From Einstein to Gravitational Waves and Beyond

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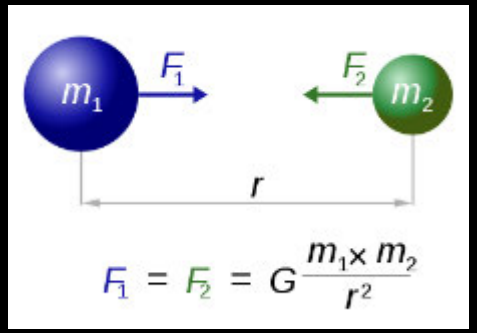
TOHOKU FORUM for CREATIVITY

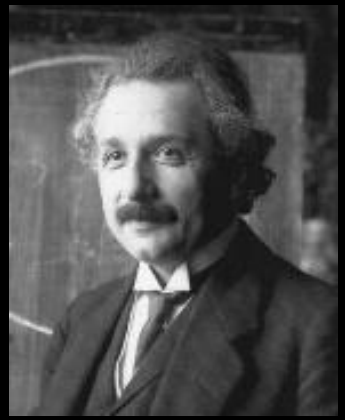
A Little History

General Relativity and Gravitational Waves

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.



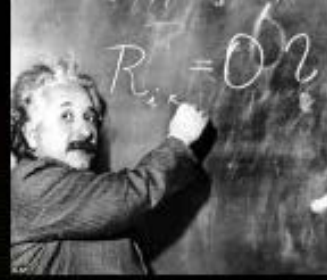
Einstein's Theory of Gravity (1915)

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

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

spacetime

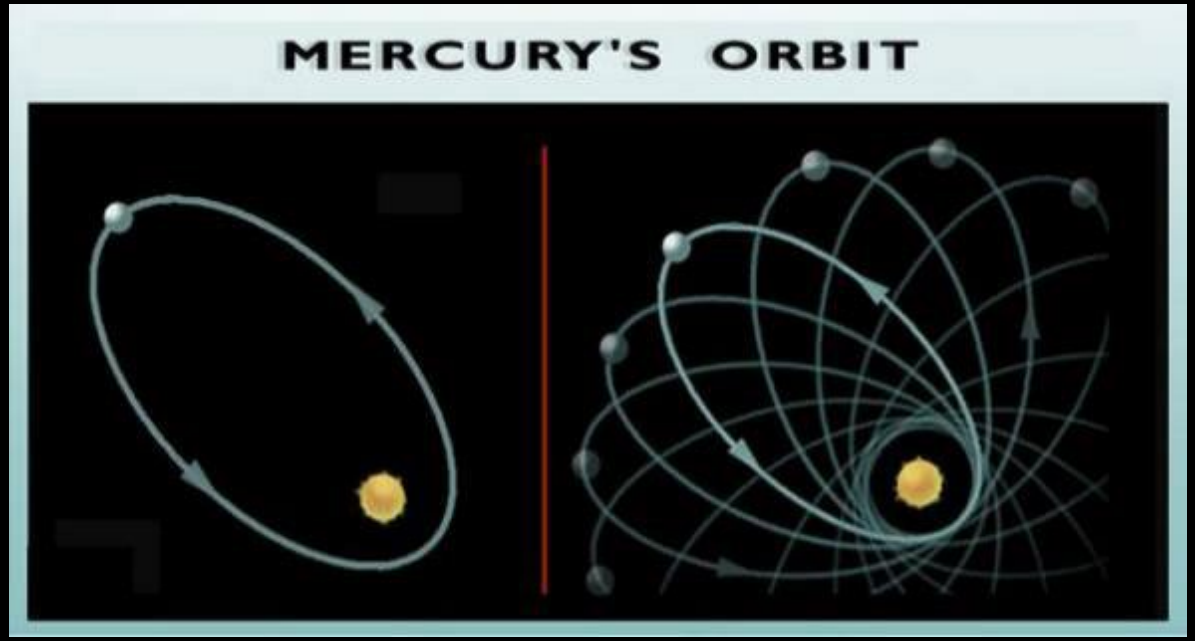
1915: Einstein formulates the Theory of General Relativity



Gravity isn't a force that acts <u>in</u> space and time, but instead is <u>built into the actual structure</u> of space and time.

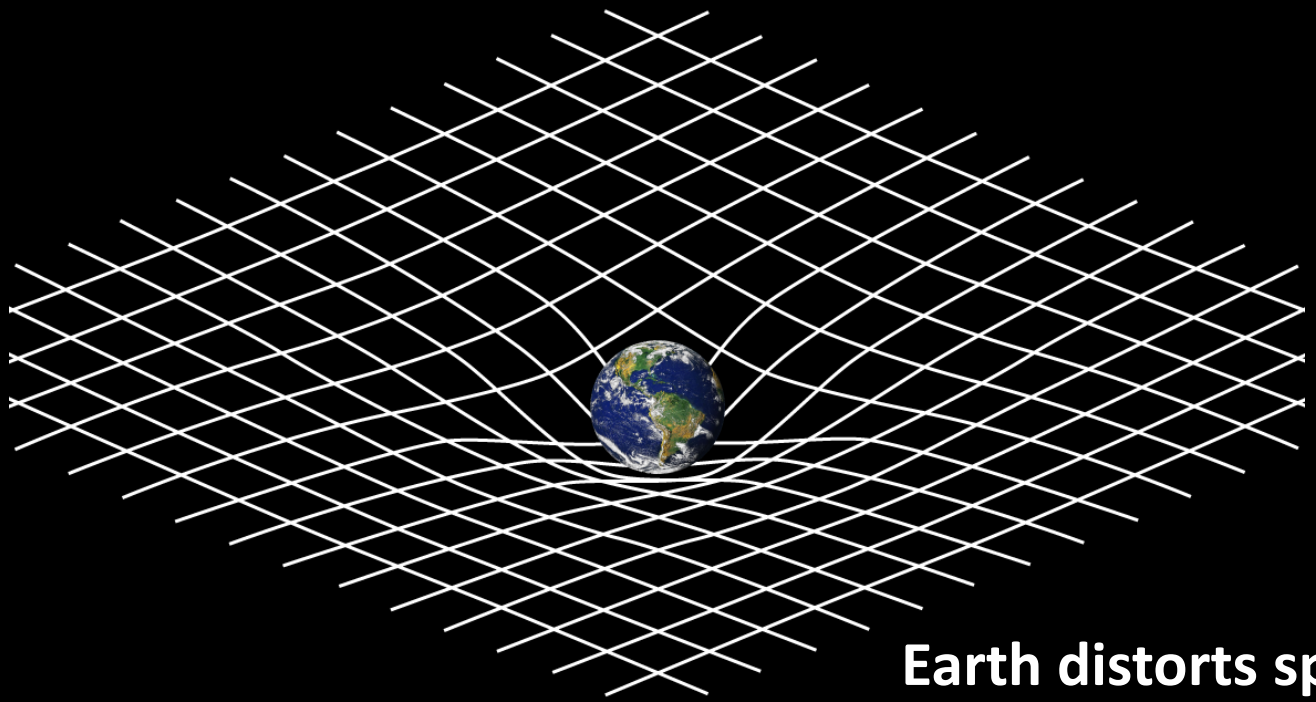
"Space-time tells mass how to move, and Mass tells space-time how to curve."

The Only Observed Problem with Newton's Gravity fixed in Einstein's Theory



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).

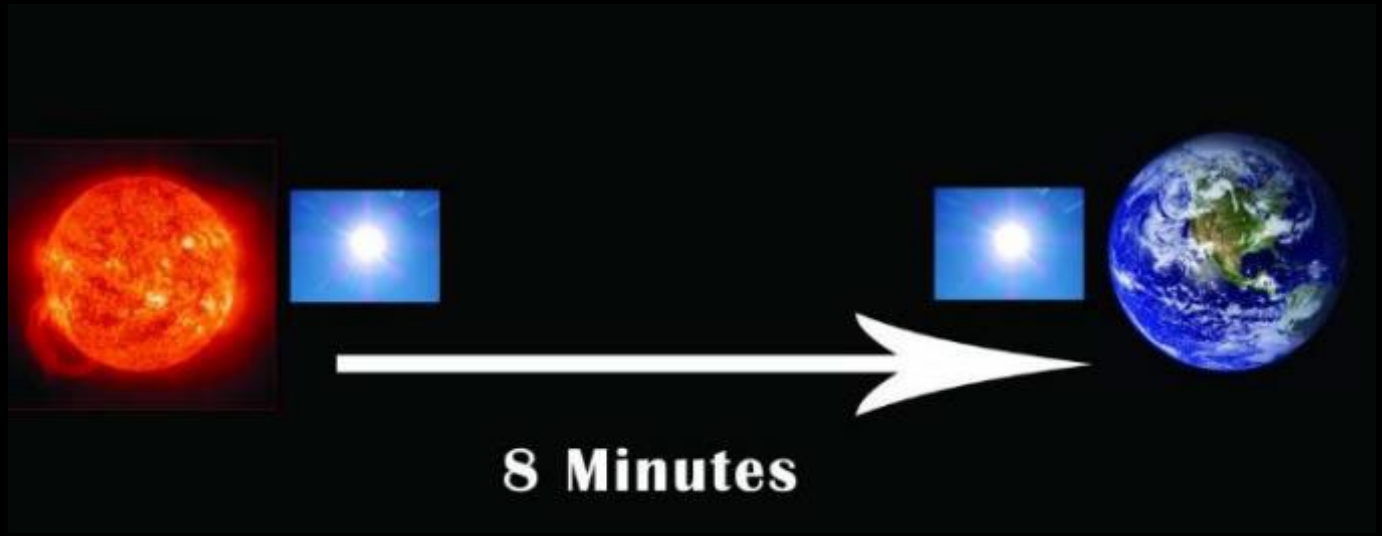
Einstein Explains WHY the apple falls!



Earth distorts spacetime

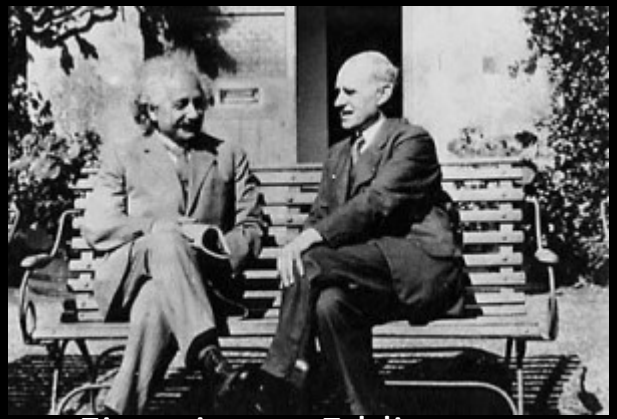
Einstein Solves a Conceptual Problem with Newton's Theory of Gravity

In Newton's Theory: "Instantaneous Action at a Distance"

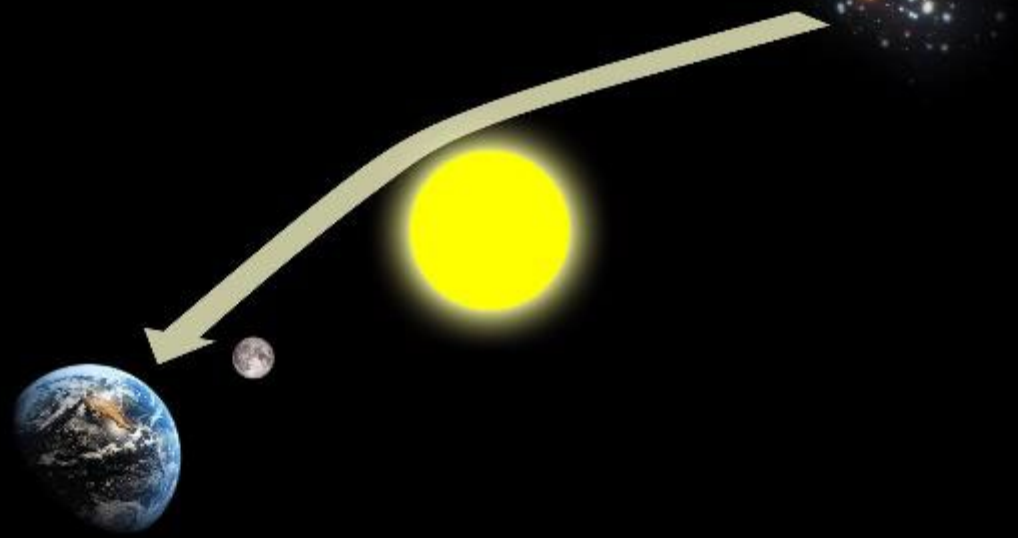


It takes finite time for information to travel from the sun to the earth

Einstein Theory Makes a ‘New’ Prediction



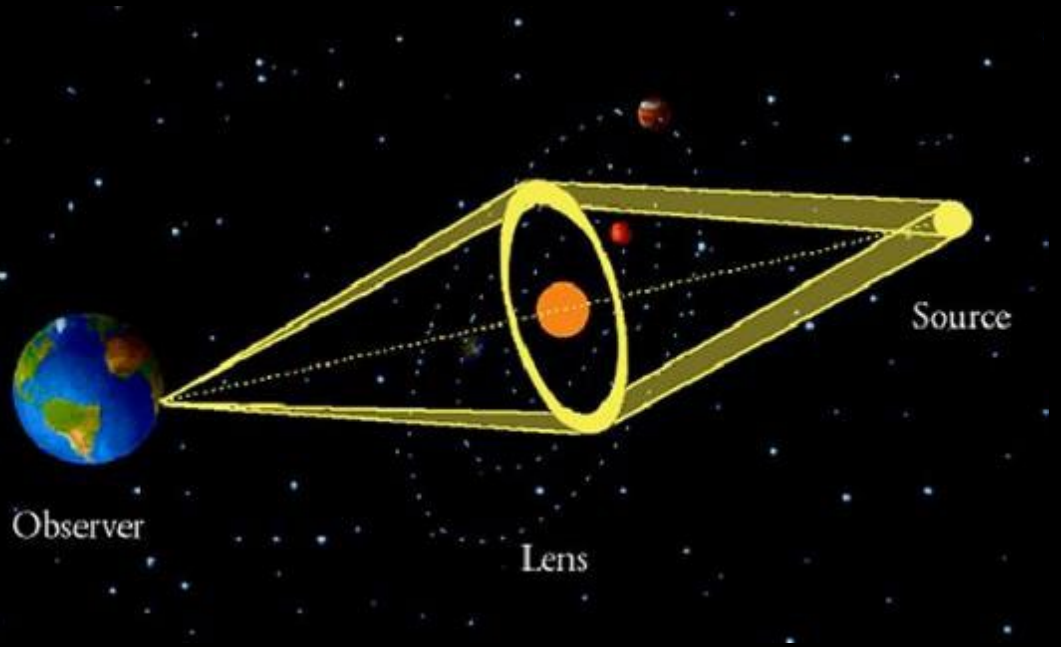
Einstein Eddington

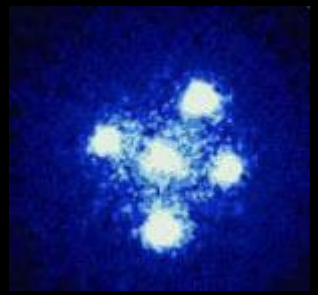


"Not only is the universe stranger than we imagine, it is stranger than we can imagine.

Sir Arthur Eddington

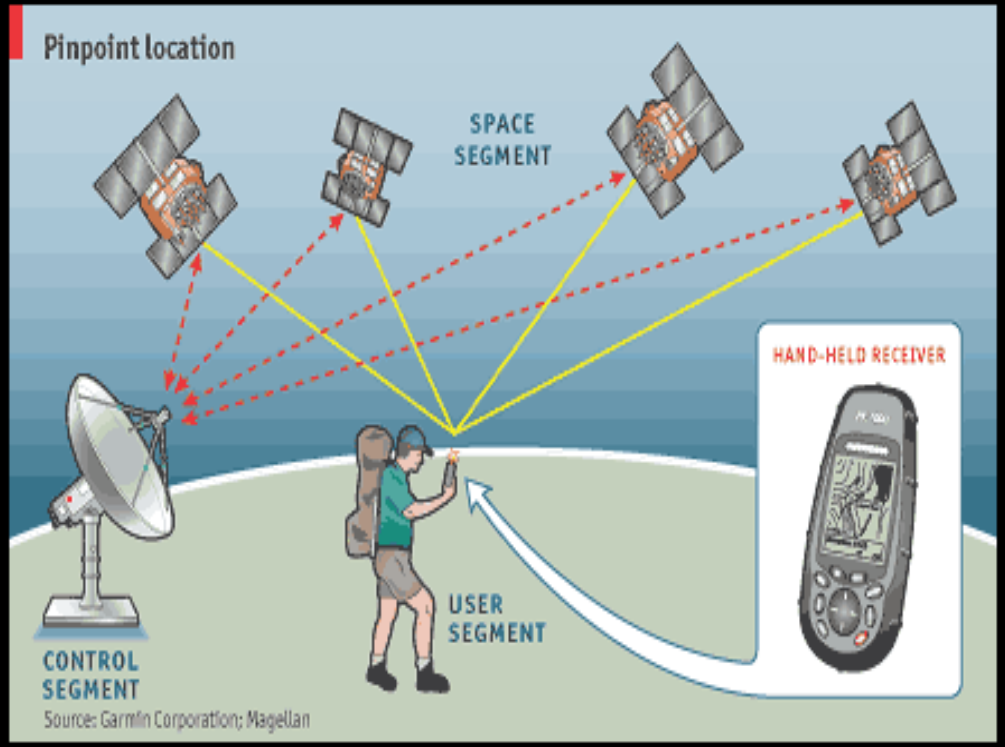
In Modern Astronomy: Gravitational Lensing





Einstein Cross

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

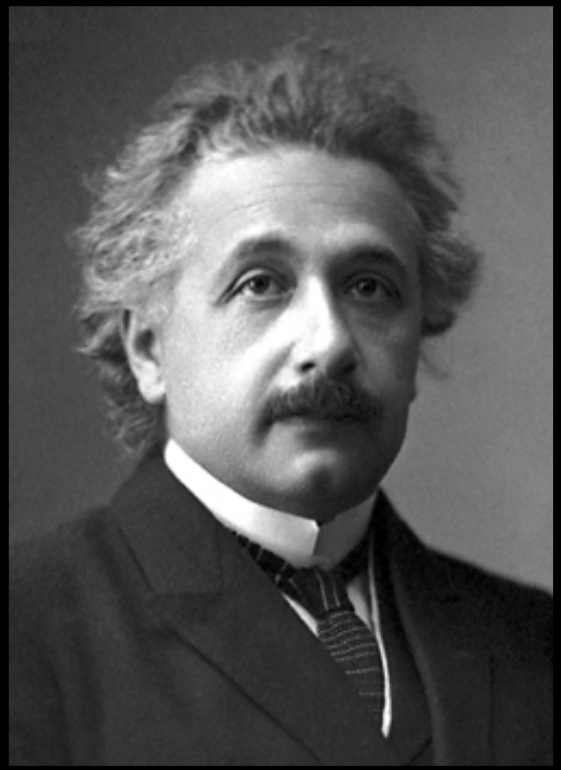
Gravity: Satellites = 1/4 x Earth

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

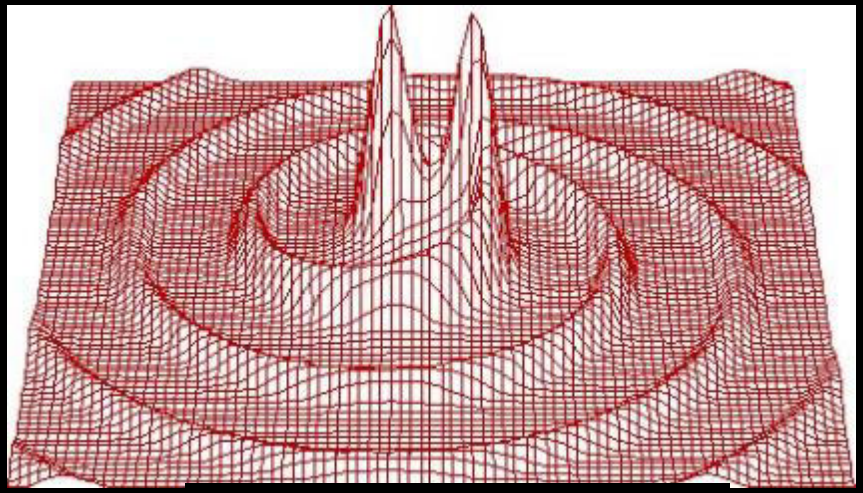
$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \qquad (1)$$

- 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 Contains Gravitational Waves

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

The Chapel Hill Conference

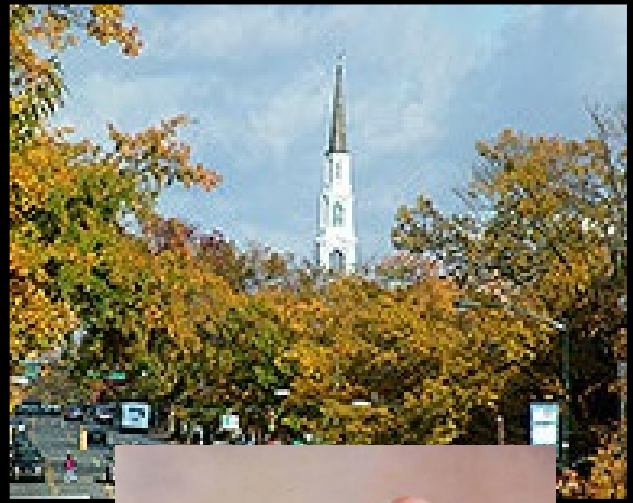
Could the waves be a coordinate effect only, with no physical reality? Einstein didn't live long enough to learn the answer.

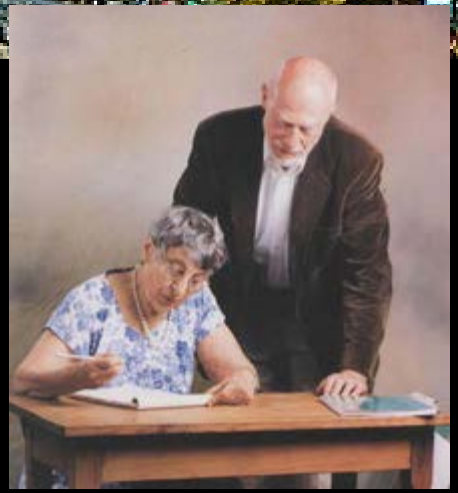
In January 1957, the U.S. Air Force sponsored the *Conference on the Role of Gravitation in Physics*, a.k.a. the Chapel Hill Conference, a.k.a. GR1.

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.

(Pirani, Feynman and Babson)

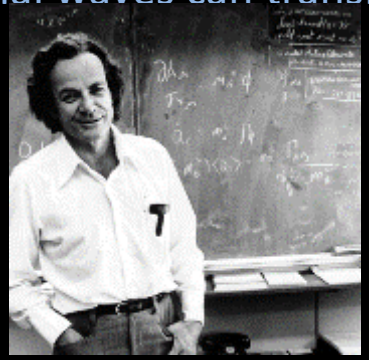


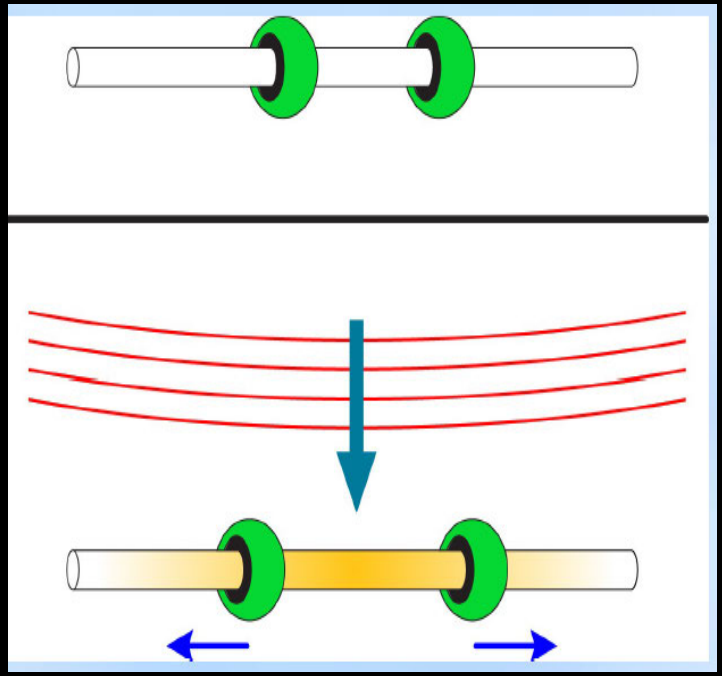


Agreement: Gravitational Waves are Real

- 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.

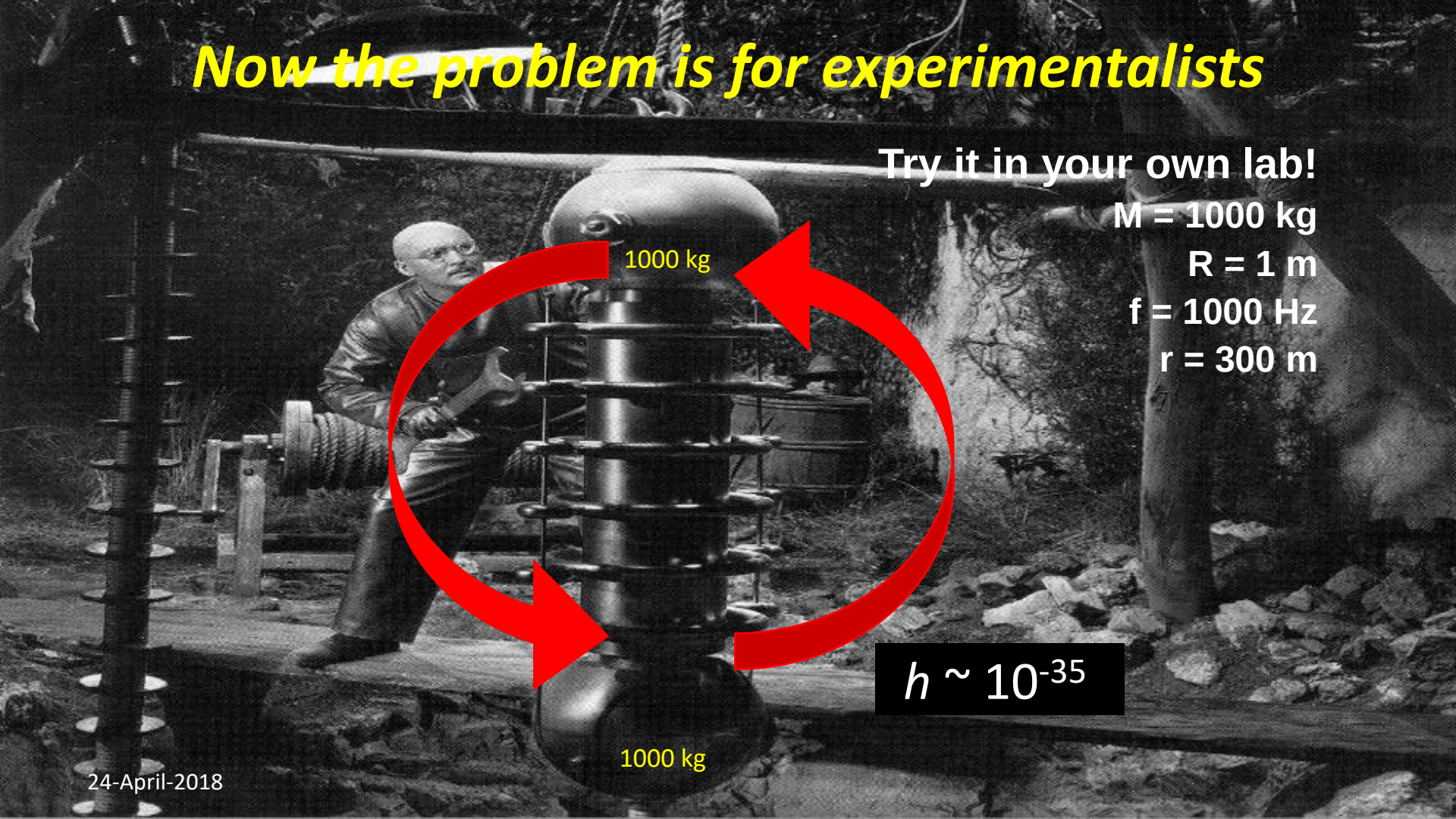
- Sticky bead argument (Feynman)
  - Gravitational waves can transfer energy?





How to Detect Gravitational Waves

Now the problem is for experimentalists



Try it in your own lab!

M = 1000 kg

R = 1 m

f = 1000 Hz

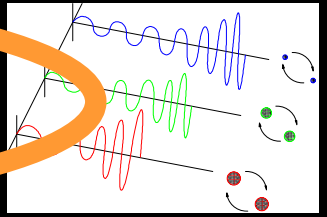
r = 300 m

$h \sim 10^{-35}$

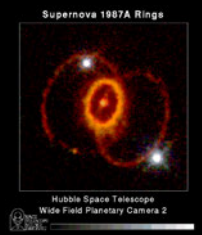
Astrophysical Sources

signatures

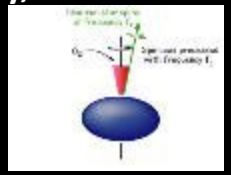
- Compact binary inspiral: *"chirps"*
  - NS-NS waveforms are well described
  - BH-BH need better waveforms
  - search technique: matched templates



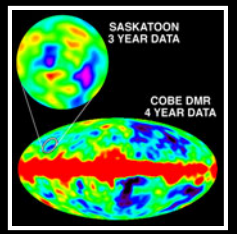
- Supernovae / GRBs: *"bursts"*
  - burst signals in coincidence with signals in electromagnetic radiation
  - prompt alarm (~ one hour) with neutrino detectors



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

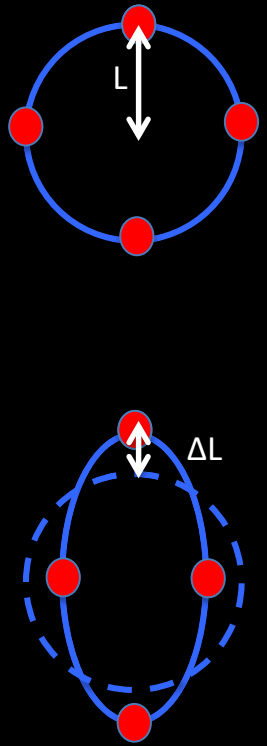


- Cosmological Signal *"stochastic background"*



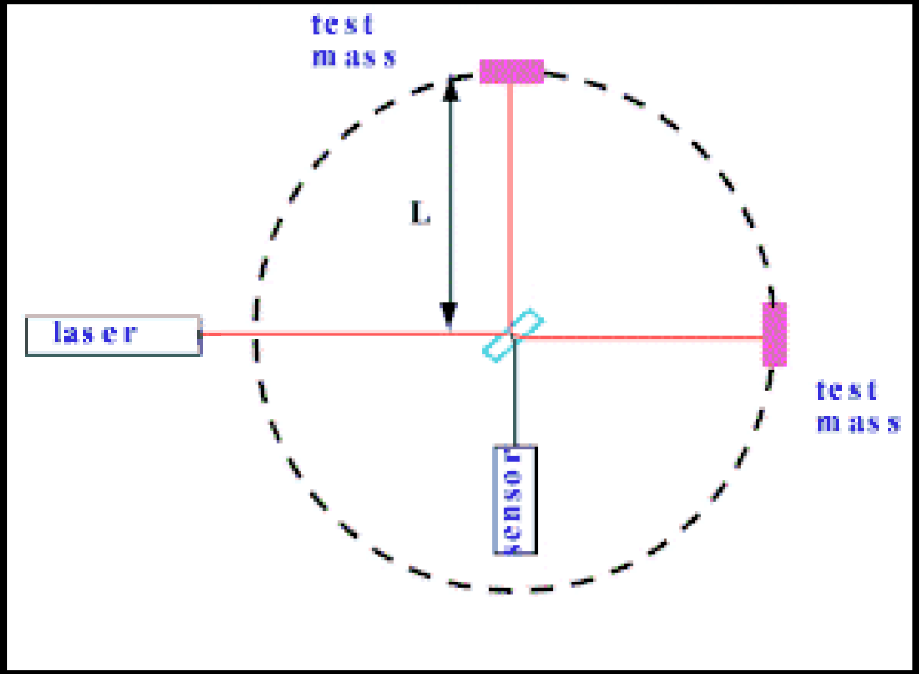
Gravitational Waves

- 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



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

Suspended Mass Interferometry



$$h = \frac{\Delta L}{L} \leq 10^{-21}$$

$$L = 4\text{km} \quad \Delta L \leq 4 \times 10^{-18} \text{ meters}$$

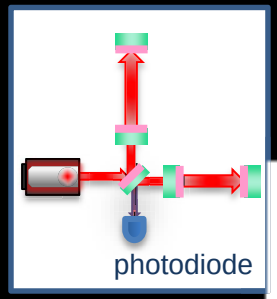
$\Delta L \sim 10^{-12}$ wavelength of light

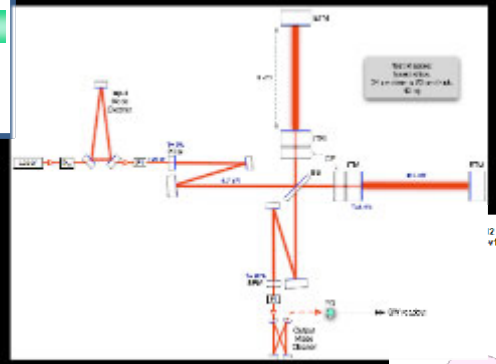
$\Delta L \sim 10^{-12}$ vibrations at earth's surface

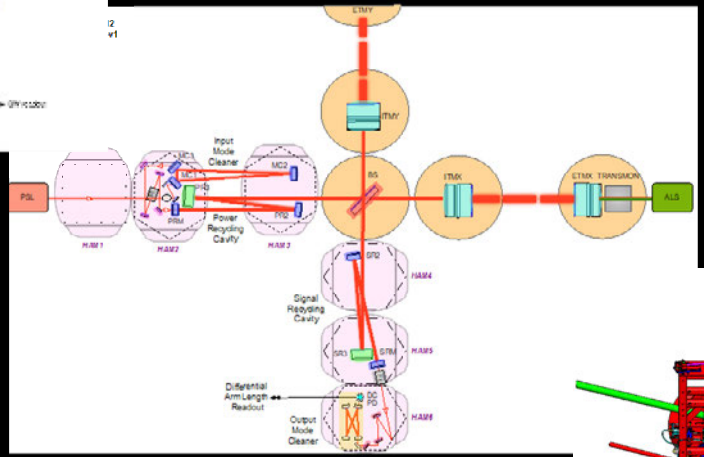
Credit: LIGO/T. Pyle

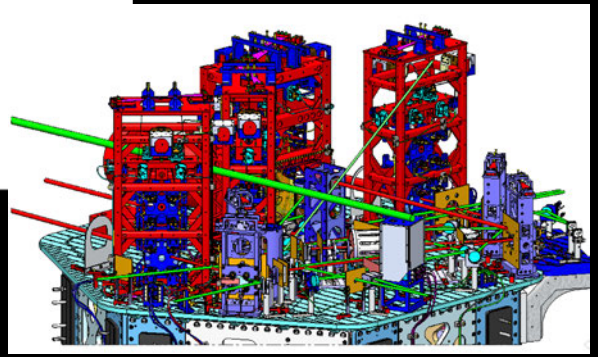
Interferometry – The scheme

LIGO: Interferometry





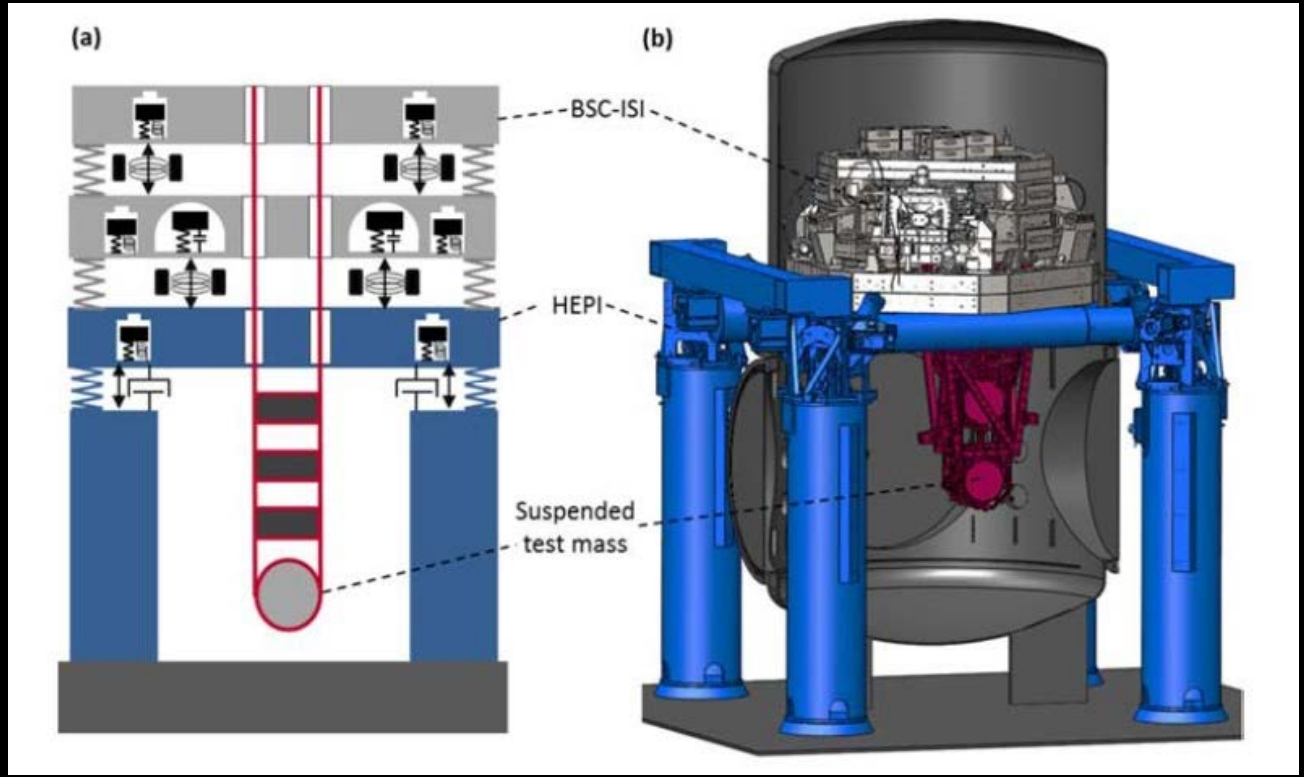




Many innovations to make the instrument so sensitive

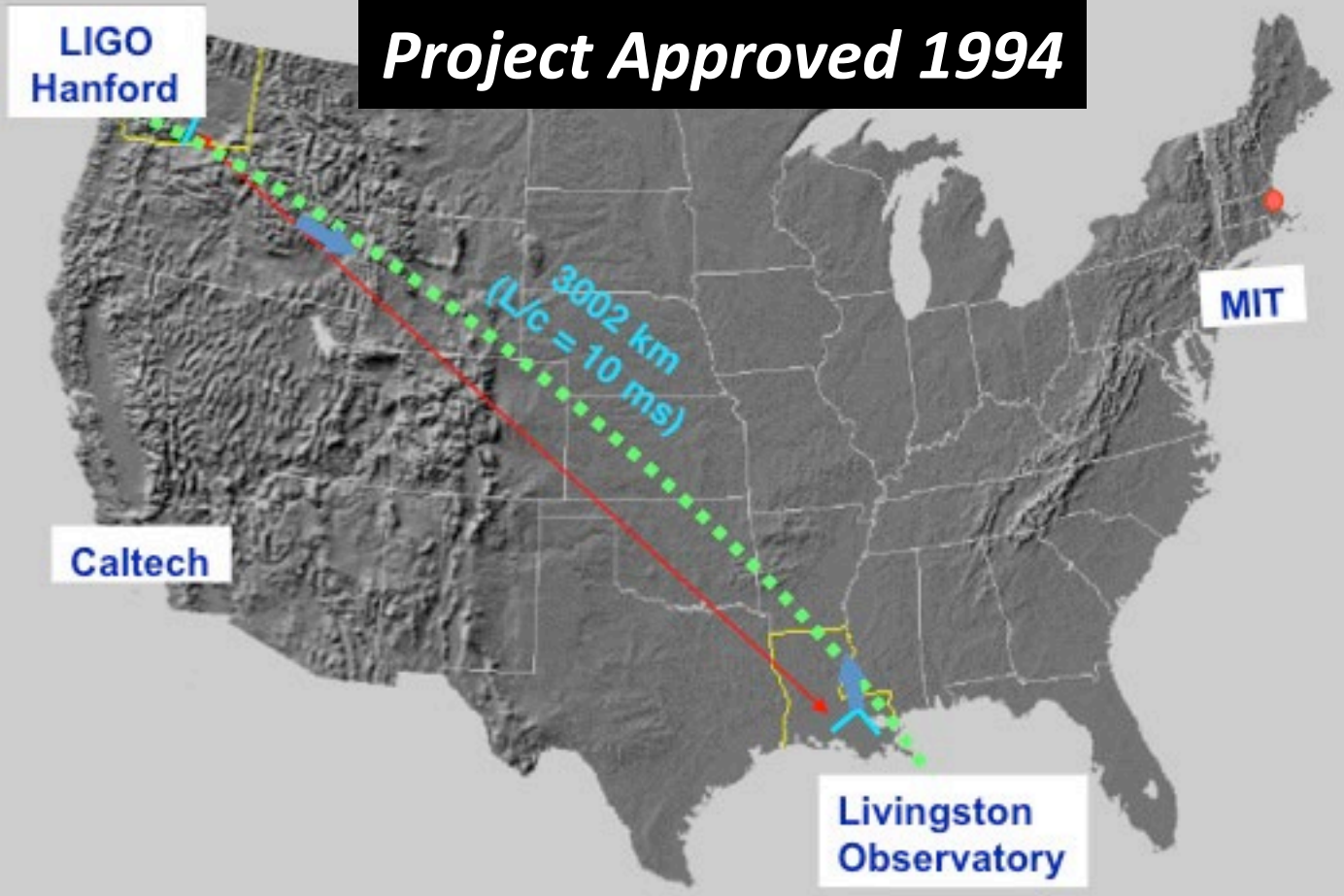
Passive / Active Multi-Stage Isolation

Advanced LIGO



LIGO Sites

Project Approved 1994



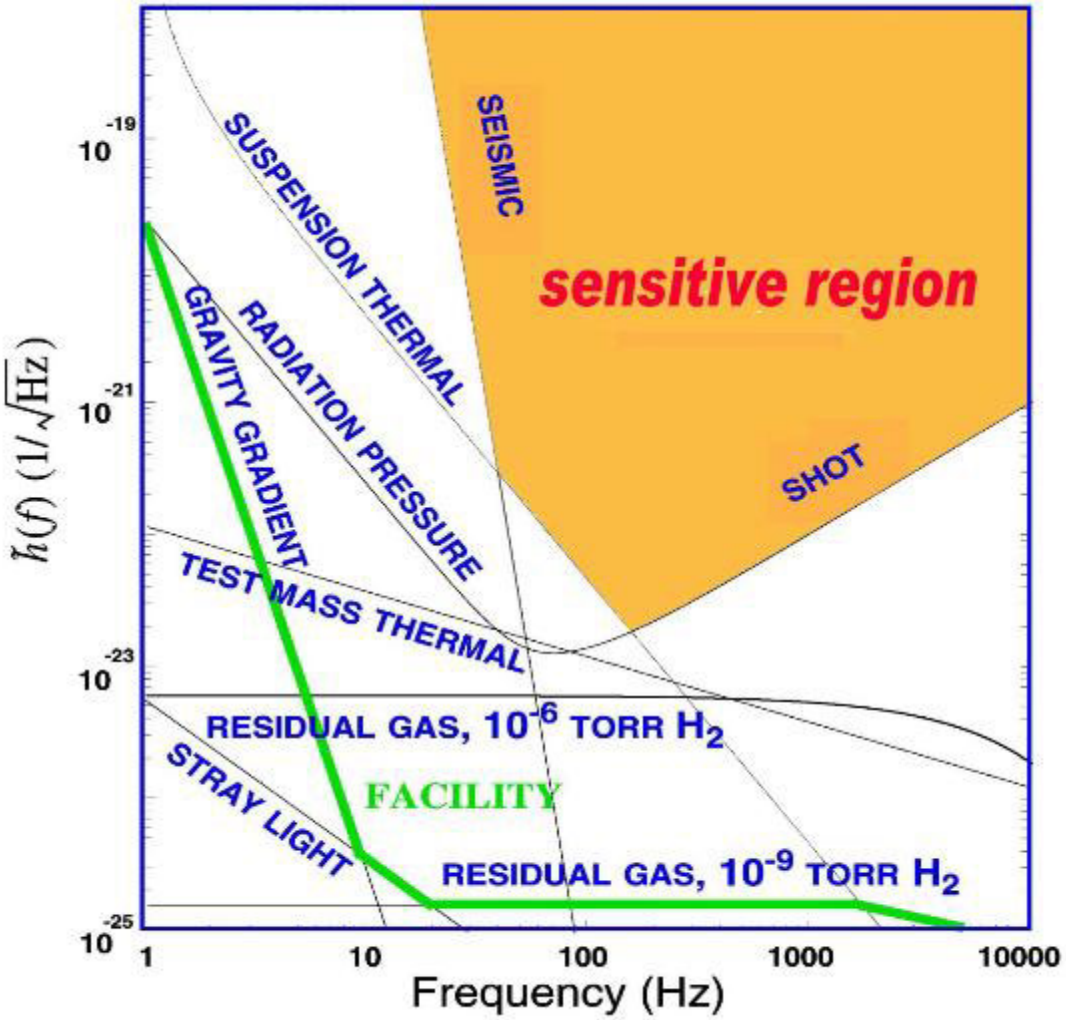
LIGO Interferometers

Hanford, WA

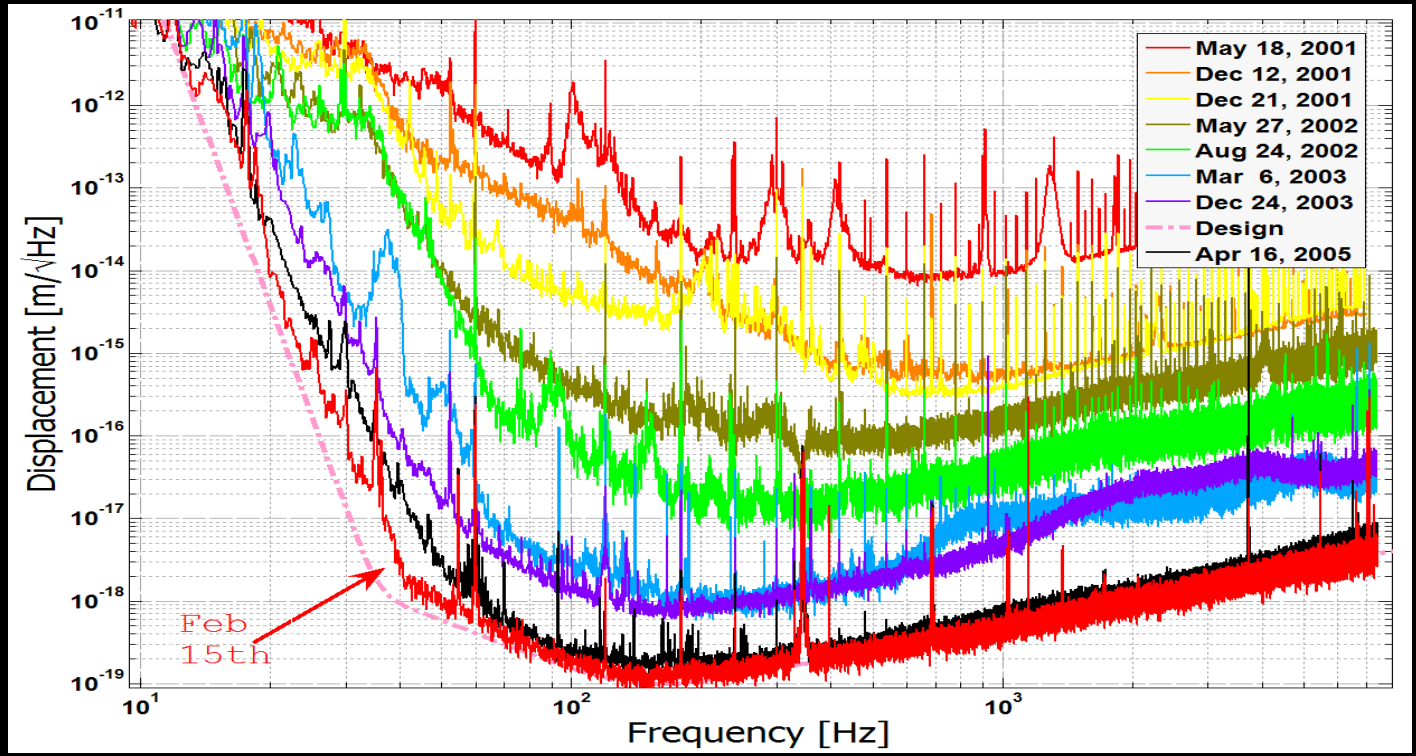
Livingston, LA

What Limits LIGO Sensitivity?

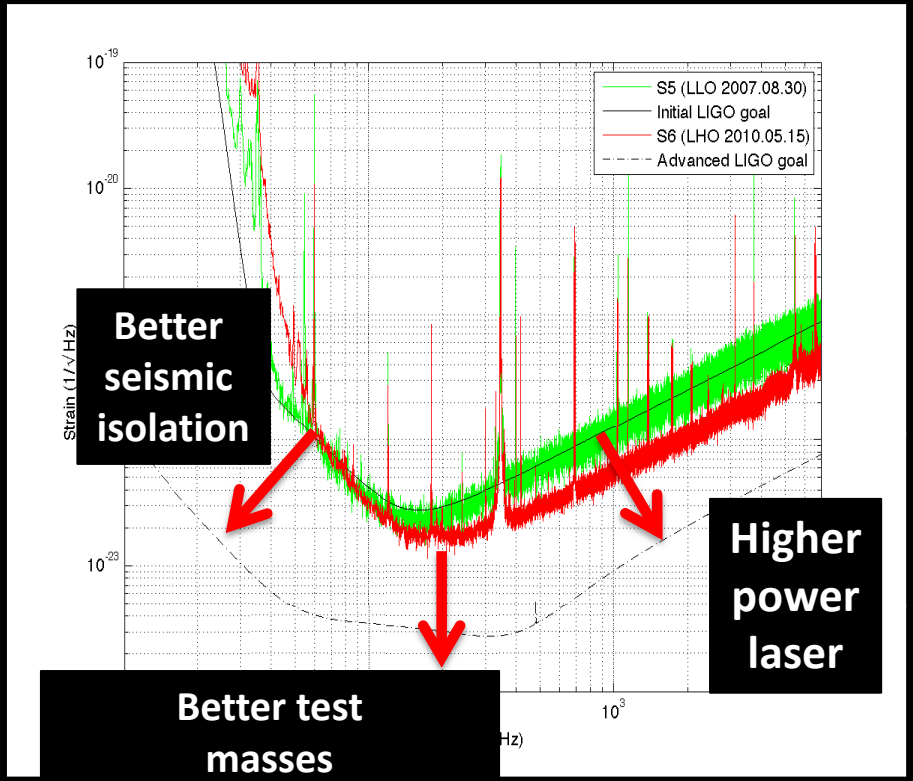
- Seismic noise limits low frequencies
- Thermal Noise limits middle frequencies
- Quantum nature of light (Shot Noise) limits high frequencies
- Technical issues - alignment, electronics, acoustics, etc limit us before we reach these design goals

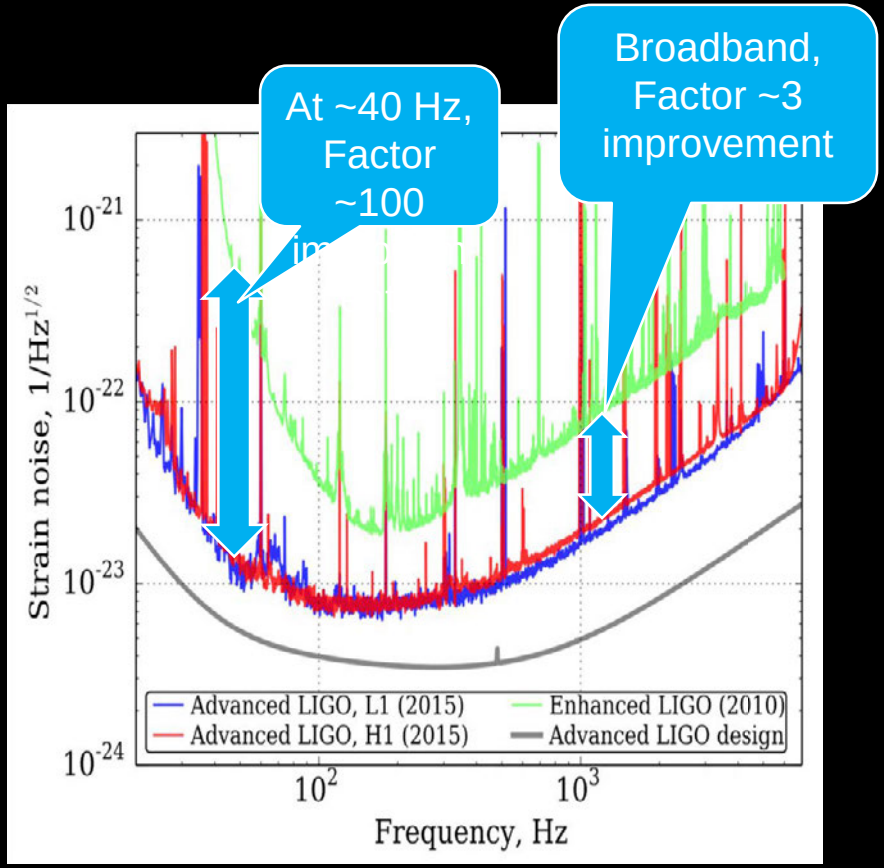


Evolution of LIGO Sensitivity



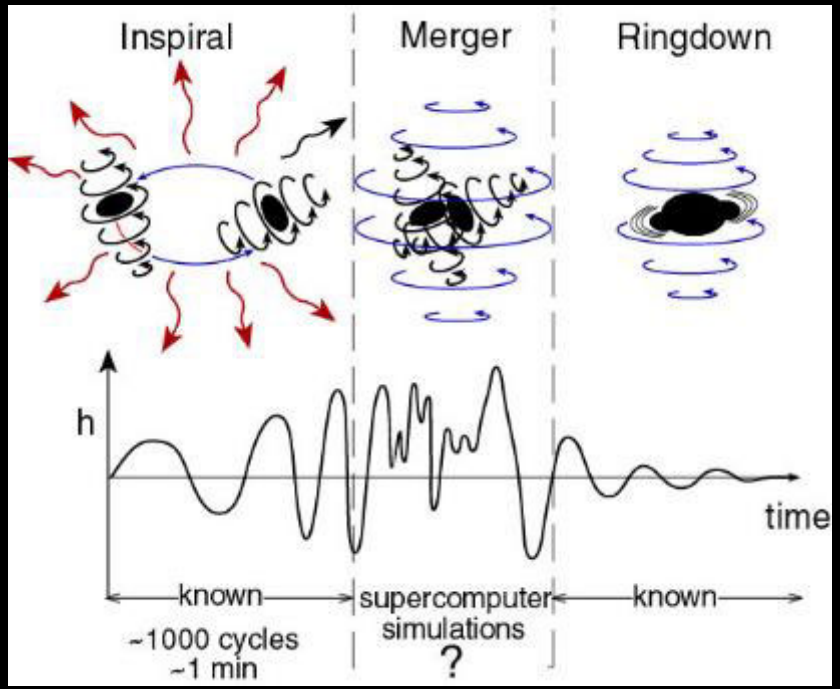
Advanced LIGO GOALS



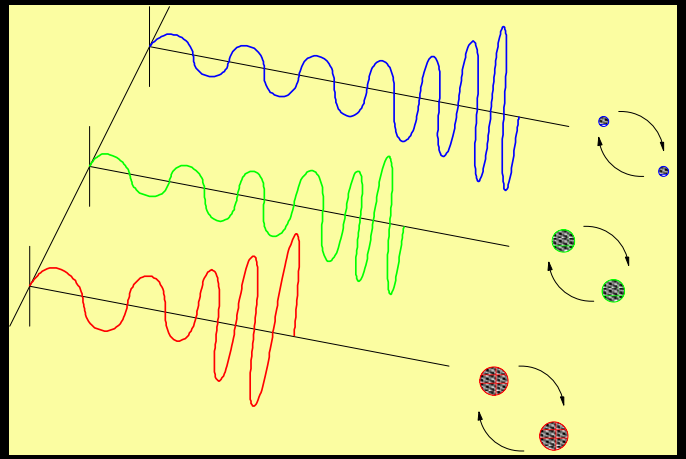


Gravitational Wave Detections

Compact Binary Collisions



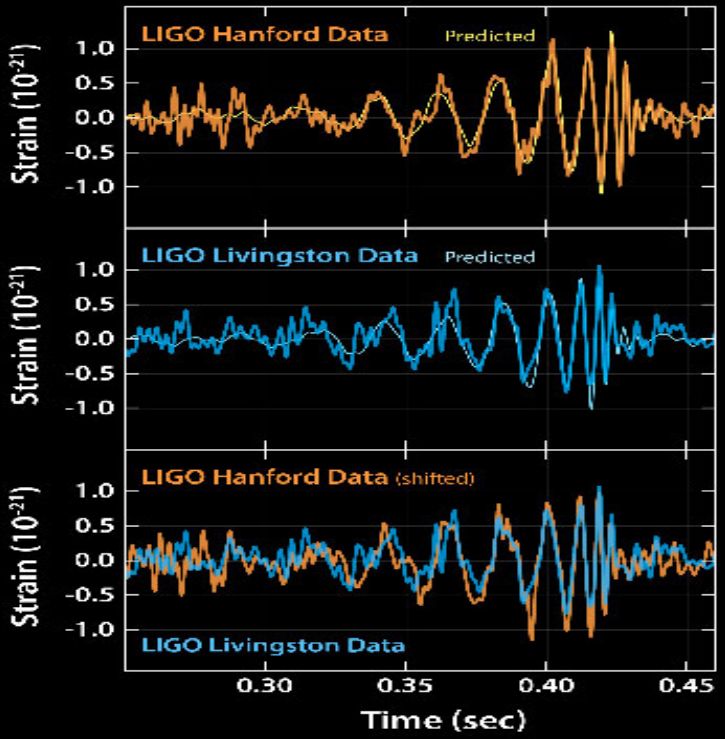
- Neutron Star – Neutron Star
  - **waveforms are well described**
- Black Hole – Black Hole
  - **Numerical Relativity waveforms**
- Search: *matched templates*

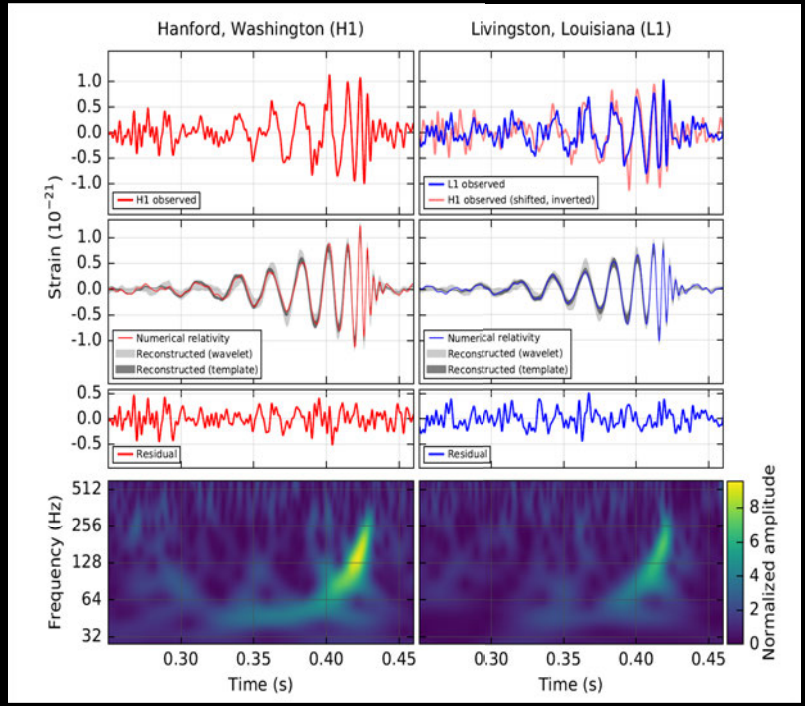


“chirps”

The Discovery of Gravitational Waves

Black Hole Merger: GW150914



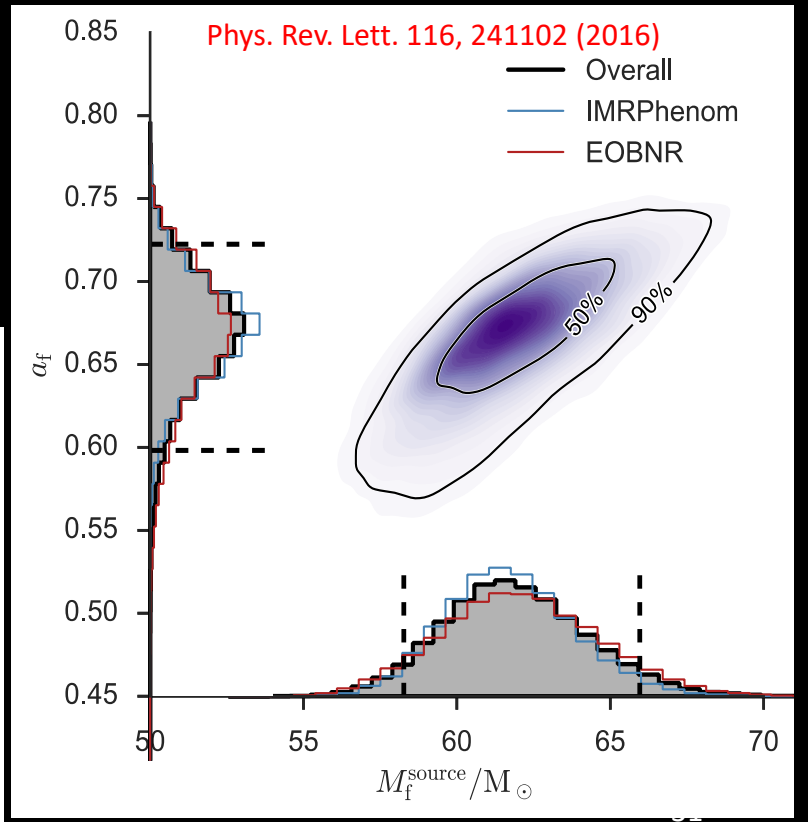


Black Hole Merger Parameters for GW150914

- Use numerical simulations fits of black hole merger to determine parameters; determine total energy radiated in gravitational waves is 3.0 ± 0.5 $M_o c^2$. The system reached a peak ~3.6 x10^{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)



Testing General Relativity – Dispersion Term?

- In GR, there is no dispersion!

Add dispersion term of form

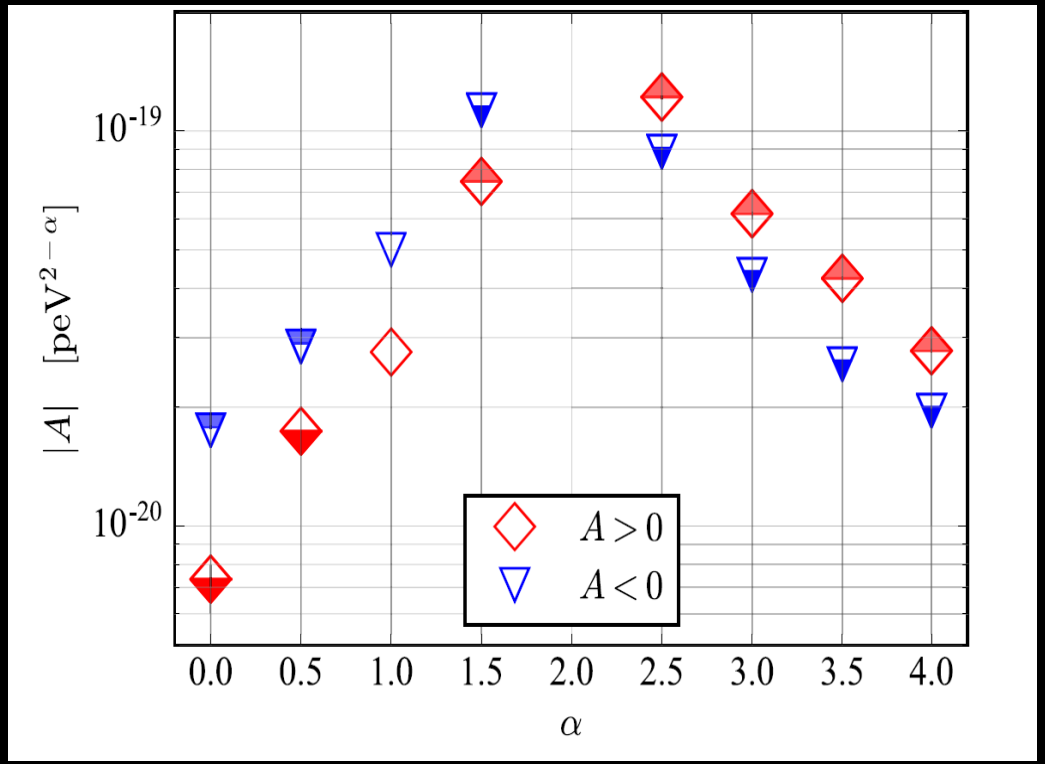
$$E^2 = p^2c^2 + Ap^\alpha c^\alpha, \quad \alpha \geq 0$$

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

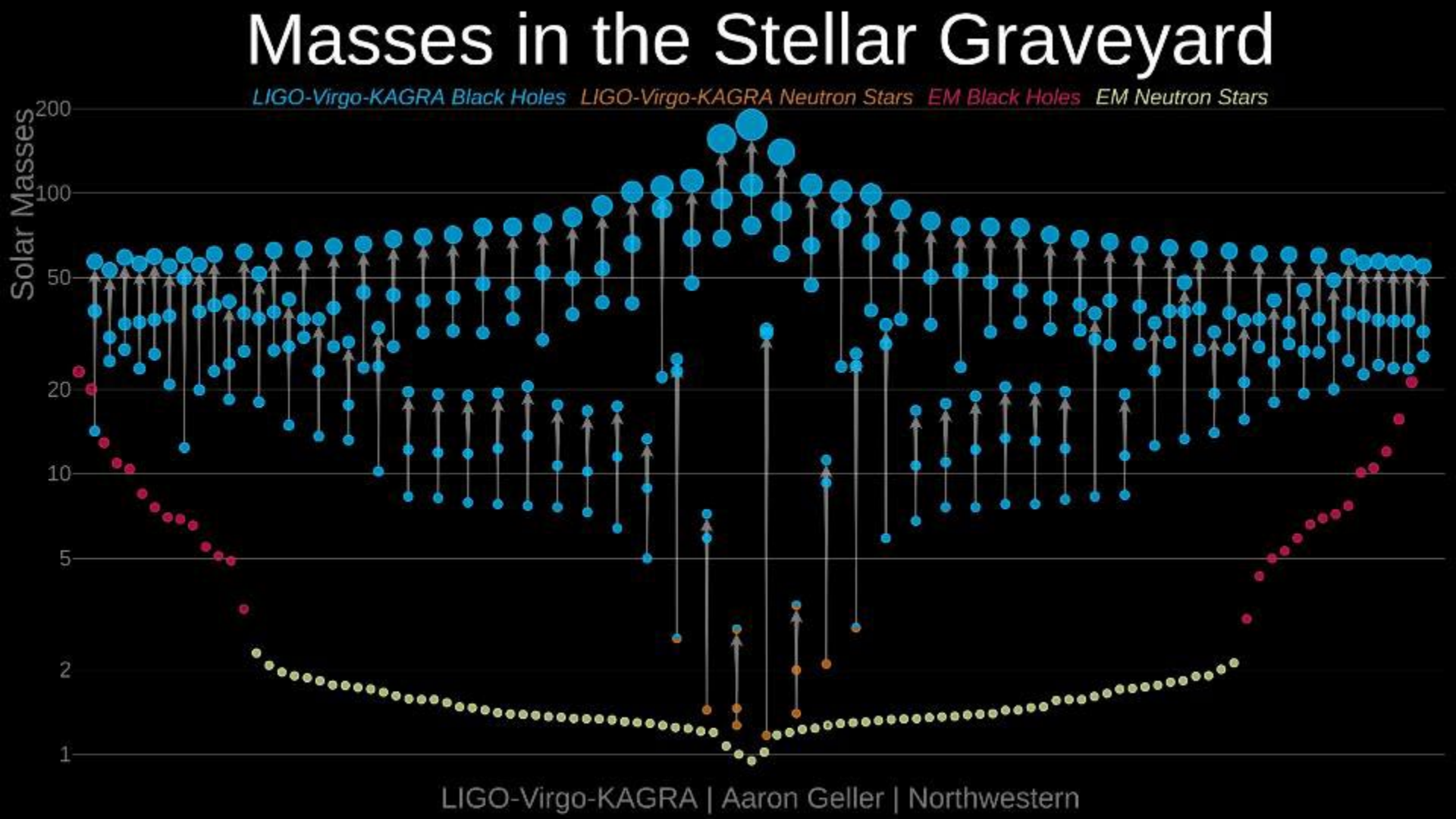
- Plot shows 90% upper bounds
- Limit on graviton mass

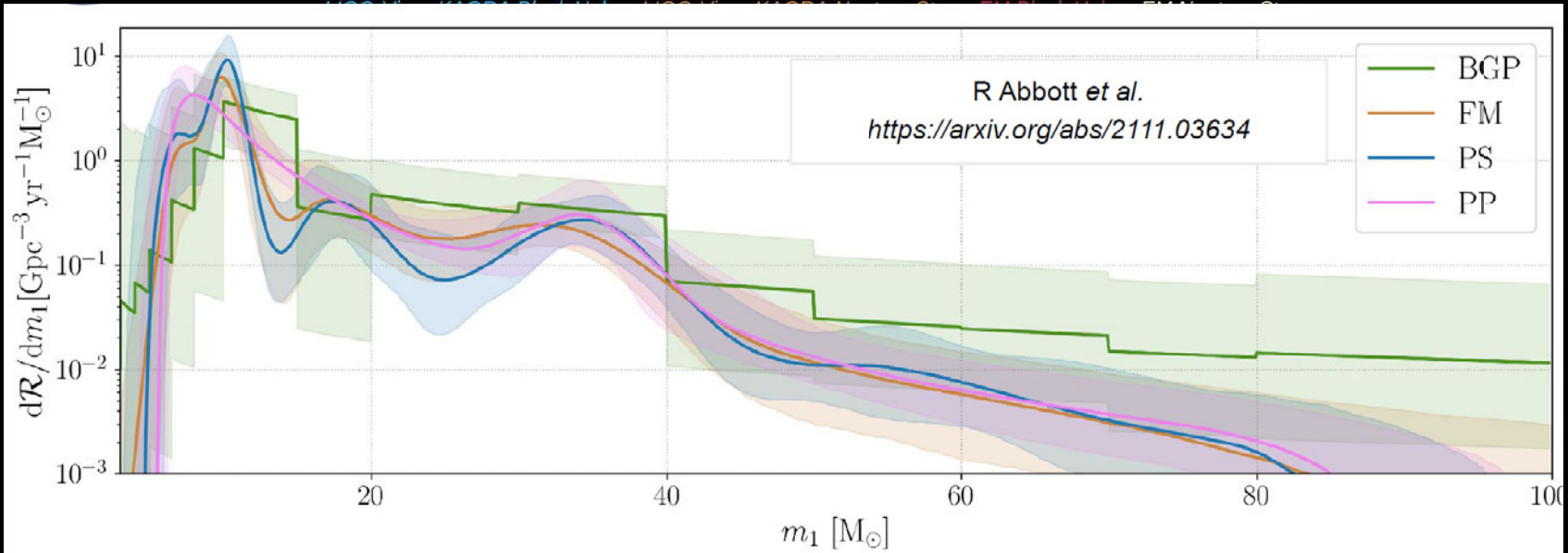
$$M_g \leq 7.7 \times 10^{-23}\ eV/c^2$$

- Null tests to quantify generic deviations from GR



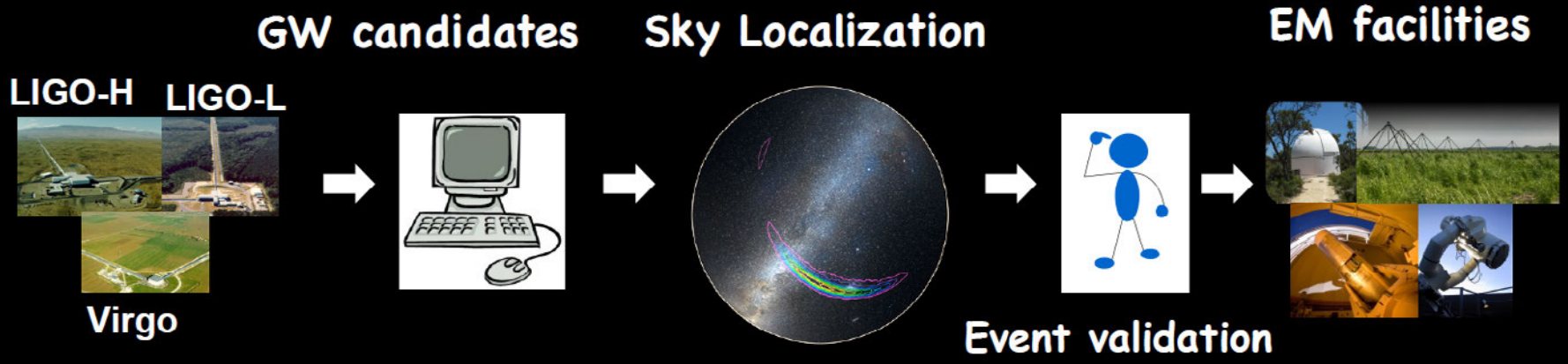
PhysRevLett.118.221101


Masses in the Stellar Graveyard
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
EM Black Holes
EM Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern



Merger rate density as a function of primary mass using 3 non-parametric models compared to the power-law+peak (pp) model.

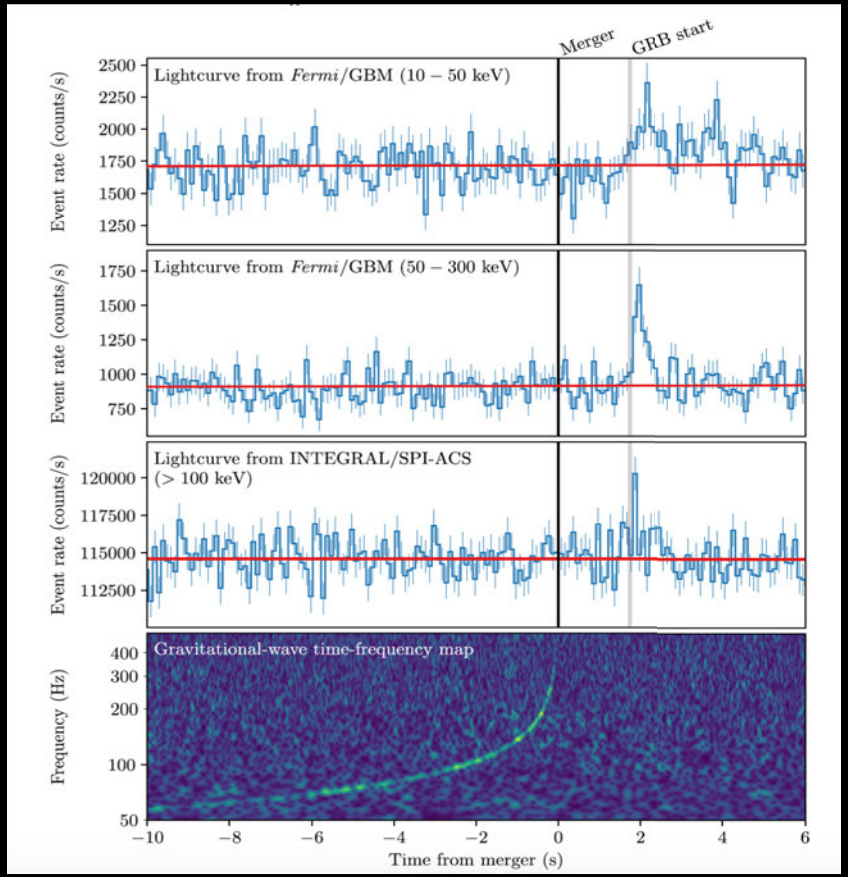
Searching for Electromagnetic Counterparts

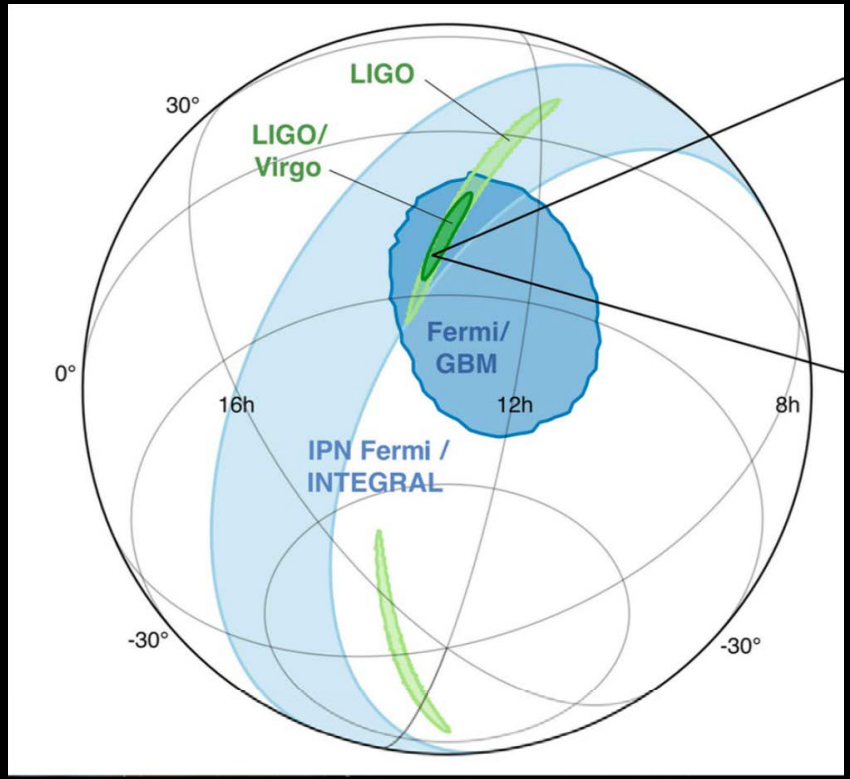


a few min → 30 min

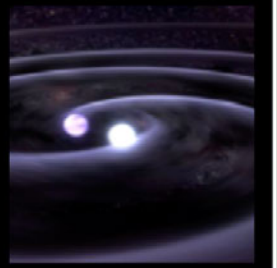
Parameter estimation codes → Hours,days, weeks → GW candidate updates

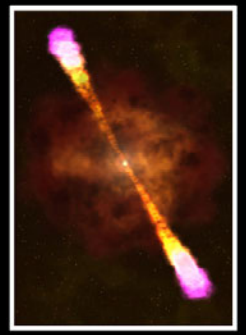
Fermi Satellite GRB detection 2 seconds later

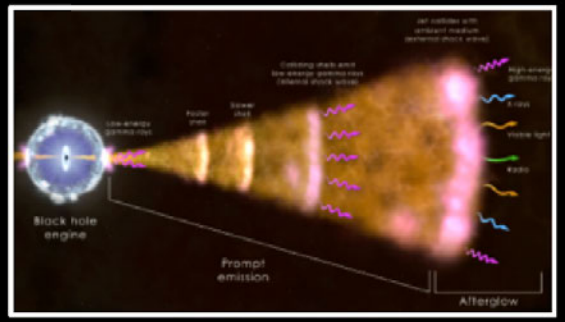




170817A" Astrophys. J. Lett., 848:L13, (2017)







NS merger

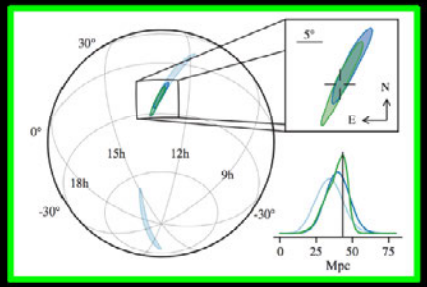
Short GRB

X-ray

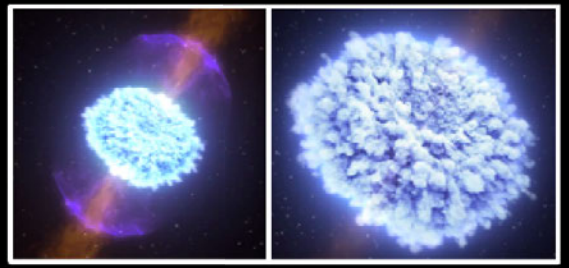
Radio afterglow

t0 1.7s +5.23hrs +10.87 hrs +9 days +16 days

LHV sky localization

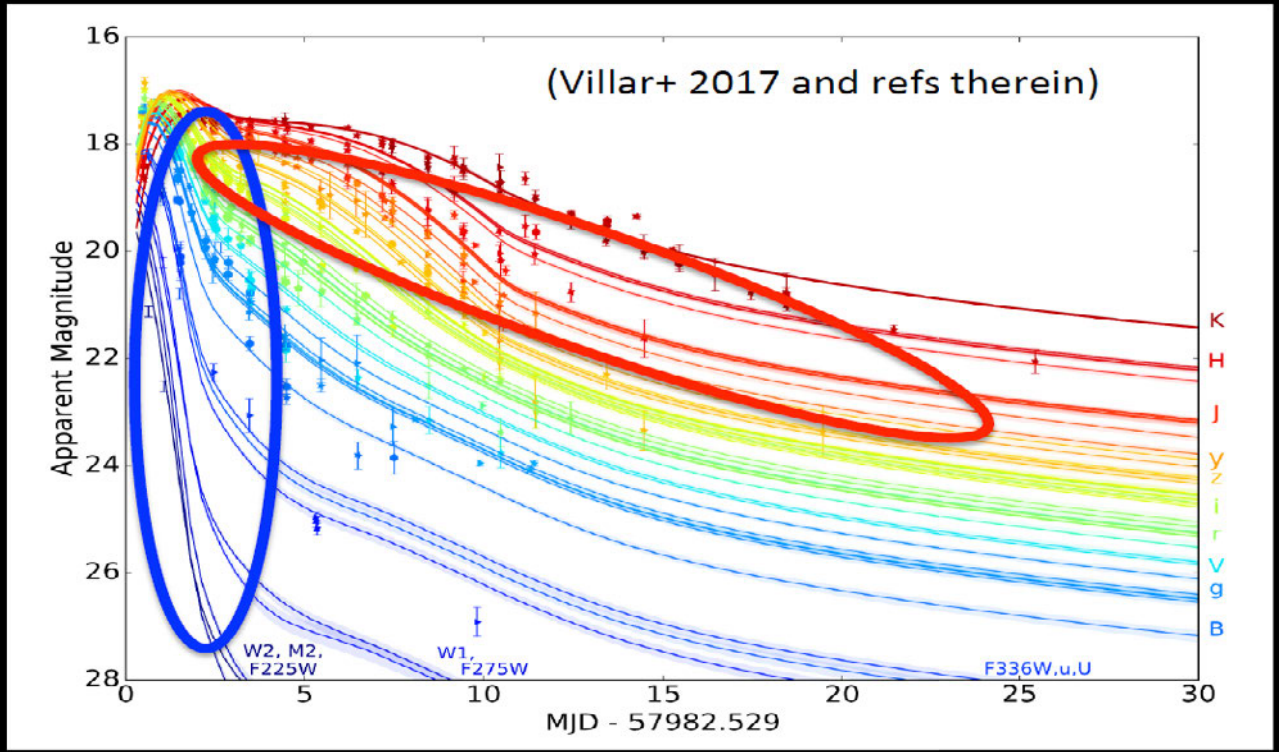


UV/Optical/NIR Kilonova



LVC + astronomers, ApJL, 848, L12

Light Curves



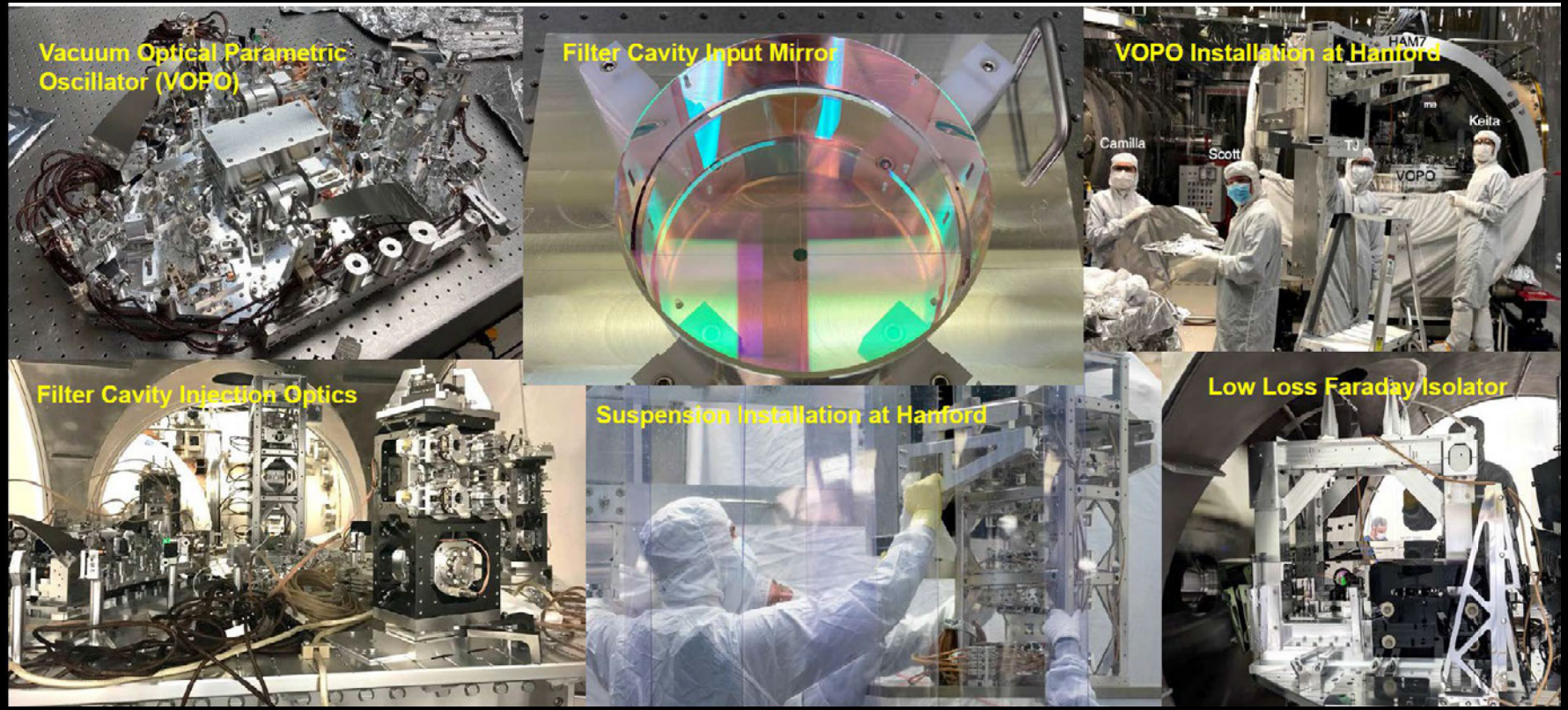
Extremely well characterized photometry of a Kilonova:

thermal emission by radiocative decay of heavy elements synthesized in multicomponent (2-3) ejecta!

NS Mergers are Incredible Gold Factories

LIGO observed Neutron Star Merger produced ~ 100 Earth Masses of Gold

The Pandemic Pause


Vacuum Optical Parametric Oscillator (VOPO)
Filter Cavity Input Mirror
VOPO Installation at Hanford
HAM7
Camilla
Scott
TJ
Keita
VOPO
Filter Cavity Injection Optics
Suspension Installation at Hanford
Low Loss Faraday Isolator

O4 Run and Upgrade Plans

LIGO and Virgo are currently engaged in an extended upgrade period in advance of the next O4 observing run

- **Advanced LIGO 'A+' and Advanced Virgo + upgrade program will implement frequency-dependent squeezing to reduce low frequency noise**
- **Also, LIGO will replace many of the primary 'test mass mirrors**

O4 will include the two LIGO Observatories, the Virgo Observatory, and the KAGRA Observatory

→ ***the first LIGO-Virgo-KAGRA 4-detector run***

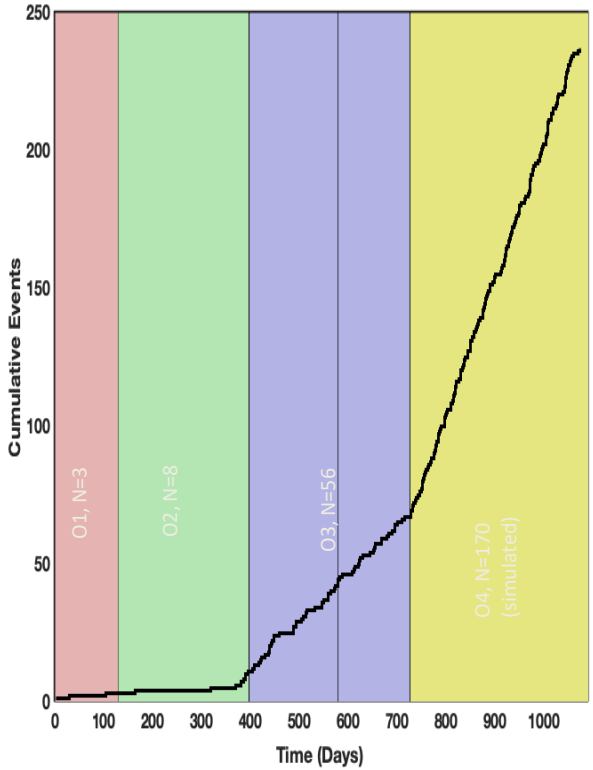
Target sensitivities (binary neutron star inspiral range):

- **LIGO: 160-190 Mpc (520 - 620 Mly)**
- **Virgo: 90 MPc (200 Mly)**
- **KAGRA: 25 - 130 MPc (80 - 425 Mly)**

→***A 2X to 3X increase in GW event rate***

O4 will start no earlier than March 2023

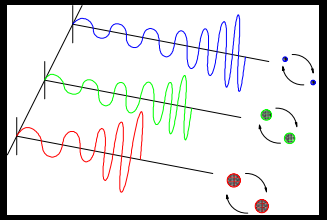
O4 run duration is still not set, but likely somewhere in the 12 – 18 month range



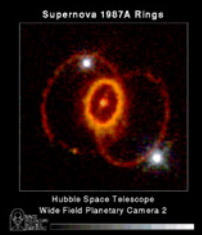
Astrophysical Sources

signatures

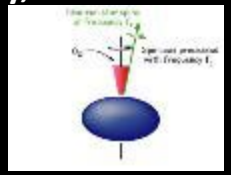
- Compact binary inspiral: *"chirps"*
  - NS-NS waveforms are well described
  - BH-BH need better waveforms
  - search technique: matched templates



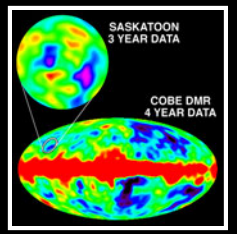
- Supernovae / GRBs: *"bursts"*
  - burst signals in coincidence with signals in electromagnetic radiation
  - prompt alarm (~ one hour) with neutrino detectors



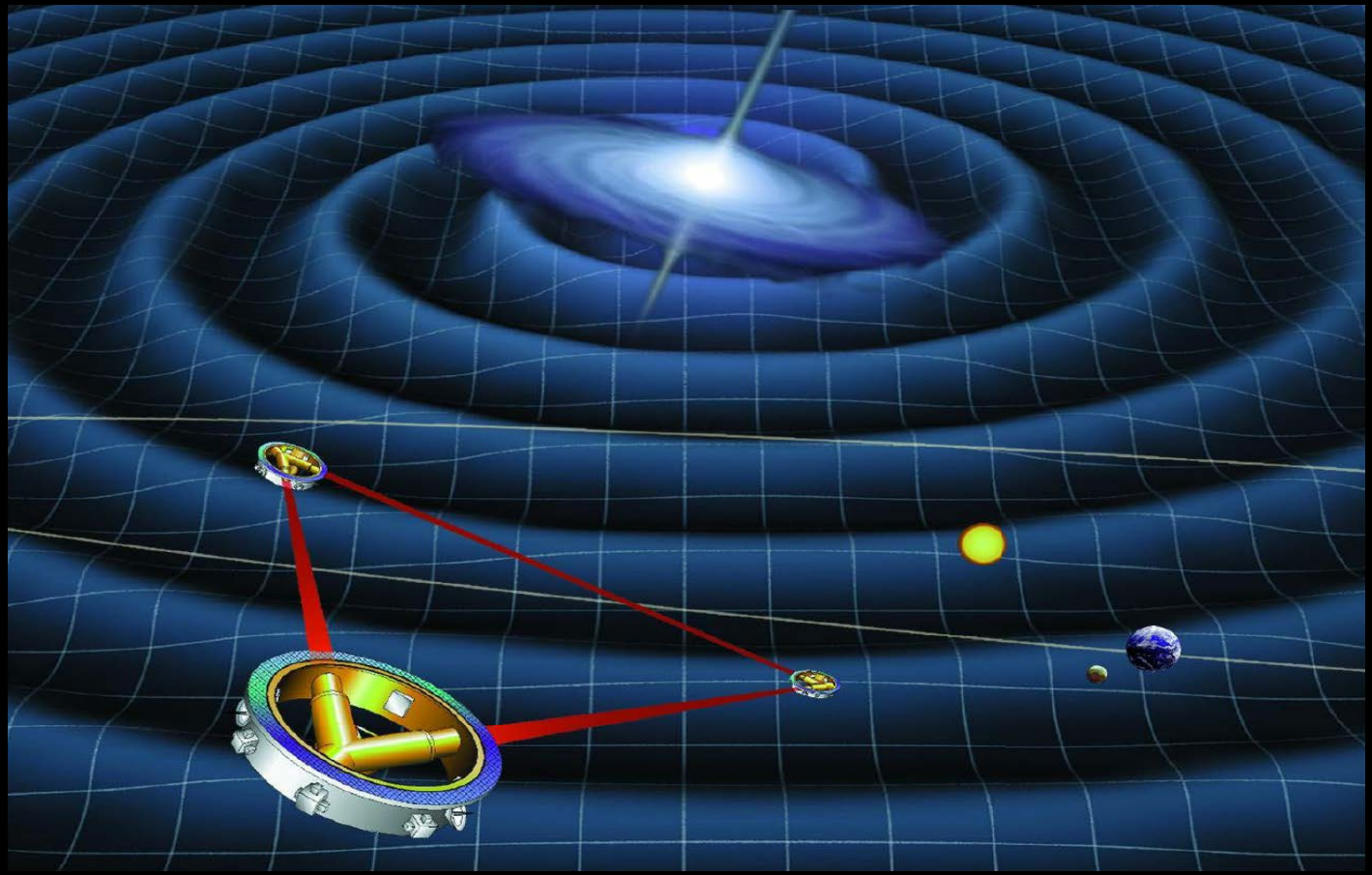
- Pulsars in our galaxy: *"periodic"*
  - search for observed neutron stars (frequency, doppler shift)
  - all sky search (computing challenge)
  - r-modes



- Cosmological Signal *"stochastic background"*



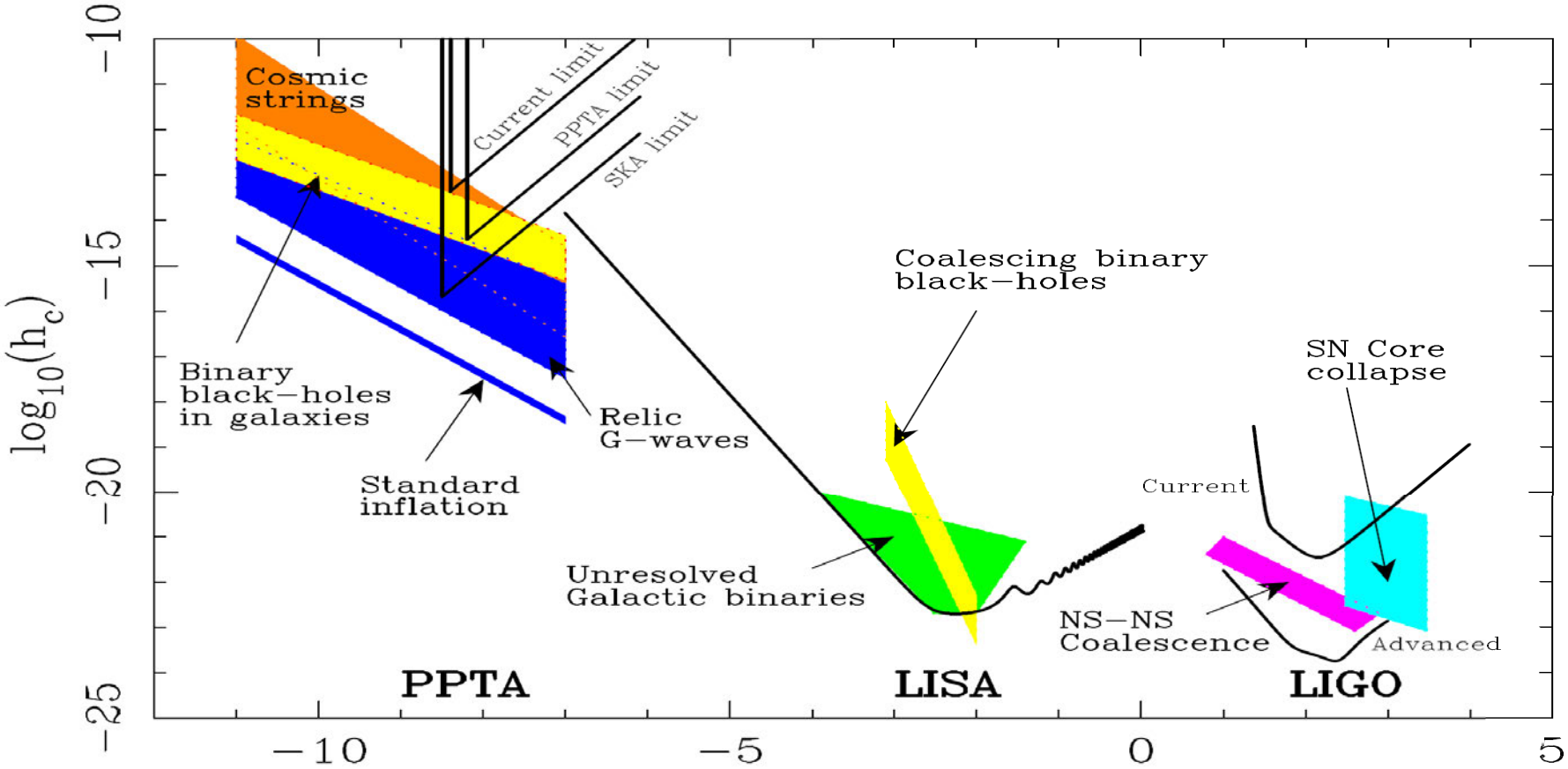
LISA: Laser Interferometer Space Array

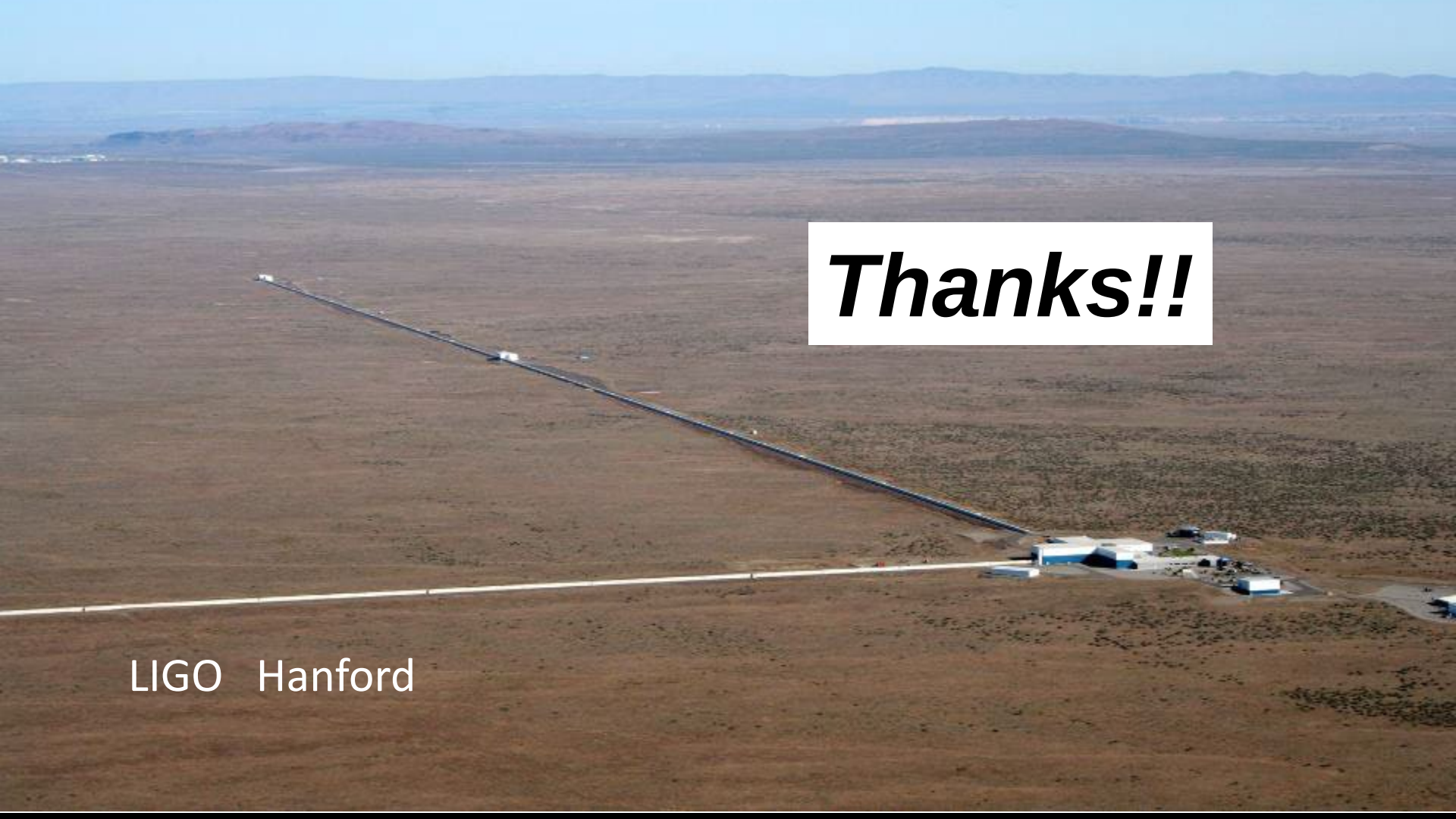


Three Interferometers

2.5 10^6 km arms

Gravitational Wave Frequency Coverage




Thanks!!
LIGO Hanford