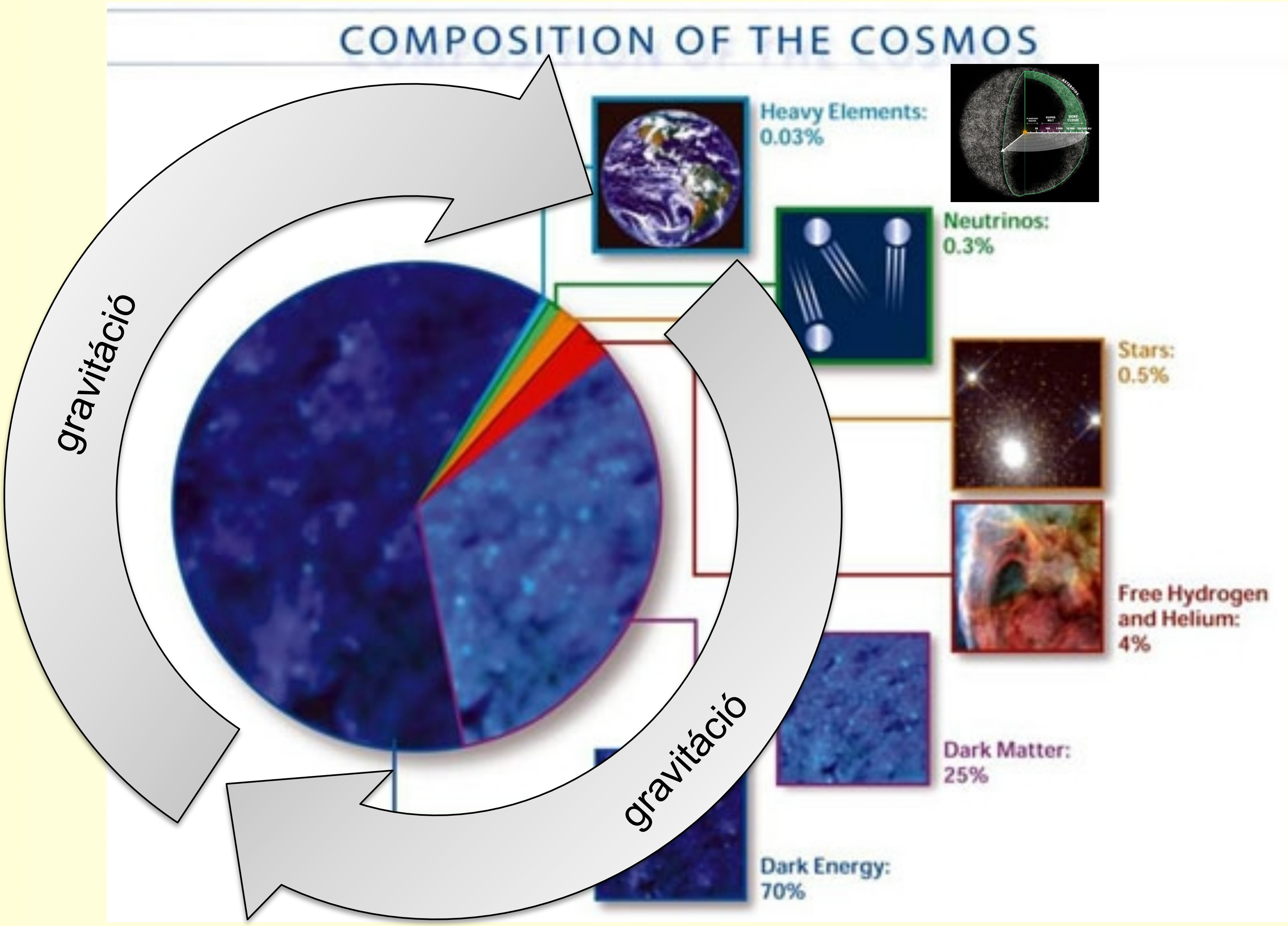
Gravitációs hullámok, felfedezésük és a 2017-es Fizikai Nobel-díj

GERGELY Árpád László

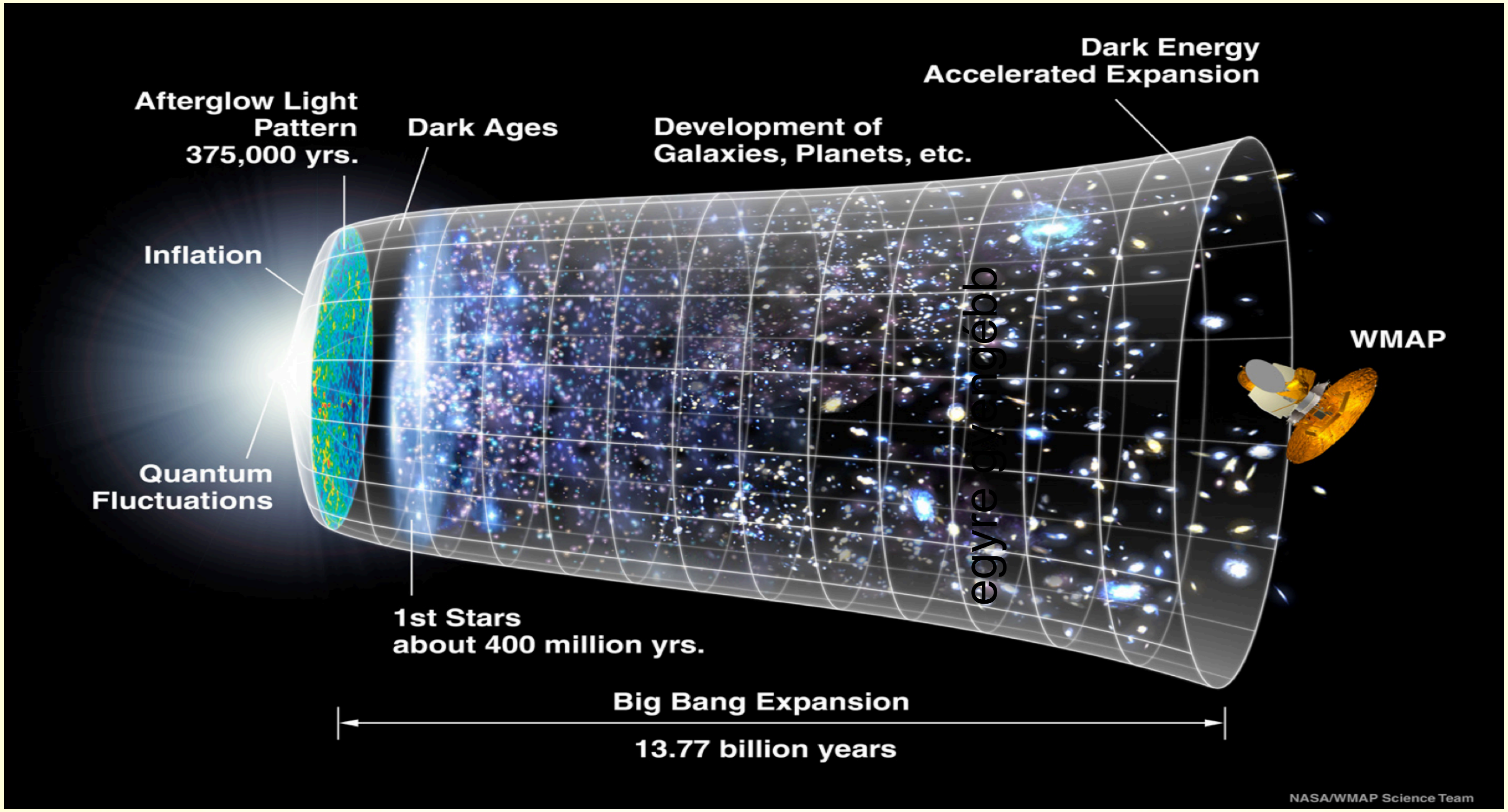
Szegedi Tudományegyetem

Eszterházy Károly Egyetem, Magyar Tudomány Ünnepe zárókonferencia, **2017**, Gyöngyös

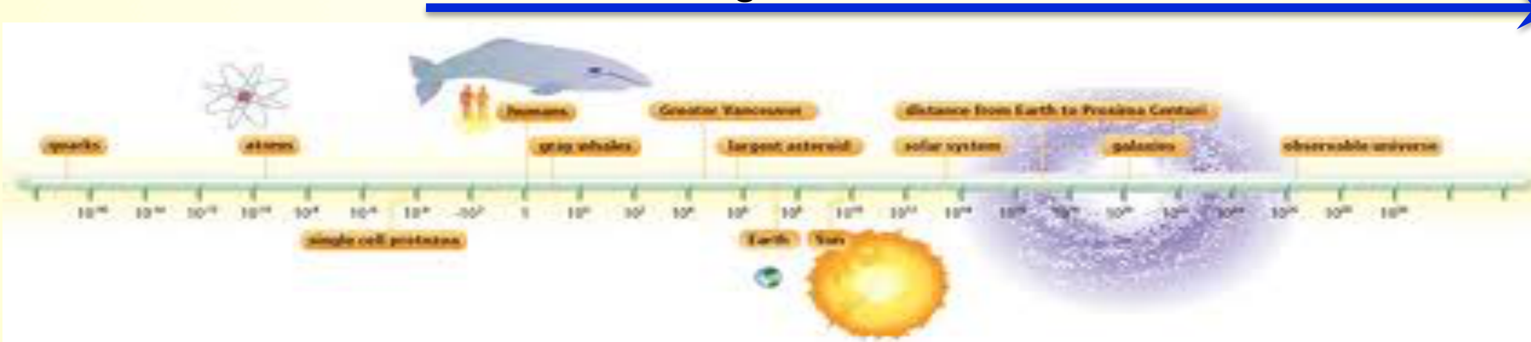
A gravitáció szerepe az ismert Univerzum összetételében



Idő- és távolságskálák az Univerzumban, melyeken a gravitáció meghatározó



gravitáció



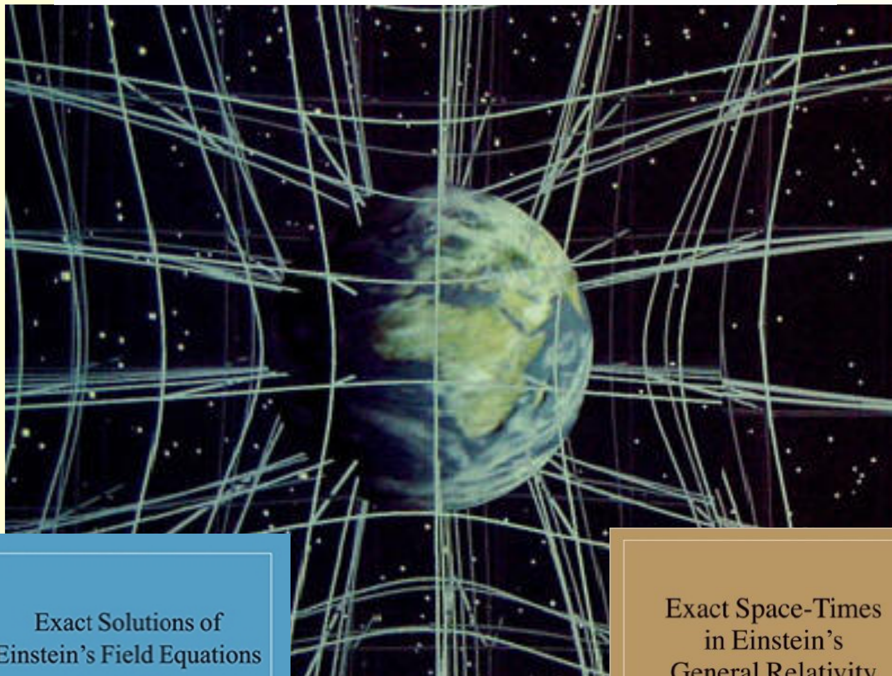
Az általános relativitáselmélet, mint gravitációelmélet

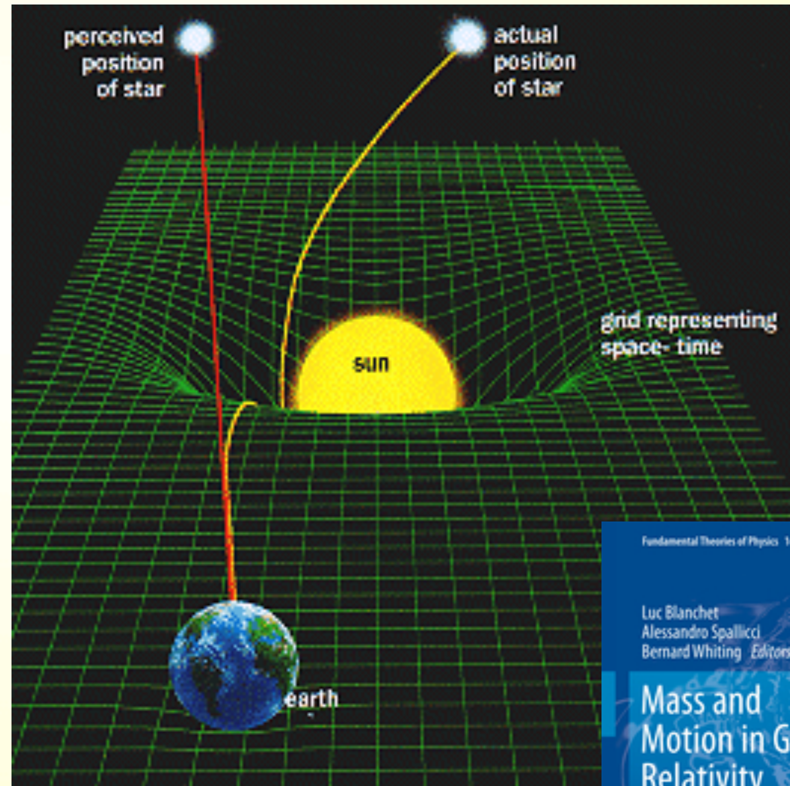
1. az anyag megmondja a téridőnek, hogyan görbüljön (Einstein egyenlet)

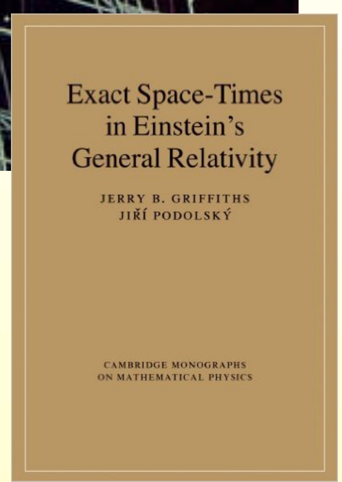
$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} + \Lambda\, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

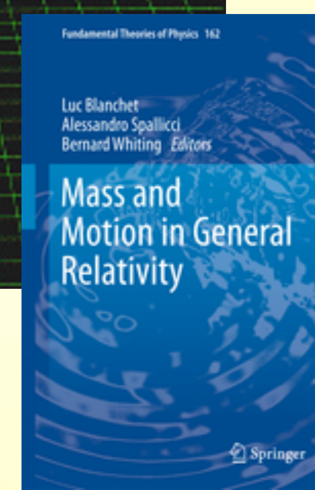
2. A téridő megmondja az anyagnak, hogyan mozogjon (geodetikus egyenlet)

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





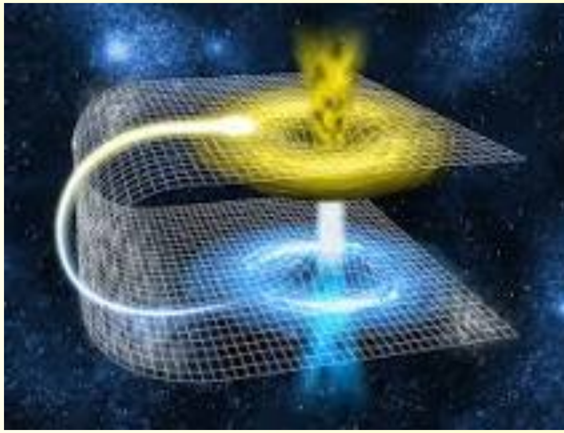




Új effektusok, új fogalmak

Új (gyenge-tér) effektusok a Naprendszerben:

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



- féreglyuk

EP=EPR, kapcsolat a kvantumelméletekkel?

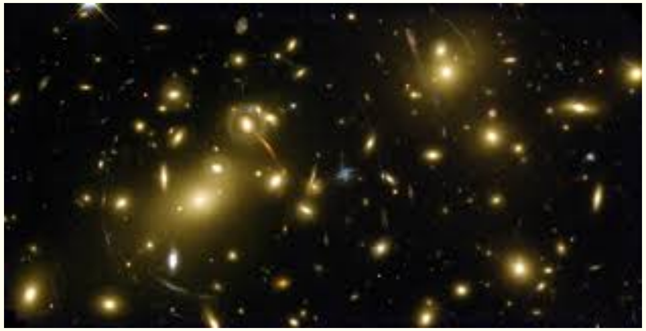
Új fogalmak:

- 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

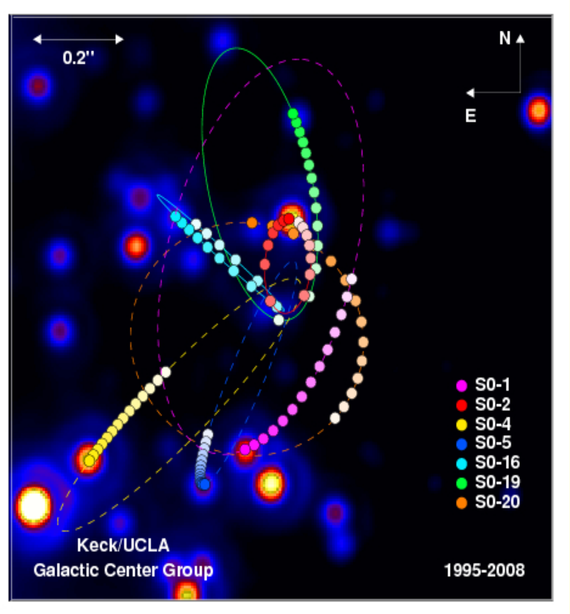
→ a sötét anyag nem WIMP

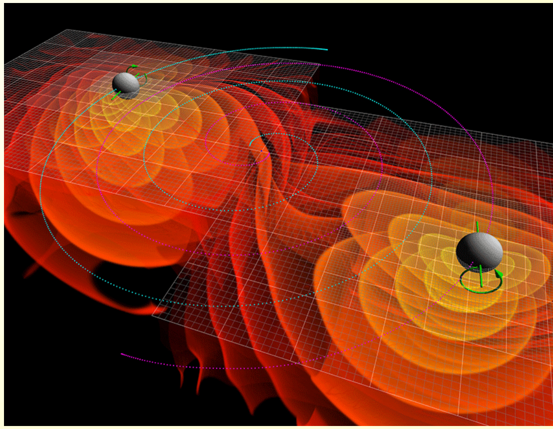
MACHO megfigyelések (Nagy Magellán felhő)

→ a sötét anyag legfeljebb 10%-a származhat csillagfejlődésből

→ közepes tömegű, elsődleges fekete lyukakból áll-e a sötét anyag?

(dedikált megfigyelési program szükséges)





- gravitációs sugárzás

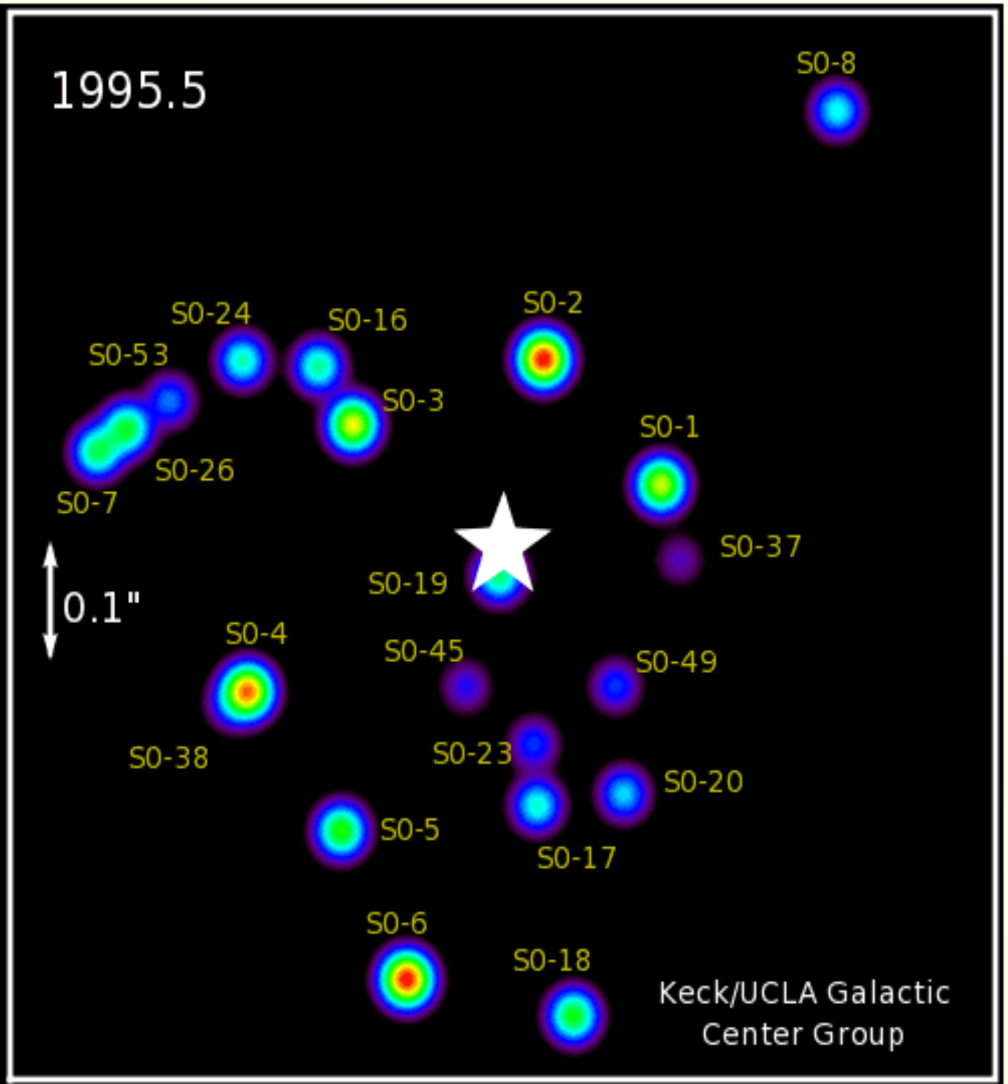
Miként észlelhetjük a fekete lyukakat?

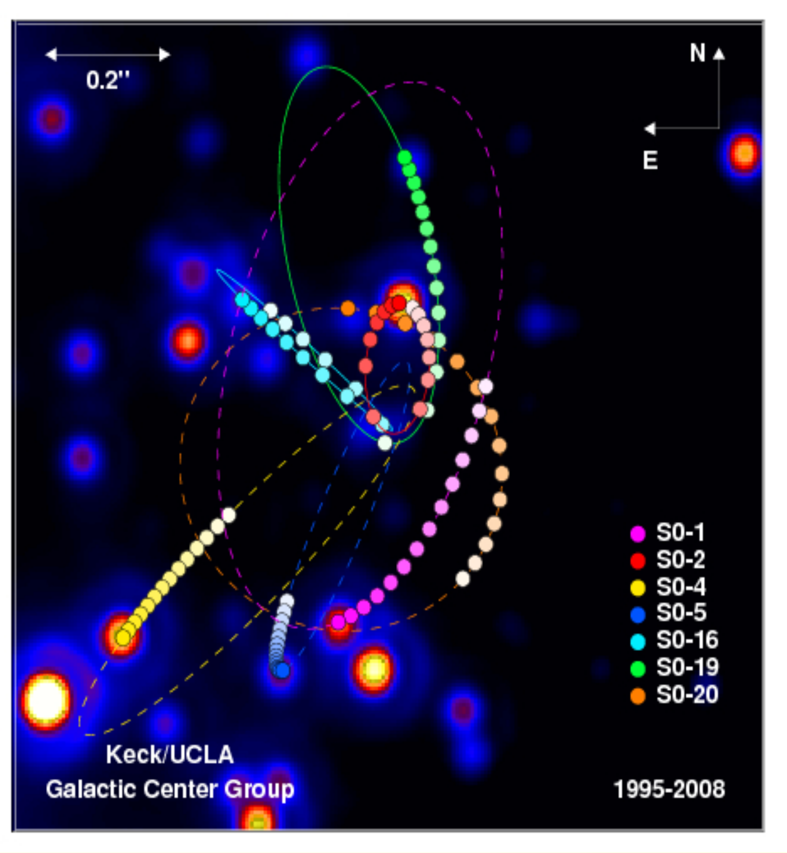
John Archibald Wheeler:

A készülő Gravitációs hullámok c. film részlete, rendezi Molnár H. Boglárka

A Tejútrendszer közepén található szupernagy tömegű fekete lyuk

Általános relativiáselmélet: gravitáció = görbület
hatalmas görbület → 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

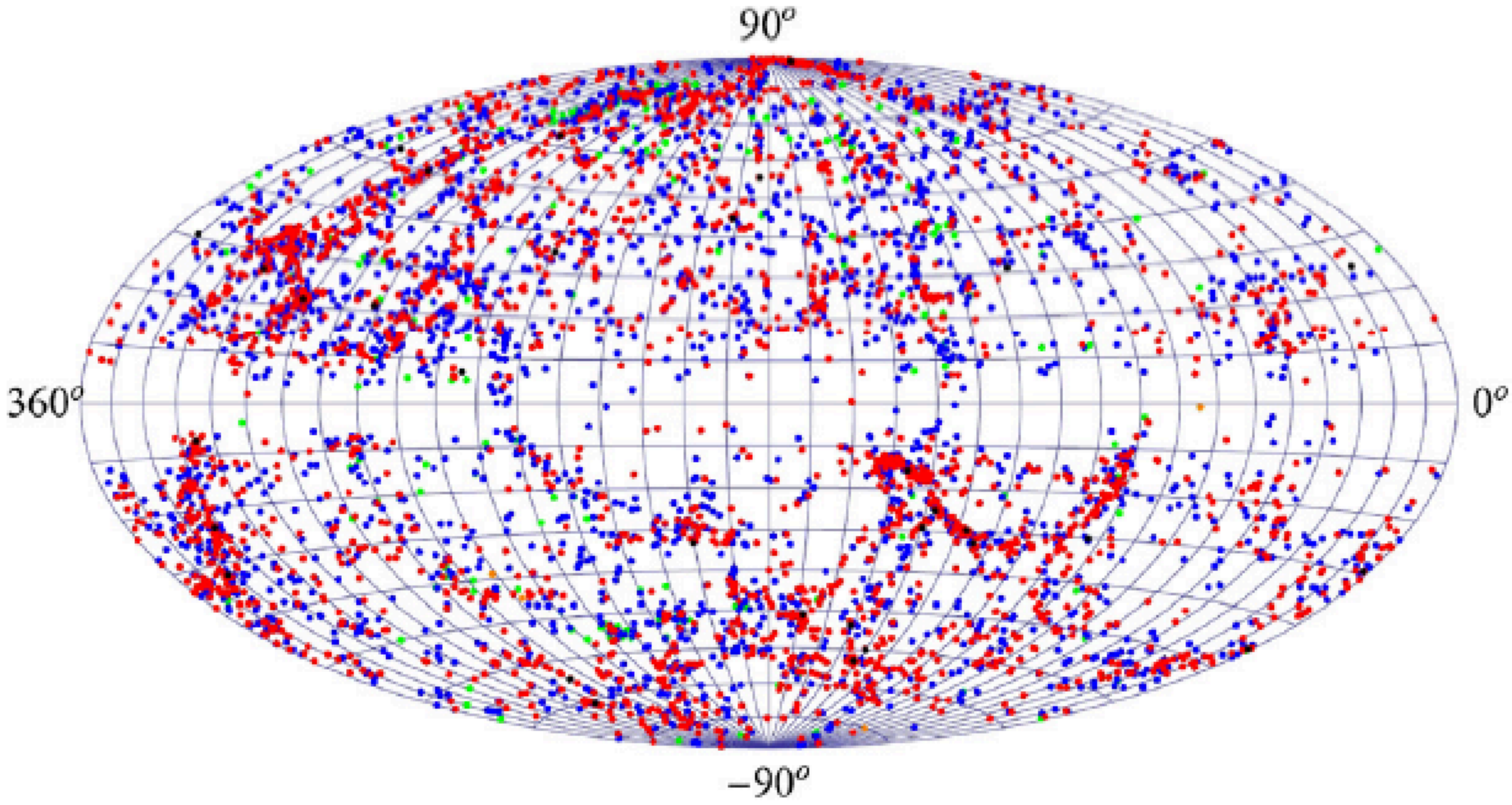
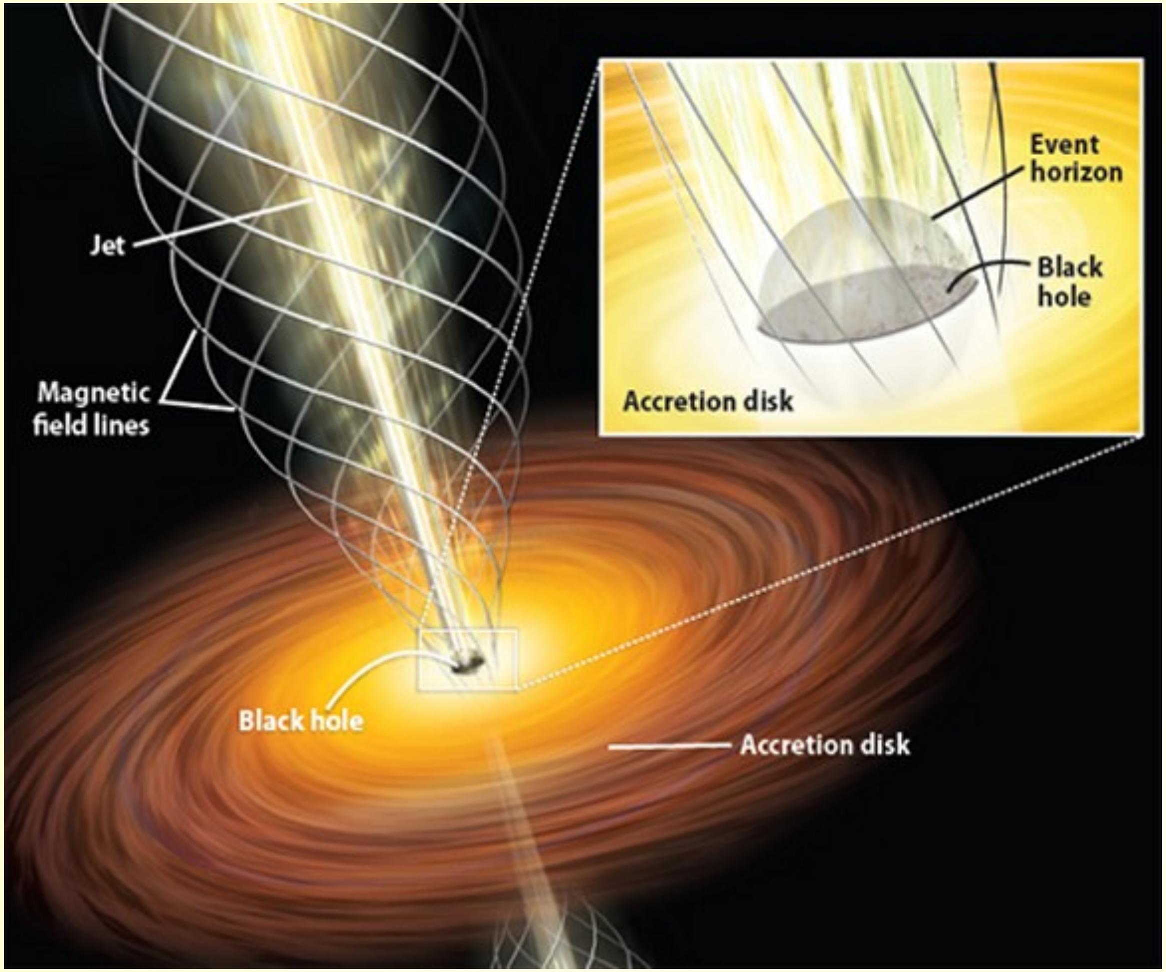
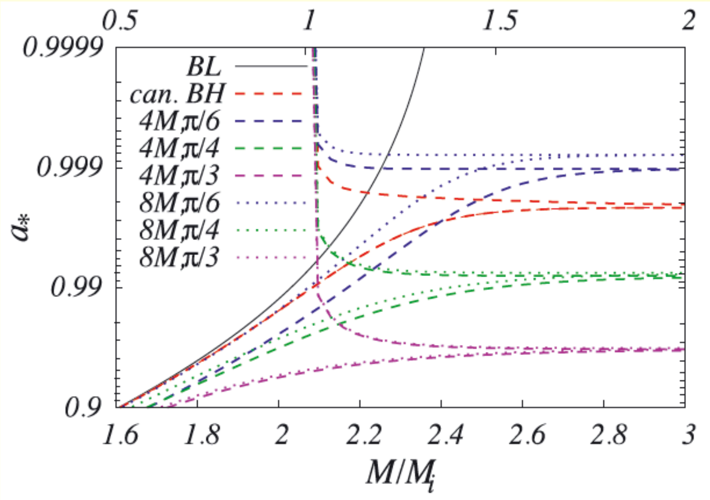


Figure 1. Aitoff projection in galactic coordinates of 5895 NED SMBH candidate sources. The sample is complete in a sensitivity sense; in order to derive densities one needs a volume correction. The color code (online only) is orange, green, blue, red, black corresponding to masses above $10^5\,M_\odot$,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

Hogyan láthatjuk még a fekete lyukakat? Akkréció és jet-ek



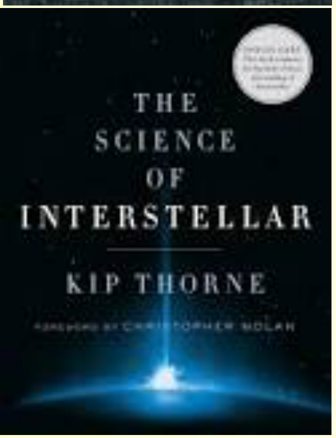


Maximal spin and energy conversion efficiency in a symbiotic system of black hole, disc and jet
Z. Kovács, L. Á. Gergely, P. L. Biermann, Mon. Not. R. Astron. Soc. **416,** 991–1009 (2011)

θ_{max}	n	a_* (I)	ϵ (I)
$\pi/6$	1	0.8961	0.309
	2	0.8901	0.301
	3	0.8803	0.285
$\pi/4$	1	0.8976	0.312
	2	0.8933	0.306
	3	0.8872	0.298
$\pi/3$	1	0.8969	0.310
	2	0.8948	0.308
	3	0.8924	0.305
$\pi/6$	1	0.8968	0.311
	2	0.8901	0.302
	3	0.8822	0.291
$\pi/4$	1	0.8983	0.313
	2	0.8939	0.308
	3	0.8879	0.300
$\pi/3$	1	0.8975	0.312
	2	0.8955	0.311
	3	0.8931	0.307

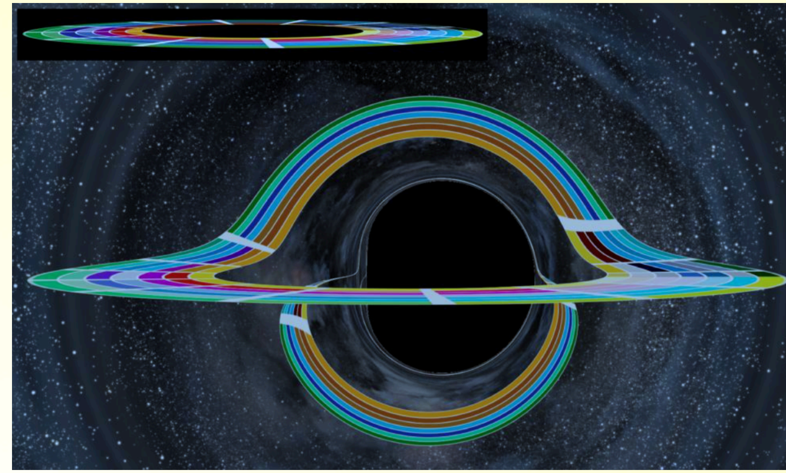
Miller & Brandt (2009)

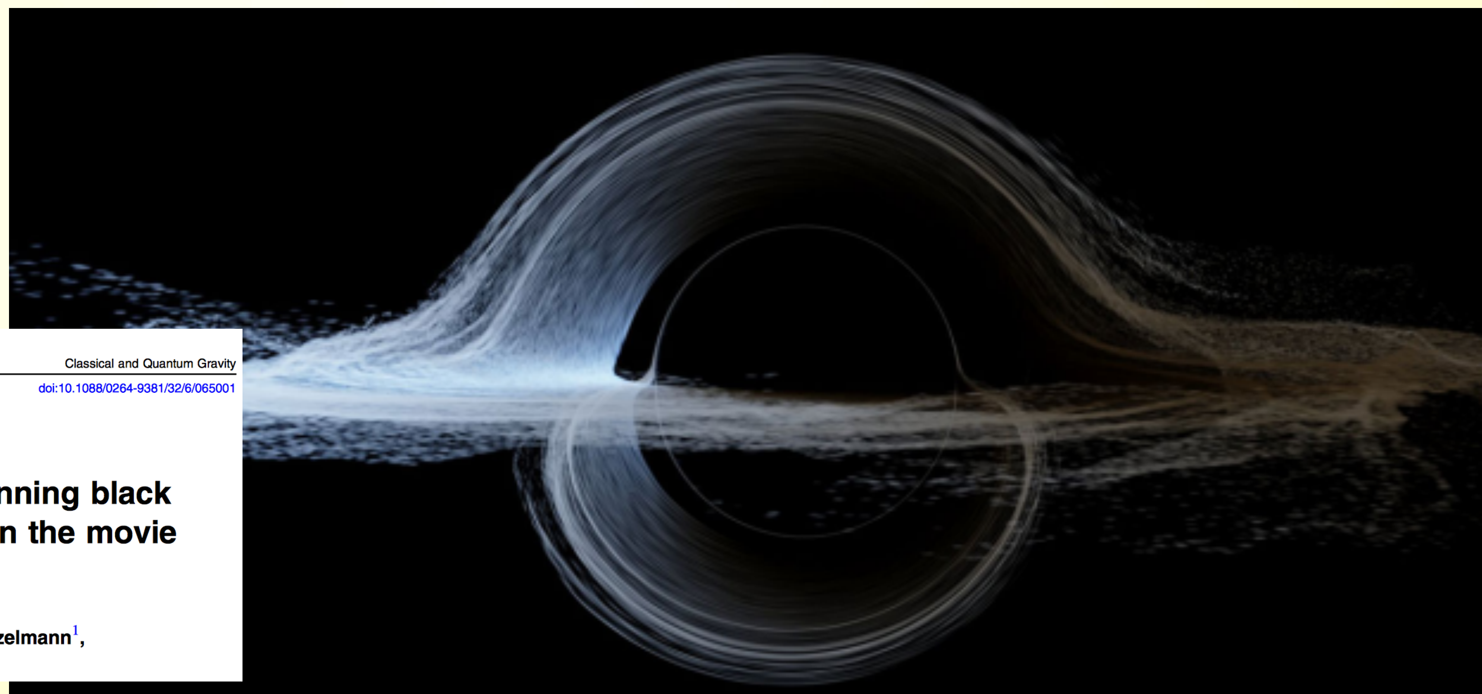
Hogyan láthatjuk még a fekete lyukakat? Gravitációs lencsézés



A fekete lyuk:

- Elhajlítja az akkréciós korong fényét
- Két képét mutatja





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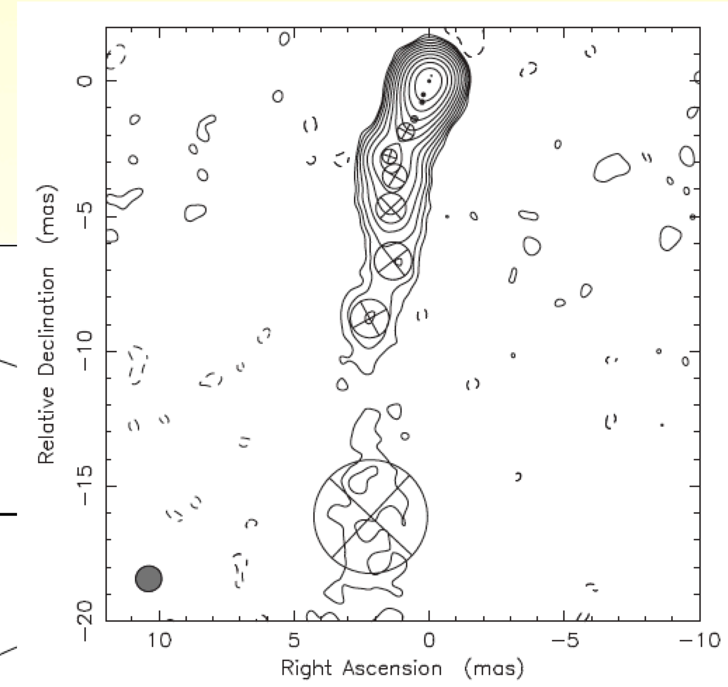
Class. Quantum Grav. **32** (2015) 065001 (41pp) doi:10.1088/0264-9381/32/6/065001

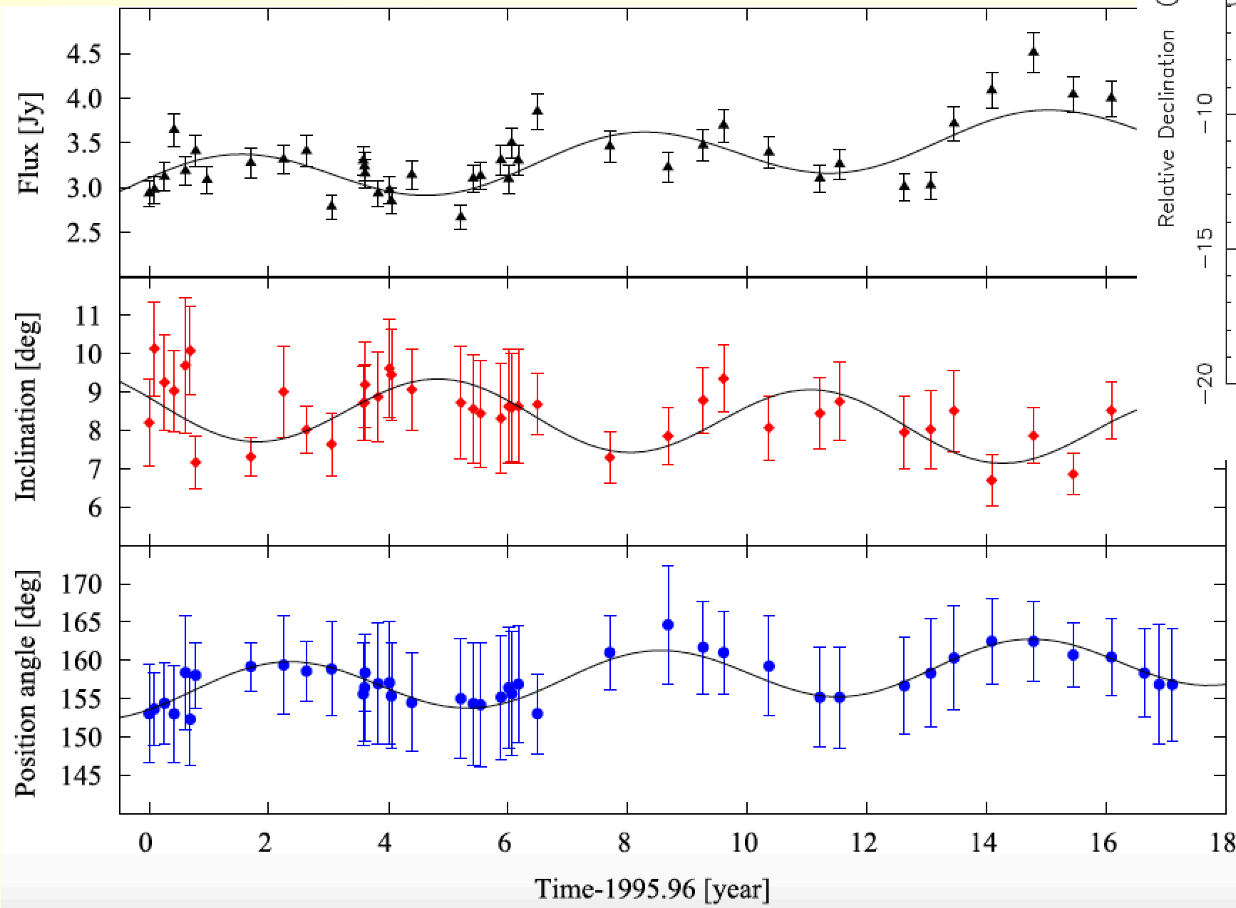
Gravitational lensing by spinning black holes in astrophysics, and in the movie *Interstellar*

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

Ütköző feketelyuk-kettős gravitációs lencsézése

Ütköző feketelyuk-kettősök jelei a jet-ek elektromágneses spektrumában





A spinning supermassive black hole binary model consistent with VLBI observations of the S5 1928+738 jet
E. Kun, K. É . Gabányi, M. Karouzos, S. Britzen, L. Á. Gergely, MNRAS **445,** 1370–1382 (2014)

Nagyenergiás neutrínók feketelyuk-kettősök ütközéséből

A nagyenergiás neutrínó-kibocsátás olyan energetikus proton–proton ütközések következménye, melyekben a protonok kinetikus energiája a pion-keltési energia fölött van.

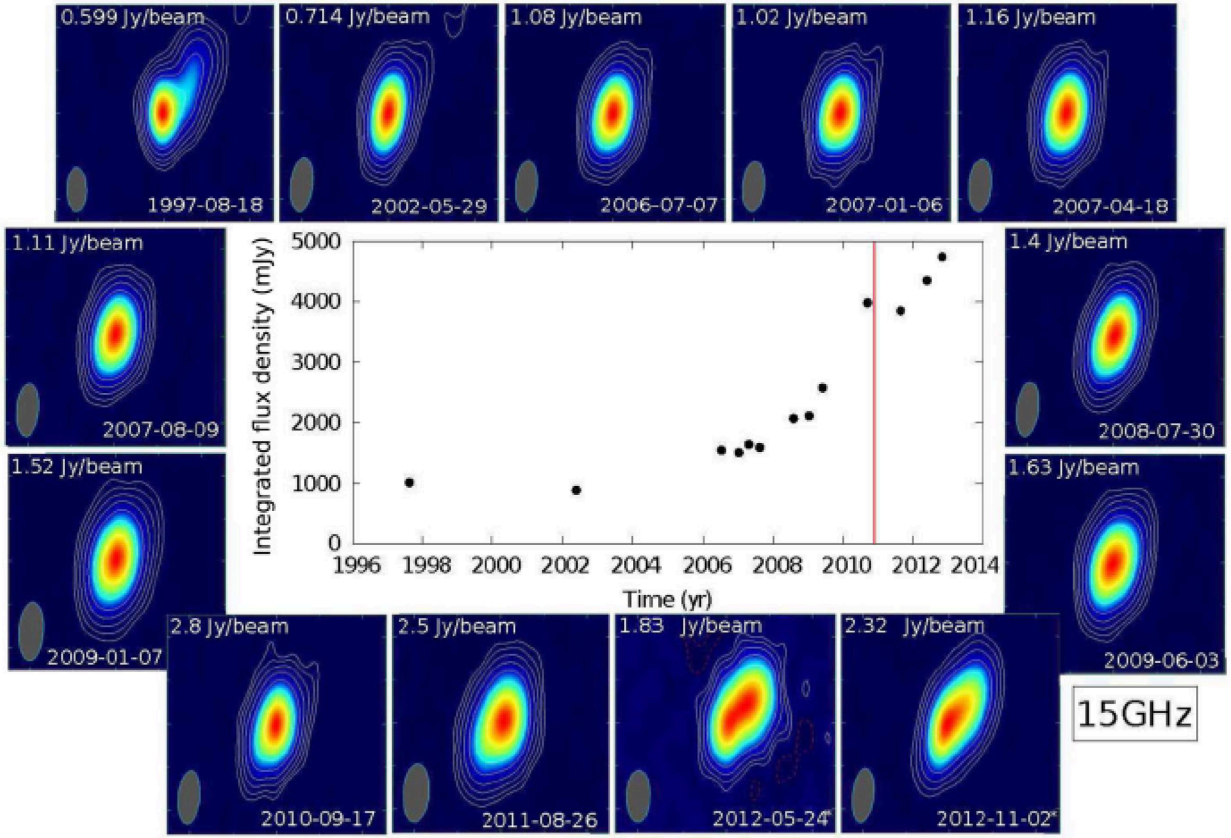


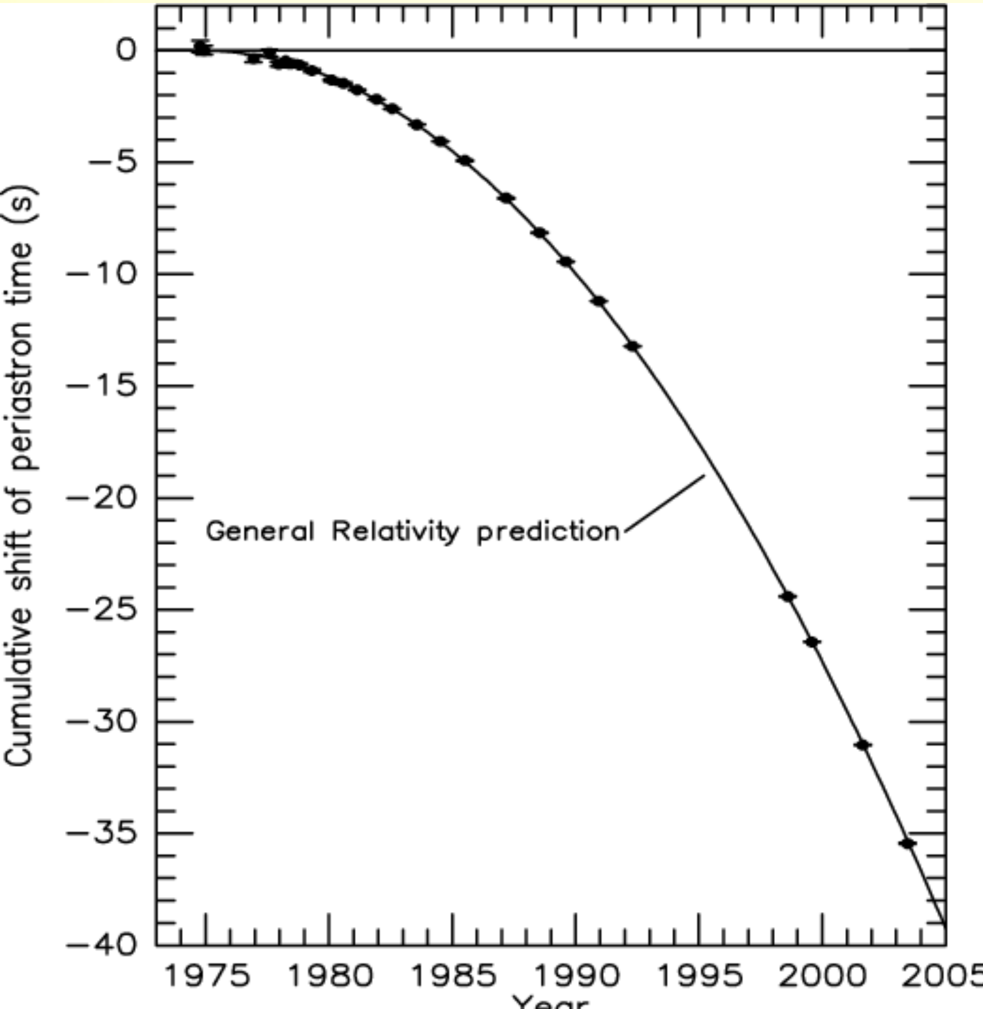
Figure 2. The radio maps of PKS 0723−008 over 12 epochs, represented on logarithmic scale with base 10. They were produced by processing the available VLBA visibilities provided by the MOJAVE team. Iso-flux density contours are in per cent of the peak flux density marked in the left upper corner of the 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.

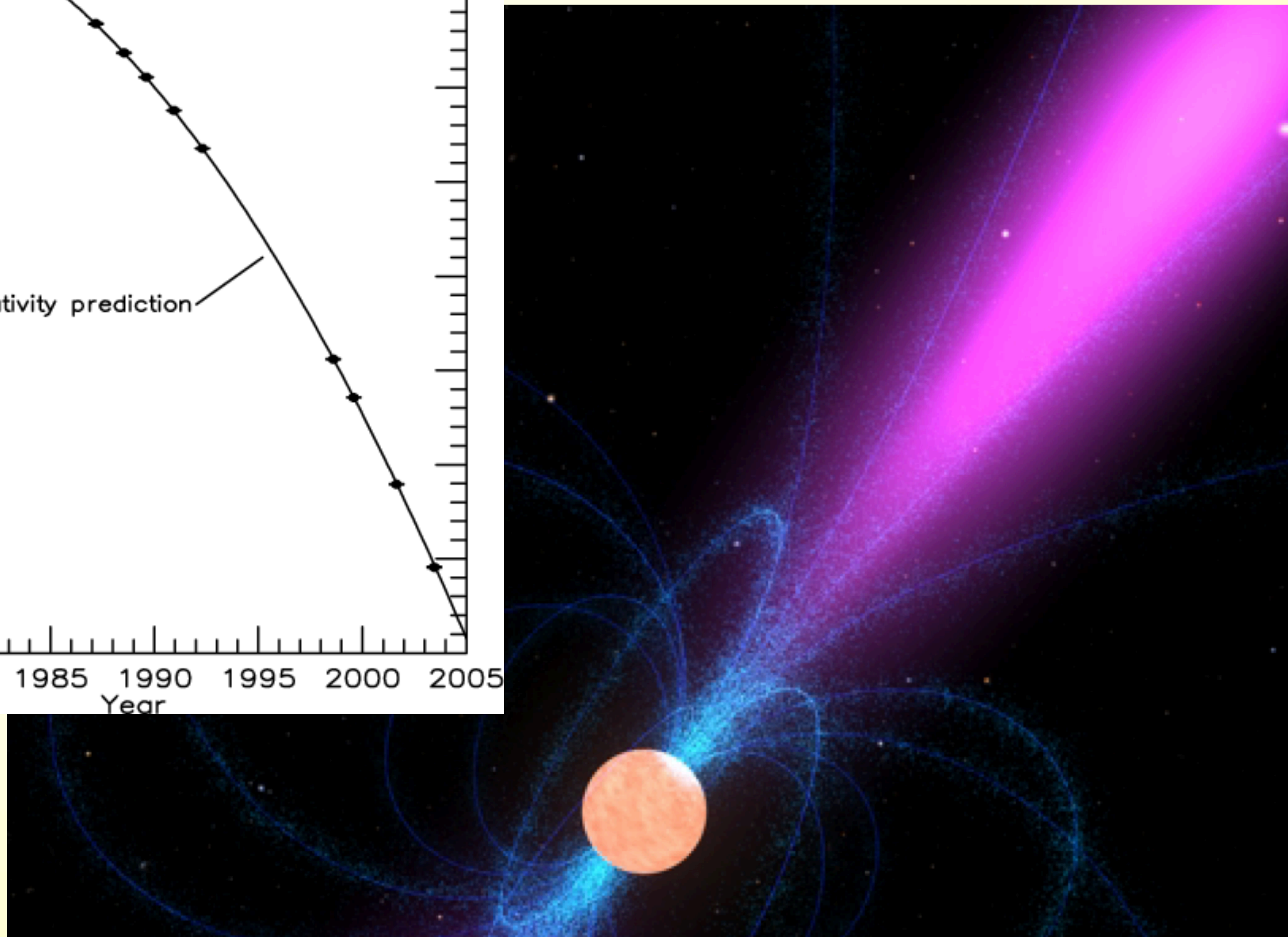
A flat-spectrum candidate for a track-type high-energy neutrino emission event, the case of blazar PKS 0723−008
E. Kun, P. L. Biermann, L. Á. Gergely, MNRAS **466,** L34–L38 (2017)

Gravitációs hullámok létezésének indirekt bizonyítéka: a Hulse-Taylor pulzár

A létező fizikai elméletek egyik legpontosabb igazolása:

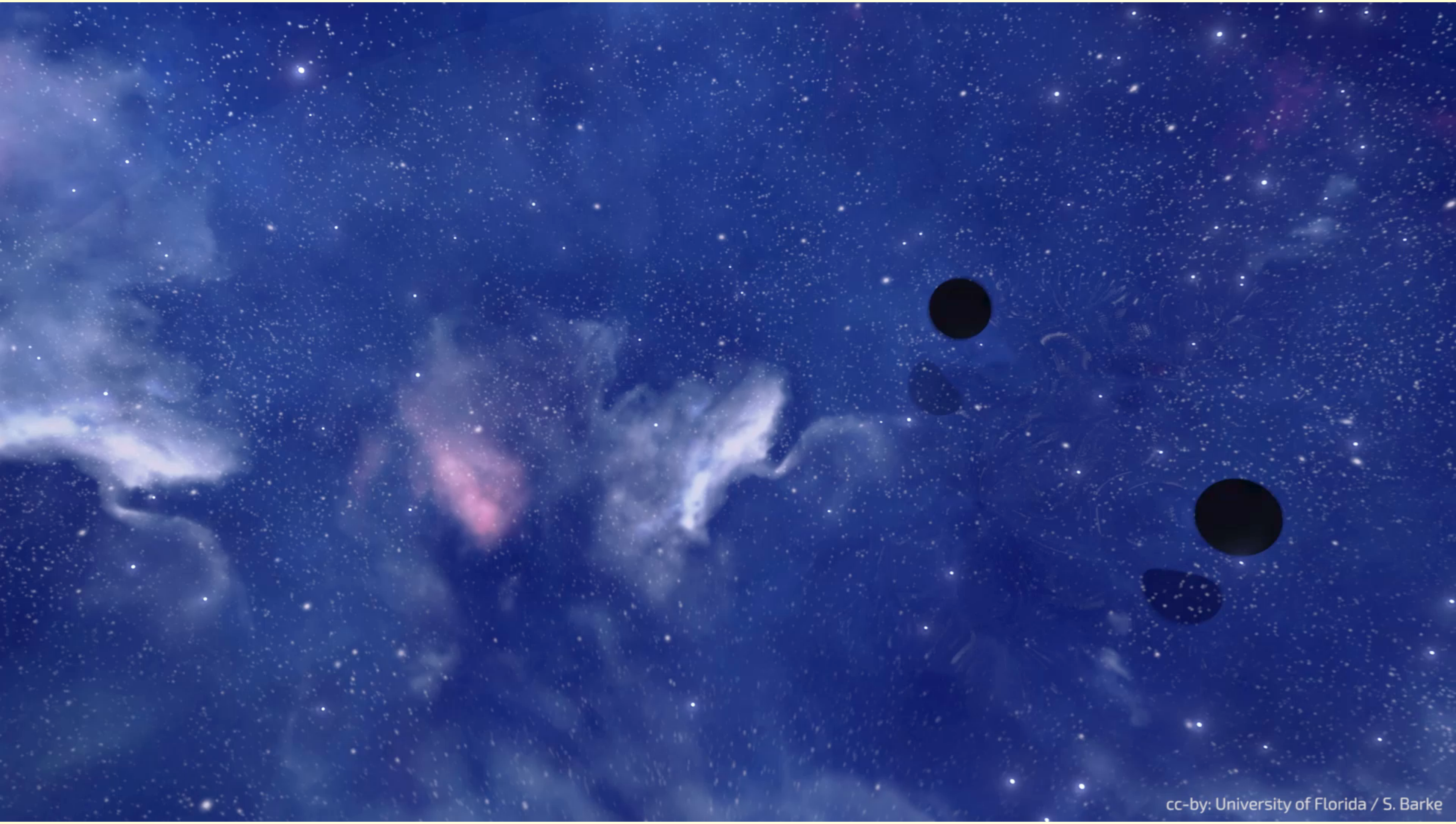
40s változás 30 év alatt !! $(4x10^{-8})$





Nobel-díj
1993

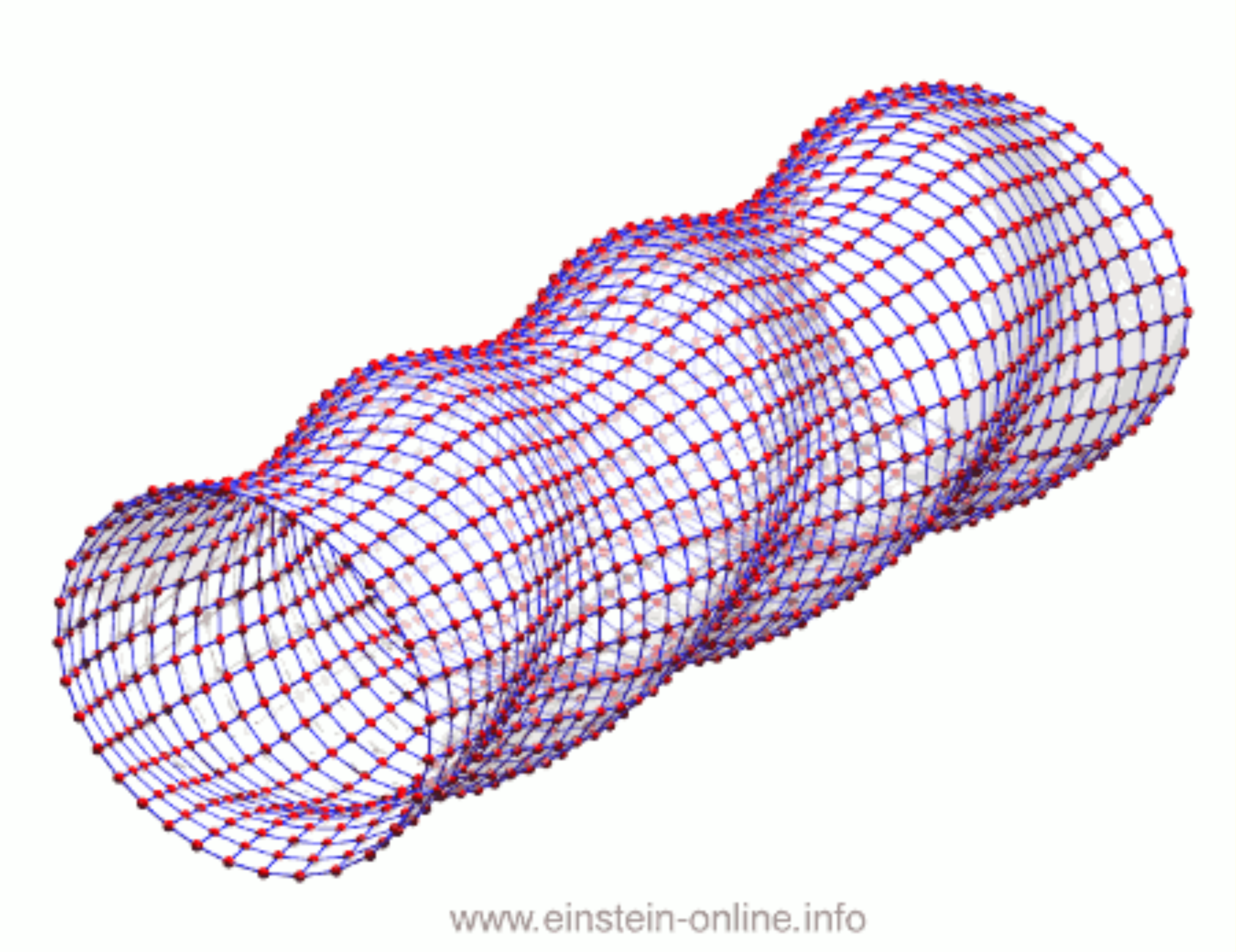
Ütköző feketelyuk-kettős gravitációs sugárzása



Mi történik, ha a gravitációs sugárzás a Földre ér?

Szerencsére nincs a közelünkben feketelyuk-kettős!!

A gravitációs hullám tranzverzális, 2 polarizációban, fénysebességgel terjed



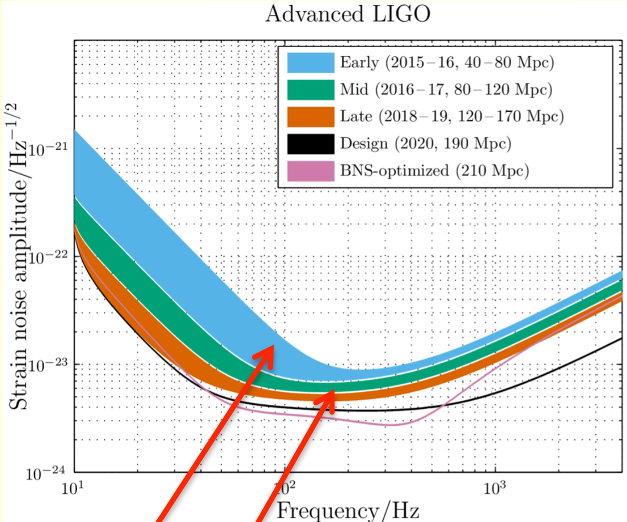
Második generációs interferometrikus gravitációshullám-detektorok hálózata

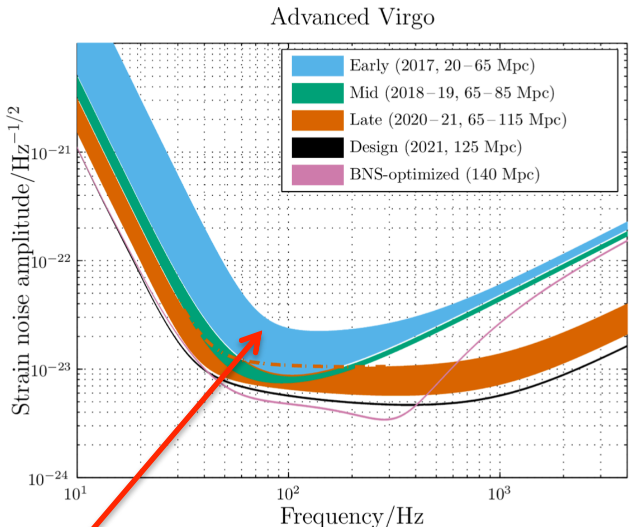
Advanced LIGO, Hanford, USA, 4km

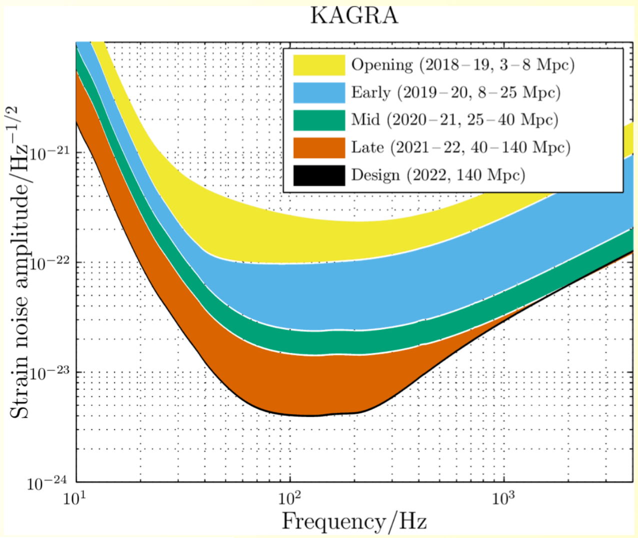
Advanced LIGO, Livingston, USA, 4km

Advanced Virgo, Cascina, Italy, 3km

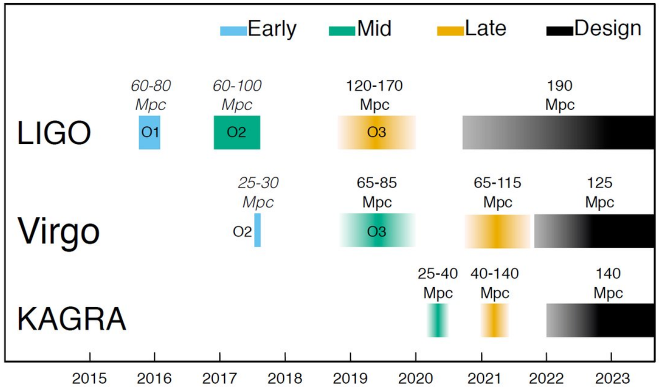
KAGRA, Kamioke, Japan, 3km







GW150914
GW151226
GW170104
GW170608
GW170814
GW170817



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

Szegedi Gravitációelméleti csoport LIGO tevékenysége

1. Gravitációs hullámok keresése

PyCBC csoportban résztvevő intézetek:

Amerikai Egyesült Államok:

- NASA Gravitational Astrophysics Laboratory
- California Institute of Technology
- Syracuse University
- Abilene Christian University

Egyesült Királyság: Cardiff University

Németország: Albert Einstein Institute, Hannover

Magyarország: Szegedi Tudományegyetem

Tápai Márton (SZTE)
az Advanced LIGO második mérési időszaka (O2) során
három mérési adatsor
PyCBC elemzéséért felelt,
melyből az egyik adatsor
gravitációs hullámot tartalmazott !

Szegedi Gravitációelméleti csoport LIGO tevékenysége

2. Gravitációs hullámok modellezése és feketelyuk-kettősök dinamikája:

Gergely Árpád László   Keresztes Zoltán

i. Relativisztikus effektusok (kaméleon pályák)

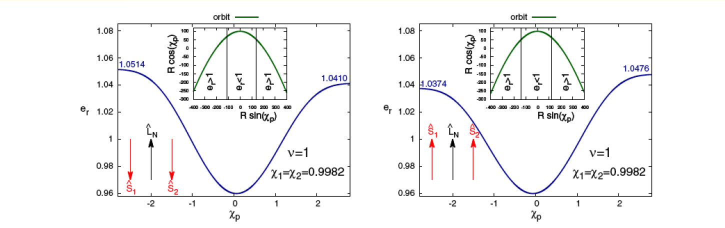
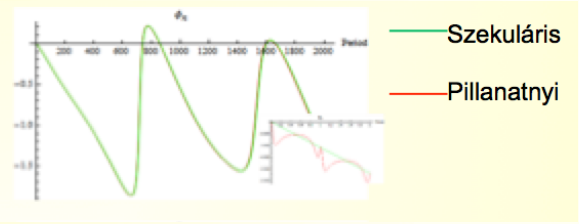
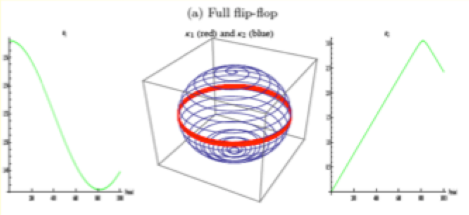


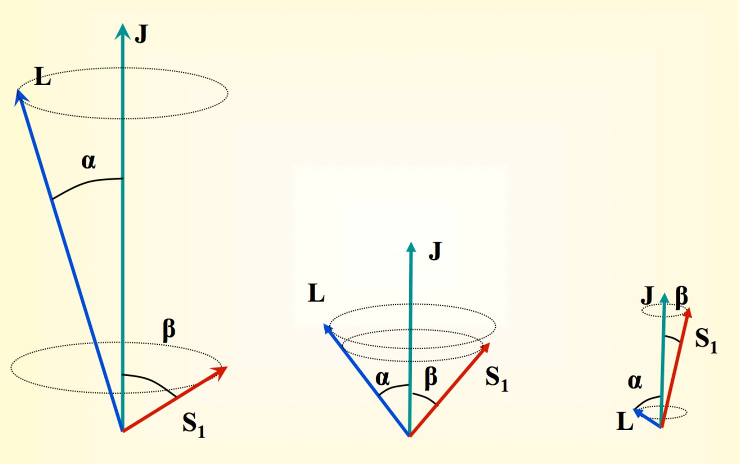
FIG. 2 (color online). Chameleon orbits due to 1PN and SO effects for binaries with equal masses and spins ($\chi_1 = \chi_2 = 0.9982$). The curves and initial conditions are as on Fig. 1. On the left (right) panel the spins are antialigned (aligned) with the orbital angular momentum.

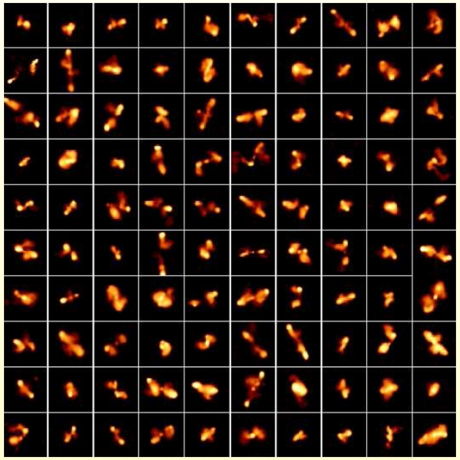
ii. Szekuláris fejlődés és effektusok (spin flip-flop jelenség)





iii. Spin-átfordulás jelensége → X-alakú rádiógalaxisok magyarázata

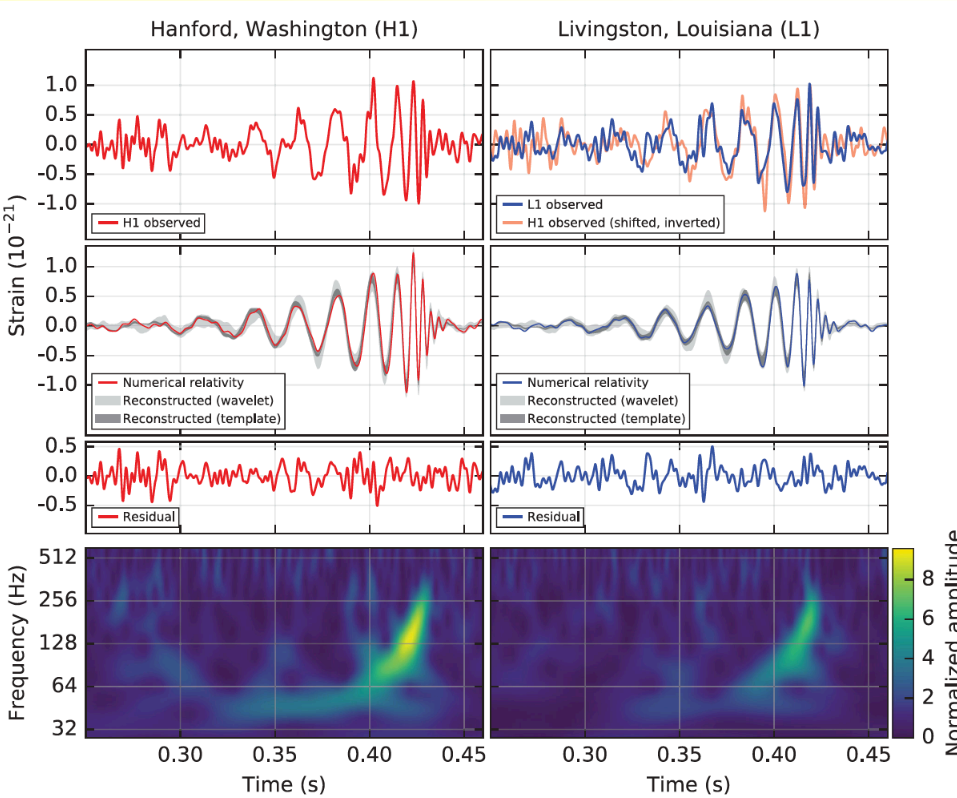




Peter Biermann
Inst. Radioastronomie Bonn

A gravitációs hullámok első közvetlen kimutatása: 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

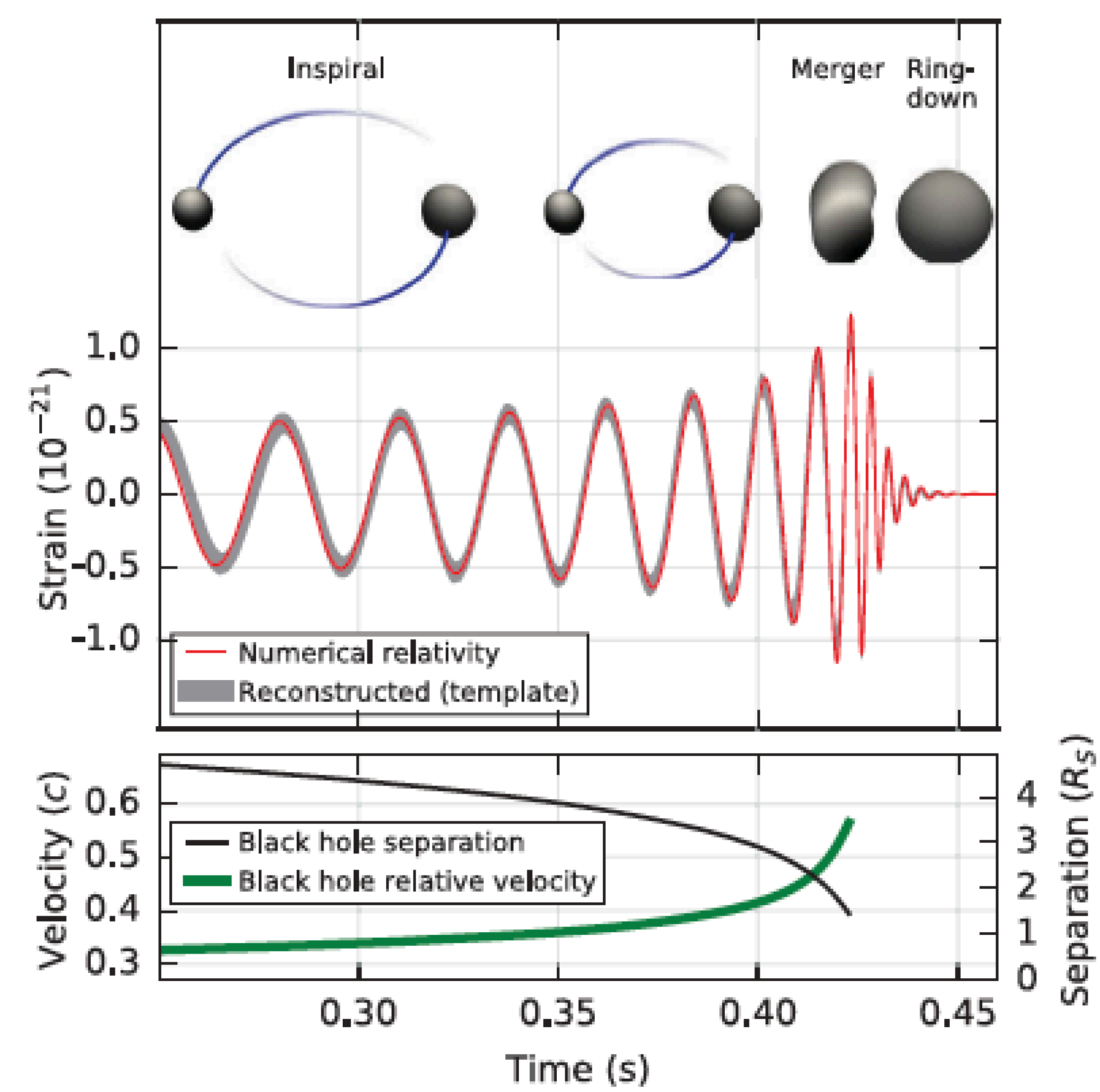
observed by	LIGO L1, H1	duration from 30 Hz	~ 200 ms
source type	black hole (BH) binary	# cycles from 30 Hz	~10
date	14 Sept 2015	peak GW strain	1 x 10^{-21}
time	09:50:45 UTC	peak displacement of interferometers arms	±0.002 fm
likely distance	0.75 to 1.9 Gly 230 to 570 Mpc	frequency/wavelength at peak GW strain	150 Hz, 2000 km
redshift	0.054 to 0.136	peak speed of BHs	~ 0.6 c
signal-to-noise ratio	24	peak GW luminosity	3.6 x 10^{56} erg s^{-1}
false alarm prob.	< 1 in 5 million	radiated GW energy	2.5-3.5 M⊙
false alarm rate	< 1 in 200,000 yr	remnant ringdown freq.	~ 250 Hz
Source Masses	M⊙	remnant damping time	~ 4 ms
total mass	60 to 70	remnant size, area	180 km, 3.5 x 10^5 km^2
primary BH	32 to 41	consistent with general relativity?	passes all tests performed
secondary BH	25 to 33		
remnant BH	58 to 67	graviton mass bound	< 1.2 x 10^{-22} eV
mass ratio	0.6 to 1	coalescence rate of binary black holes	2 to 400 Gpc^{-3} yr^{-1}
primary BH spin	< 0.7		
secondary BH spin	< 0.9	online trigger latency	~ 3 min
remnant BH spin	0.57 to 0.72	# offline analysis pipelines	5
signal arrival time delay	arrived in L1 7 ms before H1	CPU hours consumed	~ 50 million (=20,000 PCs run for 100 days)
likely sky position	Southern Hemisphere	papers on Feb 11, 2016	13
likely orientation	face-on/off	# researchers	~1000, 80 institutions in 15 countries
resolved to	~600 sq. deg.		

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 x 10^{12} km; Mpc=mega parsec=3.2 million lightyear, Gpc=10^3 Mpc, fm=femtometer=10^{-15} m, M⊙=1 solar mass=2 x 10^{30} kg

A gravitációs hullámok első közvetlen kimutatása: GW150914

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



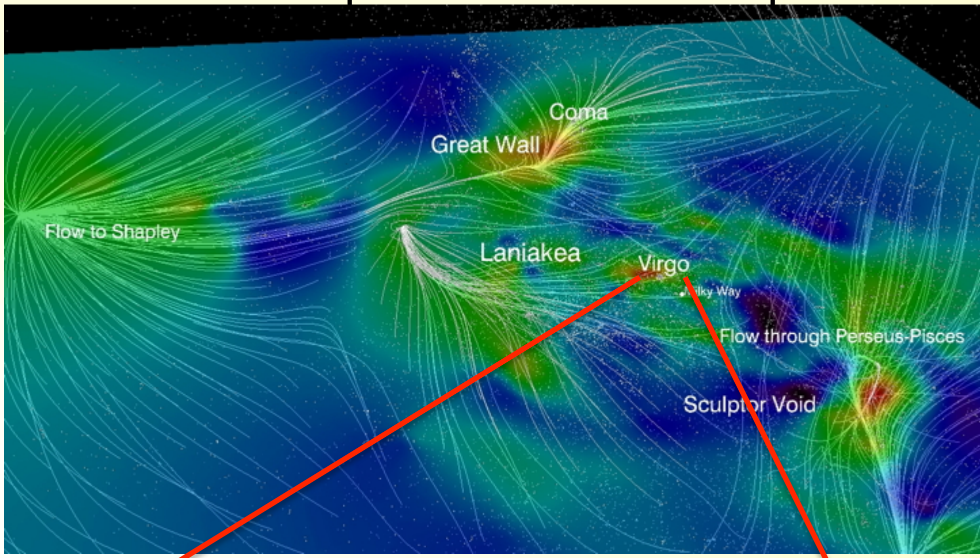
29 és 36 naptömegű fekete lyukak összeolvadása →
0,05 sec alatt 3 naptömegnyi energia szabadult fel gravitációs hullámok formájában
=
a Paksi Atomerőmű 10^{31} évi energiatermelése !

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

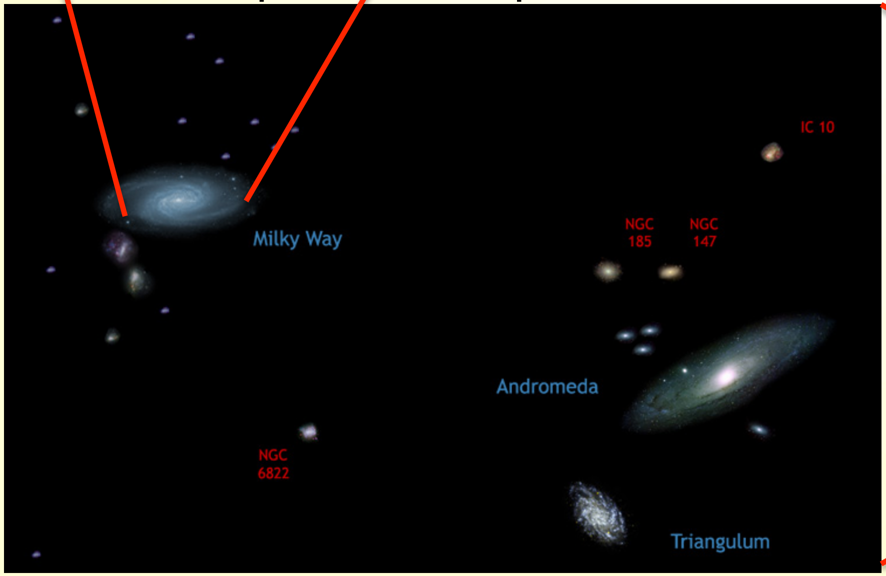
Honnan is jött a GW150914 gravitációs hullám? (230-500 Mpc)

Tejútrendszer ~ 30 kpc

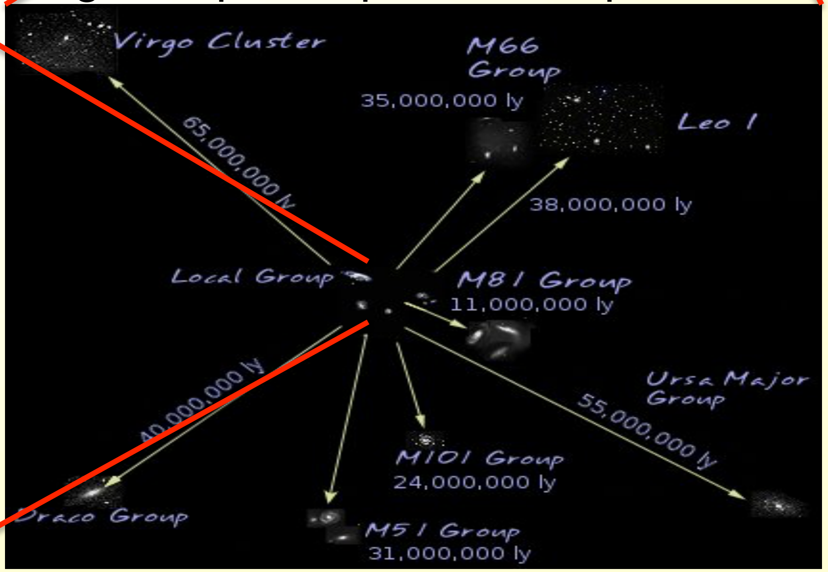
Laniakea szuperklaszter ~ 160 Mpc



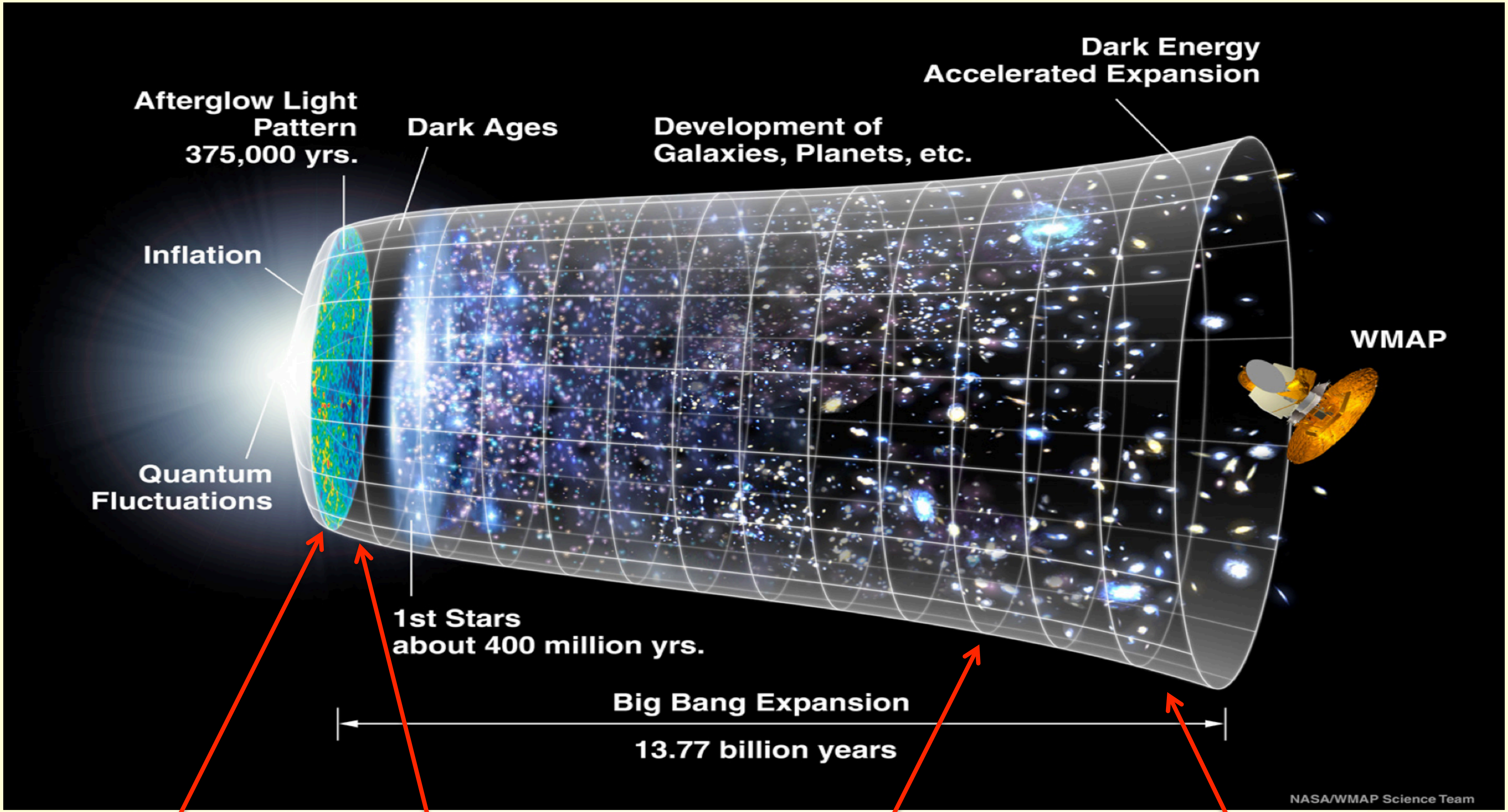
Lokális Csoport ~ 3,1 Mpc



Virgo szupercsoport ~ 33 Mpc



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



Ősrobbanás
(13,7 milliárd év)

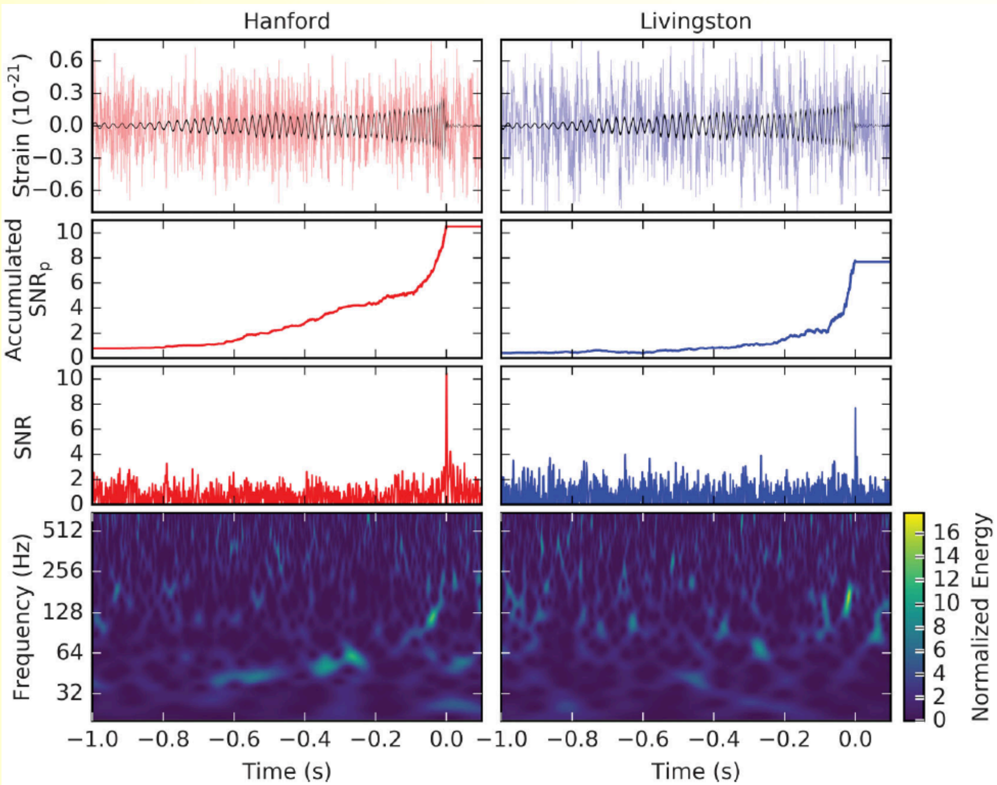
Sötét Korszak
innen fény nem,
de gravitációs hullám
érkezhet hozzánk!!

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

A gravitációs hullámok második közvetlen kimutatása: GW151226

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



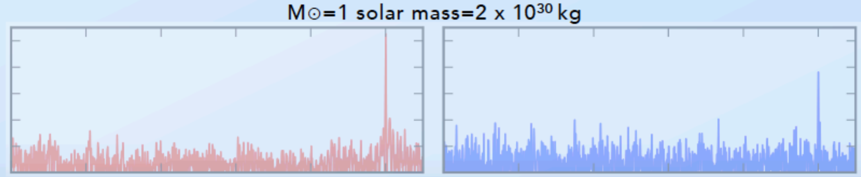
GW151226: FACTSHEET

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
source type	black hole (BH) binary
date	26 Dec 2015
time	03:38:53 UTC
distance	250 to 620 Mpc
redshift	0.05 to 0.13
signal-to-noise ratio	13
false alarm prob.	~ 1 in 10 million
Source Masses	M⊙
total mass	20 to 28
primary BH	11 to 23
secondary BH	5 to 10
remnant BH	19 to 27
mass ratio	> 0.28
spin of one of the black holes	> 0.2
remnant BH spin	0.7 to 0.8
resolved to	~850 sq. deg.

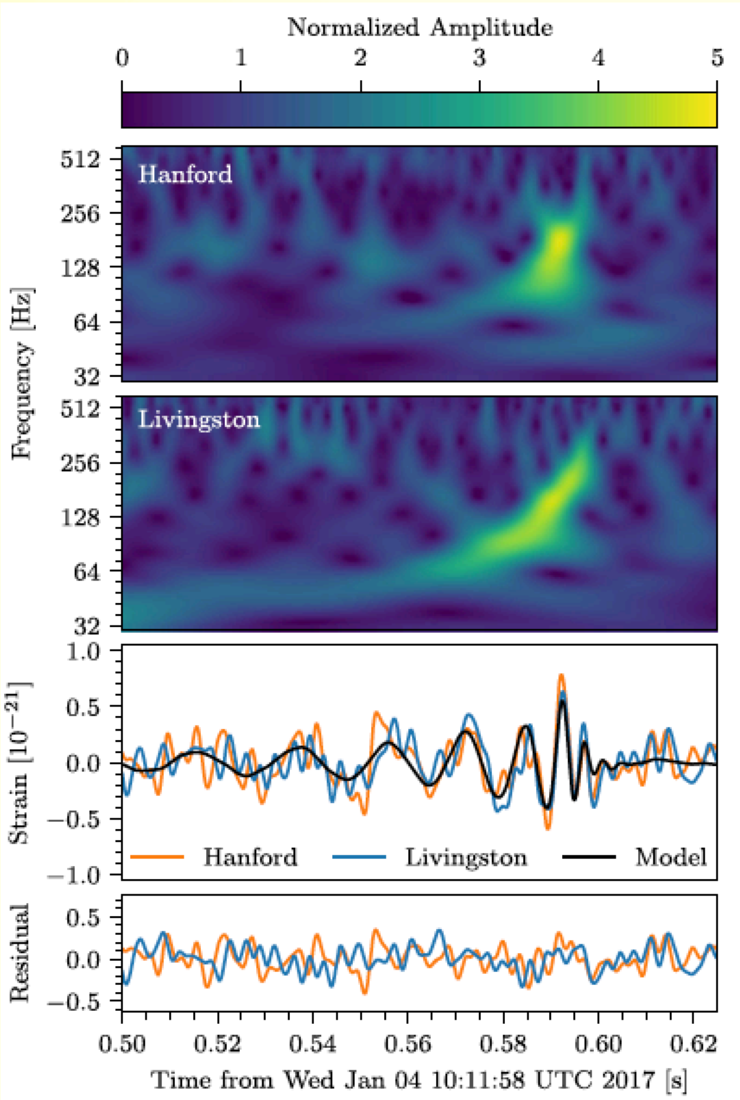
duration from 35 Hz	~1 s
# cycles from 35 Hz	~55
signal arrival time delay	arrived in H1 1 ms after L1
peak GW strain	~ 3.4×10^{-22}
peak displacement of interferometers arms	~ ±0.7 am
frequency/wavelength at peak GW strain	420 Hz, 710 km
peak speed of BHs	~ 0.6 c
peak GW luminosity	2 to 4×10^{56} erg s^{-1}
radiated GW energy	0.8-1.1 M⊙
remnant ringdown freq.	~ 750 Hz
remnant damping time	~ 1.3 ms
remnant size, area	60 km, 3.5×10^4 km^2
online trigger latency	~ 67 s
# 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=2×10^{30} kg



A gravitációs hullámok harmadik közvetlen kimutatása: 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)

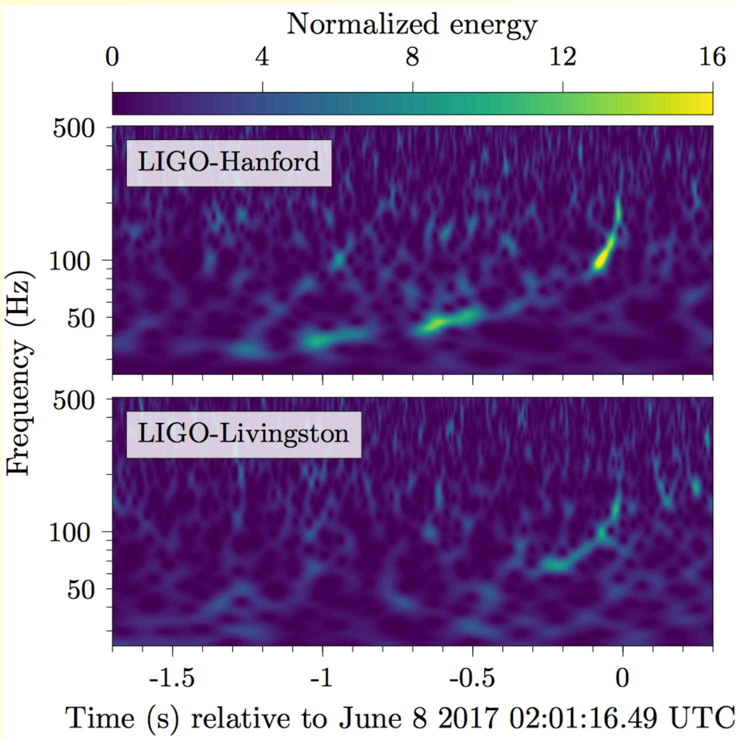
observed by	LIGO L1, H1
source type	black hole (BH) binary
date	04 Jan 2017
time	10:11:58.6 UTC
signal-to-noise ratio	13
false alarm rate	< 1 in 70,000 years
probability of astrophysical origin	> 0.99997
distance	1.6 to 4.3 billion light-years
redshift	0.10 to 0.25
total mass	46 to 57 $M_\odot$
primary 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 × 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 × 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

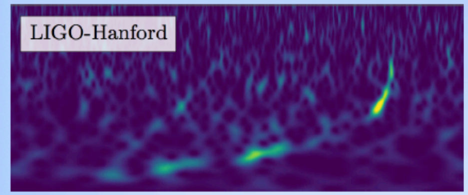
Parameter ranges correspond to 90% credible intervals.
Acronyms:
L1/H1=LIGO Livingston/Hanford, am=attometer=10^{-18} m, $M_\odot$=1 solar mass=2 x 10^{30} kg

A gravitációs hullámok negyedik közvetlen kimutatása: GW170608

arXiv:1711.05578 (2017)



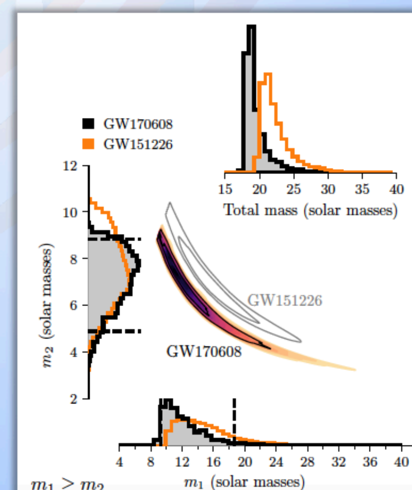
GW170608 FACTSHEET



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 $M_\odot c^2$

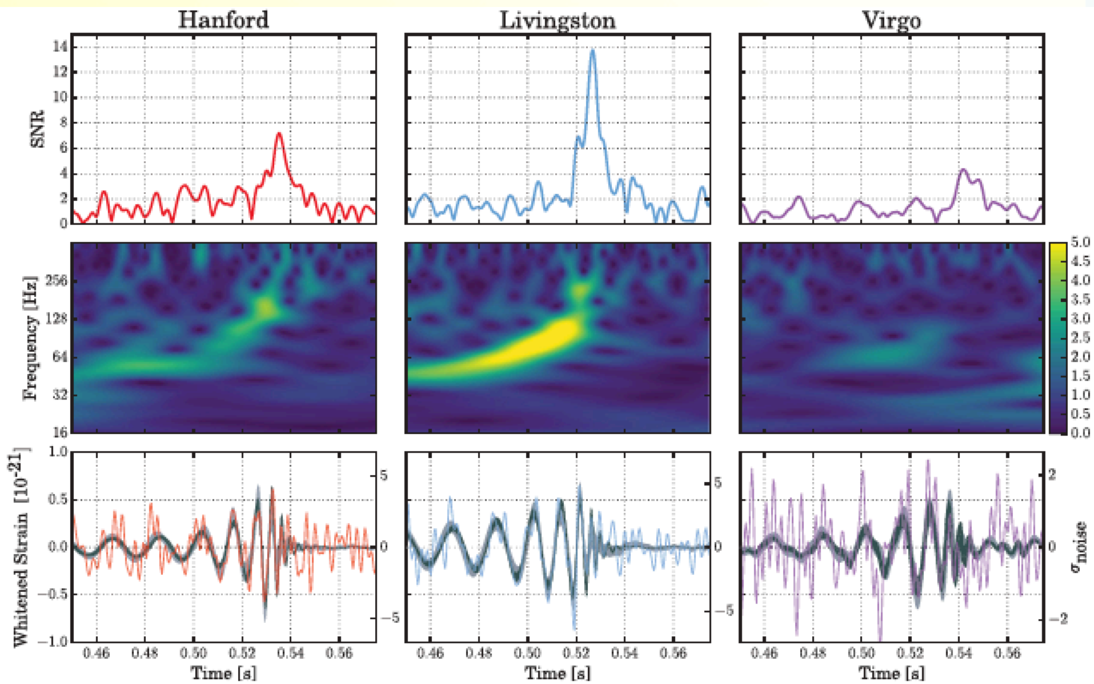
duration from 30 Hz	~ 2 s
# of GW cycles from 30 Hz	~ 100
signal arrival time delay	arrived at H ~ 7 ms before L
HL sky area†	~ 520 deg^2
peak GW strain (10^{-22})	~ 4 (H), 3 (L)
peak stretch of interferometer arm	~ ± 0.8 am (H), 0.6 am (L)
frequency at peak GW strain	453 to 610 Hz
wavelength at peak 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

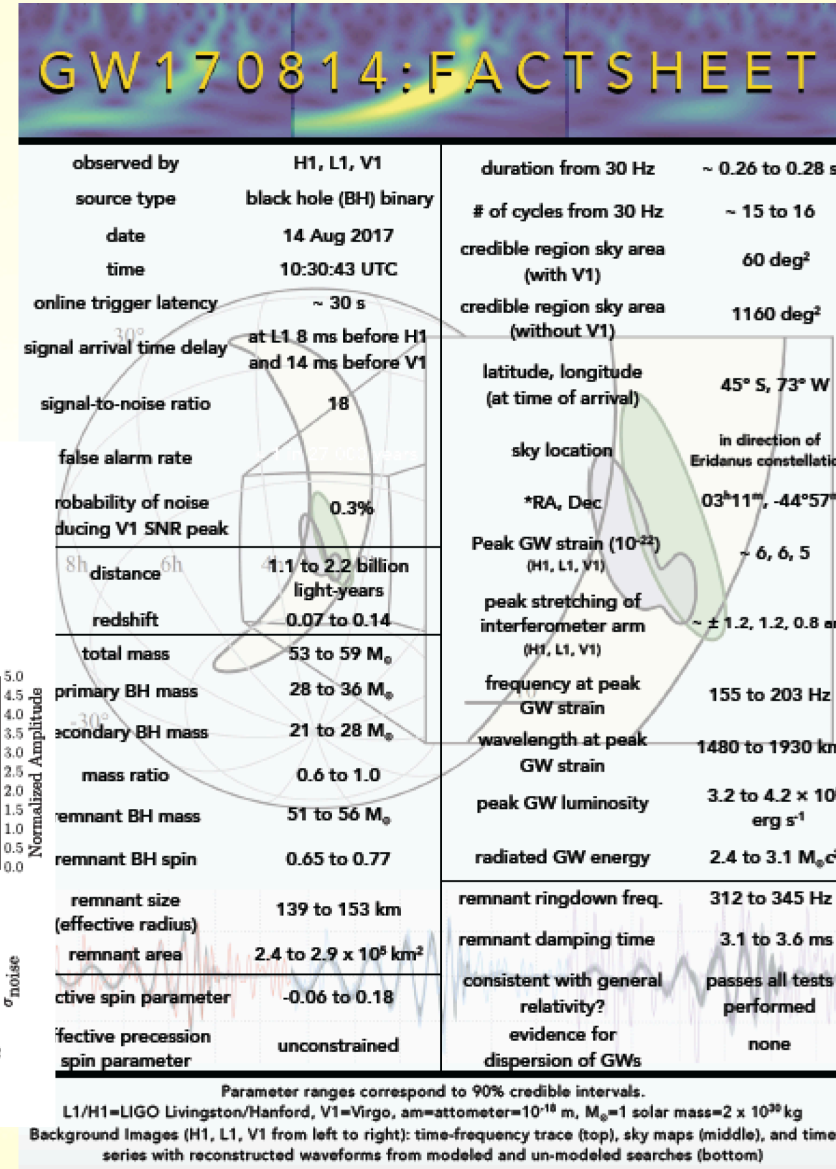
Images: time-frequency traces (top), mass distributions (bottom right)
GW=gravitational wave, $M_\odot$=1 solar mass=2x10^{30} kg, am=attometer (10^{-18} m), H/L=LIGO Hanford/Livingston
Parameter ranges are 90% credible intervals.
†90% credible region



A gravitációs hullámok ötödik közvetlen kimutatása: GW170814

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

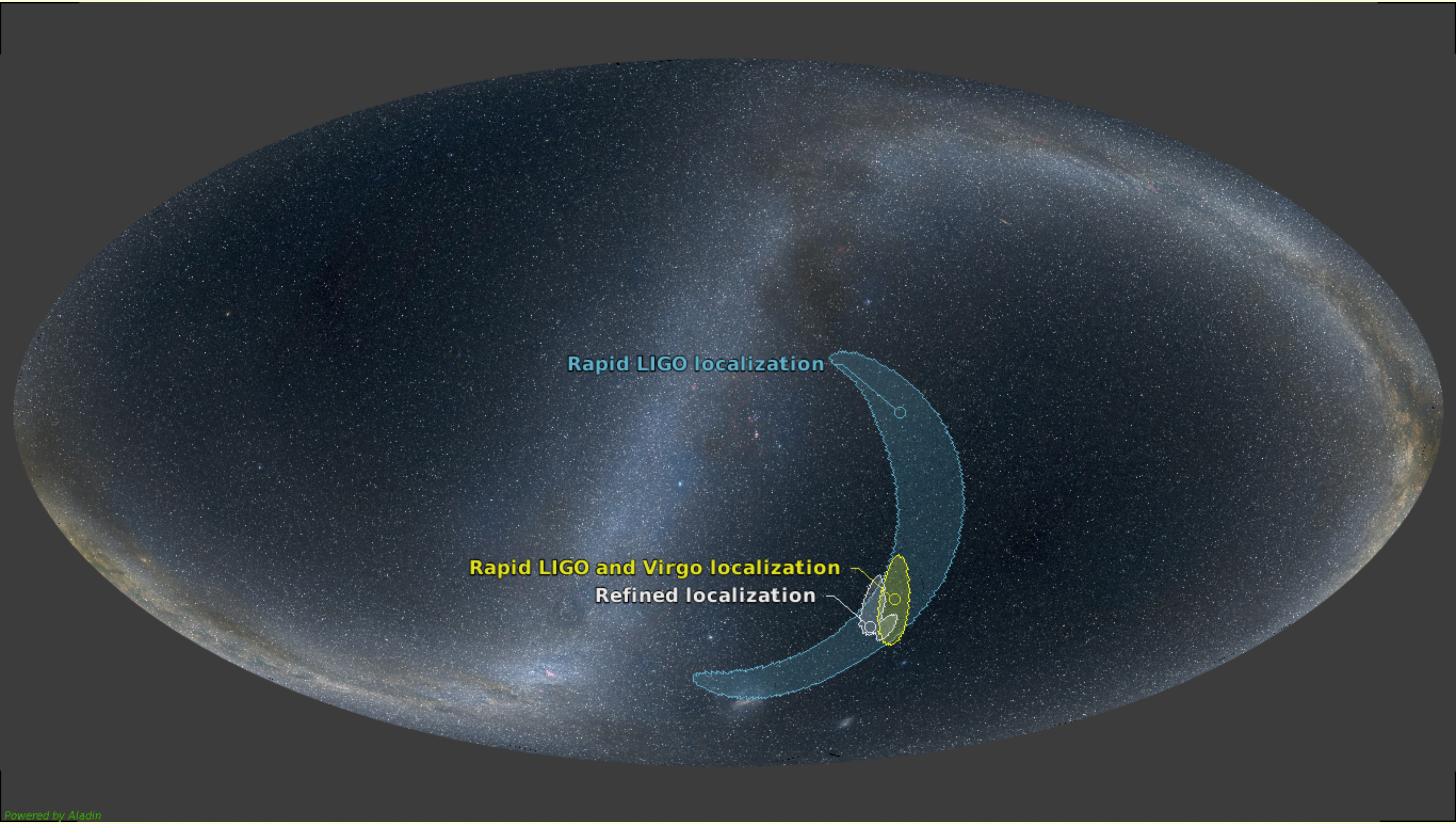



GW170814:FACTSHEET

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
probability of noise producing 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 $M_\odot c^2$
secondary 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
remnant 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		
effective spin parameter	-0.06 to 0.18		
effective precession spin parameter	unconstrained		

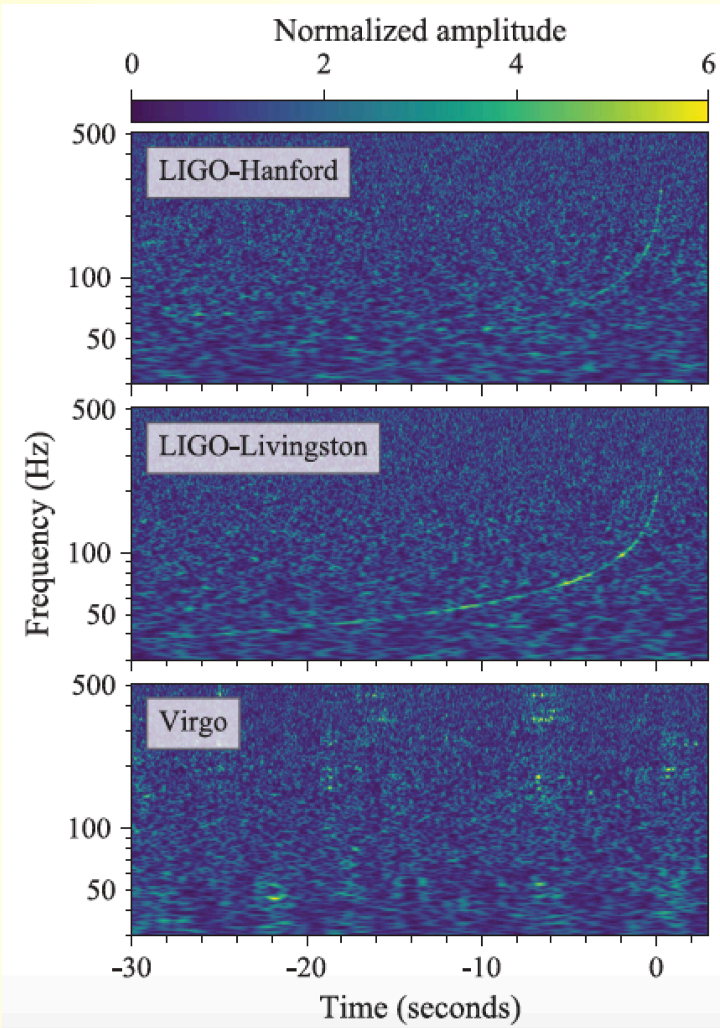
Parameter ranges correspond to 90% credible intervals.
L1/H1=LIGO Livingston/Hanford, V1=Virgo, am=attometer=10^{-18} m, $M_\odot$=1 solar mass=2 x 10^{30} kg
Background Images (H1, L1, V1 from left to right): time-frequency trace (top), sky maps (middle), and time series with reconstructed waveforms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

A harmadik detektor szerepe a lokalizációban

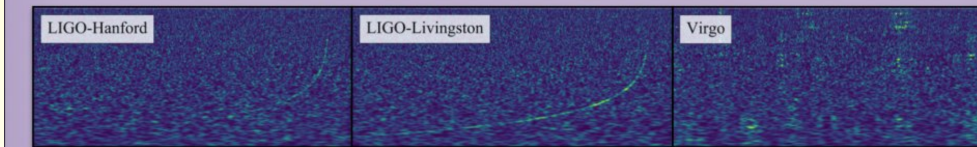


A gravitációs hullámok hatodik közvetlen kimutatása: GW170817

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

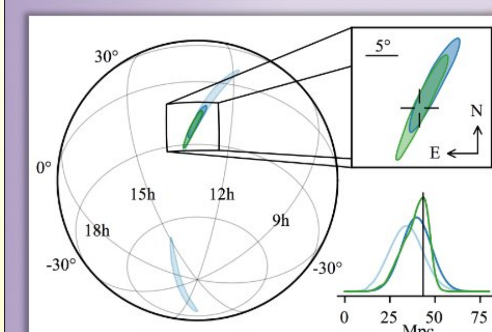


GW170817 FACTSHEET



observed by	H, L, V
source type	binary neutron star (NS)
date	17 August 2017
time of merger	12:41:04 UTC
signal-to-noise ratio	32.4
false alarm rate	< 1 in 80 000 years
distance	85 to 160 million light-years
total mass	2.73 to 3.29 $M_\odot$
primary NS mass	1.36 to 2.26 $M_\odot$
secondary NS mass	0.86 to 1.36 $M_\odot$
mass ratio	0.4 to 1.0
radiated GW energy	> 0.025 $M_\odot c^2$
radius of a 1.4 $M_\odot$ NS	likely ≲ 14 km
effective spin parameter	-0.01 to 0.17
effective precession spin parameter	unconstrained
GW speed deviation from speed of light	< few parts in 10^{15}

inferred duration from 30 Hz to 2048 Hz**	~ 60 s
inferred # of GW cycles from 30 Hz to 2048 Hz**	~ 3000
initial astronomer alert latency*	27 min
HLV sky map alert latency*	5 hrs 14 min
HLV sky area†	28 deg^2
# of EM observatories that followed the trigger	~ 70
also observed in	gamma-ray, X-ray, ultraviolet, optical, infrared, radio
host galaxy	NGC 4993
source RA, Dec	$13^h09^m48^s$, -23°22'53"
sky location	in Hydra constellation
viewing angle (without and with host galaxy identification)	≤ 56° and ≤ 28°
Hubble constant inferred from host galaxy identification	62 to 107 km s^{-1} Mpc^{-1}

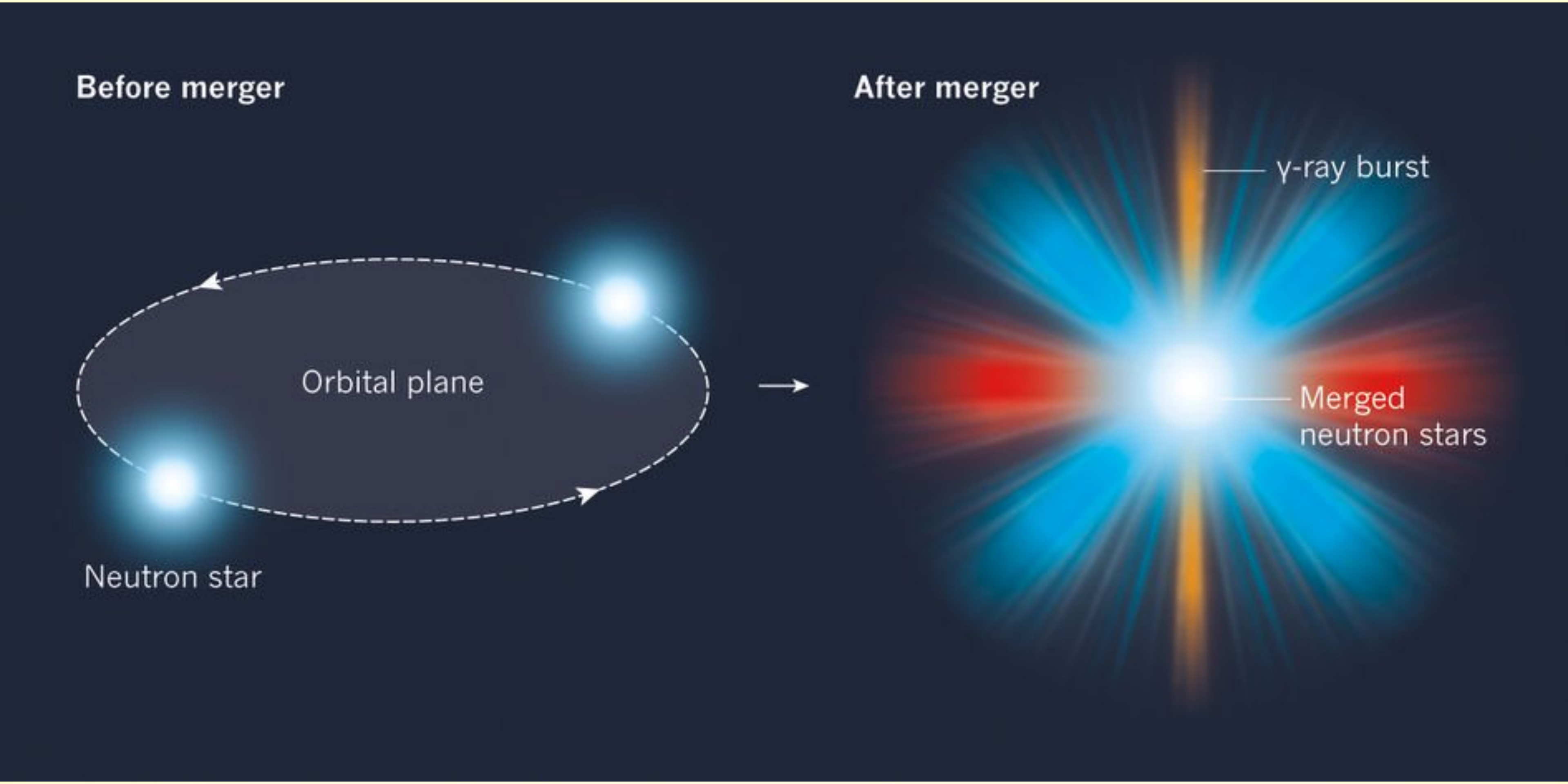


Images: time frequency traces (top), GW sky map (left, HL = light blue, HLV = dark blue, improved HLV = green, optical source location = cross-hair)

GW=gravitational wave, EM = electromagnetic, $M_\odot$=1 solar mass=2x10^{30} kg, H/L=LIGO Hanford/Livingston, V=Virgo

Parameter ranges are 90% credible intervals.
*referenced to the time of merger
**maximum likelihood estimate
†90% credible region

GW170817 keletkezése



GW170817 és a kísérő gamma-kitörés

GW170817 és kísérőjelenségeinek felfedezése

GW170817

Binary neutron star merger

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

H L V

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.

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

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

+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

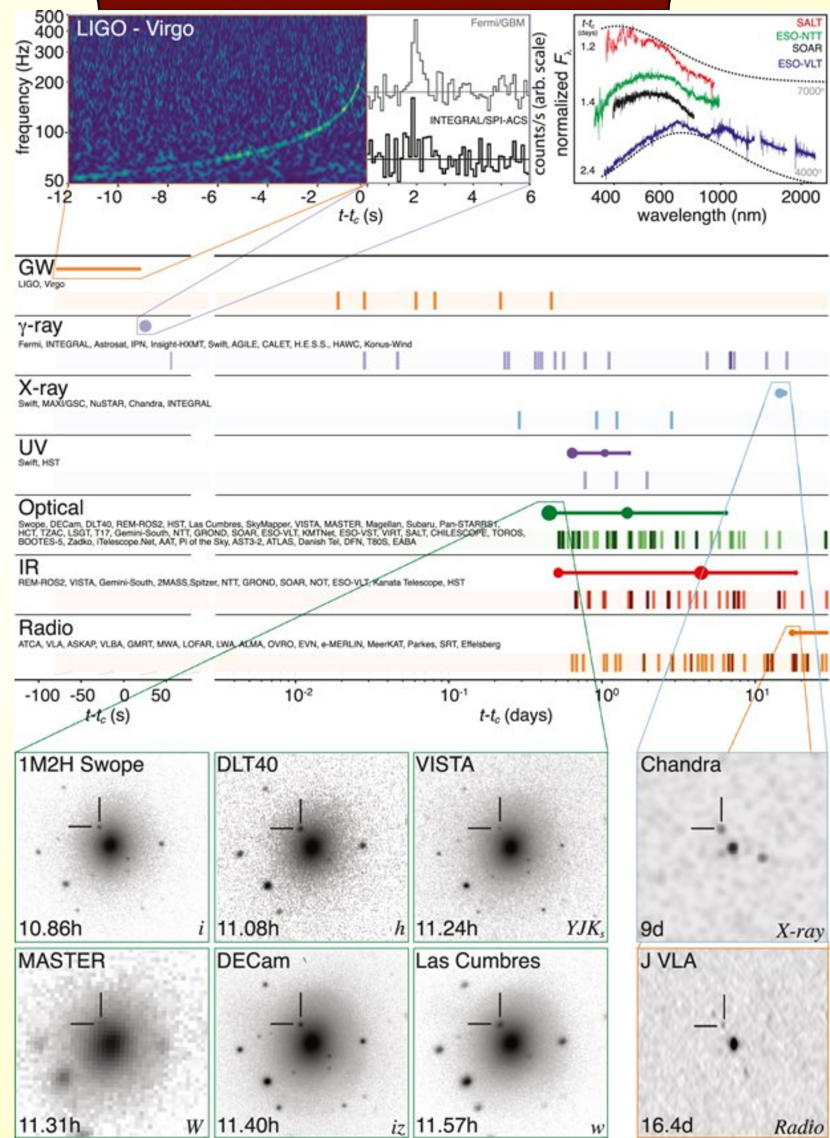
Detecting gravitational waves from a neutron star merger allows us to find out more about the structure of these unusual objects.

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

Au

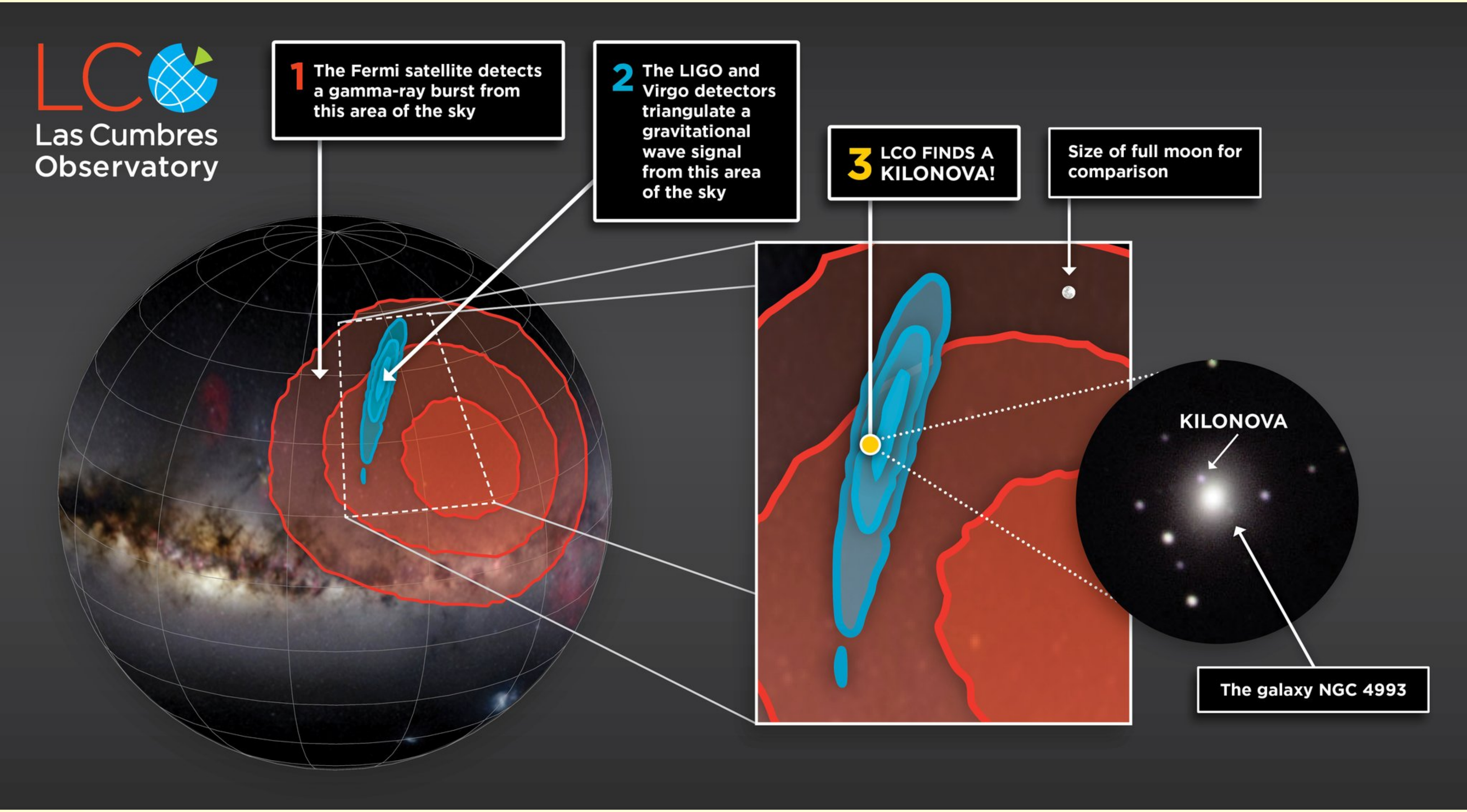
The observation of a kilonova allowed us to show that neutron star mergers could be responsible for the production most of the heavy elements, like gold, in the universe.

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

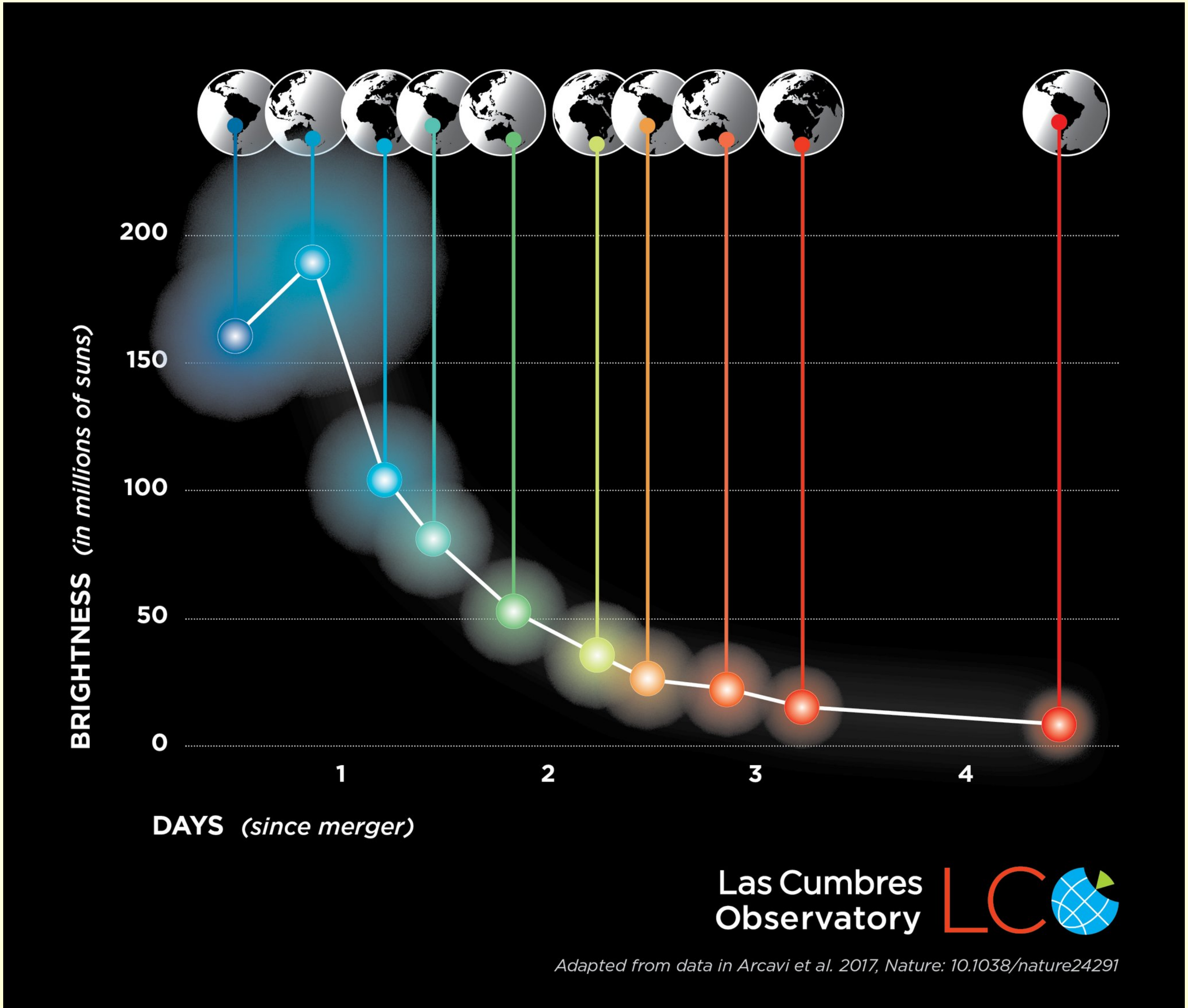


GW170817 és kísérőjelenségeinek felfedezése

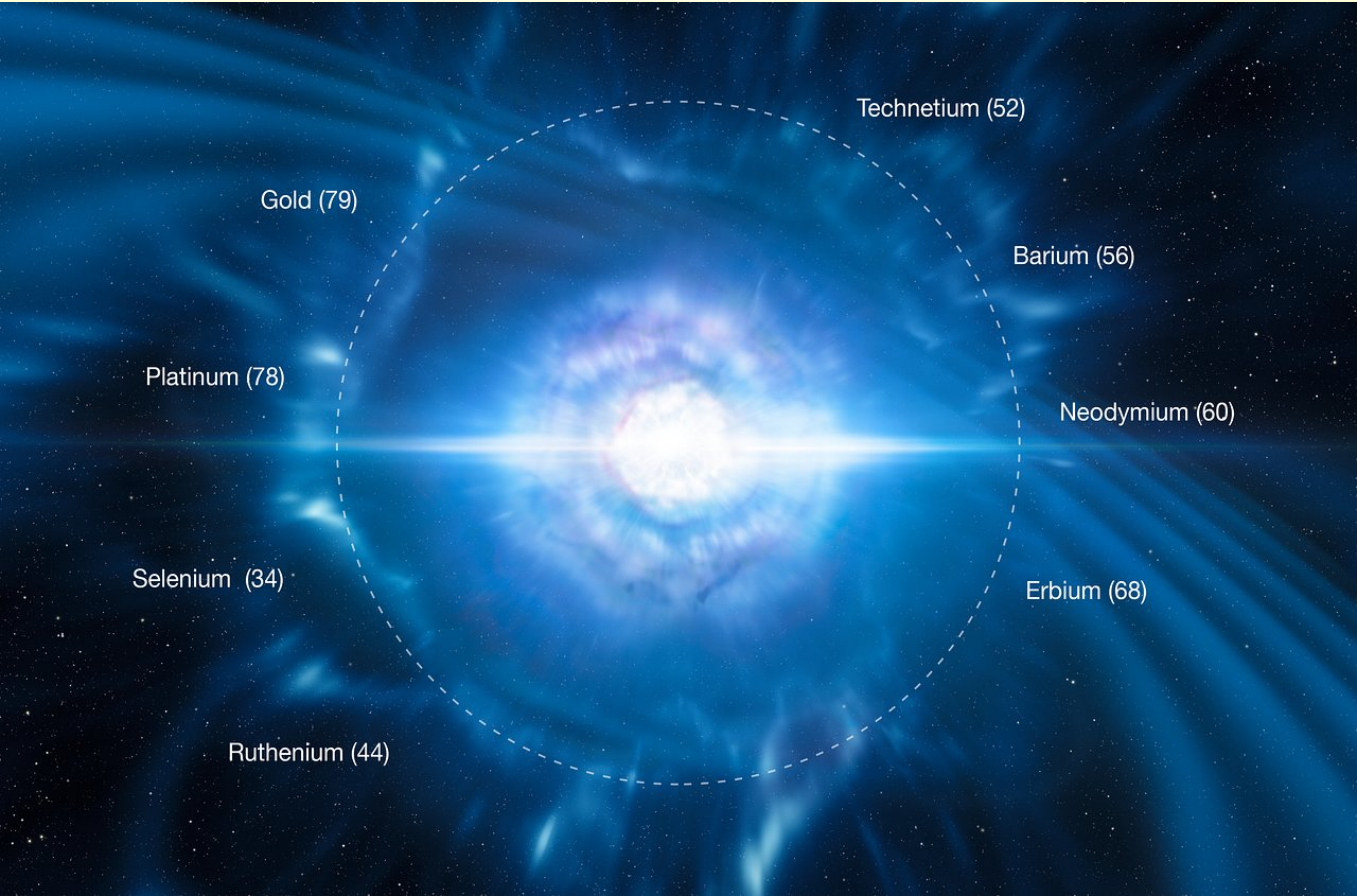
GW170817 és kísérőjelenségeinek felfedezése



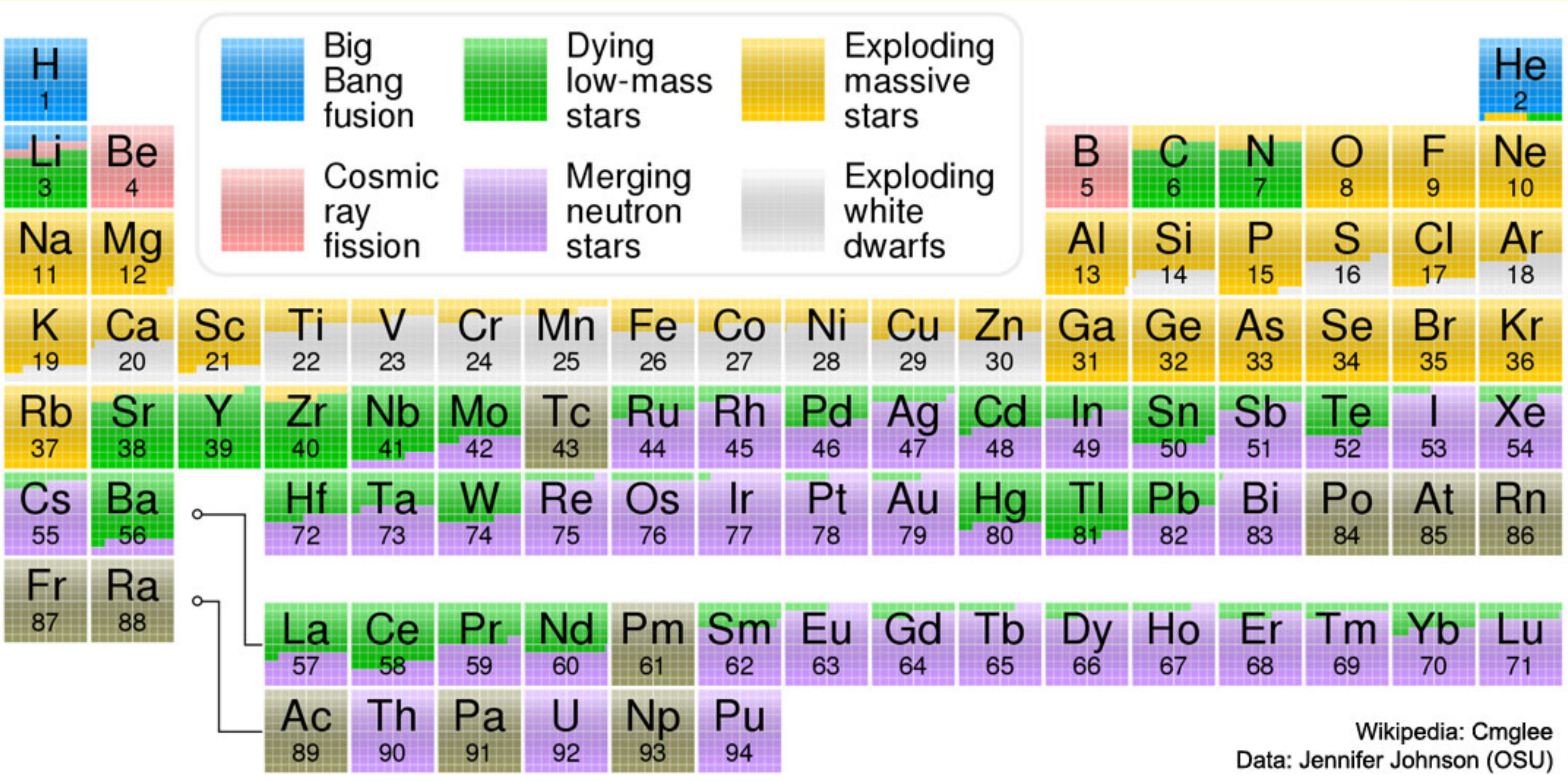
GW170817 maradványa: kilonóva



GW170817: nehéz elemek keletkezése

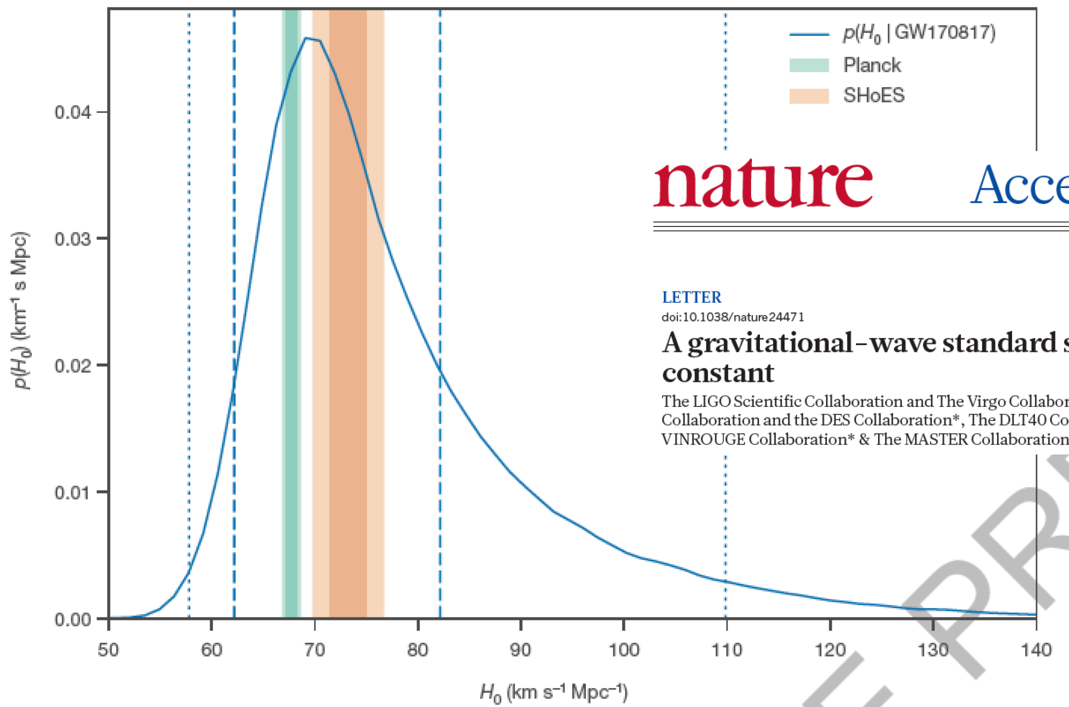


GW170817: nehéz elemek keletkezése



GW170817 kozmológiai következményei

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. Marginalized posterior density for H_0 (blue curve). Constraints at 1σ and 2σ from Planck[20] and SHoES[21] are shown in green and orange. The maximum a posteriori value and minimal 68.3% credible interval from this PDF 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.

1. Gravitációs hullám forrásának paraméterbecslése
   → d_L luminozitás-távolság
2. optikai tranziensmeghatározésa: a forrás az NGC 4993 galaxistól legfeljebb 10 arcsec-ra található
   → pekuliáris sebesség meghatározása
3. Elektromágneses spektrum vöröseltolódásának mérése
   → v_H kozmológiai tágulási sebesség

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

→ Hubble állandó

Lokális Lorentz-invariancia sértés 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:

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

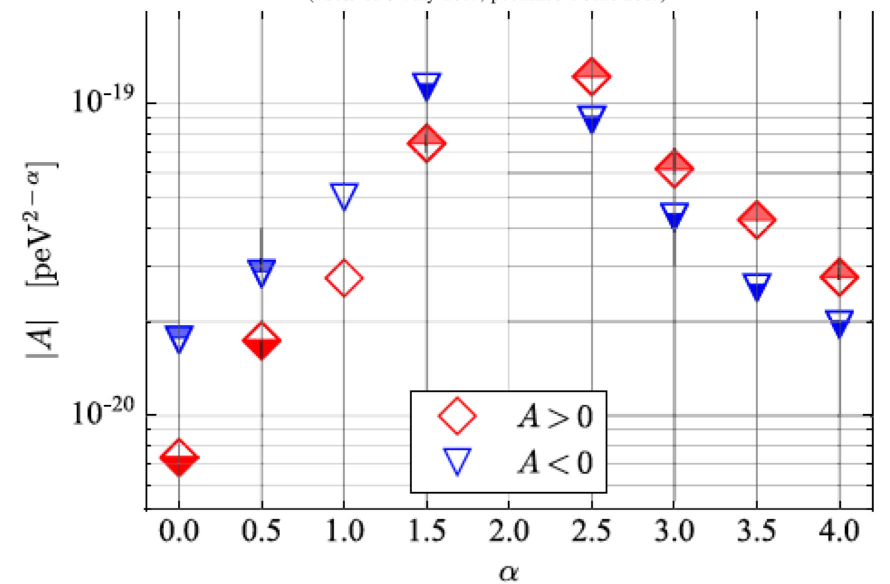
N. Yunes, K. Yagi, and F. Pretorius, Phys. Rev. D 94, 084002 (2016).

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)

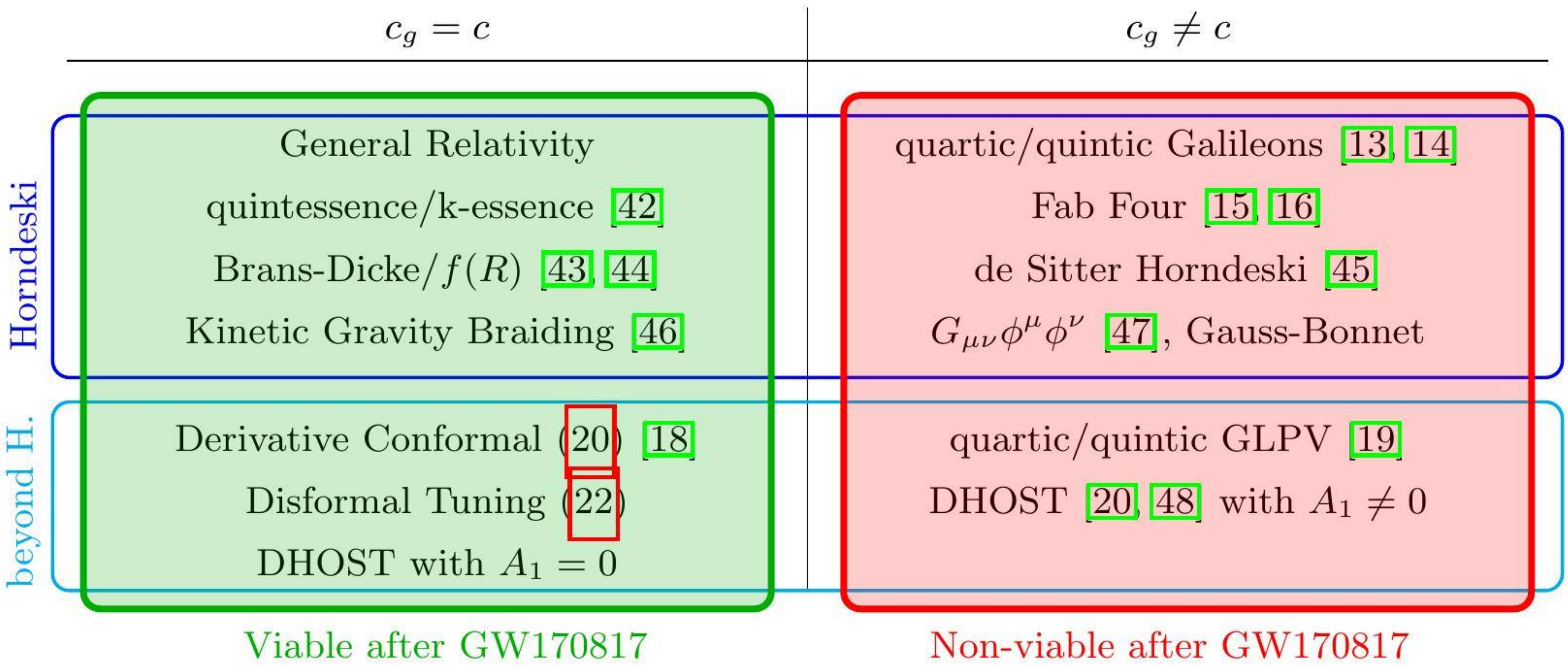


Első GH-kból levezetett kényszer a Lorentz-invariancia sértésre !

Az első 3 észlelt GH-ból:

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

Korlátok a módosított gravitációelméletekre



[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

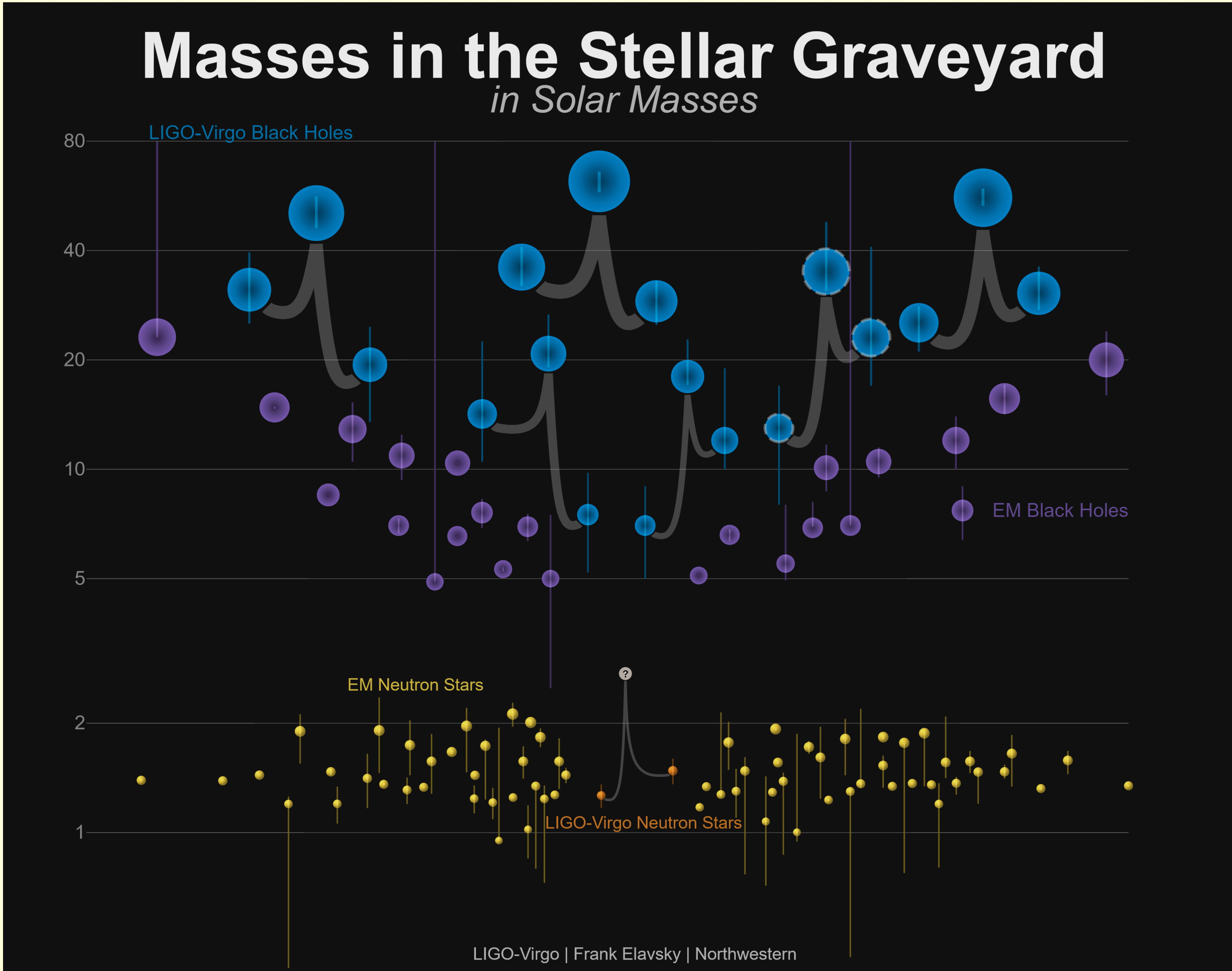
Paolo Creminelli, Filippo Vernizzi

Comments: 5 pages

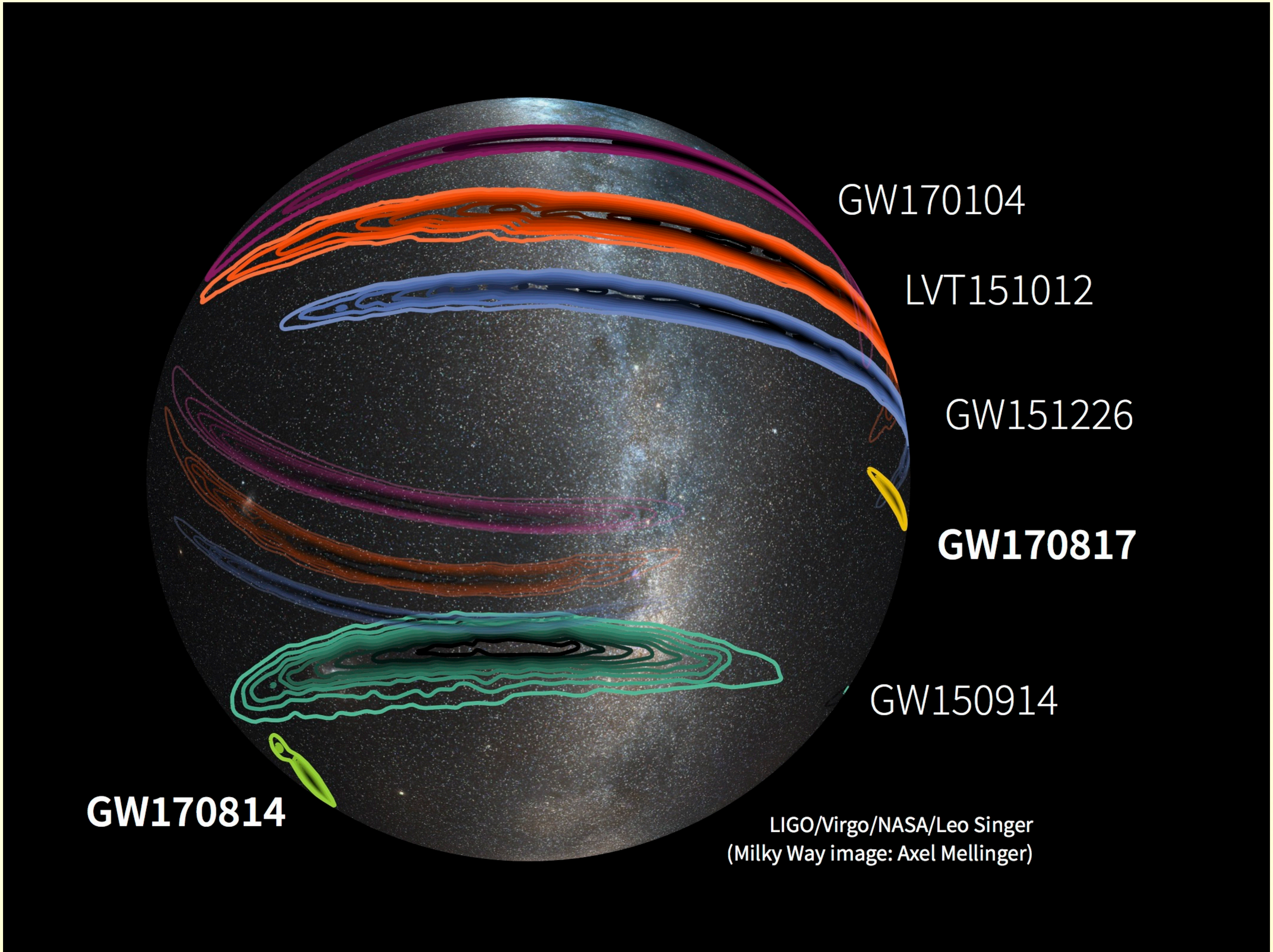
Subjects: **Cosmology and Nongalactic Astrophysics (astro-ph.CO)**; General Relativity and Quantum Cosmology (gr-qc); High Energy Physics -

A hullámok összehasonlítása

Források tömegei



Források égi helyzete



Fizikai Nobel-díj 2017

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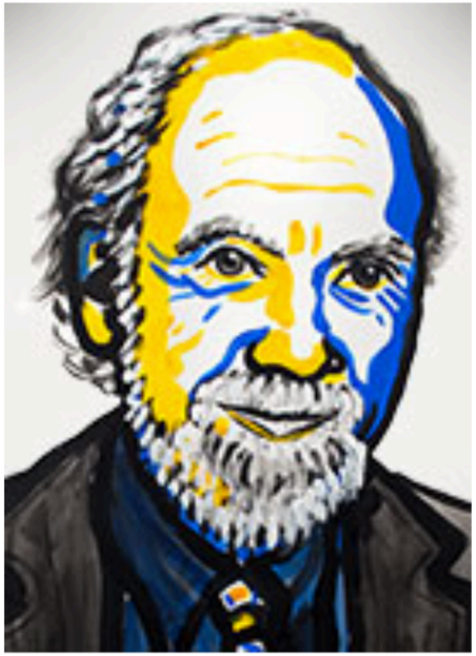
Rainer Weiss

Prize share: 1/2



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Barry C. Barish

Prize share: 1/4

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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"*.

A LIGO Tudományos Kollaboráció által elnyert egyéb kitüntetések

2016

Special Breakthrough Prize in Fundamental Physics

https://breakthroughprize.org/News/32

BREAKTHROUGH PRIZE

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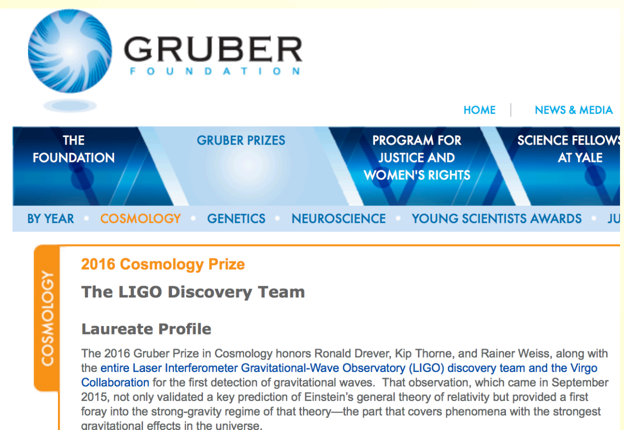
SPECIAL BREAKTHROUGH PRIZE IN FUNDAMENTAL PHYSICS AWARDED FOR DETECTION OF GRAVITATIONAL WAVES 100 YEARS AFTER ALBERT EINSTEIN PREDICTED THEIR EXISTENCE

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

http://gruber.yale.edu/cosmology/2016/ligo-discovery-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

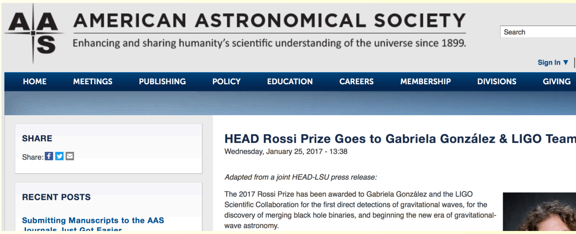
Citation for the 2017 RAS Group Achievement Award 'A'
The Laser Interferometer Gravitational-Wave Observatory (LIGO) team

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

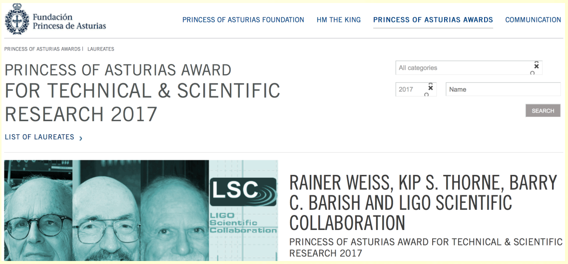
Wednesday, January 25, 2017 - 13:38

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=0&anio=2017&especifica=0



Ami a GW150914 után történt: LIGO India – jóváhagyva !

02/18/2016

LIGO-India Gets Green Light

Following this month's announcement of the first observation of gravitational waves arriving at the earth from a cataclysmic event in the distant universe, the Indian Cabinet, chaired by Prime Minister Shri Narendra Modi, has granted in-principle approval to the Laser Interferometer Gravitational-wave Observatory in India (LIGO-India) Project. The project will build an Advanced LIGO Observatory in India, a move that will significantly improve the ability of scientists to pinpoint the sources of gravitational waves and analyze the signals. Approval was granted on February 17, 2016.

Ami a GW150914 után történt: LISA Pathfinder

NATURE | BREAKING NEWS

Successful test drive for space-based gravitational wave detector

Mission paves the way for

Elizabeth Gibney

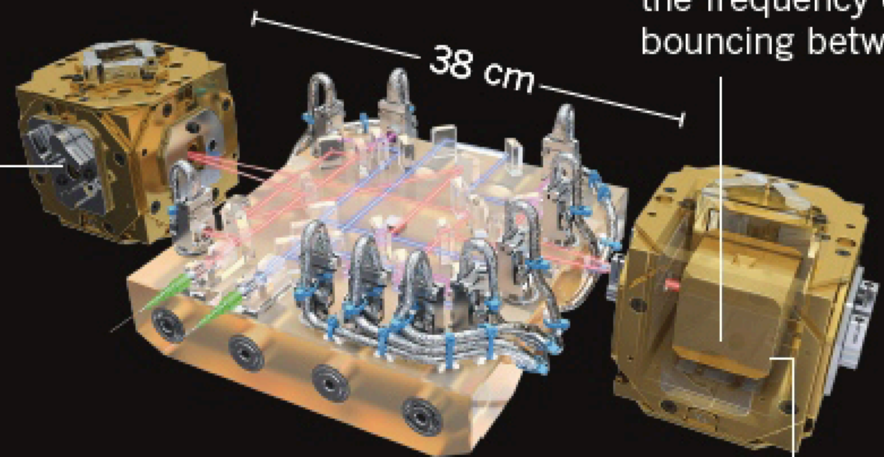
25 February 2016

PRECISION LAB IN SPACE

LISA Pathfinder has shown that an intricate experiment consisting of two metal cubes in freefall, isolated from all forces except gravity, can operate in space.

At the heart of Pathfinder are two free-falling metal cubes, shielded from all forces except gravity by their housing.

Any disturbance to the relative motion of the cubes affects the frequency of the laser bouncing between them.



The housing monitors each cube's position and commands the craft to move so that the cube is always at its centre.

The cubes float in a vacuum, surrounded by instruments that mitigate stray forces.

Megnyitotta az utat a LISA fellövéséhez

A GW150914 után: az inflációs korszakban született gravitációs hullámok detektálásának terve

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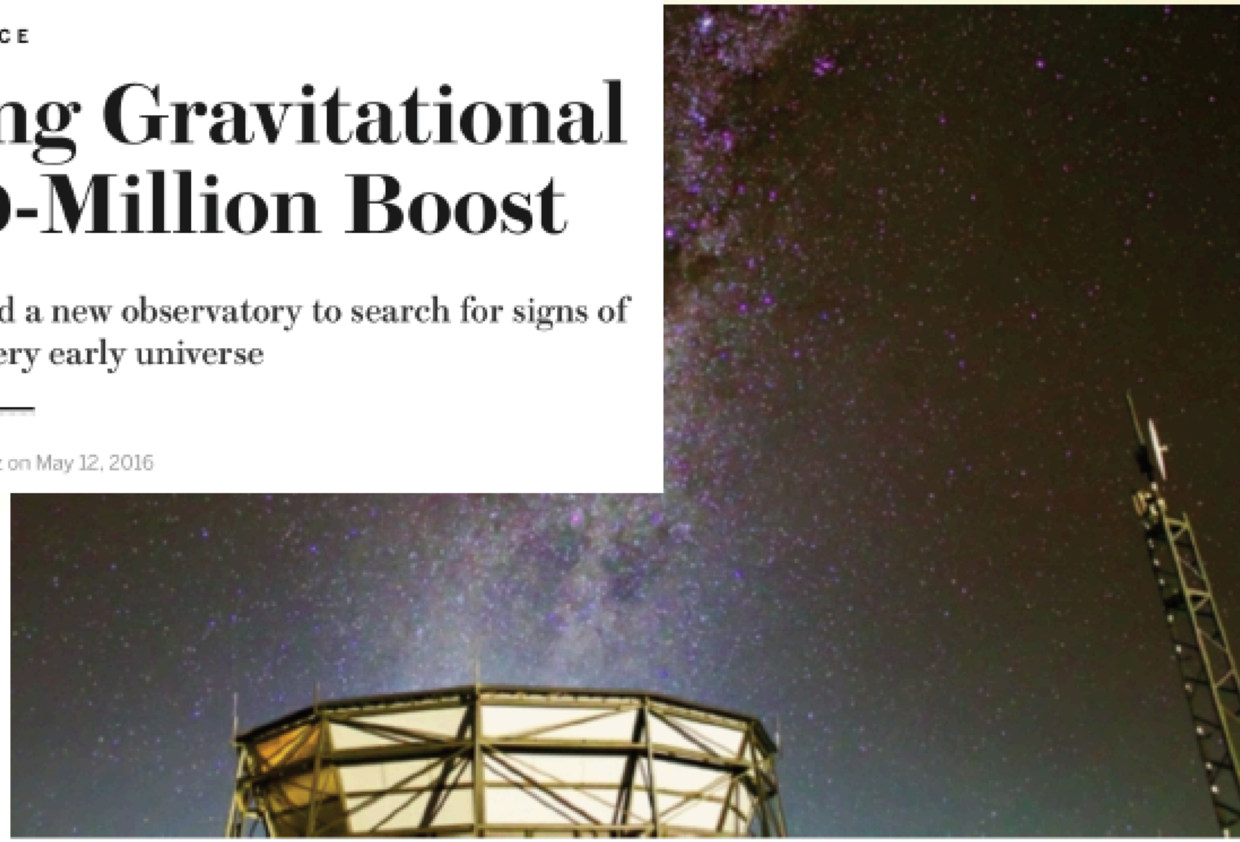
SPACE

Hunt for Big Bang Gravitational Waves Gets $40-Million Boost

The nonprofit Simons Foundation will fund a new observatory to search for signs of stretching in the very early universe

By Clara Moskowitz on May 12, 2016

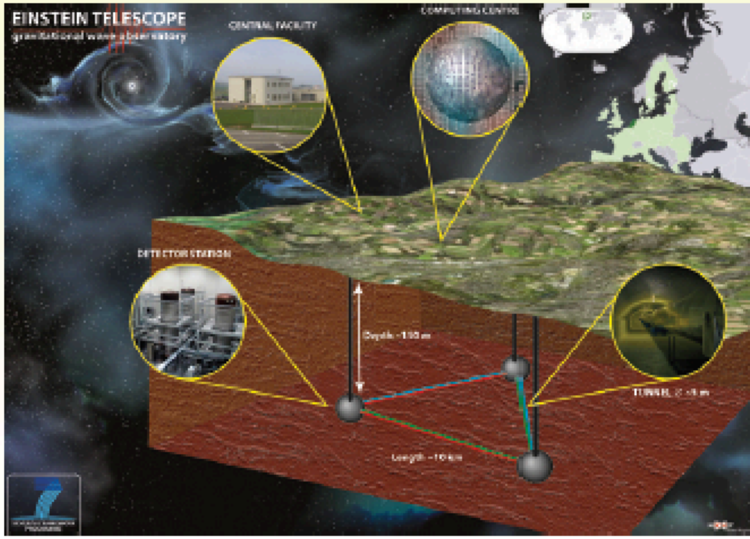
Gravitációs hullámok keresése a kozmikus mikrohullámú háttérsugárzás polarizációnak B-módusaiból

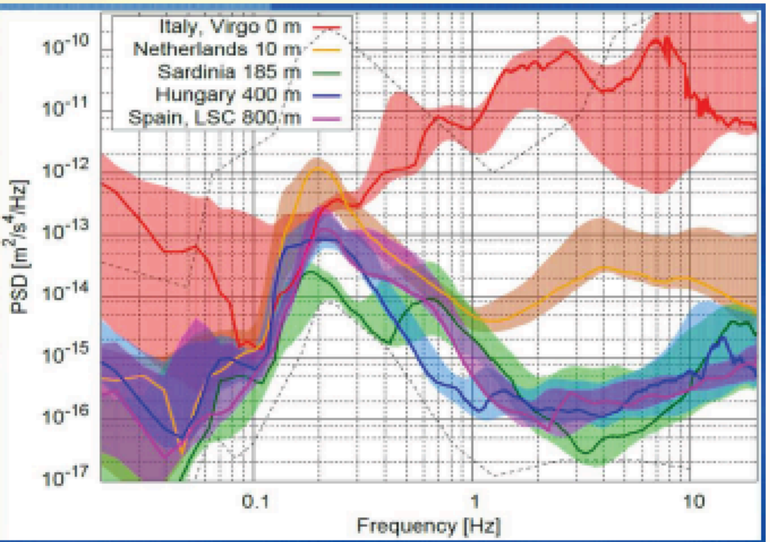


The Simons Observatory will search for gravitational waves in the cosmic microwave background, using telescopes based on the technology of current projects such as the Atacama Cosmology Telescope, pictured here, in Chile. *Credit: University of Pennsylvania*

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





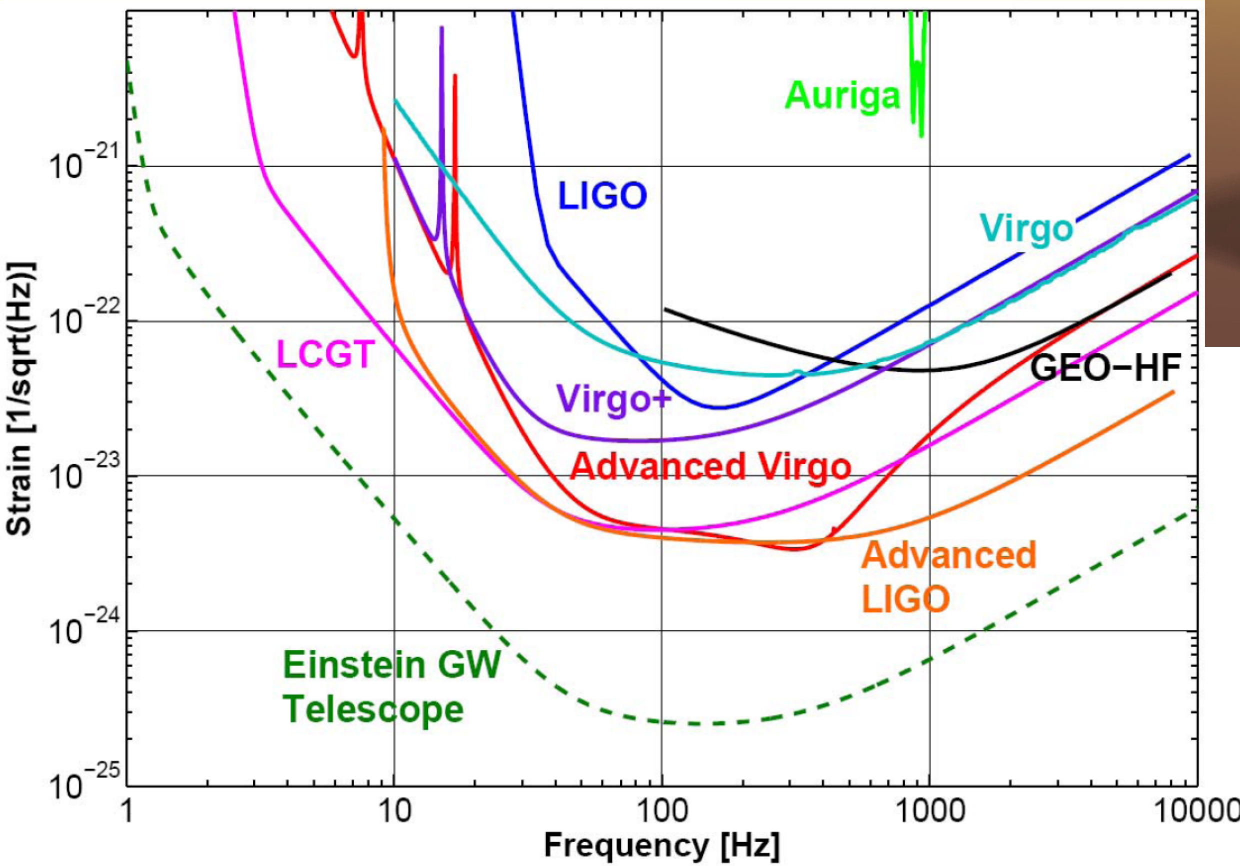
http://www.et-gw.eu/

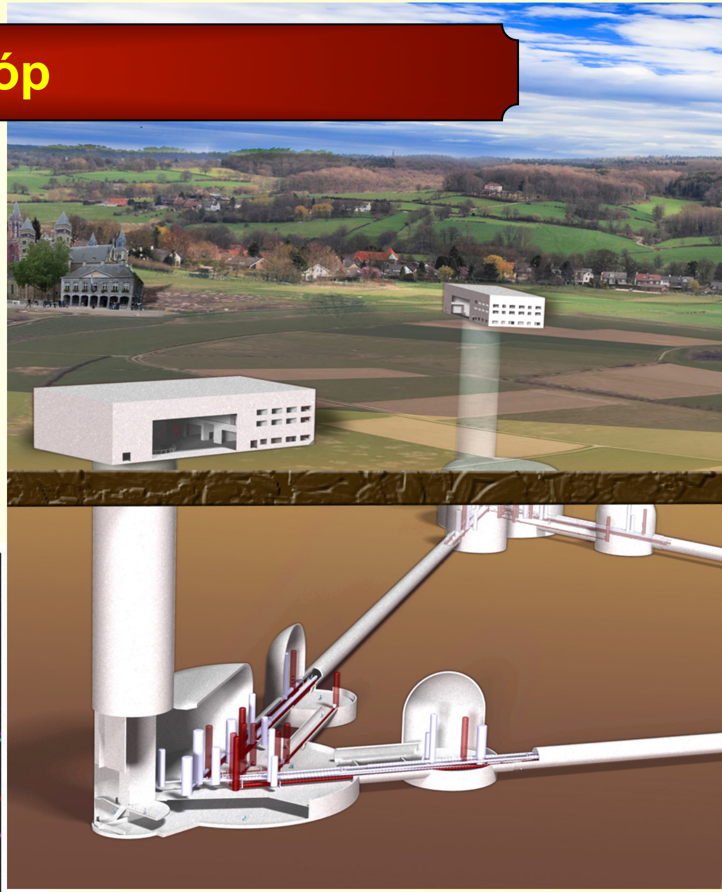
Mátra: kedvező szeizmikus adottságok

- 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: Einstein teleszkóp

Az általános relativitáselmélet még pontosabb tesztelése:
- kizárhatók-e az új polarizációk?
- pontosan nulla-e a graviton tömege?
- az univerzum gyorsuló tágulásának független ellenőrzése





Várható források:
- nagyobb tömegű feketelyuk-kettősök összeolvadása
- neutroncsillag-rezgések
- aszimetrikus szupernova-robbanások
- gamma-kitörések

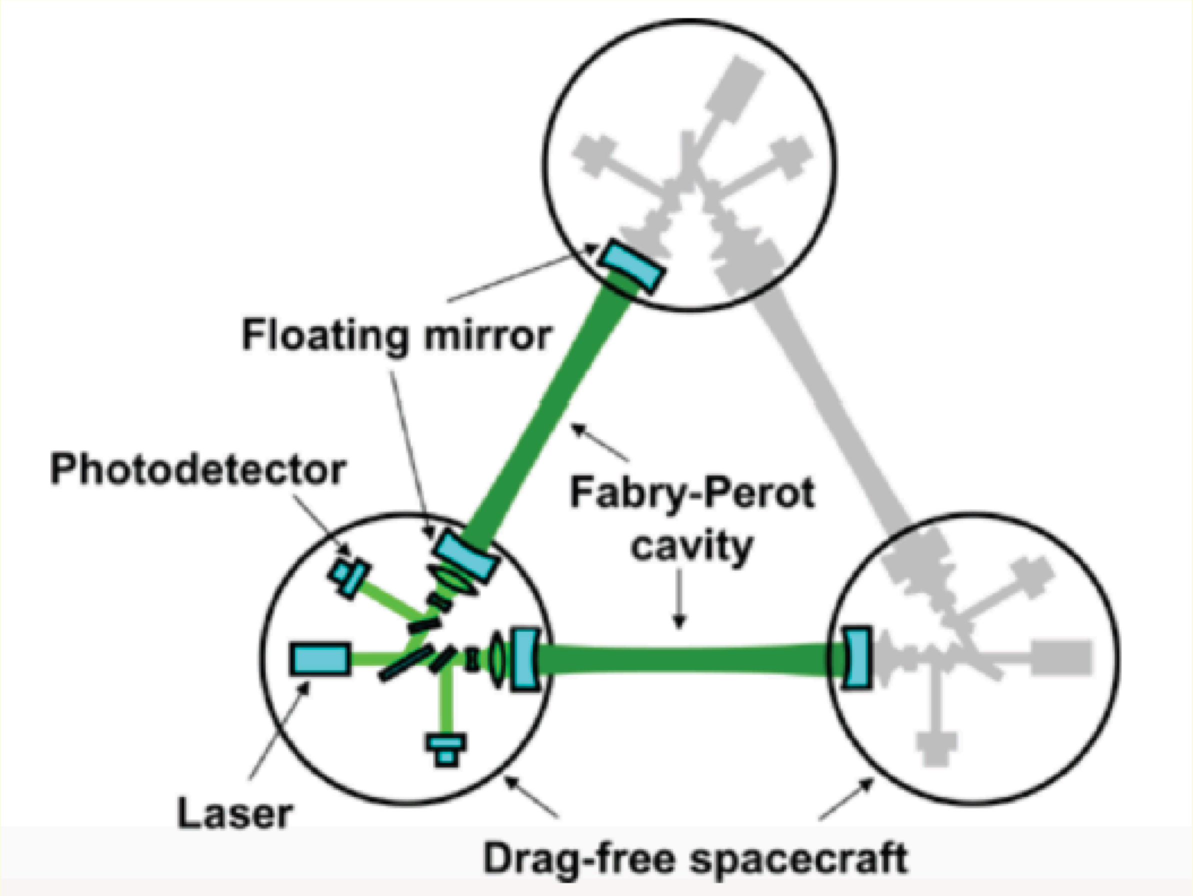
A jövő: Einstein teleszkóp

- az Einstein-teleszkóp tudományos potenciálja vitathatatlan
- mintegy 50 évre a tudományos világ térképére helyezi a helyszínt
- infrastruktúrális, kulturális, gazdasági húzóerőt fejt ki
  a régió fejlődésére

EZ EGY BEFEKTETÉS A JÖVŐBE !

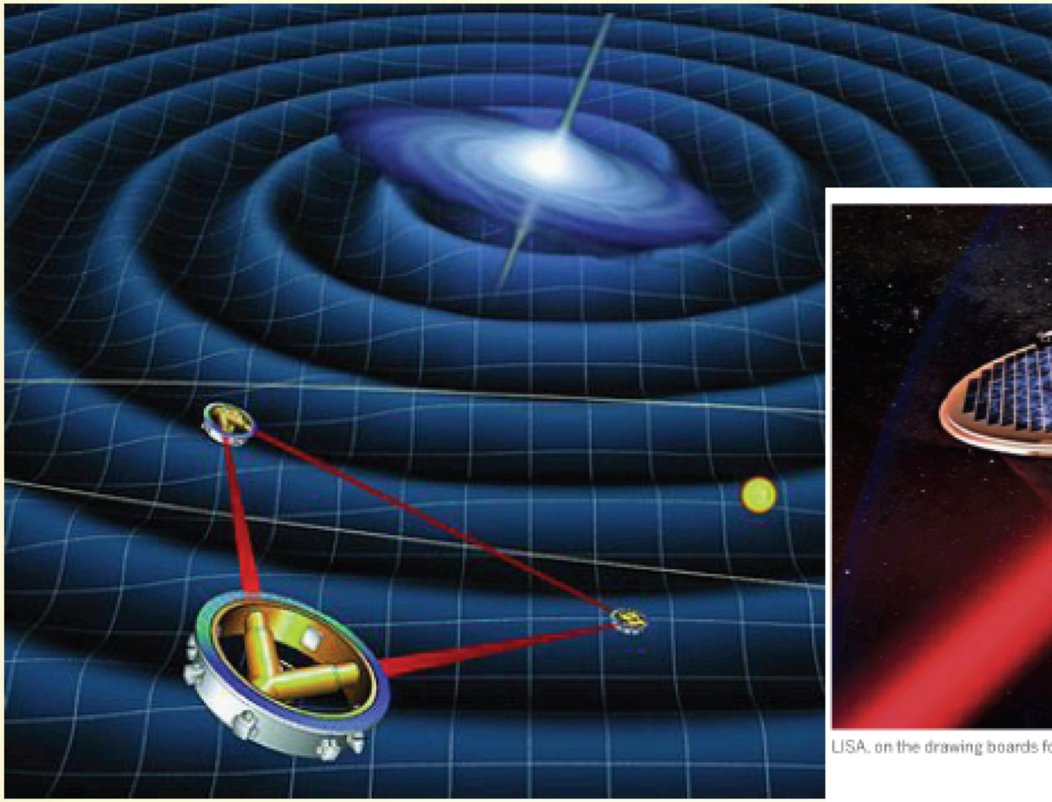
- az Einstein-teleszkóp tudományos közösségébe való magyar beágyazás és kedvező adottságok
  (Wigner Kutatóintézet részvétele,
  más Magyarországon, gravitációs
  hullámok területén dolgozó
  kutatók kapcsolatrendszere,
  szeizmikus mérések) nem elegendőek
- regionális, országos, talán Közép-Európai
  összefogás !
- helyi és országos támogatás,
  felajánlások szükségesek !

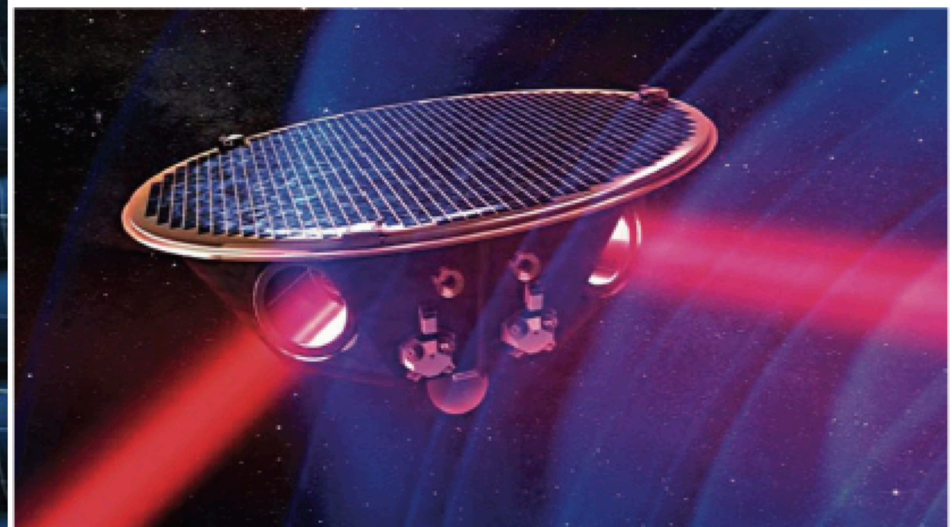
A jövő: DECIGO



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.

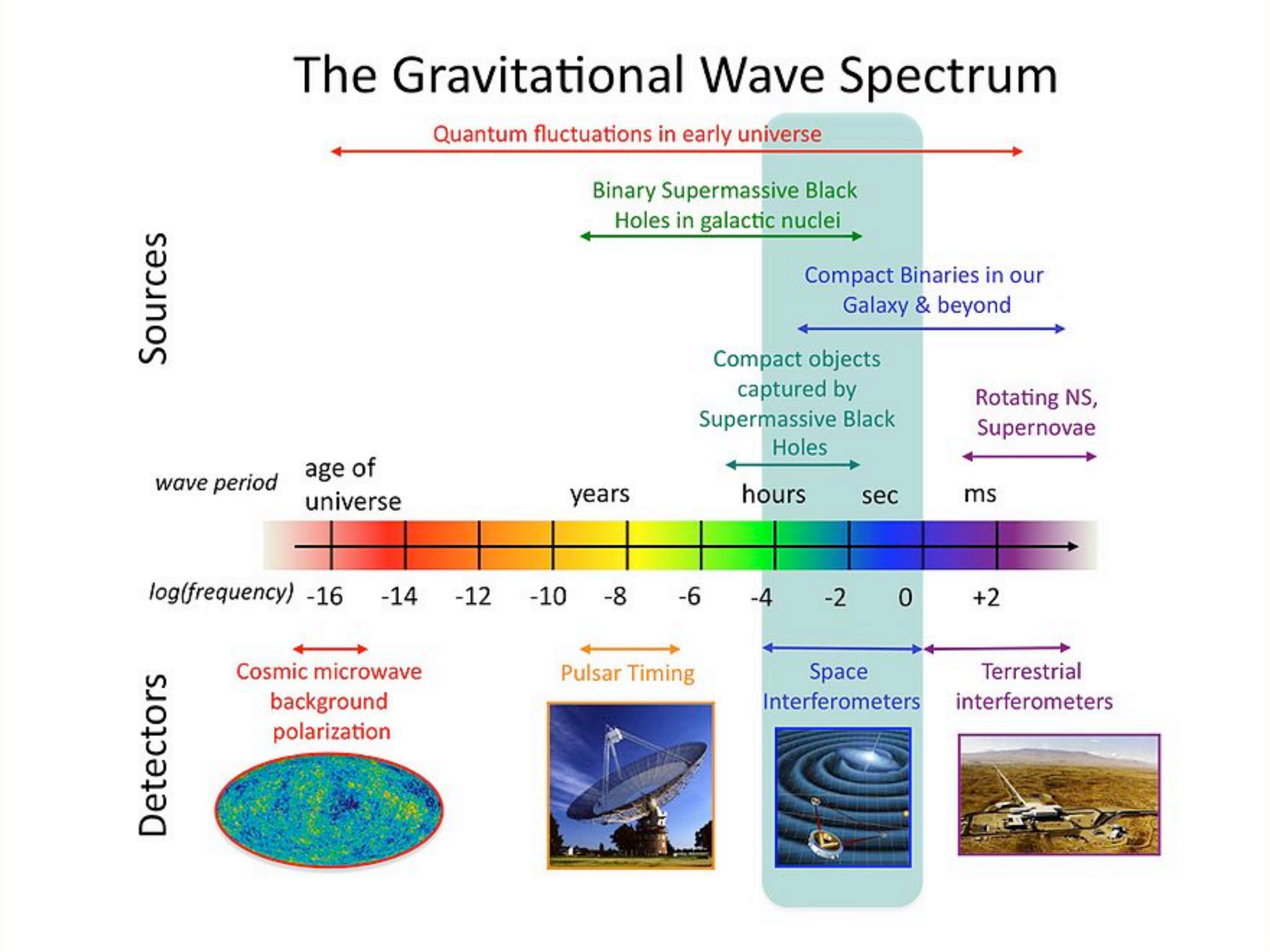
Albert Einstein Institute/Milde Marketing/exozet; GW simulation: NASA/C. Henze

NASA moves to rejoin sped-up gravitational wave mission

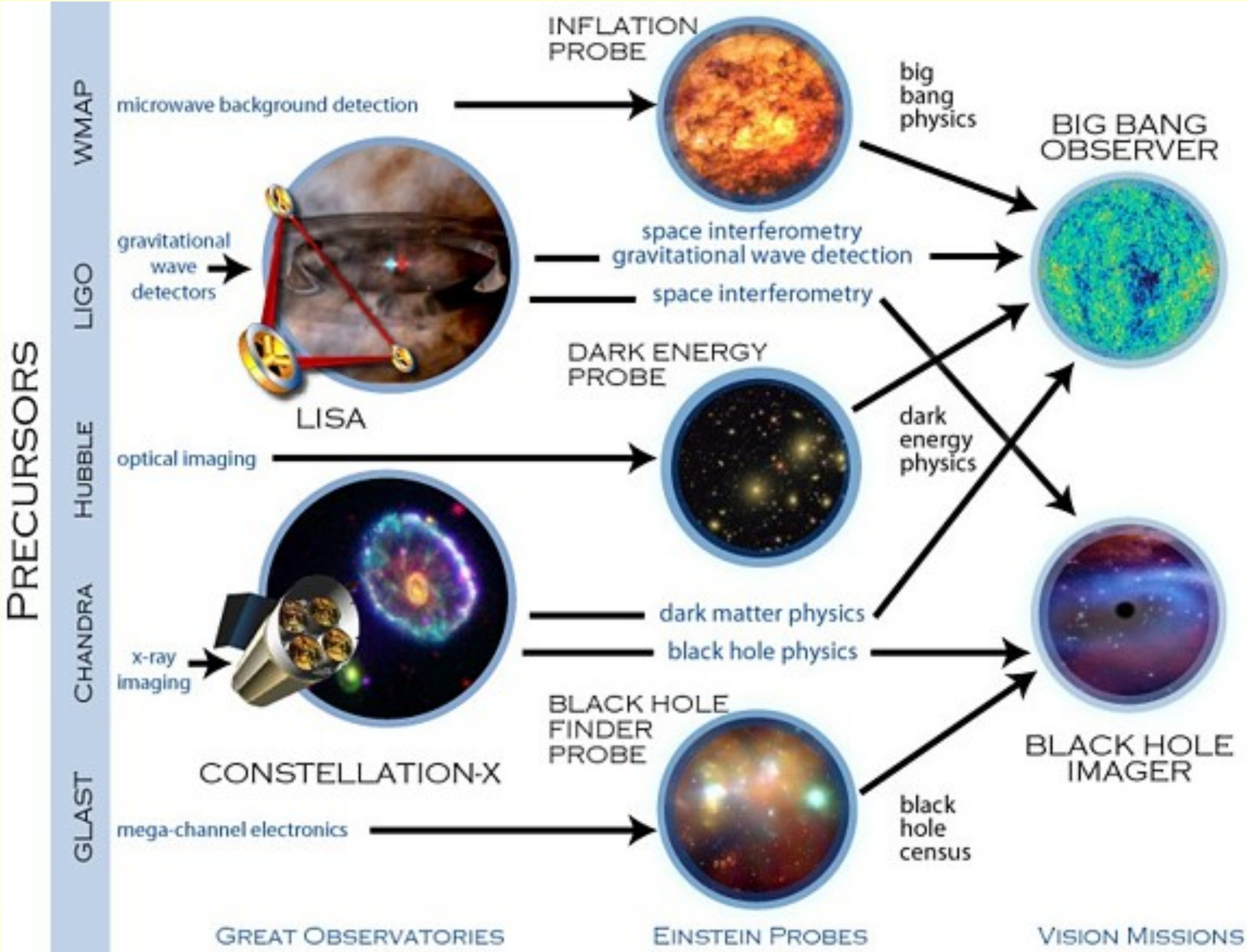
By Govert Schilling | Sep. 9, 2016 , 3:00 PM

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 !