Astrofizyka Cząstek w Polsce 2017
Kraków
20 - 22 września 2017

New probes of cosmological expansion

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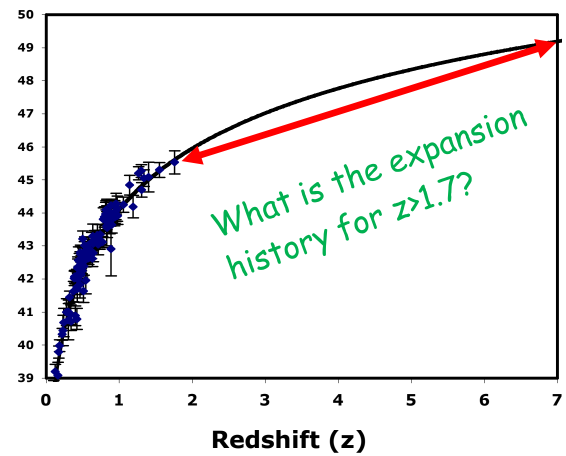
im. Augusta Chełkowskiego

UNIVERSITY OF SILESIA
IN KATOWICE



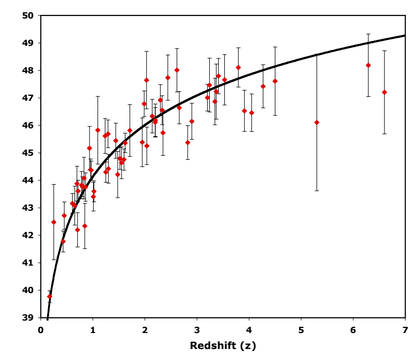
Standard candles:

•Supernovae Ia

Riess 1998, Perlmutter 1999, Wood-Vasey 2007, Kowalski 2008, Amanullah 2010

Gamma Ray Bursts (GRBs)

Schaffer 1996 ,
Ghirlanda 2004, Amati 2006,
Capozziello et al. 2011; Dainotti 2009



Standard sirens (inspiralling binaries)

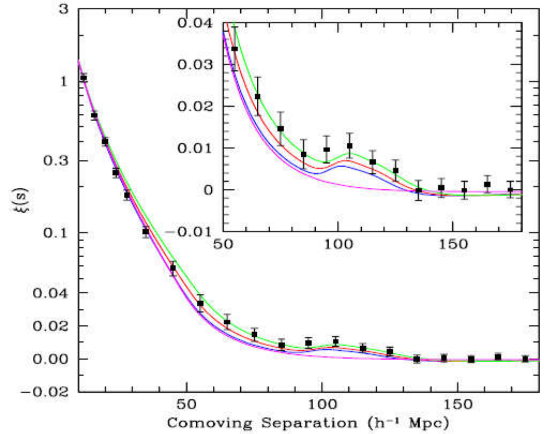
we are in era of GW astronomy !

Standard rulers:

Statistical standard rulers:

*CMBR acoustic peaks Spergel et al. 2007, Komatsu et al. 2011,

* BAO Eisenstein 2005

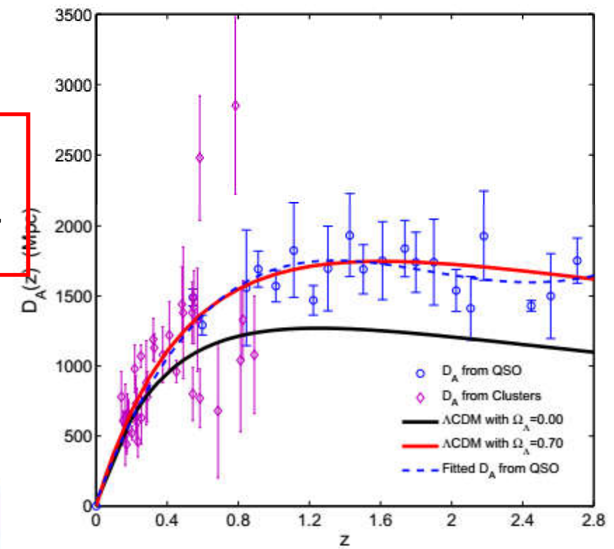


Individual standard rulers:

* Ultracompact radio sources

Kellermann 1993, Gurvitz 1994

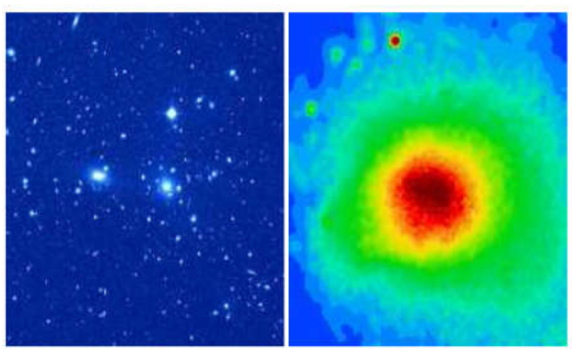
New well calibrated sample !
S.Cao, M.B. et al. 2017



* Fanaroff-Riley type IIb double-sided radio sources

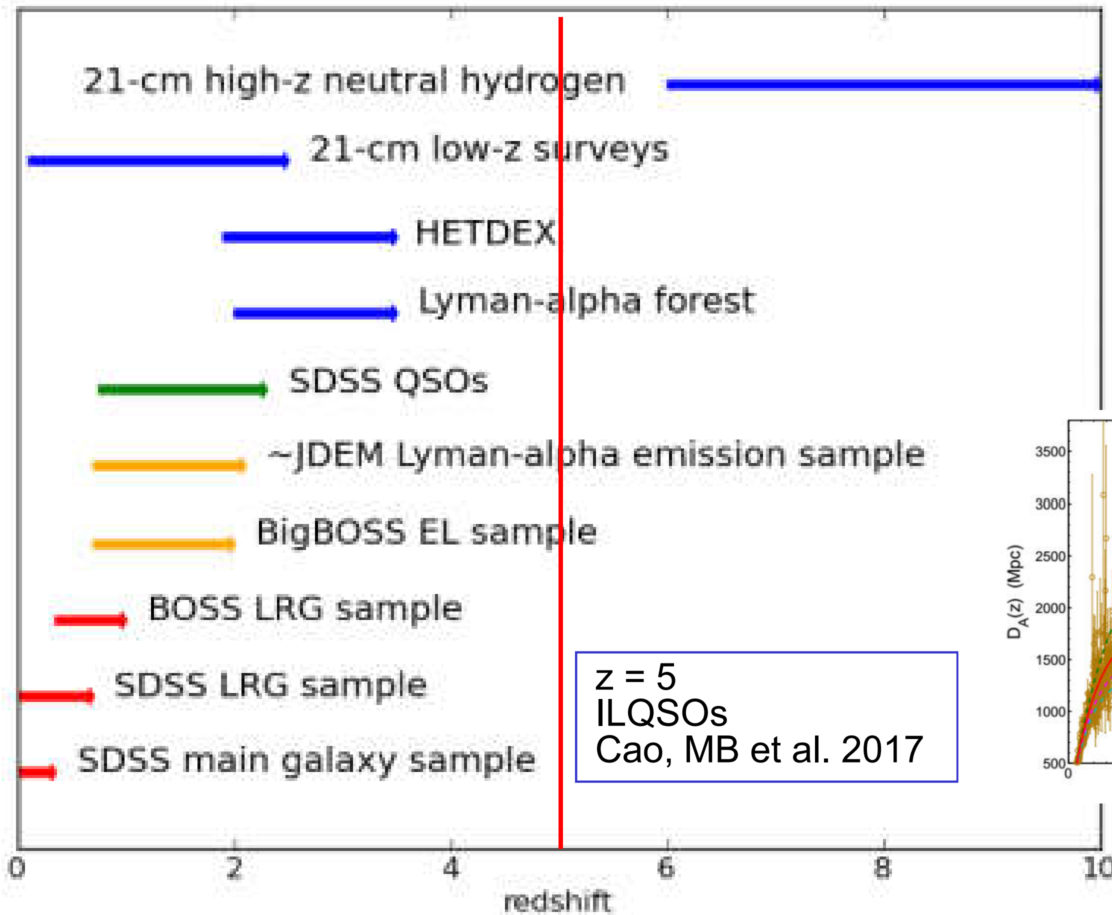
Daly 1994, Daly et al. 2002, 2007

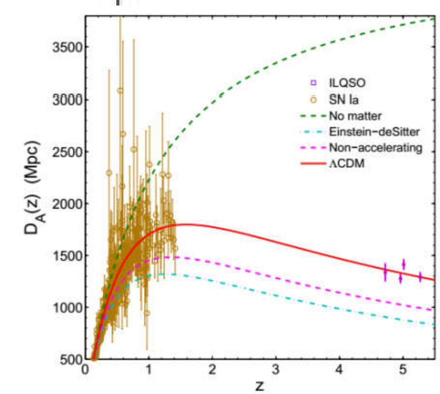
* Clusters of galaxies: combined X-ray + SZ data



*Gravitational Lenses – a new class of standard(izable) rulers
M.B., S. Cao, et al.

Redshift reach of different cosmological probes





THE ASTROPHYSICAL JOURNAL, 806:66 (7pp), 2015 June 10 doi:10.1088/0004-637X/806/1/66

EXPLORING THE PROPERTIES OF MILLIARCSECOND RADIO SOURCES

SHUO CAO[1], MAREK BIESIADA[1,2], XIAOGANG ZHENG[1], AND ZONG-HONG ZHU[1]
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Received 2015 January 7; accepted 2015 April 9; published 2015 June 9

$$\boxed{\theta(z) = \frac{l_m}{D_A(z)}}$$

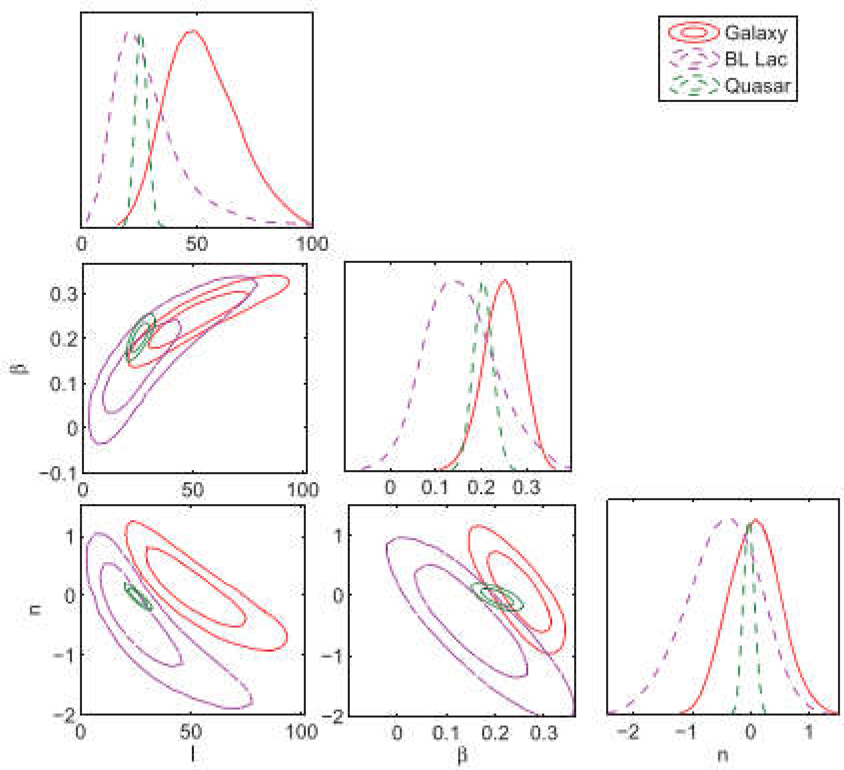


Figure 3. Constraints on compact source parameters obtained from three subsamples with different optical counterparts.

$$l_m = l\left(\frac{L}{L_0}\right)^{\beta}(1+z)^n$$

Conclusion:

only radio quasars are promissing for further calibration

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Measuring the speed of light with ultra-compact radio quasars

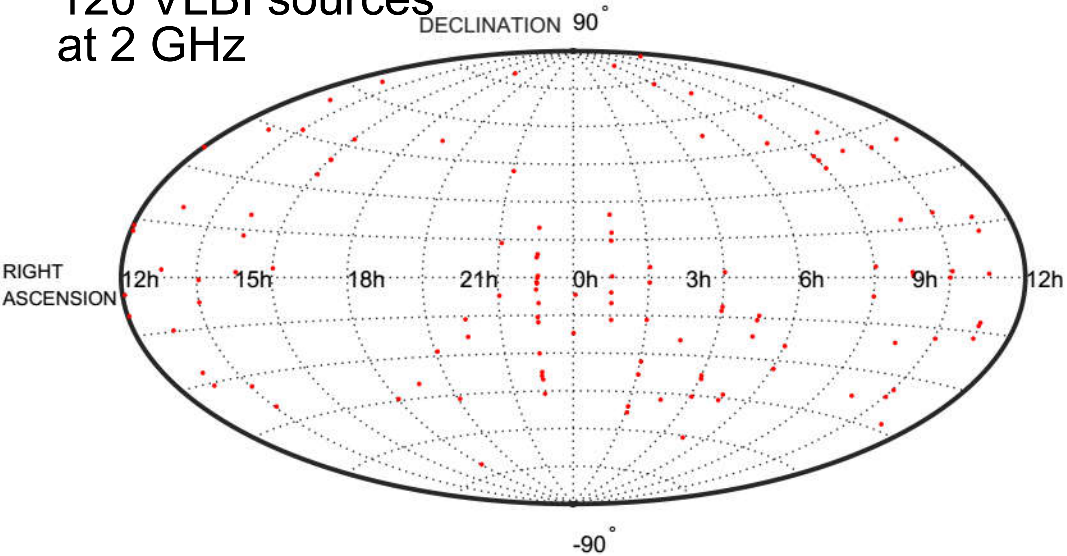
Shuo Cao,[a] Marek Biesiada,[a,b] John Jackson,[a] Xiaogang Zheng,[a] Yuhang Zhao[a] and Zong-Hong Zhu[a]

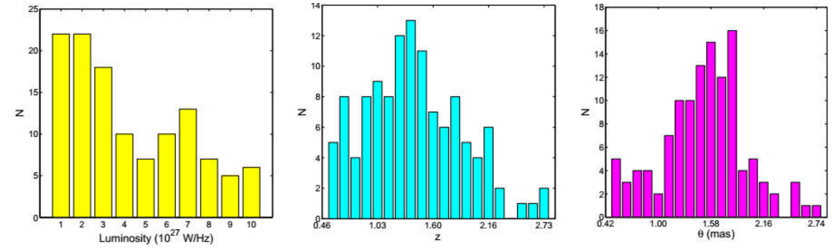
JCAP02(2017)01

Ultra-compact structure in intermediate-luminosity radio quasars: building a sample of standard cosmological rulers and improving the dark energy constraints up to $z \sim 3$

Shuo Cao[1], Xiaogang Zheng[1,2], Marek Biesiada[1,2], Jingzhao Qi[1], Yun Chen[3], Zong-Hong Zhu[1,*]

120 VLBI sources
at 2 GHz





l = 11.03 ±0.25 pc

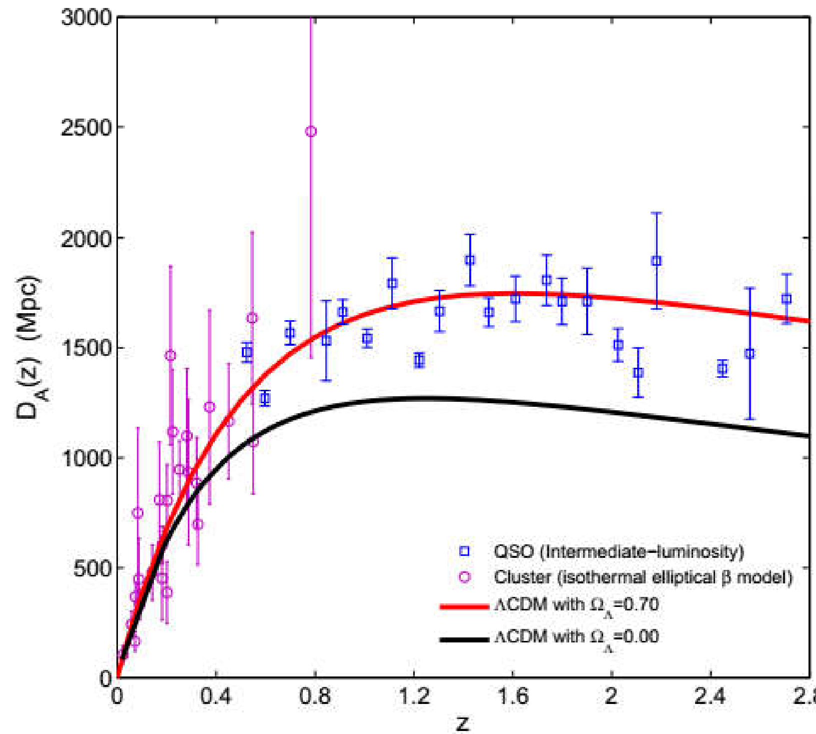
Steps:

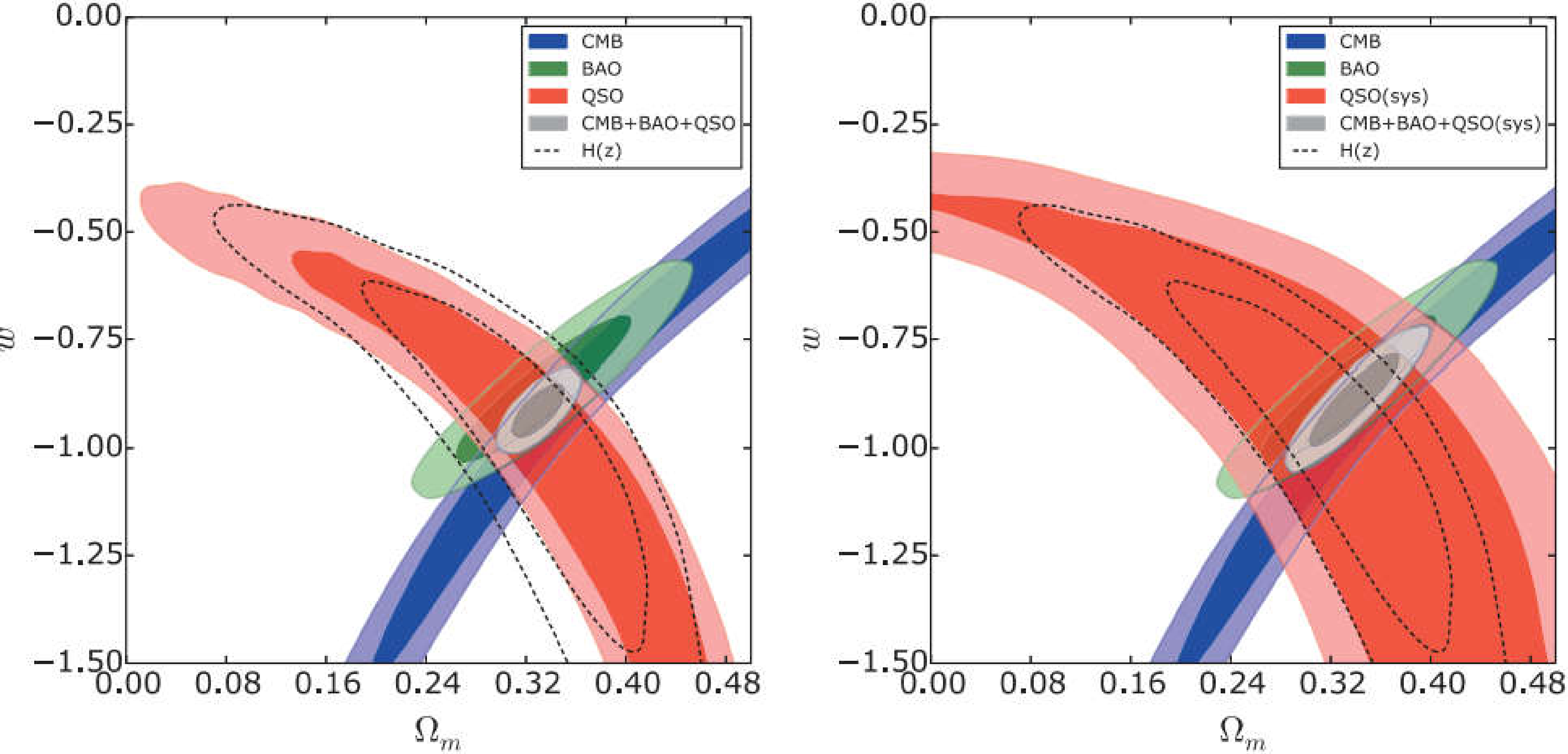
1. expansion rate reconstruction from H(z) data (cosmic chronometers)

2. robust selection of luminosity sample

3. calibration of standard rulers

4. $D_A(z)$ reconstruction (GP) from binned ILQSO data or use of calibrated ILQSO for cosmological parameter inference




CMB
BAO
QSO
CMB+BAO+QSO
H(z)
QSO(sys)
CMB+BAO+QSO(sys)
w
Ω_m
0.00
−0.25
−0.50
−0.75
−1.00
−1.25
−1.50
0.00
0.08
0.16
0.24
0.32
0.40
0.48

GP reconstructed $D_A(z)$ from ILQSO (+ clusters right panel)

GP reconstructed H (z) from cosmic chronometers

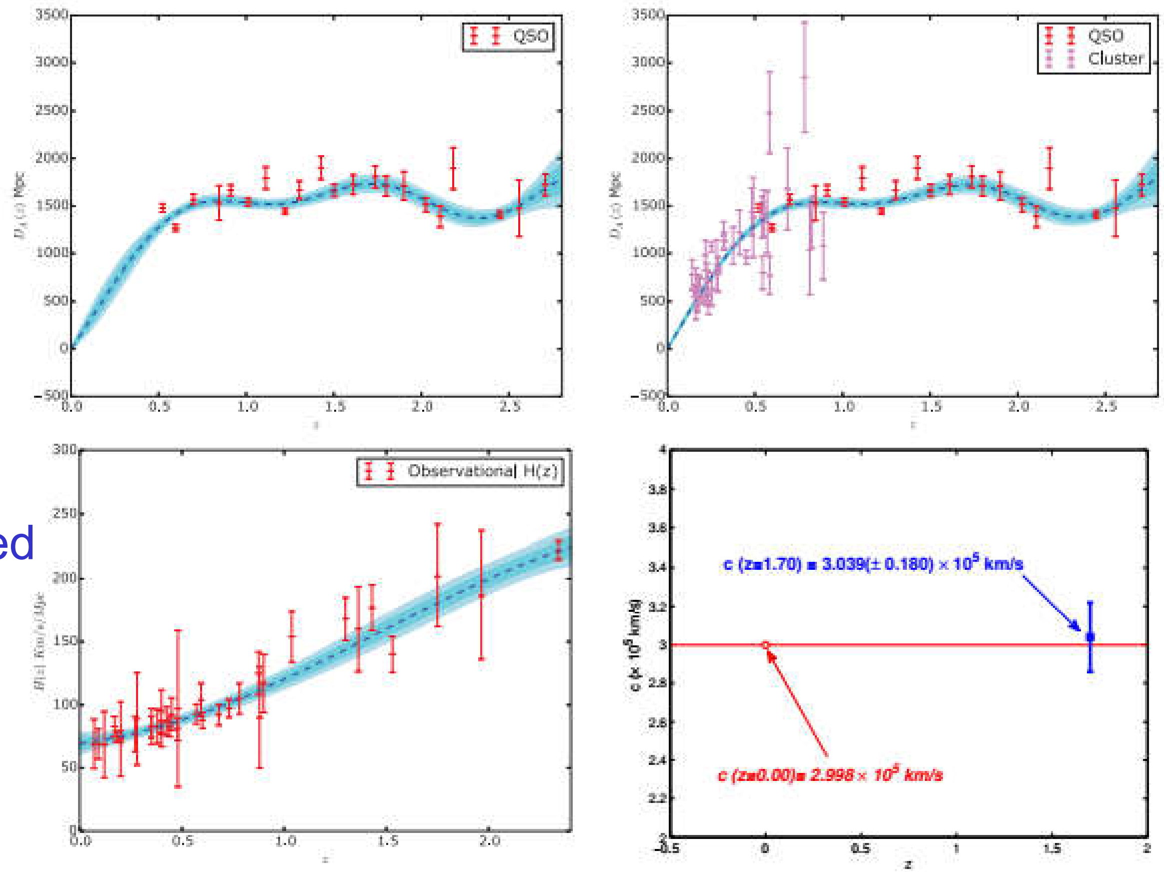


Figure 7. Upper left: GP reconstructed $D_A(z)$ using the data concerning quasars; Upper right: GP reconstructed $D_A(z)$ using the data with both quasar and cluster observations; Lower left: GP reconstructed $H(z)$ data with Hubble parameter observations; Lower right: the measured speed of light c at redshift $z = 1.70$ (blue square with error bars) and c_0 at redshift $z = 0$ (red circle). Standard assumes that c is a universal constant c_0 so the red horizontal line has also been added for comparison.

Speed of light derived

accroding to the idea of

V.Salzano , M.P. Dabrowski R Lazkoz *Phys. Rev. Lett.* **114** (2015) 101304

Eur. Phys. J. C (2017) 77:502
DOI 10.1140/epjc/s10052-017-5069-1

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Theoretical Physics

New observational constraints on $f(T)$ cosmology from radio quasars

Jing-Zhao Qi[1], **Shuo Cao**[1,a], **Marek Biesiada**[1,2], **Xiaogang Zheng**[1,2], **Zong-Hong Zhu**[1]

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[2] Department of Astrophysics and Cosmology, Institute of Physics, University of Silesia, Uniwersytecka 4, 40-007 Katowice, Poland

Original idea of using strong lensing systems as a tool for cosmology

velocity dispersion - spectroscopy

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

Astrometry – location of images

distance ratio sensitive to cosmology

PHYSICAL REVIEW D 73, 023006 (2006)

Strong lensing systems as a probe of dark energy in the universe

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[1]*Department of Astrophysics and Cosmology, University of Silesia, Uniwersytecka 4, 40-007*

(Received 3 November 2005; published 23 January 2006)

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]

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

Mon. Not. R. Astron. Soc. **406**, 1055–1059 (2010) doi:10.1111/j.136

Cosmic equation of state from strong gravitational lensing systems

Marek Biesiada,★ Aleksandra Piórkowska★ and Beata Malec★

Department of Astrophysics and Cosmology, Institute of Physics, University of Silesia, Uniwersytecka 4, 40-007 Katowice, Poland

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

118 lenses:

SLACS	57
BELLS	25
SL2S	5
LSD	5

Spherical power-law mass distribution

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

Stellar dynamics (spherical Jeans equation): mass inside projected aperture radius scaled to Einstein radius

Lensing: mass inside Einstein radius

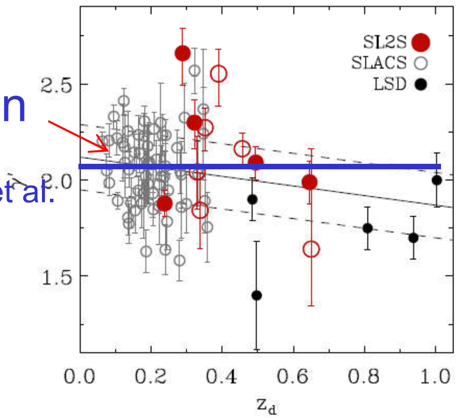
$$M_{\rm lens} = \frac{c^2}{4G}\frac{D_s D_l}{D_{ls}}\theta_E^2$$

+

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

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

Based on SLACS
Koopmans et al. 2006



A.Ruff , R.Gavazzi et al. 2010

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

γ slope evolution

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

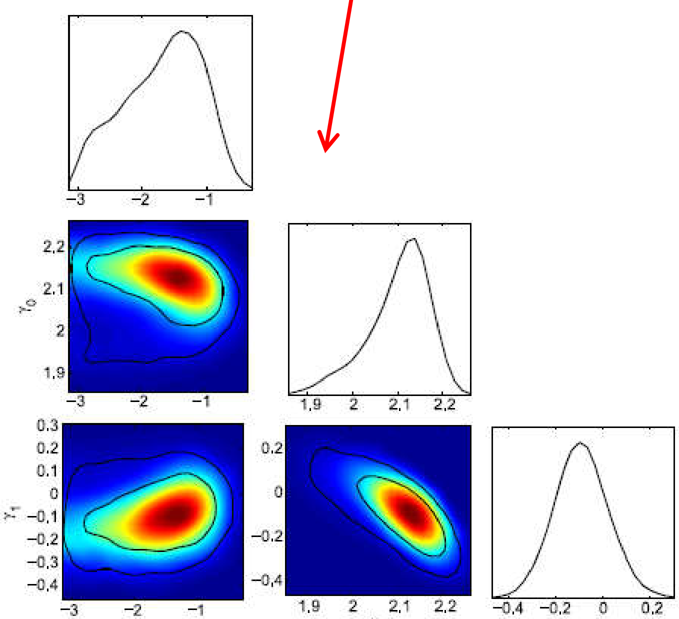
vs.

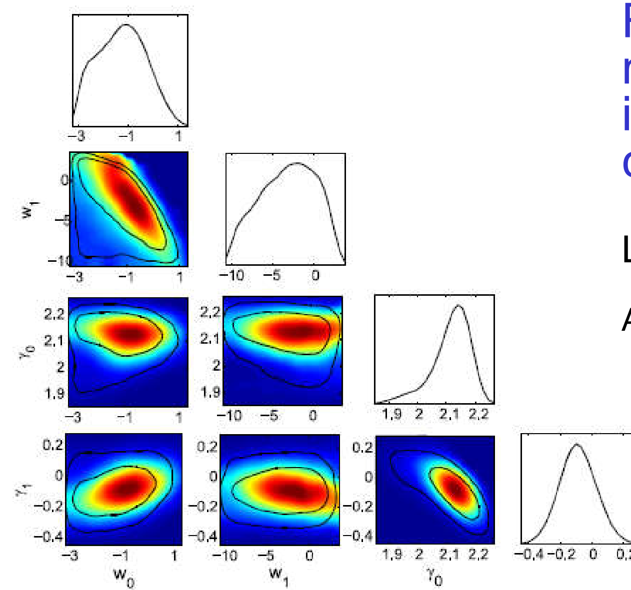
$$D^{\rm th}(z_l, z_s; p) = \frac{D_{ls}(p)}{D_s(p)} = \frac{\int_{z_l}^{z_s}\frac{dz'}{h(z';p)}}{\int_0^{z_s}\frac{dz'}{h(z';p)}}$$

The Astrophysical Journal, 806:185 (12pp), 2015 June 20 Cao et al.

Table 2
Dark Energy (XCDM Model and CPL Parametrization) Constraints Obtained on the Full 118 Strong-lensing (SL) Sample[a]

Cosmology (Sample)	w_0	w_1	γ_0	γ_1
XCDM1 (SL; σ_{ap})	$w_0 = -1.45^{+0.54}_{-0.95}$	$w_1 = 0$	$\gamma_0 = 2.03 \pm 0.06$	$\gamma_1 = 0$
XCDM1 (SL; σ_0)	$w_0 = -1.15^{+0.56}_{-1.20}$	$w_1 = 0$	$\gamma_0 = 2.07 \pm 0.07$	$\gamma_1 = 0$
XCDM2 (SL; σ_{ap})	$w_0 = -1.48^{+0.54}_{-0.94}$	$w_1 = 0$	$\gamma_0 = 2.06 \pm 0.09$	$\gamma_1 = -0.09 \pm 0.16$
XCDM2 (SL; σ_0)	$w_0 = -1.35^{+0.67}_{-1.50}$	$w_1 = 0$	$\gamma_0 = 2.13^{+0.07}_{-0.12}$	$\gamma_1 = -0.09 \pm 0.17$
CPL1 (SL; σ_{ap})	$w_0 = -0.15^{+1.27}_{-1.60}$	$w_1 = -6.95^{+7.25}_{-3.05}$	$\gamma_0 = 2.08 \pm 0.09$	$\gamma_1 = -0.09 \pm 0.17$
CPL1 (SL; σ_0)	$w_0 = -1.00^{+1.54}_{-1.95}$	$w_1 = -1.85^{+4.85}_{-6.75}$	$\gamma_0 = 2.14^{+0.07}_{-0.10}$	$\gamma_1 = -0.10 \pm 0.18$
CPL2 (SL; σ_{ap})	$w_0 = -0.16^{+1.21}_{-1.48}$	$w_1 = -6.25^{+6.25}_{-3.75}$	$\gamma_0 = 2.08$	$\gamma_1 = -0.09$
CPL2 (SL; σ_0)	$w_0 = -1.05^{+1.43}_{-1.77}$	$w_1 = -1.65^{+4.25}_{-6.35}$	$\gamma_0 = 2.14$	$\gamma_1 = -0.10$
CPL2 (SN)	$w_0 = -1.00 \pm 0.40$	$w_1 = -0.12^{+1.58}_{-2.78}$	□	□





Robust inference of mass density profile – irrespective of cosmological model

Li, Cao, Zheng, M.B., Zhu
2015
ApJ submitted

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

SHUO CAO[1], XIAOLEI LI[1], MAREK BIESIADA[1,2], TENGPENG XU[1], YONGZHI CAI[1], AND ZONG-HONG ZHU[1]
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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

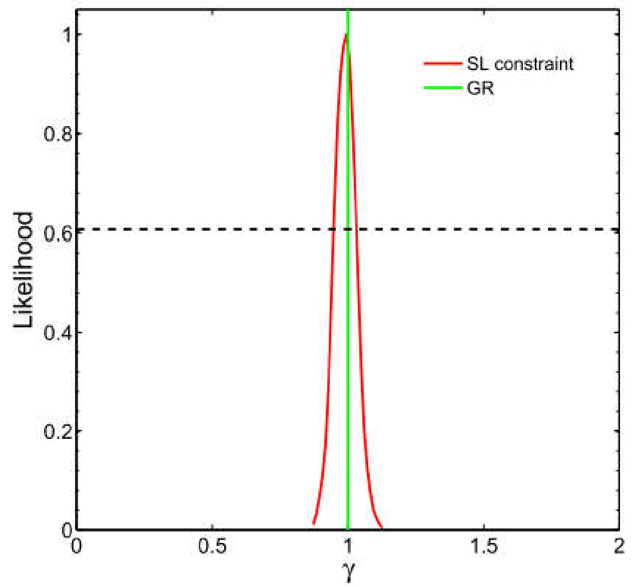
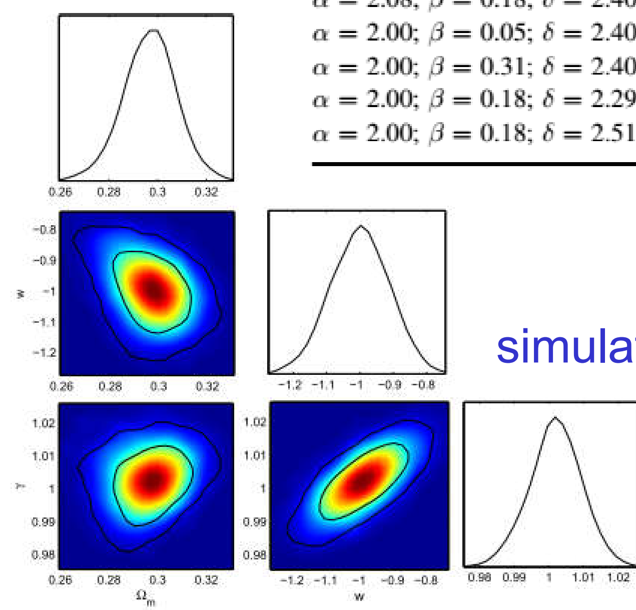


Figure 3. Normalized posterior likelihood of the PPN γ parameter obtained with rigid priors on the nuisance parameters (α, β, δ).

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

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.

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

THE ASTROPHYSICAL JOURNAL, 822:74 (5pp), 2016 May 10
doi:10.3847/0004-637X/822/2/74

THE DISTANCE DUALITY RELATION FROM STRONG GRAVITATIONAL LENSING

KAI LIAO[1], ZHENGXIANG LI[2], SHUO CAO[2], MAREK BIESIADA[2,3], XIAOGANG ZHENG[2], AND ZONG-HONG ZHU[2]
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[2] Department of Astronomy, Beijing Normal University, Beijing 100875, China
[3] Department of Astrophysics and Cosmology, Institute of Physics, University of Silesia, Uniwersytecka 4, 40-007 Katowice, Poland
Received 2016 January 10; accepted 2016 March 15; published 2016 May 10

$$\boxed{\frac{D_A(z)(1+z)^2}{D_L(z)} \equiv 1}$$

Etherington reciprocity relation
<u>Pre-assumptions:</u>
- metric theory of gravity
- photon number conserved in the beam

D_A dist. ratios from SL systems

D_L dist. ratios from SN Ia

$$\frac{D^A(z)(1+z)^2}{D^L(z)} = \eta(z) \approx 1 + \eta_0 z.$$

	SL
η_0	$\boxed{-0.005^{+0.351}_{-0.215}(1\sigma)^{+0.907}_{-0.386}(2\sigma)}$
α	$0.129^{+0.092}_{-0.088}(1\sigma)^{+0.189}_{-0.176}(2\sigma)$
β	$6.700^{+2.017}_{-1.415}(1\sigma)^{+3.264}_{-1.957}(2\sigma)$
f_e	$1.022^{+0.029}_{-0.030}(1\sigma)^{+0.055}_{-0.062}(2\sigma)$
M_B	...

stretching factor

color factor

velocity dispersion factor

cancels for the ratios

Gravitational waves detected 100 years after Einstein's prediction

LIGO PRESS RELEASE

Selected for a Viewpoint in *Physics*
PRL **116**, 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

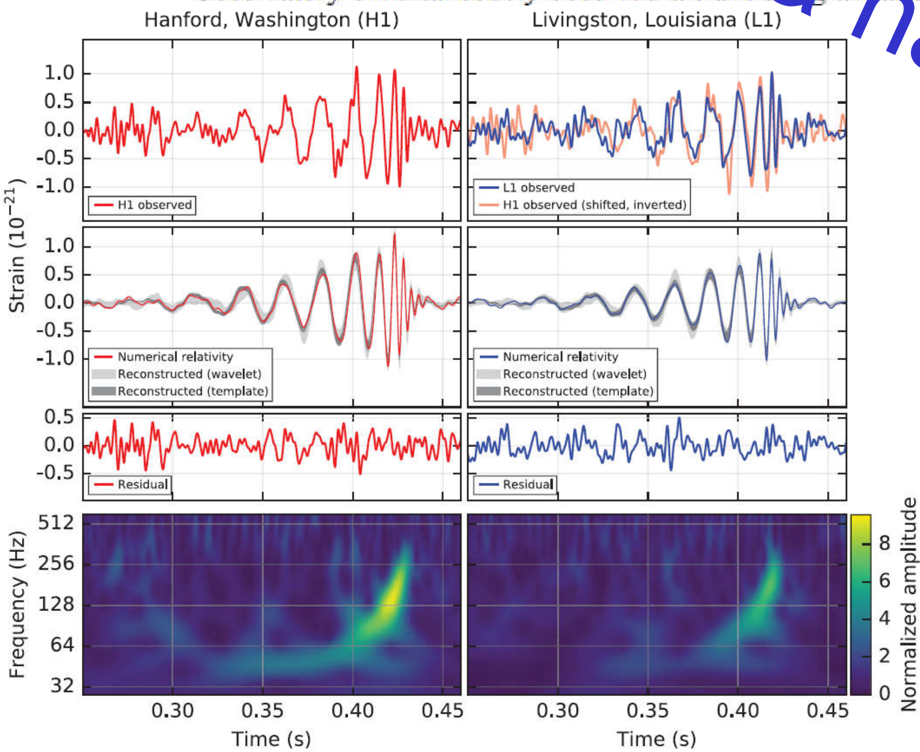
Observation of Gravitational Waves from a Binary Black Hole Merger

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

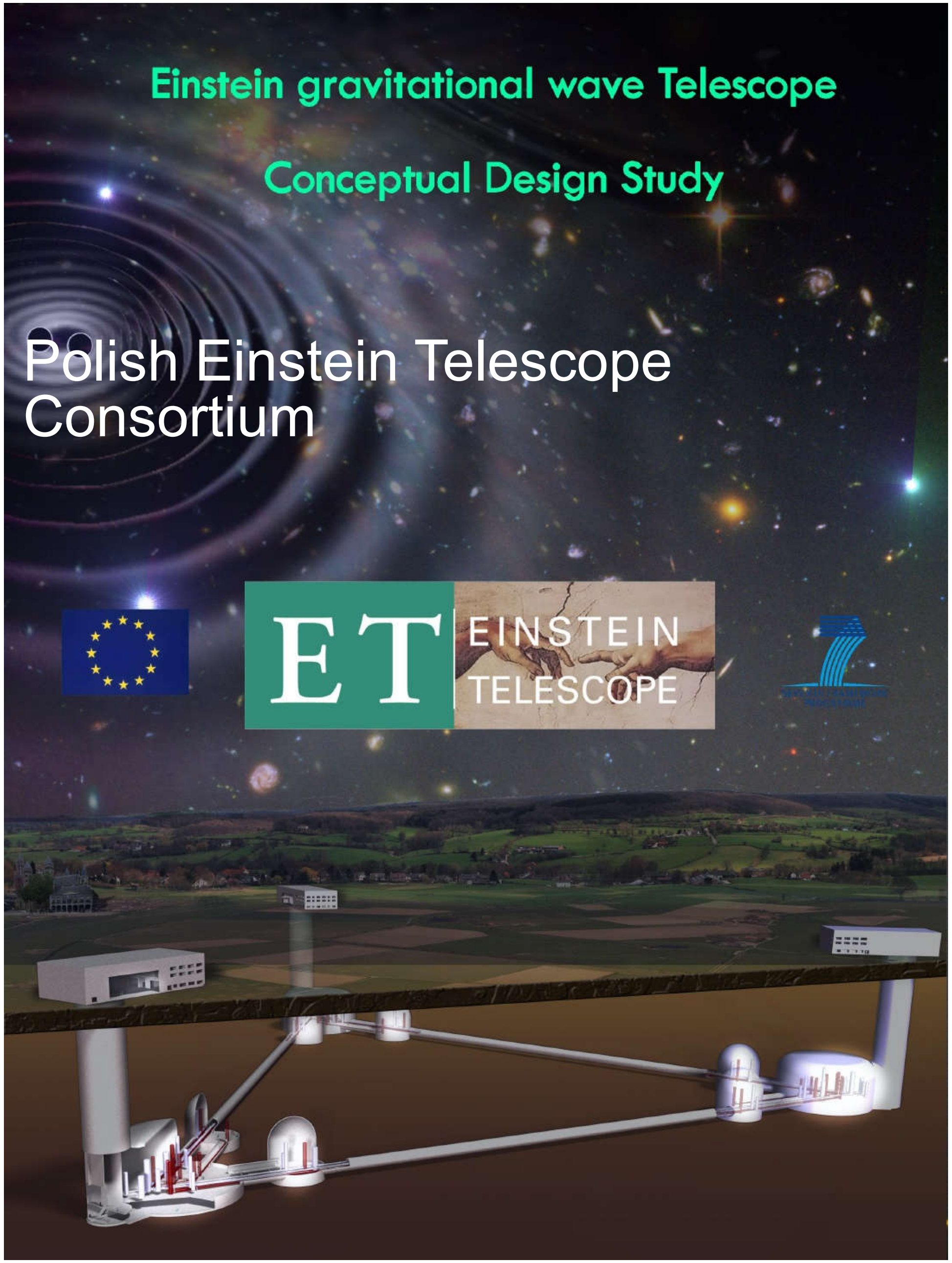
(Received 21 January 2016; published 11 February 2016)

New era has begun

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gr
Observatory simultaneously observed a transient gravitational-wave signal. The signal sw
strain of 1.0×10^{-21}. It match
a pair of black holes and the
matched-filter signal-to-noise r
000 years, equivalent to a sig
Mpc corresponding to a redsh
and $29^{+4}_{-4} M_\odot$, and the final bl
. All uncertainties define 90% cre
ar-mass black hole systems. This is
of a binary black hole merger.



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



looking to the future:

Einstein Telescope

- Increased sensitivity
great expectations

- Big catalogs of inspiral events up to cosmological distances

- Multi-messenger astrophysics

- Some of them would be gravitationally lensed

Predictions in papers:

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)022

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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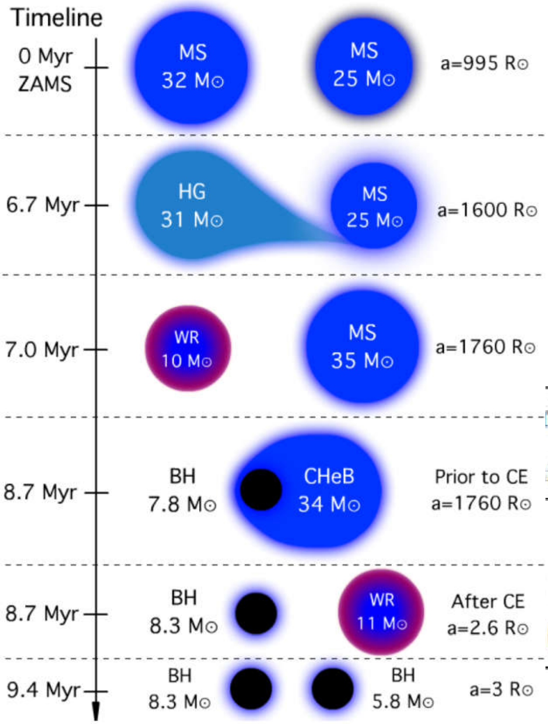
[b]Department of Astrophysics and Cosmology, Institute of Physics, University of Silesia, Uniwersytecka 4, 40-007 Katowice, Poland
[c]Kavli Institute for Theoretical Physics China, CAS, Beijing 100190, China
E-mail: dingxuheng@mail.bnu.edu.cn, marek.biesiada@us.edu.pl, zhuzh@bnu.edu.cn

JCAP12(2015)

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

StarTrack intrinsic merger rates

M. Biesiada et al JCAP10(2014)080



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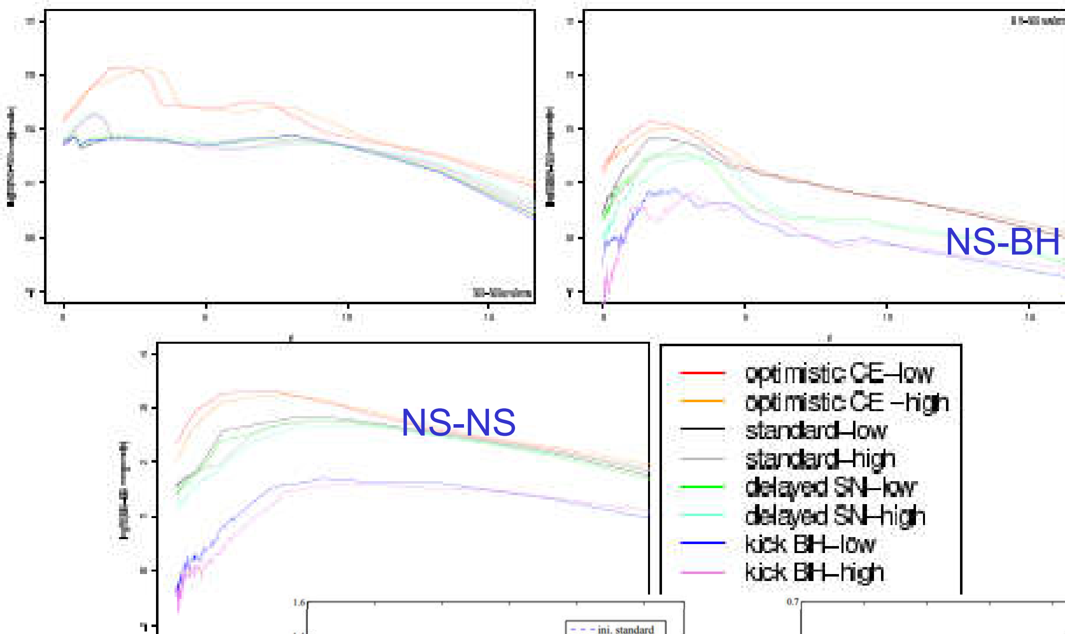
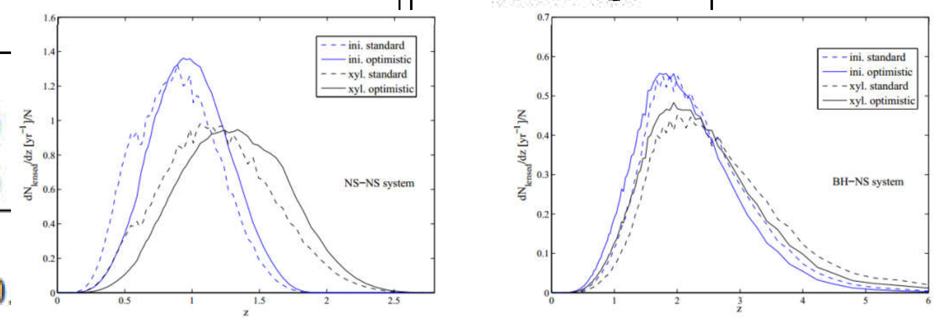
inuous)

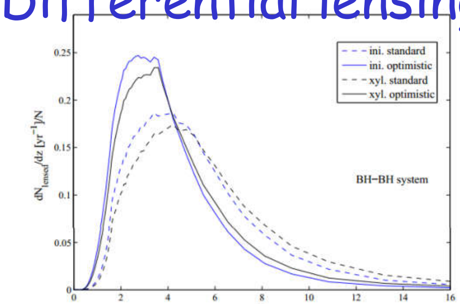
0.07)

0.2)





Differential lensing rate



initial design	(0.4; 0.5; 0.5)	(1.1; 1.3; 1.3)
xylophone	(0.9; 1.1; 1.1)	(2.1; 2.4; 2.5)
BH-BH		
initial design	(30.3; 36.1; 37.6)	(99.1; 116.0; 120.
xylophone	(45.8; 54.9; 57.2)	(136.7; 160.8; 166
TOTAL		
initial design	(30.8; 36.7; 38.2)	(100.4; 117.4; 121
xylophone	(46.9; 56.2; 58.5)	(139.5; 164.2; 170

Table 3. Expected numbers of lensed GW events from der different evolutionary scenarios. "High-end" metallic Einstein Telescope in the initial and "xylophone" configuration.

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

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

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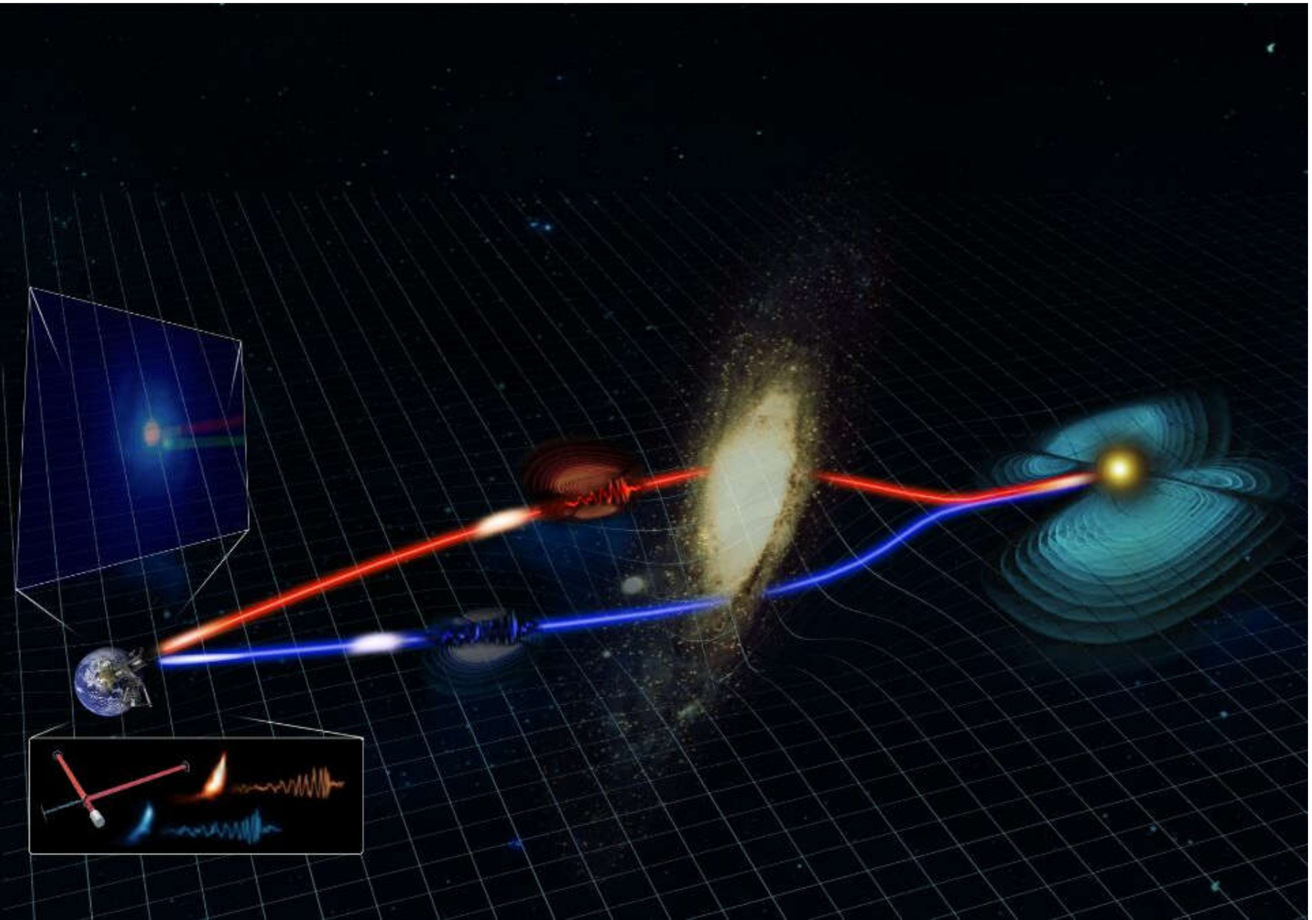

Difference in SL time delays in EM and GW windows

allow testing propagation speed of GWs

New opportunity for multimessenger astronomy

THE ASTROPHYSICAL JOURNAL LETTERS, 803:L22 (5pp), 2015 April 20 doi:10.1088/2041-8205/803/2/L22

IS THERE EVIDENCE FOR DARK ENERGY EVOLUTION?

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$$\tilde{h}(z) \equiv H(z)/H_0$$

$$\boxed{\mathrm{Om}(z) = \frac{\tilde{h}^2(z) - 1}{(1 + z)^3 - 1}}$$

Sahni, V., Shafieloo, A. & Starobinsky, A.A., 2008, Phys. R ev. D, 78, 103502 [arXiv:0807.3548]

$$Om(z)_{\Lambda CDM} = \Omega_{m,0}$$

THE ASTROPHYSICAL JOURNAL, 825:17 (9pp), 2016 July 1 doi:10.3847/0004-637X/825/1/17

WHAT ARE THE Omh^2 (z_1, z_2) AND Om (z_1, z_2) DIAGNOSTICS TELLING US IN LIGHT OF $H(z)$ DATA?

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Two-point Om(z_1, z_2) diagnostic:

$$Om(z_1, z_2) \equiv Om(z_1) - Om(z_2)$$
$$= \boxed{\frac{\tilde{h}^2(z_1) - 1}{(1+z_1)^3 - 1} - \frac{\tilde{h}^2(z_2) - 1}{(1+z_2)^3 - 1}}$$

Shafielo o, A., Sahni, V. & Starobinsky, A.A., 2012, Phys. Rev. D, 86, 1 03527 [arXiv:1205.2870]

Left side: $\boxed{H(z), H_0}$

Right side: $\boxed{\mathrm{Om}(z_i, z_j)_{\Lambda CDM} = 0}$

Two-point Omh^2(z_1, z_2) diagnostic:

$$Omh^2(z_i, z_j) = \boxed{\frac{h^2(z_i) - h^2(z_j)}{(1+z_i)^3 - (1+z_j)^3}}$$

Sahni, V., Shafielo o, A. & Starobinsky, A.A., 2014, Astrophys. J., 793, L40 [arXiv:1406.2209]

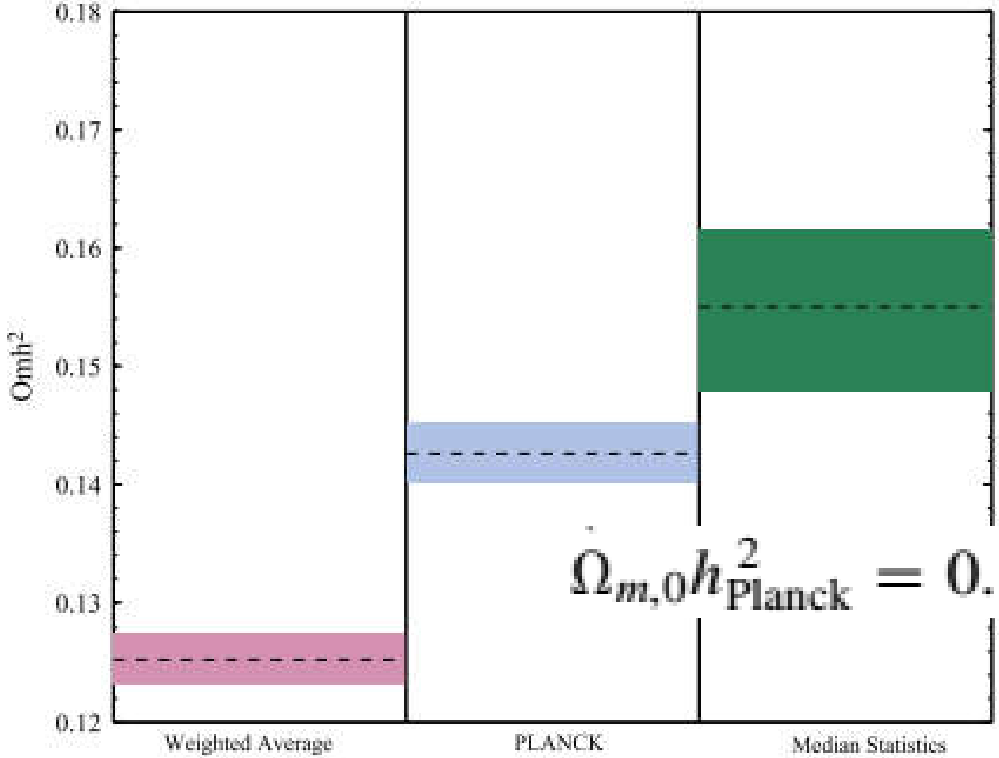
$\boxed{h(z) \equiv H(z)/100\ km\ s^{-1}\ Mpc^{-1}}$

Left side: $\boxed{\mathrm{H(z)}}$

Right side: $\boxed{\mathrm{Omh}^2(z_i, z_j)_{\Lambda CDM} = \Omega_{m,0} h^2}$

A sample of n measurements offers us n(n−1)/2 different values of two point diagnostics.

The price is – manifestly non-Gaussian, heteroscedastic



$$\mathrm{Om}h^2_{(\mathrm{median})} = 0.1550^{+0.0065}_{-0.0072}$$

$$\Omega_{m,0}h^2_{\mathrm{Planck}} = 0.1426 \pm 0.0025$$

$$\mathrm{Om}h^2_{(w.m.)} = 0.1253 \pm 0.0021$$

LCDM model is not passing a litmus test …

Results obtained in collaboration with China

Beijing Normal University, Beijing, China

Group led by prof. Zong-Hong Zhu

> 20 common papers
during last 3 years

A.Piórkowska
visiting scientist
2014

Conclusion:

Incoming era of precision cosmology requires not only more accurate but also independent probes of the Universe

Stay tuned !