The roles of Supermassive Black Holes in AGNs

Qingwen Wu
Department of Astronomy
Huazhong University of Science and Technology

華中科技大學 天文学系
HUAZHONG UNIVERSITY OF SCIENCE AND TECHNOLOGY Department of Astronomy

Outline

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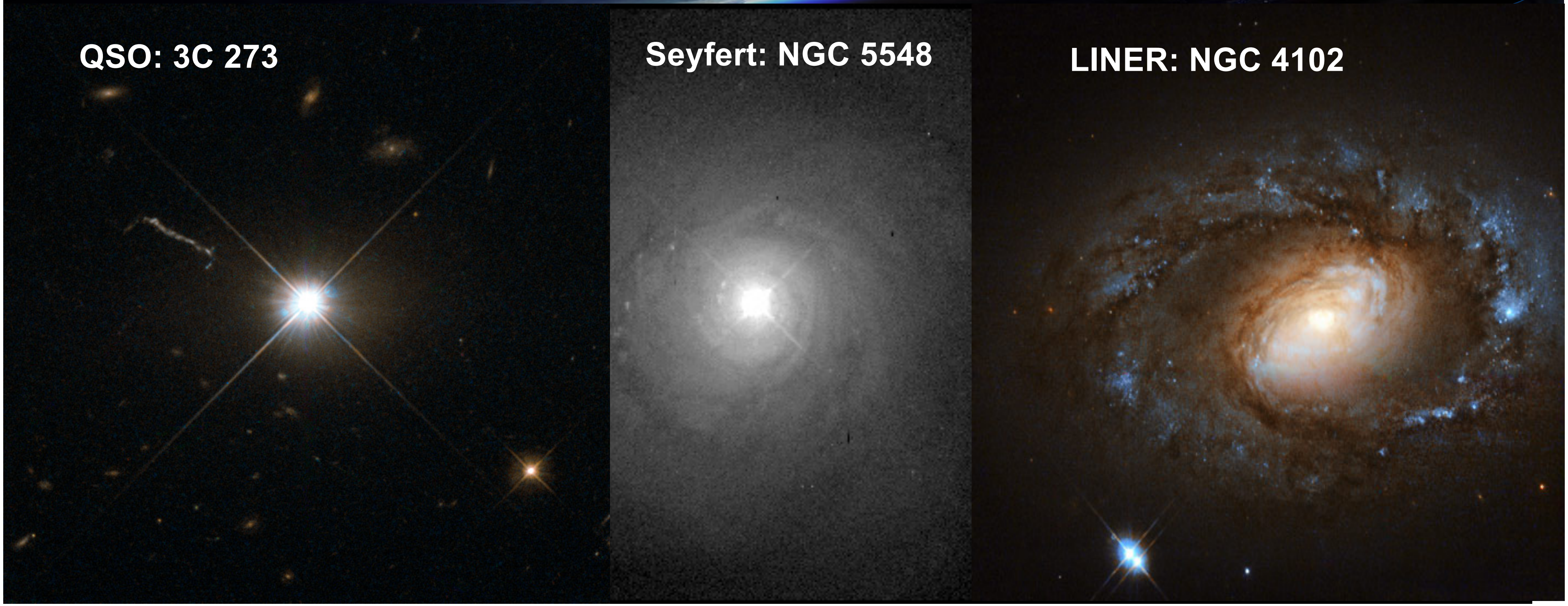
1) Single AGN and Dual AGNs

: Single & Binary MBHs

2) Massive BH TDE/QPE/EMRI

: Nuclear Invironment

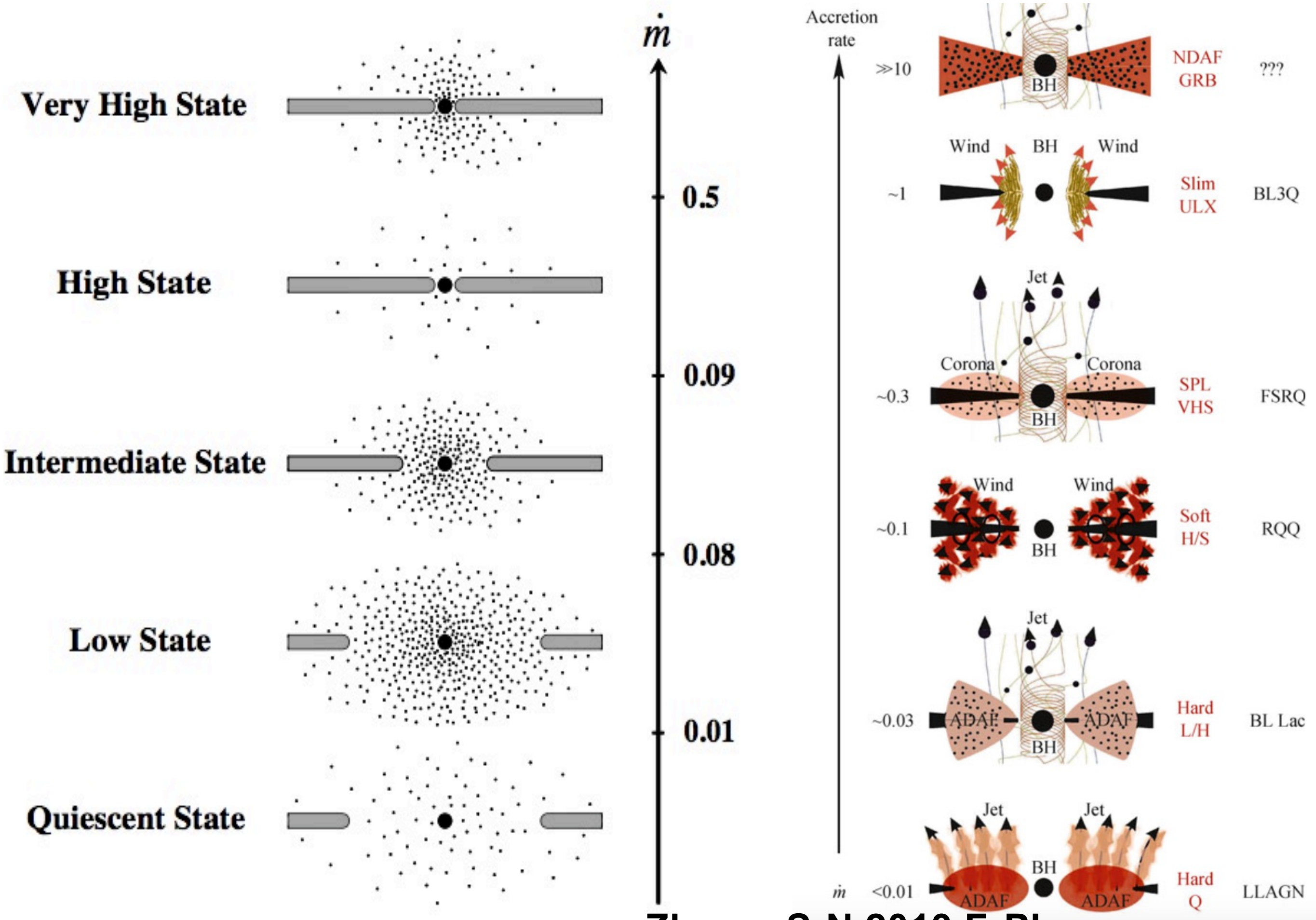
1) Active Galactic Nuclei



The active nuclei become weaker and host galaxy become more dominant from QSO to normal galaxies.

1) Active Galactic Nuclei

Central engine: BH + accretion (+) jet



Slim disk

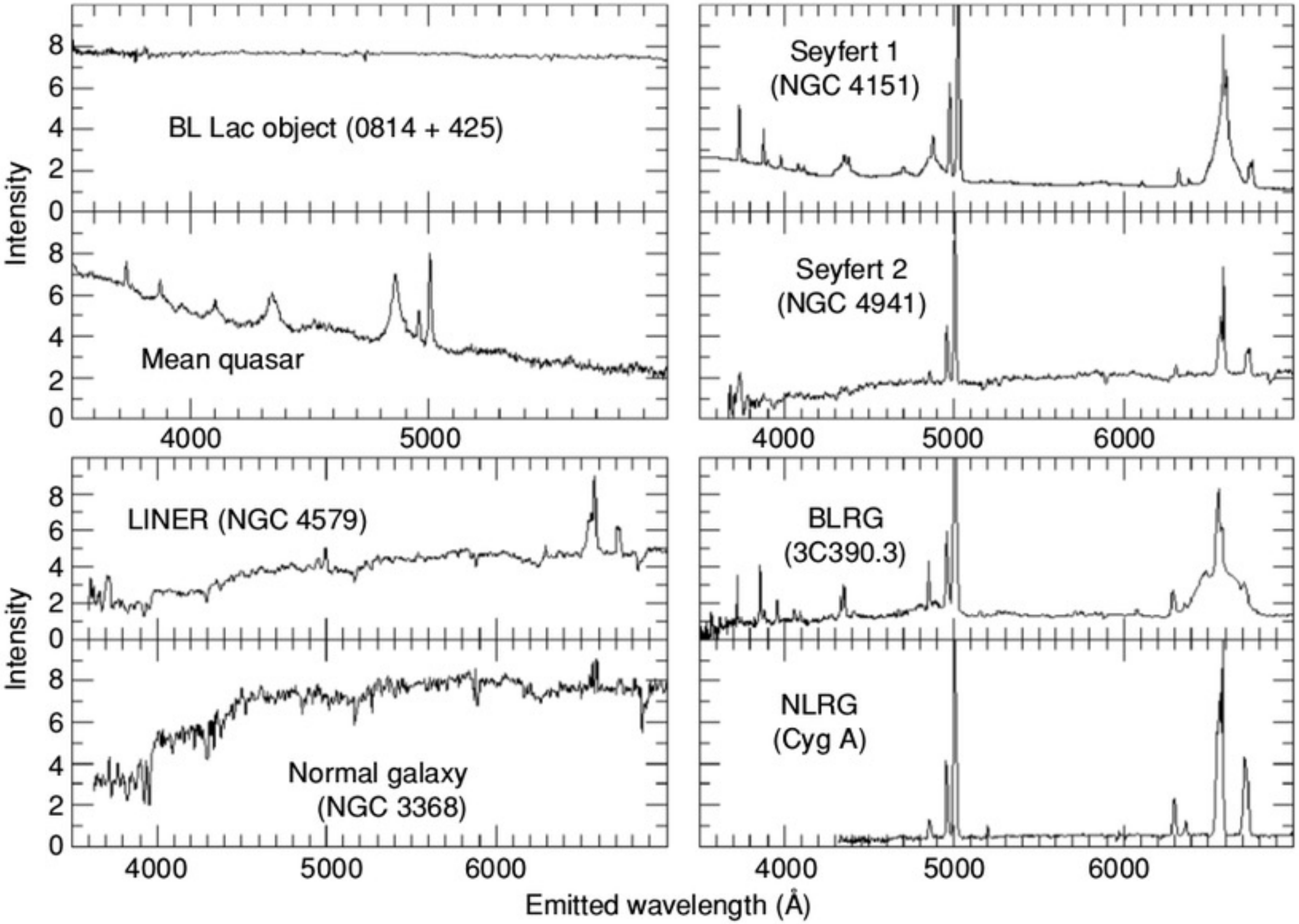
Standard accretion disk

ADAF

Zhang, S-N 2013 FrPhy

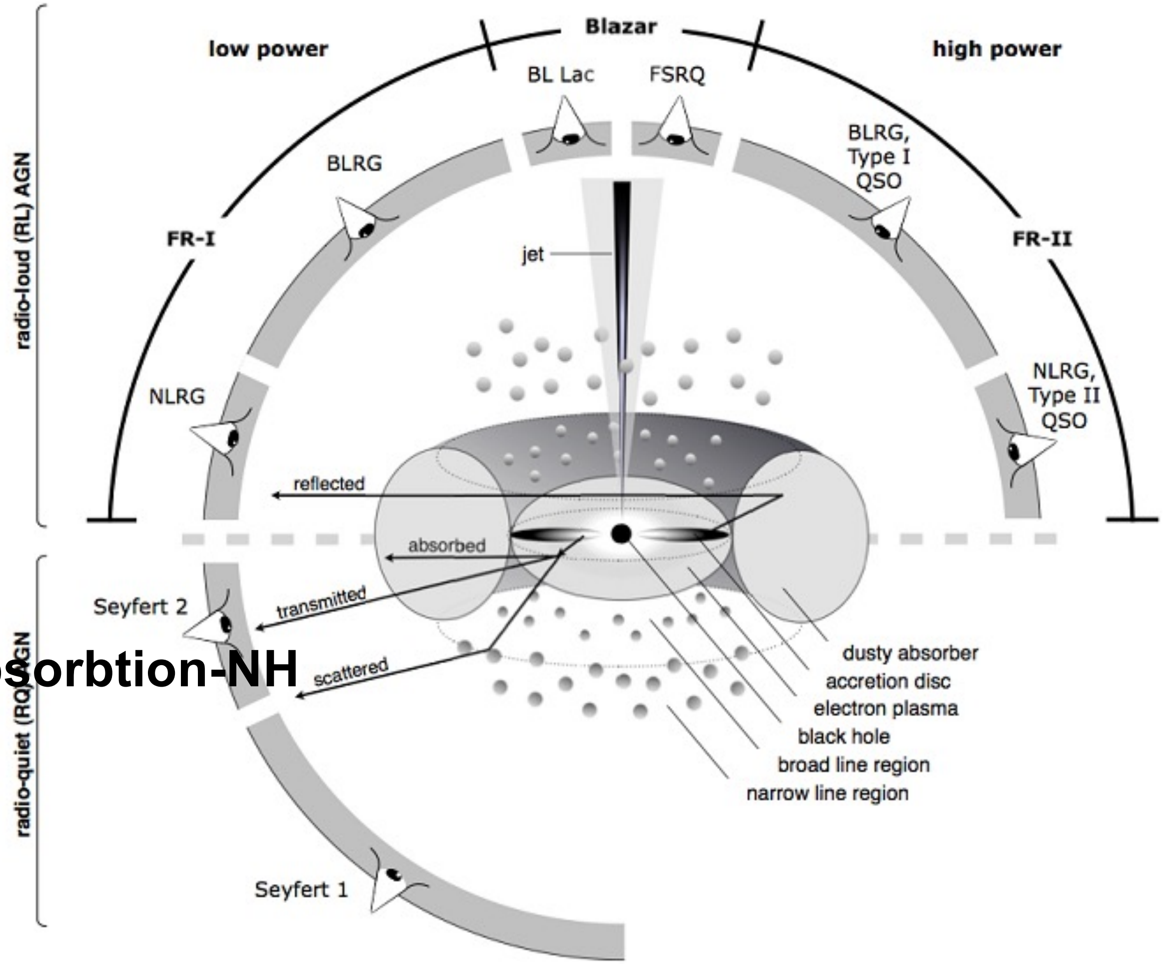
Evolution of accretion and jet in Quasar (AGN) and micro-quasar (XRB).

1) Active Galactic Nuclei



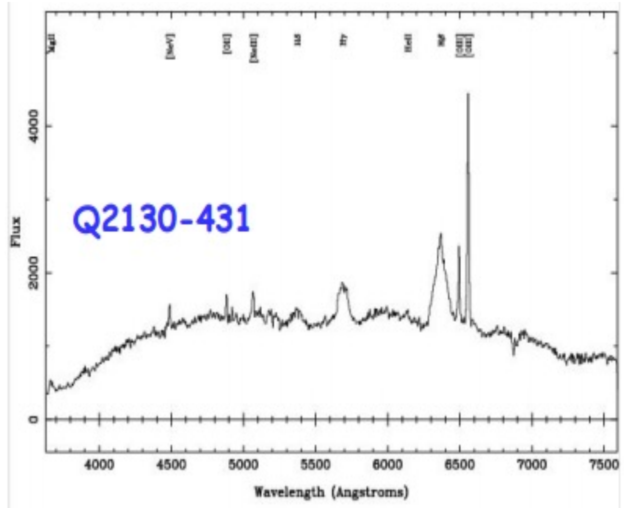
Broad emission lines: FWHM~ serval thousands km/s
Narrow emission lines: FWHM~ serval hundreds km/s
No lines: BL lac (weak lines or jet contamination)

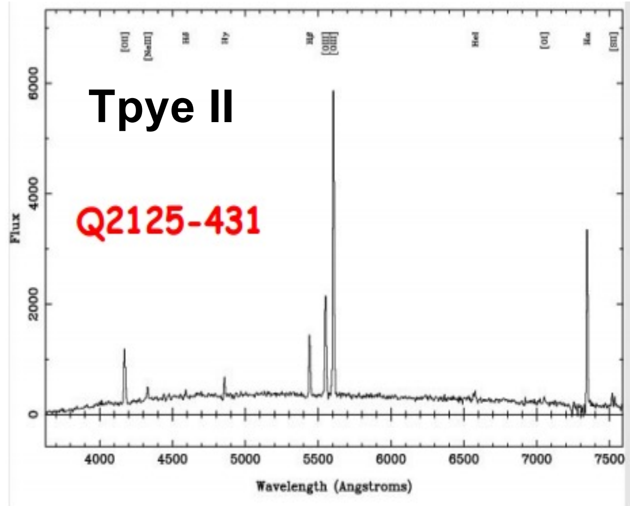
1) AGN unification



absorbtion-NH

Type I with broad lines

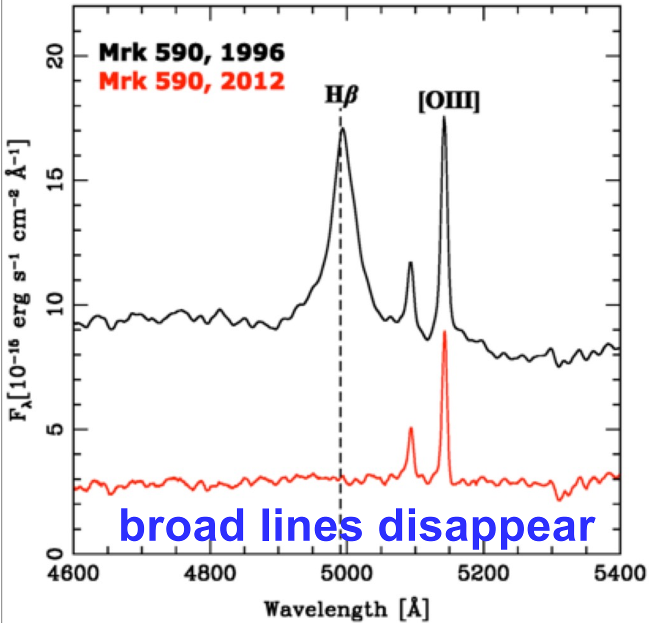


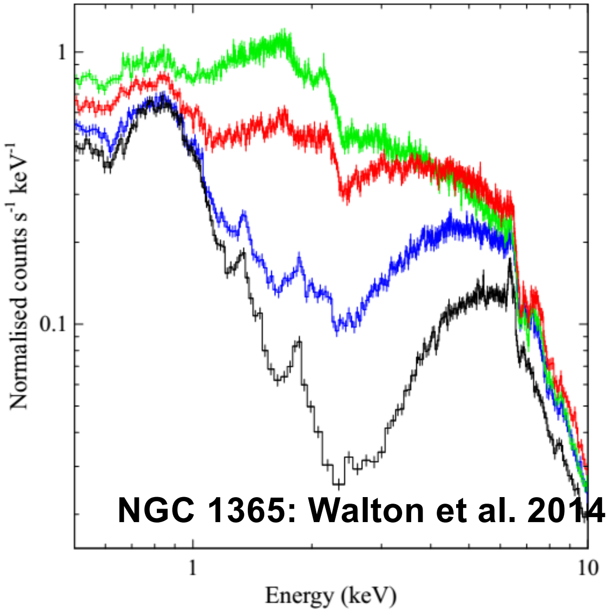


Key parameter: inclination angle

TORUS (NH)

1) Changing-look AGNs





1)Disappearing or re-appear of broad emission lines.

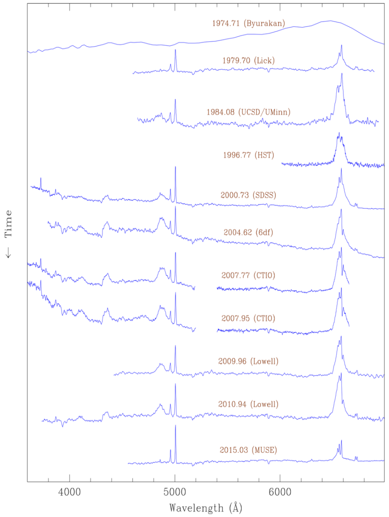
2)Column density (torus?) show strong variation within several years.

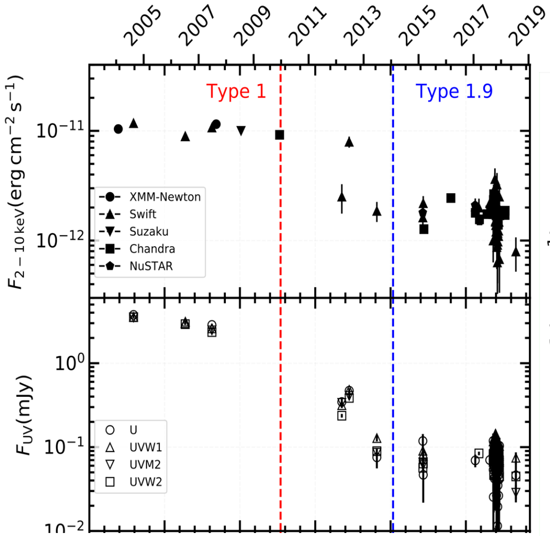
Chanllenge the AGN unification model.

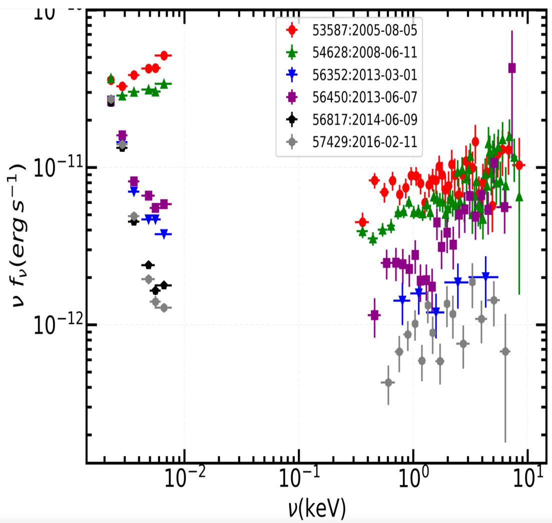
Torus cannot change its inclination angle within several years for a galaxy!

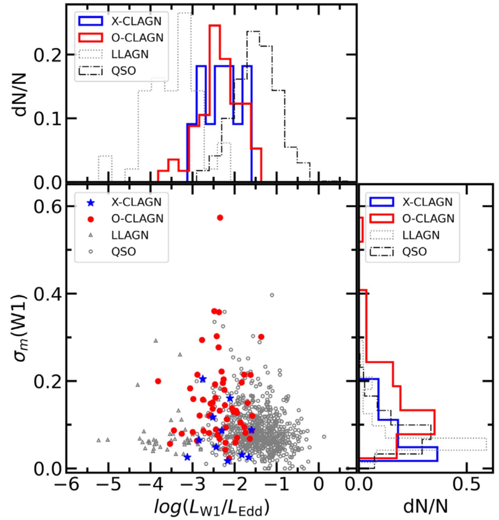
1) Changing-look AGNs

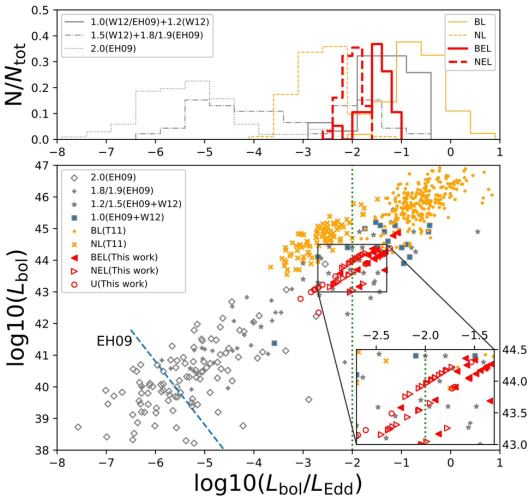
Evidence for strong evolution of accretion disk for CLAGNs

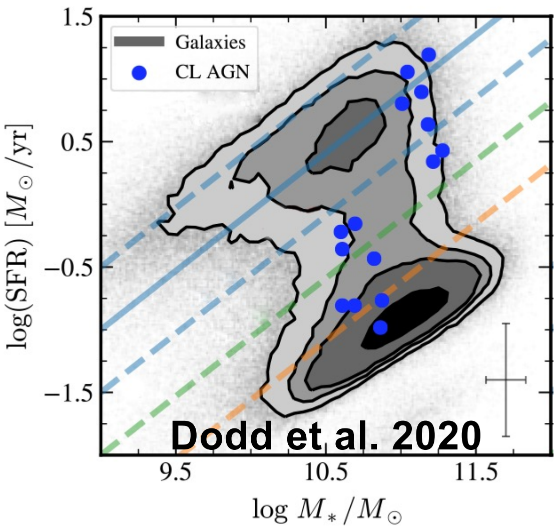












CLAGNs provide a probability to explore the galaxy evolution in human timescale.

Lyu, B… Wu et al. 2021 MNRAS, 2022 ApJ
Liu, Wu et al. 2021 ApJ

1) Tidal Disruption Event (TDE)

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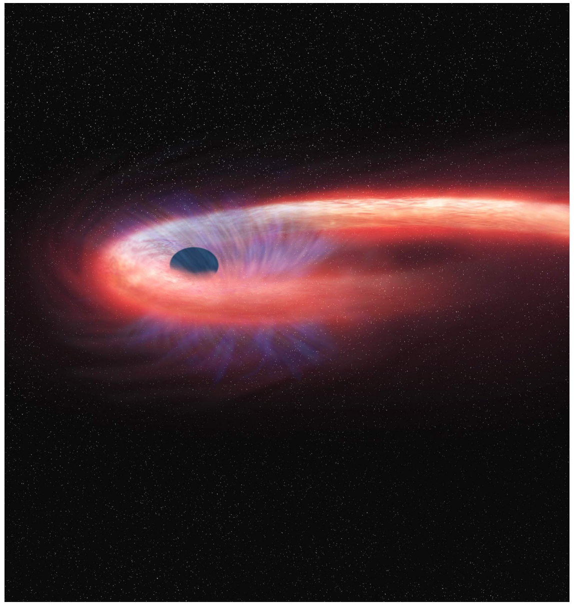
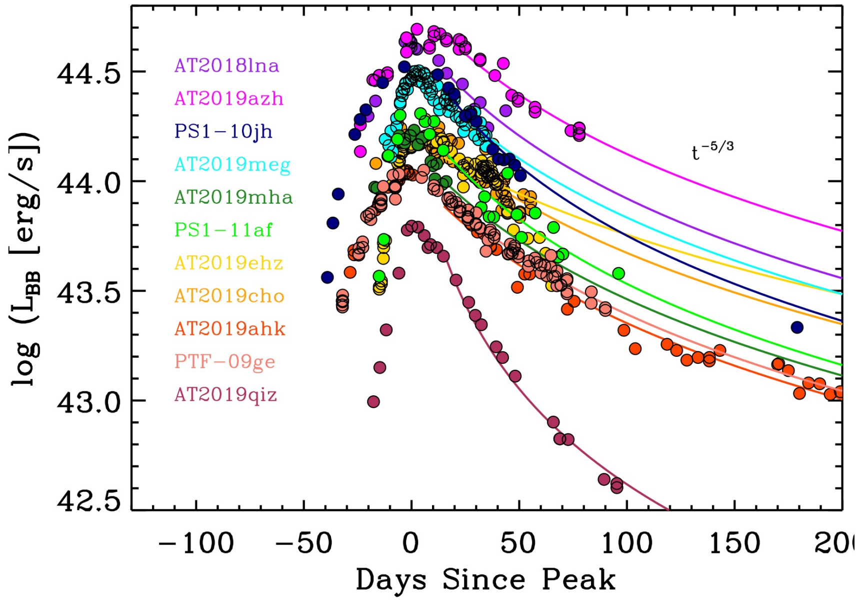
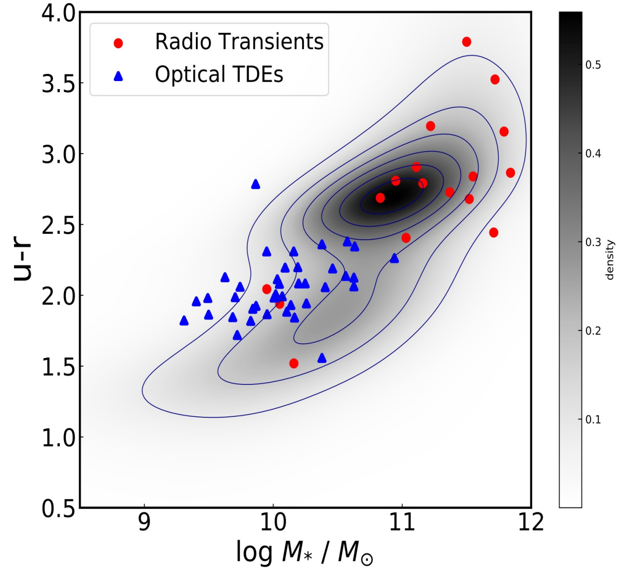
Tidal disruption event: light up the dormant MBHs





Gezari 2021 ARA&A

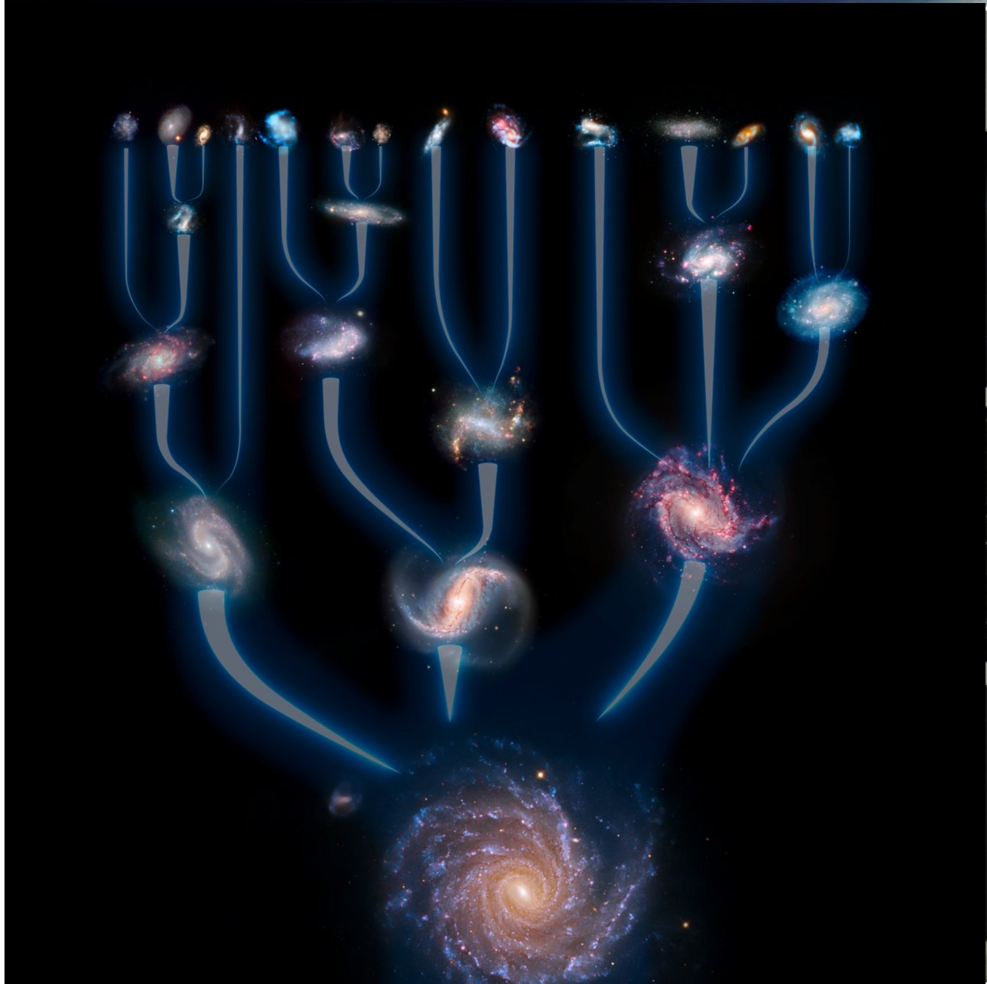


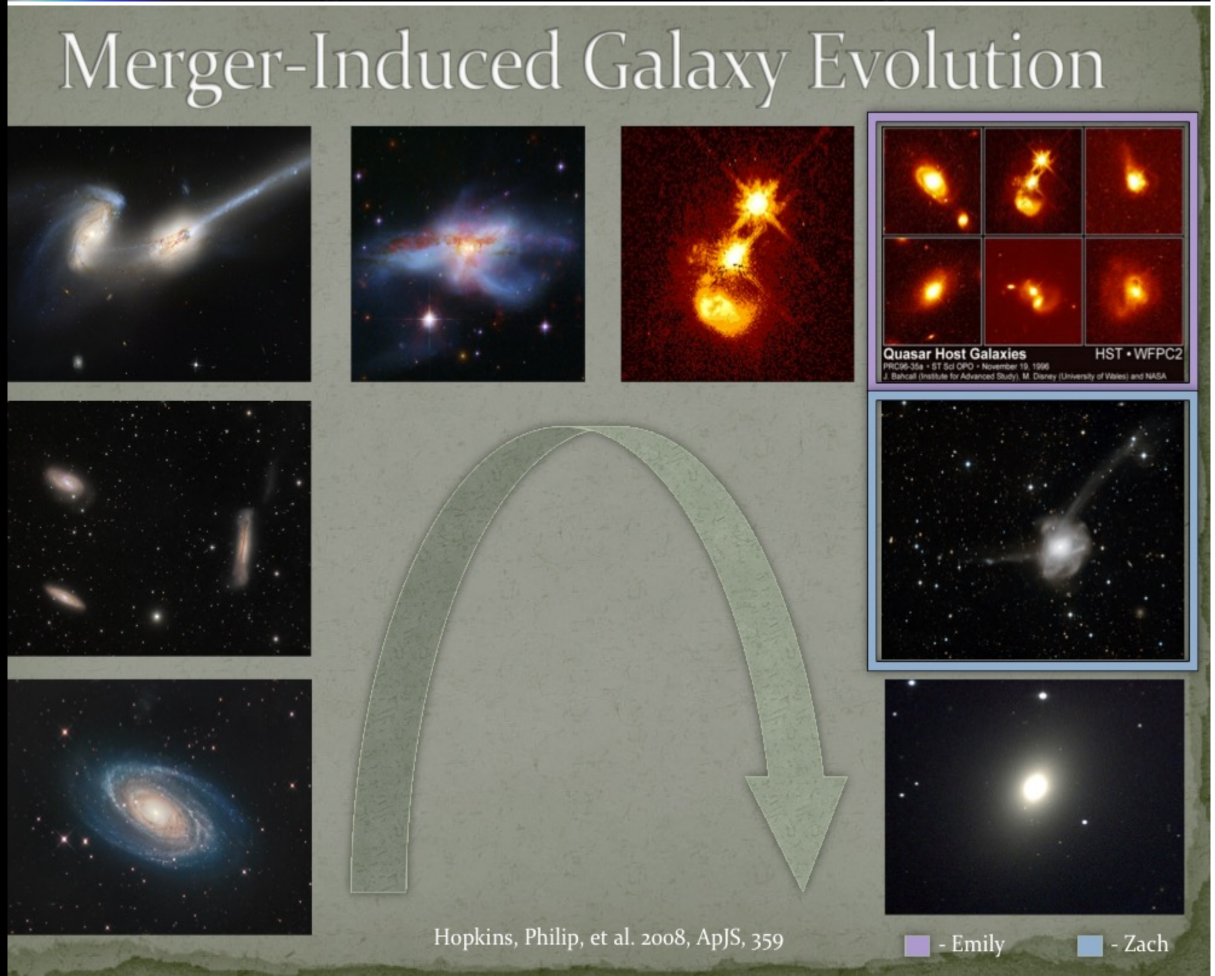
…Shu et al. 2022

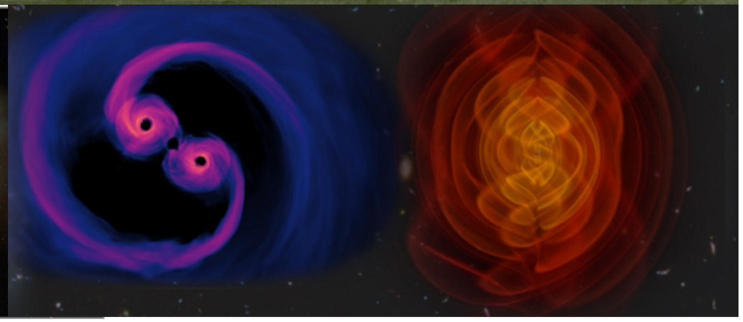
TDE provide a chance to learn the dormant MBHs, evolution of accretion/jet.

TDE event rate is related the single/binary MBH, the stage of galaxy evolution (star scattering, nuclear environment, e.g., core-cusp structure).

2 Galaxy merger and binary SMBHs







2 Galaxy merger and binary SMBHs

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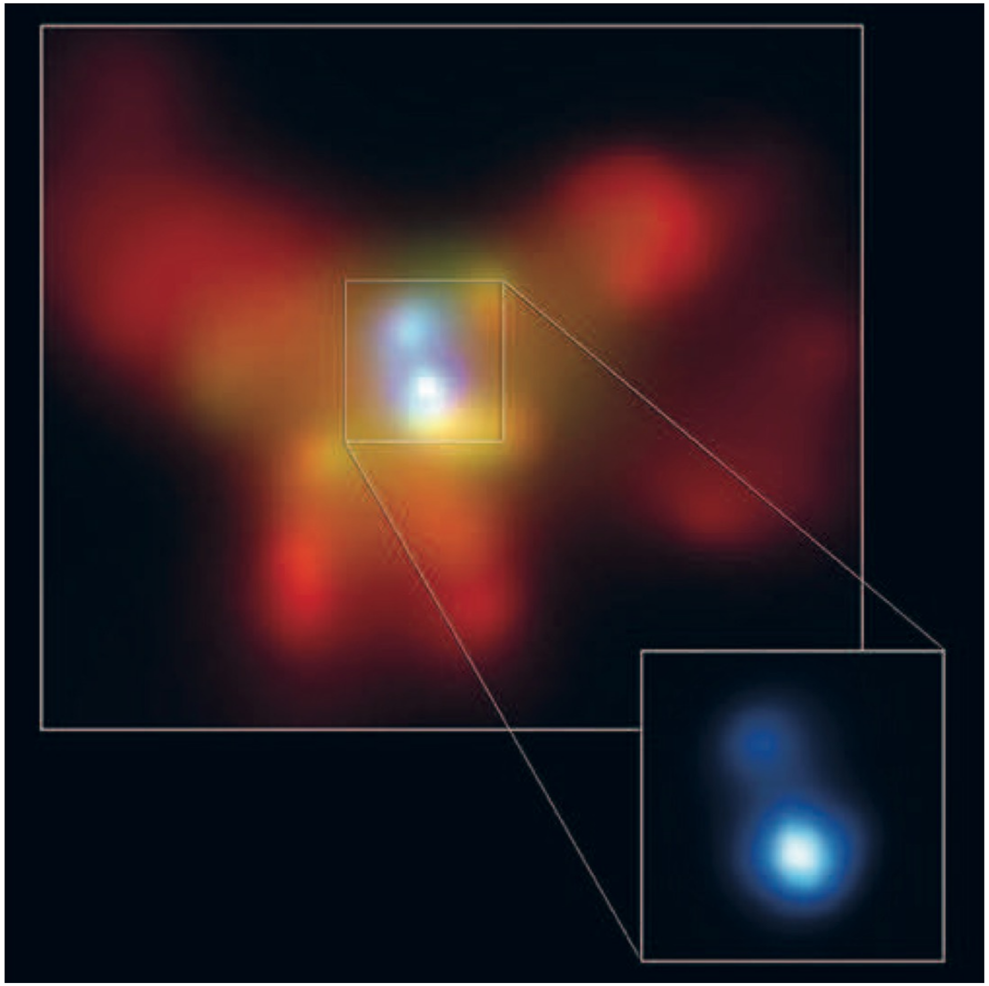
Large Separations (~kpc): Dynamical friction drags each SMBH, along with bound gas and stars, towards the center of the common potential

Intermediate Separations (~pc): Three-body interactions with stars in the galactic core and interactions with a nuclear disk

Small Separations (~mpc): The SMBHB decay is dominated by the emission of GWs.

2 Dual AGNs in X-ray observations



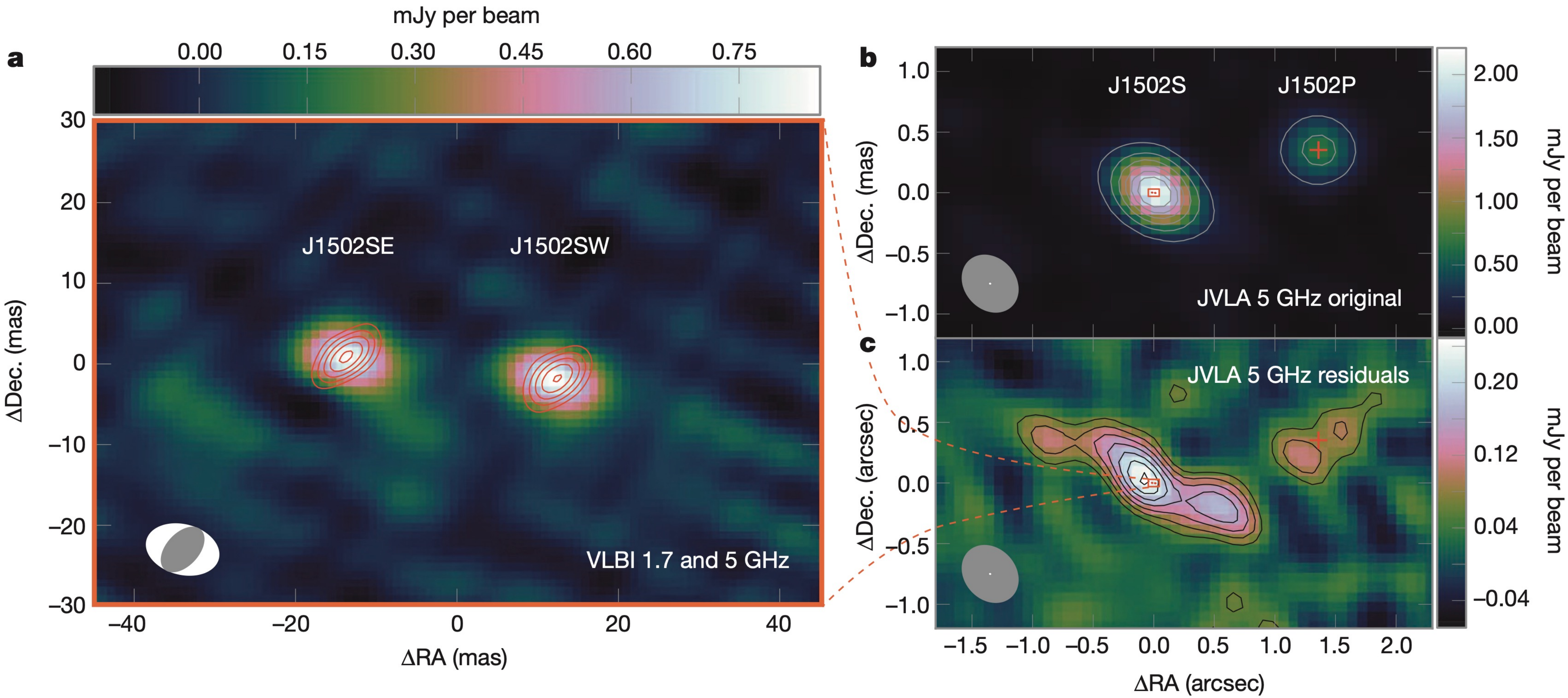
Separation: ~ 1.3 kpc

Pair of active SMBHs at the core of the NGC 6240

Komossa et al. 2003

2 Dual AGNs in VLBI observations

A close-pair binary in a triple supermassive black hole system

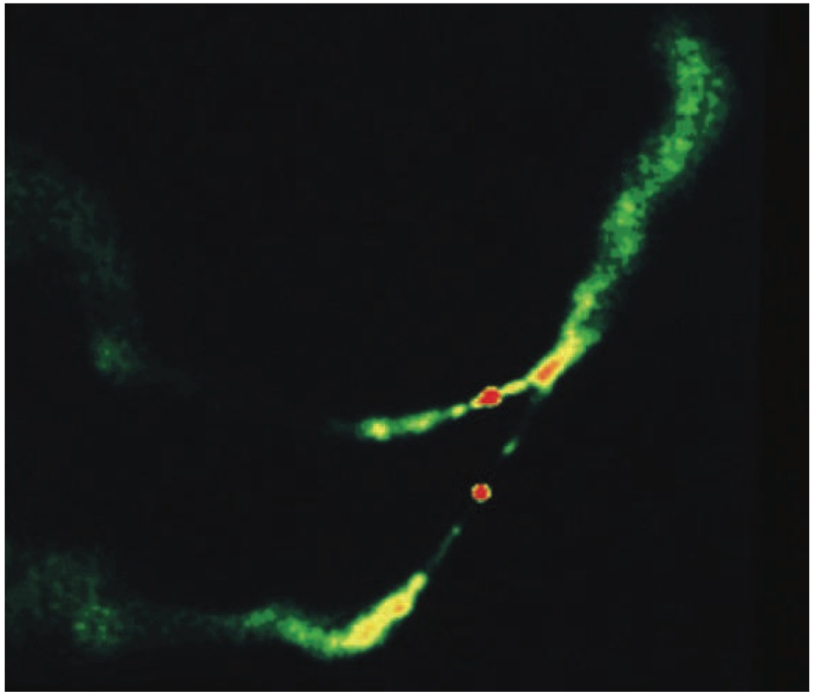


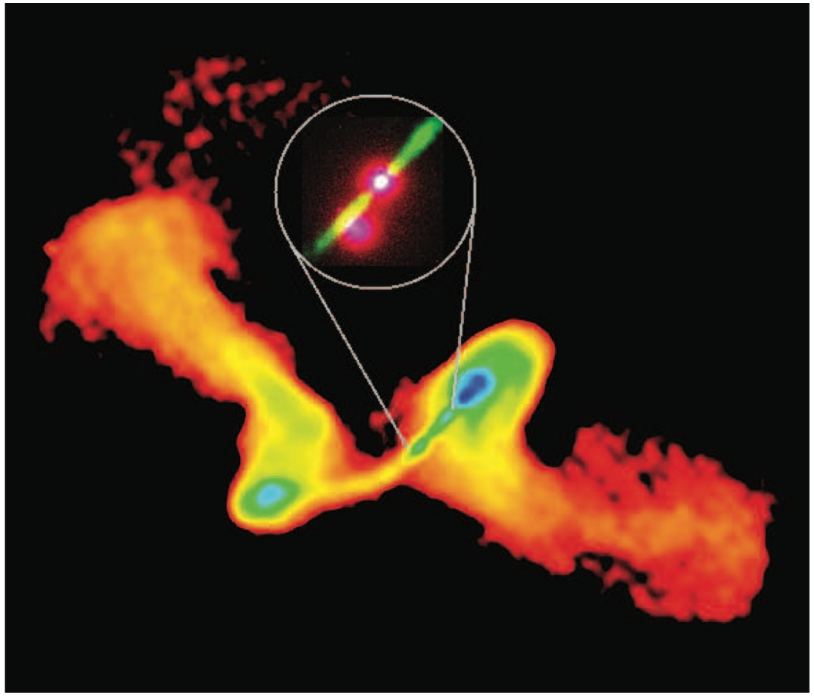
Deane et al. 2014, Nature

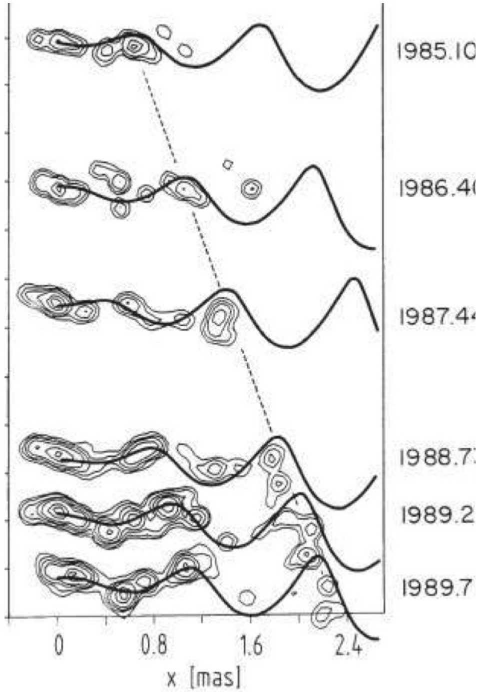
<100 pc

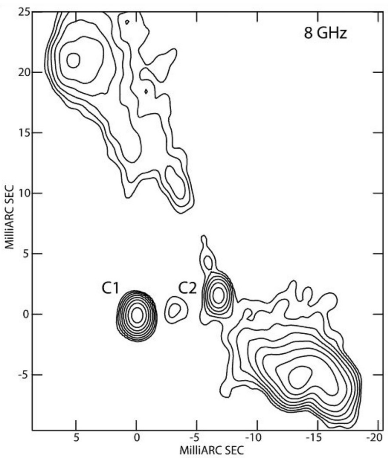
2 Dual AGNs in VLBI observations

Examples of dual AGN in radio observations







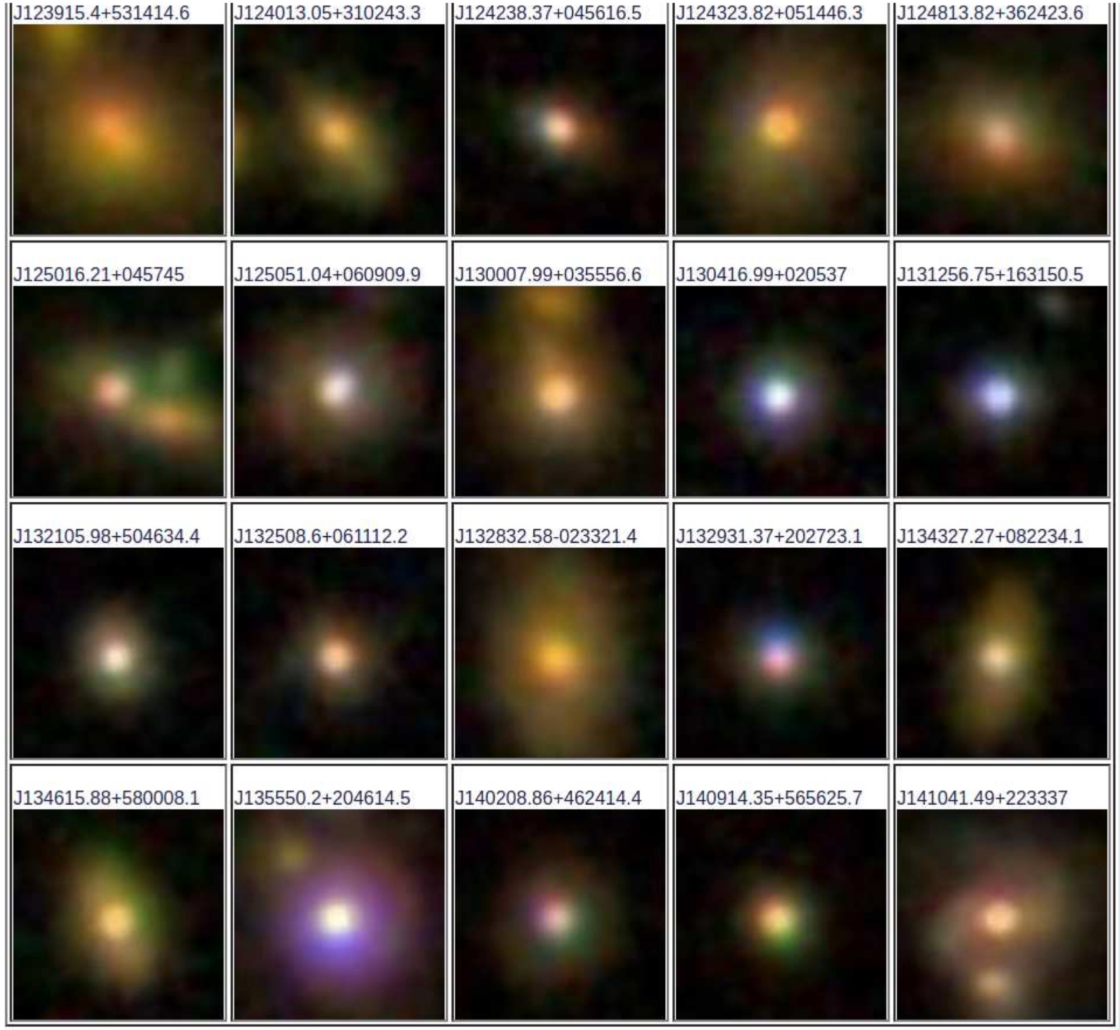


0402+379

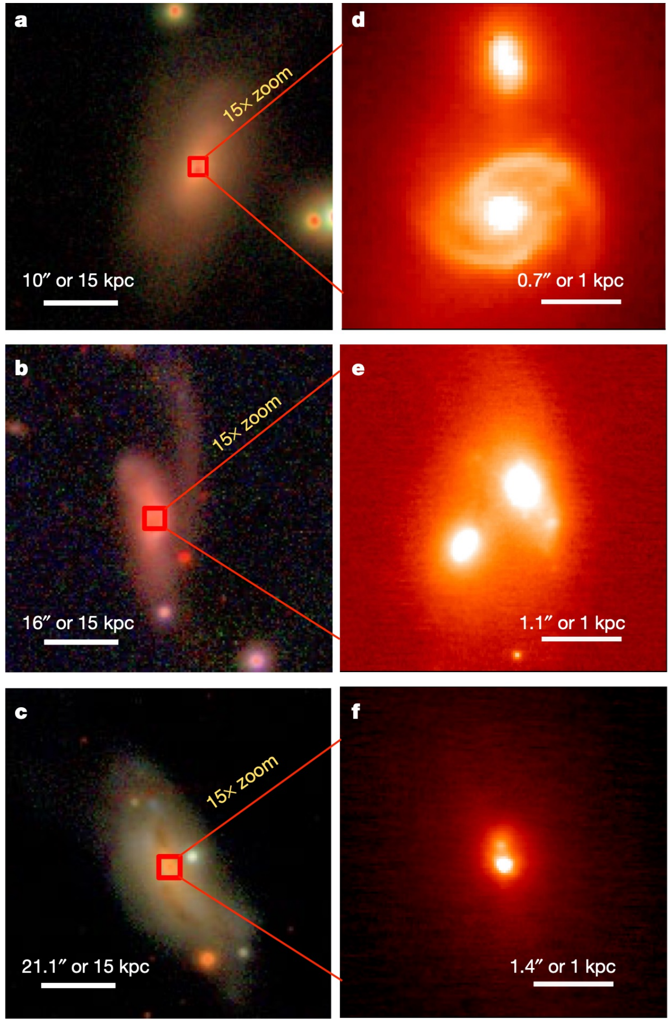
Rodriguez+2006

Credit: NRAO

2 Dual AGNs in optical observations



Kim et al. 2020



Koss et al. 2020

Merger-triggered dual AGNs are preferentially found at the late phases of the mergers at the 1-10 kpc range of nuclear separation (Van Wassenhove et al. 2012)

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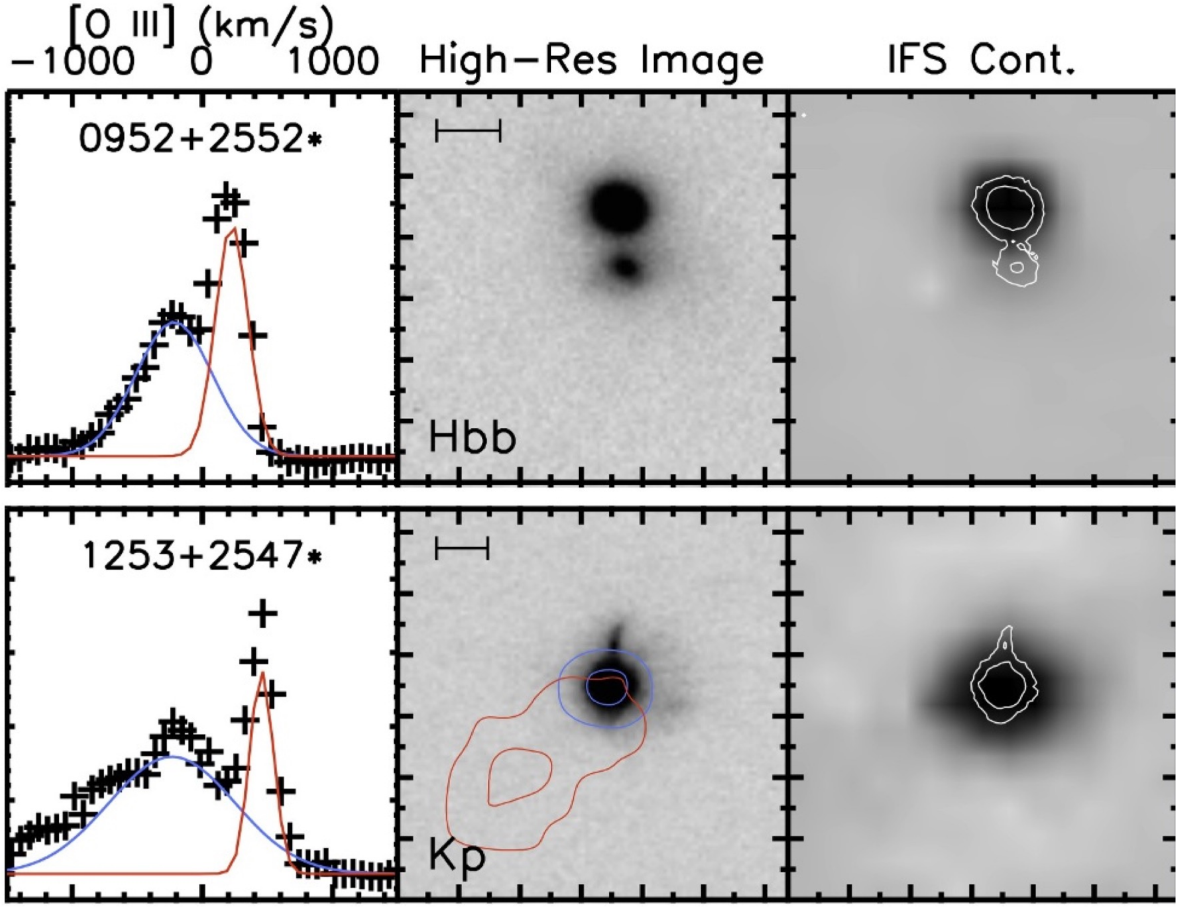
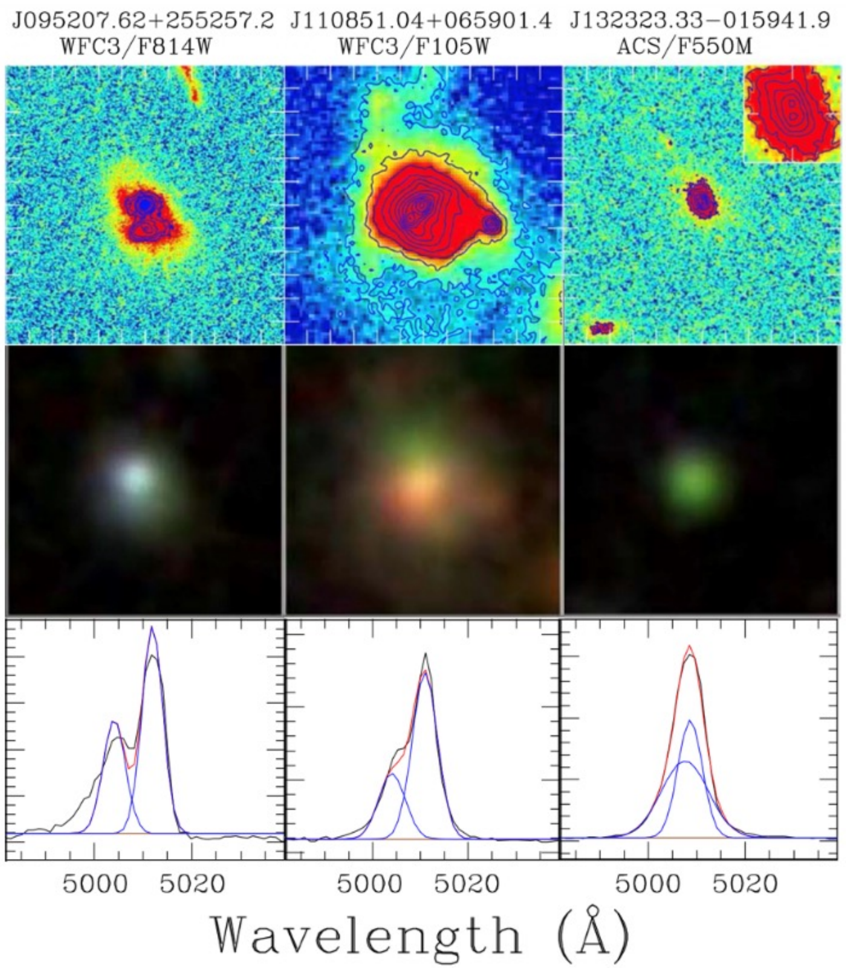
Dual AGNs and double-peak narrow lines

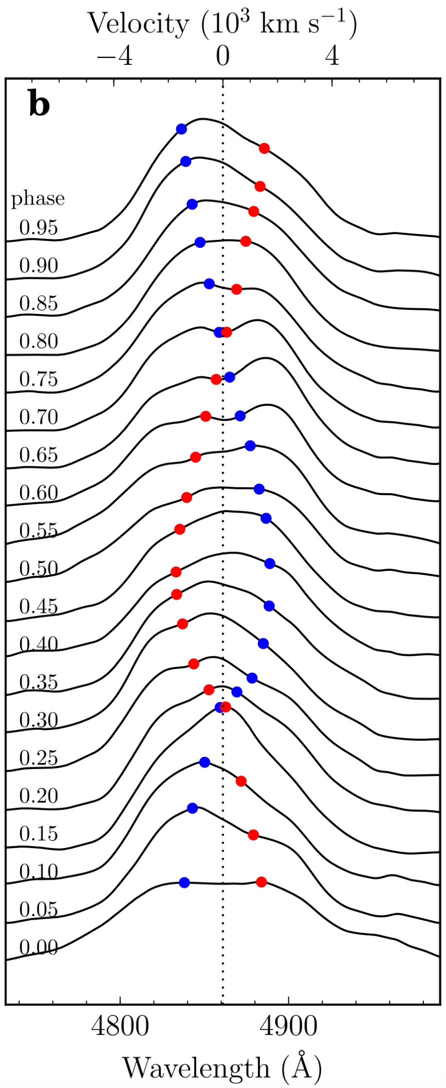


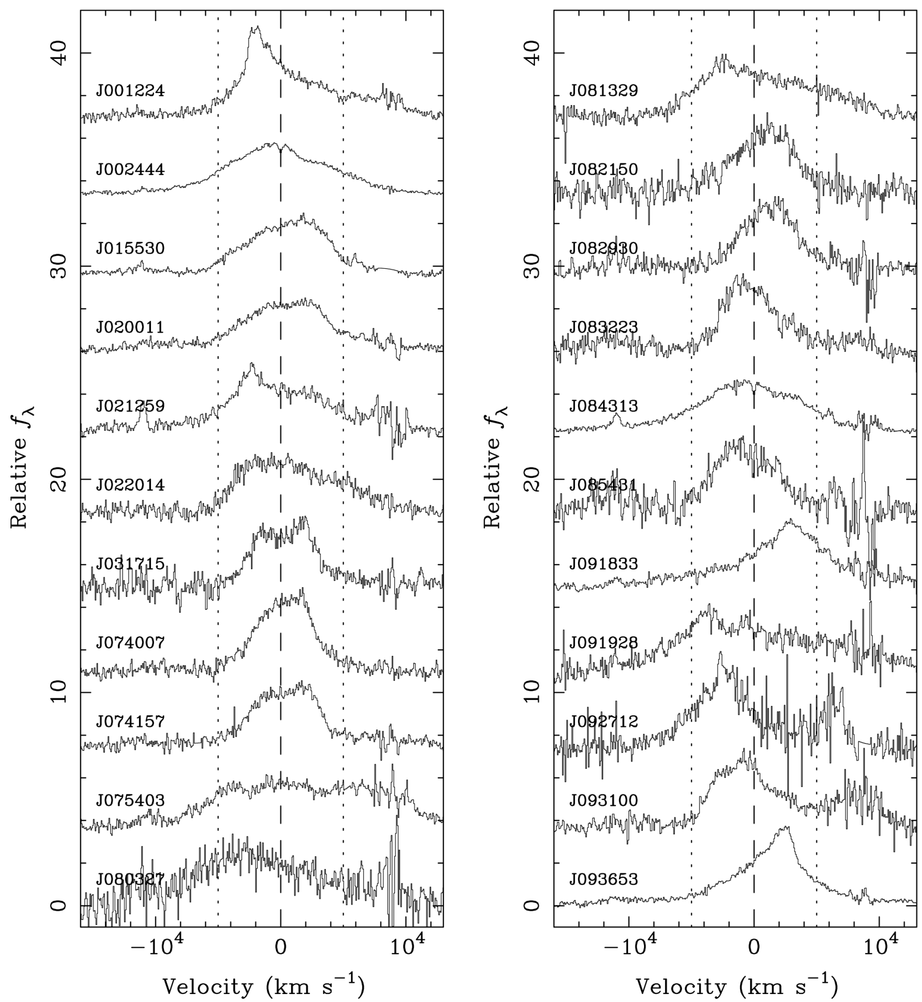


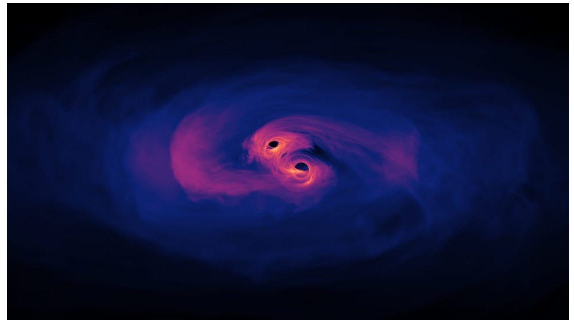
Fu et al. 2012 **Kim et al. 2020**

2 Evidences for Massive black hole binaries

MBH binaries at sub-pc separation & Double-peak broad lines







Two broad line regions for each MBH, which produce blue and red shift.

NGC 5548 Li et al. 2016
MBH binary ~ 18 milli-pc?

Eracleous et al. 2012
Systimatically search for the BH binaries

2 Evidences for Massive black hole binaries

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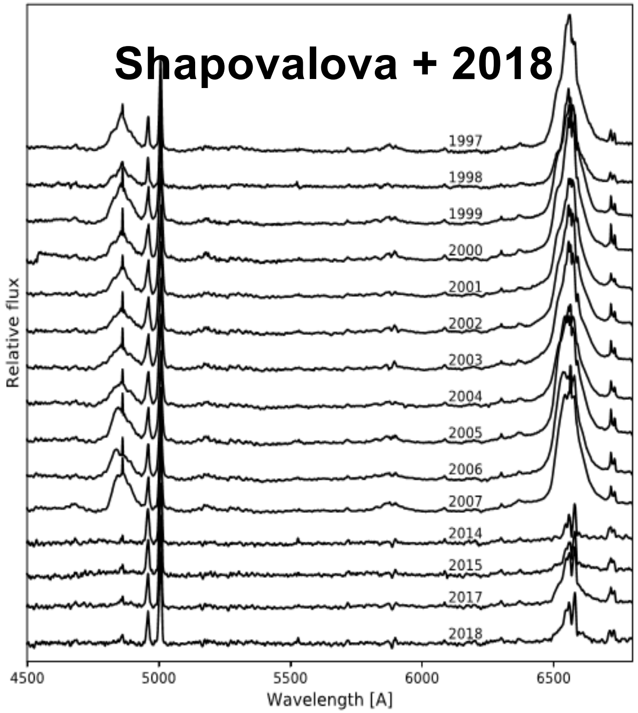
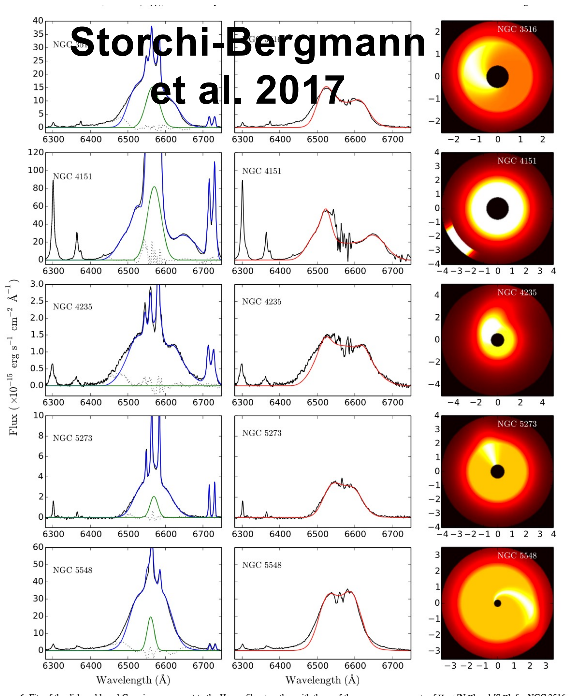
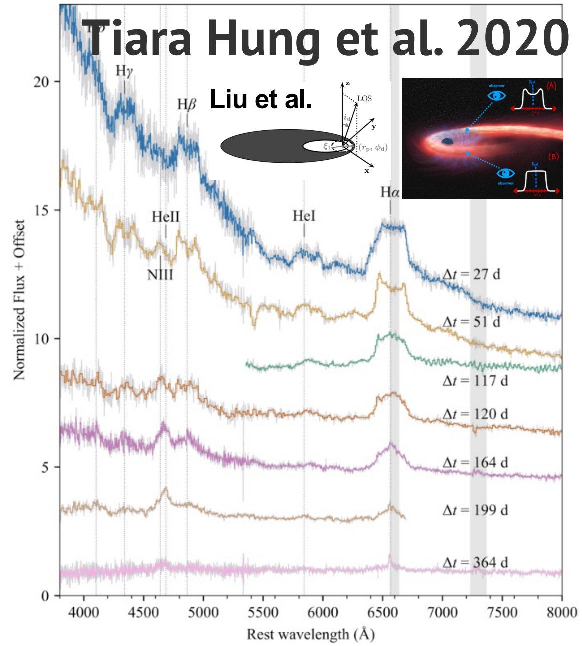
Double-peak broad lines are preferred found in AGNs with moderate Eddington ratios： just caused by accretion disk?

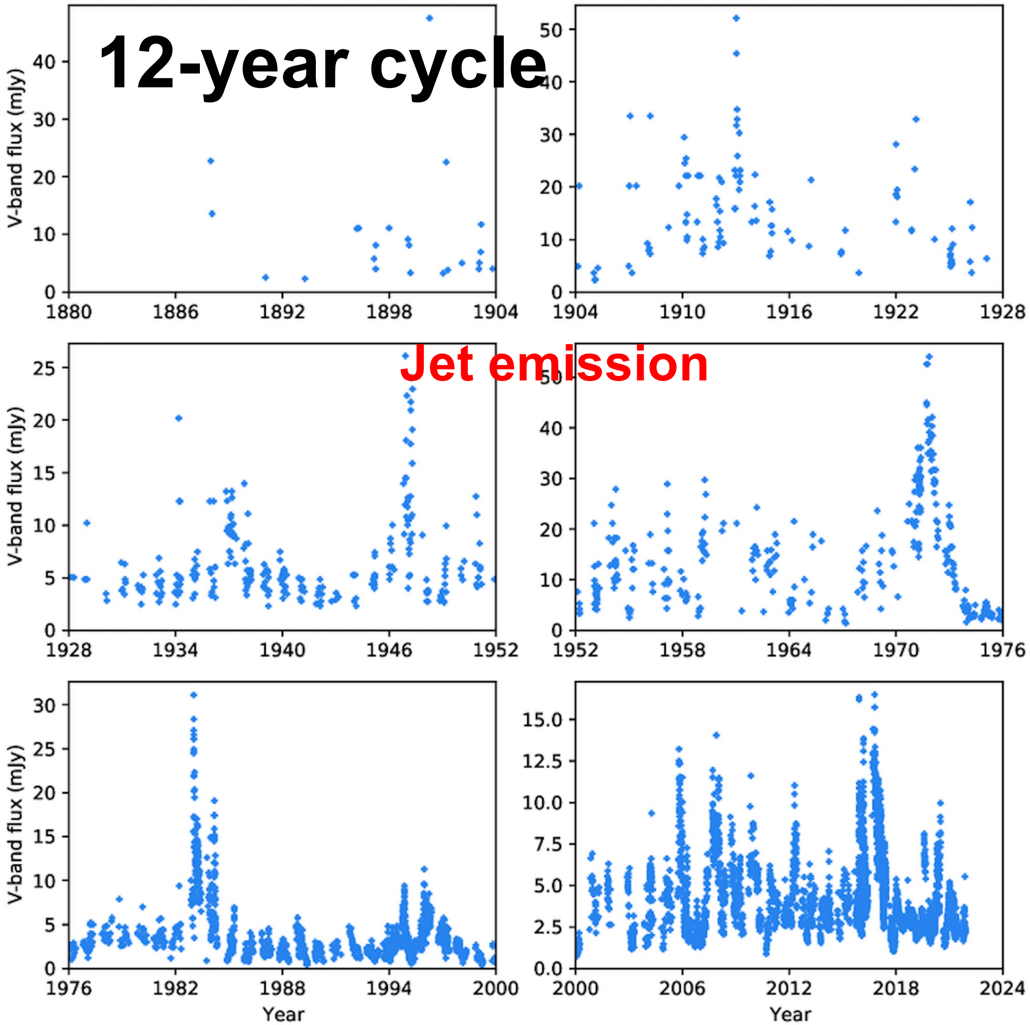


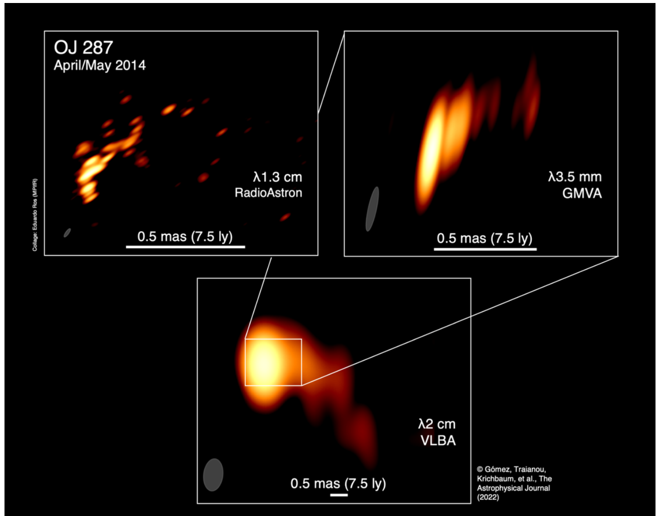


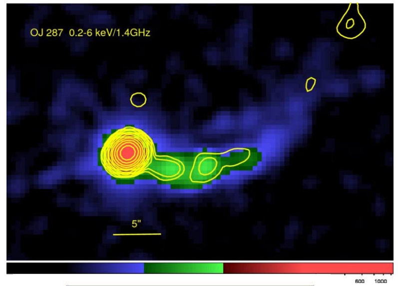


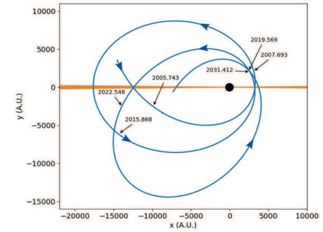
Double peak lines appear in some stage of Changing-look AGNs and TDEs, which suggest that the double peak may be caused by accretion process, not caused by binary MBHs.

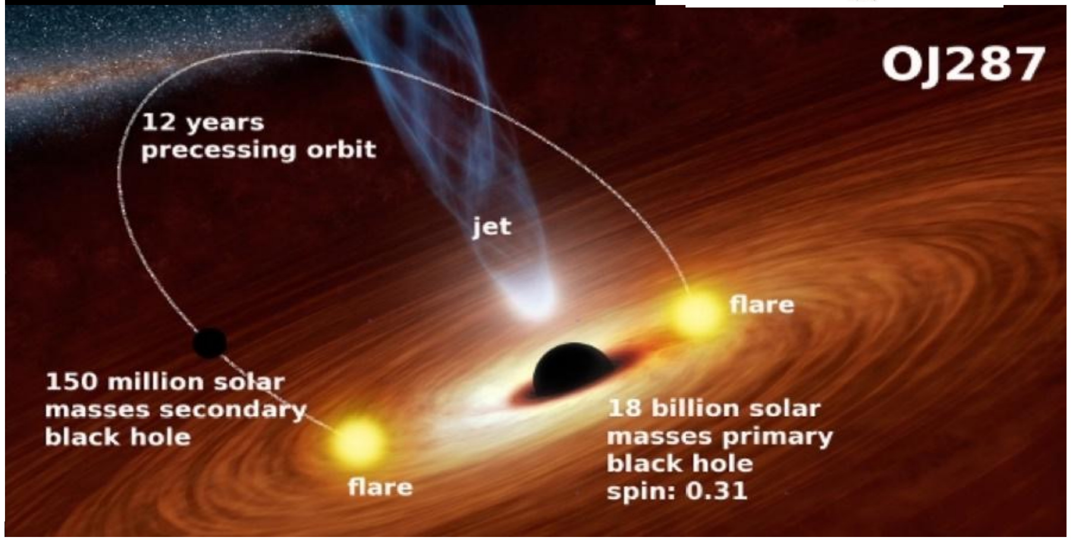
2 Periodic variability in AGNs









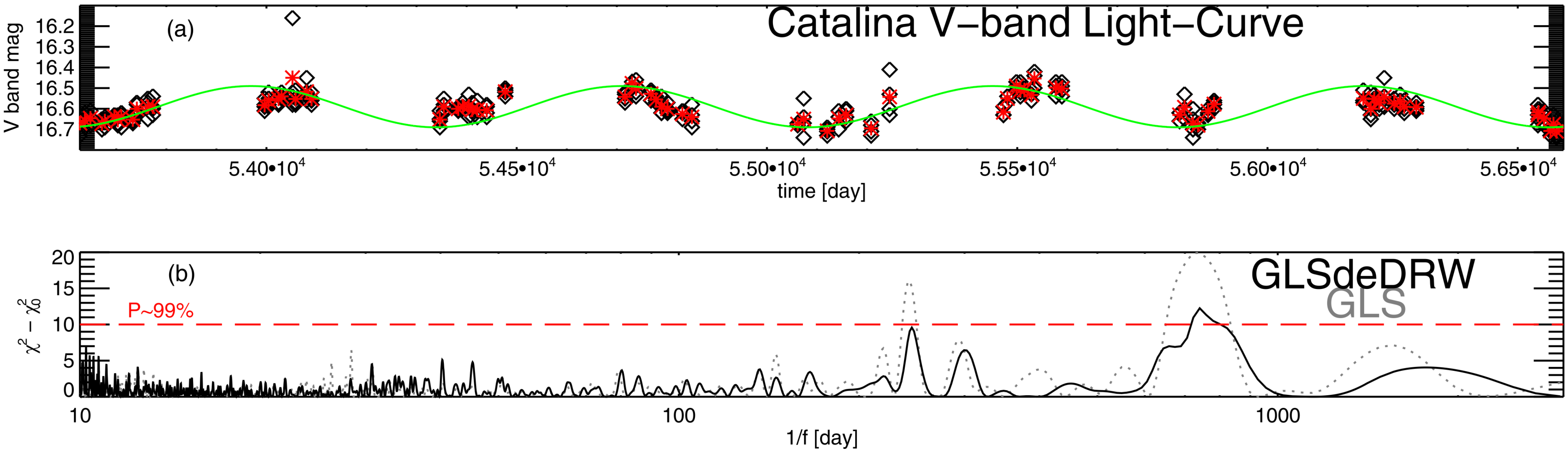


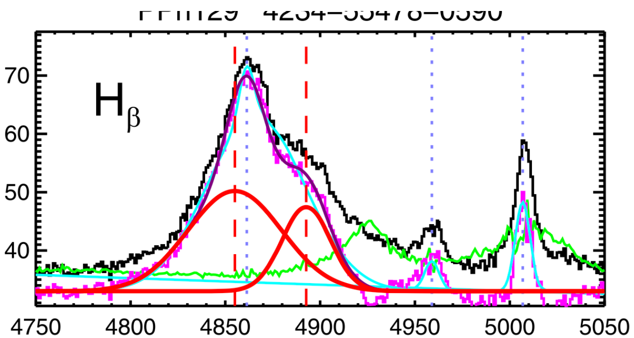
Periodic variability & Highly curved inner jet in OJ 287:
evidence BH binaries?

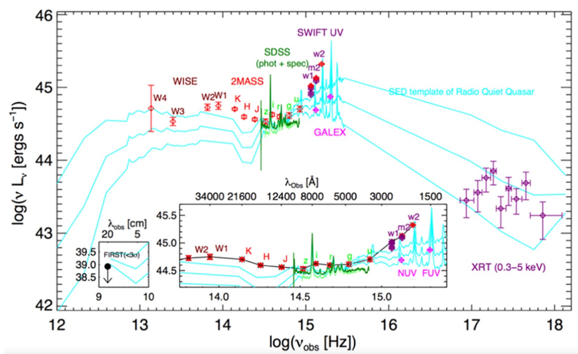
resolution ~ 50uas, Gomez et al. 2022 ApJ

2 Periodic variability in AGNs

SDSS J0159+0105: a centi-parsec MBHB?







Total Mbh: ~10^8 Msun

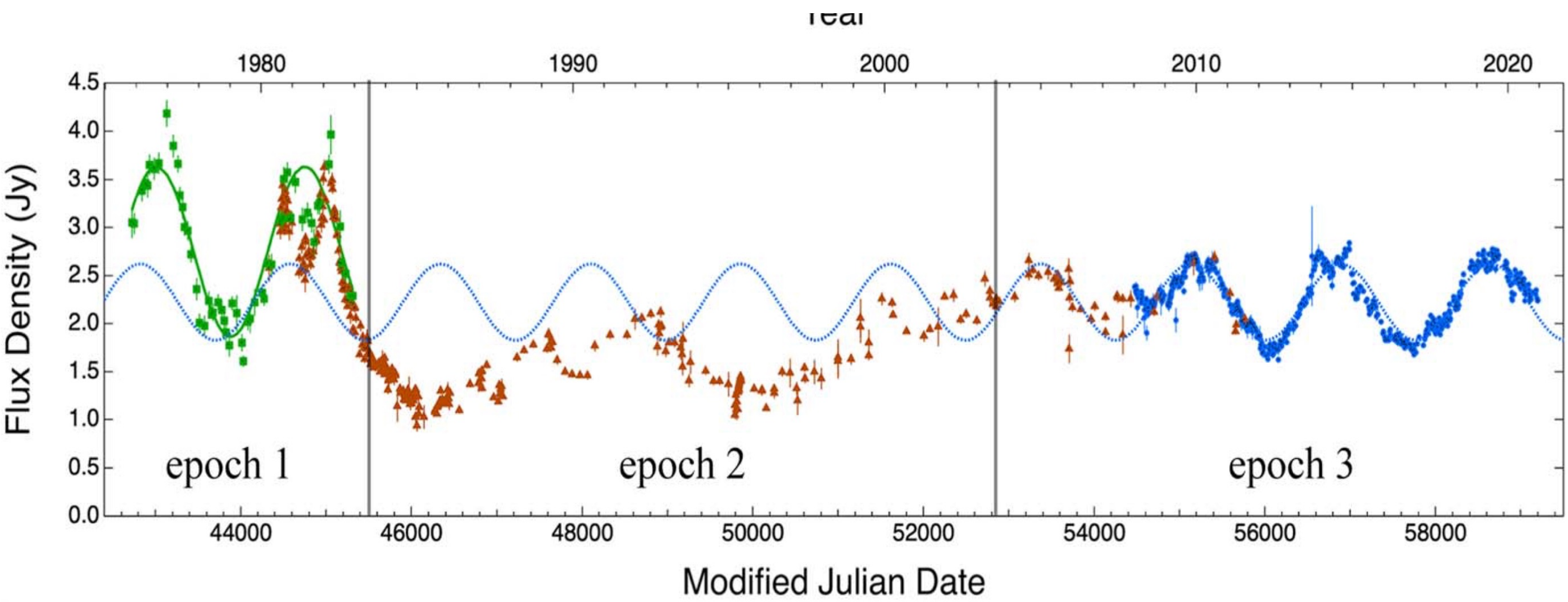
Separation: ~ 0.01 pc

Double peak lines: line shift

Unusual SED: circum binary disk+mini-disk?

Zhen Z Y et al. 2016 ApJ

2 Periodic variability in AGNs

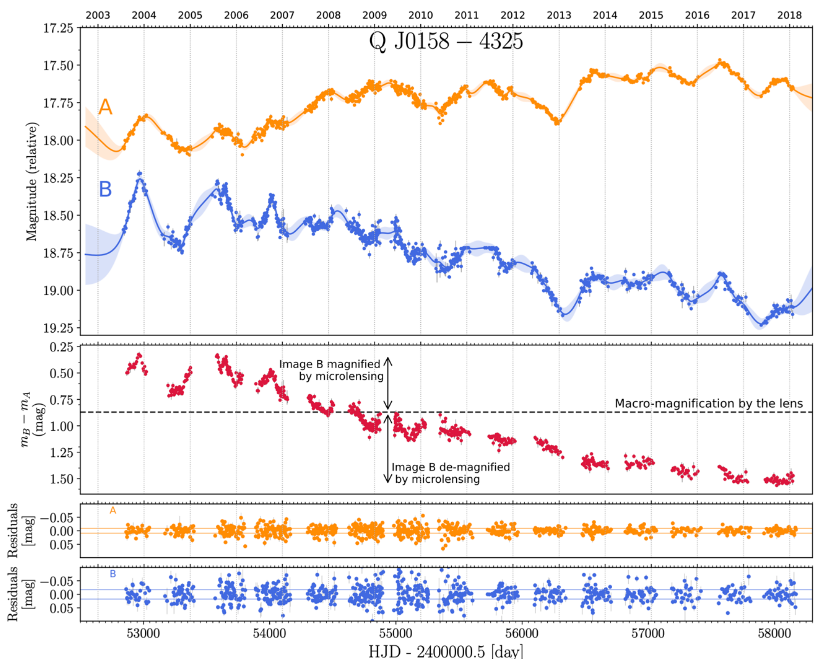


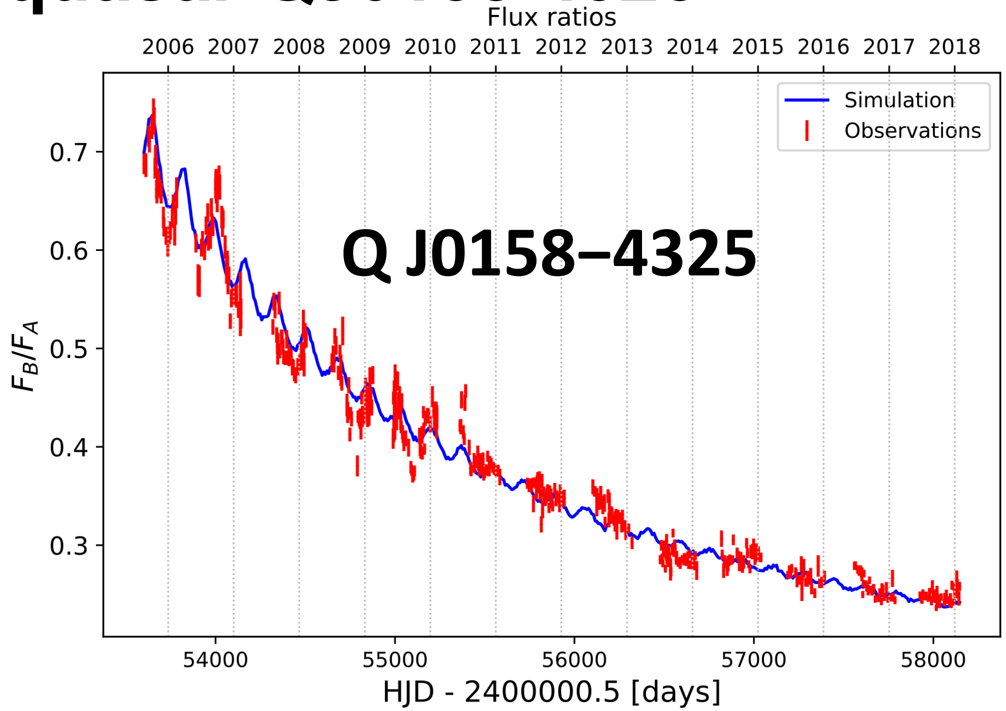
15 GHz light curve of PKS 2131−021

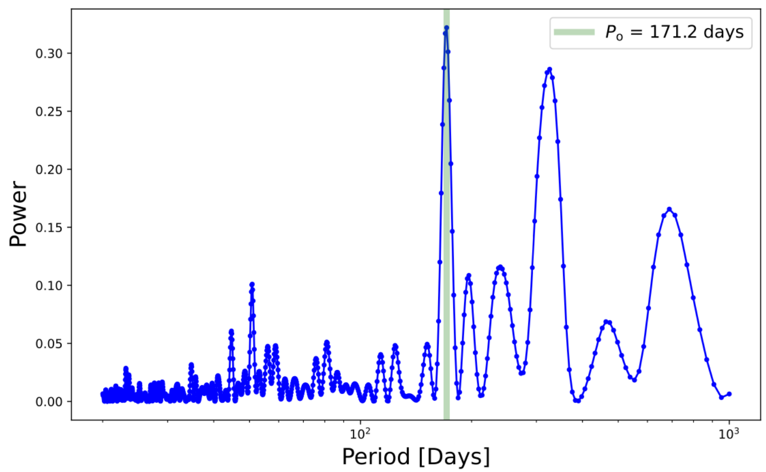
an orbital separation of ∼0.001–0.01 pc?

O'Neill et al. 2022

Periodic oscillations in the 15-year long optical light curve of the gravitationally lensed quasar QJ0158-4325





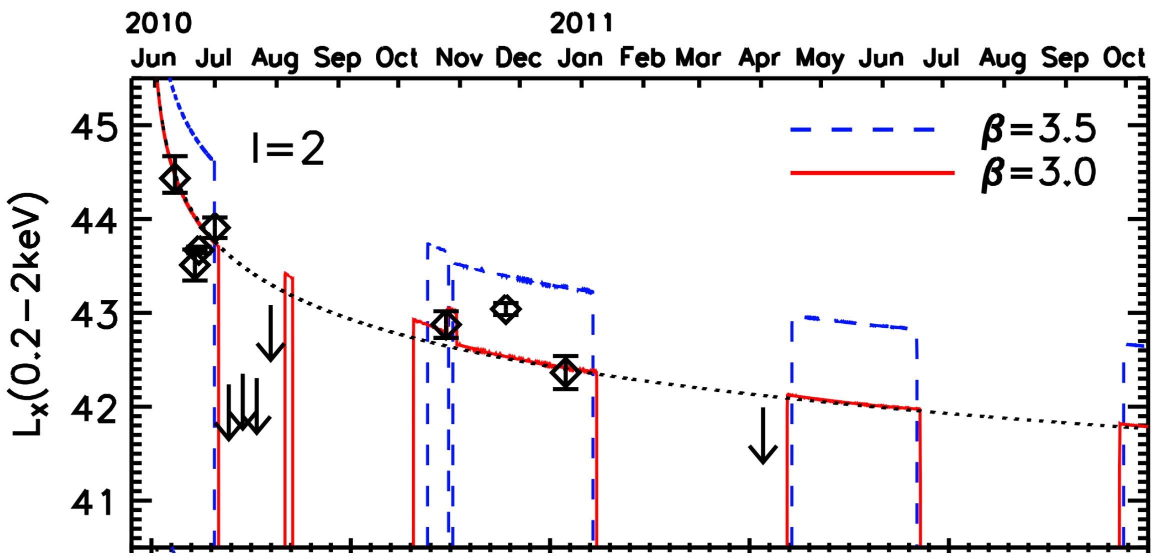


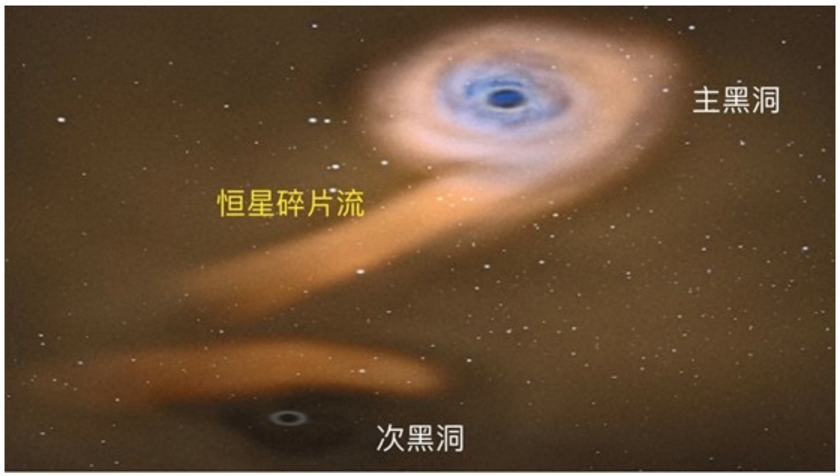
milli-parsec separation

Millon et al. 2022 A&A

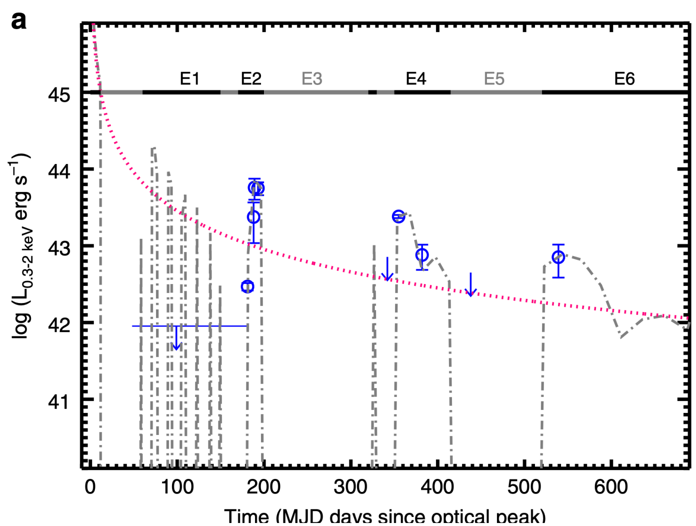
2 BH binary & TDE light curve

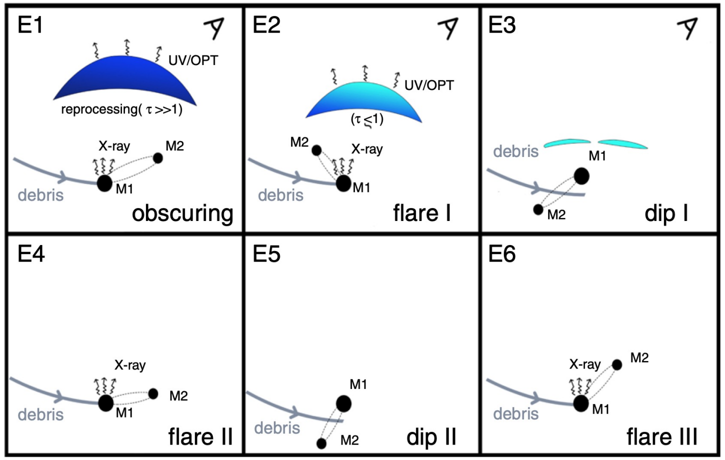
milli-parsec massive BH binary candidate：Dips in light curve





Liu et al. 2014 ApJ





Shu et al. 2020 NC

2 Periodic variability in AGNs

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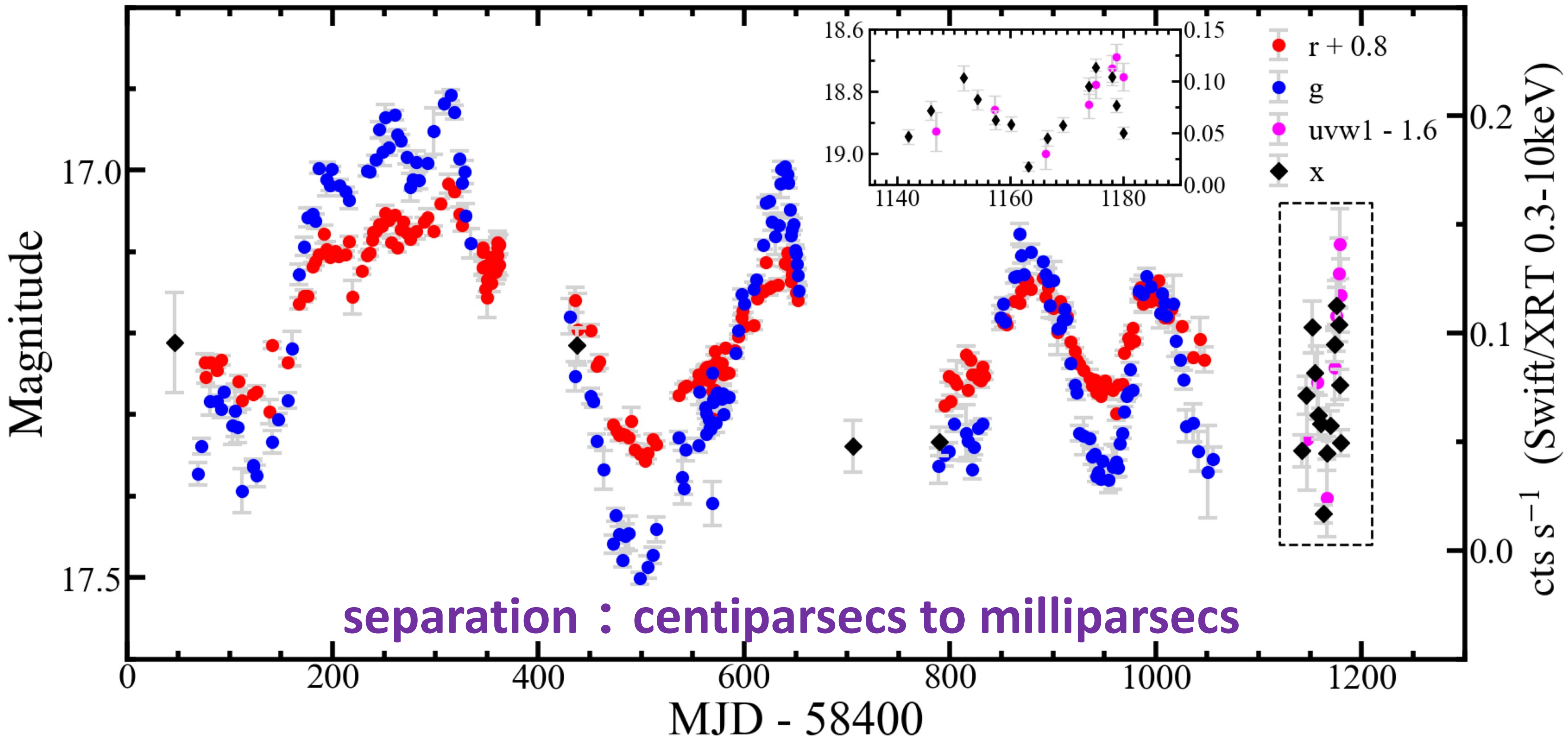
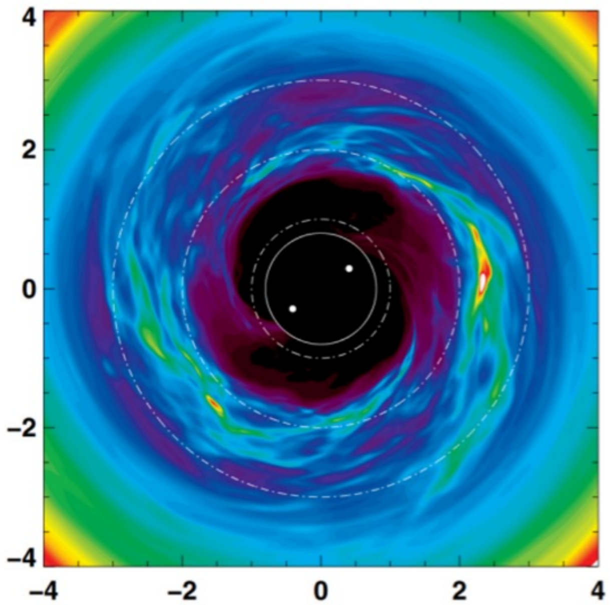
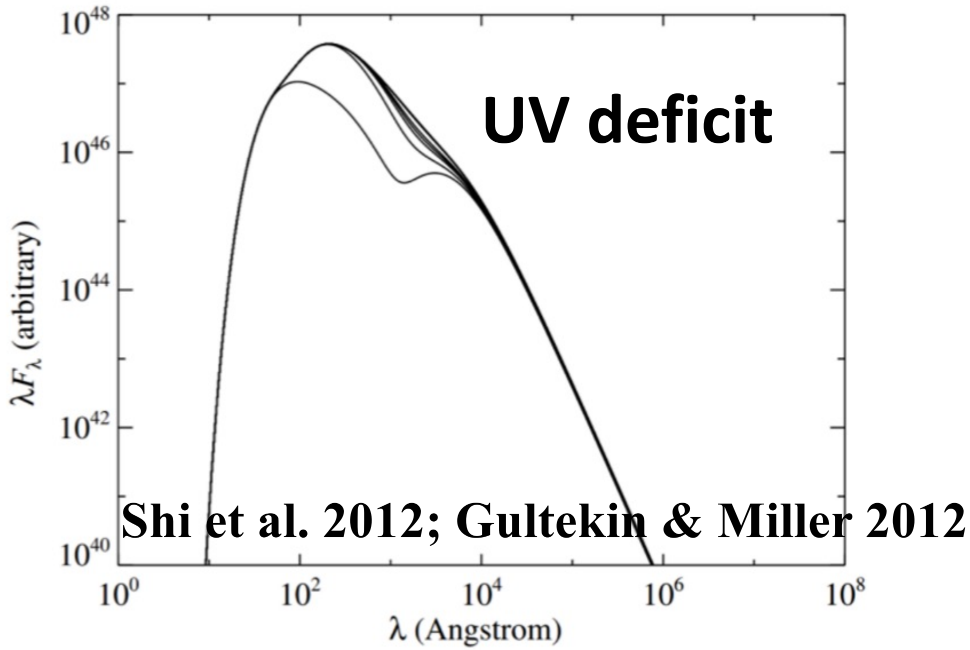


SDSSJ1430+2303, merger within 3 years!

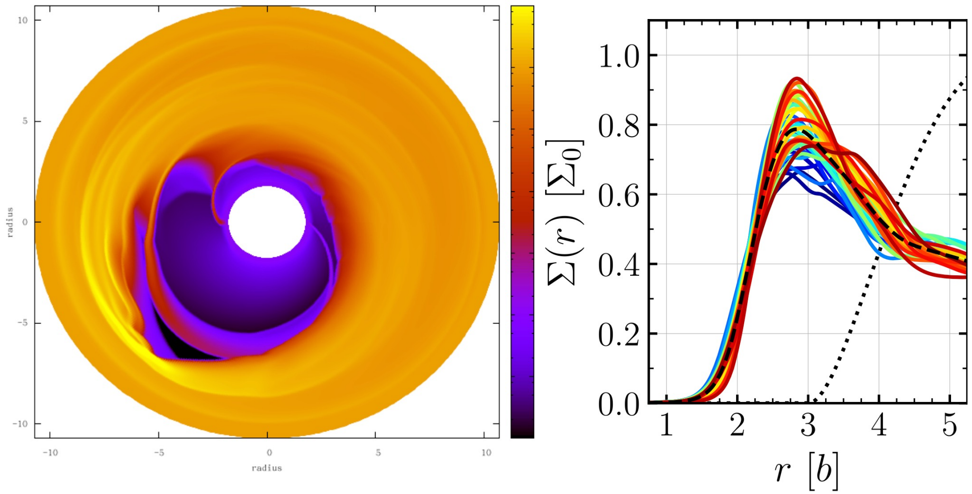
Jiang et al. 2022

2 Binary MBHs from SED and variability

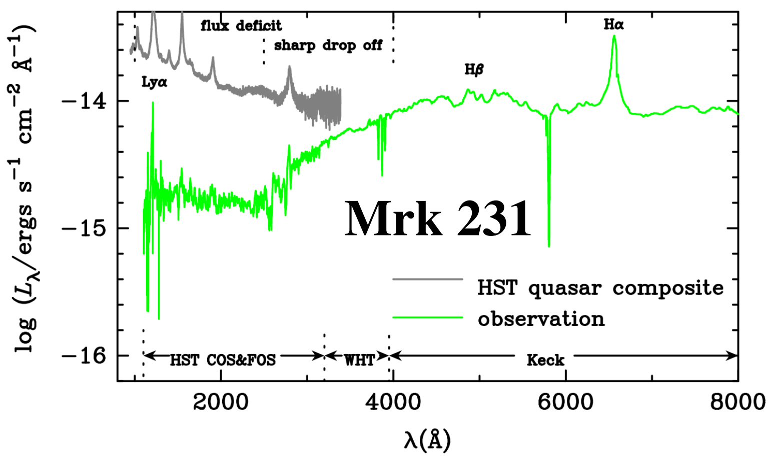




Shi et al. 2012; Gultekin & Miller 2012



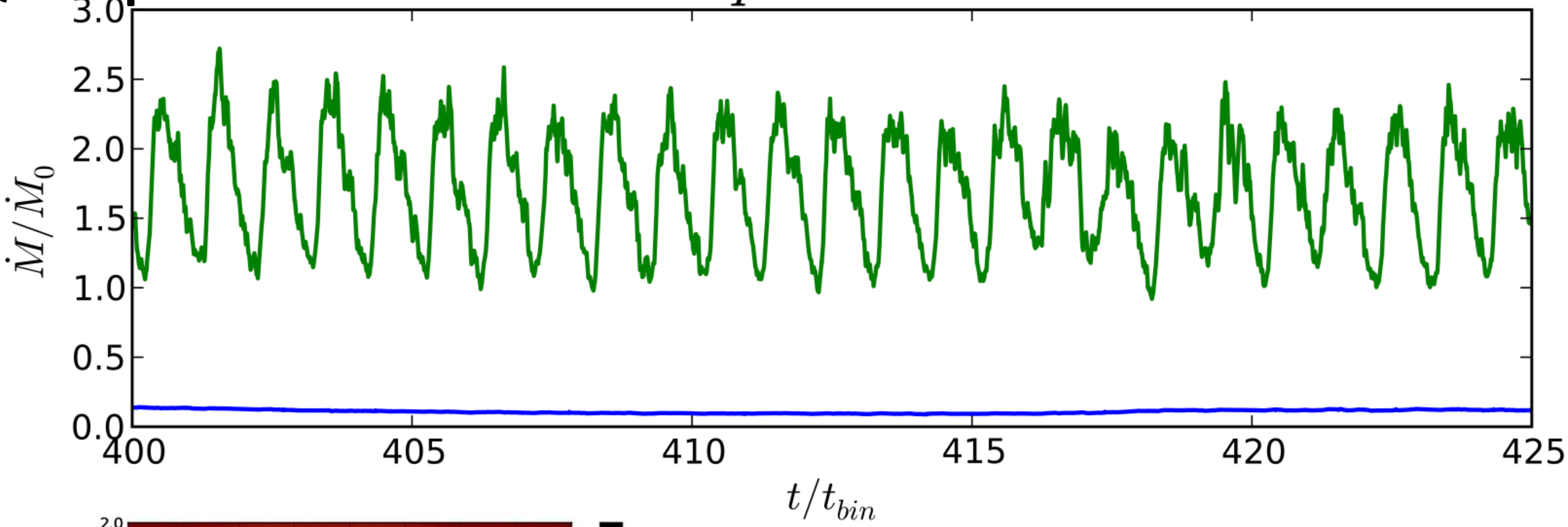
post-Newton hydrodynamics Liu 2022 ApJ

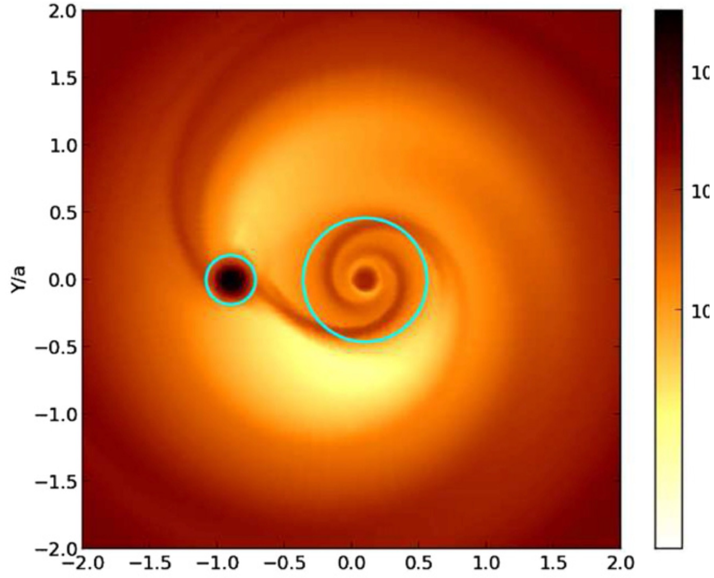


Yan et al. 2015 ApJ

2 Binary MBHs from SED and variability

Quasi-periodic variabilities





Mass ratio q>0.1, the binary excites eccentricity in the inner region of the circumbinary disk, creating an over-dense lump，gives rise to enhanced periodicity in the accretion rate.

Farris et al. 2014 ApJ

2 LSST era for ultra-short period binaries

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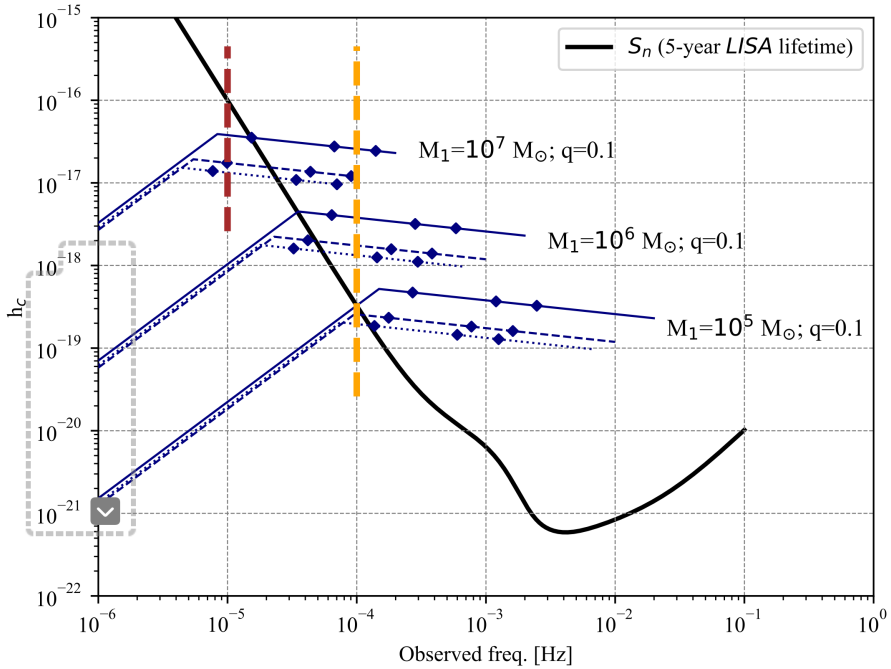
Space GW Verification MBH binaries?

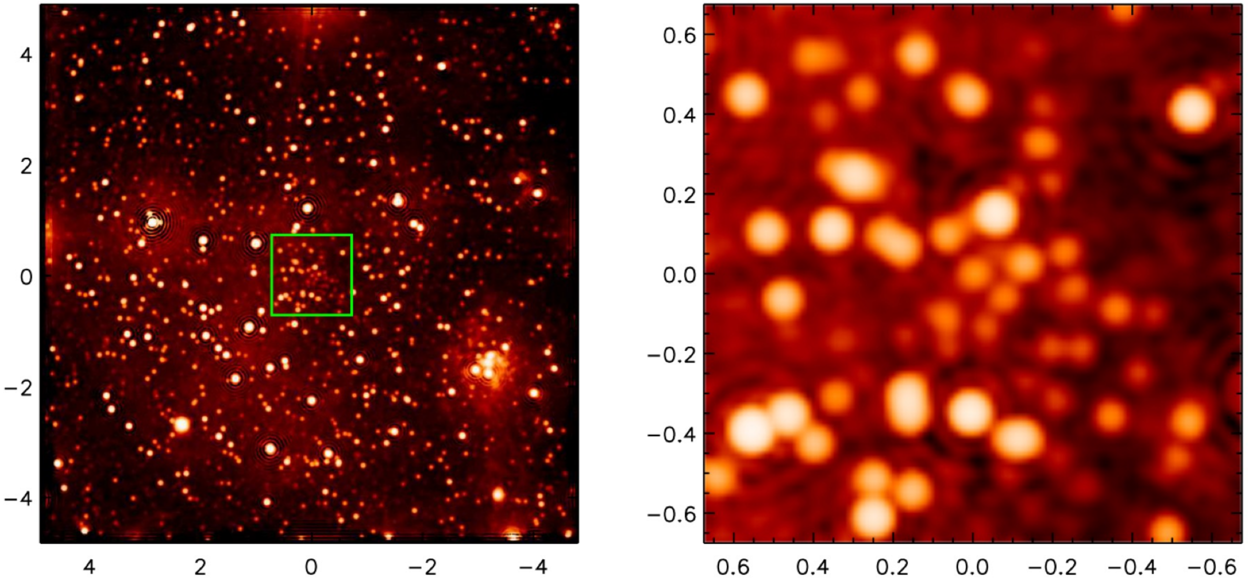
Searching Ultra-Short-Period Massive Black Hole Binary in LSST era.



Xin & Haiman 2021

Massive Black Hole
&
Nuclear environments

3 Nuclear stellar cluster （NSC）

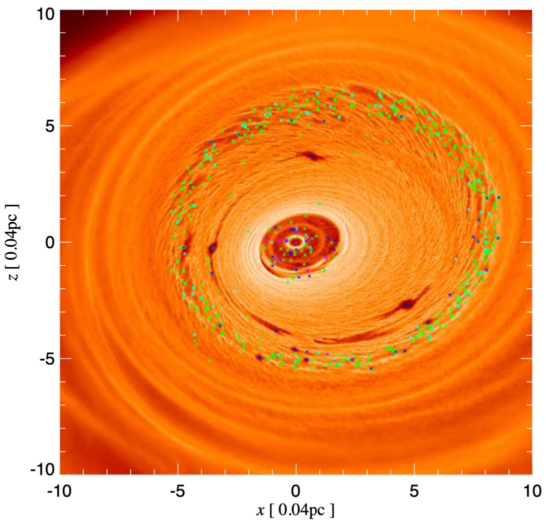


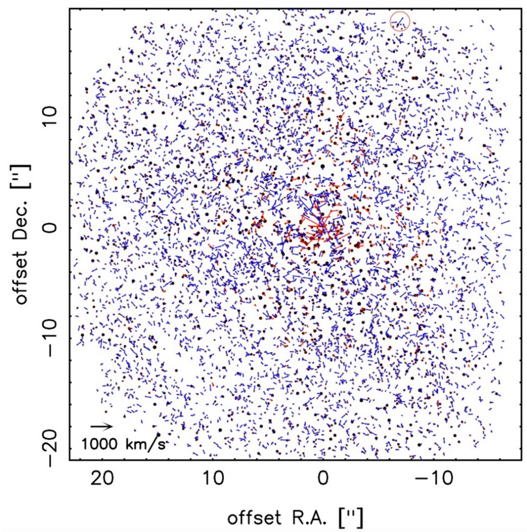
Schodel et al. 2020

Sgr A* NSC

~100 OB and Wolf-Rayet within 0.05-0.5 pc of Sgr A*
The age is ~4-6 Myr.

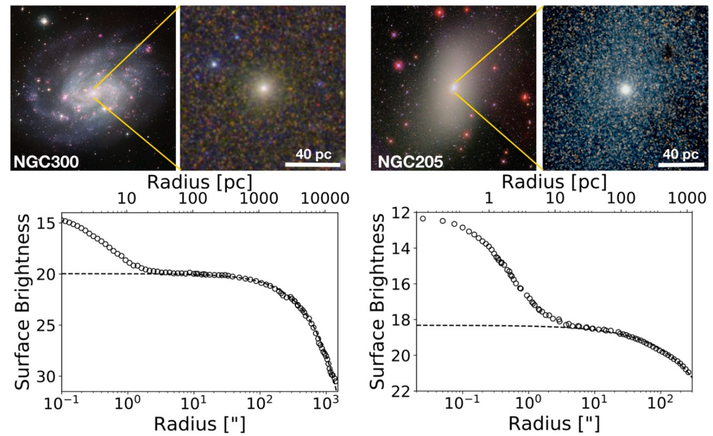
Locally formed or captured?



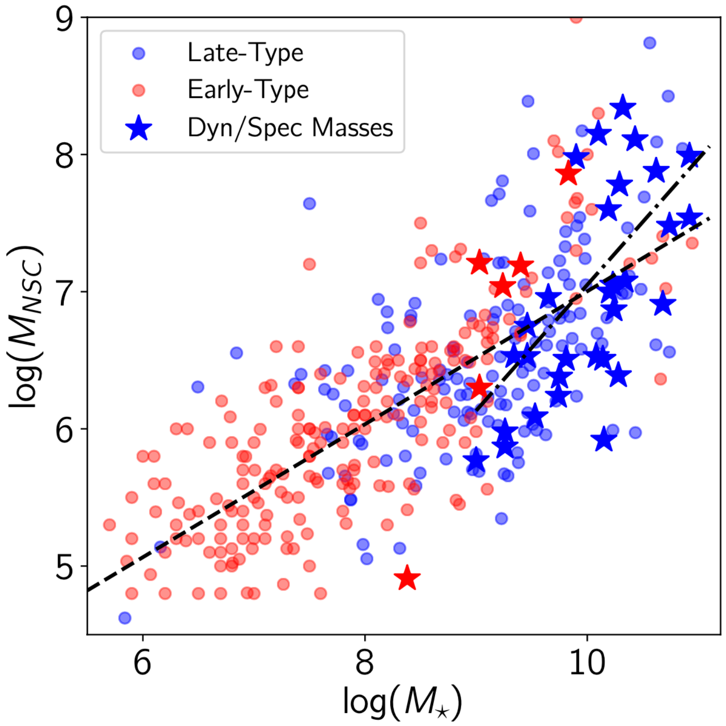


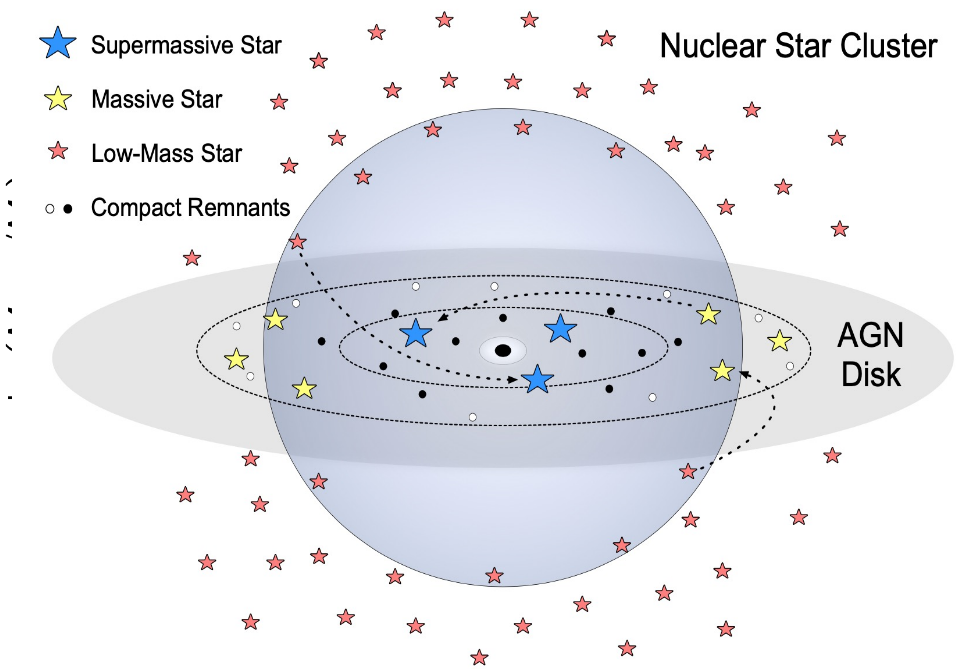
Schodel et al. 2009

Late-type spiral NGC 300 and early type NGC 205



3 Nuclear stellar cluster（NSC）



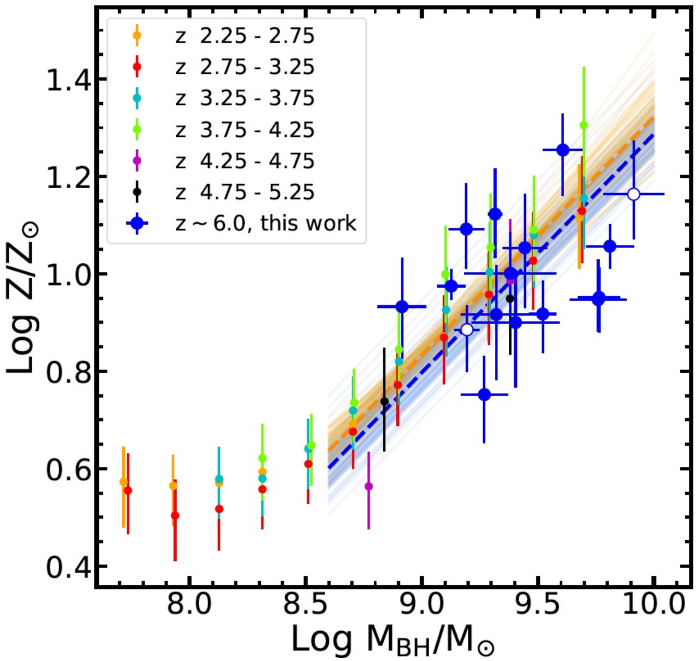


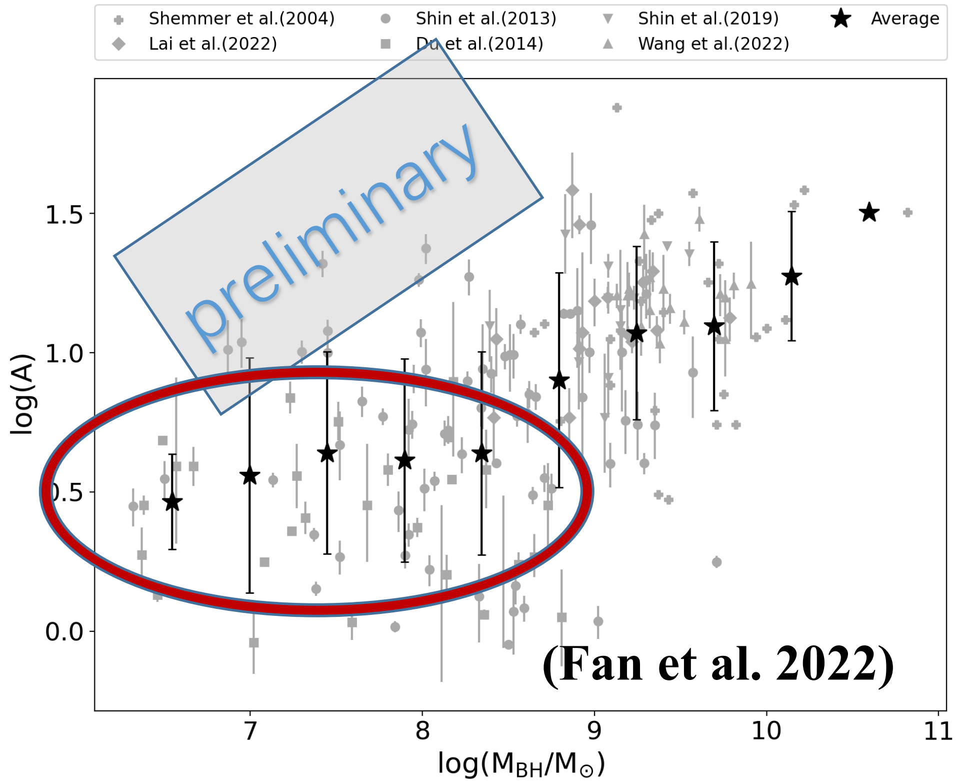
Higher-mass galaxies have a lower fraction of their mass in their NSC

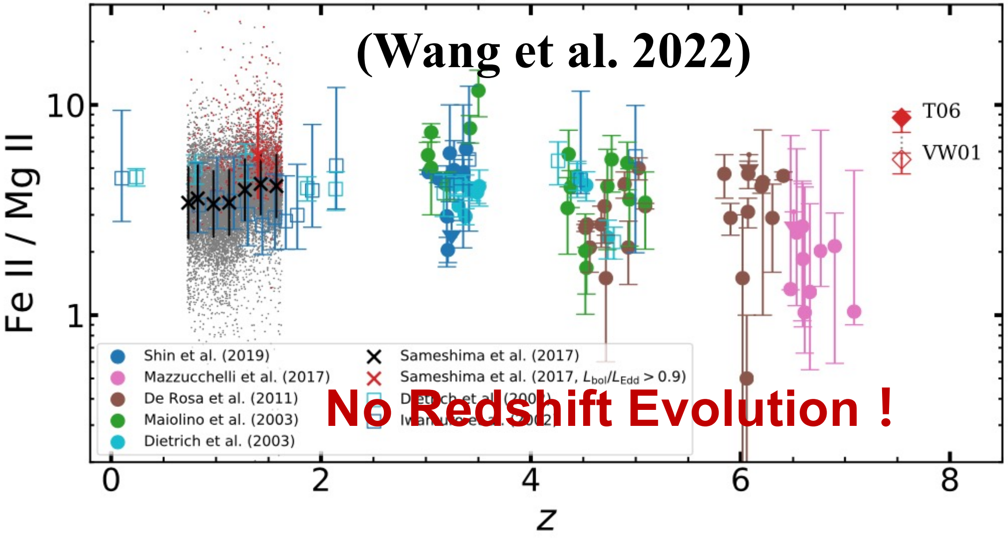
NSC，MBH and host galaxy may be co-evolved.

NSC is gas reservoir for MBH accretion.

3 High metallicity in AGNs







Metallicity is averagely constant at low-mass MBHs.

<Z> ~ 3-20 in AGNs, it is much higher than that of host galaxies

3 AGN disk star

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in-Situ Formation of star due to disk instability

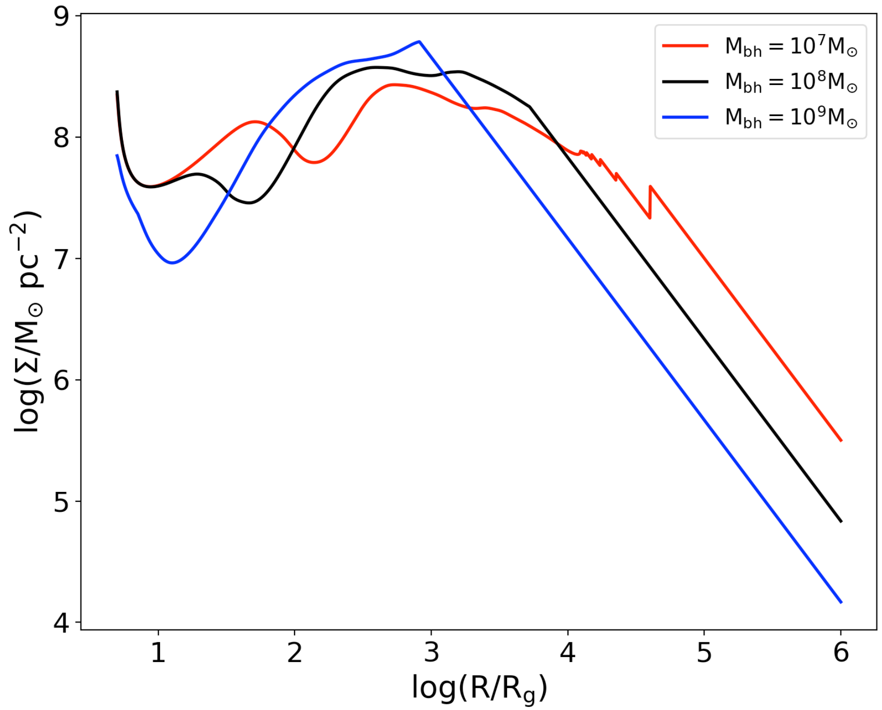
Model

Self-gravitating disk

(Sirko & Goodman 2003) :

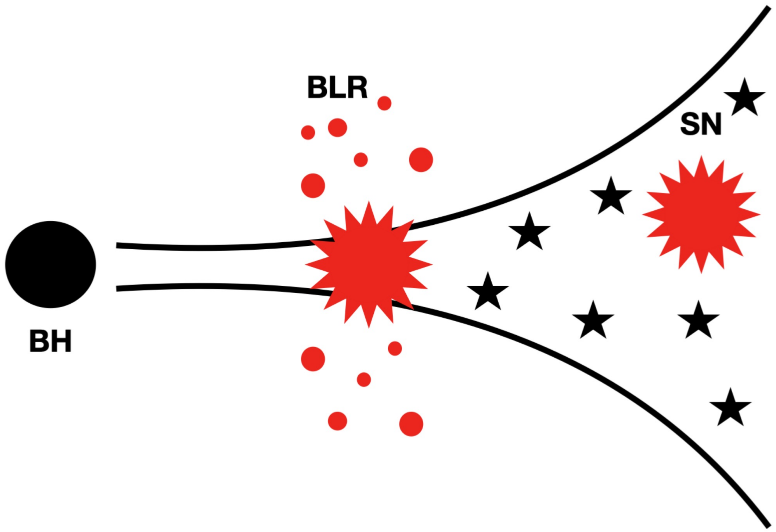
$R < R_{sg}$: similar to SSD

$R > R_{sg}$: Toomre's parameter Q=1



metal mass contribution per solar mass

$$Z(t)M_{\rm gas} = \int_0^t (Z_0 \dot{M}_{\rm out} + \bar{m}_Z \dot{R}_* - Z(\tau)\dot{M}_{\rm BH} - Z(\tau)\bar{f}_{\rm rem}\dot{R}_*)d\tau$$

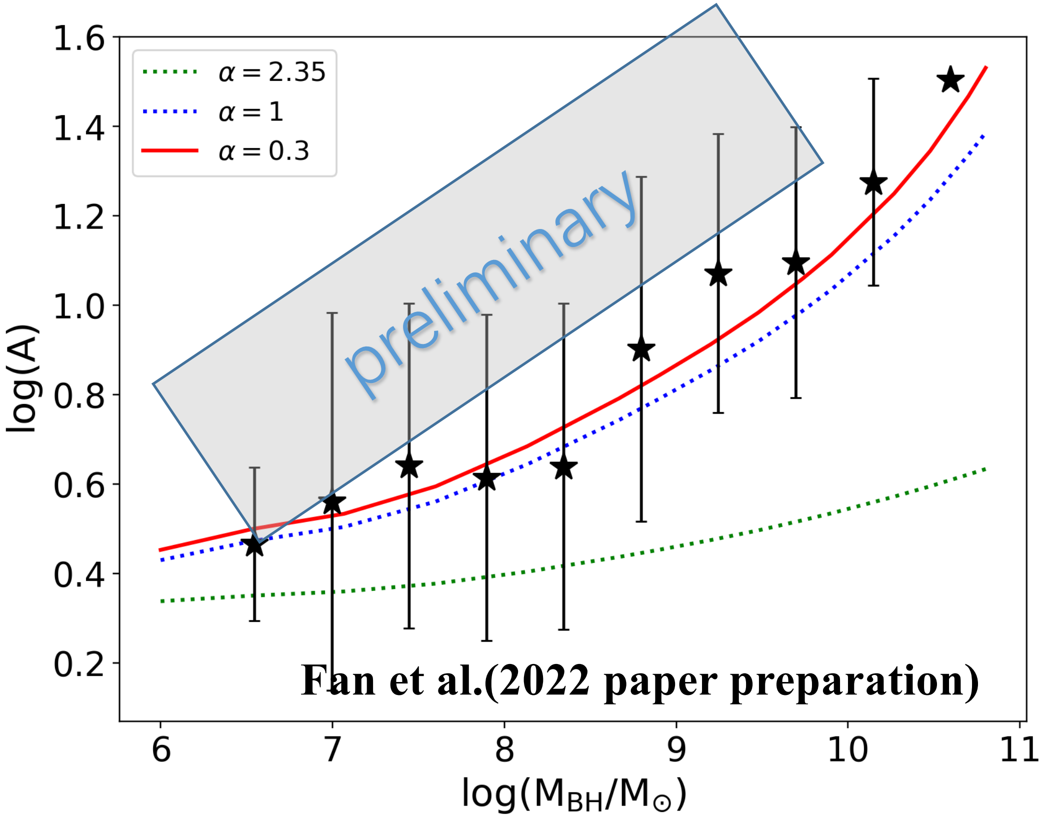


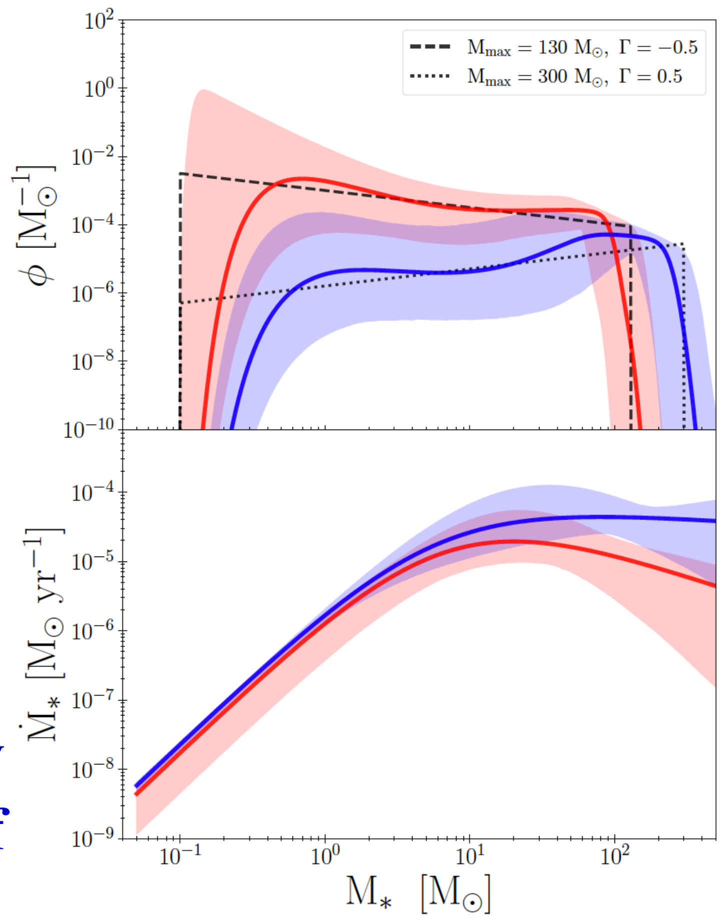
Model

- Stars form in the outer region of the disk.
- Disk stars nucleosynthetic products enrich the gas metallicity (especially via SN)

Metallicity of BLR

$$Z(t)M_{\rm gas} = \int_0^t (Z_0\dot{M}_{\rm out} + \bar{m}_{\rm Z}\dot{R}_* - Z(\tau)\dot{M}_{\rm BH} - Z(\tau)\bar{f}_{\rm rem}\dot{R}_*)d\tau$$

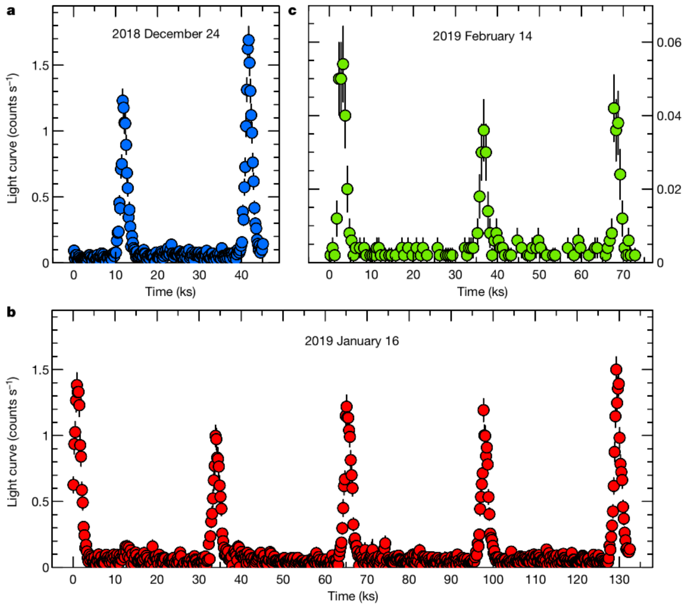




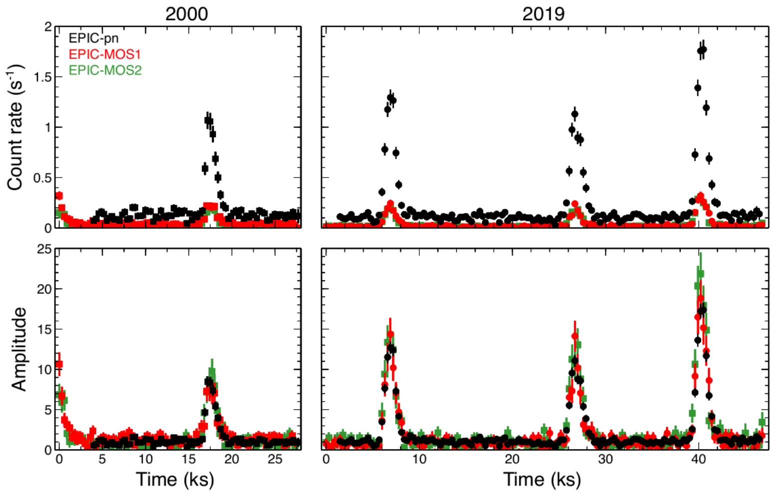
Toyouchi et al.(2021)

In-situ star-formation caused by disk instability can reproduce mass-metallicity relation. IMF of these disk stars may be top-heavy.

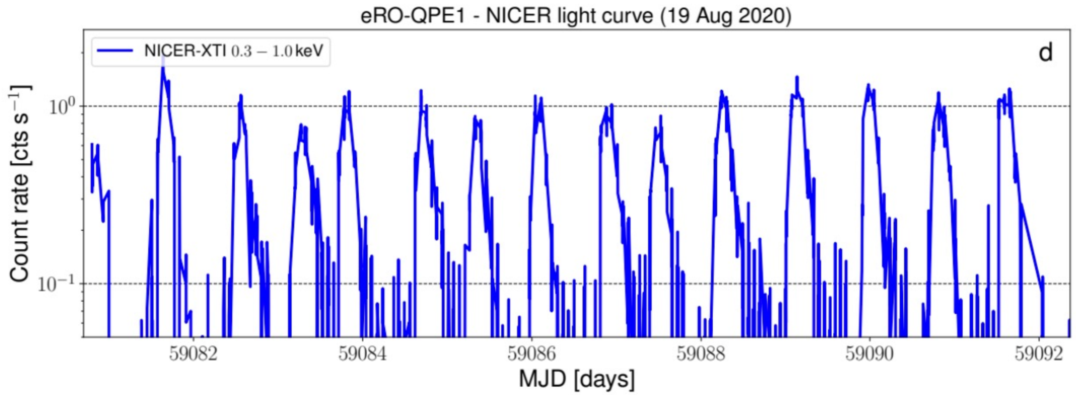
4 Quasi-periodic eruption (QPE) and EMRI



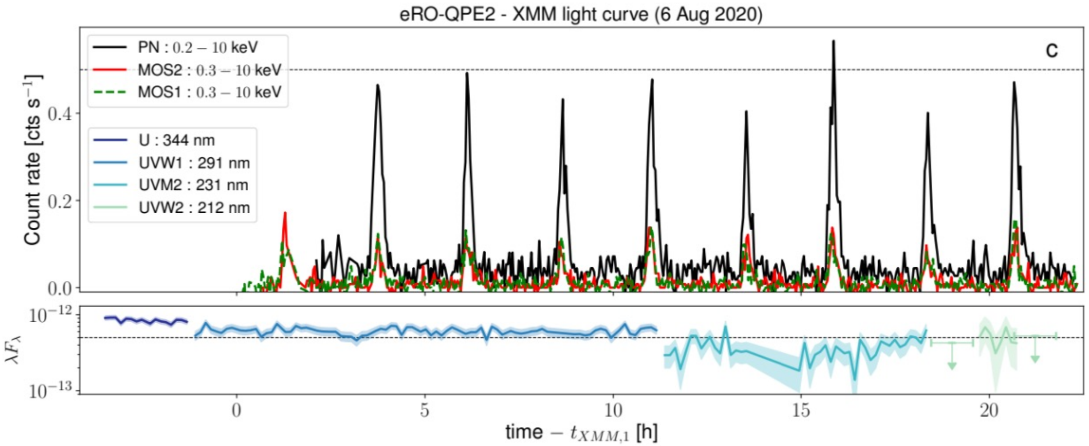
GSN 069



RXJ1301.9+2747



eRO-QPE1



eRO-QPE2

Period: 2.4-18.5h   Peak : $10^{42-43}erg/s$

Soft X-ray band   Duration time: one hour

4 Quasi-periodic eruption (QPE) and EMRI

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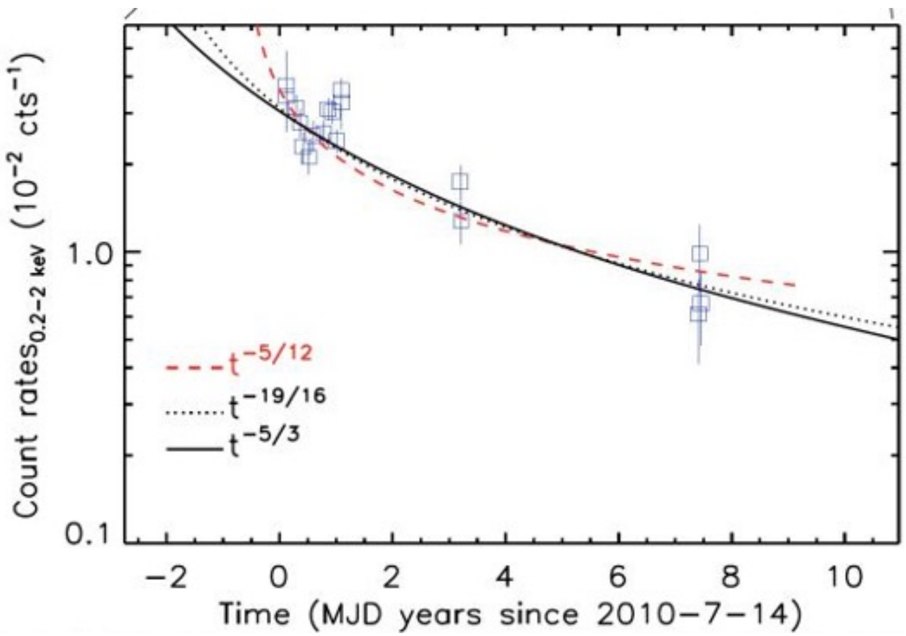
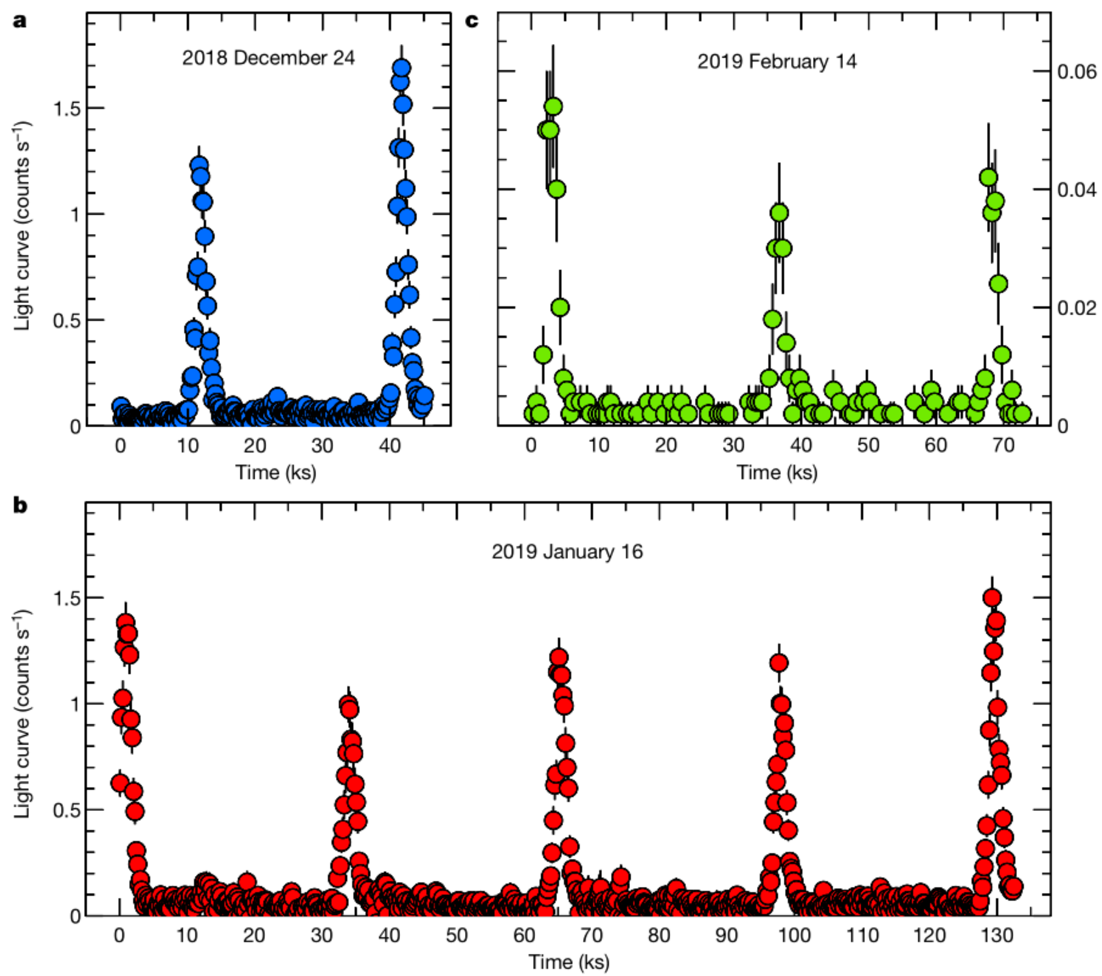
GSN 069
A possible TDE + QPE source



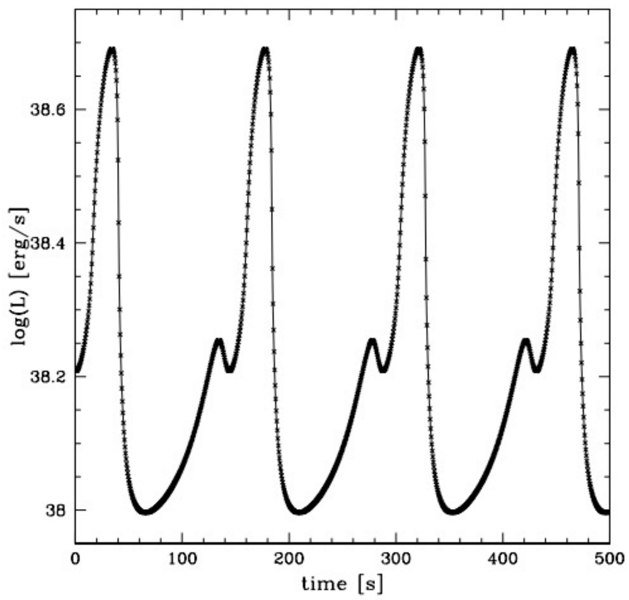
TDE-like flare (2010)



QPEs Miniutti et al. 2019 Nature

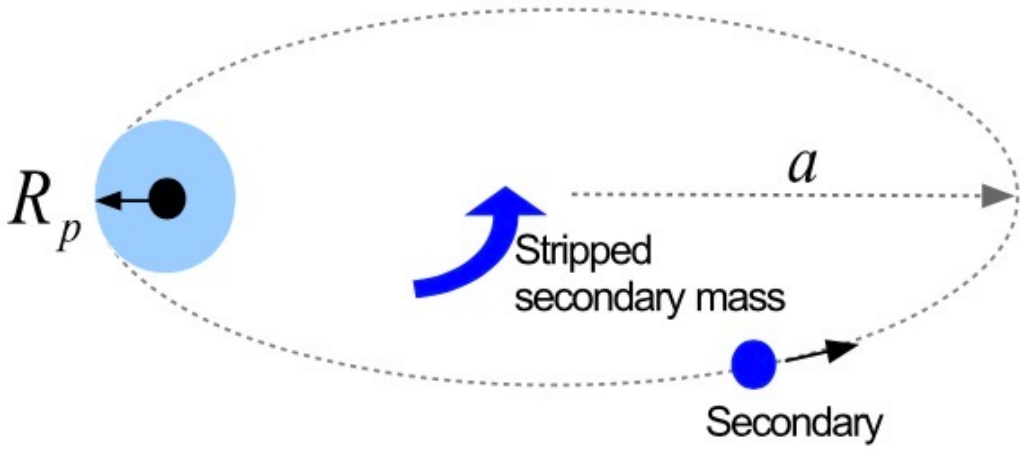
Possible mechanisms

- Radiation-pressure accretion instabilities



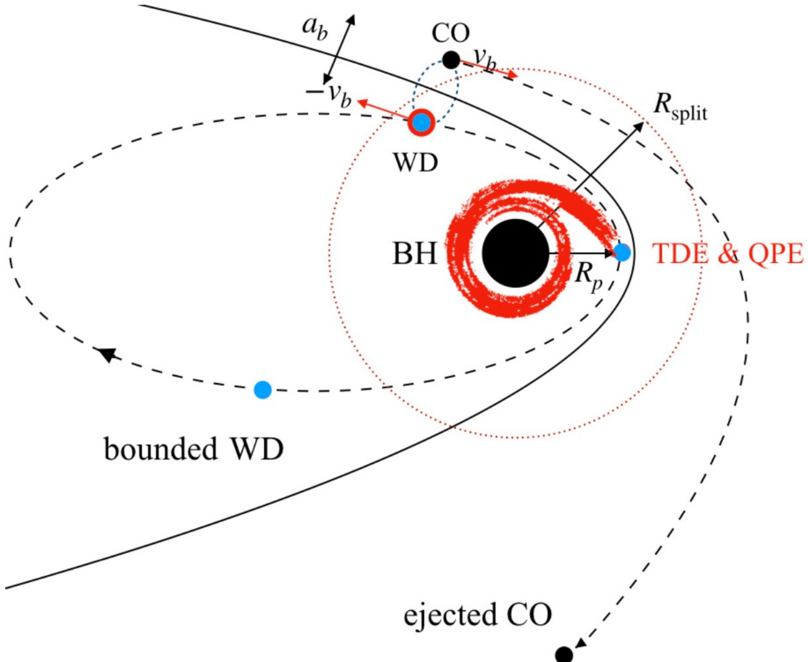
Only appear at high-Eddington sources, **but most QPE sources have weak BH activity.**

- **EMRI : WD-MBH**



4 Quasi-periodic eruption (QPE) and EMRI

- White dwarfs
  - Envelop
    - TDE-like flare
  - Remaining core
    - QPEs



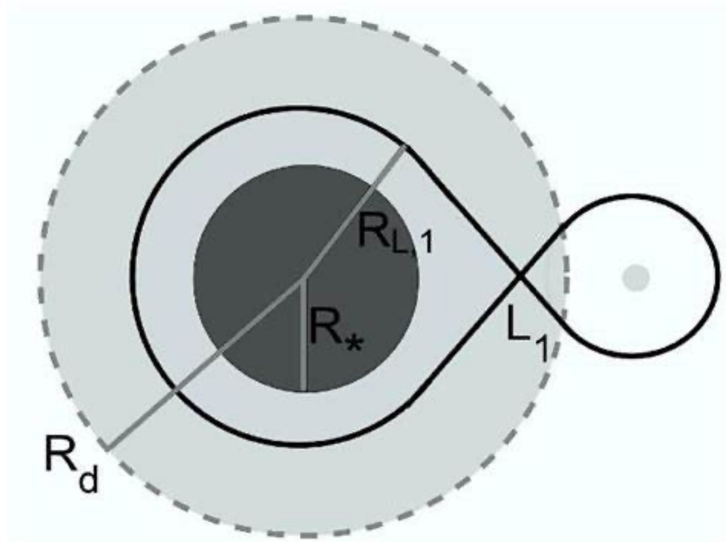
Wang et al. 2022 ApJ

Roche lobe overflow

$$R_{\rm wd} = 9.04 \times 10^8 \left(\frac{M_{\rm wd}}{M_{\rm ch}}\right)^{-1/3} \left(1 - \frac{M_{\rm wd}}{M_{\rm ch}}\right)^{0.447} \quad {\rm cm},$$

$$R_L = r_p \frac{0.49q^{2/3}}{0.6q^{2/3} + \ln(1 + q^{1/3})}$$

$$r_{p0} = 2R_{\rm wd}\left(\frac{M_{\rm BH}}{M_{\rm wd}}\right)^{1/3} = 2R_t$$



4 Quasi-periodic eruption (QPE) and EMRI

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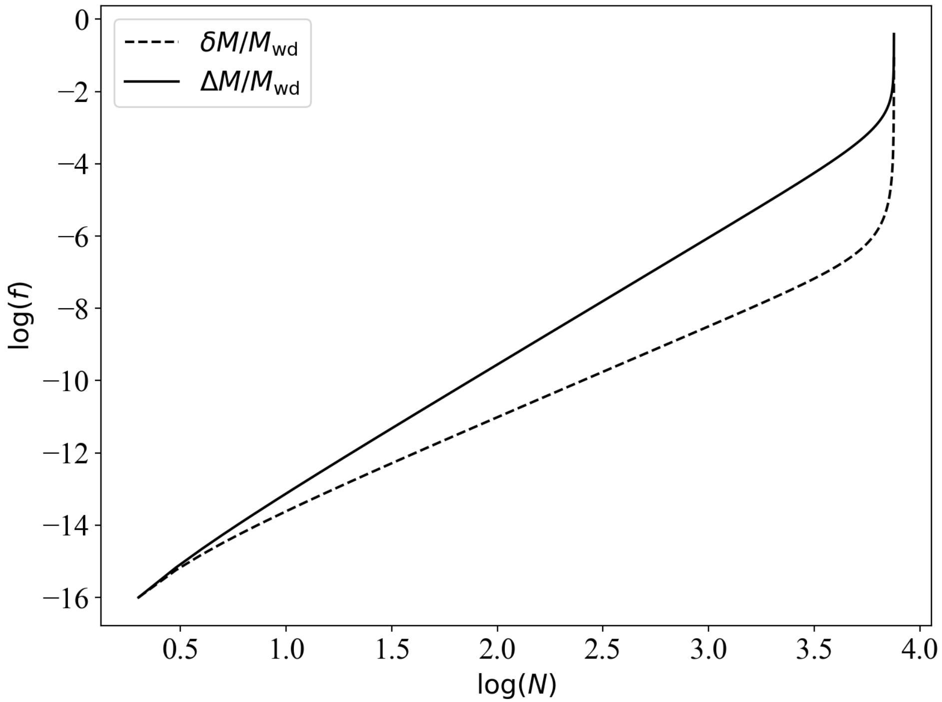
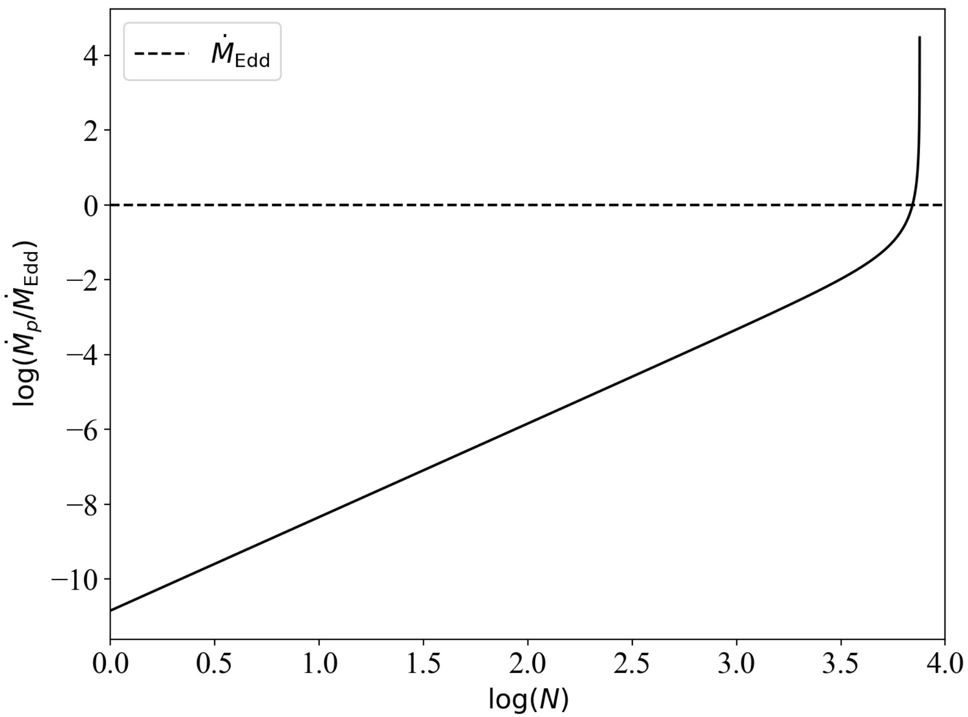
The fallback rate



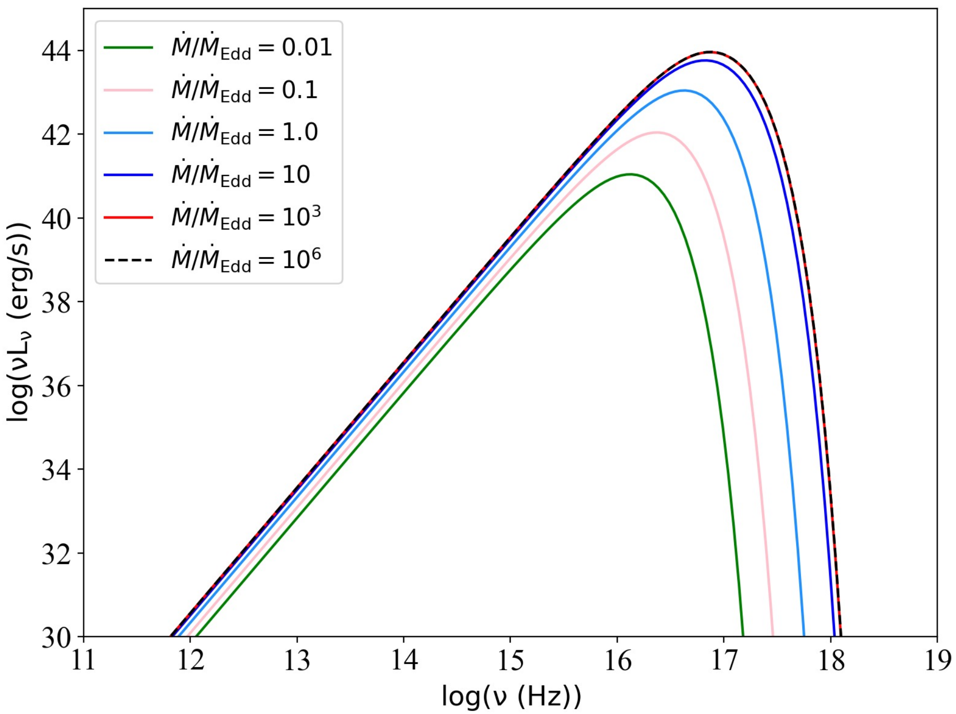
The fraction of mass transfer

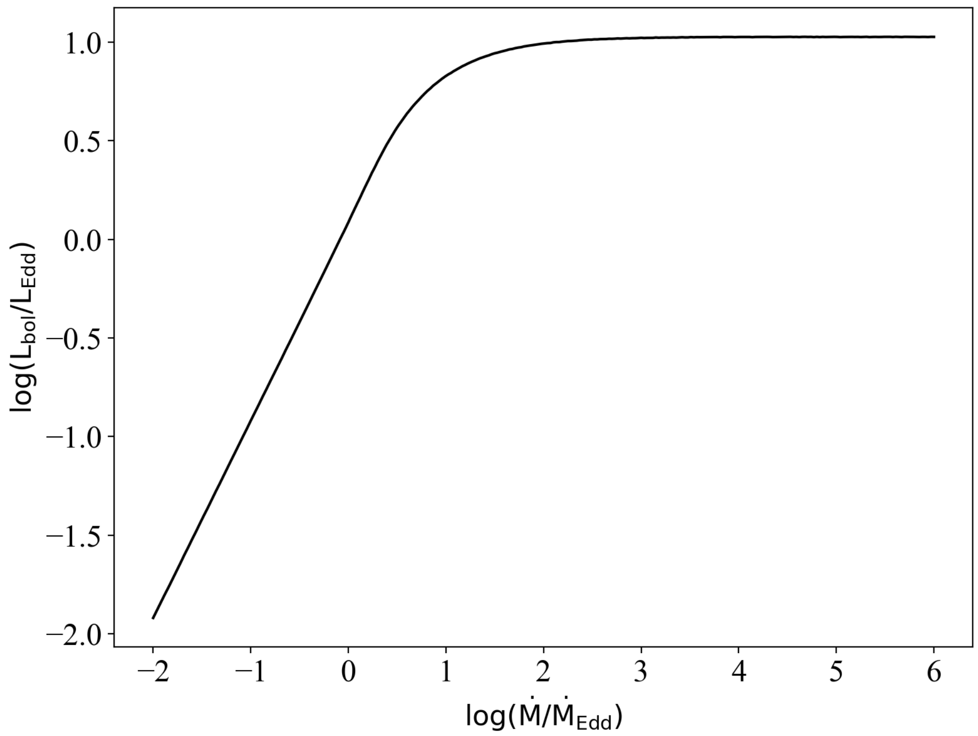


The Fallback Rate

Super Eddington rate in the last several tens orbits

Super-Eddington Accretion: the slim disk model





Distance candle?

The saturation luminosity can serve as a standard candle and provide an independent method to measure the distance of the WD-MBH system.

4 Quasi-periodic eruption (QPE) and EMRI

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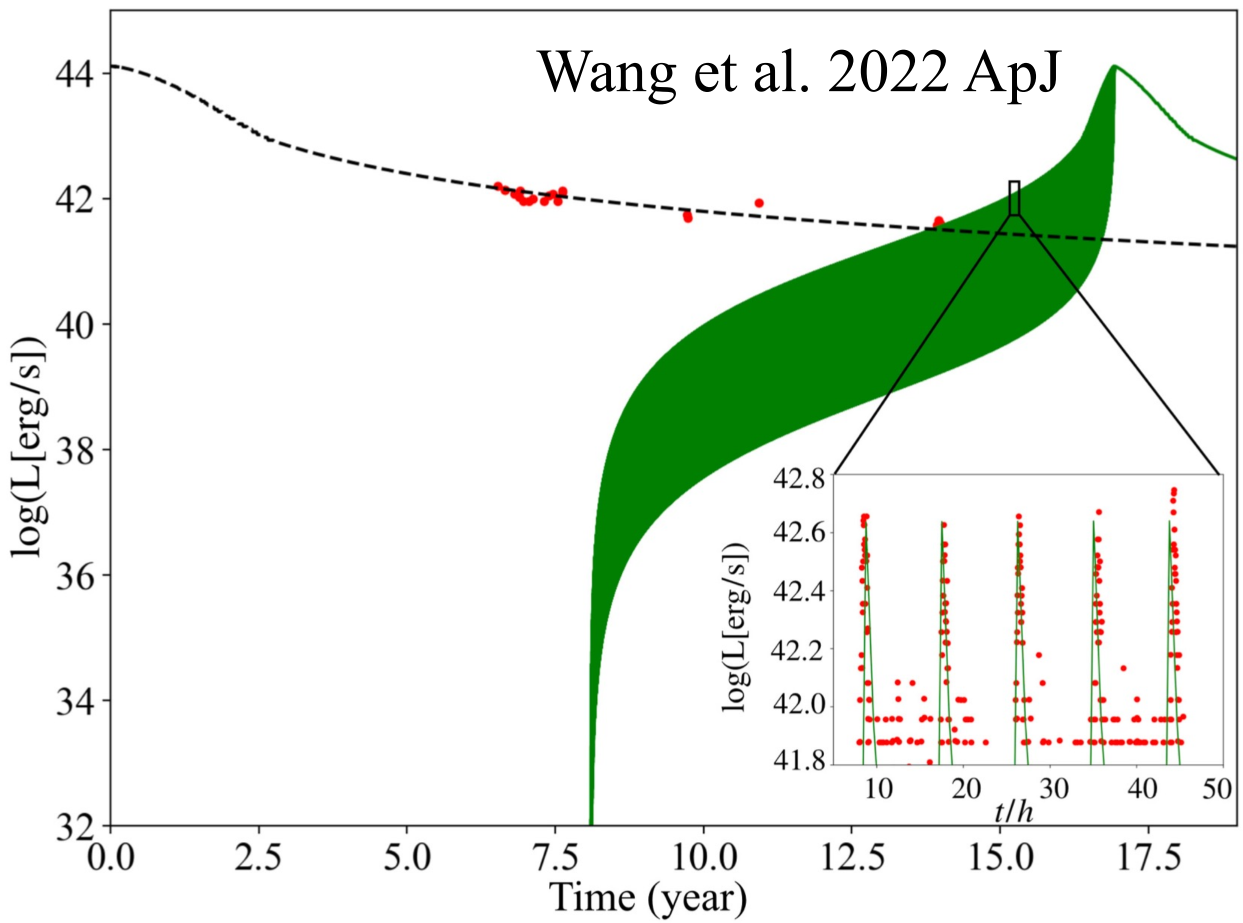
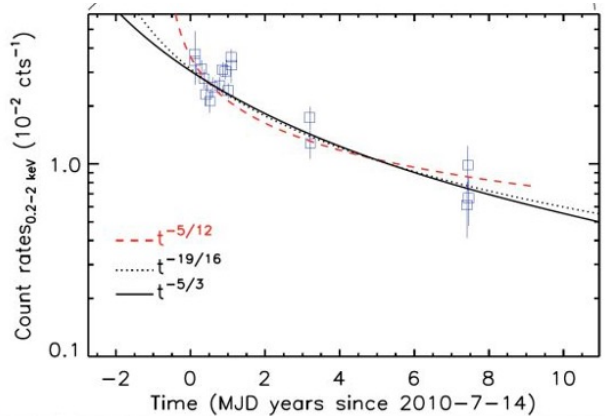
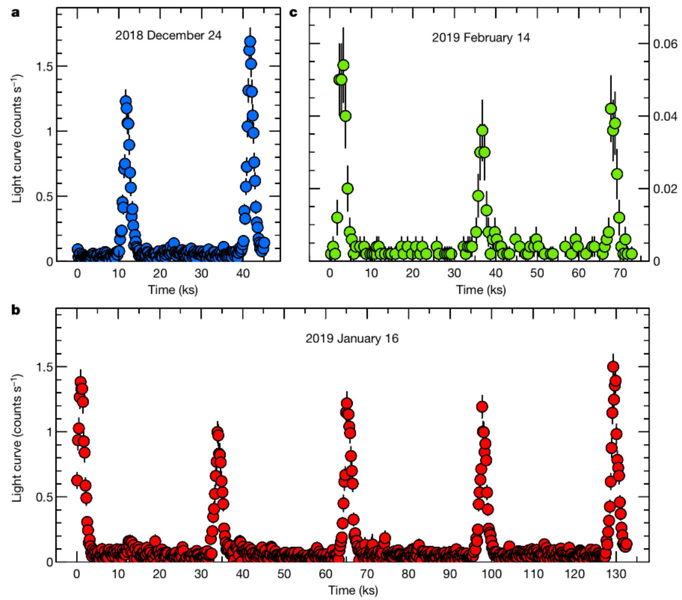
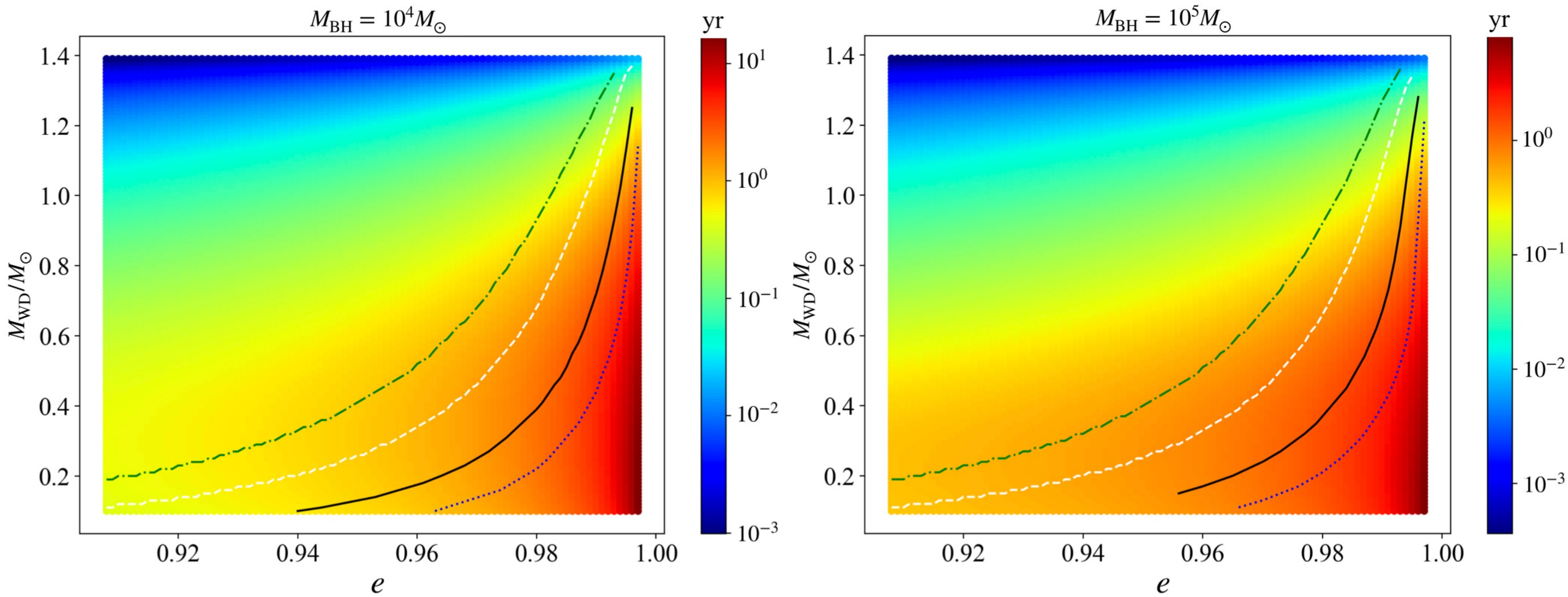






Our model can naturally explain the TDE and QPE phenomena as found in GSN 069.

Duration time from tidal stripping to disruption ($2R_t > r_p > R_t$)



1) Low mass WD and high eccentricity are needed for QPEs.
2) Most of QPE sources will be fully disrupted within a couple of years after the QPE stage.

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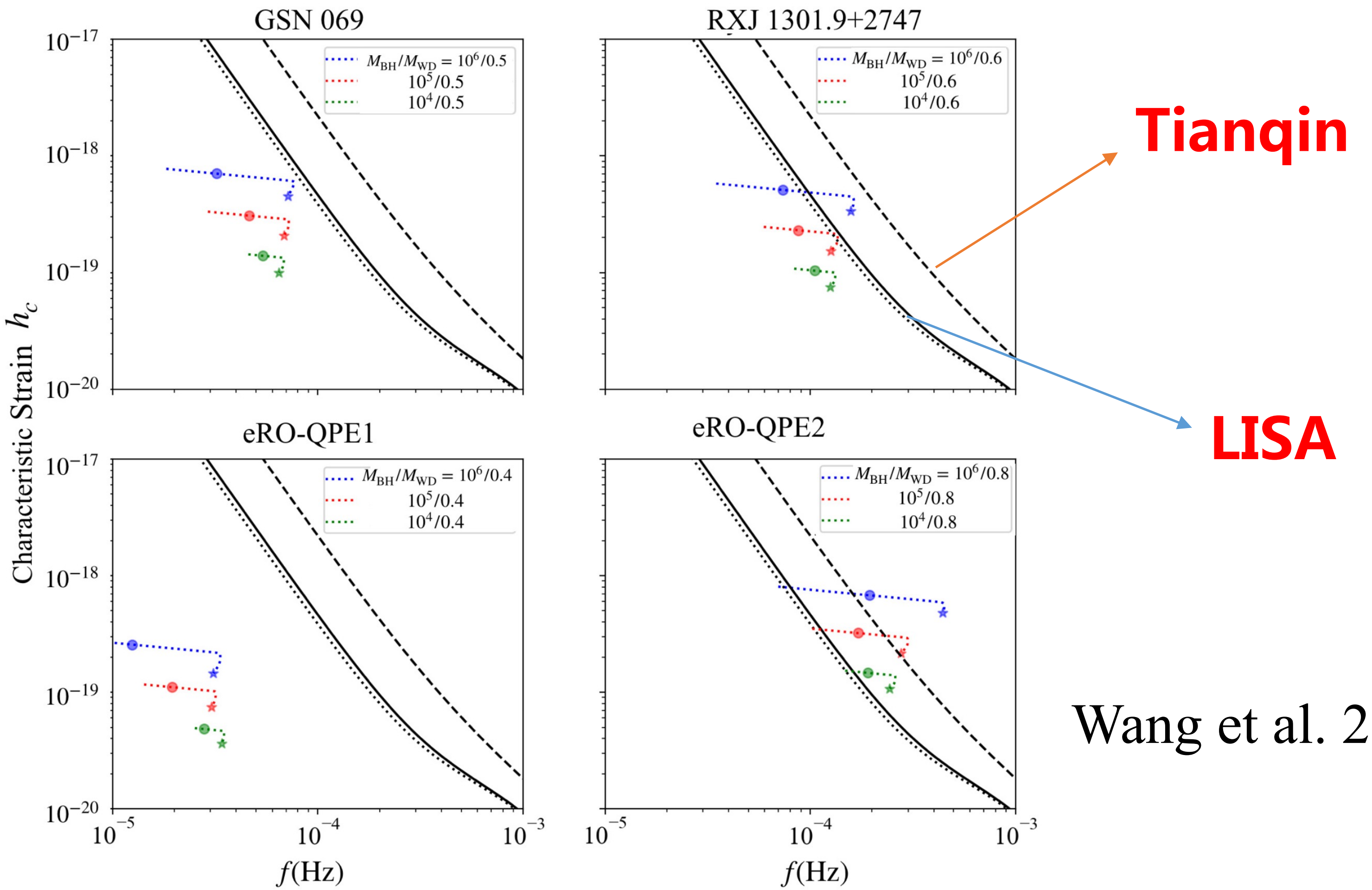
GW radiation (EMRI)

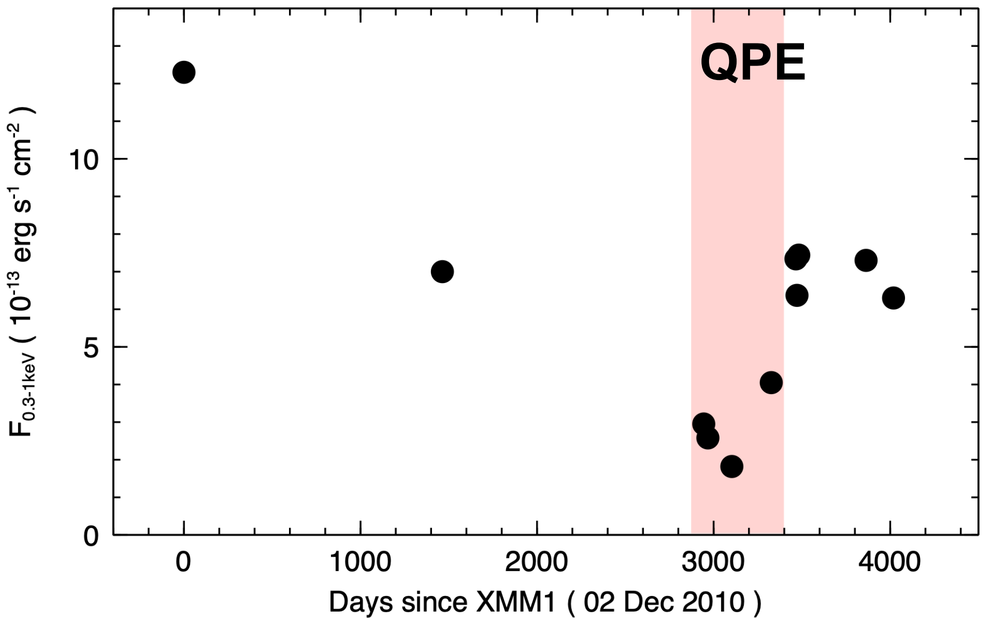


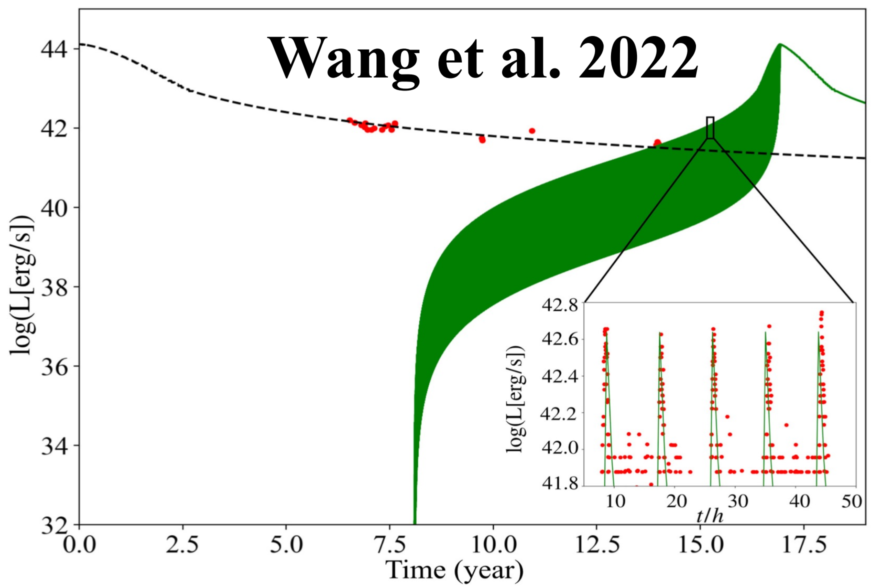
Wang et al. 2022 ApJ

Some QPE sources are above the detection sensitivity limit of future space-based gravitational wave projects.

Disappearance of quasi periodic-eruptions (QPEs) in GSN 069!!

Miniutti et al. 2022





In summary, the model proposed by Wang et al. (2022) for QPEs in GSN 069 appears highly succesfull in several aspects: it can explain the initial TDE-like flare (back in 2010) and the QPE late-time appearance (few years after the initial TDE-like event), the overall life-time of the QPE phenomenon in GSN 069, and it predicts the final disruption of the WD core at the end of the QPE phase, consistent with the X-ray re-brightening we observe simultaneously with the QPE disappearance.

Summary

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- The galaxy and central black hole suffer strong evolution after their formation.
- The evolution of galaxies and central massive black holes play a key role in understanding the possible formation of black hole binaries.
- The binary massive BH should exist based on the galaxy evolution, but strong observational evidences are still lack.
- Tidal disruption event (TDE), quasi-periodic event (QPE) and EMRI events are good candidates to explore the nuclear environments near the central SMBH.

Thanks for your attention!