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What Can We Learn from Searches for Sub-parsec Supermassive Black Hole Binaries?

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in collaboration with

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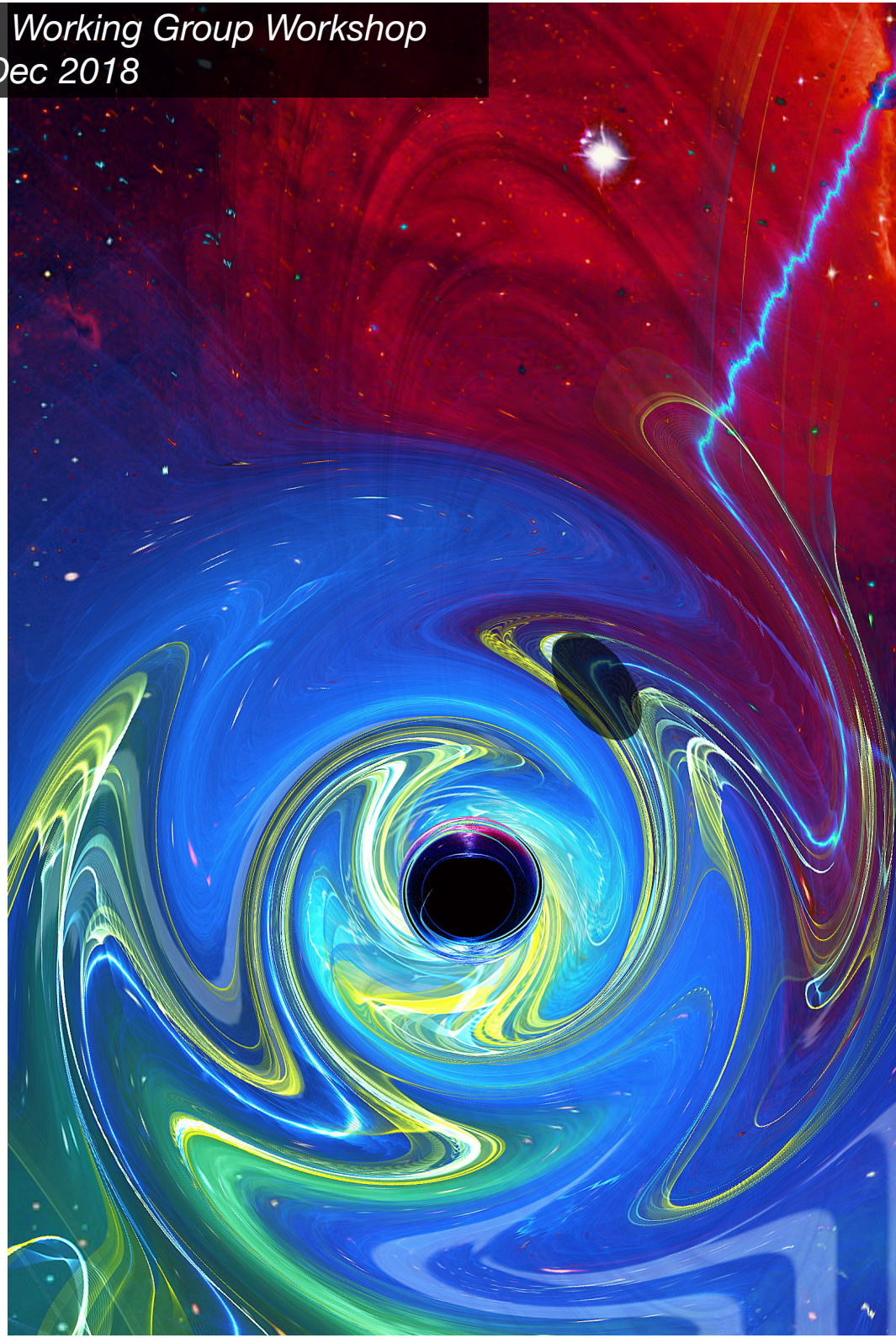
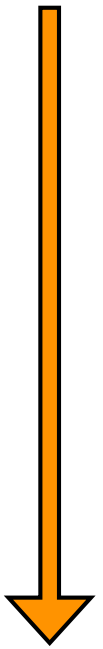


Observational evidence for sub-pc SBHBs comes in several flavors...

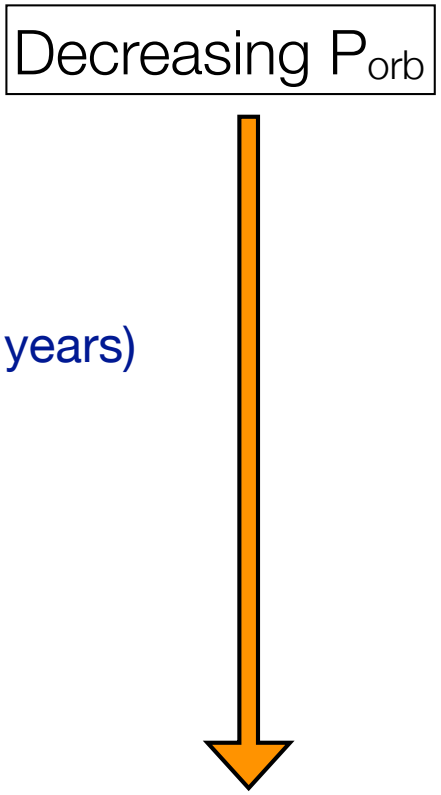
More direct



Less direct

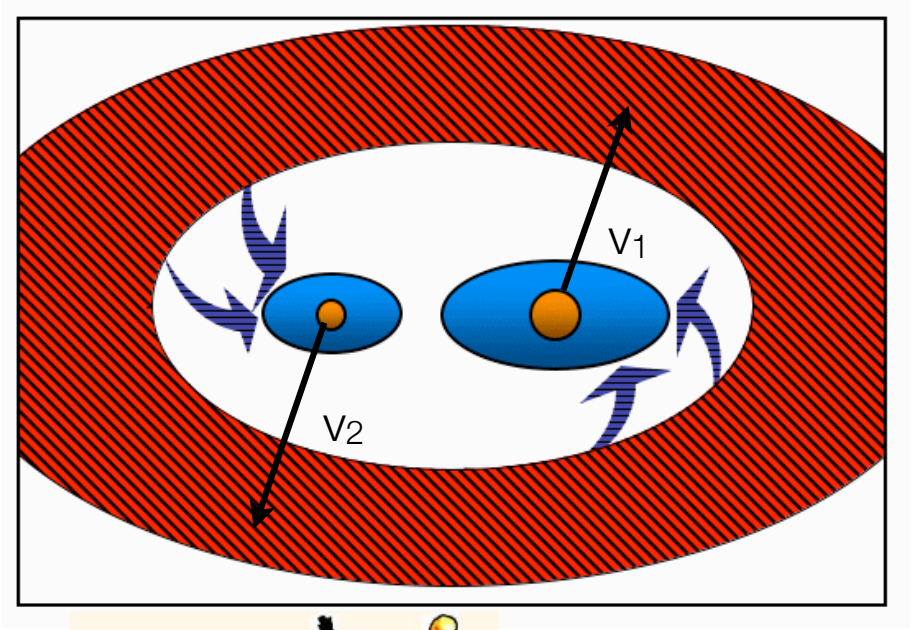
1. GW emission: PTAs (near future) and LISA (2030 and onward)
2. Direct (VLBI) imaging: Double nuclei (~1 candidate)
3. Photometry: Quasi-periodic variability (~150 candidates)
4. Spectroscopy: Offset broad emission lines (~100 candidates)

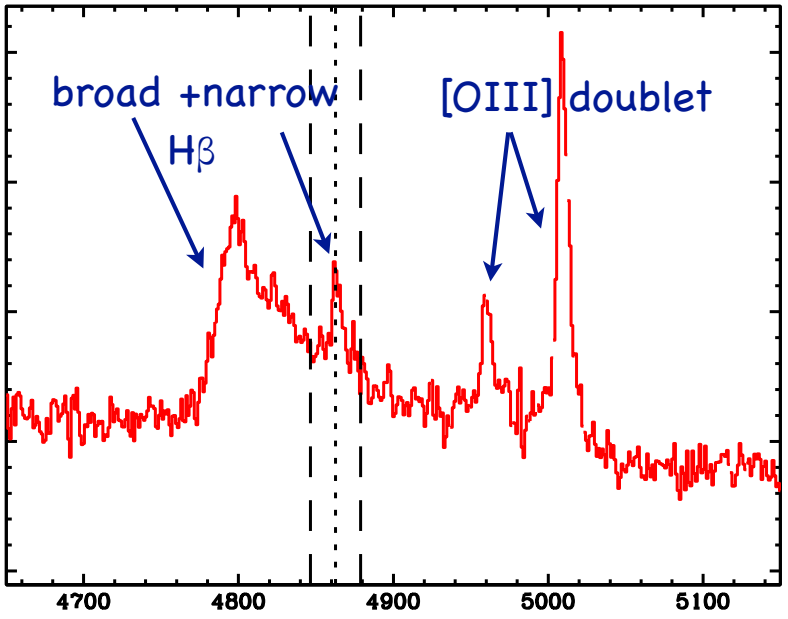
Observational evidence for sub-pc SBHBs comes in several flavors...



1. Direct (VLBI) imaging: Double nuclei (so far $\gg 10^2$ years)
2. Spectroscopy: Offset broad emission lines (~10s —100s years)
3. Photometry: Quasi-periodic variability (few—10 years)
4. GW emission: PTAs and LISA (0 — few years)

Spectroscopic searches for SBHBs



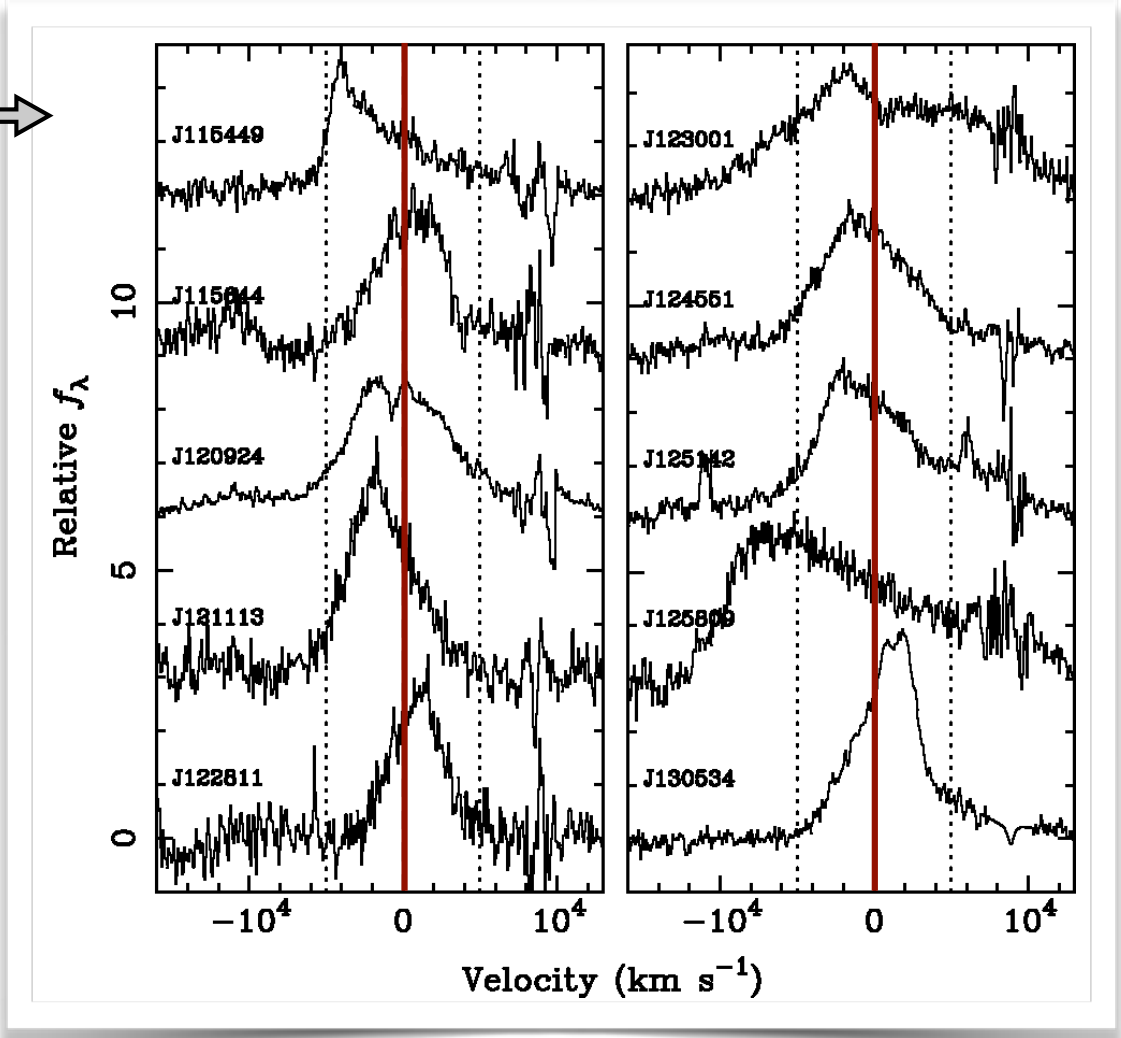


- **Caveat:** Displaced peaks not a unique signature of binarity

Observational search: offset optical broad emission-lines

broad Hβ emission line profiles
(Eracleous+ 12, Runnoe+ 15, 17)

- ~16k SDSS QSOs triaged to 88 based on shifted broad Hβ emission line profiles
- 29 exhibit profile modulation in time, consistent with SBHB model.
  (see also: Bon+ 12, 16; Decarli+ 13; Shen+ 13; Ju+ 13; Liu+ 14; Li+ 16; Wang+ 17)
- Inferred P_{orb} ~ 10s — 100s of years
  (Pflueger, Nguyen, TB+ 18)

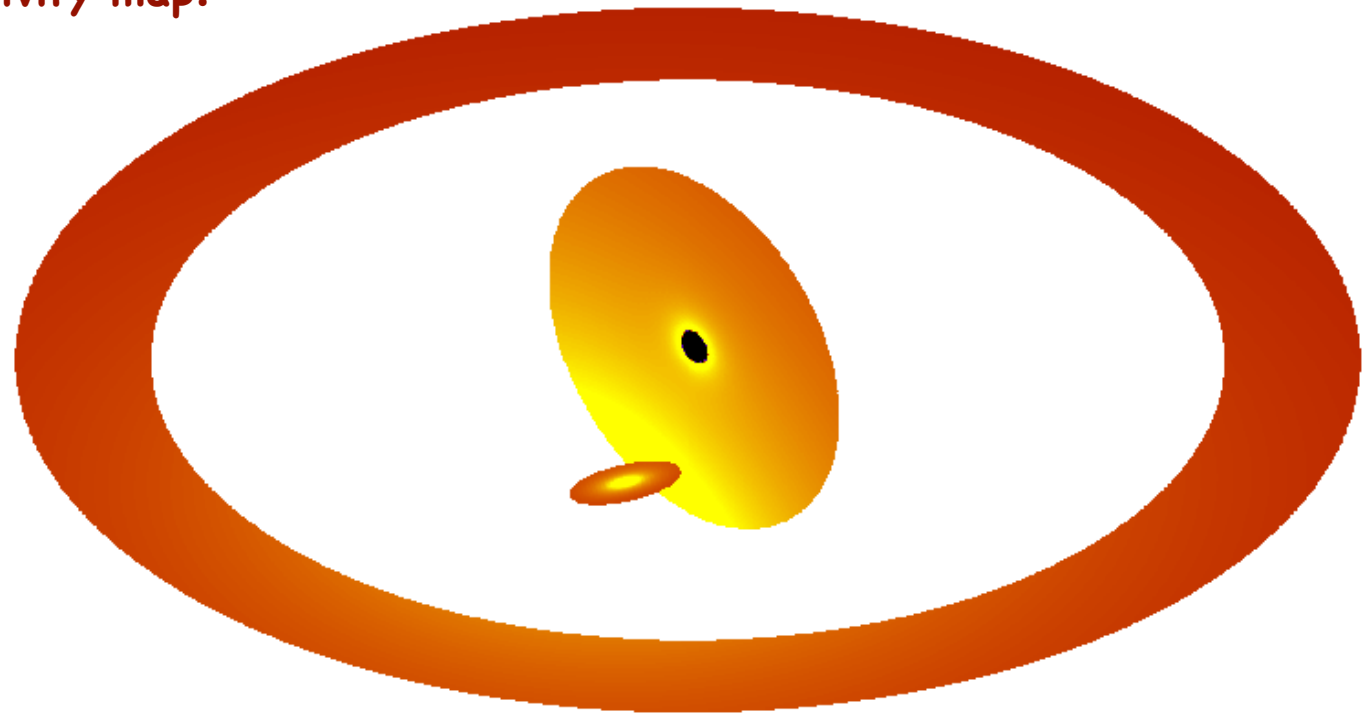


NOT MEASURING MULTIPLE ORBITAL CYCLES

What can be learned from a sample of SBHBs?

- **Key parameters:** separation, eccentricity, mass ratio, triple disk alignment
- **BLR model:** SBH mini-disks + circumbinary disk + 2 sources of illumination

BLR emissivity map:

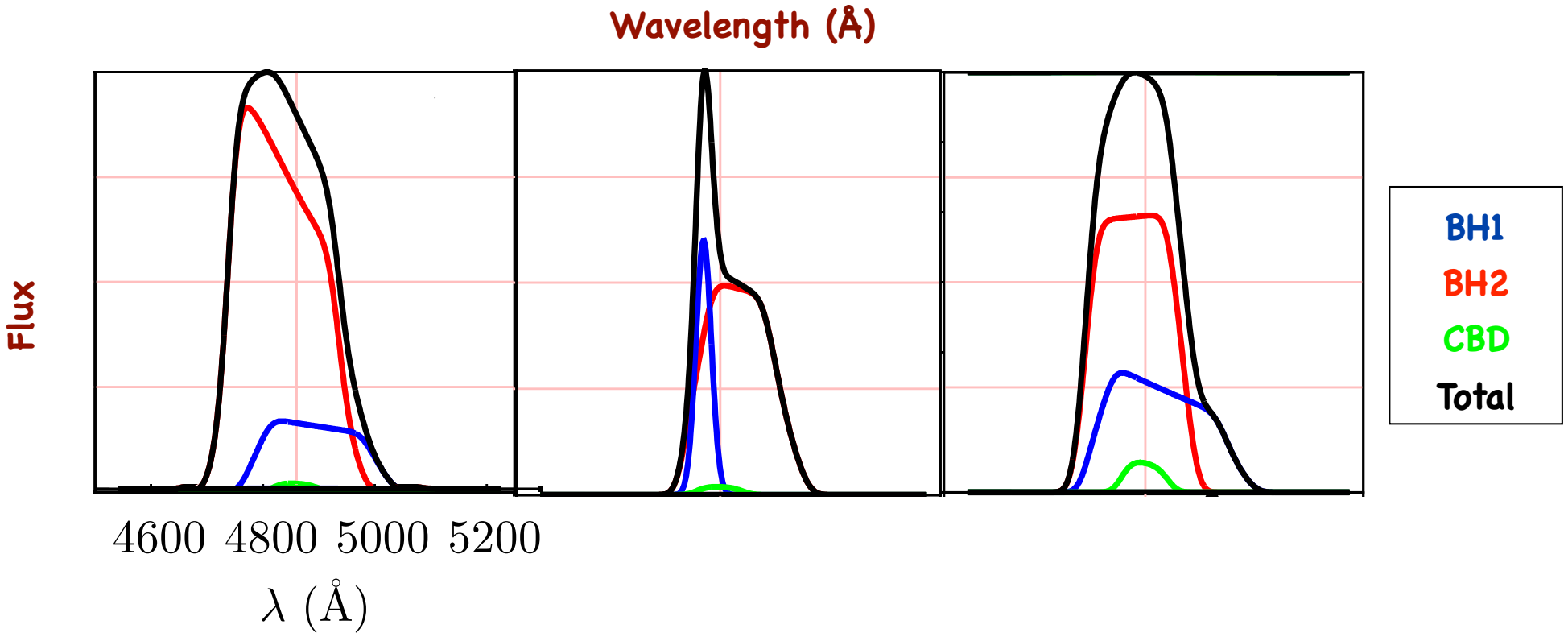


(credit: Khai Nguyen)

Synthetic emission line profiles

(Nguyen & TB+ 16, 18)

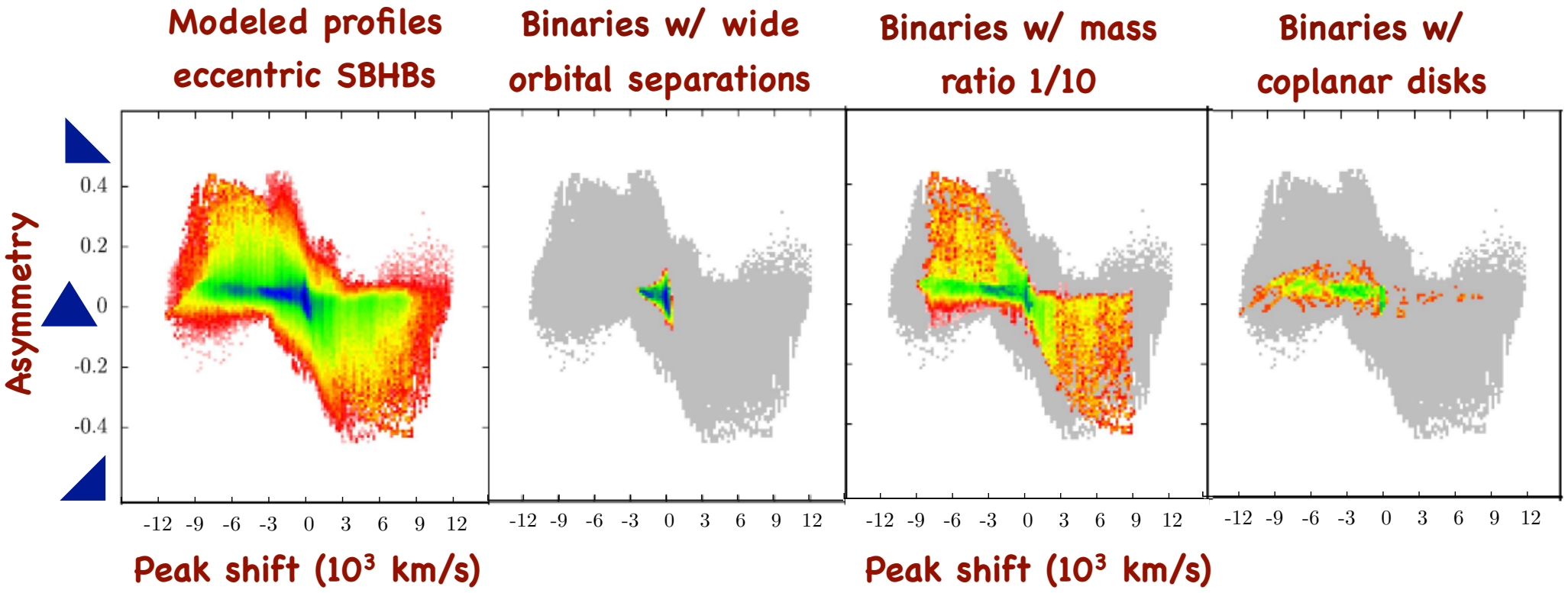
- Database of > 40 million Hβ profiles



Analysis of synthetic database of profiles

(Nguyen & TB+ 16, 18)

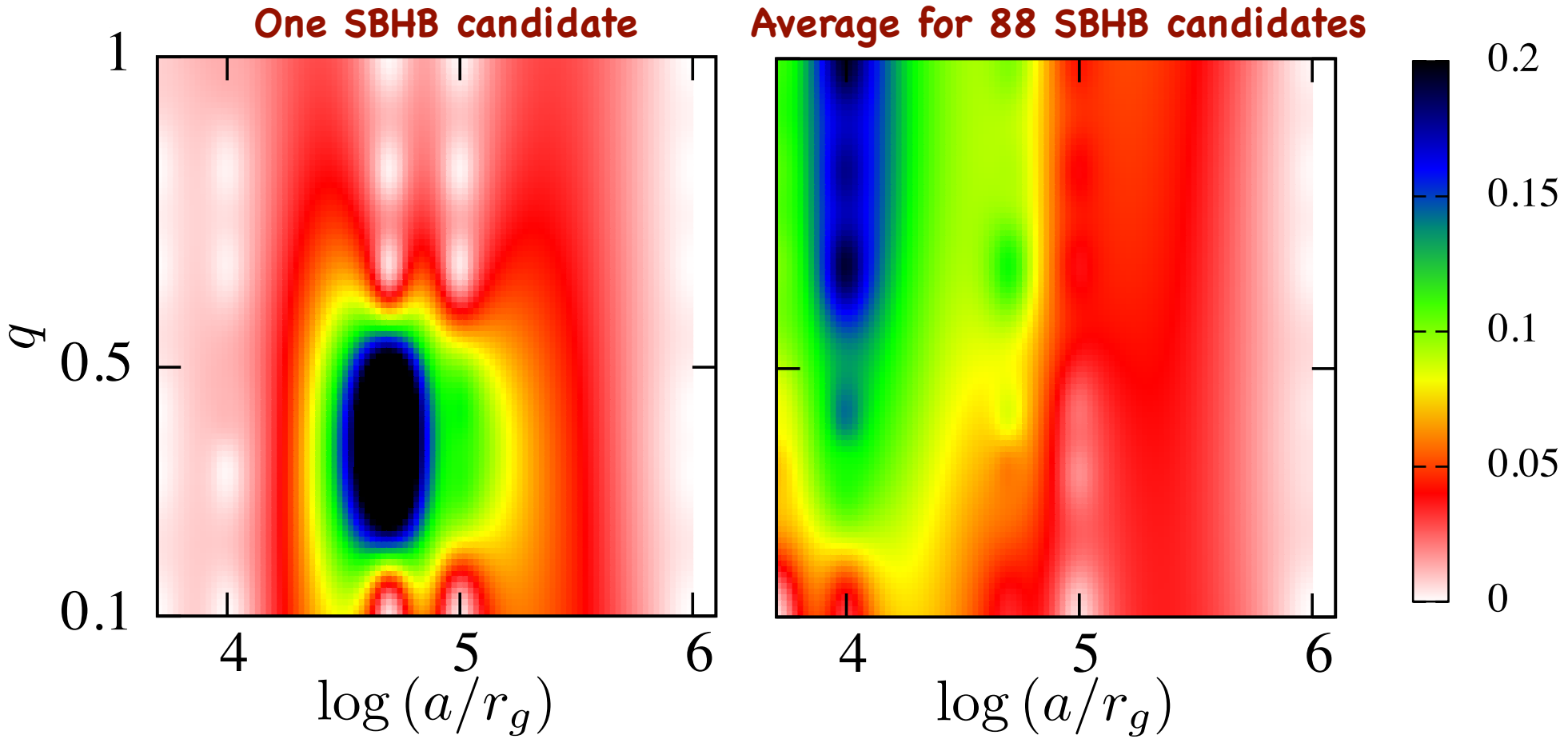
- FWHM, asymmetry, “boxiness”, peak shift



Properties of binary candidates

(Nguyen, TB+ 19, in prep.)

- Observed candidates mapped into SBHB parameter space



$$r_g = GM/c^2$$

Implications for LISA

- SBHBs are a natural product of galaxy evolution and the prime sources of GWs — our best chance to find them is (still) through EM observations.

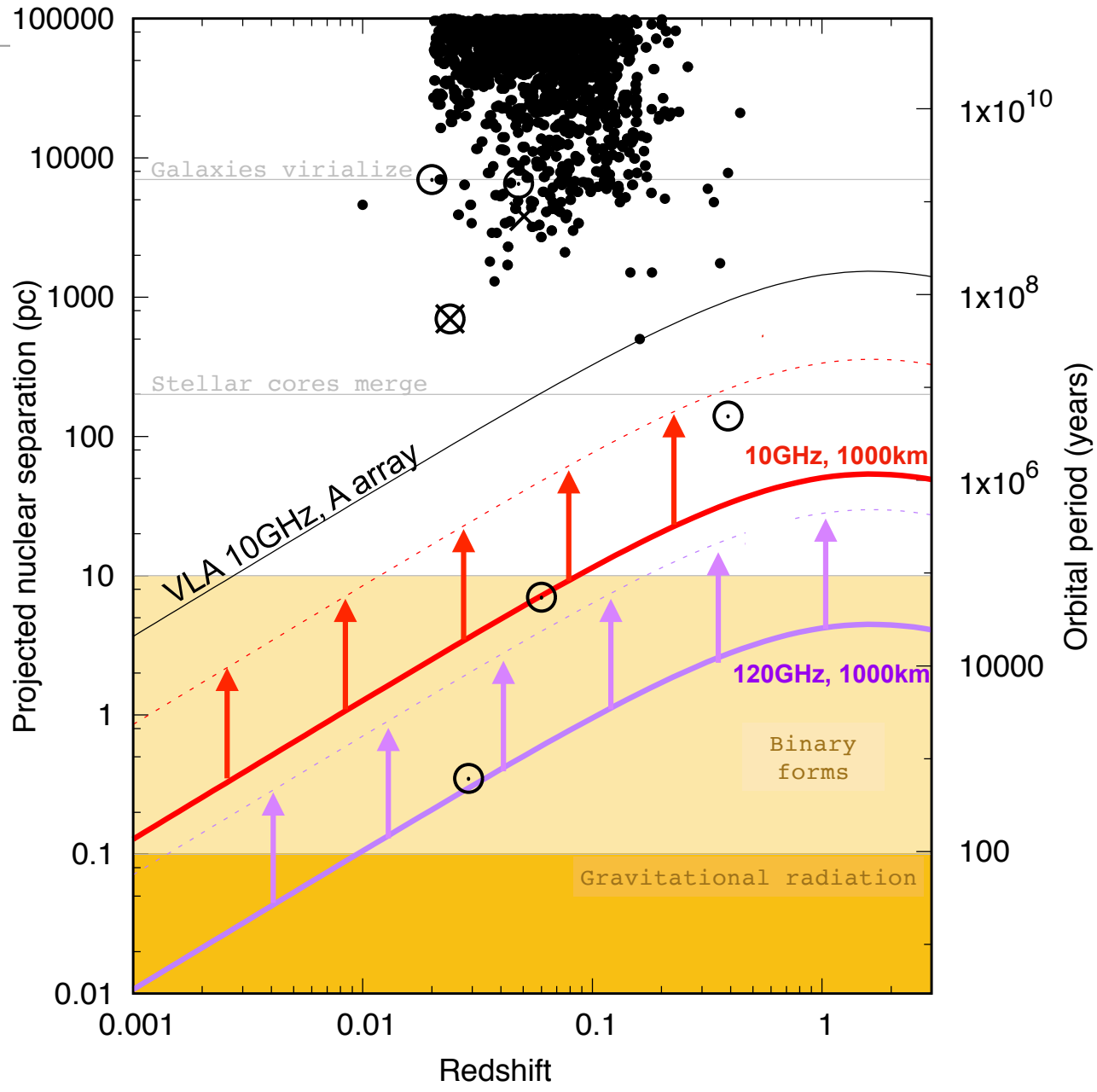
- **Observations:** Identification of sub-pc SBHBs has been challenging. Gains inevitable through (a) continued long term monitoring and (b) new surveys and observatories.

- **Modeling:** Once a robust sample is detected modeling of broad emission line profiles is one promising way to learn about the properties of sub-pc SBHBs and make predictions for LISA.

Future Prospects: Direct Imaging w/ Next Generation VLA w/ VLBI

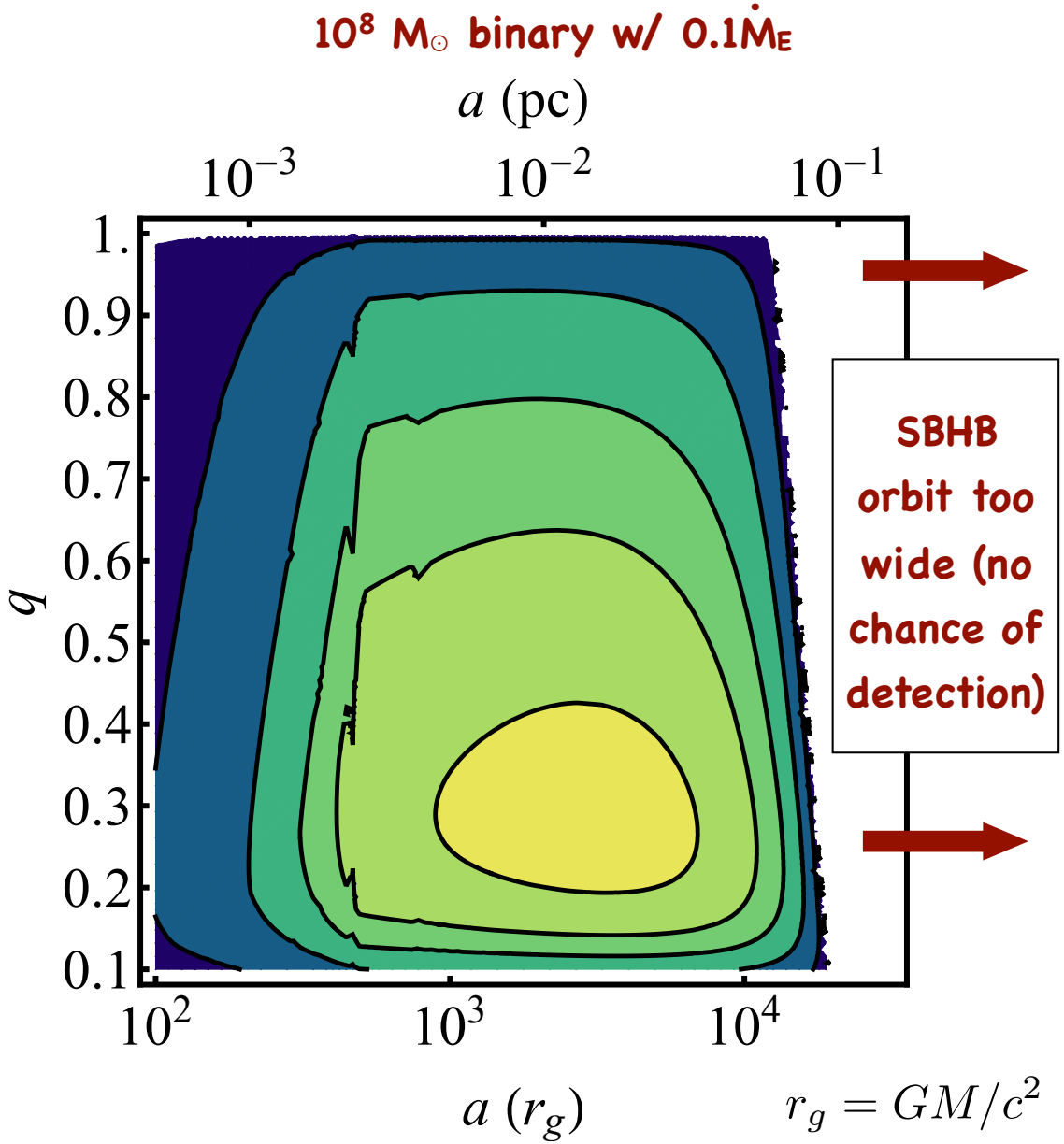
- ngVLA: Proposed VLA extension
- 2024 — Construction
- 2034 — Full operations
- Longer baselines + higher radio-frequencies can provide sub-pc resolution

(Burke-Spolaor+ 18)



(Pflueger, Nguyen, TB+ 18)

SBHBs targeted by spectroscopic searches



- Targeted SBHBs are progenitors of GW binaries
- Their orbital periods are 10s to 100s of years