Új ablak a világegyetemre:

csillagászat gravitációshullám-detektorokkal

Raffai Péter

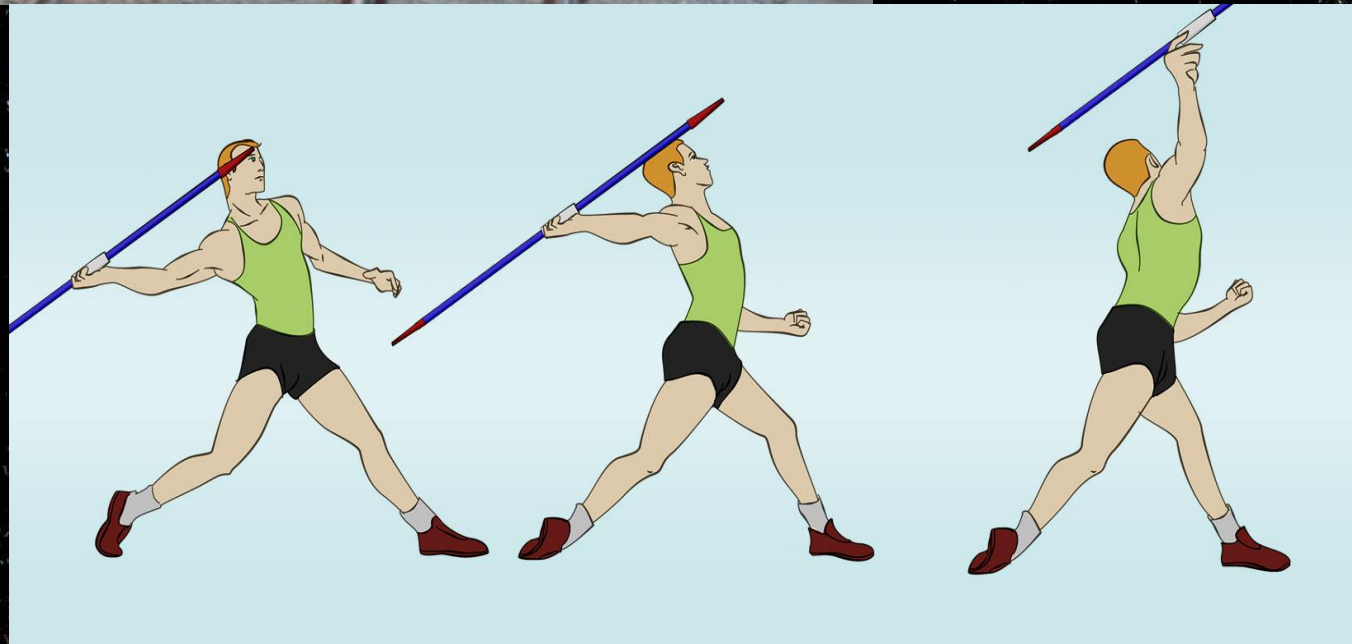
ELTE Atomfizikai Tanszék

2016. október 15.

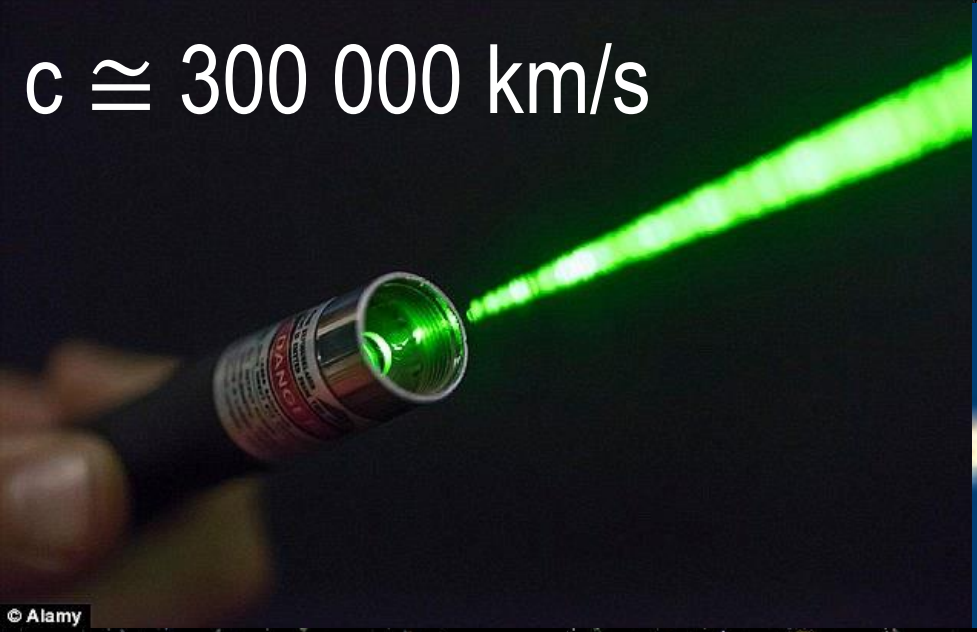
Eötvös Gravity Research Group

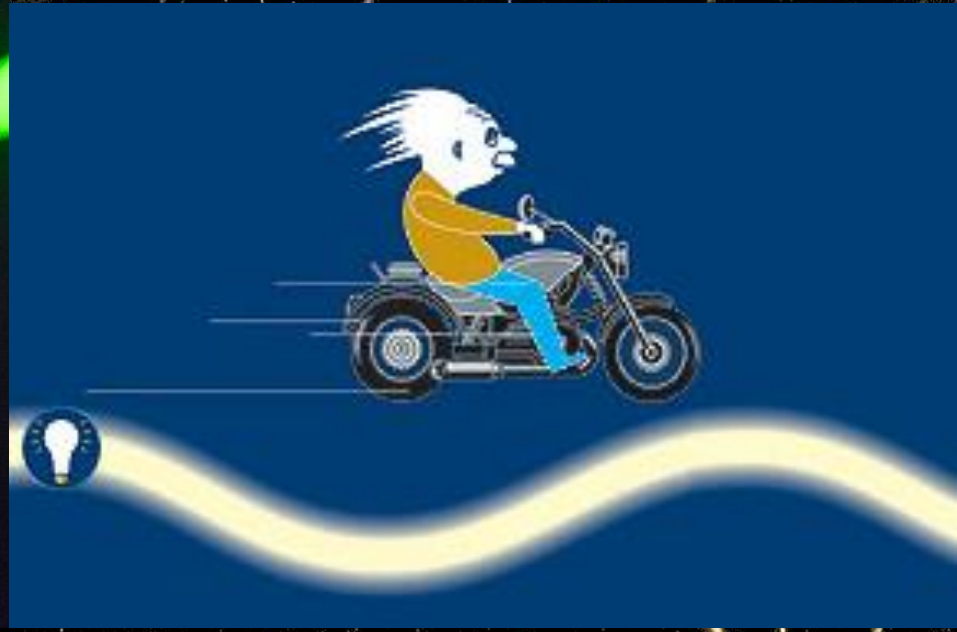
EGRG

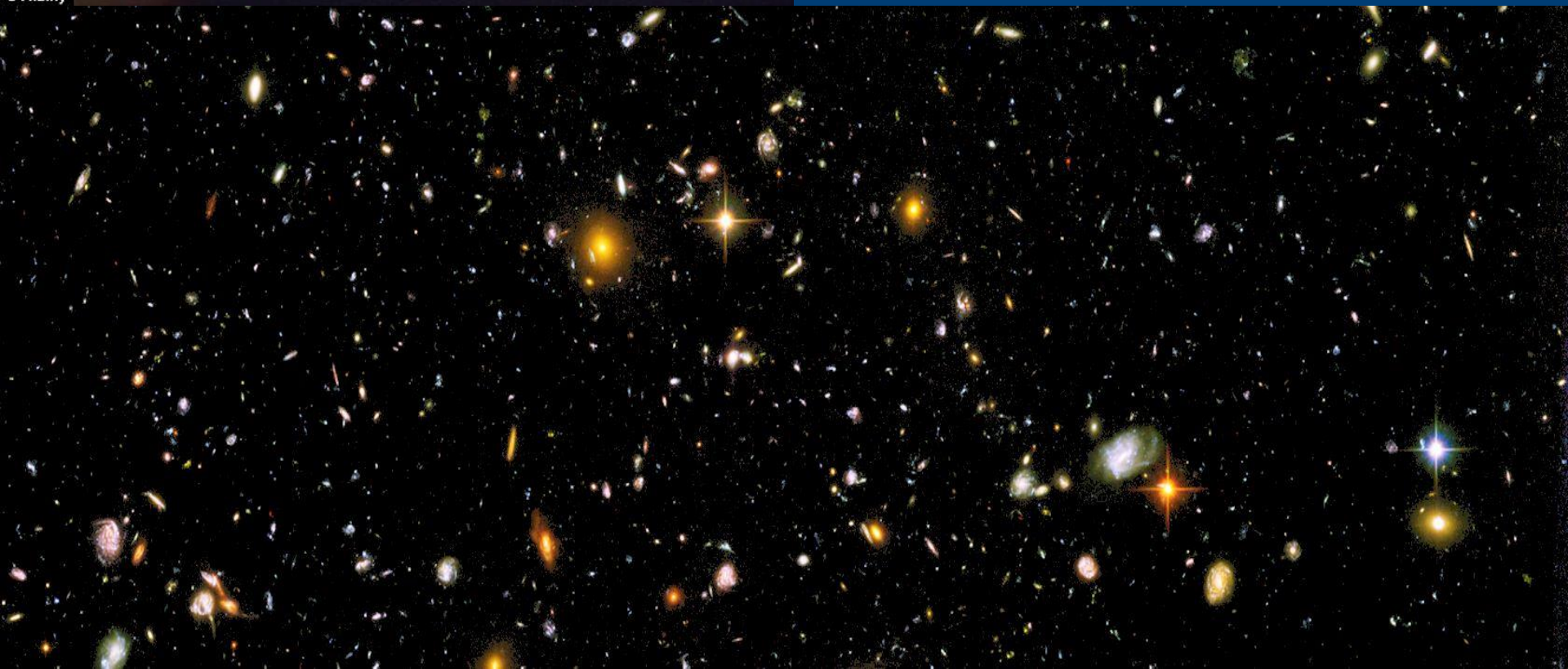
egrg.elte.hu



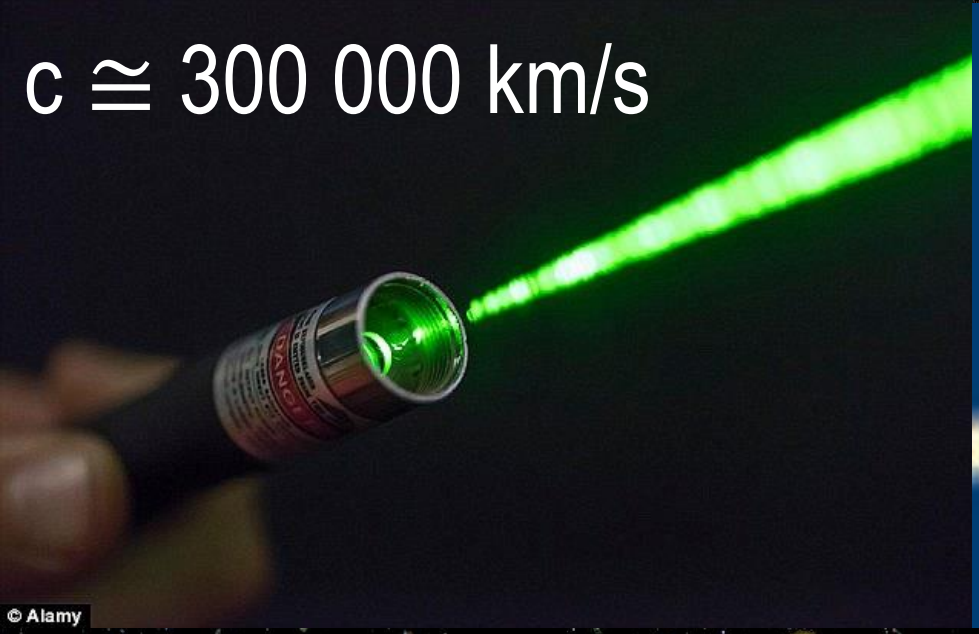
$c \cong 300\,000$ km/s

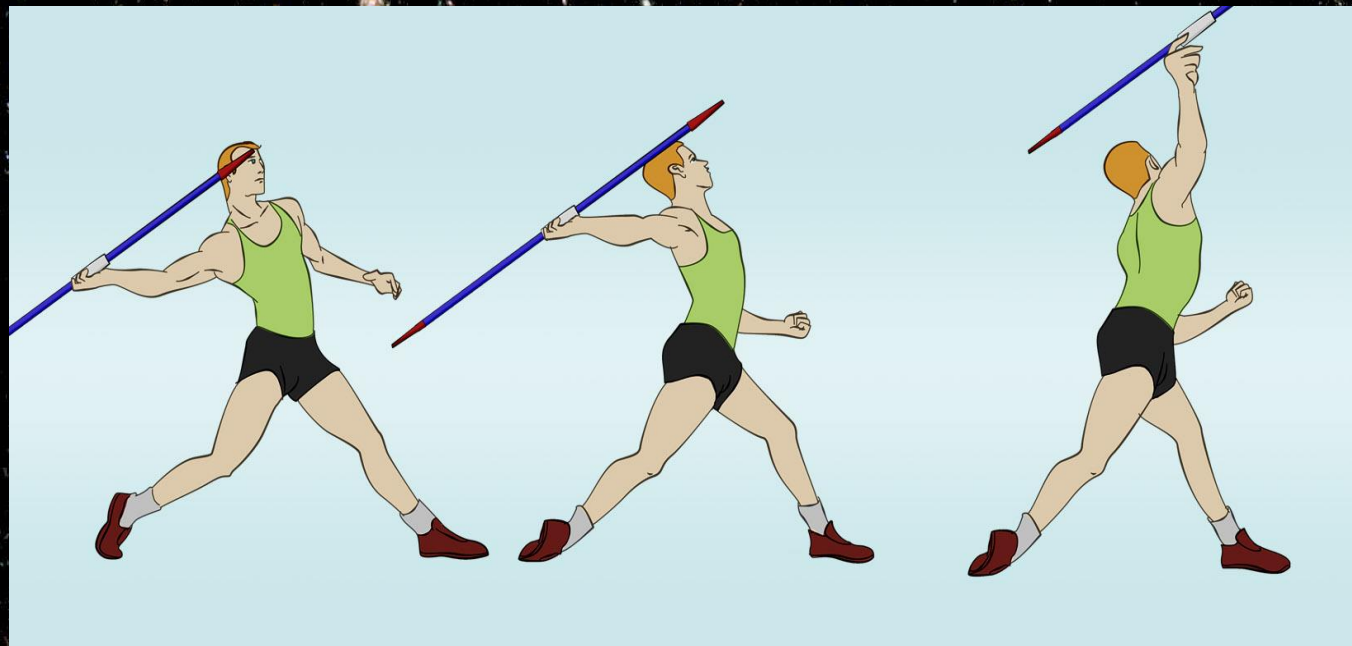


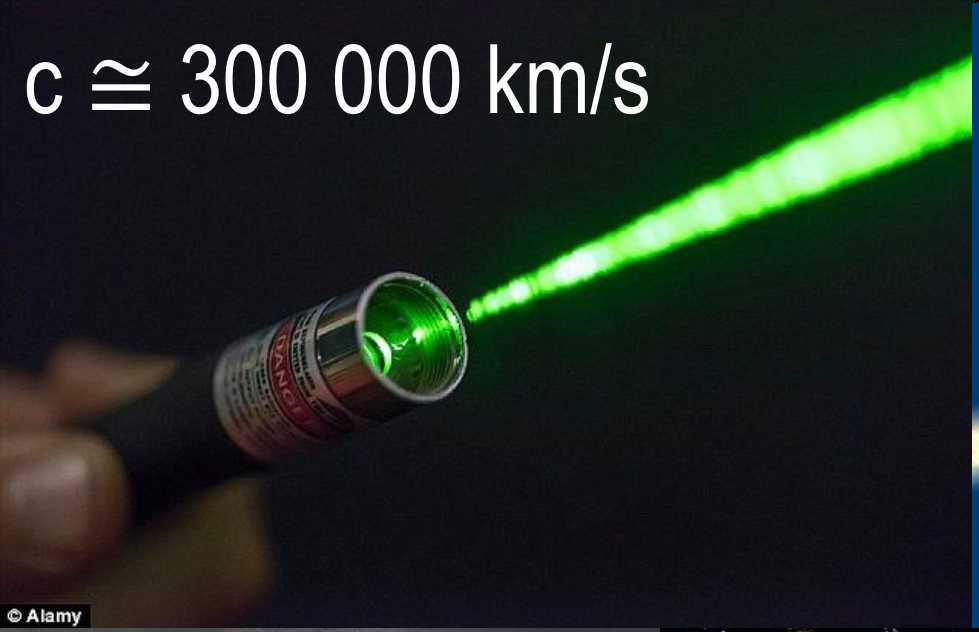


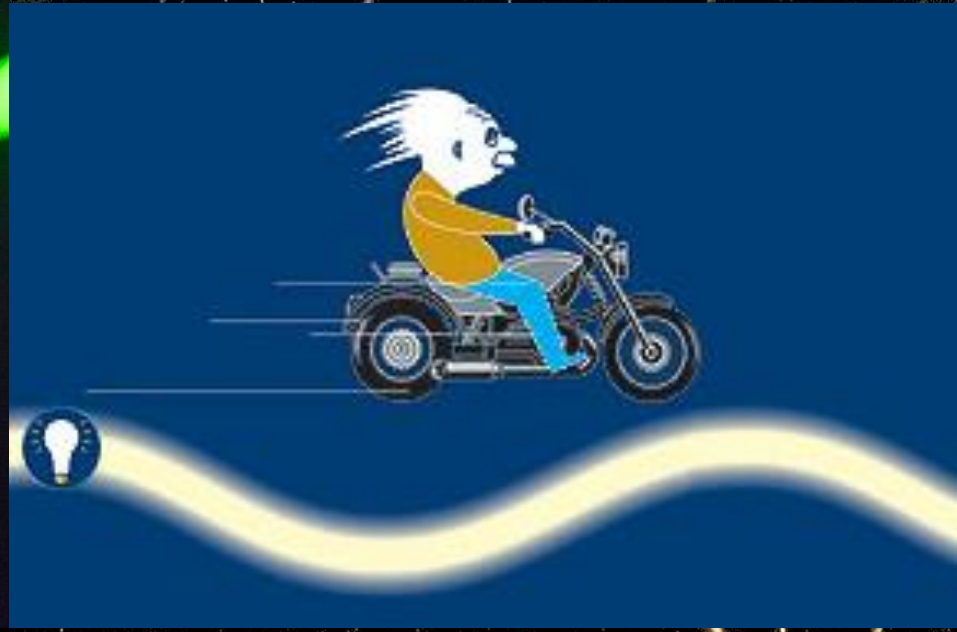


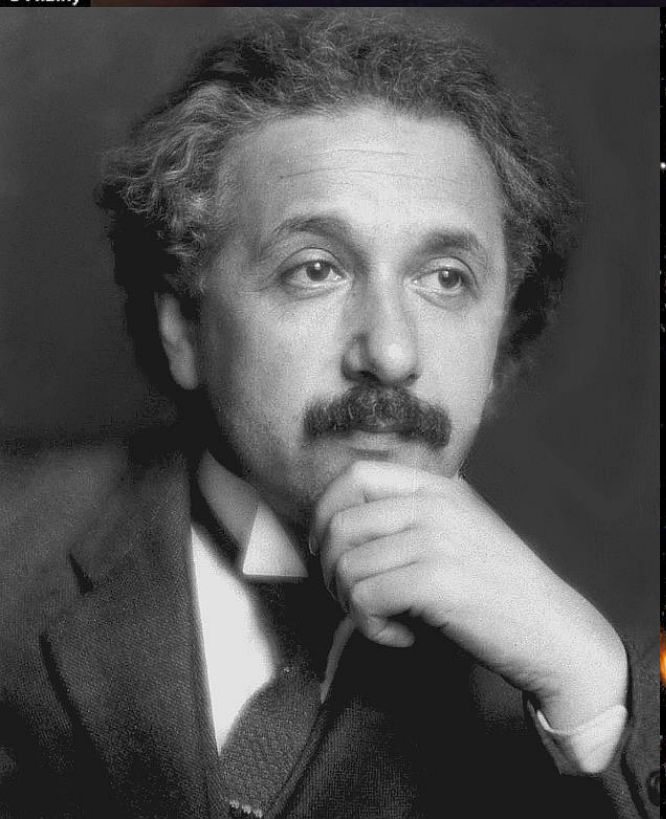
$c \cong 300\,000$ km/s







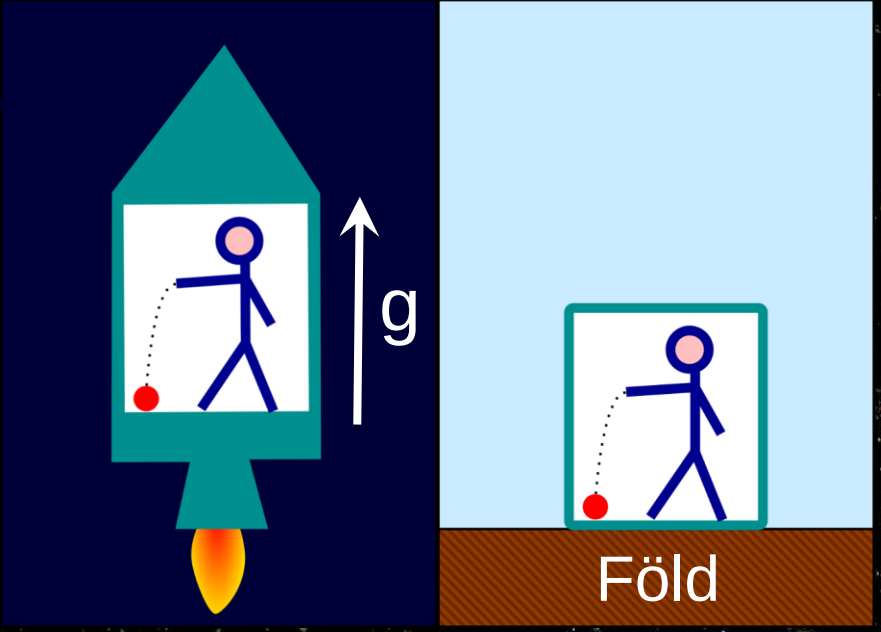




Einstein A., Annalen der Physik 322, 10, 891-921 (1905)

$$v' = \frac{u+v}{1+uv/c^2}$$

$$t' = t/\sqrt{1-\frac{v^2}{c^2}} \qquad L' = L\sqrt{1-\frac{v^2}{c^2}}$$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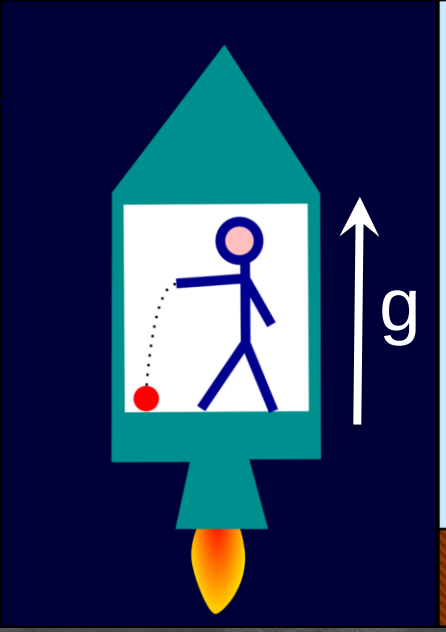
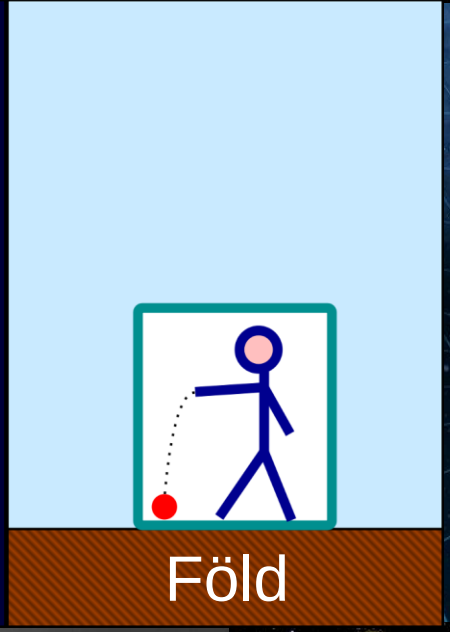
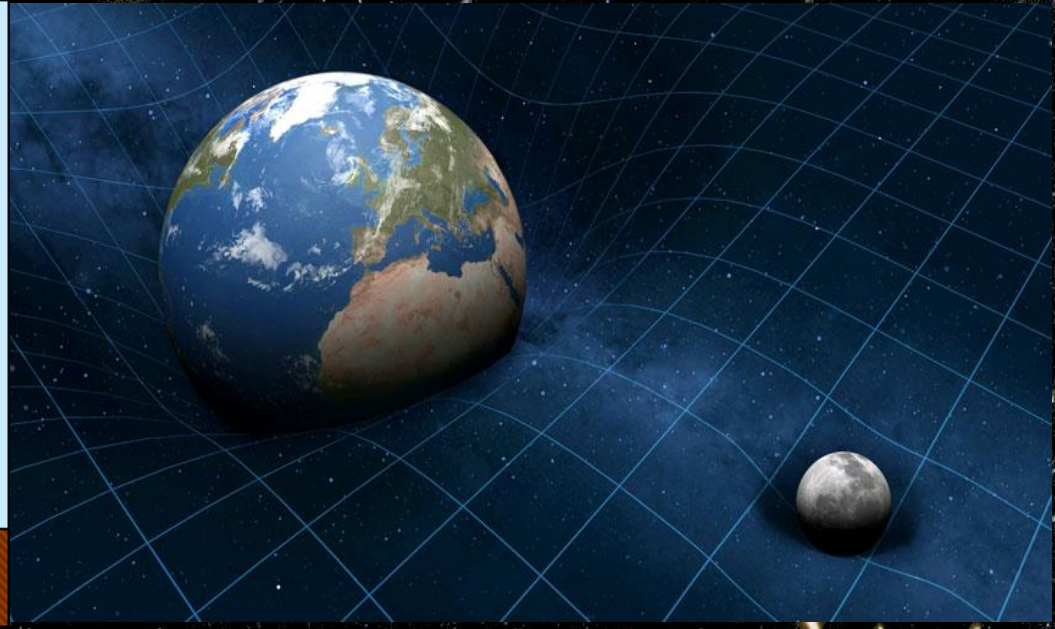
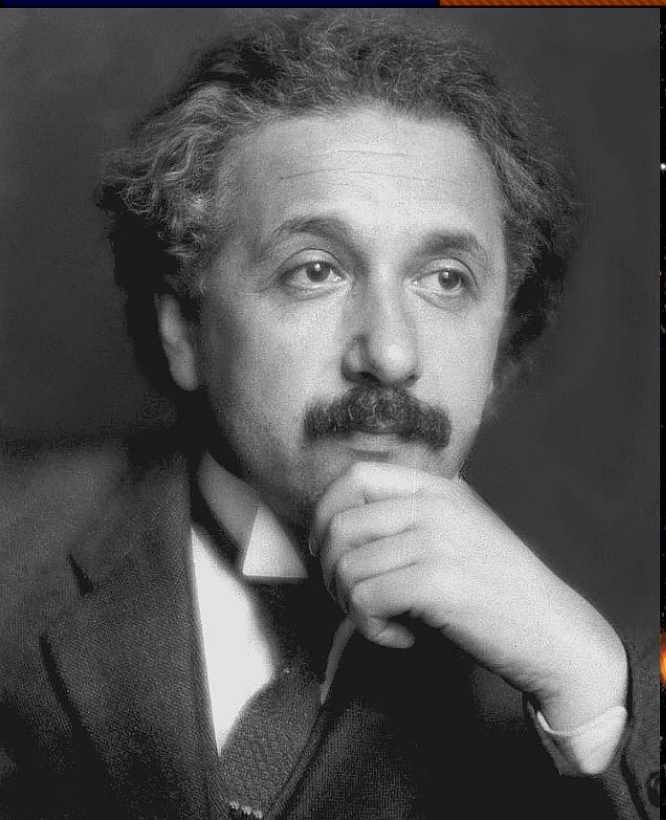
Föld





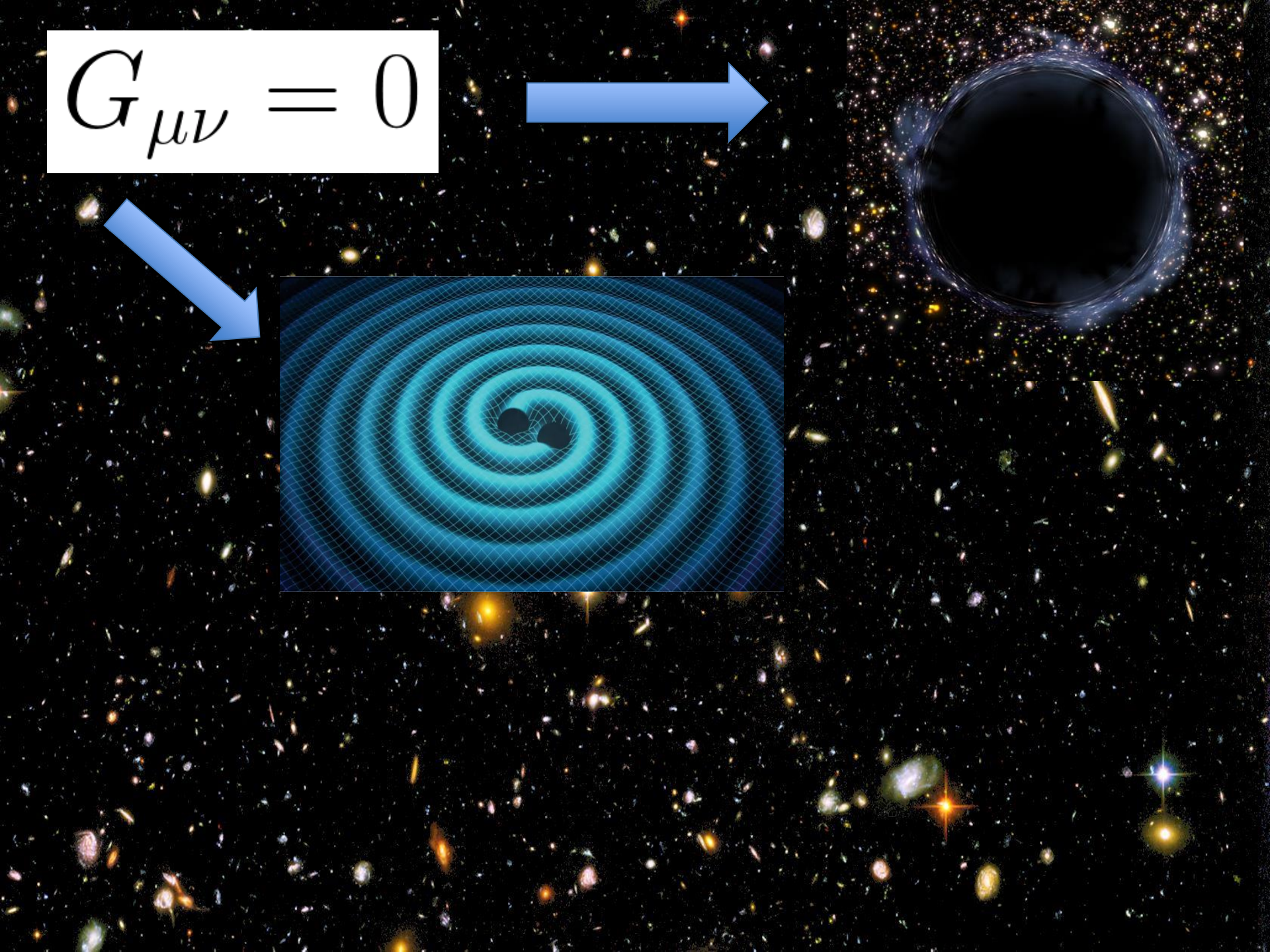




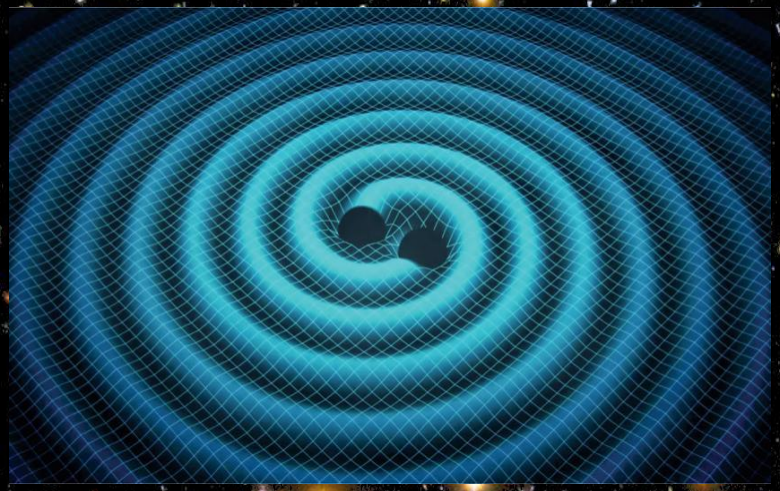
Einstein A., SPAWB, 844-847 (1915)

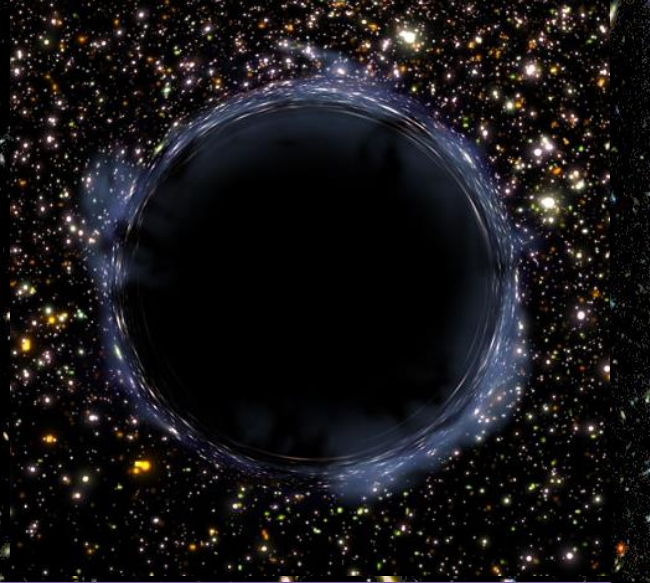
$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

$$G_{\mu\nu} = 0$$

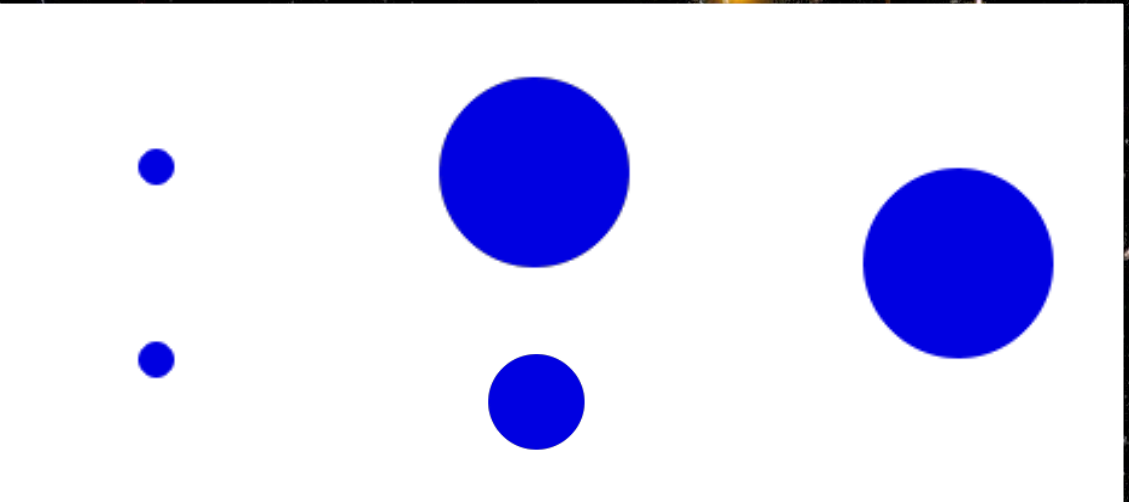


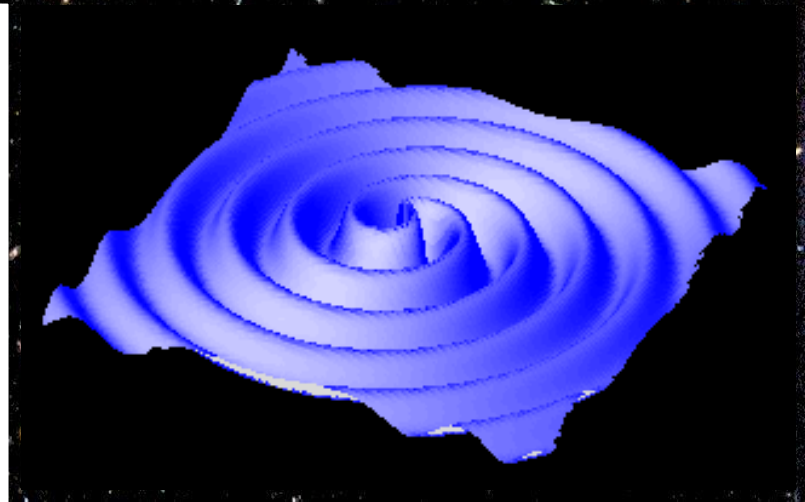
$$G_{\mu\nu} = 0$$





Einstein A., SKPAWB, 688-696 (1916) 154-167 (1918)

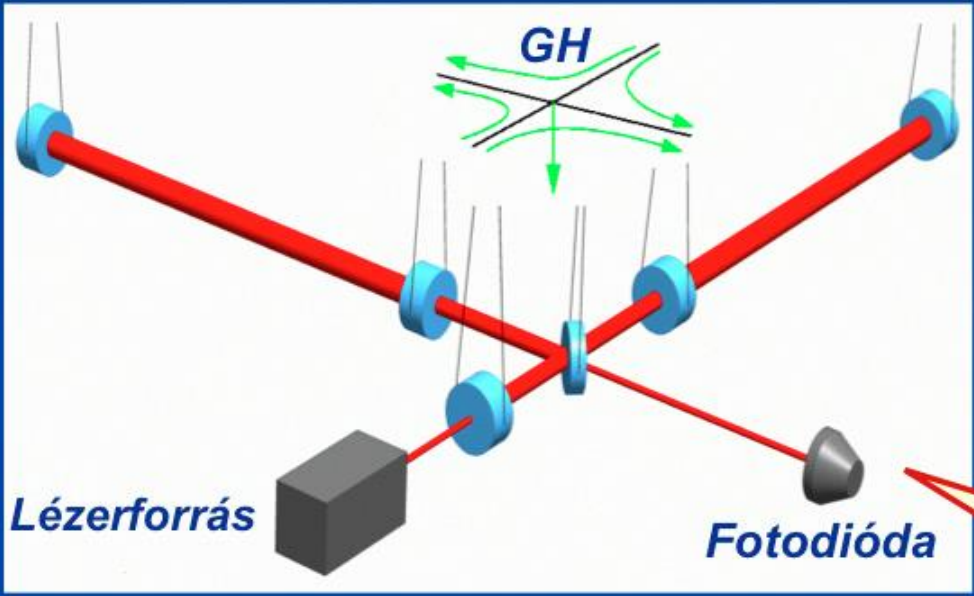


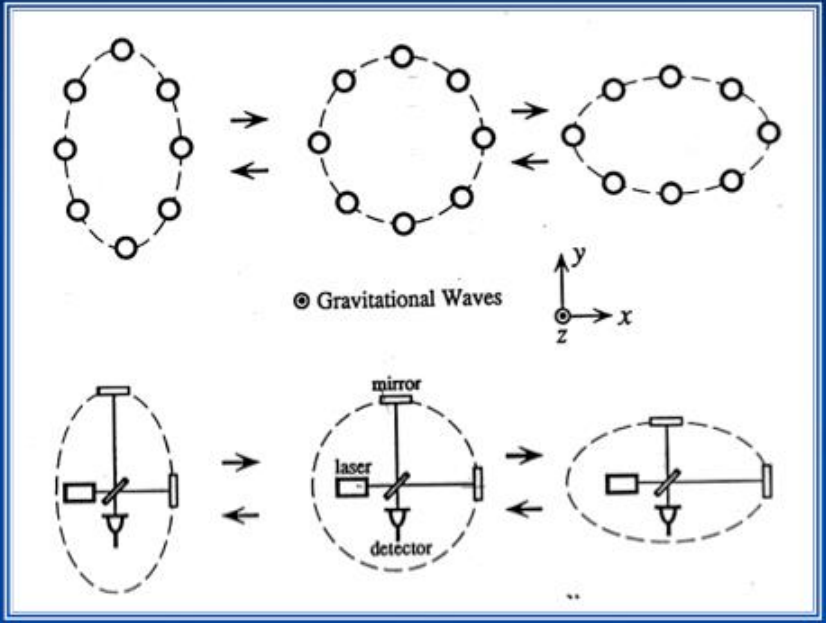


Interferométerek

Merőlegesen osztott lézernyaláb öninterferenciája fotodióda felületén

Ahogy a hullám a berendezésen áthalad, a karok relatív hosszváltozást szenvednek…

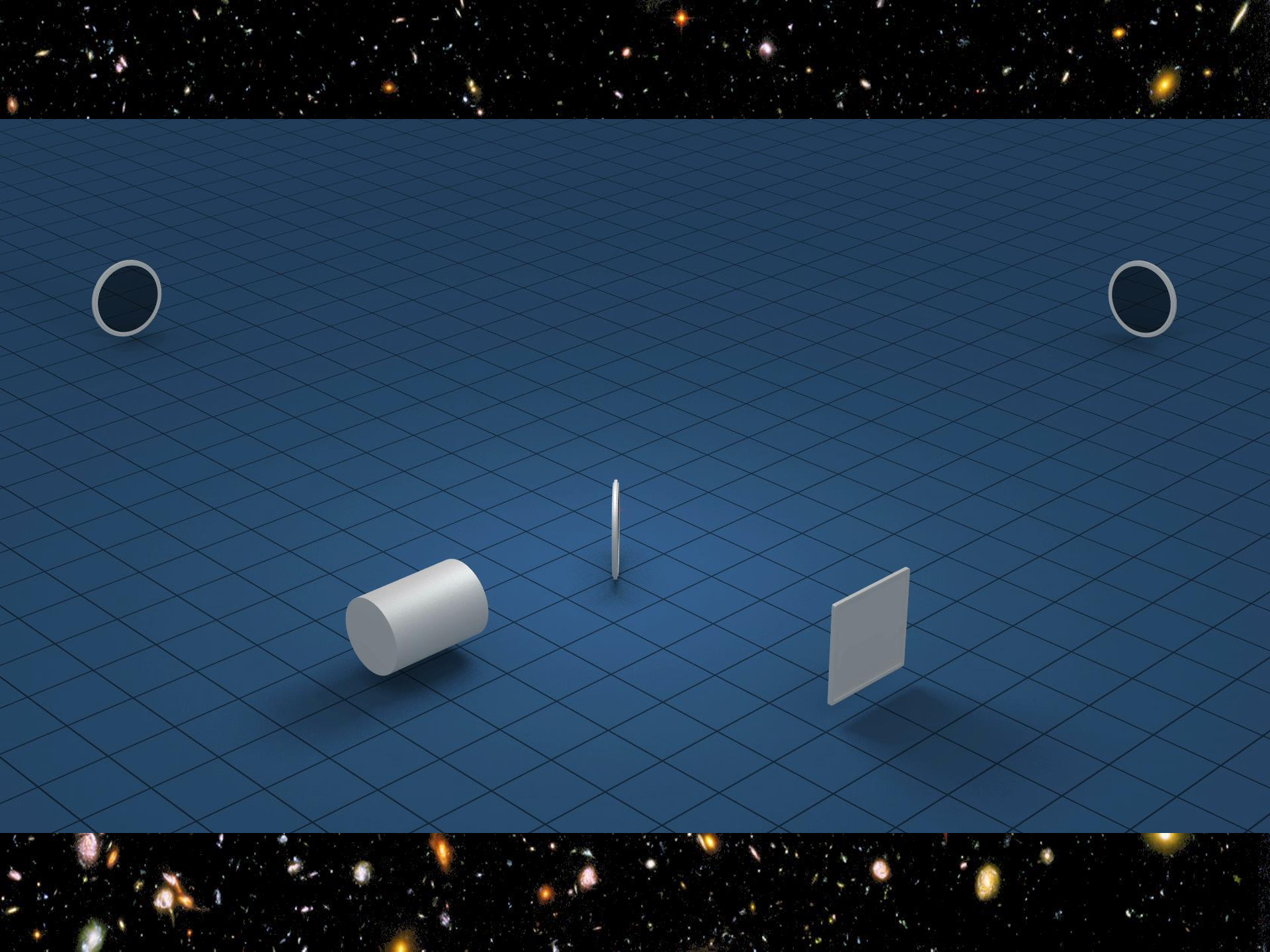




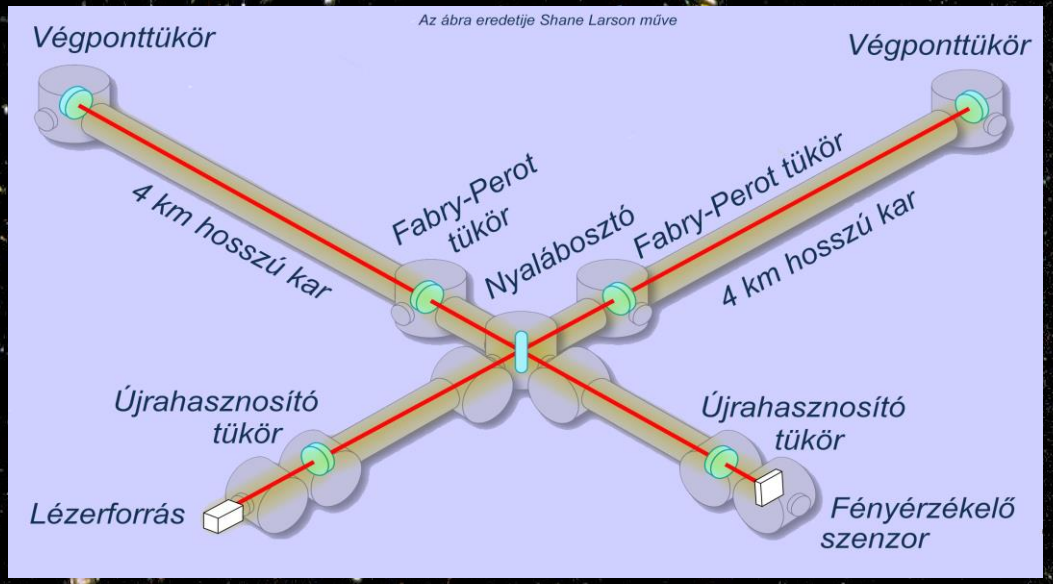
…ami a fotodiódával mért interferenciaképet is megváltoztatja

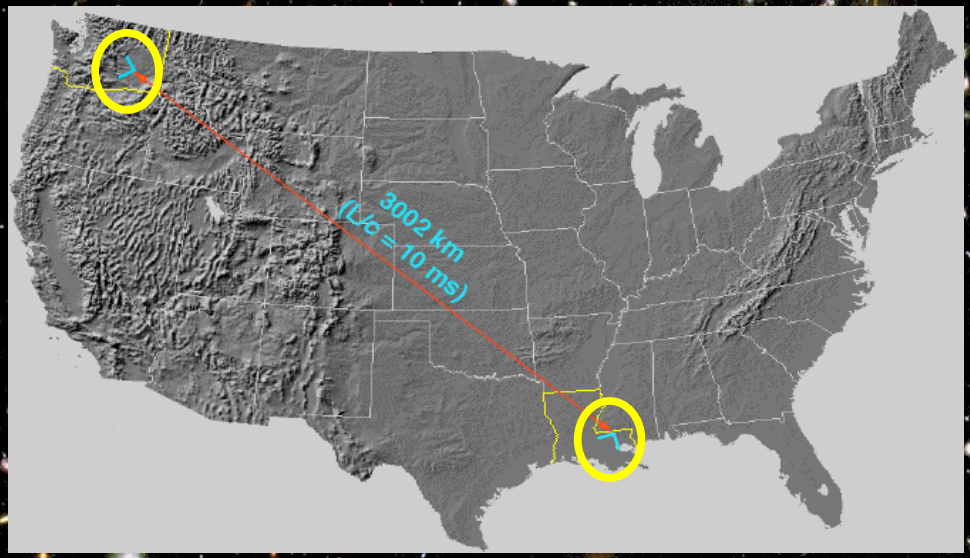
Relatív hosszváltozás: $h = \Delta L / L$
Mérhető: ΔL

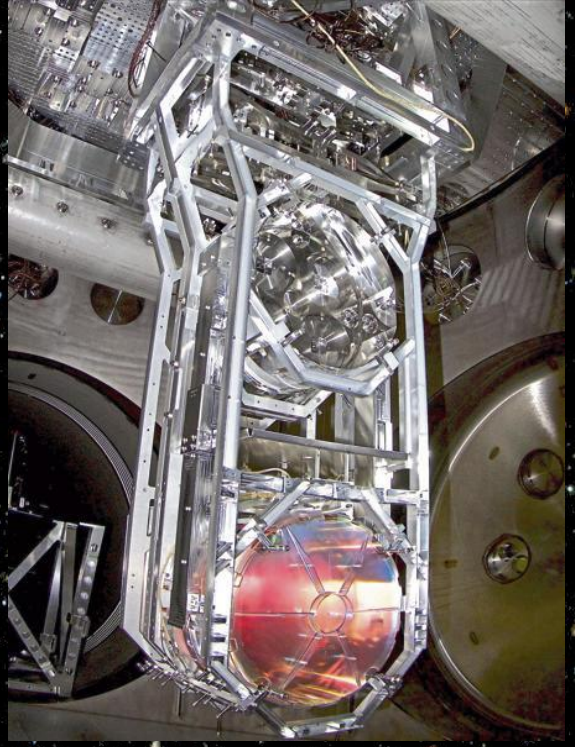
Mivel h kicsi, L legyen minél nagyobb!=> L = 4 km; $\Delta L \sim 10^{-19} m$!

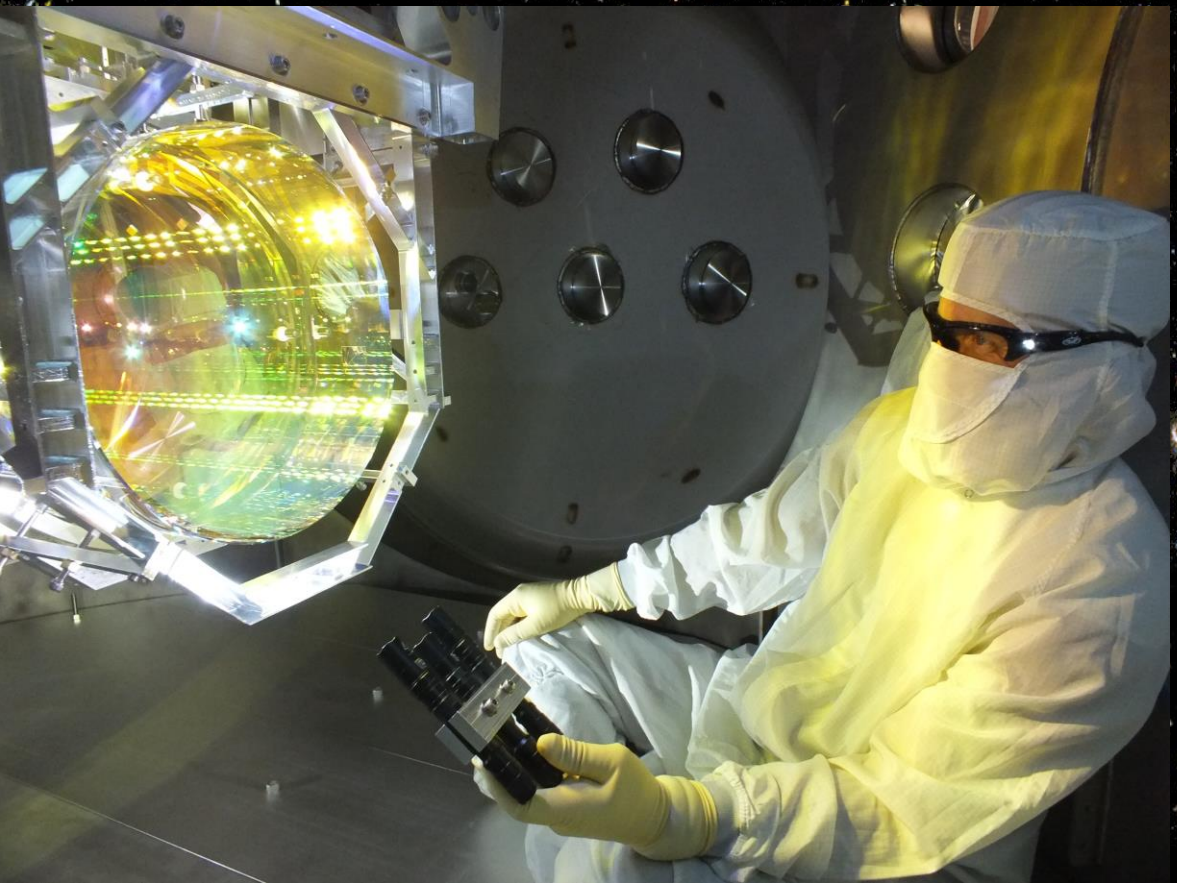


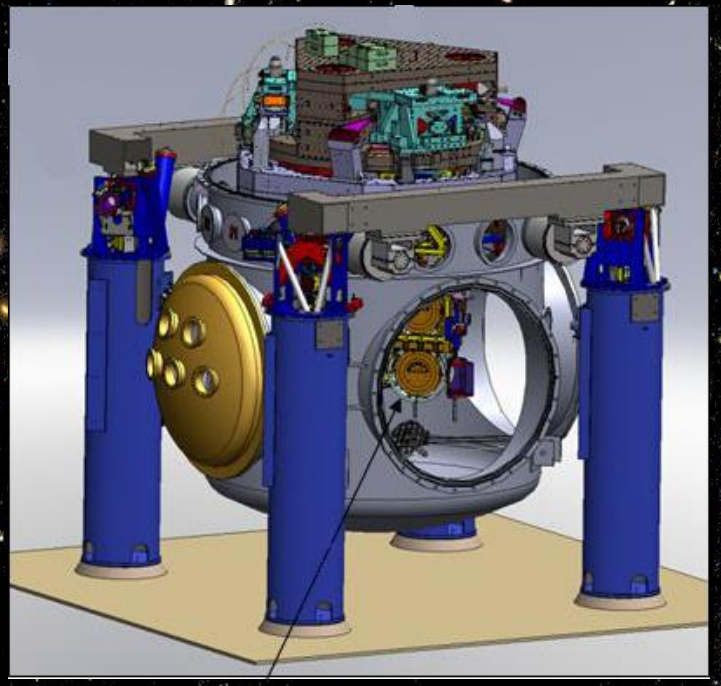
Laser Interferometer Gravitational-wave Observatory (LIGO)





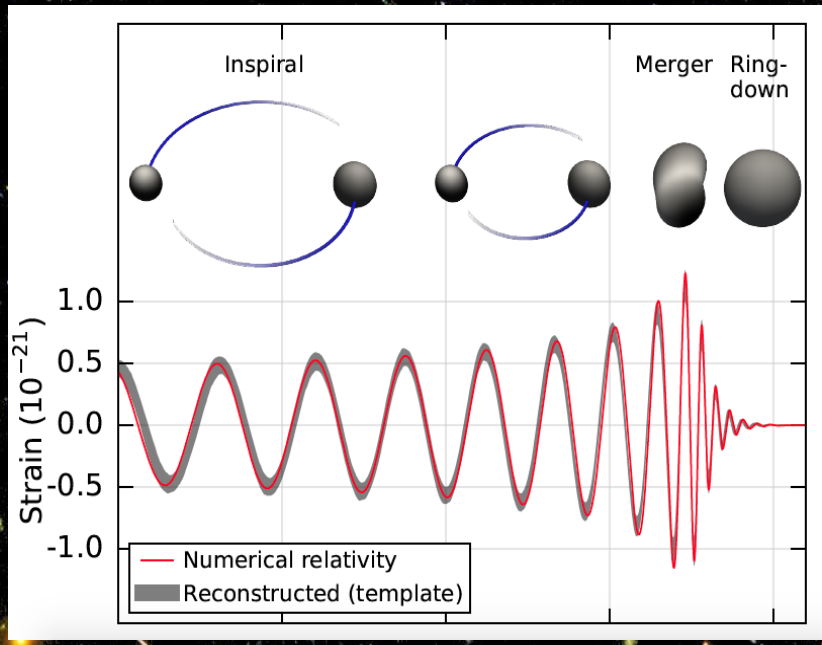


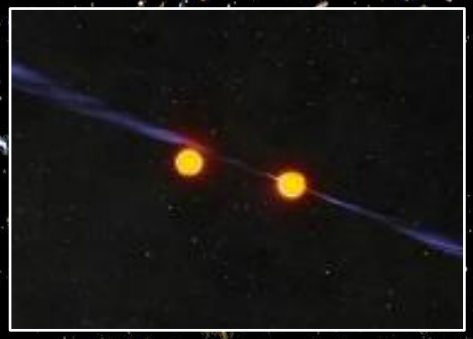


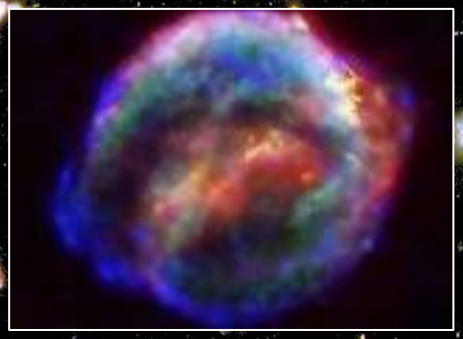


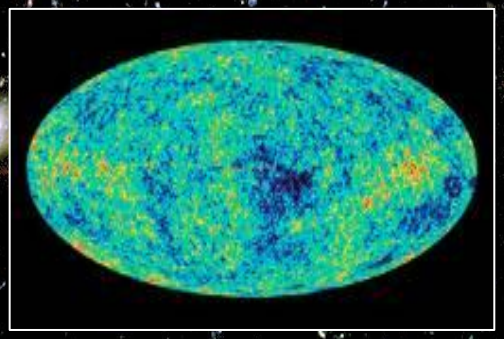
Egy gravitációshullám-detektor háttérzajának hangja

A LIGO-val figyelt jelek alaptípusai









GW150914

Megtörtént a felfedezés! - A GW150914 az elsőnek észlelt gravitációshullám-jel fekete lyukak összeolvadásából

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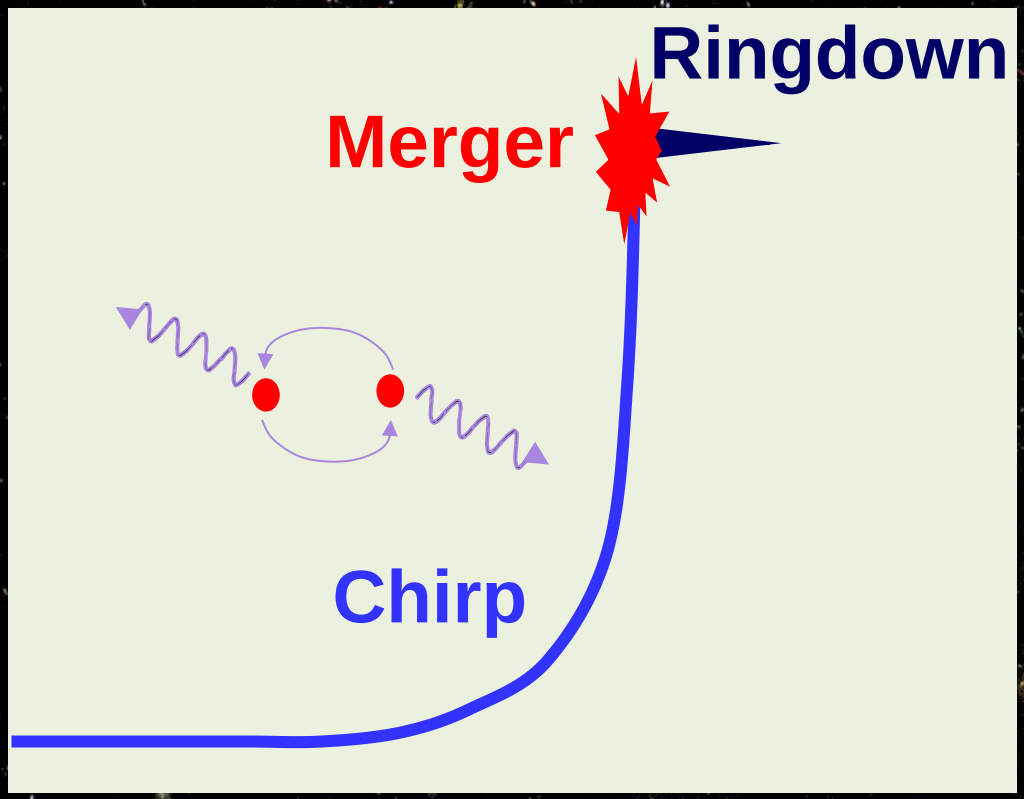
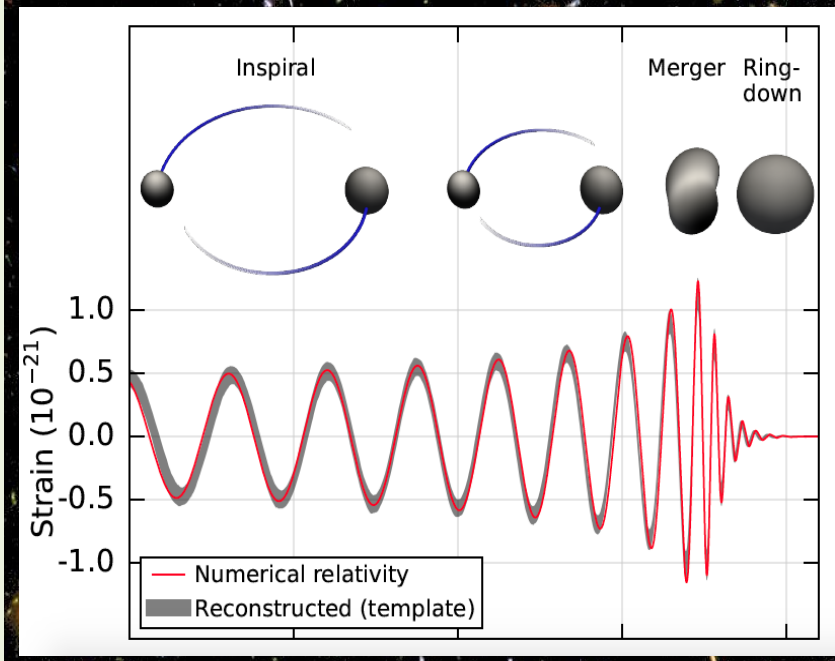

Ringdown
Merger
Chirp
Frekvencia
Idő


Inspiral
Merger
Ring-
down
1.0
0.5
0.0
-0.5
-1.0
Strain (10^{-21})
Numerical relativity
Reconstructed (template)

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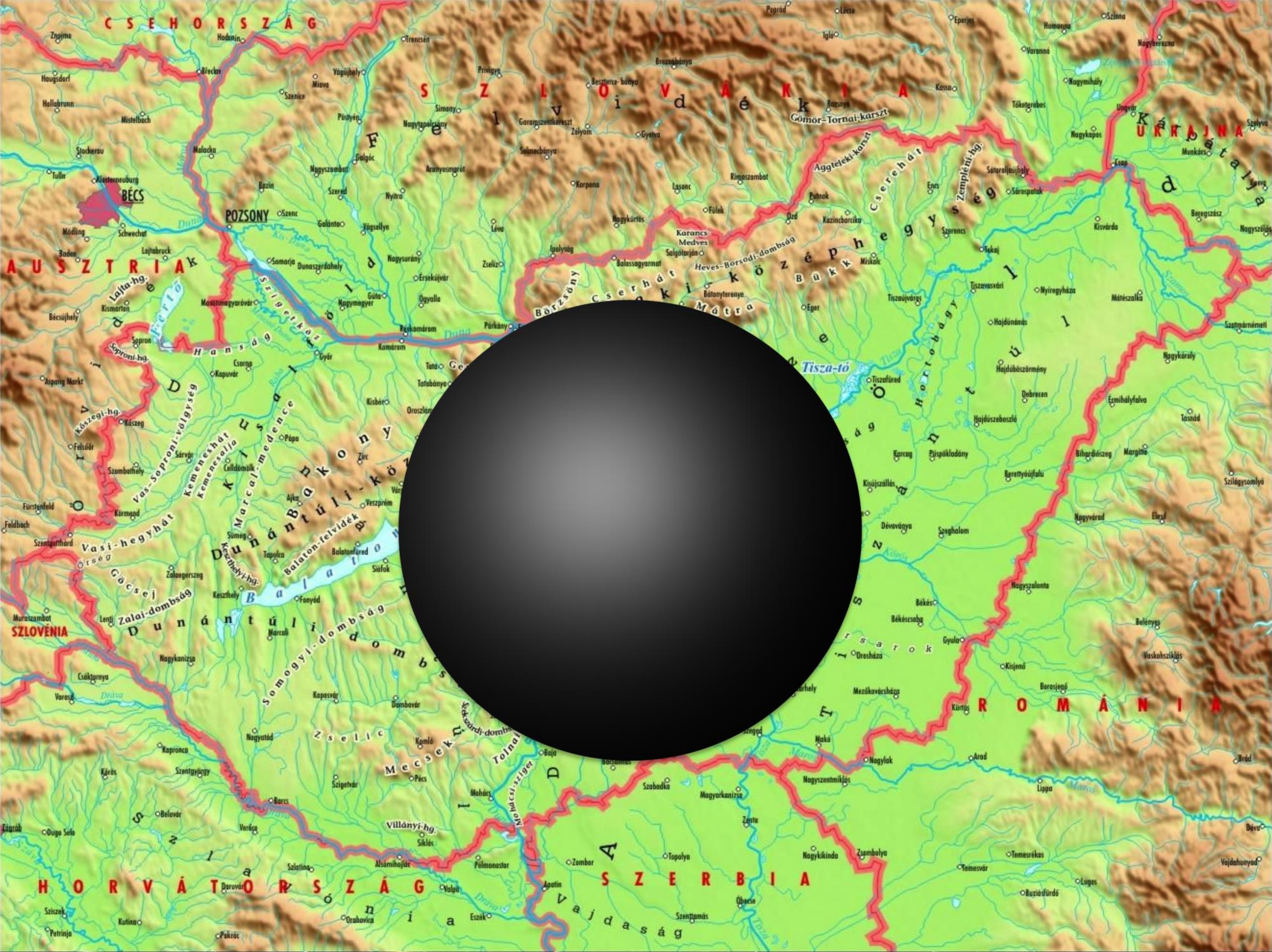
GW150914: FACTSHEET

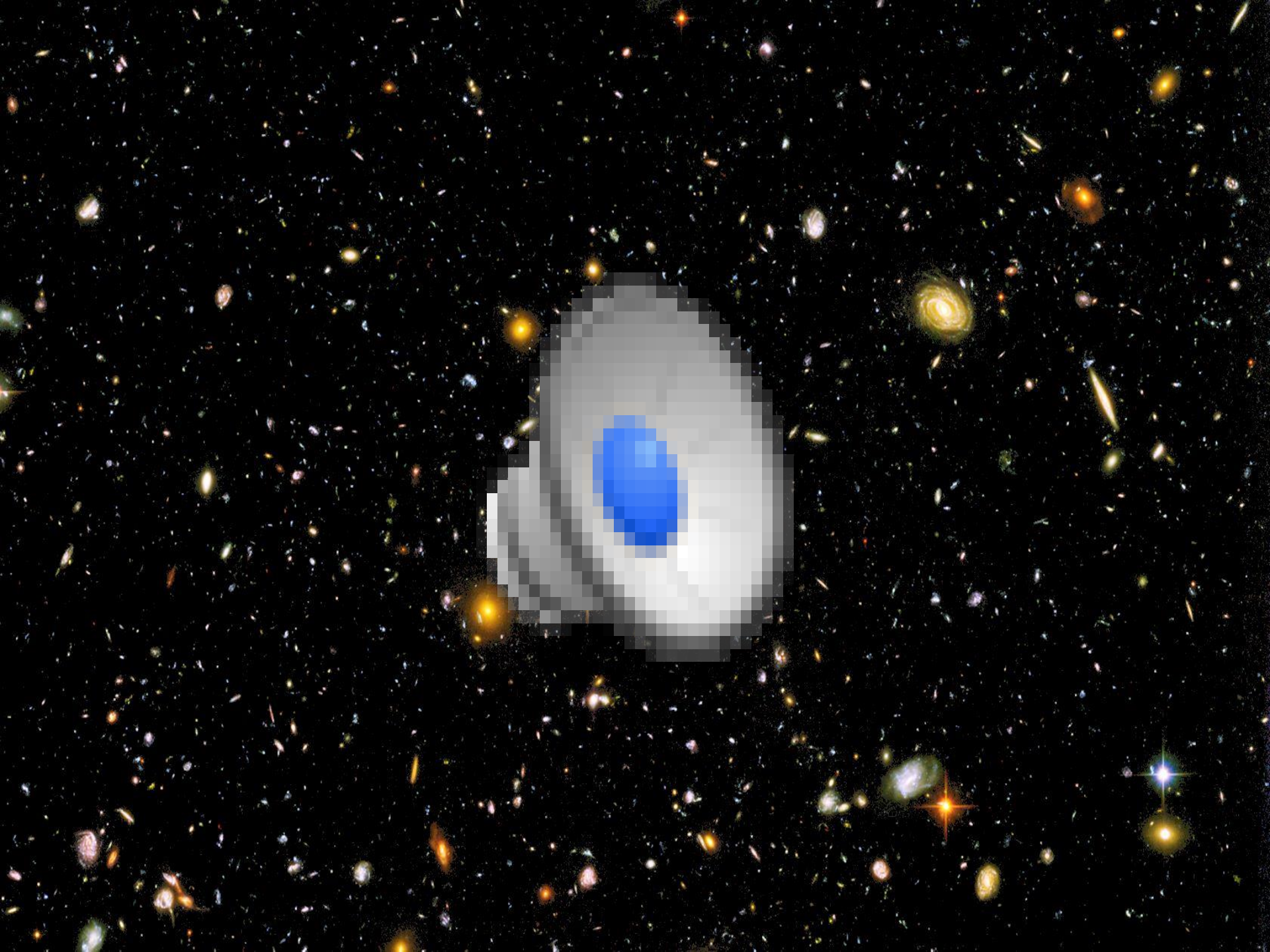
ligo.elte.hu

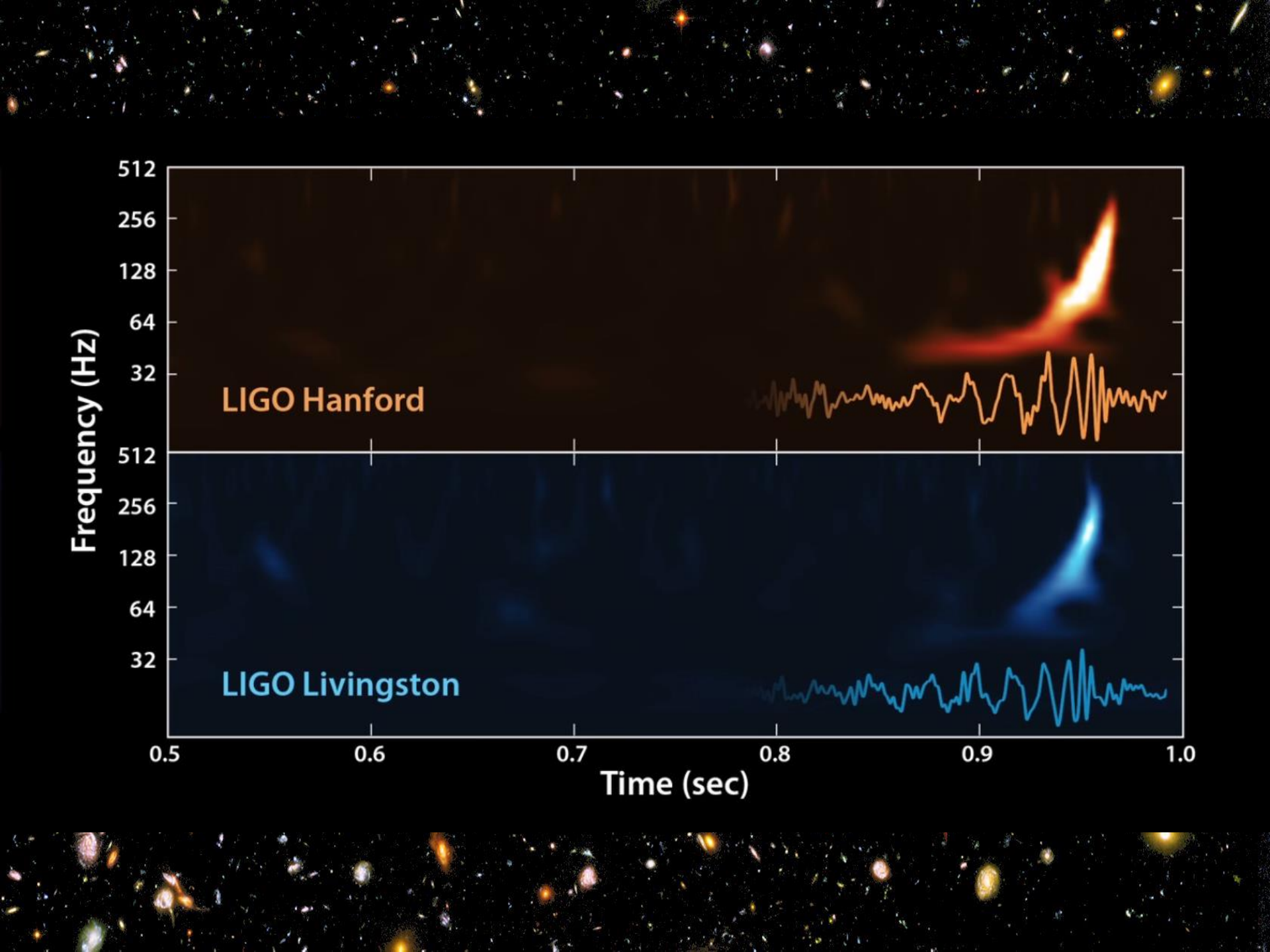
observed by	LIGO L1, H1
source type	black hole (BH) binary
date	14 Sept 2015
time	09:50:45 UTC
likely distance	0.75 to 1.9 Gly 230 to 570 Mpc
redshift	0.054 to 0.136
signal-to-noise ratio	24
false alarm prob.	less than 1 in 5 million
false alarm rate	1 in 200,000 yr
Source Masses	**M⊙**
total mass	65
chirpmass	28
primary BH	32 to 41
secondary BH	25 to 33
remnant BH	62
mass ratio	0.6 to 1
primary BH spin	< 0.7
secondary BH spin	< 0.9
remnant BH spin	0.7
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	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



CSEHORSZÁG
SZLOVÁKIA
AUSZTRIA
UKRAJNA
ROMÁNIA
SZERBIA
HORVÁTORSZÁG
SZLOVÉNIA
BÉCS
POZSONY
Felvidék
Kárpátalja
Gömör-Tornai-karszt
Aggteleki-karszt
Cserehát
Zempléni-hg.
Karancs-Medves
Heves-Borsodi-dombság
Bükk
Mátra
Cserhát
Börzsöny
Hortobágy
Tisza-tó
Szigetköz
Hanság
Lajta-hg.
Fertő
Soproni-hg.
Kőszegi-hg.
Vas-Soproni-völgység
Kemeneshát
Kemenesalja
Marcal-medence
Bakony
Balaton-felvidék
Keszthelyi-hg.
Balaton
Vasi-hegyhát
Őrség
Göcsej
Zalai-dombság
Somogyi-dombság
Zselic
Mecsek
Szekszárdi-dombság
Villányi-hg.
Mohácsi-sziget
Vajdaság
Győr
Komárom
Esztergom
Sopron
Szombathely
Zalaegerszeg
Nagykanizsa
Kaposvár
Pécs
Veszprém
Siófok
Baja
Szeged
Makó
Békéscsaba
Gyula
Debrecen
Nyíregyháza
Miskolc
Eger
Salgótarján
Kassa
Szabadka
Zenta
Arad
Nagyvárad
Temesvár
Eszék
Zágráb
Varasd
Kapronca




512
256
128
64
32
LIGO Hanford
512
256
128
64
32
LIGO Livingston
Frequency (Hz)
0.5
0.6
0.7
0.8
0.9
1.0
Time (sec)

GW151226

A LIGO ismét gravitációs hullámot észlelt!

A GW151226 a második észlelés fekete lyukak összeolvadásából

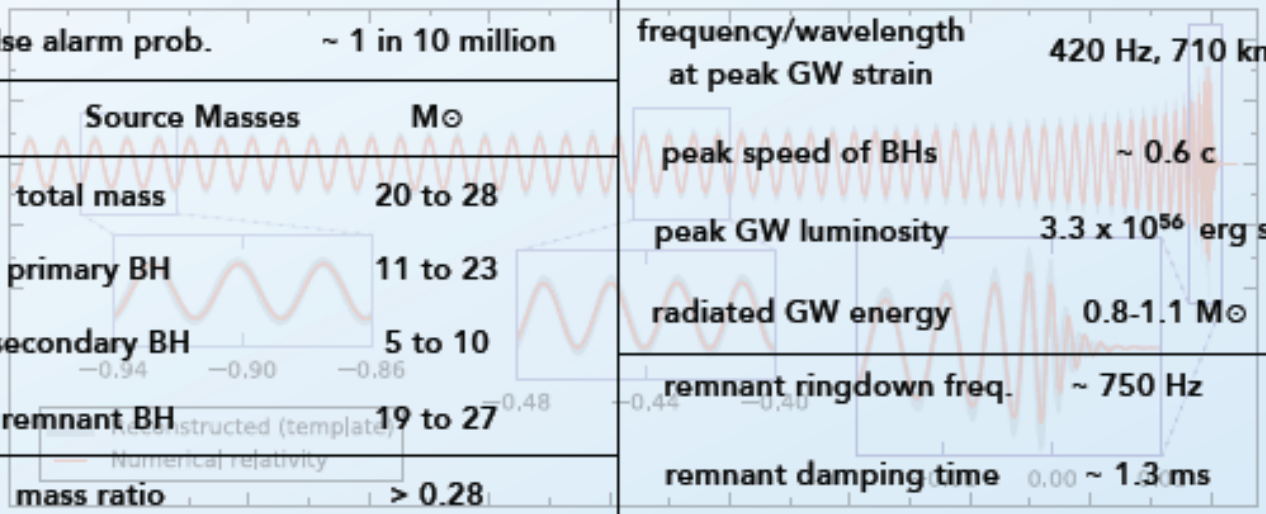
ligo.elte.hu

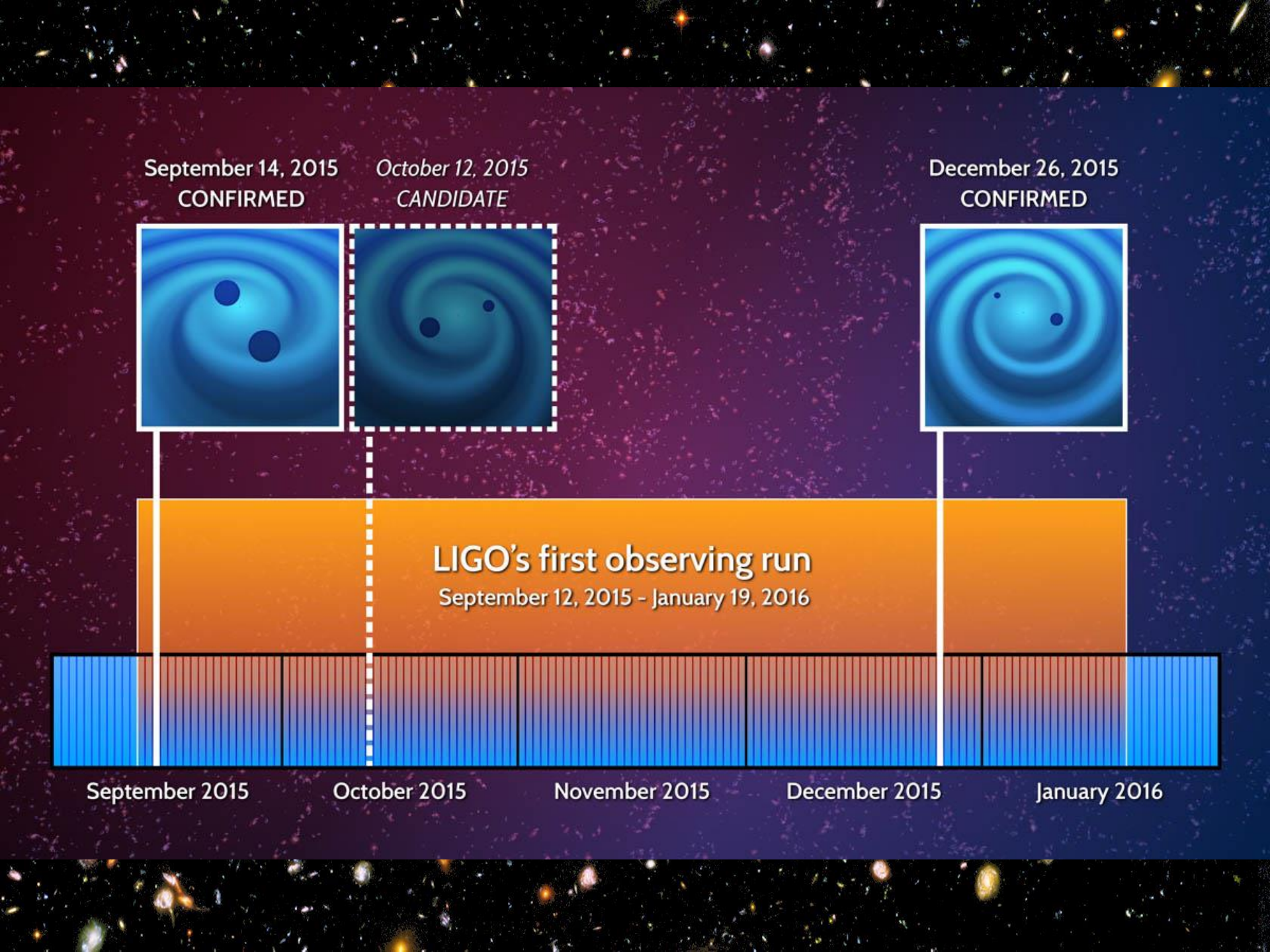
GW151226: FACTSHEET

ligo.elte.hu

observed by	LIGO L1, H1
source type	black hole (BH) binary
date	26 Dec 2015
time	03:38:53 UTC
likely distance	250 to 620 Mpc
redshift	0.05 to 0.12
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
primary BH spin	> 0.2
remnant BH spin	0.7 to 0.8
resolved to	~850 sq. deg.

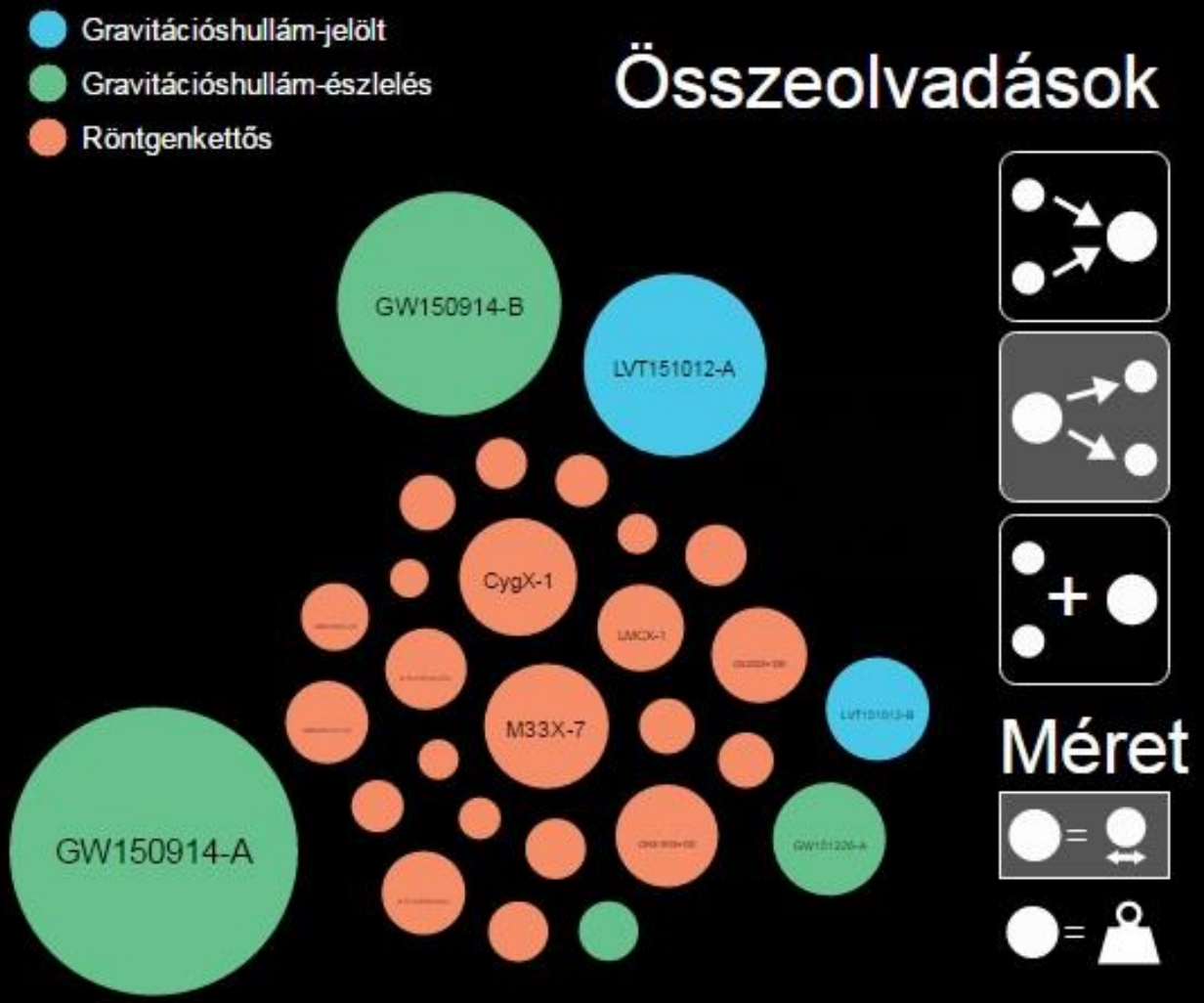
duration from 35 Hz	1.0 s
# cycles from 35 Hz	55
signal arrival time delay	arrived in H1 1 ms after L1
peak GW strain	3.5×10^{-22}
peak displacement of interferometers arms	±0.7 am
frequency/wavelength at peak GW strain	420 Hz, 710 km
peak speed of BHs	~ 0.6 c
peak GW luminosity	3.3×10^{56} erg s^{-1}
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	~ 3 min
# offline analysis pipelines	2



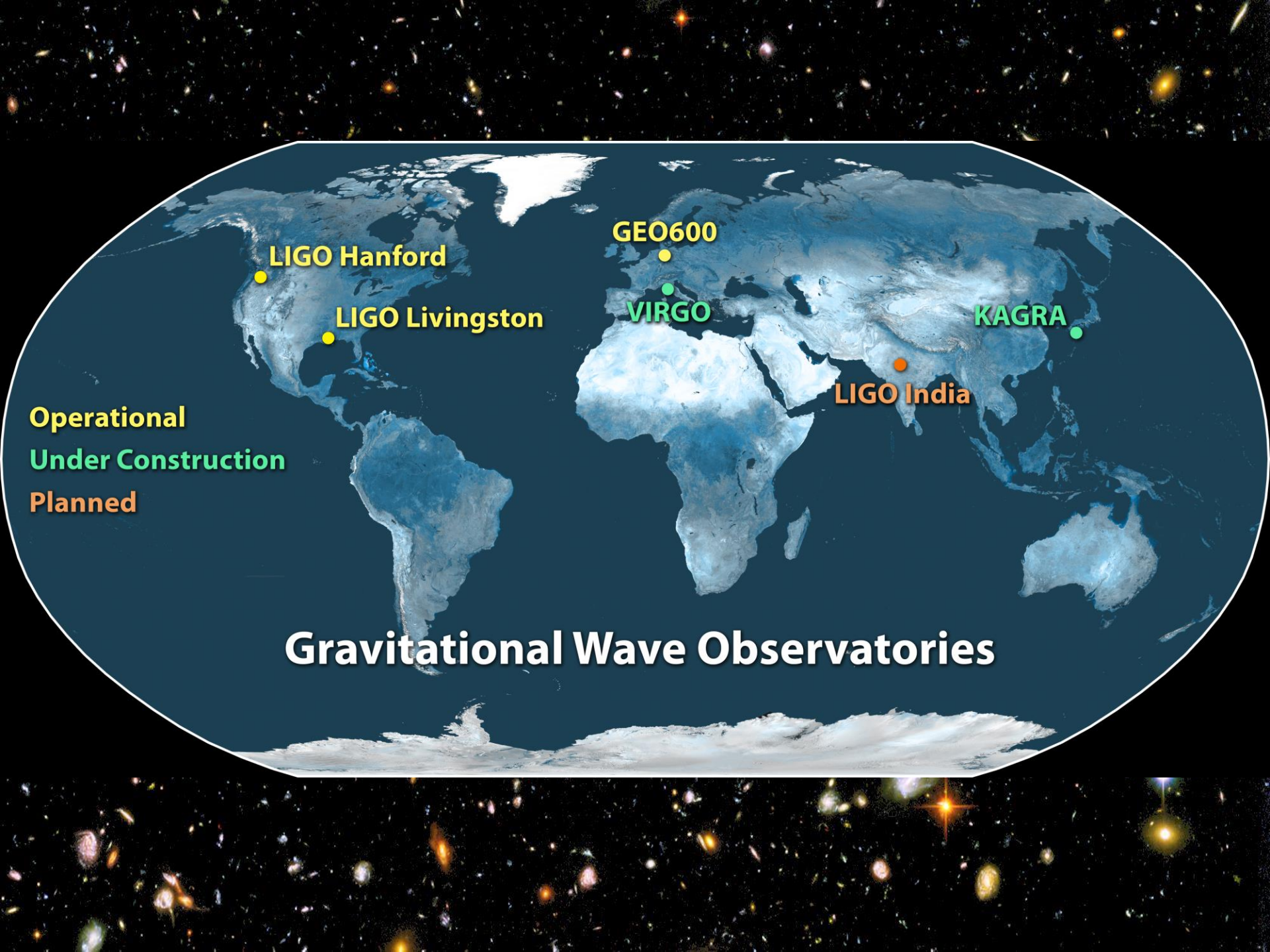

September 14, 2015
CONFIRMED
October 12, 2015
CANDIDATE
December 26, 2015
CONFIRMED
LIGO's first observing run
September 12, 2015 - January 19, 2016
September 2015
October 2015
November 2015
December 2015
January 2016

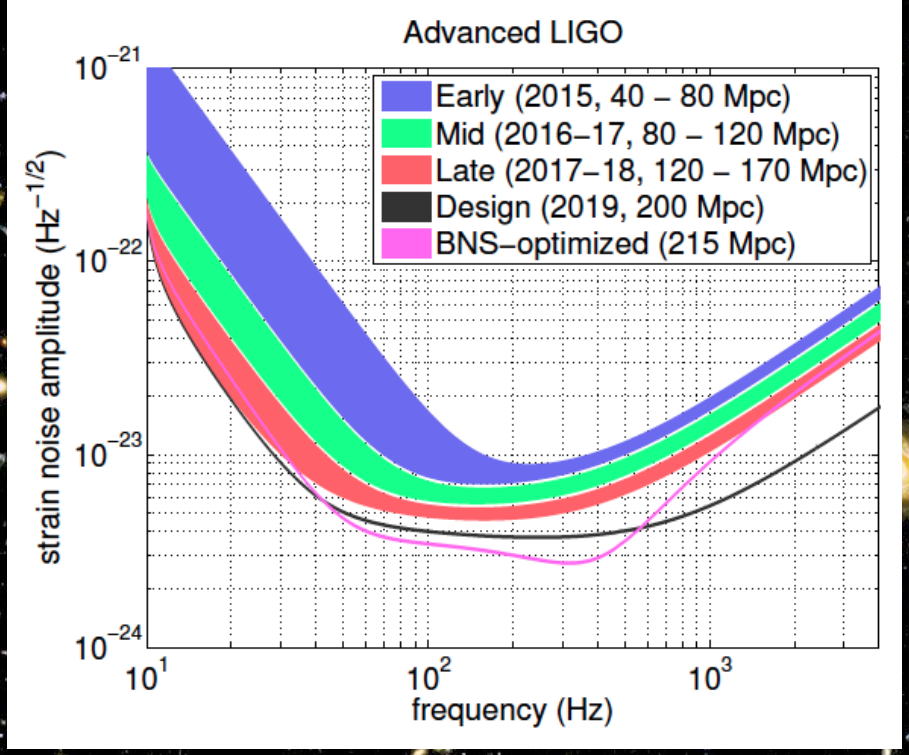
ligo.elte.hu

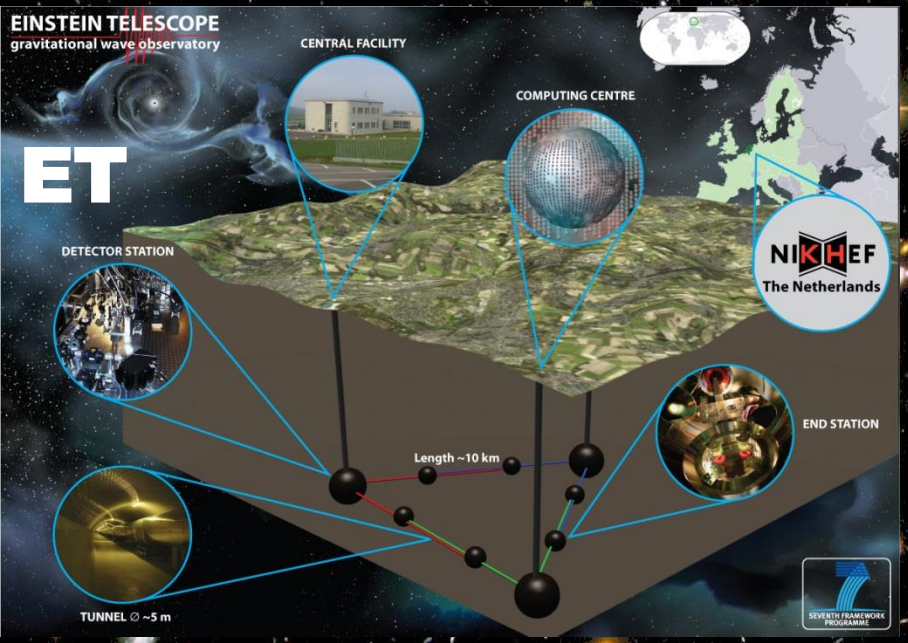
Ismert sztelláris fekete lyukak

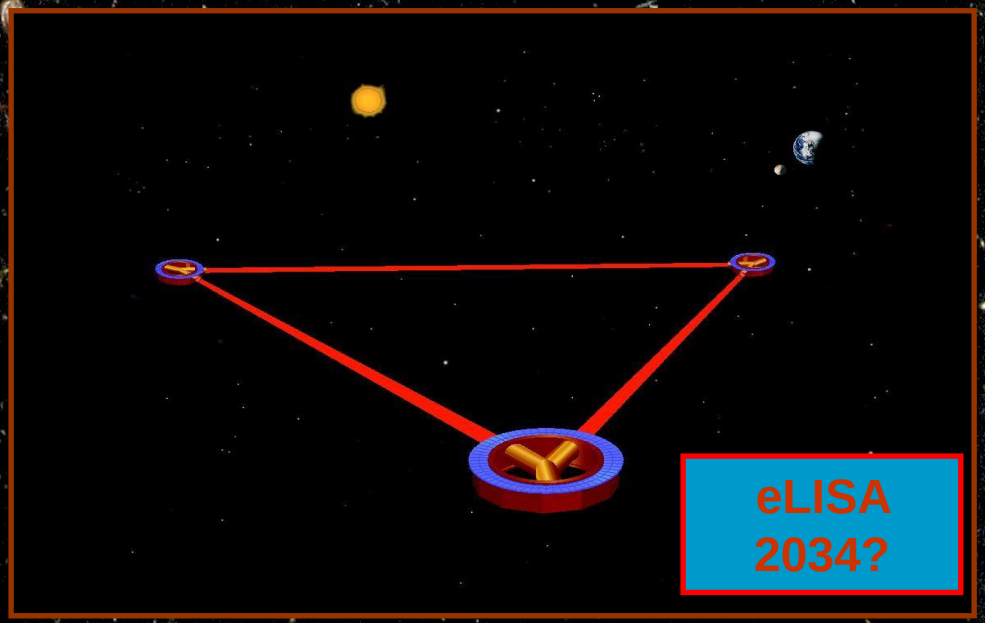


Forrás: Cardiff University School of Physics and Astronomy
Magyar szöveg: Szölgyén Ákos, Dálya Gergely, Raffai Péter
Fejlesztő: Chris North a LIGO Scientific Collaboration megbízásából.
Forráskód megtekintése a GitHub-on.
A röntgenkettősök adatainak forrása: stellarcollapse.org


LIGO Hanford
LIGO Livingston
GEO600
VIRGO
KAGRA
LIGO India
Operational
Under Construction
Planned
Gravitational Wave Observatories


Advanced LIGO
Early (2015, 40 – 80 Mpc)
Mid (2016–17, 80 – 120 Mpc)
Late (2017–18, 120 – 170 Mpc)
Design (2019, 200 Mpc)
BNS–optimized (215 Mpc)
strain noise amplitude (Hz$^{-1/2}$)
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{1}
10^{2}
10^{3}
frequency (Hz)


EINSTEIN TELESCOPE
gravitational wave observatory
ET
CENTRAL FACILITY
COMPUTING CENTRE
DETECTOR STATION
NIKHEF
The Netherlands
END STATION
Length ~10 km
TUNNEL ∅ ~5 m
SEVENTH FRAMEWORK PROGRAMME


eLISA
2034?

Új ablak a világegyetemre

- Általános relativitáselmélet ellenőrzése
  - Erős gravitációs tér
  - GH hullámterjedés
- Asztrofizika
  - Fekete lyuk, NS ütközések
  - NS, WD struktúra
  - Pulzárok
  - Szupernóva robbanás
  - Gamma felvillanás
  - Akkréciós fizika
  - Eddington arány
- Precíziós Kozmológia
  - “Standard szirénák”
- Kis skálás struktúra
  - Gömbhalmazok
  - Galaxismagok
- Nagy skálás struktúra
  - Hierarchikus struktúraképződés
- Nagy Bumm
  - Gravitációs háttér


A világegyetem zenéje...

ARECIBO 305m rádióteleszkóp

R. Hulse

J. Taylor