Środowiskowe Seminarium Fizyki Jądrowej
Wydział Fizyki UW

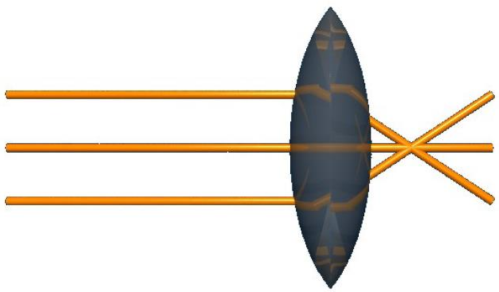
6 Maja 2021

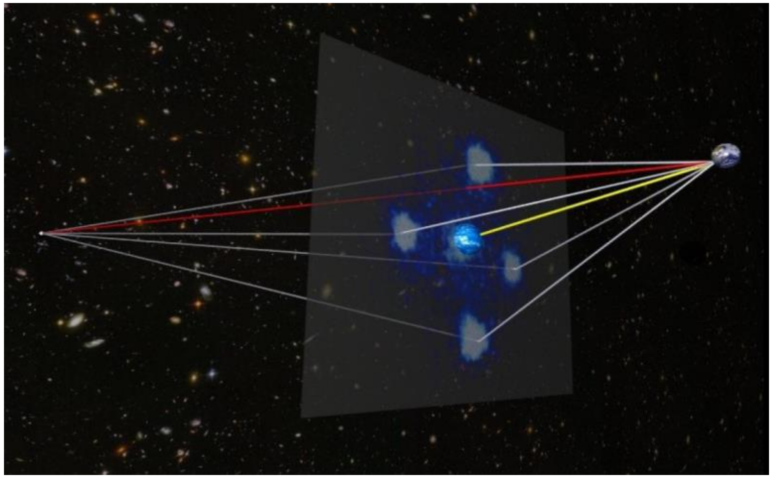
Nowe zastosowania soczewek grawitacyjnych

Marek Biesiada
Zakład Astrofizyki
Narodowe Centrum Badań Jądrowych
Warszawa

NATIONAL CENTRE
FOR NUCLEAR RESEARCH
ŚWIERK

Istota zjawiska

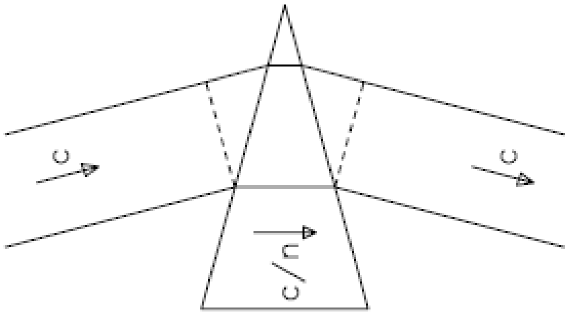


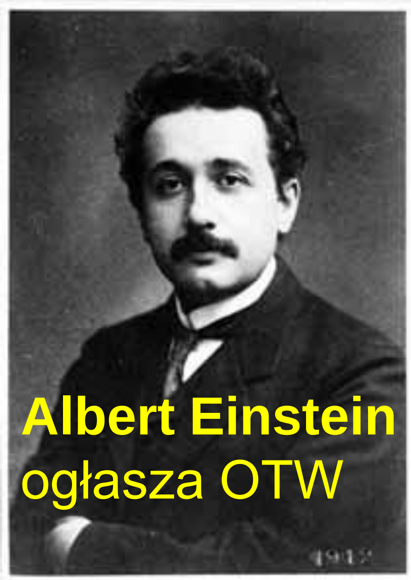


Zwykła Soczewka zakrzywia promienie światła dzięki różnicy we współczynniku załamania ośrodków

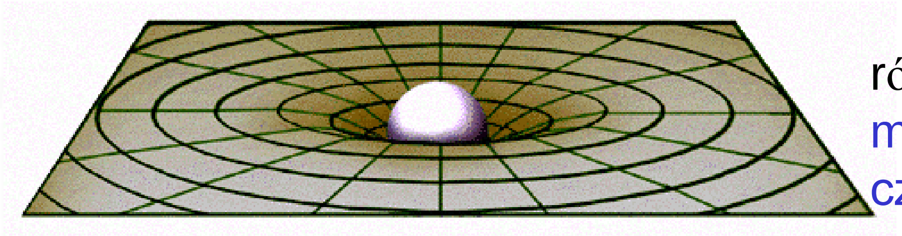
Soczewka grawitacyjna ?

Dlaczego ?!!!





Albert Einstein
ogłasza OTW



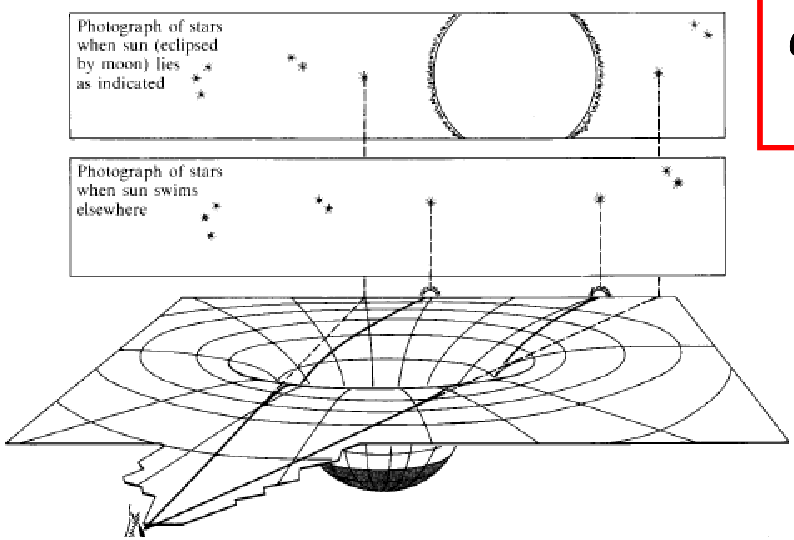
równania pola Einsteina – jak materia zakrzywia czasoprzestrzeń

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

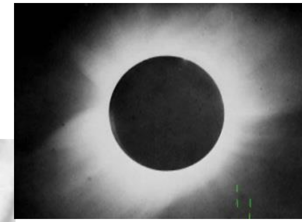
$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

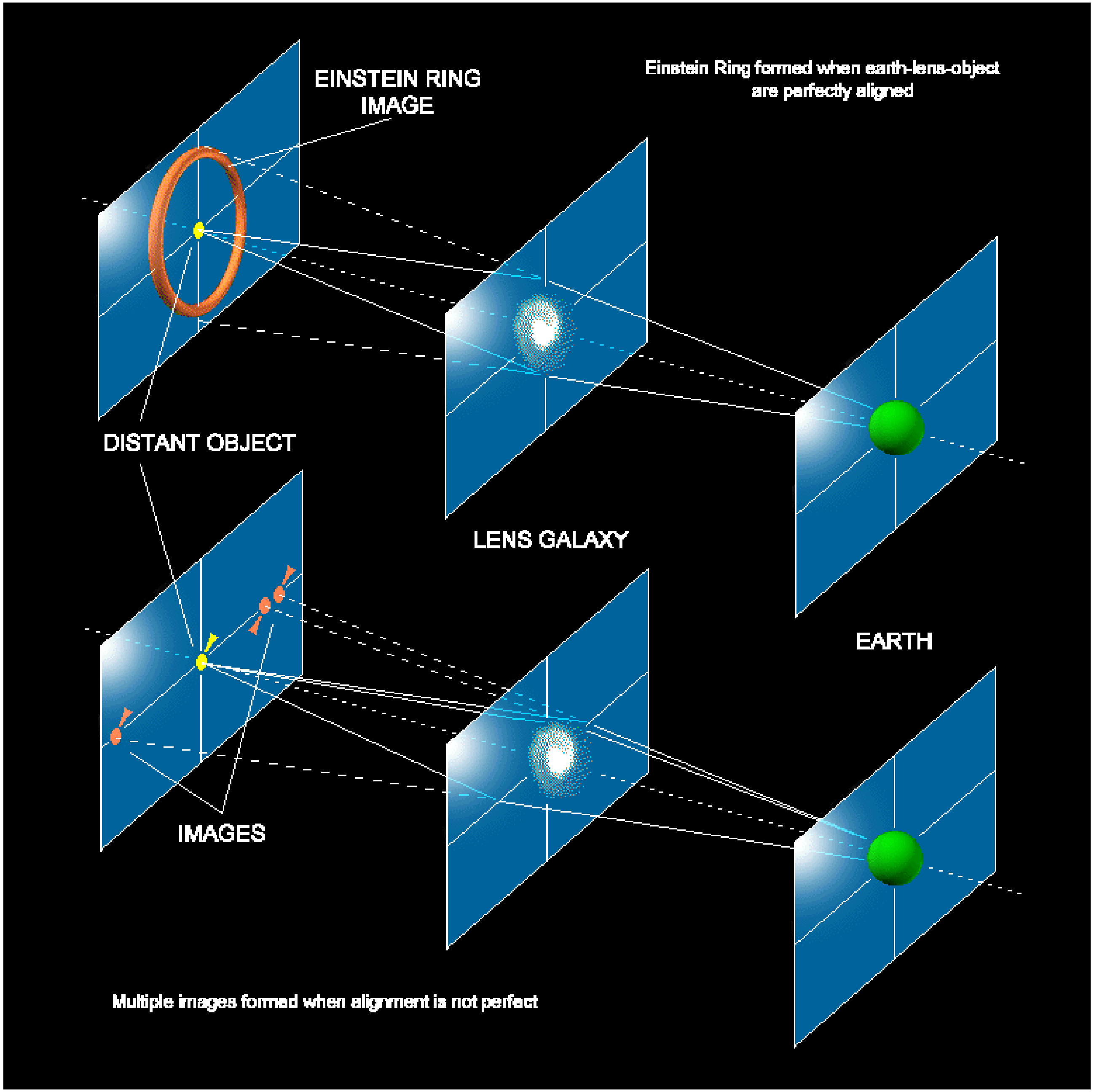
Ugięcie światła w pobliżu brzegu tarczy Słońca Zakrzywienie czasoprzestrzeni czują nie tylko ciała masywne, ale także światło !

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



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





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_0 przy odległościach wzajemnych typowych dla Galaktyki 5 – 10 kpc mają promienie Einsteina rzędu 0".001 – **nieobserwowalne !**

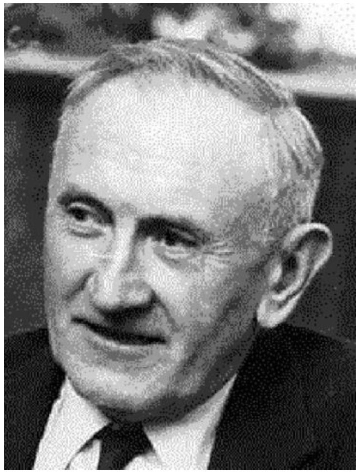
•Zwicky 1937 (!) galaktyki w roli soczewek

Galaktyki mają masy rzędu 10^{11} – 10^{12} M_0

ich wzajemne odległości to 10 Mpc – 1 Gpc

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

To już można zobaczyć !



Fritz Zwicky
1898 - 1974

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.

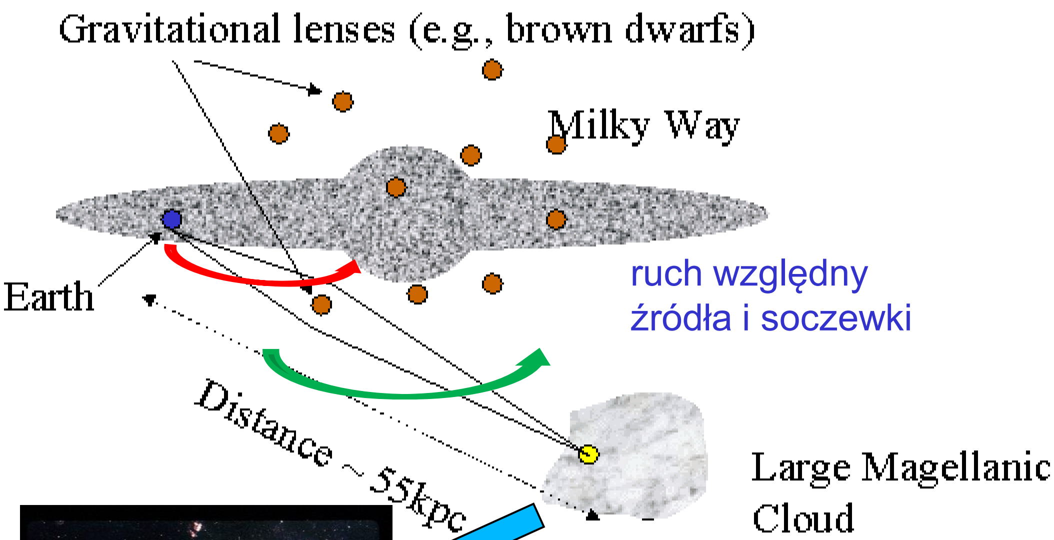
Bohdan Paczyński (1940 – 2007)

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”

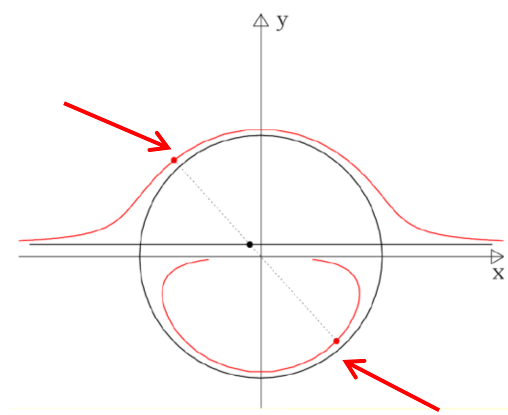
Gdy źródło przekracza pierścień Einsteina pojawiają się 2 obrazy

* 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



Bohdan Paczyński 1986

pomysł obserwacji mikrosoczewkowania

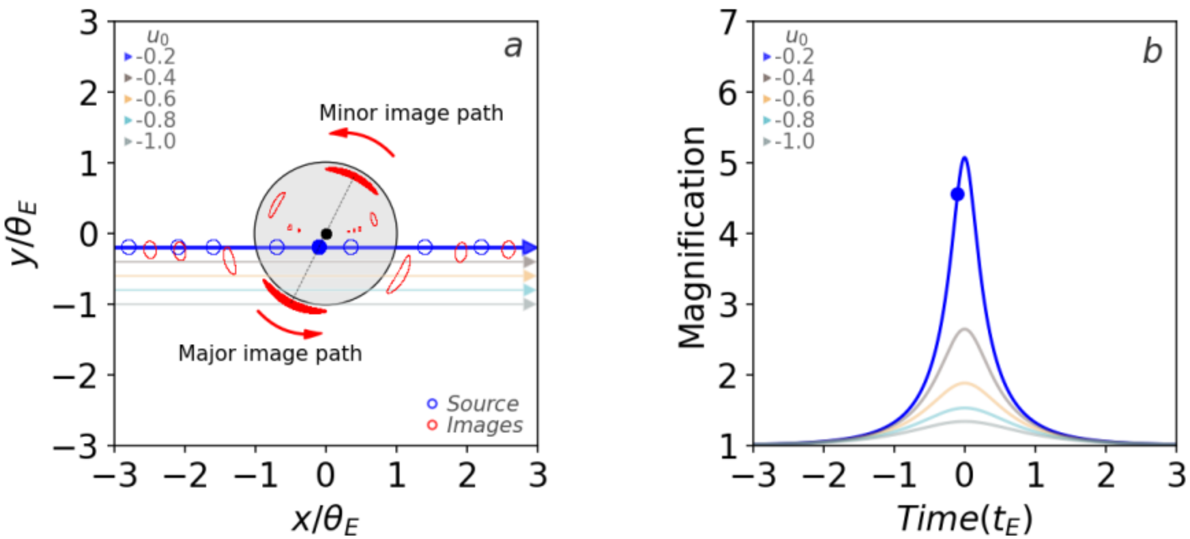


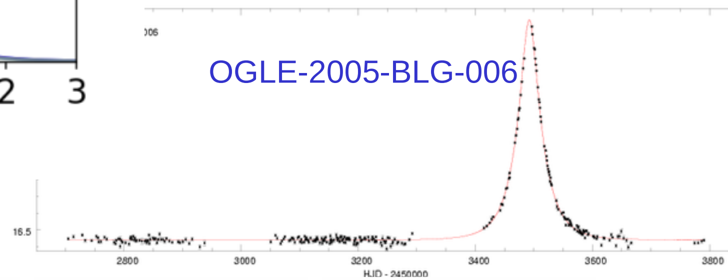
Eksperyment OGLE

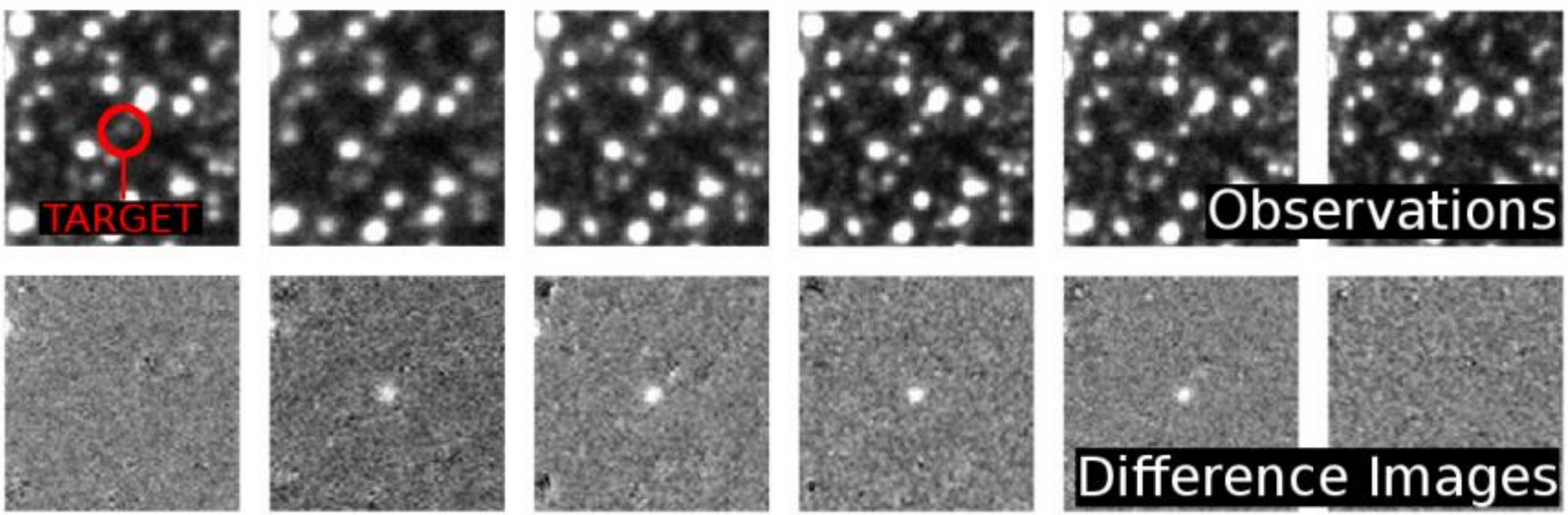
OA UW – prof. Andrzej Udalski

Krzywa blasku w zjawisku mikrosoczewkowania

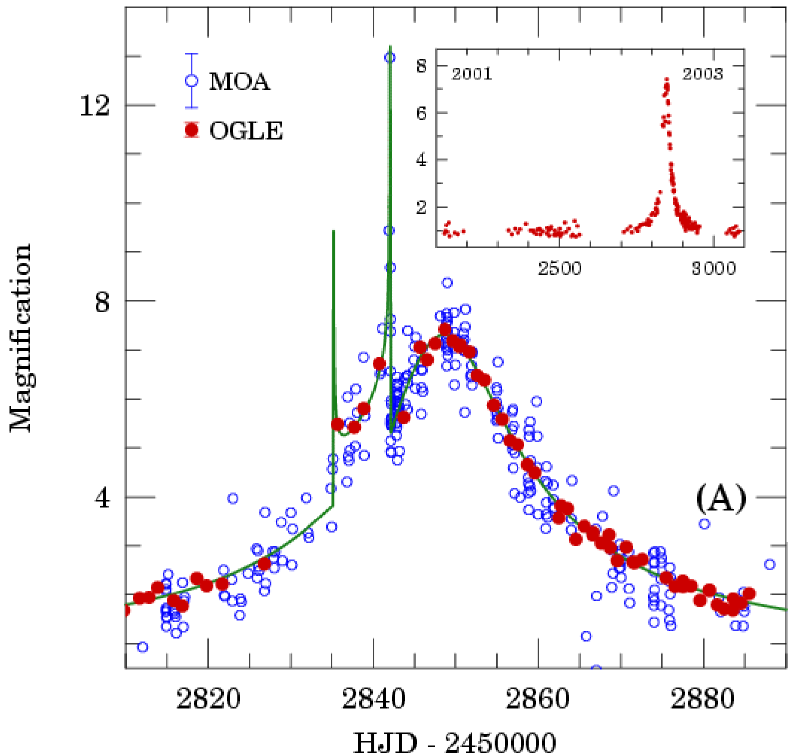
soczewkowana

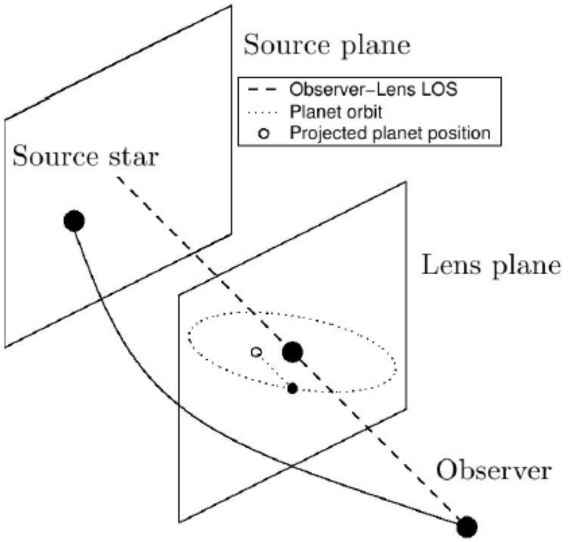




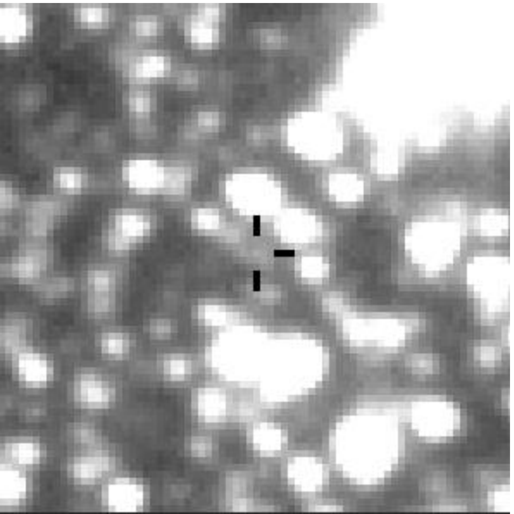


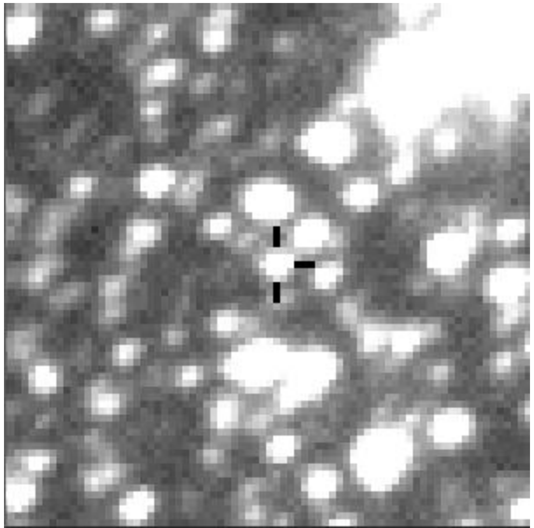
Poszukiwania planet pozasłonecznych – B.Paczyński, Shude Mao 1991



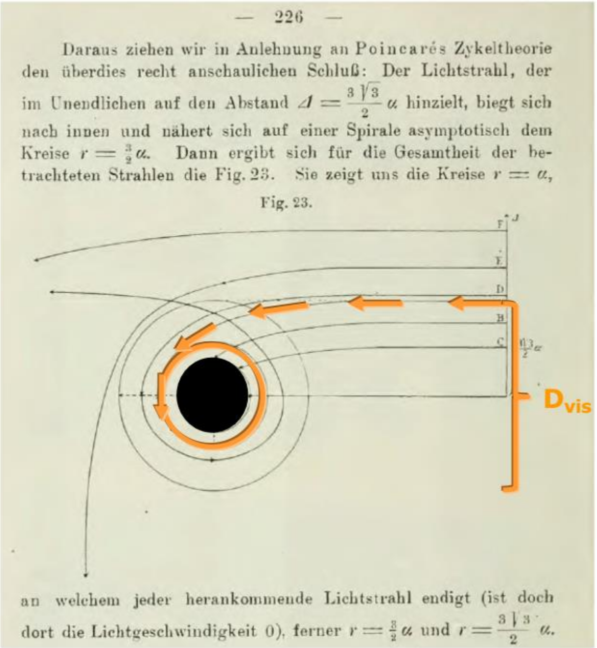


Obecnie prof. w Tshinghua U.
+ Manchester U. (Jodrell Bank)





tą techniką odkryto już
19 pozasłonecznych
układów planetarnych



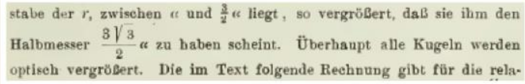
— 226 —

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":

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

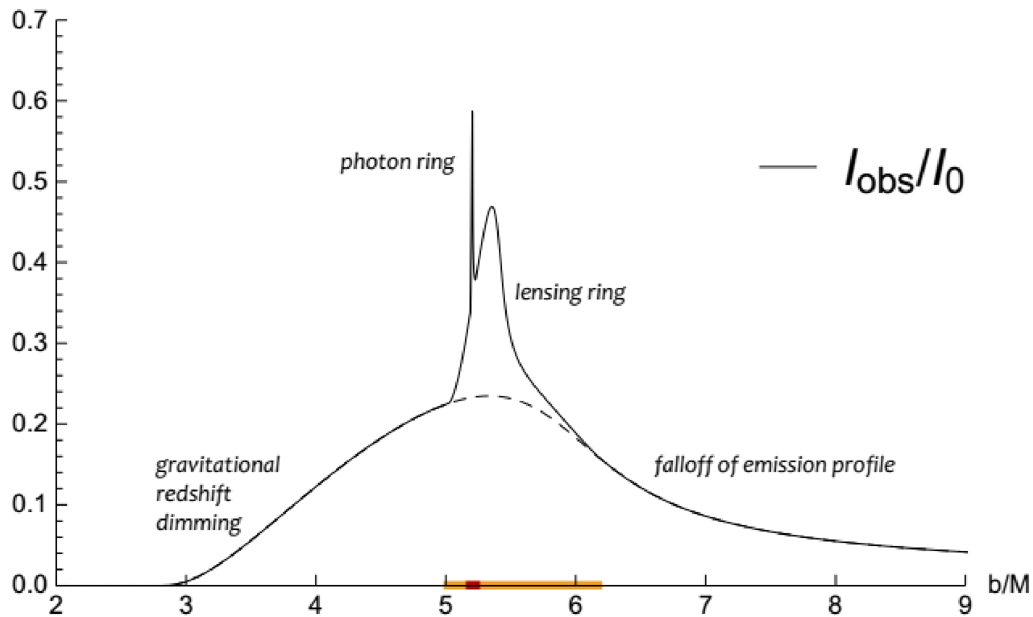
Black Hole "cross section":

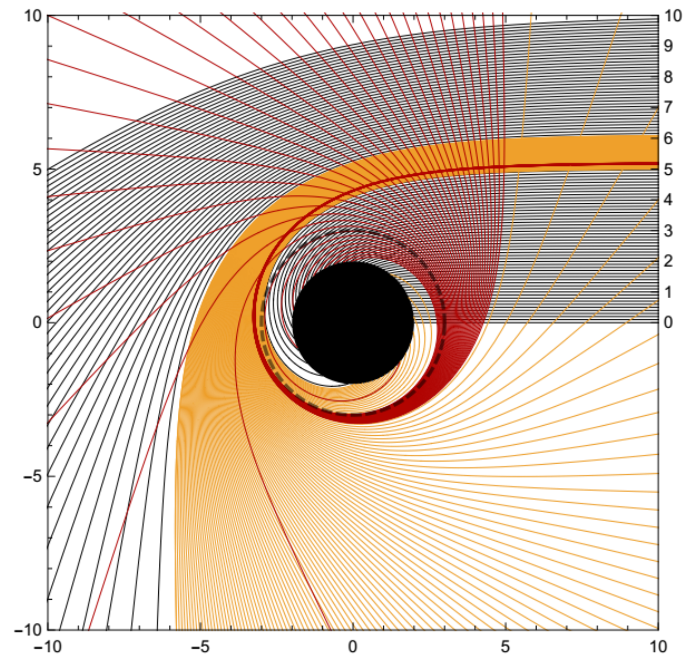
$$D = 3\sqrt{3}R_S \sim 5.2 R_S$$

Credit: Heino Falcke "Imagining black holes"

Ekstremalny przypadek soczewkowania grawitacyjnego

Obraz horyzontu czarnej dziury





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

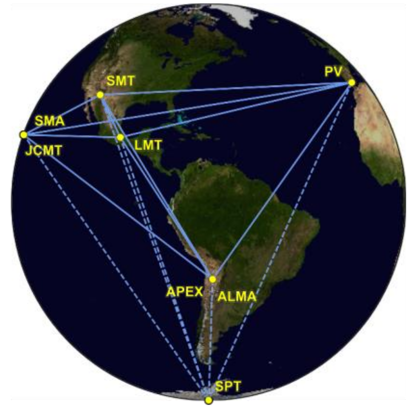


Figure 1. Eight stations of the EHT 2017 campaign over six geographic locations as viewed from the equatorial plane. Solid baselines represent mutual visibility on M87* (+12° declination). The dashed baselines were used for the calibration source 3C279 (see Papers III and IV).

Monika Mościbrodzka
Maciej Wielgus

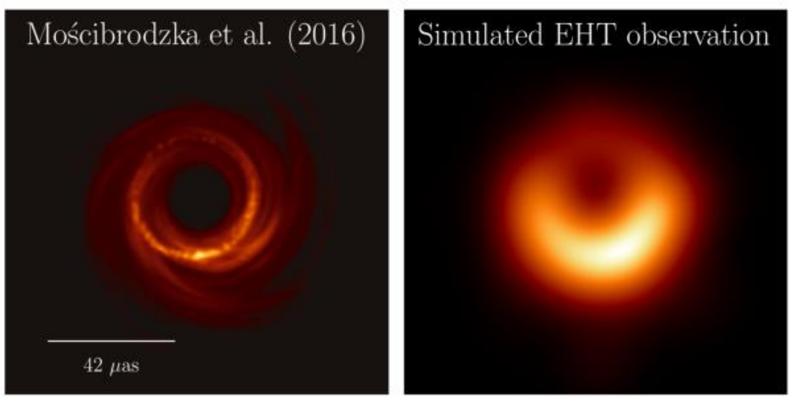
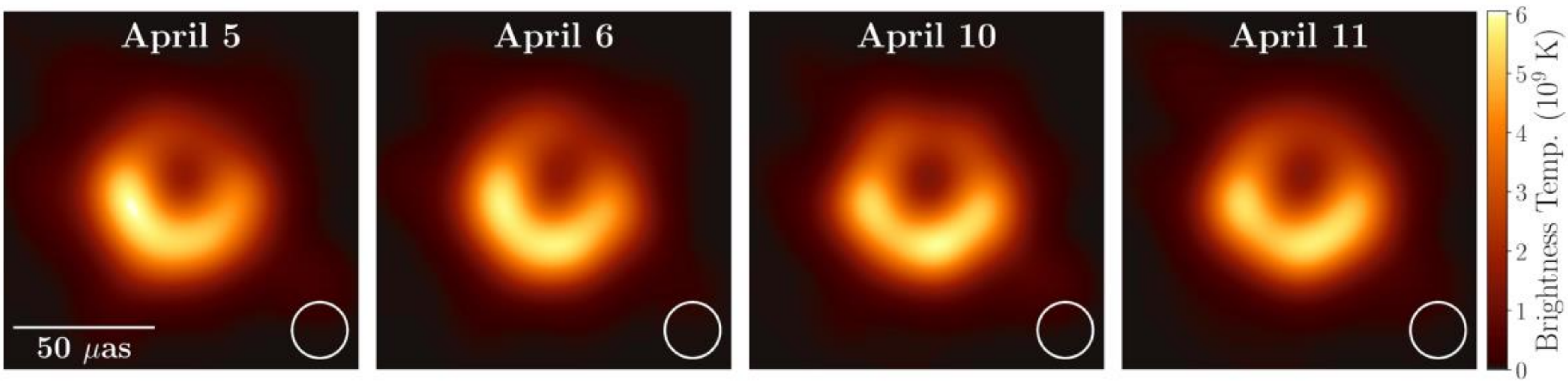
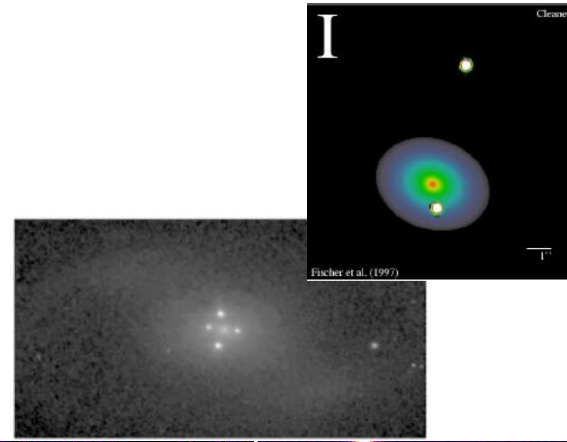


Table 1
Parameters of M87*

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]	$(6.5 \pm 0.7) \times 10^9\ M_\odot$



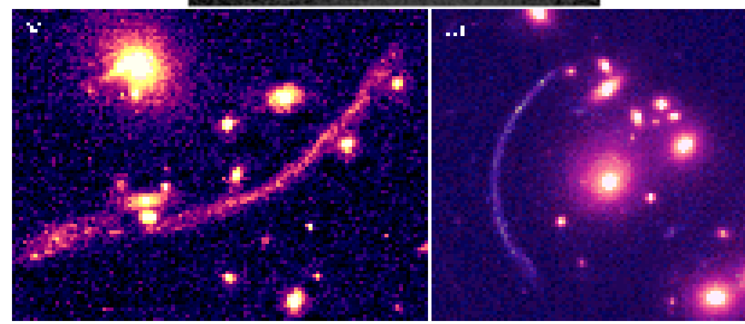
Soczewkowanie grawitacyjne



• 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

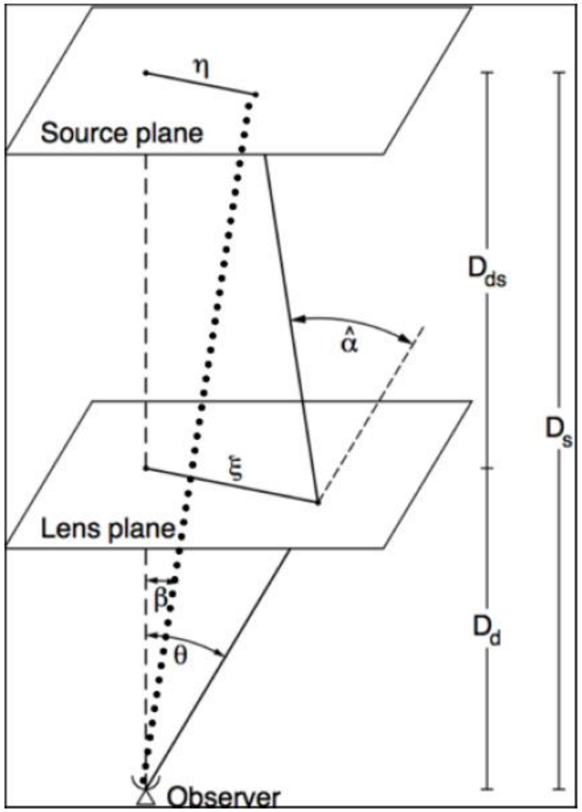

Credit: cfhtlens.org

•obecnie ponad **300** soczewek: bieżące przeglądy SLACS, BELLS, CFHT – SL2S, CLASS, SQLS, HAGGLeS, AEGIS, COSMOS, CASSOWARY

•w przyszłości Pan-STARRS, **LSST**, JDES, SKA dostarczą **tysięcy** nowych silnie soczewkowanych układów

Gravitational lensing – geometric optics

Light rays formalism



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

$$\boldsymbol{\theta} - \boldsymbol{\beta} - \nabla_{\boldsymbol{\theta}}\phi = 0$$

$$A(\boldsymbol{\theta}) = \frac{\partial \boldsymbol{\beta}}{\partial \boldsymbol{\theta}} \qquad \mu(\boldsymbol{\theta}) = \frac{1}{\det A(\boldsymbol{\theta})}.$$

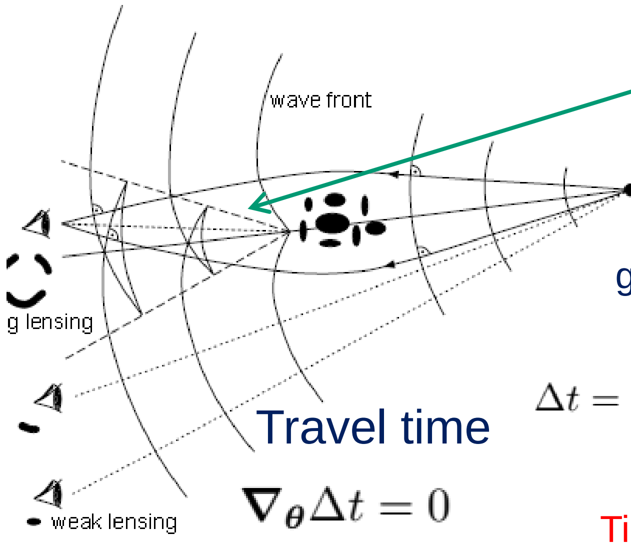
$$\boldsymbol{\alpha} = \nabla_{\boldsymbol{\theta}}\phi$$

magnification

Wavefront formalism

(Fermat principle)

caustics



$$\phi(\boldsymbol{\theta}) = \frac{D_{ls}}{D_l D_s}\frac{2}{c^2}\int \Phi(D_l\boldsymbol{\theta}, z)dz$$

Newtonian potential at lens plane

geometrical term

Travel time

$$\Delta t = \frac{1+z_l}{c}\frac{D_{\rm ol}D_{\rm os}}{D_{\rm ls}}\left[\frac{(\boldsymbol{\theta}-\boldsymbol{\beta})^2}{2} - \phi(\boldsymbol{\theta})\right]$$

$$\nabla_{\boldsymbol{\theta}}\Delta t = 0$$

Time delay distance

Fermat potential

Lens equation

$$\theta_{\rm E} = 4\pi\frac{\sigma_{\rm ap}^2}{c^2}\frac{D_{\rm ls}}{D_{\rm s}}\left(\frac{\theta_{\rm E}}{\theta_{\rm ap}}\right)^{2-\gamma} f(\gamma)$$

Einstein radius

Observables:

* image positions and shape distortions
* time delay between images
* flux ratios magnification ratios

Dygresja

Zasada Fermata

współczynnik załamania światła

$$\delta \int_A^B n(\vec{x}(l))\mathrm{d}l = 0$$

Światło porusza się po drodze, wzdłuż której

czas przelotu $\int \frac{n}{c}\mathrm{d}l$ jest ekstremalny

przybliżenie słabego pola w OTW

$$\mathrm{d}s^2 = g_{\mu\nu}\mathrm{d}x^\mu \mathrm{d}x^\nu = \left(1 + \frac{2\Phi}{c^2}\right) c^2 \mathrm{d}t^2 - \left(1 - \frac{2\Phi}{c^2}\right)(\mathrm{d}\vec{x})^2$$

geodetyki zerowe

$$\left(1 + \frac{2\Phi}{c^2}\right) c^2 \mathrm{d}t^2 = \left(1 - \frac{2\Phi}{c^2}\right)(\mathrm{d}\vec{x})^2$$

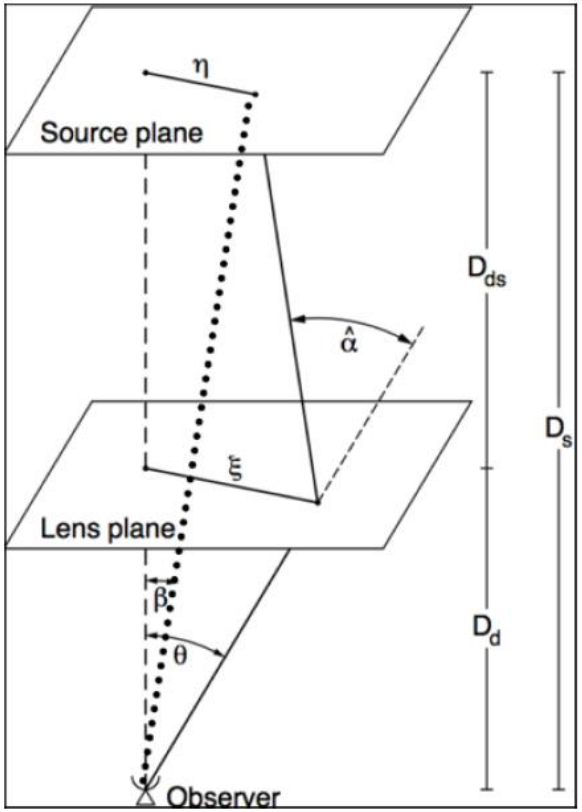
$$c' = \frac{|\mathrm{d}\vec{x}|}{\mathrm{d}t} = c\sqrt{\frac{1 + \frac{2\Phi}{c^2}}{1 - \frac{2\Phi}{c^2}}} \approx c\left(1 + \frac{2\Phi}{c^2}\right)$$

$$\boxed{n = c/c' = \frac{1}{1 + \frac{2\Phi}{c^2}} \approx 1 - \frac{2\Phi}{c^2}}$$

Efektywny współczynnik załamania
w obecności ciał masywnych

Gravitational lensing – geometric optics

Light rays formalism



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

$$\boldsymbol{\theta} - \boldsymbol{\beta} - \nabla_{\boldsymbol{\theta}} \phi = 0$$

Lens equation

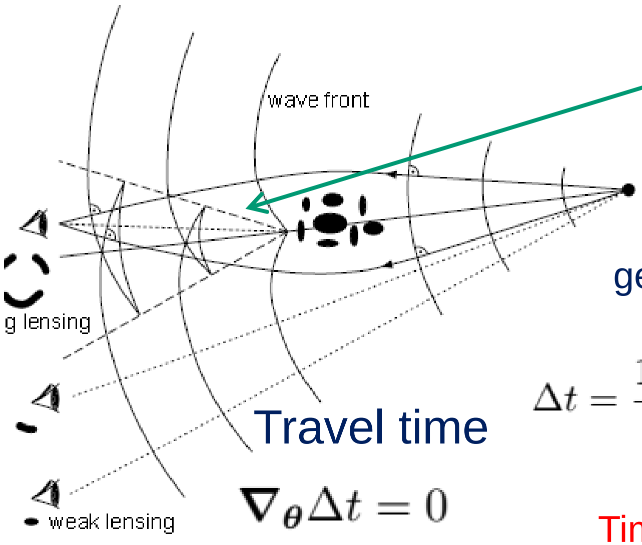
$$A(\boldsymbol{\theta}) = \frac{\partial \boldsymbol{\beta}}{\partial \boldsymbol{\theta}} \qquad \mu(\boldsymbol{\theta}) = \frac{1}{\det A(\boldsymbol{\theta})}.$$

$$\boldsymbol{\alpha} = \nabla_{\boldsymbol{\theta}} \phi$$

magnification

Wavefront formalism

(Fermat principle)



caustics

$$\phi(\boldsymbol{\theta}) = \frac{D_{ls}}{D_l D_s} \frac{2}{c^2} \int \Phi(D_l \boldsymbol{\theta}, z) dz$$

Newtonian potential at lens plane

geometrical term

Travel time

$$\Delta t = \frac{1+z_l}{c} \frac{D_{ol} D_{os}}{D_{ls}} \left[\frac{(\boldsymbol{\theta} - \boldsymbol{\beta})^2}{2} - \phi(\boldsymbol{\theta}) \right]$$

$$\nabla_{\boldsymbol{\theta}} \Delta t = 0$$

Time delay distance

Fermat potential

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

Einstein radius

Observables:

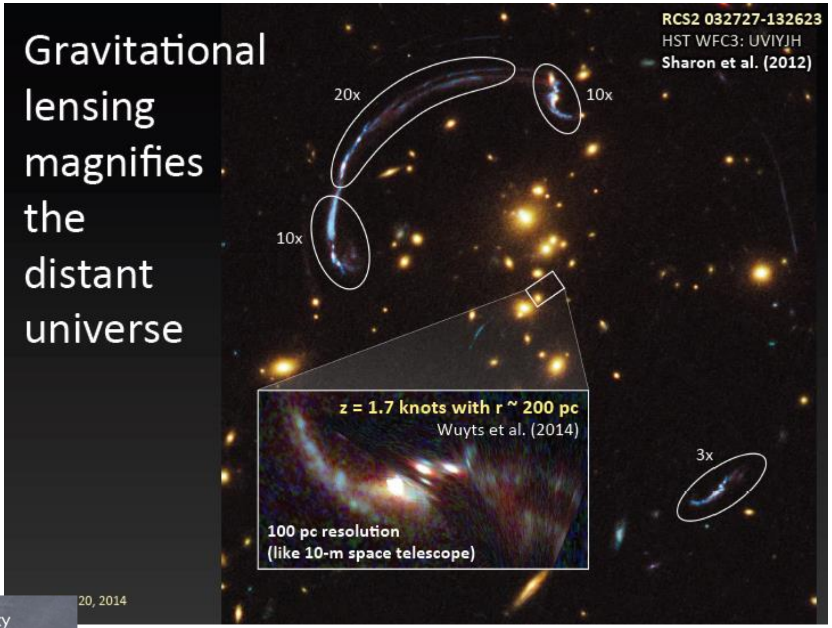
* image positions
and shape distortions

* time delay between images

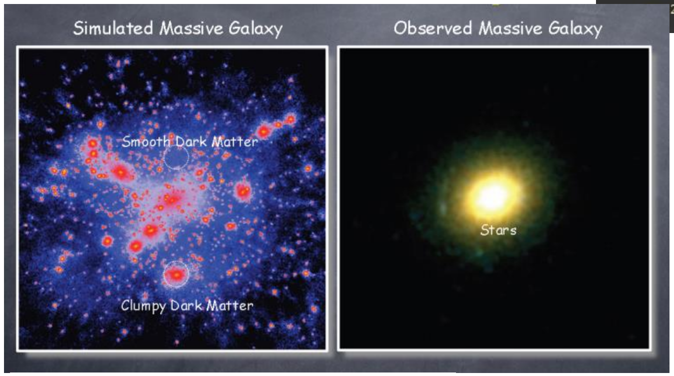
* flux ratios
magnification ratios

Zastosowania silnego soczewkowania

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

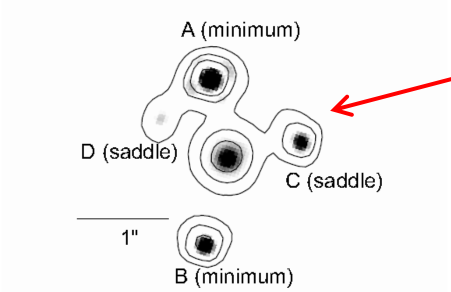


Badania ciemnej materii w skali galaktyk:
„brakujące” skupiska masy na małych skalach:
anomalne jasności makroobrazów
mikrosoczewkowanie



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

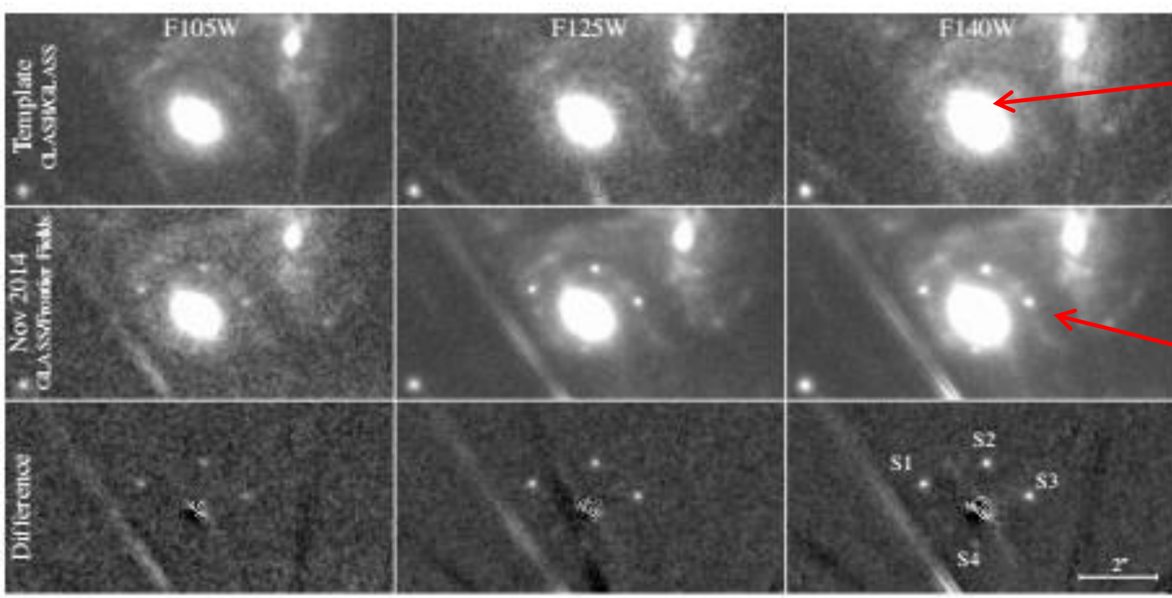


Fig. 1: *HST* WFC3-IR images showing the simultaneous appearance of four point sources around a cluster member galaxy. From left to right the columns show imaging in the *F105W* filter (*Y* band), *F125W* (*J*), and *F140W* (*JH*). From top to bottom the

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

galaktyka spiralna z=1.49
źródło

galaktyka macierzysta SNII

Supernowa „Refsdala”

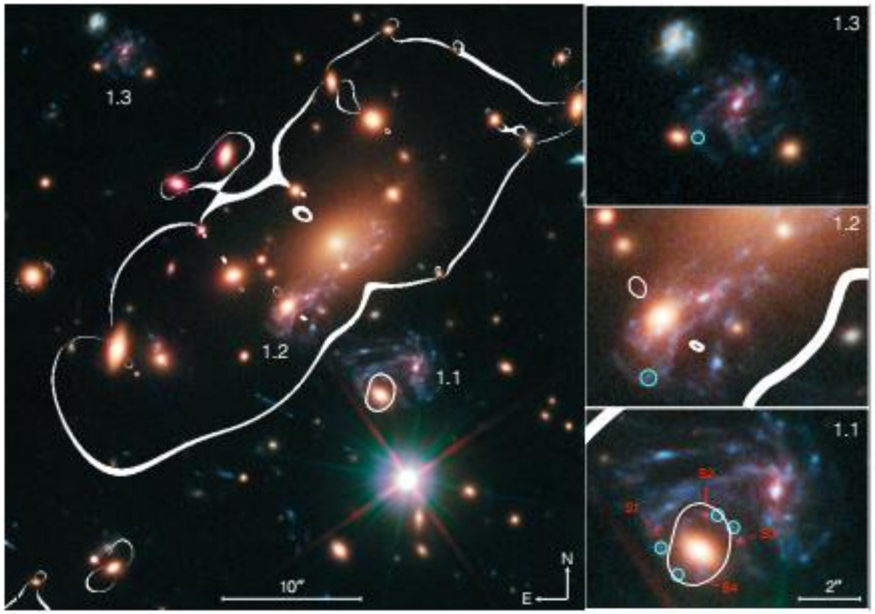
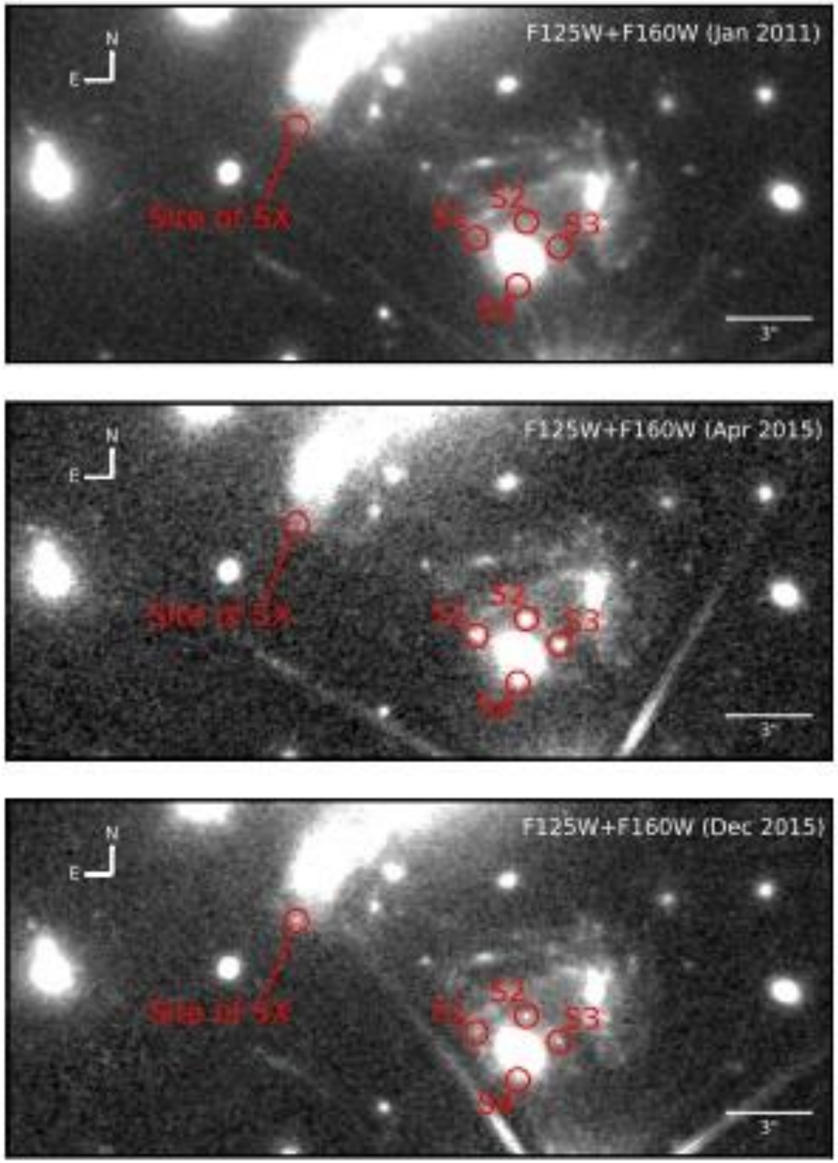


Fig. 2: Color-composite image of the galaxy cluster MACSJ1149.6+2223, with critical curves for sources at the $z = 1.49$ redshift of the host galaxy overlaid. Three images of the host galaxy formed by the cluster are marked with white labels (1.1, 1.2, and 1.3) in the left panel, and each is enlarged 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”



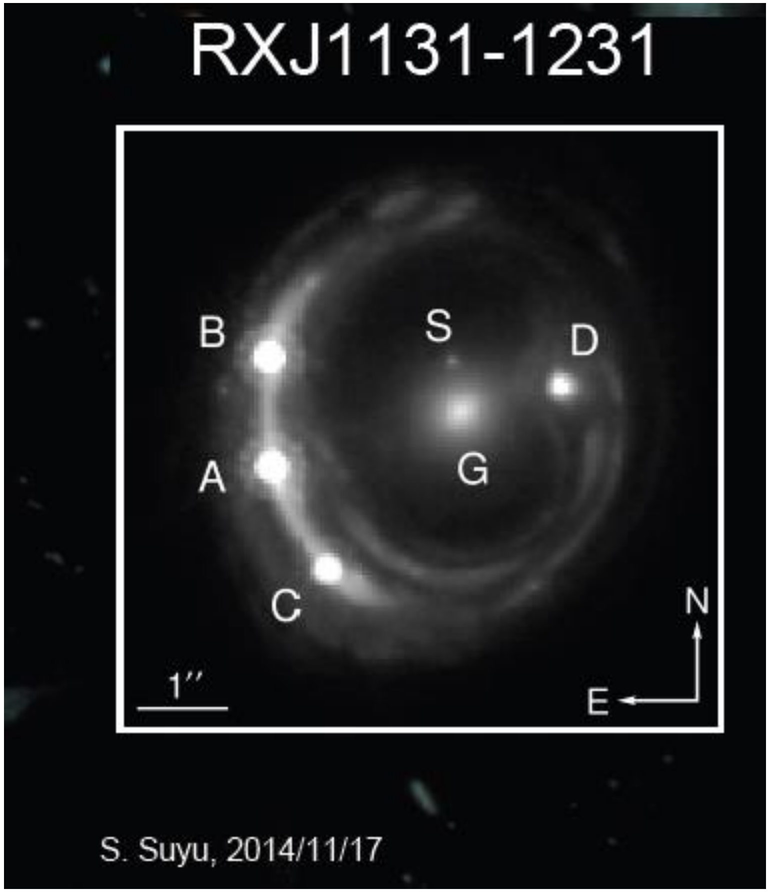
Kelly et al. (2016) ApJL

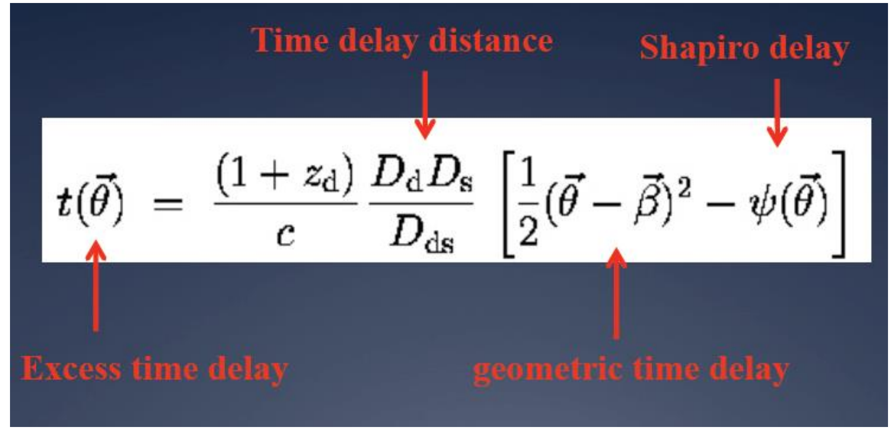
11 grudnia 2015
SNII zaobserwowana
w obrazie SX –
zgodnie z przewidywaniami

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

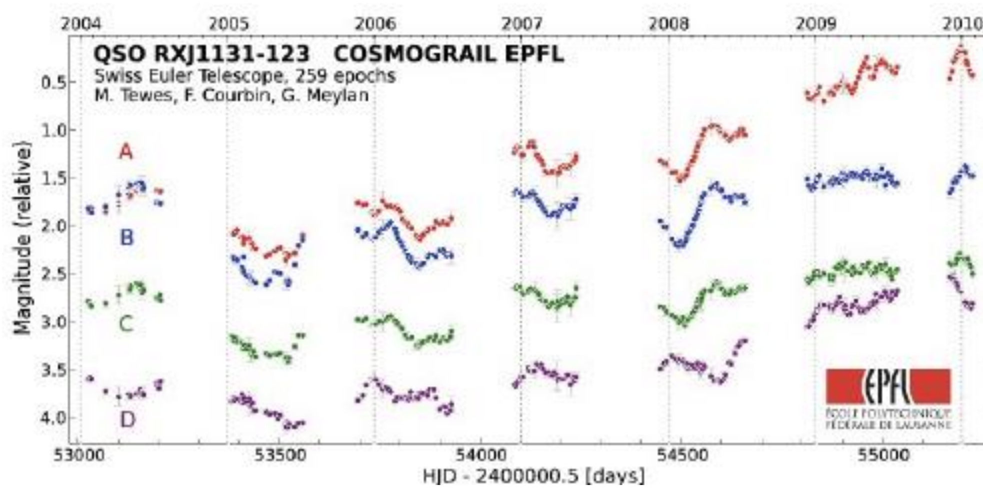
Porównywalny z triumfem
mechaniki niebieskiej w XIX w.
przy odkryciu Neptuna

Metoda opóźnień czasowych w Kosmologii





Opóźnienie czasowe – największa osiągalna dokładność 1.5%

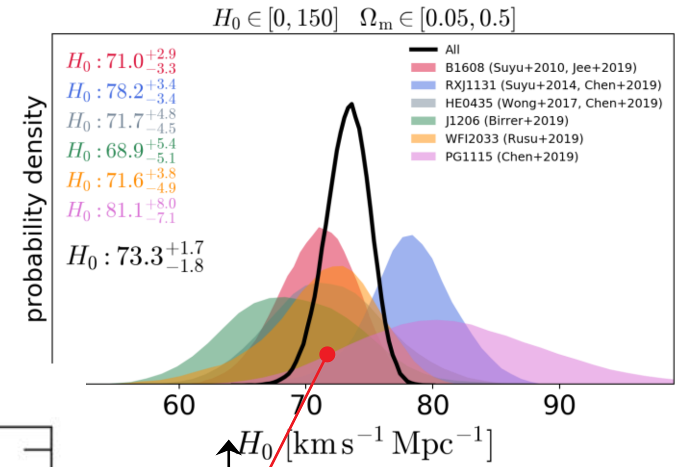


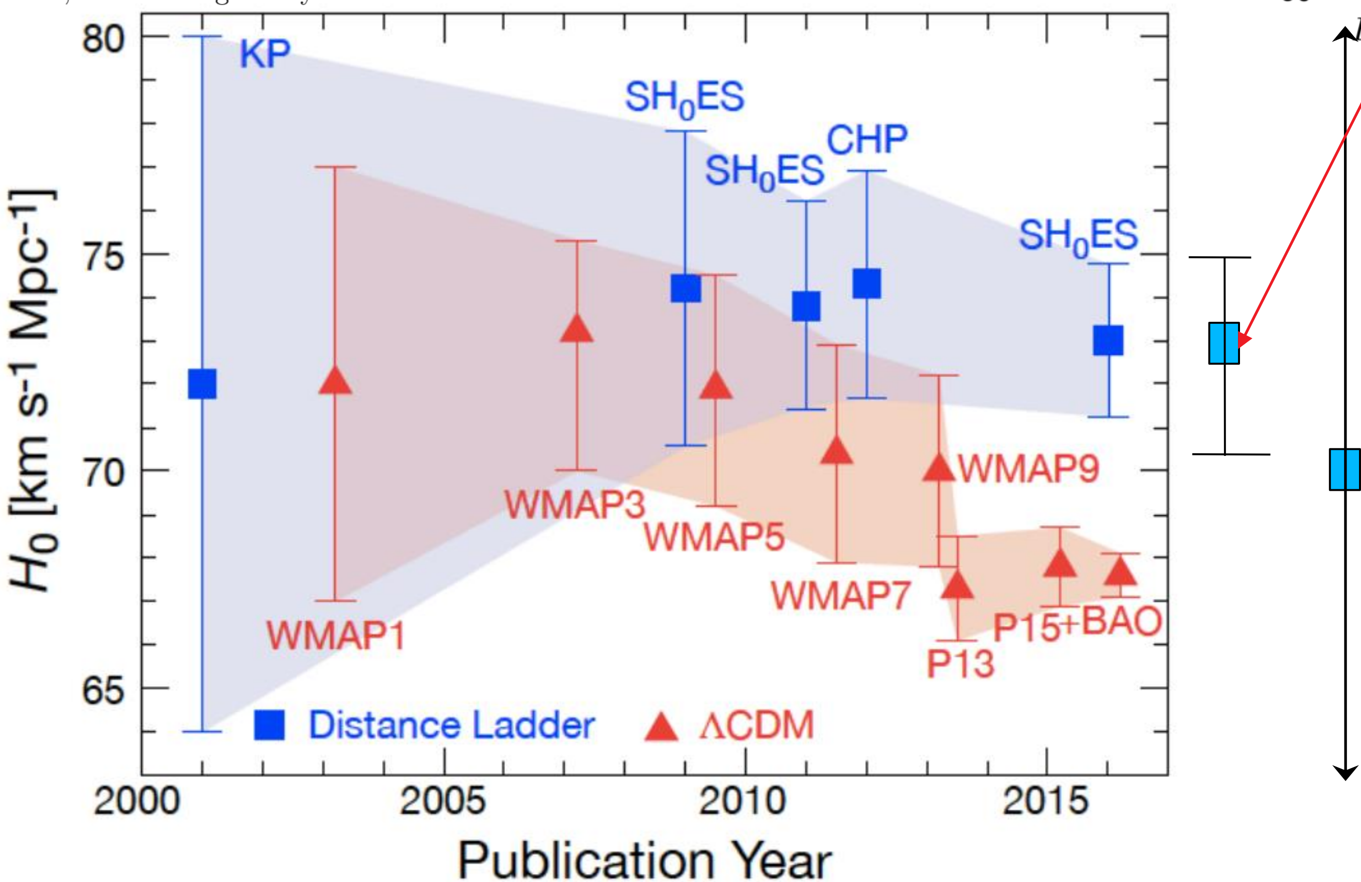
Results: Wong, Suyu et al. 2020

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

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 …



Nagroda Nobla z Fizyki 2011

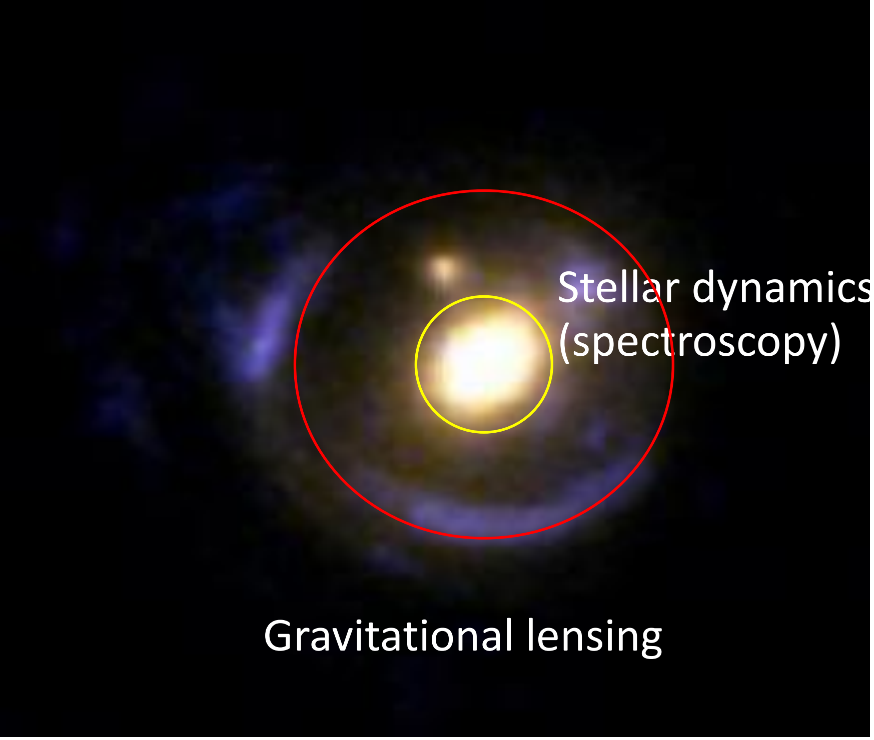
Co jest za to odpowiedzialne?

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

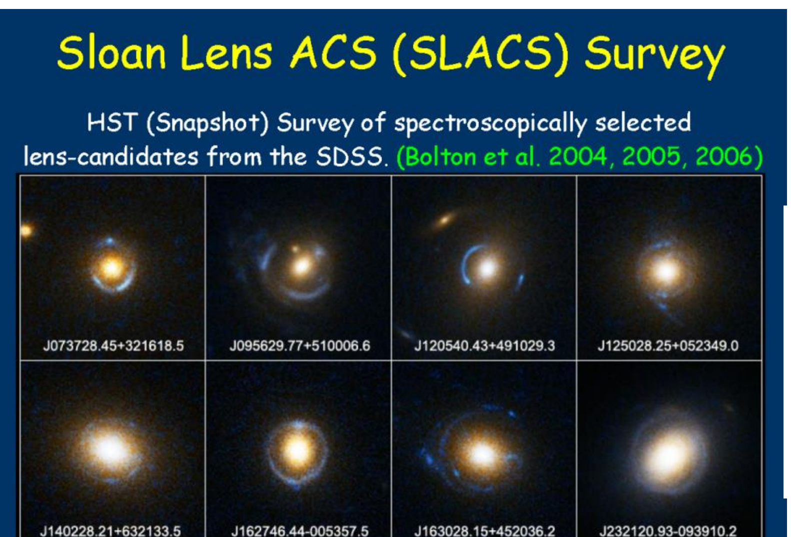
dyspersja prędkości – spektroskopia

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

z astrometrii obrazów

Iloraz odległości

zależy od modelu kosmologicznego



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

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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]

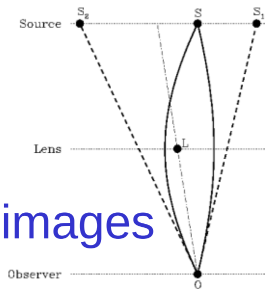
JCAP03(2012)016

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

Próbka układów
z 2 obrazami

36 SLACS lenses

2 images



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

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

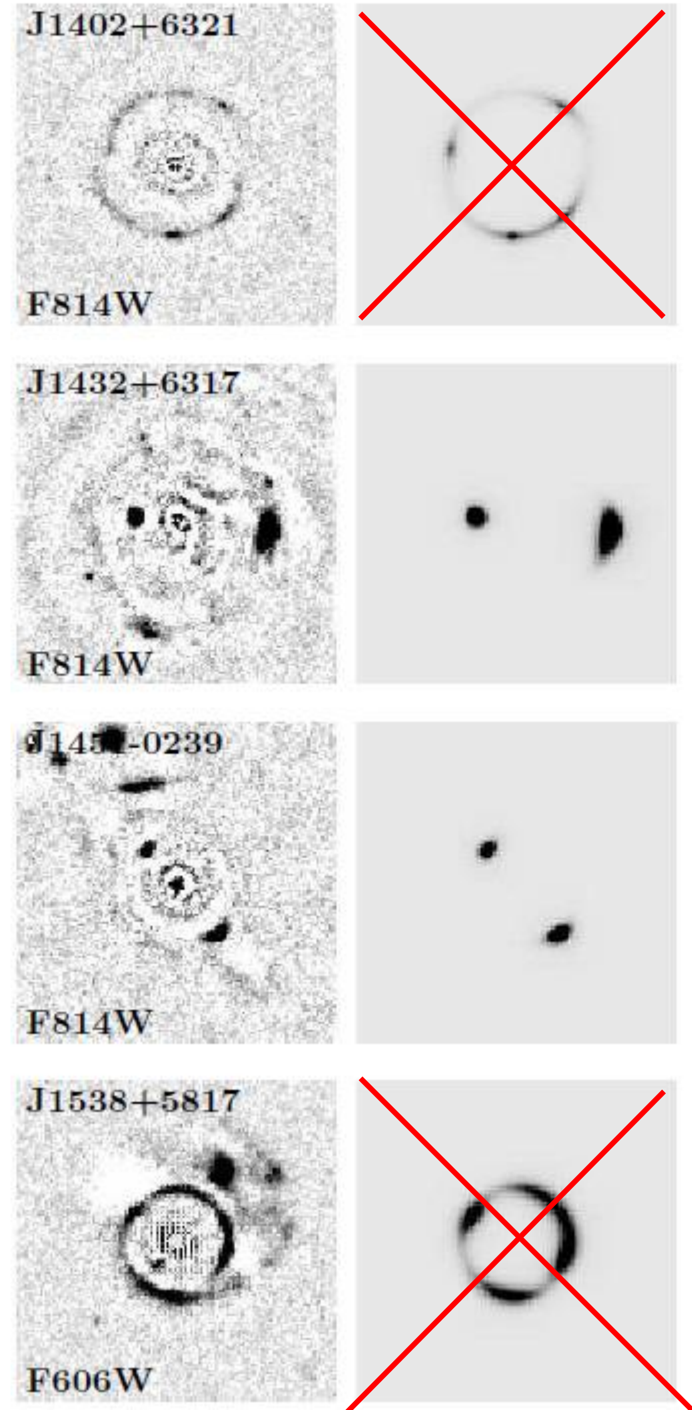
$$\mathcal{D}^{obs} = \frac{c^2 \theta_E}{4\pi \sigma_0^2 f_E^2}$$

Marginalizacja po **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	$w_0 = 0.60 \pm 1.76$	$w_0 = -0.24 \pm 2.42$
	$w_a = -7.37 \pm 8.05$	$w_a = -6.35 \pm 9.75$

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

$$M_{\rm lens} = \frac{c^2}{4G}\frac{D_{\rm s} D_{\rm l}}{D_{\rm ls}}\theta_{\rm E}^2$$

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

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

$$= \frac{\pi}{G}\sigma_{\rm ap}^2 D_{\rm l}\theta_{\rm E}\left(\frac{\theta_{\rm E}}{\theta_{\rm ap}}\right)^{2-\gamma} f(\gamma)$$

$$\gamma(z_{\rm l}) = \gamma_0 + \gamma_1 z_{\rm l}$$

ewolucja γ
A.Ruff , R.Gavazzi et al. 2010

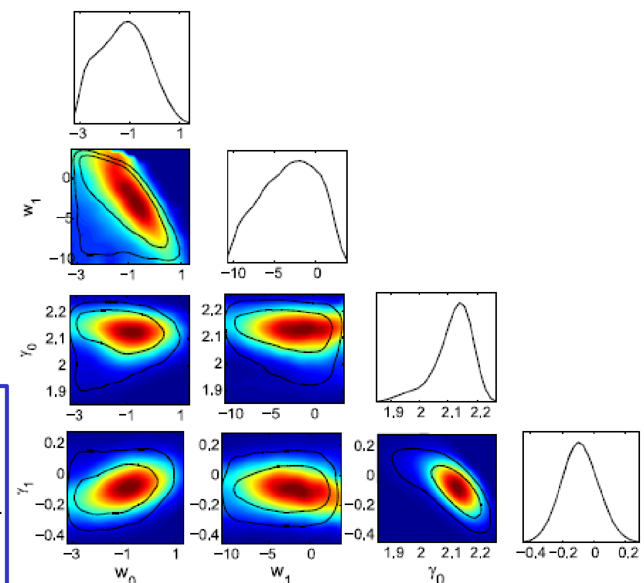
118 soczewek z przeglądu SLACS

$$\theta_{\rm E} = 4\pi\frac{\sigma_{\rm ap}^2}{c^2}\frac{D_{\rm ls}}{D_{\rm s}}\left(\frac{\theta_{\rm E}}{\theta_{\rm ap}}\right)^{2-\gamma} f(\gamma)$$

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

vs.

$$\mathcal{D}^{\rm th}(z_{\rm l}, z_{\rm s}; \mathbf{p}) = \frac{D_{\rm ls}(\mathbf{p})}{D_{\rm s}(\mathbf{p})} = \frac{\int_{z_{\rm l}}^{z_{\rm s}} \frac{dz'}{h(z';\mathbf{p})}}{\int_0^{z_{\rm s}} \frac{dz'}{h(z';\mathbf{p})}}$$



1. Strong lensing systems as a new probe of parametrized post-Newtonian (PPN) gravity

Parametrized post-Newtonian (PPN) formalism is a very convenient way to study and compare gravity theories beyond GR

One useful PPN parameter γ measures ammount of spatial curvature generated by unit mass

In the weak field limit the metric is characterized by two potentials

$$ds^2 = a^2(\tau)\left[\left(1+\frac{2\Phi}{c^2}\right)c^2dt^2 - \left(1-\frac{2\Psi}{c^2}\right)g_{ij}dx^idx^j\right] \qquad \gamma = \frac{\Psi}{\Phi}$$

Motion of massive bodies (e.g. stellar dynamics) is sensitive to the Newtonian potential

Trajectory of light is sensitive to both potentials, as a result:

deflection angle is

$$\hat{\vec{\alpha}}_{PPN} = \frac{1+\gamma}{2}\hat{\vec{\alpha}}_{GR}$$

$$\theta_{\rm E} = \sqrt{\frac{1+\gamma}{2}}\left(\frac{4GM_{\rm E}}{c^2}\frac{D_{ls}}{D_sD_l}\right)^{1/2}$$

And the Einstein radius of spherically symmetric lens is

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

CrossMark

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

We used a catalog of 80 intermediate mass lensing systems from SLACS,BELLS, LSD and SL2S

$200\,\mathrm{km\,s^{-1}} < \sigma_{ap} \leqslant 300\,\mathrm{km\,s^{-1}}$

(Cao et al. 2015, ApJ 806:185)

lensing gives

$$\frac{GM_E}{R_E} = \frac{2}{(1+\gamma)}\frac{c^2}{4}\frac{D_s}{D_{ls}}\theta_E$$

lens model

mass $\rho(r) = \rho_0\left(\frac{r}{r_0}\right)^{-\alpha}$

luminosity $\nu(r) = \nu_0\left(\frac{r}{r_0}\right)^{-\delta}.$

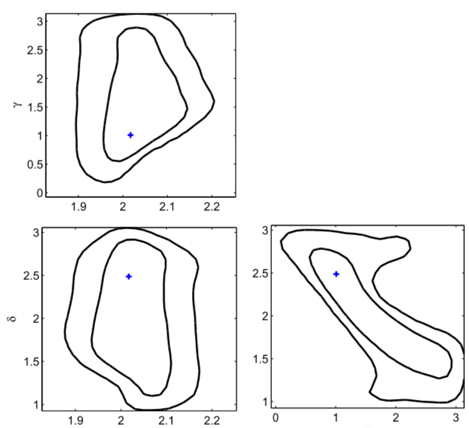
anisotropy $\beta(r) = 1 - \sigma_t^2/\sigma_r^2$

$\beta = 0.18 \pm 0.13$

stellar velocity dispersion gives

$$\sigma_r^2(r) = \left[\frac{GM_E}{R_E}\right]\frac{2}{\sqrt{\pi}(\xi - 2\beta)\lambda(\alpha)}\left(\frac{r}{R_E}\right)^{2-\alpha}$$

Best fits



$$\alpha = 2.017^{+0.093}_{-0.082},$$
$$\delta = 2.485^{+0.445}_{-1.393},$$
$$\gamma = 1.010^{+1.925}_{-0.452}.$$

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

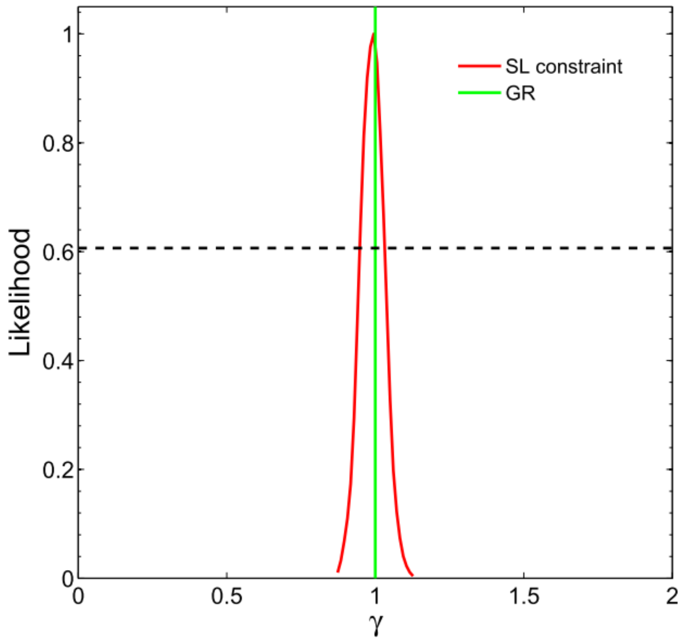


Figure 3. Normalized posterior likelihood of the PPN γ parameter obtained with rigid priors on the nuisance parameters (α, β, δ).

With priors

$$\langle\alpha\rangle = 2.00;\ \sigma_\alpha = 0.08$$

$$\langle\delta\rangle = 2.40;\ \sigma_\delta = 0.11.$$

$$\beta = 0.18 \pm 0.13$$

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

NCBJ
is
participating

LSST simulated
strong lensing systems
with prior on Ω_k

$$\frac{\Delta\gamma}{\gamma} \sim 10^{-3} - 10^{-4}$$

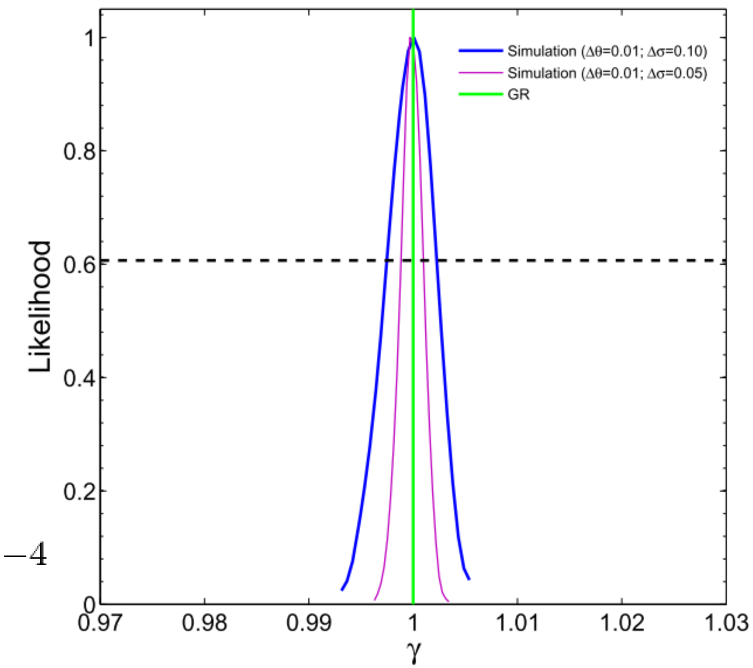


Figure 8. Constraints on the PPN parameter from simulated LSST strong lensing data, with a prior on the cosmic curvature $-0.007 < \Omega_k < 0.006$ from *Planck*.

GRAVITATION

A precise extragalactic test of General Relativity

Thomas E. Collett[1*], Lindsay J. Oldham[2], Russell J. Smith[3], Matthew W. Auger[2], Kyle B. Westfall[1,4], David Bacon[1], Robert C. Nichol[1], Karen L. Masters[1,5], Kazuya Koyama[1], Remco van den Bosch[6]

Einstein's theory of gravity, General Relativity, has been precisely tested on Solar System scales, but the long-range nature of gravity is still poorly constrained. The nearby strong gravitational lens ESO 325-G004 provides a laboratory to probe the weak-field regime of gravity and measure the spatial curvature generated per unit mass, γ. By reconstructing the observed light profile of the lensed arcs and the observed spatially resolved stellar kinematics with a single self-consistent model, we conclude that $\gamma = 0.97 \pm 0.09$ at 68% confidence. Our result is consistent with the prediction of 1 from General Relativity and provides a strong extragalactic constraint on the weak-field metric of gravity.

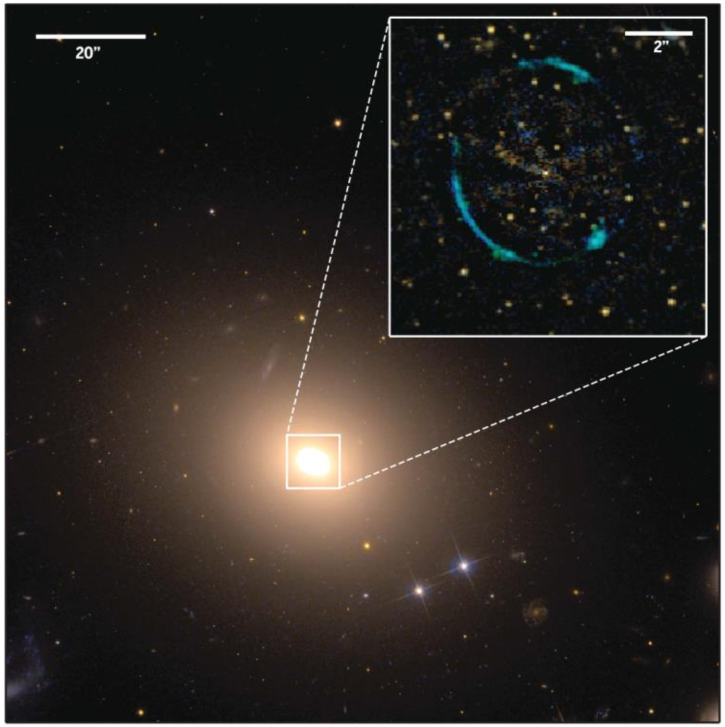
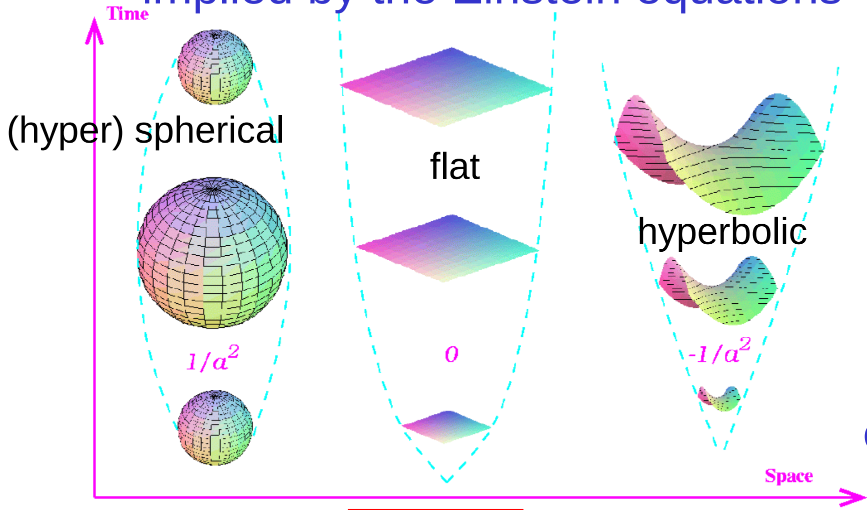


Fig. 1. Color composite image of ESO325-G004. Blue, green, and red channels are assigned to the F475W, F606W, and F814W HST imaging. The inset shows a F475W and F814W composite of the arcs of the lensed background source after subtraction of the foreground lens light. Scale bars are in arc seconds.

Science **360**, 1342–1346 (2018)

2. Strong lensing systems as new probes of cosmic curvature

Geometry of the Universe implied by the Einstein equations



k = +1	k = 0	k = -1	curvature
$\Omega_{tot} > 1$	$\Omega_{tot} = 1$	$\Omega_{tot} < 1$	density parameter

homogeneous, isotropic
Friedman-Lemaitre-Robertson-Walker models

$$ds^2 = dt^2 - a^2(t)\left(\frac{dr^2}{1-kr^2} + r^2 d\Omega^2\right)$$

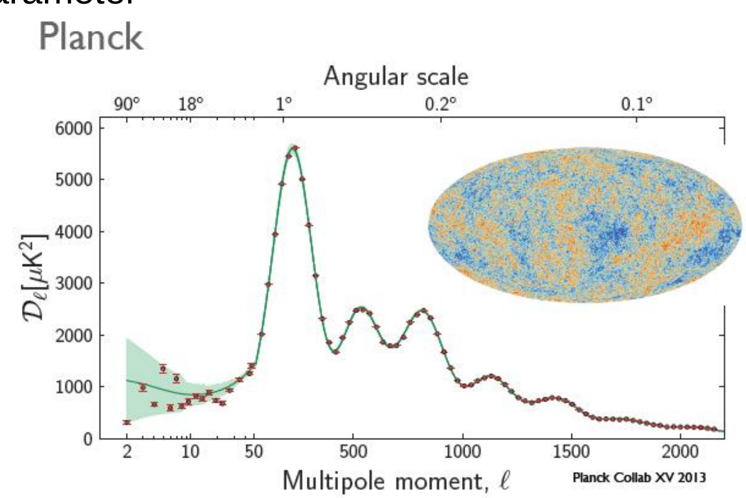
all spatial distances
(including wavelength of light)
are scaled by *a(t)*
which changes in time

$$\Omega_k = -\frac{k}{a_0^2 H_0^2}$$

Cosmic curvature parameter

Universe is spatially flat - inference from the first acoustic peak

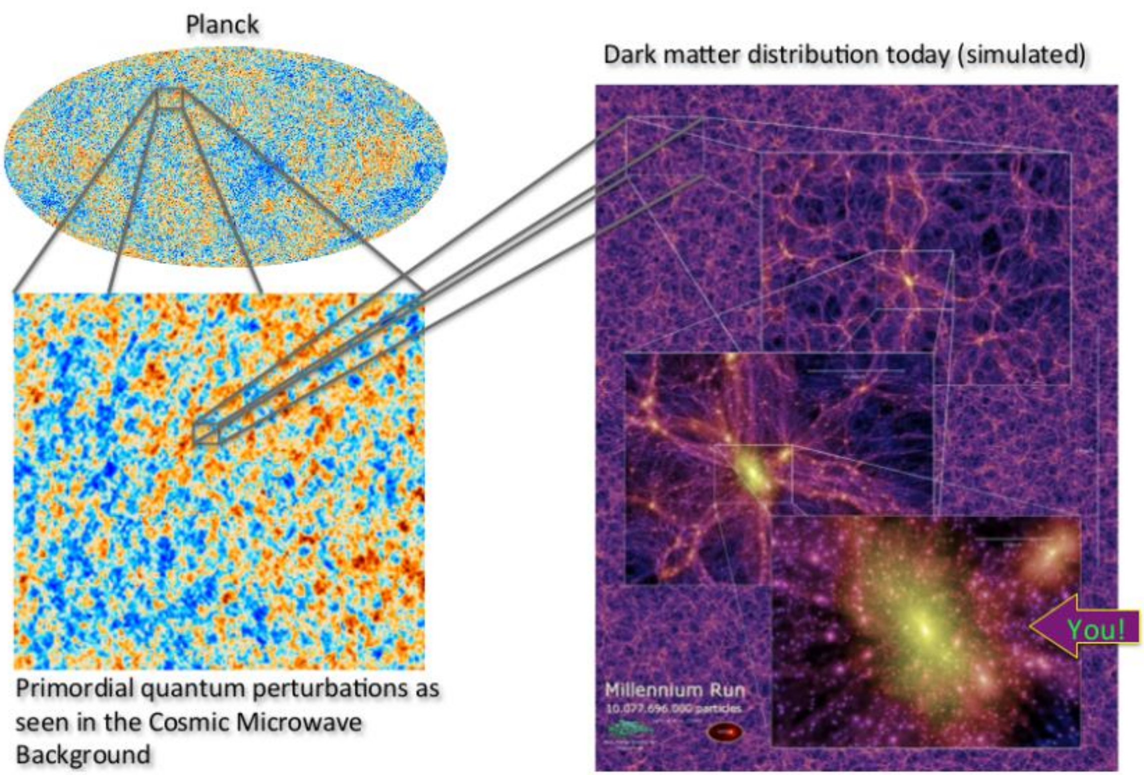
$$\Omega_{\rm tot} = 1.003^{+0.013}_{-0.017}$$



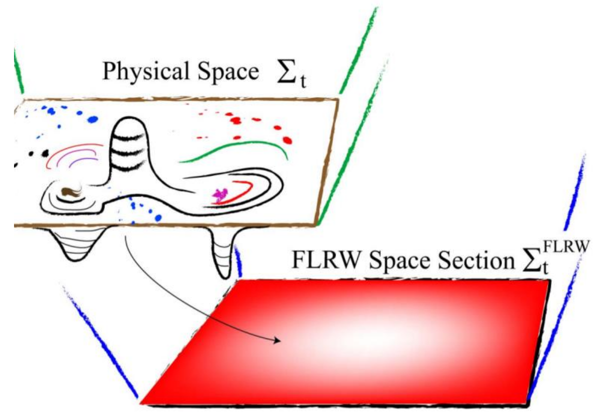
$$\Omega_K = -0.005^{+0.016}_{-0.017} \quad (95\%, \textit{Planck}\ \text{TT+lowP+lensing}).$$

Coherent picture of emergence of the large scale structure

Emerging spatial curvature

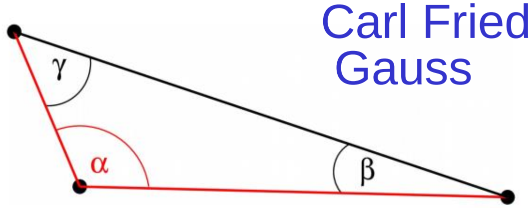


Credit: F. Leclercq, A. Pisani , B.D. Wandeldt arXiv:1403.1260v1



Buchert, Carfora, *Class. Quant. Grav.* 25 , 195001 (2008)

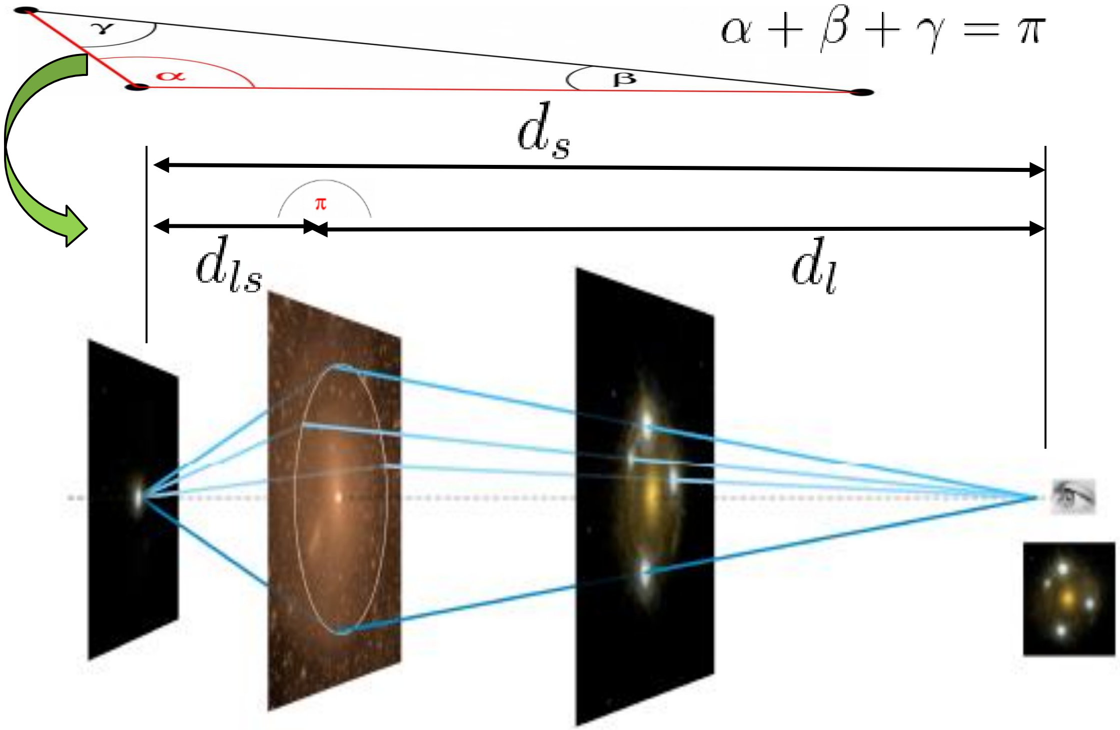
Formation of the large scale structure induces non-zero curvature at local scales



$$\alpha + \beta + \gamma = \pi$$

Carl Friedrich Gauss

It is important to measure curvature with more local objects



Strong lenisng systems offer us „degenerated triangles”

$$d_{ls} = d_s - d_l$$ rule valid in flat FLRW metric

Distance sum rule – valid in any FLRW metric

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

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

This is a function of two redshifts, but within the FLRW metric it should be just a single number !

One can obtain Ω_k if

d_l, d_s, d_{ls} are known

Observations:
z_l , z_s – known

Images -- > d_{ls} / d_s

Time delays -- > $d_l d_s$ / d_{ls}

So: d_l is measurable
=================

d_s – match by redshift some standard candle (or ruler)

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

Możliwość wyznaczenia krzywizny Wszechświata z soczewkowanych SN Ia

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

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[1]*Department of Physics, College of Sciences, Northeastern University, Shenyang 110819, China*
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[3]*Department of Astrophysics and Cosmology, Institute of Physics, University of Silesia, 75 Pułku Piechoty 1, 41-500, Chorzów, Poland*
[4]*School of Physics and Technology, Wuhan University, Wuhan 430072, China*

(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.

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

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

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

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

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

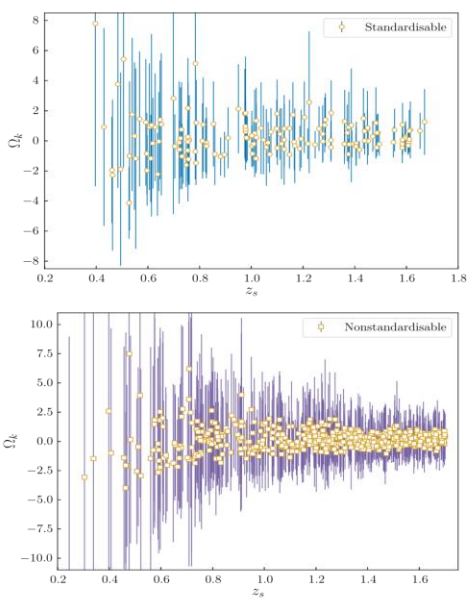

FIG. 1. An example of the simulated measurements of Ω_k from future observations of SGLSNe Ia: without and with the effect of microlensing. The blue lines denote the associated error bars (68.3% C.L.) of Ω_k when all the uncertainties are included.

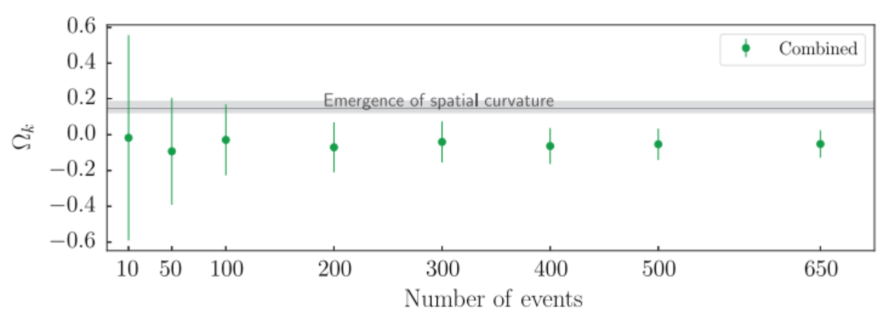

FIG. 3. Inferred Ω_k parameter as a function of the number of SGLSNe Ia, with the prediction of a silent universe added for comparison.

650 soczewkowanych SN Ia z LSST

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **496**, 708–717 (2020)
Advance Access publication 2020 June 3

doi:10.1093/mnras/staa1539

NCBJ is participating

VERA C. RUBIN OBSERVATORY

Testing the cosmic curvature at high redshifts: the combination of LSST strong lensing systems and quasars as new standard candles

Tonghua Liu,[1] Shuo Cao,[1★] Jia Zhang,[2] Marek Biesiada,[1,3★] Yuting Liu[1★] and Yujie Lian[1]

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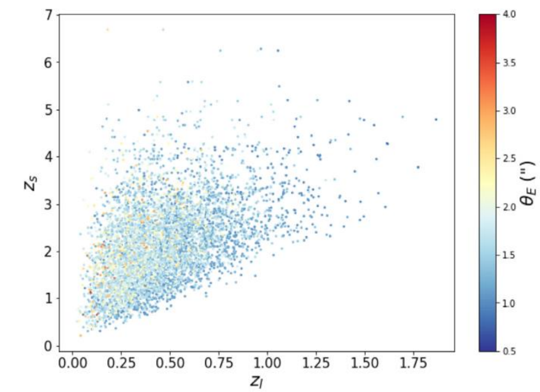
[2]*School of Physics and Electrical Engineering, Weinan Normal University, Shanxi 714099, China*
[3]*National Centre for Nuclear Research, Pasteura 7, PL-02-093 Warsaw, Poland*

LSST

Simulated sample of SGL systems detectable in LSST (code of Collett 2015)

5000 ellipticals

$$200\ km\ s^{-1} < \sigma_{ap} < 300\ km\ s^{-1}$$



$$\frac{d_{ls}}{d_s}$$

Distances matched to QSO[UV-X] standard candles (Risaliti & Lusso 2019)

$$d_s \quad d_l$$

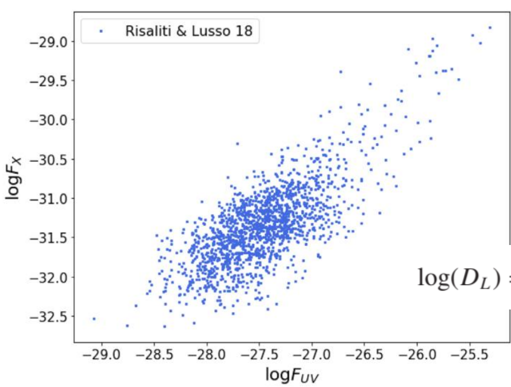
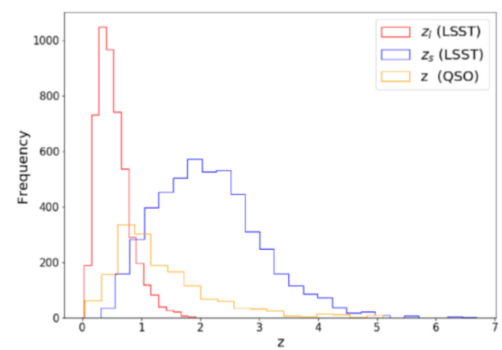


Figure 1. Scatter plot of the flux measurements of 1598 quasars (Risaliti & Lusso 2019).

$$\log(D_L) = \frac{1}{2 - 2\hat{\gamma}} \times [\hat{\gamma}\log(F_{\rm UV}) - \log(F_{\rm X}) + \hat{\beta}]$$

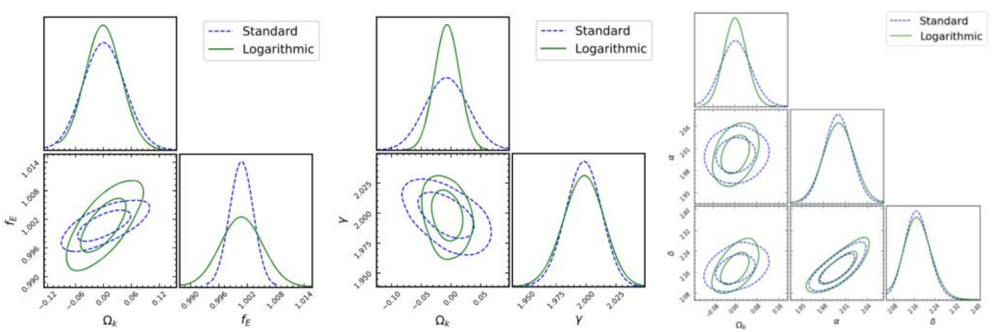


SGL systems & QSO[UV-X] overlap well in z

Results

Table 1. Constraints on the cosmic curvature and lens profile parameters for three types of lens models, in the framework of standard polynomial and logarithmic polynomial cosmographic reconstructions.

Standard polynomial	Ω_k	f_E	γ	α	δ
SIS	0.002 ± 0.035	1.000 ± 0.002	□	□	□
Power-law spherical	-0.007 ± 0.029	□	2.000 ± 0.012	□	□
Extended power law	0.003 ± 0.045	□	□	2.000 ± 0.014	2.171 ± 0.035
Power-law spherical (with *HST* imaging)	-0.008 ± 0.028	□	2.000 ± 0.012	□	□
Logarithmic polynomial	Ω_k	f_E	γ	α	δ
SIS	-0.001 ± 0.030	1.000 ± 0.003	□	□	□
Power-law spherical	-0.007 ± 0.016	□	2.000 ± 0.013	□	□
Extended power law	0.002 ± 0.031	□	□	2.002 ± 0.016	2.172 ± 0.035



Different lens models +
different cosmographic distance reconstructions

redshift bins

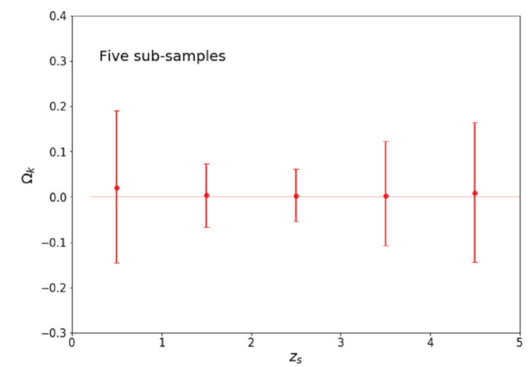


Figure 7. Determination of cosmic curvature with five subsamples $0 < z < 1.0$, $1.0 < z < 2.0$, $2.0 < z < 3.0$, $3.0 < z < 4.0$ and $4.0 < z < 5.0$ based on the source redshifts of SGL sample characterized by the SIS lens model.

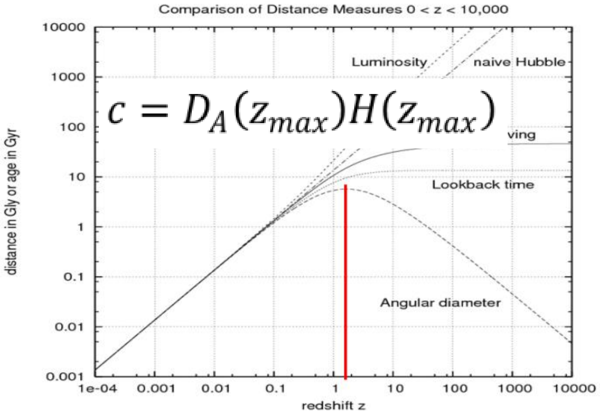
Conclusion: LSST data (+follow-up) would allow **sub-percent** accuracy of local Ω_k measurement

3. Strong lensing systems as a new tool to measure the speed of light using extragalactic objects

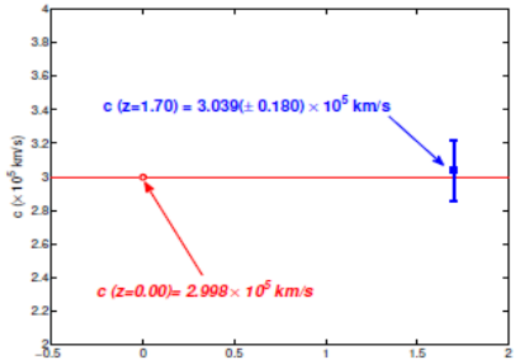
Ole Rømer XVII/XVIII w,
James Bradley XVIII w

Measurements of **c** using extragalactic objects is an unexplored territory:

first proposal:
Salzano, Dąbrowski, Lazkoz (2015) PRL, 114:101304
to be tested with future BAO data



first measurement on extragalactic sources:
Cao, Biesiada, Jackson, Zheng, Zhu (2017) JCAP 02, 012
H(z) from passive evolving galaxies; $D_A(z)$ from intermediate L compact radio QSOs (standard rulers)



Cao, Qi, Biesiada, Zheng, Xu, Zhu (2018) ApJ 867:50
Combination of strongly lensed and unlensed SN Ia
predictions for the LSST

$$\Delta c/c = 0.005$$

THE ASTROPHYSICAL JOURNAL, 867:50 (6pp), 2018 November 1
https://doi.org/10.3847/1538-4357/aae5f7

CrossMark

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

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[2] Department of Astrophysics and Cosmology, Institute of Physics, University of Silesia, 75 Pułku Piechoty 1, 41-500 Chorzów, Poland; marek.biesiada@us.edu.pl
Received 2018 August 4; revised 2018 September 23; accepted 2018 October 1; published 2018 October 30

from lensed images

$$c_{z_s} = \frac{D_l(1+z_l)D_s(1+z_s)}{(1+z_s)D_s - (1+z_l)D_l}\frac{1}{\Delta t_{i,j}}\Delta\phi_{i,j},$$

from lensed SNIa

from redshift matched
unlensed SNIa

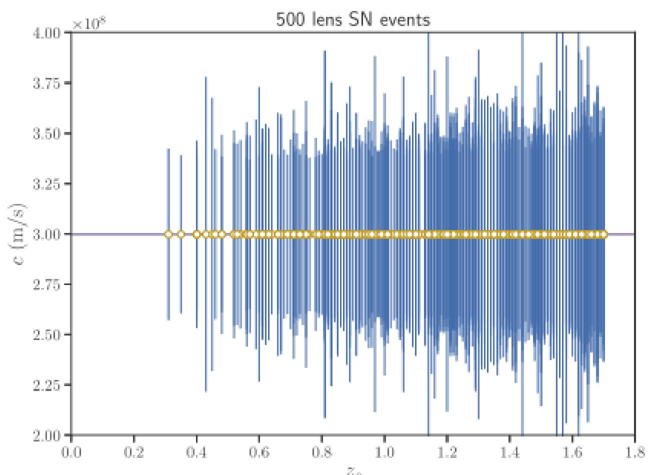

Figure 1. Individual measurements of the speed of light from the forthcoming LSST survey.

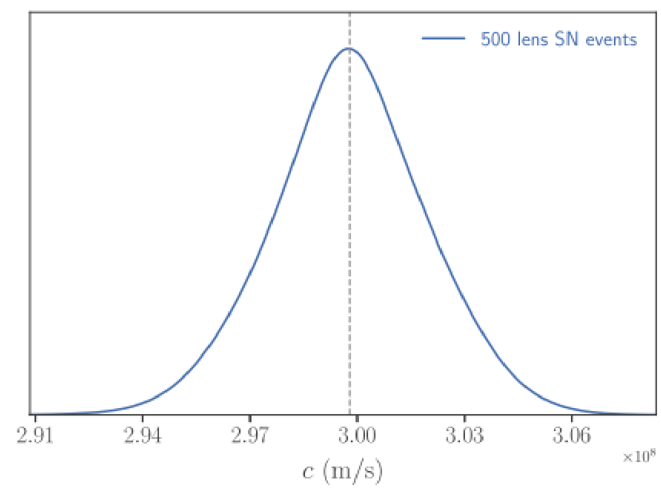

Figure 2. Probability distribution of the speed of light c possible to obtain from the forthcoming LSST survey.

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

The Astrophysical Journal Letters, 888:L25 (6pp), 2020 January 10 https://doi.org/10.3847/2041-8213/ab63d6

Precise Measurements of the Speed of Light with High-redshift Quasars: Ultra-compact Radio Structure and Strong Gravitational Lensing

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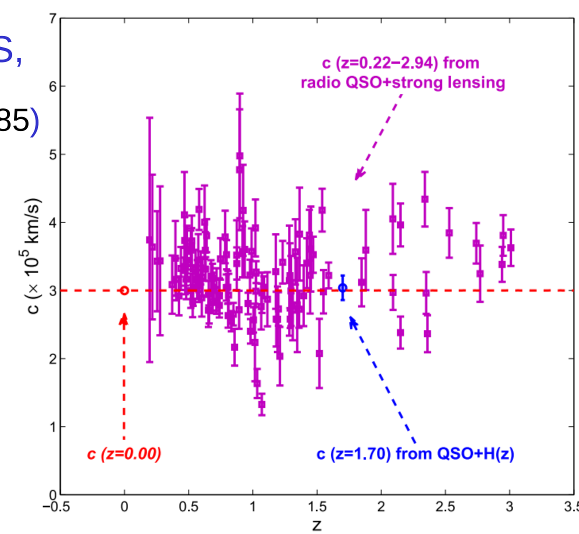
[2] Department of Physics, College of Sciences, Northeastern University, Shenyang 110004, People's Republic of China; qijingzhao@mail.neu.edu.cn
[3] National Centre for Nuclear Research, Pasteura 7, 02-093 Warsaw, Poland
Received 2019 November 7; revised 2019 December 18; accepted 2019 December 18; published 2020 January 16

We used a catalog of 118 lensing systems from SLACS, BELLS, LSD and SL2S (Cao, MB, et al. 2015, ApJ 806:185)

observable / measureable

$$c_{z_s} = \sigma_{\mathrm{ap}} \sqrt{\frac{4\pi}{\theta_E}\left(1 - \frac{1+z_l}{1+z_s}\frac{D_l}{D_s}\right)\left(\frac{\theta_E}{\theta_{\mathrm{ap}}}\right)^{2-\gamma} f(\gamma)}$$

obtainable from (redshift matched) ultra-compact radio QSOs



$$c(z_s) = 3.005(\pm 0.060) \times 10^5\ \mathrm{km\,s^{-1}}$$

summary

Prediction for the LSST and future VLBI compact radio QSOs

NCBJ is participating

VERA C. RUBIN OBSERVATORY

LSST

$$\frac{\Delta c}{c} = 10^{-4}$$

Table 1

Best-fit Values with 1σ Uncertainty for the Speed of Light Derived from Forthcoming Wide-area Surveys, with the Best Single Epoch, the Full and the Optimal Stack Imaging

Survey	DES (Best)	DES (Full)	DES (Optimal)
c (10^5 km s^{-1})	2.994 ± 0.016	2.995 ± 0.014	2.994 ± 0.015
Survey	LSST (best)	LSST (full)	LSST (optimal)
c (10^5 km s^{-1})	2.996 ± 0.004	2.995 ± 0.002	2.995 ± 0.003

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

• 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”**

Selected for a Viewpoint in *Physics*

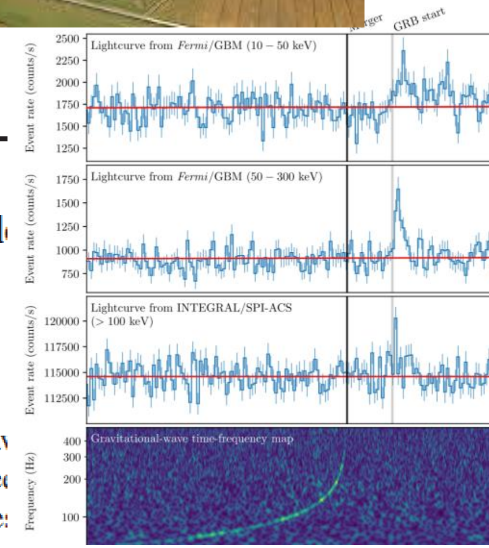
PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS

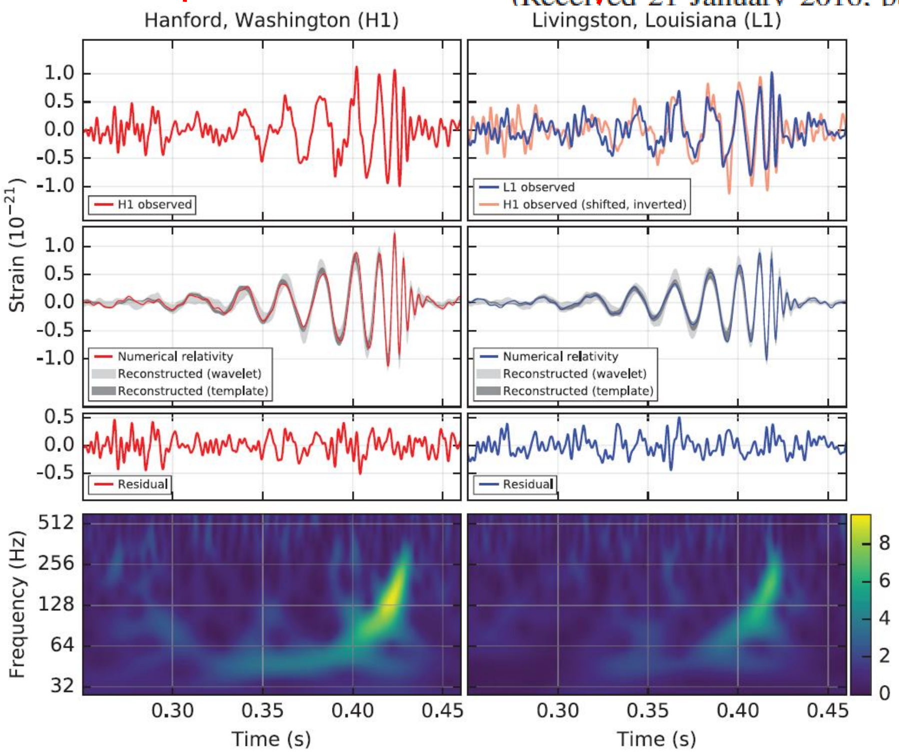
Observation of Gravitational Waves from a Binary Black Hol

B. P. Abbott *et al.*[*]

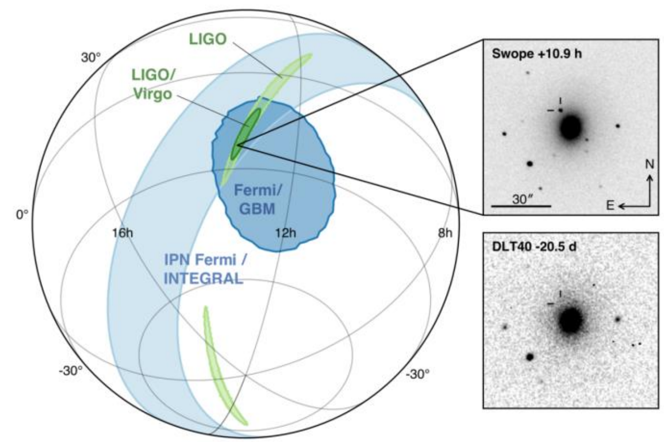
(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)





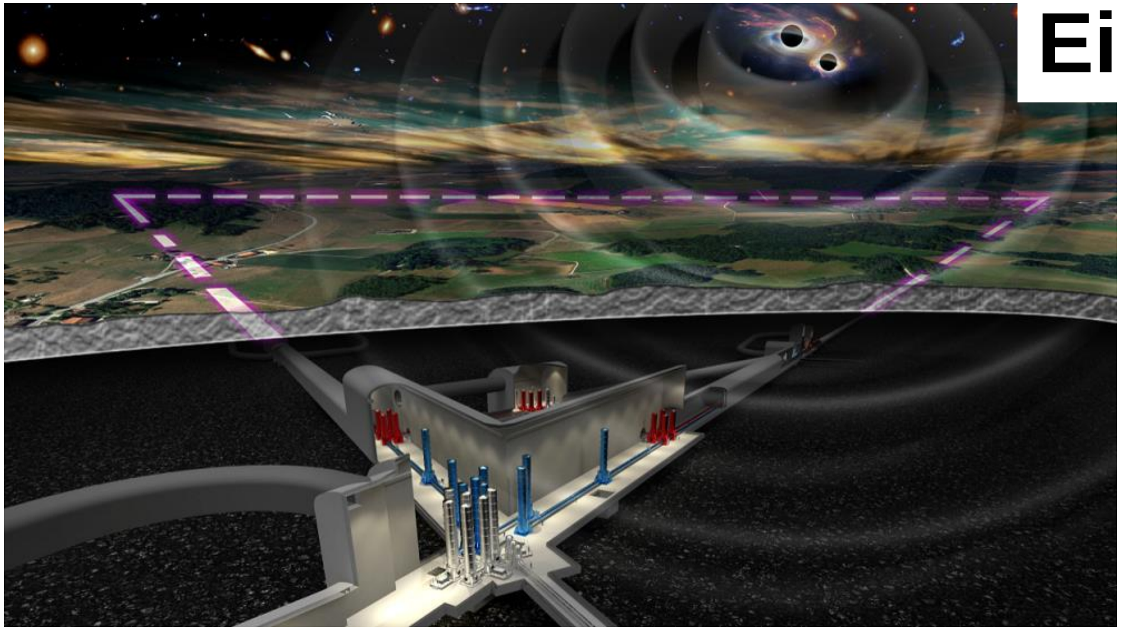
tors of the Laser Interferometer Grav
tional-wave signal. The signal swee
ave strain of 1.0×10^{-21}. It matche
r of a pair of black hol
ı a matched-filter signa
03 000 years, equivale
$^{160}_{180}$ Mpc correspondin



So far 50 registered gravitational signals in O1-O3 runs

GW150914 first ever
GW170817 first NS-NS
GW190426 first BH-NS

Einstein Telescope



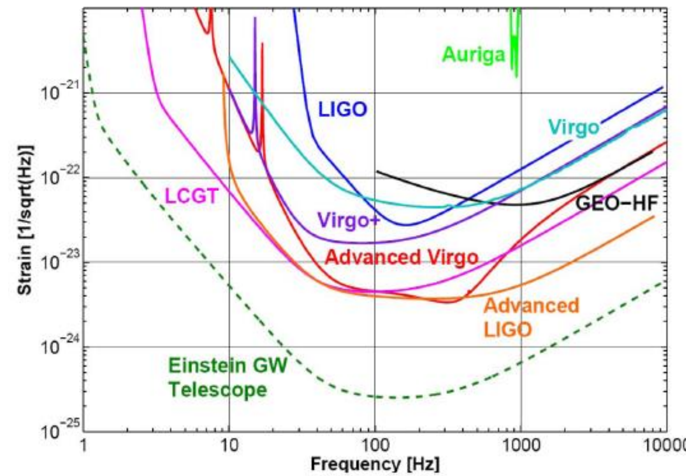


Figure 5: Sensitivities of gravitational wave detectors from the first to the third generation.

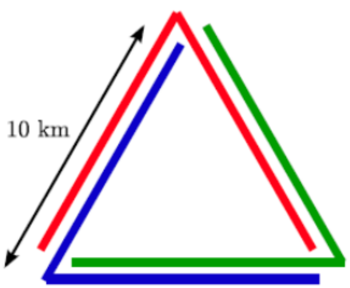


Figure 6: Three nested detectors in a triangular arrangement will form the final Einstein Telescope geometry.

Mpc^3 per Myr in the local universe ($z \simeq 0$). Also shown ar
)) and ET.

	BNS	NS-BH	BBH
	0.1–6	0.01–0.3	2×10^{-3}–0.04
aLIGO	0.4–400	0.2–300	2–4000
ET	$\mathcal{O}(10^3\text{–}10^7)$	$\mathcal{O}(10^3\text{–}10^7)$	$\mathcal{O}(10^4\text{–}10^8)$

- Increased sensitivity
  great expectations
- Big catalogs of inspiral events up to cosmological distances
- Some of them would be gravitationally lensed

Discussed in papers

A. Piórkowska *et al.* JCAP10(2013)022 (NS-NS only)

M. Biesiada *et al.* JCAP10(2014)080 (full DCO: NS-NS, BH-NS, BH-BH)

X. Ding *et al.* JCAP12(2015)006 (relaxing intrinsic SNR=8 demand; magnification bias)

50 – 100 lensed events per year

BH-BH systems contribute 91 – 95%;
NS-NS systems 1 – 4%

The Astrophysical Journal, 874:139 (6pp), 2019 April 1 https://doi.org/10.3847/1538-4357/ab095c

CrossMark

How Does the Earth's Rotation Affect Predictions of Gravitational Wave Strong Lensing Rates?

Lilan Yang[1], Xuheng Ding[1], Marek Biesiada[2,3], Kai Liao[4], and Zong-Hong Zhu[1,2]
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[3] Department of Astrophysics and Cosmology, Institute of Physics, University of Silesia, 75 Pułku Piechoty 1, 41-500, Chorzów, Poland
[4] School of Science, Wuhan University of Technology, Wuhan 430070, People's Republic of China
Received 2018 September 3; revised 2019 January 10; accepted 2019 February 20; published 2019 April 1

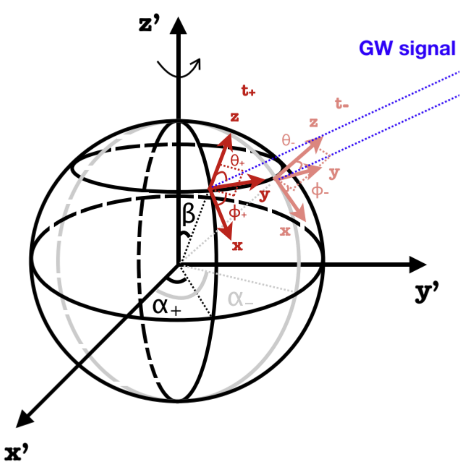

Table 1
Predictions of Yearly Lensed GW Event Rates for which Only I_- Image or Both I_- and I_+ Images are Magnified above the Threshold $\rho_0 = 8$

Metallicity Evolution Which Event Rate	High Only I_-	High I_- and I_+	Low only I_-	Low I_- and I_+
NS–NS				
Initial Design	0.7	0.4	0.6	0.4
Xylophone	1.4	1.1	1.2	0.7
BH–NS				
Initial Design	2.2	1.8	2.9	2.3
Xylophone	3.5	2.9	4.3	3.6
BH–BH				
Initial Design	106.6	94.3	130.3	115.4
Xylophone	143.5	128.0	177.6	159.2
Total				
Initial Design	109.5	96.5	133.8	118.1
Xylophone	148.4	132	183.1	163.5

Note. Results are shown for the standard model of DCO formation and two configurations of the ET. The "high" and "low" represent the "high-end" and "low-end" galaxy metallicity evolution.

In agreement with

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **476**, 2220–2229 (2018) doi:10.1093/mnras/sty411
Advance Access publication 2018 February 16

Gravitational lensing of gravitational waves: a statistical perspective

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[2] *School of Astronomy and Space Science, University of Chinese Academy of Sciences, Beijing 100049, China*
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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.

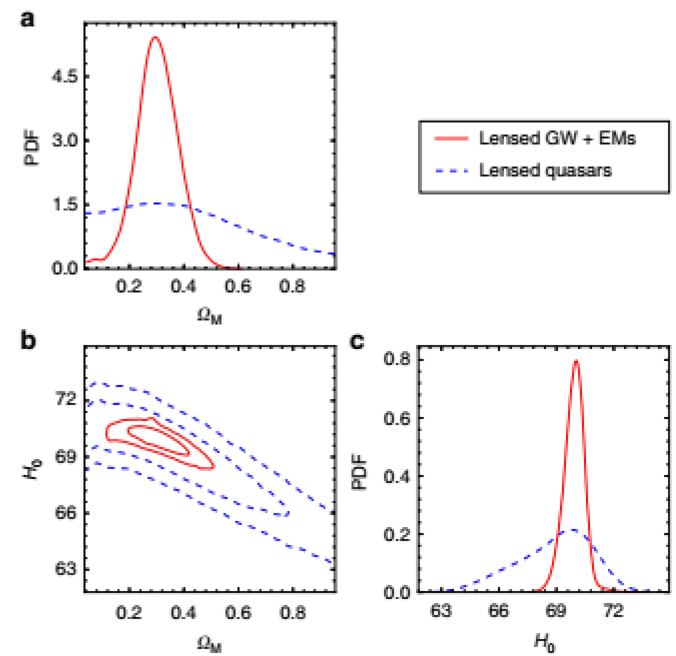

Table 2 The average constraining power of 10 lensed gravitational wave + electromagnetic systems

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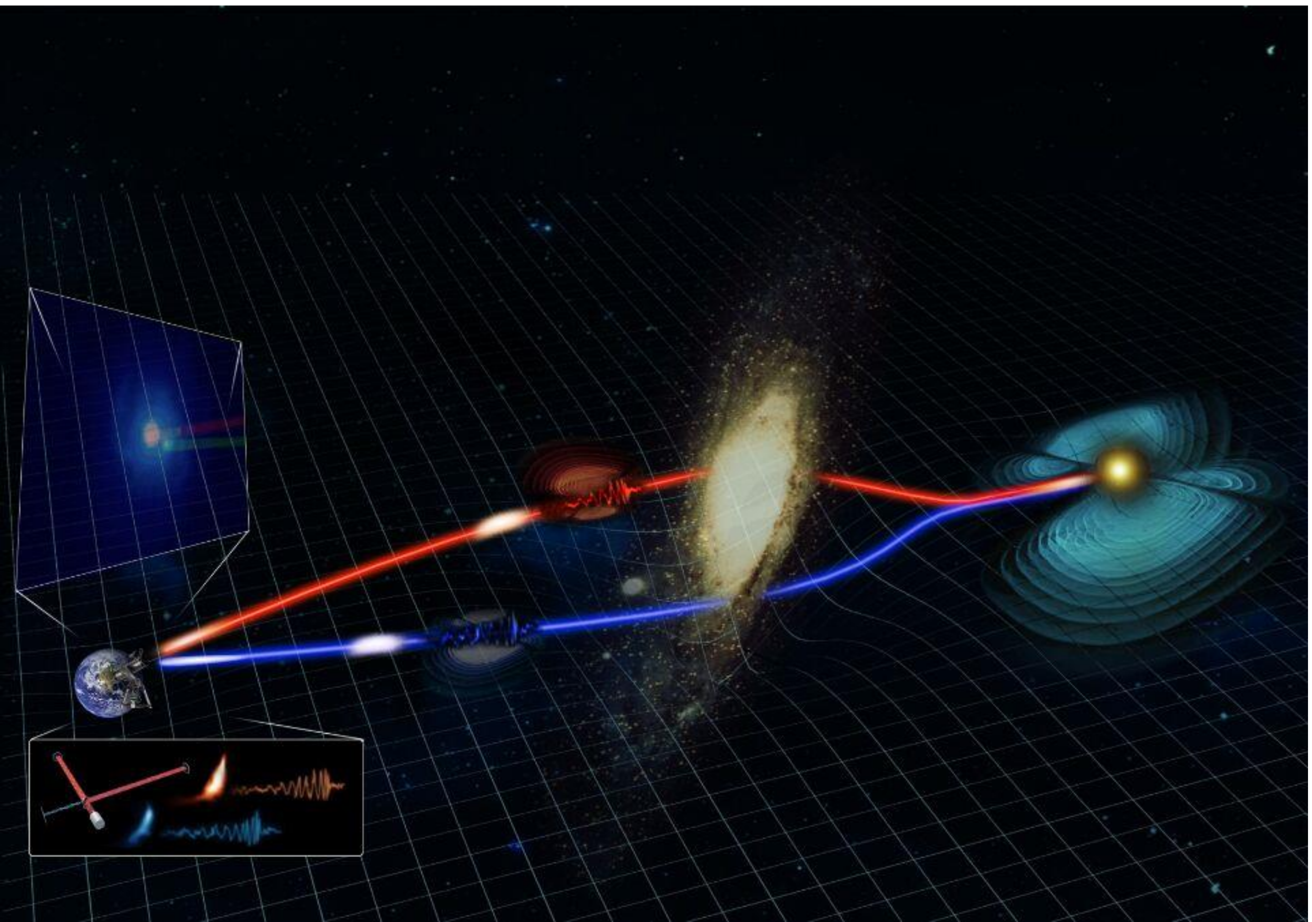
[4]*Department of Astrophysics and Cosmology, Institute of Physics, University of Silesia, Uniwersytecka 4, 40-007 Katowice, Poland*
[5]*Department of Astronomy, Beijing Normal University, Beijing 100875, China*



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

Idea

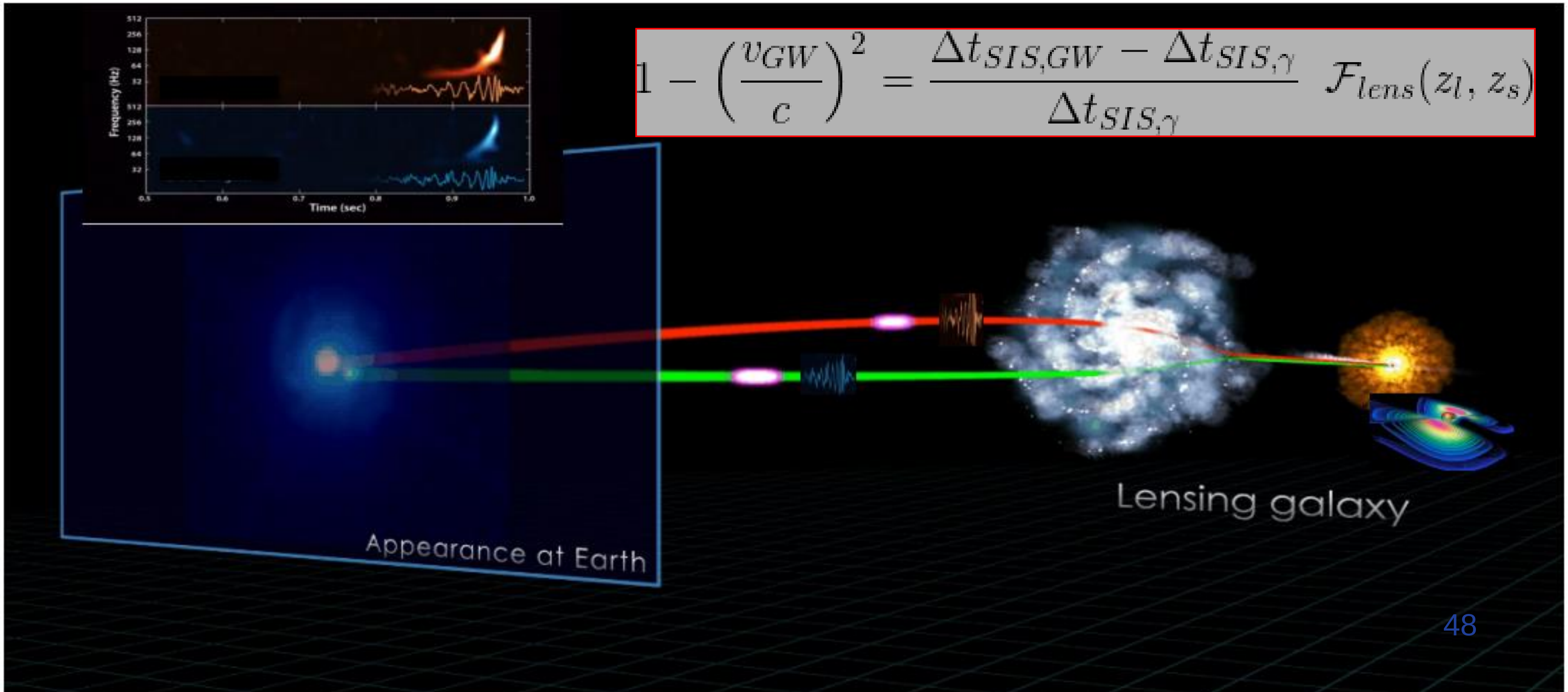
OTW - fale grawitacyjne (GW) rozchodzą się z prędkością światłą c, w zmodyfikowanych teoriach grawitacji mogą się propagować z inną prędkością v_{GW} (różną od c)

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

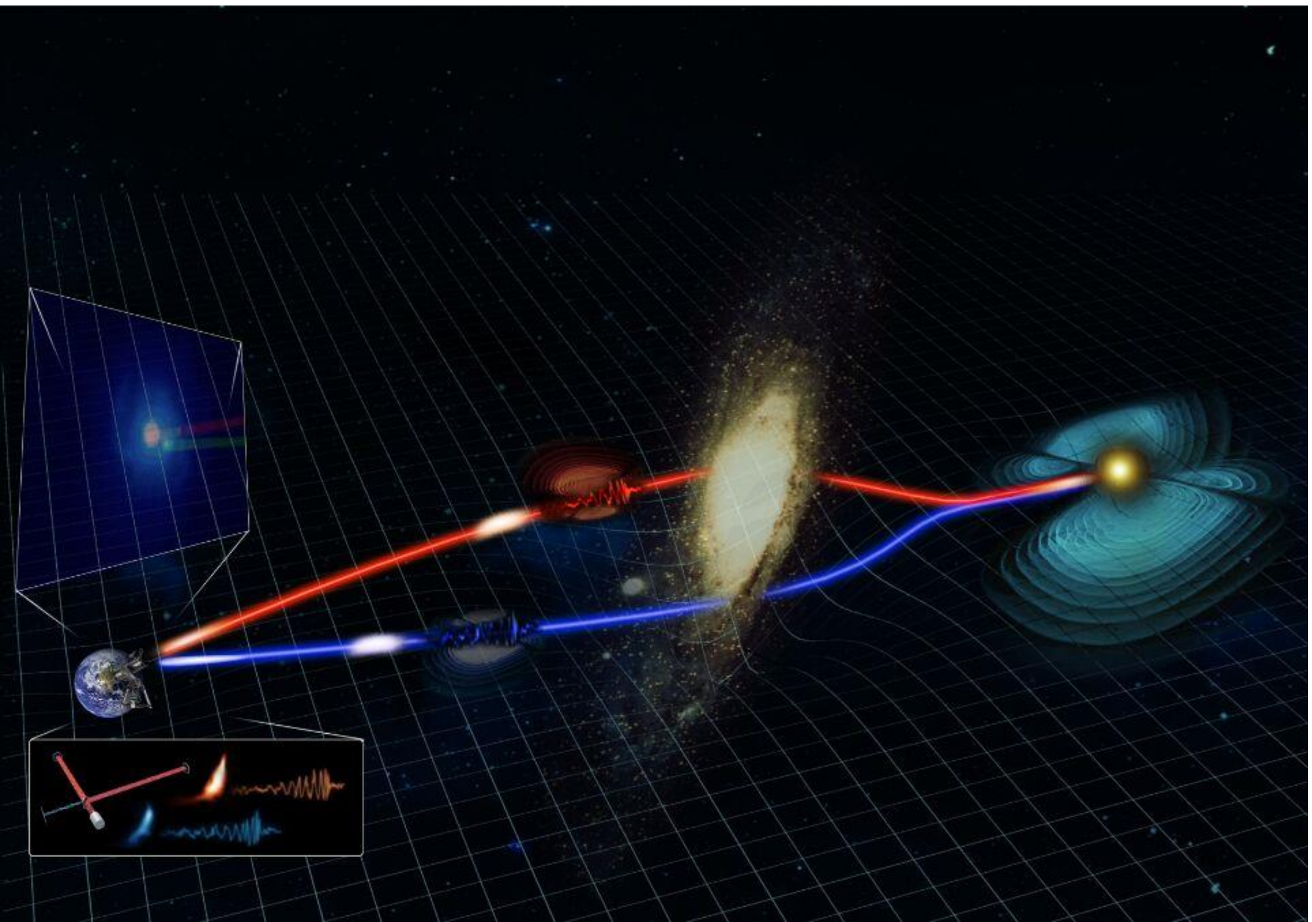
$$1 - \left(\frac{v_{GW}}{c}\right)^2 = \frac{\Delta t_{SIS,GW} - \Delta t_{SIS,\gamma}}{\Delta t_{SIS,\gamma}} \; \mathcal{F}_{lens}(z_l, z_s)$$



Mon. Not. R. Astron. Soc. **396,** 946–950 (2009) doi:10.1111/j.1365-2966.2009.14748.x

Gravitational lensing time delays as a tool for testing Lorentz-invariance violation

Marek Biesiada★ and Aleksandra Piórkowska★
Department of Astrophysics and Cosmology, Institute of Physics, University of Silesia, Uniwersytecka 4, 40-007 Katowice, Poland



Podobnie można będzie testować teorie łamiące niezmienniczość Lorentza (LIV
Lorentz Invariance Violation)

Zmodyfikowana relacja dyspersyjna dla fotonów (zależna od energii)


DZIĘKUJĘ ZA UWAGĘ !