nHz gravitational waves with PTAs:
their sources and electromagnetic counterparts

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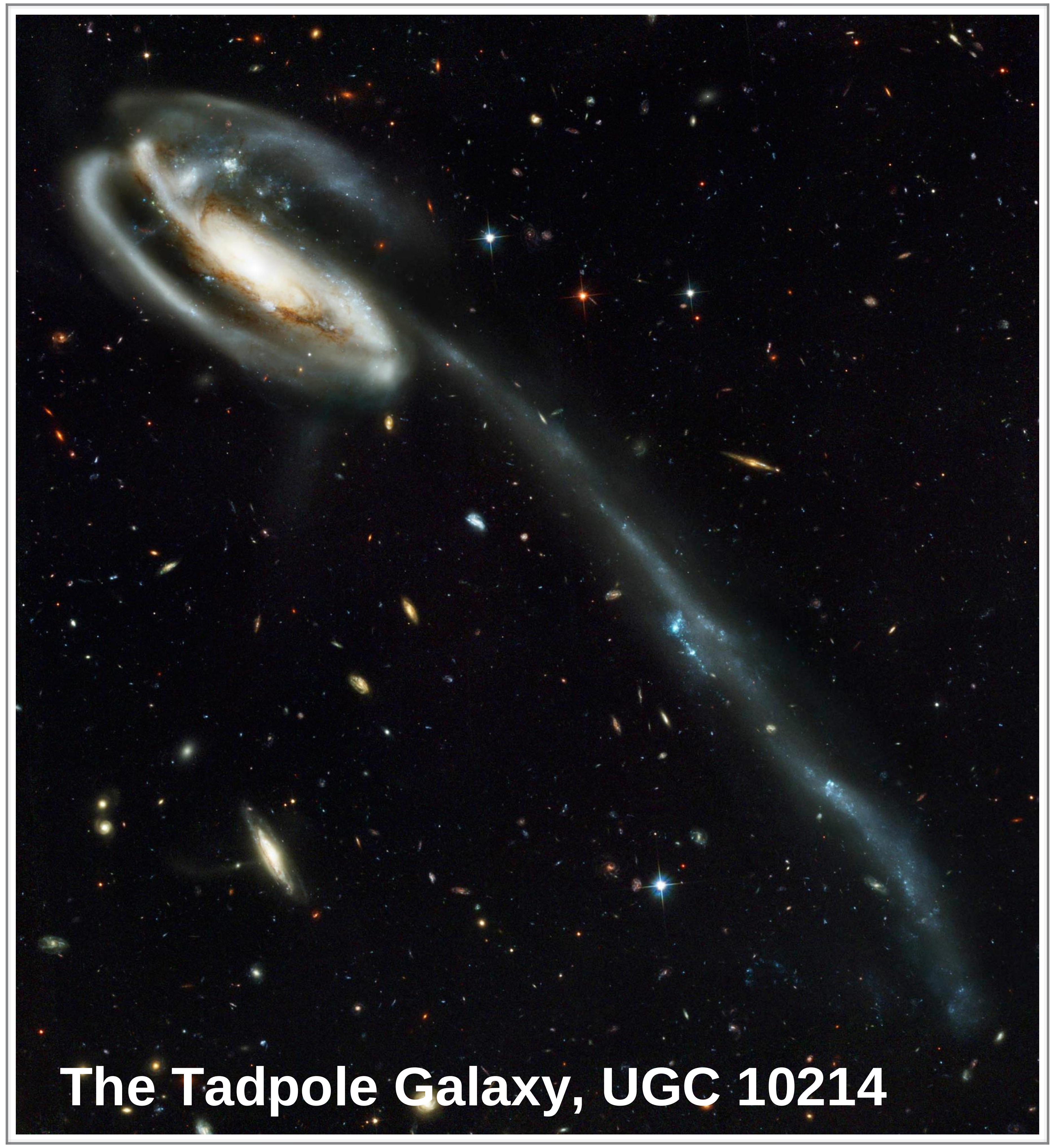
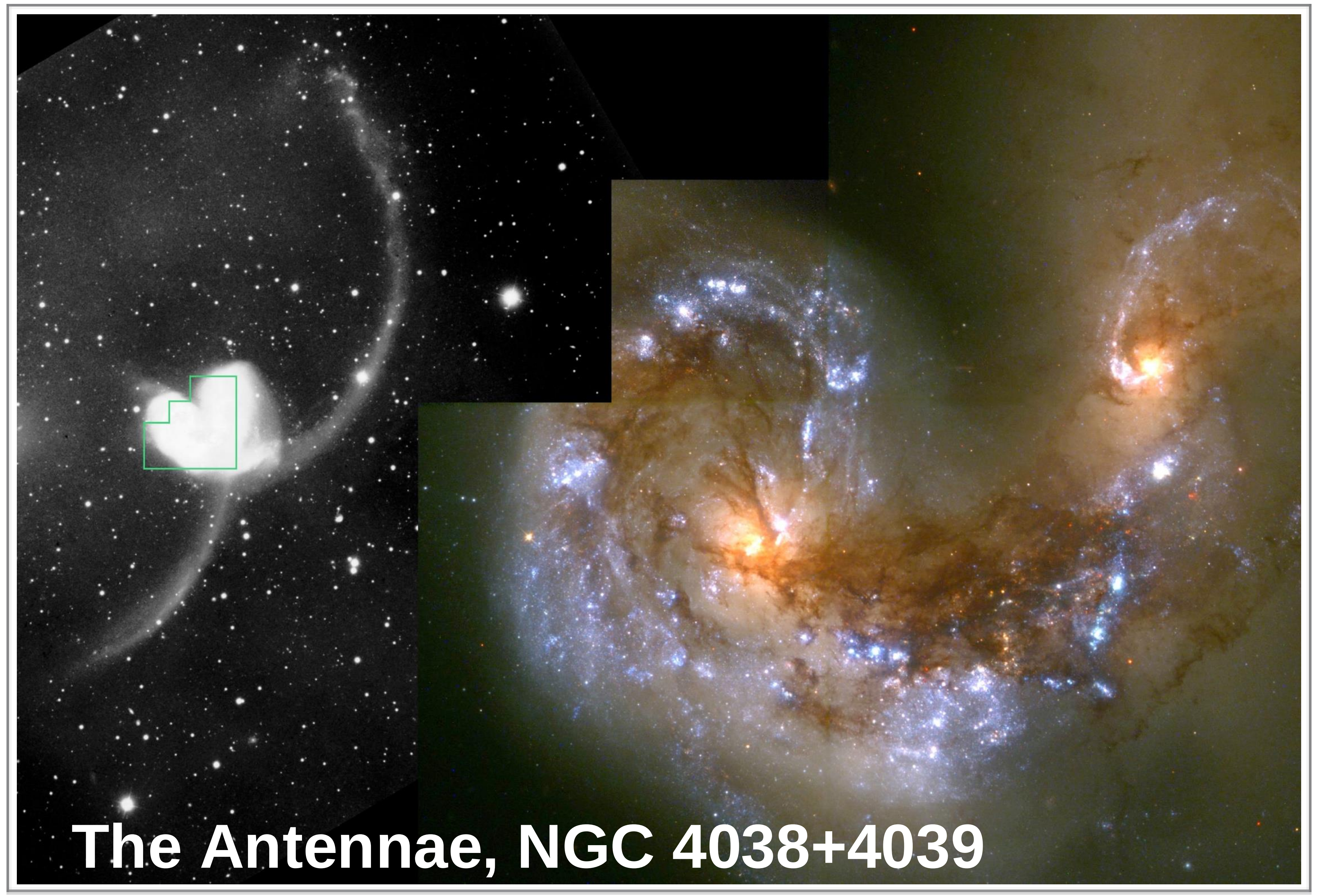
SMBHBs: an inevitable product of galaxy mergers?


The Mice, NGC 4676


The Tadpole Galaxy, UGC 10214


The Antennae, NGC 4038+4039

SMBHBs: orbital evolution

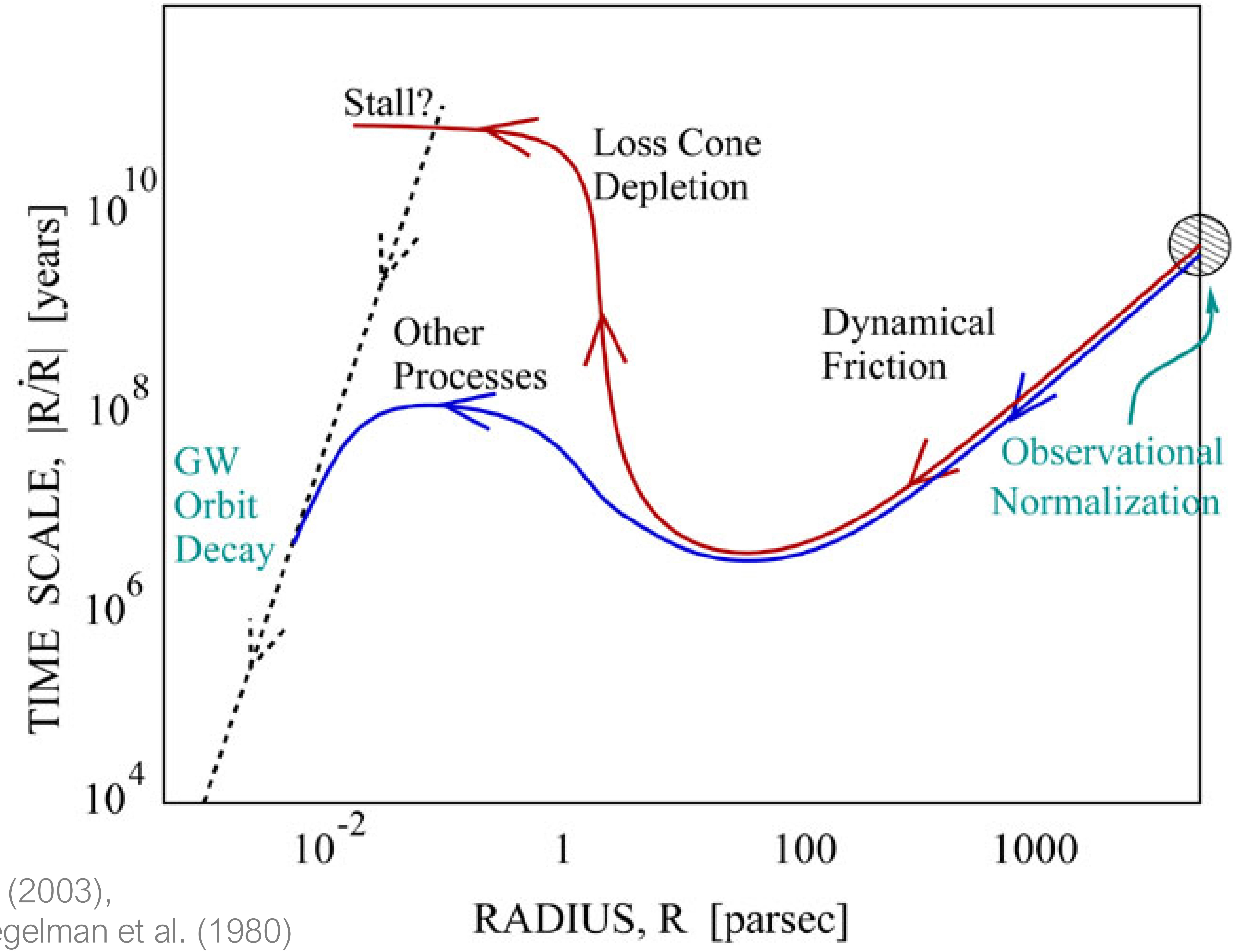


figure from Backer et al. (2003),
based on the work of Begelman et al. (1980)

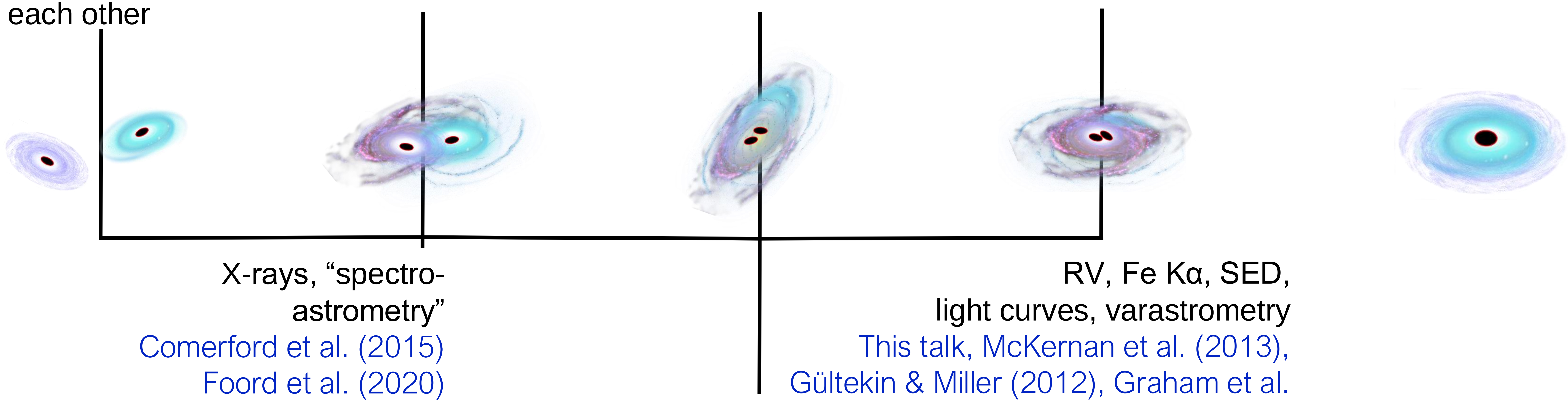
SMBHBs: lifecycle and methods for finding them

Galaxies approach each other

Dual AGN
0.1-10 kpc

Bound BH
<10 pc

Close binary
<1 pc



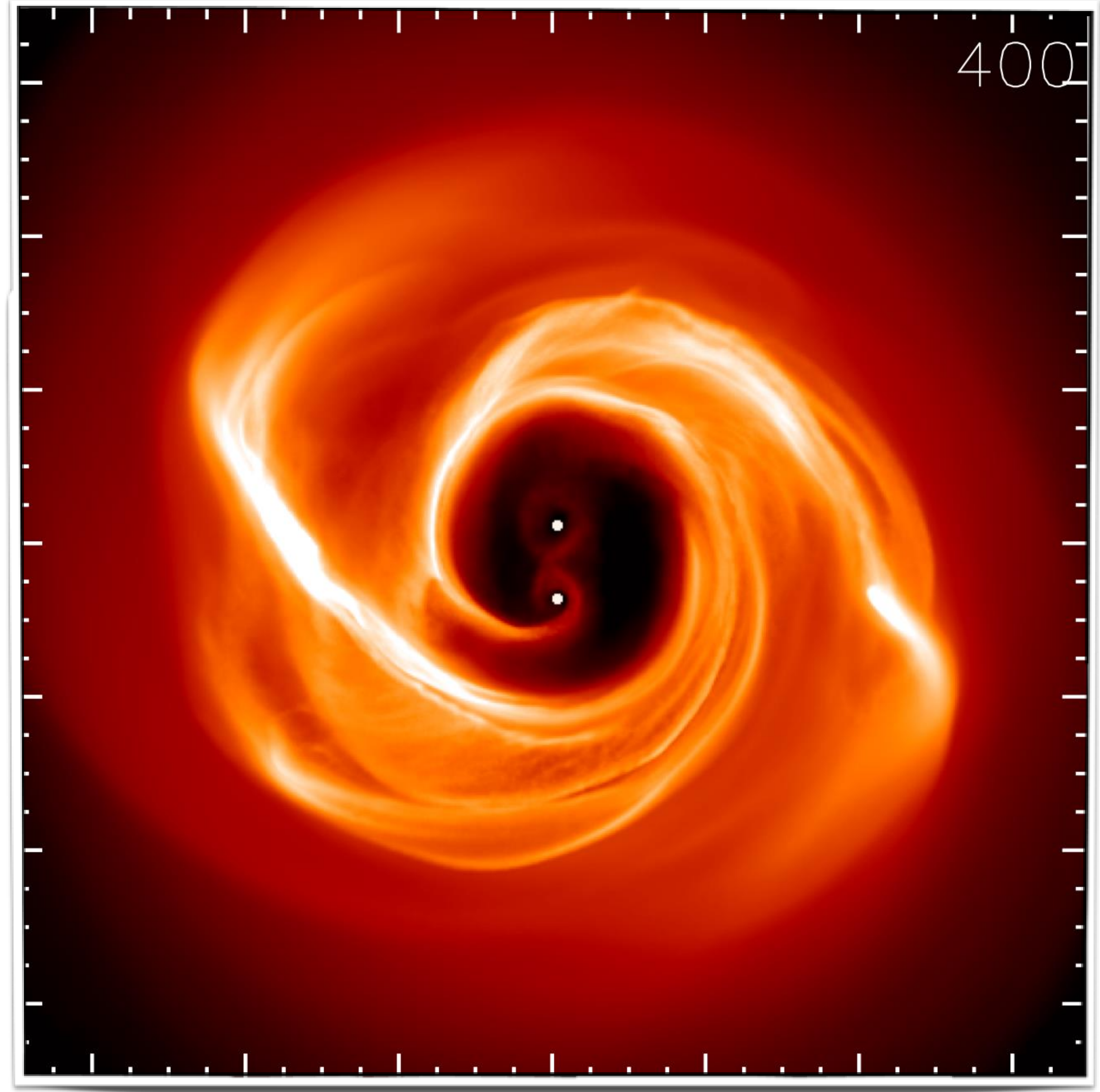
X-rays, “spectro-astrometry”
Comerford et al. (2015)
Foord et al. (2020)

radio interferometry
Rodriguez et al. (2006), Burke-Spolaor et al. (2011), Bansal et al. (2017), Breiding et al. (2021)

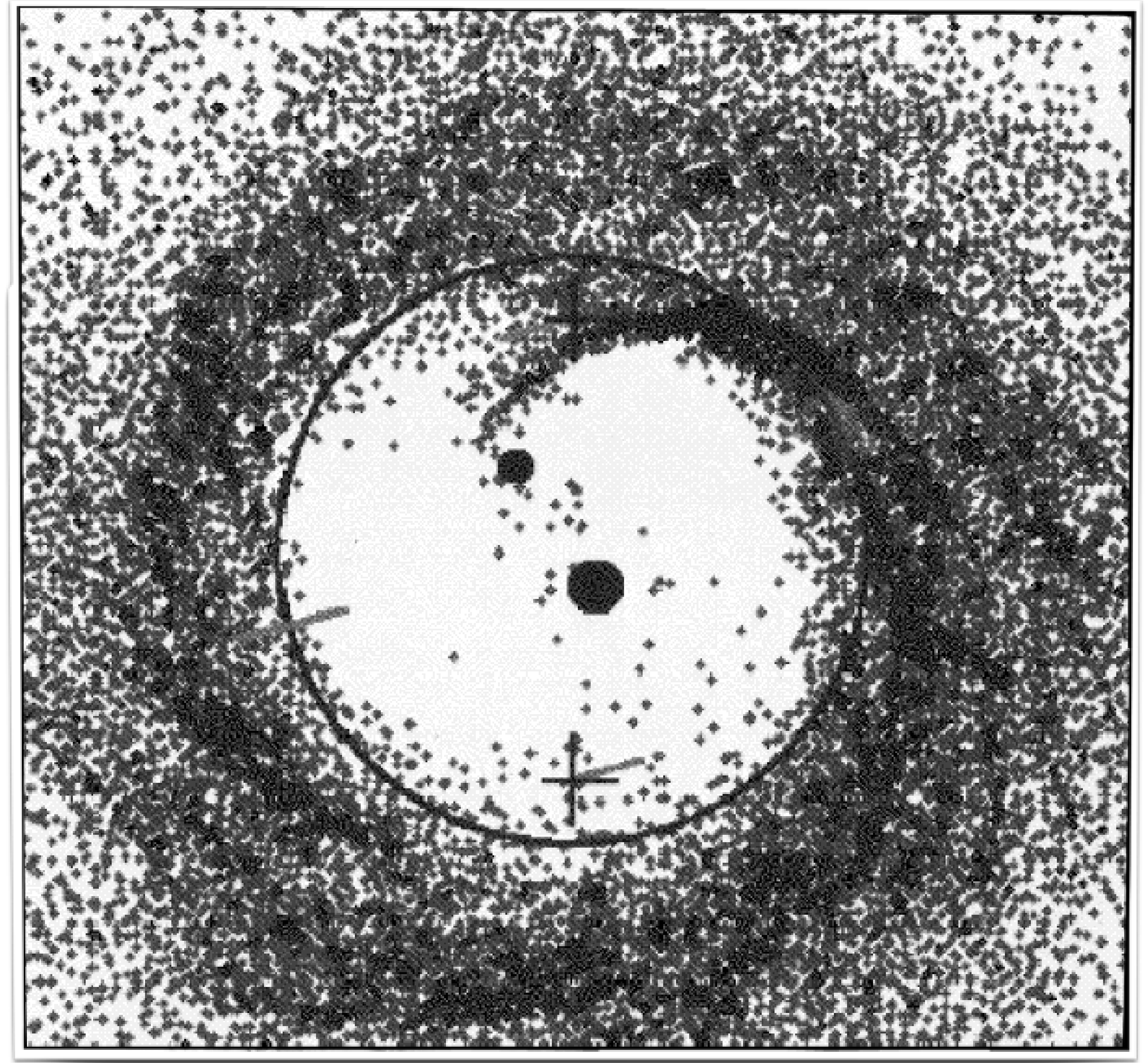
ngVLA is a binary discovery workhorse (Wilner et al. 2024; Burke-Spolaor et al. 2018)

RV, Fe Kα, SED,
light curves, varastrometry
This talk, McKernan et al. (2013), Gültekin & Miller (2012), Graham et al. (2015), Charisi et al. (2016), Liu et al. (2014), Hwang et al. (2020)

RV method: the physical picture

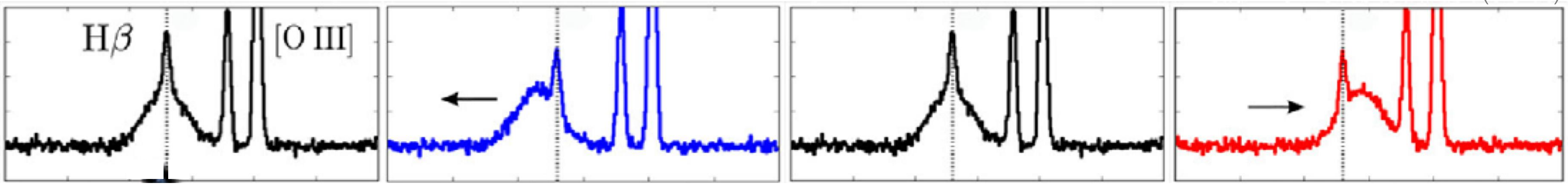


Cuadra et al. (2009),
See also Hayasaki et al. (2007).

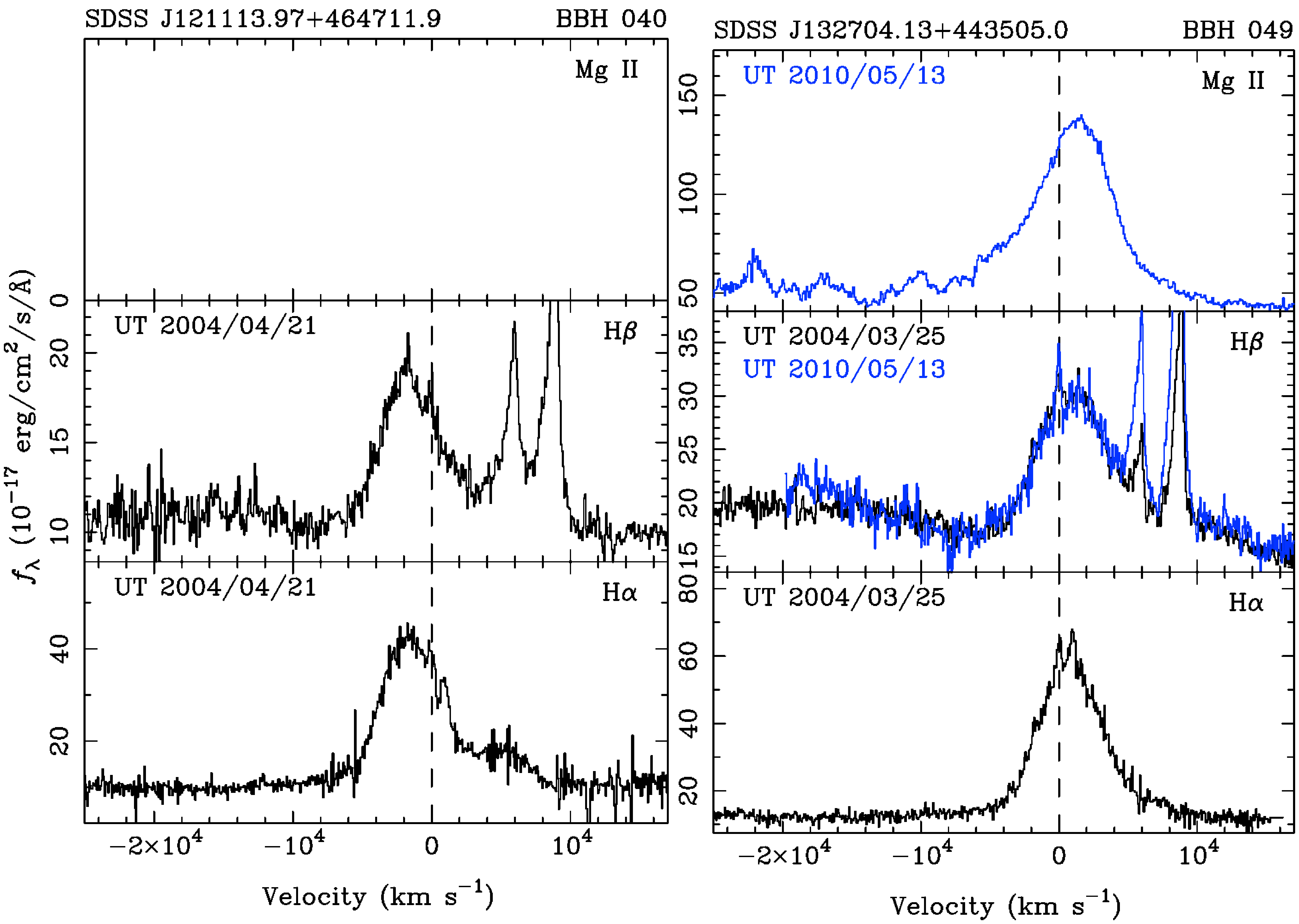


Artymowicz & Lubow (1996)

Guo et al. (2019)



The search: one black hole active



Binary candidates:

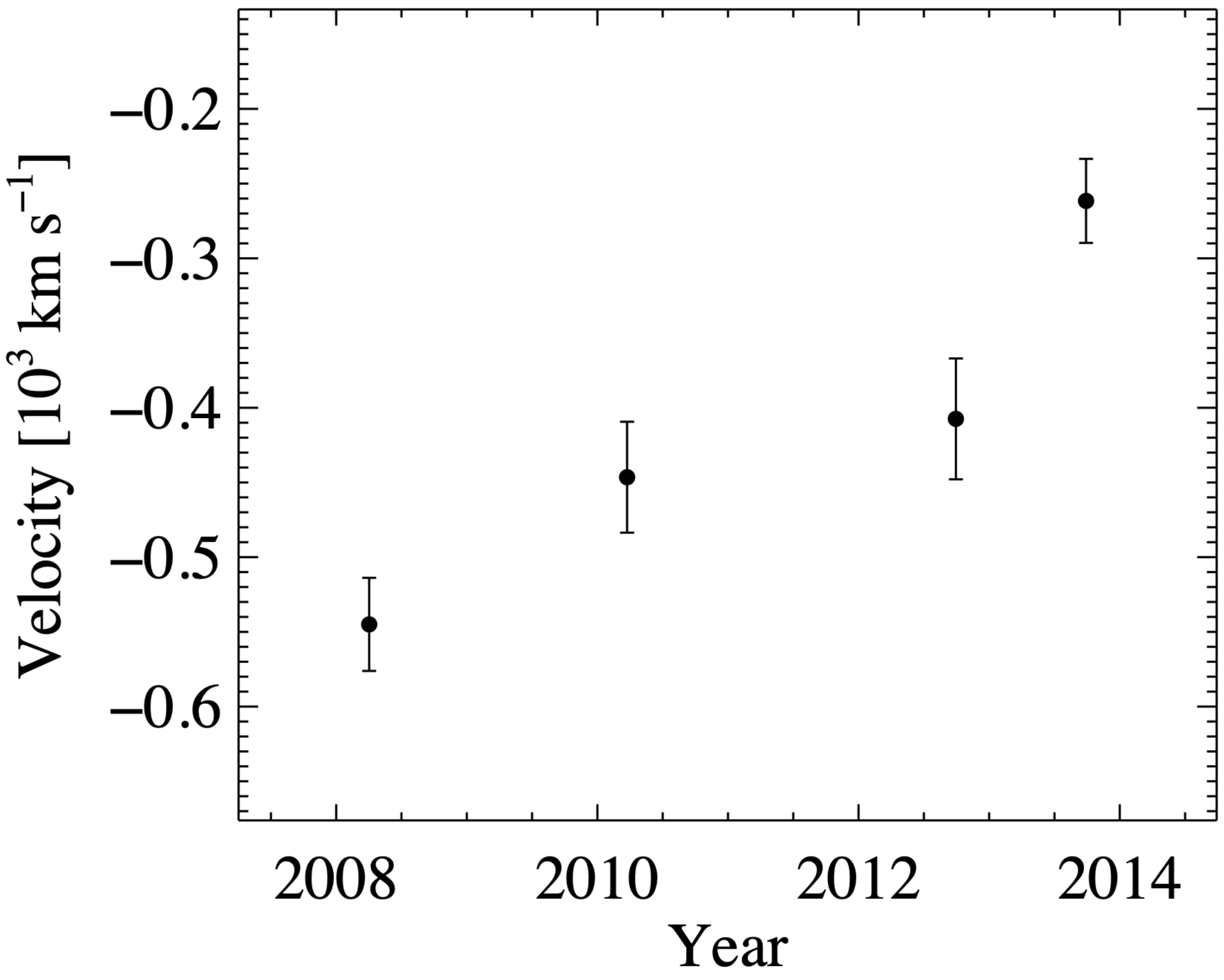
- Hypothesis: quasars with single-peaked velocity offset Hβ are the active secondary in a binary.
- Selection:
  88 Sloan quasars

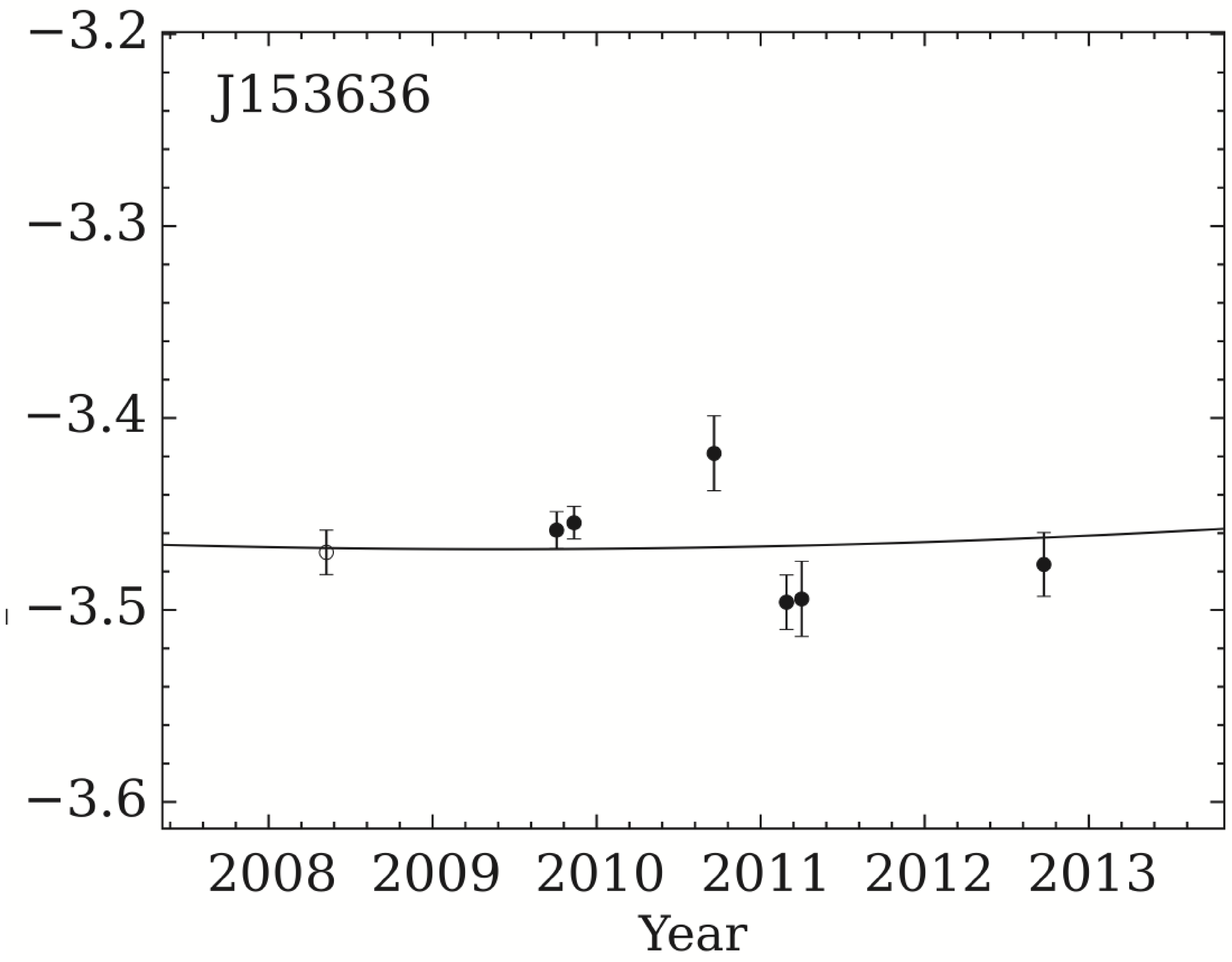
  $0.1 < z < 0.8$

  Single peaked velocity offset Hβ.

Eracleous et al. (2012)

The search: Radial velocity curves for ~100 candidates





Runnoe et al. (2017)

Other searches: Tsalmantza et al. (2011), Decarli et al. (2013), Ju et al. (2013), Shen et al. (2013), Liu et al. (2014), Guo et al. (2019)

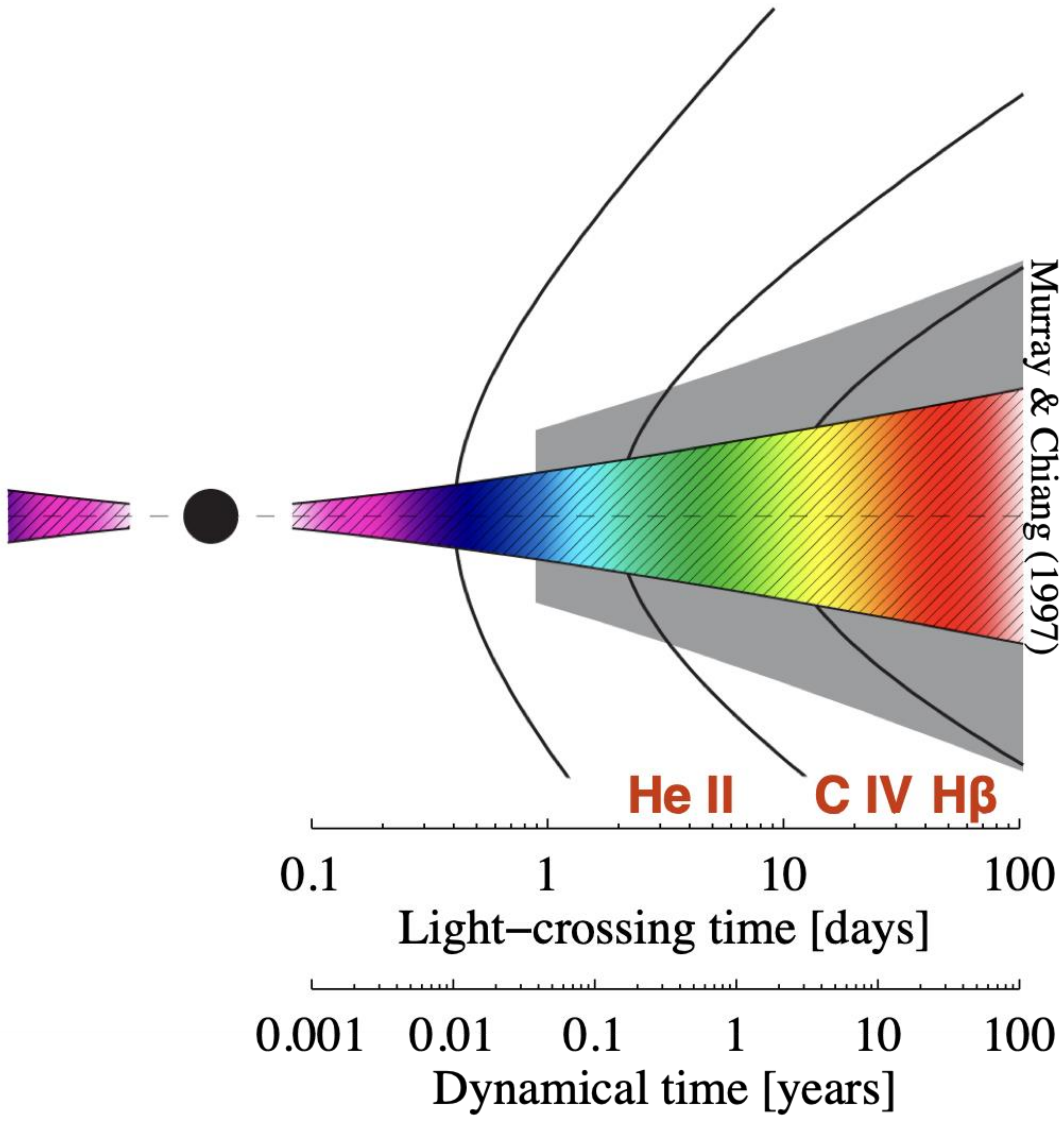
See also: Shen & Loeb (2010), Pflueger et al. (2018), Kelley et al. (2021)

- Can limit P, M_{tot}, a.
  (e.g., Runnoe et al. 2017)
- Main interloper: quasar variability.

The main interloper: Regular quasar variability

- Profile variability in a single quasars.
  (Bon et al. 2016; Li et al. 2016)
- Shape changes include: flux, centroid, width, asymmetry, boxiness, number of peaks.
- All of these complicate the effort to identify radial velocity trends due to orbital motion.
  (e.g., Shen et al. 2013; Runnoe et al. 2017)

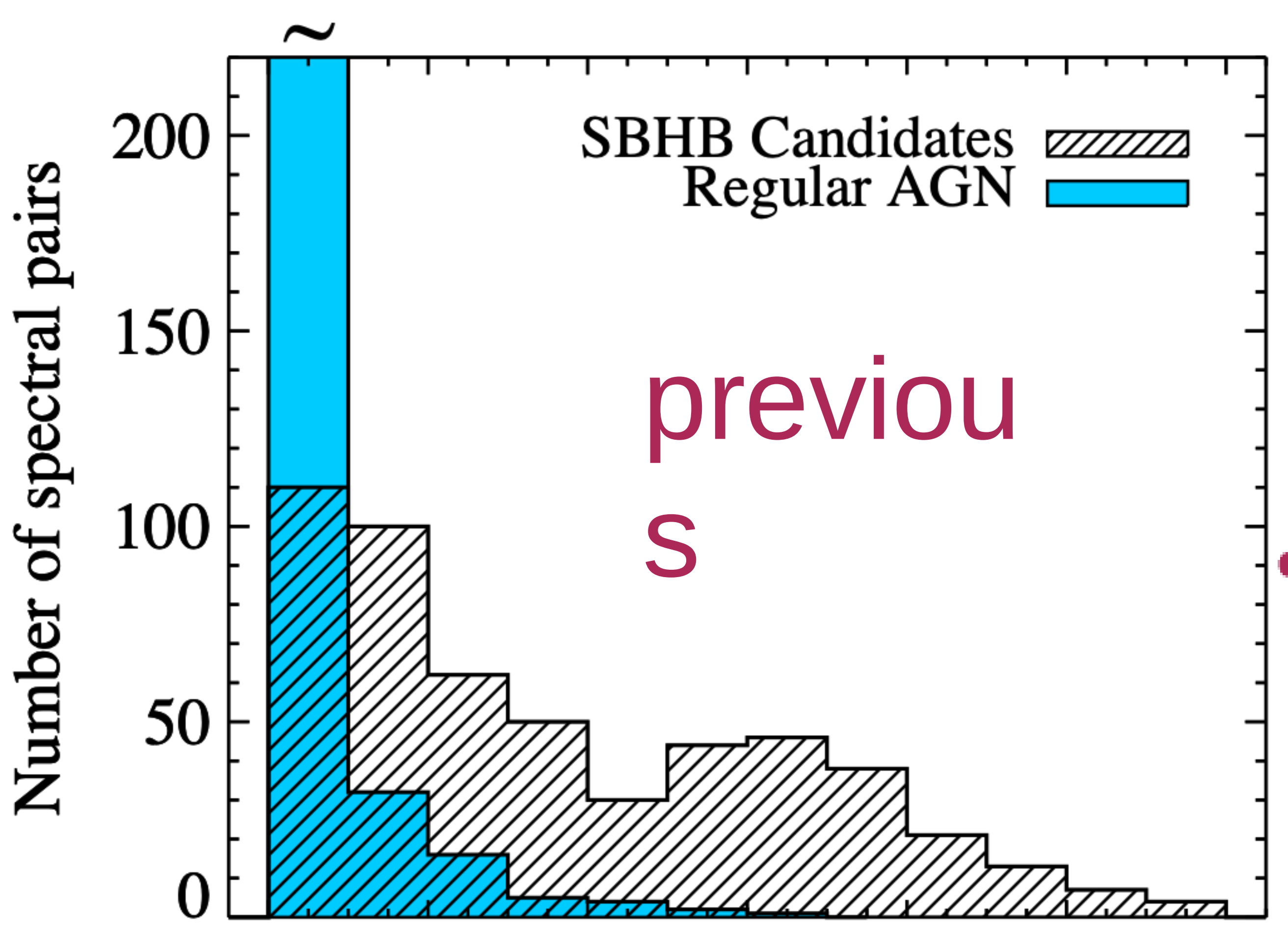
The main interloper: What about timescales?

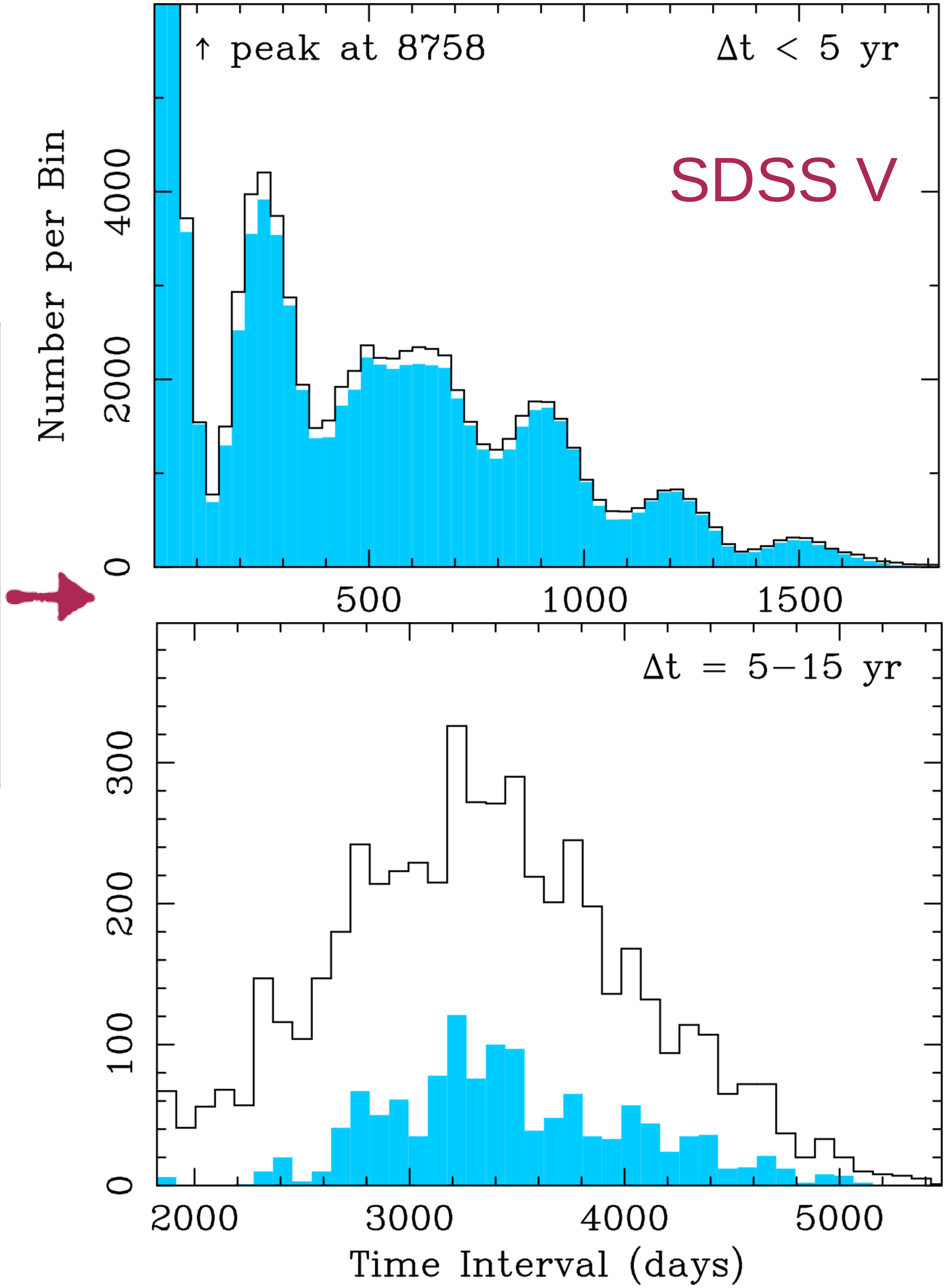


What causes profile variability?

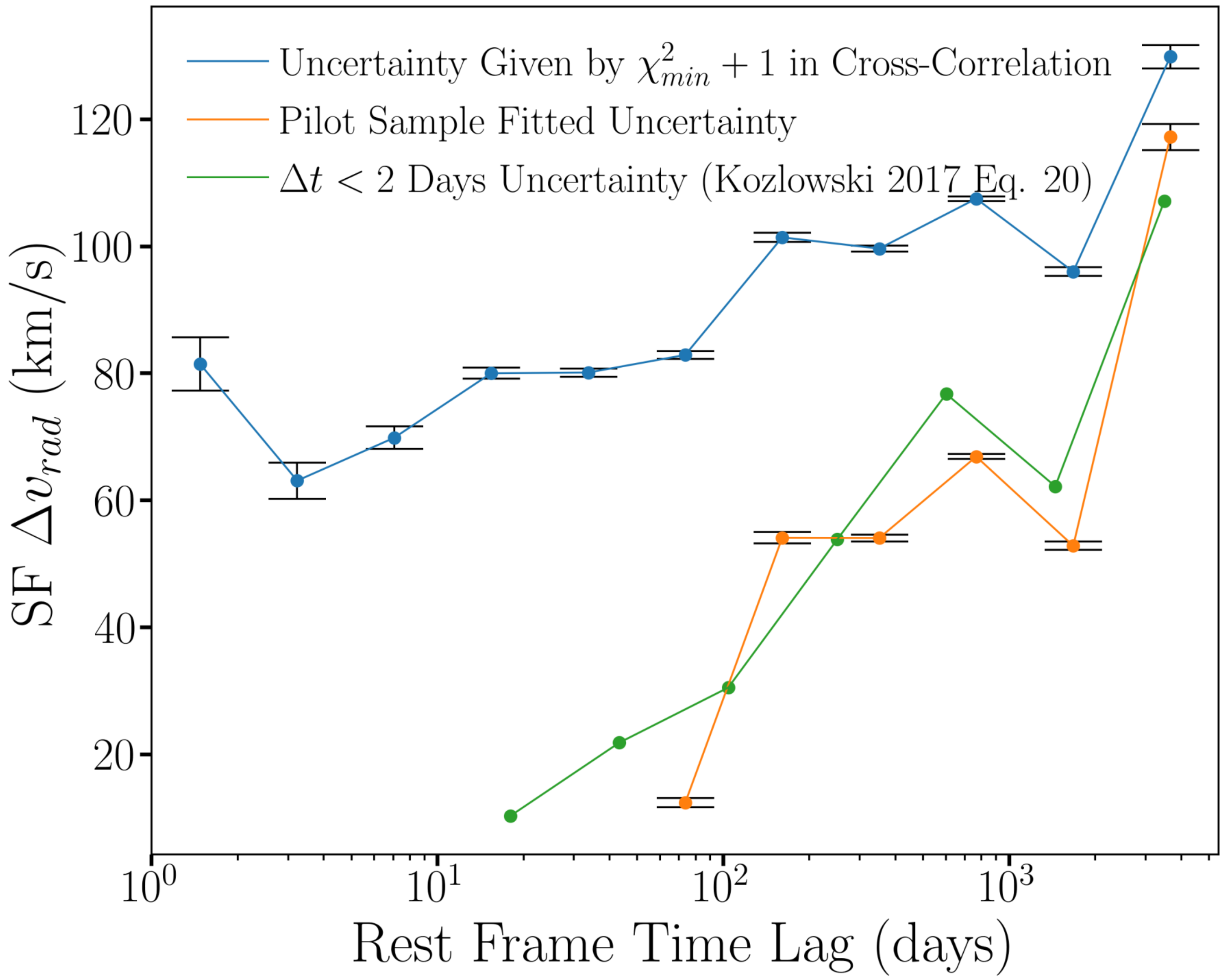
- Reverberation on short timescales.
  e.g., Barth et al. (2017)
- May be due to other physical mechanisms on long timescales.
  Sergeev et al. (2007); Guo et al. (2019); Doan et al. (2020); Fries et al. (2023)

Future: large time-domain spectroscopic surveys





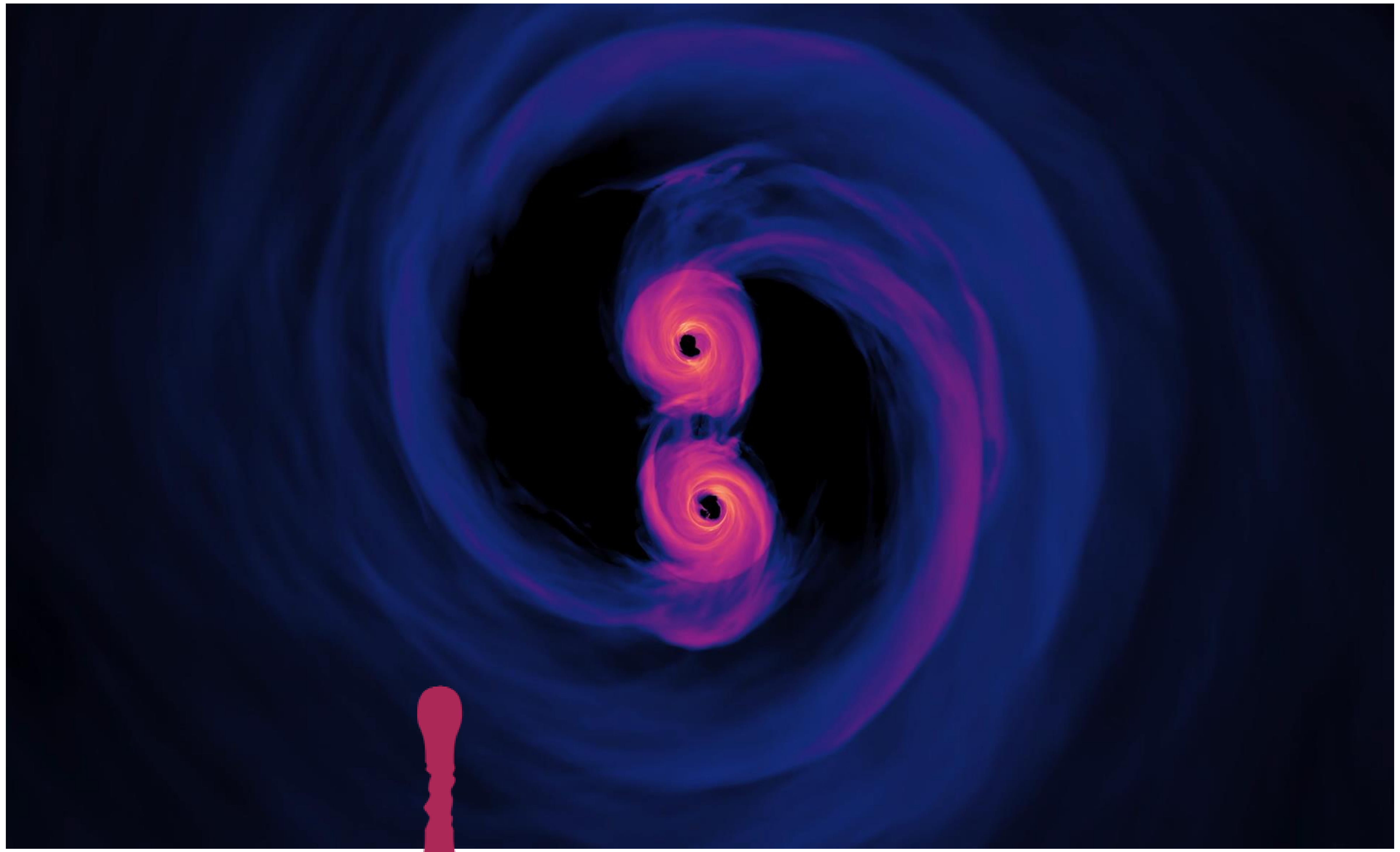
Dabbieri et al. (in prep.)



Slide credit: M. Charisi

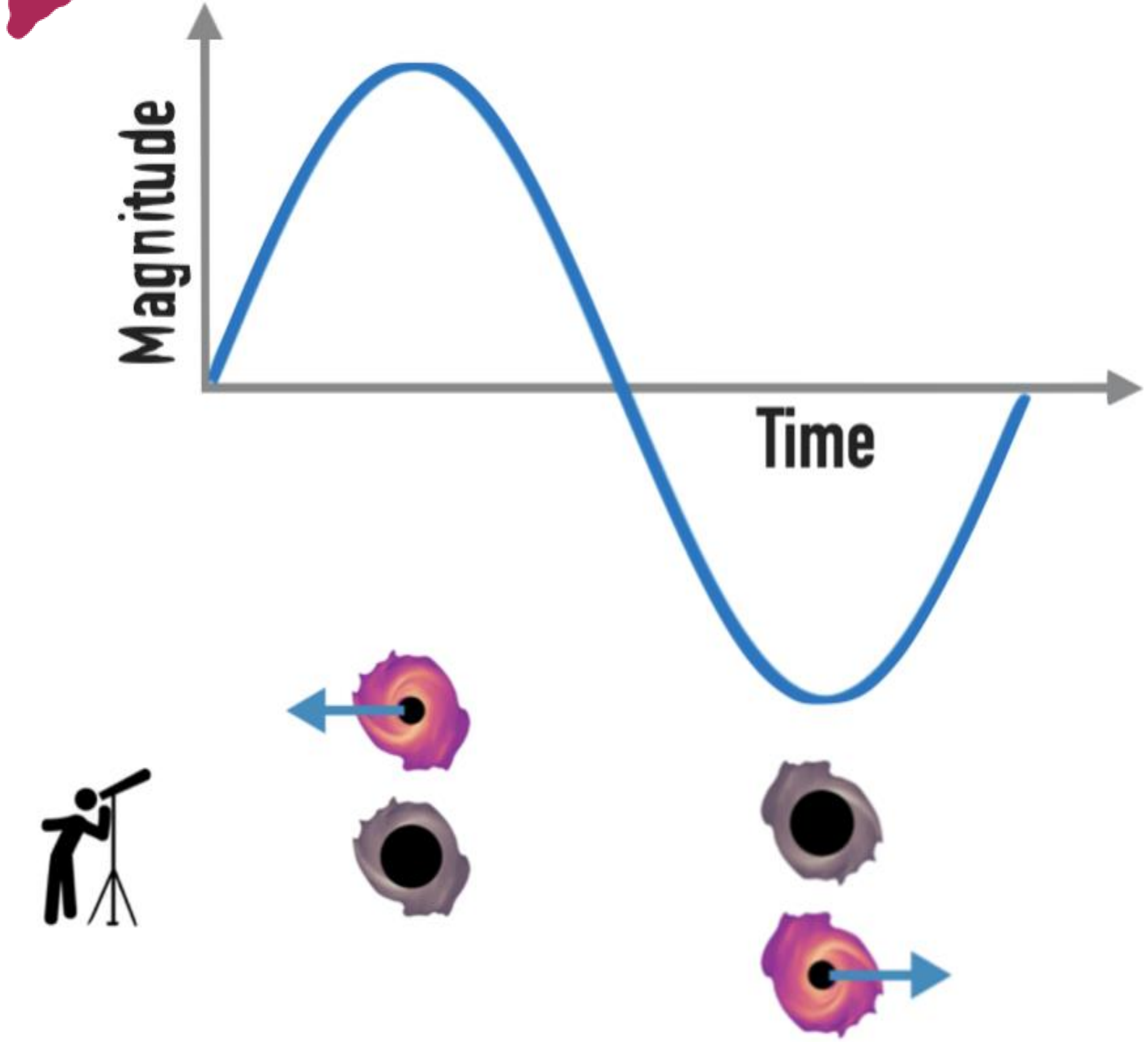
Periodic brightness changes: via multiple mechanisms

NASA GSFC/S. Noble

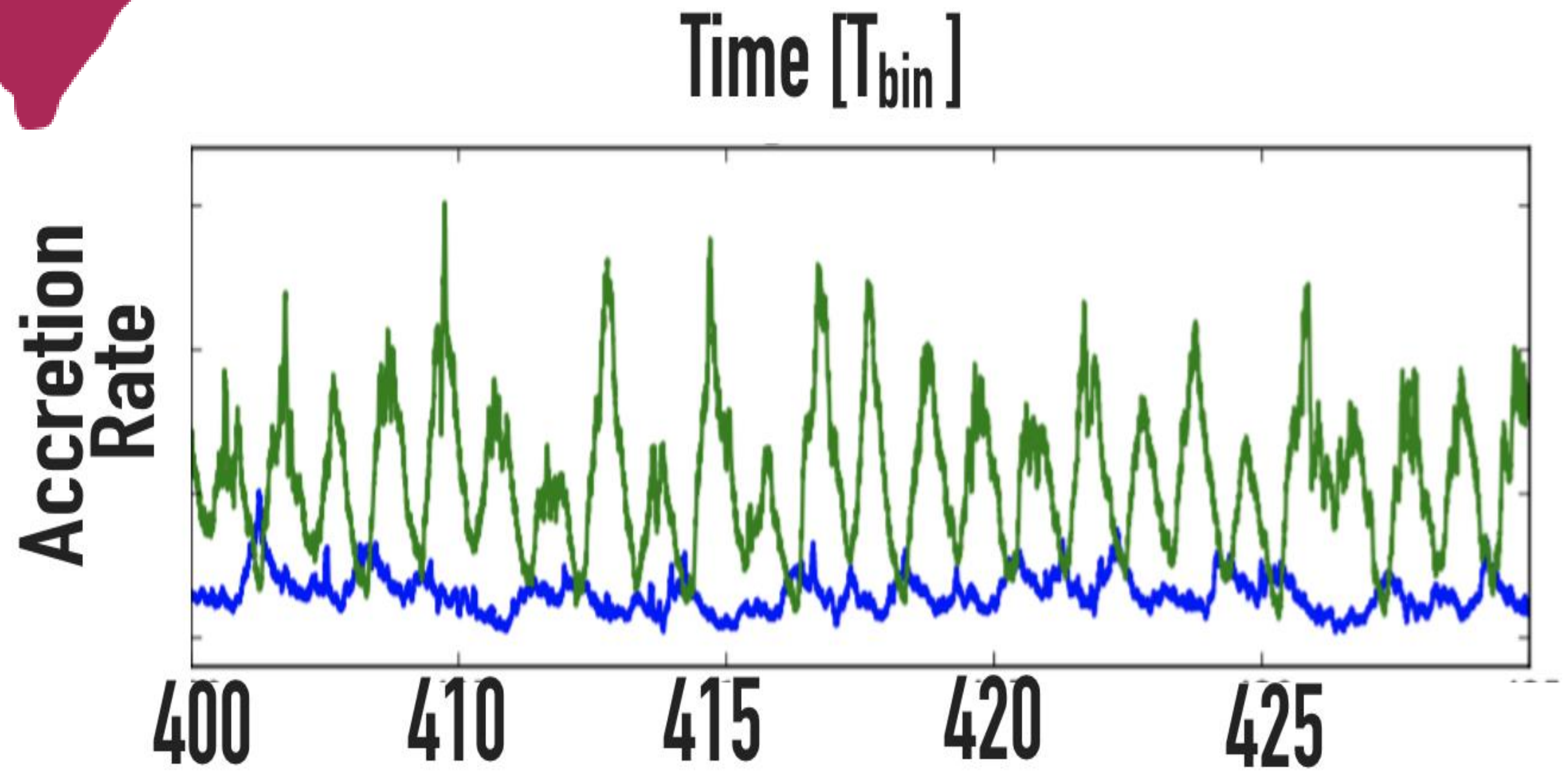


- Bright quasar-like emission.
- Periodic variability.

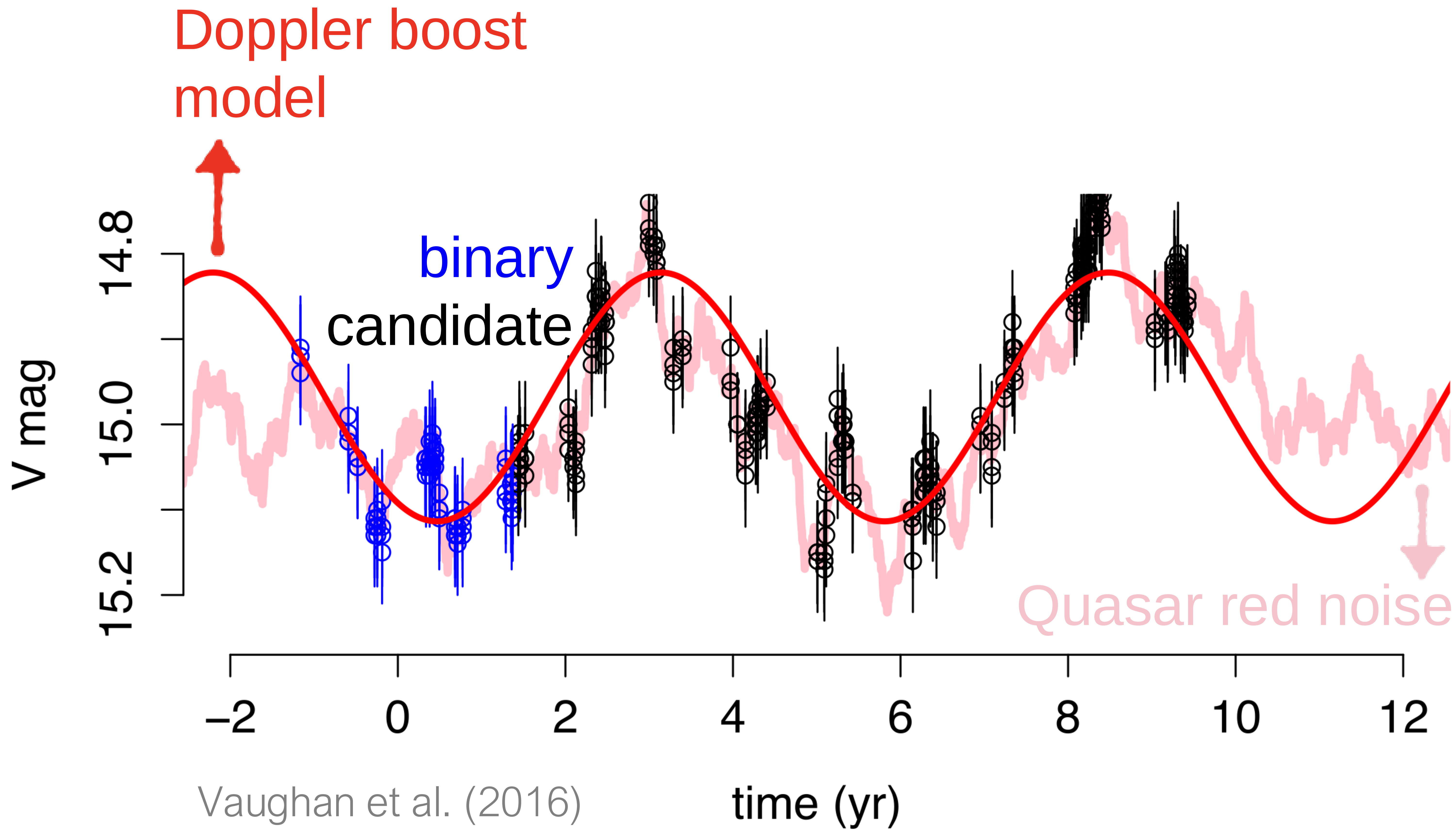
Relativistic Doppler boost



Periodic accretion



Periodic brightness changes: the challenge

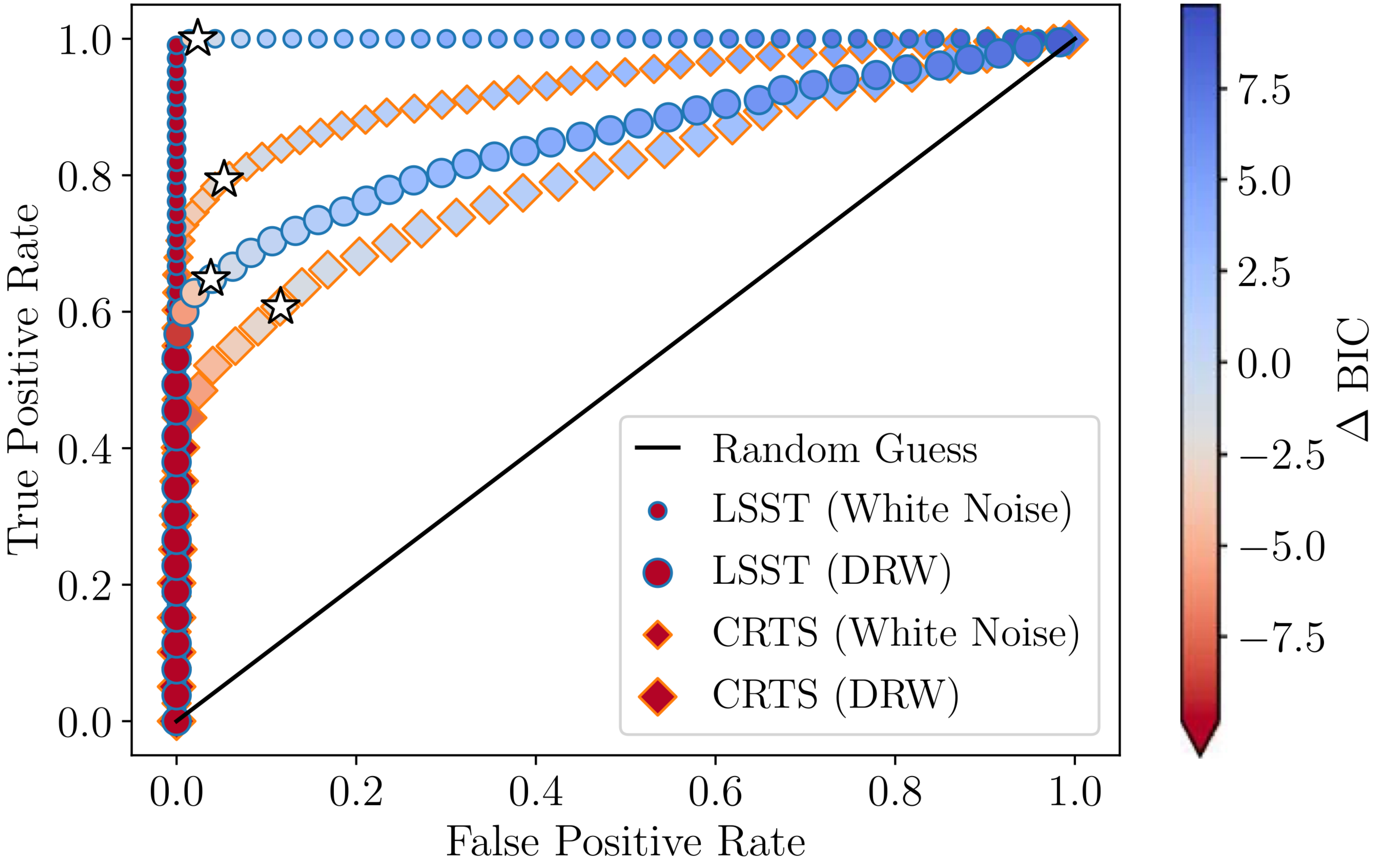


- Main interloper:
  regular quasar variability
- Red noise mimics periodicity and hinders detection.
  Davis et al. incl. JCR (2024)
- The current samples contain false detections.
  Sesana et al. (2018)
- Need more orbital cycles and/or complementary approaches.

Periodic brightness changes: the future is bright

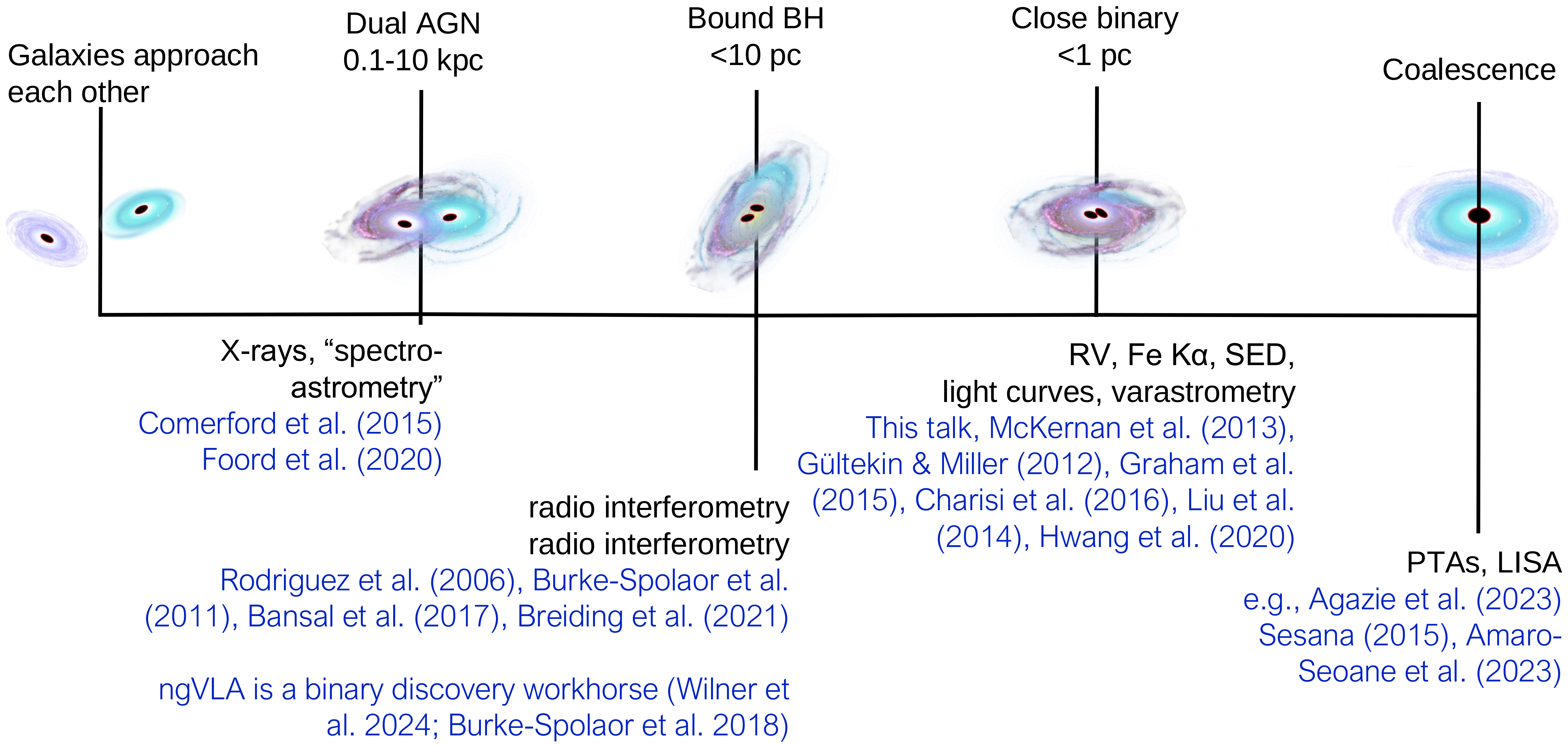
Credit: LSST Coorporation

Witt et al. (2022)

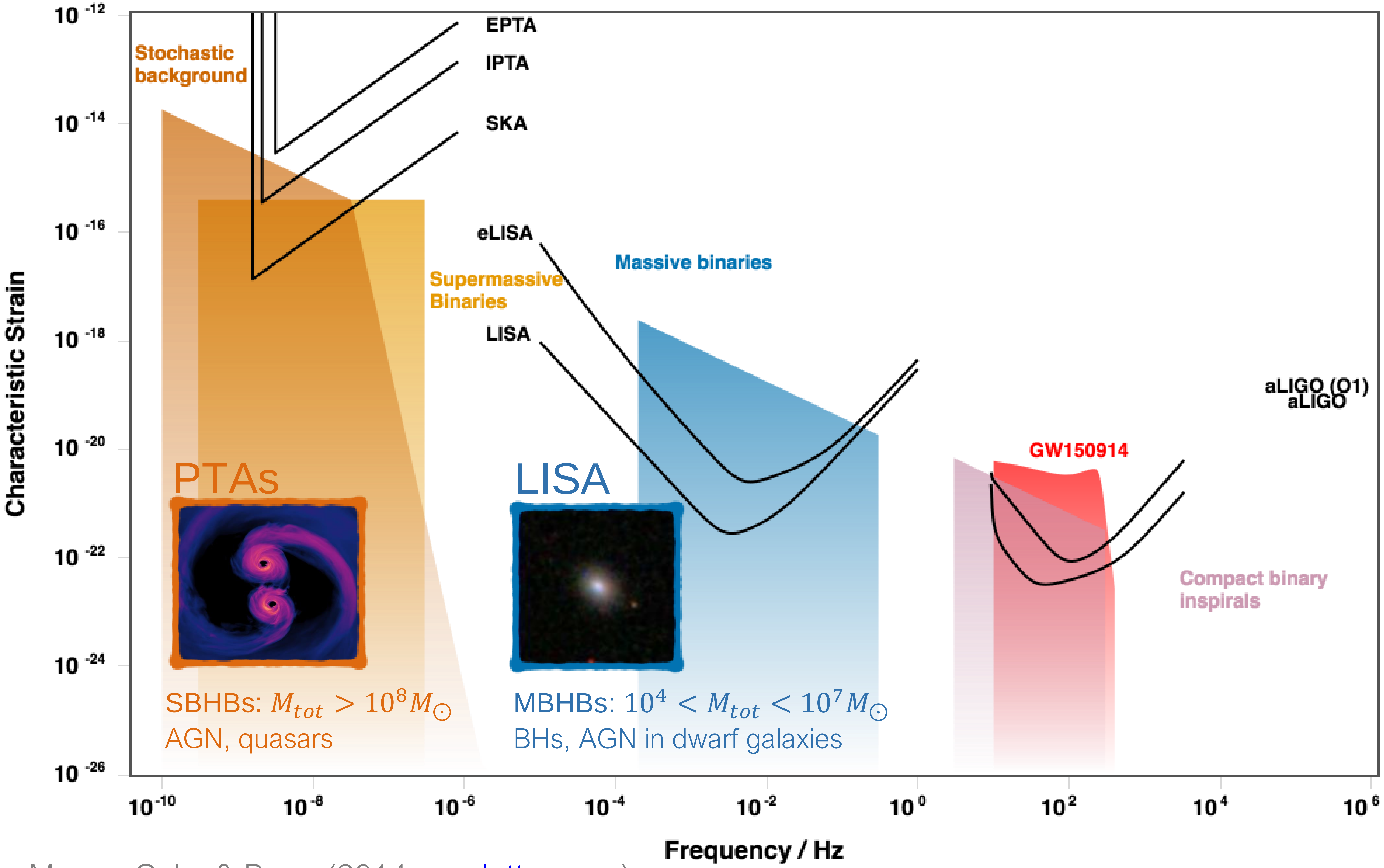


- AGN sample 2-3 orders of magnitude larger than we currently have.
- Unprecedented data quality.
- LSST data quality helps detection, AGN variability hinders it.

SMBHBs: lifecycle and methods for finding them



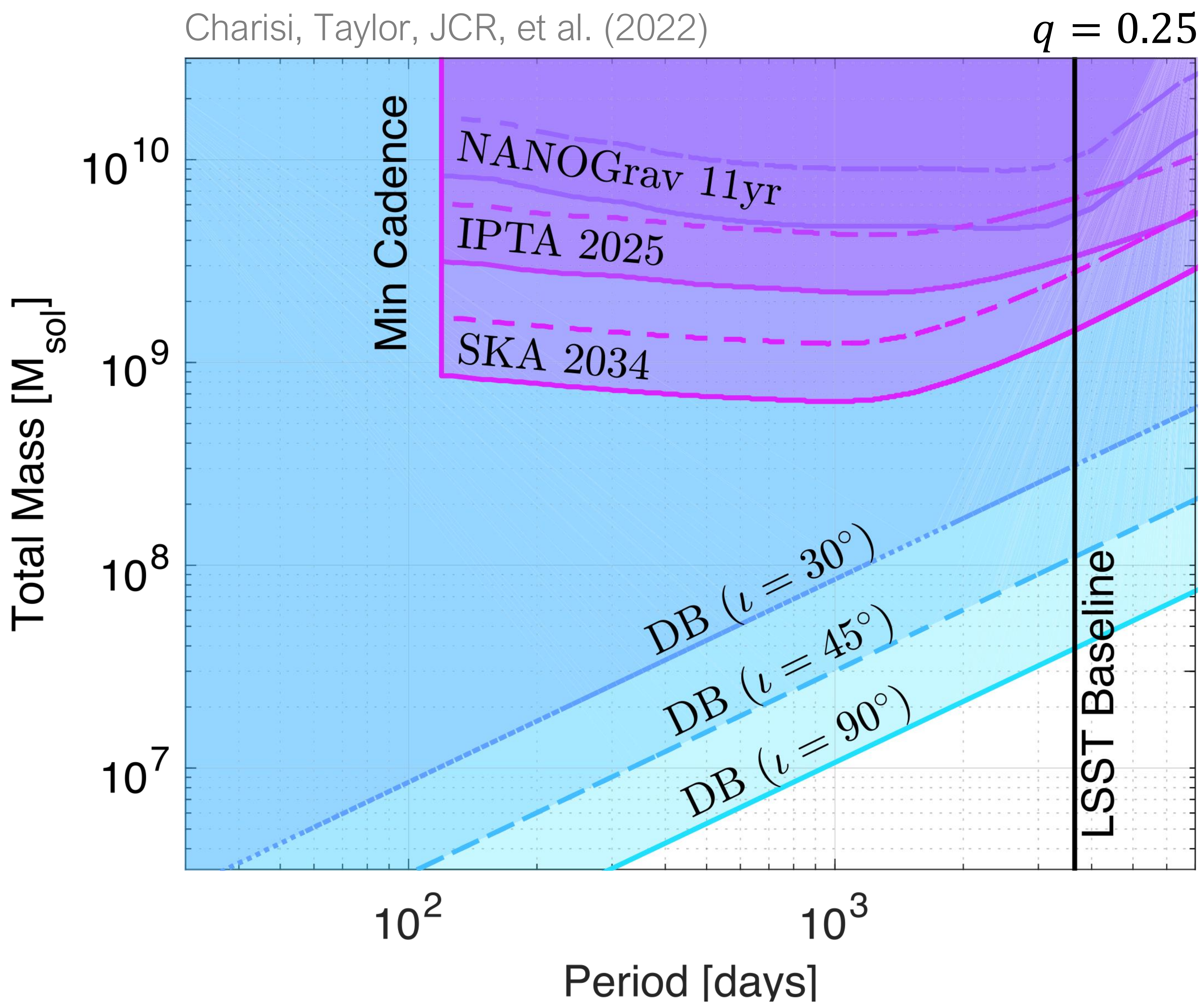
Multi-messenger approach: and loud



Moore, Cole, & Berry (2014, gwplotter.com)

- Evidence for gravitational wave background from PTAs.
  e.g., Agazie et al. (2023a)
- SBHBs can produce the gravitational wave background that PTAs observe.
  Agazie et al. incl. JCR (2023d)

Multi-messenger approach: An EM+GW framework



- Orbital dynamics connect at least period in EM+GW, potentially amplitude and phase.
- Many approaches to multi-messenger astronomy.
- A pipeline for joint analysis of photometric light curves and PTA data sets.
  Charisi et al. (in prep.)
- PTA improvements from ngVLA: benefits of high-frequency sensitivity

Summary: The future is loud and bright

Supermassive black hole binaries

Close binaries will help constrain binary evolution so we are motivated to find them. Radial velocity monitoring reveals compelling candidates but more tests are needed to rule out single quasars. Ultraviolet spectra provide one such test that has proven effective.

Multi-messenger opportunities

Time domain surveys like Vera Rubin Observatory's Legacy Survey of Space and Time or SDSS V will be machines for identifying binaries, but regular quasar variability presents a challenge. The combination of electromagnetic signals with gravitational waves from pulsar timing arrays will be a powerful approach to find binaries.

Where do we go from here?

A new window is opening on quasar variability with enormous investments in the time domain. Also, PTAs will improve with time. ngVLA will contribute both to the PTA effort and direct detection of SBHBs. We aim for multi-messenger EM+GW detections of SBHBs.