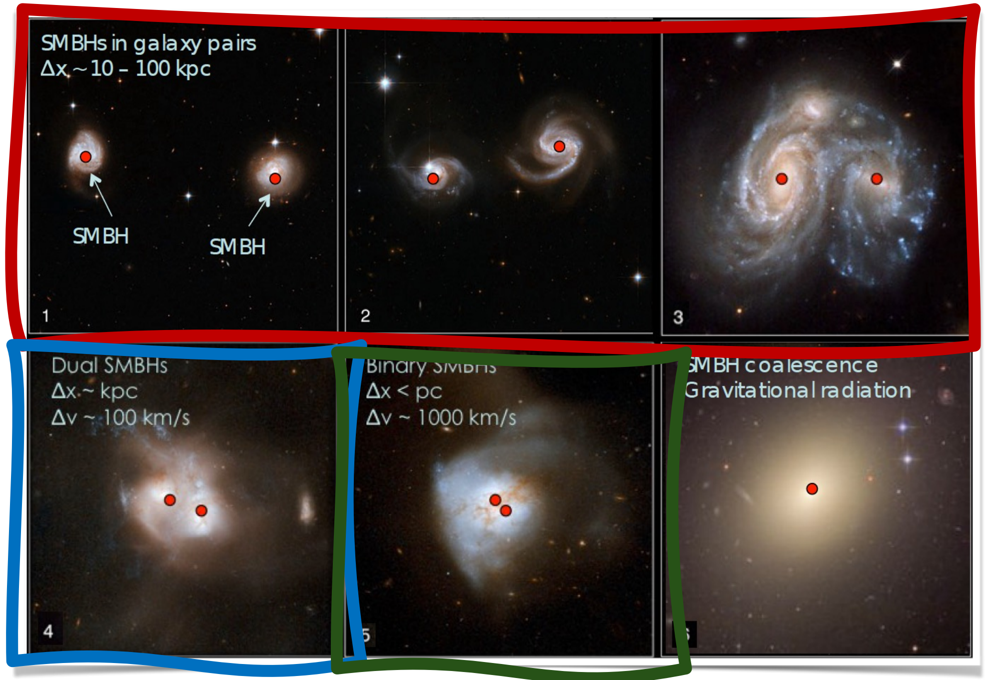
Dual & Binary Active Supermassive Black Holes

Cristian Vignali
(Physics and Astronomy Department 'Augusto Righi', University of Bologna)
in close collaboration with P. Severgnini (INAF Brera),
A. De Rosa (IAPS Roma), and F. Mannucci (INAF Arcetri)

Outline of the talk

- Scientific case: dual and binary AGN, and their role in galaxy evoltuion
- Dual AGN in early stages of merger: detection and properties, link with obscuration
- Dual AGN in late stages of merger: detection and properties
- Binary AGN: radio imaging vs. general (indirect) methods. Potentialities of X-rays



Dual AGN ($M_{BH}>10^5\ M_{sun}$):
sep.: several/tens kpc down to (sub)-kpc
(**early** and **late** stage of galaxy merger)

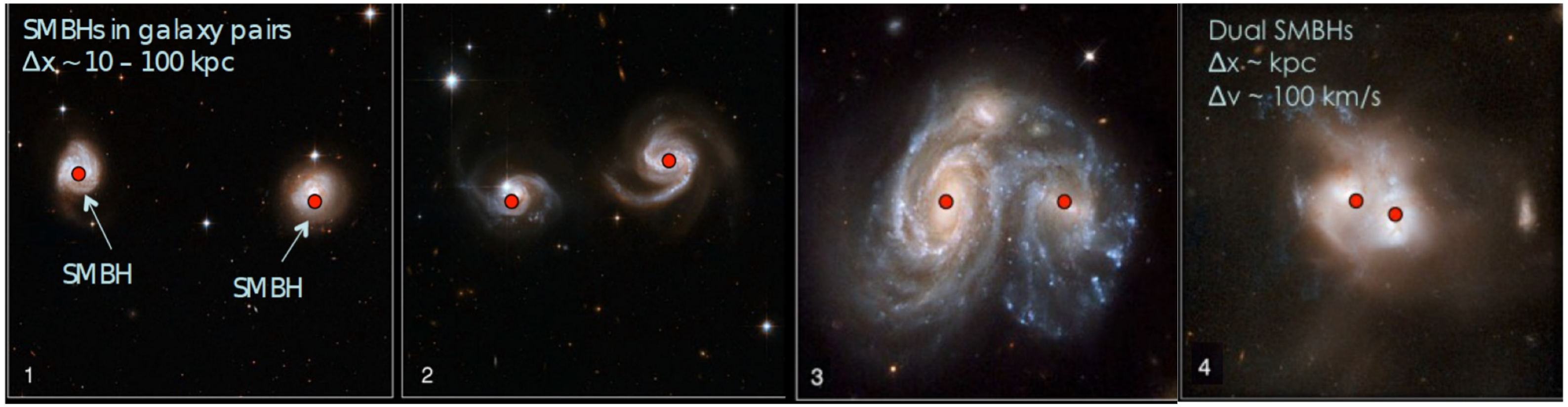
Binary AGN: gravitational bound SMBHs
(pc/sub-pc sep., post-merger galaxy)

Coalescence: the two SMBHs
merge, producing a single black hole

Scientific case: dual and binary AGN

OBSERVATIONS: Super massive black holes (SMBH, $M_{BH}>10^5\ M_{\odot}$) reside at the centers of most of the galaxies [e.g., Kormendy & Richstone 1995; Ferrarese & Ford 2005; Vestergaard & Peterson 2006; Kormendy & Ho 2013; Savorgnan+16]

SMBH PAIRS are the **natural consequence** of the current **hierarchical models** predicting galaxies evolve mainly through merger



THEORETICAL MODELS & SIMULATIONS

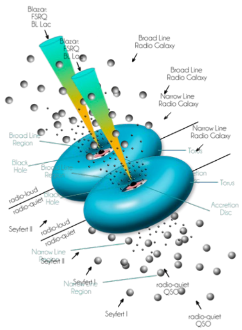
Major galaxy merger → efficient mechanism to remove angular momentum and drive large-scale gas inflows toward the nuclear regions of galaxies → triggering nuclear activity and star formation

[Olson & Kwan1990; Barton+00; Kauffmann & Haehnelt 2000; Nikolicet+04; Di Matteo+05; Kewley+06; Van Wassenhove+12; Blecha+13; Capelo+15; Goulding+18; Blumenthal & Barnes 2018; Volonteri+22]

→ Active SMBH
kpc/sub-kpc relative separations

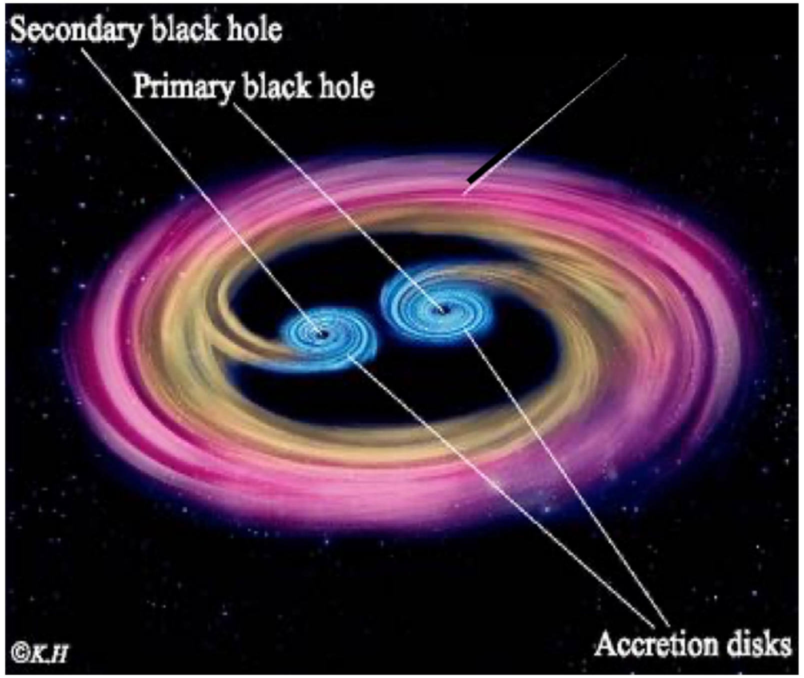
DUAL AGN (Active Galactic Nuclei)

Scientific case: dual and binary AGN

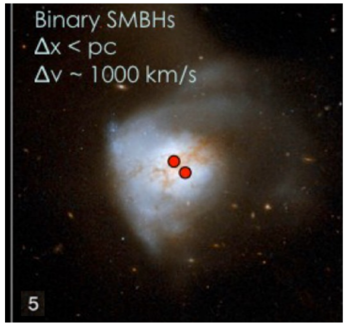


After the dual phase

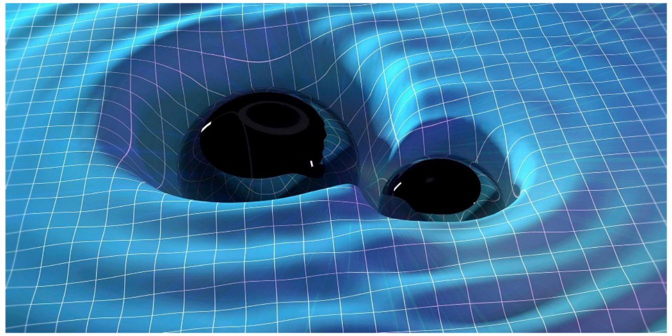
The two AGN are dragged towards the center of the remnant galaxy [Begelman+1980] thanks to the dynamical friction caused by the stars and gas



Binary AGN: gravitationally bound SMBHs (pc/sub-pc separation, post-merger galaxy)



Orbital phase: may produce continuous GW in the low-frequency range (Pulsar Timing Array - PTA)



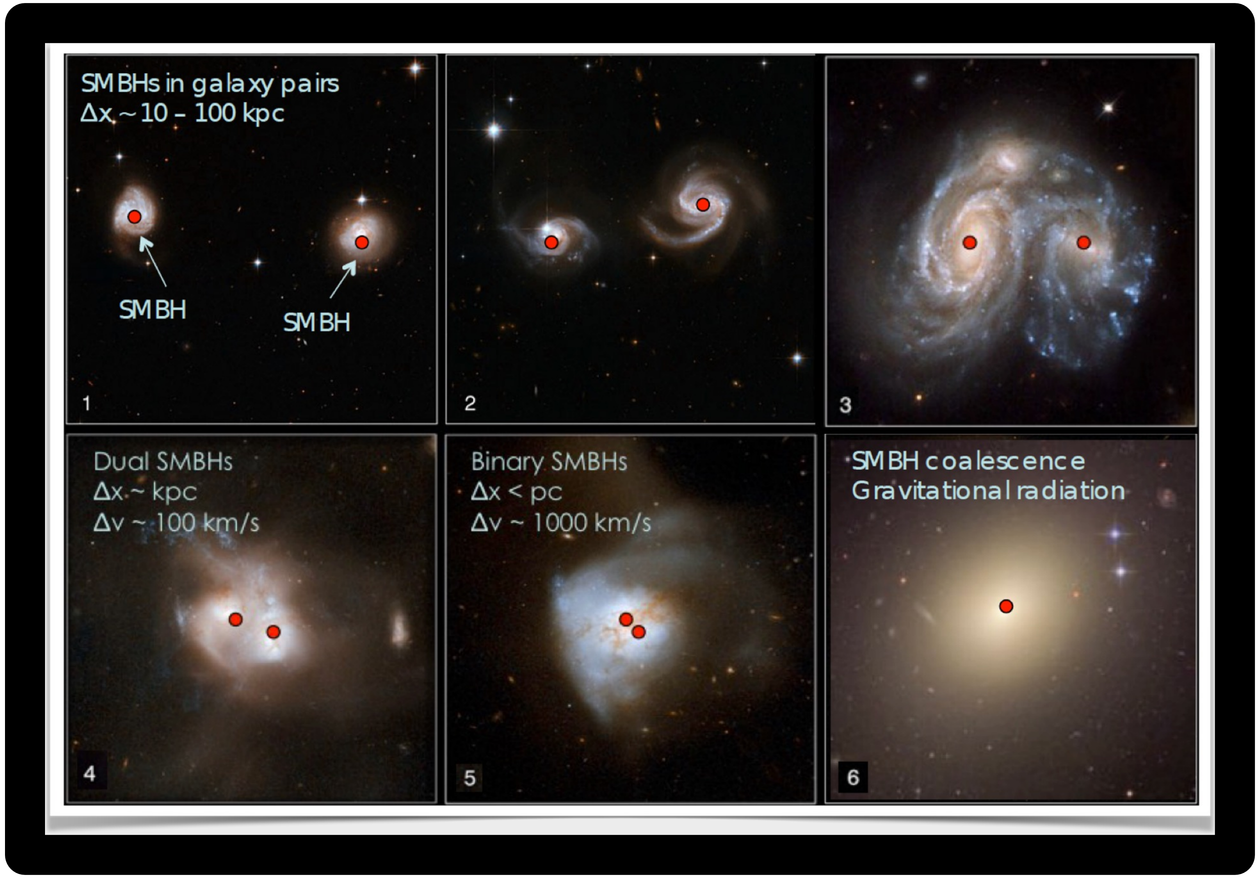
Coalescence: the two SMBHs merge, producing a single black hole and emitting impulsive GW (LISA, LGWA)

adapted from Burke+18

The importance of dual and binary SMBH studies

- High relevance in understanding SMBHs formation and evolution, and galaxy-SMBH (including the active, AGN, phase) co-evolution

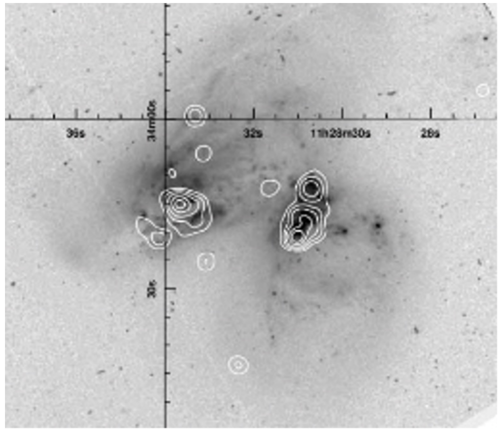
- Binary SMBHs are expected to be amongst the loudest emitters of gravitational waves (GWs) in the low-frequency ranges with great relevance for GW experiments (PTAs, LISA, LGWA, ET), depending on the BH mass range



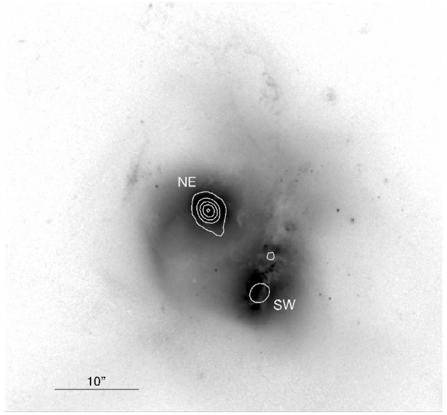
Dual AGN in the local Universe

Mostly have been identified serendipitously through optical and X-ray observations

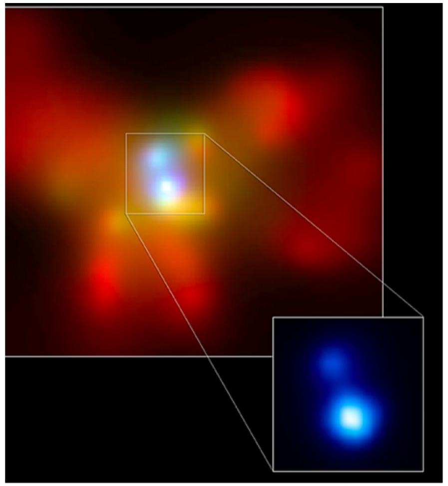
[e.g., Komossa+03; Ballo+04; Piconcelli+05, Guainazzi+06; Bianchi+08; Koss+11,22; McGurk+11; Iwasawa+18; Preifle+19; Foord+19,20; Hou+20; Gross+22]



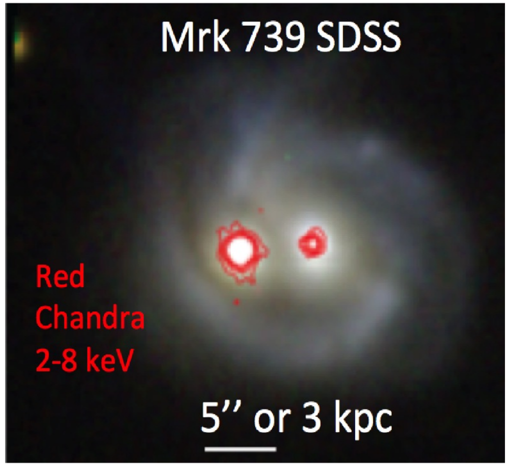
Arp299 (Ballo+04)
z=0.001
HST WFPC2 image + Chandra contours
Proj. sep. ~ 4.5 kpc (22'')



Mrk 266 (Iwasawa+20)
z=0.027
HST WFPC2 image + Chandra contours
Proj. sep. ~ 6 kpc (10'')



NGC6240 (Komossa+03)
z=0.024
Chandra color-image
Proj. sep. ~2 kpc (1.8'')



Mrk 739 (Koss+11)
z=0.03
SDSS image + Chandra contours
Proj. sep. ~3 kpc (15'')

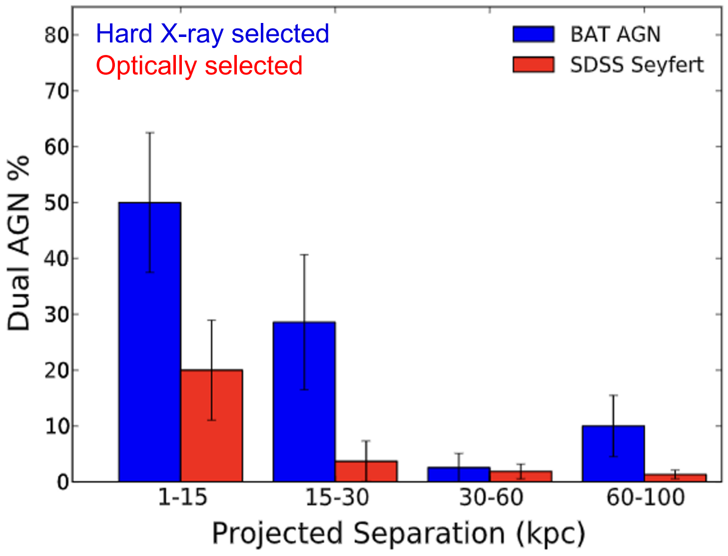
Challenges/problems:

- Not-complete selection/census → needs to recover the 'real' dual AGN fraction
- Observational biases (optical vs. near/mid-IR vs. X-rays)
- Follow-ups to further characterize the multi-wavelength AGN vs. host galaxy properties
- At which scales the nuclear activity is ON? For how long? Synergies with simulations, not always a clear answer

Dual AGN in **early** stages of mergers (kpc/tens of kpc)

Systematic searches started addressing statistical properties

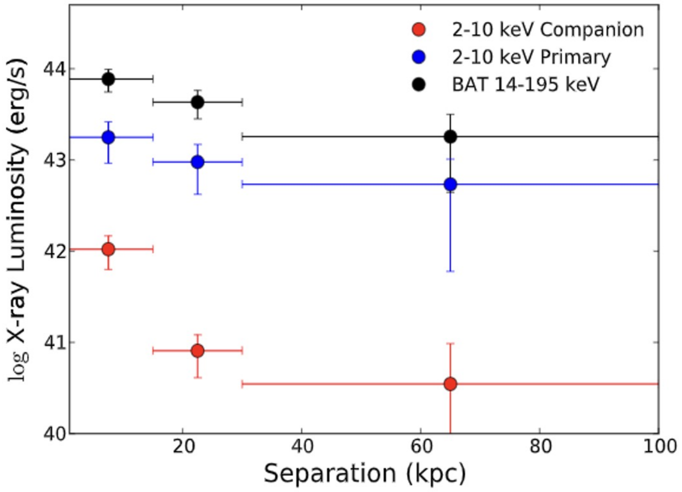
[see also Liu+11; Koss+12; Teng+12; De Rosa+15,18; Satyapal+17; Ricci+17,21; Pfeifle+19; Guainazzi+21]

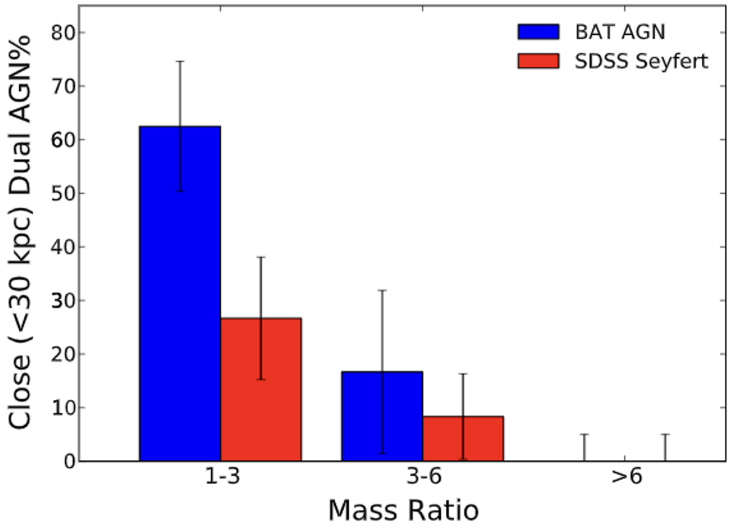


Dual AGN fraction increases at decreasing separation

[Koss+12]

Luminosity of both AGN increases at decreasing galaxy separation





Dual AGN are more likely to occur in major mergers

Dual AGN observations
- AGN luminosity increases at decreasing separations
- Merger may trigger more luminous AGN

Major merging events are key in powering dual AGN
but
the bulk of BH accretion has not been triggered by major galaxy mergers.
Alternative scenarios have been invoked like as secular or minor interaction processes
(e.g., Cisternas+11)

Dual AGN in **early** stages of mergers

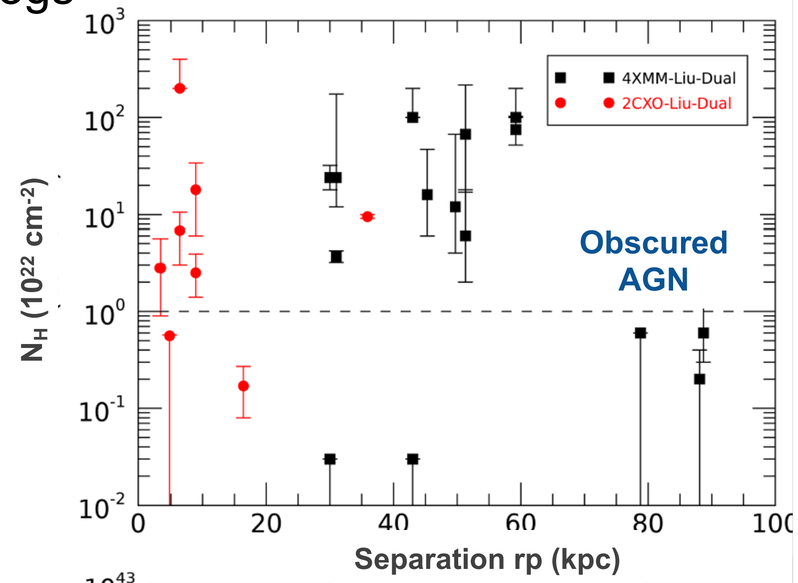
De Rosa+23: **multi-wavelength** (X-ray, mid-IR, BPT diagram) characterization of 26 X-ray emitting dual systems (i.e. 52 sources) from SDSS-selected AGN pairs at 3-100 kpc relative separations (Liu+11) − XMM-Newton (Webb+20) and Chandra (CSC2-Evans+10,20) catalogs

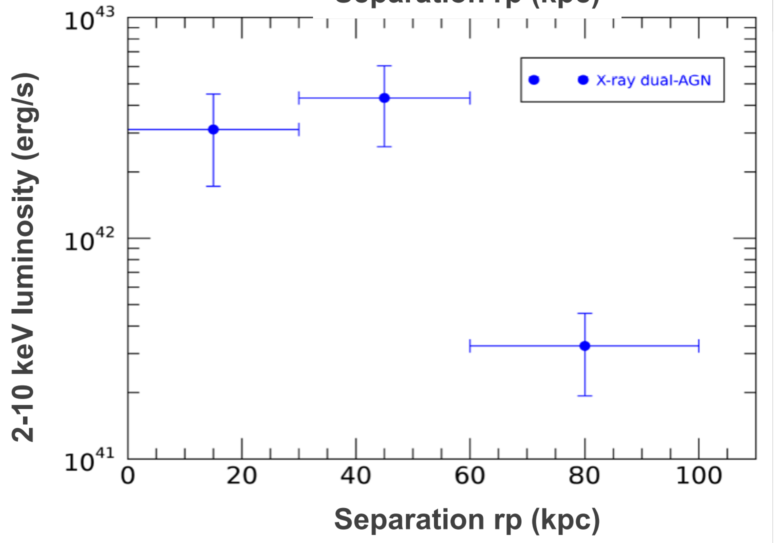
- ❑ Obscured fraction in dual AGN is ~80% (vs 45% in isolated BAT)
  → Pairs of AGN are more heavily obscured than isolated AGN

- ❑ Obscuration increases with decreasing separations
  → Gas is (efficiently) transported closer to the nuclear regions

- ❑ AGN luminosity increases with decreasing separations
  → Merger may trigger more luminous AGN

Overall, good agreement with simulations and model predictions (e.g., Blecha+18)

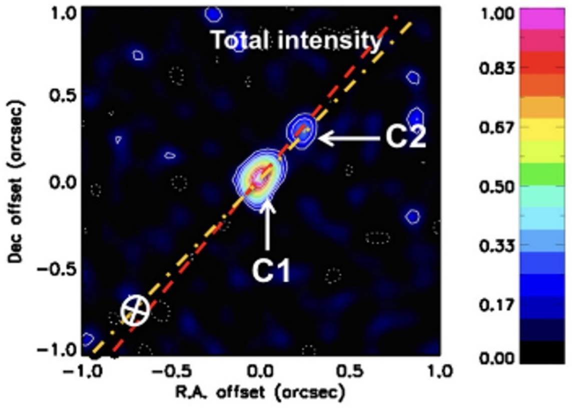




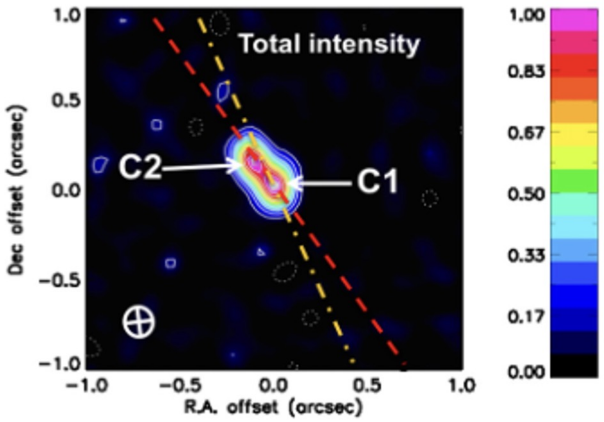
[De Rosa, Vignali, Severgnini et al. (2023)
see also Guainazzi+21; De Rosa+15,18, 19 review]

Dual AGN in **late** stages of mergers (kpc/sub-kpc)

Very few confirmed kpc/sub-kpc dual AGN in the Local Universe, and limited number of systems known with separations below ~6 kpc at z>0.5. **Very stringent angular resolution requirements are required**



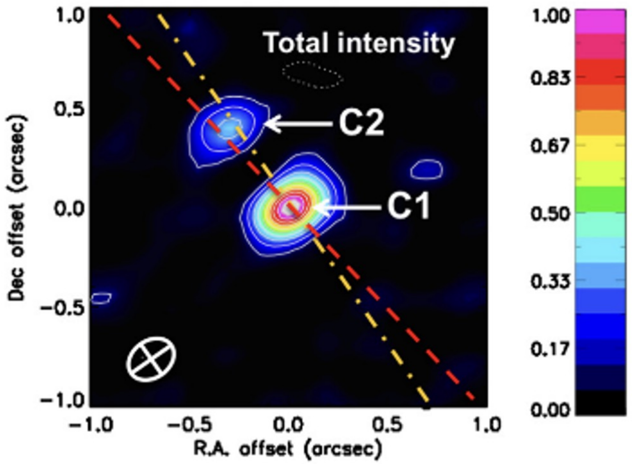
z=0.13, sep=0.6 kpc



z=0.17, sep=0.6 kpc

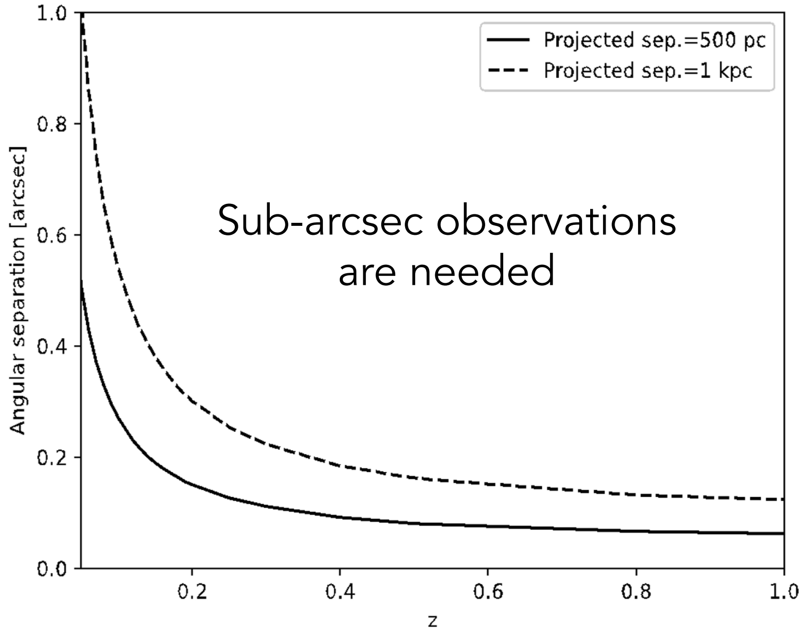
High resolution radio observations (VLA, VLBI)

Less than 10% of the **AGN** population are **radio emitting** [Kellermann+89]



z=0.19 sep=1.6 kpc

VLA images; Müller-Sánchez+15



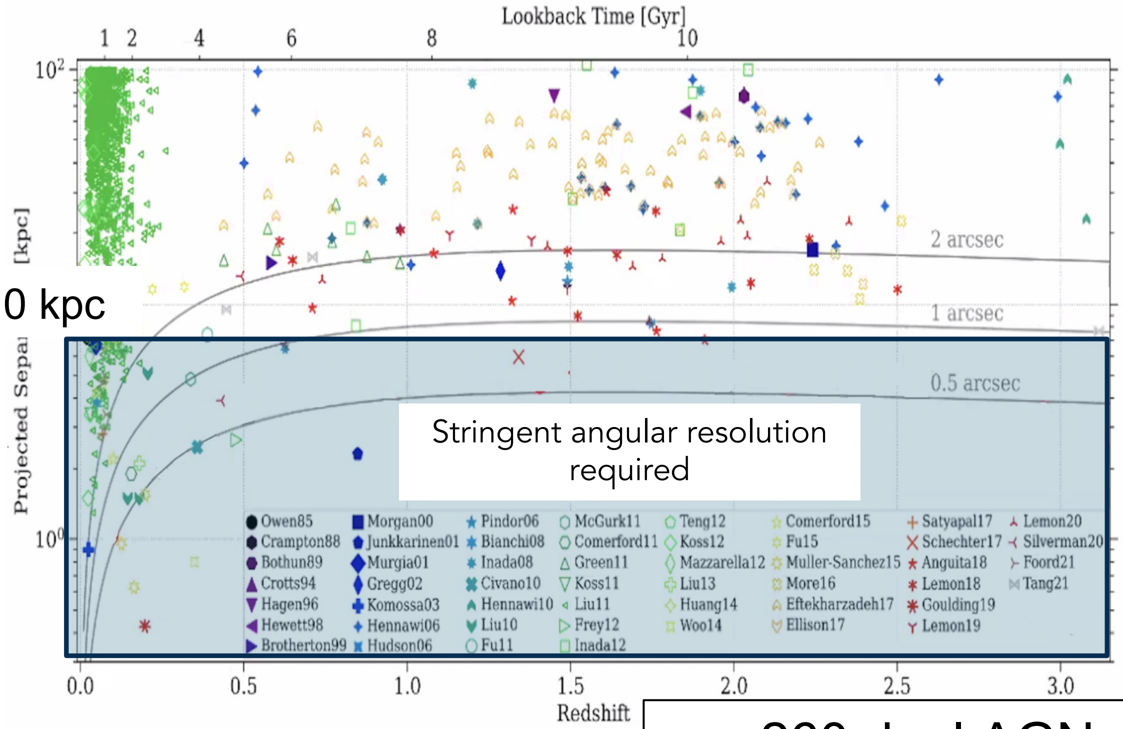
Radio-quiet AGN: sub-arcsec optical/NIR imaging mainly with AO systems and/or space-based observations – see the following slides

Dual AGN in **late** stages of mergers

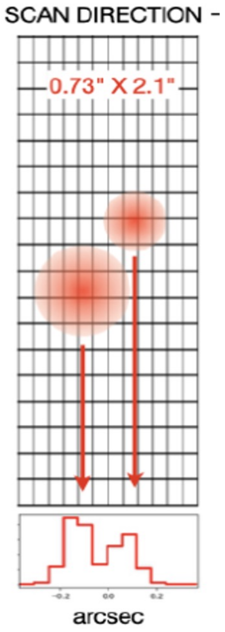
Different proposed methods using GAIA data: **Varstrometry, Multiplicity**
[Lemon+17,18; Agnello+18; Shen+19,21; Hwang+20; Chen+22, Gross+23, Wang+23]

GMP - The Gaia (EDR3) Multi Peak method

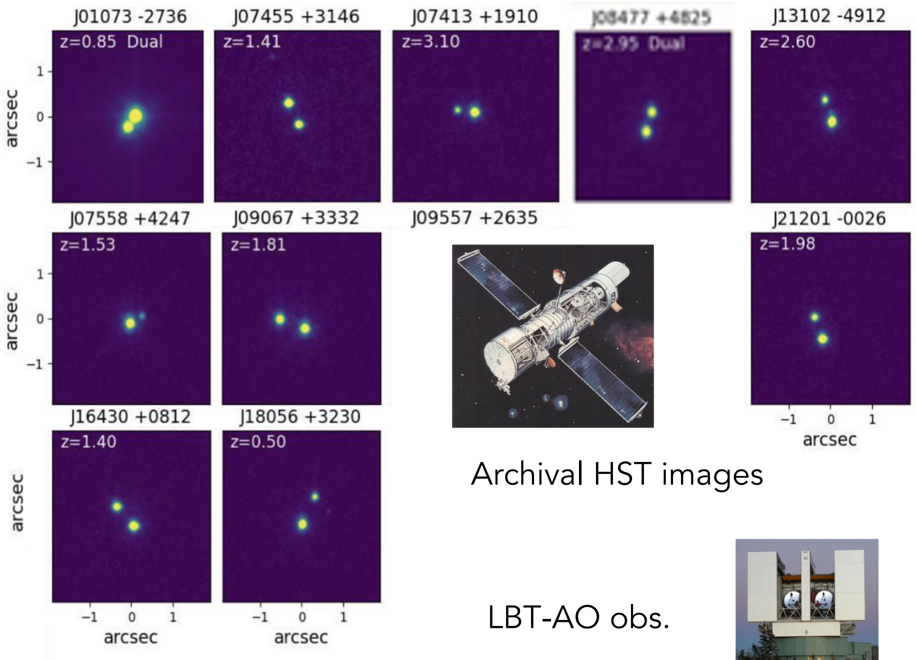
[Mannucci+22,+23; Ciurlo+23; Scialpi+24]
It selects all of the GAIA entries with a high probability of having a double profile in almost all scan directions



Adapted from Chen+22

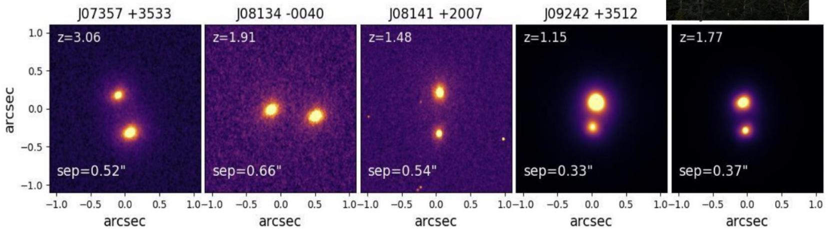


Exploiting excellent Gaia PSF in the scan direction (FWHM~0.11'')
G-band selection



Archival HST images

LBT-AO obs.



~260 dual AGN candidates
0.15''<sep<0.7'', 0.5<z<4

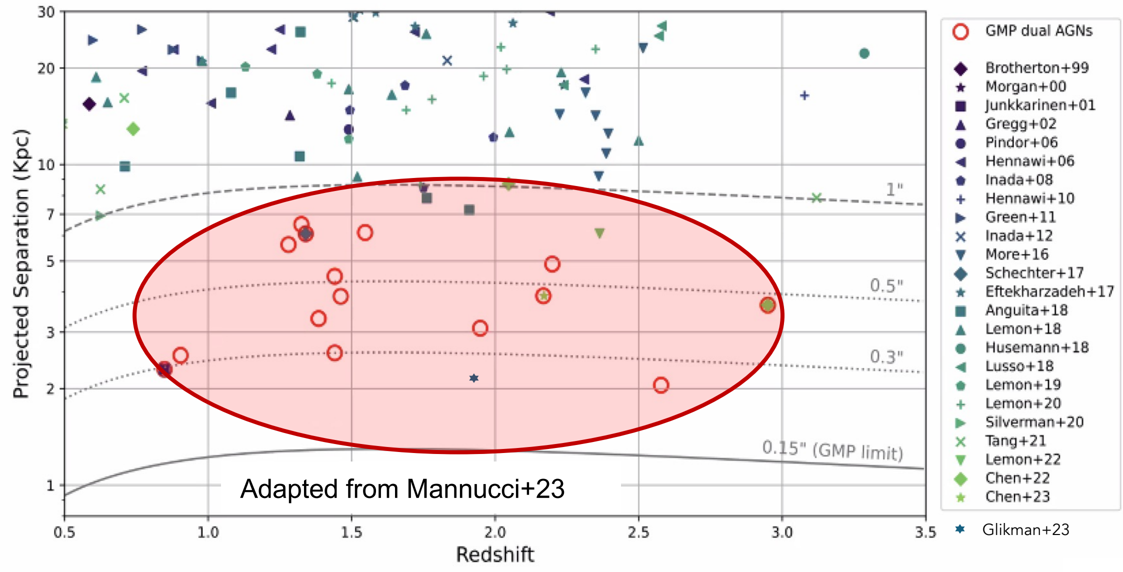
Possibilities: dual AGN/AGN vs. star/lensed syterm

Dual AGN in **late** stages of mergers

About 20 systems already observed spectroscopically

15 new dual AGN confirmed @z>0.5 & sep <7-10 kpc

Some more coming soon …



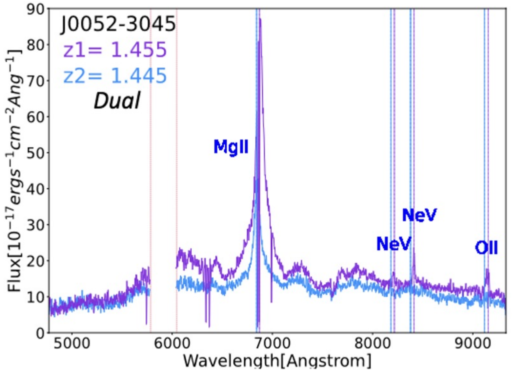
GMP method

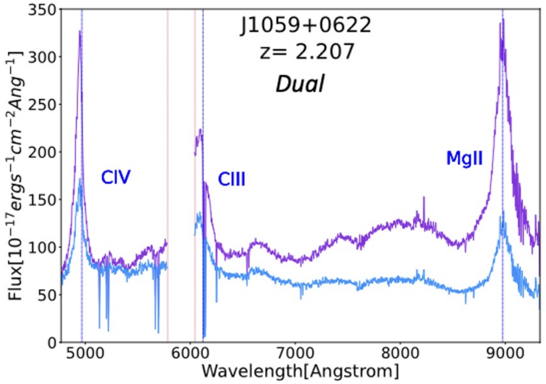
HST
STIS
slit/less
optical

Keck
OSIRIS
IFU
near-IR

VLT
MUSE-NFM
IFU
near-IR

VLT
ERIS
IFU
near-IR





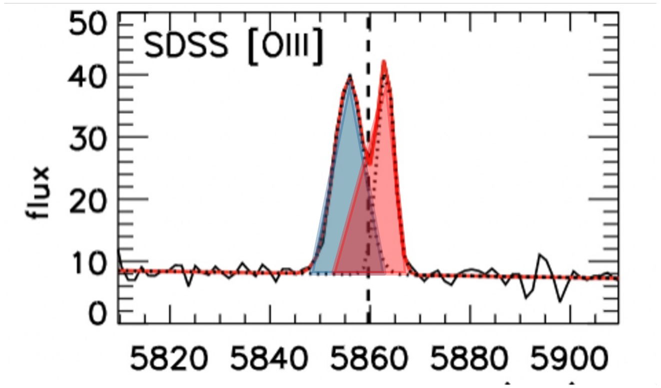
Filling the gap at closer separation & high z
Only for unobscured sources (Gaia selection)

Dual AGN in **late** stages of mergers

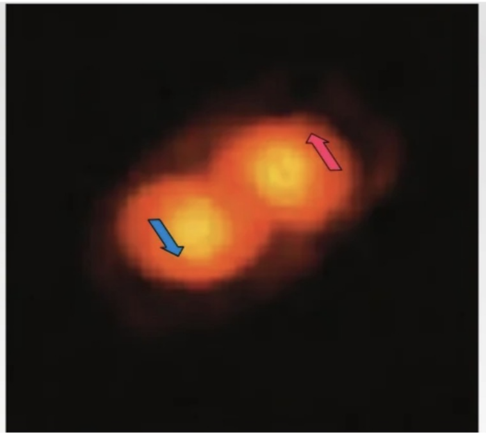
Double-peaked emission line AGN (DPAGN)

Double-peaked emission lines in the optical spectra have been used to select dual AGN candidates

Each AGN in a pair carries its own Narrow-line Emission Region tracing the relative velocity of the two AGN with respect to the systemic velocity of the host galaxy

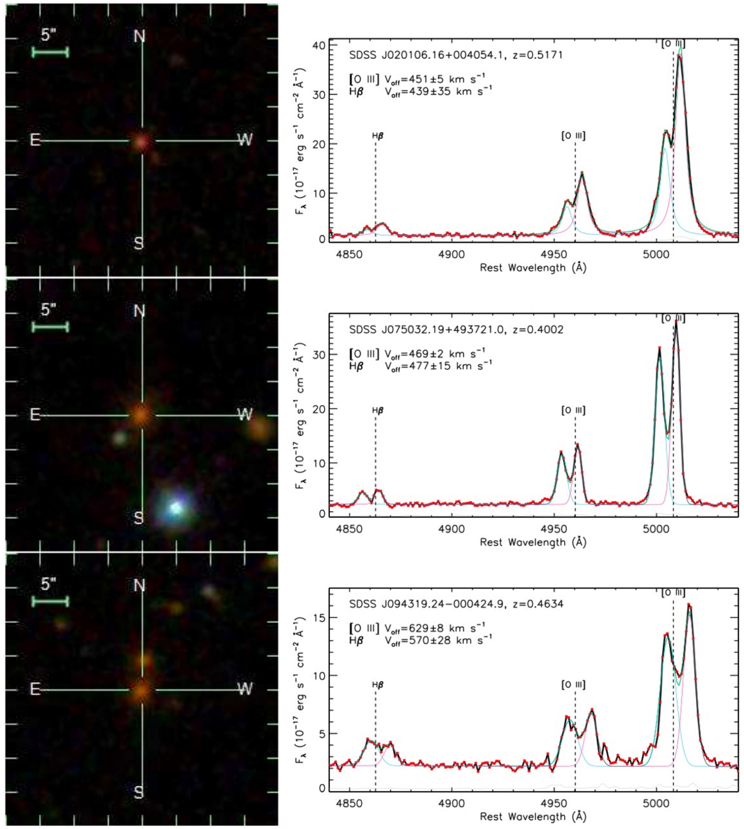


McGurk+15



Lame'e+11

About 1% of the SDSS AGN population exhibits double peaks in the high-ionization lines

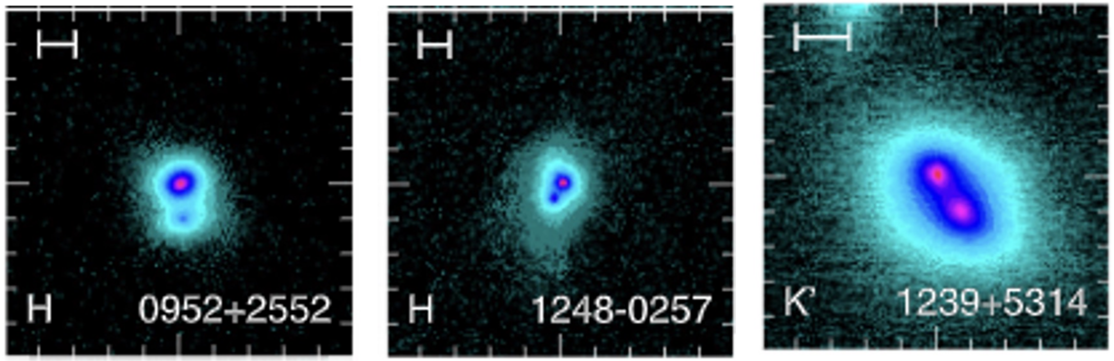


[e.g., Hennawi+06,10; Myers+08; Wang+09; Shen+10; Smith+10; Liu+10; Ge+12; Pilyugin+12; Barrows+13; Lyu+16; Sandrinelli+18; Lusso+18; Lena+18]

Dual AGN in **late** stages of mergers - DPAGN

BUT different kinematics effects could produce double-peaked: dual AGN, outflow or narrow emission region rotation of a single AGN

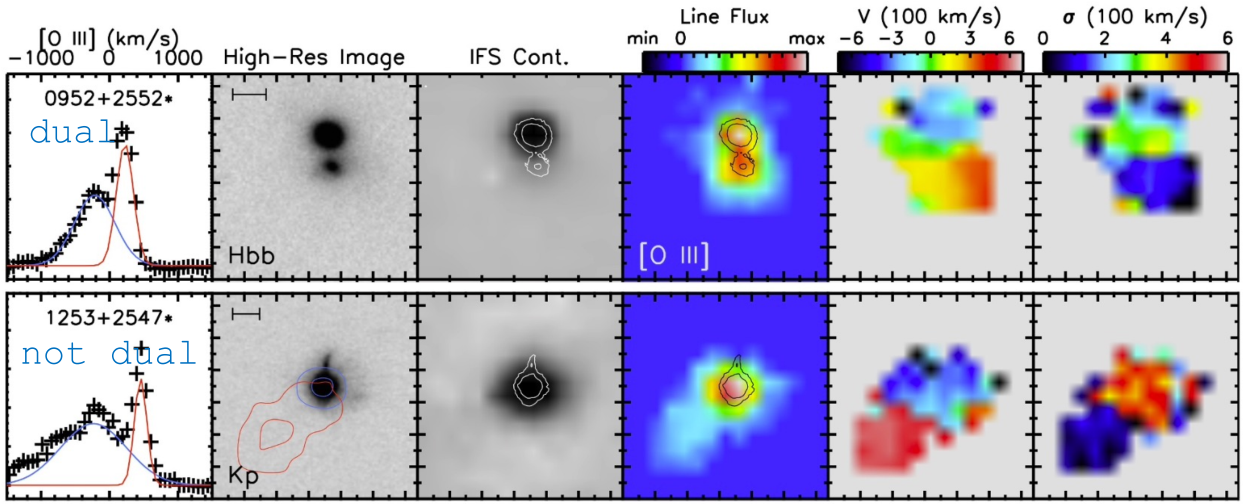
Follow-up high-spatial resolution imaging



Keck NIRC2 images. Scale bars mark 5 kpc at the z of the system

[McGurk+15]

Spatially resolved spectroscopy (IFU)



Only ~2% of double-peaked AGN has been confirmed as dual AGN

About an order of magnitude lower with respect to the model predictions (Volonteri+03)

This fraction may be significantly underestimated

[Severgnini+21]

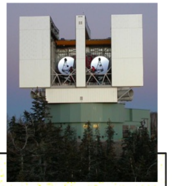
[e.g., Heckman+84; Whittle+05; Xu & Komossa 2009; Crenshaw+10; Rosario+10; Fu+11,12; Müller-Sánchez+11,+15; Comerford+12; McGurk+15; Gabányi+17]

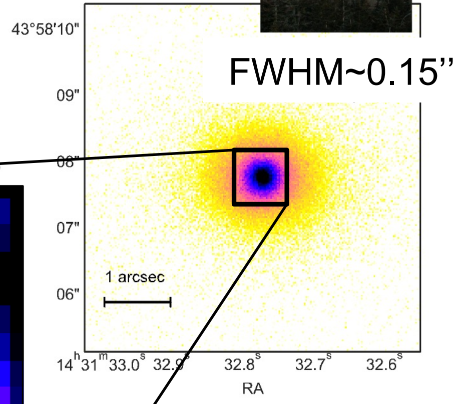
Dual AGN in **late** stages of mergers - DPAGN

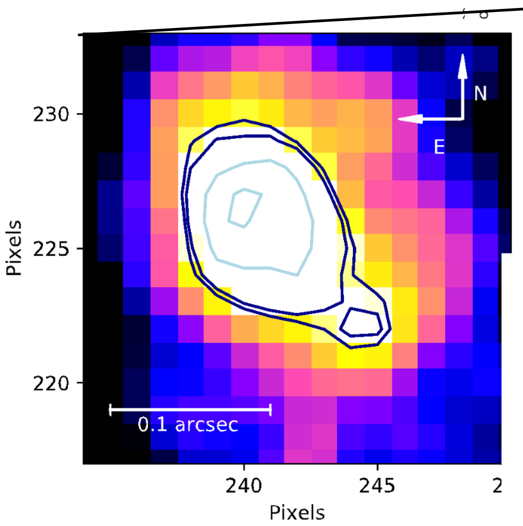
We may expect a large still poorly explored population of obscured AGN pairs

DPAGN selection, then

1. High-resolution imaging follow-up







SDSSJ1431+4358
Obscured dual AGN,
sep. ~0.4 kpc of sep.
[Severgnini+21]

2. Subtracting the host galaxy contribution using the 2-D fitting algorithm GALFIT (Peng+02,10)

Adopted strategy

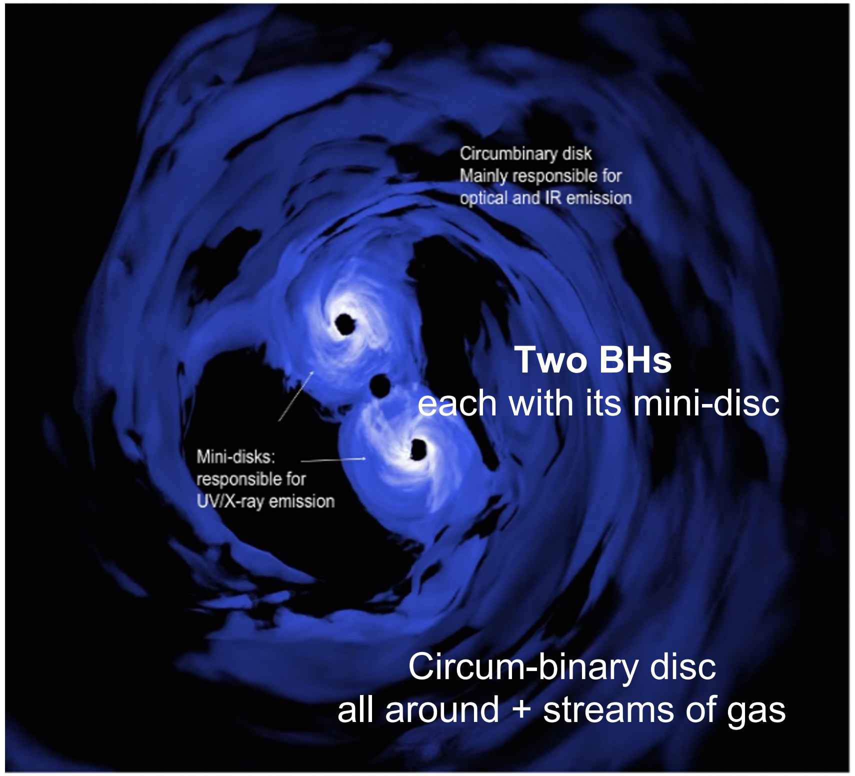
- ❑ High-resolution optical/near-IR imaging is mandatory
- ❑ The dominant contribution of the host galaxy must be properly subtracted
- ❑ Indications of a companion galaxy → follow-up (IFU spectroscopy?)

Binary SMBHs (pc/sub-pc scale)

Radio-loud systems:

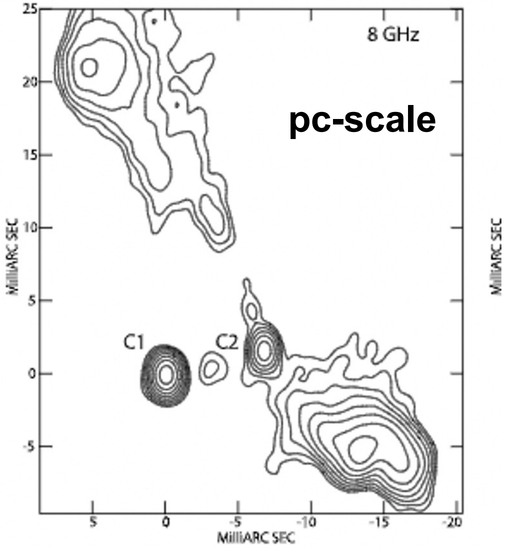
direct imaging, the power of high-resolution in radio interferometric observations

The framework: two BHs, each with its own mini-disc, one circumbinary disc

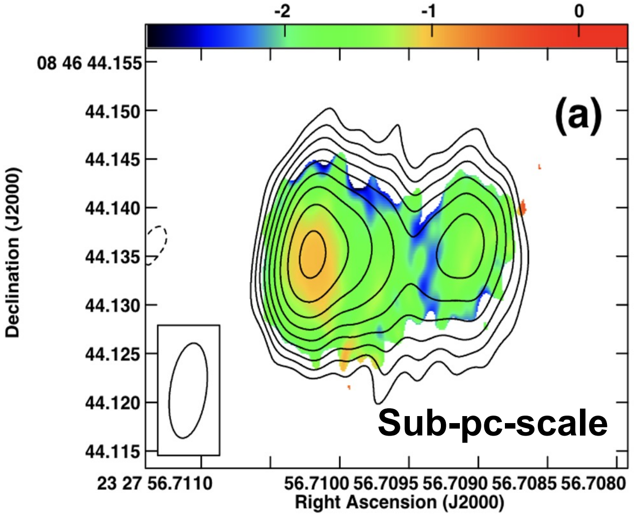


Resolved by high-resolution radio obs.
but see Burke-Spolaor (2011)

VLBA image of the radio galaxy 0402+379
z=0.055 - Proj. sep. ~ 7.3 pc (0.03'')
[Rodriguez+06]



VLBI 2−5 GHz spectral index image of the core of NGC 7674
z= 0.0289 - Proj. sep.=0.35 pc (0.0006'')
[Kharb+17]



Binary BHs:

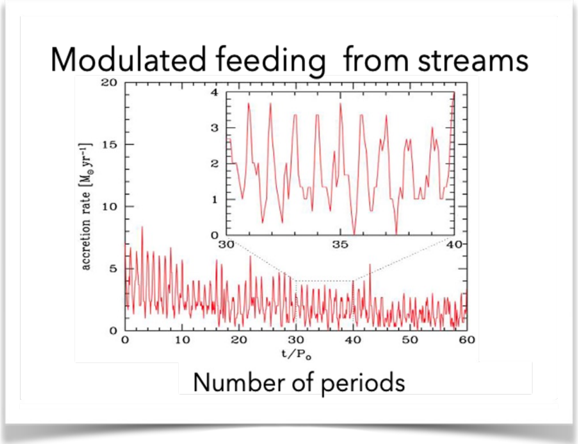
- time spent at close separations is low → deep and large-area surveys are needed
- the EM signatures are not ubiquitously associated with binary systems

Binary SMBHs

Radio-quiet systems:

Indirect methods: EM signatures of gas accretion onto the two SMBHs [e.g., De Rosa+19, Bogdanovic+21]

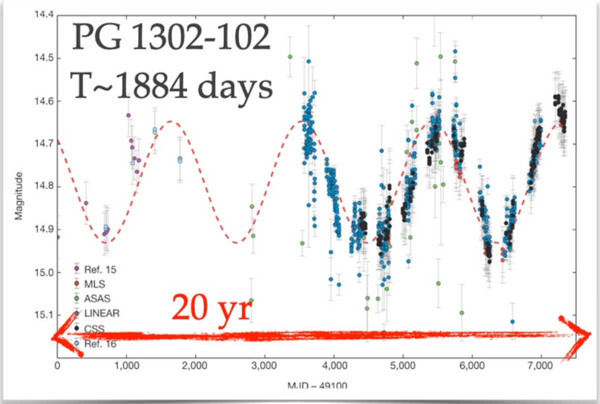
1. Periodic UV and X-ray emission related to the periodicity of the mini-disc (P_X~few months or less)



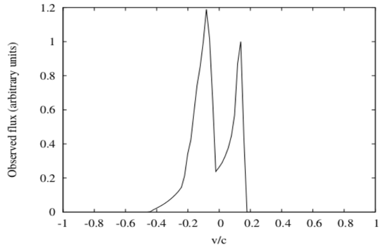
[Sesana+12]

2. Periodic optical emission related to the circumbinary disc (P_{OPT}~few years or less)

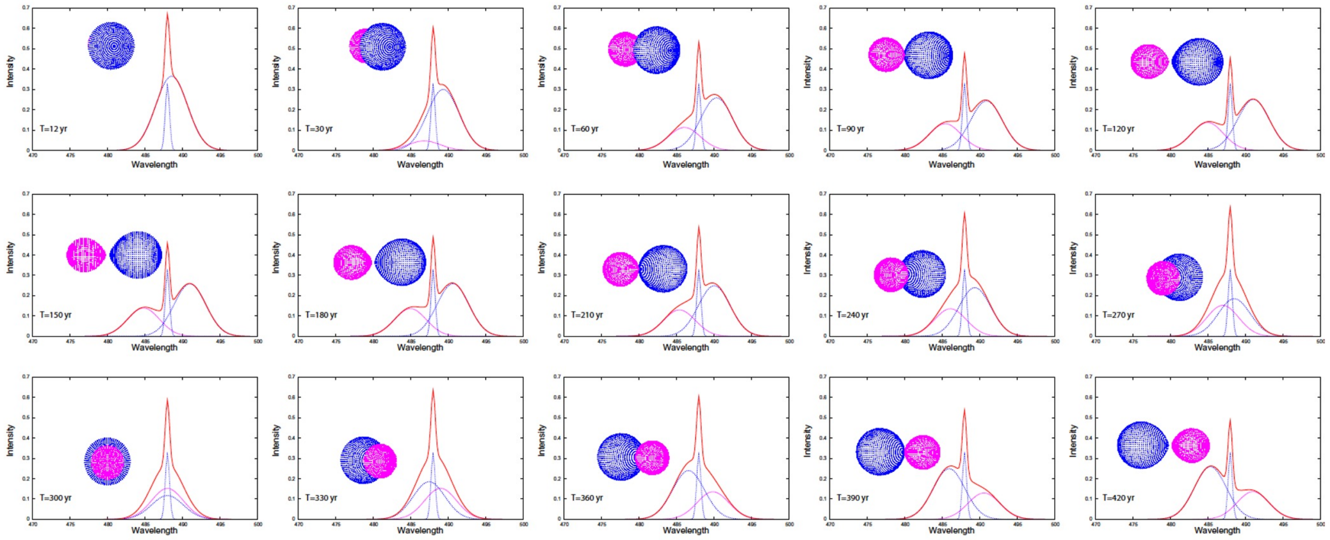
REQUIREMENTS: long-term monitoring facilities (e.g., Catalina Real-Time and Palomar Transient Survey)



3. Double and variable peaked broad emission lines in the X-ray and optical [Tanaka & Haiman 2009; Sesana+12; Popovic+12,21; McKernan & ford 2015]

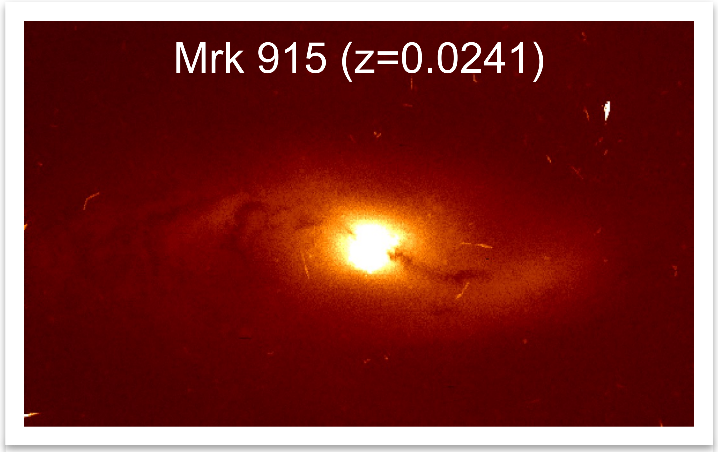


[Popovic+12]



[e.g.; Farris+15,17; Graham+15,18; Charisi+16,22; Tang+18; D'Orazio+18; D'Ascoli+18, Bowen+18; De Rosa+19; Bogdanovic+21]

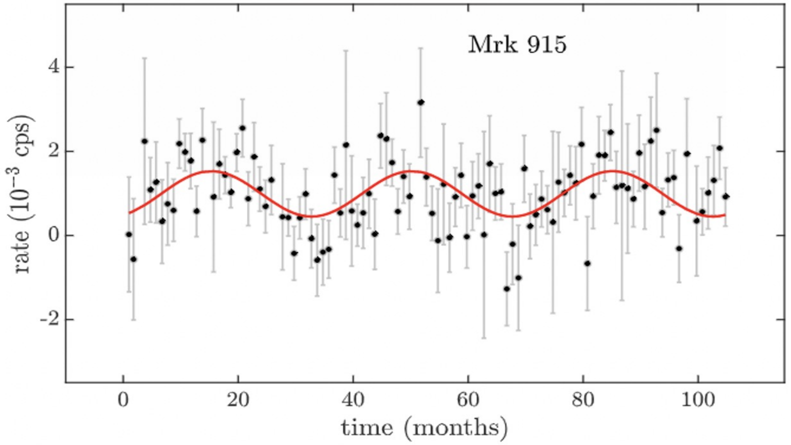
Binary SMBHs: potentialities of X-ray observations

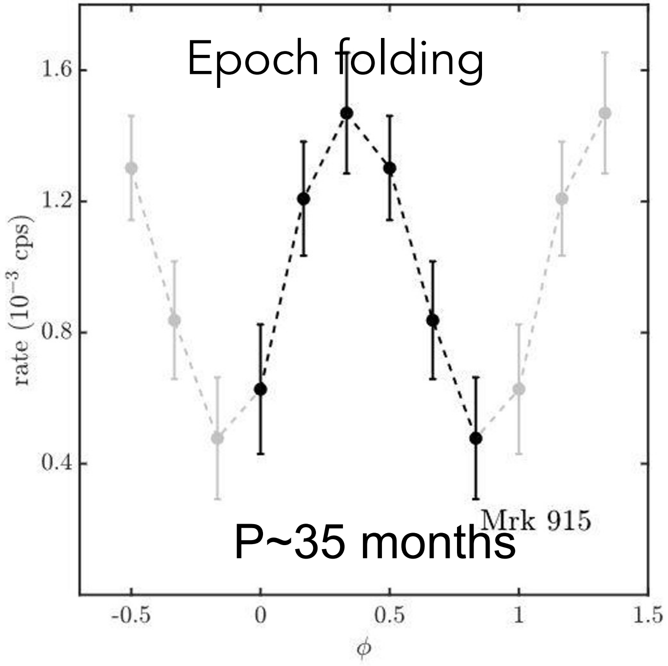


105-month BAT light curve catalogue
(14-195 keV)

⬇

Detection of X-ray periodic variability in the Swift-BAT light curve





Promising SMBH candidate
M_{BH}~10^8 $M_\odot$

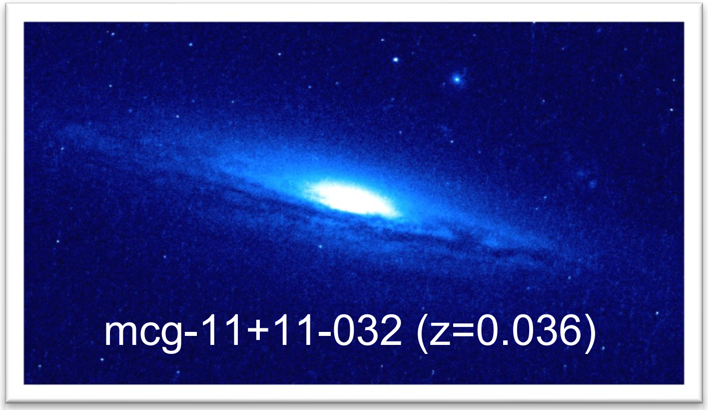
Sep~5×10^{-3} pc
T_{coal}~2 Myrs

$$T_{gw} = \frac{5c^5(1+q)^2a^4}{256G^3M^3q}$$ [Peters 1964]

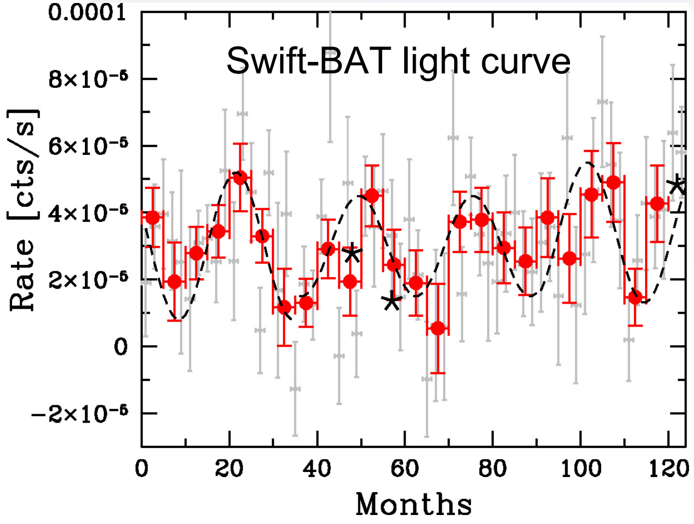
[Serafinelli+20, Severgnini+22; Severgnini, De Rosa, Vignali et al. 2024]

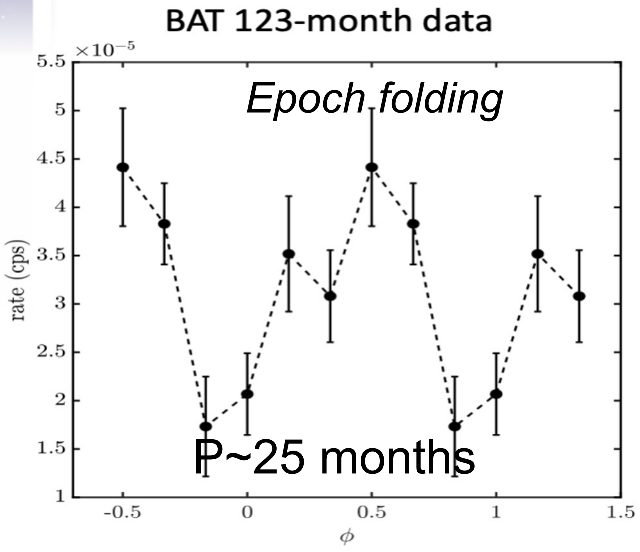
Binary SMBHs: potentialities of X-ray observations

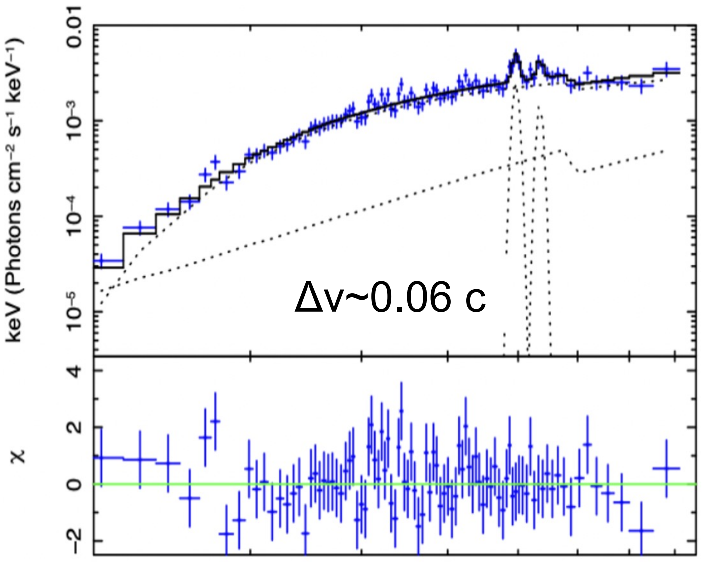
Detection of X-ray periodic variability in the Swift-BAT light curve
and of double broad Kα iron lines



Possible Doppler-shifted iron emission lines, reflecting high orbital velocities in a close binary





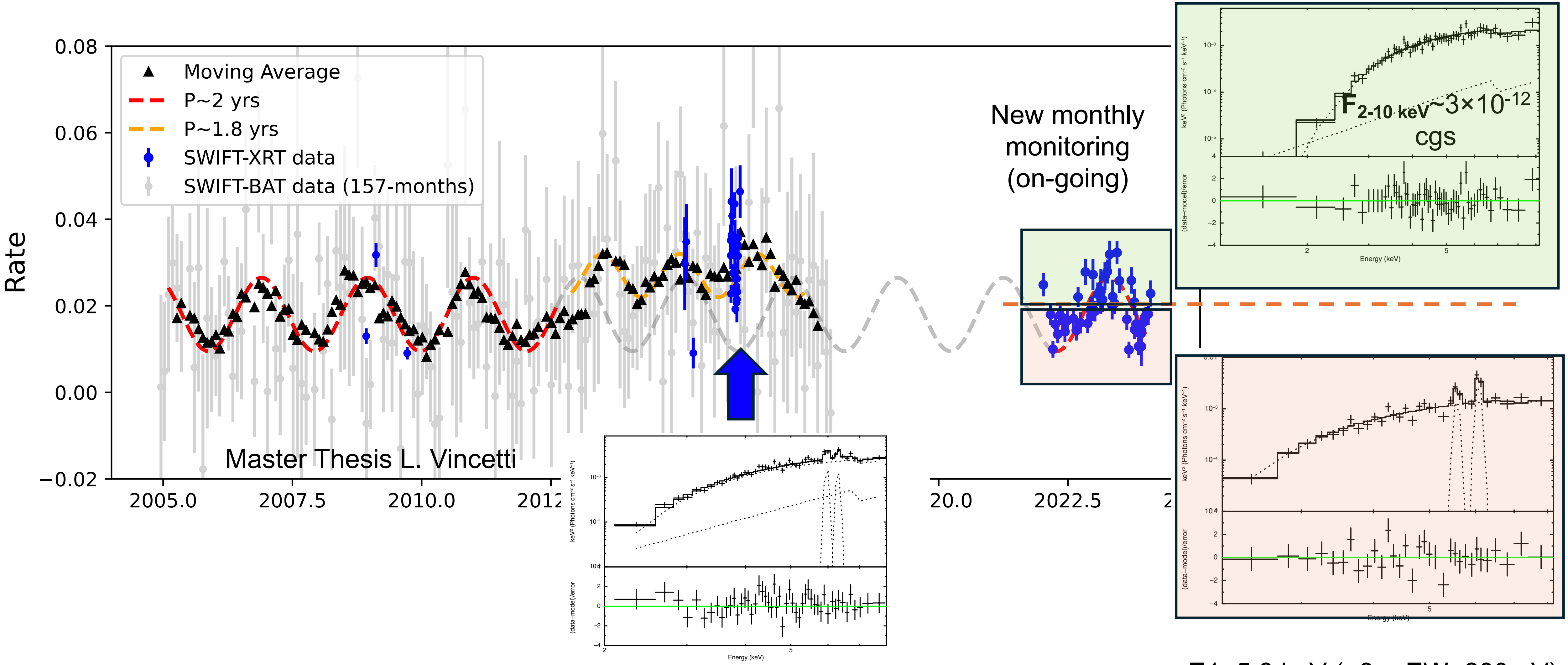


SMBH candidate
M_{BH}~5×10^8 $M_\odot$

Sep~6×10^{-3} pc
T_{coal}~3×10^4 yrs
Δv~0.06 c (relative velocity)

[Severgnini+18,+22, Serafinelli+20]

157-month BAT light curve + XRT data: preliminary resuts from the ongoing Swift monitoring



E1~6.16 keV (3σ, EW~120 eV)
E2~6.56 keV (2σ, EW~90 eV)
Δv (velocity offset)~0.06c
$F_{2\text{-}10\ keV}$~4.3×10^{-12} cgs

E1~5.8 keV (<3σ, EW~200 eV)
E2~6.3 keV (3σ, EW~350 eV)
Δv~0.06c
$F_{2\text{-}10\ keV}$~2.3×10^{-12} cgs

Summary

- ❑ We are starting to set some statistical properties for **dual AGN in early stage of merger**
  - SMBH growth seems to be powered by the merger process
  - Dual AGN found in environments where gas is transported closer to the AGN, producing obscuration in the nuclear regions (and triggering activity)

- ❑ Identification of **dual AGN in late stage of merger**
  - Comparison with models is still difficult, needs for enlarged samples also at high z (e.g., JWST; see Perna+24, Maiolino+24)
  - A novel technique - GMP method – provides the selection of low-obscuration pairs of AGN at kpc separations up to high z and to study their incidence
  - Many (most?) obscured dual AGN are missed in the systematic searches conducted so far → their fraction largely underestimated. Need for high-resolution imaging and IFU spectroscopy

- ❑ **Binary AGN**
  - They could be unveiled through the presence of a double nucleus in radio-emitting systems and via X-ray/optical periodic variability + possibly double (broad) X-ray/optical emission lines. Some promising candidates in X-rays (expected to GW at nano-Hz).