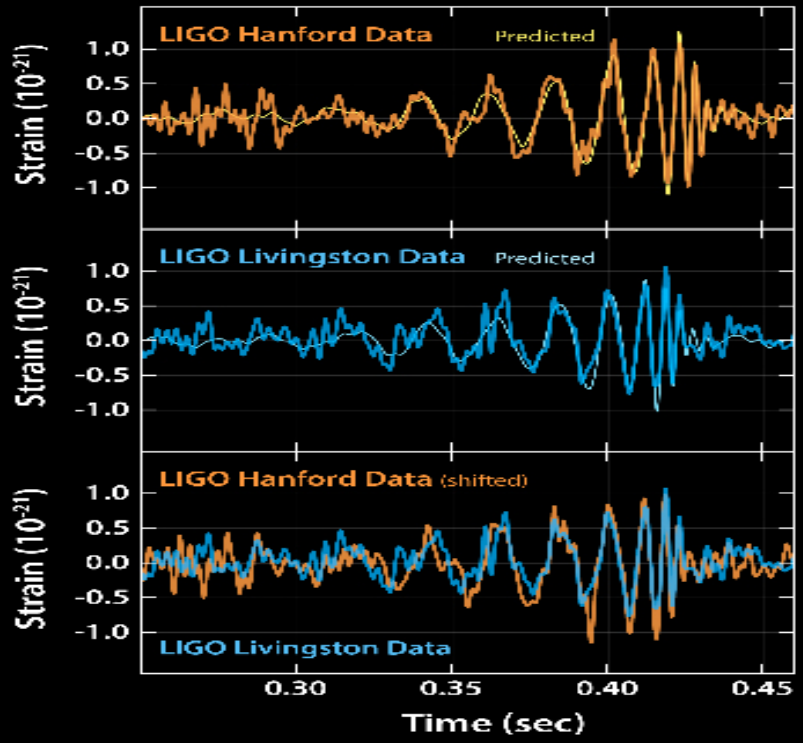
# Gravitational Waves





***Barry C Barish***

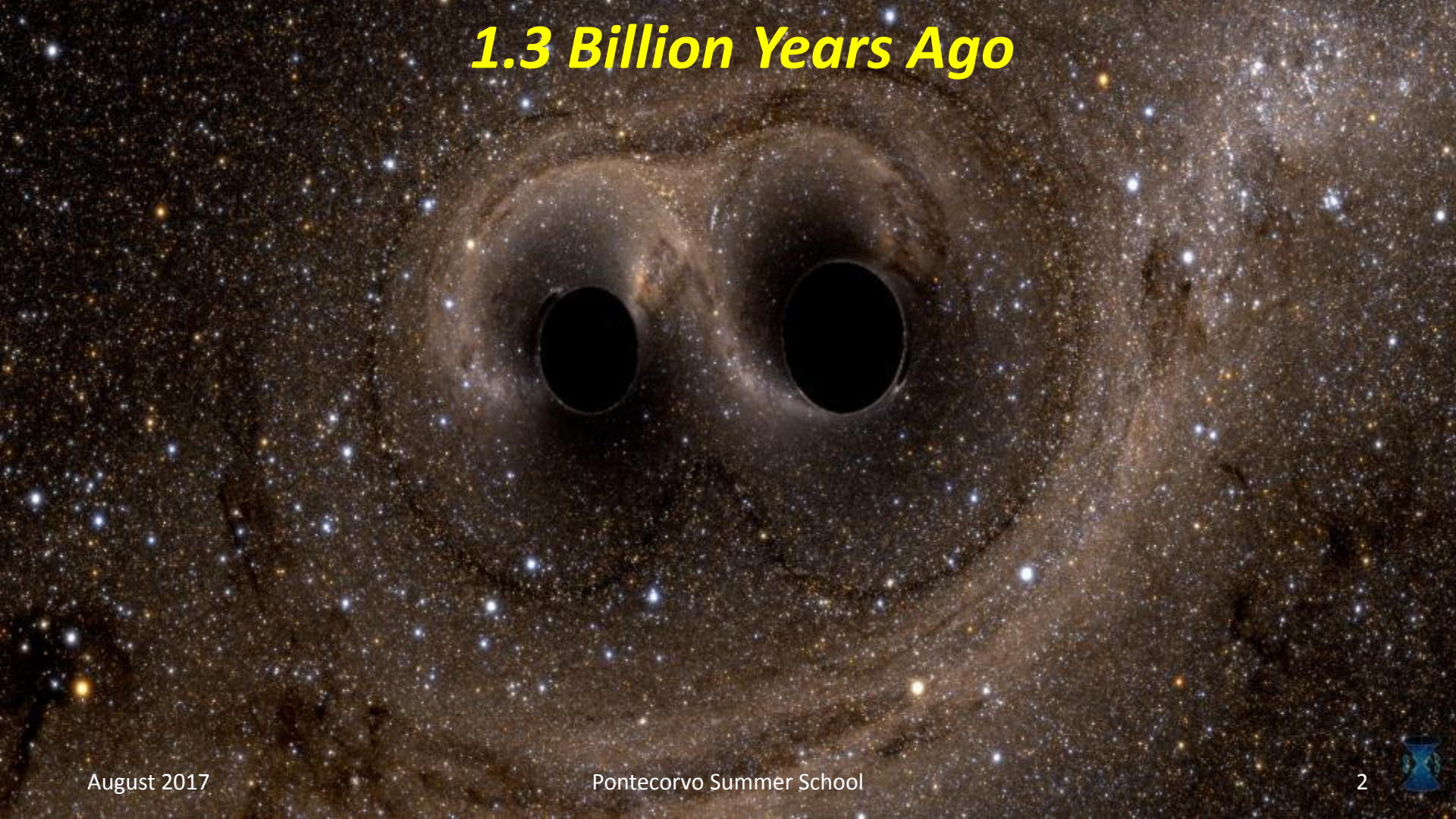
*Caltech*

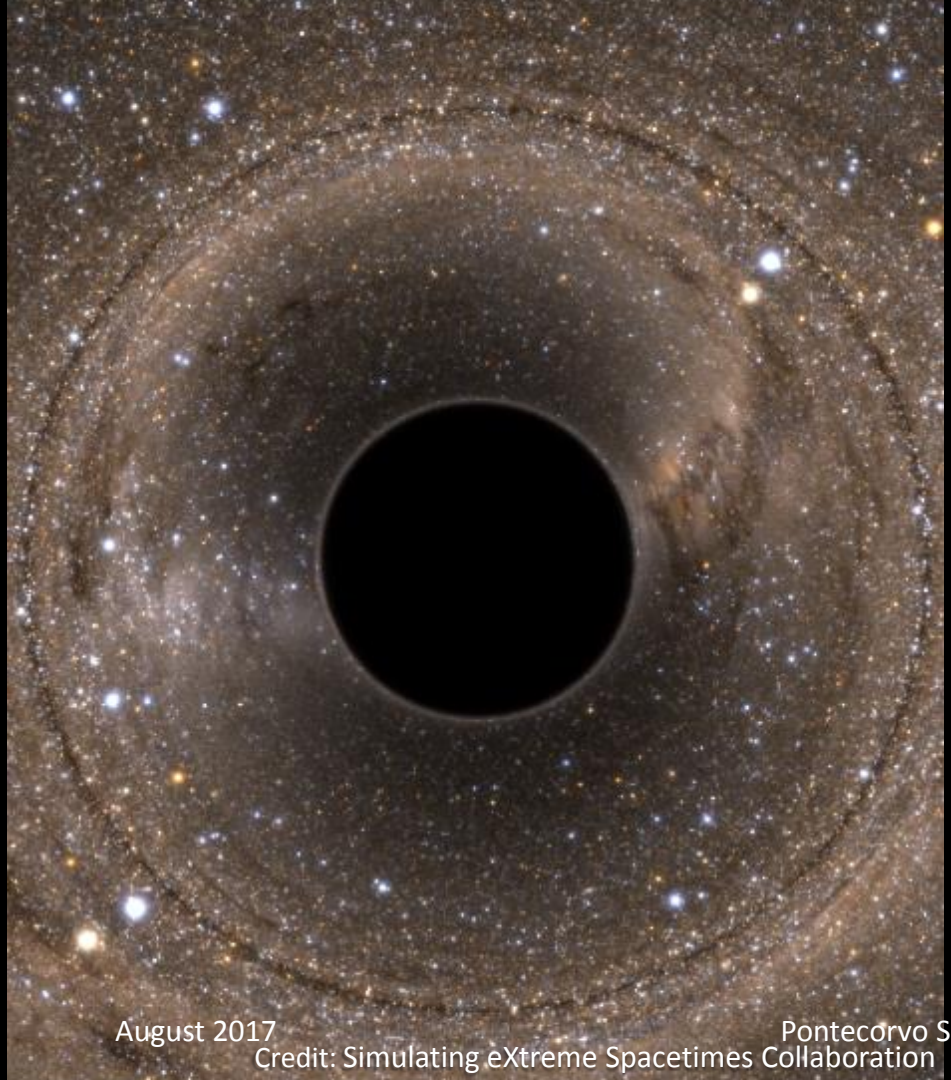

*Pontrecorvo Summer School*

*Prague*

*22-Aug-2017*

# *1.3 Billion Years Ago*

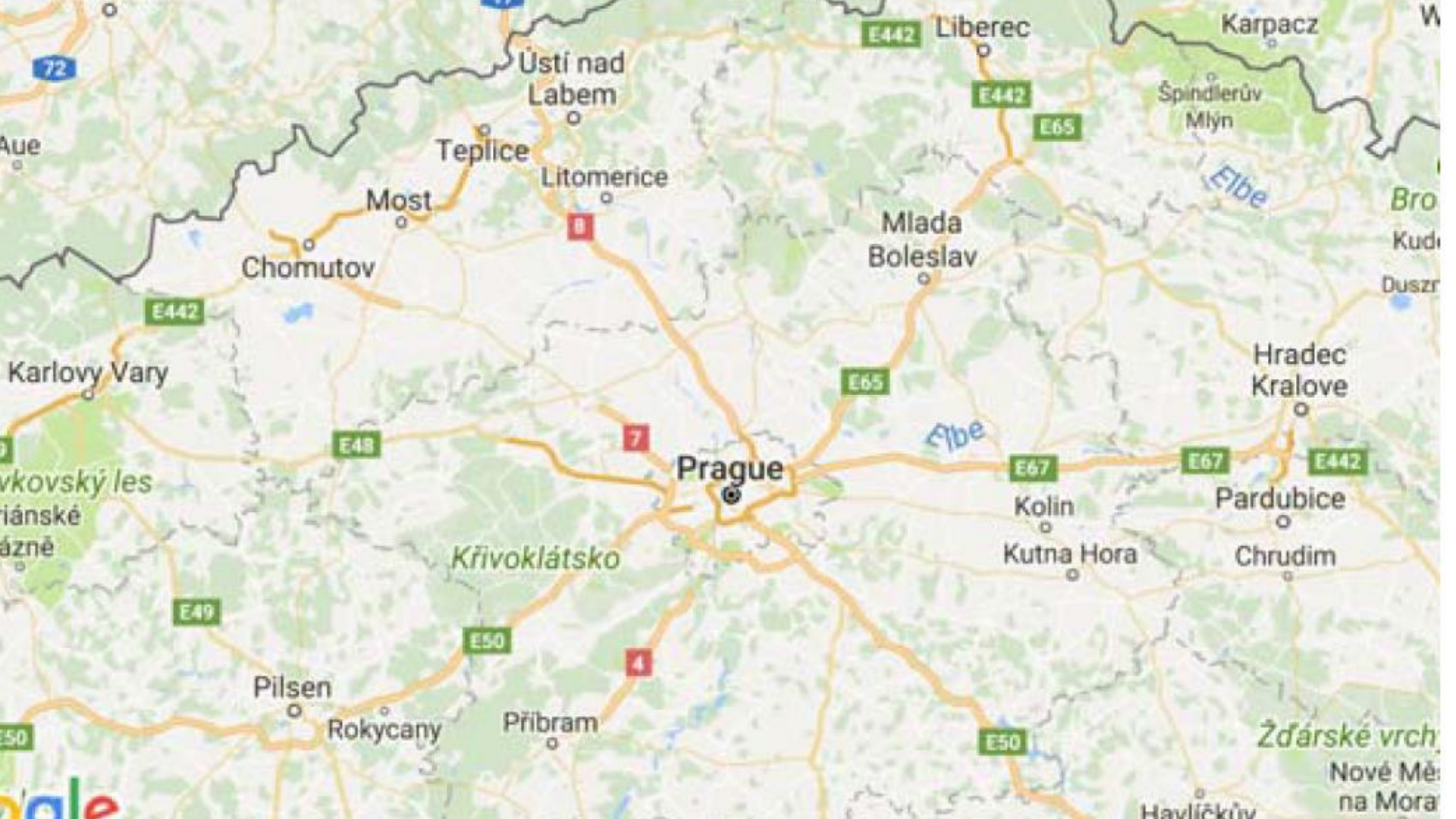




Credit: Simulating eXtreme Spacetimes Collaboration

# Black Holes

- Regions of space created by super dense matter from where nothing can escape due to the strength of gravity
- Some may form when very large stars collapse and die
- Expected to have masses from around 3 to 100s of times the mass of the Sun
- Others may have been created in the Big Bang
- Supermassive black holes weighing as much as millions of stars reside in the centers of most galaxies (including our own)


Liberec
Karpacz
Ústí nad Labem
Špindlerův Mlýn
Teplice
Litomerice
Most
Elbe
Chomutov
Mlada Boleslav
Karlovy Vary
Hradec Kralove
Prague
Elbe
Křivoklátsko
Kolin
Pardubice
Kutna Hora
Chrudim
Pilsen
Rokycany
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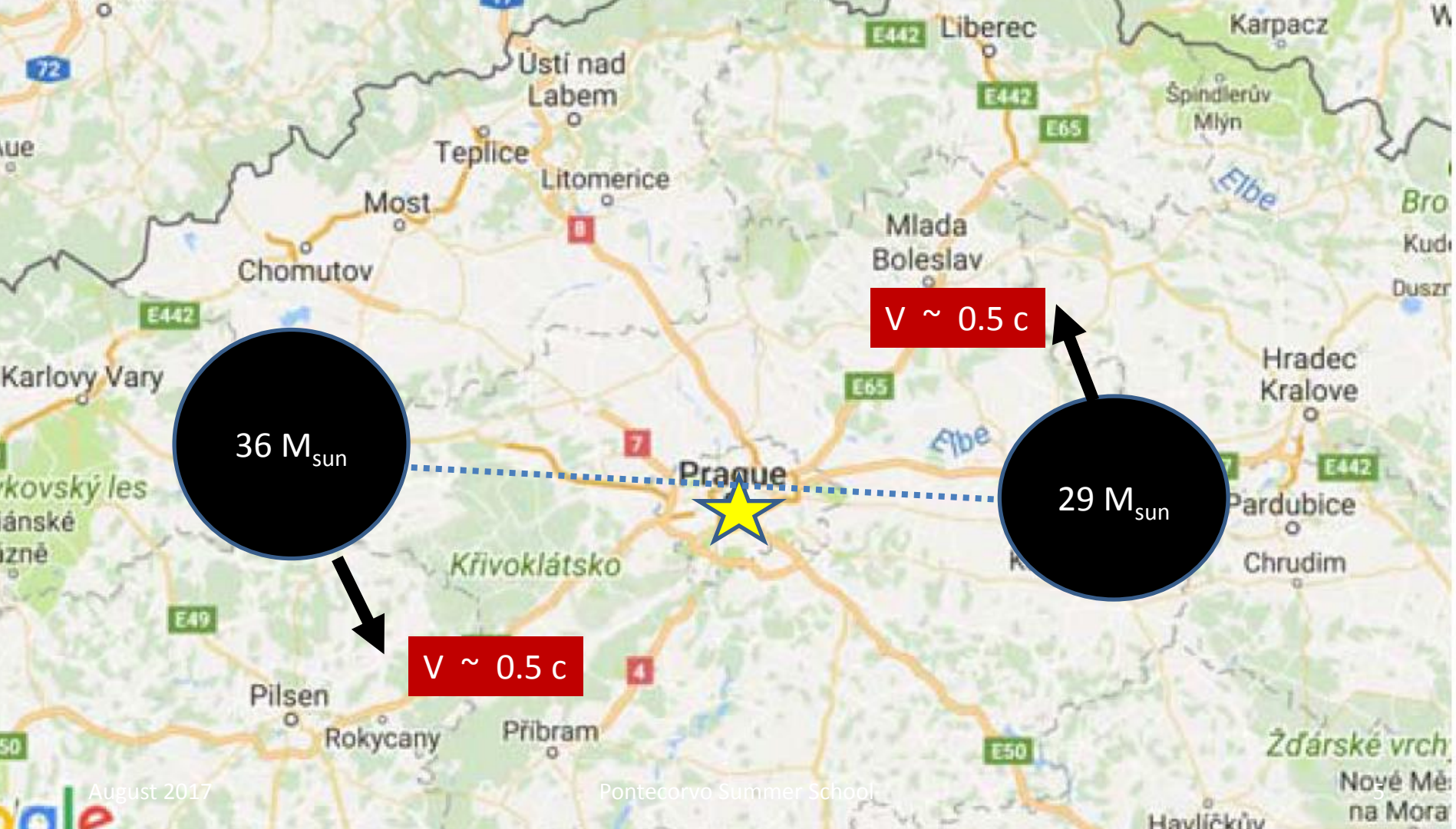
36 $M_{sun}$
29 $M_{sun}$
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V ~ 0.5 c
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Karpacz
Ústí nad Labem
Teplice
Litomerice
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Chomutov
Mlada Boleslav
Špindlerův Mlýn
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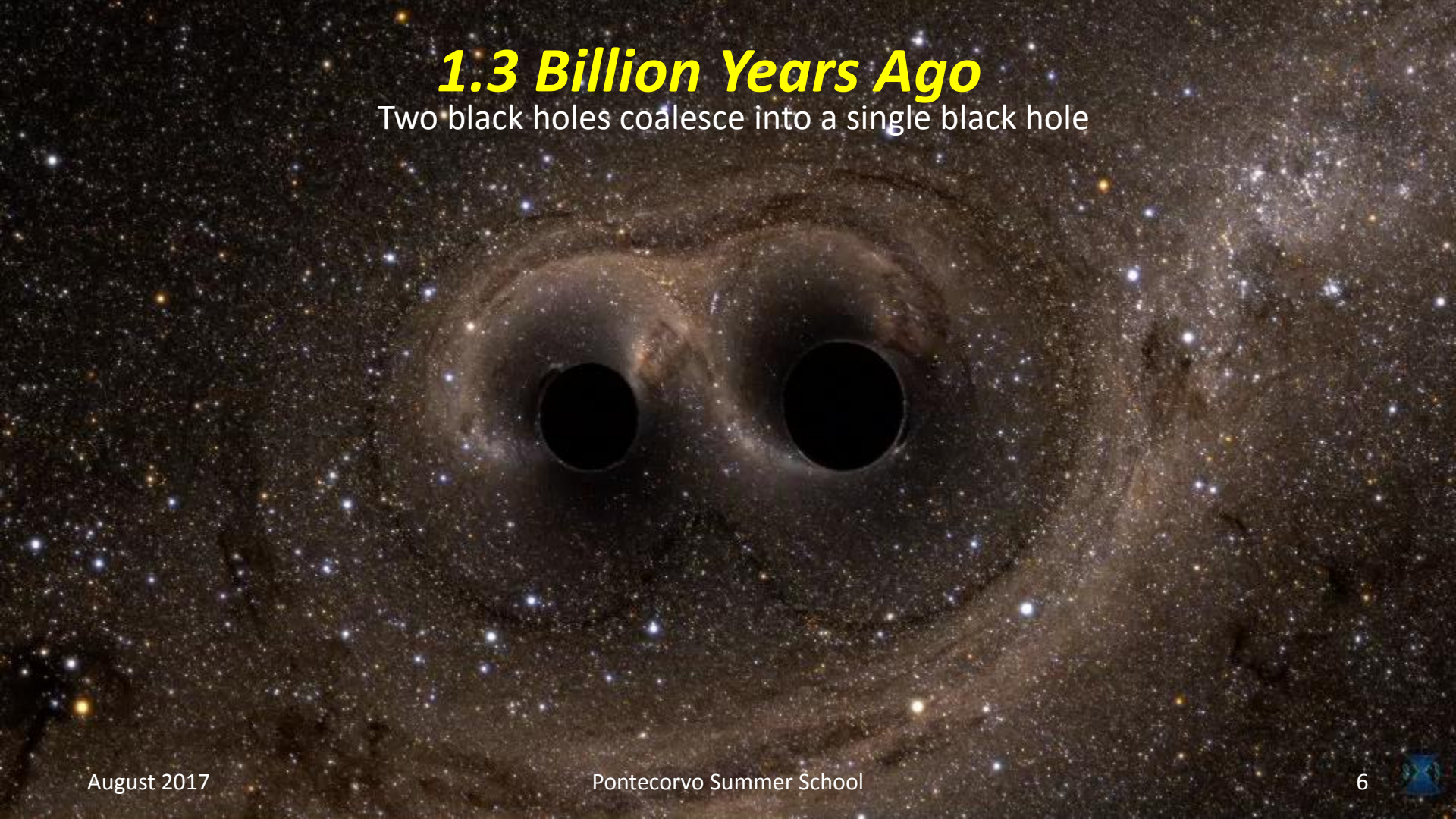
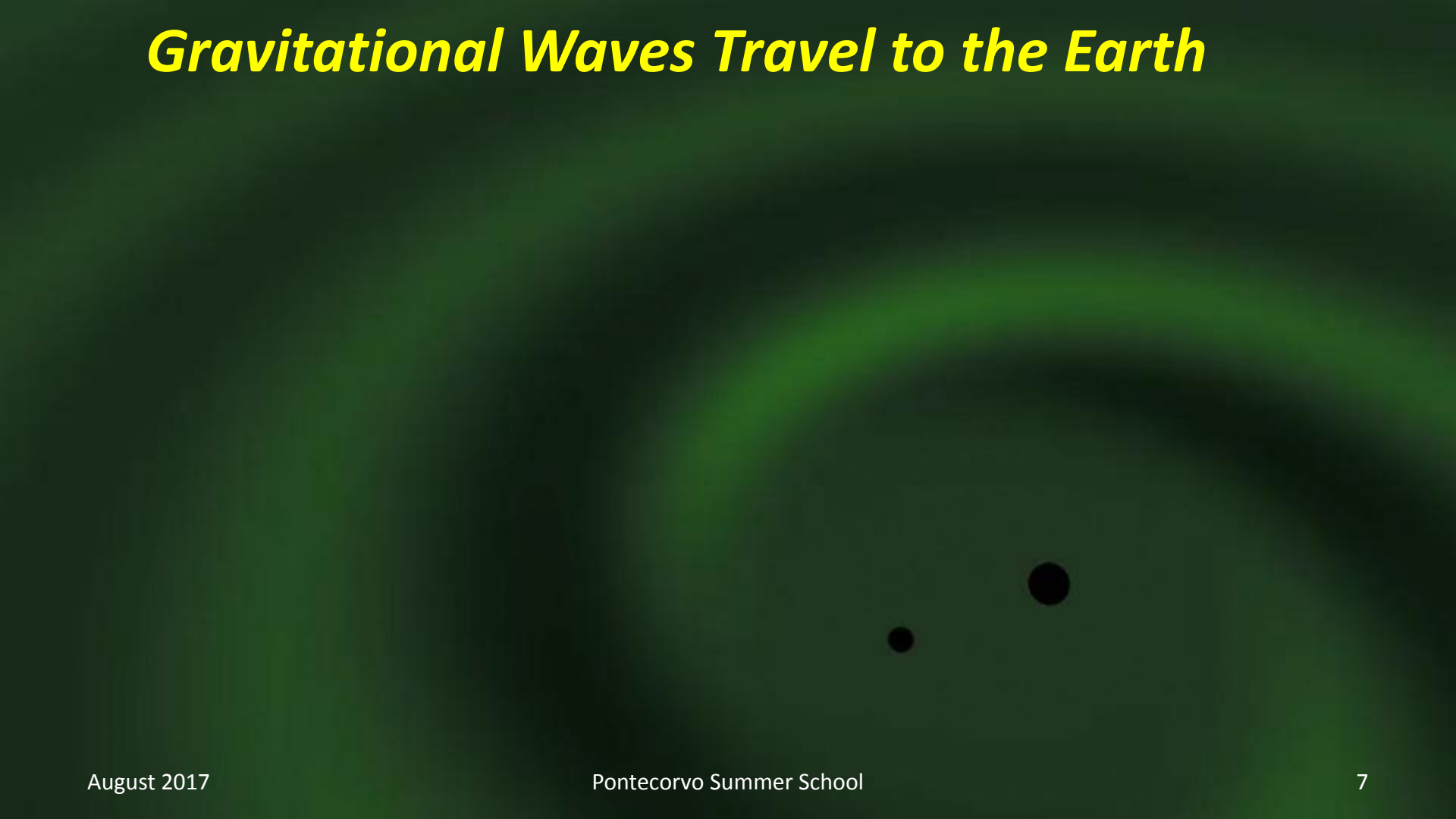
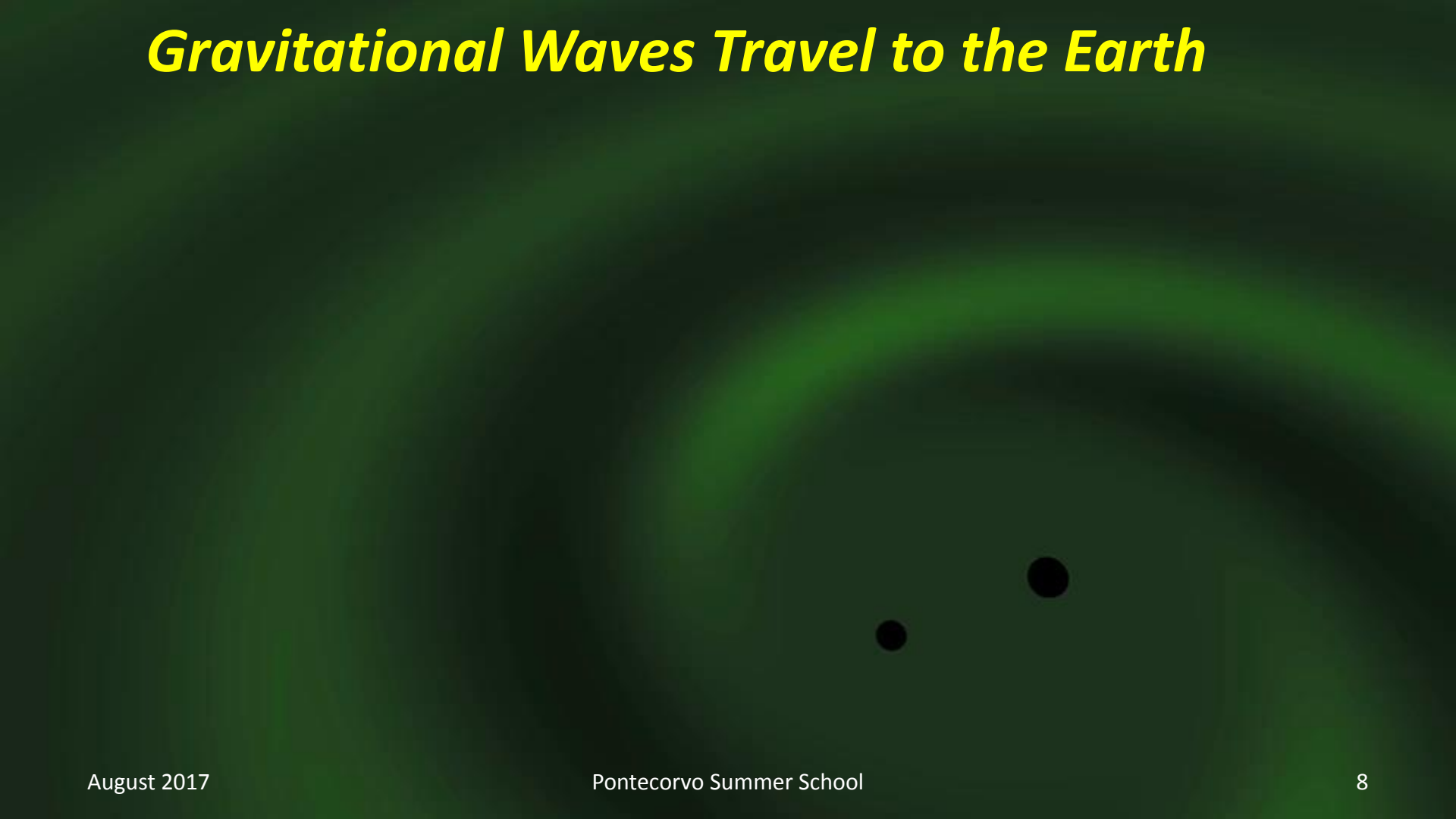

1.3 Billion Years Ago
Two black holes coalesce into a single black hole

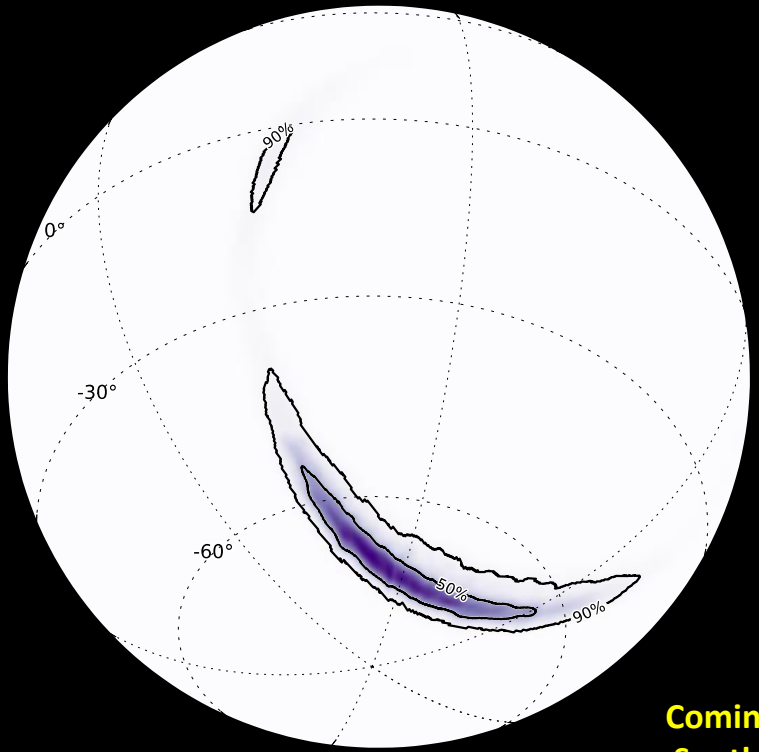
# *Gravitational Waves Travel to the Earth*



# *Gravitational Waves Travel to the Earth*

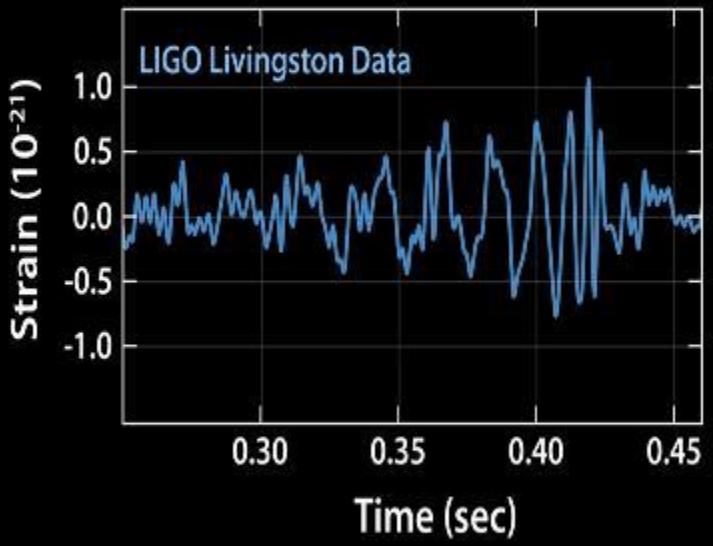


# Sept 14, 2015

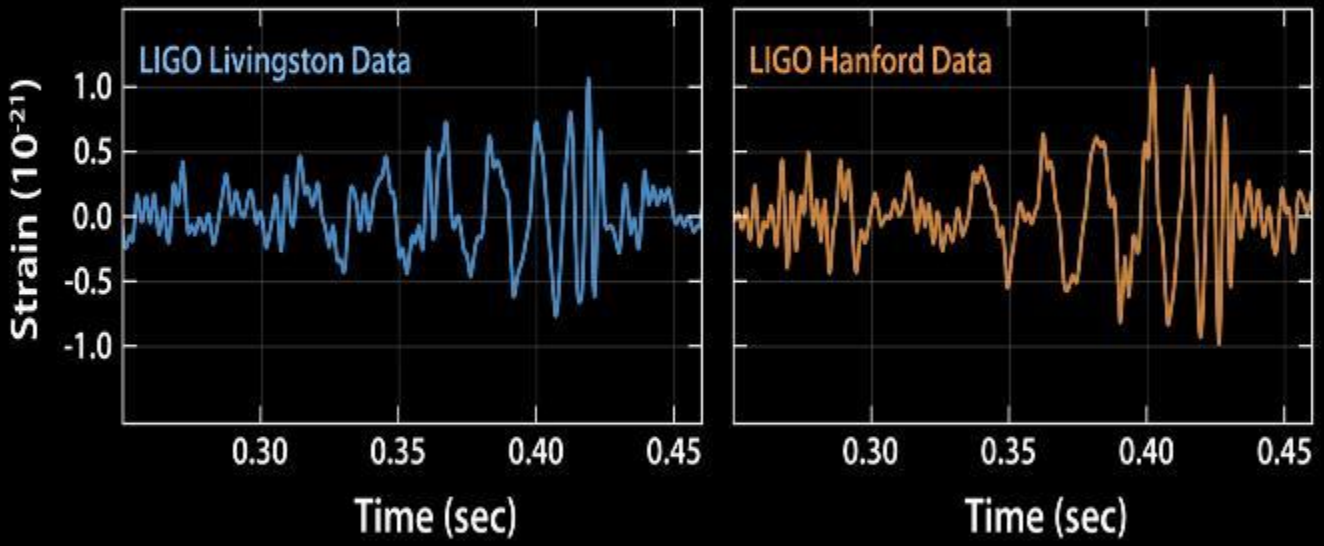



**Coming up from Southern Hemisphere**

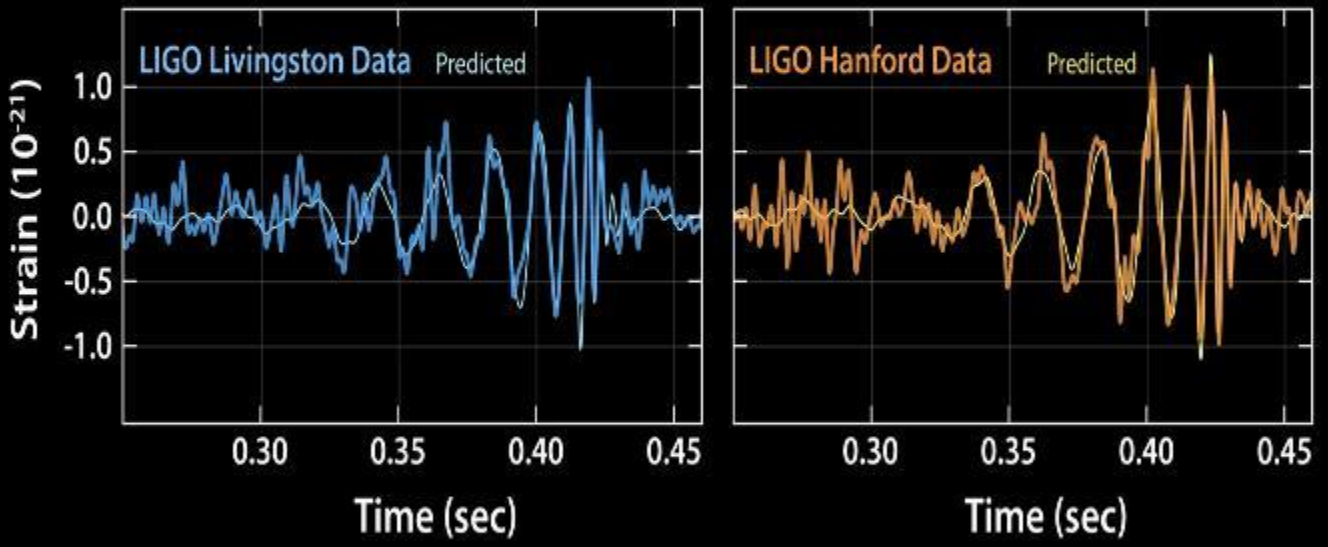
# ~ 20 msec later



# *After another 7 msec*

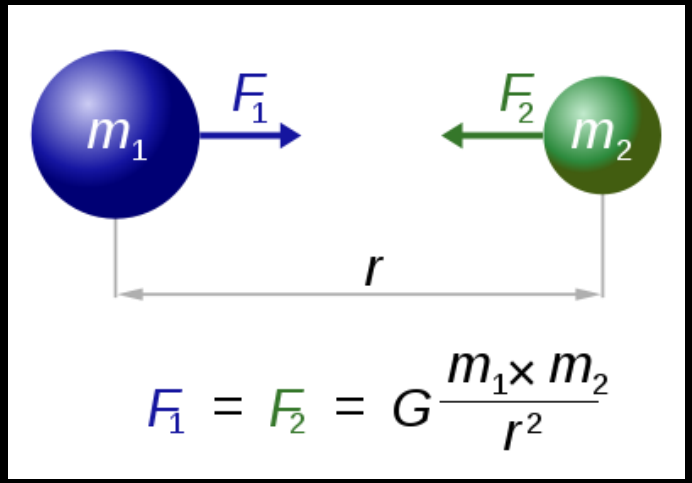


# GR Prediction for BH merger



# Newton's Theory of Gravity

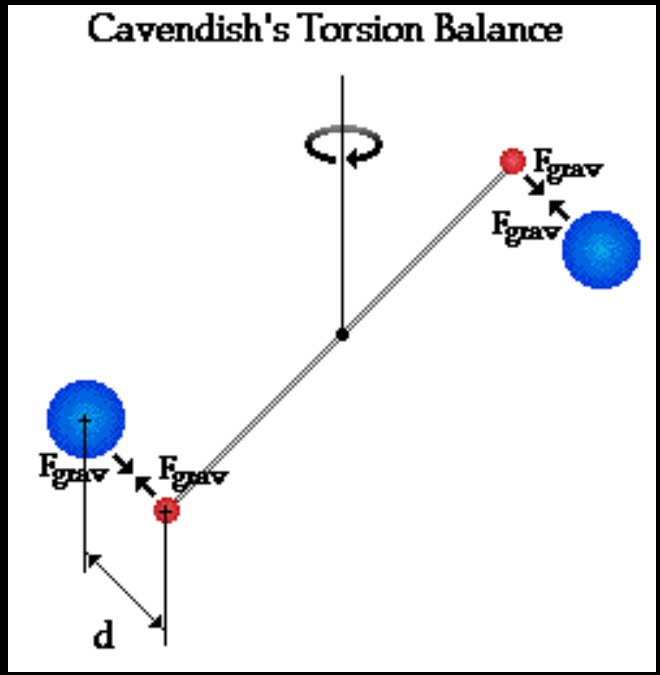
1687




**Universal Gravity:** force between massive objects is directly proportional to the product of their masses, and inversely proportional to the square of the distance between them.

# Newton's Universal Gravitation

**Henry Cavendish:**
Experimental Physicist was first to study Newton's law of gravitation in the laboratory. He determined the value of G in 1798, about 100 years later.




Cavendish: $G = 6.75\ 10^{-11}$ $Nm^2/kg^2$
Now: $G = 6.67259\ 10^{-11}$ $Nm^2/kg^2$

Universal gravitation successfully determined the orbits of planets, escape velocity from the earth, the tides, etc.

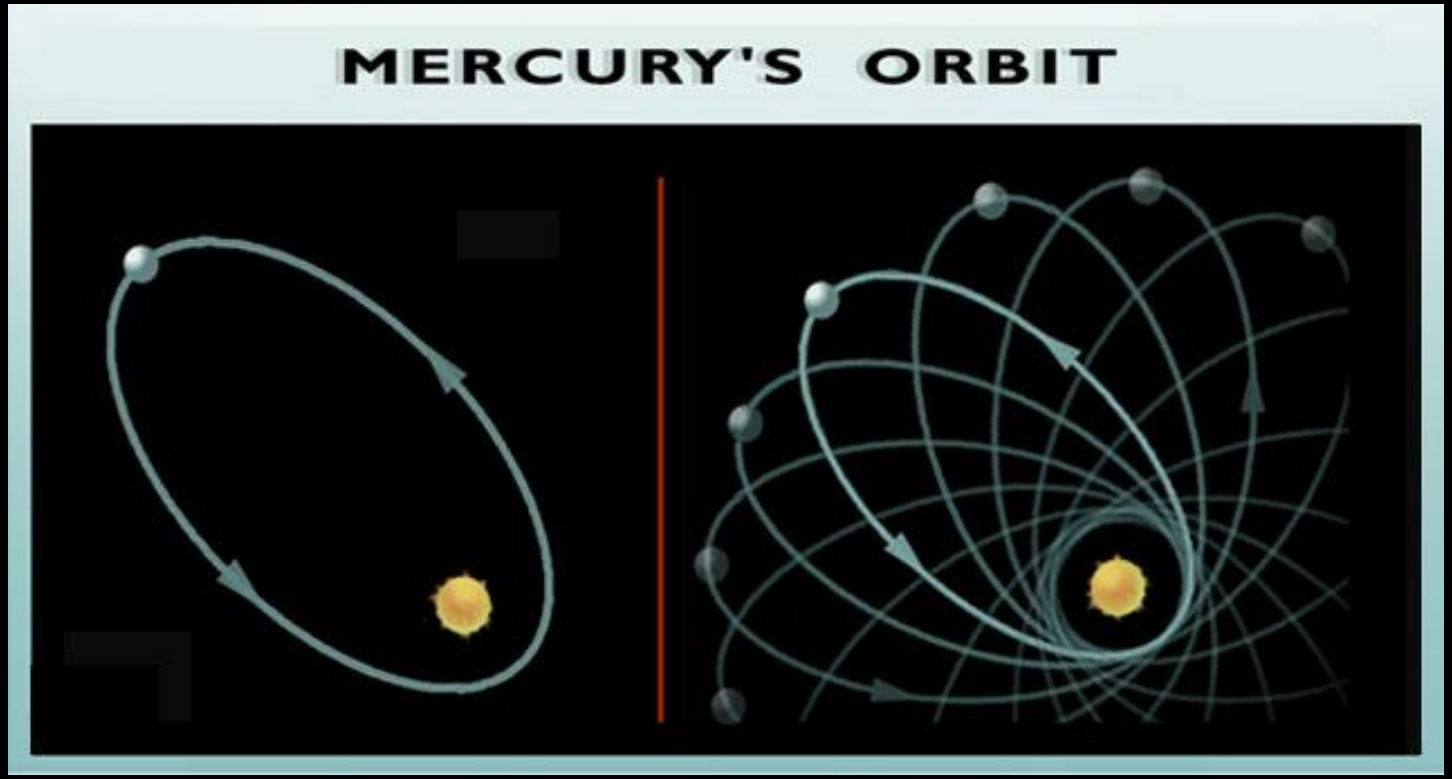
# *Urban le Verrier*

## Mathematician – Celestial Mechanics.

Famous for validation of "Celestial Mechanics." He **predicted the existence and position of Neptune** by calculating the discrepancies between Uranus's orbit and the laws of Kepler and Newton.

He sent his prediction to a German astronomer who found Neptune within 1 degree of prediction the same night. (1846)

Then, in the 1850s he discovered a problem with the orbit of Mercury around the sun




Mercury's elliptical path around the Sun. Perihelion shifts forward with each pass. (Newton 532 arc-sec/century vs Observed 575 arc-sec/century)
(1 arc-sec = 1/3600 degree).

# *Urban le Verrier*

Verrier predicted the existence of a small body or bodies between Mercury and the Sun and called it “Vulcan.” (1859)

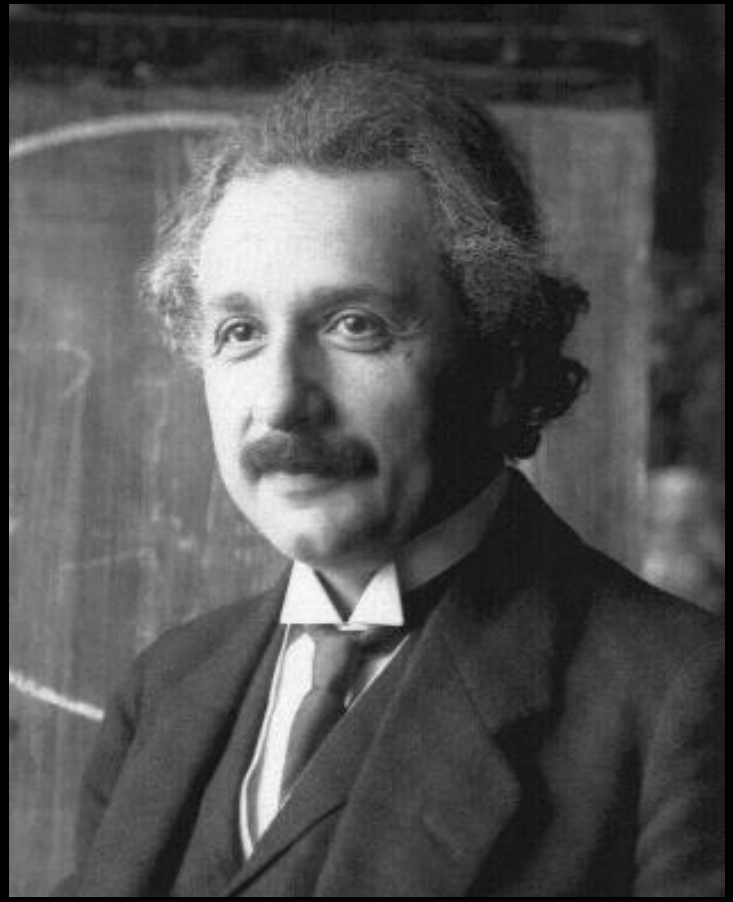
Vulcan was not found by the time Einstein developed General Relativity!

Later, looked for by NASA, but never found

But, finally, it was re-invented for STAR TREK

# *Einstein's Theory of Gravity*

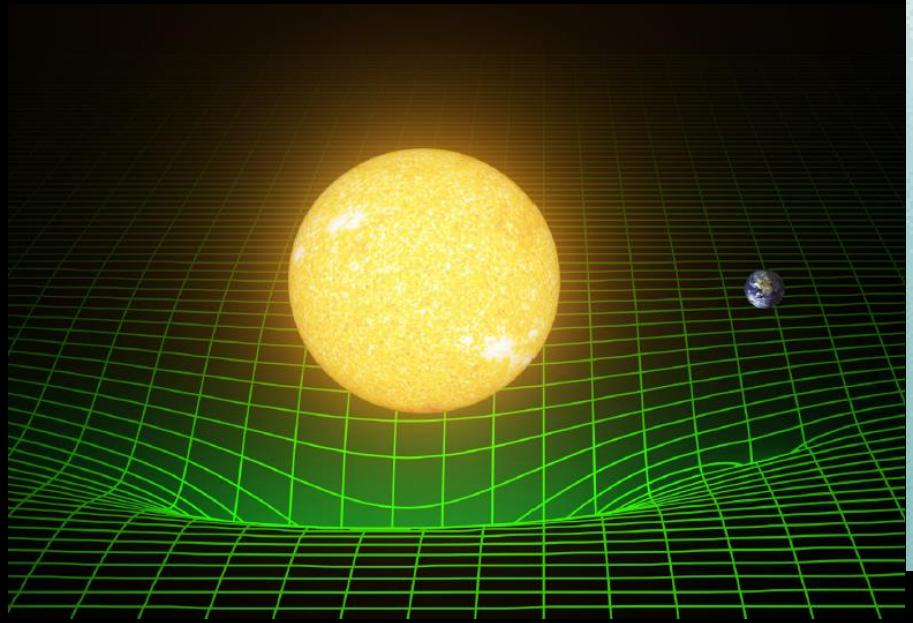
**1915**

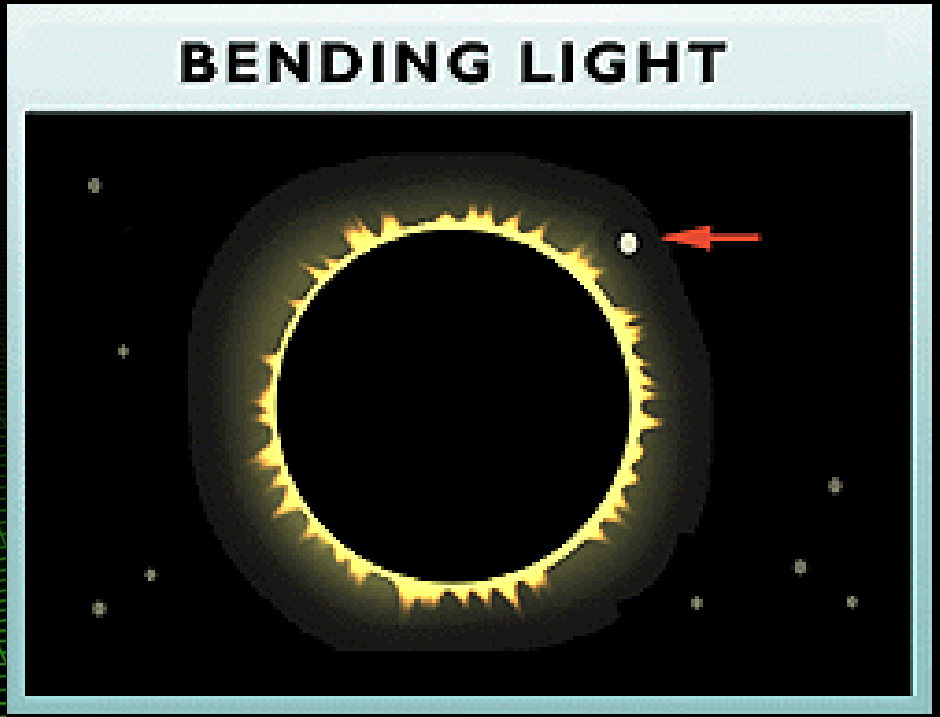


$$G_{ab} \equiv R_{ab} - \frac{1}{2} g_{ab} R = \frac{8\pi G}{c^4} T_{ab}$$

Space *and* Time are ***unified***
in a four dimensional

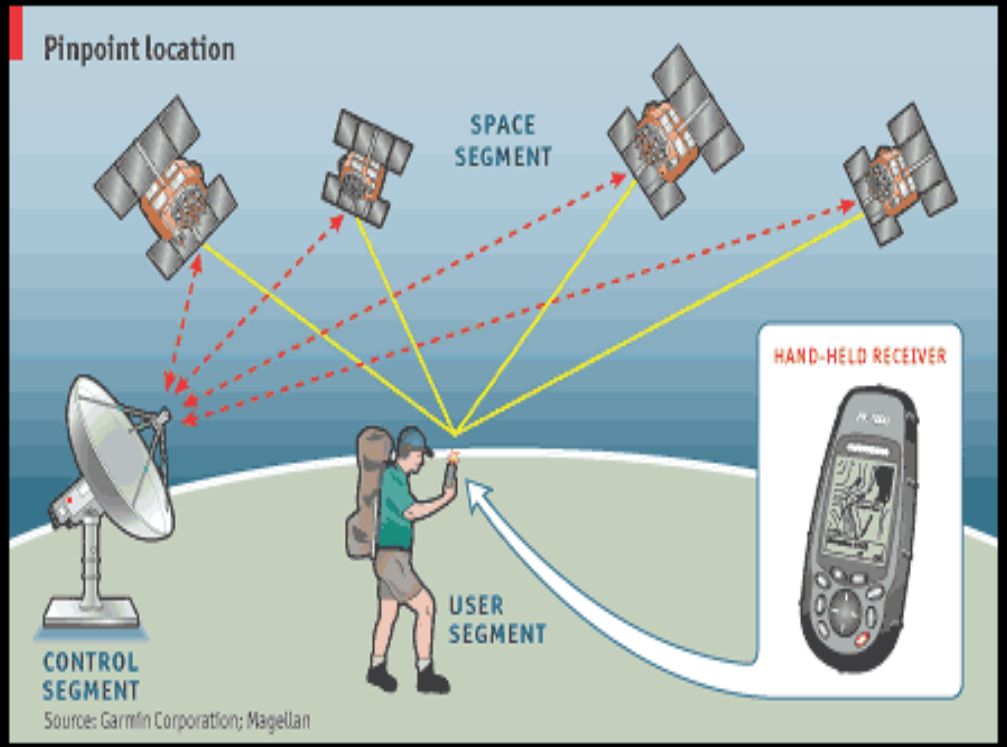
***spacetime***






First observed during the solar eclipse of 1919 by Sir Arthur Eddington, when the Sun was silhouetted against the Hyades star cluster

# GPS: General Relativity in Everyday Life




**Special Relativity**

(Satellites v = 14,000 km/hour

"moving clocks tick more slowly"

Correction = - 7 microsec/day

**General Relativity**

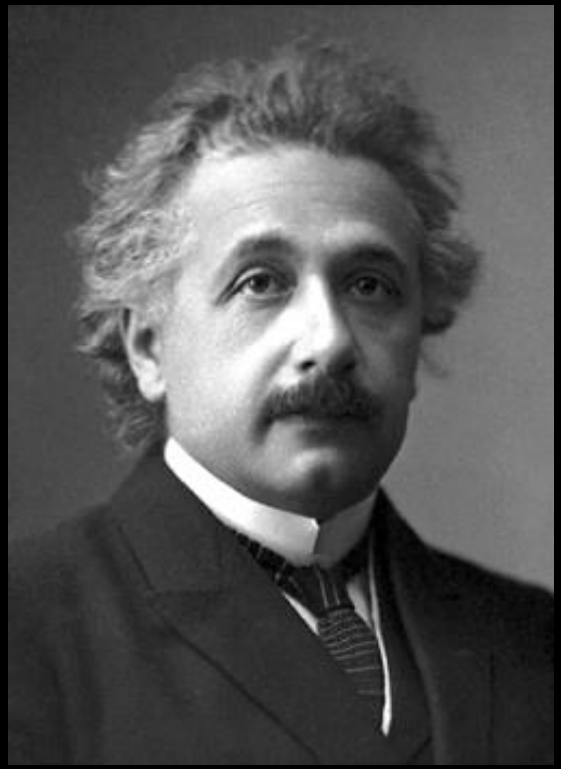
Gravity: Satellites = 1/4 x Earth

Clocks faster = + 45 microsec/day

**GPS Correction = + 38 microsec/day**

(Accuracy required ~ 30 nanoseconds to give 10 meter resolution

# *Einstein Predicted Gravitational Waves in 1916*



Näherungsweise Integration der Feldgleichungen der Gravitation.

Von A. Einstein.

Bei der Behandlung der meisten speziellen (nicht prinzipiellen) Probleme auf dem Gebiete der Gravitationstheorie kann man sich damit begnügen, die $g_{\mu\nu}$ in erster Näherung zu berechnen. Dabei bedient man sich mit Vorteil der imaginären Zeitvariable $x_4 = it$ aus denselben Gründen wie in der speziellen Relativitätstheorie. Unter »erster Näherung« ist dabei verstanden, daß die durch die Gleichung

$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \qquad (1)$$

- 1st publication indicating the existence of gravitational waves by Einstein in 1916
  - Contained errors relating wave amplitude to source motions
- 1918 paper corrected earlier errors (factor of 2), and it contains the quadrupole formula for radiating source

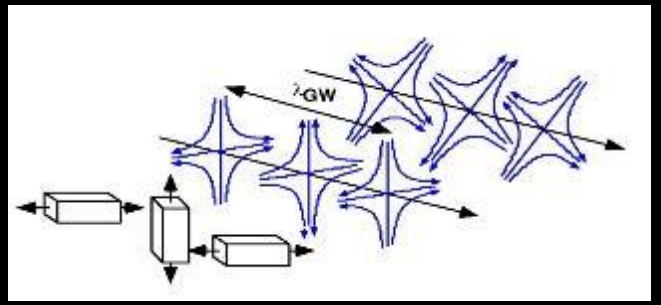
# *Einstein's Theory of Gravitation*

## Gravitational Waves

• Using Minkowski metric, the information about space-time curvature is contained in the metric as an added term, $h_{\mu\nu}$. In the weak field limit, the equation can be described with linear equations. If the choice of gauge is the *transverse traceless gauge* the formulation becomes a familiar wave equation

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

• The strain $h_{\mu\nu}$ takes the form of a plane wave propagating at the speed of light (c).




• Since gravity is spin 2, the waves have two components, but rotated by $45^0$ instead of $90^0$ from each other.

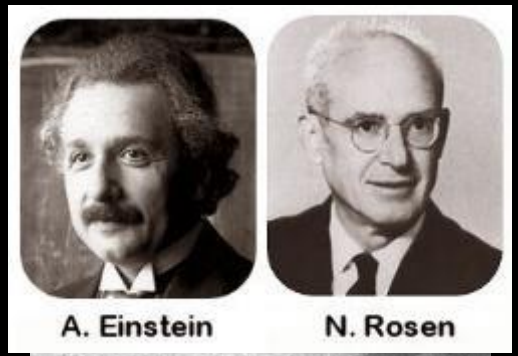
$$h_{\mu\nu} = h_+(t - z/c) + h_x(t - z/c)$$

# *Einstein vs Physical Review*

**1936**

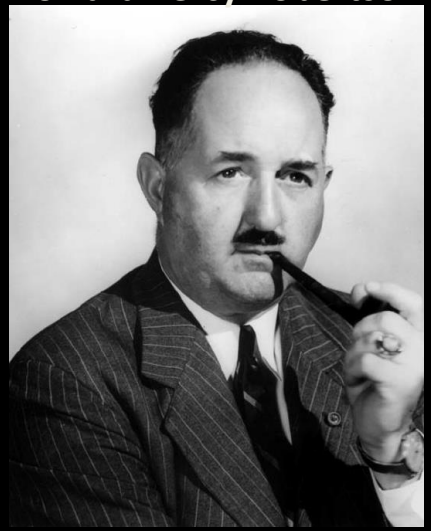
Einstein and Rosen Submited an article to Physical Review

***"Do Gravitational Waves Exist?"***

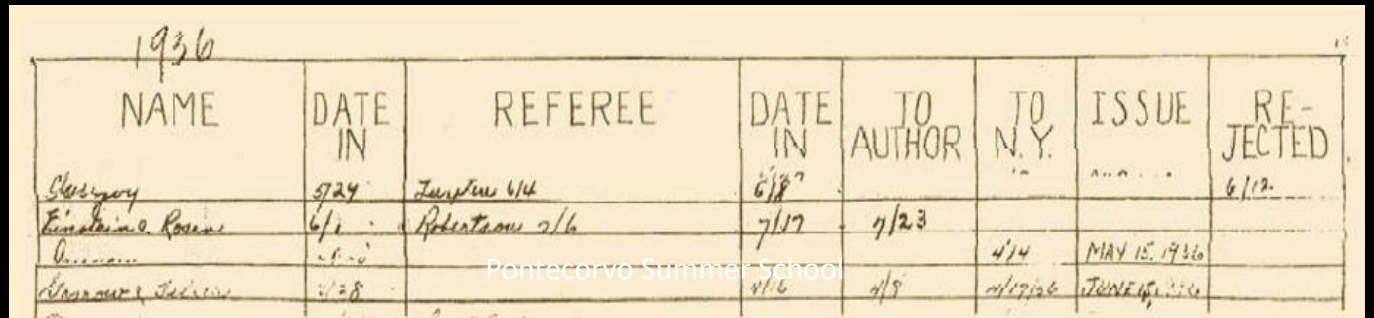


# John Tate sends the Paper for "Peer Review"

**Howard Percy Robertson**



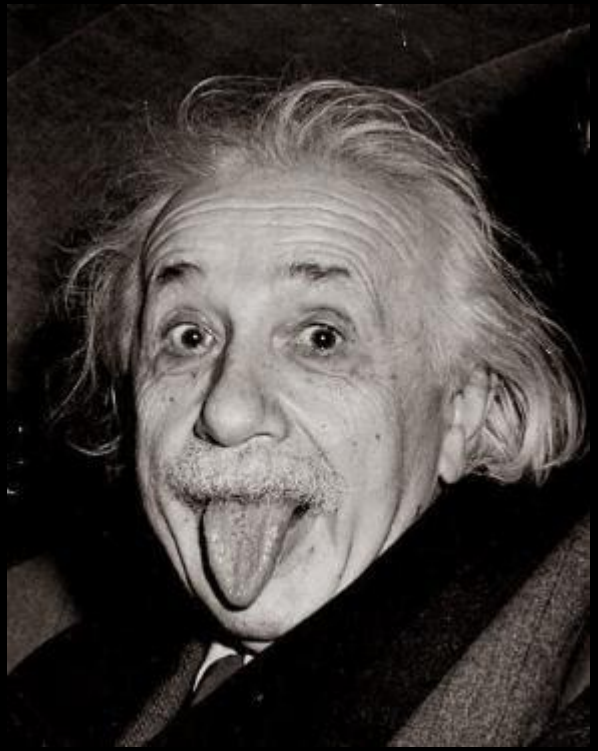
- Einstein/Rosen used a single coordinate system to cover all of space-time and encountered a singularity.
- Robertson found the error and showed that casting metric in cylindrical coordinates removed the difficulty.
- Tate sent Einstein a mild letter stating "would be glad to have (Einstein's) reaction to referee comments and criticisms".



1936

| NAME | DATE IN | REFEREE | DATE IN | TO AUTHOR | TO N.Y. | ISSUE | RE-JECTED |
|---|---|---|---|---|---|---|---|
| [illegible] | 5/24 | [illegible] 6/4 | 6/8 | | | | 6/12 |
| Einstein & Rosen | 6/[illegible] | Robertson 7/6 | 7/17 | 7/23 | | | |
| [illegible] | [illegible] | | | | 4/14 | MAY 15, 1936 | |
| [illegible] | [illegible] | | [illegible] | [illegible] | [illegible] | [illegible] | |

# *Einstein's Reply to Tate*



*Dear Sir*

*We (Mr. Rosen and I) had sent you our manuscript for publication and had not authorized you to show it to specialists before it is printed. I see no reason to address the --- in any case erroneous --- comments of your anonymous expert. On the basis of this incident, I prefer to publish the paper elsewhere.*

*Respectfully,*

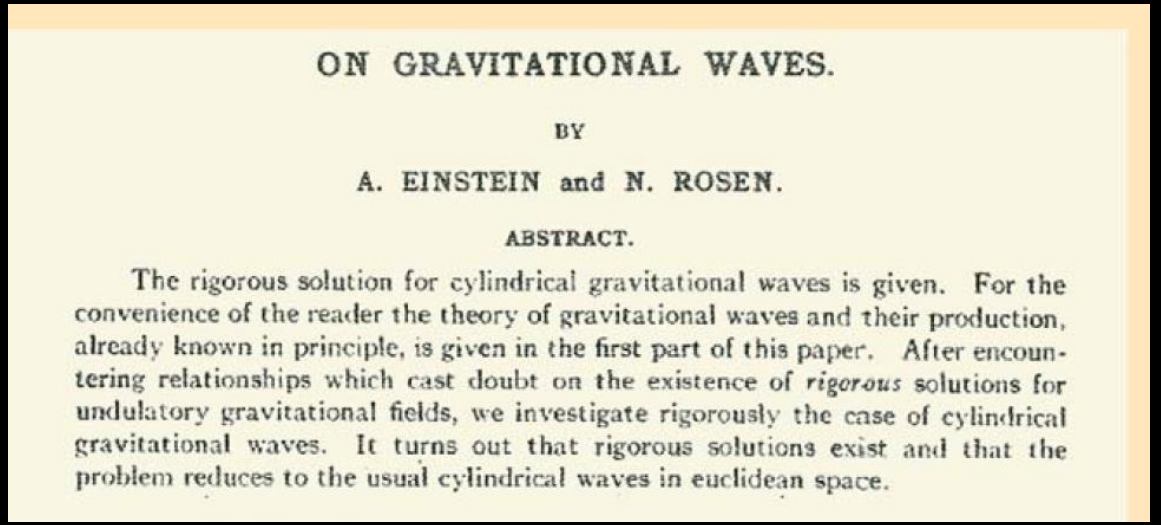
# *Einstein then Submitted to Franklin Institute Journal*

Infeld

# *All's well that ends well …*

- **Robertson returned from Caltech sabbatical a while later, struck up a friendship with Infeld. Robertson told Infeld he didn't believe Einstein's result, and went over Infeld's version of the argument. Robertson pointed out the error.**

- **Infeld reported to Einstein, and Einstein said he independently had found the error himself. He then completely modified the paper.**



ON GRAVITATIONAL WAVES.

BY

A. EINSTEIN and N. ROSEN.

ABSTRACT.

The rigorous solution for cylindrical gravitational waves is given. For the convenience of the reader the theory of gravitational waves and their production, already known in principle, is given in the first part of this paper. After encountering relationships which cast doubt on the existence of *rigorous* solutions for undulatory gravitational fields, we investigate rigorously the case of cylindrical gravitational waves. It turns out that rigorous solutions exist and that the problem reduces to the usual cylindrical waves in euclidean space.

# *The Chapel Hill Conference*

Could the waves be a coordinate effect only, with no physical reality? Einstein didn't live long enough to learn the answer.

In January 1957, the U.S. Air Force sponsored the *Conference on the Role of Gravitation in Physics*, a.k.a. the Chapel Hill Conference, a.k.a. GR1.

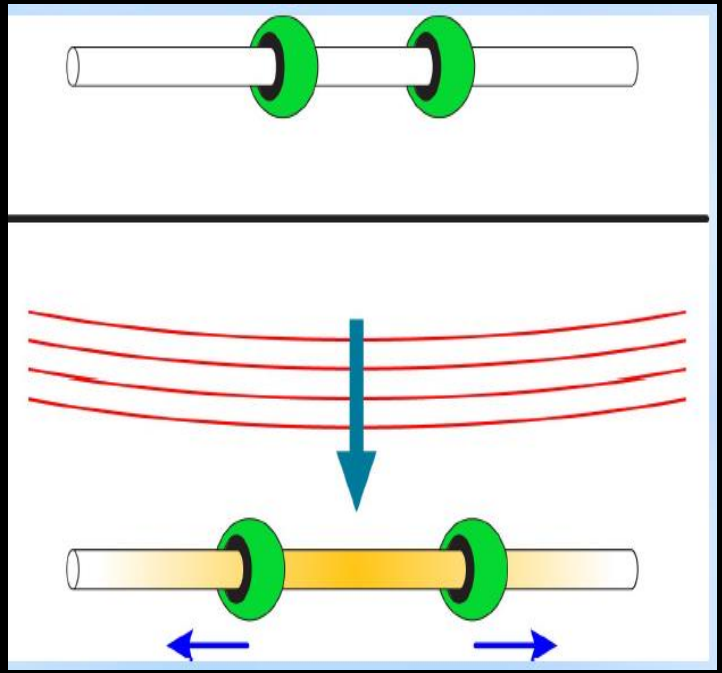
The organizers were Bryce and Cecile DeWitt. 44 of the world's leading relativists attended.

**The "gravitational wave problem" was solved there, and the quest to detect gravitational waves was born.**

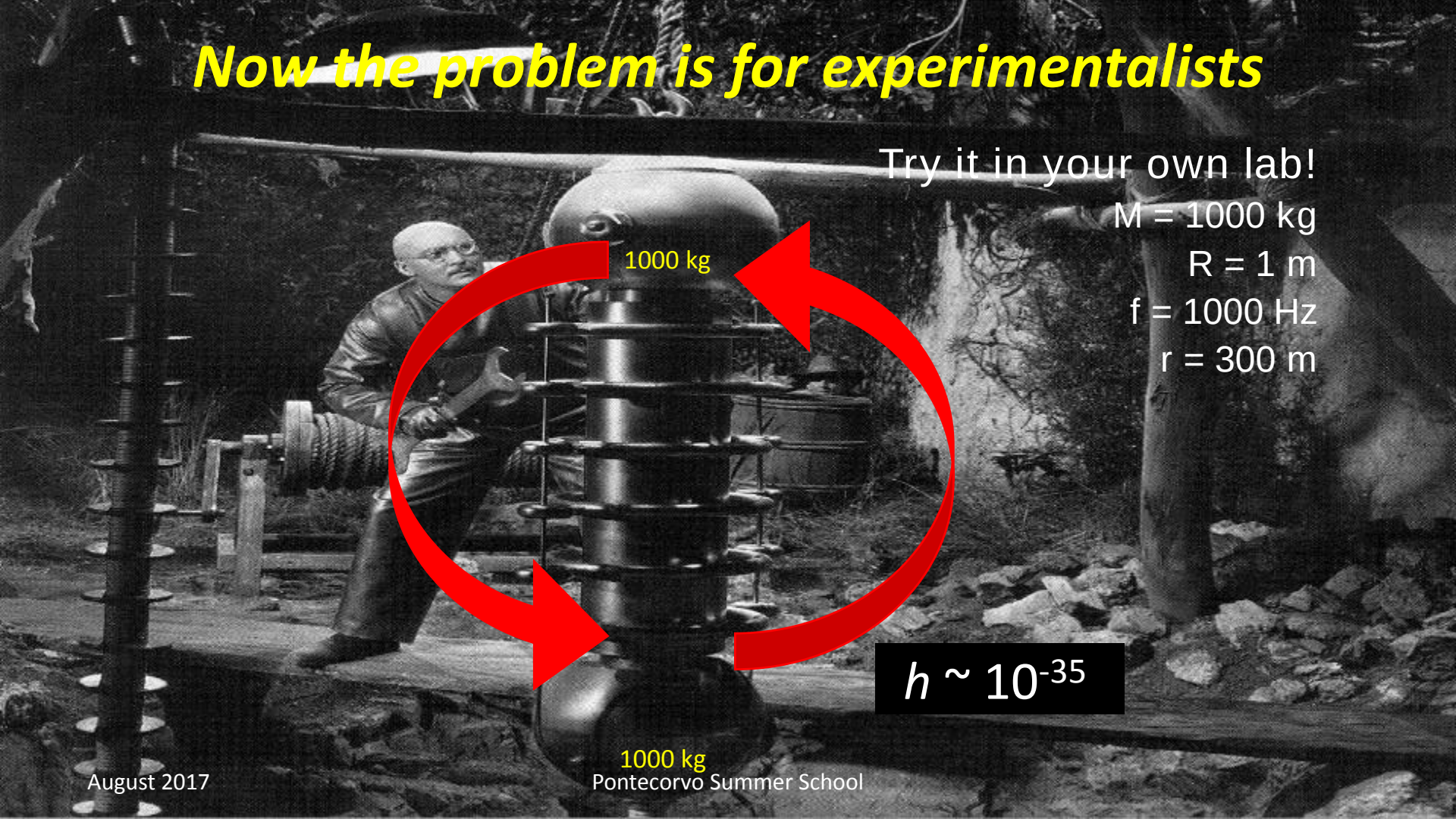
# Agreement: Gravitational Waves are Real

- Felix Pirani presentation: relative acceleraton of particle pairs can be associated with the Riemann tensor. The interpretation of the attendees was that non-zero components of the Riemann tensor were due to gravitational waves.

- Sticky bead argument (Feynman)
  - Gravitational waves can transfer energy?



# *Now the problem is for experimentalists*




Try it in your own lab!

M = 1000 kg

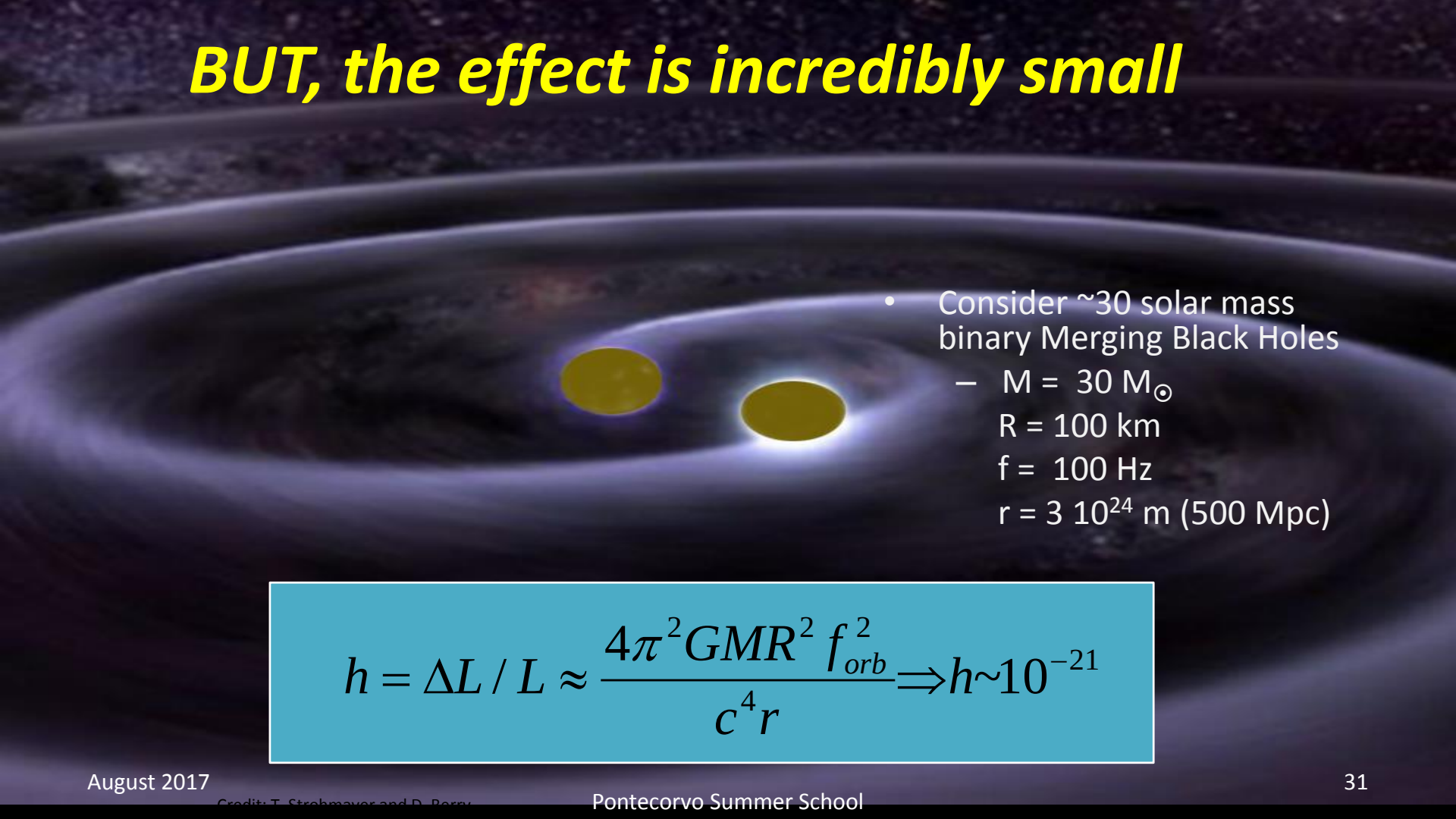
R = 1 m

f = 1000 Hz

r = 300 m

$h \sim 10^{-35}$

# BUT, the effect is incredibly small



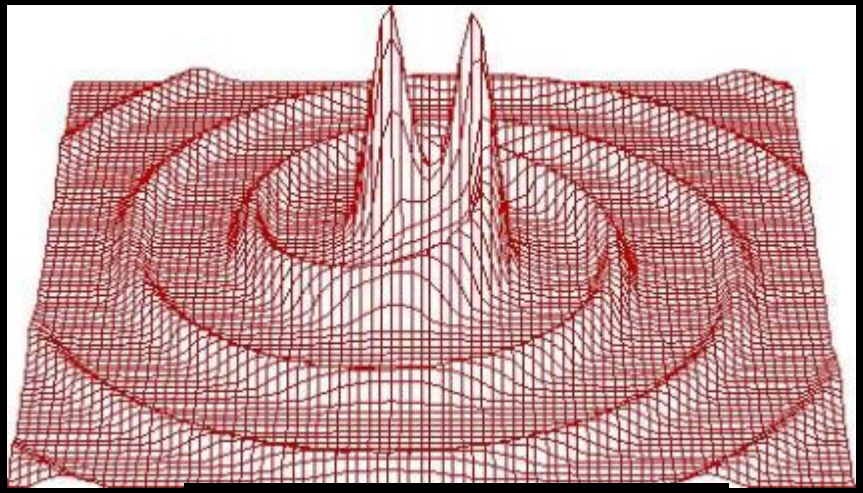
- Consider ~30 solar mass binary Merging Black Holes
  - M = 30 $M_\odot$
    R = 100 km
    f = 100 Hz
    r = 3 $10^{24}$ m (500 Mpc)

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

# *Einstein's Theory of Gravitation*

**A necessary consequence of Special Relativity with its finite speed for information transfer**

**Gravitational waves come from the acceleration of masses and propagate away from their sources as a space-time warpage at the speed of light**



**gravitational radiation**
**binary inspiral**
**of**
**compact objects**

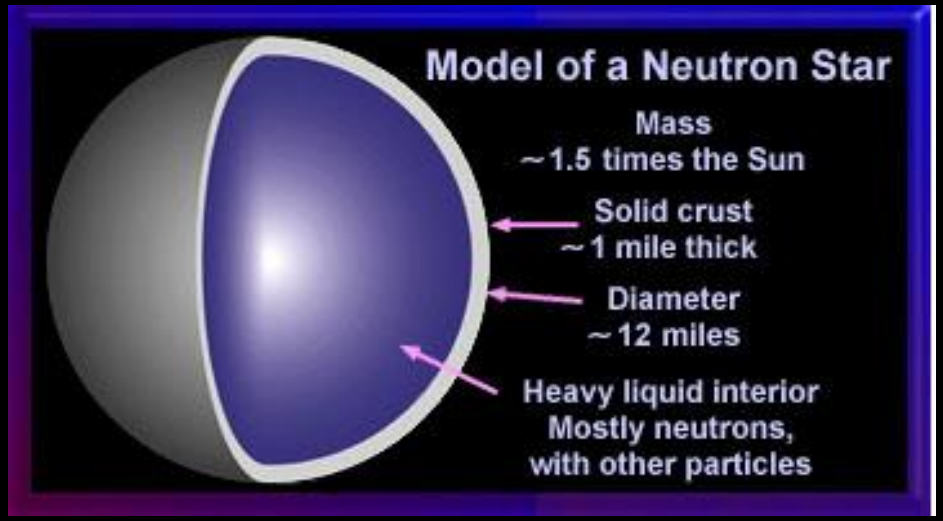
**Discovered and Studied**
**Pulsar System**
**PSR 1913 + 16**
**with**
**Radio Telescope**

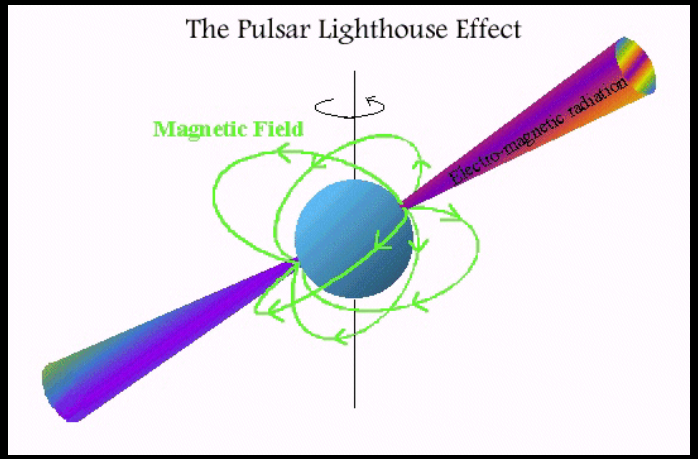
# First Evidence for Gravitational Waves

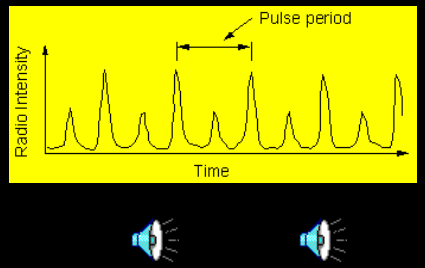
# Neutron Star

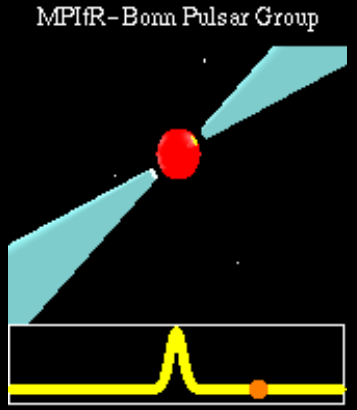
⇩

# Radio Pulsar



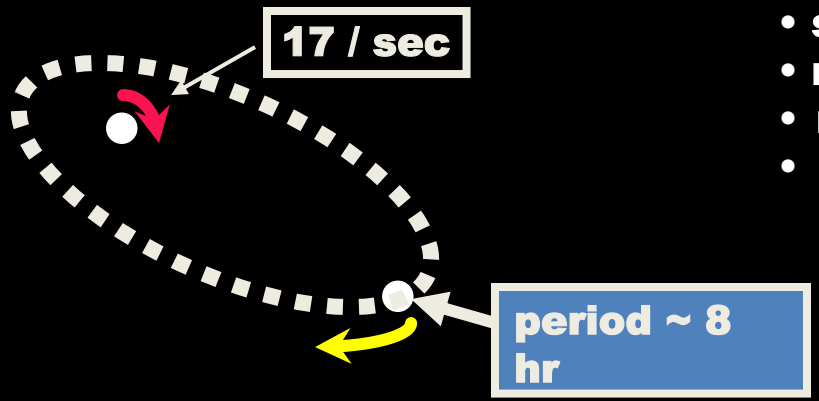



# *Evidence for emission of gravitational radiation*

***Hulse & Taylor***




**PSR 1913 + 16**

**Timing of pulsars**

**Neutron binary system**

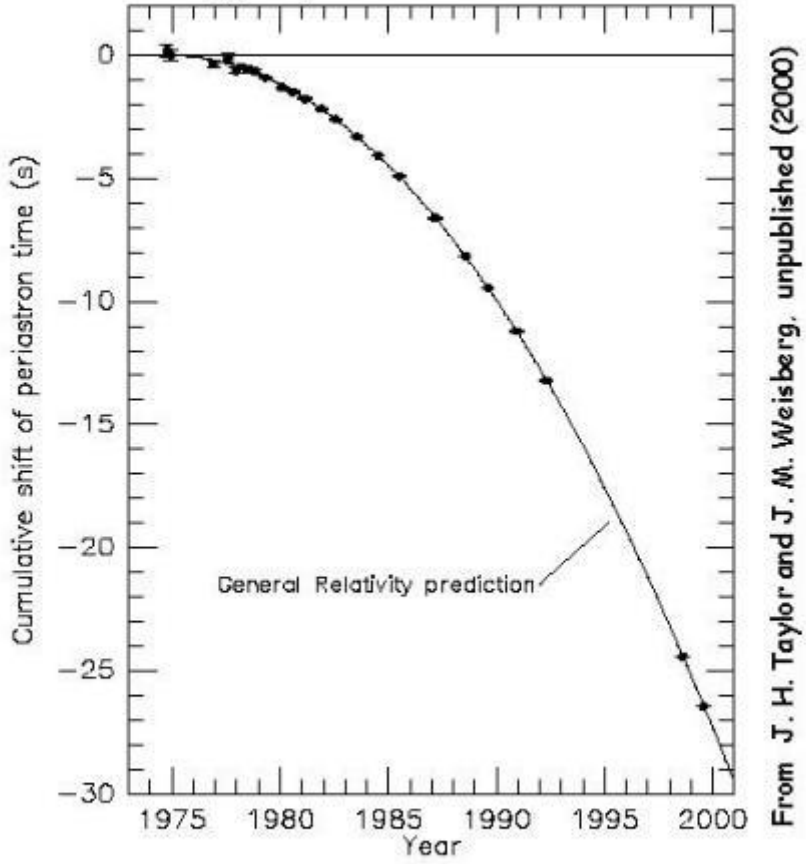
- separation = $10^6$ miles
- $m_1 = 1.4m_\odot$
- $m_2 = 1.36m_\odot$
- e = 0.617

**Prediction from general relativity**

- spiral in by 3 mm/orbit
- rate of change orbital period

# “Indirect” evidence for gravitational *waves*

Comparison between observations of the binary pulsar PSR1913+16, and the prediction of general relativity based on loss of orbital energy via gravitational waves



# General Relativity

**Einstein's equations have form similar to the equations of elasticity.**

**P = E*h*  (P = stress, *h* = strain, E = Young's mod.)**

**T = ($c^4/8\pi G$)*h*  T = stress tensor, G = Curvature tensor and $c^4/8\pi G \sim 10^{42}$N is a space-time "stiffness" (energy density/unit curvature)**

- **Space-time can carry waves.**
- **They have very small amplitude**
- **There is a large mismatch with ordinary matter, so very little energy is absorbed (very small cross-section)**

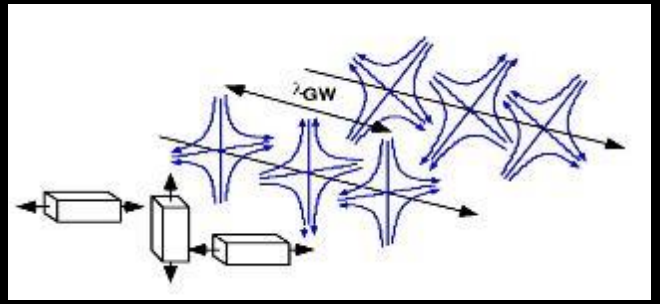
# *Einstein's Theory of Gravitation*

## Gravitational Waves

• Using Minkowski metric, the information about space-time curvature is contained in the metric as an added term, $h_{\mu\nu}$. In the weak field limit, the equation can be described with linear equations. If the choice of gauge is the *transverse traceless gauge* the formulation becomes a familiar wave equation

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

• The strain $h_{\mu\nu}$ takes the form of a plane wave propagating at the speed of light (c).

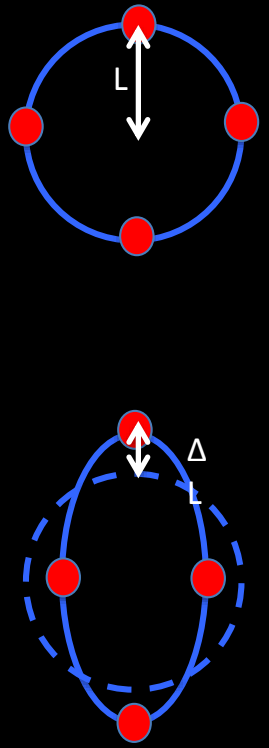



• Since gravity is spin 2, the waves have two components, but rotated by $45^0$ instead of $90^0$ from each other.

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

# *Gravitational Waves*

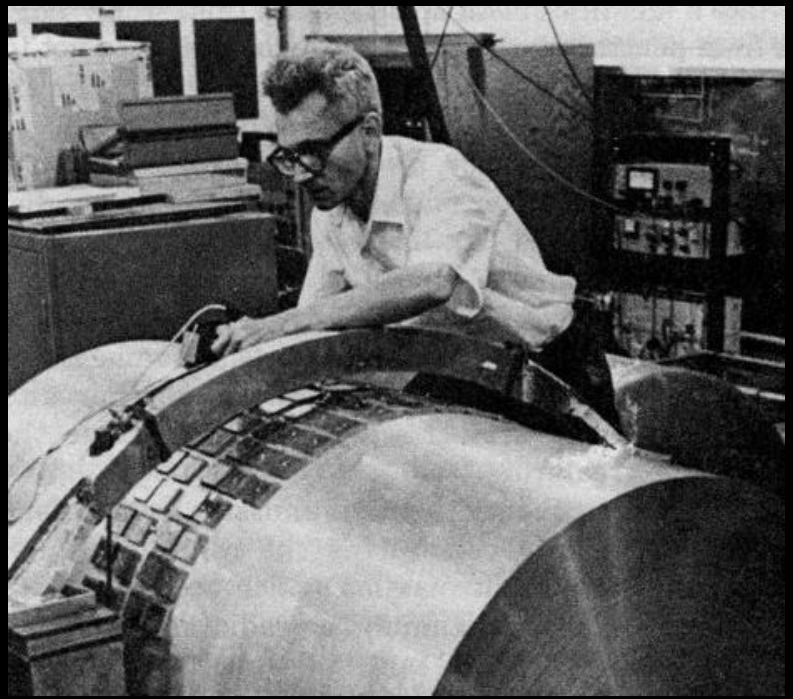
- Ripples of spacetime that stretch and compress spacetime itself
- The amplitude of the wave is $h \approx 10^{-21}$
- Change the distance between masses that are free to move by $\Delta L = h \times L$
- Spacetime is “stiff” so changes in distance are very small




$$\Delta L = h \times L = 10^{-21} \times 1\,\mathrm{m} = 10^{-21}\,\mathrm{m}$$

# *The Experimental Search Begins*

Joseph Weber



First Gravitational-wave experimental research began in 1960's using 'resonant bars"

A cylinder of aluminum - each end acts like a test mass. The center is like a spring. PZT's around the midline absorb energy to send to an electrical amplifier.

# First Searches

**Phys. Rev. Lett. 22, 1320 – Published 16 June 1969**

- Weber claimed detection in Physical Review in 1969 (First of several claimed detections)

- Weber's Legacy includes:
  - Sensitivity calculation noise analysis
  - Coincidence for background rejection
  - Time slides for background estimate

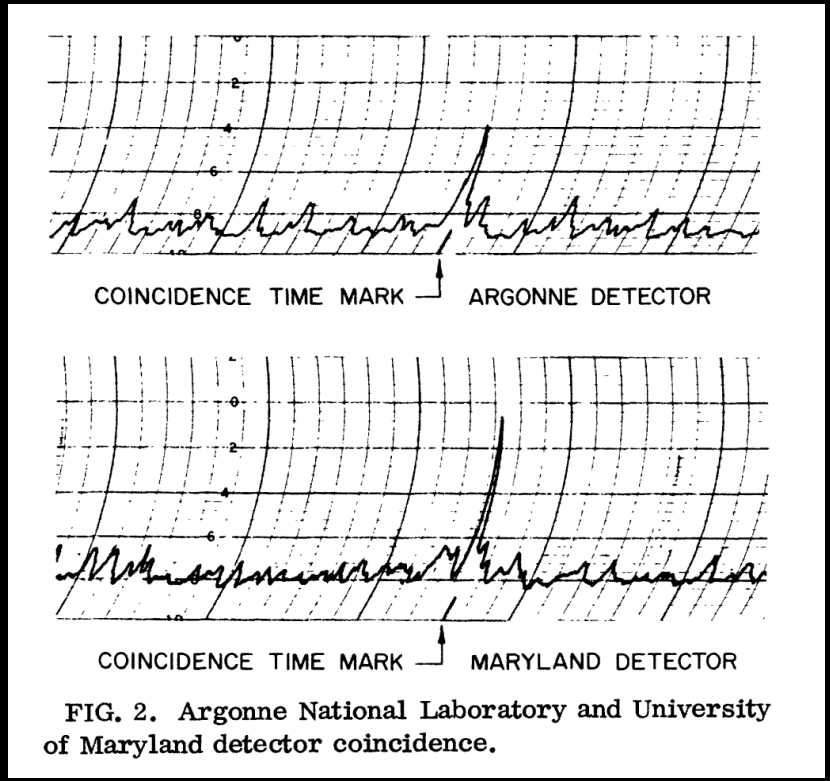
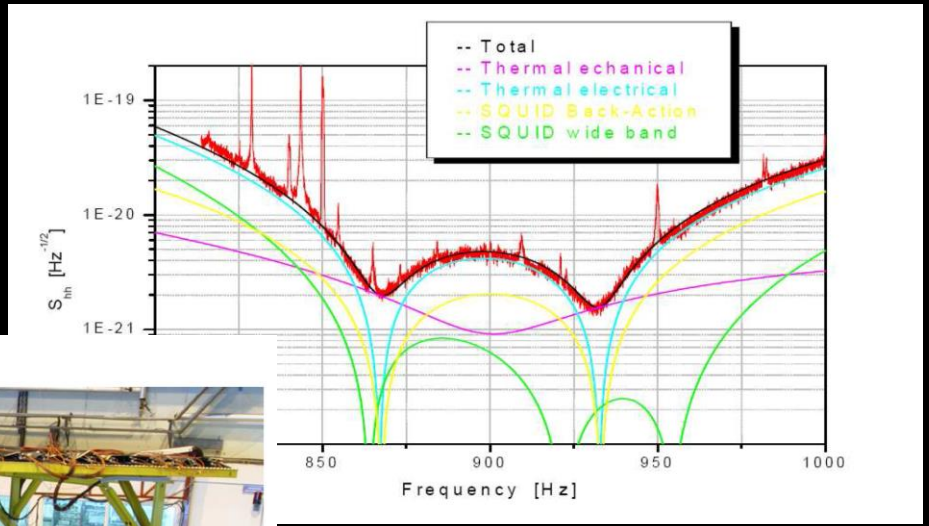



FIG. 2. Argonne National Laboratory and University of Maryland detector coincidence.

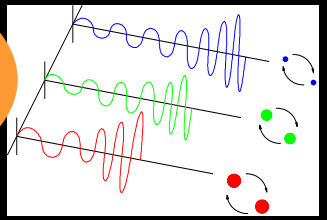
# *Resonant Bars "Evolution"*



- **Cryogenic** – reduce termal noise
- **Network** – sky location
- Broader Band - ~ 100 Hz

# Astrophysical Sources

- Compact binary inspiral: *"chirps"*
  - NS-NS waveforms are well described
  - BH-BH need better waveforms
  - search technique: matched templates



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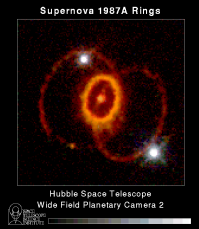
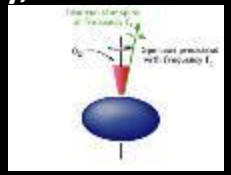
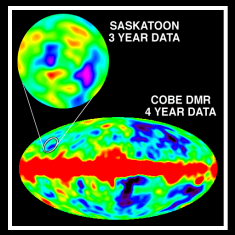
  - burst signals in coincidence with signals in electromagnetic radiation
  - prompt alarm (~ one hour) with neutrino detectors



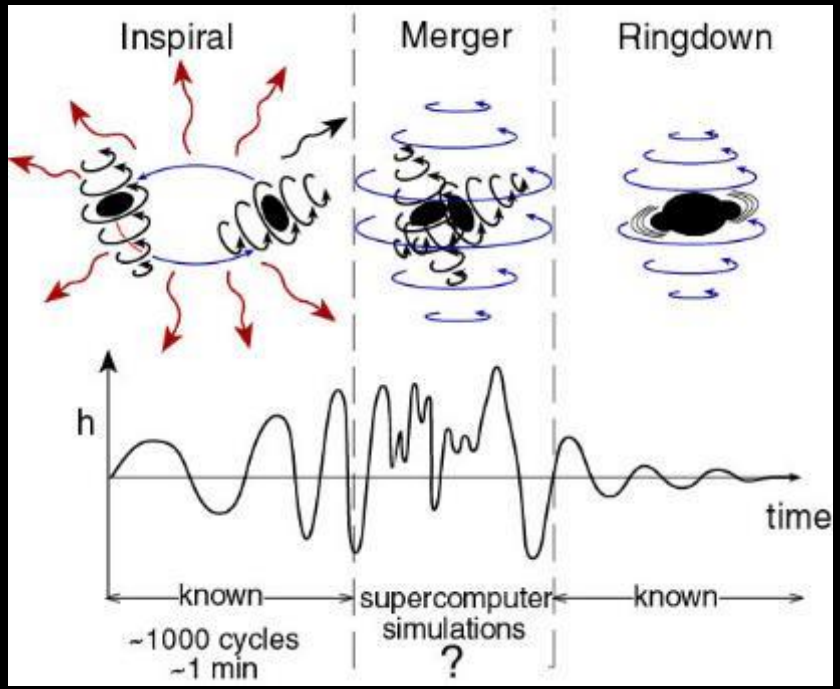

- Pulsars in our galaxy: *"periodic"*
  - search for observed neutron stars (frequency, doppler shift)
  - all sky search (computing challenge)
  - r-modes



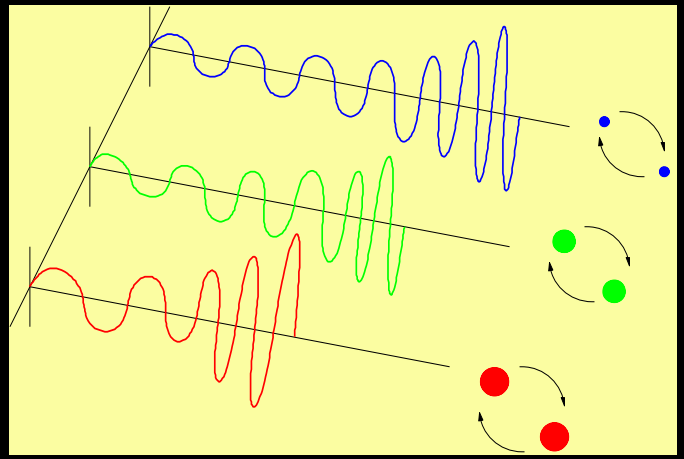
- Cosmological Signal *"stochastic background"*



# Compact Binary Collisions



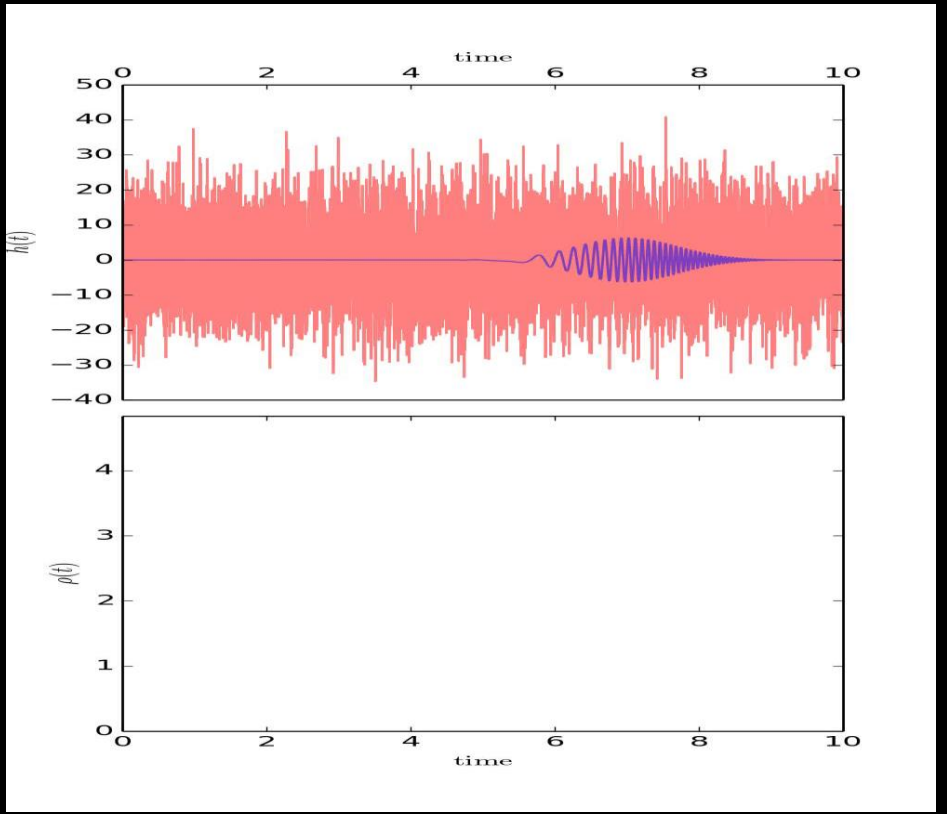

- Neutron Star – Neutron Star
  - **waveforms are well described**
- Black Hole – Black Hole
  - **Numerical Relativity waveforms**
- Search: *matched templates*



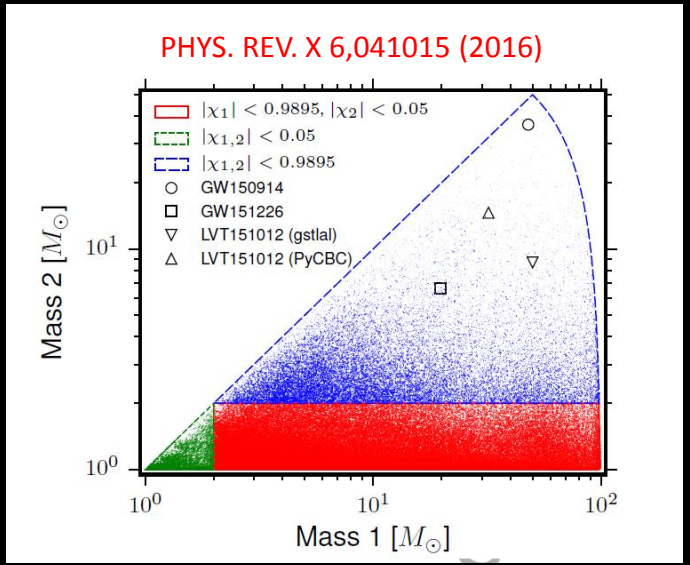
**“chirps”**

# Finding a weak signal in noise

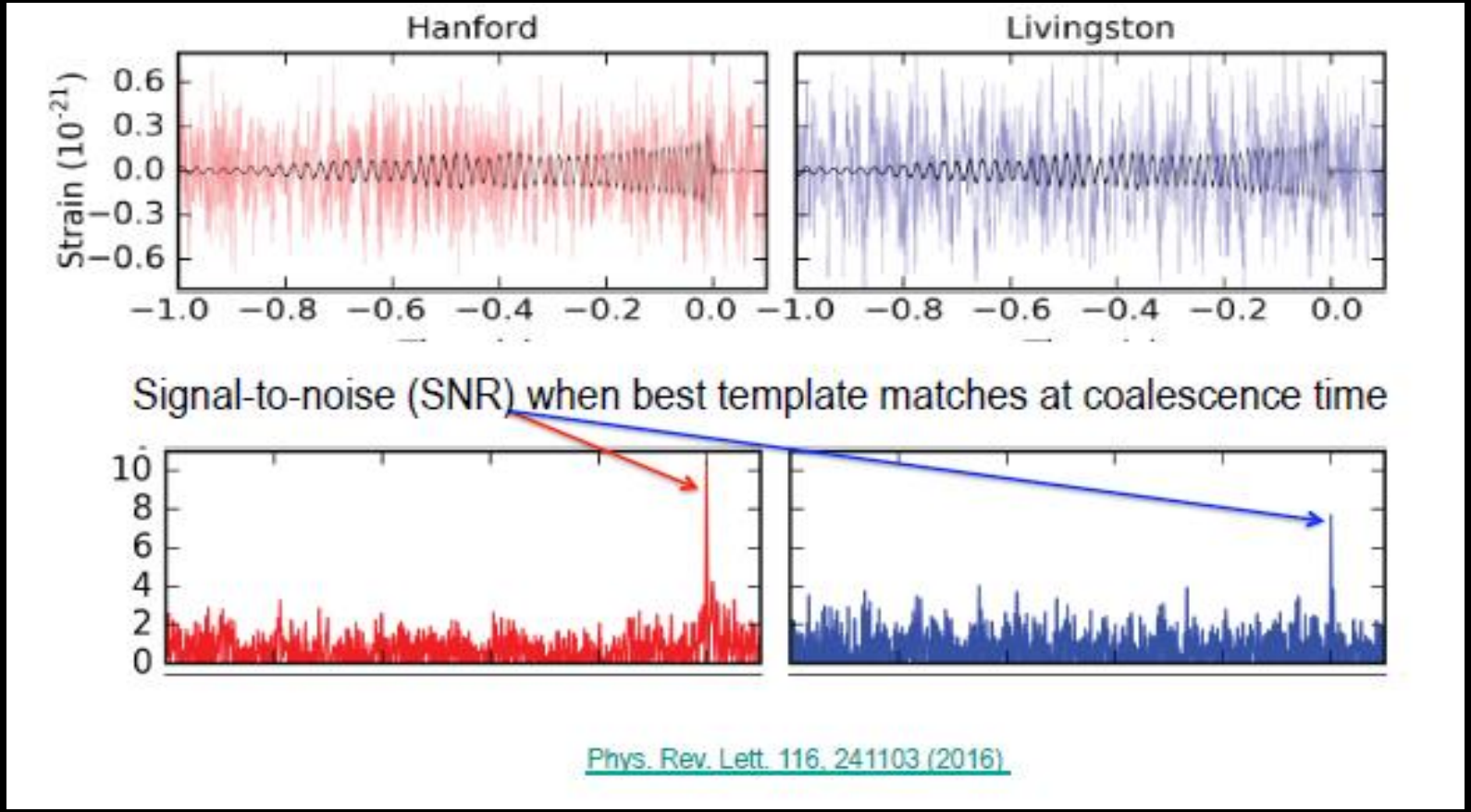
- "Matched filtering" lets us find a weak signal submerged in noise.
- For calculated signal waveforms, multiply the waveform by the data
- Find signal from cumulative signal/noise



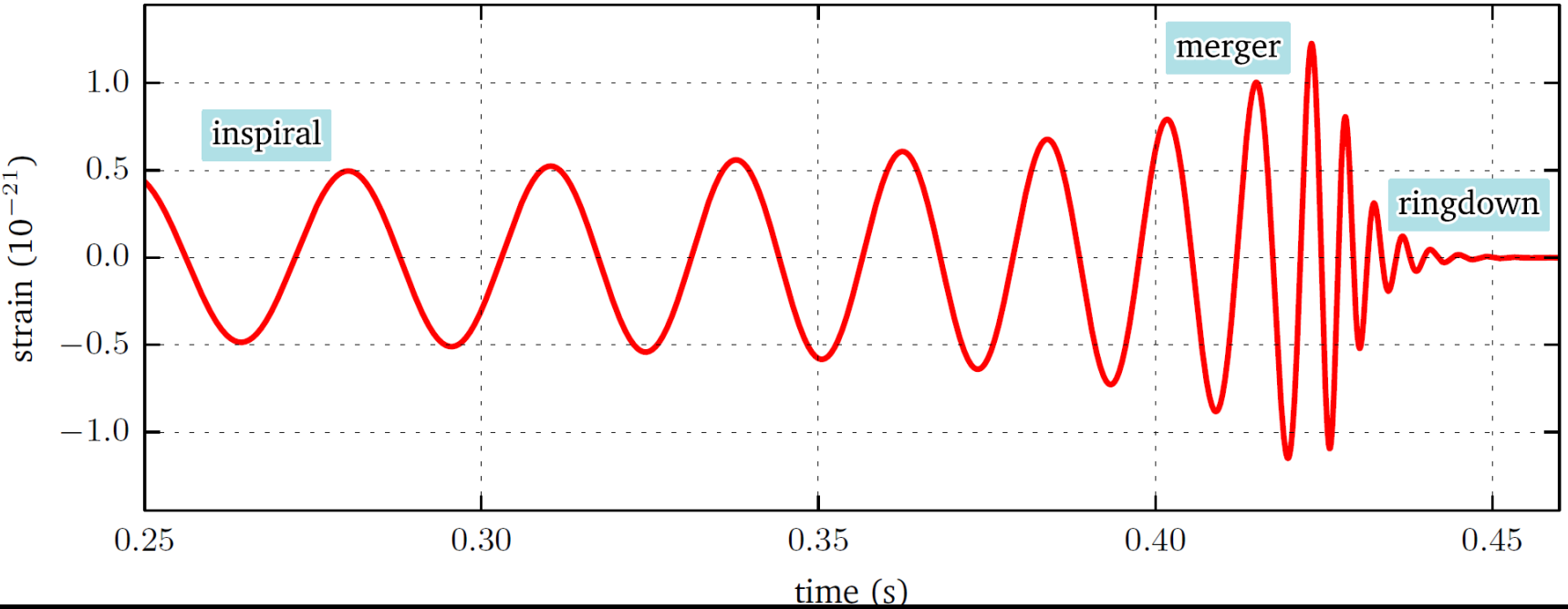

PHYS. REV. X 6,041015 (2016)



# GW151226 – Matched Filter



# Emission of Gravitational Waves



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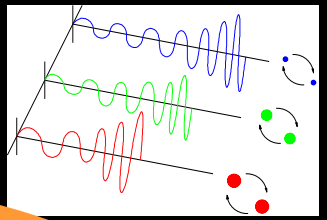

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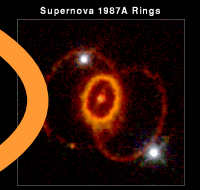


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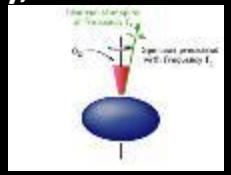

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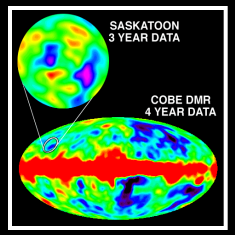
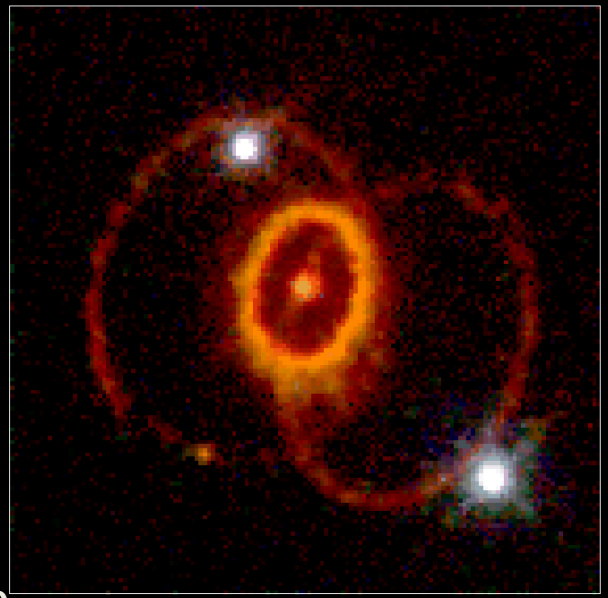


# Detection of Burst Sources

- **Known sources -- Supernovae & GRBs**
  - » Coincidence with observed electromagnetic observations.
    - » **No close supernovae occurred during the science runs, so far.**
  - » Model Dependent Search for Binary Inspiral
    - »**GW150914 first detected by Burst Trigger**
- **Unknown phenomena**
  - » Emission of short transients of gravitational radiation of unknown waveform (e.g. black hole mergers).

Supernova 1987A Rings



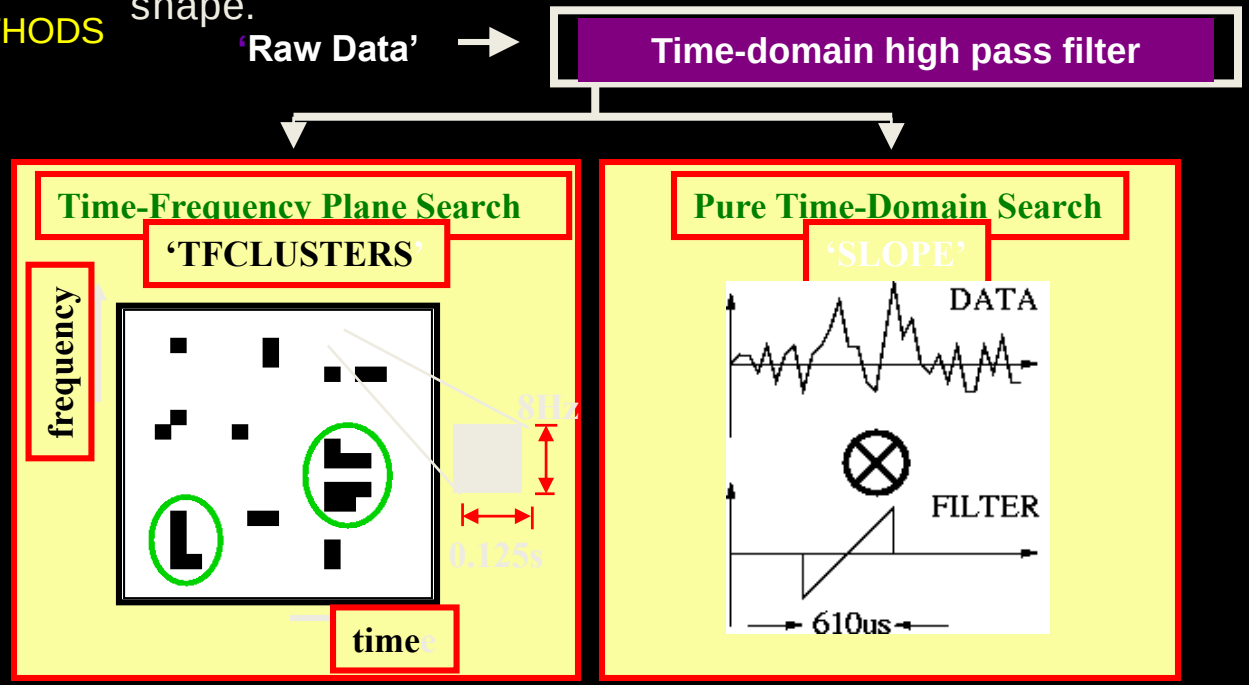
Hubble Space Telescope
Wide Field Planetary Camera 2

SPACE TELESCOPE SCIENCE INSTITUTE

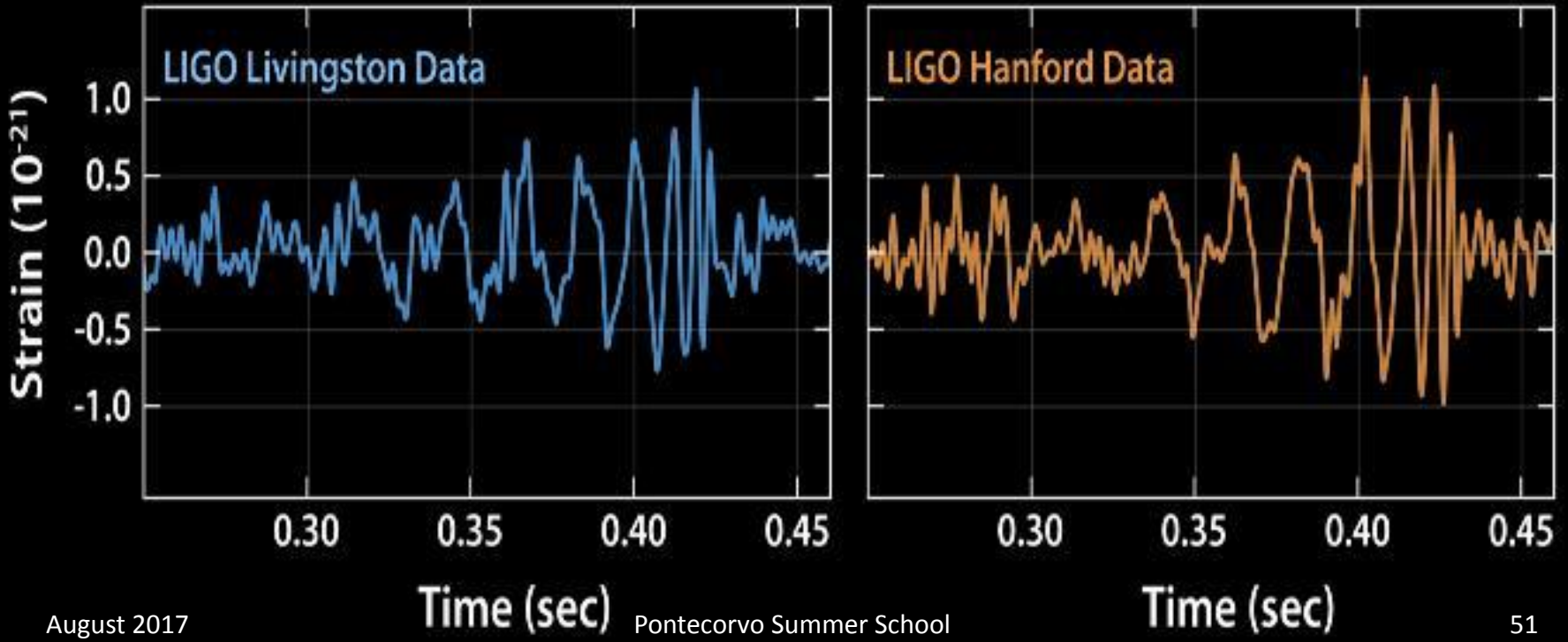
# ‘Unmodeled’ Bursts

GOAL search for waveforms from sources for which we cannot currently make an accurate prediction of the waveform shape.

METHODS



# *Observed Signals – Sept 14, 2015*



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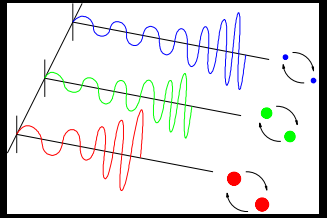
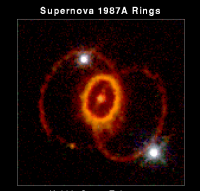


- Supernovae / GRBs: *"bursts"*
  - burst signals in coincidence with signals in electromagnetic radiation
  - [illegible] with neutrino detectors

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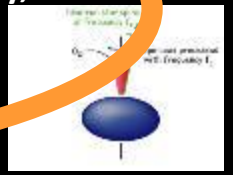

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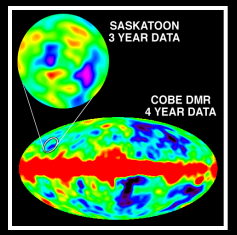
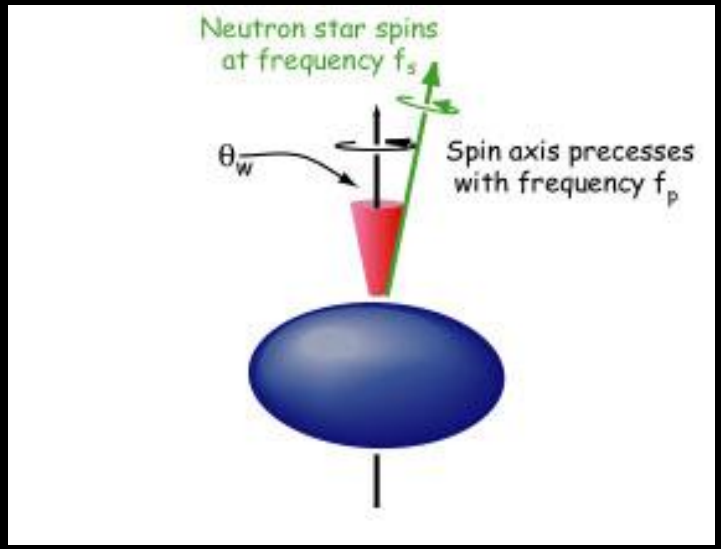


# Detection of Periodic Sources

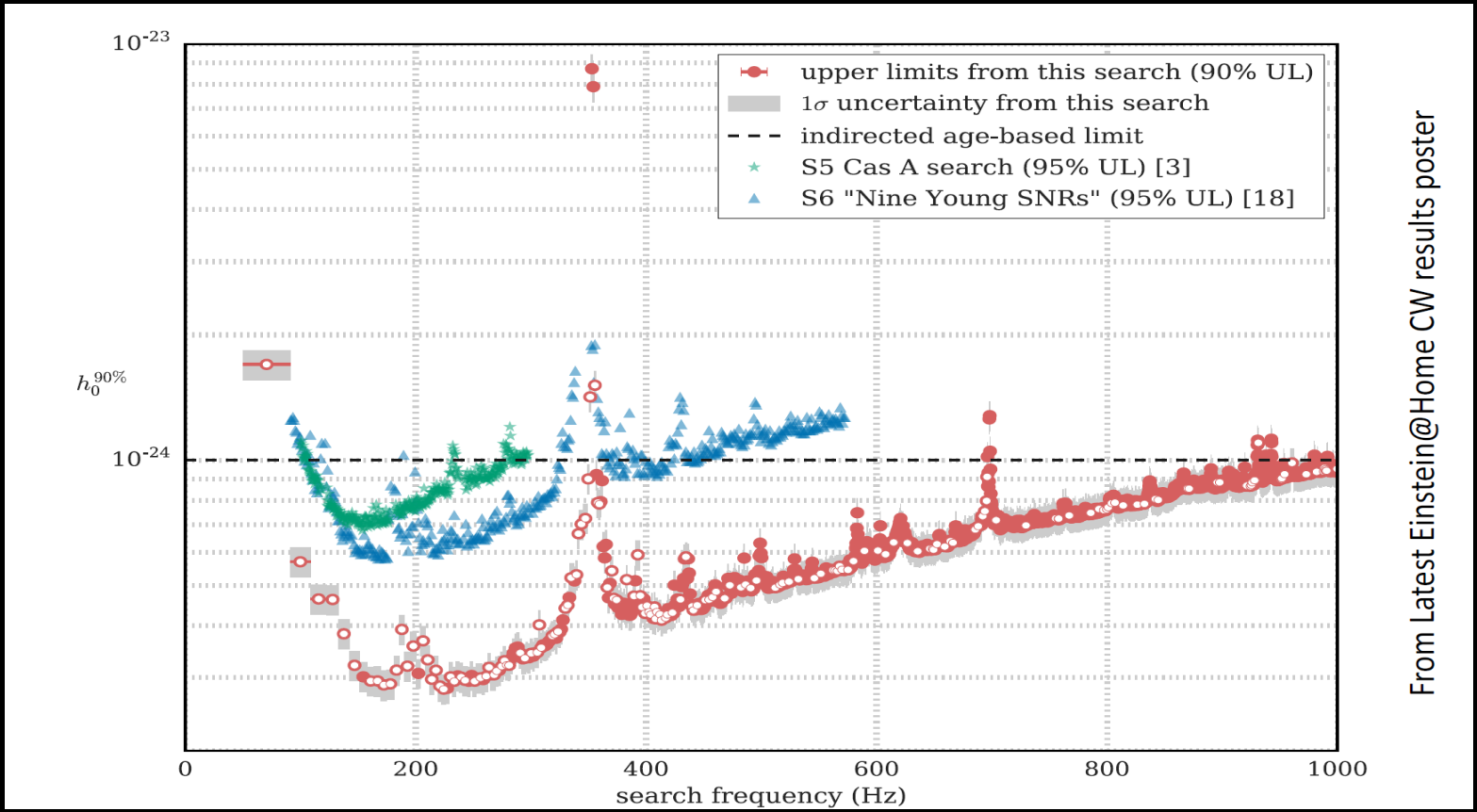
- **Pulsars in our galaxy: *"periodic"***
  - **search for observed neutron stars**
  - **all sky search (computing challenge)**
  - **r-modes**



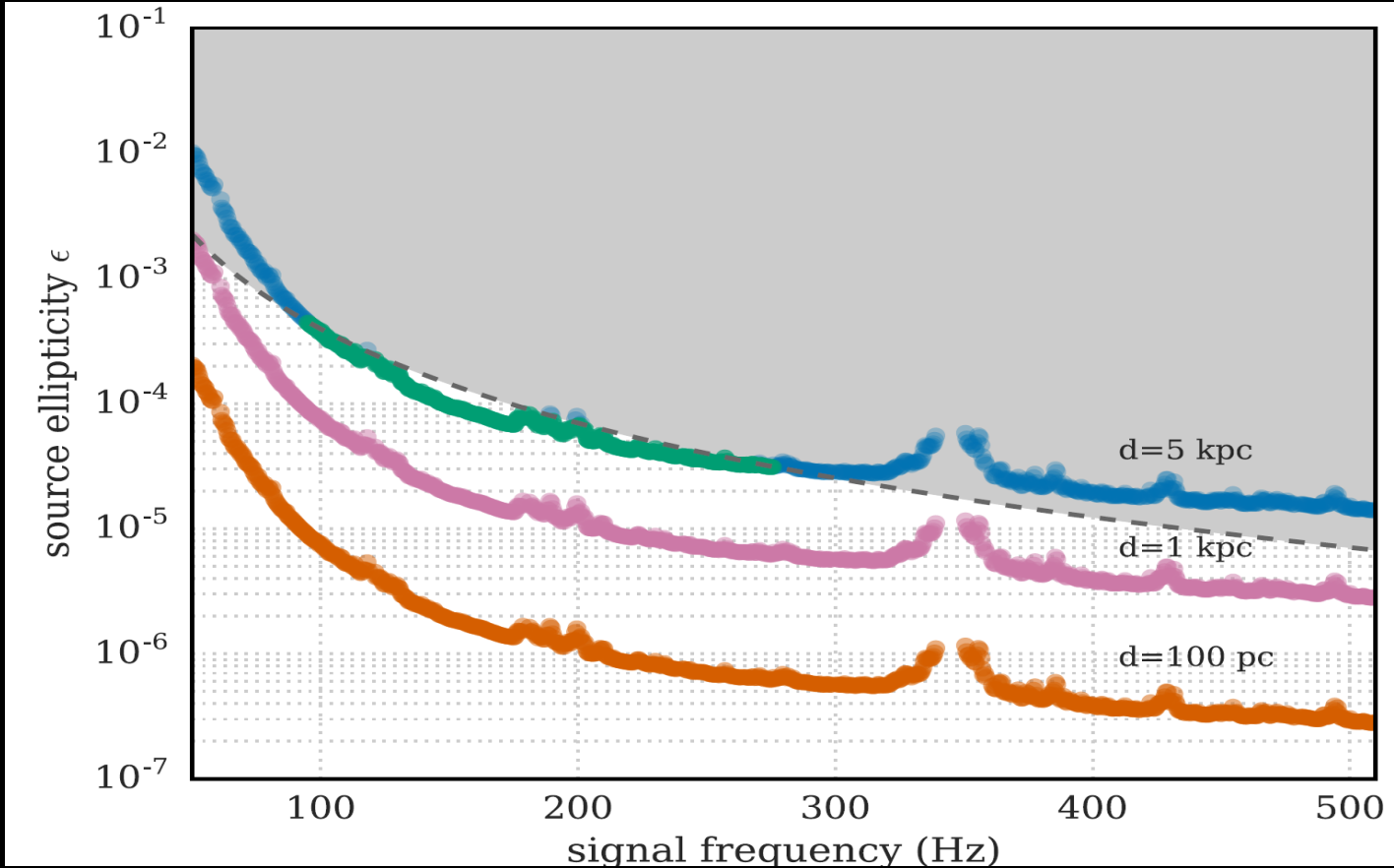

- Frequency modulation of signal **due to Earth's motion** relative to the Solar System Barycenter, intrinsic frequency changes.

- Amplitude modulation due to **the detector's antenna pattern**.

# Continuous Gravitational Wave Search

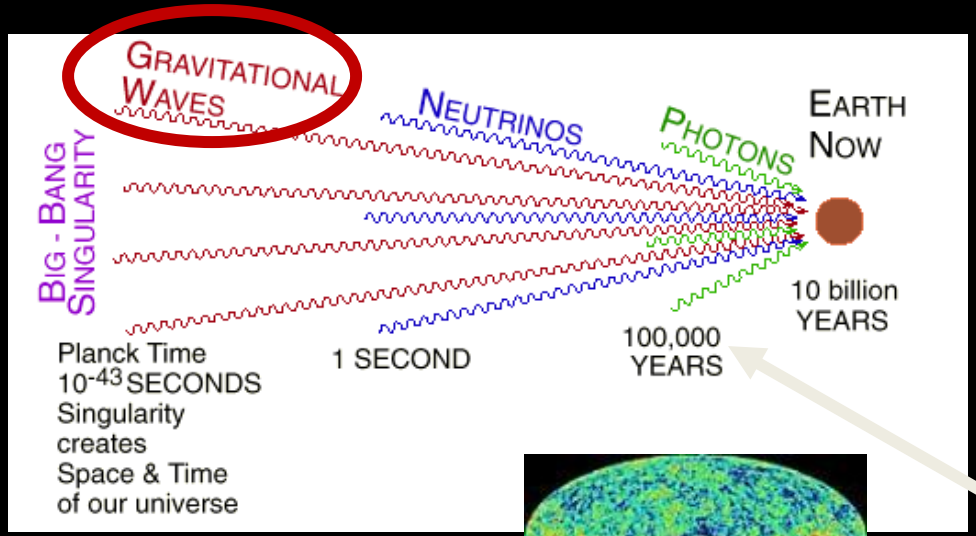


# Continuous Gravitational Wave Search

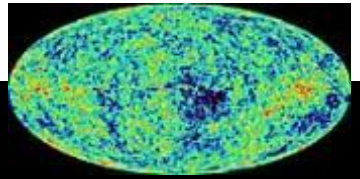


# Signals from the Early Universe

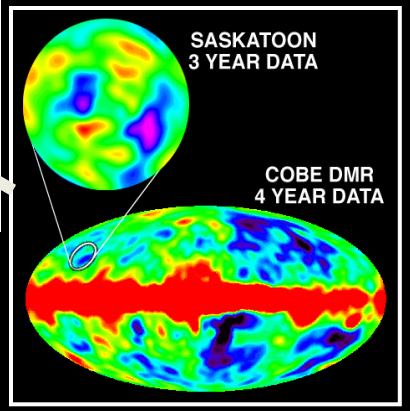
**stochastic background**




**Cosmic Microwave background**



**WMAP**



# Signals from the Early Universe

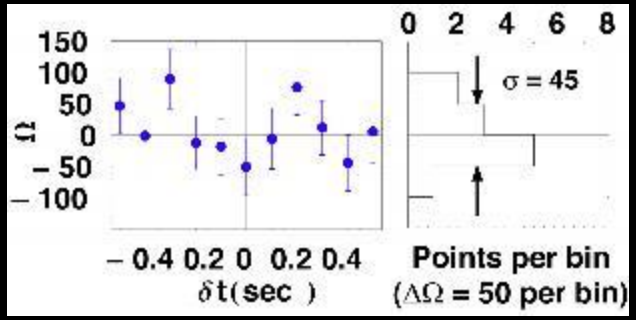
- Strength specified by *ratio of energy density in GWs to total energy density* needed to close the universe:

$$\Omega_{GW}(f) = \frac{1}{\rho_{critical}} \frac{d\rho_{GW}}{d(lnf)}$$

- Detect by *cross-correlating* output of two GW detectors:

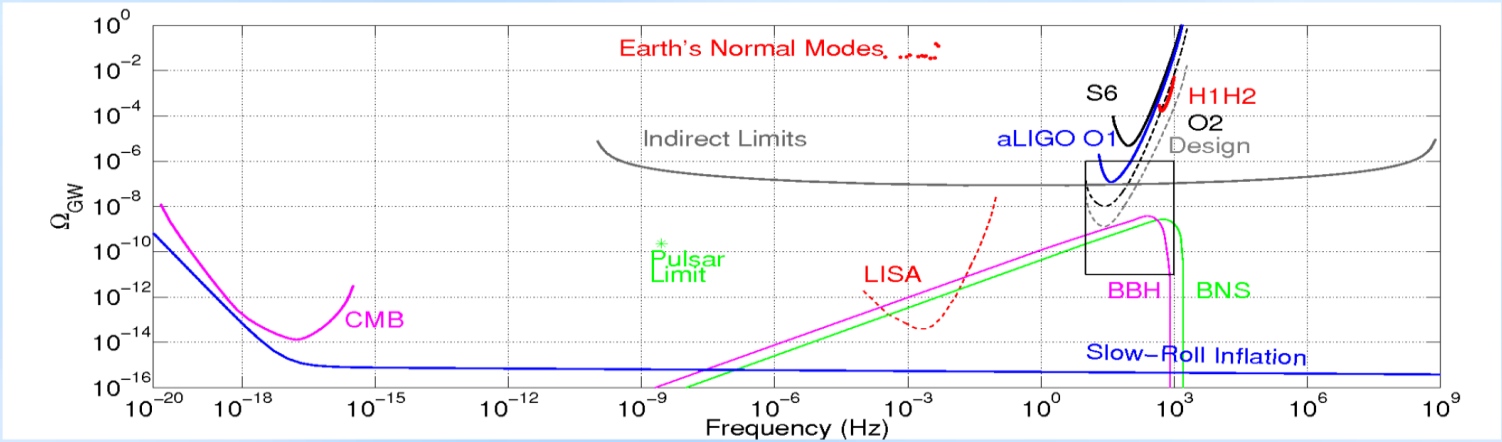
Science Data

Hanford - Livingston



# Gravitational Waves from the Early Universe

*O1 isotropic stochastic search*

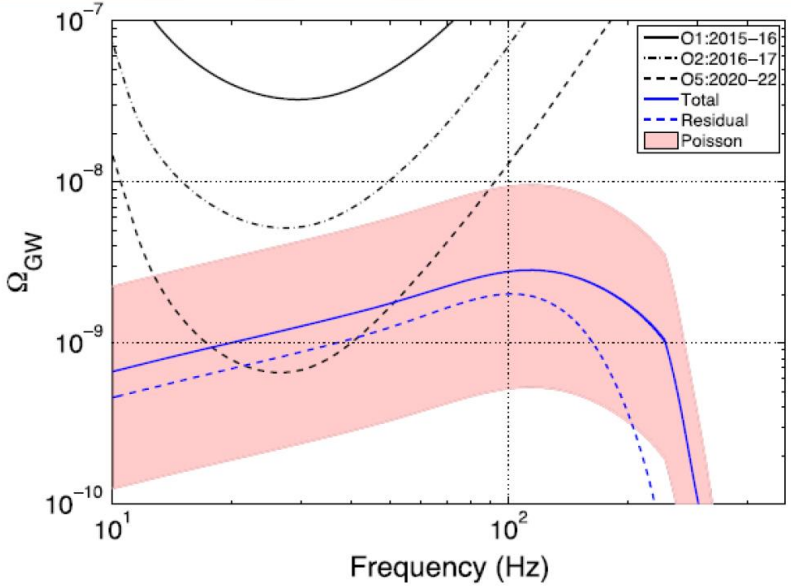


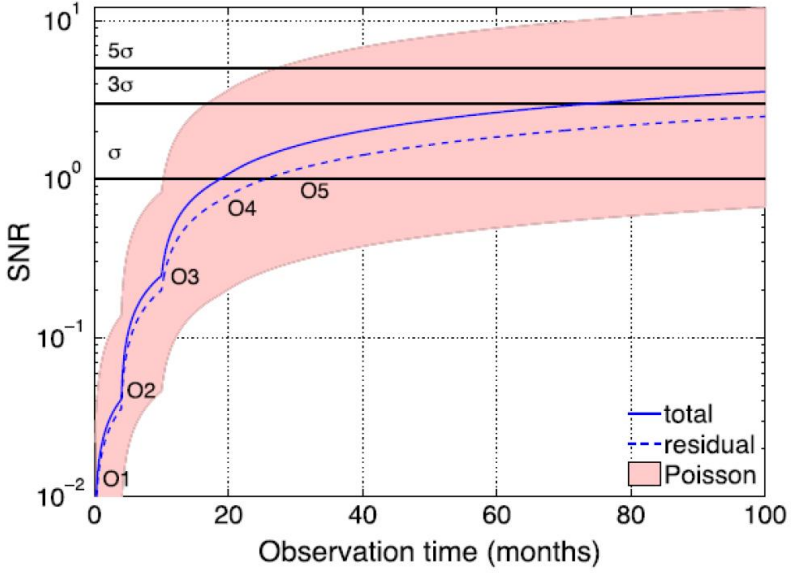

Phys. Rev. Lett. 118, 121101 (2017)

**Indirect limits:** PhysRevX.6.011035
*"CMB temperature and polarization power spectra, lensing, BAOs and BBN"*

$$\Omega_{gw}(25\text{Hz}) < 1.7 \times 10^{-7}$$

# Stochastic Background Signal from Gravitational Wave Sources

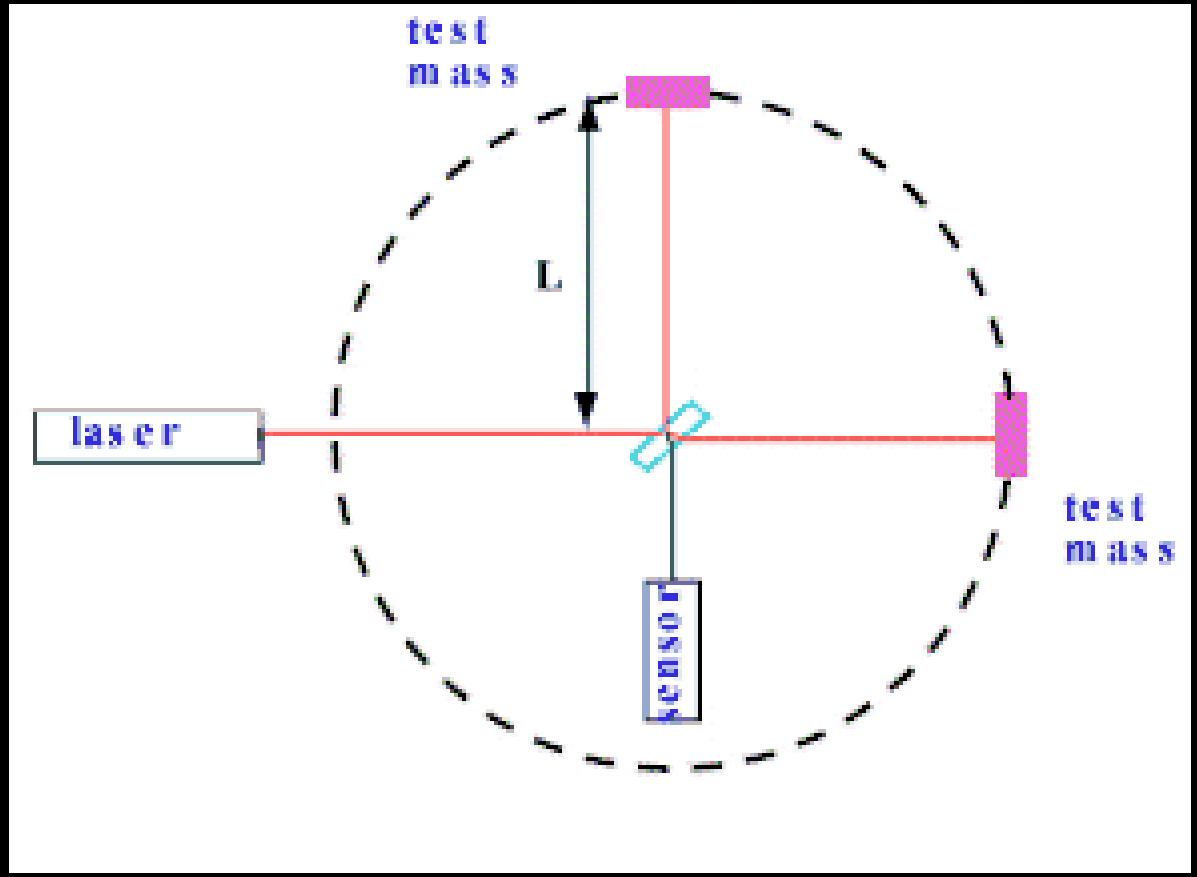



Based on the Field formation mechanism, assuming GW150914 parameters.

# LECTURE 2 - PONTECORVO

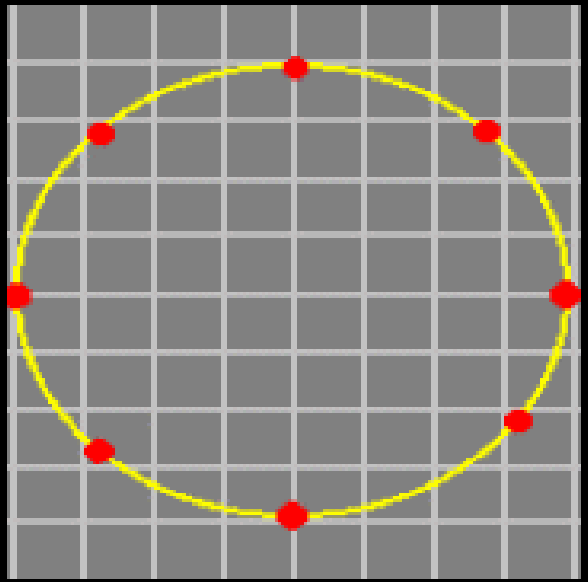
# Suspended Mass Interferometry



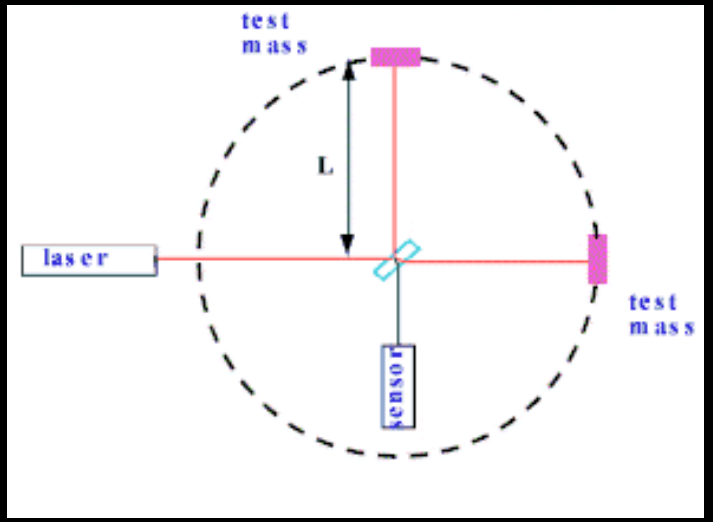
# Gravitational Wave – The Effect

Gravitational wave traveling into the picture

Change in separation ($\Delta L$) proportional to initial separation (L))

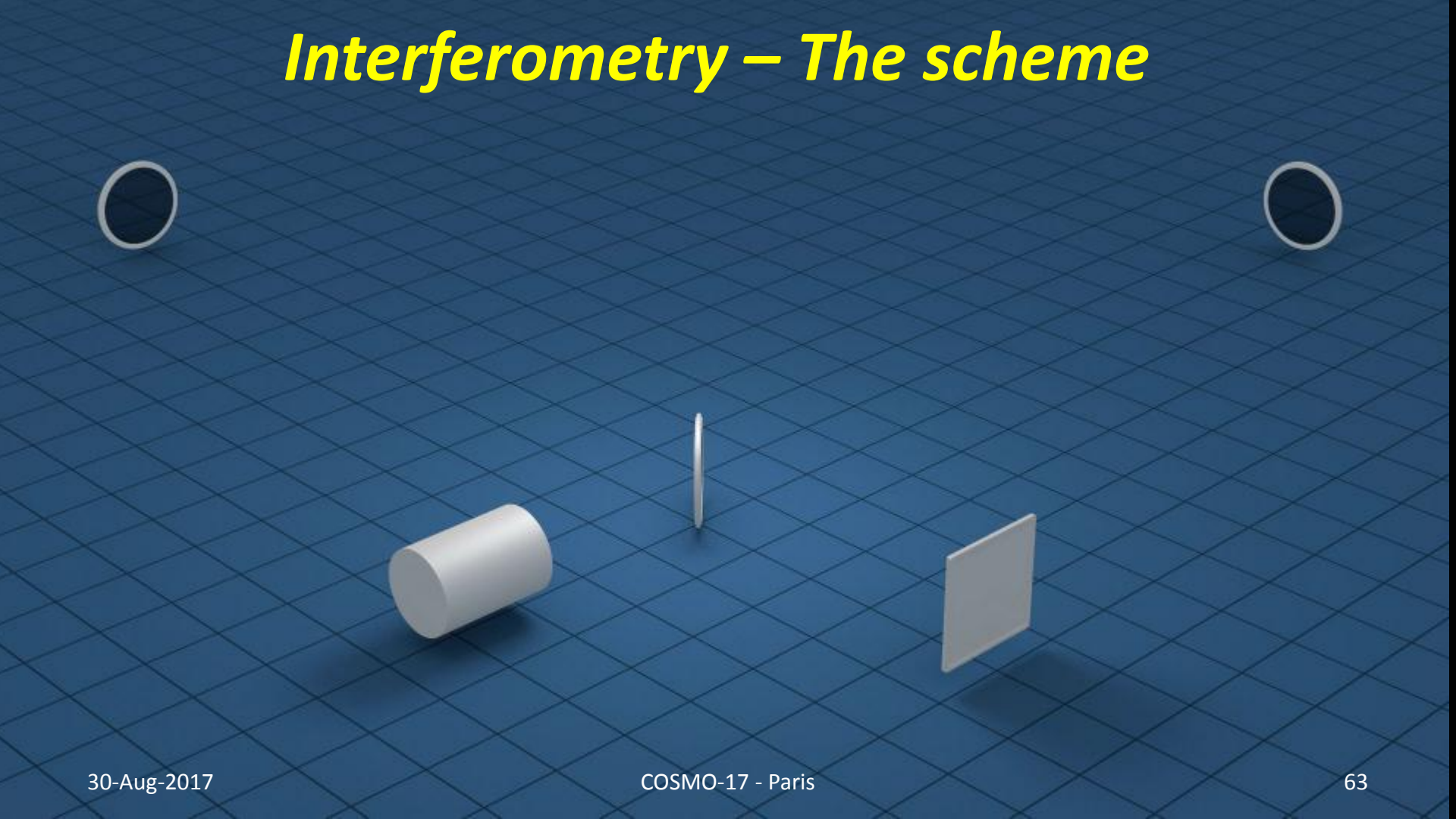


Detection
Michelson Interferometer



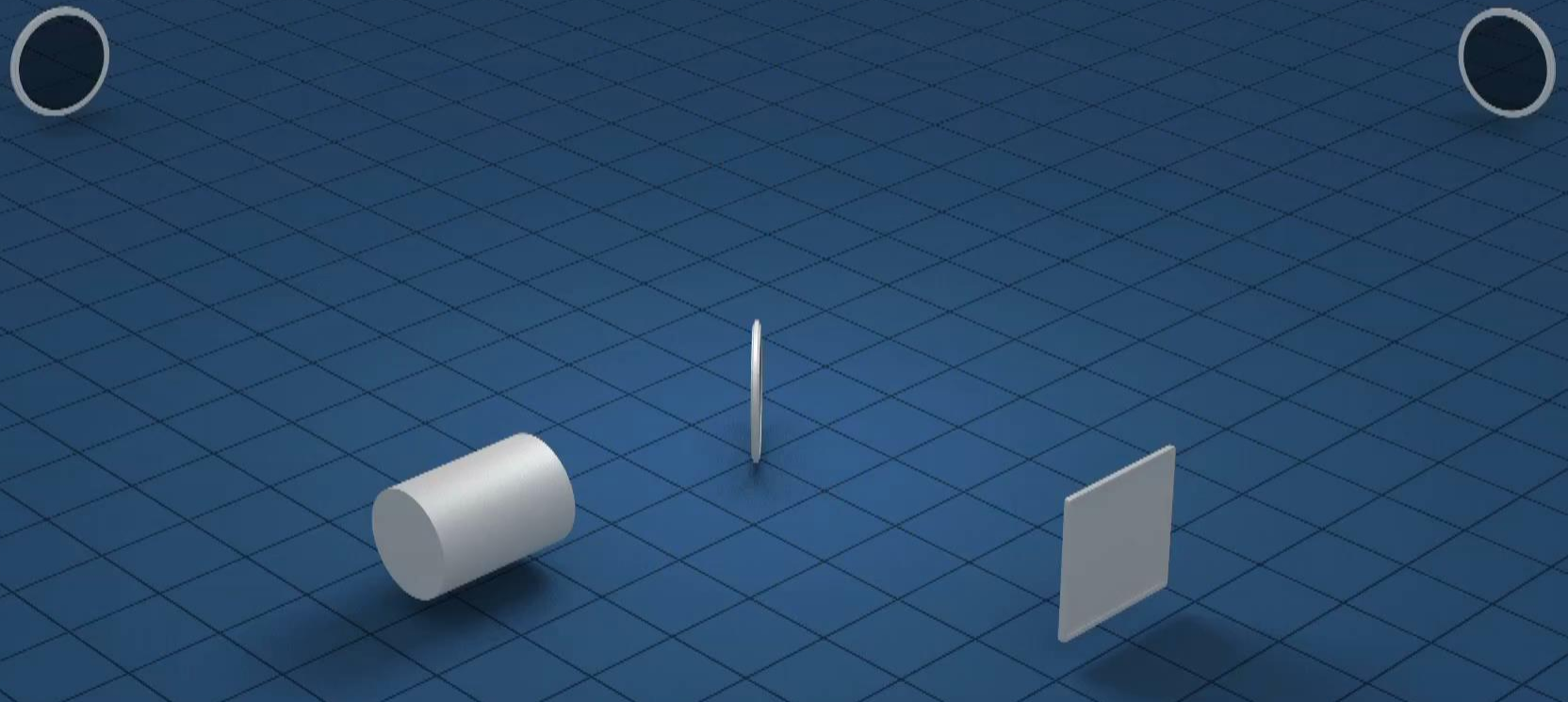

Effect – Greatly exaggerated !!

# *Interferometry – The scheme*



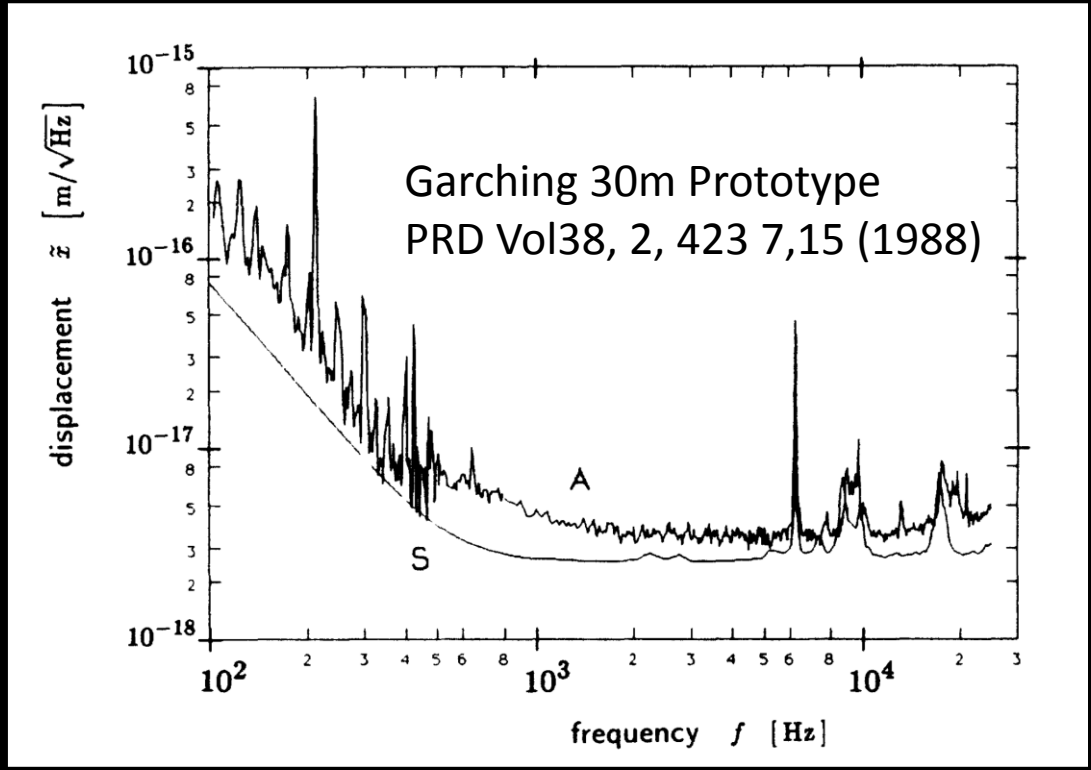
Credit: LIGO/T. Pyle

# *Interferometry – The scheme*



# *Developing Suspended Mass Interferometry*

- Gertsenshtein and Pustovoit, Sov Phys JETP 16, 433 (1962)
- GE Moss, LR Miller and RL Forward Appl Opt 10,2495 (1971)
- R. Weiss MIT Report 105 1972
- Garching 30m and Caltech 40m prototypes.



# LIGO Sites

LIGO
Hanford
3002 km
(L/c = 10 ms)
MIT
Caltech
Livingston
Observatory

# *LIGO Construction Began in 1994*

Evolution over 22 years to Advanced LIGO

# *LIGO Infrastructure beam tube*

# *LIGO Interferometers*

Hanford, WA

Livingston, LA

***GEO 600***

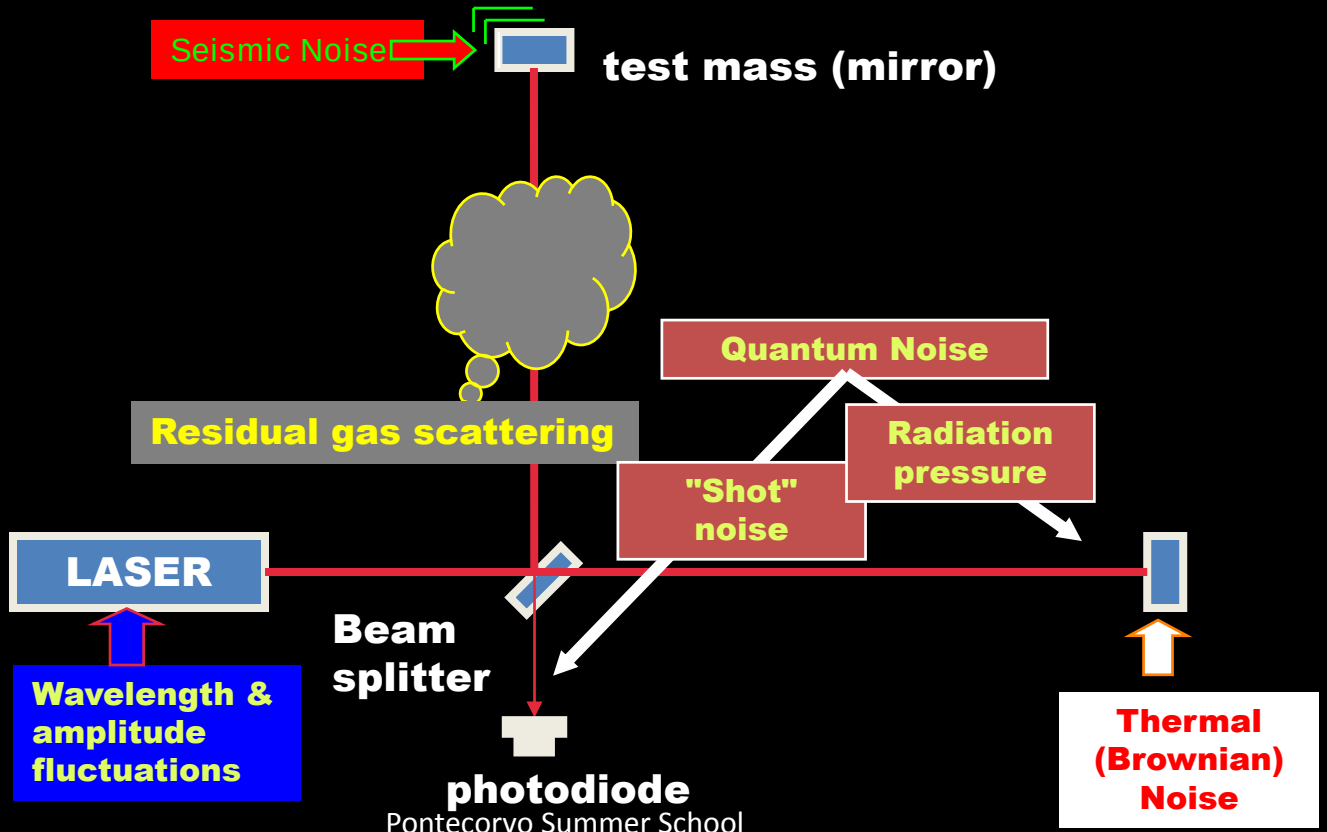
Approved 1995

***Virgo – 3 km***

Approved 1993

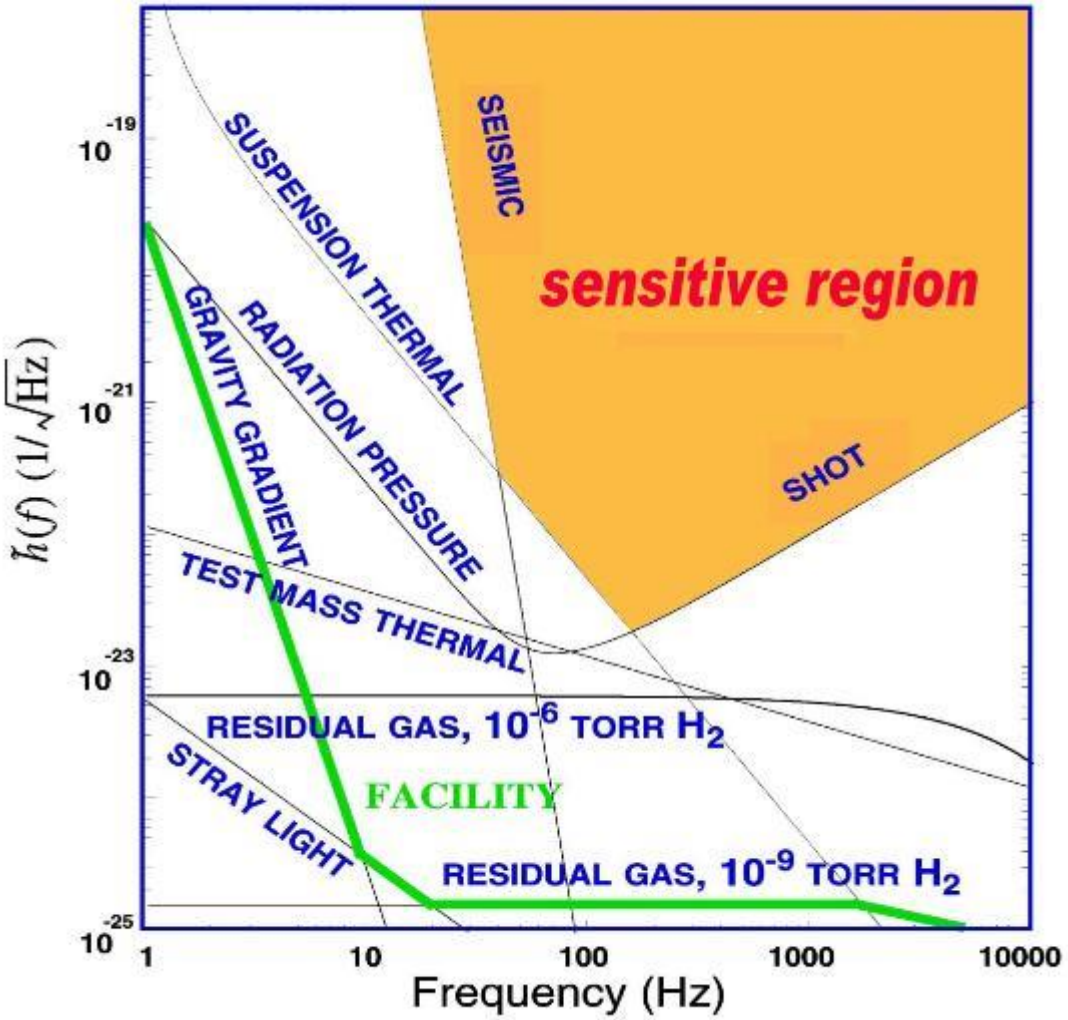
# LIGO Interferometer Infrastructure

# Interferometer Noise Limits

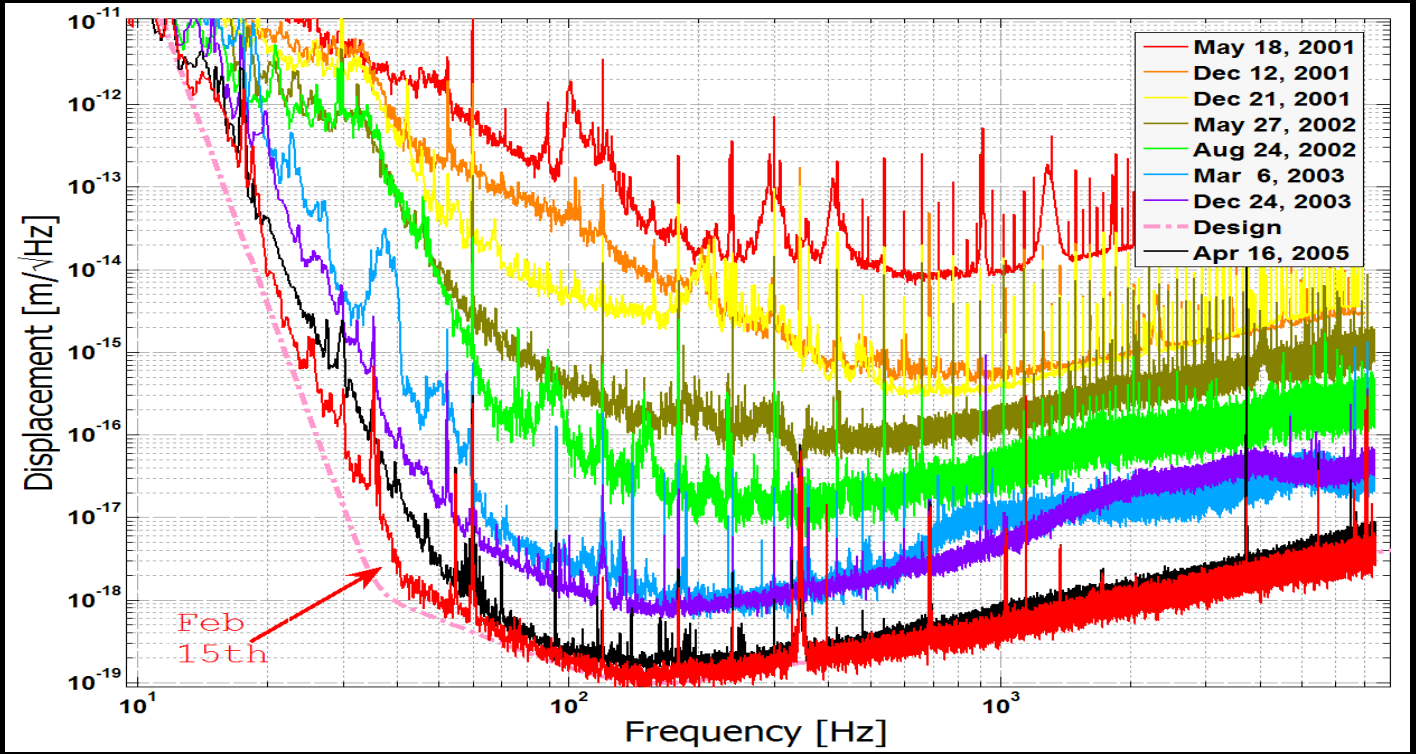


# What Limits LIGO Sensitivity?

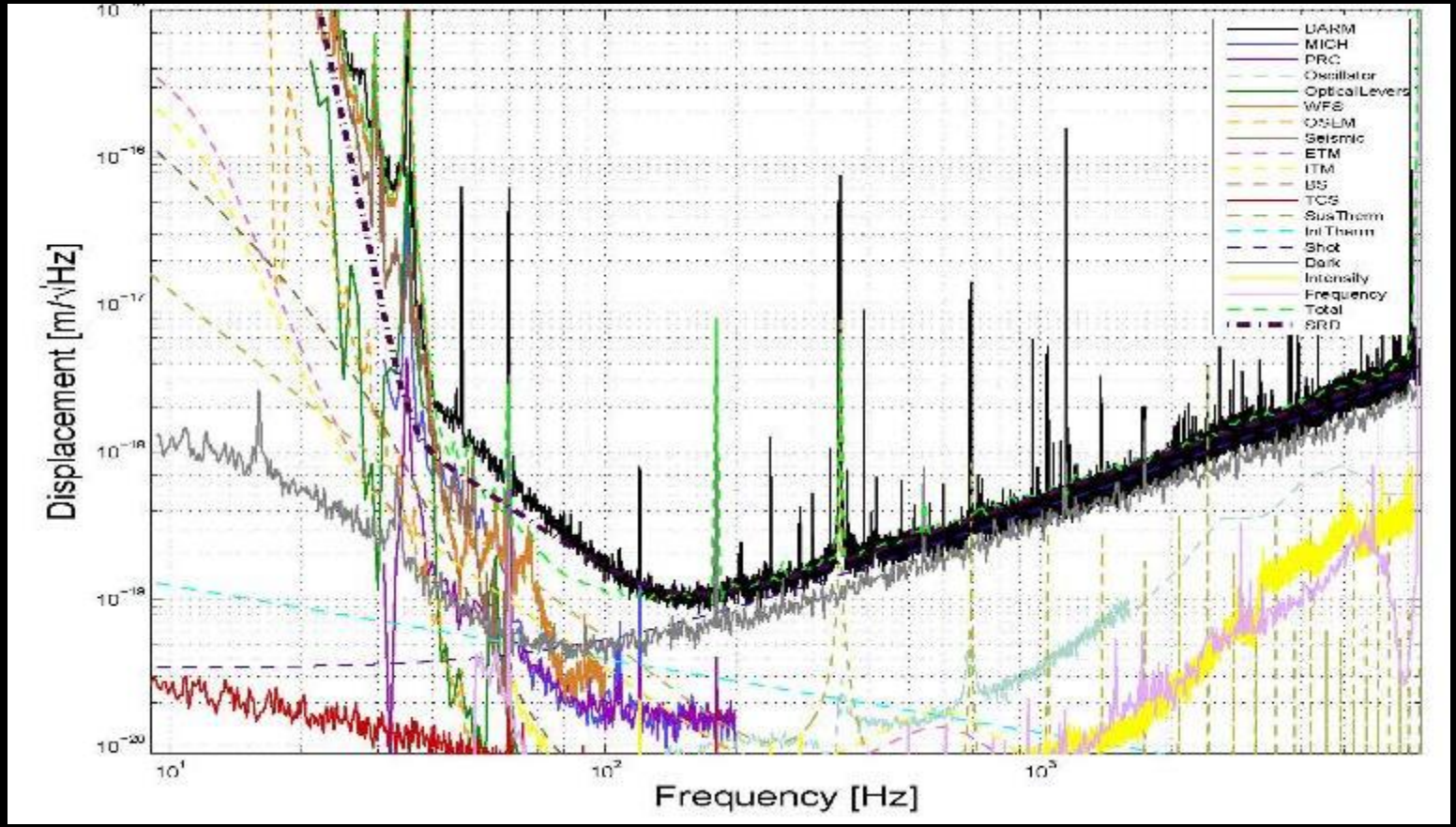
- Seismic noise limits low frequencies
- Thermal Noise limits middle frequencies
- Quantum nature of light (Shot Noise) limits high frequencies
- Technical issues - alignment, electronics, acoustics, etc limit us before we reach these design goals



# Evolution of LIGO Sensitivity



# Initial LIGO Performance (Final)



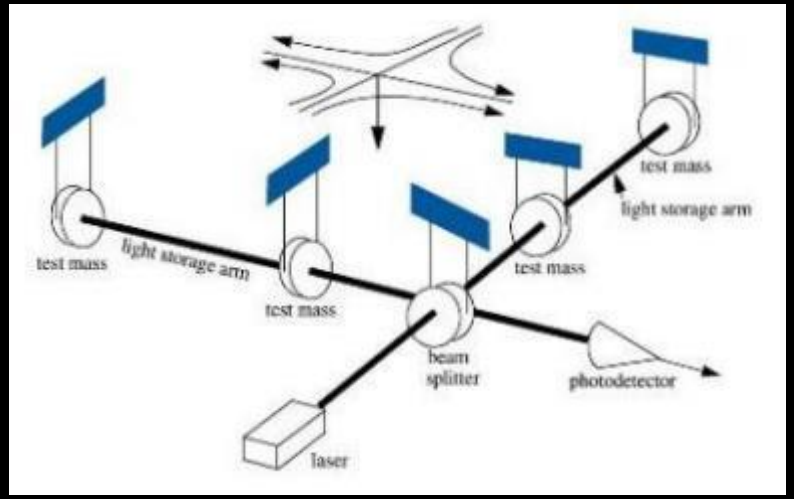
# Passive Seismic Isolation

## Initial ILIGO

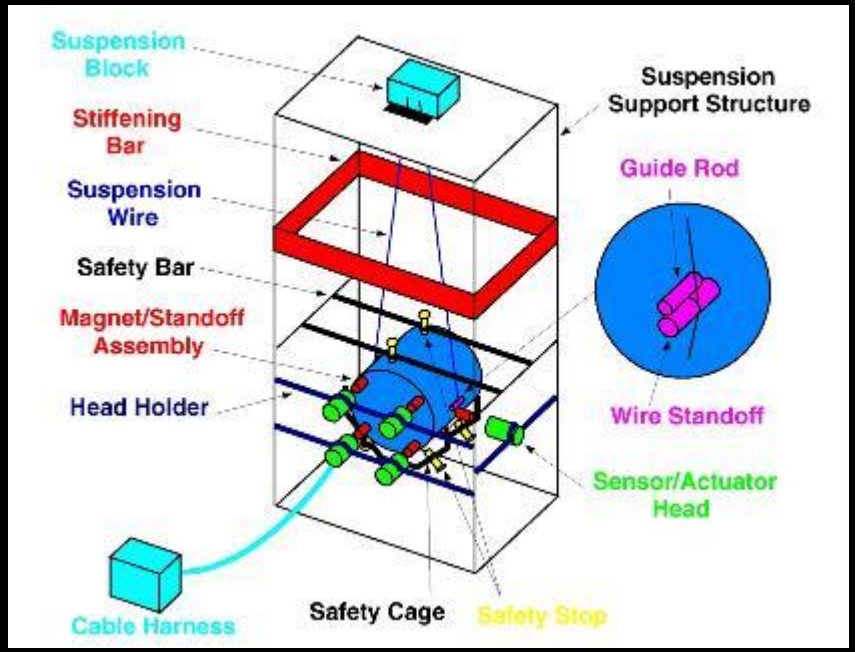
damped spring

# Suspension System

## Initial LIGO

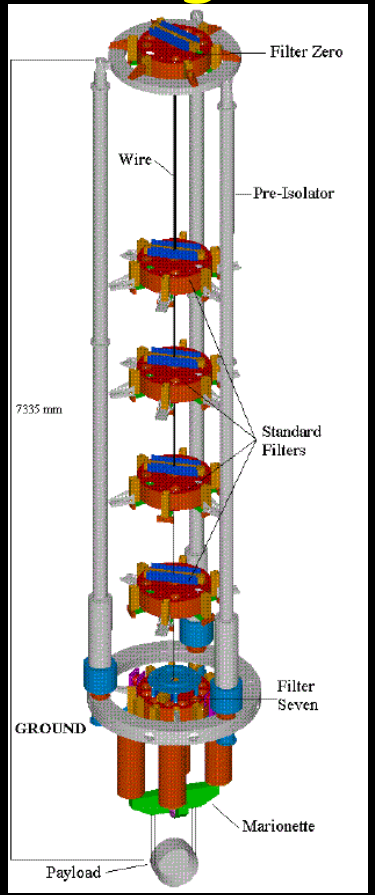


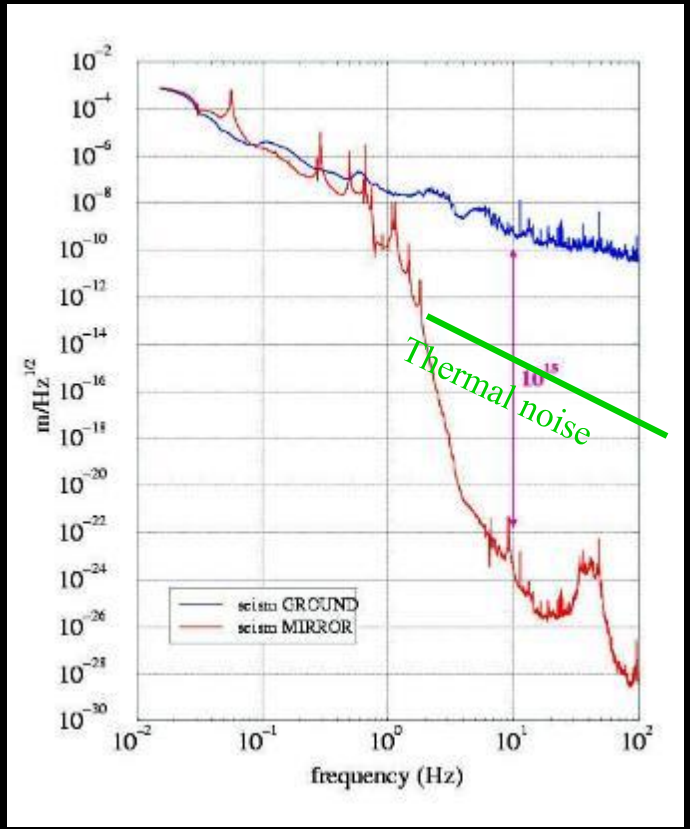

suspension assembly for a core optic



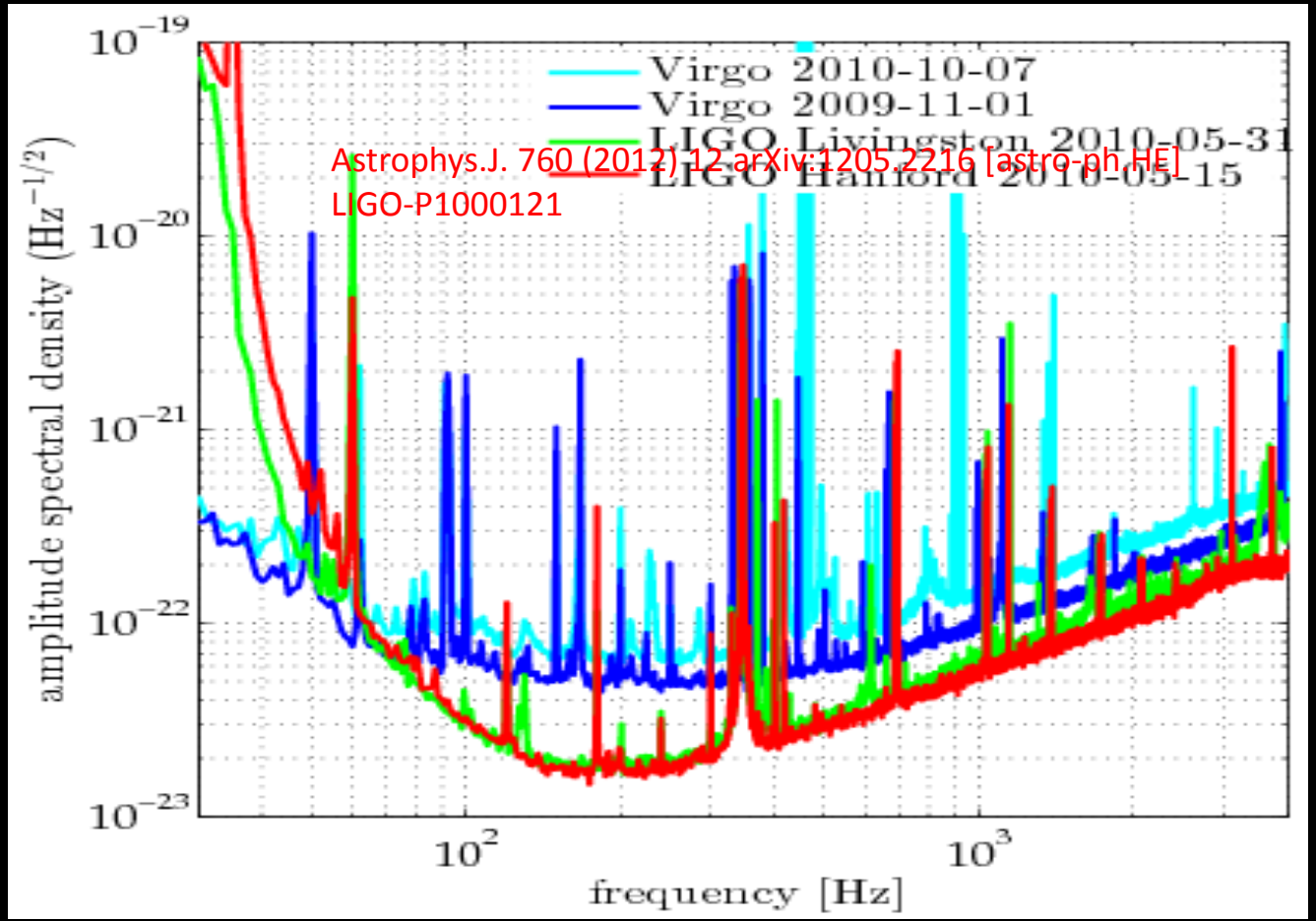

- support structure is welded tubular stainless steel
- suspension wire is 0.31 mm diameter steel music wire
- fundamental violin mode frequency of 340 Hz

# Virgo Seismic Performance

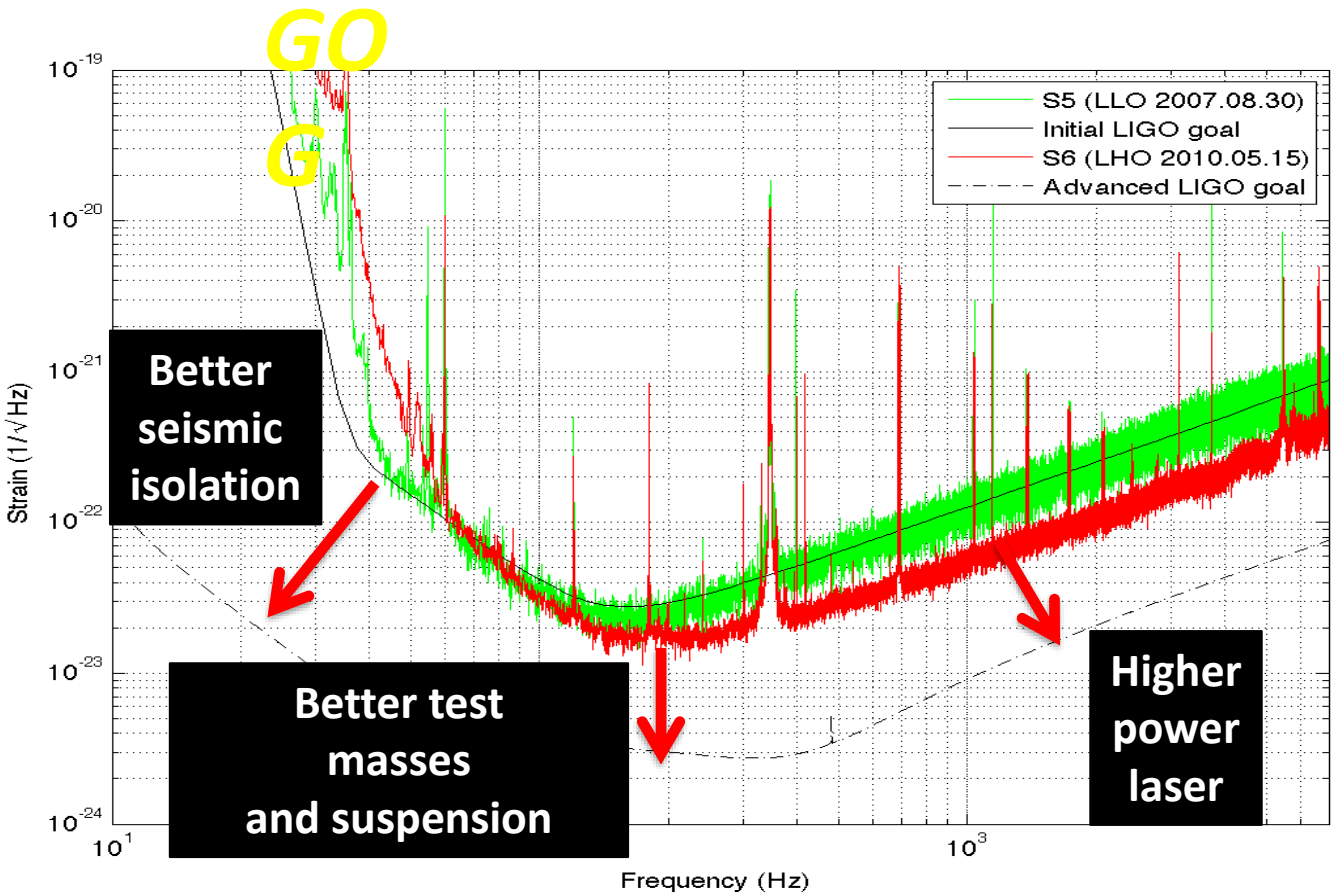


# Sensitivity of Initial LIGO-Virgo

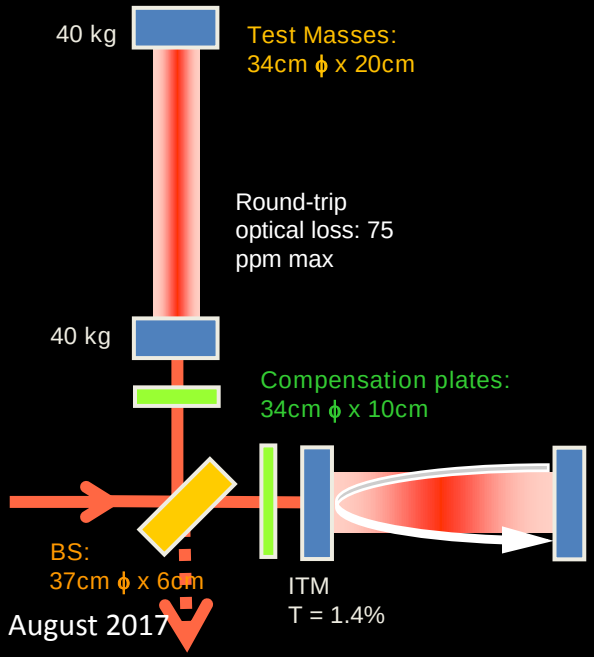


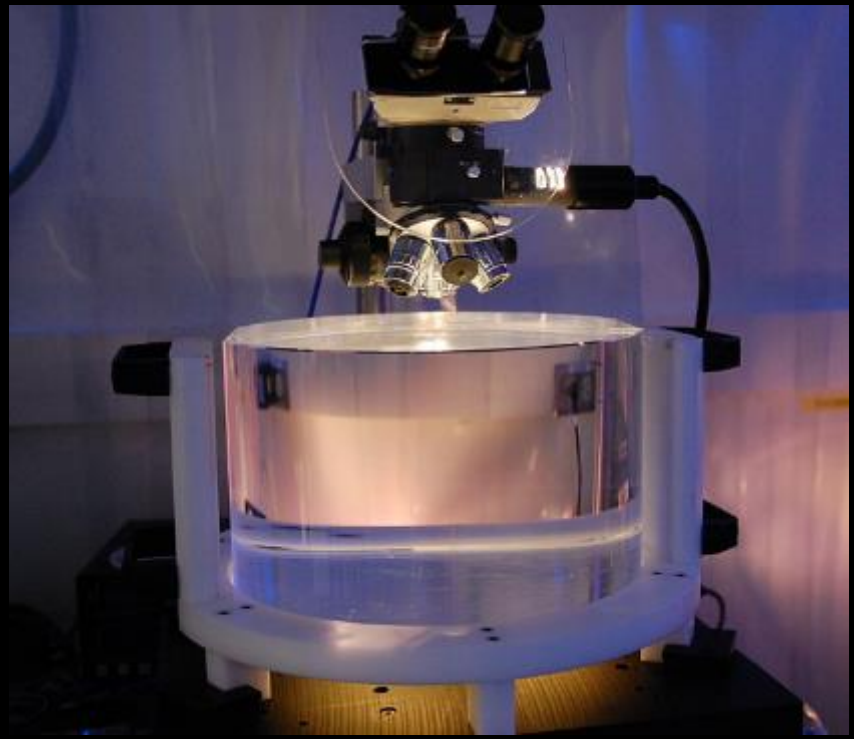
# Advanced LIGO GOALS



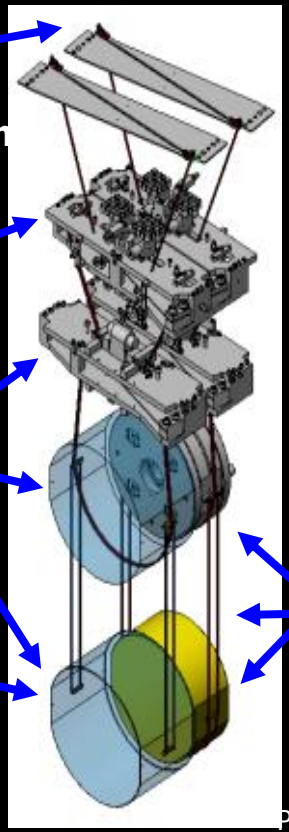
# Mirror / Test Masses

- **Mechanical requirements: bulk and coating thermal noise, high resonant frequency**
- **Optical requirements: figure, scatter, homogeneity, bulk and coating absorption**



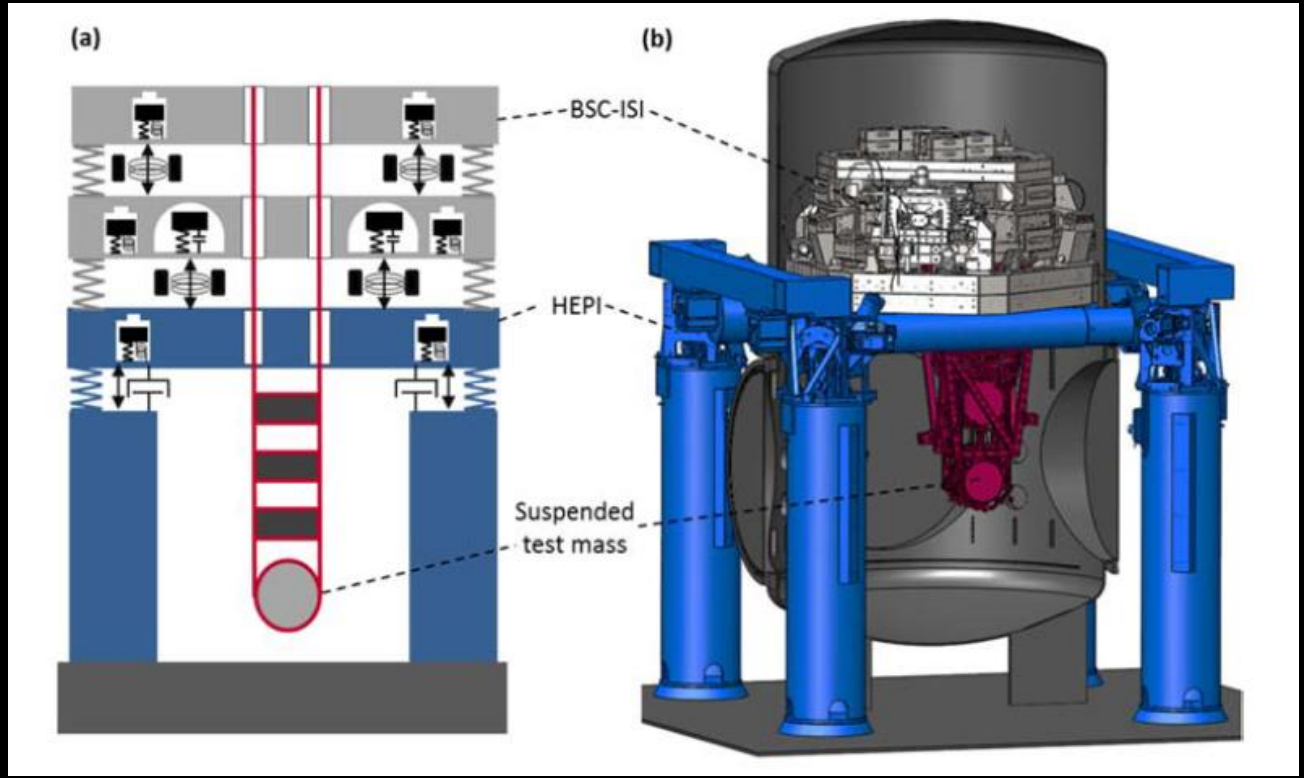



# Test Mass
# Quadruple Pendulum Suspension



# *Passive / Active Multi-Stage Isolation*

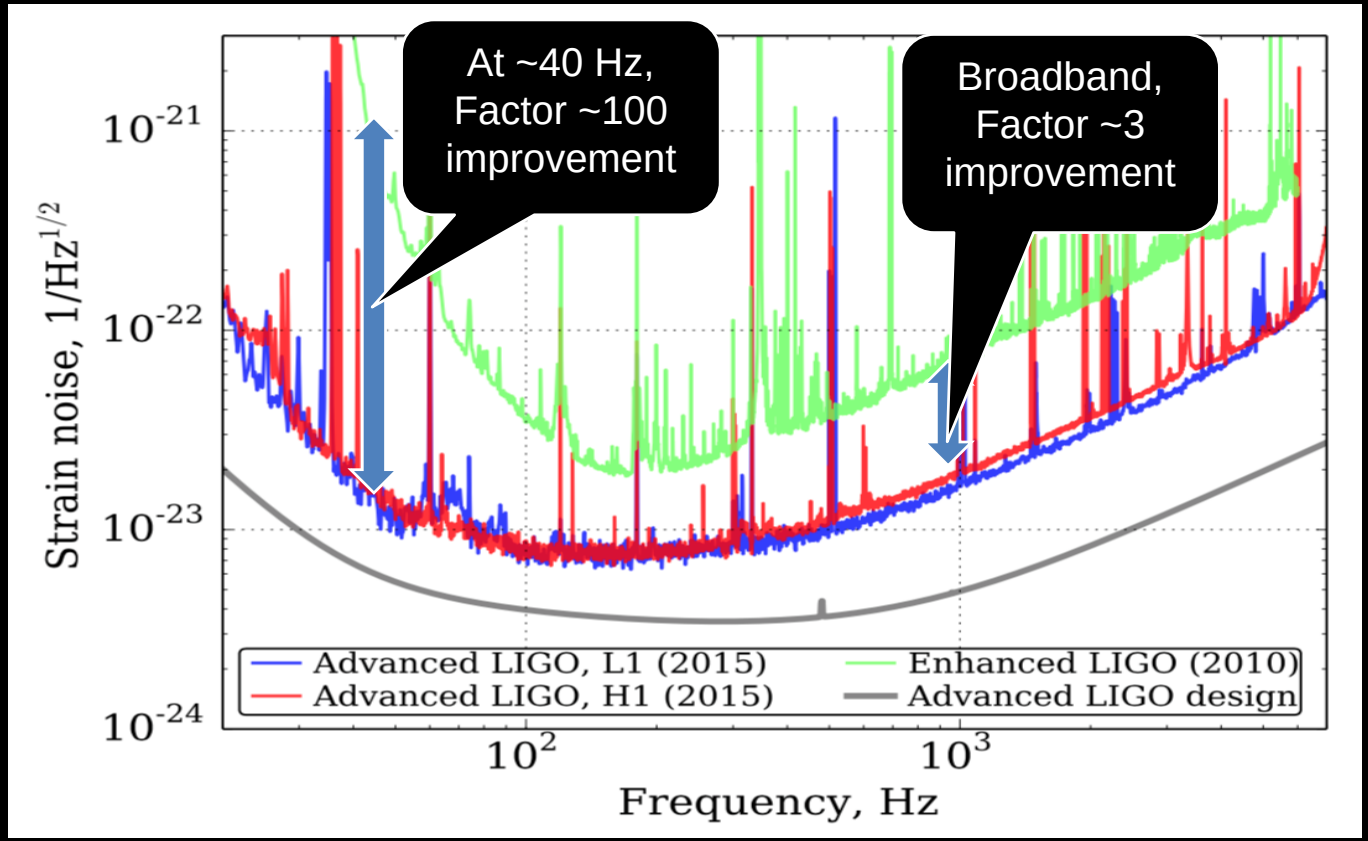
## Advanced LIGO



# 200W Nd:YAG Laser

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

# Sensitivity for first Observing run




Initial LIGO

O1 aLIGO

Design aLIGO

Phys. Rev. D 93, 112004 (2016

# Gravitational Wave Event

## GW150914

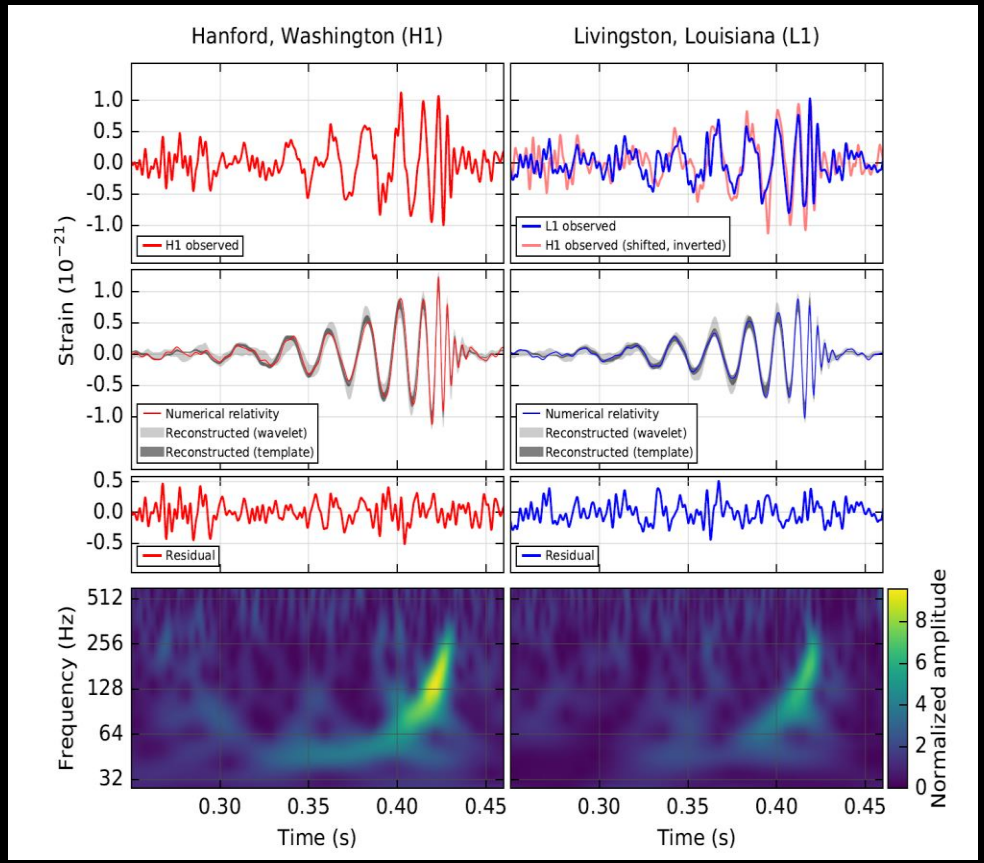
Data bandpass filtered between 35 Hz and 350 Hz

Time difference 6.9 ms with Livingston first

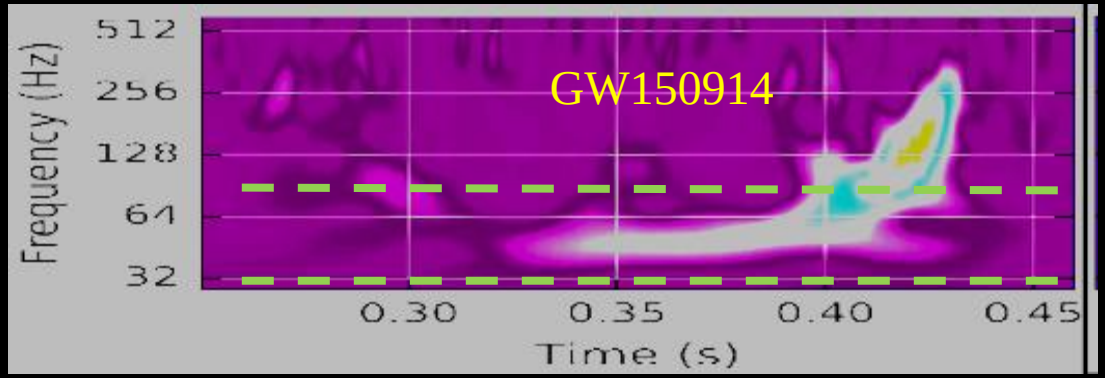
Second row – calculated GW strain using Numerical Relativity Waveforms for quoted parameters compared to reconstructed waveforms (Shaded)

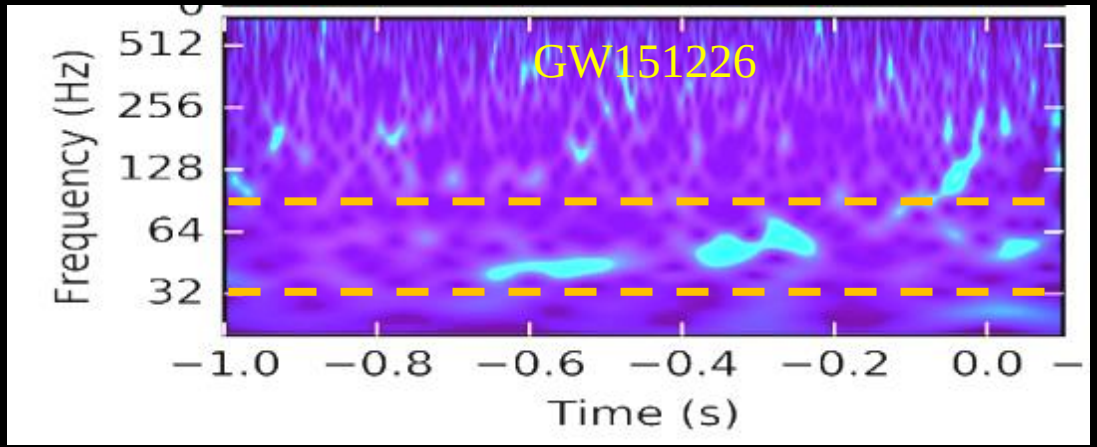
Third Row –residuals

bottom row – time frequency plot showing frequency increases with time (chirp)

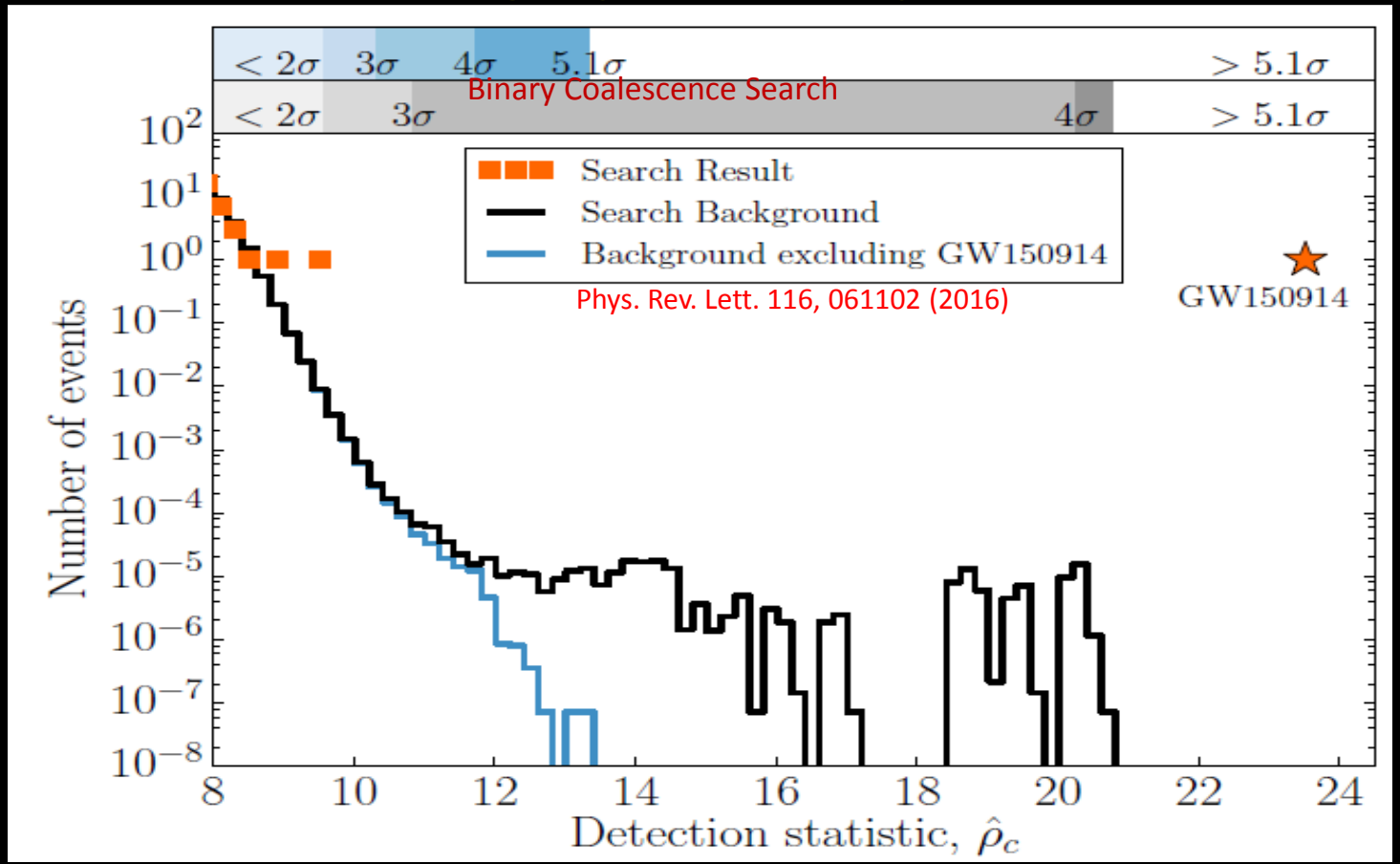


# Black Hole Merger Events and Low Frequency Sensitivity



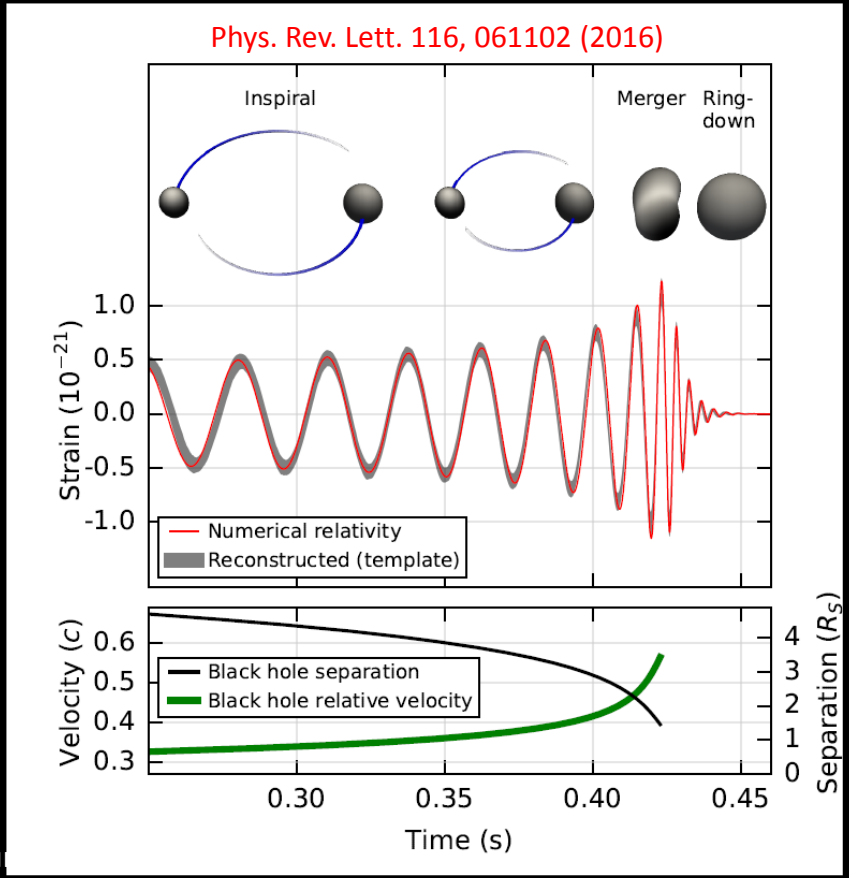
# Statistical Significance of GW150914



# Black Hole Merger: GW150914

Full bandwidth waveforms without filtering. Numerical relativity models of black hole horizons during coalescence

Effective black hole separation in units of Schwarzschild radius ($R_s=2GM_f/c^2$); and effective relative velocities given by post-Newtonian parameter $v/c = (GM_f \pi f/c^3)^{1/3}$



# *Measuring the parameters*

- Orbits decay due to emission of gravitational waves
  - **Leading order** determined by “chirp mass”

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

  - Next orders allow for measurement of mass ratio and spins
  - We directly measure the red-shifted masses (1+z) m
  - Amplitude inversely proportional to luminosity distance
- Orbital precession occurs when spins are misaligned with orbital angular momentum – no evidence for precession.
- Sky location, distance, binary orientation information extracted from time-delays and differences in observed amplitude and phase in the detectors

# Black Hole Merger Parameters for GW150914

- Use numerical simulations fits of black hole merger to determine parameters; determine total energy radiated in gravitational waves is $3.0 \pm 0.5$ $M_o c^2$ . The system reached a peak ~3.6 x$10^{56}$ ergs, and the spin of the final black hole < 0.7 (not maximal spin)

| | |
|---|---|
| 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, $z$ | $0.09^{+0.03}_{-0.04}$ |

Phys. Rev. Lett. 116, 061102 (2016)

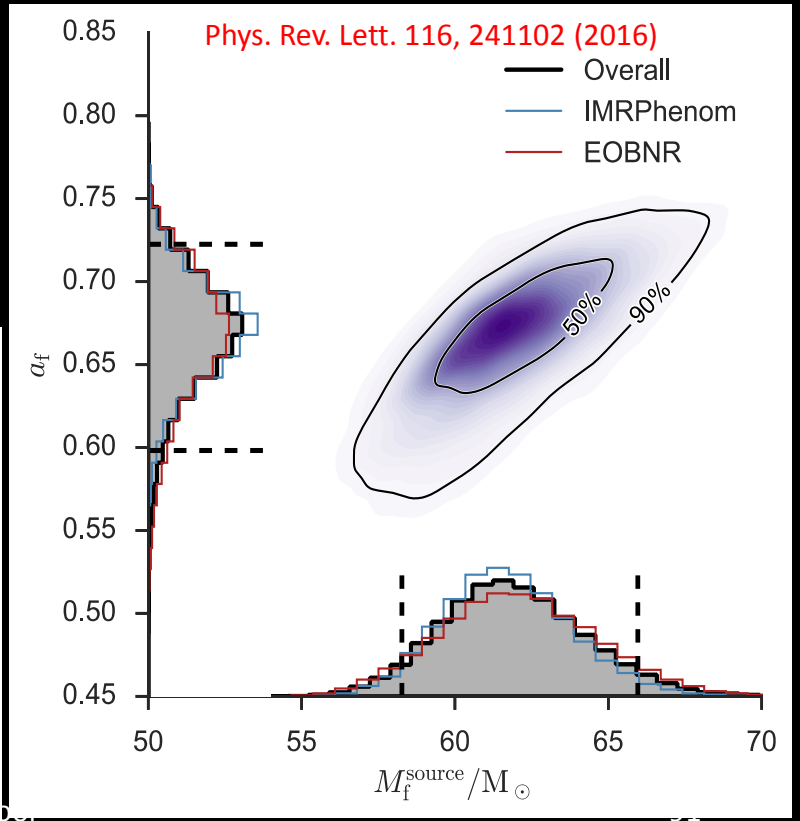
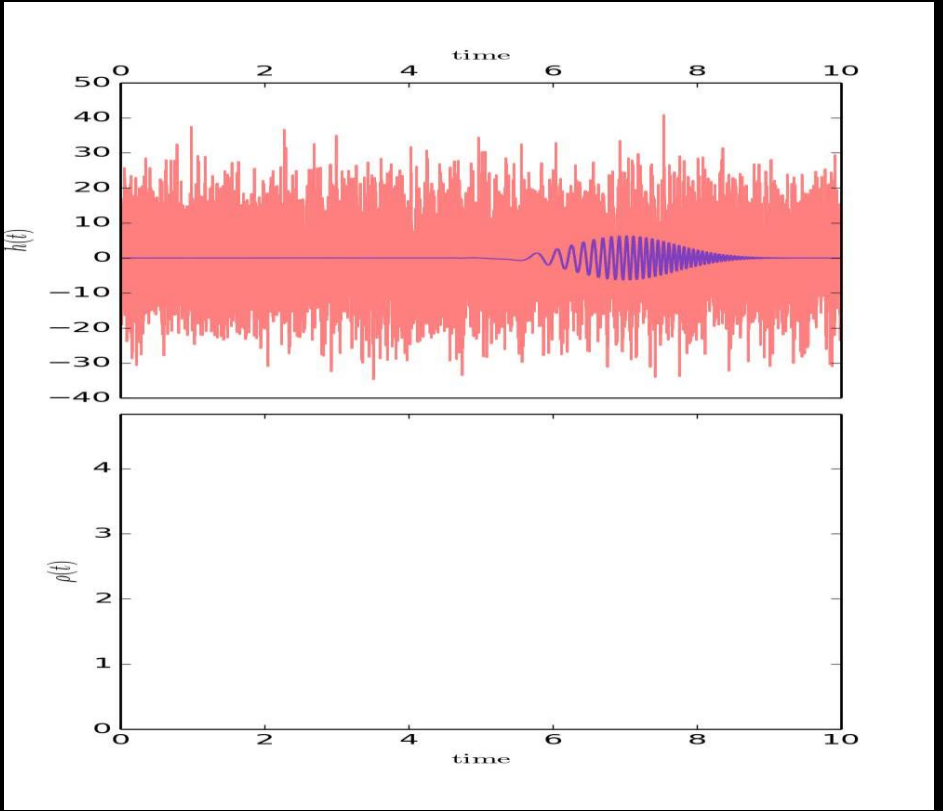


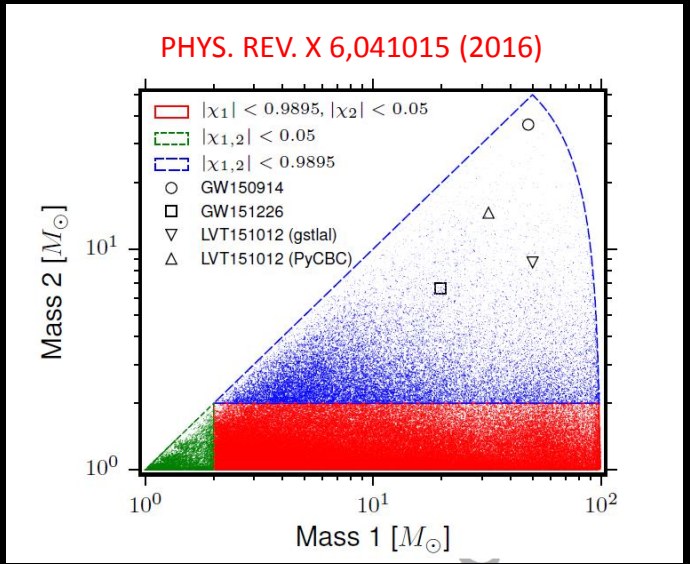
Image credit: LIGO

# Finding a weak signal in noise

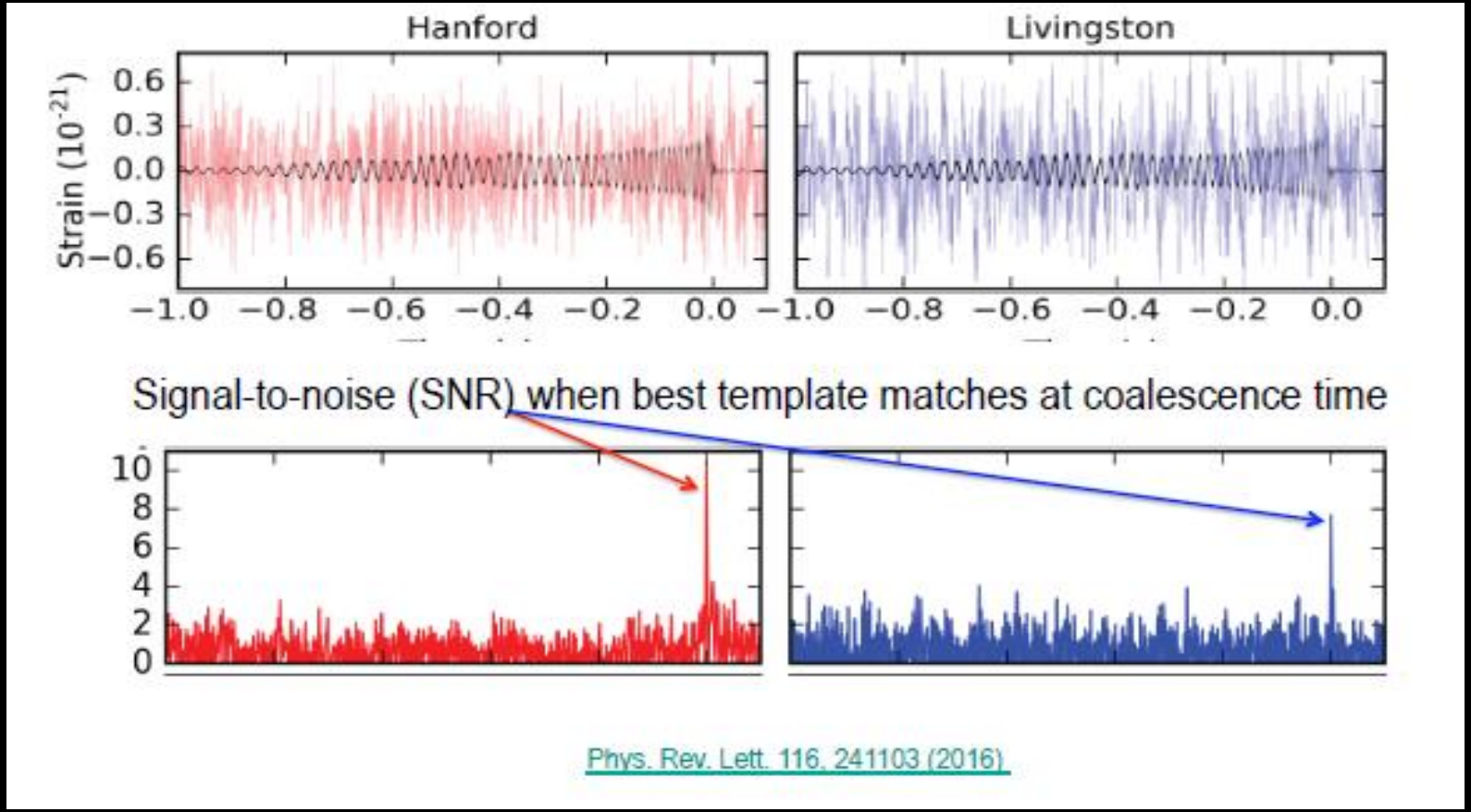
- "Matched filtering" lets us find a weak signal submerged in noise.
- For calculated signal waveforms, multiply the waveform by the data
- Find signal from cumulative signal/noise



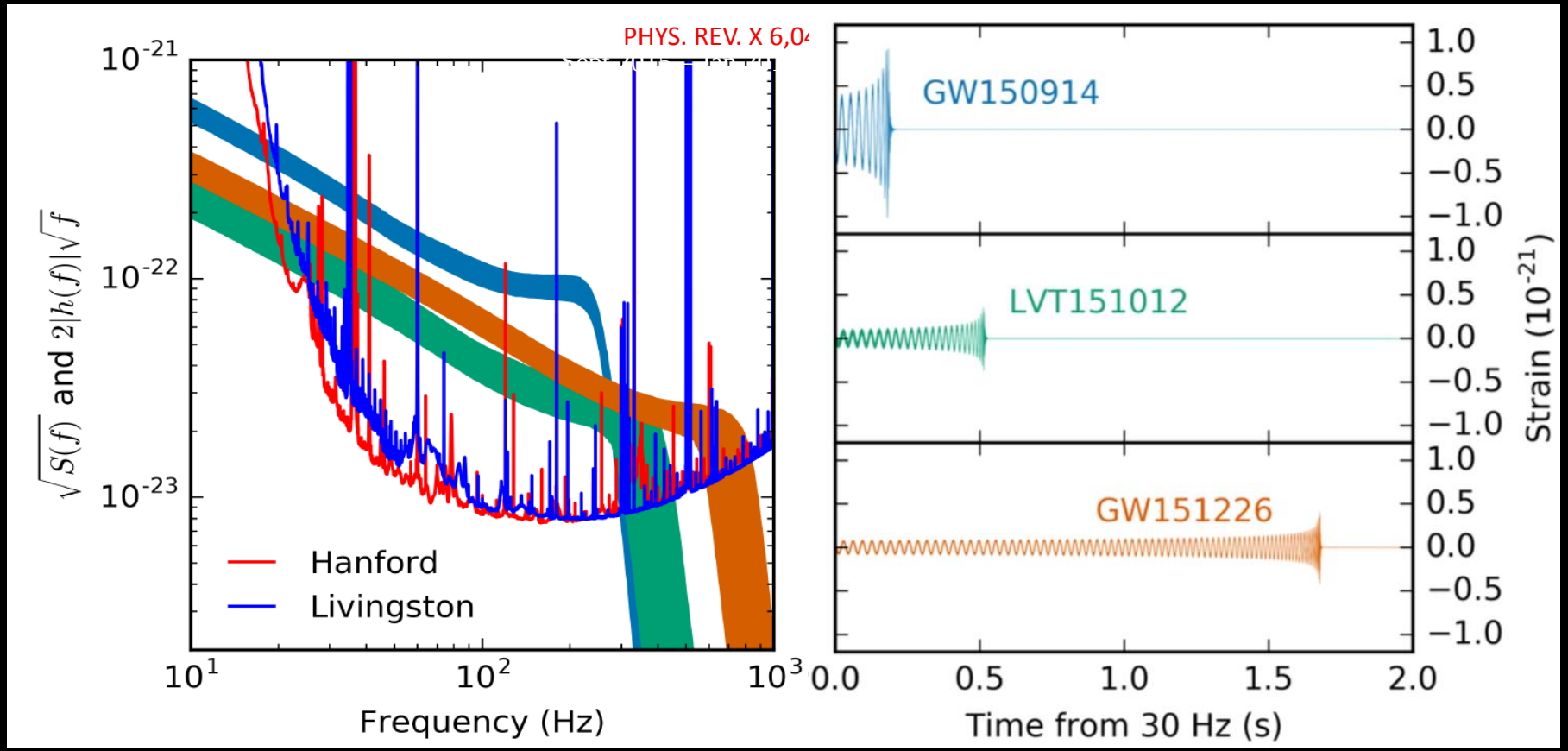

PHYS. REV. X 6,041015 (2016)



# GW151226 – Matched Filter



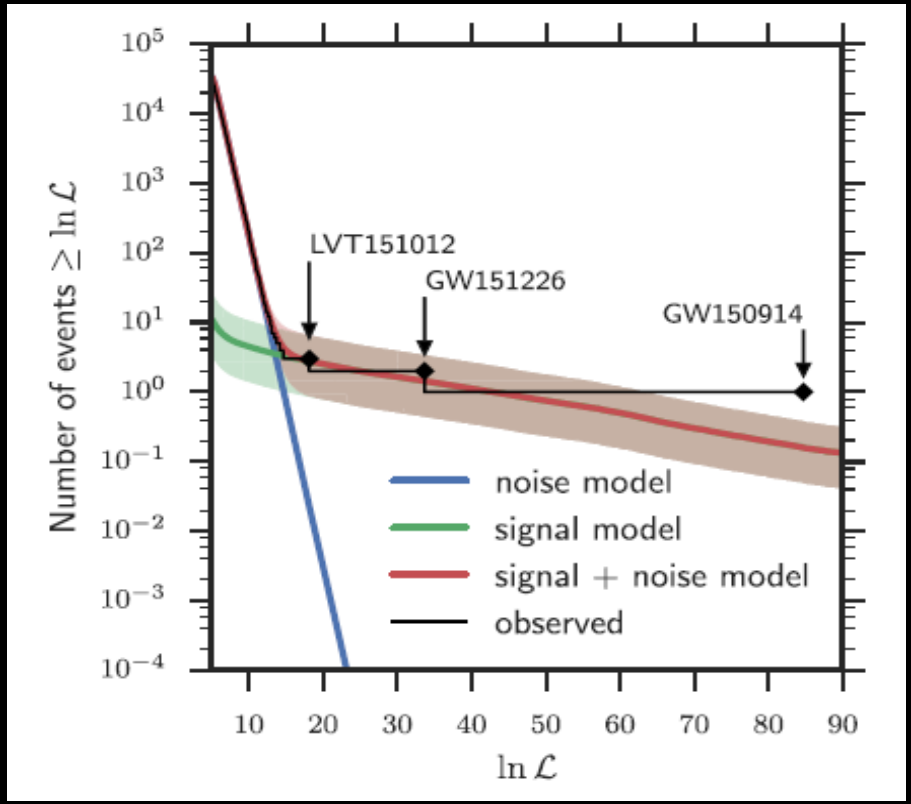
# Second Event, Plus another Candidate



# Sensitivity

Lessons from LIGO O1

- Steep drop in false alarm rate versus size means edge of observable space is very sharp
  - » Very far out on tail of noise due to need to overcome trials factor




O1 BBH Search

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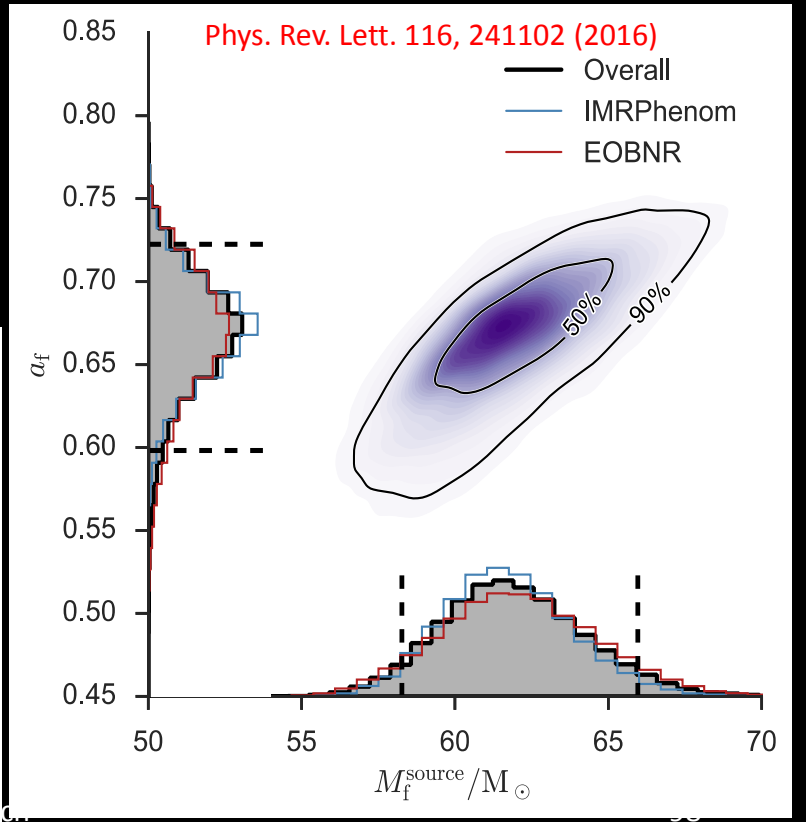
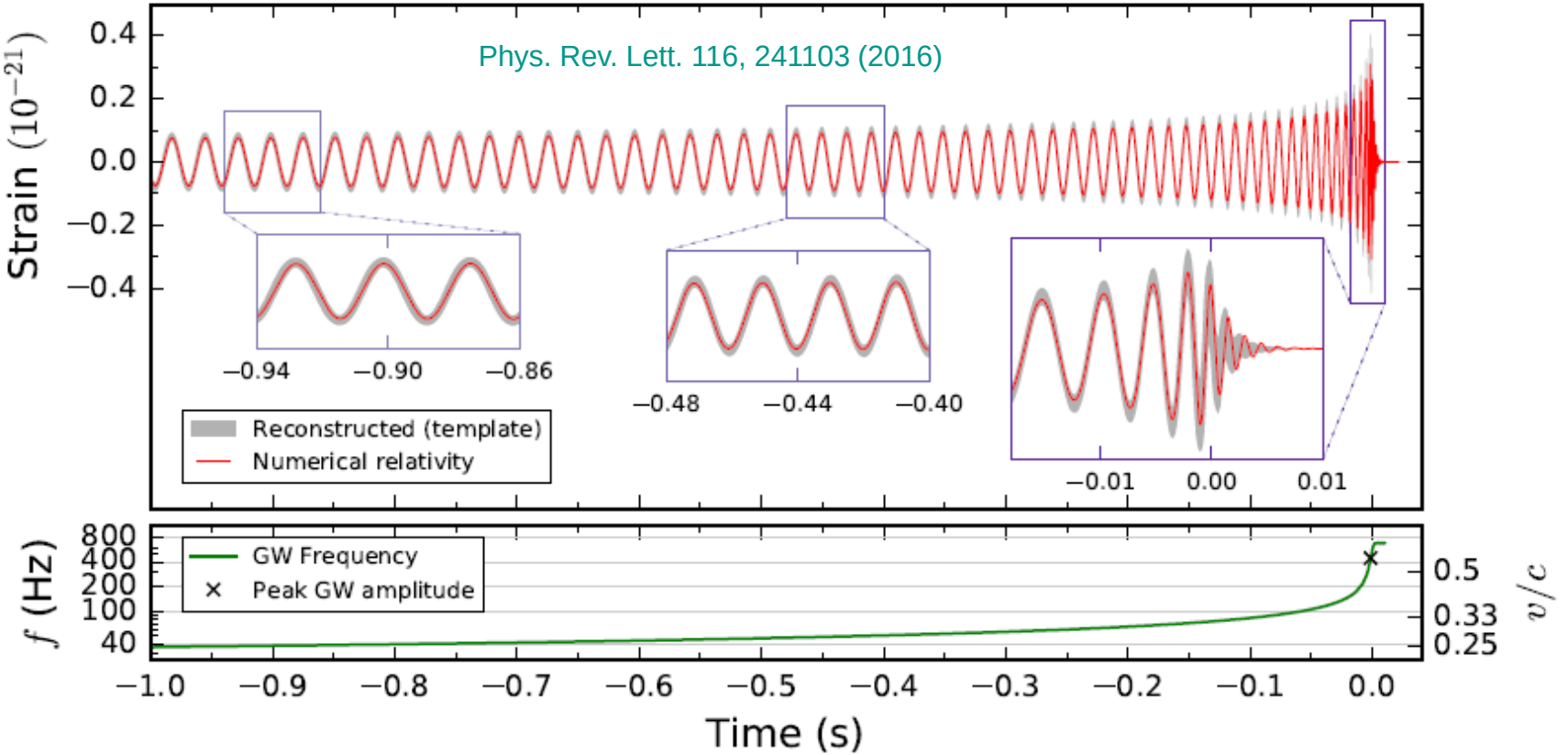
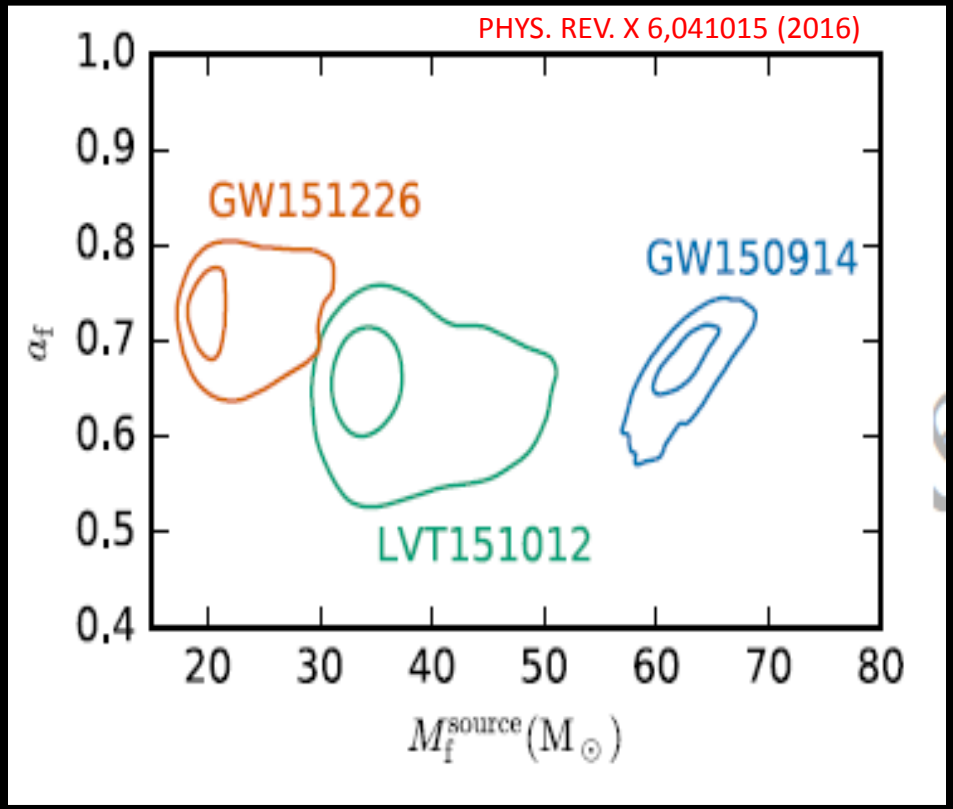


# “Second Event” Inspiral and Merger GW151226



# Final Black Hole Masses, Spins and Distance

PHYS. REV. X 6,041015 (2016)

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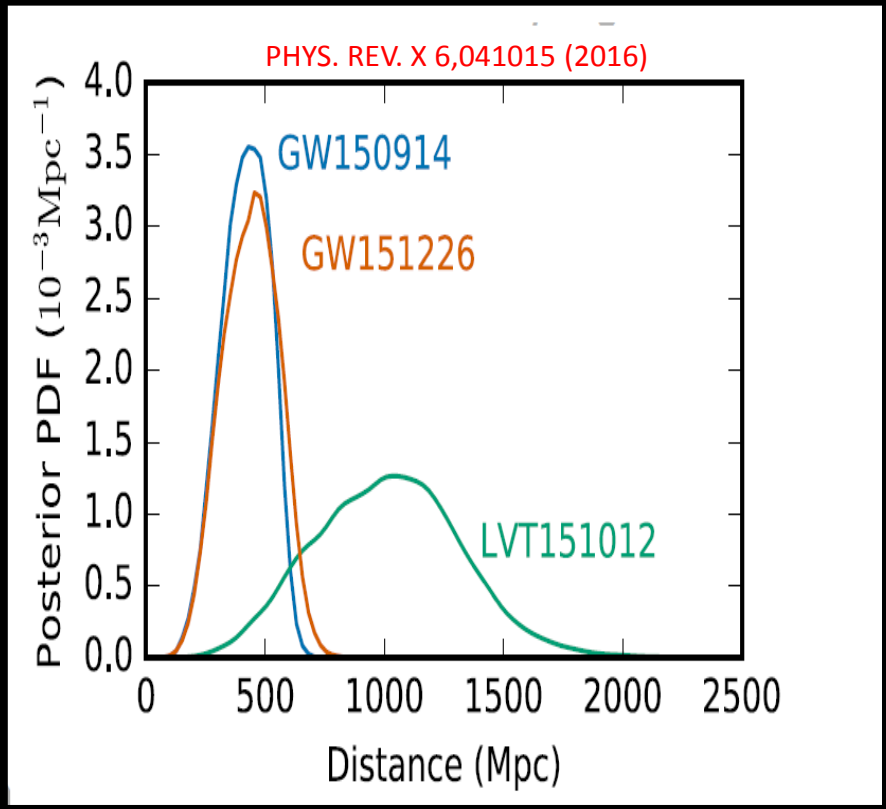
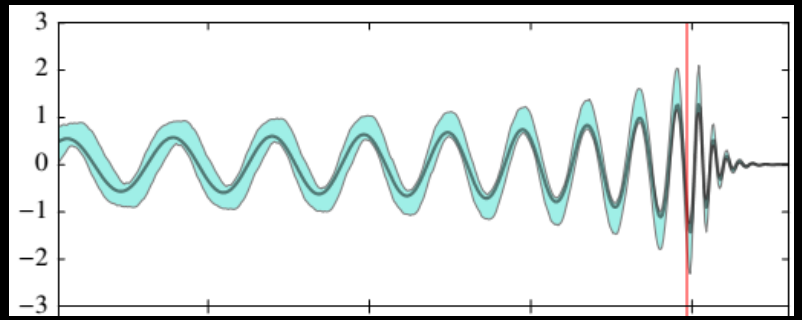
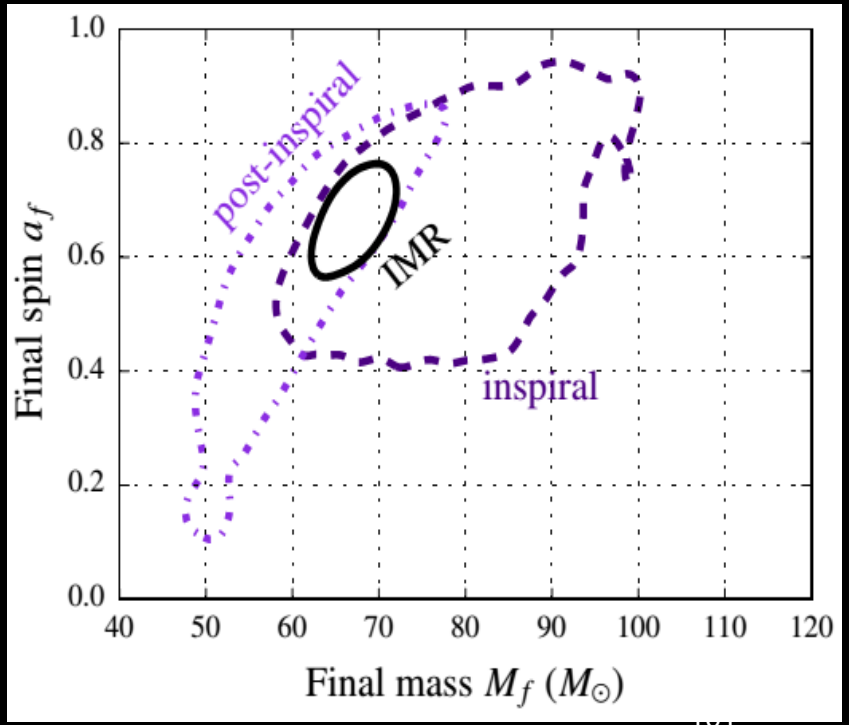


# Consistency with General Relativity

- We examined the detailed waveform of GW150914 in several ways to see whether there is any deviation from the GR predictions
  - Known through post-Newtonian (analytical expansion) and numerical relativity
- Inspiral / merger / ringdown consistency test
  - Compare estimates of mass and spin from before vs. after merger




- Pure ringdown of final BH?
  - Not clear in data, but consistent

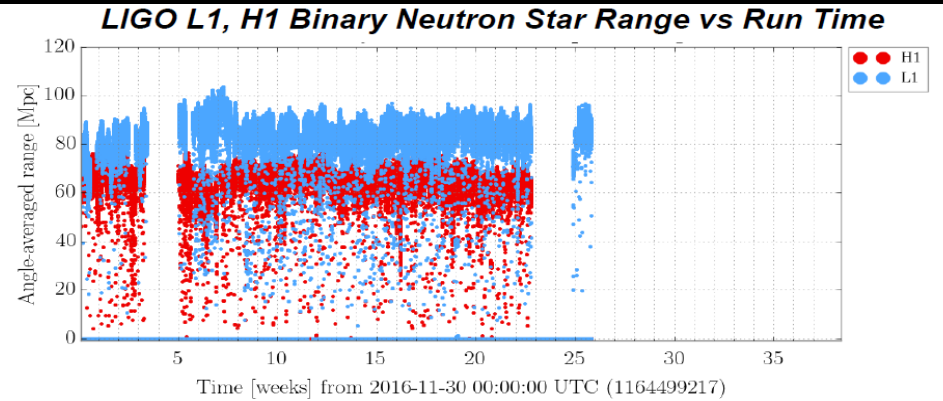


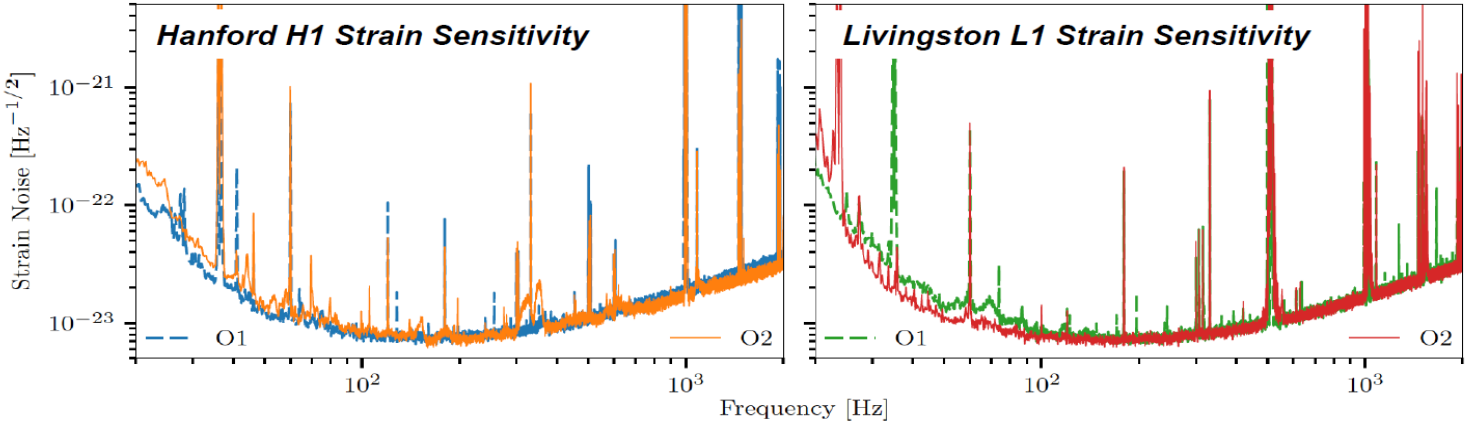

PRL 116, 221101 (2016)

# LIGO O2 Observational Run Underway

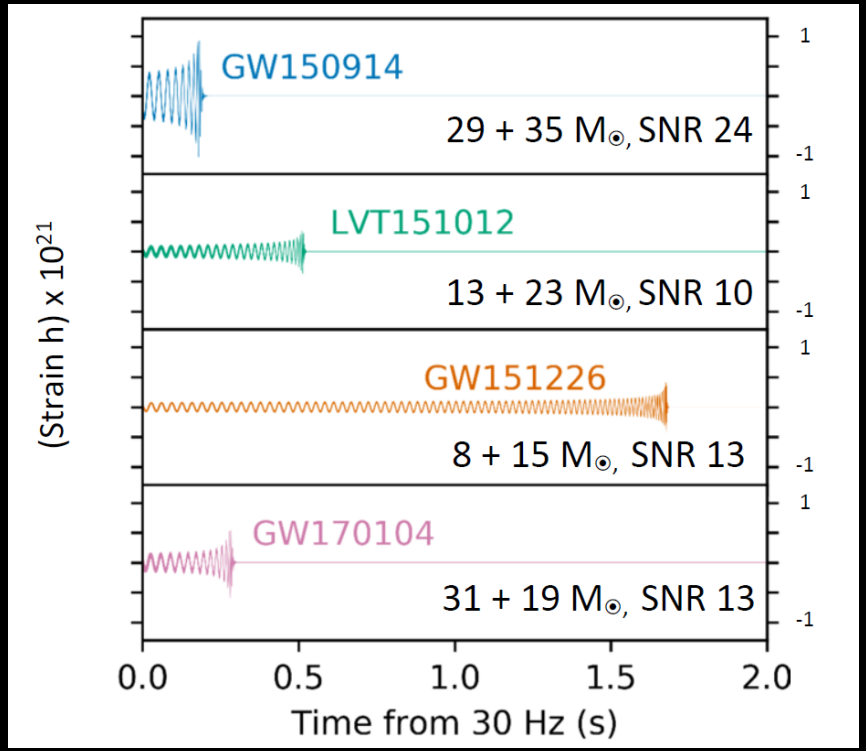
O2 began on November 30, 2016

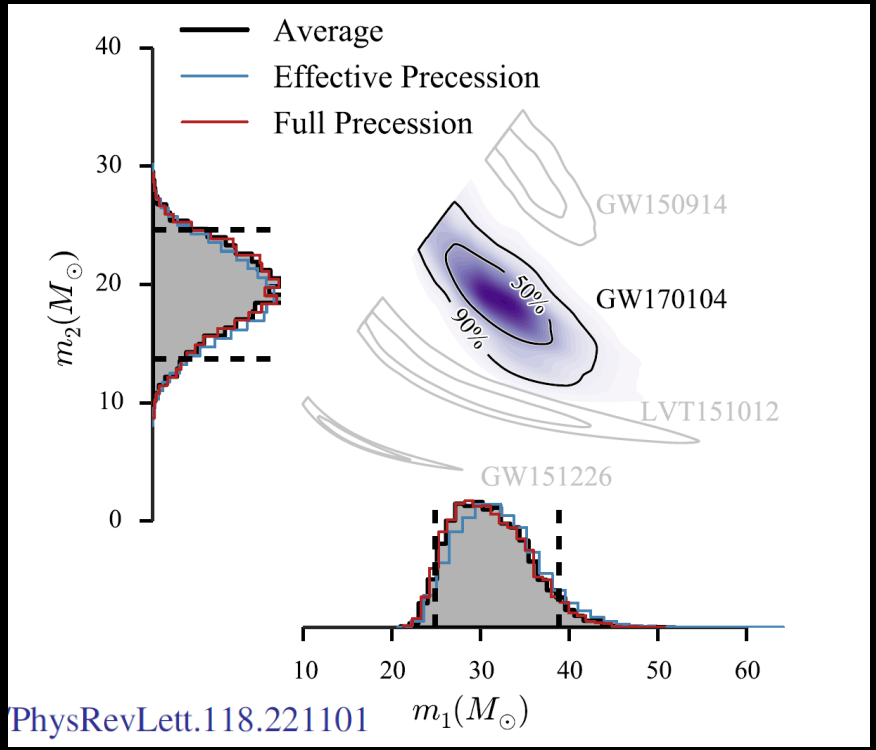
Planned end date is August 25, 2017



# Third Blackhole Binary Coalescence




Posterior probability density for the source-frame masses

# New Astrophysics

- Stellar binary black holes exist
- They form into binary pairs
- They merge within the lifetime of the universe
- The masses ($M > 20\ M_{\odot}$) are much larger than what was known about stellar mass Black Holes.

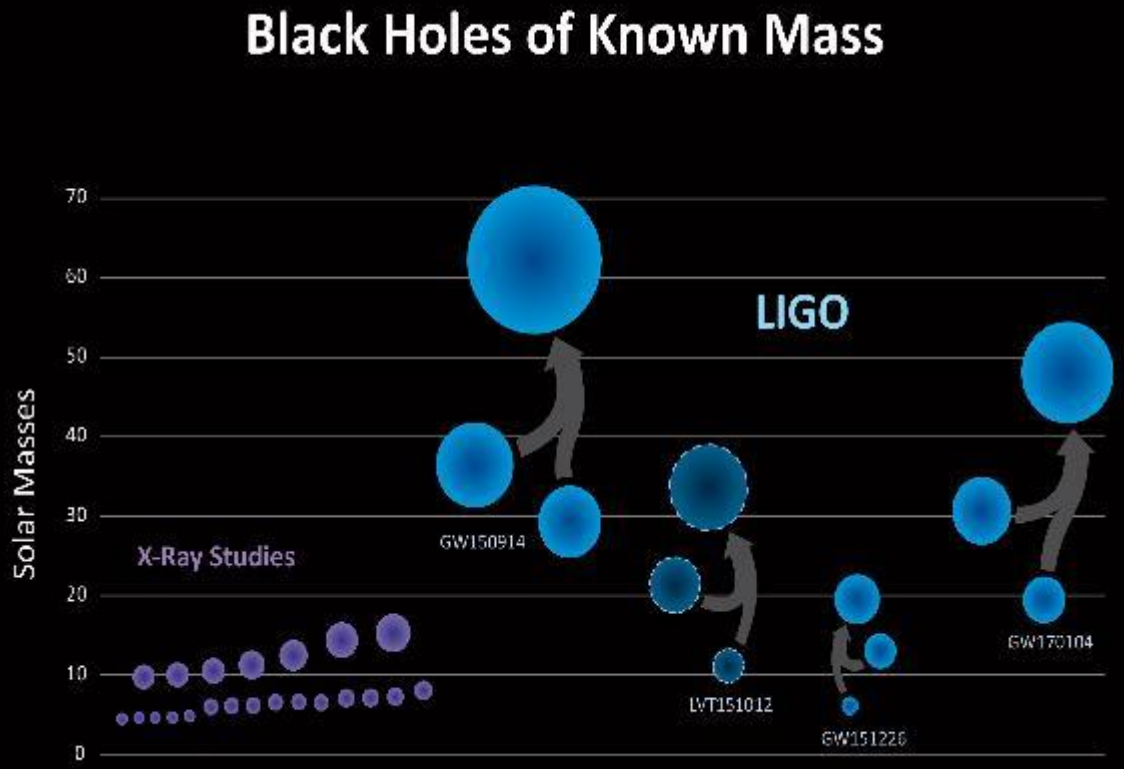





Image credit: LIGO

# *Testing GR – Dispersion Term?*

- In GR, there is no dispersion!

Add dispersion term of form

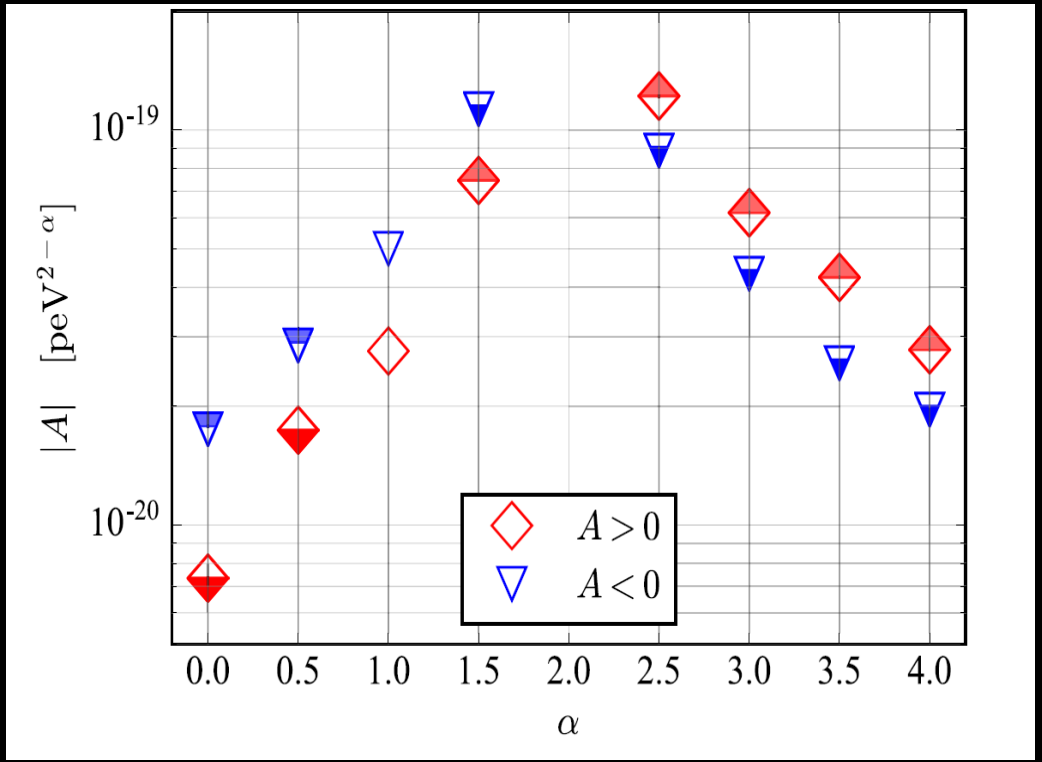
$$E^2 = p^2c^2 + Ap^\alpha c^\alpha, \quad \alpha \geq 0$$

(E, p are energy, momenturm of GW, A is amplitude of dispersion)

- Plot shows 90% upper bounds
- Limit on graviton mass

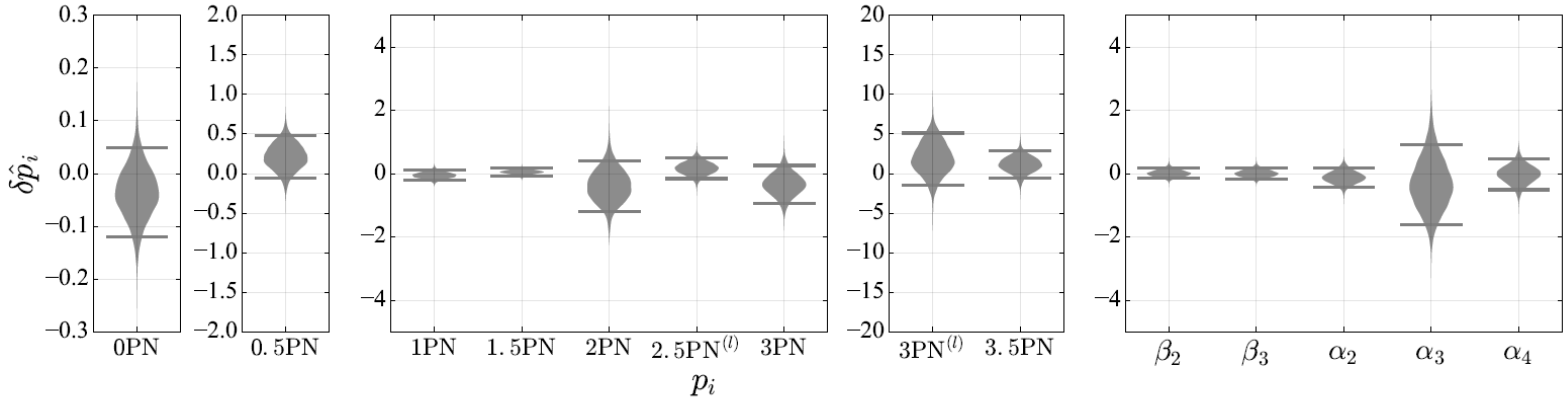
$$M_g \leq 7.7 \times 10^{-23}\ eV/c^2$$

- Null tests to quantify generic deviations from GR




PhysRevLett.118.221101

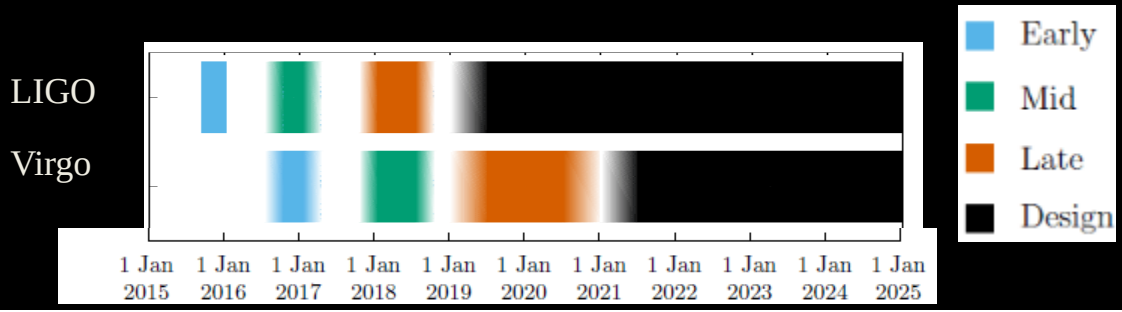
# Testing General Relativity

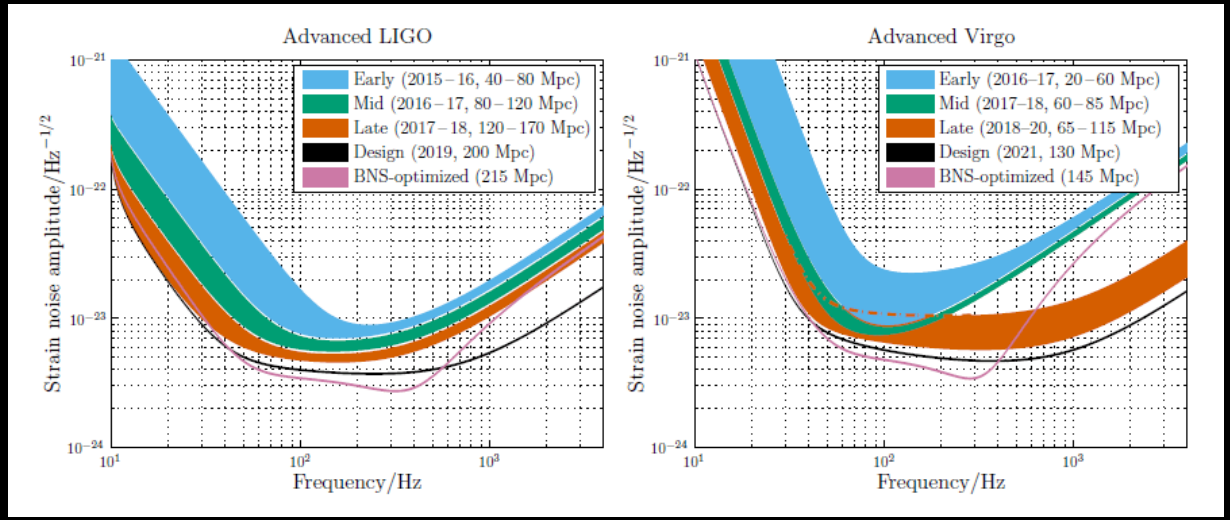



/PhysRevLett.118.221101
Supplemental materials

- Violin Plot: GW150915, GW151226 and GW160104) combined
- Order of post-Newtonian expansion, then β and α parameters
- All are consistent with no deviations from GR

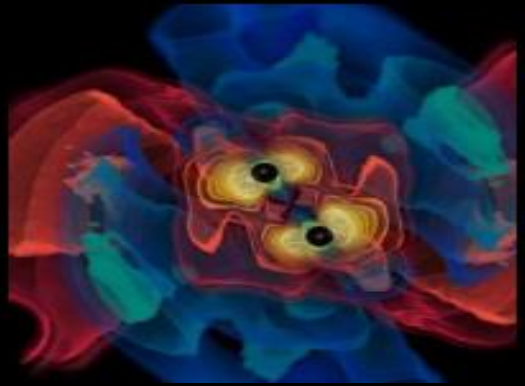
# LIGO-Virgo Observing Plans




Living Rev. Relativity 19 (2016), 1

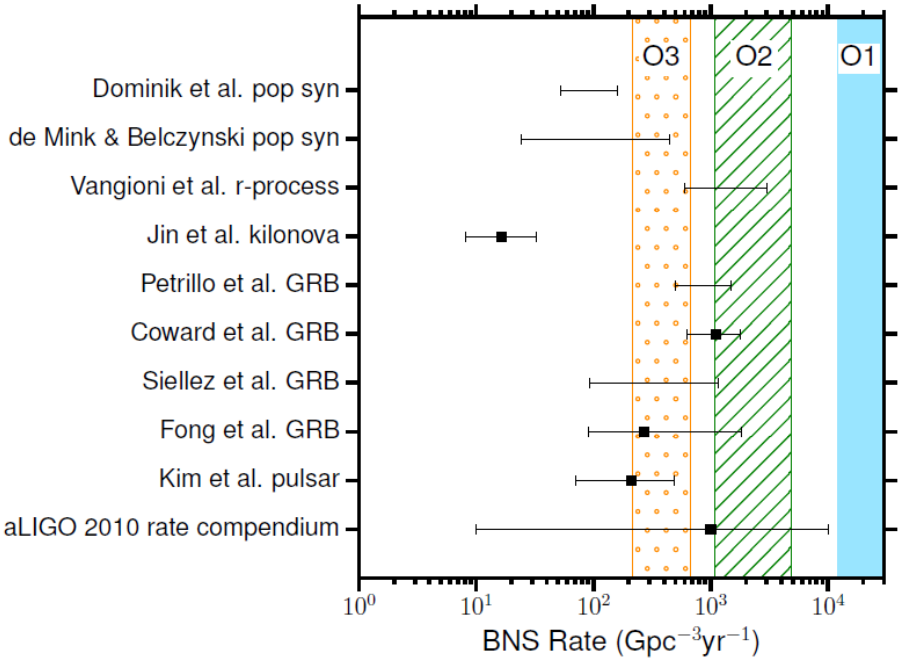
# *Next Steps : Other Gravitational Wave Sources*

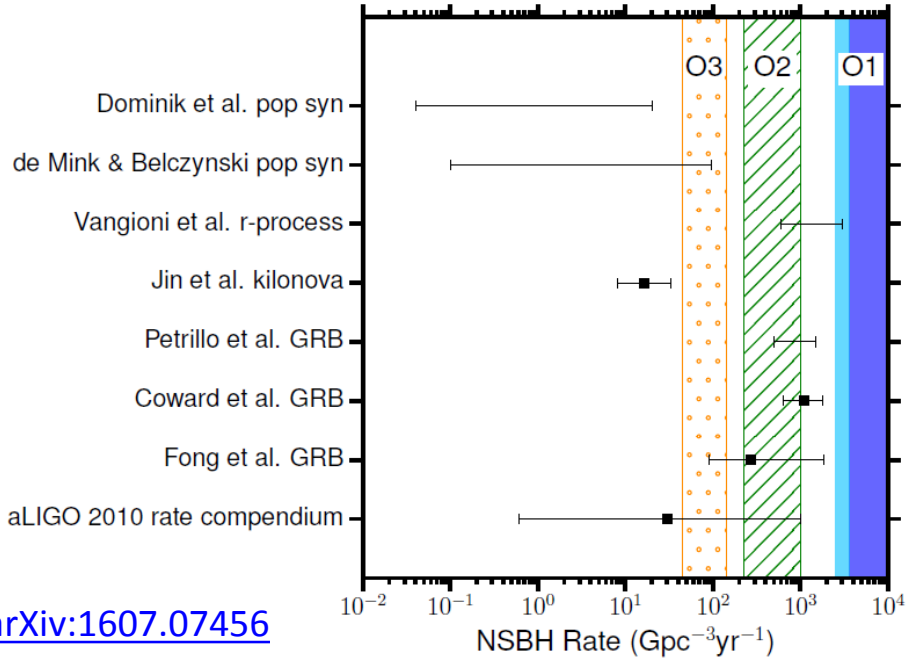


*Coalescing Binary Systems*

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

# Predicted Rates BNS and NSBH merger

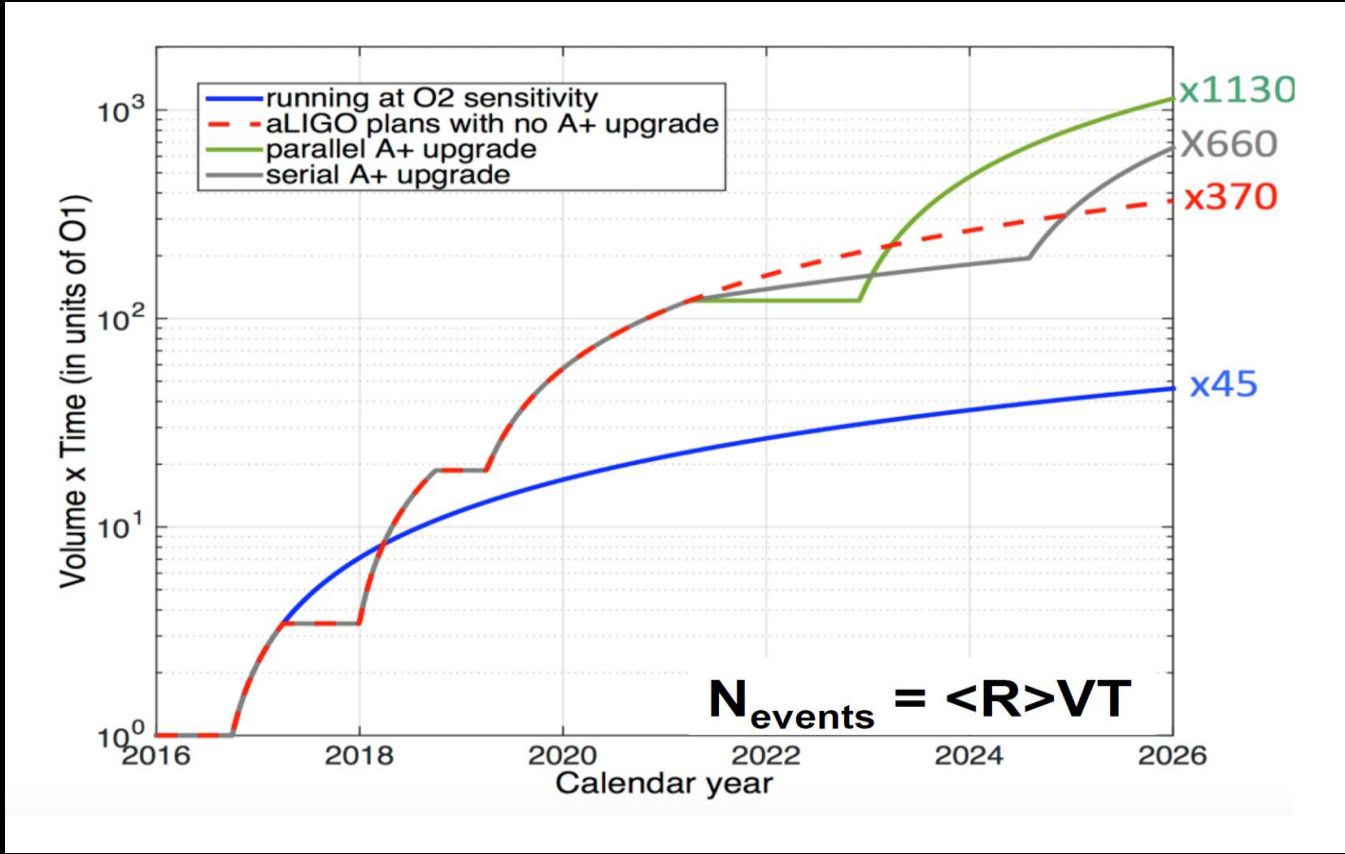


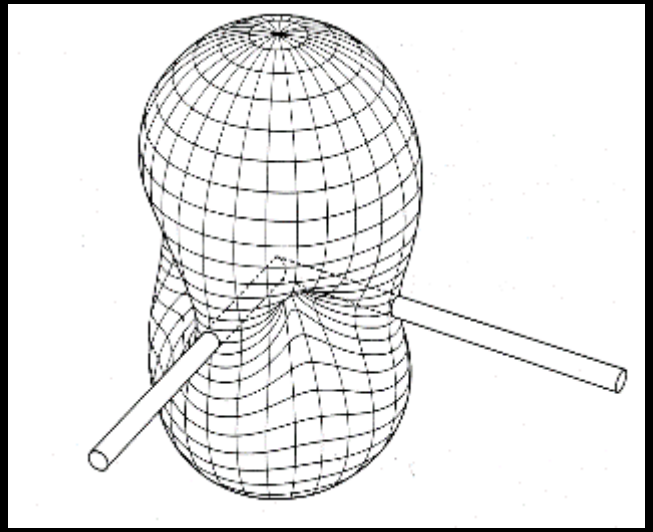

arXiv:1607.07456

- Left – Comparison of BNS merger rates and O1 low spin exclusion region (blue)
- Right – Comparison of NSBH merger rates and O1 exclusion regions for 10-1.4 Solar masses (blues)

# Next Steps: Increase Sensitivity / Rates



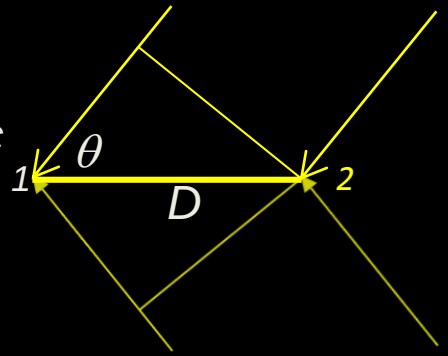
# Source Localization Using Time-of-flight



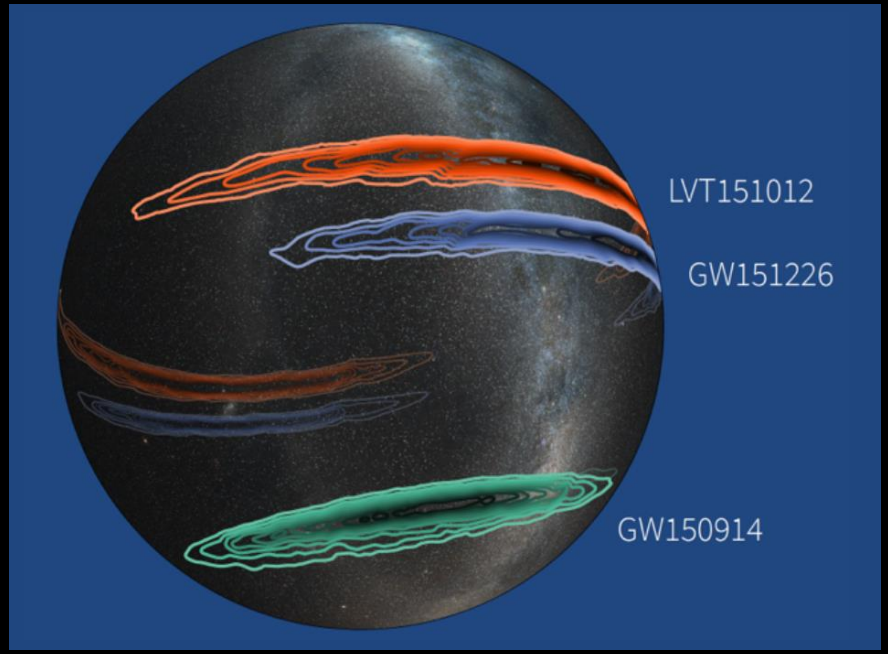
- LIGO detectors are nearly omni-directional
  - Individually they provide almost no directional information
- Array working together can determine source location
  - Analogous to “aperture synthesis” in radio astronomy

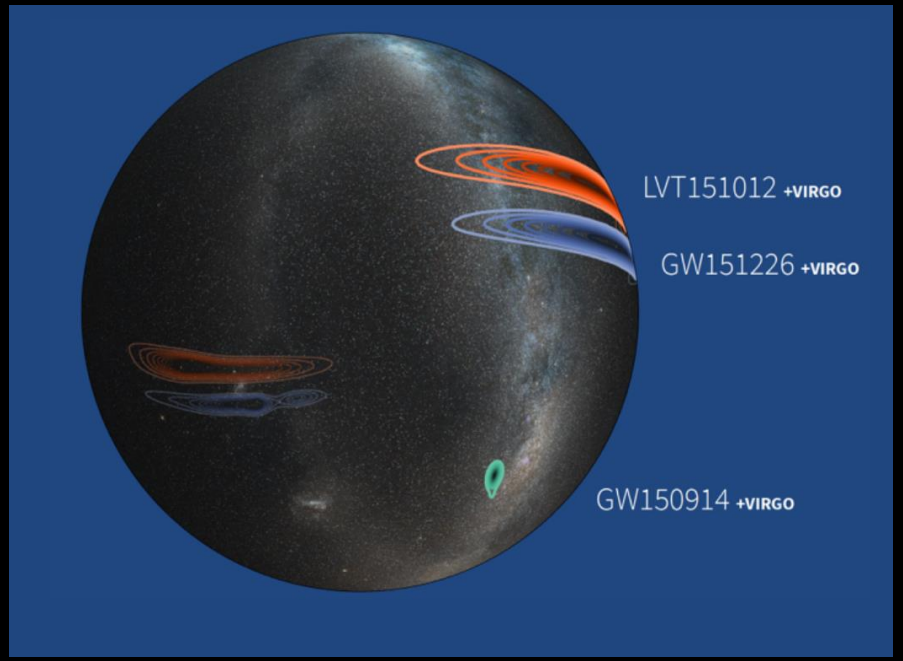
- Accuracy tied to diffraction limit

$$\Delta t = (D \cos \theta)/c$$



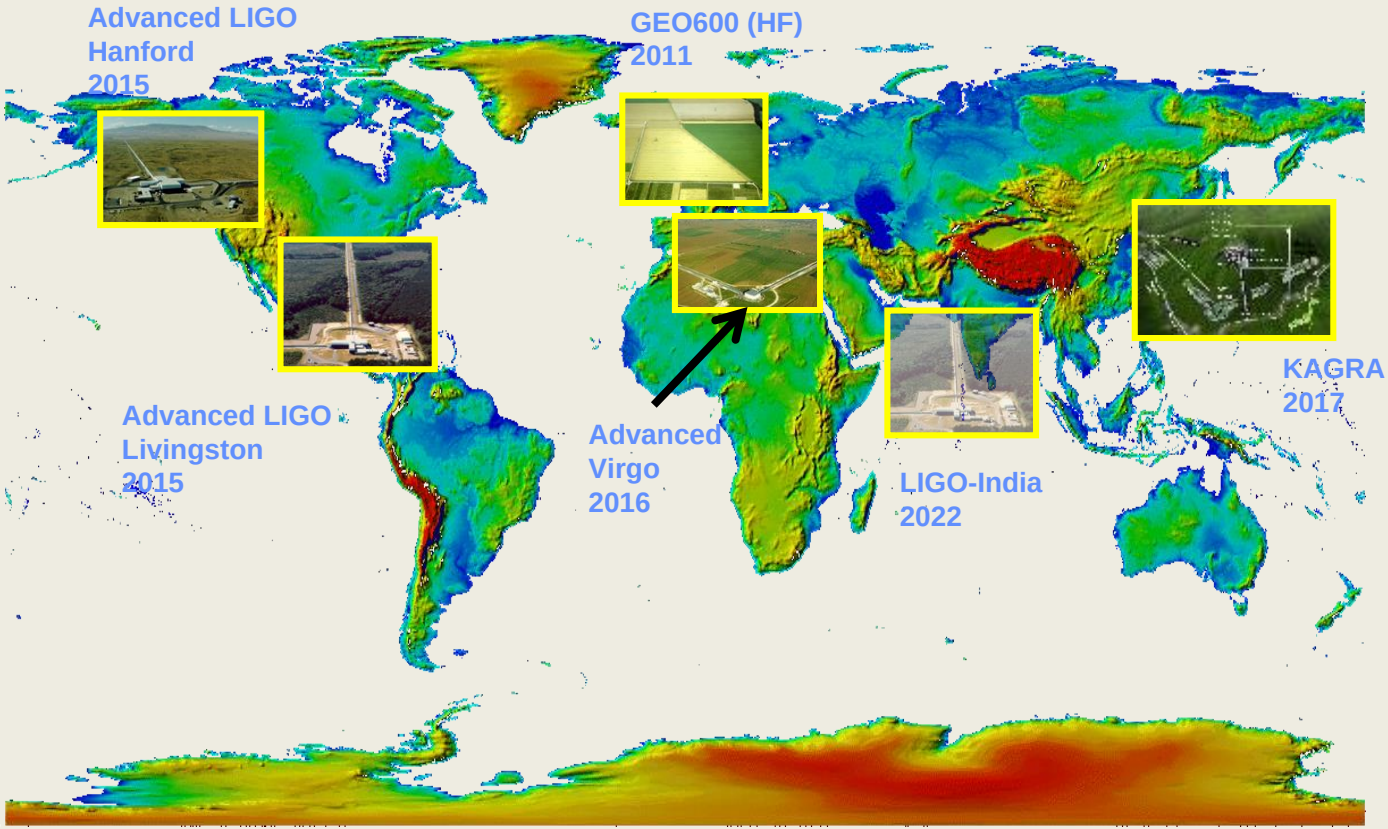
# *Localization LIGO O1 Events Simulated with Virgo*




for GW150914: Astrophys. J. Lett. 826, L13 (2016)

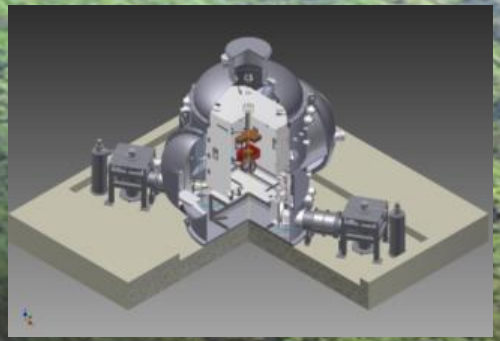
# GW detector network: 2015-2025



# KAGRA

*Kamioka Mine*

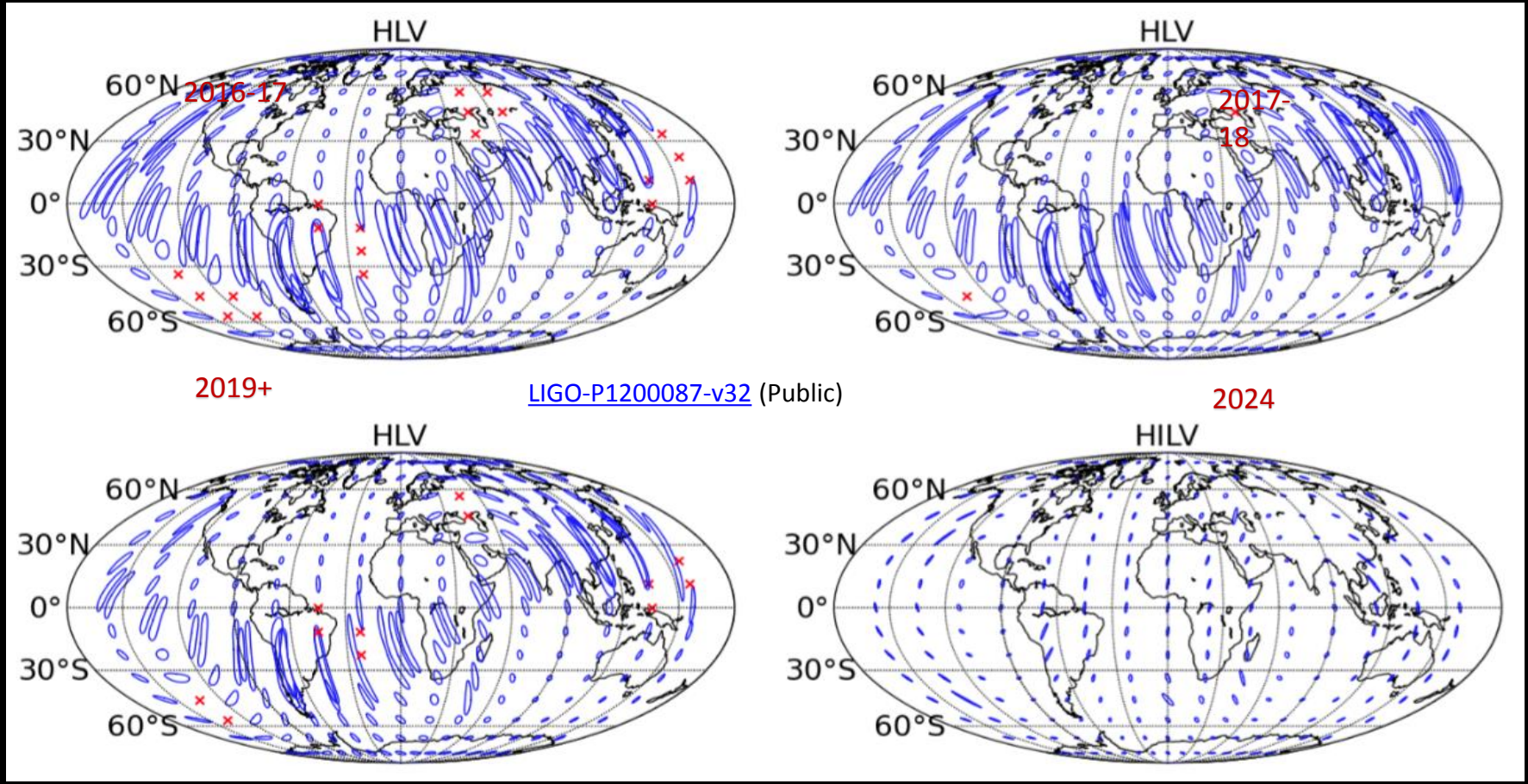
## Cryogenic Mirror



## Underground

**Technologies crucial for next-generation detectors;**
**KAGRA can be regarded as a 2.5-generation detector.**

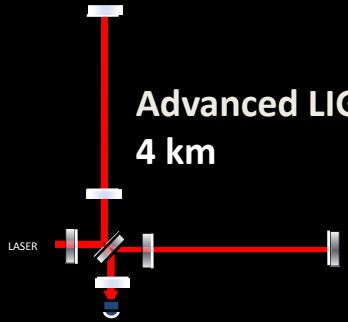
# Improving Localization



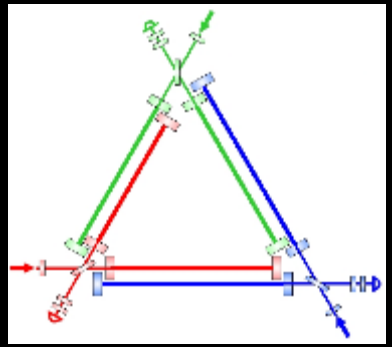
# ASPERA: Proposed 3rd Generation Detector

The Einstein Telescope: x10 aLIGO

- Deep Underground;
- 10 km arms
- Triangle (polarization)
- Cryogenic
- Low frequency configuration
- high frequency configuration




**Einstein Telescope 10 km**



# *The Future for Gravitational Wave Astronomy*

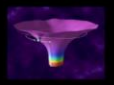
# The Gravitational Wave Spectrum

Sources

Big Bang

Supermassive Black Hole Binary Merger

Compact Binary Inspiral & Merger



Extreme Mass-Ratio Inspirals

Pulsars, Supernovae

age of the universe

Wave Period

years

hours

seconds

milliseconds

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

Wave Frequency

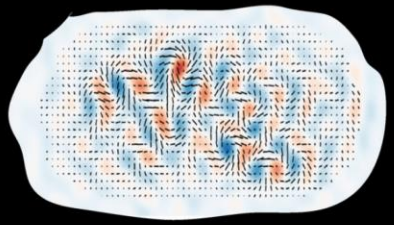
CMB Polarization

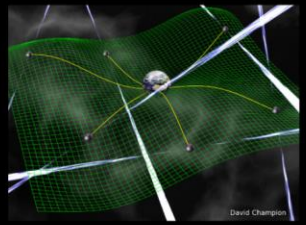
Radio Pulsar Timing Arrays

Space-based interferometers

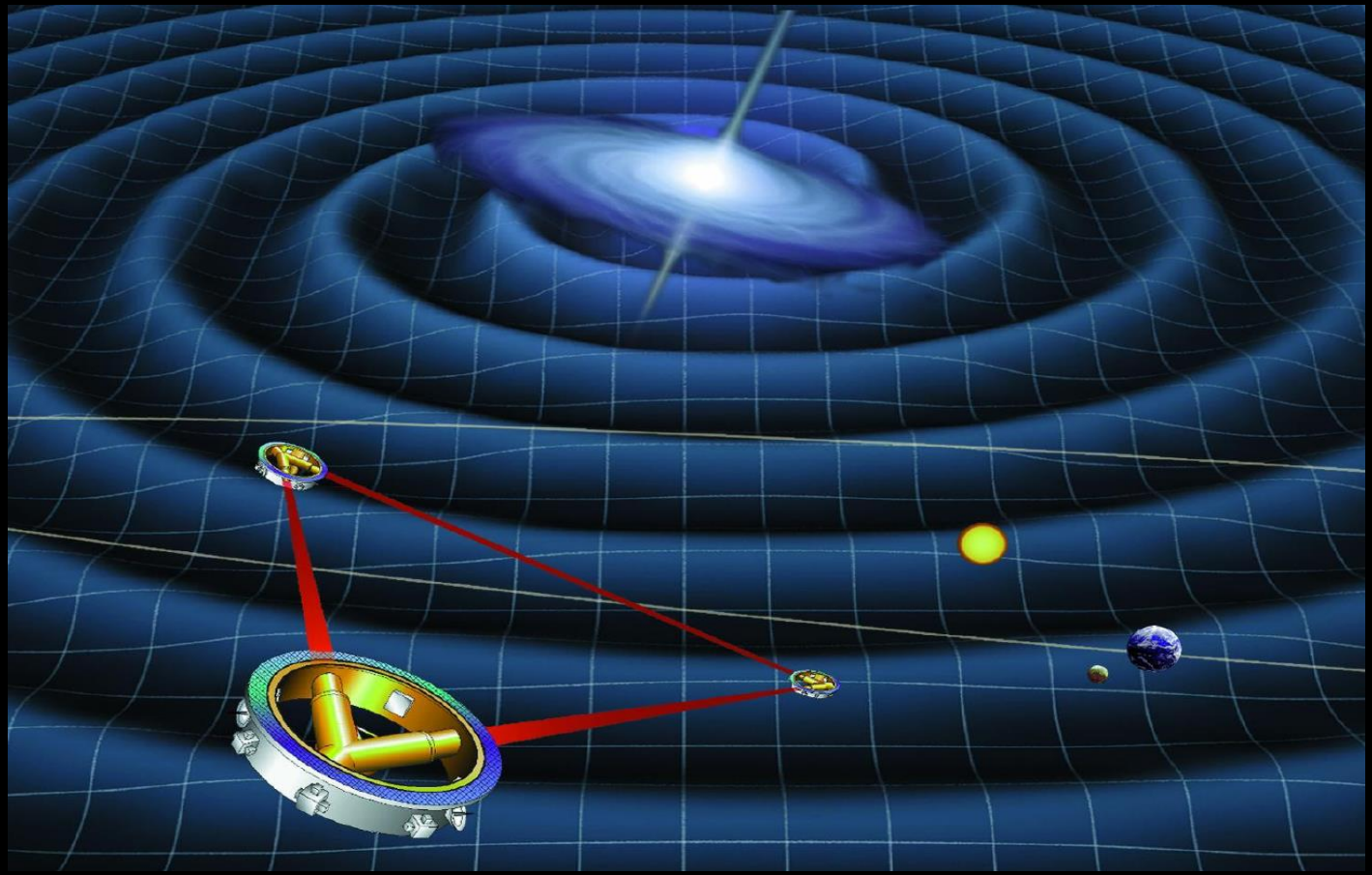
Terrestrial interferometers

Detectors





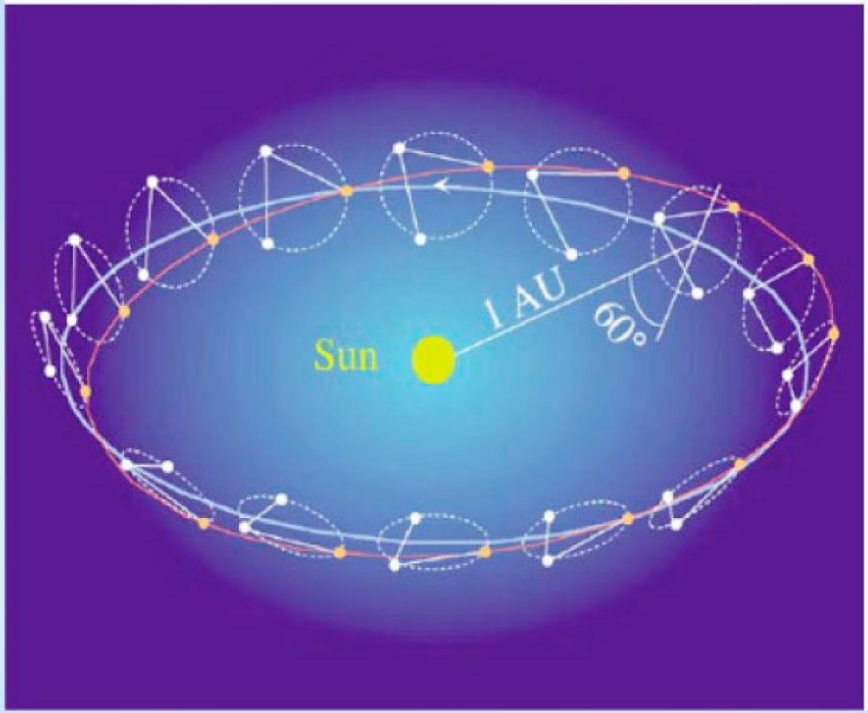
# *LISA: Laser Interferometer Space Array*

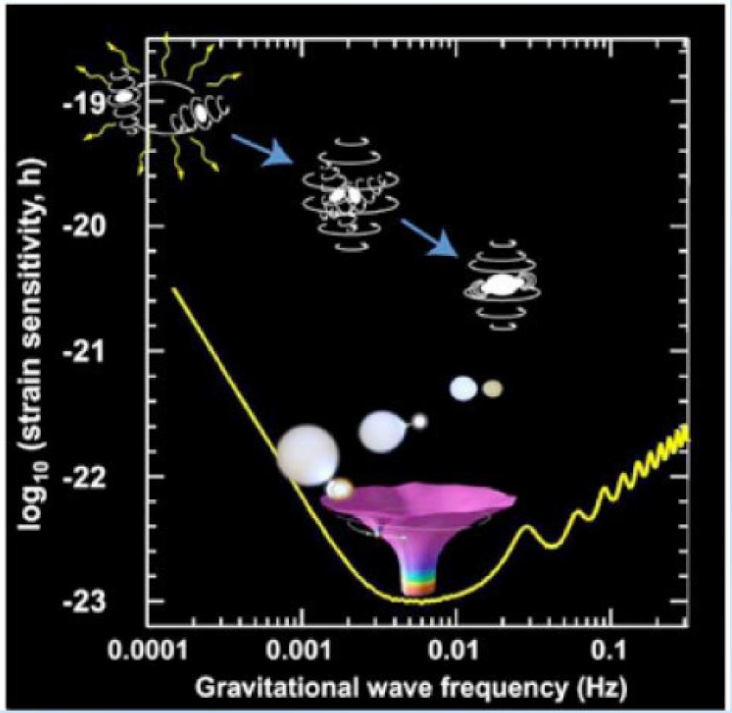


Three Interferometers

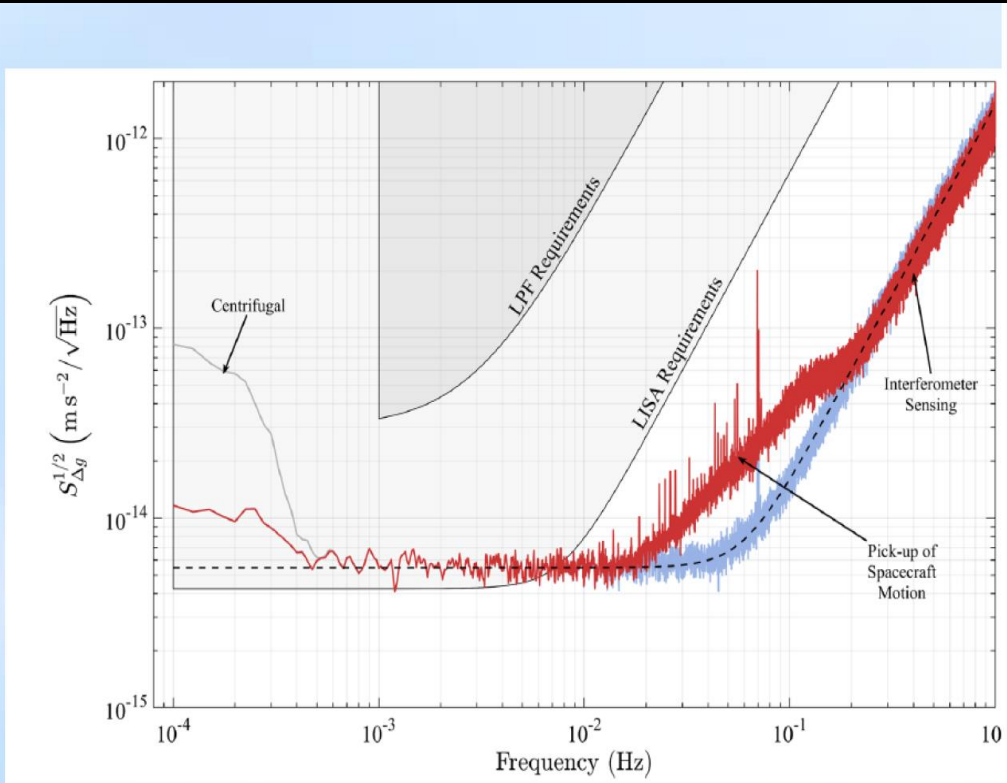
2.5 $10^6$ km arms

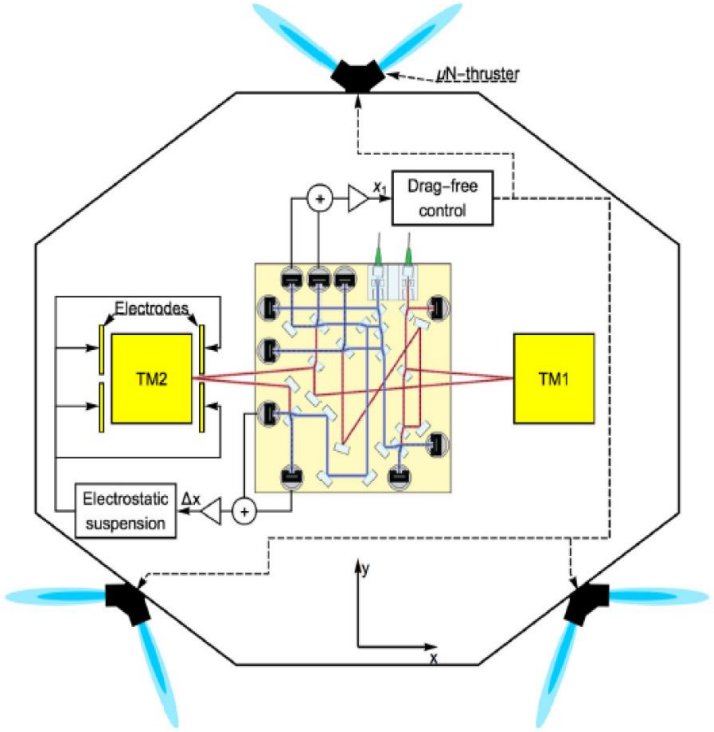
# LISA Orbit and Sensitivity



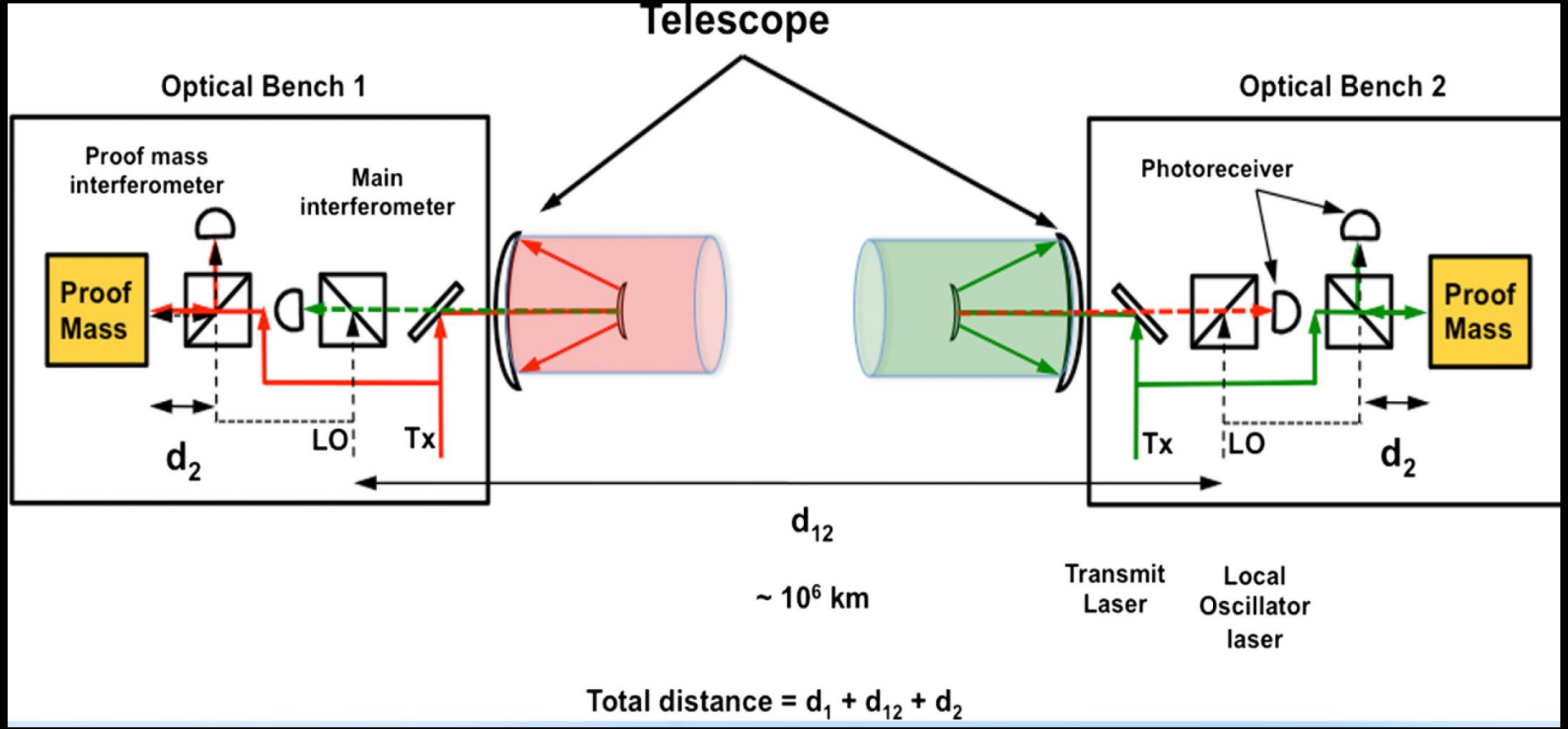



# LISA Pathfinder – Technology Demonstration

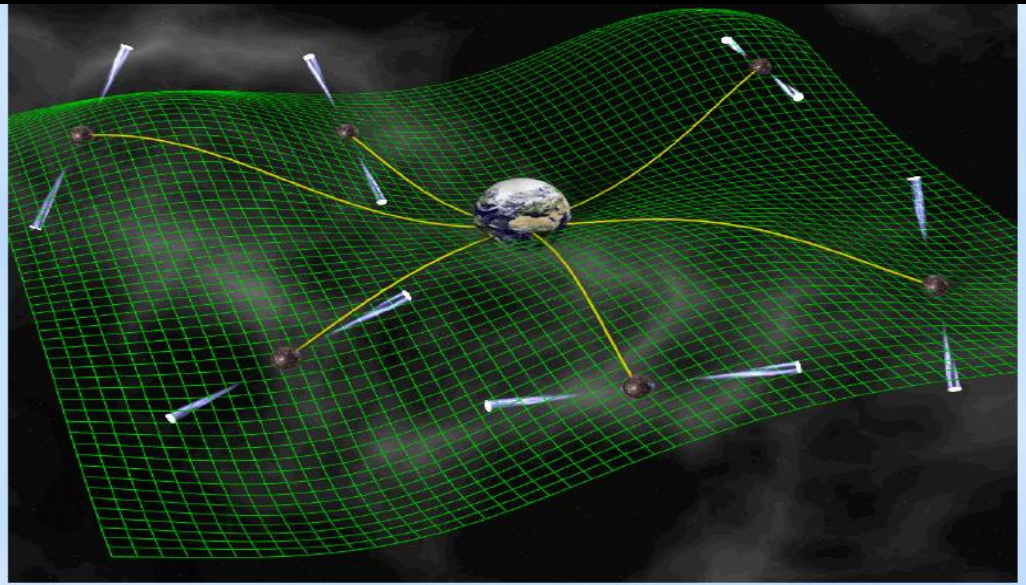


# LISA Proof Masses, Optical Bench, Interferometry and Telescope



# Pulsar Timing Arrays

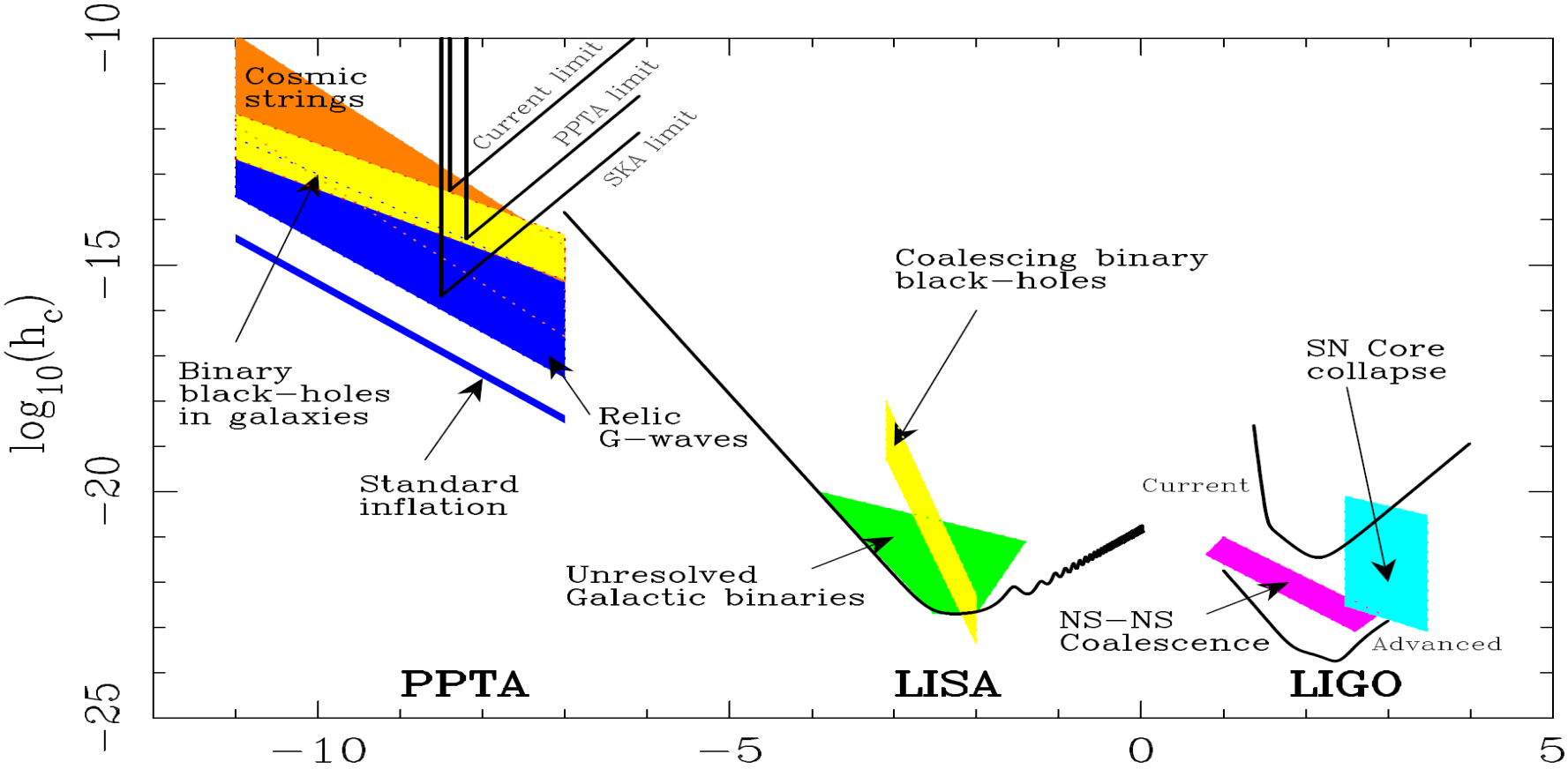


Distant pulsars send regular radio pulses – highly accurate clocks.
A passing gravitational wave would change the arrival time of the pulse.

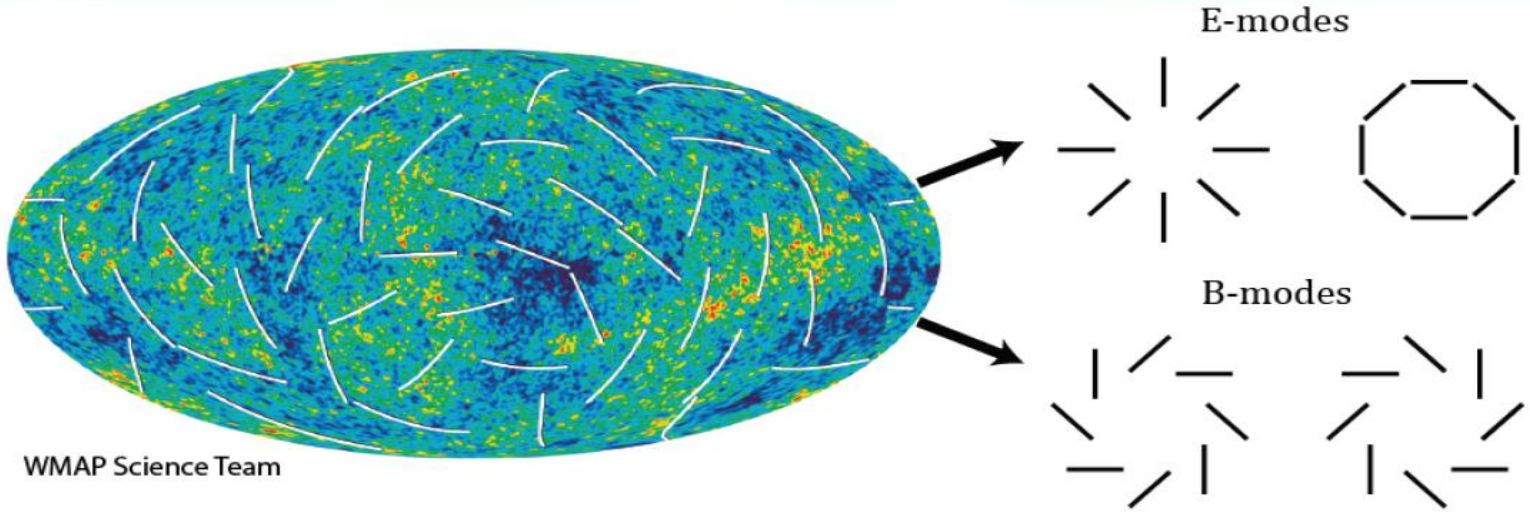
Numerous collaborations around the world. Interesting upper limits and likely detections in the near future.

arXiv:1211.4590

# Gravitational Wave Frequency Coverage



# Polarization Maps for CMB Experiments




The CMB anisotropy polarization map may be decomposed into curl-free even-parity E-modes and divergence-free odd-parity B-modes.

Gravitational waves in the early universe imparts a “curl” on CMB polarization. 67
arXiv:1407.2584

***Thanks!***