Seminarium Astrofizyczne
WFAIS UJ oraz Komisji Astrofizyki PAU
Kraków, 15.01.2020

Soczewki grawitacyjne:

od ekspedycji Eddingtona do pierwszego obrazu horyzontu czarnej dziury

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Warszawa

NATIONAL CENTRE
FOR NUCLEAR RESEARCH
ŚWIERK

Rok 2019 kolejna 100 rocznica

związana z Ogólną Teorią Względności

29 maja 1919 ekspedycja Eddingtona

28 lipca 1919 **powstaje IAU** – komitet C1:
Teorii względności – przewodniczy mu
Sir Arthur Eddington

Listopad 1919 – wyniki ekspedycji
Eddingtona ogłoszone drukiem

Historycznie:

John Michell (1724-1793) w liście
do Henry’ego Cavendisha (1731-1810)   [niezależnie Soldner 1801]

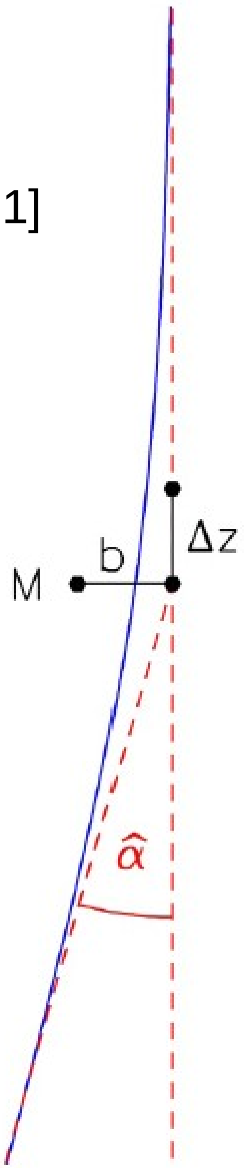
- założmy, że światło składa się z cząstek
- w polu grawitacyjnym Słońca cząstka światła doznaje przyspieszenia

$$\frac{d^2\vec{r}}{dt^2} = -\frac{Gm\vec{r}}{r^3}$$

- ogólnie trajektoria jest jednym z przekrojów stożkowych (elipsa, parabola, hiperbola)
- dla światła będzie to hiperbola (c >> V_{esc})
- stąd wyliczamy

$$\alpha = \frac{2GM}{c^2 b}$$

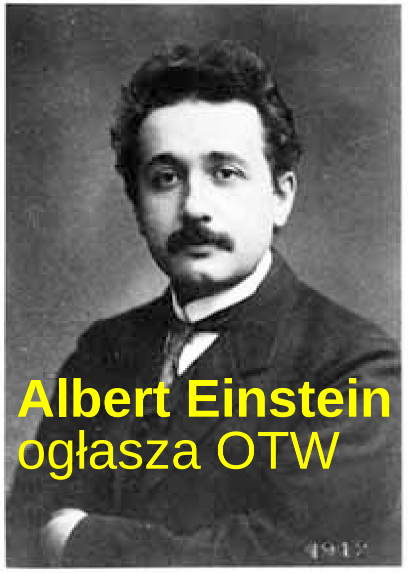
- dla promienia świetlnego stycznego do brzegu tarczy Słońca



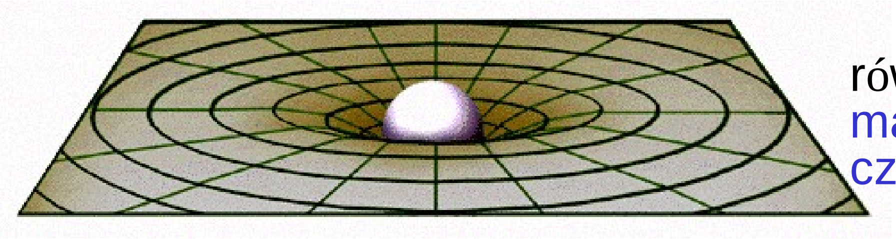
$$\alpha = \frac{2GM}{c^2 R} = 0''.875$$

$$m = M_\odot = 1.989 \times 10^{30}\mathrm{kg}$$
$$R = R_\odot = 6.96 \times 10^{8}\mathrm{m}$$

turbulencja atmosfery
„seeing” 0.”5 – 1.”



Albert Einstein
ogłasza OTW



równania pola Einsteina – jak materia zakrzywia czasoprzestrzeń

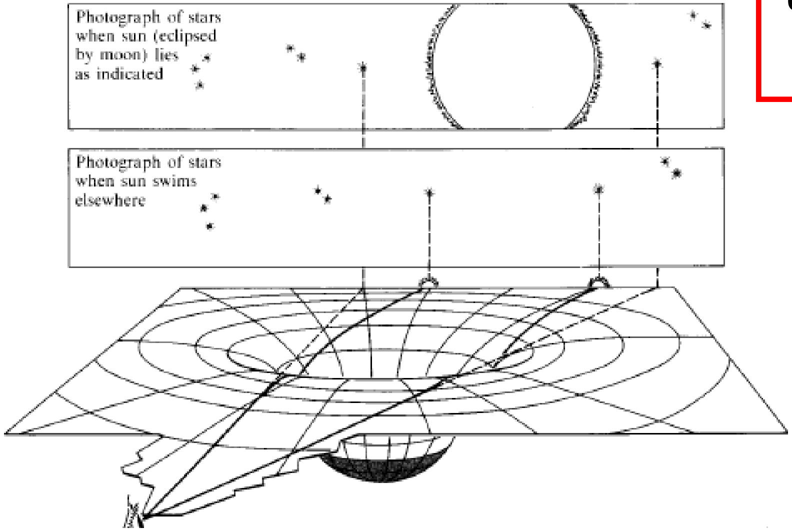
$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

w zakrzywionej czasoprzestrzeni ruch swobodny ciał odbywa się po geodetykach
(tj. najkrótszych drogach)

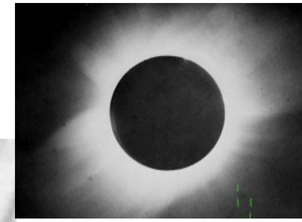
Ugięcie światła w pobliżu brzegu tarczy Słońca

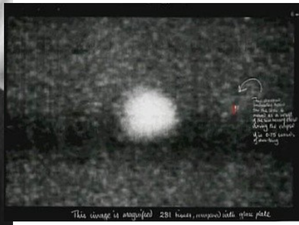
Zakrzywienie czasoprzestrzeni czują nie tylko ciała masywne, ale także światło !

$$\boxed{\alpha = \frac{4GM}{c^2 R} = 1''.75}$$

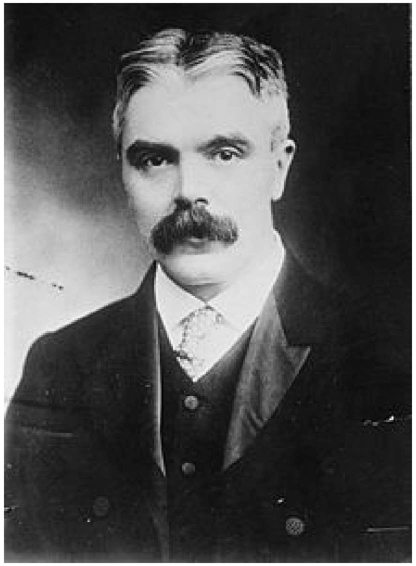


29.V.1919
Sir Arthur Eddington
Całkowite zaćmienie Słońca na tle Hiad



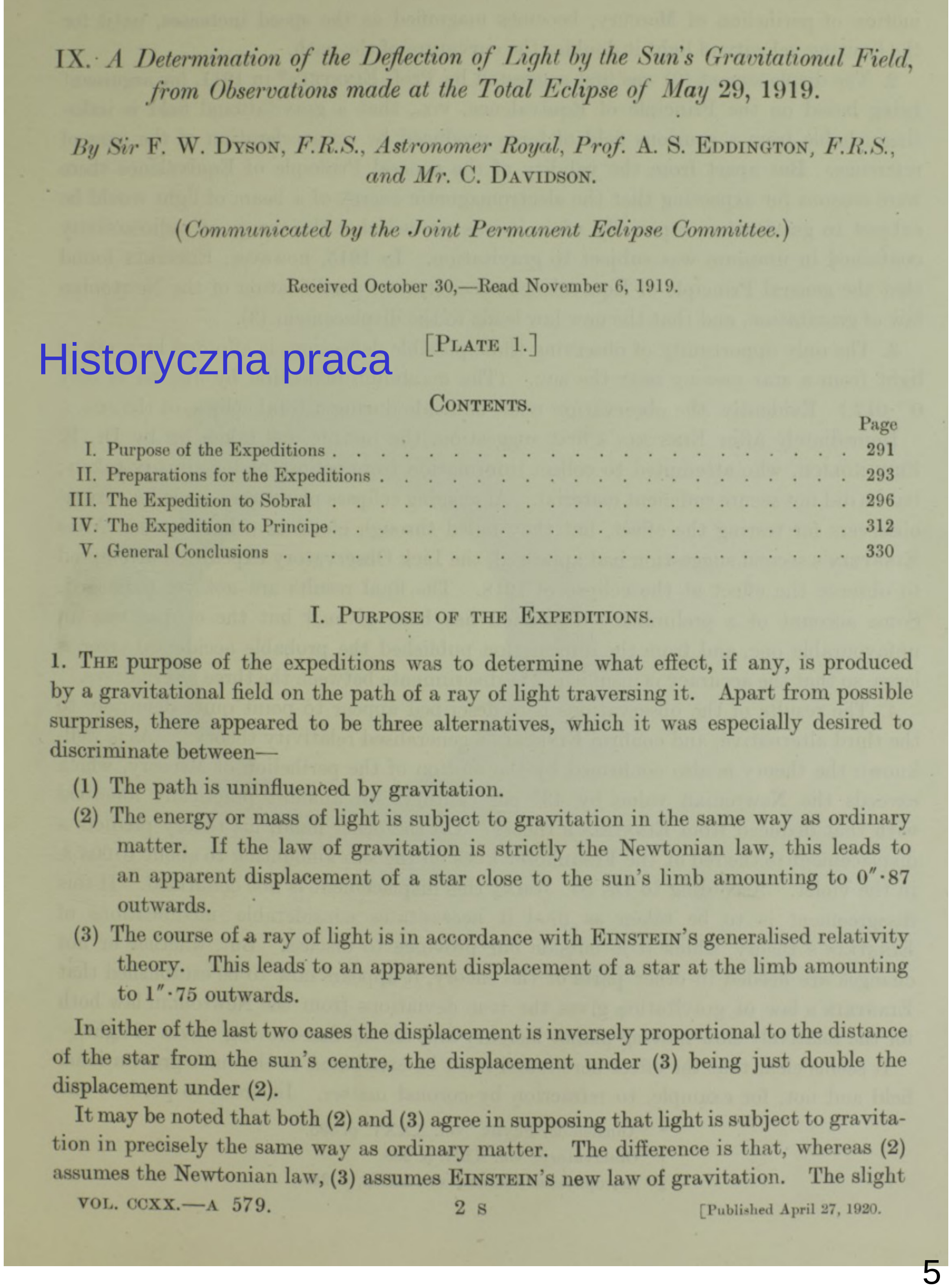


Sir Arthur Stanley Eddington
1882 - 1944



Sir Frank Watson Dyson
1868 - 1939

Historyczna praca



IX. *A Determination of the Deflection of Light by the Sun's Gravitational Field, from Observations made at the Total Eclipse of May 29, 1919.*

By Sir F. W. Dyson, *F.R.S., Astronomer Royal, Prof.* A. S. Eddington, *F.R.S., and Mr.* C. Davidson.

(*Communicated by the Joint Permanent Eclipse Committee.*)

Received October 30,—Read November 6, 1919.

[Plate 1.]

Contents.

I. Purpose of the Expeditions.

1. The purpose of the expeditions was to determine what effect, if any, is produced by a gravitational field on the path of a ray of light traversing it. Apart from possible surprises, there appeared to be three alternatives, which it was especially desired to discriminate between—

(1) The path is uninfluenced by gravitation.

(2) The energy or mass of light is subject to gravitation in the same way as ordinary matter. If the law of gravitation is strictly the Newtonian law, this leads to an apparent displacement of a star close to the sun's limb amounting to $0''\cdot 87$ outwards.

(3) The course of a ray of light is in accordance with Einstein's generalised relativity theory. This leads to an apparent displacement of a star at the limb amounting to $1''\cdot 75$ outwards.

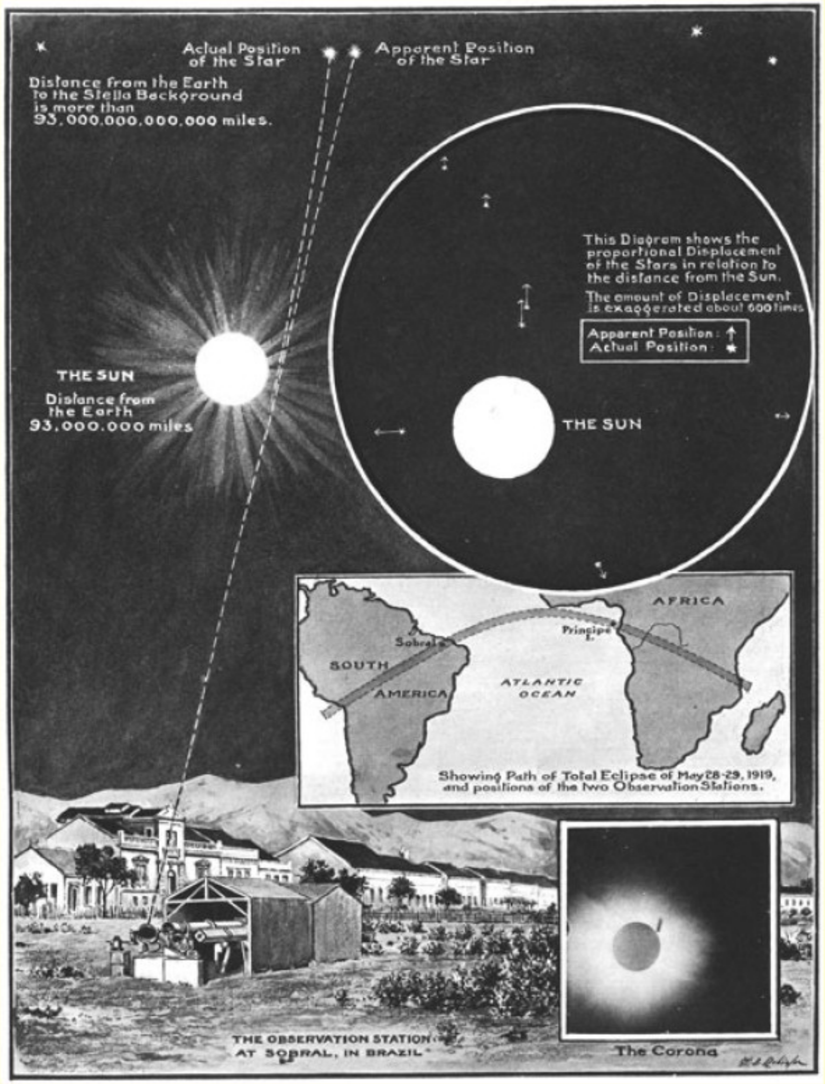
In either of the last two cases the displacement is inversely proportional to the distance of the star from the sun's centre, the displacement under (3) being just double the displacement under (2).

It may be noted that both (2) and (3) agree in supposing that light is subject to gravitation in precisely the same way as ordinary matter. The difference is that, whereas (2) assumes the Newtonian law, (3) assumes Einstein's new law of gravitation. The slight

Phil. Trans. Roy. Soc. A. ***220*** *(571–581): 291–333*

Obserwacje Eddingtona

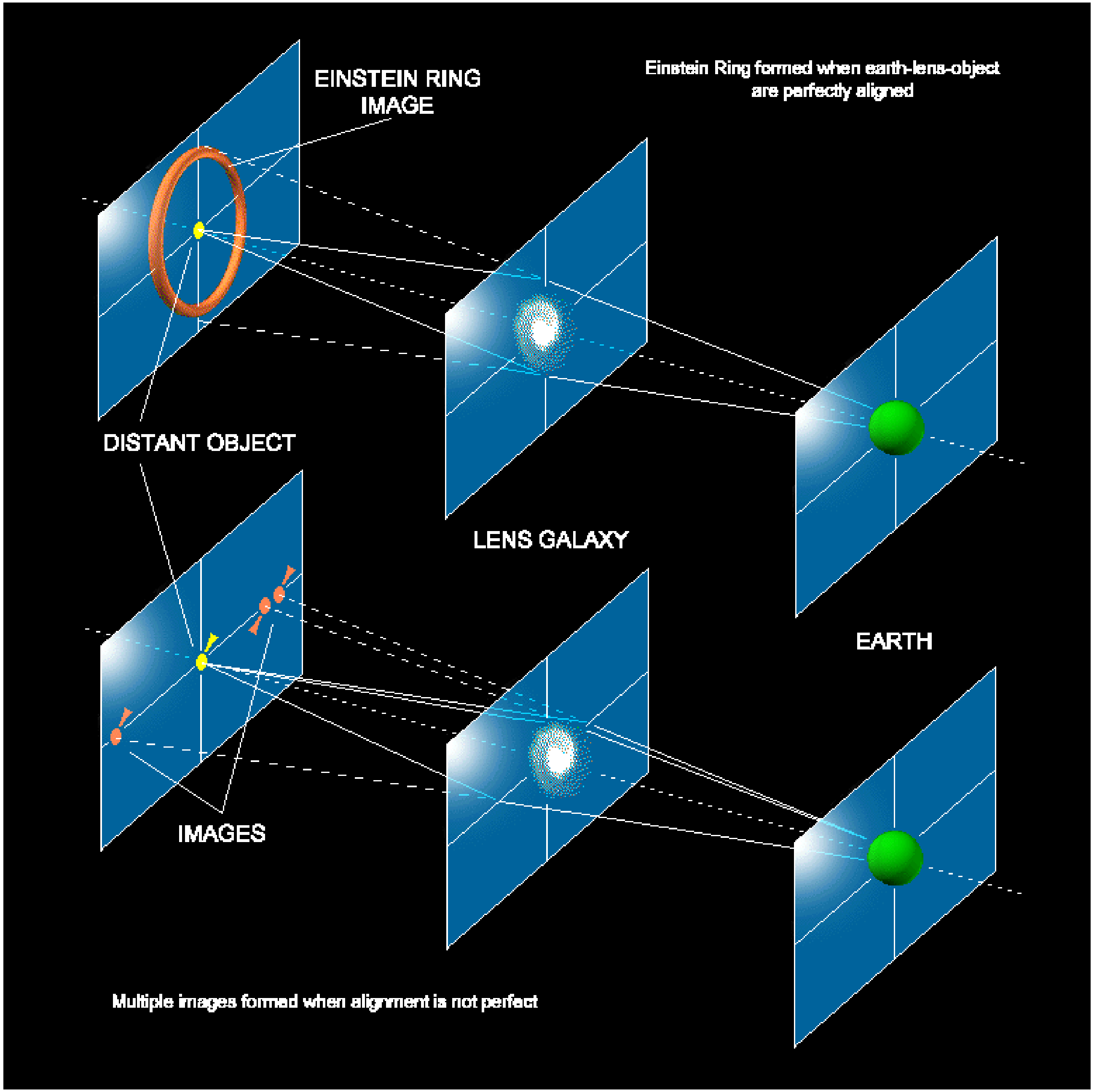
The results obtained by the British expeditions to observe the total eclipse of the sun last May verified Professor Einstein's theory that light is subject to gravitation. Writing in our issue of November 15 [1919], Dr. A.C. Crommelin, one of the British observers, said: "The eclipse was specially favourable for the purpose, there being no fewer than twelve fairly bright stars near the limb of the sun. The process of observation consisted in taking photographs of these stars during totality, and comparing them with other plates of the same region taken when the sun was not in the neighbourhood. Then if the starlight is bent by the sun's attraction, the stars on the eclipse plates would seem to be pushed outward compared with those on the other plates. The second Sobral camera and the one used at Principe agree in supporting Einstein's theory. It is of profound philosophical interest. Straight lines in Einsteins space cannot exist; they are parts of gigantic curves."



Einstein staje się celebrytą !

Illustrated London News of November 22, 1919.

wg. M. Jaroszyński



Konsekwencja:

soczewkowanie grawitacyjne

Einstein – pierścień Einsteina

$$\theta_E = \sqrt{\frac{4GM}{c^2} \frac{D_{LS}}{D_L D_S}}$$

Eddington 1920

idea wielokrotnych obrazów

Soczewkowanie grawitacyjne

- Einstein sceptyczny co do obserwowalności efektu

soczewki o masach rzędu masy Słońca 1 $M_\odot$ przy odległościach wzajemnych typowych dla Galaktyki 5 – 10 kpc mają promienie Einsteina rzędu 0”.001 – **nieobserwowalne !**

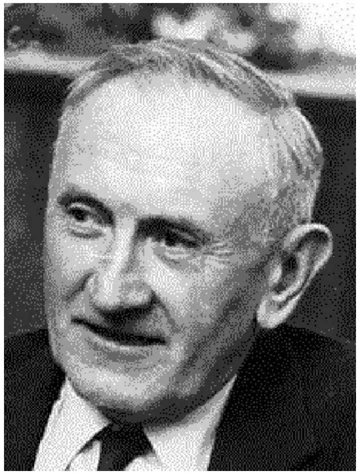
- Zwicky 1937 (!) galaktyki w roli soczewek

Galaktyki mają masy rzędu 10^{11} – 10^{12} $M_\odot$

ich wzajemne odległości to 10 Mpc – 1 Gpc

daje to promień Einsteina rzędu **1”.**

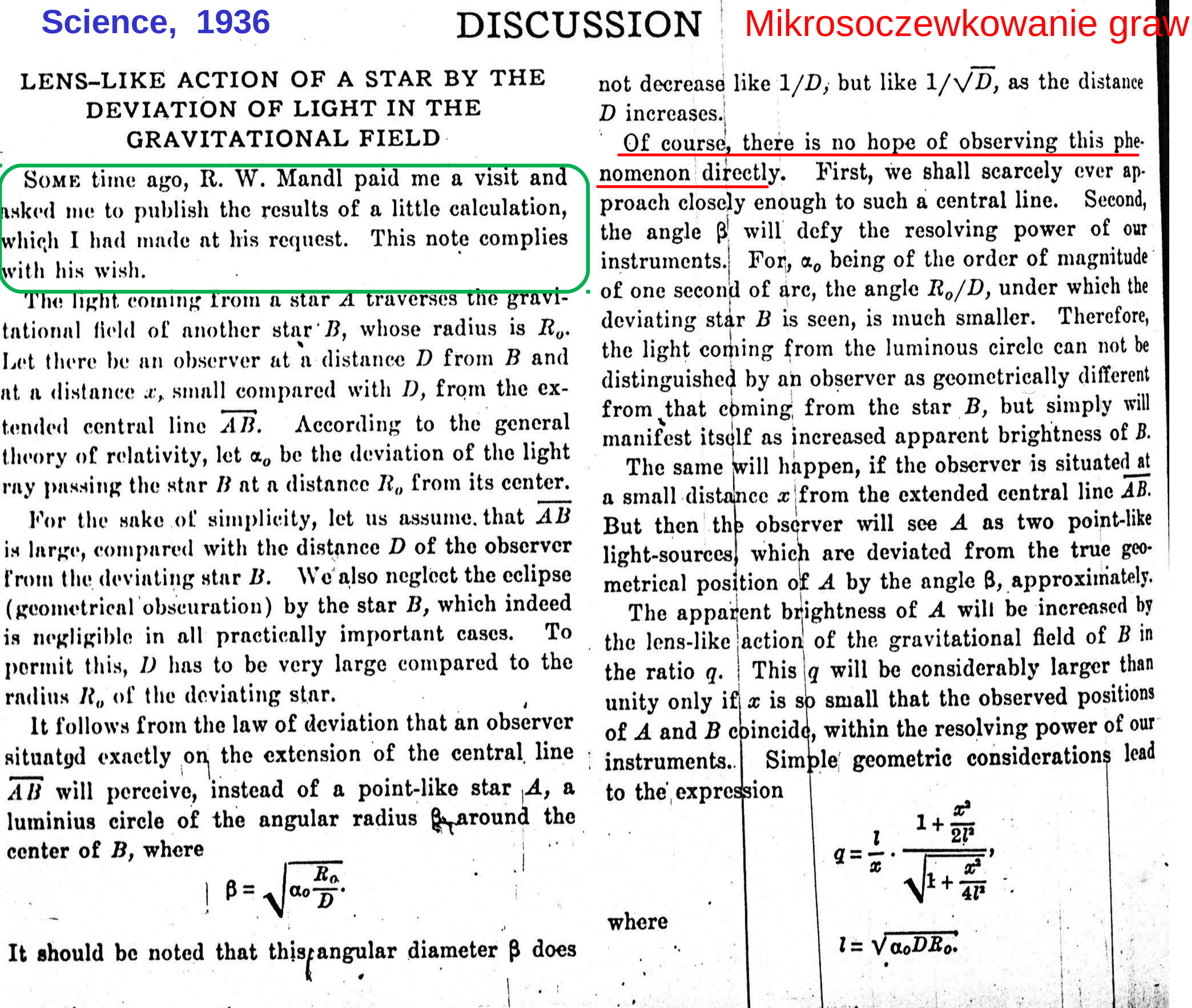
To już można zobaczyć !



Fritz Zwicky
1898 - 1974

Science, 1936

Mikrosoczewkowanie grawitacyjne



DISCUSSION

LENS-LIKE ACTION OF A STAR BY THE DEVIATION OF LIGHT IN THE GRAVITATIONAL FIELD

SOME time ago, R. W. Mandl paid me a visit and asked me to publish the results of a little calculation, which I had made at his request. This note complies with his wish.

The light coming from a star A traverses the gravitational field of another star B, whose radius is R_o. Let there be an observer at a distance D from B and at a distance x, small compared with D, from the extended central line $\overline{AB}$. According to the general theory of relativity, let α_o be the deviation of the light ray passing the star B at a distance R_o from its center.

For the sake of simplicity, let us assume that $\overline{AB}$ is large, compared with the distance D of the observer from the deviating star B. We also neglect the eclipse (geometrical obscuration) by the star B, which indeed is negligible in all practically important cases. To permit this, D has to be very large compared to the radius R_o of the deviating star.

It follows from the law of deviation that an observer situated exactly on the extension of the central line $\overline{AB}$ will perceive, instead of a point-like star A, a luminius circle of the angular radius β around the center of B, where

$$\beta = \sqrt{\alpha_o \frac{R_o}{D}}.$$

It should be noted that this angular diameter β does not decrease like $1/D$, but like $1/\sqrt{D}$, as the distance D increases.

Of course, there is no hope of observing this phenomenon directly. First, we shall scarcely ever approach closely enough to such a central line. Second, the angle β will defy the resolving power of our instruments. For, α_o being of the order of magnitude of one second of arc, the angle R_o/D, under which the deviating star B is seen, is much smaller. Therefore, the light coming from the luminous circle can not be distinguished by an observer as geometrically different from that coming from the star B, but simply will manifest itself as increased apparent brightness of B.

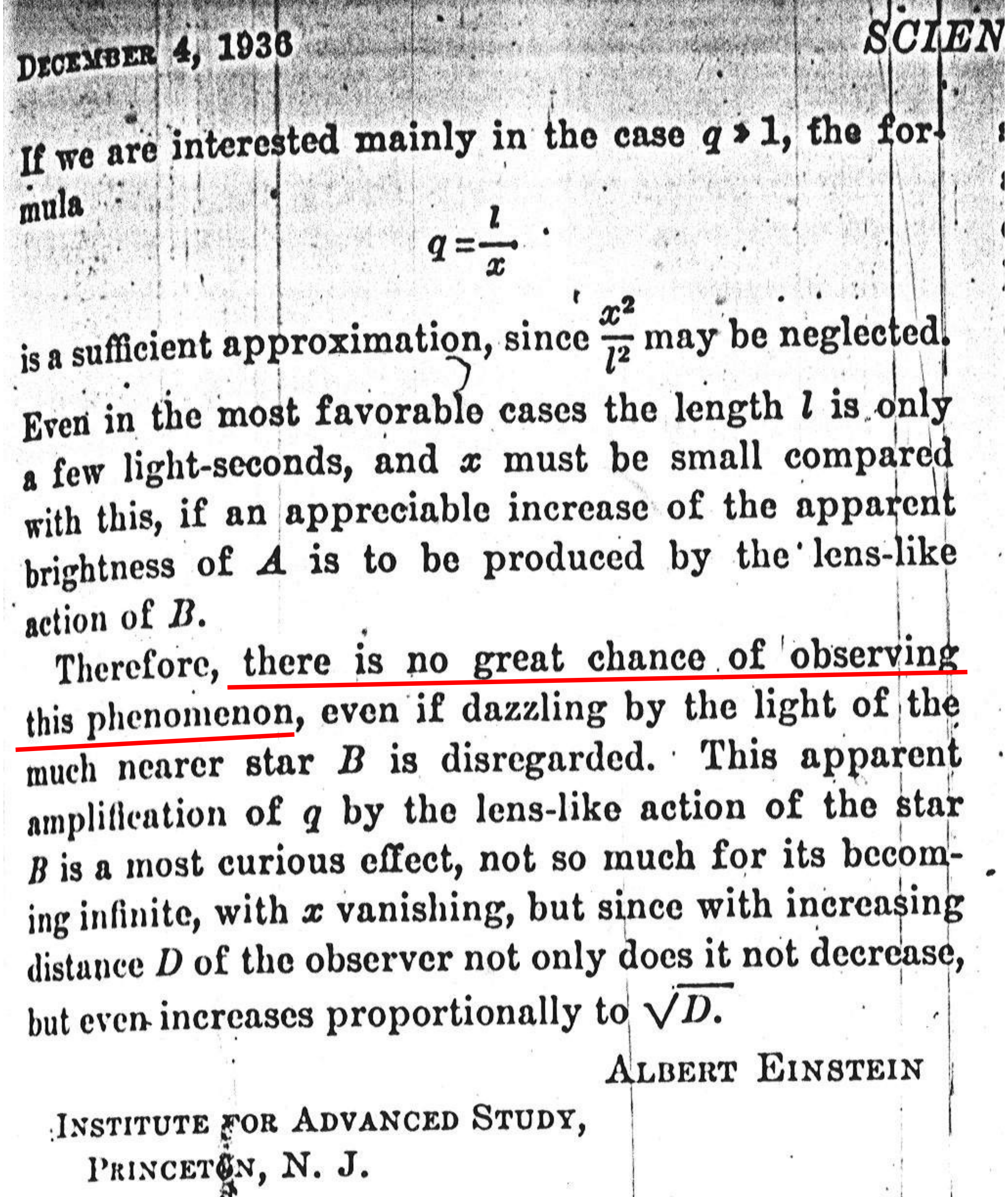
The same will happen, if the observer is situated at a small distance x from the extended central line $\overline{AB}$. But then the observer will see A as two point-like light-sources, which are deviated from the true geometrical position of A by the angle β, approximately.

The apparent brightness of A will be increased by the lens-like action of the gravitational field of B in the ratio q. This q will be considerably larger than unity only if x is so small that the observed positions of A and B coincide, within the resolving power of our instruments. Simple geometric considerations lead to the expression

$$q = \frac{l}{x} \cdot \frac{1 + \frac{x^2}{2l^2}}{\sqrt{1 + \frac{x^2}{4l^2}}},$$

where

$$l = \sqrt{\alpha_o D R_o}.$$



If we are interested mainly in the case $q \gg 1$, the formula

$$q = \frac{l}{x}$$

is a sufficient approximation, since $\frac{x^2}{l^2}$ may be neglected.

Even in the most favorable cases the length l is only a few light-seconds, and x must be small compared with this, if an appreciable increase of the apparent brightness of A is to be produced by the lens-like action of B.

Therefore, there is no great chance of observing this phenomenon, even if dazzling by the light of the much nearer star B is disregarded. This apparent amplification of q by the lens-like action of the star B is a most curious effect, not so much for its becoming infinite, with x vanishing, but since with increasing distance D of the observer not only does it not decrease, but even increases proportionally to $\sqrt{D}$.

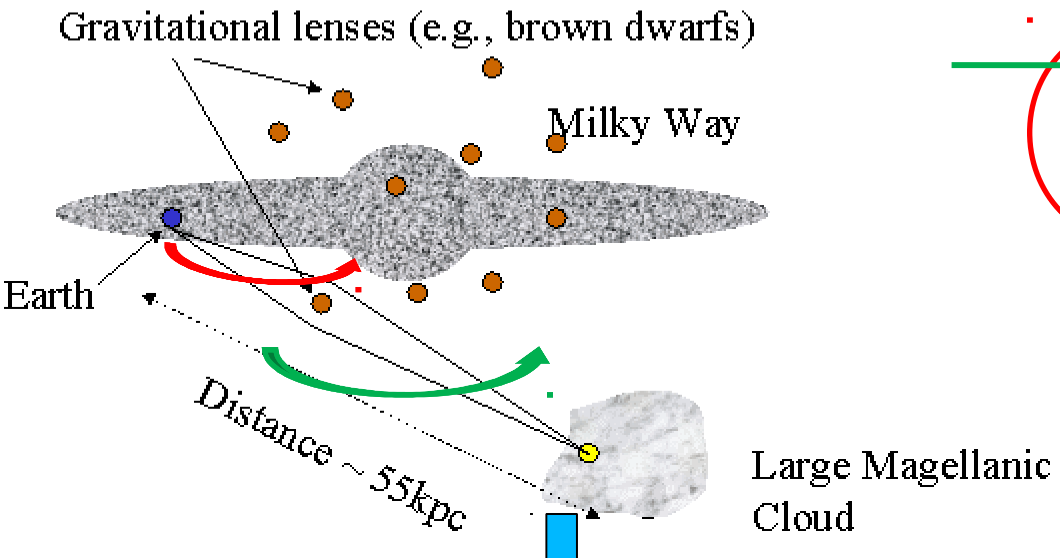
ALBERT EINSTEIN

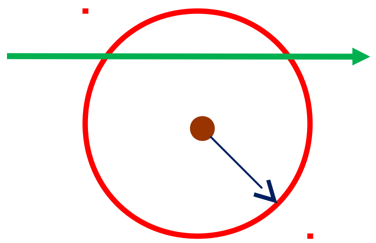
INSTITUTE FOR ADVANCED STUDY,
PRINCETON, N. J.

Bohdan Paczyński (1940 – 2007)

Wybitny polski astrofizyk: pracujący od 1981 w Princeton

zapoczątkował:
teorię ewolucji gwiazd w układach podwójnych
jako pierwszy przewidział rolę emisji fal grawitacyjnych w ewolucji ciasnych układów podwójnych
teorię dysków akrecyjnych
teorię mikrosoczewkowania grawitacyjnego („poprawił Einsteina”)
wyjaśnił naturę błysków gamma
rozwój „terabajtowej astronomii”



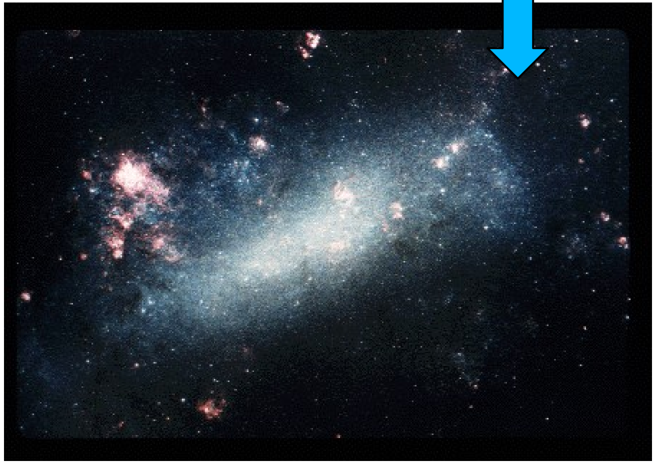


ruch względny
źródła i soczewki

promień Einsteina
soczewki

Bohdan Paczyński 1986

**pomysł obserwacji
mikrosoczewkowania**



Chile,
Las Campanas

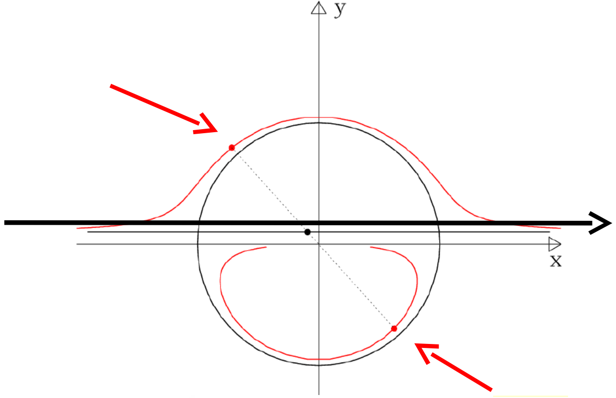
Eksperyment OGLE

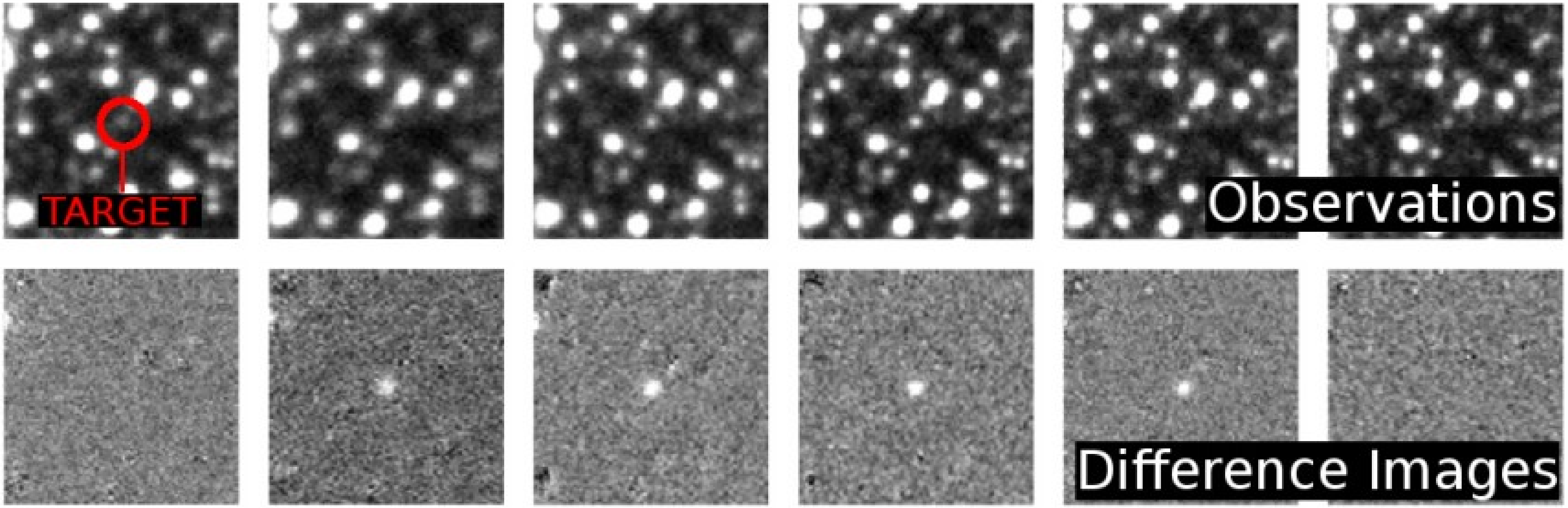
OA UW – prof. Andrzej Udalski
warszawski teleskop w Chile
Las Campanas

Gdy źródło przekracza pierścień Einsteina pojawiają się 2 obrazy

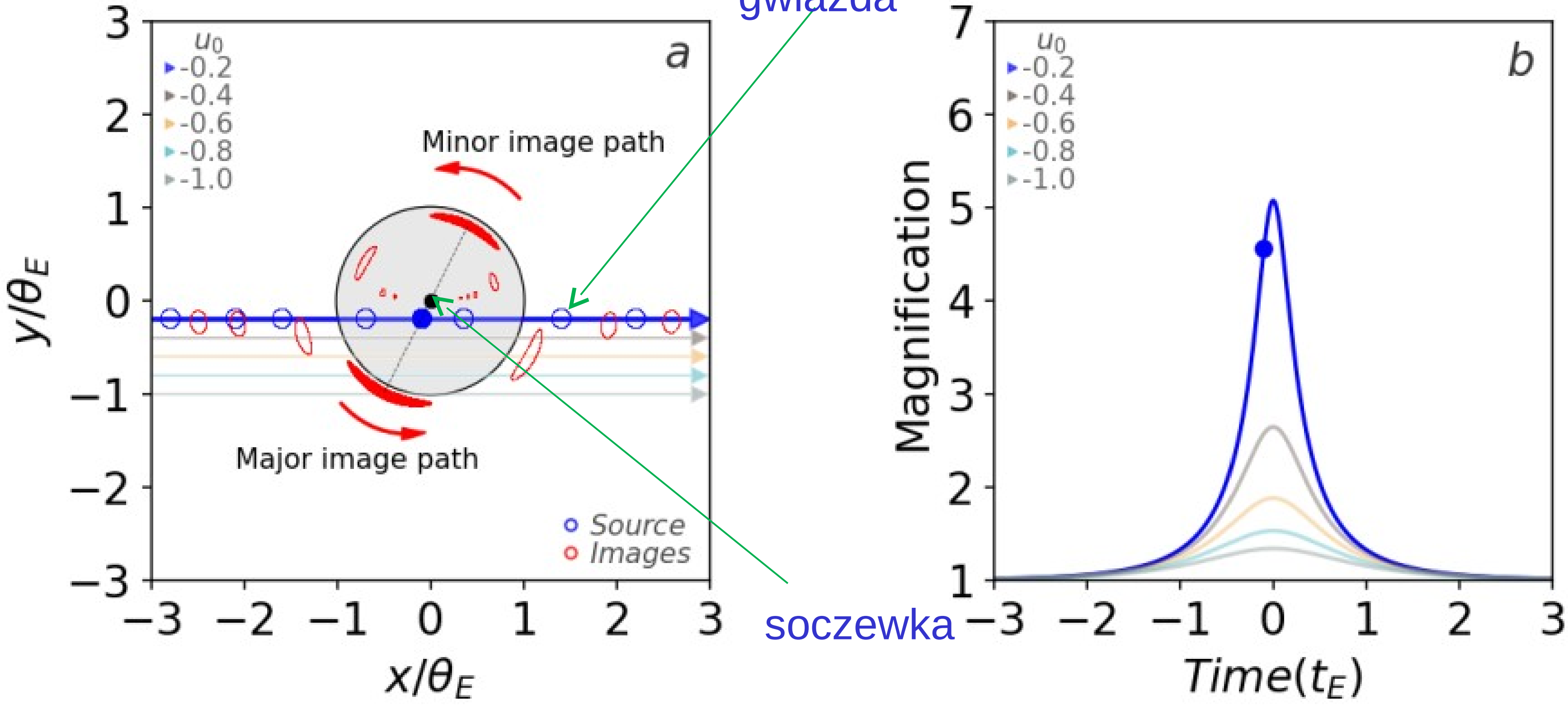
* odległe o ok. 1 mas
nie sposób ich zobaczyć oddzielnie
widzimy 1 obraz źródła, lecz jaśniejszy niż bez soczewkowania

* ruch względny soczewki i źródła przejawia się zmianą jasności źródła w czasie



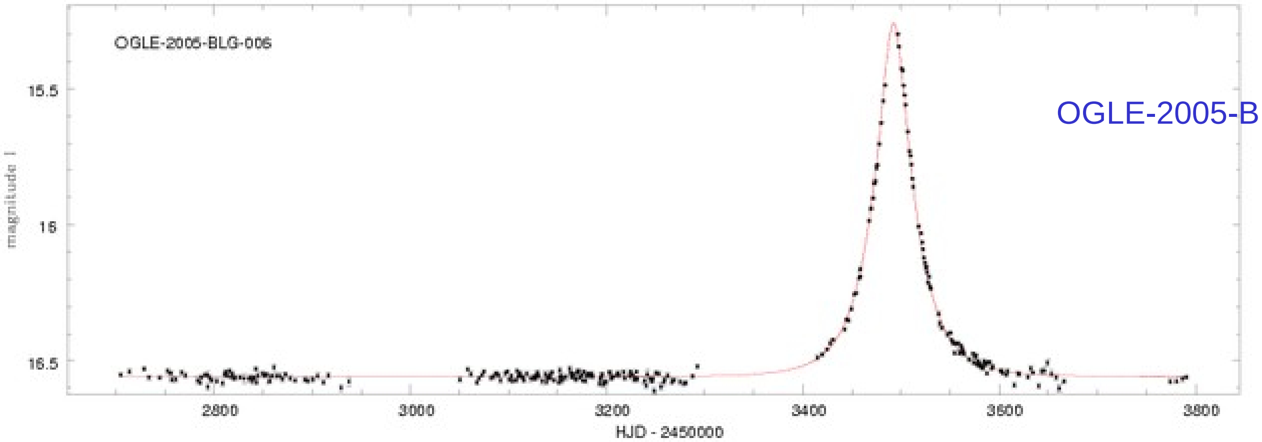


Krzywa blasku w zjawisku mikrosoczewkowania



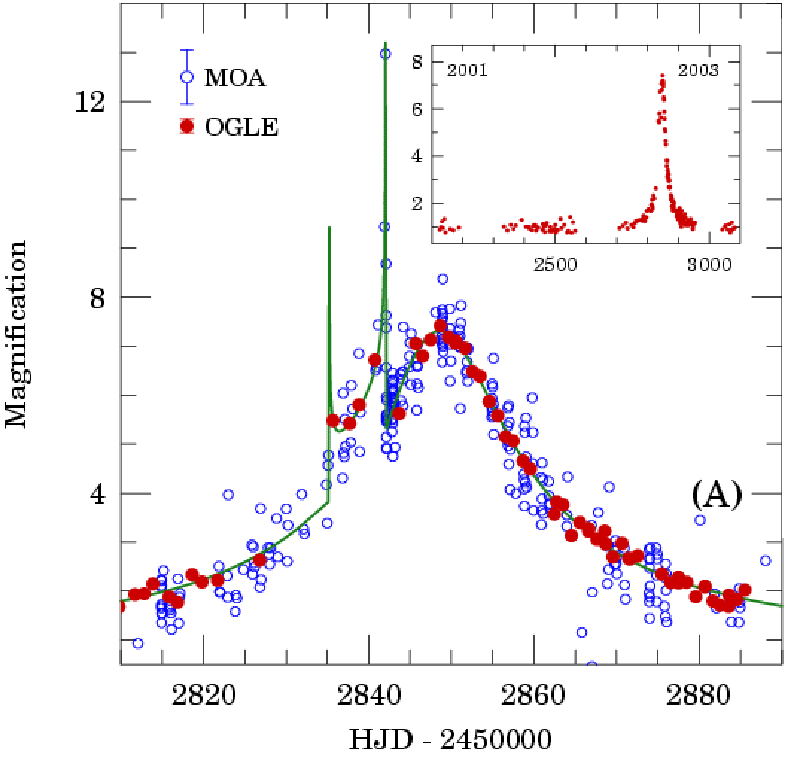
soczewkowana gwiazda

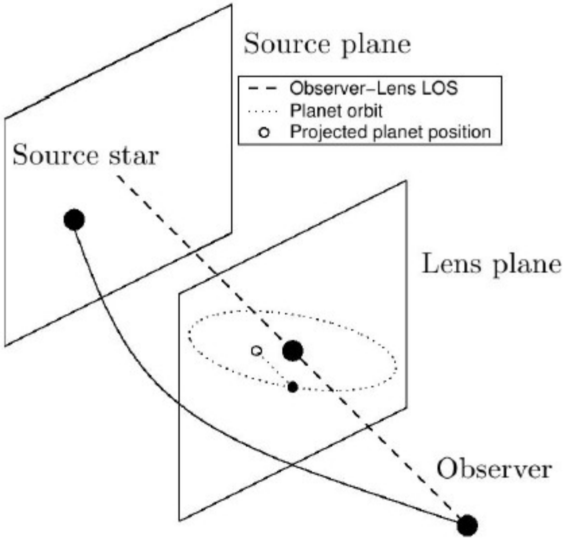
soczewka



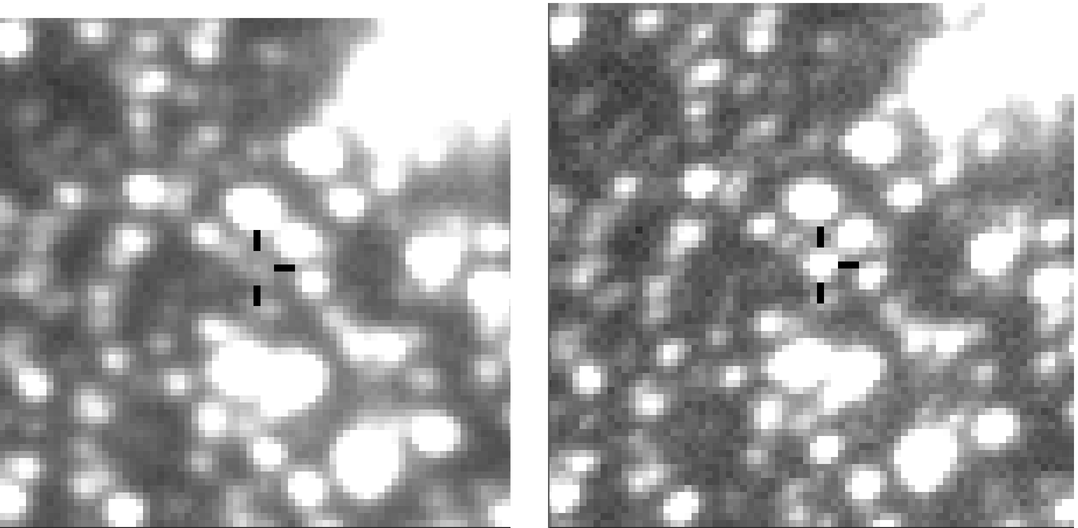
OGLE-2005-BLG-006

Poszukiwania planet pozasłonecznych – B.Paczyński, Shude Mao 1991





Obecnie prof. w Tshinghua U.
+ Manchester U. (Jodrell Bank)

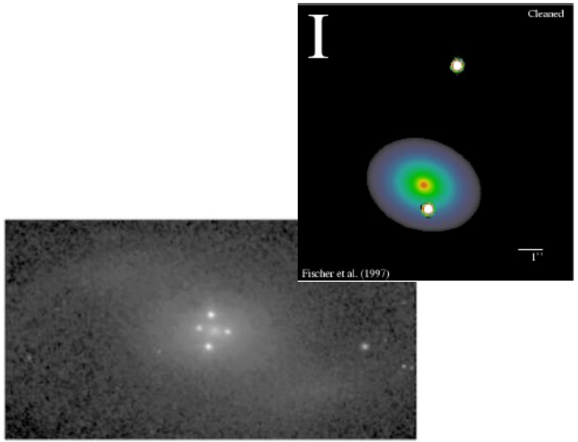


tą techniką odkryto już
19 pozasłonecznych
układów planetarnych

Soczewkowanie grawitacyjne

- Refsdal 1964 pomiary H_0 z soczewkowania

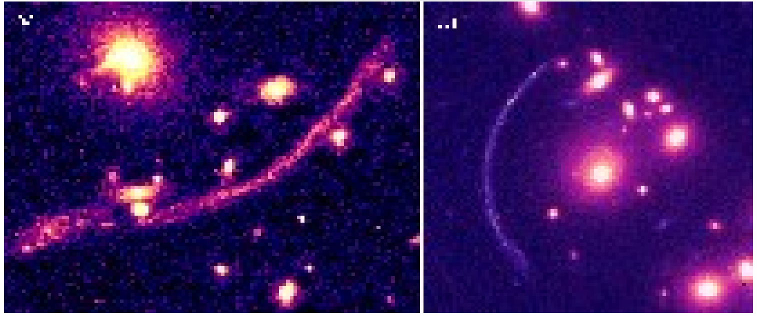
- Walsh, Carswell & Weynmann 1979 - QSO-0957+561A,B



- „tajemnicze” olbrzymie łuki w gromadach

w gromadach A370,Cl2244 (Paczyński sugeruje soczewkowanie)

Soucail, Fort, Mellier 1987 potwierdzają to spektroskopowo

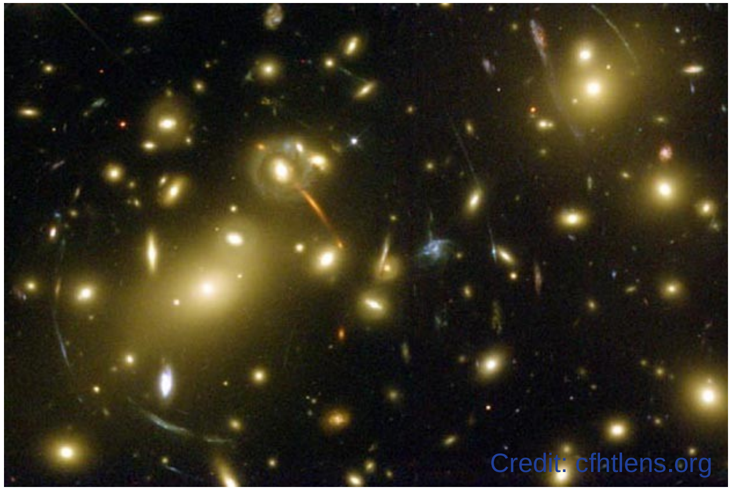


- w okresie 1978 – 1992 odkryto 11 soczewek

- w 2006 znano ich ok. 70

- obecnie ponad **300** soczewek: bieżące przeglądy

SLACS, BELLS, CFHT – SL2S, CLASS, SQLS, HAGGLeS, AEGIS, COSMOS, CASSOWARY



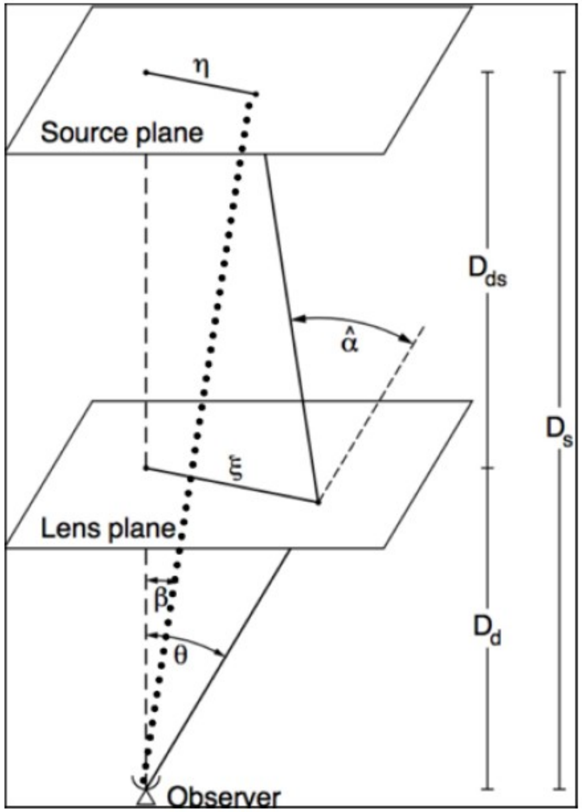
Credit: cfhtlens.org

- w przyszłości Pan-STARRS, **LSST**, JDES, SKA

dostarczą **tysięcy** nowych silnie soczewkowanych układów

Soczewkowanie grawitacyjne

Formalizm promieni świetlnych

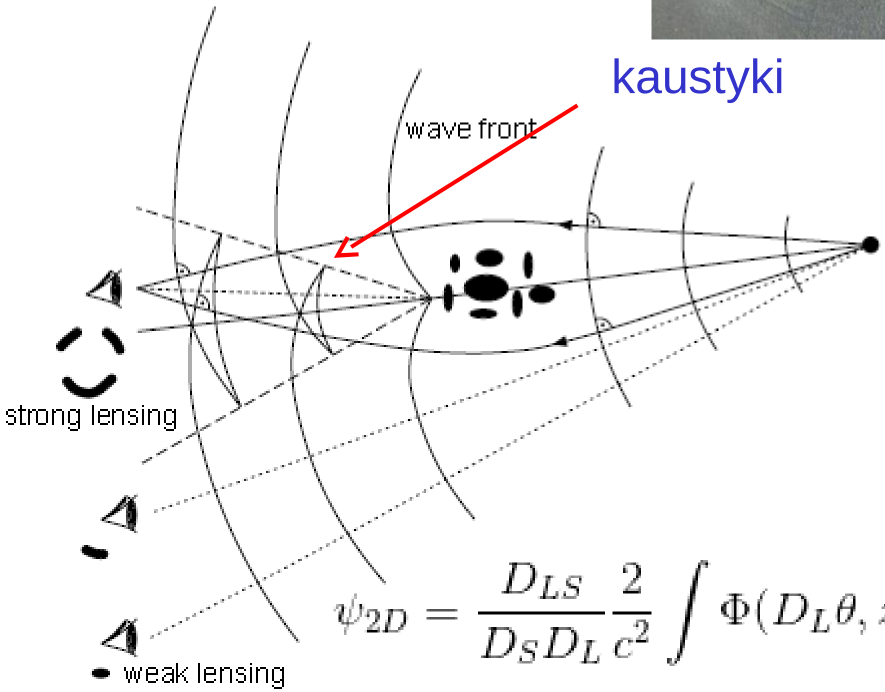


$$\hat{\boldsymbol{\alpha}}\left(\boldsymbol{\theta}\right) D_{ls} + \boldsymbol{\beta} D_s = \boldsymbol{\theta} D_s$$

$$\boxed{\boldsymbol{\beta} = \boldsymbol{\theta} - \boldsymbol{\alpha}\left(\boldsymbol{\theta}\right)}$$

gradient Ψ_{2D}

Formalizm frontów falowych
(zasada Fermata)



kaustyki

$$\psi_{2D} = \frac{D_{LS}}{D_S D_L}\frac{2}{c^2}\int \Phi(D_L\theta, z)dz$$

Czas przelotu

$$\tau = \frac{1+z_L}{c}\frac{D_L D_S}{D_{LS}}\left[\frac{1}{2}(\vec{\theta}-\vec{\beta})^2 - \psi_{2D}(\vec{\theta})\right]$$

Człon geometryczny

efekt Shapiro

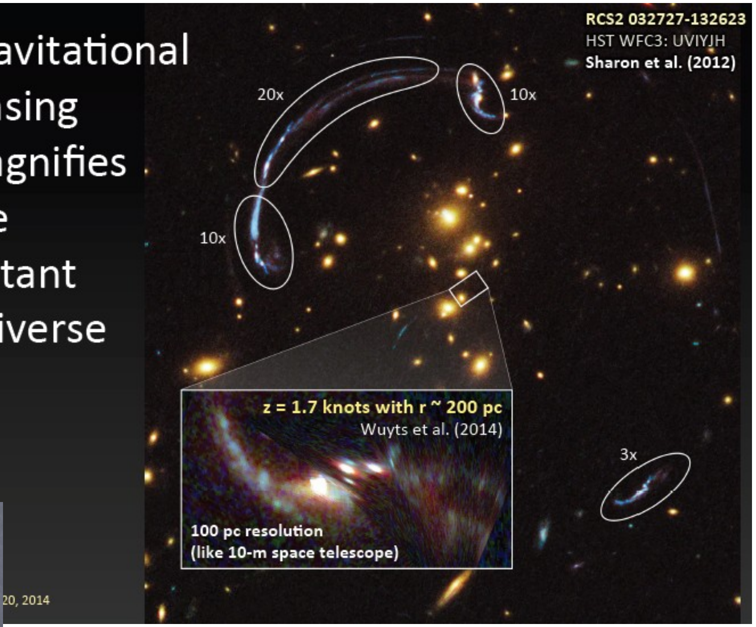
$$\nabla\tau(\boldsymbol{\theta};\boldsymbol{\beta}) = 0.$$

$$\boxed{\vec{\theta} - \vec{\beta} - \frac{\partial\psi_{2D}}{\partial\vec{\theta}} = 0}$$

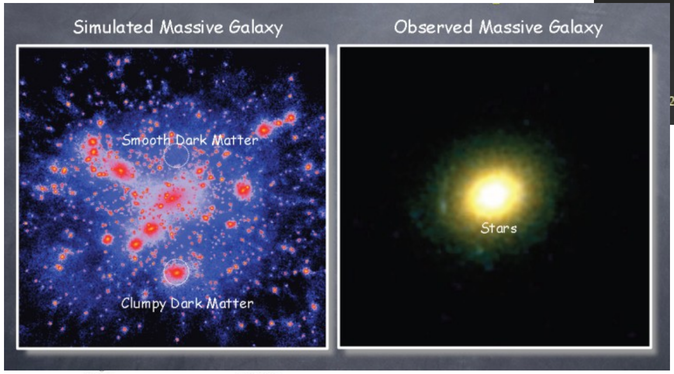
Równanie soczewki

Zastosowania silnego soczewkowania

Badanie struktury galaktyk w różnych stadiach ewolucji:
soczewkowanie + kinematyka gwiazd
soczewki jako „kosmiczne teleskopy”

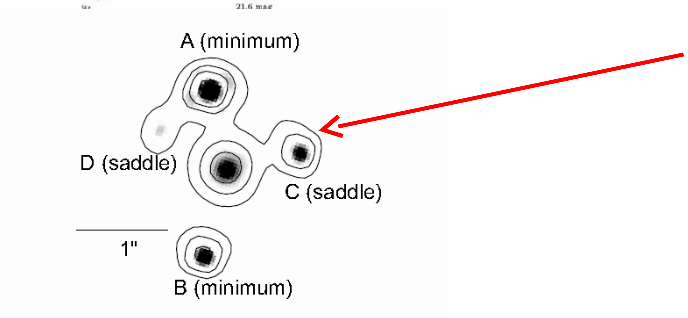


Badania ciemnej materii w skali galaktyk:
„brakujące” skupiska masy na małych skalach:
anomalne jasności makroobrazów
mikrosoczewkowanie



Różnice jasności makro-obrazów;

Teoria podpowiada sekwencję jasności



Anomalie jasności

Efekt soczewkowania przez zagęszczenia ciemnej materii (?)

Supernowa „Refsdala”

Supernowa „Refsdala” odkryta 11 listopada 2014
Kelly et al. (2015) *Science* 347, 1123

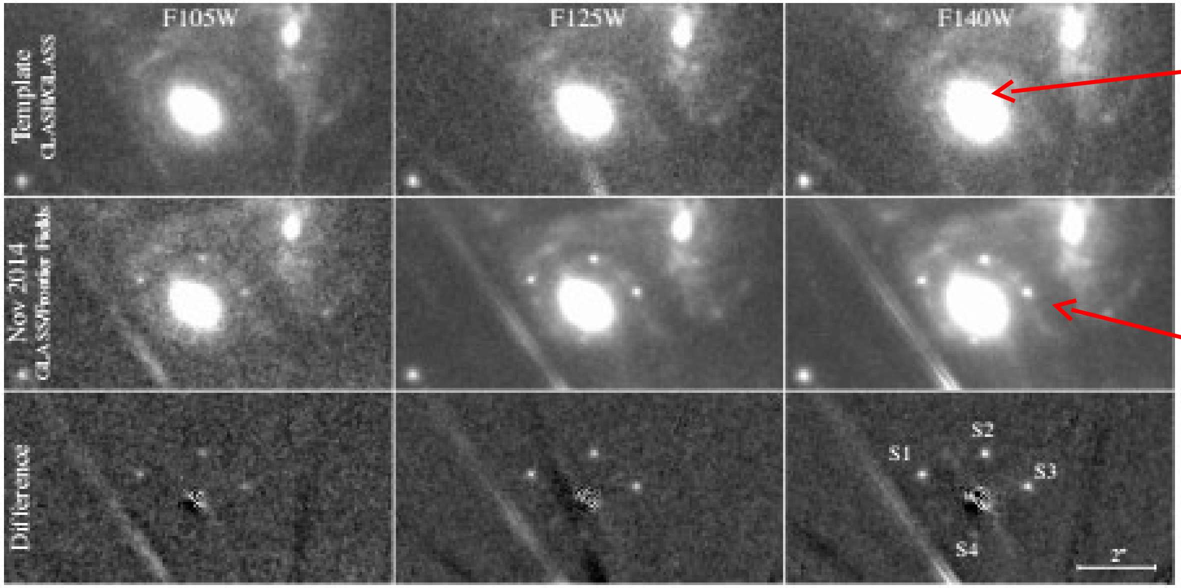


Fig. 1: *HST* WFC3-IR images showing the simultaneous appearance of four point sources around a cluster member galaxy. From left to right the columns show imaging in the *F105W* filter (*Y* band), *F125W* (*J*), and *F140W* (*JH*). From top to bottom the

galaktyka eliptyczna z=0.54
należąca do gromady
MACS J1149.6+2223

galaktyka spiralna z=1.49
źródło

galaktyka macierzysta SNII

Supernowa „Refsdala”

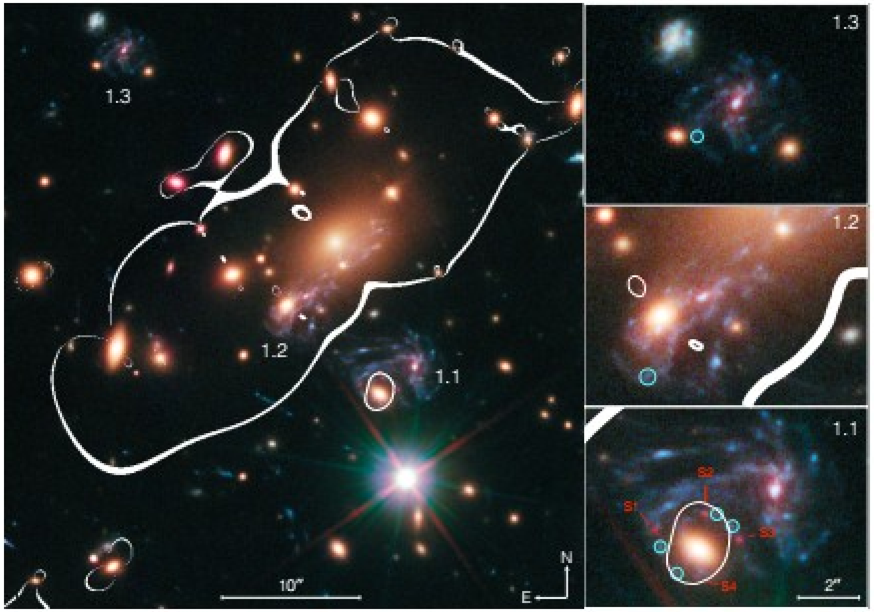
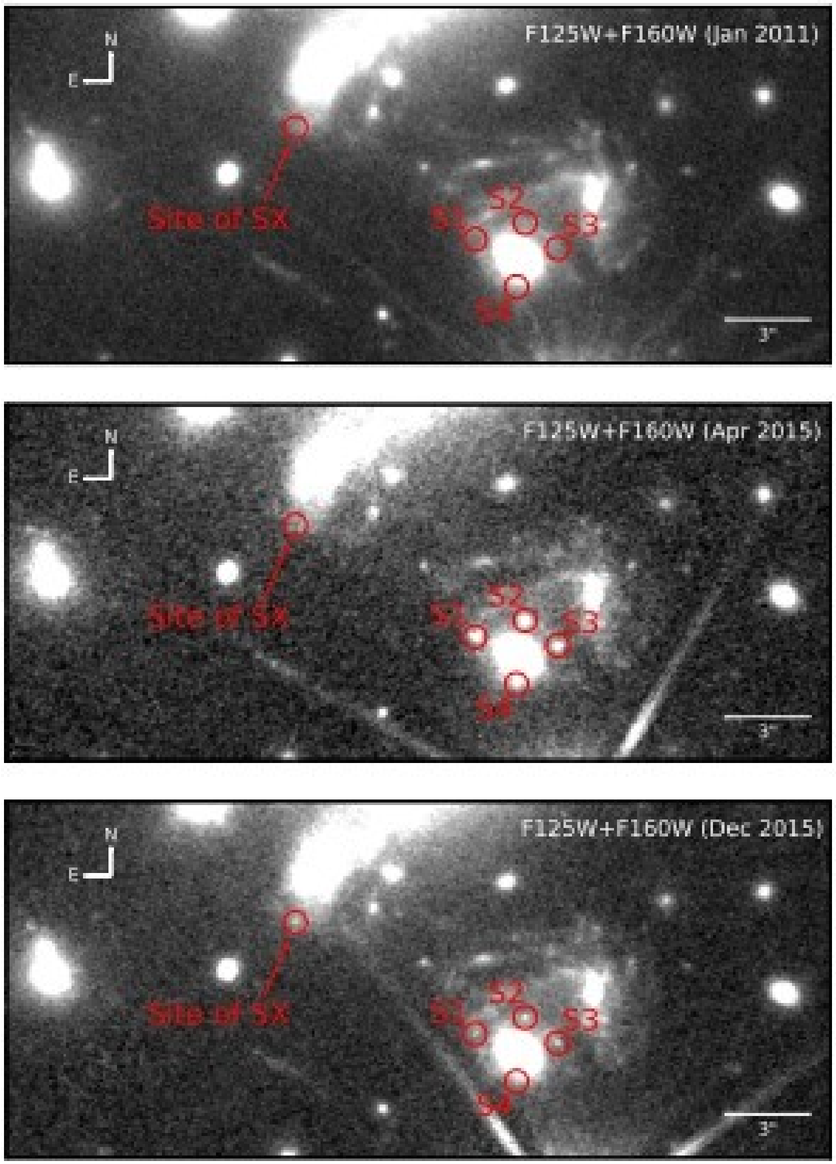


Fig. 2: Color-composite image of the galaxy cluster MACSJ1149.6+2223, with critical curves for sources at the $z = 1.49$ redshift of the host galaxy overlaid. Three images of the host galaxy formed by the cluster are marked with white labels (1.1, 1.2, and 1.3) in the left panel, and each is enlarged at right. The four current images of SN Refsdal that we detected (labeled S1 to S4 in red) appear as red point sources in image 1.1. Our model indicates that an image of the SN appeared in the past in image 1.3, and that one will appear in the near future in image 1.2. The extreme red hue of the SN may be somewhat exaggerated, because the blue and green channels include only data taken before the SN erupted. In image 1.1, both a single bright blue knot (cyan circles) and SN Refsdal are multiply imaged into four distinct locations. The image combines infrared and optical *HST* imaging data from the Frontier Fields and GLASS programs, along with images from the CLASH and the FrontierSN programs (GO-13790, PI: S.A.R.).

Powtórne pojawienie się przewidziane za ok. 1 rok

W jednym z obrazów galaktyki macierzystej soczewkowanej przez gromadę

Supernowa „Refsdala”



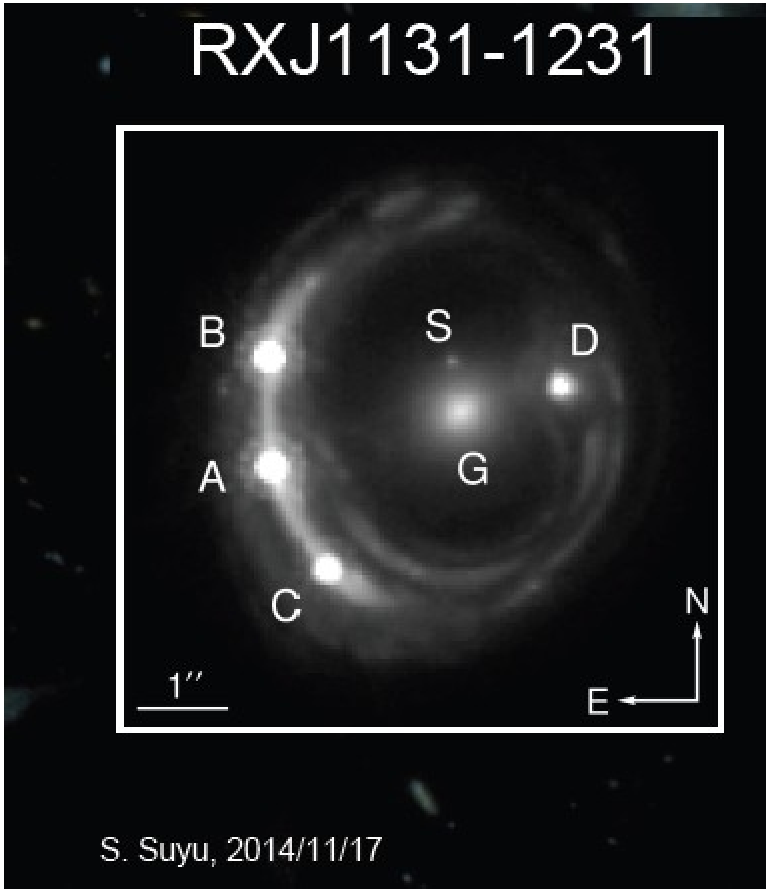
Kelly et al. (2016) ApJL

11 grudnia 2015
SNII zaobserwowana
w obrazie SX –
zgodnie z przewidywaniami

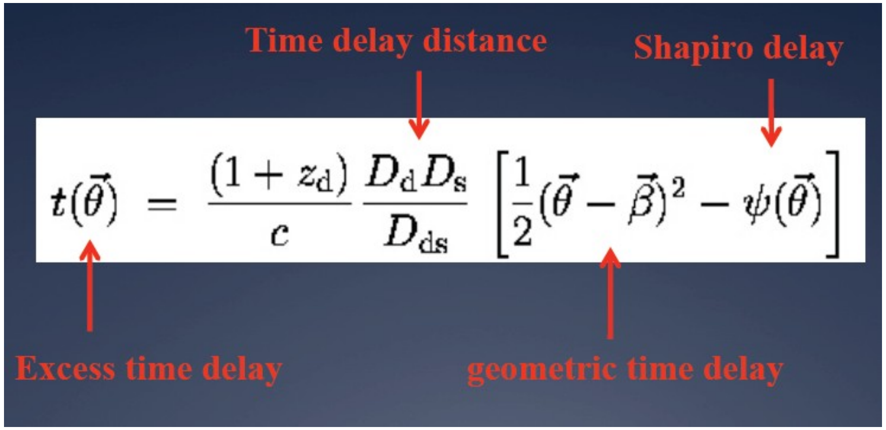
Wielki sukces astrofizyki
(OTW + teoria soczewkowania
+ modelowanie rozkładu
masy)

Porównywalny z triumfem
mechaniki niebieskiej w XIX w.
przy odkryciu Neptuna

Metoda opóźnień czasowych w Kosmologii



S. Suyu, 2014/11/17



Time delay distance

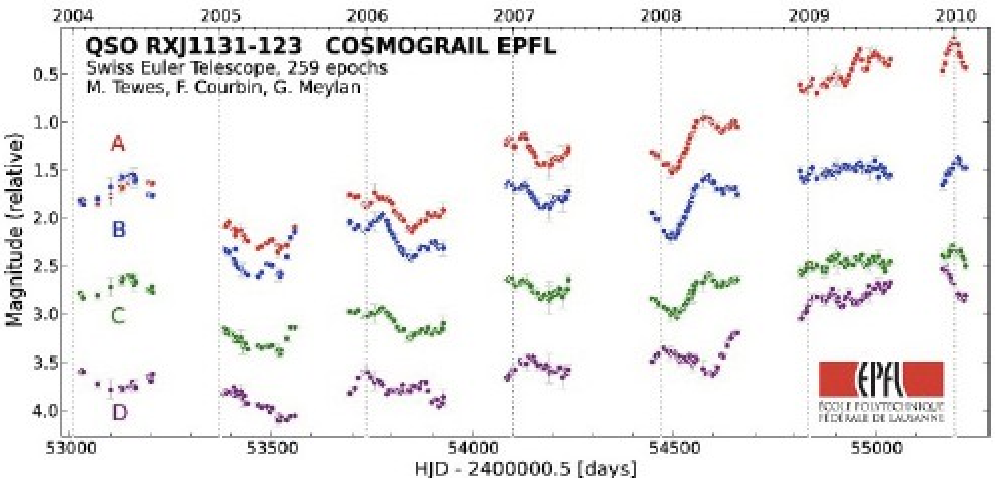
Shapiro delay

$$t(\vec{\theta}) = \frac{(1+z_{\rm d})}{c} \frac{D_{\rm d} D_{\rm s}}{D_{\rm ds}} \left[\frac{1}{2}(\vec{\theta} - \vec{\beta})^2 - \psi(\vec{\theta}) \right]$$

Excess time delay

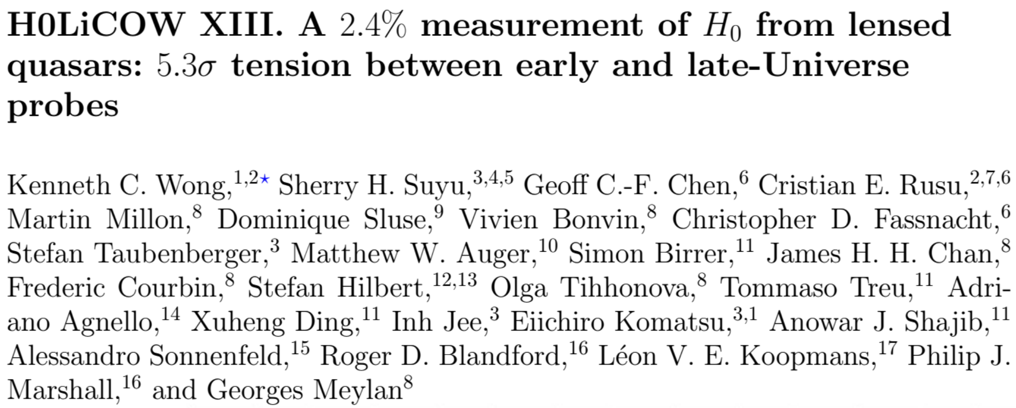
geometric time delay

Opóźnienie czasowe – największa osiągalna dokładność 1.5%



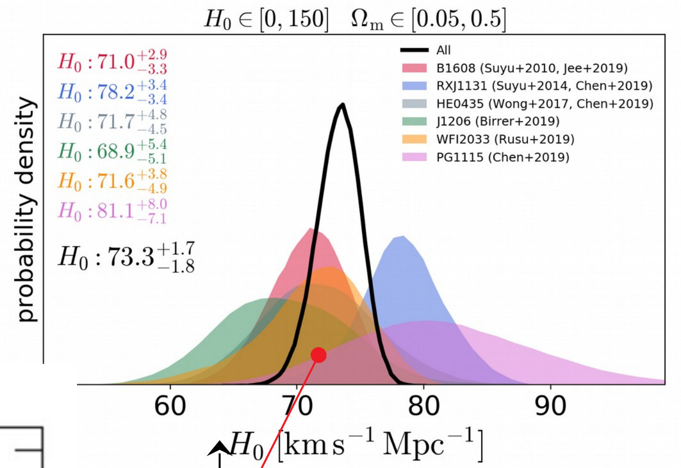
Results: Suyu et al. 2013

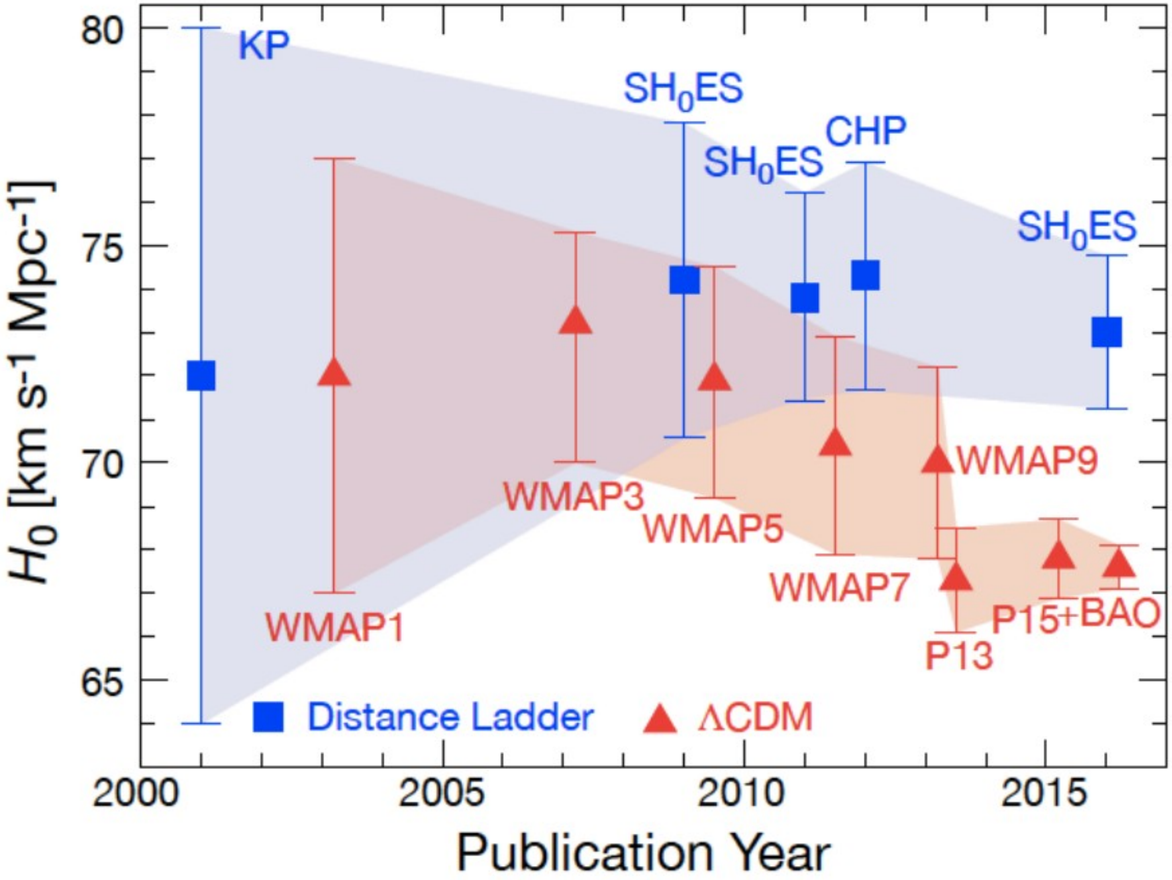
$$H_0 = 73.3^{+1.7}_{-1.8}\ km\ s^{-1}\ Mpc^{-1}$$

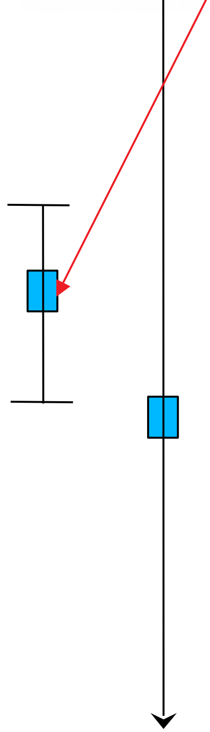


H0LiCOW XIII. A 2.4% measurement of H_0 from lensed quasars: 5.3σ tension between early and late-Universe probes

Kenneth C. Wong,[1,2★] Sherry H. Suyu,[3,4,5] Geoff C.-F. Chen,[6] Cristian E. Rusu,[2,7,6] Martin Millon,[8] Dominique Sluse,[9] Vivien Bonvin,[8] Christopher D. Fassnacht,[6] Stefan Taubenberger,[3] Matthew W. Auger,[10] Simon Birrer,[11] James H. H. Chan,[8] Frederic Courbin,[8] Stefan Hilbert,[12,13] Olga Tihhonova,[8] Tommaso Treu,[11] Adriano Agnello,[14] Xuheng Ding,[11] Inh Jee,[3] Eiichiro Komatsu,[3,1] Anowar J. Shajib,[11] Alessandro Sonnenfeld,[15] Roger D. Blandford,[16] Léon V. E. Koopmans,[17] Philip J. Marshall,[16] and Georges Meylan[8]







LIGO/Virgo
2017
GW170817

70^{+12}_{-8} km s^{-1} Mpc^{-1}

Zagadką jest przyspieszające tempo ekspansji Wszechświata

Znane jako „problem ciemnej energii”

Równania Einsteina przewidują, że tempo ekspansji powinno spowalniać (jeśli Wszechświat byłby wypełniony zwykłą materią), natomiast widzimy, że przyspiesza …

Co jest za to odpowiedzialne?

Nagroda Nobla z Fizyki 2011

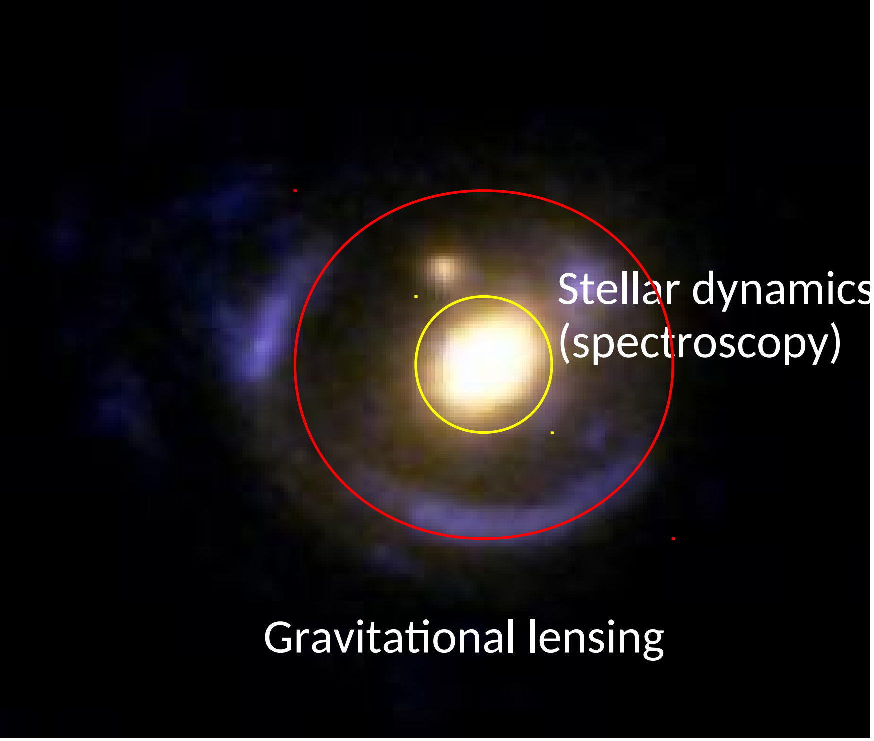
Pytania fizyki fundamentalnej

Czy ogólna teoria względności jest właściwą teorią grawitacji ?

Czy stałe fundamentalne mogą mieć naturę dynamiczną ?

Czy można testować kwantową teorię grawitacji ?

Pomysł



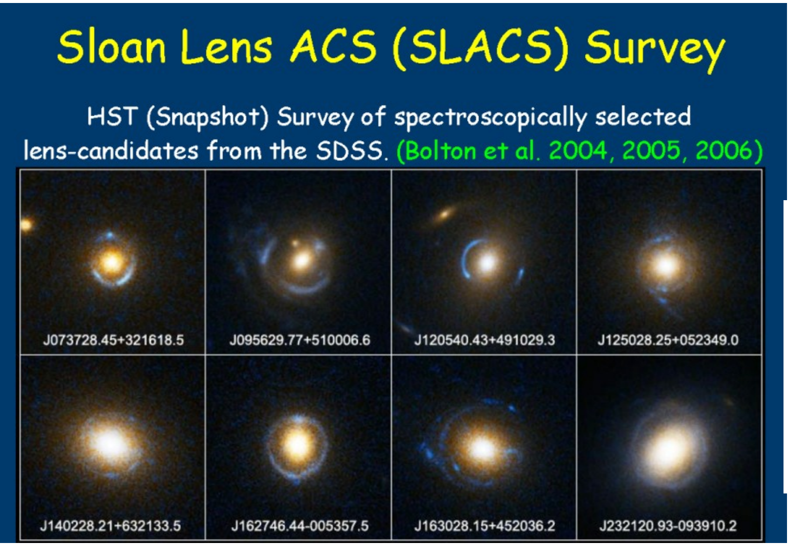
dyspersja prędkości –
spektroskopia

$$\theta_E = 4\pi \left(\frac{\sigma_v}{c}\right)^2 \boxed{\frac{D_{LS}}{D_S}}$$

z astrometrii
obrazów

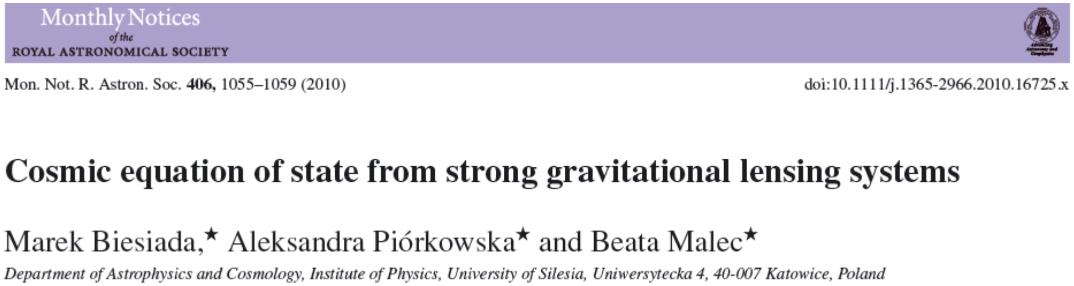
Iloraz odległości

zależy od modelu
kosmologicznego



Sloan Lens ACS (SLACS) Survey

HST (Snapshot) Survey of spectroscopically selected lens-candidates from the SDSS. (Bolton et al. 2004, 2005, 2006)



Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

Mon. Not. R. Astron. Soc. **406,** 1055–1059 (2010) doi:10.1111/j.1365-2966.2010.16725.x

Cosmic equation of state from strong gravitational lensing systems

Marek Biesiada,★ Aleksandra Piórkowska★ and Beata Malec★

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Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Constraints on cosmological models from strong gravitational lensing systems

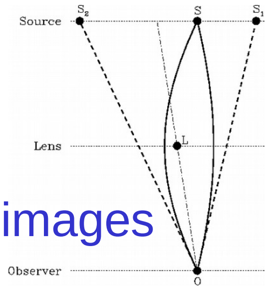
Shuo Cao,[a] Yu Pan,[a,b] Marek Biesiada,[c] Wlodzimierz Godlowski[d] and Zong-Hong Zhu[a,1]

JCAP03(2012)016

10 gromad w roli soczewek
70 galaktyk w roli soczewek
z przeglądu SLACS

Próbka układów
z 2 obrazami

36 SLACS lenses



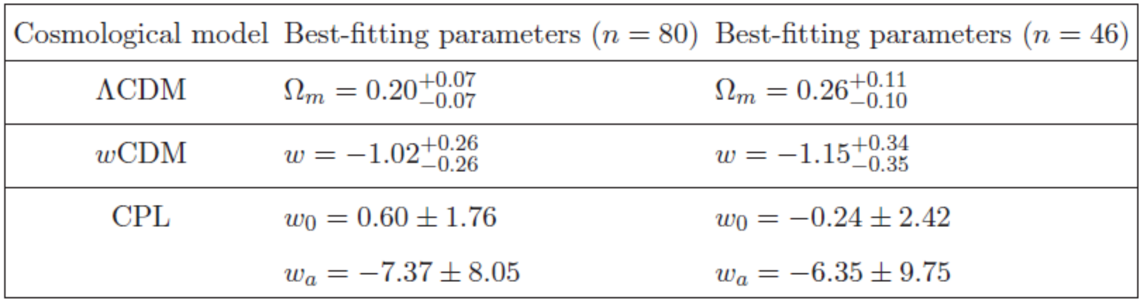
2 images

$$\theta_E = 4\pi \frac{\sigma_{SIS}^2}{c^2} \frac{D_{ls}}{D_s}$$

$$\boxed{\sigma_{SIS} = f_E \sigma_0}$$

$$\mathcal{D}^{obs} = \frac{c^2 \theta_E}{4\pi \sigma_0^2 f_E^2}$$

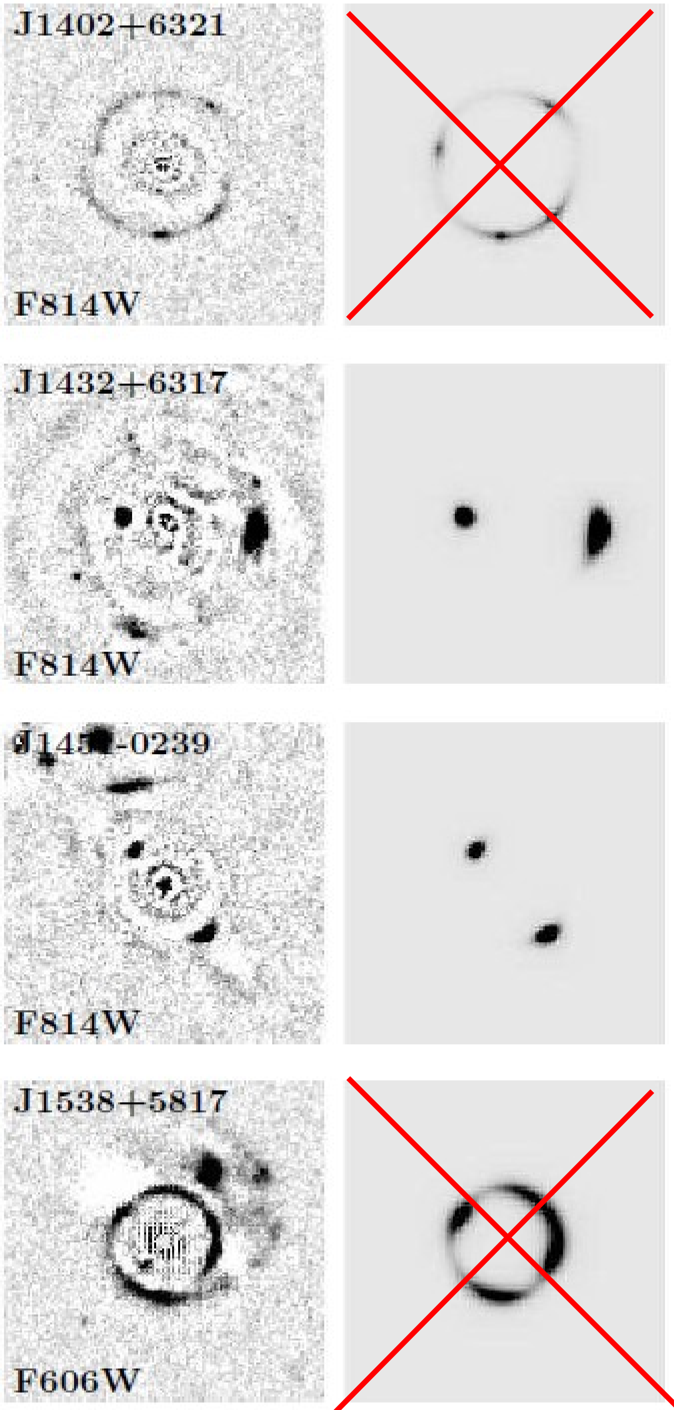
Marginalizacja po $\mathbf{f_E}$



Cosmological model	Best-fitting parameters ($n = 80$)	Best-fitting parameters ($n = 46$)
ΛCDM	$\Omega_m = 0.20^{+0.07}_{-0.07}$	$\Omega_m = 0.26^{+0.11}_{-0.10}$
wCDM	$w = -1.02^{+0.26}_{-0.26}$	$w = -1.15^{+0.34}_{-0.35}$
CPL	$w_0 = 0.60 \pm 1.76$ $w_a = -7.37 \pm 8.05$	$w_0 = -0.24 \pm 2.42$ $w_a = -6.35 \pm 9.75$

WMAP7+BAO+H0

$\Omega_m = 0.272$
$w = -1.10 \pm 0.14$
$w_0 = -0.93 \pm 0.13$
$w_a = -0.41 \pm 0.71$
Komatsu et al. 2011



The Astrophysical Journal, 806:185 (12pp), 2015 June 20 doi:10.1088/0004-637X/806/2/185

COSMOLOGY WITH STRONG-LENSING SYSTEMS

Shuo Cao[1], Marek Biesiada[1,2], Raphaël Gavazzi[3], Aleksandra Piórkowska[2], and Zong-Hong Zhu[1]
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Received 2015 January 23; accepted 2015 May 1; published 2015 June 17

Sferycznie symetryczny potęgowy profil rozkładu masy

$$\rho \propto r^{-\gamma}$$

Soczewkowanie: masa wewnątrz promienia Einsteina

$$M_{\mathrm{lens}} = \frac{c^2}{4G}\frac{D_s D_l}{D_{ls}}\theta_E^2$$

+

Dynamika gwiazd (sferyczne równanie Jeans'a): zrzutowana masa wewnątrz promienia apertury przeskalowana do promienia Einsteina

$$M_{\mathrm{dyn}} = \frac{\pi}{G}\sigma_{\mathrm{ap}}^2 R_E \left(\frac{R_E}{R_{\mathrm{ap}}}\right)^{2-\gamma} f(\gamma)$$

$$= \frac{\pi}{G}\sigma_{\mathrm{ap}}^2 D_l \theta_E \left(\frac{\theta_E}{\theta_{\mathrm{ap}}}\right)^{2-\gamma} f(\gamma)$$

$$\gamma(z_l) = \gamma_0 + \gamma_1 z_l$$

ewolucja γ

A.Ruff , R.Gavazzi et al. 2010

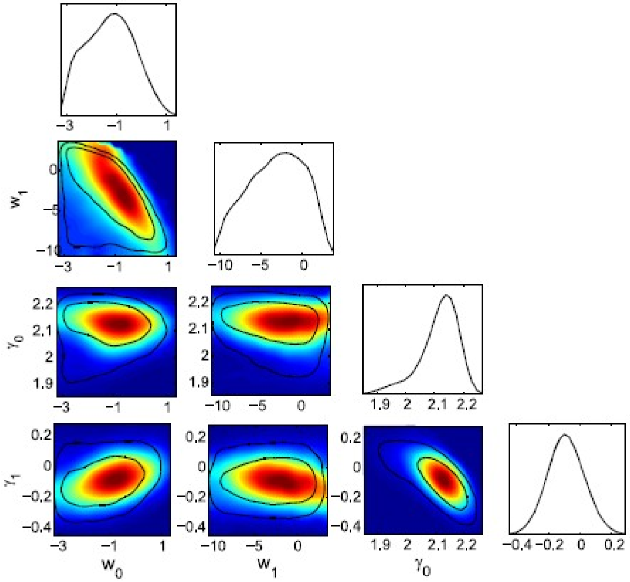
118 soczewek z przeglądu SLACS

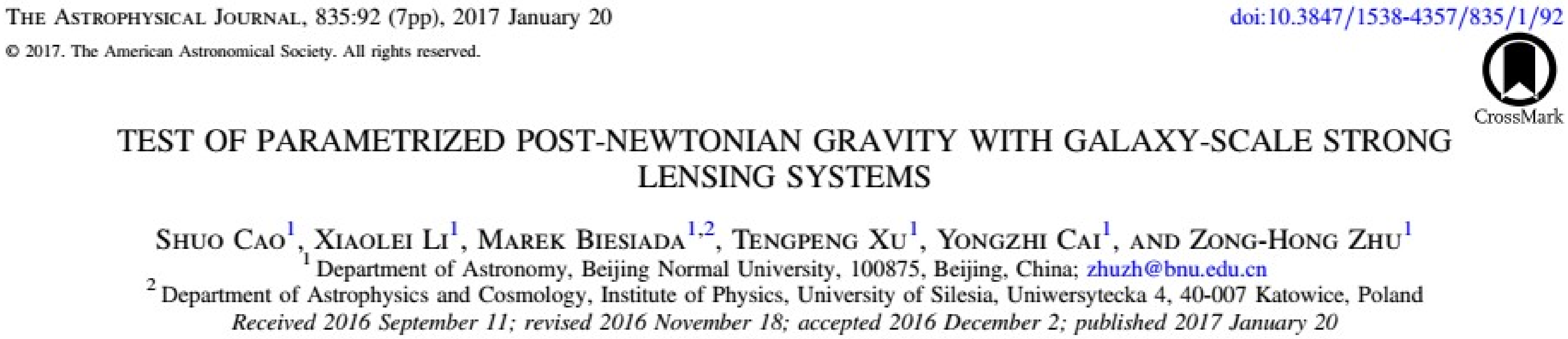
$$\boxed{\theta_E = 4\pi\frac{\sigma_{\mathrm{ap}}^2}{c^2}\frac{D_{ls}}{D_s}\left(\frac{\theta_E}{\theta_{\mathrm{ap}}}\right)^{2-\gamma} f(\gamma)}$$

$$\mathcal{D}^{\mathrm{obs}} = \frac{c^2\theta_E}{4\pi\sigma_{\mathrm{ap}}^2}\left(\frac{\theta_{\mathrm{ap}}}{\theta_E}\right)^{2-\gamma} f^{-1}(\gamma)$$

vs.

$$\mathcal{D}^{\mathrm{th}}(z_l, z_s; p) = \frac{D_{ls}(p)}{D_s(p)} = \frac{\int_{z_l}^{z_s}\frac{dz'}{h(z';p)}}{\int_0^{z_s}\frac{dz'}{h(z';p)}}$$





The Astrophysical Journal, 835:92 (7pp), 2017 January 20
doi:10.3847/1538-4357/835/1/92

TEST OF PARAMETRIZED POST-NEWTONIAN GRAVITY WITH GALAXY-SCALE STRONG LENSING SYSTEMS

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Received 2016 September 11; revised 2016 November 18; accepted 2016 December 2; published 2017 January 20

The Astrophysical Journal, 835:92 (7pp), 2017 January 20

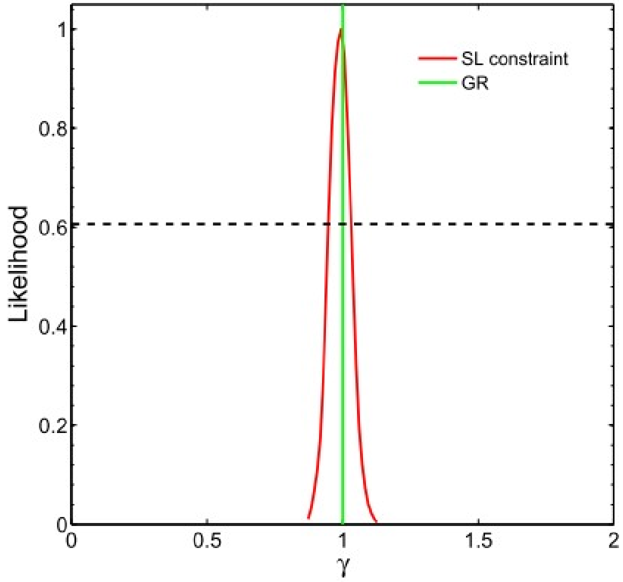


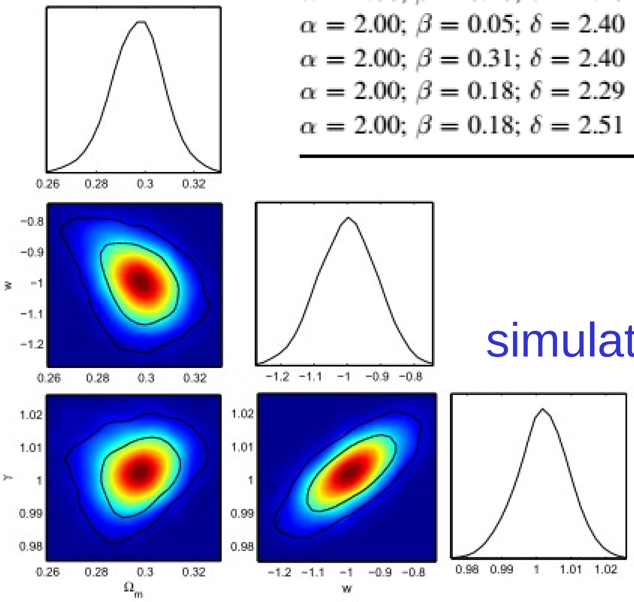
Figure 3. Normalized posterior likelihood of the PPN γ parameter obtained with rigid priors on the nuisance parameters (α, β, δ).

$$\gamma = 0.995^{+0.037}_{-0.047}$$

How much space curvature g_{ij} is produced by unit rest mass ?

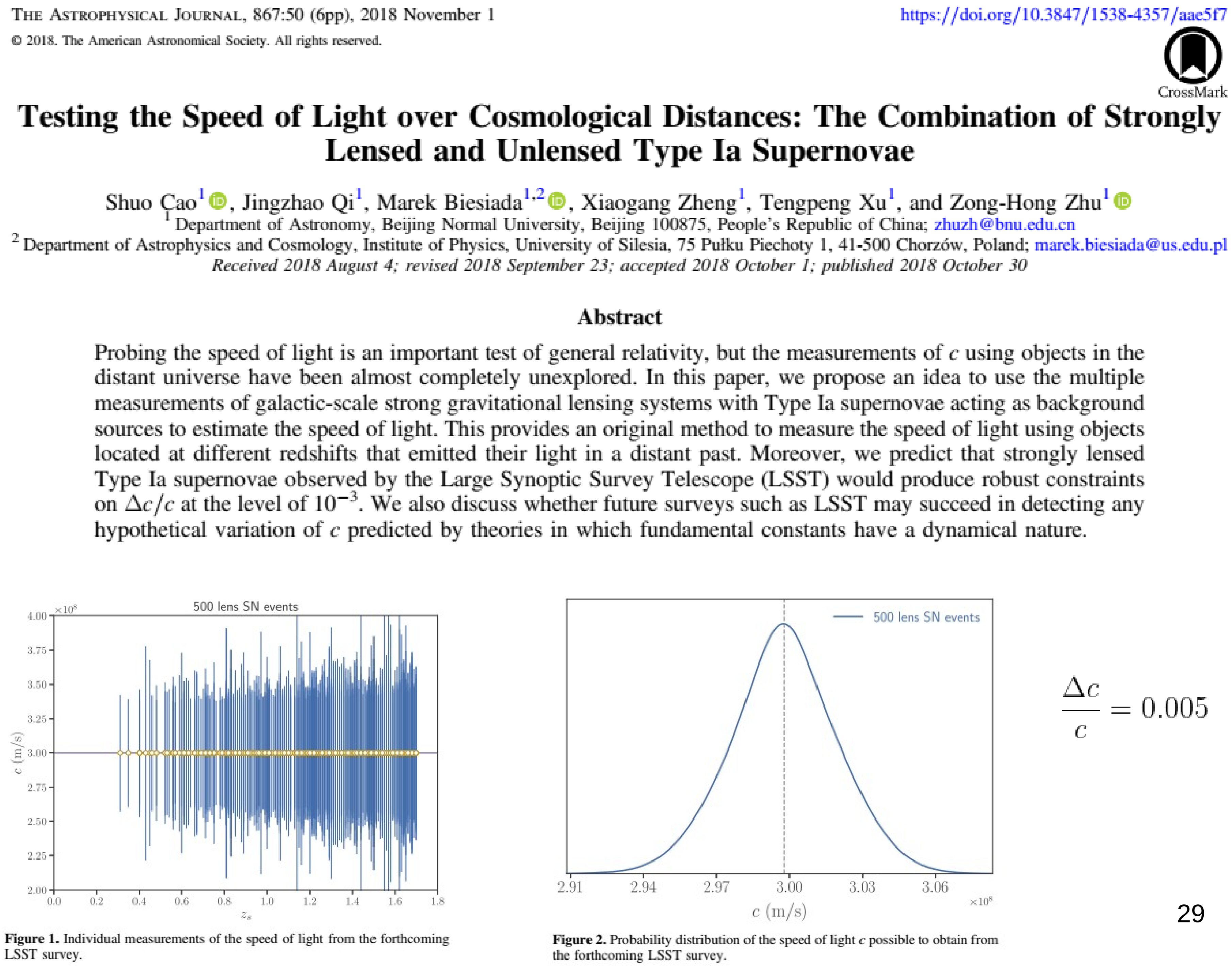
Table 1
Sensitivity of Constraints on γ with Respect to the Galaxy Structure Parameters

Systematics	PPN Parameter
$\alpha = 2.00$; $\beta = 0.18$; $\delta = 2.40$	$\gamma = 0.995^{+0.037}_{-0.047}$
$\alpha = 1.92$; $\beta = 0.18$; $\delta = 2.40$	$\gamma = 0.860 \pm 0.040$
$\alpha = 2.08$; $\beta = 0.18$; $\delta = 2.40$	$\gamma = 1.169 \pm 0.050$
$\alpha = 2.00$; $\beta = 0.05$; $\delta = 2.40$	$\gamma = 0.914 \pm 0.043$
$\alpha = 2.00$; $\beta = 0.31$; $\delta = 2.40$	$\gamma = 1.087 \pm 0.043$
$\alpha = 2.00$; $\beta = 0.18$; $\delta = 2.29$	$\gamma = 1.111 \pm 0.044$
$\alpha = 2.00$; $\beta = 0.18$; $\delta = 2.51$	$\gamma = 0.883 \pm 0.039$



simulated LSST data

Figure 7. Constraints on the PPN parameter and cosmological parameters from the simulated LSST strong lensing data.



The Astrophysical Journal, 867:50 (6pp), 2018 November 1 https://doi.org/10.3847/1538-4357/aae5f7

Testing the Speed of Light over Cosmological Distances: The Combination of Strongly Lensed and Unlensed Type Ia Supernovae

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Abstract

Probing the speed of light is an important test of general relativity, but the measurements of c using objects in the distant universe have been almost completely unexplored. In this paper, we propose an idea to use the multiple measurements of galactic-scale strong gravitational lensing systems with Type Ia supernovae acting as background sources to estimate the speed of light. This provides an original method to measure the speed of light using objects located at different redshifts that emitted their light in a distant past. Moreover, we predict that strongly lensed Type Ia supernovae observed by the Large Synoptic Survey Telescope (LSST) would produce robust constraints on $\Delta c/c$ at the level of 10^{-3}. We also discuss whether future surveys such as LSST may succeed in detecting any hypothetical variation of c predicted by theories in which fundamental constants have a dynamical nature.

Figure 1. Individual measurements of the speed of light from the forthcoming LSST survey.

Figure 2. Probability distribution of the speed of light c possible to obtain from the forthcoming LSST survey.

$$\frac{\Delta c}{c} = 0.005$$

Możliwość wyznaczenia krzywizny Wszechświata z soczewkowanych SN Ia

PHYSICAL REVIEW D **100,** 023530 (2019)

Strongly gravitationally lensed type Ia supernovae: Direct test of the Friedman-Lemaître-Robertson-Walker metric

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(Received 13 October 2018; published 19 July 2019)

We present a new idea of testing the validity of the Friedman-Lemaître-Robertson-Walker (FLRW) metric, through the multiple measurements of galactic-scale strong gravitational lensing systems with type Ia supernovae in the role of sources. Each individual lensing system will provide a model-independent measurement of the spatial curvature parameter referring only to geometrical optics independently of the matter content of the Universe. This will create a valuable opportunity to test the FLRW metric directly. Our results show that with hundreds of strongly lensed SNe Ia observed by the Large Synoptic Survey Telescope, one would produce robust constraints on the spatial curvature with accuracy $\Delta\Omega_k = 0.04$ comparable to the *Planck* 2015 results.

$$\frac{d_{ls}}{d_s} = \sqrt{1+\Omega_k d_l^2} - \frac{d_l}{d_s}\sqrt{1+\Omega_k d_s^2}.$$

$$D_l = (1+z_l)D_{\Delta t}\frac{D^A_{ls}}{D^A_s}.$$

$$D_s = \frac{10^{(\mu_D+2.5\log\mu)/5-5}}{1+z_s}(Mpc).$$

PHYS. REV. D **100,** 023530 (2019)

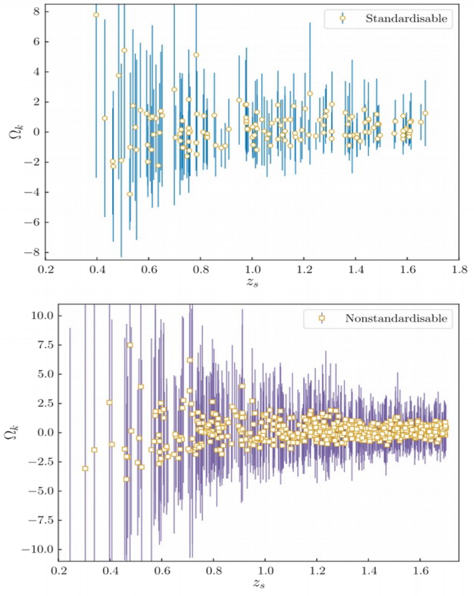
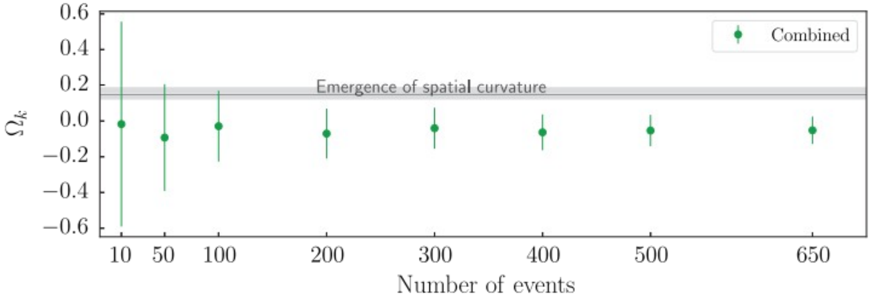


FIG. 1. An example of the simulated measurements of Ω_k from future observations of SGLSNe Ia: without and with the effect of microlensing. The blue lines denote the associated error bars (68.3% C.L.) of Ω_k when all the uncertainties are included.

$$\Omega_k(z_l,z_s) = \frac{d_l^4+d_s^4+d_{ls}^4-2d_l^2d_s^2-2d_l^2d_{ls}^2-2d_s^2d_{ls}^2}{4d_l^2d_s^2d_{ls}^2}$$



650 soczewkowanych SN Ia z LSST

FIG. 3. Inferred Ω_k parameter as a function of the number of SGLSNe Ia, with the prediction of a silent universe added for comparison.

Perspektywy:

- Silnie soczewkowane układy o zmierzonych dyspersjach prędkości w galaktykach soczewkujących stanowią nową klasę "standardowych linijek"
(promień Einstein wystandaryzowany przez kinematykę gwiazd)

- już dostarczyły pierwszych ocen parametrów kosmologicznych

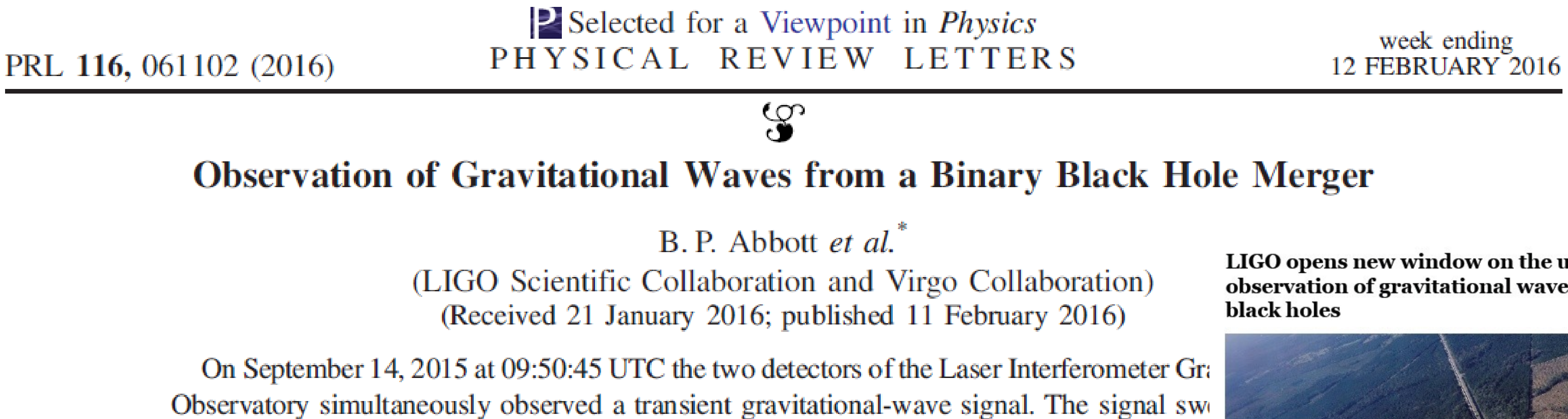
- atrakcyjne z punktu widzenia degeneracji pomiędzy współczynnikami w_0 i w_a w równaniu stanu „ciemnej energii”
- przy pomocy soczewek można wyznaczyć **krzywiznę przestrzeni** !

- z pewnością staną się techniką komplementarną do innych metod

- za pomocą soczewek będzie też można testować **„egzotyczną fizykę”**

Fale grawitacyjne zarejestrowane dokładnie 100 lat po powstaniu OTW

LIGO PRESS RELEASE



Selected for a Viewpoint in *Physics*

PRL **116,** 061102 (2016)

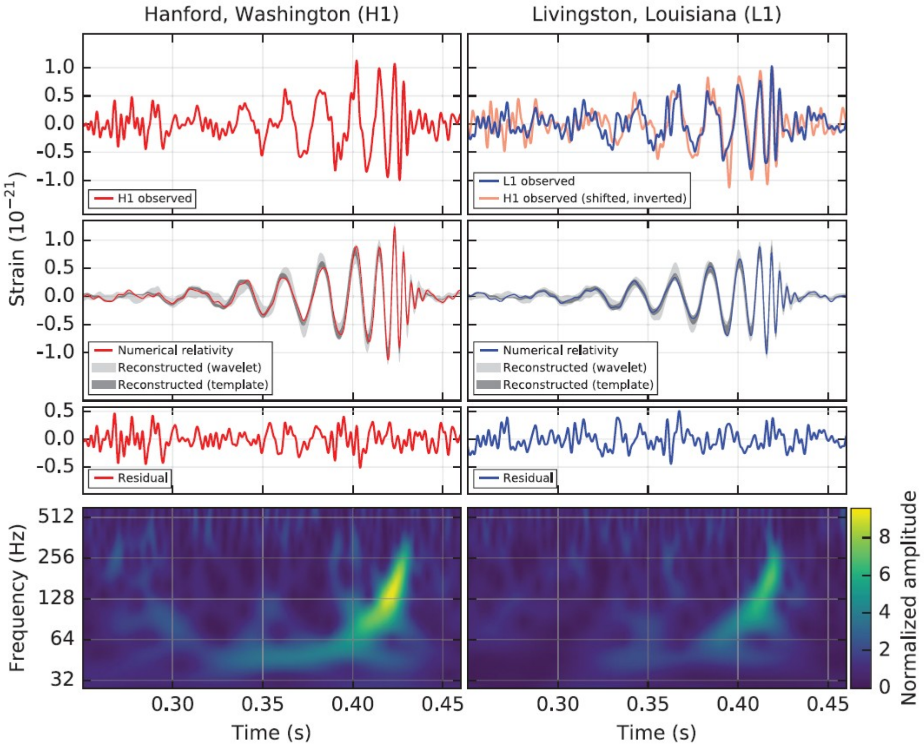
PHYSICAL REVIEW LETTERS

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 Gra
Observatory simultaneously observed a transient gravitational-wave signal. The signal sw
e strain of 1.0×10^{-21}. It match
of a pair of black holes and the
matched-filter signal-to-noise r

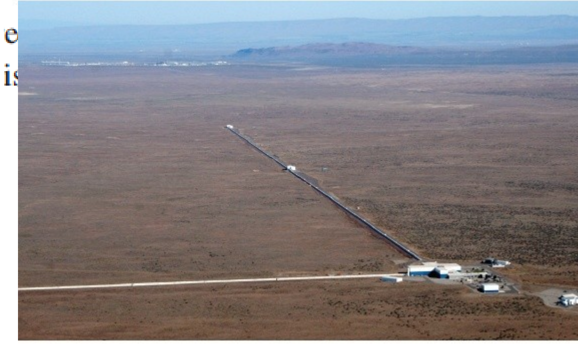


Zarejestrowano

dotychczas 11 sygnałów grawitacyjnych

GW150914
GW151012
GW151226
GW170104
GW170608
GW170814
GW170817
+

LIGO opens new window on the universe with observation of gravitational waves from colliding black holes



e
is

GW170729; GW170809
GW170818
GW170823

Electromagnetic emission

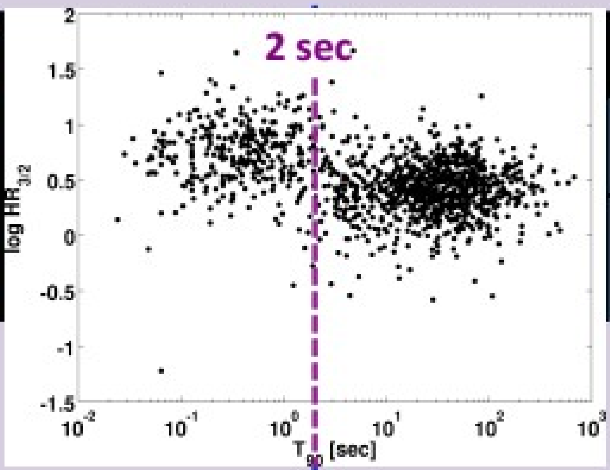
Merger of NS-NS / NS-BH

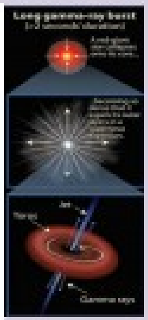
Core collapse of massive star

Gamma-Ray Burst

Short Hard GRB

Progenitor indications:
- lack of observed SN
- association with older stellar population
- larger distance from the host galaxy center (~ 5-10 kpc)





Long Soft GRB

Progenitor strong evidence: observed Type Ic SN spectrum

Kilonovae

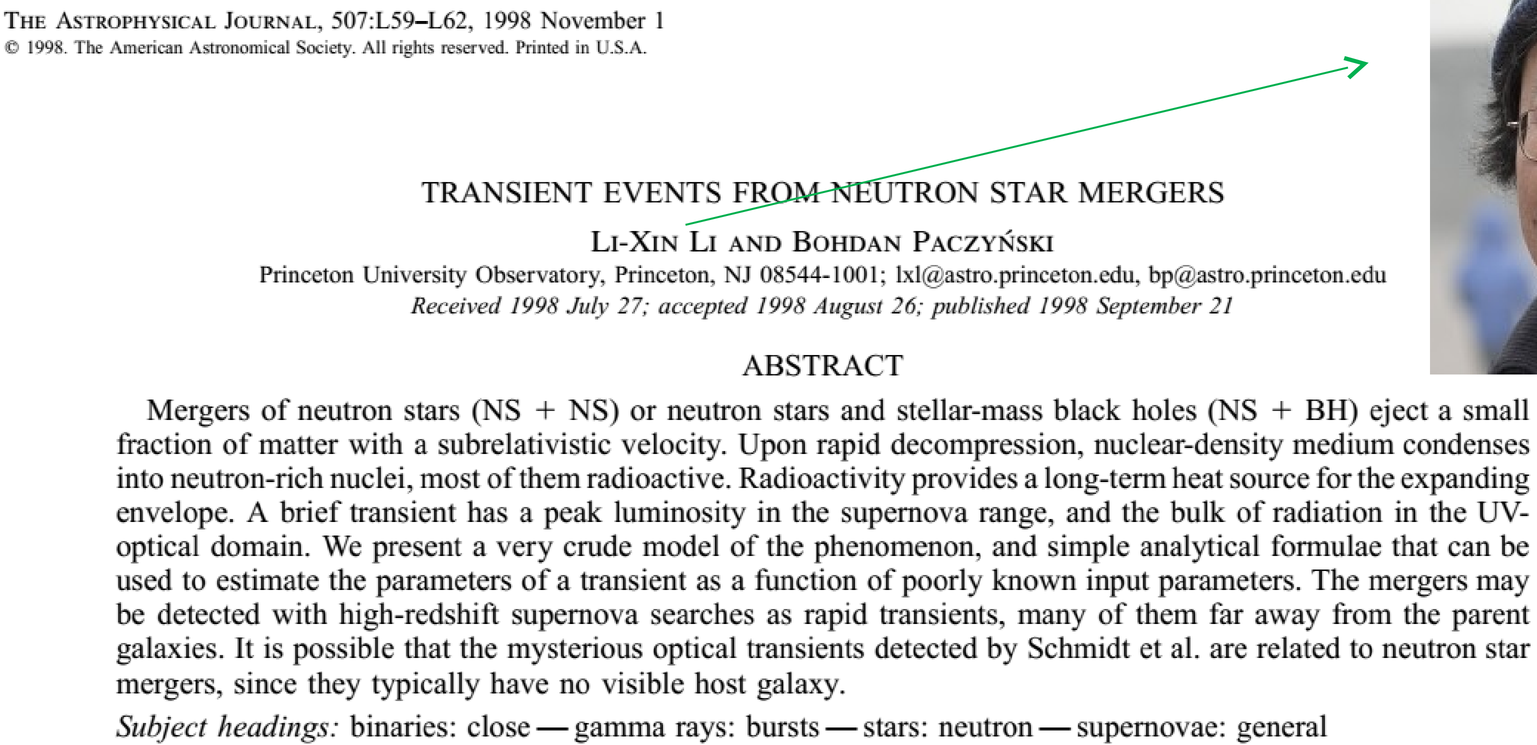
(Optical/IR, radio remnant)

Supernovae

Type II, Ib/c

Pierwszy model kilo-nowej (koalescencji dwóch gwiazd neutronowych)

ważny dla zrozumienia kosmicznej nukleosyntezy …



THE ASTROPHYSICAL JOURNAL, 507:L59–L62, 1998 November 1

TRANSIENT EVENTS FROM NEUTRON STAR MERGERS

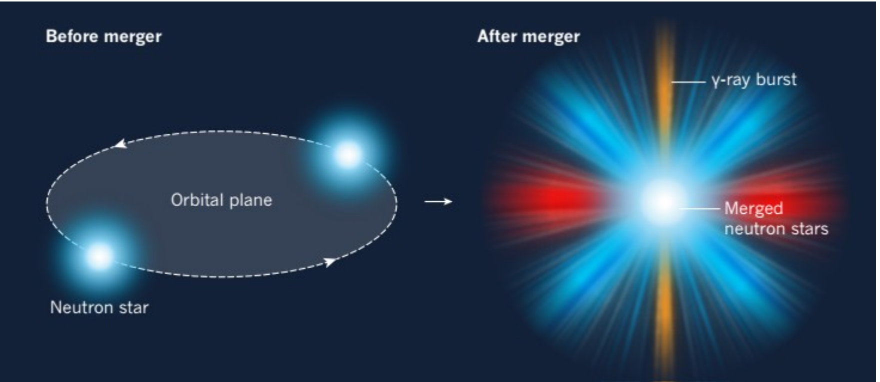
LI-XIN LI AND BOHDAN PACZYŃSKI
Princeton University Observatory, Princeton, NJ 08544-1001; lxl@astro.princeton.edu, bp@astro.princeton.edu

Received 1998 July 27; accepted 1998 August 26; published 1998 September 21

ABSTRACT

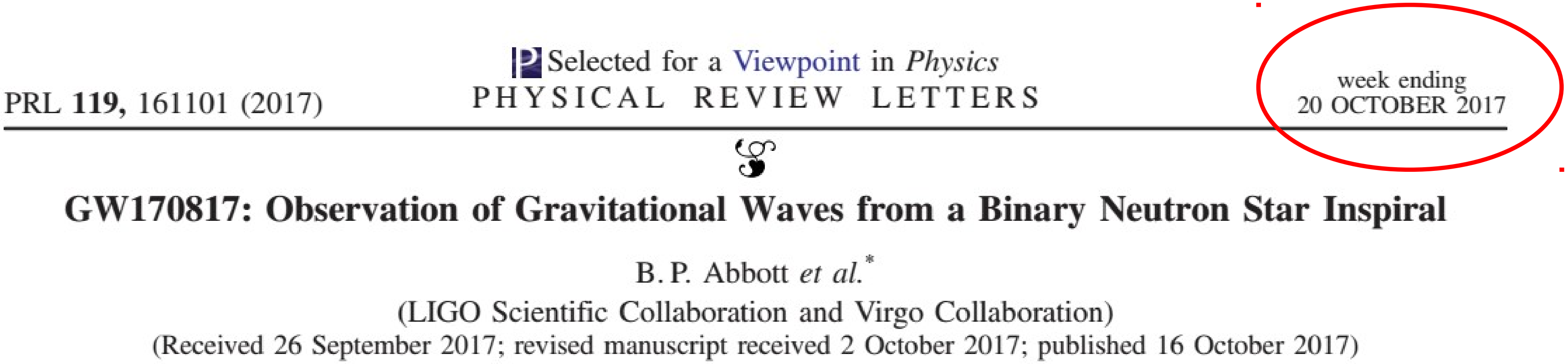
Mergers of neutron stars (NS + NS) or neutron stars and stellar-mass black holes (NS + BH) eject a small fraction of matter with a subrelativistic velocity. Upon rapid decompression, nuclear-density medium condenses into neutron-rich nuclei, most of them radioactive. Radioactivity provides a long-term heat source for the expanding envelope. A brief transient has a peak luminosity in the supernova range, and the bulk of radiation in the UV-optical domain. We present a very crude model of the phenomenon, and simple analytical formulae that can be used to estimate the parameters of a transient as a function of poorly known input parameters. The mergers may be detected with high-redshift supernova searches as rapid transients, many of them far away from the parent galaxies. It is possible that the mysterious optical transients detected by Schmidt et al. are related to neutron star mergers, since they typically have no visible host galaxy.

Subject headings: binaries: close — gamma rays: bursts — stars: neutron — supernovae: general



Lixin Li
Obecnie prof. w Peking U.
Kavli Institute of Astronomy
and Astrophysics

GW 170817 – Nowa era astronomii wielu nośników informacji
(multimessenger astronomy)


Selected for a Viewpoint in *Physics*

PRL **119,** 161101 (2017) PHYSICAL REVIEW LETTERS week ending 20 OCTOBER 2017

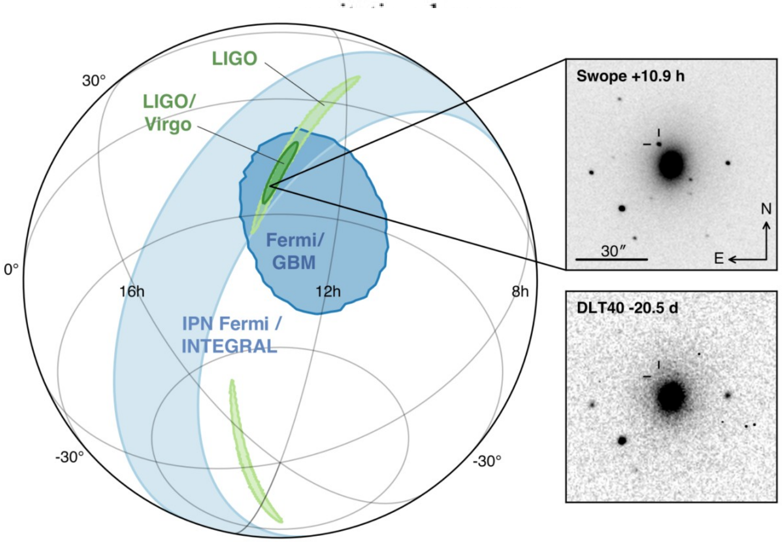
GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

B. P. Abbott *et al.**

(LIGO Scientific Collaboration and Virgo Collaboration)

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

17 sierpnia 2017 o godz. 12:41:04 UTC detektory LIGO/Virgo zarejestrowały pierwszy w historii sygnał grawitacyjny z koalescencji układu dwóch gwiazd neutronowych (NS-NS)

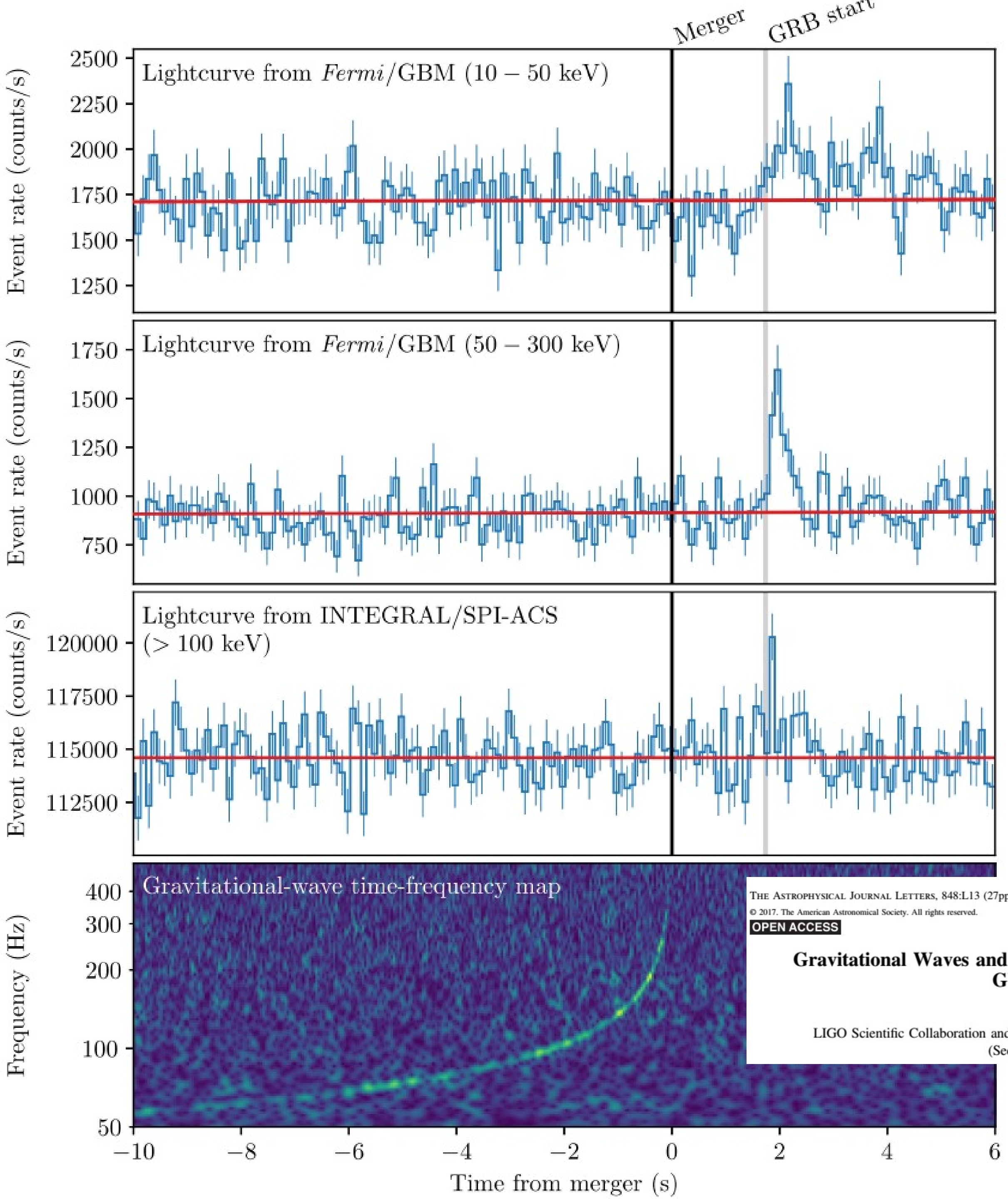


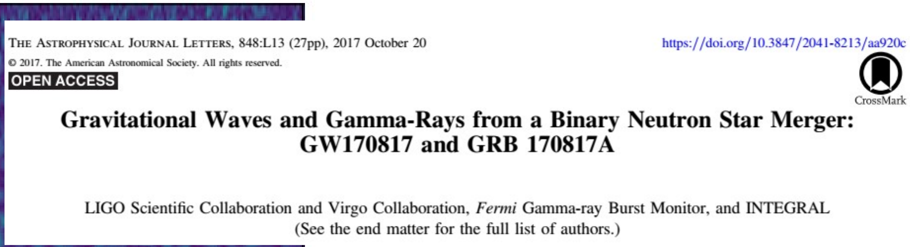
Odpowiadający temu zdarzeniu sygnał elektromagnetyczny został zarejestrowany

- w promieniach gamma 1.7 s po koalescencji (Fermi Gamma-ray Space Telescope NASA, INTERGAL, Agile)
- w promieniach rentgena (Swift, Magic, Integral)
- w świetle widzialnym
- w podczerwieni

- 5 artykułów w Nature
- dedykowany numer ApJ
- ponad 100 prac ukazało się 17.10.2017

Joint multi-messenger detection of GW170817 and GRB170817A




The Astrophysical Journal Letters, 848:L13 (27pp), 2017 October 20 https://doi.org/10.3847/2041-8213/aa920c

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OPEN ACCESS

Gravitational Waves and Gamma-Rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A

LIGO Scientific Collaboration and Virgo Collaboration, *Fermi* Gamma-ray Burst Monitor, and INTEGRAL
(See the end matter for the full list of authors.)

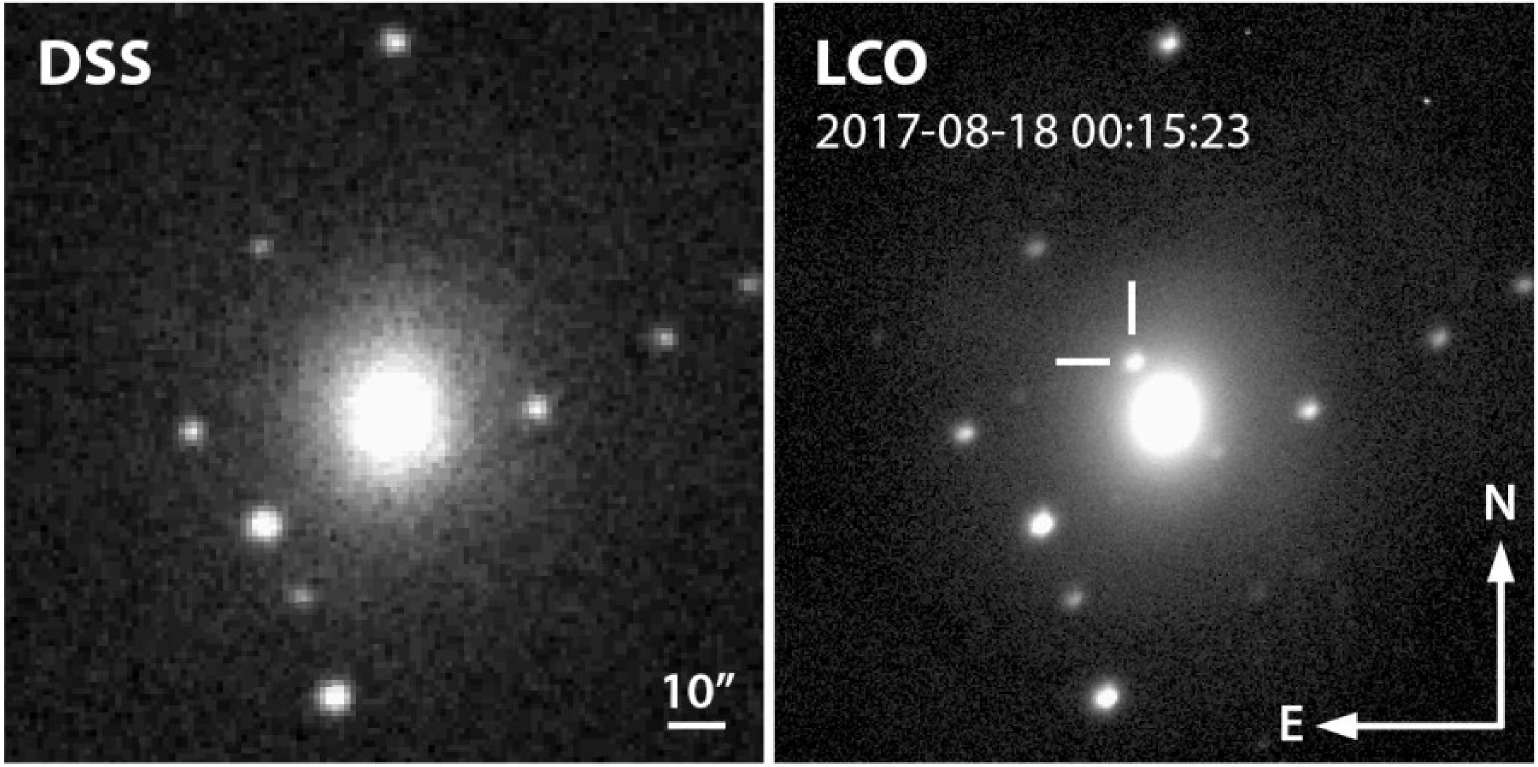
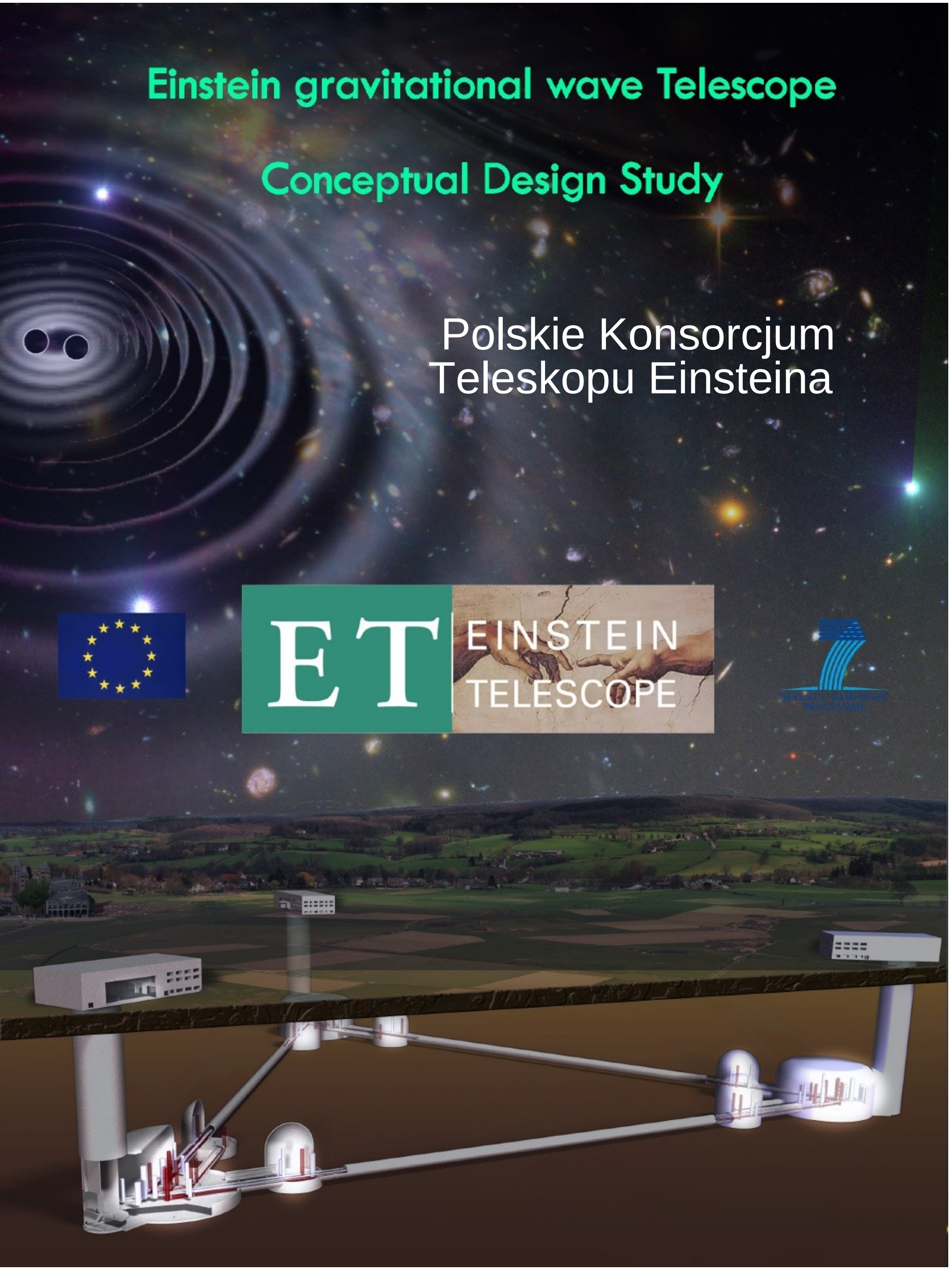


Figure 2 | LCO discovery image of the kilonova AT 2017gfo in the galaxy NGC 4993. The *w*-band LCO image (right), centered on NGC 4993, clearly shows a new source (marked with white ticks) compared to an archival image (left) taken on 1992 April 9 with the RG610 filter as part of the AAO-SES survey, retrieved via the Digitized Sky Survey (DSS).

LCO – Las Cumbres Observatory; CTIO – Cerro Tololo Inter-American Observatory



Polskie Konsorcjum
Teleskopu Einsteina

Co dalej?

Teleskop Einsteina

- Czułość przewyższająca LIGO II generacji

- Potężne katalogi zjawisk w skalach kosmologicznych

10^3 - 10^8 zjawisk rocznie !
Odległość do 2 Gpc (z=17)

- Duże nadzieje

- Obecnie w fazie badań lokalizacyjnych

Niektóre z tych sygnałów będą soczewkowane

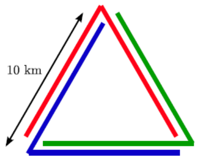
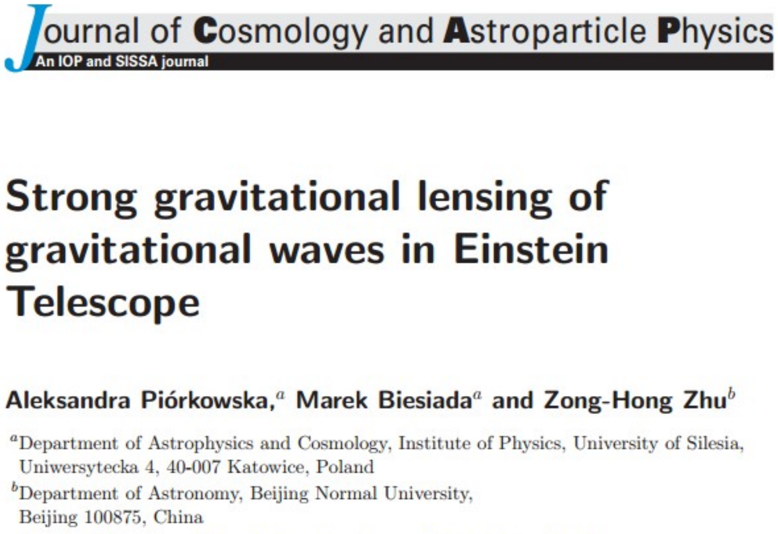


Figure 6: Three nested detectors in a triangular arrangement will form the final Einstein Telescope geometry.

Przewidywania częstości soczewkowanych sygnałów grawitacyjnych



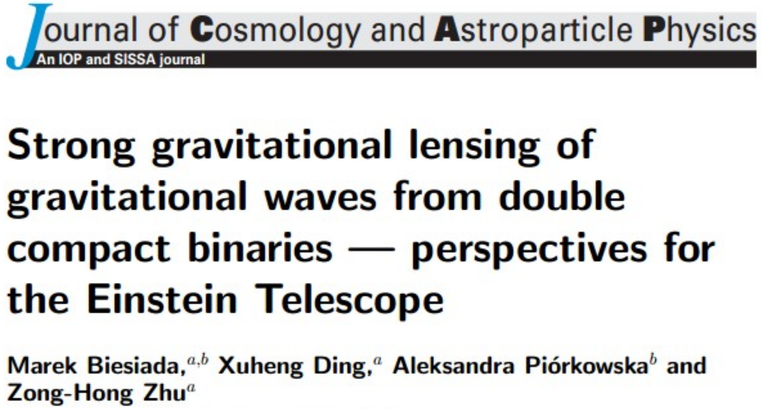
Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Strong gravitational lensing of gravitational waves in Einstein Telescope

Aleksandra Piórkowska,[a] **Marek Biesiada**[a] **and Zong-Hong Zhu**[b]

[a]Department of Astrophysics and Cosmology, Institute of Physics, University of Silesia,
Uniwersytecka 4, 40-007 Katowice, Poland
[b]Department of Astronomy, Beijing Normal University,
Beijing 100875, China

A. Piórkowska *et al.* JCAP10(2013)02

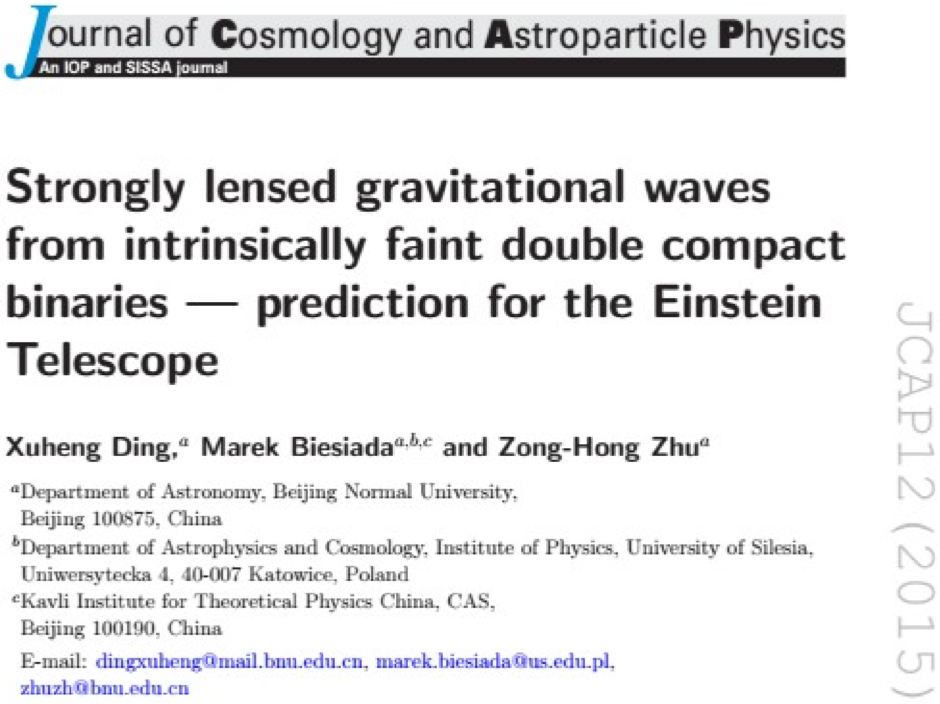


Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Strong gravitational lensing of gravitational waves from double compact binaries — perspectives for the Einstein Telescope

Marek Biesiada,[a,b] **Xuheng Ding,**[a] **Aleksandra Piórkowska**[b] **and Zong-Hong Zhu**[a]

M. Biesiada et al JCAP10(2014)080



Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Strongly lensed gravitational waves from intrinsically faint double compact binaries — prediction for the Einstein Telescope

Xuheng Ding,[a] **Marek Biesiada**[a,b,c] **and Zong-Hong Zhu**[a]

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JCAP12(2015)

X. Ding *et al.* JCAP12(2015)006

50 – 100 rocznie

ARTICLE

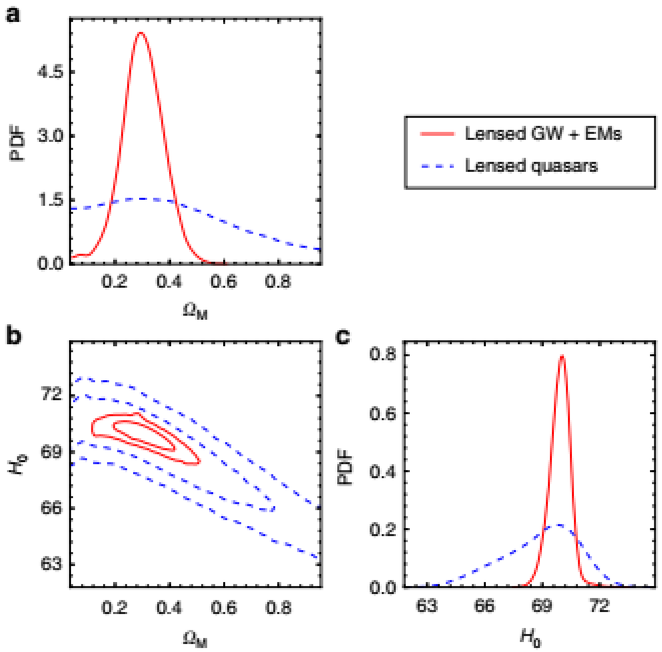
DOI: 10.1038/s41467-017-01152-9 OPEN

Precision cosmology from future lensed gravitational wave and electromagnetic signals

Kai Liao[1,2], Xi-Long Fan[3], Xuheng Ding[1,4,5], Marek Biesiada[4,6] & Zong-Hong Zhu[1,4]

Wielka precyzja pomiaru opóźnień czasowych między obrazami będzie przełomowa !

The standard siren approach of gravitational wave cosmology appeals to the direct luminosity distance estimation through the waveform signals from inspiralling double compact binaries, especially those with electromagnetic counterparts providing redshifts. It is limited by the calibration uncertainties in strain amplitude and relies on the fine details of the waveform. The Einstein telescope is expected to produce 10^4–10^5 gravitational wave detections per year, 50–100 of which will be lensed. Here, we report a waveform-independent strategy to achieve precise cosmography by combining the accurately measured time delays from strongly lensed gravitational wave signals with the images and redshifts observed in the electromagnetic domain. We demonstrate that just 10 such systems can provide a Hubble constant uncertainty of 0.68% for a flat lambda cold dark matter universe in the era of third-generation ground-based detectors.



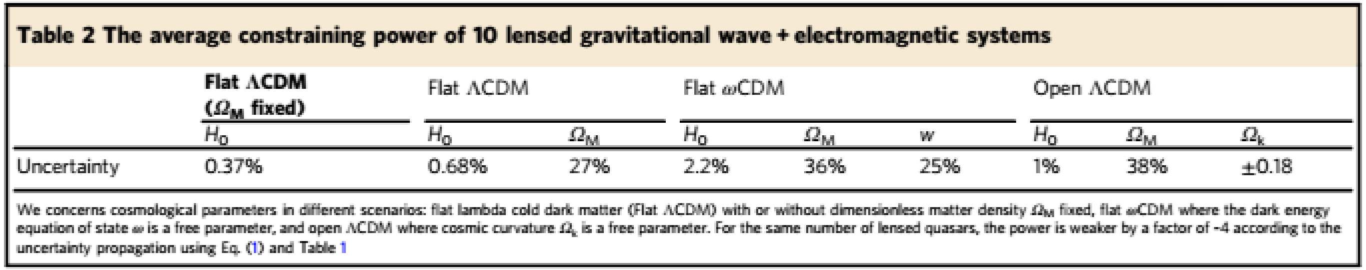
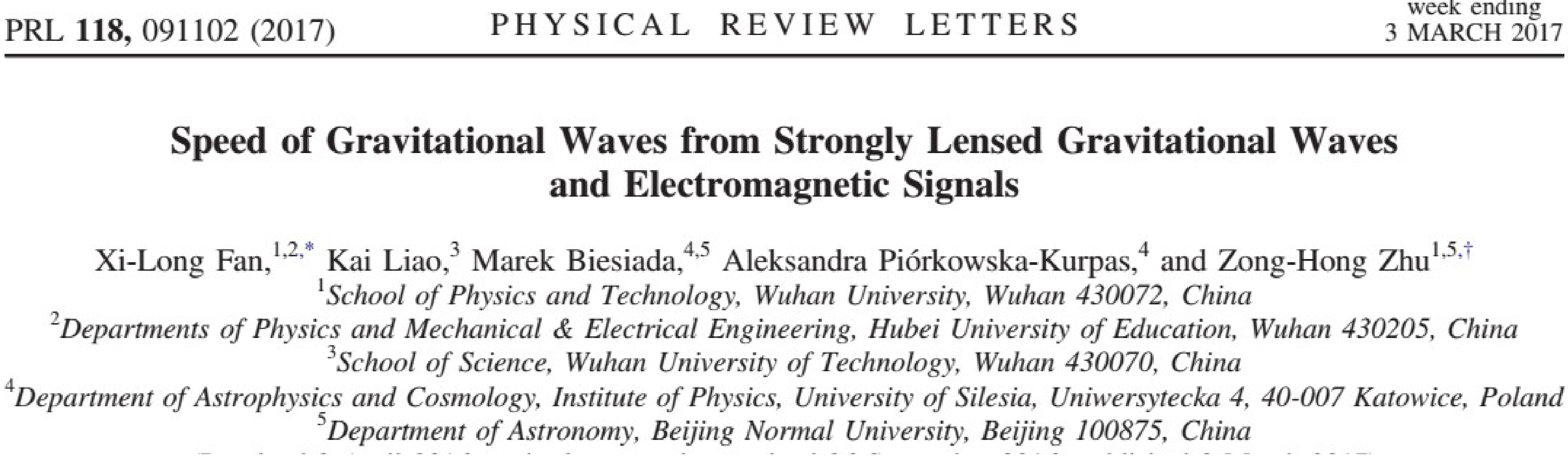


Table 2 The average constraining power of 10 lensed gravitational wave + electromagnetic systems

	Flat ΛCDM (Ω_M fixed)	Flat ΛCDM		Flat ωCDM			Open ΛCDM		
	H_0	H_0	Ω_M	H_0	Ω_M	w	H_0	Ω_M	Ω_k
Uncertainty	0.37%	0.68%	27%	2.2%	36%	25%	1%	38%	±0.18

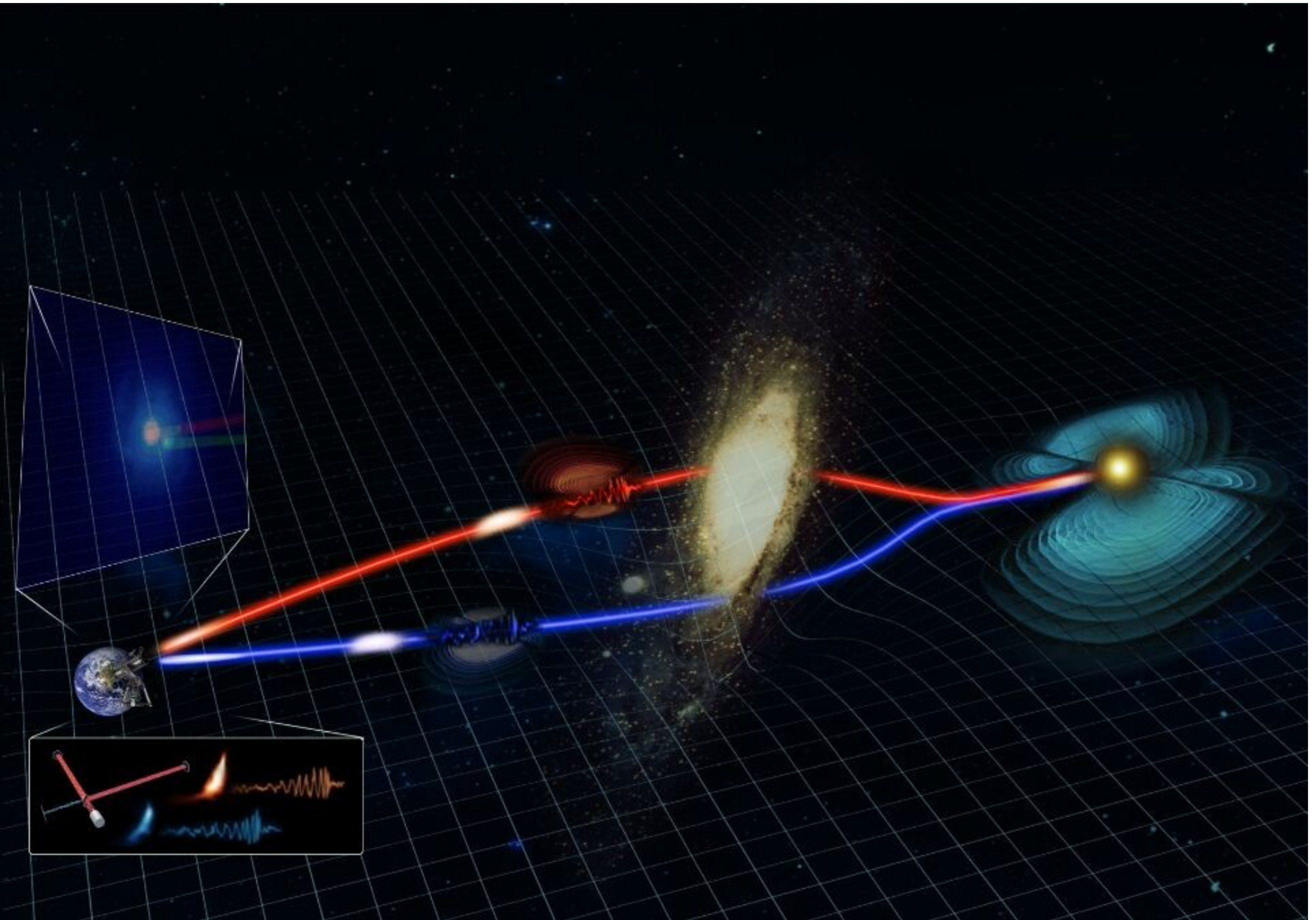
We concerns cosmological parameters in different scenarios: flat lambda cold dark matter (Flat ΛCDM) with or without dimensionless matter density Ω_M fixed, flat ωCDM where the dark energy equation of state ω is a free parameter, and open ΛCDM where cosmic curvature Ω_k is a free parameter. For the same number of lensed quasars, the power is weaker by a factor of ~4 according to the uncertainty propagation using Eq. (1) and Table 1



PRL **118,** 091102 (2017) PHYSICAL REVIEW LETTERS week ending 3 MARCH 2017

Speed of Gravitational Waves from Strongly Lensed Gravitational Waves and Electromagnetic Signals

Xi-Long Fan,[1,2,*] Kai Liao,[3] Marek Biesiada,[4,5] Aleksandra Piórkowska-Kurpas,[4] and Zong-Hong Zhu[1,5,†]
[1]*School of Physics and Technology, Wuhan University, Wuhan 430072, China*
[2]*Departments of Physics and Mechanical & Electrical Engineering, Hubei University of Education, Wuhan 430205, China*
[3]*School of Science, Wuhan University of Technology, Wuhan 430070, China*
[4]*Department of Astrophysics and Cosmology, Institute of Physics, University of Silesia, Uniwersytecka 4, 40-007 Katowice, Poland*
[5]*Department of Astronomy, Beijing Normal University, Beijing 100875, China*



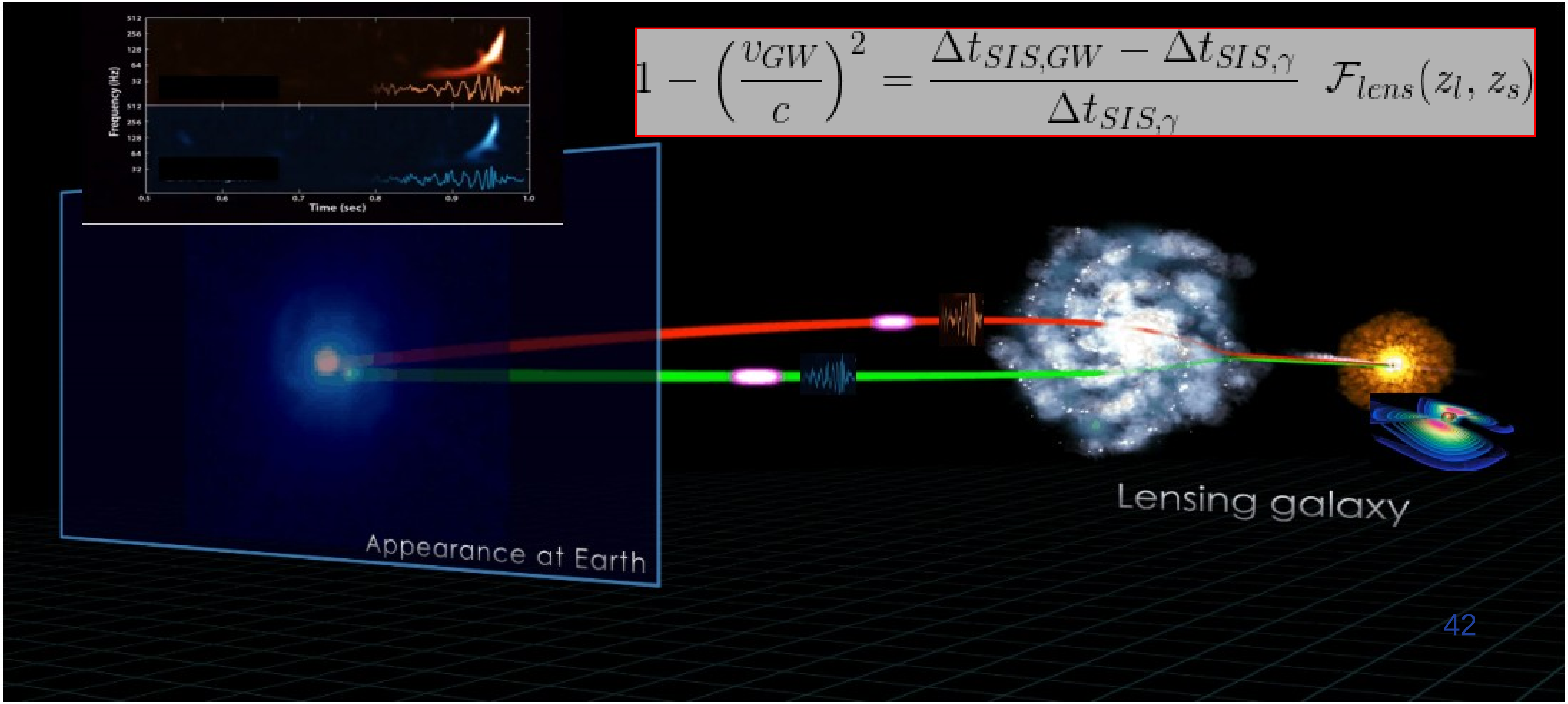
Różnice w opóźnieniach czasowych między soczewkowanym sygnałem EM i GW pozwolą testować prędkość propagacji fal grawitacyjnych

Idea

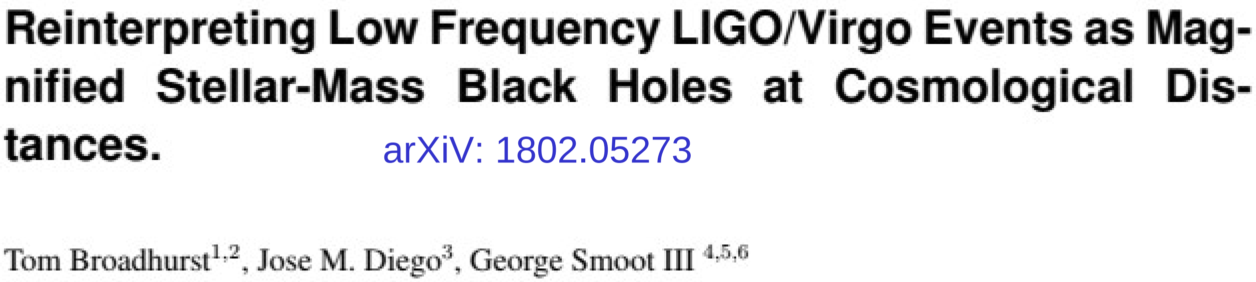
OTW - fale grawitacyjne (GW) rozchodzą się z prędkością światłą c, w zmodyfikowanych teoriach grawitacji mogą się propagować z inną prędkością v_{GW} (różną od c)

Opóźnienia czasowe Δt_{GW} między soczewkowanymi sygnałami grawitacyjnymi oraz odpowiednimi sygnałami świetlnymi (EM) Δt_{γ} będą różne

Metoda jest **wolna** od założeń odnośnie czasu emisji GW i EM ze źródła



$$1-\left(\frac{v_{GW}}{c}\right)^2 = \frac{\Delta t_{SIS,GW} - \Delta t_{SIS,\gamma}}{\Delta t_{SIS,\gamma}} \mathcal{F}_{lens}(z_l, z_s)$$



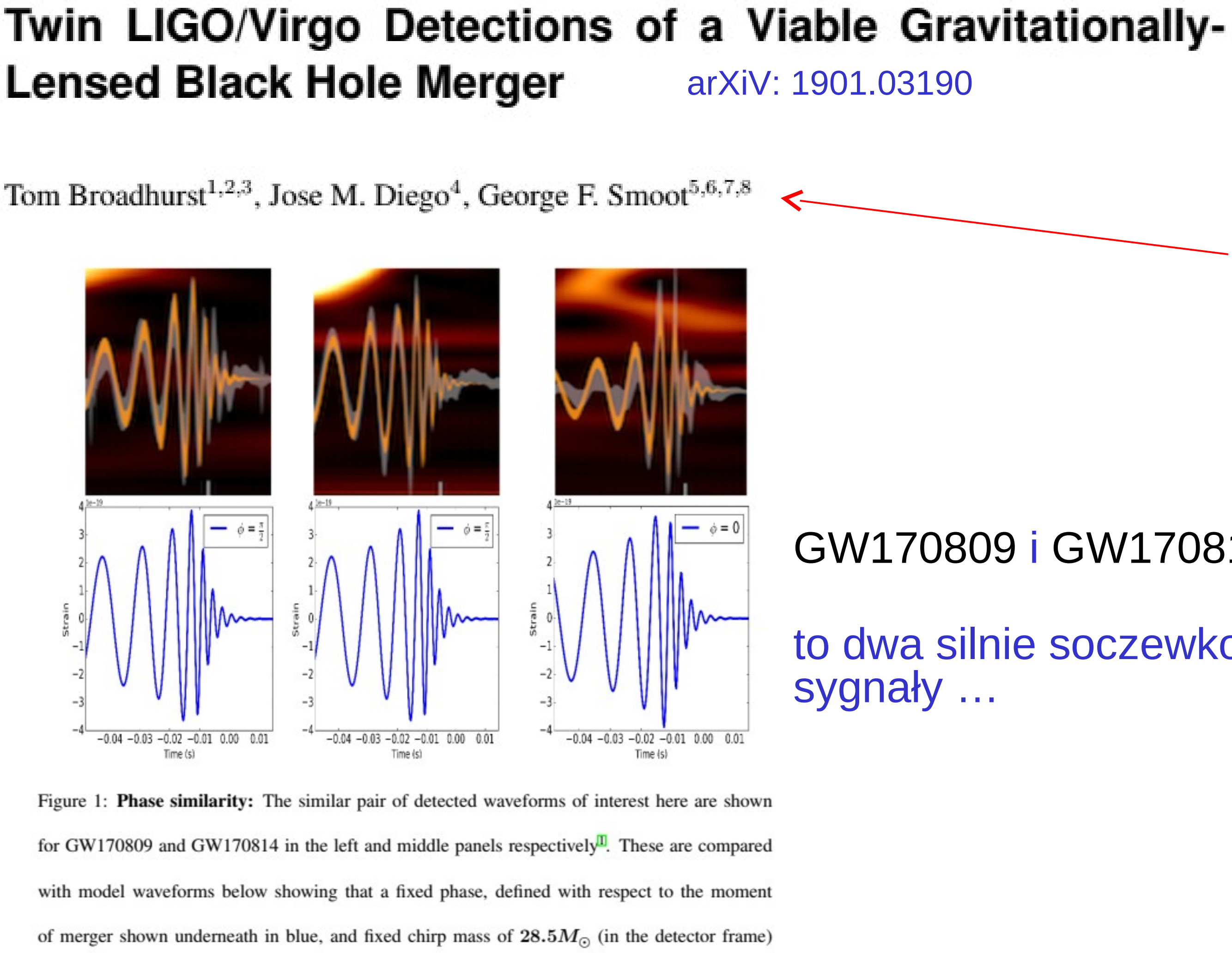
Reinterpreting Low Frequency LIGO/Virgo Events as Magnified Stellar-Mass Black Holes at Cosmological Distances.

arXiV: 1802.05273

Tom Broadhurst[1,2], Jose M. Diego[3], George Smoot III [4,5,6]

BH-BH zaobserwowane w LIGO miały duże masy, bo wszystkie były soczewkowane

Bardzo mało prawdopodobne … !



Twin LIGO/Virgo Detections of a Viable Gravitationally-Lensed Black Hole Merger

arXiV: 1901.03190

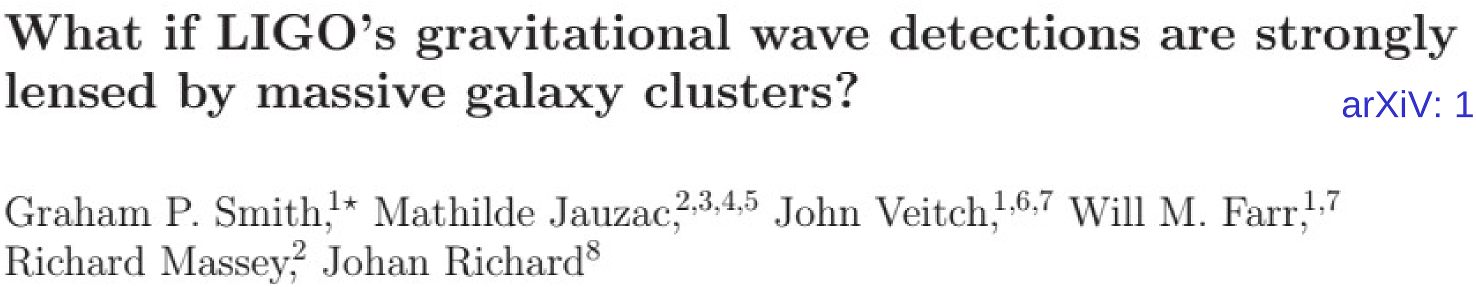
Tom Broadhurst[1,2,3], Jose M. Diego[4], George F. Smoot[5,6,7,8]

Figure 1: **Phase similarity:** The similar pair of detected waveforms of interest here are shown for GW170809 and GW170814 in the left and middle panels respectively[1]. These are compared with model waveforms below showing that a fixed phase, defined with respect to the moment of merger shown underneath in blue, and fixed chirp mass of $28.5M_\odot$ (in the detector frame)

Nagroda Nobla 2006

GW170809 i GW170814

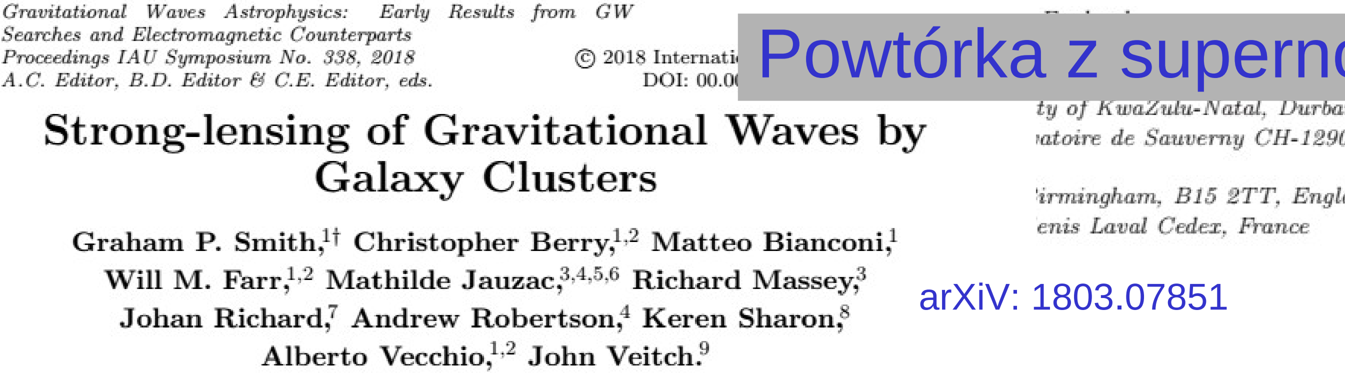
to dwa silnie soczewkowane sygnały …



What if LIGO's gravitational wave detections are strongly lensed by massive galaxy clusters?

arXiV: 1707.03412

Graham P. Smith,[1★] Mathilde Jauzac,[2,3,4,5] John Veitch,[1,6,7] Will M. Farr,[1,7]
Richard Massey,[2] Johan Richard[8]



Gravitational Waves Astrophysics: Early Results from GW
Searches and Electromagnetic Counterparts
Proceedings IAU Symposium No. 338, 2018
A.C. Editor, B.D. Editor & C.E. Editor, eds.

© 2018 Internati
DOI: 00.00

Powtórka z supernowej Refsdala ?

ty of KwaZulu-Natal, Durban 4041, South Africa
atoire de Sauverny CH-1290 Versoix, Switzerland
irmingham, B15 2TT, England
enis Laval Cedex, France

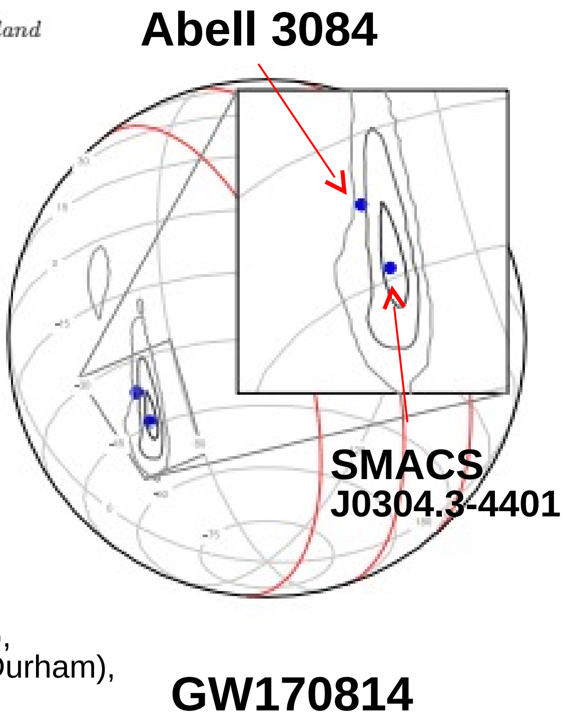
Strong-lensing of Gravitational Waves by Galaxy Clusters

Graham P. Smith,[1†] Christopher Berry,[1,2] Matteo Bianconi,[1]
Will M. Farr,[1,2] Mathilde Jauzac,[3,4,5,6] Richard Massey,[3]
Johan Richard,[7] Andrew Robertson,[4] Keren Sharon,[8]
Alberto Vecchio,[1,2] John Veitch.[9]

arXiV: 1803.07851

GCN: The Gamma-ray Coordinates Network (TAN: Transient Astronomy Network)

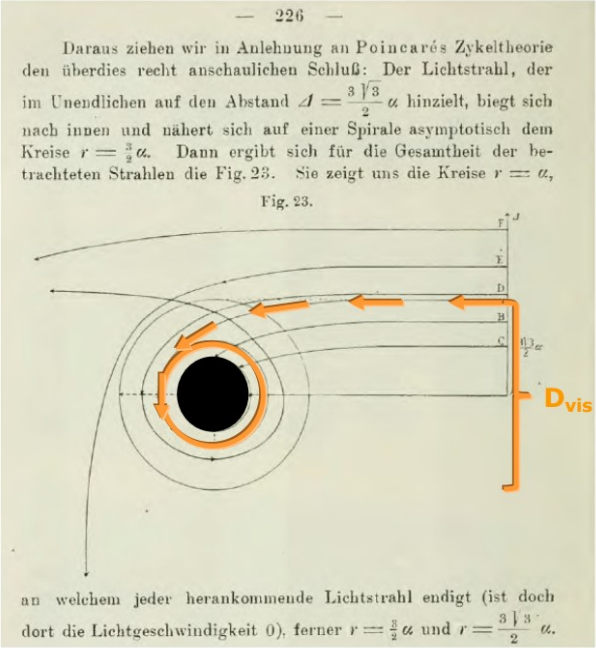
TITLE: GCN CIRCULAR NUMBER: 21692
SUBJECT: LIGO/Virgo G297595: Gemini and VLT observations by GLGW Hunters
DATE: 17/08/25 14:18:20 GMT
FROM: Graham P Smith at U of Birmingham <gps@star.sr.bham.ac.uk>
G. P. Smith (Birmingham), M. Jauzac (Durham), M. Bianconi (Birmingham), J. Richard (Lyon),
C. P. L. Berry (Birmingham), W. M. Farr (Birmingham), R. Massey (Durham), A. Robertson (Durham),
K. Sharon (Michigan), A. Vecchio (Birmingham), J. Veitch (Glasgow)



The **Gravitationally-lensed Gravitational Wave Hunters collaboration** report observations of strong-lensing galaxy clusters located within the sky localisation of the LIGO/Virgo trigger G297595 (LVC GCN Circ. 21474).

Ekstremalny przypadek soczewkowania grawitacyjnego

Obraz horyzontu czarnej dziury



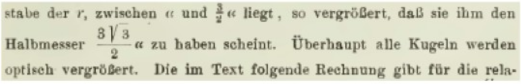
— 226 —

Daraus ziehen wir in Anlehnung an Poincarés Zykeltheorie den überdies recht anschaulichen Schluß: Der Lichtstrahl, der im Unendlichen auf den Abstand $\Delta = \frac{3\sqrt{3}}{2}\alpha$ hinzielt, biegt sich nach innen und nähert sich auf einer Spirale asymptotisch dem Kreise $r = \frac{3}{2}\alpha$. Dann ergibt sich für die Gesamtheit der betrachteten Strahlen die Fig. 23. Sie zeigt uns die Kreise $r = \alpha$,

Fig. 23.

an welchem jeder herankommende Lichtstrahl endigt (ist doch dort die Lichtgeschwindigkeit 0), ferner $r = \frac{3}{2}\alpha$ und $r = \frac{3\sqrt{3}}{2}\alpha$.

Max von Laue (1921):
“Die Relativitätstheorie. Zweiter Band”, Vieweg, 1921



stabe der r, zwischen α und $\frac{3}{2}\alpha$ liegt, so vergrößert, daß sie ihm den Halbmesser $\frac{3\sqrt{3}}{2}\alpha$ zu haben scheint. Überhaupt alle Kugeln werden optisch vergrößert. Die im Text folgende Rechnung gibt für die rela-

Based on **David Hilbert (1916)**: lectures, “Die Grundlagen der Physik”

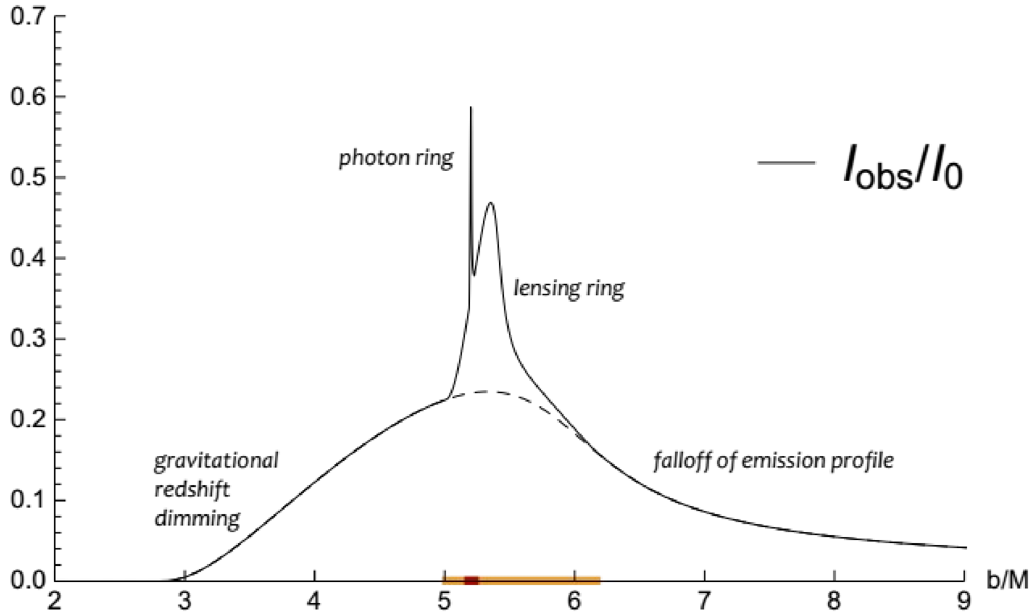
Black Hole “photon orbit”:

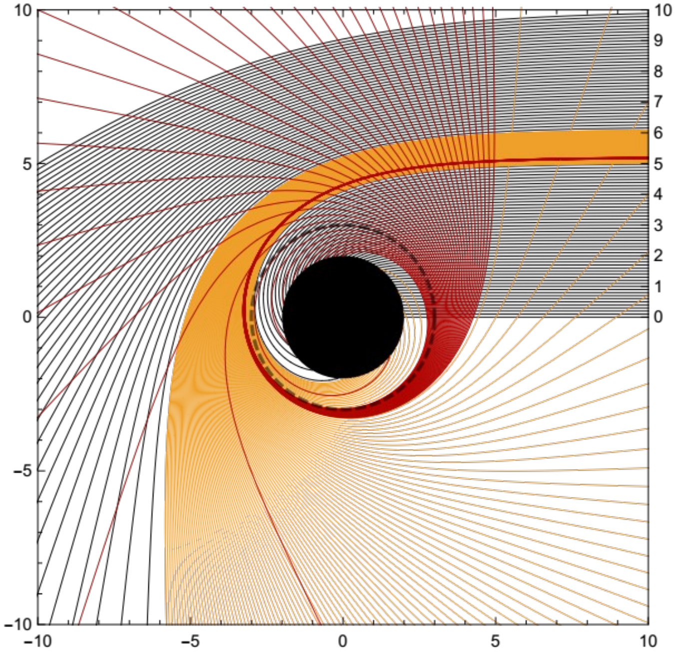
$$R_{ph} = \frac{3}{2} R_S$$

Black Hole “cross section”:

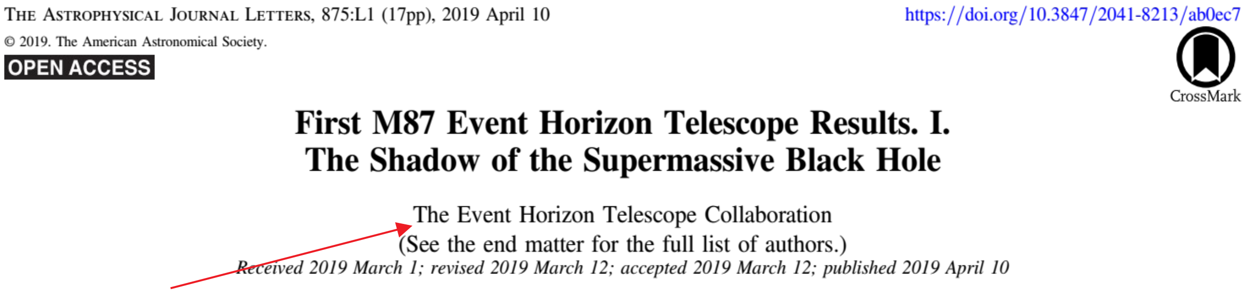
$$D = 3\sqrt{3} R_S \sim 5.2 R_S$$

Credit: Heino Falcke “Imagining black holes”





Credit: S.E. Gralla, D.E. Holz, R.W. Wald arXiv:1906.00873



The Astrophysical Journal Letters, 875:L1 (17pp), 2019 April 10 https://doi.org/10.3847/2041-8213/ab0ec7

First M87 Event Horizon Telescope Results. I. The Shadow of the Supermassive Black Hole

The Event Horizon Telescope Collaboration
(See the end matter for the full list of authors.)

Received 2019 March 1; revised 2019 March 12; accepted 2019 March 12; published 2019 April 10

Monika Mościbrodzka
Maciej Wielgus

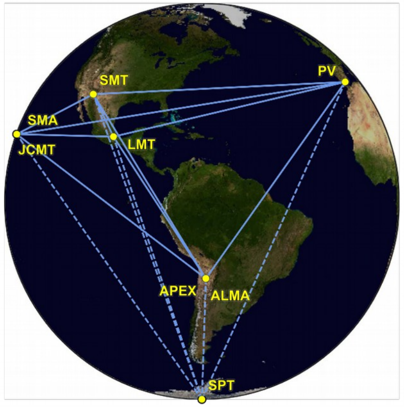


Figure 1. Eight stations of the EHT 2017 campaign over six geographic locations as viewed from the equatorial plane. Solid baselines represent mutual visibility on M87* (+12° declination). The dashed baselines were used for the calibration source 3C279 (see Papers III and IV).

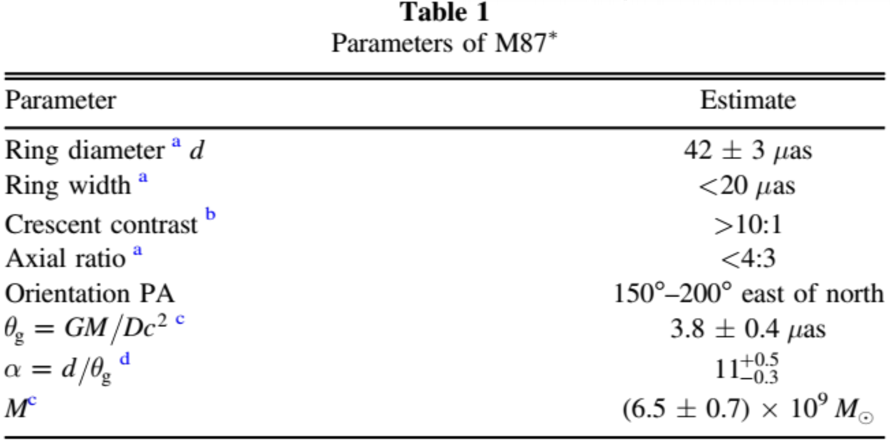
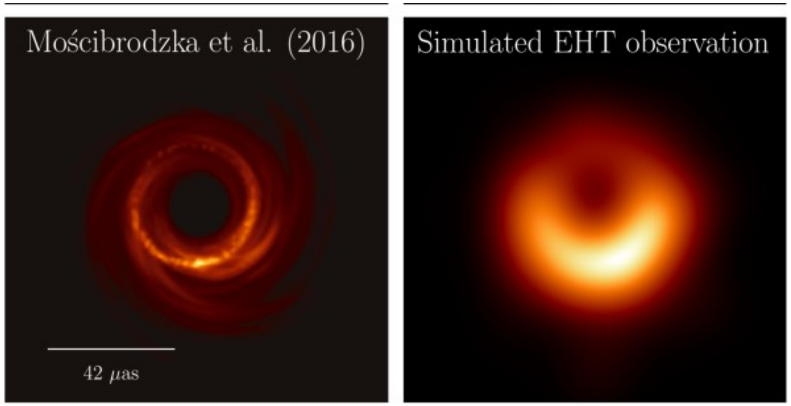
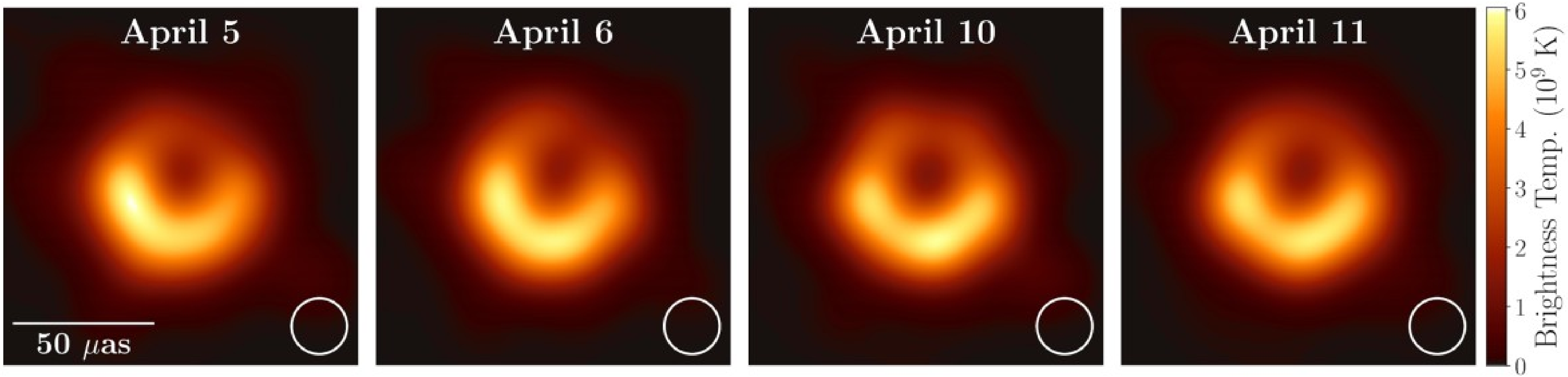


Table 1
Parameters of M87*

Parameter	Estimate
Ring diameter [a] d	42 ± 3 μas
Ring width [a]	<20 μas
Crescent contrast [b]	$>10:1$
Axial ratio [a]	$<4:3$
Orientation PA	150°–200° east of north
$\theta_g = GM/Dc^2$ [c]	3.8 ± 0.4 μas
$\alpha = d/\theta_g$ [d]	$11^{+0.5}_{-0.3}$
M[c]	$(6.5 \pm 0.7) \times 10^9\ M_\odot$





DZIĘKUJĘ ZA UWAGĘ !