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Prospects of testing Dark Matter
with gravitational lensing and gravitational waves

Marek Biesiada
Department of Astrophysics
National Centre for Nuclear Research
Warsaw, Poland

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Dark matter (satellite) halo mass deficit?

1. Dark matter cores of kpc size are preferred by observed circular velocities in dwarf/low-surface-brightness (LSB) galaxies, while simulations suggest cusps [Moore 1994; Burkert 1995, …].

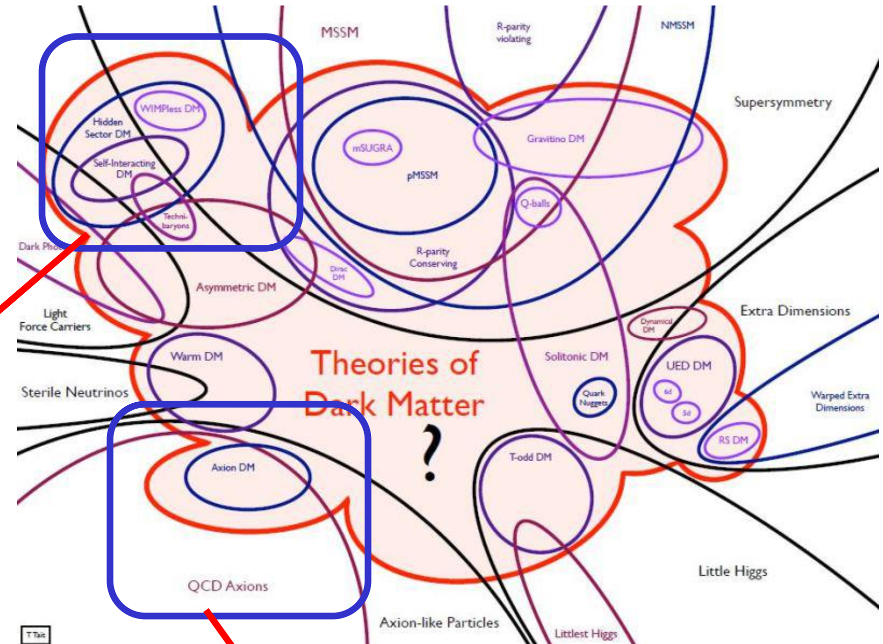
   (core/cusp problem)

2. Non-observation of very massive satellite halos predicted by simulations in our Milky Way [M.Boylan-Kolchin et al. 2011, 2012] and others [Ferrero et al. 2011].

   (too-big-to-fail problem)

3. Given the long lifetime of dwarfs, some globular/star clusters are expected to be destroyed, or sink to the center if their host halos are cuspy [J. Binney & S.Tremaine 2008, F. Contenta et al. 2017, P. Boldrini et al. 2018, …].

   (GC timing problem)

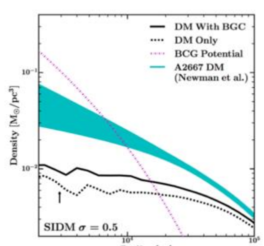


- Self-interacting dark matter (SIDM)?
  - Stronger self-scattering needed for (dwarf-sized) halos [O. D. Elbert et al. 2016, K. Bondarenko 2016,….]

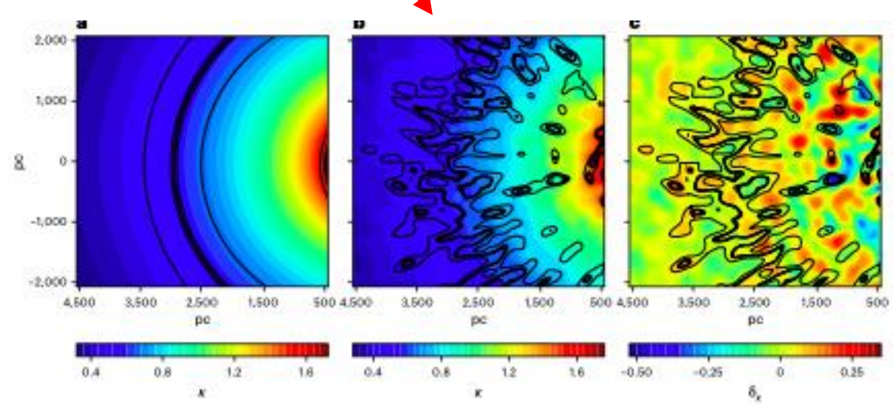
    😁 $\frac{\sigma_{\rm SI}}{m_{\rm DM}} \sim 0.5 - 10 {\rm cm}^2/{\rm g}$ at dwarf scales of DM velocity ~ 10 km/s

  - Weaker self-scattering favored by cluster merging/halo profiles etc. [O. D. Elbert et al. 2016, K. Bondarenko 2016,….]

    😭 $\frac{\sigma_{\rm SI}}{m_{\rm DM}} \leq 0.2 - 1 {\rm cm}^2/{\rm g}$ at cluster scales of DM velocity ~ 1000km/s

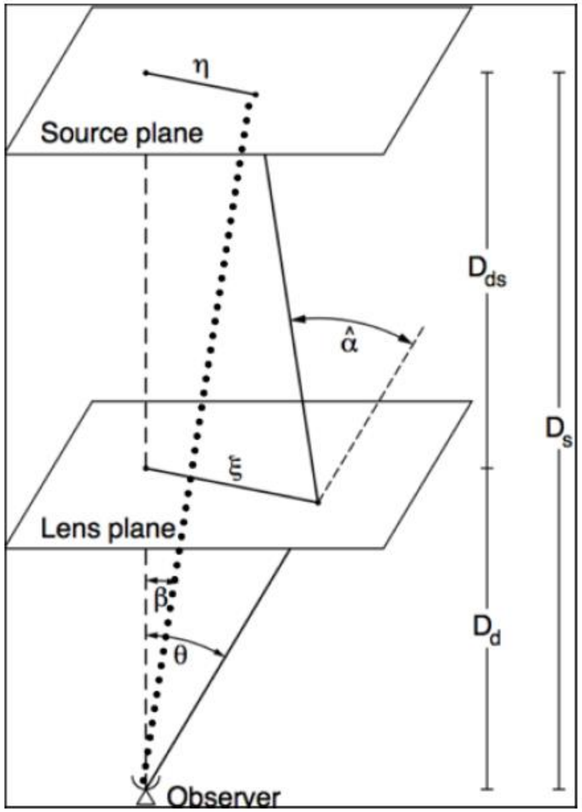


$$\lambda_{\rm dB} = 150\left(\frac{10^{-22}\,{\rm eV}}{m_\phi}\right)\left(\frac{M_h}{10^{12}M_\odot}\right)^{-1/3}\,{\rm pc}.$$



Gravitational lensing

Light rays formalism



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

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

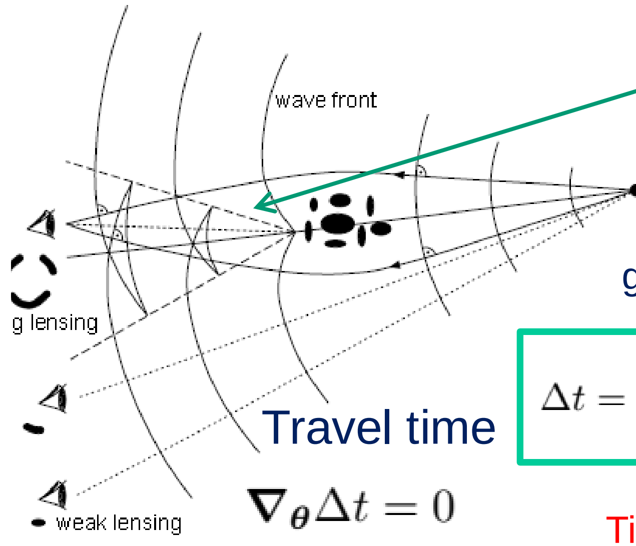
$$A(\boldsymbol{\theta}) = \frac{\partial \boldsymbol{\beta}}{\partial \boldsymbol{\theta}} \qquad \mu(\boldsymbol{\theta}) = \frac{1}{\det A(\boldsymbol{\theta})}.$$

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

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:

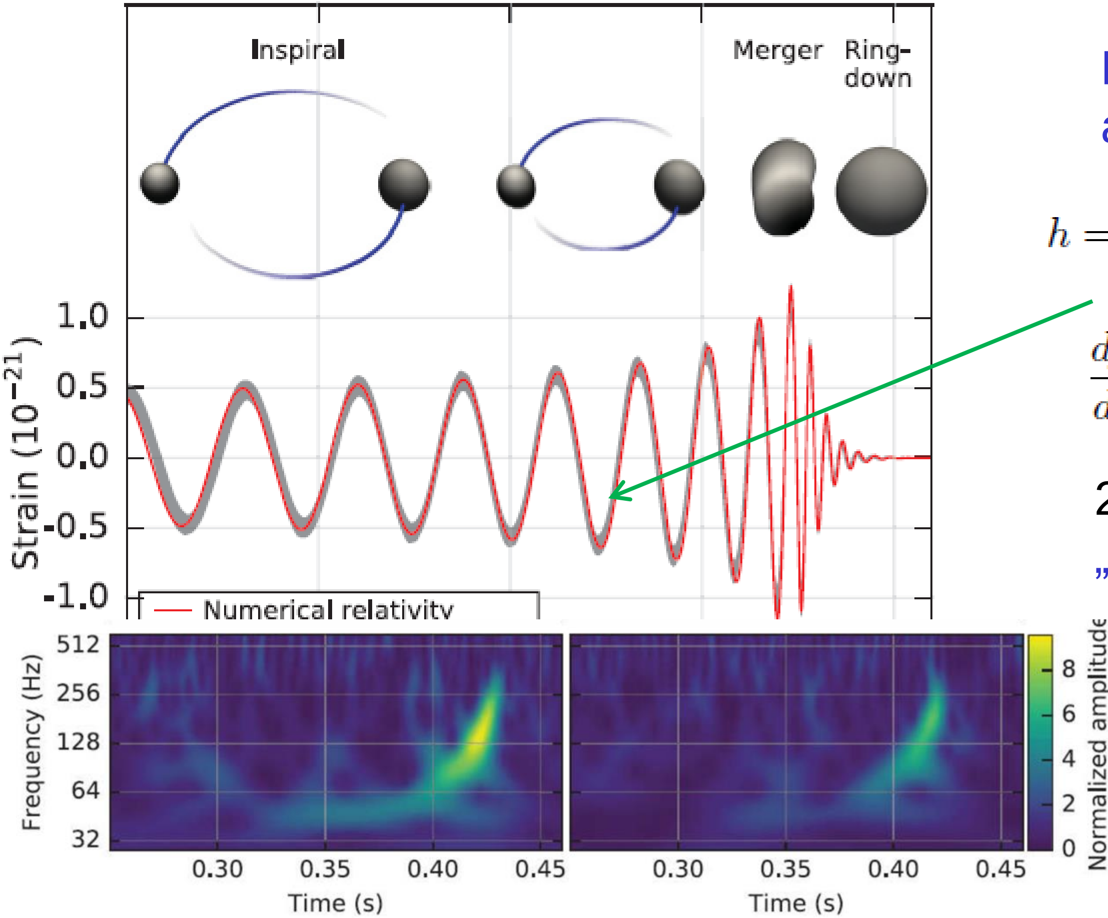
* image positions
and shape distortions

* time delay between images

* flux ratios
magnification ratios

The idea of „standard sirens”

B. Schutz 1986
B.Schutz, A. Królak 1987



Measure the strain h(t)
and frequency drift df/dt

$$h = \frac{4\pi^{2/3}(G\mathcal{M})^{5/3}}{c^4 D} f(t)^{2/3} \cos\left[\int_0^t f(t')\,\mathrm{d}t'\right]$$

$$\frac{df}{dt} = \frac{96\pi^{8/3}}{5}\left(\frac{G\mathcal{M}}{c^3}\right)^{5/3} f^{11/3}$$

2 equations for 2 unknowns:
„chirp mass” *M* & distance D

$$\mathcal{M} = \frac{c^3}{G}\left(\frac{5}{96\pi^{8/3}}\frac{df}{dt}\right)^{3/5} f^{-11/5}$$

$$D = \frac{4c}{\pi^2 h}\frac{df(t)}{dt} f^{-3} \cos\left(\int_0^t f(t')dt'\right)$$

$$M_c \to (1+z)M_c$$

$$t \to (1+z)t$$

$$f \to \frac{1}{1+z} f$$

$$\frac{df}{dt} \to \frac{1}{(1+z)^2}\frac{df}{dt}$$

for cosmological sources

The distance inferred is the **luminosty distance**

$$D_L = (1+z)\,D$$

Plane GW Traveling Through Homogeneous Matter

- **Fluid:**
  - GW shears the fluid, (rate of shear) = $\sigma_{jk} = \frac{1}{2}\dot{h}_{jk}^{\mathrm{GW}}$
  - no resistance to shear, so no action back on wave
  - Viscosity $\eta \sim \rho v s = (\text{density})(\text{mean speed of particles})(\text{mean free path})$ produces stress $T_{jk} = -2\eta\sigma_{jk} = -\eta\dot{h}_{jk}^{\mathrm{GW}}$ **NOTE:** s must be $< \lambda\!\!\!^{-}$
  - Linearized Einstein field equation: $\Box h_{jk}^{\mathrm{GW}} = -16\pi(T_{jk})^{\mathrm{TT}} = 16\pi\eta\dot{h}_{jk}^{\mathrm{GW}}$
  - Wave attenuates: $h_{jk}^{\mathrm{GW}} \sim \exp(-z/\ell_{\mathrm{att}})$ where $\ell_{\mathrm{att}} = \frac{1}{8\pi\eta} = \frac{1}{8\pi\rho v s}$

In the fluid with shear viscosity

$$h_{\alpha,\mathrm{visc}} = h_{\alpha}\mathrm{e}^{-\beta D/2}$$

attenuated wave leads
to biased luminosity distance

$$D_{\mathrm{L,eff}}(z,\beta) = D_{\mathrm{L}}(z)\mathrm{e}^{\beta D(z)/2}$$

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Measuring the viscosity of dark matter with strongly lensed gravitational waves

Shuo Cao,[1★] Jingzhao Qi,[2] Marek Biesiada,[1,3★] Tonghua Liu,[1] Jin Li[4] and Zong-Hong Zhu[1★]
[1]*Department of Astronomy, Beijing Normal University, Beijing 100875 , China*
[2]*Department of Physics, College of Sciences, Northeastern University, Shenyang 110004, China*
[3]*National Centre for Nuclear Research, Pasteura 7, PL-02-093 Warsaw, Poland*
[4]*Department of physics, Chongqing University, 400044 Chongqing, China*

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Astronomy & Astrophysics

Letter to the Editor

Direct measurement of the distribution of dark matter with strongly lensed gravitational waves

Shuo Cao[1,2], Jingzhao Qi[3], Zhoujian Cao[1,2], Marek Biesiada[4], Wei Cheng[5], and Zong-Hong Zhu[1,2]

$$h_{\alpha,\mathrm{visc}} = h_\alpha \mathrm{e}^{-\beta D/2}$$

attenuated wave leads
to biased luminosity distance

$$D_{\mathrm{L,eff}}(z, \beta) = D_{\mathrm{L}}(z)\mathrm{e}^{\beta D(z)/2}$$

lensed transitents (GW, SNIa) signal leads to very precise determination of „time delay distance"

$$\Delta t_{i,j} = \frac{D_{\Delta \mathrm{t}}(1+z_{\mathrm{l}})}{c}\Delta\phi_{i,j}$$

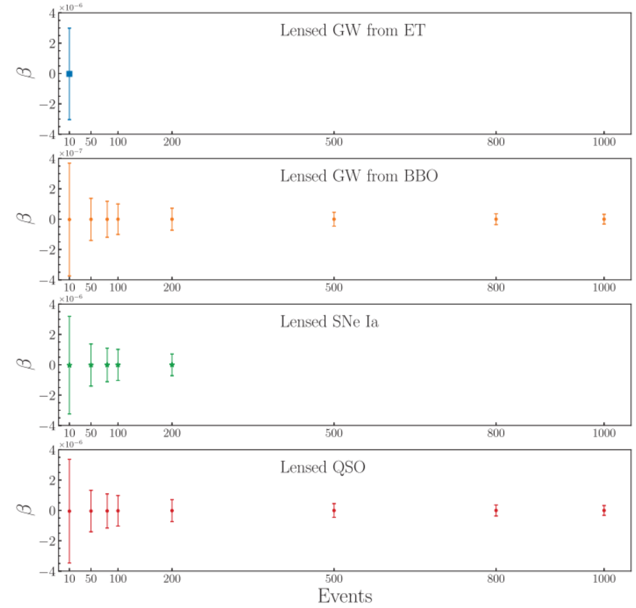
$$D_{\Delta\mathrm{t}}(z_l, z_s) \equiv \frac{D_A(z_l)D_A(z_s)}{D_A(z_l, z_s)}$$

To be determined by unlensed standard sirens

$$D_{\Delta\mathrm{t}} = \frac{D_{\mathrm{L}}(z_l)D_{\mathrm{L}}(z_s)}{(1+z_l)^2 D_{\mathrm{L}}(z_s) - (1+z_s)(1+z_l)D_{\mathrm{L}}(z_l)}$$

$$\chi^2 = \sum_{i=1}^{i} \frac{\left(D_{\Delta t,i}^{lens}(z_{l,i}, z_{s,i}) - D_{\Delta t,i}^{unlens}(z_{l,i}, z_{s,i}; \beta)\right)^2}{\sigma_{i,\text{lens}}^2 + \sigma_{i,\text{unlens}}^2}$$

objective function fitted for beta **lensed**



relation with DM physical parameters

$$\frac{\langle \sigma_\chi \rangle}{m_\chi} = \frac{6.3\pi G \langle v \rangle}{c^3 \beta}$$

Table 1. Summary of the constraints obtained from different observations. Type I and II, respectively, correspond to the two cases of self-interacting DM in galaxies and galaxy clusters.

Data	$\Delta\beta$	$\Delta(\sigma_\chi/m_\chi)(I)$	$\Delta(\sigma_\chi/m_\chi)(II)$
GW (lensed; ET) + GW (unlensed)	10^{-6} Mpc^{-1}	10^{-4} cm^2 g^{-1}	10^{-3} cm^2 g^{-1}
GW (lensed; BBO) + GW (unlensed)	10^{-8} Mpc^{-1}	10^{-6} cm^2 g^{-1}	10^{-5} cm^2 g^{-1}
QSO (lensed; LSST) + GW (unlensed)	10^{-7} Mpc^{-1}	10^{-5} cm^2 g^{-1}	10^{-4} cm^2 g^{-1}
SNe Ia (lensed; LSST) + GW (unlensed)	10^{-6} Mpc^{-1}	10^{-4} cm^2 g^{-1}	10^{-3} cm^2 g^{-1}

1 cm^2 g^{-1} = 1.8 barn GeV^{-1}

it would be able to DM viscosity and differentiate cluster and small scale scenarios

nature astronomy

Article

https://doi.org/10.1038/s41550-023-01943-9

Einstein rings modulated by wavelike dark matter from anomalies in gravitationally lensed images

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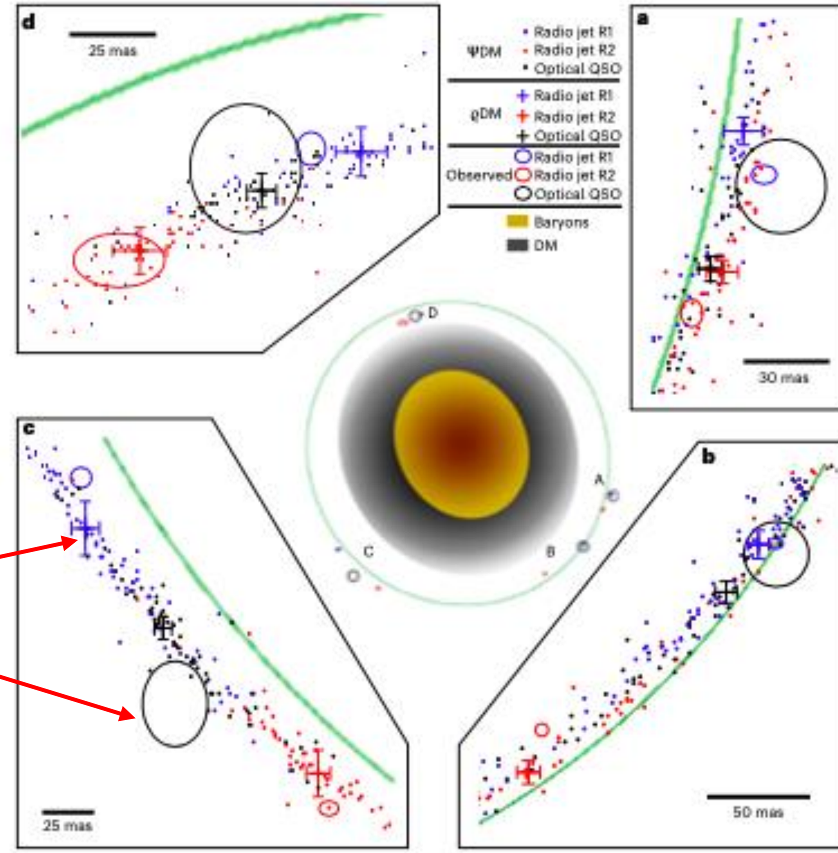
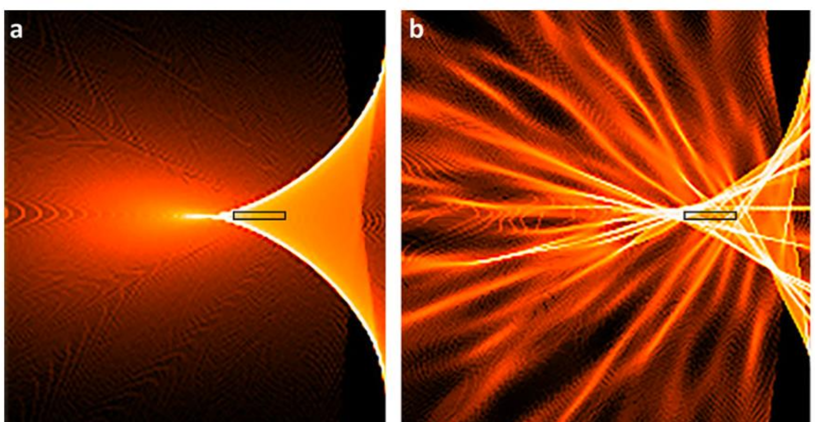
Alfred Amruth[1], Tom Broadhurst[2,3,4], Jeremy Lim[1], Masamune Oguri[5,6,7], George F. Smoot[3,8,9,10], Jose M. Diego[11], Enoch Leung[12], Razieh Emami[13], Juno Li[1], Tzihong Chiueh[14,15,16], Hsi-Yu Schive[14,15,16,17], Michael C. H. Yeung[1] & Sung Kei Li[1]

Positions predicted by best fit smooth potential

Positions observed





Lens HS 0810+2554 observed by VLBI

QSO by HST; radio. Jets by VLBI

$z_s = 1.51$ $z_l = 0.89$

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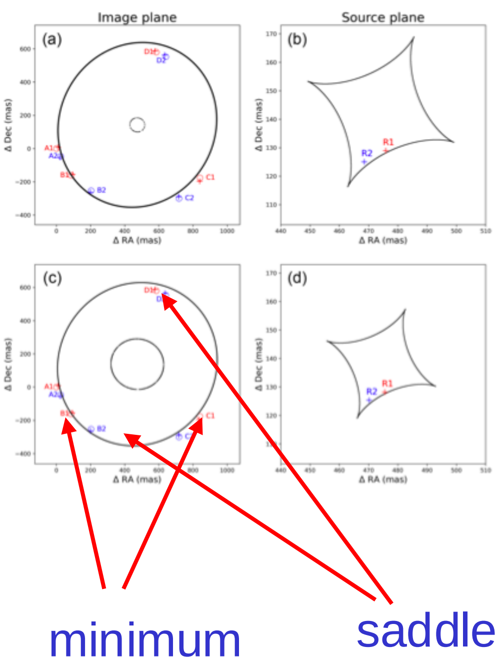
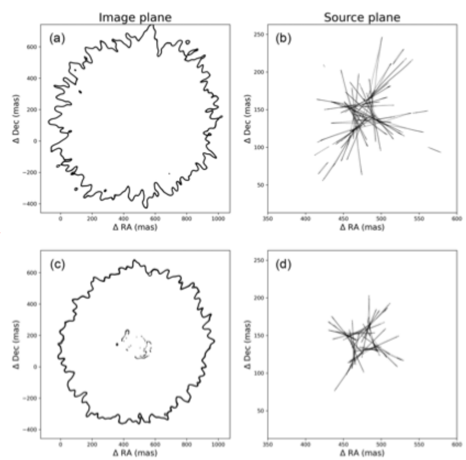
Time delay anomalies of fuzzy gravitational lenses

Jianxiang Liu,[1] Zijun Gao,[1] Marek Biesiada,[2] and Kai Liao[1,*]
[1] *School of Physics and Technology, Wuhan University, Wuhan 430072, China*
[2] *National Centre for Nuclear Research, Pasteura 7, PL-02-093 Warsaw, Poland*





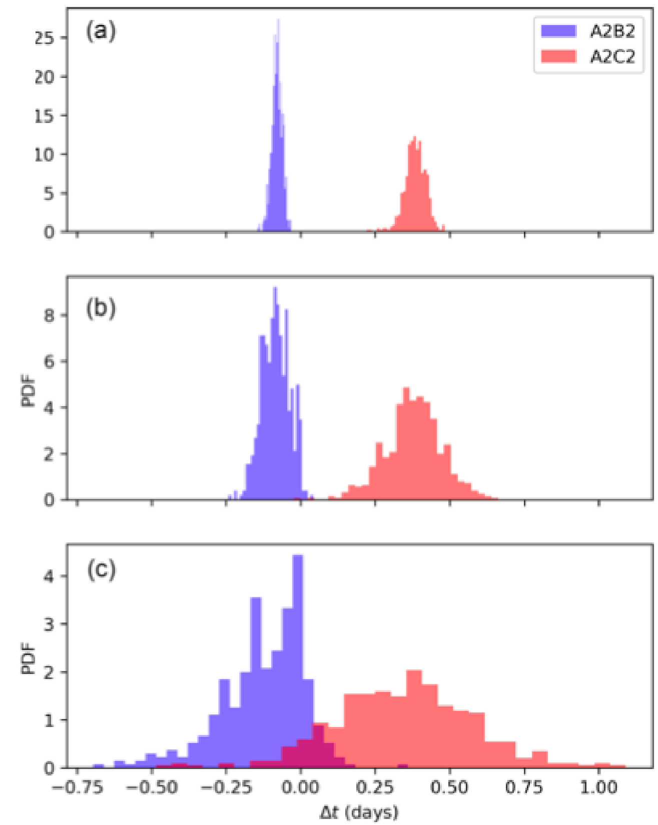


FIG. 7. Time delays anomalies of A2B2 and A2C2. A2 and C2 are minimum points; B2 is the saddle point. Strength of the ψDM perturbation is $d = 0.3$ with different de Broglie wavelength: $\lambda_{\mathrm{dB}} = 60$ pc panel (a), $\lambda_{\mathrm{dB}} = 120$ pc panel (b) and $\lambda_{\mathrm{dB}} = 240$ pc panel (c).

Conclusions

- Vera Rubin Observatory (LSST survey) will become a game changer in strong lensing

  10 000 strong lensing systems including 1000 quasar lenses.

- Great opportuinity from lensed transients and multiwavelength studies

  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, FRBs

- New generation of ground-based and space-borne GW detectors (ET, CE, DECIGO, LISA) will considerably enhance the statistics of GW events – lensed signals will be detected

- Opportunity to explore the fundamental questions in Physics, like the nature of DM.

Thank you !