Potential gravitational lensing on a CMB cosmic string candidate

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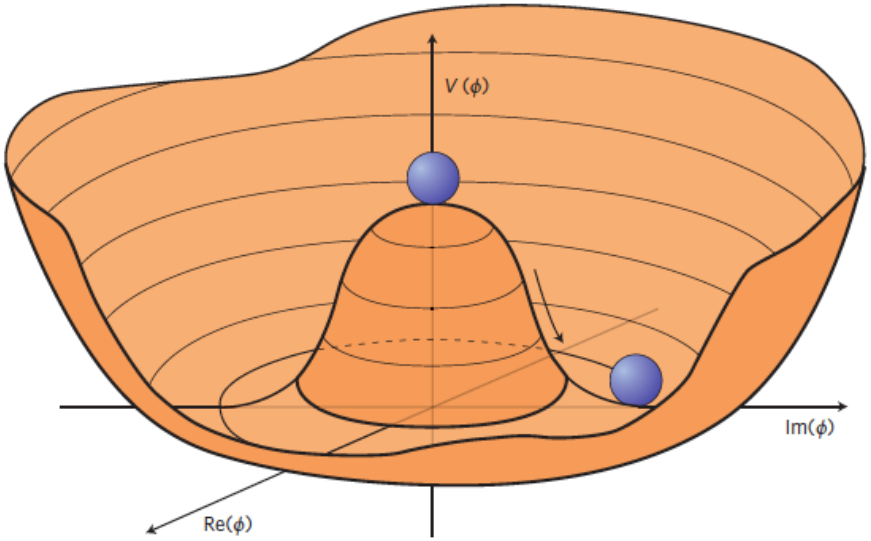
Introduction

GUT $\rightarrow$ EFT $\rightarrow$ worldsheet action



Vacuum formation

Nambu-Goto action:

$$S = \mu \int_{\text{worldsheet}} d^2\zeta \sqrt{-\det \gamma_{ab}} + O\left(R_s^{-1}\right)$$

where γ_{ab} is induced metric on a worldsheet.
EoM:

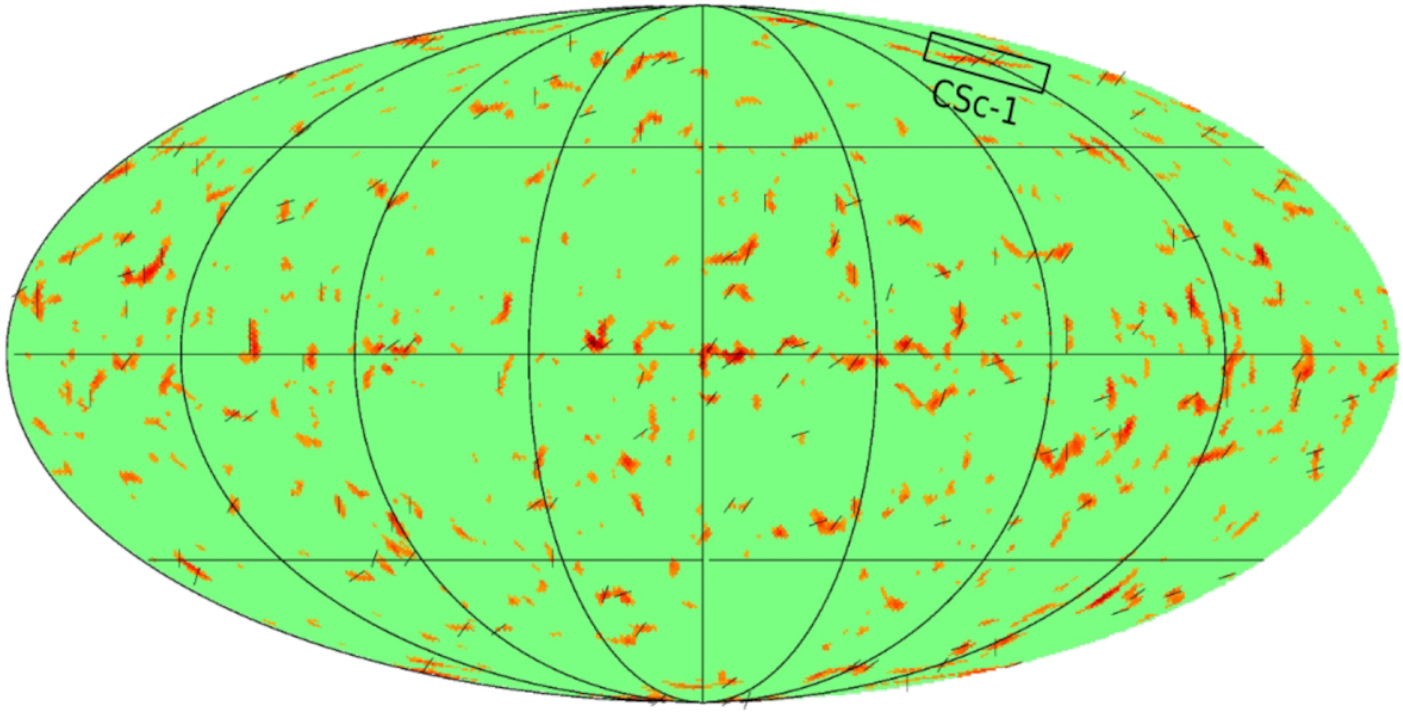
$$\begin{cases} \partial_\tau^2 \mathbf{X} - \partial_\sigma^2 \mathbf{X} = 0 \\ \partial_\tau \mathbf{X} \cdot \partial_\sigma \mathbf{X} = 0 \\ (\partial_\tau \mathbf{X})^2 + (\partial_\sigma \mathbf{X})^2 = 1 \end{cases}$$

String detection in CMB

Cone-like metric singularity. CMB map variation (Kaiser-Stebbins effect):

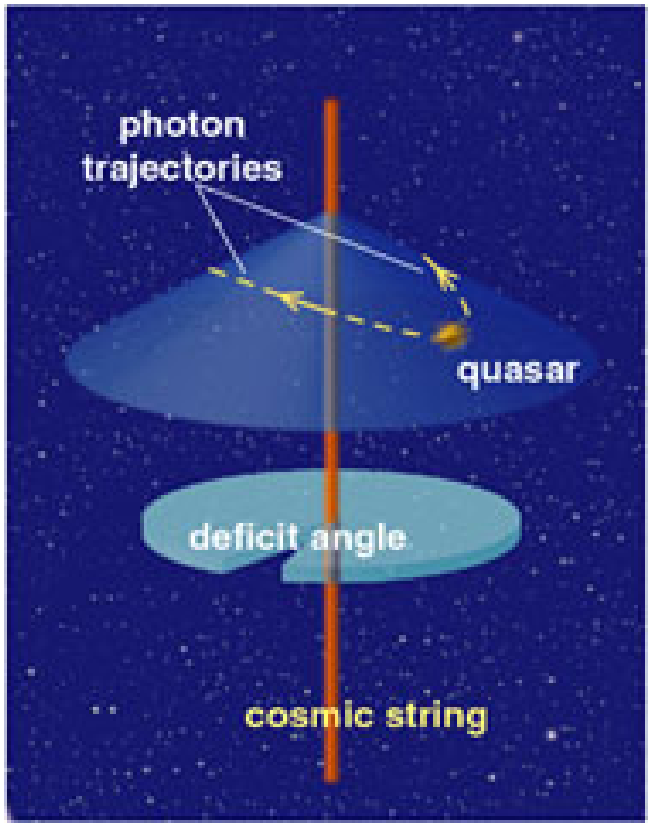
$$\frac{\Delta T}{T} \approx 8\pi G\mu\gamma \cdot \frac{v_\perp}{c}$$

3σ candidate (CSc-1):



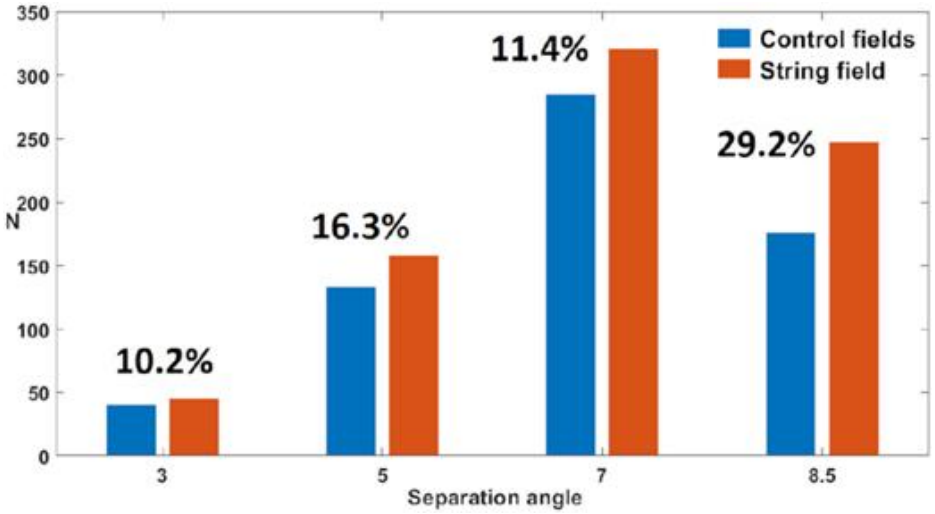
String detection by lenses 1/4

GR solution for straight infinite string:



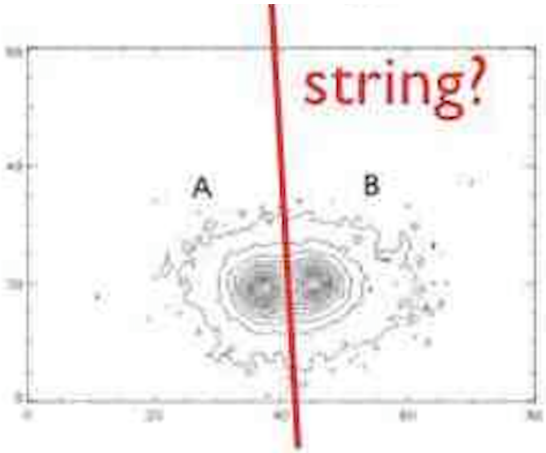
2 images

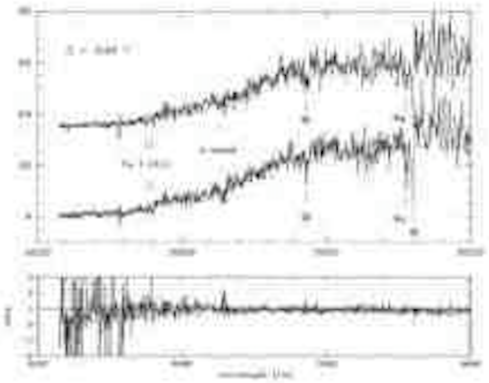
Cone-like metric with angle deficit $8\pi G\mu$ can create double images of distant galaxies.
Statistical approach to a number of galaxy pairs:



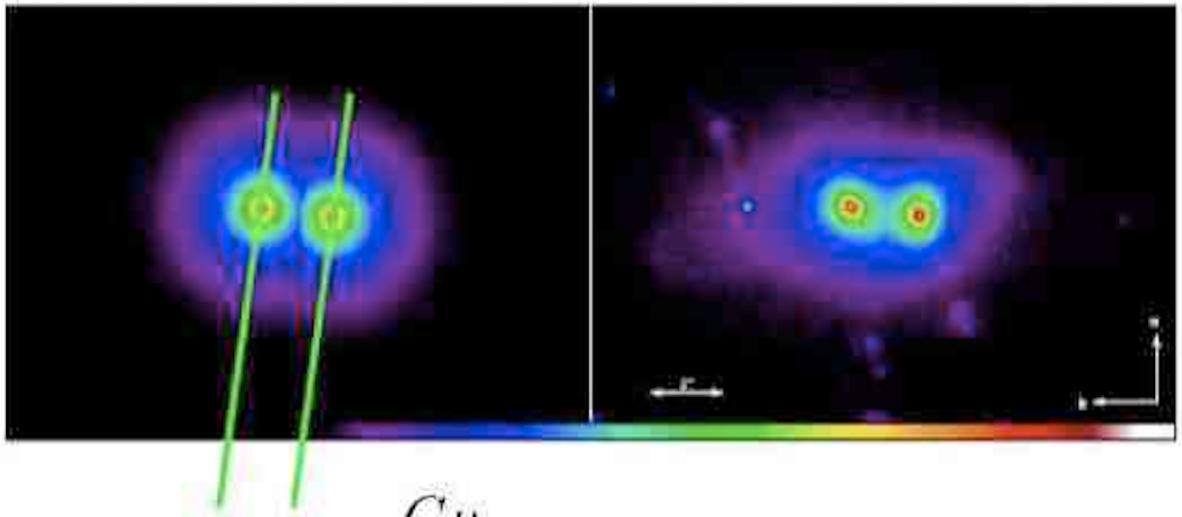
String detection by lenses 2/4

CSl-1 object:





Sazhin *et al*
2002



Sazhin *et al*
2006

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

String detection by lenses 3/4

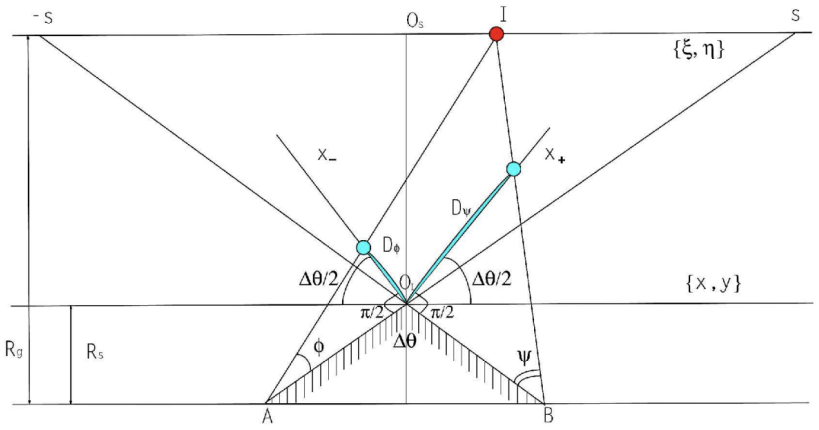
Inclination i is introduced in the work. Image $I(\eta, \xi)$ changes like so:

$$\theta_E(i, \xi) = \Delta\theta\,(\cos i + \xi \sin i))\left(1 - \frac{R_s}{R_g(1 + \xi \tan i)}\right)$$

"Einstein ring"

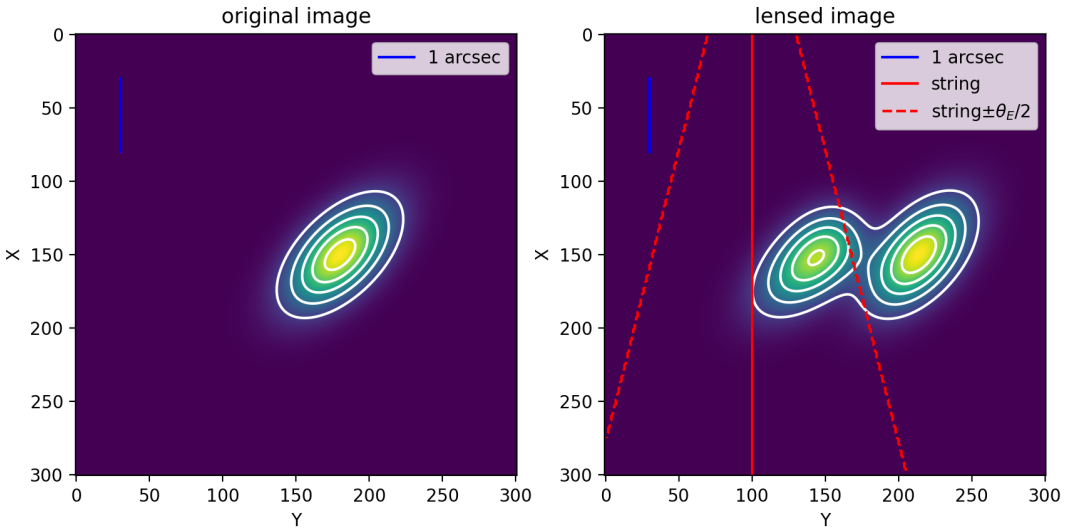
$$I_{1+2}(\eta, \xi) = \begin{cases} I(\eta + \theta_E(i, \xi)/2, \xi),\ \eta < -\theta_E(i, \xi) \\ I(\eta + \theta_E(i, \xi)/2, \xi) + I(\eta - \theta_E(i, \xi)/2, \xi),\ |\eta| \leq \theta_E(i, \xi) \\ I(\eta - \theta_E(i, \xi)/2, \xi),\ \eta > \theta_E(i, \xi) \end{cases}$$

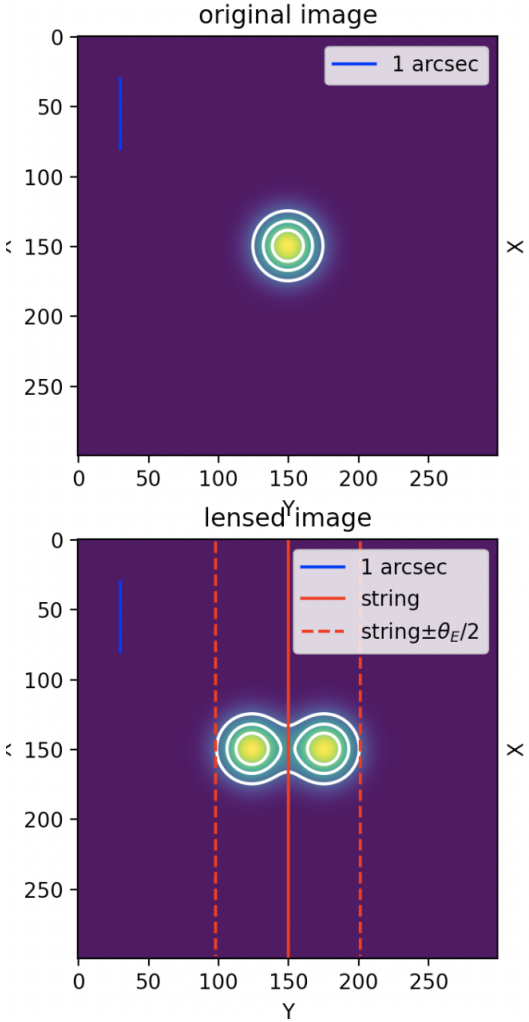
Picture transformation $I(\eta, \xi)$



String detection by lenses 4/4

Object modeling script.
Examples:

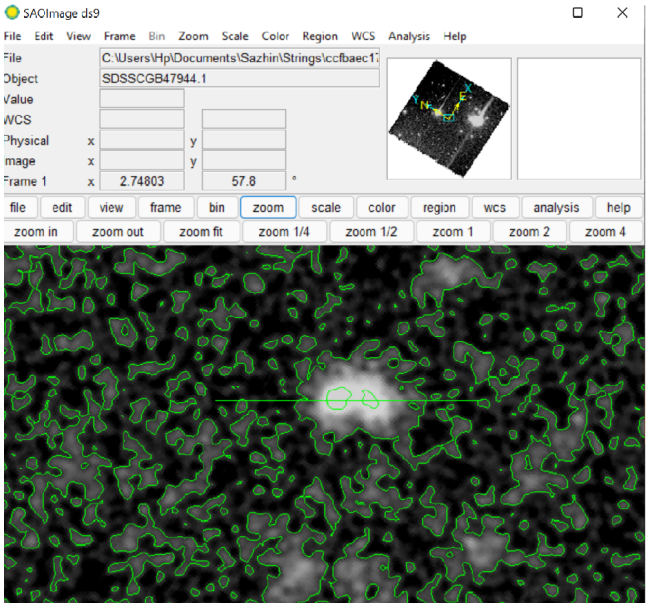


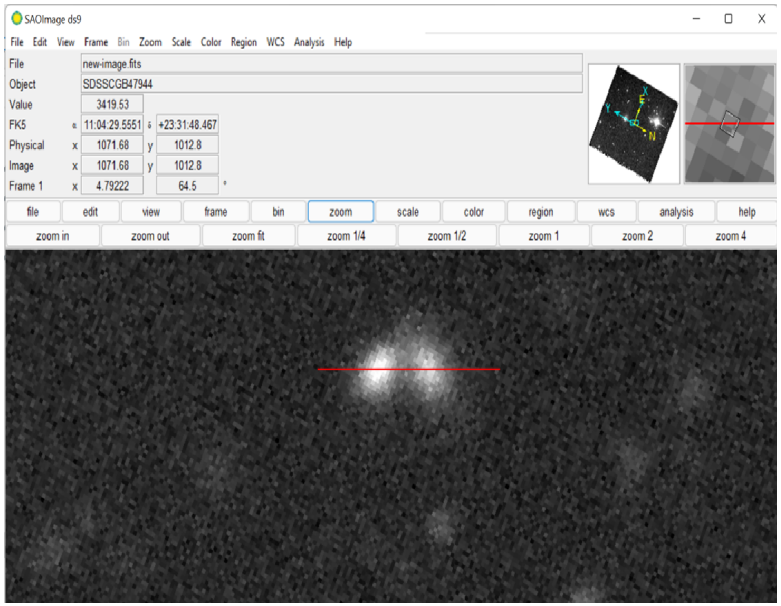


Lens candidate, observations.

Taken on Himalayan Chandra Telescope, 7th of March 2022.

- $D = 2.0$ m
- $R = 2190$
- $\lambda\lambda\ 5800 - 8350$ Å$(\delta\lambda \sim 3$ Å$)$
- 3 shots with exp. time 1800 s for good SNR.

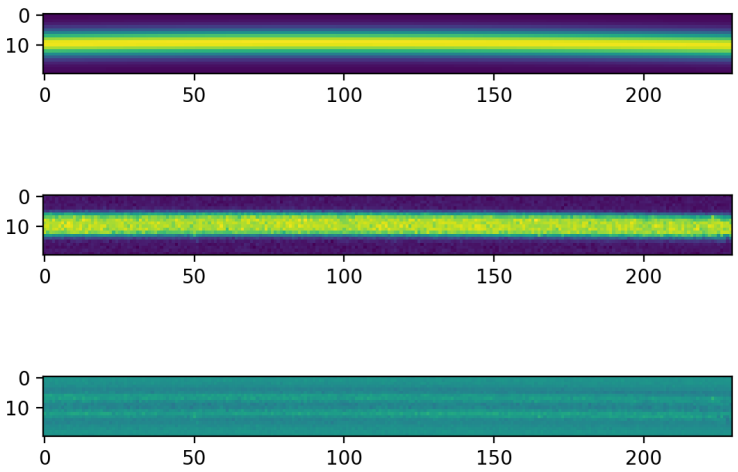




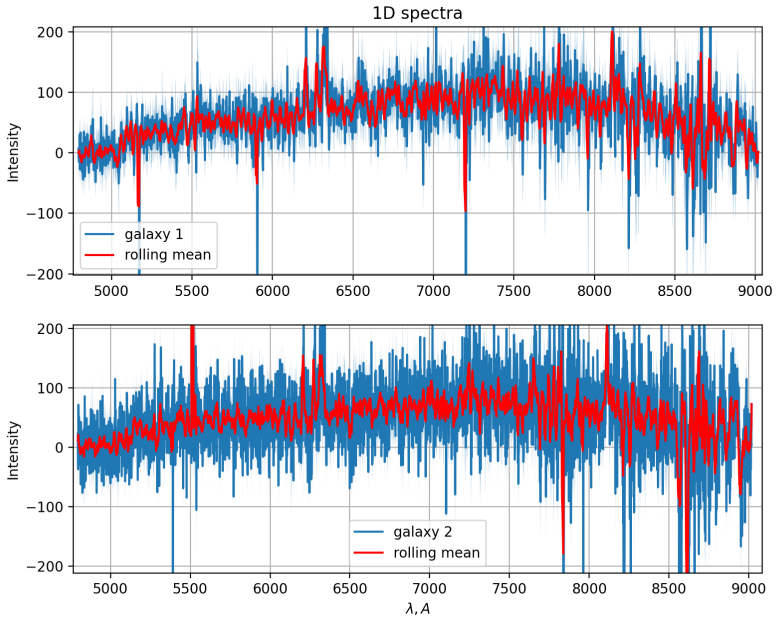
Lens candidate. Spectral analysis 1/3

Spectrum reduction:

1. Cleaning CR.
2. First reduction (BIAS, DARK, FLAT).
3. Geometry, atmosphere.



Line removal

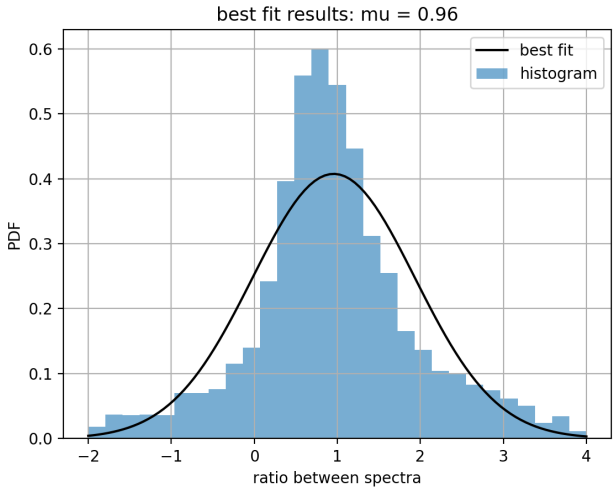


Result

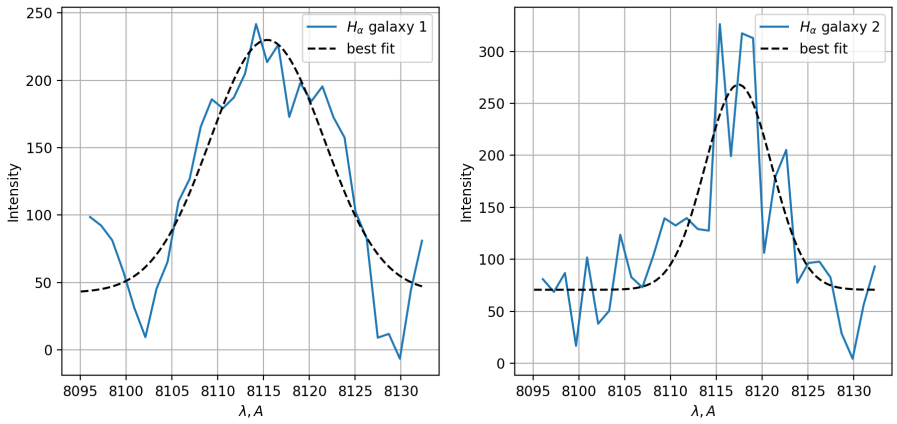
Lens candidate. Spectral analysis 2/3

Statistical significance:

1. Correlation ~ 0.62
2. $\chi^2/\text{DOF} \sim 0.8$ by the main lines ($H_\alpha, H_\beta, [OIII], [NII]$ etc.)
3. Similarity:



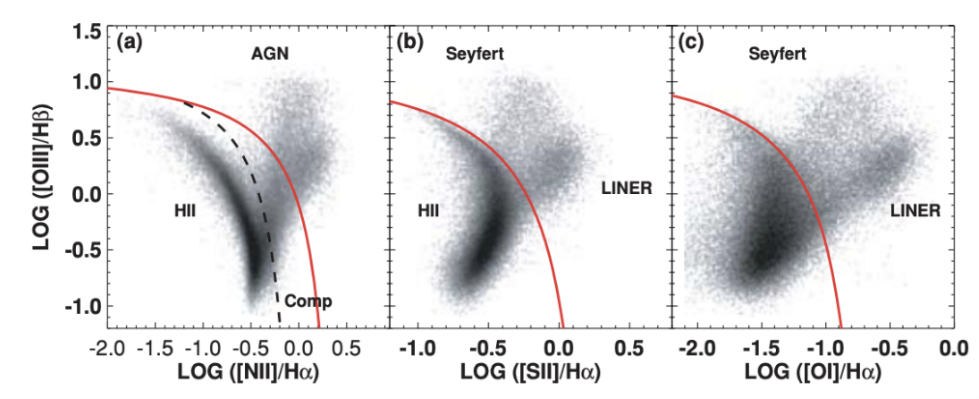
Histogram of ratio of spectra



Fit example of H_α

Lens candidate. Spectral analysis 3/3

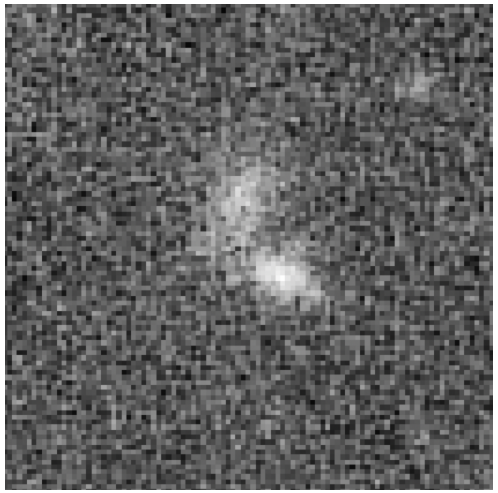
Star formation:

galaxy	1	2
$\log[OIII]/H_\beta$ - $\log[NII]/H_\alpha$	(-0.09, -0.80)	(0.29, -0.88)
$\log[OIII]/H_\beta$ - $\log[SII]/H_\alpha$	(-0.09, -0.59)	(0.29, -0.30)
$\log[OIII]/H_\beta$ - $\log[OI]/H_\alpha$	(-0.09, -0.78)	(0.29, -0.24)
		

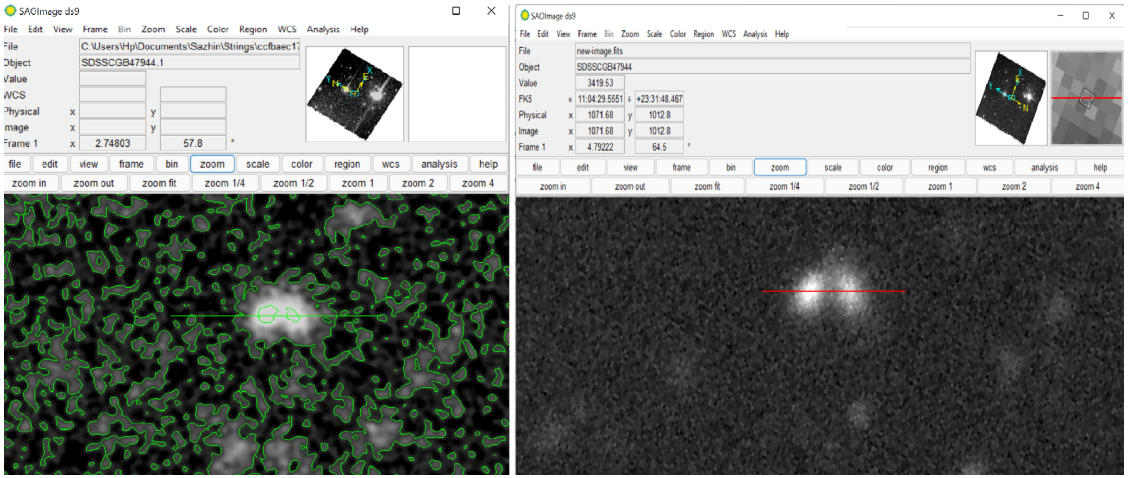
Both are HII-type, so SF scenario should be included.

Lens candidate. Image analysis 1/3

Pictures are taken from:
1. MAST, Pan-STARRS 1. $\mu \approx 0.25''$/pix, PSF from athmosphere (the nearest stars give FWHM).
2. Himalayan Chandra Telescope



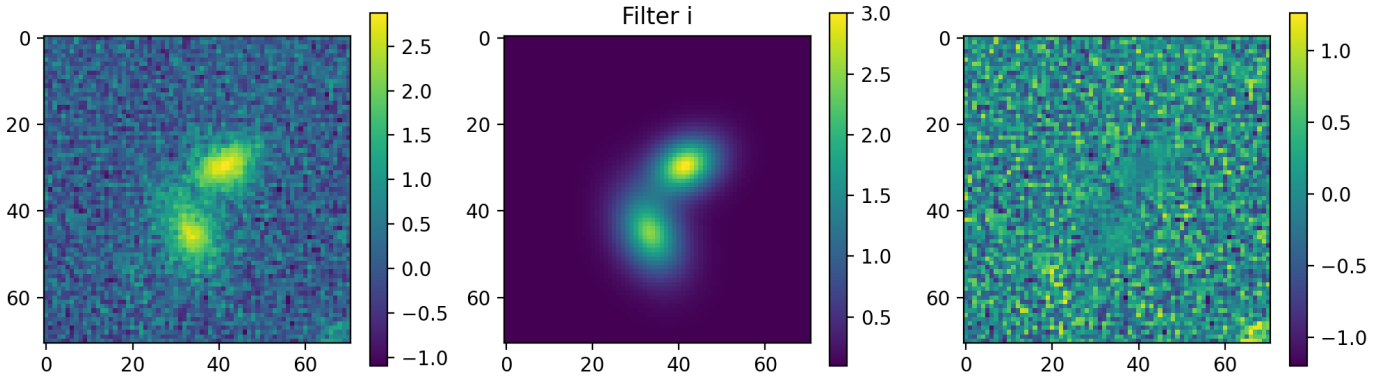
Pan-STARRS 1



Himalayan Chandra Telescope

Lens candidate. Image analysis 2/3

GALFIT modeling:
$\chi^2/$ DOF ≈ 0.7 for all the filters.

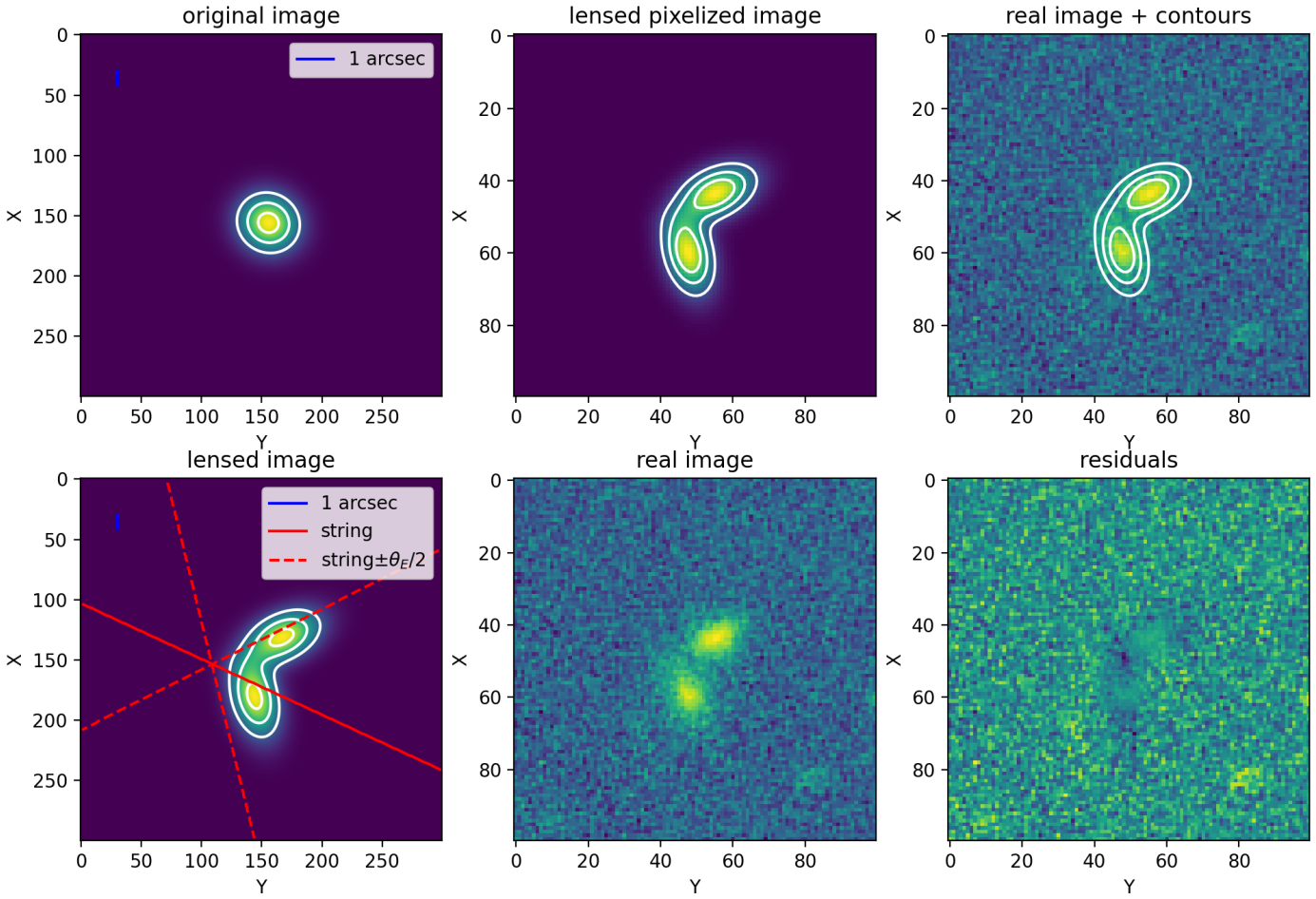


Filter	θ_1, deg	θ_2, deg
g	64.91	-18.21
r	63.31	-24.31
i	60.28	-20.55
y	58.50	-42.38
z	63.30	-34.72

$\rightarrow$ Inclination and bending are needed.

Lens candidate. Image analysis 3/3

χ^2- minimizer with gradient decent for 12 parameters.
PSF, Nyquist sampling, sigma-matrix.



Conclusions

Spectral analysis:

- Significant correlation was found both across the entire spectrum and along individual lines
- There is the possibility that these are two physically different interacting galaxies with active star formation. But these case is difficult to verify only using spectra. Comparing the spectra and identifying their coincidence is now the best method for determining gravitational lenses.

General:

- The GL scenario of the studied by HCT double candidate is statistically significant.
- CS lensing simulations also shows that such a configuration for pair components is possible.
- CSc-1 string candidate is confirmed by two independent methods: using radio data from WMAP and Planck, and using optical data (statistical significance of GL candidates distribution, and spectral confirmation of one GL candidate)

Thank you for your attention!

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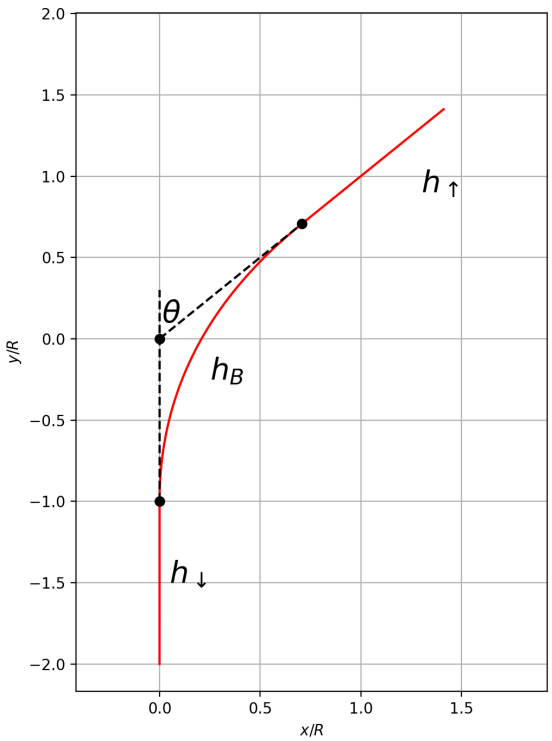
Work in progress: bending

The model of bending: 2 straight lines that are connected by Bezier curve.

$$\mathbf{X}(\sigma, t) \to T_{\mu\nu}(\mathbf{x}, t) \to h_{\mu\nu}(\mathbf{x}, t) \to \text{photon scattering} \to \text{image construction}$$

$$h_{\mu\nu} = \begin{pmatrix} (h_\uparrow + h_\downarrow) & 0 & 0 & 0 \\ 0 & -\sin^2\theta(h_\uparrow + h_B) & -\sin\theta\cos\theta(h_\uparrow + h_B) & 0 \\ 0 & -\sin\theta\cos\theta(h_\uparrow + h_B) & -(h_\downarrow + h_\uparrow\cos^2\theta - h_B\sin^2\theta) & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$



$h_\uparrow$ and $h_\downarrow$ diverge in weak field limit, but we only need Γ for ray-tracing