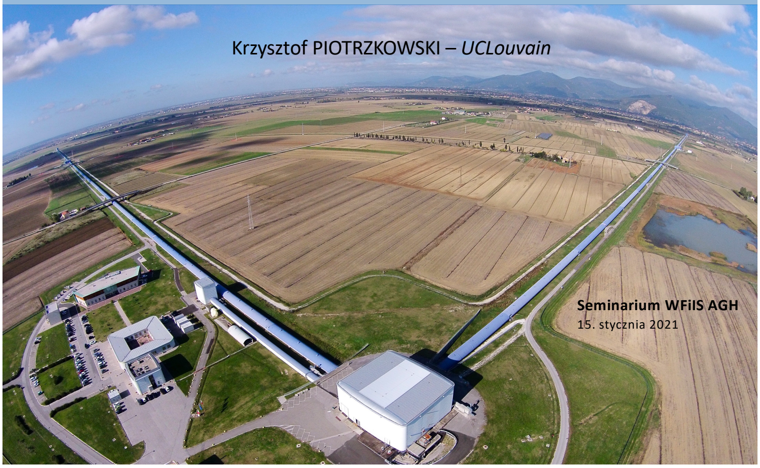
Anteny Fal Grawitacyjnych Dzisiaj oraz Plany Rozwoju Anten Następnej Generacji



Do gravitational waves exist, or not?

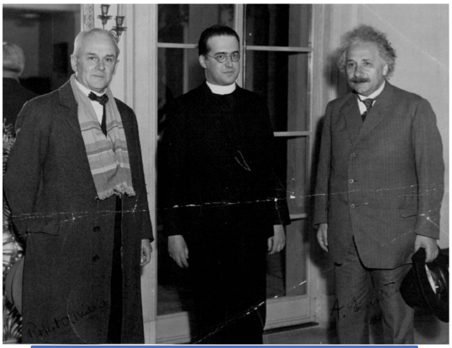
Already back in 1905 Henri Poincaré proposed that gravity was transmitted through gravitational waves (*ondes gravifiques*)!

On February 19, 1916 Einstein wrote in his letter to Karl Schwarzschild : *"Since then I have handled Newton's case differently, of course, according to the final theory. Thus there are no gravitational waves analogous to light waves. This probably is also related to the one-sidedness of the sign of the scalar T, incidentally".*

In 1936 Einstein wrote to Max Born: "*Together with a young collaborator [Rosen], I arrive at the interesting result that gravitational waves do not exist, though they have been assumed a certainty to the first approximation*". On June 1 Einstein and Rosen sent an article entitled "Are there any gravitational waves?" to *Physical Review* but an anonymous referee (Howard P. Robertson) made several negative comments and Einstein withdraw the paper and published it in 1937 with changed content: "The second part of this article was considerably altered by me after the departure to Russia of Mr. Rosen as we had misinterpreted the results of our formula. I want to thank my colleague Professor Robertson for his friendly help in clarifying the original error."

Confusion still continued for many years: "*Gravitational waves were to be my subject and Plebański warned me that Infeld did not believe in their existence. Infeld was in Princeton at the time when Einstein, working with Nathan Rosen, came to the conclusion that gravitational waves did not exist*"
(Andrzej Trautman – *LIGO/Virgo Meeting*, Warszawa 5 IX 2019)

Side story: A. Einstein, Abbé Lemaître & Big Bang



Abbé Georges Lemaître (b. 1894) between Robert Millikan and Albert Einstein, in California Institute of Technology, Pasadena, January 10, 1933

(*Source: UCLouvain*)

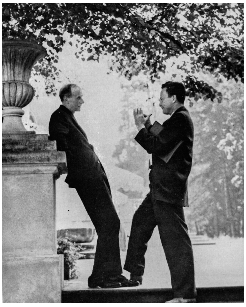
Einstein said to Lemaître, at the 1927 Solvay Conference: Your calculations are correct, but your physical insight is « *tout à fait abominable* ». Later Einstein claimed it was inspired « *by the Christian dogma of creation, and totally unjustified from the physical point of view* ». The old mentor of Lemaître, Eddington added: « *The notion of a beginning of the world is repugnant to me* ».

He was the first to theorize that the recession of nearby galaxies can be explained by an expanding universe [2] He first derived "Hubble's law", now called the Hubble–Lemaître law by the IAU,[5][6] and published the first estimation of the Hubble constant in 1927, two years before Hubble's article.[7][8][9][10] Lemaître also proposed the "Big Bang theory" of the origin of the universe, calling it the "hypothesis of the primeval atom",[11] and later calling it "the beginning of the world".[12]

Warsaw and Gravitation

After a visit in Warsaw Felix Pirani published his "decisive" article on observables applicable to gravitational waves: *On the physical significance of the Riemann tensor* by F.A.E. Pirani, *Acta Physica Polonica* **15**, 389–405 (1956)

International Jablonna Conference on General Relativity and Gravitation was held in Warsaw and Jabłonna in 1962. The conference attracted 114 participants, including: P.A.M. Dirac, R.P. Feynman, J.A. Wheeler, P.G. Bergmann, H. Bondi, S. Chandrasekhar, B. DeWitt, V. Ginzburg, D. Ivanenko, A. Lichnerowicz, C. Moller, L. Rosenfeld and **J. Weber**.



Warsaw then and now

R. Penrose and I. Robinson came for the conference with plane to Berlin, were they rent a *garbus* and went to Poland. On the photo standing near car from left: **Roger Penrose**, Dennis William Sciama, Joshua N. Goldberg, Rainer Ray Sachs. From the left in white shirt Alfred Schild and Stanley Mandelstam.
http://trautman.fuw.edu.pl/photos-2/jablonna-conference.html

"Trautman otrzymał Krzyż Komandorski Orderu Odrodzenia Polski za wybitne zasługi w pracy naukowo-badawczej i za osiągnięcia w międzynarodowej współpracy naukowej, natomiast Penrose został uhonorowany Krzyżem Komandorskim Orderu Zasługi Rzeczypospolitej Polskiej za wybitne osiągnięcia naukowe w dziedzinie fizyki, za rozwijanie polsko-brytyjskiej współpracy naukowej." (PAP, XII 2016)

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics 2020 with one half to
Roger Penrose
for the discovery that black hole formation is a robust prediction of the general theory of relativity
———
"Gravitational collapse and space-time singularities", Physical Review Letters, vol. 14, no. 3. pp. 57–59, **1965**

General Relativity and Cosmology

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

where $R_{\mu\nu}$ is the Ricci tensor, R is the Ricci scalar, $T_{\mu\nu}$ is the energy-momentum tensor, Λ is the cosmological constant and $g_{\mu\nu}$ is the metric tensor which defines the infinitesimal distance element ds between two points x^μ and $x^\mu + dx^\mu$: $ds^2 = g_{\mu\nu} x^\mu x^\nu$.

General Relativity and Cosmology

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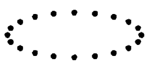
Cosmological implications (in three lines…):

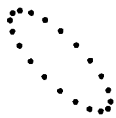
- from homogeneity and isotropy one gets the FLRW metric (for flat Universe): $ds^2 = a(t)^2(dr^2 + r^2 d\Omega^2) - c^2 dt^2$, where $a(t)$ is the scale factor at a given time
- from the Einstein equation $a(t) = a_0 (t/t_0)^{\frac{2}{3(w+1)}}$ where $w = 0$ for the matter dominated and $= 1/3$ for radiation dominated universe
- cosmological "redshift" means wavelength increase: $\frac{\lambda_{now}}{\lambda_{then}} = \frac{a_{now}}{a_{then}} = 1 + z$

Gravitational waves

In weak field, linear approximation: $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$ where $\eta_{\mu\nu}$ accounts for flat space without gravity – Minkowski metric, and $h_{\mu\nu}$ is very small – $|h_{\mu\nu}| \ll 1$. Far from any sources the plane wave solution is (in *Transverse-Traceless gauge*):



$$h_{\mu\nu}^{TT} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} e^{-i(\omega t - kz)}$$



$$h_+(t) = A_{\rm GW}(t)(1 + \cos^2\iota)\cos\phi_{\rm GW}(t),$$
$$h_\times(t) = -2A_{\rm GW}(t)\cos\iota\sin\phi_{\rm GW}(t),$$

where A_{GW} and ϕ_{GW} are the GW amplitude and phase, and for *a binary* viewed face-on ($\cos\iota = \pm 1$) GWs are **circularly polarized**, whereas for a binary observed edge-on ($\cos\iota = 0$), GWs are **linearly polarized**

GW propagation:
$h \propto 1/r$
Negligible absorption over cosmological distances!
(*Nota bene:* GW do interact between themselves)

Sources of gravitational waves (Chris van den Broek)

No monopole radiation – from energy-mass conservation – as well as **no dipole radiation** as there is no "negative" mass, hence a "mass dipole" = 0 in the center-of-mass frame

Typical neutron star: Isolated

- Mass $m \simeq 1.4\, M_\odot$
- Radius $R \simeq 10\,\mathrm{km}$

$f_{GW} = 2\, f_{rot}$

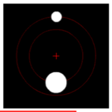
Hence $I_3 \simeq (2/5)\, m\, R^2 \simeq 10^{38}\,\mathrm{kg\,m^2}$

- Frequency $f_{\rm rot} \sim 1\,\mathrm{kHz}$ (higher end)
- Located near center of Milky Way: $r \sim 10\,\mathrm{kpc}$
- Ellipticity unknown; $\epsilon \sim 10^{-6}$ is possible

$$\boxed{\mathcal{A} \simeq 10^{-25} \left(\frac{10\,\mathrm{kpc}}{r}\right) \left(\frac{I_3}{10^{38}\,\mathrm{kg\,m^2}}\right) \left(\frac{f_{\rm rot}}{1\,\mathrm{kHz}}\right)^2 \left(\frac{\epsilon}{10^{-6}}\right)}$$

- Define **chirp mass**:

$$\mathcal{M}_c \equiv \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$



... then

$$\begin{aligned} h_+ &= \frac{4}{r}\frac{G\mathcal{M}_c^{5/3}\omega^{2/3}}{c^4}\frac{1+\cos^2(\iota)}{2}\cos(2\omega t_{\rm ret} + 2\phi) \\ h_\times &= \frac{4}{r}\frac{G\mathcal{M}_c^{5/3}\omega^{2/3}}{c^4}\cos(\iota)\,\sin(2\omega t_{\rm ret} + 2\phi) \end{aligned}$$

- Frequency evolution:

$$f_{\rm gw} = \frac{1}{\pi}\left(\frac{G\mathcal{M}_c}{c^3}\right)^{-5/8}\left(\frac{5}{256}\frac{1}{\tau}\right)^{3/8} \qquad \tau = t_{\rm coal} - t$$

- Invert to get time evolution:

$$\tau = 2.18\,\mathrm{sec}\left(\frac{1.21\,M_\odot}{\mathcal{M}_c}\right)^{5/3}\left(\frac{100\,\mathrm{Hz}}{f_{\rm gw}}\right)^{8/3}$$

- Binary neutron stars:

$$f_{\rm gw} = 20\,\mathrm{Hz} \;\leftrightarrow\; \tau = 160\,\mathrm{sec} \qquad f_{\rm gw,isco} = 1566\,\mathrm{Hz} \;\leftrightarrow\; \tau = 0.0014\,\mathrm{sec}$$

... hence in band for several minutes

- Compare 36+29 solar mass binary black hole: inspiral in band for 0.85 secs

Filling in some values for binary neutron star inspiral:

$m_1 = m_2 = 1.4\,M_\odot \to \mathcal{M}_c \simeq 1.21\,M_\odot$

$R = 100\,\mathrm{km} \to \omega = \sqrt{GM/R^3} \simeq 611\,\mathrm{Hz}$

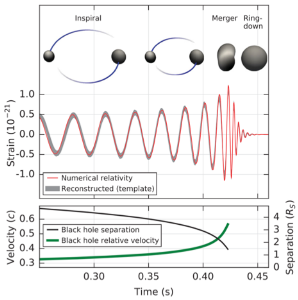
$r = 50\,\mathrm{Mpc}, \quad \iota = \phi = 0$

$\to h_+, h_\times \sim 10^{-22}$

BUT all these results assume (very) weak fields...

Gravitational (exact) waveforms

In 2005 a key theoretical breakthrough took place*: it became possible numerically to solve **exactly** the problem of GW radiation by black hole binary systems – it was therefore possible to predict very precisely the gravitational waveform – **before and through** the black hole merger until the **ringdown** (nota bene: neutron stars are much more complex objects themselves with tidal deformations etc.).



No-hair theorem states that a (non-charged) black hole is completely characterized by its **mass and angular momentum** (spin).

As the orbit shrinks and the GW frequency grows rapidly, the GW phase is increasingly influenced by relativistic effects related to the **mass ratio**, as well as spin-orbit and spin-spin couplings.

From the GW signal alone one can directly measure the *luminosity distance*, but **not** the redshift.

*) **F. Pretorius** (b.1973) – *Evolution of binary black-hole spacetimes*, Phys. Rev. Lett. (2005); and other authors

Resonant bar detectors

EVIDENCE FOR DISCOVERY OF GRAVITATIONAL RADIATION*

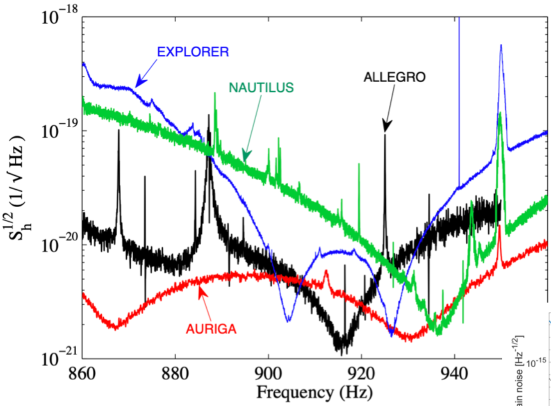
J. Weber
Department of Physics and Astronomy, University of Maryland, College Park, Maryland 20742
(Received 29 April 1969)

Coincidences have been observed on gravitational-radiation detectors over a base line of about 1000 km at Argonne National Laboratory and at the University of Maryland. The probability that all of these coincidences were accidental is incredibly small. Experiments imply that electromagnetic and seismic effects can be ruled out with a high level of confidence. These data are consistent with the conclusion that the detectors are being excited by gravitational radiation.

Big embarrassment was "covered" by the Hulse-Taylor discovery in 1974…

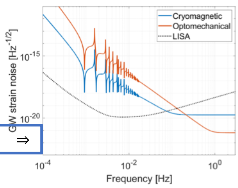
Recently: Set of 3 m long Aluminum bars, suspended in vacuum in a cryogenic environment

International Gravitational Event Collaboration



"We present here the results of a 515 day search for short burst of gravitational waves by the IGEC2 observatory… The sensitivity was the best ever obtained by a bar network: we could detect impulsive events with a burst strain amplitude $h \sim 10^{-19}$ with an efficiency ~50%."
June 25, 2010

Using Moon as a Weber's "bar" – https://arxiv.org/abs/2006.16116 ⇒



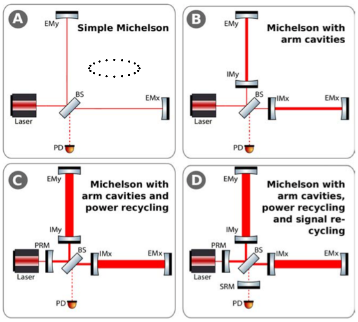
Laser Interferometers as GW antennas

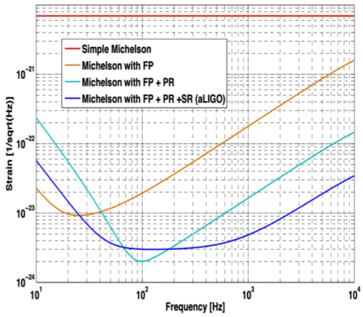
First explicit suggestion, but quickly forgotten, of a laser interferometer GW detector was outlined in the USSR by Gertsenshtein&Pustovoid in 1962 (!). In the 1970s, R. Weiss at MIT conceived the idea of building such a detector, inspired by an article written by F. Pirani, and in 1978 K. Thorne offered to **Ronald Drever** a job at Caltech – the rest is history…

LIGO Example

$\Delta L/L\ (t) = h(t)$

"Strain"(f) = √(Power spectral density of noise)





Optimal arm length (S. Hild)

Maximum Signal: $$\boxed{\Delta\varphi(t) = h_0 \frac{\omega_0}{\omega_g} \underbrace{\sin(\omega_g \frac{\tau}{2})}_{=1} \cos(\omega_g (t - \frac{\tau}{2})).}$$ $\tau = 2L/c$

Optimal Arm length: $$\boxed{L = \frac{\lambda_g}{4}}$$ GW wavelength

Example: GW signal at 100 Hz
=> optimal arm length of 750 km (!!) ⇒Fabry-Pérot!

For short arms: develop sine term
- ⇒ Signal proportional to h_0, w_0, L
- ⇒ Signal independent from GW frequency

In observation mode, to obtain the maximum sensitivity, the interferometer is tuned to have a **dark fringe** on the photodetector (no GW ≃ no signal).

OK. But, how to make the end mirrors still down to $\ll 4\text{ km} \times 10^{-21} = 0.004\text{ fm}$?!

End mirrors as (multi-stage) pendula

Simple pendulum transfer function

at low frequencies ($\omega \ll \omega_0$)

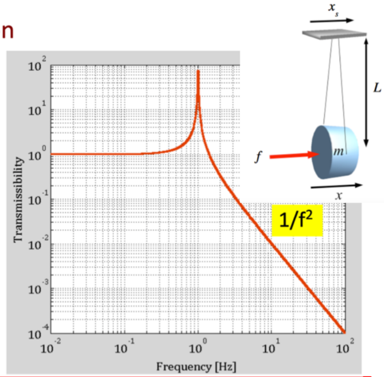
$$X \simeq X_s + F/m{\omega_0}^2$$

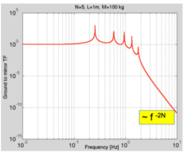
at the natural frequency ($\omega = \omega_0$)

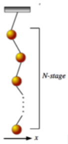
$$X \simeq Q(X_s + F/m{\omega_0}^2)$$

while at high frequency ($\omega \gg \omega_0$)

$$X \simeq \frac{{\omega_0}^2}{\omega^2} X_s + F/m\omega^2$$







End mirrors are suspended in vacuum as pendula, and are acting as “free falling” (in 2D) test masses!

The most precise (distance) measurement ever

The simplest* measurement principle – one determines *h(t)* just from variation in time of the relative distance $\Delta L/L$, but the achieved sensitivity, (much) better than 10^{-21}, is simply mind-blowing:

- 10^{-21} is equivalent to the relative error of determining the distance to the α *Centauri* of **4.4 light-years with precision of hair-width** (≈ 40 μm)

  or,

- it is equivalent to the relative error of determining the **Earth-Sun distance with precision of atom-size** (1.5 Å)

—

*) Except for the data analysis – fitting proper waveforms is still a huge challenge both theoretically and computing wise (CPU!)

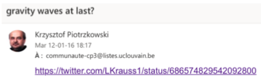
https://en.wikipedia.org/wiki/Pound–Drever–Hall_technique
https://en.wikipedia.org/wiki/Hughes–Drever_experiment

GW150914: Grand discovery

"At 11:53 a.m. local time on **14 September 2015**, an automated e-mail appeared in the inbox of Marco Drago, a physicist at the Max Planck Institute for Gravitational Physics in Hannover, Germany. It contained links to two plots, each showing a wave shaped like a bird's chirp that emerged suddenly from a noisy background and ended in a crash. It was a signal that Drago had been trained to spot and that the US-led Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) that he works on was built to detect […]

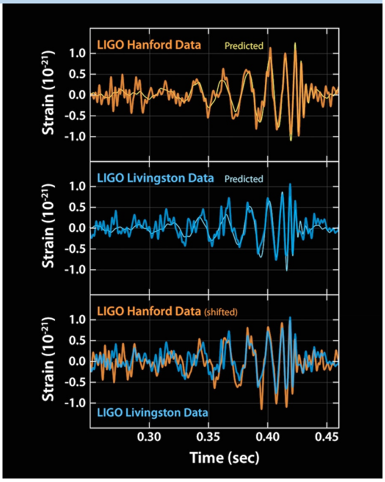
That night at home, I celebrated by just smiling to myself, because I could not tell my wife yet, Thorne says."

https://www.nature.com/news/gravitational-waves-how-ligo-forged-the-path-to-victory-1.19382


gravity waves at last?

Krzysztof Piotrzkowski
Mar 12-01-16 18:17
À : communaute-cp3@listes.uclouvain.be

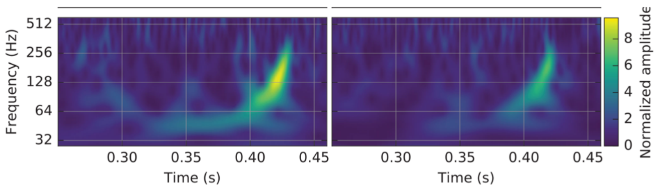
https://twitter.com/LKrauss1/status/686574829542092800



First observation of a merger of two black holes

"On 11 February, the LIGO collaboration announced that it had made the first detection of gravitational waves from a black-hole merger that occurred about 400 million parsecs (**1.3 [1.4*] billion light years**) from Earth. […] To extract as much information as possible, the researchers then performed lengthy supercomputer simulations, Allen says. These confirmed that the data beautifully matched the predictions of Einstein's general theory of relativity in 1915, and the theoretical work that in the past few decades has led physicists to understand the theory's implications in fine detail.

From the waveforms, the researchers were able to deduce that one black hole was about **36 [35]** times the mass of the Sun, and the other was about **29 [30]** solar masses."



*) https://journals.aps.org/prx/pdf/10.1103/PhysRevX.6.041014
(the final black hole mass = 62 solar masses)

Instantaneous recognition…

PRESS RELEASE

3 October 2017

The Nobel Prize in Physics 2017

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics 2017

with one half to

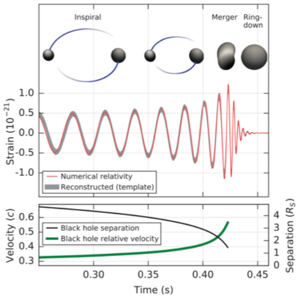
Rainer Weiss
LIGO/VIRGO Collaboration

and the other half jointly to

Barry C. Barish and **Kip S. Thorne**
LIGO/VIRGO Collaboration — LIGO/VIRGO Collaboration

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

[18] I. Robinson and A. Trautman, *Spherical gravitational waves*, Phys. Rev. Lett. 4, 431 (1960); I. Robinson and A. Trautman, *Some spherical gravitational waves in general relativity*, Proc. Roy. Soc. Lond. A265, 463 (1962); A. Trautman, *Boundary conditions at infinity for physical theories*, Bull. Acad. Polon. Sci. 6, 403 (1958); A. Trautman, *Radiation and boundary conditions in the theory of gravitation*, Bull. Acad. Polon. Sci. 6, 407 (1958)



Reminder:

The Nobel Prize in Physics 2020

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics 2020

with one half to

Roger Penrose
University of Oxford, UK

and the other half jointly to

Reinhard Genzel
Max Planck Institute for Extraterrestrial Physics, Garching, Germany and University of California, Berkeley, USA

Andrea Ghez
University of California, Los Angeles, USA

"for the discovery that black hole formation is a robust prediction of the general theory of relativity"

"for the discovery of a supermassive compact object at the centre of our galaxy"

… and many more to come…

A proper game changer

GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 26 September 2017; revised manuscript received 2 October 2017; published 16 October 2017)

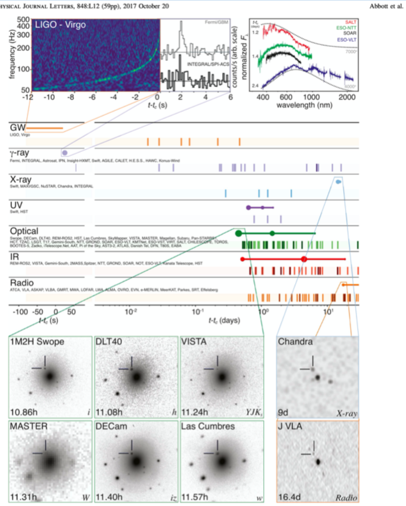
On August 17, 2017 at 12:41:04 UTC the Advanced LIGO and Advanced Virgo gravitational-wave detectors made their first observation of a binary neutron star inspiral. The signal, GW170817, was detected with a combined signal-to-noise ratio of 32.4 and a false-alarm-rate estimate of less than one per 8.0×10^4 years. We infer the component masses of the binary to be between 0.86 and 2.26 $M_\odot$, in agreement with masses of known neutron stars. Restricting the component spins to the range inferred in binary neutron stars, we find the component masses to be in the range 1.17–1.60 $M_\odot$, with the total mass of the system $2.74^{+0.04}_{-0.01} M_\odot$. The source was localized within a sky region of 28 deg^2 (90% probability) and had a luminosity distance of 40^{+8}_{-14} Mpc, the closest and most precisely localized gravitational-wave signal yet. The association with the γ-ray burst GRB 170817A, detected by Fermi-GBM 1.7 s after the coalescence, corroborates the hypothesis of a neutron star merger and provides the first direct evidence of a link between these mergers and short γ-ray bursts. Subsequent identification of transient counterparts across the electromagnetic spectrum in the same location further supports the interpretation of this event as a neutron star merger. This unprecedented joint gravitational and electromagnetic observation provides insight into astrophysics, dense matter, gravitation, and cosmology.

Reminder: a BH merger is (usually) a **purely** gravitational phenomenon, in contrast, a NS merger involves **all** types of interactions ⇒ "pros/cons" = complementarity

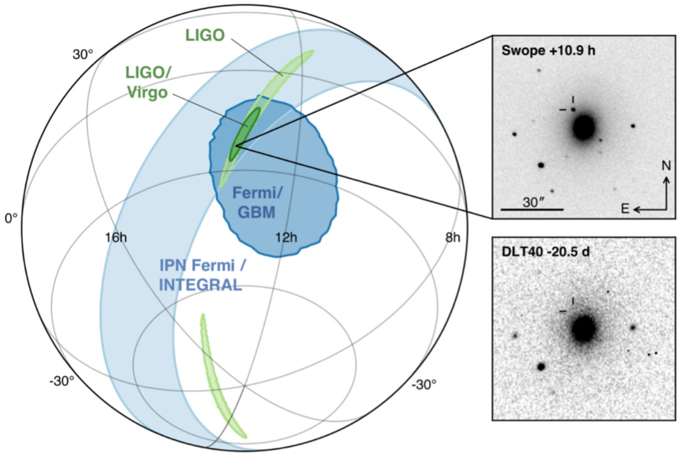
THE top scientific picture of XXI century

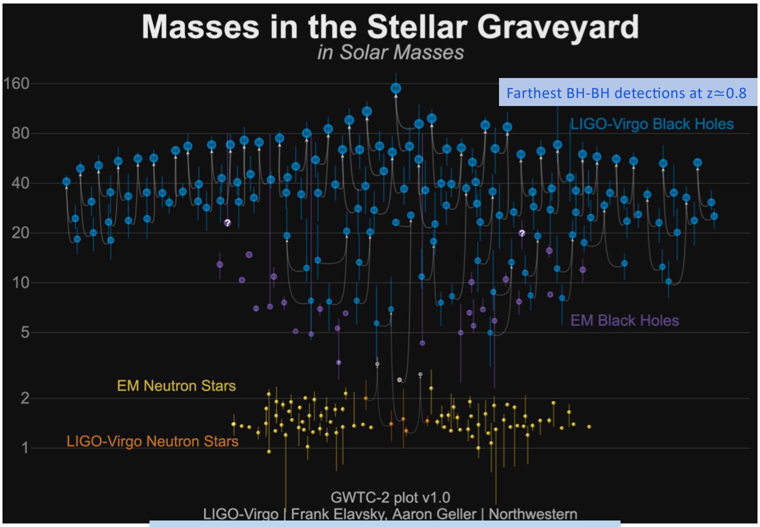
The gravitational wave signal **GW170817** lasted for approximately 100 seconds starting from a frequency of 24 Hz. It covered approximately 3,000 cycles, increasing in amplitude and frequency to a few hundred Hz in the proper inspiral chirp pattern. It arrived first at the Virgo detector in Italy, then 22 milliseconds later at the LIGO-Livingston detector in Louisiana, and another 3 milliseconds later at the LIGO-Hanford detector in Washington.

The first electromagnetic signal detected was **GRB170817A**, a short gamma-ray burst, detected 1.74±0.05 s after the merger time and lasting for about 2 seconds. GRB170817A was discovered by the Fermi Gamma-ray Space Telescope, and the difference in arrival time between Fermi and INTEGRAL helped to improve the sky localization. This GRB was relatively faint given the proximity of the host galaxy NGC4993.



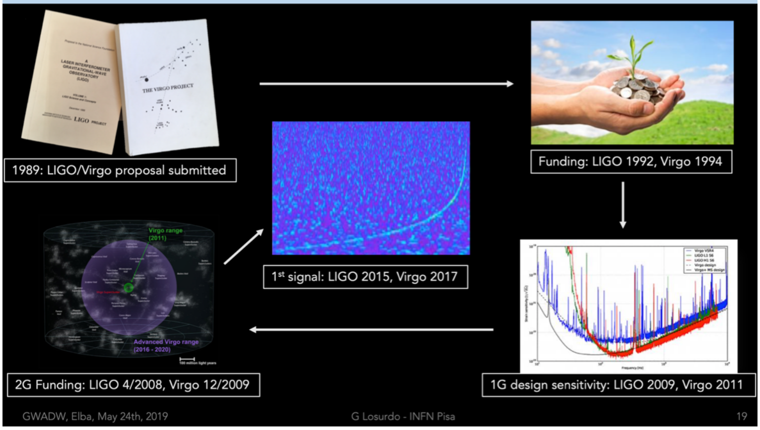
Birth of multi-messenger astronomy





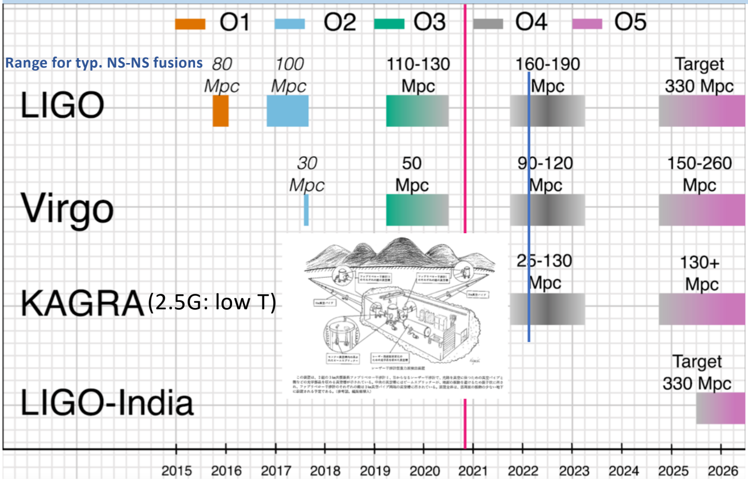
Nota bene: All scientific results are published by LIGO/Virgo together

Brief history of funding success/struggles

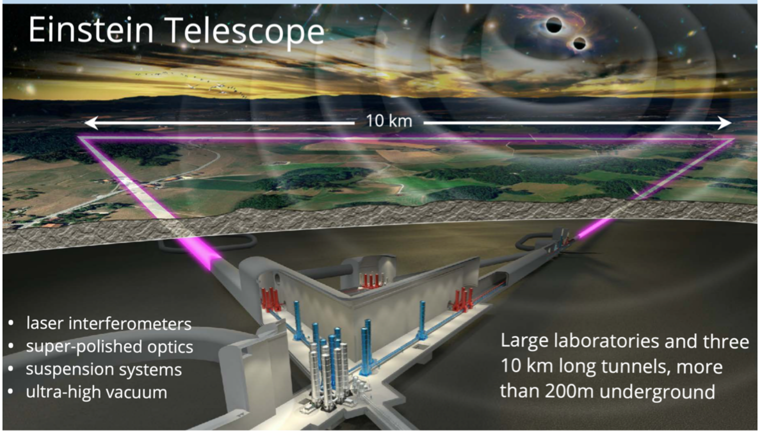


aLIGO funded by NSF ($205M + $15M UK, $15M Germany, $5M Australia, or so) – Virgo by CNRS + INFN (nuclear/particle physics), Poland joined in 2008 (PolGraw)

Next years…

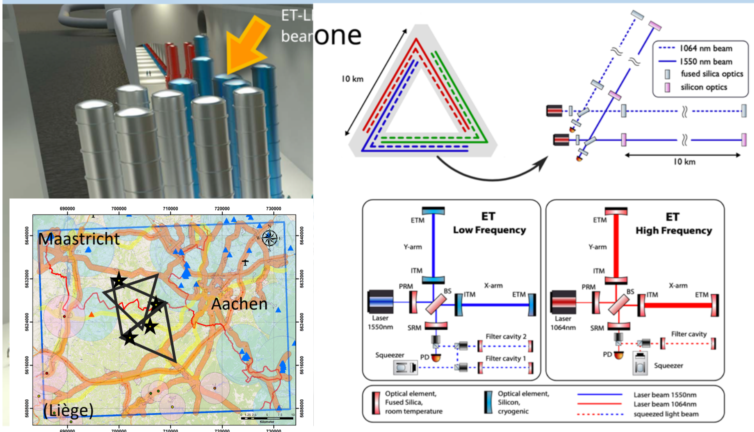


The race has begun…



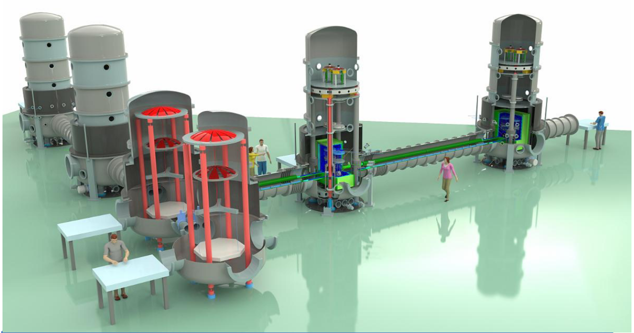
American *Cosmic Explorer* probably will be a 40 km L “on-ground” (± 30 m…)

“LHC” for GW



Two sites considered for ET: BDN border + Sardinia

ETpathfinder: future “CERN for GW”?



“In order to develop new technologies required for the Einstein Telescope, scientists and companies from the Netherlands, Belgium and Germany are setting up a joint R&D facility: *ETpathfinder*, which is intended to develop the precision technology, coatings and optics as well as special measurement and control technology, seismic isolation, required for the Einstein Telescope and to test them in an ET-like environment.”

https://www.etpathfinder.eu/research/

Polska i Teleskop Einsteina

ASTROCENT — PARTICLE ASTROPHYSICS SCIENCE AND TECHNOLOGY CENTRE INTERNATIONAL RESEARCH AGENDA — NICOLAUS COPERNICUS ASTRONOMICAL CENTER OF THE POLISH ACADEMY OF SCIENCES

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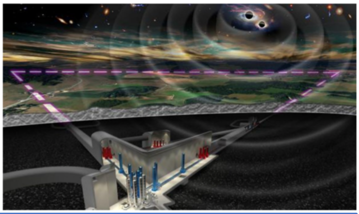
11 September 2020

The Einstein Telescope: a new stage in the development of gravitational wave astronomy

The proposal to include the Einstein Telescope, a pioneering third-generation gravitational-wave (GW) observatory, in the 2021 update of the European Strategic Forum for Research Infrastructures (ESFRI) roadmap has been submitted. The ESFRI roadmap describes the future major research infrastructures in Europe. The Einstein Telescope (ET) is the most ambitious project for a future terrestrial observatory for GWs. The amazing scientific achievements of Advanced Virgo (in Europe) and Advanced LIGO (in the USA) in the last 5 years initiated the era of GW astronomy. The adventure began with the first direct detection of

https://astrocent.camk.edu.pl/?p=3609

The Einstein Telescope related activities in Poland are conducted within the Polish ET Consortium led by the University of Warsaw, with the following members: Nicolaus Copernicus Astronomical Center, National Center for Nuclear Research, Institute of Mathematics (Polish Academy of Science), Białystok University and Warsaw University of Technology. Prof. Tomasz Bulik (University of Warsaw and AstroCeNT NCAC) is the coordinator of the Consortium and a member of the Einstein Telescope Steering Committee. The teams are led by: prof. Dorota Rosińska (University of Warsaw), prof. Michał Bejger (NCAC), prof. Marek Biesiada (NCNR) and prof. Andrzej Królak (Institute of Mathematics).



ET developments have highly interdisciplinary character as they involve enormous challenges as well as opportunities across many cutting-edge technologies related to:

foundations of quantum physics and laser physics, nanolayers and material science, cryogenics and very high vacuum, ultra-precise sensing and metrology, geophysics and ultra-high mechanical isolation techniques, machine learning and control systems, deep statistical reasoning and computing challenges

GW antennas – *where Gravity meets Quantum Physics!*

Highlights of ET science

Astrophysics

Black hole properties
– origin (stellar vs. primordial)
– evolution, populations

Neutron star properties
– interior structure (QCD at ultra-high densities, exotic states of matter)
– populations

Multi-messenger astronomy
– joint GW/EM observations (GRB, kilonova,...)
– multiband GW detection (LISA)
– neutrinos

Detection of new astrophysical sources
– core collapse supernovae
– isolated neutron stars
– stochastic background of astrophysical origin

Fundamental physics and cosmology

• The nature of compact objects
– near-horizon physics
– tests of no-hair theorem
– exotic compact objects

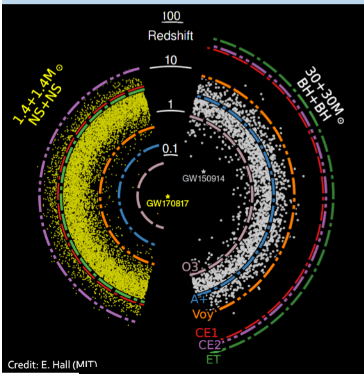
• Tests of General Relativity
– post-Newtonian expansion
– strong field regime

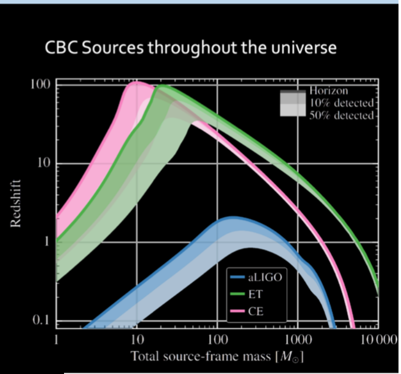
• Dark matter
– primordial BHs
– axion clouds, dark matter accreting

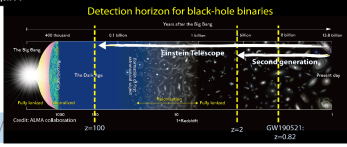
• Dark energy and modifications of gravity
– DE equation of state
– modified GW propagation

• Stochastic backgrounds of cosmological origin and connections with high-energy physics
– inflation – phase transitions – cosmic strings – ...

Einstein Telescope & Cosmic Explorer reach







Starting from 2035, or so: (almost) ALL fusions in Observable Universe will be detected!!

a BH-BH fusion detected every minute

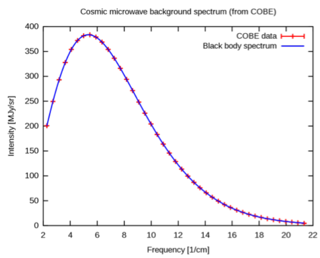
a NS-NS detection every 10 minutes

Outlook, and a lesson from the past?

In 15-20 years the number of GW detections will be truly gigantic – we might suffer from that, as already did in the past: Willis Lamb, in his **1955** Nobel Prize Lecture, joked that he had heard it said that *"the finder of a new elementary particle used to be rewarded by a Nobel Prize, but such a discovery now ought to be punished by a 10,000 dollar fine."*

FIG. 1. A 63 million volt positron ($H\rho=2.1\times10^5$ gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ($H\rho=7.5\times10^4$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

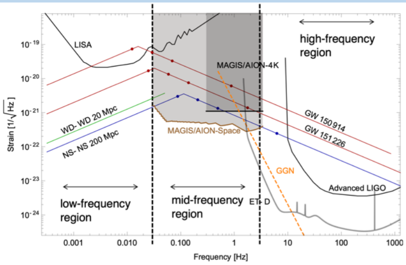
My own inspiration: "the COBE-project can also be regarded as the starting point for cosmology as a **precision** science" -- Nobel Committee 2006

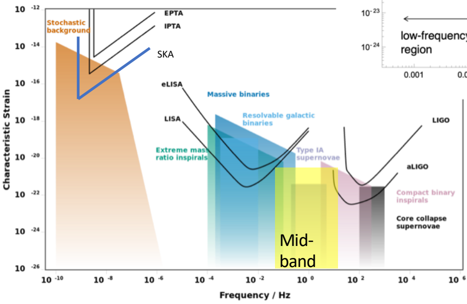


(Extremely) Bright future for GW science

SKA will start (GW via *Pulsar Timing*) before ET/CE and LISA + Atomic Interferometers as MAGIS (+ LHC as a GW antenna too??)

In addition, studies of the CMB polarization will continue – all in all, an enormous variety of techniques and sensitivities…





Two examples in RF:

GWs produced at energies around the **scale of grand unification** have frequencies in the MHz and GHz regime today⇒Gertsenshtein effect

Primordial BH signals – "the future SKA Pulsar Timing Arrays could probe the existence of even a **single** stellar-mass PBH in our Observable Universe"

Z ostatniej chwili…

The Astrophysical Journal Letters, 905:L34 (18pp), 2020 December 20
https://doi.org/10.3847/2041-8213/abd401

The NANOGrav 12.5 yr Data Set: Search for an Isotropic Stochastic Gravitational-wave Background

6.2. Astrophysical Implications

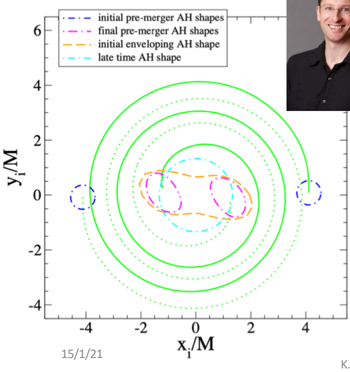
The first hint of a signal from our analysis of NG12 is indeed tantalizing. However, without definite evidence for HD correlations in the recovered common-spectrum process, there is little we can say about the physical origin of this signal.

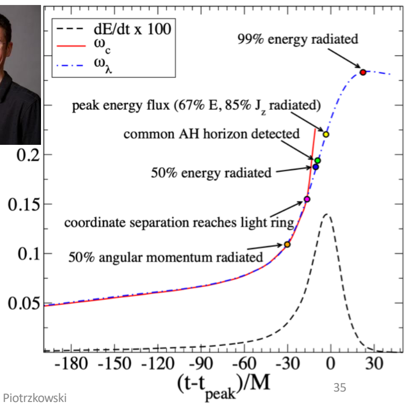
Dziękuję za uwagę!

Extracting the Gravitational Recoil from Black Hole Merger Signals

Vijay Varma,[1,*] Maximiliano Isi,[2,†] and Sylvia Biscoveanu[2,‡]
[1] *TAPIR 350-17, California Institute of Technology, 1200 E California Boulevard, Pasadena, CA 91125, USA*
[2] *LIGO Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
(Dated: March 11, 2020)

https://arxiv.org/abs/0710.1338v1

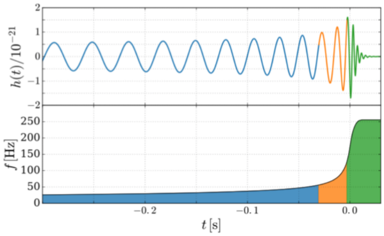




- Dispersion relation:
  $E^2 = p^2c^2 + m_g^2c^4$
- Group velocity:
  $v_g/c = 1 - m_g^2c^4/(2E^2)$
- Modification to the gravitational wave phase:
  $\delta\Psi(f) \propto Dm_g^2/f$
  where D distance, f frequency

Result:

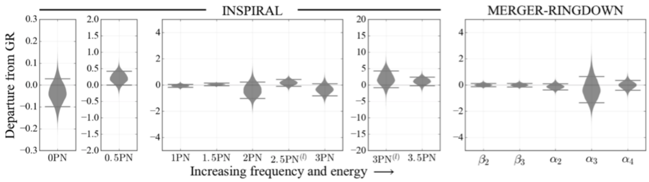
$\boxed{m_g \leq 7.7 \times 10^{-23}\,\mathrm{eV}/c^2}$



➢ Inspiral-merger-ringdown process
- "Post-Newtonian" description of inspiral:

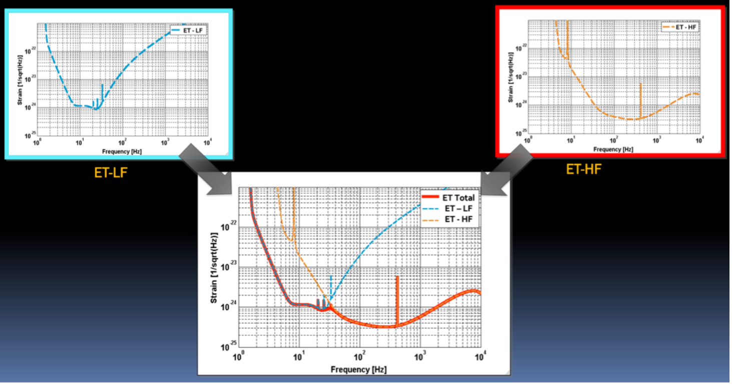
$$\Phi(v) = \left(\frac{v}{c}\right)^{-5}\left[\varphi_{0\mathrm{PN}} + \varphi_{0.5\mathrm{PN}}\left(\frac{v}{c}\right) + \varphi_{1\mathrm{PN}}\left(\frac{v}{c}\right)^2 + \ldots + \varphi_{2.5\mathrm{PN}^{(l)}}\log\left(\frac{v}{c}\right)\left(\frac{v}{c}\right)^5 + \ldots + \varphi_{3.5\mathrm{PN}}\left(\frac{v}{c}\right)^7\right]$$

- Merger-ringdown governed by additional parameters β_n , α_n



ET EINSTEIN TELESCOPE

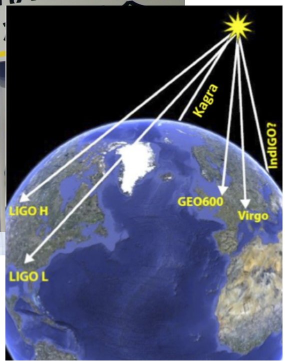
ET Xylophone Sensitivity



Draft version December 25, 2020
Typeset using LaTeX **twocolumn** style in AASTeX62

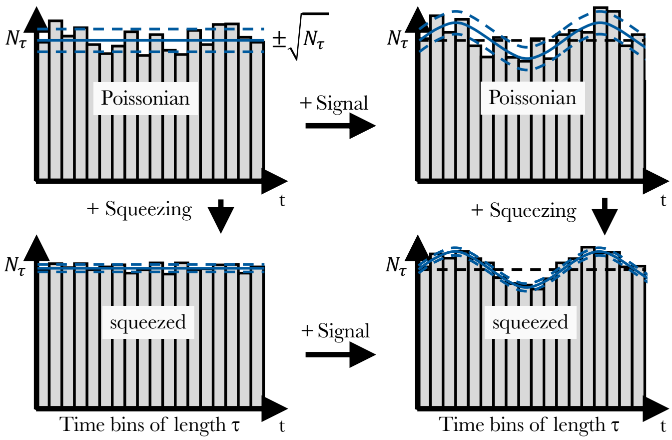
Diving below the spin-down limit: Constraints on gravitational waves from the energetic young pulsar PSR J0537−6910

R. Abbott,[1] T. D. Abbott,[2] S. Abraham,[3] F. Acernese,[4,5] K. Ackley,[6] A. Adams,[7] C. Adams,[8] R. X. Adhikari,[1]



15/1/21 K. Piotrzkowski

Photon statistic on the photodiode (R. Schnabel)



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