GW150914:
First Observation Of Gravitational Waves

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University of Roma Tor Vergata and INFN

For the LIGO Scientific Collaboration
and the Virgo Collaboration

The Discovery Paper

Observation of Gravitational Waves from a Binary Black Hole Merger

The LIGO Scientific Collaboration and The Virgo Collaboration

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-wave Observatory (LIGO) simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 Hz 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 $5.1\,\sigma$. 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 $36^{+5}_{-4}\,\mathrm{M}_\odot$ and $29^{+4}_{-4}\,\mathrm{M}_\odot$, and the final black hole mass is $62^{+4}_{-4}\,\mathrm{M}_\odot$, with $3.0^{+0.5}_{-0.5}\,\mathrm{M}_\odot c^2$ 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.

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GWs in a nutshell

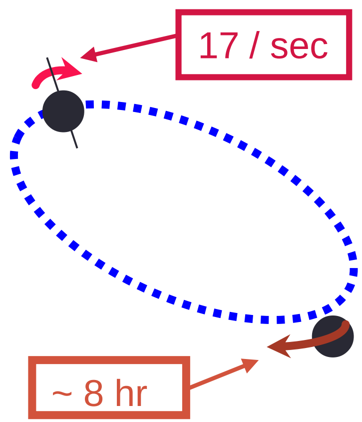
- Gravitational waves are dynamic fluctuations in the fabric of space-time, propagating at the speed of light
- Predicted by Einstein 100 years ago
- First indirect confirmation by Hulse & Taylor

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

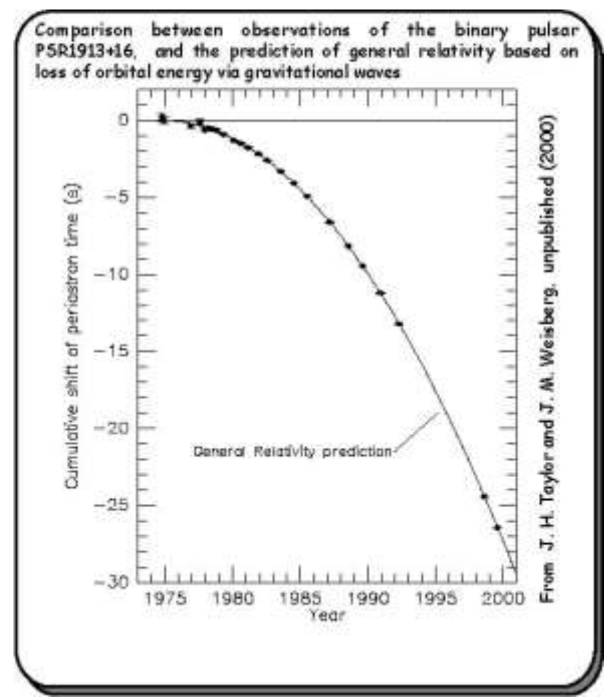
$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

$$\left| h_{\mu\nu} \right| << 1 \qquad \left(\nabla^2 - \frac{1}{c^2} \frac{\partial^2}{\partial t^2} \right) h_{\mu\nu} = 0$$

$$h_{\mu\nu} = h_{+}(t - z/c) + h_{x}(t - z/c)$$

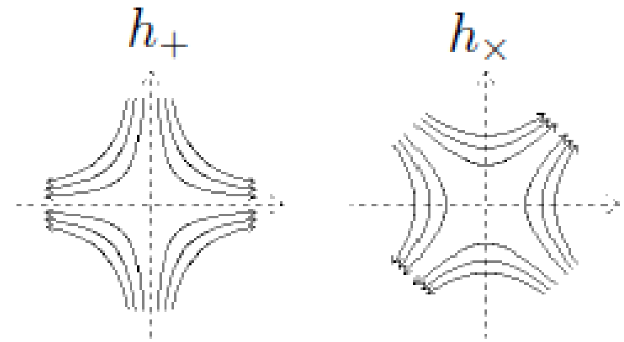


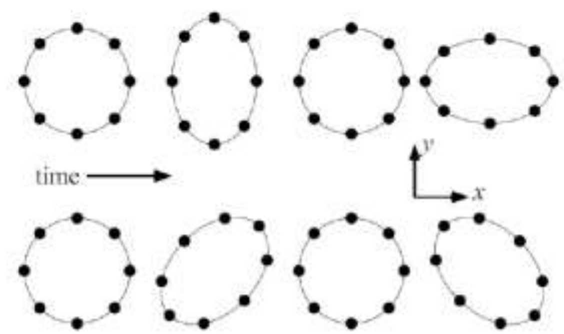
$dP_b/dt = -(2.40 \pm 0.01) \times 10^{-12}$ s/s



GWs in a nutshell

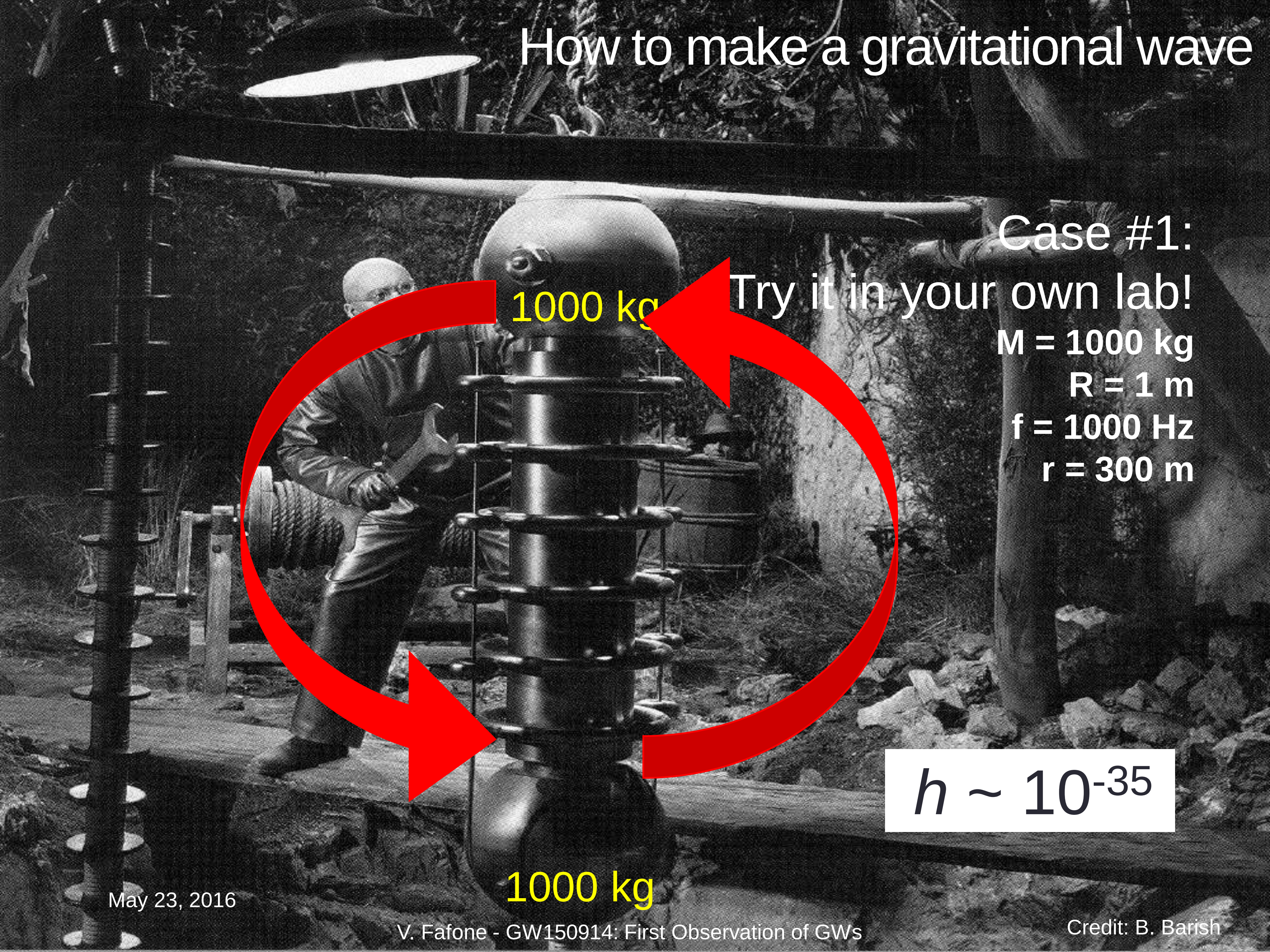
- Emitted from accelerating mass distributions (quadrupole mass moment – no dipole radiation)
- GWs carry *direct* information about the relativistic motion of bulk matter
- GWs interaction with matter is very very weak
  - Possibility to measure events very far from us (in space and time)
  - Their detection is a technical challenge





$$\boxed{\Delta l = \frac{h}{2} l}$$

How to make a gravitational wave



Case #1:

Try it in your own lab!

M = 1000 kg
R = 1 m
f = 1000 Hz
r = 300 m

$h \sim 10^{-35}$

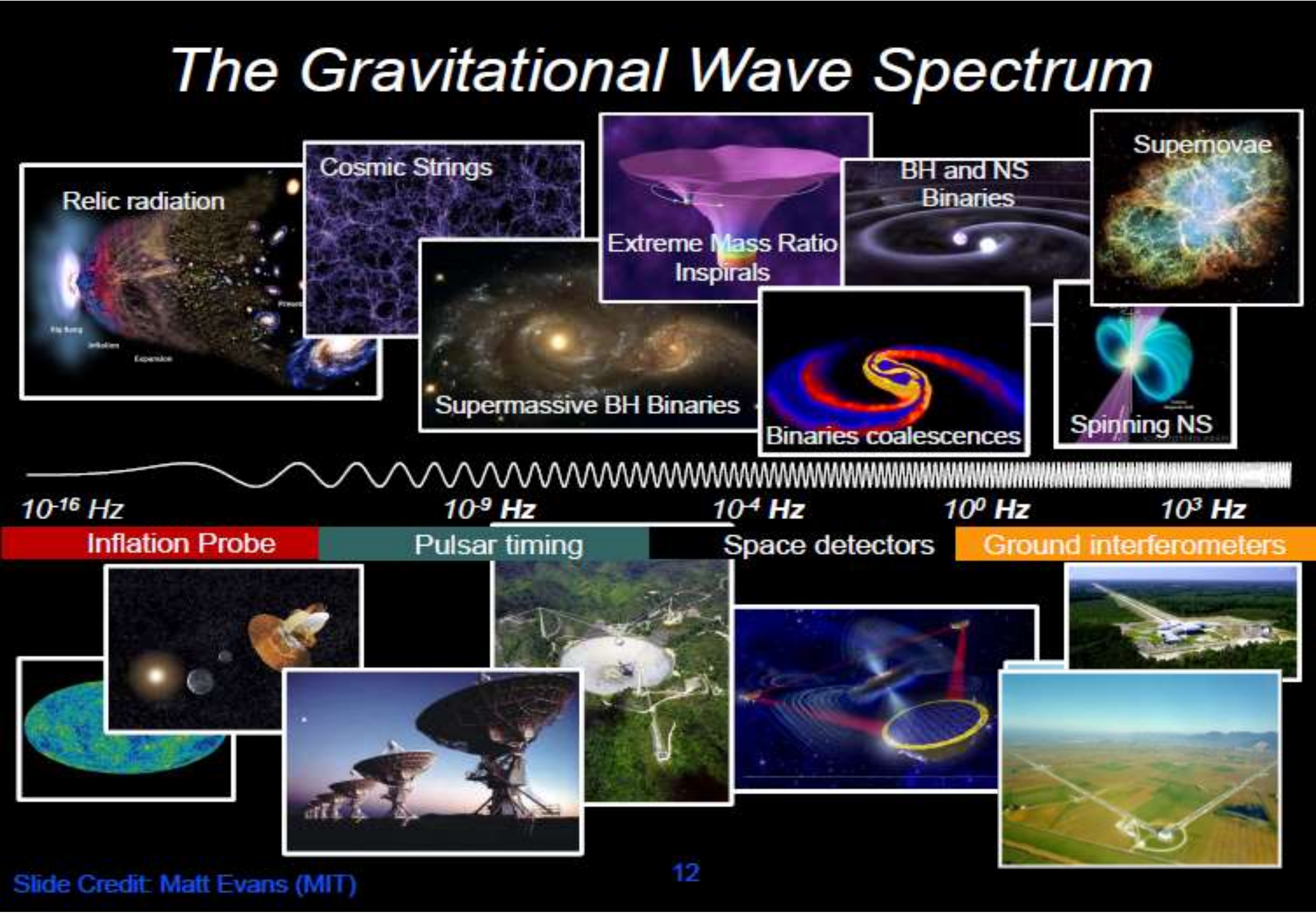
Credit: B. Barish

How to make a gravitational wave that might be detectable

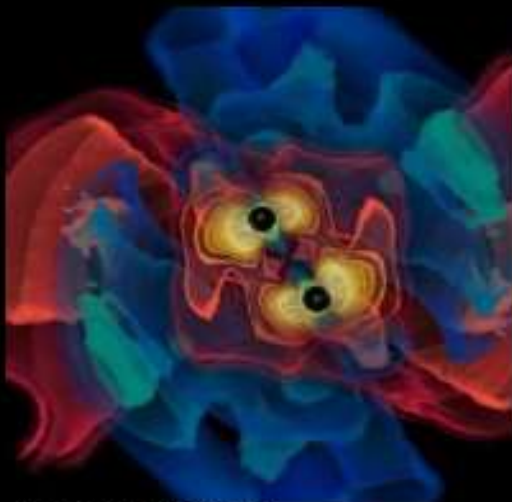
- Consider 1.4 solar mass binary neutron star pair
  - M = 1.4 $M_\odot$
  - R = 20 km
  - f = 400 Hz
  - r = 5 10^{23} m (15Mpc)

$$h \approx \frac{4\pi^2 G M R^2 f_{orb}^2}{c^4 r} \quad \Rightarrow \quad h \sim 10^{-21}$$

Credit: T. Strohmayer and D. Berry


The Gravitational Wave Spectrum
Relic radiation
Cosmic Strings
Extreme Mass Ratio Inspirals
BH and NS Binaries
Supernovae
Supermassive BH Binaries
Binaries coalescences
Spinning NS
10-16 Hz
10-9 Hz
10-4 Hz
100 Hz
103 Hz
Inflation Probe
Pulsar timing
Space detectors
Ground interferometers
Slide Credit: Matt Evans (MIT)
12

Astrophysical targets for ground-based detectors

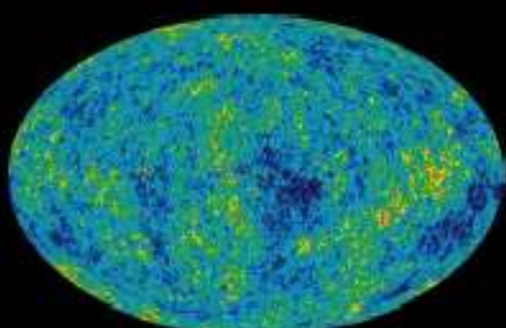

Credit: AEI, CCT, LSU

Coalescing Binary Systems

- Neutron stars, low mass black holes, and NS/BS systems

'Bursts'

- galactic asymmetric core collapse supernovae
- cosmic strings
- ???


NASA/WMAP Science Team

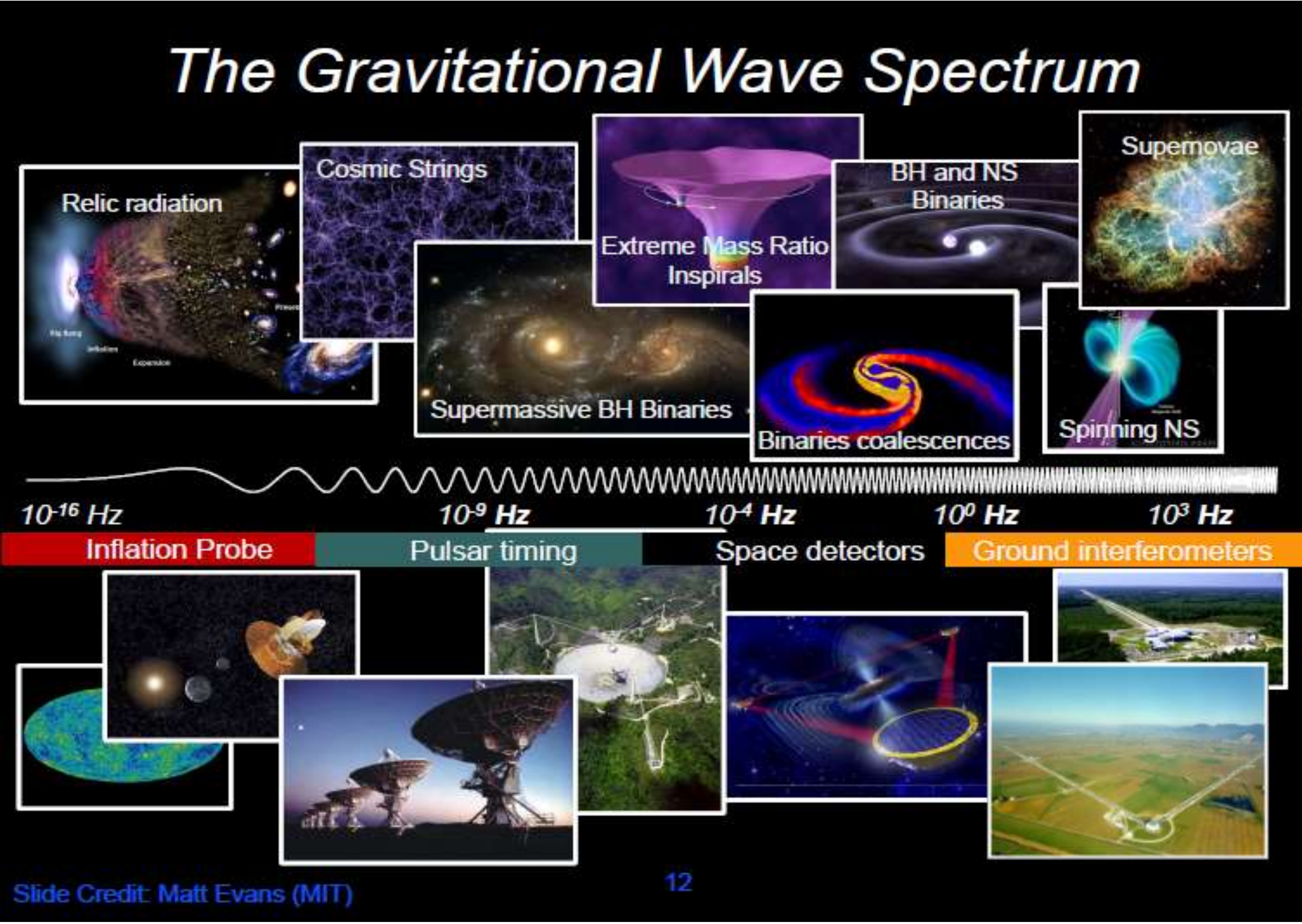
Stochastic GWs

- Incoherent background from primordial GWs or an ensemble of unphased sources
- primordial GWs unlikely to detect, but can bound in the 10-10000 Hz range


Casey Reed, Penn State

Continuous Sources

- Spinning neutron stars
- probe crustal deformations, 'EOS, quarki-ness'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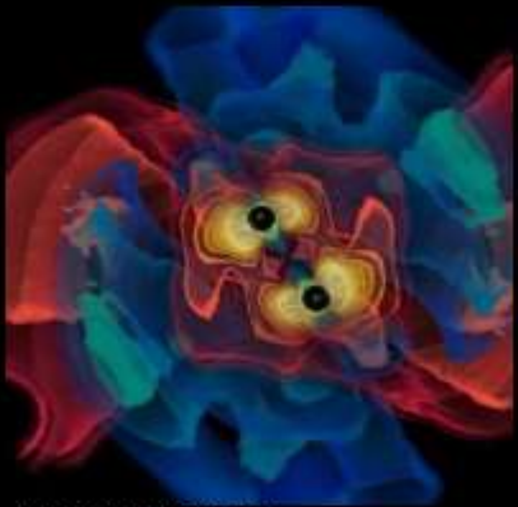

Credit: AEI, CCT, LSU

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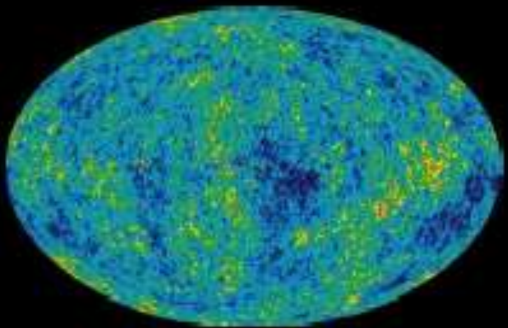

NASA/WMAP Science Team

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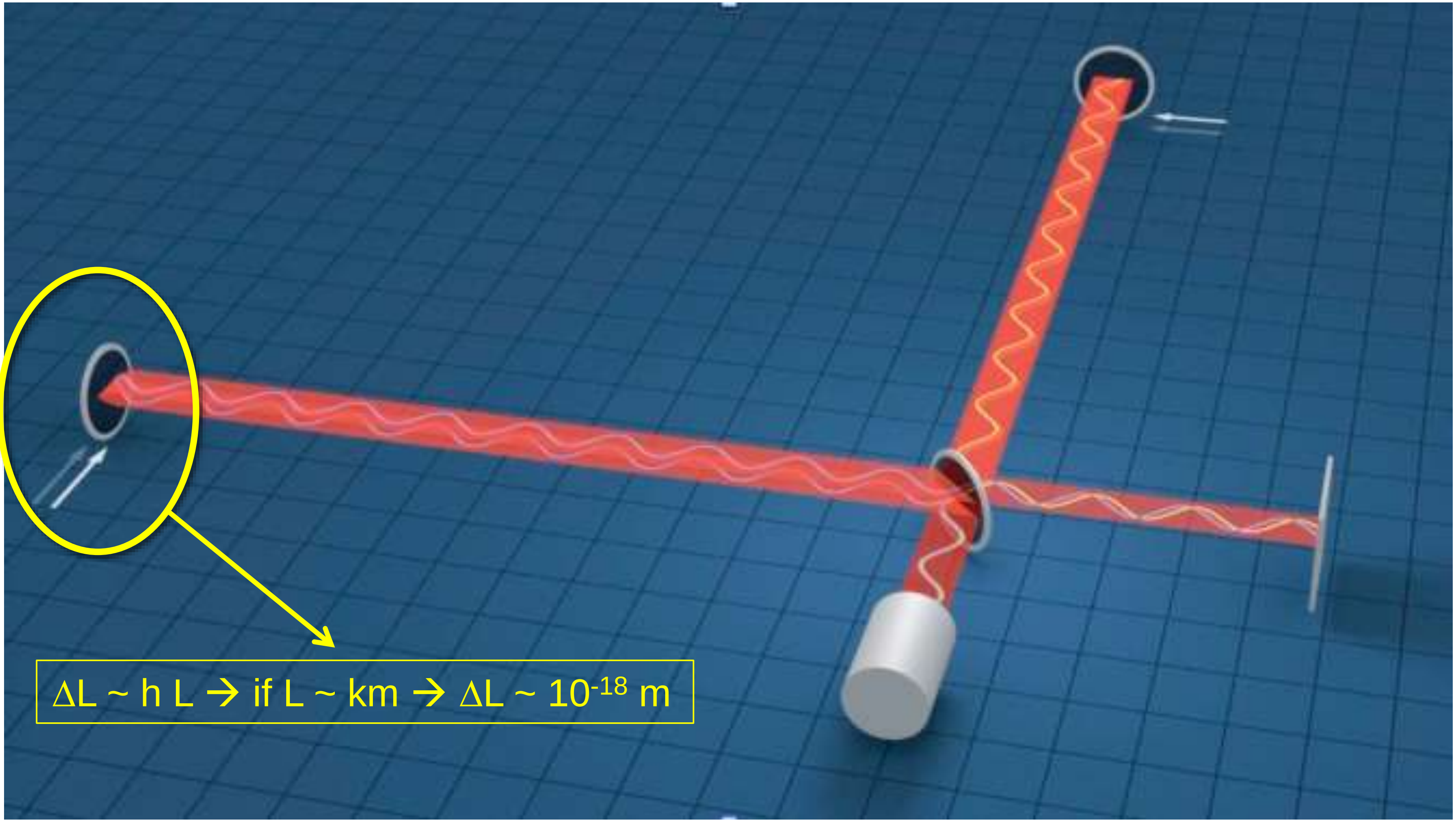
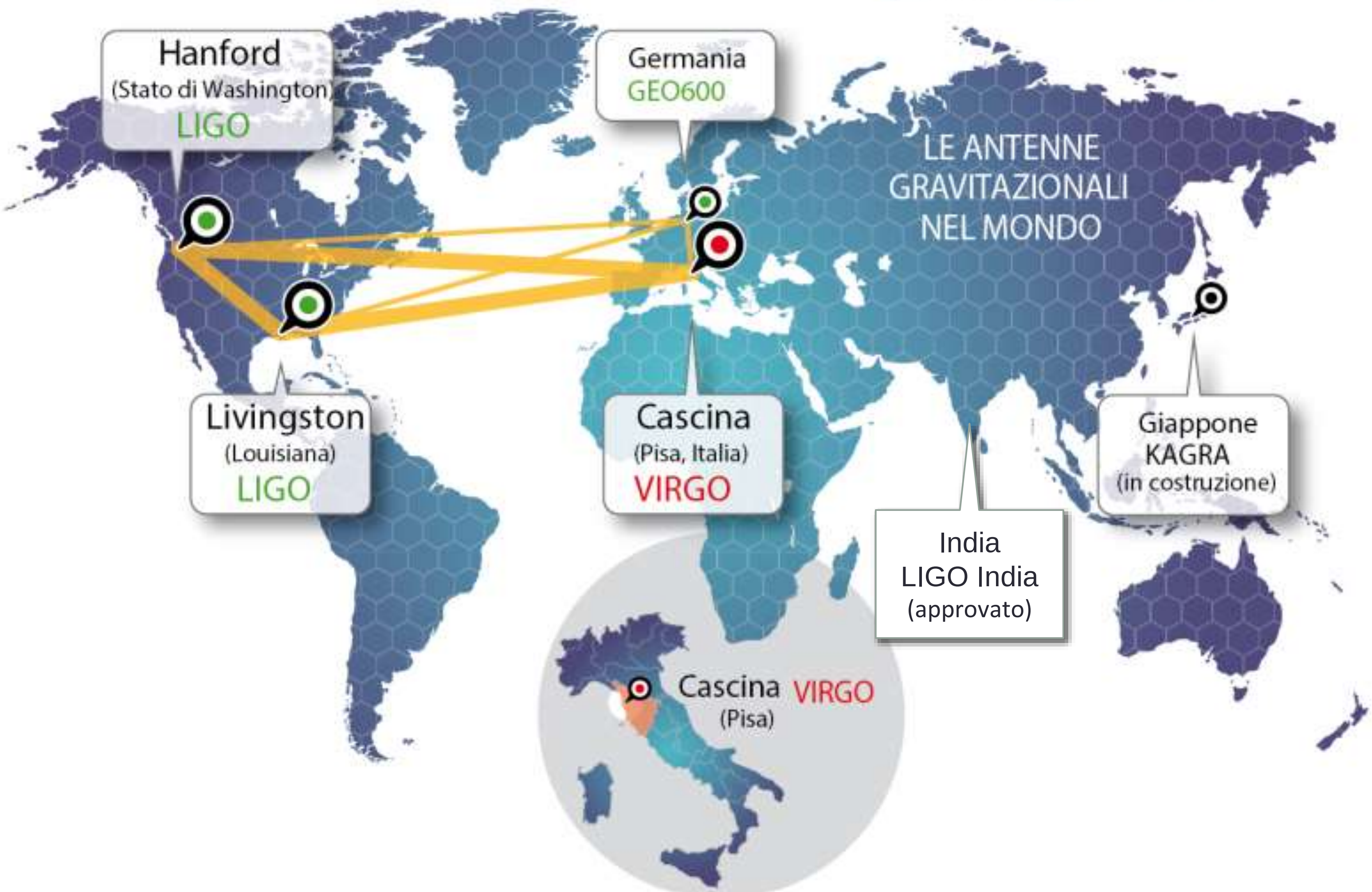
Interferometer: a GW transducer



Global Network of Detectors



India
LIGO India
(approvato)

LIGO Scientific Collaboration

www.ligo.org

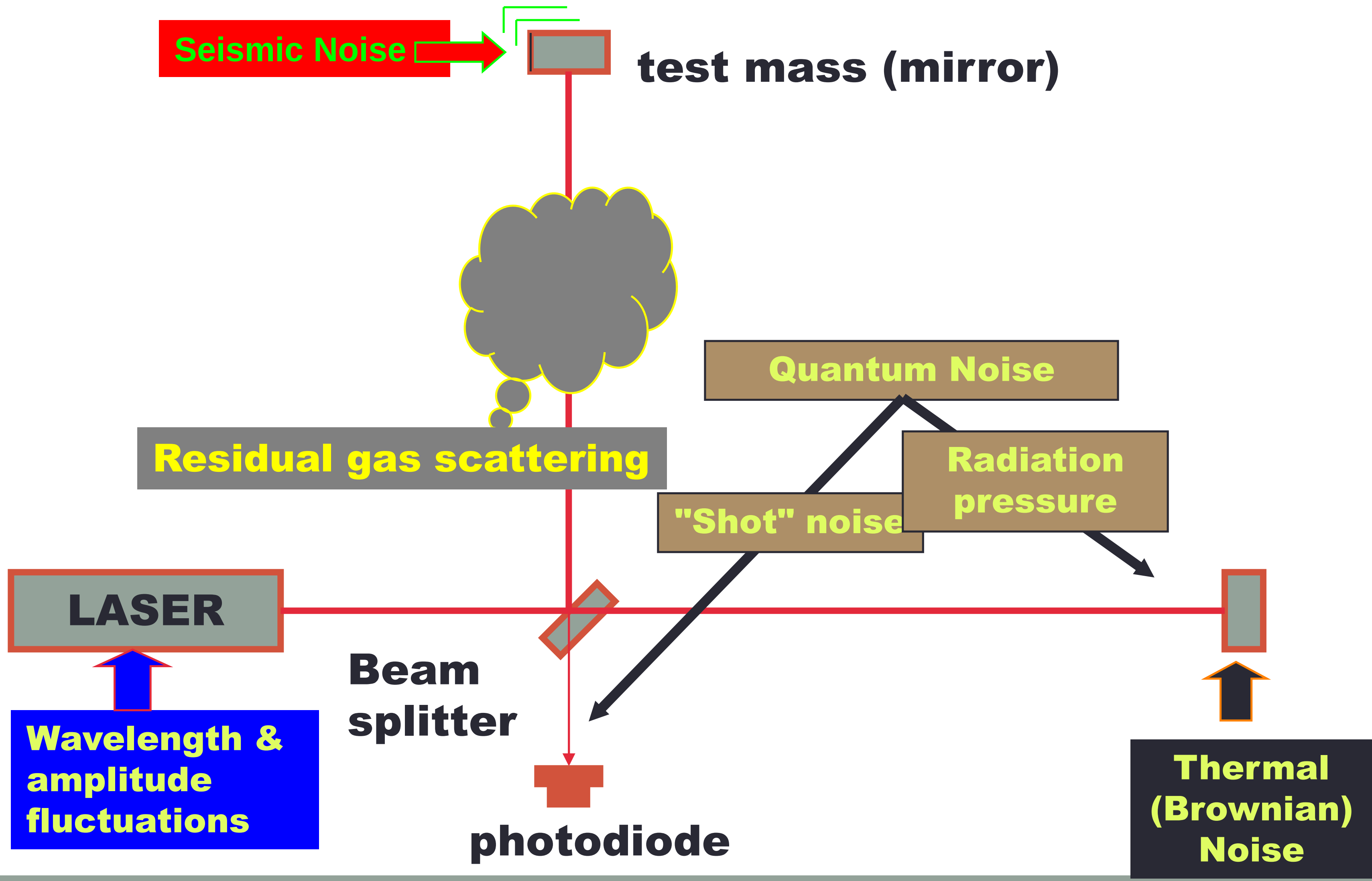
900+ members, 80+ institutions, 16 countries

Virgo Collaboration

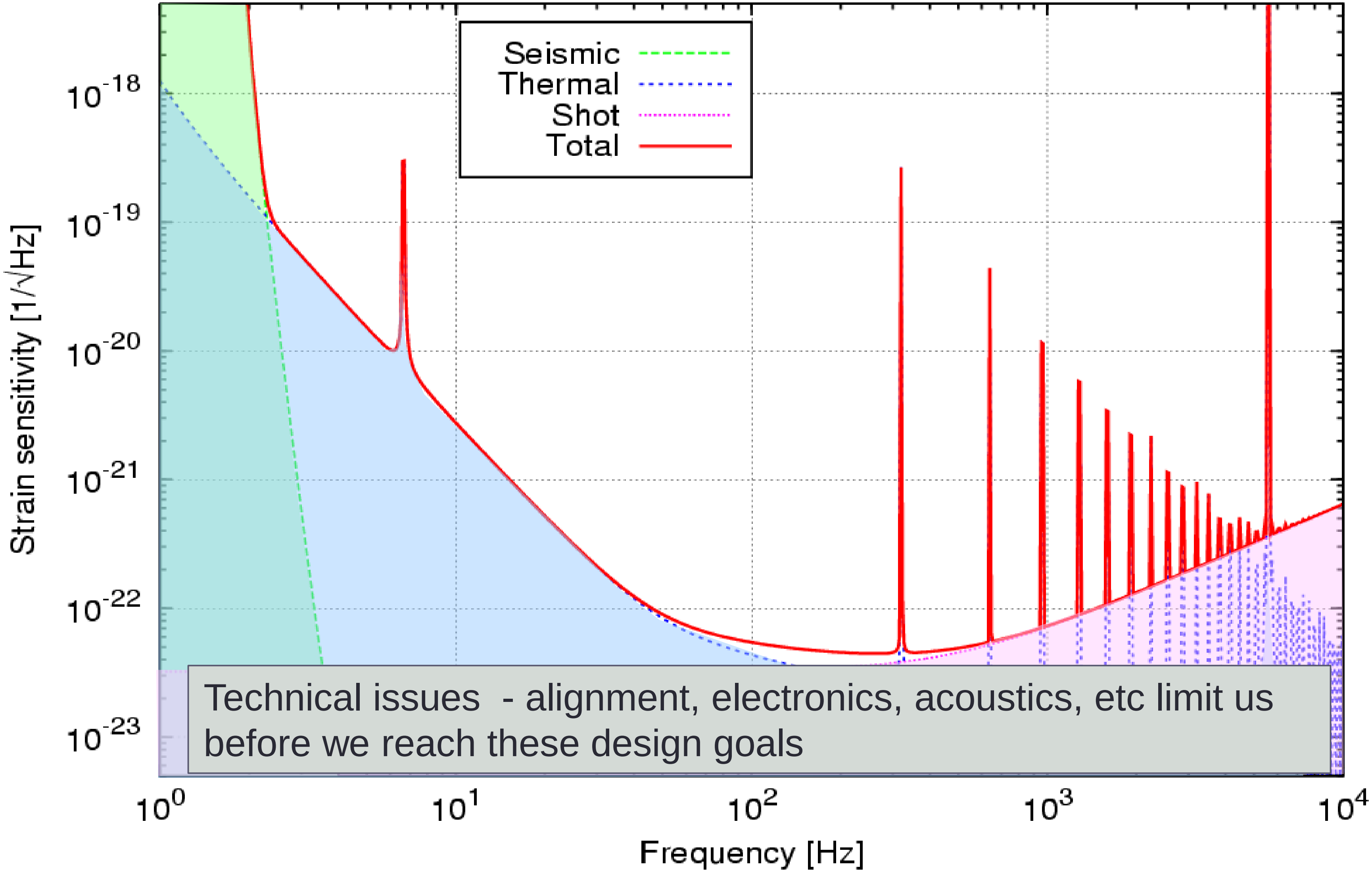
- 5 European countries, 19 labs, ~250 members
- Scientists from Italy and France (former founders of Virgo), The Netherlands, Poland and Hungary

APC Paris
ARTEMIS Nice
EGO Cascina
INFN Firenze-Urbino
INFN Genova
INFN Napoli
INFN Perugia
INFN Pisa
INFN Roma La Sapienza
INFN Roma Tor Vergata
INFN Trento-Padova
LAL Orsay – ESPCI Paris
LAPP Annecy
LKB Paris
LMA Lyon
NIKHEF Amsterdam
POLGRAW(Poland)
RADBOUD Uni. Nijmegen
RMKI Budapest

Interferometer Noise Limits

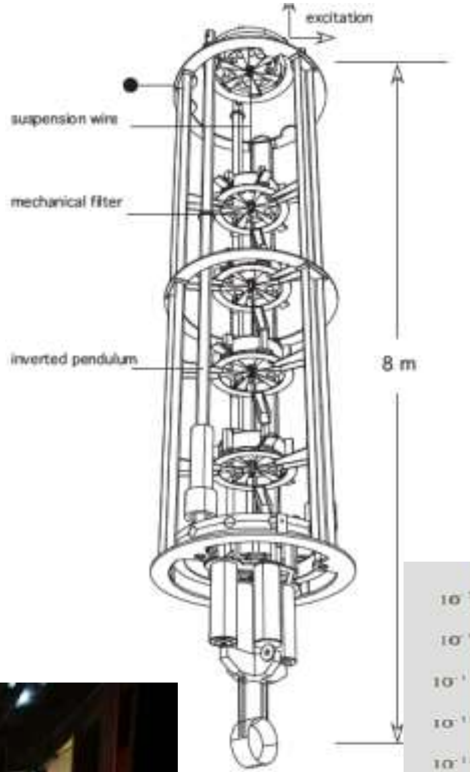


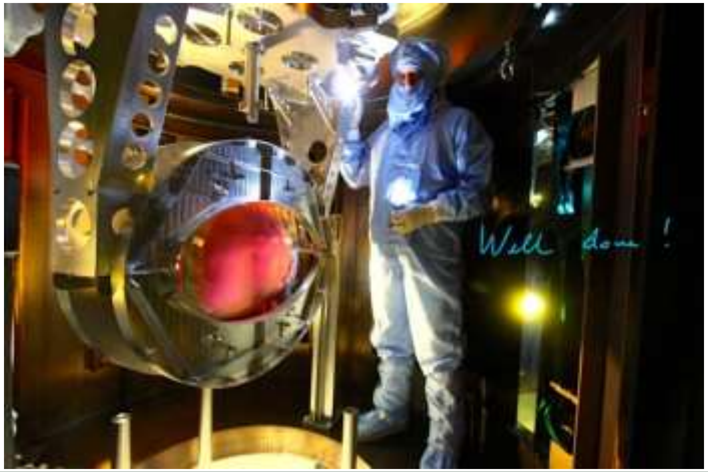
Sensitivity

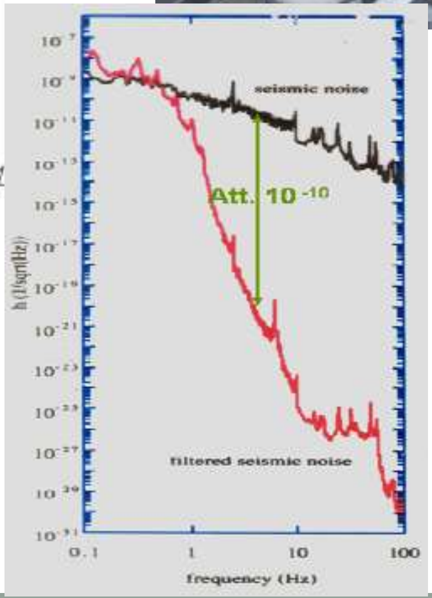


Technical issues - alignment, electronics, acoustics, etc limit us before we reach these design goals

Vibration isolation system

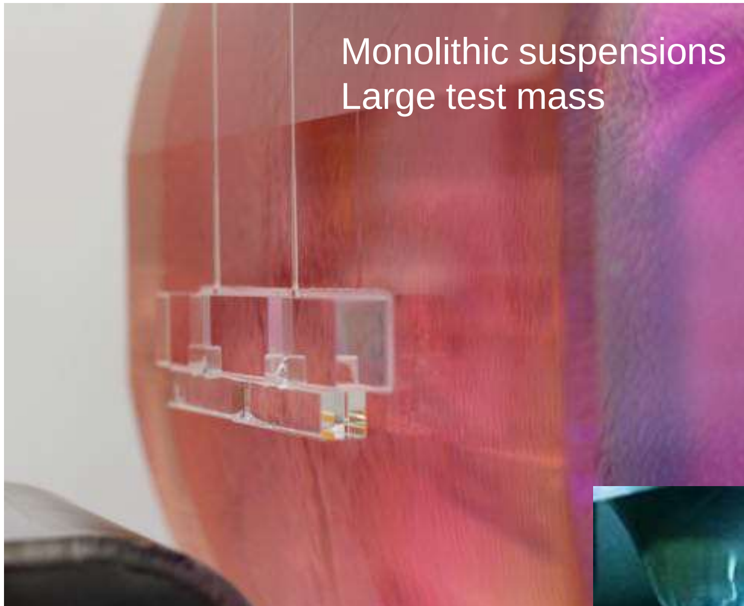


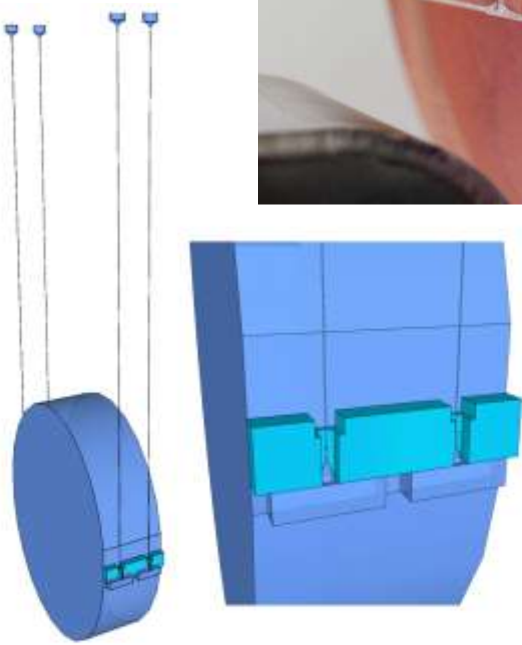


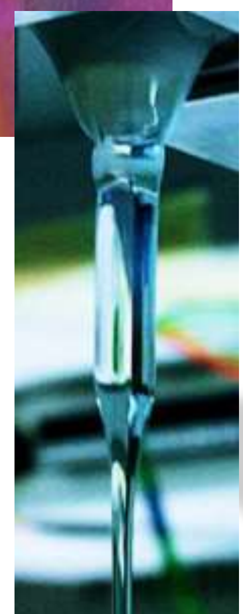


Reduce in-band seismic motion by 10 orders of magnitude

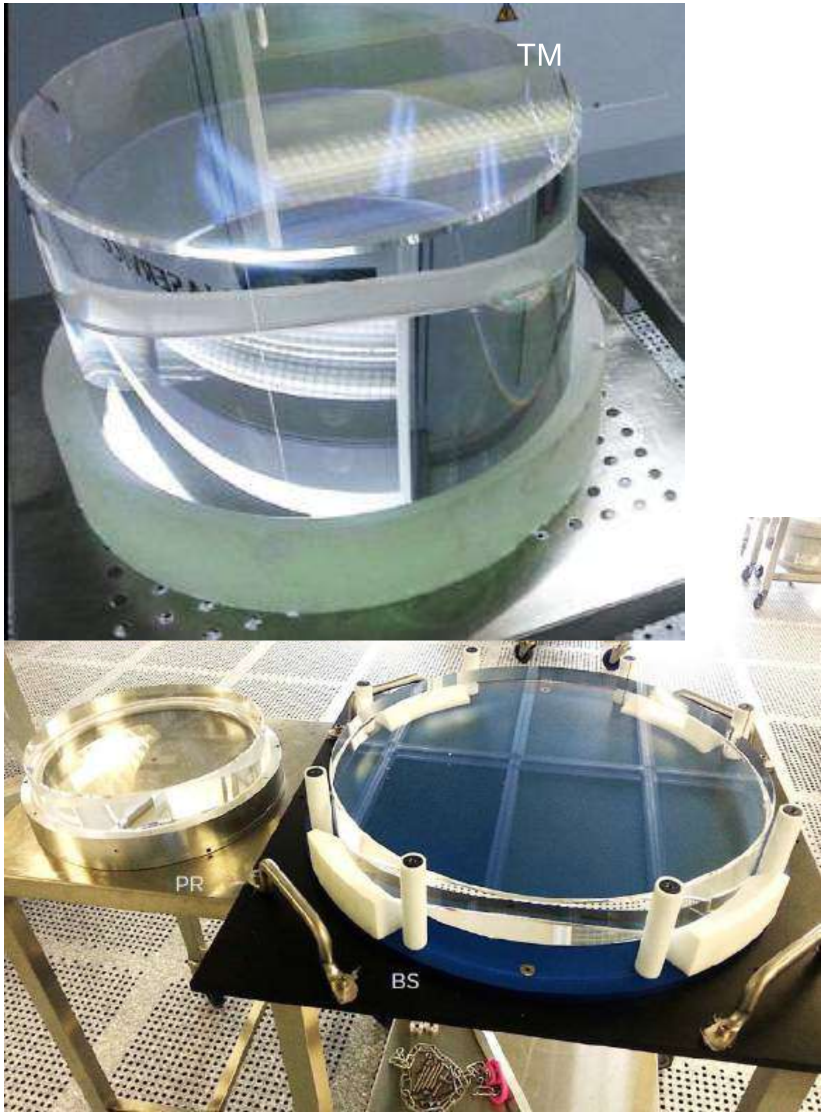
Monolithic suspension



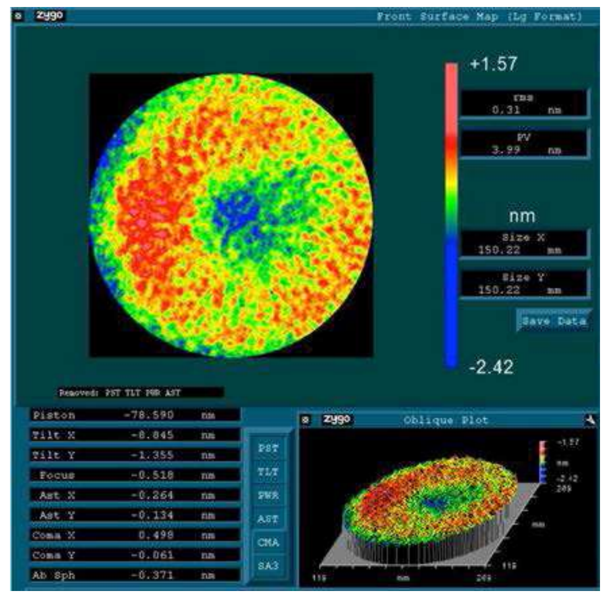




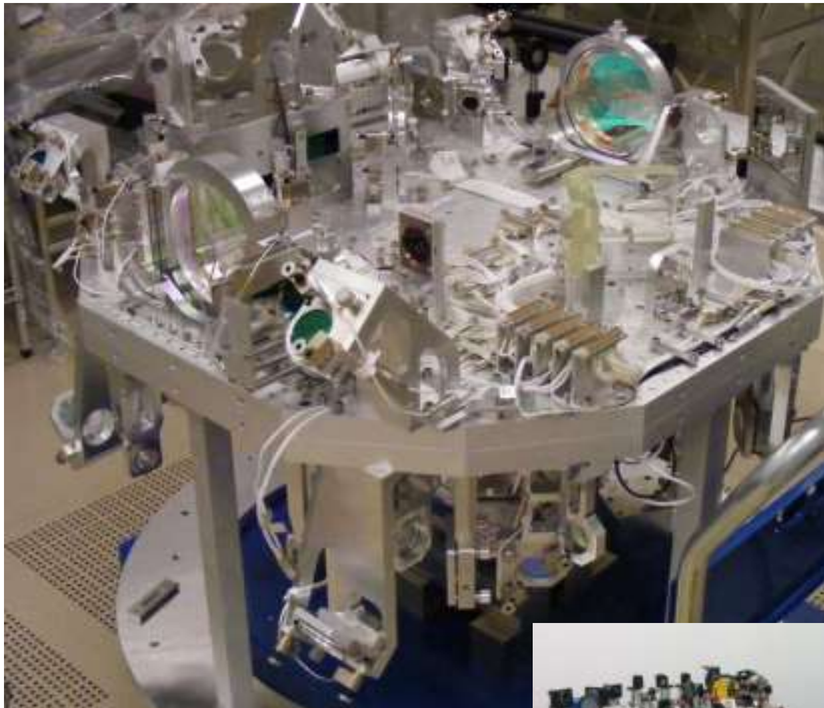
Mirrors



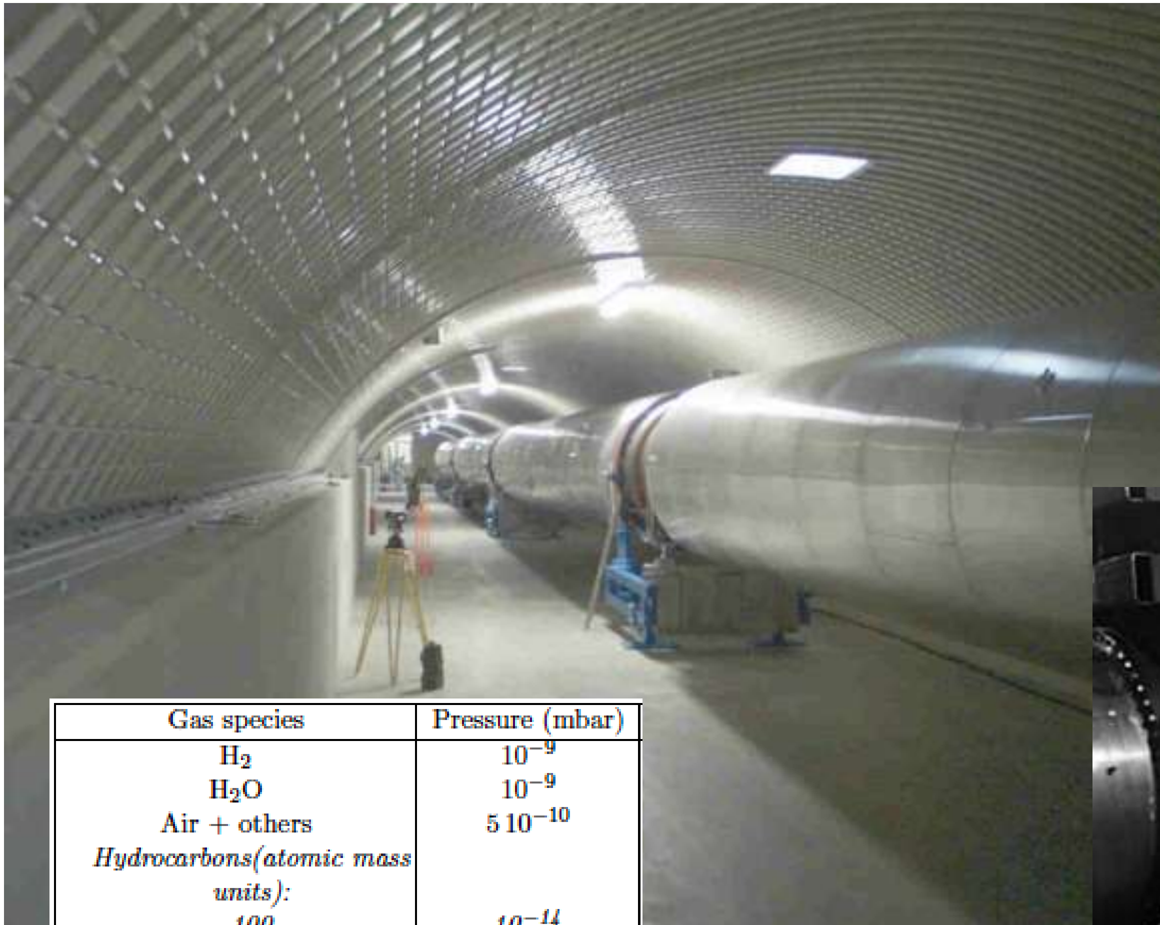
- Surface uniformity < 0.2 nm rms
- Scatter < 50 ppm
- Absorption < 0.2 ppm
- Internal mode Q's > 2 x 10^6



High precision optical systems



Virgo vacuum system

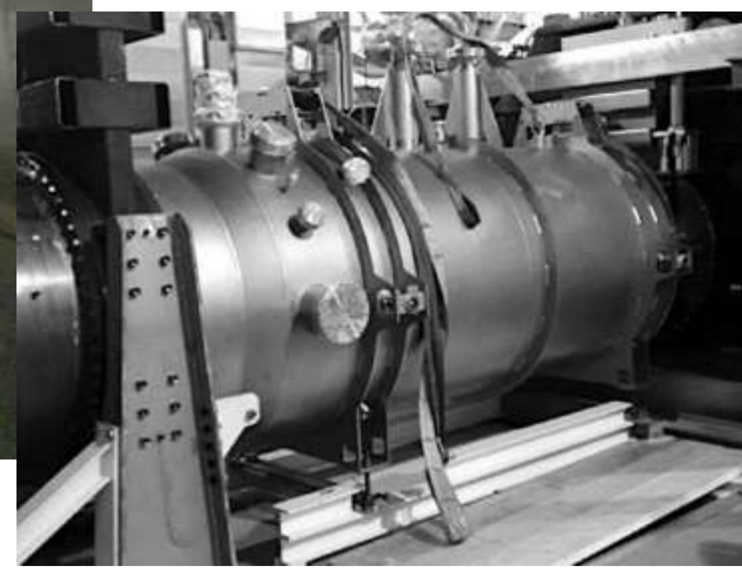


Gas species	Pressure (mbar)
H_2	10^{-9}
H_2O	10^{-9}
Air + others	$5\,10^{-10}$
Hydrocarbons(atomic mass units):	
100	*10^{-14}*
300	
500	
Total	$2.5\,10^{-9}$

Pressures required for Advanced Virgo

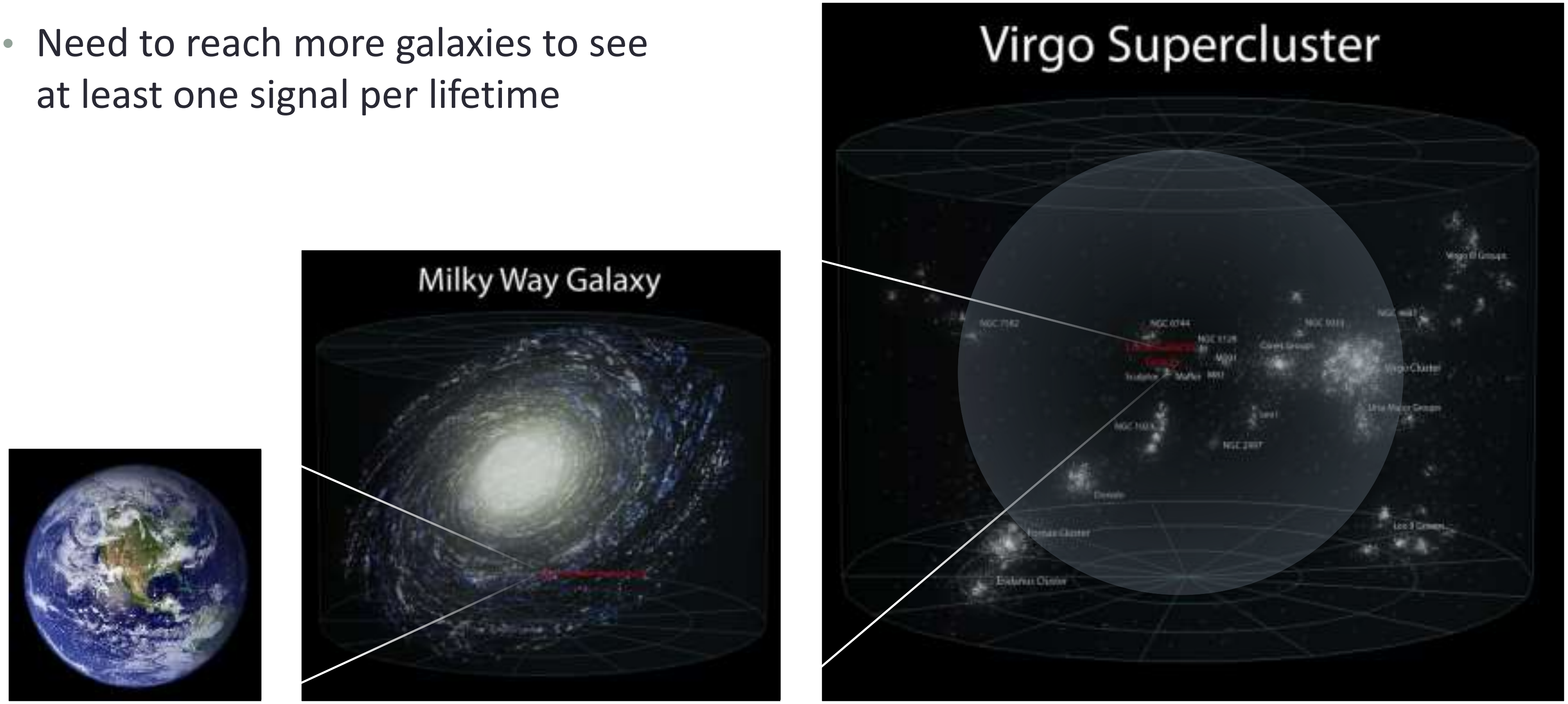
Largest ultra-high-vacuum system in Europe ~7000m^3

Liquid Nitrogen cryotraps



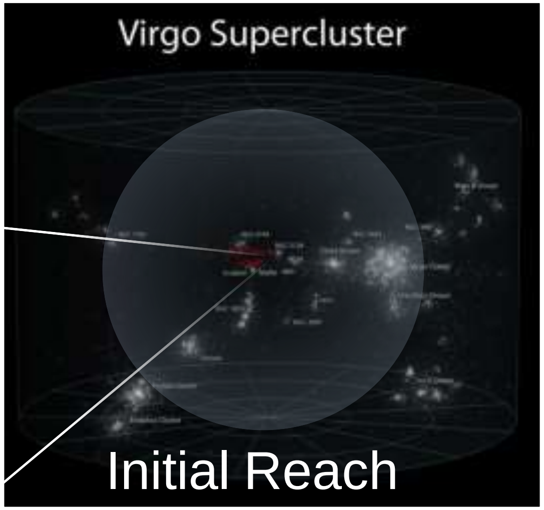
First generation detectors

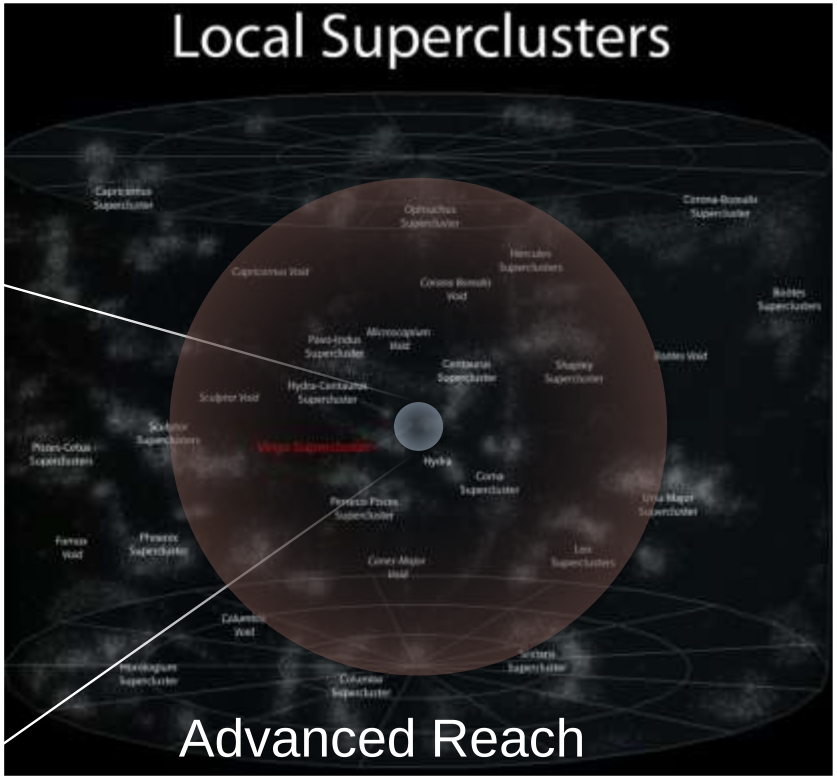
- First generation detectors and infrastructure built from mid-'90s to mid-2000; commissioned to design sensitivity; and observed for several years
- In case of NS-NS coalescence:
  - Sensitivity sufficient to reach about 100 galaxies; however…
  - Expected rate is low: events happen once every 10,000 years per galaxy…
- Need to reach more galaxies to see at least one signal per lifetime



Advanced Detectors Sensitivity: a *qualitative* difference

- While observing with initial detectors, parallel R&D led to better concepts
- 'Advanced detectors' are ~10x more sensitive
- → detection rate 10^3 larger
- NS-NS detection rate order of 1 per month (will reach about 100,000 galaxies)
- BH-BH detectable at cosmological distances (~1 Gpc)

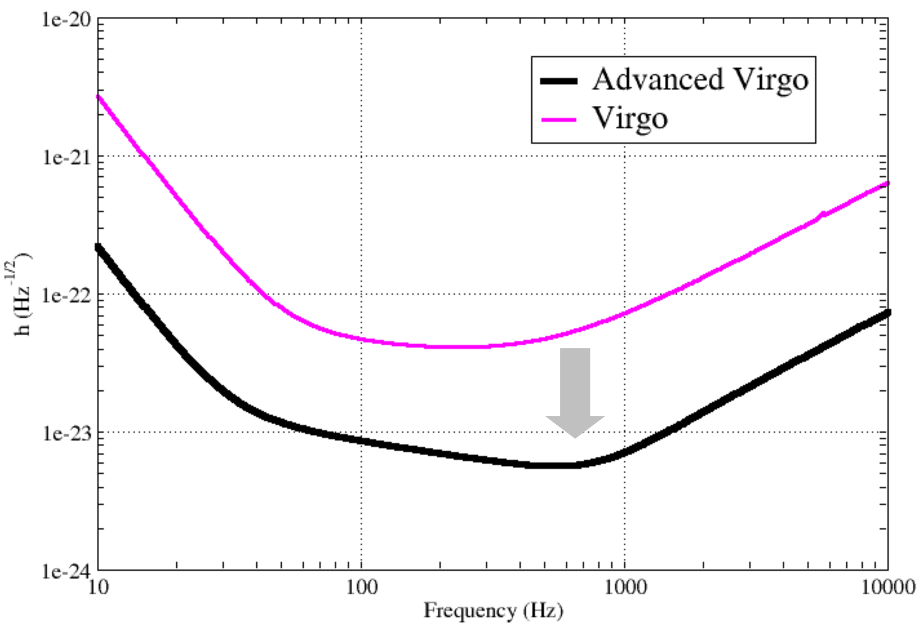


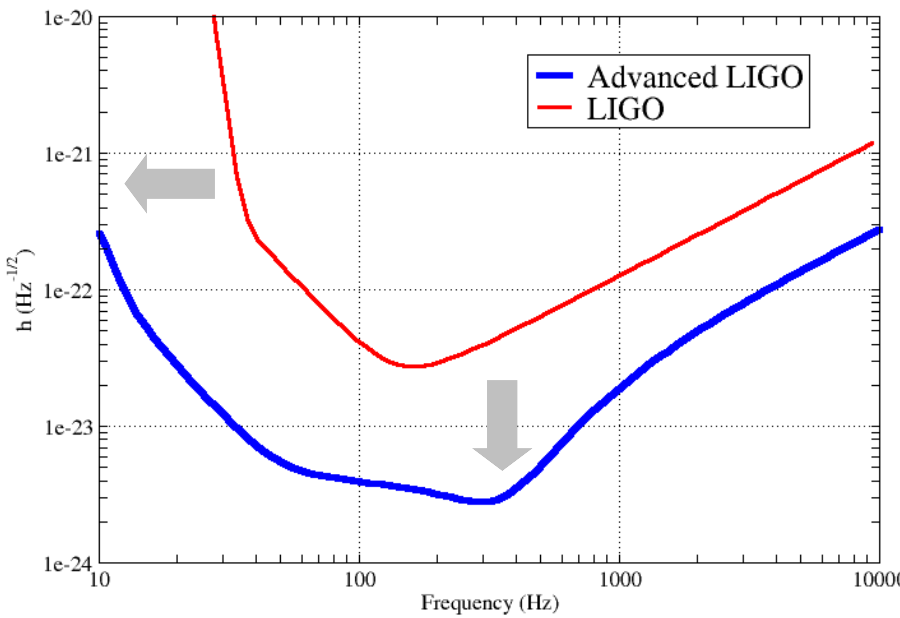


Advanced Virgo / Advanced LIGO

- Project start 2011 (INFN+CNRS)
- Construction almost completed
- Commissioning is starting
- First data taking in 2016

- Project start 2008 (NSF)
- Completed 2015
- First data taking run (O1) end 2015
- Commissioning toward final sensitivity underway

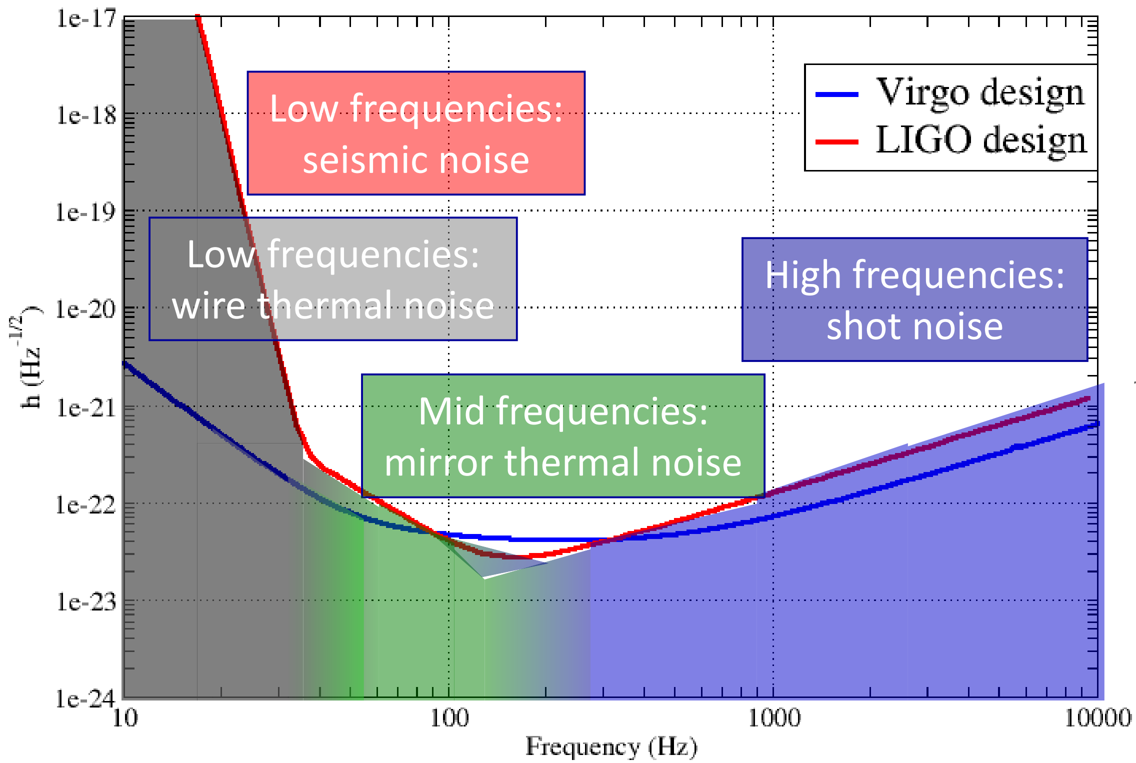


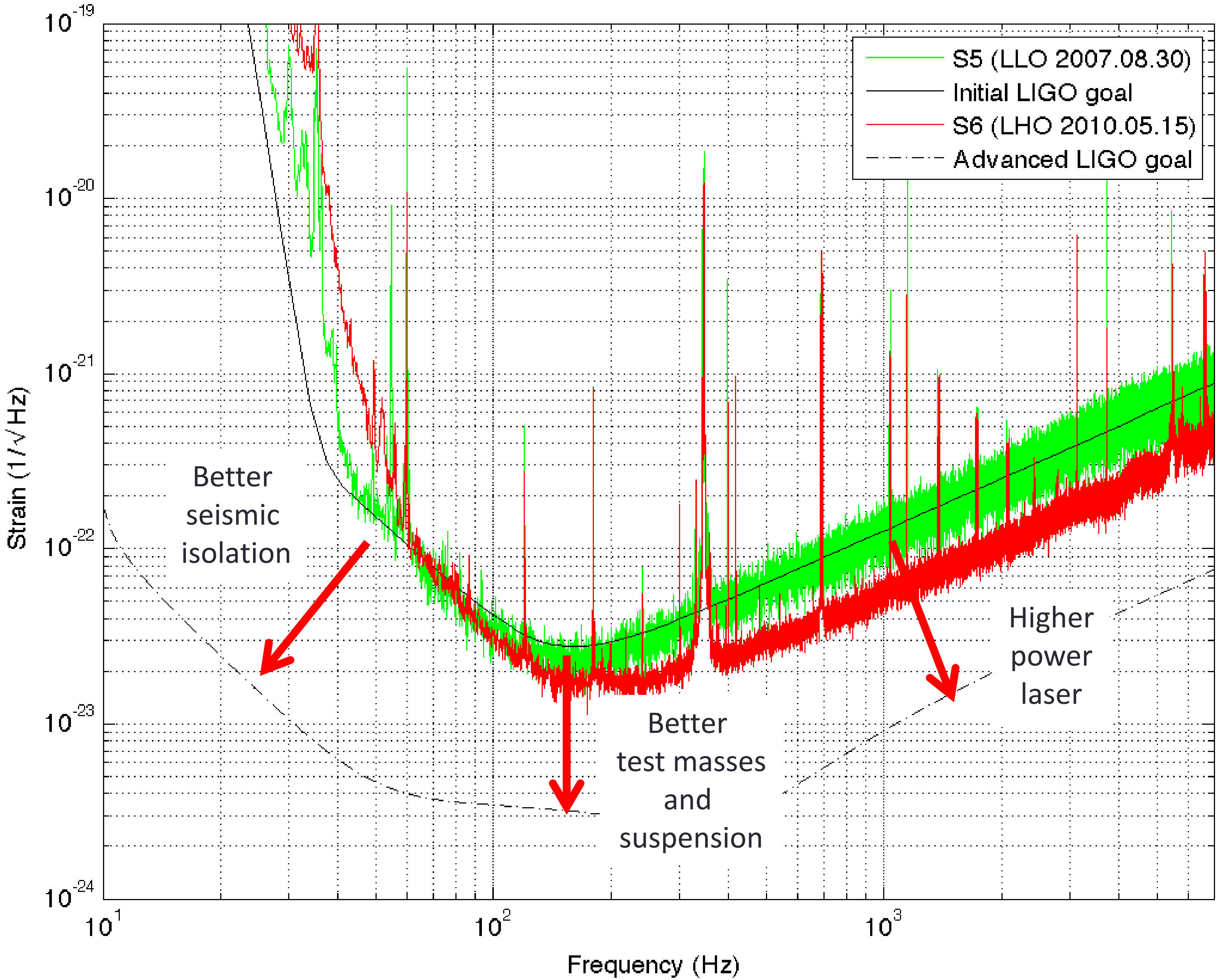


Achieving the Sensitivity Goal

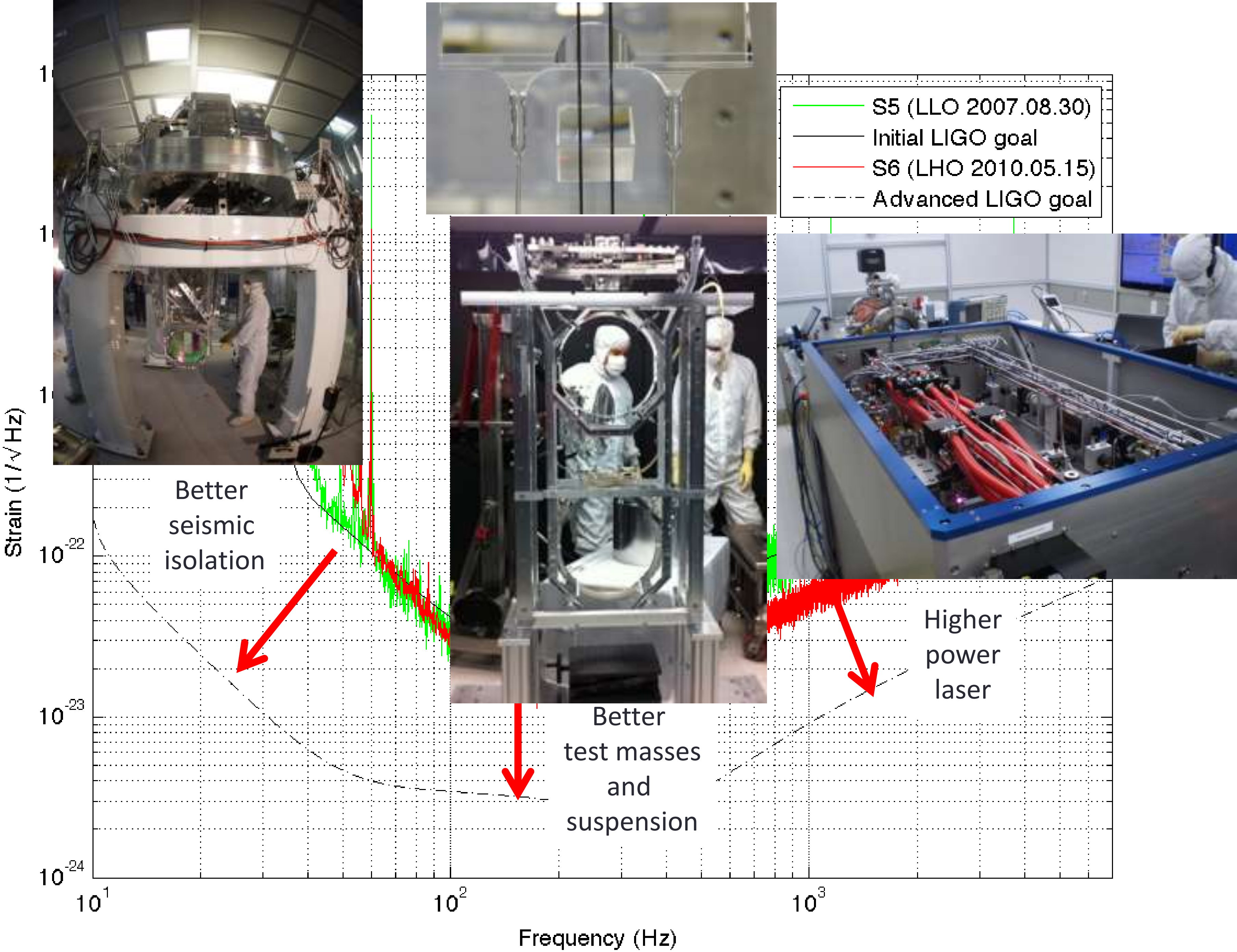
Achieving a sensitivity 10x better is ambitious.

Act on different noise sources: new ideas and a wide R&D program have been necessary





S5 (LLO 2007.08.30)
Initial LIGO goal
S6 (LHO 2010.05.15)
Advanced LIGO goal
Better seismic isolation
Better test masses and suspension
Higher power laser
Strain (1/√Hz)
Frequency (Hz)
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{1}
10^{2}
10^{3}



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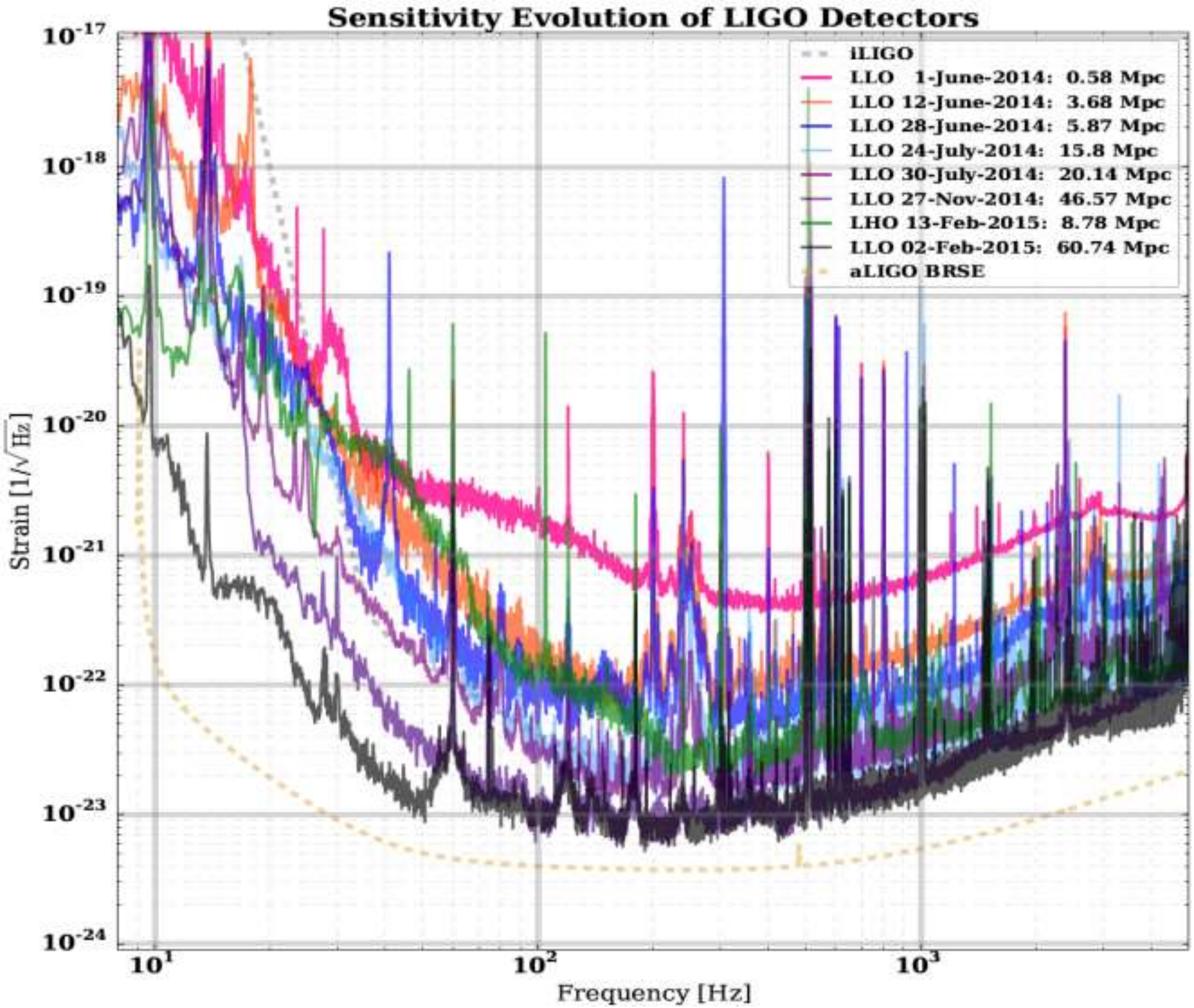
LIGO Sensitivity Progression



O1 aLIGO science run

- Last September 2015, LIGO was in the final stages of preparation for the first Advanced LIGO data run (O1).
- The very last step is a short “Engineering Run,” during which on Sept 14 the online monitor recorded GW150914.
- LIGO responded by starting the data run officially, keeping all settings fixed and ran for 16 live days **coincidence time** (long enough to assess background levels, etc). Analyzed data period from Sept 12th to Oct 20th with a coincidence duty cycle ~ 48%.
- PRL paper reports on that data, including GW150914

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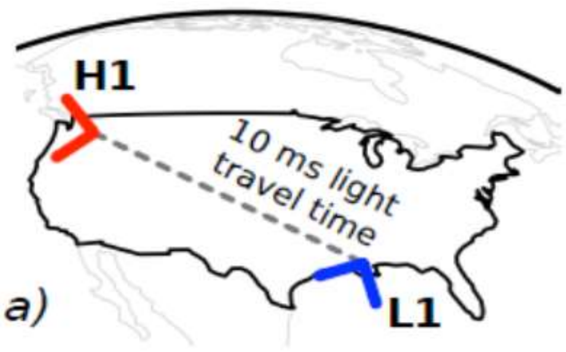
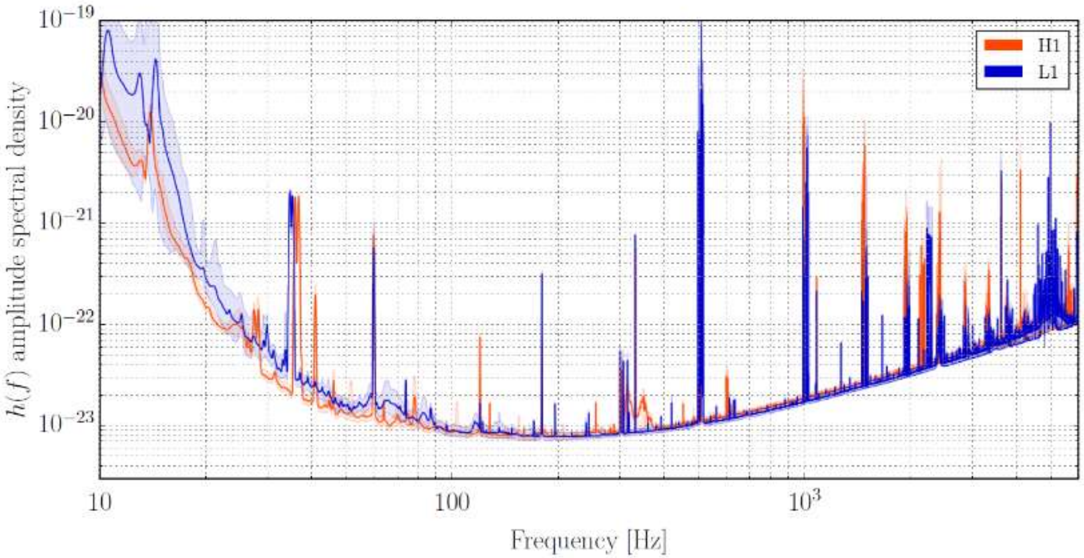
- O1 continued data taking until 12 Jan 2016. Data analysis is ongoing and we’ll report on the full O1 results as the data analysis is complete.

O1 aLIGO science run

- Hanford and Livingstone running with similar sensitivities:
  - $10^{-23}/\sqrt{Hz}$ @ 100 Hz (improvement by 3-4 times wrt 2010 between 100-300 Hz)
  - 10 times better at low frequency

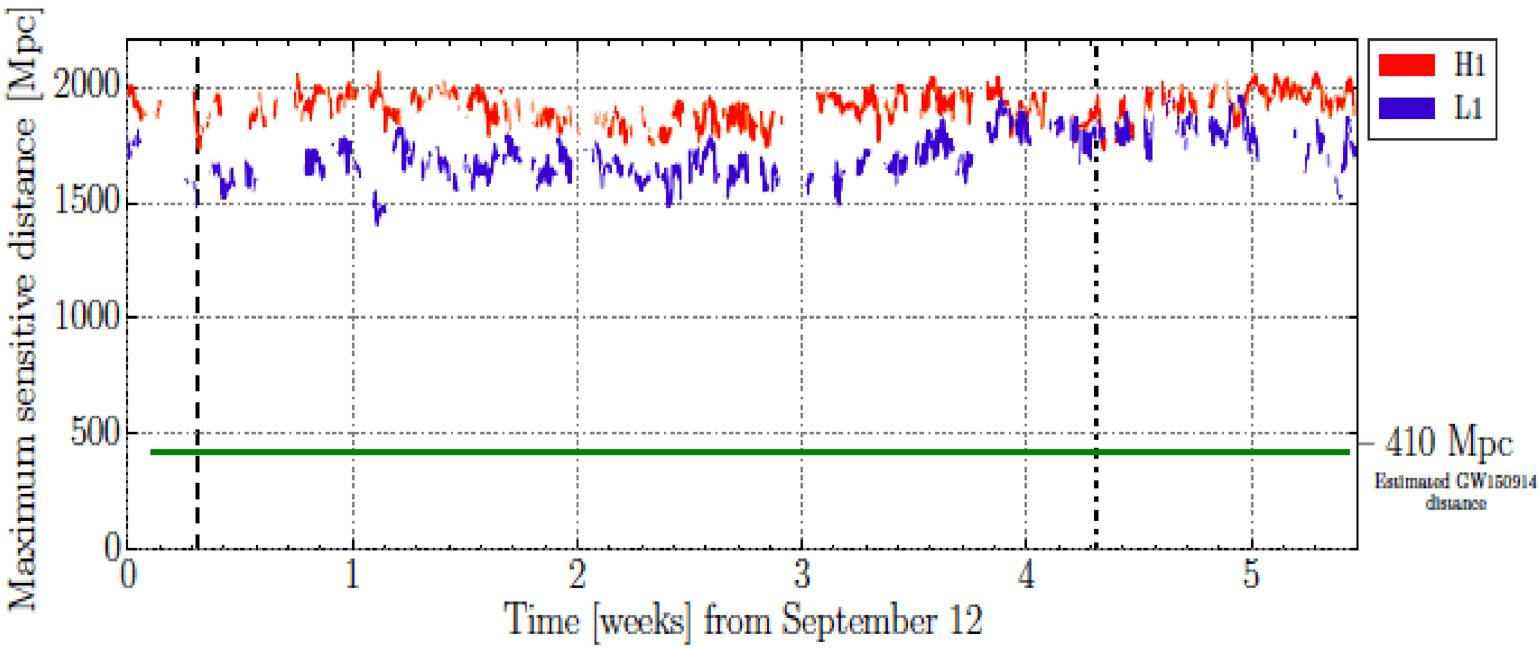




O1 aLIGO science run

LIGO range into space for BH-BH coalescence (Mpc)

The maximum sensitivity of LIGO-Hanford (red) and LIGO-Livingston (blue) during the analyzed period (September 12 - October 20, 2015) to a BBH system with the same observed spin and mass parameters as GW150914 for optimal sky location and source orientation and detected with a SNR of 8.

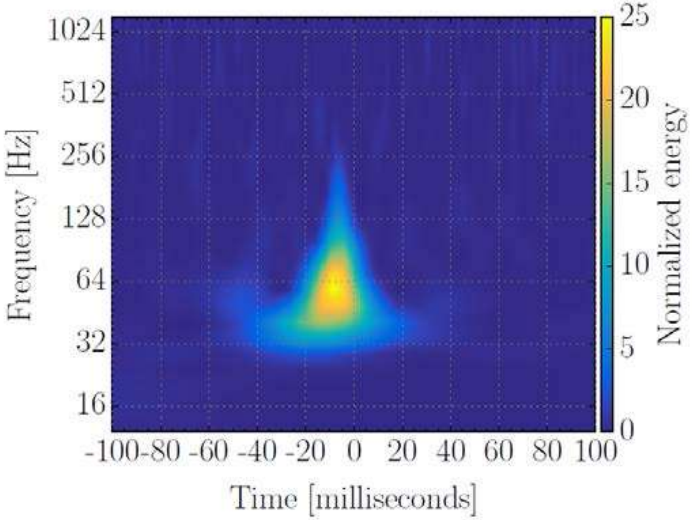


Monitoring channels

- Interferometer monitoring
  - Transmitted light beams, optics alignment sensors, feedback signal
- Environmental monitoring
  - Seismic sensors, microphones, magnetometers, radio-frequency antennas
- Detailed study of the couplings between auxiliary channels/environmental disturbances and detector output
  - Injections of external disturbances
- Potential noise sources
  - Anthropogenic noise, Earthquakes, Radio Frequency noise
  - Lightning, Cosmic rays

Data quality flags

- Category 1. Well know problems
  - data are not analyzed
- Category 2. Known noise correlations
  - veto may be applied after the analysis (depending on the search)
- Category 3. Not understood correlations or recurrent uncorrelated transients
  - veto may be applied after the analysis (depending on the search)
    - Ex. “Blip noise”

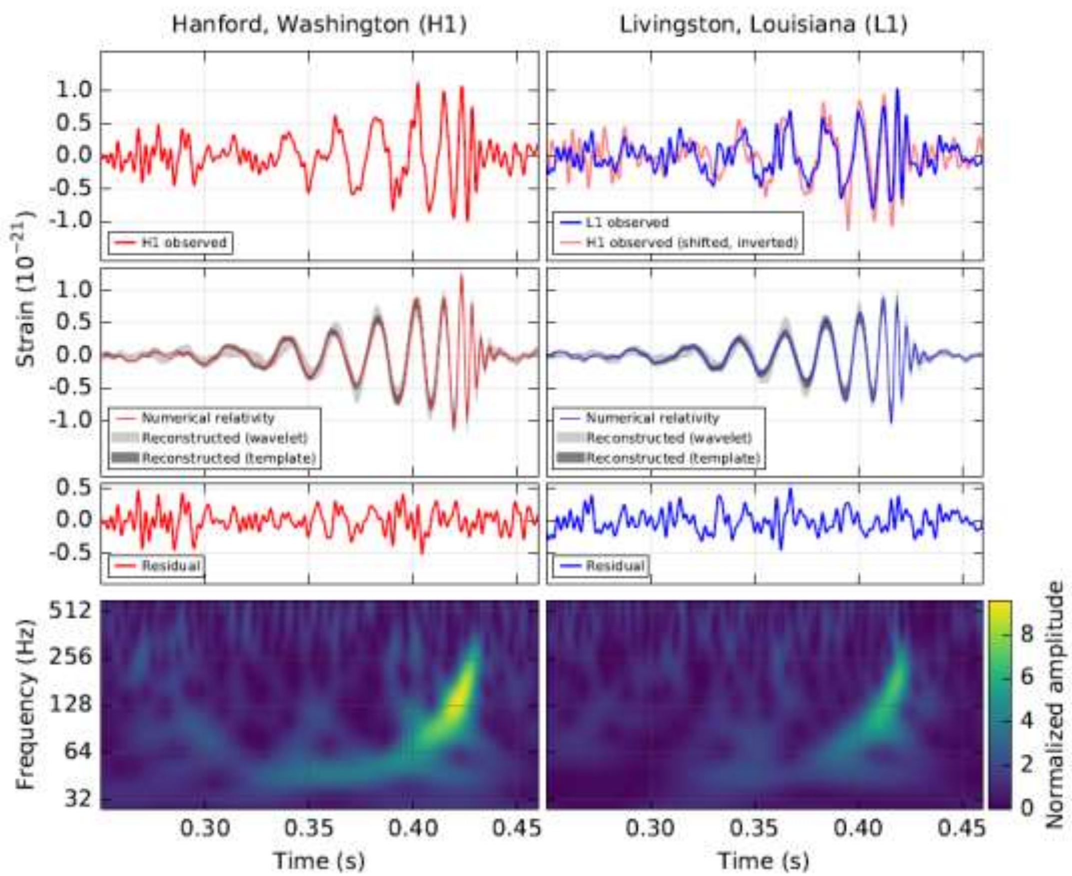


- Data collection: September 12th–October 20th i.e. 38.6 days of data collection
- Coincident operation 18.4 days
- After data quality 17.5 days

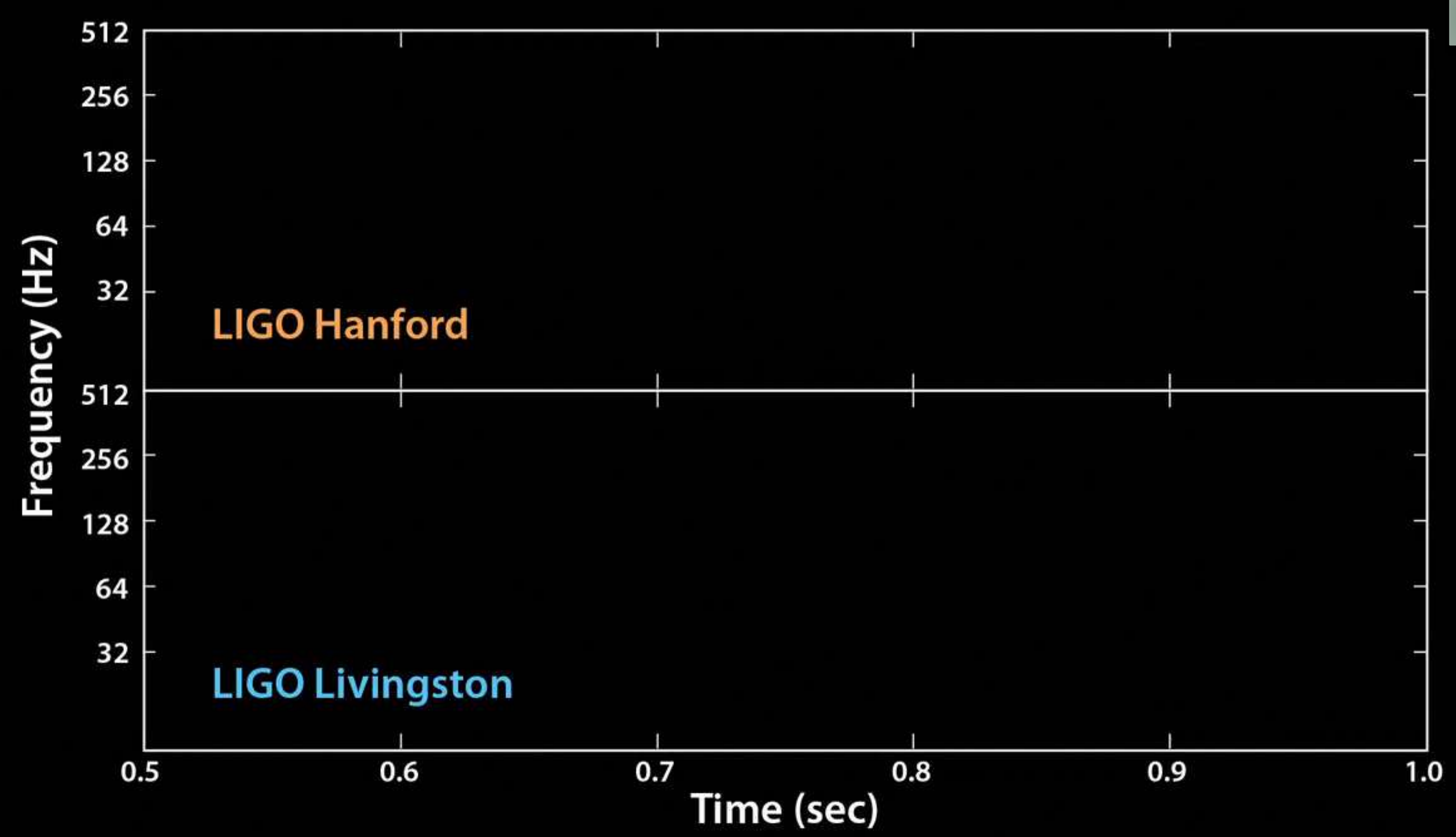
GW150914: the signal

- Top row left: Hanford. Top row right: Livingston
- Time difference ~ 6.9 ms with Livingston first
- Second row – calculated GW strain using Numerical Relativity Waveforms for quoted parameters compared to reconstructed waveforms (Shaded)
- Third Row –residuals
- Bottom row – time frequency plot showing frequency increases with time (chirp)

September 14th, 2015 at 09:50:45 UTC



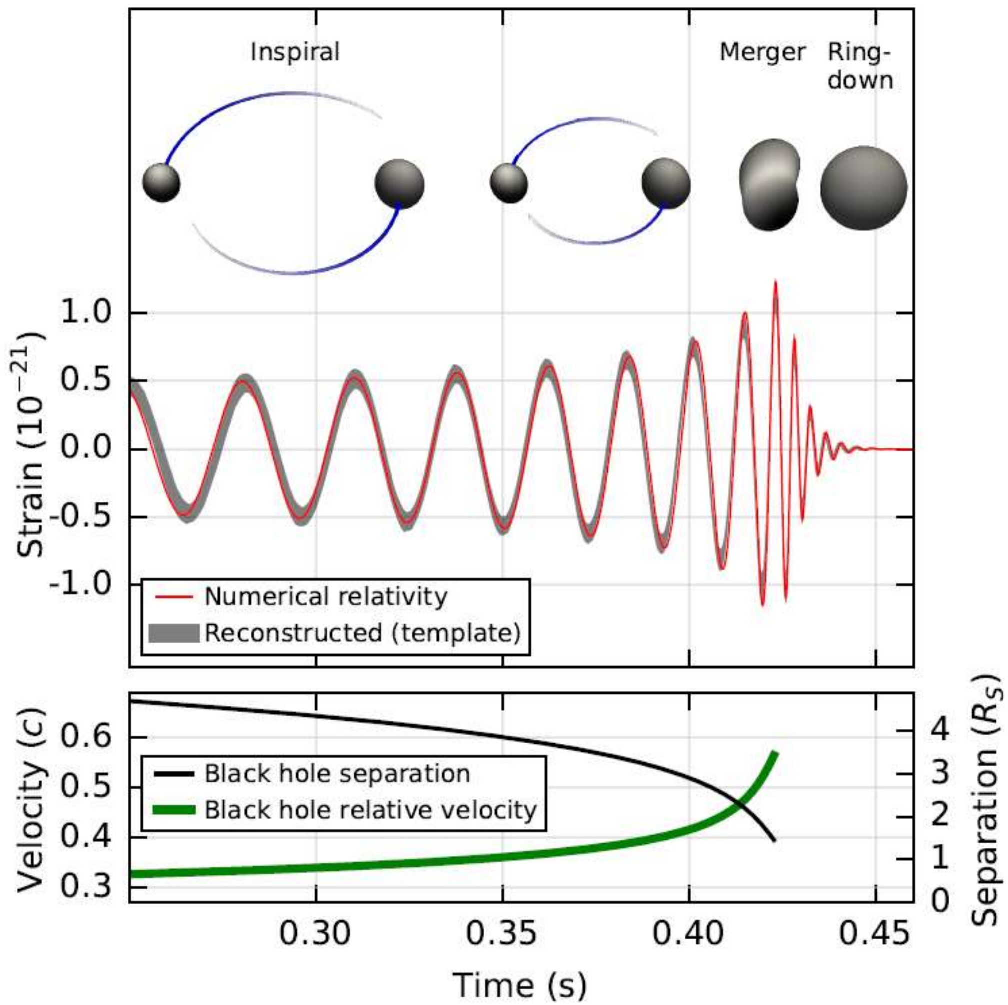
GW150914: the signal



GW150914: Estimated Strain Amplitude

- Numerical relativity models of the BH horizon as the BHs coalesce.
- Over 0.2 s the signal increases in frequency and amplitude in about 8 cycles from 35 to 150 Hz where the amplitude reaches a maximum.
- Effective BH separation in units of Schwarzschild radius ($R_s=2GM_{tot}/c^2=210km$) and effective relative velocities given by post-Newtonian parameter v/c

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}} = \frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3} \dot{f}\right]^{3/5} \qquad M_{ratio} \propto \frac{m_1}{m_2}$$



Binary Black Hole System

- M1 = 36 +5/-4 M_{sol}
- M2 = 29 +/- 4 M_{sol}
- Final Mass = 62 +/- 4 M_{sol}
- Distance = 410 +160/-180 MPc (redshift z = 0.09)

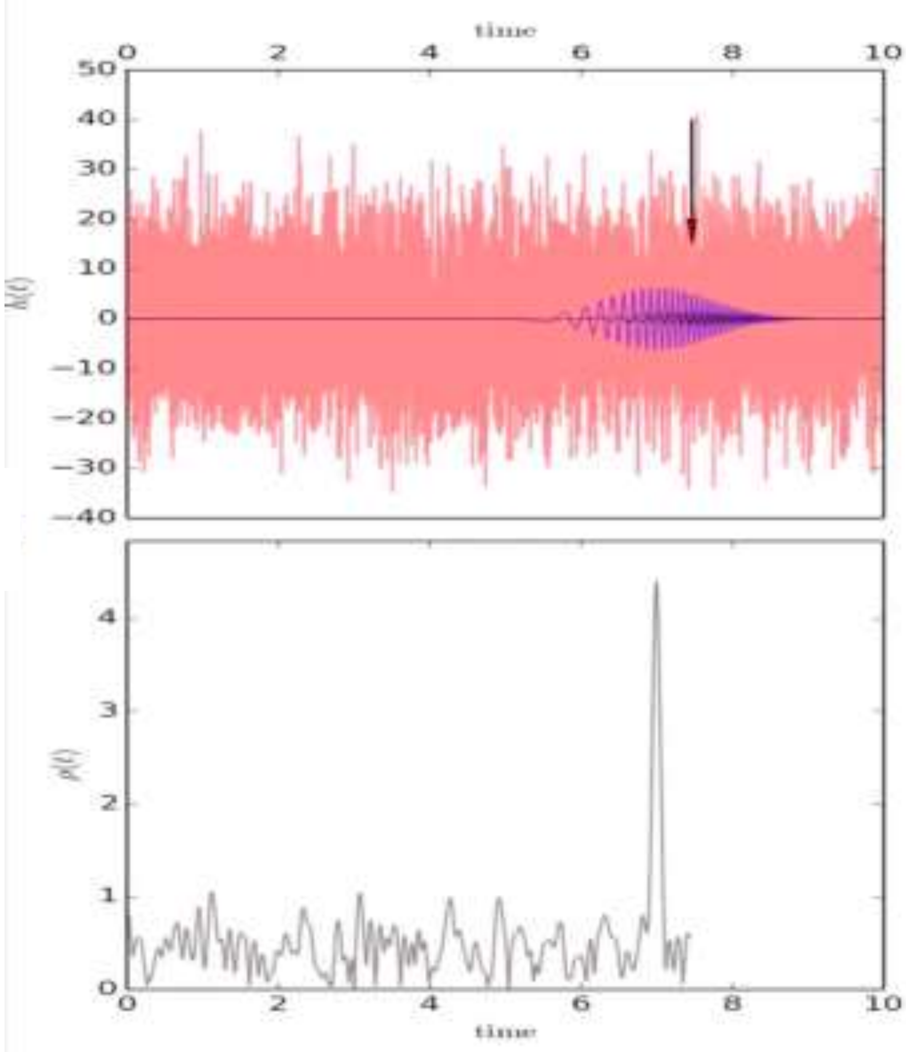
Transient Event Searches

- Analyzed 16 days of coincidence observation from September 12th to October 20th 2015.
- Two searches:
  - Generic transient search
  - Binary coalescence search

Transient Event Searches
Binary Coalescence search

- Target searches for GW emission from binary sources
- Search for individual masses from 1 to 99 solar masses; total mass < 100 solar masses
- Model system with combination of Post-Newtonian, black hole perturbation theory and numerical relativity
- ~250,000 wave forms are used to cover the parameter space
- Calculate matched filter SNR $\rho(t)$ as function of time for each template

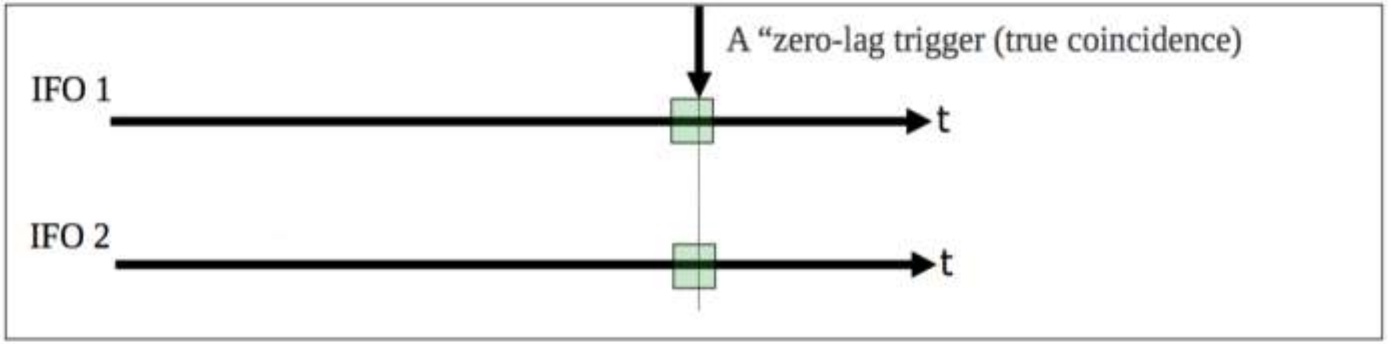
Matched filter search

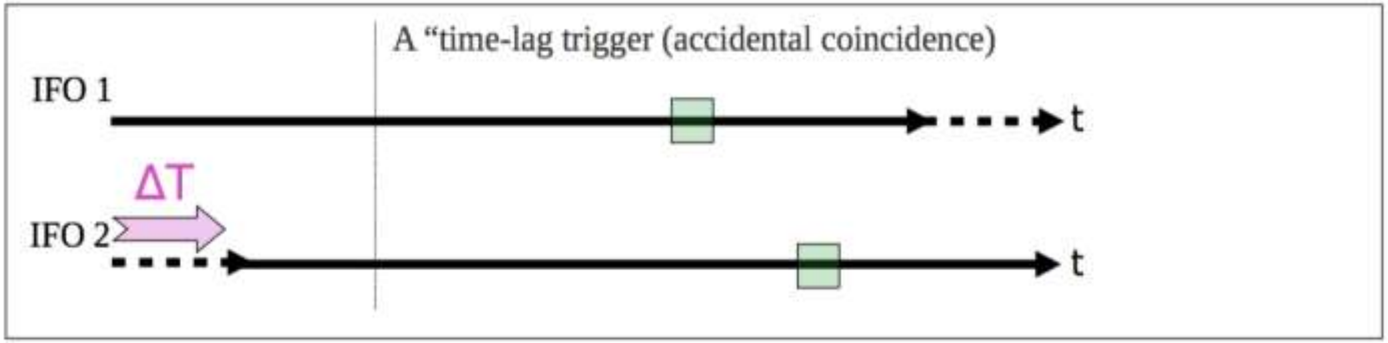


Transient Event Searches
Binary Coalescence search

- Target searches for GW emission from binary sources
- Search for individual masses from 1 to 99 solar masses; total mass < 100 solar masses
- Model system with combination of Post-Newtonian, black hole perturbation theory and numerical relativity
- ~250,000 wave forms are used to cover the parameter space
- Calculate matched filter SNR $\rho(t)$ as function of time for each template
- Identify maxima and calculate χ^2 to test consistency with matched template
- Produce lists of candidate events for each detector
- Then compare lists of events of the two detectors

Background estimation





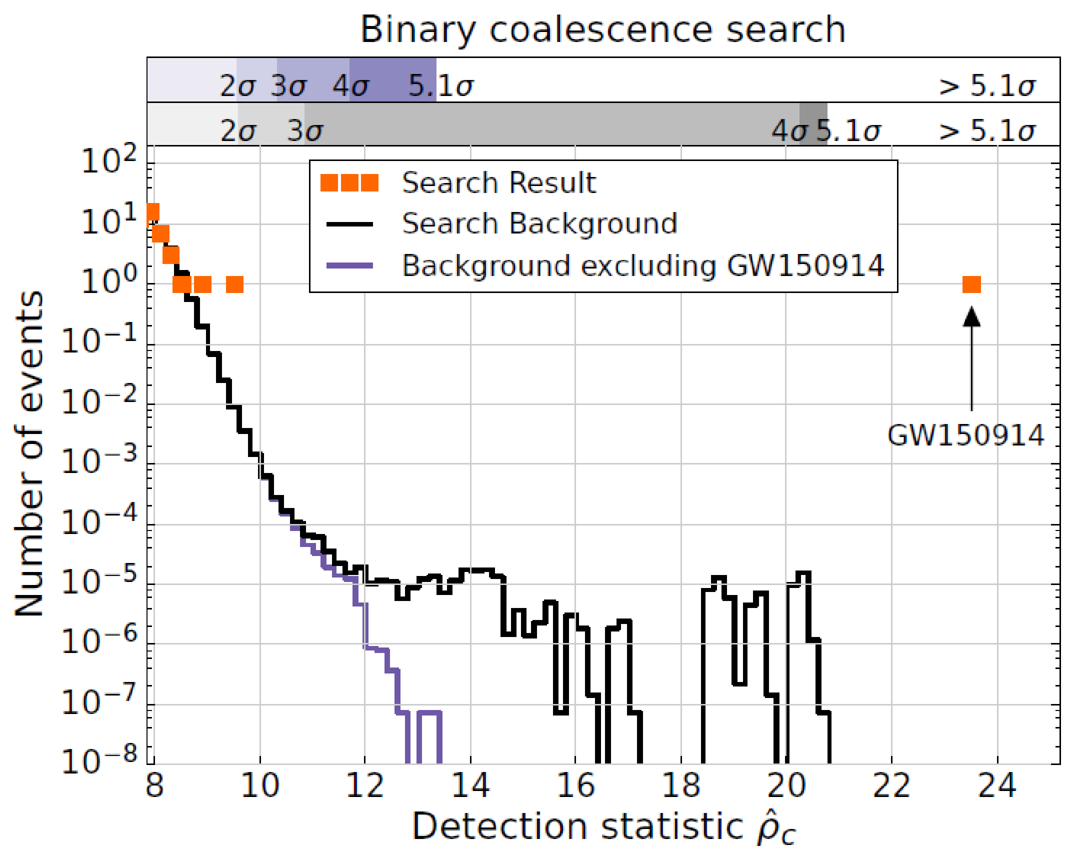
- Background estimation:
  - Time shift one list wrt the other
  - All coincidences are now only due to chance
  - Repeat ~10^7 times (equivalent to observing for 608,000 years)
  - Count number of times that each ρ_c has been found by chance (low SNRs have a higher probability to occur by chance)

Transient Event Searches
Binary Coalescence search

- Coincidences are searched within 15 msec (10 msec intersite travel time + 5 msec due to uncertainty in arrival time of weak signals), coming from the same template.
- Coincident events ranked by the quadrature sum, ρ_c, of the SNR of each detector
- Significance: GW150914 has $\rho_c = 23.6$ (largest signal), associated to
  - False alarm rate < 1 per 203,000 years,
  - Poissonian false alarm probability $< 2 \times 10^{-7}$
  - Significance > 5.1 σ

Statistical significance of GW150914

- number of candidate events (orange markers)
- number of background events (black-purple lines)
- significance of an event in Gaussian standard deviations based on the corresponding noise background

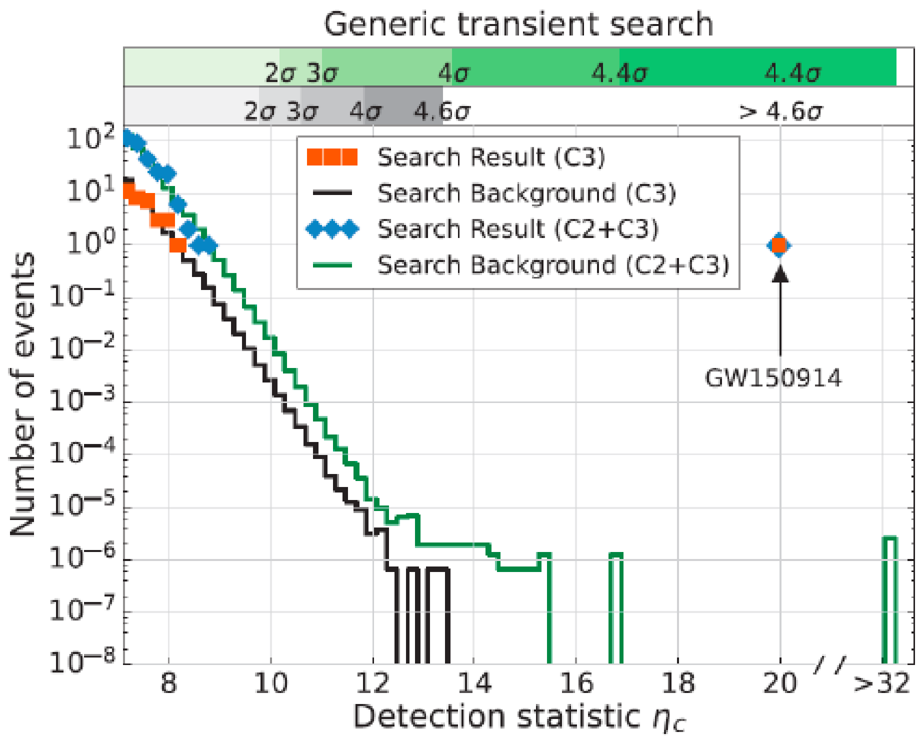


- False alarm rate < 1 per 203,000 years,
- Poissonian false alarm probability < 2 x 10^{-7}
- Significance > 5.1 σ

Transient Event Searches

Generic transient search

- Search for coherent transients signals in the two detectors
- Use $\eta_c=\sqrt{[2E_c/(1+E_n/E_c)]}$ as detection statistic (E_c dimensionless energy of coherent signal; E_n dimensionless energy of residual noise)



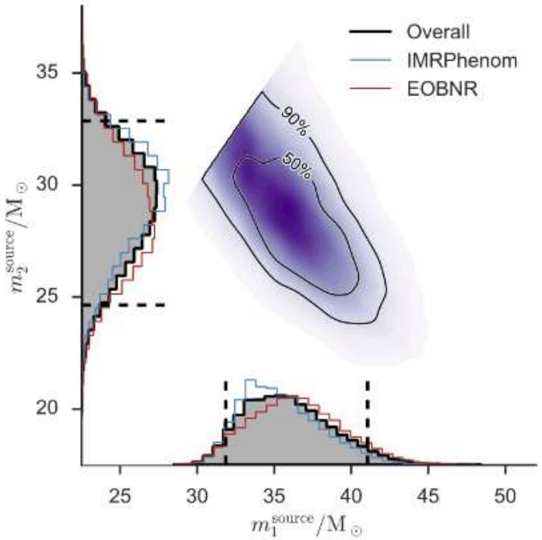
Source Parameters for GW150914

Estimated source parameters from GW150914. We report median values with 90% credible intervals that include statistical errors from averaging the results of different waveform models. Masses are given in the source frame: to convert in the detector frame multiply by (1+z). The source redshift assumes standard cosmology: $D_L \Rightarrow z$ assuming ΛCDM with H_0 = 67.9 km s^{-1} Mpc^{-1} and Ω_m =0.306

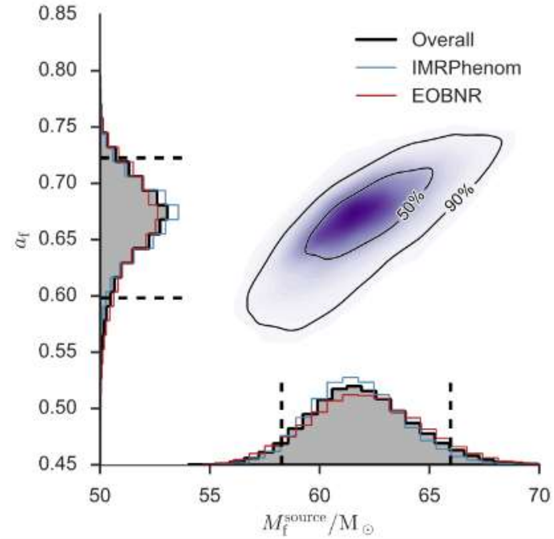
Using numerical simulation fits of black hole merger to determine parameters, we determine total energy radiated in gravitational waves is 3.0±0.5 $M_o c^2$. The system reached a peak luminosity ~3.6 $x10^{56}$ erg, and the spin of the final black hole is < 0.7

Primary black hole mass	36^{+5}_{-4} $M_\odot$
Secondary black hole mass	29^{+4}_{-4} $M_\odot$
Final black hole mass	62^{+4}_{-4} $M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift, z	$0.09^{+0.03}_{-0.04}$

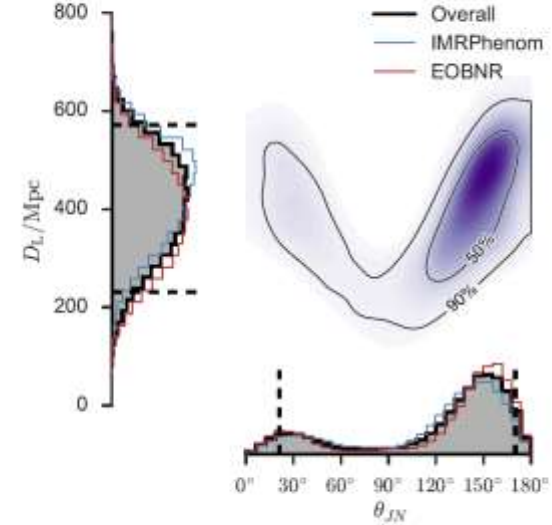
Source parameters



Component masses



Final black hole mass and spin



Luminosity distance and source inclination

EOBNR: effective-one-body formalism + numerical relativity

IMRPhenom: phenomenological formalism hybridizing PN + EOB + NR

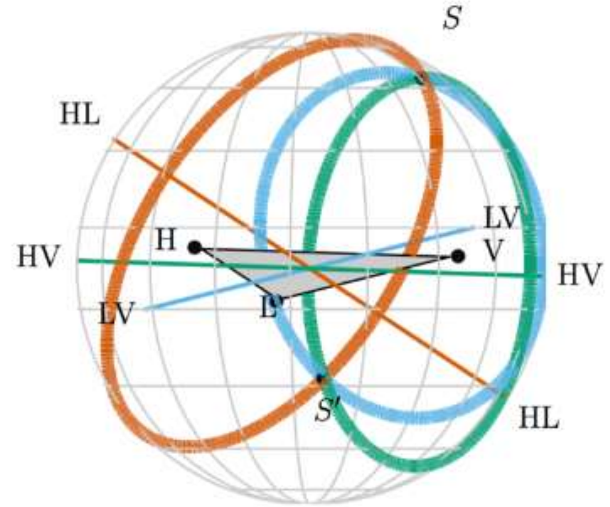
θ_{JN}: angle between the total angular momentum and the line of sight

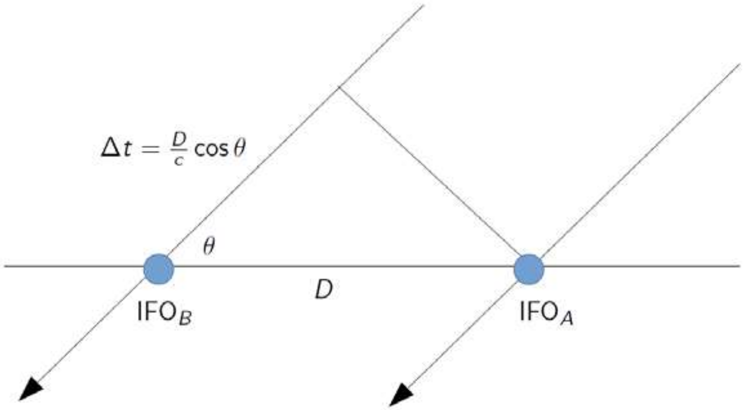
Sky localization

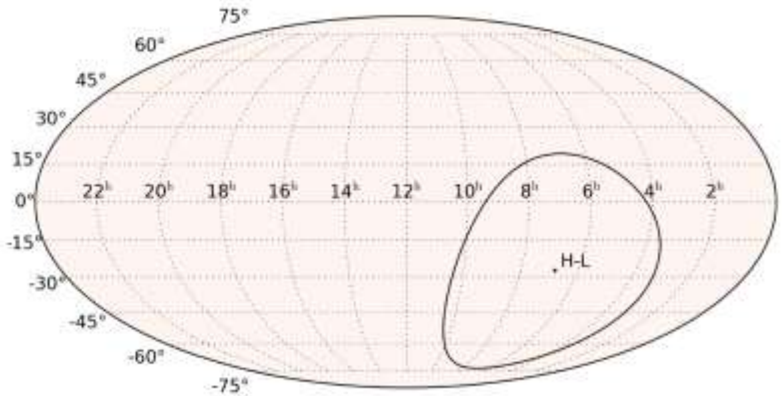
Sky location reconstructed through the time of arrival of GW radiation at the different detector sites

→

two interferometers (HL), each with poor directionality, determine an **annulus** in the sky.

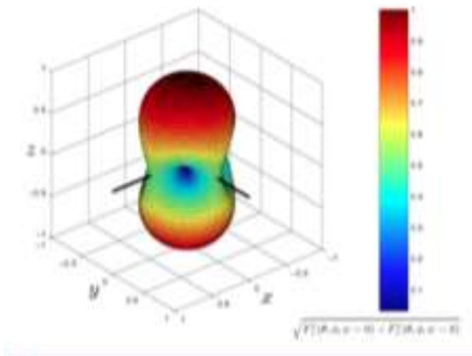


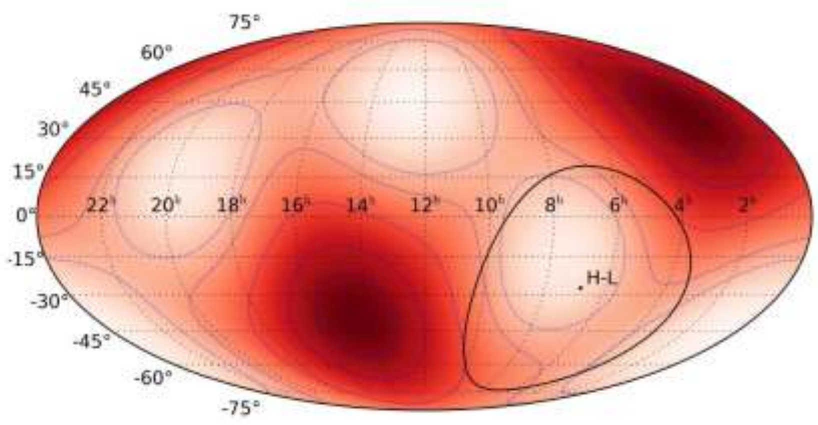


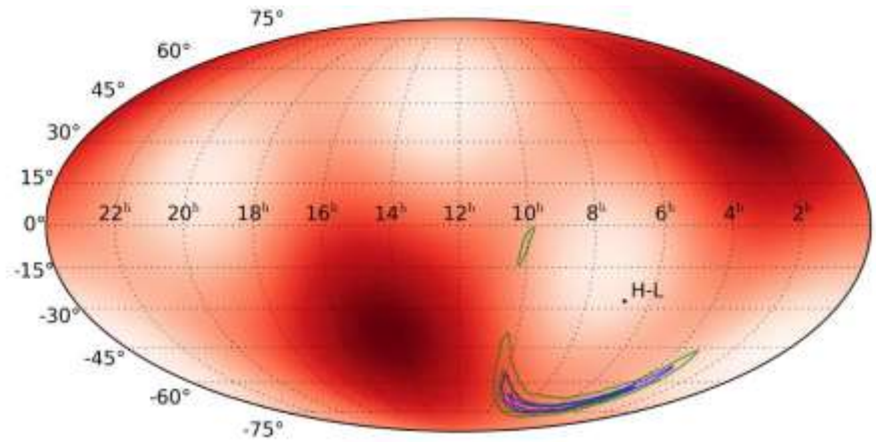


Sky localization

- Antenna pattern "excludes" part of the annulus (exclude = less probable)
- Calibration error makes the annulus larger
- Result: Area ~ 600 deg^2 (90 % confidence level)



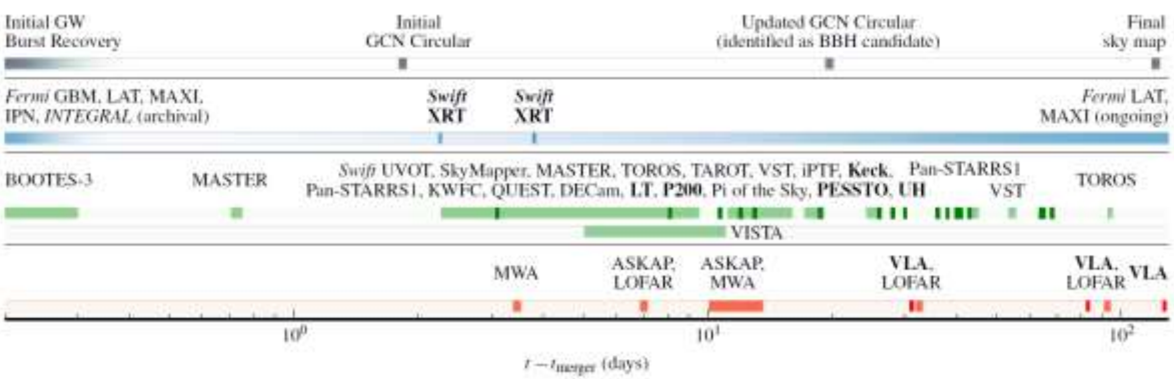


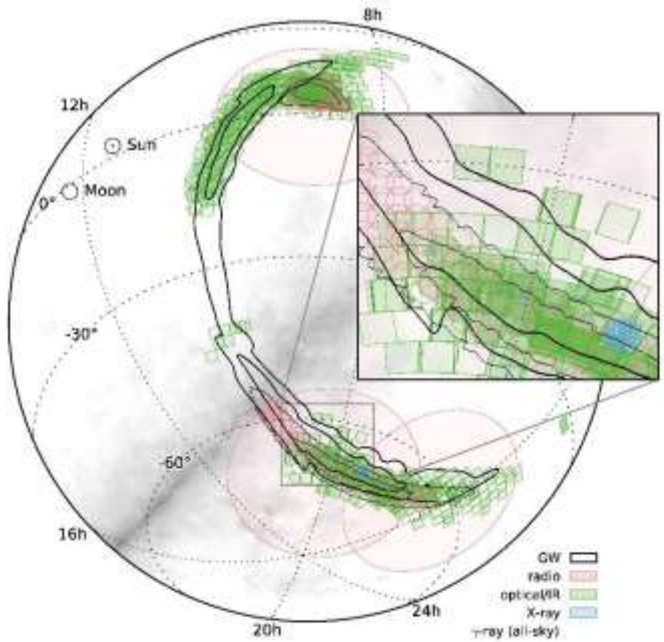


This signals had a high SNR. Virgo or KAGRA needed to do better

EM follow-up

- LVC called for EM observers to join a follow-up program
  - LIGO and Virgo share promptly interesting triggers
  - 70 MoUs, 160 instruments covering full spectrum from radio to very HE γ-rays

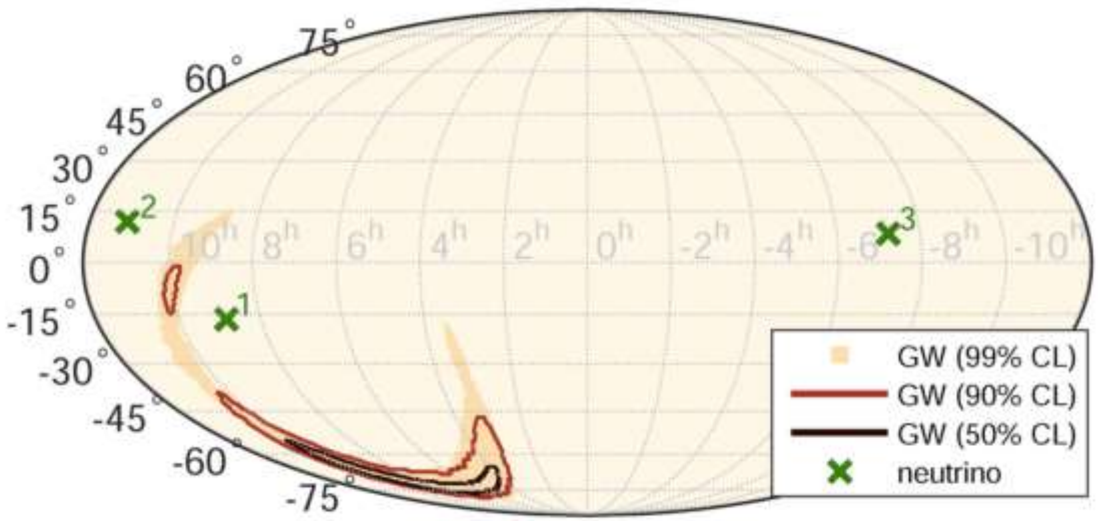




- Big participation to GW150914 observation:
  - 24 groups carried out observations
  - Challenging! Source location with large uncertainty ~ 600 deg^2

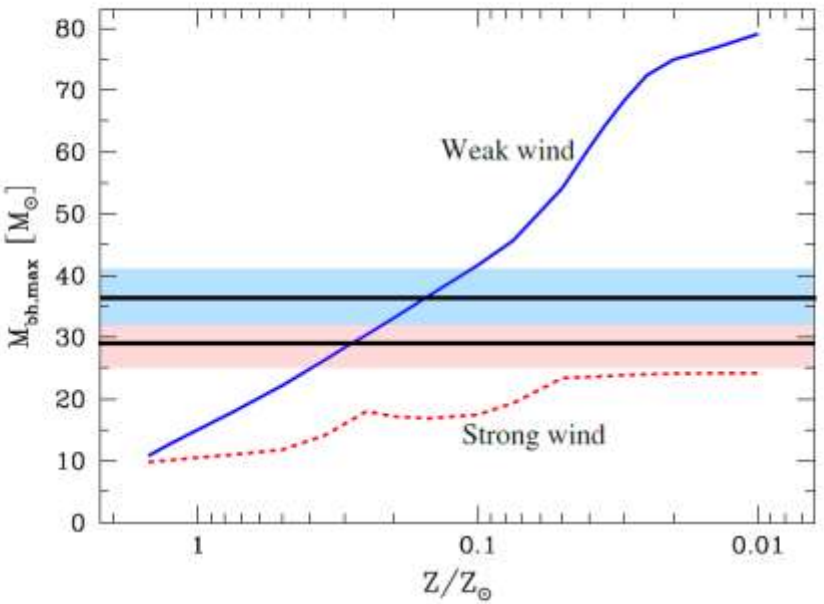
Follow-up with high energy ν

- Search for coincident high energy neutrino candidates in IceCube and ANTARES data
  - HEN ν expected in (unlikely) scenario of BH + accretion disk system
  - Search window ± 500 s
- No ν candidate in both temporal and spatial coincidence
  - 3 ν candidates in IceCube and 0 ν candidate in ANTARES
    - Consistent with expected atmospheric background
  - None of ν candidates directionally coincident with GW150914



Astrophysical implications

- Existence of binary black holes systems proved
  - **Form** and **merge** within the Hubble time
  - Previous predictions ranged $[0.1 – 10^3] / (Gpc^3\ yr)$
  - lowest end excluded: **rate > 1 / (Gpc^3 yr)**
- Component masses ($M > 20\ M_\odot$) large compared with *known* stellar mass BHs
- Stellar progenitors are
  - Likely **heavy**, $M > 60\ M_\odot$
  - Likely with a **low metallicity**, $Z < 0.25\ Z_\odot$
- Measured redshift $z \sim 0.1$
- Low metallicity models can produce low-*z* mergers at rates consistent with our observation



Tests on General Relativity

Most relativistic binary system known till GW150914: J0737-3039

- Orbital velocity v/c ~ 2 x 10^{-3}

GW150914: Higly relativistic black holes (v/c ~0.6)

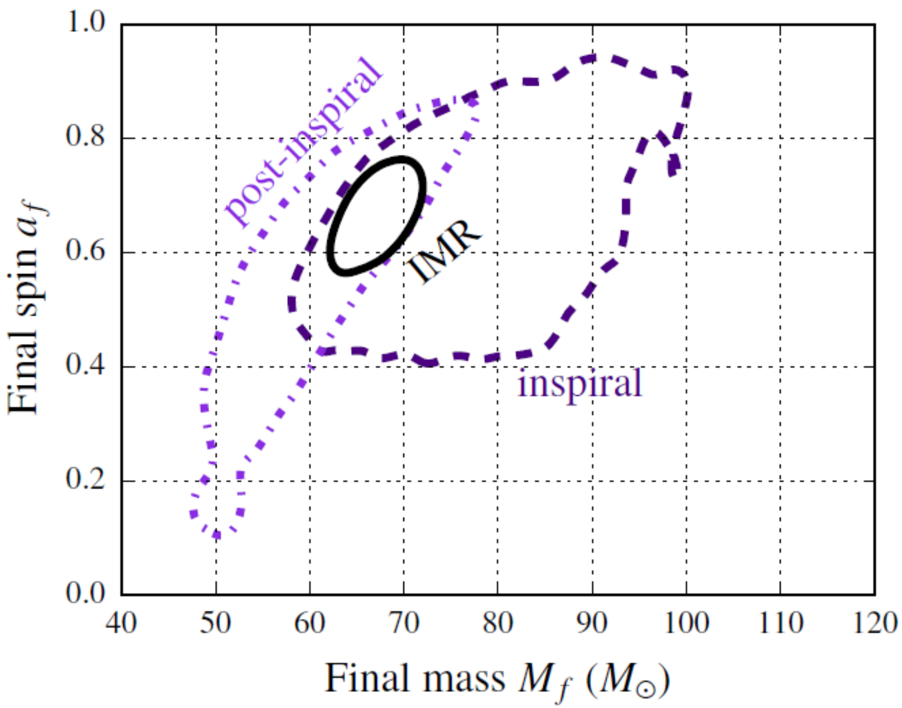
- Non linear dynamics
- Strong field, high velocity regime testable for the first time

Tests :

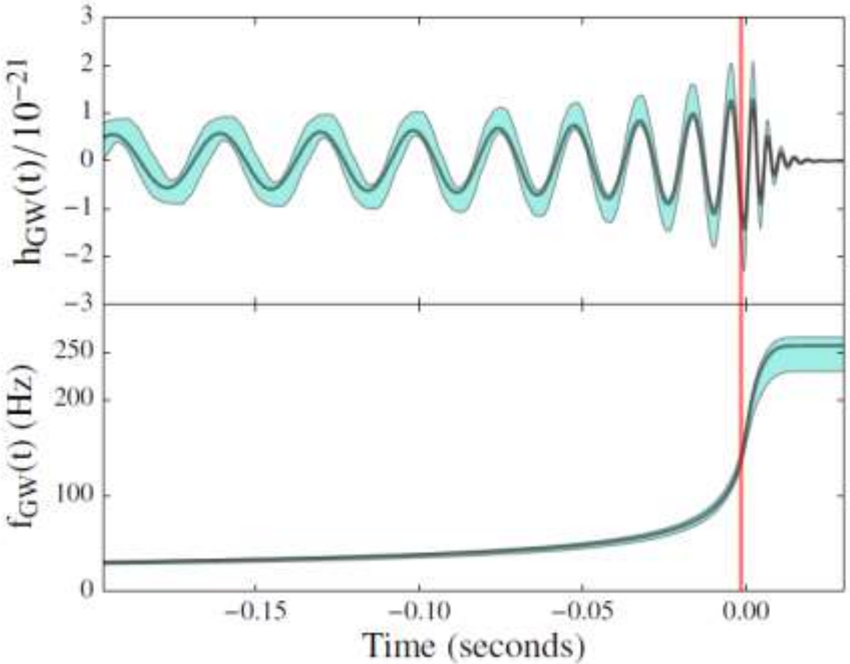
- Waveform internal consistency check
- Bound on graviton mass

All tests are consistent with predictions of General Relativity

Waveform consistency



Prediction of final black hole mass and spin



90% credible regions for the waveform and GW frequency of GW150914 versus time. The solid lines in each panel indicate the most probable waveform from GW150914 and its GW frequency.

Bound on graviton mass

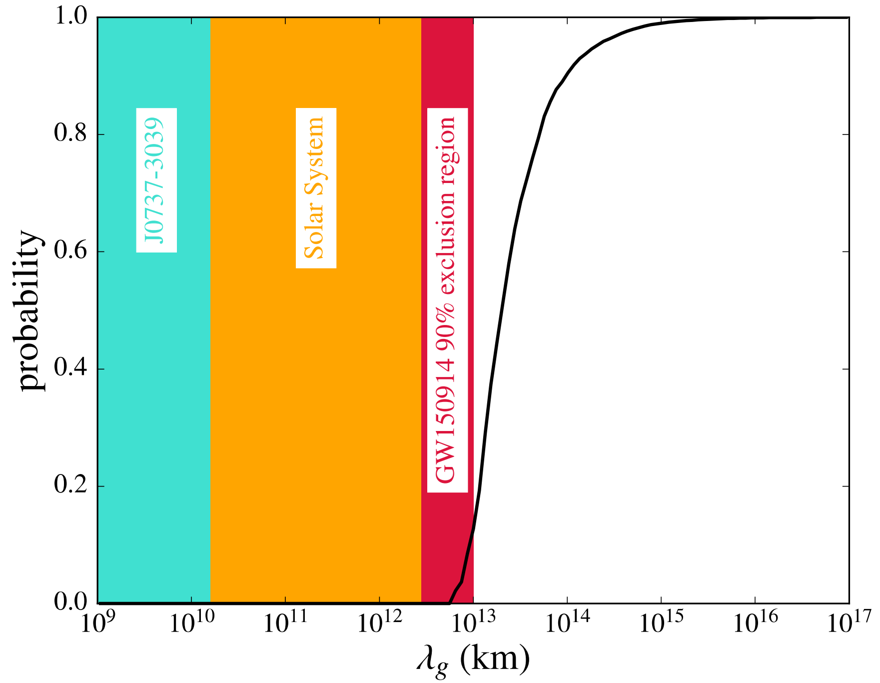
If graviton speed less than c → GWs obey a modified dispersion relation

$$\frac{v_g}{c} = 1 - \left(\frac{c}{f \lambda_g}\right)^2$$

$\lambda_g = h/m_g c$ is the graviton Compton wavelenght

GW150914: $\lambda_g > 10^{13}$ km with 90% CL
or
$m_g < 1.2 \times 10^{-22}$ eV/c^2

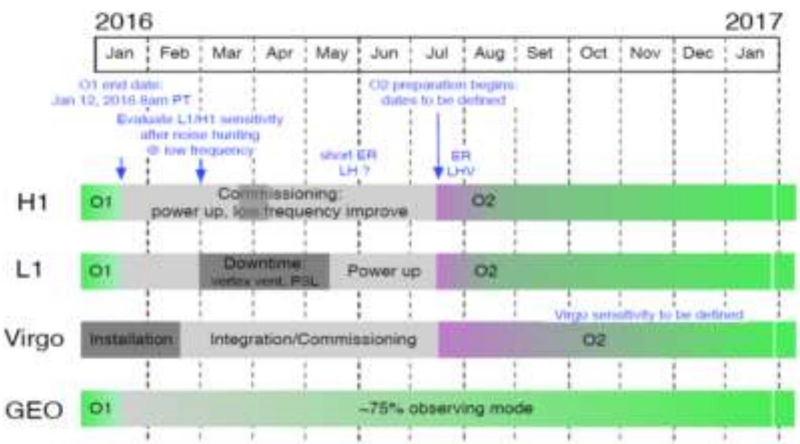
- limit better than that set by Solar System observations
- thousand time better of the binary pulsar bounds
- worse than bounds from dynamics of galaxy clusters and weak lensing observations (model-dependent bounds)

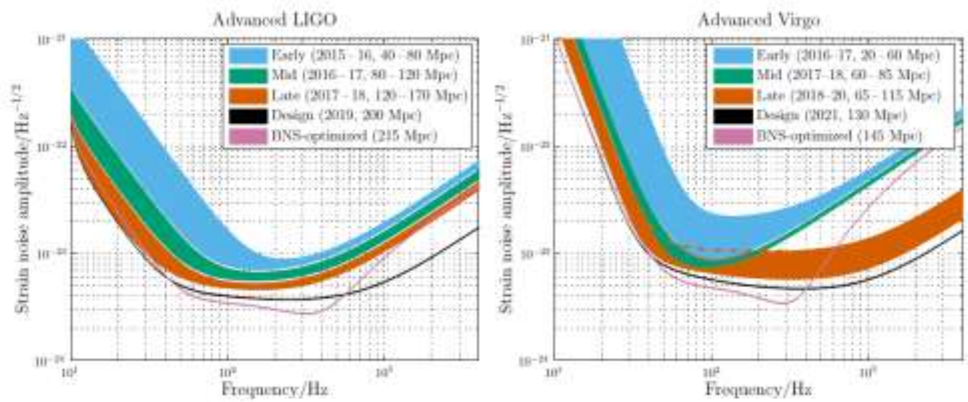


Cumulative posterior probability distribution for λg (black curve) and exclusion regions for λg from GW150914. The shaded areas show exclusion regions from the double pulsar observations (turquoise), the static Solar System bound (orange) and the 90% (crimson) region from GW150914.

LIGO/Virgo next science run: O2

- LIGO and Virgo are now off-line for commissioning/integration

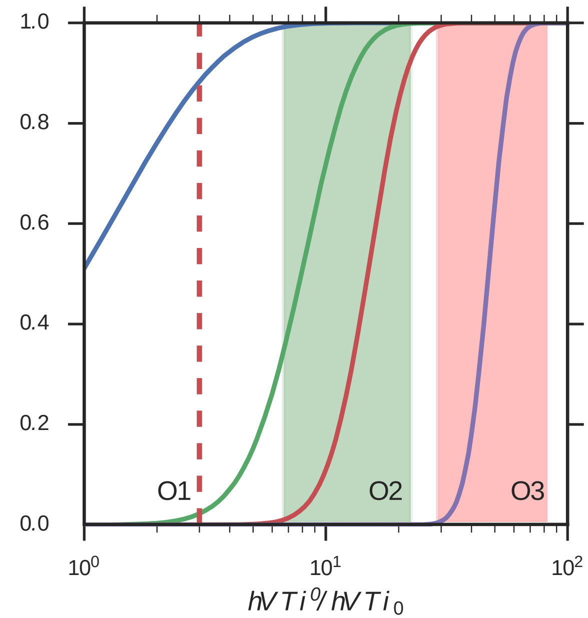




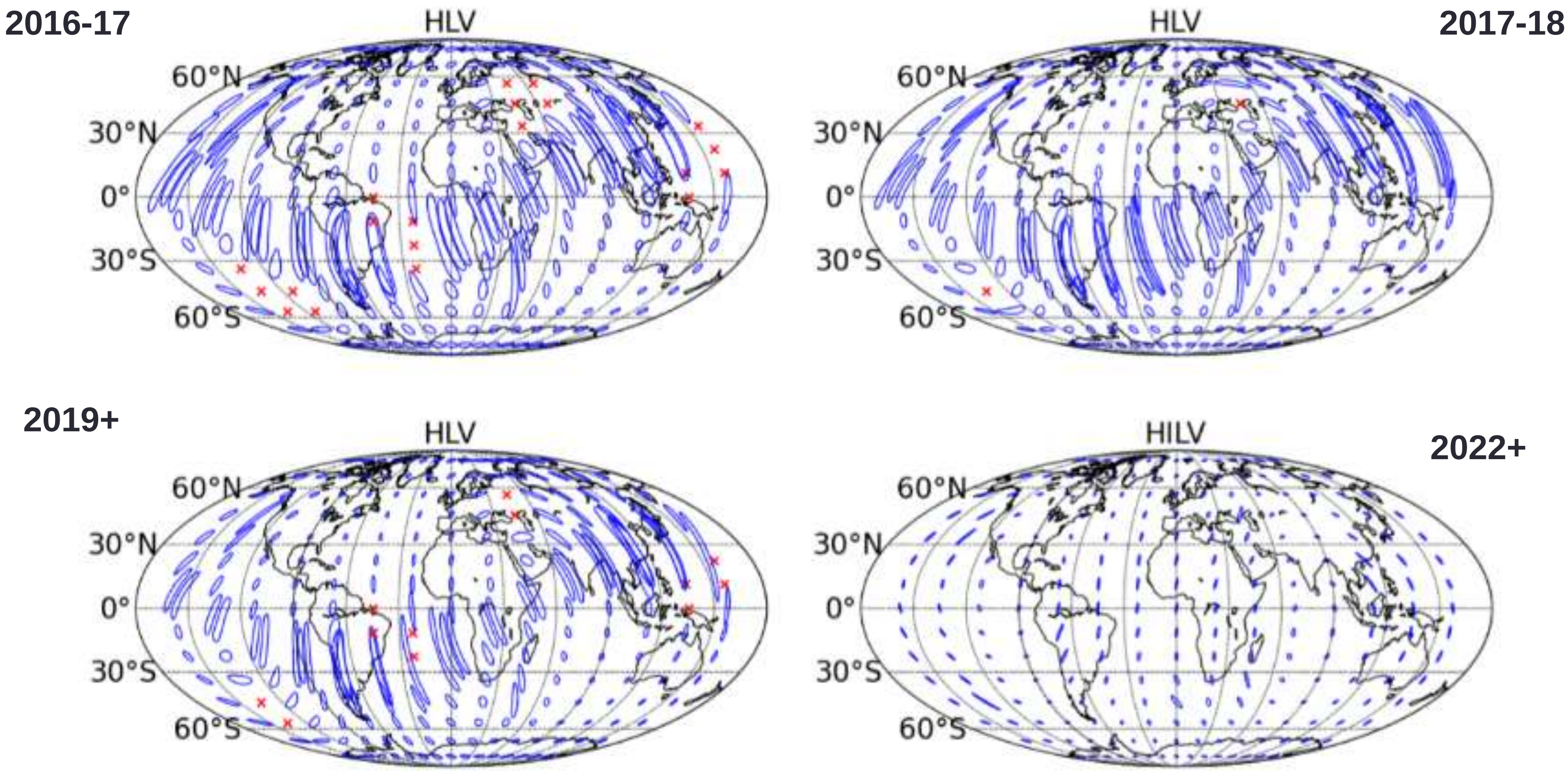
Probability of observing

- N > 0 (blue)
- N > 5 (green)
- N > 10 (red)
- N > 35 (purple)

highly significant events, (FARs <1/century) as a function of surveyed time-volume.



Sky localization perspectives



- With Virgo, no more annulus
- As sensitivity improves, so does the localization
- With LIGO-Virgo network at design sensitivity, GW150914 could have been localized to less than 20 deg^2

Summary

- Gravitational waves from the merger of two stellar mass black holes have been observed

- The detected waveforms match the prediction of general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting black hole.

- **This observation is the first direct detection of gravitational waves and the first observation of a binary black hole merger.**

- Next run together with Advanced Virgo in 2016-2017

GW150914 Companion papers

Detection Paper
Phys. Rev. Lett. 116, 061102 (2016)
arXiv:1602.03837

Observing scenario
Living Rev. Relativity 19, 1 (2016)

Astrophysics implications
ApJL, 818, L22, 2016
arXiv:1602.03846

Test of GR
arXiv:1602.03841

Rates
arXiv:1602.03842

Stochastic Background
arXiv:1602.03847

EM follow-up and HE ν
arXiv:1602.05411
arXiv:1602.08492

CBC searches
arXiv:1602.03839

Unmodeled searches
arXiv:1602.03843

Parameter Estimation
arXiv:1602.03840

Instrument
arXiv:1602.03838

DetChar
arXiv:1602.03844

Calibration
arXiv:1602.03845

Public data release
https://losc.ligo.org/events/GW150914

Conclusion?

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News & Comment > News > 2016 > May > Article

NATURE | NEWS

Gravitational waves: 6 cosmic questions they can tackle

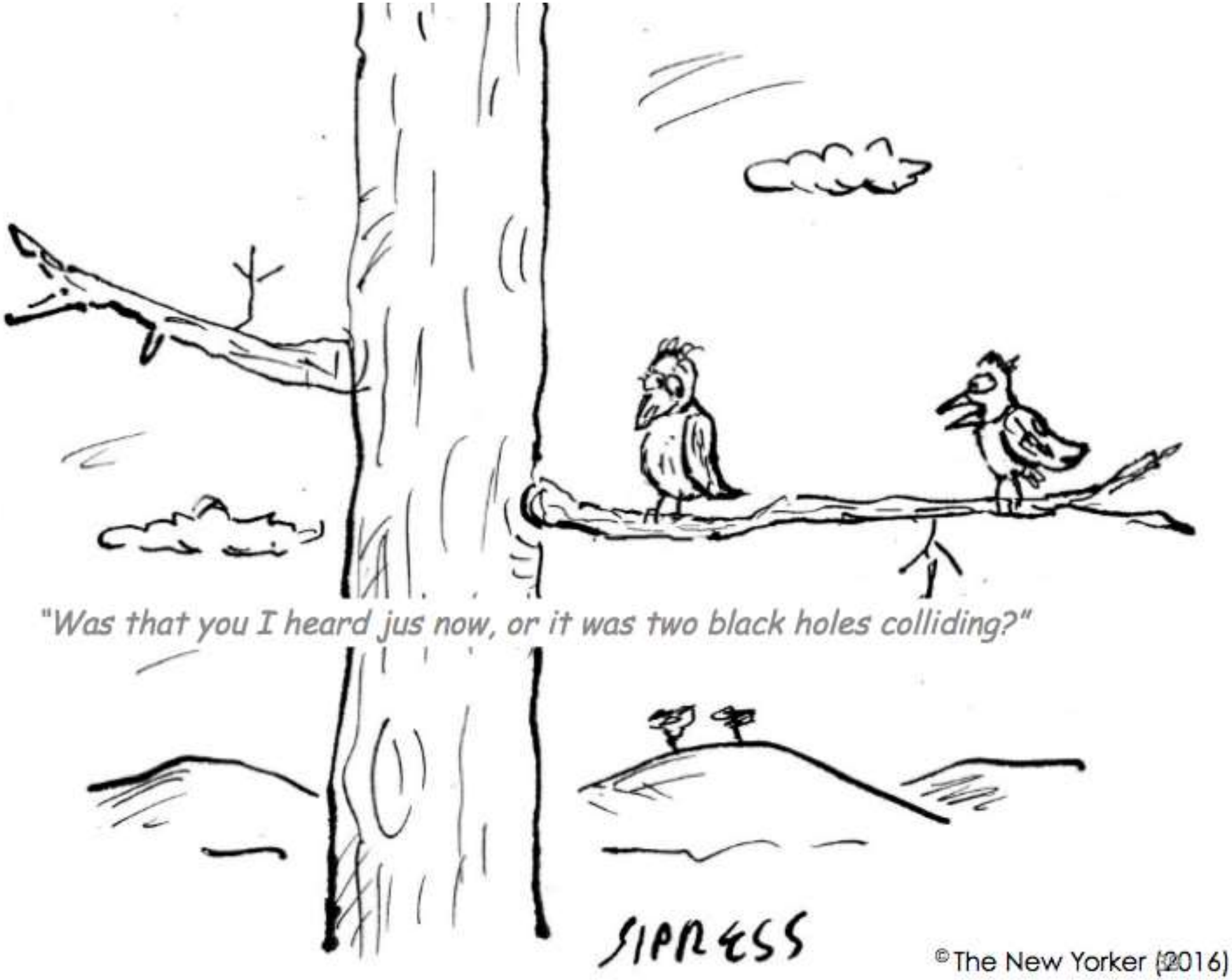
The discovery of ripples in space-time has vindicated Einstein — but it can also do so much more.

Davide Castelvecchi

09 February 2016 | Updated: 11 February 2016

- ✓ **Do black holes actually exist?**
- **Do gravitational waves travel at the speed of light?**
- **Is space-time made of cosmic strings?**
- **Are neutron stars rugged?**
- **What makes stars explode?**

Conclusion?


"Was that you I heard jus now, or it was two black holes colliding?"
SIPRESS
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