

Gravitational waves, dual and binary black holes

Alessandra De Rosa



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Most of the content in this presentation is based on the exceptional work of a group of people, and it is supported by the *INAF Bando Ricerca Fondamentale - Large Grants 2022 and 2024*.

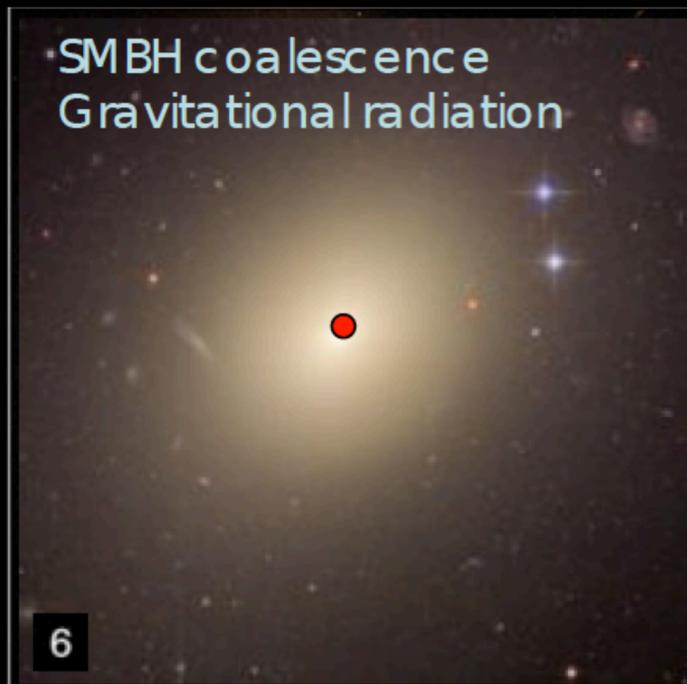
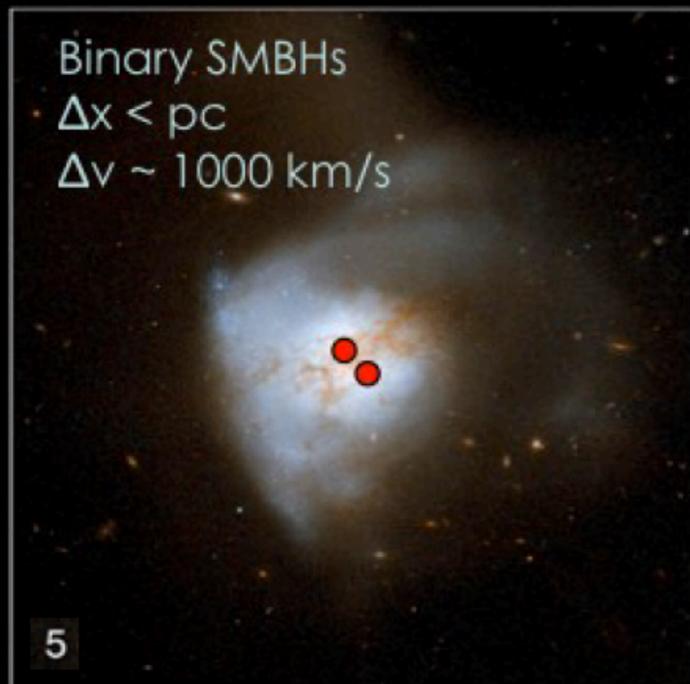
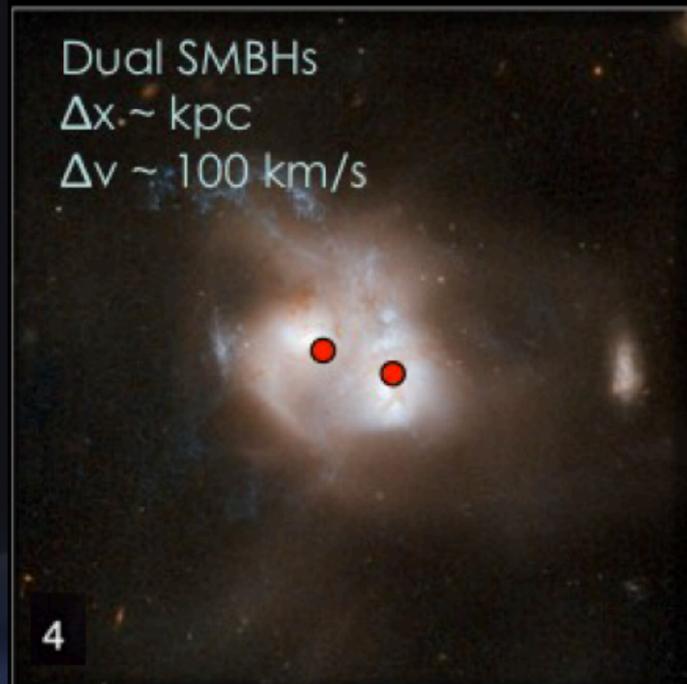
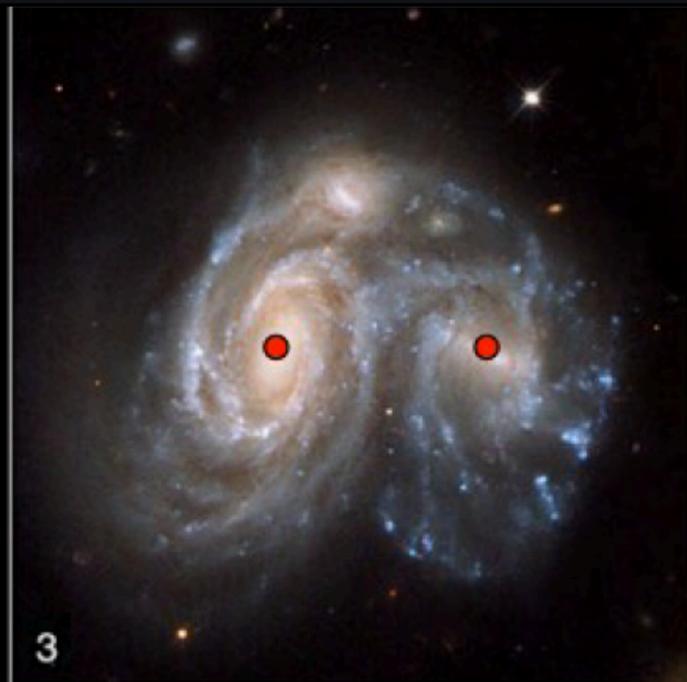
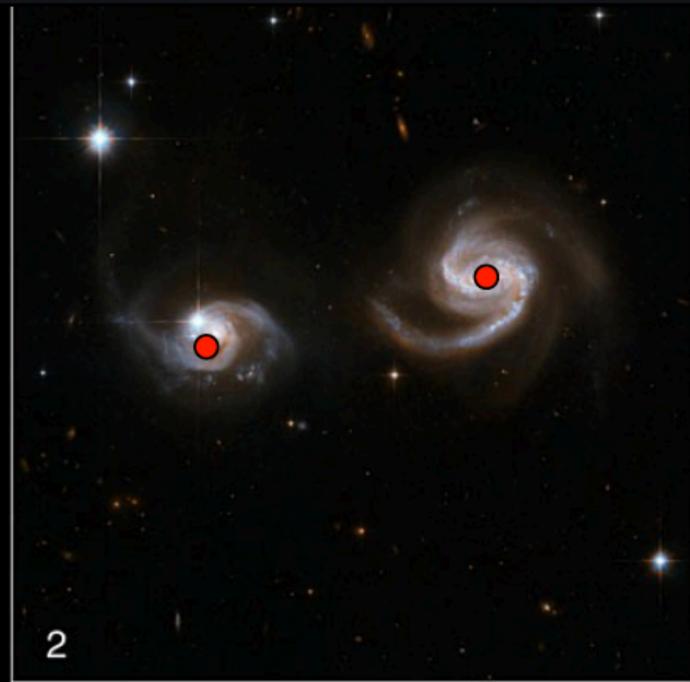
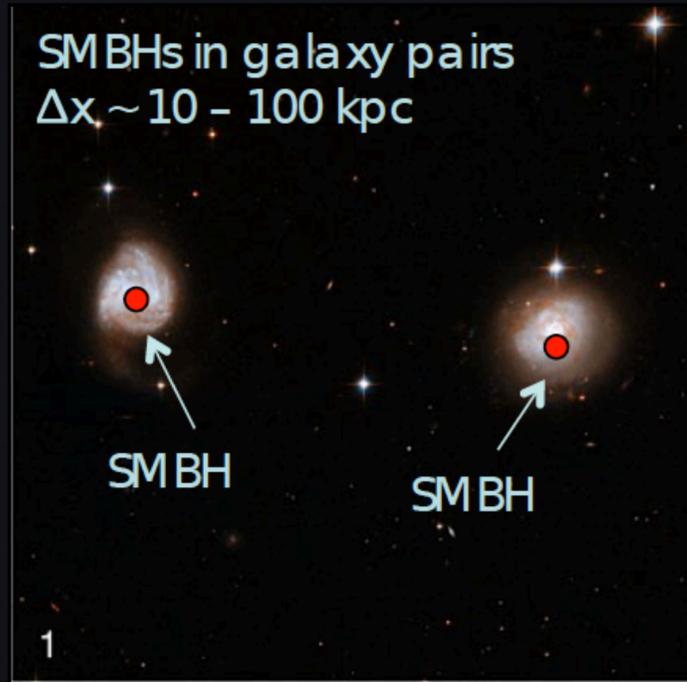
L. Battistini, F. Belfiore, E. Bertola, C. Bracci, S. Bianchi, S. Carniani, P. R. Capelo, E. Cataldi, M. Ceci, A. Chakraborty, C. Cicone, A. Ciurlo, G. Cresci, Q. D'Amato, R. Della Ceca, E. Di Teodoro, A. Feltre, M. Frailis, M. Fumagalli, M. Ginolfi, M. Guainazzi, B. Hagedorn, R. Khatun, F. La Franca, I. Lamperti, E. Lusso, C. Marconcini, F. Mannucci, A. Marconi, B. Moreschini, E. Nardini, M. Scialpi, M. Parvatikar, M. Perna, E. Piconcelli, F. Ricci, F. Rigamonti, P. Rosati, P. Severgnini, J. Singh, A. Sonnenfeld, C. Spingola, D. Tavagnacco, G. Tozzi, L. Ulivi, R. Valiante, G. Venturi, C. Vignali, M. Volonteri, S. Yeh, A. Zacchei, M. V. Zanchettin



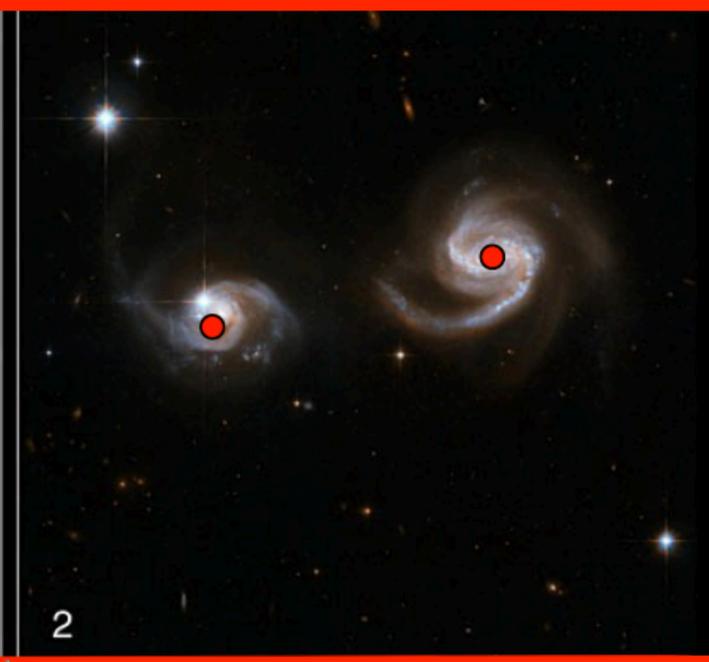
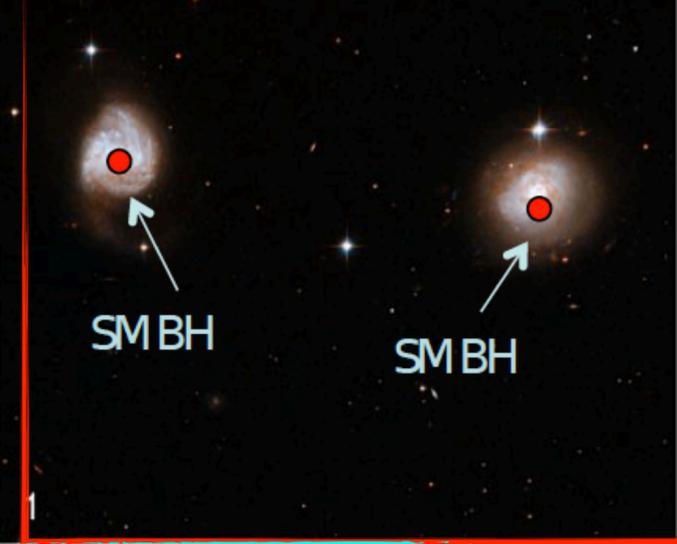
IAPS OA-Brera OA-Arcetri OA-Roma OA-Abruzzo
Univ: Bicocca - Sapienza - Roma Tre - Trento - Bologna
RSN1 - RSN4 - RSN5



Key questions



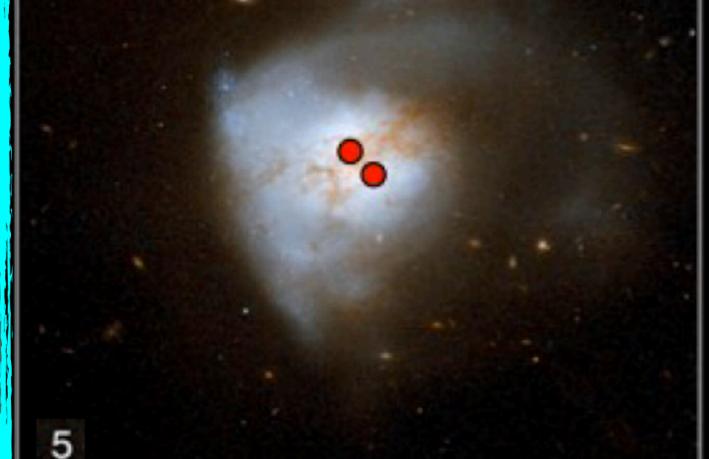
SMBHs in galaxy pairs
 $\Delta x \sim 10 - 100 \text{ kpc}$



Dual SMBHs
 $\Delta x \sim \text{kpc}$
 $\Delta v \sim 100 \text{ km/s}$



Binary SMBHs
 $\Delta x < \text{pc}$
 $\Delta v \sim 1000 \text{ km/s}$

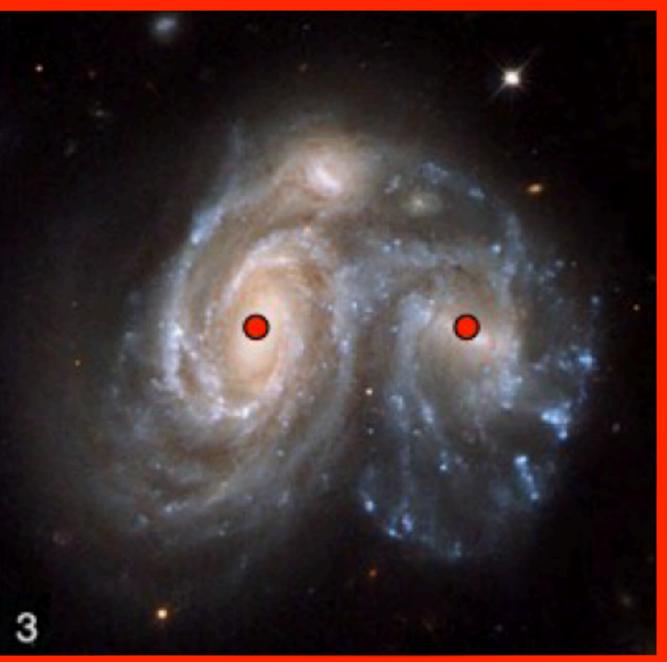
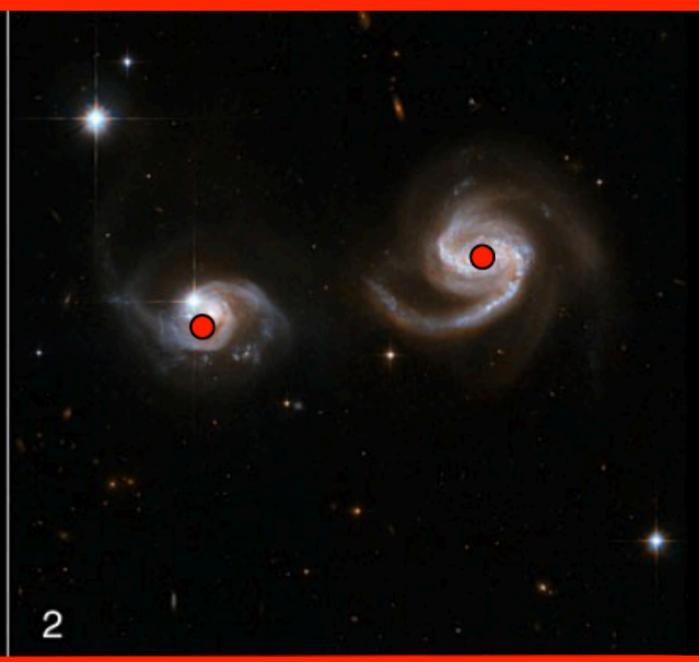
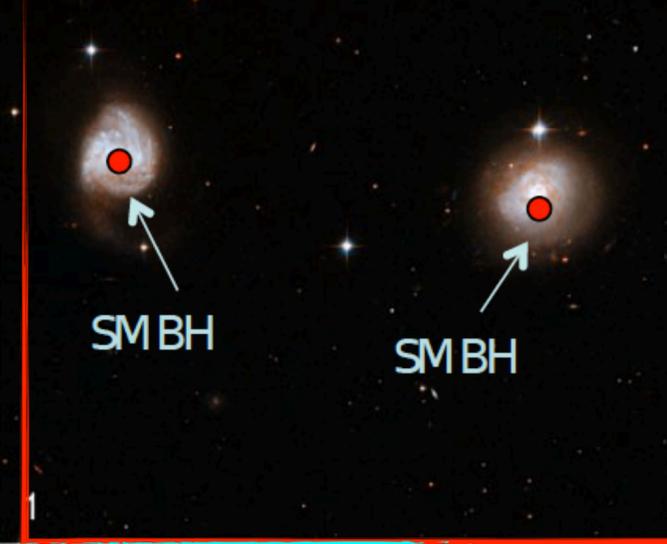


SMBH coalescence
Gravitational radiation



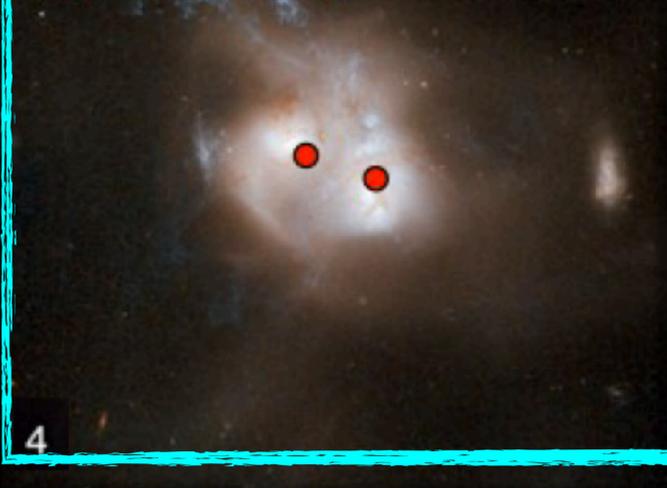
Dual AGN sep.: several/tens kpc down to (sub)-kpc (early and late stage of galaxy merger)

SMBHs in galaxy pairs
 $\Delta x \sim 10 - 100 \text{ kpc}$

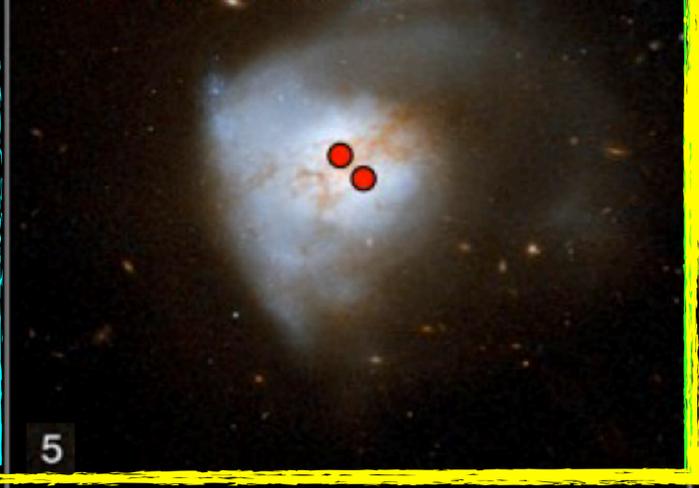


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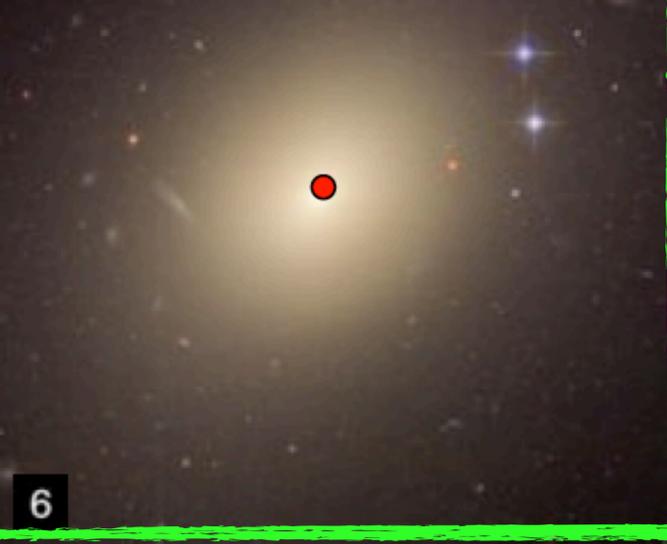
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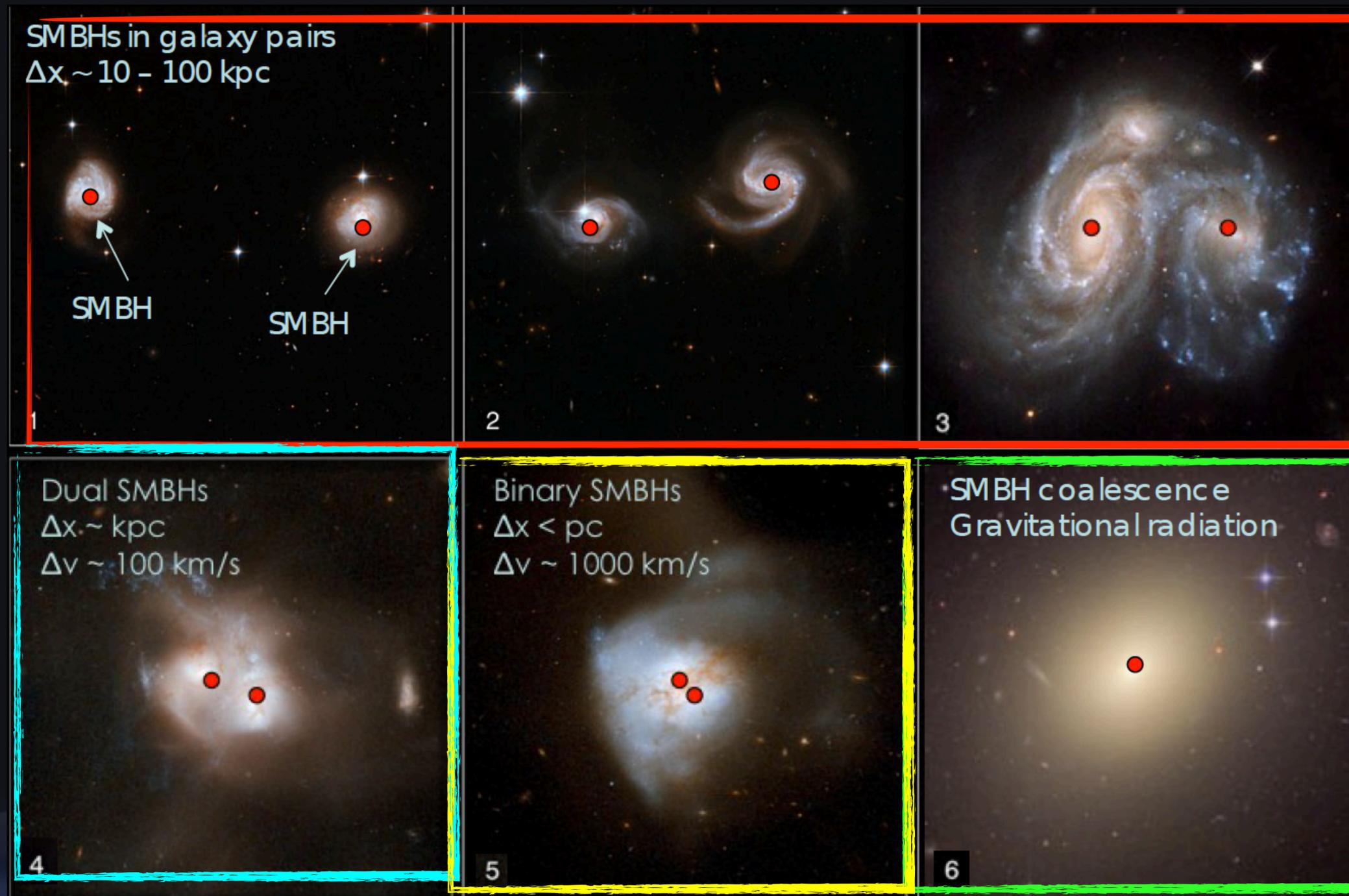
Binary SMBHs
 $\Delta x < \text{pc}$
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SMBH coalescence
Gravitational radiation



Binary AGN: gravitational bound SMBHs (pc/sub-pc sep., post-merger galaxy).
Coalescence: the two SMBHs merge, producing a single black hole



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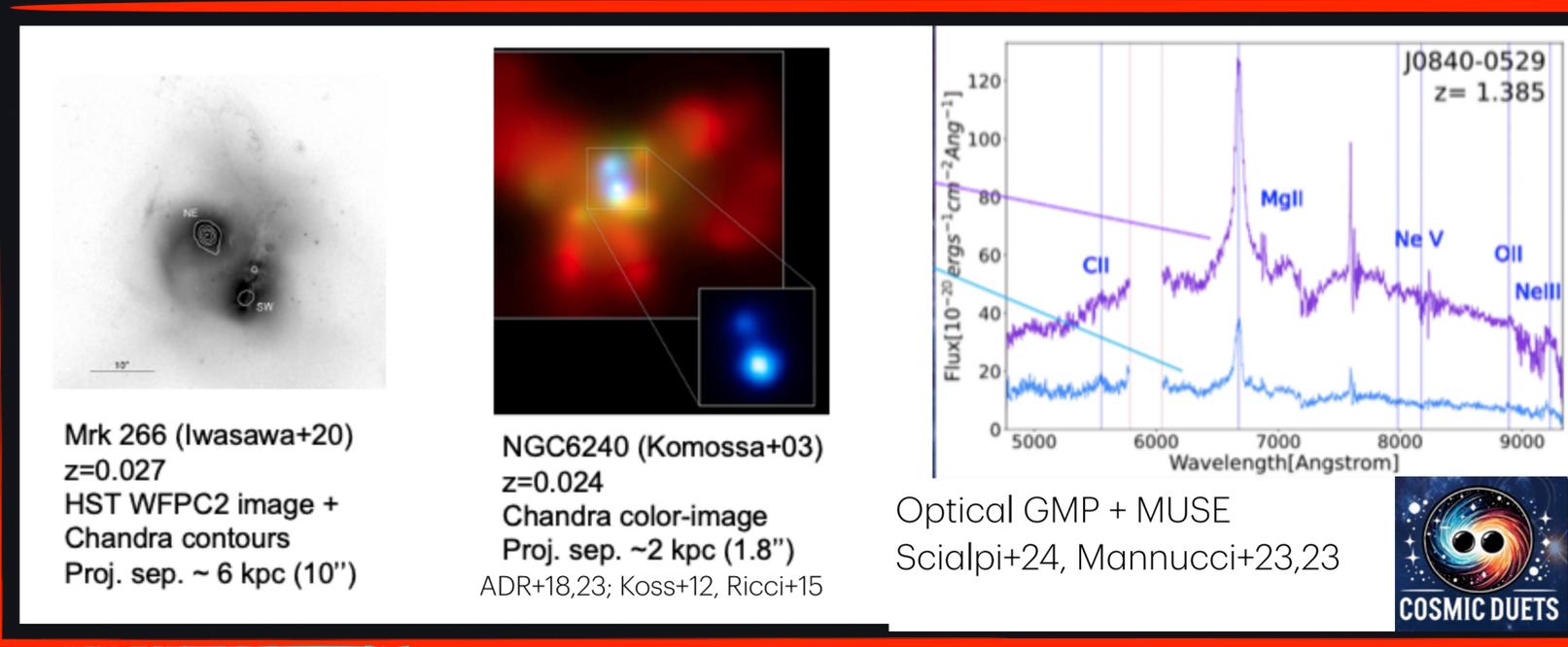
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NASA/ESA/STScI

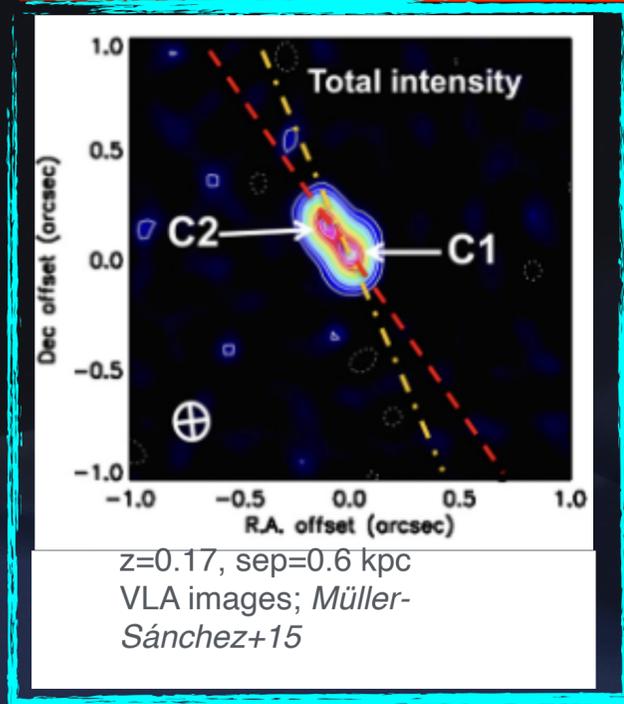
Binary AGN: the Orbital phase may produce continuous GW in the low-frequency range (Pulsar Timing Array)

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

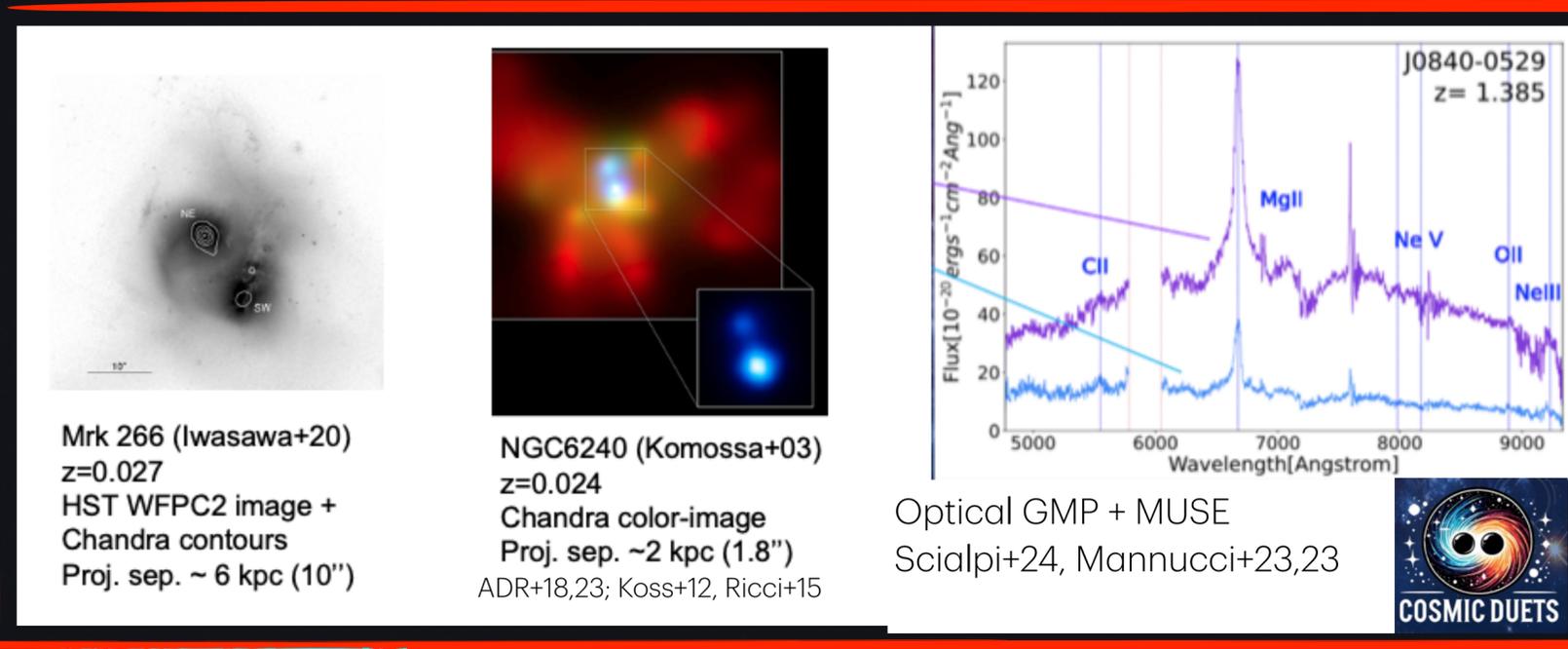
On the way to merging: observing three stages



Dual AGN early late: direct imaging, X-ray/
optical spectroscopy, IR photometry
Wide surveys + high spatial resolution
follow-ups

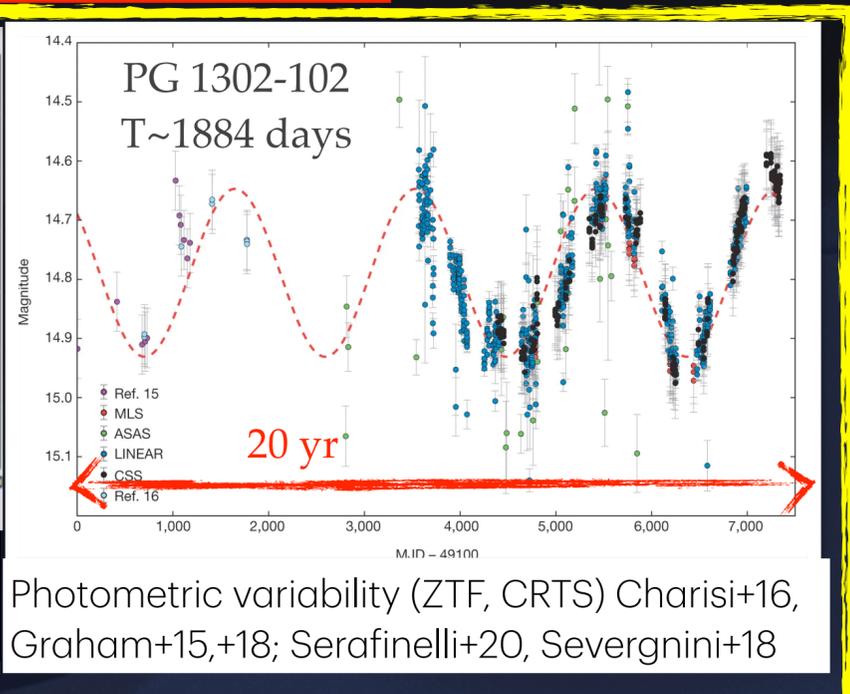
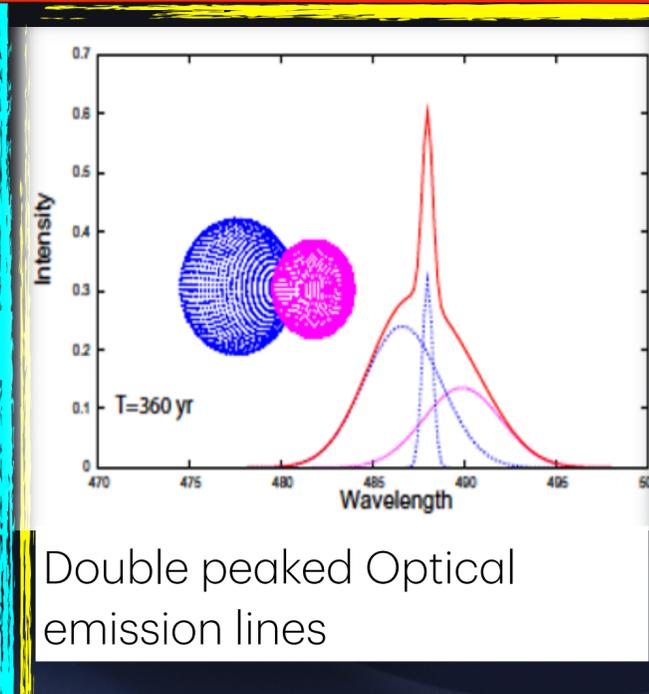
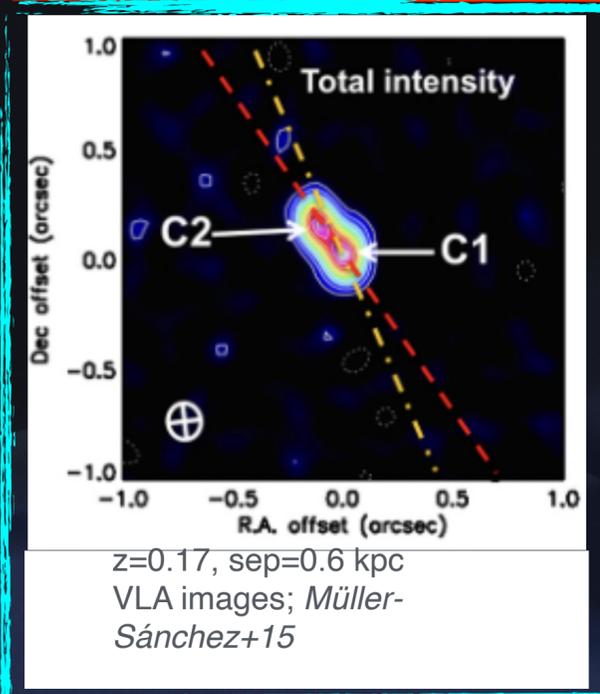


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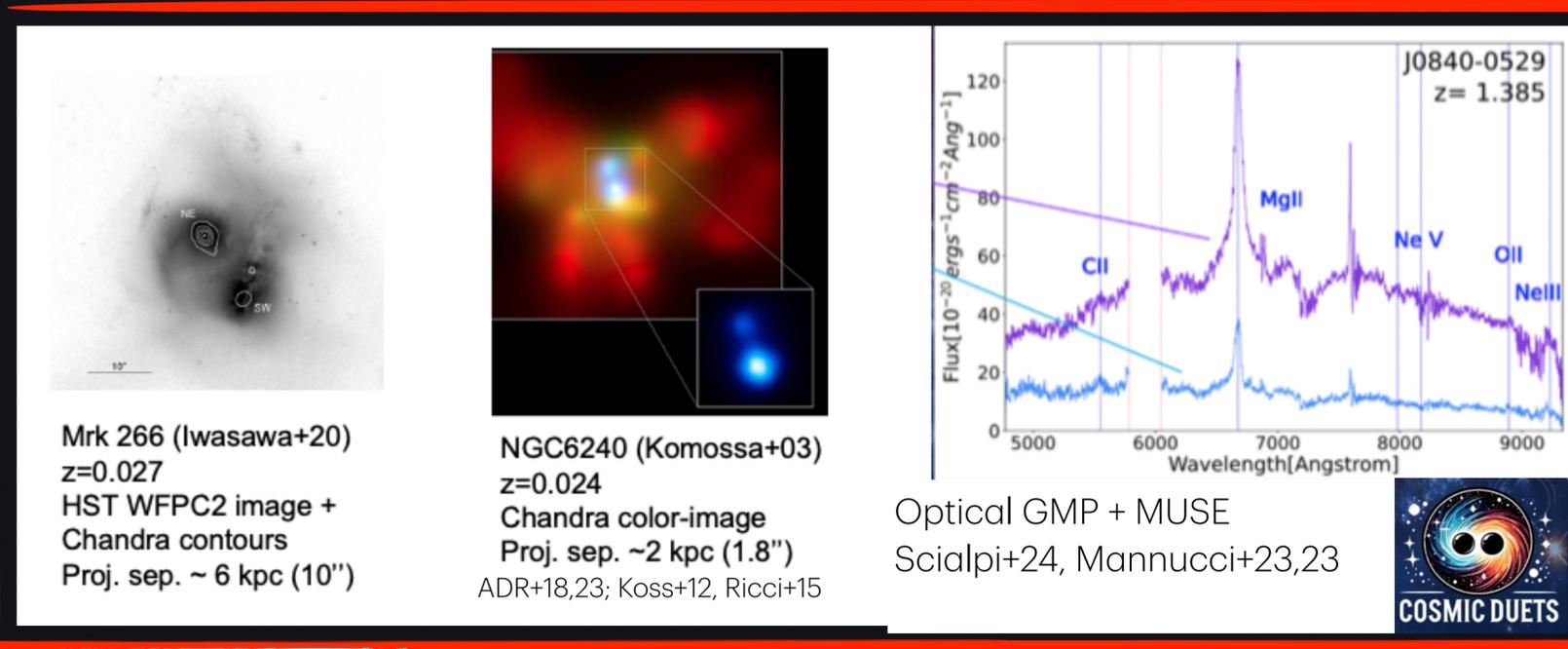


Dual AGN early late: direct imaging, X-ray/optical spectroscopy, IR photometry
 Wide surveys + high spatial resolution follow-ups

Binary AGN: indirect techniques: optical spectroscopy, X-ray/optical variability

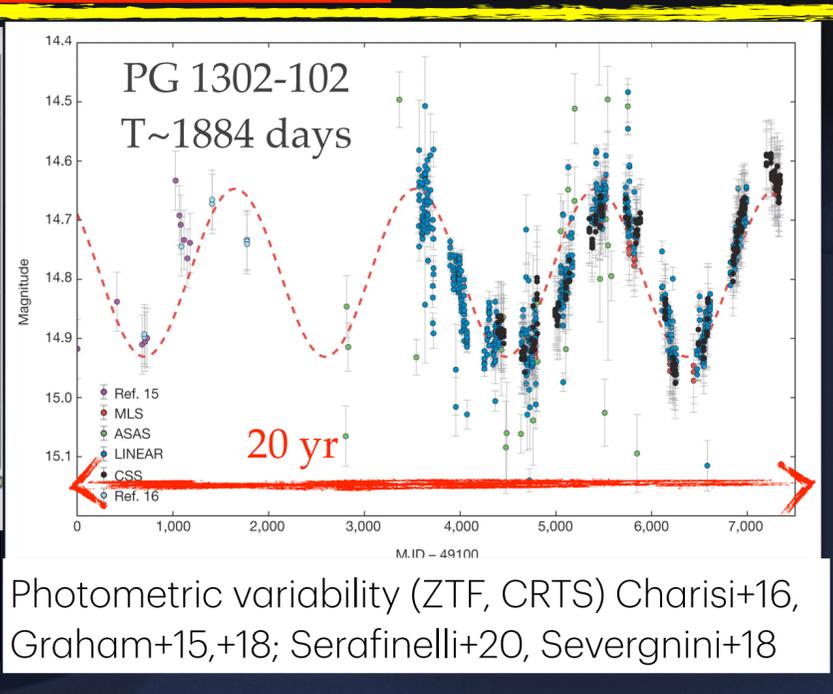
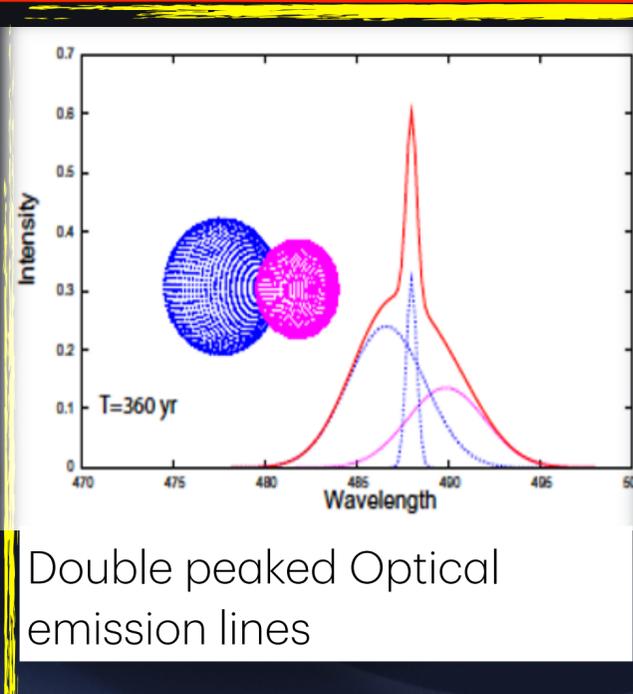
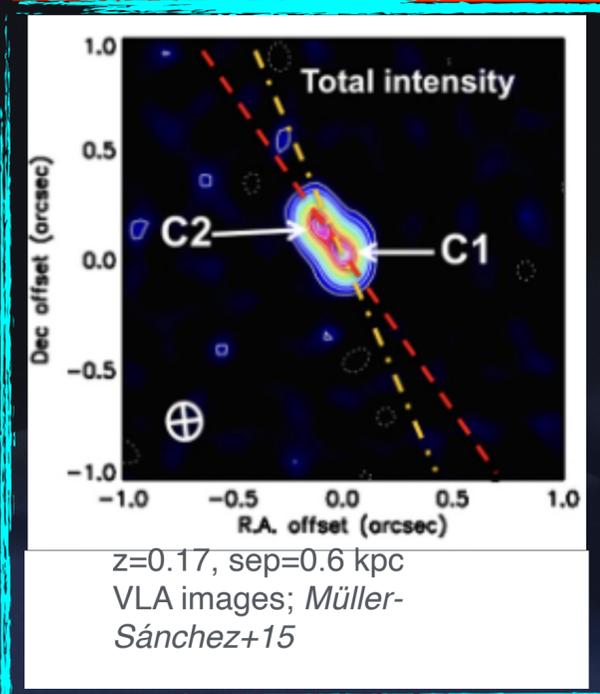


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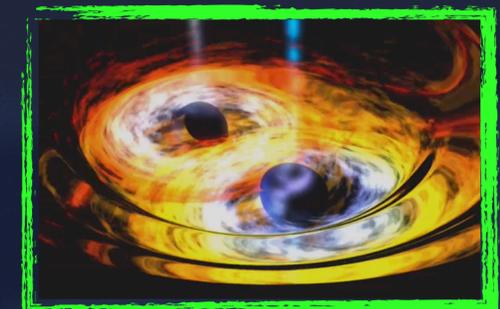


Dual AGN early late: direct imaging, X-ray/optical spectroscopy, IR photometry
Wide surveys + high spatial resolution follow-ups

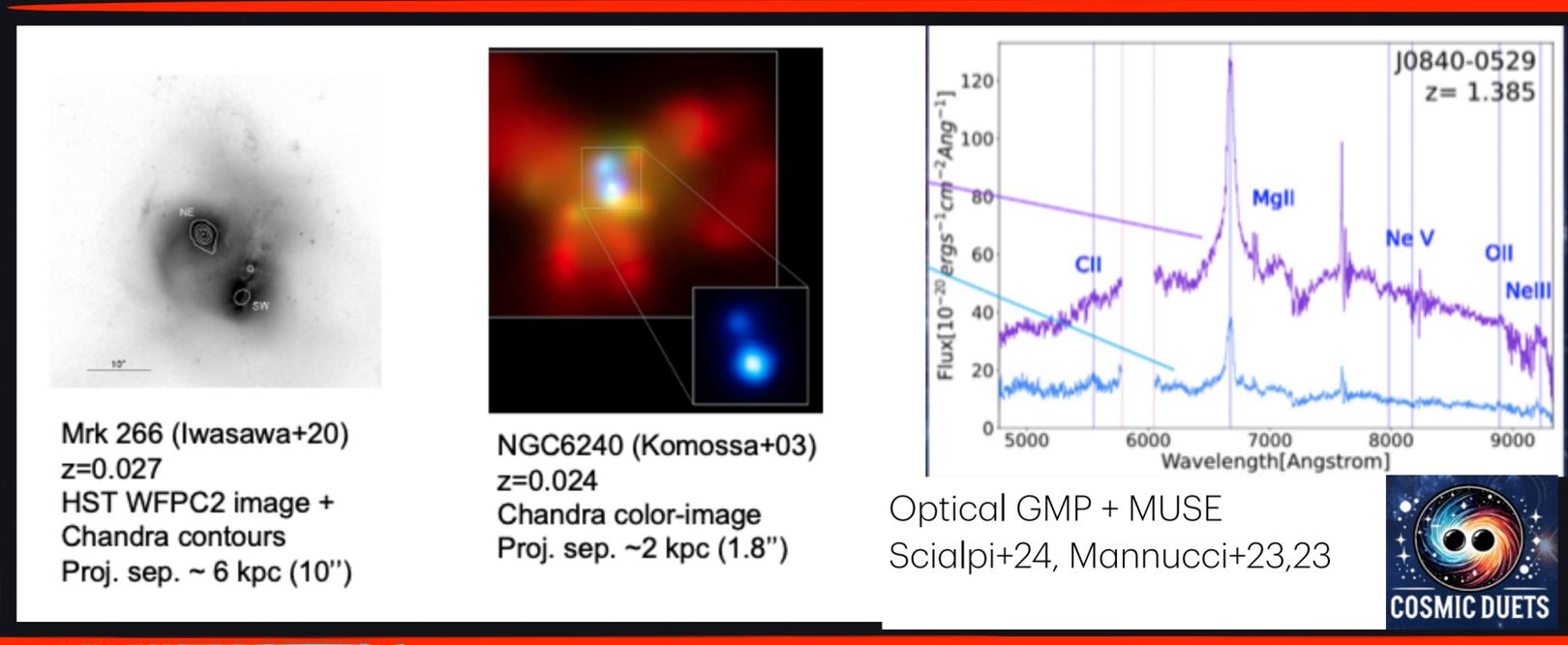
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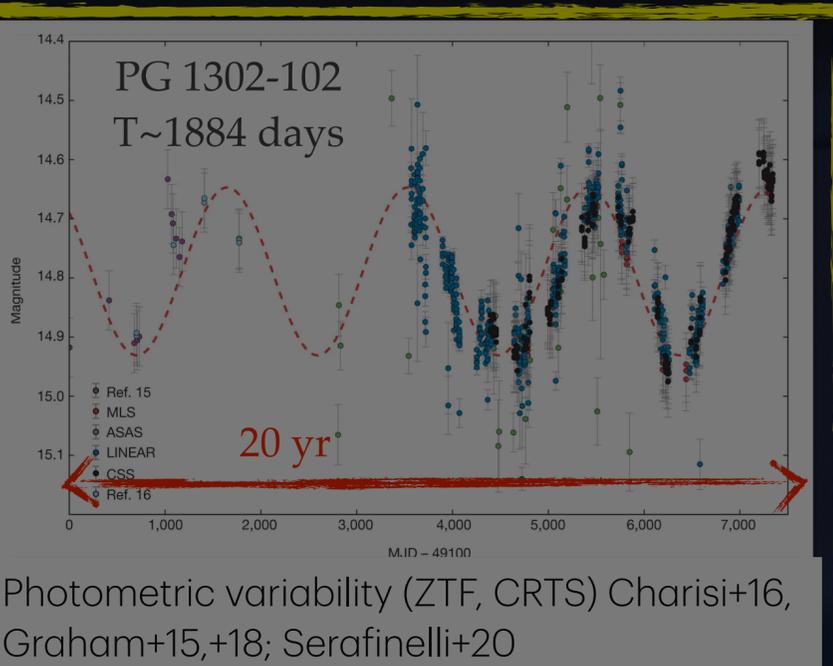
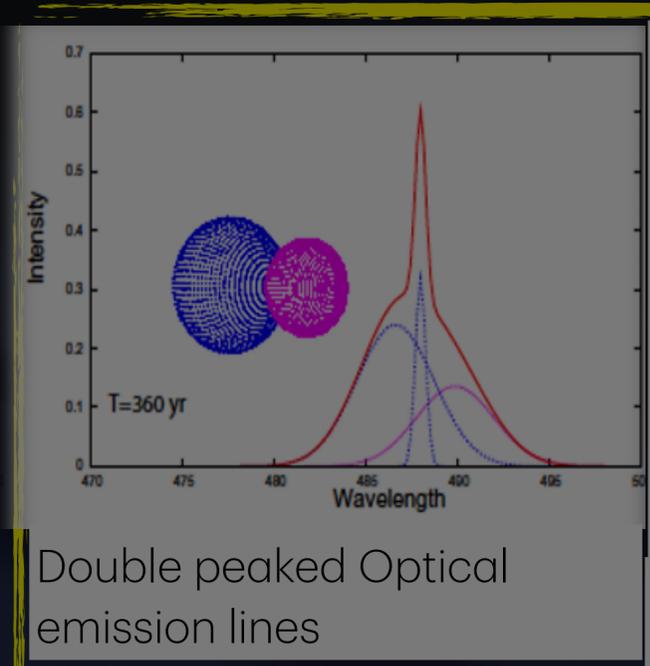
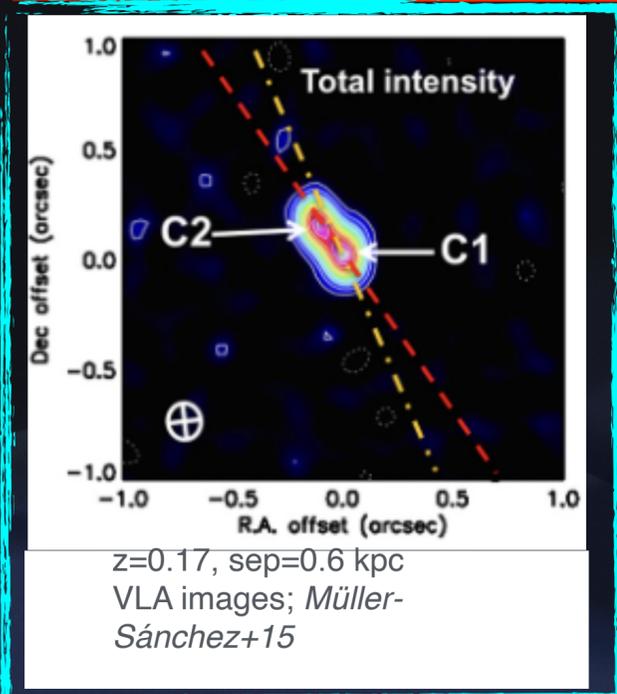
Coalescence: X-ray/optical spectroscopy, variability
Multi-messenger in act!



On the way to merging: observing three stages

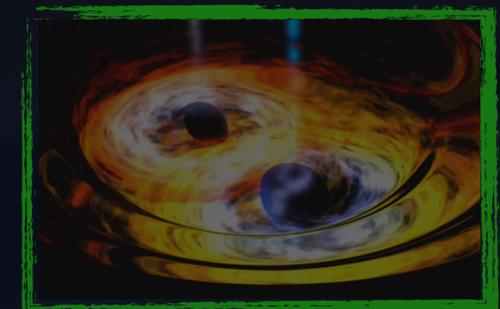


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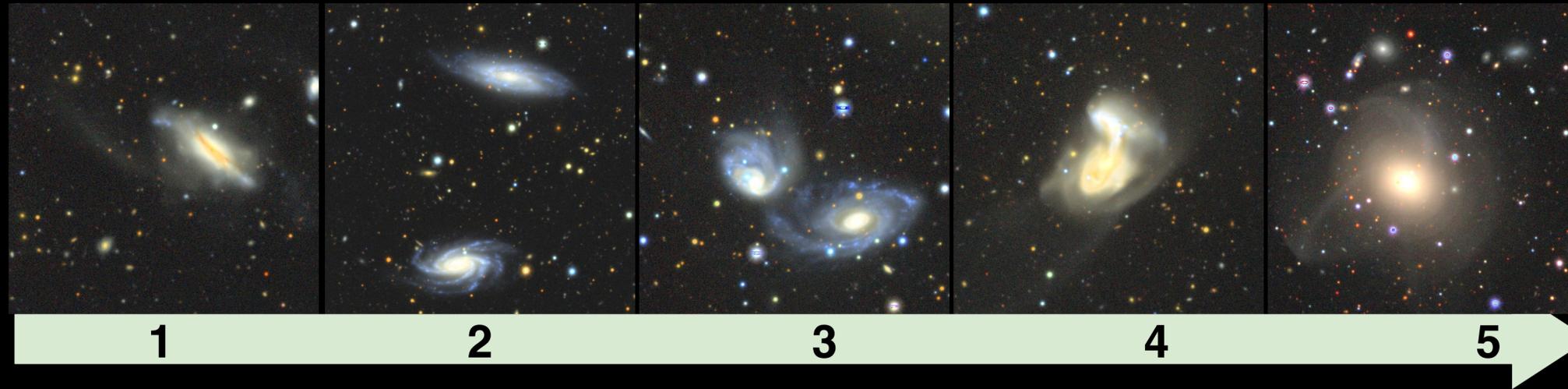
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Merger vs triggering/starforming with IFU spectroscopy

M. Parvatikar PhD

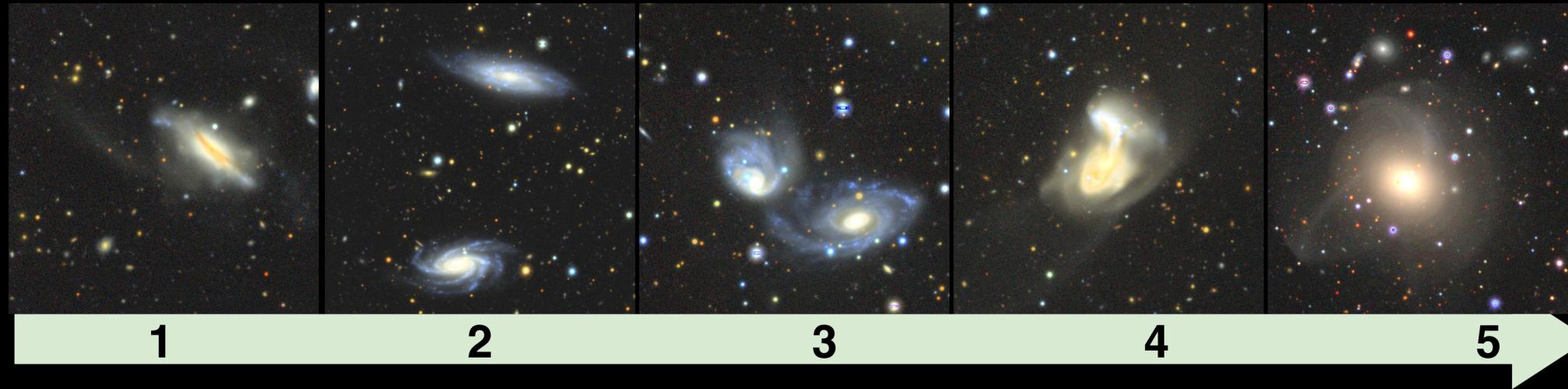


- MUSE/VLT spectrum of 120 mergers
- Merger Stage: Deep Images - DESI & HST
- MUSE WFM 9x9 binning (1.8"/pix)

do merger trigger nuclear activity?
merger vs star formation

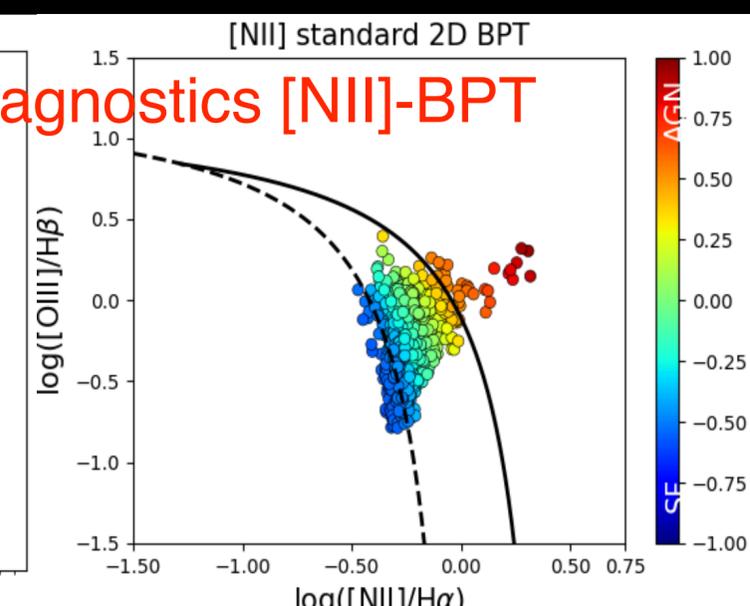
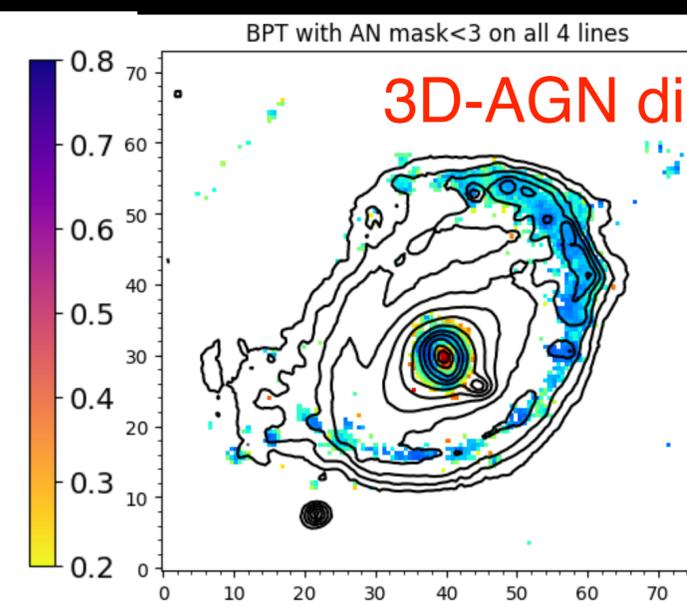
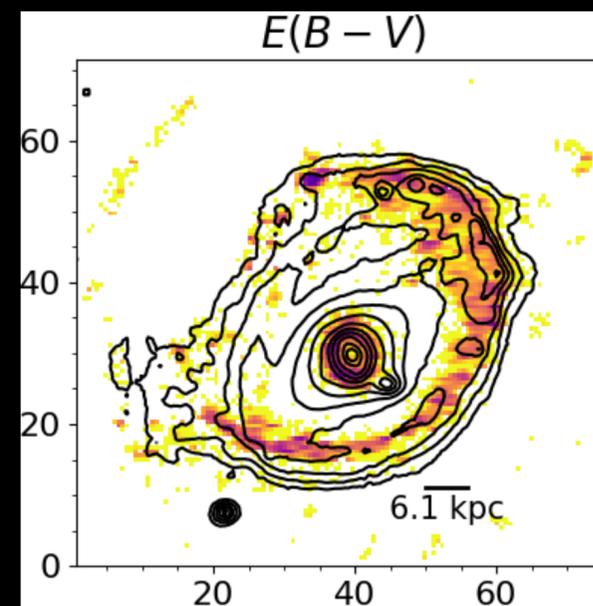
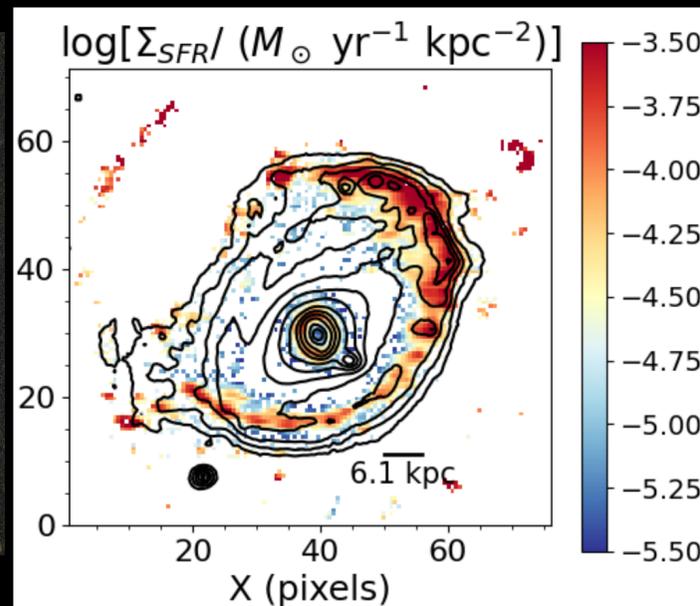
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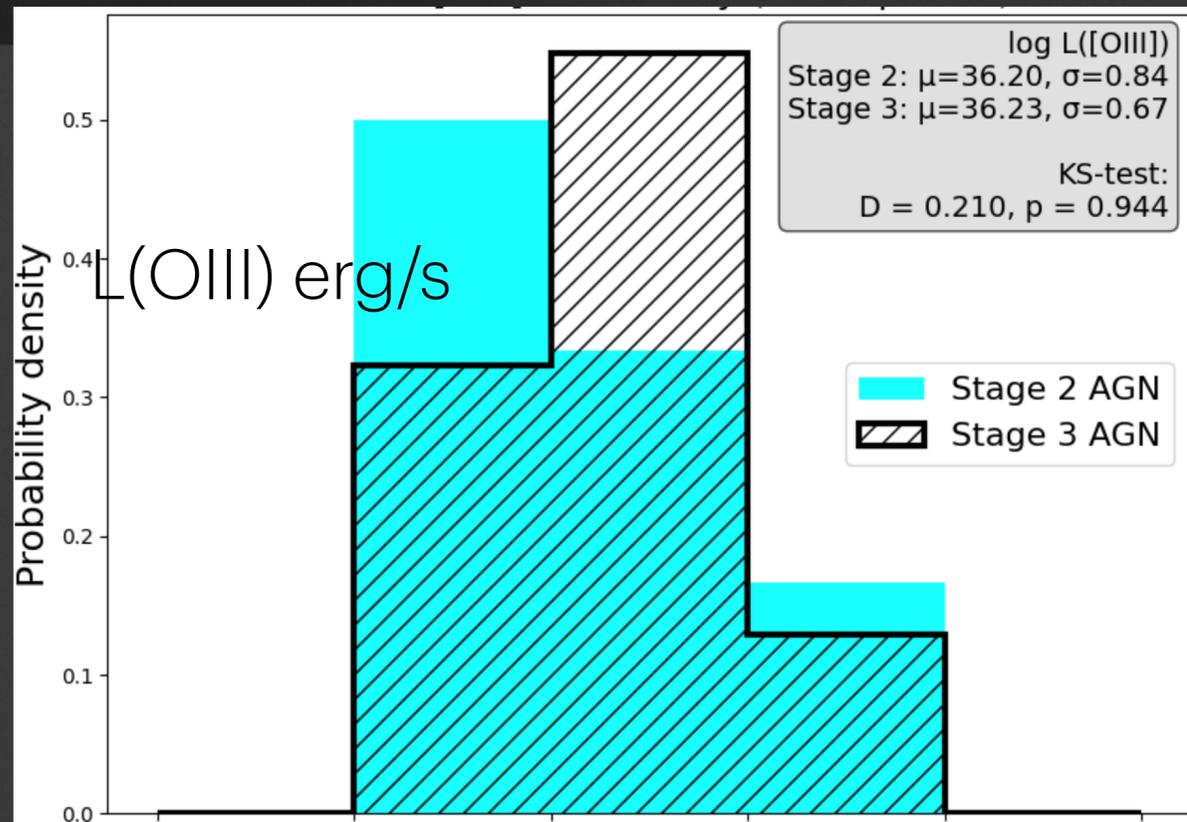
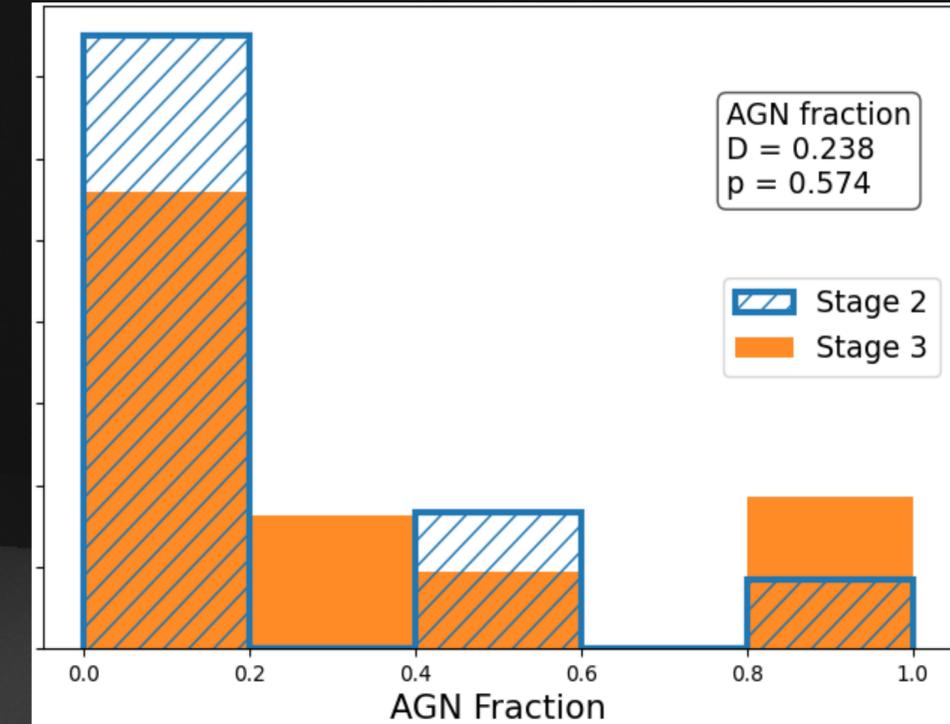
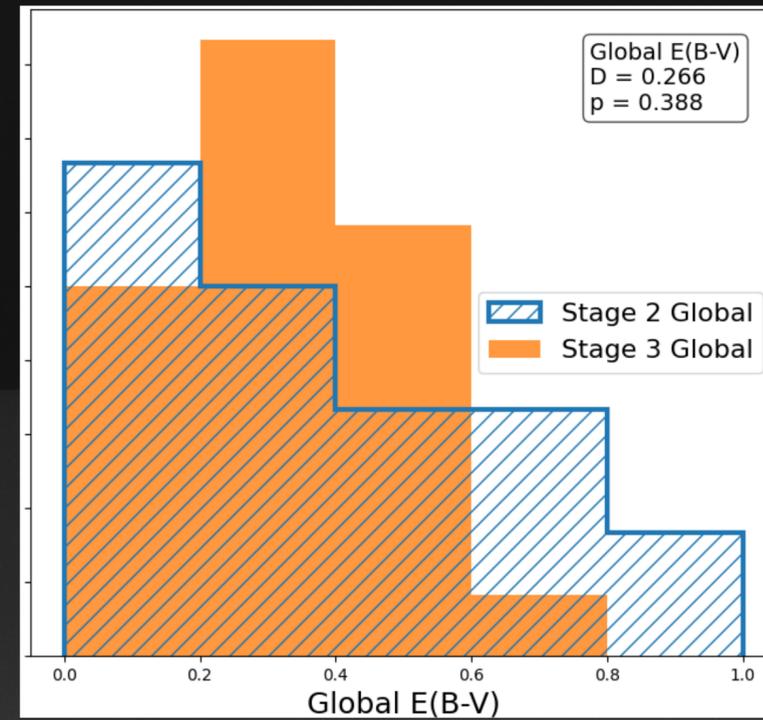
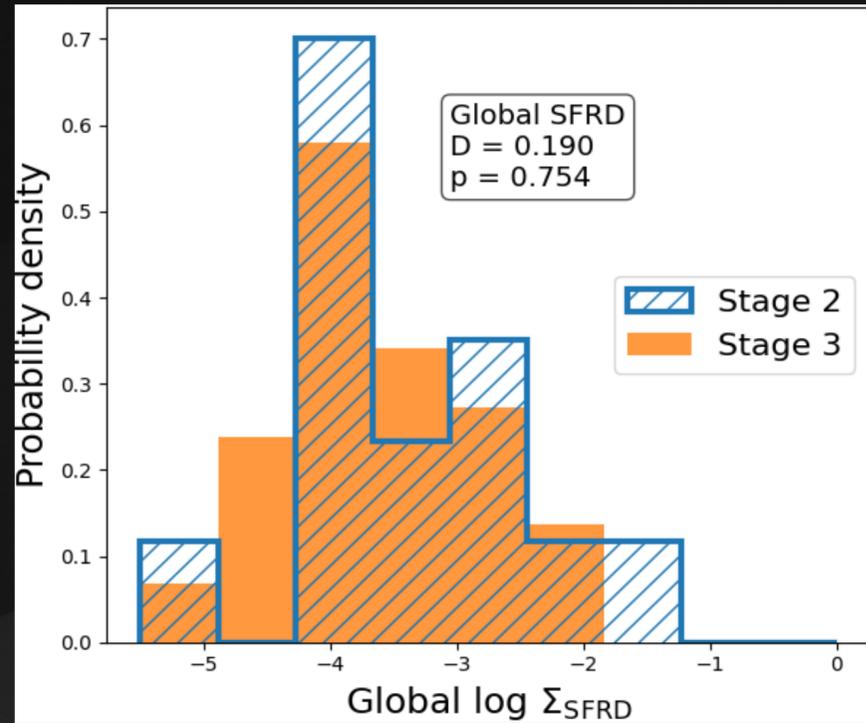


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do merger trigger nuclear activity?
merger vs star formation



early (stage 2) and advanced (stage 3) merger stage



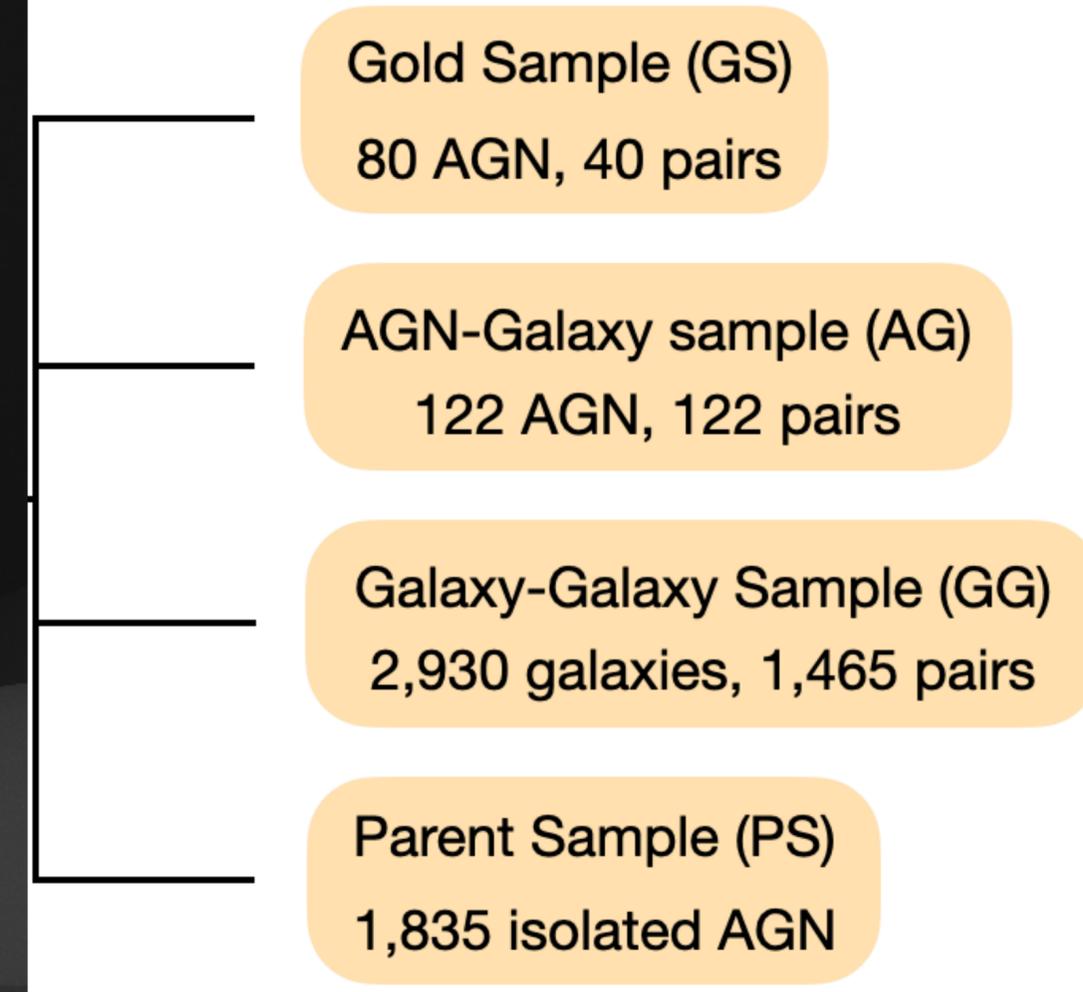
No significant difference in Stage 2 vs Stage 3 mergers for SFRD, E(B-V), AGN spaniel concentration

X-ray view of dual AGN

- X-ray (4XMM and 2CSC) dual AGN search with spec z
- $r \sim 3 - 100$ kpc separation ; $\langle z \rangle \sim 0.1$
- X+midIR (WISE) and optical (BPT) information

Excess of AGN in pairs

Accretion properties vs projected separation r_p



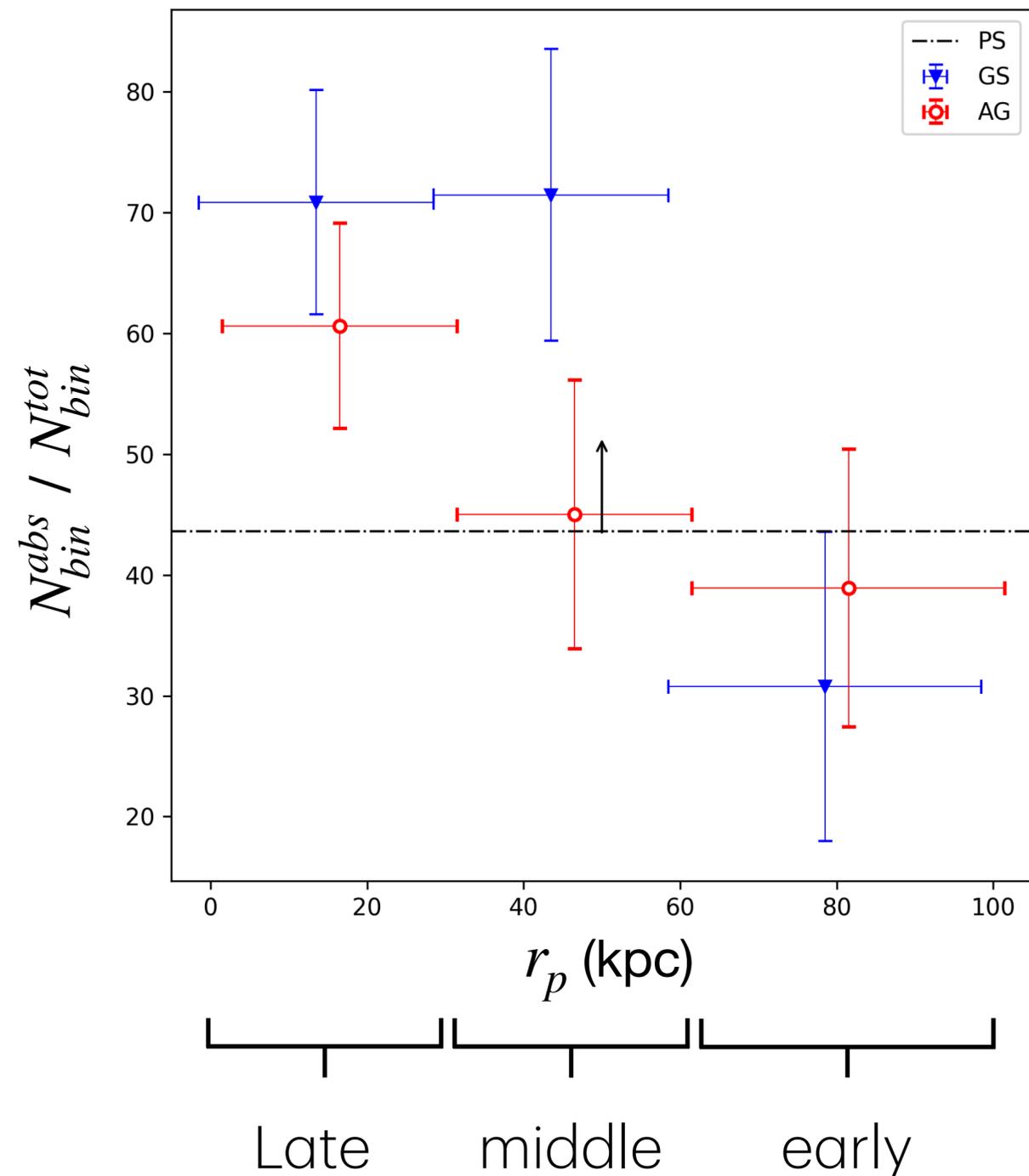
Total AGN: 2,037	AGN-AGN	AGN-galaxy
Fraction (with respect to total)	4%	6%

L. Battistini, PhD

X-ray dual AGN: obscuration and excess

L. Battistini, PhD

Fraction of absorbed ($>10^{22}$ cm $^{-2}$) AGN in pairs

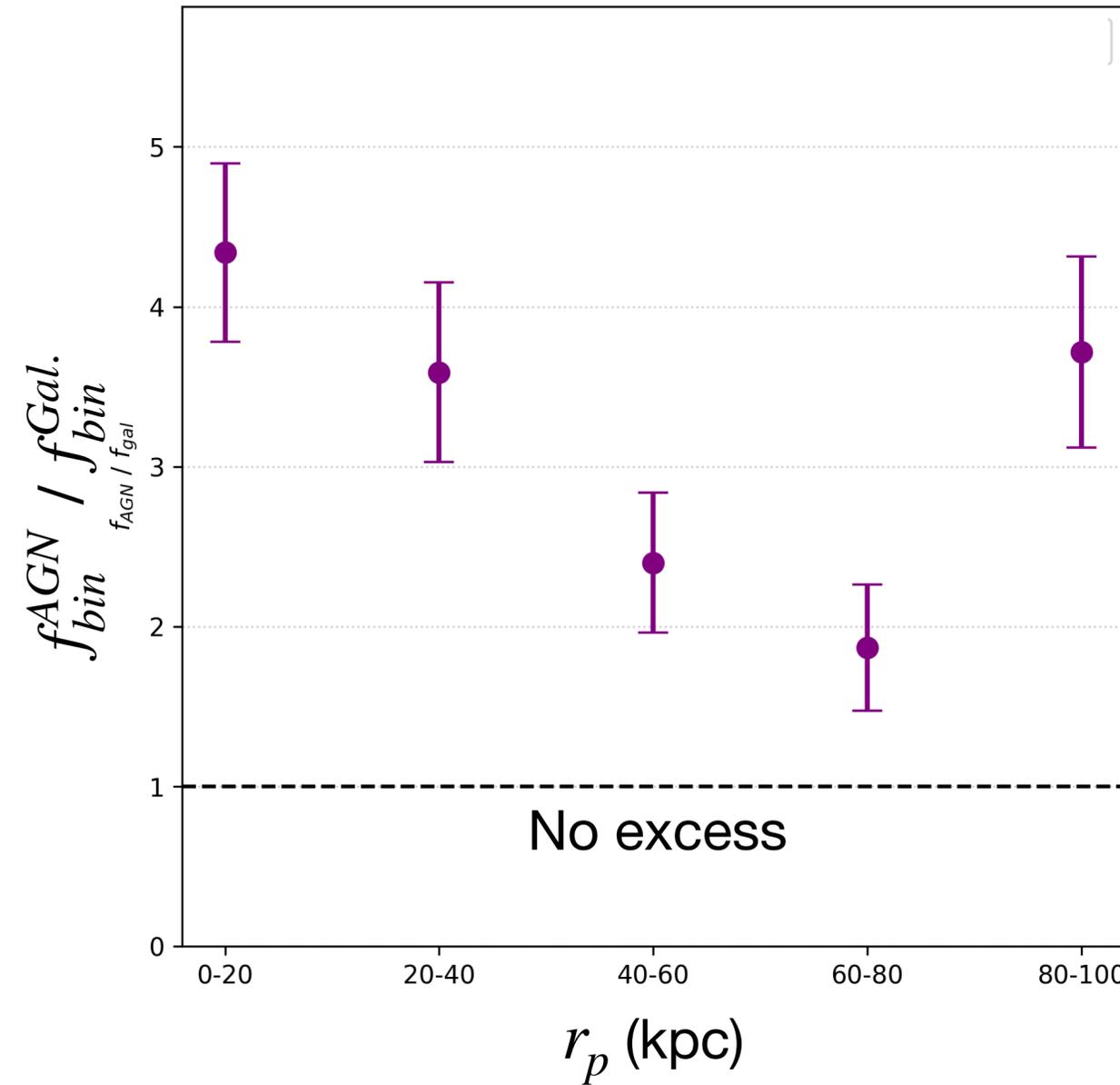
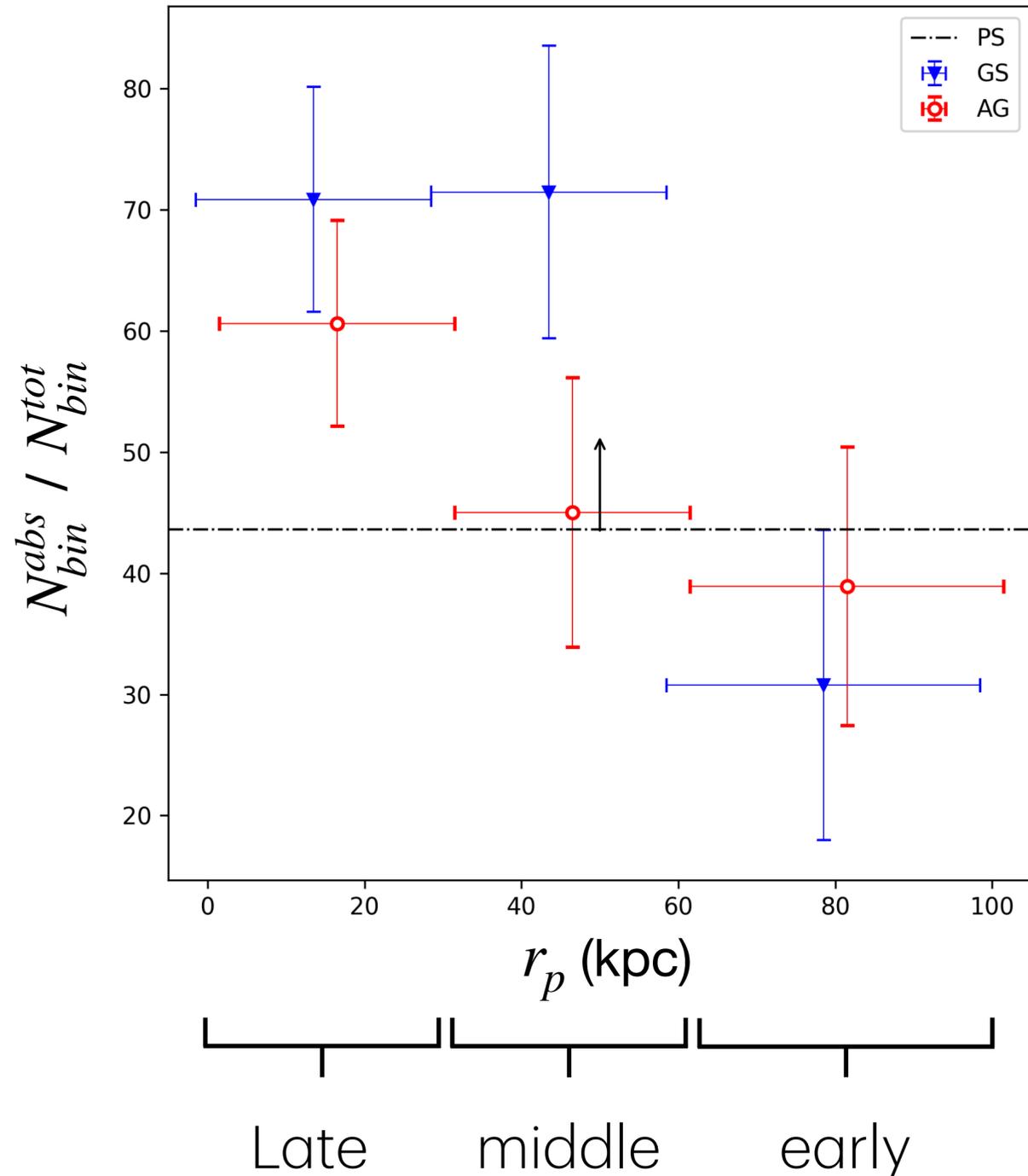


X-ray dual AGN: obscuration and excess

L. Battistini, PhD

Fraction of absorbed ($>10^{22}$ cm $^{-2}$) AGN in pairs

excess of AGN pairs with respect to inactive galaxy pairs
the excess evolves with r_p



$$f_{bin}^{AGN} = N_{bin}^{AGN} / N_{iso+pairs}^{AGN}$$

$$f_{bin}^{Gal.} = N_{bin}^{Gal.} / N_{iso+pairs}^{Gal.}$$

$$N_{iso+pairs}^{AGN} = 2,037$$

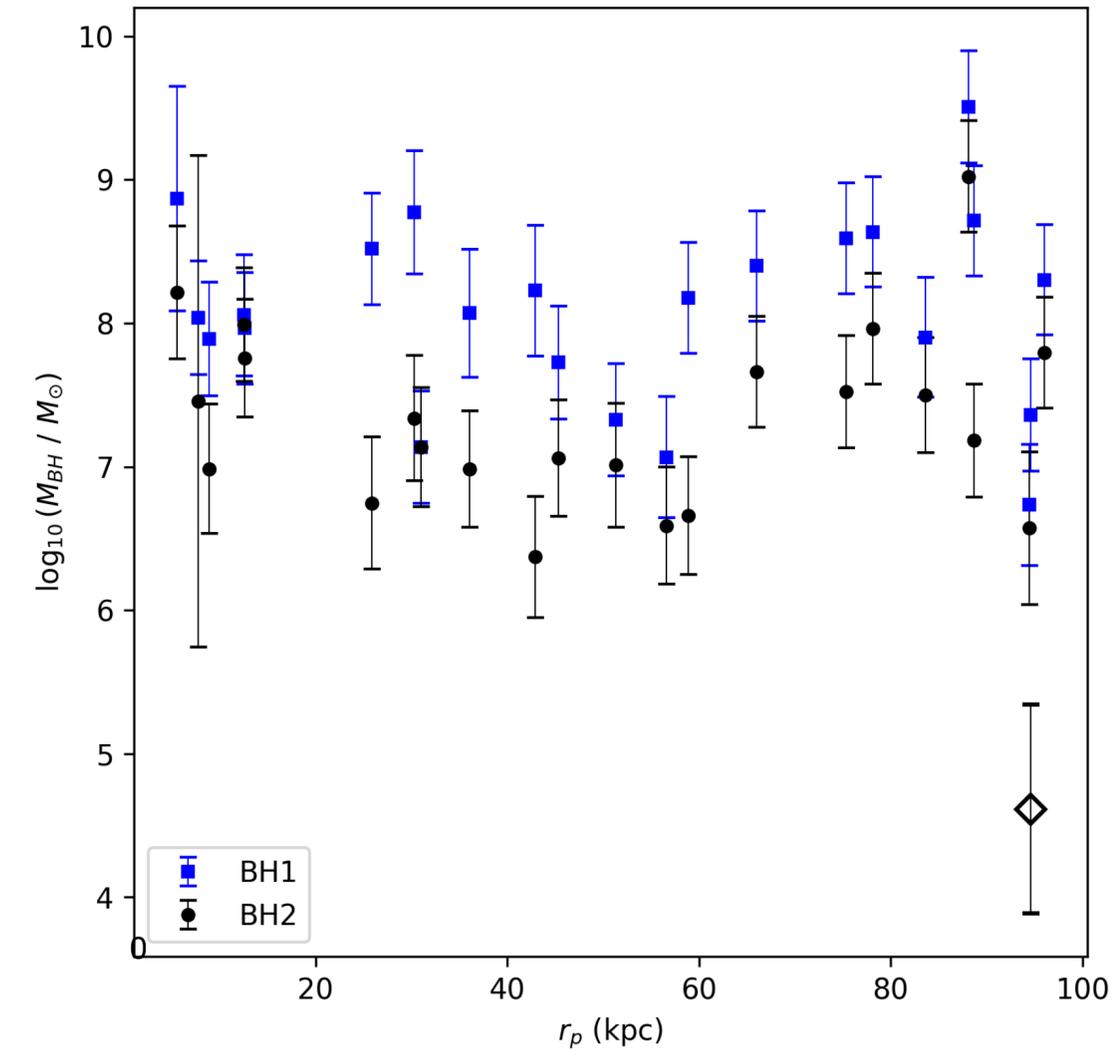
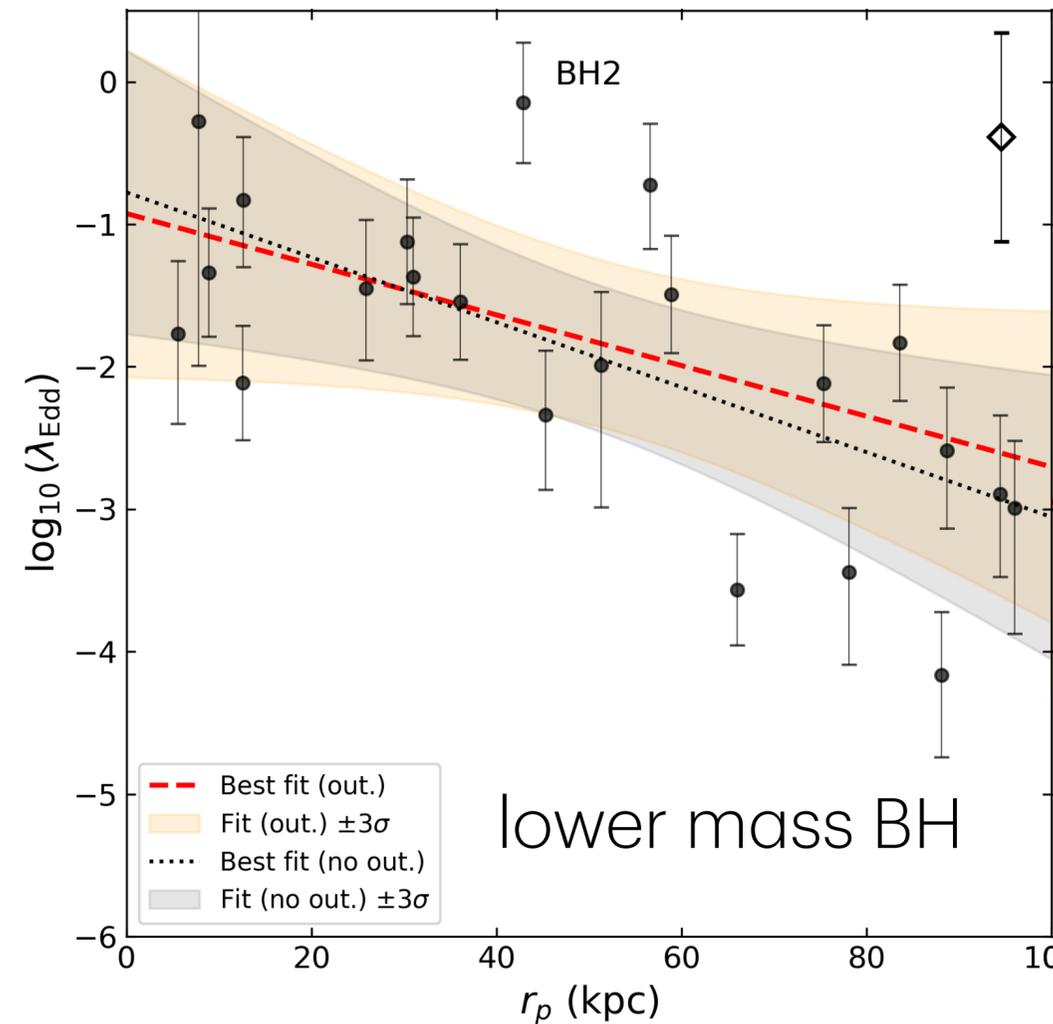
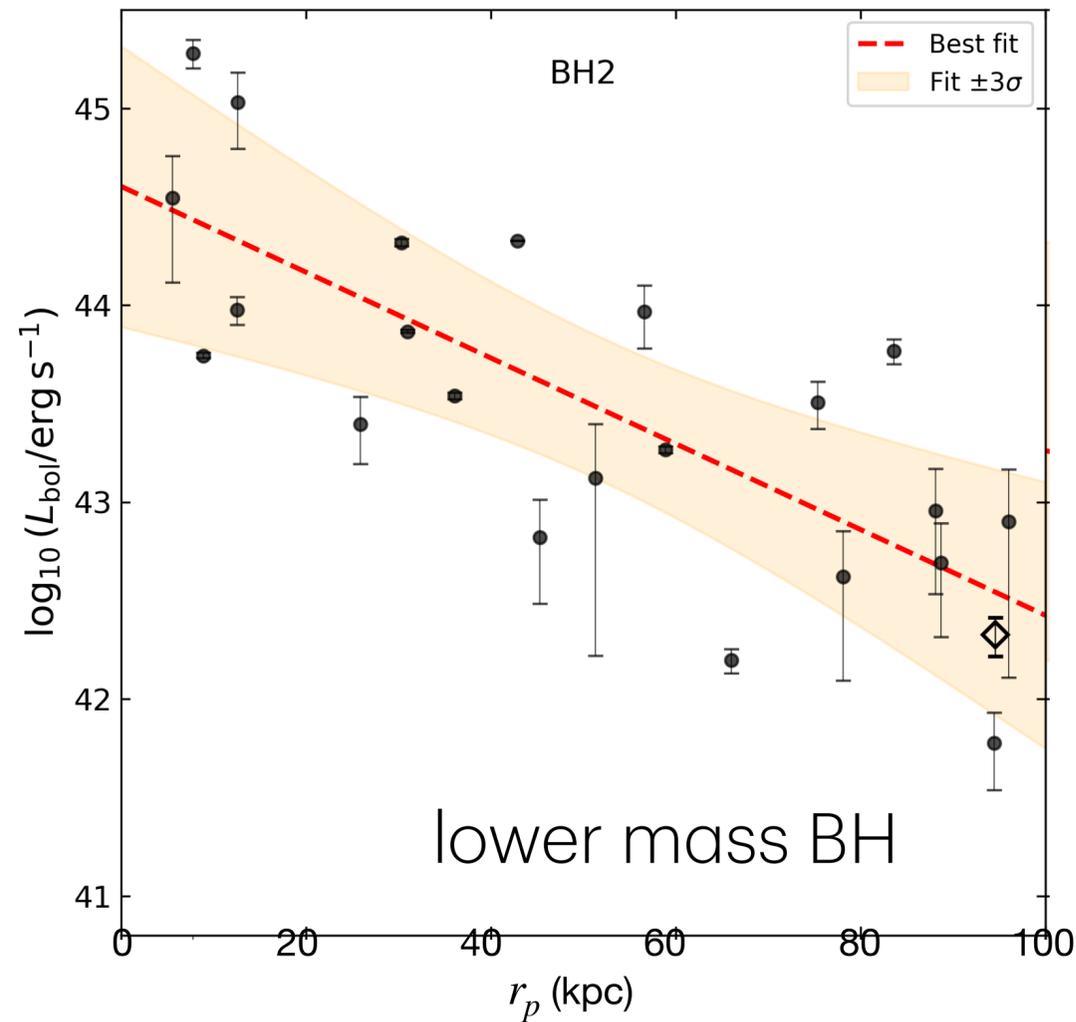
$$N_{iso+pairs}^{Gal} = 94,732$$

No excess

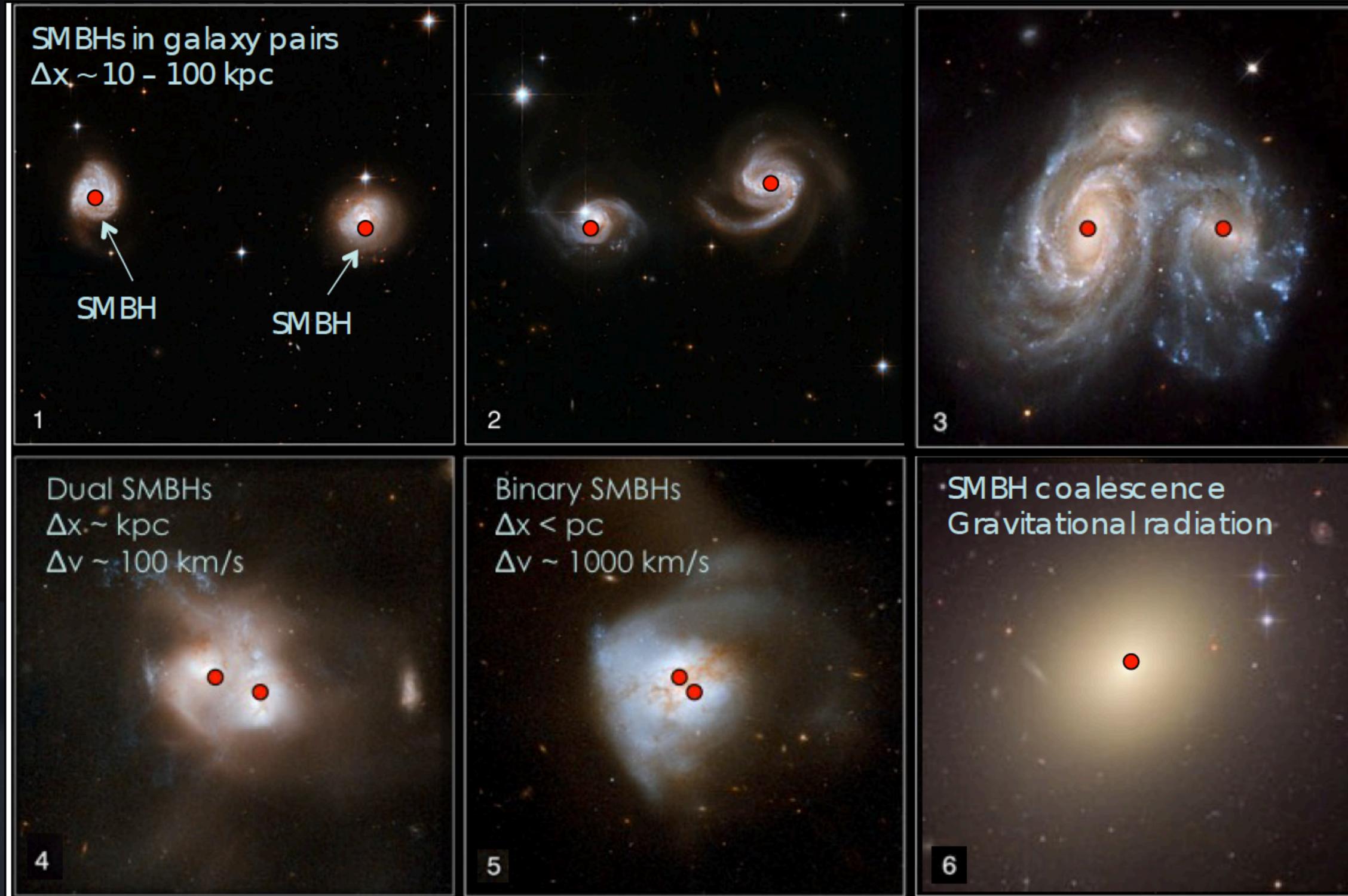
AGN triggering vs mergers

L. Battistini PhD

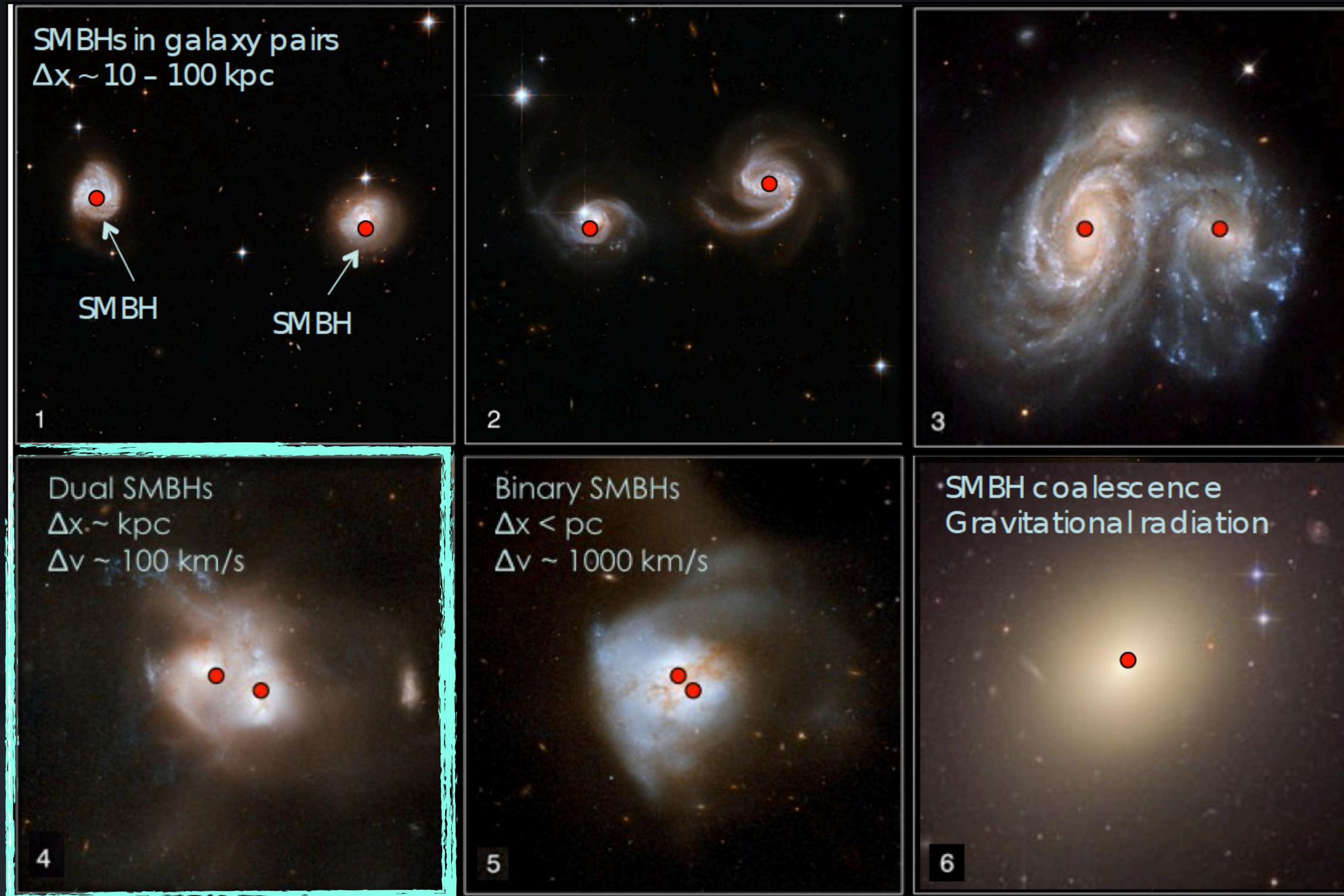
- Statistical evidence of correlation between $L_{\text{bol}}(\text{BH2})$ and $\Lambda_{\text{Edd}}(\text{BH2})$ vs separations
- In minor mergers the less massive SMBH may be more powered the more it gets closer to its (more massive) companion (in agreement with numerical simulations, Capelo+2015).



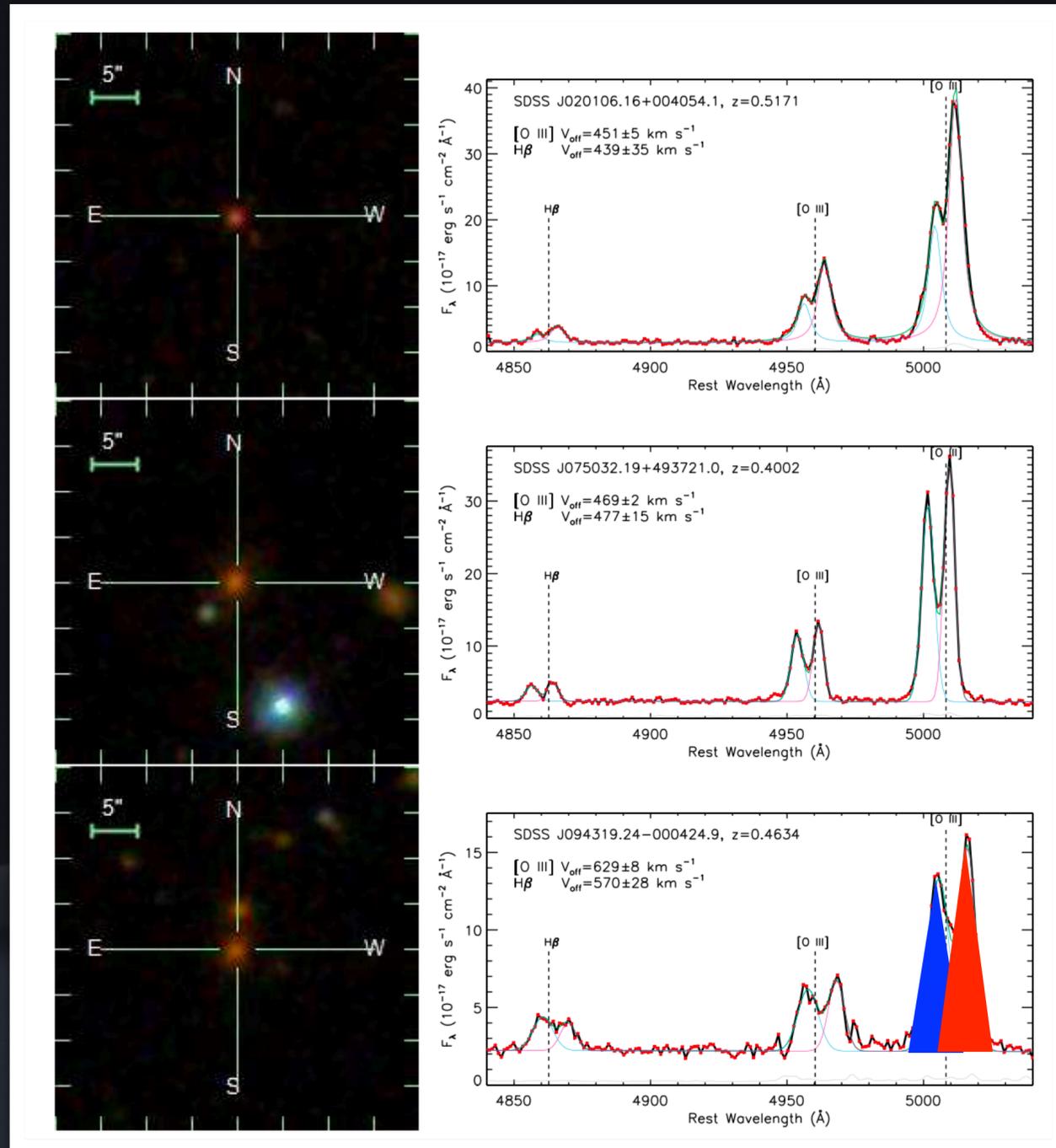
let's go closer kpc/sub-kpc..



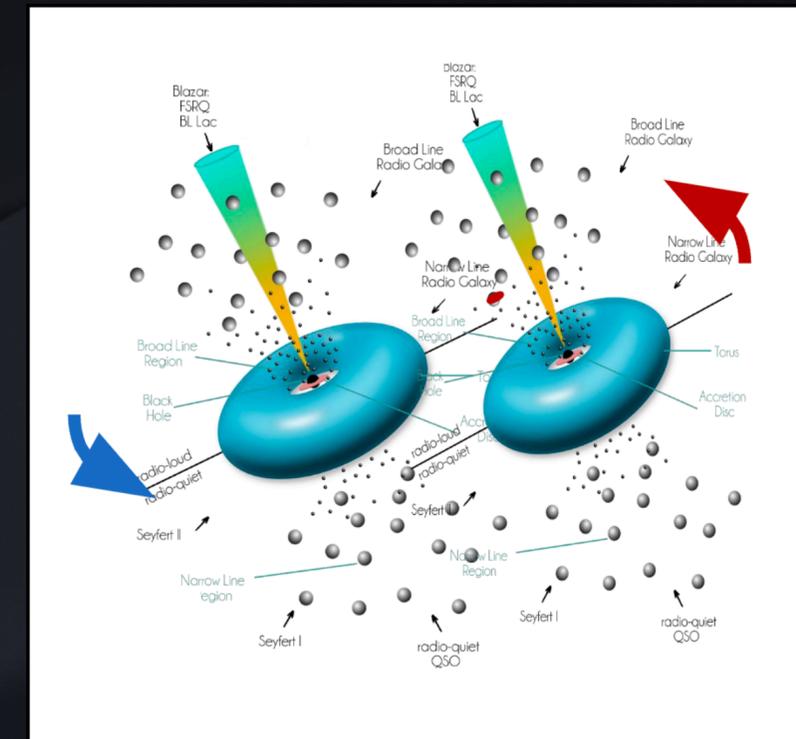
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dual AGN (kpc/sub-kpc): optical spectroscopy

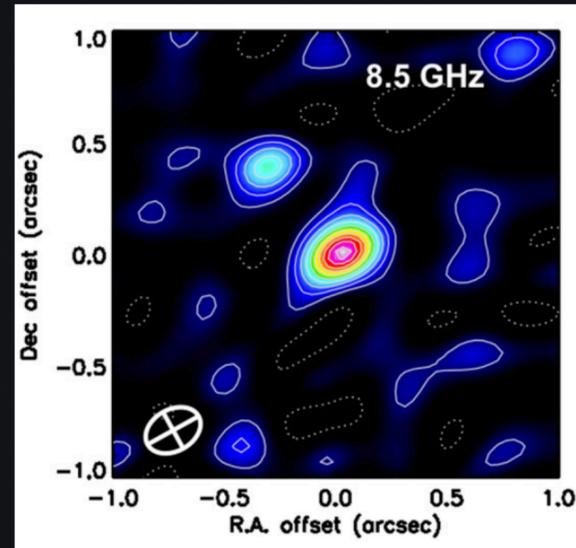


- **Double peaked AGN:** each AGN in a pair carries its own NLR which trace the systemic velocity of the AGN as they move in their common gravitational potential.
- Systematic studies (SDSS, LMOST, DEEP2, AGES) revealed that roughly 1% of the AGN population exhibit double peaks in the high-ionization lines

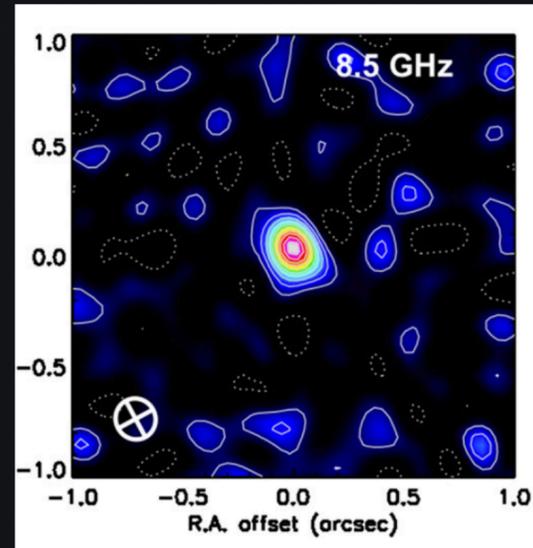


Different kinematics effects could produce double-peaked: dual AGN, outflow or narrow emission region rotation of a single AGN

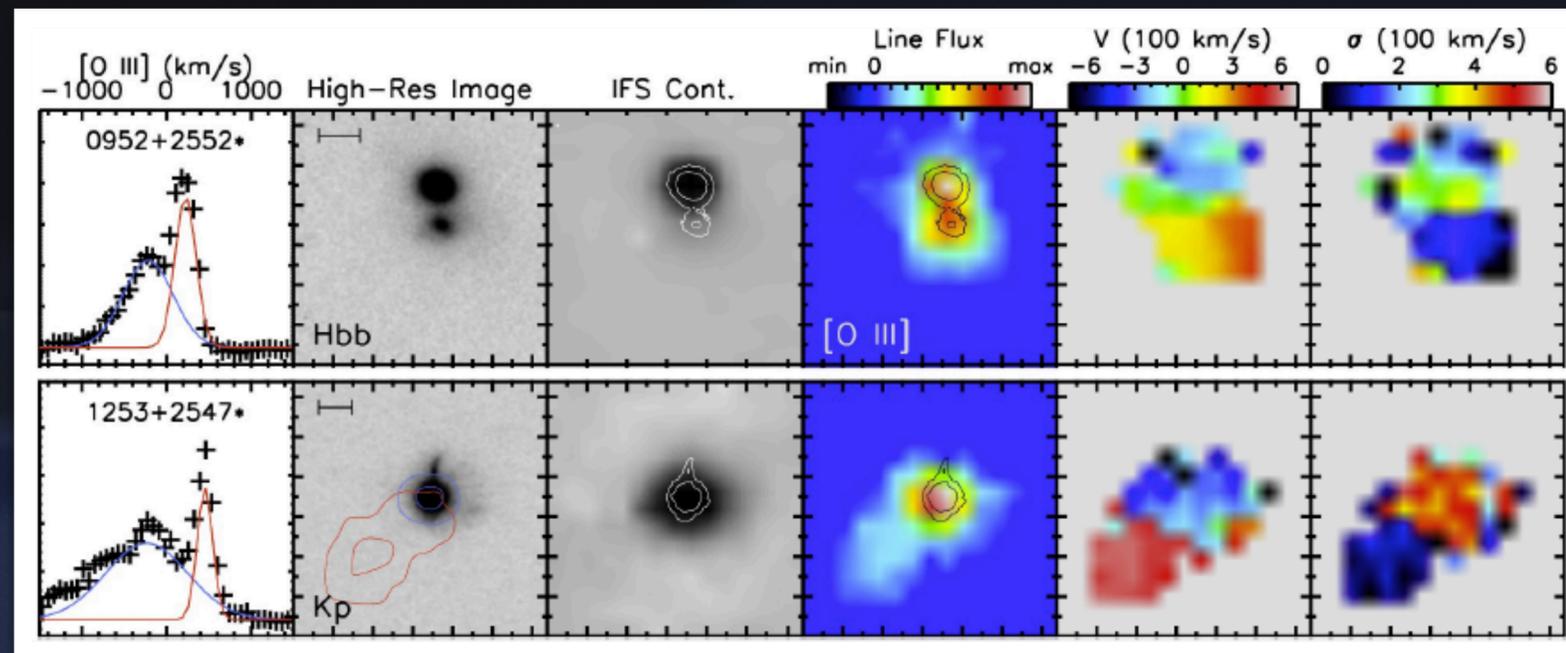
VLA
Dual AGN
(15%)



VLA
jet-driven outflow
(75%)



integral field spectroscopy

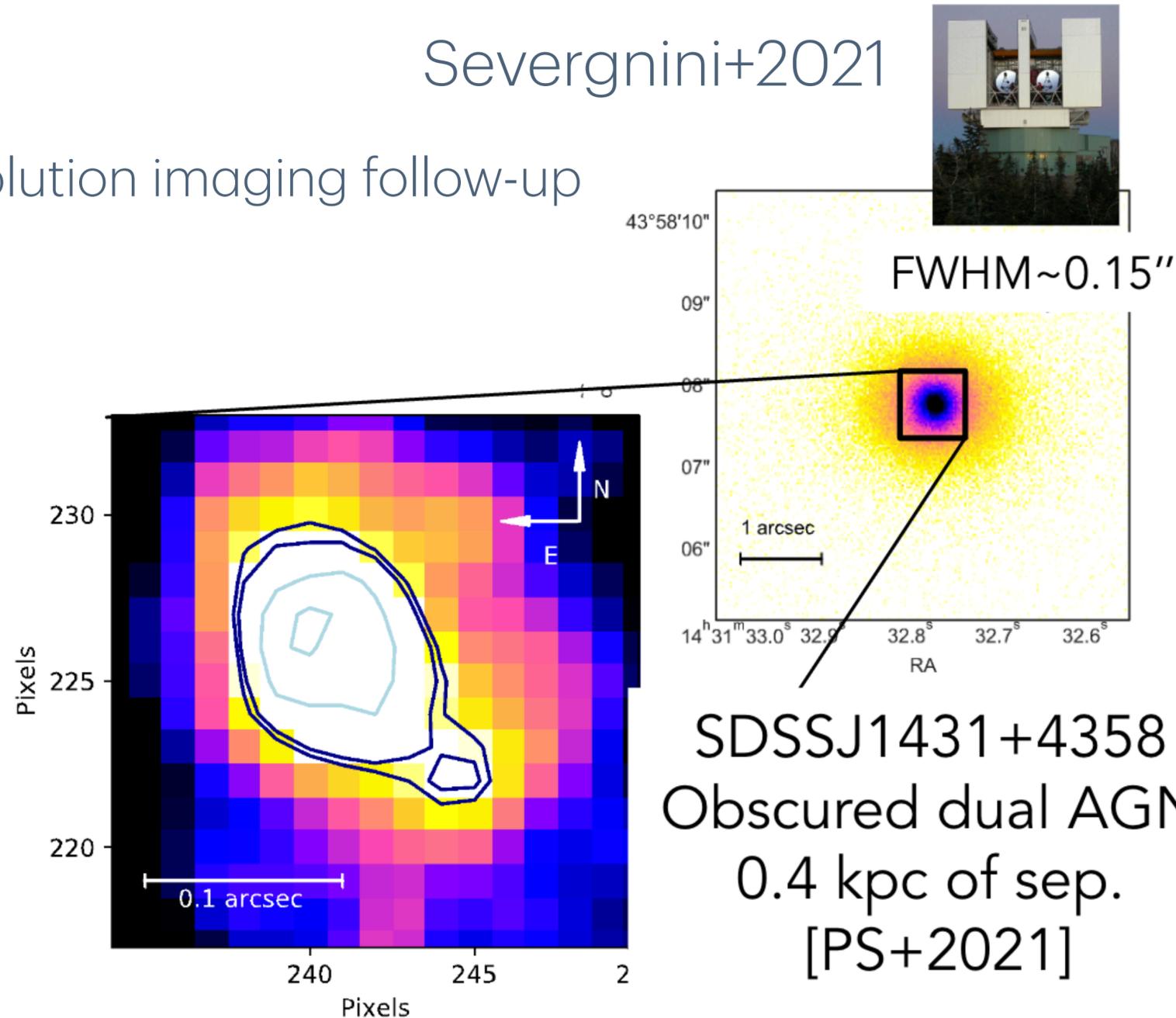


2% of the double-peaked profiles being produced by the relative velocity of merging systems

A still unknown fraction of strongly obscured AGN hosted in dual peaked systems

Severgnini+2021

High resolution imaging follow-up



SDSSJ1431+4358
Obscured dual AGN
0.4 kpc of sep.
[PS+2021]

On-going LBT prproject; LBT Adaptive Optics with LUCI

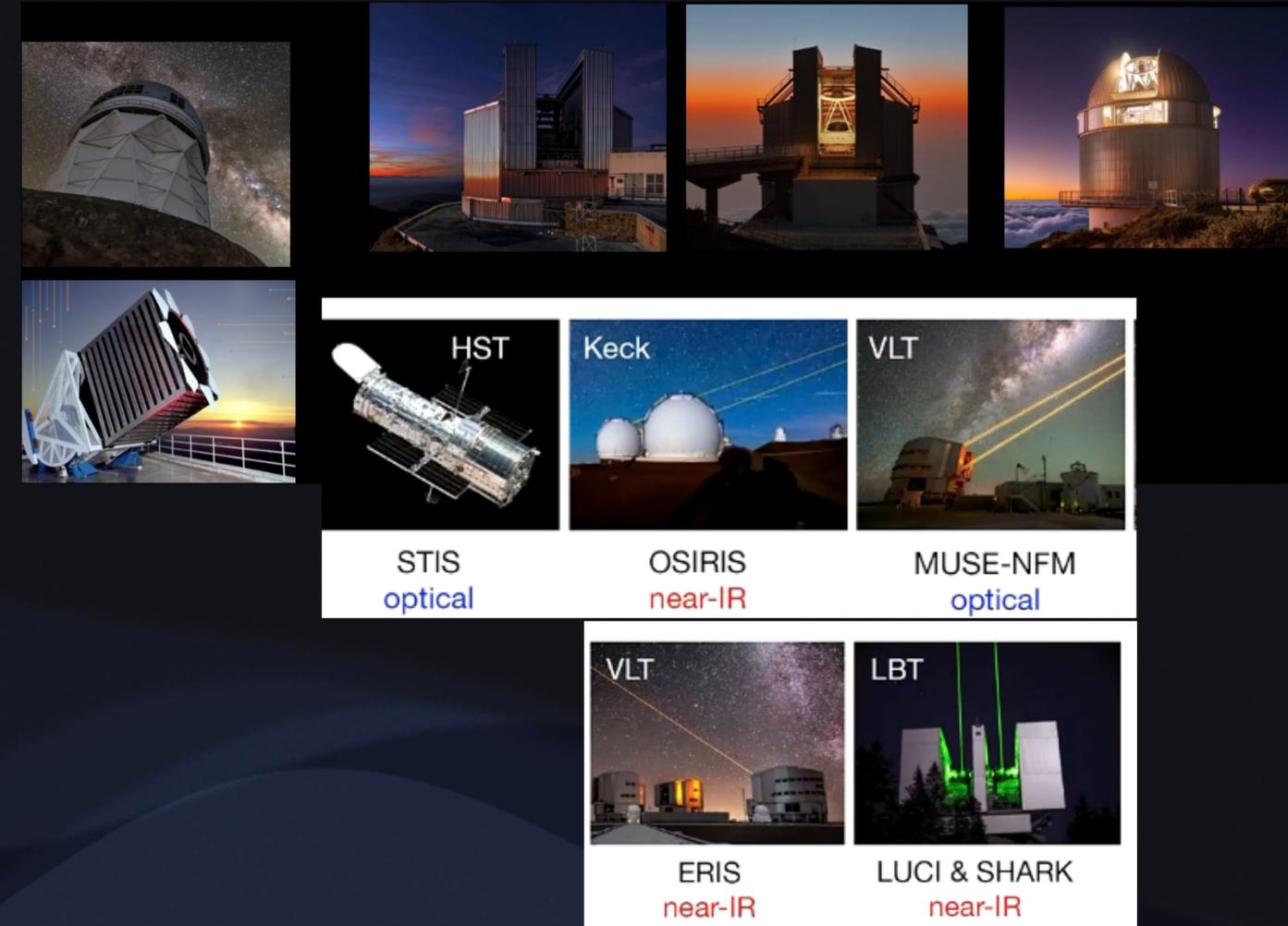
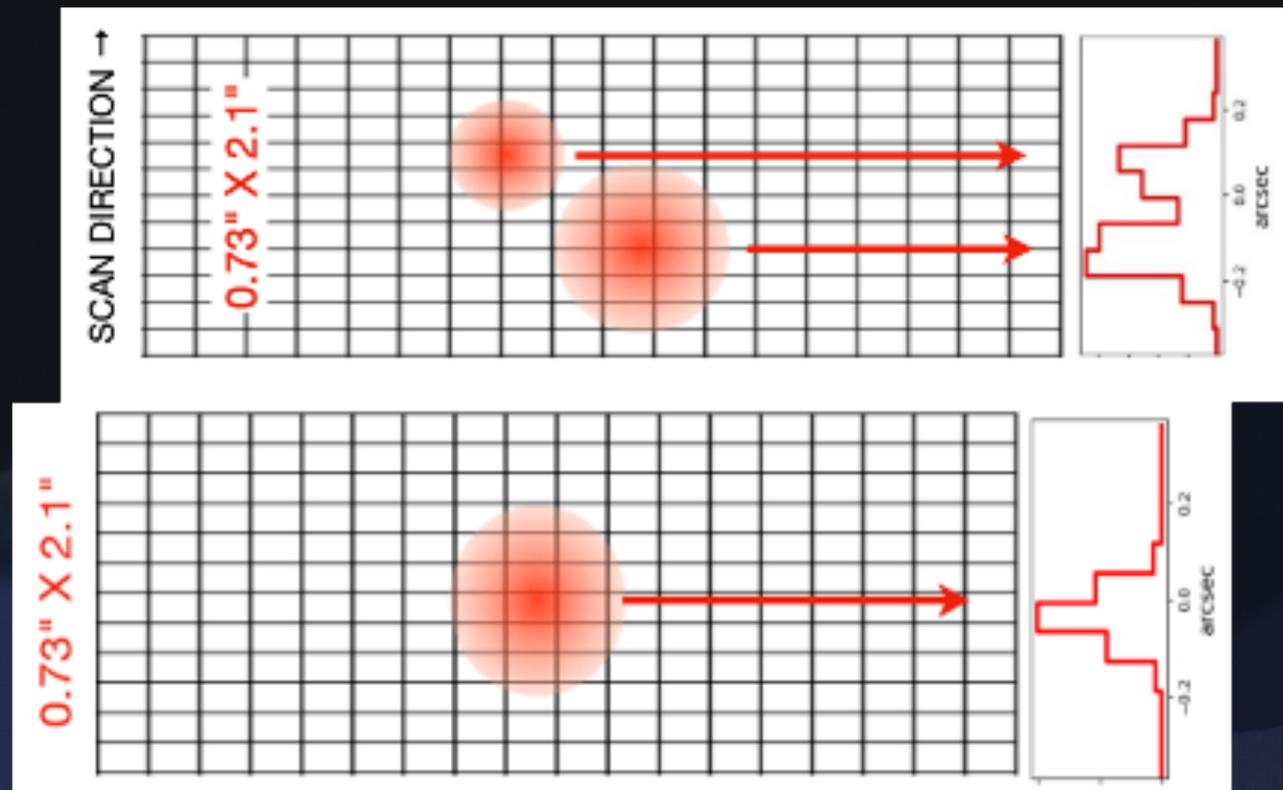
Candidate DP AGN, after a proper galaxy subtraction seconds nuclei detected

Two distinct nuclear components with separation of $\sim 0.2'' \sim 0.4$ kpc

cosmic duets: dual AGN sub-kpc at high-z

Gaia Multi Peak (GMP): Exploiting excellent Gaia PSF in the scan direction (FWHM~0.11")
G-band selection all sky $0.5 < z < 3$

1200 candidates (dual AGN, AGN-Star, lensed AGN)

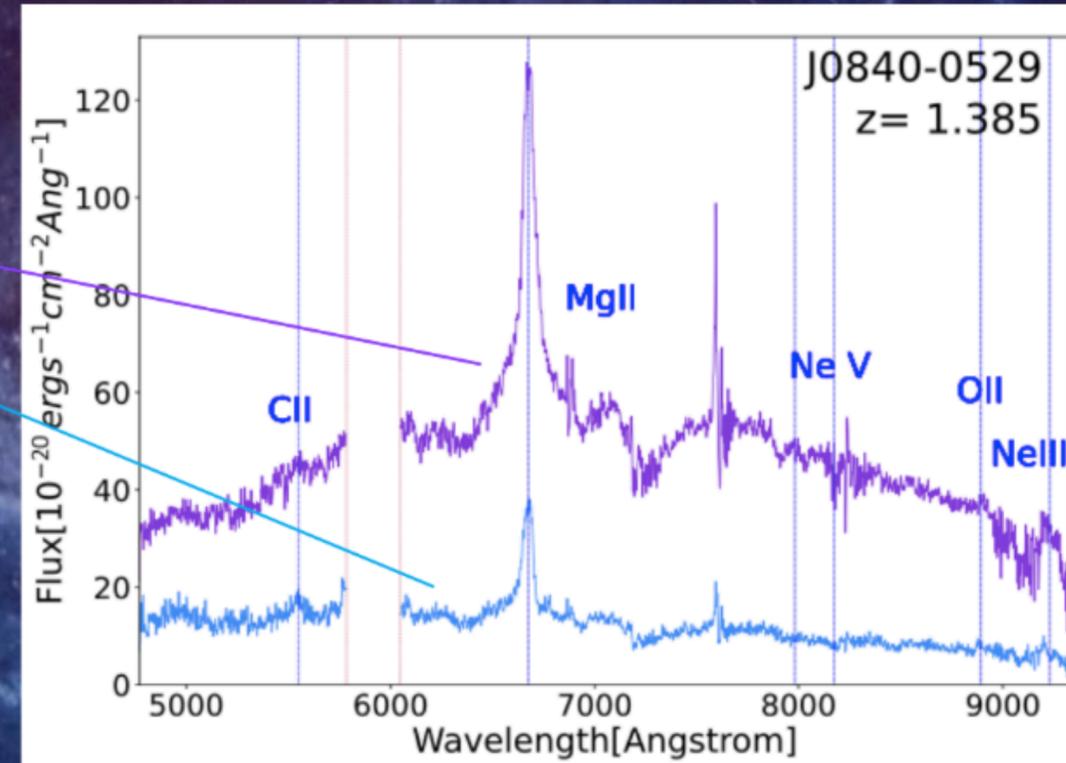
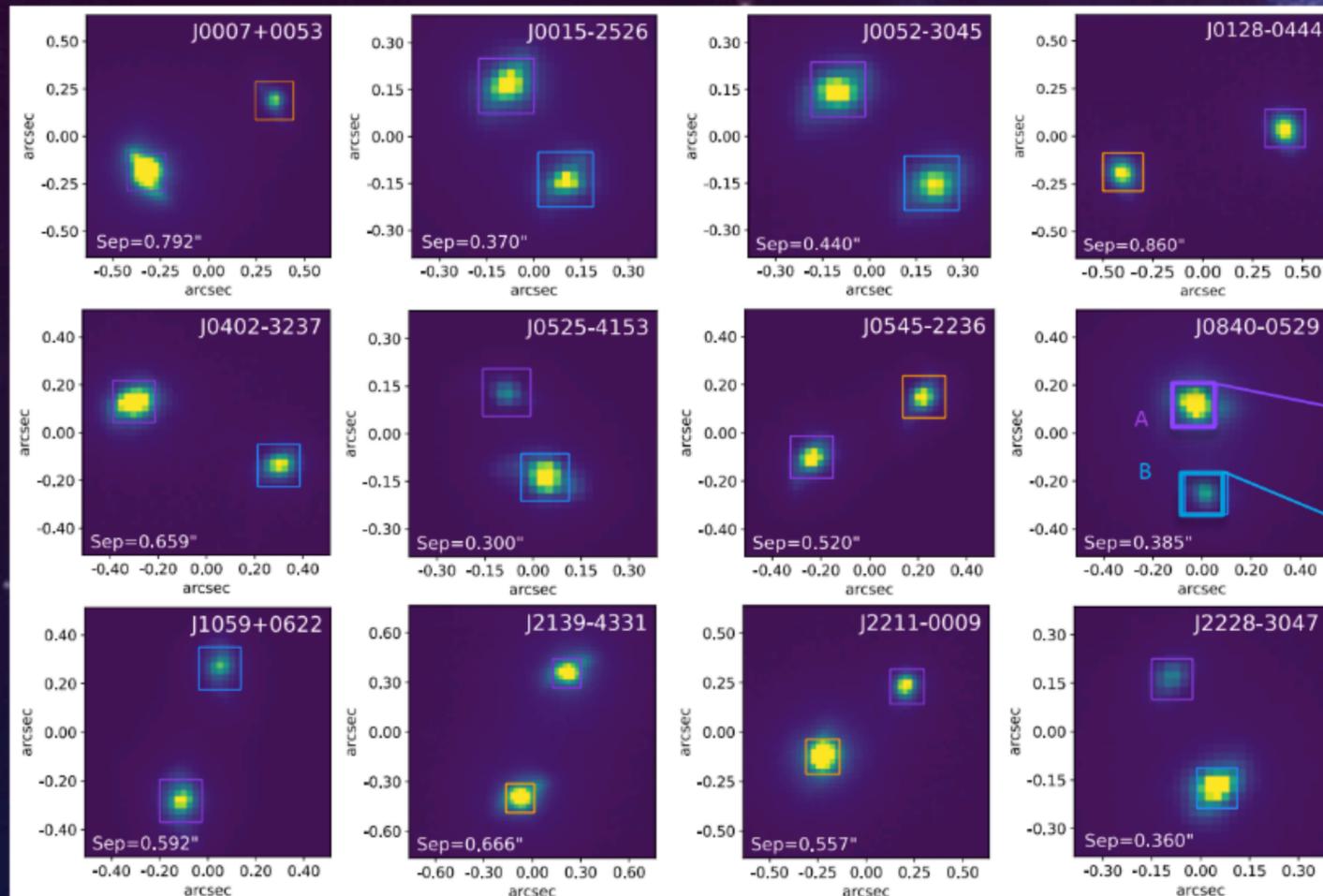


Credits F. Mannucci

GAIA Varstrometry: exploits the photometric variability
Chen+2022; Shen+2021, Hwang+2020

Mannucci+22,23; Ciurlo+2023; Scialpi+24,+26, D'Amato+26,

cosmic duets: dual AGN sub-kpc at high-z



dual-AGN census.

How to distinguish a dual AGN from a lens?

different z

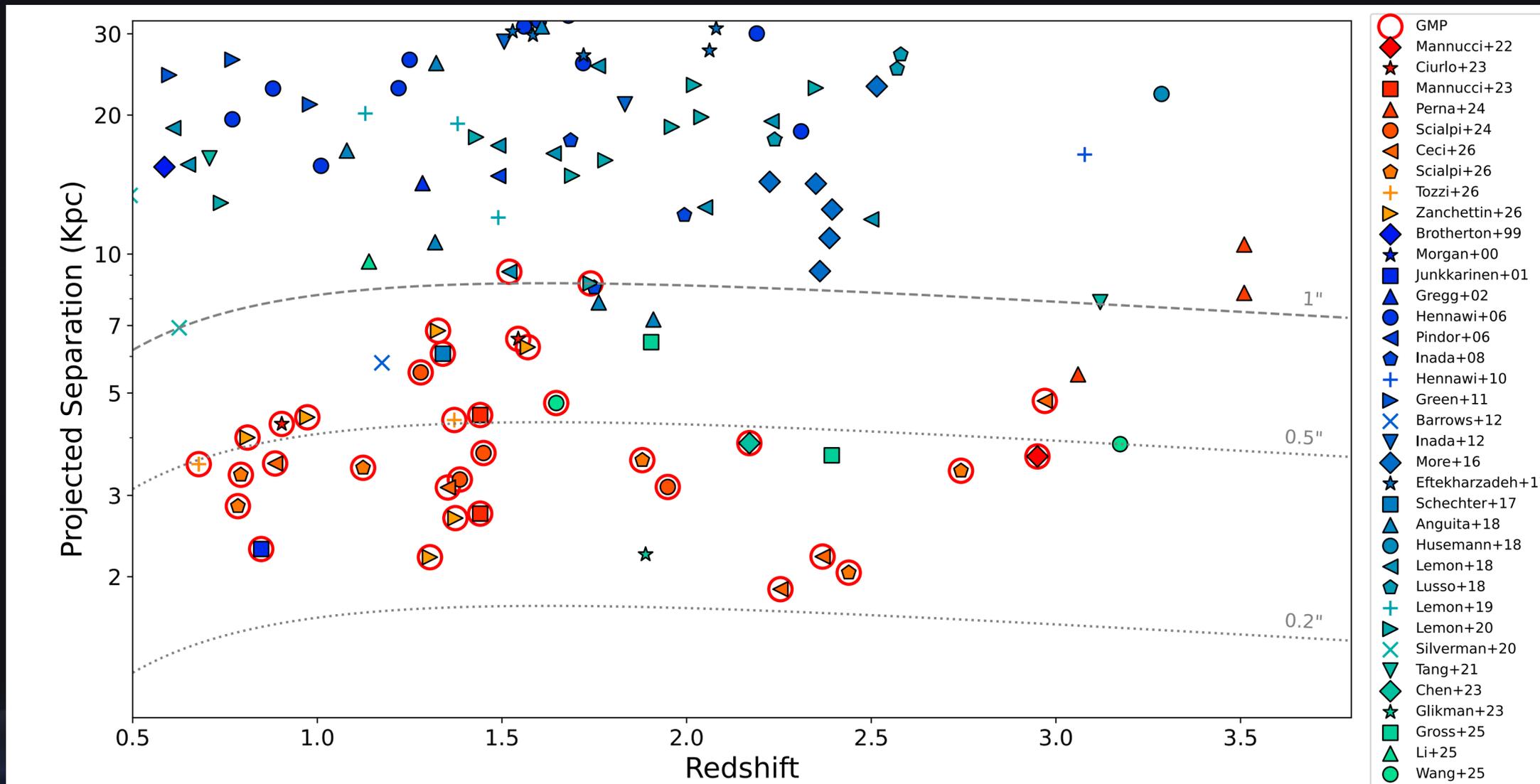
different shape, EW and lines ratio

different Narrow Lines

Credits M. Scialpi, F. Mannucci and the Cosmic Duets group

Mannucci+22,23; Scialpi+24,+26, D'Amato+26, Ciurlo+2023

cosmic duets: dual AGN sub-kpc at high-z



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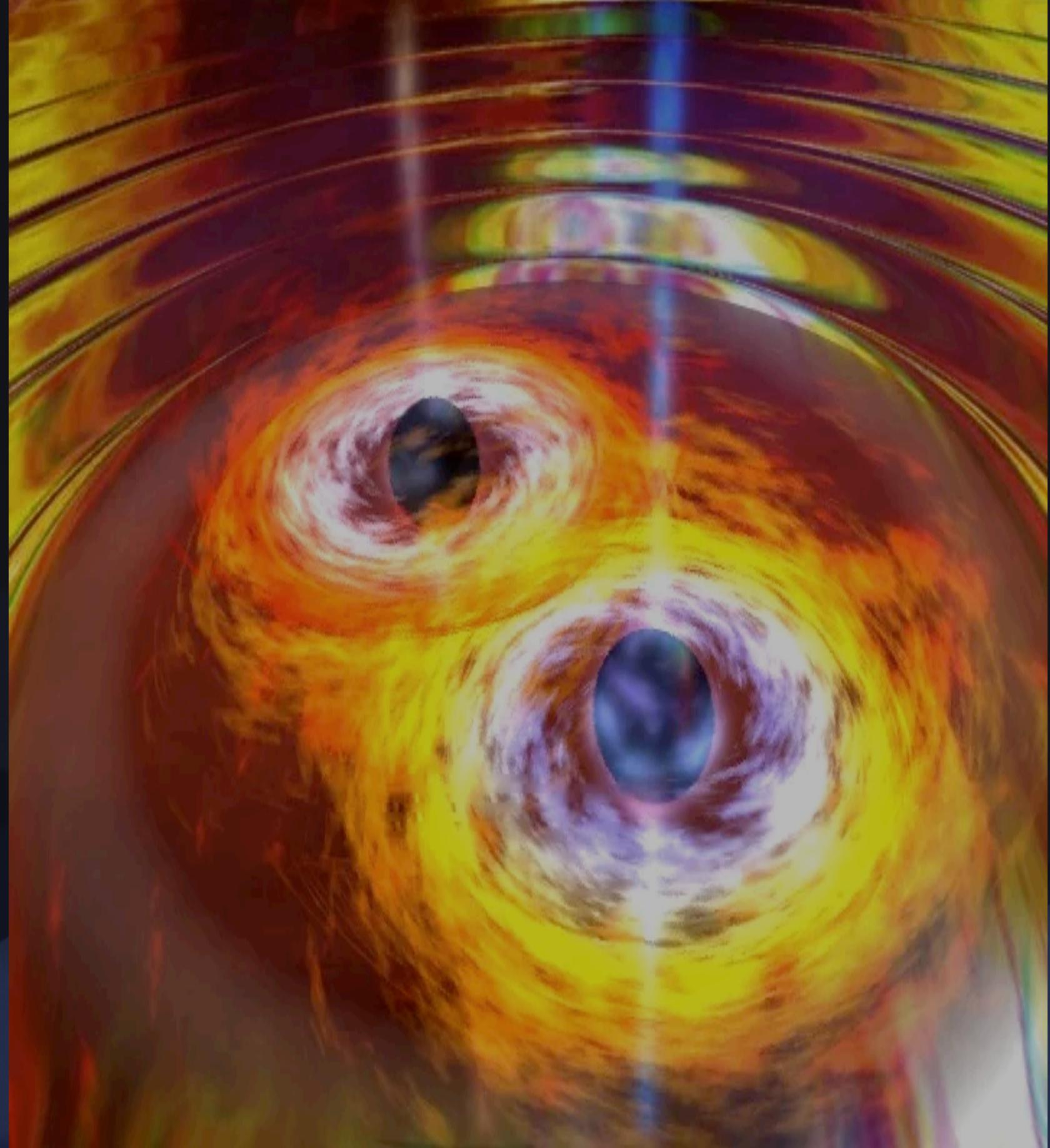
141 GMP systems already observed spectroscopically
43 new dual AGN confirmed @ $z > 0.5$ & sep < 7 kpc (65% GMP selected)

EM observation of binary MBHS: Summary

Direct imaging nearly impossible.
Most of the methods used to identify MBH binaries rely on tracers not uniquely tied to binaries.

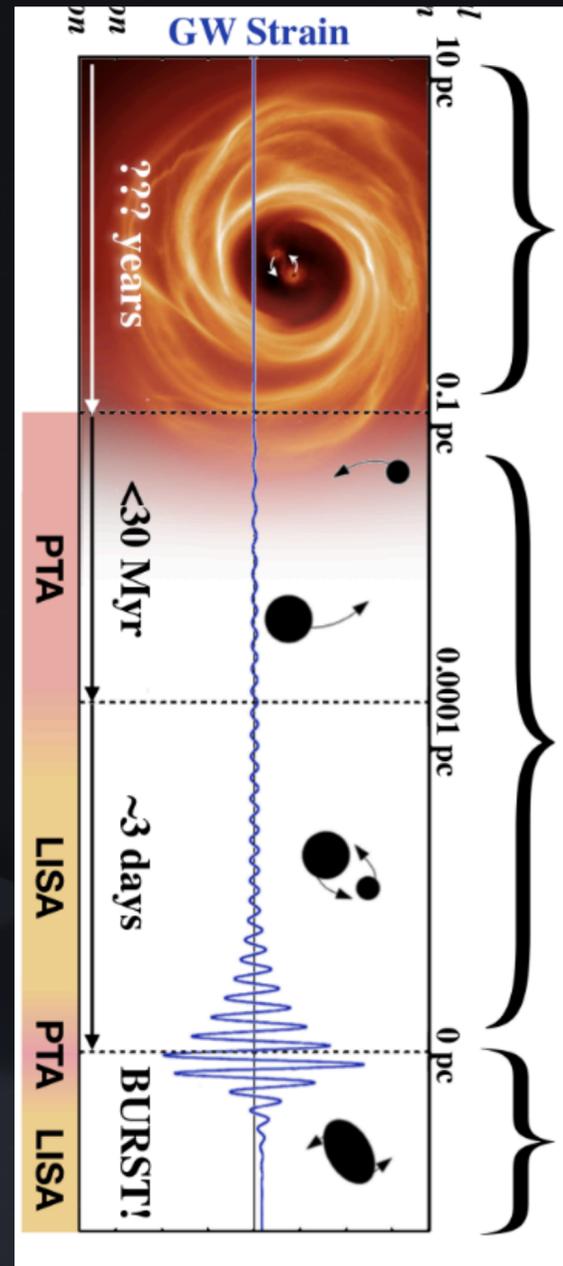
Observations lag behind theoretical models

Confirming an EM counterpart even for just one of these systems would be a great success!



Last steps before the encounter

multi-messenger astrophysics



observational techniques Binary AGN

spatial separation

Orbital Period

direct image with radio interferometry

pc

2Myr

doppler shift emission line (spectroscopy)

0.1 pc

2 kyr

AGN periodicity (photometry)

mpc

6 yr

GW pre merger

2 μ pc

1.6 hours

GW at merger

0.1 μ pc

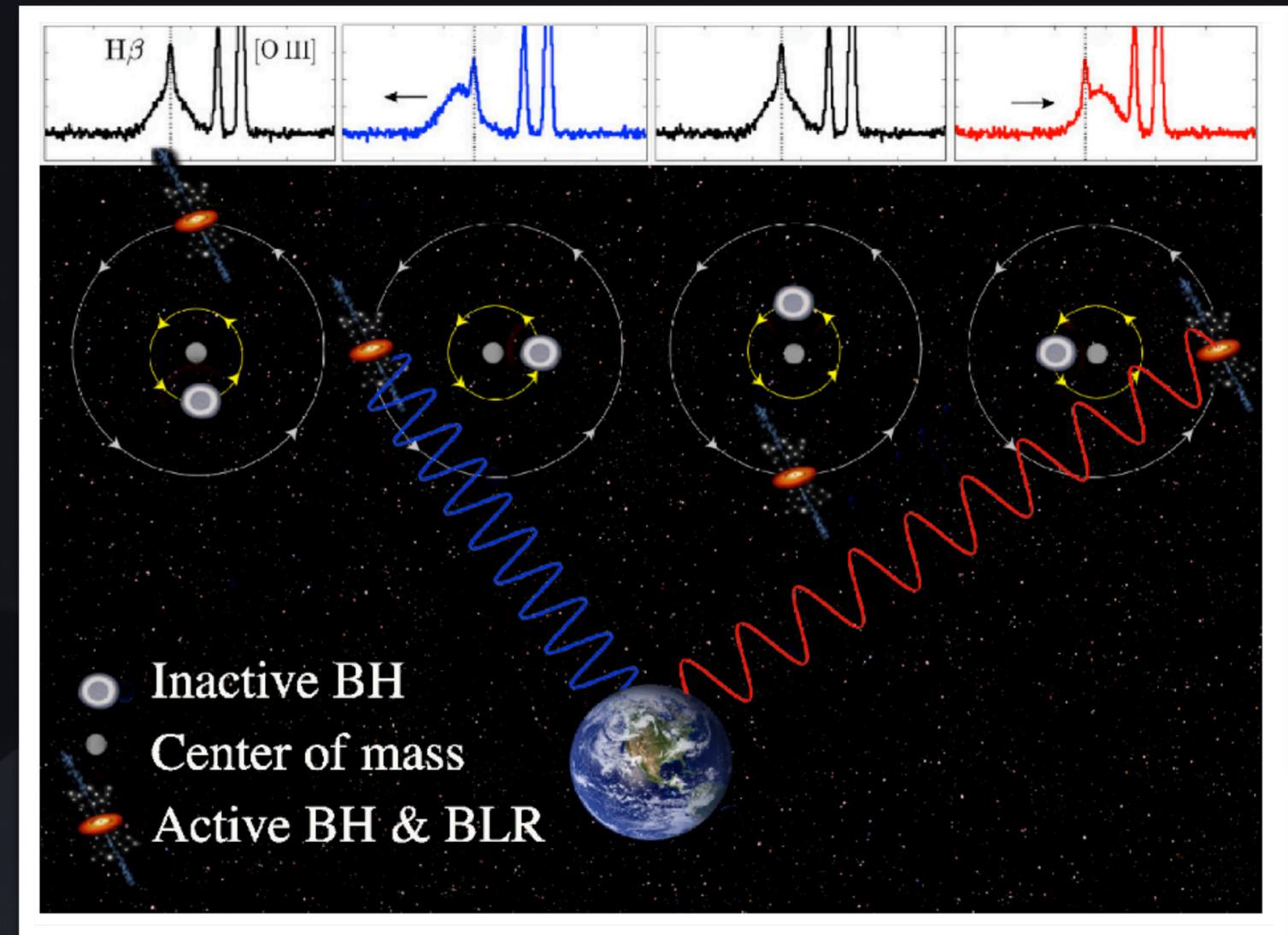
min

Unresolved binaries: doppler shift emission lines

double and variable broad emission lines

Spectroscopic searches of the Doppler shift of BLR lines ($H\alpha$ $\lambda 6563$, $H\beta$ $\lambda 4861$ and $Mg II$ $\lambda 2798$) in the spectrum of a MBHB host caused by the binary orbital motion.

The bulk orbital motion of the BLR is observable as a time-dependent velocity shift in the broad lines relative to the narrow lines emitted from larger size scales in the host galaxy

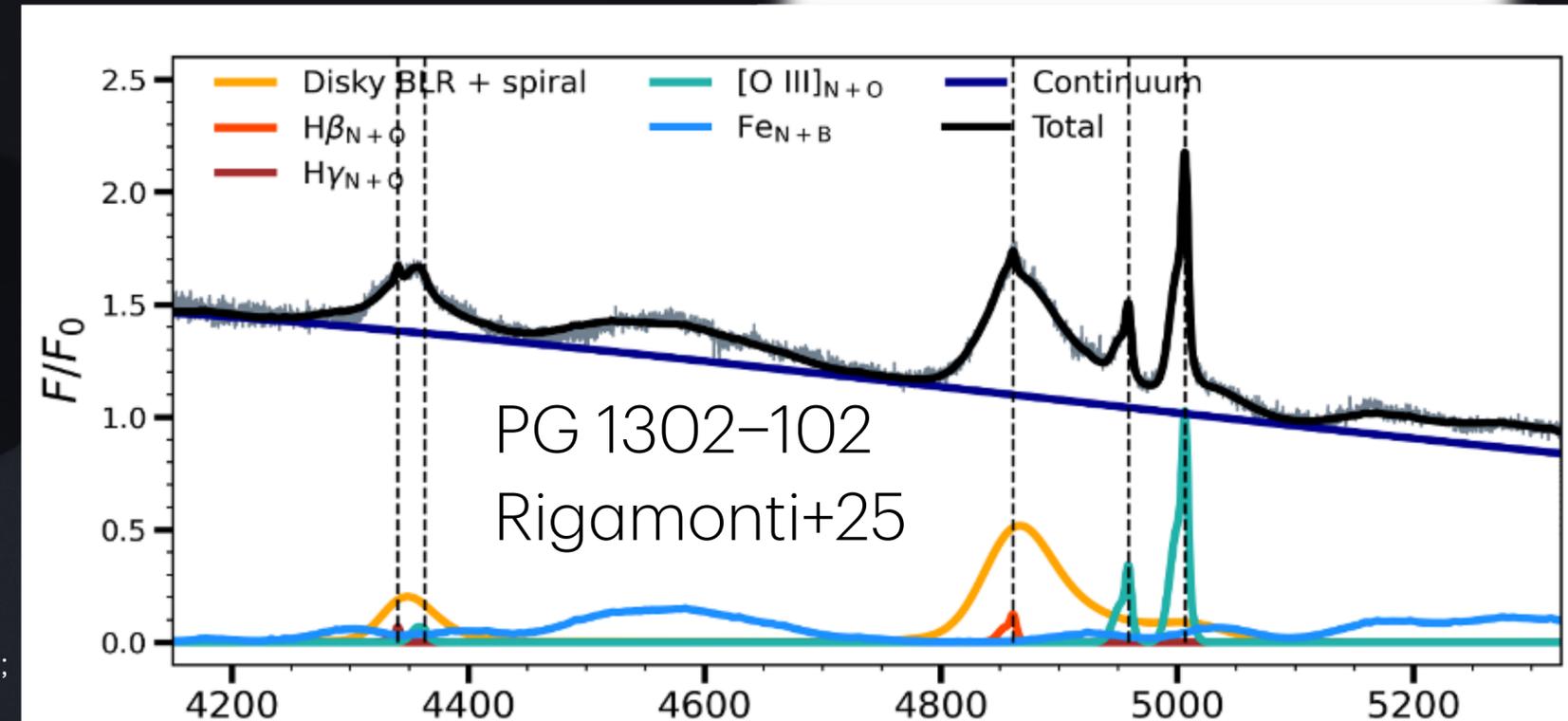
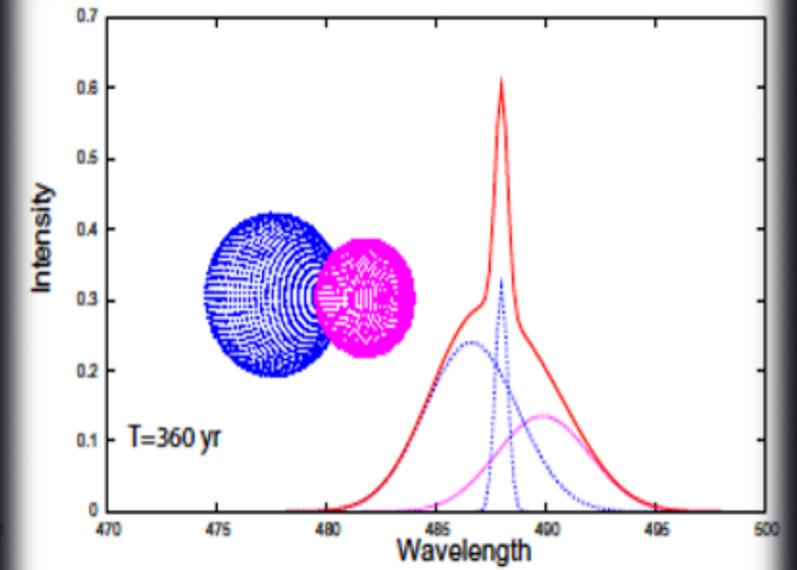
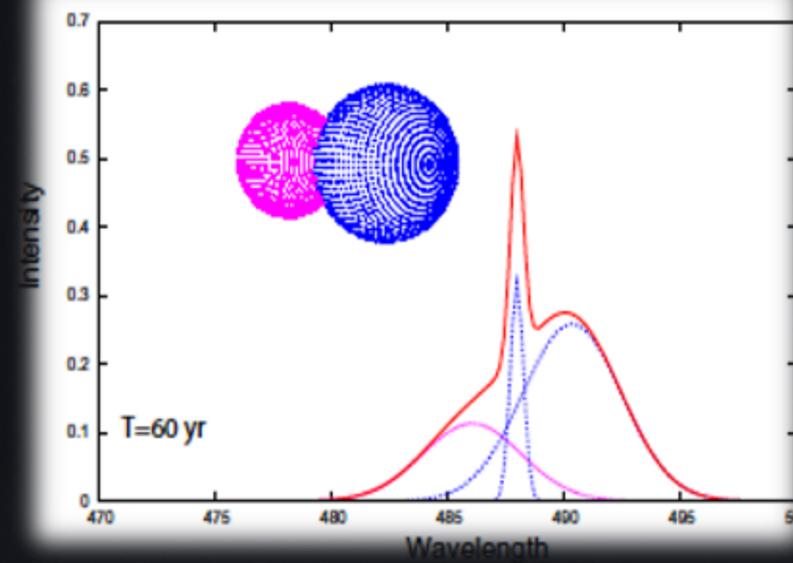


Searching for unresolved MBHs BINARY CANDIDATES

Asymmetric/shifted/double-peaked BROAD emission lines in single epoch spectrum

THESE FEATURES are not ubiquitously associated with binary systems:

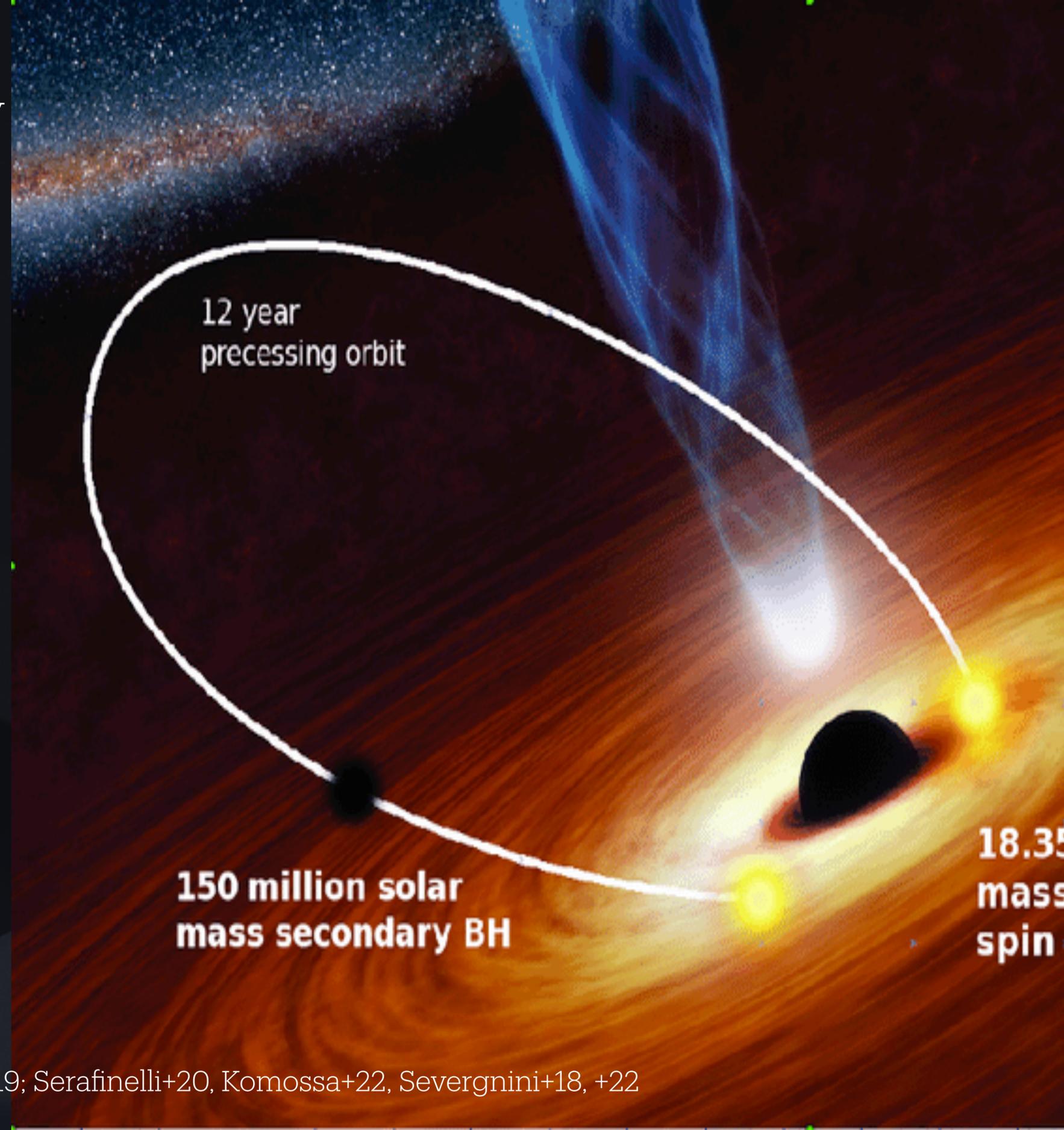
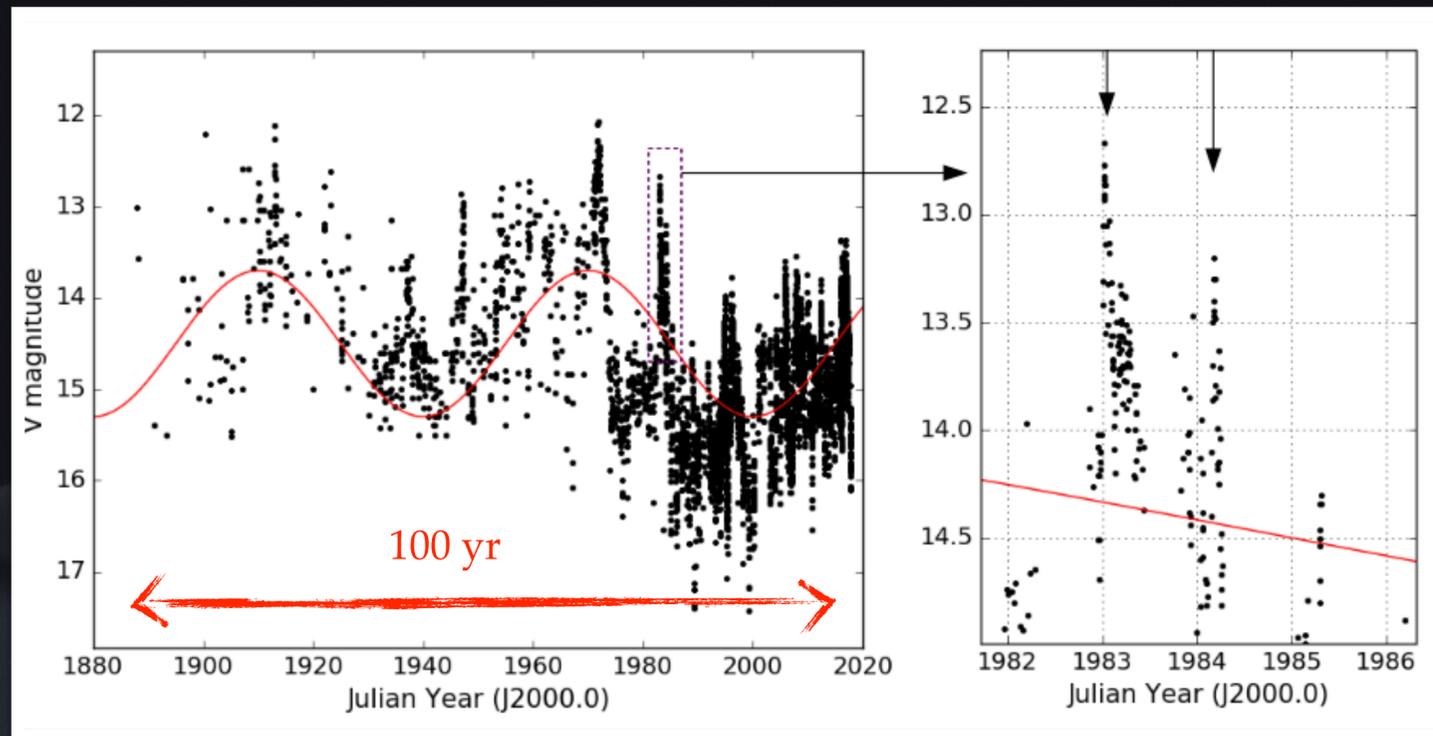
- Chance superposition
- Strong gas outflows, jets of a single BH
- Recoiling MBHs
- Non-symmetric distribution of a single BLR can reproduce the observed spectrum



Unresolved binaries: AGN periodicity

Photometric optical variability

Binary AGN candidates at mpc separation
($T \sim$ years, EM accessible on human timescales):
periodic variability in the lightcurves: OJ 287



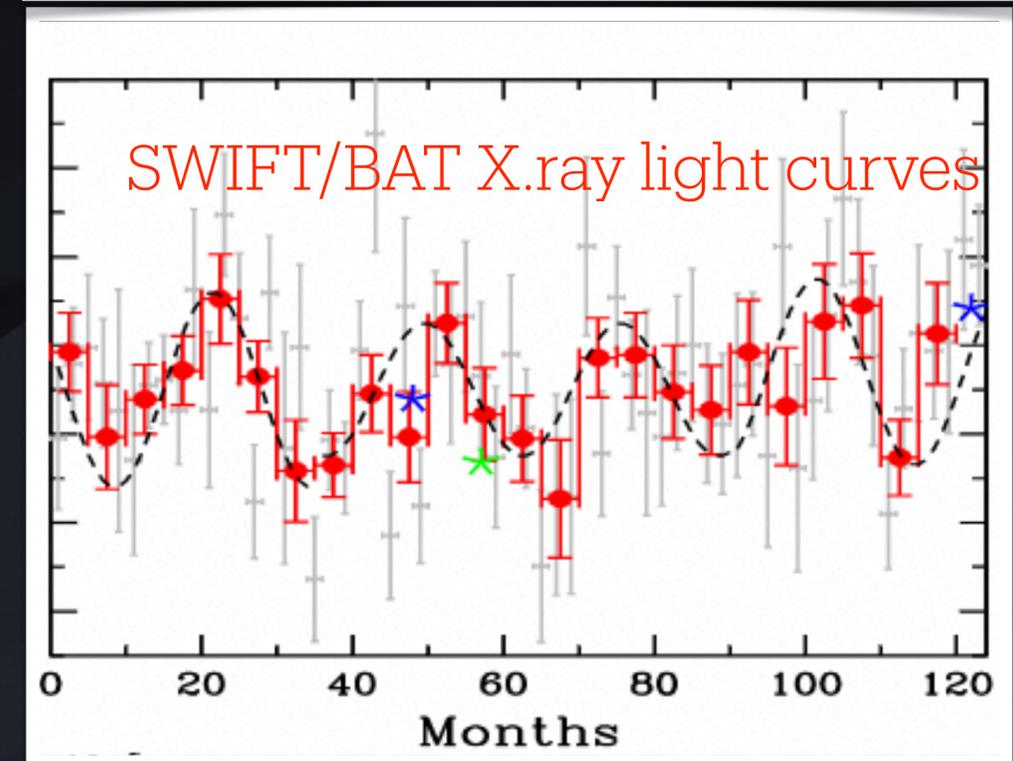
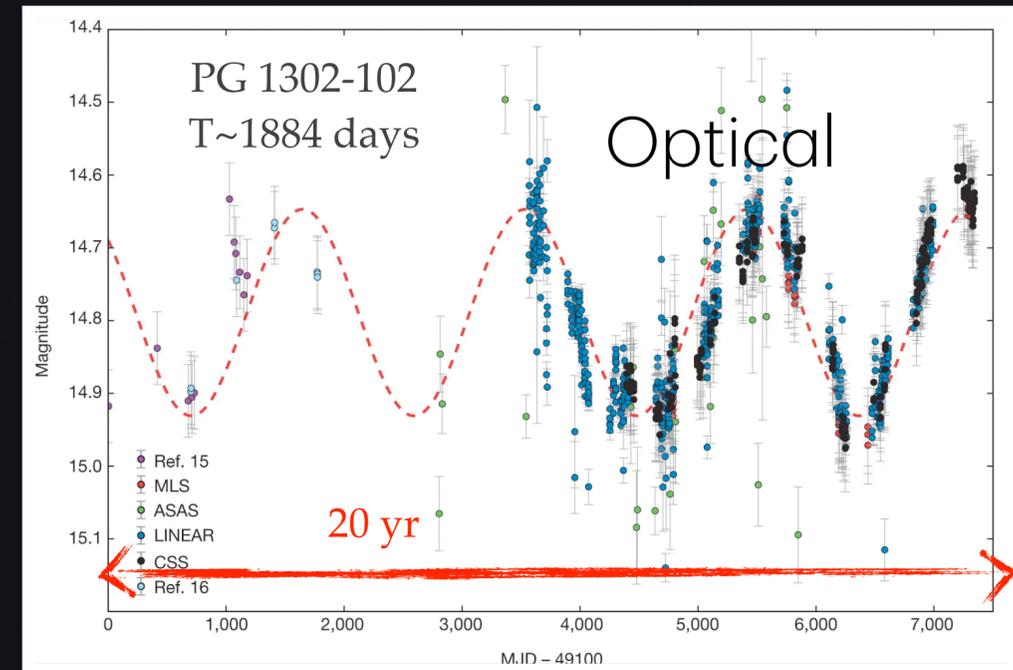
Searching for unresolved MBHs BINARY CANDIDATES

Photometric optical and X-ray variability

In order to record many cycles in surveys (CRT and PTF in optical and Swift/BAT in X-rays) most identified MBHB candidates with relatively short orbital periods (few years or less)

Intermittent time sampling and low S/N make it easier to mistake a phantom periodicity for a real one.

A smooth and systematic period could indicate the presence of an optical quasi-periodic oscillation (QPO), e.g. a strong resonance in the accretion flow not related to the orbit of a binary SMBH.



Unresolved binaries: X-ray spectral variability and spectroscopy the case of MCG+11-11-032

The CASE of MCG+11...

SMBH BINARY candidate

$$M_{\text{BH}} \sim 5 \times 10^8 M_{\odot}$$

$$\text{Sep} \sim 6 \times 10^{-3} \text{ pc}$$

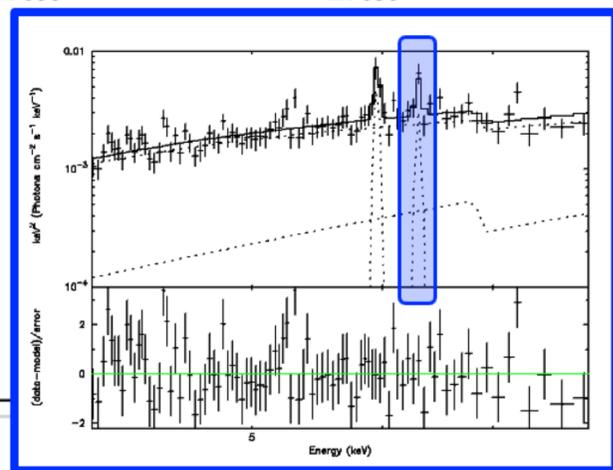
$$T_{\text{coal}} \sim 3 \times 10^4 \text{ yrs}$$

GW in the PTA range

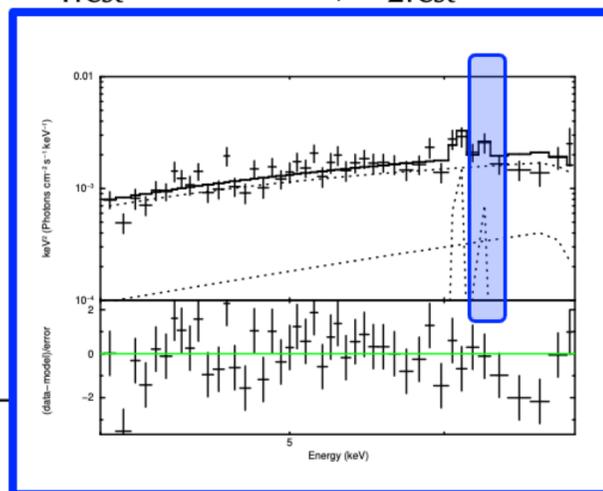
Master Thesis L. Vincetti

See also Severgnini+18

XRT (2015-2016)
 $E_{1\text{rest}} \sim 6.16 \text{ keV}, E_{2\text{rest}} \sim 6.56 \text{ keV}$



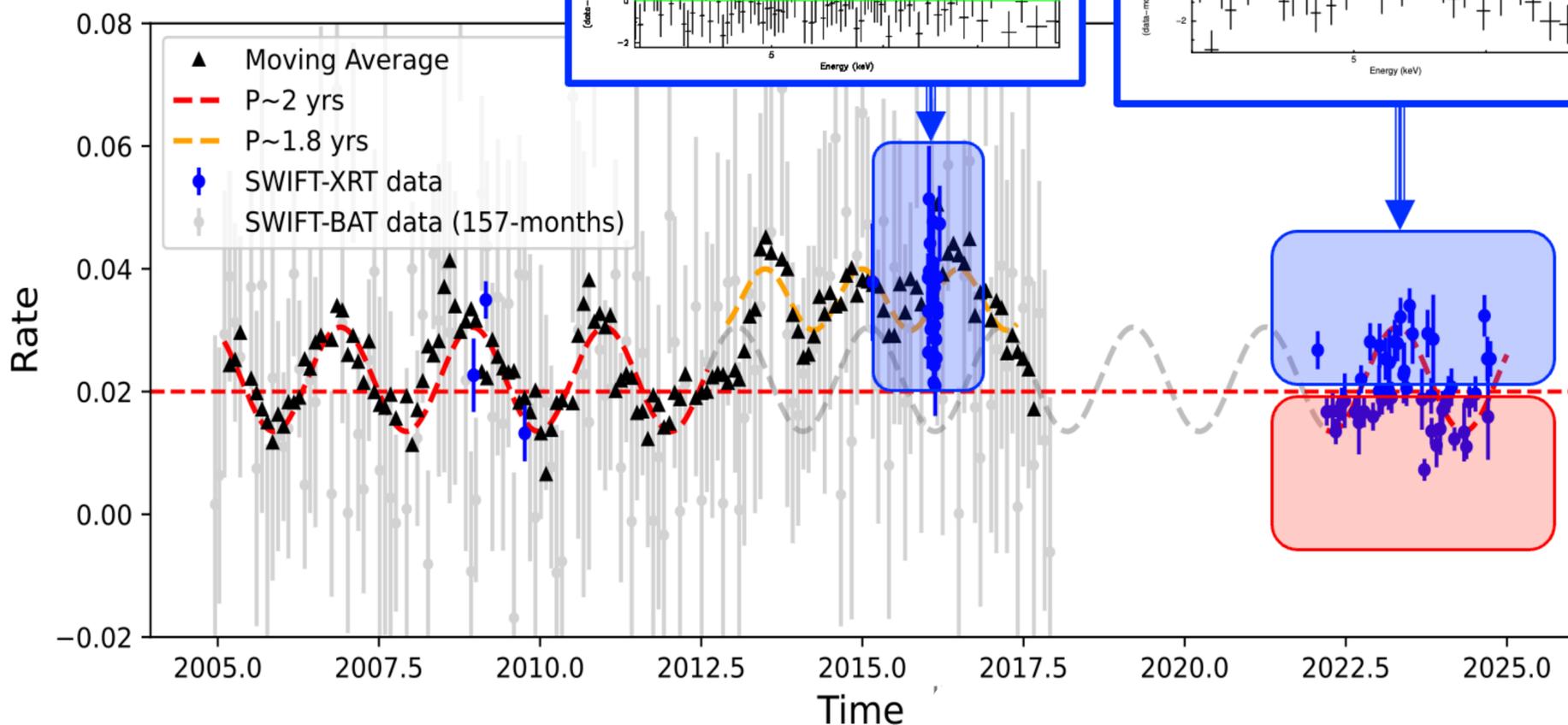
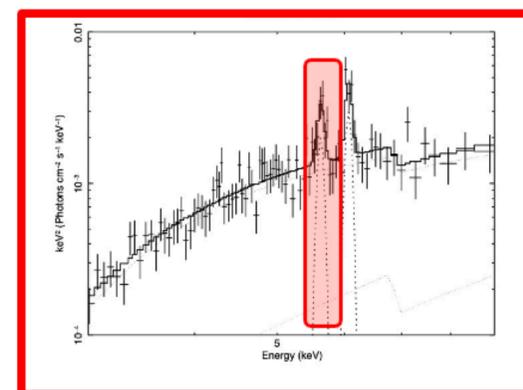
Chandra (2023)
 $E_{1\text{rest}} \sim 6.35 \text{ keV}, E_{2\text{rest}} \sim 6.51 \text{ keV}$



HIGH FLUX STATE

LOW FLUX STATE

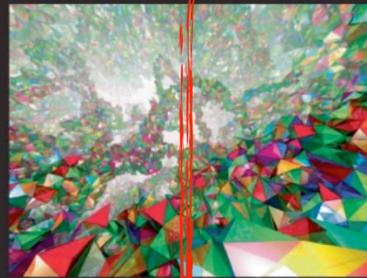
XRT (2022-2024) - low-state
 $E_{1\text{rest}} \sim 5.83 \text{ keV}, E_{2\text{rest}} \sim 6.3 \text{ keV}$



This calls for X-ray telescopes with large collecting area and high spectral resolution (e.g., XRISM, Athena, AXIS, Lynx).

Credit P. Severgnini

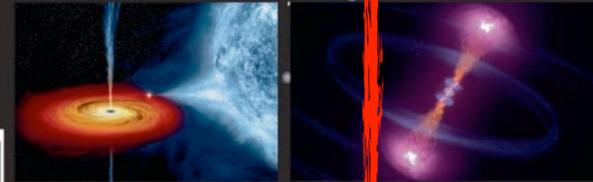
Sources



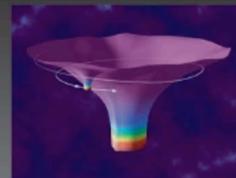
Big Bang



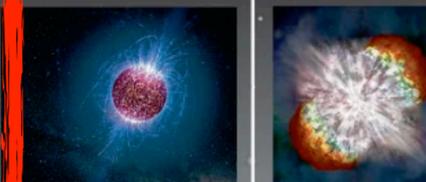
(Super-)massive black hole inspiral and merger



Compact binary inspiral and merger



Extreme-mass-ratio inspirals



Pulsars, supernovae

Wave period

Wave frequency

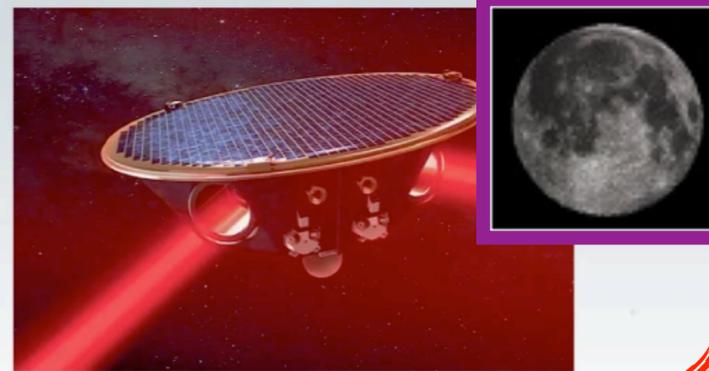
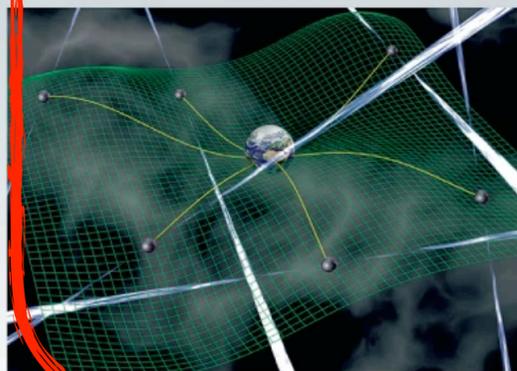


Radio pulsar timing arrays

Space-based interferometers

Terrestrial interferometers

Detectors



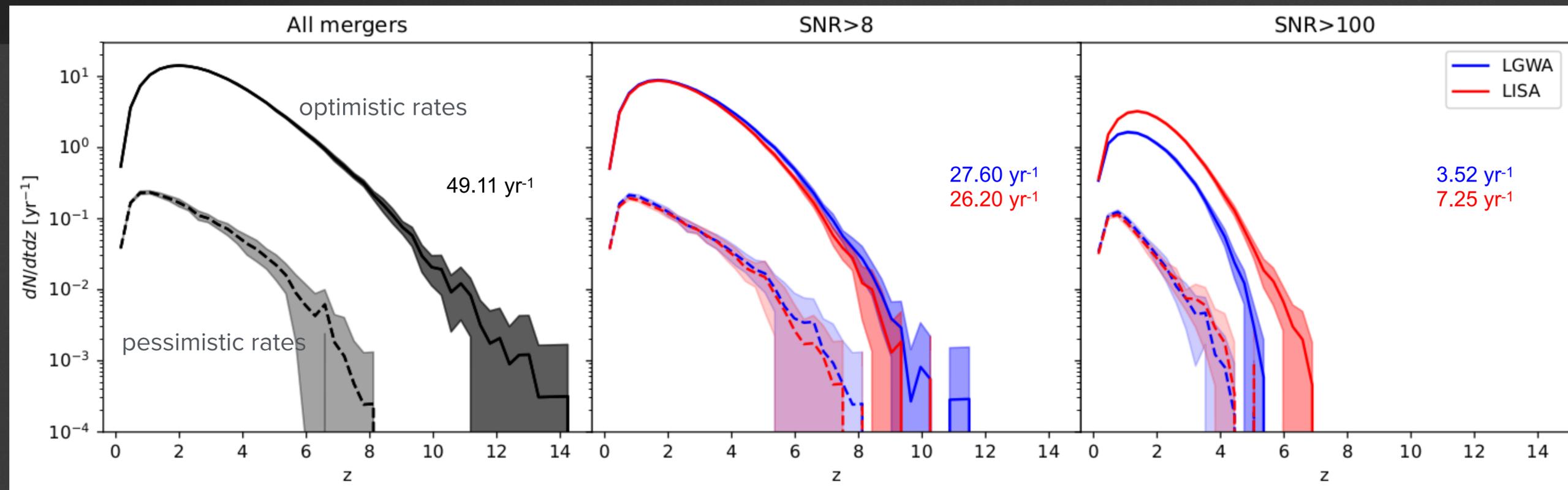
adapted from Bailes+2021

Black hole merger rates for LISA and LGWA from semi-analytical modelling of light seeds

J. Singh+25, arXiv:2512.06094

Combining dark matter halo merger trees from **PINOCCHIO** simulation (Monaco+02) of $(60 \text{ Mpc})^3$ volume with the semi-analytical model presented in Cammelli+25 to construct a population of massive black hole pairs. Then using a simple prescription of dynamical friction for the orbital decay of black hole pairs within galaxies to calculate the rate of merger of these pairs, after convolving with the sensitivity curves of LISA and LGWA.

Number of mergers per unit redshift per year at different redshifts.



INAF contribution to LISA

LISA-Science@INAF member groups

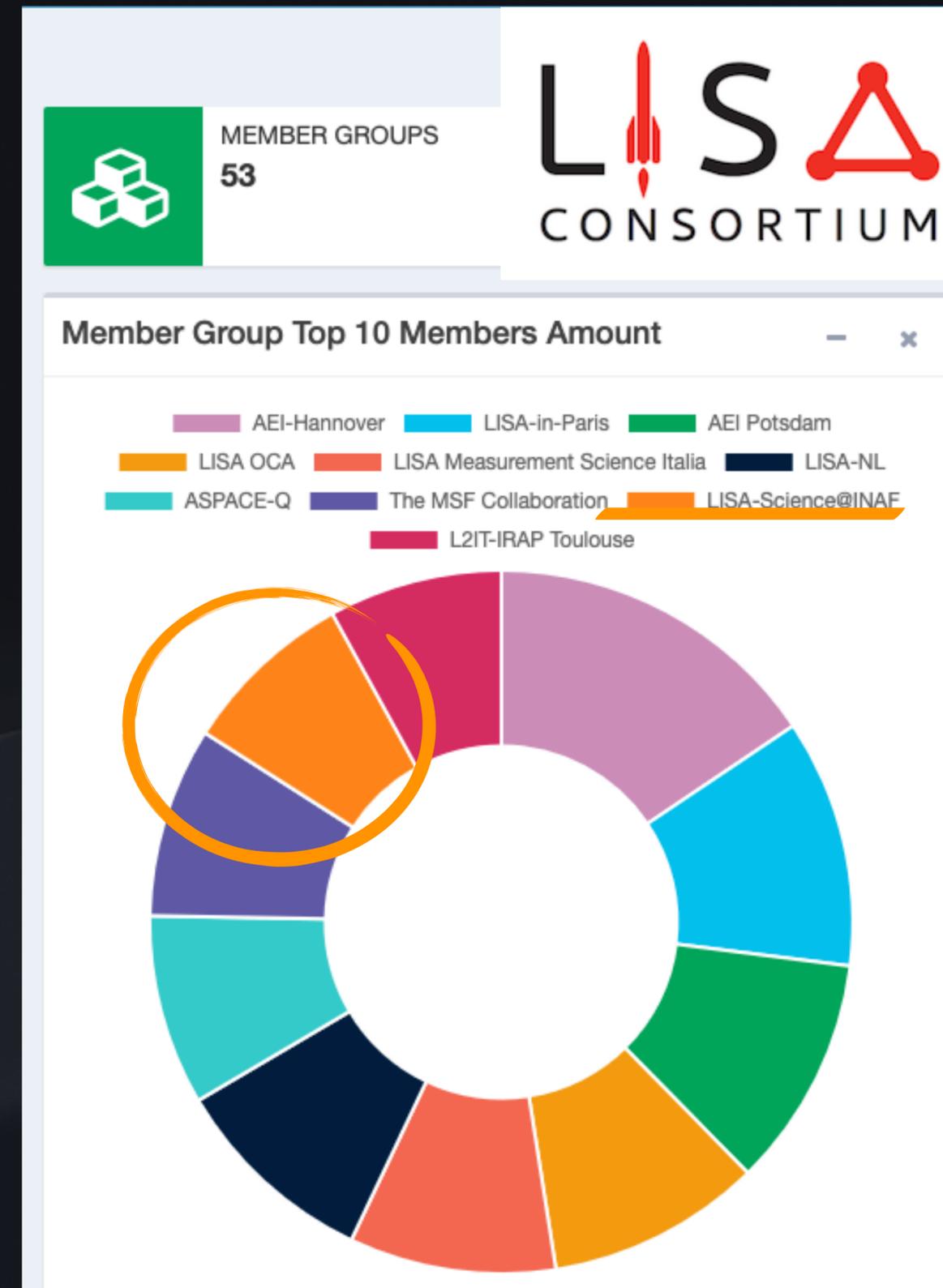
Chair A. De Rosa (IAPS)

Group Comment: The group will coordinate the scientific activities conducted at INAF. The proposed activities encompass a broad range of LISA-related science, including astrophysics (such as the study of massive black hole catalogs and simulations, compact objects, and multi-messenger astronomy) and cosmology. The group will also oversee data analysis efforts, including INAF's contributions to the DDPC.

It is among the largest Member groups in LISA (24)

Italy LISA Data Analysis: E. Barausse (SISSA) 2 INAF + 2 INAF Ass

Italy LISA Astrophysics: A. Lupi (U Bicocca, INAF Ass), 6 INAF Ass



LISA ASI Contribution: INAF addendum

ASI-INAFA addendum

Low latency pipeline, SMBH simulations and catalogues, Italian DCC (Data Computing Center)

Definition and development of the IT infrastructure (in collaboration with SSDC) necessary for simulations and data analysis.

The program is part of the following LISA DDPC (Distributed data processing center) branches: Simulations and external data (Source population generation); Low Latency alert (LA2); Catalogues (L3C); System Engineering and DCC

OA Trieste (PI. D. Tavagnacco)

IAPS (A. De Rosa)

OA Arcetri (F. Mannucci)

OA Brera (P. Severgnini)

OA Roma (R. Valiante)



IAPS OA-Brera OA-Arcetri OA-Roma OA-Abruzzo
 Univ: Bicocca - Sapienza - Roma Tre - Trento - Bologna
 RSN1 - RSN4 - RSN5

Observation

- Selection bias matters!
- Galaxy interactions may contribute significantly to the population of obscured and most luminous AGN
- Large volume surveys will be fundamental to increase sample (Cosmic Duets) and improve our knowledge of single and dual AGN variability (Rubin/LSST, SDSS-V, Roman Space, Euclid, SKA)
- Alternative periodicity mechanisms in single AGN ? can we distinguish from Binaries?

Simulations

- Space of parameters which would maximize the probability dual/binary AGN from the theoretical/simulation point of view: Edd. ratio, BH mass ratio, M^* ratio, ...
- How far are we from 'realistic' simulations: AGN with 'proper' coronal emission and obscuration, Eddington ratio distribution, mass ratio: Are larger variety of assumptions wrt. 'standard' SMBHs needed?

Thank you!