Otranto School

XXXII International Seminar of Nuclear and Subnuclear Physics

“Francesco Romano”

Gravitational Waves

detection and selected observations

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Plan of this lecture

- **introducing motivations**
- **basics of gravity and gravitational waves**
- **introduction to current detectors**
- **the gravitational wave observatory and basic data analysis methods**
- **selected observational results**
- **outlook and challenges**

Gravitational Wave Open Science Center

Virgo, LIGO, KAGRA

Einstein Telescope

LISA

International Pulsar Timing Array

why Gravitational Waves ?

- **Gravity is space-time**
  - **everything is affected by and produces gravity**
    any matter-energy distribution
  - **dominates at large-scales over the other fundamental interactions**
  - **space-time is dynamical**
    matter-energy
- **Gravitational Waves (GW)**
  - **the «sound waves» of space-time**
    «ripples» of the space-time fabric curvature
    a new window on the universe
  - **complementary information wrt other messengers**
    entire mass-energy and momentum distributions of an astronomical source produce GW
  - **travel unperturbed over cosmological distances**
    detection is very challenging

?

General Relativity
vs
Quantum Mechanics

vacuum field

no hair theorem
for Black Holes

Hubble flow

quark/hyperon/neutron star

Formation of super massive
Black Holes and cosmological
structures

evolution of stars

Gravitational Waves are essential messengers

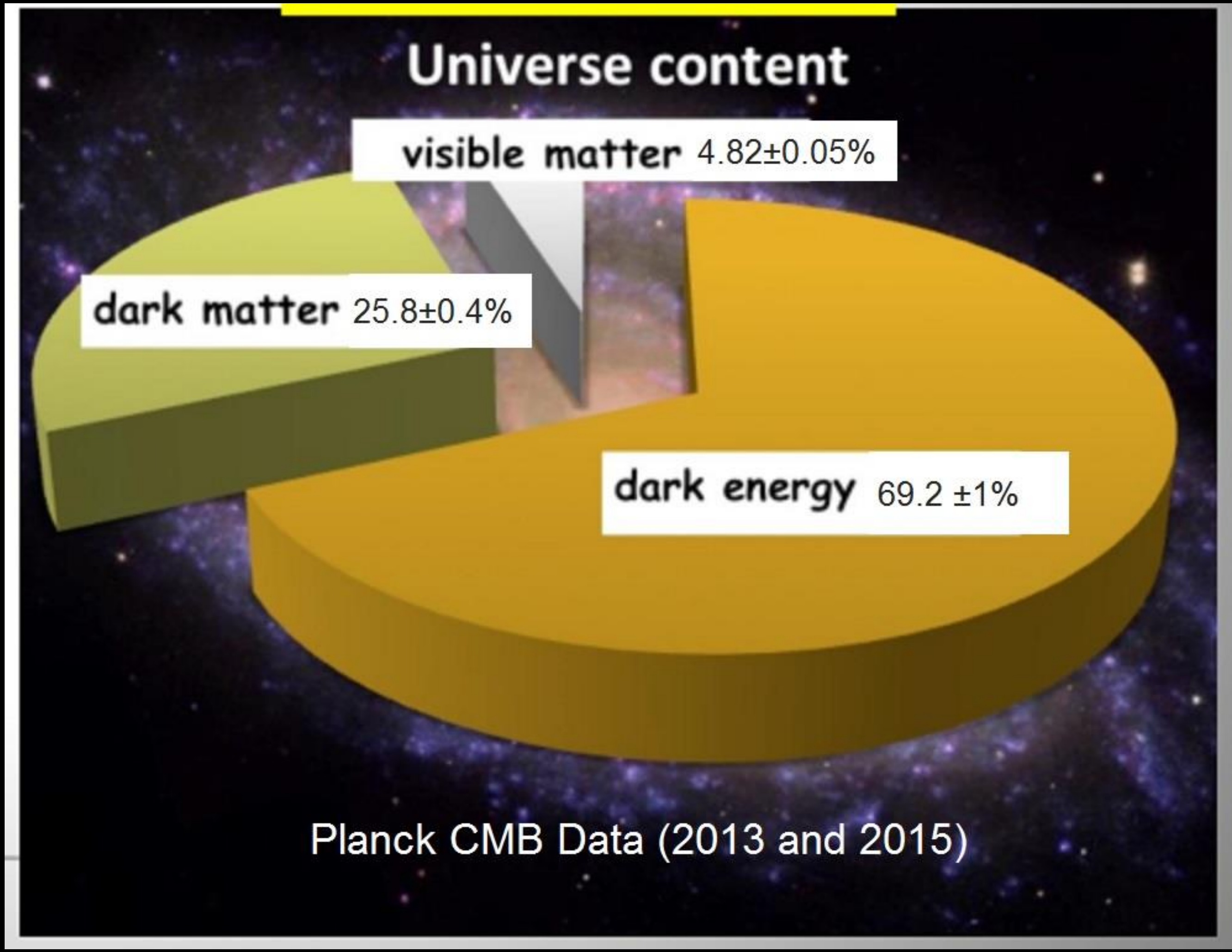
the Universe is dark:

- < 5% of the universe is coupled to light.
- < 0.5% is bright in the electromagnetic messenger

Gravity is sourced from all mass-energy components

Gravitational Waves are essential messengers to explore our Universe:

- record the dynamics of all mass-energy
  - the only predicted emission from the horizon of a black-hole
- cross undisturbed any matter
  - crossed the universe from Big Bang to us



why Gravitational Waves ?

- **Fundamental Physics:**
  - **Gravity and Space-Time**
    - ✓ strong Field Gravity & relativistic motion
    - ✓ Black Hole properties and Event Horizon
    - ...
  - **Equation of State of matter beyond nuclear density**
    - Neutron Star Physics
    - ...
- **Cosmology**
  - **Dark Energy and accelerated expansion**
  - **Dark Matter**
  - **...**
- **Astrophysics**
  - **Compact Objects and stellar evolution**
  - **Nucleosynthesis of elements**
  - **large scale structures**
  - **Gamma Ray Bursts**
  - **...**

?

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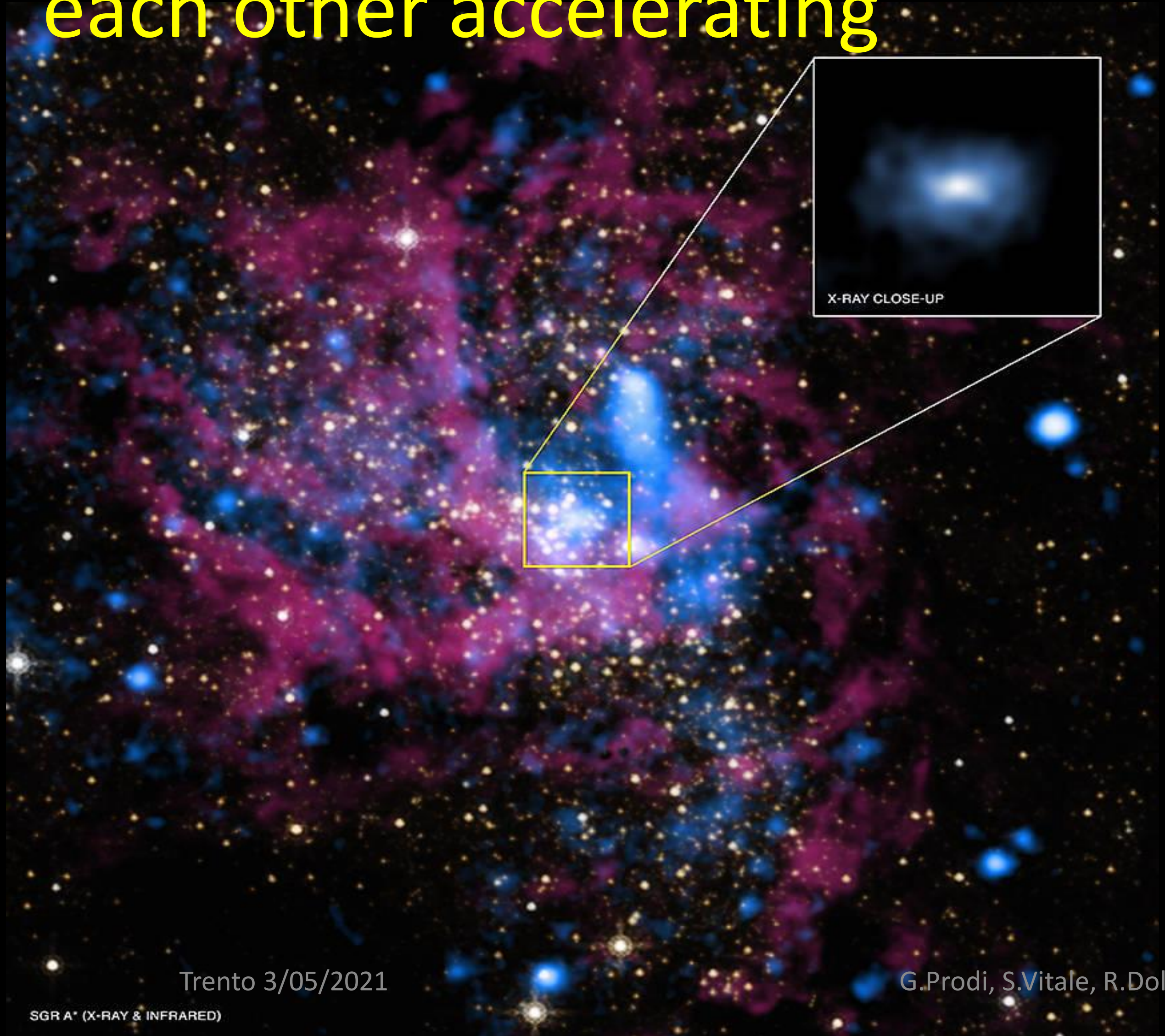
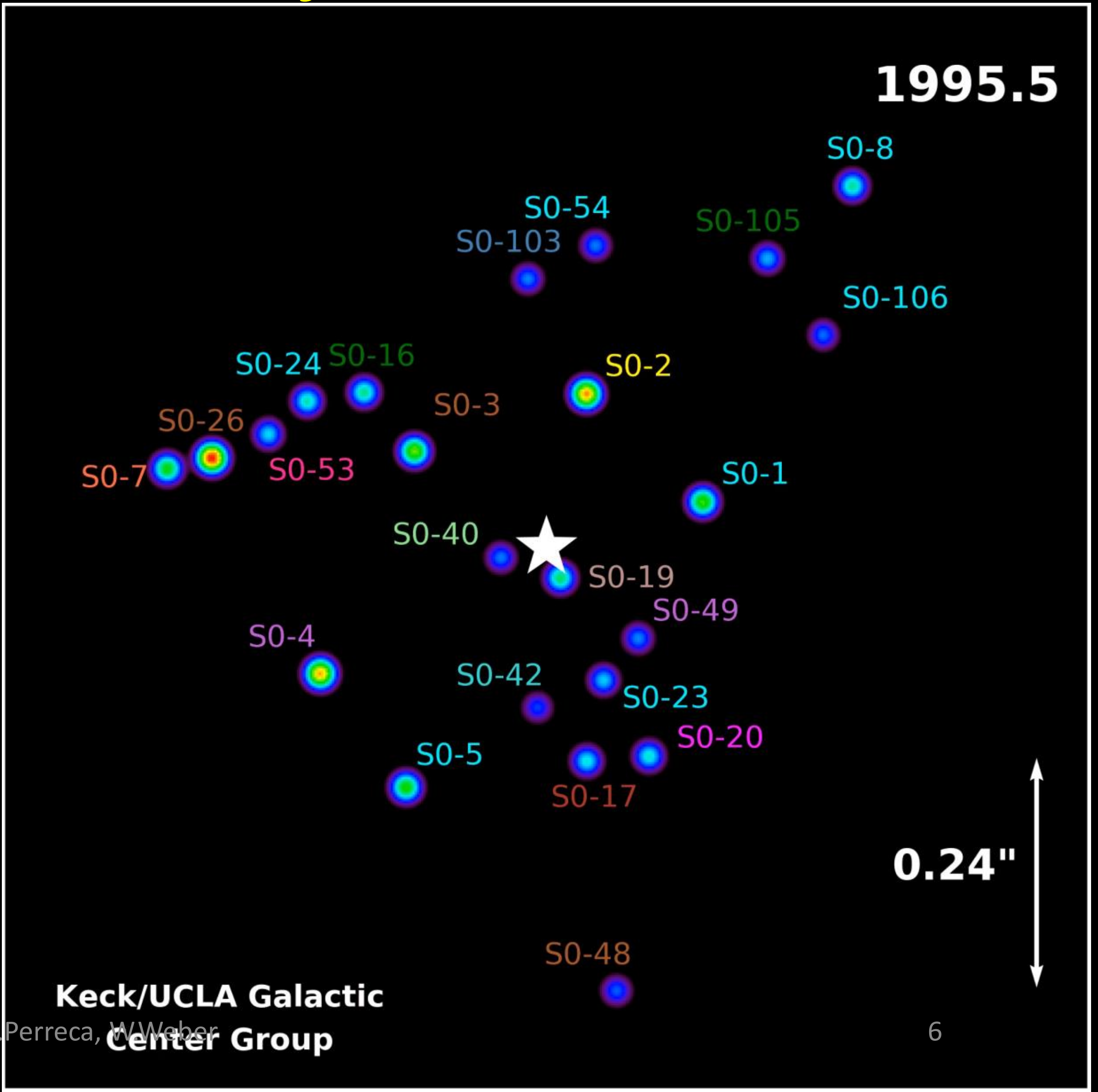
Gravity forges space-time geometry

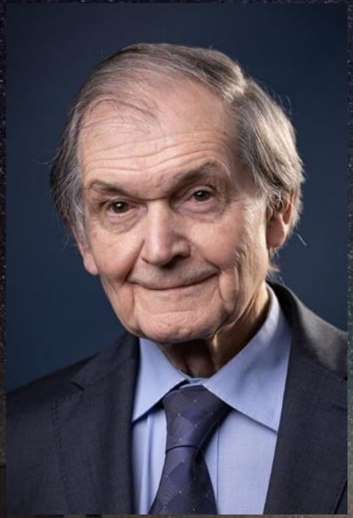
free-falling test-masses follows curved trajectories and see each other accelerating



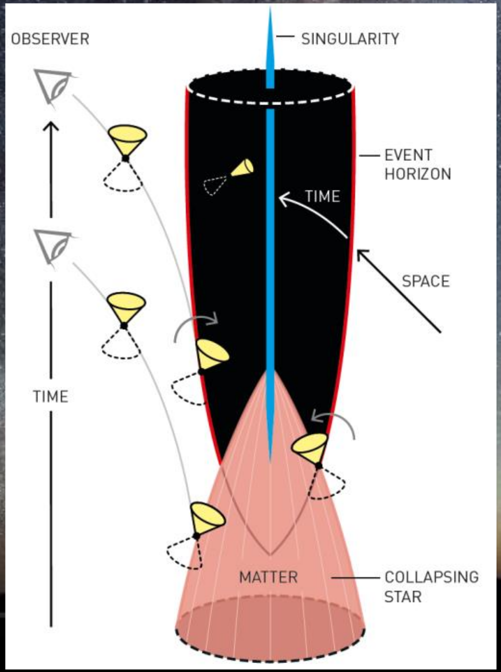


Nobel Prize for Physics 2020

Black Holes https://www.nobelprize.org



Roger Penrose

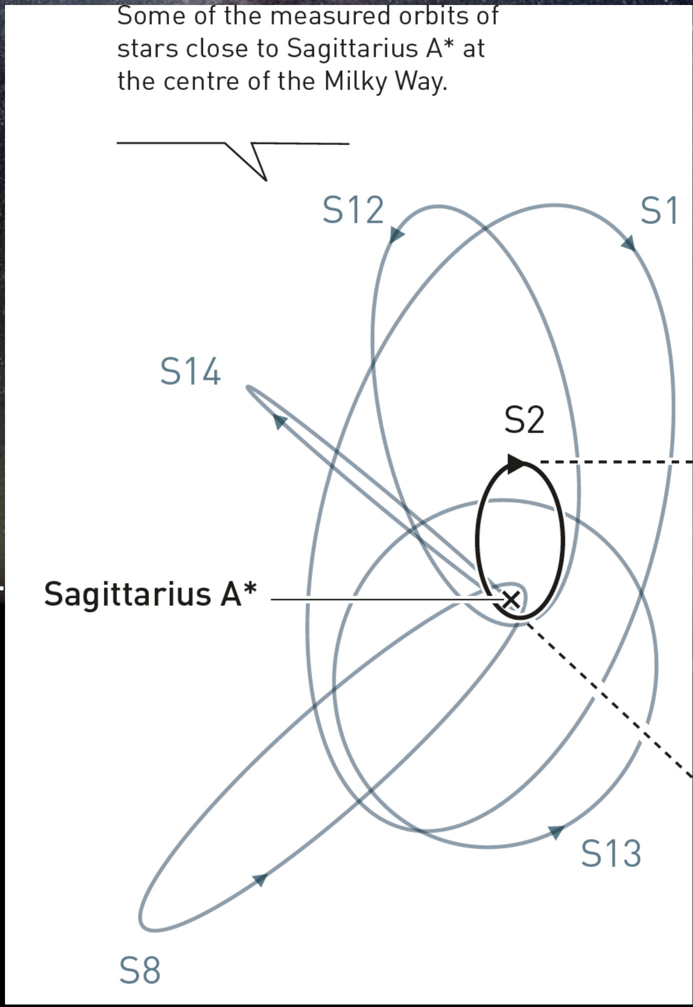


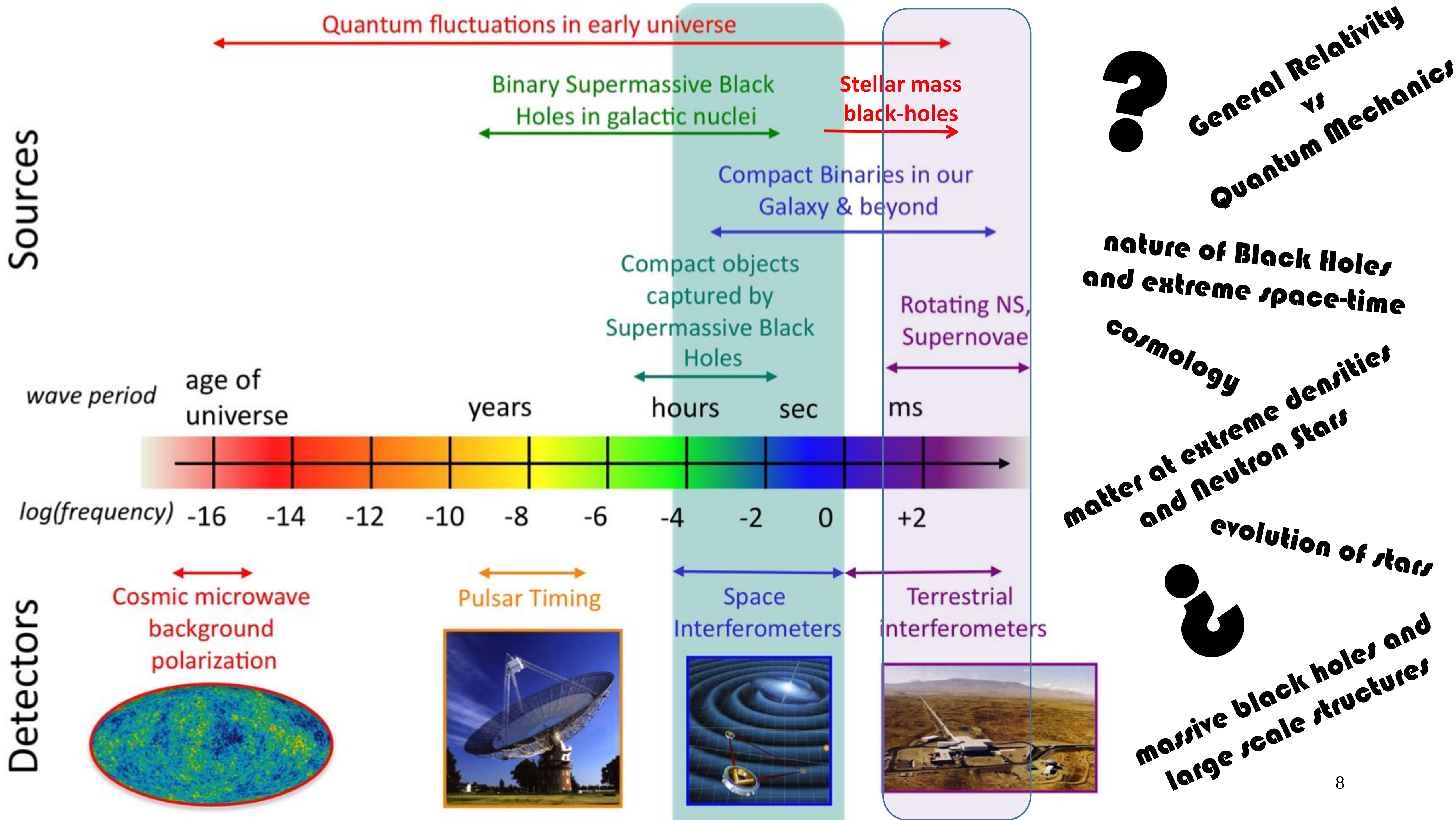
for the discovery that black hole formation is a robust prediction of the general theory of relativity (1965)

Reinhard Genzel

Andrea Ghez

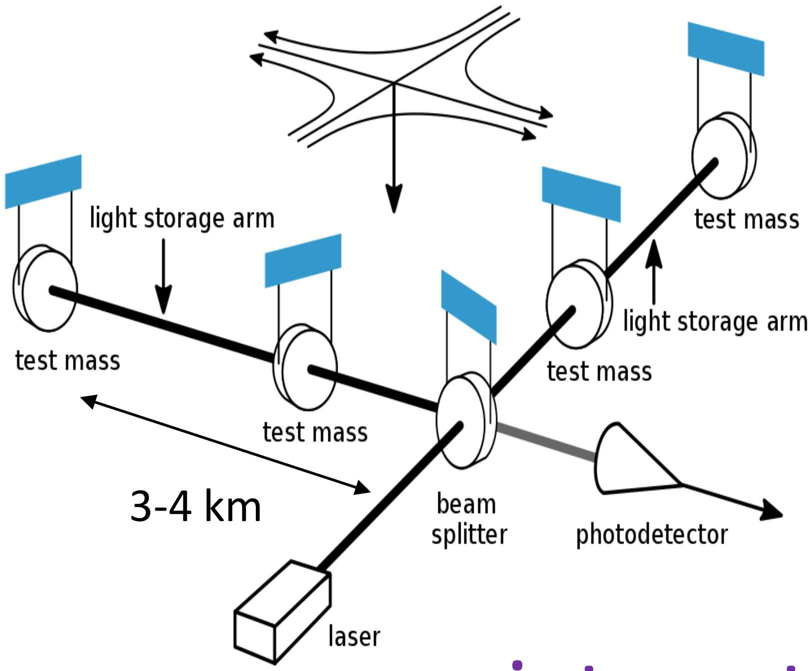
for the discovery of a supermassive compact object at the centre of our galaxy.
(4 million Msun, 1990's ->)

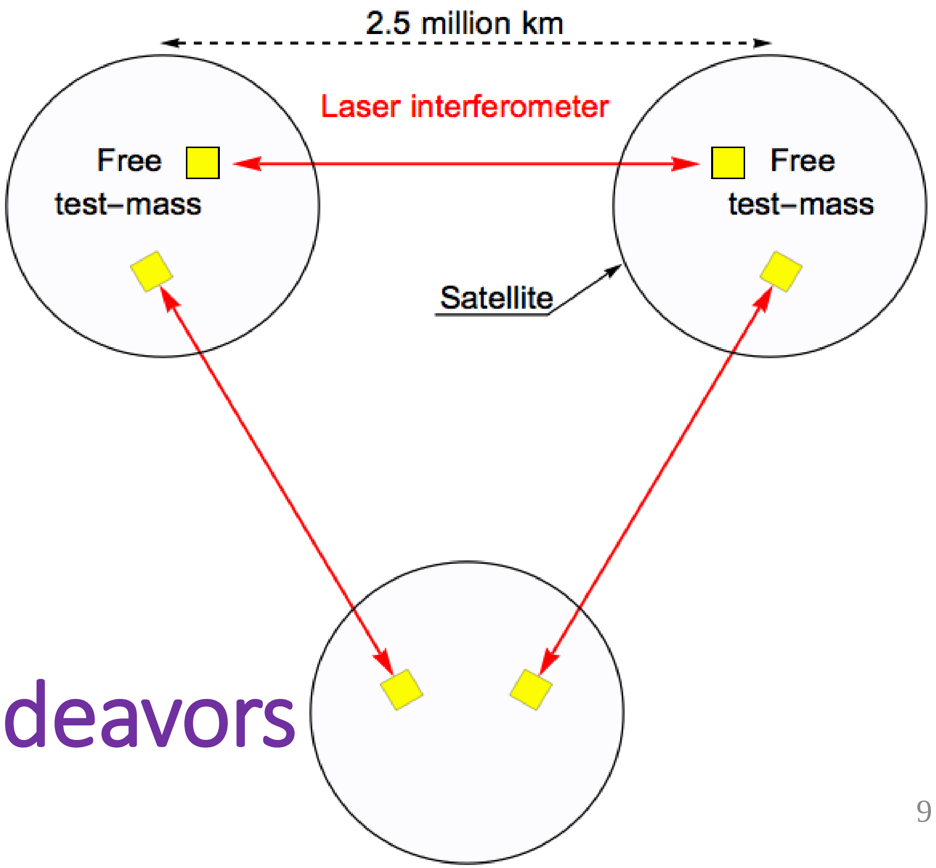



Quantum fluctuations in early universe
Binary Supermassive Black Holes in galactic nuclei
Stellar mass black-holes
Compact Binaries in our Galaxy & beyond
Compact objects captured by Supermassive Black Holes
Rotating NS, Supernovae
Sources
wave period
age of universe
years
hours
sec
ms
log(frequency)
-16
-14
-12
-10
-8
-6
-4
-2
0
+2
Detectors
Cosmic microwave background polarization
Pulsar Timing
Space Interferometers
Terrestrial interferometers
?
General Relativity vs Quantum Mechanics
nature of Black Holes and extreme space-time
cosmology
matter at extreme densities and Neutron Stars
evolution of stars
¿
massive black holes and large scale structures

Gravitational Wave Detectors

	LIGO/Virgo/KAGRA: in operation	LISA: preparing the mission
Size	3-4 km	2.5×10^6 km
Frequency	10 Hz ÷ few kHz	20 μHz ÷ 1 Hz





international endeavors

BASICS: Equivalence Principle

- Albert Einstein, 1907

from A.E. essay *"The Fundamental Idea of General Relativity in Its Original Form"*, 1919 (New York Times, 1972)

… At that point there came to me ***the happiest thought of my life***, in the following form: just as in the case where an electric field is produced by electromagnetic induction, the gravitational field similarly has only a relative existence. ***Thus, for an observer in free fall from the roof of a house there exists, during his fall, no gravitational field***—at least not in his immediate vicinity.

… The extraordinarily curious, empirical law that all bodies in the same gravitational field fall with the same acceleration immediately took on, through this consideration, a deep physical meaning. For if there is even one thing which falls differently in a gravitational field than do the others, the observer would discern by means of it that he is in a gravitational field and that he is falling in it. But if such a thing does not exist—as experience has confirmed with great precision—the observer lacks any objective ground to consider himself as falling in a gravitational field. Rather, he has the right to consider his state as that of rest, and his surroundings (with respect to gravitation) as field-free.

The fact, known from experience, that acceleration in free fall is independent of the material is therefore a mighty argument that the postulate of relativity is to be extended to coordinate systems that are moving non-uniformly relative to one another.

Equivalence Principle

Einstein Equivalence Principle:

- ✓ **Weak Equivalence Principle**: inertial mass = gravitational mass, or universality of free fall for (small enough) test bodies independently of their mass-energy composition. **Strong Equivalence Principle**: include also the gravitational self binding energy of the body.

AND

- ✓ **Local Lorentz Invariance**: outcomes of any **local** non-gravitational experiment are independent of the velocity of the freely-falling reference frame in which it is performed

AND

- ✓ **Local Positional Invariance**: outcomes of any **local** non-gravitational experiment are independent of where and when in the universe it is performed

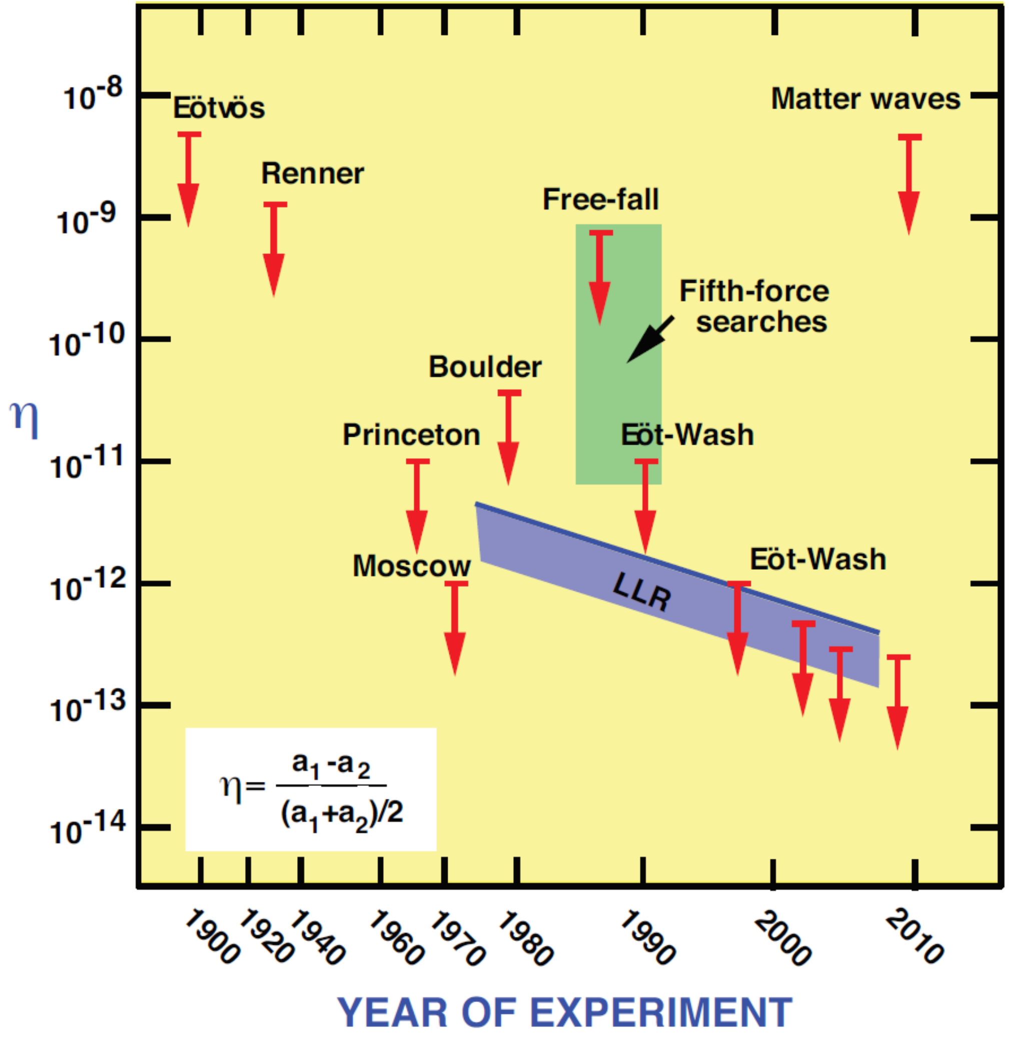
$\Rightarrow$ **gravity must be a curved space-time phenomenon:**

1. spacetime is endowed with a symmetric metric.
2. the trajectories of freely falling test bodies are geodesics of that metric.
3. in local freely falling reference frames, the non-gravitational laws of physics are compliant to special relativity.

not compatible (yet) with a quantum mechanical theory !

Tests of the Equivalence Principle

C.M.Will, Living Rev. Relativity, 17, (2014), 4
http://www.livingreviews.org/lrr-2014-4



Weak Equivalence Principle

limits on η, fractional difference in the acceleration of different test bodies

Strong Equivalence Principle

Baessler+ Phys. Rev. Lett., 83, 3585–3588 (1999)

Earth's self gravitating energy contributes a fraction $4.6*10^{-10}$ to Earth's total mass-energy,

>> Moon's case $0.2*10^{-10}$

Lunar Laser Ranging tests of free fall of Earth and Moon in the Sun's gravitational field

laboratory torsion balance experiment tests of differential accelerations between a mock Earth's core (Fe-Ni) and Moon's mantle (quartz-Mg)

both set $|\eta| < 5*10^{-13}$

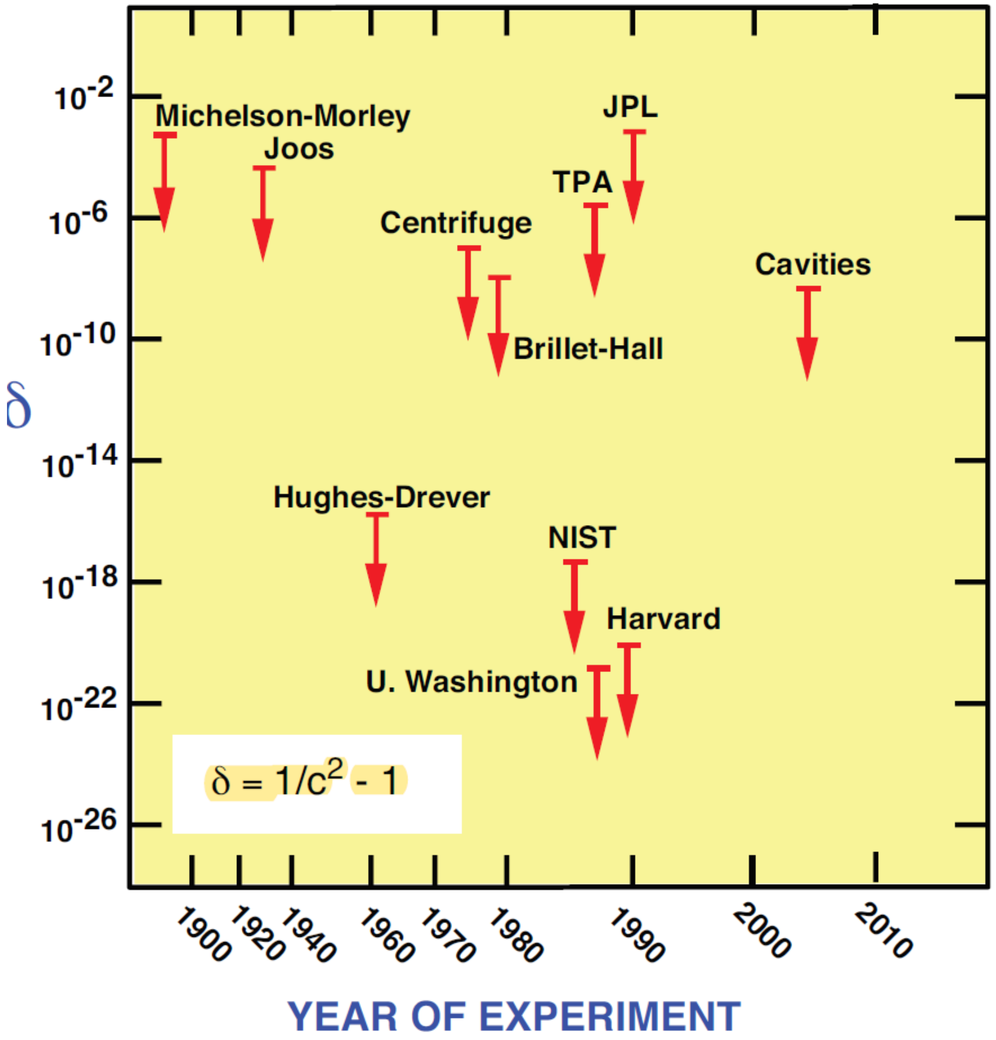
$\Rightarrow$ no deviation up to 10^{-3} of the self gravitating energy component

Tests of the Equivalence Principle

C.M.Will, Living Rev. Relativity, 17, (2014), 4
http://www.livingreviews.org/lrr-2014-4

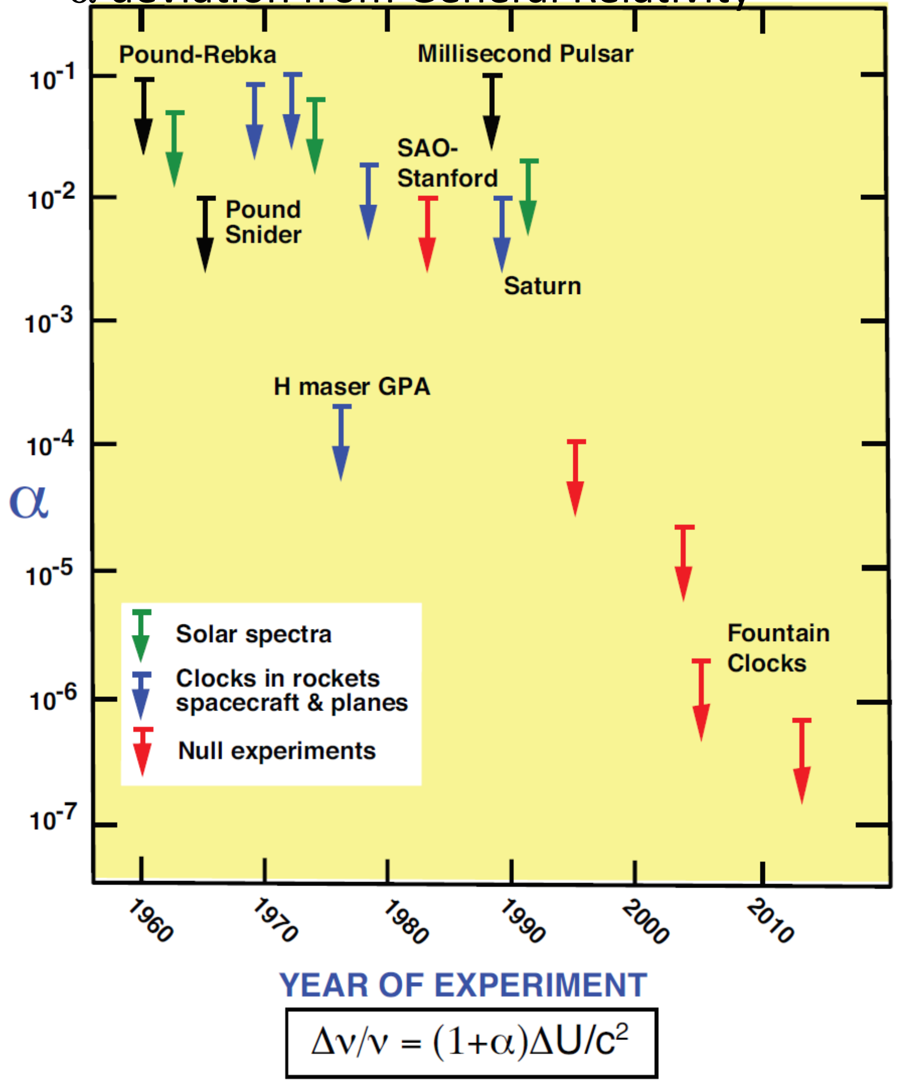
Local Lorentz Invariance in electromagnetism

c light speed in vacuum differing from unity



Local Positional Invariance with gravitational redshift experiments

α deviation from General Relativity



understanding Gravity, i.e. Space-Time

ALBERT EINSTEIN

1907

Principle of Equivalence

in inertial reference frames all physical laws are invariant and effects of Gravity can be nulled LOCALLY

1911

Gravitational Redshift of "photons"

1915-1916

General Relativity

space-time is dynamical, *loosely elastic*

$$\boldsymbol{strain} = \frac{1}{\boldsymbol{stiffness}}\,\boldsymbol{stress}$$

of Space-Time (strain) — ***generated by mass and energy*** (stress)

first success:
accounting the perihelium precession of Mercury

Gravitational Field Equations

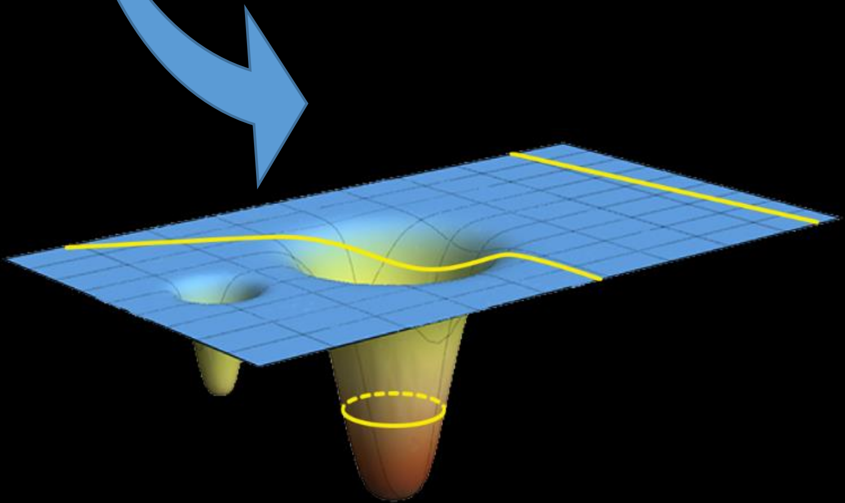
$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} = \frac{8\pi G}{c^4}\, T_{\mu\nu}$$

curvature — *strain of space − time*

field source — mass-energy tensor

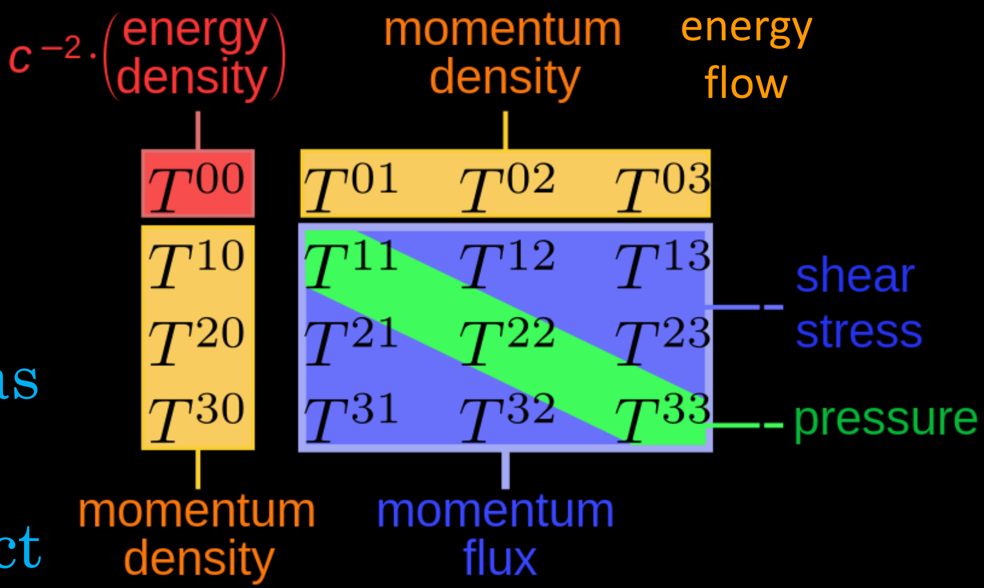
$$\textit{stiffness}\ \frac{c^4}{8\pi G} \approx \frac{10^{42} N}{\textit{degree of freedom}}$$

extremely rigid



curvature contributes as source

highly NON linear effect



general remarks

Einstein Field Equations cannot be "derived", they are fundamental and motivated by Equivalence Principle and known relativistic physics

surviving all experimental tests to date

Non local effects (Equivalence Principle)

need extended space-time volumes to identify gravitational effects

Measuring Curvature

- gravitational redshift: when comparing "clocks" at rest at different gravitational potential energies, the "deeper" one is slower (Pound & Rebka, PRL (1960) 337)
- "geodesic deviations": relative accelerations of close-by freely falling particles not affected by other interactions (gravitational lensing of light rays, tidal deformations of extended systems of test masses, …)

  note the fundamental role of trajectories, in contrast to the Heisenberg Uncertainty Principle and Quantum Mechanics

general remarks

NON linearity

- no superposition principle here: the few analytical solutions of the field equations available for point-like sources cannot be used to build more general solutions.
- approximate analytical solutions are available at different levels of accuracies in (v/c) and (Gm / rc^2) for simpler bodies/test particles, but Numerical Relativity methods are the only ones treating strong field, highly relativistic and complex "micro-physics" such as in collisions of compact astrophysical objects, Supernovae, …

I dropped the "cosmological constant" term for simplicity

the additional term on left hand-side $\Lambda \, g_{\mu\nu}$ is a possible option. Initially introduced to tune the universe evolution to scientists's desires (e.g. preserve stationary model).

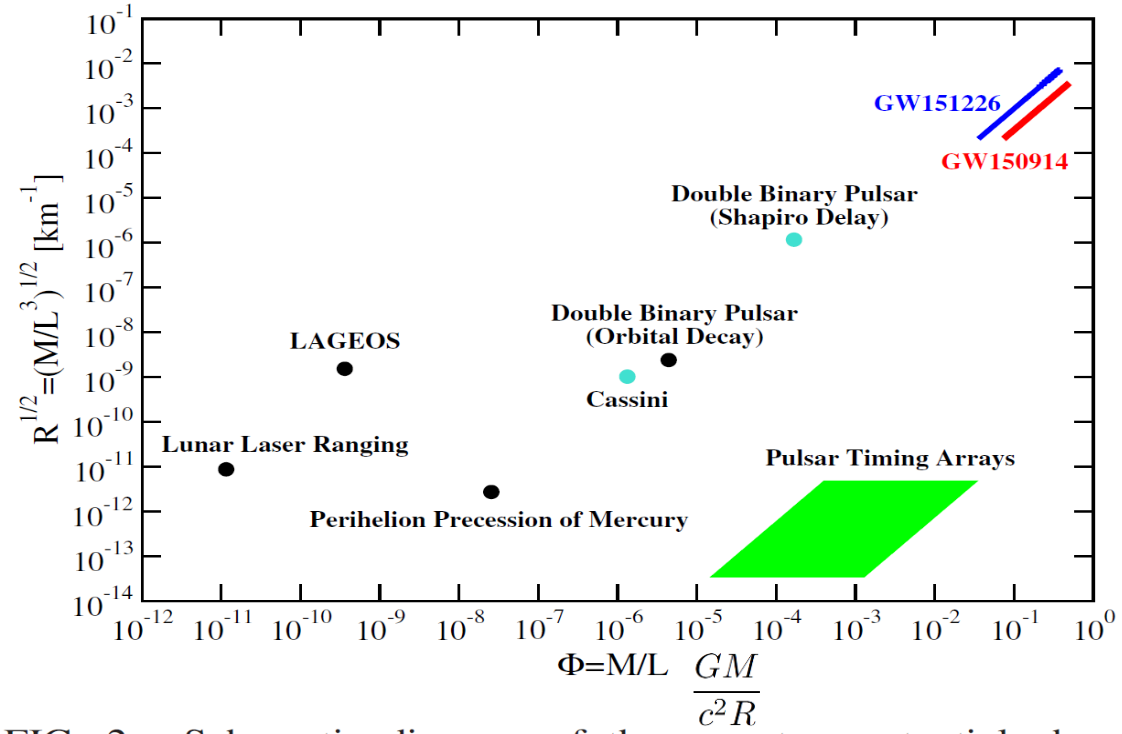
It became recently the way in which we describe the dark energy which "explains" the accelerated expansion of the universe.

This is needed to discuss large scale and evolutionary cosmology, therefore affects Gravitational Wave propagation but not its emission and detection processes.

investigating gravity (space-time dynamics) 1

PHYSICAL REVIEW D **94,** 084002 (2016)
YUNES, YAGI, and PRETORIUS

curvature



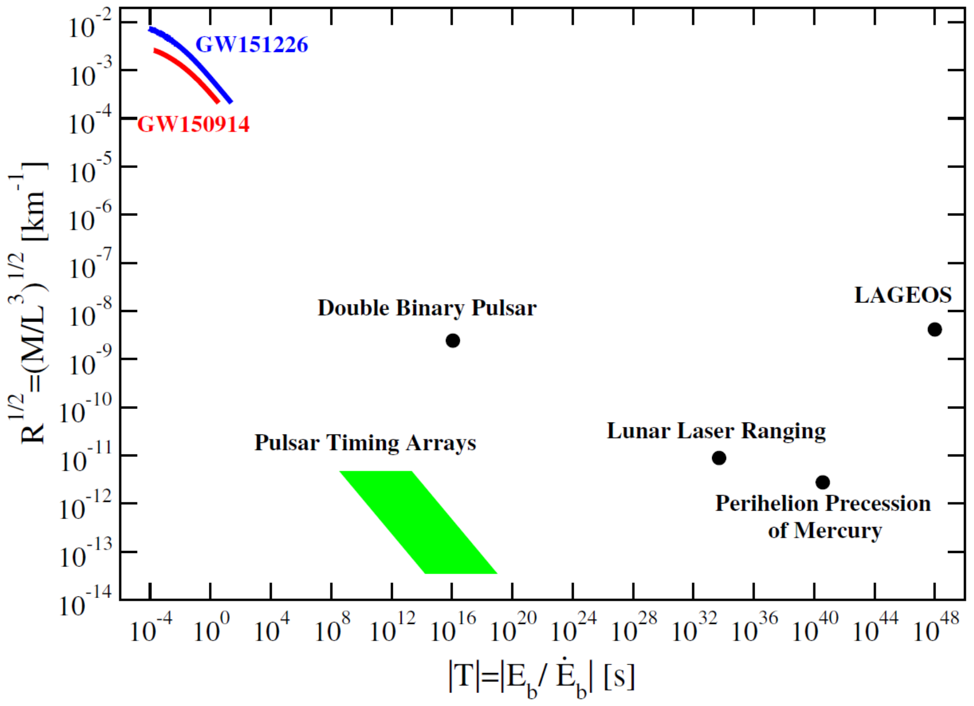


FIG. 2. Schematic diagram of the curvature-potential phase space sampled by various experiments that test GR. The vertical axis shows the inverse of the characteristic curvature length scale, while the horizontal axis shows the characteristic gravitational potential, based on Table II. GW150914 and GW151226 sample

except that the abscissa is now the radiation-reaction time scale sampled by each observation. We model this via $|T| = |E_b/\dot{E}_b|$, where E_b is the characteristic gravitational binding energy and $\dot{E}_b$ is the rate of change of this energy,

investigating gravity 2

THE ASTROPHYSICAL JOURNAL, 802:63 (19pp), 2015 March 20 BAKER, PSALTIS, & SKORDIS

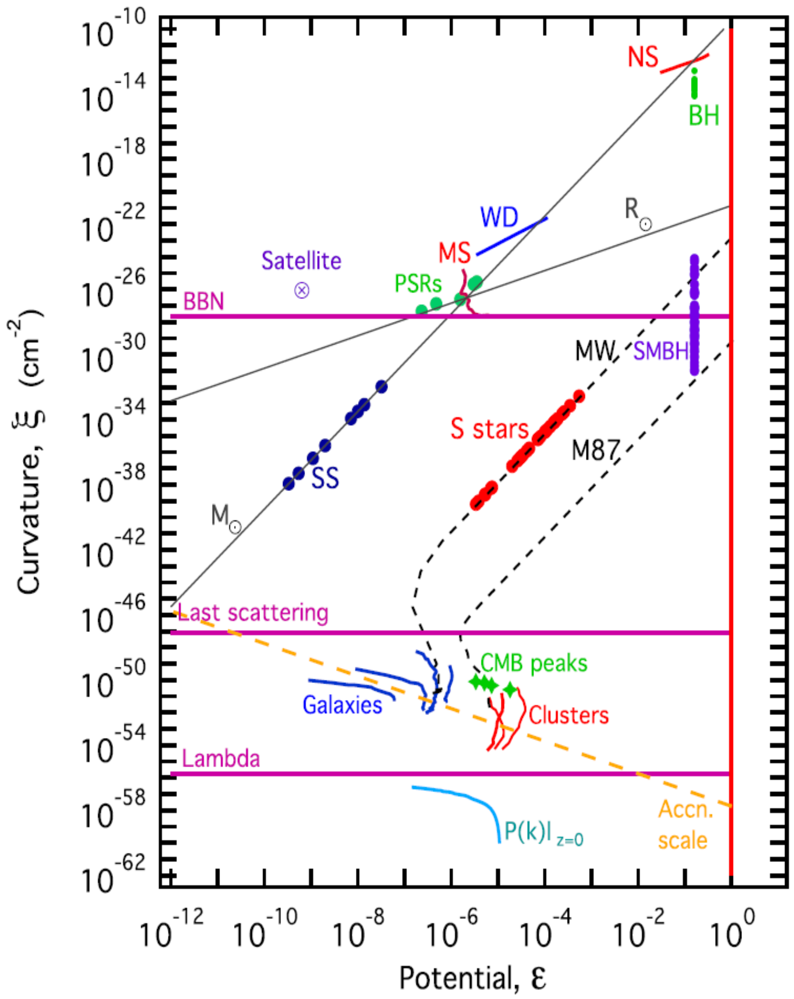


Figure 1. A parameter space for gravitational fields, showing the regimes probed by a wide range of astrophysical and cosmological systems. The axes variables are explained in Section 2 and individual curves are detailed in Section 3. Some of the label abbreviations are: SS—planets of the Solar System, MS—Main Sequence stars, WD—white dwarfs, PSRs—binary pulsars, NS—individual neutron stars, BH—stellar mass black holes, MW—the Milky Way, SMBH—supermassive black holes, BBN—Big Bang Nucleosynthesis.

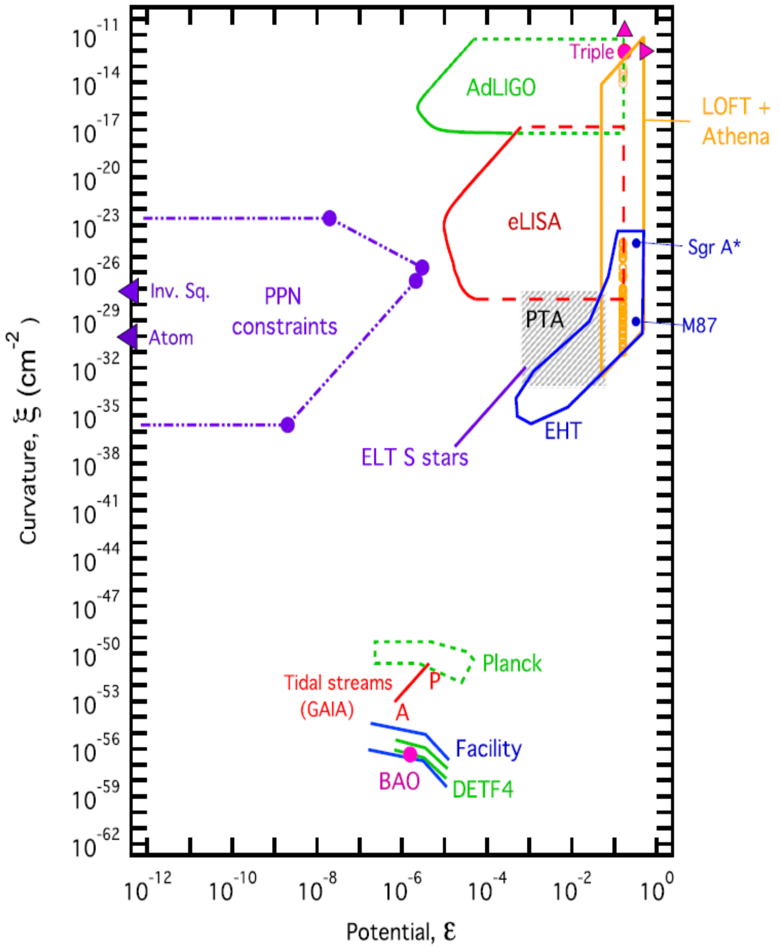


Figure 2. The experimental version of the gravitational parameter space (axes the same as in Figure 1). Curves are described in detail in the text (Section 4). Some of the abbreviations in the figure are: PPN—Parameterized Post-Newtonian region, Inv. Sq.—laboratory tests of the $1/r^2$ behavior of the gravitational force law, Atom—atom interferometry experiments to probe screening mechanisms, EHT—the Event Horizon Telescope, ELT—the Extremely Large Telescope, DETF4—a hypothetical "stage 4" experiment according to the classification scheme of the Dark Energy Task Force (Albrecht et al. 2006), Facility—a futuristic large radio telescope such as the Square Kilometre Array.

Gravitational plane Waves far away from sources

❑ weak-field linear approximation of General Relativity: $g_{\alpha\beta} = \eta_{\alpha\beta} + h_{\alpha\beta}$ $|h_{\alpha\beta}| << 1$

oversimplified separation between GWs and static space-time in the background

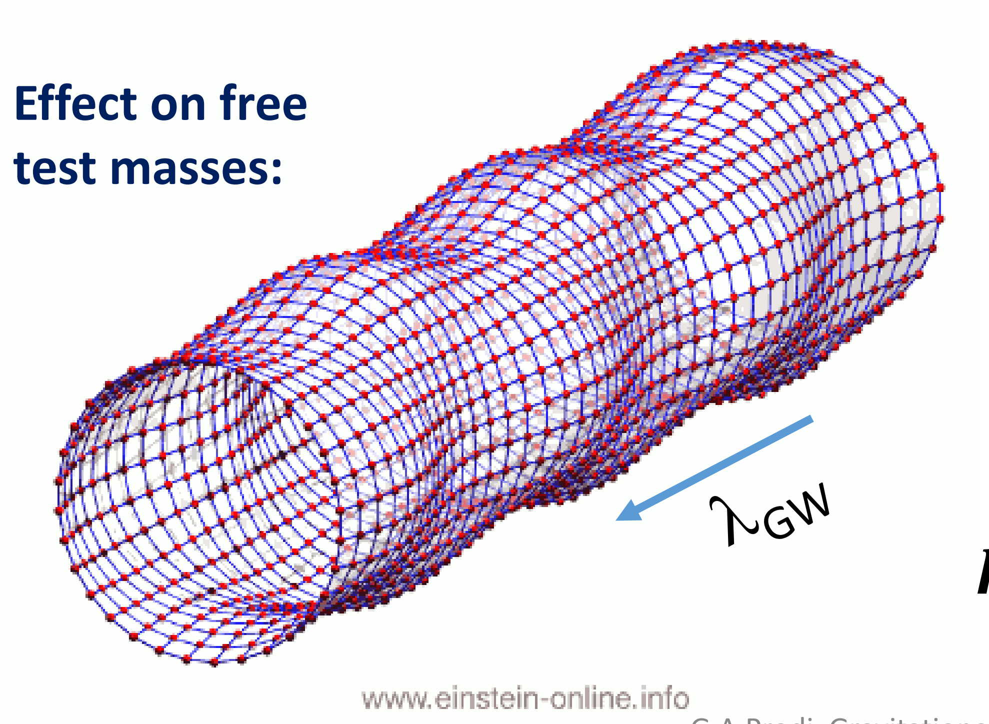
- analogies with electromagnetic waves:

  light speed, transverse, 2 polarization components

- peculiarities of GWs:

  tidal deformations of extended bodies, no measurable local effect

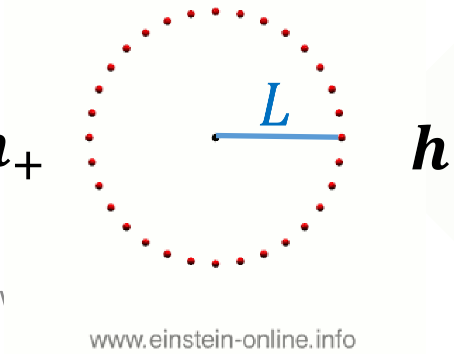
Effect on free test masses:



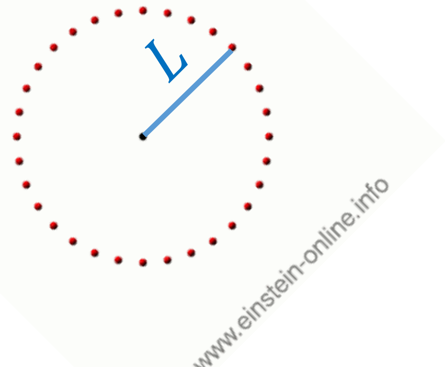
GW amplitude is strain: $\frac{\Delta L}{L} = \frac{1}{2}\boldsymbol{h}$

tensor polarizations $\boldsymbol{h}_+$ $\boldsymbol{h}_\times$ *rotated by* $\frac{\pi}{4}$ ***in the wavefront plane:***

$\boldsymbol{h}_+$



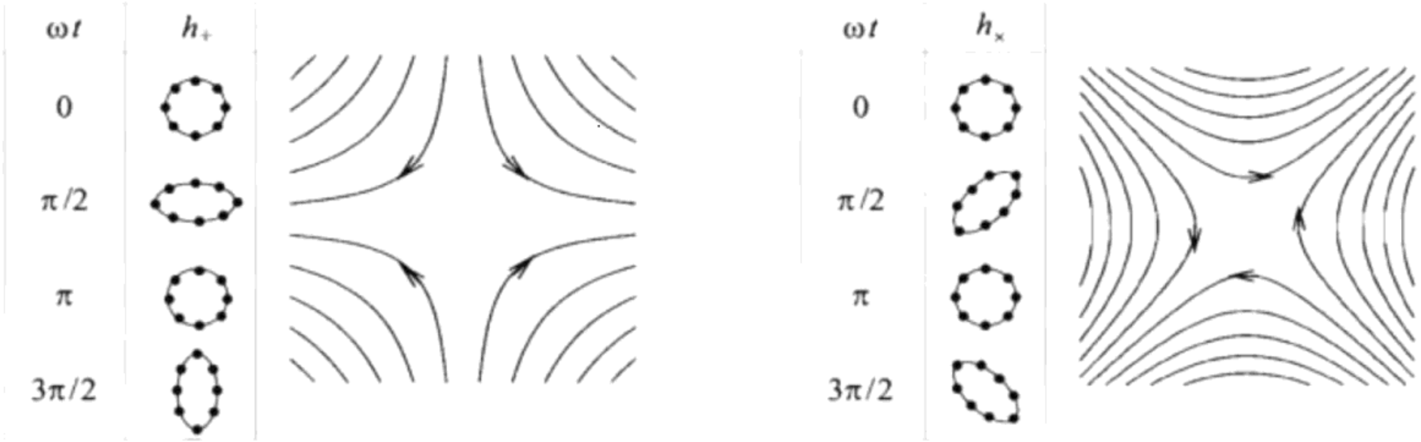
$\boldsymbol{h}_\times$



general remarks on Gravitational Waves in vacuum

doubts on GW effects, hence GW existence, were solved only in 1957: Felix Piran + demonstrated they can release energy in a detector.

tidal deformation of a **small detector** by GW



- linearized gravity
- in vacuum
- separations $|\xi| \ll$ wavelength of GW

$\Rightarrow$ in all freely falling frames the geodesic equation simplifies to:

$$\ddot{\xi}_i = \frac{1}{2}\ddot{h}_{ij}\,\xi_j$$

- the relative accelerations $\ddot{\xi}_i$ can be interpreted as Newtonian forces per unit mass
- tidal: it is proportional to the separations ξ_j
- moreover in freely falling frames separations are = proper distances, so that the above result is invariant

Warning: this is not applicable to large detectors such as LISA or Pulsar Timing Array

general remarks on Gravitational Waves

- the linear approximation of GR used to compute the GW ***h*** field components cannot account for **GW energy** which is a quadratic effect.
- dropping the linear approximation, there is **no general way to separate the propagating GW from a "background" curvature**.

$g_{\alpha\beta} = \overline{g_{\alpha\beta}} + h_{\alpha\beta}$ where $\overline{g_{\alpha\beta}}$ stands for the curved background in place of the flat spacetime $\eta_{\alpha\beta}$

separing the GW requires an additional assumption "**short wavelength approximation**":

A. smallness of GW wavelength wrt length scale of change of background curvature

OR

B. faster temporal variation of GW wrt background curvature

neither assumptions are valid in the most relevant GW emission processes: close to the source the gravitational field is fully mixed up.

at the detectors we have some serious problems as well: there are "environmental/local" gravitational field gradients which can be separated from the GW only if they occur at lower frequencies, which is not always the case (see Gravity Gradient noise contribution !).

general remarks on Gravitational Waves

- equivalence principle **prohibits a local notion of GW**, including GW energy and momentum: in a local inertial frame any gravitational effect is nulled.

GW energy and momentum need to be defined as average densities over suitably large space-time volumes

GW are contributing as source term (stress energy tensor) in Einstein Field Equations: $T_{\mu\nu}^{matter} + t_{\mu\nu}^{gravity}$

…far from the source, short wavelength approximation, and for weak GW field…

$\Rightarrow \; t_{00}^{gw} = \frac{c^2}{16\,\pi\,G} \left\langle \dot{h}_+^2 + \dot{h}_\times^2 \right\rangle$ GW energy density, averaged on space-time

$\frac{dE}{dA\,dt} = c\; t_{00}^{gw}$ GW power per unit area (luminosity per unit area), which is obviously subtracting energy from the source

$T_{\mu\nu}^{matter} + t_{\mu\nu}^{gravity}$ has to obey local conservation laws

simplified Gravitational Wave emission

consistent set of simplifying assumptions for self gravitating systems:

- weak gravity also inside the source, almost flat space-time
- non relativistic motions inside the source
- case of long GW wavelength wrt source dimension, or low enough GW frequency that is consistent with the non relativistic motions inside the source

… expansion in terms of source dimension / distance of observation … $T_{\mu\nu}^{matter}$ conservation laws …

resulting first non zero term is **quadrupolar** i.e. time derivatives of the second order mass moment

$$h_{ij}^{TT} \cong \frac{1}{R}\frac{2G}{c^4}\ddot{Q}_{ij}\left(t-\frac{R}{c}\right)$$

where R is the distance from the source, Q_{ij} is the second order central mass moment of the source [M L^2], i.e. traceless or estimated in the center of mass system

back of the envelope estimate for a compact source with evolving mass quadrupole at ω $(e.g.\ 2\omega_{rotation})$

$$Q_{ij} \sim m_{eff} D_{eff}^2\, e^{i\omega t} \Rightarrow |\ddot{Q}_{ij}| \sim m_{eff} D_{eff}^2 \omega^2 \sim m_{eff} v_{eff}^2$$

$\Rightarrow |h| \sim \boldsymbol{\frac{G\, m_{eff}}{Rc^2}} \frac{v_{eff}^2}{c^2}$ and for self gravitating sources $\frac{v_{eff}^2}{c^2} \sim$ gravitational field at source (virial theorem)

~ gravitational field at observer

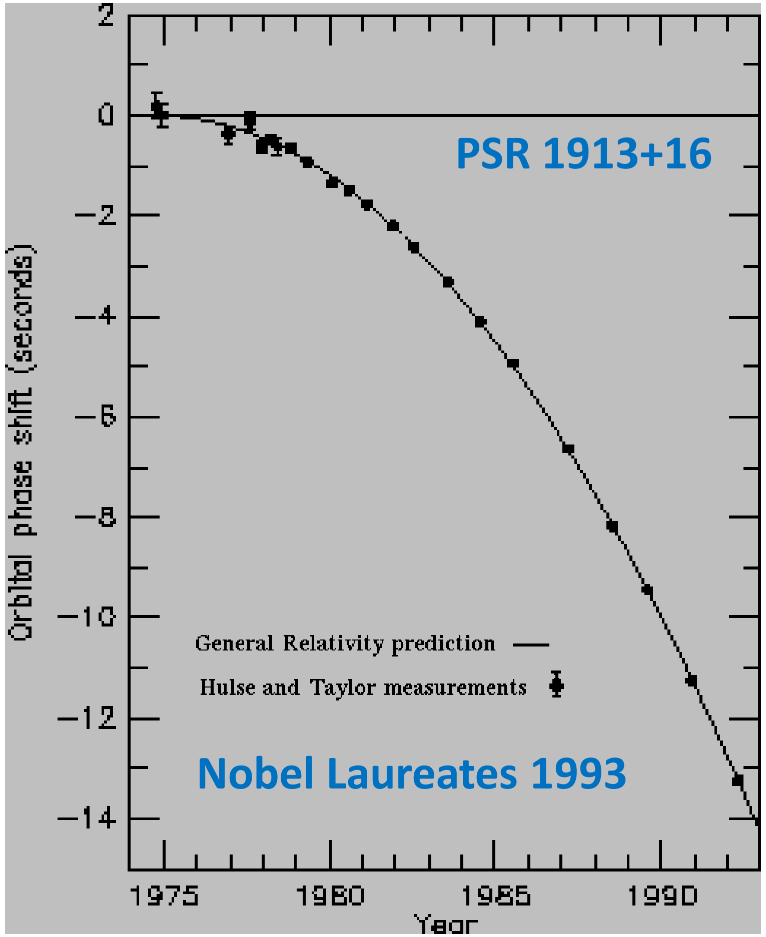
Sources of Gravitational Waves

- **mass-Dipole Moment**, [M R], position of the Center of Mass of the system:
  "almost forbidden" dipolar emission of GWs from isolated systems

- leading order emission is **mass-Quadrupole Moment $Q_{\mu\nu}$** , [M R^2] :
  GW Luminosity is driven by $\dddot{Q}_{\mu\nu} \neq 0$

$$P \approx \frac{G}{5c^5} \dddot{Q}_{\mu\nu} \dddot{Q}^{\mu\nu} \sim 10^{39} W \left(\frac{f}{Hz}\right)^2 \left(\frac{M}{M_\odot}\right)^2 \left(\frac{v}{c}\right)^4$$

dimensional argument



- generating detectable GWs as in Hertz-like experiment is NOT feasible

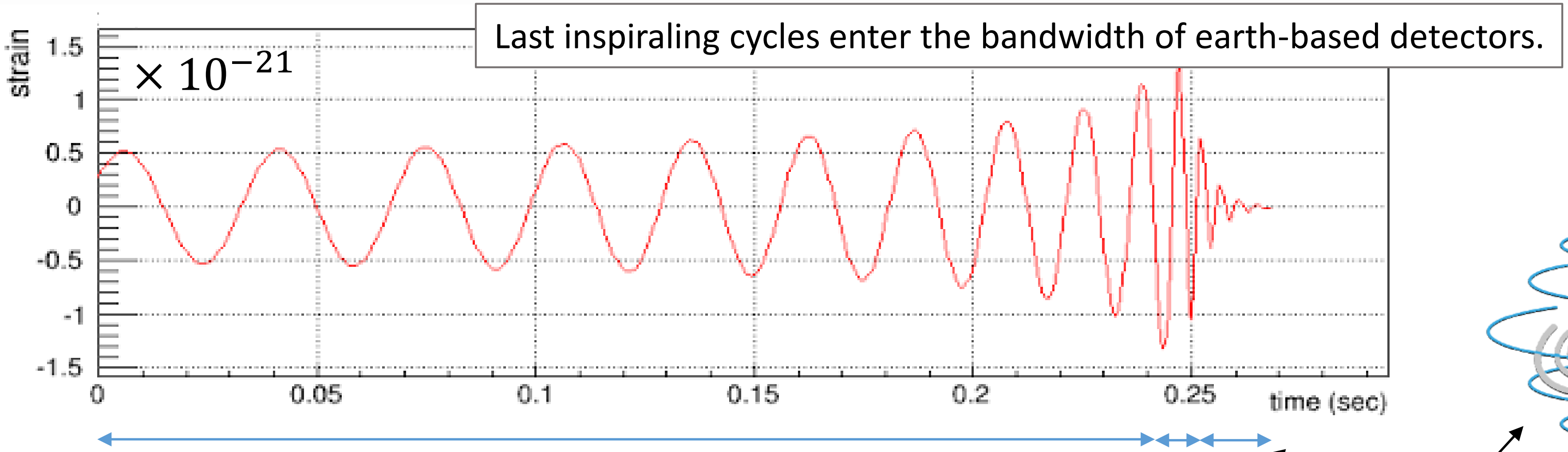
- astrophysical sources (e.g. **Hulse & Taylor binary pulsar**) are emitting in agreement with General Relativity

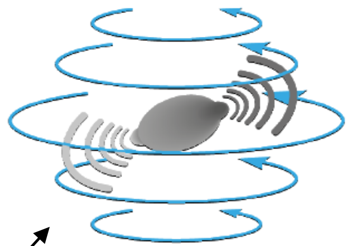
GWs from compact binary coalescences

- The most efficient emitters among expected GW sources
  - Up to ~ **10%** total mass converted in gravitational radiation

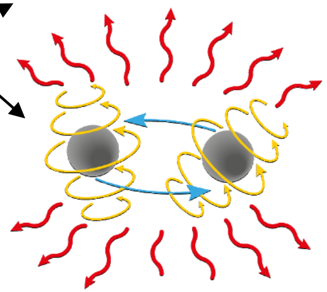
h

at least 15 parameters in the waveform model (BBH circular orbit)

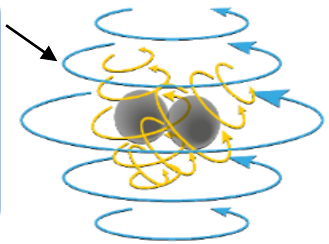




INSPIRAL
GW emission described by quadrupole formula. Analytical solution available



MERGER
Only numerical solution available



RINGDOWN
Perturbative and numerical solutions

GW can be used as a standard candle.

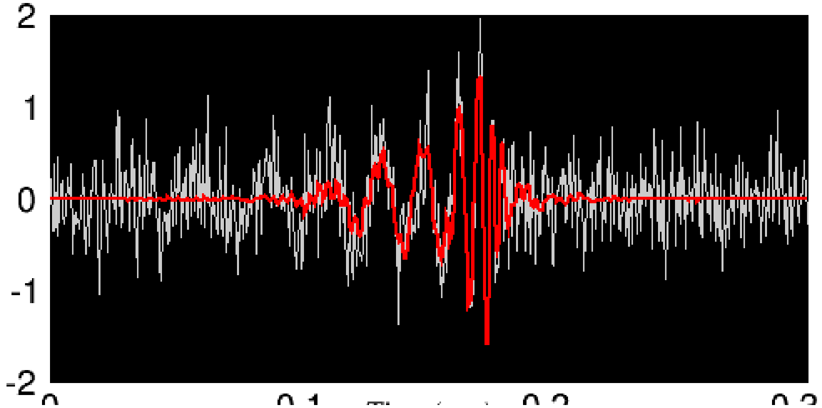
Chirp Mass $(m_1\, m_2)^{3/5}\, (m_1 + m_2)^{-1/5}$

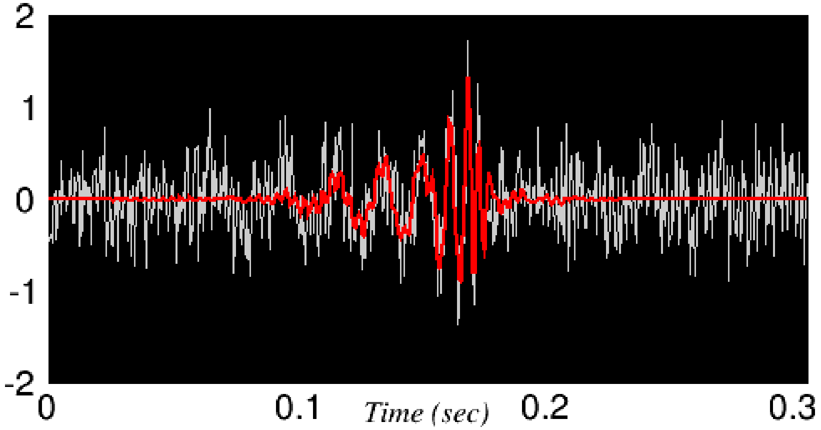
General Relativity in strong field
highly non-linear regime
NS would bring more physics (Equation of State, ...)

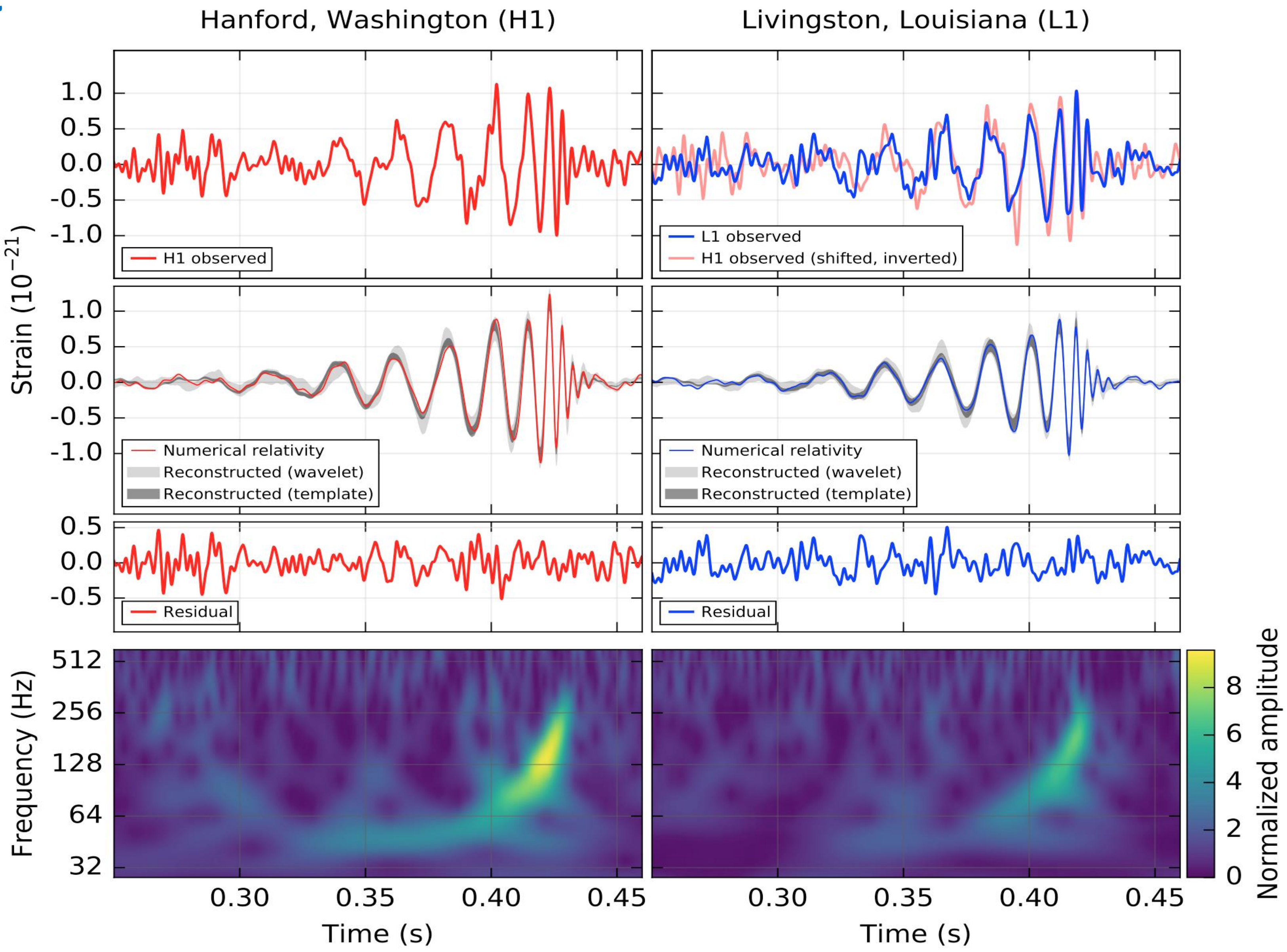
GW150914: the first direct observation

PRL 116, 061102 (2016)

unexpected signal: detected first by wide-scope transient search not assuming waveform model

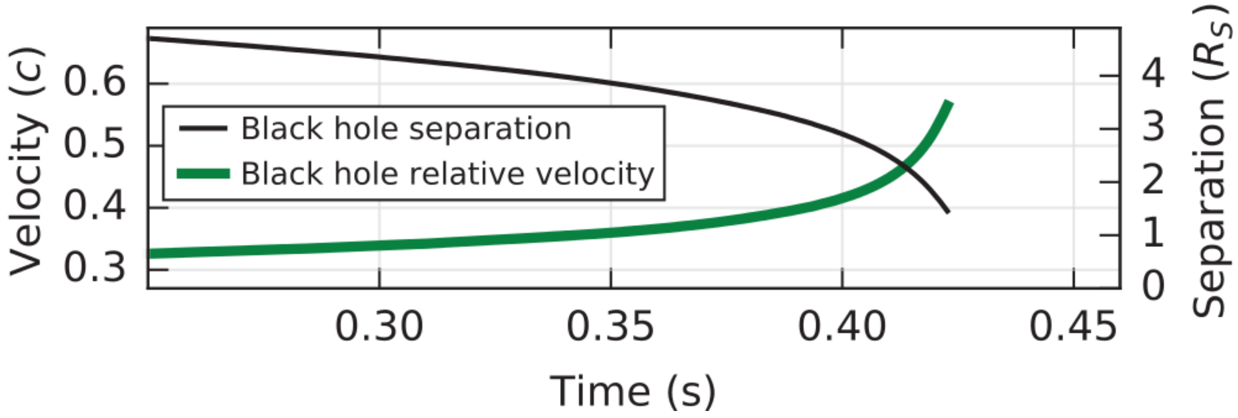






GW150914: inspiral

- time-frequency evolution is typical of the inspiral-merger-ringdown of a compact binary coalescence
- f and $\dot{f}$ in inspiral cycles measure the chirp mass $M_{chirp} = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}} \approx 30\ M_\odot$ and lower limits total mass $M = m_1 + m_2 \gtrsim 70\ M_\odot$



$R_S = \frac{2GM}{c^2} \cong 210\ km$

Lower limit to the sum of Schwarzschild radii of progenitors

Newtonian approximations for:

- **orbital separation** $R \approx \left(\frac{GM}{4\pi^2 f^2}\right)^{1/3} \approx 350km$ at end of inspiral (orbital frequency ≈75 *Hz*)
- **orbital speed** up to 0.5 *c*

Black Holes progenitors are the only known compact objects that can orbit up to frequency ≈ *75Hz* before collision

Annalen der Physik **529**, 1600209 (2017)

Phys. Rev. Lett. **116**, 061102

GW150914 parameters [Phys. Rev. Lett. **116**, 241102 (2016)]

- **Parameter Estimation** is achieved by Bayesian model selection over a template bank of analytical waveforms calibrated against numerical relativity simulations of the merger

Monte Carlo methods on 17 Parameters: 2 masses, 2x3 spin, distance, 2 sky coordinates, 4 orbital parameters, time and phase of coalescence.

Mass 1	$36.3^{+5.3}_{-4.5} M_\odot$
Mass 2	$28.6^{+4.4}_{-4.2} M_\odot$
Final mass	$62.0^{+4.4}_{-4.0} M_\odot$
Energy radiated in GW	$3.0^{+0.5}_{-0.5} M_\odot$
Final spin $\|a_f\|$	$0.67^{+0.06}_{-0.08}$
Luminosity distance	$410^{+160}_{-180} Mpc$

higher mass values than expected

$$\gtrsim 30 M_\odot$$

$3 M_\odot$ unbalance:

very high GW luminosity

$$L_{peak} \approx 3.6 \cdot 10^{49} W$$

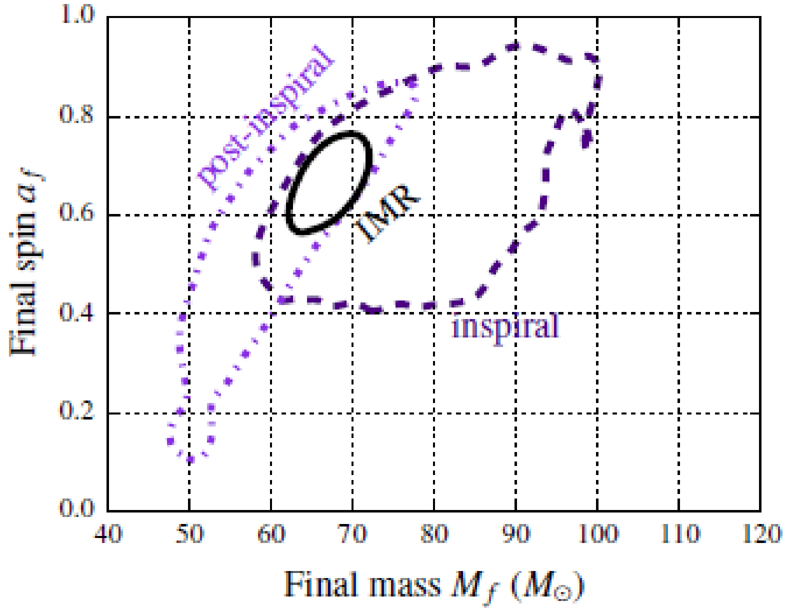
most energetic astrophysical event observed

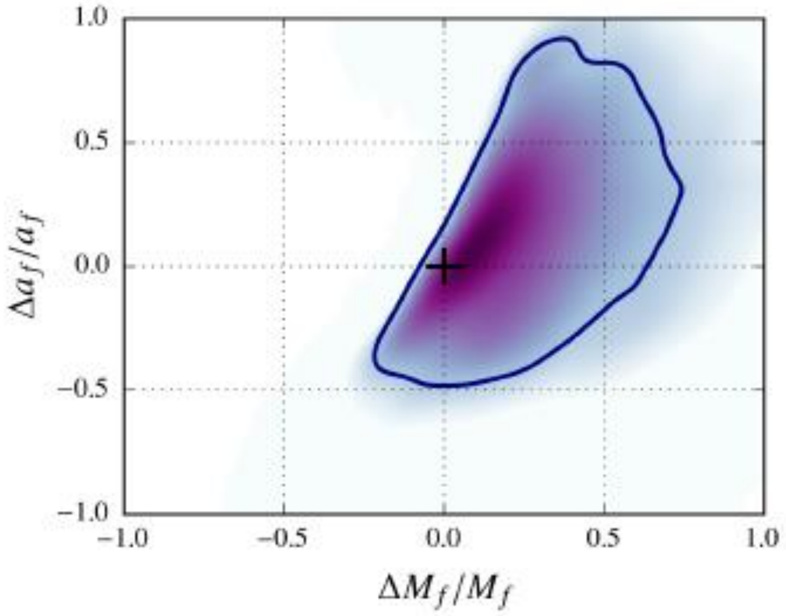
high uncertainty: degeneracy between distance and inclination angle to the source, since the LIGOs are sensitive to only one polarization of the GW

Consistency with GR Black Hole solution [Phys. Rev. Lett. **116**, 221101 (2016)]

- ❑ Leftover residuals of GW150914 are not statistically distinguishable from instrumental noise

- ❑ Mass and spin of the remnant BH are predicted using separately inspiral phase and post inspiral phase. No evidence of inconsistency with the inspiral-merger-ringdown analysis.





- Test of GR consistency of the measured quasi normal mode observation (3-5ms after merger)

$$f_{220}^{QNM} = 251^{+8}_{-8}\,\text{Hz} \qquad \tau_{220}^{QNM} = 4.0^{+0.3}_{-0.3}$$

spare slides

test of Strong Equivalence Principle: gravitational self energy

Baessler+ Phys. Rev. Lett., 83, 3585–3588 (1999)

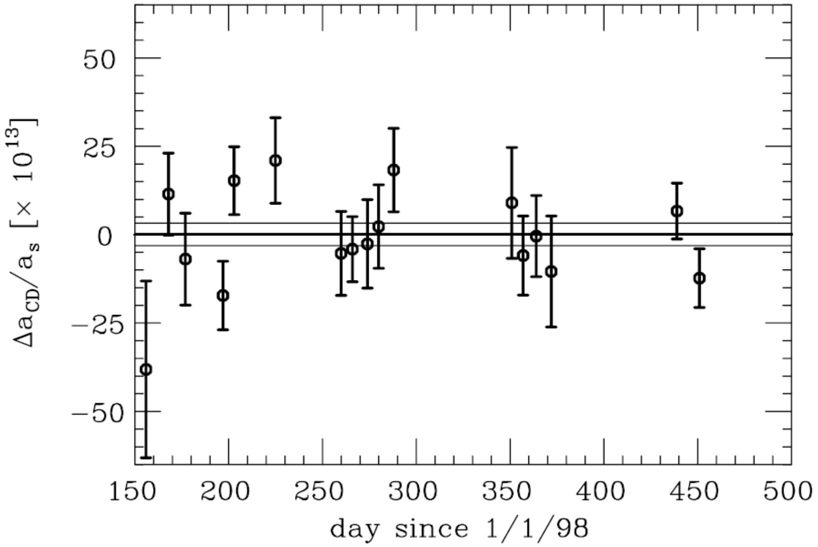


FIG. 4. Each point represents a 4-day measurement of Δa_{CD}. The periods with no points were spent checking for systematic errors or making improvements to the apparatus. The horizontal lines show the 1σ statistical plus systematic limits from the combined data.

"Nordtvedt effect"

$$\frac{m_p}{m} = 1 - \eta_N \frac{E_g}{m\,c^2}, \quad \text{in GR } (\eta_N = 0)$$

E_g is the negative of the gravitational self-energy of the body ($E_g > 0$)

4.6×10^{-10} for the Earth, 0.2×10^{-10} for the Moon

The Lunar Laser Ranging measures no deviations for the SEP

$|\eta_{SEP}| \leq 5.5 \times 10^{-13}$

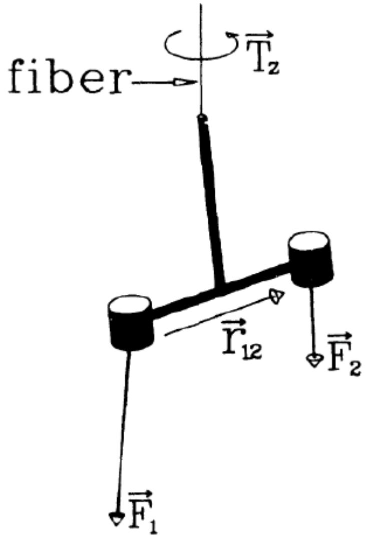
this is the overall effect of earth-moon differences in both composition and gravitational self-energy altogether

to extract a specific limit related to gravitational self-energy alone a lab torsion balance experiment in the gravitational field of the sun was setup with test masses mimicking earth Fe-Ni core and the Moon compositions:
this measured the composition-dependent only deviation with upper limit value similar to the LLR one

subtracting this prediction for the composition-dependent effect to the result from Lunar Laser Ranging of earth and moon in the sun gravitational field

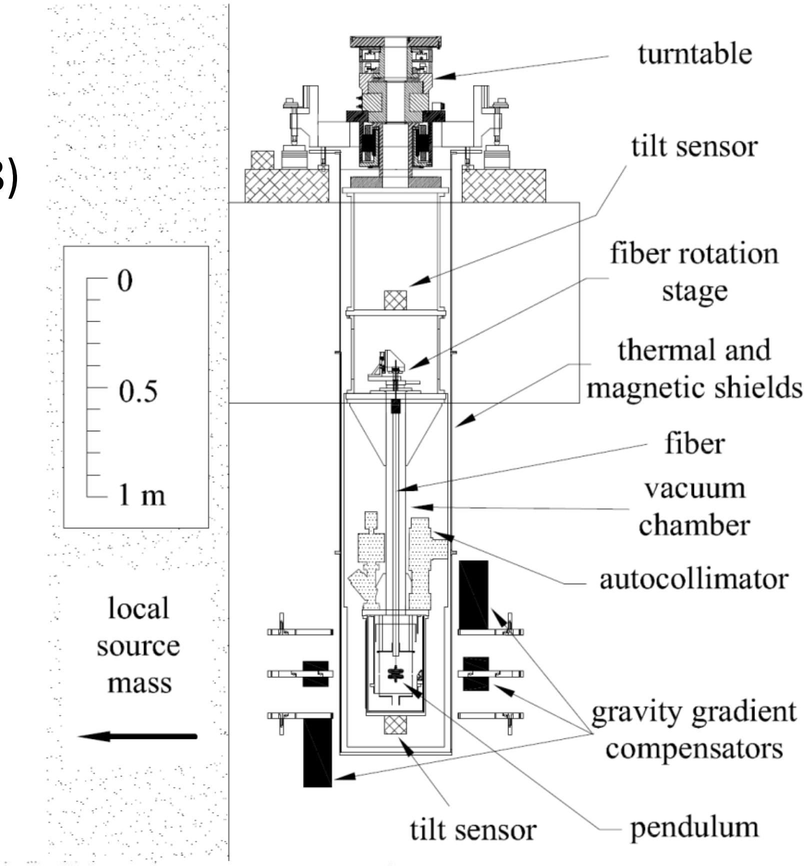
obtain the net Strong EP limit related to gravitational self-energy of the earth (20 times that of the moon):

$$|\eta_{grav}| = \frac{|\eta_{SEP}|}{4.4 \times 10^{-10}} \leq 1.3 \times 10^{-3}.$$



Eot-Wash torsion balance

Schlamminger+ Phys. Rev. Lett., 100, 041101 (2008)
Wagner+ Class. Quantum Grav., 29, 184002 (2012)



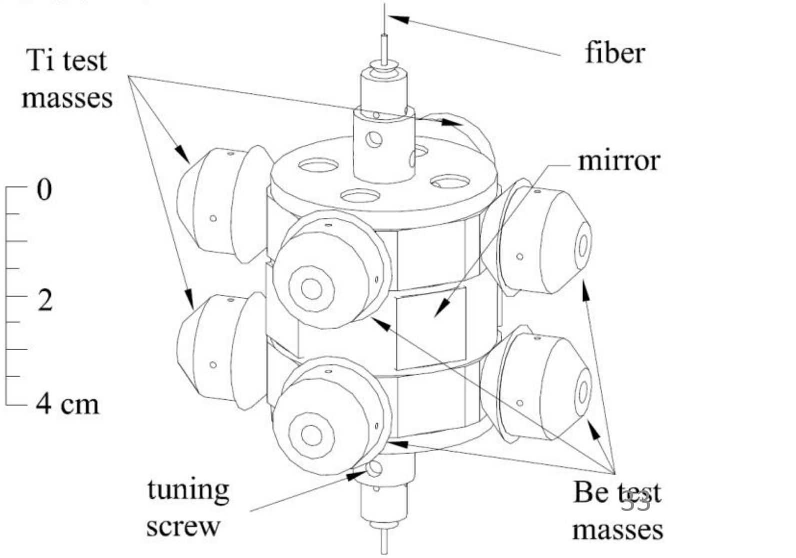
torque along the fiber is driven by non zero angle within the Forces

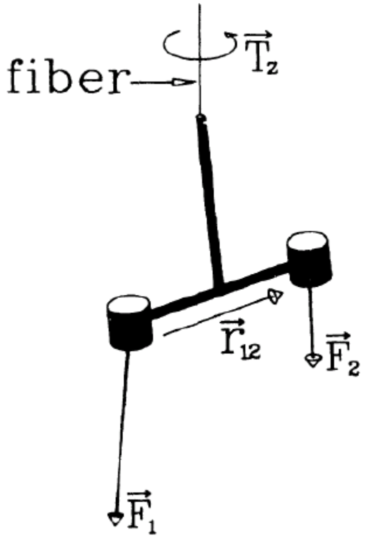
$$T_z = (\boldsymbol{F}_1 \times \boldsymbol{F}_2 \cdot \boldsymbol{r}_{12})/|\boldsymbol{F}_1 + \boldsymbol{F}_2|$$

null measurement: allows to achieve relative precisions of 1E-13
even if instrument tolerances are at 1E-5

systematic uncertainties from gravity gradients: highly symmetrical pendulum

uniform rotation to modulate the signal





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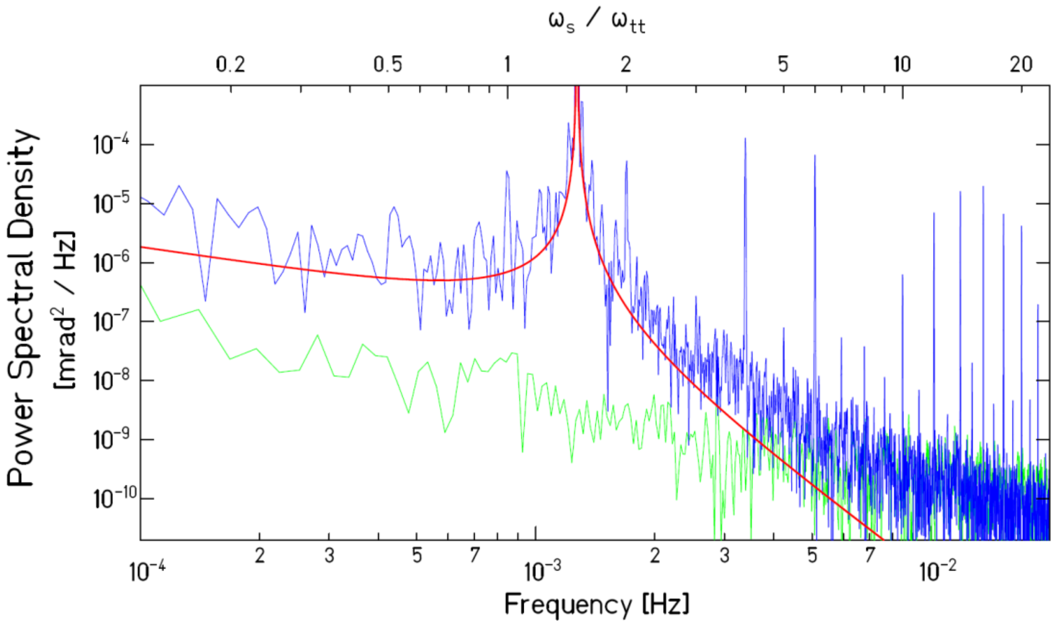
systematic uncertainties from gravity gradients: highly symmetrical pendulum

uniform rotation to modulate the signal

thermal noise in terms of PSD of torque at input of the single-mode torsional oscillator:

$$\tau(f)^2 = 4k_B T\kappa/(2\pi f Q)$$

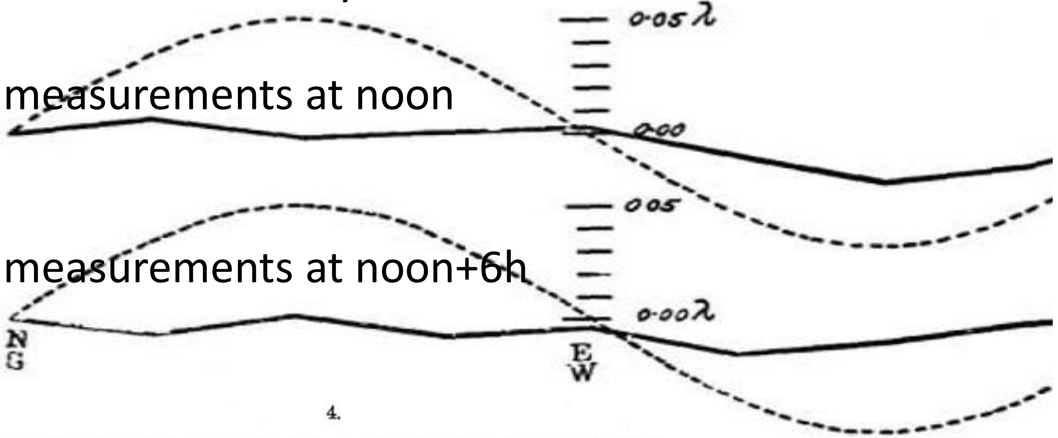


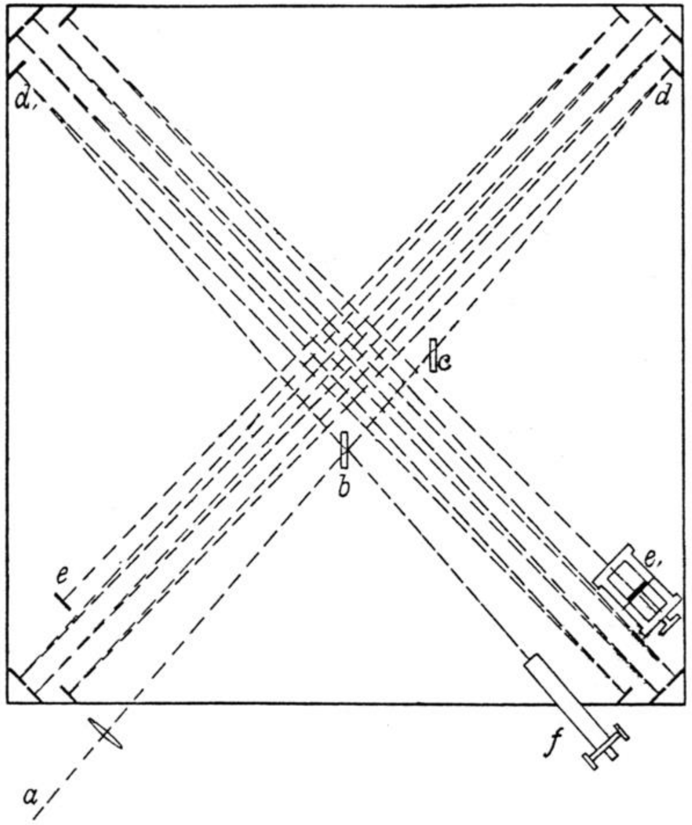
tests of Local Lorentz Invariance in electromagnetism

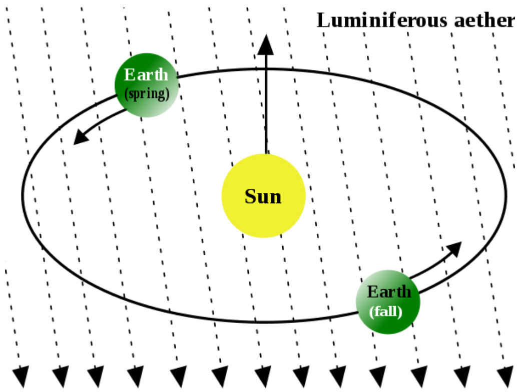
Michelson-Morley 1887:

measurements at noon

measurements at noon+6h







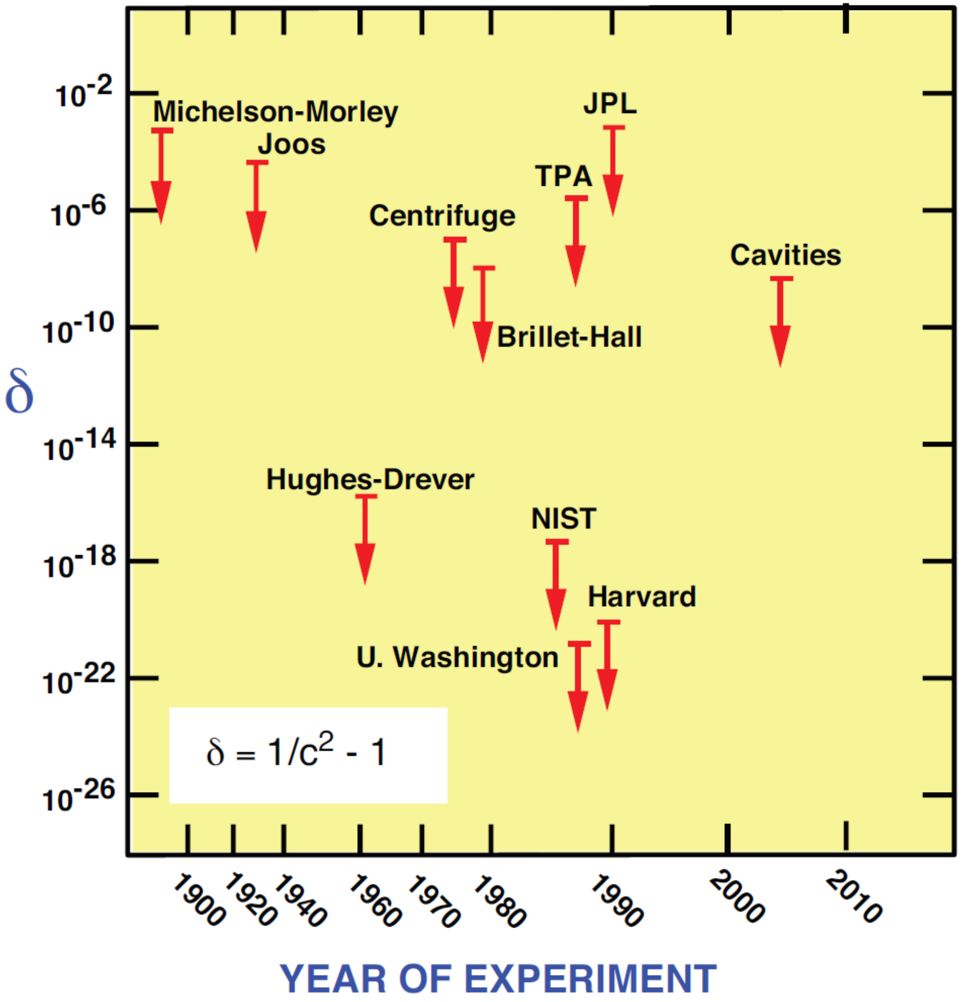


Figure 2: Selected tests of local Lorentz invariance showing the bounds on the parameter δ, which measures the degree of violation of Lorentz invariance in electromagnetism. The Michelson–Morley, Joos, Brillet–Hall and cavity experiments test the isotropy of the round-trip speed of light. The centrifuge, two-photon absorption (TPA) and JPL experiments test the isotropy of light speed using one-way propagation. The most precise experiments test isotropy of atomic energy levels. The limits assume a speed of Earth of 370 km s^{-1} relative to the mean rest frame of the universe.

tests of Local Position Invariance: gravitational redshift

PHYSICAL REVIEW
LETTERS

VOLUME 4 APRIL 1, 1960 NUMBER 7

APPARENT WEIGHT OF PHOTONS*

R. V. Pound and G. A. Rebka, Jr.
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts
(Received March 9, 1960)

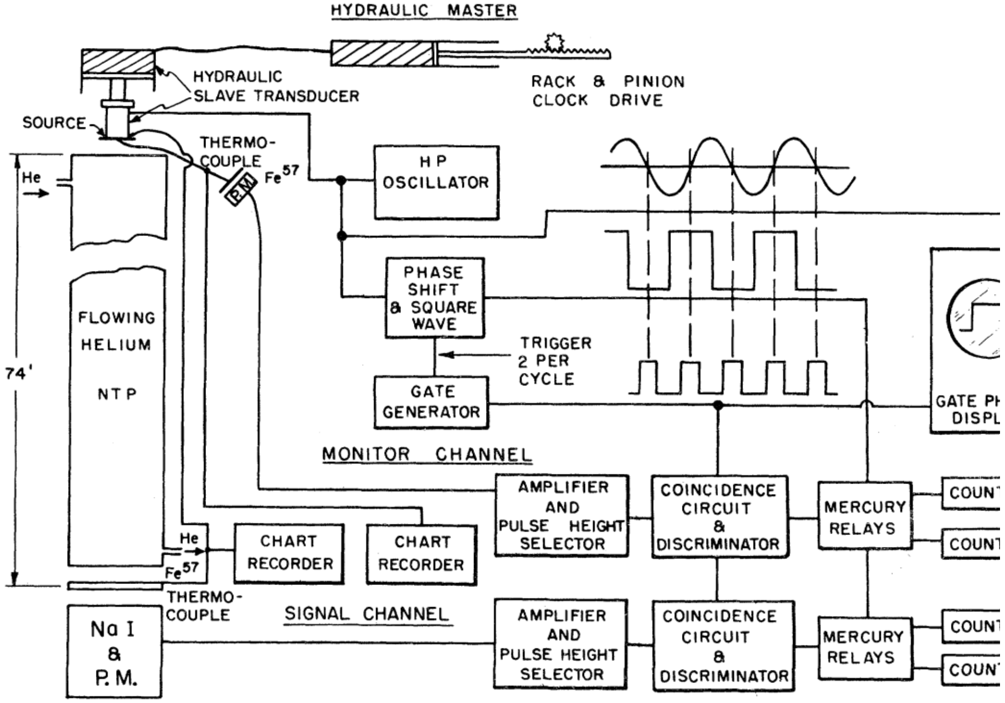


FIG. 1. A block diagram of the over-all experimental arrangement. The source and a
sorber-detector units were frequently interchanged. Sometimes a ferroelectric and som
times a moving-coil magnetic transducer was used with frequencies ranging from 10 to 5

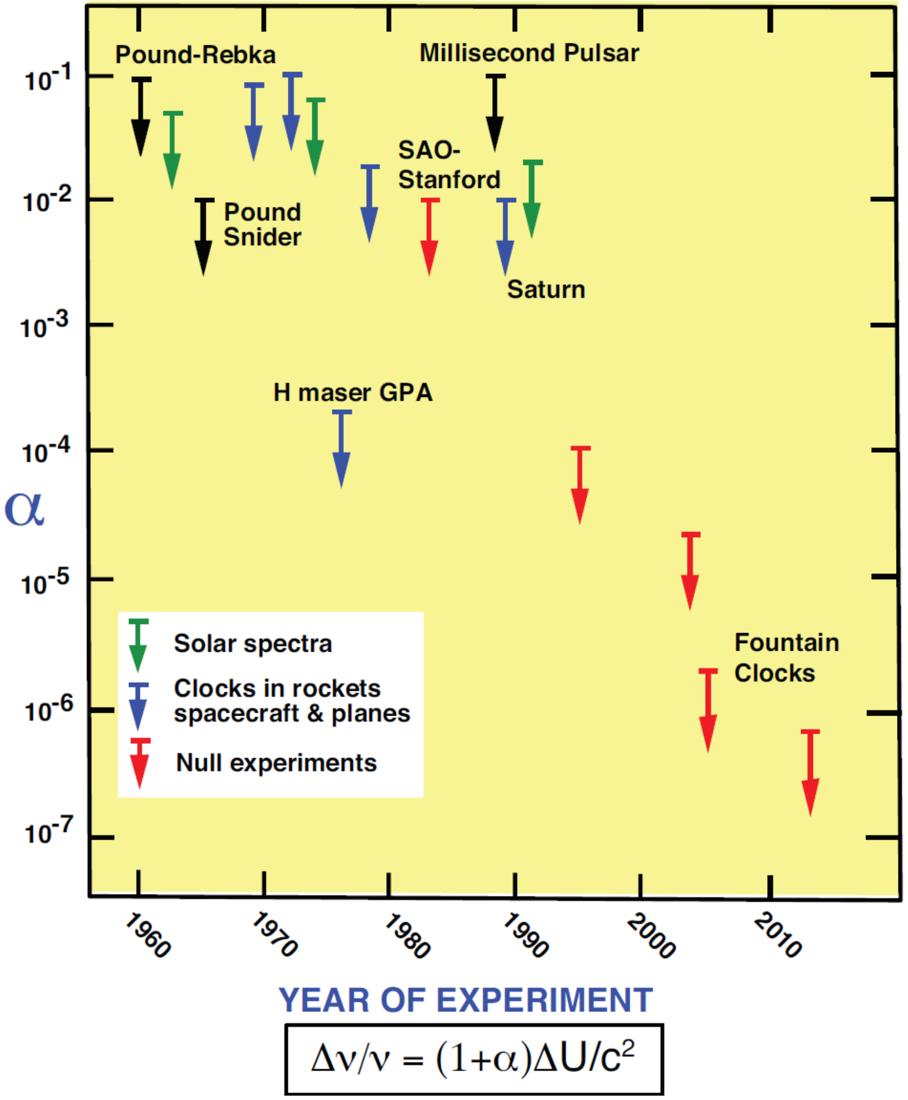


Figure 3: Selected tests of local position invariance via gravitational redshift experiments, showing bounds on α, which measures degree of deviation of redshift from the formula $\Delta\nu/\nu = \Delta U/c^2$. In null redshift experiments, the bound is on the difference in α between different kinds of clocks.

latest on Black Holes, as seen with light

- **Event Horizon Telescope (EHT)**

https://eventhorizontelescope.org/

Virtual Earth-sized radiotelescope

image of accretion disk around the 6.5-billion-solar-mass supermassive black hole at the core of Messier 87 (M87), a large galaxy some 55 million light-years from Earth in the Virgo galaxy cluster (2019)

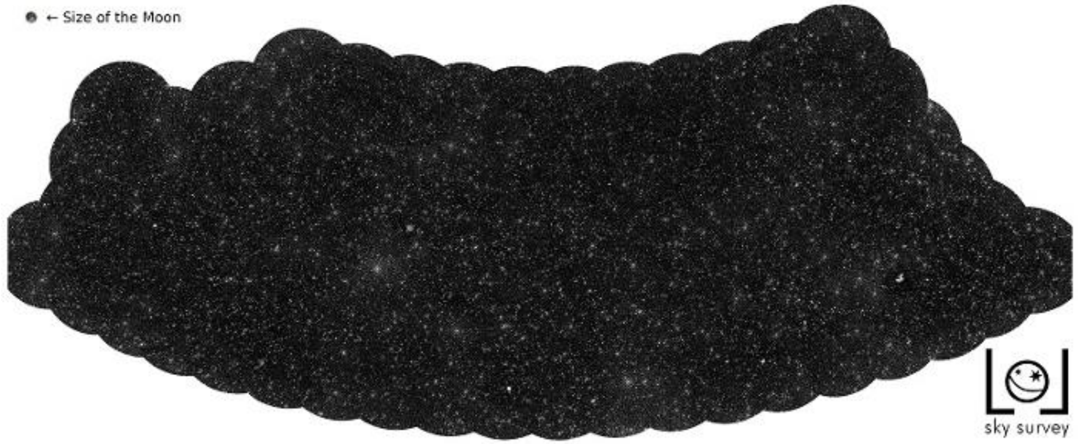
angular resolution of 20 micro-arcseconds (data 2017)

- **LOw Frequency ARray (LOFAR)**

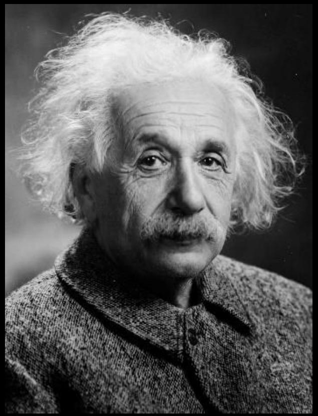
network of 52 radiotelescopes for ultra-low frequencies (< 100MHz).

article Astronomy & Astrophysics, Feb 2021

map of 25000 supermassive Black Holes in 2% of the sky:



La GRAVITA' FORGIA lo SPAZIO-TEMPO



alcune predizioni della teoria di Einstein erano molto ardite:
mezzo secolo di ricerche teoriche per convincere della loro ragionevolezza !

BUCHI NERI

attrazione gravitazionale intrappola anche la luce nell'orizzonte degli eventi

1916 soluzione matematica con singolarità

1920's non sfuggirebbe neppure la luce

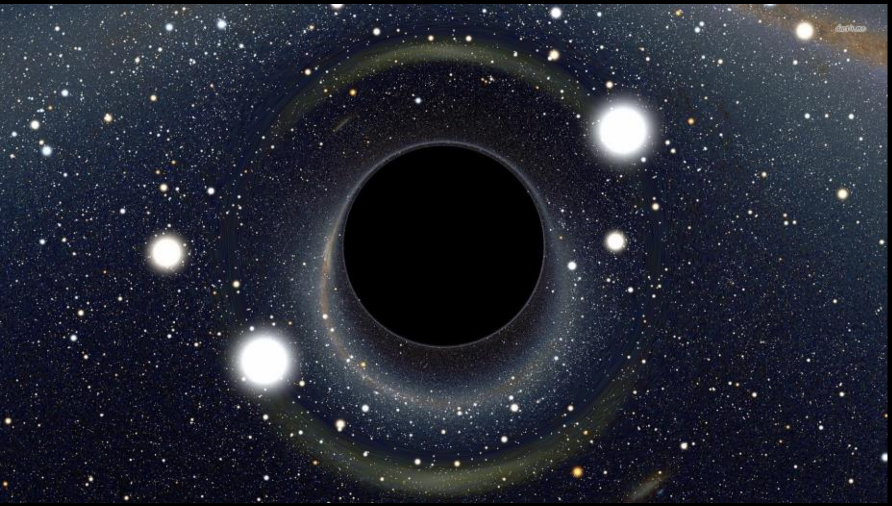
1940's osservatore esterno vedrebbe il tempo congelarsi sull'orizzonte degli eventi

1958 orizzonte degli eventi come membrana unidirezionale

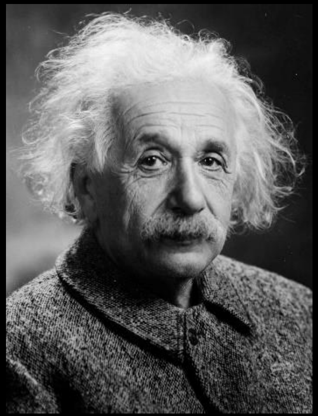
1960's coniato il termine *Buco Nero*

1970's una fioritura di studi

...



La GRAVITA’ FORGIA lo SPAZIO-TEMPO



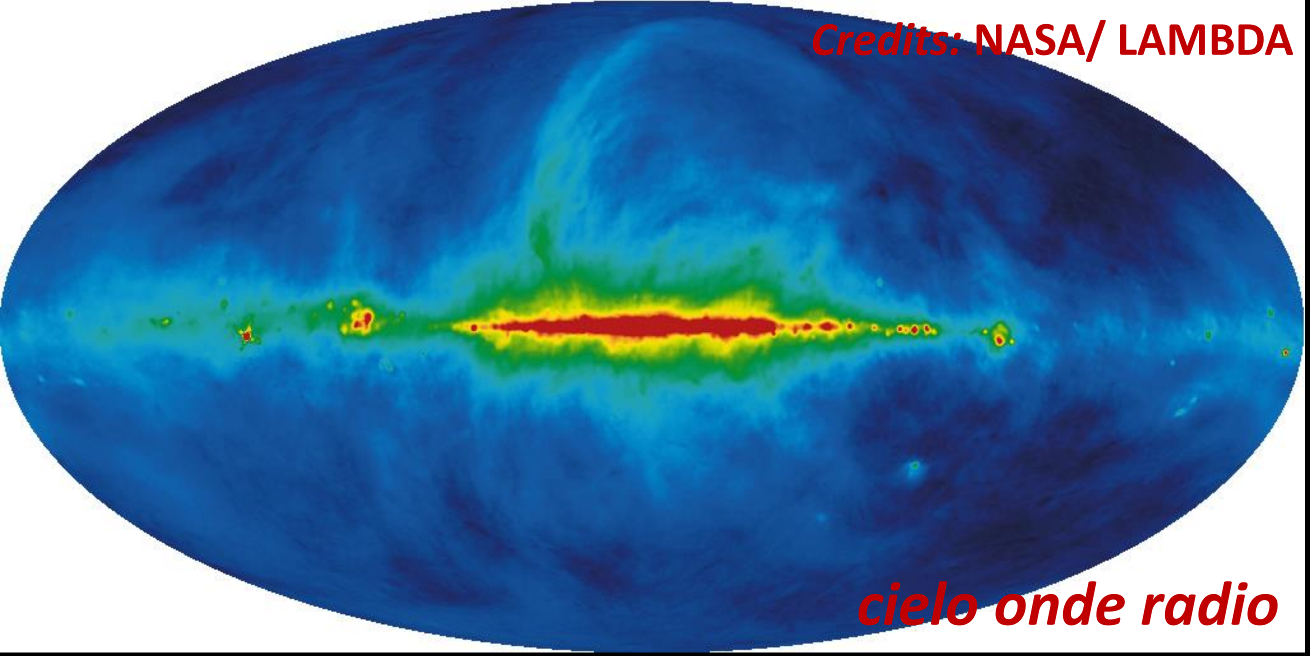
alcune predizioni della teoria di Einstein erano molto ardite:
mezzo secolo di ricerche teoriche per convincere della loro ragionevolezza !

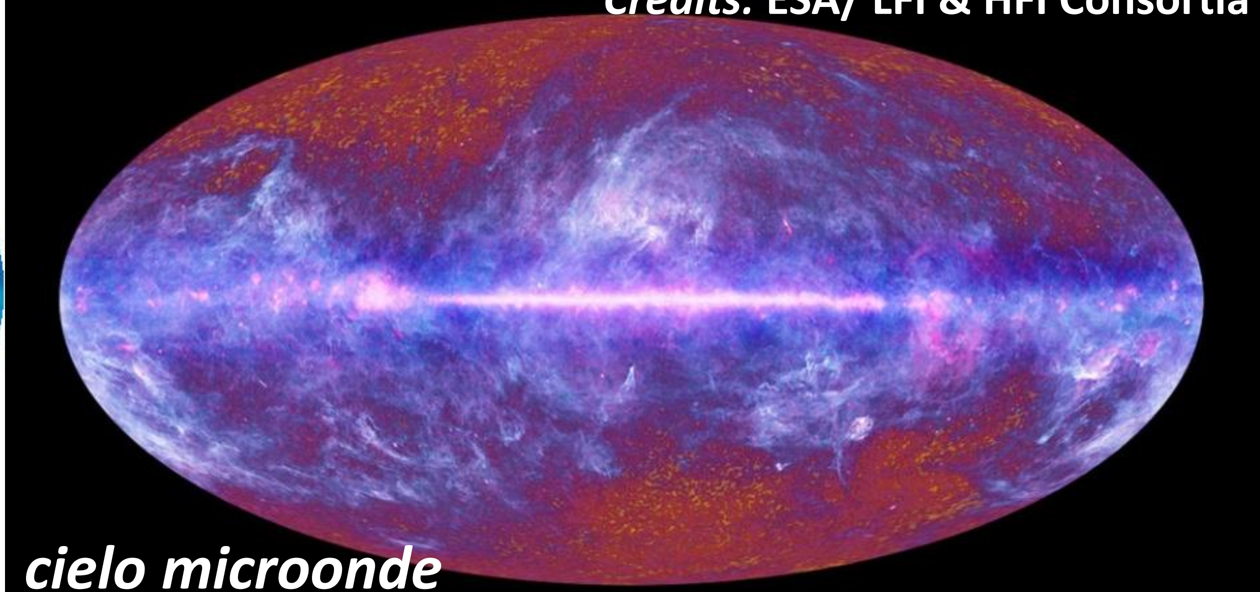
ONDE GRAVITAZIONALI

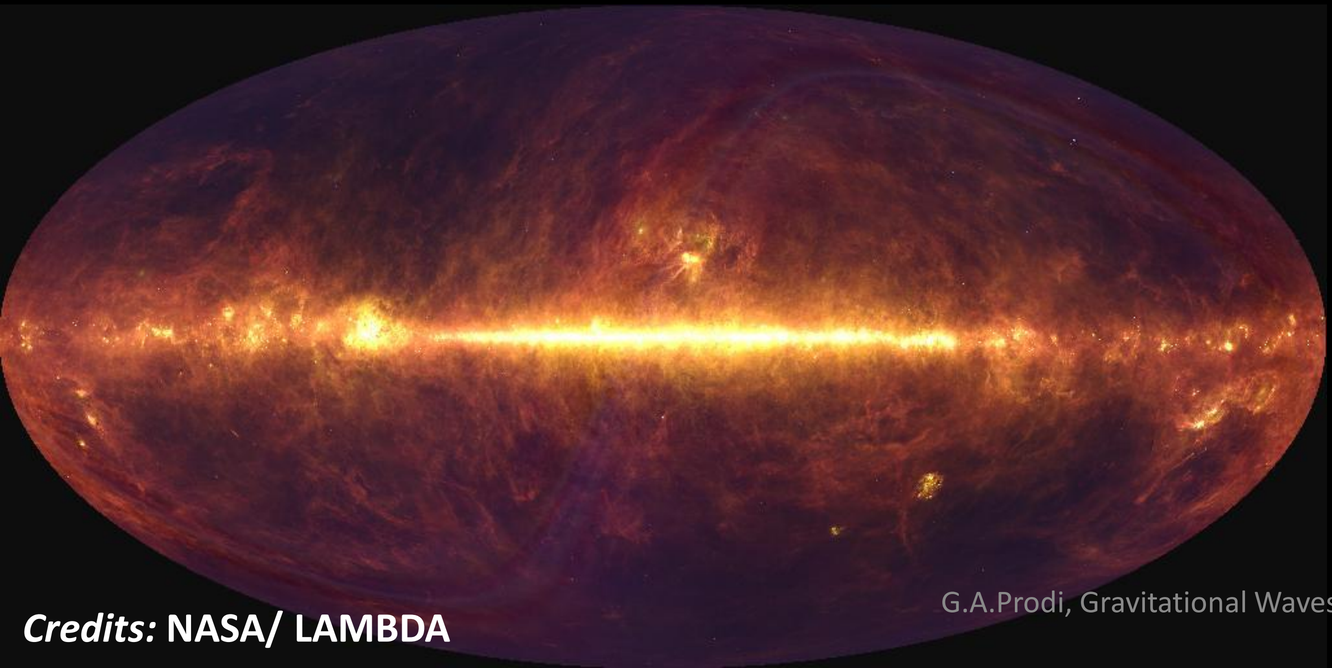
grandi masse che si muovono veloci riescono a far vibrare la struttura dello spazio-tempo

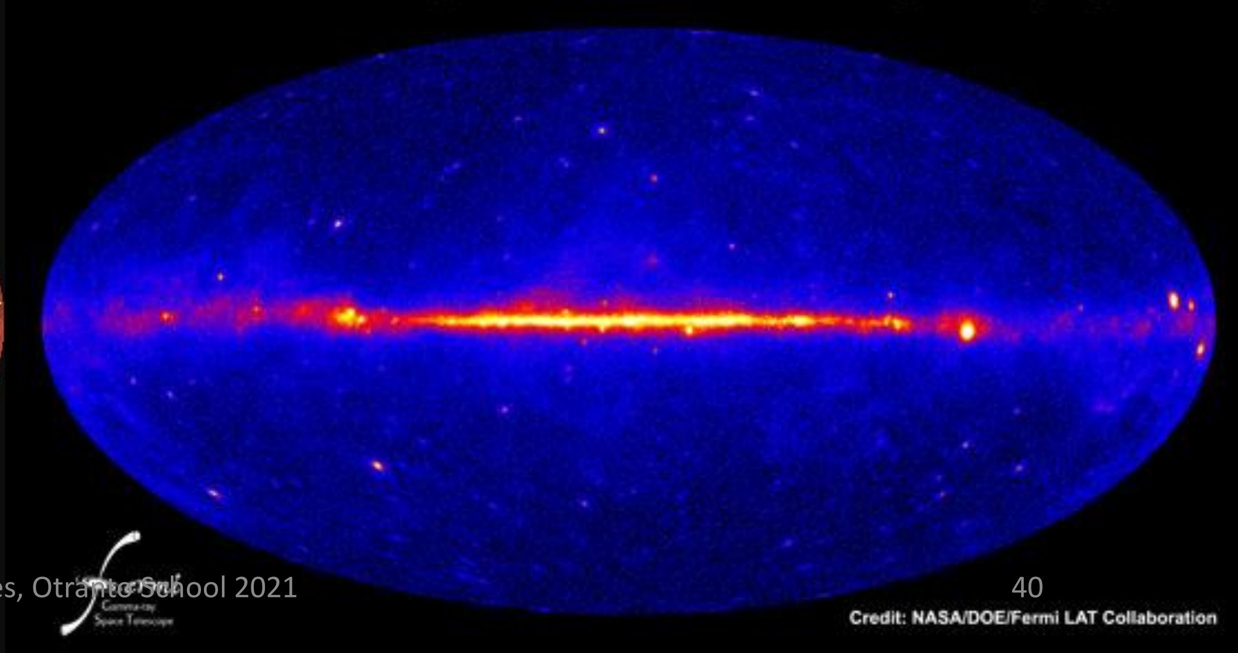
viaggiano alla velocità della luce
sono praticamente inarrestabili
un linguaggio del cosmo prima sconosciuto

- **1916** soluzione matematica
- **1930’s** Einstein abiura
- **1957** sono reali, portano energia
- **1970’s** predizioni emissione da binaria
- **1990’s** predizioni emissione da binaria coalescente
- **2005** soluzioni numeriche della fusione della binaria


Credits: NASA/ LAMBDA
cielo onde radio


Credits: ESA/ LFI & HFI Consortia
cielo microonde


cielo infrarosso
Credits: NASA/ LAMBDA


cielo raggi gamma
NASA's Fermi telescope reveals best-ever view of the gamma-ray sky
Credit: NASA/DOE/Fermi LAT Collaboration

L'Esplorazione dell'Universo

tappe dei premi Nobel per la Fisica

Luce + **1974** + **1978** + **1983** + **2002** + **2006** + **2011**

1974	1978	1983	2002	2006	2011
pulsars *Hewish 1967,* **astronomia radio** *Ryle*	**radiazione cosmica di fondo microonde** *Penzias, Wilson 1964*	**evoluzione stelle** *Chandrasekhar,* **sintesi elementi chimici** *Fowler*	**astronomia raggi X** *Giacconi 1960's*	**proprietà radiazione cosmica di fondo microonde** *Mather, Smoot 1989*	**espansione accelerata dell'Universo** *Perlmutter, Schmidt, Riess 1998*

L’Esplorazione dell’Universo

tappe dei premi Nobel per la Fisica

1936 — **2002**

Particelle elementari + +

raggi cosmici
Hess 1912

astronomia dei neutrini
Davis 1960’s, *Koshiba* 1987

1993 — **2017**

Astronomia gravitazionale + +

pulsar binaria
(esistenza onde gravitazionali)
Hulse, Taylor
1974

osservazione
onde gravitazionali
Weiss, Barish, Thorne
2015

foto: ESO/H.H. Heyer

Physics Nobel prize 2017

for decisive contributions to the LIGO detector and the observation of gravitational waves

foto: Bryce Vickmark

Rainer Weiss

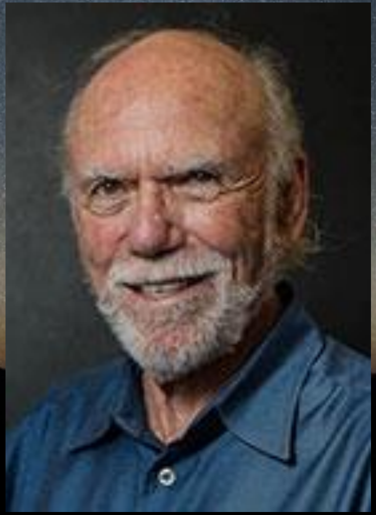


foto: Caltech

Barry C. Barish

foto: Caltech Alumni Ass.

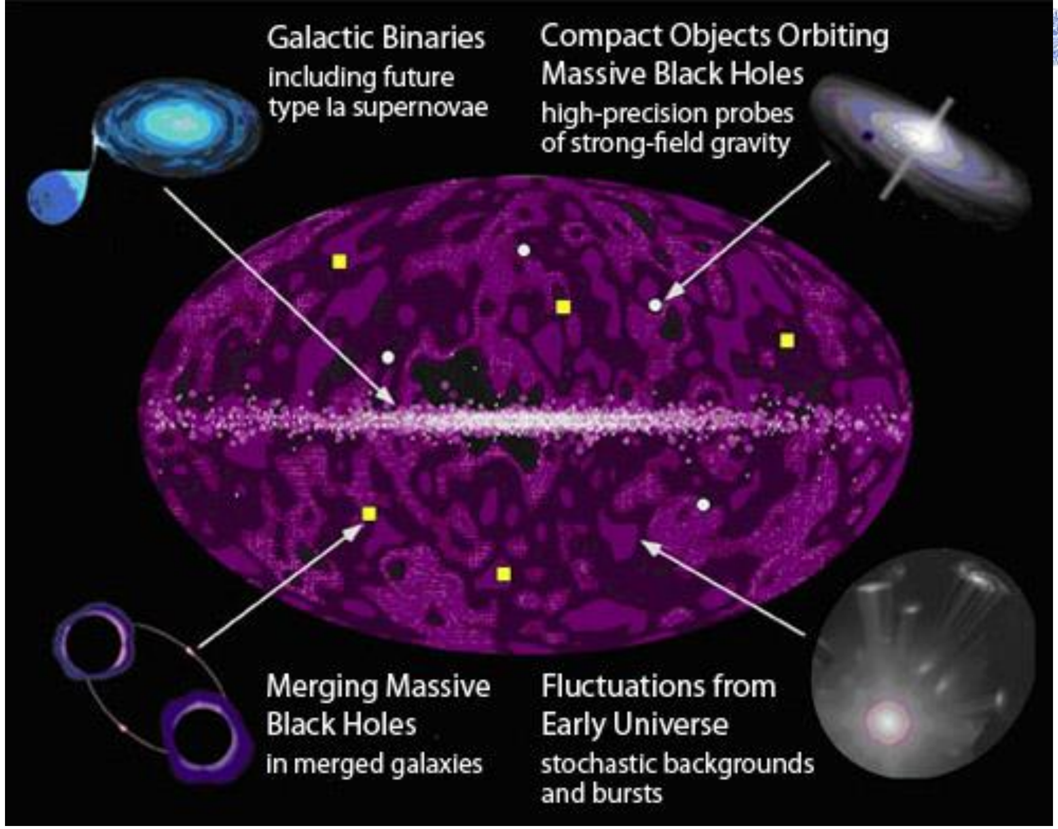
Kip S. Thorne

sviluppo concetto dell'osservatorio LIGO per onde gravitazionali

45 anni

prima osservazione delle onde gravitazionali da parte delle collaborazioni LIGO e Virgo

GW: like *listening* to the universe



- GW cross undisturbed any matter
- GW have crossed the universe from Big Bang to us
- GW only are emitted near the surface of a black-hole
- GW bear analogies to sound:
  - They record the motion of their celestial sources
  - Detectors are "microphones" and allow to "listen" to motion of bodies that may be invisible or too far away
- GW astronomy adds the audio dimension to our ability to observe the universe.

Otranto School

XXXII International Seminar of Nuclear and Subnuclear Physics

"Francesco Romano"

Gravitational Waves

part 2

Giovanni A. Prodi, Università di Trento and INFN-TIFPA, Trento

giovanniandrea.prodi@unitn.it

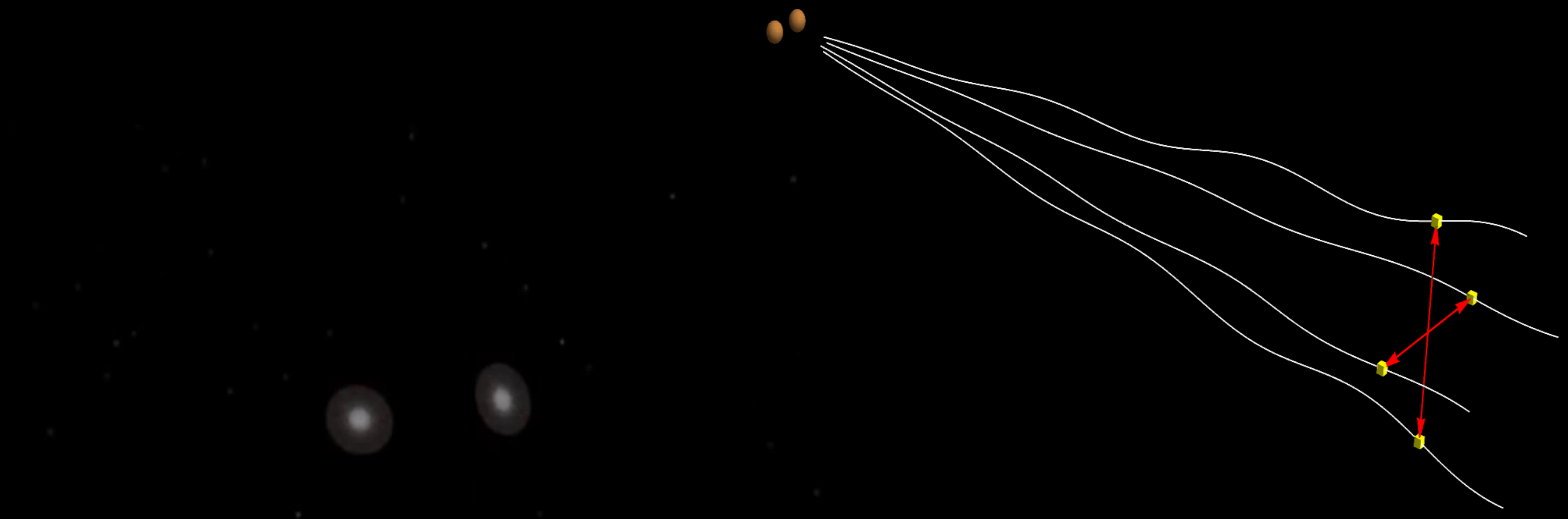
UNIVERSITÀ DI TRENTO

INFN Istituto Nazionale di Fisica Nucleare

TIFPA Trento Institute for Fundamental Physics and Applications

Gravitational waves

- Waves of curvature due to acceleration of matter-energy
- Can be detected from relative acceleration of free falling test-masses



Directional Sensitivity of Detectors

Each differential measurement senses only one of the two GW polarizations:

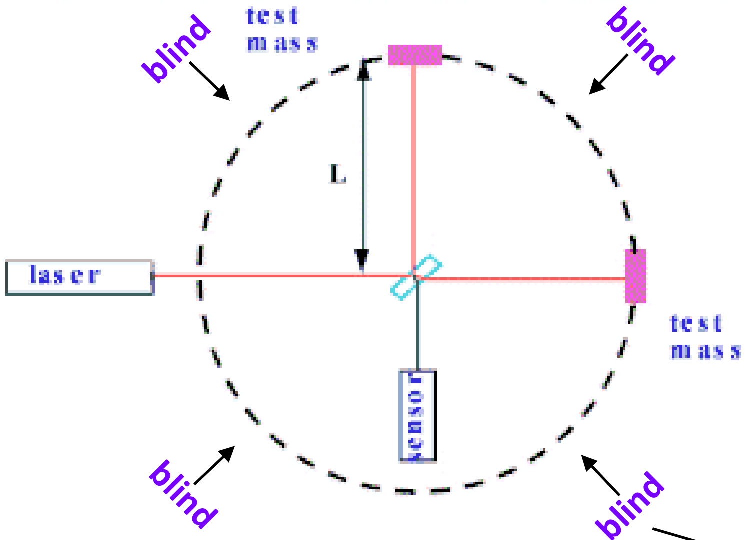
- measures the linear combination

$$h_{det} = F_+ h_+ + F_\times h_\times$$

$$F_{+,\times}(\text{sky direction})$$

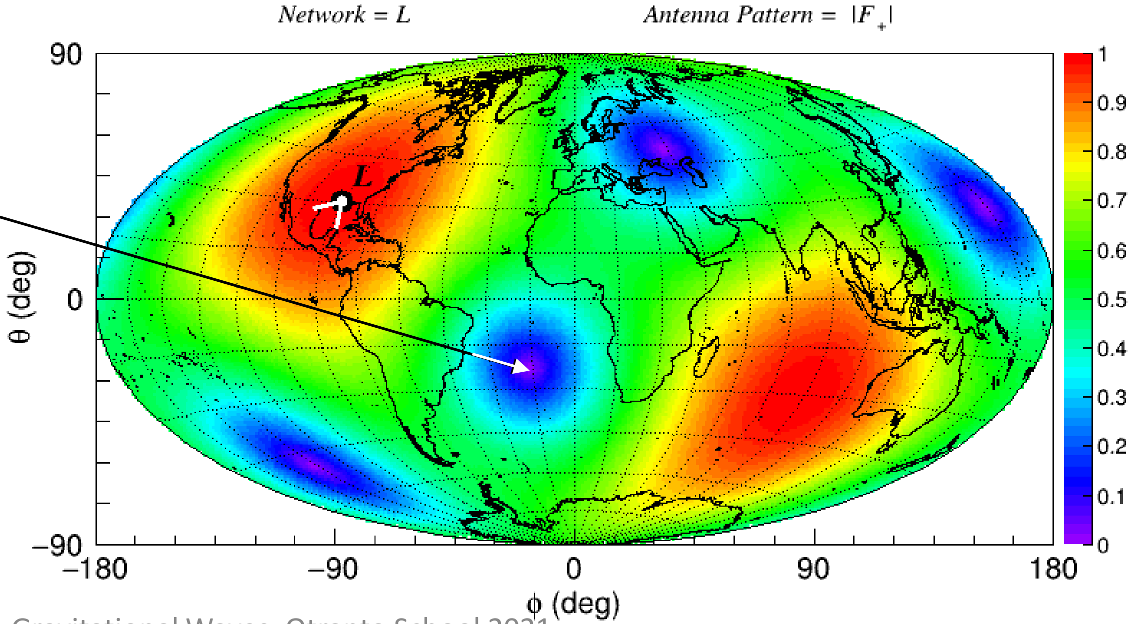
antenna patterns for + and x

- misses the orthogonal combination

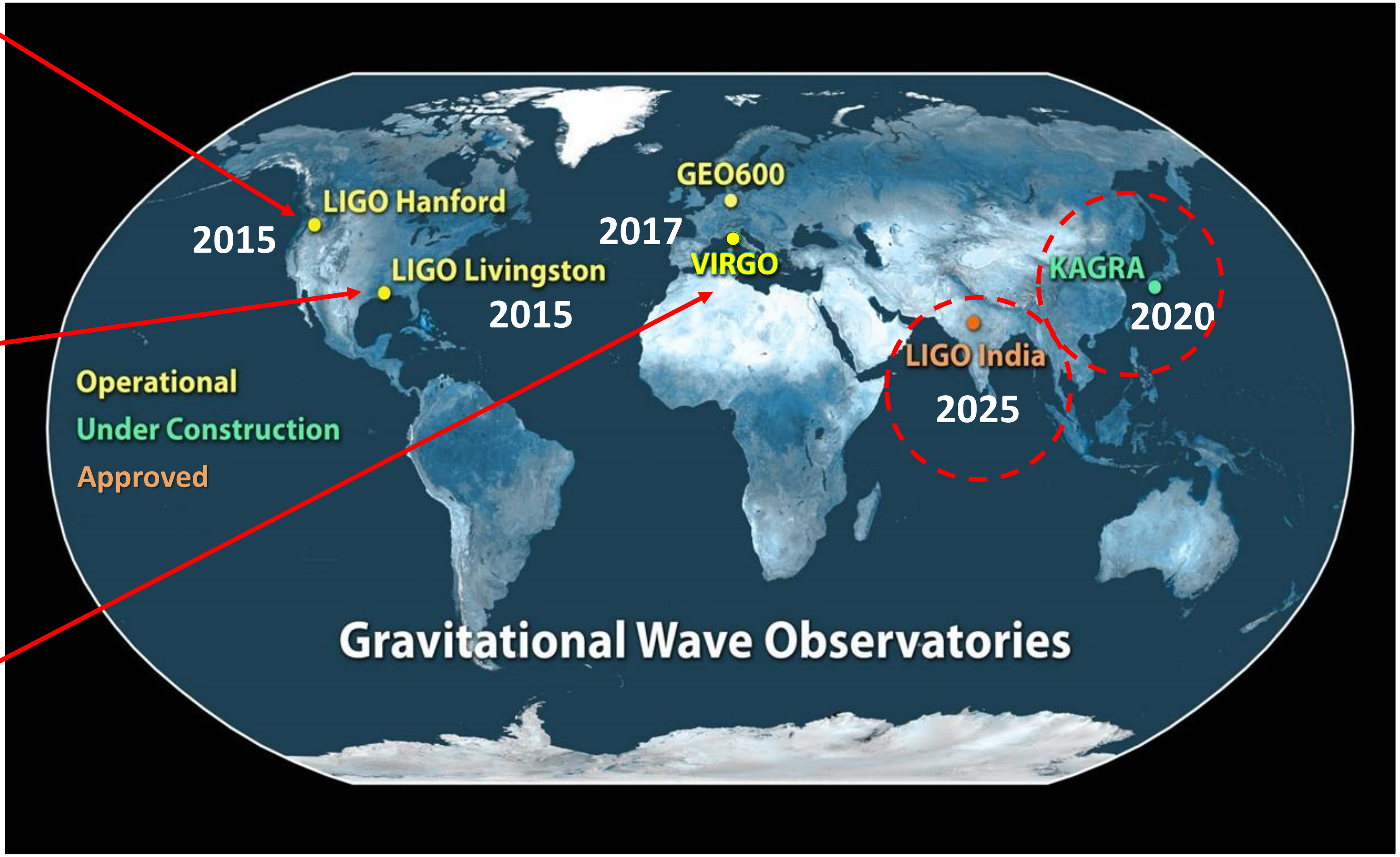


Broad directional sensitivity:

LIGO Livingston



The Network of Gravitational Wave Detectors



Increase detection confidence

Better source localization

Enhance sky coverage

Reduce downtime

More reliable source parameter estimation [open data workshops](#)

intended for students and more experienced scientists

learn how to access public LIGO and Virgo data available through the [Gravitational Wave Open Science Center](#) and how to use the associated software libraries

LIGO - Virgo Collaboration

Gravitational Wave

Open Data Workshop #4

May 10 - 14, 2021

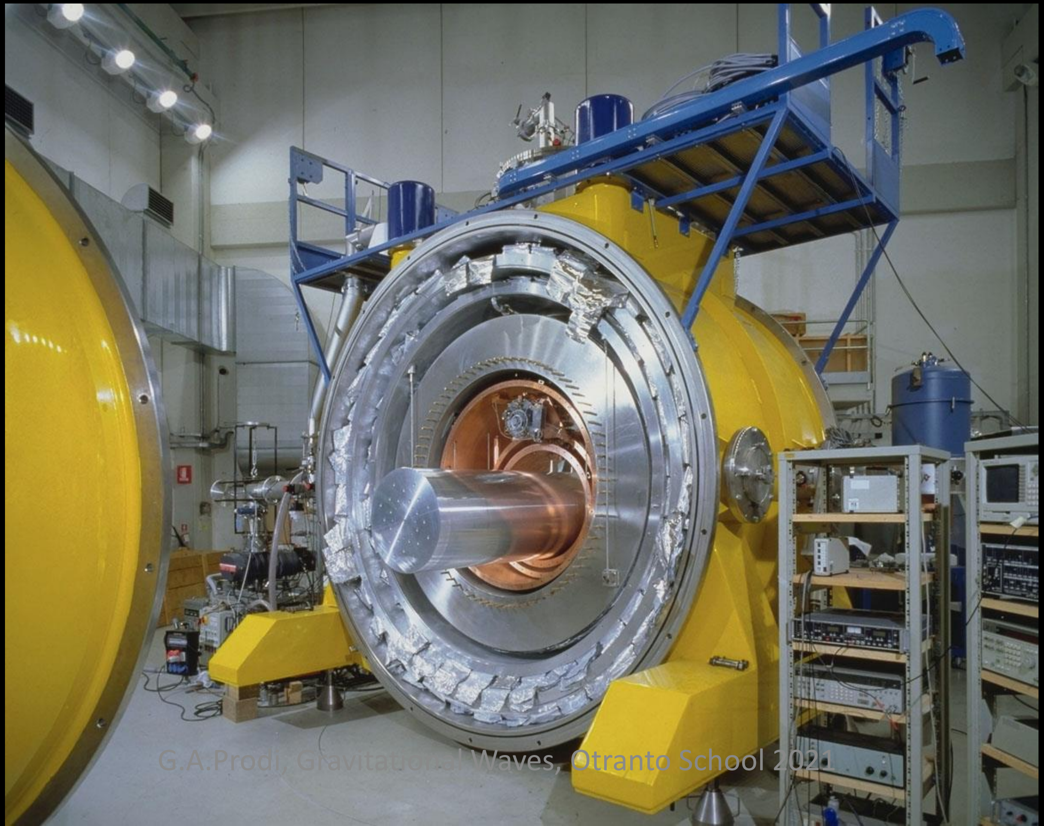
GW ODW #4 | General Info | Registration | Program | GWOSC

Welcome to the LIGO-Virgo Open Data Workshop #4!

This is the fourth in a series of workshops focussed on the analysis of gravitational wave data made publicly available by the LIGO and Virgo Collaborations.

metodologie concorrenti

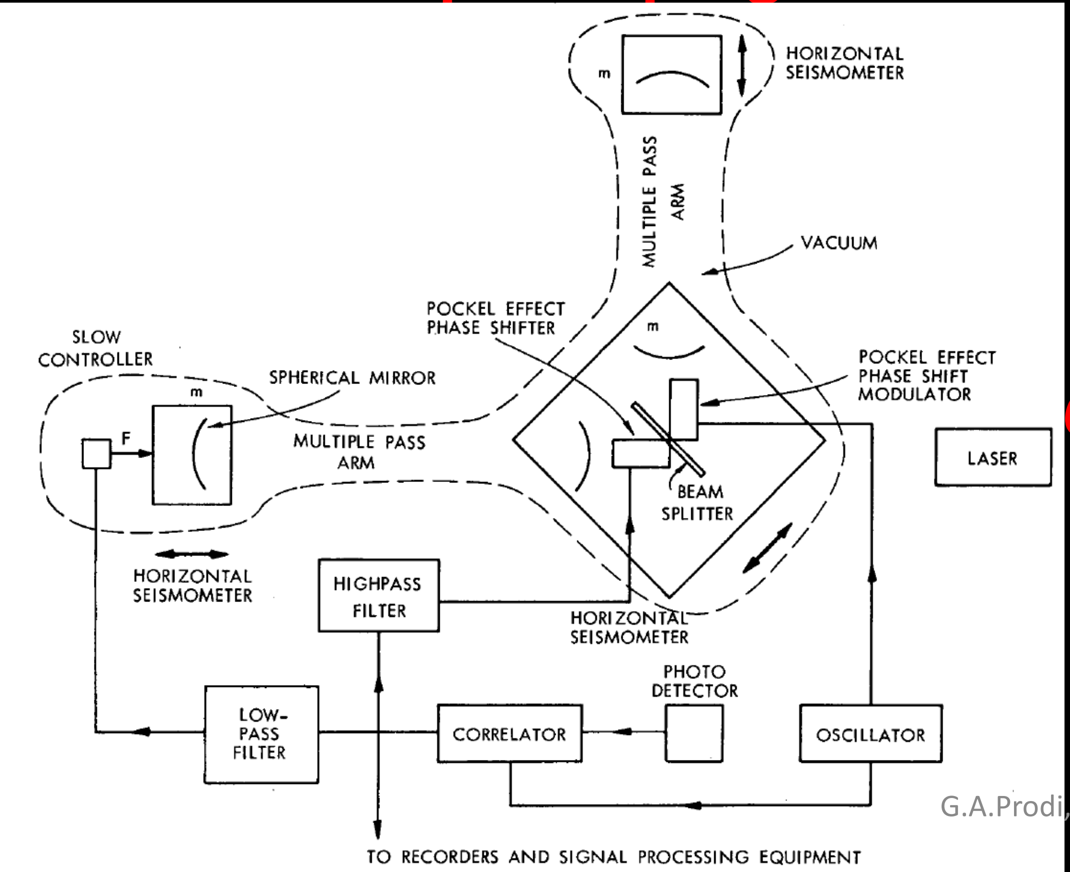
	1960's	1980's	1990's	2000's
rivelatori risonanti	+	+	+	+
simili a diapason	*Weber*	criogenici *In USA e Italia*	ultra-criogenici *USA, Australia e Italia*	rete di molti *prima capacità di identificare con confidenza Il passaggio di un'onda*



Antenne interferometriche

1960's + primi tests

1972 + *Weiss* primo progetto:



1970's-80's + *prototipi ~10m:*

MIT
CalTech
Garching
Glasgow

Caso scientifico:

segnali da rivelare

Thorne

1980's + *progetti ~1km:*

MIT & CalTech
Garching & Glasgow
Francia & Italia

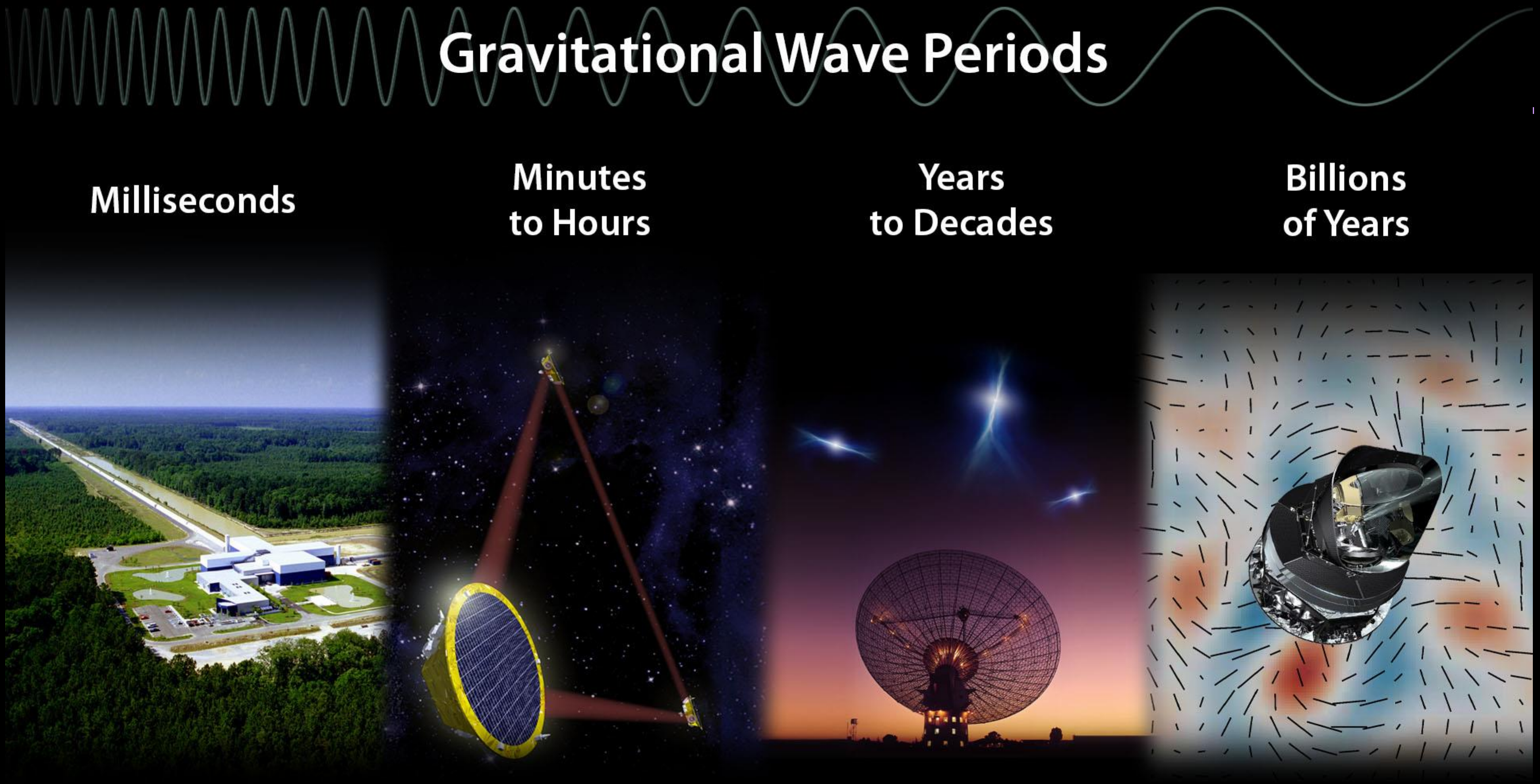
1990's + *costruzione:*

LIGO
+ *Barish*

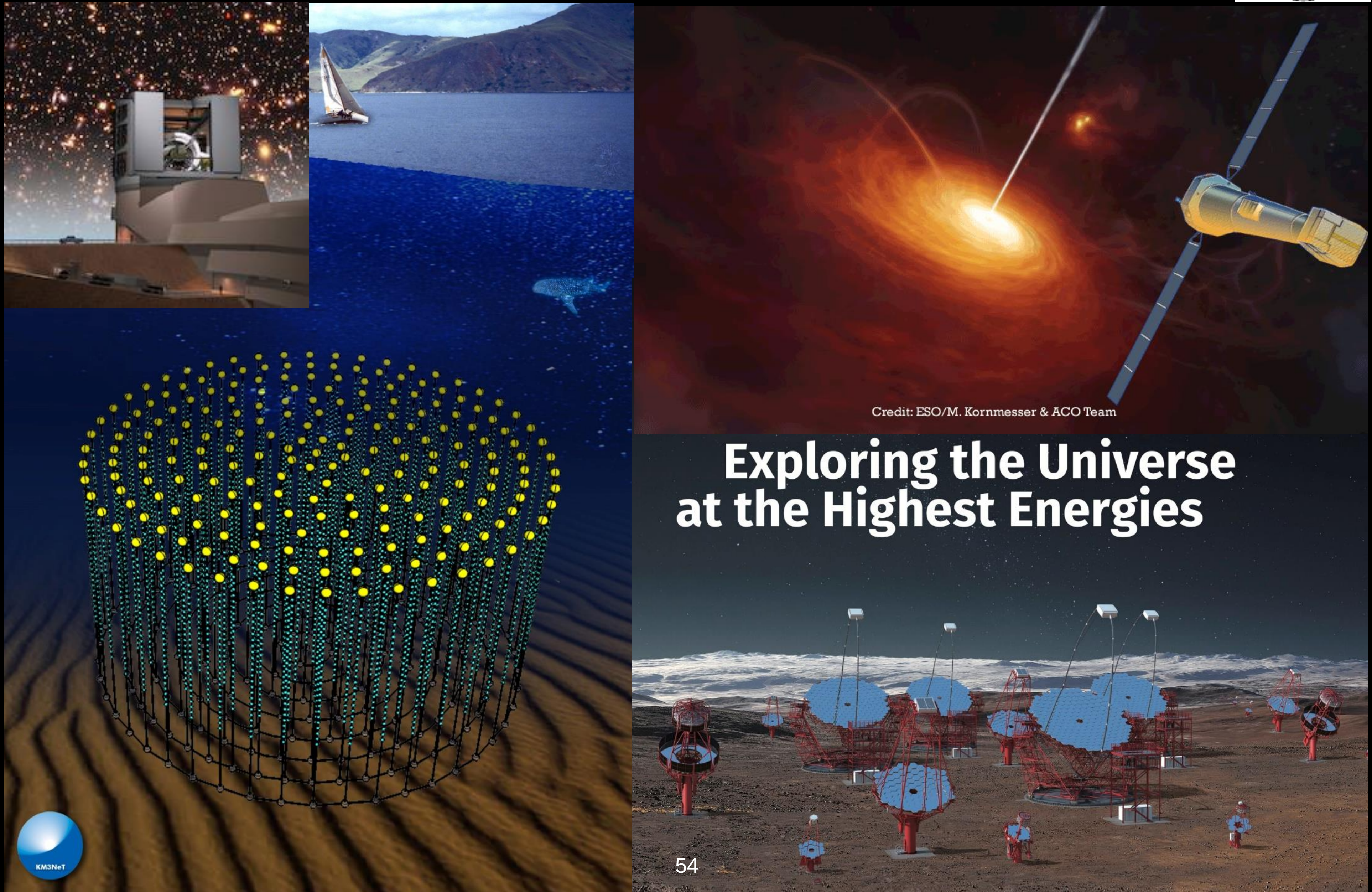
Virgo
Giazzotto
Brillet

GEO600

observatories of gravitationala waves
present and future



assieme a futuri rivelatori di neutrini, raggi cosmici, onde elettromagnetiche



Gravitational Waves Energy (and momentum)

- gravitational waves are physical: carry curvature, energy, momentum, angular momentum (1950's)

- these cannot be described in the weak-field linear approximation of General Relativity
  - energy is quadratic in ***h***
  - GW energy density bends the background space-time

- **equivalence principle prohibits a local notion of physical properties of GWs:** average over some volume of spacetime

- **in the quadrupolar approximation:** $$h \approx \frac{G\ddot{Q}}{c^4 r} \leq 10^{-21}$$

- **energy flux** $$\frac{dE}{dt\, dA} = \frac{c^3}{16\pi G} \langle \dot{h}_+^2 + \dot{h}_\times^2 \rangle$$

averaging on volumes of size $l \gg \lambda_{GW}$ $\quad l \ll L_{Background}$

replay of collision