

Gravitační vlny: další okno do Vesmíru dokořán

Petr Dvořák

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6. dubna 2021, ASTRONOMIE aneb blíže ke hvězdám X online, U3V, Brno

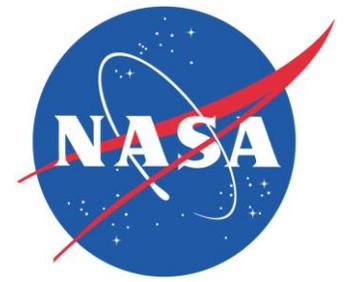
Obsah

- Teorie gravitace (OTR)
- **Gravitační vlny** a jejich vlastnosti
- Zdroje gravitačních vln
- Historie detekce
- Nepřímý důkaz gravitačních vln
- LIGO a interferometrické detektory
- První detekce spojení černých děr
- První detekce kilonovy
- Současný stav a novinky
- Budoucnost



RNDr. Jiří Grygar, CSc.
(17. března 1936)

Okna Vesmíru dokořán (1981-1991)



WIKIPEDIA
The Free Encyclopedia



MAX-PLANCK-GESELLSCHAFT

Zdroje: ESA, NASA, LIGO, VIRGO, einstein-online.info
Max Planck institute, en.wikipedia.org, gwplotter.com

844 Sitzung der physikalisch-mathematischen Klasse vom 25. November 1915

25. listopadu 1915

Die Feldgleichungen der Gravitation.

VON A. EINSTEIN.

In zwei vor kurzem erschienenen Mitteilungen¹ habe ich gezeigt, wie man zu Feldgleichungen der Gravitation gelangen kann, die dem Postulat allgemeiner Relativität entsprechen, d. h. die in ihrer allgemeinen Fassung beliebigen Substitutionen der Raumzeitvariablen gegenüber kovariant sind.

Der Entwicklungsgang war dabei folgender. Zunächst fand ich Gleichungen, welche die NEWTONSCHE Theorie als Näherung enthalten und beliebigen Substitutionen von der Determinante 1 gegenüber kovariant waren. Hierauf fand ich, daß diesen Gleichungen allgemein kovariante entsprechen, falls der Skalar des Energietensors der »Materie« verschwindet. Das Koordinatensystem war dann nach der einfachen Regel zu spezialisieren, daß $\sqrt{-g}$ zu 1 gemacht wird, wodurch die Gleichungen der Theorie eine eminente Vereinfachung erfahren. Dabei mußte aber, wie erwähnt, die Hypothese eingeführt werden, daß der Skalar des Energietensors der Materie verschwinde.

Neuerdings finde ich nun, daß man ohne Hypothese über den Energietensor der Materie auskommen kann, wenn man den Energietensor der Materie in etwas anderer Weise in die Feldgleichungen einsetzt, als dies in meinen beiden früheren Mitteilungen geschehen ist. Die Feldgleichungen für das Vakuum, auf welche ich die Erklärung der Perihelbewegung des Merkur gegründet habe, bleiben von dieser Modifikation unberührt. Ich gebe hier nochmals die ganze Betrachtung, damit der Leser nicht genötigt ist, die früheren Mitteilungen unausgesetzt heranzuziehen.

Aus der bekannten RIEMANNSCHEM Kovariante vierten Ranges leitet man folgende Kovariante zweiten Ranges ab:

$$G_{im} = R_{im} + S_{im} \tag{1}$$

$$R_{im} = -\sum_l \frac{\partial \left\{ \begin{matrix} im \\ l \end{matrix} \right\}}{\partial x_l} + \sum_l \left\{ \begin{matrix} il \\ \rho \end{matrix} \right\} \left\{ \begin{matrix} m\rho \\ l \end{matrix} \right\} \tag{1a}$$

$$S_{im} = \sum_l \frac{\partial \left\{ \begin{matrix} il \\ l \end{matrix} \right\}}{\partial x_m} - \sum_l \left\{ \begin{matrix} im \\ \rho \end{matrix} \right\} \left\{ \begin{matrix} \rho l \\ l \end{matrix} \right\} \tag{1b}$$

¹ Sitzungsber. XLIV. S. 778 und XLVI, S. 799, 1915.

ERWEITERUNG: Die Feldgleichungen der Gravitation 845

Die allgemein kovarianten zehn Gleichungen des Gravitationsfeldes in Räumen, in denen »Materie« fehlt, erhalten wir, indem wir ansetzen

$$G_{im} = 0. \tag{2}$$

Diese Gleichungen lassen sich einfacher gestalten, wenn man das Bezugssystem so wählt, daß $\sqrt{-g} = 1$ ist. Dann verschwindet S_{im} wegen (1b), so daß man statt (2) erhält

$$R_{im} = \sum_l \frac{\partial \Gamma_{im}^l}{\partial x_l} + \sum_l \Gamma_{il}^l \Gamma_{ml}^l = 0 \tag{3}$$

$$\sqrt{-g} = 1. \tag{3a}$$

Dabei ist

$$\Gamma_{im}^l = -\left\{ \begin{matrix} im \\ l \end{matrix} \right\} \tag{4}$$

gesetzt, welche Größen wir als die »Komponenten« des Gravitationsfeldes bezeichnen.

Ist in dem betrachteten Raume »Materie« vorhanden, so tritt deren Energietensor auf der rechten Seite von (2) bzw. (3) auf. Wir setzen

$$G_{im} = -\kappa \left(T_{im} - \frac{1}{2} g_{im} T \right), \tag{2a}$$

wobei

$$\sum_r g^{ir} T_{ir} = \sum_r T_r = T \tag{5}$$

gesetzt ist; T ist der Skalar des Energietensors der »Materie«, die rechte Seite von (2a) ein Tensor. Spezialisieren wir wieder das Koordinatensystem in der gewohnten Weise, so erhalten wir an Stelle von (2a) die äquivalenten Gleichungen

$$R_{im} = \sum_l \frac{\partial \Gamma_{im}^l}{\partial x_l} + \sum_l \Gamma_{il}^l \Gamma_{ml}^l = -\kappa \left(T_{im} - \frac{1}{2} g_{im} T \right) \tag{6}$$

$$\sqrt{-g} = 1. \tag{3a}$$

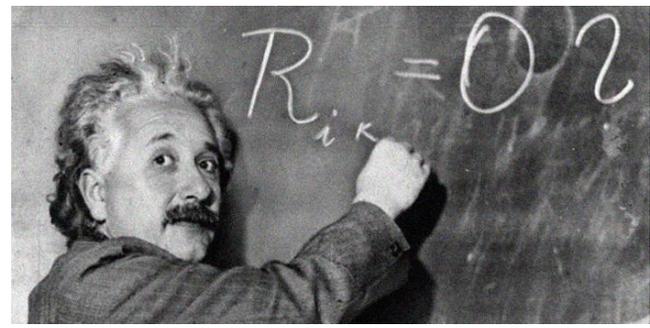
Wie stets nehmen wir an, daß die Divergenz des Energietensors der Materie im Sinne des allgemeinen Differentialkalküls verschwinde (Impulsenergiesatz). Bei der Spezialisierung der Koordinatenwahl gemäß (3a) kommt dies darauf hinaus, daß die T_{im} die Bedingungen

$$\sum_\lambda \frac{\partial T_\lambda^i}{\partial x_\lambda} = -\frac{1}{2} \sum_{\mu\nu} \frac{\partial g^{\mu\nu}}{\partial x_i} T_{\mu\nu} \tag{7}$$

oder

$$\sum_\lambda \frac{\partial T_\lambda^i}{\partial x_\lambda} = -\sum_{\mu\nu} \Gamma_{\mu\nu}^i T_{\mu\nu} \tag{7a}$$

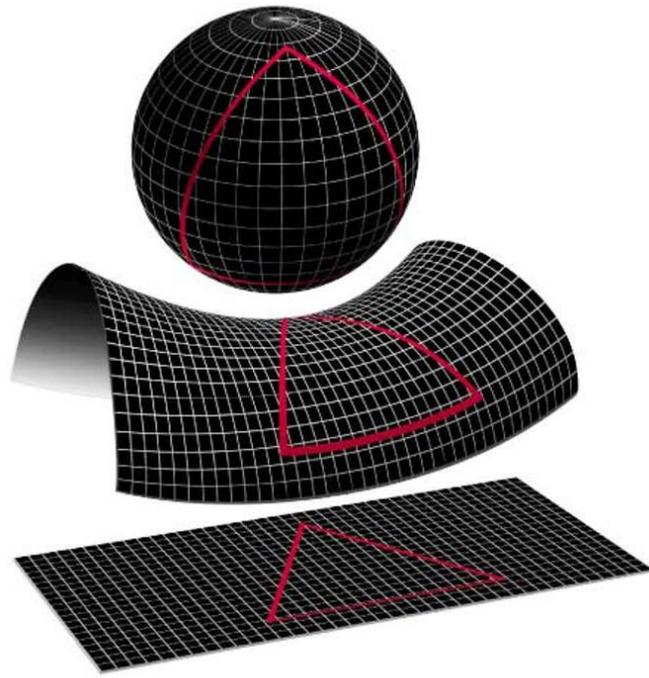
erfüllen sollen.



A. Einstein (1879 – 1955)

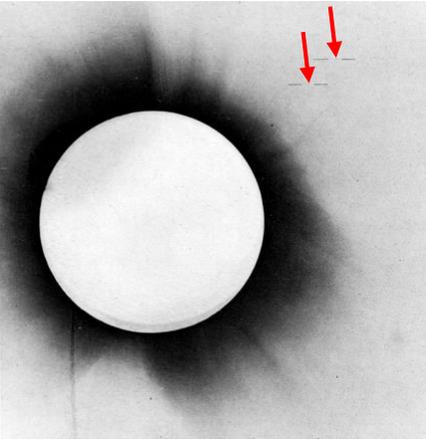
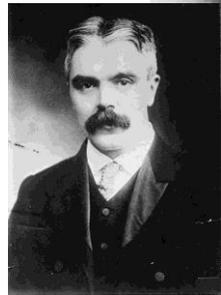
$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Geometrie prostoru = zdroje deformace

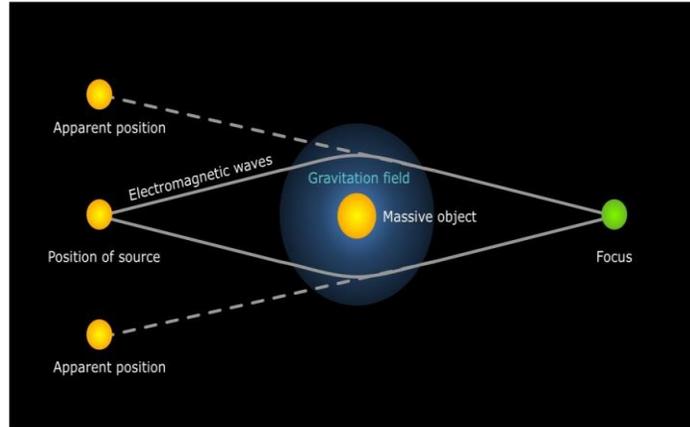


Obecná teorie relativity

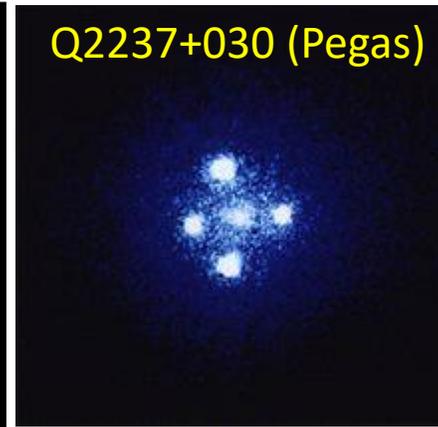
Úplné zatmění Slunce (1919)



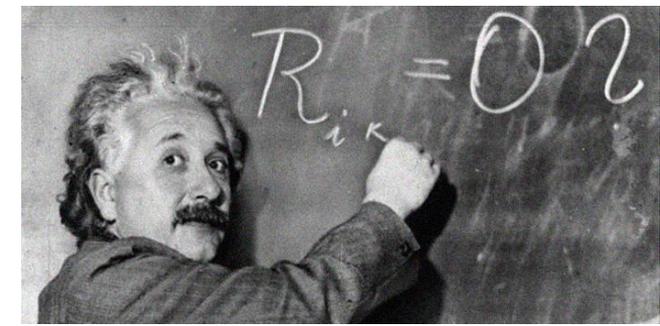
A. Eddington (1882 – 1944)
F. W. Dyson (1868 – 1939)



Gravitační čočka



Einsteinův kříž

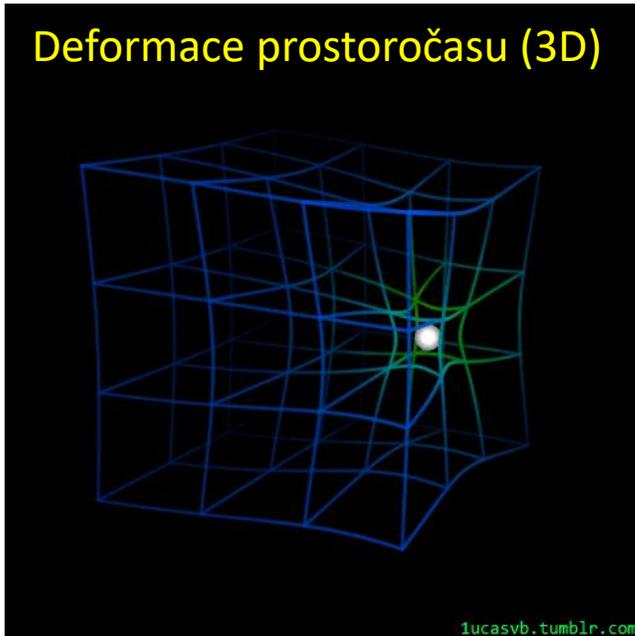


A. Einstein (1879 – 1955)

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

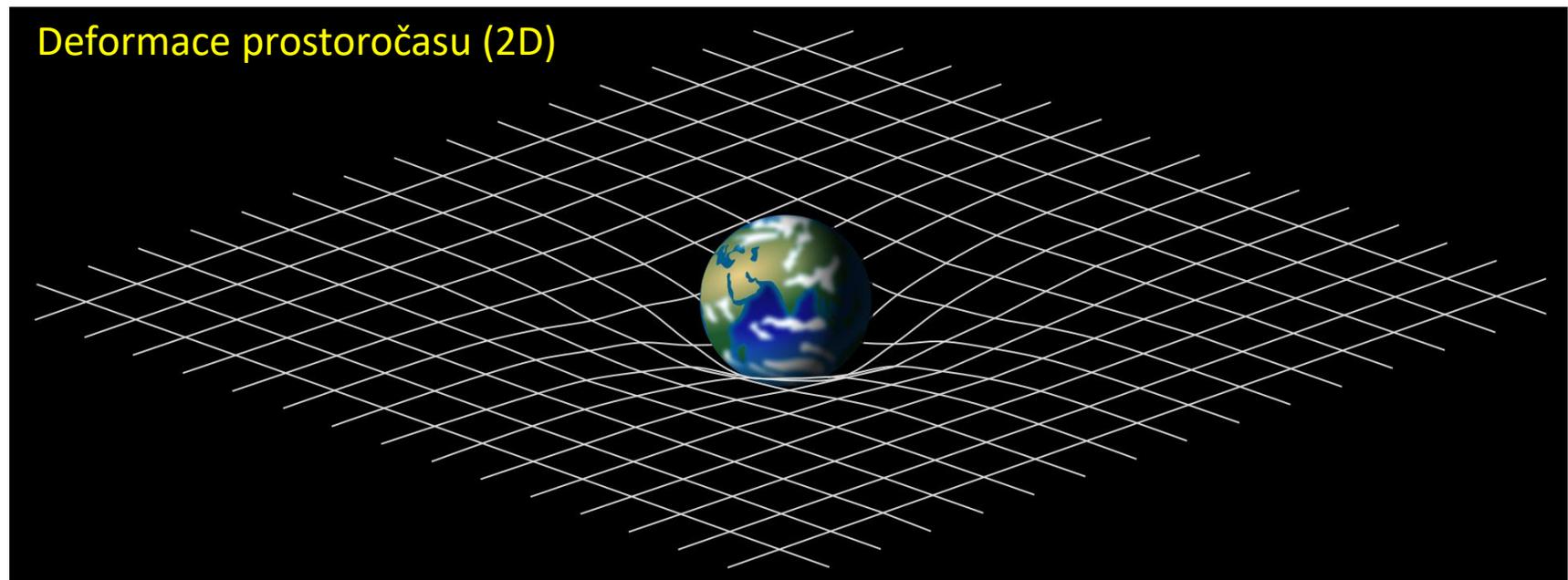
Geometrie prostoru = zdroje deformace

Deformace prostoročasu (3D)



lucasvb.tumblr.com

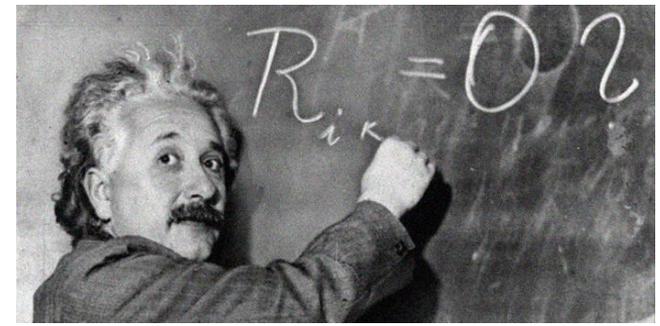
Deformace prostoročasu (2D)



Obečná teorie relativity



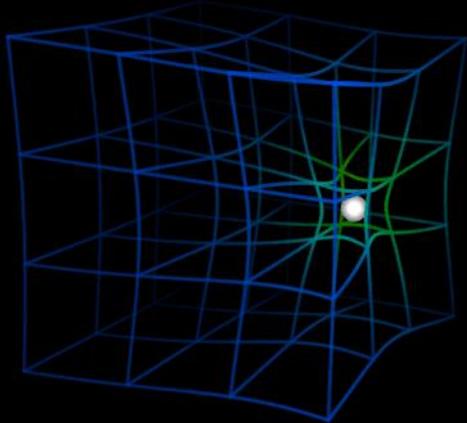
2D mechanické vlny



A. Einstein (1879 – 1955)

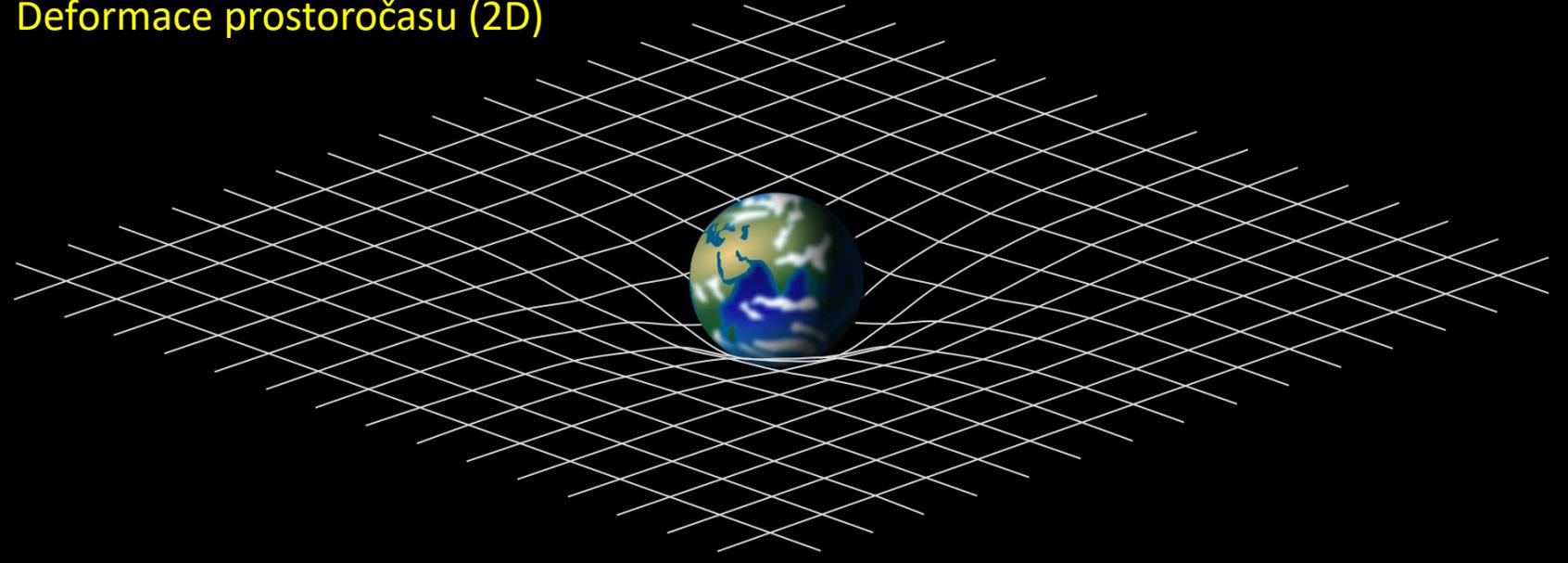
$$R_{\mu\nu} - \frac{1}{2}R g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

Deformace prostoročasu (3D)

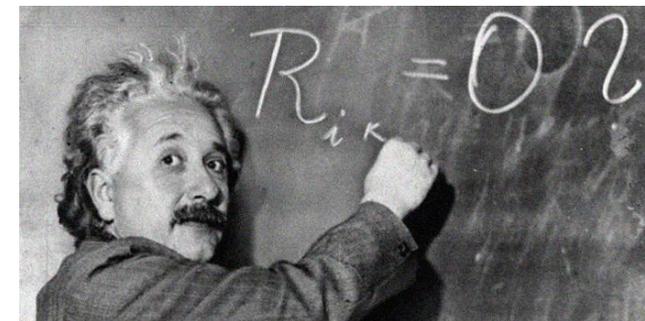
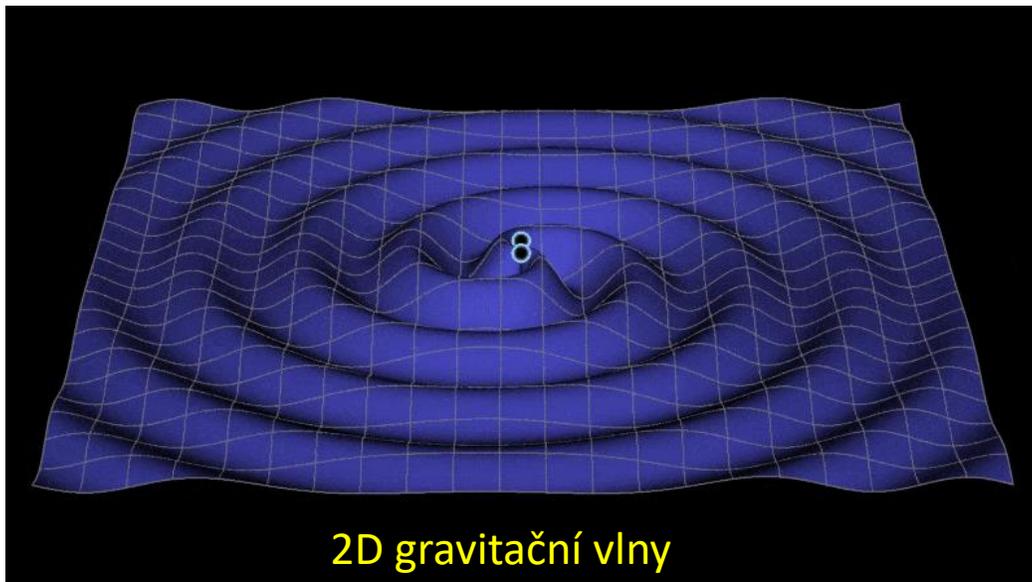


lucasvb.tumblr.com

Deformace prostoročasu (2D)



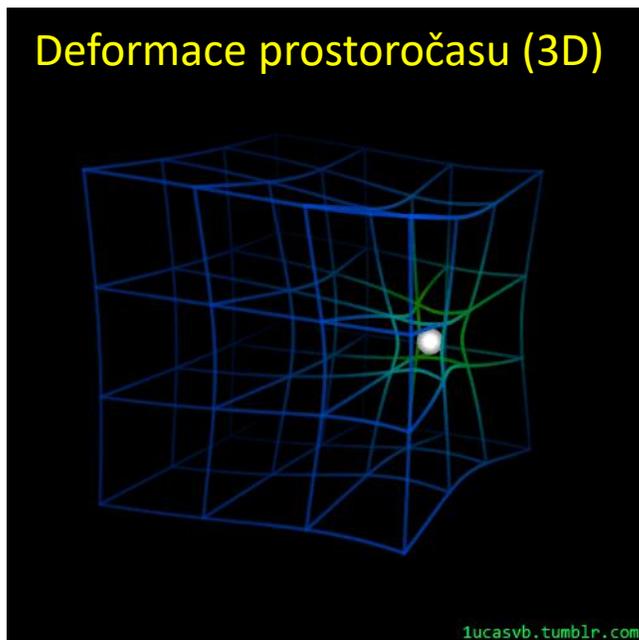
Obecná teorie relativity



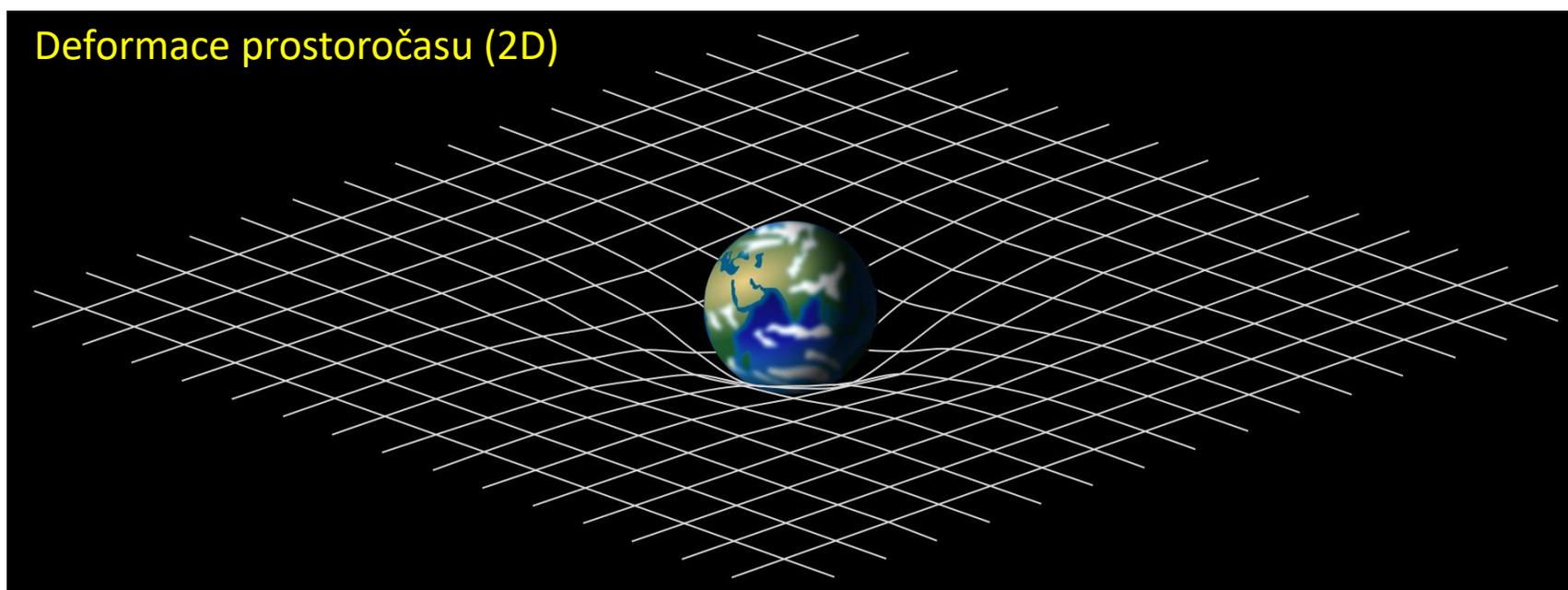
A. Einstein (1879 – 1955)

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

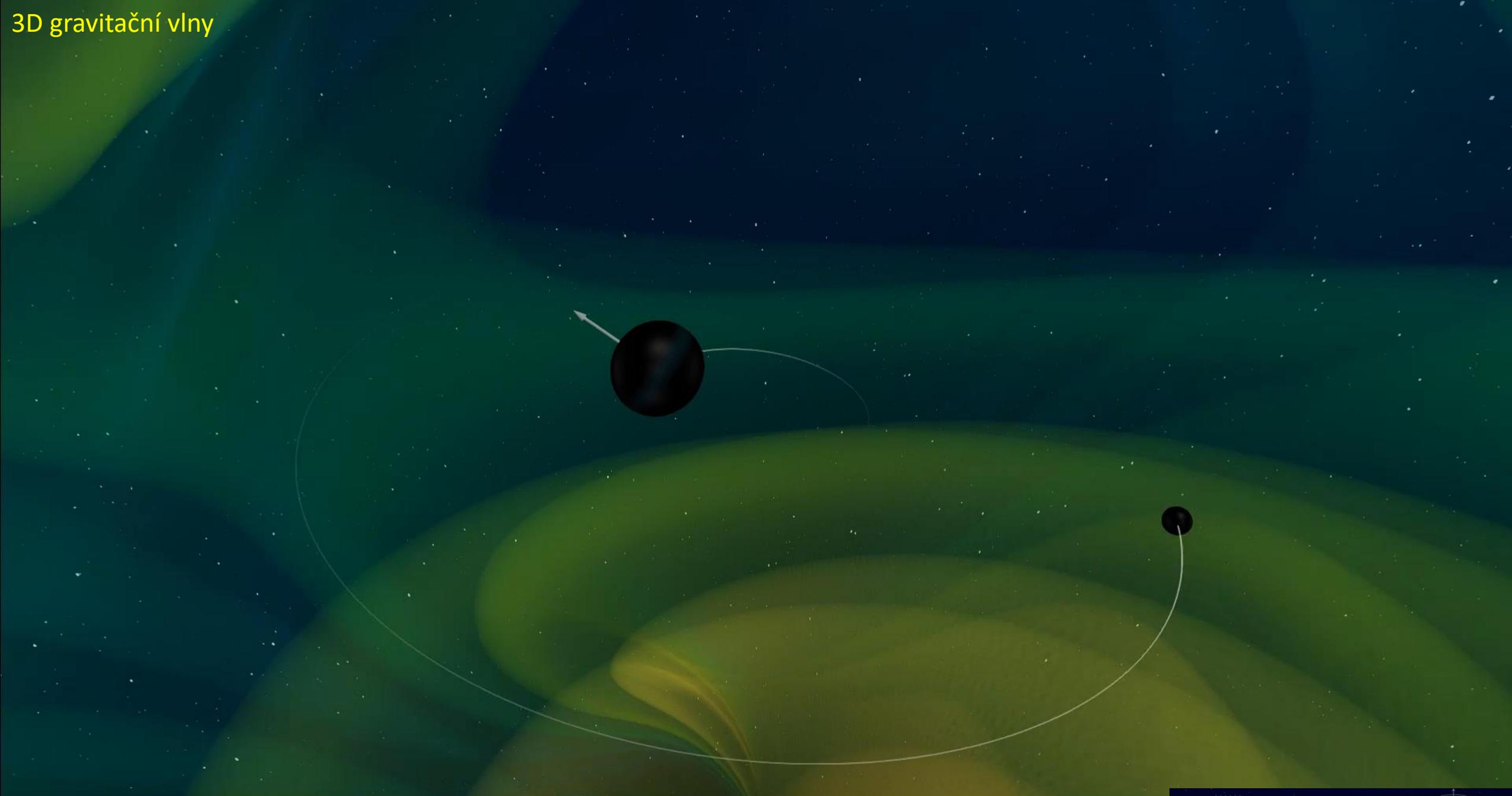
Deformace prostoročasu (3D)



Deformace prostoročasu (2D)

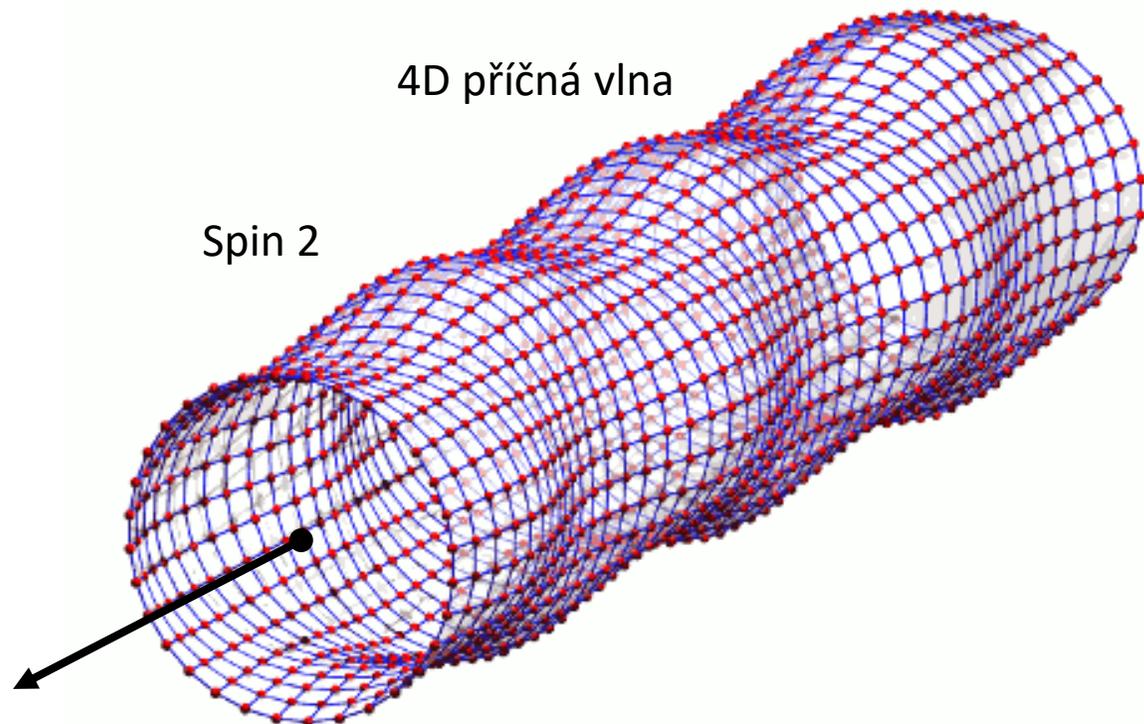


3D gravitační vlny



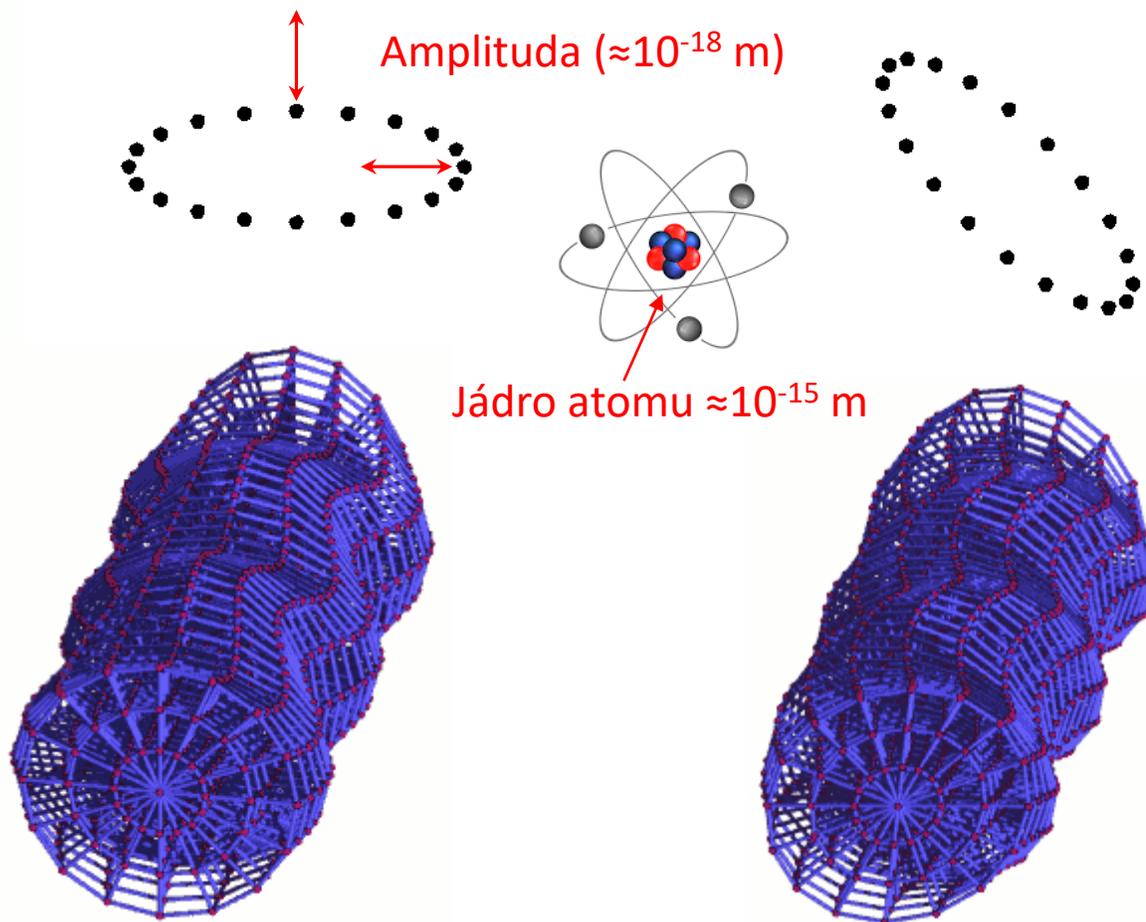
Gravitační vlny (GW)

4D příčná vlna, se spinem 2, amplituda 10^{-18} m, šířící se rychlostí světla bez disperze (slabá interakce s látkou => pozorování počátku Vesmíru), lineární a eliptická polarizace, přenáší energii a hybnost, intenzita klesá úměrně $1/r$, zdroj GW musí mít kvadratický moment

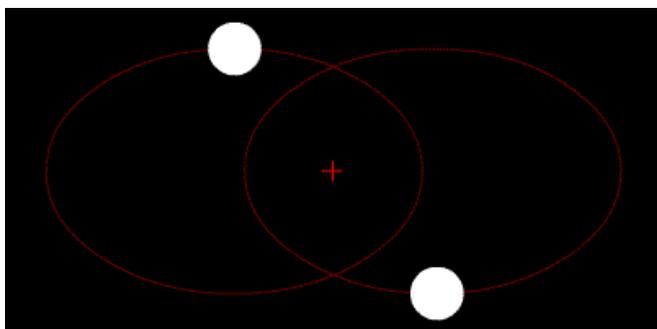
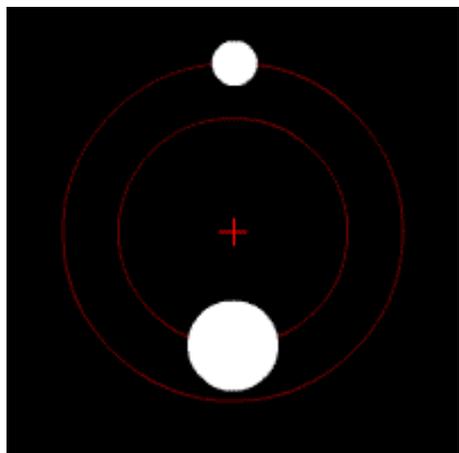
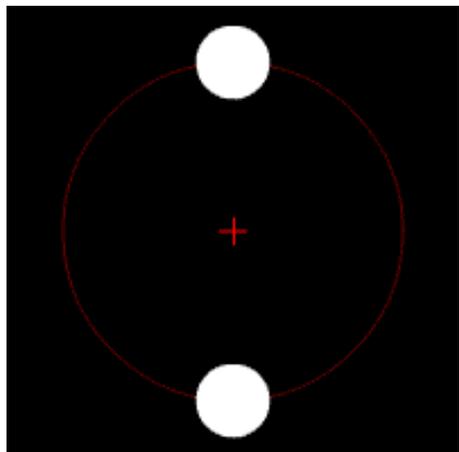


Lineární polarizace

Eliptická polarizace



Binární systémy hmotných těles



Zdroje gravitační vln

Spektrum gravitačních vln

Perioda vlny

Frekvence

Věk Vesmíru

Roky

Hodiny

Sekundy

Milisekundy



10^{-16}

10^{-14}

10^{-12}

10^{-10}

10^{-8}

10^{-6}

10^{-4}

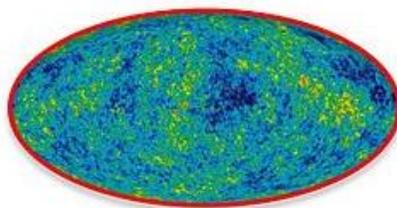
10^{-2}

10^0

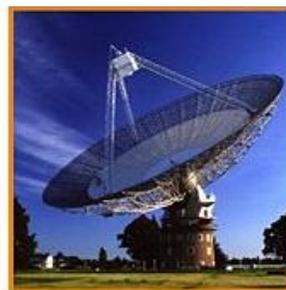
10^2

Detektory

Polarizace
reliktního záření



Časování pulzarů



Vesmírné
interferometry



Pozemní
interferometry



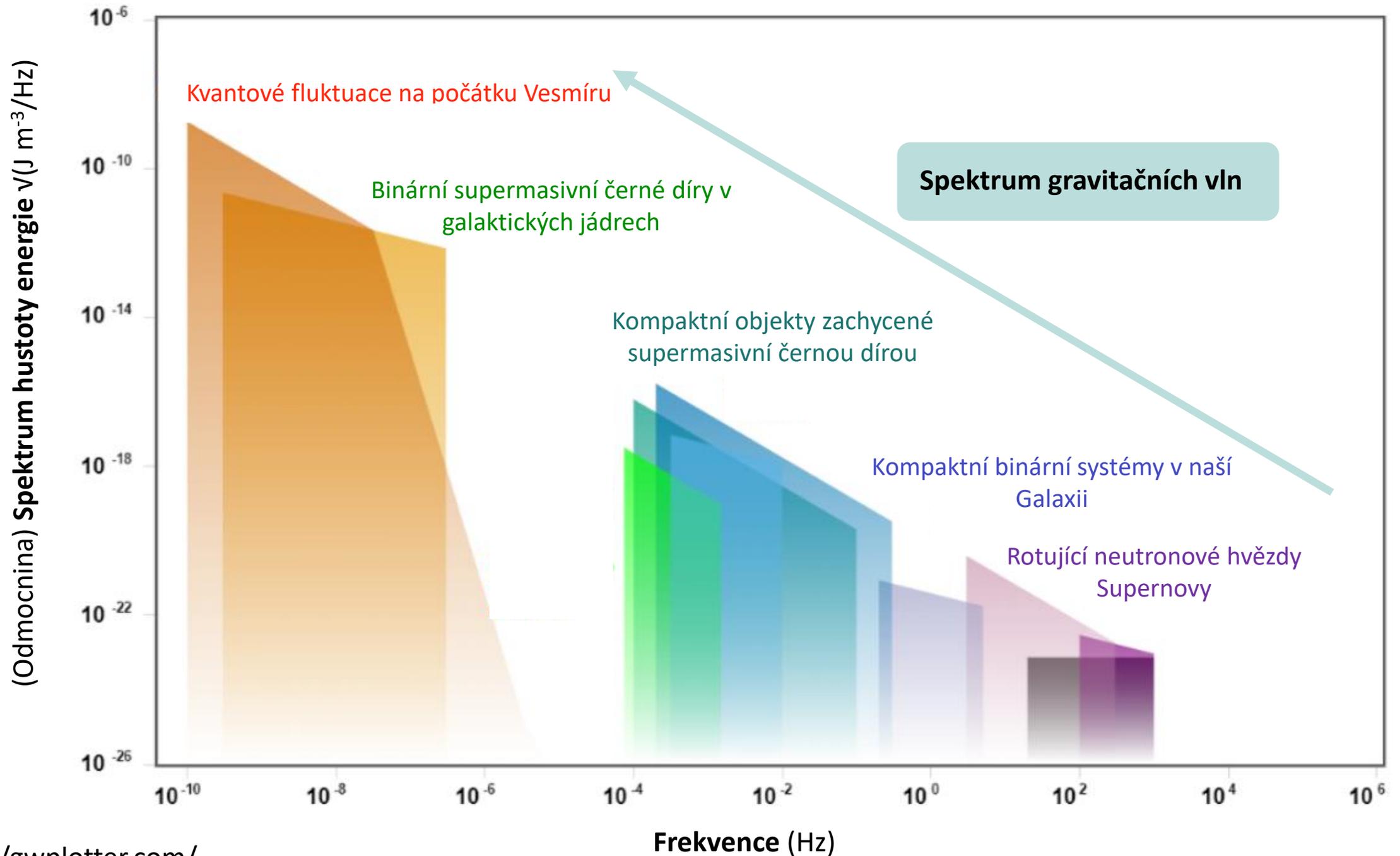
Kvantové fluktuace na počátku Vesmíru

Binární supermasivní černé díry v
galaktických jádrech

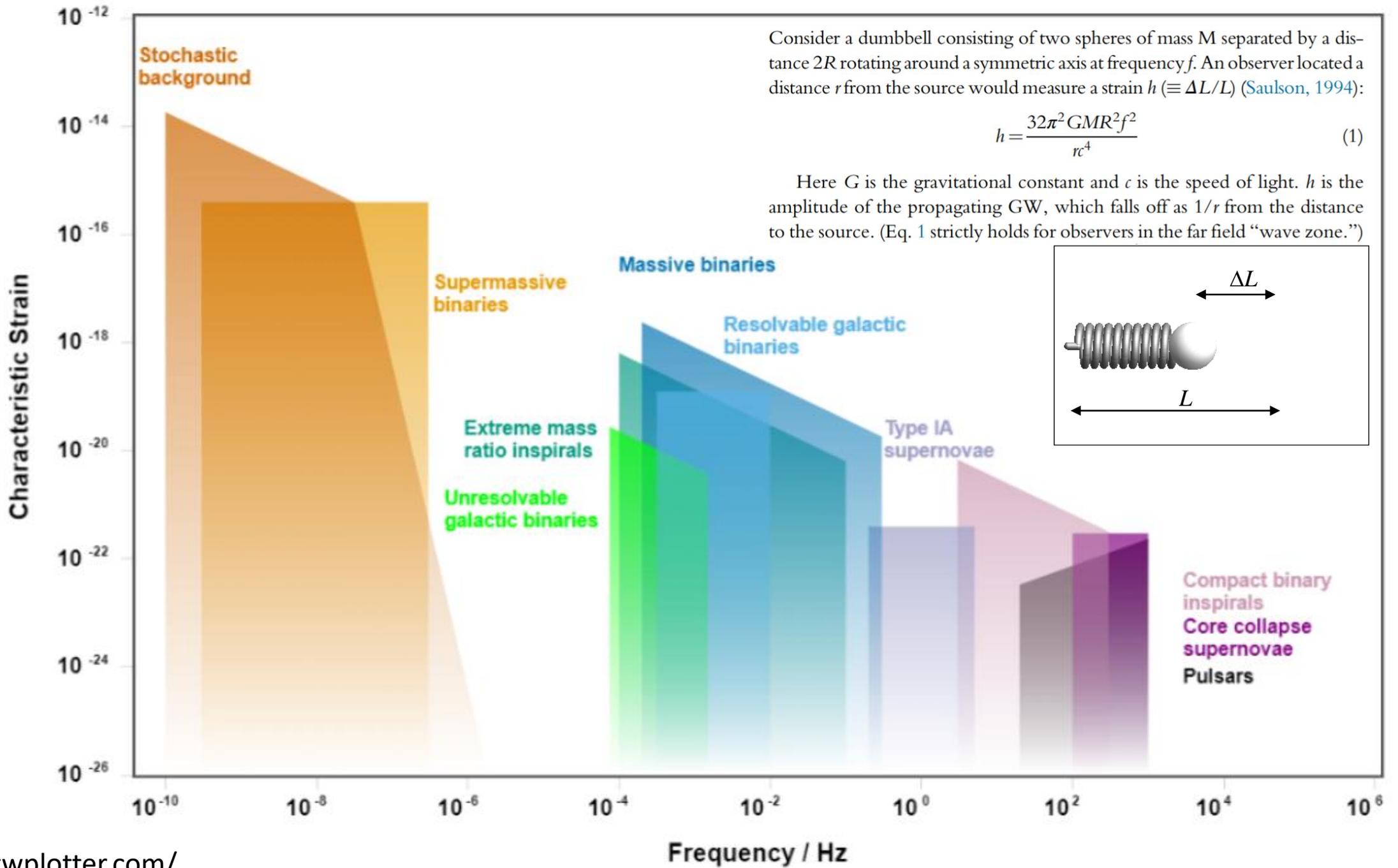
Kompaktní binární systémy v naší
Galaxii

Kompaktní objekty zachycené
supermasivní černou dírou

Rotující neutronové hvězdy
Supernovy



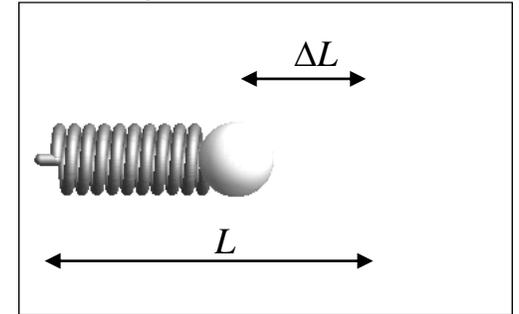
Charakteristické natažení ($h = \Delta L / L$)



Consider a dumbbell consisting of two spheres of mass M separated by a distance $2R$ rotating around a symmetric axis at frequency f . An observer located a distance r from the source would measure a strain h ($\equiv \Delta L/L$) (Saulson, 1994):

$$h = \frac{32\pi^2 GMR^2 f^2}{rc^4} \quad (1)$$

Here G is the gravitational constant and c is the speed of light. h is the amplitude of the propagating GW, which falls off as $1/r$ from the distance to the source. (Eq. 1 strictly holds for observers in the far field “wave zone.”)



Historie detekce gravitačních vln a detektory



Joseph Weber (1919 – 2000)

- Citlivost okolo 10^{-18} Hz^{-1} a pouze pro úzký rozsah frekvencí

PHYSICAL REVIEW

VOLUME 117, NUMBER 1

JANUARY 1, 1960

Detection and Generation of Gravitational Waves*

J. WEBER
University of Maryland, College Park, Maryland

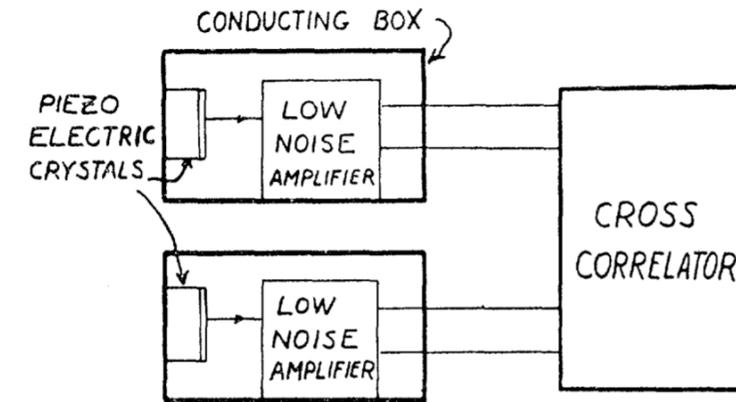


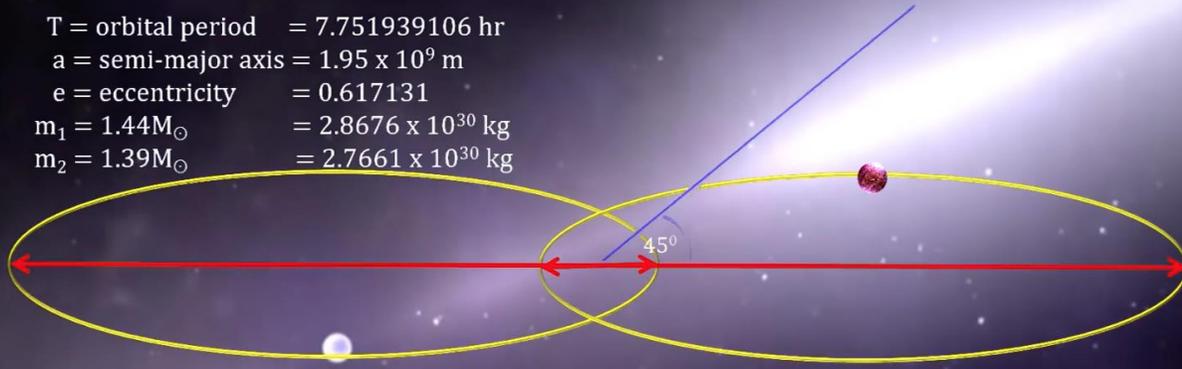
FIG. 3. Schematic diagram of cross correlation detection of gravitational waves.

Korelativní měření z dvou stanic!

Nepřímý důkaz gravitačních vln

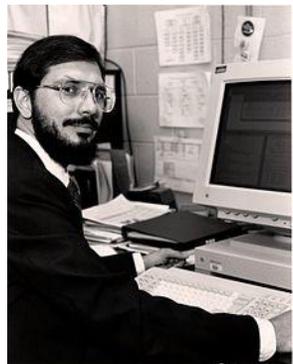
PSR B1913+16

T = orbital period = 7.751939106 hr
 a = semi-major axis = 1.95×10^9 m
 e = eccentricity = 0.617131
 $m_1 = 1.44M_{\odot} = 2.8676 \times 10^{30}$ kg
 $m_2 = 1.39M_{\odot} = 2.7661 \times 10^{30}$ kg



Periastron = 0.746×10^6 km
Apastron = 3.153×10^6 km
Inclination = 45°

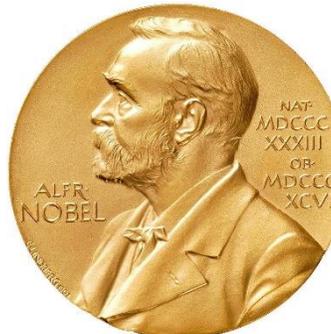
Prodloužení periody 76,5 μ s za rok
Přiblížení objektů 3,5 m za rok



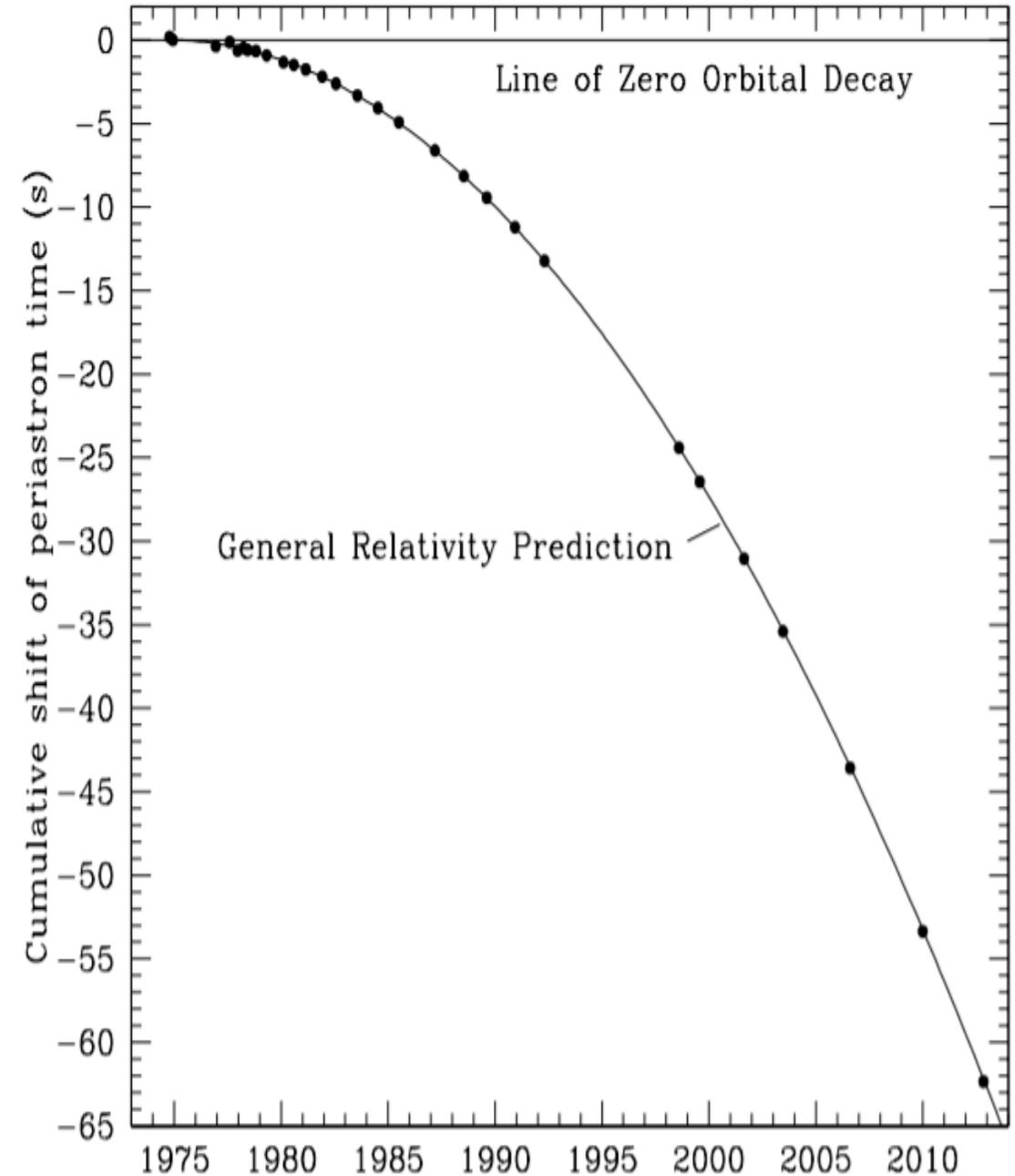
R. A. Hulse



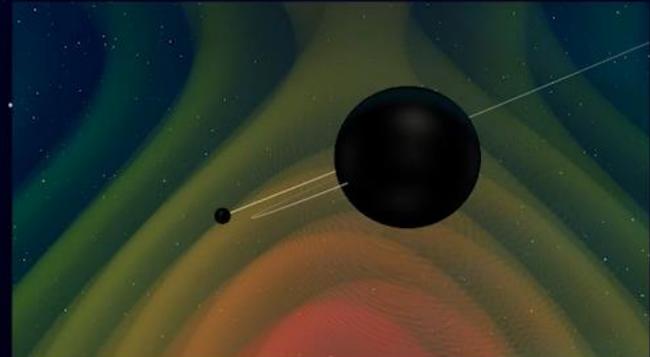
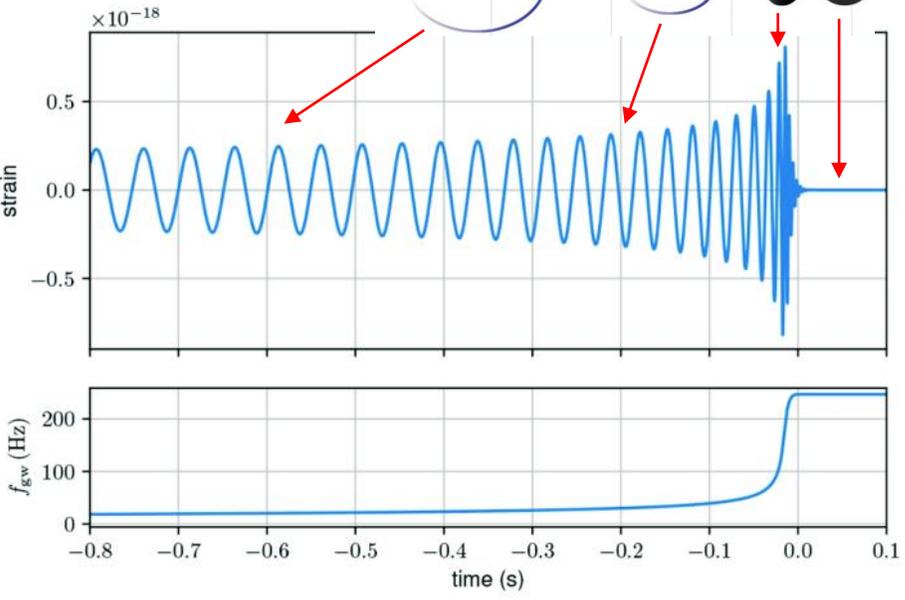
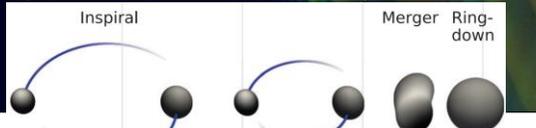
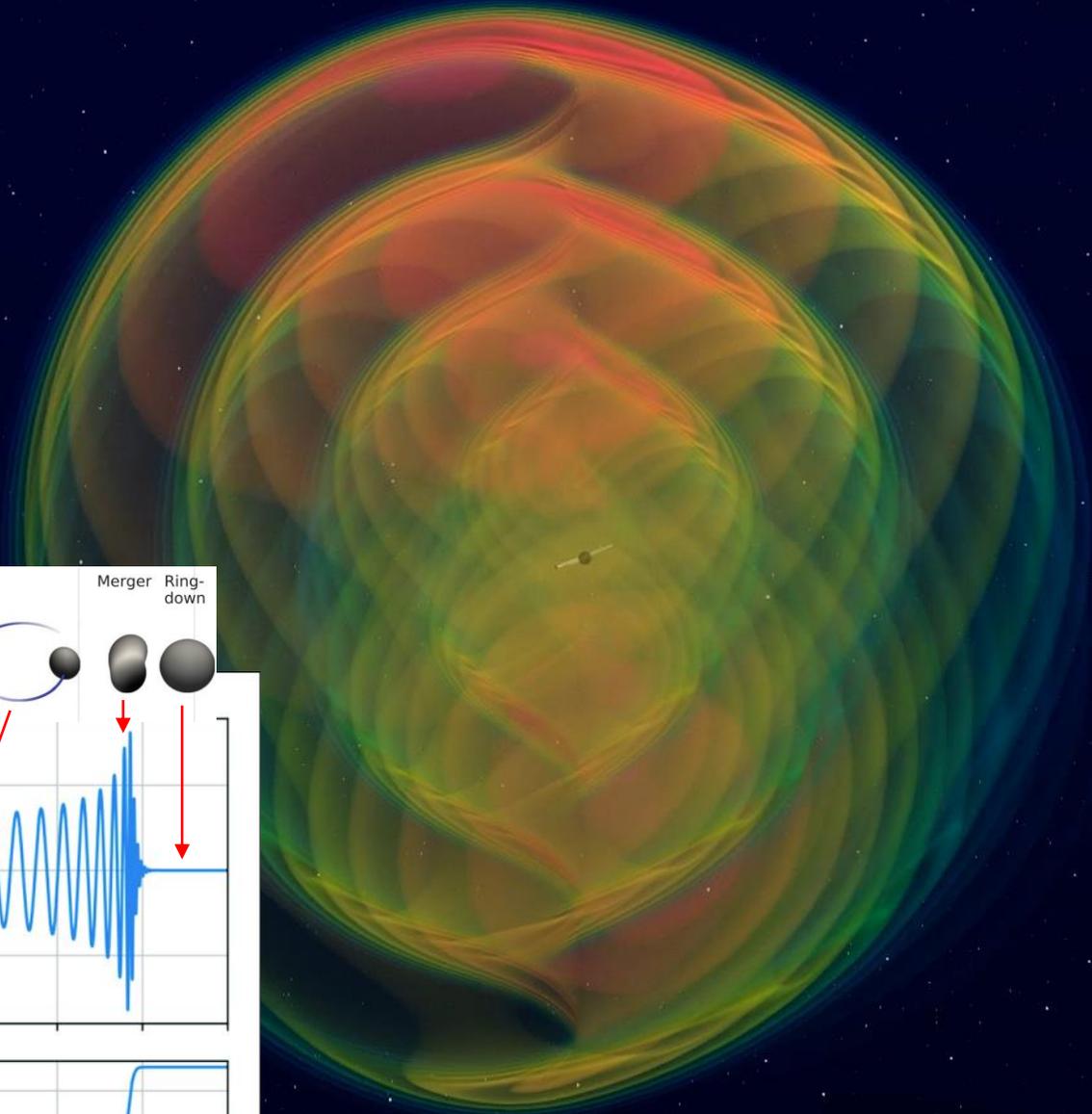
J. H. Taylor



1993



Co tedy hledáme (= snažíme se změřit)?

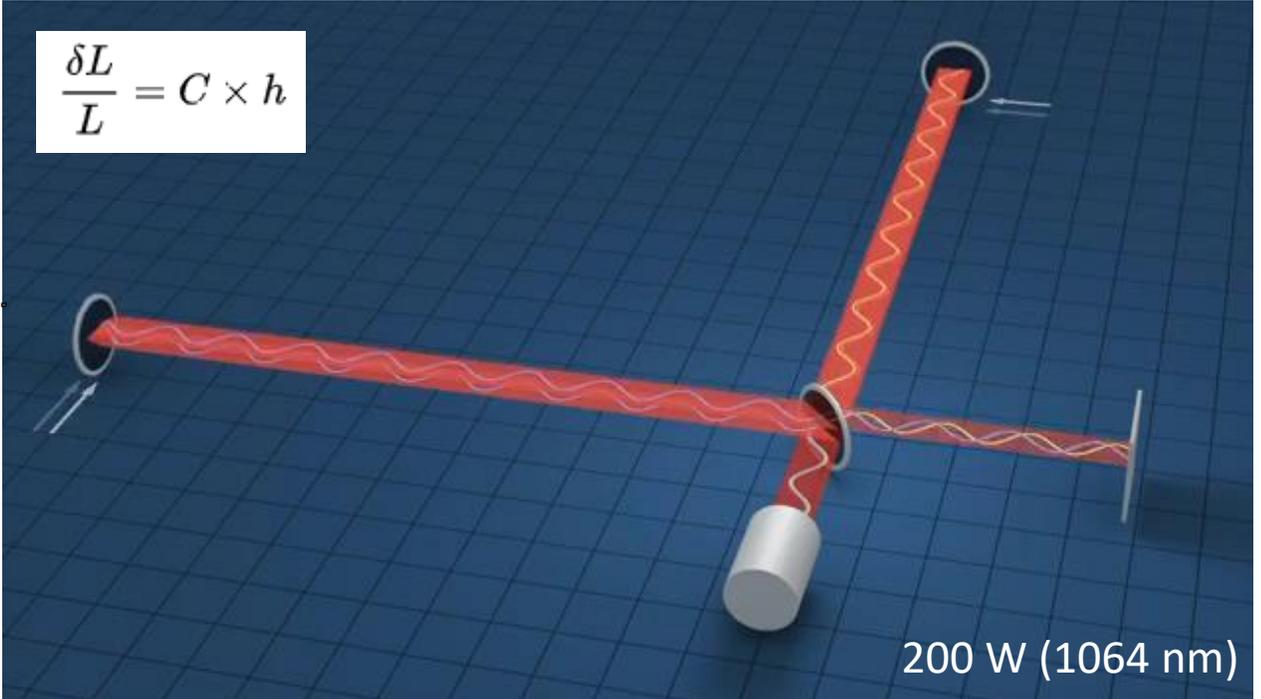


Interferometrické detektory GW

Detekce frekvencí 10^0 až 10^4 Hz
 Za 1 ms světlo urazí 300 km



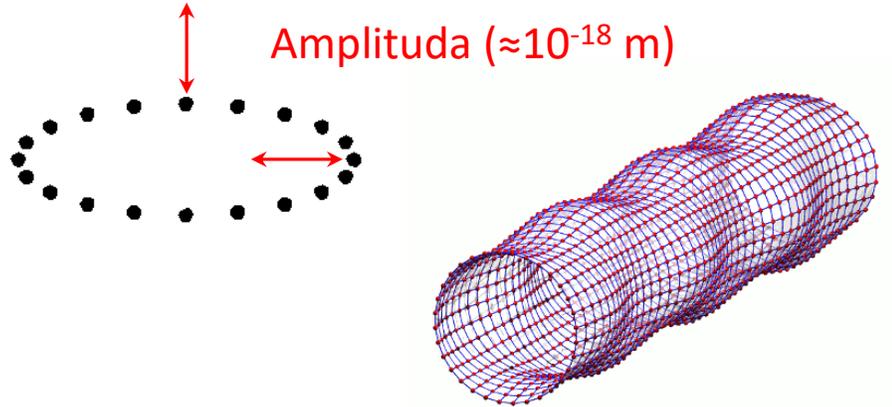
Virgo
 3 km ramena



GEO 600



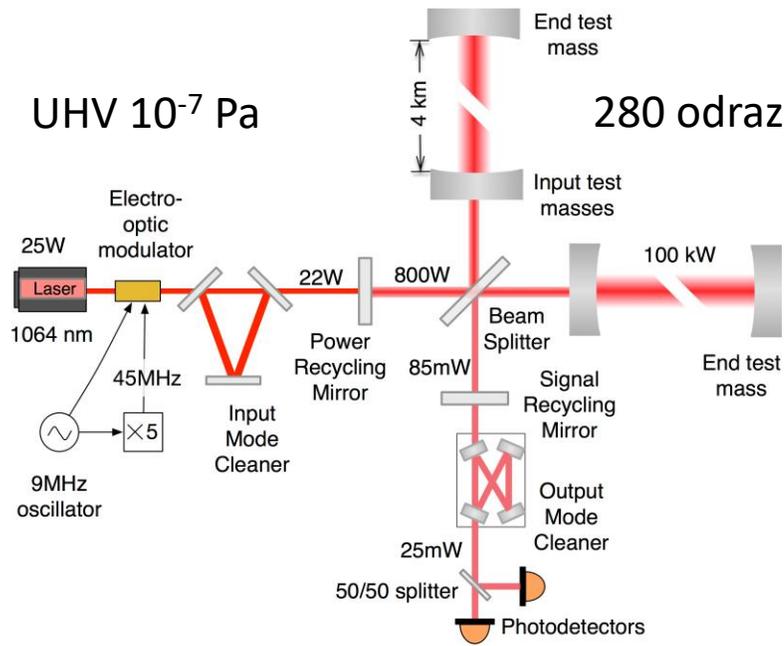
KAGRA 3 km ramena



Laser Interferometer Gravitational-wave Observatory (LIGO)

UHV 10^{-7} Pa

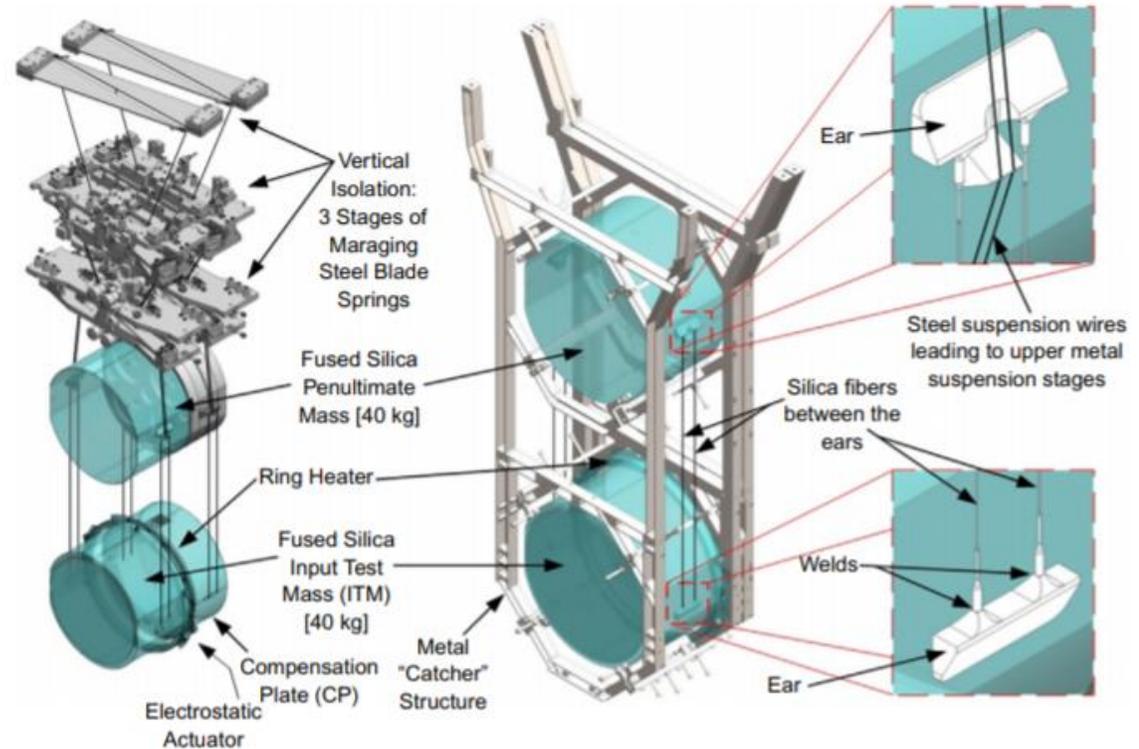
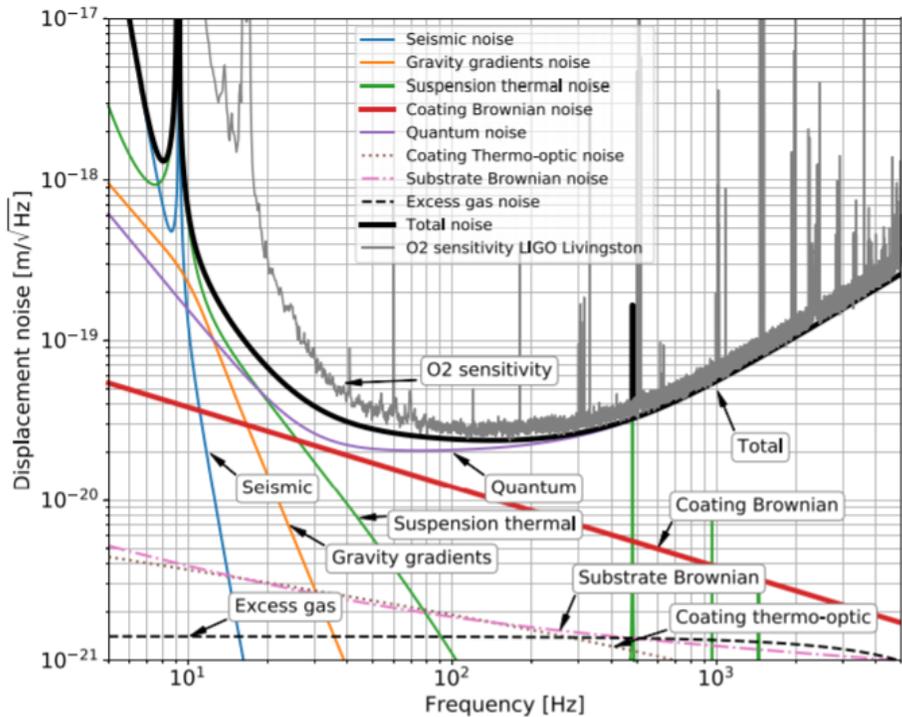
280 odrazů



LIGO Hanford



LIGO Livingston



První detekce GW150914

1 Mpc = 3,26 mil. Ly
410 Mpc = 1,33 mld. Ly

PRL 116, 061102 (2016)

 Selected for a *Viewpoint* in *Physics*
PHYSICAL REVIEW LETTERS

week ending
12 FEBRUARY 2016



Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**

(LIGO Scientific Collaboration and Virgo Collaboration)

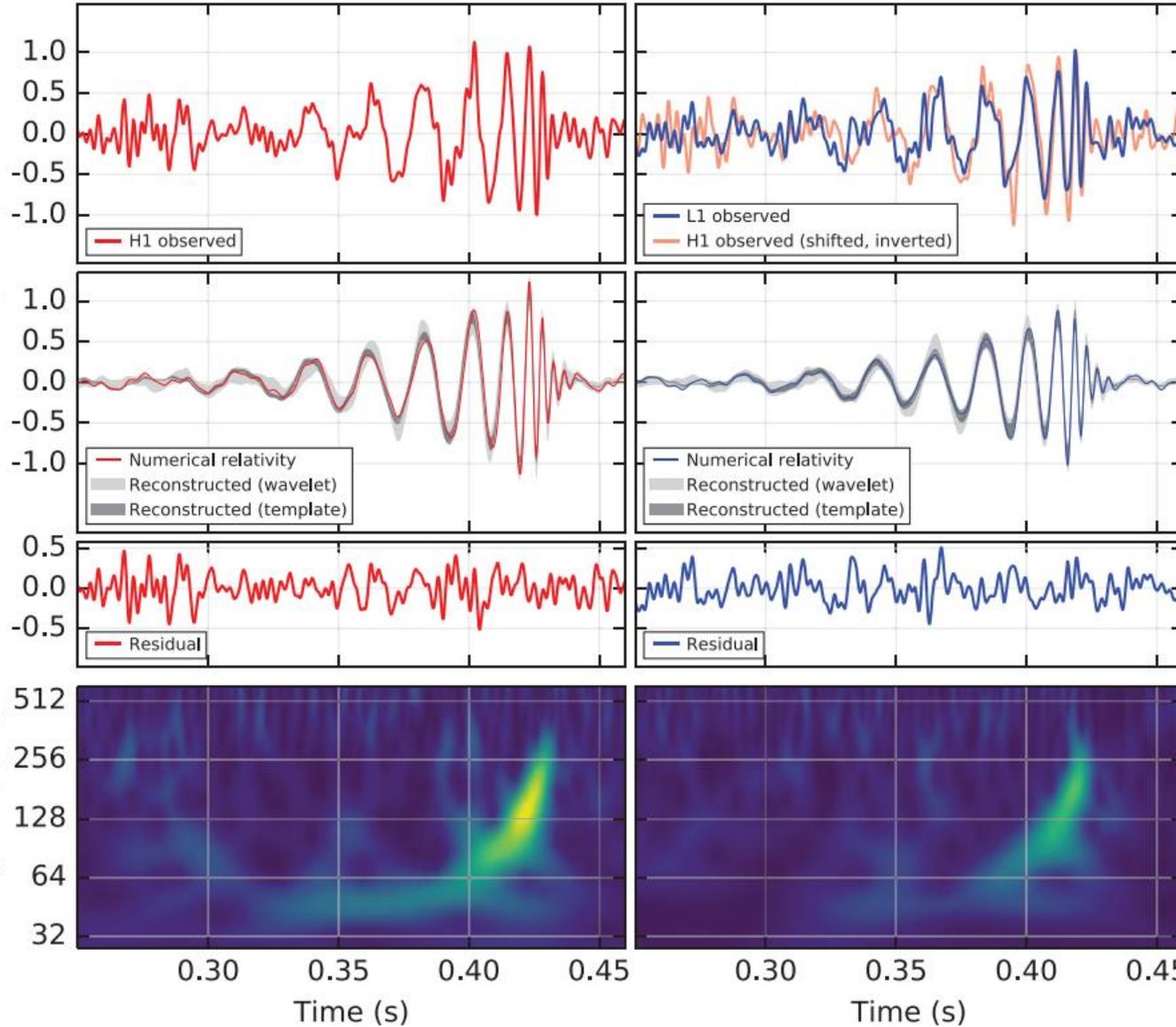
(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21} . It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ . The source lies at a luminosity distance of 410_{-180}^{+160} Mpc corresponding to a redshift $z = 0.09_{-0.04}^{+0.03}$. In the source frame, the initial black hole masses are $36_{-4}^{+5} M_{\odot}$ and $29_{-4}^{+4} M_{\odot}$, and the final black hole mass is $62_{-4}^{+4} M_{\odot}$, with $3.0_{-0.5}^{+0.5} M_{\odot} c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

První detekce GW150914

Hanford, Washington (H1)

Livingston, Louisiana (L1)



2017



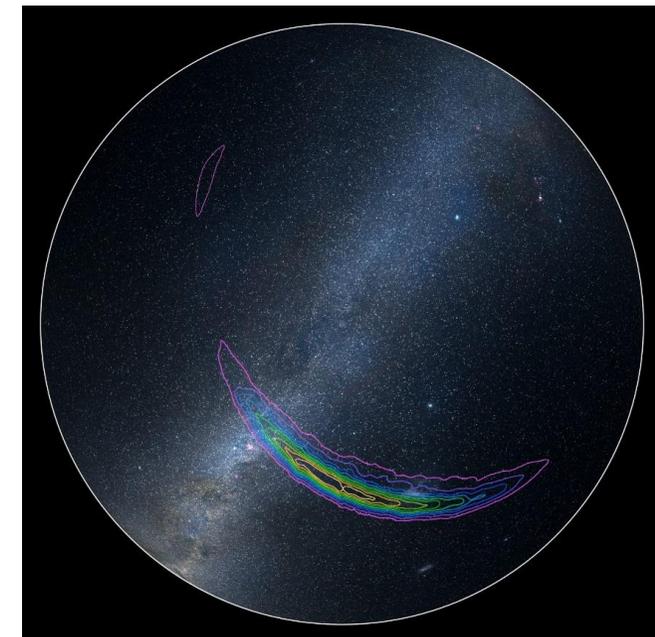
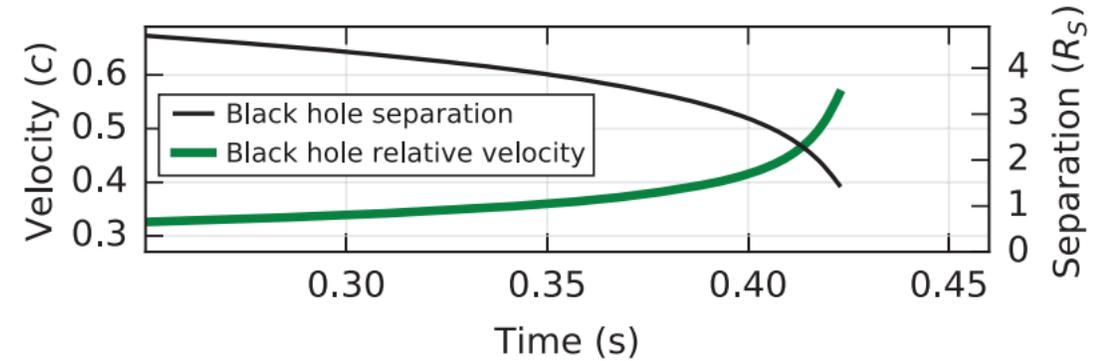
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Rainer Weiss
Prize share: 1/2



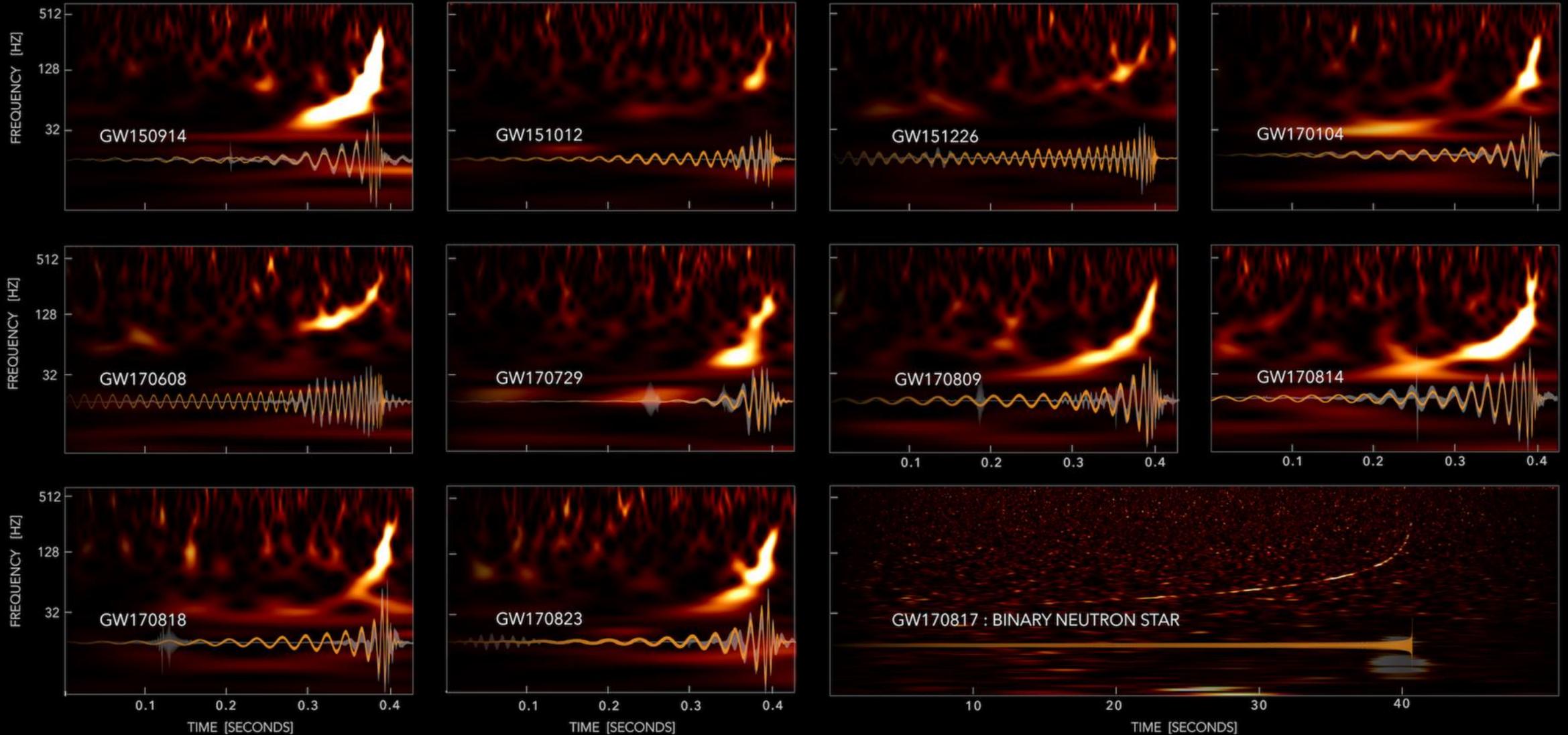
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Barry C. Barish
Prize share: 1/4



© Nobel Media. Ill. N. Elmehed
Kip S. Thorne
Prize share: 1/4



GRAVITATIONAL-WAVE TRANSIENT CATALOG-1



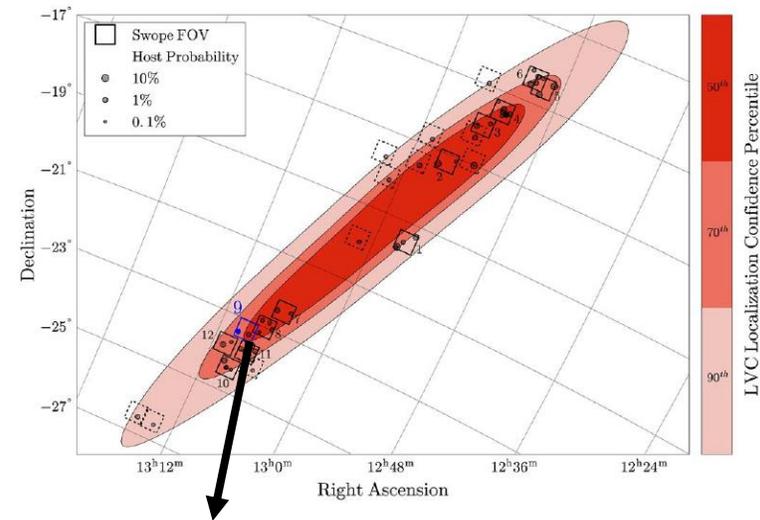
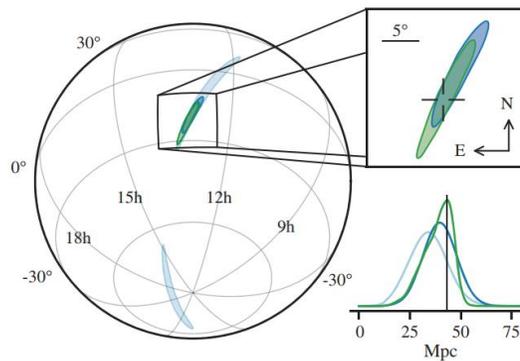


GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

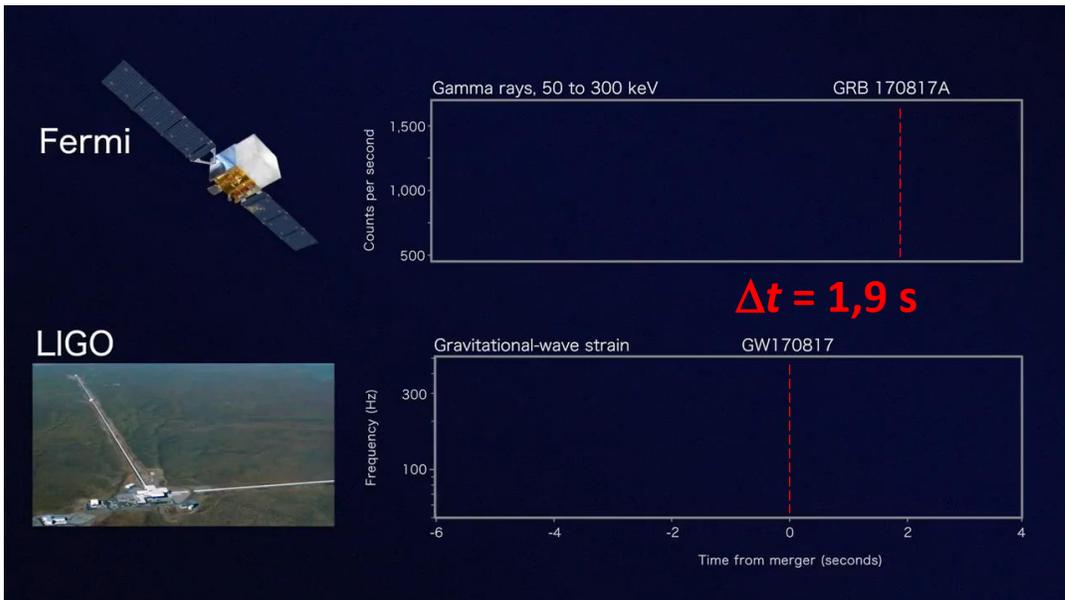
B. P. Abbott *et al.**
 (LIGO Scientific Collaboration and Virgo Collaboration)

Low-spin priors ($|\chi| \leq 0.05$)

Primary mass m_1	1.36–1.60 M_\odot
Secondary mass m_2	1.17–1.36 M_\odot
Chirp mass \mathcal{M}	1.188 $^{+0.004}_{-0.002}$ M_\odot
Mass ratio m_2/m_1	0.7–1.0
Total mass m_{tot}	2.74 $^{+0.04}_{-0.01}$ M_\odot
Radiated energy E_{rad}	$> 0.025 M_\odot c^2$
Luminosity distance D_L	130 mil. Ly = 40 $^{+8}_{-14}$ Mpc
Viewing angle Θ	$\leq 55^\circ$
Using NGC 4993 location	$\leq 28^\circ$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800
Dimensionless tidal deformability $\Lambda(1.4M_\odot)$	≤ 800



Galaxie NGC 4993 (souhvězdí Hydra)
 134 mil. Ly





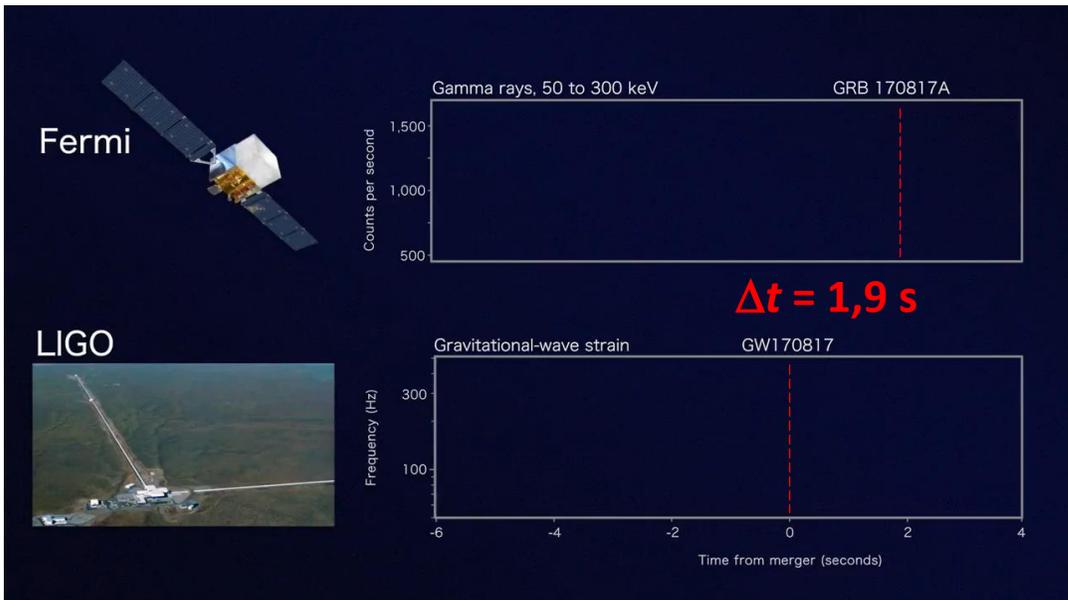
GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

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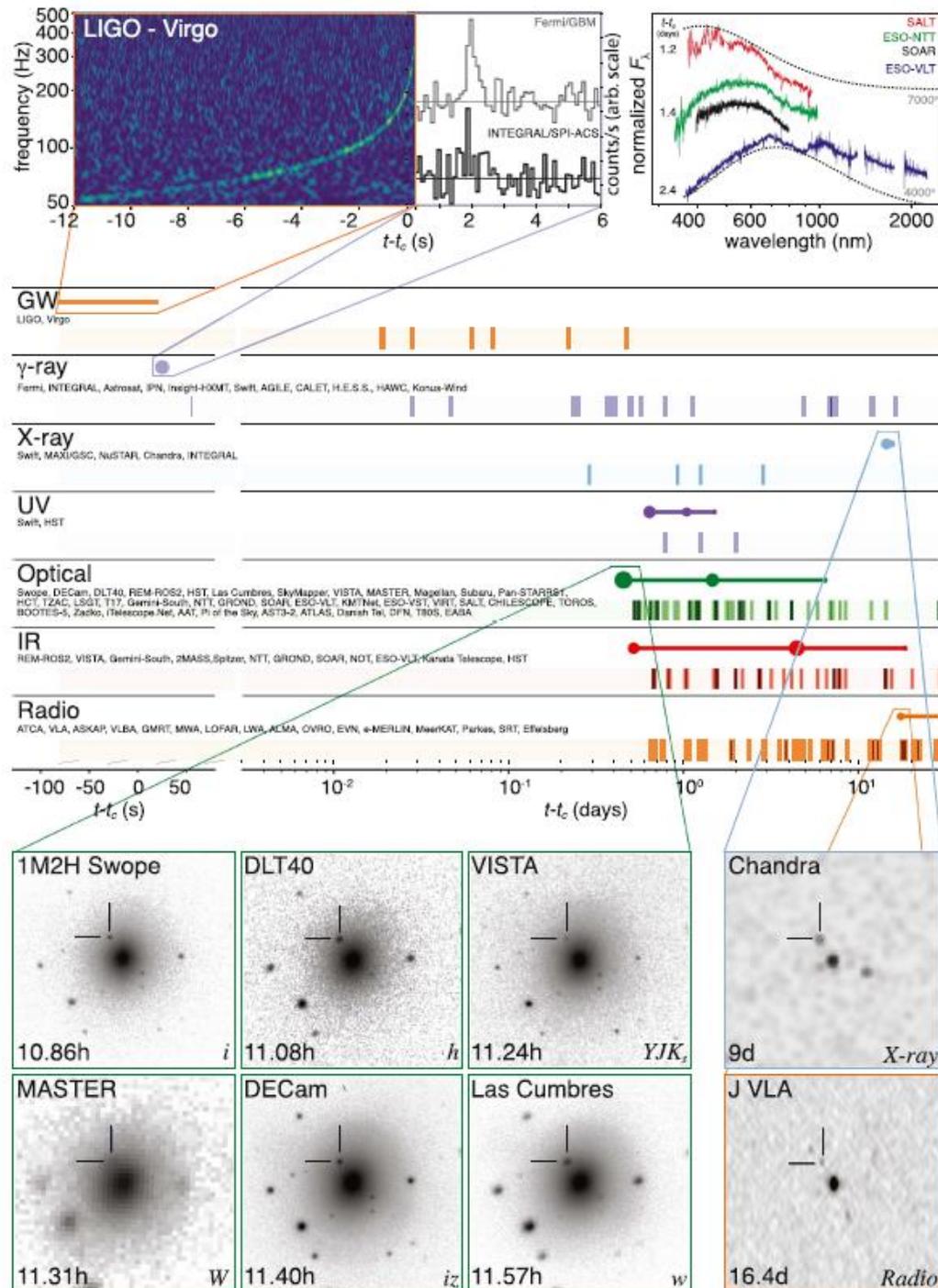
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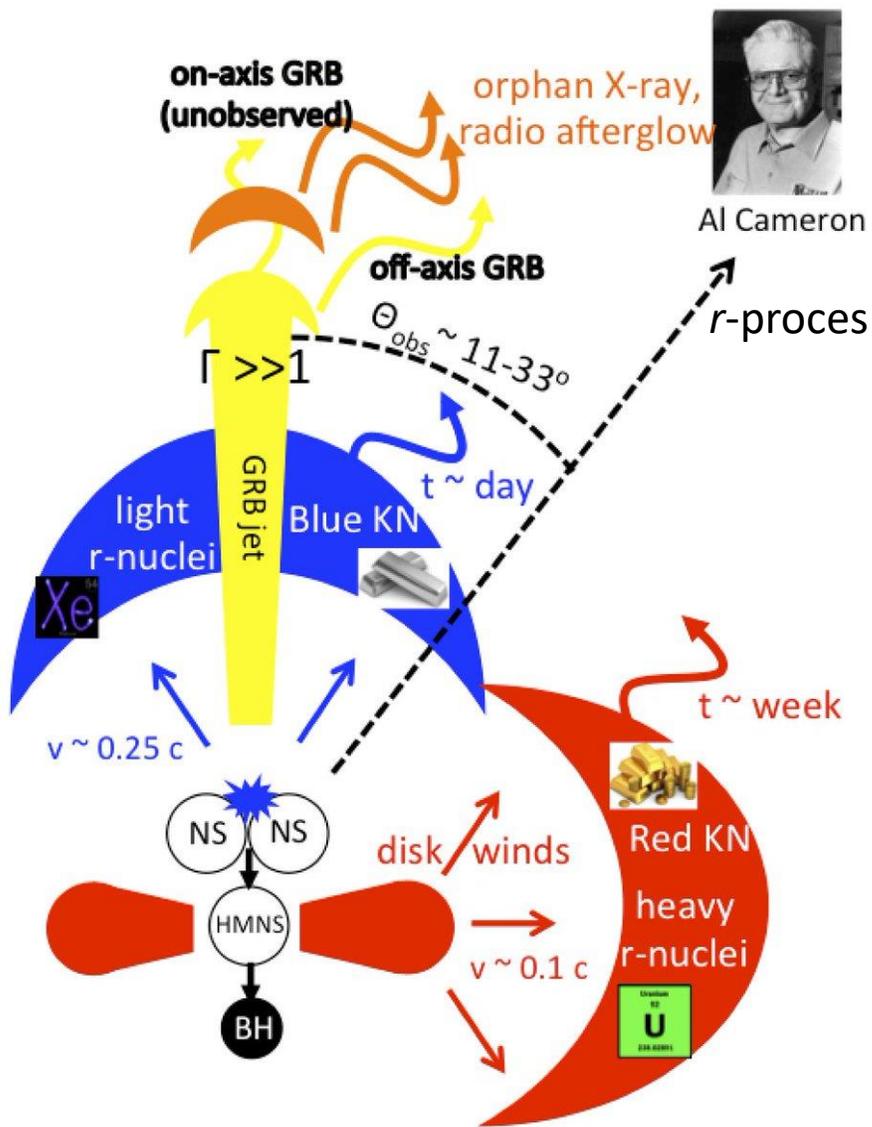
130 mil. Ly =



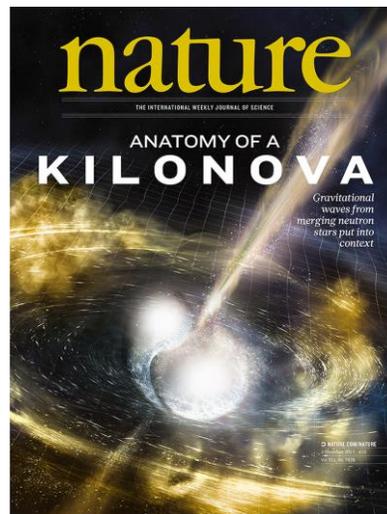
Pozorování v celém elektromagnetickém i gravitačním spektru



Nukleosyntéza



Al Cameron

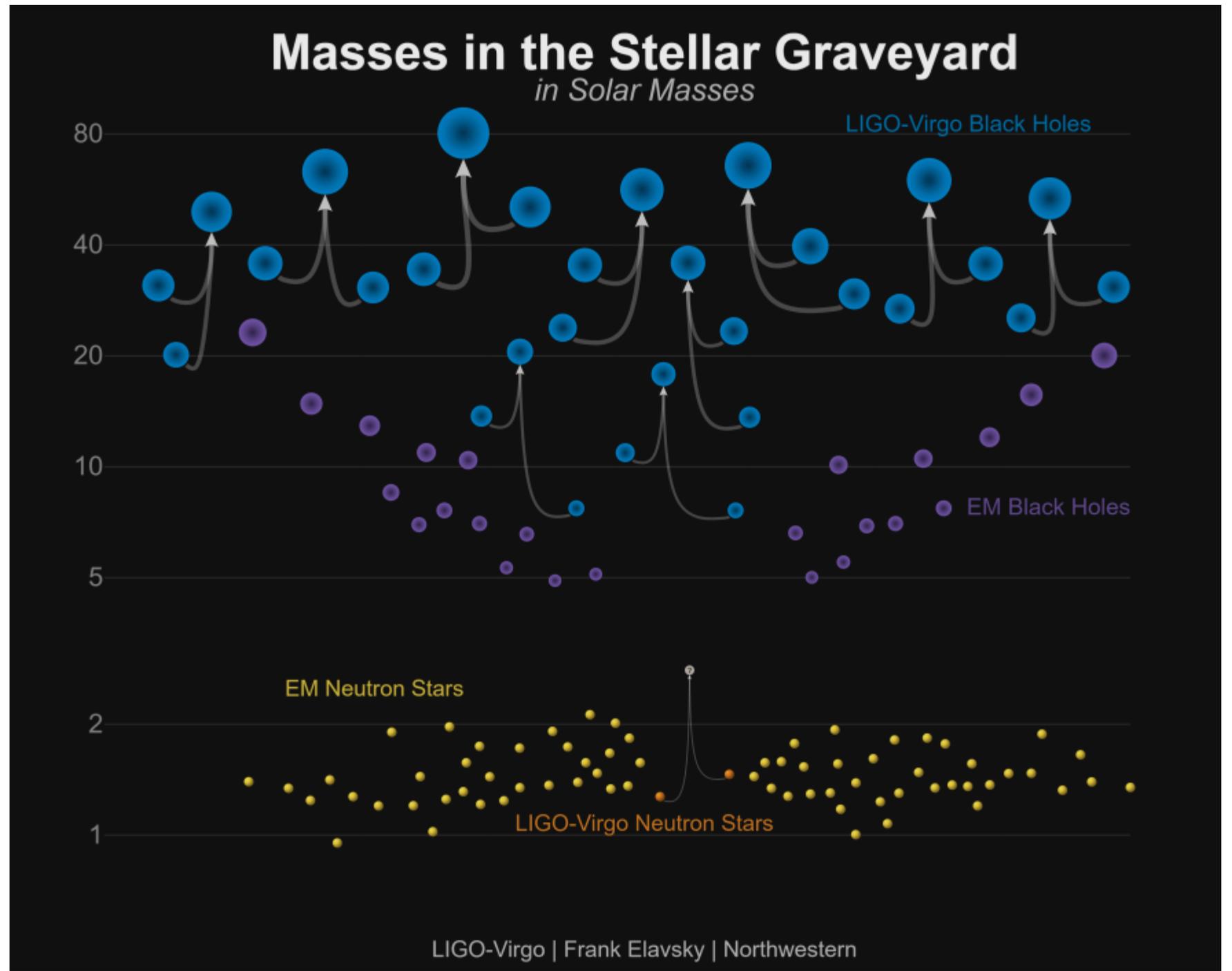


Velký třesk fúze		Zánik lehčích hvězd		Exploze hmotných hvězd		Lidská umělá syntéza nestabilní izotopy											
H 1	Li 3	Be 4	B 5	C 6	N 7	O 8	F 9	Ne 10									
Na 11	Mg 12	Al 13	Si 14	P 15	S 16	Cl 17	Ar 18	Kr 36									
K 19	Ca 20	Sc 21	Ti 22	V 23	Cr 24	Mn 25	Fe 26	Co 27	Ni 28	Cu 29	Zn 30	Ga 31	Ge 32	As 33	Se 34	Br 35	Kr 36
Rb 37	Sr 38	Y 39	Zr 40	Nb 41	Mo 42	Tc 43	Ru 44	Rh 45	Pd 46	Ag 47	Cd 48	In 49	Sn 50	Sb 51	Te 52	I 53	Xe 54
Cs 55	Ba 56	Hf 72	Ta 73	W 74	Re 75	Os 76	Ir 77	Pt 78	Au 79	Hg 80	Tl 81	Pb 82	Bi 83	Po 84	At 85	Rn 86	
Fr 87	Ra 88	La 57	Ce 58	Pr 59	Nd 60	Pm 61	Sm 62	Eu 63	Gd 64	Tb 65	Dy 66	Ho 67	Er 68	Tm 69	Yb 70	Lu 71	
		Ac 89	Th 90	Pa 91	U 92	Np 93	Pu 94	Am 95	Cm 96	Bk 97	Cf 98	Es 99	Fm 100	Md 101	No 102	Lr 103	

B. D. Metzger, *arXiv:1710.05931*, (2017)
 A. Cameron, *PASP*, vol. 69, (1957)
 M. R. Drout *et al.*, *Science* 10.1126/science.aag0049 (2017)

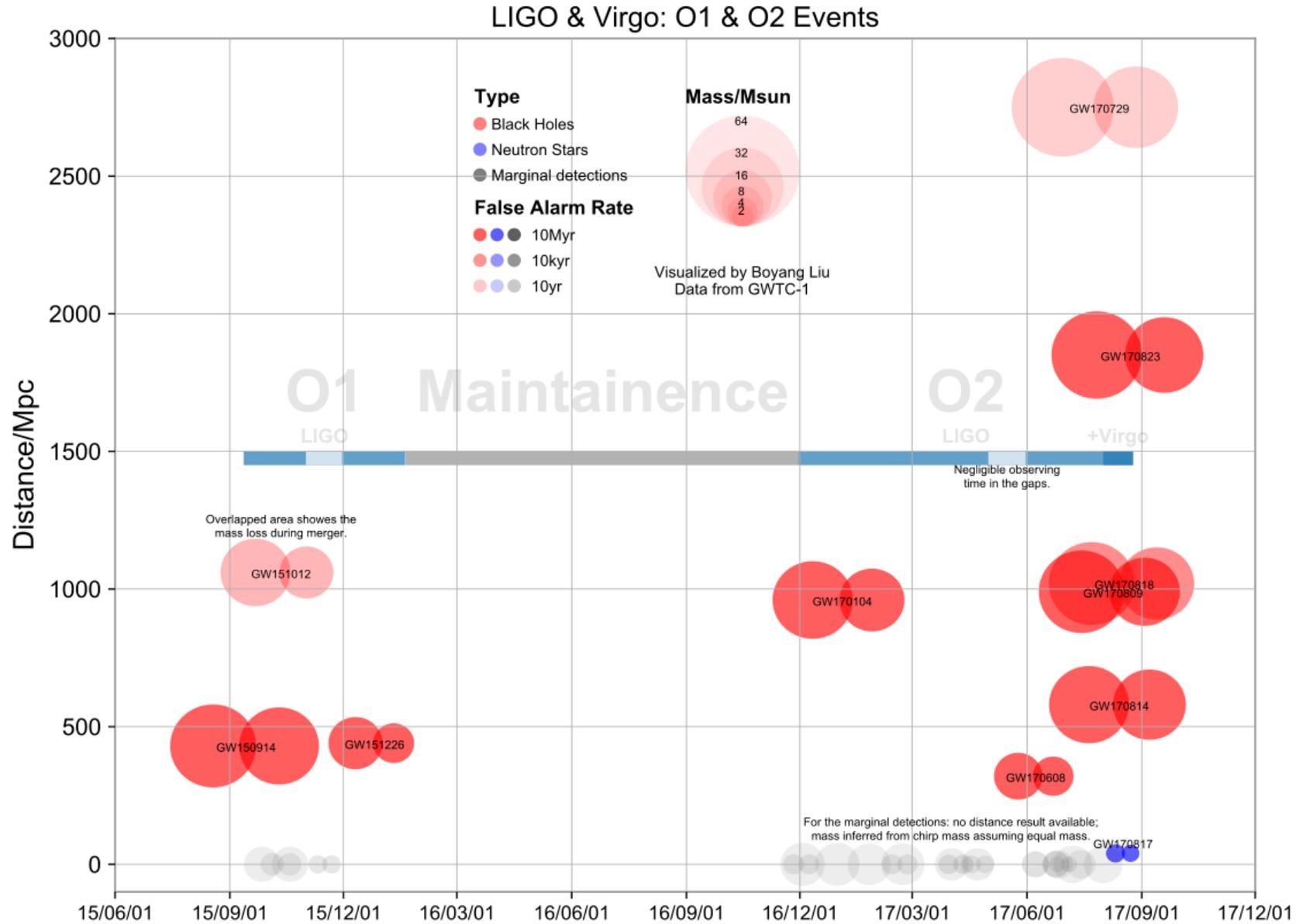
První a druhé měřicí okno
2015 & 2017

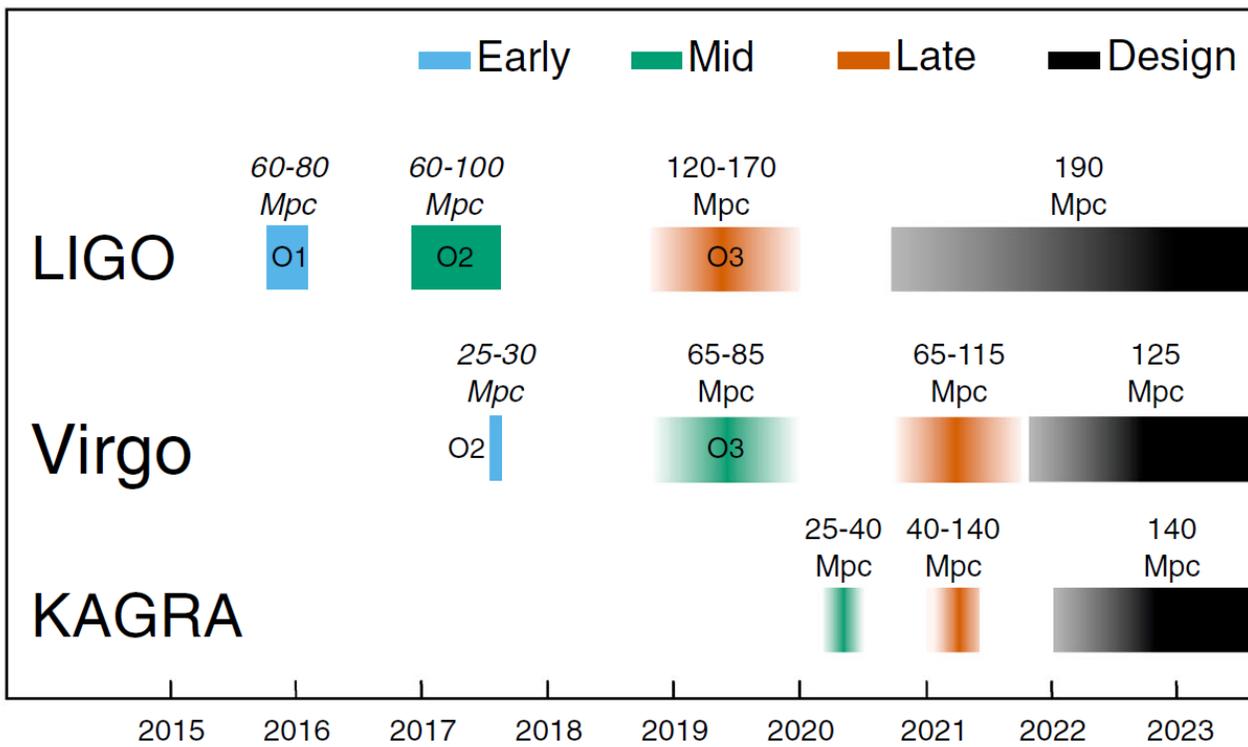
Hmotnost Slunce
 $1,99 \times 10^{30}$ kg



První a druhé měřicí okno 2015 & 2017

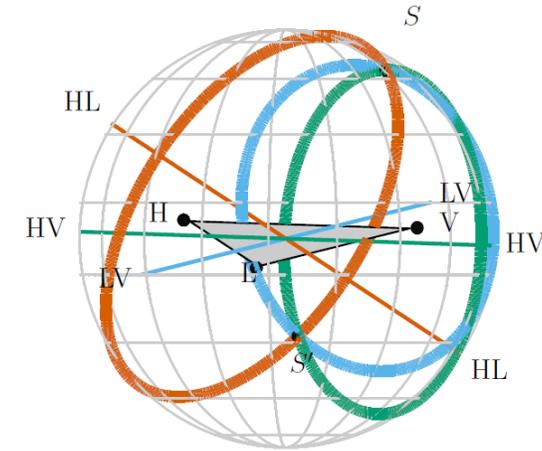
1 Mpc = 3,26 Mly
1 Ly = $9,46 \times 10^{12}$ km



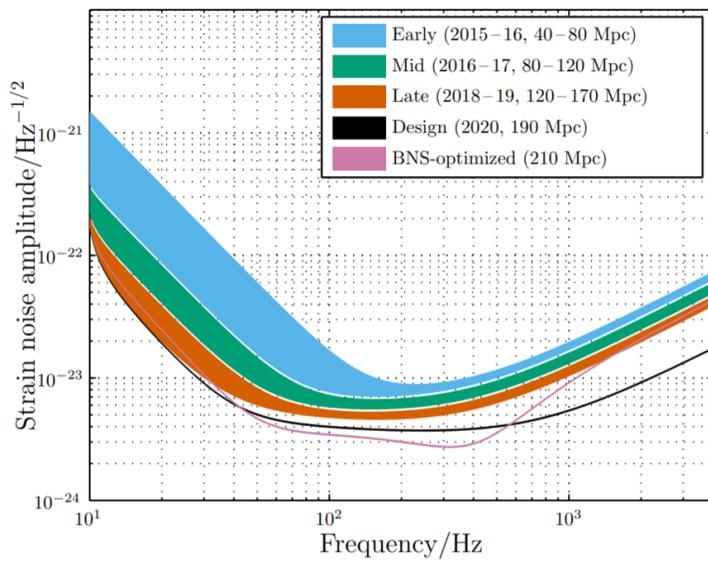


Třetí měřicí okno O3

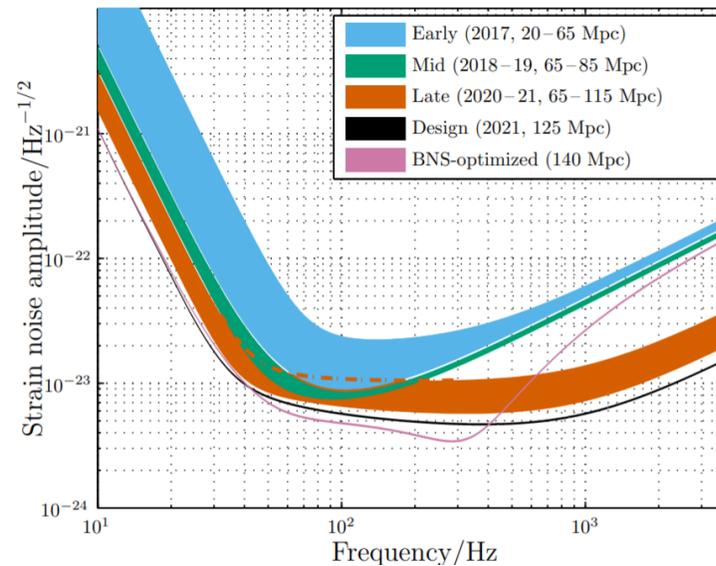
- Třetí okno začalo 1. dubna 2019
- Odstávka říjen 2019
- Zastaven provoz březem 2020 (covid-19)



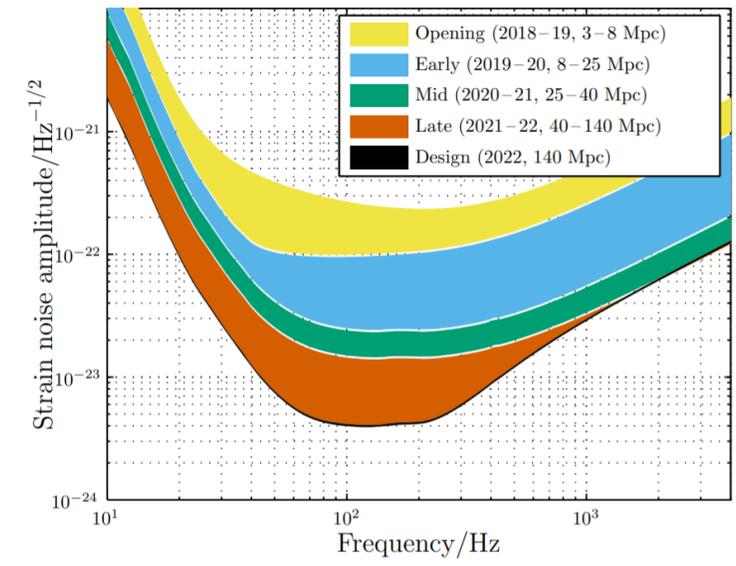
Advanced LIGO



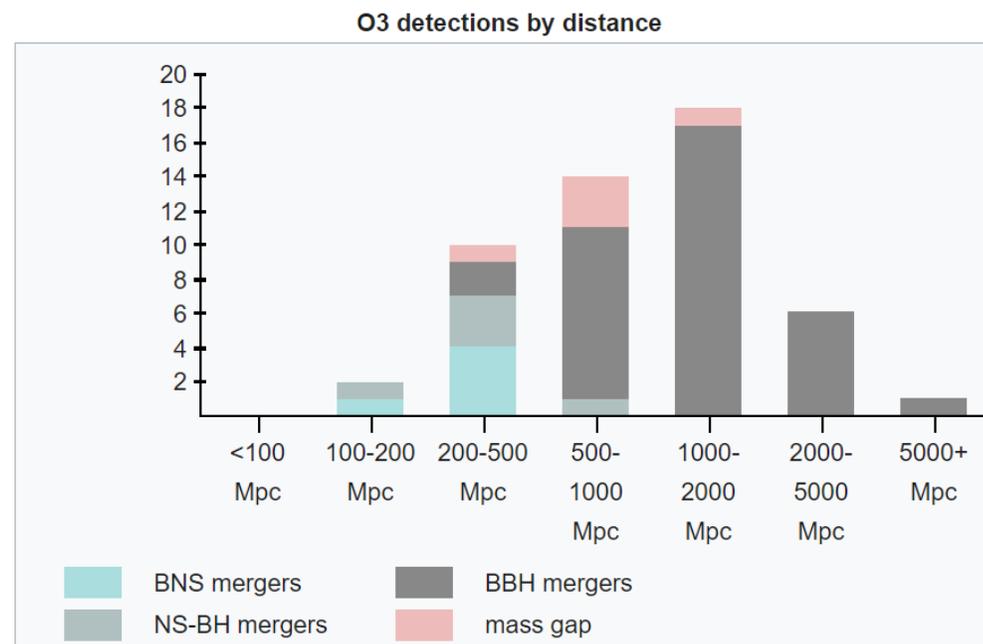
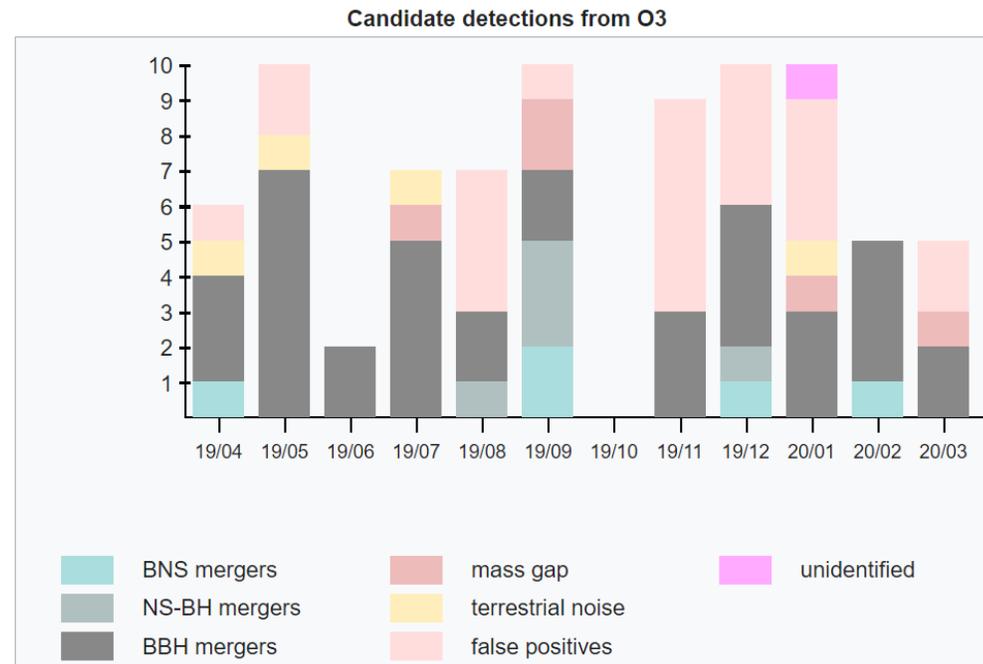
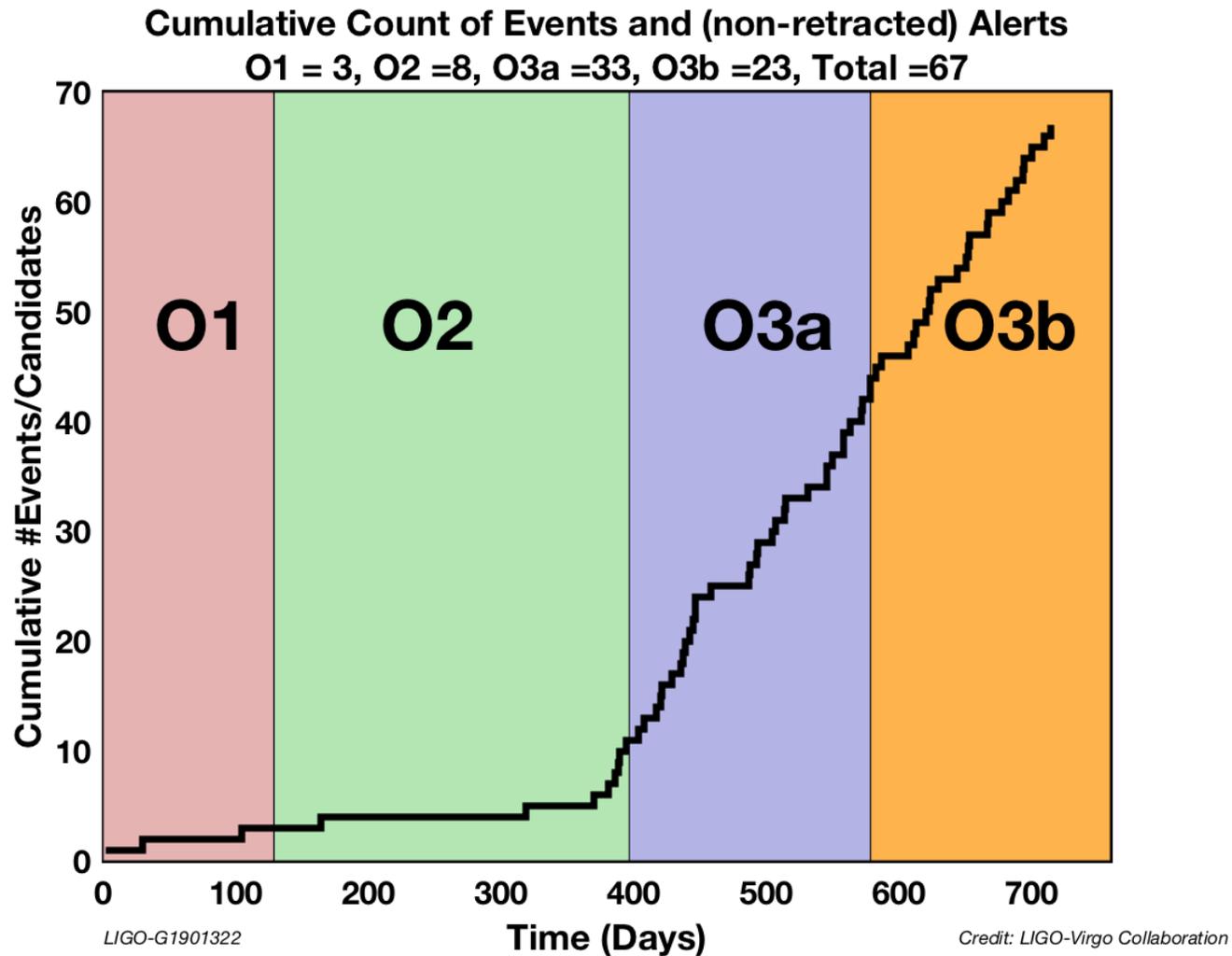
Advanced Virgo



KAGRA



Třetí měřicí okno O3



GW

The first
the merger

Discovery

12 April 2019

Binary Black Hole



Unequal Masses

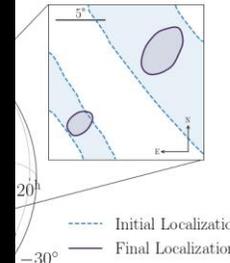
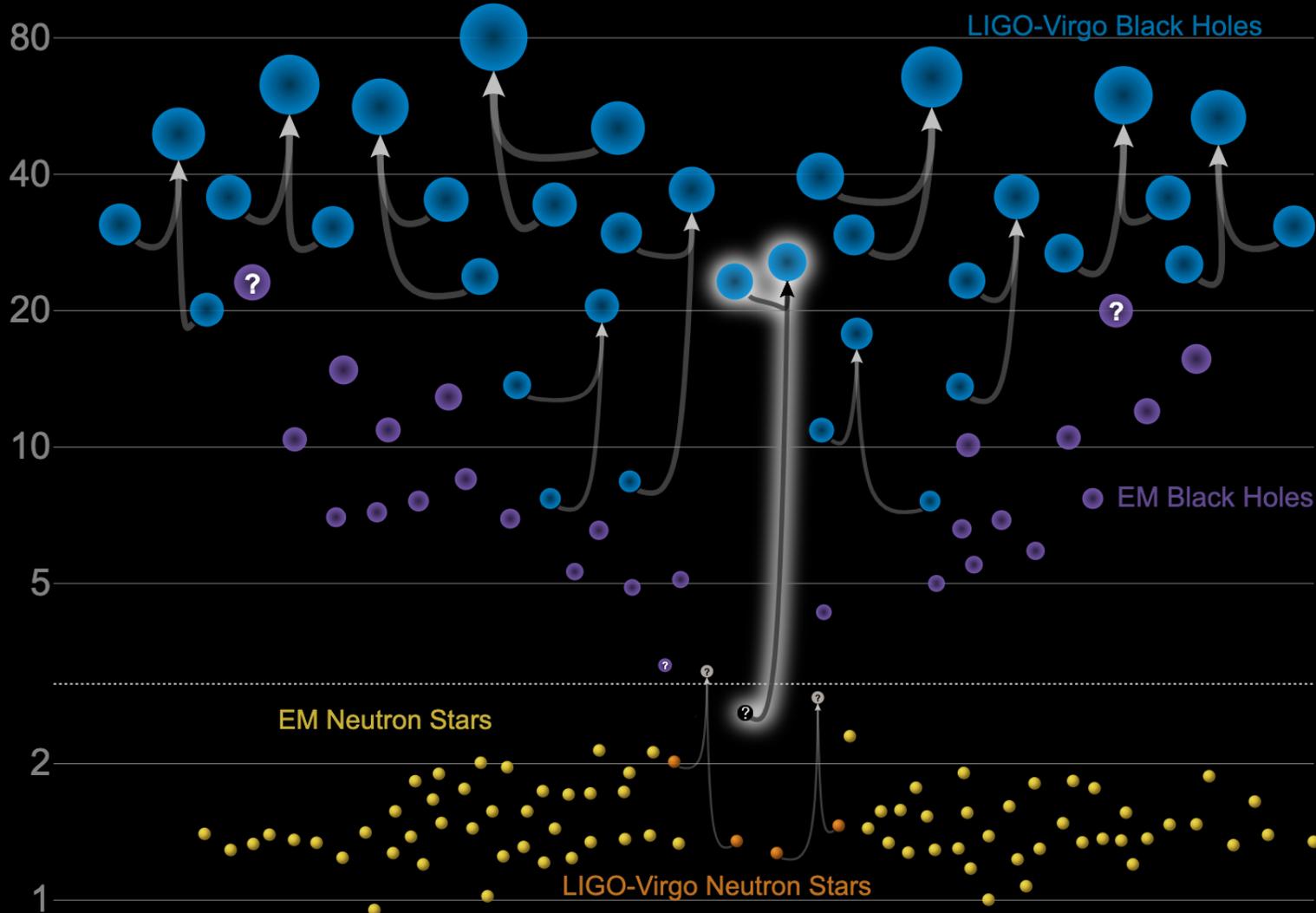
This is the first BBH
detection where the
two black holes had
very different
masses

Higher Ha



Masses in the Stellar Graveyard

in Solar Masses



Updated 2020-05-16

LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

GW190521

The most massive black hole collision observed so far

Discovery

21 May 2019

Distance

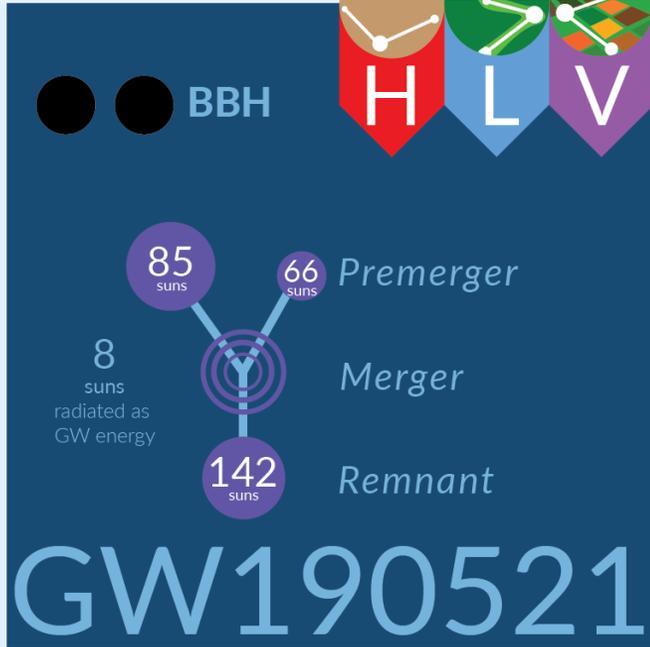
17 billion light years away

3 Detectors

Three detectors made the observation: the two LIGO detectors in the USA and Virgo in Italy.



Binary Black Hole Merger



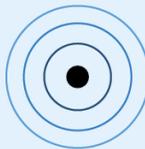
High Masses

This is the heaviest pair of black holes which have ever been observed colliding.



Origin Story

The black holes which collided to make GW190521 are so massive that we're not sure how they were formed. One option is that they are both the result of previous black hole collisions.

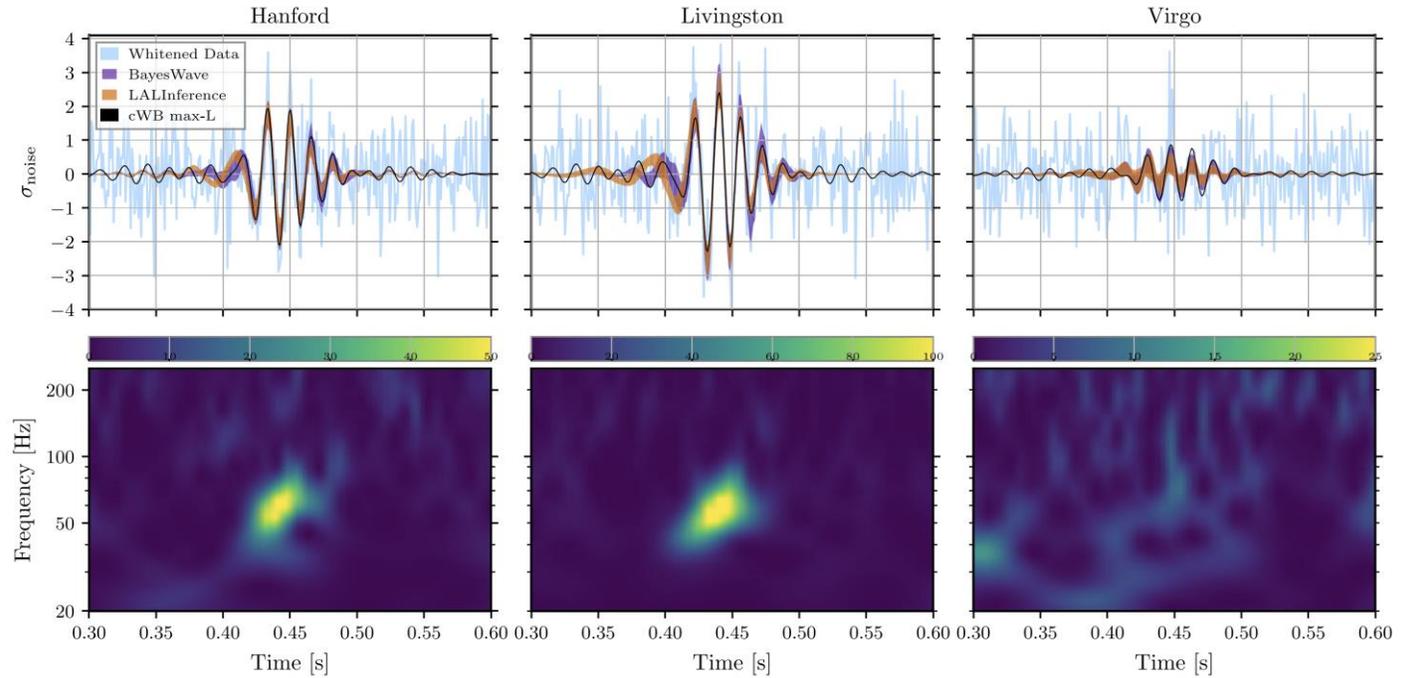


Ringdown

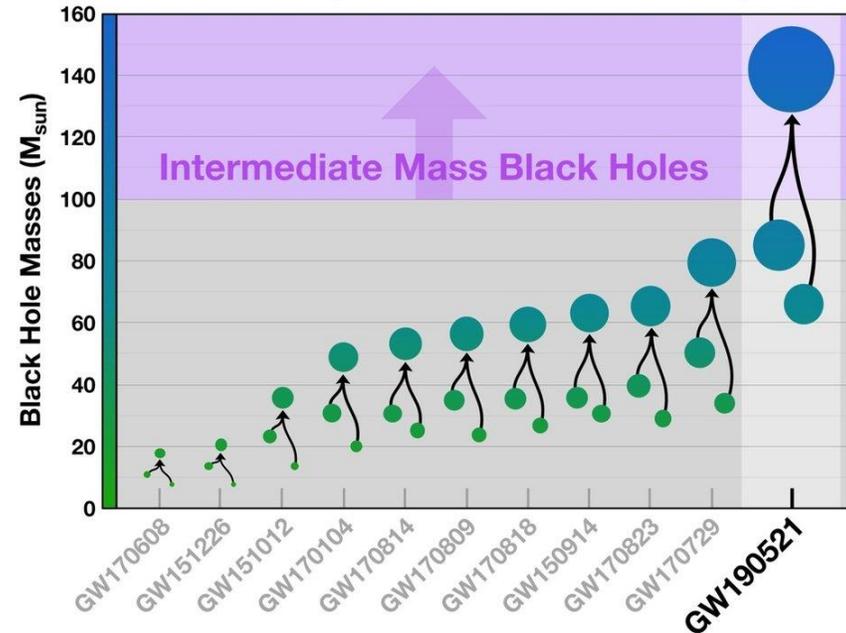
The black hole formed in the collision continues to vibrate after the merger, and "rings" like a bell for a while. This lets us test our theories.

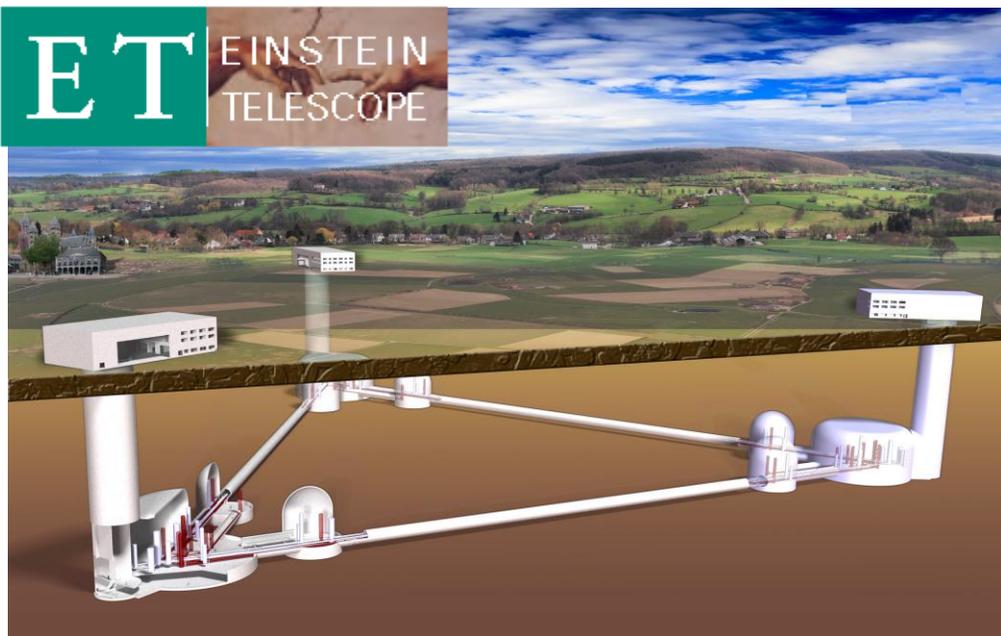


Once again Einstein's General Relativity passed this test.

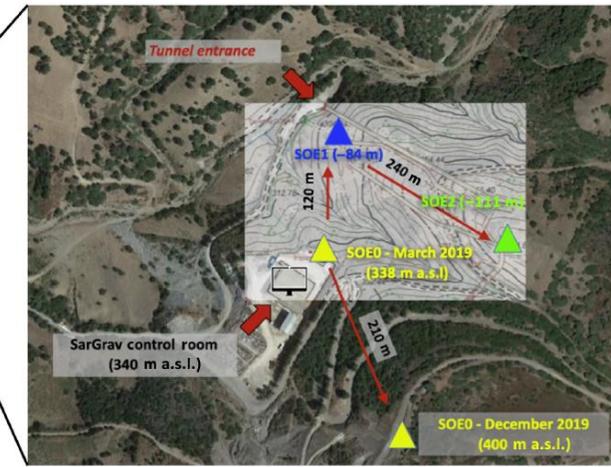
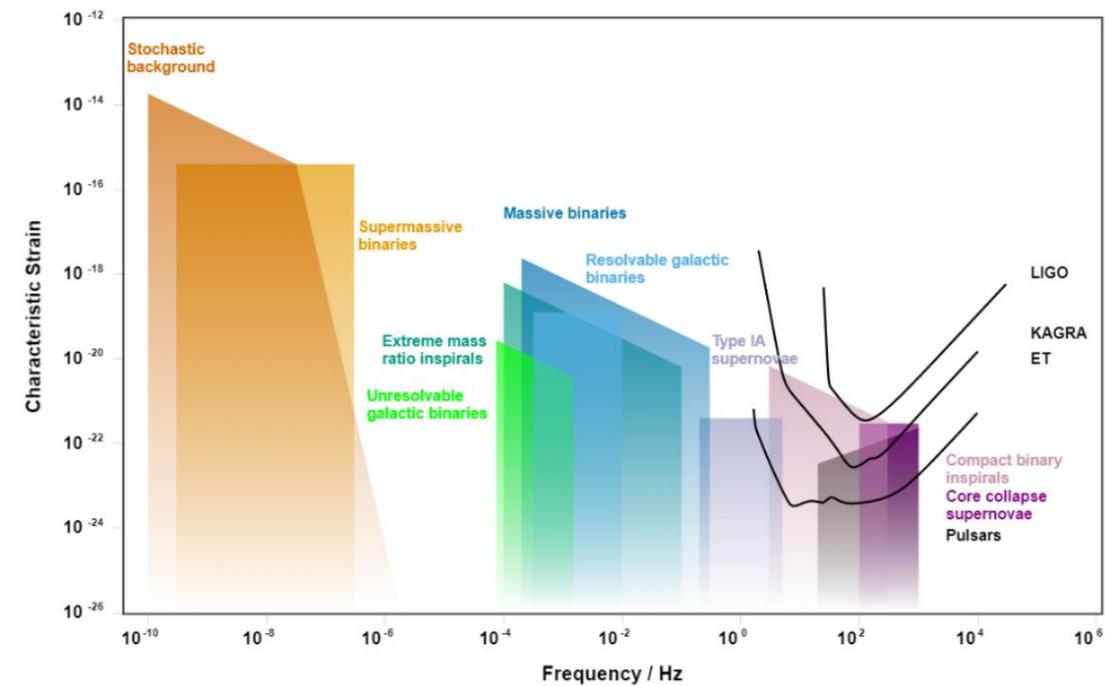
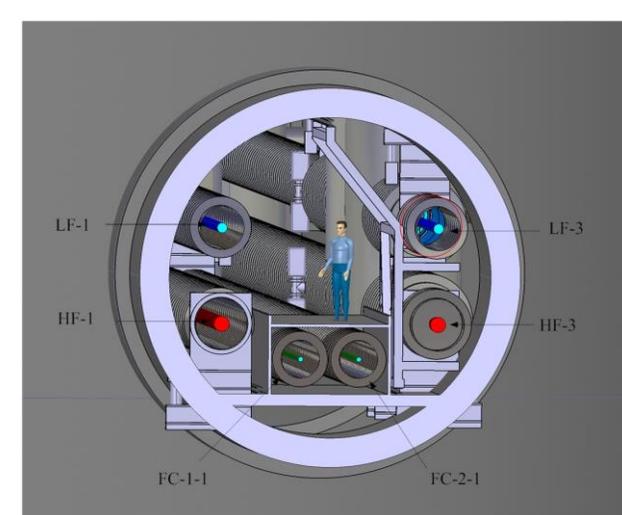
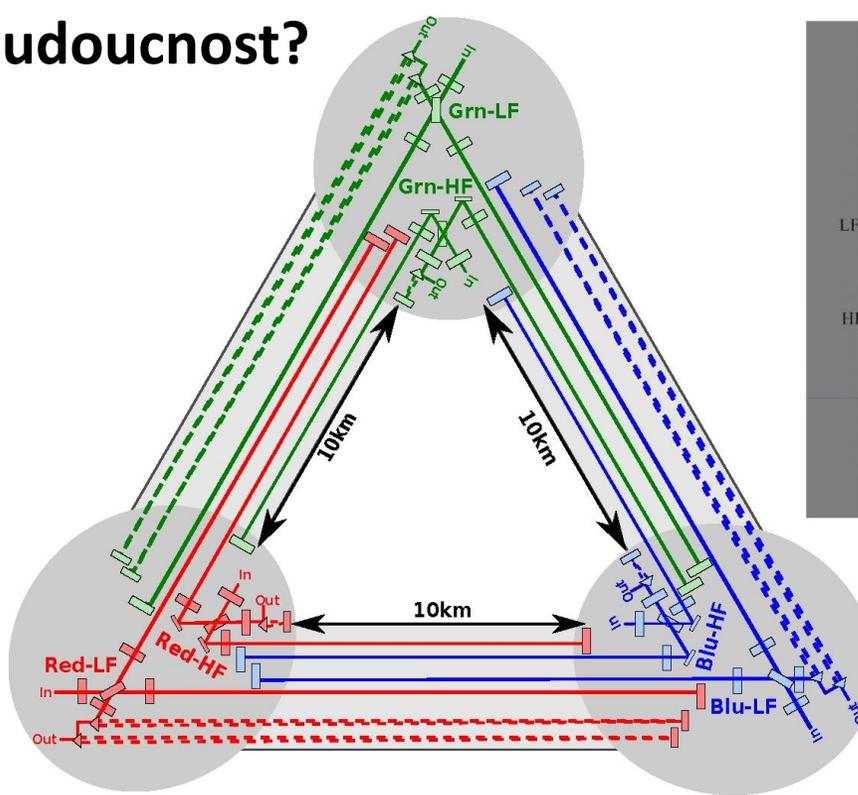


LIGO-Virgo Black Hole Mergers





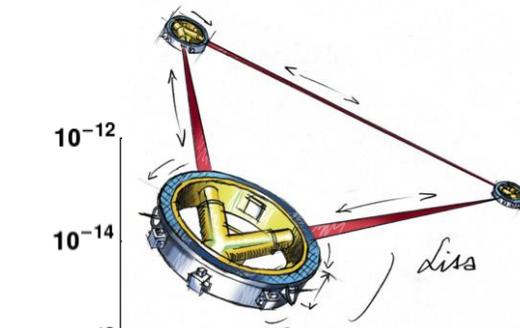
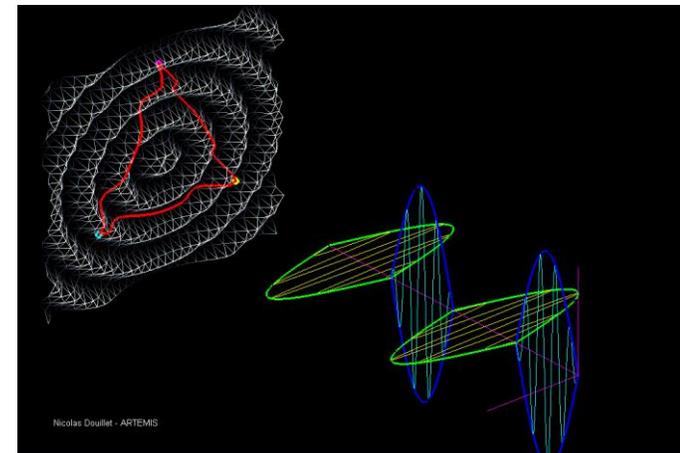
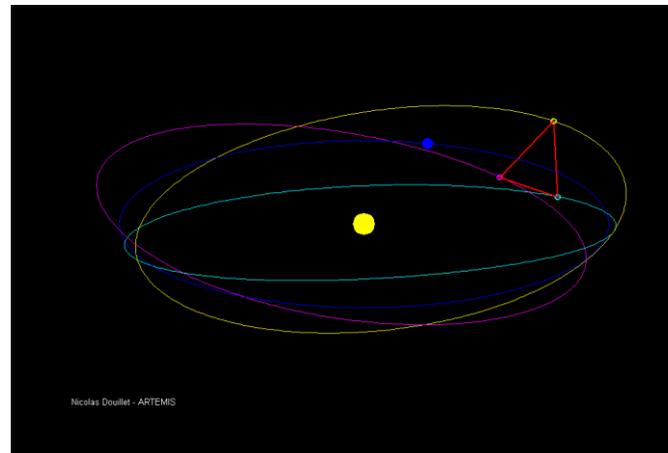
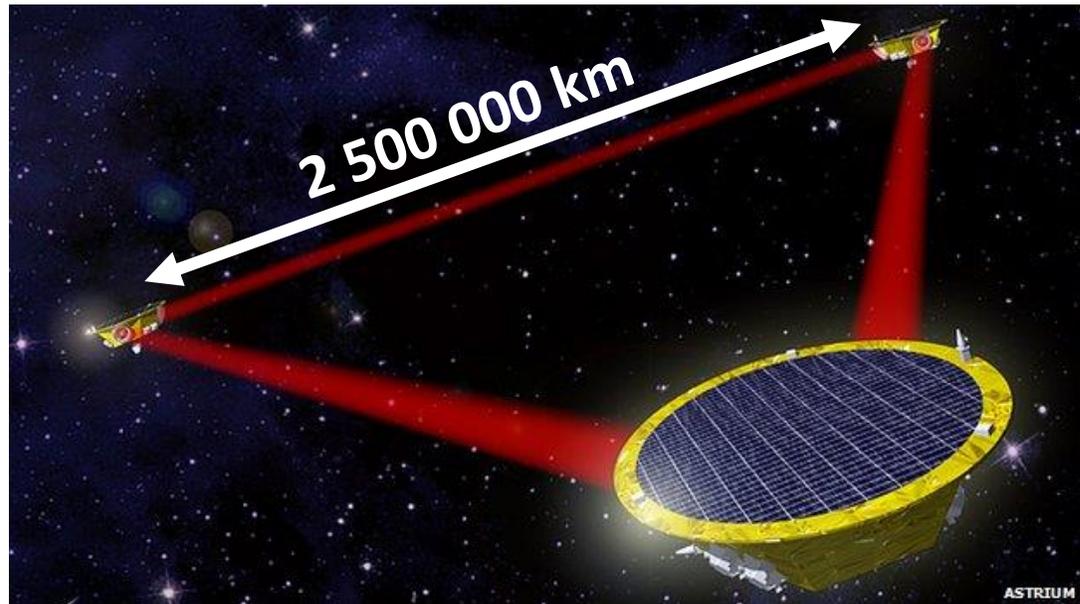
Budoucnost?



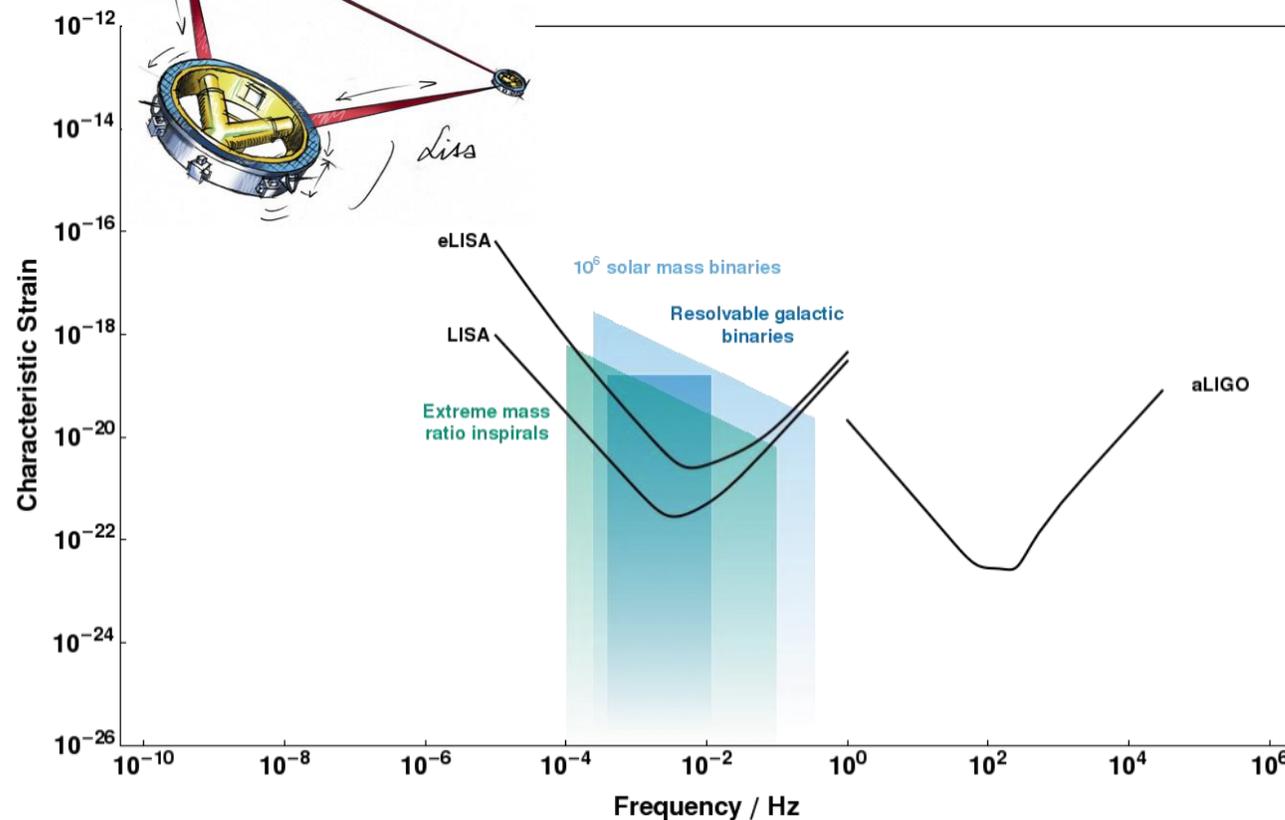
Sardinie

Budoucnost (2034)?

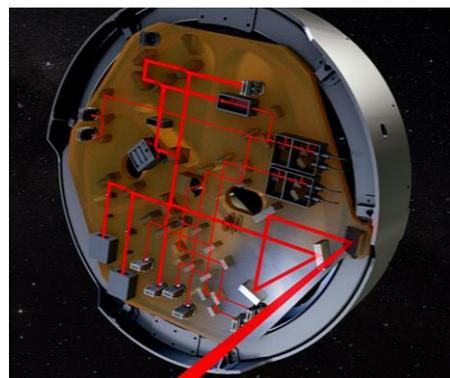
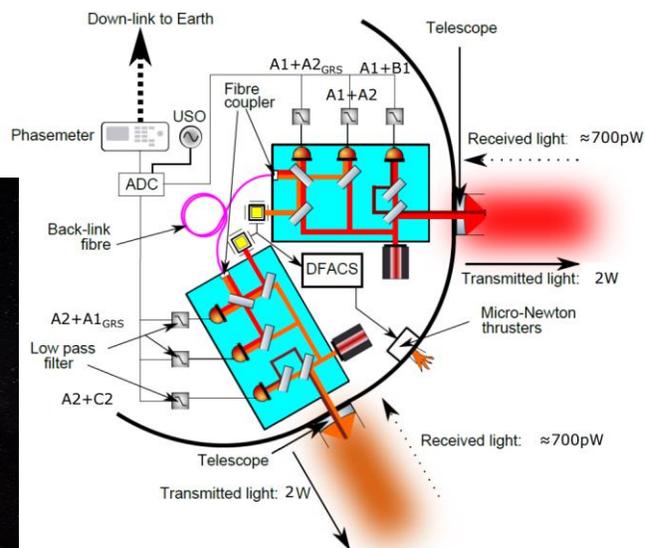
Laser Interferometer Space Antenna (LISA)



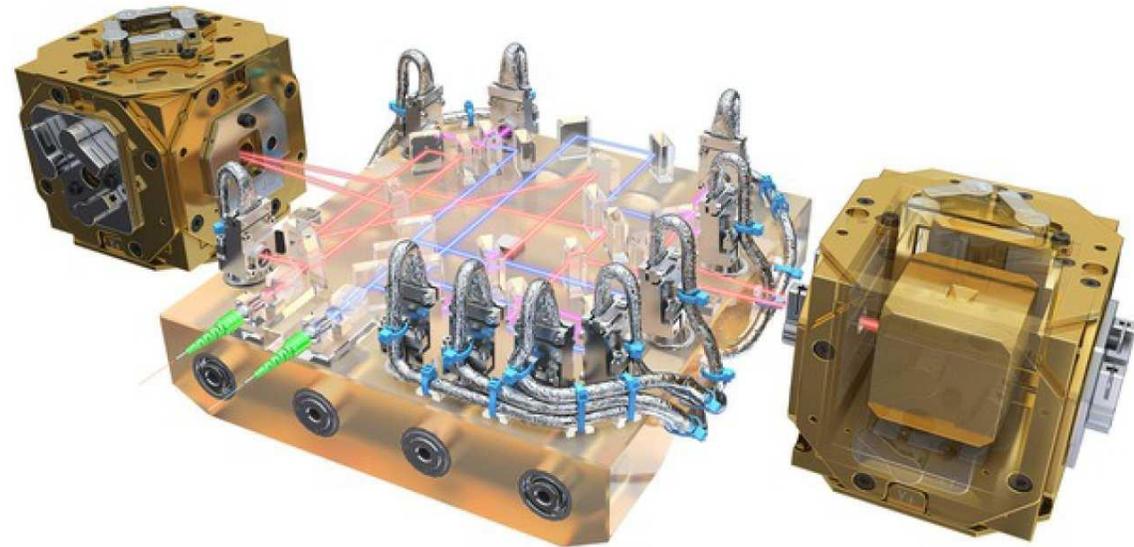
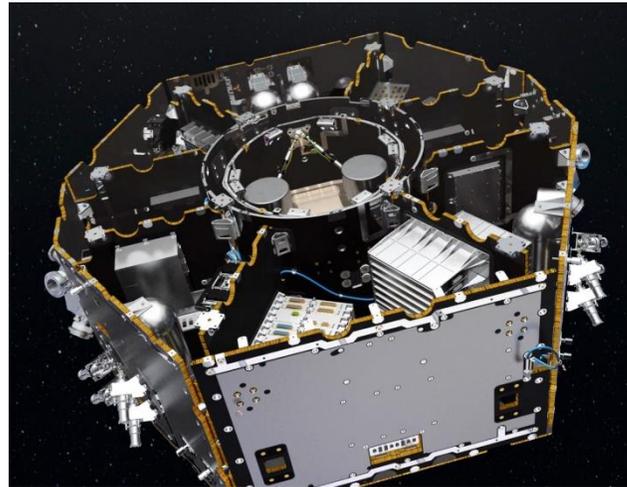
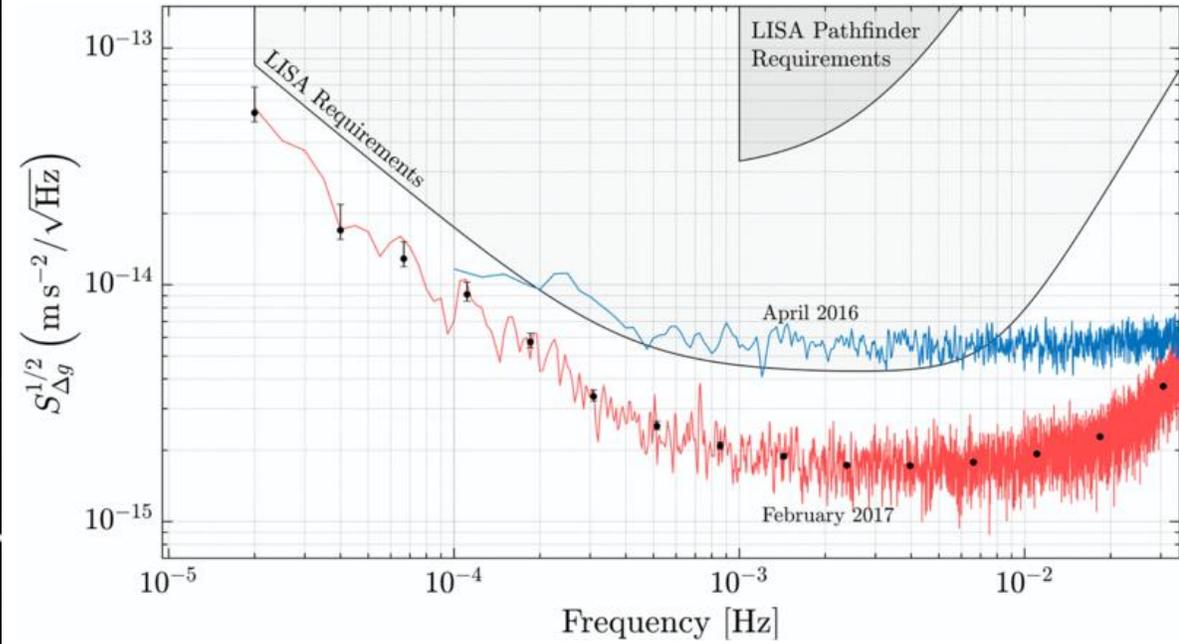
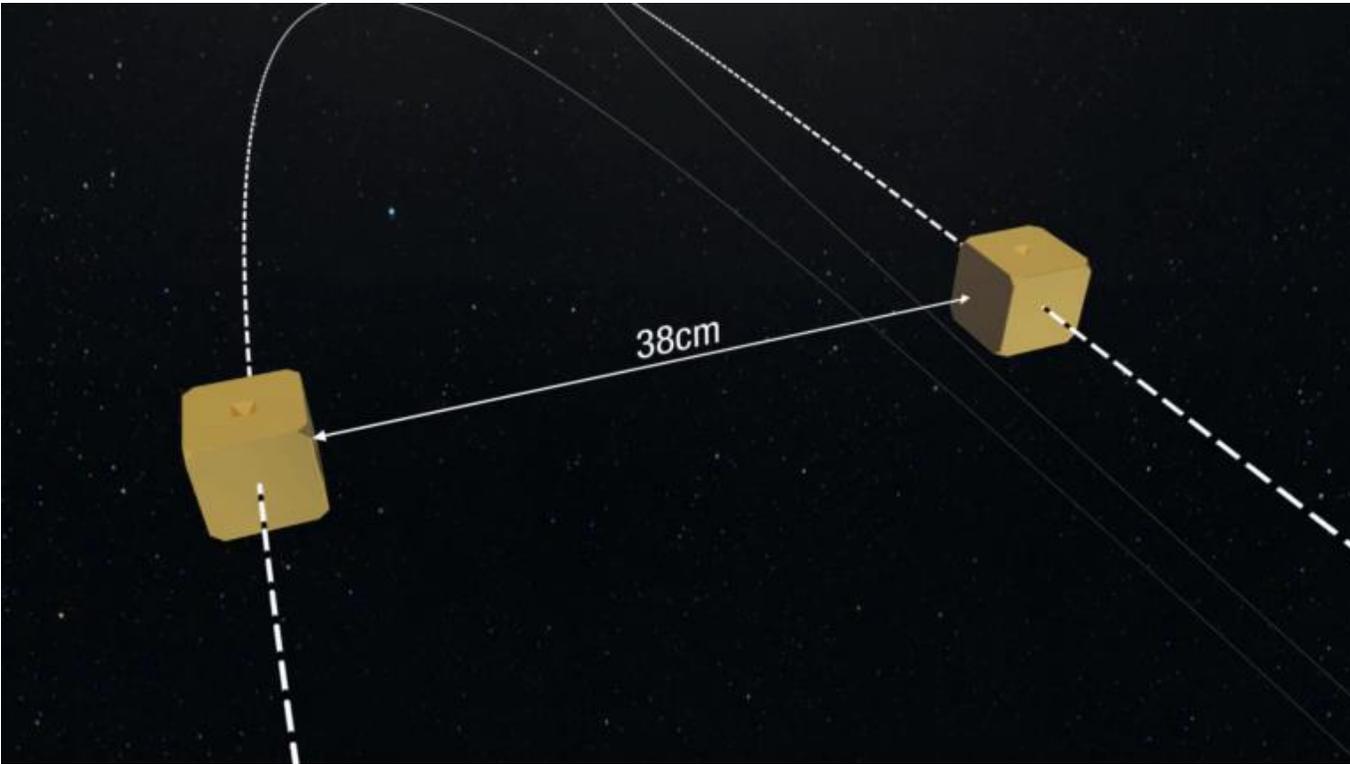
Rozpočet: 1050 mil. eur



Spacecraft A



LISA Pathfinder (2015/2016)



Závěrem...

