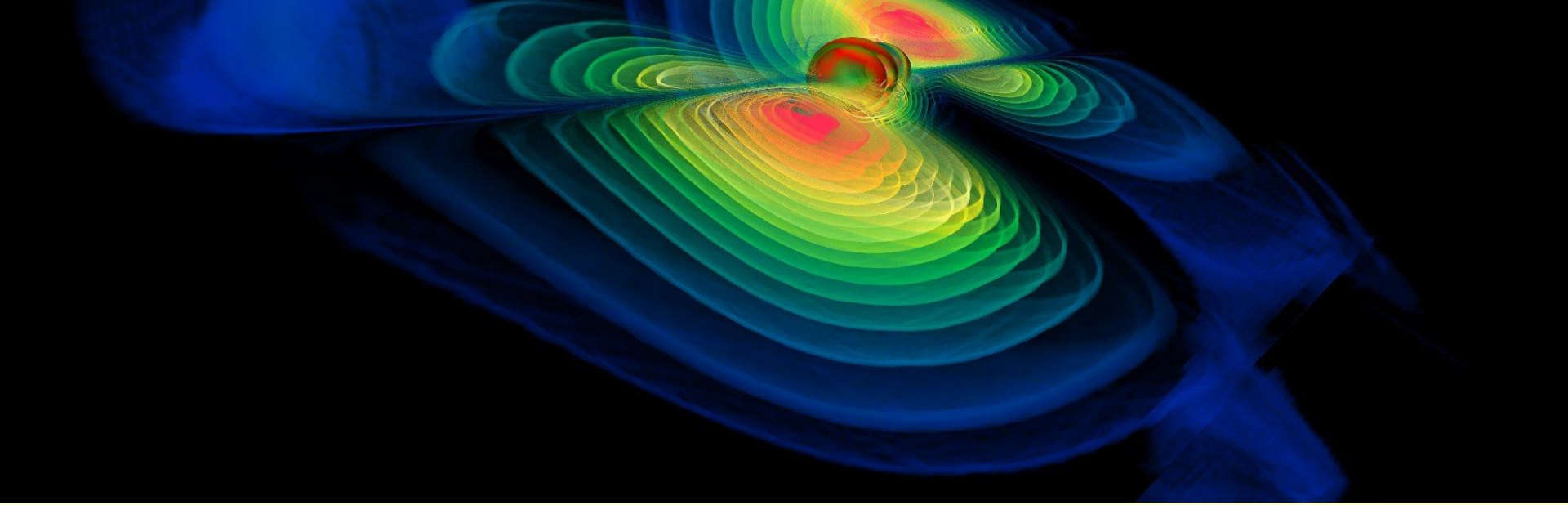


Gravitációs hullámok és a 2017. évi Fizikai Nobel-díj

GERGELY Árpád László

Fizikai Intézet, Szegedi Tudományegyetem

Fizikatanári Ankét, Szeged

2018

Gravitáció a modern fizikában: a 4 kölcsönhatás egyike

Csökkenő erősség

1. Erős kölcsönhatás (magerők)
2. Elektromágnesesség
3. Gyenge kölcsönhatás (radioaktív bomlás)

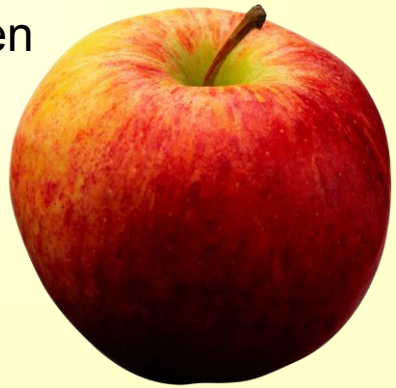
Kvantált kölcsönhatások

sík téridőben

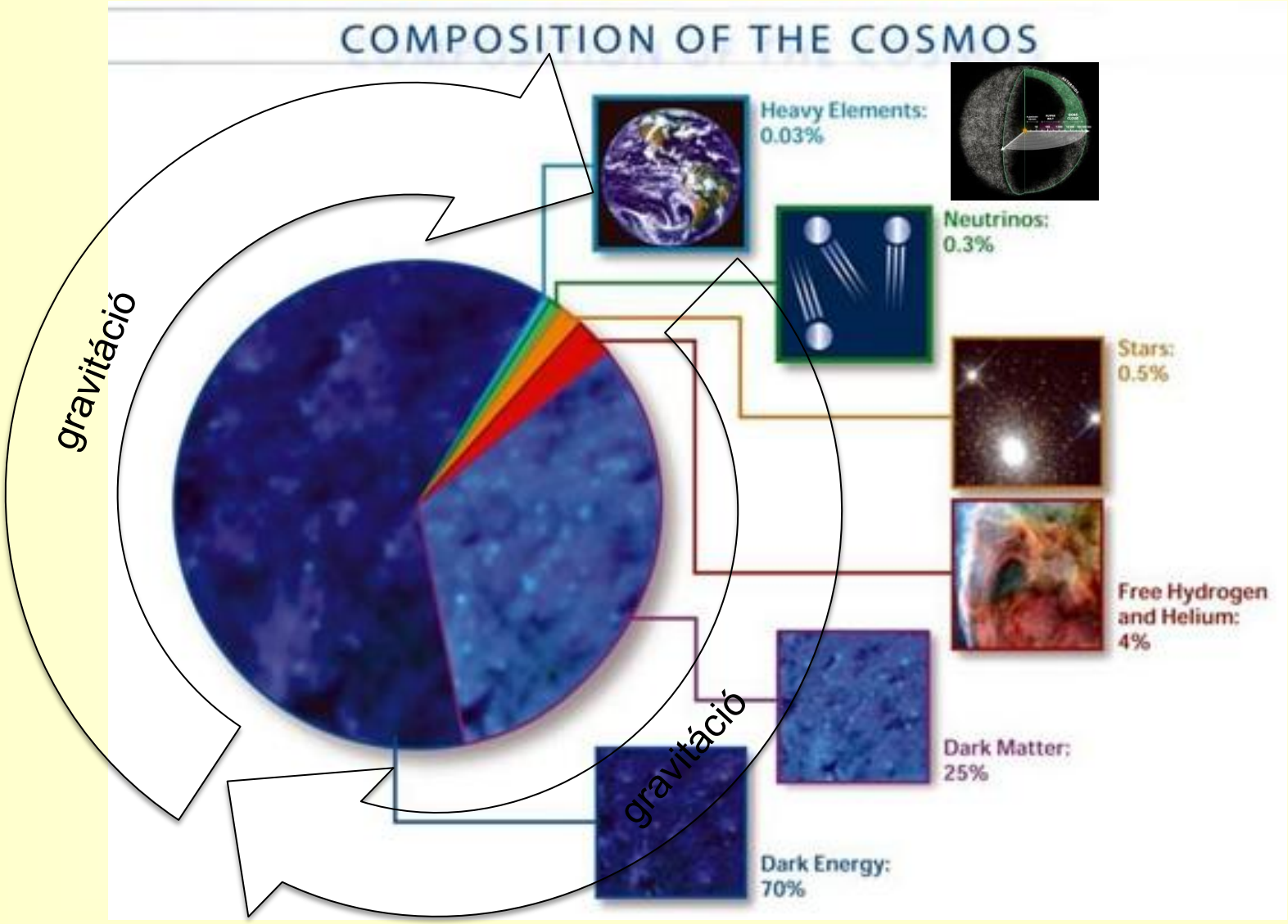
4. Gravitáció

Klasszikus „kölcsönhatás”

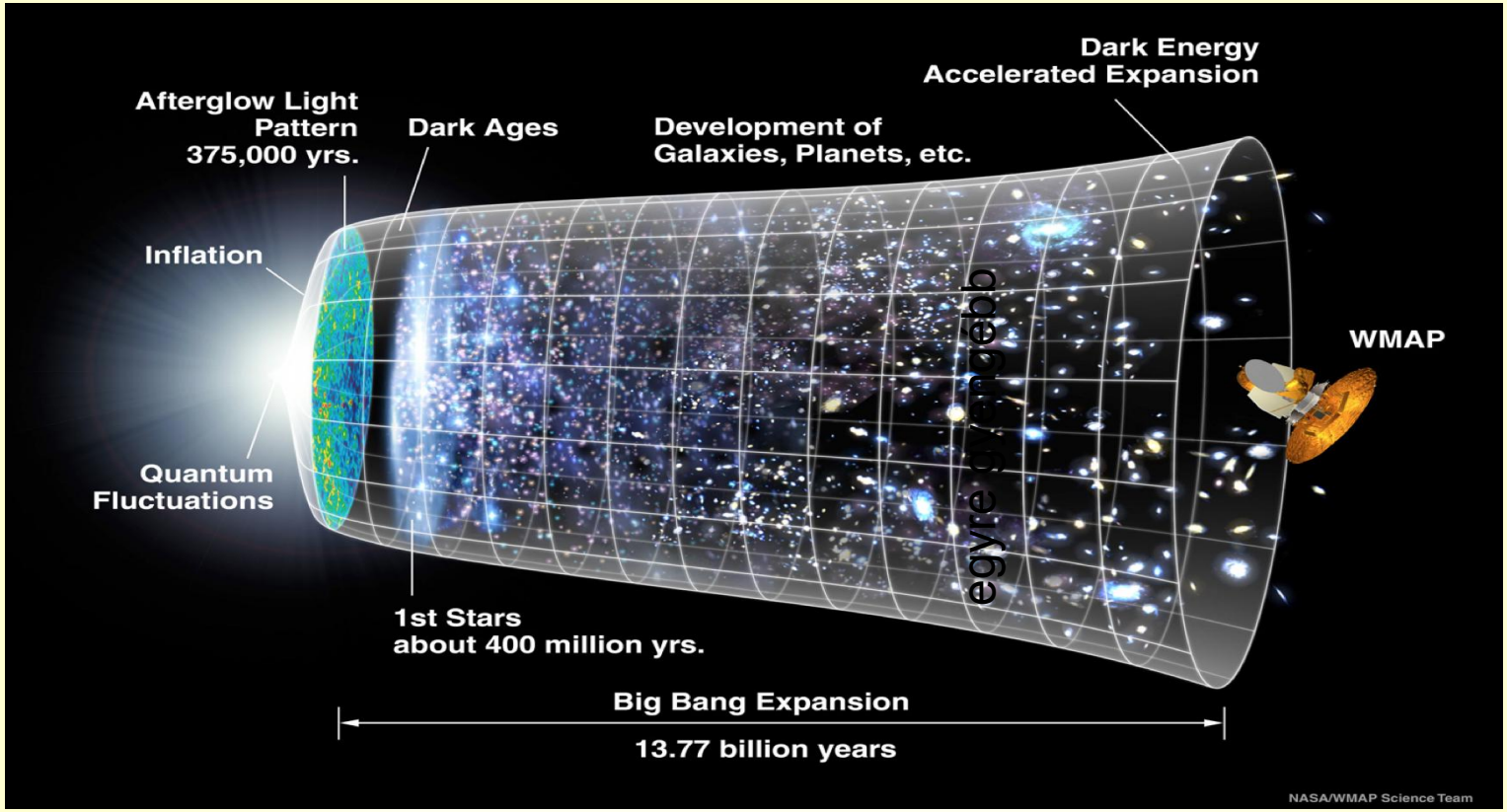
görbült téridőben



Az ismert Univerzum összetétele

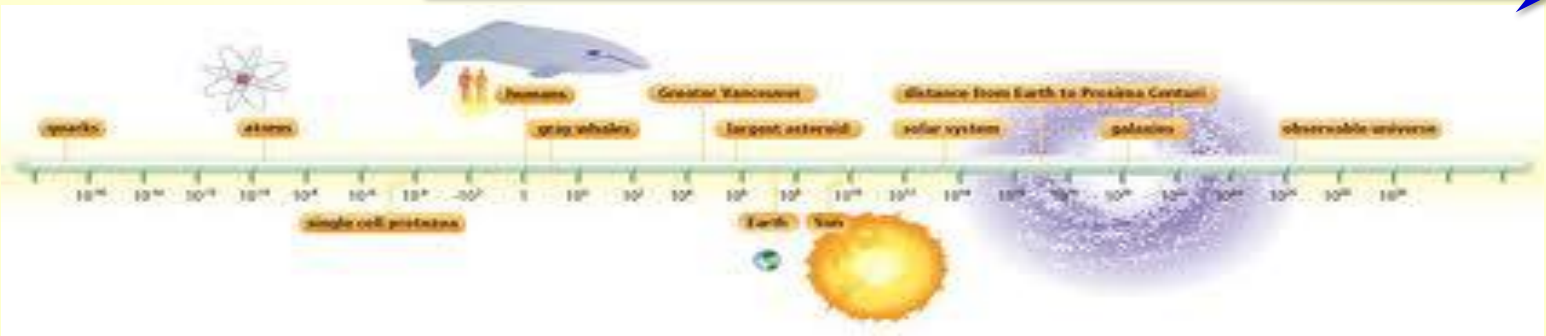


Idő- és távolságskálák az Univerzumban



egyre gyorsabb

gravitáció



Newton gravitációelméletének sikere és korlátai

Pro:

- Az ismert jelenségeket (égitestek mozgása, tömegvonzás a Földön) egyetlen logikai rendszerbe rendezte
- Megjósolta a Neptunusz létezezését az Uránusz mozgásának elemzéséből (Le Verrier)
- Gyenge gravitációban és lassú mozgások esetén (földi viszonyok közt) rendkívül pontos
- Egyszerű: egyetlen skalármező

Kontra:

- Felteszi az éter létezését
- A bolygók mozgását nem teljesen pontosan adja meg (perihéliumvándorlás értéke)
- Földi viszonyok közt is pontatlan, ha GPS-t szeretnénk használni (15m-es pontossághoz az idő 50ns pontossága kell,
  SpecRel: -7μs, ÁltRel: 45μs,
  nélkülük az eltérés 11.4 km/nap !)
- A gravitáció terjedési sebessége végtelen (pillanatszerű kölcsönhatás)

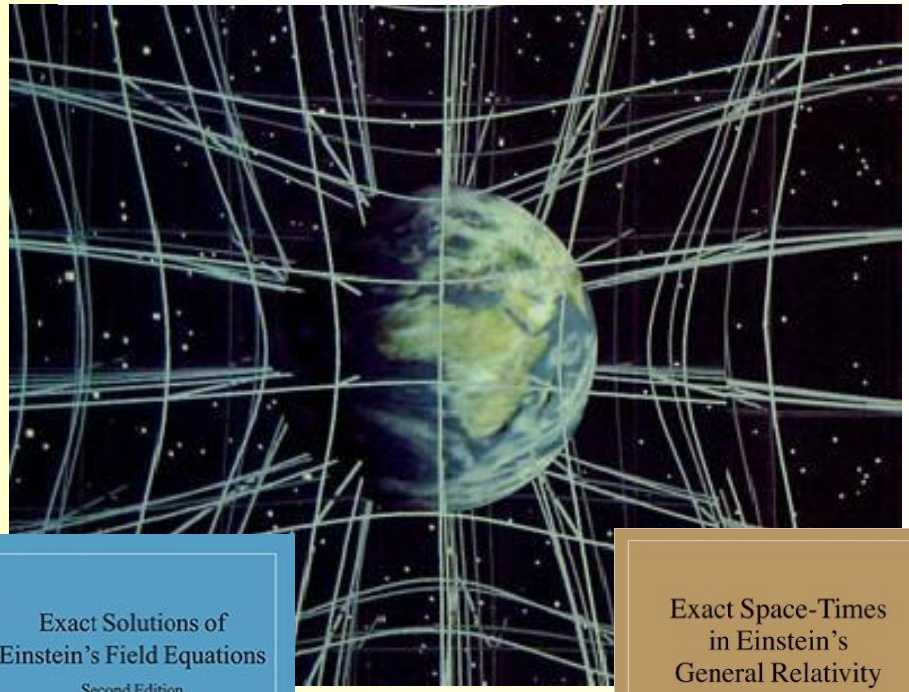
Az általános relativitáselmélet, mint gravitációelmélet

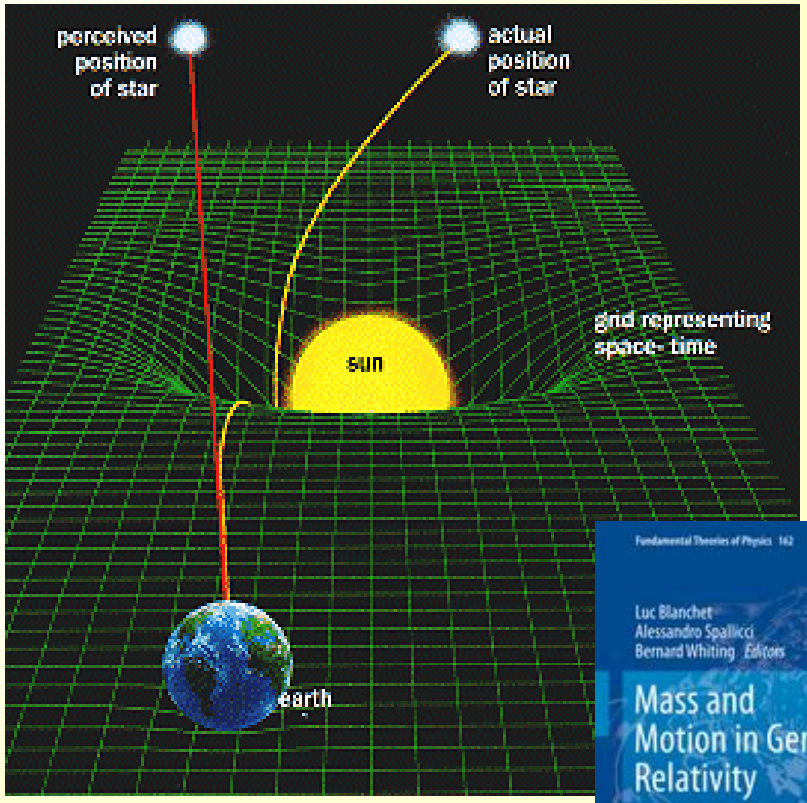
1. az anyag megmondja a téridőnek, hogyan görbüljön (Einstein egyenlet)

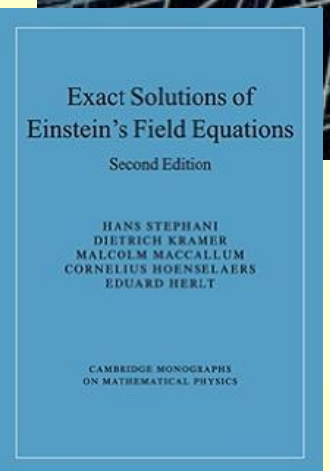
$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} + \Lambda\, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

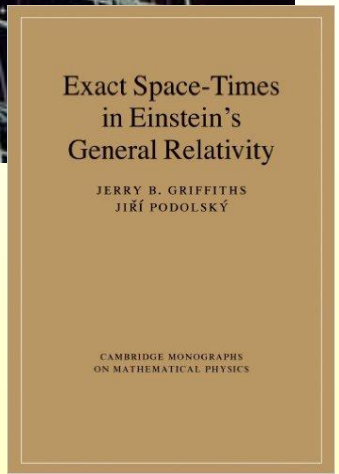
2. A téridő megmondja az anyagnak, hogyan mozogjon (geodetikus egyenlet)

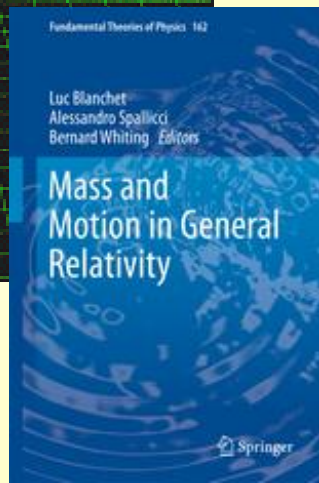
$$\frac{d^2 x^\mu}{ds^2} = -\Gamma^\mu{}_{\alpha\beta} \frac{dx^\alpha}{ds} \frac{dx^\beta}{ds}$$











Új effektusok, új fogalmak

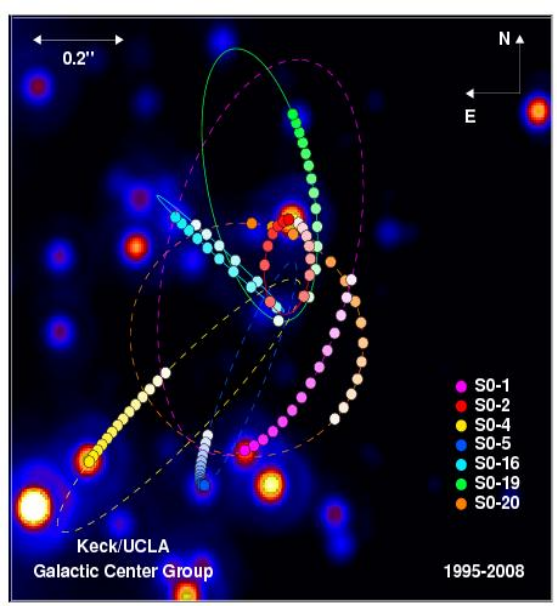
Új (gyenge-tér) effektusok a Naprendszerben:

- Merkúr perihélium-precessziója
- gravitációs fényelhajlás (Napfogyatkozás)
- gravitációs vöröseltolódás / időtágulás (GPS)
- Shapiro-késés / radarvisszhang

Új fogalmak:

- fekete lyuk

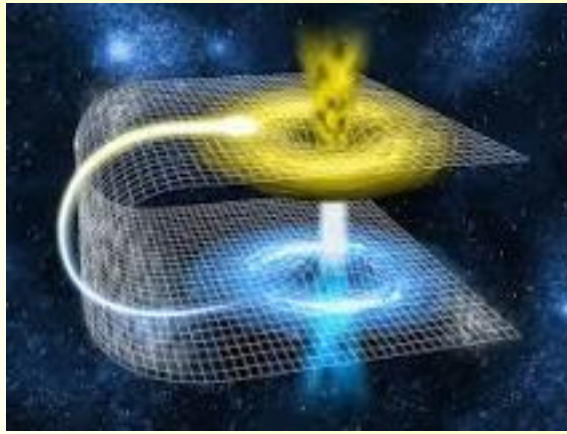
csillagfejlődésből $M \leq 20M_\odot$
közepes tömegű $20M_\odot < M < 10^5 M_\odot$
szupernagy tömegű



- gravitációs (mikro)lencsézés

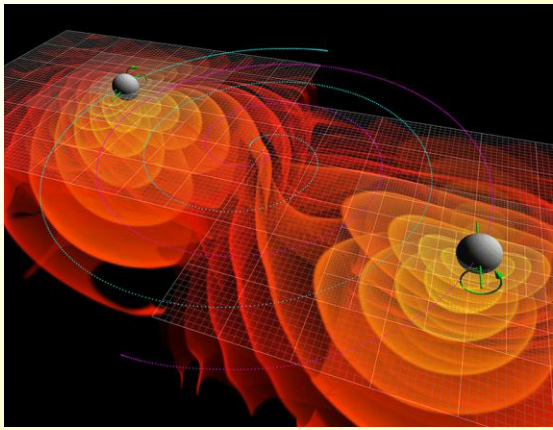
LHC nem lát szuperszimmetriát
→ a sötét anyag nem WIMP
MACHO megfigyelések (Nagy Magellán felhő)
→ a sötét anyag legfeljebb 10%-a származhat csillagfejlődésből

→ közepes tömegű, elsődleges fekete lyukakból áll-e a sötét anyag?
(dedikált megfigyelési program szükséges)



- féreglyuk

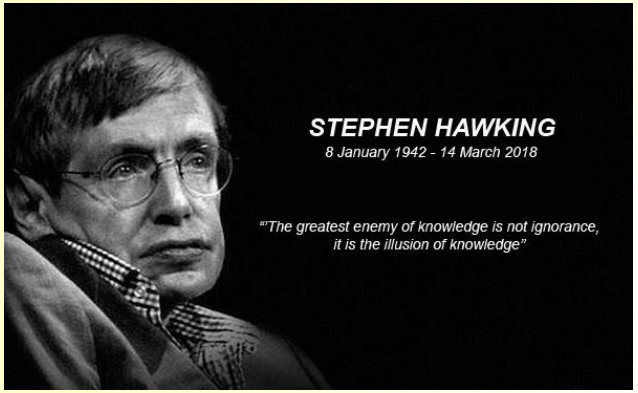
ER=EPR, magyarázat a kvantumos összefonódásra?

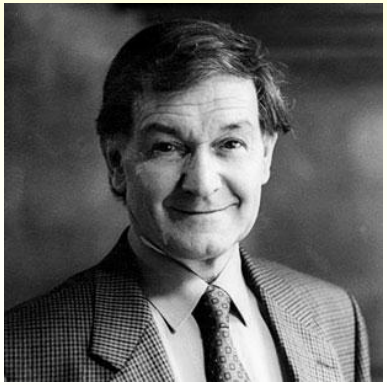


- gravitációs sugárzás

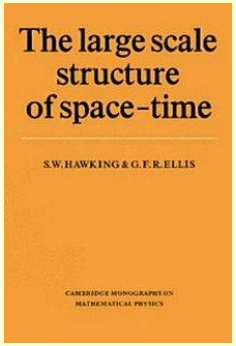
A fekete lyukak matematikai vizsgálata

Stephen Hawking és **Roger Penrose** szingularitás-tételei:





A csillagok összeomlása szingularitásba szimmetriák hiányában is megtörténik → a fekete lyukak kialakulása általános jelenség



Hawking egyéb eredményei:

- A szingularitások a kozmológiai elméletekben is mindig megjelennek
  Ősrobbanás
- A fekete lyukak horizontja egyirányú membrán,

felszíne nem csökkenhet, entrópiaként viselkedik

→ Hawking-Bekenstein entrópia

→ Feketelyuk-termodinamika alapjai

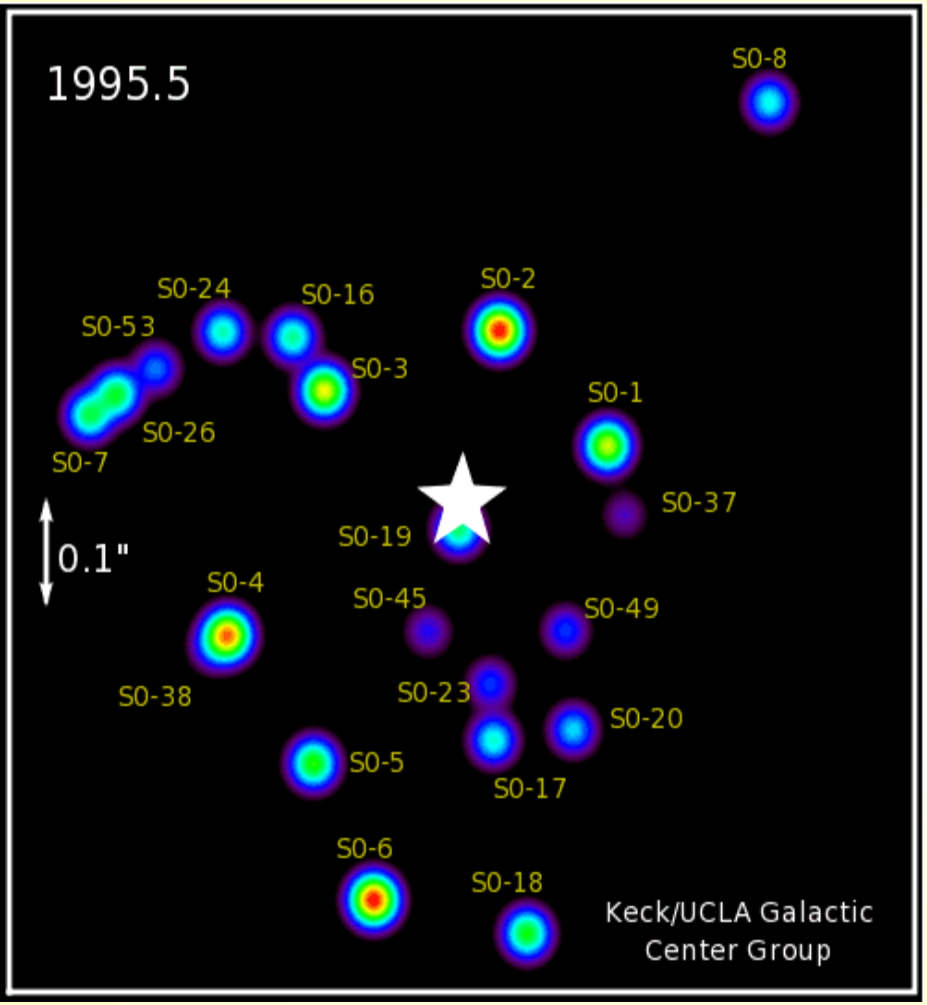
→ ellenőrízhető majd precíz gravitációs sugárzás megfigyelésekkel ! !

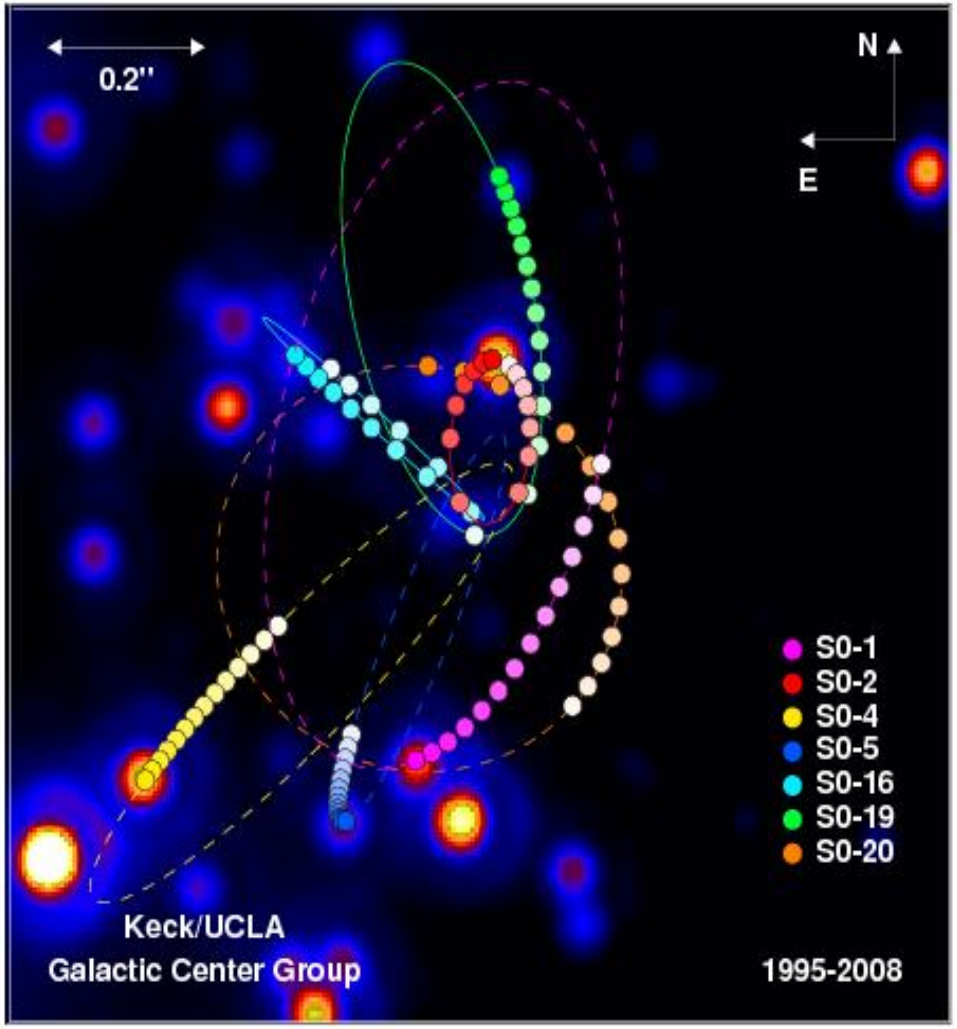
- A kvantumos viselkedés figyelembevétele a horizont feketetest-sugárzásához vezet

→ Hawking-sugárzás

→ ha elég időt várunk, az egész Univerzum feketetest-sugárzássá alakul

A Tejútrendszer közepén található szupernagy tömegű fekete lyuk





Az égbolt (közeli) szupernehéz fekete lyukakban

Supermassive black hole spin-flip during the inspiral
L. Á. Gergely, P. L. Biermann, L. I. Caramete, Class. Quantum Grav. **27** (2010) 194009

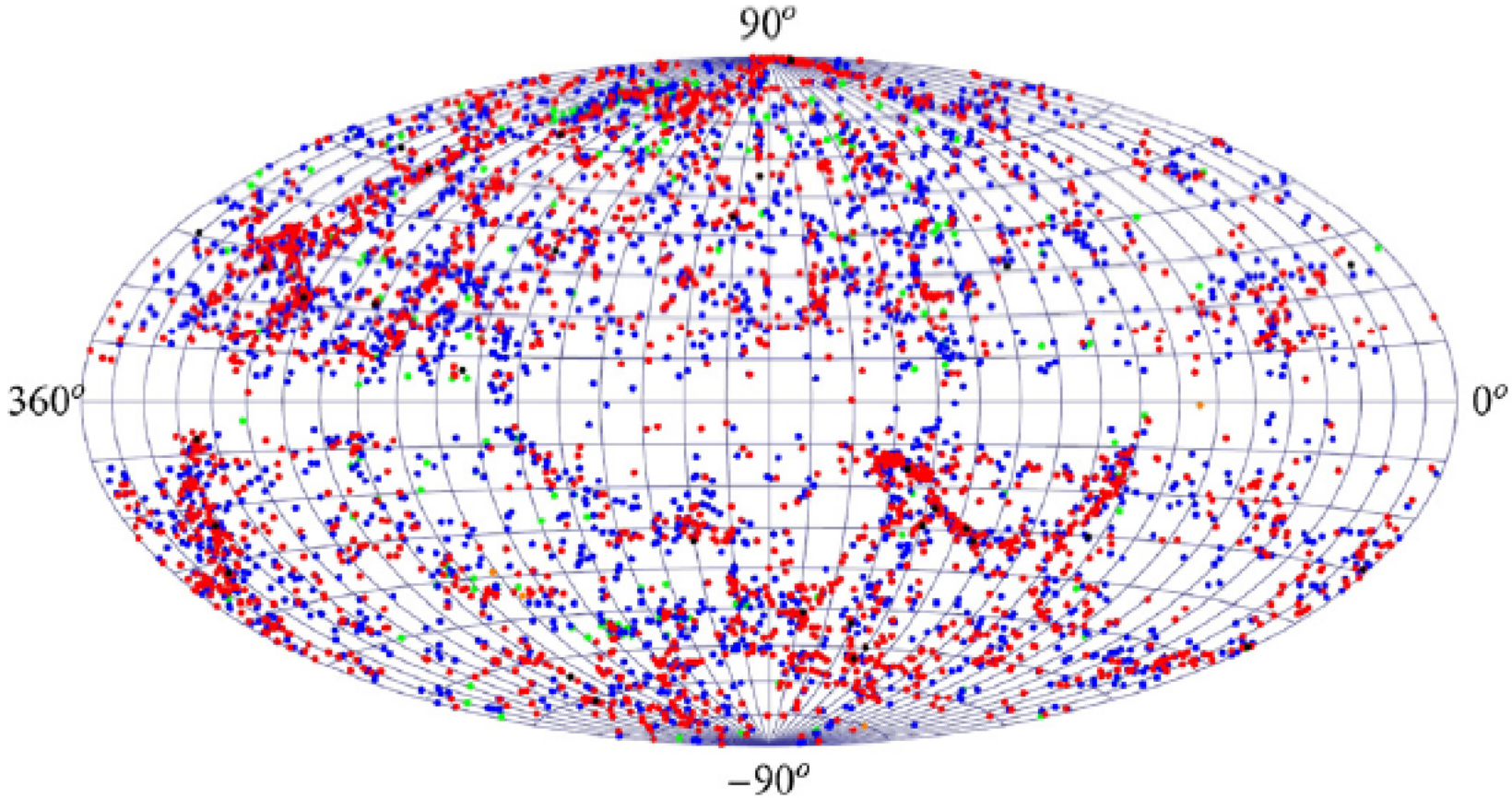
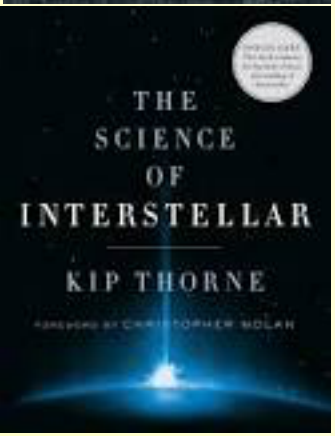


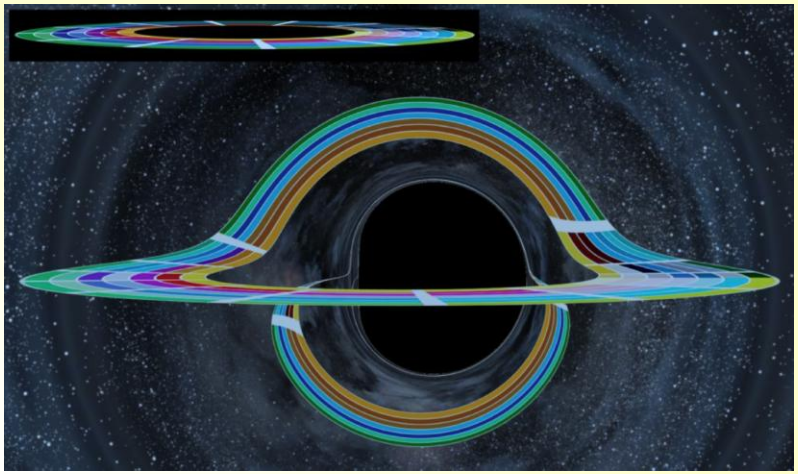
Figure 1. Aitoff projection in galactic coordinates of 5895 NED SMBH candidate sources. The sample is complete in a sensitivity sense; in order to derive densities one needs a volume correction. The color code (online only) is orange, green, blue, red, black corresponding to masses above $10^5\,M_\odot$, $10^6\,M_\odot$, $10^7\,M_\odot$, $10^8\,M_\odot$, $10^9\,M_\odot$, respectively. With the exception of the less numerous first range (orange), representing compact star clusters, the rest are SMBHs.

Fekete lyukak gravitációs lencsézése



A fekete lyuk:

- Elhajlítja az akkréciós korong fényét
- Két képét mutatja

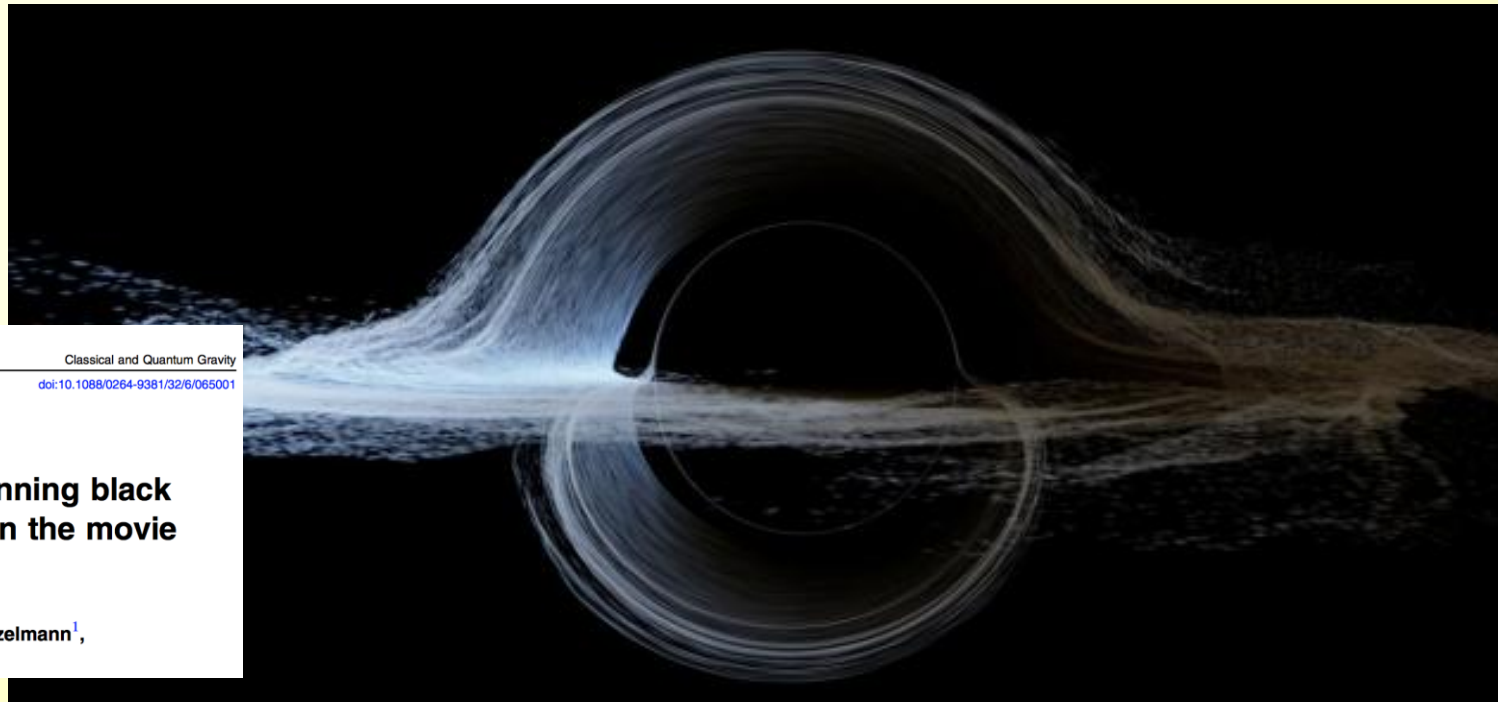


OPEN ACCESS
IOP Publishing — Classical and Quantum Gravity

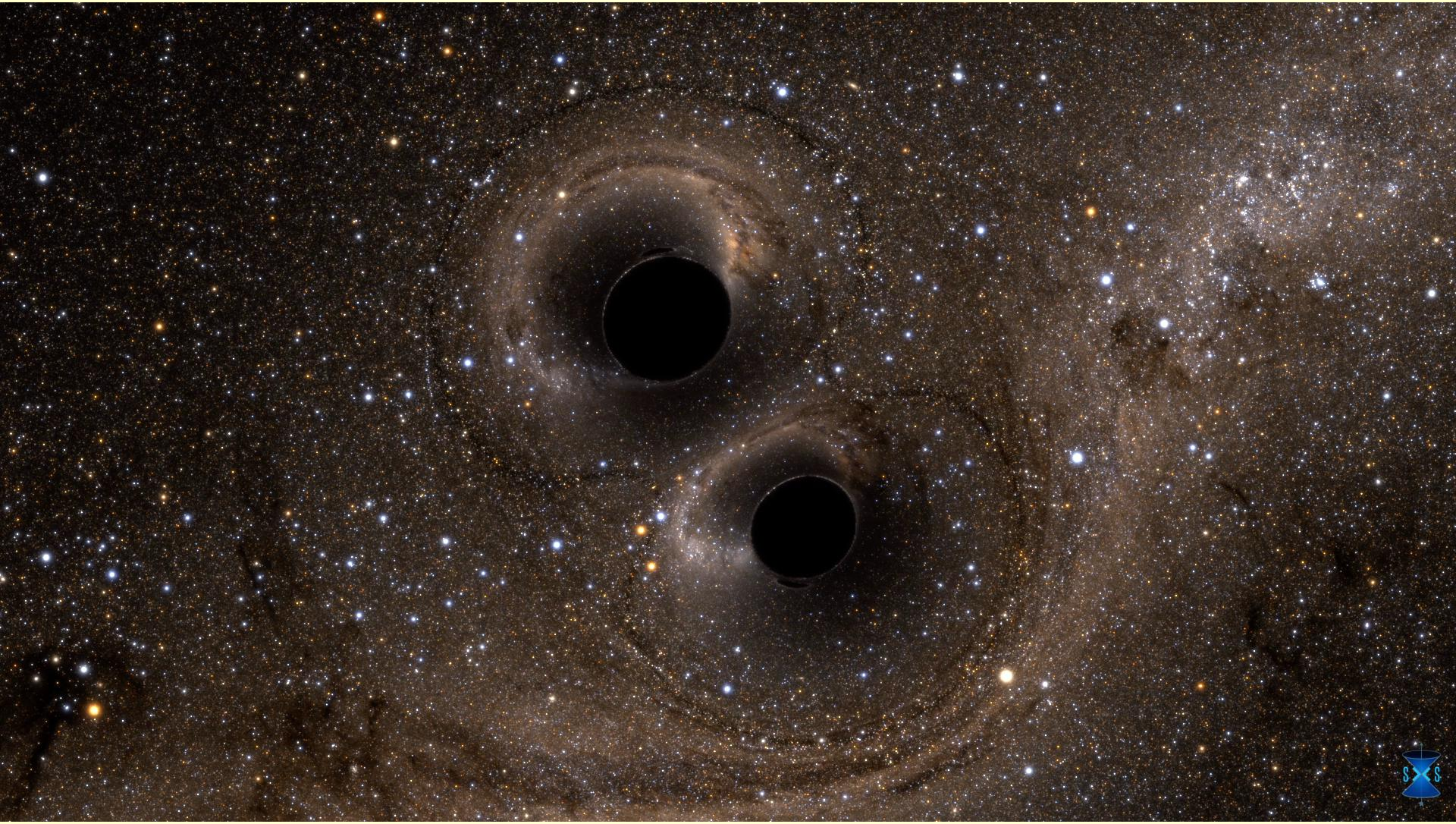
Class. Quantum Grav. **32** (2015) 065001 (41pp) — doi:10.1088/0264-9381/32/6/065001

Gravitational lensing by spinning black holes in astrophysics, and in the movie *Interstellar*

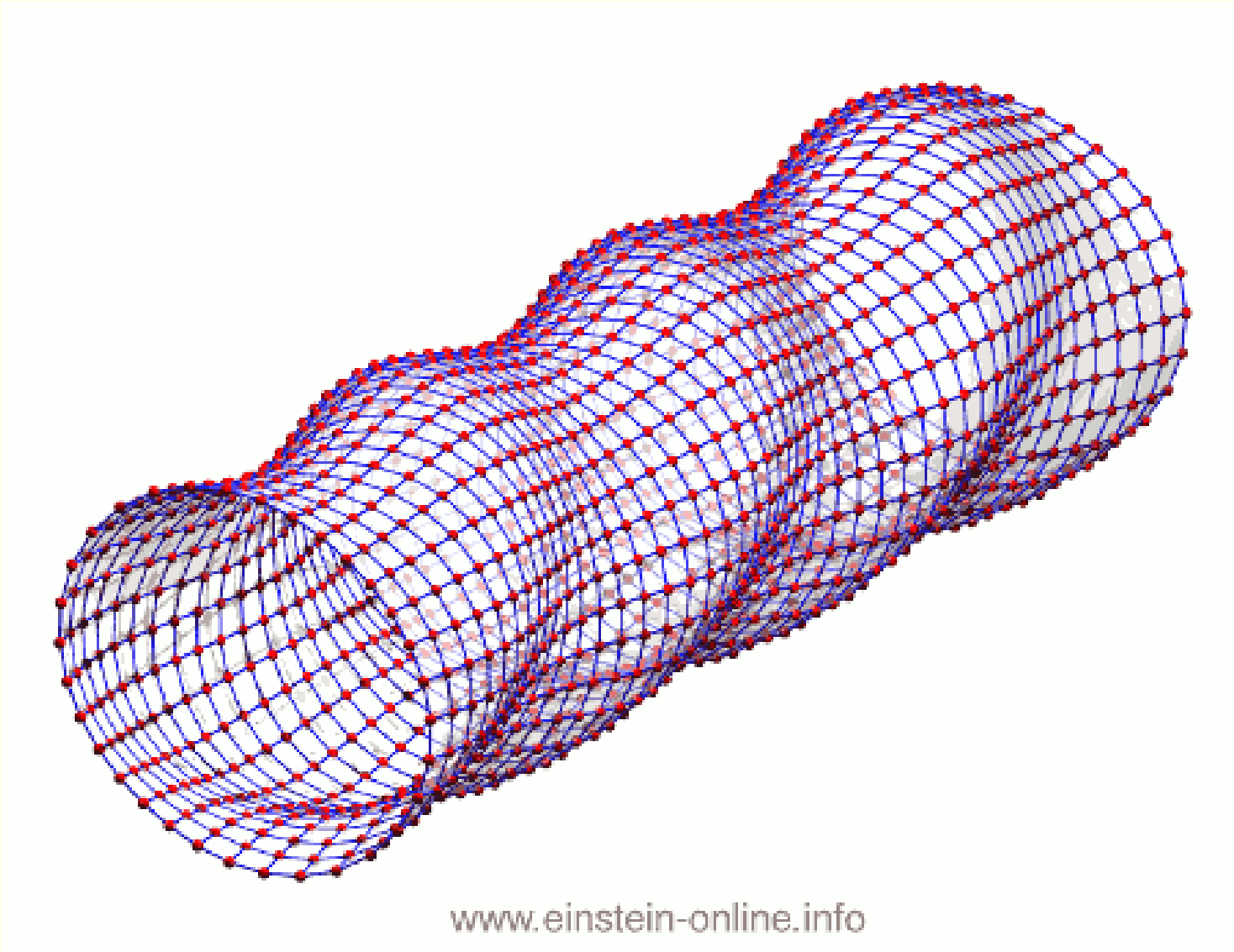
Oliver James[1,*], Eugénie von Tunzelmann[1], Paul Franklin[1] and Kip S Thorne[2]



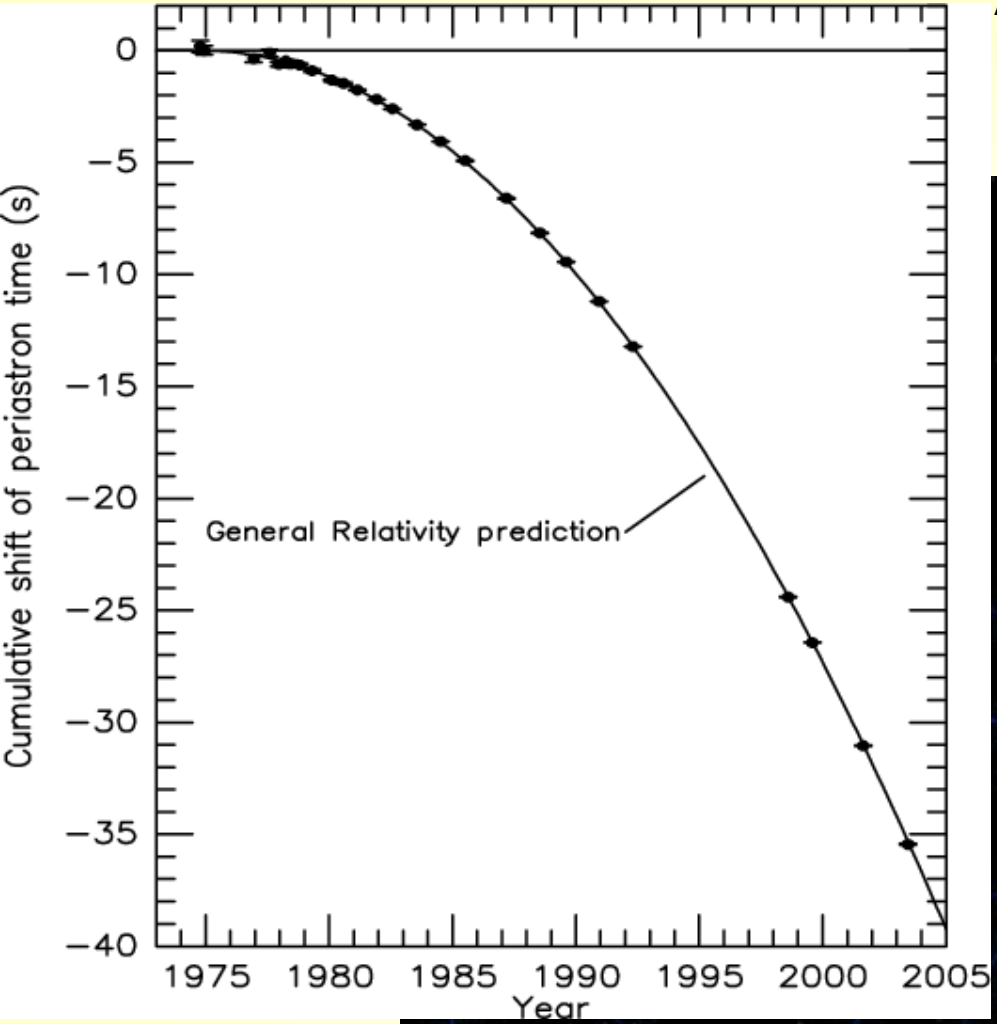
Ütköző feketelyuk-kettős gravitációs lencsézése



A gravitációs hullám tranzverzális, 2 polarizációban, fénysebességgel terjed

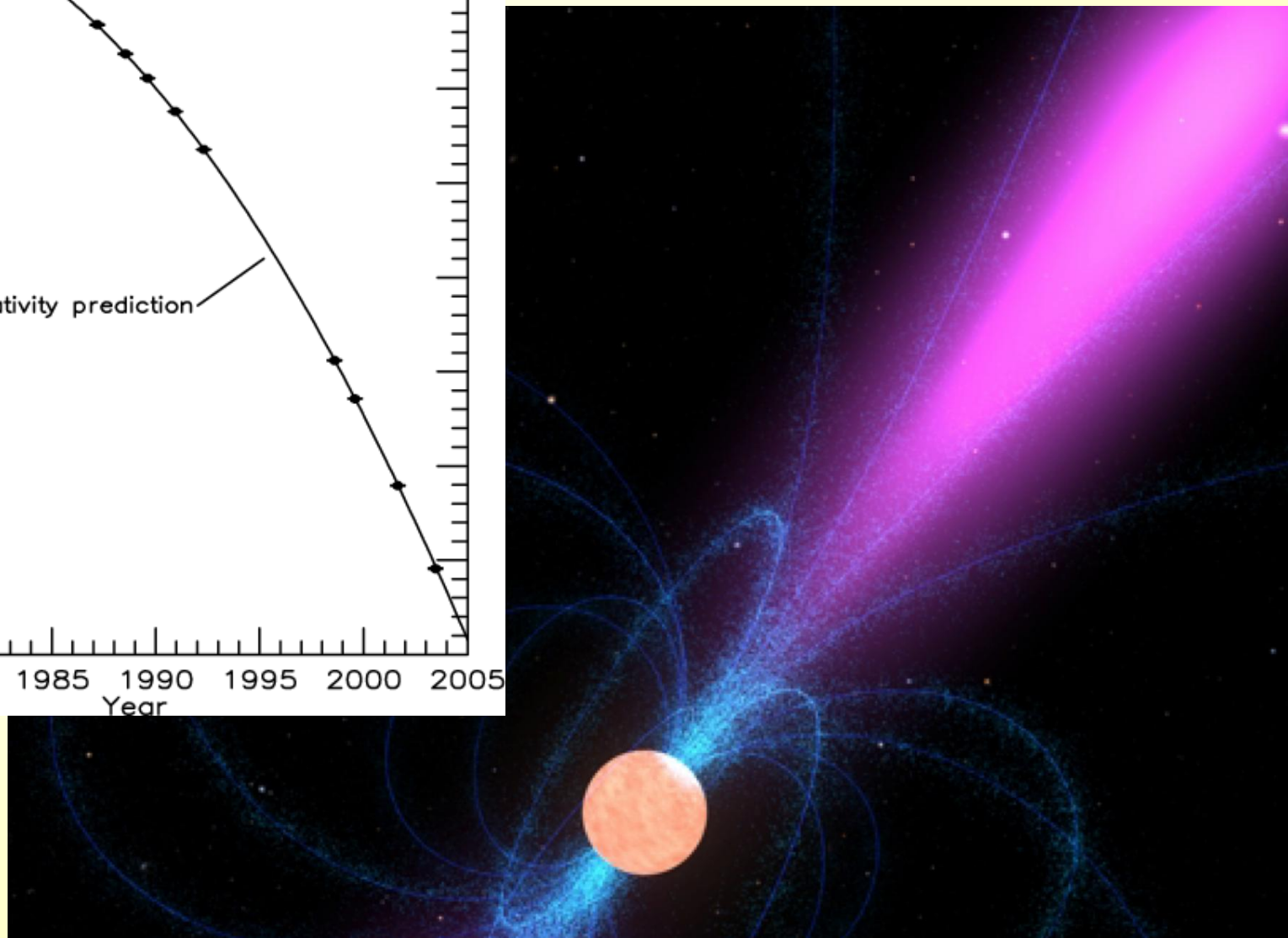


Gravitációs hullámok létezésének indirekt bizonyítéka: a Hulse-Taylor pulzár



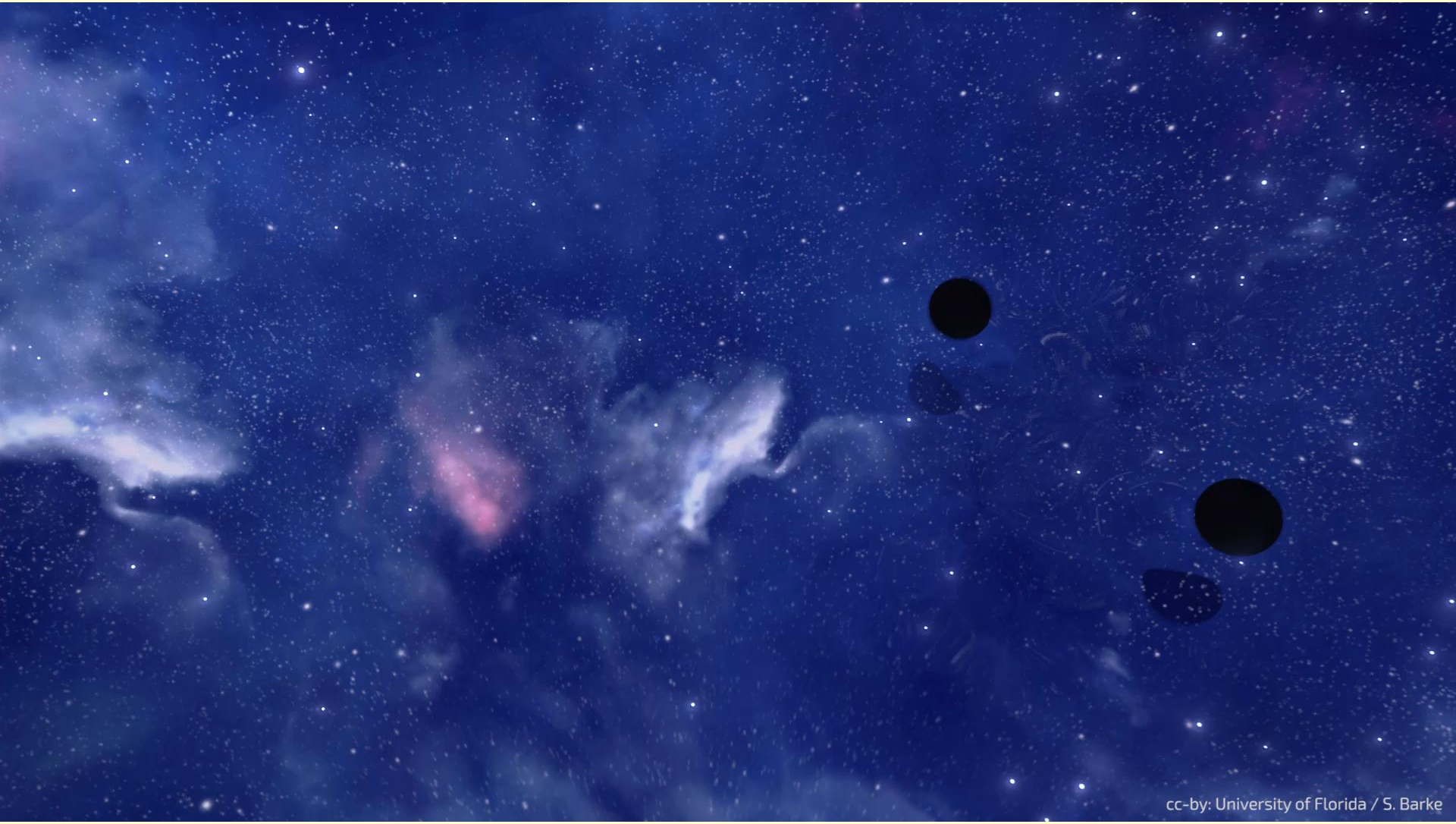
A létező fizikai elméletek egyik legpontosabb igazolása:

40s változás 30 év alatt !! (4×10^{-8})



Nobel-díj
1993

Ütköző feketelyuk-kettős gravitációs sugárzása

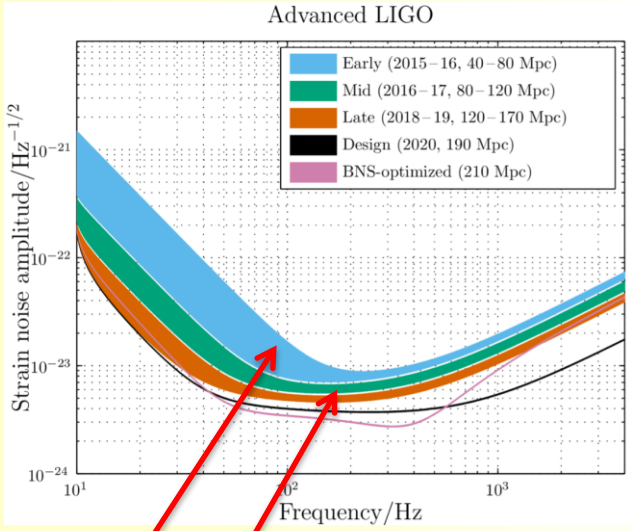


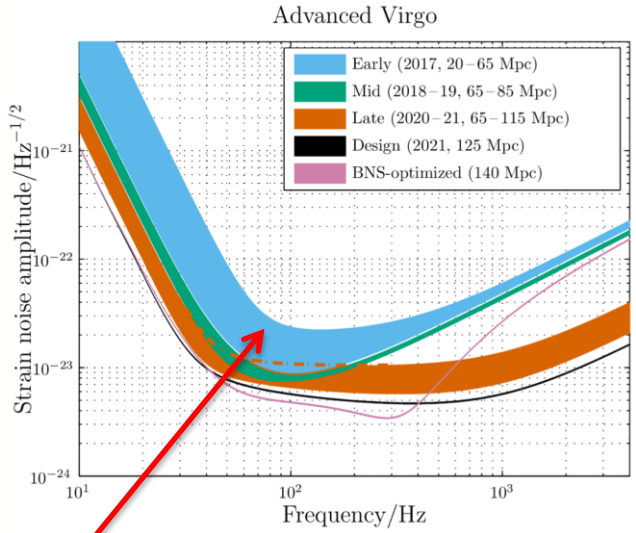
A gravitációs sugárzás Földre gyakorolt hatása

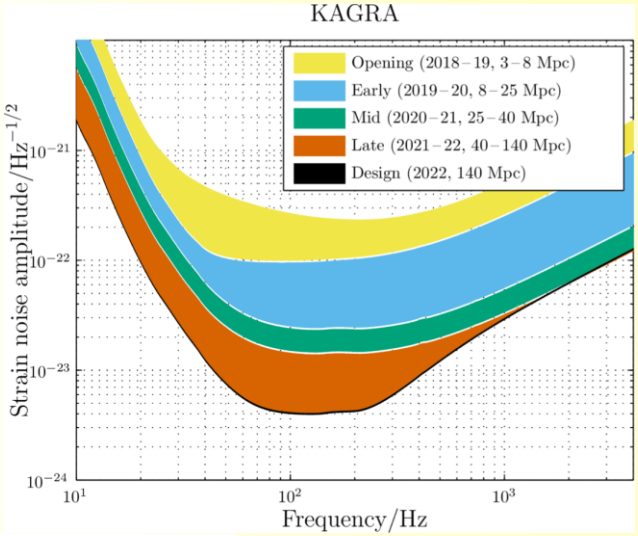
Szerencsére nincs a közelünkben feketelyuk-kettős!!

Második generációs interferometrikus gravitációshullám-detektorok hálózata

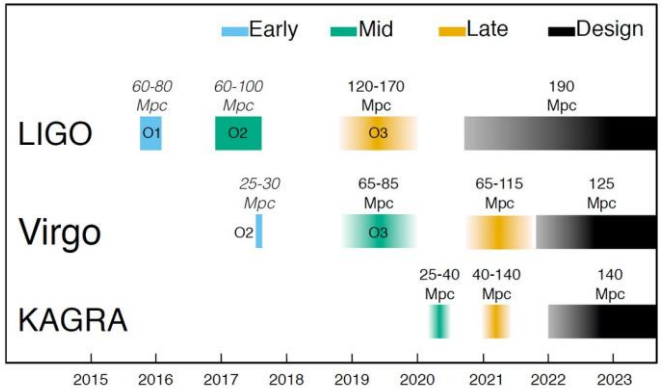
Advanced LIGO, Hanford, USA, 4km Advanced LIGO, Livingston, USA, 4km Advanced Virgo, Cascina, Italy, 3km KAGRA, Kamioke, Japan, 3km







GW150914
GW151226
GW170104
GW170608
GW170814
GW170817



Fizikai Nobel-díj 2017

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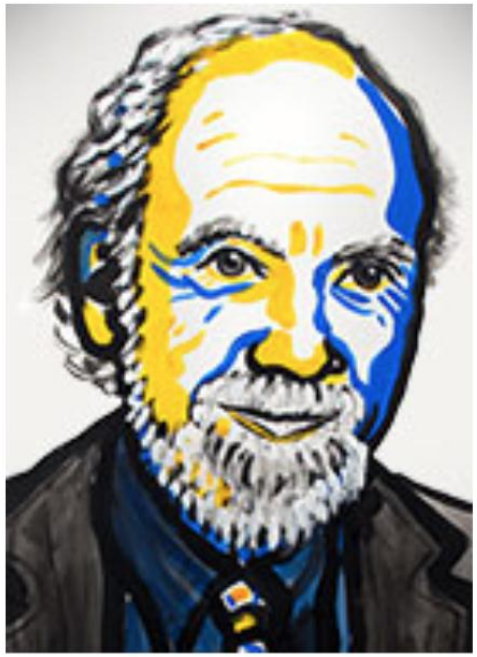
Rainer Weiss

Prize share: 1/2



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Barry C. Barish

Prize share: 1/4

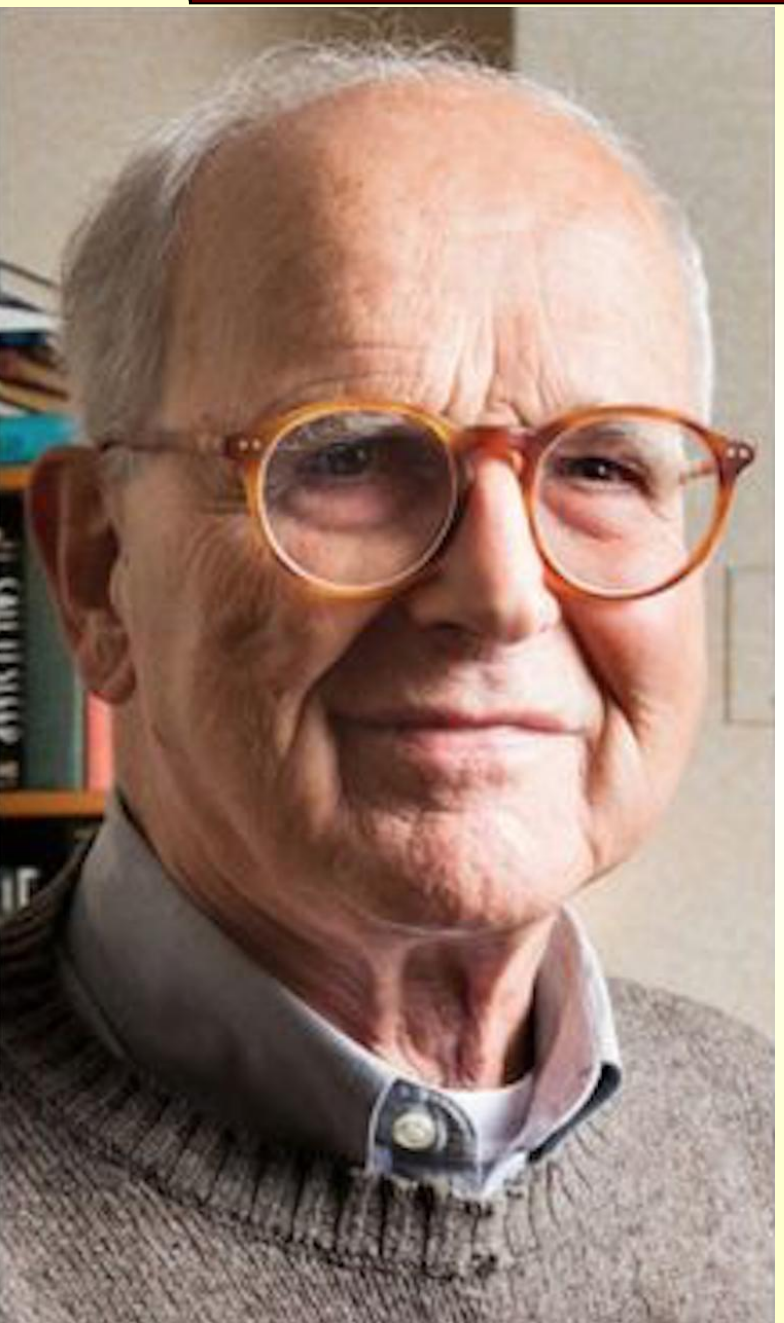
© Nobel Media. Ill. N. Elmehed

Kip S. Thorne

Prize share: 1/4

The Nobel Prize in Physics 2017 was divided, one half awarded to Rainer Weiss, the other half jointly to Barry C. Barish and Kip S. Thorne *"for decisive contributions to the LIGO detector and the observation of gravitational waves"*.

Fizikai Nobel-díj 2017: Rainer Weiss

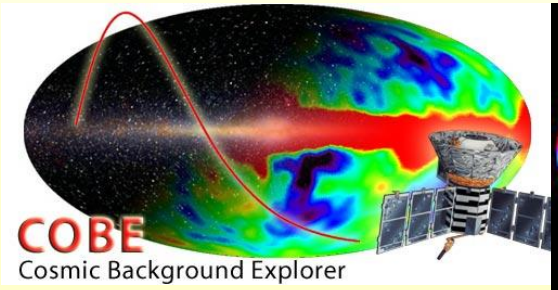


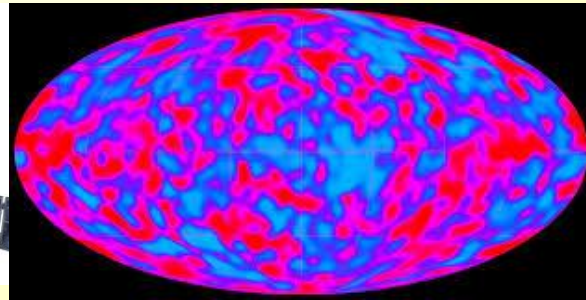
Született: 1932. szeptember 29, Németország
PhD: MIT 1962
Posztdoktor: Princeton 1962-64
1964 óta az MIT professzora, jelenleg emeritus

A lézer-interferometrián alapuló gravitációs hullám detektor megálmodója (1967),
zajforrások feltátárása (1972)

a LIGO alapító tagja (1984, de források csak 1988 tól álltak rendelkezésre)

A NASA COBE (Cosmic Background Explorer) űrszondájának tudományos tanácsadója
-> Gruber Cosmology Prize 2006





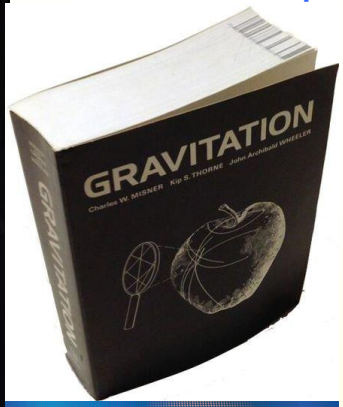
Fizikai Nobel-díj 2017: Kip Thorne

Született: 1940. június 1, Utah
PhD: Princeton 1965, “Geometrodynamics of Cylindrical Systems”, témavezető: J. A. Wheeler
1967 óta a CalTech professzora, jelenleg emeritus Feynmann prof., 50 PhD témavezetője,
1968-tól gravitációs hullámokkal foglalkozó kutatócsoport vezetője

a LIGO alapító tagja (1984)

Multipole expansions of gravitational radiation
Kip S. Thorne
Rev. Mod. Phys. **52**, 299 – Published 1 April 1980

Article | References | Citing Articles (570) | PDF | Export Citation



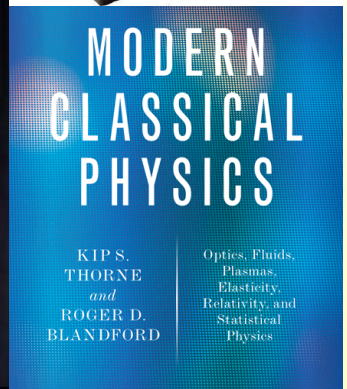
Multipole expansions of gravitational radiation*†

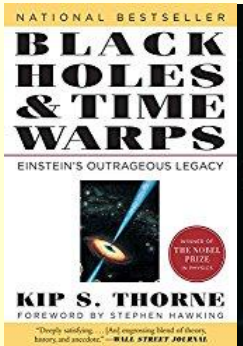
Kip S. Thorne

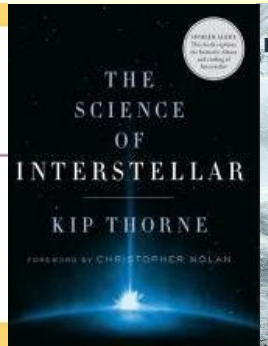
W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125 and Center for Radiophysics and Space Research, Cornell University, Ithaca, New York 14853

This paper brings together, into a single unified notation, the multipole formalisms for gravitational radiation which various people have constructed. It also extends the results of previous workers. More specifically:

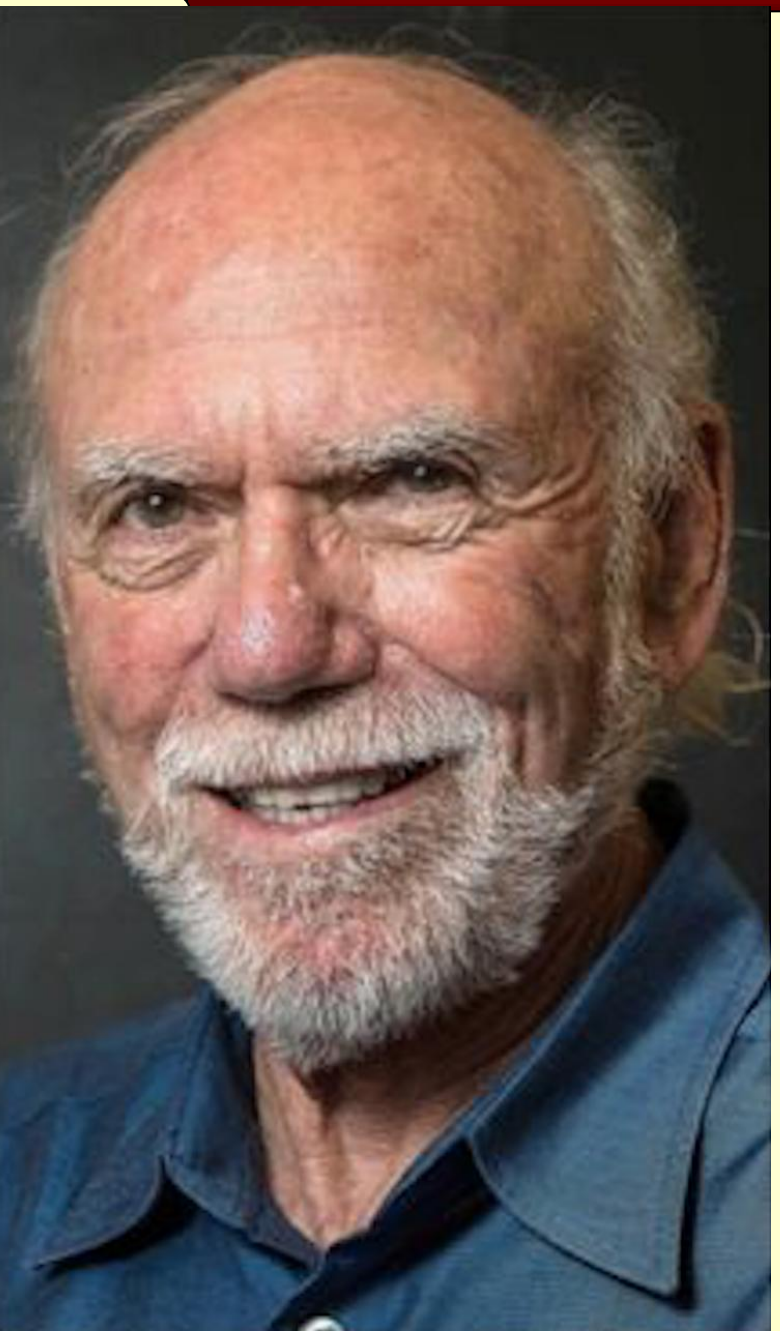
Part One of this paper reviews the various scalar, vector, and tensor spherical harmonics used in the general relativity literature—including the Regge–Wheeler harmonics, the symmetric, trace-free (“STF”) tensors of Sachs and Pirani, the Newman–Penrose spin-weighted harmonics, and the Mathews–Zerilli Clebsch–Gordan-coupled harmonics—which include “pure-orbital” harmonics and “pure-spin” harmonics. The relationships between the various harmonics are presented. Part One then turns attention to gravitational radiation. The concept of “local wave zone” is introduced to facilitate a clean separation of “wave generation” from “wave propagation.” The generic radiation field in the local wave zone is







Fizikai Nobel-díj 2017: Barry Barish



Született: 1936. január 29, Nebraska
PhD: Berkeley 1962 (Kísérleti nagyenergiás részecskefizika témában)
1963 óta a Caltech professzora, jelenleg emeritus

a LIGO Laboratórium igazgatója (1994 – 2005)
a kétfázisú LIGO kezdeményezője (eredeti LIGO 2002-2010, Advanced LIGO 2015-től)
LIGO Tudományos Kollaboráció megalakítója (1997)
LIGO megépítése (1999 – 2002)
első gravitációs hullám keresések (2002 – 2005)

Egyéb tevékenységek:

Az 1980-as években a MACRO (Monopoles, Astrophysics and Cosmic Ray Observatory) igazgatója – mágneses monopólust nem, neutrínóoszcillációkra utaló jeleket találtak

2005-2013, a tervezett ILC (International Linear Collider) igazgatója – az LHC a Higgs részecskén kívül mást nem talált, ezért veszélyben a projekt

A LIGO Tudományos Kollaboráció

LIGO

LIGO Scientific Collaboration

LSC

Abilene Christian University
Albert-Einstein Institut
American University
Andrews University
Bellevue College
California Institute of Technology
California State Univ., Fullerton
California State Univ., Los Angeles
Canadian Inst. Th. Astrophysics
Carleton College
Chinese University of Hong Kong
College of William and Mary
Colorado State University
Columbia U. in the City of New York
Cornell University
Embry-Riddle Aeronautical Univ.
Eötvös Loránd University
Georgia Institute of Technology
Goddard Space Flight Center
GW-INPE, Sao Jose Brasil
Hillsdale College
Hobart & William Smith Colleges
IAP – Nizhny Novogorod
IIP-UFRN
IndIGO
Kenyon College
Korean Gravitational-Wave Group
Louisiana State University
Marshall Space Flight Center
Montana State University
Montclair State University
Moscow State University
National Tsing Hua University

NCSARG – Univ. of Illinois, Urbana-Champaign
Northwestern University
Penn State University
Rochester Institute of Technology
Sonoma State University
Southern University
Stanford University
Syracuse University
Texas Tech University
Trinity University
Tsinghua University
U. Montreal / Polytechnique
University of Brussels
University of Chicago
University of Florida
University of Maryland
University of Michigan
University of Minnesota
University of Mississippi
University of Oregon
University of Sannio
University of Szeged
University of Texas Rio Grande
University of the Balearic Islands
University of Tokyo
University of Washington
University of Washington Bothell
University of Wisconsin – Milwaukee
USC – Information Sciences Institute
Washington State University – Pullman
West Virginia University
Whitman College

LIGO Laboratory: California Institute of Technology, Massachusetts Institute of Technology, LIGO Hanford Observatory, LIGO Livingston Observatory

Australian Consortium for Interferometric Gravitational Astronomy (ACIGA):
Australian National University, Charles Sturt University, Monash University, Swinburne University, University of Adelaide, University of Melbourne, University of Western Australia

German/British Collaboration for the Detection of Gravitational Waves (GEO600):
Albert-Einstein Institut, Hannover, Cardiff University, King's College University of London, Leibniz Universität Hannover, University of Birmingham, University of Cambridge, University of Glasgow, University of Hamburg, University of Sheffield, University of Southampton, University of Strathclyde, University of the West of Scotland, University of Zurich

A LIGO Tudományos Kollaboráció által elnyert kitüntetések

2016

Special Breakthrough Prize in Fundamental Physics

BREAKTHROUGH PRIZE

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SPECIAL BREAKTHROUGH PRIZE IN FUNDAMENTAL PHYSICS AWARDED FOR DETECTION OF GRAVITATIONAL WAVES 100 YEARS AFTER ALBERT EINSTEIN PREDICTED THEIR EXISTENCE

Selection Committee of previous Breakthrough Prize winners recognizes contributors to experiment recording waves from two black holes colliding over a billion light years away.

$3 million prize shared between LIGO founders Ronald W. P. Drever, Kip S. Thorne and Rainer Weiss and 1012 contributors to the discovery.

Gruber Cosmology Prize

liscovery-team

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COSMOLOGY

2016 Cosmology Prize

The LIGO Discovery Team

Laureate Profile

The 2016 Gruber Prize in Cosmology honors Ronald Drever, Kip Thorne, and Rainer Weiss, along with the entire Laser Interferometer Gravitational-Wave Observatory (LIGO) discovery team and the Virgo Collaboration for the first detection of gravitational waves. That observation, which came in September 2015, not only validated a key prediction of Einstein's general theory of relativity but provided a first foray into the strong-gravity regime of that theory—the part that covers phenomena with the strongest gravitational effects in the universe.

2017

Royal Astronomical Society RAS Group Achievement Award 'A'

https://www.ras.org.uk/images/stories/awards/winners/2017/LIGO%202017%20Group%20Achievement%20Award%20A.pdf

Citation for the 2017 RAS Group Achievement Award 'A'
The Laser Interferometer Gravitational-Wave Observatory (LIGO) team

The Group Achievement Award in astronomy is given to the Laser Interferometer Gravitational-Wave Observatory (LIGO) team.

The direct detection of gravitational waves by the LIGO detectors situated in Livingston and Hanford in the US is an epochal event in physics and astronomy. This extraordinary achievement is the culmination of many decades of work, including US-based instruments

Rossi Prize of the American Astronomical Society

https://aas.org/posts/news/2017/01/head-rossi-prize-goes-gabriela-gonzález-ligo-team

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HEAD Rossi Prize Goes to Gabriela González & LIGO Team

Wednesday, January 25, 2017 - 13:38

Adapted from a joint HEAD-LSU press release:

The 2017 Rossi Prize has been awarded to Gabriela González and the LIGO Scientific Collaboration for the first direct detections of gravitational waves, for the discovery of merging black hole binaries, and beginning the new era of gravitational-wave astronomy.

Princess of Asturias Award for Technical and Scientific Research

http://www.fpa.es/en/princess-of-asturias-awards/laureates/2017-rainer-weiss-kip-s-thorne-barry-c-barish-and-ligo-scientific-collaboration.html?especifica=0&idCategoria

Fundación Princesa de Asturias

PRINCESS OF ASTURIAS FOUNDATION | HM THE KING | PRINCESS OF ASTURIAS AWARDS | COMMUNICATION

PRINCESS OF ASTURIAS AWARD FOR TECHNICAL & SCIENTIFIC RESEARCH 2017

LIST OF LAUREATES

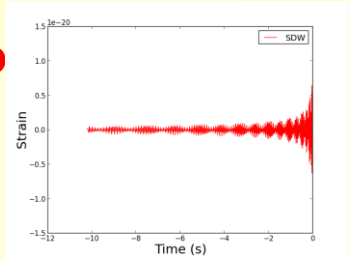
RAINER WEISS, KIP S. THORNE, BARRY C. BARISH AND LIGO SCIENTIFIC COLLABORATION

PRINCESS OF ASTURIAS AWARD FOR TECHNICAL & SCIENTIFIC RESEARCH 2017

LIGO / gravitációshullám-kutatások a Szegedi Tudományegyetemen

1. Gravitációs hullámok közvetlen keresése: **Tápai M. + PyCBC csopo**

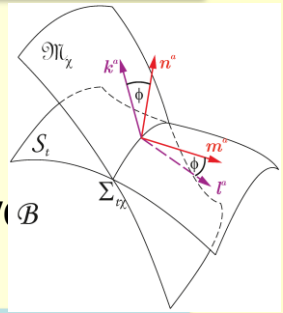
- NASA Gravitational Astrophysics Laboratory
- California Institute of Technology
- Abilene Christian University
- Syracuse University
- Cardiff University
- Albert Einstein Institute, Hannover



2. Módosított gravitációelméletek tesztelése gravitációs hullámokkal

Gergely Á.L., Racskó B., Gergely C. + TestingGR csoport

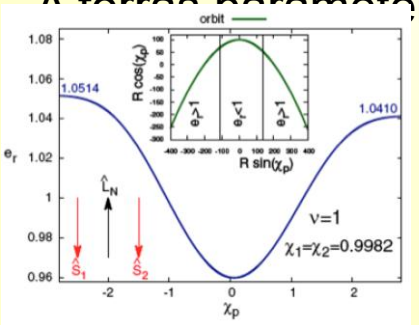
- Fényszerű lökéshullámok terjedése Brans-Dicke elméletekben
- Brans-Dicke elméletekre adódó kényszerek gravitációs hullám megfigy
- Feketelyuk-perturbációk stabilitása skalár-tenzor elméletekben

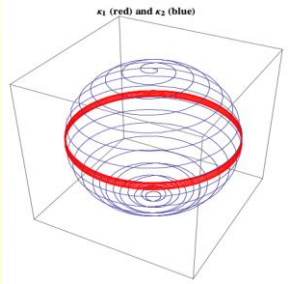


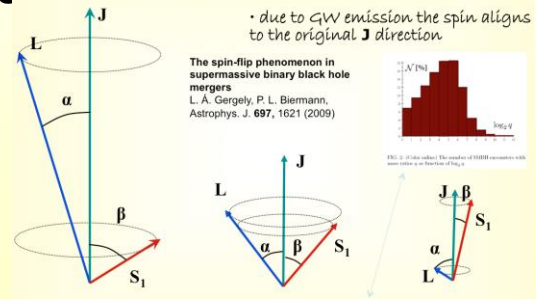
3. Gravitációs hullámformák és feketelyuk-kettősök dinamikája

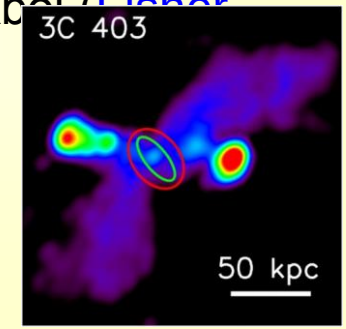
Gergely Á.L., Keresztes Z., Tápai M., Kövér K. + P.L. Biermann (Inst. Radioastronomie Bonn)

- Relativisztikus pályamódosulások (kaméleon pályák), spin flip-flop effektus
- Spin-flip effektus → magyarázat az X-alakú rádiógalaxiskokra
- A forrás paramétereinek meghatározása a gravitációs hullámformákból (Fisher









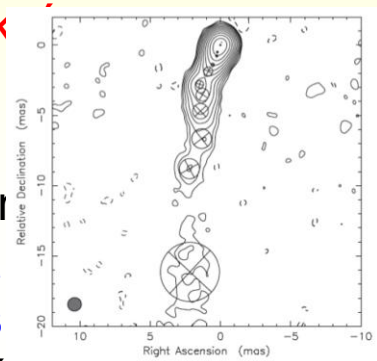
Hodges-Kluck Reynolds, 2011

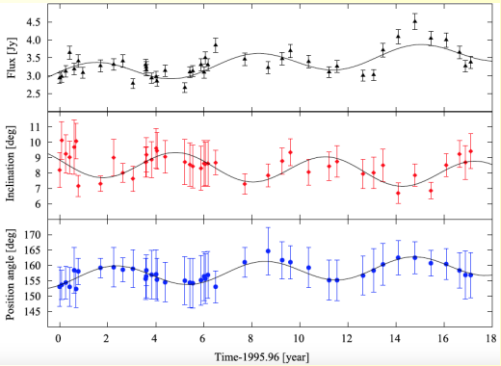
Többeshírnök-asztrofizikai kutatások a Szegedi Tudományegyetemen

Gravitációs hullámok / elektromágneses sugárzás minden frekvencián / nagyenergiás részecskék

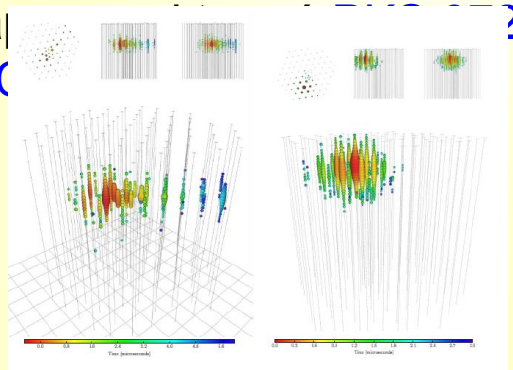
4. Feketelyuk-összeolvadás előjelei VLBI adatokban:
   Kun E., Gergely Á.L. + Gabányi K ervato
Radioastronomie Bonn)
   + M. Karouzos (Seoul Nat. Univ.)

- Jet-adatok periodicitása a jet-alapı
  feketelyuk-kettős keringése miatt
- Az első feketelyuk-spin detektálás
  (spin-pálya kölcsönhatás kimutatása) az
  S5 1928+738 kvazár jetadataiban





5. Feketelyuk-összeolvadás utózöngéi
   Kun E., Gergely Á.L.
   + P.L. Biermann (Inst. Radioastronom
- A la 23−008 bl
  IceC neutrinó



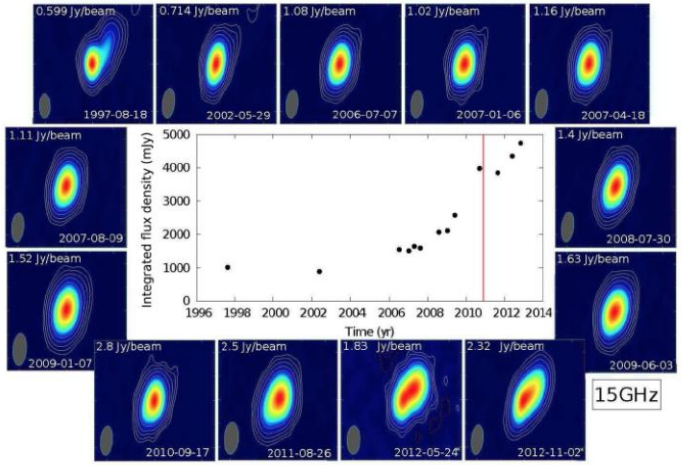


Figure 2. The radio maps of PKS 0723−008 over 12 epochs, represented on logarithmic scale with base 10. They were produced by processing the available VLBA visibilities provided by the MOJAVE team. Iso-flux density contours are in per cent of the peak flux density marked in the left upper corner of the maps. They increase by factors of 1, except the last two epochs (marked by stars), where the contours increase by factors of 2. In the middle, the integrated flux density of the source at 15 GHz is represented as a function of the time. The time of the corresponding neutrino detection (ID5) is indicated by a red vertical line.

Tervezett kutatásaink

NKFI 123996 pályázat
(2017 – 2021)

Gravitációs hullámok és forrásaik az általánosított gravitációelméletek erős tér tartományaiban

Szenior résztvevők:
Gergely Árpád László
Keresztes Zoltán

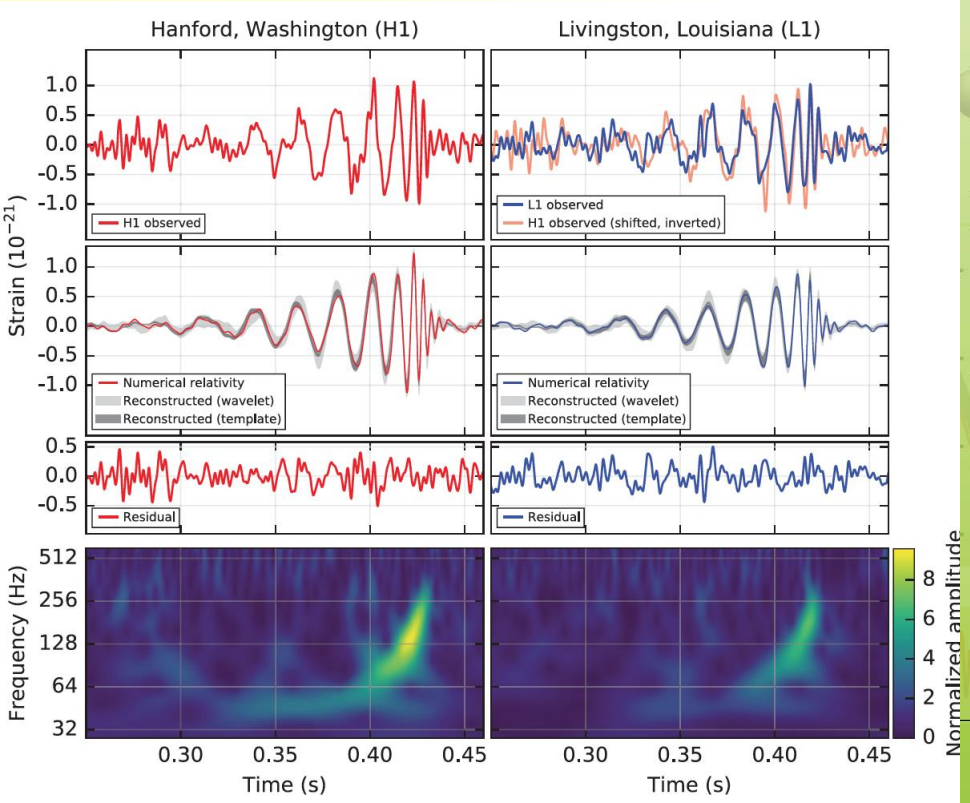
Junior résztvevők:
Kun Emma
Tápai Márton

+ hallgatók

A) Gravitációs hullámok nemlineáris hatásai az erős gravitáció tartományában (geometriai optikai közelítés)
B) A téridő és a gravitációs dinamika 2+1+1 felbontásai
C) Alkalmazásuk gömbszimmetrikus téridők páros szektorú perturbációinak vizsgálatára (dinamika és stabilitás) általánosított gravitációelméletekben
D) Gömbszimmetrikus és hengerszimmetrikus gravitációshullám-téridők analitikus és numerikus vizsgálata általánosított gravitációelméletekben
E) Gravitációshullám-terjedés vizsgálata általánosított gravitációelméletekben (fényszerű felületek menti illesztési feltételek kidolgozása)
F) Sötét anyag modellek és módosított gravitációelméletek tesztelése galaktikus forgásgörbékkel
G) Feketelyuk-kettősök keresése AGN jetek periódikus struktúráiban
H) Advanced LIGO adatainak feldolgozása

A gravitációs hullámok első közvetlen észlelése: GW150914

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



GW150914: FACTSHEET

BACKGROUND IMAGES: TIME-FREQUENCY TRACE (TOP) AND TIME-SERIES (BOTTOM) IN THE TWO LIGO DETECTORS; SIMULATION OF BLACK HOLE HORIZONS (MIDDLE-TOP), BEST FIT WAVEFORM (MIDDLE-BOTTOM)

first direct detection of gravitational waves (GW) and first direct observation of a black hole binary

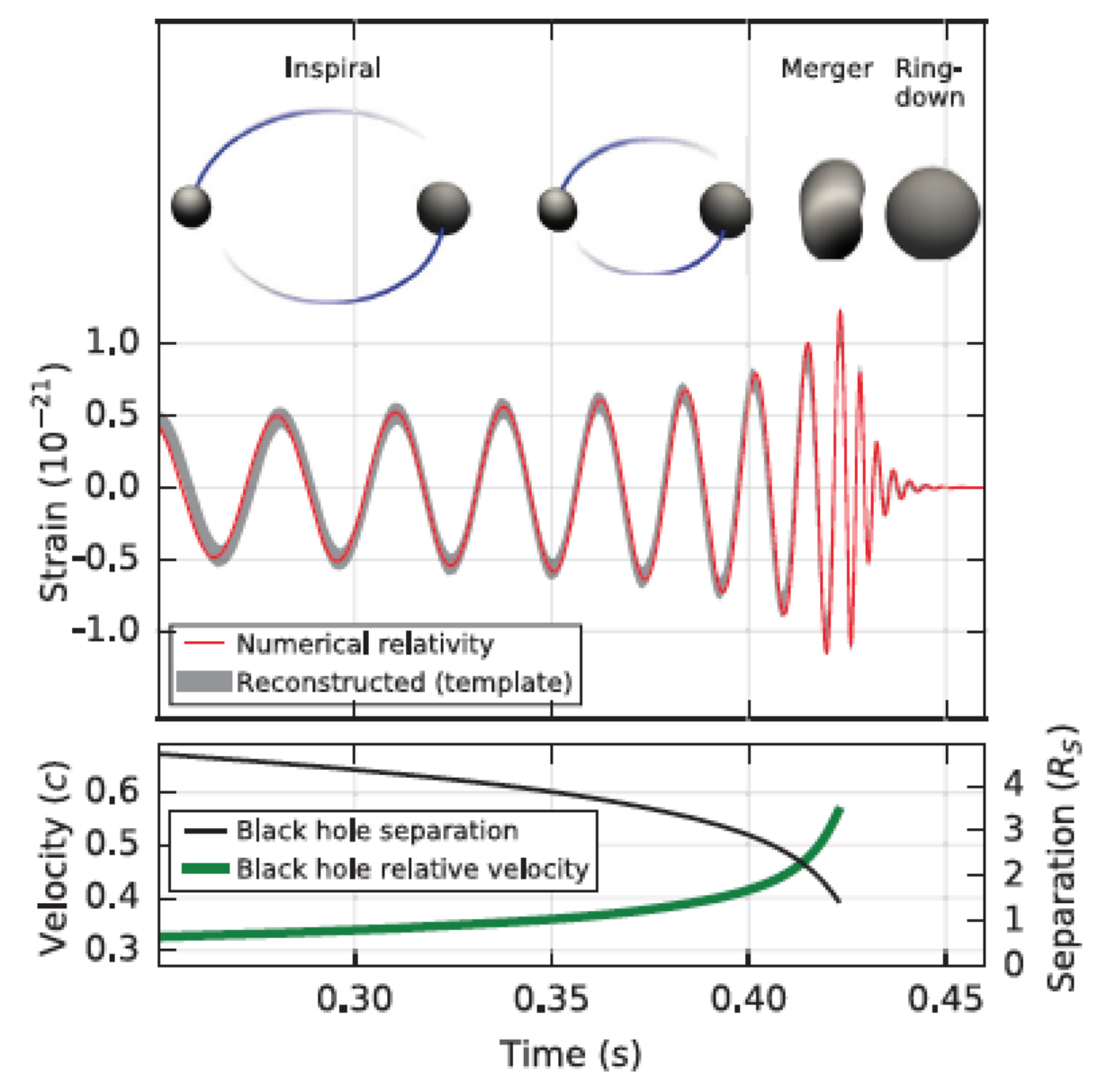
observed by	LIGO L1, H1
source type	black hole (BH) binary
date	14 Sept 2015
time	09:50:45 UTC
likely distance	0.75 to 1.9 Gly 230 to 570 Mpc
redshift	0.054 to 0.136
signal-to-noise ratio	24
false alarm prob.	< 1 in 5 million
false alarm rate	< 1 in 200,000 yr
Source Masses	M⊙
total mass	60 to 70
primary BH	32 to 41
secondary BH	25 to 33
remnant BH	58 to 67
mass ratio	0.6 to 1
primary BH spin	< 0.7
secondary BH spin	< 0.9
remnant BH spin	0.57 to 0.72
signal arrival time delay	arrived in L1 7 ms before H1
likely sky position	Southern Hemisphere
likely orientation resolved to	face-on/off ~600 sq. deg.

duration from 30 Hz	~ 200 ms
# cycles from 30 Hz	~10
peak GW strain	1×10^{-21}
peak displacement of interferometers arms	±0.002 fm
frequency/wavelength at peak GW strain	150 Hz, 2000 km
peak speed of BHs	~ 0.6 c
peak GW luminosity	3.6×10^{56} erg s^{-1}
radiated GW energy	2.5-3.5 M⊙
remnant ringdown freq.	~ 250 Hz
remnant damping time	~ 4 ms
remnant size, area	180 km, 3.5×10^5 km^2
consistent with general relativity?	passes all tests performed
graviton mass bound	$< 1.2 \times 10^{-22}$ eV
coalescence rate of binary black holes	2 to 400 Gpc^{-3} yr^{-1}
online trigger latency	~ 3 min
# offline analysis pipelines	5
CPU hours consumed	~ 50 million (=20,000 PCs run for 100 days)
papers on Feb 11, 2016	13
# researchers	~1000, 80 institutions in 15 countries

Detector noise introduces errors in measurement. Parameter ranges correspond to 90% credible bounds.
Acronyms: L1=LIGO Livingston, H1=LIGO Hanford; Gly=giga lightyear=9.46×10^{12} km; Mpc=mega parsec=3.2 million lightyear, Gpc=10^3 Mpc, fm=femtometer=10^{-15} m, M⊙=1 solar mass=2×10^{30} kg

A gravitációs hullámok első közvetlen észlelése: GW150914

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



29 és 36 naptömegű fekete lyukak összeolvadása → 0,05 sec alatt 3 naptömegnyi energia szabadult fel gravitációs hullámok formájában

=

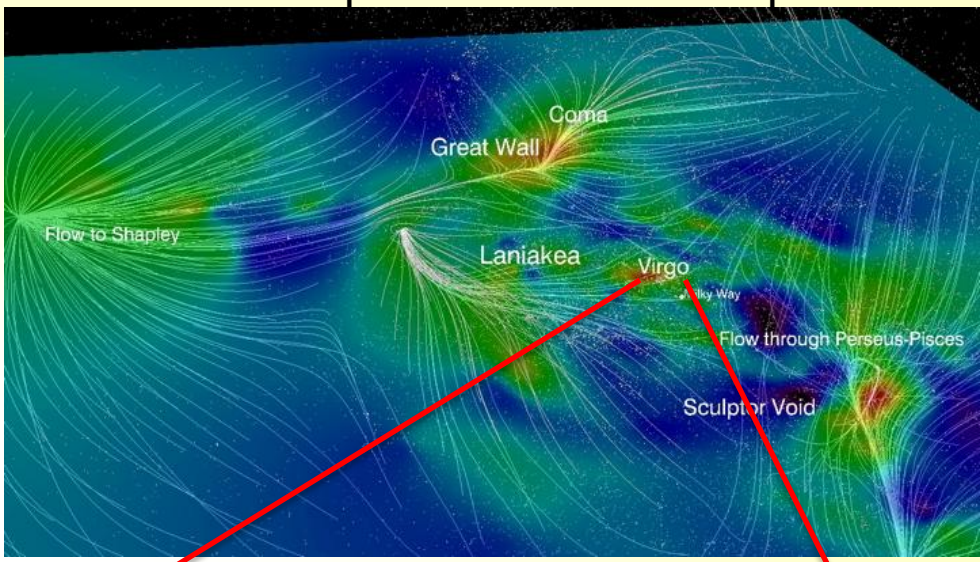
a Paksi Atomerőmű 10^{31} évi energiatermelése !

a nagy távolság miatt az Advanced LIGO lézerinterferométereiben a proton méretének ezredrésznyi változását okozta !

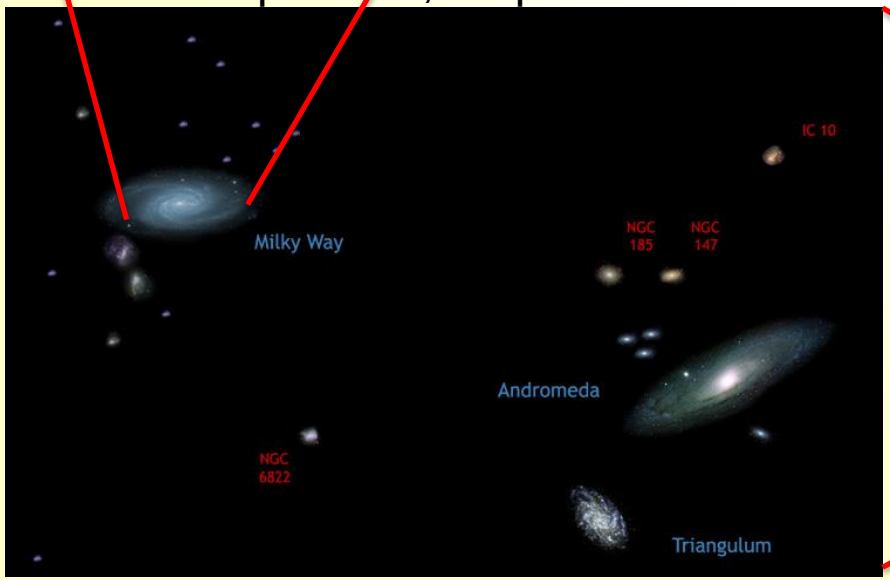
Honnan is jött a GW150914 gravitációs hullám? (230-500 Mpc)

Tejútrendszer ~ 30 kpc

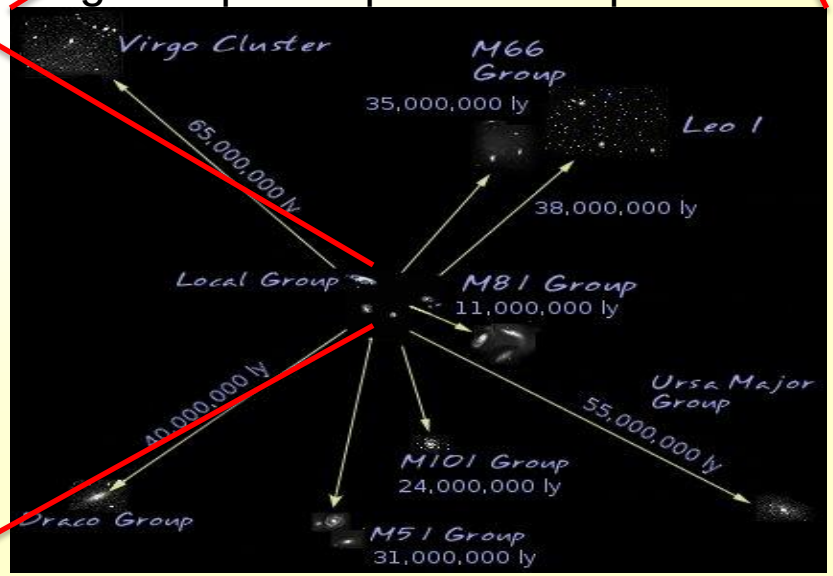
Laniakea szuperklaszter ~ 160 Mpc



Lokális Csoport ~ 3,1 Mpc



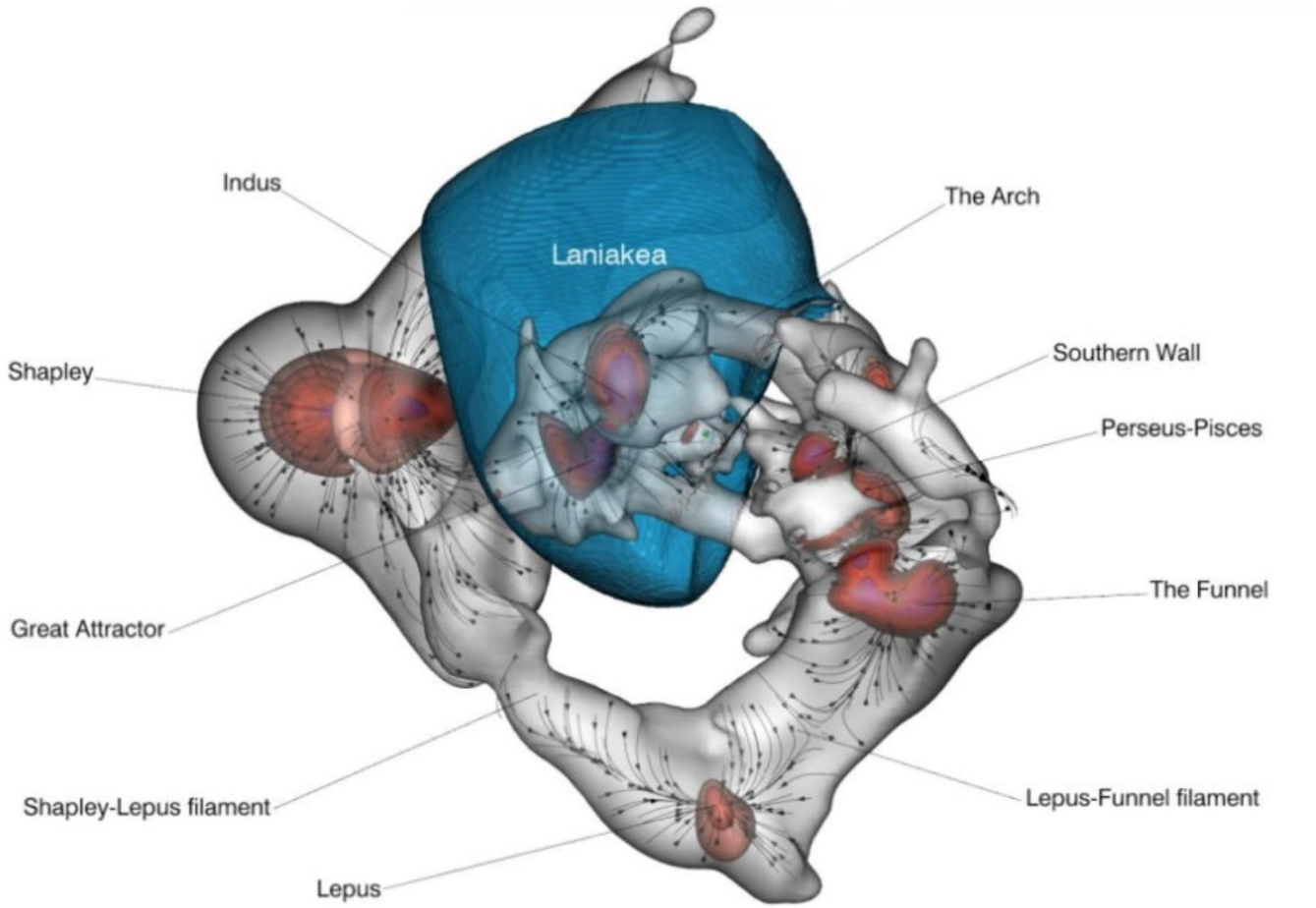
Virgo szupercsoport ~ 33 Mpc



A lokális Univerzum feltérképezésének új módja !

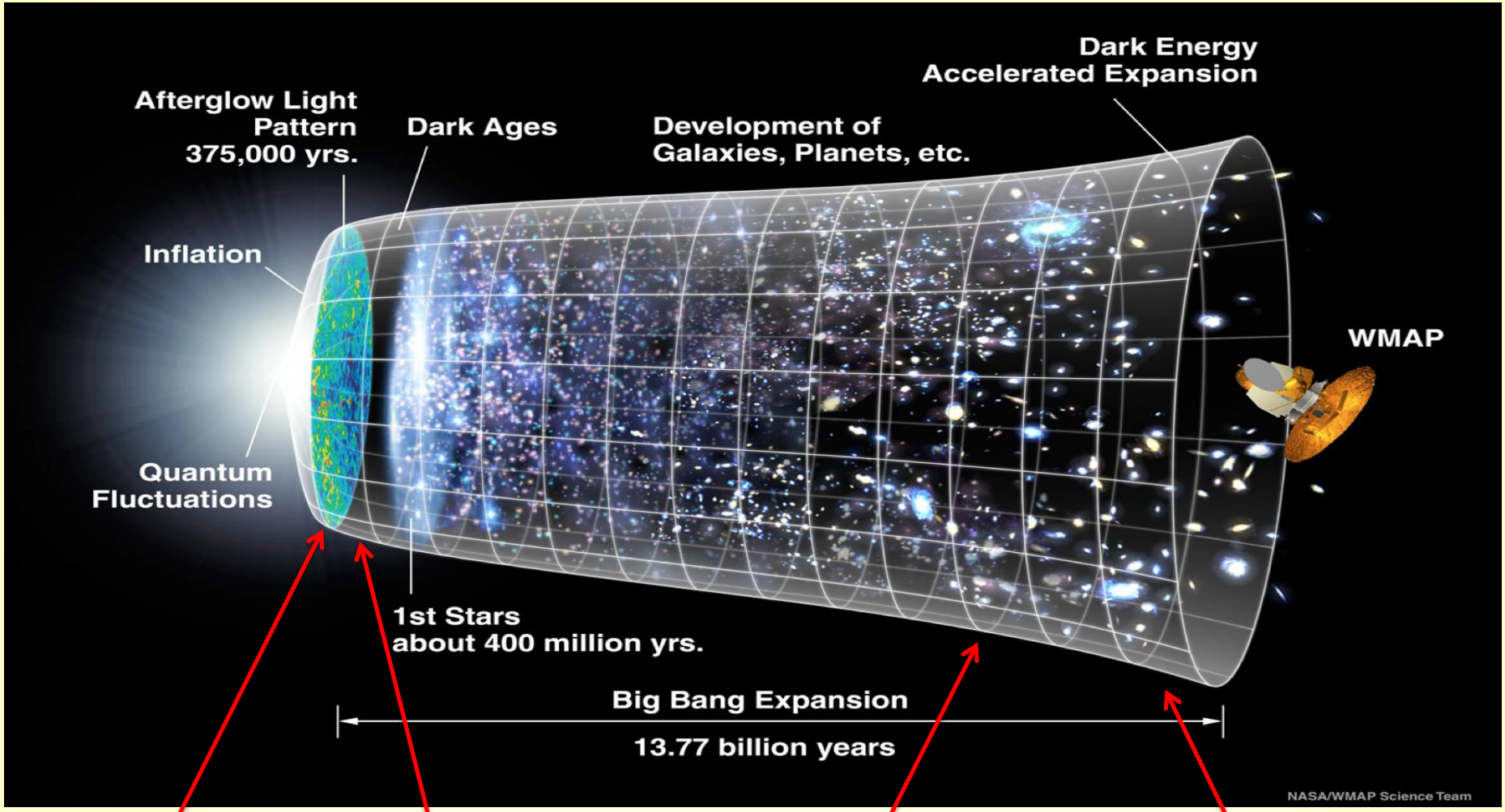
https://pionic.org/motions-of-thousands-of-galaxies-mapped
https://player.vimeo.com/video/206210825?byline=0&badge=0&portrait=0&title=0&api=1&autoplay=1

Motions Of Thousands Of Galaxies Mapped



The cosmic velocity web is represented by surfaces of knots in red and surfaces of filaments in gray. The black lines with arrows illustrate local velocity flows within filaments and toward knots. The Laniakea Supercluster basin of attraction that includes our Milky Way galaxy is represented by a blue surface. The region being displayed extends across one billion light years. Credit: Daniel Pomarede, Yehuda Hoffman, R. Brent Tully and Helene Courtois. Credit: Daniel Pomarede, Yehuda Hoffman, R. Brent Tully, Helene Courtois

Honnan is jött a GW150914 gravitációs hullám? (230-500 Mpc)



Ősrobbanás
(13,7 milliárd év)

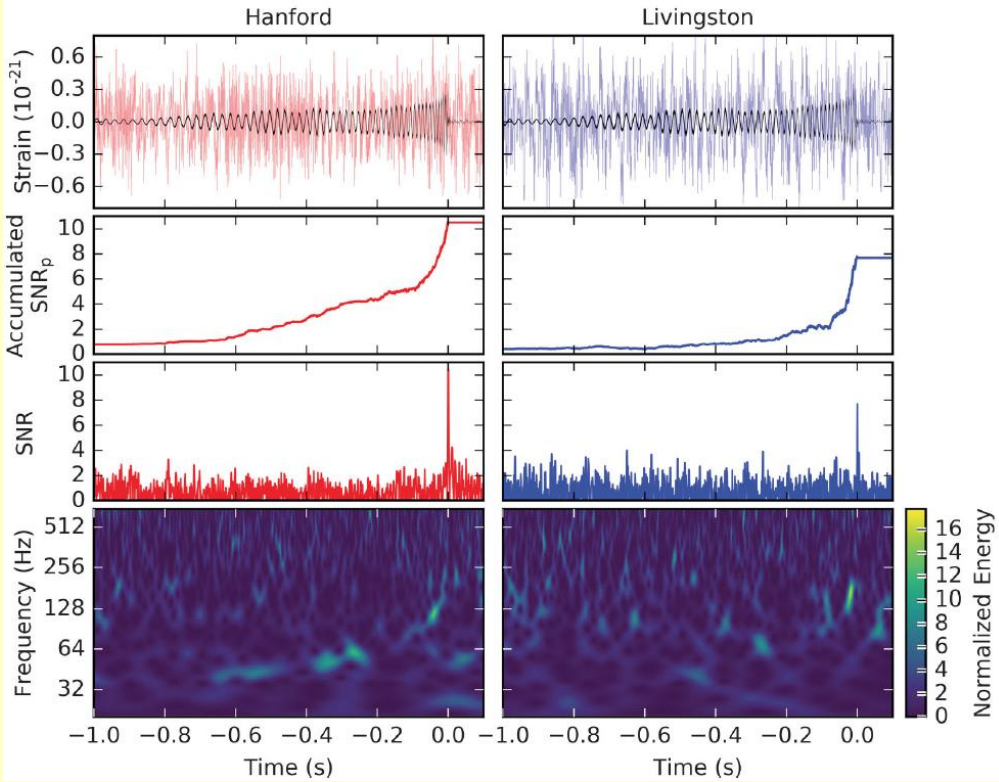
Sötét Korszak
innen fény nem,
de gravitációs hullám
érkezhet hozzánk!!

elkezdődik a
gyorsuló tágulás
~ z=0,4 (1700 Mpc)

kb. innen érkezett
~ z=0,1 (1,3 milliárd év)
a Földön kialakul
az oxigénnel telített
légkör

Második közvetlen észlelés: GW151226

Phys. Rev. Lett.
116, 241103 (2016)

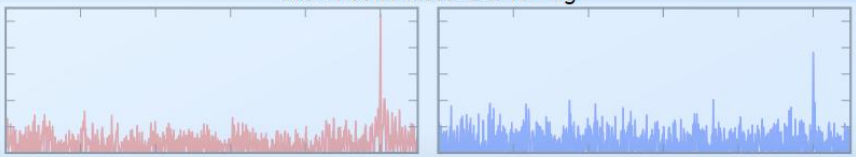


GW151226: FACTSHEET

BACKGROUND IMAGES: TIME-FREQUENCY TRACE (TOP) AND SIGNAL-TO-NOISE RATIO TIME-SERIES (BOTTOM) IN THE TWO LIGO DETECTORS; EXAMPLE WAVEFORM (MIDDLE)

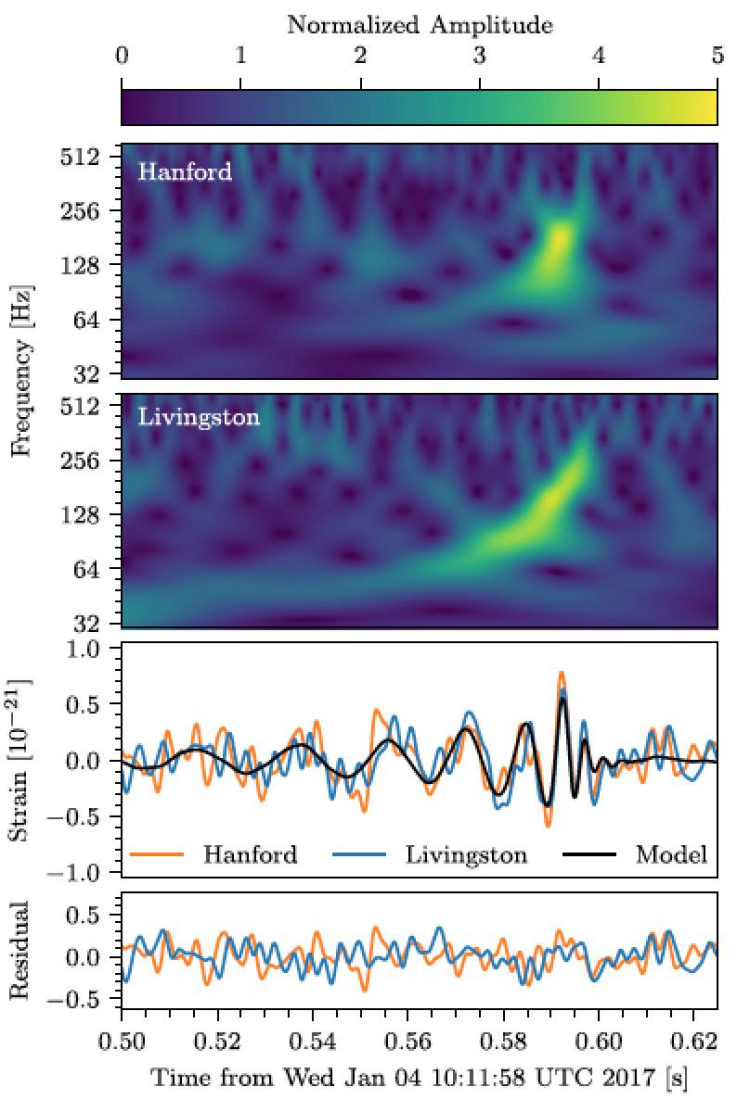
observed by	LIGO L1, H1	duration from 35 Hz	~1 s
source type	black hole (BH) binary	# cycles from 35 Hz	~55
date	26 Dec 2015	signal arrival time delay	arrived in H1 1 ms after L1
time	03:38:53 UTC		
distance	250 to 620 Mpc	peak GW strain	~ 3.4 x 10^{-22}
redshift	0.05 to 0.13	peak displacement of interferometers arms	~ ±0.7 am
signal-to-noise ratio	13		
false alarm prob.	~ 1 in 10 million	frequency/wavelength at peak GW strain	420 Hz, 710 km
Source Masses	M⊙	peak speed of BHs	~ 0.6 c
total mass	20 to 28	peak GW luminosity	2 to 4 x 10^{56} erg s^{-1}
primary BH	11 to 23	radiated GW energy	0.8-1.1 M⊙
secondary BH	5 to 10	remnant ringdown freq.	~ 750 Hz
remnant BH	19 to 27		
mass ratio	> 0.28	remnant damping time	~ 1.3 ms
spin of one of the black holes	> 0.2	remnant size, area	60 km, 3.5 x 10^4 km^2
remnant BH spin	0.7 to 0.8	online trigger latency	~ 67 s
resolved to	~850 sq. deg.	# offline analysis pipelines	2

Parameter ranges correspond to 90% credible bounds. Acronyms: L1/H1=LIGO Livingston/Hanford; Mpc=mega parsec=3.2 million lightyear, am=attometer=10^{-18} m, M⊙=1 solar mass=2 x 10^{30} kg



Harmadik közvetlen észlelés: GW170104

Phys. Rev. Lett.
118, 221101 (2017)



GW170104: FACTSHEET

Background Images: time-frequency trace (top), H1 and L1 time series and maximum-likelihood binary black hole model (middle top), residuals between data and best-fit model (middle bottom), reconstructed waveforms from wavelet and binary black hole analyses (bottom)

observed by	LIGO L1, H1
source type	black hole (BH) binary
date	04 Jan 2017
time	10:11:58.6 UTC
signal-to-noise ratio	13
false alarm rate	< 1 in 70,000 years
probability of astrophysical origin	> 0.99997
distance	1.6 to 4.3 billion light-years
redshift	0.10 to 0.25
total mass	46 to 57 $M_\odot$
primary BH mass	25 to 40 $M_\odot$
secondary BH mass	13 to 25 $M_\odot$
mass ratio	0.36 to 0.94
remnant BH mass	44 to 54 $M_\odot$
remnant BH spin	0.39 to 0.7
remnant size (effective radius)	123 to 150 km
remnant area	1.9 to 2.8 x 10^5 km^2
effective spin parameter	-0.42 to 0.09
effective precession spin parameter	unconstrained

duration from 30 Hz	~ 0.25 to 0.31 s
# of cycles from 30 Hz	~ 14 to 16
signal arrival time delay	arrived at H1 3 ms before L1
credible region sky area	1200 sq. deg.
peak GW strain	~ 5 x 10^{-22}
peak displacement of interferometer arm	~ ± 1 am
frequency at peak GW strain	160 to 199 Hz
wavelength at peak GW strain	1510 to 1880 km
peak GW luminosity	1.8 to 3.8 x 10^{56} erg s^{-1}
radiated GW energy	1.3 to 2.6 $M_\odot$
remnant ringdown freq.	297 to 373 Hz
remnant damping time	2.5 to 3.2 ms
consistent with general relativity?	passes all tests performed
graviton mass combined bound	≤ 7.7 x 10^{-23} eV/c^2
evidence for dispersion of GWs	none

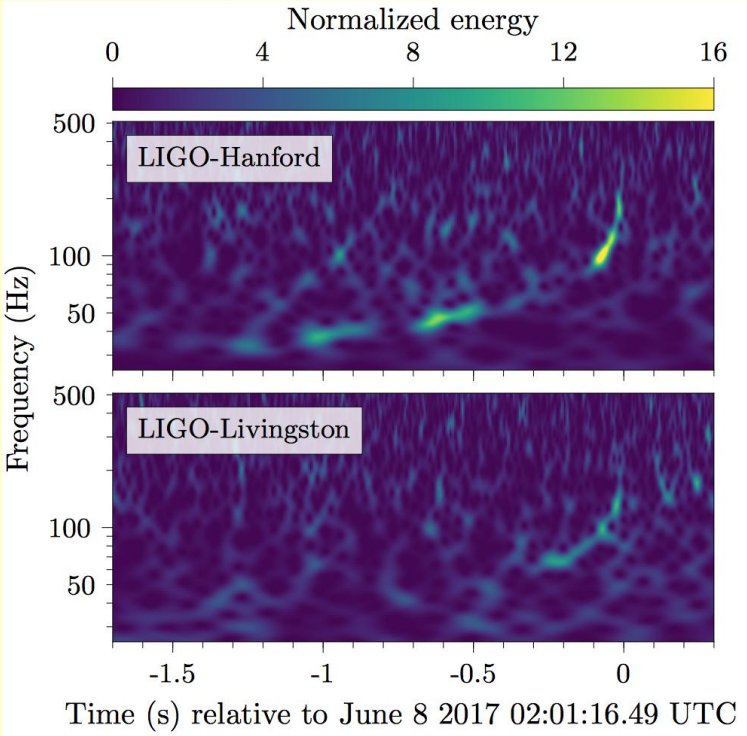
Parameter ranges correspond to 90% credible intervals.

Acronyms:

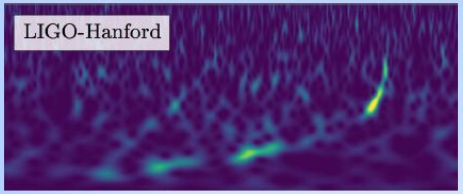
L1/H1=LIGO Livingston/Hanford, am=attometer=10^{-18} m, $M_\odot$=1 solar mass=2 x 10^{30} kg

Negyedik közvetlen észlelés: GW170608

Phys. Rev. Lett.
119, 141101 (2017)

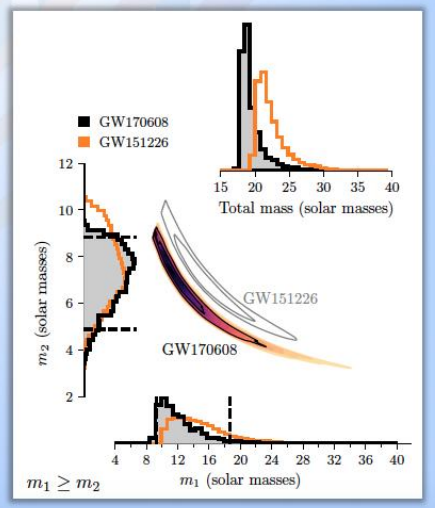


GW170608 FACTSHEET



observed by	H, L
source type	black hole (BH) binary
date	08 June 2017
time of merger	02:01:16 UTC
signal-to-noise ratio	13
false alarm rate	< 1 in 3 000 years
distance	0.7 to 1.5 billion light-years
redshift	0.04 to 0.1
total mass	18 to 24 $M_\odot$
primary BH mass	9 to 19 $M_\odot$
secondary BH mass	5 to 9 $M_\odot$
mass ratio	0.3 to 1.0
remnant BH mass	17 to 23 $M_\odot$
remnant BH spin	0.64 to 0.72
remnant size (effective radius)	47 to 63 km
remnant area	2.7 to 5.0 × 10^4 km^2
effective spin parameter	-0.01 to 0.30
effective precession spin parameter	unconstrained
peak GW luminosity	1.8 to 3.9 × 10^{56} erg s^{-1}
radiated GW energy	0.68 to 0.91 $M_\odot c^2$

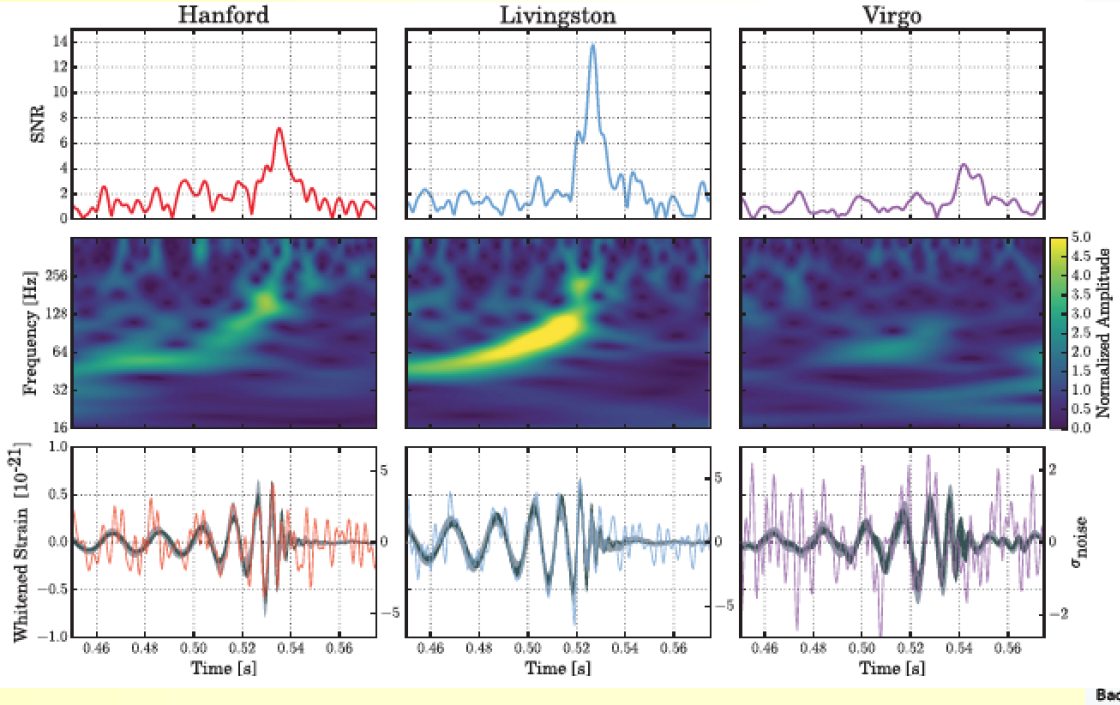
duration from 30 Hz	~ 2 s
# of GW cycles from 30 Hz	~ 100
signal arrival time delay	arrived at H ~ 7 ms before L
HL sky area†	~ 520 deg^2
peak GW strain (10^{-22})	~ 4 (H), 3 (L)
peak stretch of interferometer arm	~ ± 0.8 am (H), 0.6 am (L)
frequency at peak GW strain	453 to 610 Hz
wavelength at peak GW strain	492 to 662 km
remnant ringdown frequency	745 to 1013 Hz
remnant damping time	1.0 to 1.4 ms
consistent with general relativity?	passes all tests performed



Images: time-frequency traces (top), mass distributions (bottom right)
GW=gravitational wave, $M_\odot$=1 solar mass=2x10^{30} kg, am=attometer (10^{-18} m), H/L=LIGO Hanford/Livingston
Parameter ranges are 90% credible intervals.
†90% credible region

Ötödik közvetlen, első hármas észlelés: GW170814

Phys. Rev. Lett.
119, 141101 (2017)

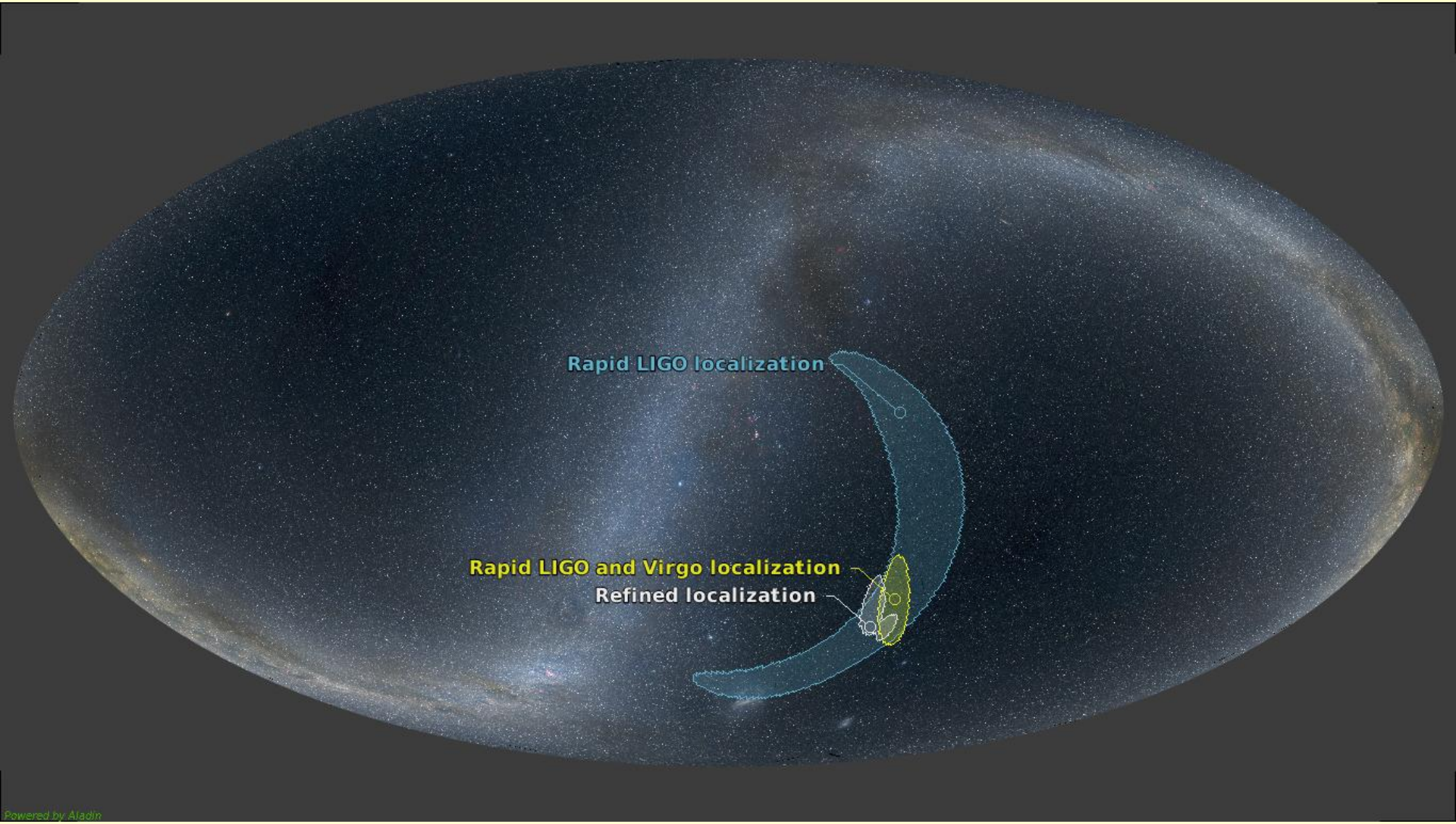


GW170814: FACTSHEET

observed by	H1, L1, V1	duration from 30 Hz	~ 0.26 to 0.28 s
source type	black hole (BH) binary	# of cycles from 30 Hz	~ 15 to 16
date	14 Aug 2017	credible region sky area (with V1)	60 deg^2
time	10:30:43 UTC	credible region sky area (without V1)	1160 deg^2
online trigger latency	~ 30 s	latitude, longitude (at time of arrival)	45° S, 73° W
signal arrival time delay	at L1 8 ms before H1 and 14 ms before V1	sky location	in direction of Eridanus constellation
signal-to-noise ratio	18	*RA, Dec	03^h11^m, -44°57^m
false alarm rate		Peak GW strain (10^{-22}) (H1, L1, V1)	~ 6, 6, 5
robability of noise ducing V1 SNR peak	0.3%	peak stretching of interferometer arm (H1, L1, V1)	~ ± 1.2, 1.2, 0.8 am
distance	1.1 to 2.2 billion light-years	frequency at peak GW strain	155 to 203 Hz
redshift	0.07 to 0.14	wavelength at peak GW strain	1480 to 1930 km
total mass	53 to 59 $M_\odot$	peak GW luminosity	3.2 to 4.2 × 10^{56} erg s^{-1}
primary BH mass	28 to 36 $M_\odot$	radiated GW energy	2.4 to 3.1 $M_\odot c^2$
econdary BH mass	21 to 28 $M_\odot$	remnant ringdown freq.	312 to 345 Hz
mass ratio	0.6 to 1.0	remnant damping time	3.1 to 3.6 ms
emnant BH mass	51 to 56 $M_\odot$	consistent with general relativity?	passes all tests performed
remnant BH spin	0.65 to 0.77	evidence for dispersion of GWs	none
remnant size (effective radius)	139 to 153 km		
remnant area	2.4 to 2.9 x 10^5 km^2		
ctive spin parameter	-0.06 to 0.18		
fective precession spin parameter	unconstrained		

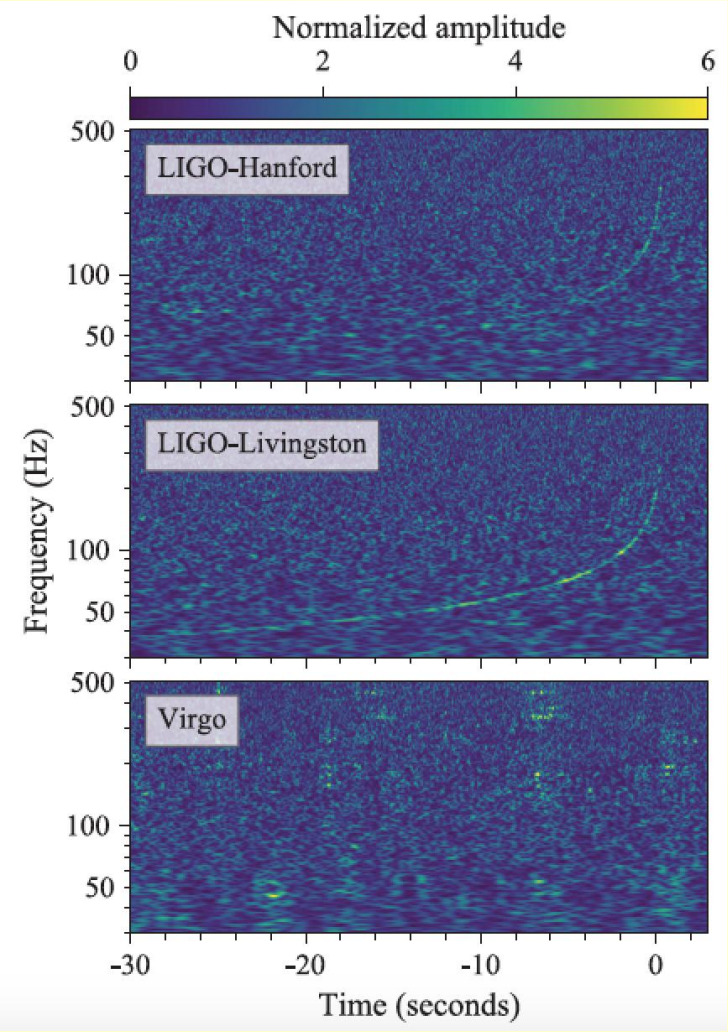
Parameter ranges correspond to 90% credible intervals.
L1/H1=LIGO Livingston/Hanford, V1=Virgo, am=attometer=10^{-18} m, $M_\odot$=1 solar mass=2 x 10^{30} kg
Background Images (H1, L1, V1 from left to right): time-frequency trace (top), sky maps (middle), and time series with reconstructed waveforms from modeled and un-modeled searches (bottom)
* Maximum a Posteriori estimates

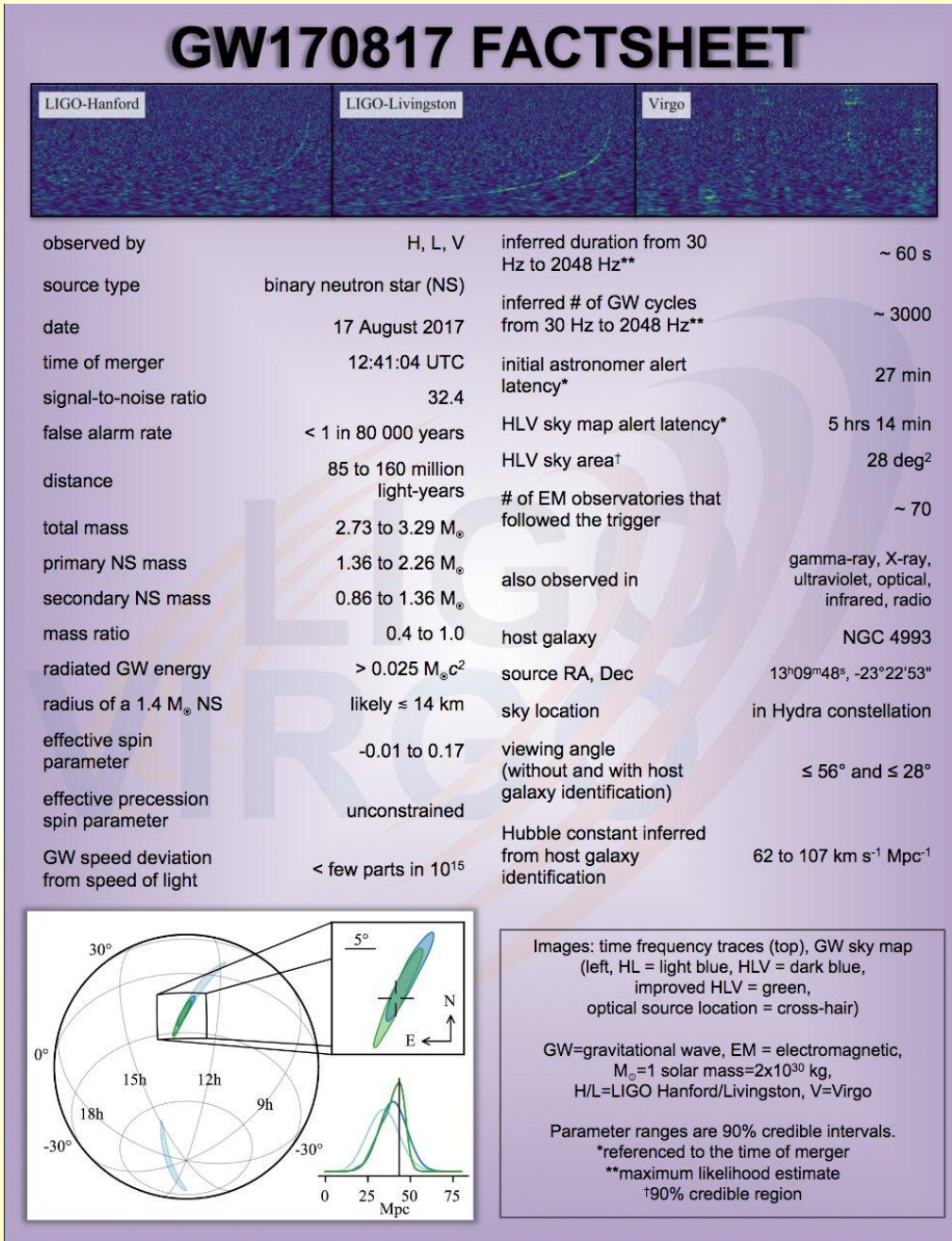
A harmadik detektor szerepe a lokalizációban



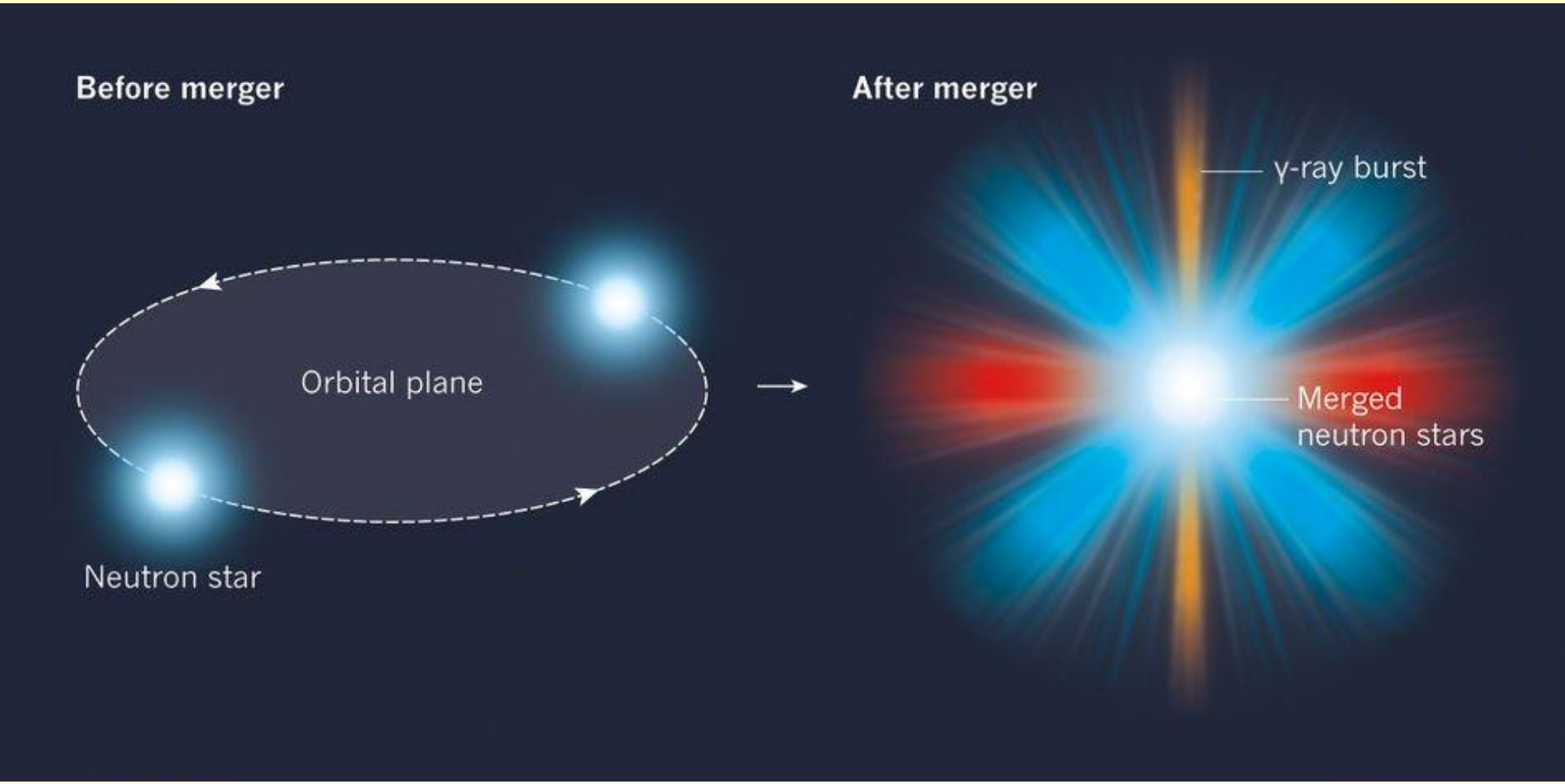
Hatodik közvetlen, első neutroncsillag-kettős összeolvadás észlelés: GW170817

Phys. Rev. Lett.
119, 161101 (2017)

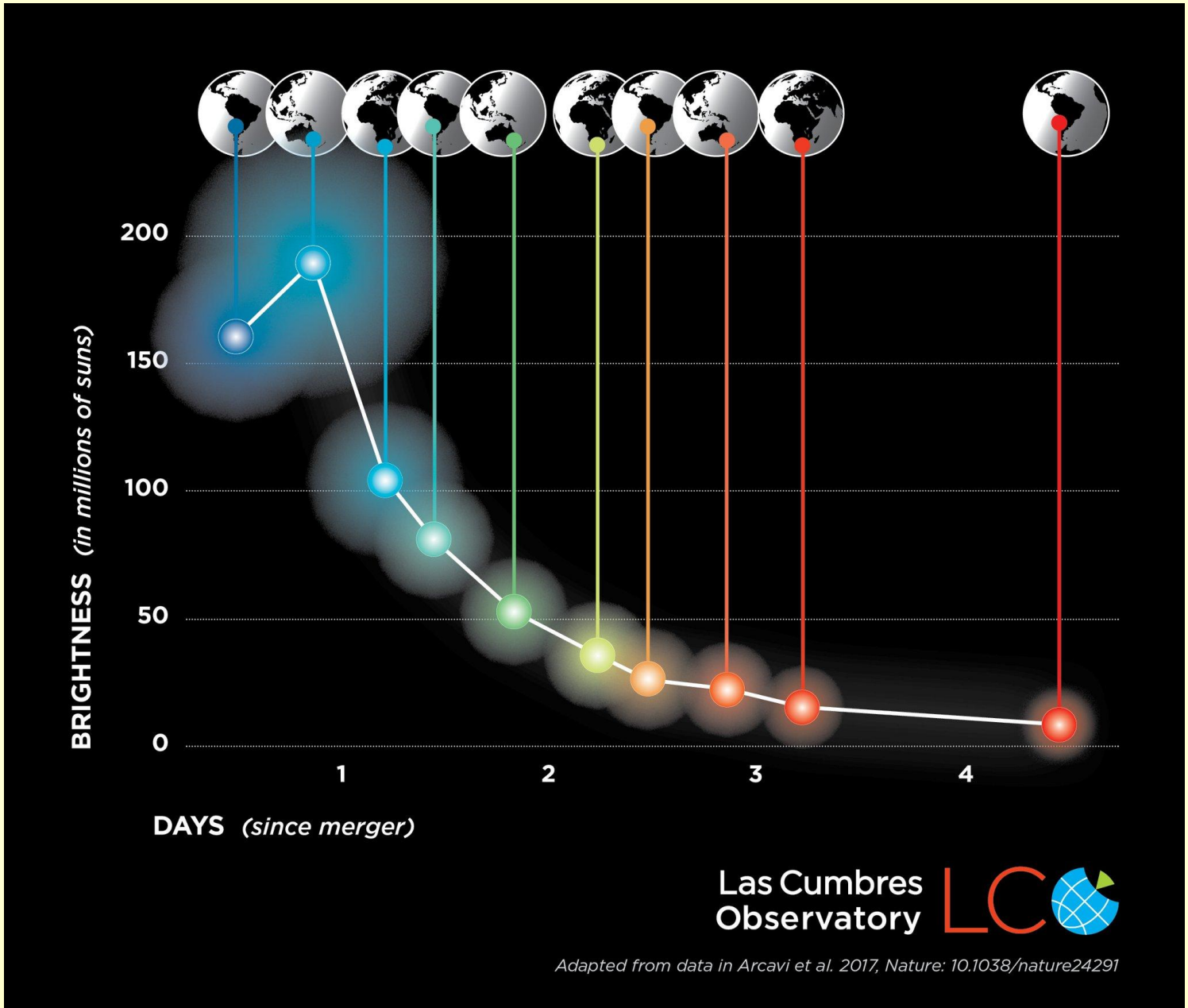




GW170817 keletkezése



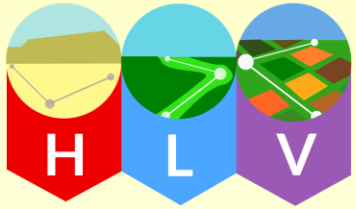
GW170817 maradványa: kilonóva



GW170817

Binary neutron star merger

A LIGO / Virgo gravitational wave detection with associated electromagnetic events observed by over 70 observatories.



Distance
130 million light years

Discovered
17 August 2017

Type
Neutron star merger

12:41:04 UTC
A gravitational wave from a binary neutron star merger is detected.

gravitational wave signal
Two neutron stars, each the size of a city but with the at least the mass of the sun, collided with each other.

gamma ray burst
A short gamma ray burst is an intense beam of gamma ray radiation which is produced just after the merger.

+ 2 seconds
A gamma ray burst is detected.

kilonova
Decaying neutron-rich material creates a glowing kilonova, producing heavy metals like gold and platinum.

+10 hours 52 minutes
A new bright source of optical light is detected in a galaxy called NGC 4993, in the constellation of Hydra.

+11 hours 36 minutes
Infrared emission observed.

+15 hours
Bright ultraviolet emission detected.

+9 days
X-ray emission detected.

radio remnant
As material moves away from the merger it produces a shockwave in the interstellar medium - the tenuous material between stars. This produces emission which can last for years.

+16 days
Radio emission detected.

GW170817 allows us to measure the expansion rate of the universe directly using gravitational waves for the first time, and gives us a new way to infer its age

Detecting gravitational waves from a neutron star merger allows us to find out more about the structure of these unusual objects.

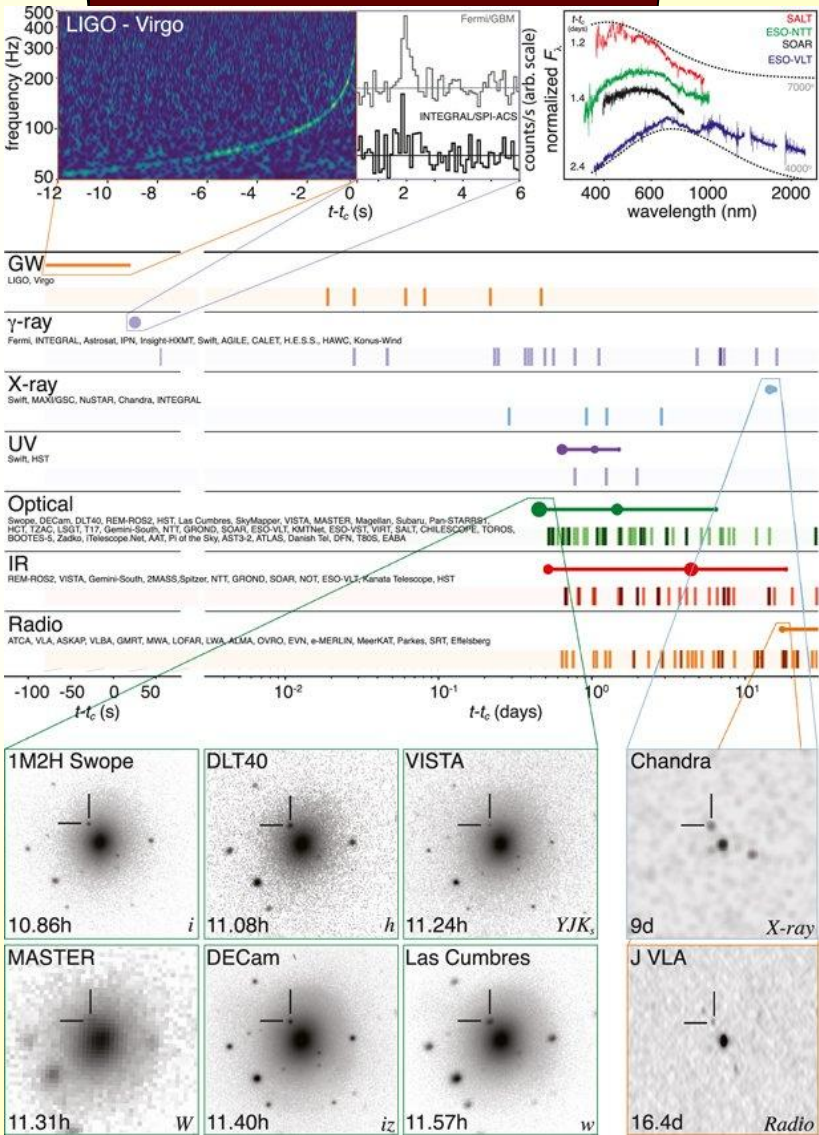
This multimessenger event provides confirmation that neutron star mergers can produce short gamma ray bursts.

Au

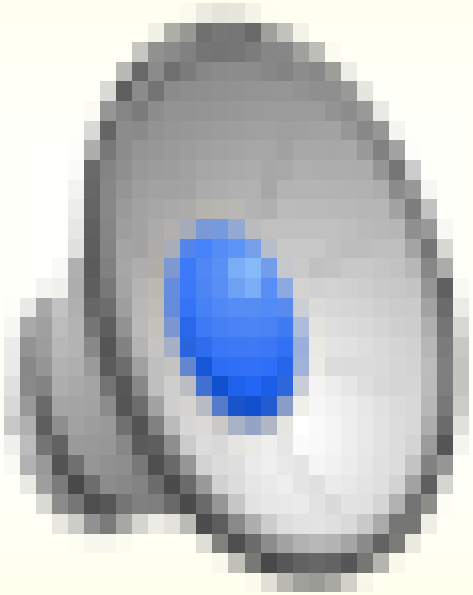
The observation of a kilonova allowed us to show that neutron star mergers could be responsible for the production most of the heavy elements, like gold, in the universe.

Observing both electromagnetic and gravitational waves from the event provides compelling evidence that gravitational waves travel at the same speed as light.

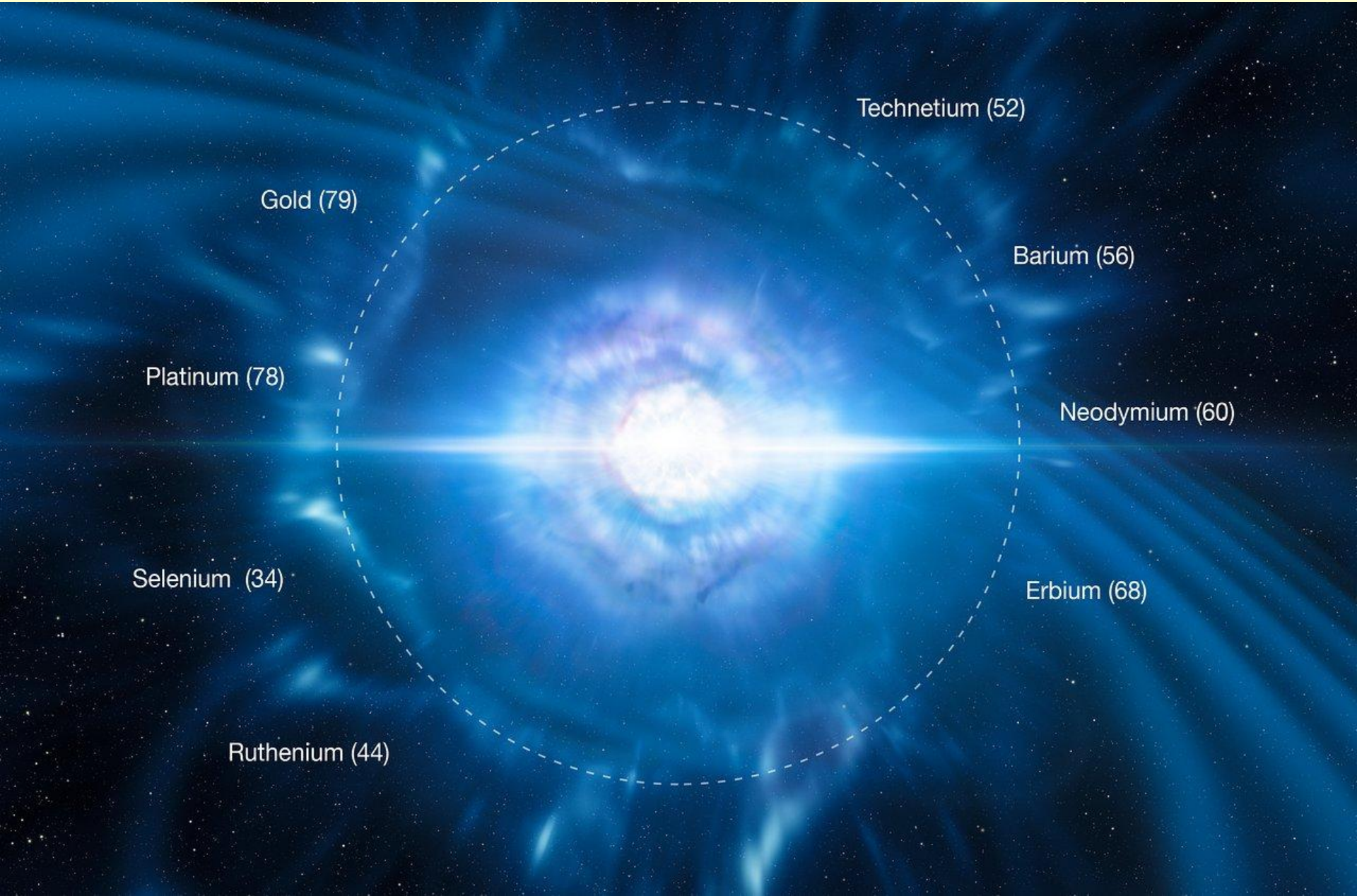
GW170817 és kísérőjelenségeinek felfedezése



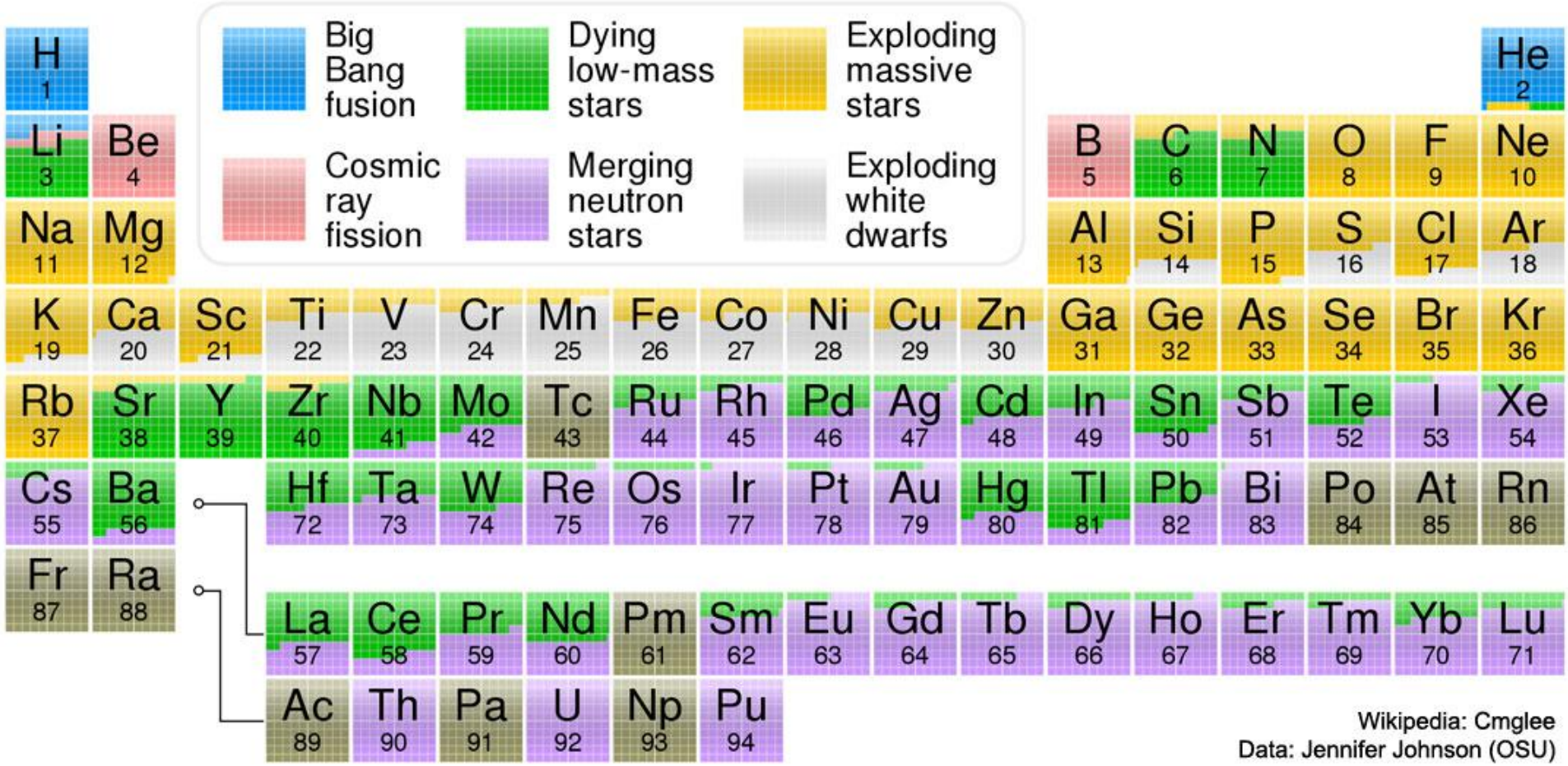
GW170817 és kísérőjelenségeinek felfedezése



GW170817: nehéz elemek keletkezése



GW170817: nehéz elemek keletkezése



GW170817: kozmológiai következmények

RESEARCH LETTER

nature Accelerated Article Preview

LETTER
doi:10.1038/nature24471

A gravitational-wave standard siren measurement of the Hubble constant

The LIGO Scientific Collaboration and The Virgo Collaboration*, The 1M2H Collaboration*, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration*, The DLT40 Collaboration*, The Las Cumbres Observatory Collaboration*, The VINROUGE Collaboration* & The MASTER Collaboration*

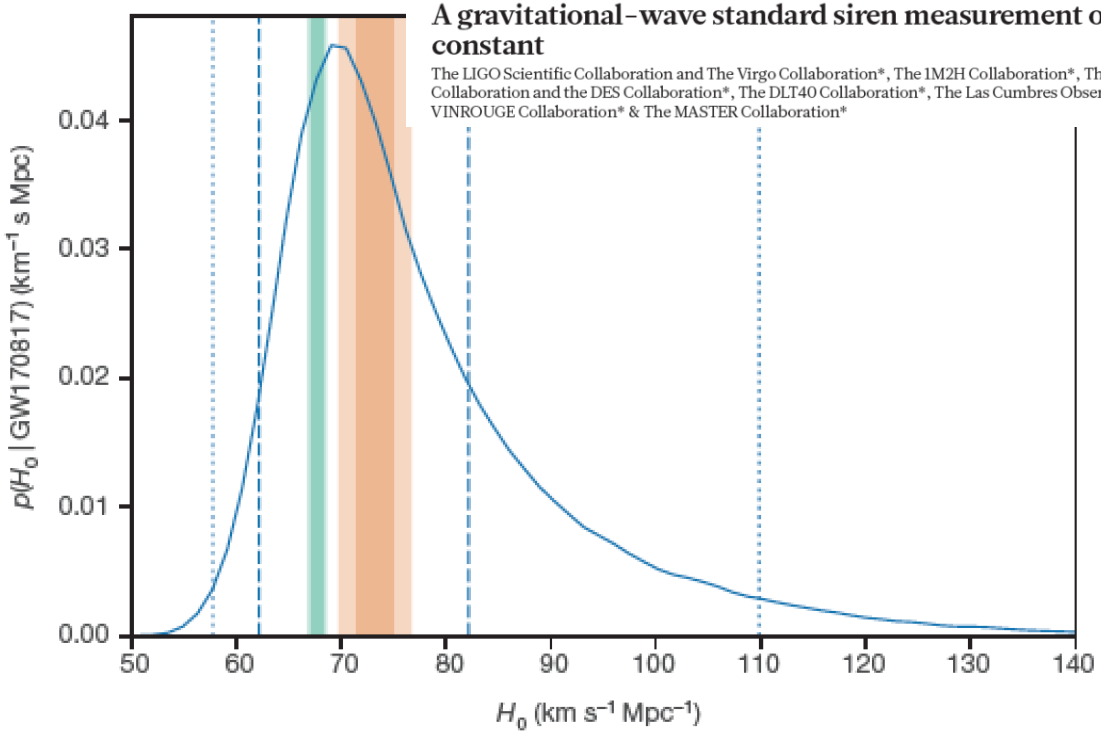


Figure 1 | GW170817 measurement of H_0. The marginalized posterior density for H_0, $p(H_0 \mid GW170817)$, is shown by the blue curve. Constraints at 1σ (darker shading) and 2σ (lighter shading) from Planck[20] and SHoES[21] are shown in green and orange, respectively. The maximum a posteriori value and minimal 68.3% credible interval from this posterior density function is $H_0 = 70.0^{+12.0}_{-8.0}$ km s^{-1} Mpc^{-1}. The 68.3% (1σ) and 95.4% (2σ) minimal credible intervals are indicated by dashed and dotted lines, respectively.

Feszültség a Hubble-állandó CMB mérésekből (Planck) (67.74 ± 0.46 km/s/Mpc) és SNIa mérésekből (SHoES21) kapott (73.24 ± 1.74 km/s/Mpc) értékei között!

1. **Gravitációs hullám forrásának paraméterbecslése**

→ **d_L luminozitás-távolság**

2. **Optikai tranziens meghatározása: a forrás az NGC 4993 galaxistól legfeljebb 10 arcsec-ra található**

→ **pekuliáris sebesség**

3. **Elektromágneses spektrum vöröseltolódásának mérése**

→ **v_H kozmológiai tágulási sebesség**

4. **Hubble-törvény (50 Mpc-ig érvényes!) $v_H = H_0\, d_L$**

→ **Hubble állandó**

A gravitáció terjedési sebessége a fénysebesség !

	$c_g = c$	$c_g \neq c$
Horndeski	General Relativity quintessence/k-essence [42] Brans-Dicke/$f(R)$ [43], [44] Kinetic Gravity Braiding [46]	quartic/quintic Galileons [13], [14] Fab Four [15], [16] de Sitter Horndeski [45] $G_{\mu\nu}\phi^\mu\phi^\nu$ [47], Gauss-Bonnet
beyond H.	Derivative Conformal (20) [18] Disformal Tuning (22) DHOST with $A_1 = 0$	quartic/quintic GLPV [19] DHOST [20], [48] with $A_1 \neq 0$
	Viable after GW170817	Non-viable after GW170817

A gamma-hullám 1.7 s-os
késéséből a gravitációs
hullámhoz képest
→ A gravitációs hullám

$$-3 \times 10^{-15} \leqslant \frac{\Delta v}{v_{\mathrm{EM}}} \leqslant +7 \times 10^{-16}.$$

[2] arXiv:1710.05901 [pdf, other]
Dark Energy after GW170817
Jose María Ezquiaga (1 and 2), Miguel Zumalacárregui (2 and 3) ((1) Madrid IFT, (2) UC Berkeley, (3) Nordita)
Comments: 9 pages, 3 figures
Subjects: **Cosmology and Nongalactic Astrophysics (astro-ph.CO)**; General Relativity and Quantum Cosmology (gr-qc); High Energy Physics -

[3] arXiv:1710.05893 [pdf, other]
Implications of the Neutron Star Merger GW170817 for Cosmological Scalar-Tensor Theories
Jeremy Sakstein, Bhuvnesh Jain
Comments: five pages, two figures
Subjects: **Cosmology and Nongalactic Astrophysics (astro-ph.CO)**; General Relativity and Quantum Cosmology (gr-qc); High Energy Physics -

[4] arXiv:1710.05877 [pdf, ps, other]
Dark Energy after GW170817
Paolo Creminelli, Filippo Vernizzi
Comments: 5 pages
Subjects: **Cosmology and Nongalactic Astrophysics (astro-ph.CO)**; General Relativity and Quantum Cosmology (gr-qc); High Energy Physics -

Lokális Lorentz-invariancia sértés, graviton-tömeg vizsgálata

Módosított diszperziós reláció:

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

S. Mirshekari, N. Yunes, and C. M. Will, Phys. Rev. D **85**, 024041 (2012).

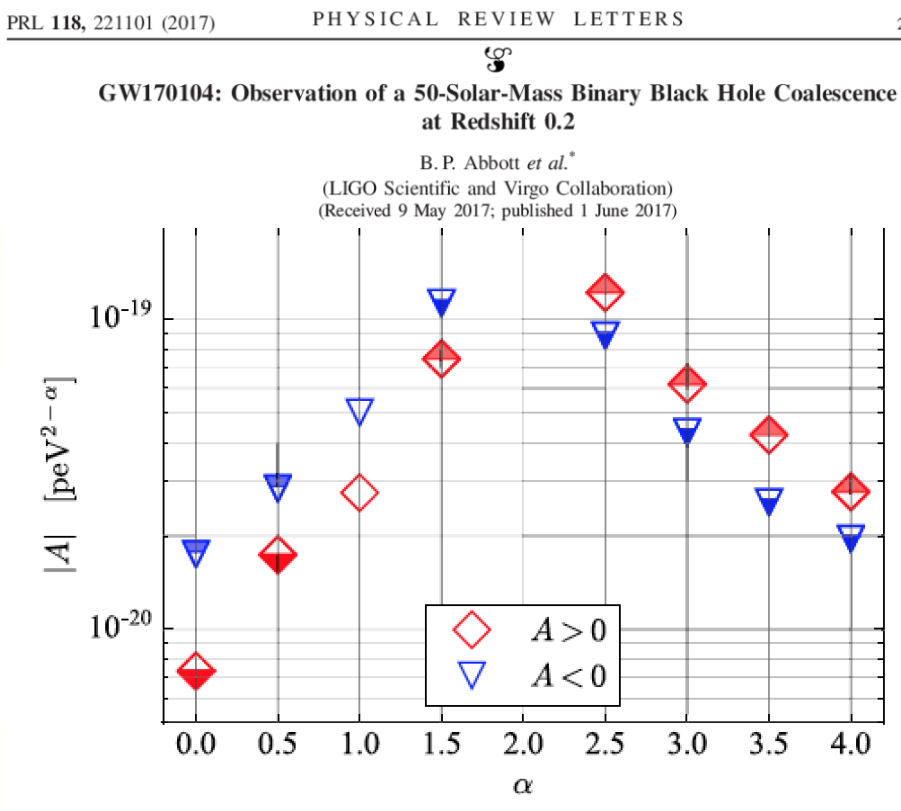
Tömeges graviton elméletek $(\alpha = 0,\ A > 0)$
Multifraktál téridők: $(\alpha = 2.5)$
Duplán speciális relativitáselmélet: $(\alpha = 3)$,
Hořava-Lifsic és extra dimenziók: $(\alpha = 4)$

Sebesség / energiafüggő frekvencia / hullámhossz:

$$v_g/c = 1 + (\alpha - 1)AE^{\alpha-2}/2$$

N. Yunes, K. Yagi, and F. Pretorius, Phys. Rev. D **94**, 084002 (2016).

Lorentz-invariancia sértés és graviton tömege egyszerre vizsgálható !


PRL 118, 221101 (2017) PHYSICAL REVIEW LETTERS

GW170104: Observation of a 50-Solar-Mass Binary Black Hole Coalescence at Redshift 0.2

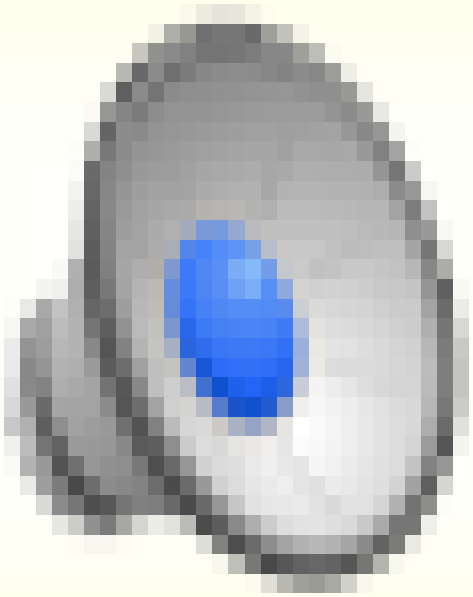
B. P. Abbott *et al.*
(LIGO Scientific and Virgo Collaboration)
(Received 9 May 2017; published 1 June 2017)

kényszer a Lorentz-invariancia sértésre !
Az első 3 észlelt GH-ból:

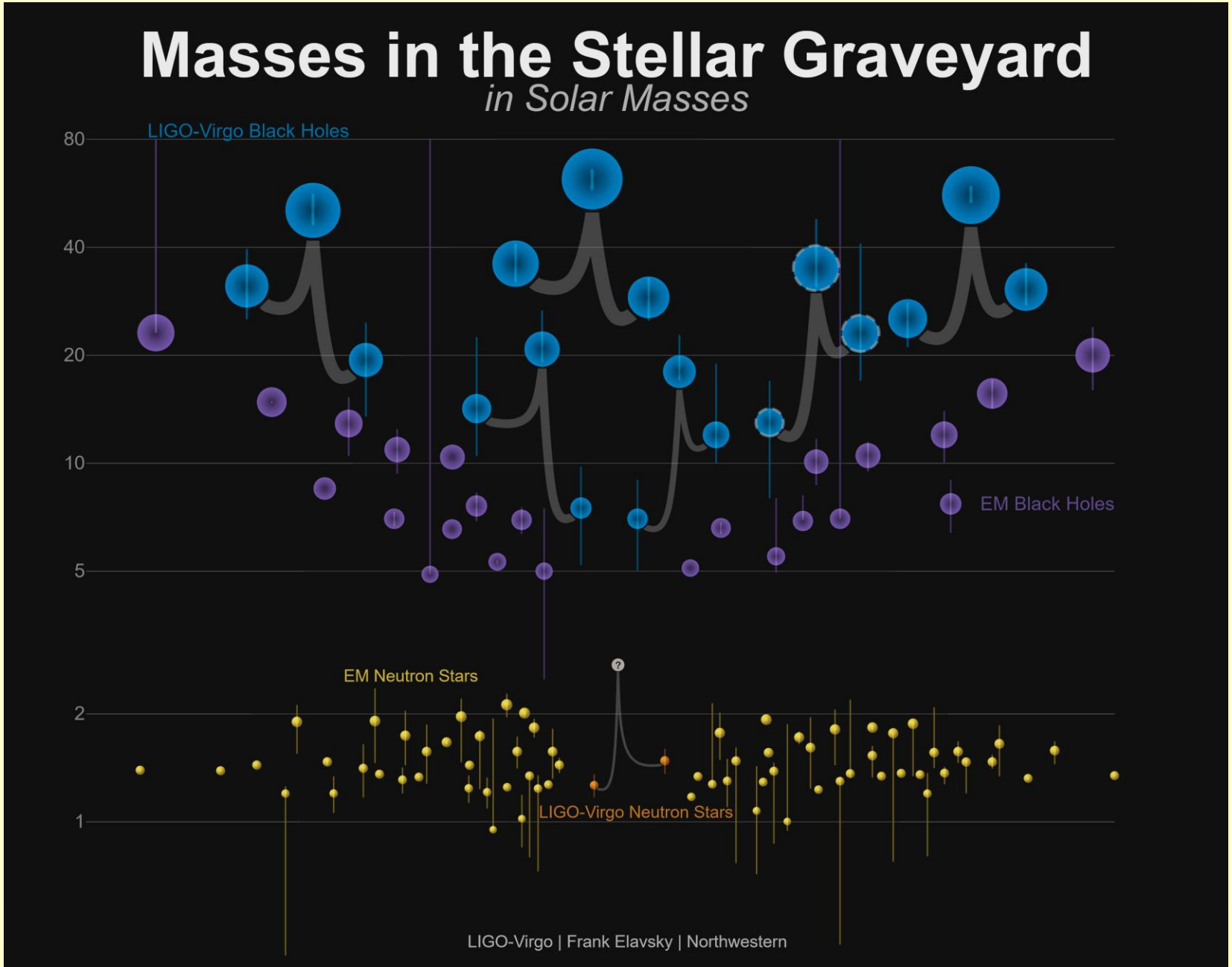
$$\lambda_g > 1.6 \times 10^{13}\ \text{km},$$
$$m_g \leq 7.7 \times 10^{-23}\ \text{eV}/c^2.$$

Összehasonlításul: $m_{gluon} \leq 10^{-4}$ eV/c^2
$m_{foton} \leq 7 \times 10^{-17}$ eV/c^2

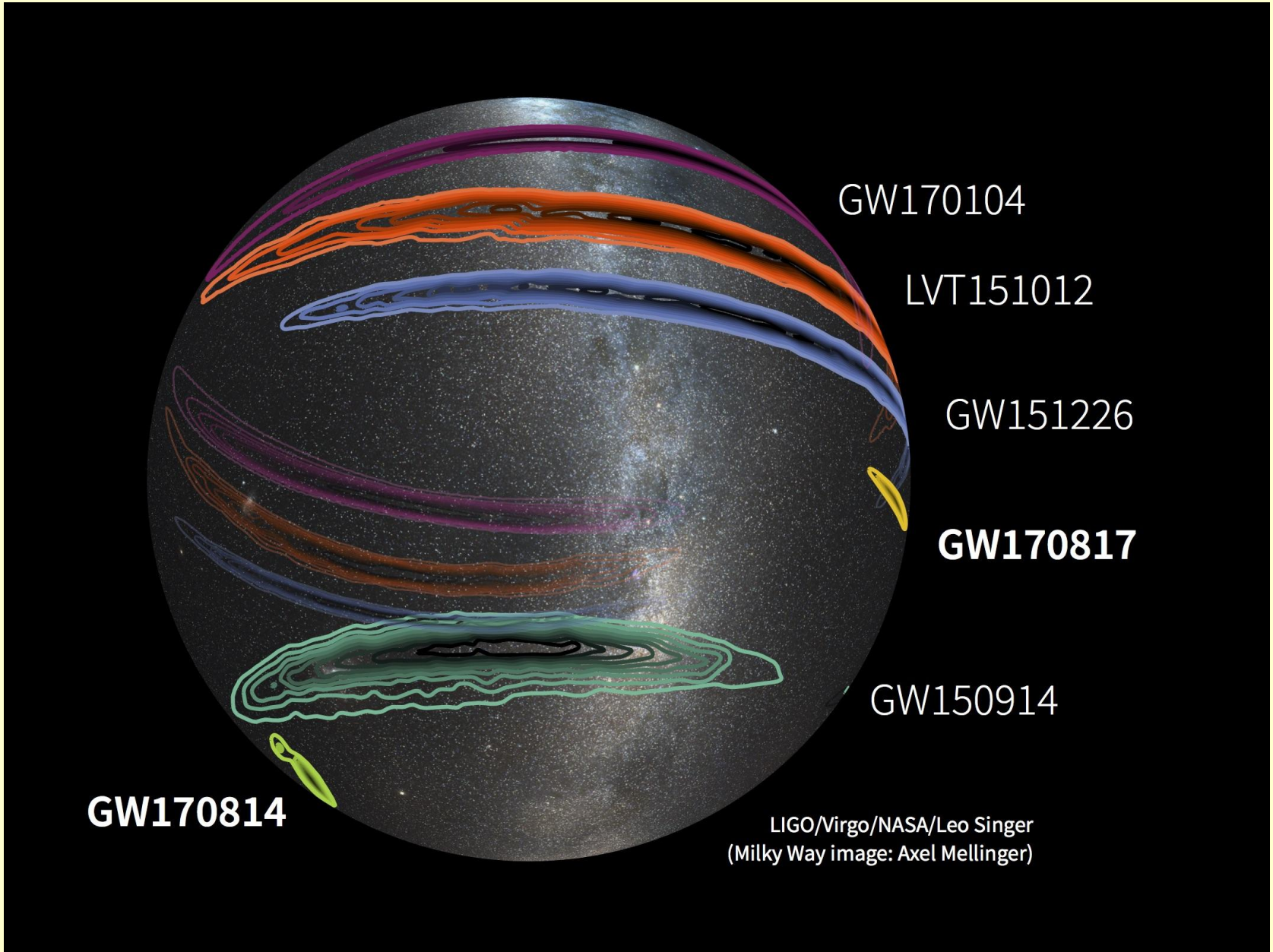
Az eddig észlelt gravitációs hullámok összehasonlítása



Források tömegei

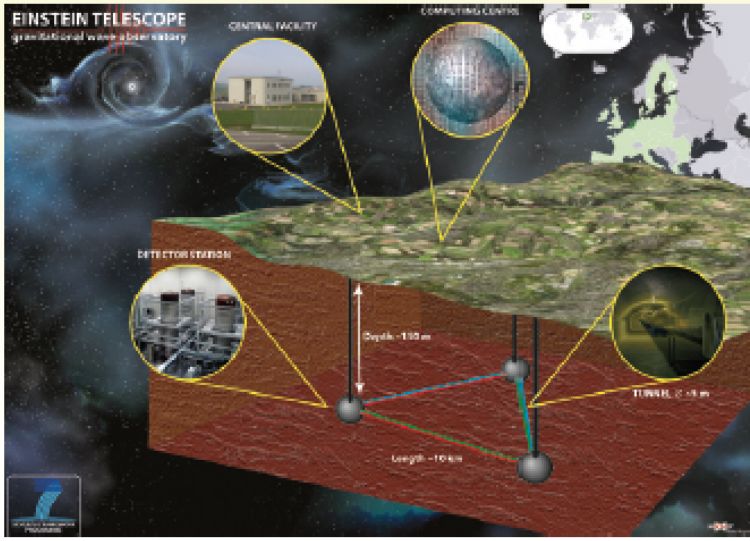


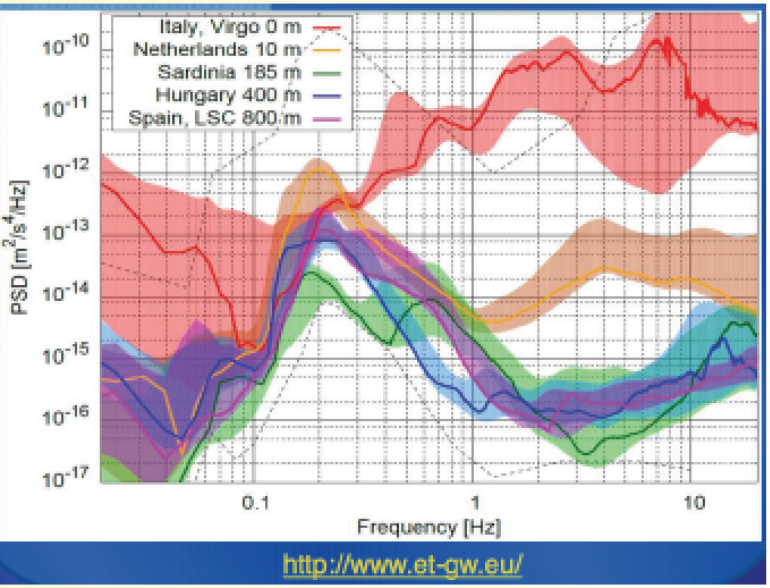
Források égi helyzete



A jövő: Einstein teleszkóp

- European Gravitational Observatory – Koordináló intézmény
- Istituto Nazionale di Fisica Nucleare
- Max-Planck-Gesellschaft zur Förderung der Wissenschaften e. V.
- Centre national de la recherche scientifique
- University of Birmingham
- University of Glasgow
- NIKHEF
- Cardiff University

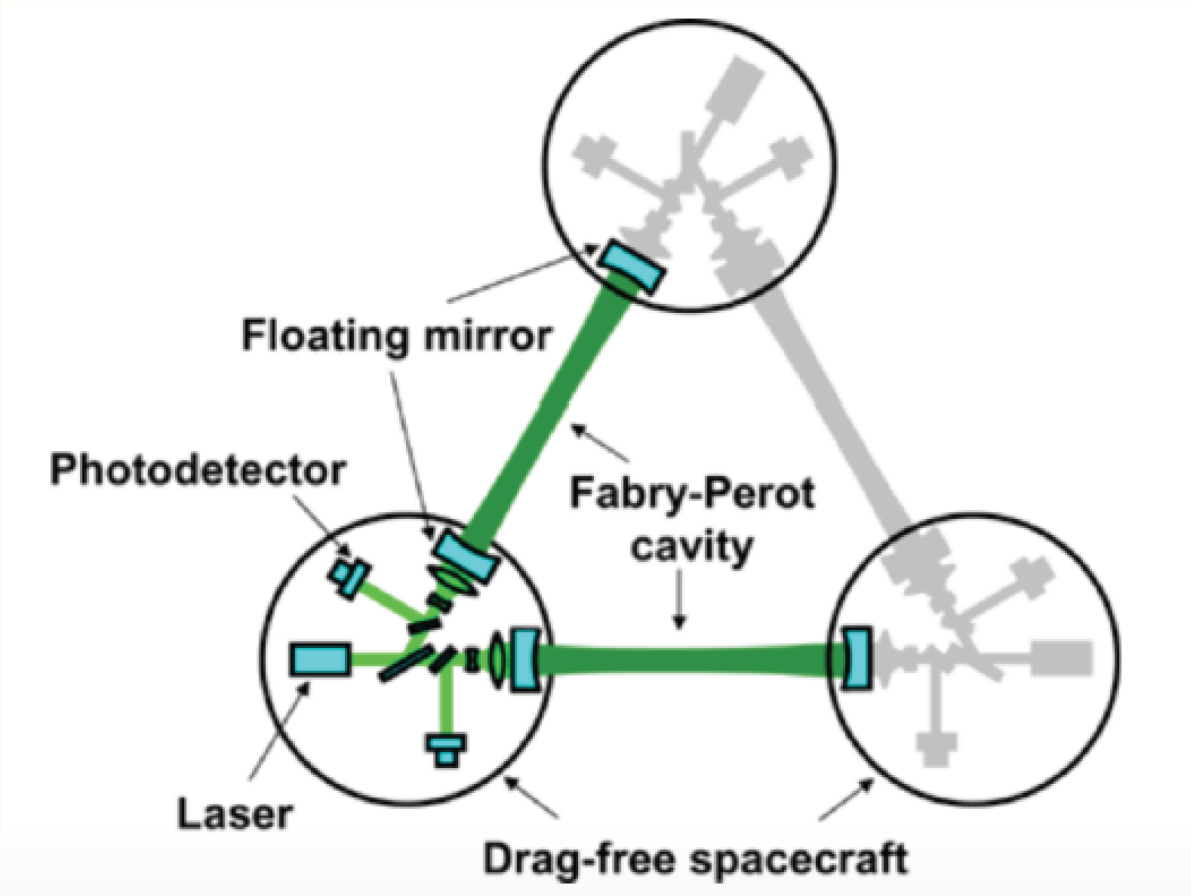




Mátra: kedvező szeizmikus adottságok

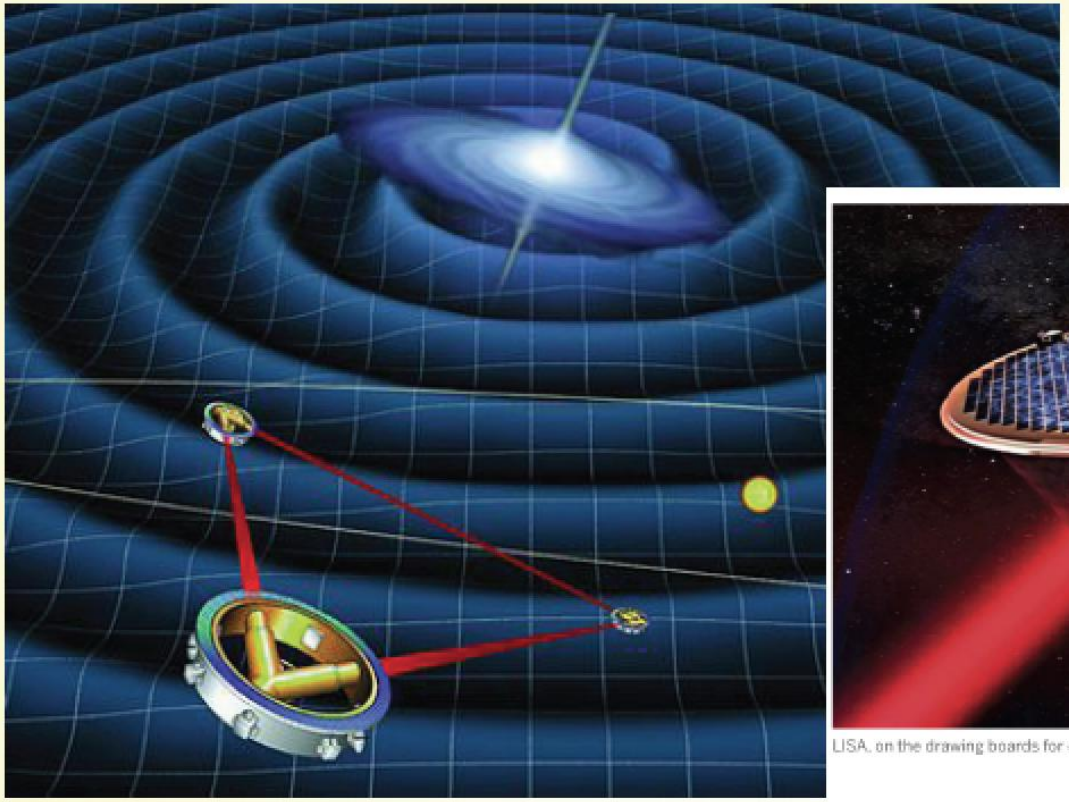
- 3 db, egyenként 10 km karhosszúságú detektor
- 3. generációs detektor: földalatti, hűtött „karok"
- legalább 10x érzékenyebb a jelenlegi detektoroknál
- érzékenység alsó küszöbe: 1 Hz
- egyik interferométer 1 ÷ 250 Hz, másik kettő 10 Hz ÷ 10 kHz frekvenciára optimalizált
- megvalósulás ~ 2025

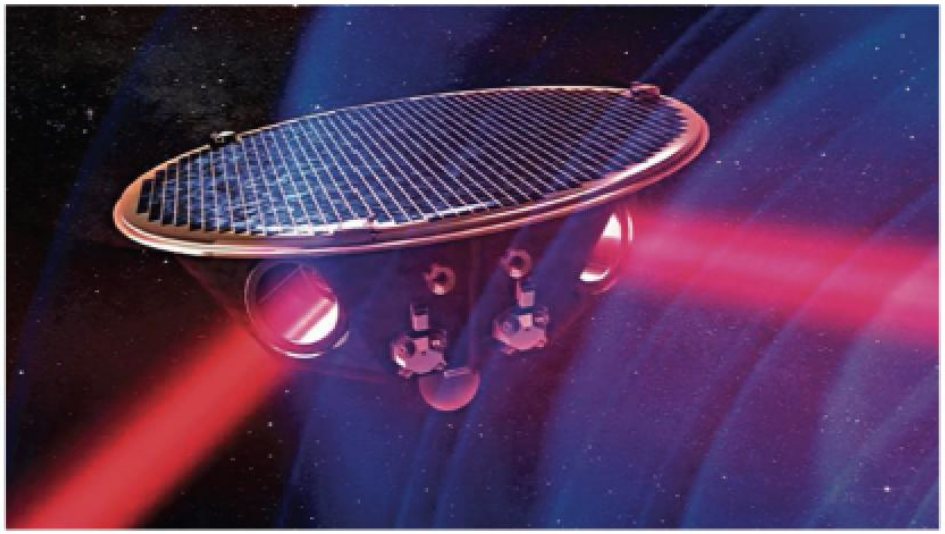
A jövő: DECIGO



Karhosszúság: 1000 km → érzékenység: 0,1 ÷ 10 Hz
Cél: az Ősrobbanást követő 380.000 évben kibocsátott gravitációs hullámok észlelése
(elektromágneses hullámok olyan távolról nem jöhetnek)

A jövő: LISA





LISA, on the drawing boards for decades, may now launch earlier than 2034.

Albert Einstein Institute/Milde Marketing/exozet; GW simulation: NASA/C. Henze

NASA moves to rejoin sped-up gravitational wave mission

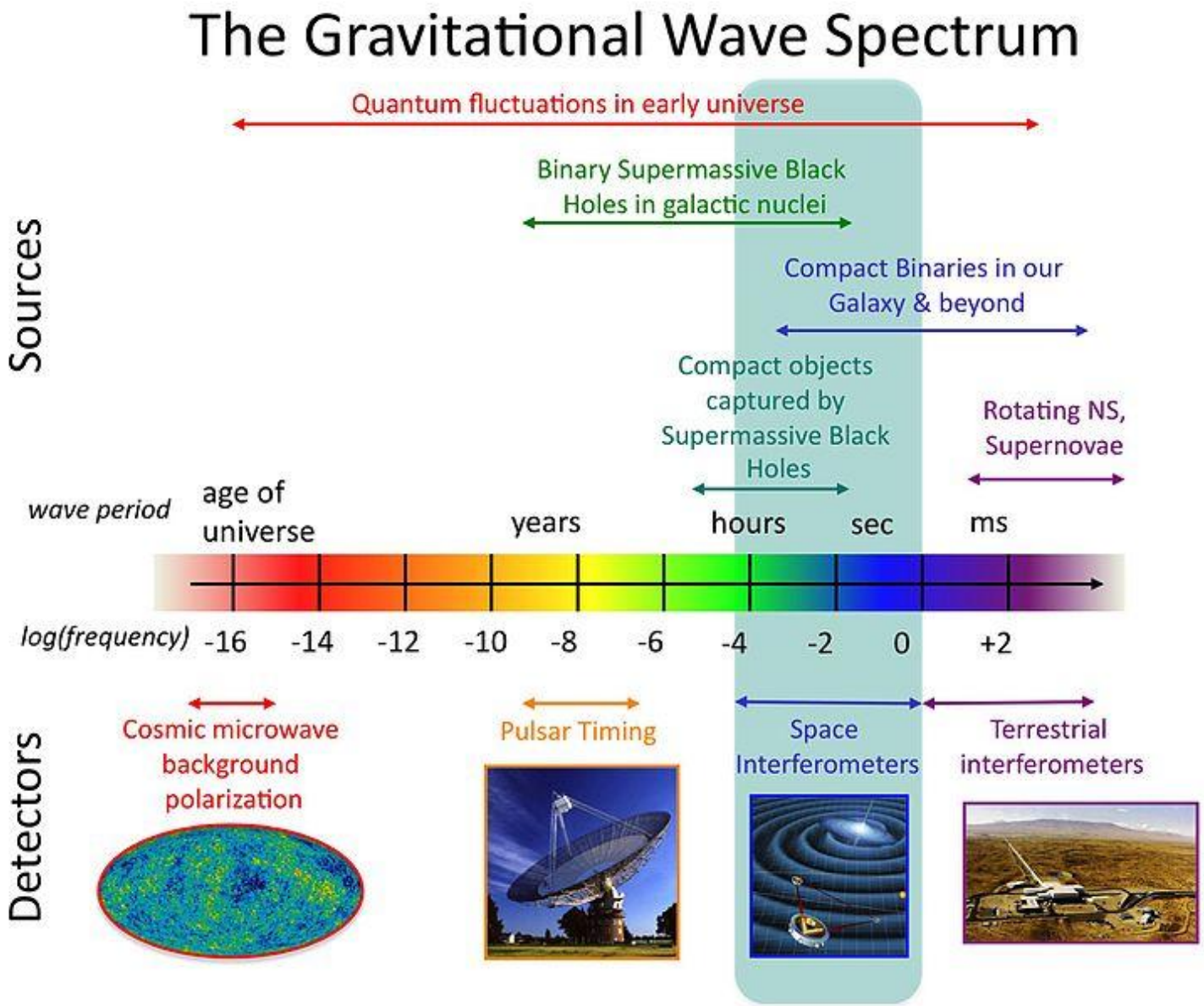
By Govert Schilling | Sep. 9, 2016 , 3:00 PM

Karhosszúság: 1-5 millió km (költségvetés függvénye)

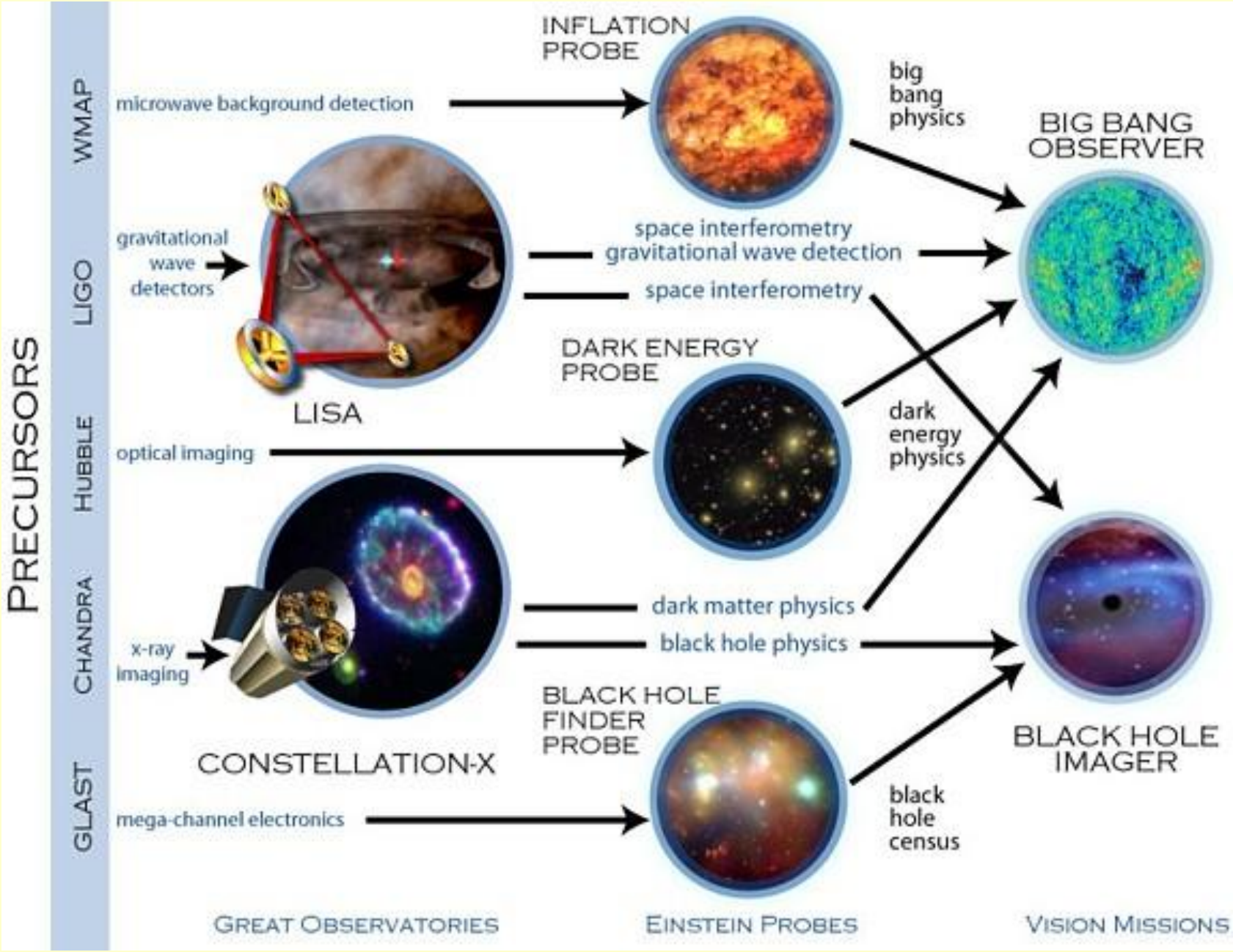
Föld-Hold rendszert követő heliocentrikus pálya

2034 → 2029 ?

A jövő: LISA, pulzárok, CMB



A jövő: Big Bang Explorer



Köszönöm
a figyelmet !