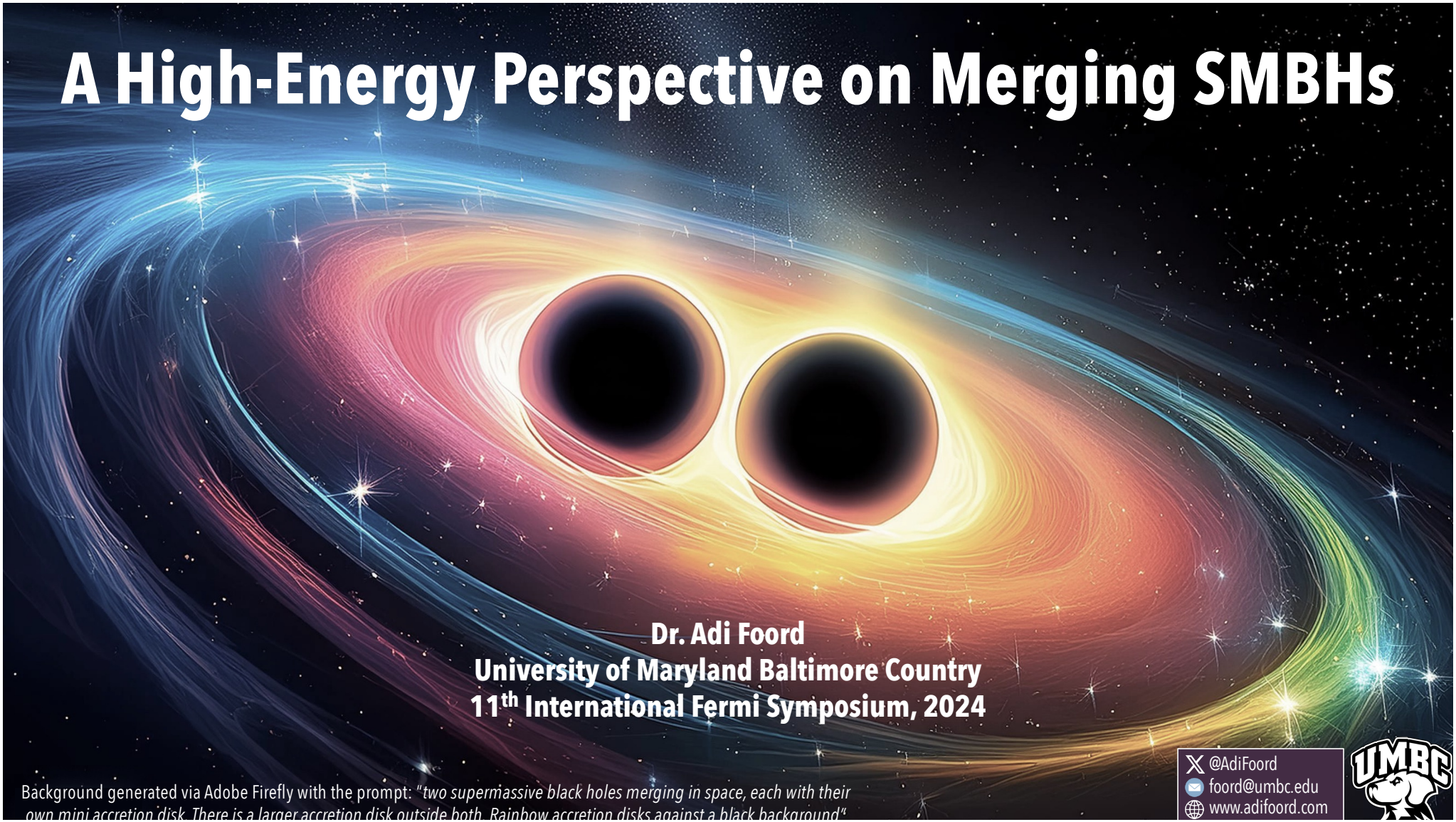
A High-Energy Perspective on Merging SMBHs



Dr. Adi Foord
University of Maryland Baltimore Country
11th International Fermi Symposium, 2024

Background generated via Adobe Firefly with the prompt: "*two supermassive black holes merging in space, each with their own mini accretion disk. There is a larger accretion disk outside both. Rainbow accretion disks against a black background*"

@AdiFoord
foord@umbc.edu
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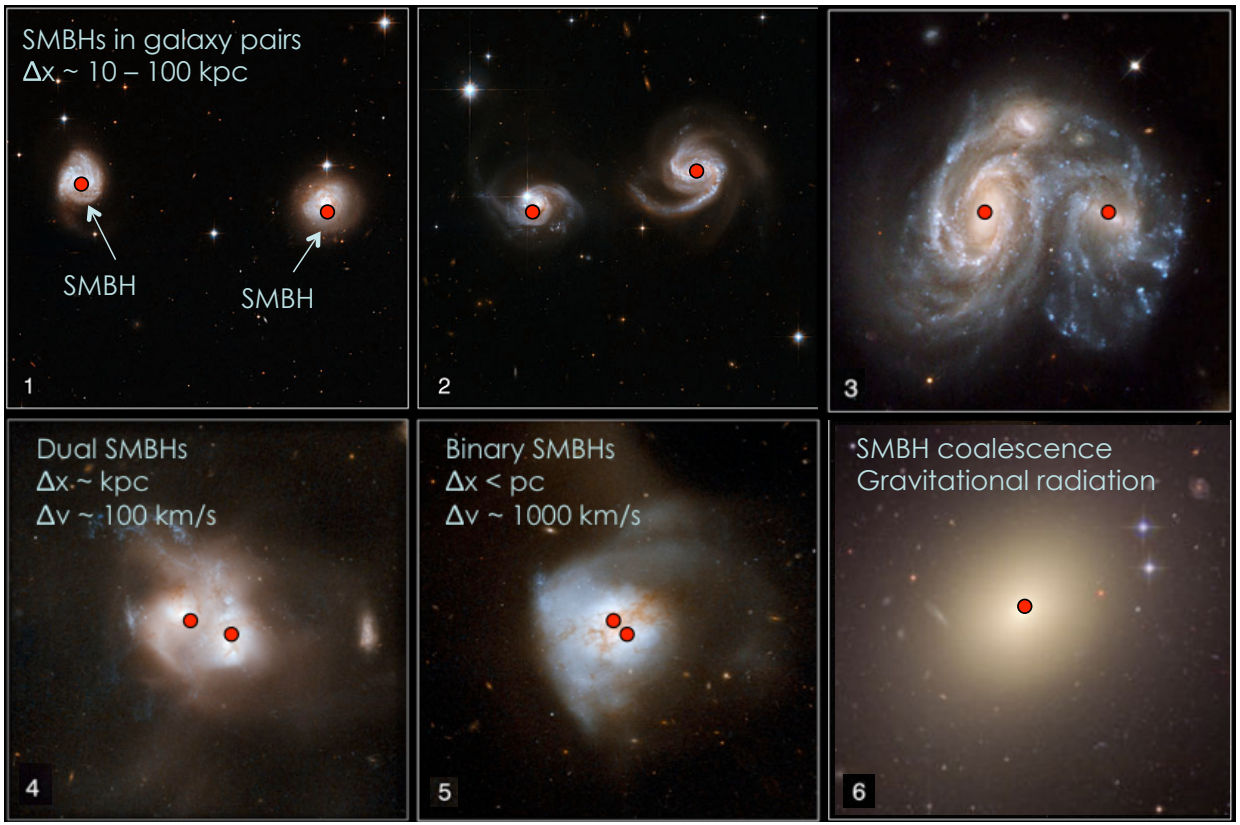
Galaxy mergers lead to dual and binary AGN



Adapted from Julie Comerford

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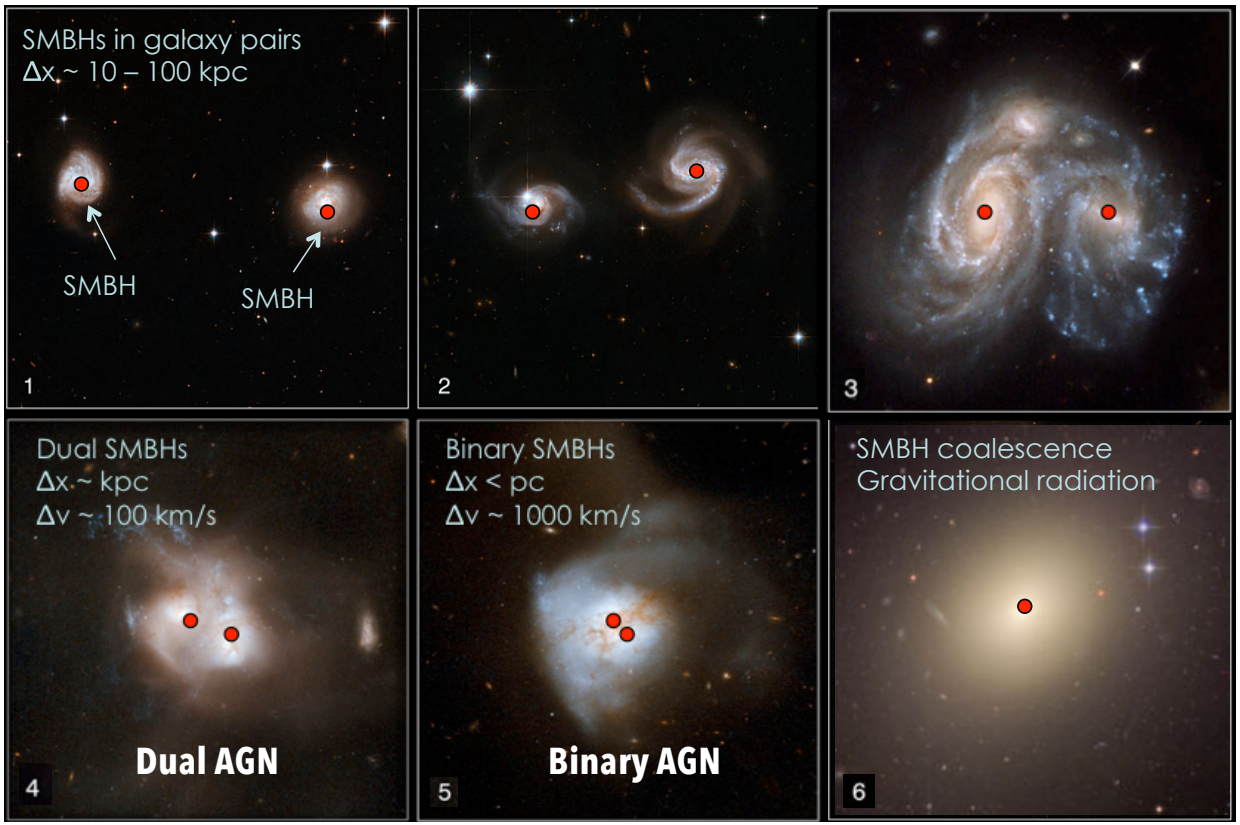

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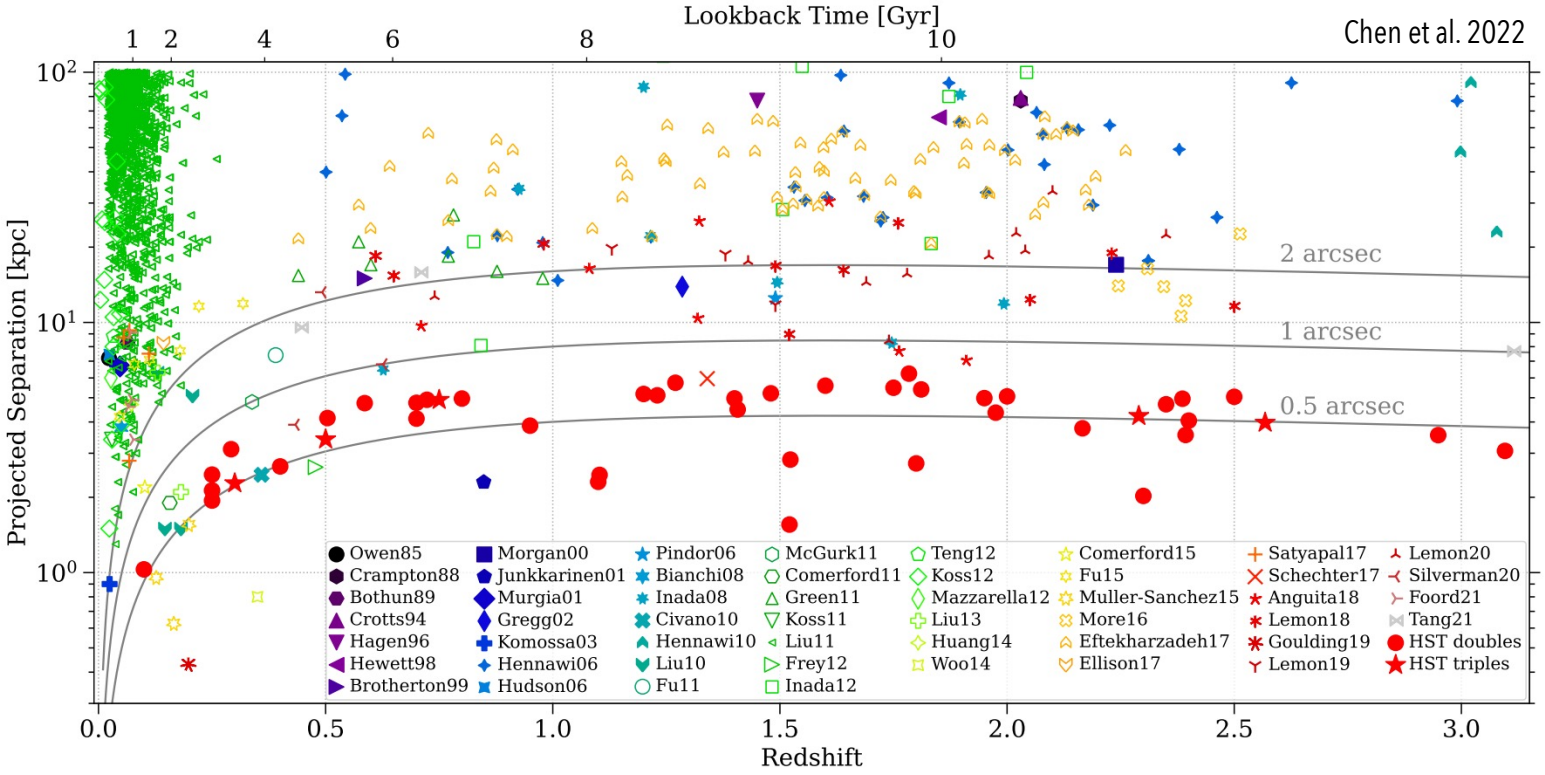
We are still trying to quantify the population of AGN pairs



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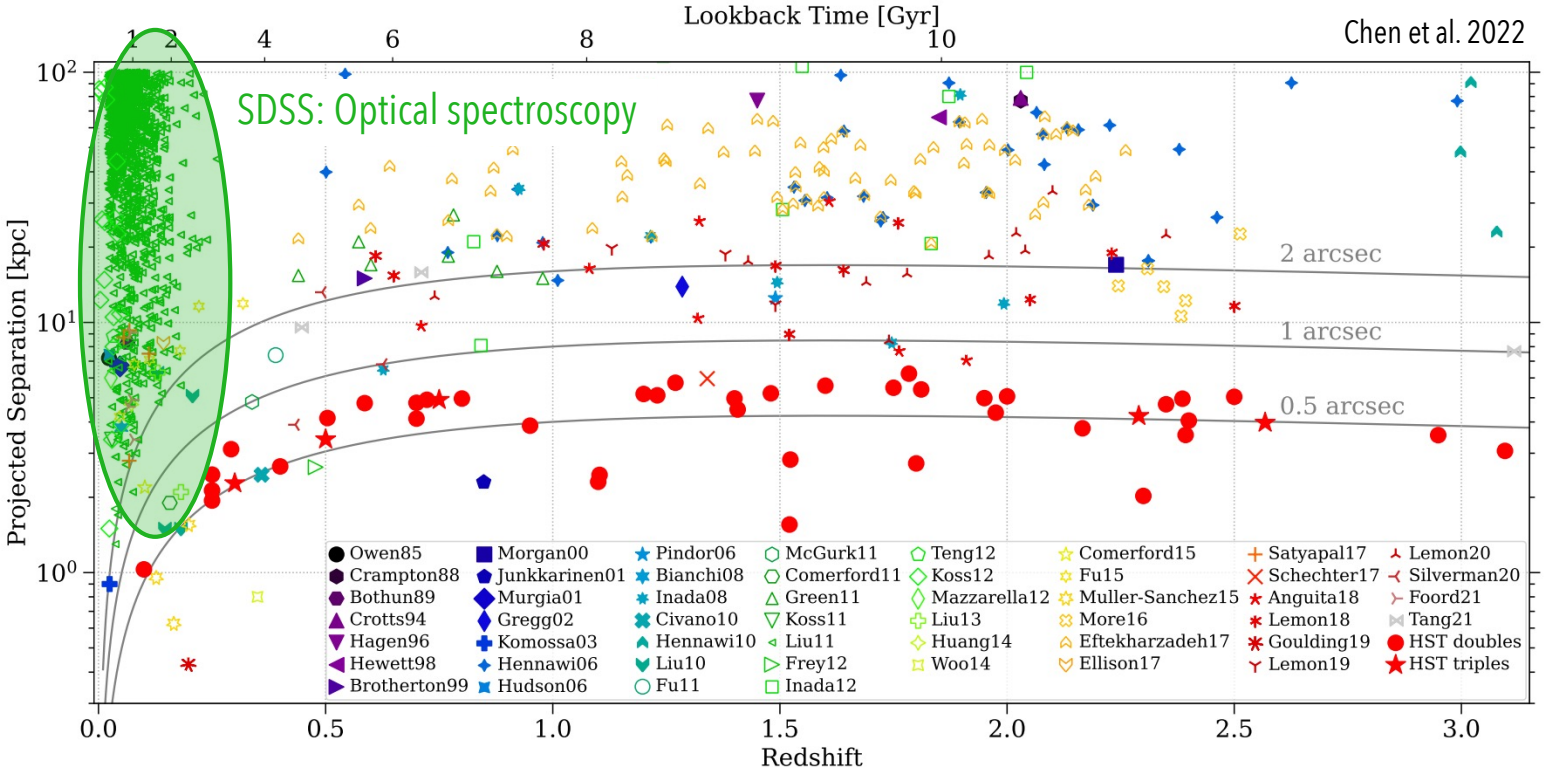

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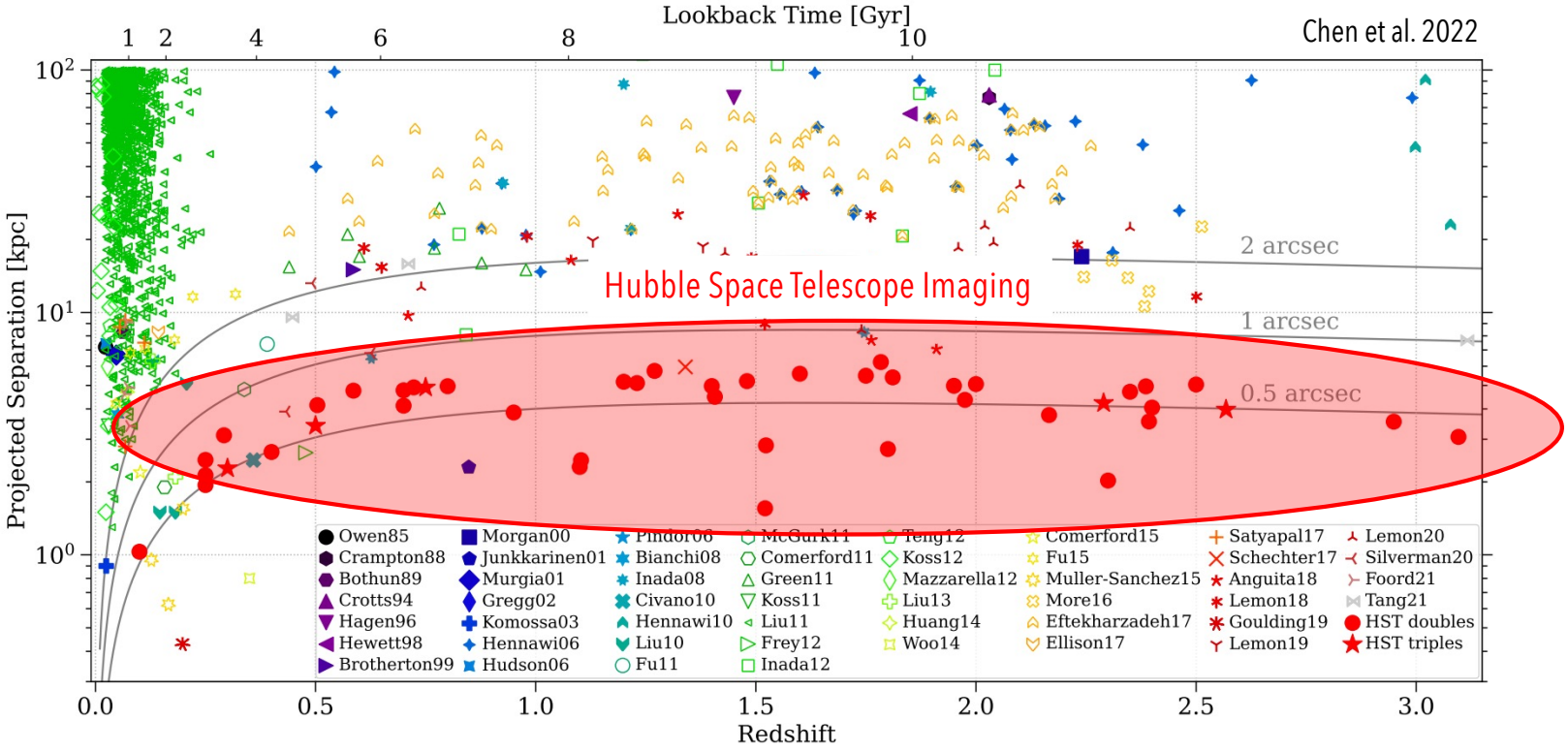

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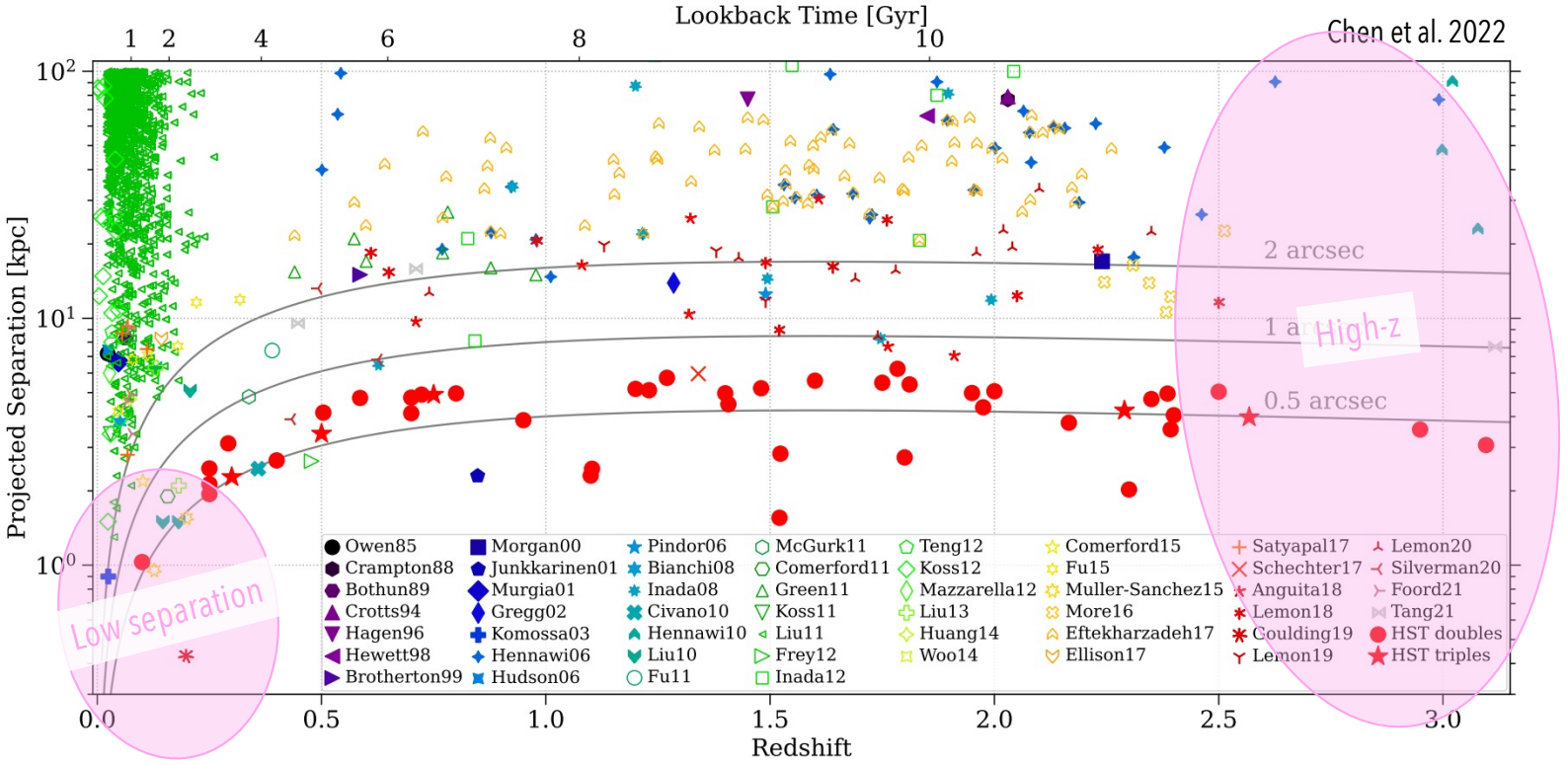
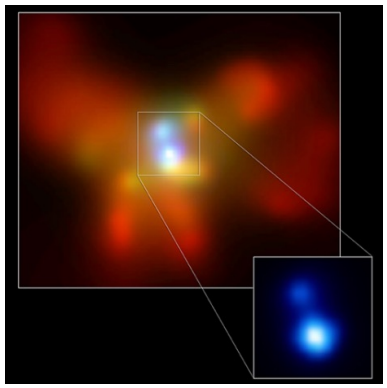
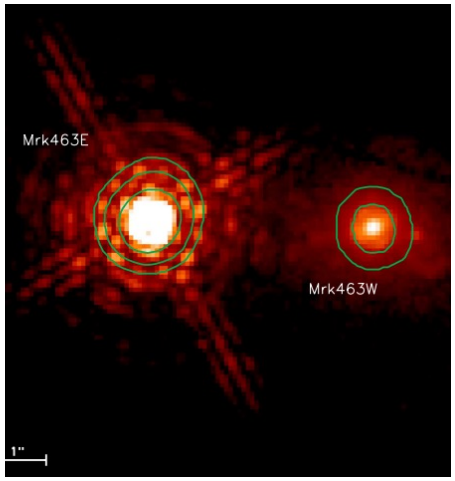


Before 2010, only a handful of AGN pairs were known …

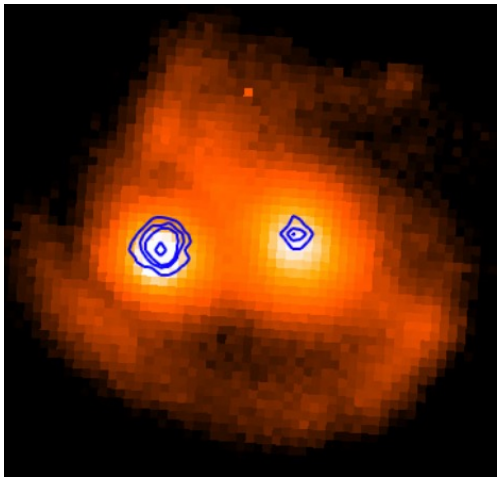
Most dual AGN were serendipitous discoveries, or follow-up X-ray/Radio observations of known galaxy mergers



NGC 6240 (Komossa+2003)
X-ray confirmation



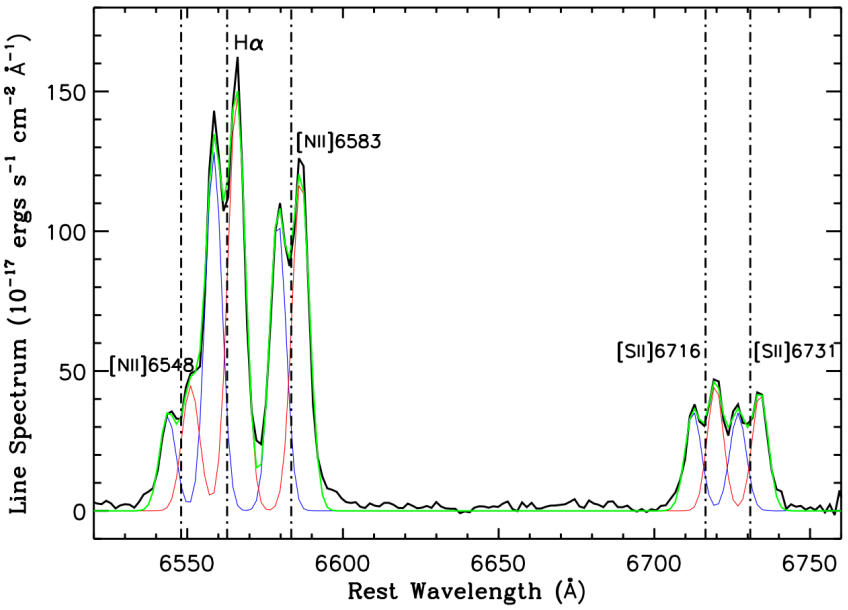
MRK 463 (Bianchi+2008)
X-ray confirmation



MRK 739 (Koss+2011)
X-ray confirmation

SDSS: Large spectroscopic searches change the field

With the advent of large spectroscopic surveys of galaxies, like SDSS, the number of dual AGN candidates exponentially increased

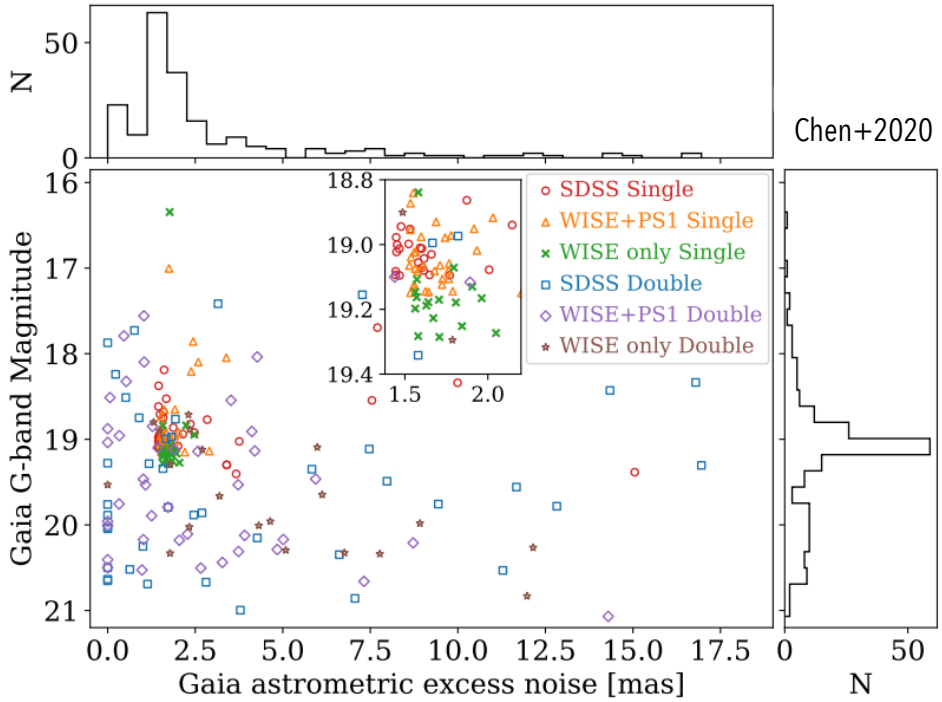


Sifting through available SDSS spectra ,100s of double peaked found in SDSS spectral archives

Check out:
Wang+2009, Comerford+2009, Smith+2010, Liu+2010

Gaia is making a mark in the dual AGN community

'Varstrometry' – where variability-induced astrometric jitter, i.e., temporal displacements of photocenter in unresolved sources, can be used to search for dual AGN.



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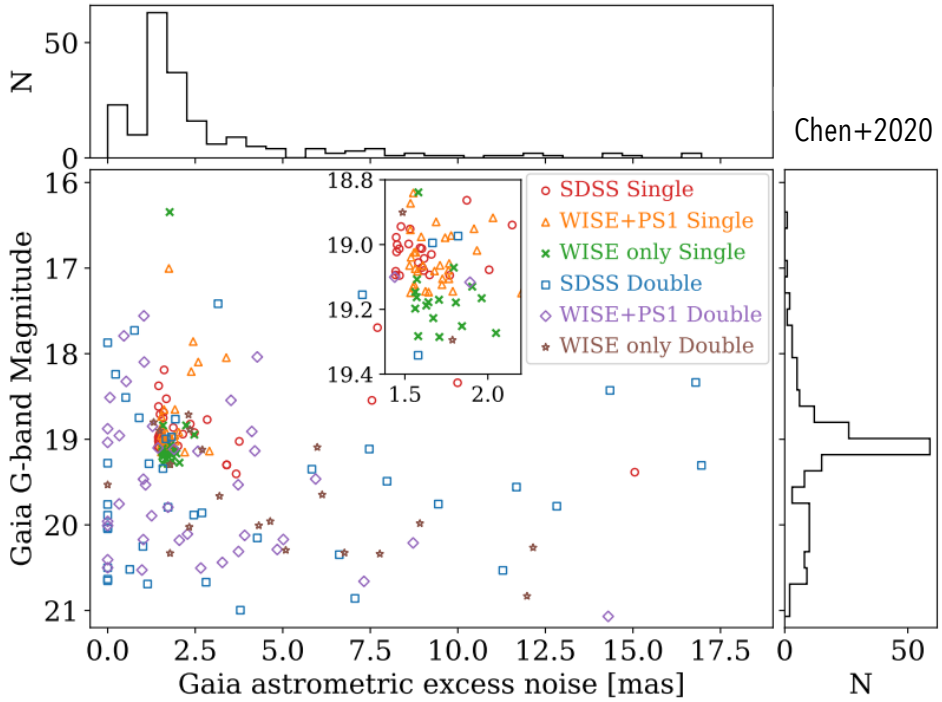
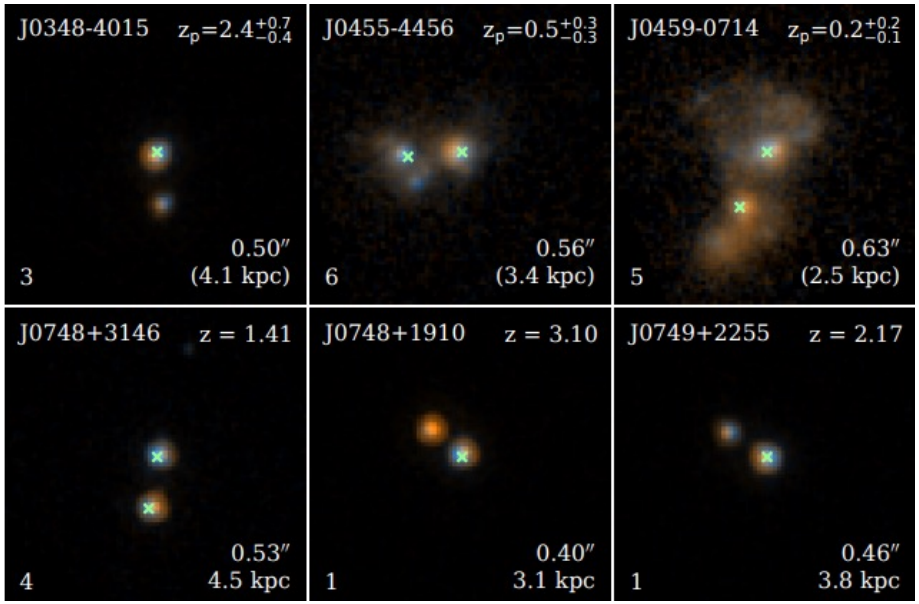


Gaia is making a mark in the dual AGN community

'Varstrometry' – follow up Hubble Space Telescope images shows multiple sources at most locations! Most have been found to be lensed systems, but some are likely dual AGN.

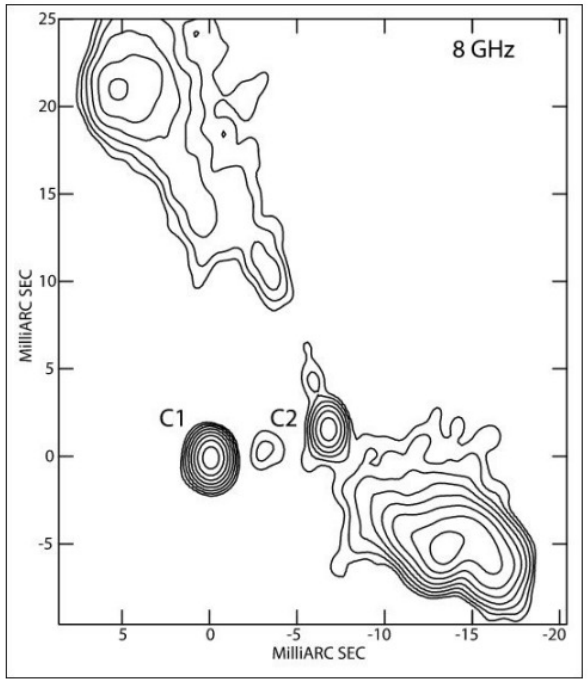
Chen+2020



***Also check out "Gaia Multipeak (GMP) method' – searching for the presence of multiple peaks in the observed 1D light profiles (Mannucci et al. 2022)**

Candidates to direct detection: follow-up is necessary

Directly detecting radio emission from each SMBH is one the best ways to confirm closely separated dual AGN

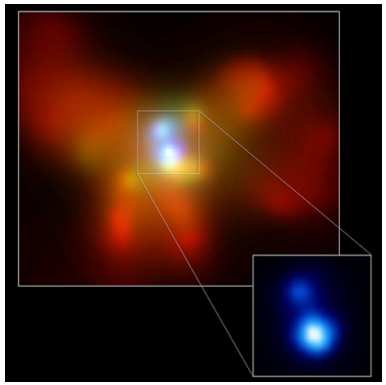


Rodriguez et al 2006

The typical mas-scale angular resolution achievable with VLBI networks allows directly resolve as small as ~1 pc in the local Universe and ~ 10 pc at any redshift.

0402+379 at 8 GHz. Components C1 and C2 correspond to the two radio nuclei at projected separation of 7.3 pc

Candidates to direct detection: follow-up is necessary



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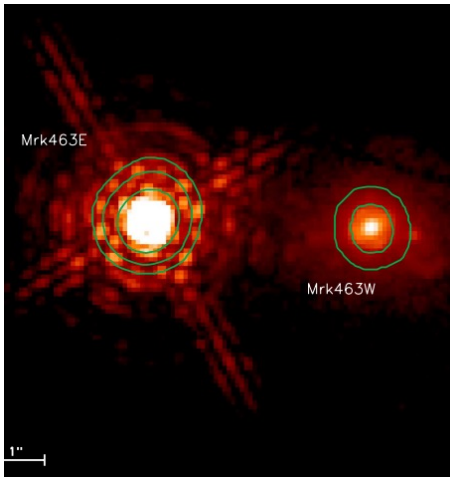

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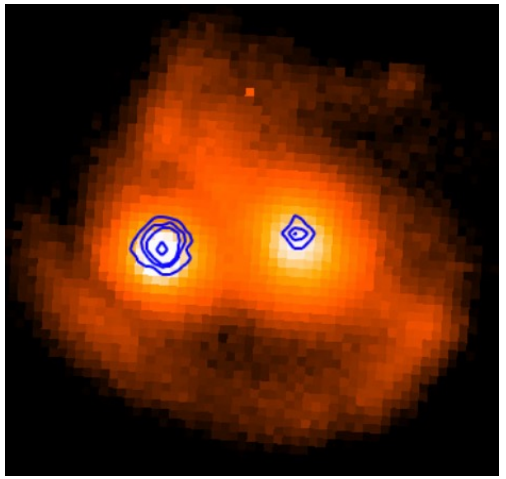

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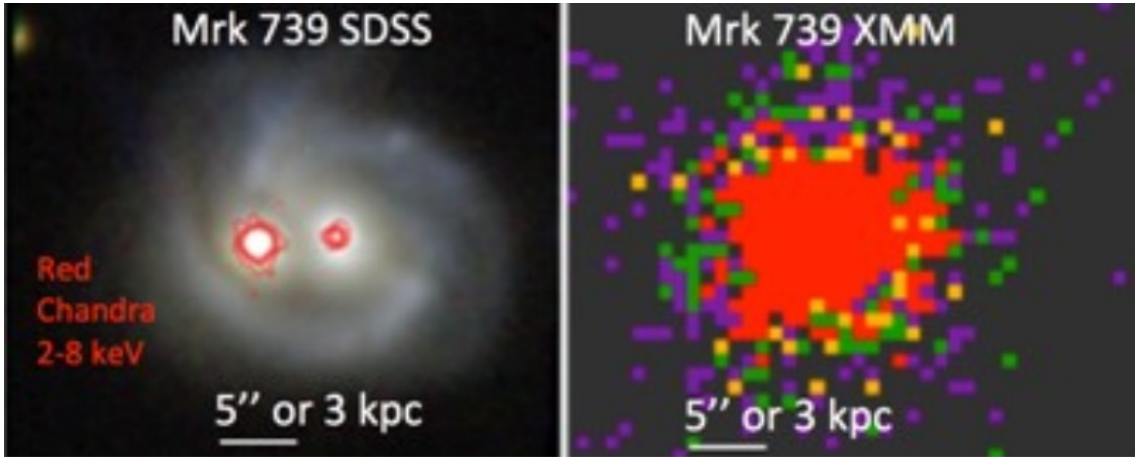
Resolving 2 X-ray point sources with X-ray luminosities $>10^{41}$ erg s^{-1} can confirm any dual AGN candidates

X-rays are great rays to confirm dual AGN (& high-resolution is the best!)



With Chandra, and future X-ray probes such as AXIS, we can find the most closely separated systems

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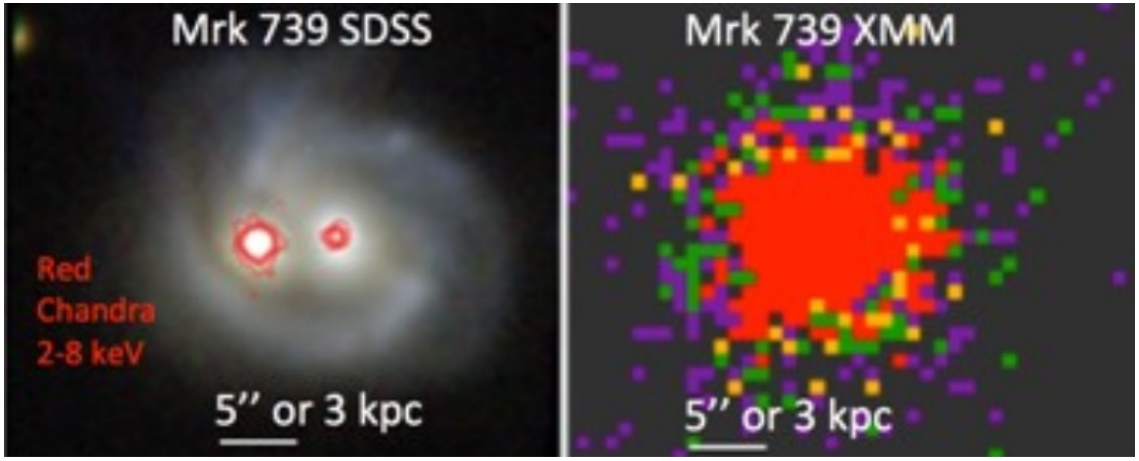
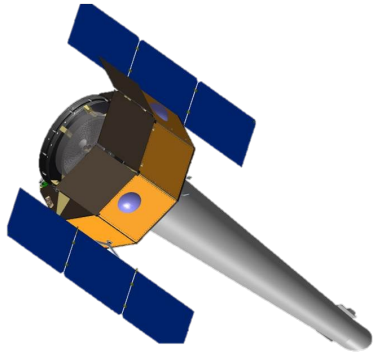




I am a Co-I on the AXIS Probe Team and Co-lead for the AGN SWG – ask me more about AXIS!

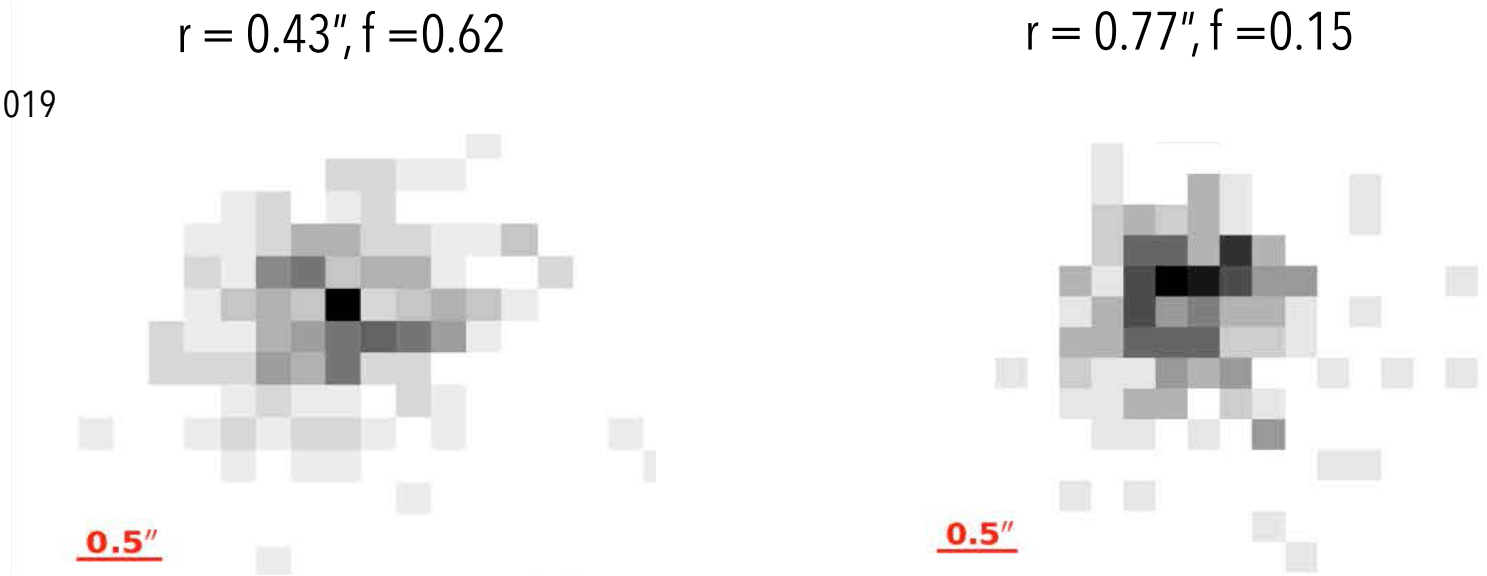
With Chandra, and future X-ray probes such as AXIS, we can find the most closely separated systems

Beyond beyond z>0.05, even Chandra can't resolve resolve sub-kpc systems

r = 0.43″, f =0.62

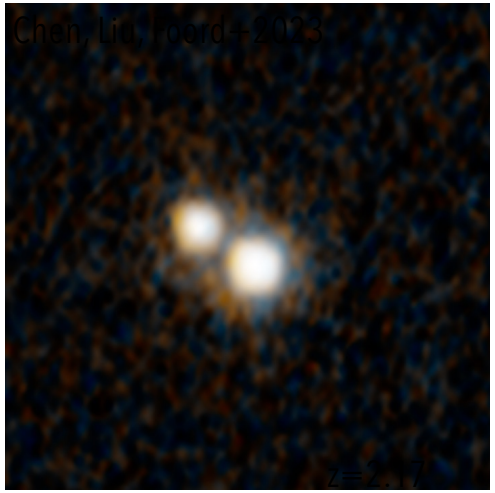
r = 0.77″, f =0.15

Foord et al. 2019

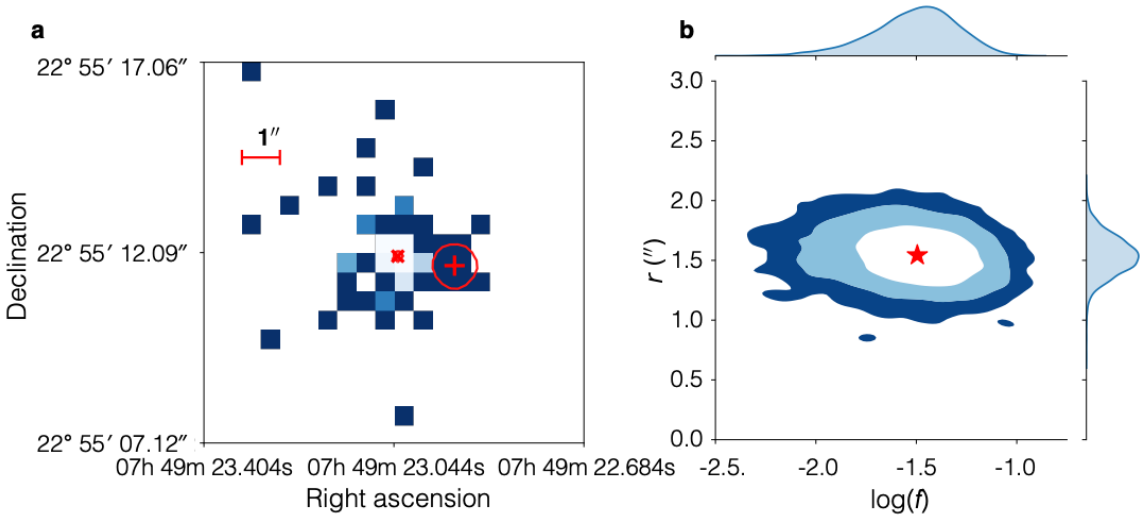


Tools such as ``**BAYMAX**'' (Bayesian AnalYsis of Multiple AGN in X-rays) have been developed to better identify dual AGN in X-ray datasets

BAYMAX has recently been used in a study on a varstrometry-identified dual AGN candidate



Chen, Liu, Foord et al., Nature, 2023



Discovered via "varstrometry" and confirmed via a multi-wavelength analysis (optical photometry and spectroscopy, radio imaging, IR imaging)

Indirect detection techniques are almost always necessary for finding binary AGN

Direct:

Radio: Imaging searches with the VLBI (0402+379, Rodriguez et al. 2006; NGC7674; Kharb et al. 2017)

Indirect:

Radio: Rotationally symmetric helical S-shaped radio structures (Begelman et al. 1980; Roos 1988; Lobanov + Roland 2005; Kun et al. 2014; Deane et al. 2014)

Optical: Broad emission-line velocity shifts (Tsalmantza et al. 2011; Eracleous et al. 2012; Liu et al. 2014b; Runnoe et al. 2015; Guo et al. 2019; Runnoe et al. 2017 , Nguyen and Bogdanović 2016)

Optical & UV: Peculiar broad emission-line ratios (Montuori et al. 2011)

Multi λ: Drop in the UV continuum due to a gap opened by the secondary BH (e.g., Gültekin & Miller 2012; Foord et al. 2017; Foord et al. 2019)

Multi λ: Search for periodic variability (e.g., Graham et al. 2015; Liu et al. 2016; Charisi et al. 2016; Zheng et al. 2016; Li et al. 2016; Bon et al. 2016; D'Orazio et al. 2015; Charisi et al. 2018; Liu et al 2019, Chen et al 2020)

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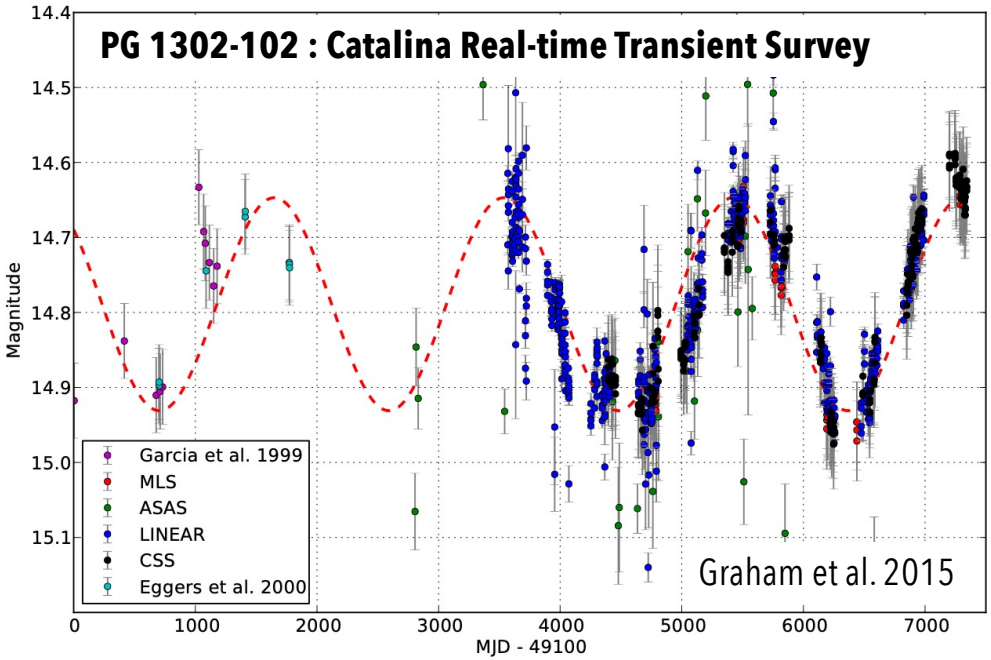
Multiwavelength Variability Searches via Time Domain Surveys



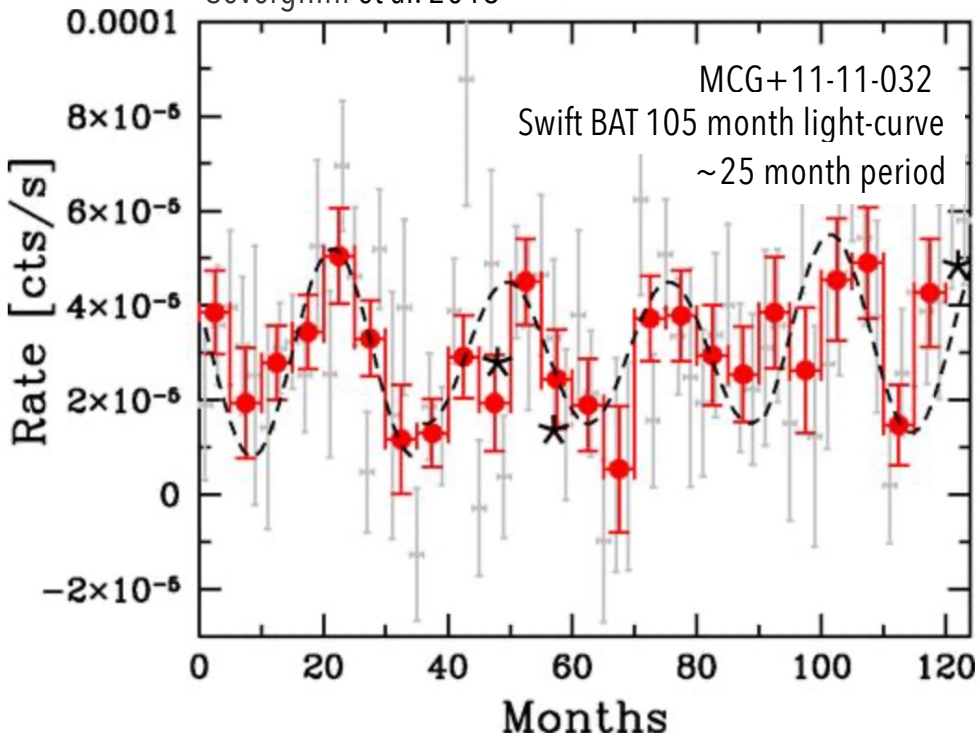
Hydrodynamic and magnetohydrodynamic simulations that show the mass accretion rate onto binary SMBHs is modulated periodically … **which may be translated into periodic modulation of the brightness**

(e.g., MacFadyen & Milosavljević 2008; Noble et al. 2012; Shi et al. 2012; D'Orazio et al. 2013; Farris et al. 2014; Gold et al. 2014; Bowen et al. 2018,2019)

Numerous candidates have been reported: Graham et al. 2015a, 2015b; Liu et al. 2015, 2016, 2019; Charisi et al. 2016, Chen et al. 2020,
The significance of the periodicity has been a topic of controversy, see Vaughan et al. 2015 …

The peculiar case of MCG+11-11-032

Severgnini et al. 2018



Variability may be expected at X-rays as well:

- X-ray emission from the gas bound to the black holes may experience Doppler boosting
- X-ray periodicity may also be produced by shocks

Considering the total SMBH mass of $\log(M/M_{\odot}) = 8.7 \pm 0.3$, the 25-month period implies a sub-pc separation with orbital velocity $\Delta v \approx 0.06\ c$

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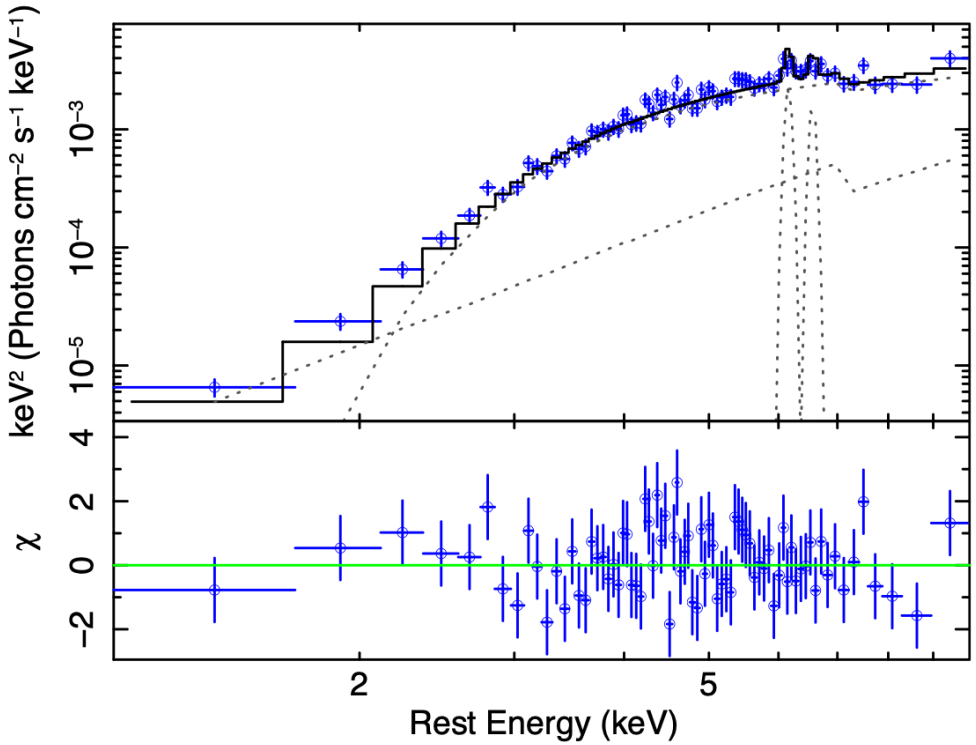
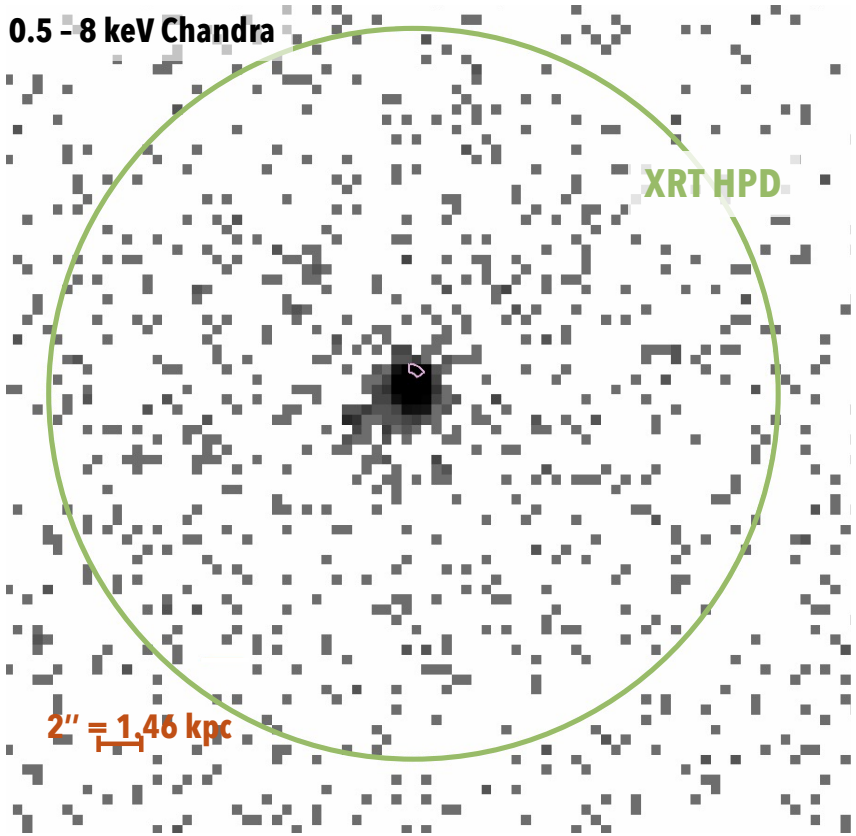


X-ray spectra hints at the presence of two Iron K-alpha, with $\Delta v \approx 0.06\ c$

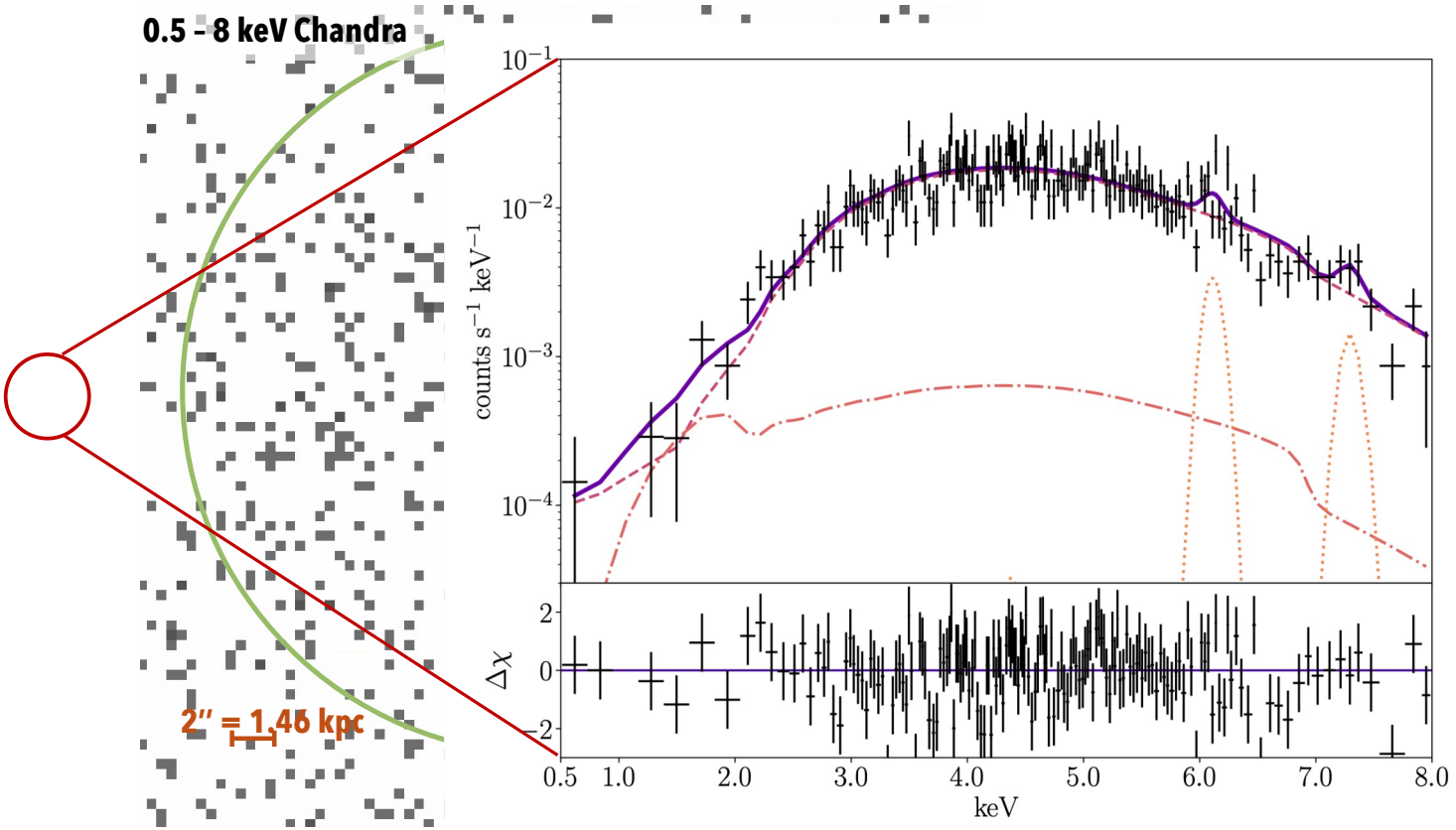
New Chandra data of MCG+11-11-032 …



Just submitted to ApJ and posted on arXiv **today**! Check it out.

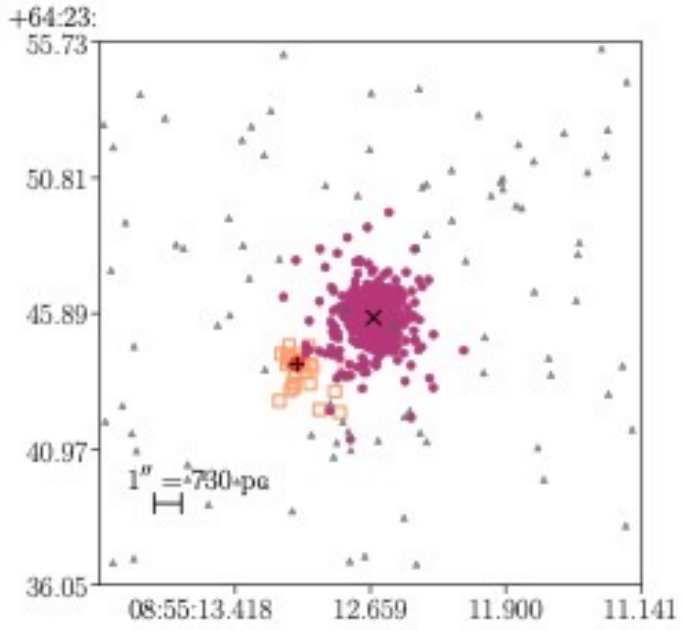
Foord, Civano, et al. 2024

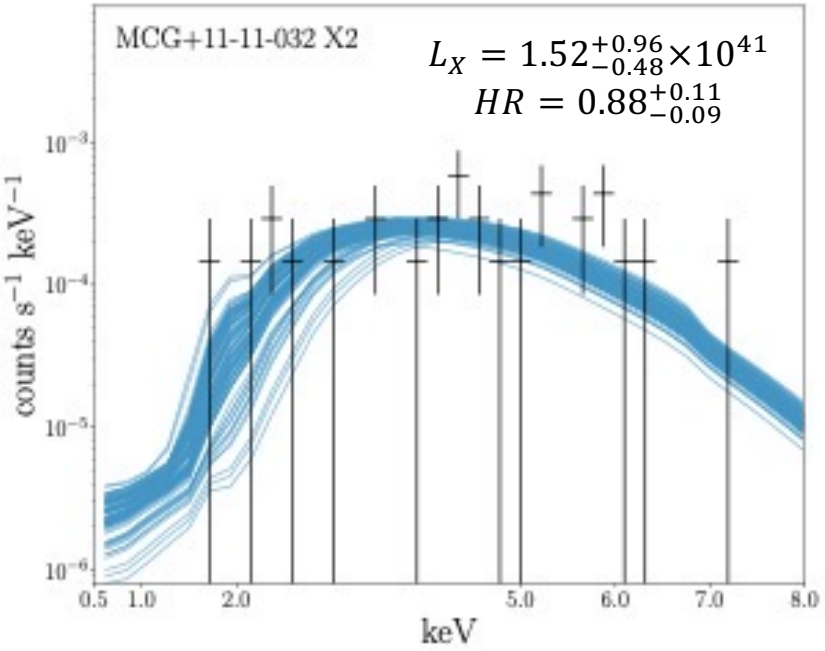
… shows no sign of a binary AGN



Foord, Civano, et al. 2024

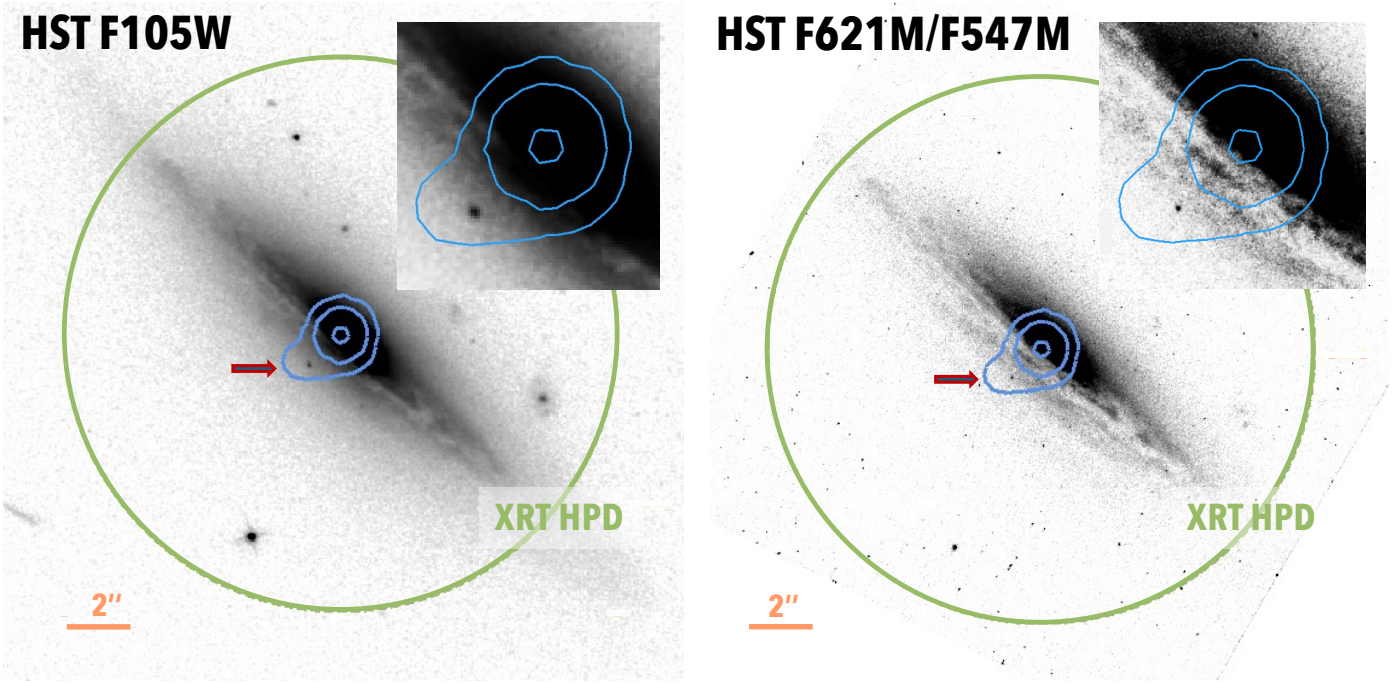
But, a nearby secondary X-ray source is detected …





Foord, Civano, et al. 2024

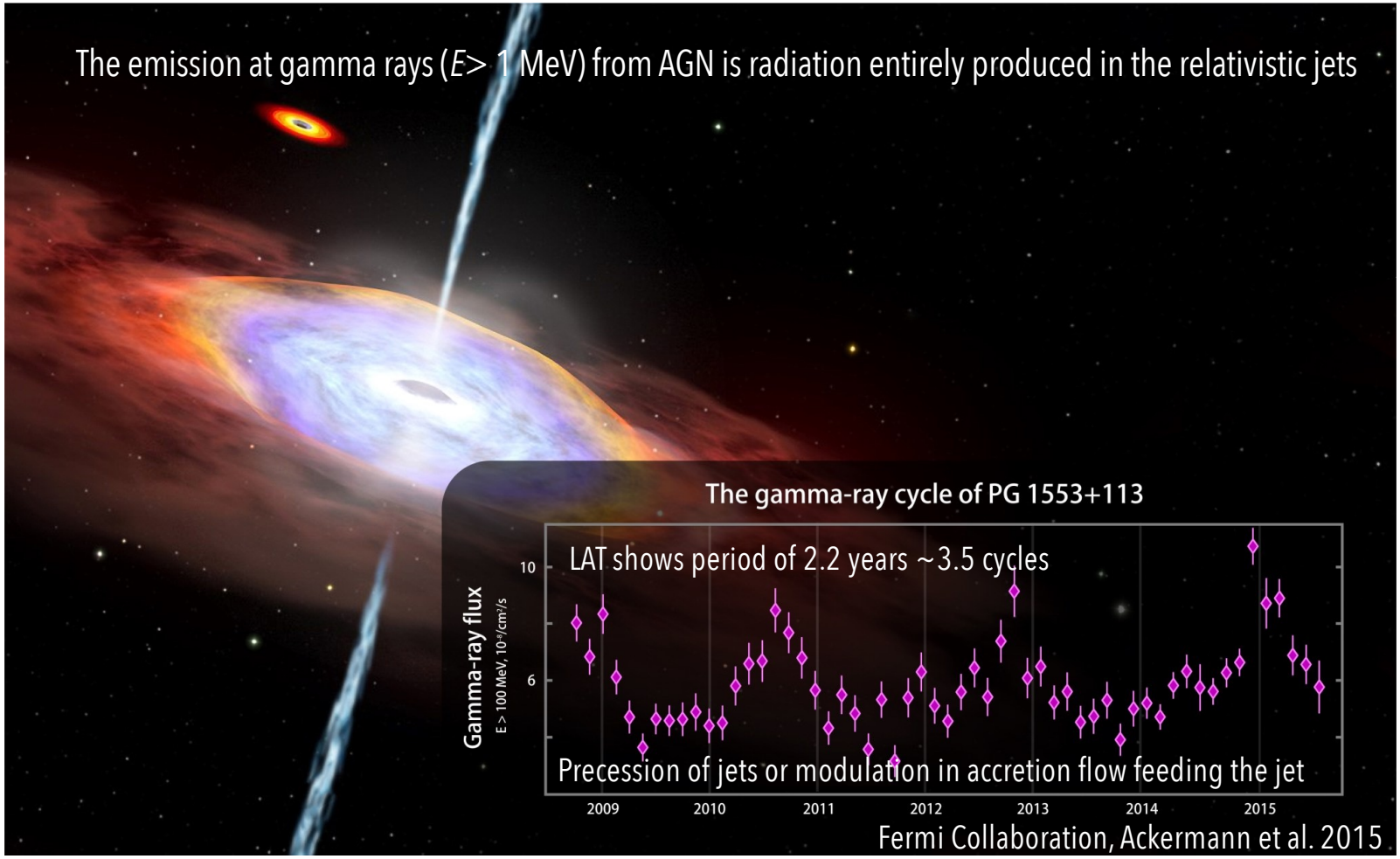
…revealing a candidate HLX!



Binary AGN interpretations from larger-aperture instruments need careful evaluation and further follow-up.
This is one of many examples where high spatial resolution in the X-ray band is extremely important.

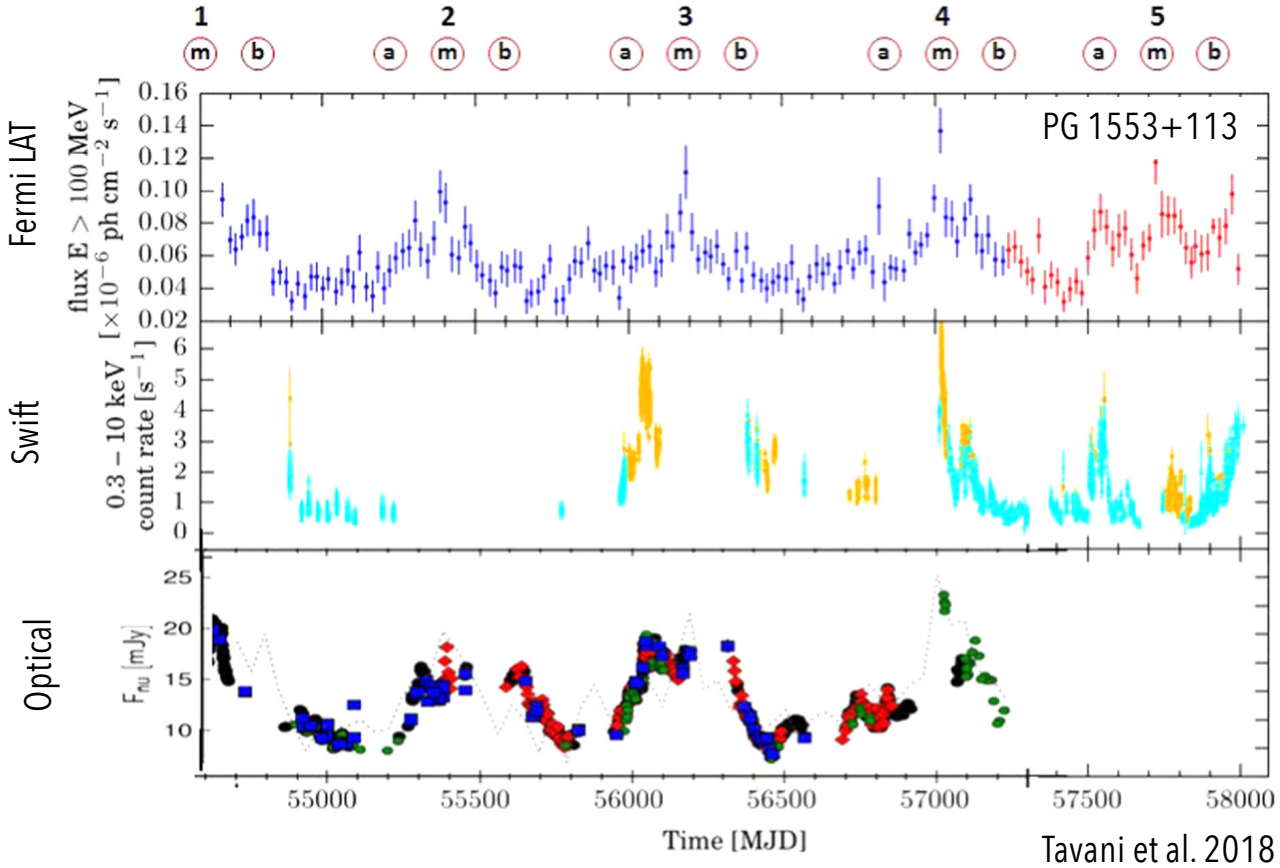
Foord, Civano, et al. 2024

Periodicity in Gamma-rays may be driven by a binary system



Periodicity in Gamma-rays may be driven by a binary system

The emission at gamma rays (E> 1 MeV) from AGN is radiation entirely produced in the relativistic jets



Tavani et al. 2018

The signature has been confirmed by many other works* (e.g.,Prokhorov & Moraghan 2017; Tavani et al. 2018; Sandrinelli et al. 2018; Covino et al. 2020; Peñil et al. 2020).

Optical fluxes claimed to correlate with gamma-ray emission shows evidence for similar modulation (e.g., Cutini et al. 2016; Sandrinelli et al. 2018; Covino et al. 2020, Agarwal et al. 2021)

*Caution has been stressed by many: Covino et al. 2019, Ait Benkhali et al. 2020, MAGIC Collaboration 2024

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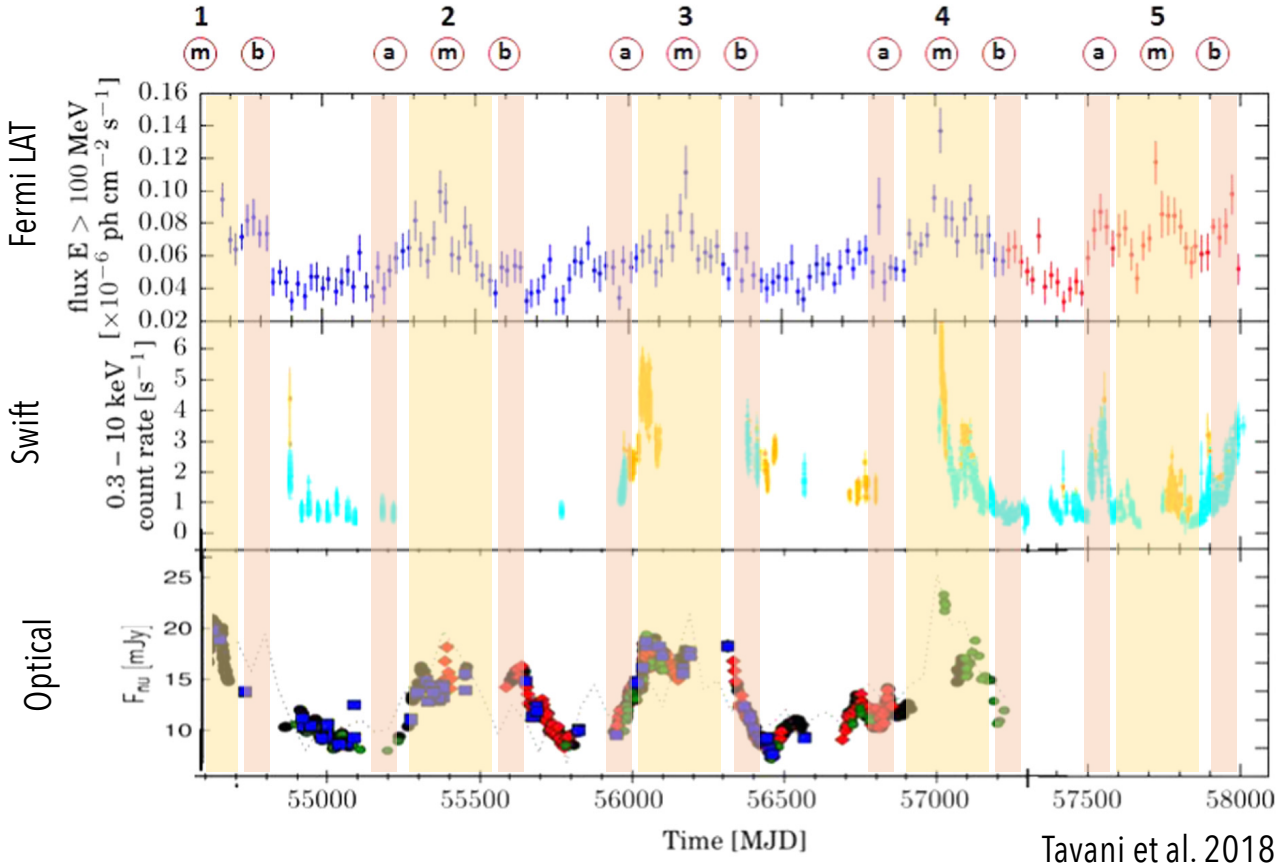

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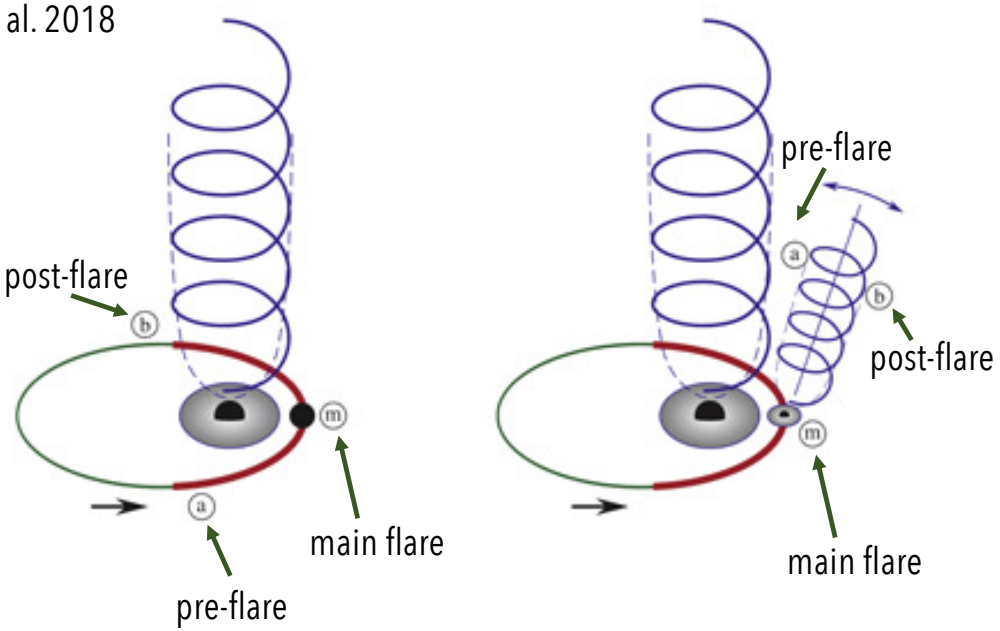

Main, pre-, and post-flares have been modeled as *dynamically* triggered evolution of the primary jet.

Large-scale MHD instabilities are triggered by the varying gravitational force exerted by the *secondary BH*

The smaller BH periodically stresses the primary's jet, triggering MHD-kinetic tearing instabilities

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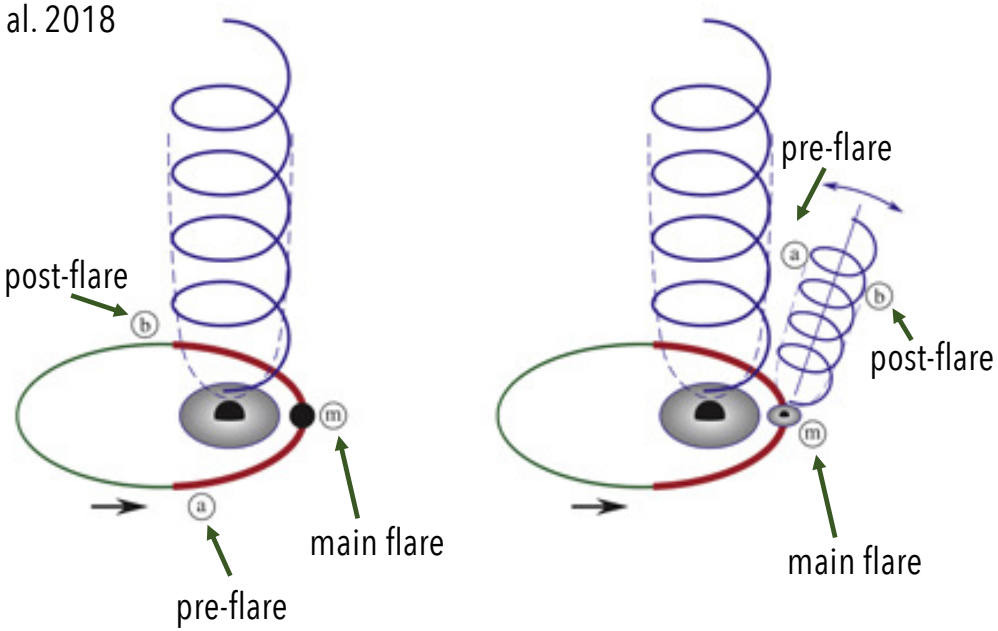

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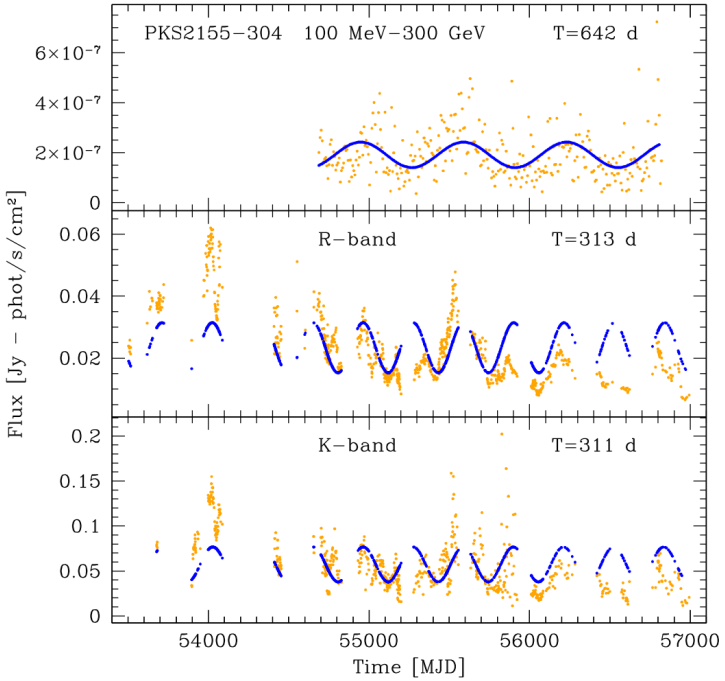
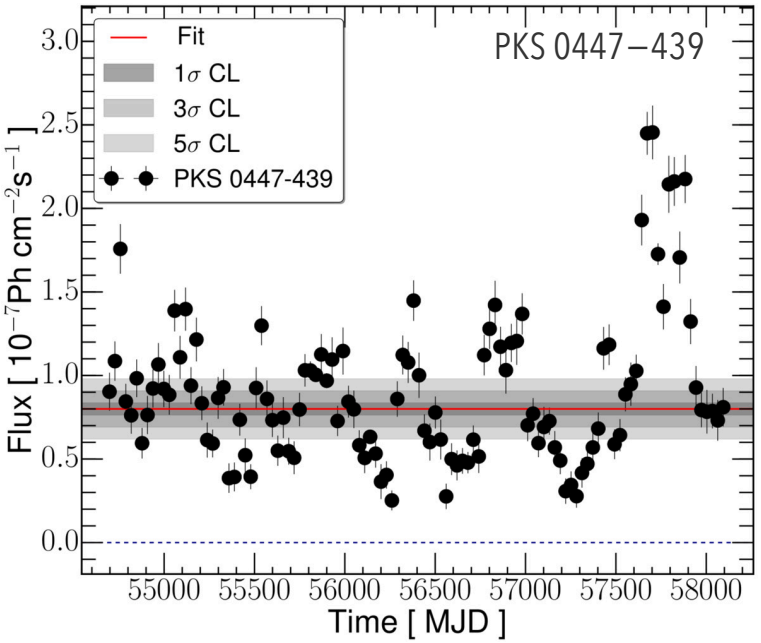
Both models leads to magnetic reconnections →accelerating electrons producing synchrotron emission from optical to X-ray bands →IC scattering into the GeV bands

Quasi-periodic variations in the Gamma-ray light curves of *Fermi*-LAT blazars

A handful of blazars (e.g., PG 1553+113, PKS 2155−304, PKS 0301−243, PKS 0426−380 and PKS 0537−441) have been reported so far to exhibit long-term quasi-periodic variability (aka QPVs)



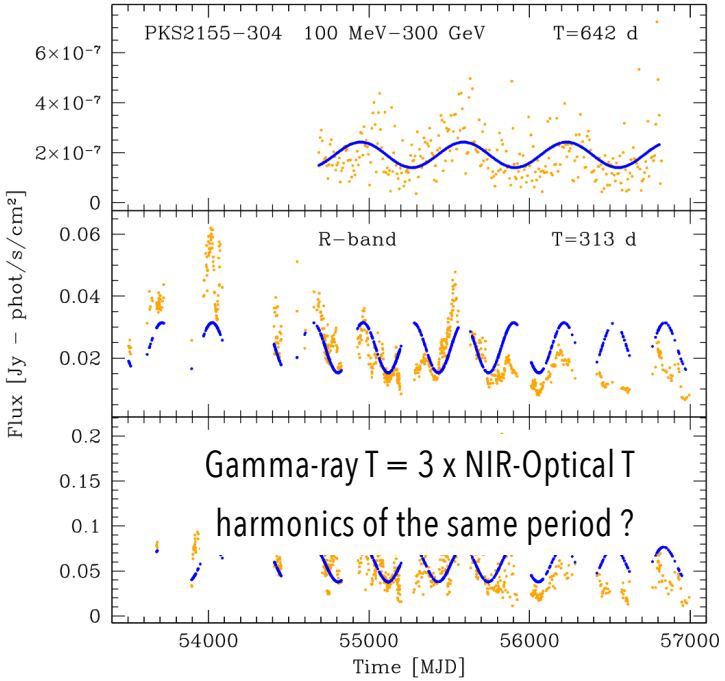
Sandrinelli et al. 2016



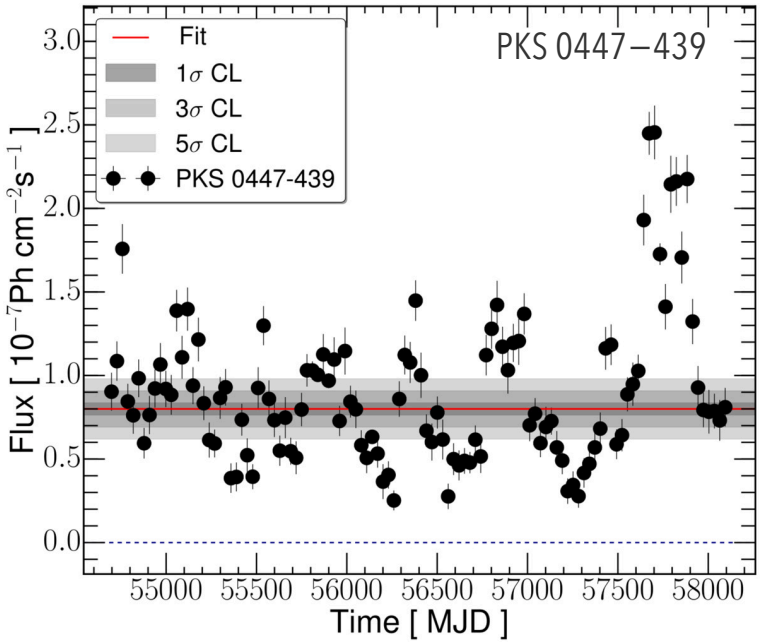
Ait Benkhal et al. 2020

Quasi-periodic variations in the Gamma-ray light curves of *Fermi*-LAT blazars

A handful of blazars (e.g., PG 1553+113, PKS 2155−304, PKS 0301−243, PKS 0426−380 and PKS 0537−441) have been reported so far to exhibit long-term quasi-periodic variability (aka QPVs)



Sandrinelli et al. 2016



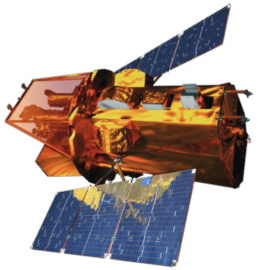
Ait Benkhal et al. 2020

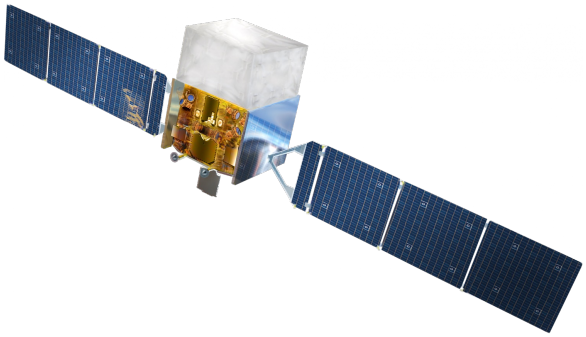
Thinking Forward: Multi-wavelength Monitoring

Current multi-wavelength searches are hampered by:

- Irregular sampling across various multi-wavelength observatories
- Frequency dependent red noise
- Various durations of monitoring constrain the minimum frequency that can be searched for
- Flares or period of high activity

Long-term, simultaneous monitoring of blazar light-curves (including optical, X-ray, and Gamma-rays) can better help identify supermassive black hole binaries.





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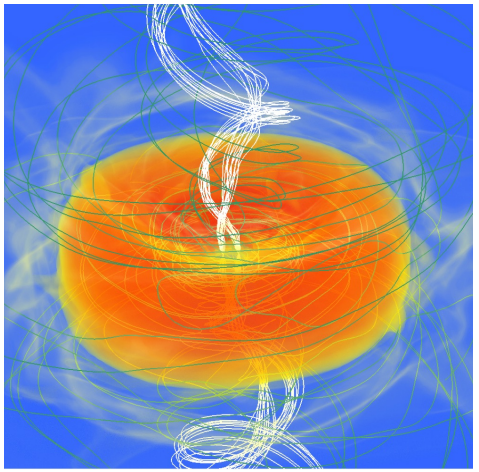
In the post-merger phase, numerical simulations show relativistic jets can be launched by the new spinning SMBH, which may spark gamma-ray emission (e.g, Gold et al. 2014).

Advanced localization of the binary by LISA weeks to months prior to merger to a few square degrees on the sky can enable a measurement of this EM event



Conclusions

Dual and binary AGN are believed to be natural consequences of galaxy mergers, but relatively few have been confirmed.

High-energy observations are a great way to find more candidates: dual AGN can be resolved by high-resolution X-ray telescopes (Chandra, future: AXIS); binary AGN candidates can be flagged by both periodic X-ray and Gamma-ray (specifically for blazars)

Multi-wavelength evidence can help make a strong argument for any binary AGN indirectly detected.

For the Gamma-ray community: Long-term, simultaneous monitoring of blazar light-curves (including optical, X-ray, and Gamma-rays) can better help identify supermassive black hole binaries.

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