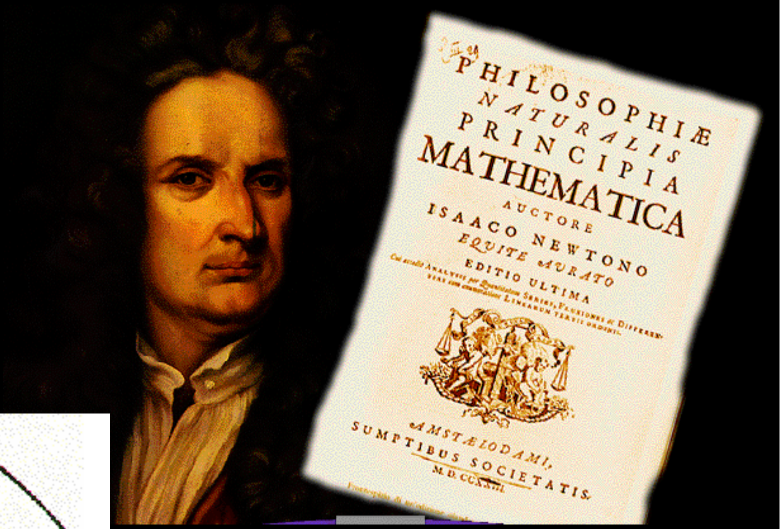
Gravitational wave astronomy

Eugenio Coccia

IFAE - Institute of High Energy Physics, Barcelona

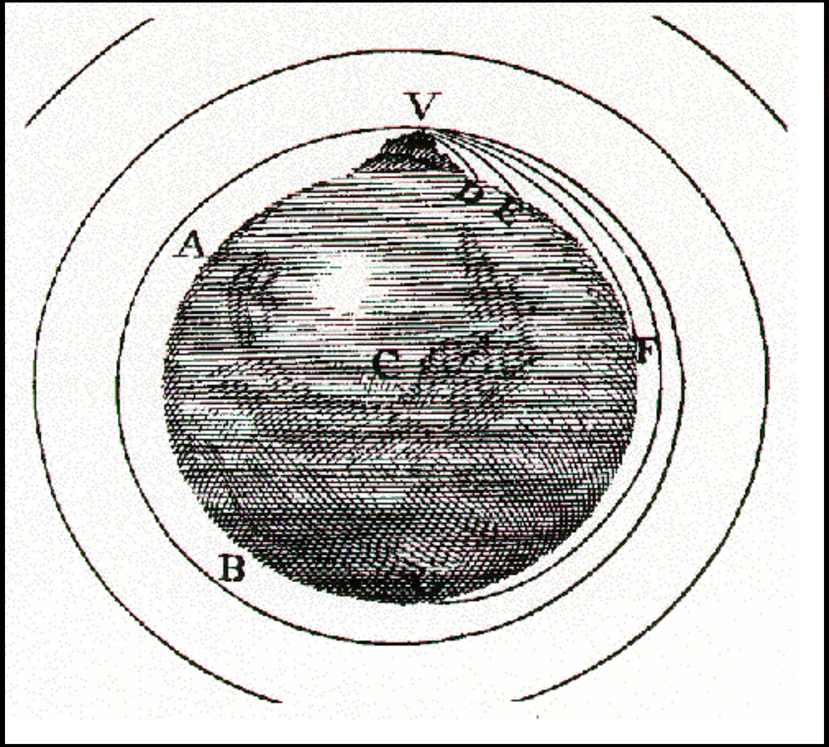
Gran Sasso Science Institute and INFN

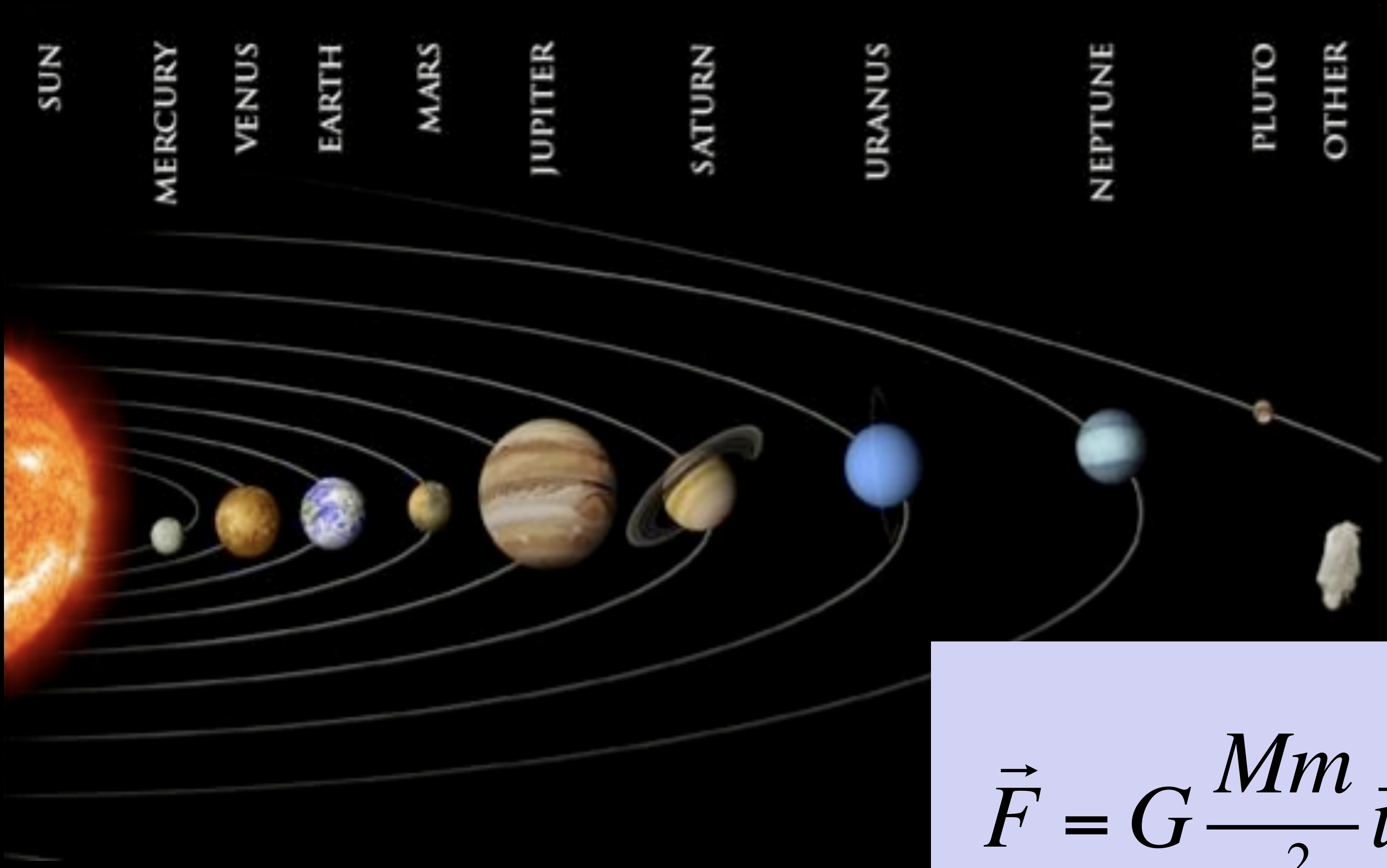
Newton



PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA
AUCTORE
ISAACO NEWTONO
EQUITE AURATO
EDITIO ULTIMA

AMSTÆLODAMI,
SUMPTIBUS SOCIETATIS.
M.D.CCXXIII.





$$\vec{F} = G\frac{Mm}{r^{2}}\vec{u}_{r}$$

1) $F = m_i a$ $\qquad F = G\frac{M\,m_g}{r^2}$

Experimental result: $\frac{m_i}{m_g} = const = 1$

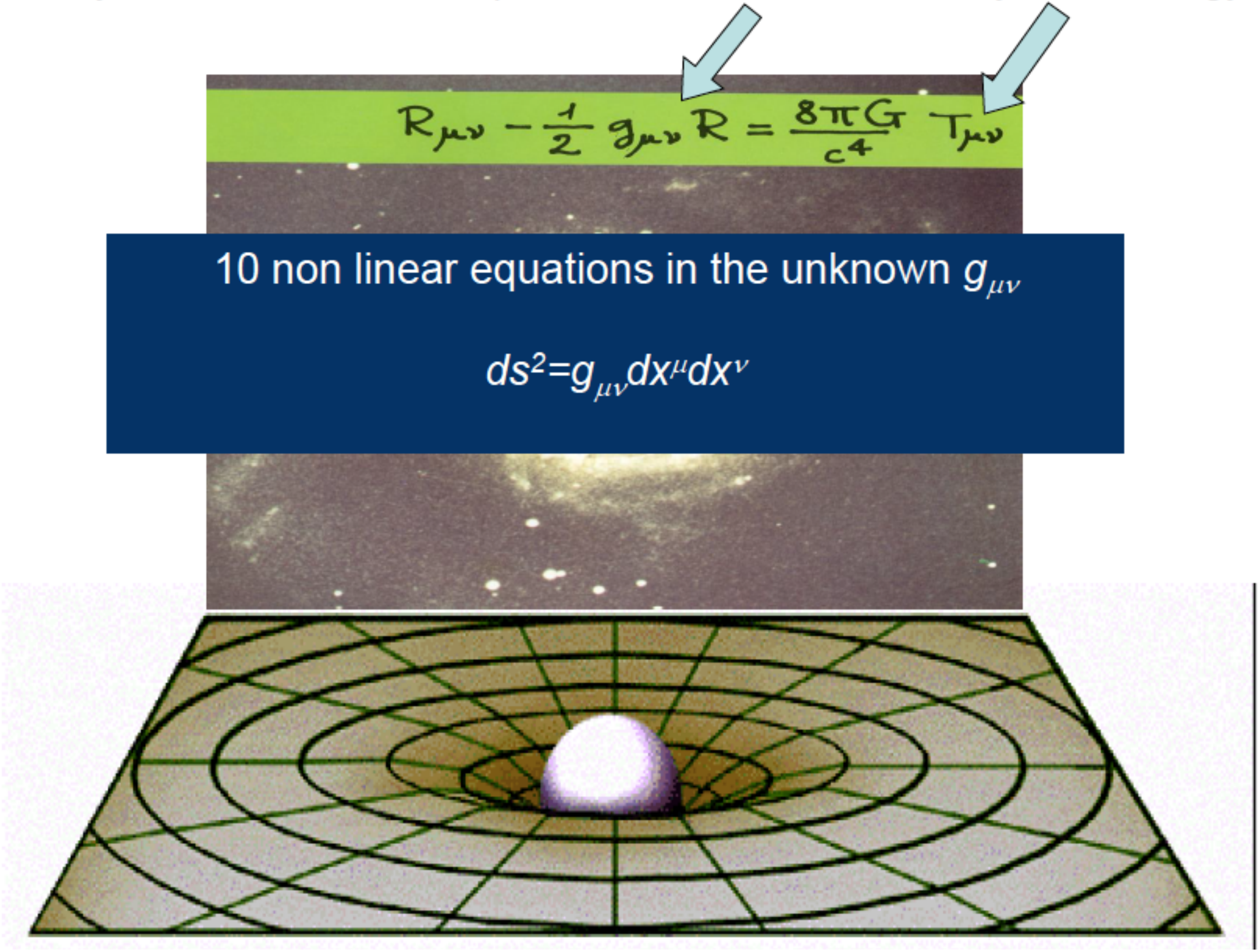
a coincidence?

2) Newtonian gravity propagates with infinite speed!

Einstein

General Relativity (1915)

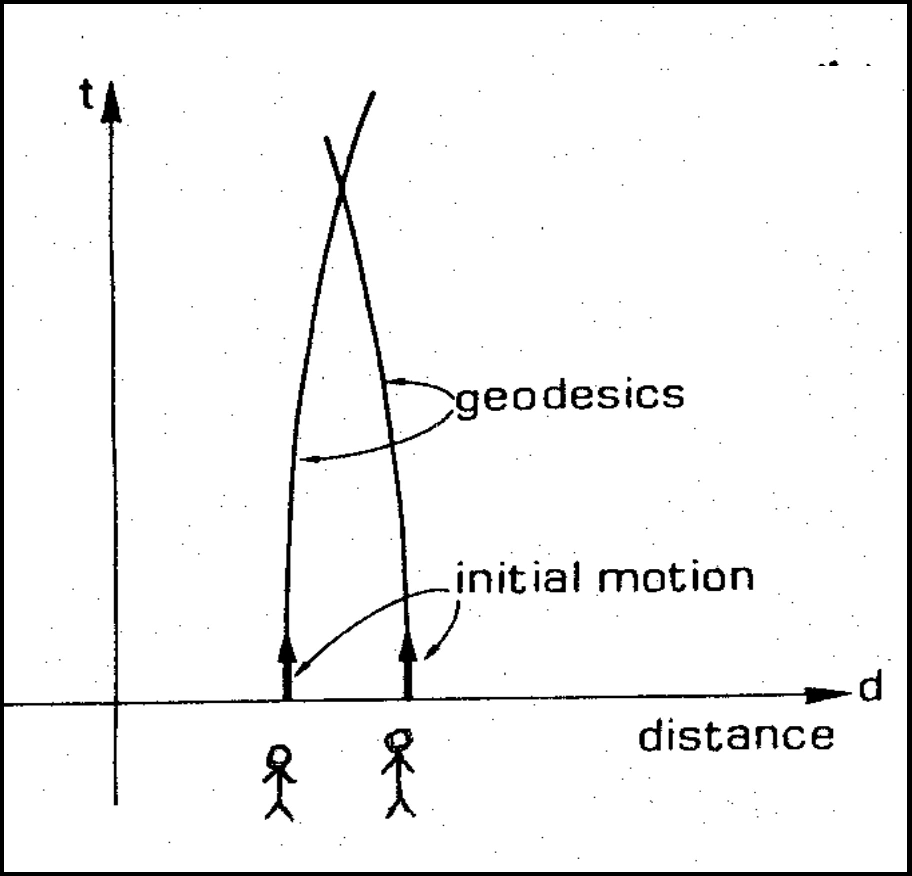
Gravity is a manifestation of spacetime curvature induced by mass-energy



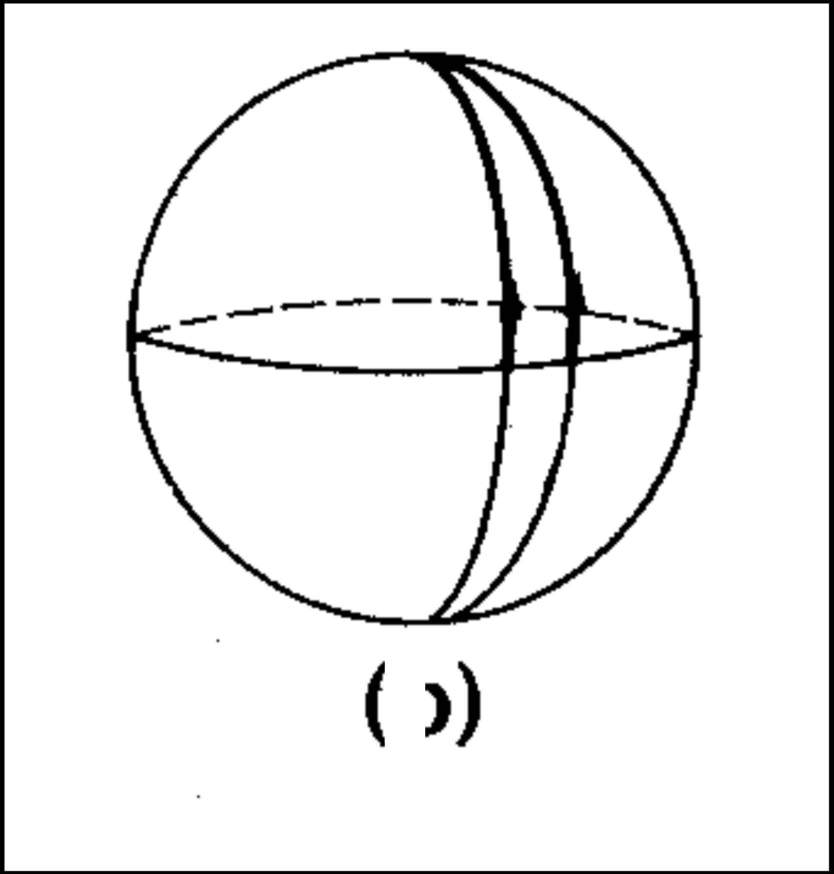
$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$$

10 non linear equations in the unknown $g_{\mu\nu}$

$$ds^2 = g_{\mu\nu} dx^{\mu} dx^{\nu}$$

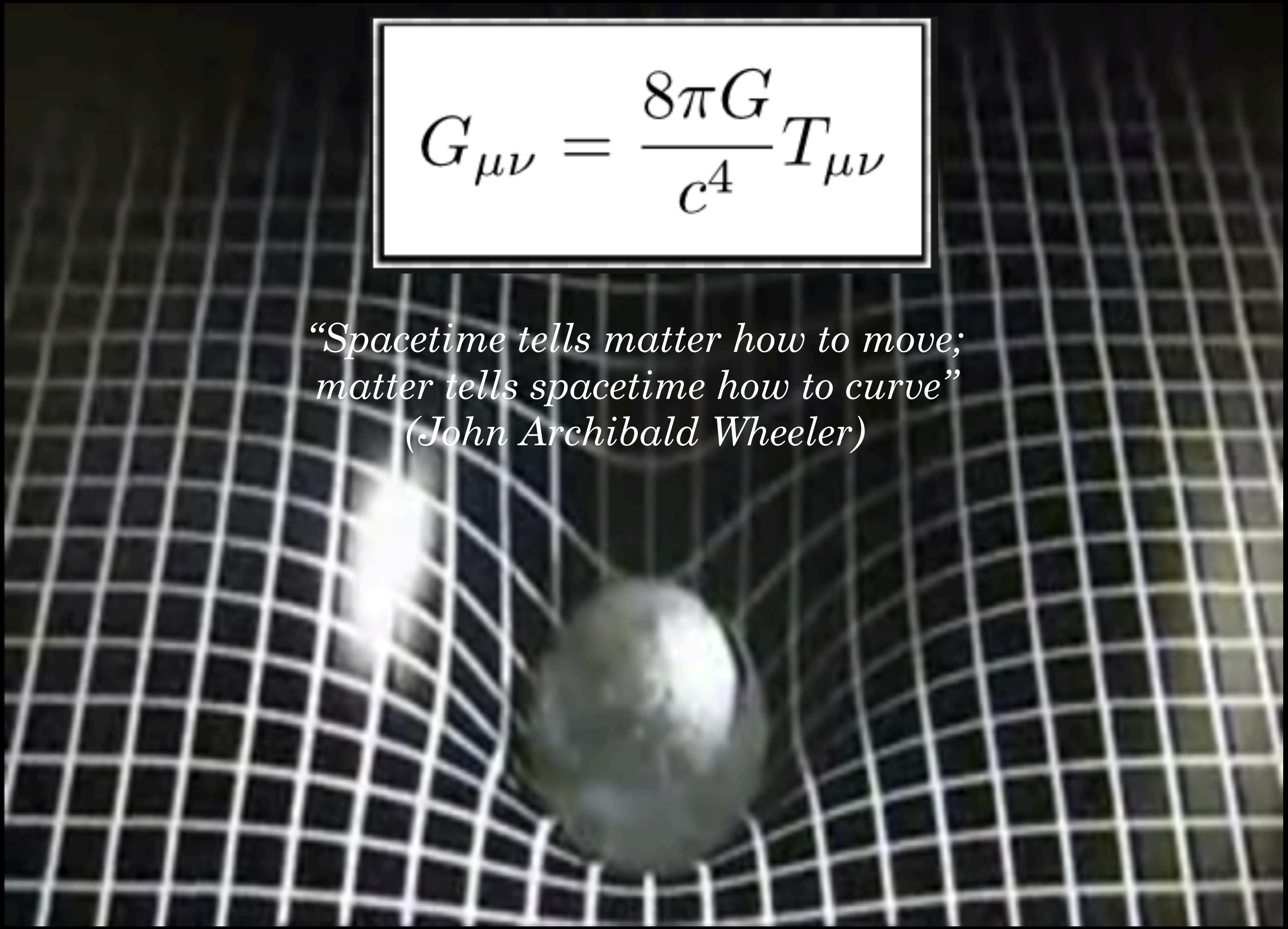


Einstein



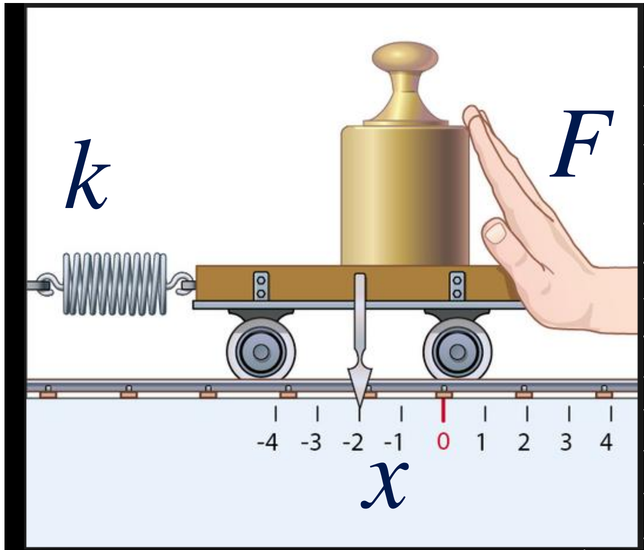
Einstein’s Theory of Gravitation

Gravity is a manifestation of spacetime curvature induced by mass-energy

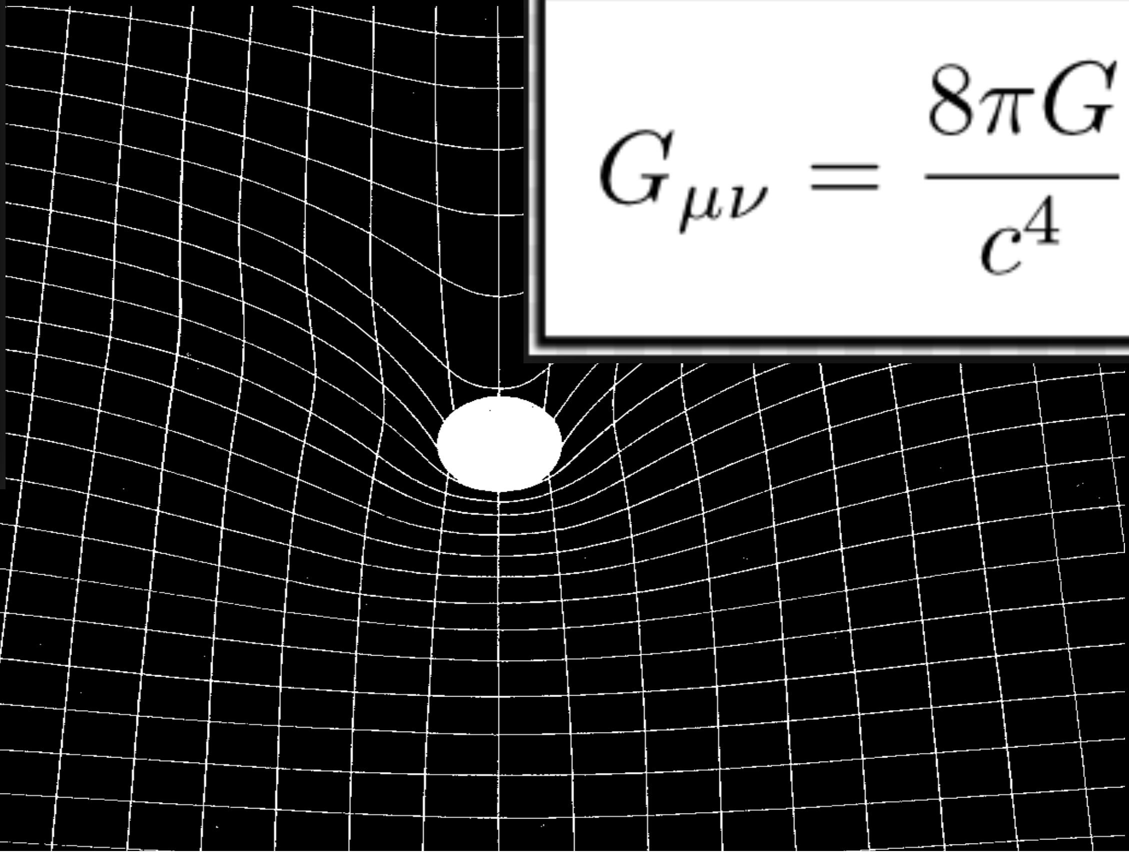


$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

“Spacetime tells matter how to move;
matter tells spacetime how to curve”
(John Archibald Wheeler)



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



$$F = -kx$$

$$F \Leftrightarrow T_{\mu\nu}$$

$$x \Leftrightarrow G_{\mu\nu}$$

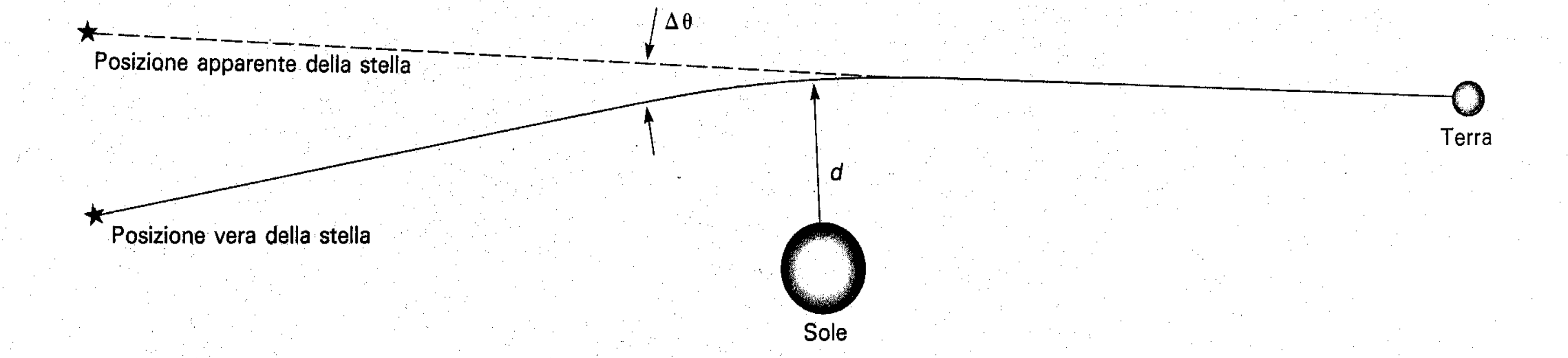
$$k \Leftrightarrow \frac{c^4}{8\pi G}$$

$$c = 299\ 792\ 458\ \ m/s = 3\times10^8\ \ m/s$$

$$G = 0{,}000\ 000\ 000\ 066\ 7\ \frac{m^3}{kg\ s^2} = 6{,}67\times10^{-11}\ \frac{m^3}{kg\ s^2}$$

$$k \approx 10^{45}\ \frac{kg}{s^2} \qquad STIFF!$$

Light deflection



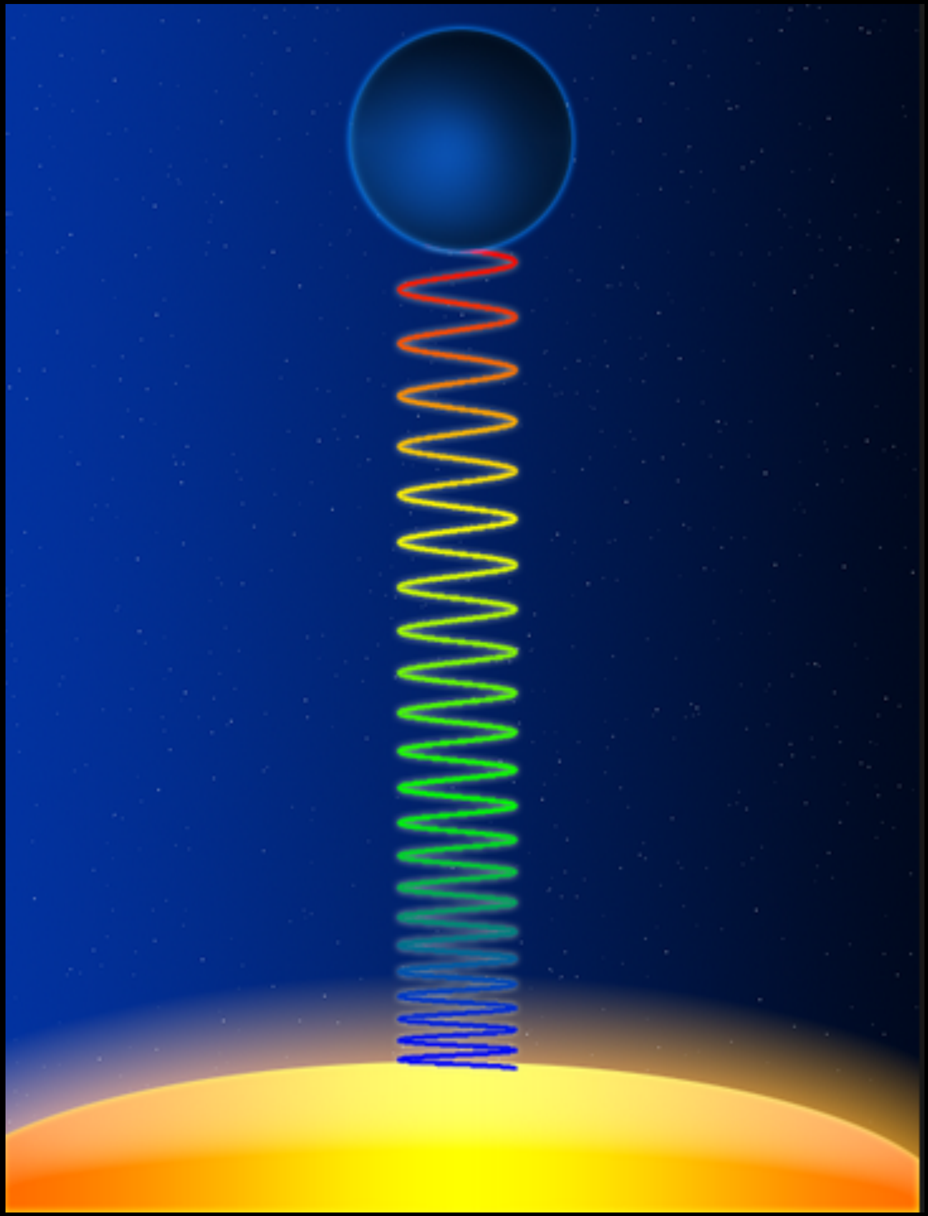
Eddington

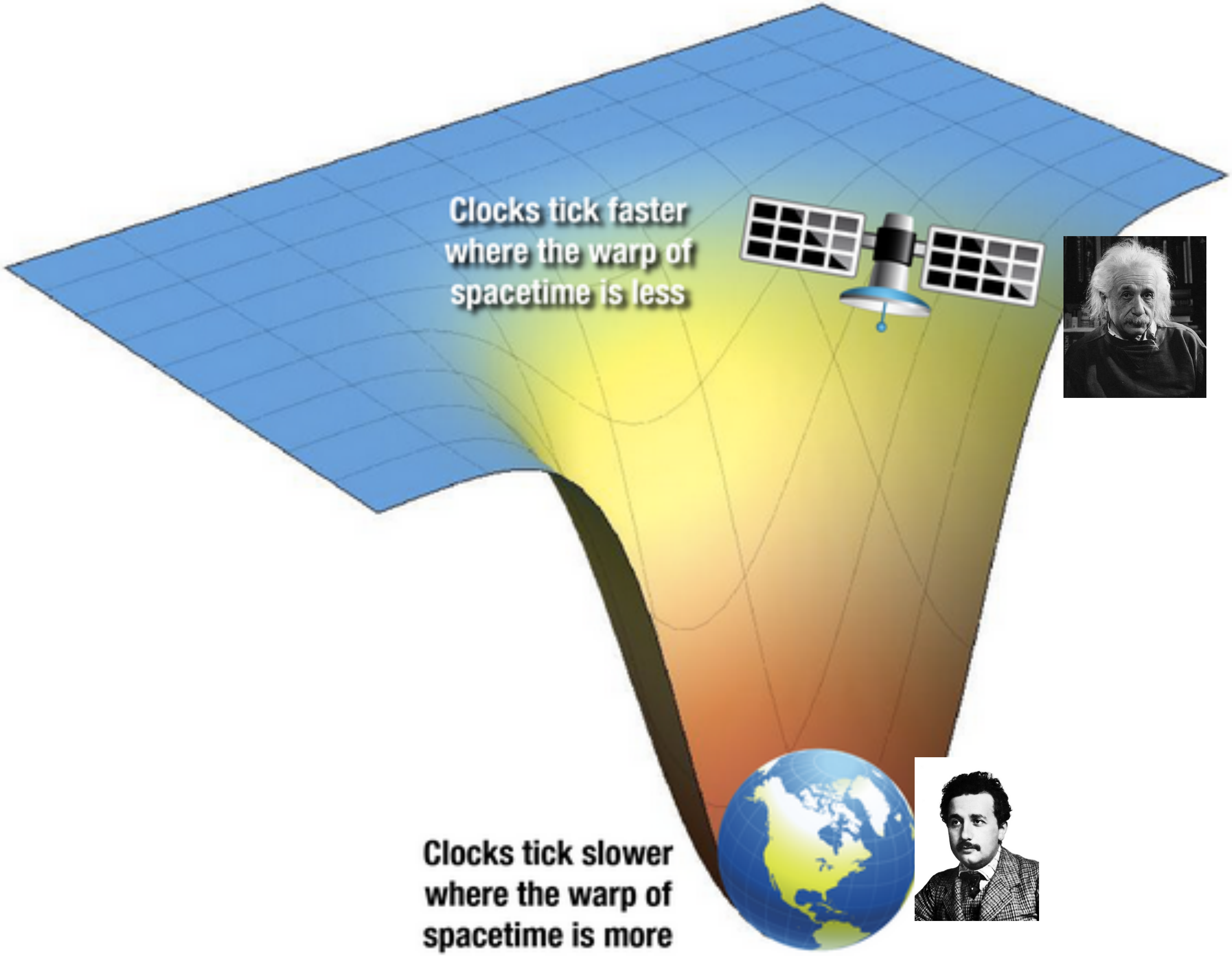
Harvard

Redshift

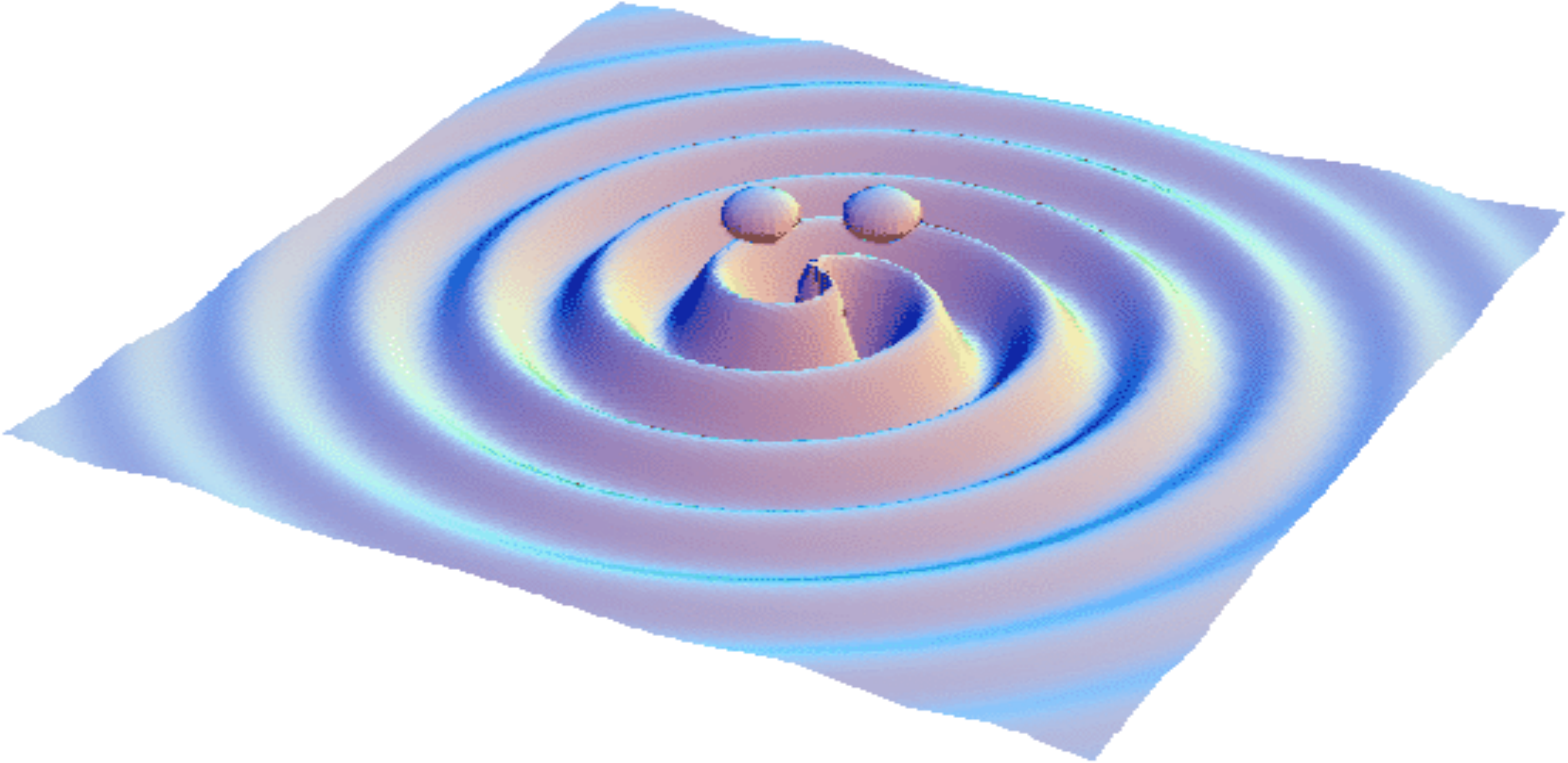
Pound and Rebka

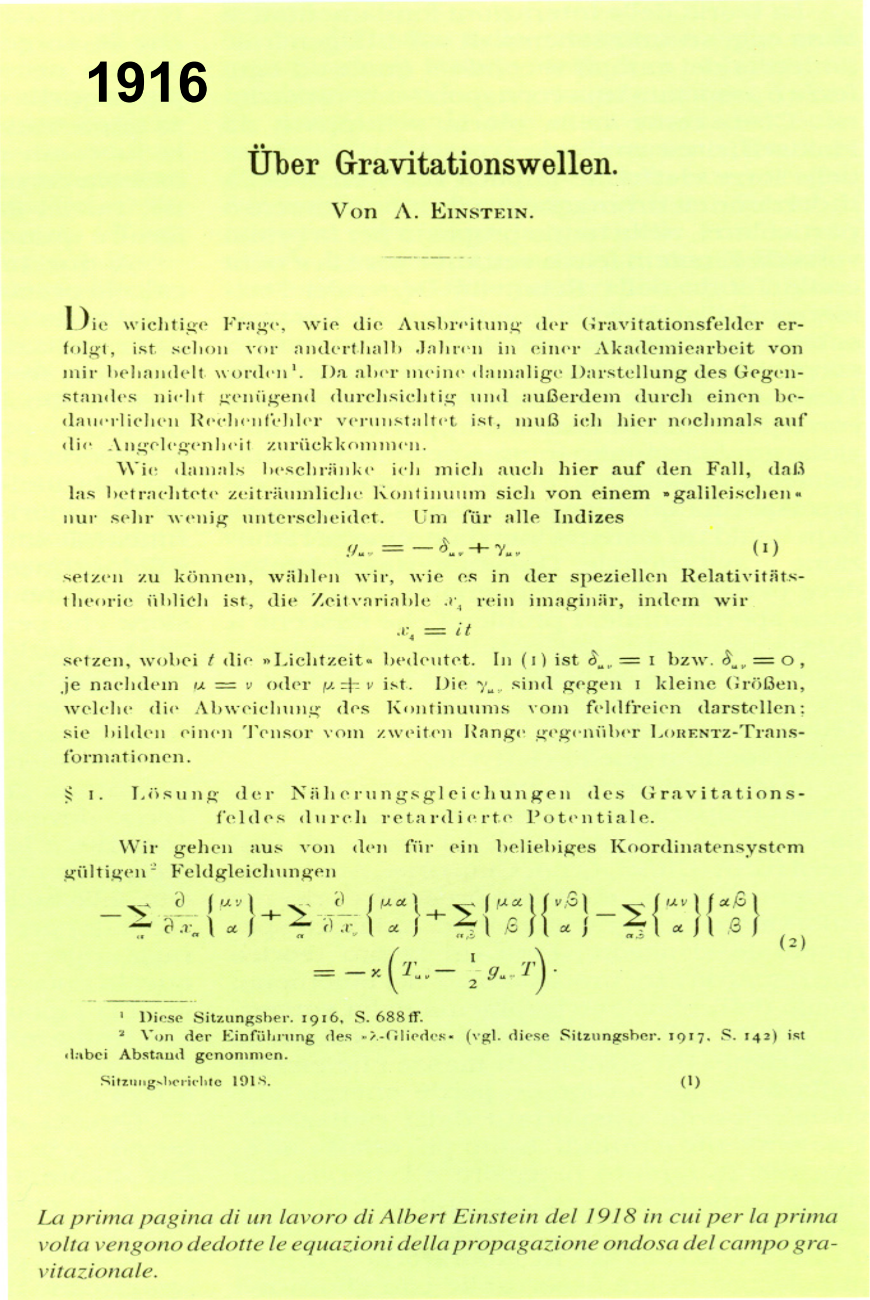
1959




Clocks tick faster where the warp of spacetime is less
Clocks tick slower where the warp of spacetime is more

Gravitational Waves





1916

Über Gravitationswellen.

Von A. Einstein.

Die wichtige Frage, wie die Ausbreitung der Gravitationsfelder erfolgt, ist schon vor anderthalb Jahren in einer Akademiearbeit von mir behandelt worden[1]. Da aber meine damalige Darstellung des Gegenstandes nicht genügend durchsichtig und außerdem durch einen bedauerlichen Rechenfehler verunstaltet ist, muß ich hier nochmals auf die Angelegenheit zurückkommen.

Wie damals beschränke ich mich auch hier auf den Fall, daß das betrachtete zeiträumliche Kontinuum sich von einem »galileischen« nur sehr wenig unterscheidet. Um für alle Indizes

$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \tag{1}$$

setzen zu können, wählen wir, wie es in der speziellen Relativitätstheorie üblich ist, die Zeitvariable x_4 rein imaginär, indem wir

$$x_4 = it$$

setzen, wobei t die »Lichtzeit« bedeutet. In (1) ist $\delta_{\mu\nu} = 1$ bzw. $\delta_{\mu\nu} = 0$, je nachdem $\mu = \nu$ oder $\mu \neq \nu$ ist. Die $\gamma_{\mu\nu}$ sind gegen 1 kleine Größen, welche die Abweichung des Kontinuums vom feldfreien darstellen; sie bilden einen Tensor vom zweiten Range gegenüber Lorentz-Transformationen.

§ 1. Lösung der Näherungsgleichungen des Gravitationsfeldes durch retardierte Potentiale.

Wir gehen aus von den für ein beliebiges Koordinatensystem gültigen[2] Feldgleichungen

$$-\sum_{\alpha} \frac{\partial}{\partial x_\alpha}\begin{Bmatrix}\mu\nu\\ \alpha\end{Bmatrix} + \sum_{\alpha} \frac{\partial}{\partial x_\nu}\begin{Bmatrix}\mu\alpha\\ \alpha\end{Bmatrix} + \sum_{\alpha\beta}\begin{Bmatrix}\mu\alpha\\ \beta\end{Bmatrix}\begin{Bmatrix}\nu\beta\\ \alpha\end{Bmatrix} - \sum_{\alpha\beta}\begin{Bmatrix}\mu\nu\\ \alpha\end{Bmatrix}\begin{Bmatrix}\alpha\beta\\ \beta\end{Bmatrix} = -\varkappa\left(T_{\mu\nu} - \frac{1}{2}g_{\mu\nu}T\right). \tag{2}$$

---

[1] Diese Sitzungsber. 1916, S. 688 ff.

[2] Von der Einführung des »λ-Gliedes« (vgl. diese Sitzungsber. 1917, S. 142) ist dabei Abstand genommen.

Sitzungsberichte 1918. (1)

La prima pagina di un lavoro di Albert Einstein del 1918 in cui per la prima volta vengono dedotte le equazioni della propagazione ondosa del campo gravitazionale.

Weak field approximation

$$g_{\mu\nu} = g^{o}_{\mu\nu} + h_{\mu\nu}$$

$$\left|h_{\mu\nu}\right| << 1$$

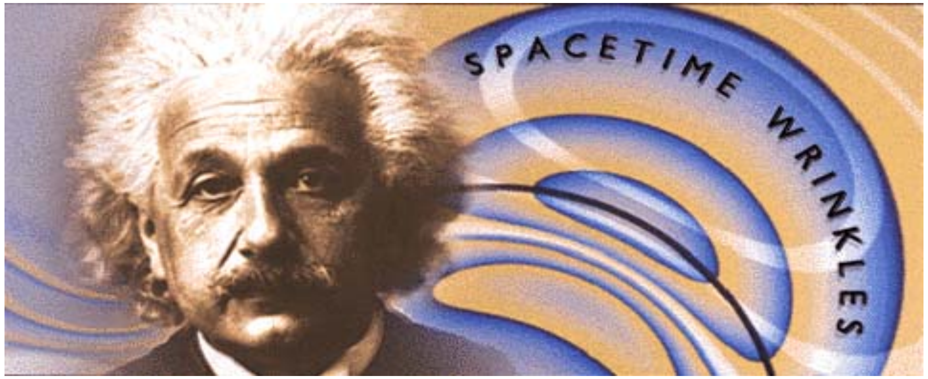
The Einstein equation in vacuum becomes

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

Having solutions

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

Spacetime perturbations, propagating in vacuum like waves, at the speed of light : gravitational waves



Gravitational waves are strain in space propagating with the speed of light

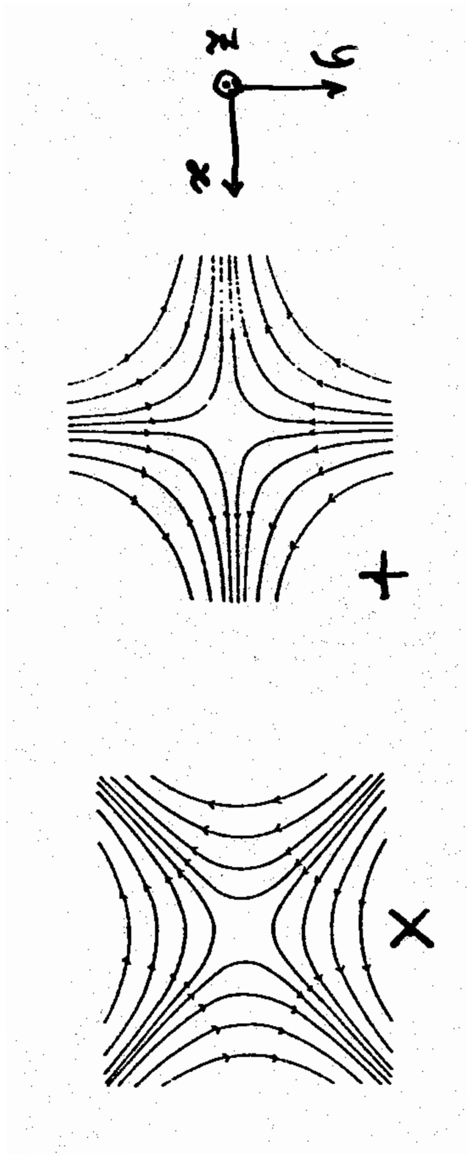
Main features

- **2 transversal polarization states**
- **Associated with massless, spin 2 particles (gravitons)**
- **Emitted by time-varying quadrupole mass moment**
  no dipole radiation because of conservation laws

$$-\frac{dE}{dt} = \cancel{\frac{2G}{3c^3}\left(\ddot{d}\right)^2} + \frac{G}{45c^5}\left(\dddot{Q}\right)^2 + \dots$$

$$\dot{d} = \sum_i m_i \dot{x}_i \Rightarrow \ddot{d} \equiv 0 \qquad Q_{ij} = \int \rho x_i x_j d^3x$$

$$\boxed{h_{ij}(t) = \frac{2G}{rc^4}\ddot{Q}_{ij}(t - r/c)}$$



- **No laboratory equivalent of Hertz experiments for production of GWs**

Luminosity due to a mass M and size R oscillating at frequency $\omega \sim v/R$:

$$L = \frac{2G}{5c^5}\left\langle \dddot{Q}^2 \right\rangle \approx \frac{GM^2v^6}{R^2c^5} \qquad Q \approx MR^2 \sin\omega t$$

M=1000 tons, steel rotor, f = 4 Hz → $L = 10^{-30}$ W
Einstein: " .. *a pratically vanishing value…*"

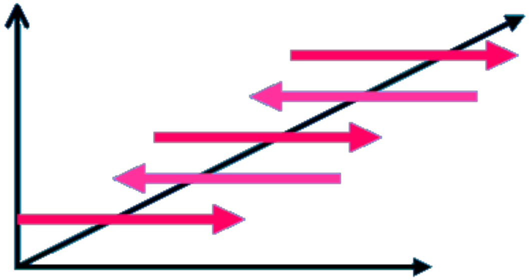
Collapse to neutron star 1.4 M_o → $L = 10^{52}$ W

$h \sim W^{1/2}d^{-1}$; source in the Galaxy ***$h \sim 10^{-18}$*** , in VIRGO cluster ***$h \sim 10^{-21}$***
Fairbank: "*...a challenge for contemporary experimental physics..*"

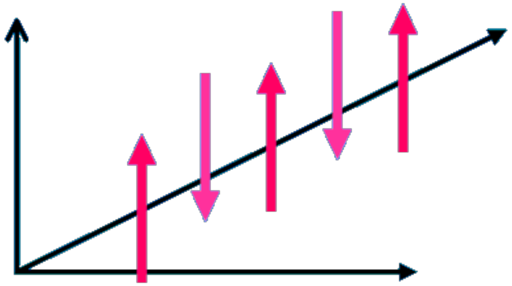
Gravitational Waves

Comparison with electromagnetic waves

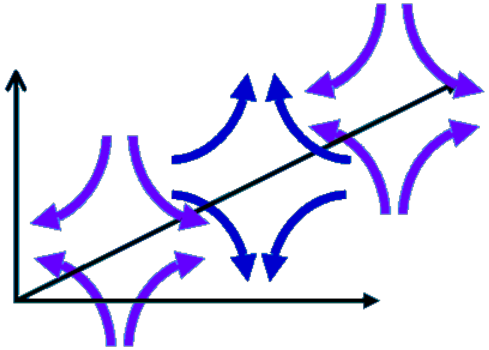
Horizontal
polarization



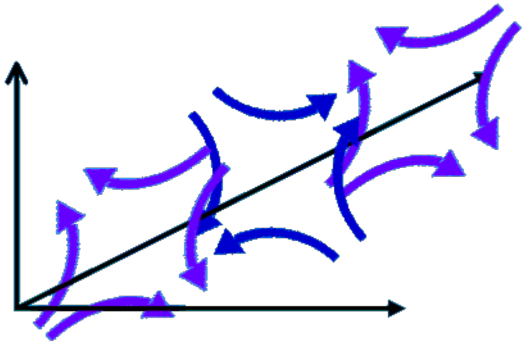
Vertical
polarization



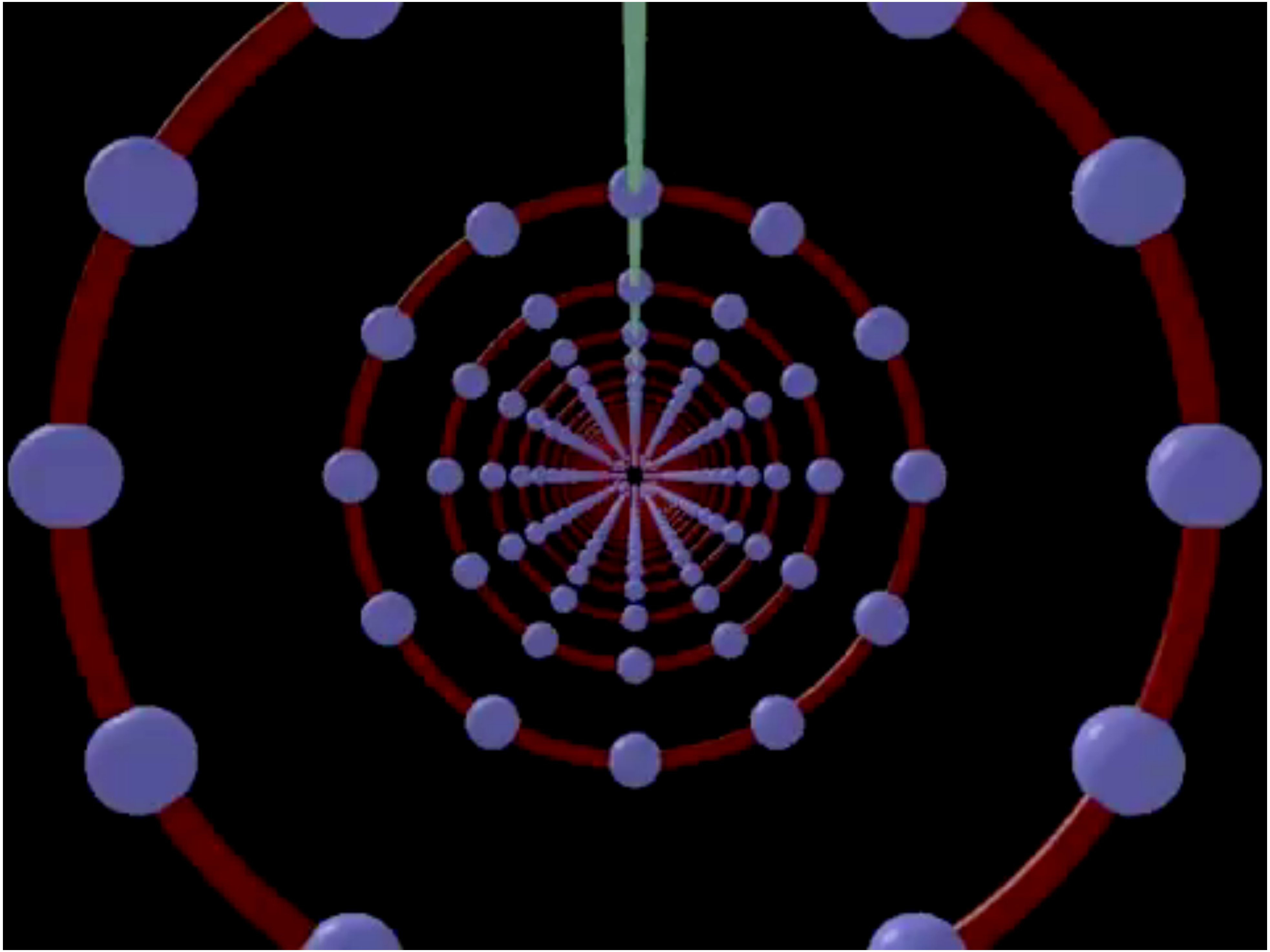
Plus
polarization



Cross
polarization



The so-called “electromagnetic theory of light” has not helped us hitherto . . it seems to me that it is rather a backward step . . . the one thing about it that seems intelligible to me, I do not think is admissible . . That there should be an electric displacement perpendicular to the line of propagation’ **Lord Kelvin**

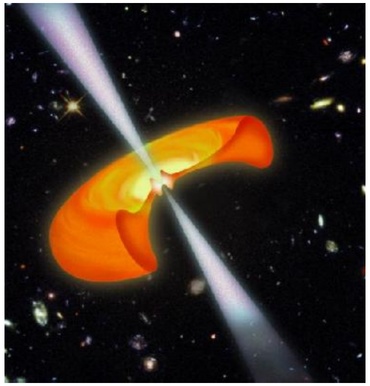


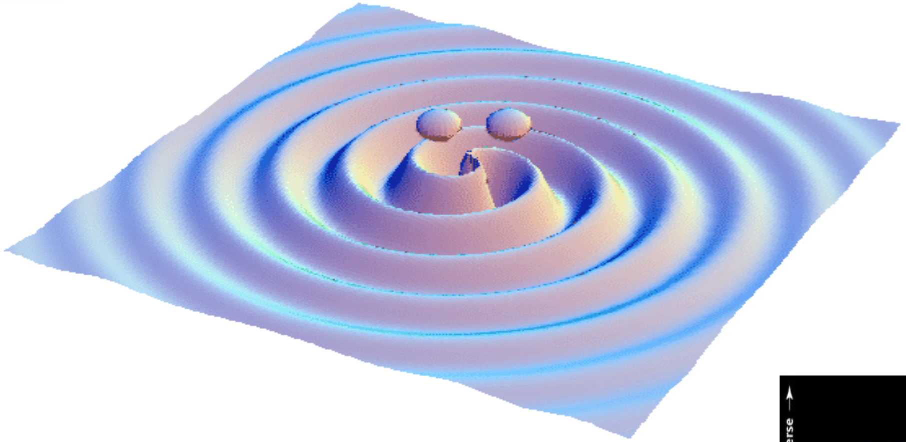
GW OBJECTIVES

FIRST DETECTION
test Einstein prediction

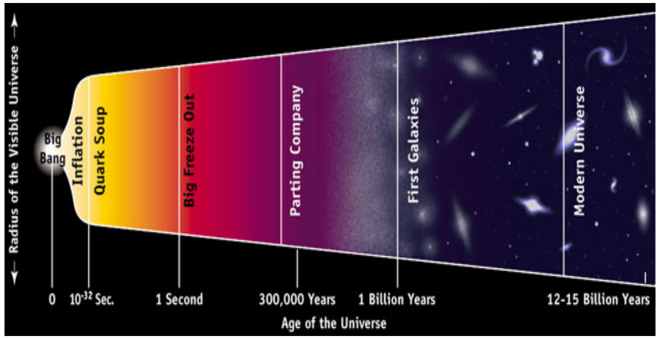
$$\mathbf{G} = \frac{8\pi G}{c^4}\mathbf{T}$$

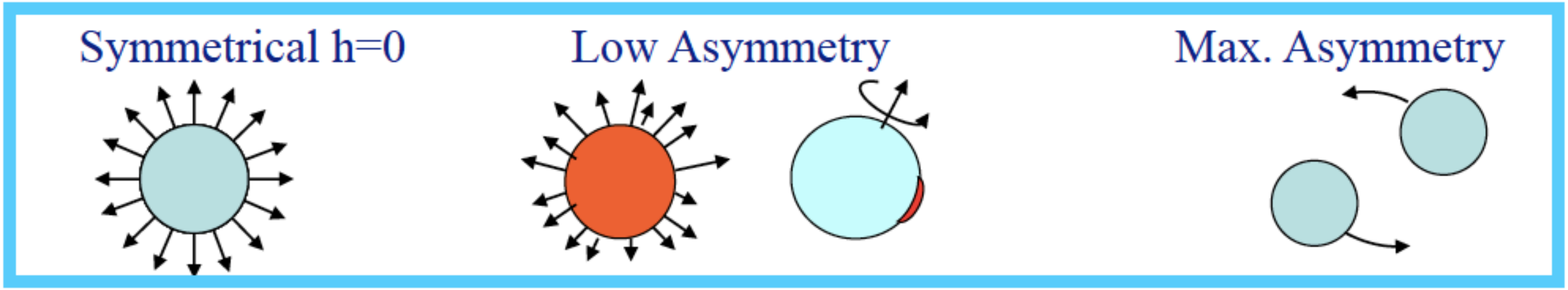
ASTRONOMY & ASTROPHYSICS
look beyond the visible,
understand Black Holes,
Neutron Stars and supernovae
understand GRB





COSMOLOGY
the Planck time:
look as back in time as theorist can conceive



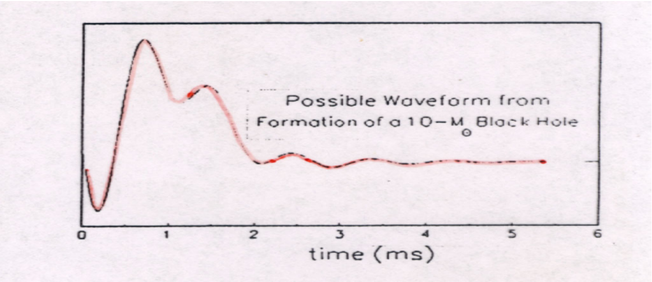


Observing gravitational radiation gives unique information complementary to those derived by em observations

- em radiation is the result of an incoherent combination of the radiation emitted by electrons, atoms and molecules ←→ gravitational radiation is the result of a coherent mass acceleration.

- em radiation interacts strongly with matter, and is absorbed significantly while travelling toward the detector ←→ gravitational radiation propagates “freely” and can bring us info from the innermost region of a star

GWs can reveal features of their sources that cannot be learnt by electromagnetic, cosmic rays or neutrino studies (Kip Thorne)

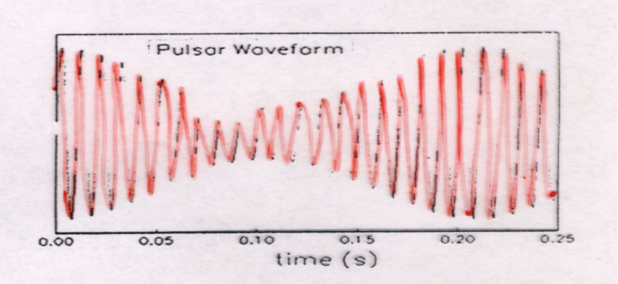


SUPERNOVAE.

If the collapse core is non-symmetrical, the event can give off considerable radiation in a millisecond timescale.

Information

Inner detailed dynamics of supernova
See NS and BH being formed
Nuclear physics at high density

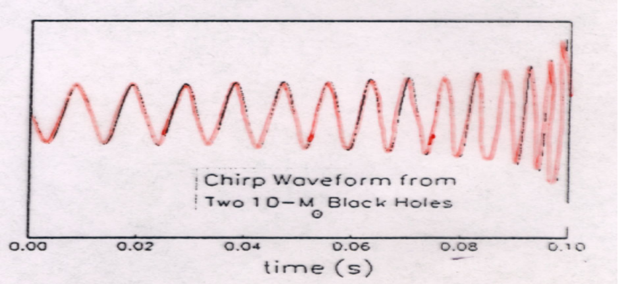


SPINNING NEUTRON STARS.

Pulsars are rapidly spinning neutron stars. If they have an irregular shape, they give off a signal at constant frequency (prec./Dpl.)

Information

Neutron star locations near the Earth
Neutron star Physics
Pulsar evolution

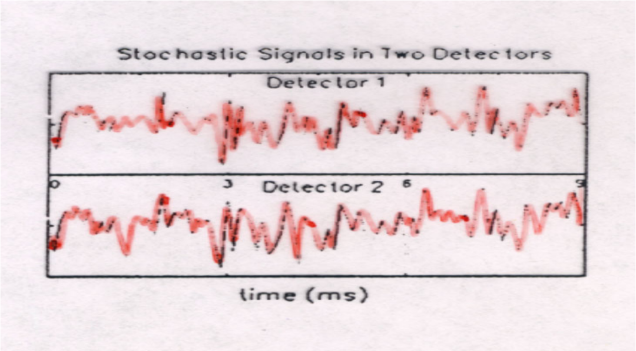


COALESCING BINARIES.

Two compact objects (NS or BH) spiraling together from a binary orbit give a chirp signal, whose shape identifies the masses and the distance

Information

Masses of the objects
BH identification
Distance to the system
Hubble constant
Test of strong-field general relativity

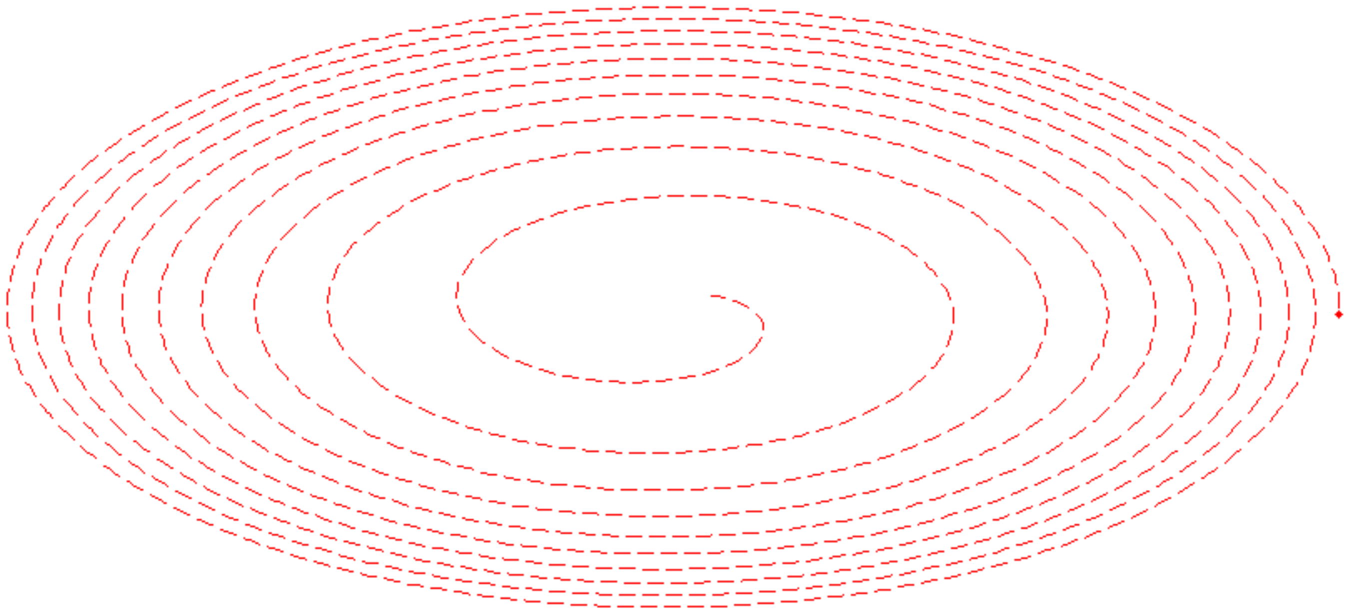


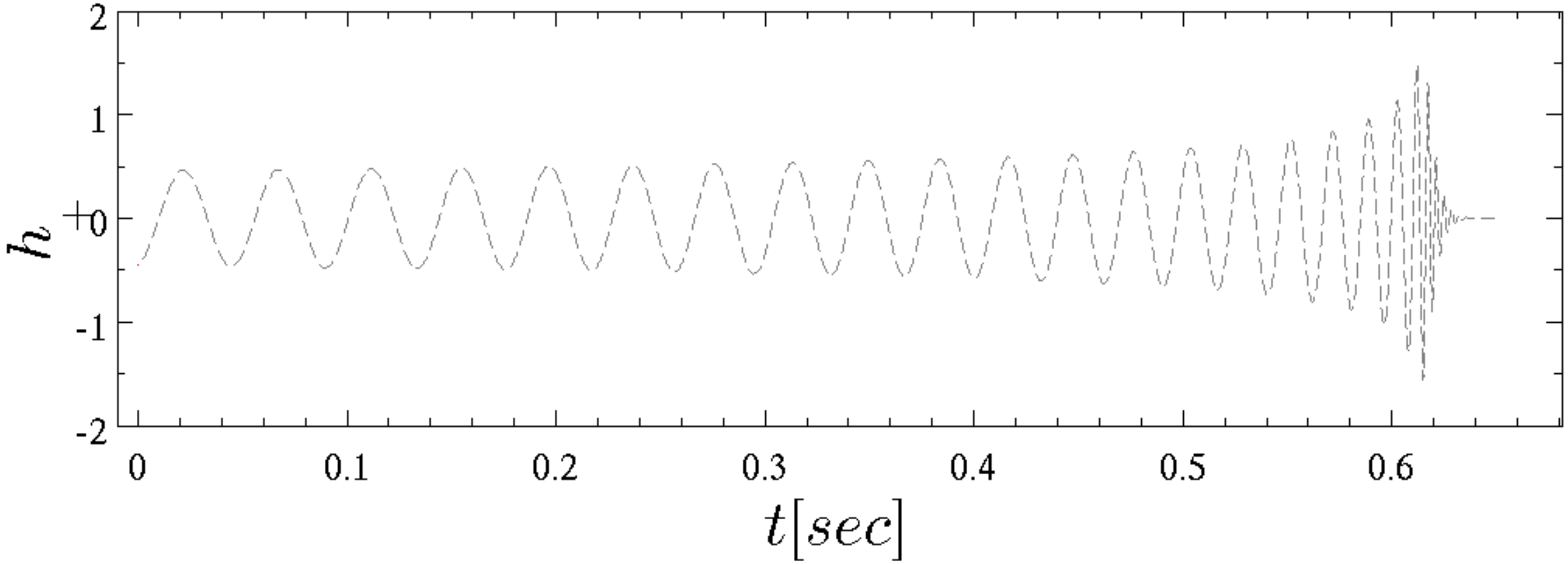
STOCHASTIC BACKGROUND.

Random background, relic of the early universe and depending on unknown particle physics. It will look like noise in any one detector, but two detectors will be correlated.

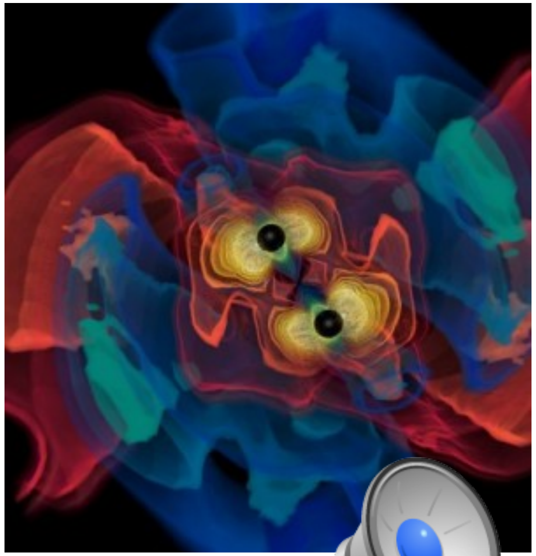
Information

Confirmation of Big Bang, and inflation
Unique probe to the Planck epoch
Existence of cosmic strings




2
1
0
-1
-2
h_+
0
0.1
0.2
0.3
0.4
0.5
0.6
$t[sec]$

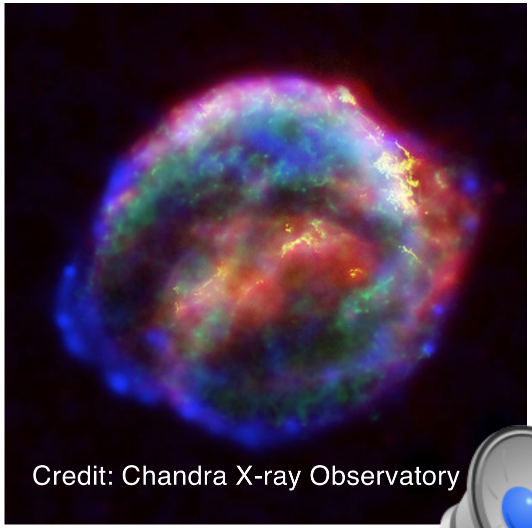
Astrophysical sources of gravitational waves



Credit: AEI, CCT, LSU

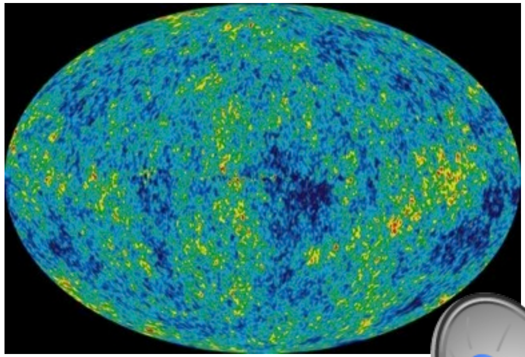
Compact

Binaries



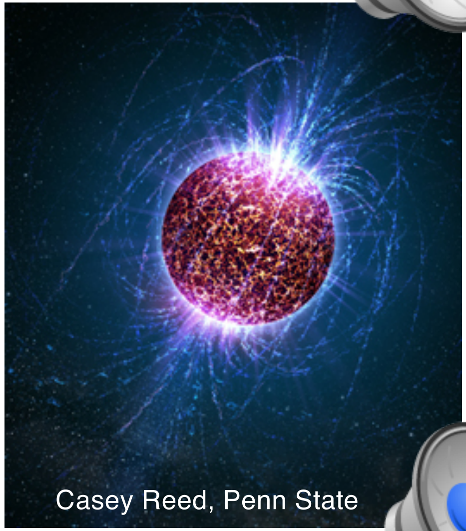
Credit: Chandra X-ray Observatory

Supernovae



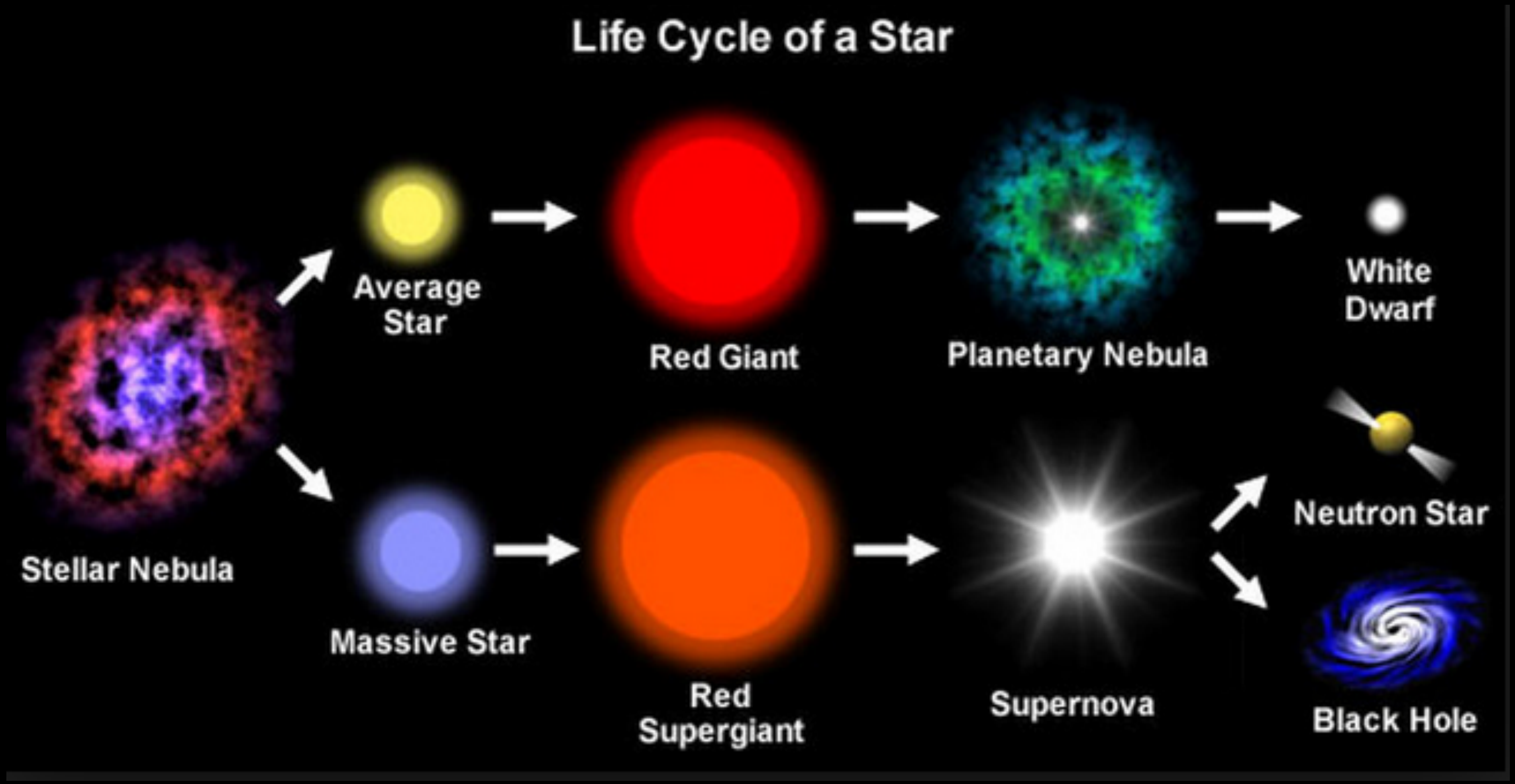
NASA/WMAP Science Team

Cosmic Gravitational-wave Background

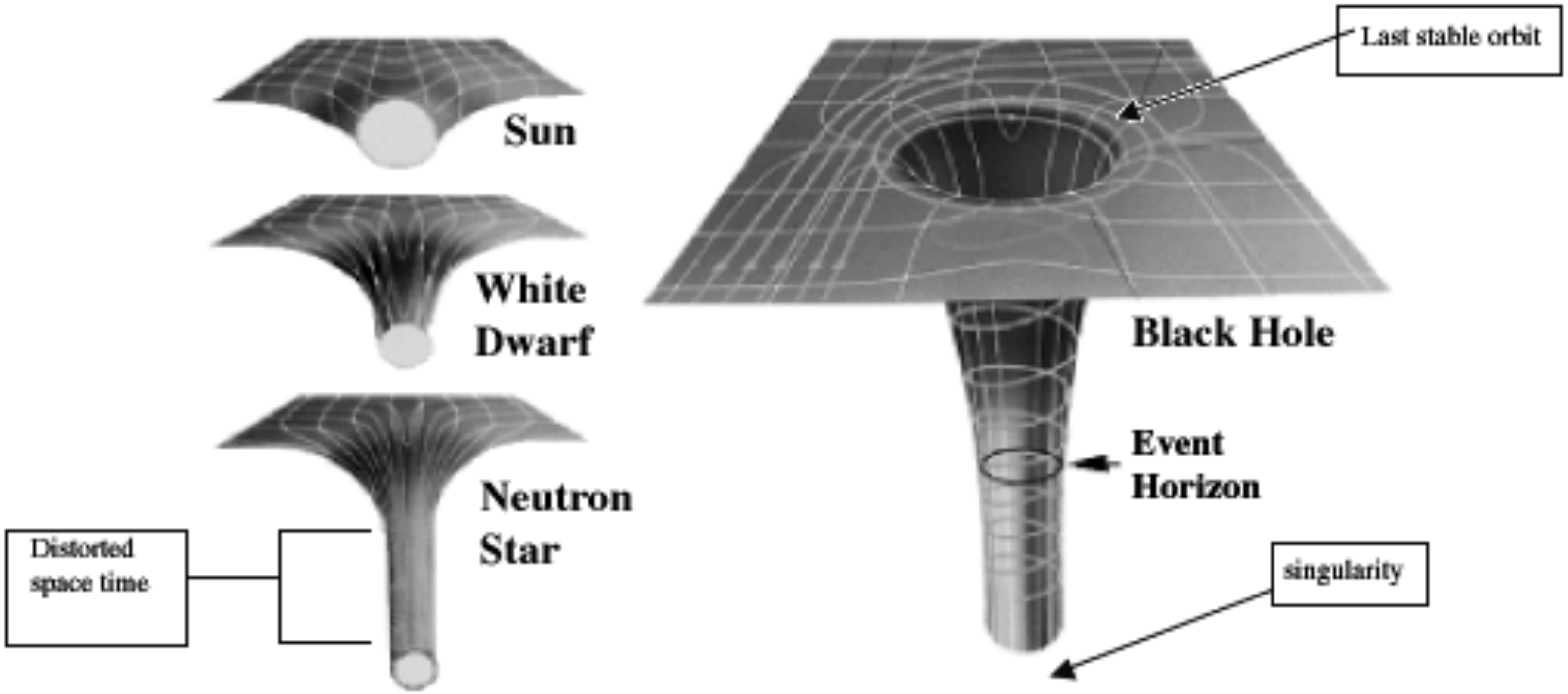


Casey Reed, Penn State

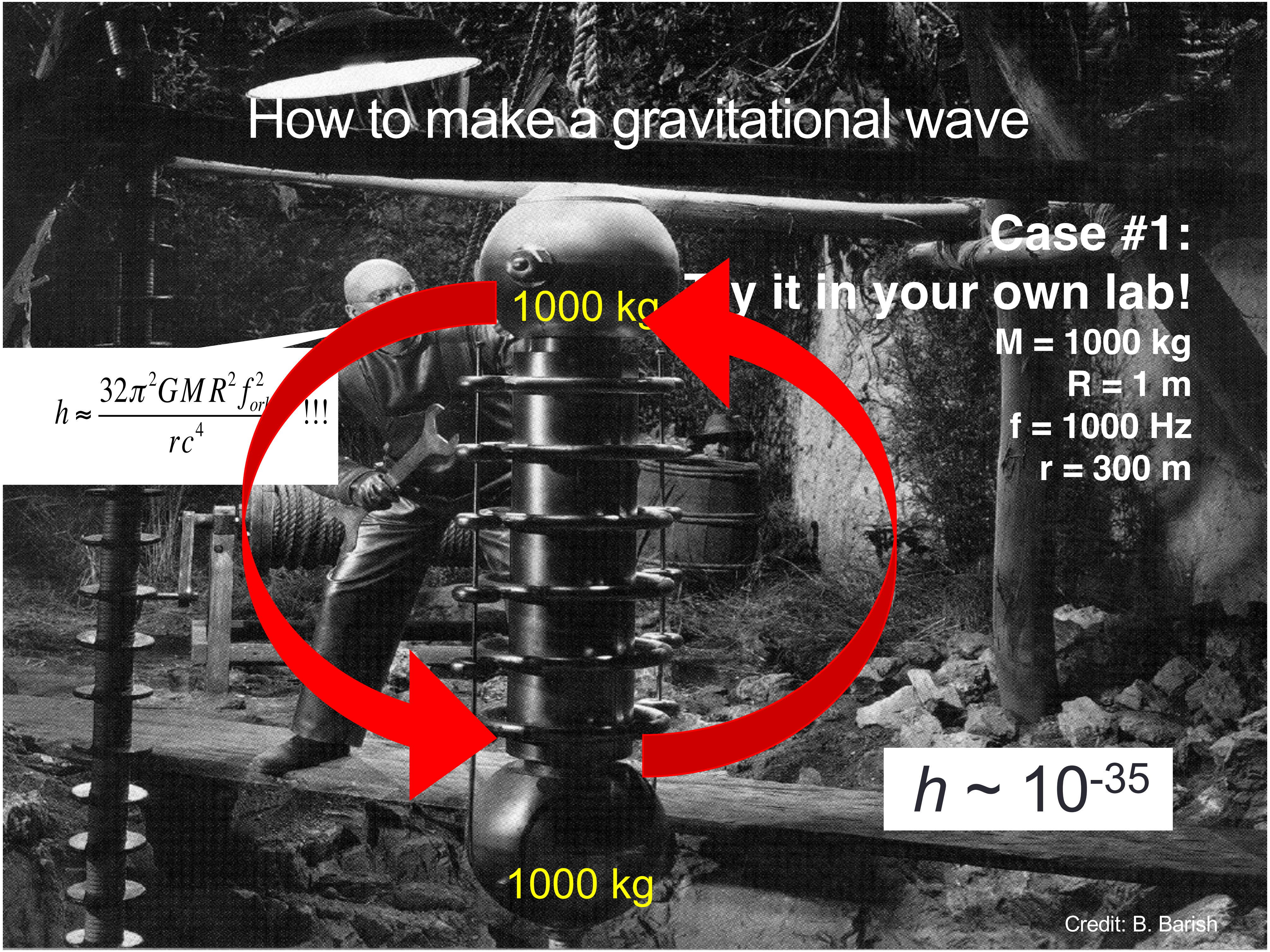
Spinning neutron stars



Life Cycle of a Star


Sun
White Dwarf
Neutron Star
Distorted space time
Last stable orbit
Black Hole
Event Horizon
singularity

How to make a gravitational wave



1000 kg

1000 kg

$$h \approx \frac{32\pi^2 G M R^2 f_{orb}^2}{rc^4} \text{ !!!}$$

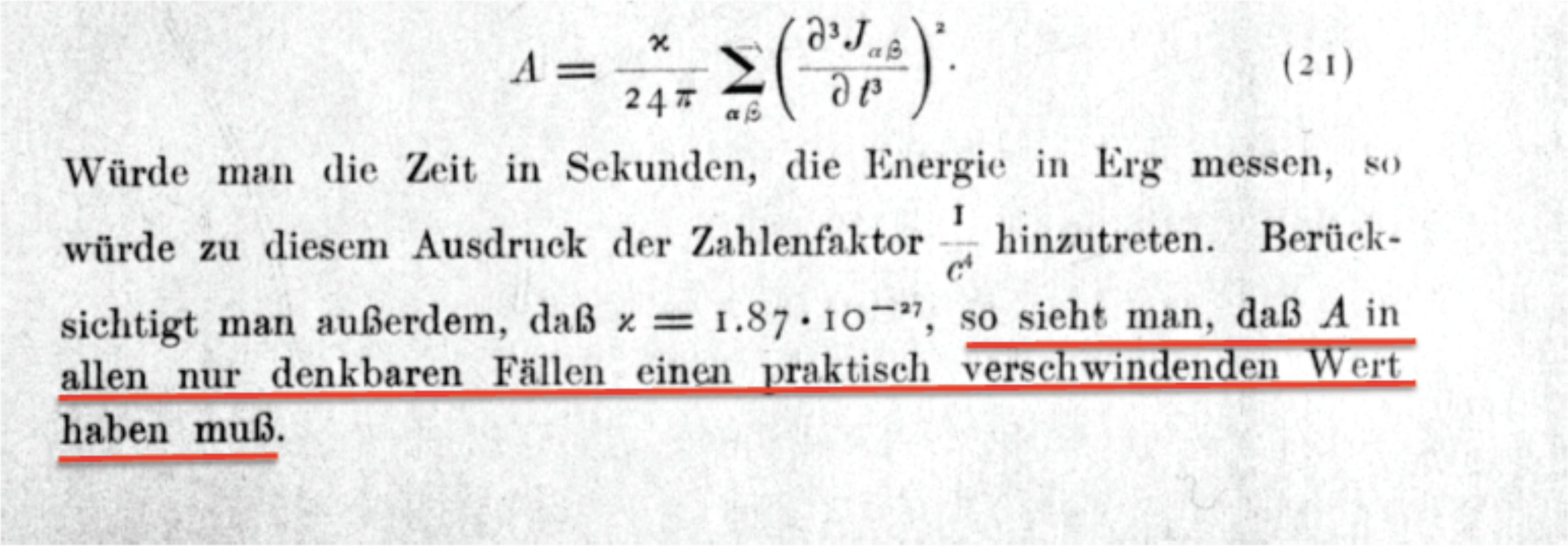
Case #1:

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

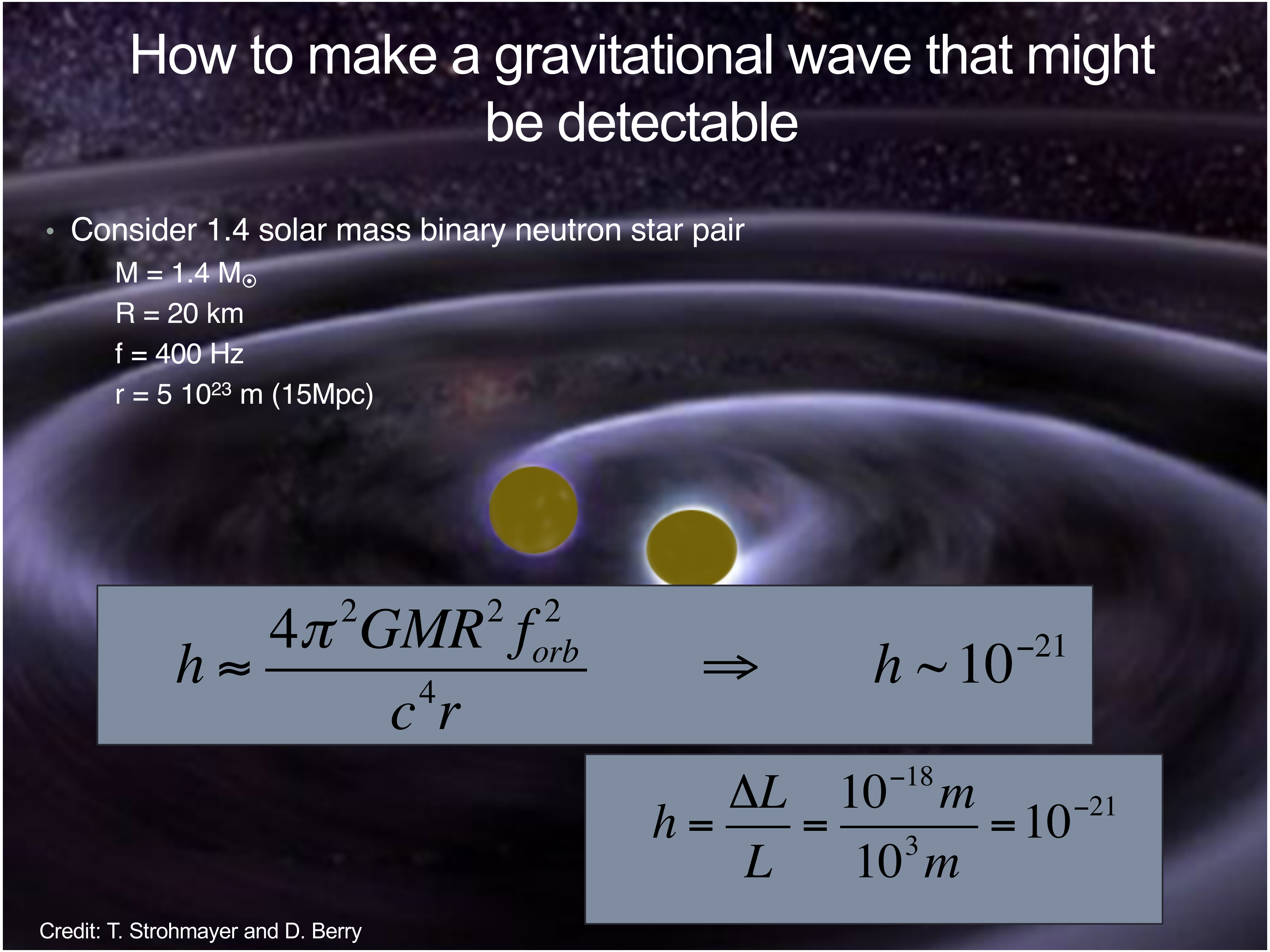


$$A = \frac{\varkappa}{24\pi}\sum_{\alpha\beta}\left(\frac{\partial^3 J_{\alpha\beta}}{\partial t^3}\right)^2. \qquad (21)$$

Würde man die Zeit in Sekunden, die Energie in Erg messen, so würde zu diesem Ausdruck der Zahlenfaktor $\frac{1}{c^4}$ hinzutreten. Berücksichtigt man außerdem, daß $\varkappa = 1.87 \cdot 10^{-27}$, so sieht man, daß A in allen nur denkbaren Fällen einen praktisch verschwindenden Wert haben muß.

“.....in any case one can think of A will have a practically vanishing value.”

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)

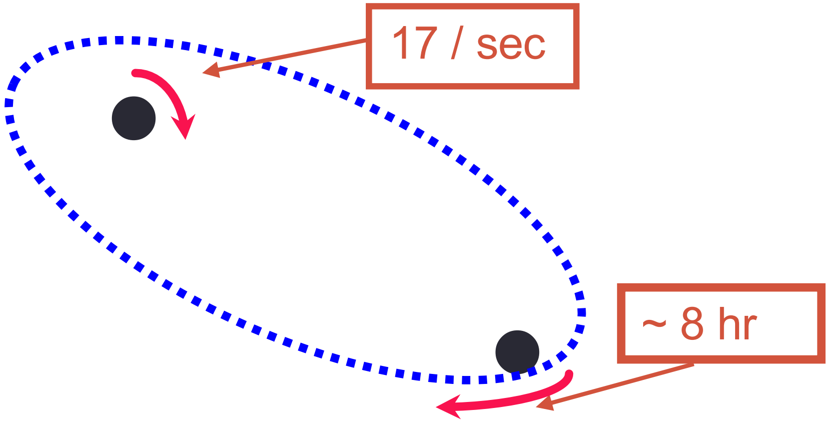
$$h \approx \frac{4\pi^2 G M R^2 f_{orb}^2}{c^4 r} \qquad \Rightarrow \qquad h \sim 10^{-21}$$

$$h = \frac{\Delta L}{L} = \frac{10^{-18}\,m}{10^3\,m} = 10^{-21}$$

Credit: T. Strohmayer and D. Berry

Indirect evidence for GWs: PSR 1913+16

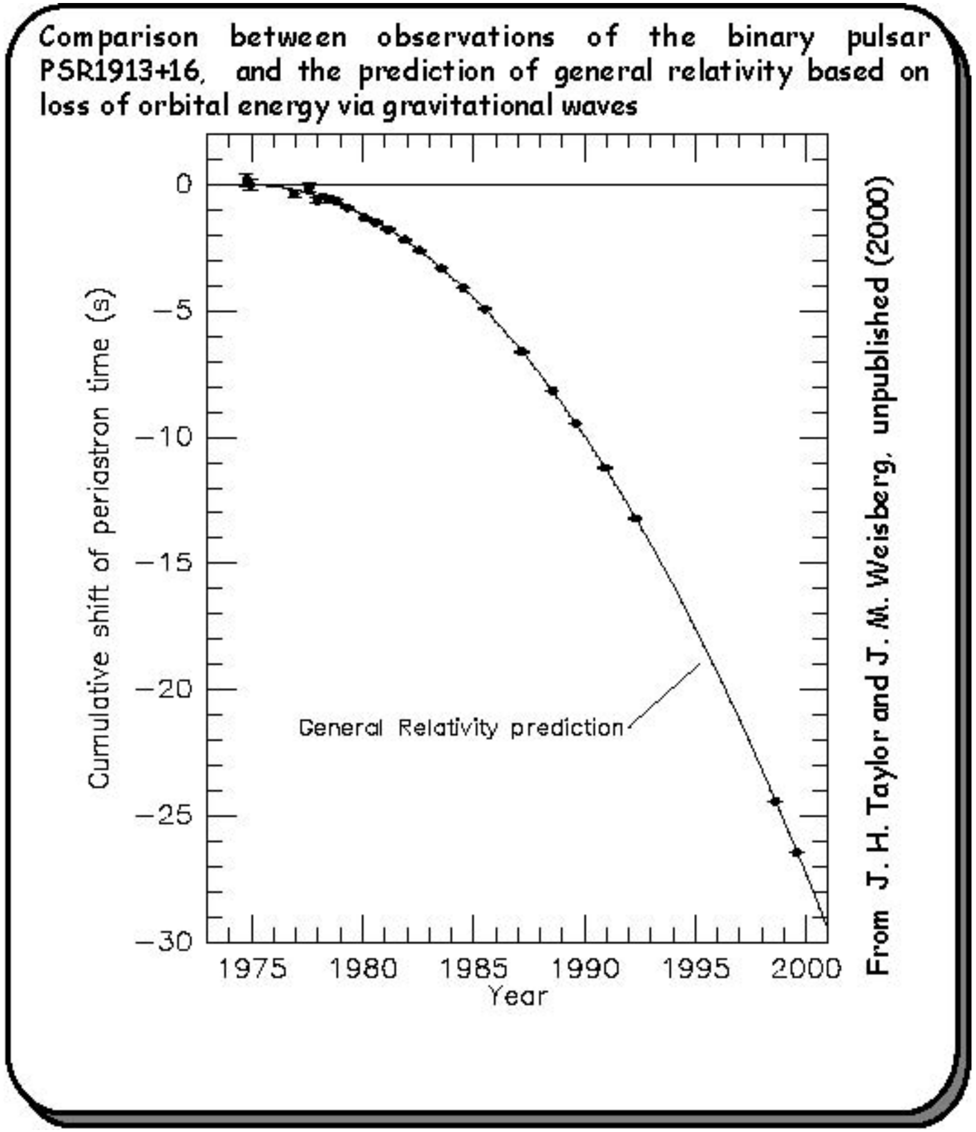
Joseph Taylor Russell Hulse



17 / sec

~ 8 hr

They will merge in 300 million years



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

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

- **GWs are detectable in principle**

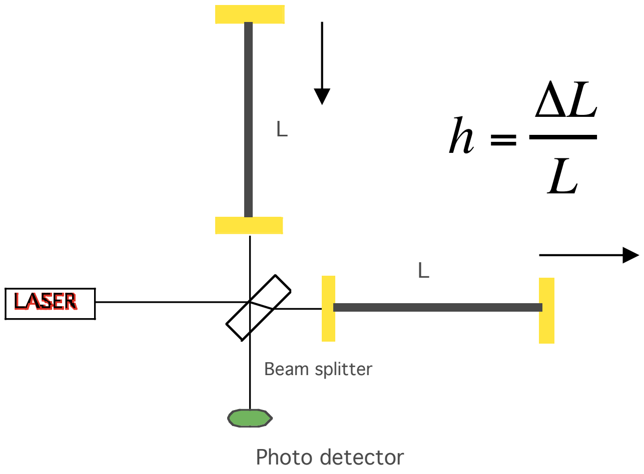
  The equation for geodetic deviation is the basis for all experimental attempts to detect GWs:

$$\frac{d^2\delta l^j}{dt^2} = -R_{joko} l^k = \frac{1}{2}\frac{\partial^2 h_{jk}}{\partial t^2} l^k$$

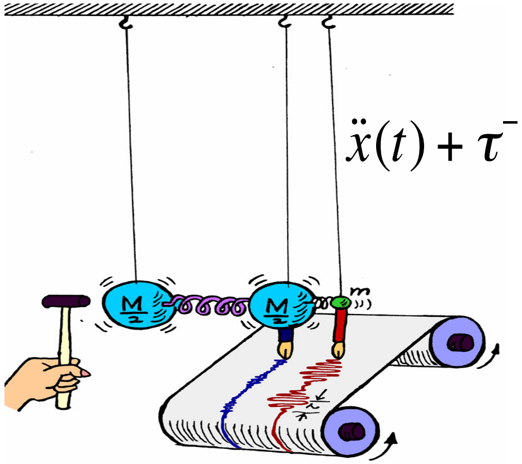
- **GWs change (δl) the distance (l) between freely-moving particles in empty space.**

  They change the proper time taken by light to pass to and fro fixed points in space

  In a system of particles linked by non gravitational (ex.: elastic) forces, GWs perform work and deposit energy in the system

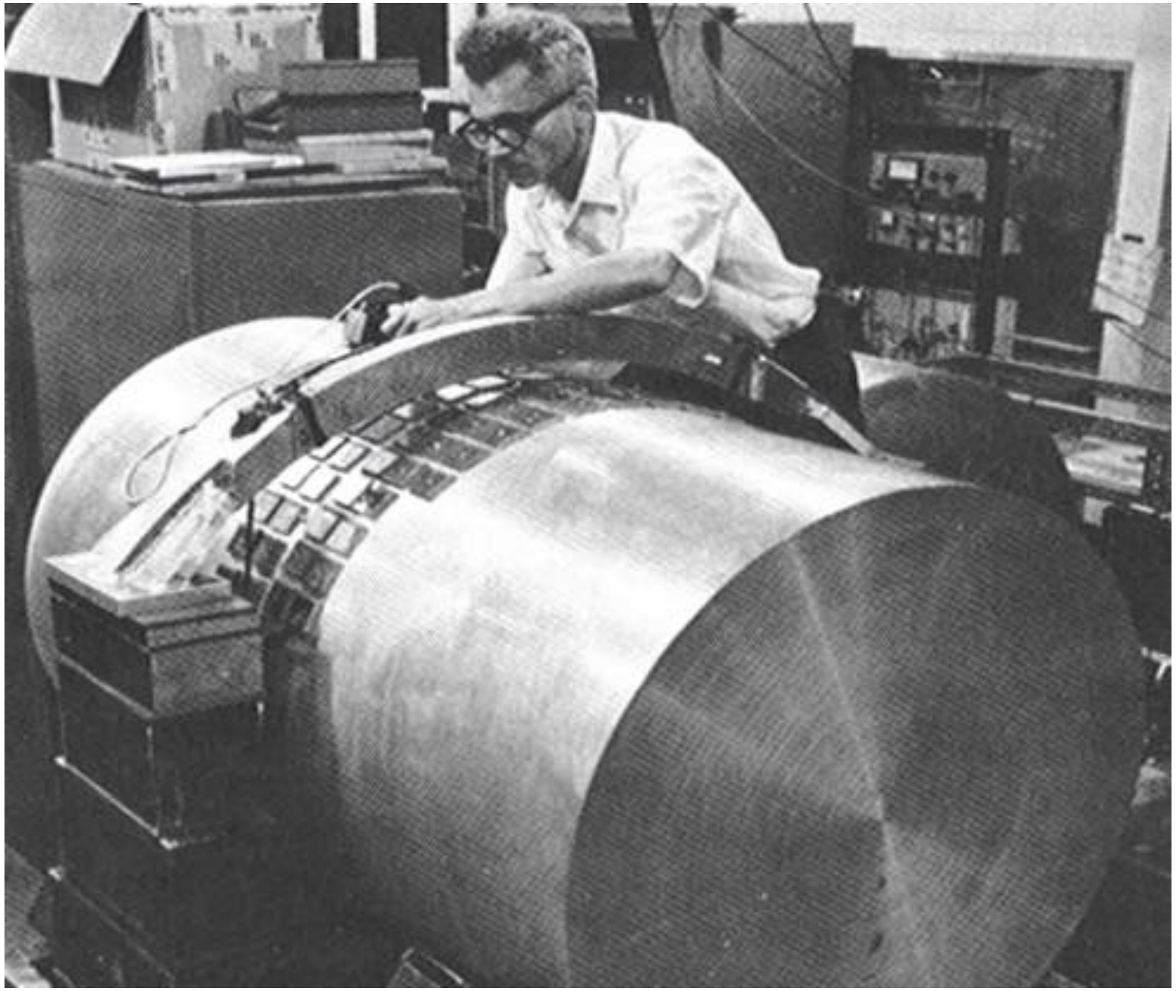


$$h = \frac{\Delta L}{L}$$

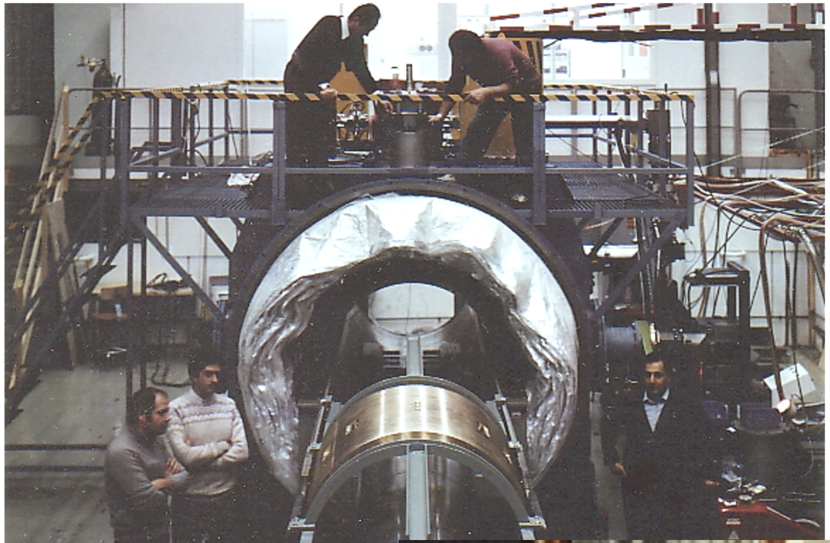


$$\ddot{x}(t) + \tau^{-1}\dot{x}(t) + \omega_0^2 x(t) = \frac{l}{2}\ddot{h}(t)$$

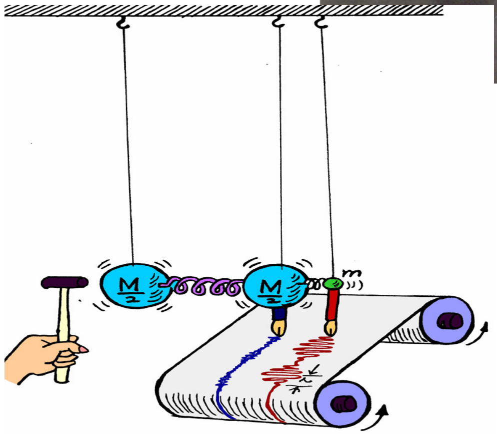
Weber’s bar

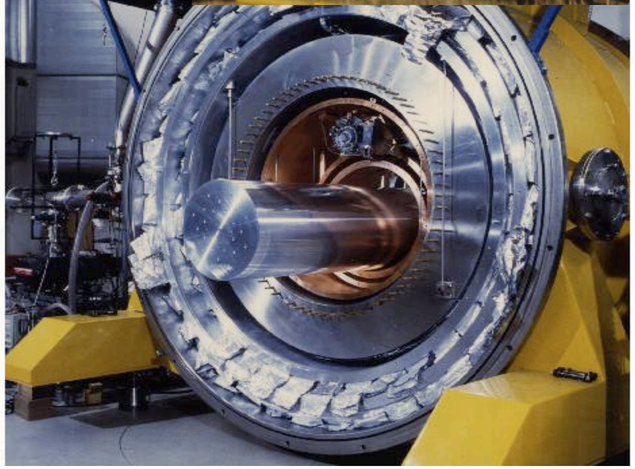


Explorer
CERN



Nautilus, LNF



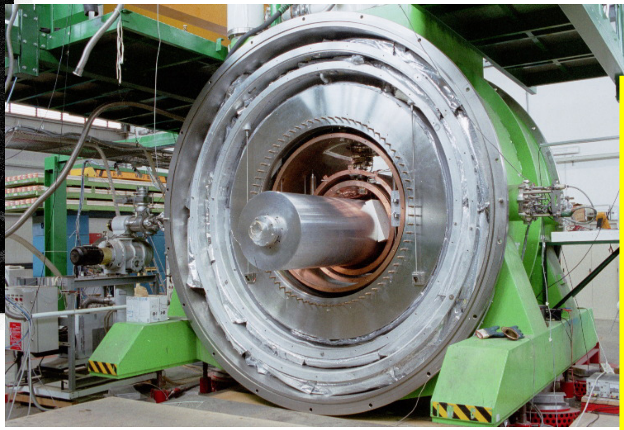


Auriga, LNL

Some perspective: 50 years of attempts at detection:

Since the pioneering work of Joseph Weber in the ‘60, the search for Gravitational Waves has never stopped, with an increasing effort of manpower and ingenuity:

60’: Joe Weber pioneering work

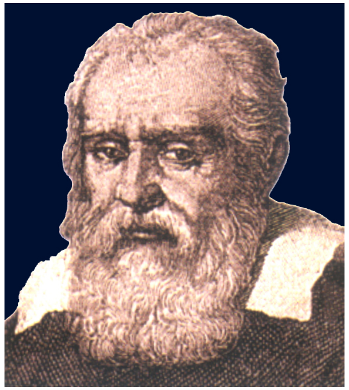


90’: Cryogenic Bars

2000’ - : Large Interferometers

1997: GWIC was formed

2nd lecture



Experimental gravitational physicists are heirs to several great traditions:

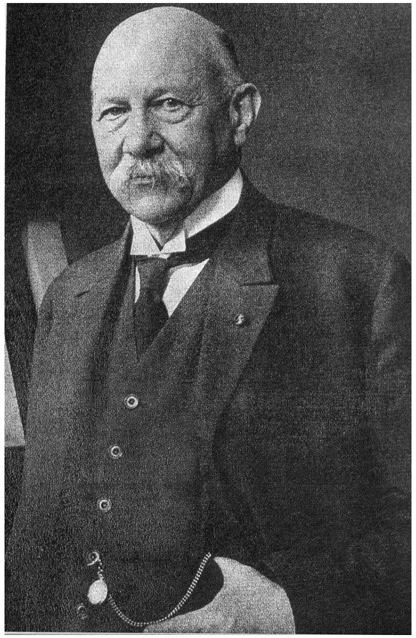
- High precision mechanical experiments (Cavendish, Eotvos, Dicke..)
  detection of weak forces applied on mechanical test bodies

- High precision optical measurements (Michelson, laser developers…)

- Operation of ultraprecise e-m measurement systems (microwave pioneers of World War II)

- Low temperature physics (K. Onnes)
  superfluids and superconductors technology

UNIVERSITY OF MARYLAND

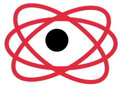


Scanned at the American Institute of Physics

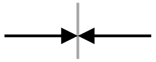
How Small 10^{-18} meter is?

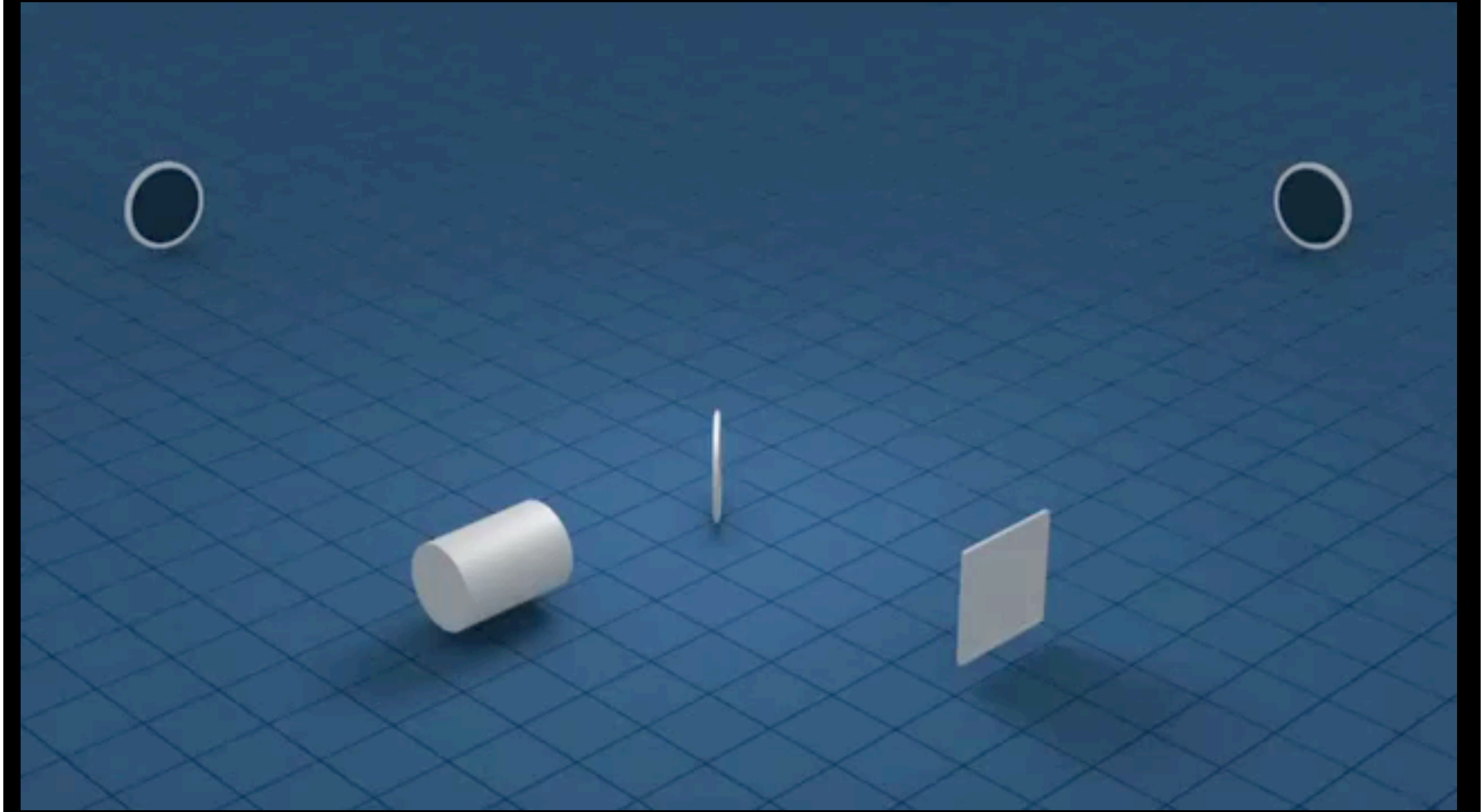

One meter

÷10,000 
Human hair ~ 10^{-4} m (0.1 mm)

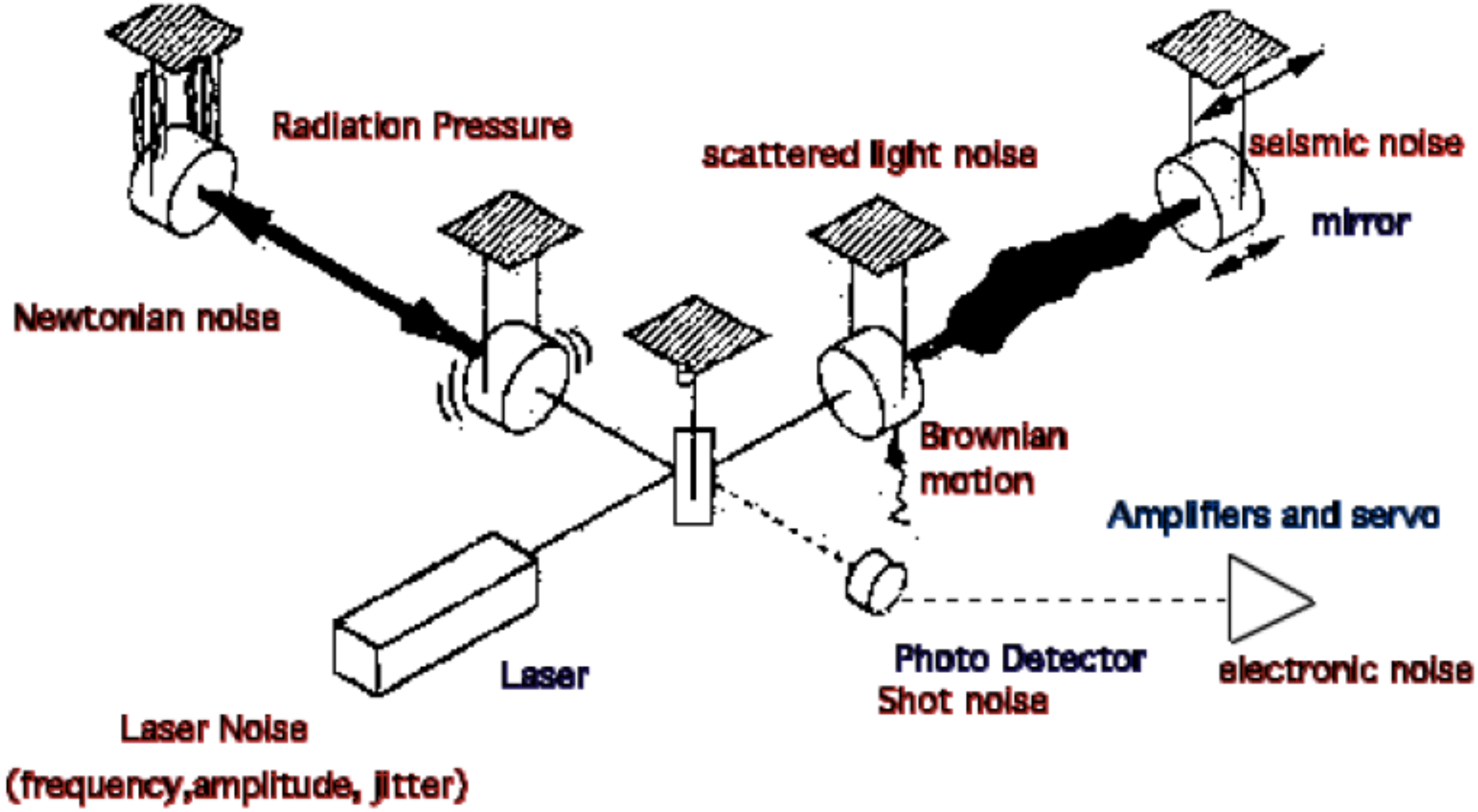
÷1,000,000 
Atomic diameter 10^{-10} m

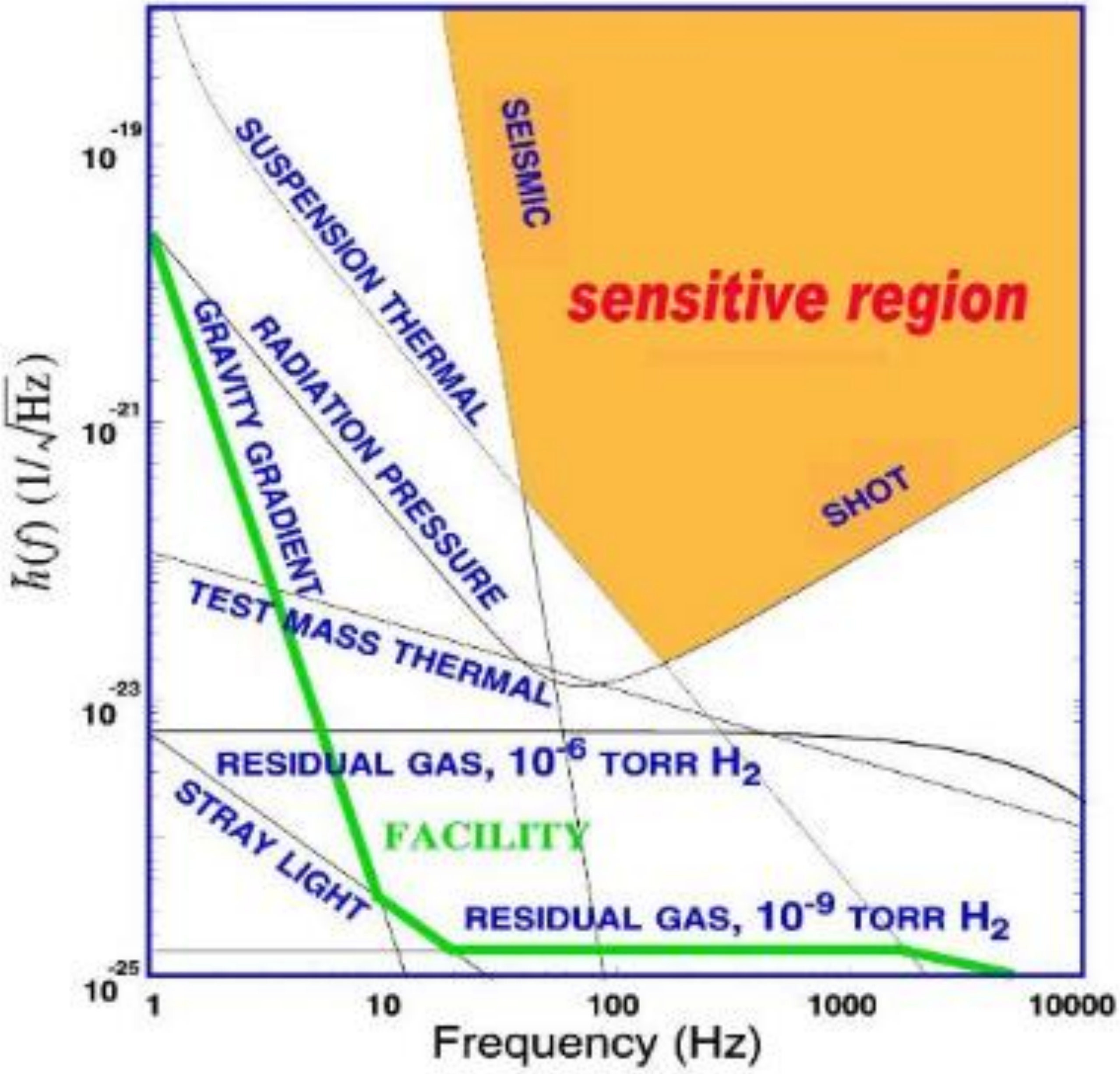
÷100,000 
Nuclear diameter 10^{-15} m

÷1,000 
GW detector 10^{-18} m

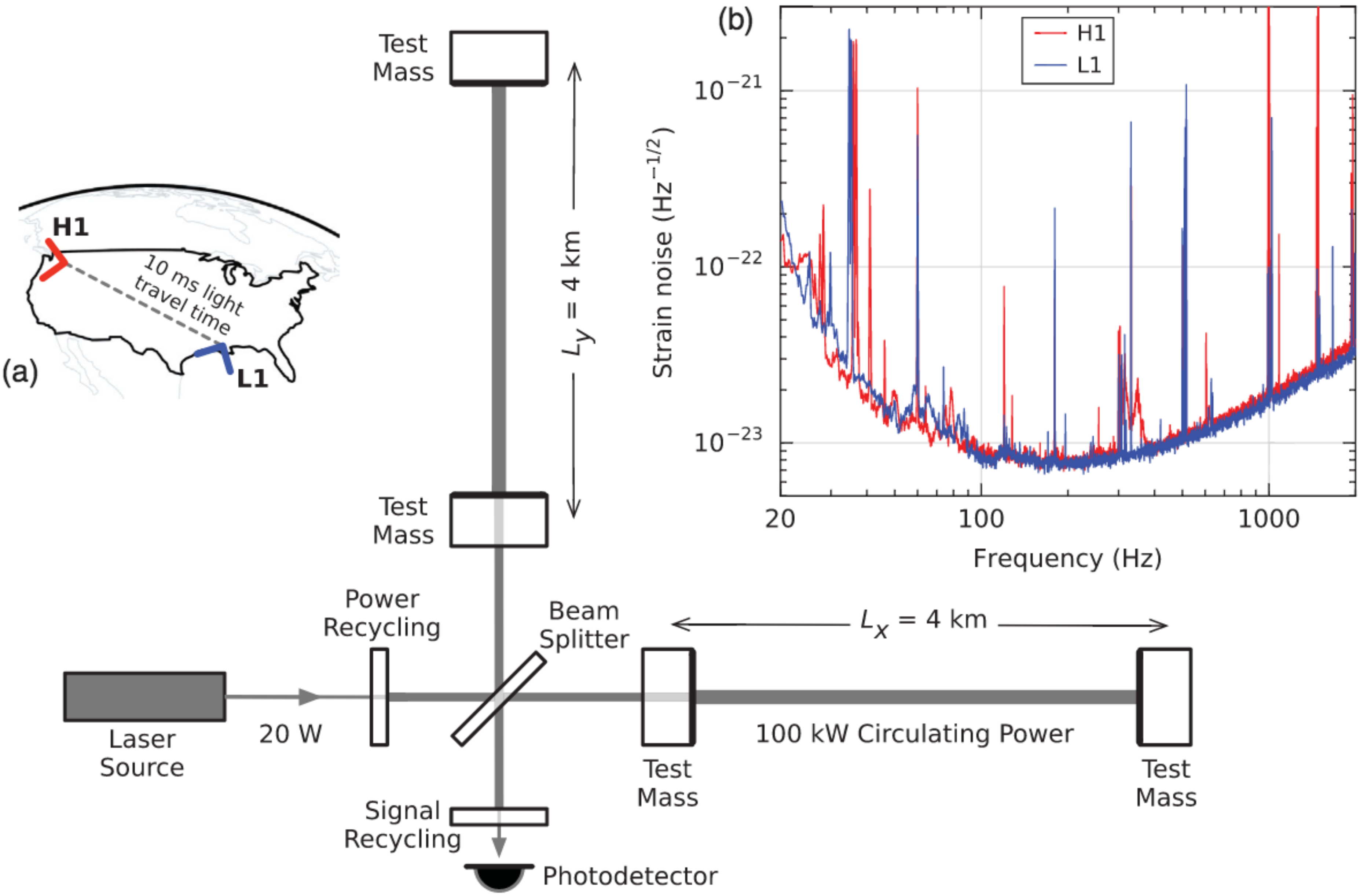


Main noise sources in interferometric GW detectors

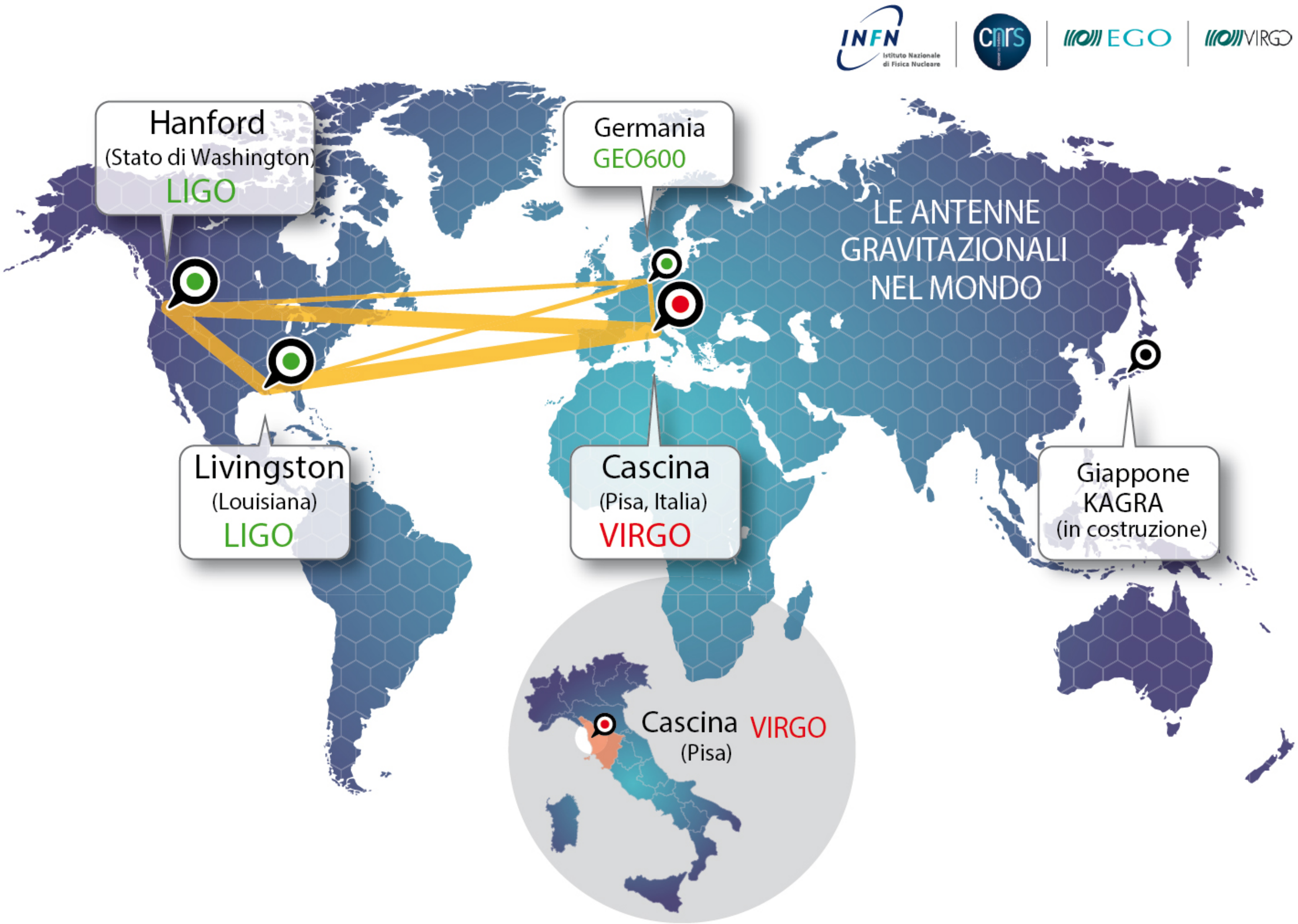




E. Coccia - 2016


(a)
H1
L1
10 ms light travel time
(b)
H1
L1
Strain noise (Hz$^{-1/2}$)
10^{-21}
10^{-22}
10^{-23}
20
100
1000
Frequency (Hz)
Test Mass
Test Mass
L_y = 4 km
Power Recycling
Beam Splitter
L_x = 4 km
Laser Source
20 W
100 kW Circulating Power
Test Mass
Test Mass
Signal Recycling
Photodetector

Global Network of Detectors



LIGO Scientific Collaboration

University of Maryland 18 56
MICHIGAN
University of Strathclyde
ACIGA
Loyola University New Orleans
Montana State University
PAH
University of Washington
ANU
The Australian National University
Montclair State University
Syracuse University Founded AD 1870
清華大學
Tsinghua University
Trinity University
San José State University
University of Wisconsin
UW Milwaukee
부산대학교
Pusan National University
The University of Western Australia
University of Glasgow
NASA
Goddard Space Flight Center
Università degli Studi del Sannio
LSU
UTB TSC
R·I·T
The University of Melbourne
KISTI
Andrews University
Massachusetts Institute of Technology
Southeastern
California Institute of Technology 1891
Northwestern University
Hanyang University 한양 1939
University of Cambridge
The University of Adelaide Australia
PAN
Moscow State University
Embry-Riddle Aeronautical University
Lund University
ISI
University of New Hampshire
PennState 1855
Carleton College
Geo 600
Cardiff University
California State University Fullerton
Washington State University
국가수리과학연구소
National Institute for Mathematical Sciences
Charles Sturt University
Universitat de les Illes Balears
UIB
UF University of Florida
Perimeter Institute
CITA-ICAT
University of Southampton
Seoul National University
The University of Mississippi 1848
University of Rochester
NAOJ
University of Minnesota
Universität Hannover
Southern University and Agricultural & Mechanical College
Hobart and William Smith Colleges
Science & Technology Facilities Council
Rutherford Appleton Laboratory

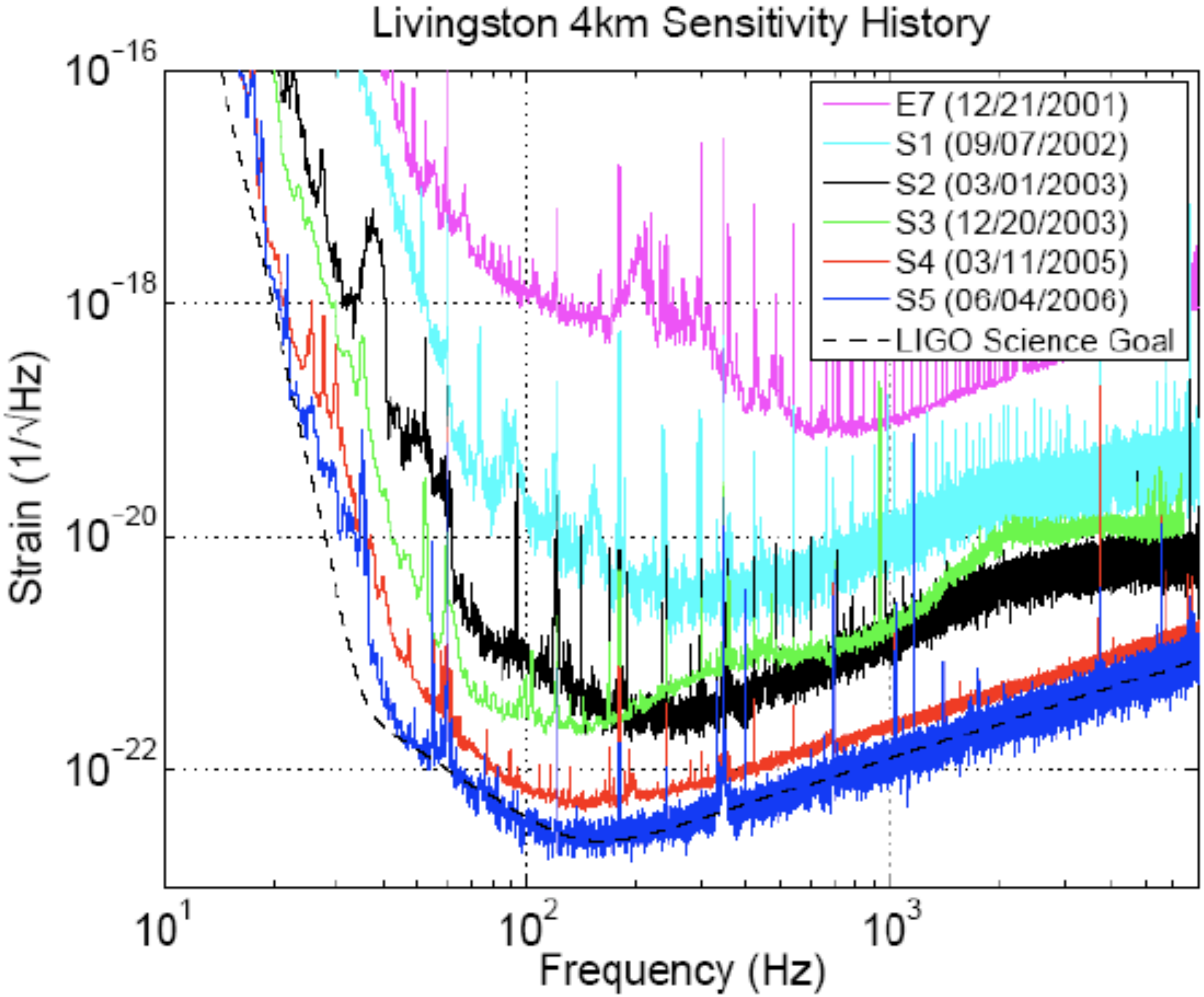
www.ligo.org

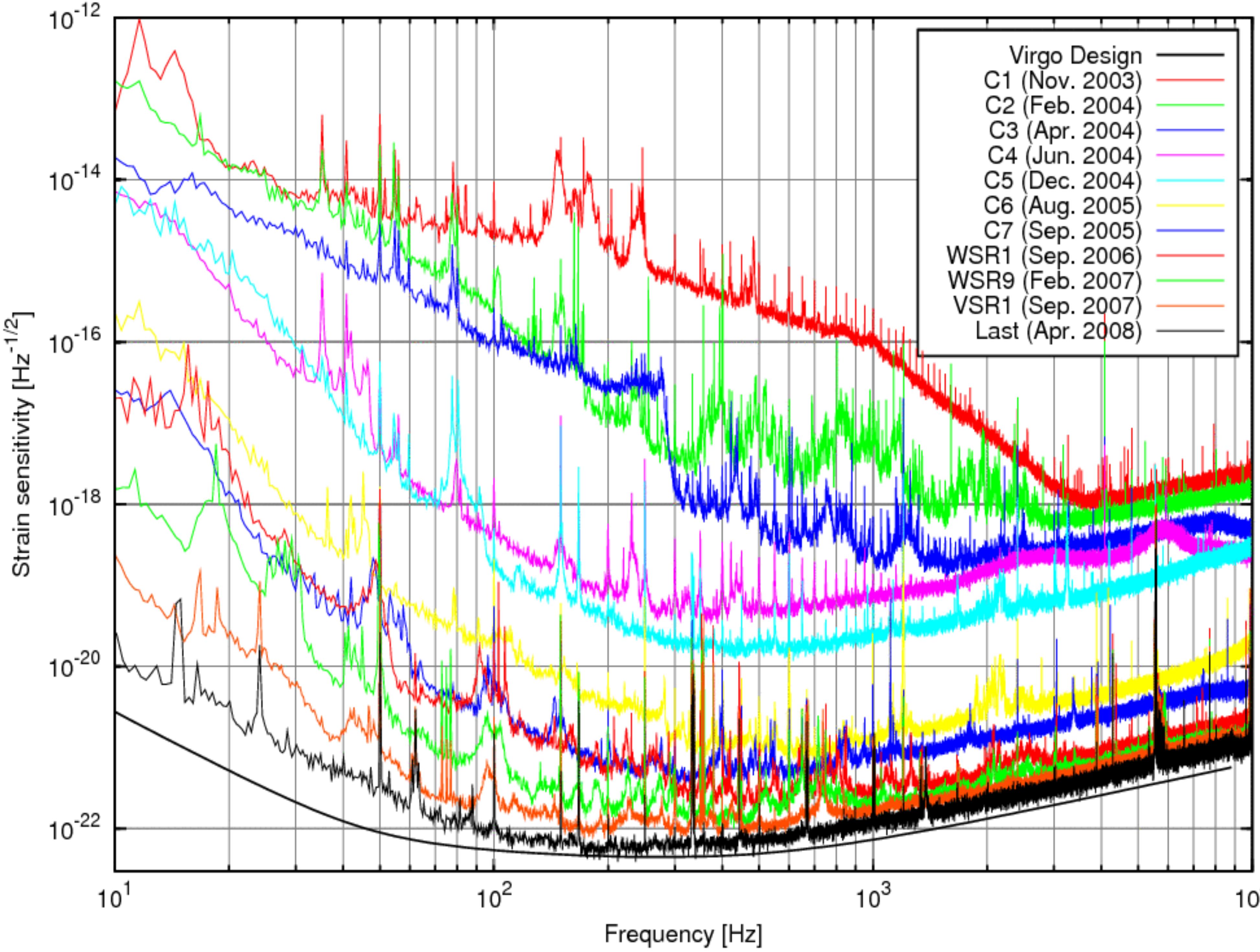
900+ members, 80+ institutions, 16 countries

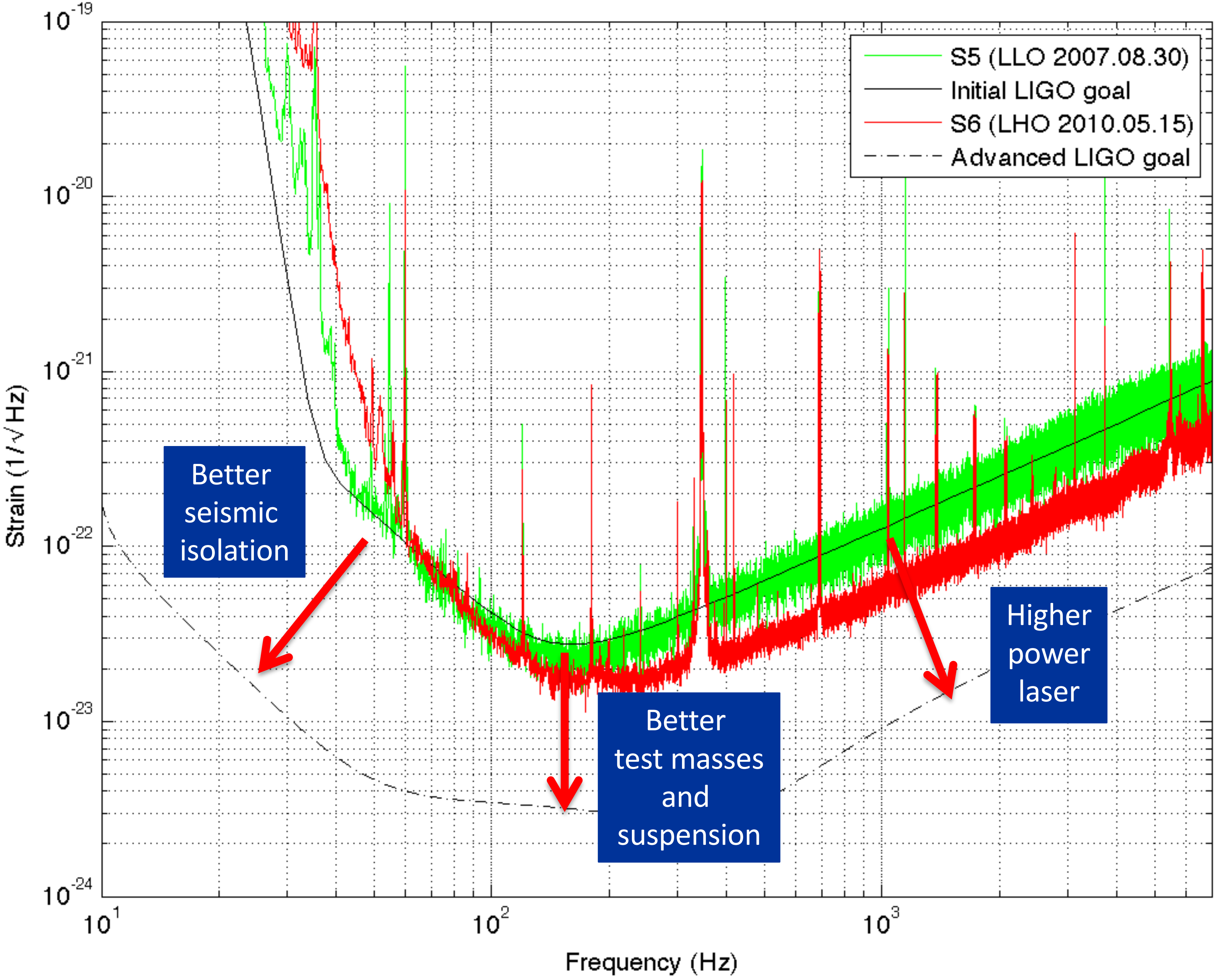
Virgo Collaboration

- 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
Gran Sasso Science Institute


Livingston 4km Sensitivity History
Strain (1/√Hz)
10^{-16}
10^{-18}
10^{-20}
10^{-22}
10^{1}
10^{2}
10^{3}
Frequency (Hz)
E7 (12/21/2001)
S1 (09/07/2002)
S2 (03/01/2003)
S3 (12/20/2003)
S4 (03/11/2005)
S5 (06/04/2006)
LIGO Science Goal

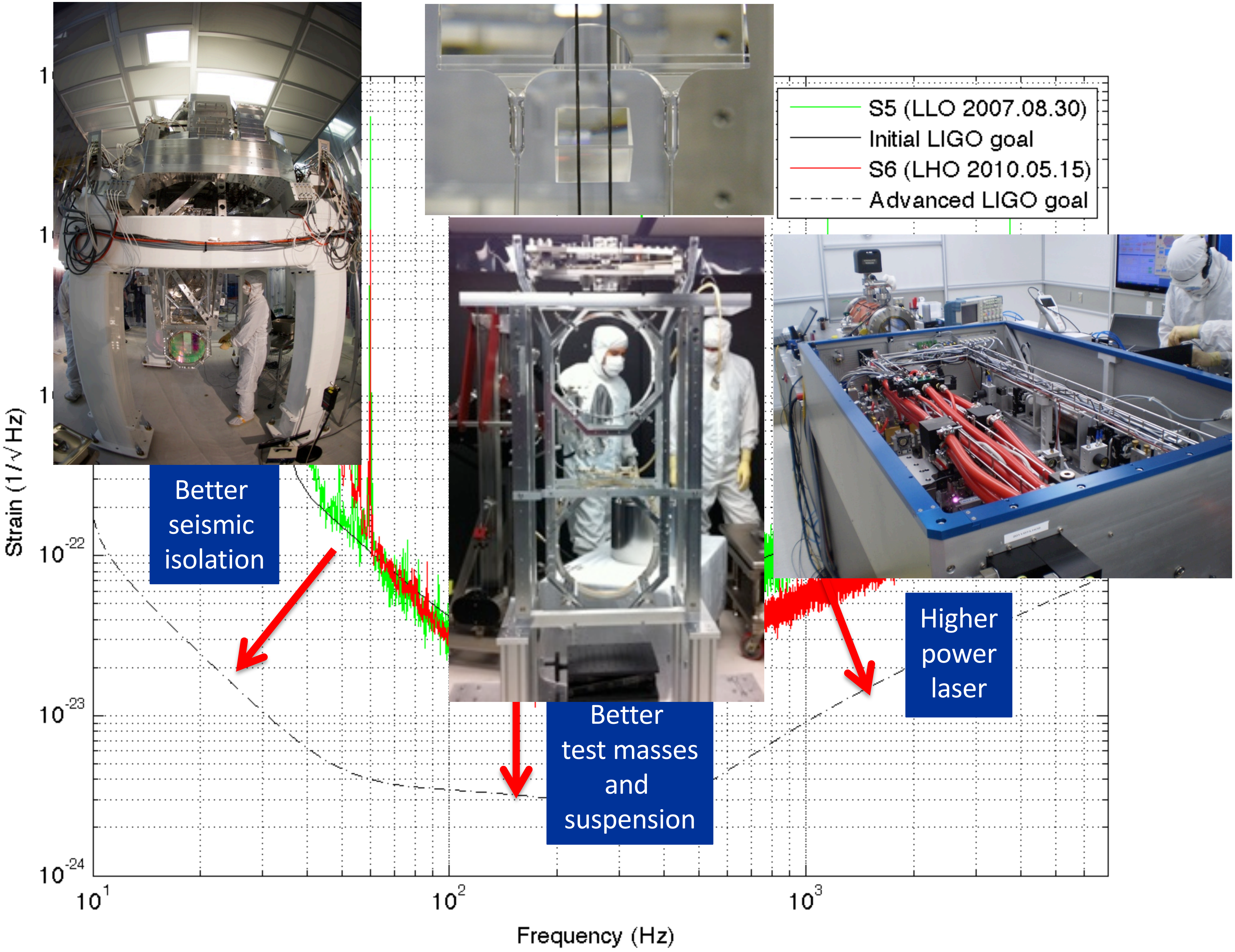

Virgo Design
C1 (Nov. 2003)
C2 (Feb. 2004)
C3 (Apr. 2004)
C4 (Jun. 2004)
C5 (Dec. 2004)
C6 (Aug. 2005)
C7 (Sep. 2005)
WSR1 (Sep. 2006)
WSR9 (Feb. 2007)
VSR1 (Sep. 2007)
Last (Apr. 2008)
Strain sensitivity [Hz$^{-1/2}$]
Frequency [Hz]
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
10^{-22}
10^{1}
10^{2}
10^{3}
10^{4}



Better seismic isolation

Better test masses and suspension

Higher power laser



Better seismic isolation

Better test masses and suspension

Higher power laser

GW150914: the signal

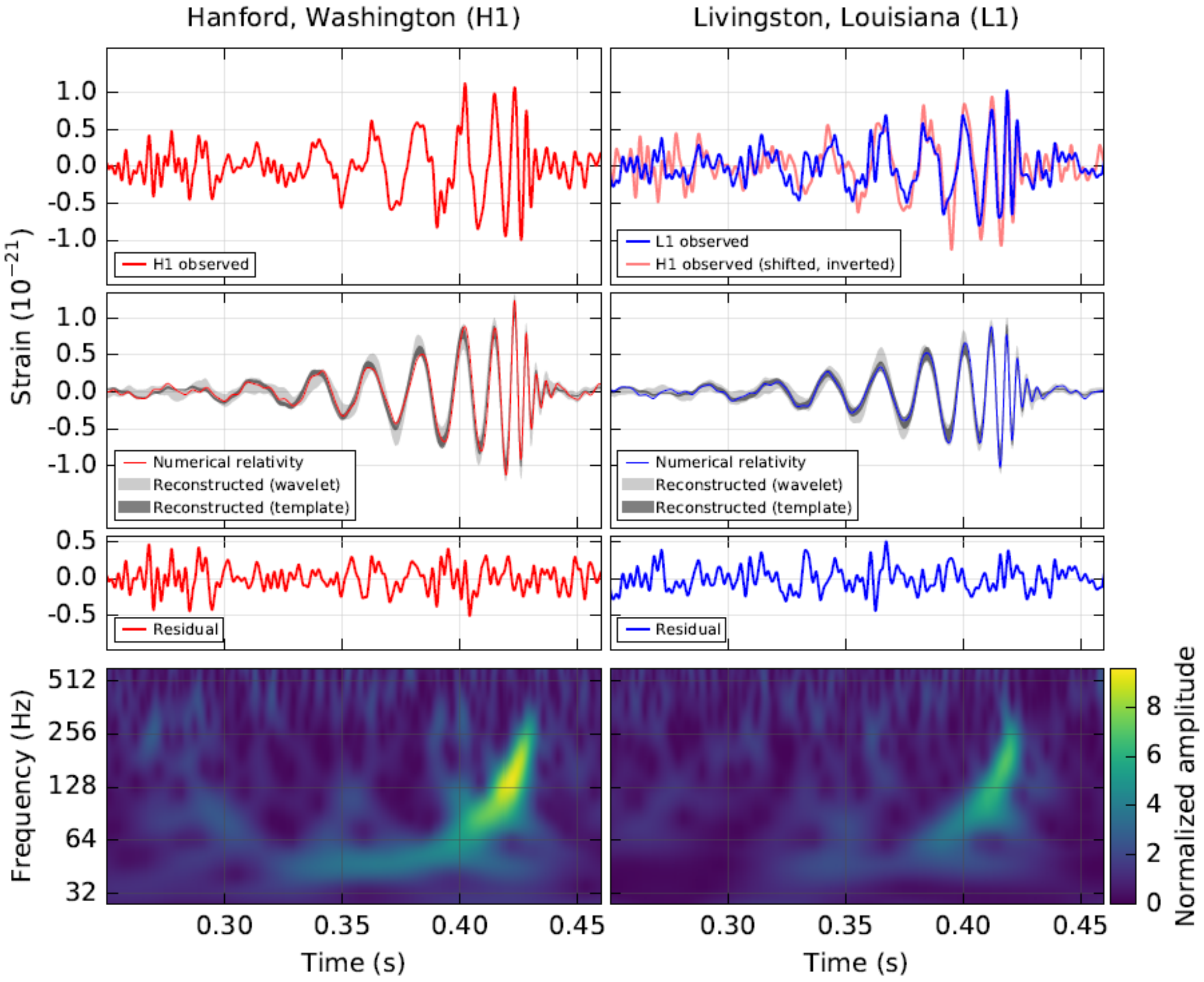
- Top row left – Hanford
- Top row right – Livingston
- Time difference ~ 6.9 ms with Livingston first

- 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



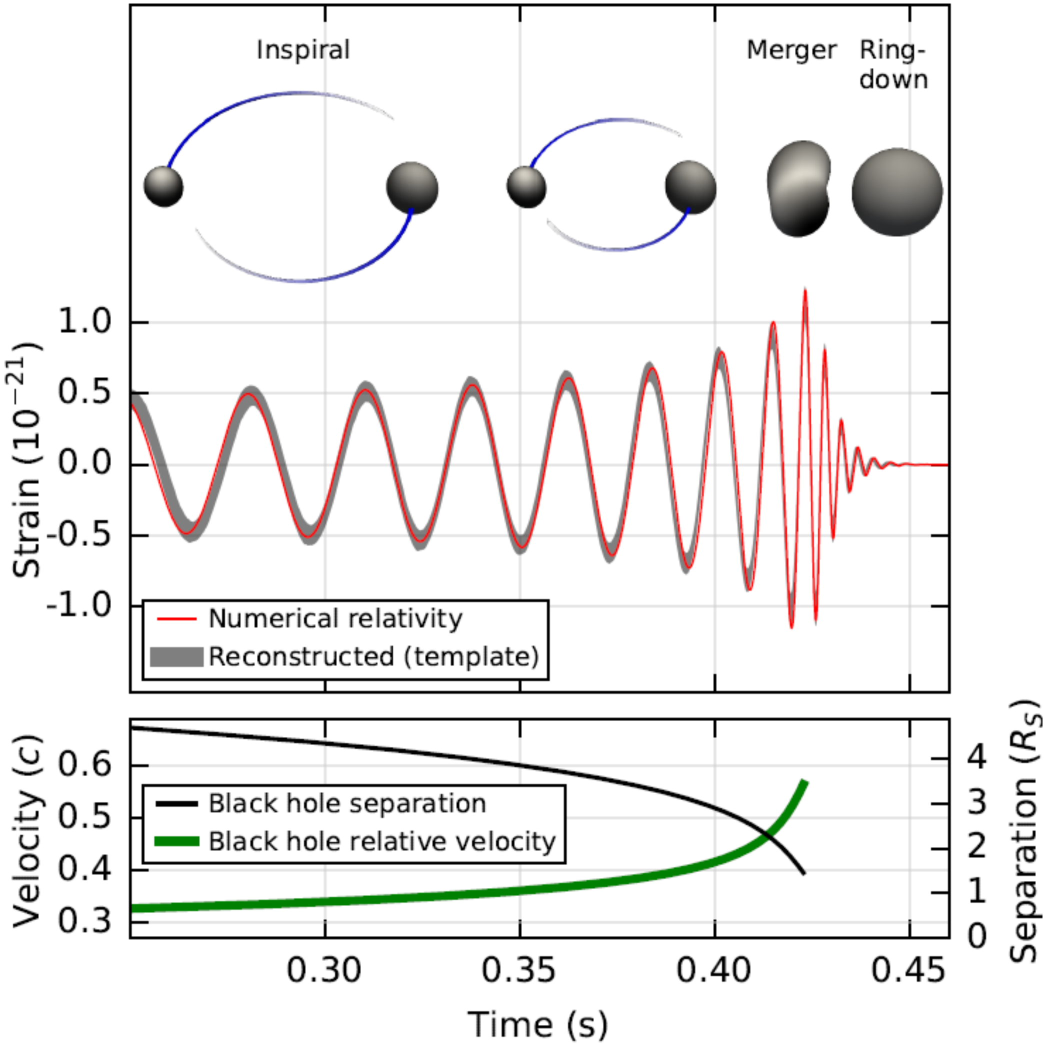
GW150914: Estimated Strain Amplitude

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

- Numerical relativity models of black hole horizons during coalescence
- Effective black hole separation in units of Schwarzschild radius ($R_s = 2GM_{tot}/c^2 = 210$km); and effective relative velocities given by post-Newtonian parameter $v/c = (GM_{tot}\pi f_{GW}/c^3)^{1/3}$

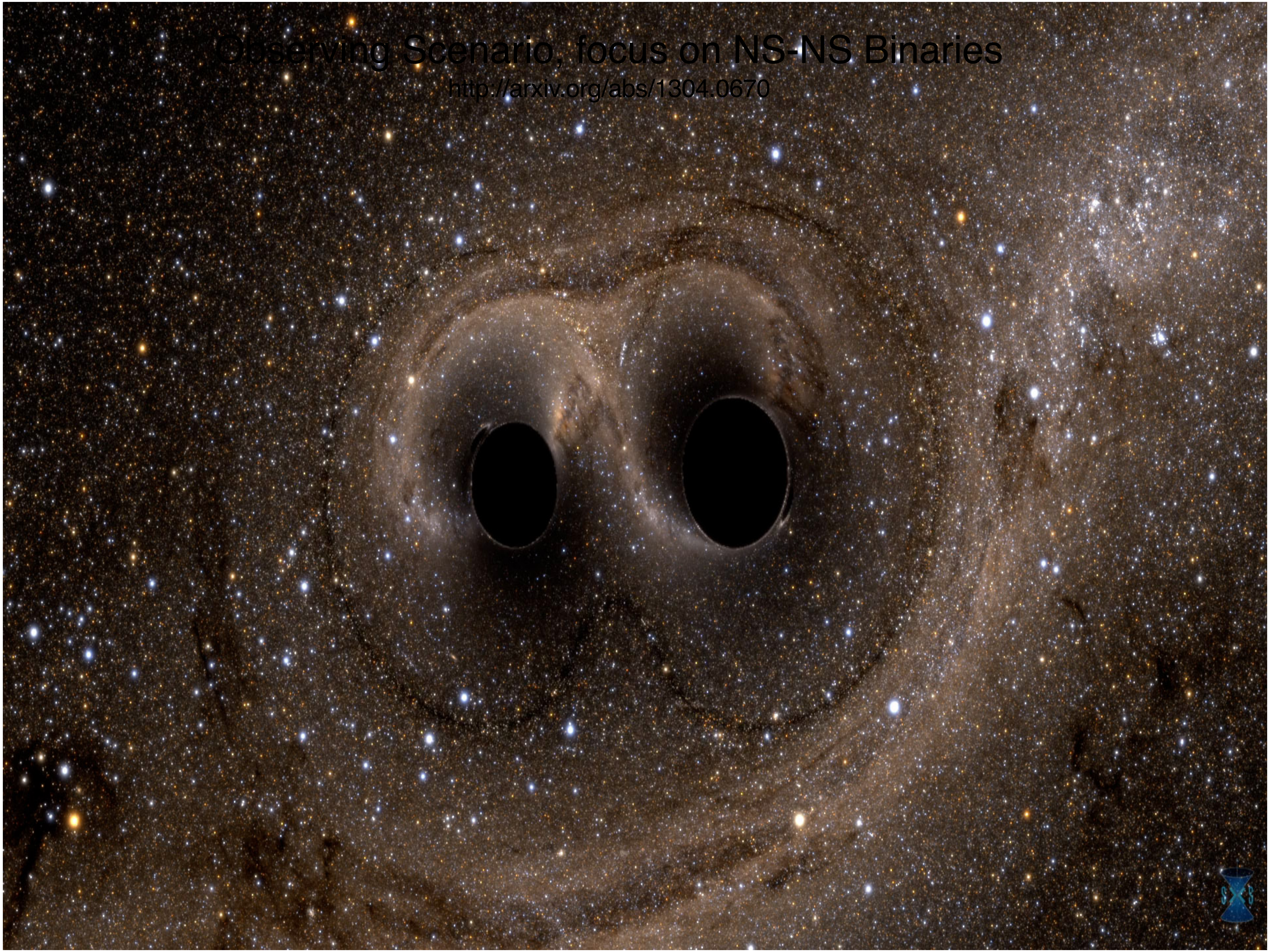
Binary Black Hole System

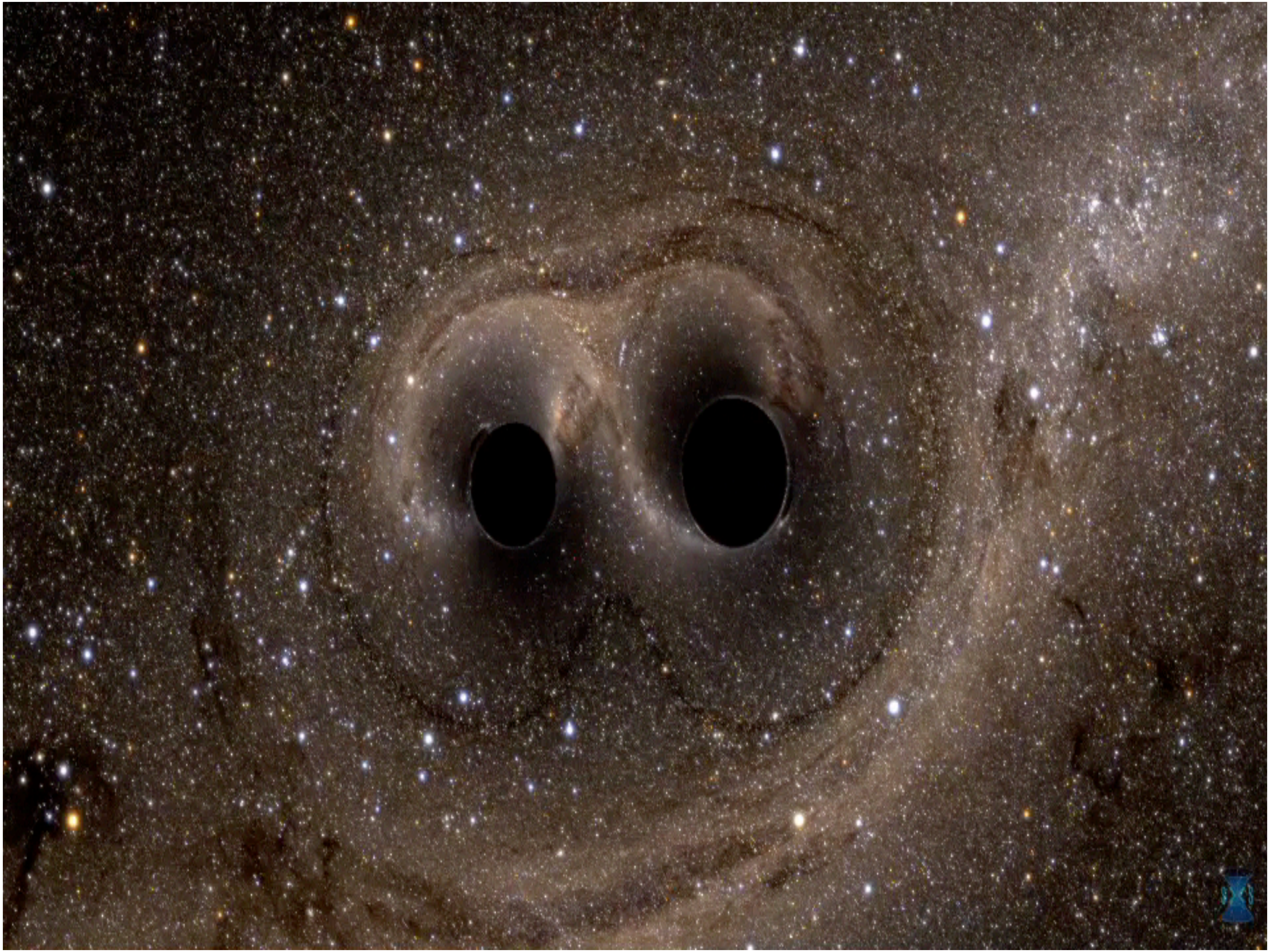
- $M1 = 36 +5/-4\ M_{sol}$
- $M2 = 29 +/- 4\ M_{sol}$
- Final Mass = $62 +/- 4\ M_{sol}$
- distance=410 +160/-180 MPc (redshift z = 0.09)

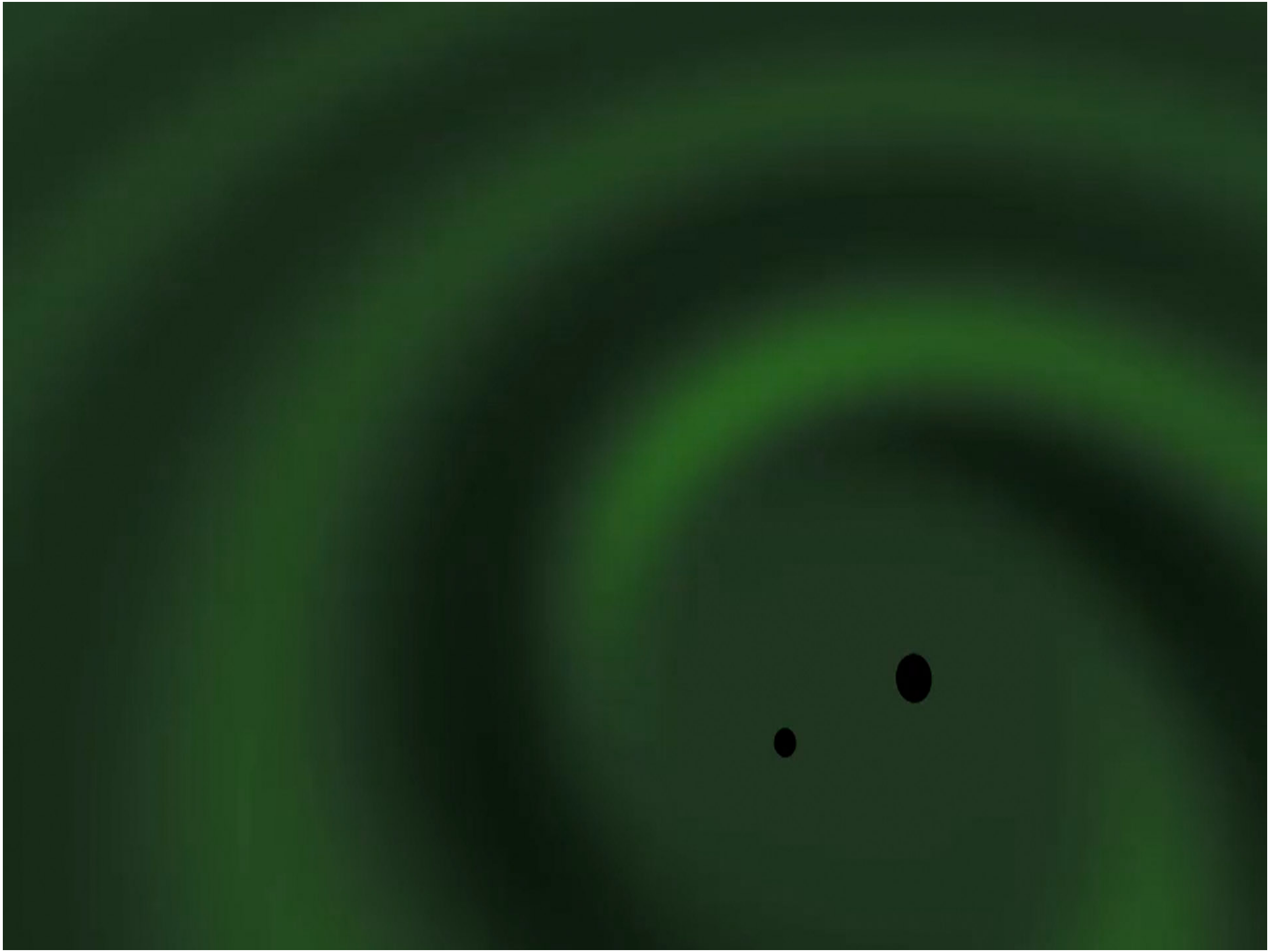


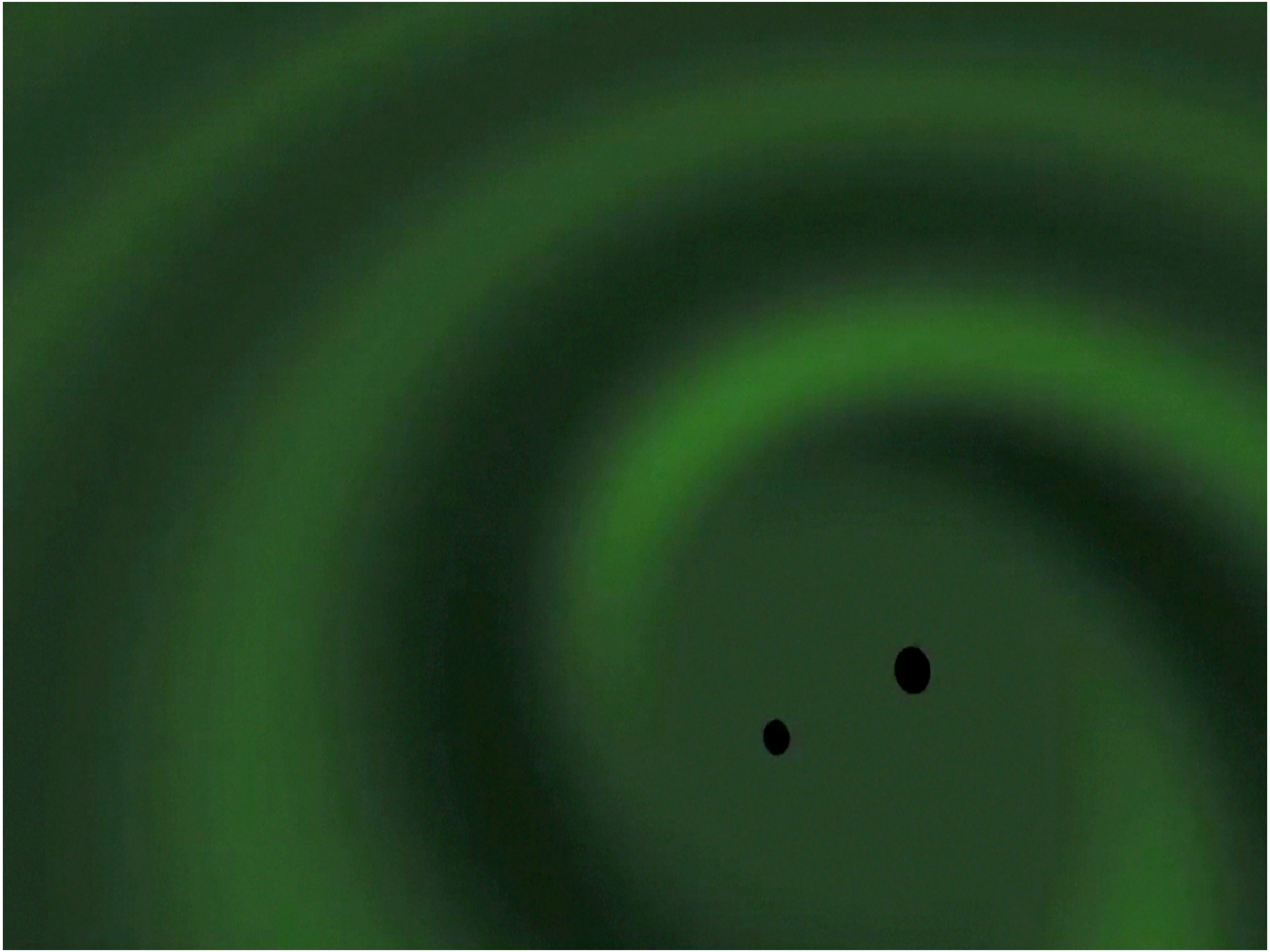
Observing Scenario, focus on NS-NS Binaries

http://arxiv.org/abs/1304.0670









PHYSICAL
REVIEW
LETTERS™

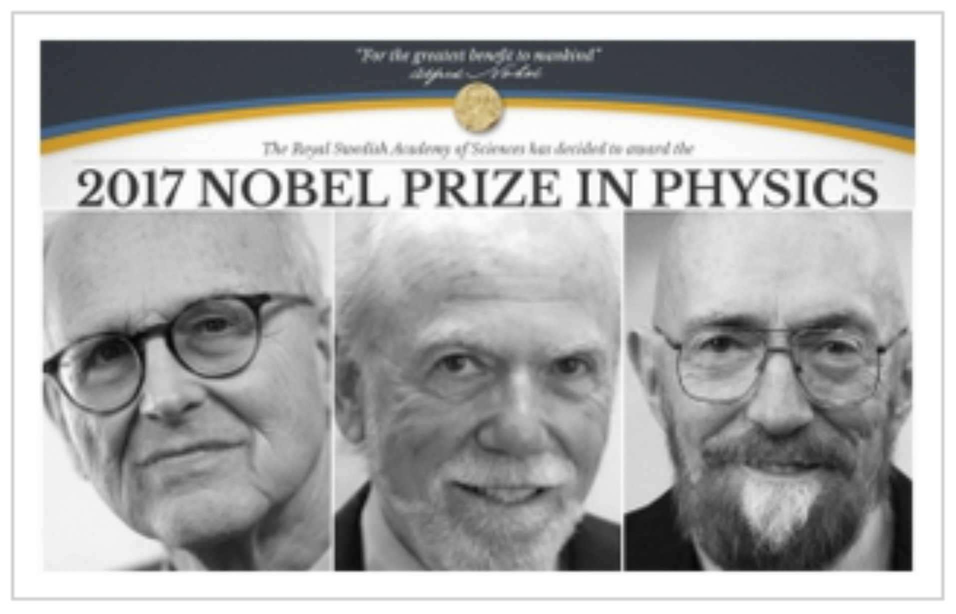
Member Subscription Copy
Library or Other Institutional Use Prohibited Until 2017

Articles published week ending 12 FEBRUARY 2016

Published by
American Physical Society™

APS physics

Volume 116, Number 6



Bounding graviton mass

- If gravitation is propagated by a massive field, then the velocity of GWs (gravitons) will depend upon their frequency as

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

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

- In the case of inspiralling compact binaries, GWs emitted at low frequency early in the inspiral will travel slightly slower than those emitted at high frequency later, resulting in an offset in the relative arrival times at a detector → the phase evolution of the observed inspiral gravitational waveform is modified.
- Matched filtering of the waveforms can bound such frequency-dependent variations in propagation speed →bound the graviton mass

Compton Wave-length of the Graviton

C. M. Will, Phys. Rev. D 57, 2061 (1998).

- We assume a modified dispersion relation for gravitational waves

$$(v_g/c)^2 = 1 - \{\hbar c/(\lambda_g E)\}^2$$

- In the massive graviton theory an extra phase term is added to the CBC evolution (formally a 1PN order term)

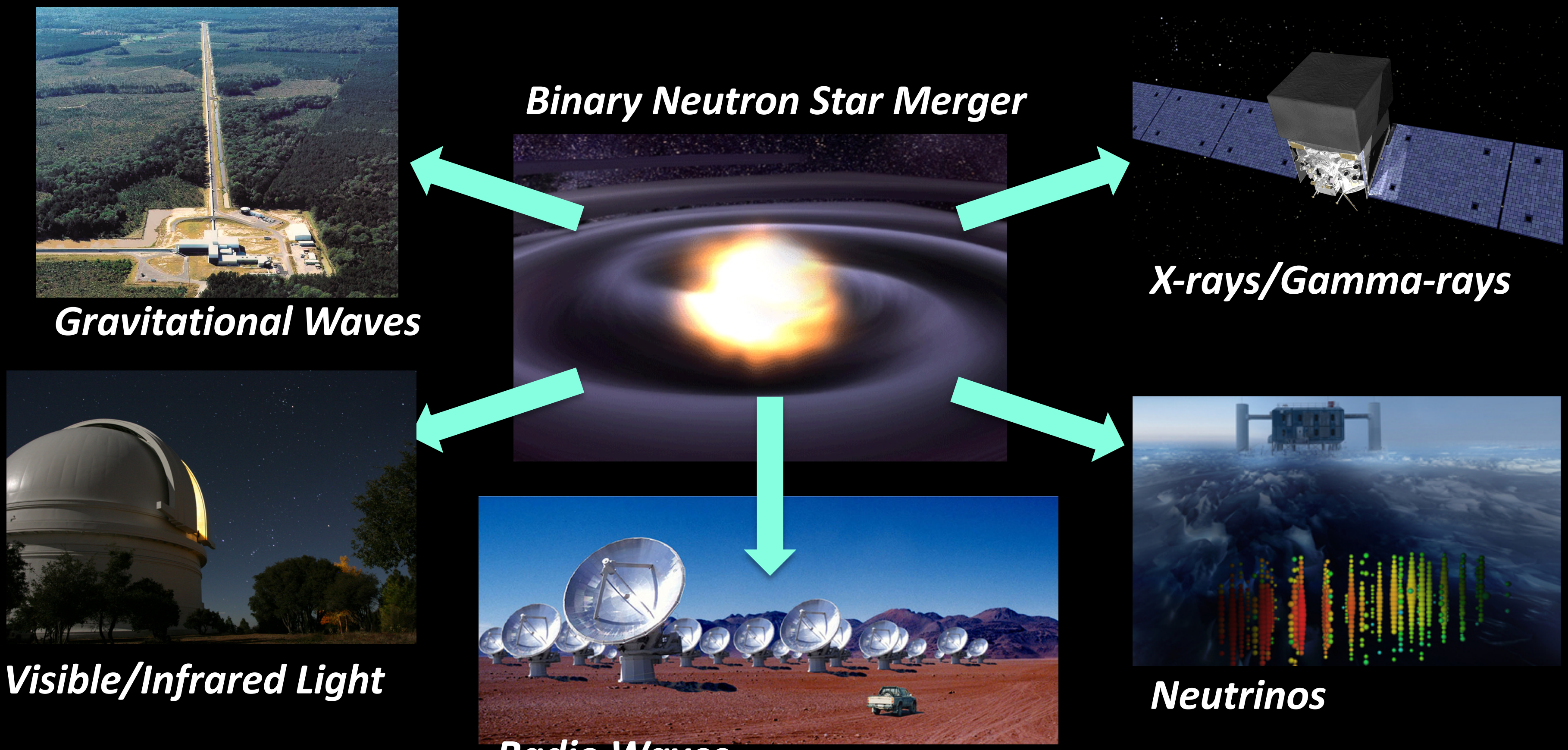
$$\phi_{MG}(f) = -(\pi D c)/[\lambda_g{}^2 (1+z) f]$$

- Our constrain on the 1PN terms permit to derive a down limit for the Compton wavelength of the graviton

$$\lambda_g = 2\pi\hbar/(m_g c) > 10^{13}\text{ km}$$

- It corresponds to a limit $m_g < 1.2 \times 10^{-22}$ 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)

Multi-Messenger Astronomy: Gravitational Wave + Photons + Neutrinos



Binary Neutron Star Merger

Gravitational Waves

X-rays/Gamma-rays

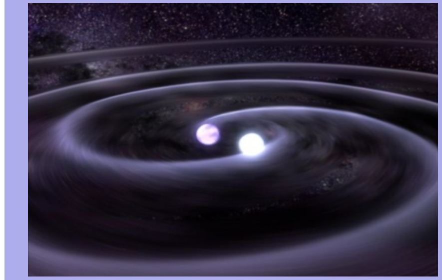
Visible/Infrared Light

Radio Waves

Neutrinos

A goal of **LIGO** and **Virgo** interferometers is the **first direct detection** of gravitational waves from **ENERGETIC ASTROPHYSICAL** events:

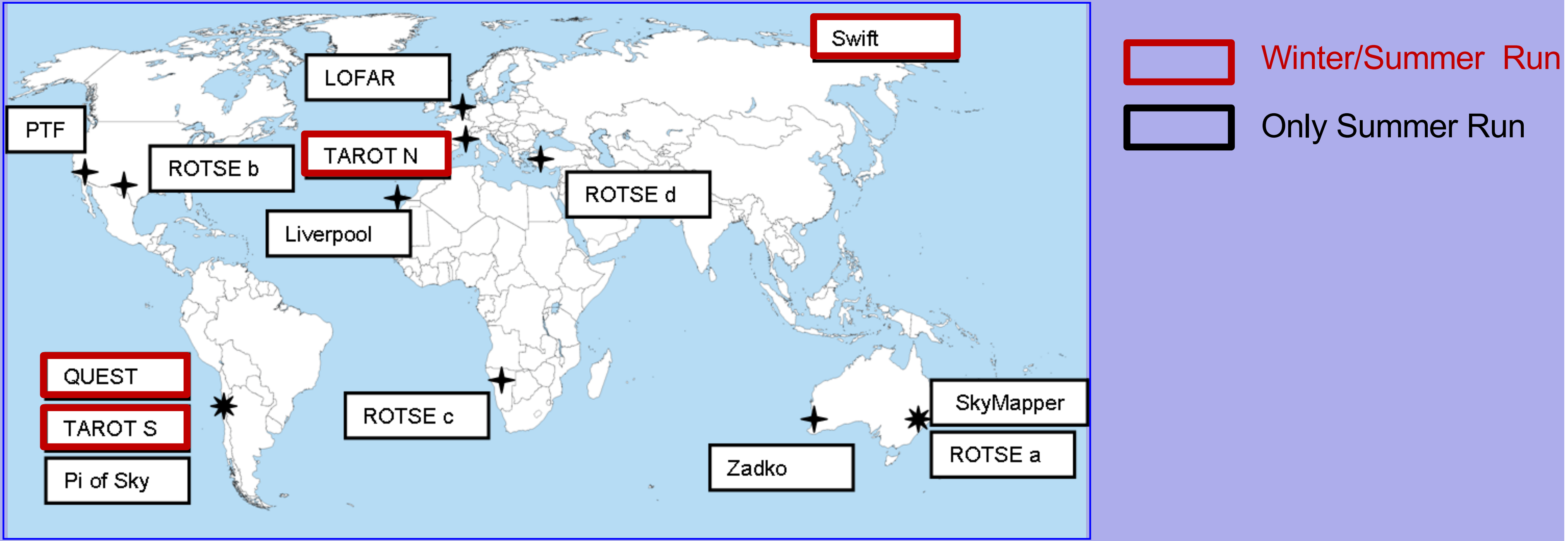
- **Mergers** of **NeutronStars** and/or **BlackHoles** ⇨ **SHORT GRB**
  ⇨ **Kilonovas**
- **Core Collapse** of **Massive Stars** ⇨ **Supernovae**
  ⇨ **LONG GRB**
- **Cosmic String Cusps** ⇨ **EM burst**



Main motivations for joint GW/EM observations:

- Increase the GW detection confidence;
- Get a precise (arcsecond) localization, identify host galaxy;
- Provide insight into the progenitor physics;
- In the long term start a joint GW/EM cosmology.

Ground-based and space EM facilities observing the sky at Optical, X-ray and Radio wavelengths involved in the follow-up program



Optical Telescopes

TAROT SOUTH/NORTH
1.86° X 1.86° FOV

Zadko
25 X 25 arcmin FOV

ROTSE
1.85 ° X 1.85° FOV

QUEST
9.4 square degree FOV

SkyMapper
5.6 square degree FOV

Pi of the Sky
20° X 20° FOV

Palomar Transient Factory
7.8 square degree FOV

Liverpool telescope
4.6 X 4.6 arcmin FOV

X-ray and UV/Optical Telescope

Swift Satellite
0.4° X 0.4° FOV

Radio Interferometer

LOFAR
10 – 250 MHz

GW Online Analysis

H1 **L1** **V1**

Omega & cWB
for Unmodeled Bursts

MBTA
for signals from Compact Binary Coalescence

- LIGO (H1 and L1) and Virgo (V1) interferometers
- Search algorithms to identify triggers

GRACE DB ARCHIVE

LUMIN
for Optical Telescopes

GEM
for Swift

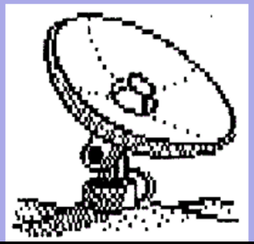
- Select Statistically Significant Triggers
- Determine Pointing Locations

10 min.

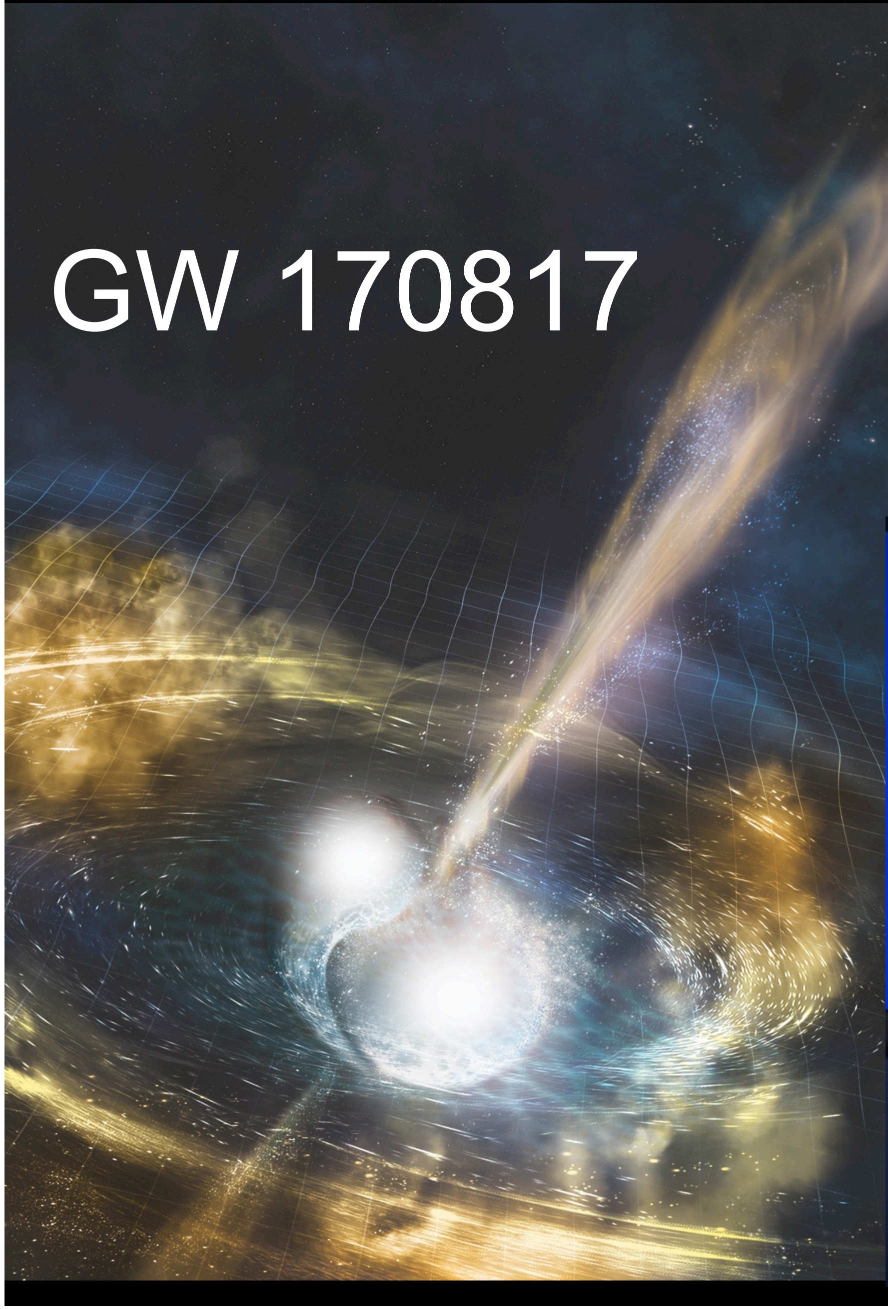
Event Validation

Send alert to telescope

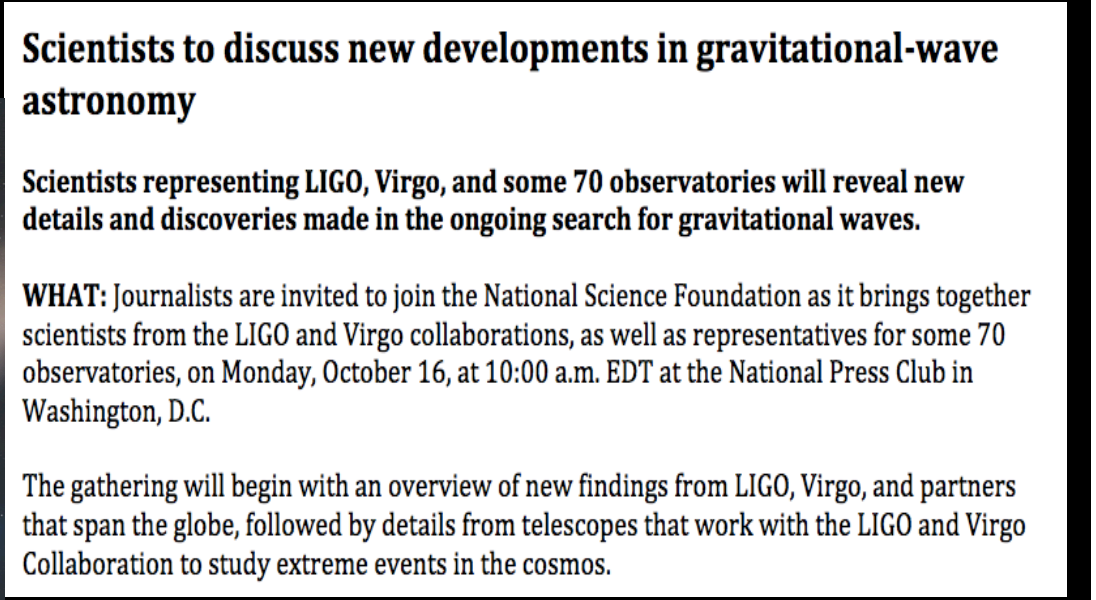
30 min.



17 August 2017



GW 170817

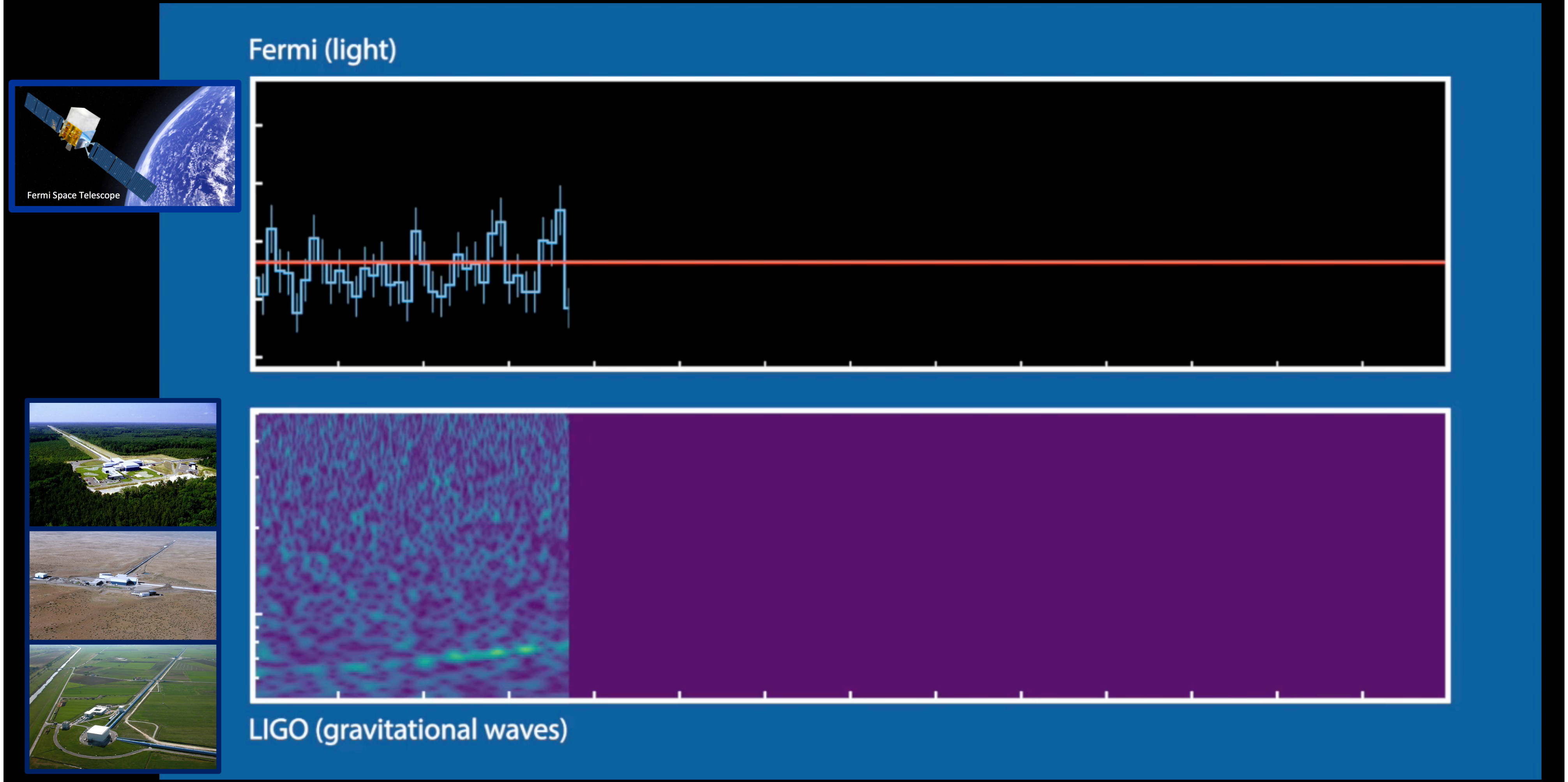


Scientists to discuss new developments in gravitational-wave astronomy

Scientists representing LIGO, Virgo, and some 70 observatories will reveal new details and discoveries made in the ongoing search for gravitational waves.

WHAT: Journalists are invited to join the National Science Foundation as it brings together scientists from the LIGO and Virgo collaborations, as well as representatives for some 70 observatories, on Monday, October 16, at 10:00 a.m. EDT at the National Press Club in Washington, D.C.

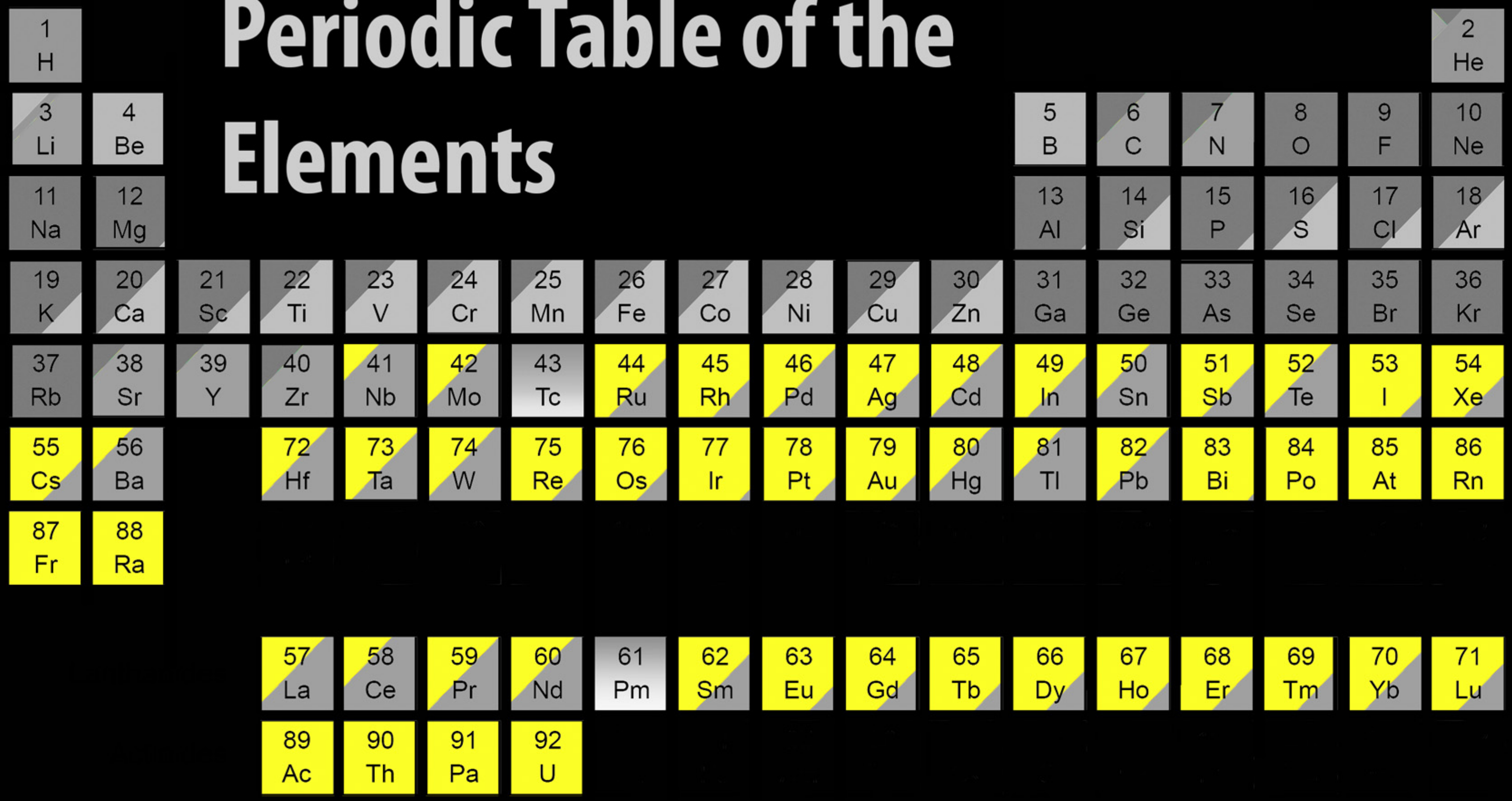
The gathering will begin with an overview of new findings from LIGO, Virgo, and partners that span the globe, followed by details from telescopes that work with the LIGO and Virgo Collaboration to study extreme events in the cosmos.



Credit: NASA's Goddard Space Flight Center/CI Lab

Credit:N. Risinger (skysurvey.org), LIGO-Virgo, Digitized Sky Survey 2, ESO.

Periodic Table of the Elements



1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra																
			57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
			89 Ac	90 Th	91 Pa	92 U											

Yellow: Formed by Merging Neutron Stars

Credit:Jennifer Johnson/

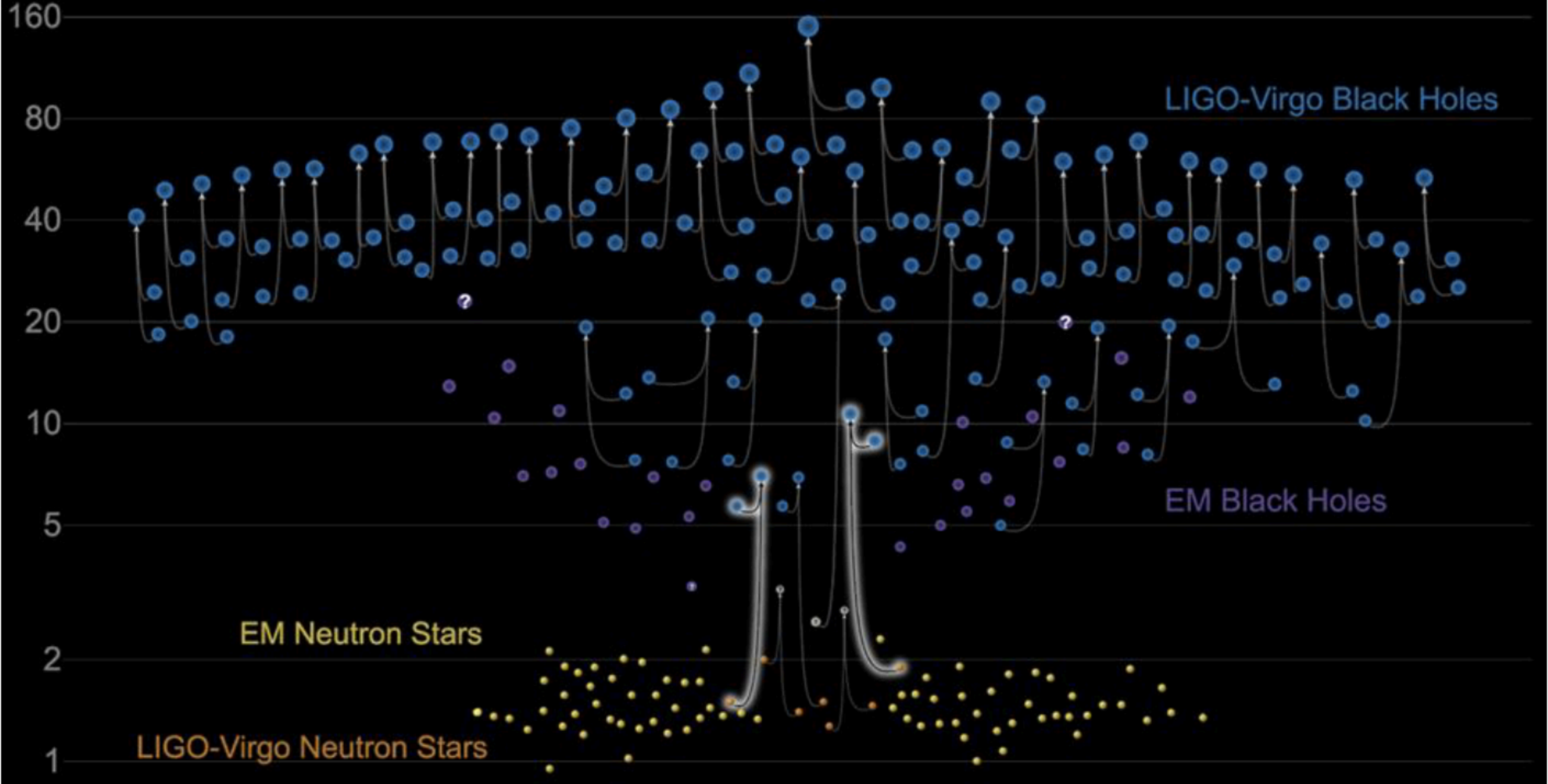
RIPPLES OF GRAVITY, FLASHES OF LIGHT:

WORLD'S OBSERVATORIES WITNESS A COSMIC CATACLYSM


Earth
Space
LIGO Hanford
Virgo
LIGO Livingston

Masses in the Stellar Graveyard

in Solar Masses



FIND OUT MORE:

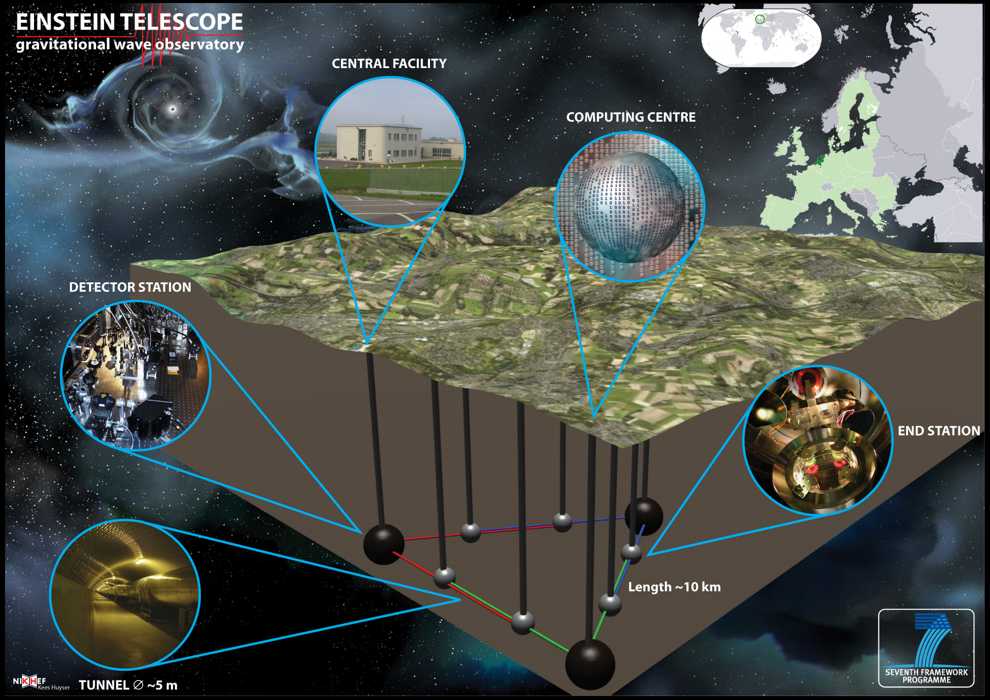
Visit our websites:

www.ligo.org, www.virgo-gw.eu, gwcenter.icrr.u-tokyo.ac.jp/en/

8 Recommendations to GWIC to guide the development of the field

8.5 Toward a third-generation global network

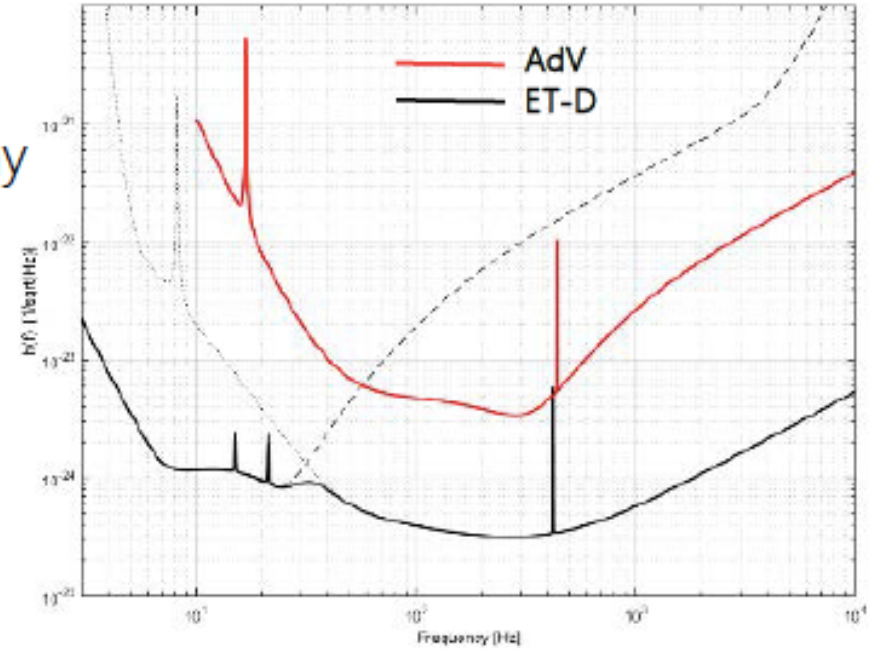
“Background— The scientific focus of a third-generation global network will be gravitational wave astronomy and astrophysics as well as cutting edge aspects of basic physics. Third-generation underground facilities are aimed at having excellent sensitivity from ~1 Hz to ~10^4 Hz. As such, they will greatly expand the new frontier of gravitational wave astronomy and astrophysics.



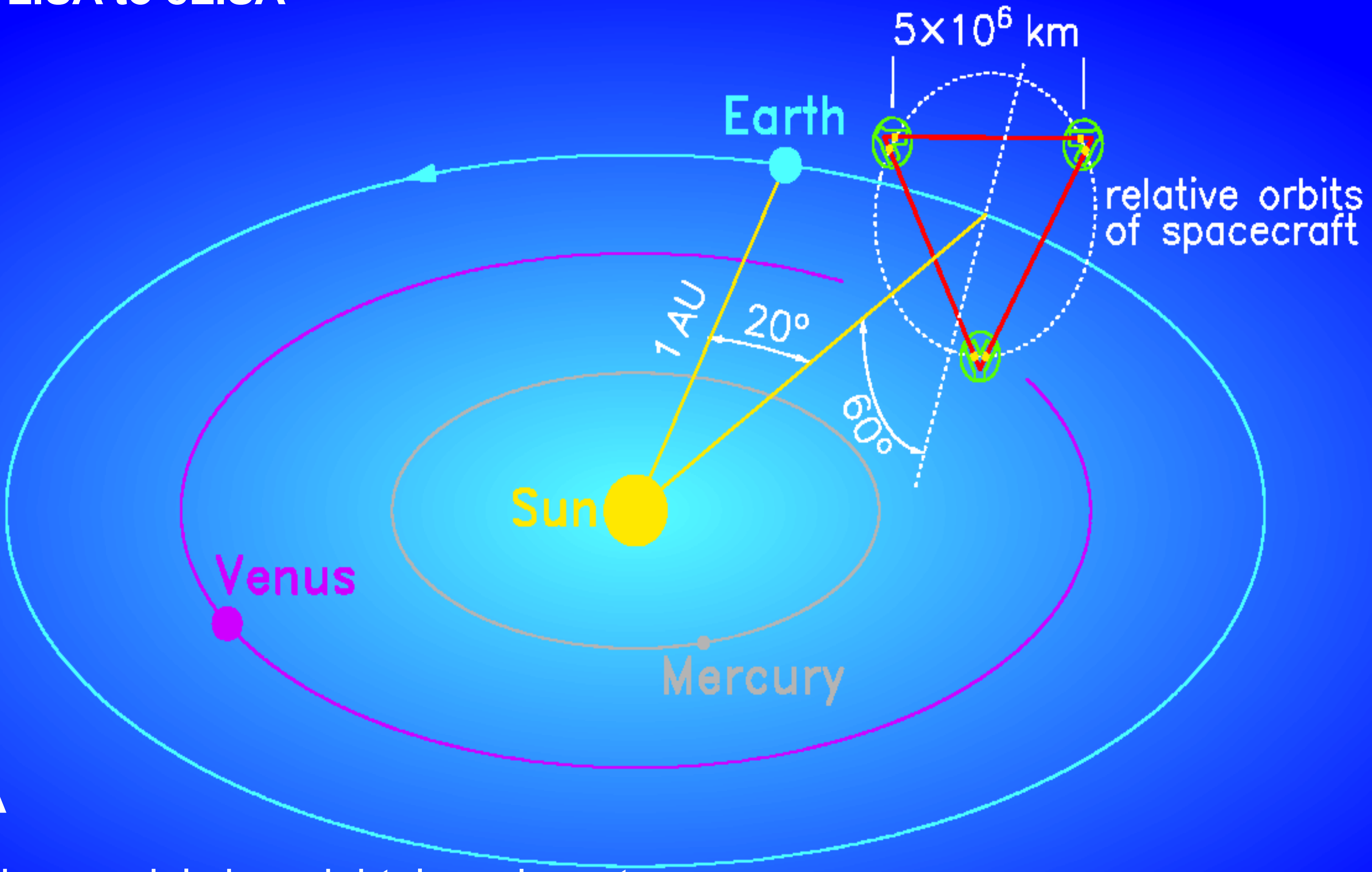
In Europe, a three year-long design study for a third-generation gravitational wave facility, the Einstein Telescope (ET), has recently begun with funding from the European Union.

EINSTEIN TELESCOPE

- ✓Design study of ET funded by the European Commission under FP7
  - – interest primarily focused on the Infrastructure rather than on the detector and its technologies
  - – The infrastructure should no limit the sensitivity of the future hosted detectors
    - Size
    - Environmental noises (seismic and NN)
  - – ET absorbed and developed many concepts in GW detectors:
    - Underground and cryo-compatible facility, pioneered in Japan by CLIO and KAGRA
    - Triangular geometry, concept used in LISA
    - Xylophone configuration



From LISA to eLISA



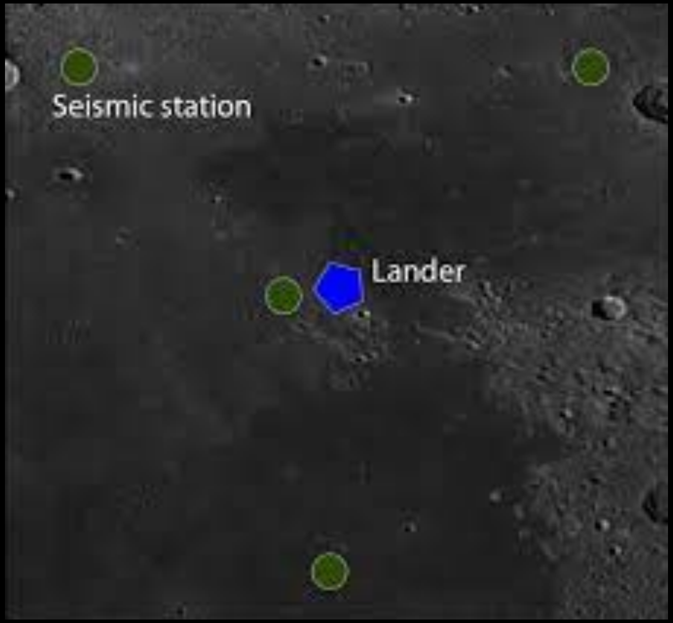
eLISA

- Savings mainly in weight, launch cost.
- Two active arms, not three;
- Smaller arms (1Gm, not 5Gm);
- Re-use LISA Pathfinder hardware;

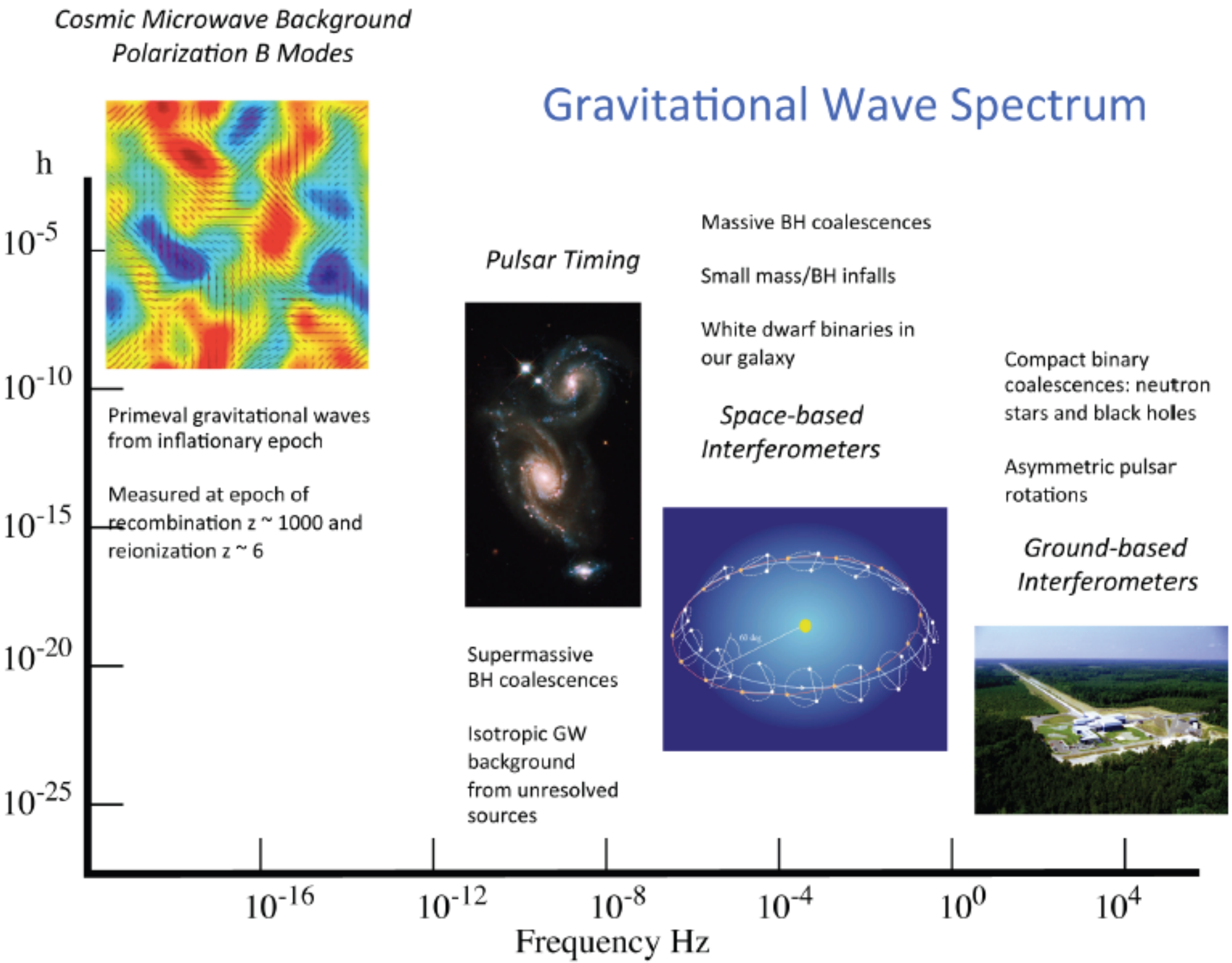
2034?

Lunar Gravitational-wave Antenna

The Astrophysical Journal,910:1(22pp), 2021 March 20



Gravitational Wave Spectrum



Cosmic Microwave Background Polarization B Modes

Primeval gravitational waves from inflationary epoch

Measured at epoch of recombination z ~ 1000 and reionization z ~ 6

Pulsar Timing

Supermassive BH coalescences

Isotropic GW background from unresolved sources

Massive BH coalescences

Small mass/BH infalls

White dwarf binaries in our galaxy

Space-based Interferometers

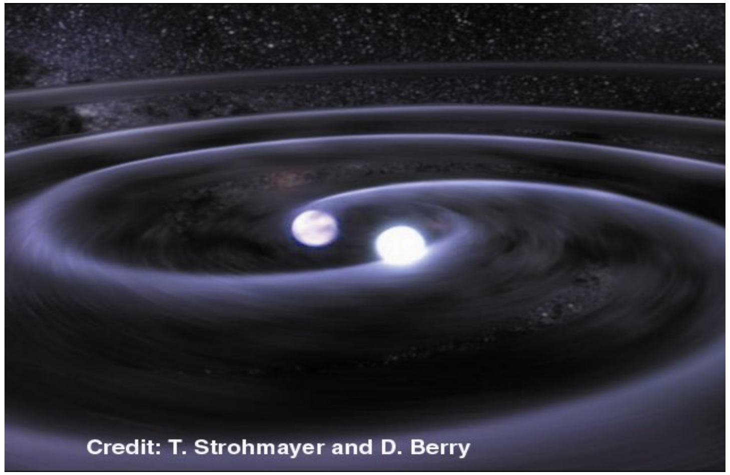
Compact binary coalescences: neutron stars and black holes

Asymmetric pulsar rotations

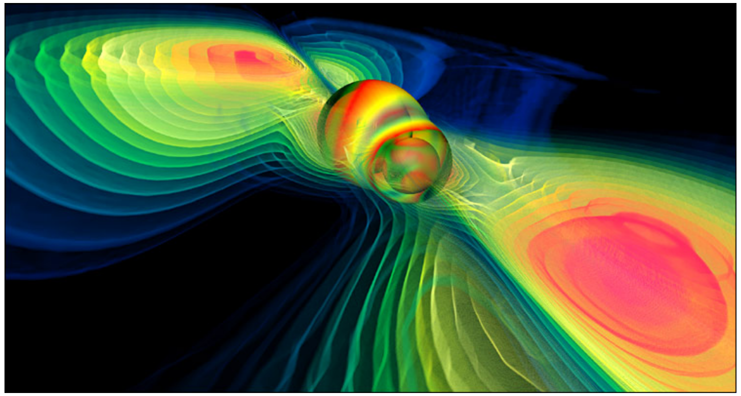
Ground-based Interferometers

THE GLOBAL PLAN

- Advanced Detectors (LIGO, VIRGO) will initiate gravitational wave astronomy through the detection of the most luminous sources - compact binary mergers.
- Third Generation Detectors (ET and Cosmic Explorer) will expand detection horizons and provide new tools for extending knowledge of fundamental physics, cosmology and relativistic astrophysics.
- Observation of low frequency gravitational wave with eLISA will probe the role of super-massive black holes in galaxy formation and evolution



Credit: T. Strohmayer and D. Berry



Every newly opened astronomical window has found unexpected results

Window	Opened	1st Surprise	Year
Optical	1609 Galilei	Jupiter’s moons	1610
Cosmic Rays	1912	Muon	1930s
Radio	1930s	Giant Radio Galaxies CMB Pulsars	1950s 1964 1967
X - ray	1948	Sco X-1 X-ray binaries	1962 1969 Uhuru
g - ray	1961	GRBs	Late 1960s+ Vela
GW	2015	Massive BH-BH mergers	2016

E. Coccia

Thank you for your attention