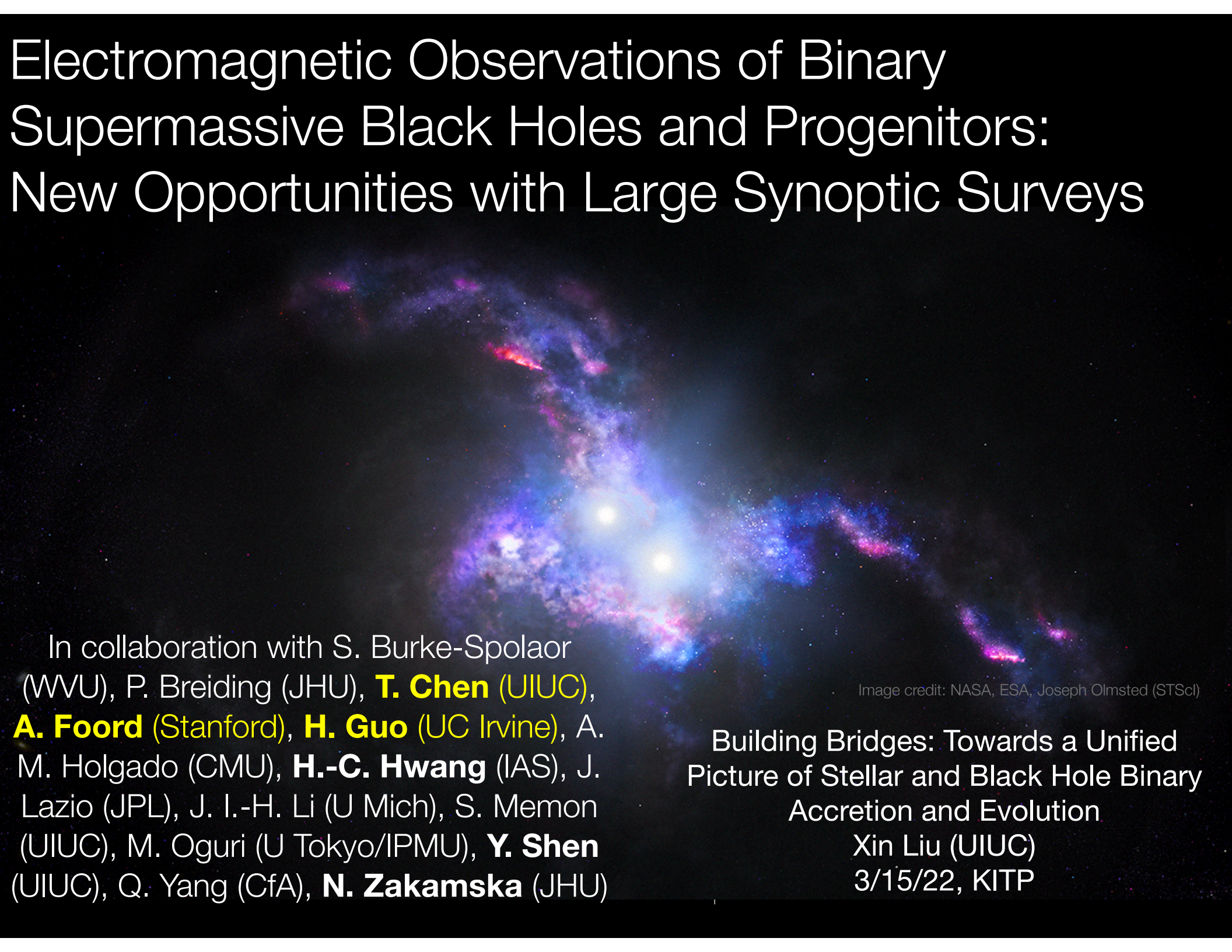
Electromagnetic Observations of Binary Supermassive Black Holes and Progenitors: New Opportunities with Large Synoptic Surveys



In collaboration with S. Burke-Spolaor (WVU), P. Breiding (JHU), **T. Chen** (UIUC), **A. Foord** (Stanford), **H. Guo** (UC Irvine), A. M. Holgado (CMU), **H.-C. Hwang** (IAS), J. Lazio (JPL), J. I.-H. Li (U Mich), S. Memon (UIUC), M. Oguri (U Tokyo/IPMU), **Y. Shen** (UIUC), Q. Yang (CfA), **N. Zakamska** (JHU)

Image credit: NASA, ESA, Joseph Olmsted (STScI)

Building Bridges: Towards a Unified Picture of Stellar and Black Hole Binary Accretion and Evolution

Xin Liu (UIUC)

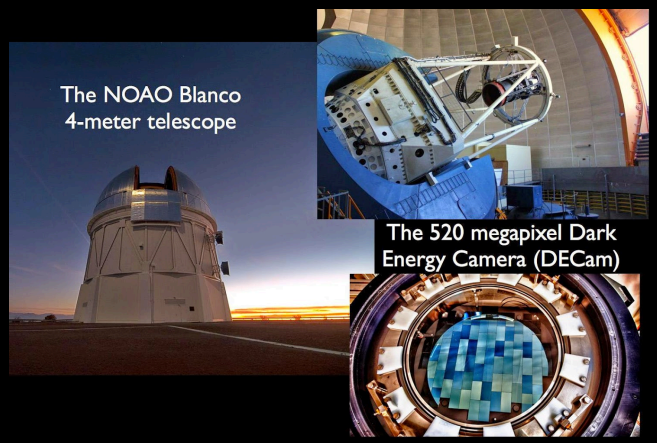
3/15/22, KITP

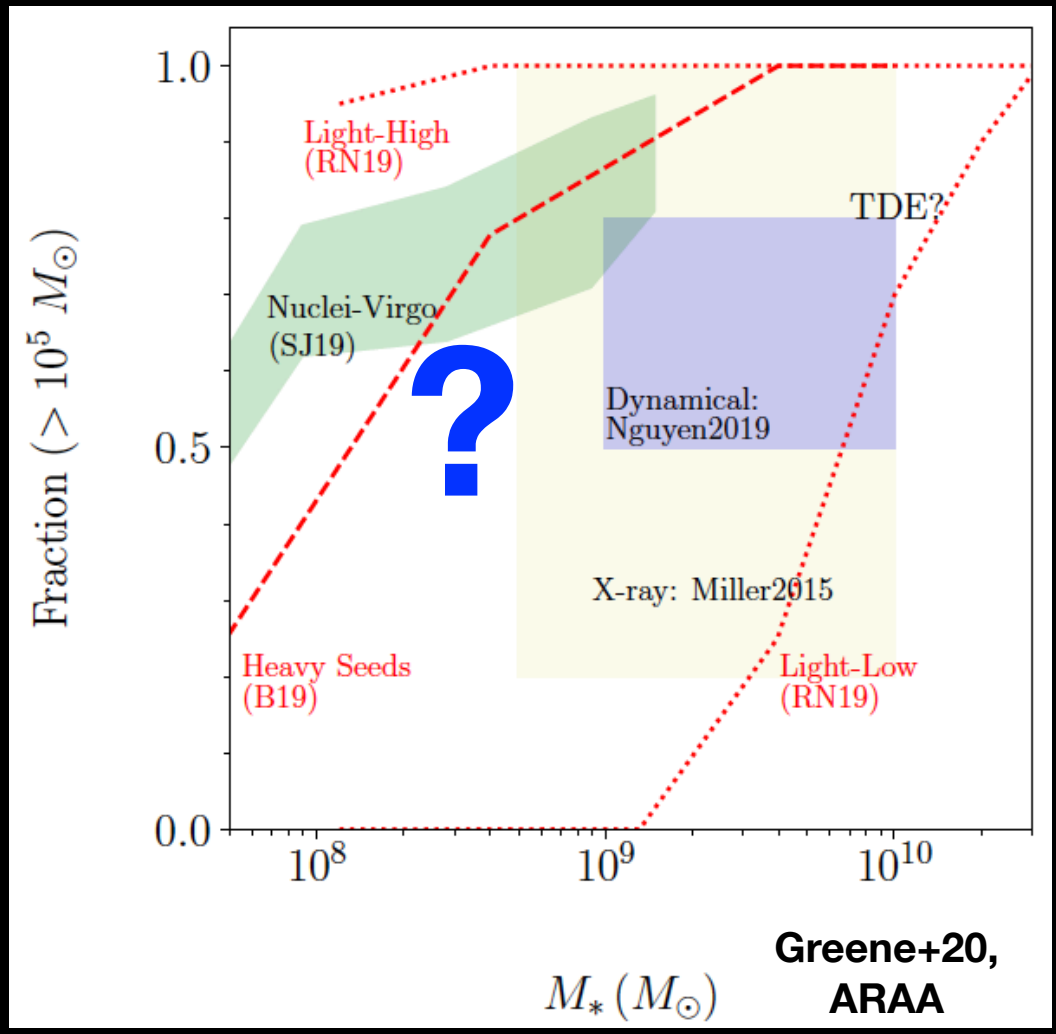
To merge, or not to merge: that is the question

I. Galaxy merger ≠ binary BH

- **Occupation function?**

Colin Burke (UIUC)
Variability-selected dwarf AGNs in the Dark Energy Survey Deep Fields (Burke+21)
Forecast for LSST (Burke+22)





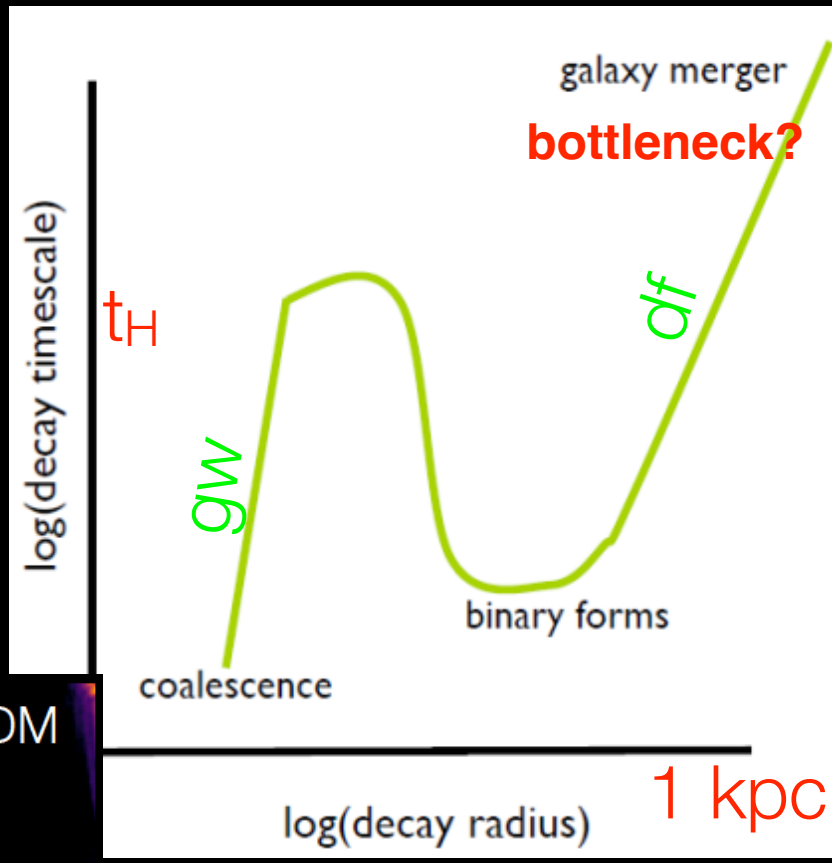
Greene+20, ARAA

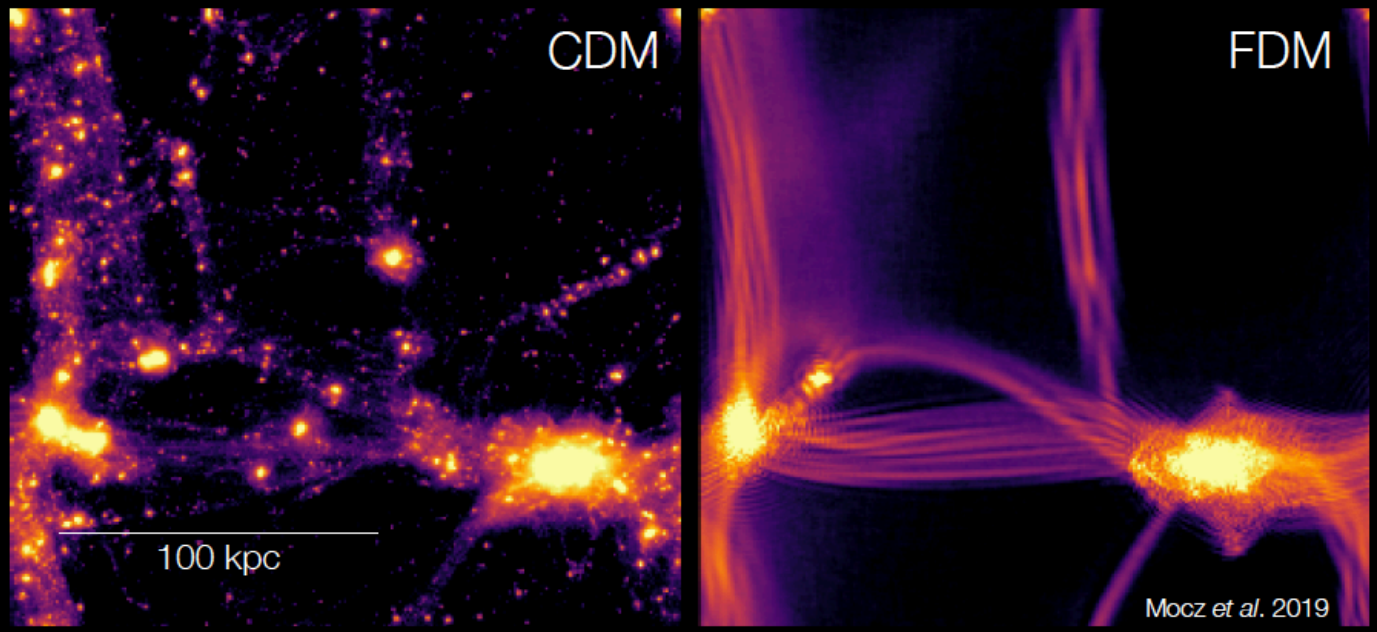
To merge, or not to merge: that is the question

I. Galaxy merger ≠ binary BH

- Occupation function?
- **Inspiral efficiency?**

Hui, Ostriker, Tremaine, Witten (2017)





To merge, or not to merge: that is the question

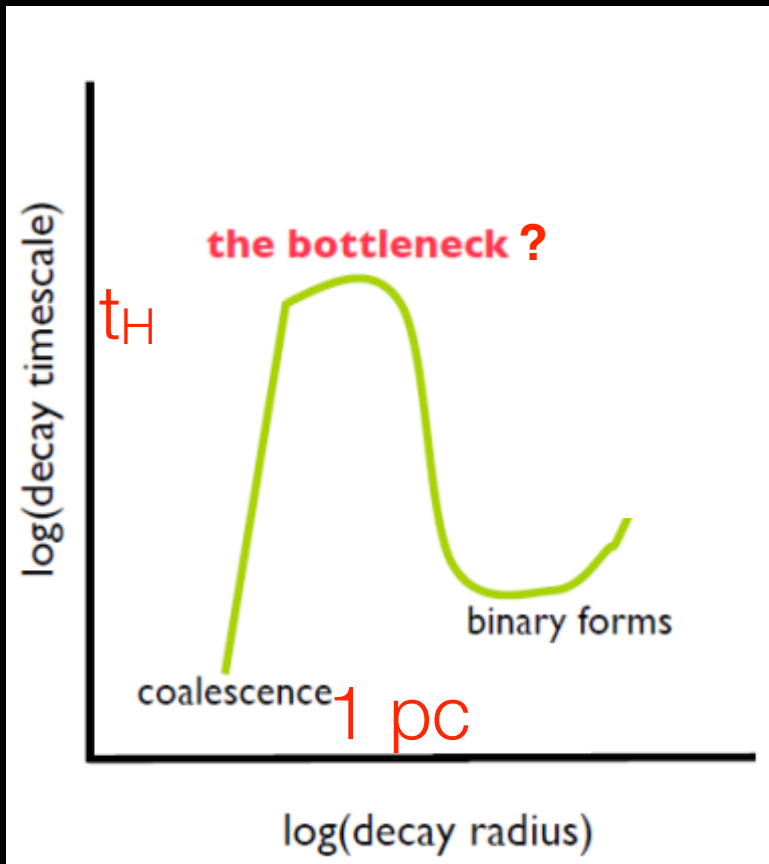
I. Galaxy merger ≠ binary BH

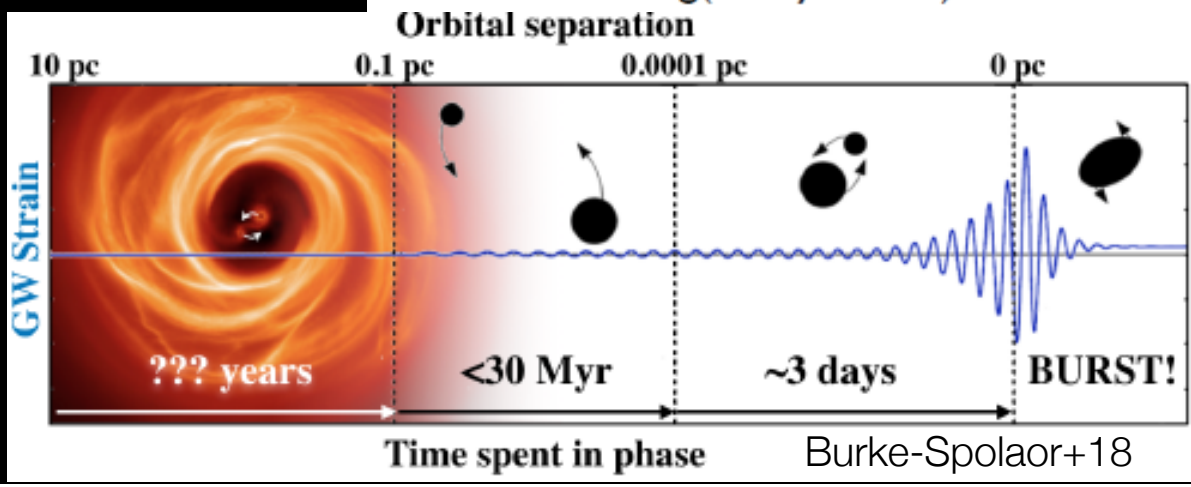
- Occupation function?
- Inspiral efficiency?

II. Binary BH ≠ BH merger

- **Dynamics (N+GR) + accretion**
- **Final-pc problem?**

(also talks by A. Lupi, S. Noble, R. Rafikov, A. Sesana)

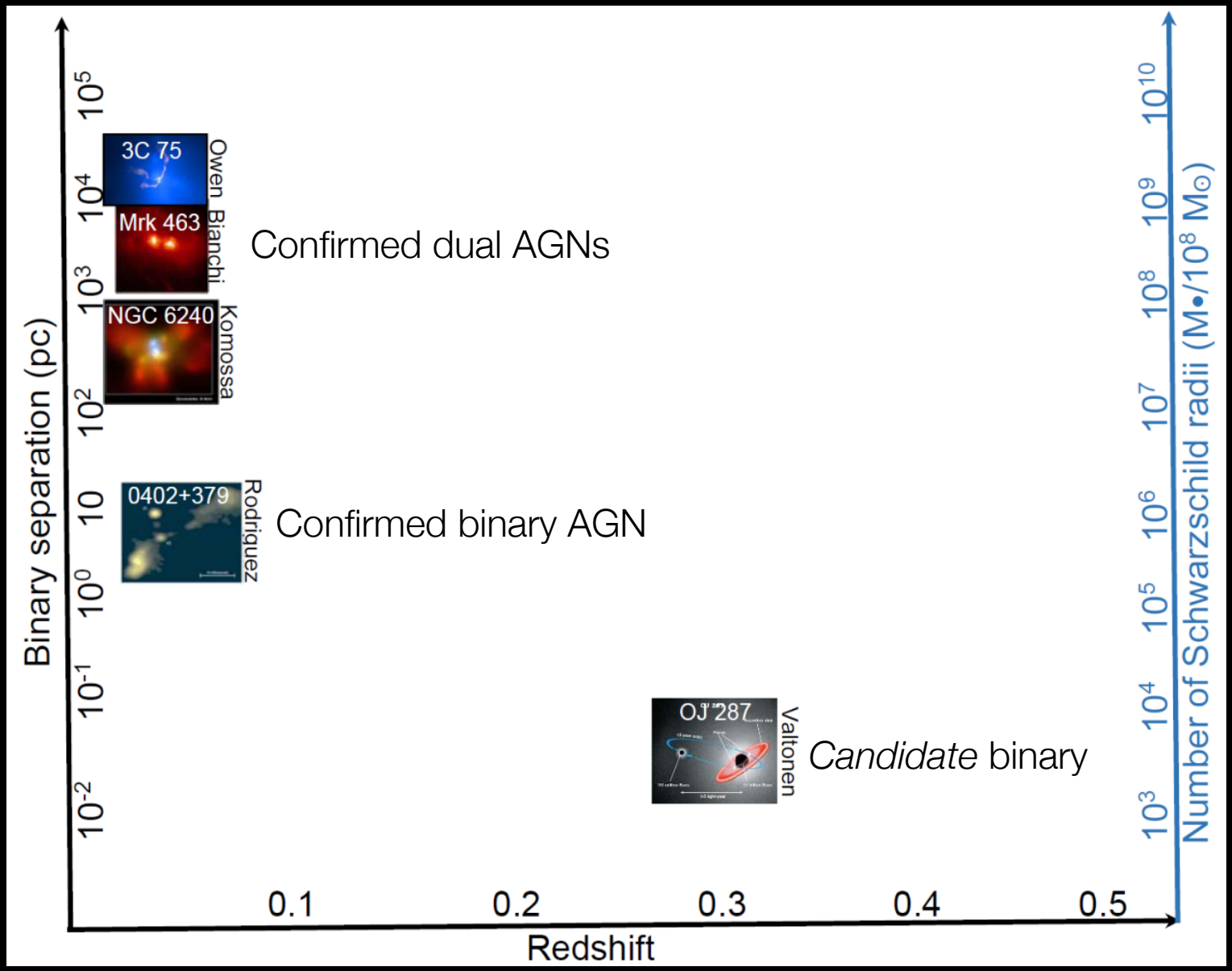




Burke-Spolaor+18

Are dual/binary AGNs rare? Special?

"All science is either physics or stamp collecting."
— Ernest Rutherford

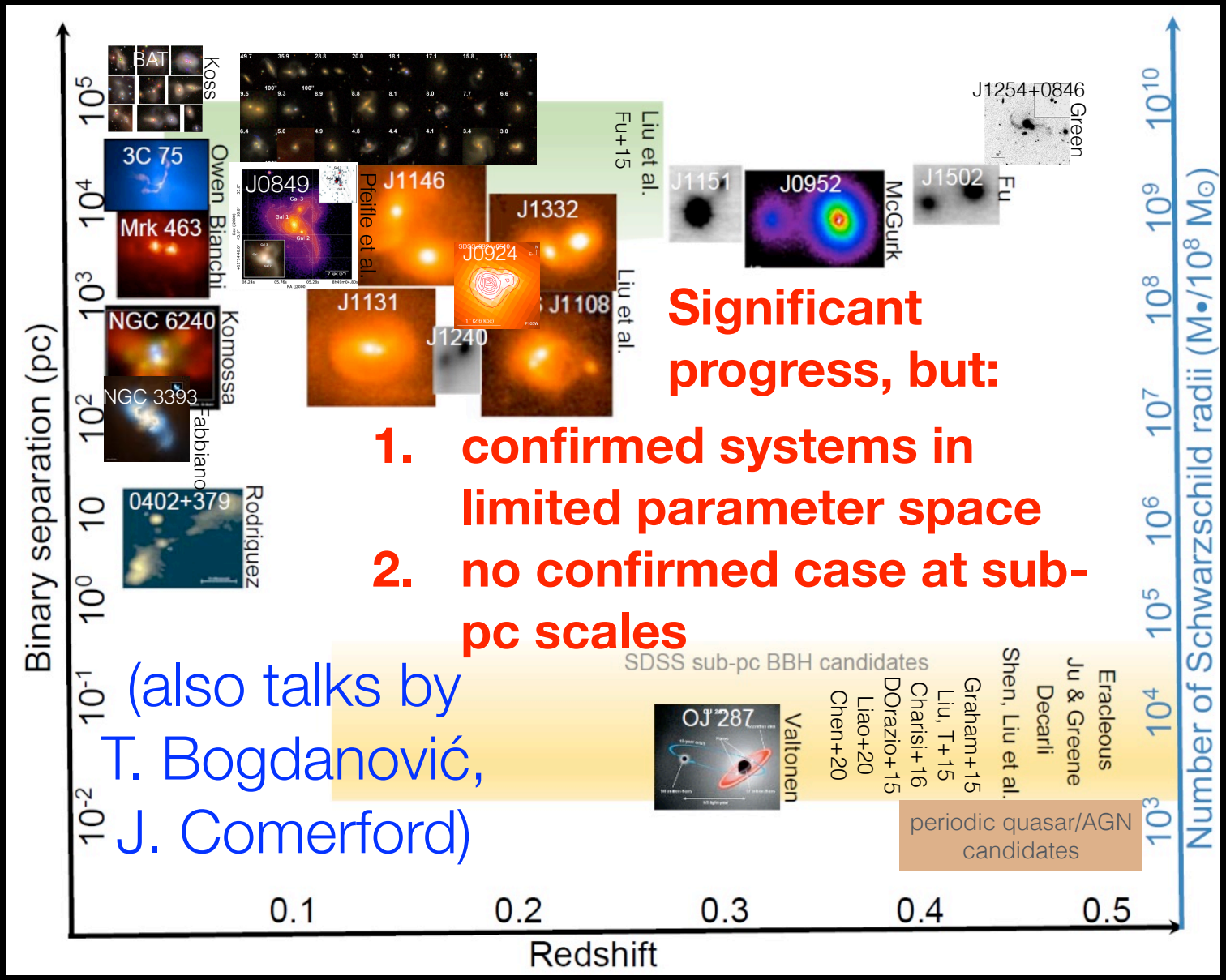


Challenges:

- Serendipitous
- Rare systems
- Difficult to resolve

Dual AGNs are common; abundance on large scales consistent with ΛCDM expectation

e.g., Yu+11



(also talks by T. Bogdanović, J. Comerford)

Challenges:

- Serendipitous
- Rare systems
- Difficult to resolve

Solutions:

- Systematic
- Large surveys
- Indirect methods (velocity/time)

Analogy with stellar binaries & exoplanets

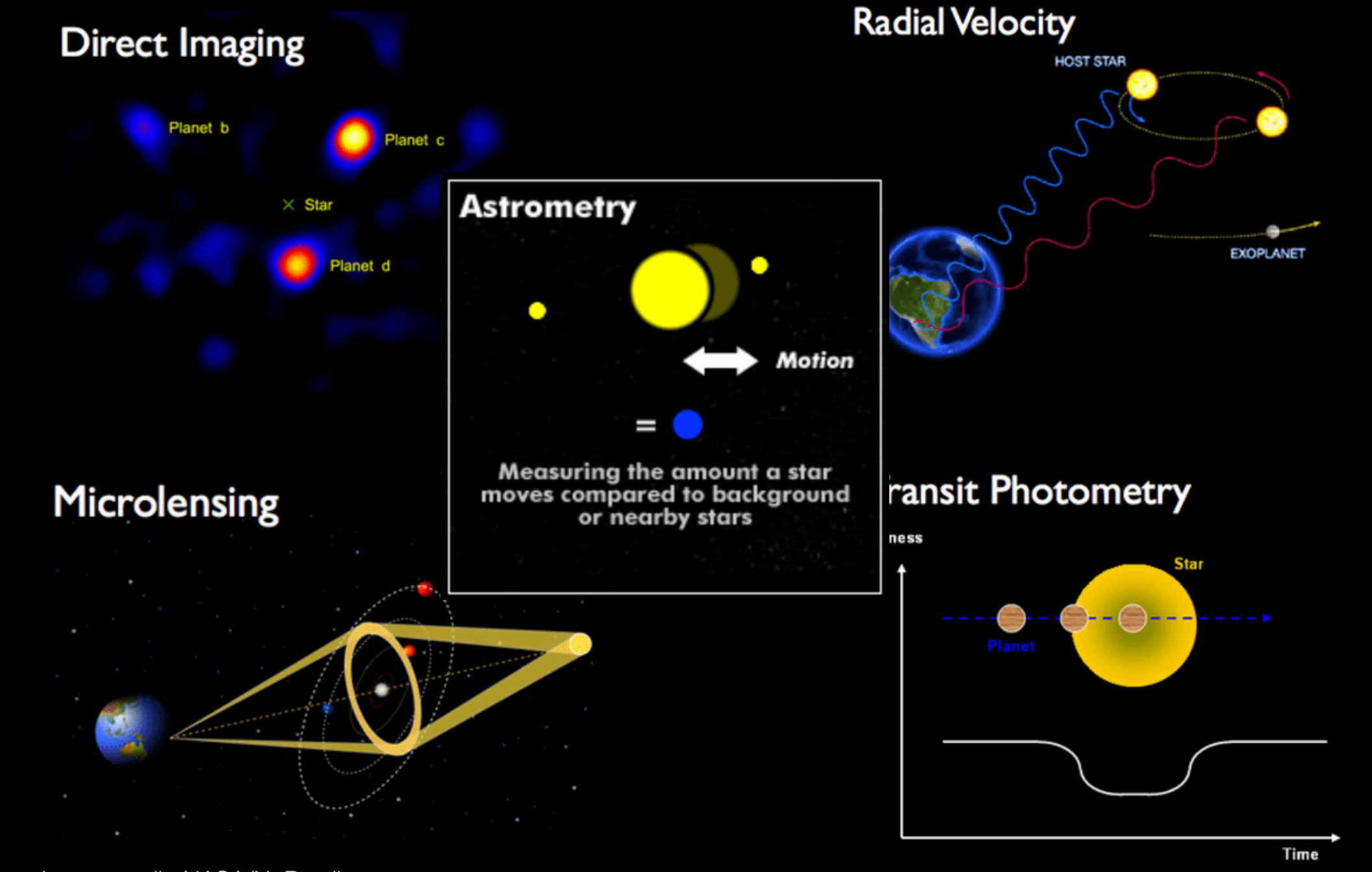


Image credit: NASA/N. Batalha

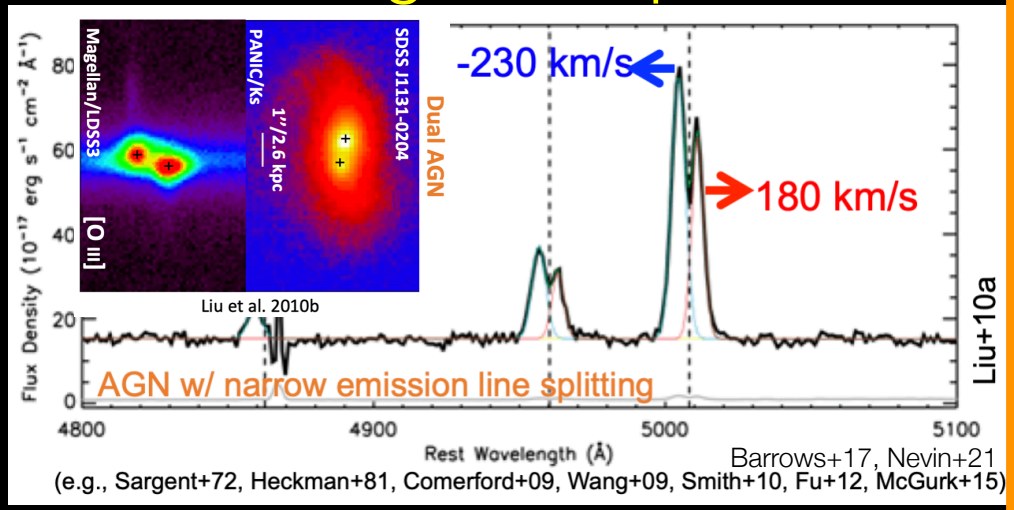
merger sequence

Direct Imaging

e.g., Liu+11, Koss+12, Stemo+21

Radial Velocity

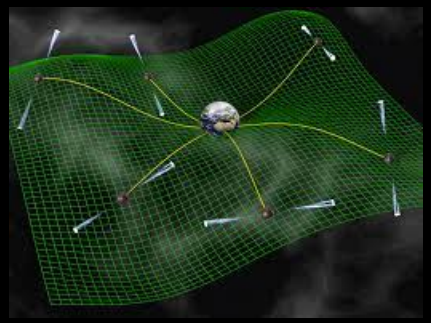
Sub-galactic pairs



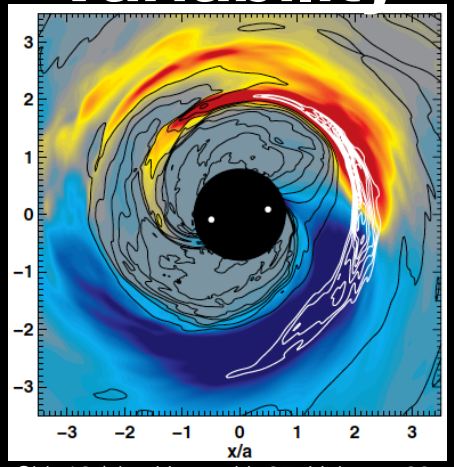
Barrows+17, Nevin+21
(e.g., Sargent+72, Heckman+81, Comerford+09, Wang+09, Smith+10, Fu+12, McGurk+15)

Candidate milli-pc binaries

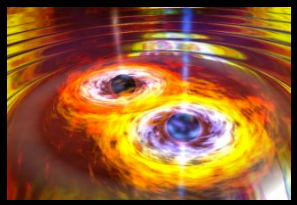
Variability



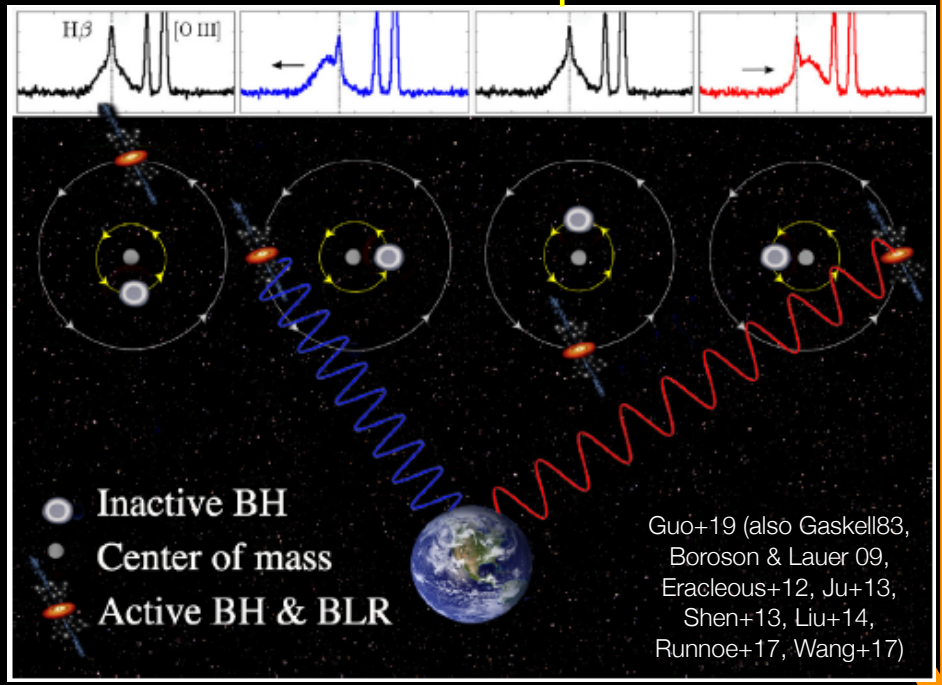
Hu+20 (also Li+12, Yan+14, D'Orazio & Di Stefano18)



Shi+12 (also Hayasaki+07, Haiman+09, Farris+14, D'Orazio+15, Gold+14, Shi & Krolik15, Duffell+19)

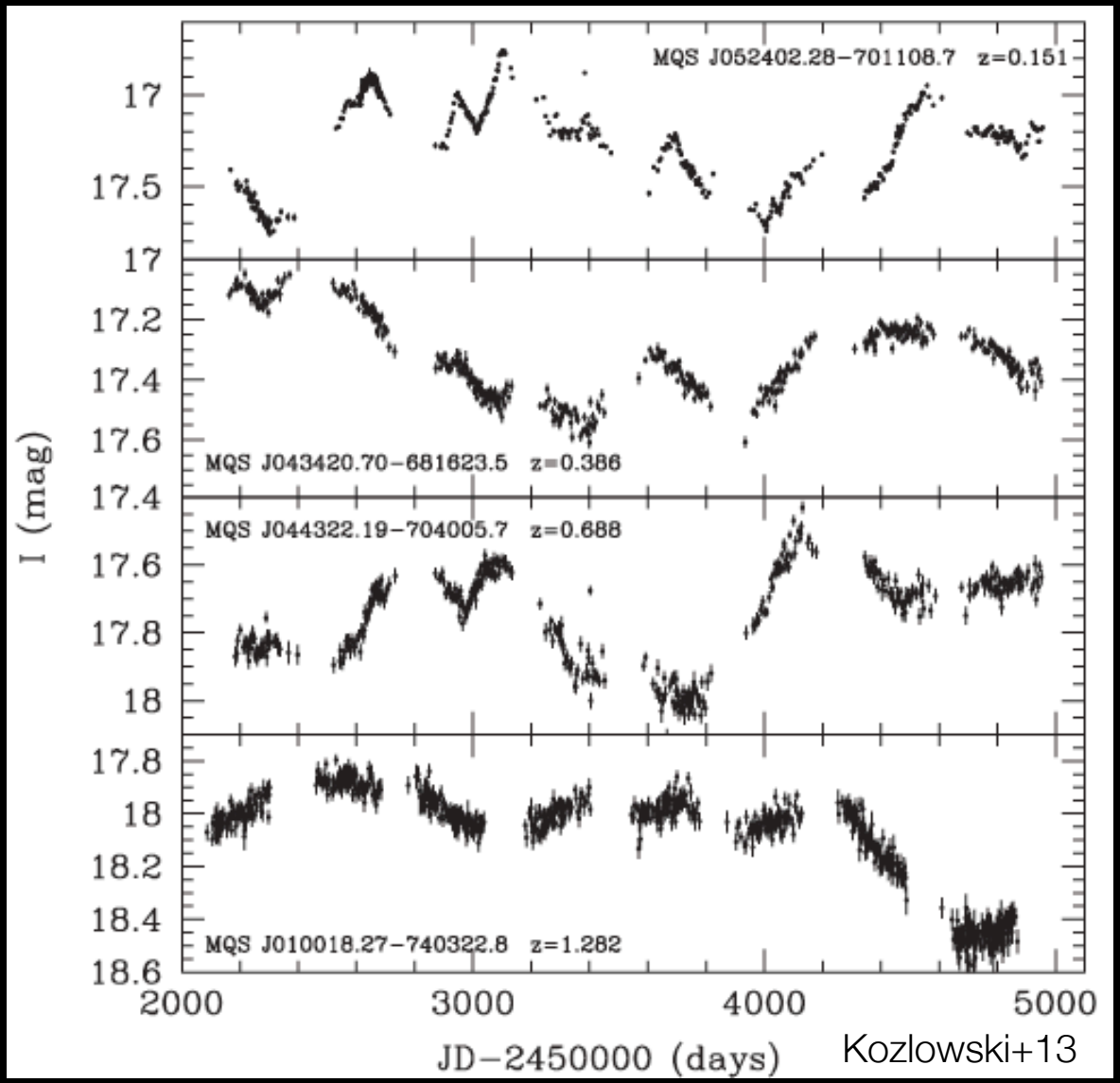


Candidate sub-pc binaries

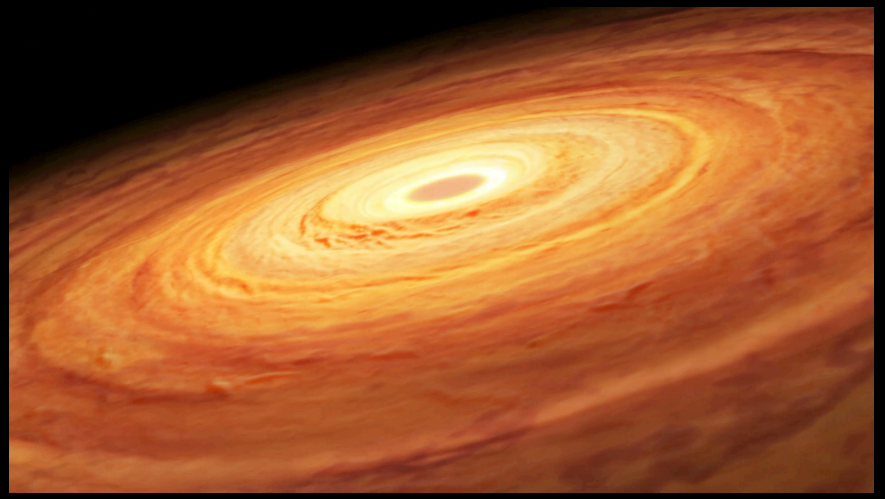


Guo+19 (also Gaskell83, Boroson & Lauer 09, Eracleous+12, Ju+13, Shen+13, Liu+14, Runnoe+17, Wang+17)

AGN luminosities vary: accretion instabilities?



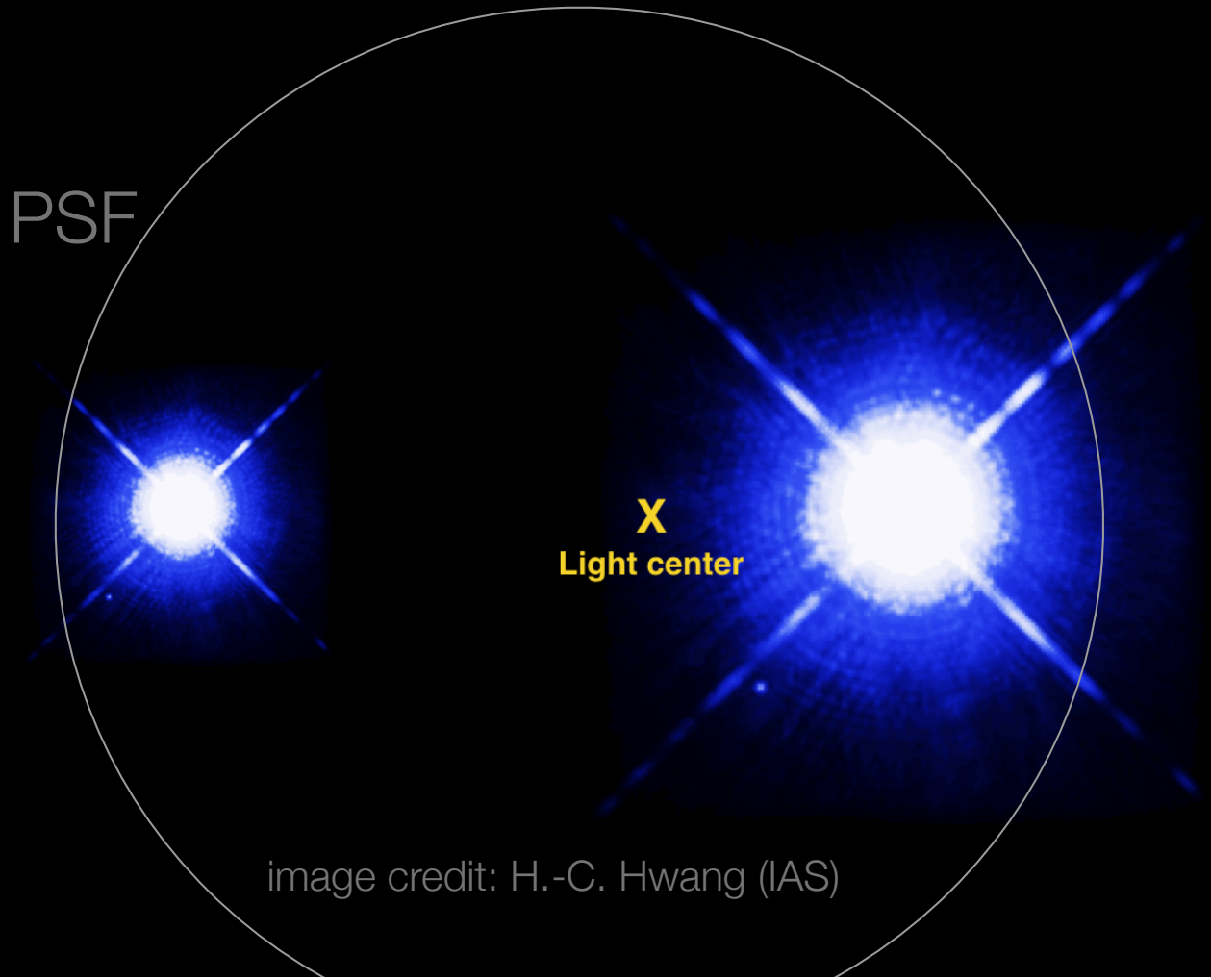
Kozlowski+13

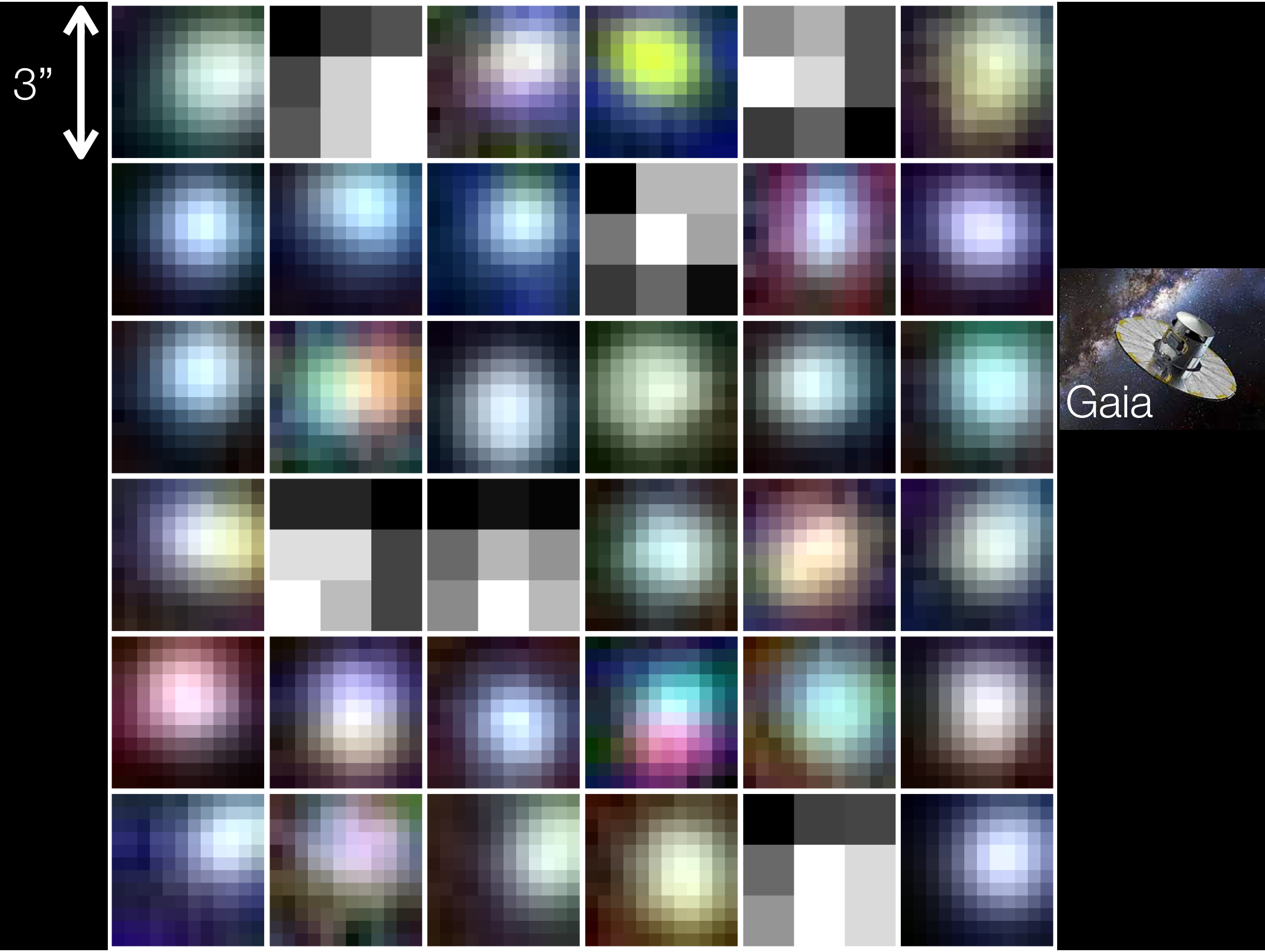


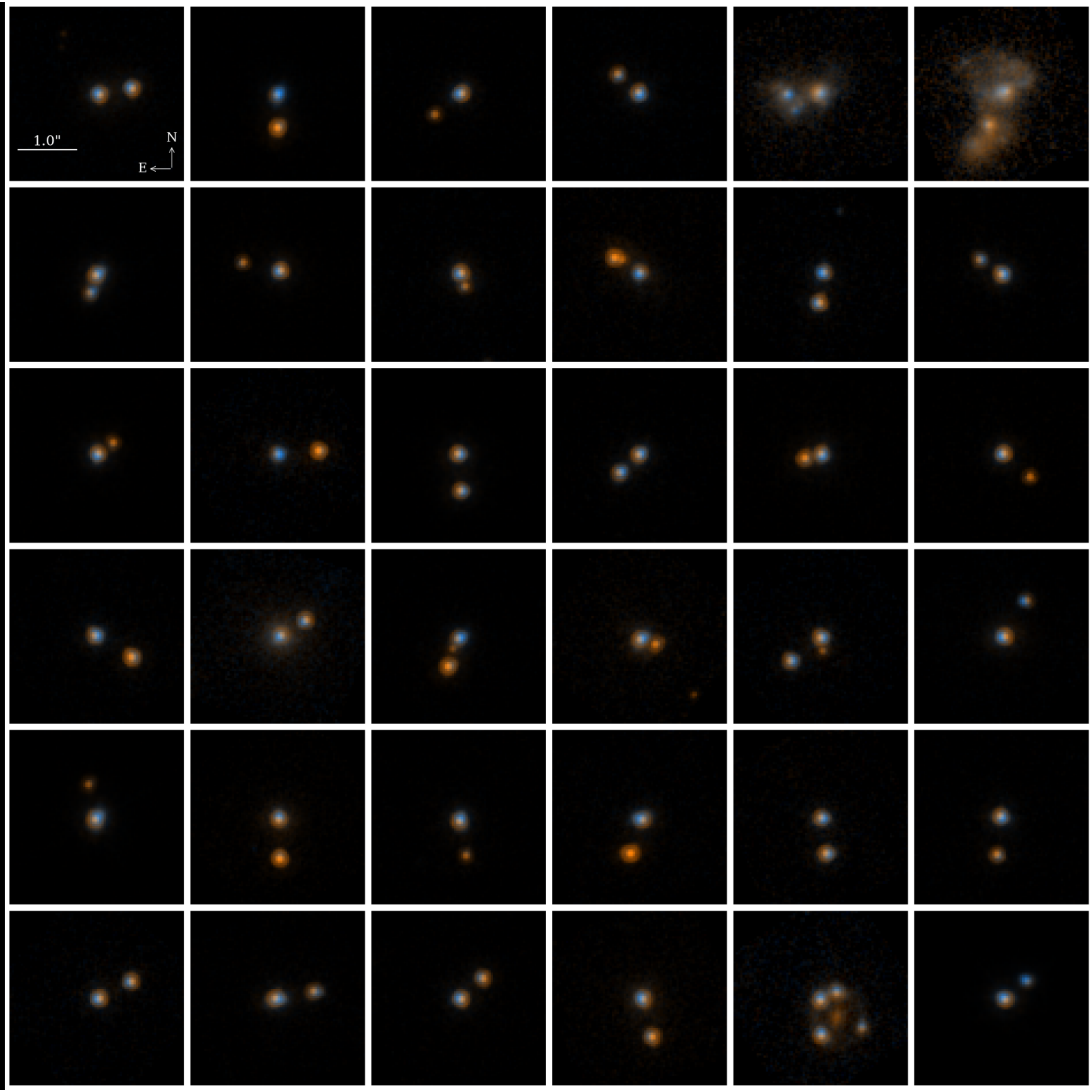
Variability+astrometry breaks the resolution limit

- Astrometry used in super-diffraction-limit applications
  (e.g., Bailey98, Shen12, Liu15,16, Stern+15, Gravity Collaboration18)
- "Varstrometry": variability-induced astrometry jitter
  (Shen+19, Hwang+20, Shen+21, Chen+22)

Hsiang-Chih Hwang (IAS)




3”
Gaia



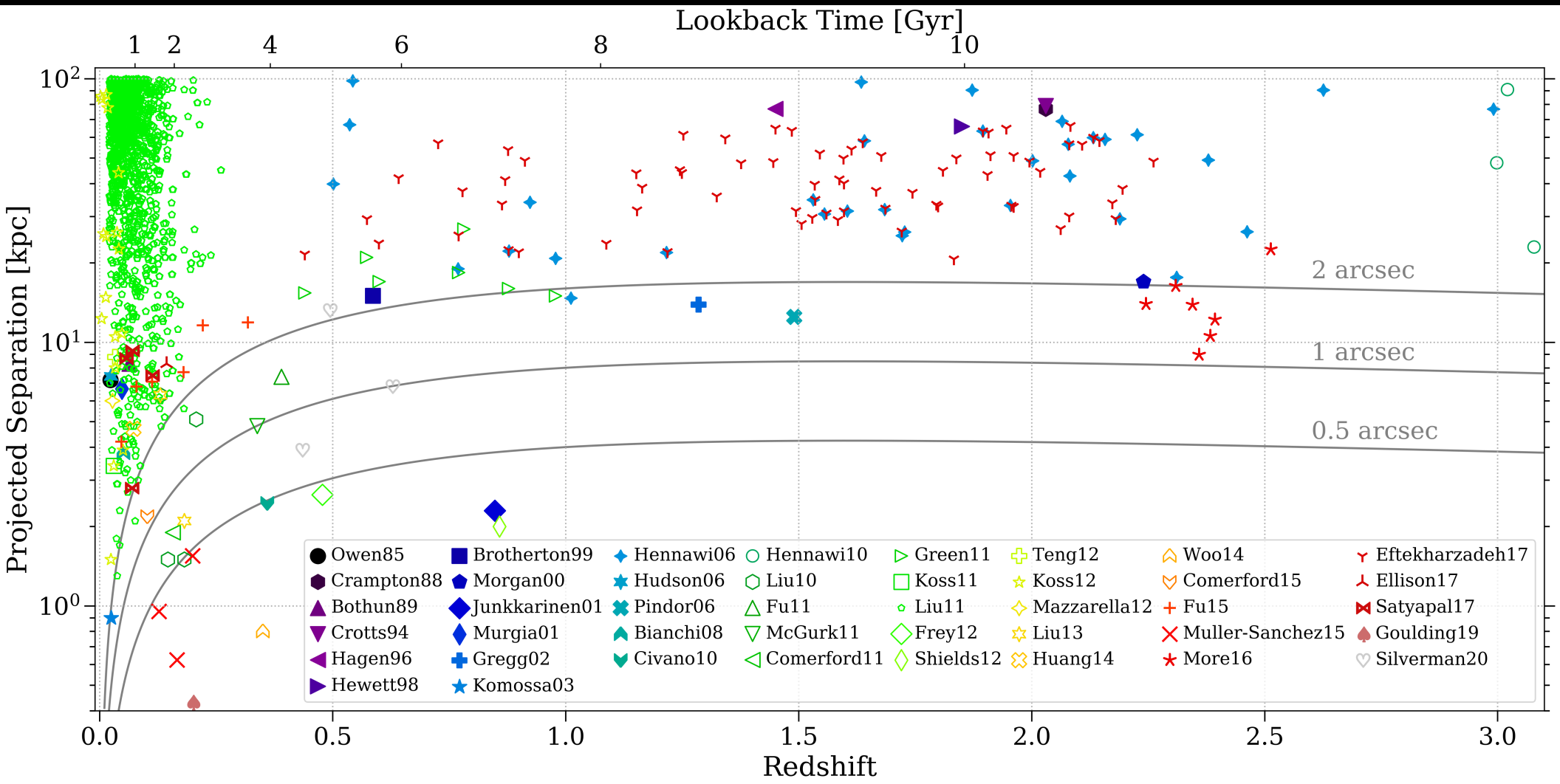
Tony Chen
(UIUC)

+

(PI Hwang)

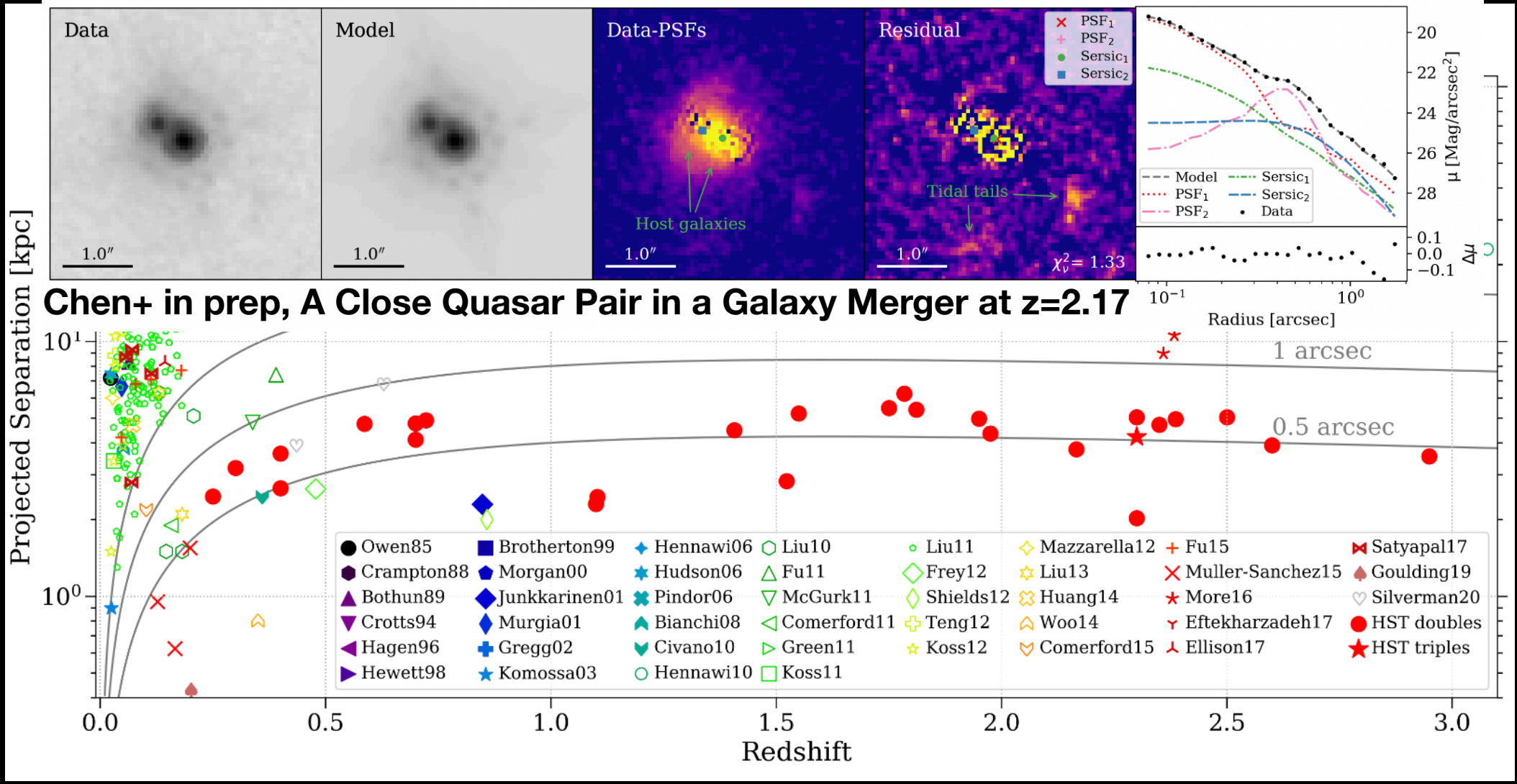
Chen+22, ApJ,
925, 162

Previous work: limited to low redshift, low AGN luminosity, and/or large separation



Chen+22, ApJ, 925, 162

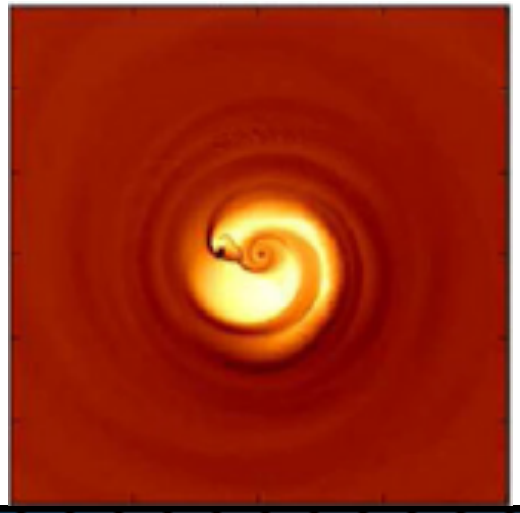
VODKA (Varstrometry for Off-nucleus and Dual sub-Kiloparsec AGN; PI Y. Shen): Discover sub-arcsecond dual/off-nuclear quasars at cosmic noon

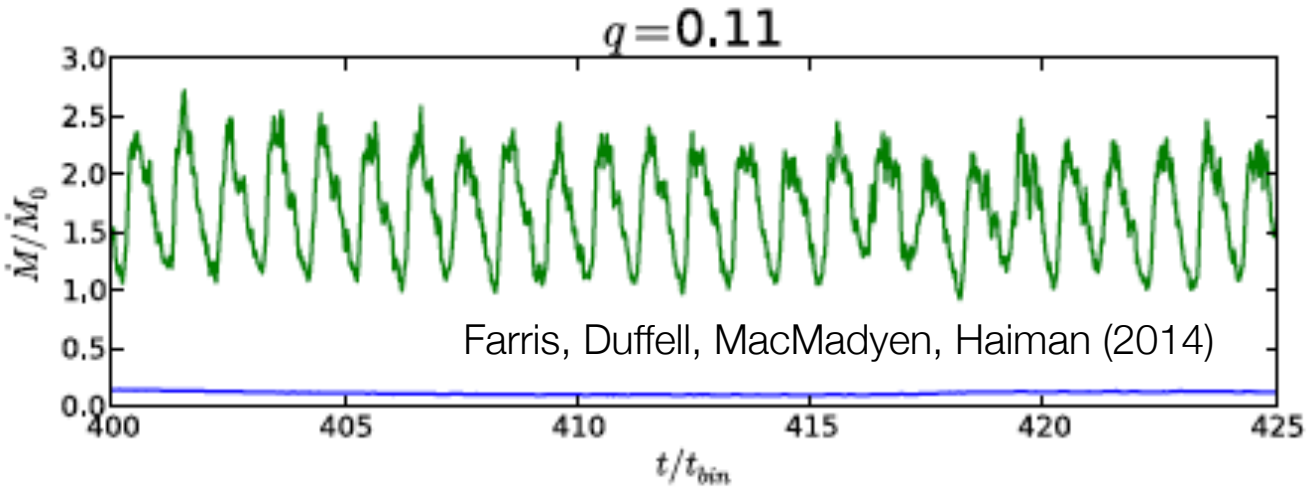


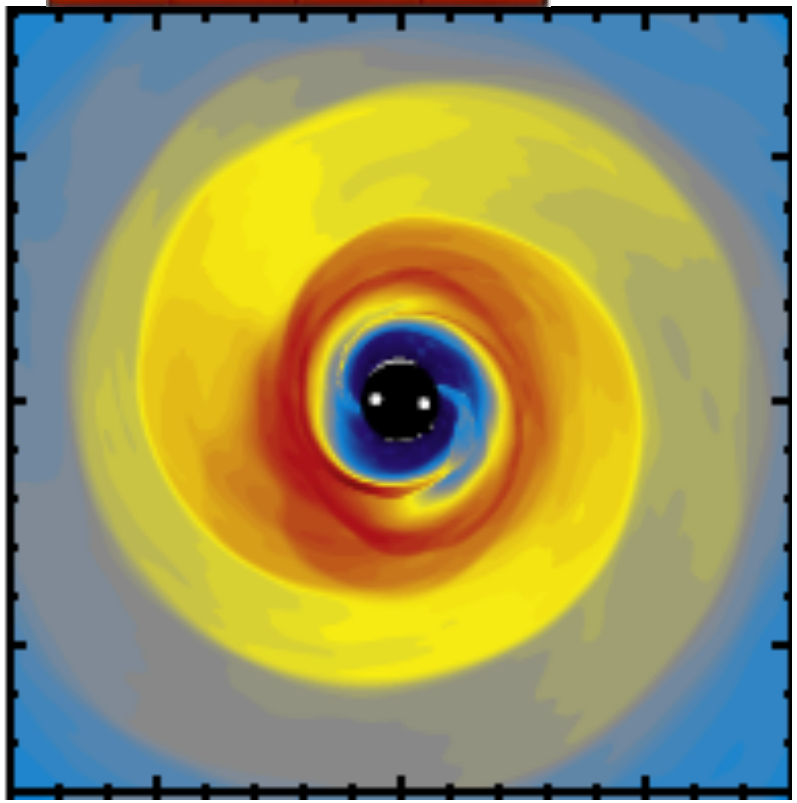
Shen+21, Chen+22, ongoing programs w/ HST, Chandra, Gemini, JWST, VLA, VLBA

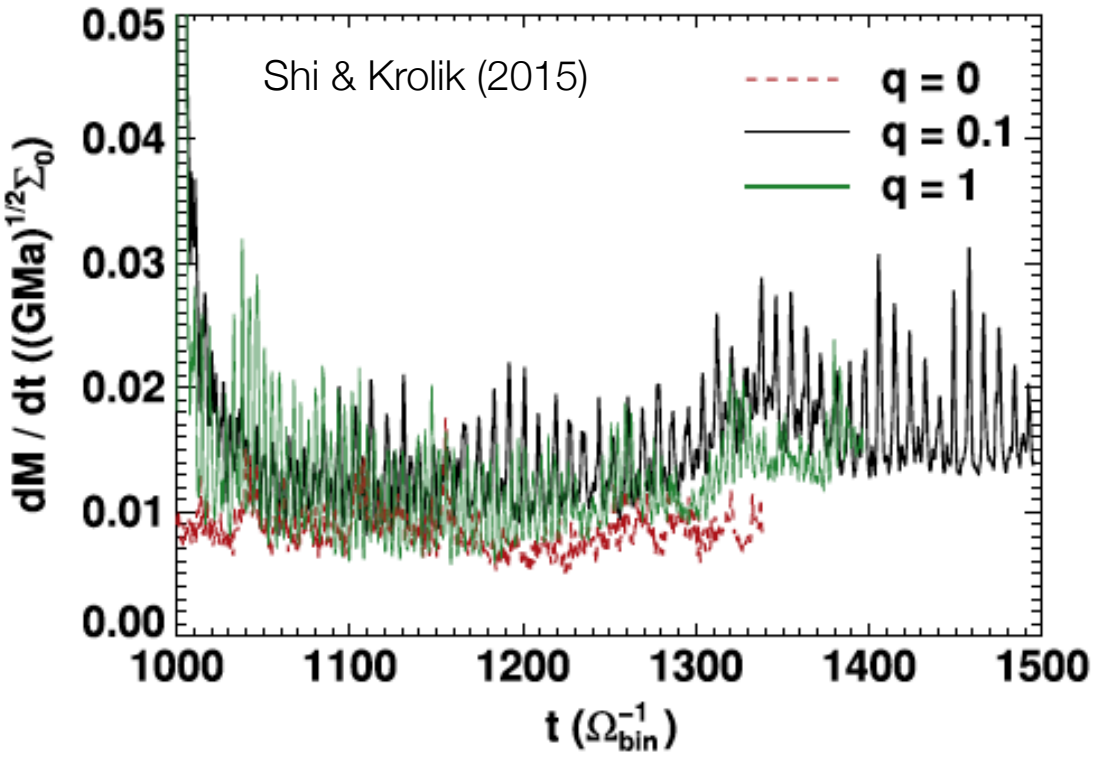
Follow-ups needed to weed out interlopers

Periodicity expected from circumbinary accretion

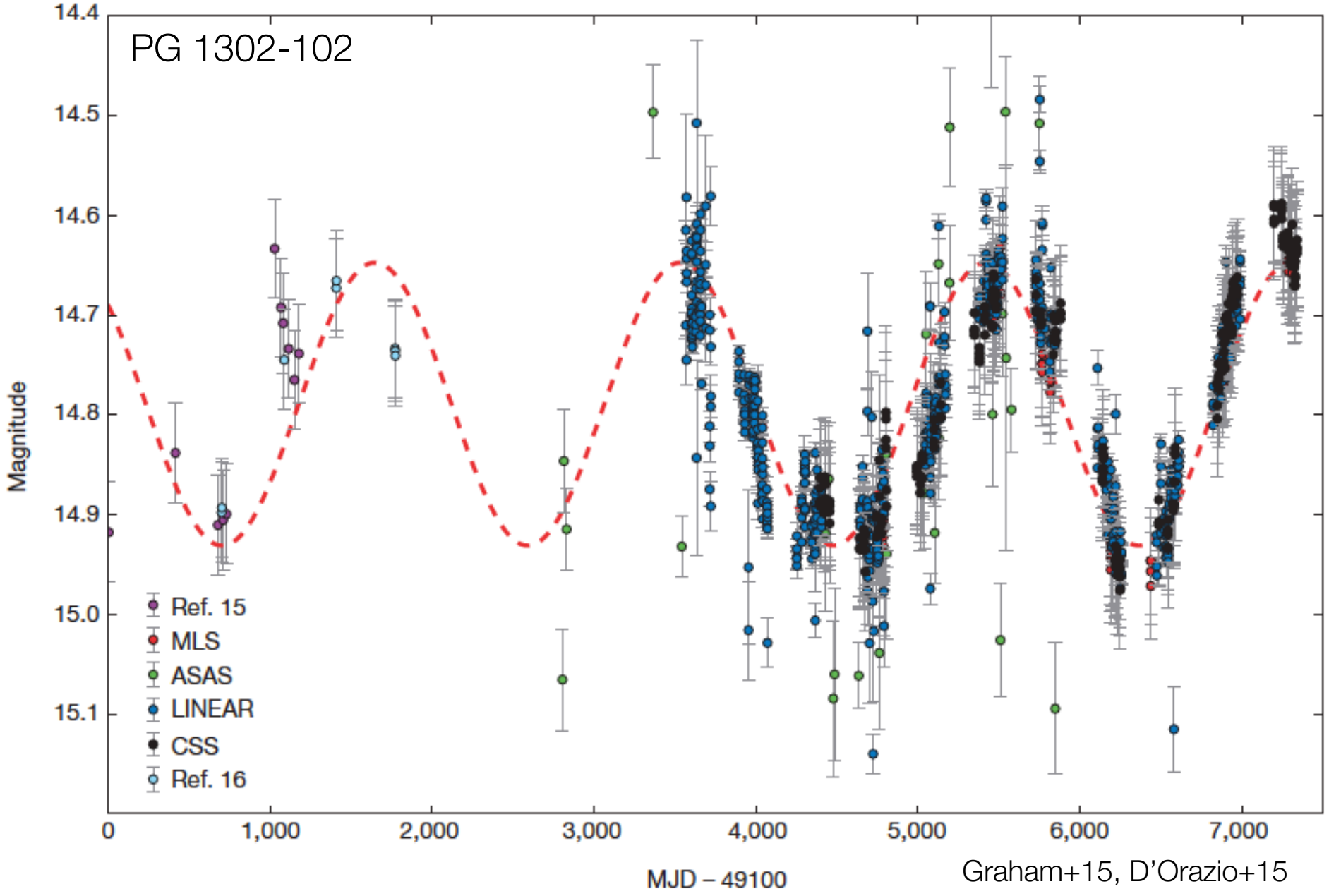






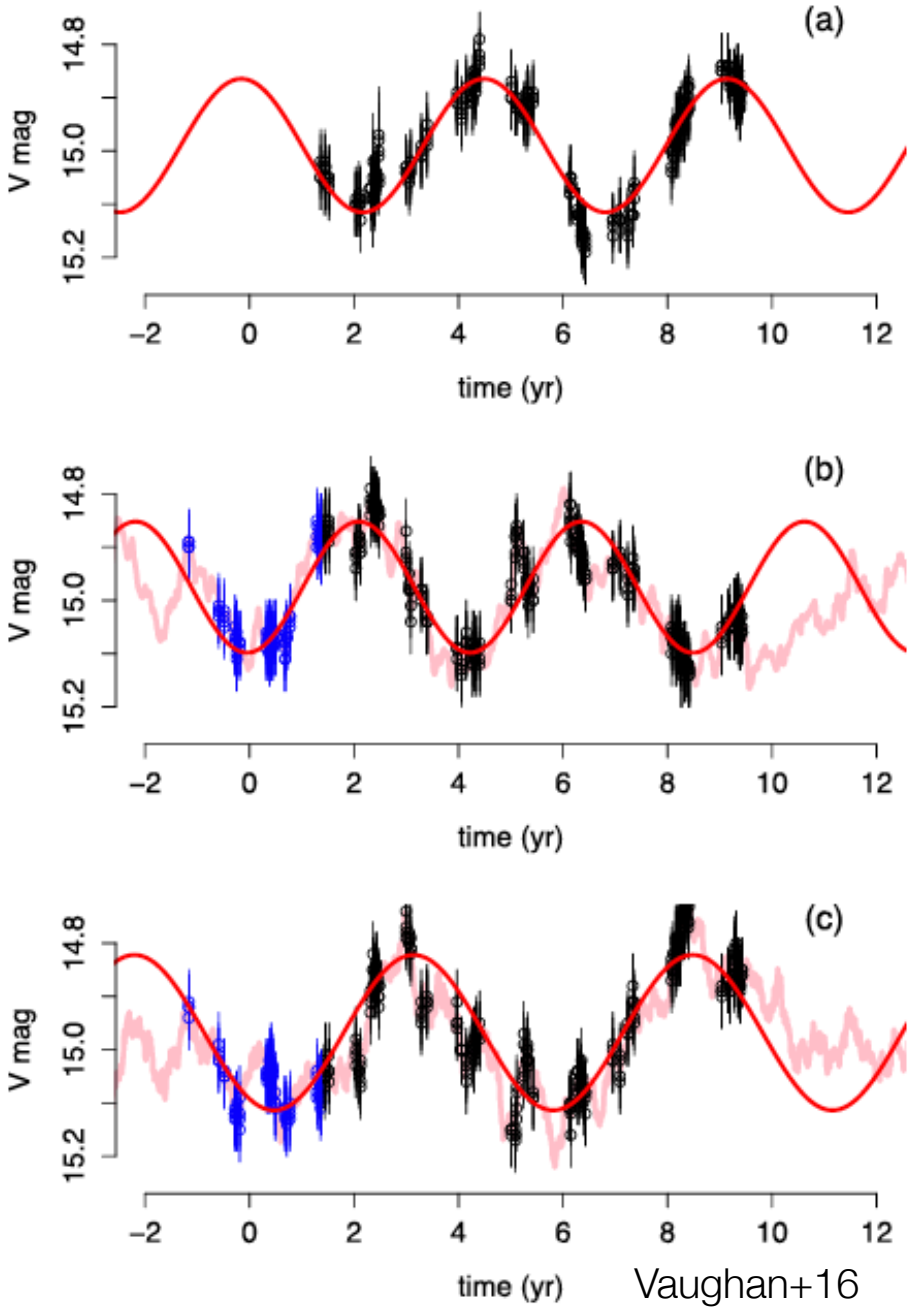


A milli-pc SBBH from Doppler beaming?



(also Charisi+ 16, Liu, T.+ 19, 20, Penil+ 20, Bao & Li 21, Xin & Haiman 21, Jiang+ 22, O'Neill+ 22 etc.)

Periodicity or (red) noise?



Vaughan+16

Which is real data and which is (simulated) noise?

Statistically indistinguishable with few cycles

(also Barth & Stern 18, Zhu & Thrane 20, Witt+21)

Combine Dark Energy Survey with SDSS

Chen+20, Liao+21

Program	Time baseline	Telescope& Aperture	Single-epoch 5σ Point-source Depth	Cadence	Mean Cadence	Area (deg^2)	Band
CRTS[1],[2],[3]	9 years	MLS/CSS/SSS, 1.5m/0.7m/0.5m	~20 (Vega)	7 days	13 days	33,000	V
PTF[4]	3.8 years	SOS, 1.2m	21.3, 20.6 (Vega)	5 days	3–50 days	2,700	gR
PanSTARRS1 MD09[5],[6],[7]	4.2 years	Haleakala, 1.8m	22.0, 21.8, 21.5, 20.9, 19.7 (AB)	3 days	6 days	8	grizY
This Work (DES+SDSS)	20 years	Blanco/APO, 4m/2.5m	24.3, 24.1, 23.5, 22.9 (AB) for DES / 22.2, 22.2, 21.3, 20.5 (AB) for SDSS	7 days for DES / 4 days for SDSS	35 days for DES+SDSS	4.69	griz

longer baseline **higher sensitivity**

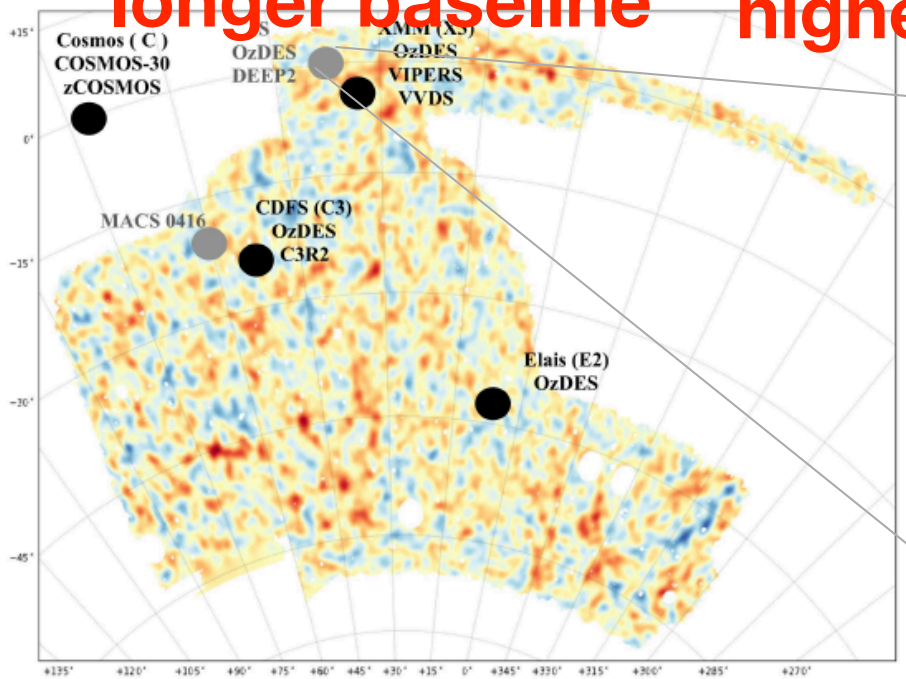


Figure: Alex Amon

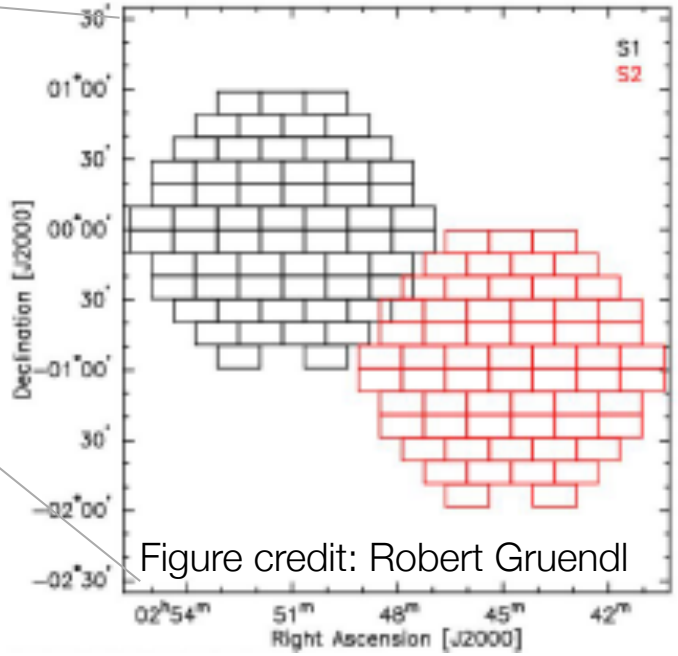
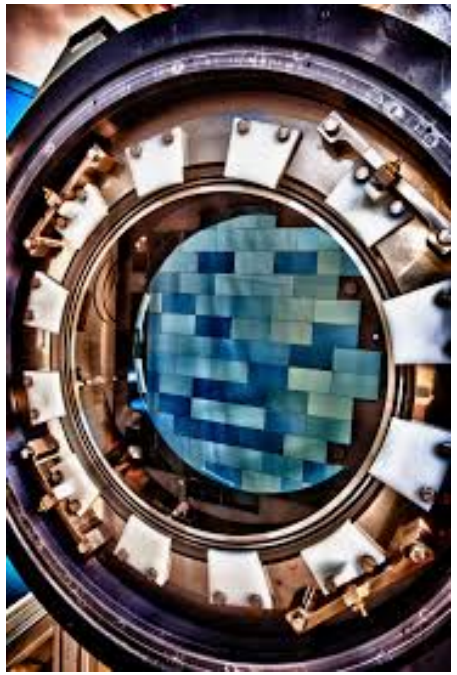
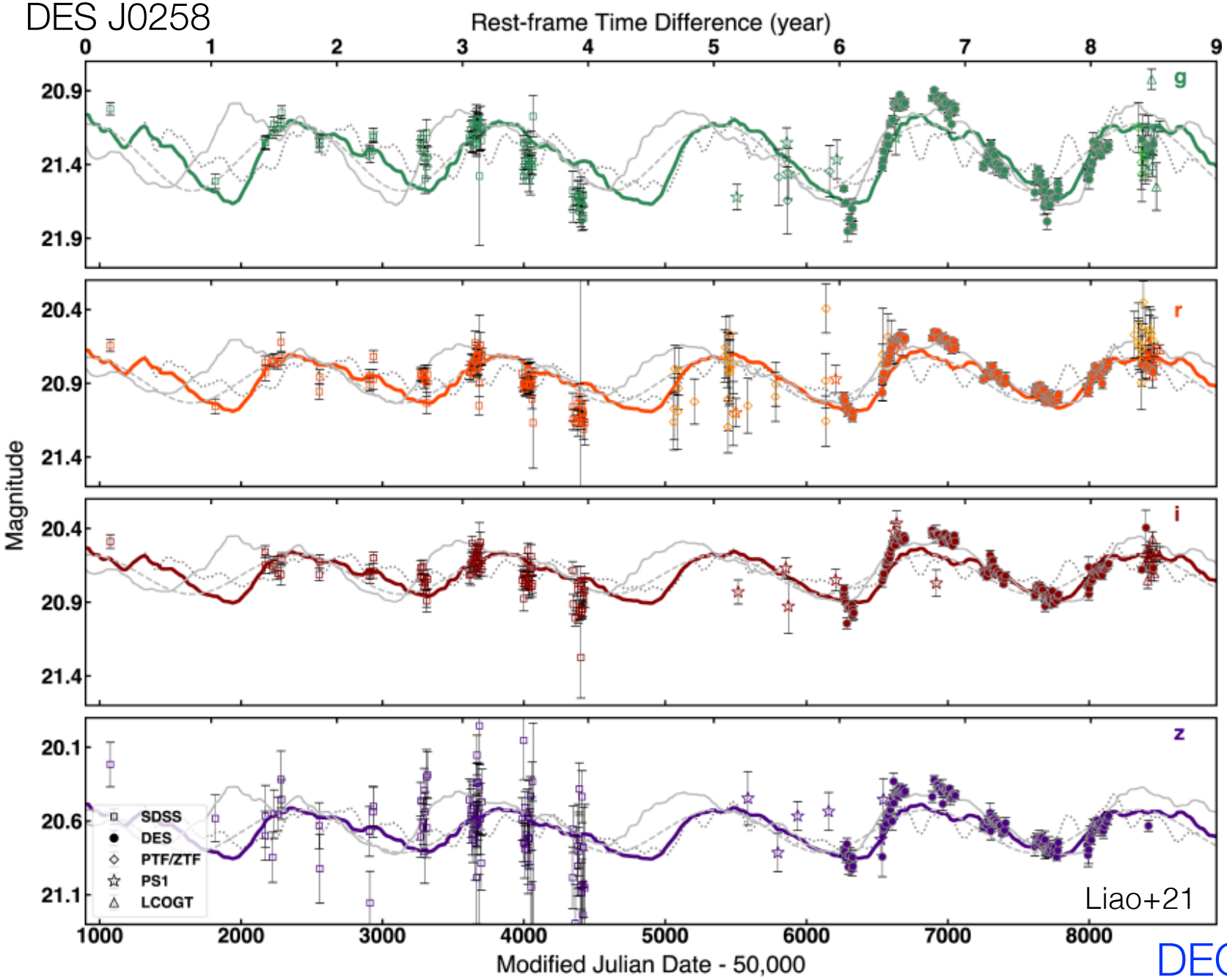


Figure credit: Robert Gruendl



Red noise? Evidence for circumbinary accretion?



1. Continued monitoring to test red noise (DECam + LSST)

Memon+ in prep

2. Multi-wavelength follow-ups (VLA, XMM, NuSTAR) to test origins

Chen+21b, Foord+22

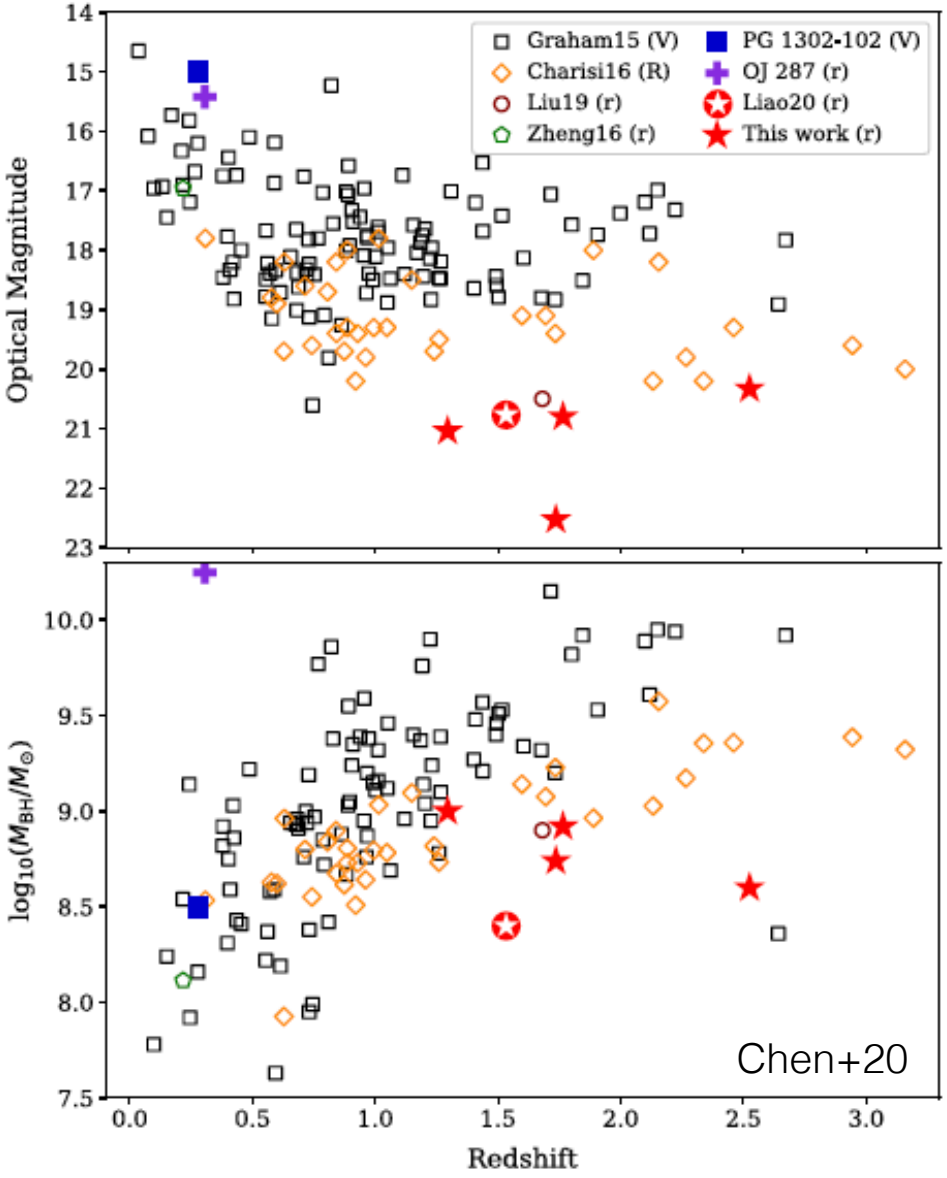
SDSS (98—07)

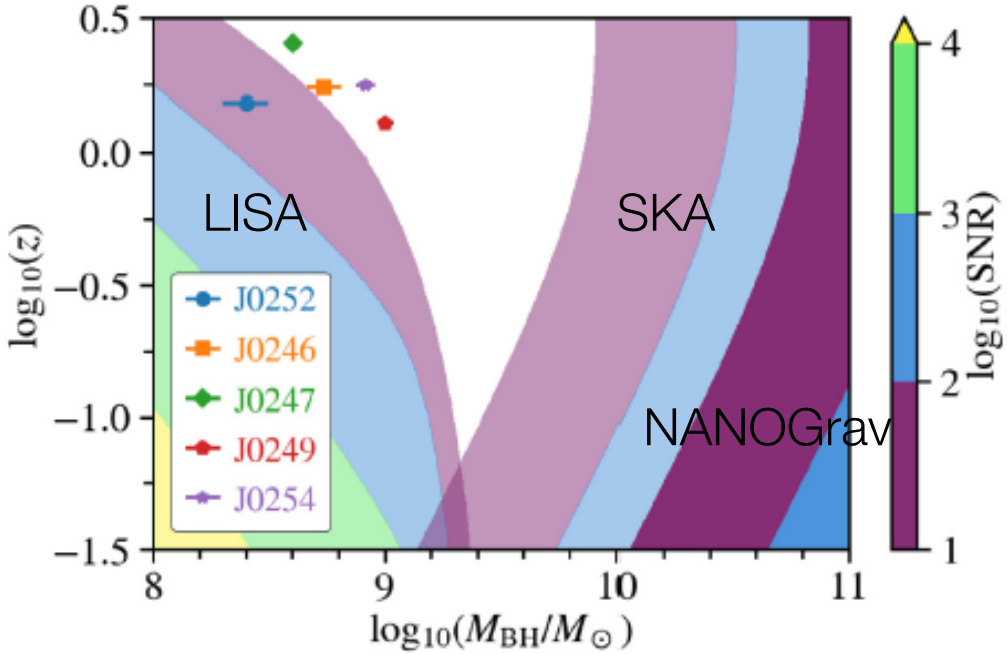
DES (12—19)

DECam (19-24)

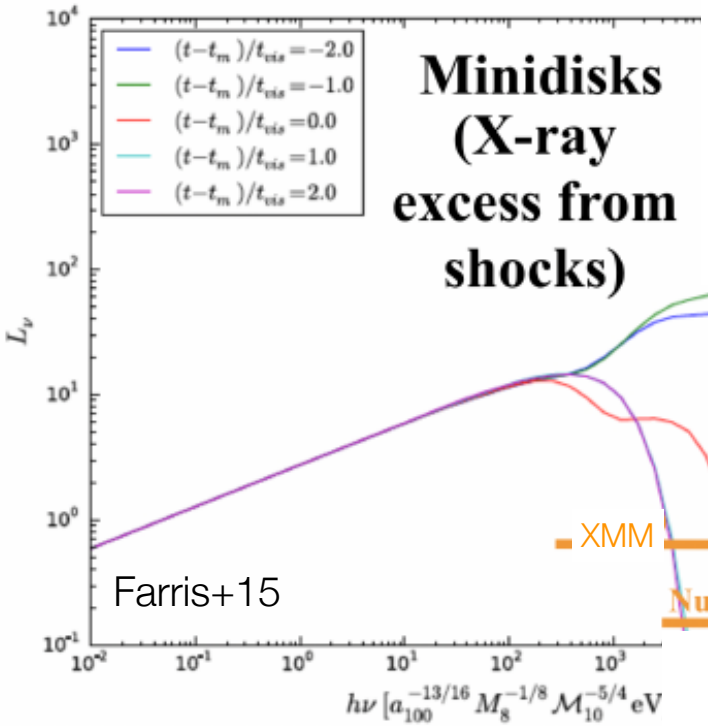
LSST (24+)

- ~2/5 candidates may be red noise accounting for the “look-elsewhere” effect.
- Compared to previous candidates from shallower surveys, DES probes higher z, less luminous quasars powered by smaller (binary) SMBHs.

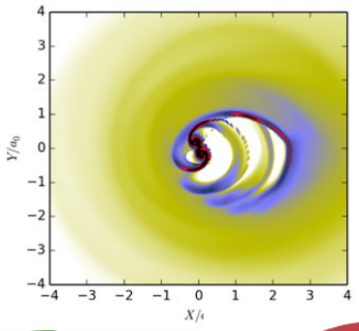




- DES deep field periodicity detection rate is 4~80 times higher than previous estimates based on shallower surveys, but still consistent with PTA upper limits.

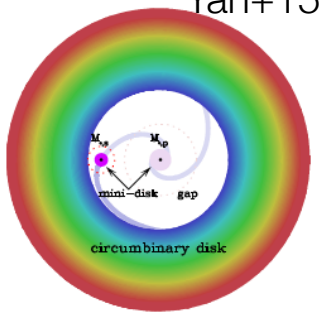


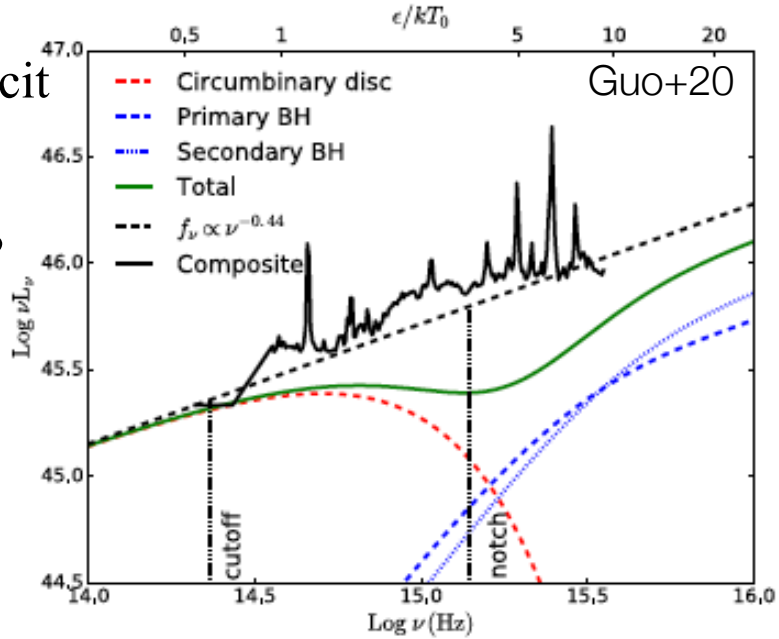
(also Milosavljević & Phinney 05)



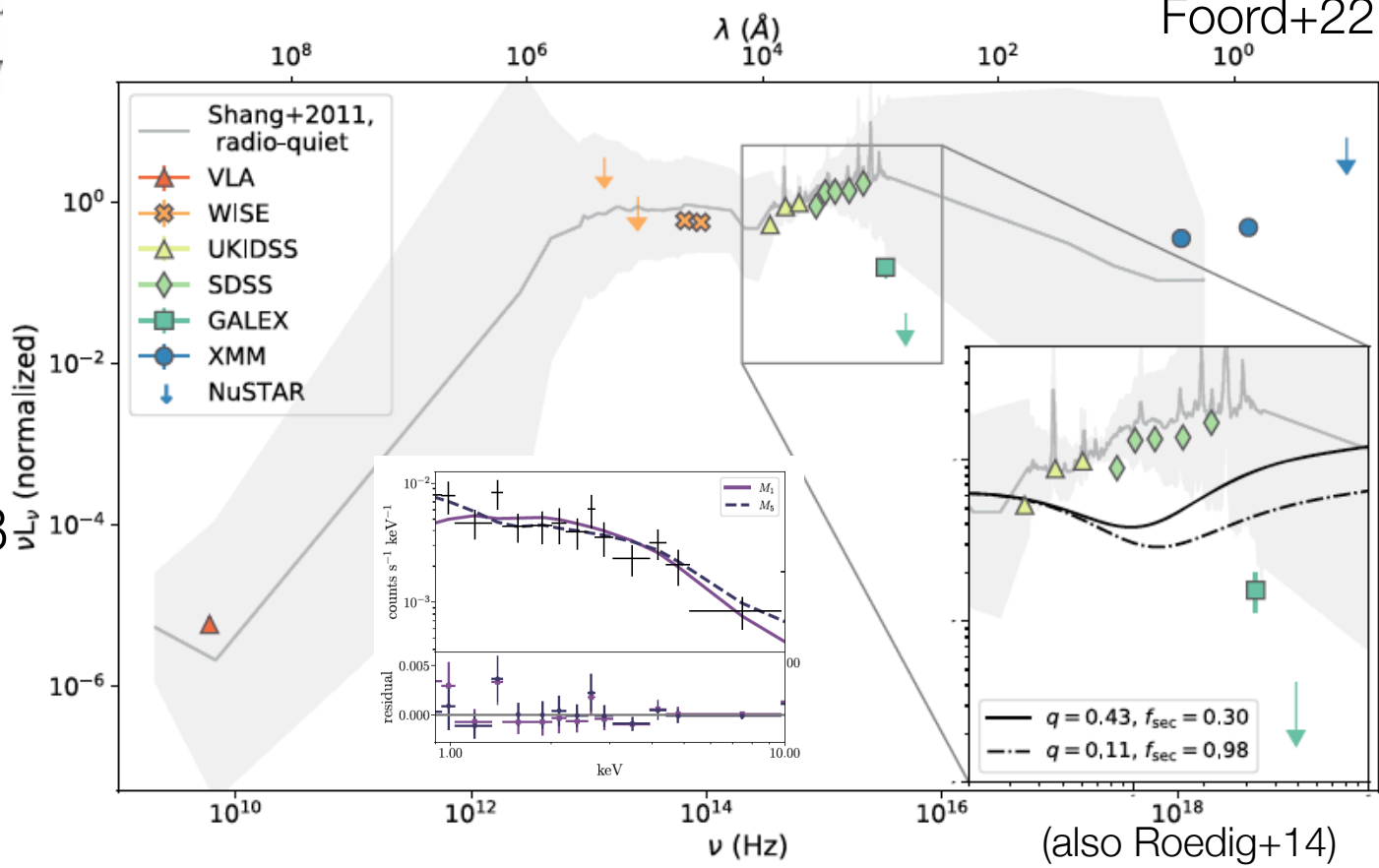
Flux deficit from a central cavity?

Yan+15





Foord+22



(also Roedig+14)

Adi Foord (Stanford)

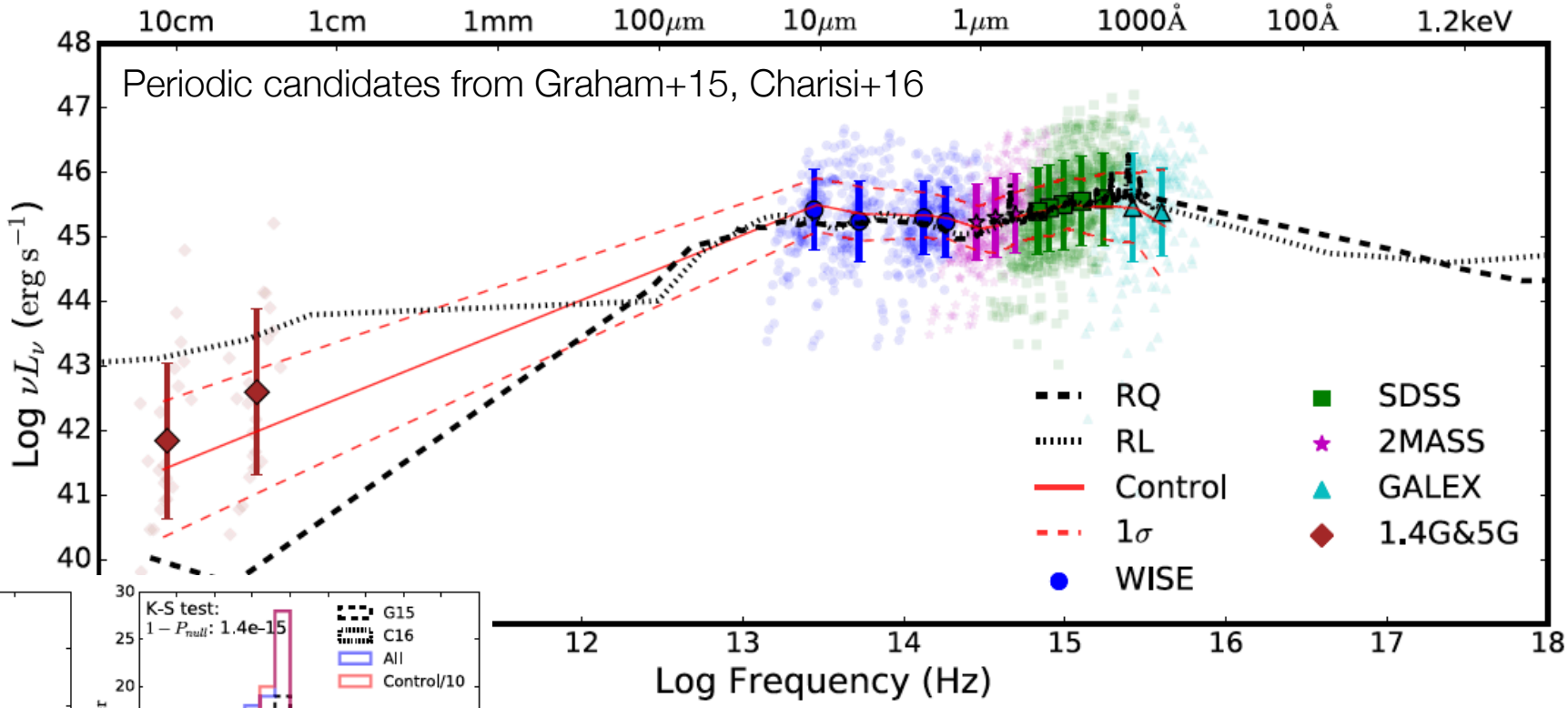
Evidence for CBD inconclusive in DES J0258 from SED. Motivates further tests.

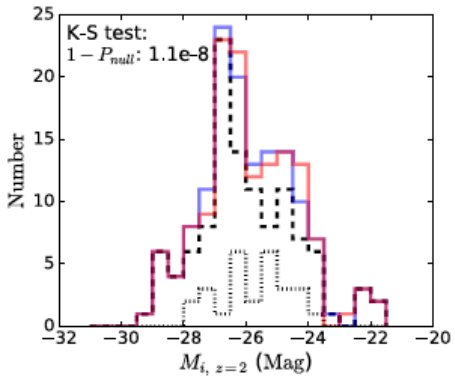
(also Foord+17, Saade+20)

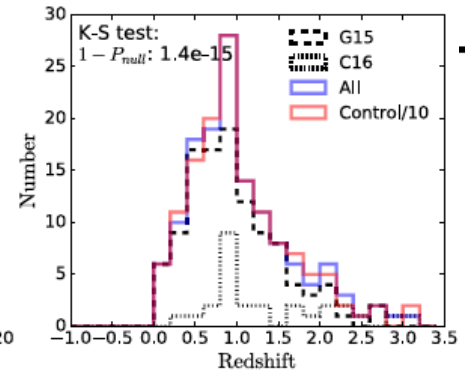
Majority of optically-selected periodic quasar candidates show similar SEDs to normal control optical quasars

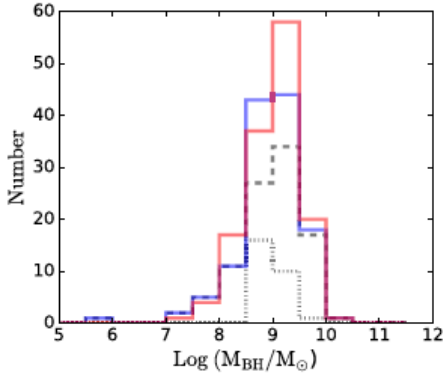
Guo+20

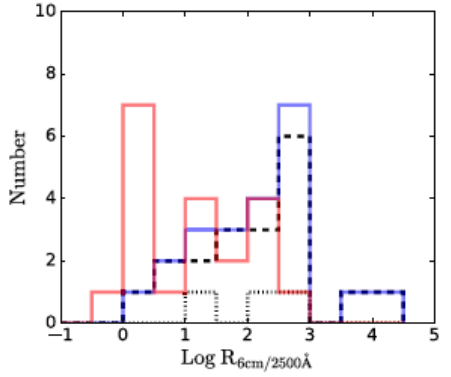
Hengxiao Guo
(UC Irvine)





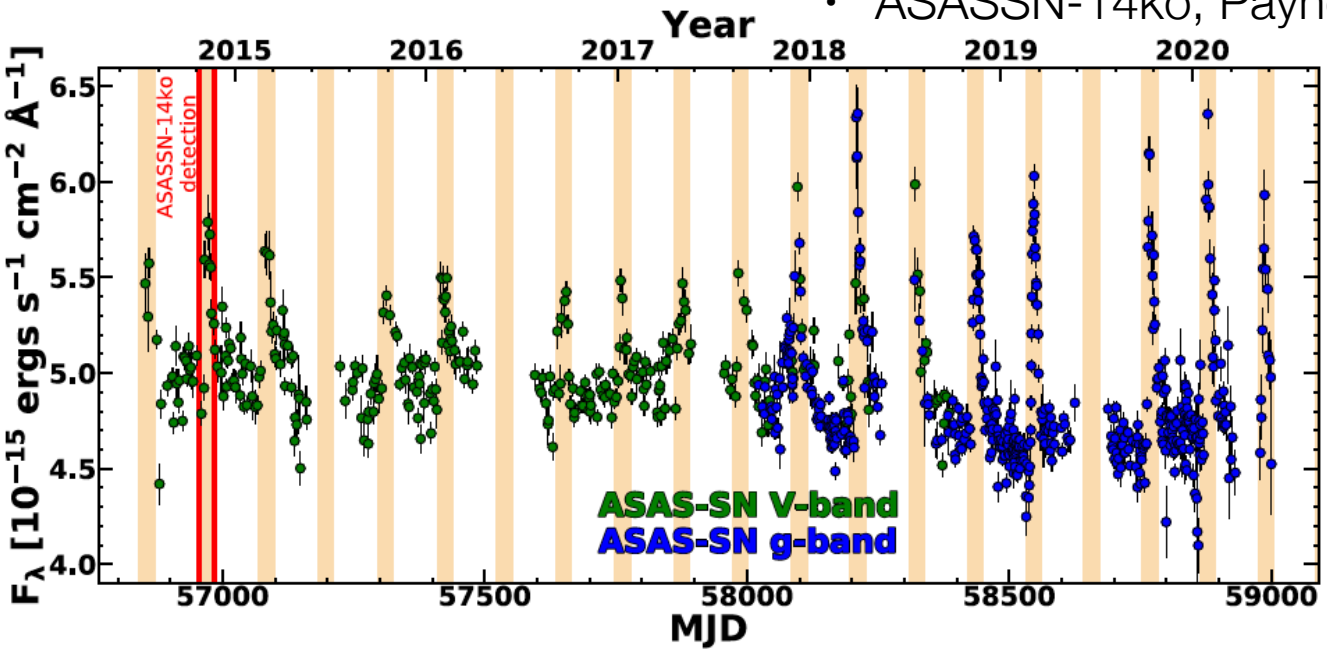


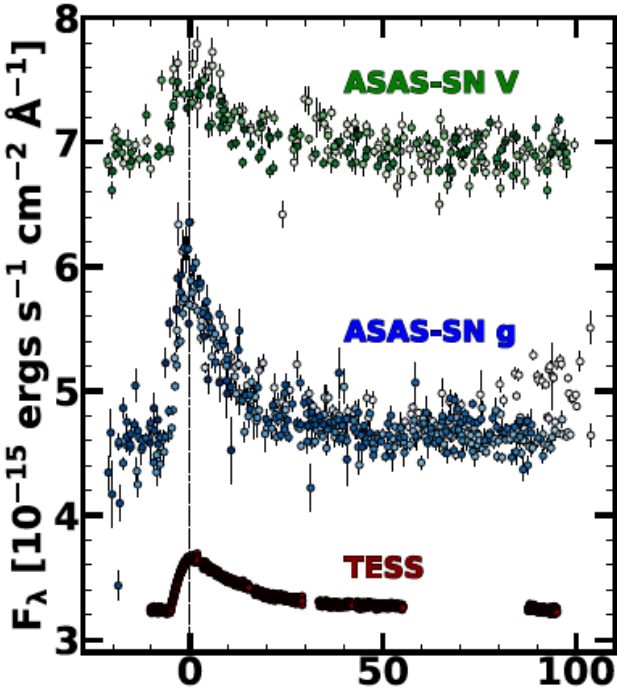




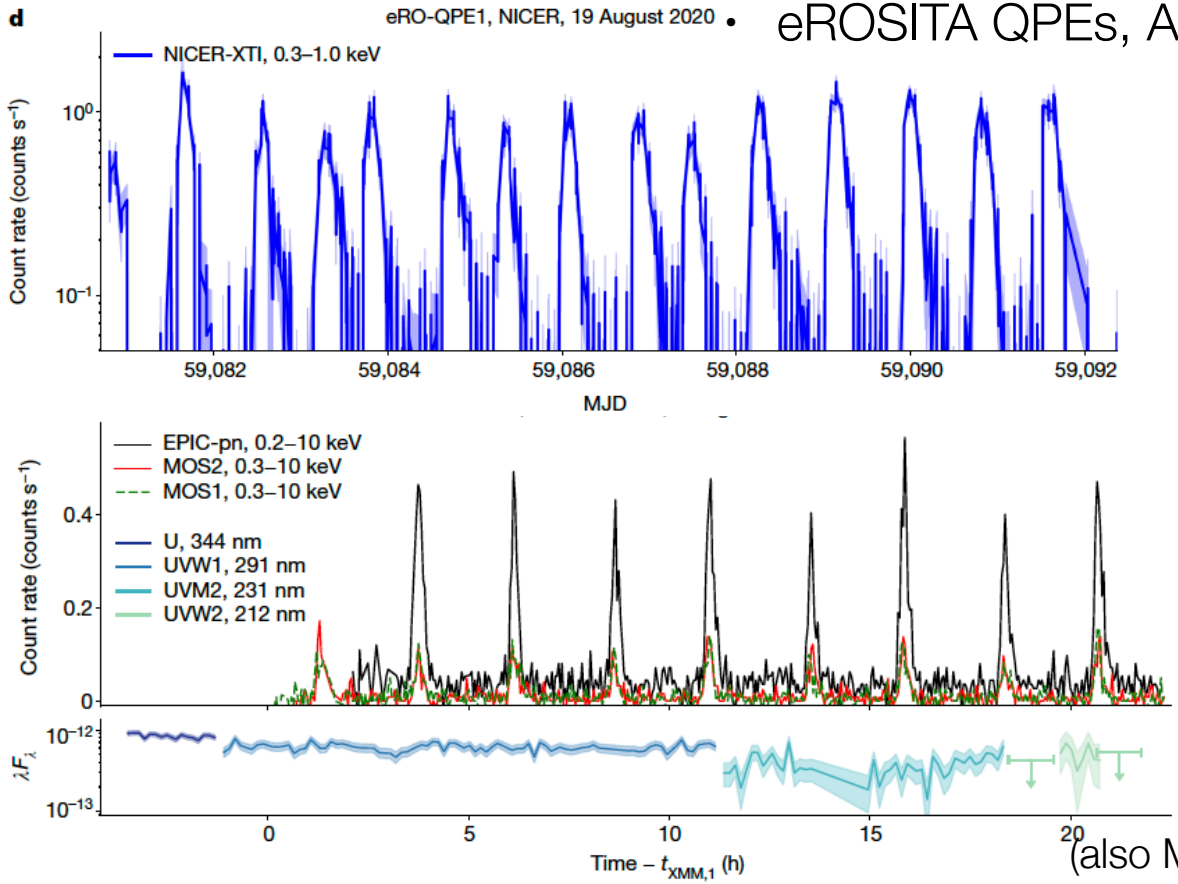
There is tentative evidence (~2.5σ) for a higher fraction of blazars (R>100) in periodic quasars than that in control quasars (jet precession?)

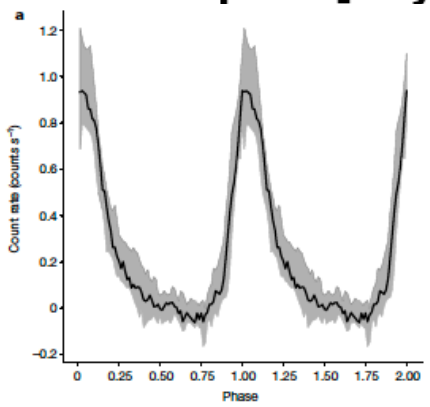
• ASASSN-14ko, Payne+21

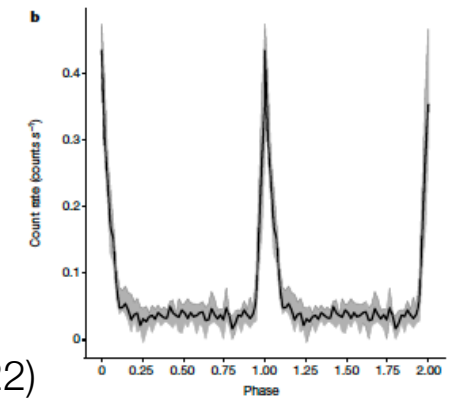




• eROSITA QPEs, Arcodia+21







(also Metzger+22)

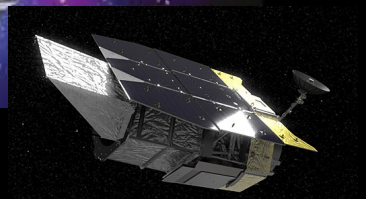
Take-home points:

- Need to study all scales for a self-consistent picture of SBBH evolution and to connect with cosmological context
- Significant progress at >~kpc scales, but more data needed at high redshift (i.e., during the “quasar epoch”) and/or small separations, e.g., from varstrometry
- No conclusive example at sub-pc scales, but many intriguing candidates from periodicity (and more to expect from LSST) - subject to interlopers, and need continued monitoring and complementary tests

merger sequence

Sub-galactic pairs

Direct Imaging



Roman (2025+)

Radial Velocity

PFS (2024-2029)

JWST (2022+)

Astrometry

ELT/GMT/TMT (2027+)

VLTI Gravity+

What next?

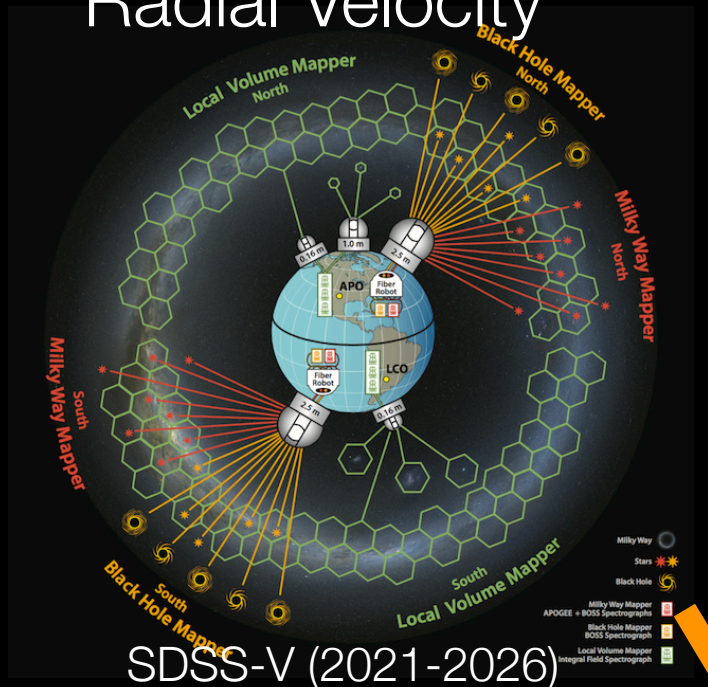
Milli-pc binaries

Variability

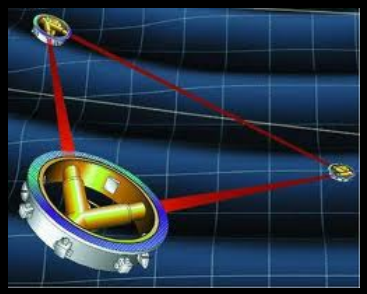
Rubin (2024-2034)

Sub-pc binaries

Radial Velocity



SDSS-V (2021-2026)



LISA (2034+)

SKA (2027+)