The Rubin – LSST Polish Consortium
Annual Meeting 2024
23 – 24 October 2024, Warsaw, Poland

Strong lensing in LSST era – new opportunities for cosmology and fundamental physics

NATIONAL CENTRE FOR NUCLEAR RESEARCH ŚWIERK

Marek Biesiada
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Our strong lensing group

LSST is expected to discover
10 000 strong lensing systems including 1000 quasar lenses

Let’s have them!

A&A 664, A4 (2022)
https://doi.org/10.1051/0004-6361/202142463

Astronomy & Astrophysics

- Hareesh Thuruthipilly

Finding strong gravitational lenses through self-attention

Study based on the Bologna Lens Challenge

Hareesh Thuruthipilly[1], Adam Zadrozny[1], Agnieszka Pollo[1,2], and Marek Biesiada[1,3]

A&A, 688, A34 (2024)
https://doi.org/10.1051/0004-6361/202449929

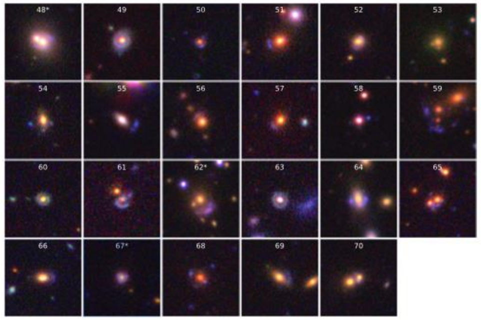
Astronomy & Astrophysics

- Margherita Grespan

TEGLIE: Transformer encoders as strong gravitational lens finders in KiDS

From simulations to surveys★

M. Grespan[1], H. Thuruthipilly[1], A. Pollo[1,2], M. Lochner[3,4], M. Biesiada[1], and V. Etsebeth[3]

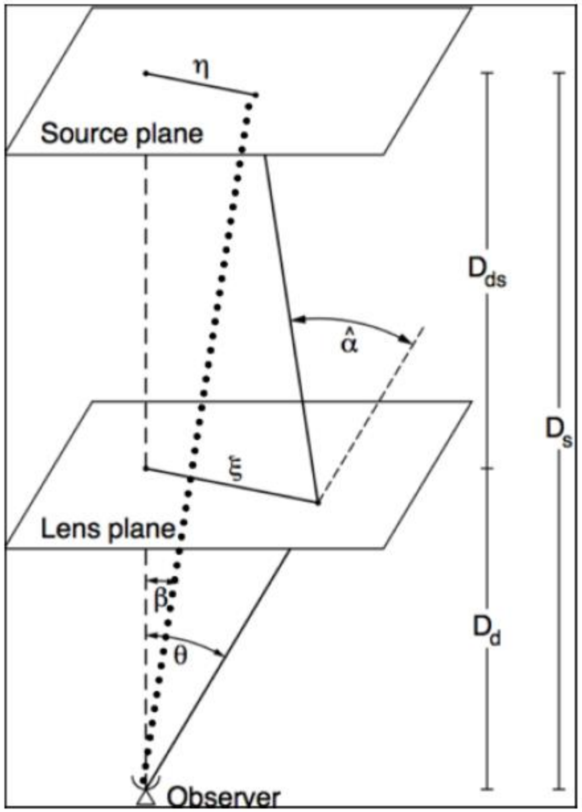


44 new discoveries

- Shuaibo Geng –science cases (next talk !)
- Sreeknath Harikumar – strong lensing of GWs
- …

Gravitational lensing in a nut shell

Light rays formalism



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

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

Lens equation

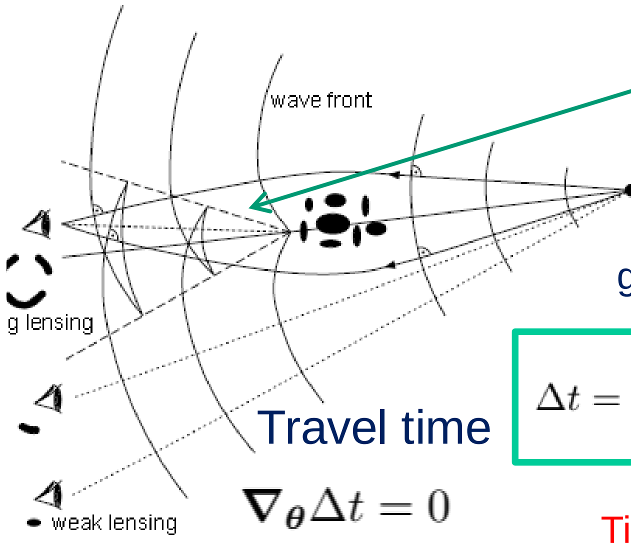
$$A(\boldsymbol{\theta}) = \frac{\partial \boldsymbol{\beta}}{\partial \boldsymbol{\theta}} \qquad \mu(\boldsymbol{\theta}) = \frac{1}{\det A(\boldsymbol{\theta})}.$$

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

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

Strong lensing - applications

- Cosmology

  alternative way to measure H_0

  cosmic e.o.s.

  curvature parameter - alternative method

- Testing modified gravity

  agnostic approach – PPN parameter

  alternative gravity with screening

- Lensed transient events

  GW from CBC

  GRBs

  FRBs

  SNIa, SNII

THE ASTROPHYSICAL JOURNAL, 941:16 (14pp), 2022 December 10
https://doi.org/10.3847/1538-4357/ac9d36

Direct Tests of General Relativity under Screening Effect with Galaxy-scale Strong Lensing Systems

Yujie Lian[1,2], Shuo Cao[1,2], Tonghua Liu[3], Marek Biesiada[4], and Zong-Hong Zhu[1,2]
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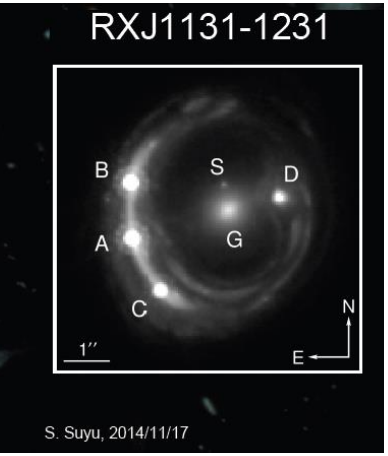
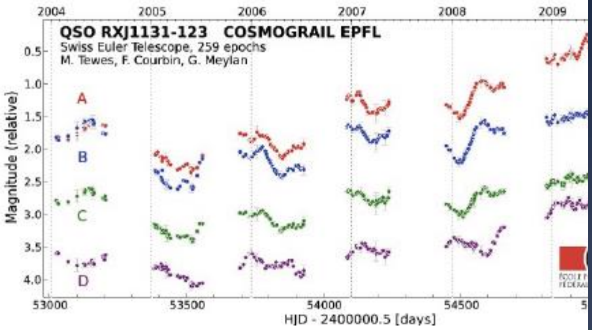
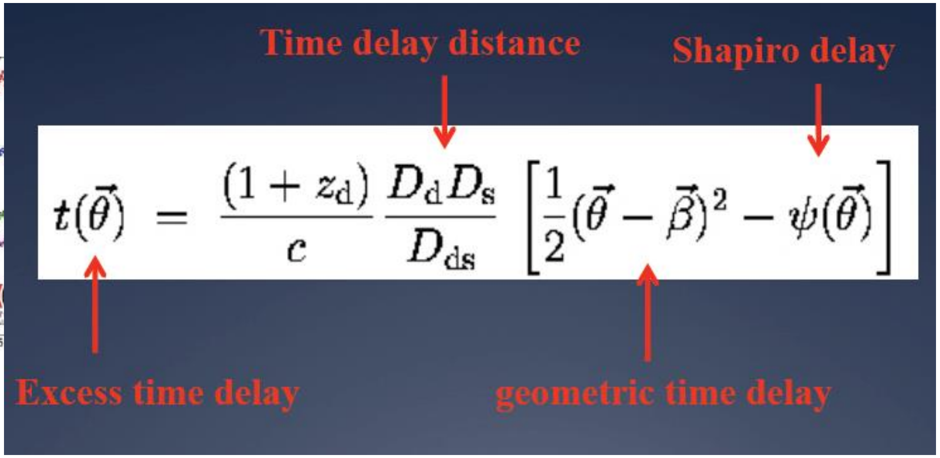
Strong lensing cosmography – H_0 from time delay







H0LiCOW currently 6 +1 lenses

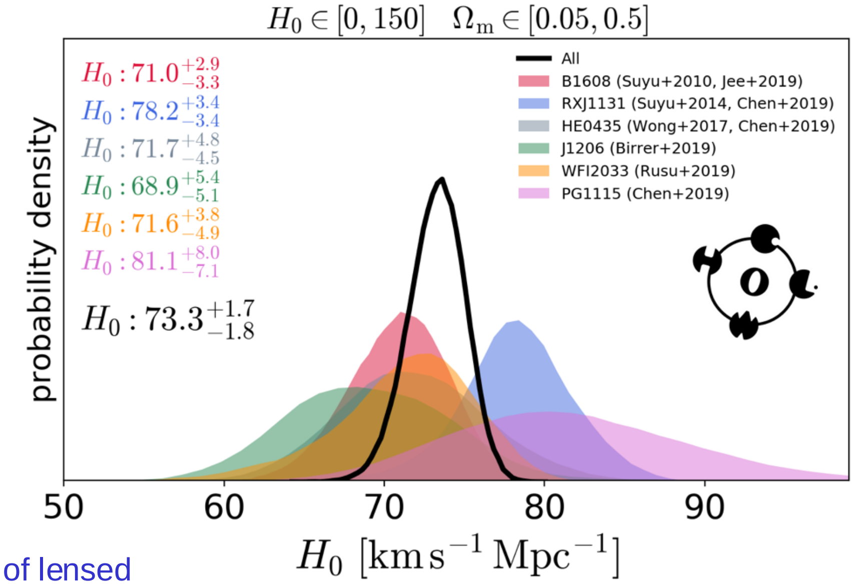


Table 1 Relative uncertainties of three factors contributing to the accuracy of time-delay distance measurement

	$\delta\Delta t$	$\delta\Delta\psi$	δLOS
Lensed GW + EM	0%	0.6%	1%
Lensed quasar	3%	3%	1%

$\delta\Delta t$, $\delta\Delta\psi$, δLOS correspond to time delay, Fermat potential difference, and light-of-sight environment, respectively. We show the case for lensed gravitational wave (GW) + electromagnetic (EM) signals compared with standard technique in the EM domain using lensed quasars

From
Liao, Fan, Ding, MB, Zhu, Nature Comm. 2018

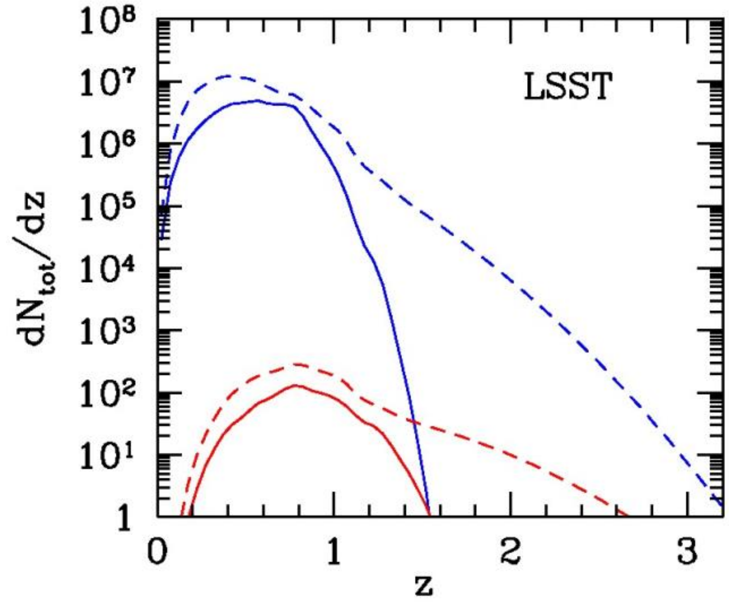
Sub percent – accuracy of H_0 possible with 10 lensed GW+EM

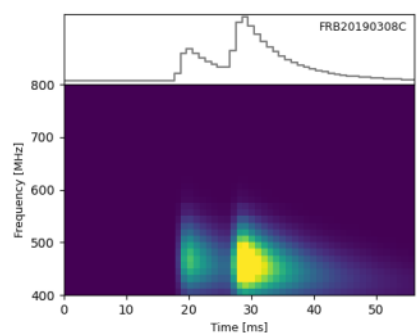
Power of lensed transient events:

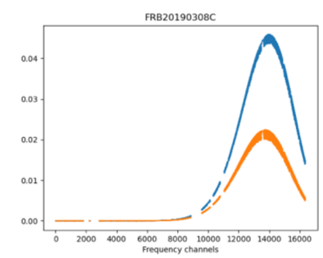
GW K.Liao et al. 2018
SN Ia S.Huber et al. 2019
GRB M. Oguri 2019
FRB Z.-X. Li et al. 2018

Strong lensing of transients

- LSST – Sne
  900 strongly lensed SN expected
  ca. 650 SNIa (Goldstein, Nugent 2017)
- GW CBC signals
  ET 50-100 lensed events yr^{-1}
  (Piórkowska et al. 2013, Biesiada et al. 2014 Ding et al. 2015, Yang et al. 2019)
  DECIGO 50-100 lensed events yr^{-1}
  (Piórkowska et al. 2021)
- GRBs
  median z ~ 2
  lensed GRB expected long time ago (Paczyński 1996)
  no fully confirmed case so far
- FRBs
  bright ms long radio flashes
  discovered 2007
  lying at cosmological distances
  expected to be lensed
  first possible lensed FRB20190308C







Transients – advantage: high temporal resolution (time delays)

Strong lensing and 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 the ammount of spatial curvature generated by unit mass

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

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

$$\gamma = \frac{\Psi}{\Phi}$$

stellar dynamics is sensitive to the Newtonian potential

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

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

and the Einstein radius of spherically symmetric lens is $$\theta_{\mathrm{E}} = \sqrt{\frac{1+\gamma}{2}}\left(\frac{4GM_{\mathrm{E}}}{c^2}\frac{D_{ls}}{D_s D_l}\right)^{1/2}$$

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

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

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

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

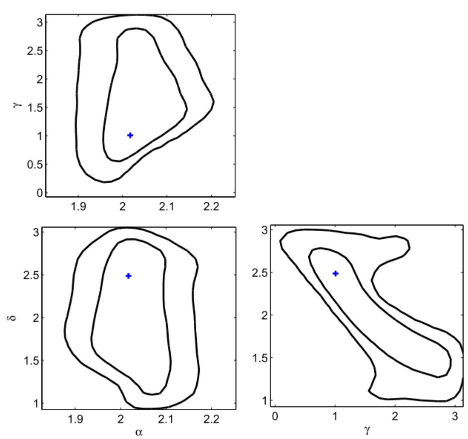
anisotropy $\beta(r) = 1 - \sigma_t^2/\sigma_r^2$

$$\beta = 0.18 \pm 0.13$$

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

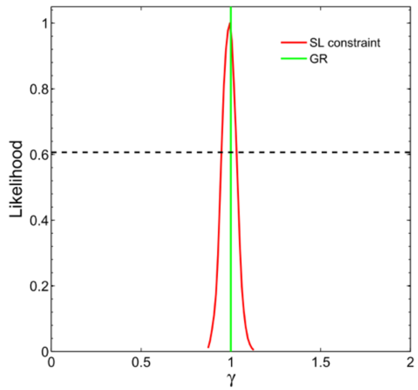


Figure 3. Normalized posterior likelihood of the PPN γ parameter obtained with rigid priors on the nuisance parameters (α, β, δ).

With priors

$$\langle\alpha\rangle = 2.00;\ \sigma_\alpha = 0.08$$
$$\langle\delta\rangle = 2.40;\ \sigma_\delta = 0.11.$$

$$\beta = 0.18 \pm 0.13$$

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

RESEARCH

Science **360**, 1342–1346 (2018)

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.

Simulated sample of SGL systems detectable in LSST (code of Collett 2015) with prior on Ω_k

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

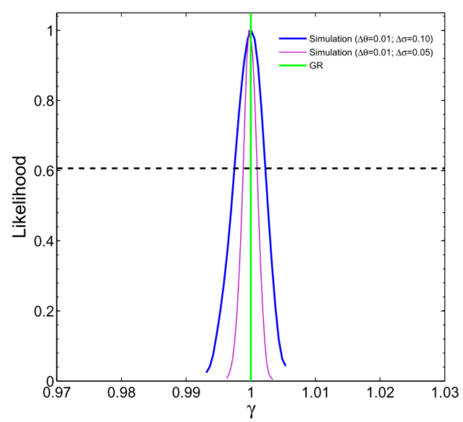


Figure 8. Constraints on the PPN parameter from simulated LSST strong lensing data, with a prior on the cosmic curvature $-0.007 < \Omega_k < 0.006$ from *Planck*.

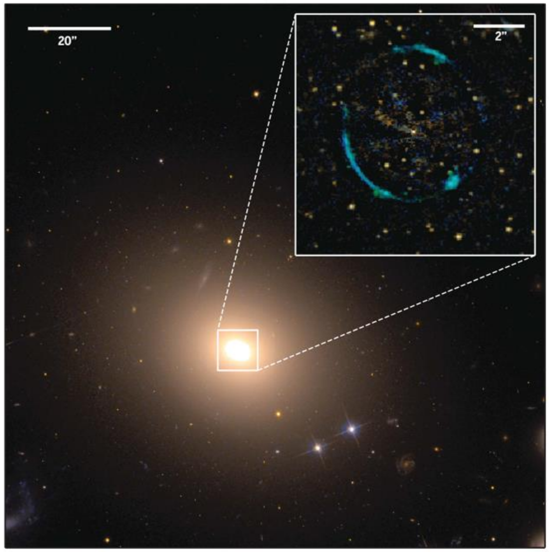
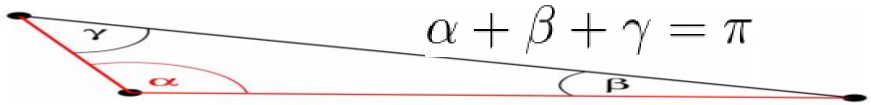
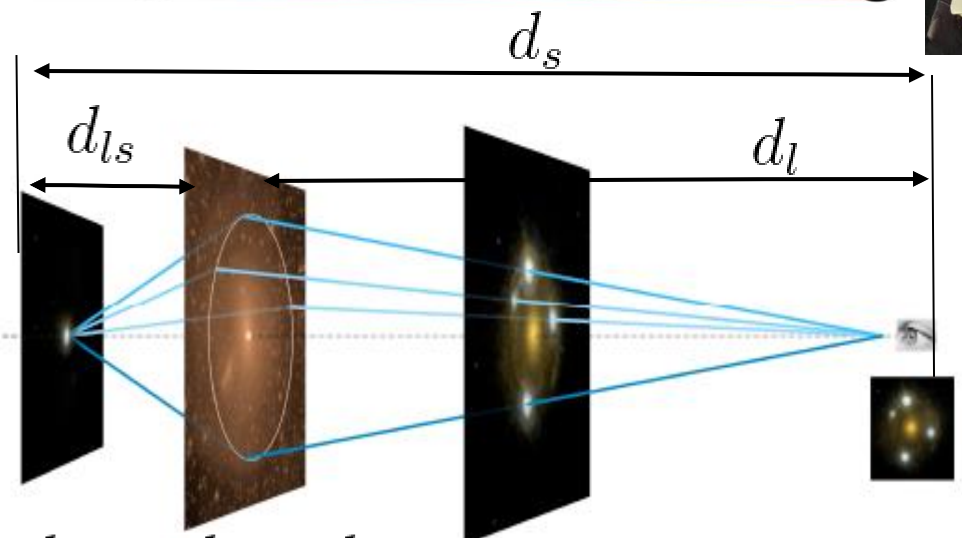


Fig. 1. Color composite image of ESO325-G004. Blue, green, and red channels are assigned to the F475W, F606W, and F814W HST imaging. The inset shows a F475W and F814W composite of the arcs of the lensed background source after subtraction of the foreground lens light. Scale bars are in arc seconds.

Strong lensing and curvature of the Universe





$$d_{ls} = d_s - d_l$$

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 !

Strong lenisng systems offer us „degenerated triangles”

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 to some standard candle (or ruler)

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

Curvature parameter from lensed SN Ia

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

Jingzhao Qi,[1,2] Shuo Cao,[2,*] Marek Biesiada,[2,3] Xiaogang Zheng,[4] Xuheng Ding,[4] and Zong-Hong Zhu[2,4,†]
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[4]*School of Physics and Technology, Wuhan University, Wuhan 430072, China*

July 2019)

	$\delta\theta_E$	$\delta\sigma_{ap}$	$\delta\gamma$
Multiple images	1%	5%	1%

	$\delta\Delta t$	$\delta\Delta t$ (ML)	$\delta\Delta\psi$	$\delta\Delta\psi$ (LOS)
Time delay	1%	1%	$\propto(\delta\theta_E, \delta\gamma)$	1%

	$\Delta\mu_D$(sta)	$\Delta\mu_D$ (ML)	$\delta\mu$	$\Delta\mu_D$(sys)
Lensed SNe Ia	σ_{stat}	0.70 mag	$\propto(\delta\theta_E, \delta\gamma)$	σ_{sys}

aître-Robertson-Walker (FLRW)
tational lensing systems with type
vill provide a model-independent
trical optics independently of the
est the FLRW metric directly. Our
l by the Large Synoptic Survey
ature with accuracy $\Delta\Omega_k = 0.04$

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

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

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

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

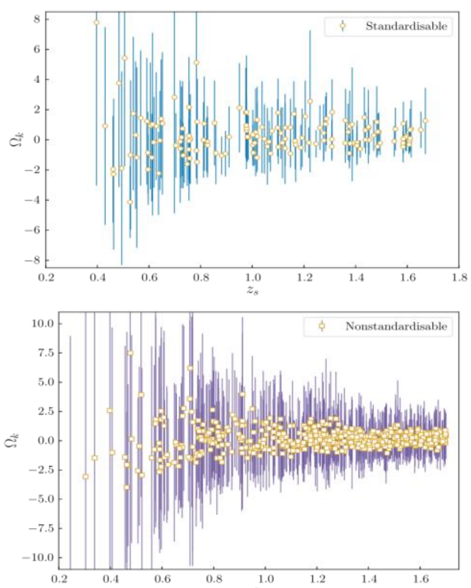


FIG. 1. An example of the simulated measurements of Ω_k from future observations of SGLSNe Ia: without and with the effect of microlensing. The blue lines denote the associated error bars (68.3% C.L.) of Ω_k when all the uncertainties are included.

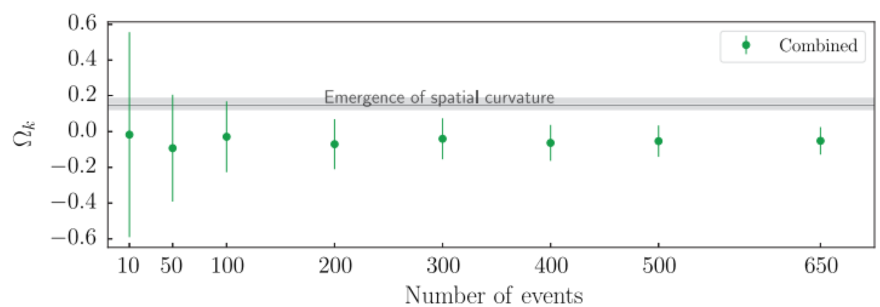
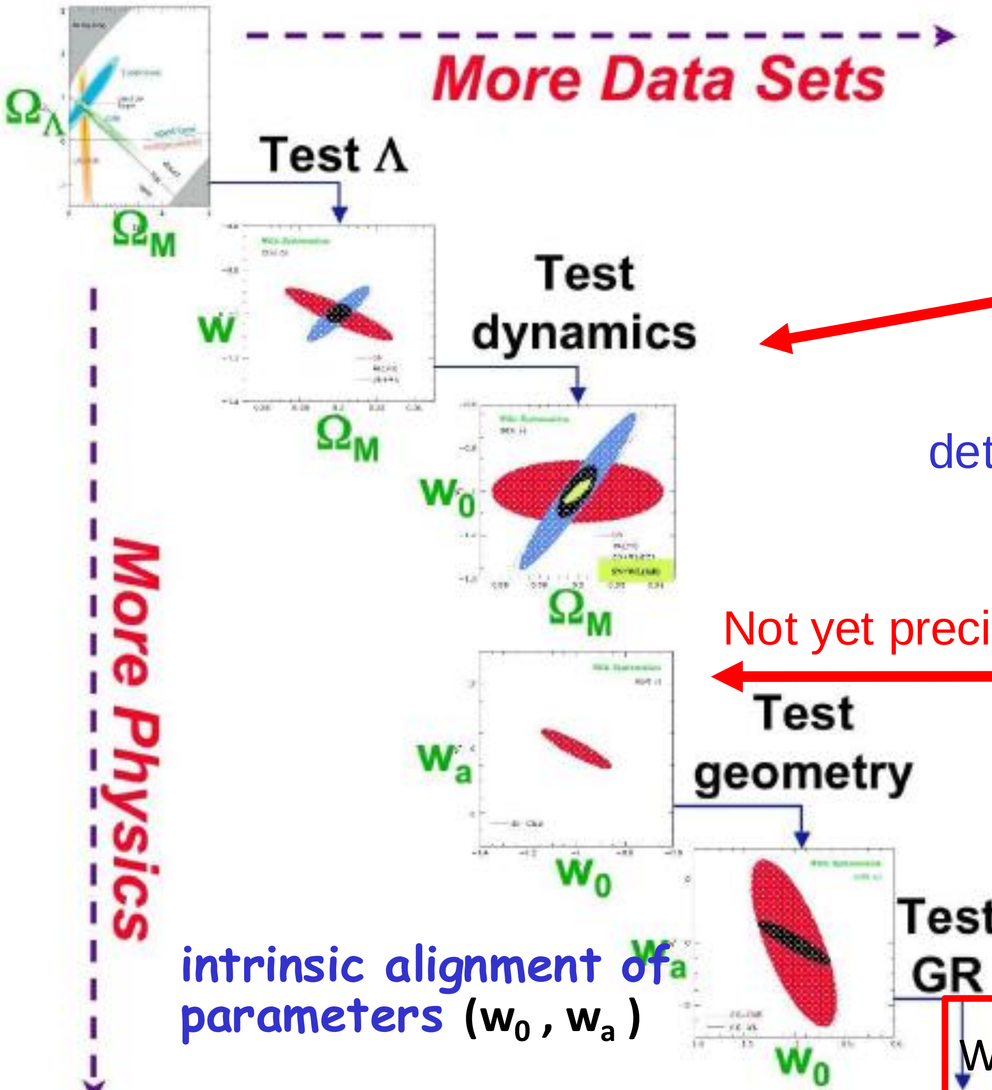


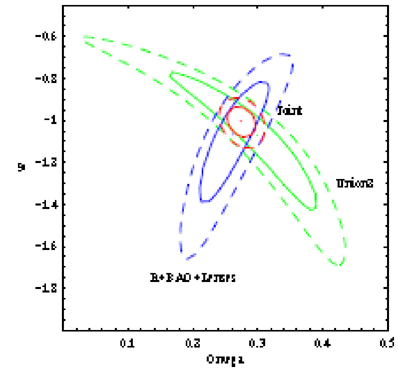
FIG. 3. Inferred Ω_k parameter as a function of the number of SGLSNe Ia, with the prediction of a silent universe added for comparison.

650 lensed SN Ia from LSST

D. A.Goldstein,
P. E. Nugent
2017

Modern cosmology: Incremental Exploration of the Unknown



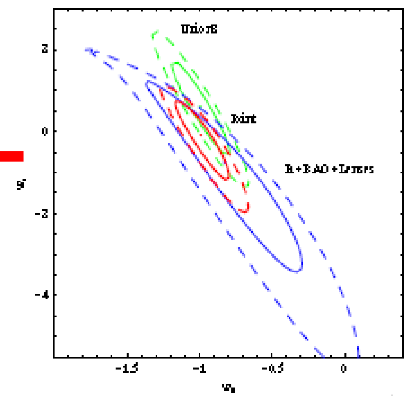


MB, B.Malec, A.Piórkowska 2011

determine DE equation of state

$$p_X = w\rho_X$$

Not yet precise



determine if it changes in time

$$w(z) = w_0 + w_a \frac{z}{1+z}$$

intrinsic alignment of parameters (w_0 , w_a)

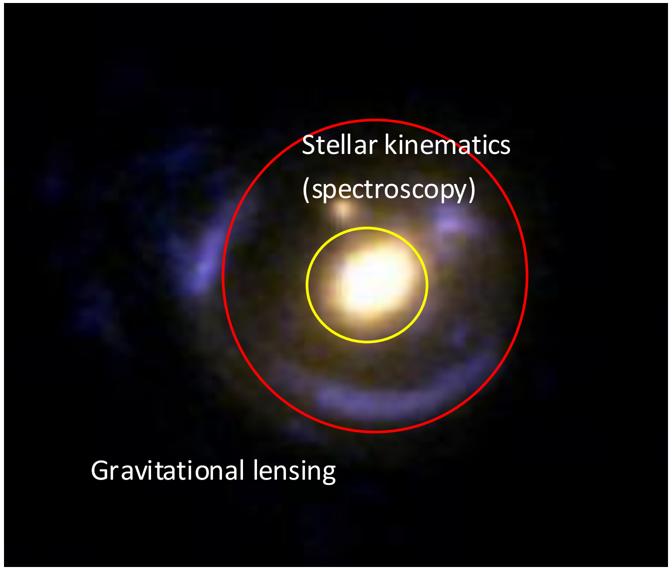
We need complementary probes –

to break degeneracies

and for cross-checks

Linder (astro-ph/0511197)

Strong lensing combined with stellar kinematics



Strong lensing: mass inside the Einstein radius

1. The simplest lens model
Singular Isothermal Sphere (SIS)

$$\rho(r) = \frac{\sigma_v^2}{2\pi G r^2}$$

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

2. Spherically symmetric power-law mass density profile

$$\rho(r) \sim r^{-\gamma}$$

stellar dynamics (spherically symmetric Jeans equation): mass projected inside the aperture radius scaled to the Einstein radius

$$M_{lens} = \frac{c^2}{4G}\frac{D_l D_s}{D_{ls}}\theta_E^2 \quad + \quad M_{dyn} = \frac{\pi}{G}\sigma_{ap}^2 D_l \theta_E \left(\frac{\theta_E}{\theta_{ap}}\right)^{2-\gamma} f(\gamma)$$

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

3. More general spherically symmetric power-law model

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

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

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

$$\theta_E = 2\sqrt{\pi}\frac{\sigma_{ap}^2}{c^2}\frac{D_{ls}}{D_s}\left(\frac{\theta_E}{\theta_{ap}}\right)^{2-\alpha}(\xi - 2\beta)\lambda(\alpha)$$

Strong lensing cosmography – e.o.s. of the Universe

PHYSICAL REVIEW D **73,** 023006 (2006)

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

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Cosmic equation of state from strong gravitational lensing systems

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20 galaxy lenses from SLACS + LSD

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

JCAP03 (2012) 016

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]

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

10 cluster lenses

70 galaxy lenses from SLACS

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

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

COSMOLOGY WITH STRONG-LENSING SYSTEMS

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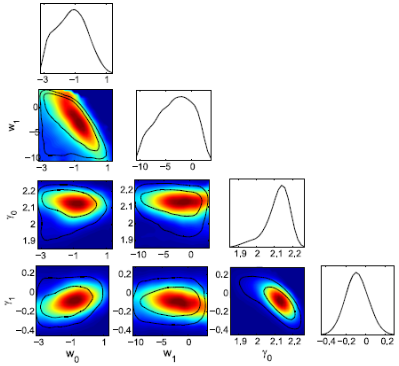

118 lenses from SLACS sample

Research in Astron. Astrophys. **2011** Vol. **11** No. **6**, 641–654
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Research in Astronomy and Astrophysics

Dark energy constraints from joint analysis of standard rulers and standard candles

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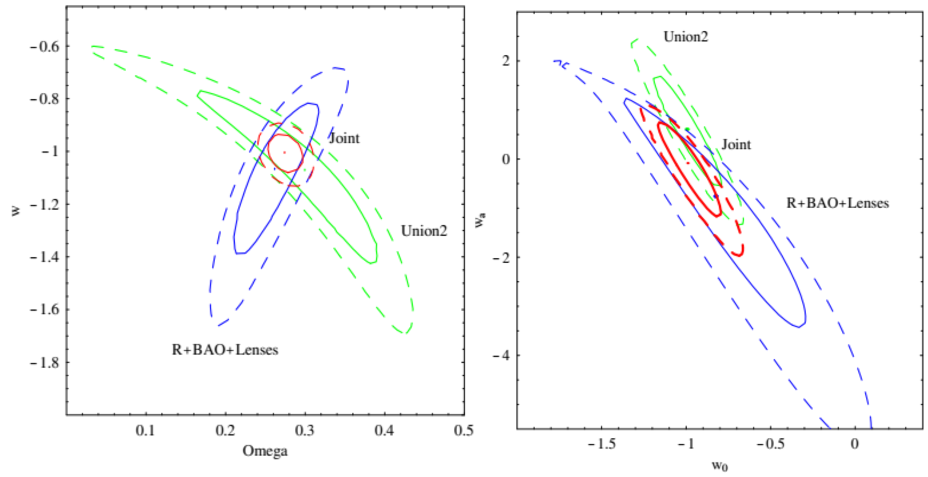

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ON THE COMPLEMENTARITY OF DIFFERENT COSMOLOGICAL PROBES WITH SLACS, BELLS AND SL2S STRONG GRAVITATIONAL LENSING DATA*

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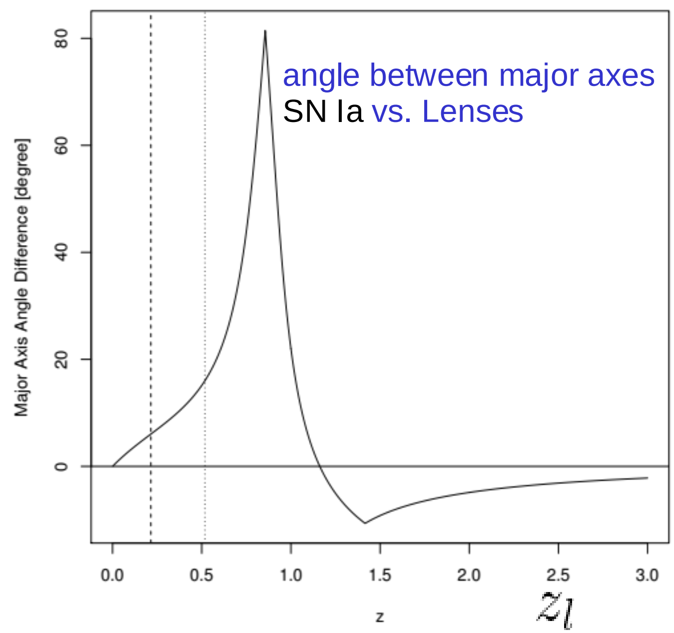


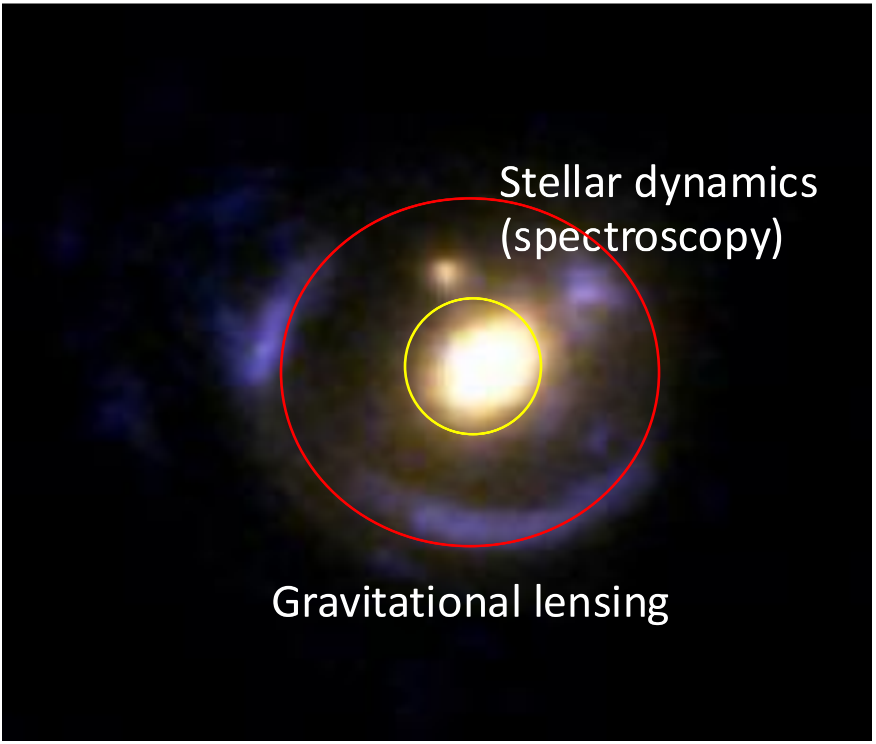
Has a potential to follow up with LSST data

assuming $z_s = 2z_l$

15

Strong lensing cosmography with LSST

Fundamental plane relation $\log R_e = a \log \sigma_v + b \log \langle I_e \rangle + c$



velocity dispersion –
~~spectroscopy~~

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

image astrometry

Distance ratio

depends on cosmological model (H_0 cancels)

Outline of our plans

- Develope an effective model of lens mass distribution based on agnostic approach to cosmological distances involved
  Shuaibo Geng et al. 2024 (A&A submitted)
- Use this model for **cosmological tests** and **beyond GR** tests (on existing data)
- LSST adopted approach – photo-z + velocity dispersions via. fundamental plane relations
- Systematic study of (w_0,w_a) degeneracy in lensing approach to cosmic e.o.s. – finding „sweet spot region" in (z_l,z_s) plane

Conclusions

- Vera Rubin Observatory (LSST survey) will become a game changer in precision cosmology

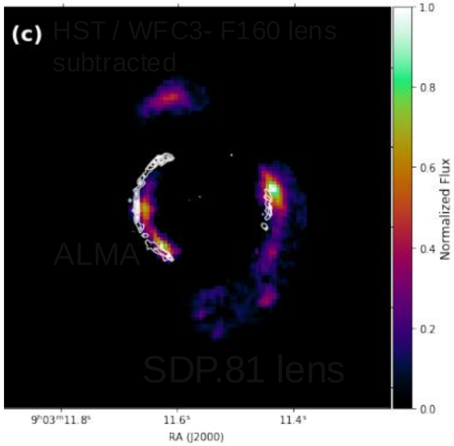
  10 000 strong lensing systems including 1000 quasar lenses.

- Great opportuinity to advance alternative cosmological probes

  strong lensing systems
  strongly lensed SN Ia (and other transient events)
  anomalies in time delays and DM substructure, fuzzy DM ?
  K.Liao, ... ,M.B., et al. ApJ 867:69, 2018

  multiwavelength (optical, IR, radio) study of SL systems

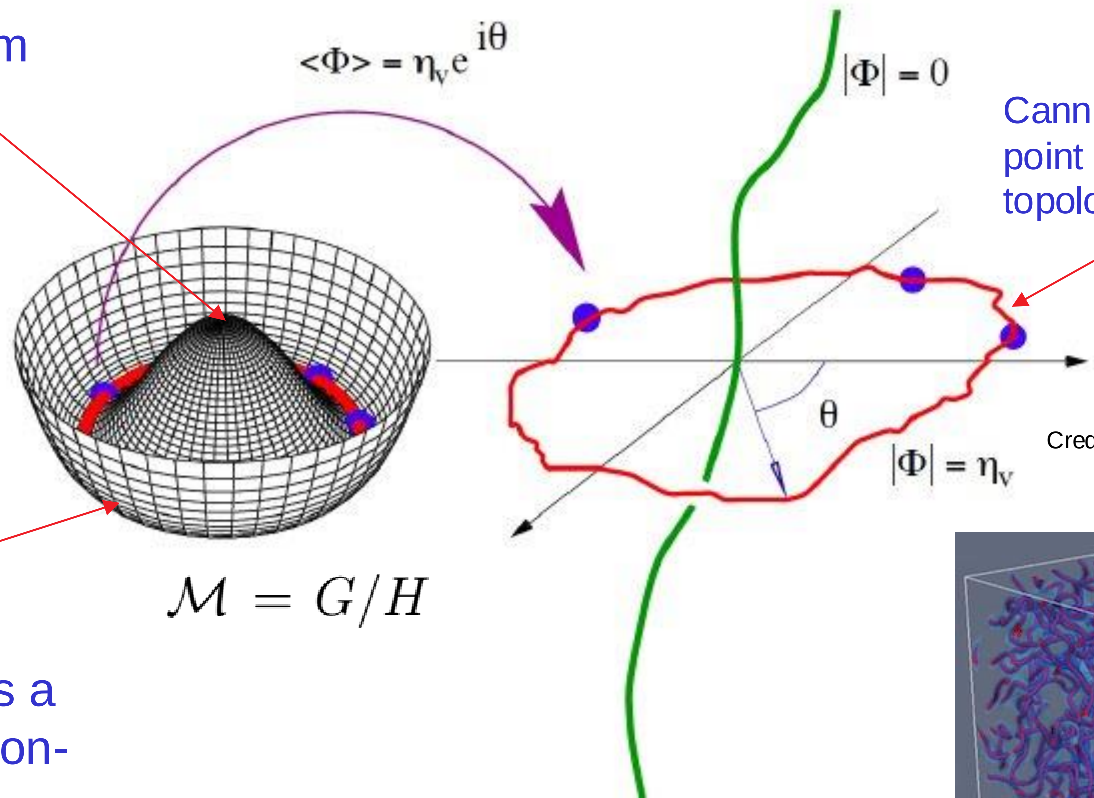
  lensed GRBs



- Opportunity to explore the fundamental questions in Physics, gravity theory beyond GR, nature of DM.

Challenge for the future: cosmic strings !

False vacuum



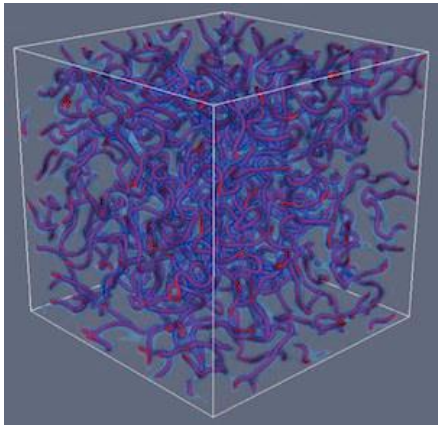
Cannot be shrinked to a point – string is a topological defect here

Credit: Vachaspati, Pogosian, Steer

$$\mathcal{M} = G/H$$

True vacuum: in general forms a manifold M of non-trivial topology $\pi_1(\mathcal{M})$

Universe populated with strings, they interact, form loops, oscillate - emit GWs !



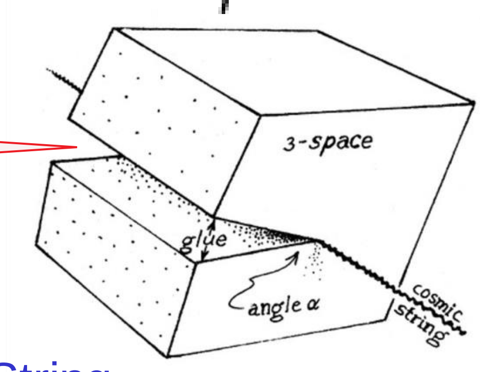
Credit: Geneva Cosmology Group

Cosmic string – cuts the wedge from the space-time

String is locally fully characterized by its tension = mass per unit length μ

Deficit angle cut by the String

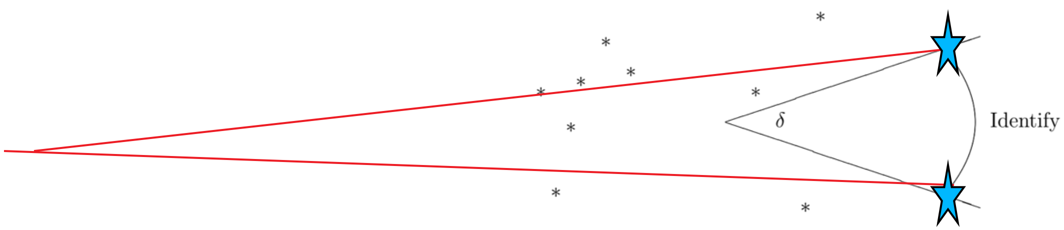
$$\delta = \frac{8\pi G\mu}{c^2}$$

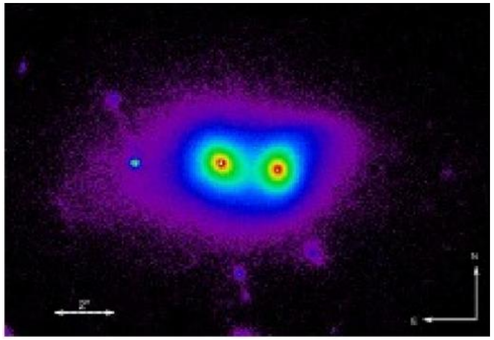


Credit: Roger Penrose

$$\Delta\vartheta = \frac{4\pi G\mu}{c^2}$$

The only direct way to observe the String is by gravitational lensing !





Source behind the cosmic string – split in two images (non-magnified !)

CSL – 1 one the most promising candidate

CSL -1 case

CSL-1: chance projection effect or serendipitous discovery of a gravitational lens induced by a cosmic string?

M. Sazhin [1,2], G. Longo [3,4], M. Capaccioli [1,3], J. M. Alcalá[1], R.Silvotti[1], G.Covone[4], O.Khovanskaya[2], M.Pavlov[1], M.Pannella[1], M.Radovich[1], V.Testa[5]

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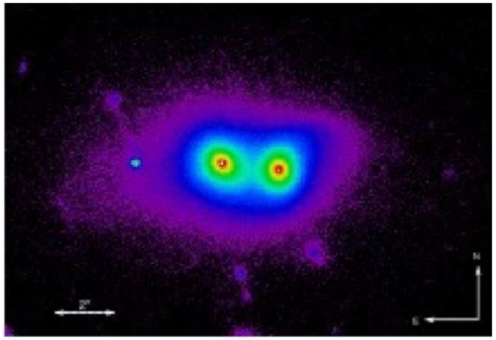
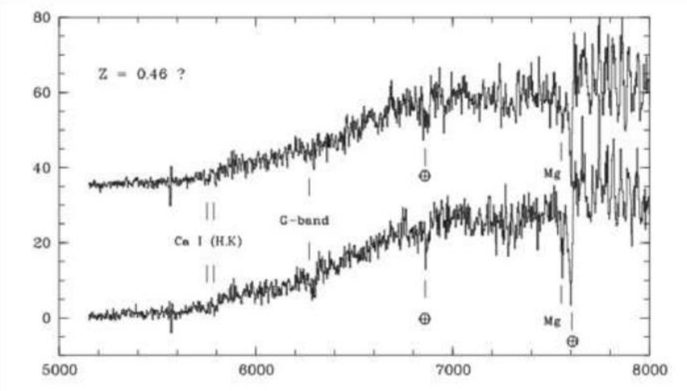
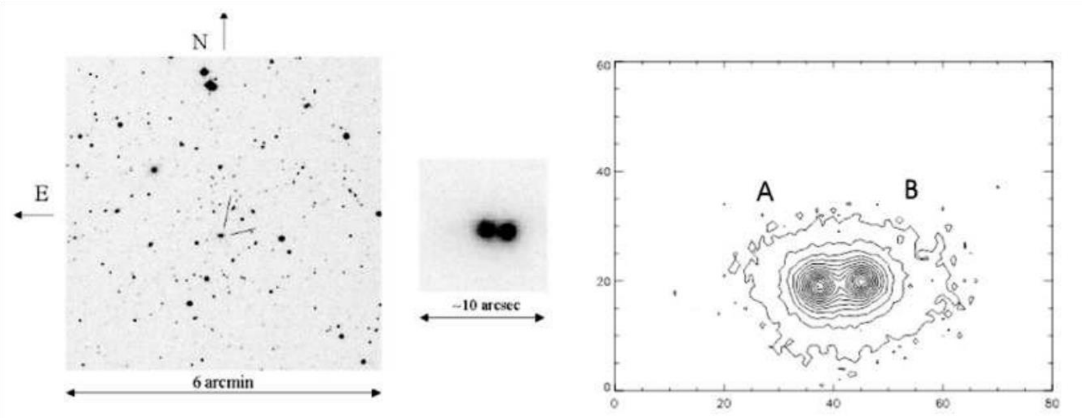
ABSTRACT
CSL-1 (Capodimonte–Sternberg–Lens Candidate, No.1) is an extragalactic double source detected in the OACDF (*Osservatorio Astronomico di Capodimonte - Deep Field*). It can be interpreted either as the chance alignment of two identical galaxies at $z = 0.46$ or as the first case of gravitational lensing by a cosmic string. Extensive modeling shows in fact that cosmic strings are the only type of lens which (at least at low angular resolution) can produce undistorted double images of a background source. We propose an *experimentum crucis* to disentangle between these two possible explanations. If the lensing by a cosmic string should be confirmed, it would provide the first measurements of energy scale of symmetry breaking and of the energy scale of Grand Unified Theory (GUT).





vertical shift in spectra – only for visualization



Eventually HST revealed a matter bridge (merger) …

But in LSST era it is worth seeking for lensing by string

Thank you !