NATIONAL CENTRE
FOR NUCLEAR RESEARCH
ŚWIERK

NCBJ
Closing Year
Seminar

15 December 2020

New applications of strong gravitational lensing systems

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Among other things ...

in 2020 I continued my
line of research concerning
novel applications of

Strong Lensing systems

1. New probes of cosmic curvature

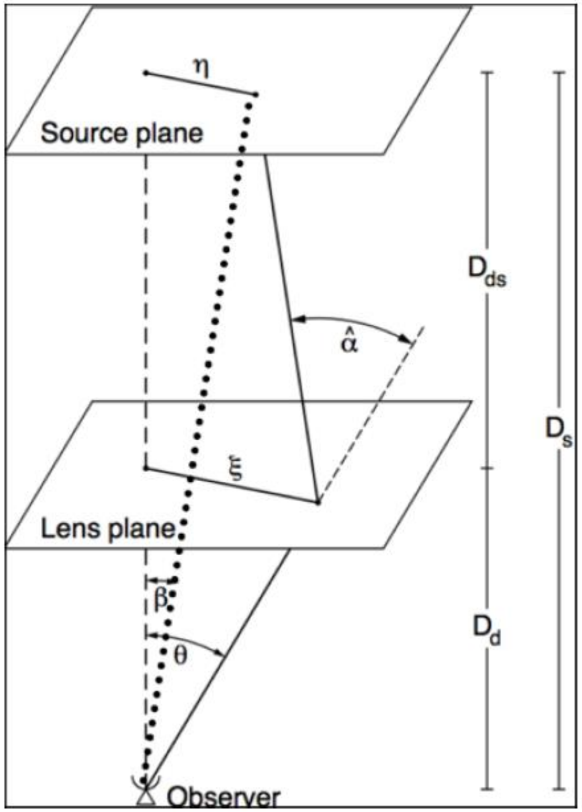
Liu T., Cao S., Zhang J., Biesiada M., Liu Y., Lian Y., *Mon. Not. Royal Astron. Soc.* **496**,708-717 (2020)

2. New tool to measure speed of light

Cao, S., Qi, J., Biesiada, M., Liu, T., Zhu, Z.-H., *Astrophys. J. Lett.* **888** (2020) L25

Gravitational lensing – geometric optics

Light rays formalism



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

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

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

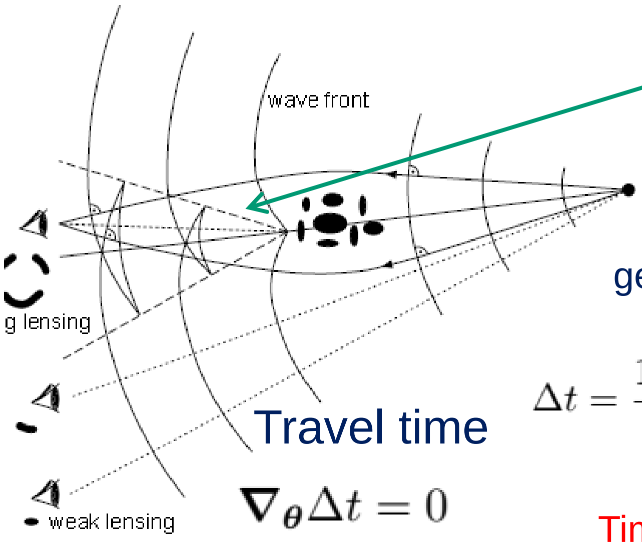
$$\boldsymbol{\alpha} = \nabla_{\boldsymbol{\theta}} \phi$$

magnification

Wavefront formalism

(Fermat principle)

caustics



Travel time

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

Lens equation

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

Newtonian potential at lens plane

geometrical term

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

Time delay distance

Fermat potential

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

Einstein radius

Observables:

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

„Refsdal" supernova

„Refsdal supernova" discovered 11 Nov. 2014
Kelly et al. (2015) *Science* 347,1123

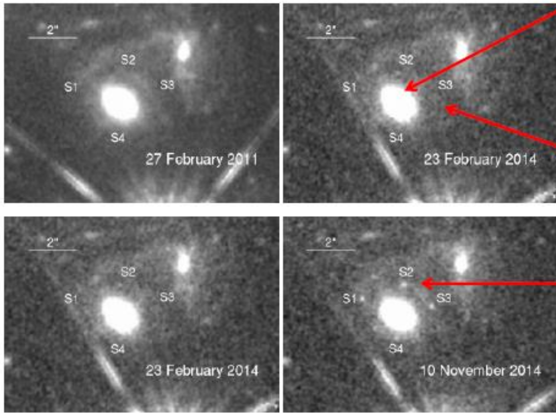
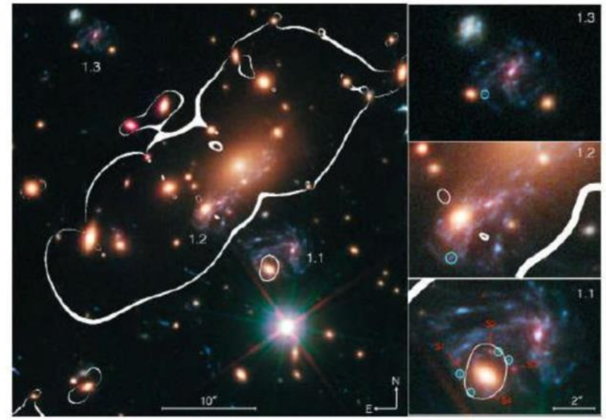


Fig. S4: Images of the lensing system from archival *HST* WFC3-IR observations in the *F140W* filter. All exposures obtained prior to 3 November 2014 show no evidence for variability at any of the positions associated with SN Refsdal.

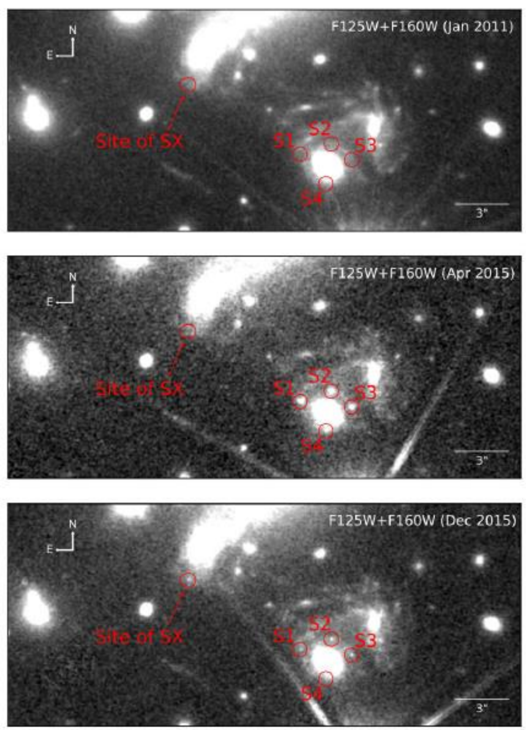
z=0.54 elliptical galaxy belonging to MACS J1149.6+2223 cluster

z = 1.49 source – spiral galaxy

host of SNII



future reappearance expected in ca. 1 yr



Kelly et al. (2016) *ApJL*

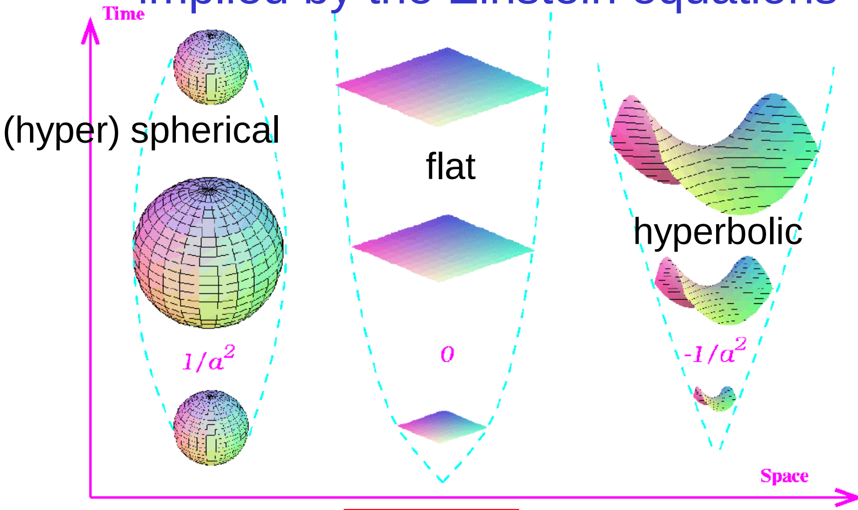
11 Dec. 2015
SNII found in SX image
as predicted !!!

Great success of GR
(mass distribution modeling
from strong lensing)

Success comparable
to the greatest triumphs of
celestial mechanics in
XIX century
(discovery of Neptune)

1. 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

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

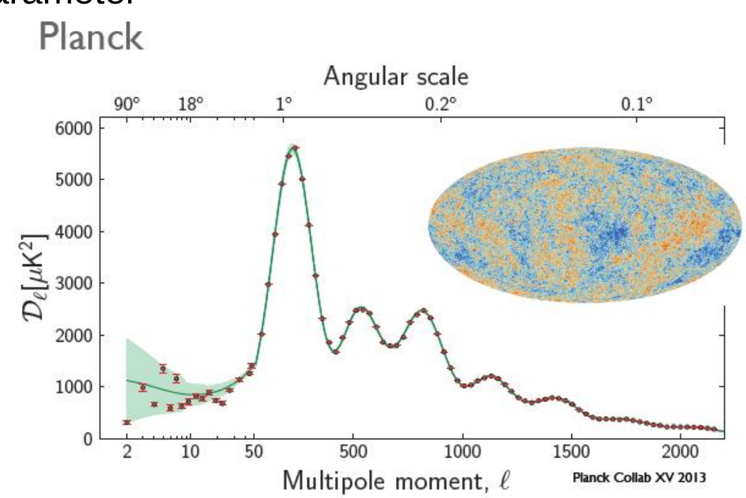
all spatial distances
(including wavelength of light)
are scaled by *a(t)*
which changes in time

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

Cosmic curvature parameter

Universe is
spatially flat
- inference from
the first acoustic peak

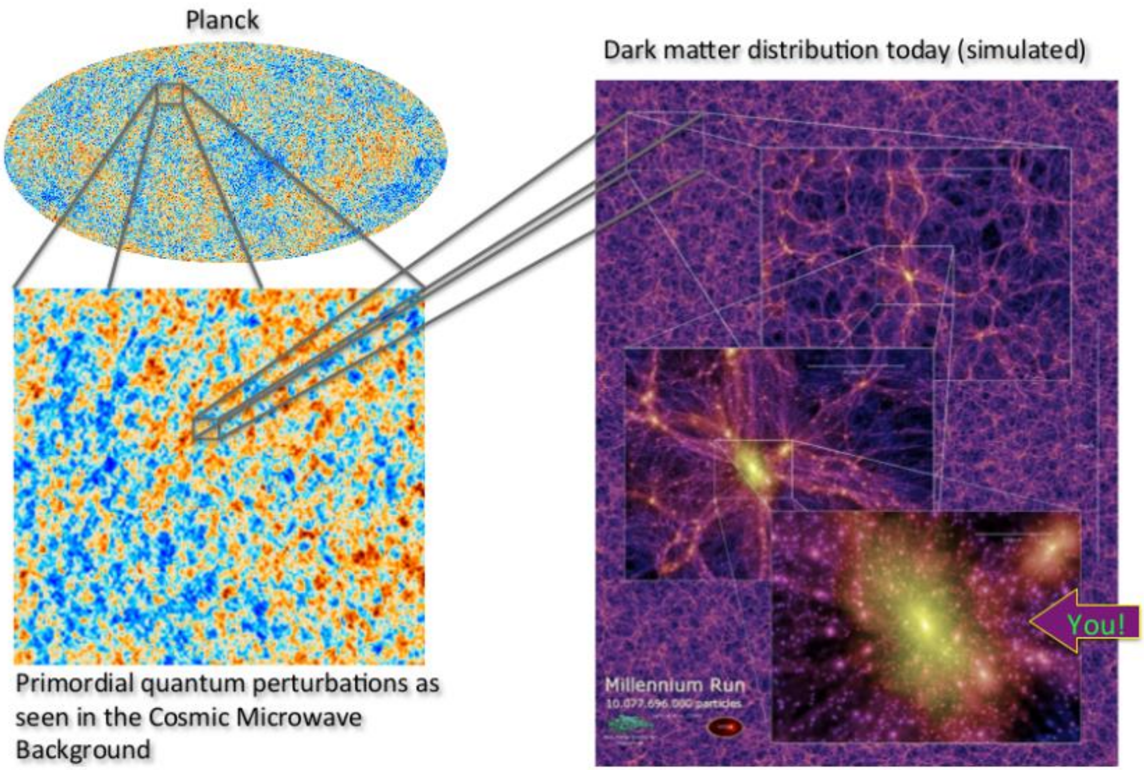
$$\Omega_{\rm tot} = 1.003^{+0.013}_{-0.017}$$



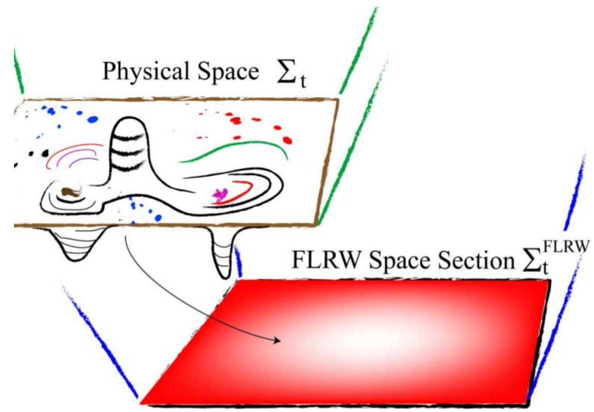
$$\Omega_K = -0.005^{+0.016}_{-0.017} \quad (95\%,\ \textit{Planck}\ \mathrm{TT{+}lowP{+}lensing}).$$

Coherent picture of emergence of the large scale structure

Emerging spatial curvature



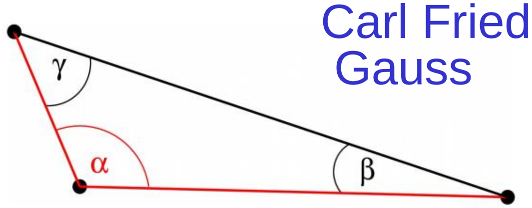
Credit: F. Leclercq, A. Pisani , B.D. Wandeldt arXiv:1403.1260v1



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

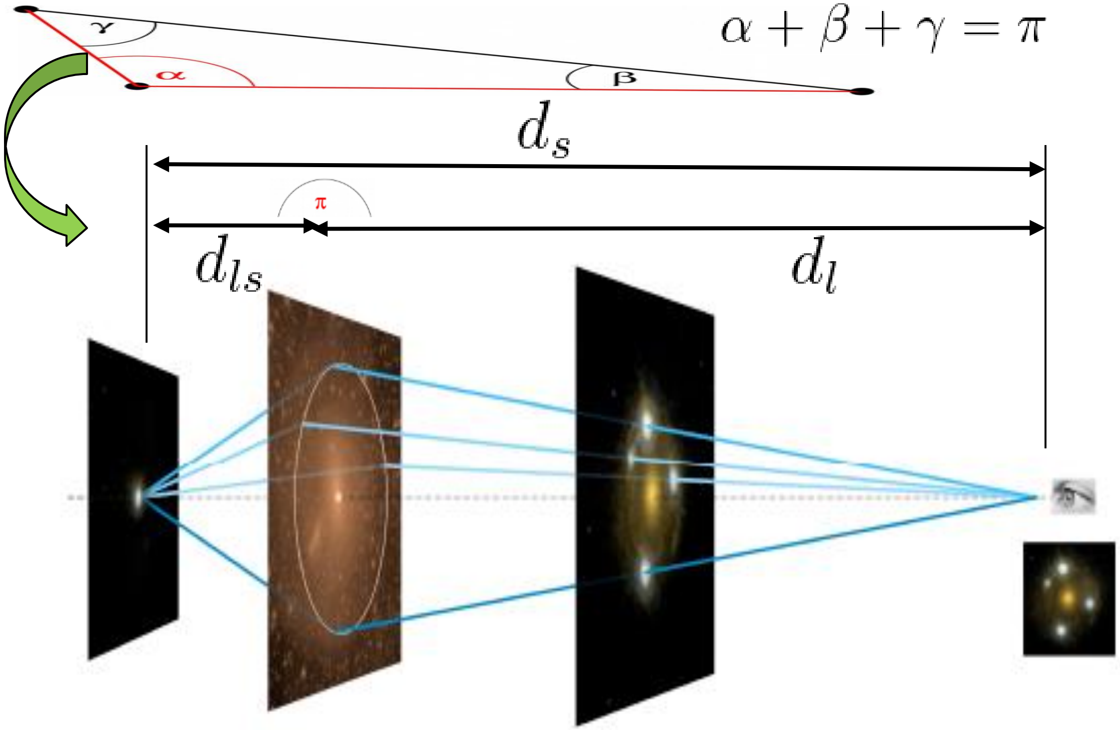
Formation of the large scale structure induces non-zero curvature at local scales

It is important to measure curvature with more local objects



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

Carl Friedrich Gauss



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)

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **496**, 708–717 (2020) doi:10.1093/mnras/staa1539
Advance Access publication 2020 June 3

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

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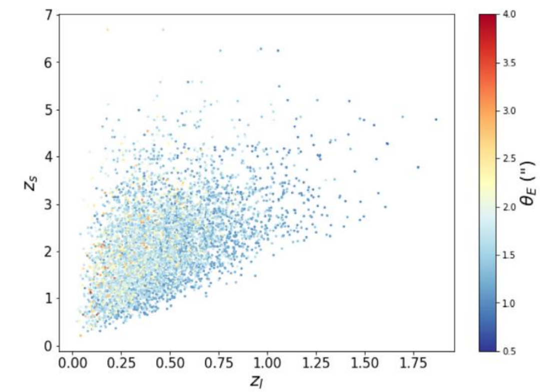
LSST

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

5000 ellipticals

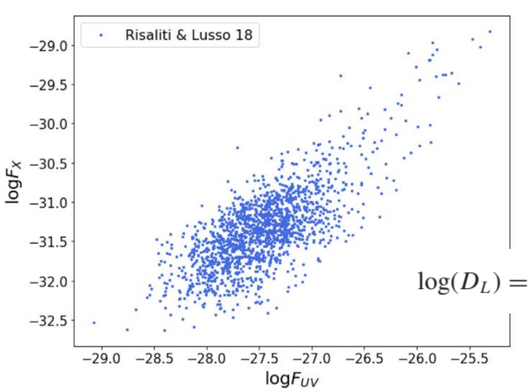
$$200\ km\ s^{-1} < \sigma_{ap} < 300\ km\ s^{-1}$$



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

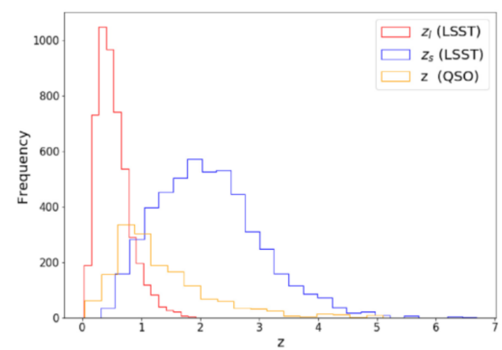
$$d_s \quad d_l$$

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



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

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

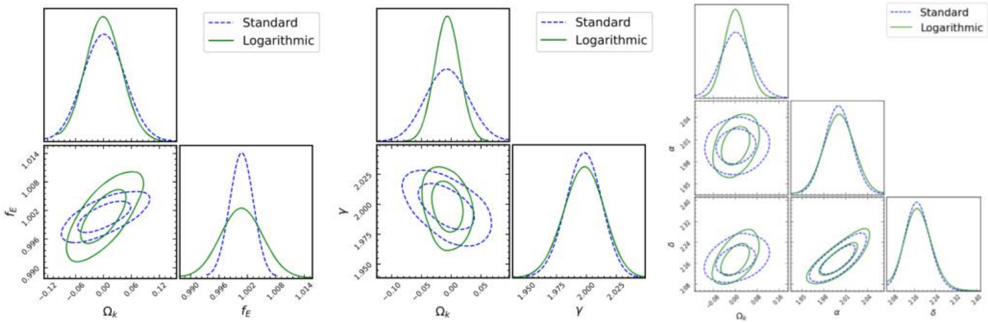


SGL systems & QSO[UV-X] overlap well in z

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

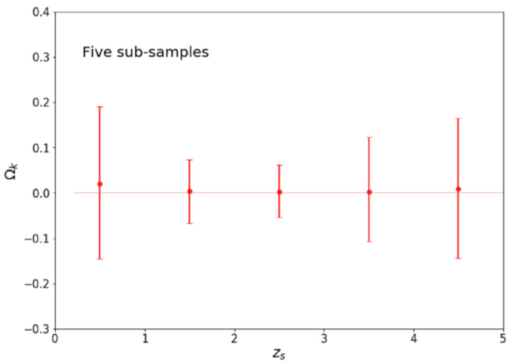
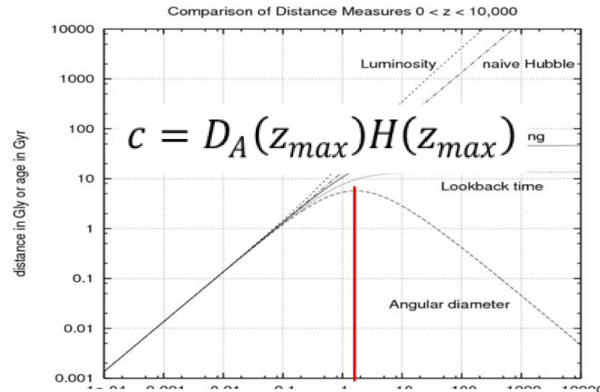


Figure 7. Determination of cosmic curvature with five subsamples $0 < z < 1.0$, $1.0 < z < 2.0$, $2.0 < z < 3.0$, $3.0 < z < 4.0$ and $4.0 < z < 5.0$ based on the source redshifts of SGL sample characterized by the SIS lens model.

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

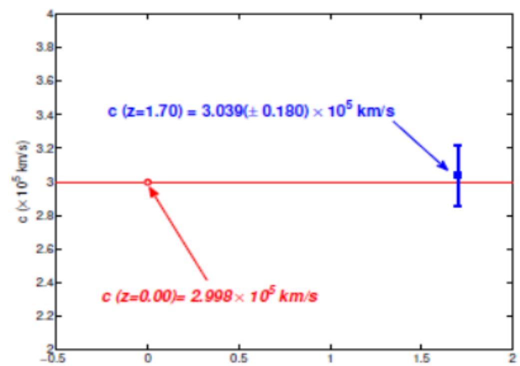
2. Strong lensing systems as a new tool to measure the speed of light using extragalactic objects

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, 0
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 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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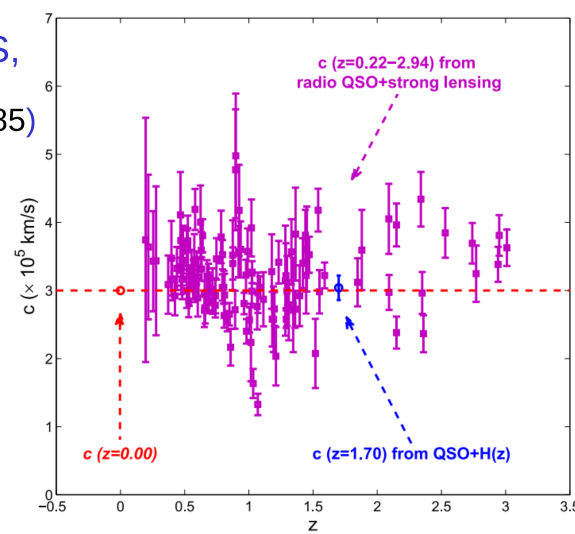
We used a catalog of 118 lensing systems from SLACS, BELLS, LSD and SL2S (Cao, MB, et al. 2015, ApJ 806:185)

observable / measureable

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

obtainable from (redshift matched) ultra-compact radio QSOs



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

summary

Prediction for the LSST and future VLBI compact radio QSOs

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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

Thank you !