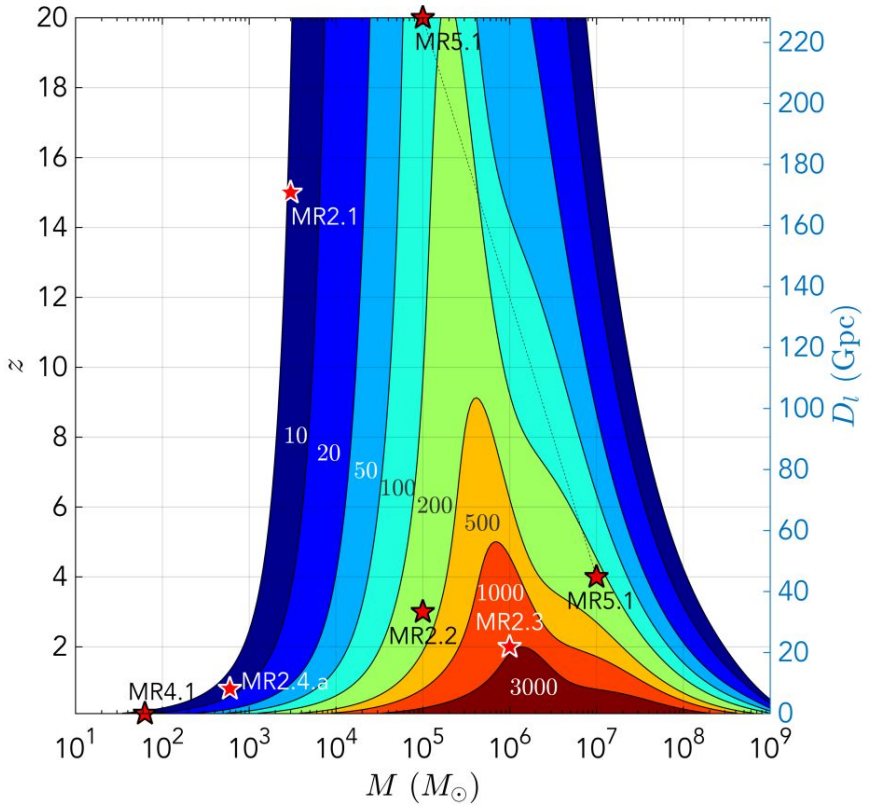
Search and characterization of massive black hole binary candidates

Massimo Dotti (University of Milano-Bicocca)

collaborators:

Roberto Decarli - Vivi Tsalmantza - Carmen Montuori - David Hogg - Marta Volonteri - Monica Colpi - Matteo Bonetti - Daniel D'Orazio - Zoltan Haiman - Stefano Covino - Matteo Fossati - Alberto Sesana - Elisa Bortolas - Alessia Franchini - Alessandro Lupi - Paola Severgnini - Roberto Serafinelli - Walter Del Pozzo - Fabio Rigamonti…

MBH binaries are loud low-frequency GW sources for LISA and PTA



Amaro-Seoane+ 2017

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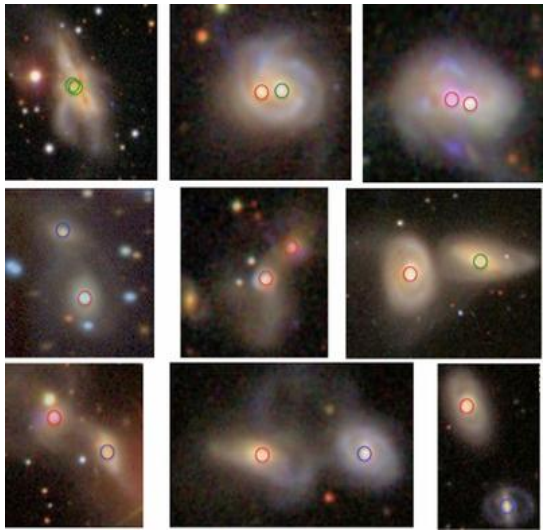
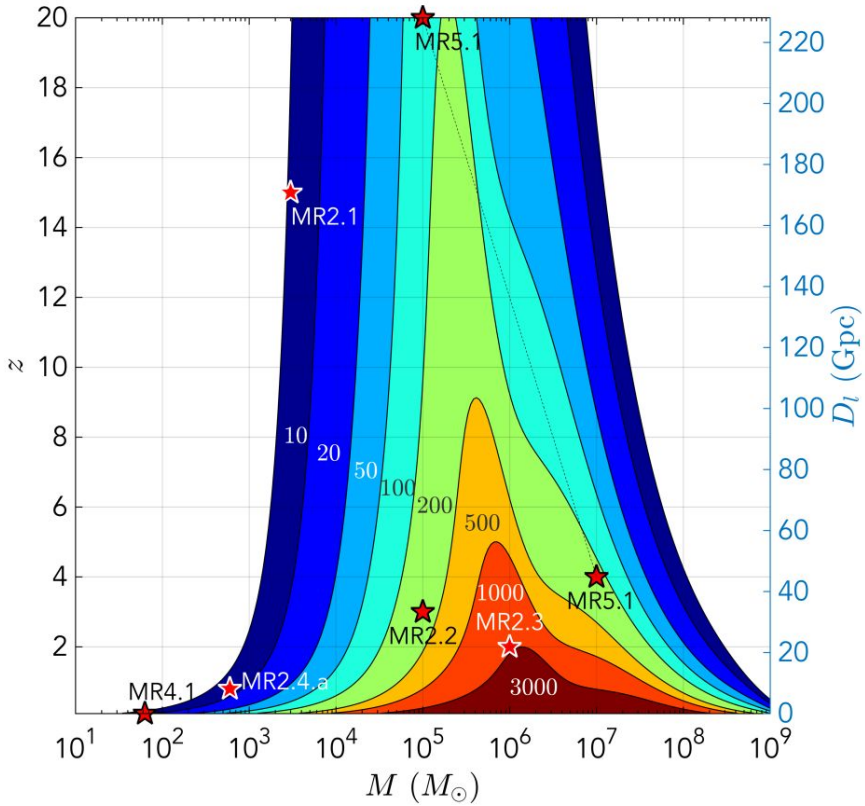
Large scale MBH pairs are known (~200, down to 100pc scales)...





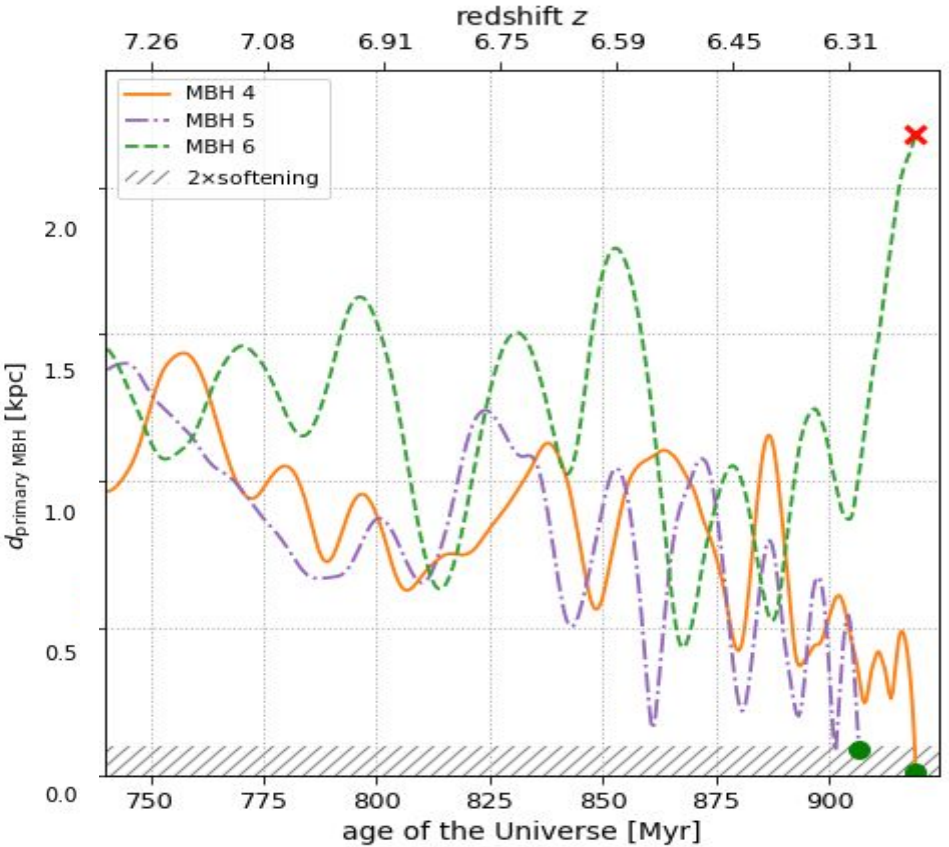
Amaro-Seoane+ 2017

from Koss+12 (BAT survey): X&opt, X-only, opt-only

MBH binaries are loud low-frequency GW sources for LISA and PTA

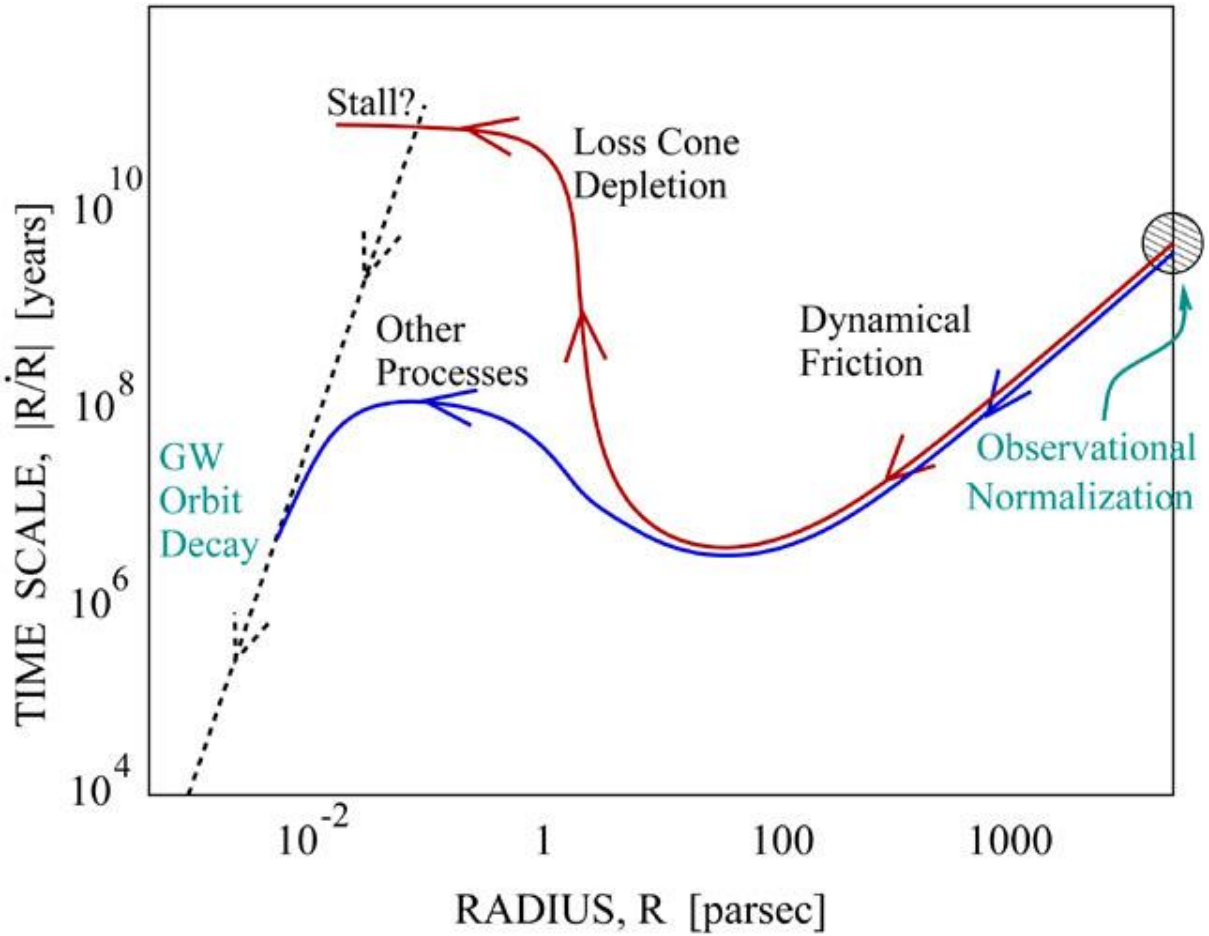
Large scale MBH pairs are known (~200, down to 100pc scales)..

but the uncertainties on their pairing efficiency are huge!

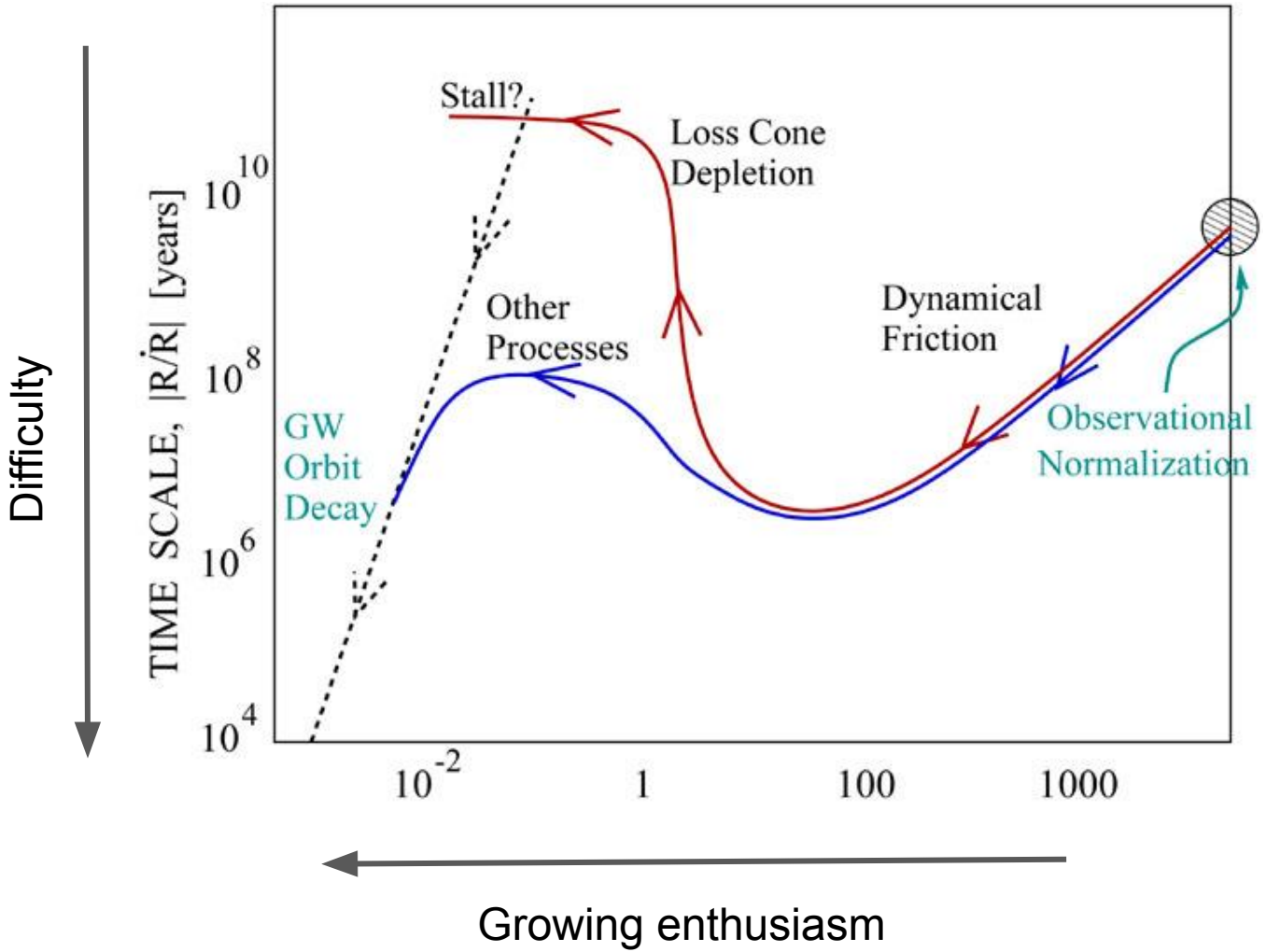


Bortolas+2020

(see also Fiacconi+2013, Del Valle+ 2015, Tamburello+2017, Souza-Lima+2017)



(adapted from Begelman+1980)


Difficulty
TIME SCALE, |R/Ṙ| [years]
10^{10}
10^{8}
10^{6}
10^{4}
Stall?
Loss Cone
Depletion
Other
Processes
GW
Orbit
Decay
Dynamical
Friction
Observational
Normalization
10^{-2}
1
100
1000
Growing enthusiasm

Scales

…i.e. when (where) binary forms:

$$a_{\rm BHB} \sim \frac{GM_{\rm BHB}}{2\sigma^2} \sim 0.2\, M_{\rm BHB,6}\, \sigma_{100}^{-2}\, {\rm pc}$$

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assuming the M-sigma relation (!!!)

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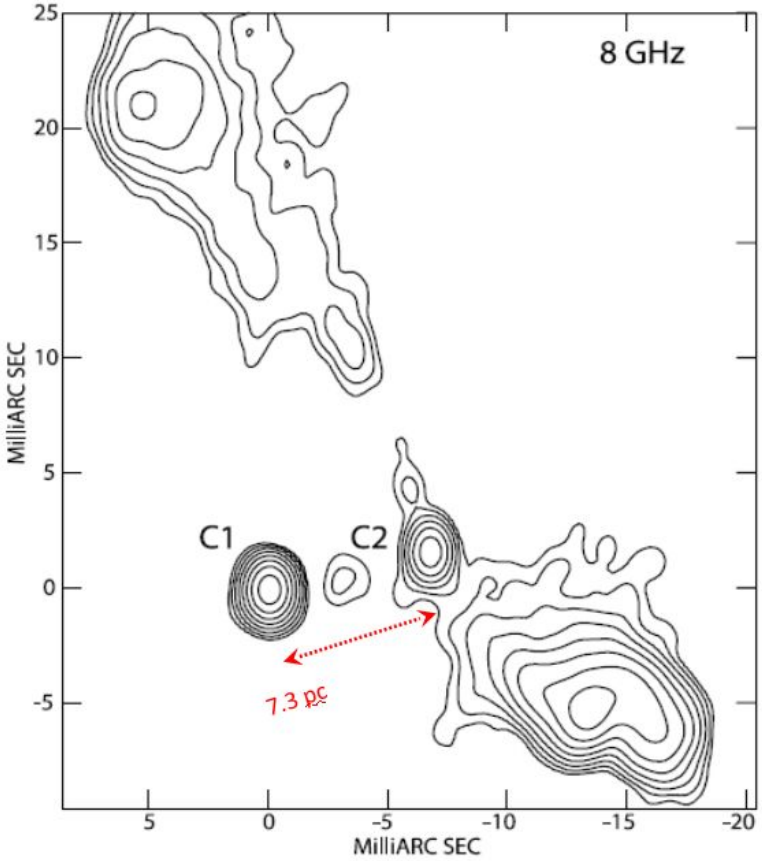
Note: 0.5 pc ~ 1 mas @ z~0.03 (d~130 Mpc)

THE BHB candidate: 0402+379



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

The M_{BH}-L_{bulge} relation implies M_{BH} ~10^8 Msun

A systematic search over >3000 radio-loud systems did not found other candidates (Burke-Spolaor 2011)

Searching for unresolved BHB candidates

At least two classes of peculiar features proposed:

Peculiar spectral properties of the broad lines in optical/UV spectra

(Quasi-)periodic variability of the continuum

Searching for unresolved BHB candidates

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Selects looser binaries
(~0.1 pc for ~10^8 M_{sun}@ 0.1 L_{Edd})

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Selects closer binaries
(the closer to coalescence the better)

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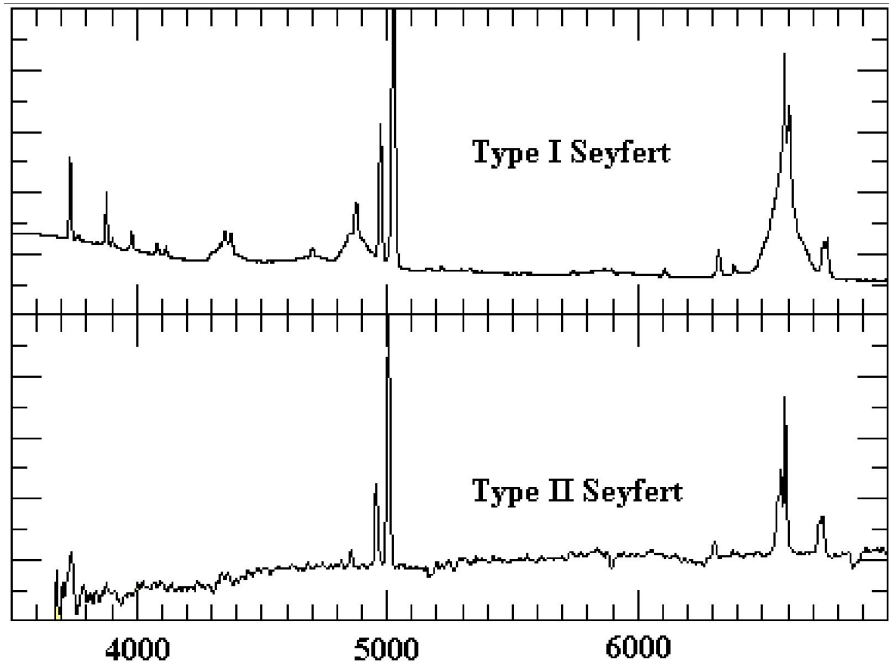
Looser binaries: prerequisites



(Morgan 2002)

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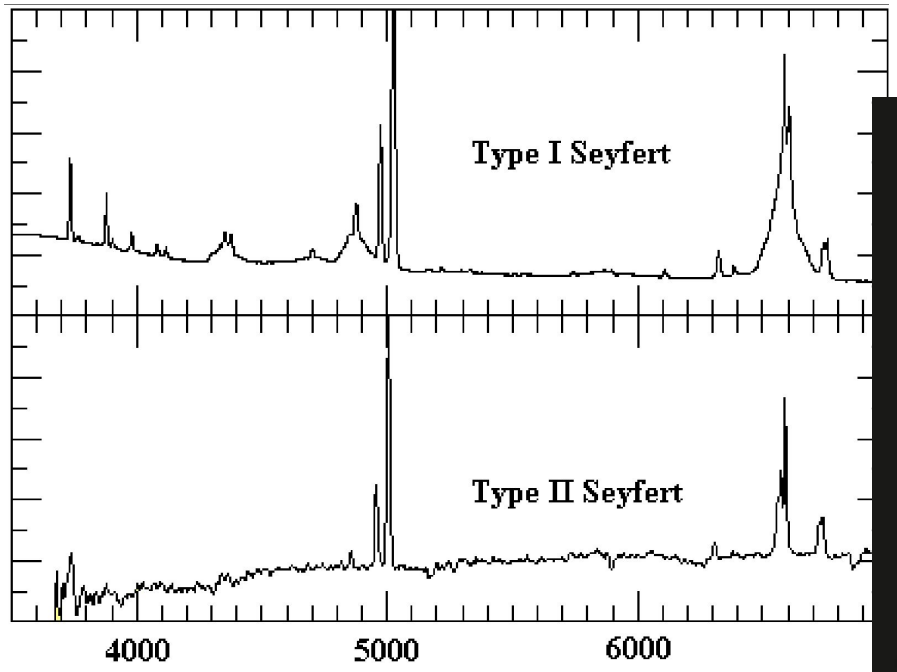
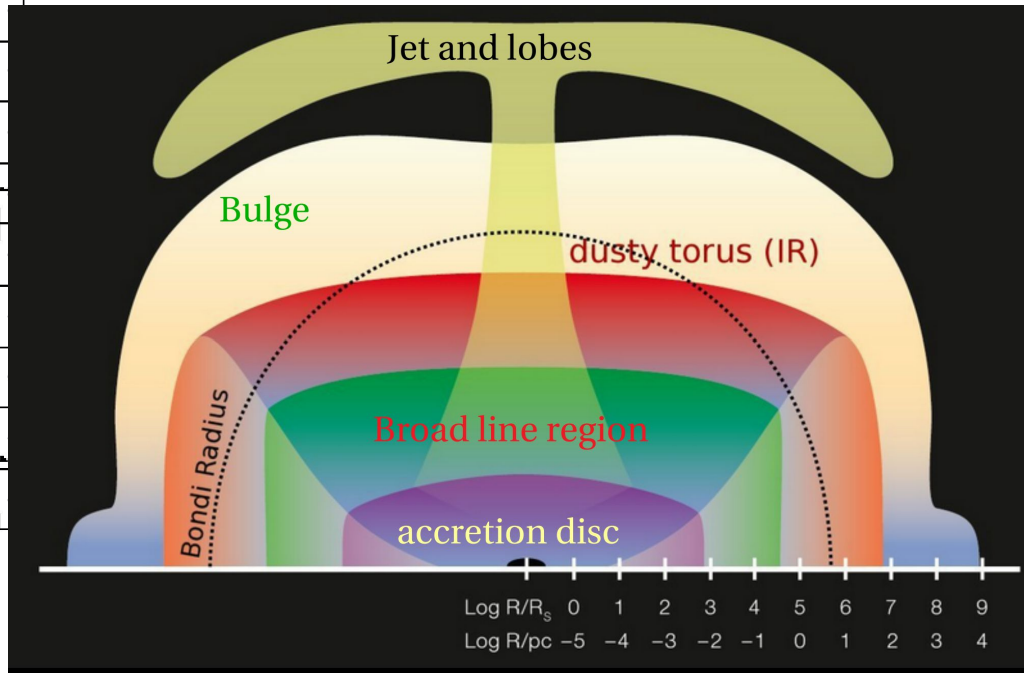
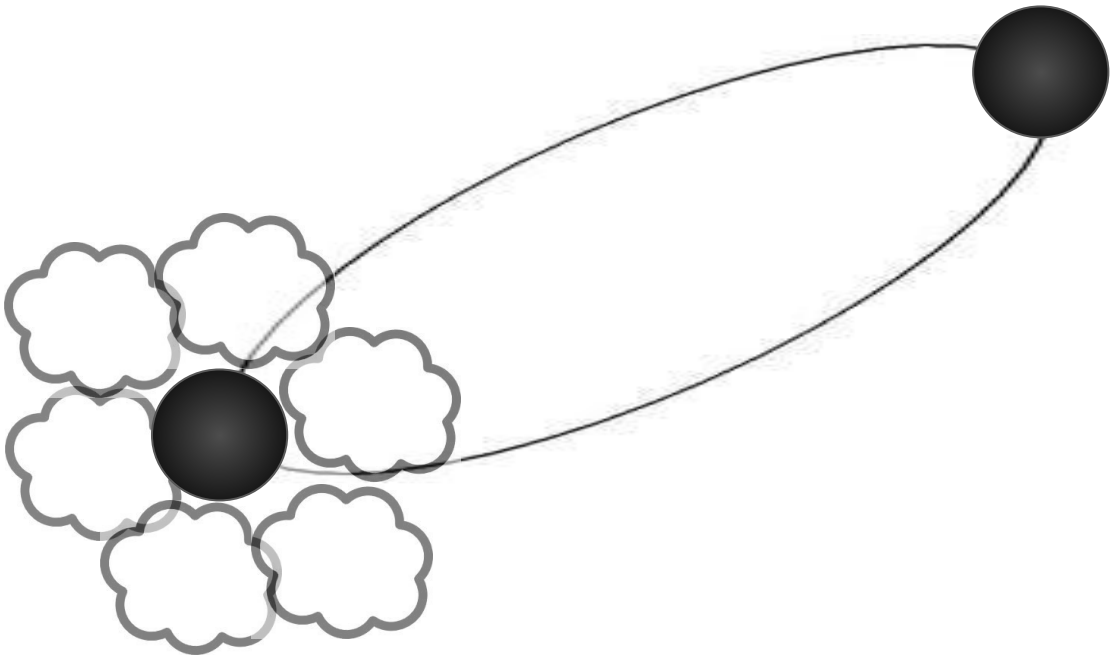


(Morgan 2002)



Credits: A. Merloni

Looser binaries
(since Begelman, Blandford & Rees 1980)



Assuming (at least) 1 MBH active with its own BLR

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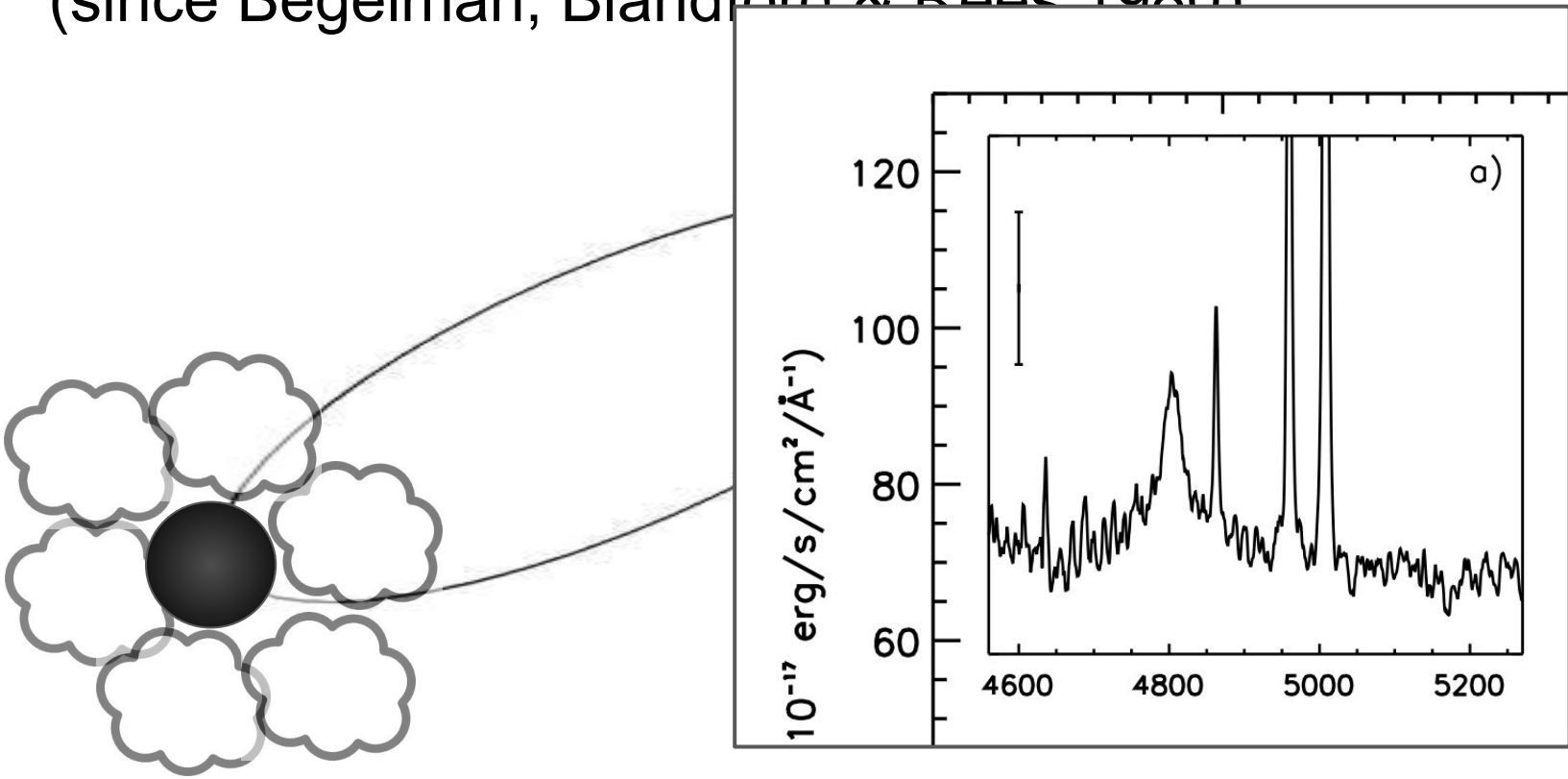

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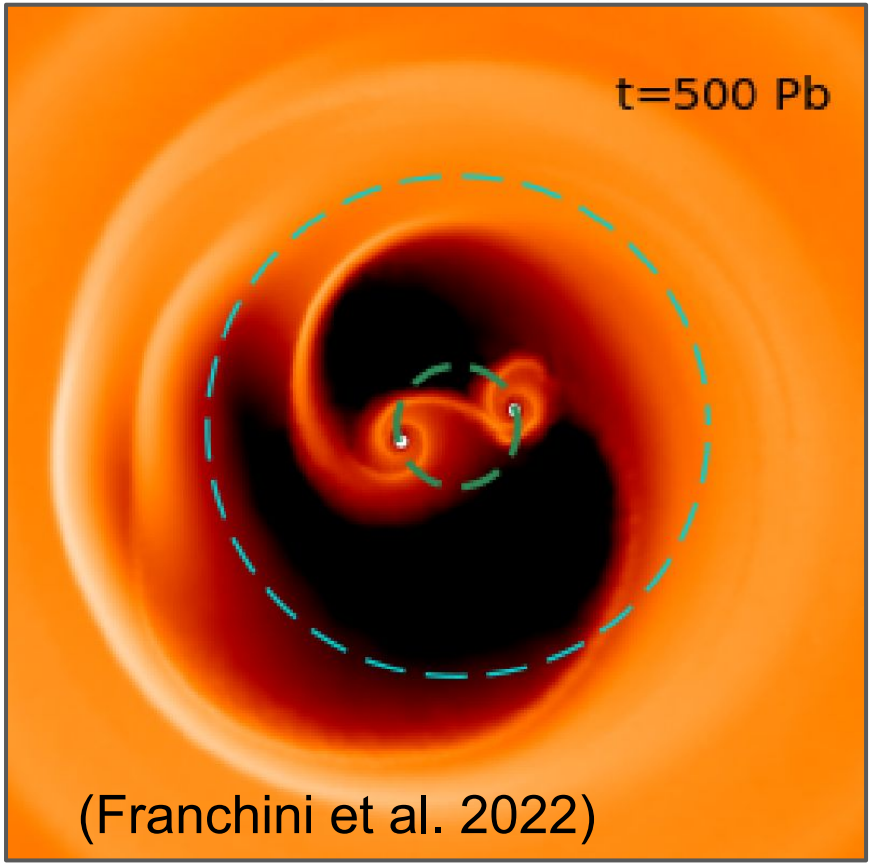
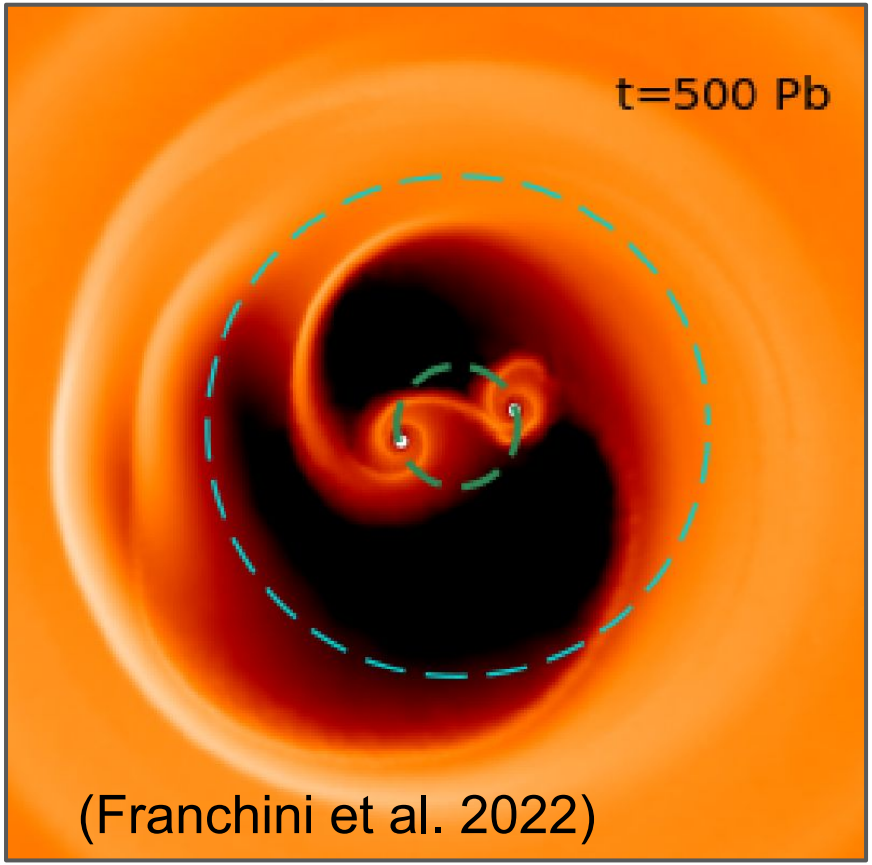


(Franchini et al. 2022)

Looser binaries

(since Begelman, Bla



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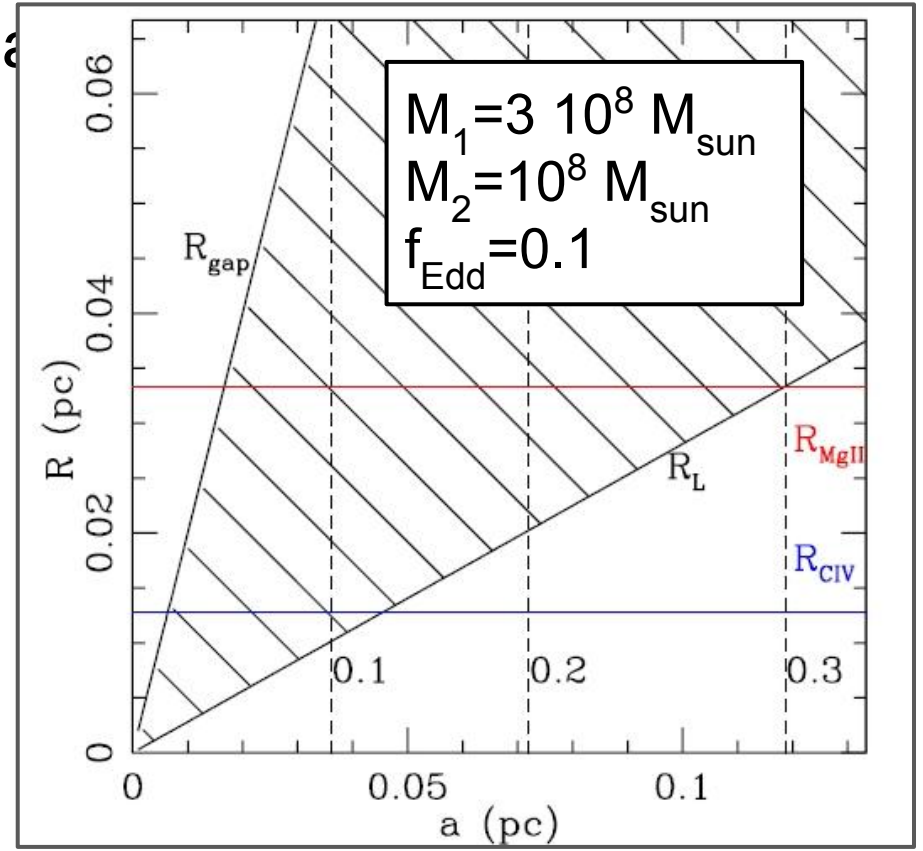


(Montuori et al. 2012)

Looser binaries
(since Begelman, Blandford & Rees 1980)

PRO:

Huge amount of data (e.g. the SDSS catalogue)

Model is falsifiable - predicts velocity shifts (!!!)

CONTRA:

Not unique (more to come…)

Expected orbital periods are (exceedingly?) long

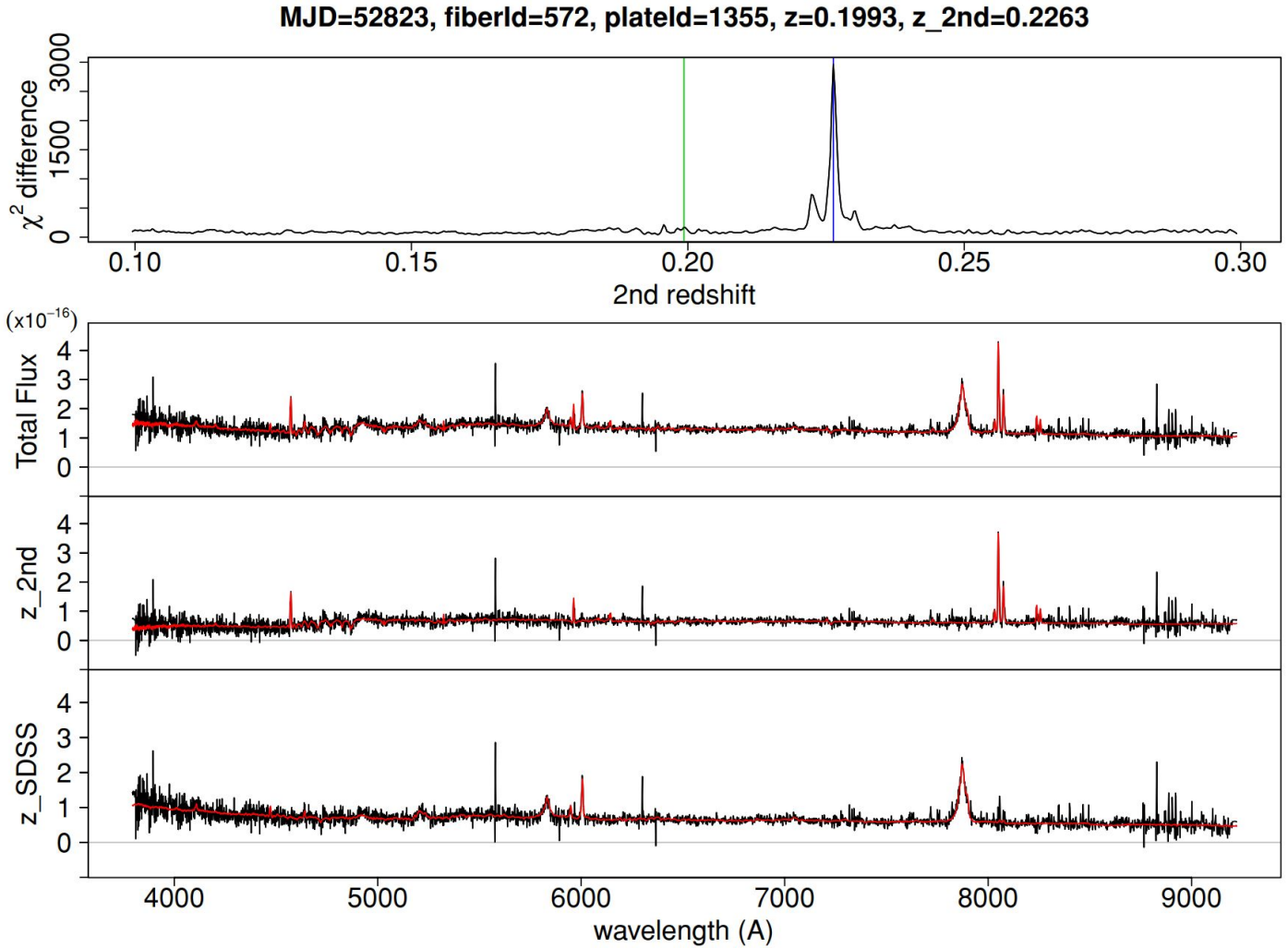
…called for a systematic search

Tsalmantza et al. (2011)

Search for multiple redshift line-sets

Eracleous et al. (2012)

Search for displaced/irregular broad Hβ


MJD=52823, fiberId=572, plateId=1355, z=0.1993, z_2nd=0.2263
χ² difference
0
1500
3000
0.10
0.15
0.20
0.25
0.30
2nd redshift
(x10⁻¹⁶)
Total Flux
z_2nd
z_SDSS
0
1
2
3
4
4000
5000
6000
7000
8000
9000
wavelength (A)

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Search for multiple redshift line-sets

32 peculiar objects, 9 considered good MBHB candidates

Eracleous et al. (2012)

Search for displaced/irregular broad Hβ

88 candidates selected

Caveats: alternative explanations

Recoiling MBHs (e.g. Komossa et al. 2008)
velocities up to ~5000 km/s (e.g. Lousto et al. 2012, the bulk expected at significantly lower velocities…)

Disky BLR (e.g. double peaked emitters, Eracleous et al. 1994)

Cosmological superposition
(sub-arcsec alignment of 2 AGN highly unlikely)

Superposition in a galaxy cluster (Heckman et al. 2009)

Alternative models do not predict Δv changes over <100 yr…

Tsalmantza sample follow-ups (other than velocity shifts)

Optical/IR imaging (Decarli et al., 2009a,b, 2014)

3 objects are actual superpositions in overdensities

Broad SED (Lusso et al. 2014)

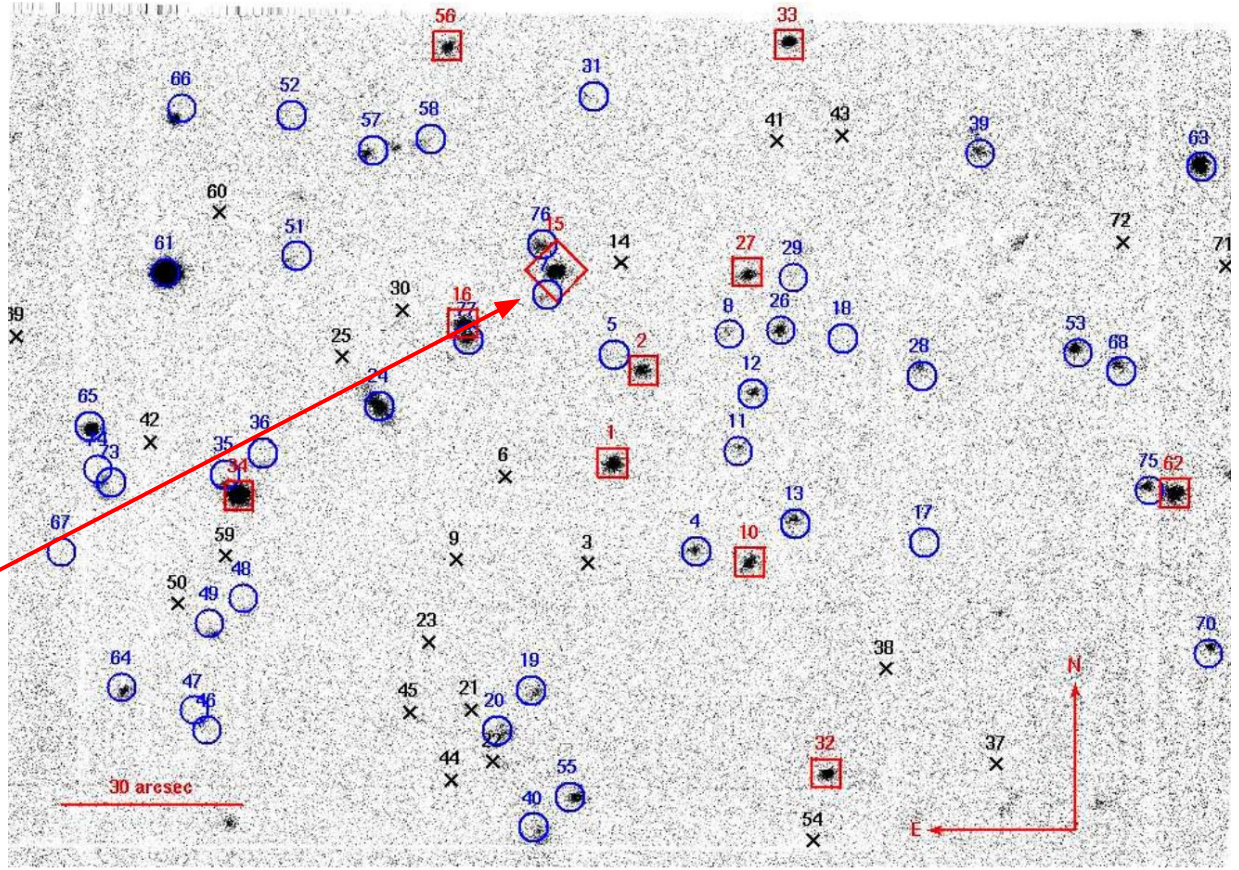
every object (except maybe one) have a bright torus

A text-book case: J0927+2943

A photometric study of the field didn't find any galaxy cluster (Decarli et al. 2009)

red - galaxies with z consistent with 0.7

diamond: J0927



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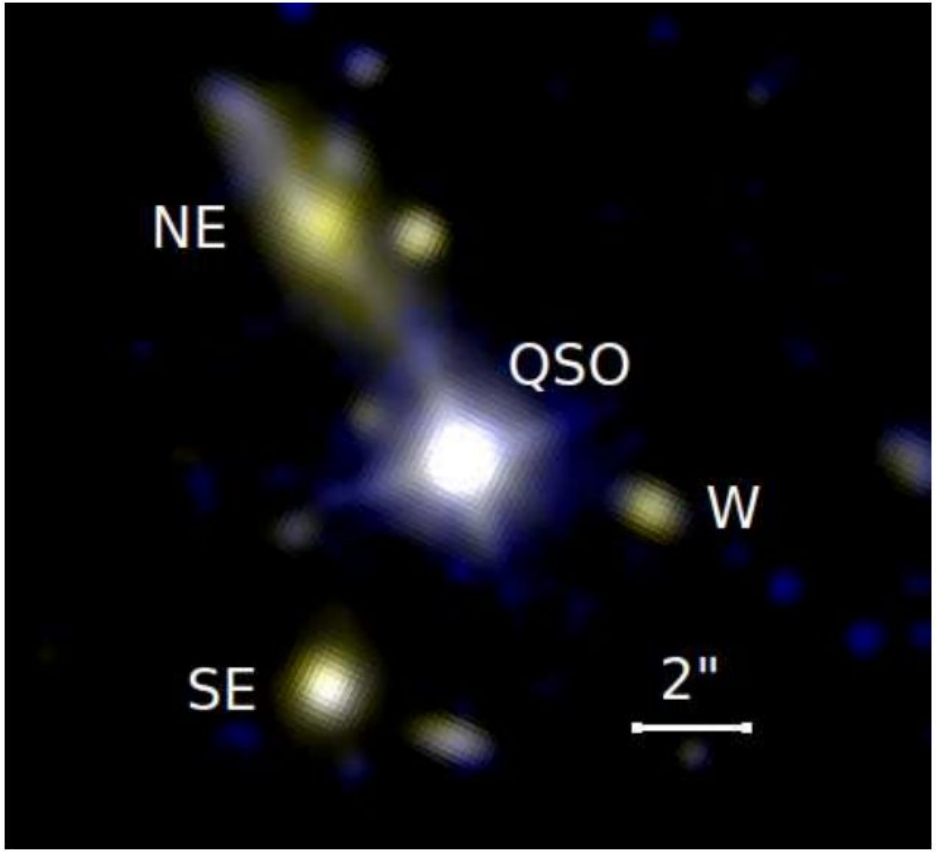
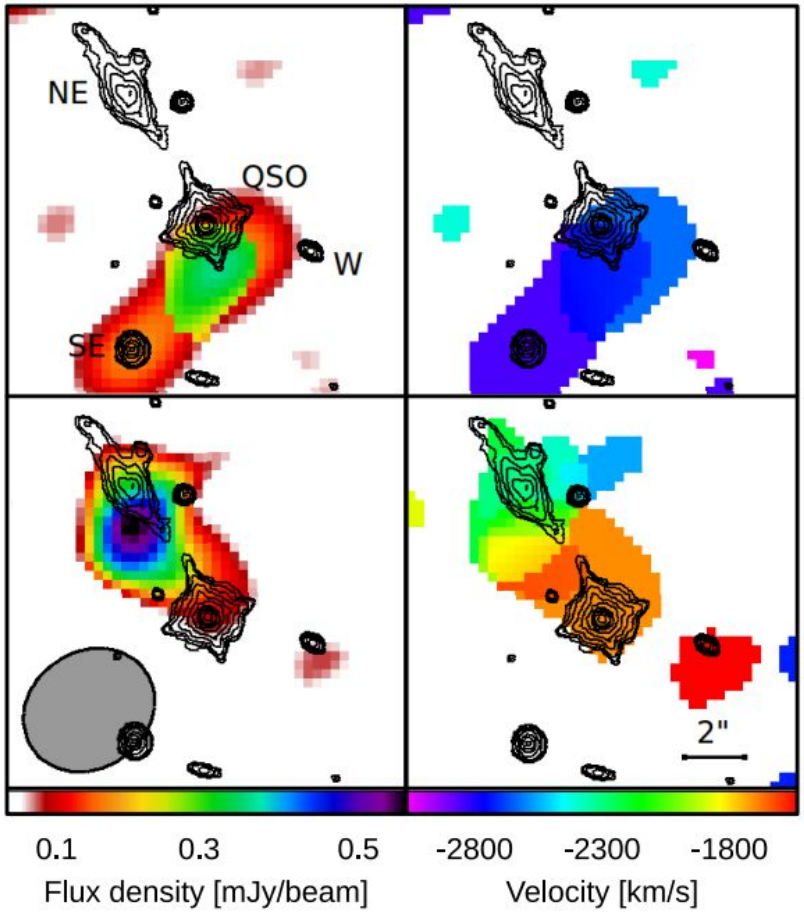
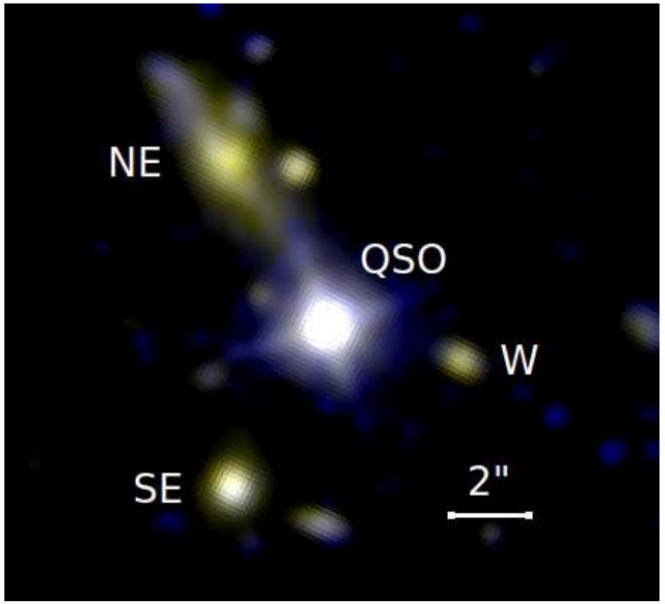
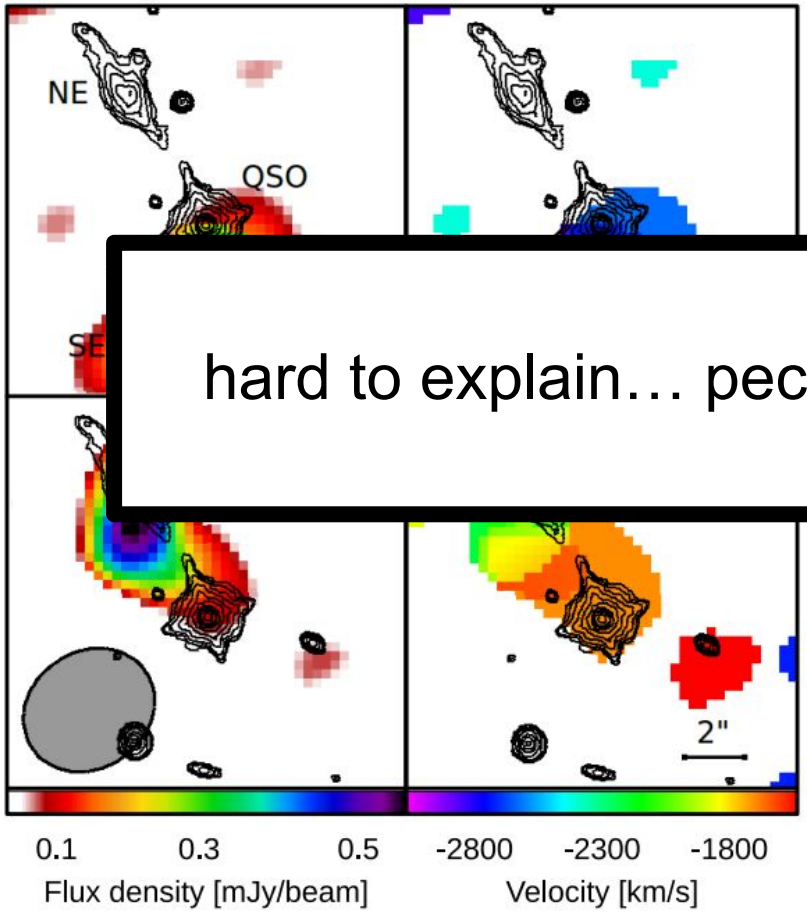






…and still, a lot of molecular gas observable at the redshift of the BELs



hard to explain… peculiar galaxy-cluster ??

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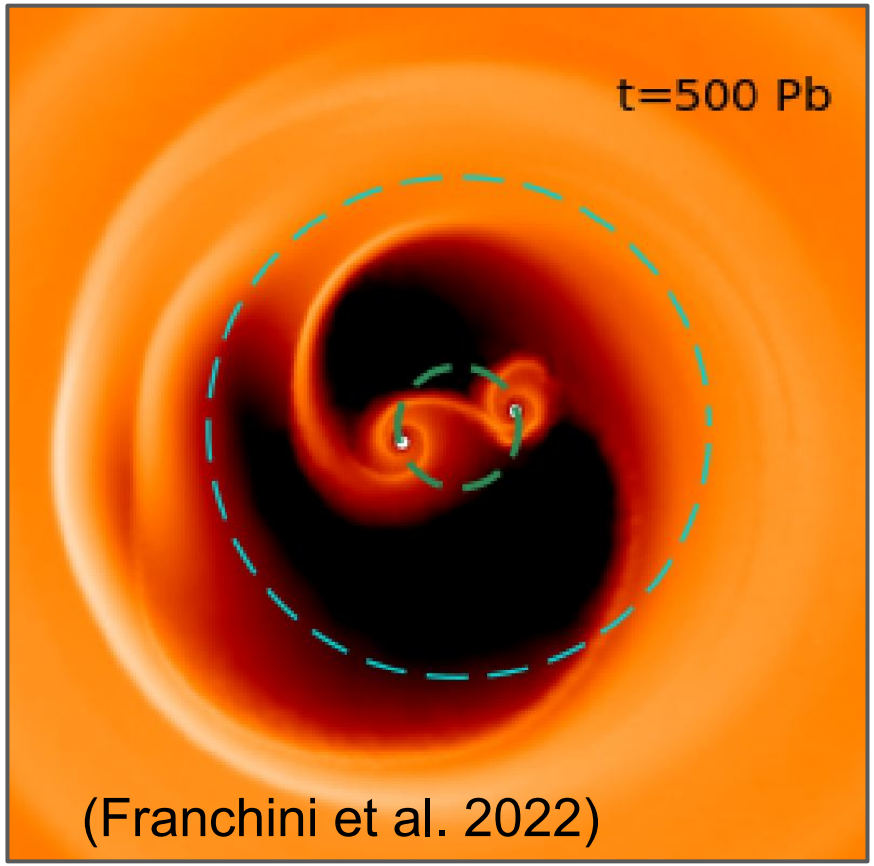
A few (1?) objects consistent with <50 yr period with Eracleous team (e.g. Runnoe+2017) working hard on the test…

Stay tuned!

A novel (and faster) binarity test (Dotti et al. subm.):



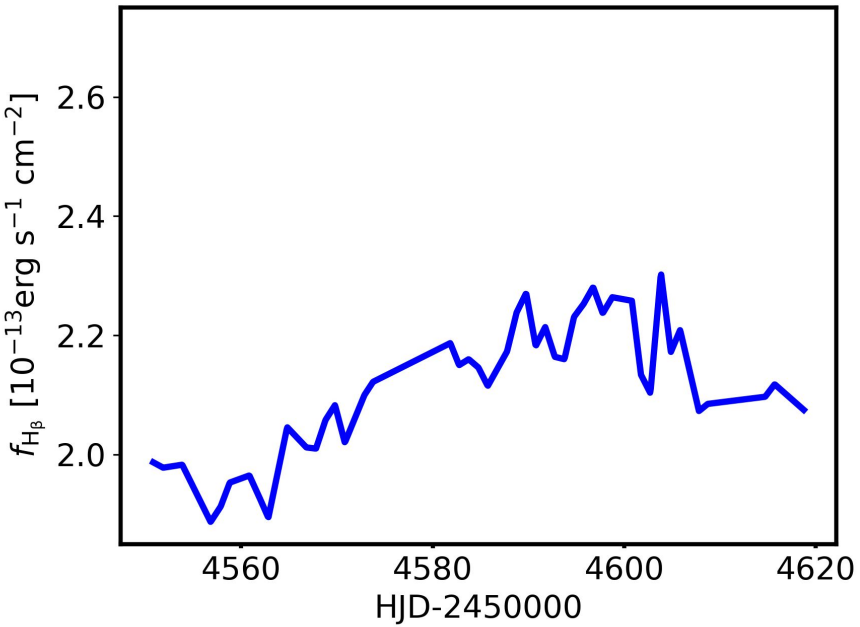
(Franchini et al. 2022)

large distances (P~100 yr) ->

natural variability of the individual accretion discs much shorter

the BLRs could reverberate on days-weeks, with the individual contributions **being uncorrelated,** (not so in the single AGN scenario)

Test using reverberation mapped AGN from Bentz et al. (2009)
e.g. NGC 4748



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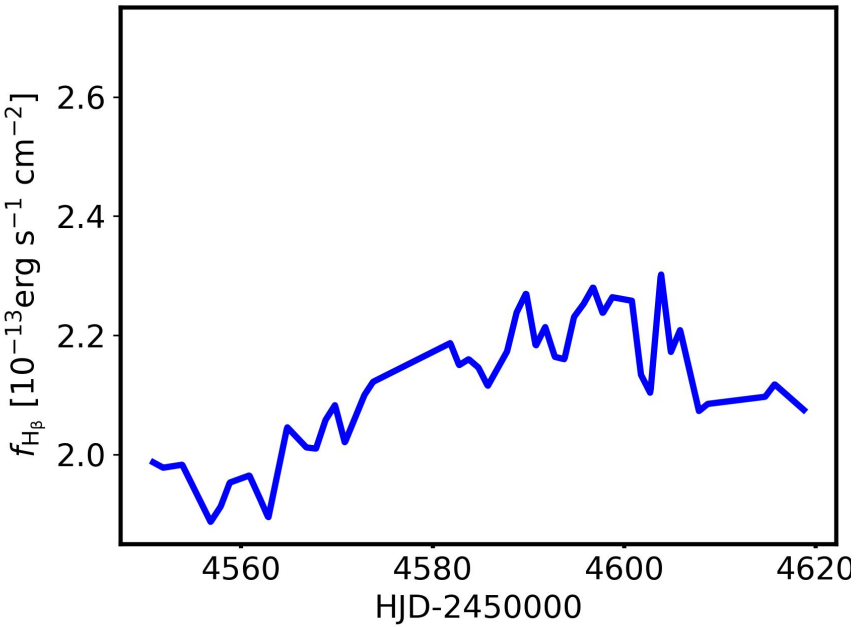

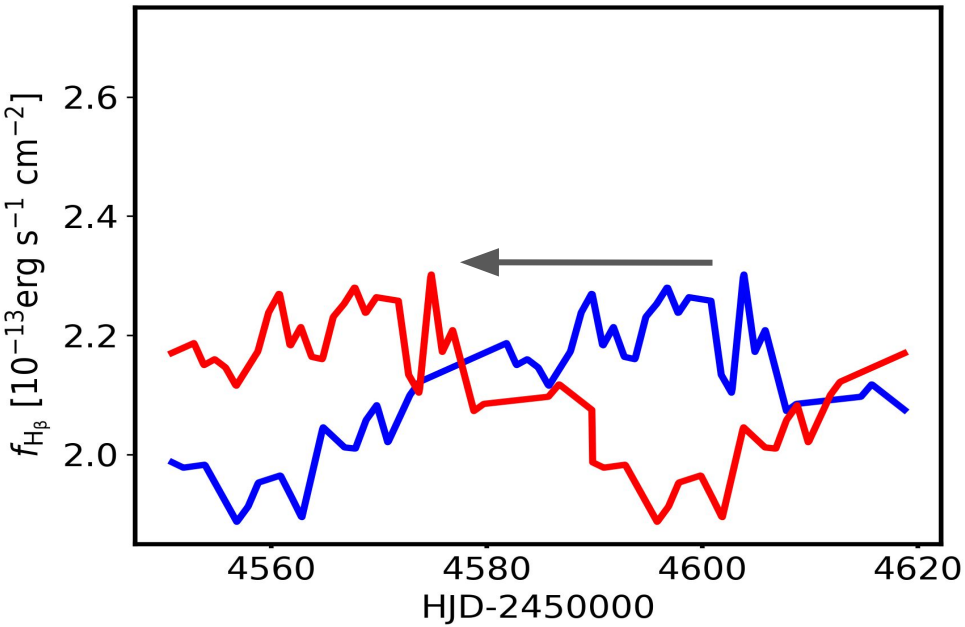

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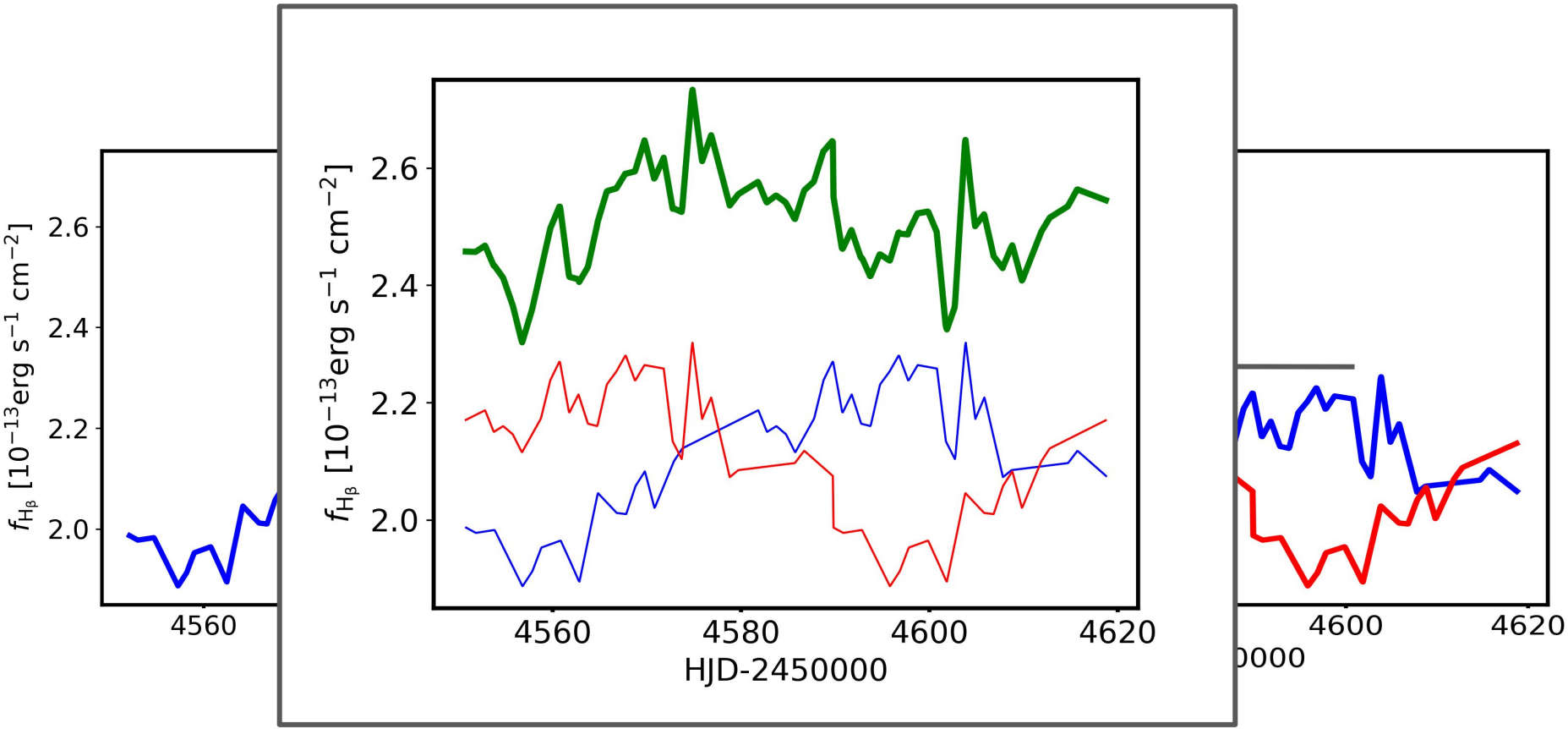

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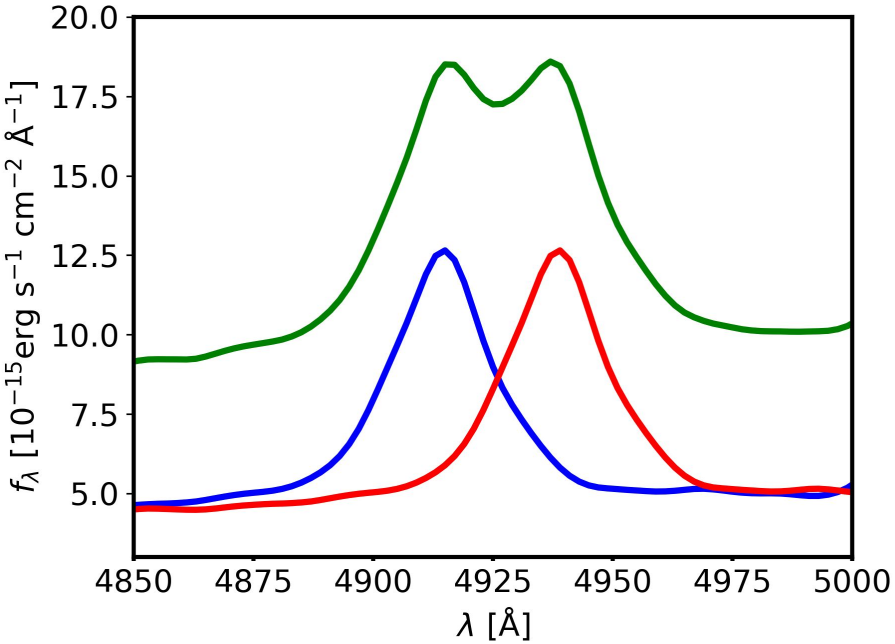

T_{orb} = 50 yr

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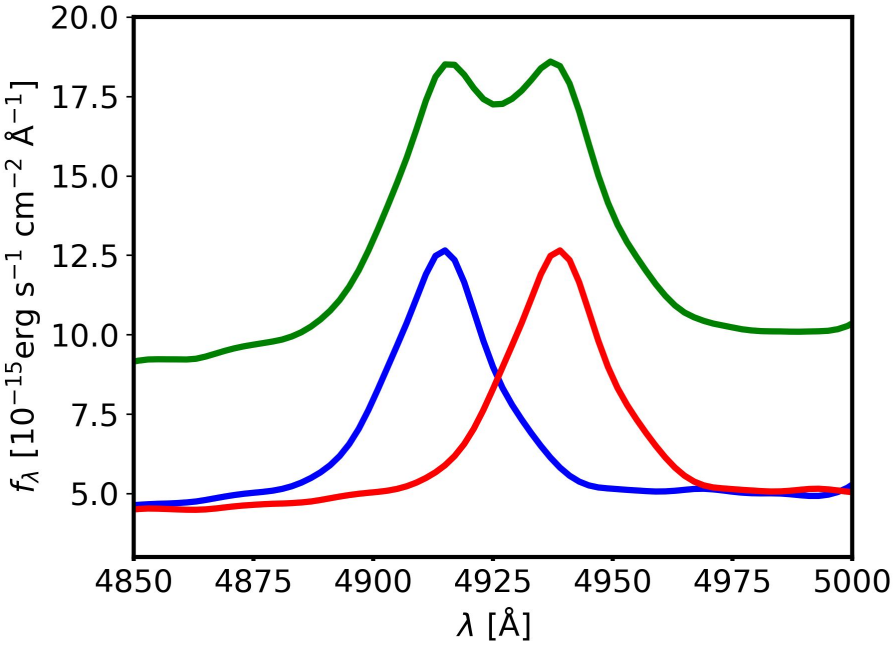

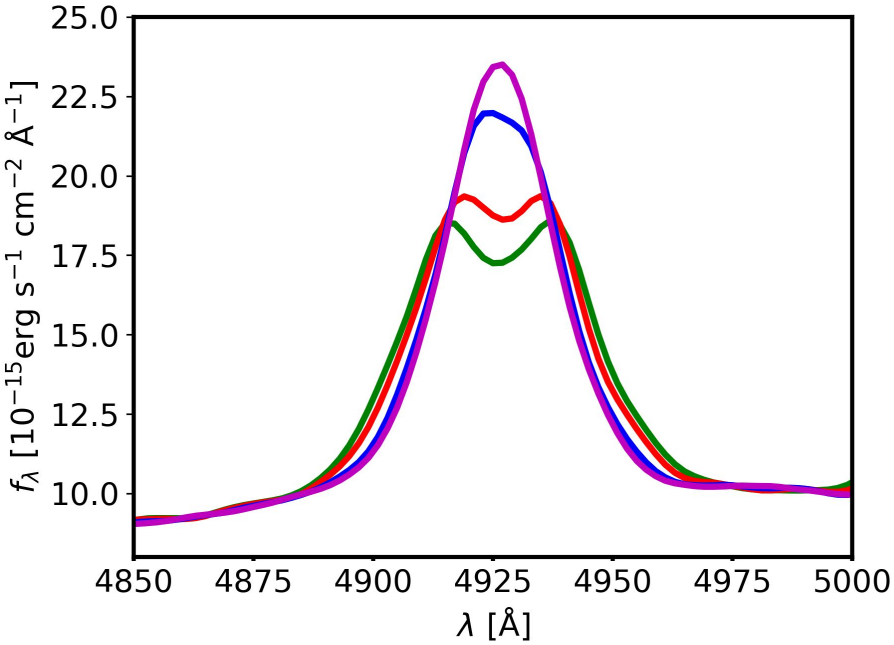

T_{orb} = 50 yr, 100 yr, 300 yr, 1000 yr

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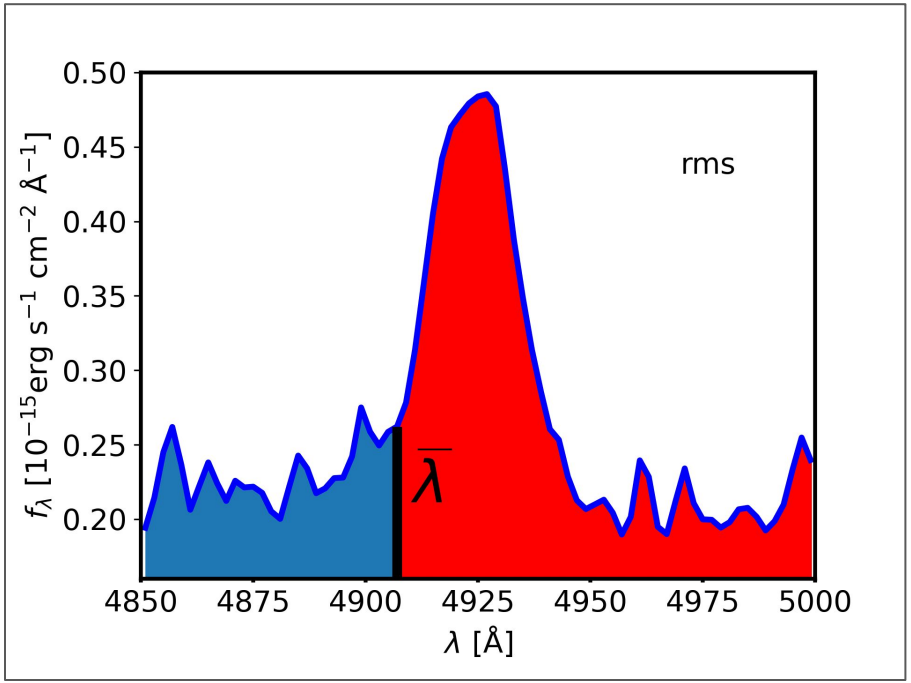

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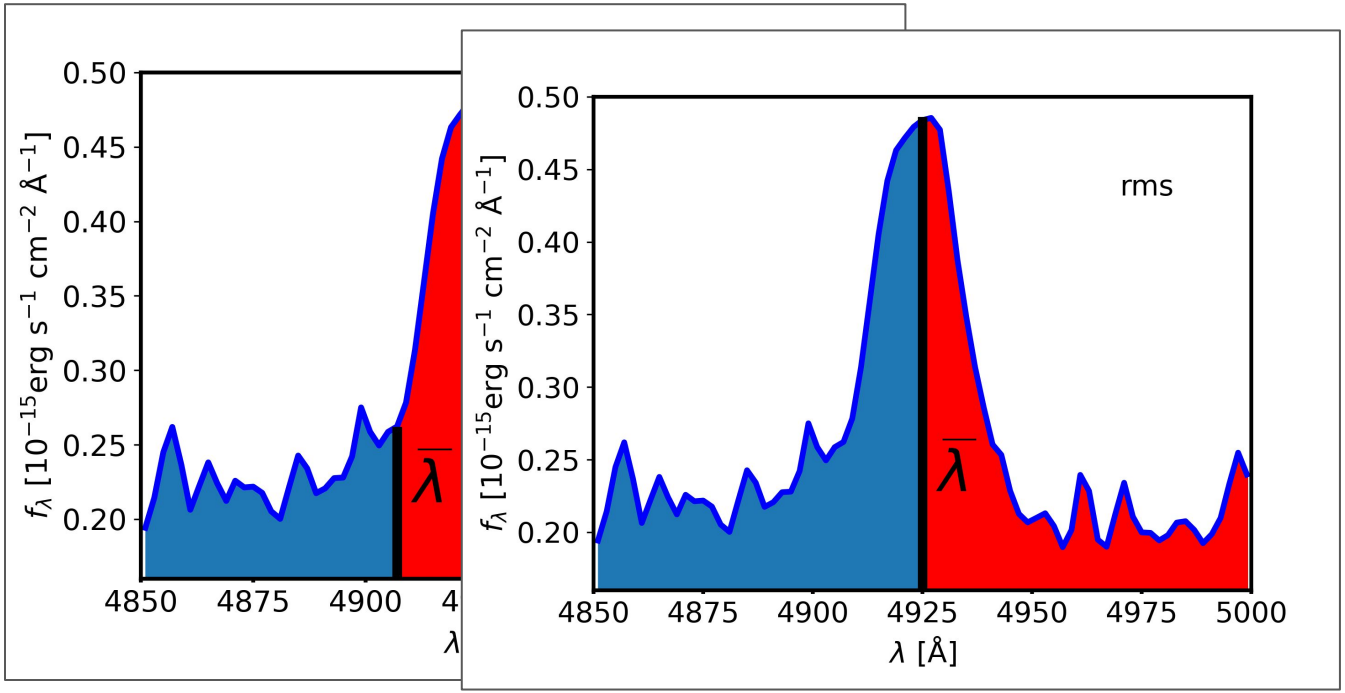

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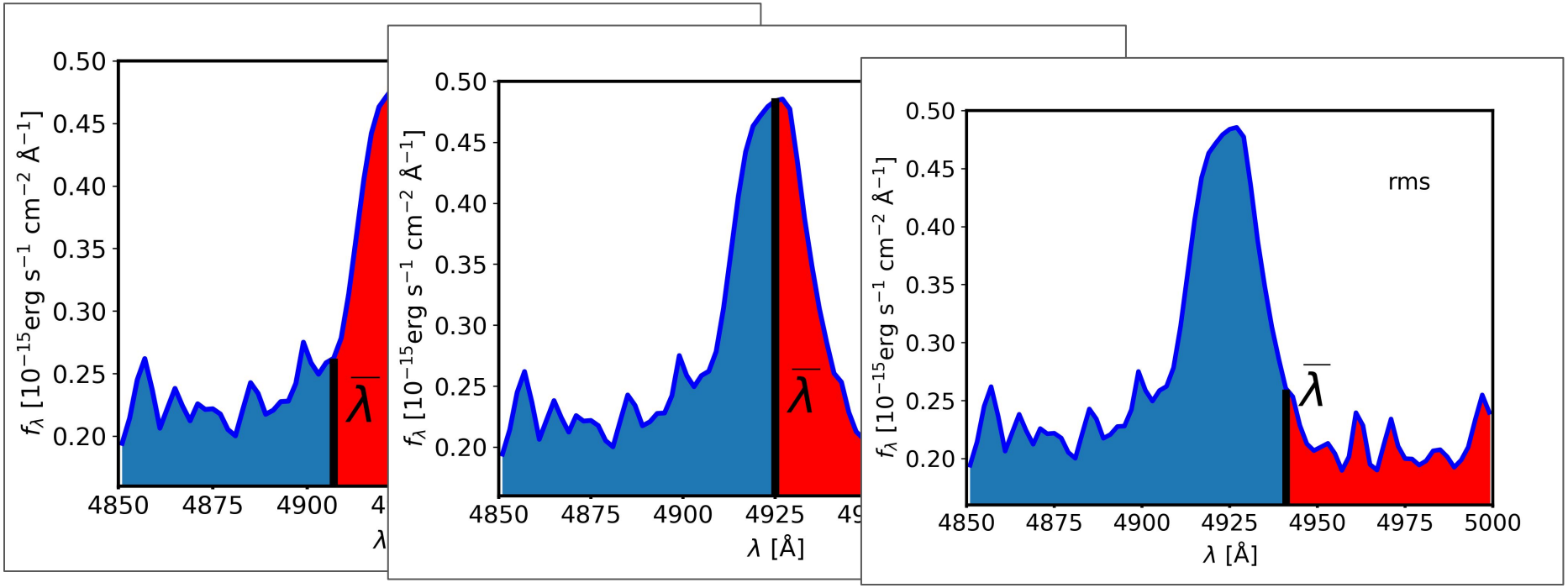

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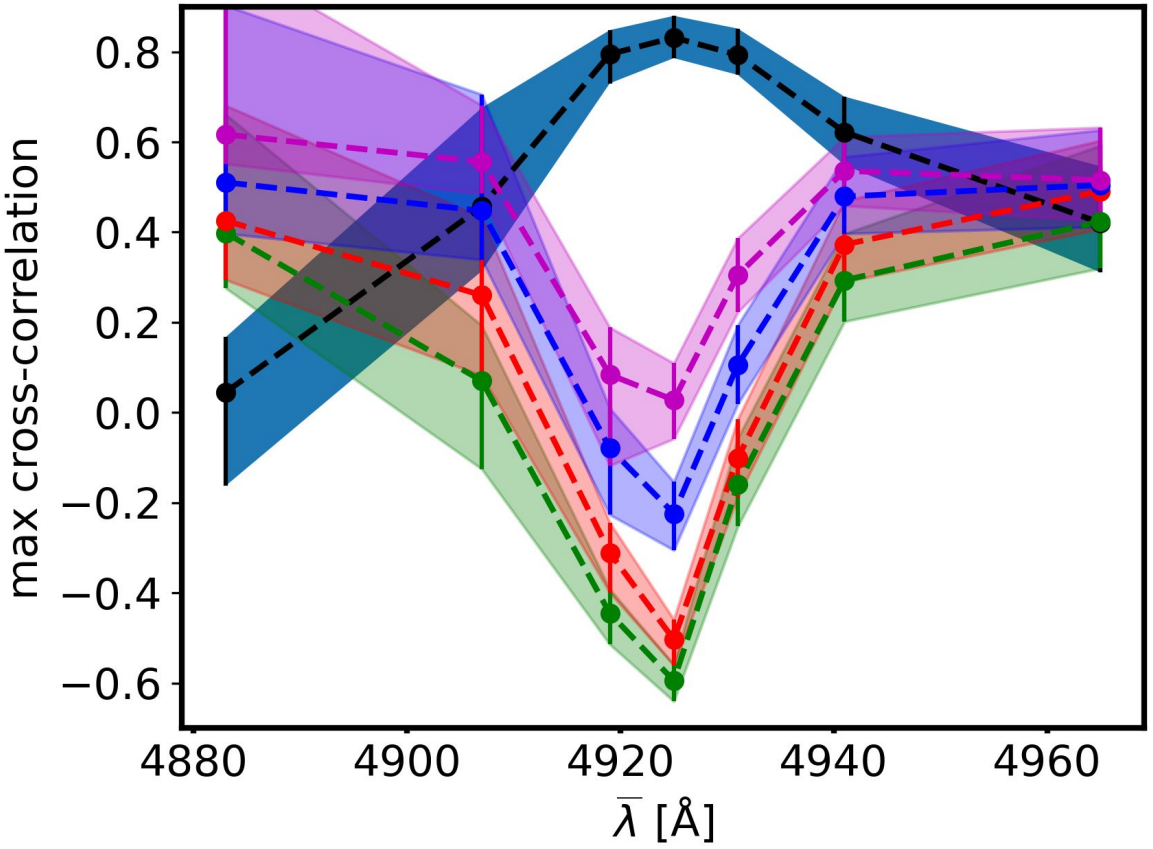
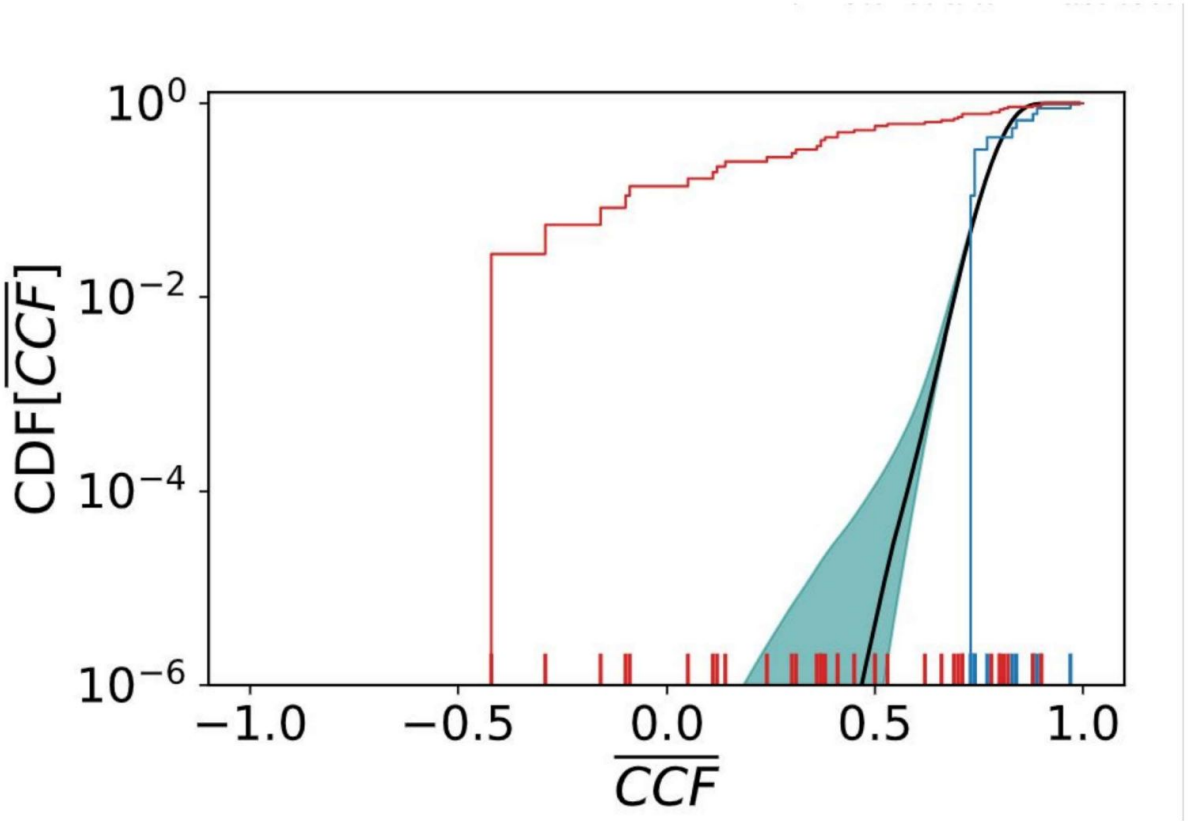


Test using **9** reverberation mapped AGN from Bentz et al. (2009)



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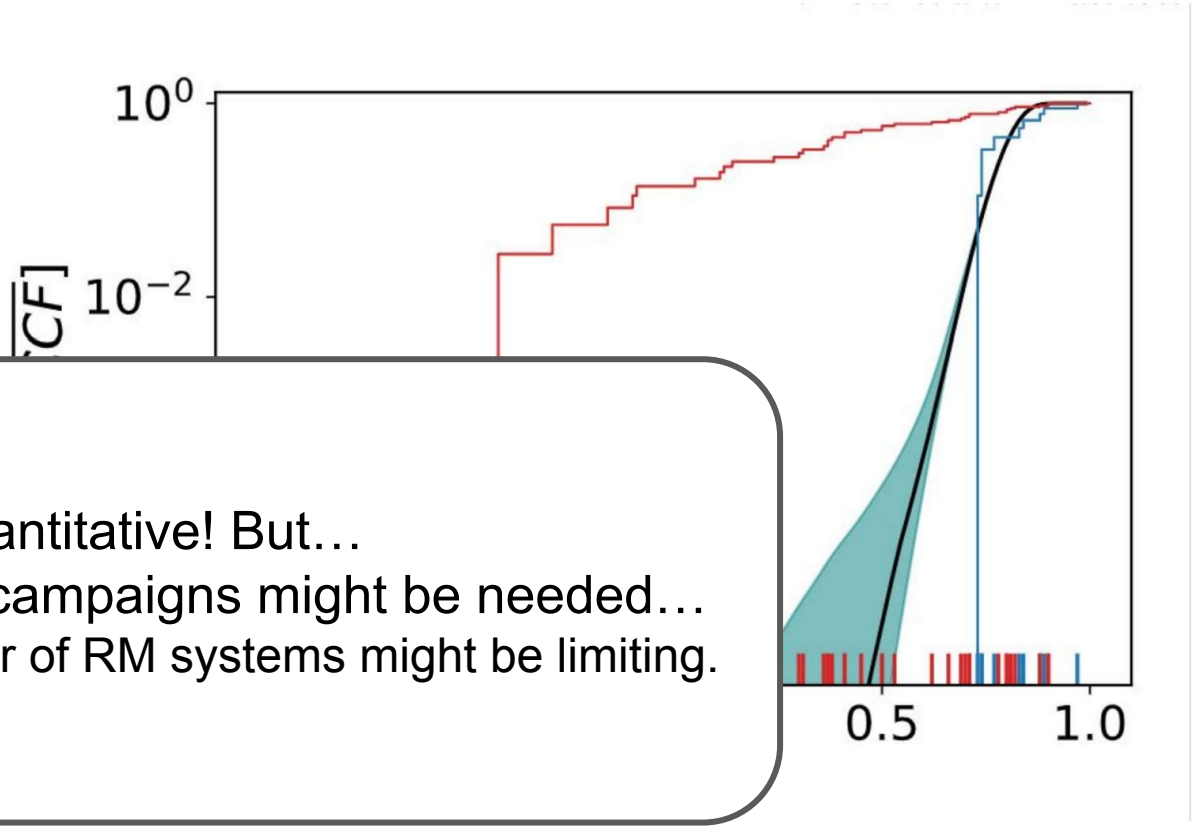

Faster and quantitative! But…

…multiple campaigns might be needed…

…the number of RM systems might be limiting.

Take home messages:

hard task

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possibly the best observational feature
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has not being identified yet

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No system in the LISA mass range (yet)!!!

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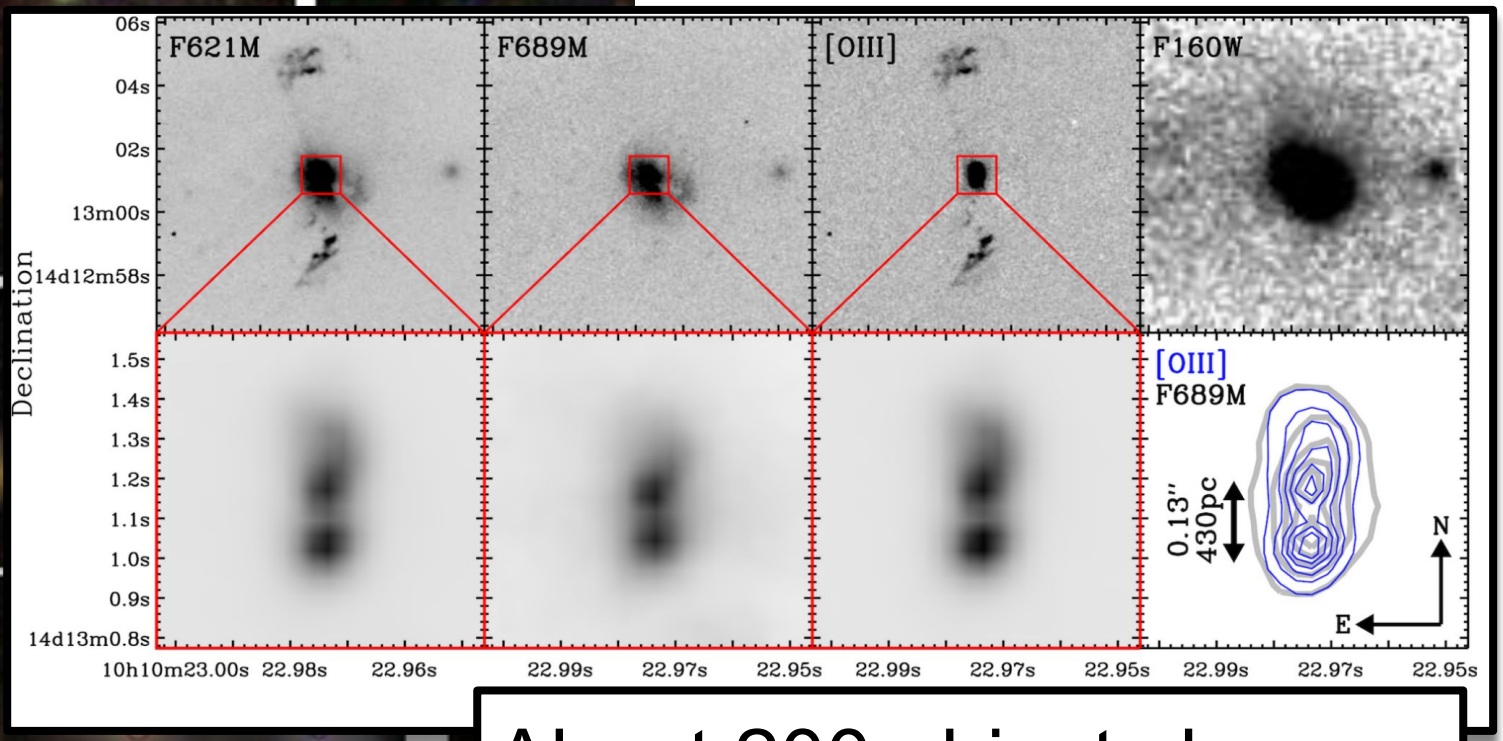
Future photometric (e.g. LSST, ULTRASAT, Roman) and spectroscopic (e.g. SDSS-V) surveys can be game-changers

Pre-merger & merger (~100 – 0.1 kpc)



About 200 objects known

from Koss+12 (BAT survey): X&opt, X-only, opt-only

Searching for unresolved BHB candidates

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Selects looser binaries
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(i.e. ~10^4 R_{Sch})

(Quasi-)periodic variability of the continuum

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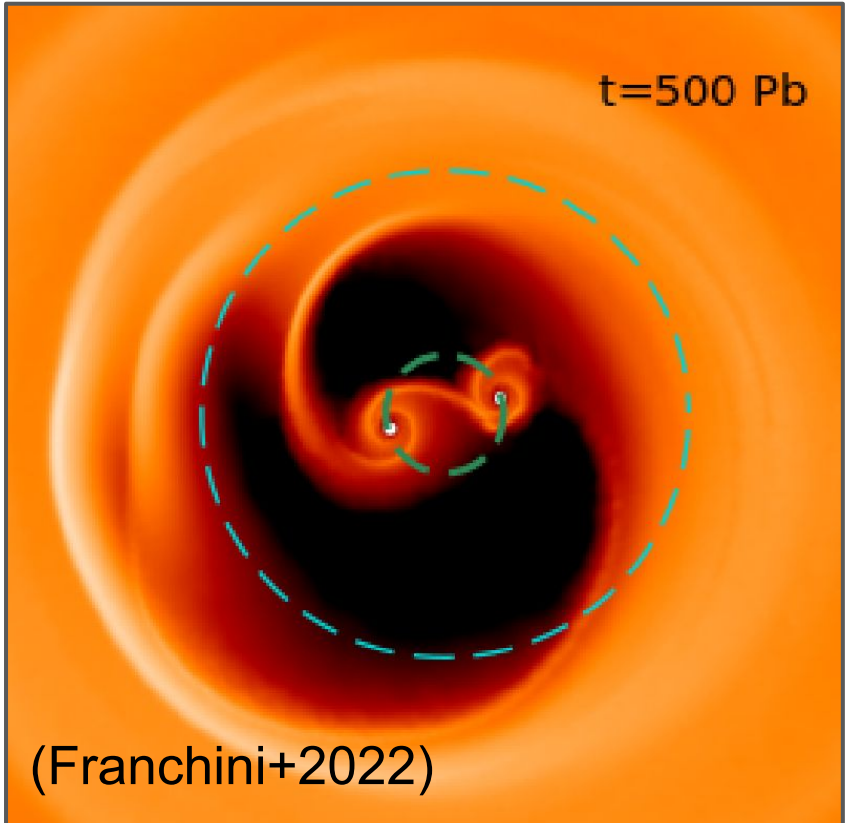
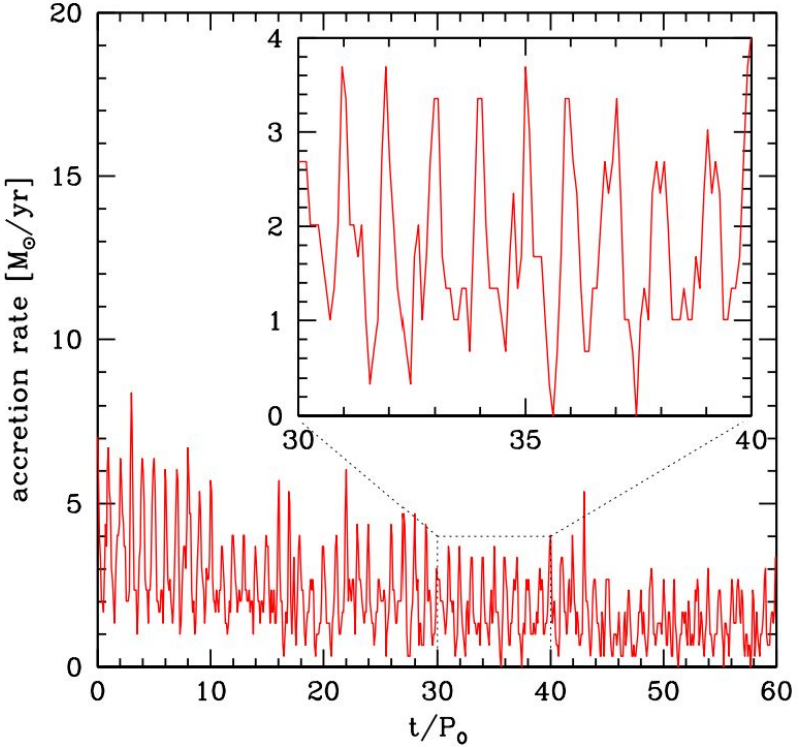
Closer binaries

Deviation from axi-symmetry → periodic inflows (huge literature for MBHBs, binary stars, star-massive planet pairs)



(Franchini+2022)

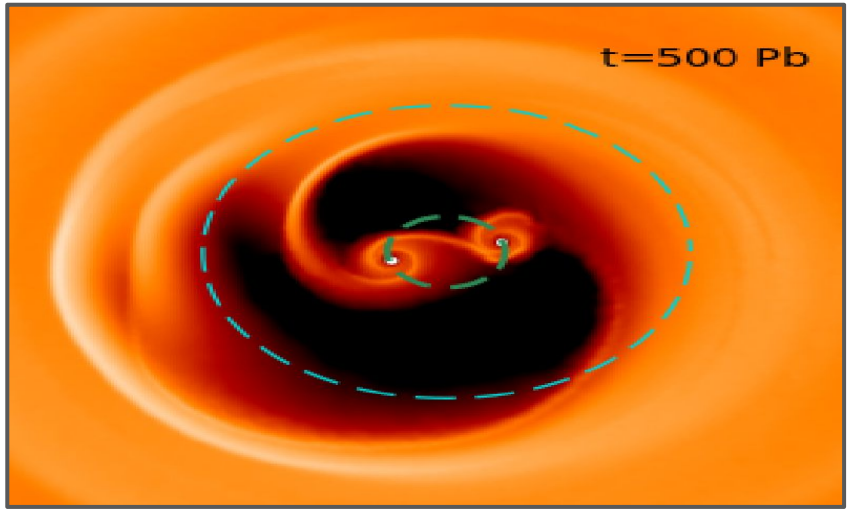


(Sesana+2012)

Closer binaries

Even a steady luminosity can result in periodic flux due to Doppler (D'Orazio+2015)

The amplitude of the fluctuations depends on the observational bands

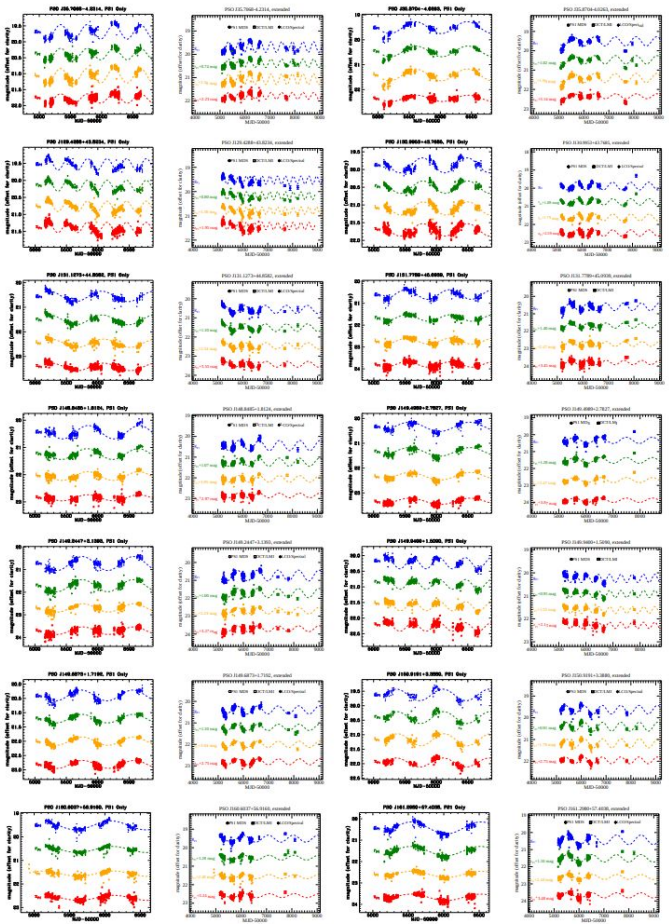


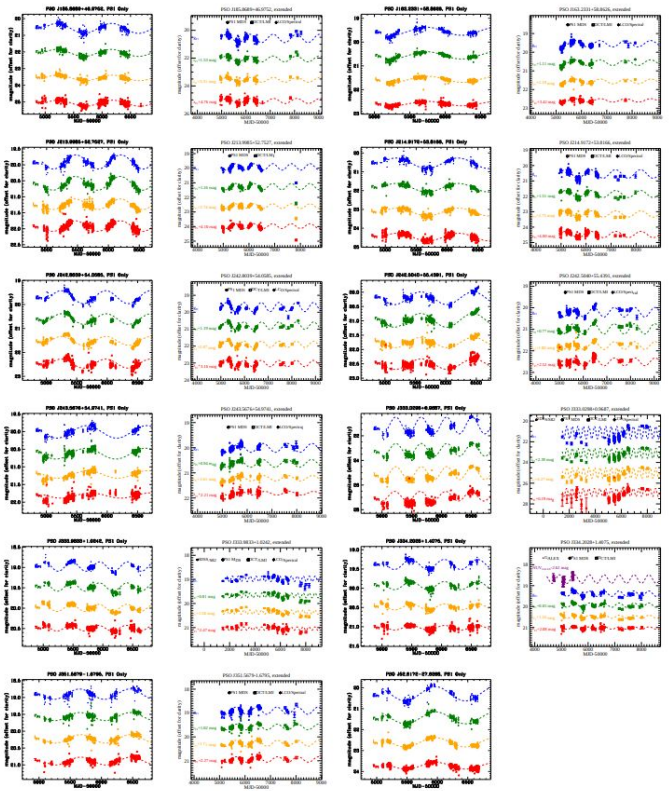
$$\frac{\Delta F_\nu}{F_\nu} = \pm(3-\alpha)\frac{v}{c}\cos\phi\sin i$$

Closer binaries

many (~150) candidates from different groups (we are guilty too), using different surveys (e.g. CRTF, PTF, or found serendipitously…)

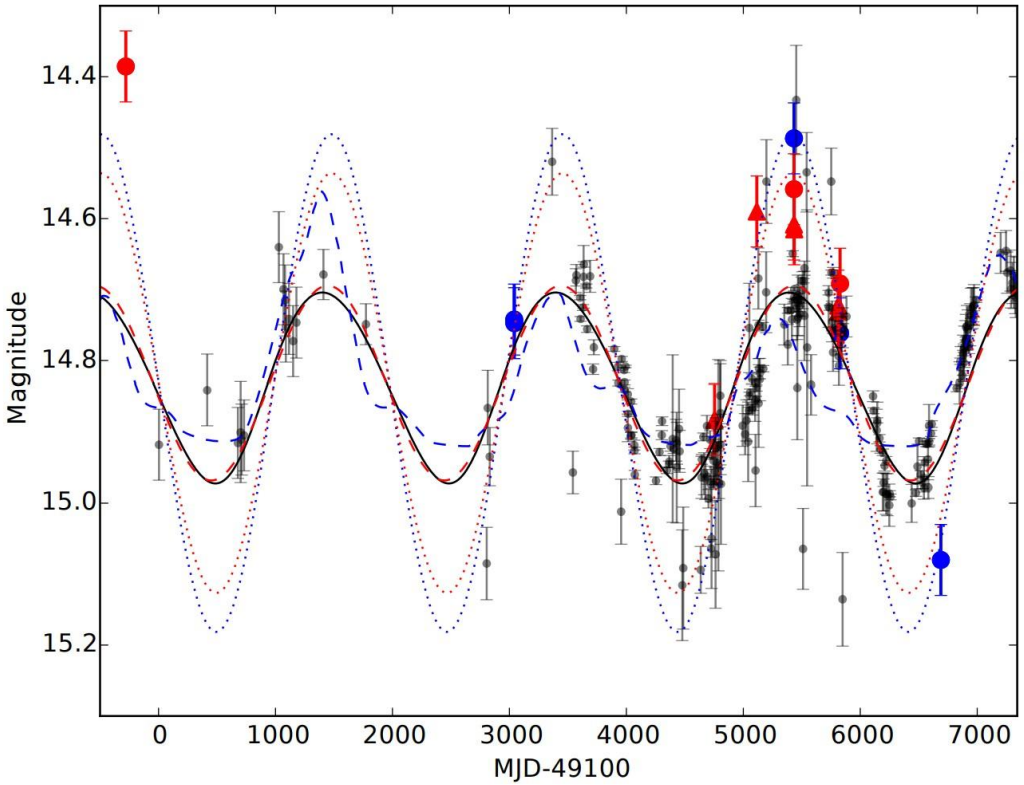
all (but 1?) with few (up to ~10) cycles and periods of ~1 yr





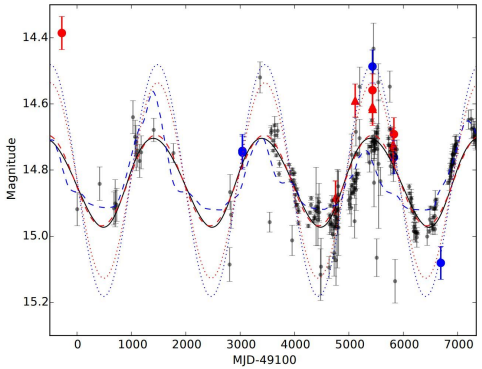
From Liu+2019, using the Pan-STARRS1 medium survey

Peculiar cases: PG 1302-102 (D'Orazio+15)



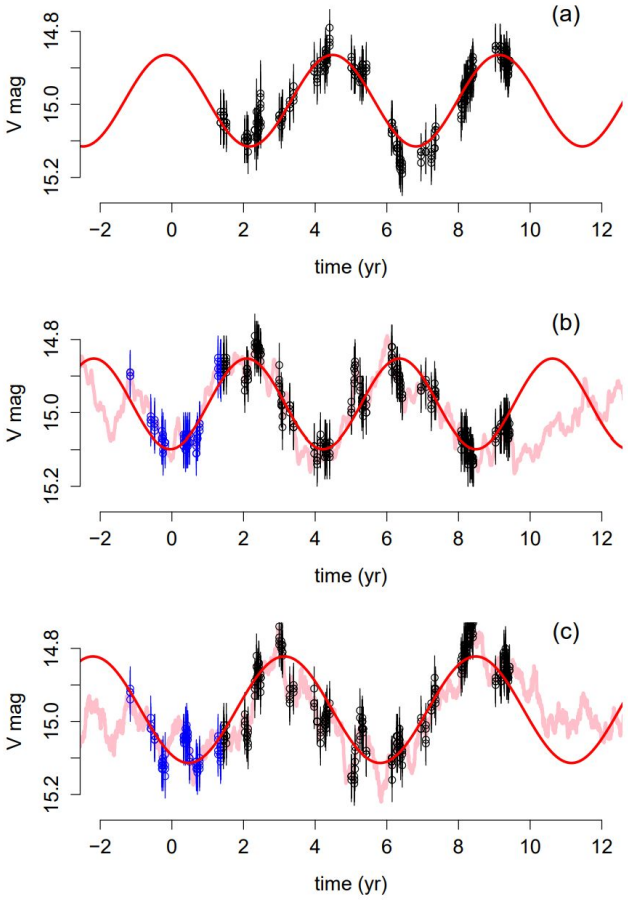
optical, near UV, far UV

Peculiar cases: PG 1302-102 (D'Orazio+15)



optical, near UV, far UV

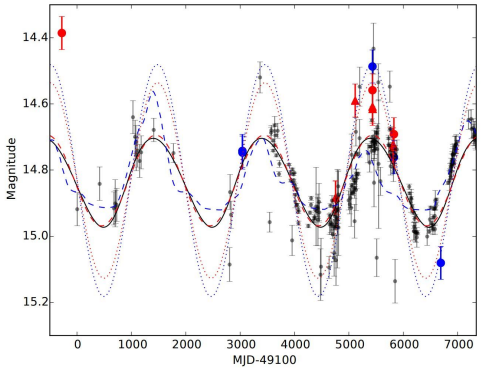
Catalina data



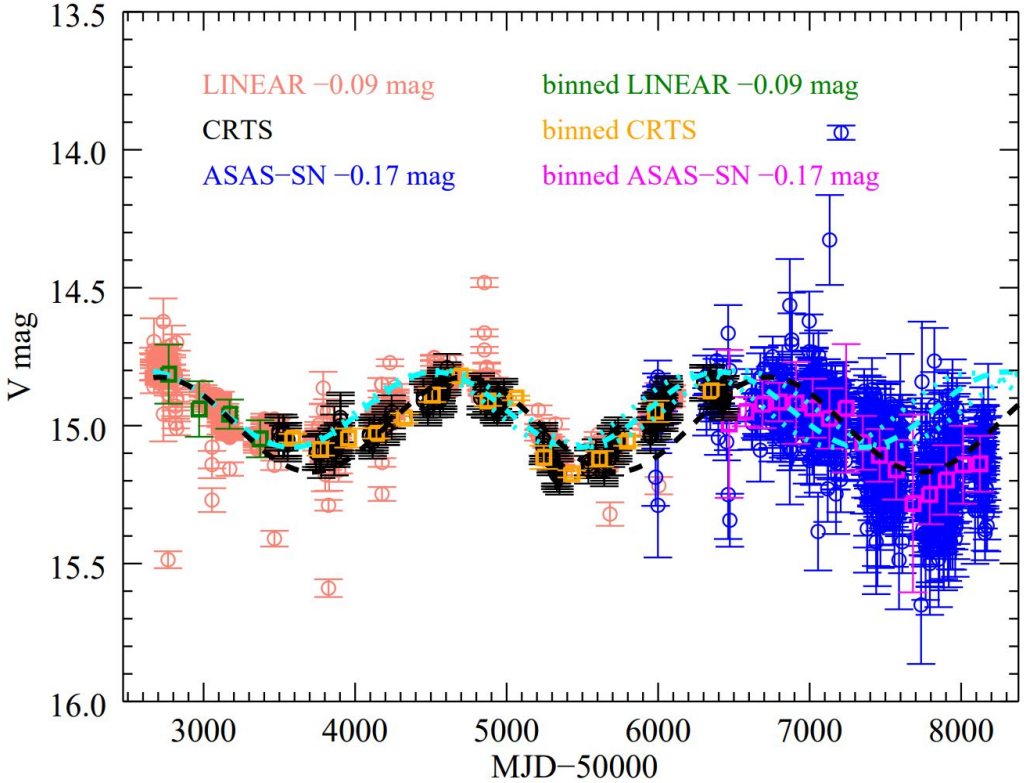
Two random red-noise realizations w same sampling pattern

Vaughan+2016

Peculiar cases: PG 1302-102 (D'Orazio+15)

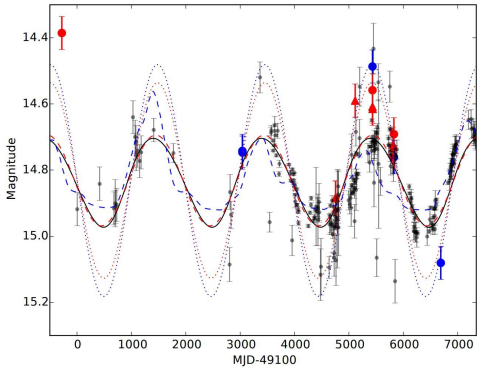


optical, near UV, far UV



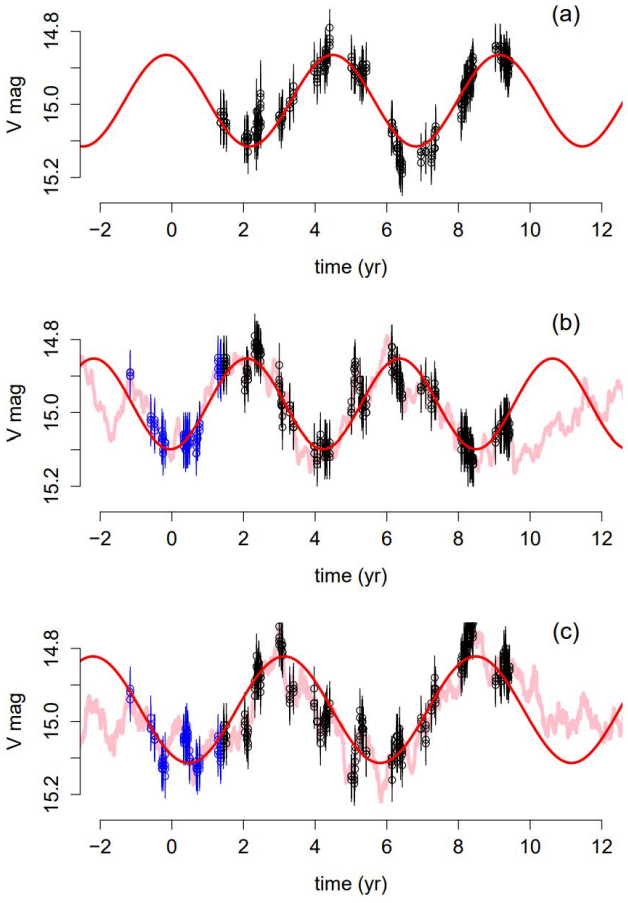
"Did ASAS-SN Kill the Supermassive Black Hole Binary Candidate PG1302-102?" (Liu+2018)

Peculiar cases: PG 1302-102 (D'Orazio+15)



optical, near UV, far UV

Catalina data



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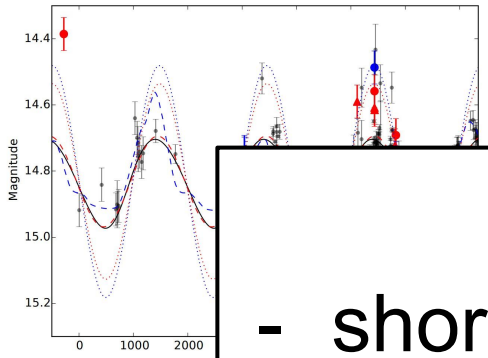
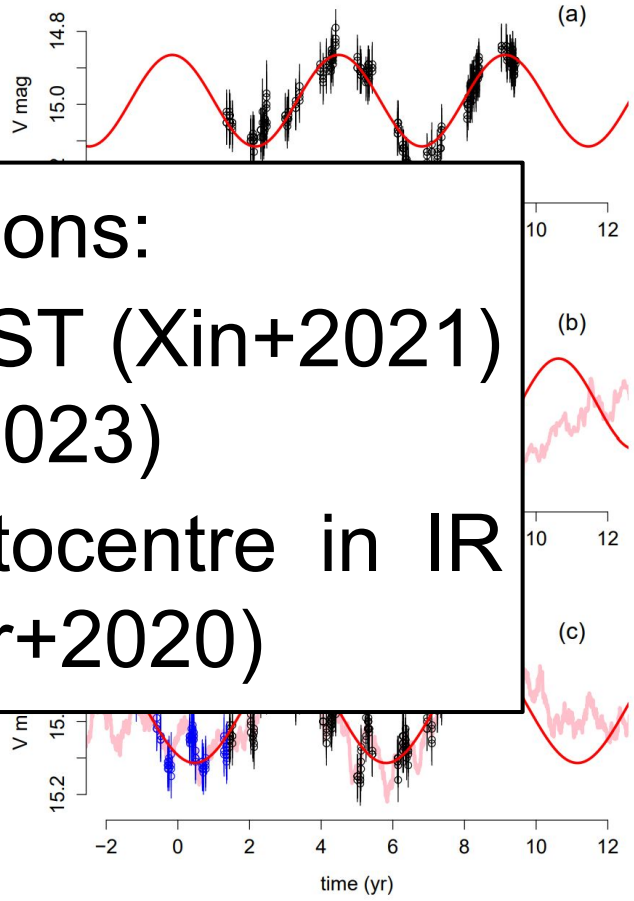


optical, ne

Catalina data

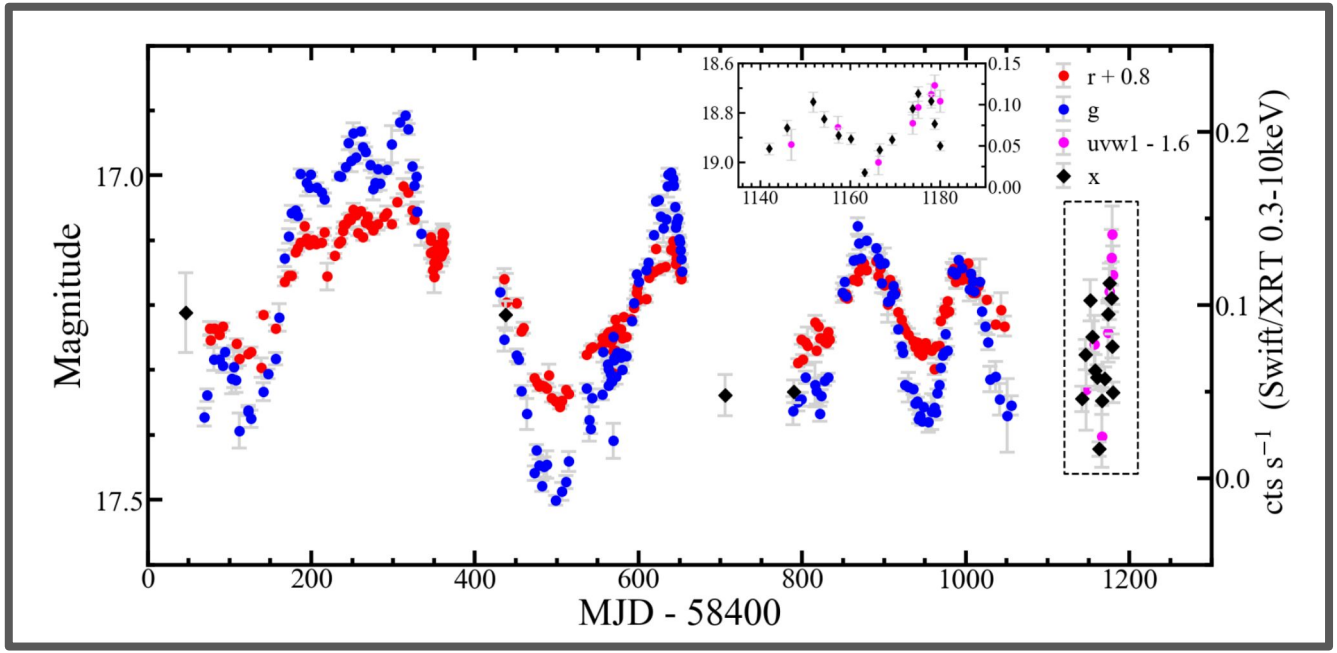


Vaughan+2016

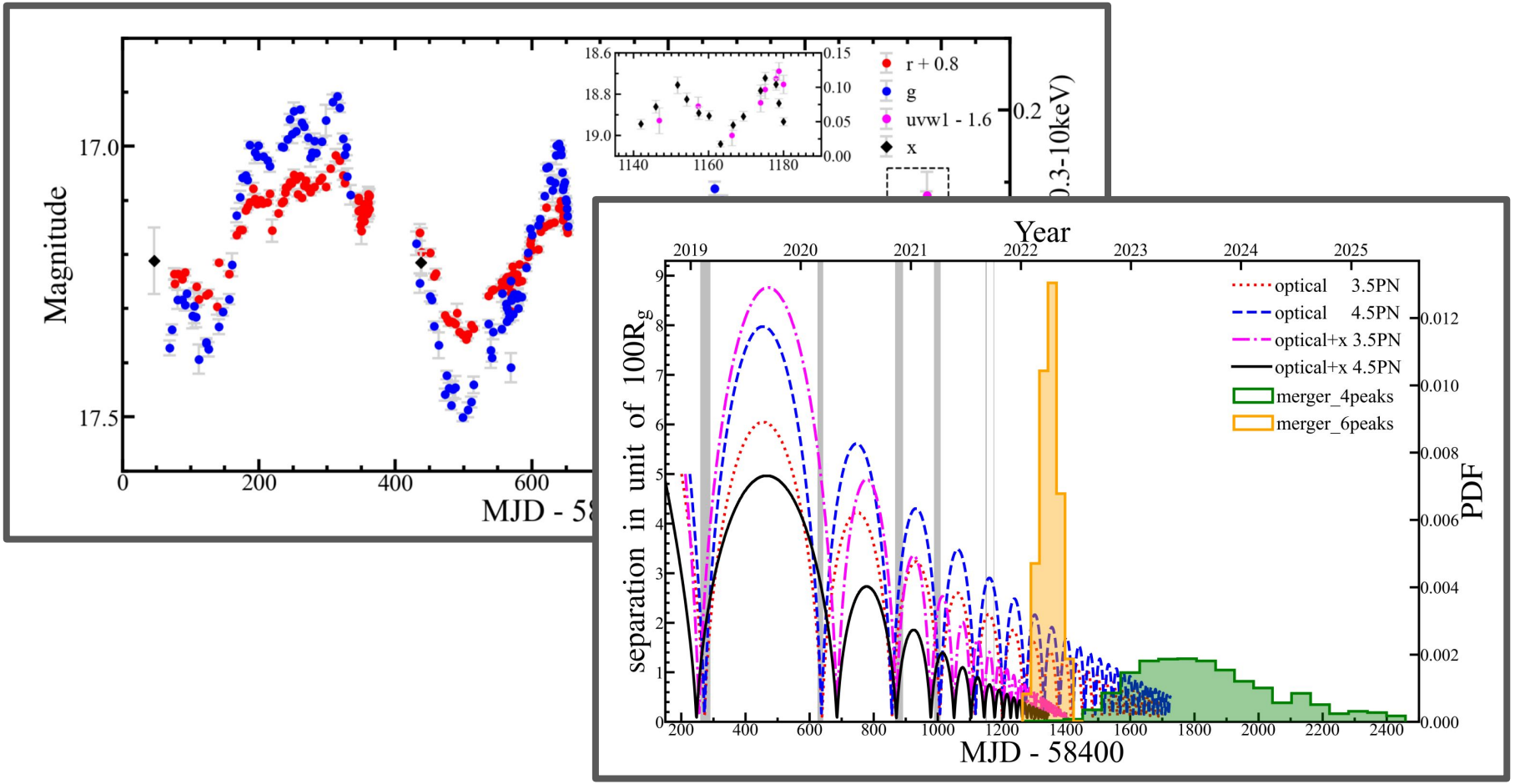
Possible solutions:

- shorter periods in LSST (Xin+2021) or Roman (Haiman+2023)
- periodic shift of photocentre in IR interferometry (Dexter+2020)

Peculiar cases: the tick-tock object (Jang+2022)



Peculiar cases: the tick-tock object (Jang+2022)



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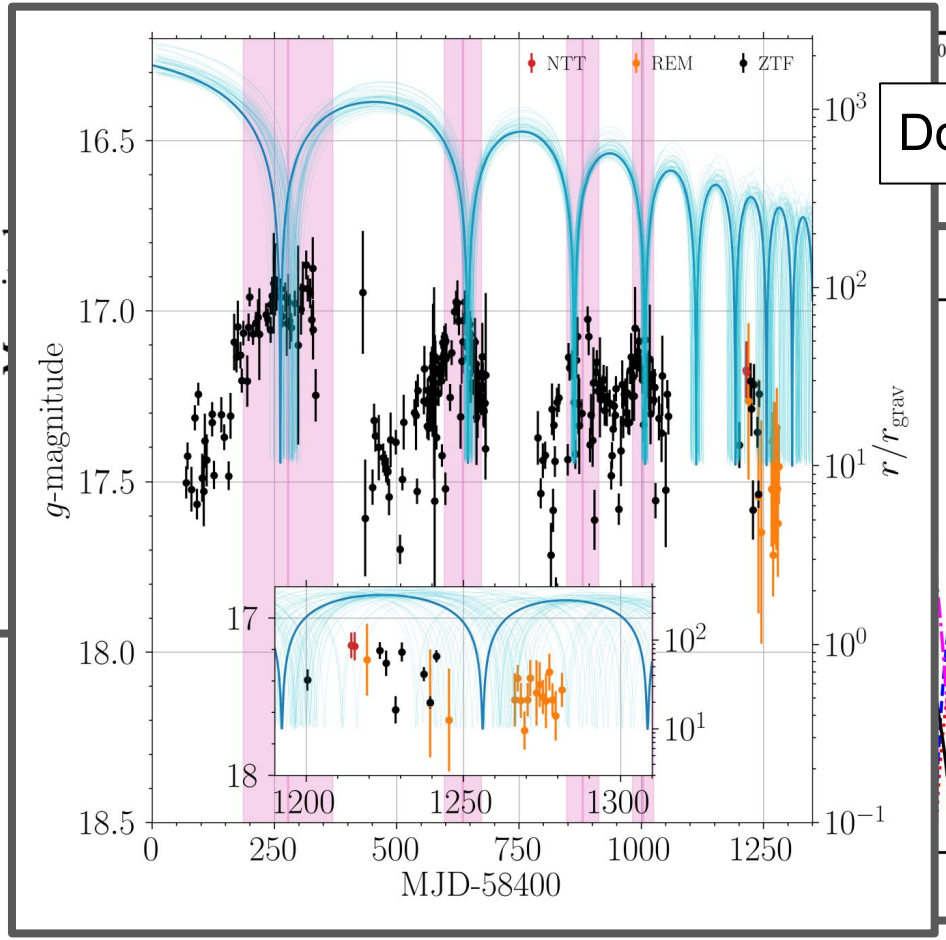
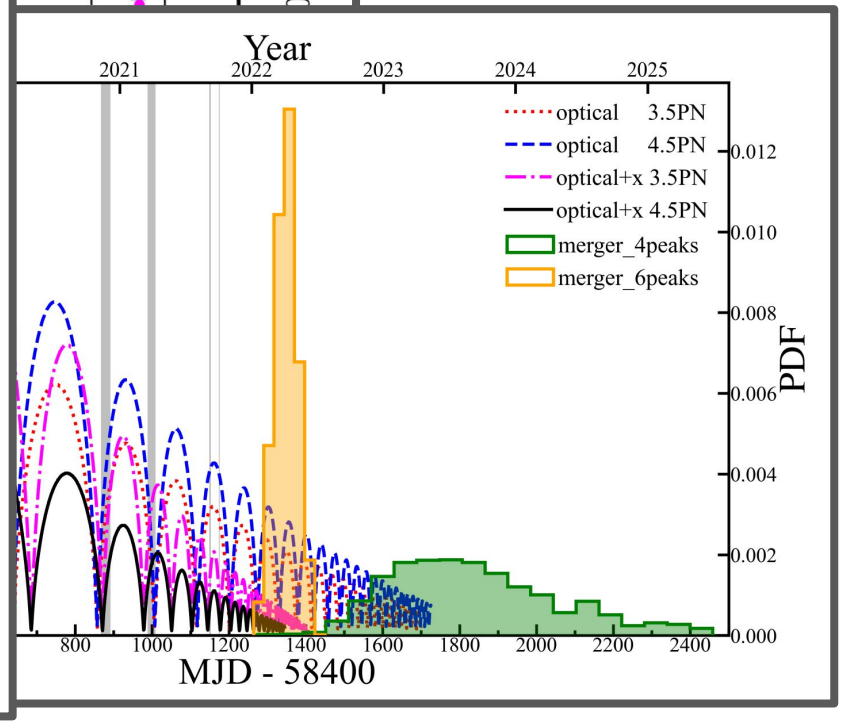


Dotti+ 2023 (see also Marin+2023)



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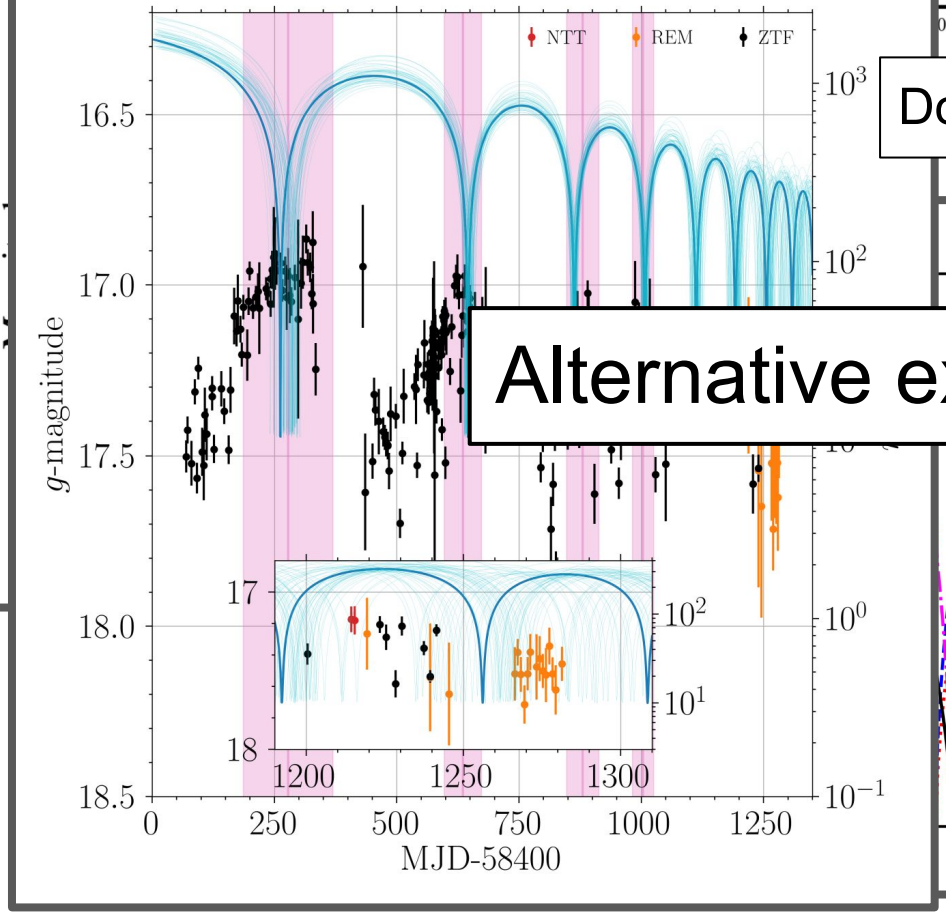
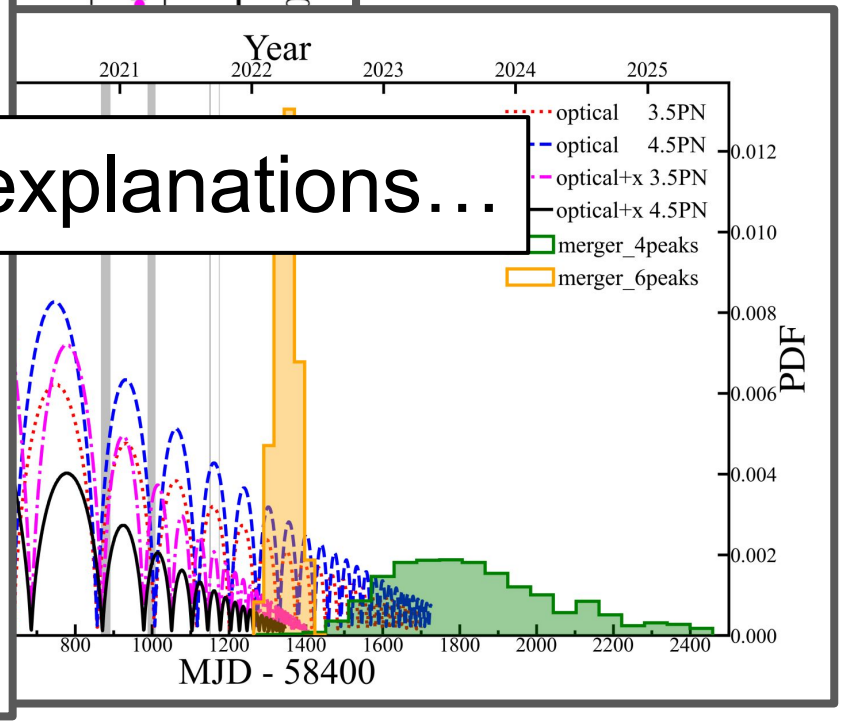
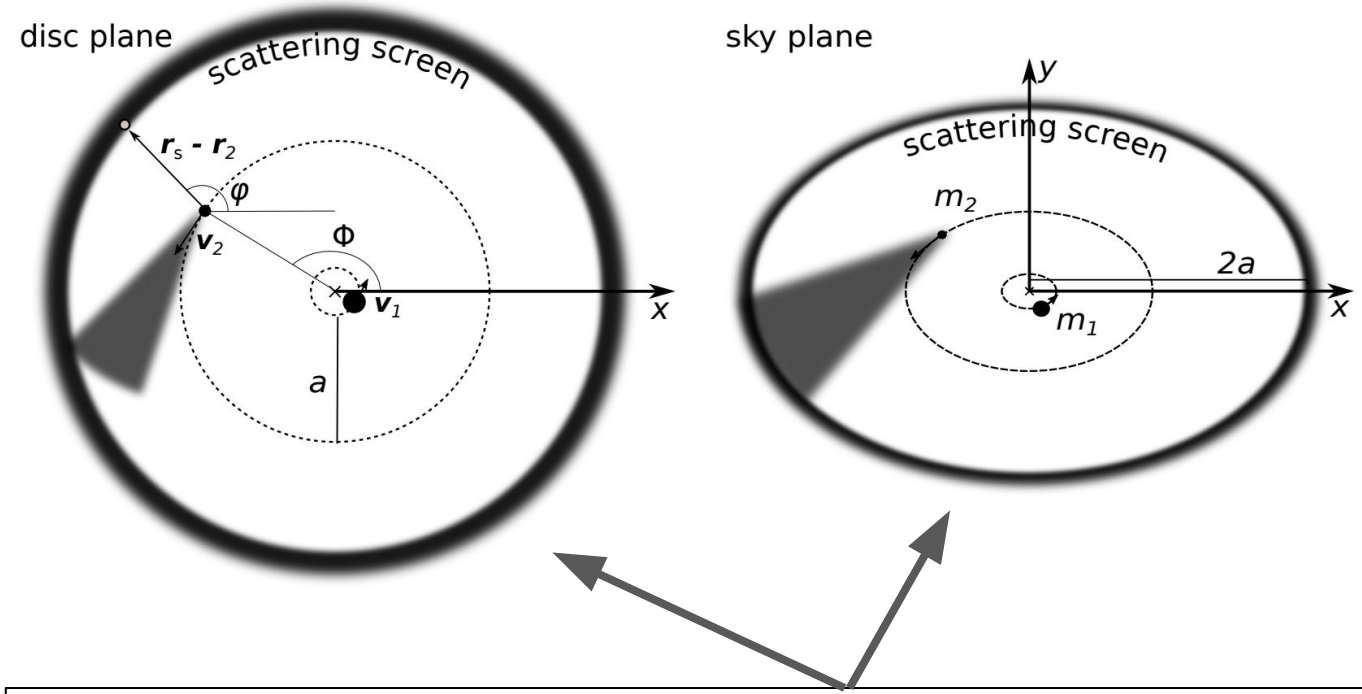


Dotti+ 2023 (see also Marin+2023)

Alternative explanations…

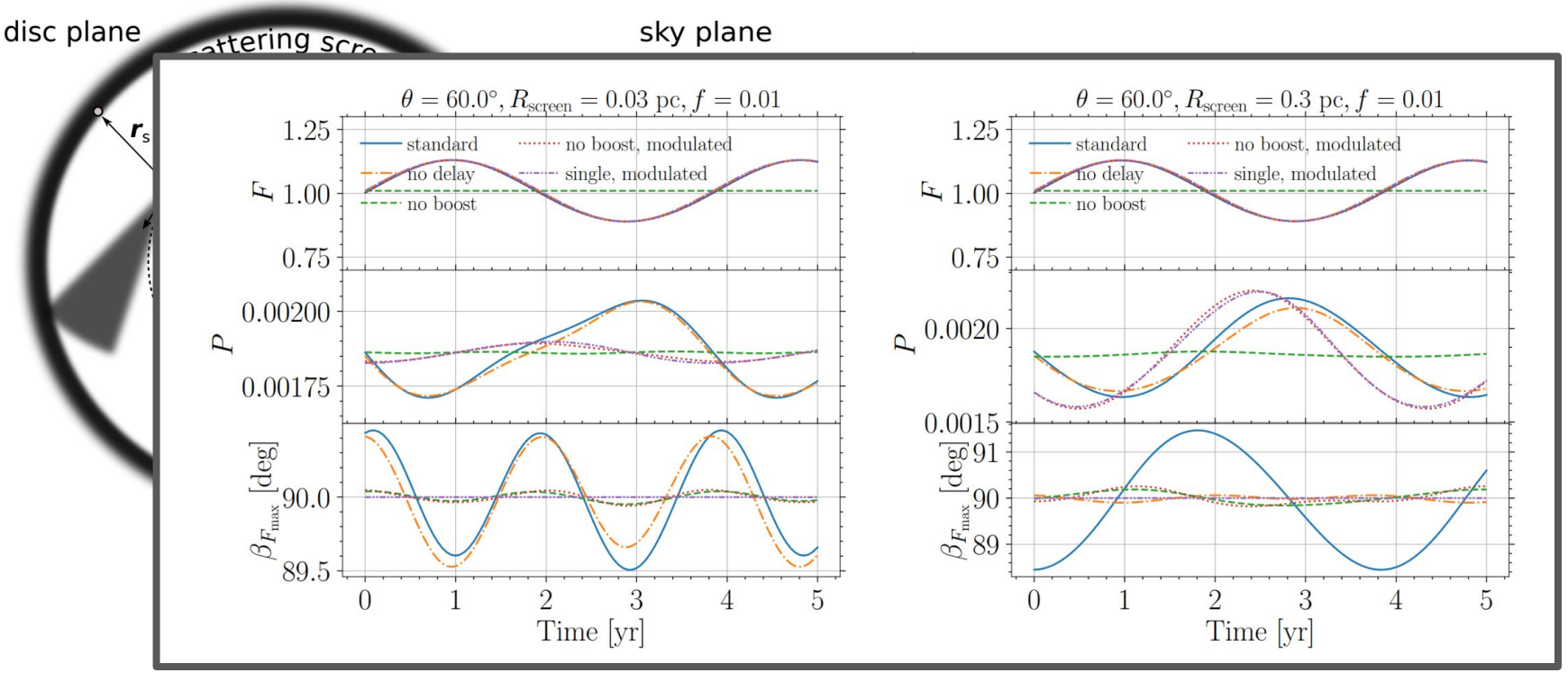


Alternative tests (on human lifetime - Dotti+2022): time dependent polarization

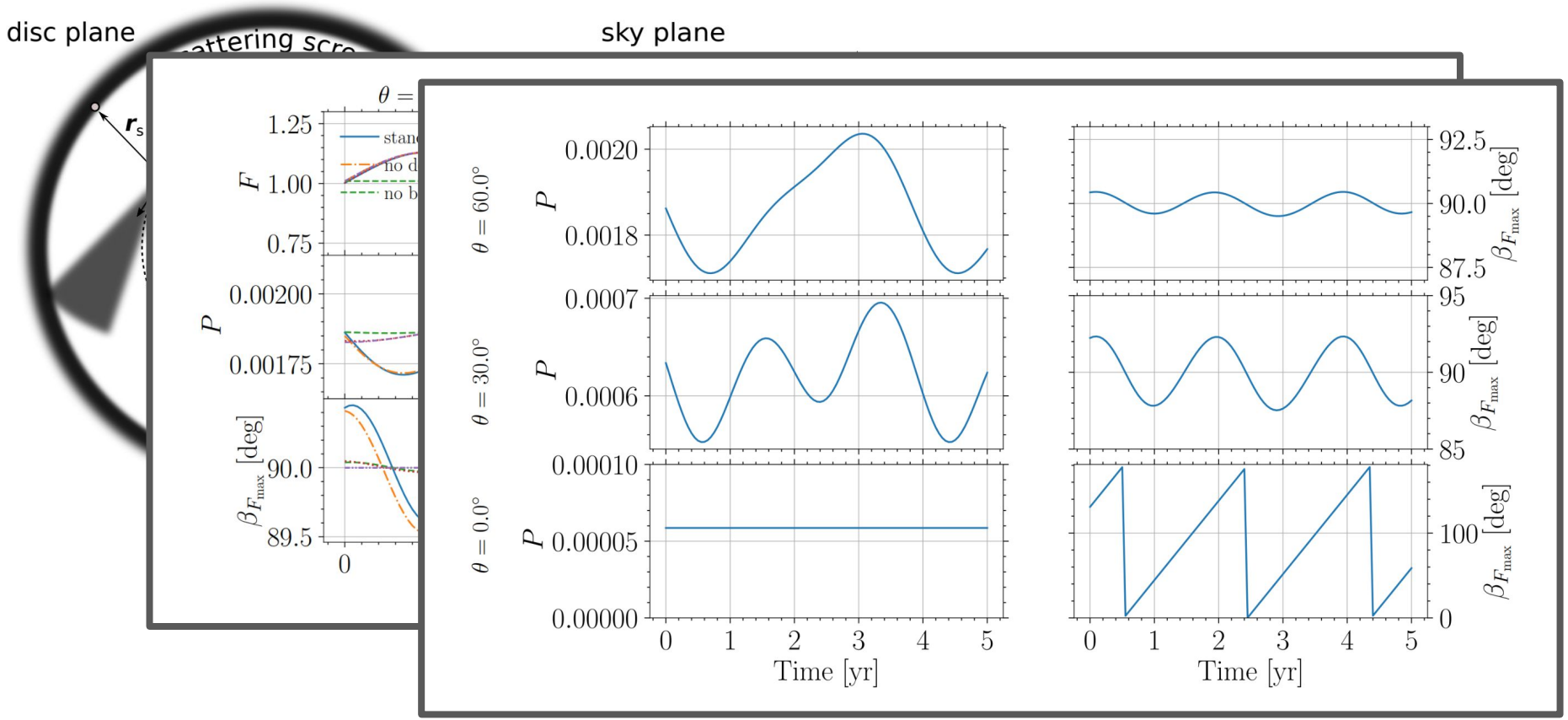


(equatorial - e.g. Antonucci 1984, Smith+2002, Gaskell+2012 - for type I AGN)

Alternative tests (on human lifetime - Dotti+2022): time dependent polarization



Alternative tests (on human lifetime - Dotti+2022): time dependent polarization



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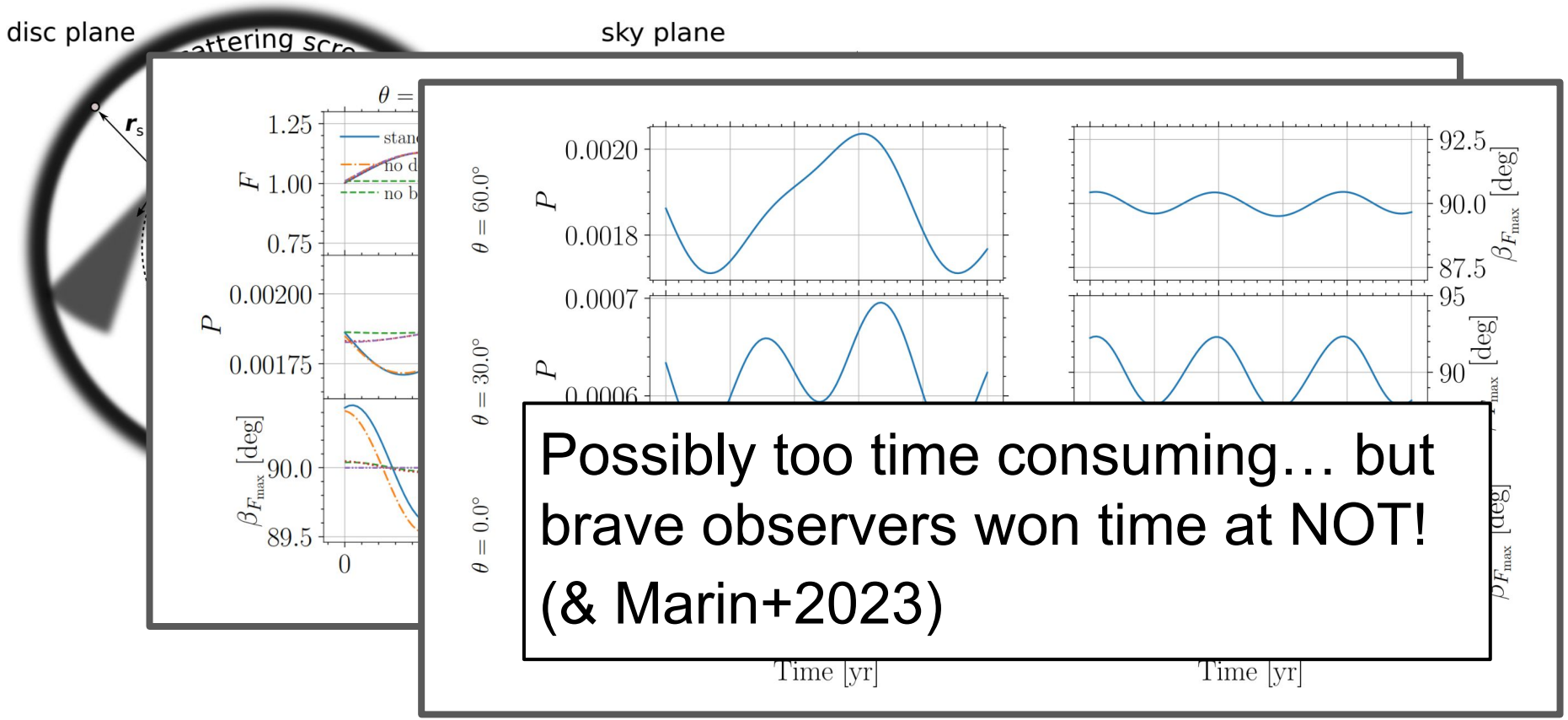

Possibly too time consuming… but brave observers won time at NOT! (& Marin+2023)