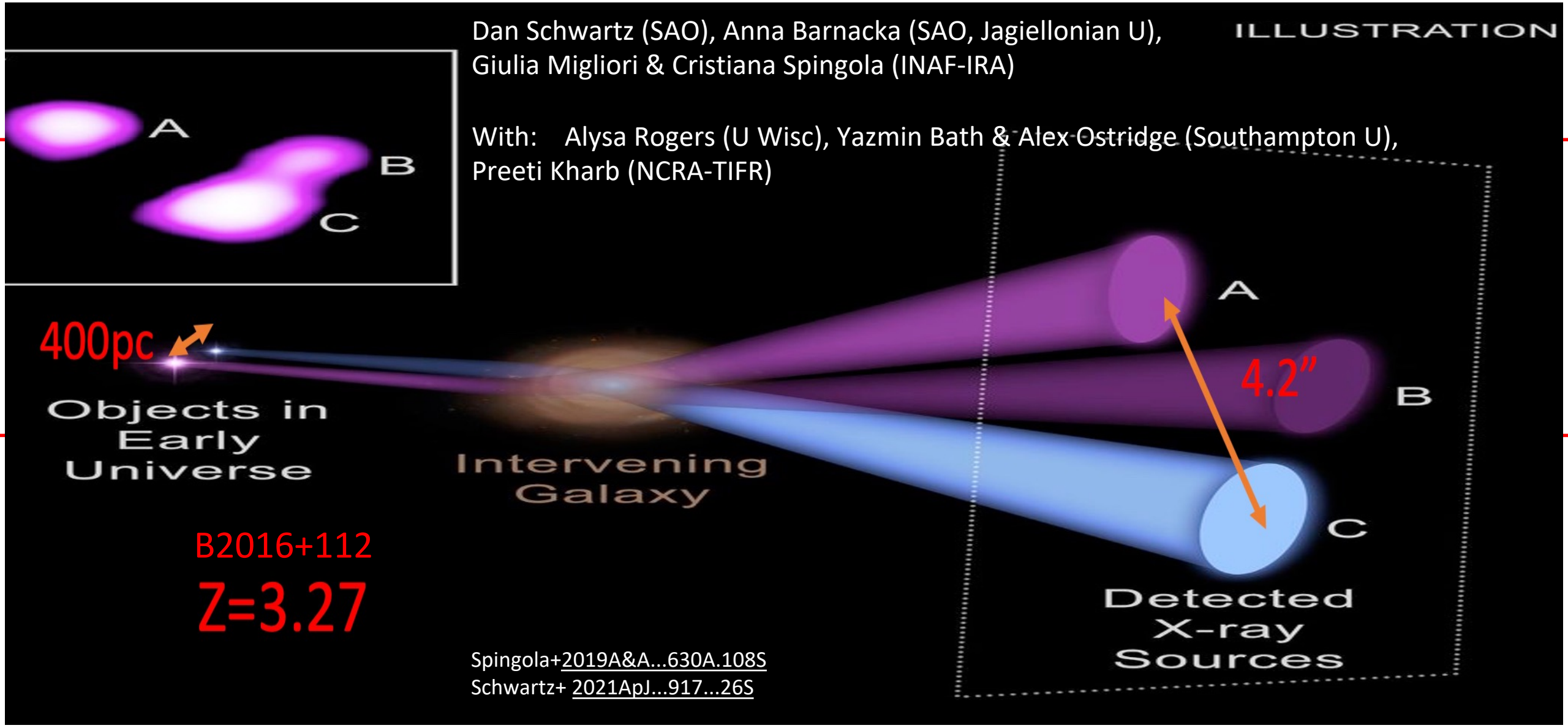
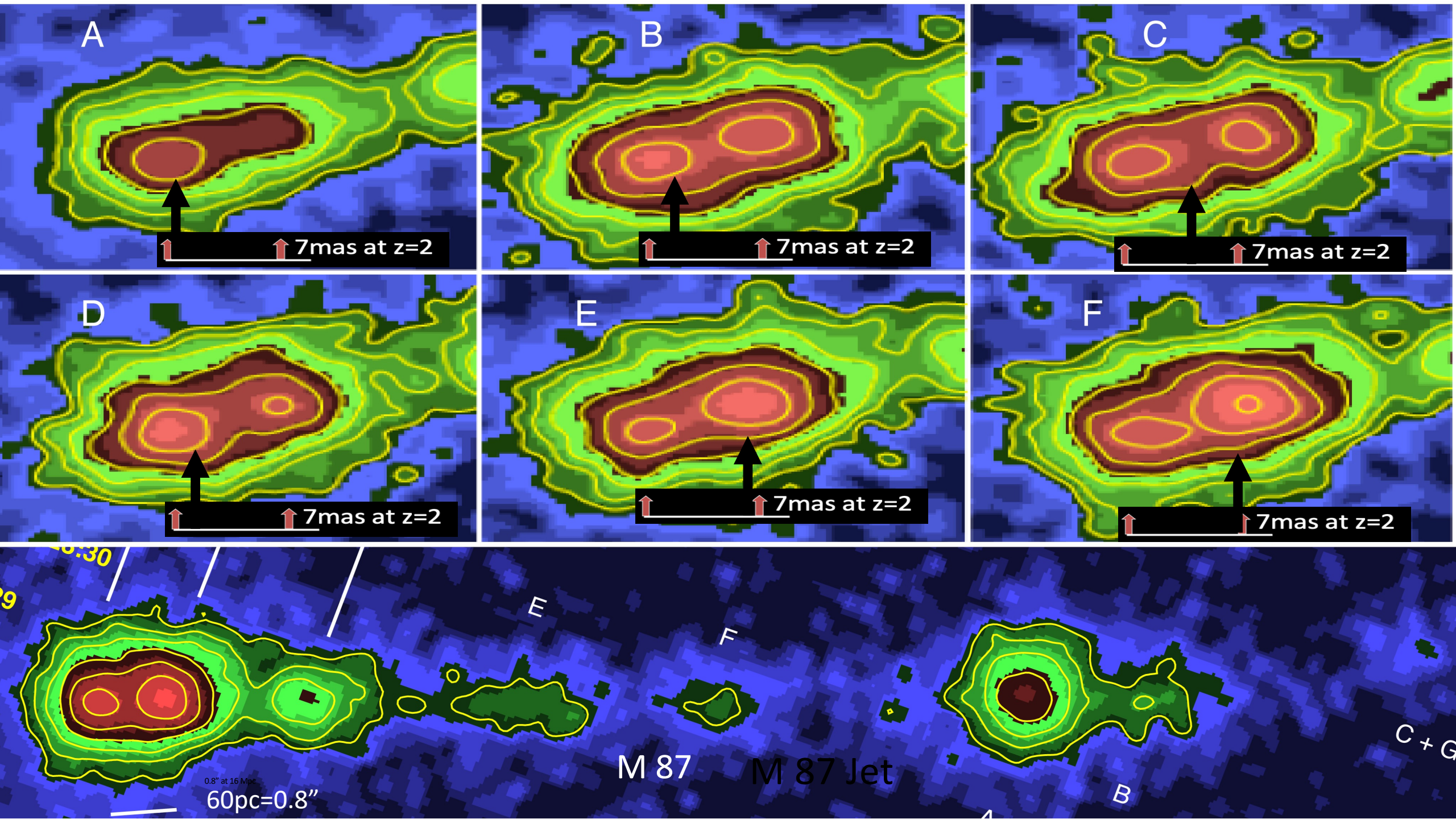
Gravitational Lensing for Astrometric Determinations: Milli-arcsec X-ray Structure in Active Galactic Nuclei

Dan Schwartz (SAO), Anna Barnacka (SAO, Jagiellonian U),
Giulia Migliori & Cristiana Spingola (INAF-IRA)

With: Alysa Rogers (U Wisc), Yazmin Bath & Alex Ostridge (Southampton U),
Preeti Kharb (NCRA-TIFR)



Spingola+2019A&A...630A.108S
Schwartz+ 2021ApJ...917...26S


A
7mas at z=2
B
7mas at z=2
C
7mas at z=2
D
7mas at z=2
E
7mas at z=2
F
7mas at z=2
E
F
M 87
M 87 Jet
B
C + G
0.8" at 16 Mpc
60pc=0.8"

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

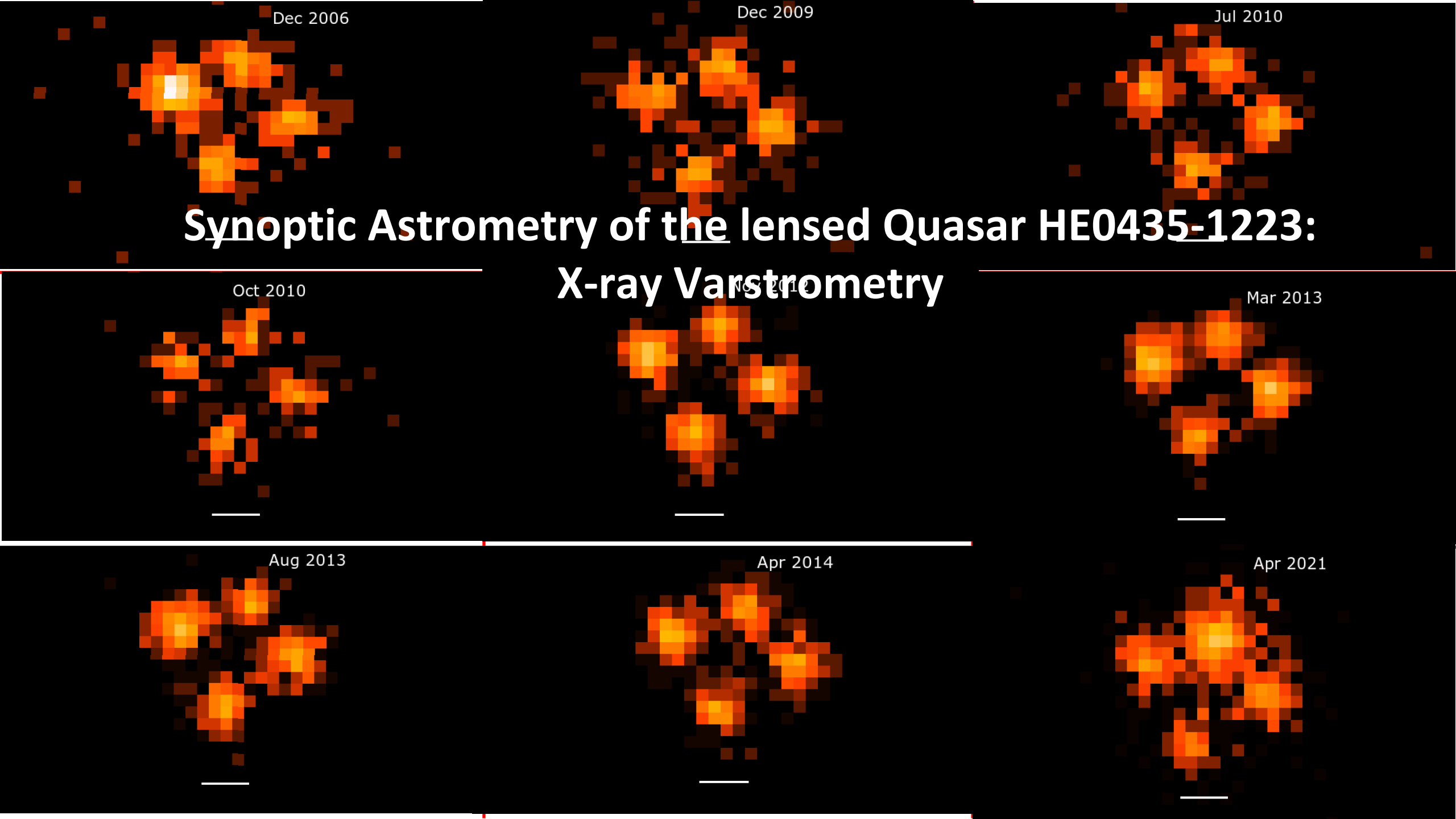
Images weakly stretched parallel to caustic.

Magnification highly variable across field

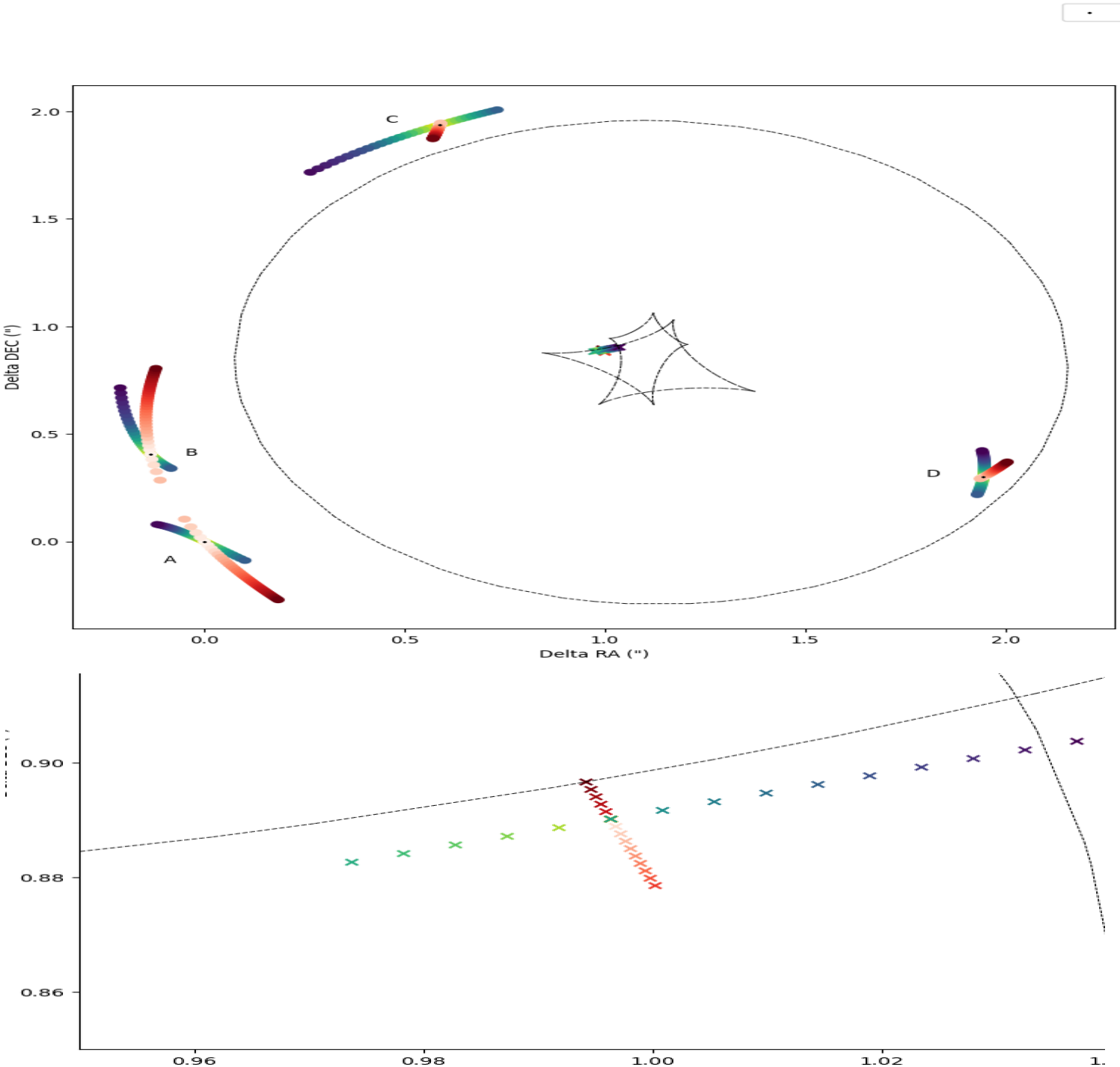
Large inside and near the caustic. Diverges on the caustic. Weaker dependence on mass of lens

Non-linear.

Allows multiple images. Four images for sources inside caustic.

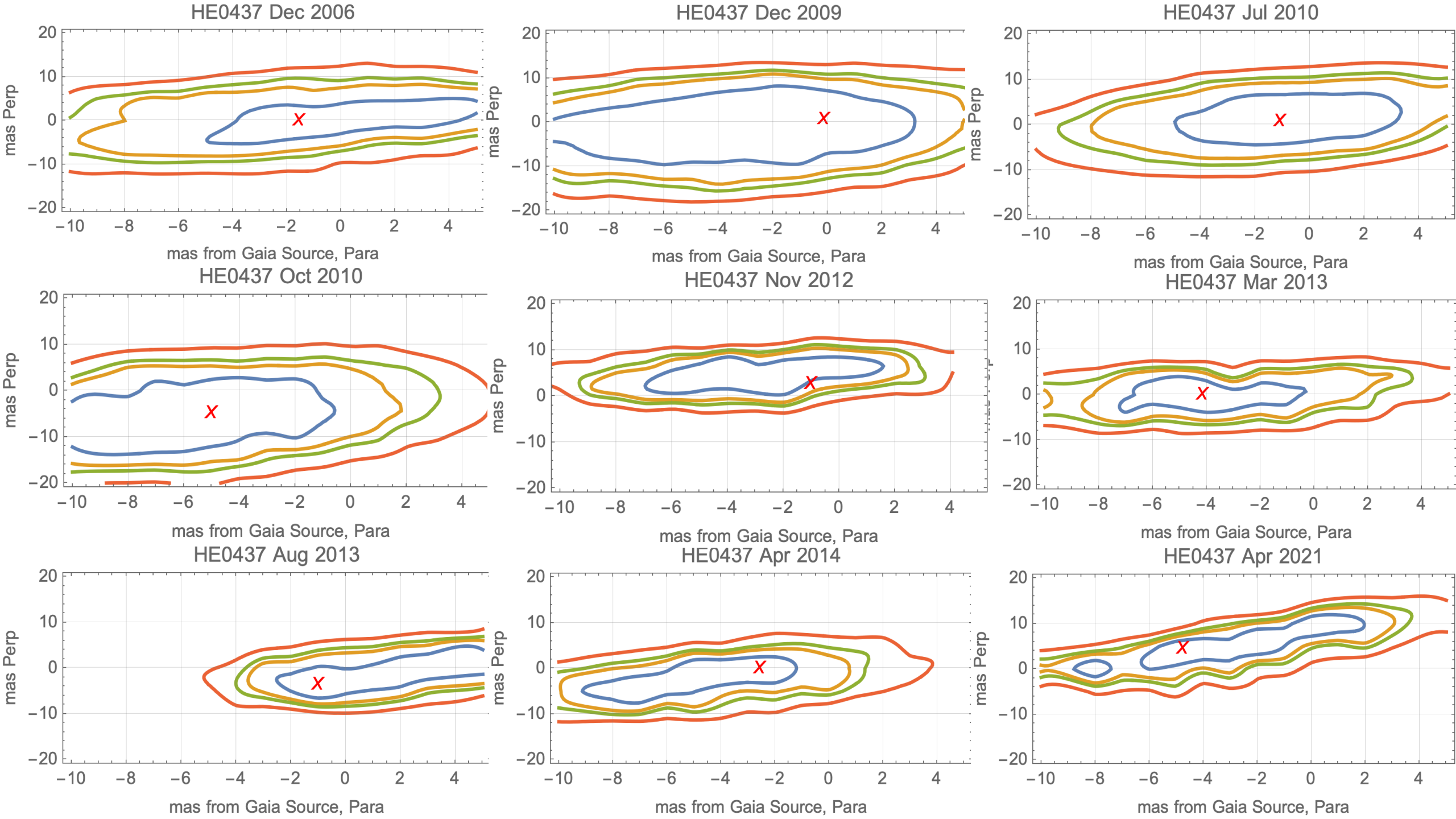


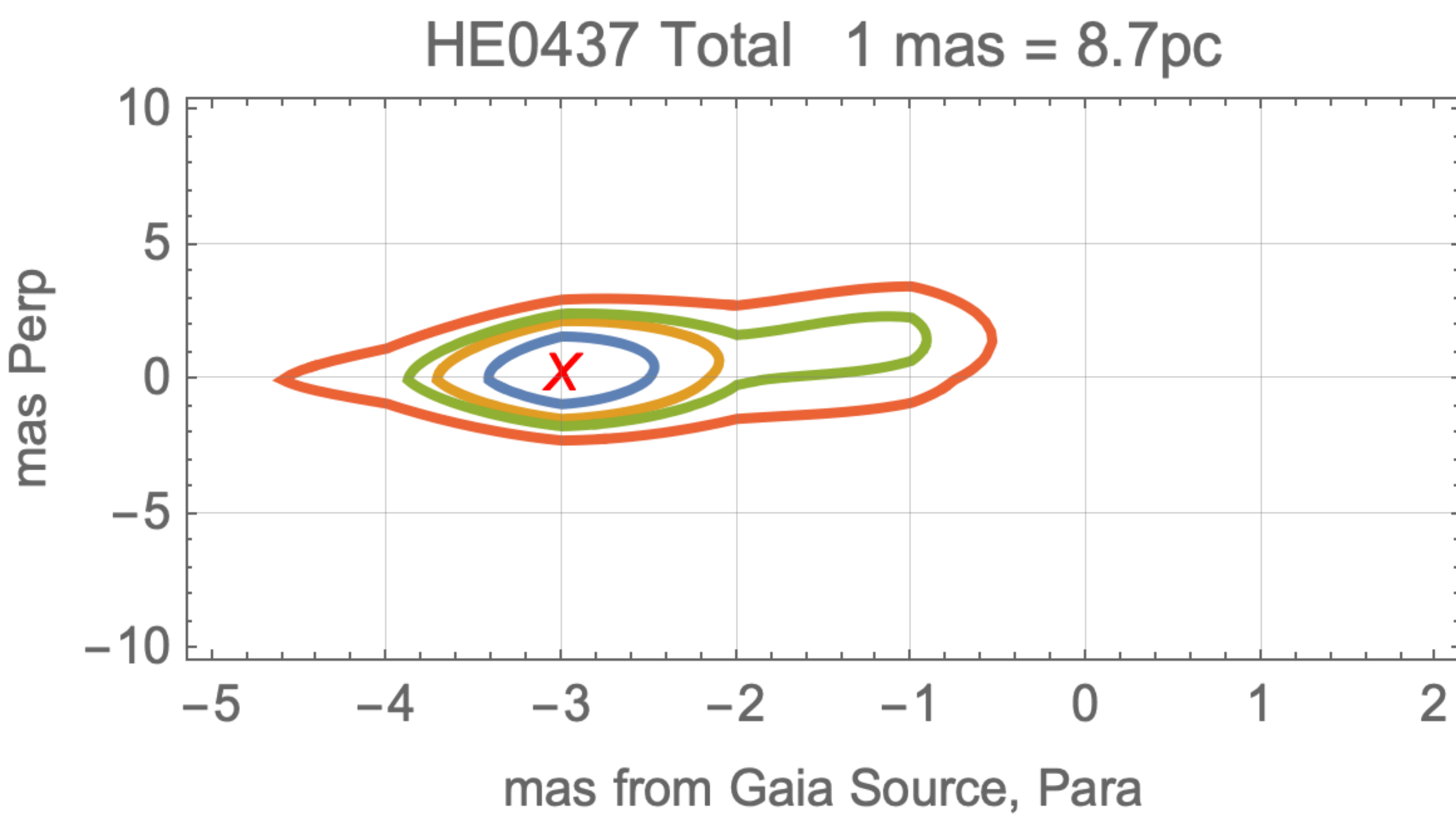
Synoptic Astrometry of the lensed Quasar HE0435-1223: X-ray Varstrometry

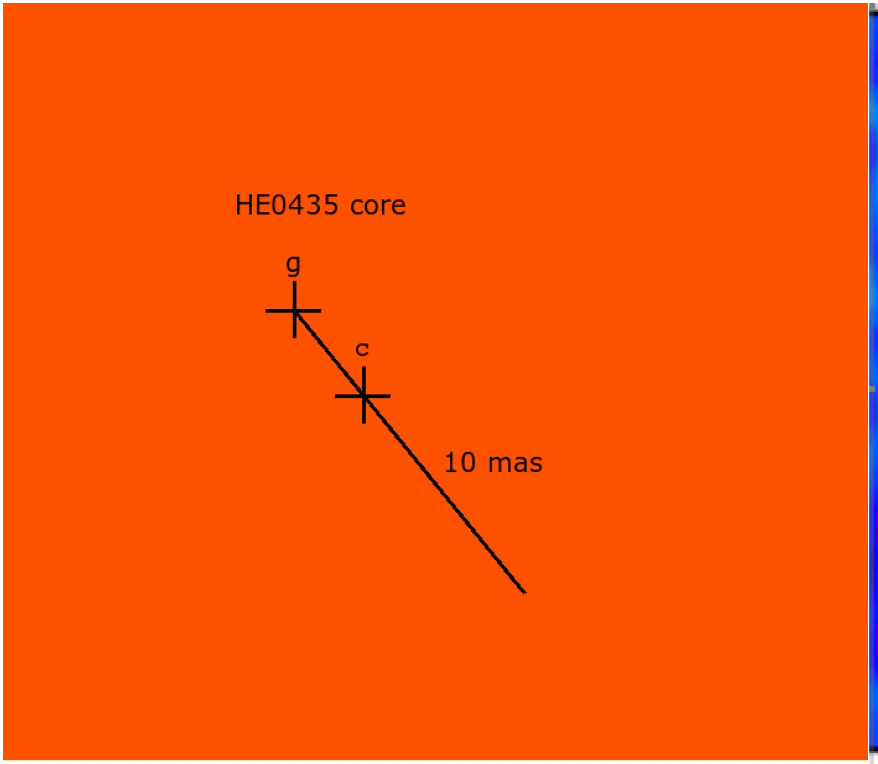


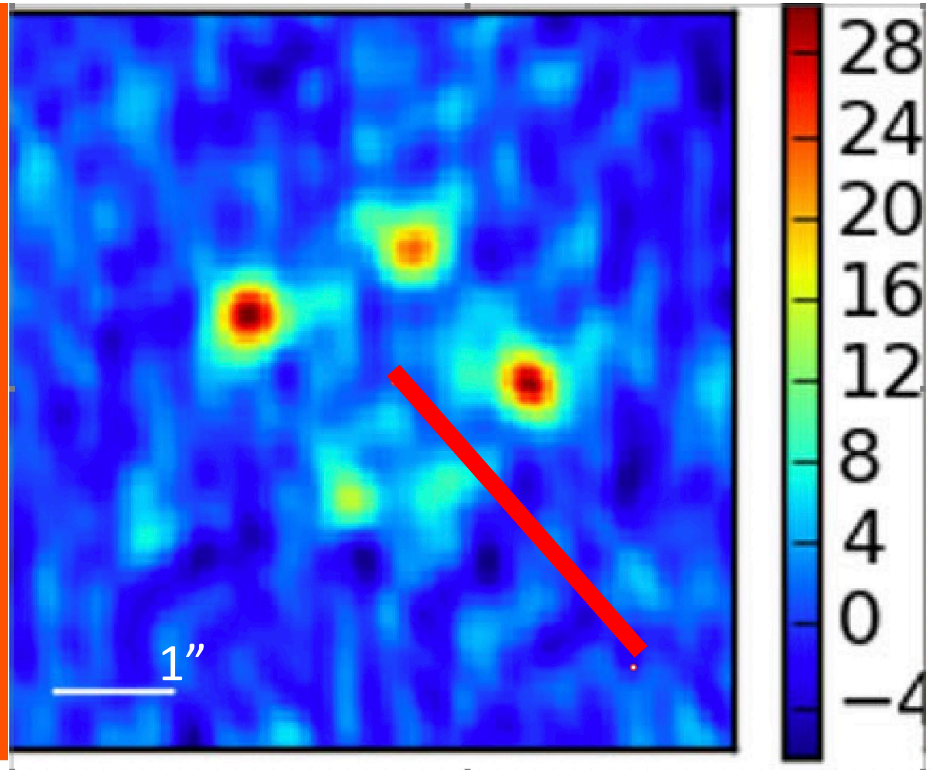
Top Panel:
Emphasis on the image plane, showing changes in image separations for different source locations.

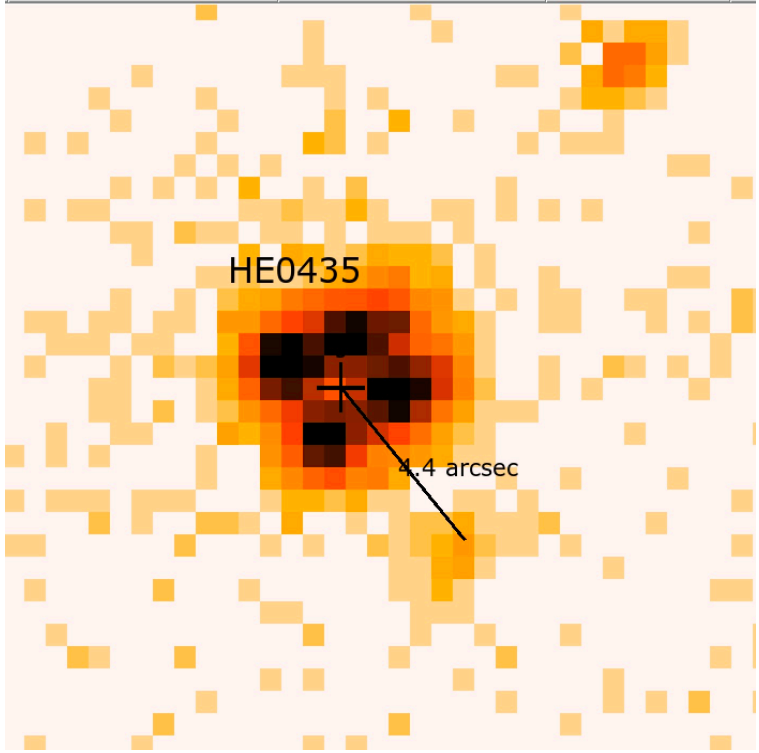
Bottom Panel:
Emphasis on source plane, showing source positions color coded to the image positions in top panel


HE0437 Dec 2006
HE0437 Dec 2009
HE0437 Jul 2010
HE0437 Oct 2010
HE0437 Nov 2012
HE0437 Mar 2013
HE0437 Aug 2013
HE0437 Apr 2014
HE0437 Apr 2021
mas Perp
mas from Gaia Source, Para
20
10
0
−10
−20
−10
−8
−6
−4
−2
0
2
4


HE0437 Total 1 mas = 8.7pc
10
5
0
−5
−10
mas Perp
−5
−4
−3
−2
−1
0
1
2
mas from Gaia Source, Para



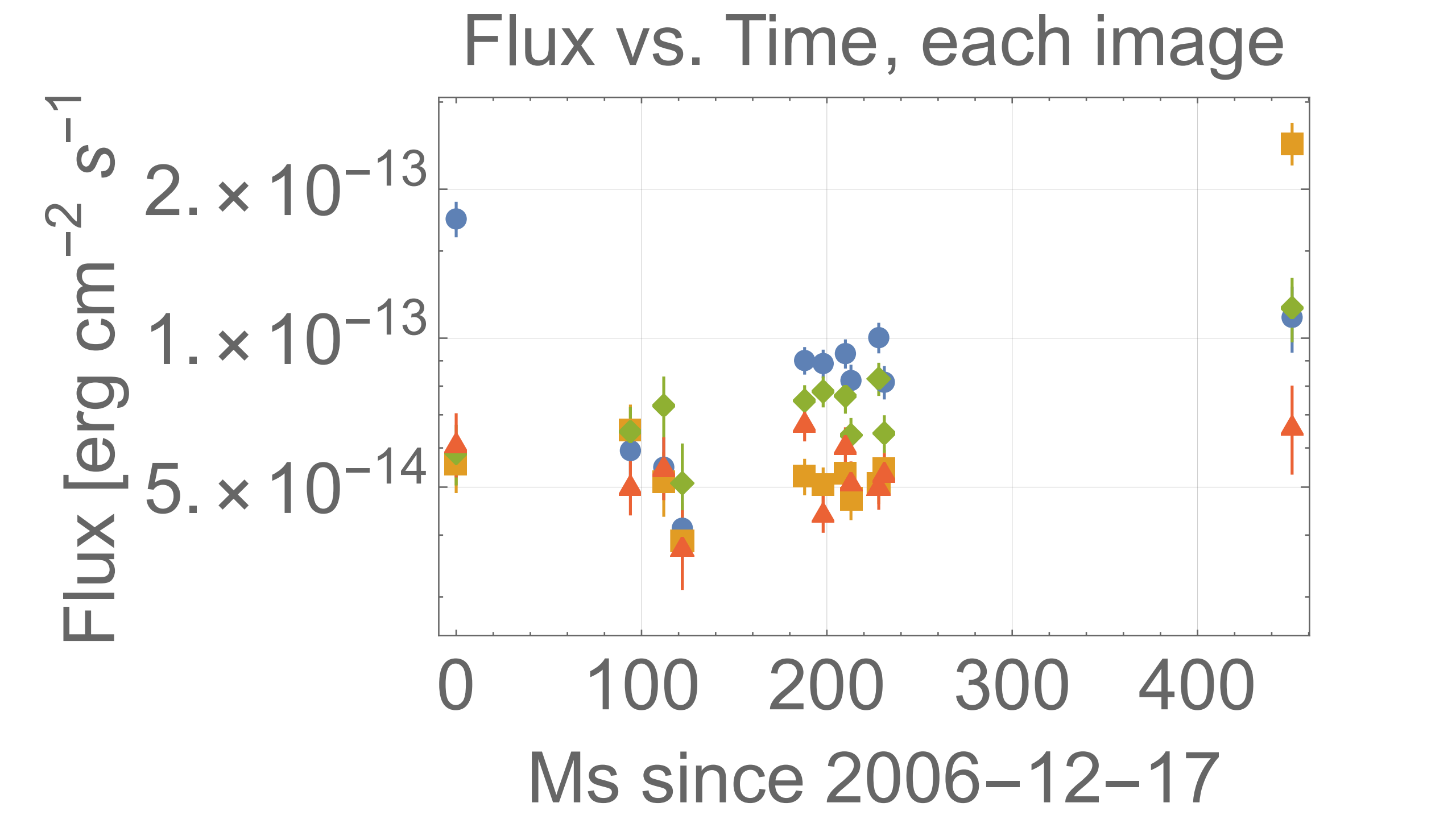




Position of the Gaia source: “g”
Position of the X-ray centroid of HE0435:, “c” , is 3 +/- 0.5 mas from “g”

VLA radio image at 5 GHz by Jackson+ MNRAS 454, 287–298 (2015).Red line is an extension of the Gaia-HE0435 X-ray offset.

285 ks Chandra observation of HE0435-1223, including two apparently unrelated galaxies


Flux vs. Time, each image
Flux [erg cm^{-2} s^{-1}]
$2. \times 10^{-13}$
$1. \times 10^{-13}$
$5. \times 10^{-14}$
0
100
200
300
400
Ms since 2006–12–17

X-ray Varstrometry

- *Varstrometry*: two unresolved, variable sources separated by θ will show an astrometric position jitter:

$$\sigma_{astro} = \theta \frac{q}{1+q} \sqrt{\sigma_F^2} / < F >$$

- For HE0435, the position rms is 3.3 mas and flux rms/mean=0.23 so statistically θ<28 mas =250 pc

Gravitational Lensing Offers a New Paradigm: 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

Gravitationally lensed quasars will reveal the first Black Holes in the universe.

Tens of thousands of quadruply lensed sources from *Rubin, SKA, Euclid,* and *Roman* will explode this field of research.

Supplementary

Gravitational Lensing for Astrometric Determinations:

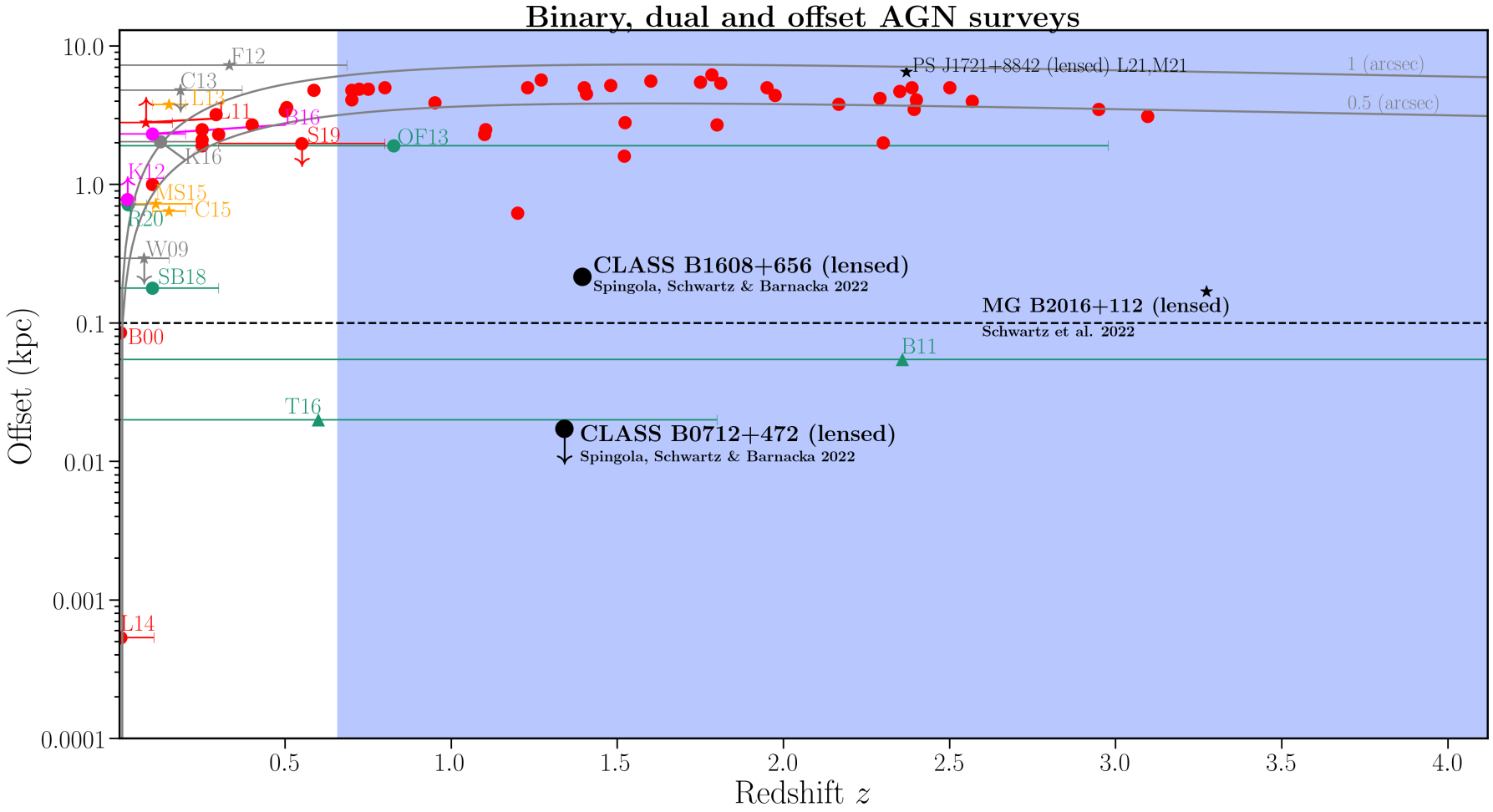
Milli-arcsec X-ray Structure in Active Galactic Nuclei

Dan Schwartz (SAO), Anna Barnacka (SAO, Jagiellonian U), Giulia Migliori & Cristiana Spingola (INAF-IRA)

With: Alysa Rogers (U Wisc), Yazmin Bath & Alex Ostridge (Southampton U), Preeti Kharb (NCRA-TIFR)

References:

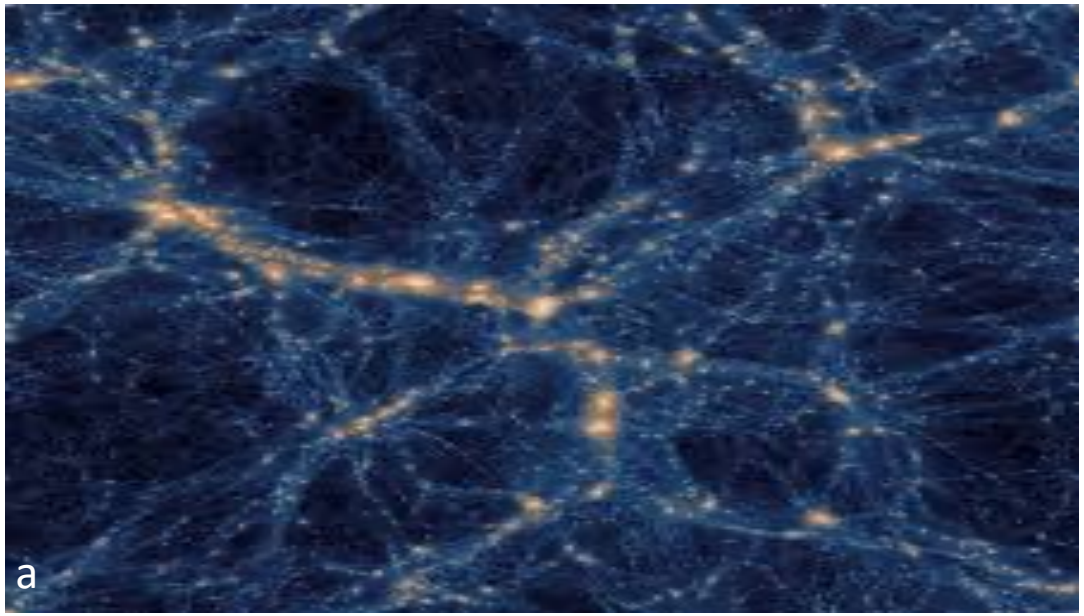
Bansal+ 2017 ApJ, 843, 14
Barnacka 2017 ApJ 846, 157
Barnacka 2018 PhRep. 778, 1
Harris+ 2003 ApJ 586, 41
Harris+ 2006 ApJ 640, 211
Jackson+ 2015 MNRAS, 287, 298
Komossa+ 2003 ApJ 582, 15
Mezcua+ 2014 ApJ 784, 16
Morgan+ 2005 AJ 129, 2531
Spingola and Barnacka 2020 MNRAS 494, 2312
Schwartz, Spingola, Barnacka 2021 ApJ 917,26
Spingola, Schwartz, Barnacka 2022 ApJ 931, 68



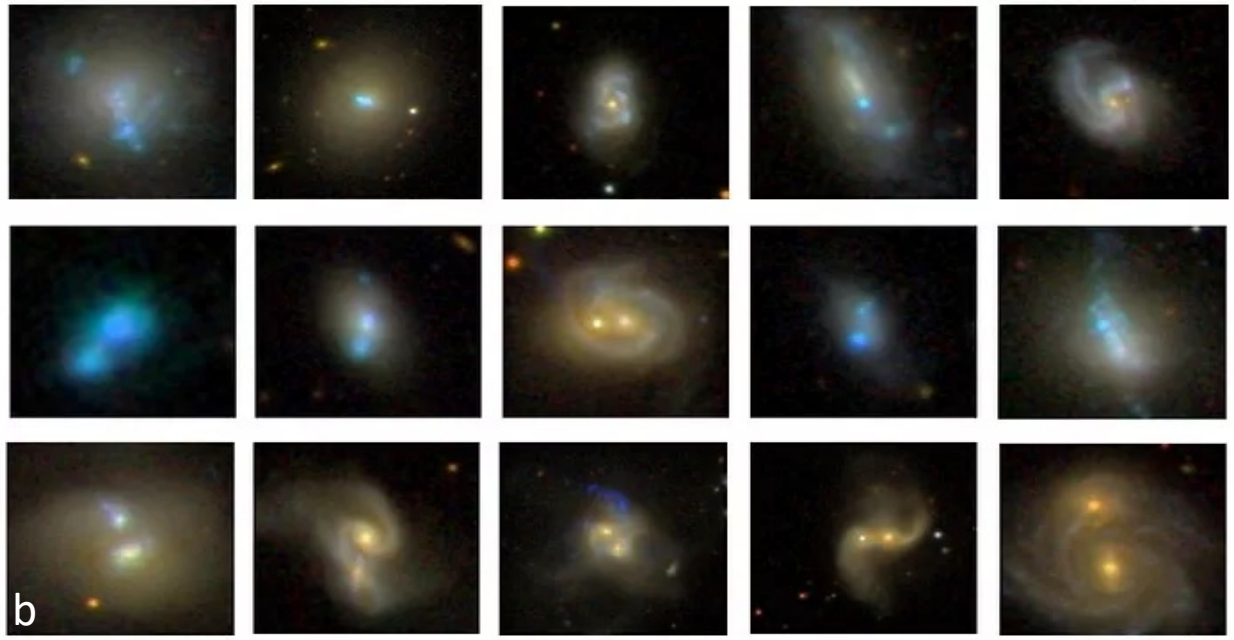
Project Goals

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

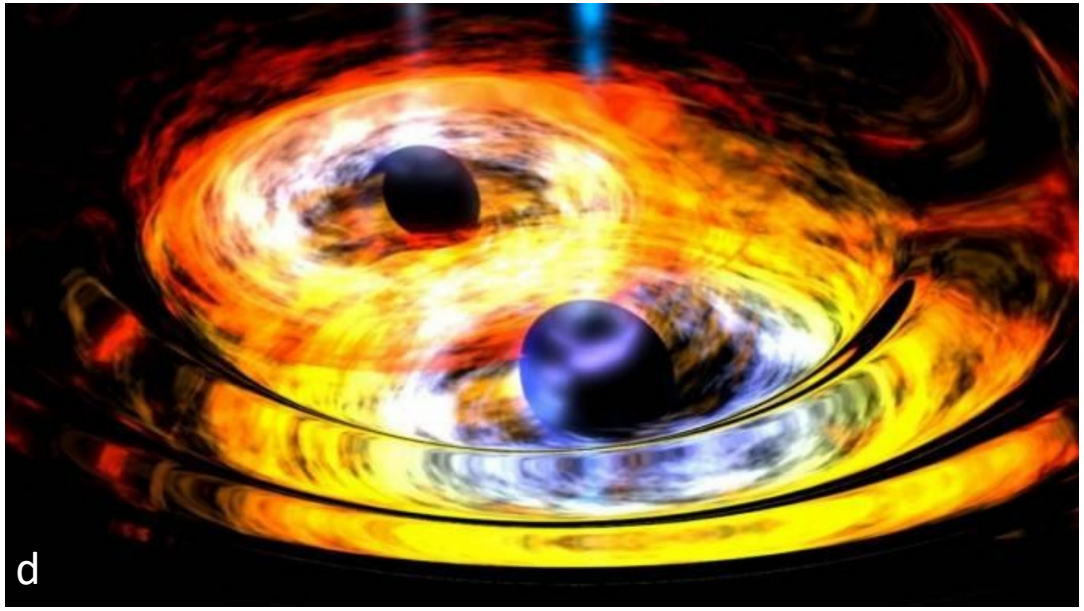
- Finding Dual/Binary supermassive black holes
  - Measuring X-ray, Radio, Optical offsets
    - Resolving pc-scale X-ray jets
    - Finding ejected Black Holes



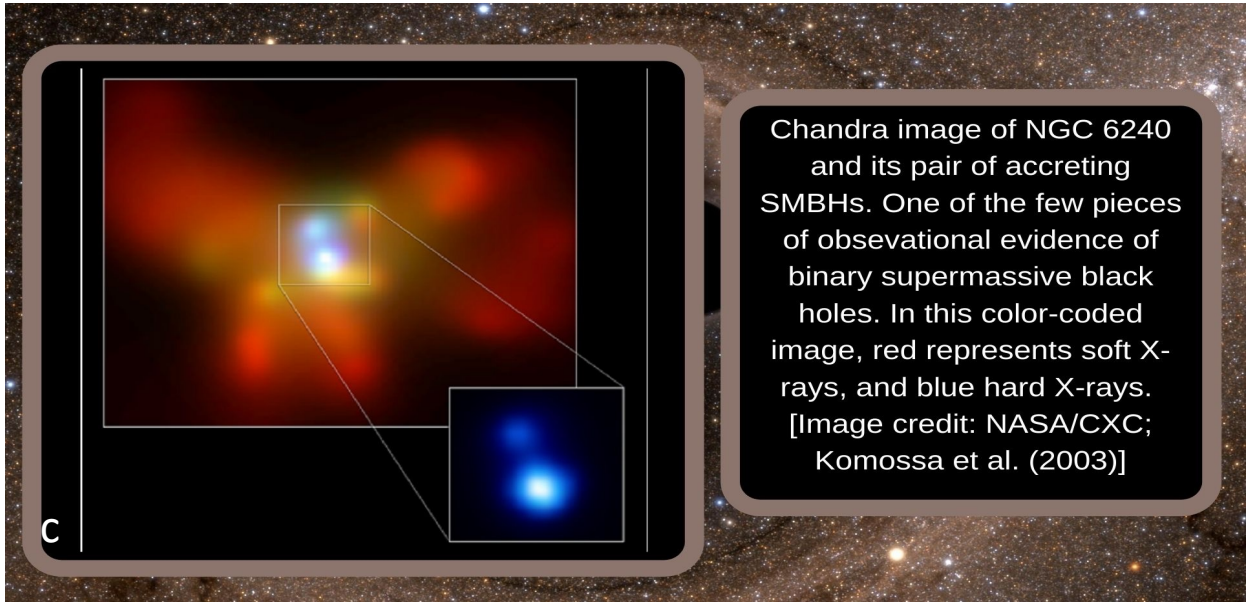
Illustris Simulation



Mezcua et al., 2014



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



Komossa et al., 2003