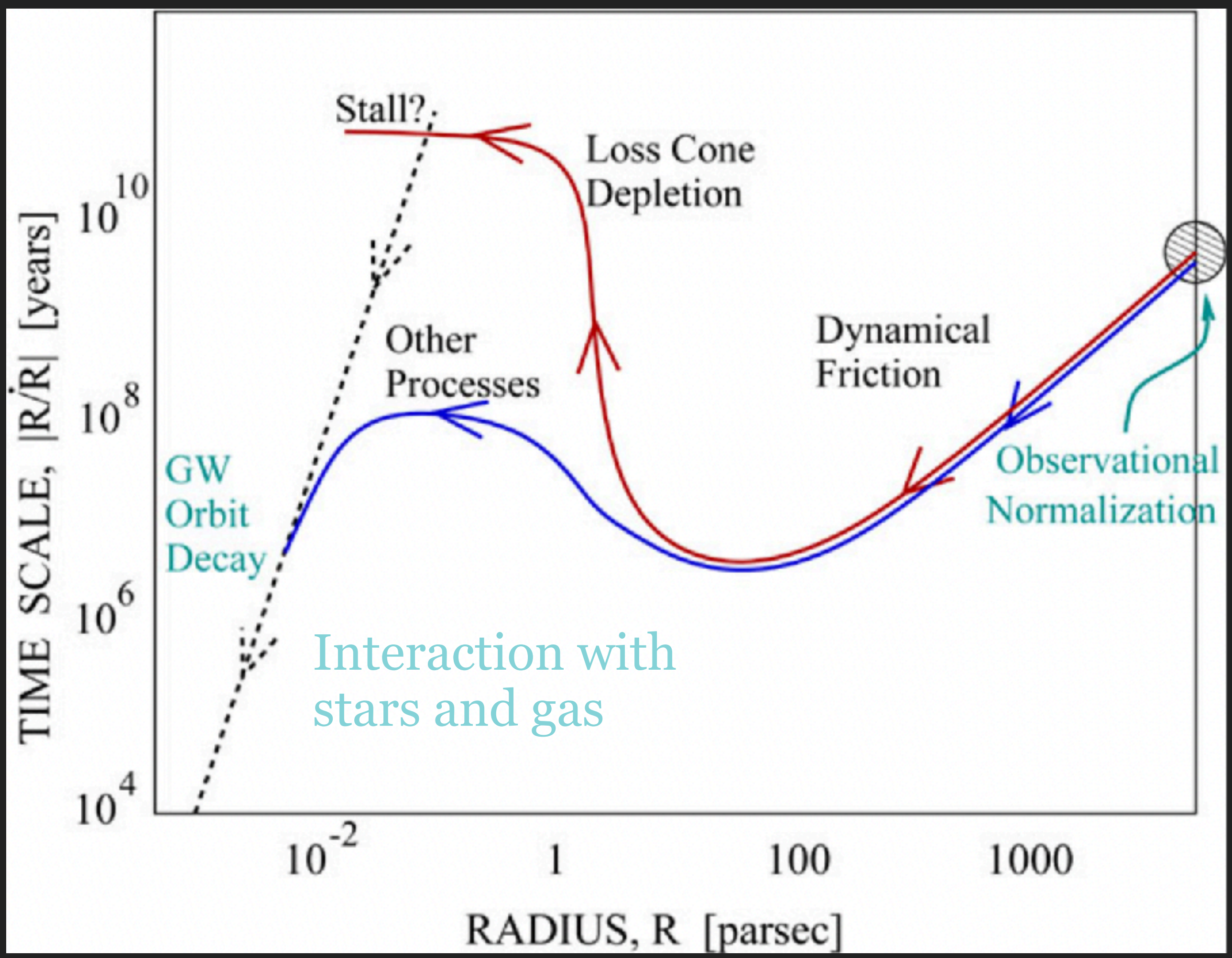
ELECTROMAGNETIC COUNTERPARTS OF SUB-PC MASSIVE BLACK HOLE BINARIES

Alessia Franchini

April 9th 2025

ACME Workshop

PATH TO COALESCENCE OF SMBHBS



Baker et al. (2003)

Stages of SMBH binary evolution:

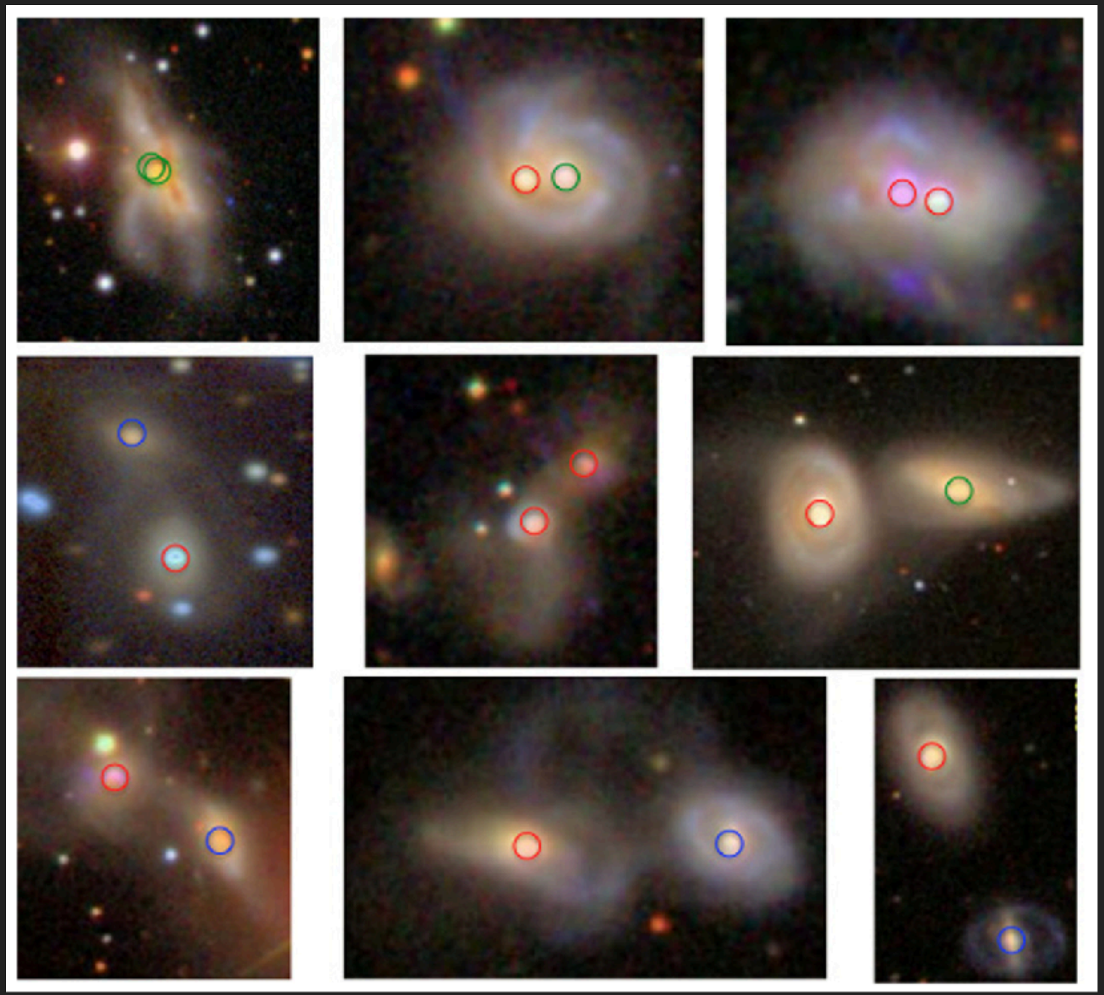
I. Galaxy merger: coalescence of galactic nuclei and SMBH pair formation inside remnant, 100 kpc - few kpc, orbital time ~ 1-few Gyr

II. Formation of SMBH binary : 1 kpc - 1 pc, orbital time $10^7 - 10^9$ yr

III. Binary hardening via gas and stars: 1 pc - 10^{-3} pc, orbital time $10^3 - 10^7$ yr

IV. Inspiral and coalescence via GW emission

STAGE I-II

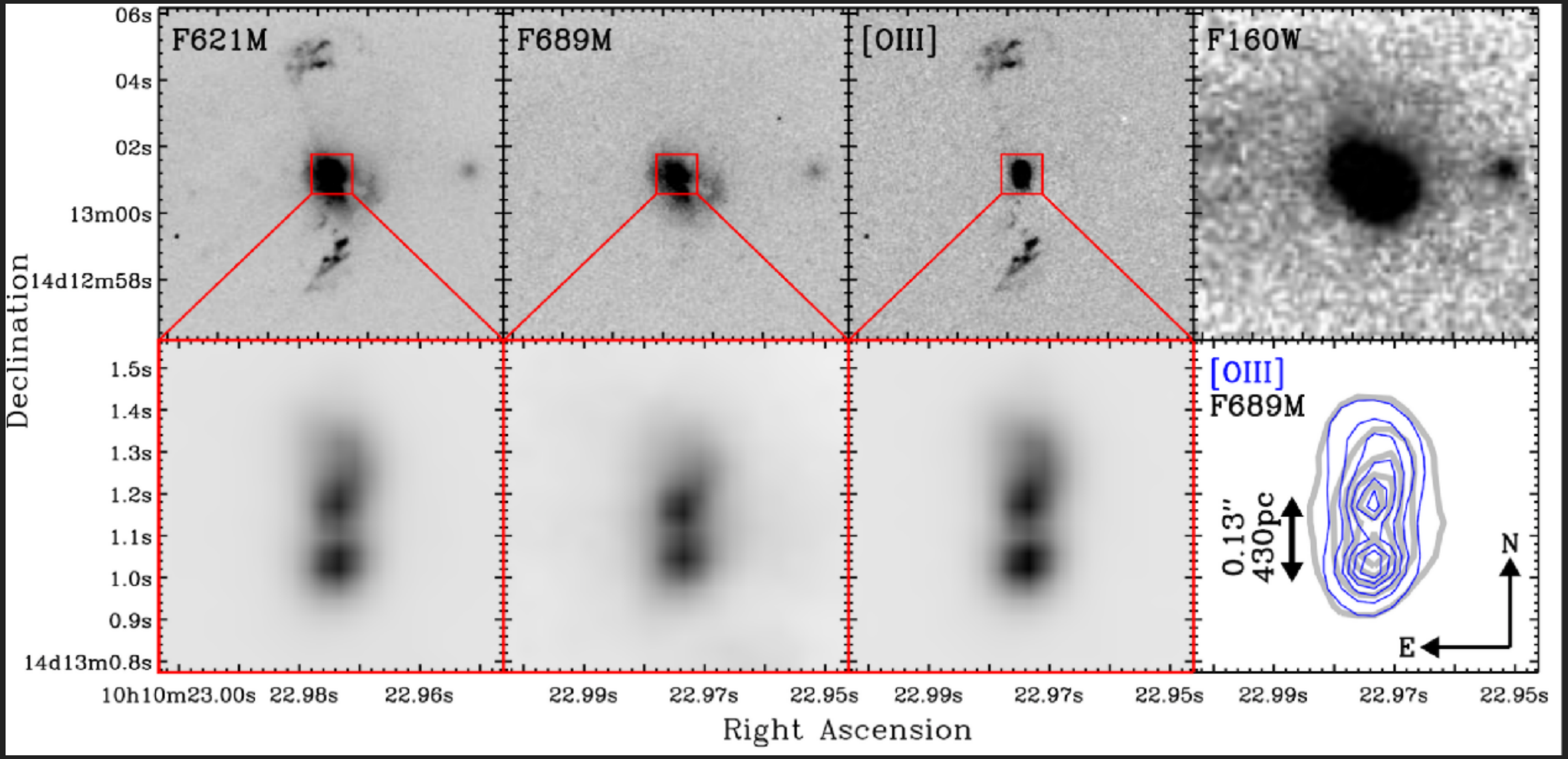


Koss et al. (2012)

BAT-detected single AGN

BAT-detected dual AGN
X&opt, X-only, opt-only

Goulding et al. (2019)

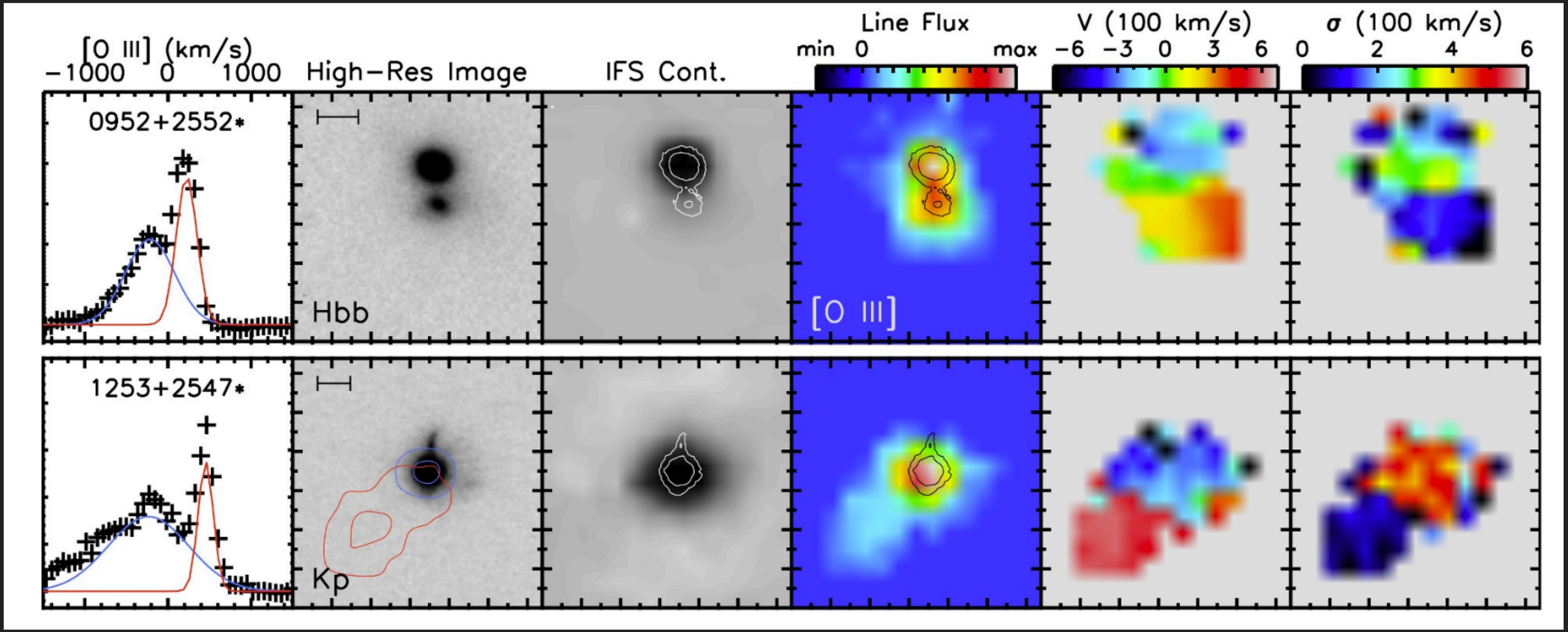


200 known objects

Dual AGN frequency is 10% at z< 0.05

STAGE I-II

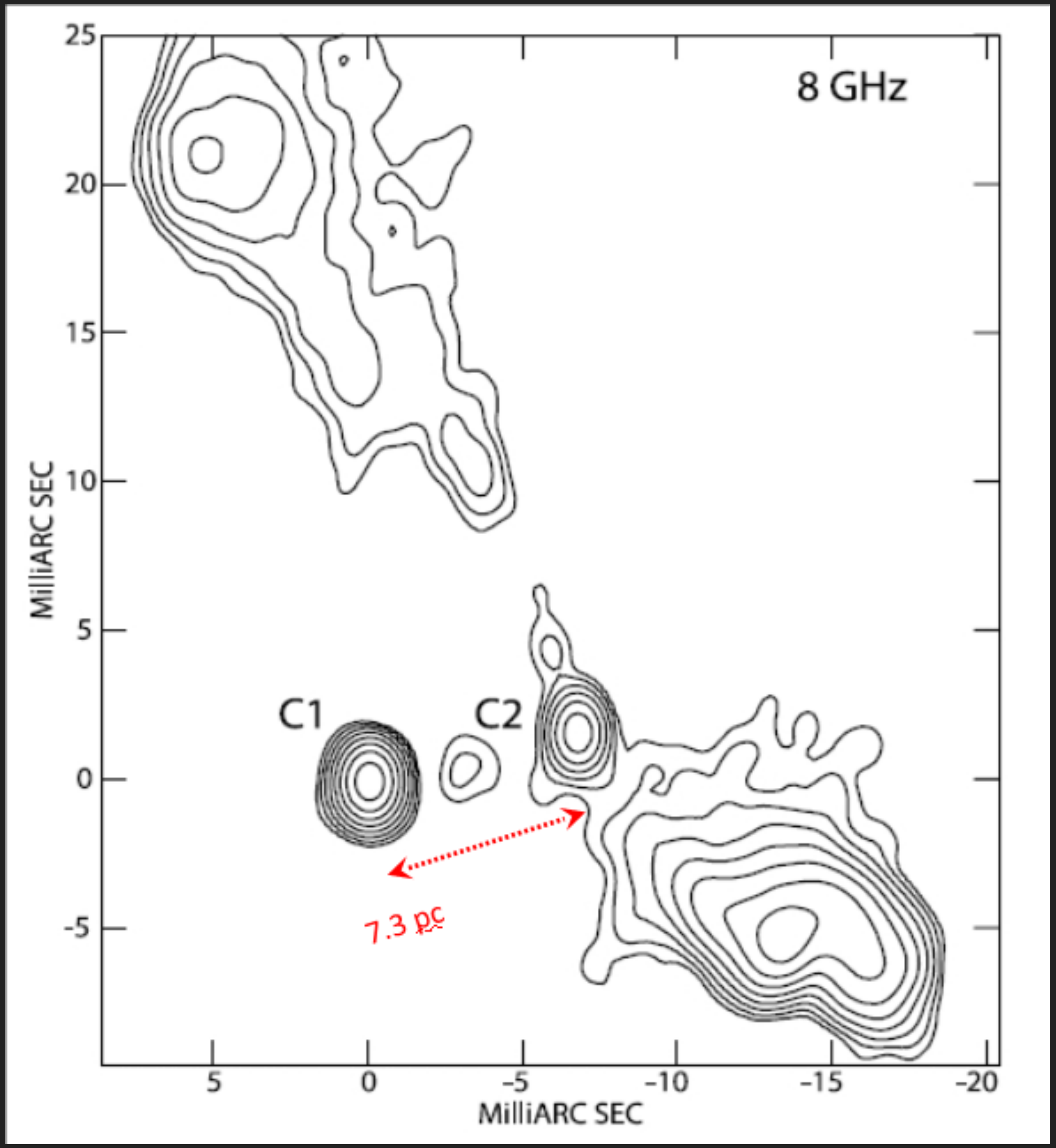
AGNs with double-peaked [O III] lines are suspected to be sub-kpc or kpc-scale binary AGNs



Fu et al. (2012)

However gas kinematics within a single AGN can provide the same double-peaked feature !

STAGE II - RADIO CANDIDATE



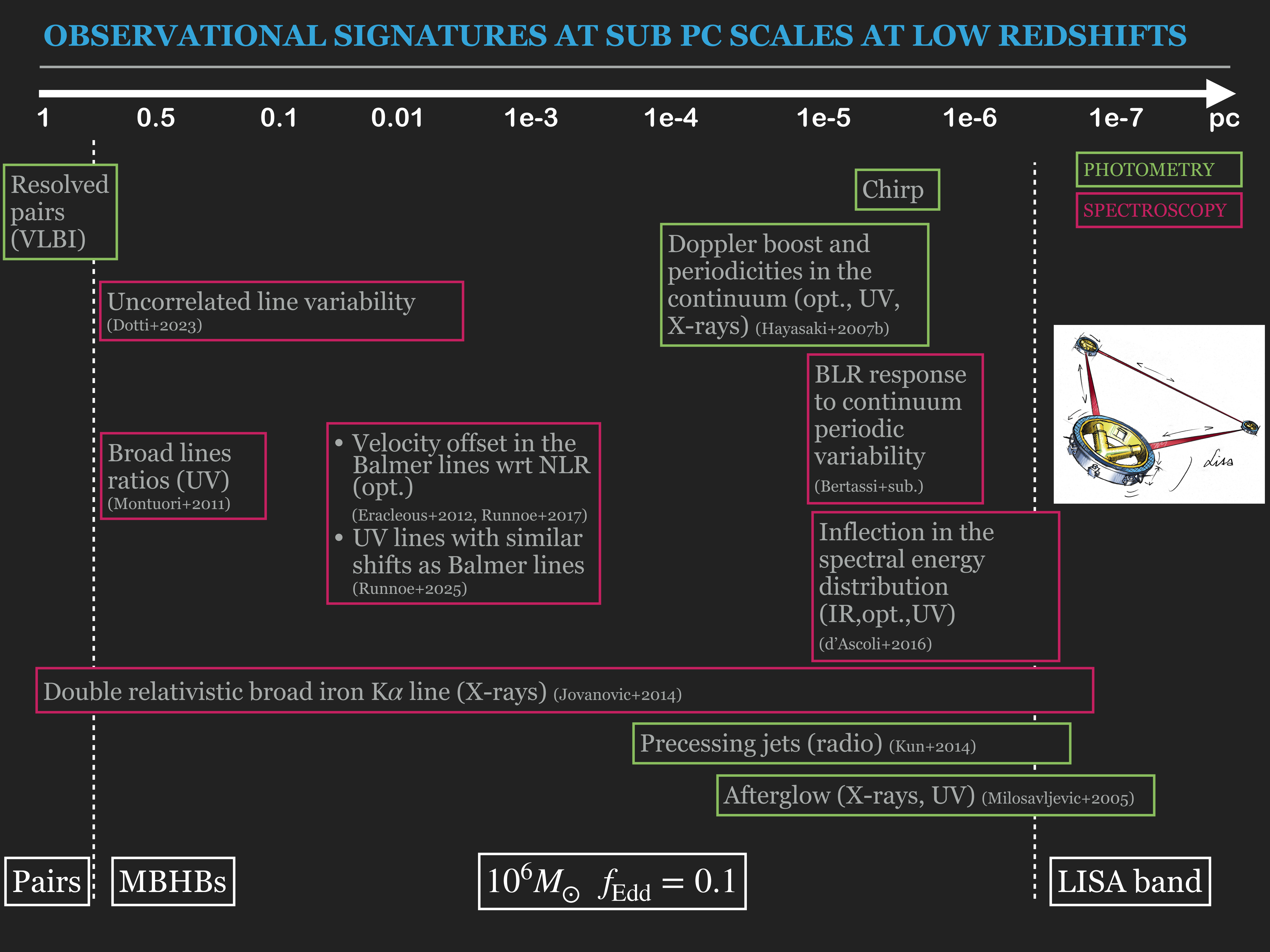
VLBA images

Two flat-spectrum radio cores (Maness et al. 2004, Rodriguez et al. 2006)

The source 0402+379 is composed by a radio galaxy and elliptical galaxy featuring binary supermassive black holes with the least separation of any directly observed binaries so far.

Estimated masses ~ $10^8 M_\odot$

$$t_{\rm merge}(a) = 5.8 \times 10^6 \left(\frac{a}{0.01\ \rm pc}\right)^4 \left(\frac{10^8\ M_\odot}{m_1}\right)^3 \frac{m_1^2}{m_2(m_1+m_2)}\ \rm yr.$$


OBSERVATIONAL SIGNATURES AT SUB PC SCALES AT LOW REDSHIFTS
1
0.5
0.1
0.01
1e-3
1e-4
1e-5
1e-6
1e-7
pc
Resolved pairs (VLBI)
Chirp
PHOTOMETRY
SPECTROSCOPY
Doppler boost and periodicities in the continuum (opt., UV, X-rays) (Hayasaki+2007b)
Uncorrelated line variability (Dotti+2023)
BLR response to continuum periodic variability (Bertassi+sub.)
Broad lines ratios (UV) (Montuori+2011)
• Velocity offset in the Balmer lines wrt NLR (opt.) (Eracleous+2012, Runnoe+2017)
• UV lines with similar shifts as Balmer lines (Runnoe+2025)
Inflection in the spectral energy distribution (IR,opt.,UV) (d'Ascoli+2016)
Double relativistic broad iron Kα line (X-rays) (Jovanovic+2014)
Precessing jets (radio) (Kun+2014)
Afterglow (X-rays, UV) (Milosavljevic+2005)
Pairs
MBHBs
$10^6 M_\odot$ $f_{\rm Edd} = 0.1$
LISA band

OBSERVATIONAL SIGNATURES AT SUB PC SCALES AT LOW REDSHIFTS

Challenging to identify due to:
- very small angular separation in the sky
- uncertainties in the uniqueness of their signatures

Spectroscopic searches

Broad emission lines velocity shifts with respect to narrow line and the host galaxy

Double peaked Balmer emission lines ..but velocity shifts too small and double peaked emitters velocity curves not consistent with MBHBs (no long term systematic changes) (Eracleous et al. 2009, 2012)

- Single peak emitters velocity offset in the Hβ broad line wrt NLR (Eracleous et al. 2012)
- 3 candidates sub-pc MBHBs through monotonic changes in the radial velocity curves of one shoulder of the Hα line (Runnoe et al. 2017)
- UV lines with same shifts as Balmer lines (Runnoe et al. 2025)

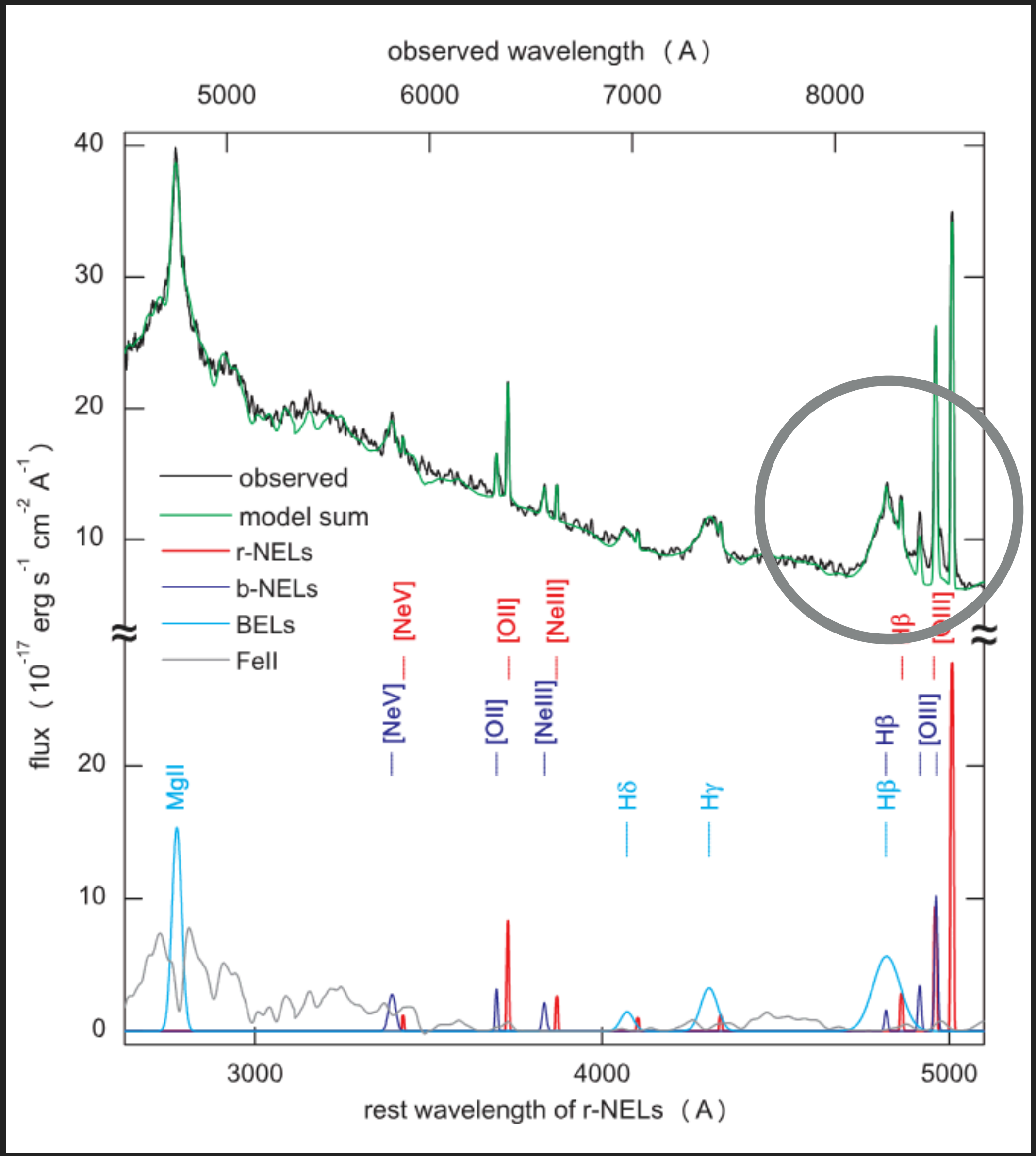
Photometric searches

Periodic modulations in the light curve (VRO, ZTF) (Roedig et al. 2012,D'Orazio et al. 2013,Farris et al. 2014,Shi et al. 2015,Charisi et al. 2015, 2018)

Very hard as the periods that need to be probed at these scales might be very long

....but **possible unique signatures!**

STAGE III - CANDIDATES?



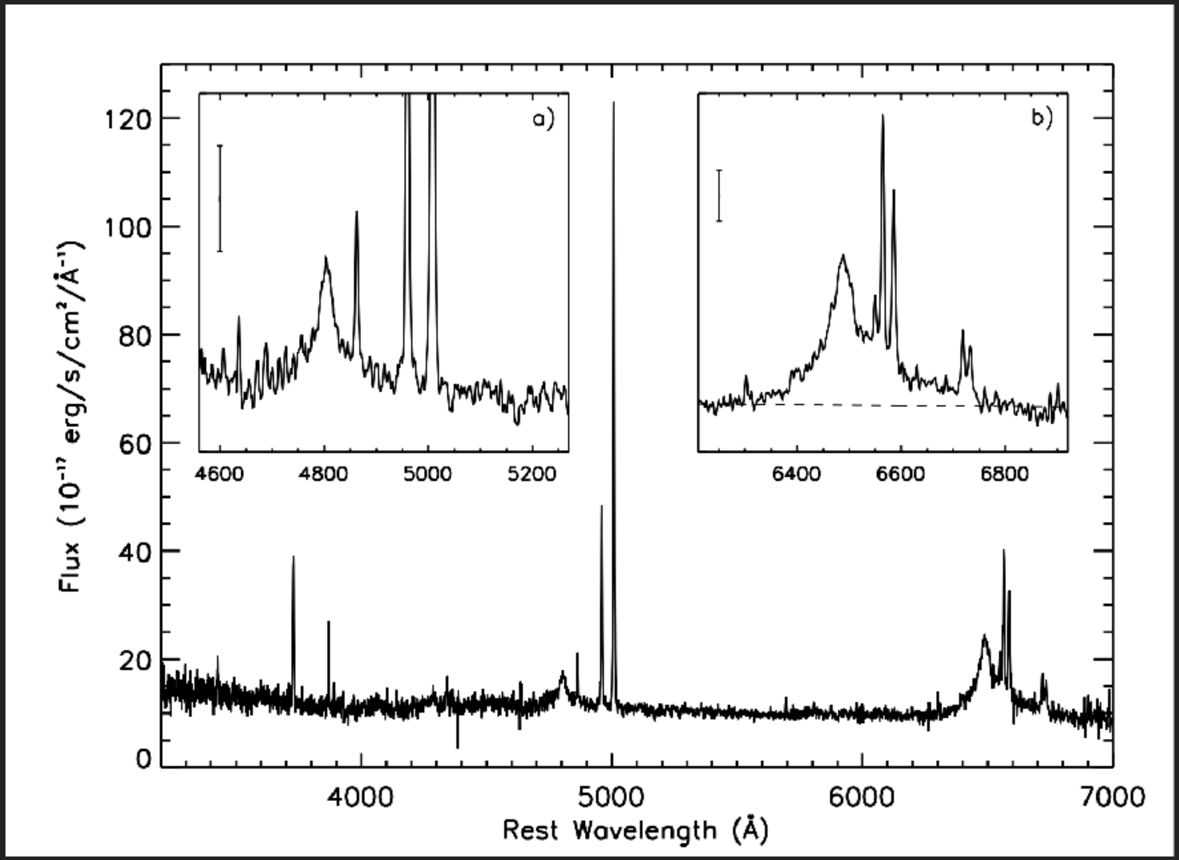
SDSS J0927+2943

Recoiling SMBH (Komossa et al. 2008, Bogdanovic et al. 2009)

Blue-shifted broad emission lines with velocity off-set of 2650 km/s —> candidate MBHB (Dotti et al. 2009)

SDSS J1050+3456 (Shields et al. 2009)
SMBH recoil or extreme double peaked emitter.

The presence of a weak but visible red wing on Hα, and the lesser blueshift of the Mg II line, suggest that this object is most likely an extreme member of the class of double-peaked emitters.

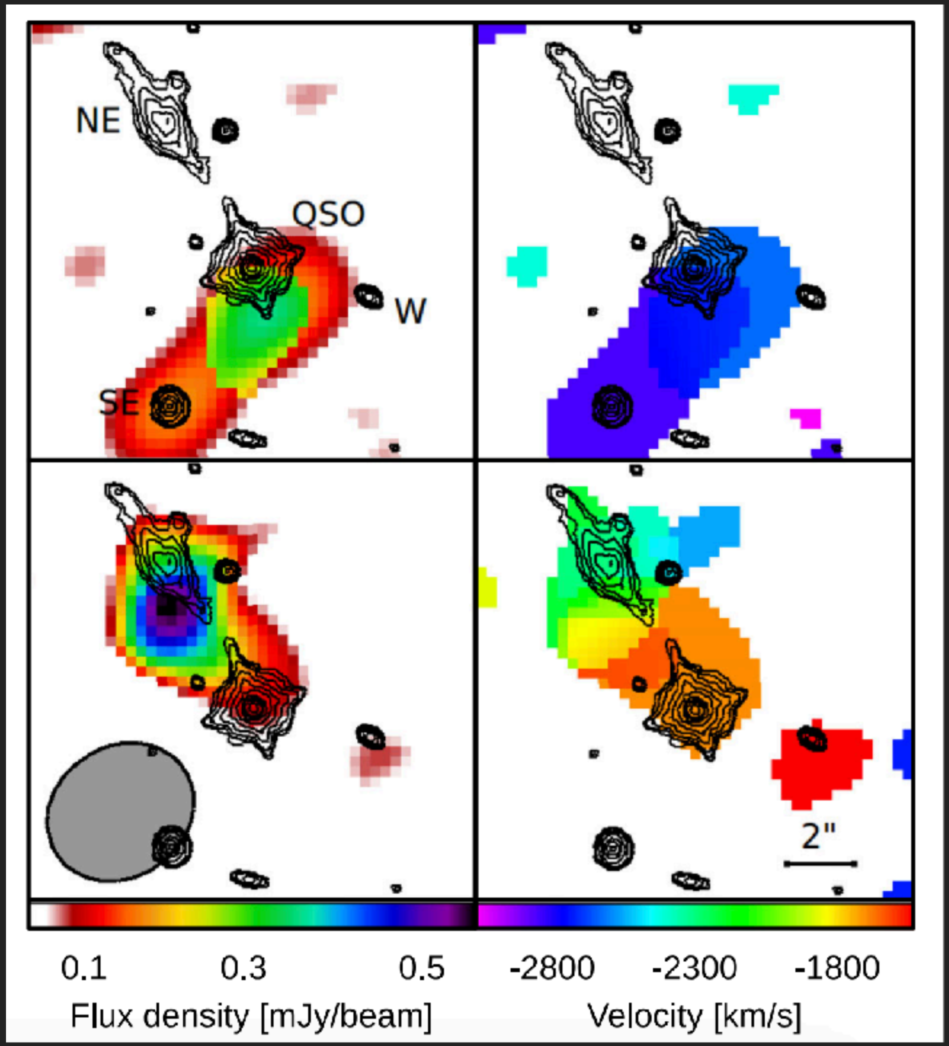


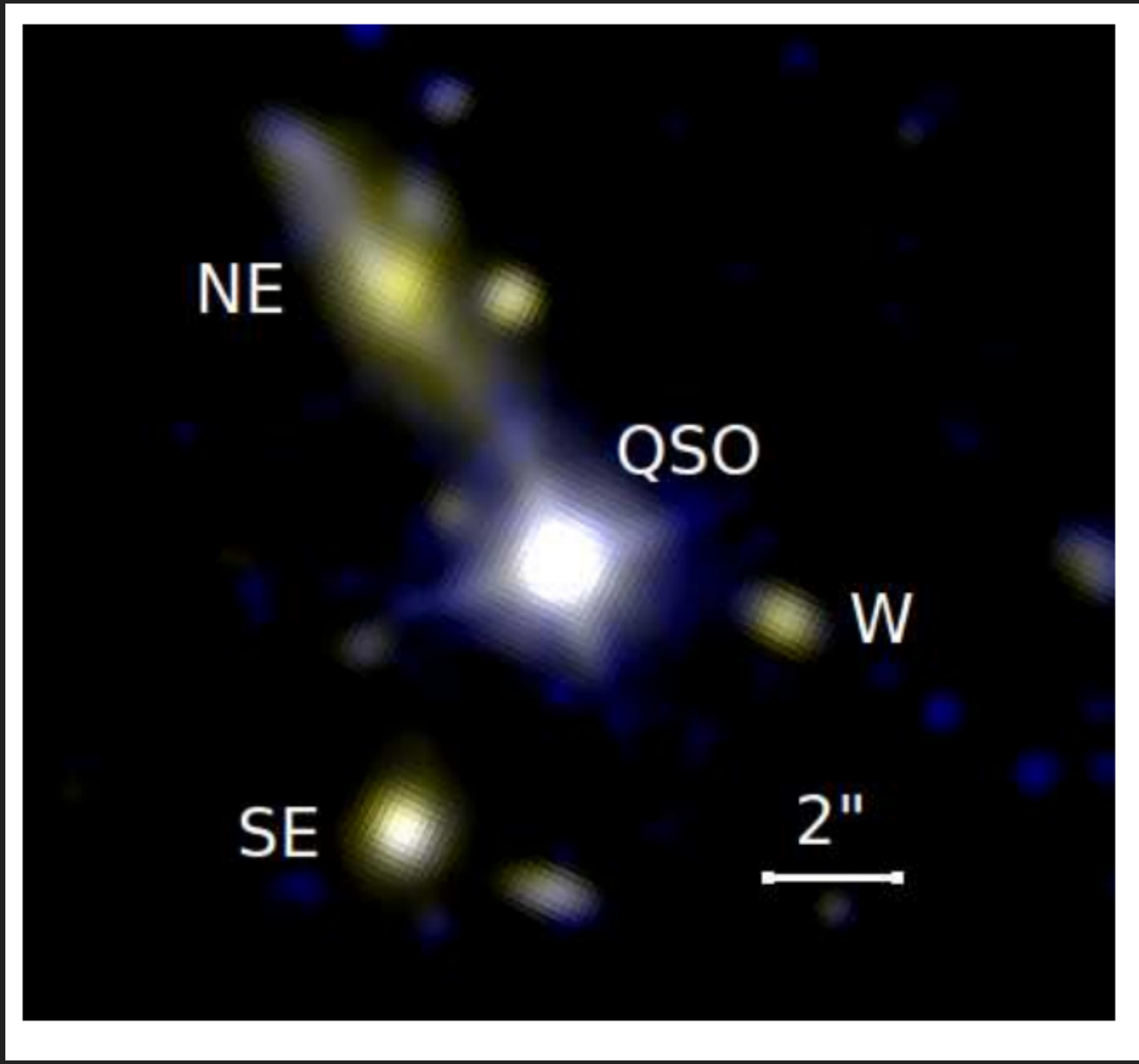
Systematic searches for multiple red shifted lines and displaced/irregular Hβ ~ 100 candidates

STAGE III - CANDIDATES? NOT REALLY

SDSS J0927+2943

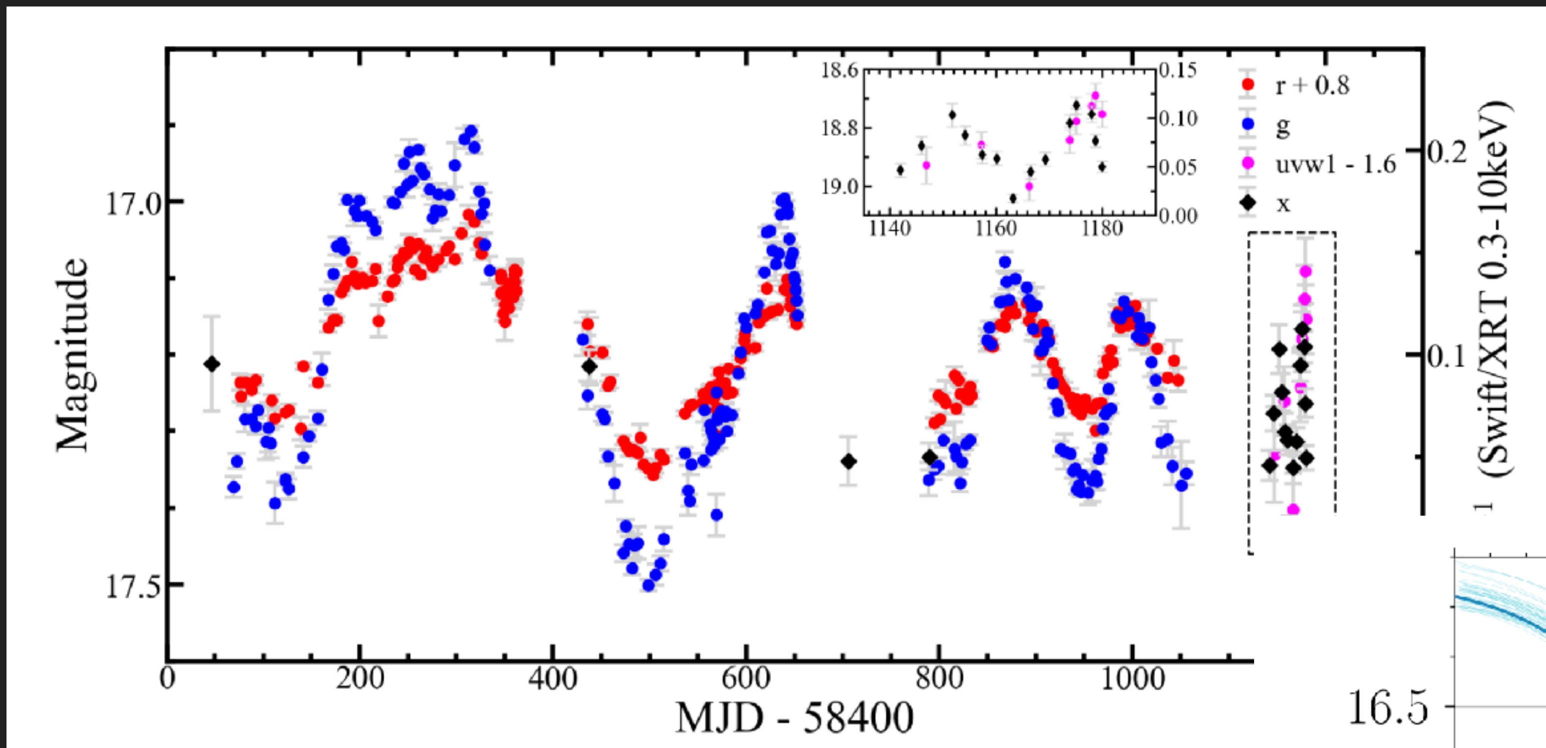
Photometric study of the field image did not find any galaxy cluster (Decarli et al. 2010) Further supported by HST images (Decarli et al. 2014)





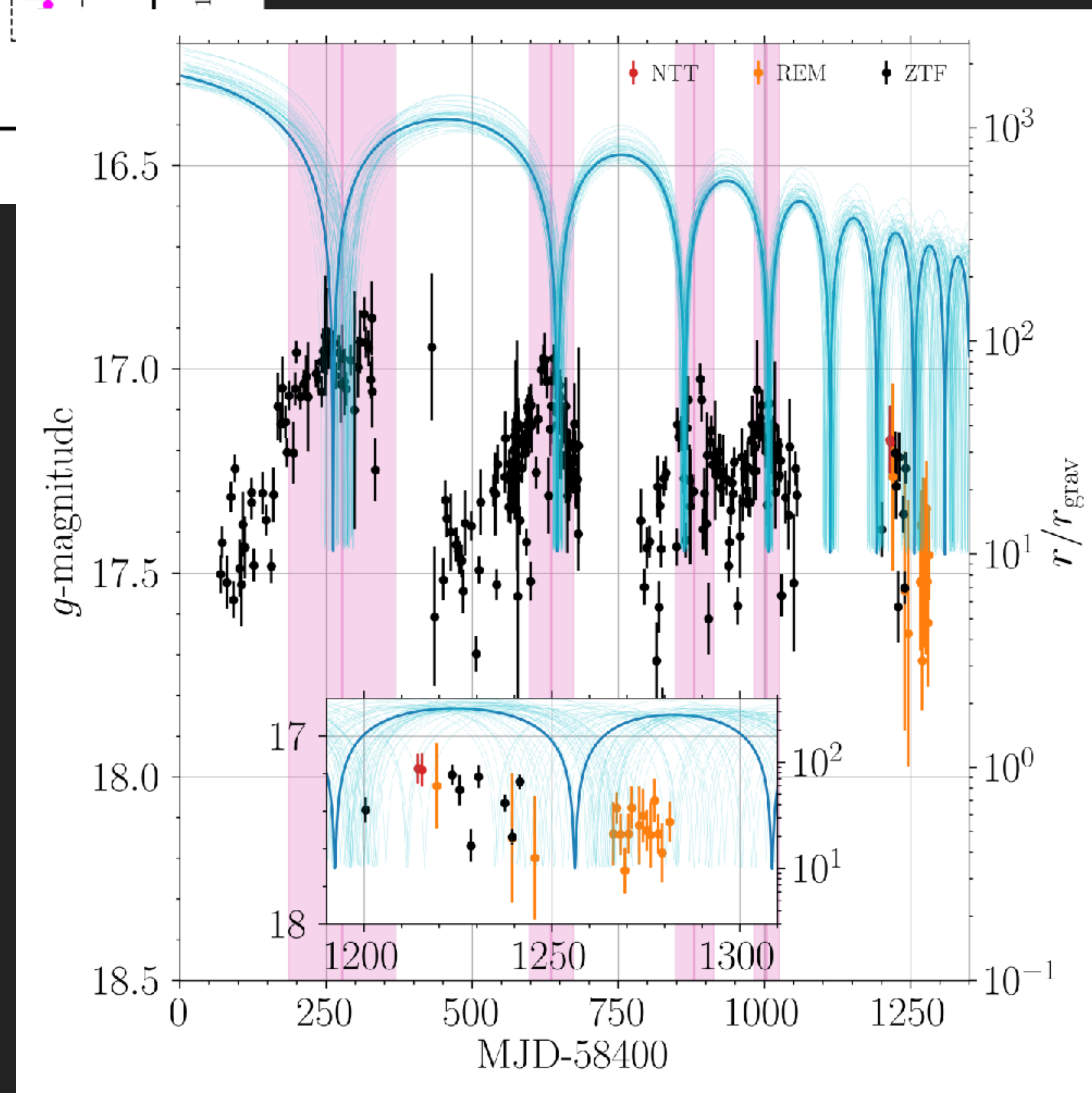
CO emission maps show a lot of molecular gas but discard both the recoil and binary scenarios.

STAGE III - CANDIDATES? THE TICK-TOCK OBJECT



Jiang et al. (2022)

Optical, UV and X-ray flux with ZTF, Swift and XRT



Optical follow up with the REM telescope shows that there are no further changes in the flux that can be consistent with the MBHB scenario.

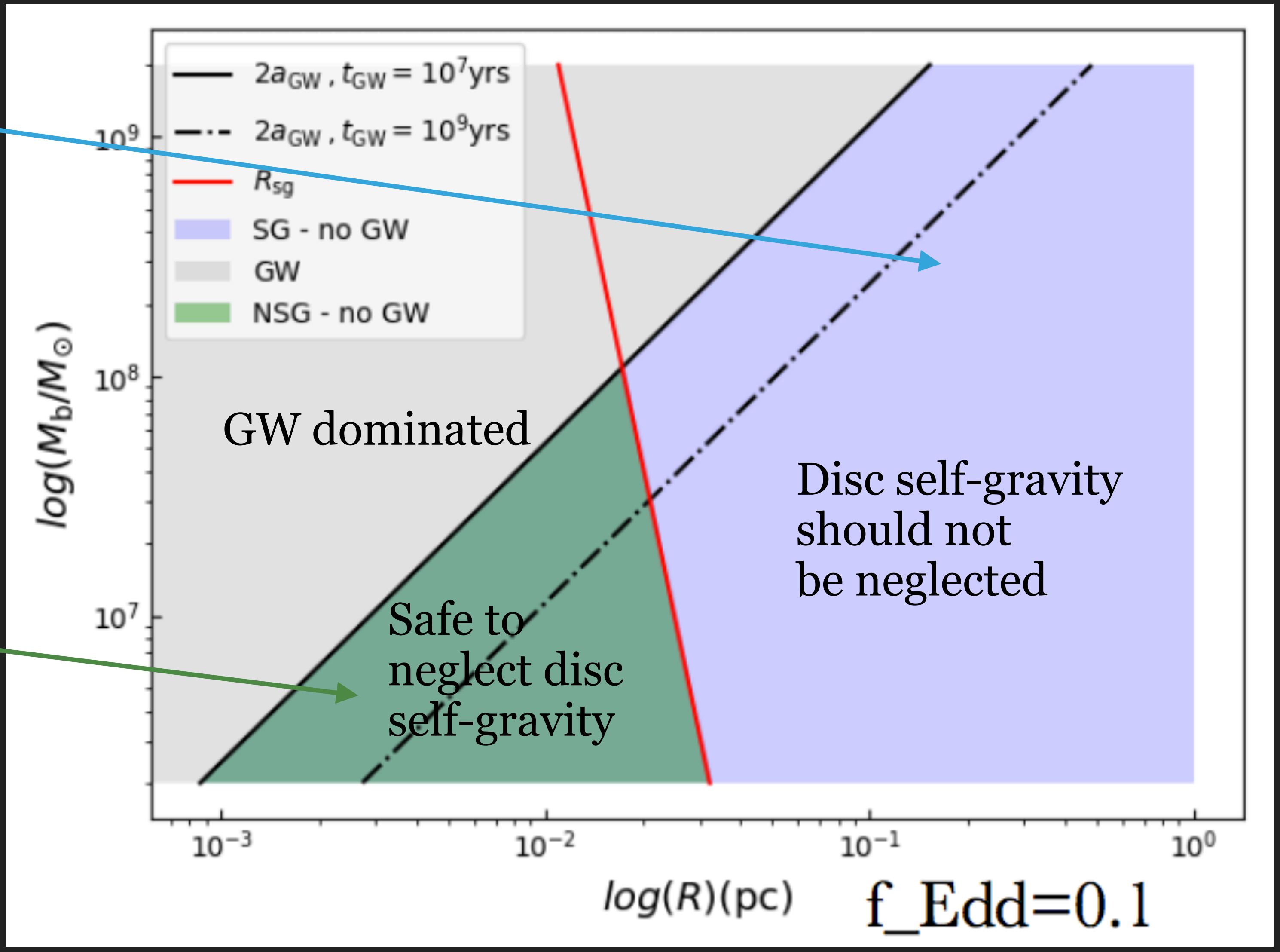
Dotti et al. (2023)

PATH TO COALESCENCE OF SUB-PC BINARIES

After a successful dynamical friction-driven inspiral, bound binaries form in the central parsec of galaxies. SMBHBs can then further shrink down to the gravitational wave emission stage through the interaction with stars and gas.

Pulsar Timing Array (PTA) binaries probably reside in massive discs whose self-gravity cannot be neglected

LISA binaries evolve within gaseous discs where the gas self-gravity can be neglected

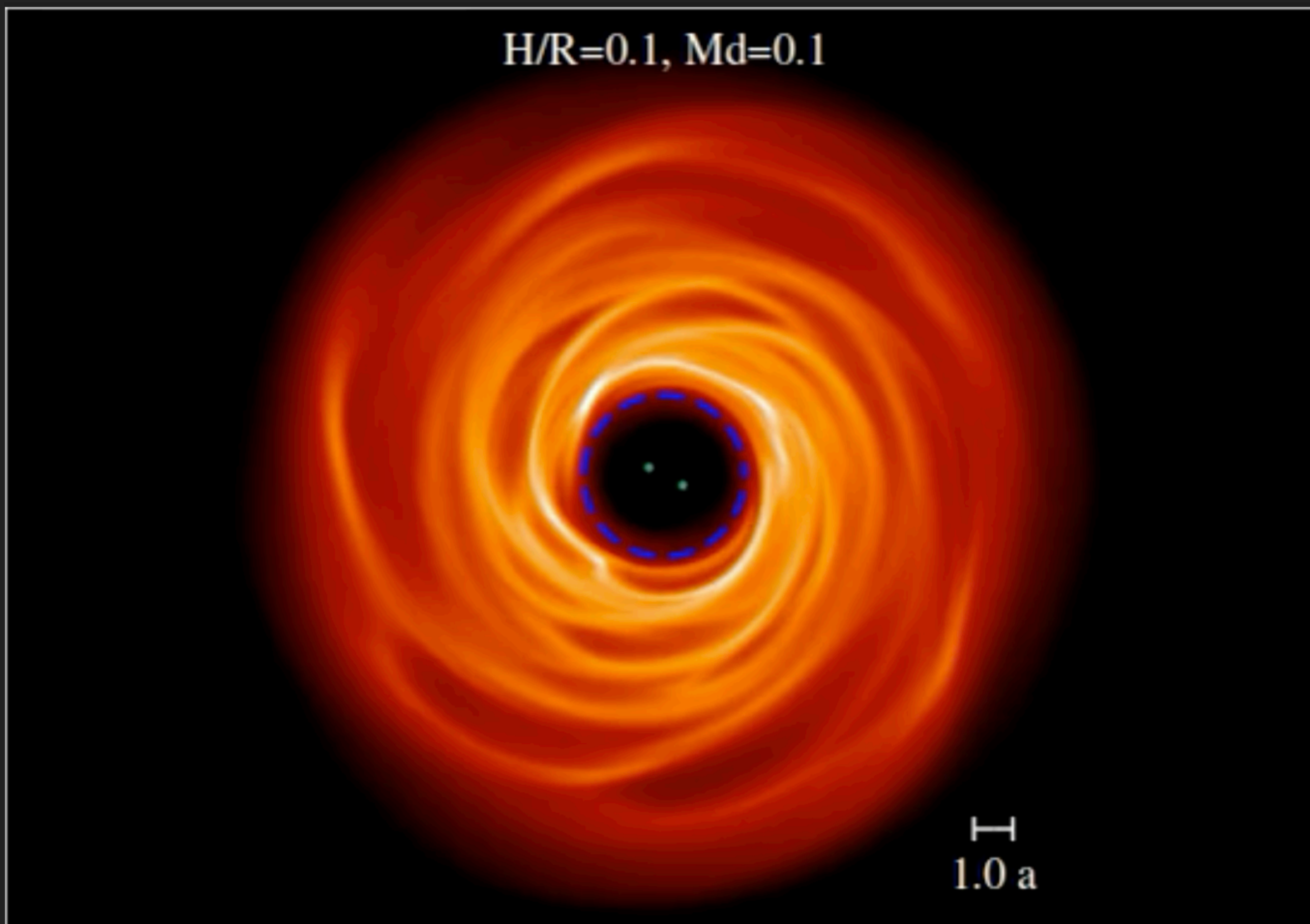


Franchini, Sesana and Dotti, MNRAS 507 (2021)

PTA BINARY-DISC INTERACTION

- Heating is provided through PdV work and shocks
- Gammie cooling with \beta=10
- Angular momentum transport regulated by Gravitational Instabilities (GIs)

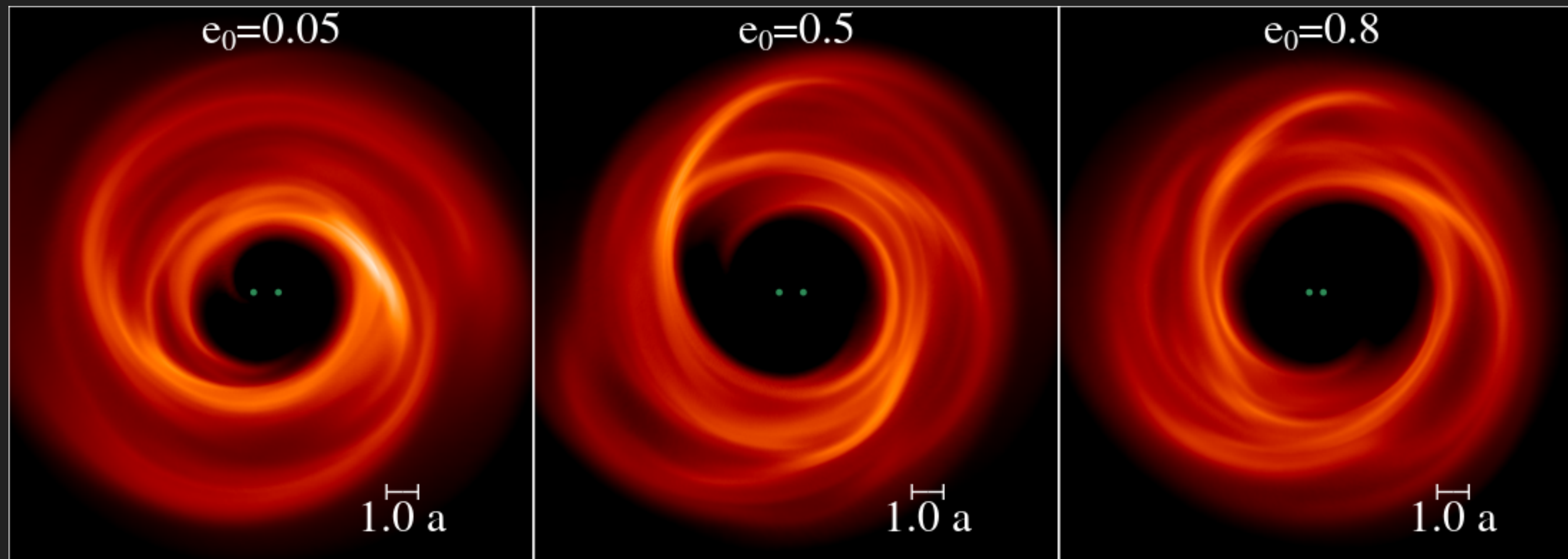
$$\beta_{\rm cool} = \Omega t_{\rm cool}$$

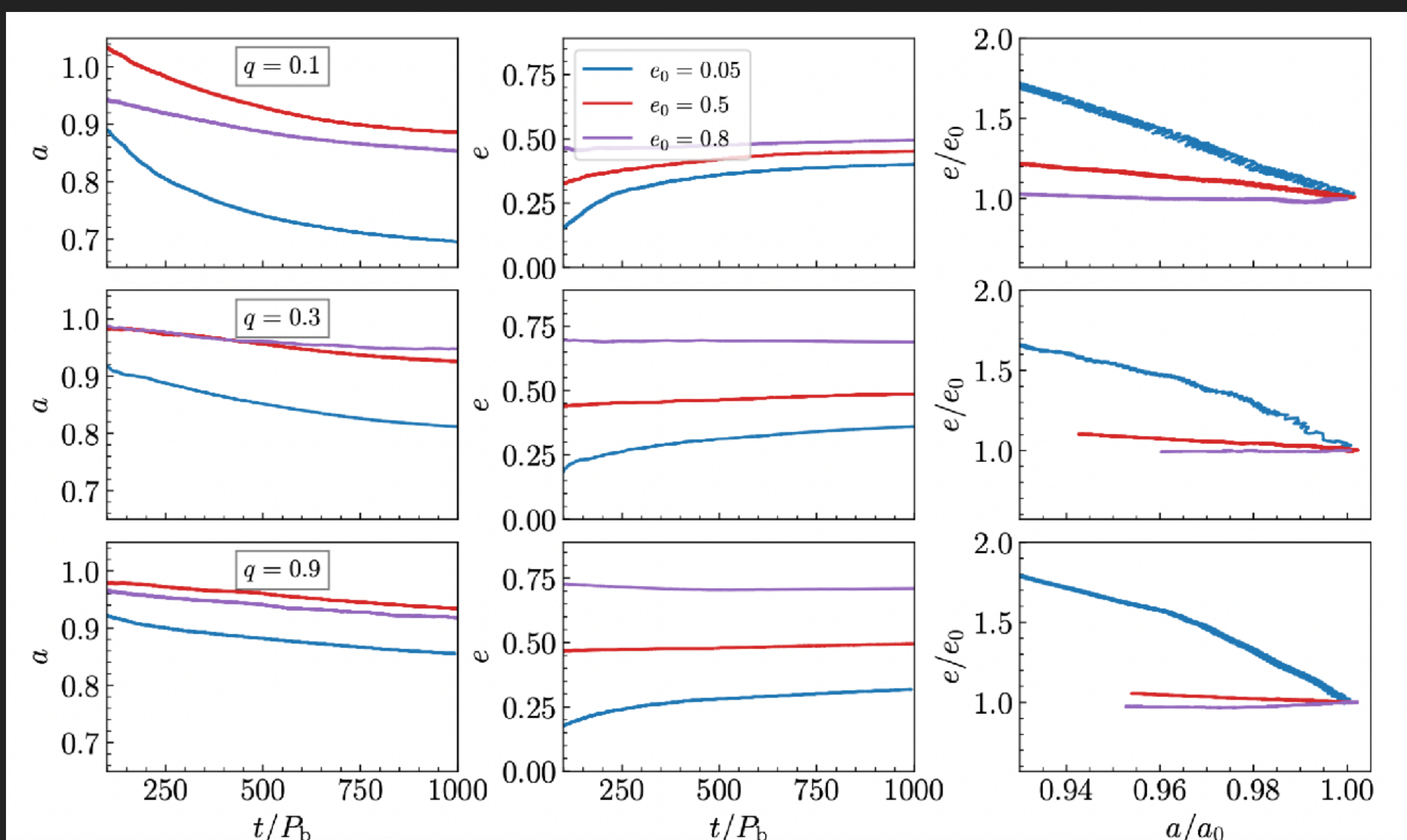


$$Q = \frac{c_s \Omega}{\pi G \Sigma}$$

Franchini, Sesana and Dotti, MNRAS 507 (2021)

PTA BINARY-DISC INTERACTION



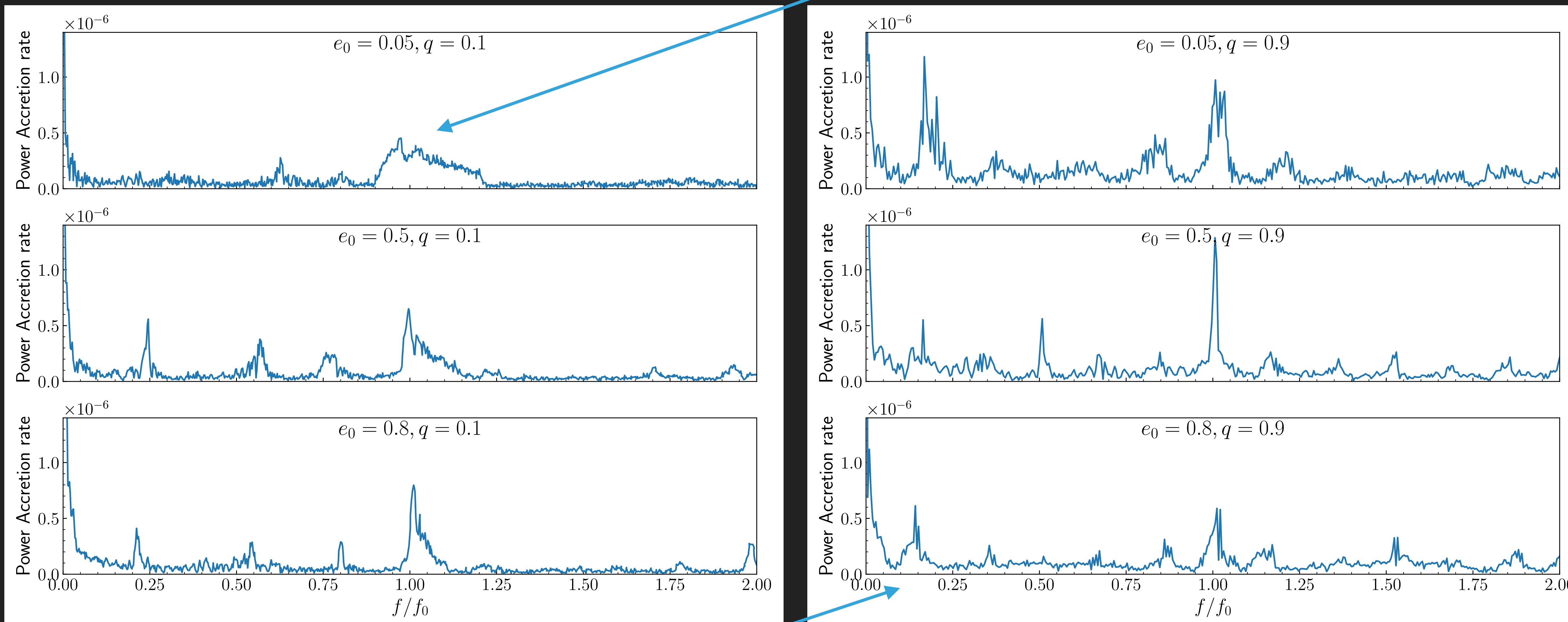


- Binary eccentricity saturates within a range that depends on the initial mass ratio
- Less eccentric binaries increase their eccentricity while more eccentric binaries tend to circularize
- The saturation value depends on the cooling timescale within the disc

Franchini, Prato, Longarini and Sesana, A&A 688 A174 (2024)

ACCRETION RATE MODULATION

binary orbital period

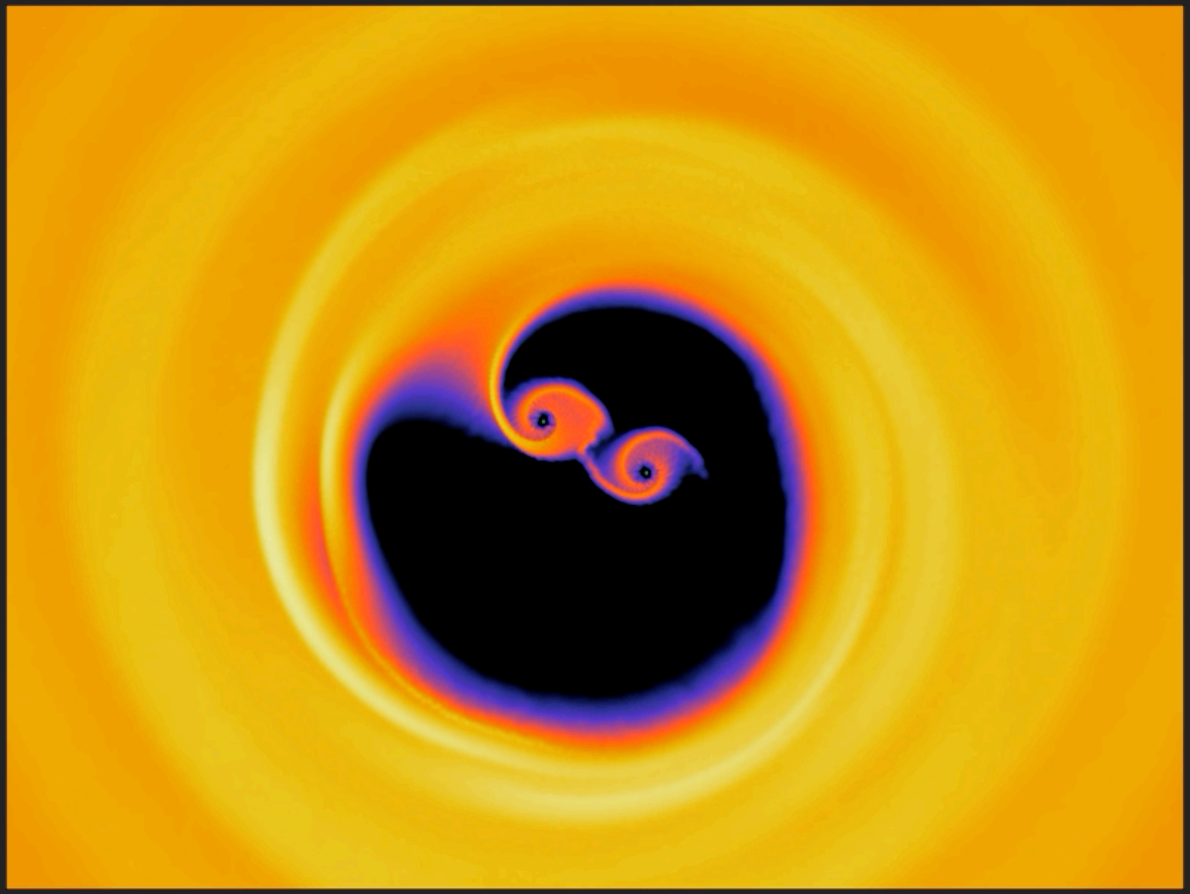


accretion disc inner edge

- Broader peaks might indicate lower mass ratios
- Higher amplitude peaks might indicate less eccentric systems

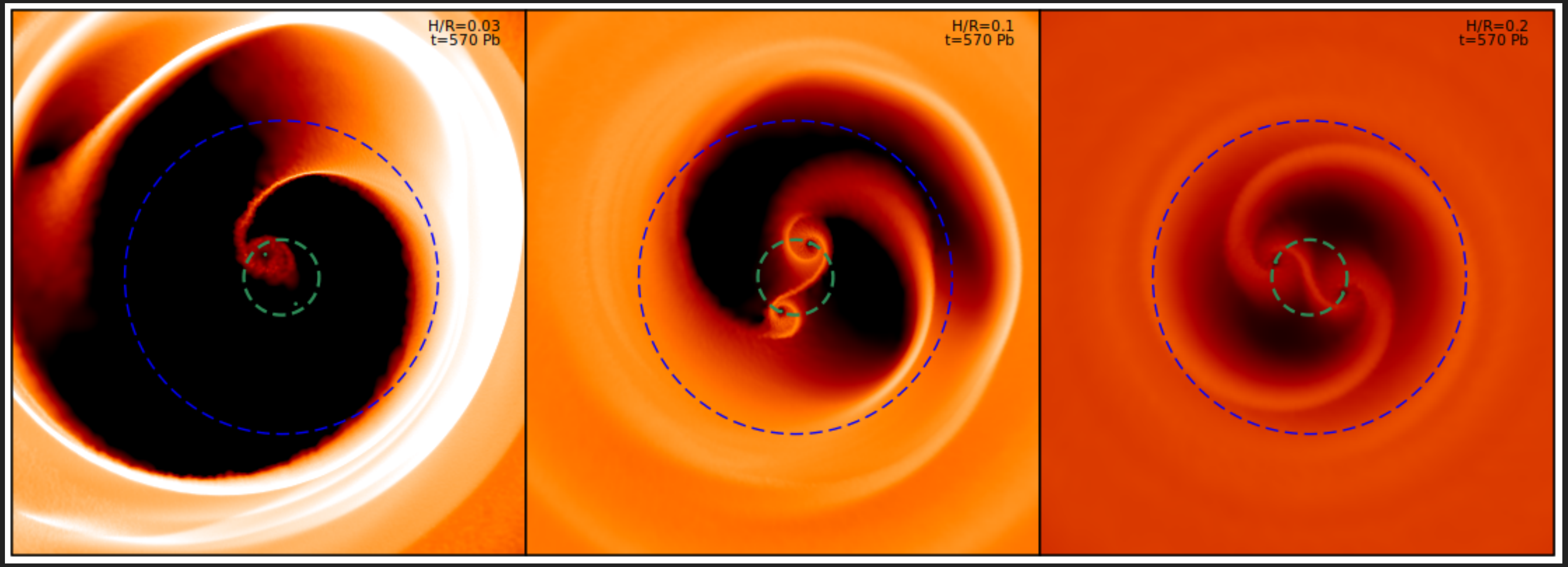
Franchini, Prato, Longarini and Sesana, A&A 688 A174 (2024)

LISA BINARY-DISC INTERACTIONS



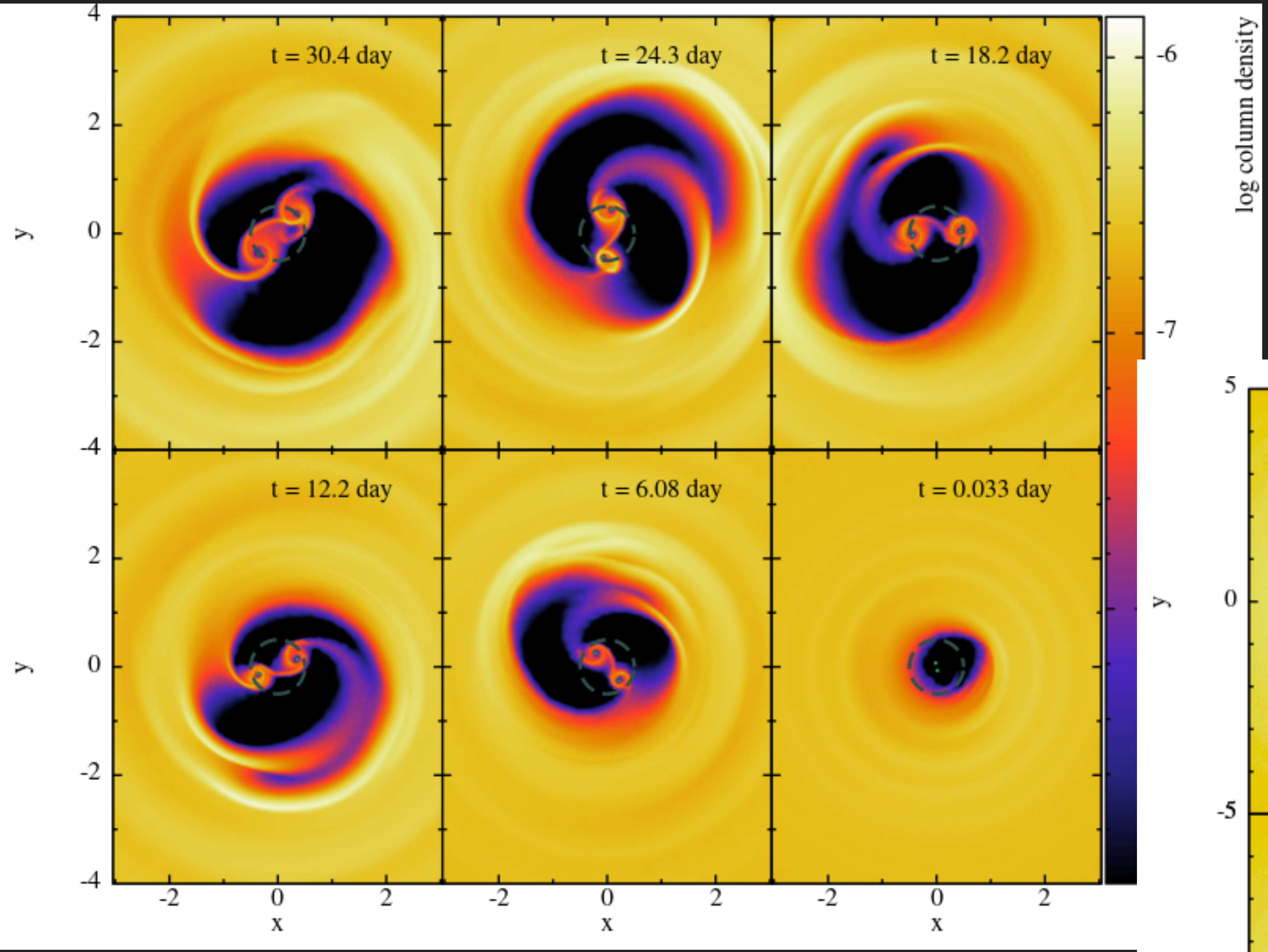
- Equal mass circular binary embedded in a locally isothermal circumbinary disc
- Viscosity is parametrised with the Shakura-Sunyaev model
- Dynamics inside the cavity is resolved with particle splitting

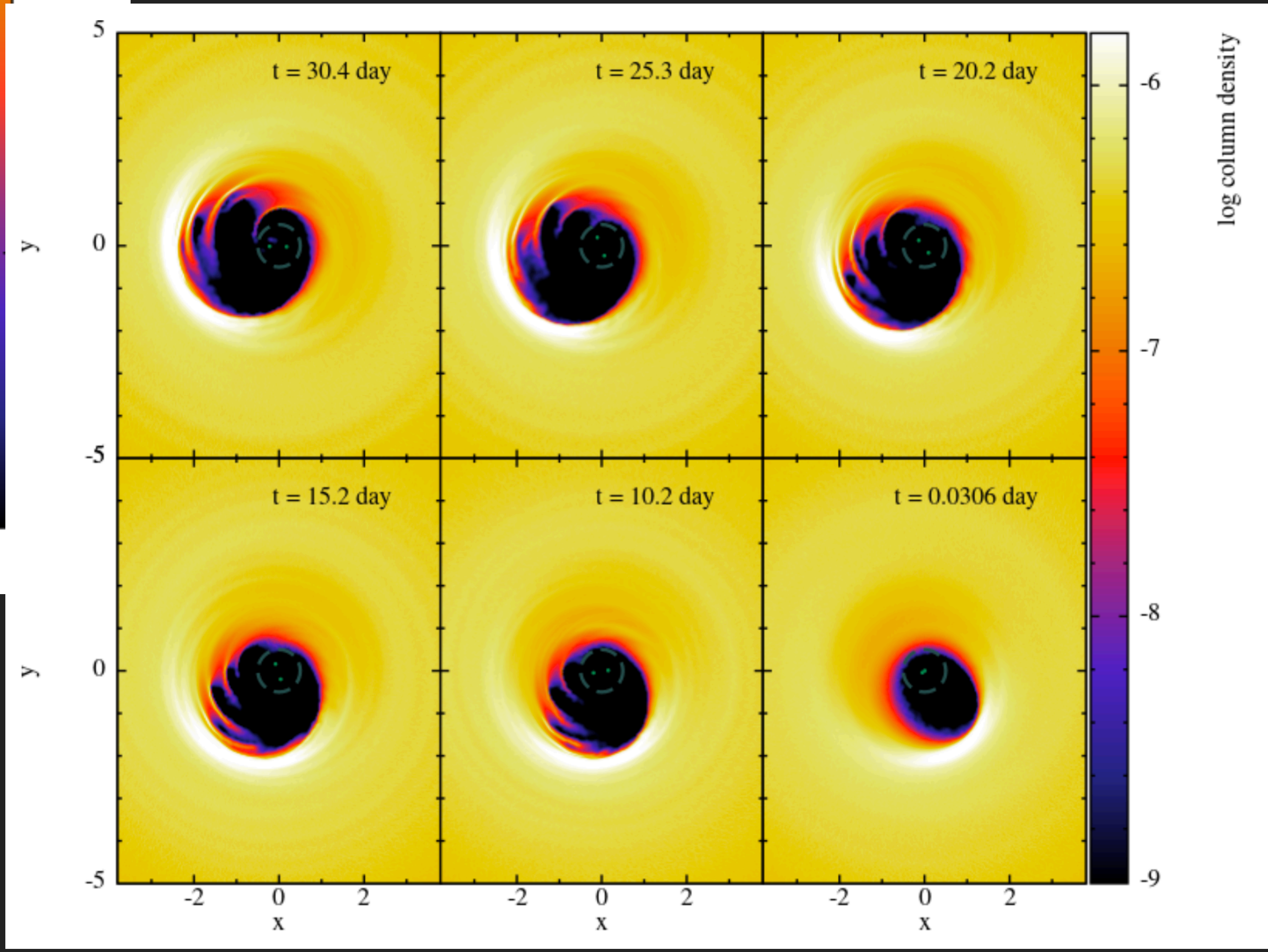
Franchini, Lupi and Sesana, ApJL 929 L13 (2022)
Franchini, Lupi, Sesana and Haiman, MNRAS 522 (2023)



FOLLOWING INSPIRAL WITH PN CORRECTIONS

Implementing Post Newtonian corrections up to 2.5PN order allows to follow the gas dynamics down to merger scales and also simulate post-merger scenarios.
This is particularly relevant for electromagnetic counterparts of GWs.

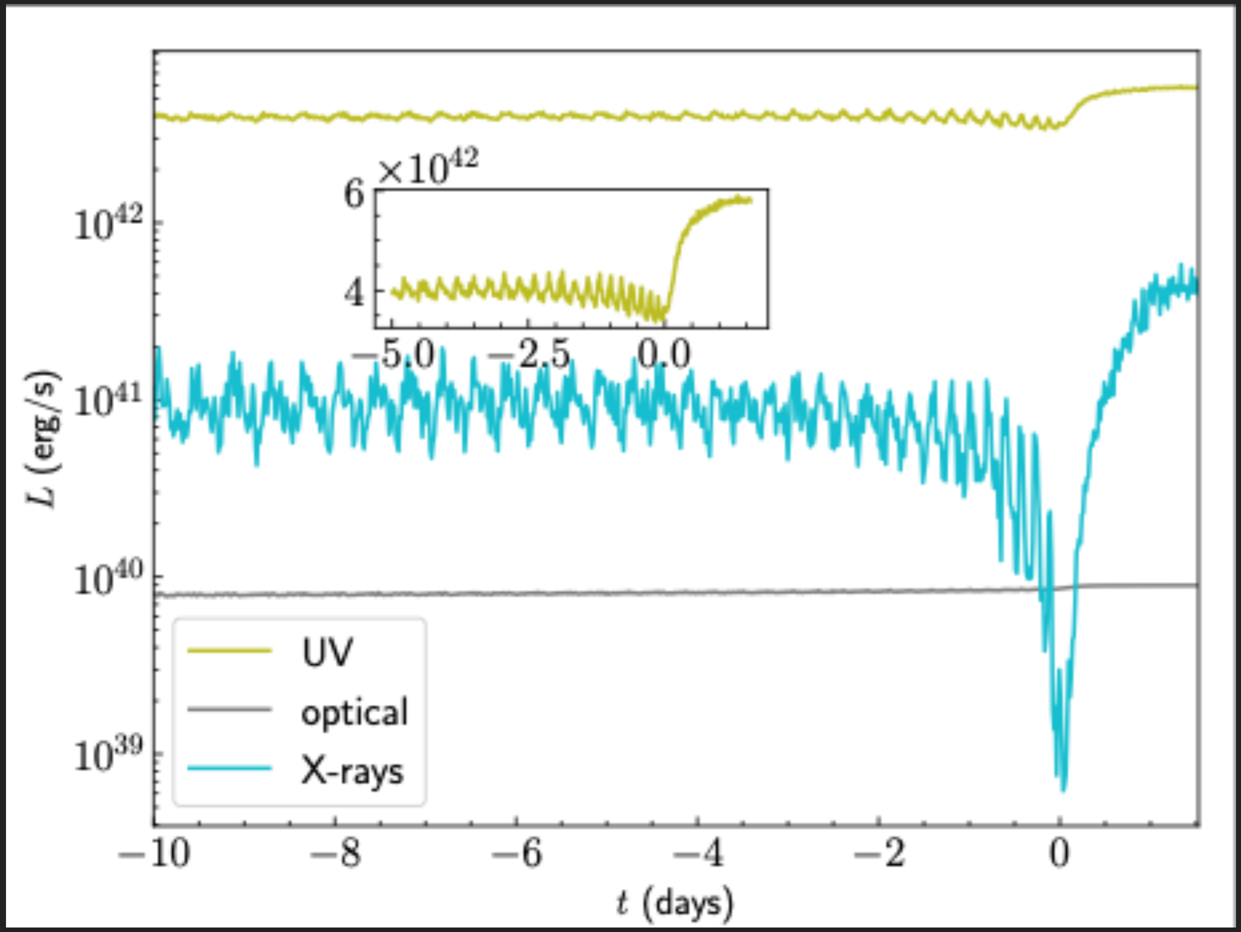


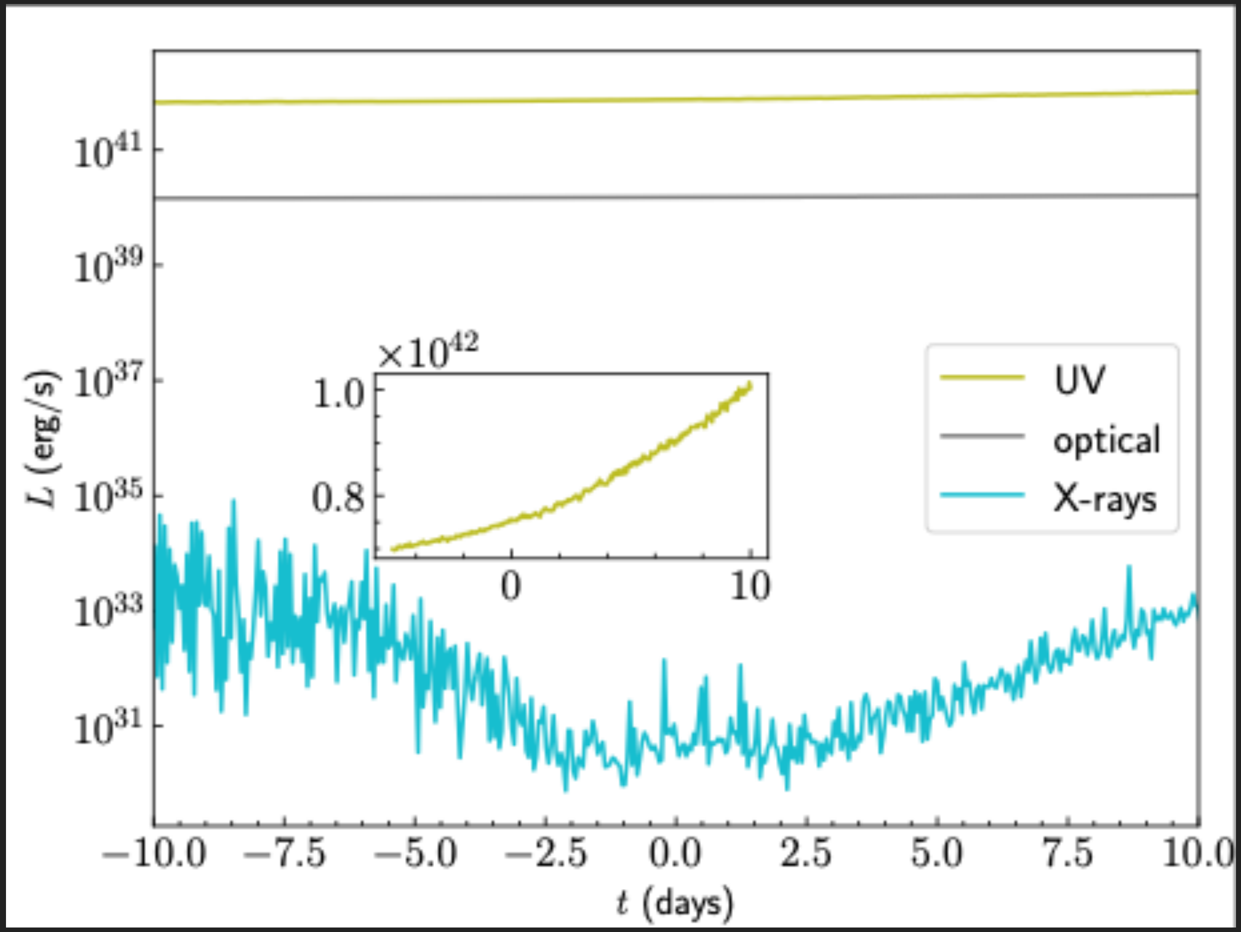


Franchini, Bonetti, Lupi and Sesana, A&A 686 (2024)

FOLLOWING INSPIRAL WITH PN CORRECTIONS

Multi-wavelengths fluxes computed from the hydro simulations showing what happens to the electromagnetic emission right before, during and after the merger.

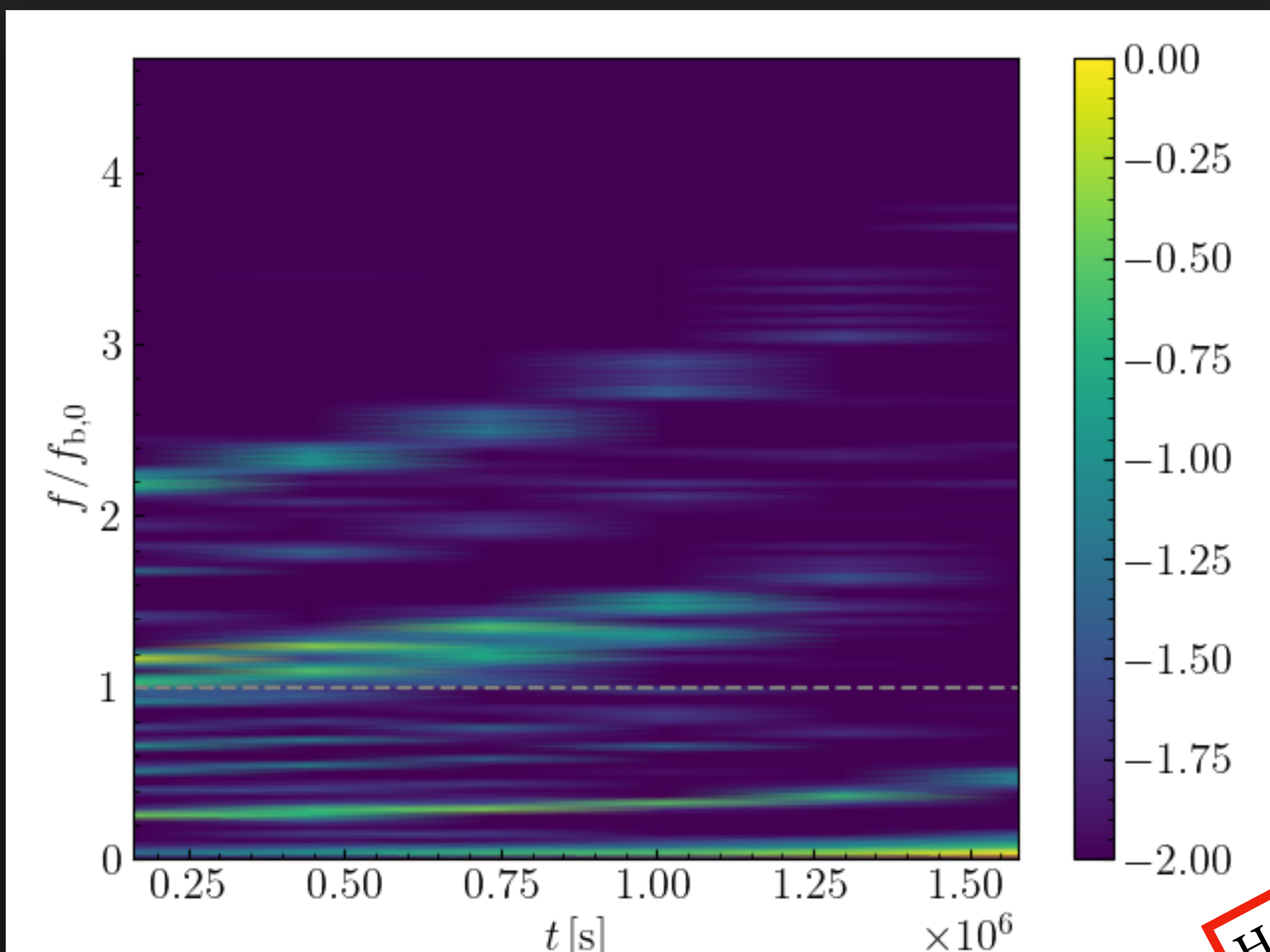




- Decrease in X-ray flux by orders of magnitude if the disc is hot (Krauth et al. 2023)
- Increase of the UV flux as the cavity closes around the merger remnant, independent of the disc temperature

Franchini, Bonetti, Lupi and Sesana, A&A 686 (2024)

CHIRPING OF MASSIVE BLACK HOLE BINARIES IN OPTICAL

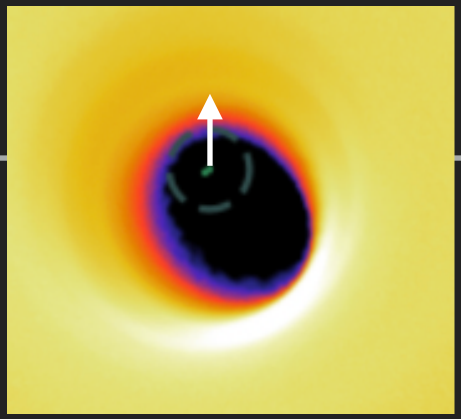


H/R = 0.1

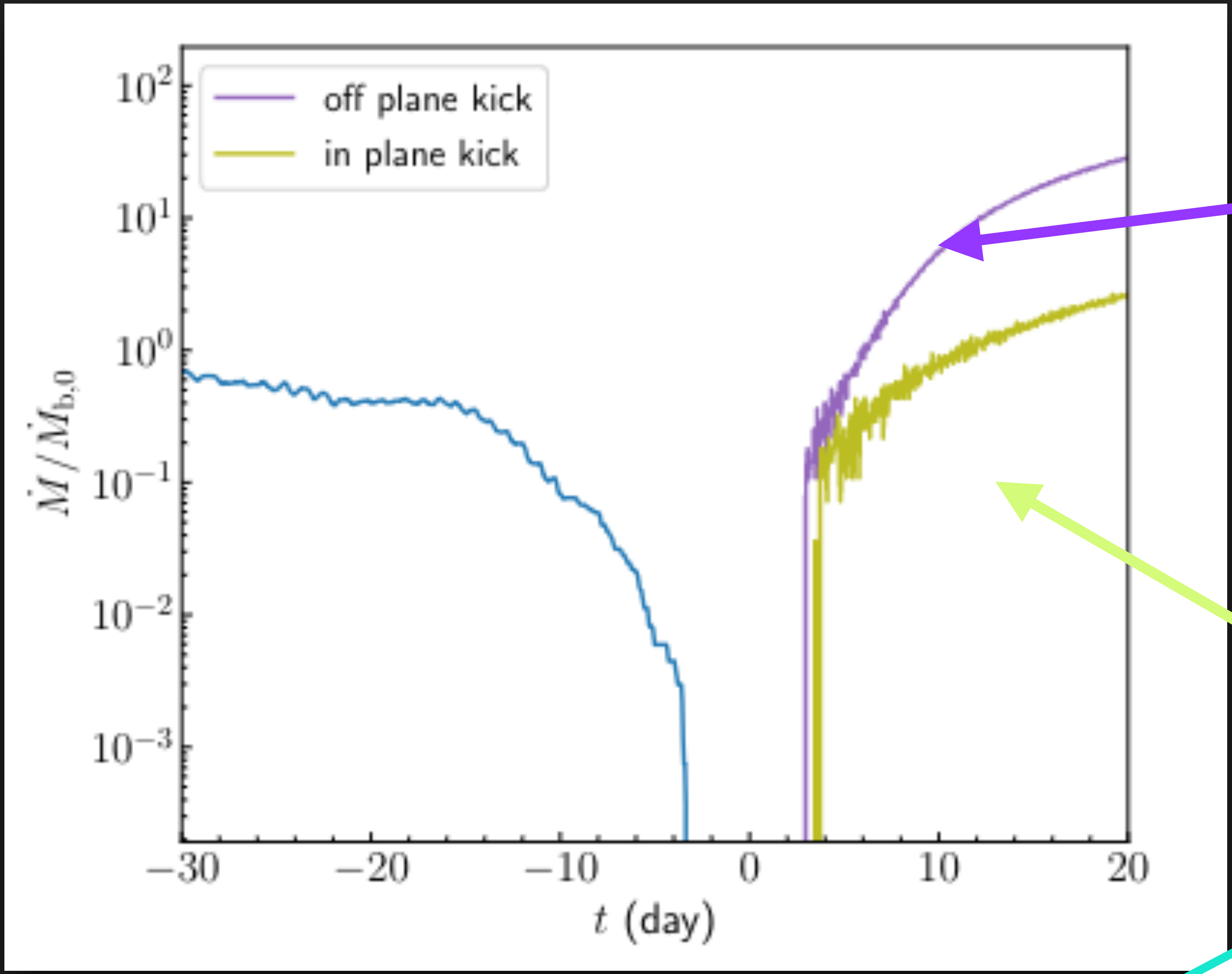
Spectrogram of in-spiral electromagnetic signal in the optical band for circular equal mass binaries.

Franchini, Bonetti, Lupi and Sesana, A&A 686 (2024)

POST MERGER SIGNATURES ?



We investigated the accretion rate onto the merger remnant in two kick scenarios.



Remnant moves along the z-axis, dragging the disc outside its initial orbital plane

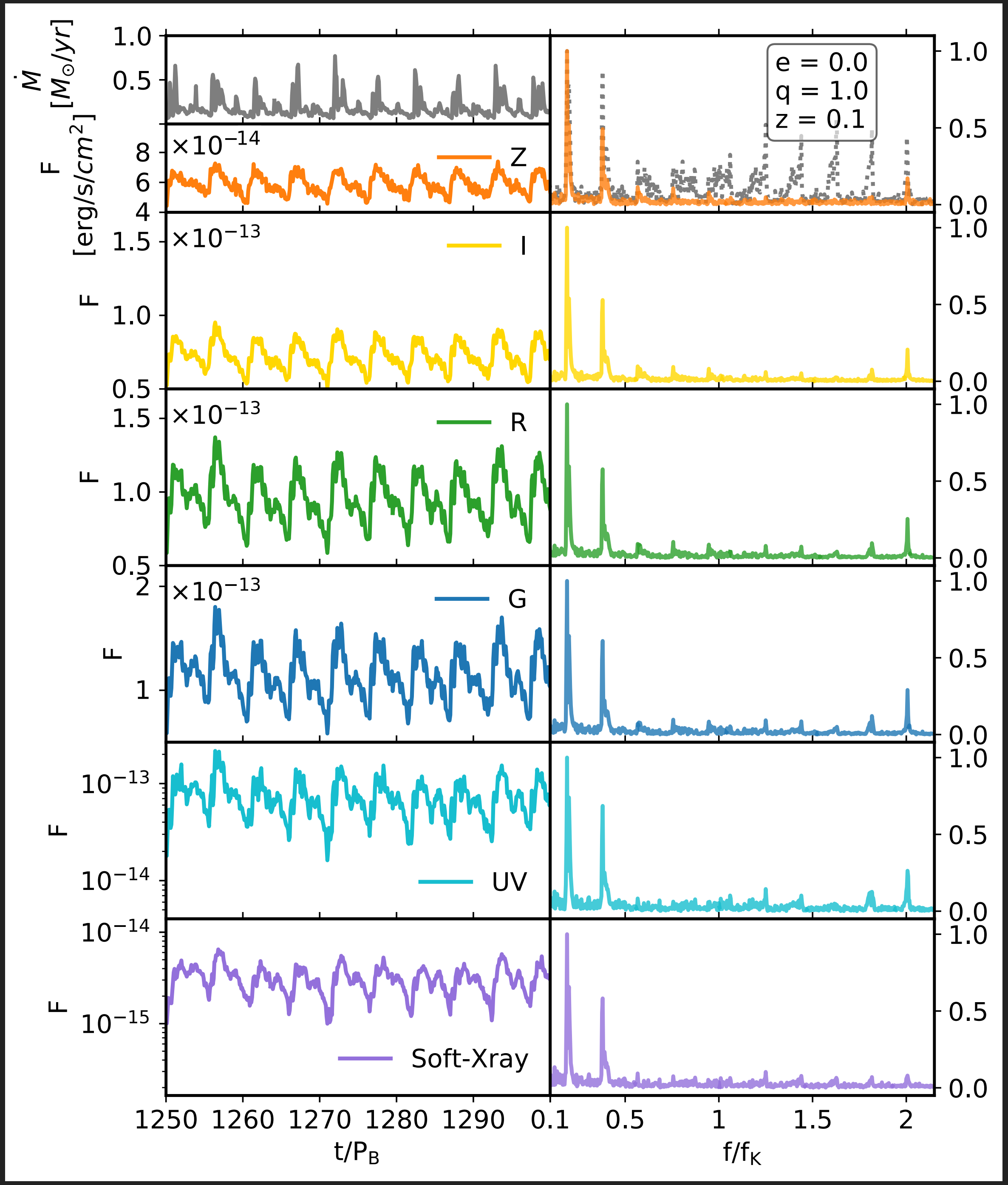
Remnant moves along the y-axis, towards the cavity pericentre

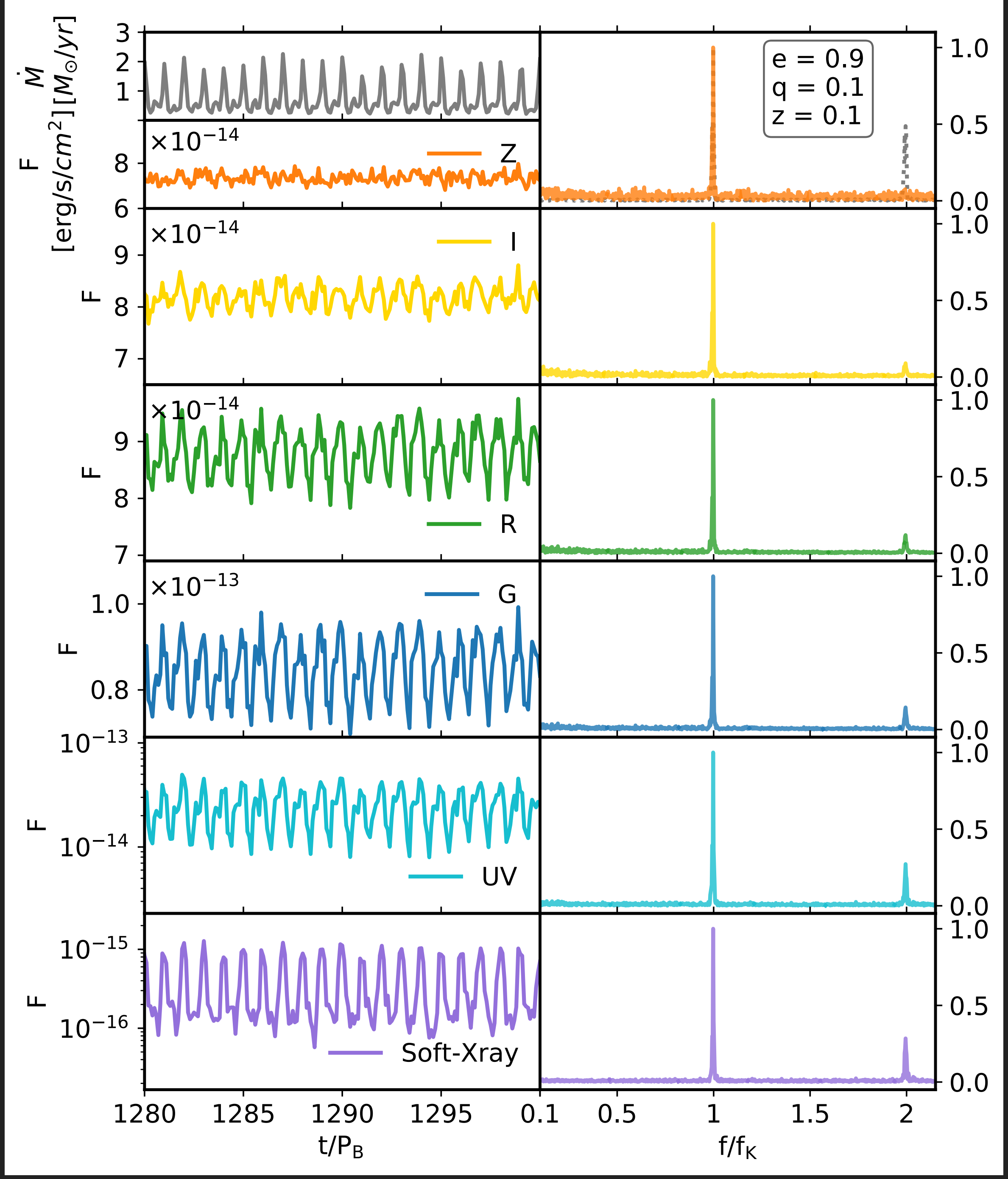
H/R = 0.03

Franchini A., Bonetti M., Lupi A. & Sesana A., A&A 686 A288 (2024)

PERIODICITIES IN THE OPTICAL BAND

- We find stronger modulation on the binary orbital period for higher mass ratios
- We find modulation on the cavity edge (i.e. lump) to be stronger for equal mass binaries

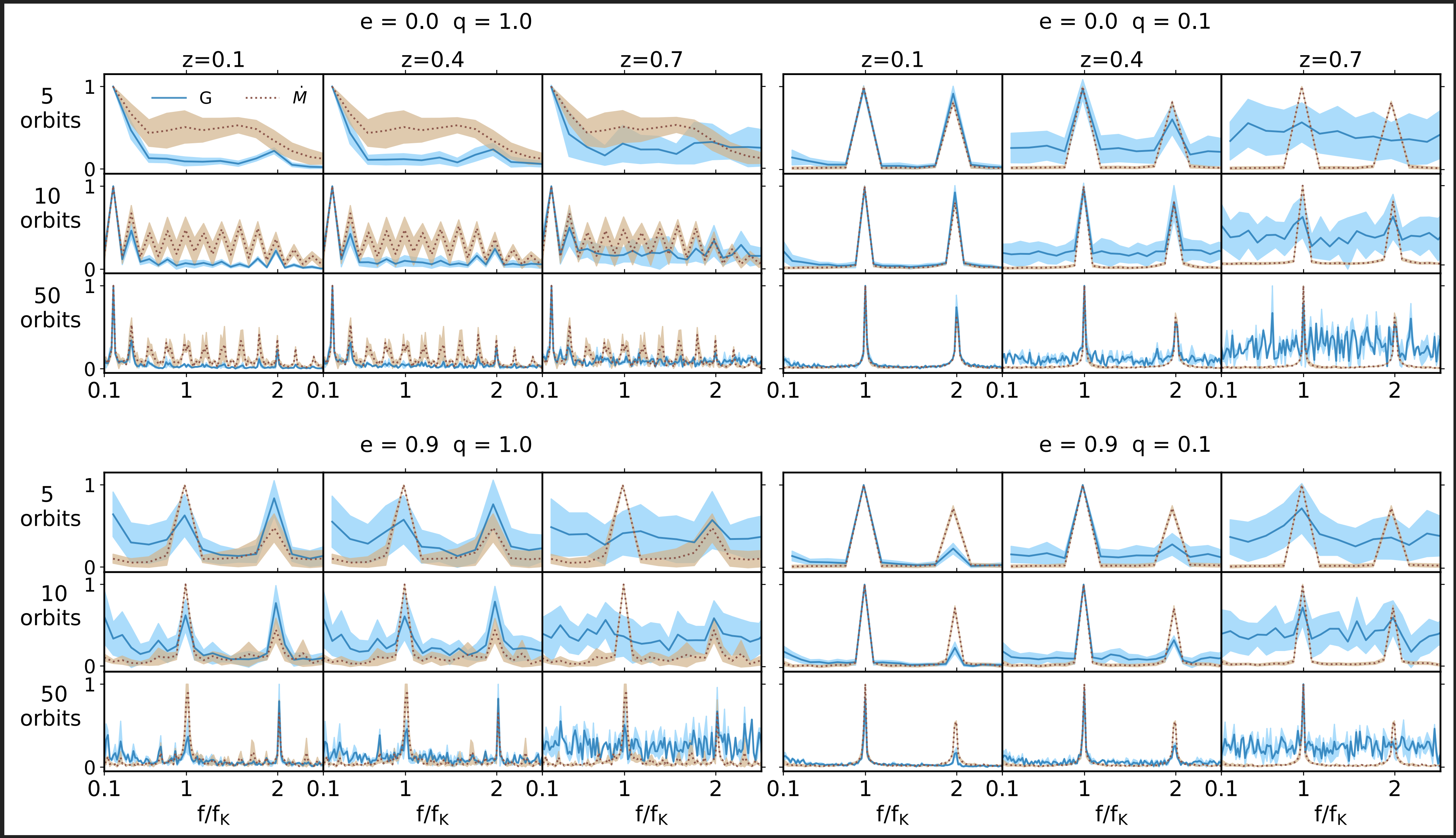




Cocchiararo F., Franchini A., Lupi A. & Sesana A., A&A (2024)

PREDICTIONS FOR VERA RUBIN OBSERVATORY

Equal mass, circular binaries are unlikely to be identified due to the lack of prominent peaks when considering few binary orbits. Conversely, unequal mass and/or eccentric binaries can be singled out up to z ~ 0.5



Cocchiararo F., Franchini A., Lupi A. & Sesana A., A&A (2024)

CONCLUSIONS

- Dual AGN candidates exist and can potentially be detected in almost all the electromagnetic wavelengths by looking at different observables
- Binaries in stage II are much more complicated to find as the variability in the emission can be associated with other scenarios that do not consider a MBHB
- Sub-pc binaries are even harder to identify due to their very small angular separation in the sky coupled with uncertainties in the uniqueness of their signatures

- Modelling the formation and evolution of MBHBs is very complex mainly due to the large dynamical range that needs to be simulated and to the several physical processes that occur at each different scale, most of which are not well understood
- The strategy consists in dividing the dynamical range in multiple phases and simulate each phase independently (with the risk of assuming unrealistic or unphysical initial conditions)
- Sub-pc binaries embedded in either massive self-gravitating or light discs can show distinctive signatures that can potentially be captured by photometric and spectroscopic searches
- Still, we need more physics included in the simulations (e.g. radiative transport, feedback, etc.) to be able to draw trustworthy conclusions on the type of signatures we can expect to detect

Identifying MBHBs through their electromagnetic emission is very important for both LISA and PTA as:

1. optical surveys (ZTF, VRO) can **identify LISA precursors well before they enter the band**
2. for nHz sources (PTA) the identification of an EM counterpart will provide a **measurement of the distance to the source, thus allowing to estimate the source chirp mass from the amplitude**