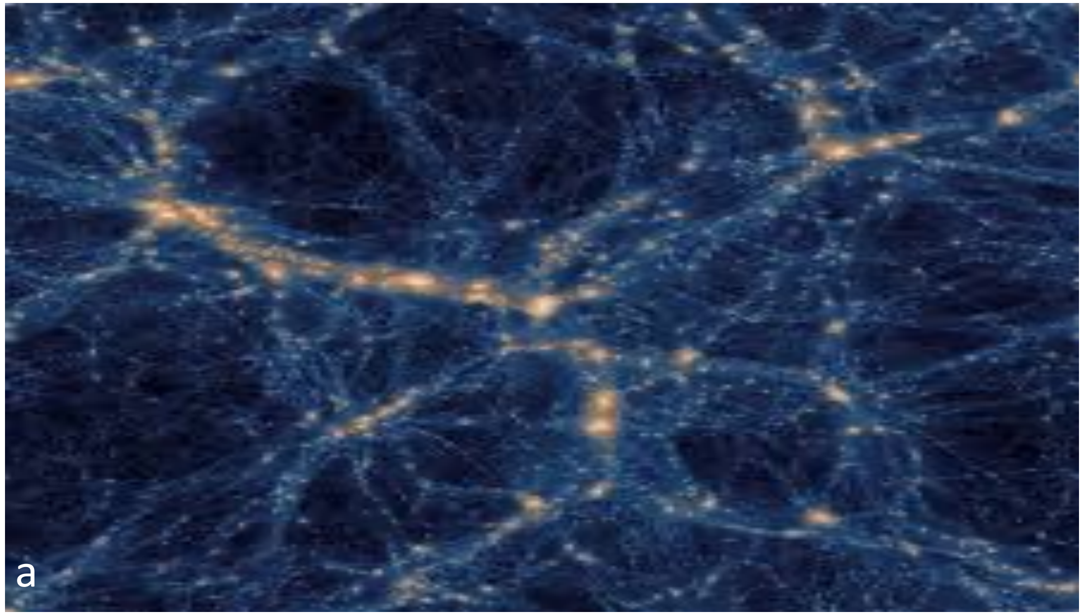
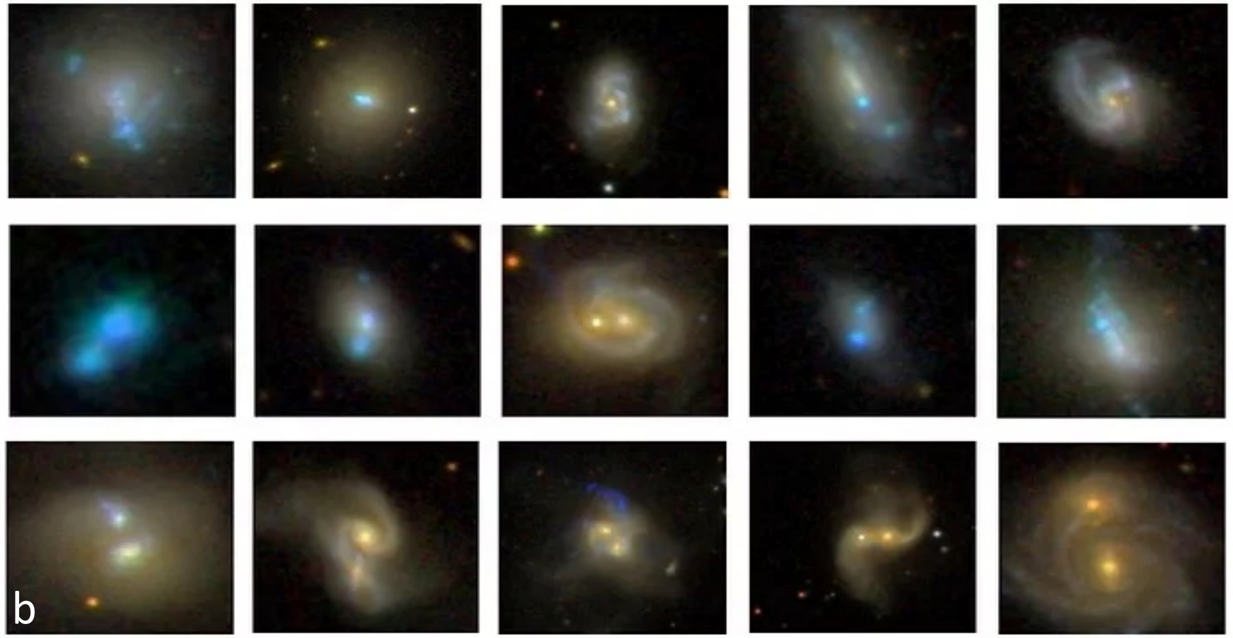
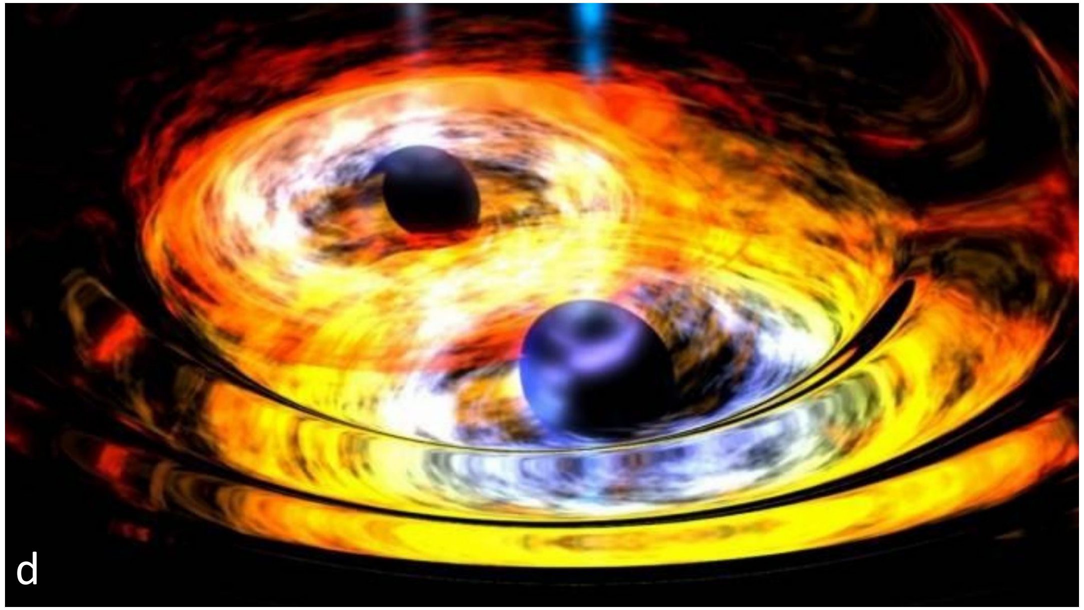


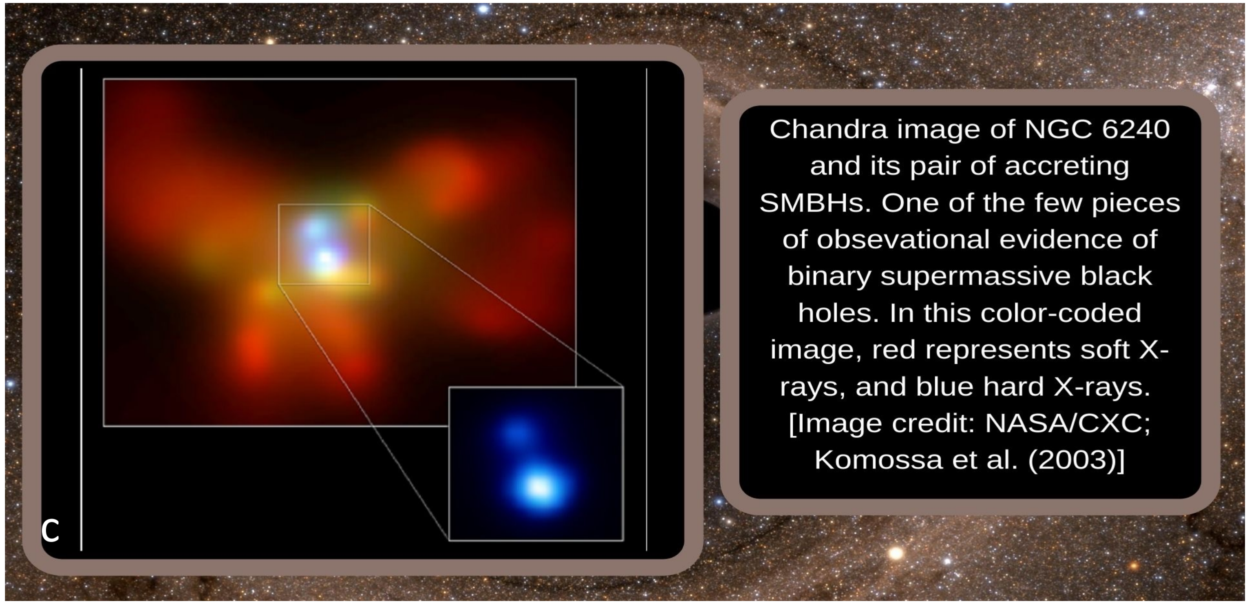
Illustris Simulation



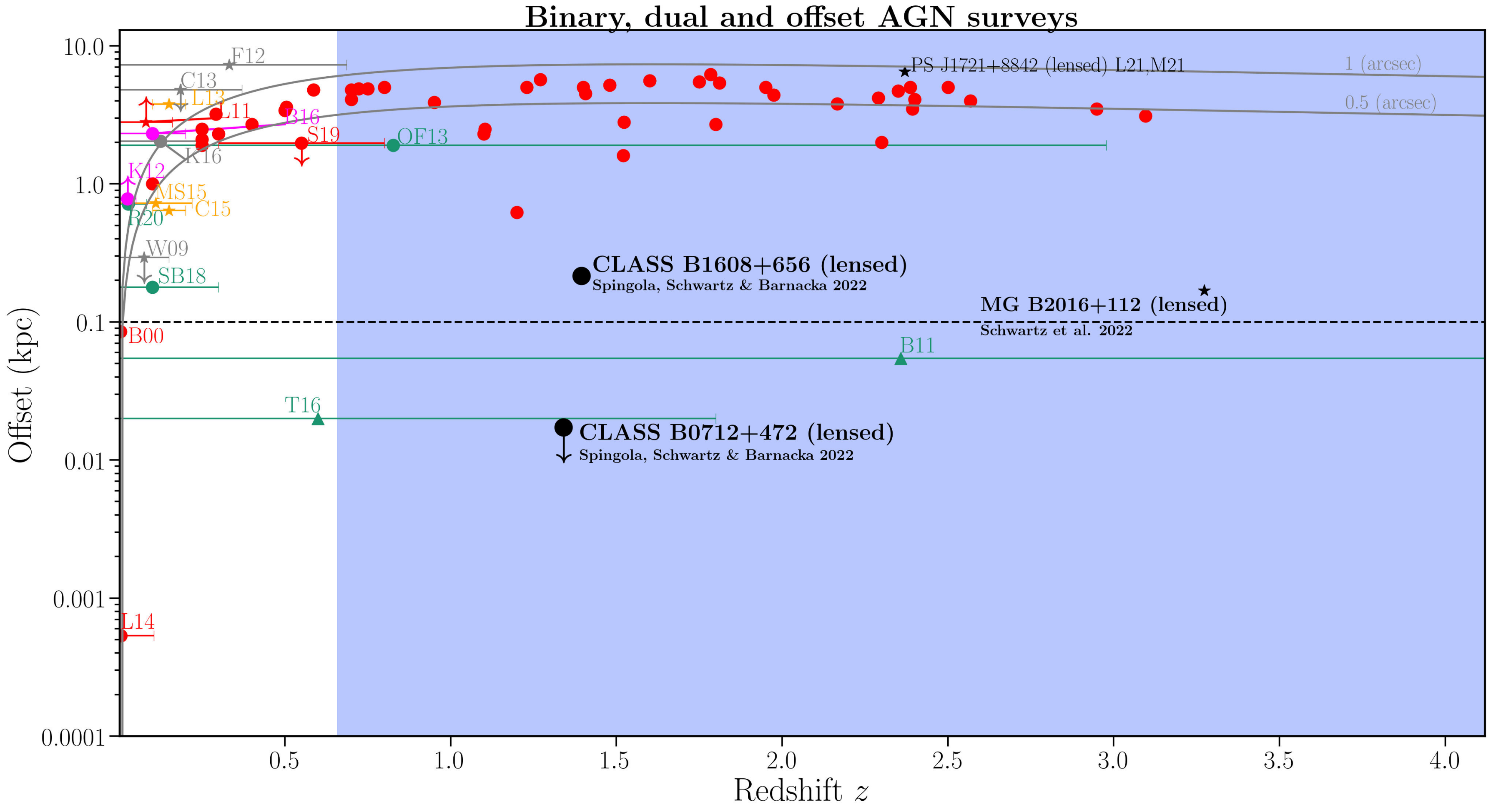
Mezcua et al., 2014



Artist’s impression of merging (NASA/ Pubic Domain)



Komossa et al., 2003



Project Goals

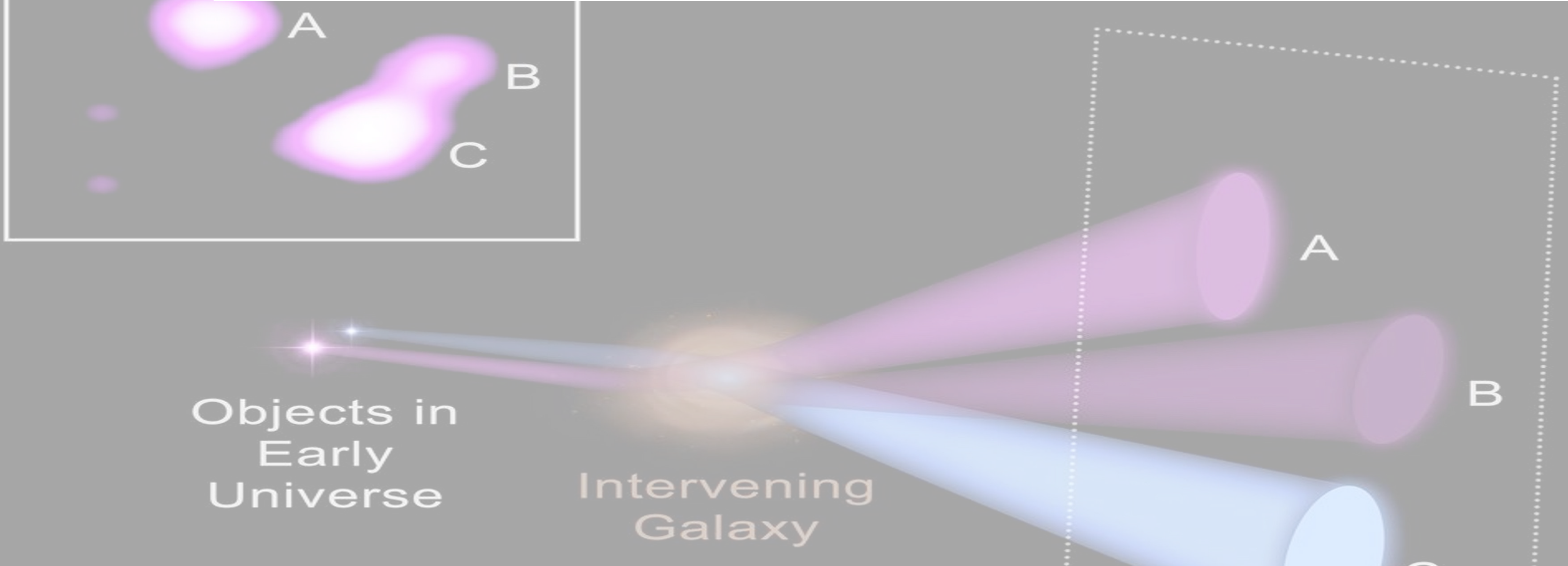
Elucidate supermassive black hole evolution in the early universe, by:

- Finding Dual/Binary supermassive black holes
- Measuring X-ray, Radio, Optical offsets
- Resolving pc-scale X-ray jets
- Finding ejected Black Holes

A Gravitational lens as the ultimate X-ray telescope

Dan Schwartz (CfA)

Alysa Rogers (U. Wisc., Madison), Cristiana Spingola (INAF), Anna Barnacka (CfA & Jagiellonian, Cracow)



Marlena Bocian Hewitt, 2018. (from Barnacka, 2018, PhysRep. 778, 1)

Optics of Gravitational Lenses

Source at $\boldsymbol{\beta}$, images at $\boldsymbol{\theta}$,
The gravitational potential $\boldsymbol{\psi}(\boldsymbol{\theta})$ is the lens.
Images satisfy Fermat's principle for the time delay: $\Delta t \propto \frac{1}{2}(\boldsymbol{\theta} - \boldsymbol{\beta})^2 - \boldsymbol{\psi}(\boldsymbol{\theta})$
Giving the lens equation: $\boldsymbol{\theta} - \boldsymbol{\beta} - \boldsymbol{\nabla}\psi(\boldsymbol{\theta}) = 0$

Purely achromatic.

If X-ray and optical/radio source are co-spatial, all images must coincide

Grossly astigmatic

Images strongly stretched perpendicular to caustic

Images weakly stretched parallel to caustic.

Magnification highly variable across field

Large inside and near the caustic. Diverges on the caustic. Weaker dependence on "size" of lens

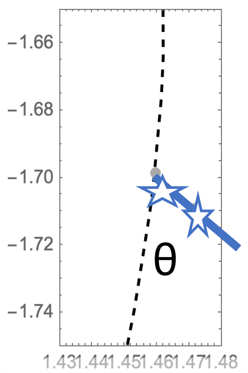
Non-linear.

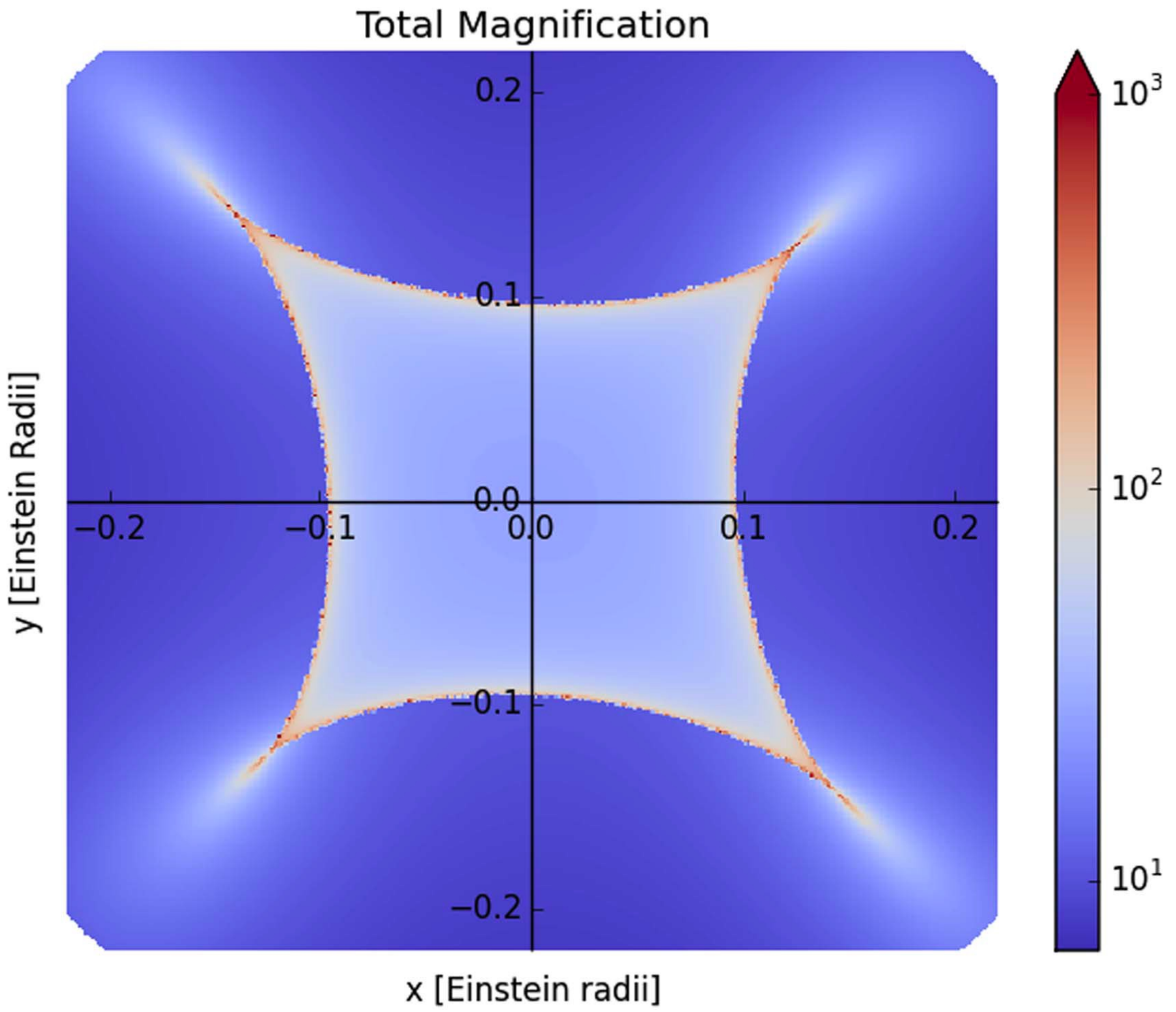
Allows multiple images. Four images for sources inside caustic.

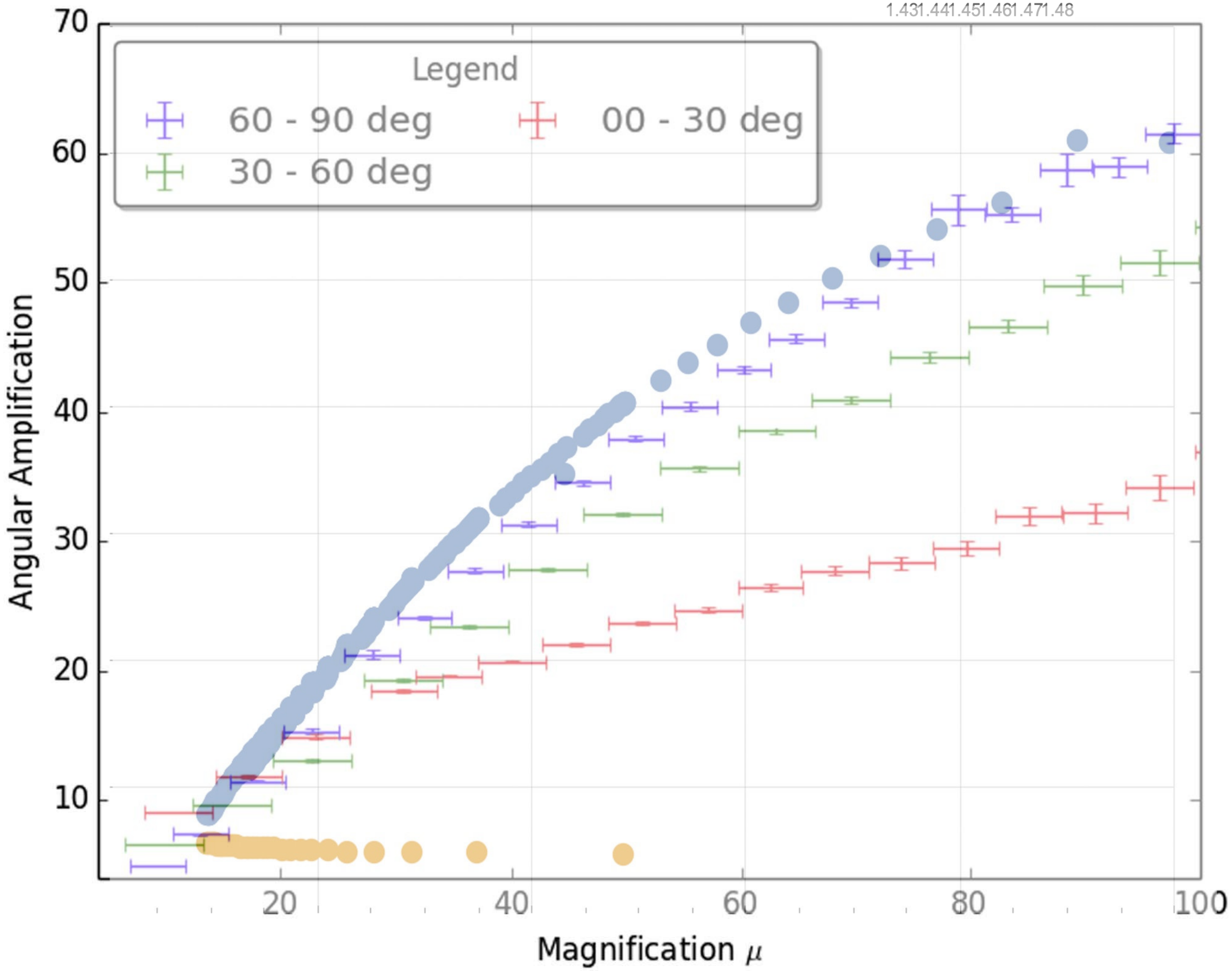
Gravitational Lenses as Telescopes:

Barnacka, A. 2017, ApJ, 846, 157

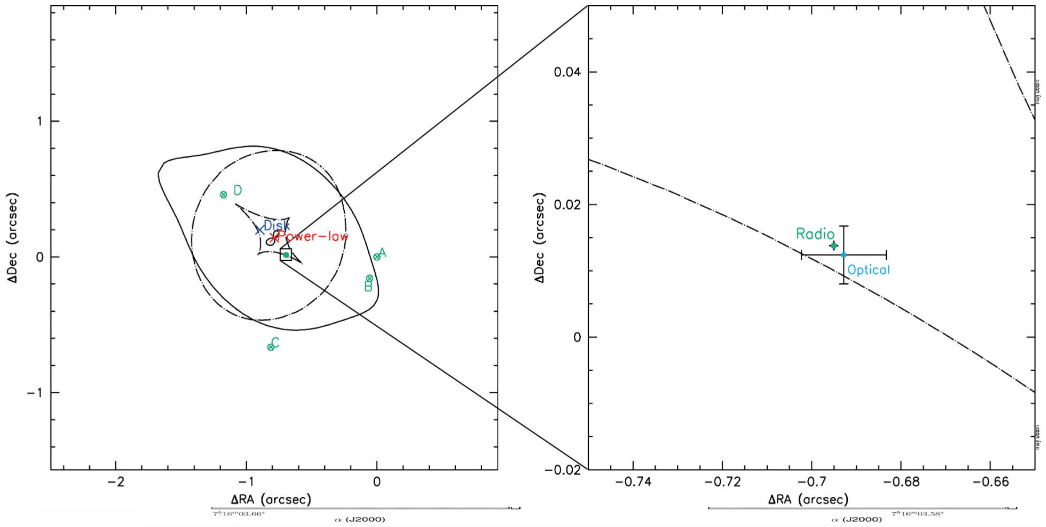
Barnacka, A. 2018, Phys. Rept. 778, 1







Toy Model: Einstein radius =0.5”. Ellipticity =0.2



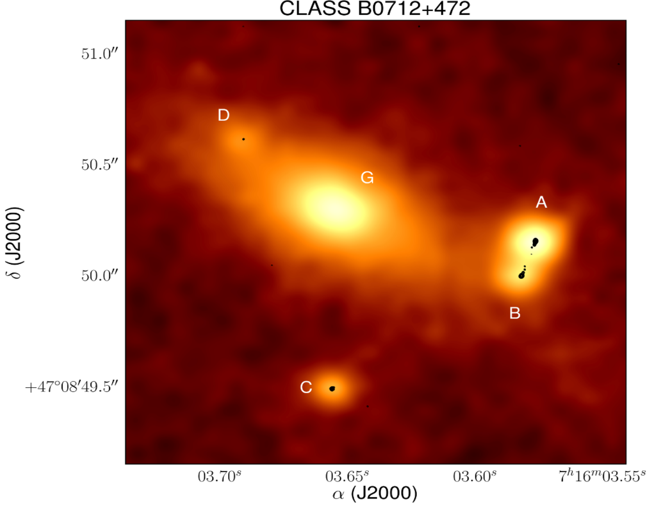
CLASS B0712+472

Z=1.34

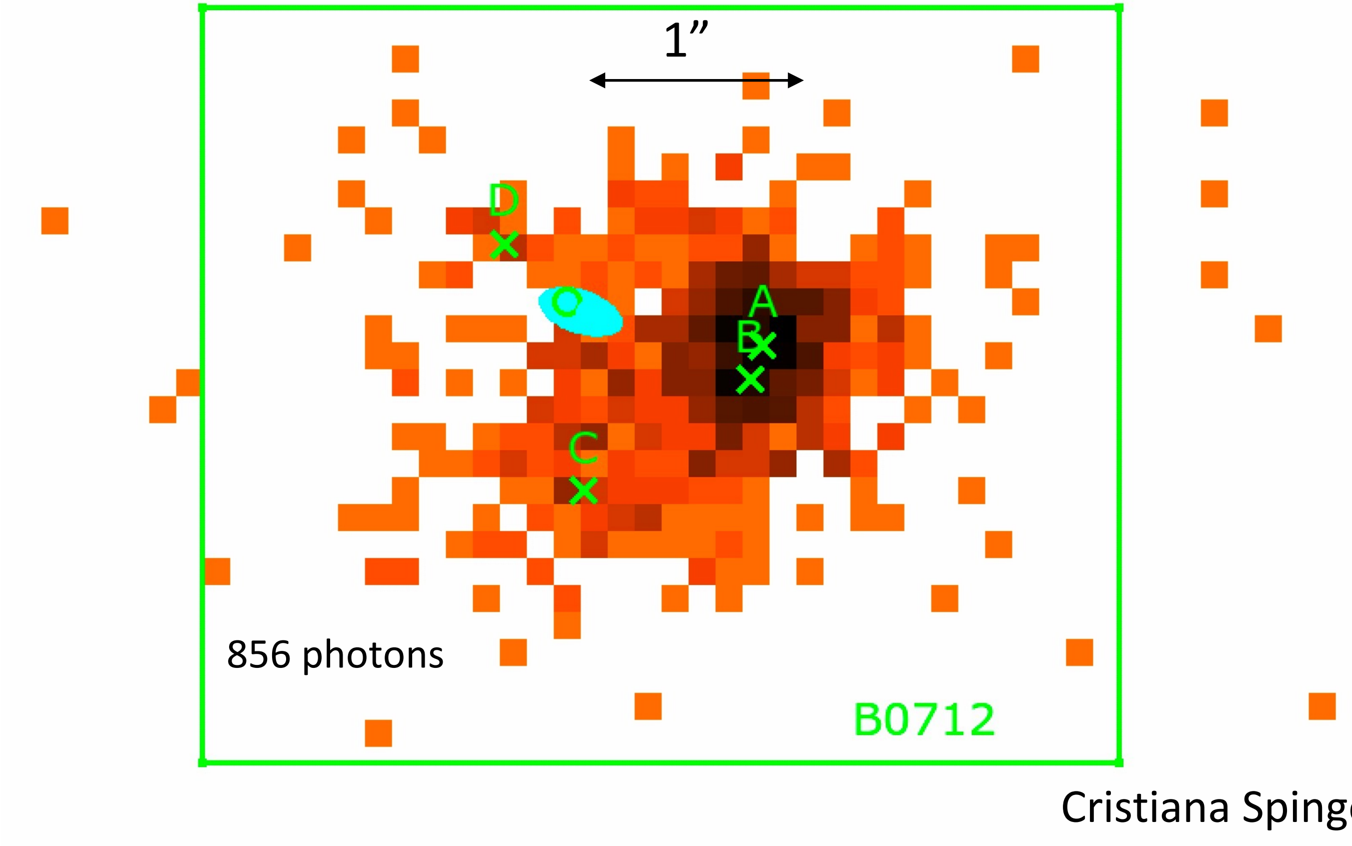
8.6 pc/mas

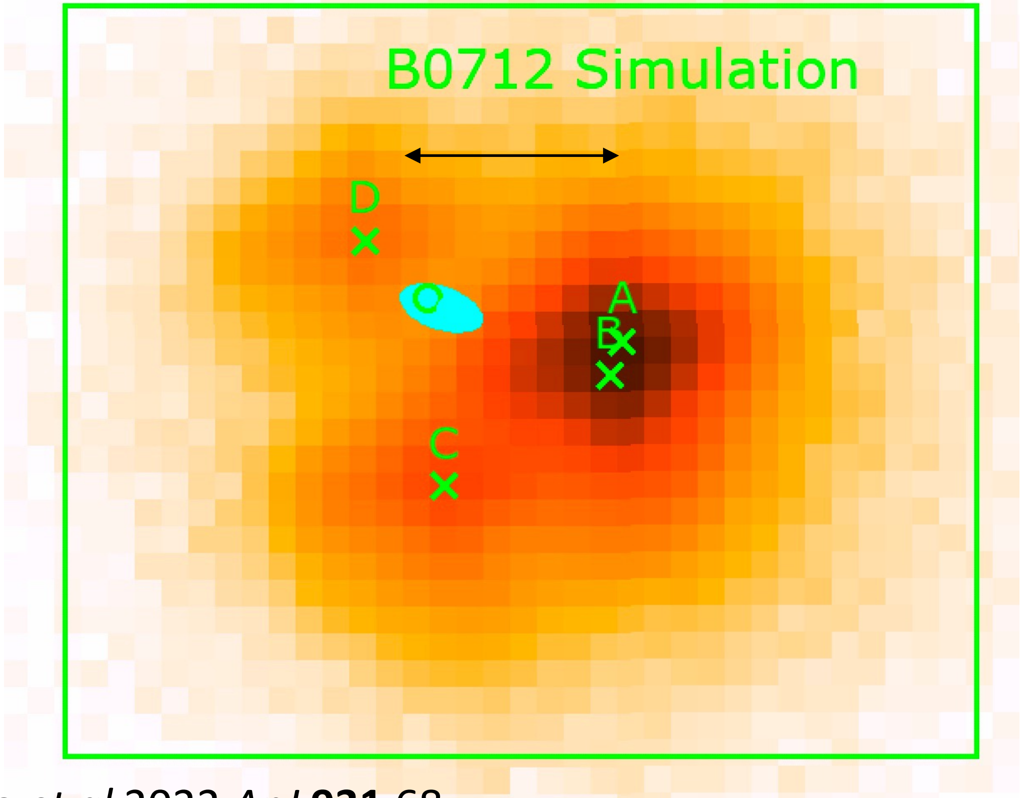
Magnification ~8

Separation: 17 ± 42 pc

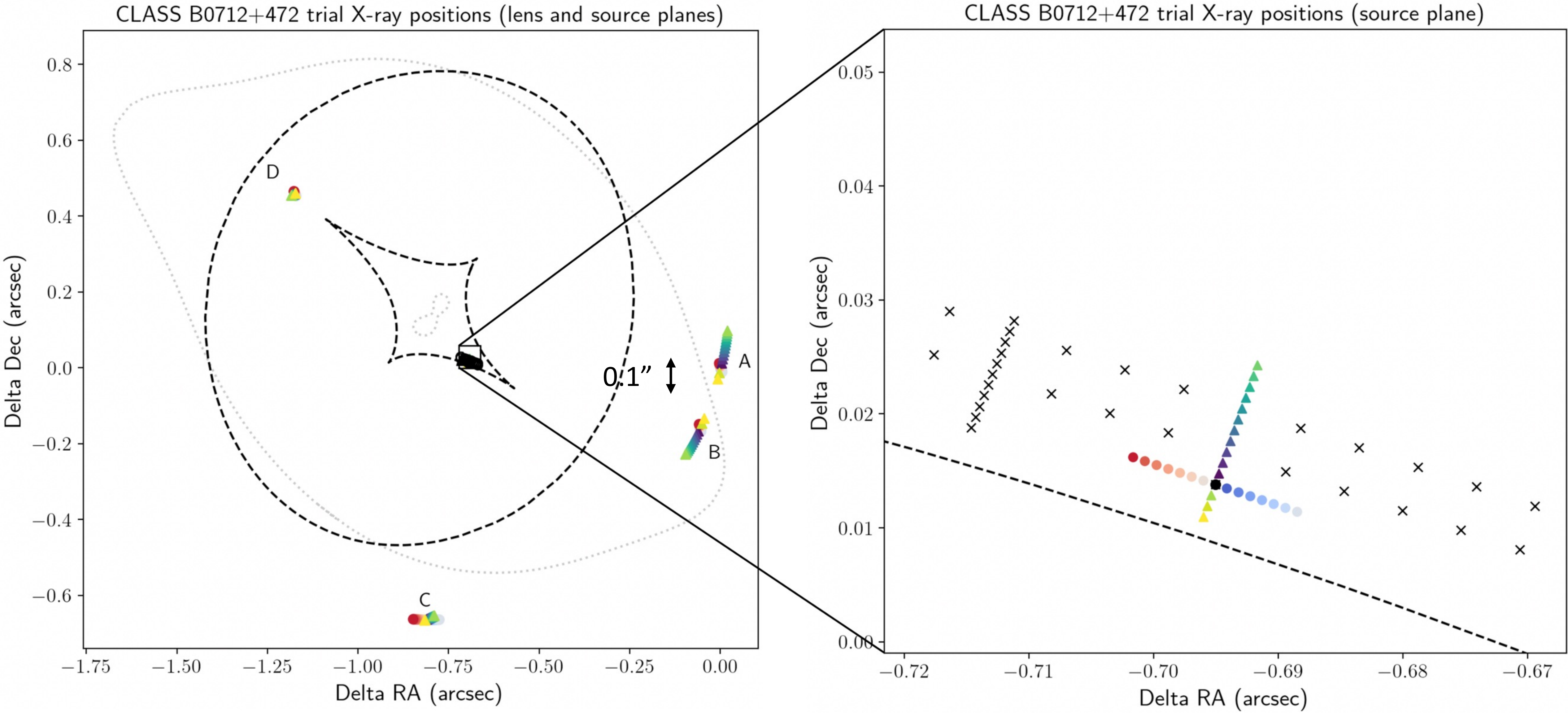


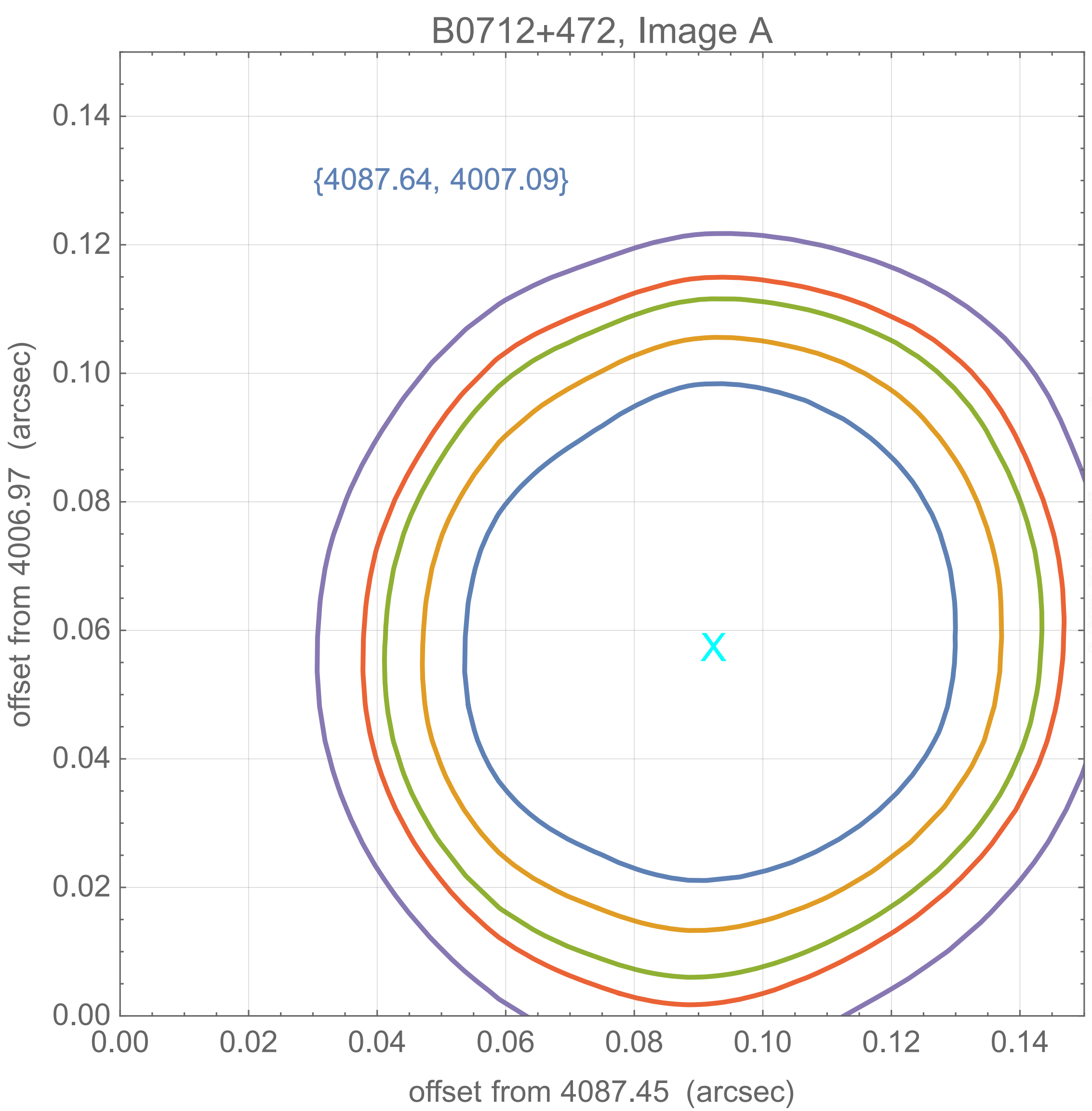
Spingola & Barnacka 2020, MNRAS 494, 2312



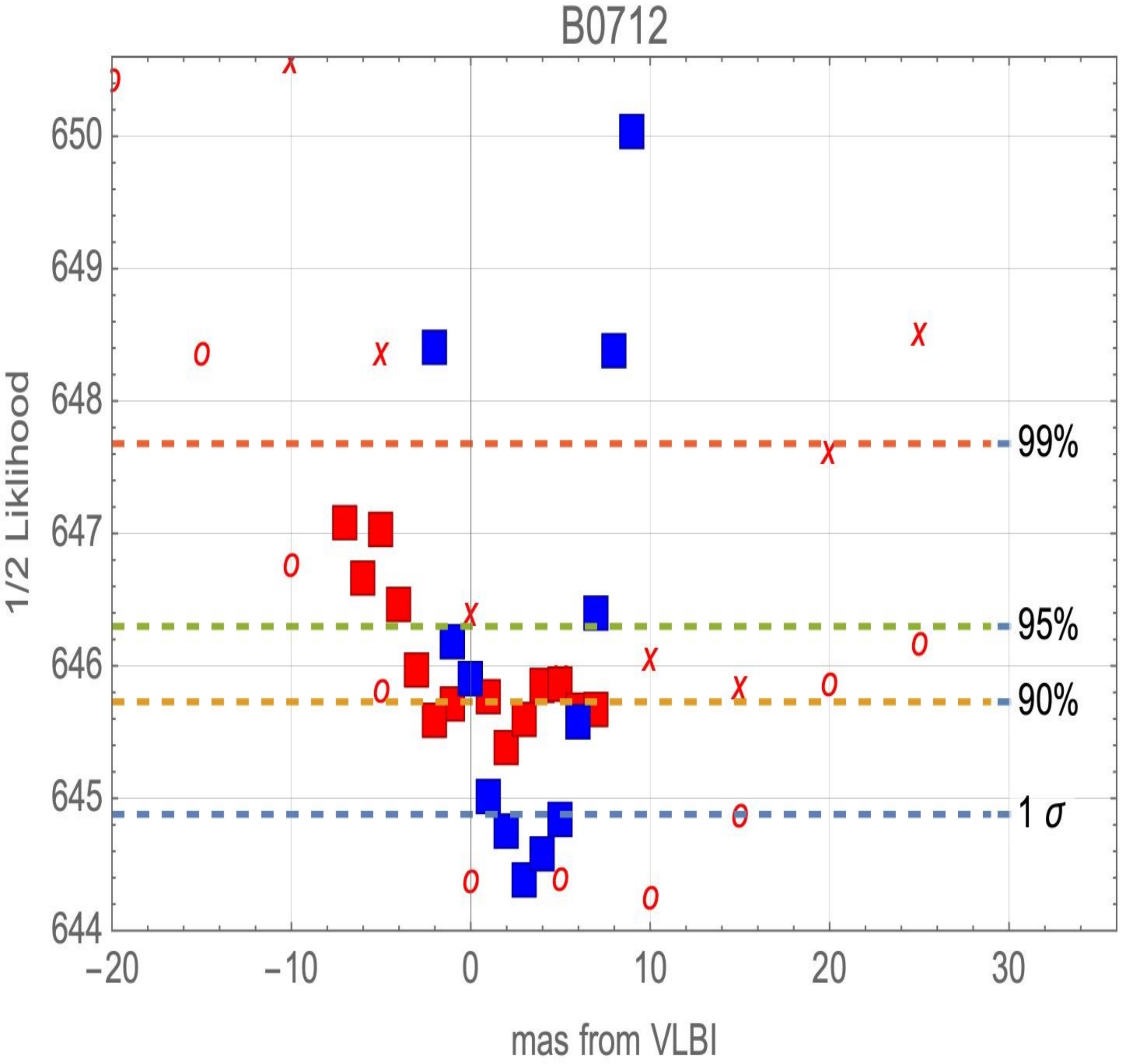


Cristiana Spingola *et al* 2022 *ApJ* **931** 68

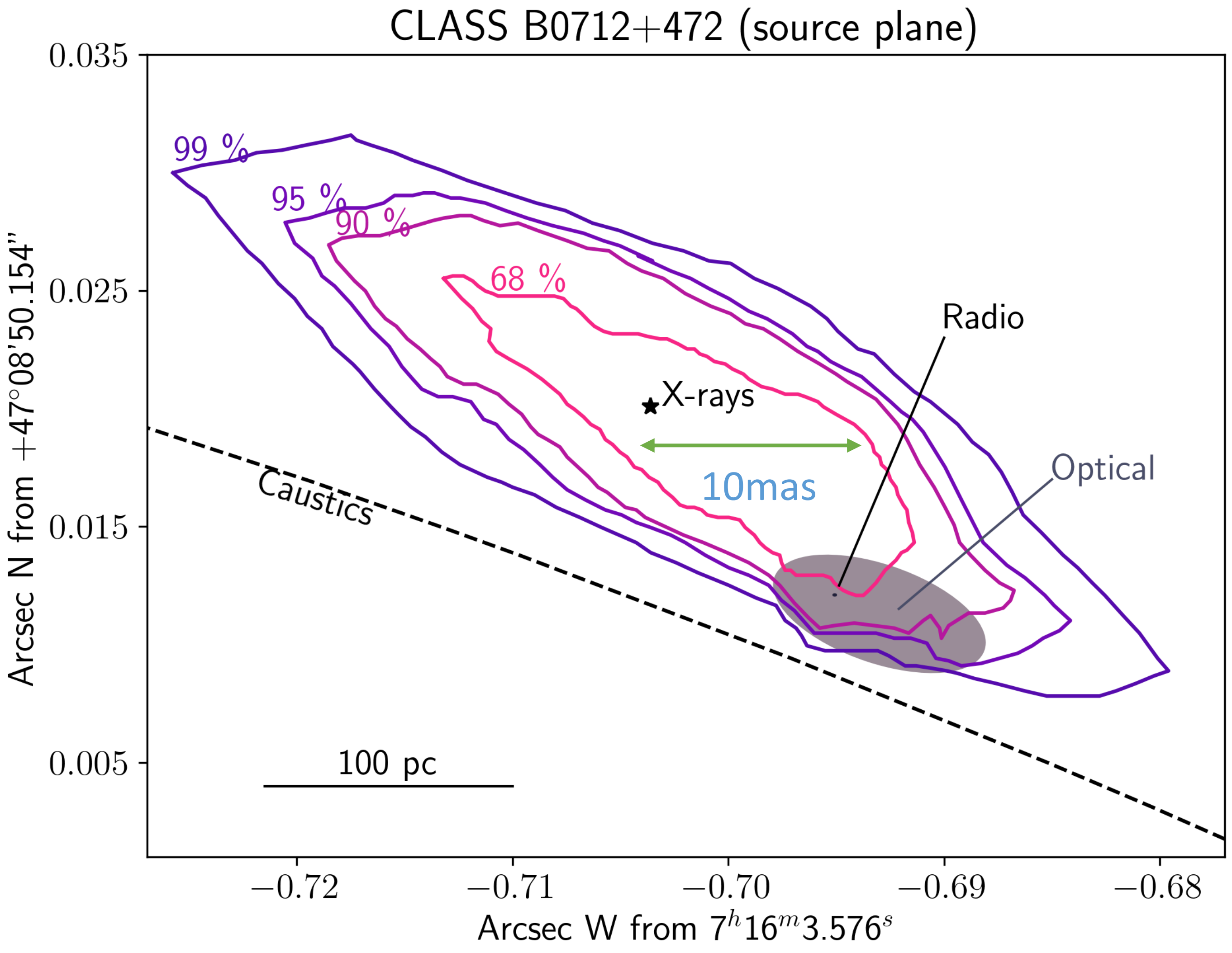

CLASS B0712+472 trial X-ray positions (lens and source planes)
Delta Dec (arcsec)
Delta RA (arcsec)
A
B
C
D
0.1”
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−1.75
−1.50
−1.25
−1.00
−0.75
−0.50
−0.25
0.00
CLASS B0712+472 trial X-ray positions (source plane)
Delta Dec (arcsec)
Delta RA (arcsec)
0.05
0.04
0.03
0.02
0.01
0.00
−0.72
−0.71
−0.70
−0.69
−0.68
−0.67



MaxLikelihood Registration



MaxLikelihood Source Position



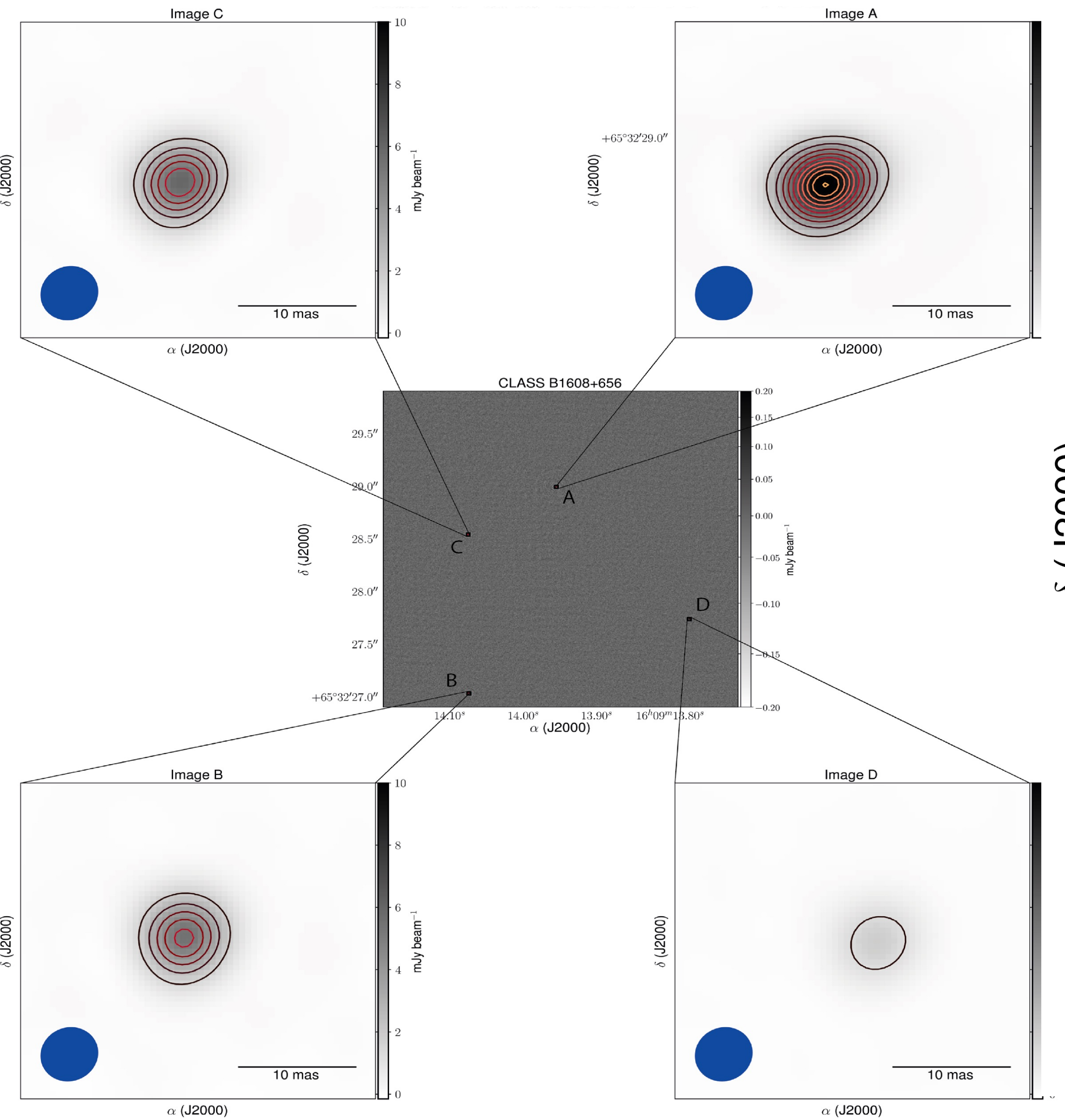
CLASS B0712+472 (z=1.34)

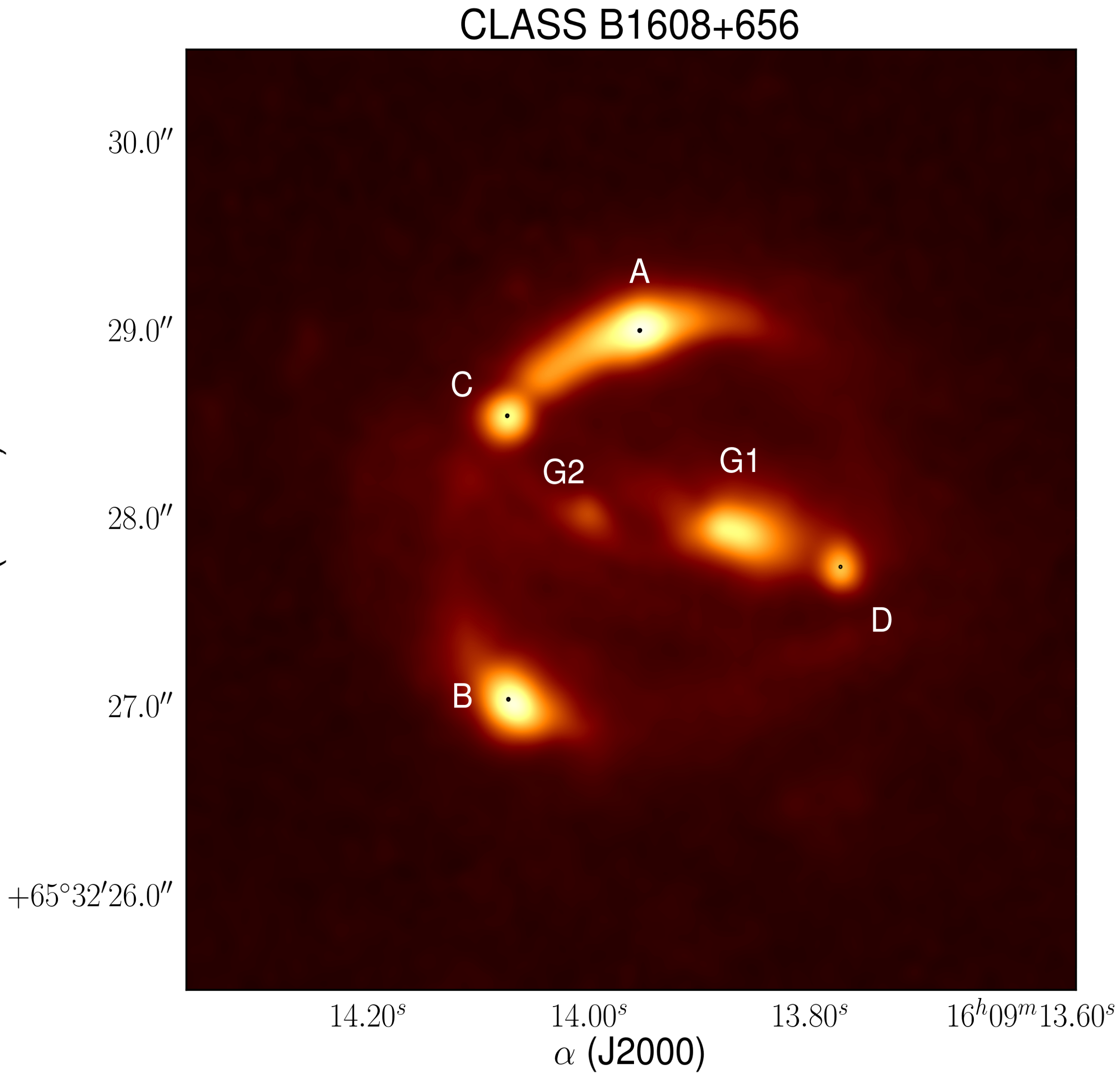
We spatially locate the X-ray source B0712+472 within 11 mas of the radio source.

We find that the X-ray emission is co-spatial with the radio and optical emission.

This high astrometric precision improves on the limitations of existing X-ray instruments by two orders of magnitude.

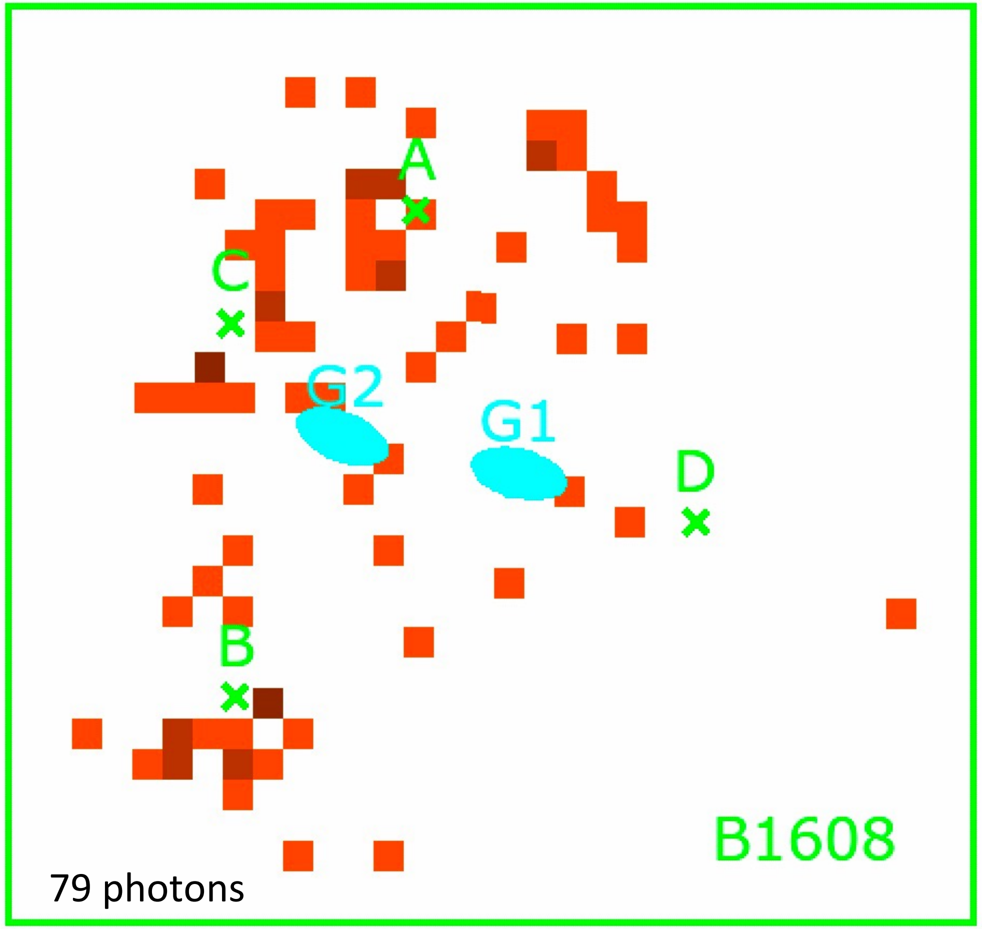
Our ~150 mas^2 absolute celestial location compares with ~3000 mas^2 relative location for a bright Chandra source, and 2 x 10^6 mas^2 absolute location of an unidentified Chandra source.

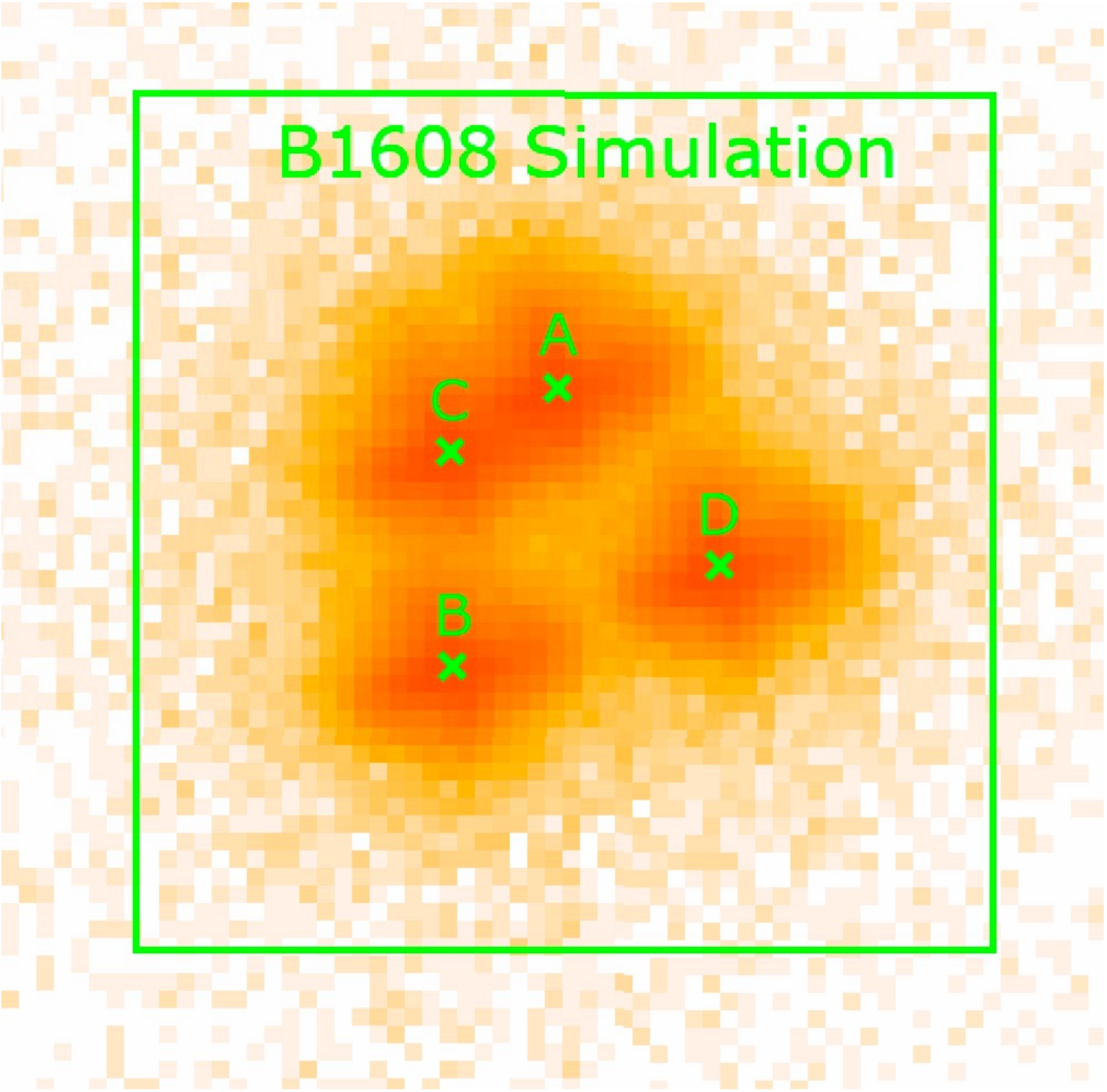


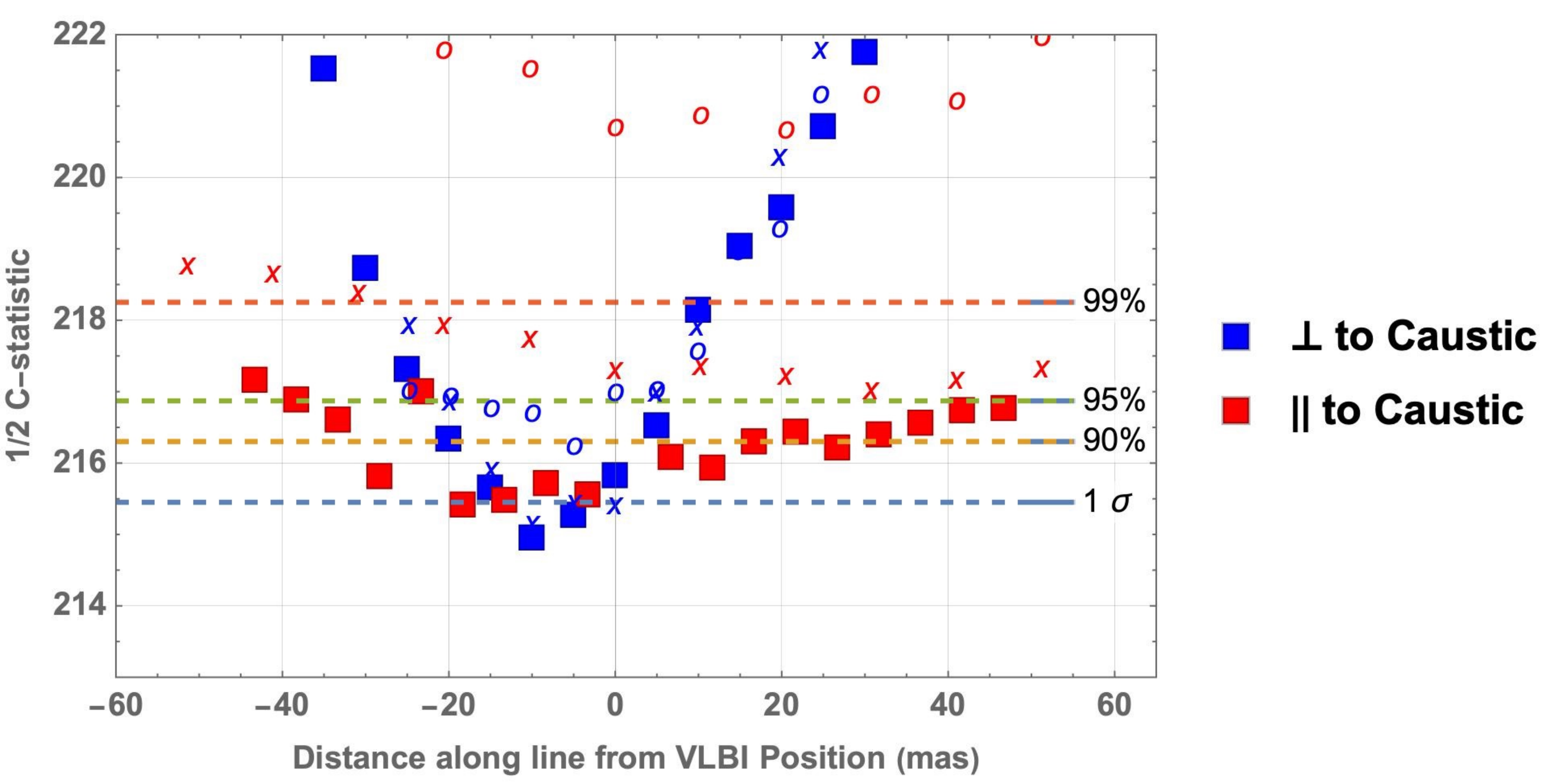


Post-Starburst Galaxy (Fassnacht and Cohen, 1998)
Candidate for an offset AGN

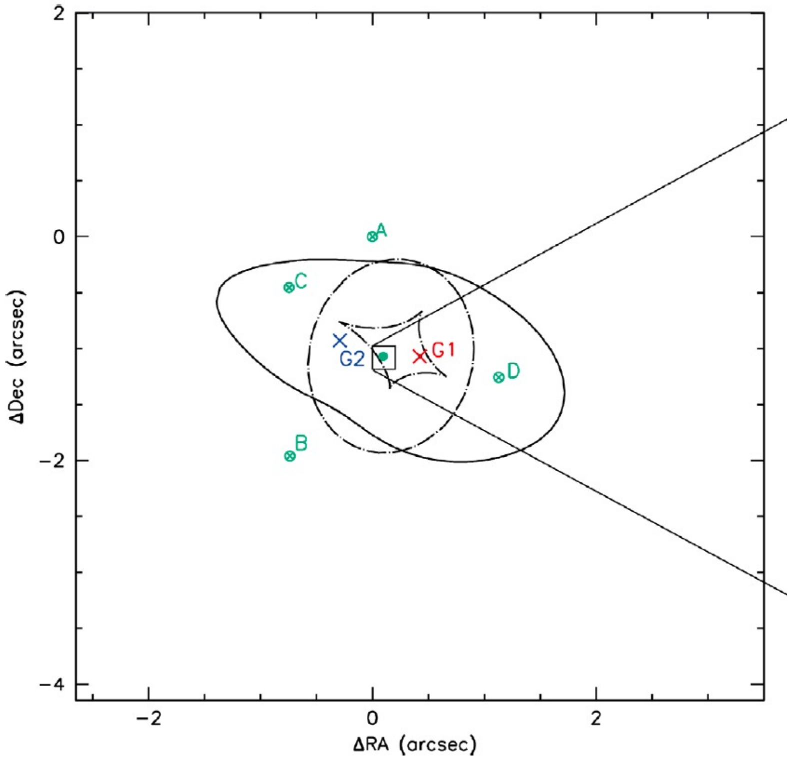
Z= 1.394, Magnification ~15
Separation: 214 ± 137 pc

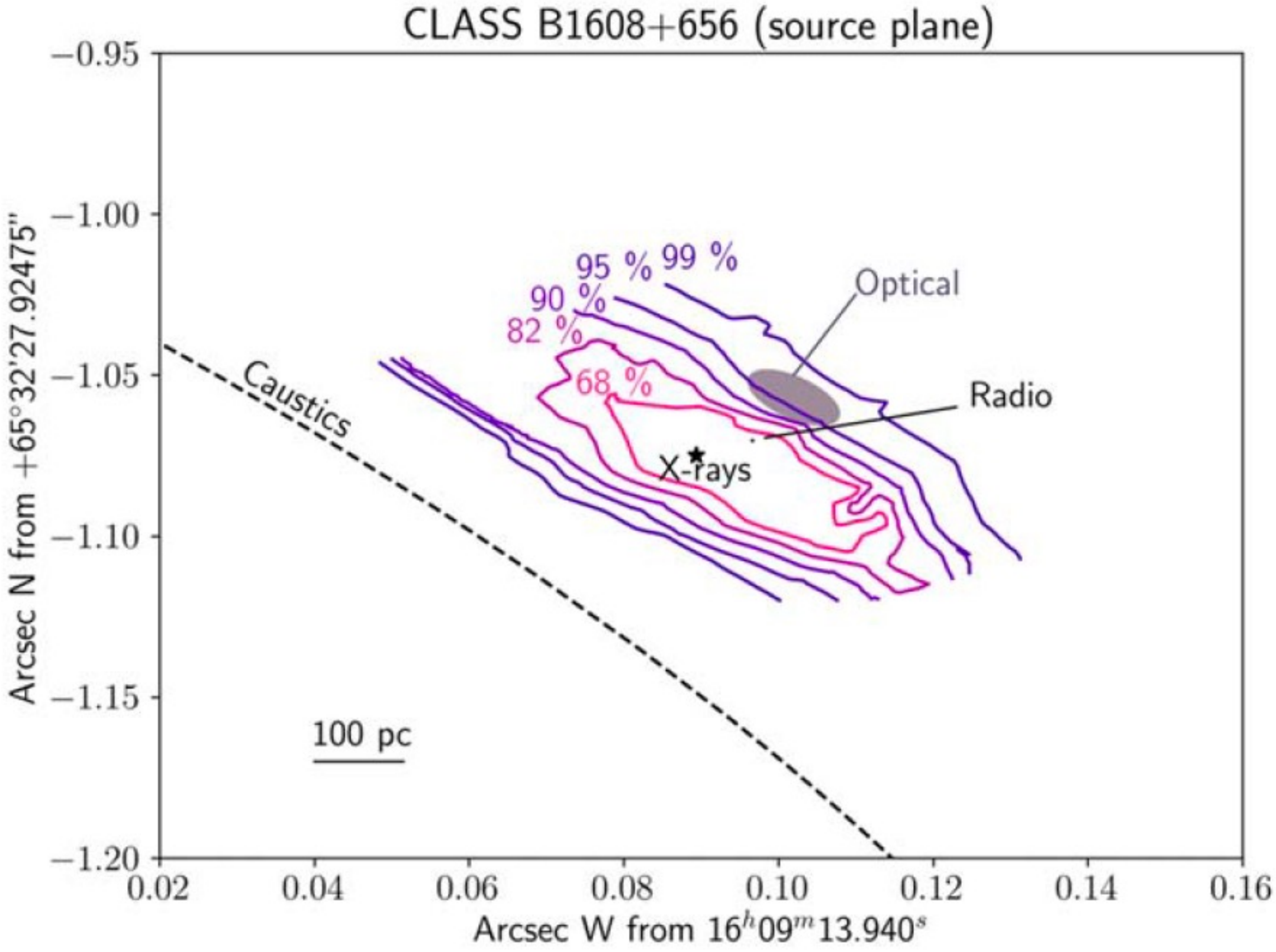

A
C
G2
G1
D
B
B1608
79 photons


B1608 Simulation
A
C
D
B



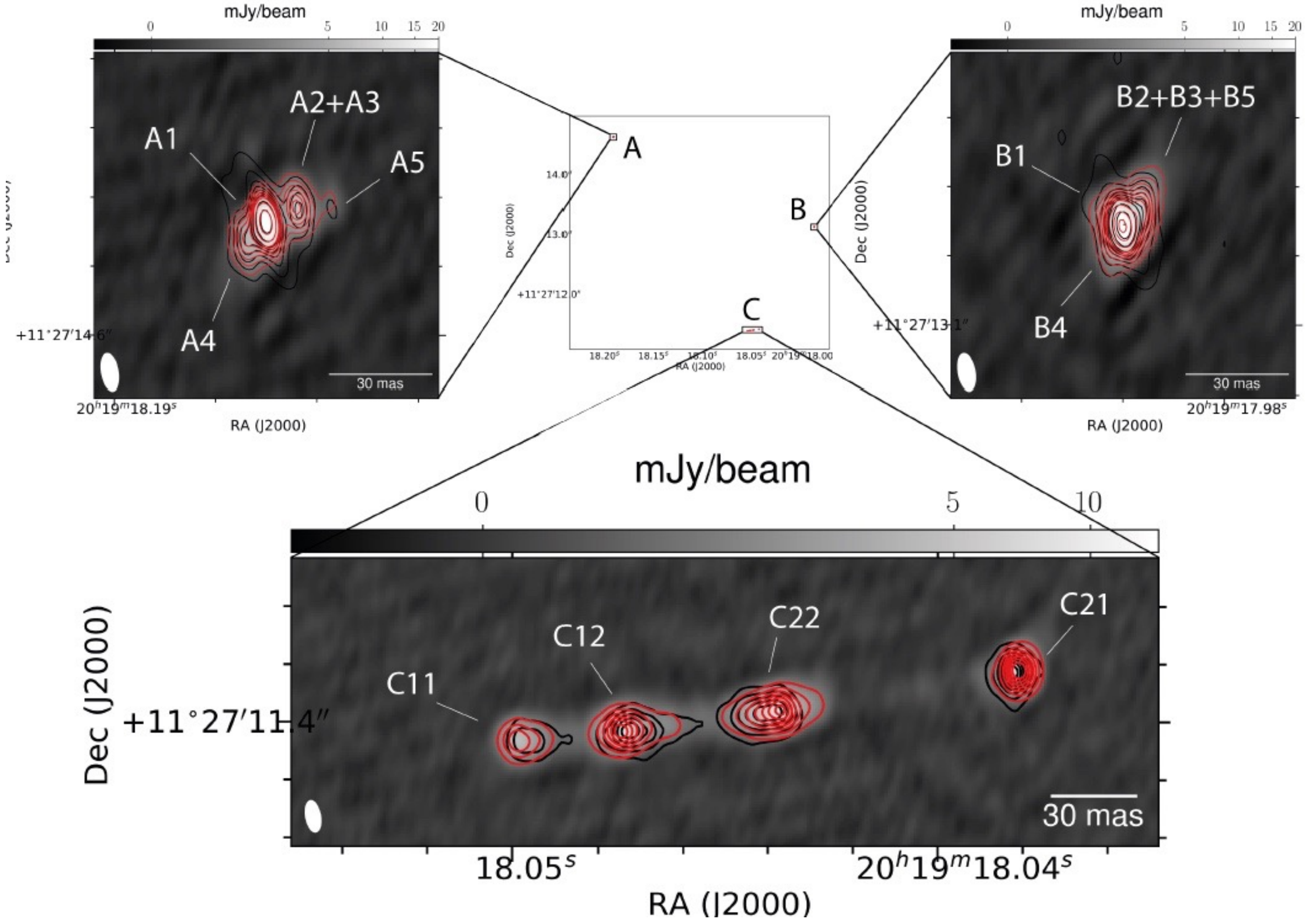
222
220
218
216
214
1/2 C–statistic
−60
−40
−20
0
20
40
60
Distance along line from VLBI Position (mas)
99%
95%
90%
1 σ
⊥ to Caustic
|| to Caustic

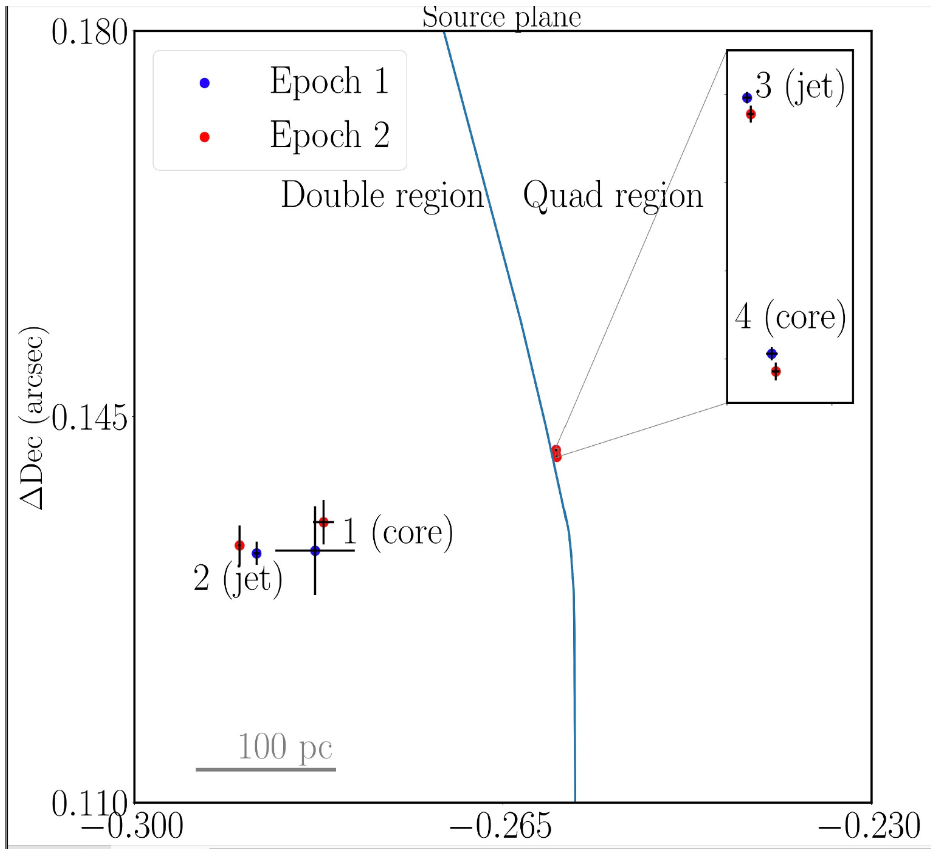




Spingola & Barnacka 2020, MNRAS 494, 2312 (Optical, Radio)
Cristiana Spingola, Dan Schwartz, Anna Barnacka 2022 *ApJ* **931** 68 (X-ray)

MG B2016+112 = J2019+1145 z=3.27



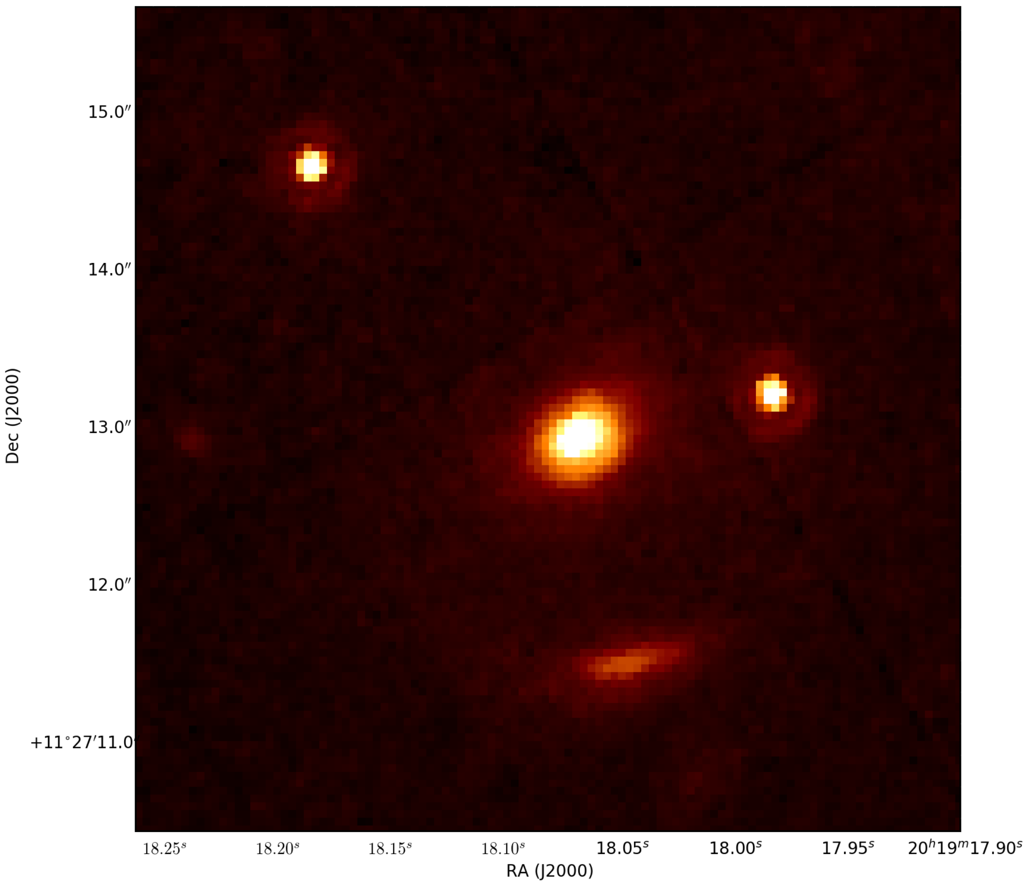


Spingola et al. 2019, A&A, 630, A108.
Detected proper motion, 10's μas/yr

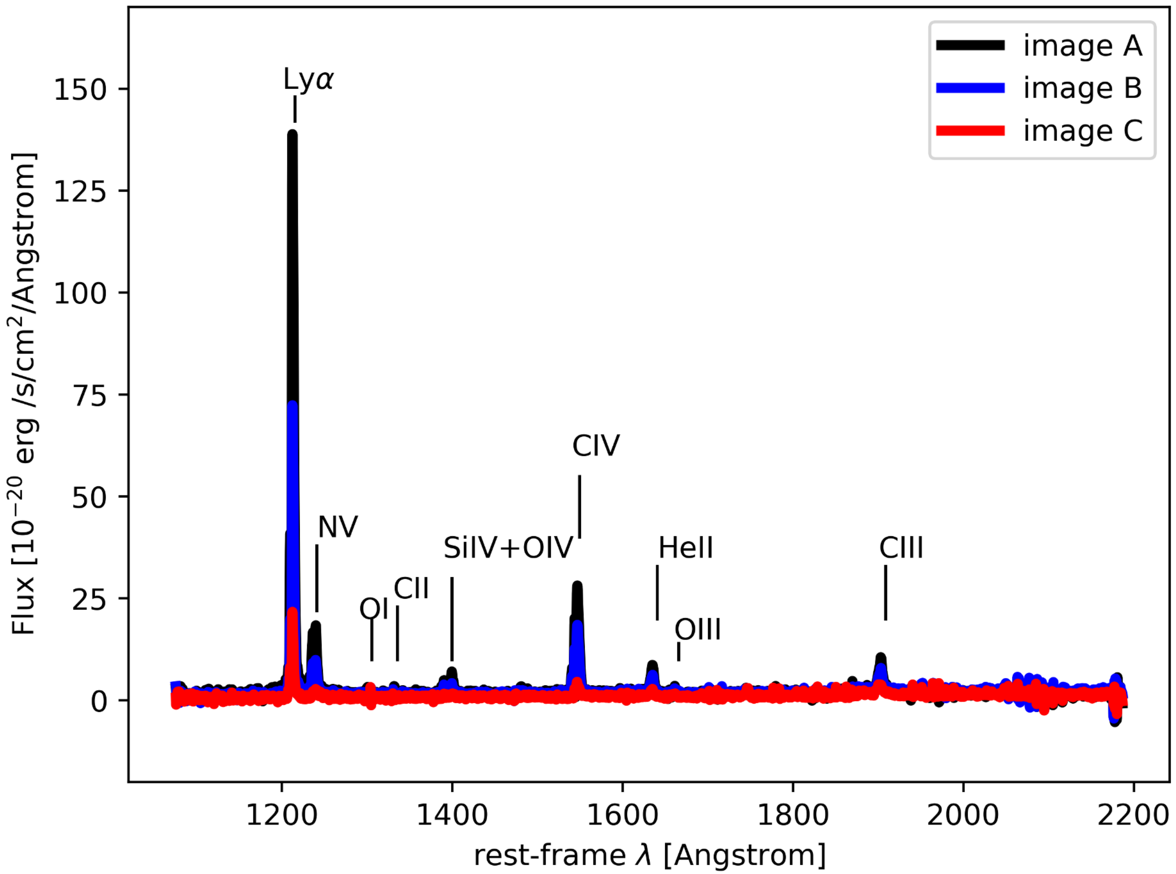
Magnification:

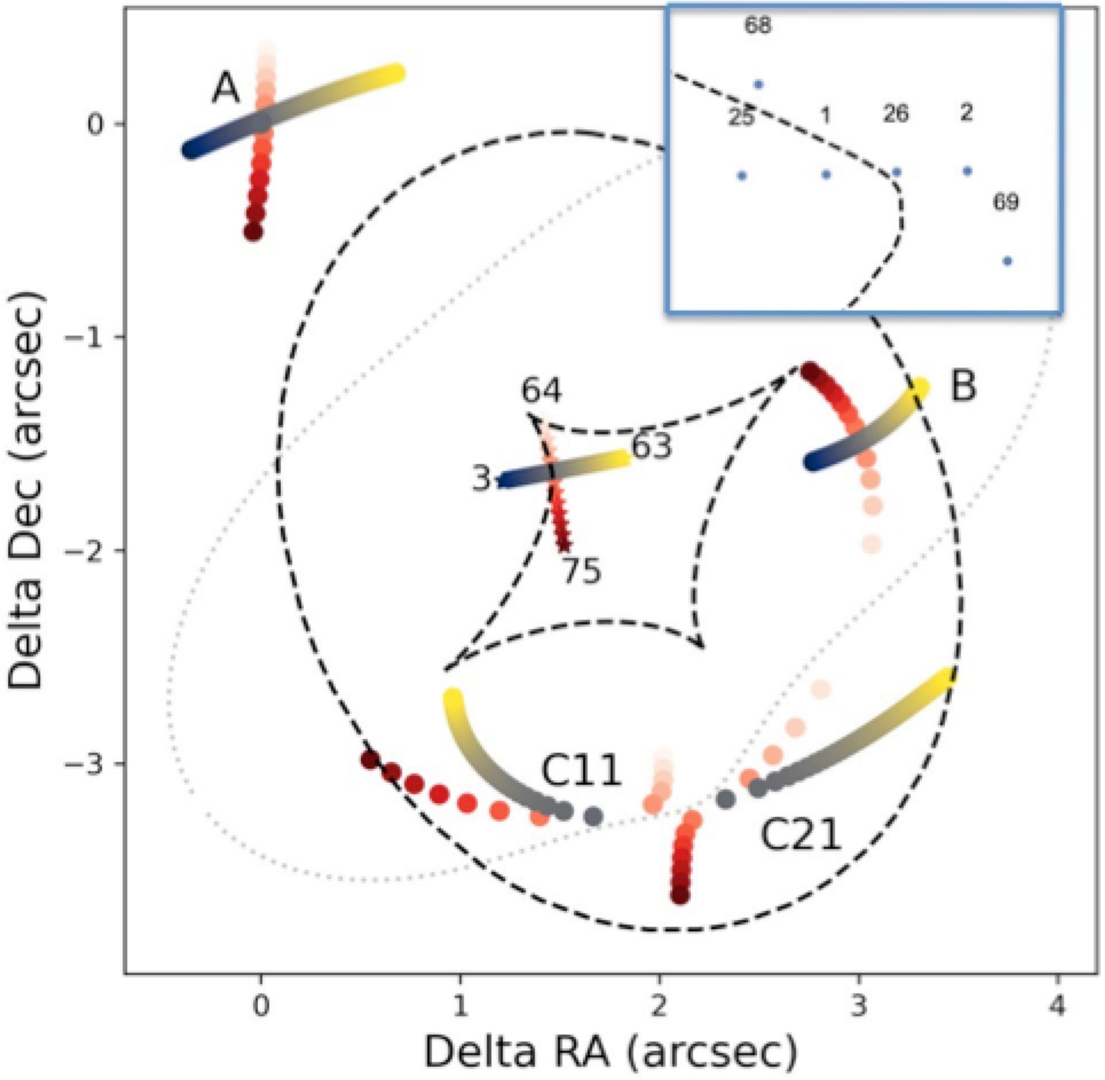
~2, 1 and 2 (A,B)

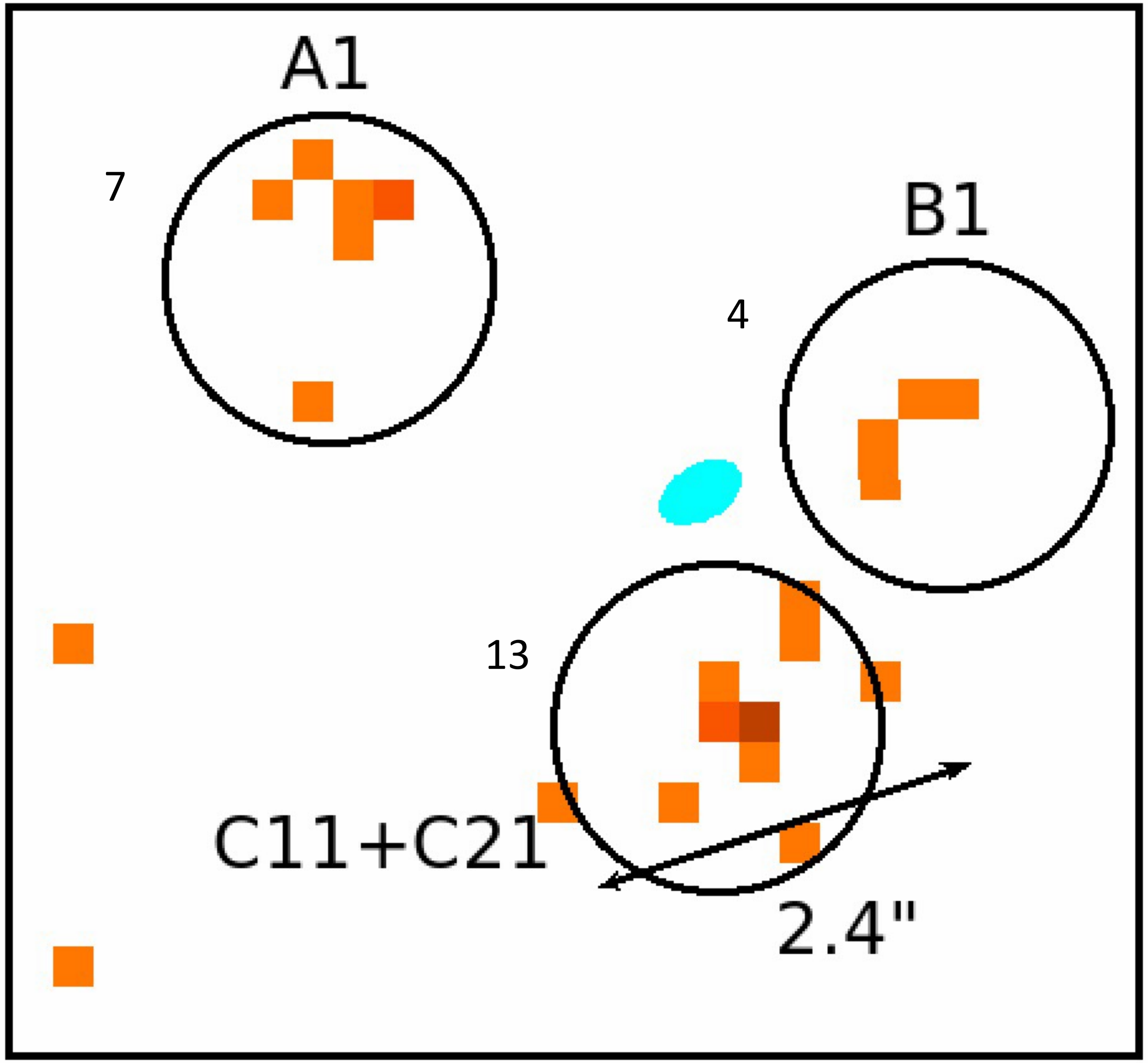
~300, 3 and 4 (C)



HST NICMOS, f160w

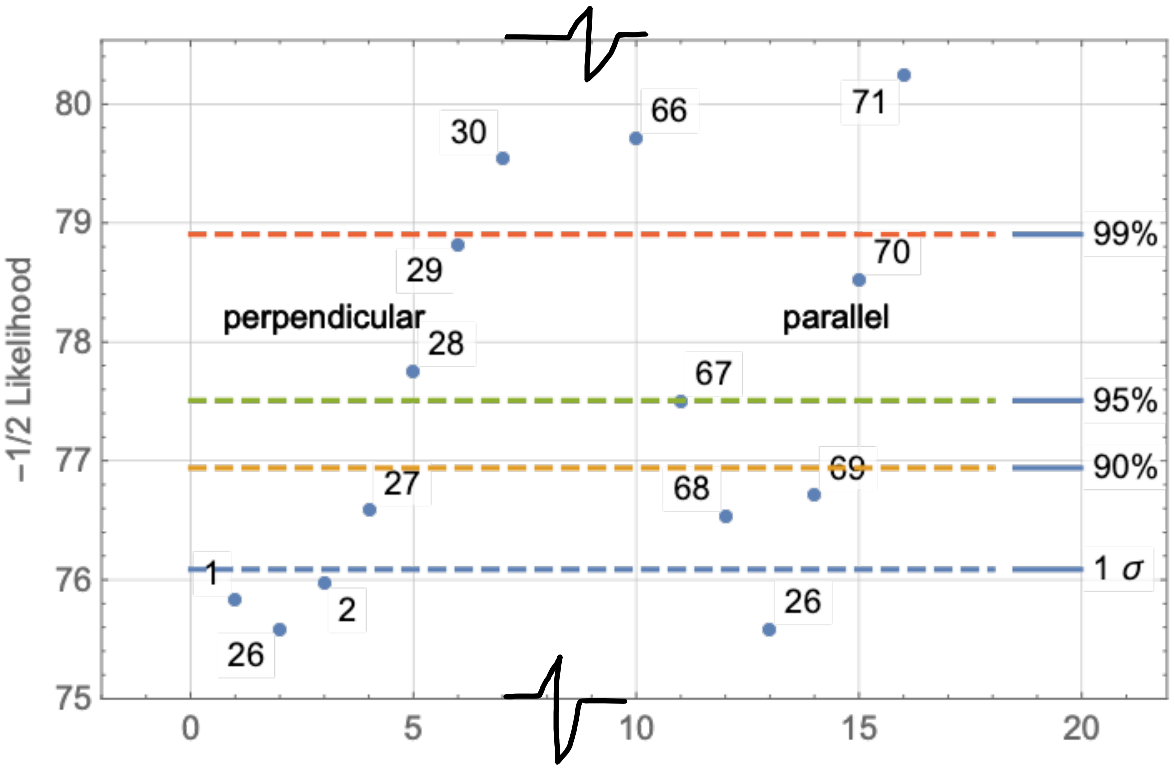






The X-ray data: 7.77ks, 24 photons.

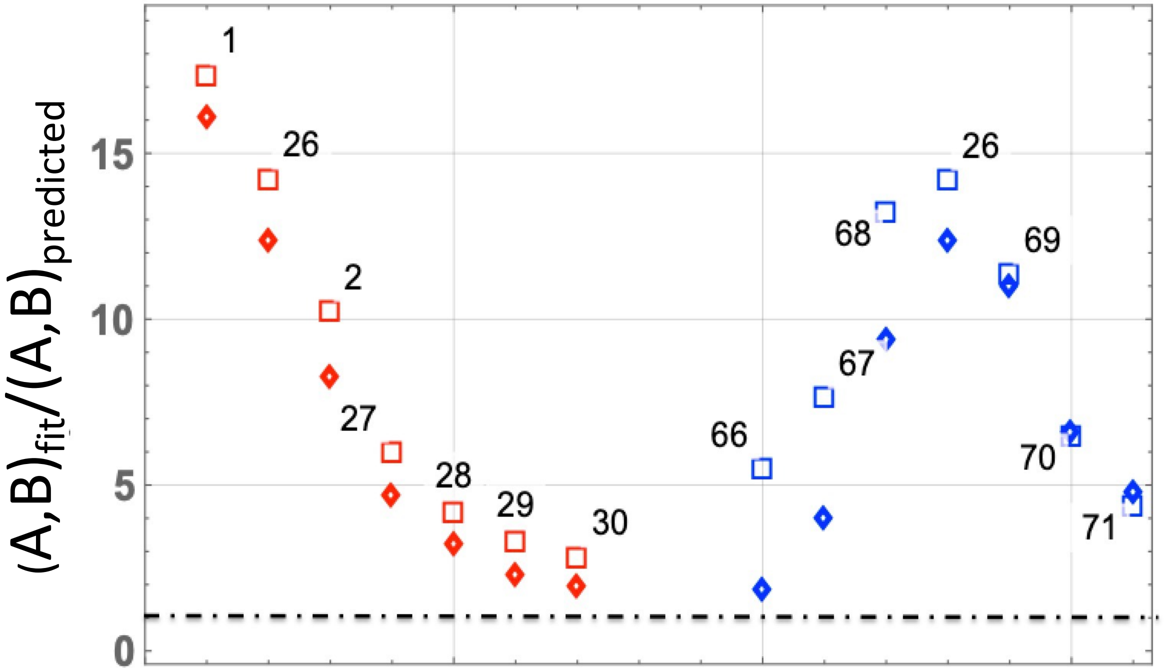
One source, Variable intensities



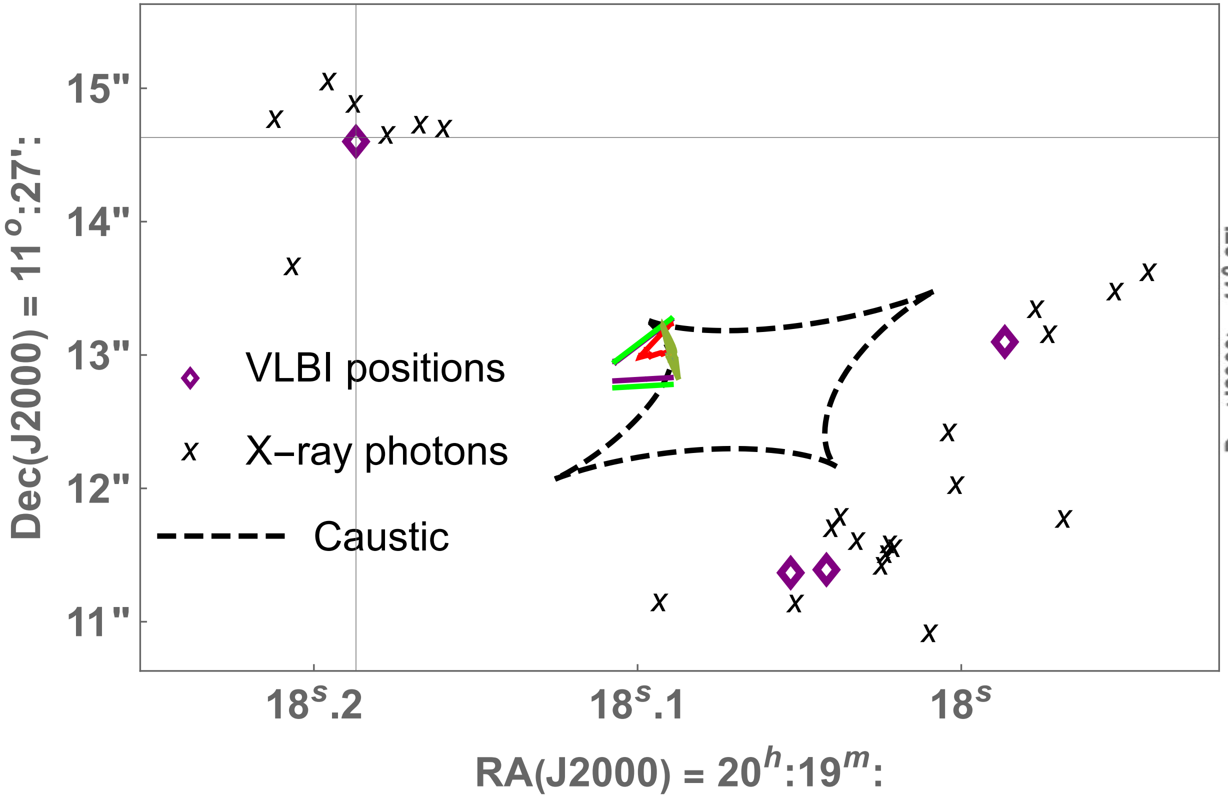
10 mas steps

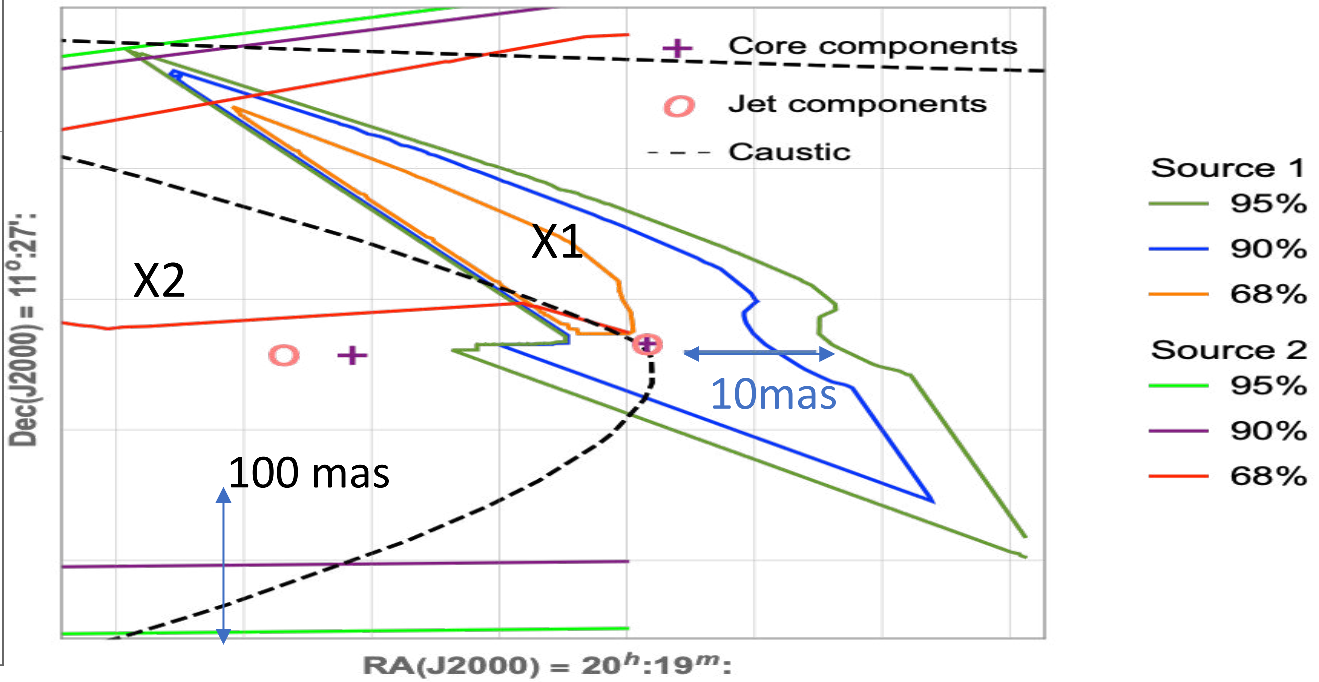
50 mas steps

Problem: Unrealistic Image Ratios



Ratios: image C to Image A (squares),
image C to Image B (diamonds)
Red: Perpendicular to caustic. Blue: Parallel to caustic.





- Two distinct X-ray sources, 650+/-650 pc apart. (7.7 pc per milli-arcsec)
- Dual AGN, OR AGN + 100-pc scale X-ray jet.
- The quadruply lensed X-ray source is within +/- 40 pc (1sig) of its VLBI counterpart.

$\Gamma = 0.8 \pm 0.4$, galactic absorption only **OR**

$\Gamma = 1.52 \pm 0.46$, intrinsic absorption $1.7 \pm 1.4 \times 10^{22}$ cm^{-2}

X1, We measure F_x=1.8 10^{-14}, Therefore L_x =1.5 10^{43} erg s^{-1}
X2, We measure F_x =1.3 10^{-14}, Therefore L_x =1.8 10^{44} erg s^{-1}

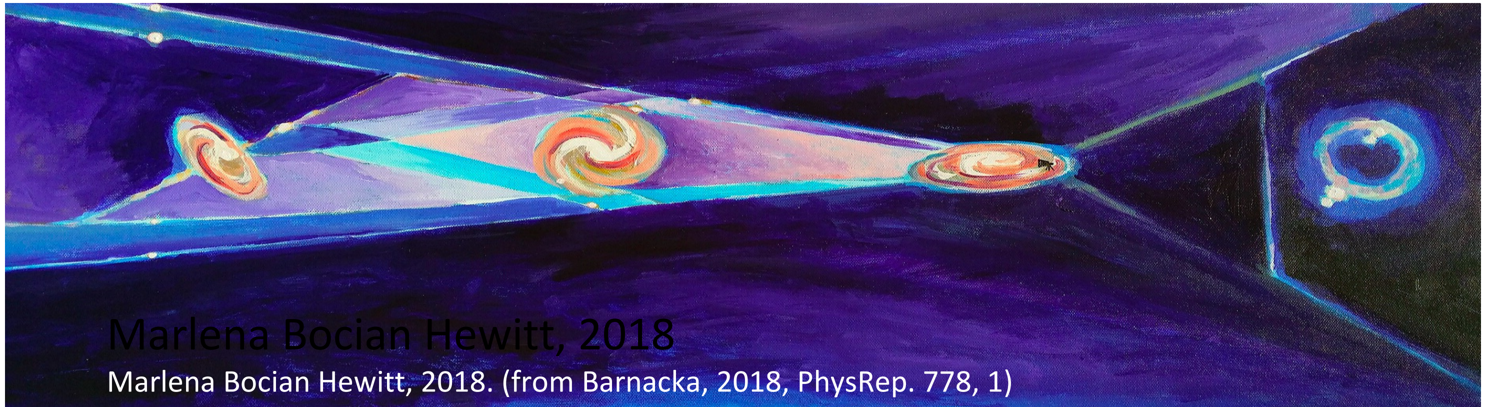
Gravitational Lensing Offers a New Channel of Data: X-ray Astrometry of High Redshift AGN

- Find Dual/Binary supermassive black holes
- Measure X-ray, Radio, Optical offsets at mas scales
- Resolve pc-scale X-ray jets
- Find ejected Black Holes

Chandra resolution is ~0.”5, Can centroid an isolated point source to ~25-50 mas

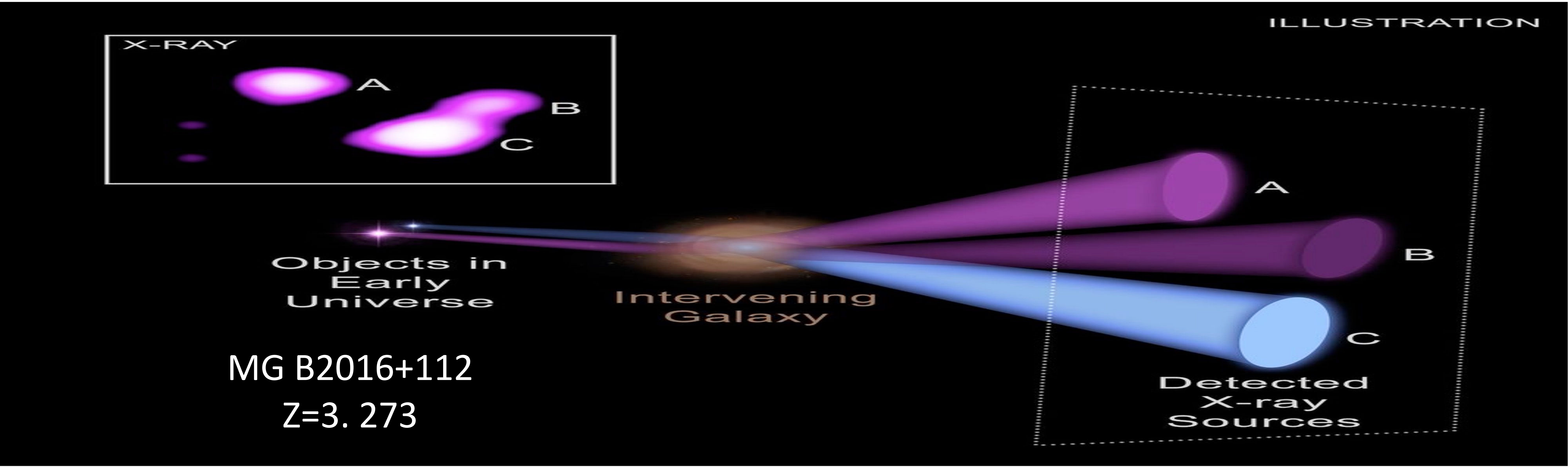
Absolute Celestial Location Astrometry is ~0.”9 (90% confidence)

- Limited to ~5kpc for z> few tenths.
- Realistically, No X-ray Telescope for >50 years will have << 0.”5 resolution



Marlena Bocian Hewitt, 2018. (from Barnacka, 2018, PhysRep. 778, 1)

Gravitationally lensed quasars will reveal the first Black Holes in the universe.
Tens of thousands of quadruply lensed sources from *Rubin, SKA,* and *Roman* will explode this field of research.
With such samples, why would you even point an X-ray telescope at a distant unlensed quasar?



Using Gravitational Lenses as Telescopes, to Resolve Complex Inner X-ray Structure of AGN at large redshift

Dan Schwartz, Cristiana Spingola, Anna Barnacka

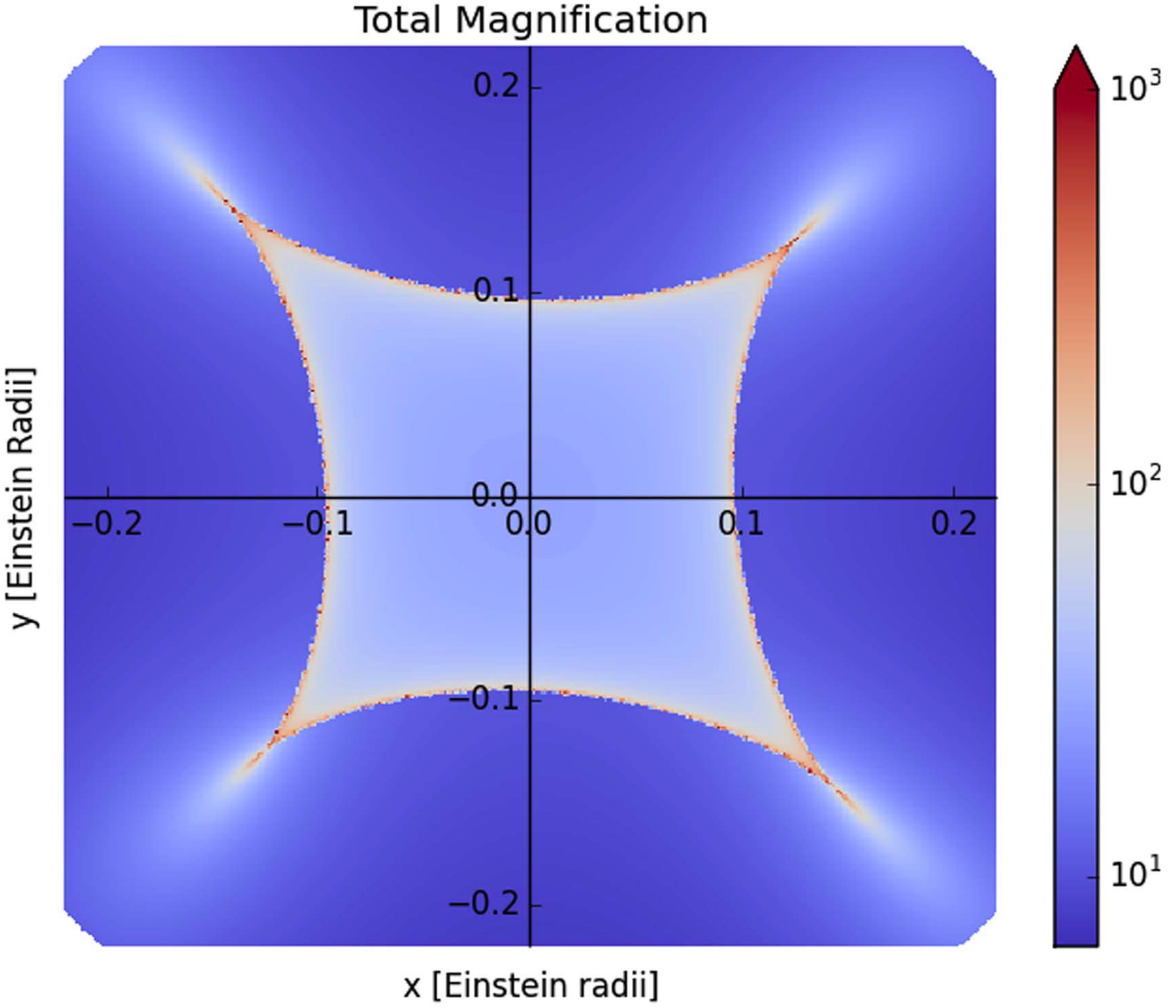
2021, ApJ, **917**, 26

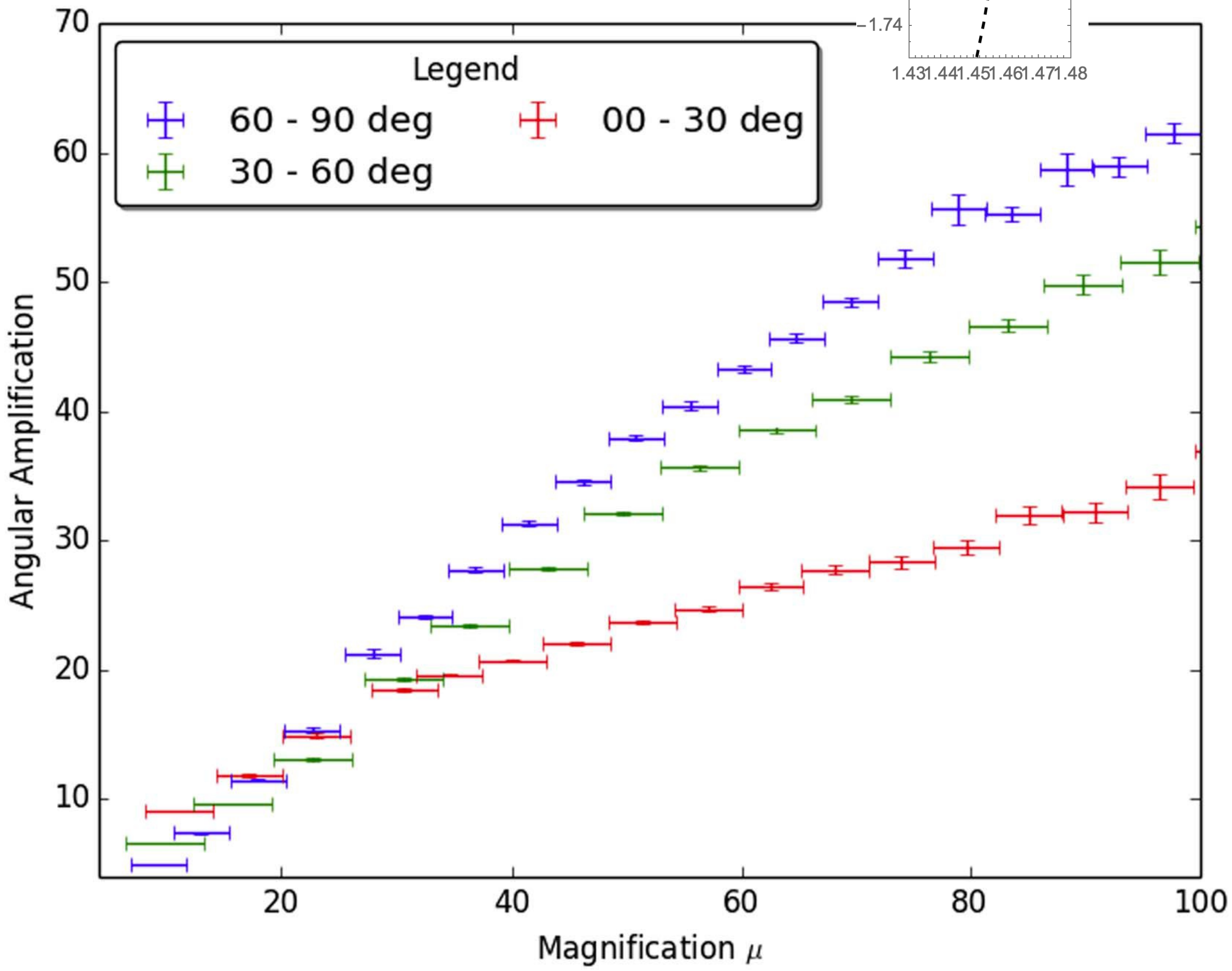
Supplementary

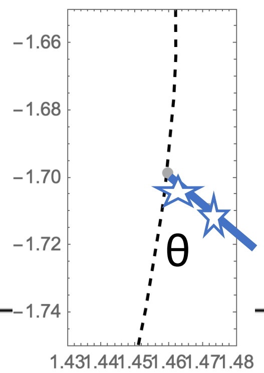
Gravitational Lenses as Telescopes:

Barnacka, A. 2017, ApJ, 846, 157

Barnacka, A. 2018, Phys. Rept. 778, 1







Toy Model: Einstein radius =0.5”. Ellipticity =0.2