ down to 0.1 mHz. This performance would allow for a space-based gravitational wave observatory with a sensitivity close to what was originally foreseen for LISA.

Pathfinder noise levels



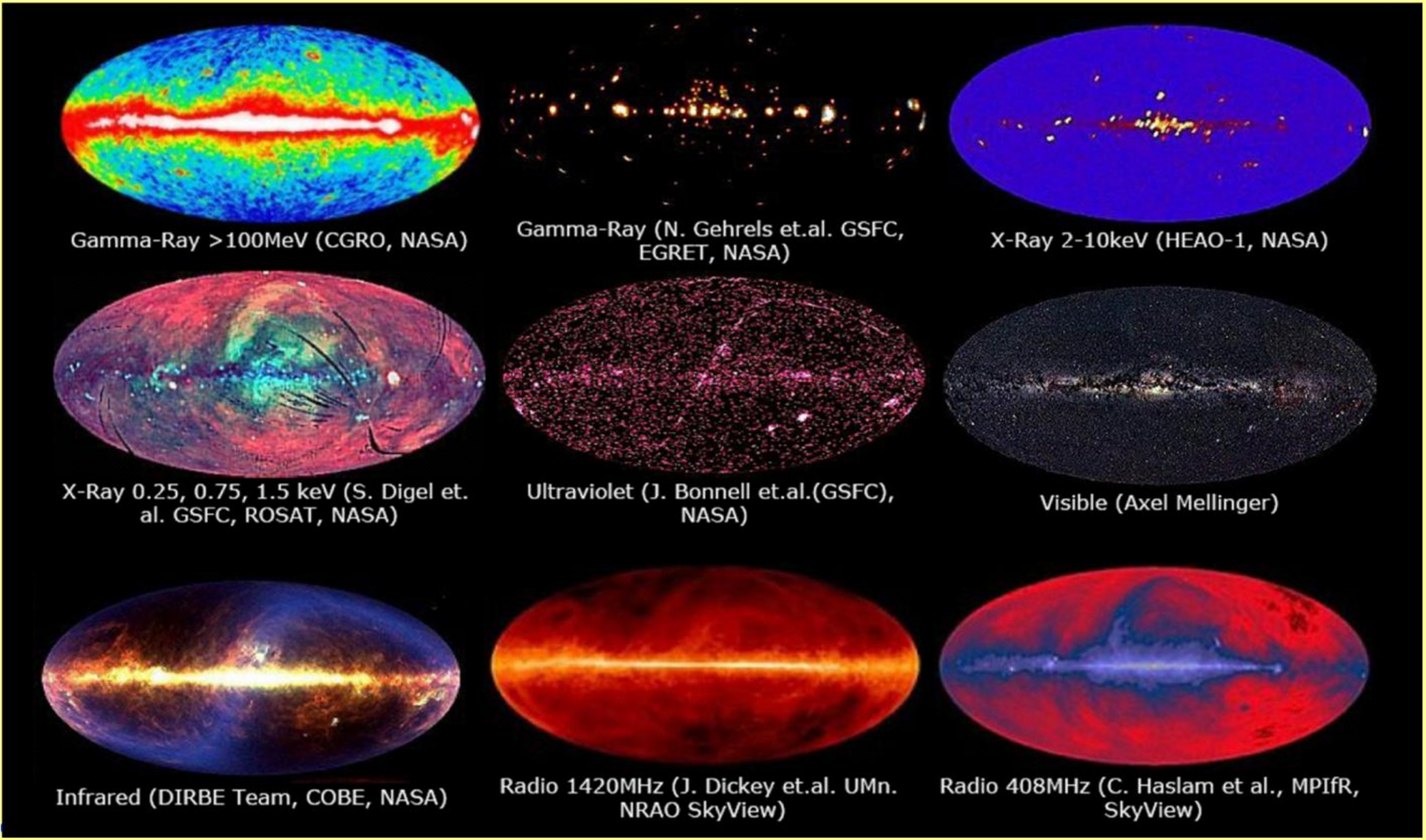
The Network of Gravitational Wave Facilities

- Advanced Detectors have made first detections! – network data to follow
  - Advanced LIGO (USA/International)
  - Advanced VIRGO (Italy/France/Netherlands)
  - KAGRA (Japan)
  - GEO-HF (UK/Germany)

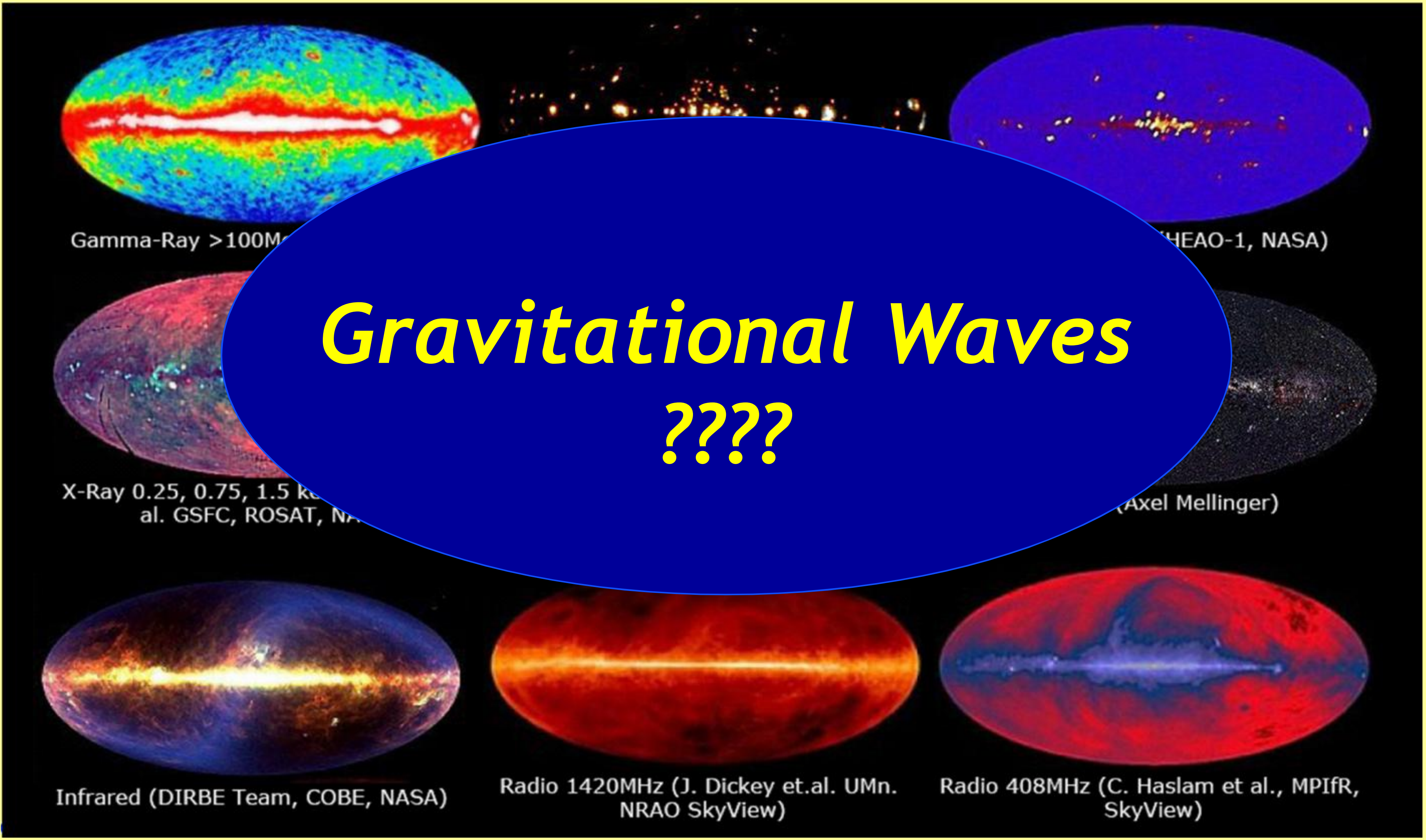
- 3rd generation
  - Lab research underway around the globe
  - 3rd generation detector in Europe? – The Einstein Telescope
  - Future upgrades in the US?

- Spaced based detector
  - Demonstrator launched 2015
  - Mission launch 2034?

As each new window on the universe has opened, it has led to completely unexpected discoveries.



What more discoveries will Gravitational Waves reveal?



Gravitational Waves

????

Latest news:
Upcoming webcast – this evening …

Wednesday, 15 June, 10:15 am PDT
Latest News from the LIGO Scientific Collaboration

Webcast link: https://aas.org/aas-briefing-webcast

Gabriela González
LIGO Scientific Collaboration Spokesperson
(Louisiana State University)

Fulvio Ricci
Virgo Spokesperson
(University of Rome Sapienza & INFN Rome)

Dave Reitze
Executive Director of LIGO
(Caltech)