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

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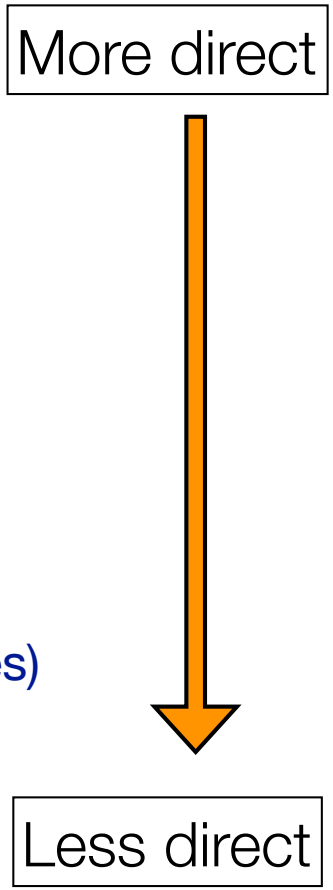
# Evidence for sub-pc SMBHBs comes in several flavors...

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



# Evidence for sub-pc SMBHBs 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)

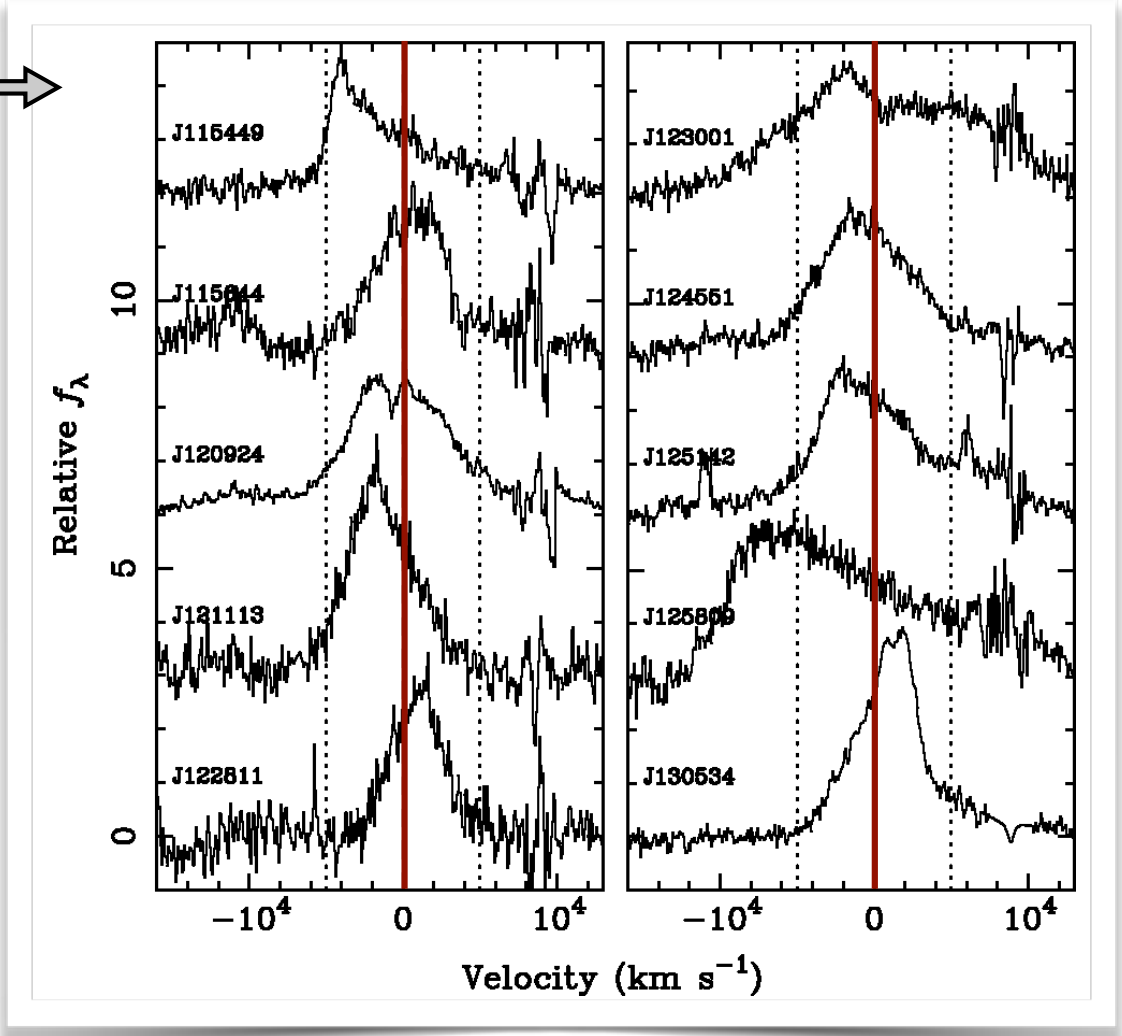
4. GW emission: PTAs and LISA (0 — few years)

# Spectroscopic 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
- 3+ spectra w/ baseline ~12 years (~350 spectra)

(see also: Bon+ 12, 16; Decarli+ 13; Shen+ 13; Ju+ 13; Liu+ 14; Li+ 16; Wang+ 17, Guo+ 19)

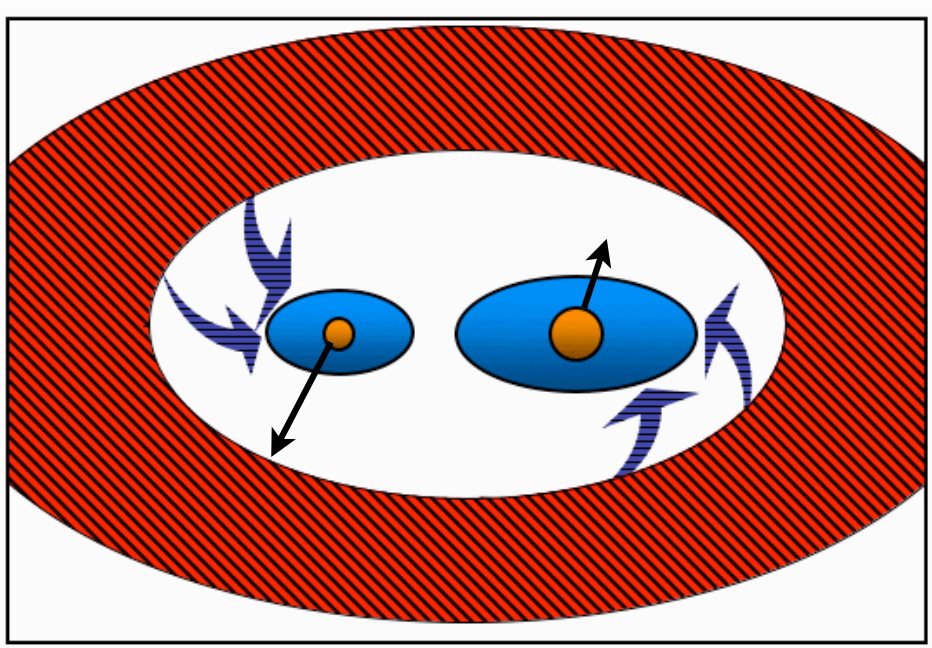


# What can be learned from a spectroscopic sample of SMBHBs?

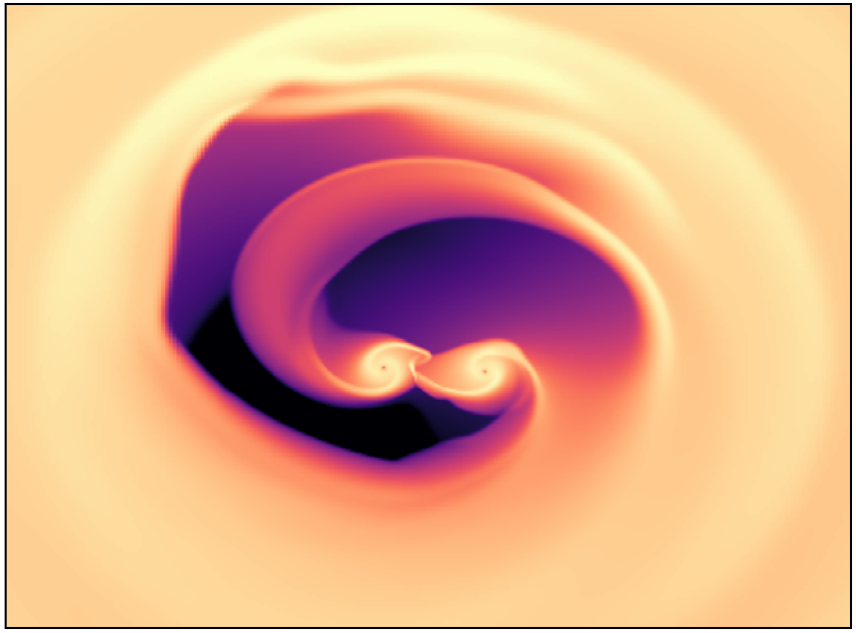
- Calculation of spectra from the first principles is presently out of reach.

- Calculation of spectra using a hybrid, phenomenological-physical model?

# Properties of SMBHBs accretion flows from simulations



Simulated gas surface density (Moody+ 19)

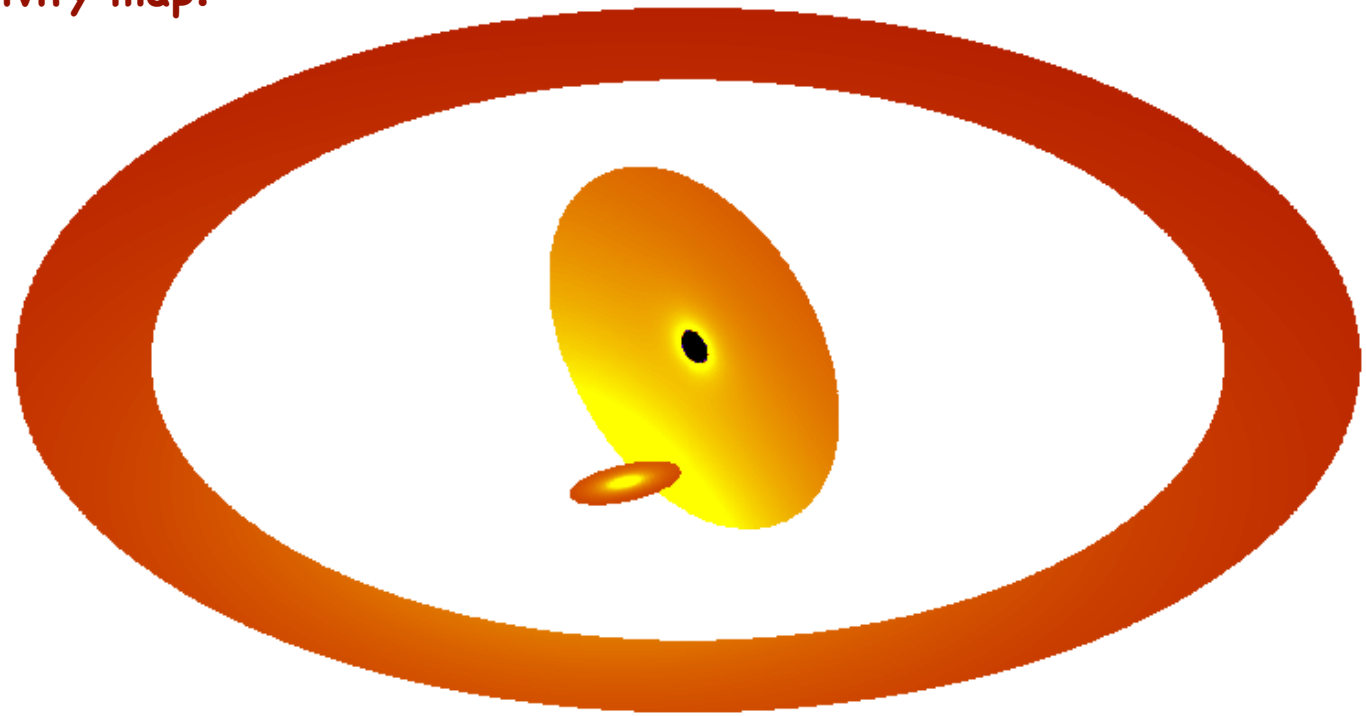


- Structure of the circumbinary accretion flow
- Accretion onto both SMBHs continues unhindered
- For q<1, secondary SMBH accretes at a higher rate

# A minimalistic model for sub-parsec SMBHBs

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

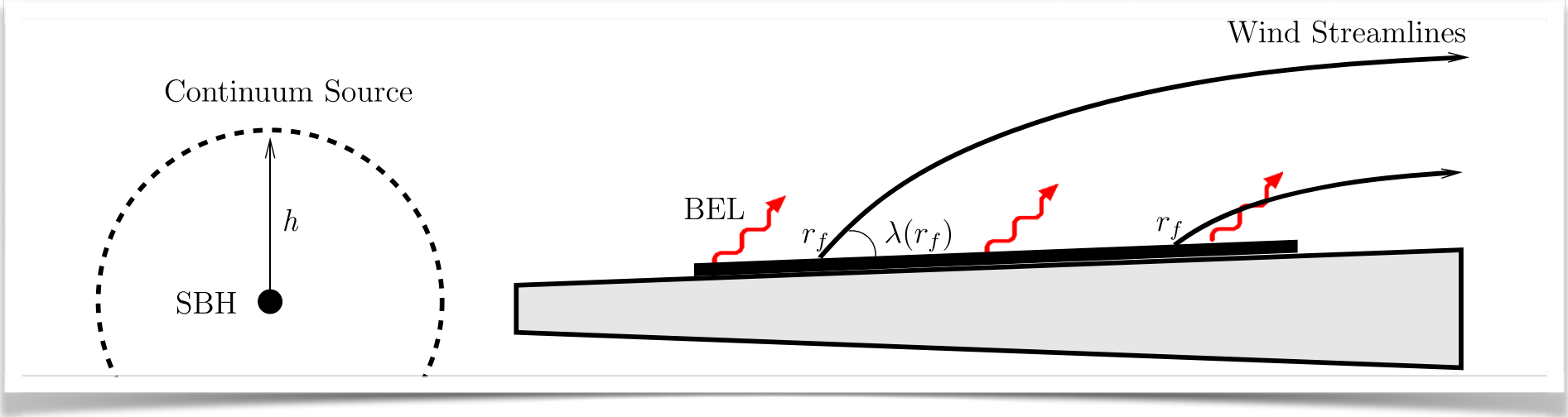
**BLR emissivity map:**



(credit: Khai Nguyen)

# A minimalistic model for sub-parsec SMBHBs

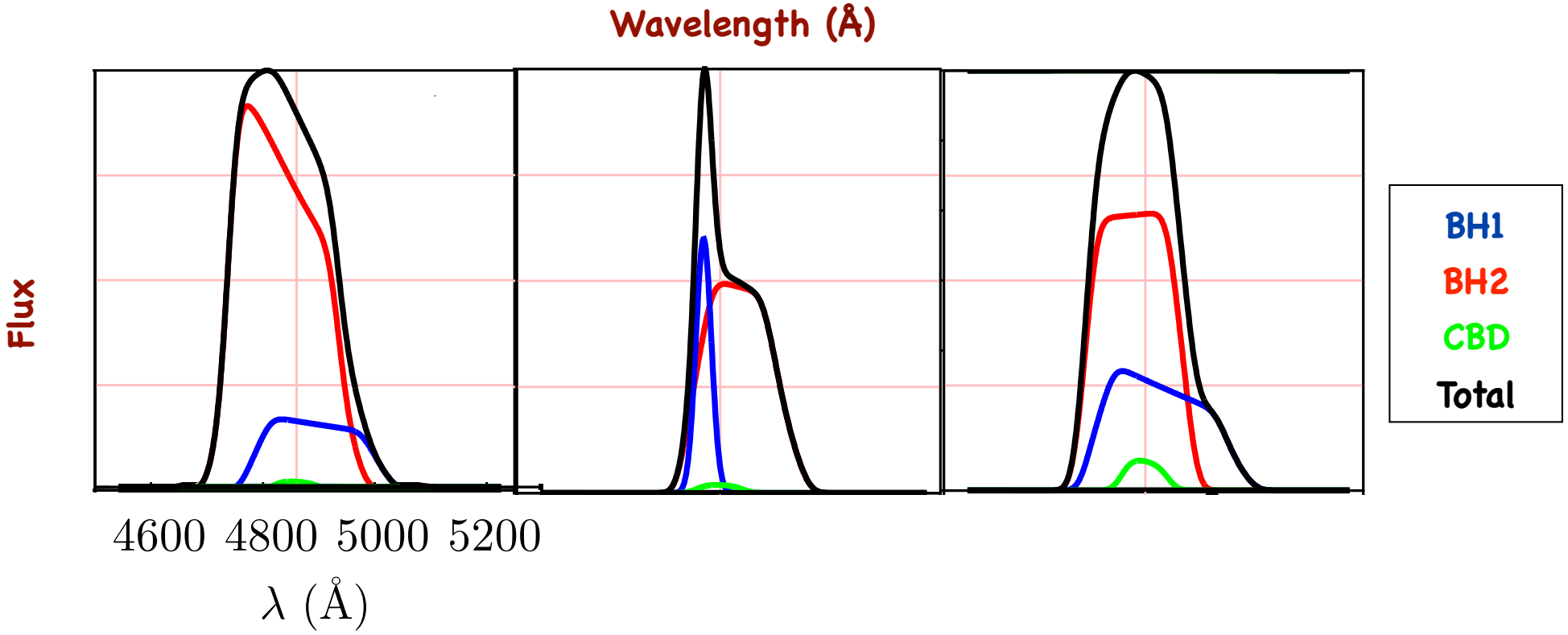
- **Key parameters:** separation, eccentricity, mass ratio, triple disk alignment
- **BLR model:** SMBH mini-disks + circumbinary disk + 2 sources of illumination
- Calculate composite broad emission line-profiles. (Chen & Halpern 89, Eracleous+ 95)
- Emission line photons affected by absorption in the line-driven accretion disk wind. (Chiang & Murray 96, Flohic+ 12)



# Synthetic emission line profiles

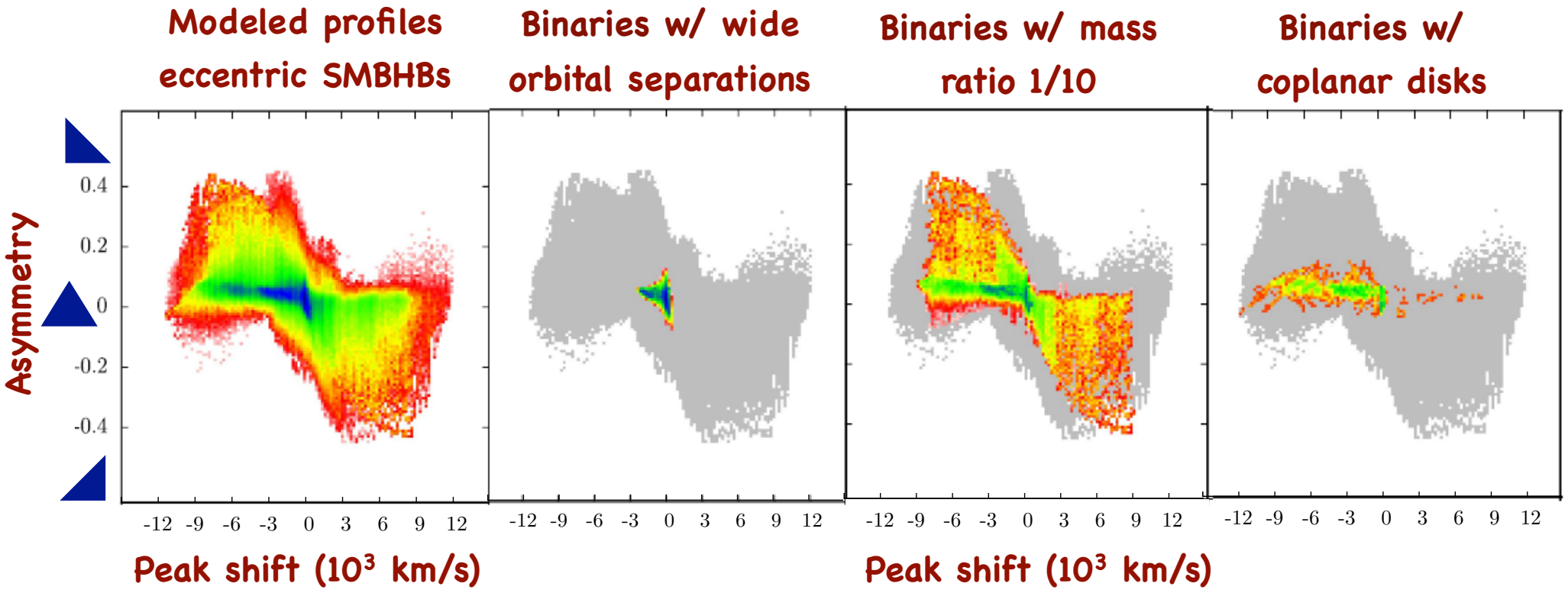
(Nguyen & TB+ 16, 19a)

- Database of 40+ million Hβ profiles

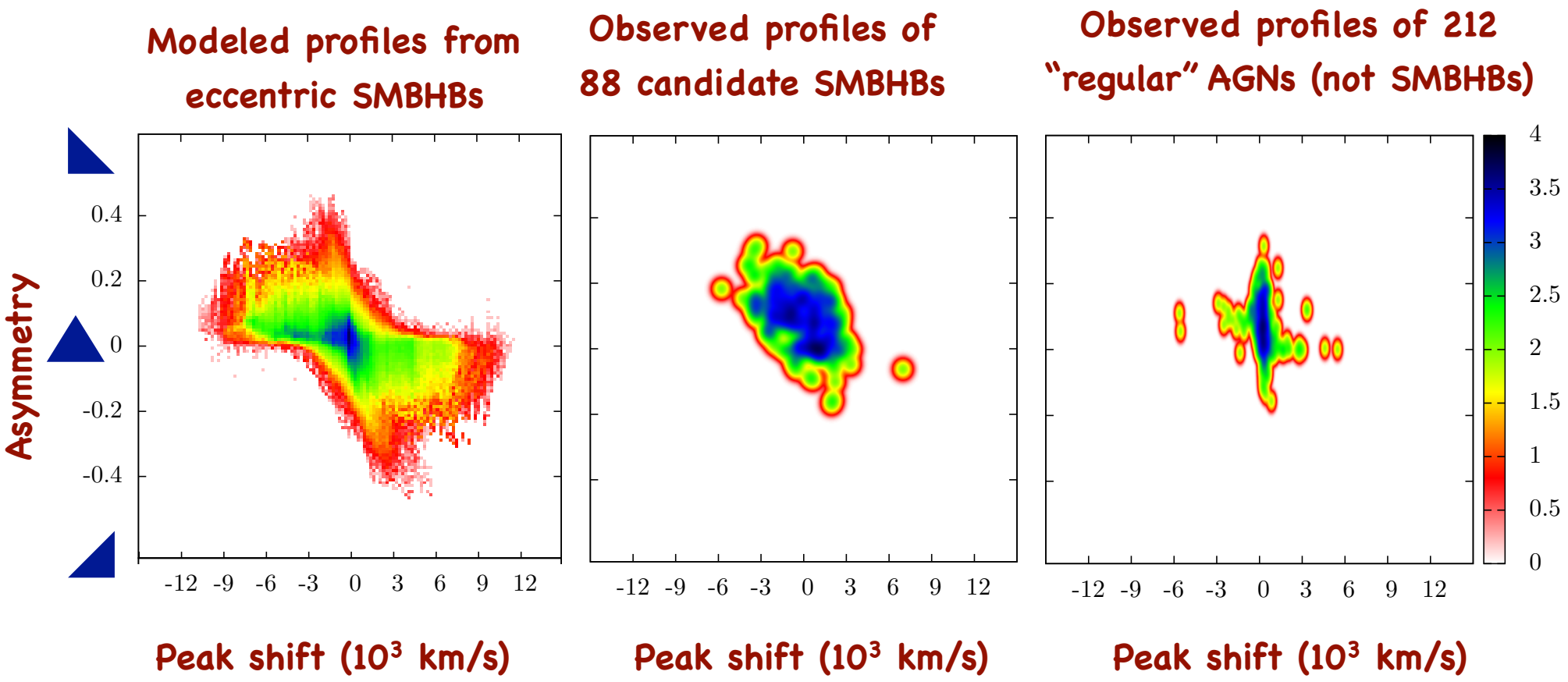


# Analysis of synthetic database of profiles (Nguyen & TB+ 16, 19a)

- FWHM, asymmetry, “boxiness”, peak shift



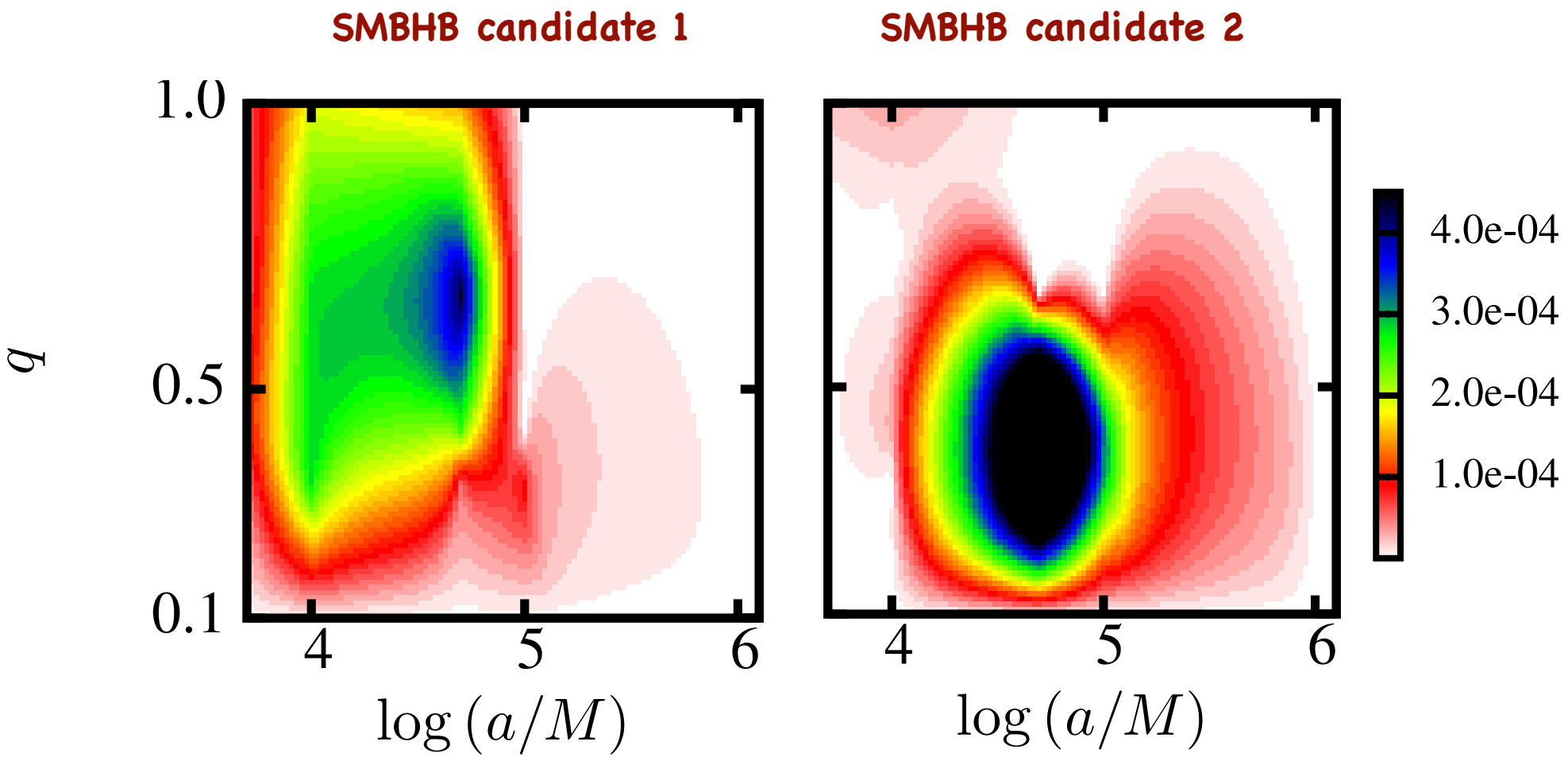
# Comparison of synthetic w/ observed profiles (Nguyen, TB+ 19a)



# Properties of individual SMBHB candidates

(Nguyen, TB+ 19b, arXiv:1908.01799)

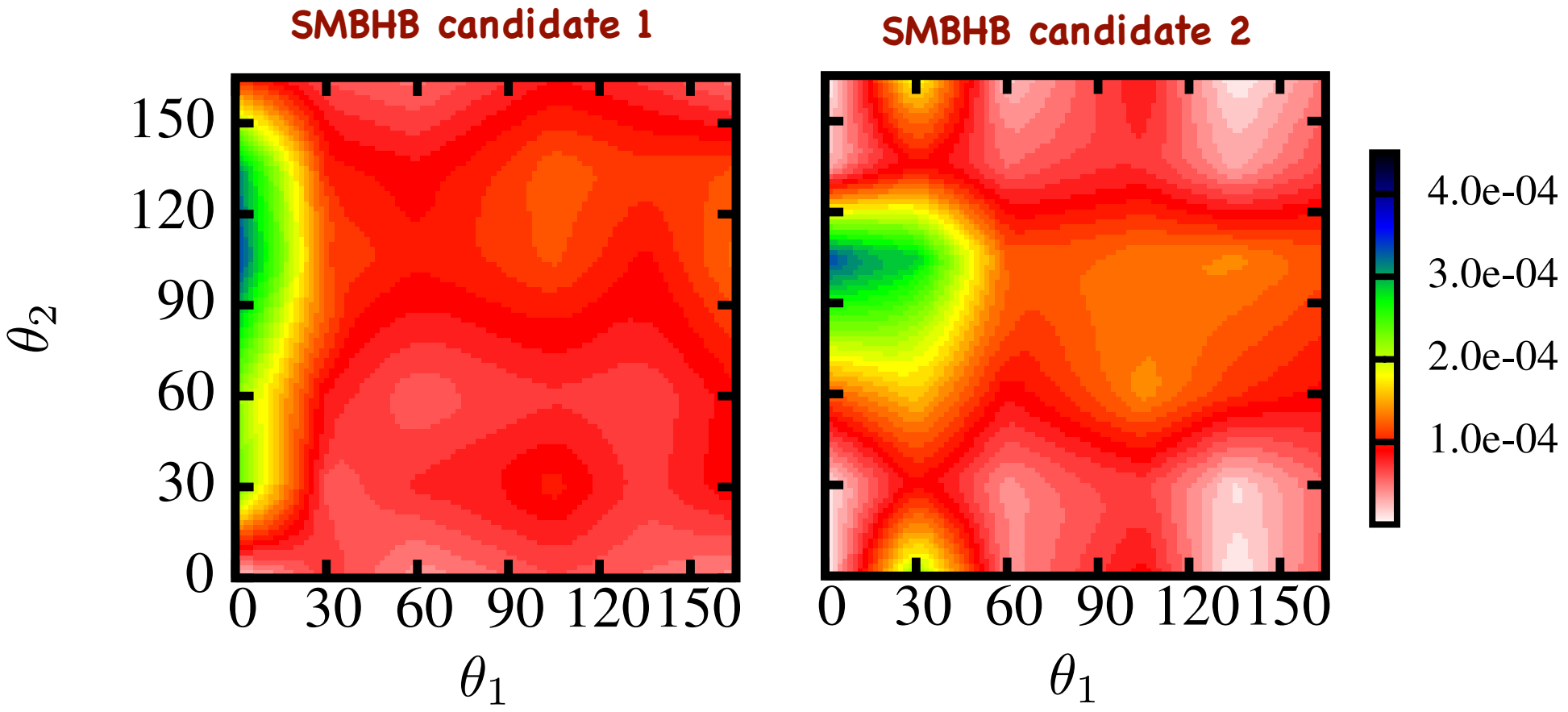
- Observed candidates mapped into SMBHB parameter space



# Properties of individual SMBHB candidates

(Nguyen, TB+ 19b, arXiv:1908.01799)

- Misaligned or warped disks?



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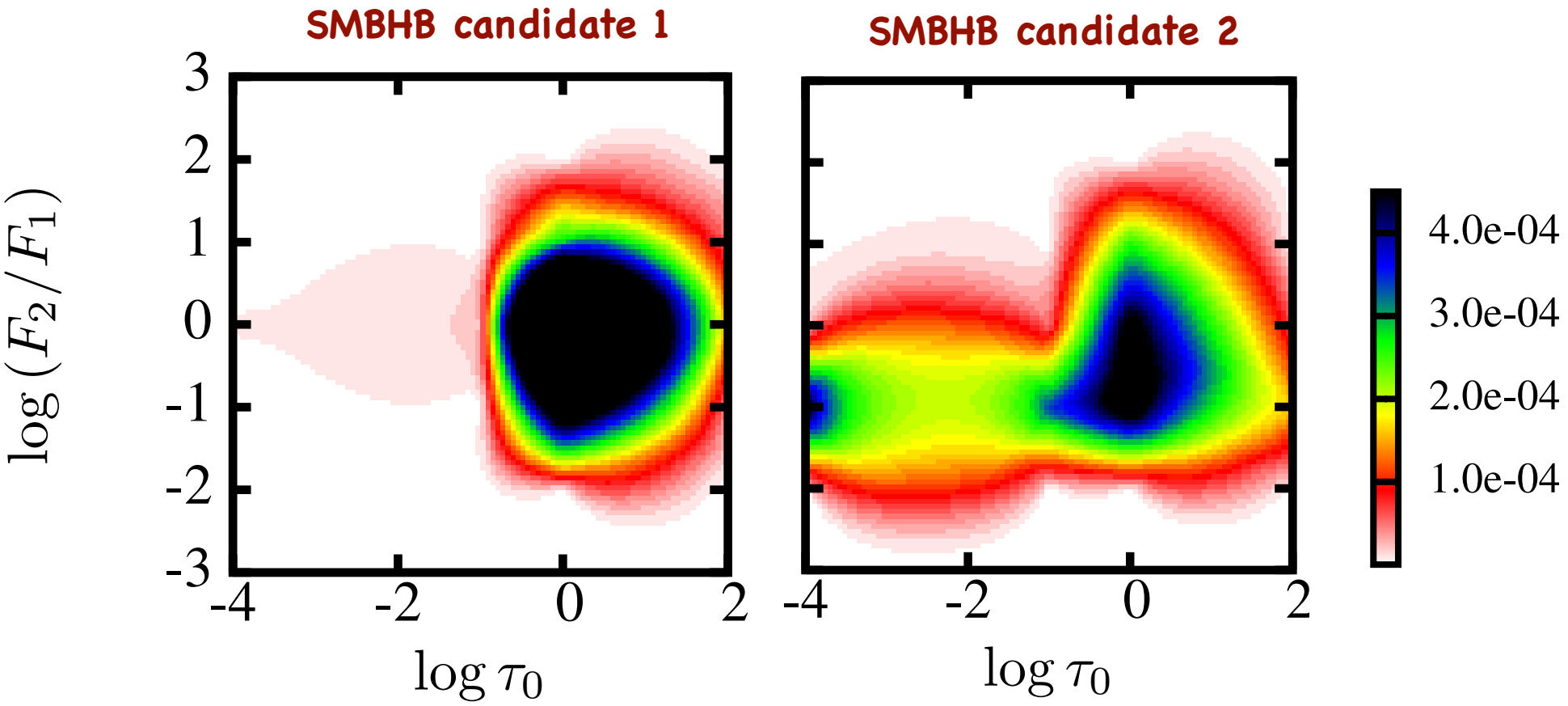
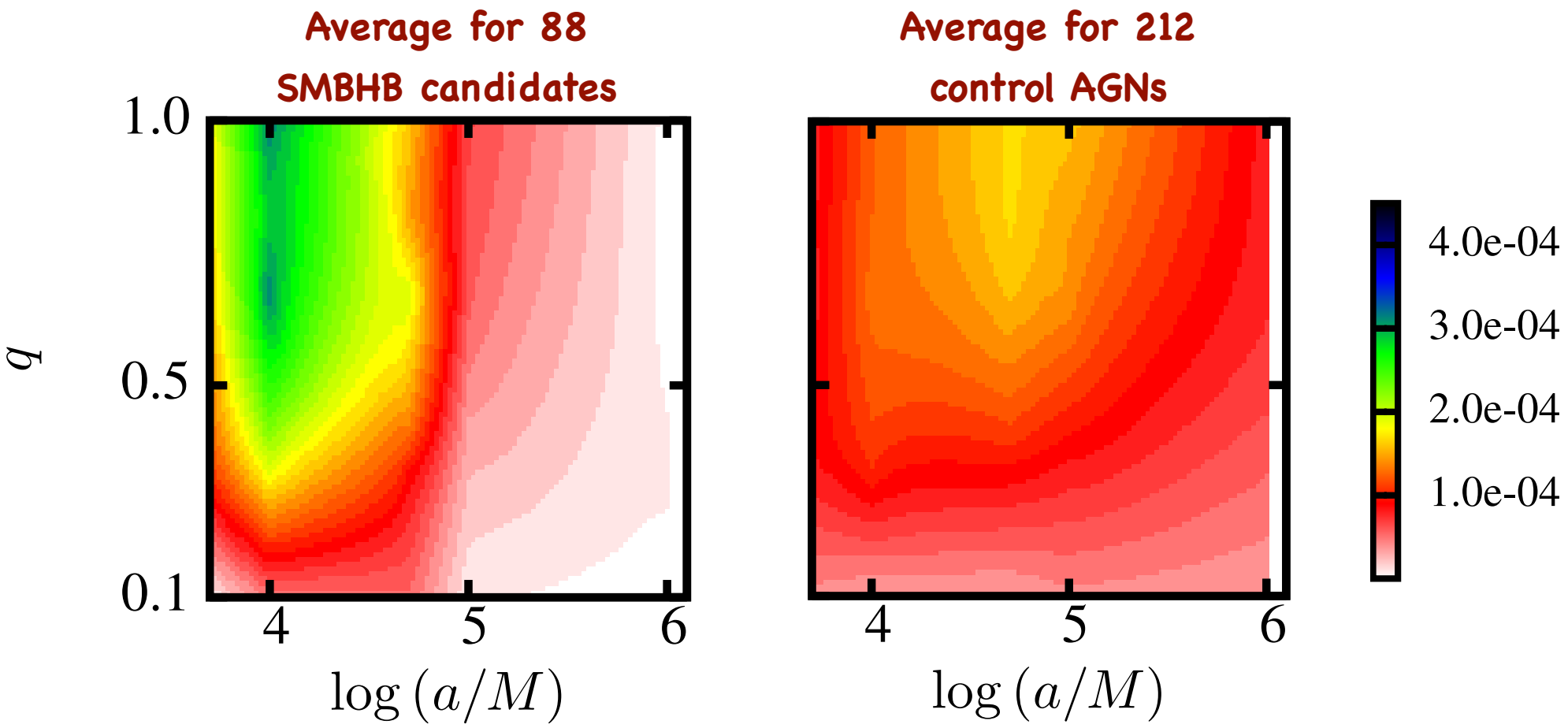



- No useful constraints on orbital eccentricity.

# Properties of a sample of 88 SMBHB candidates

(Nguyen, TB+ 19b, arXiv:1908.01799)




On average for SMBHB candidates:

$\log(a/M) \approx 4.20 \pm 0.42 \qquad q > 0.5$

# In summary...


- SMBHBs 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 SMBHBs has been challenging. Gains inevitable through (a) continued long term monitoring and (b) new surveys and observatories.

- **Simulations:** Lots has been learned already. The next frontier is a new generation of simulations of accreting SMBHBs which account for effects of radiation and magnetic fields.

- **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 SMBHBs and make predictions for GW observatories.