Texas in Shanghai

Future (survey) facilities for electromagnetic observations of dual and binary massive black holes
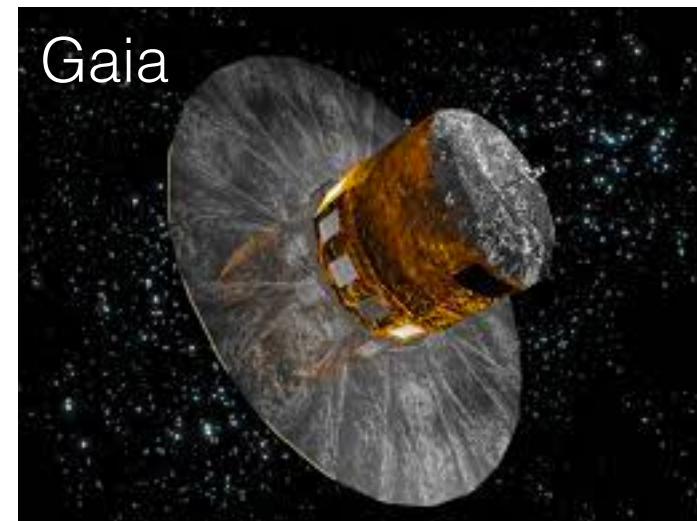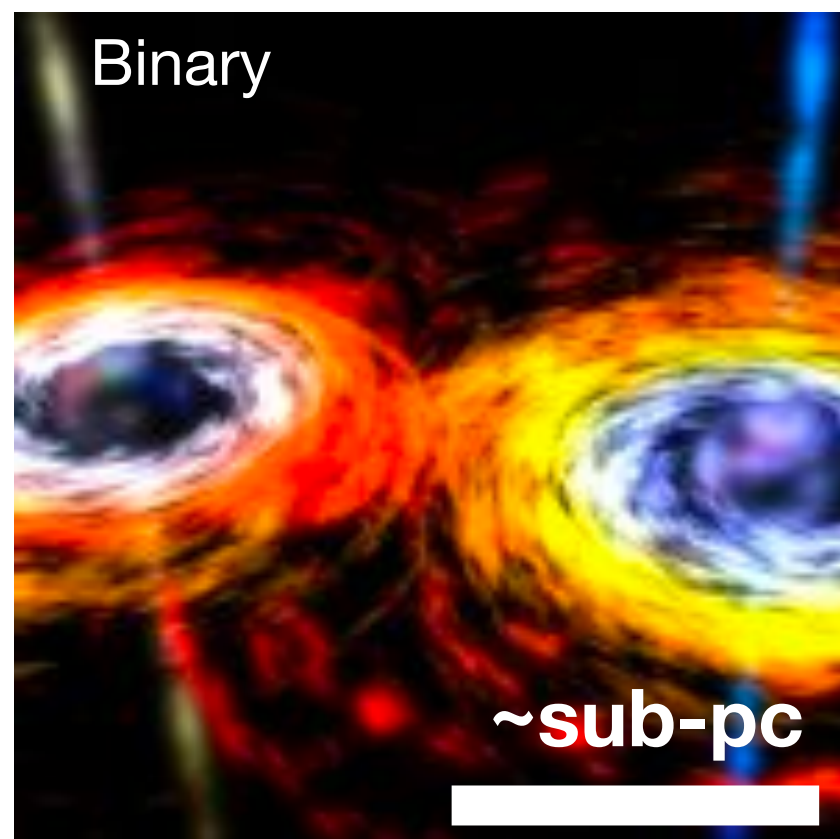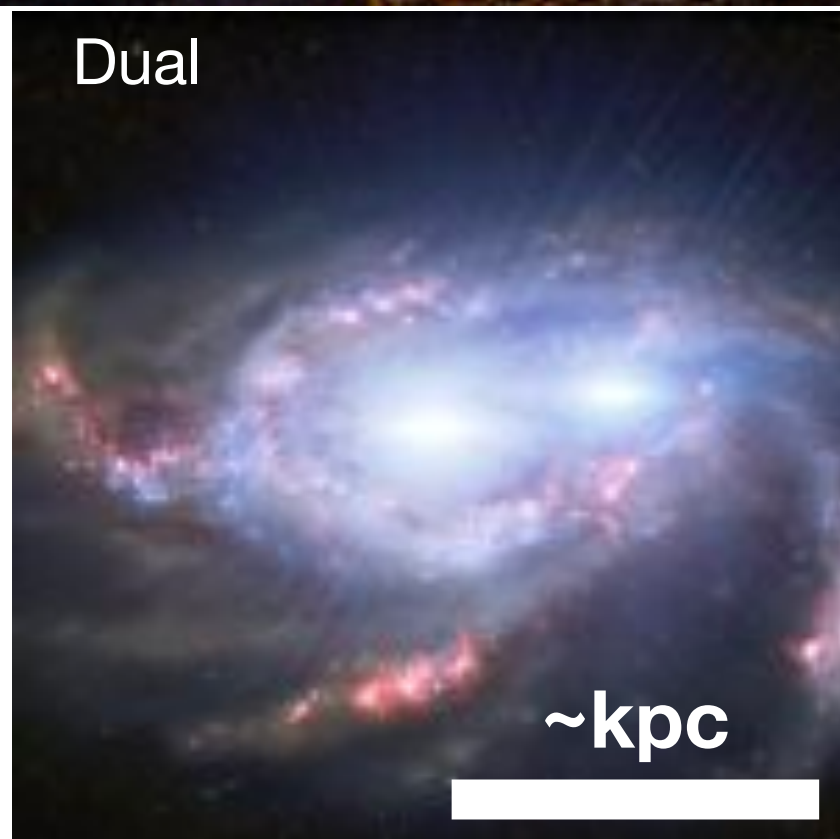
Dual

~kpc

Binary

~sub-pc

Gaia

SDSS-V

DECam

Euclid

Rubin (2025+)

Roman (2027+)
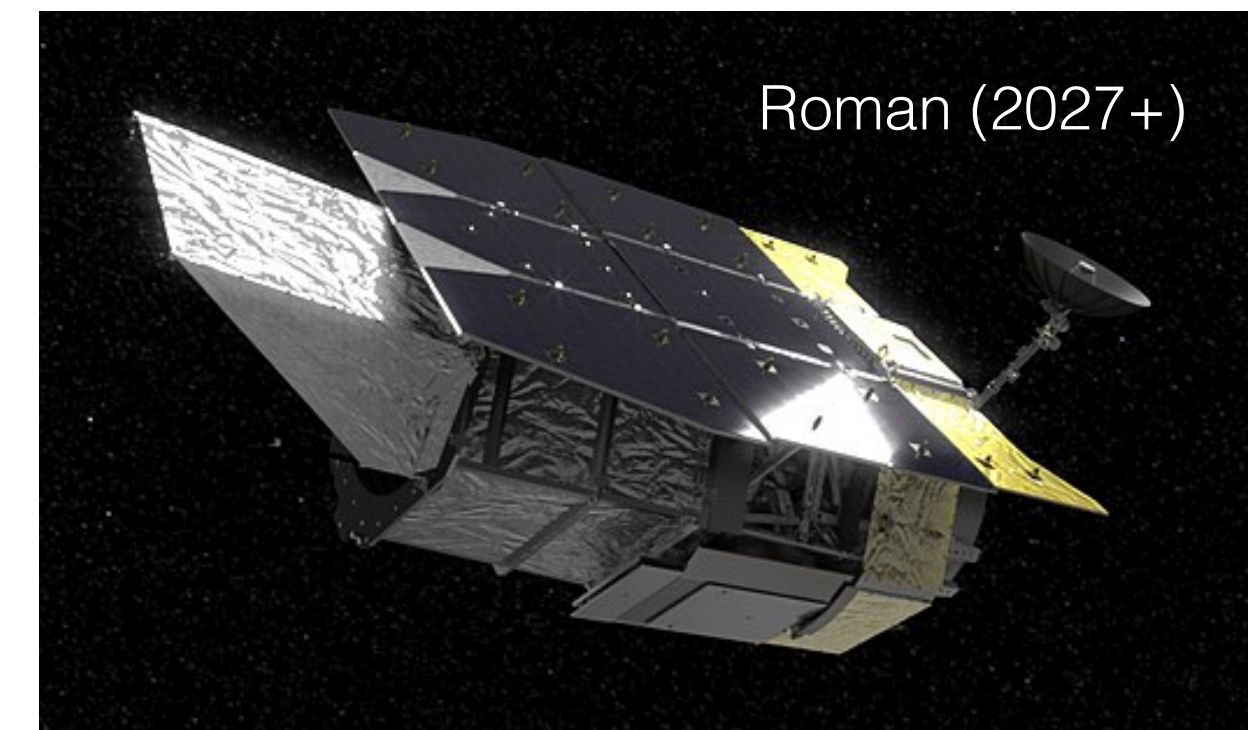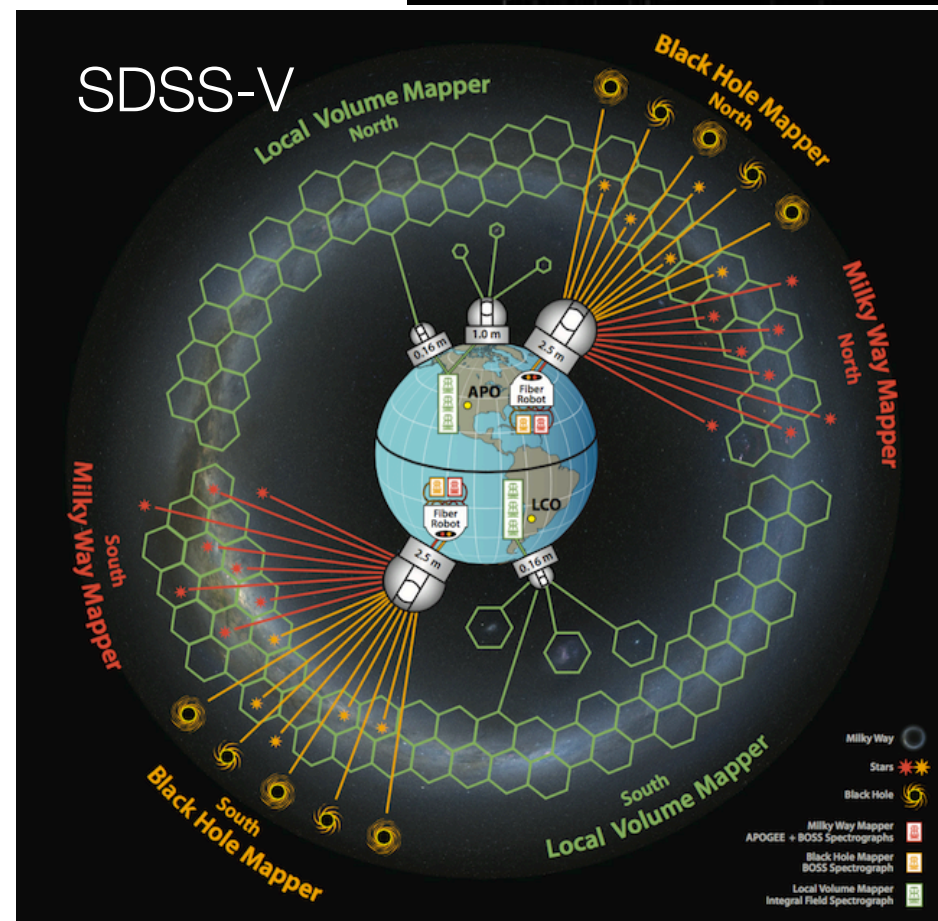
Xin Liu (UIUC), Texas Symposium, 12/15/23, Shanghai

UNIVERSITY OF ILLINOIS
URBANA-CHAMPAIGN

AST-2108162
AST-2206499
AST-2308077

Science Theme: New Messengers and New Physics

Priority Area: New Windows on the Dynamic Universe
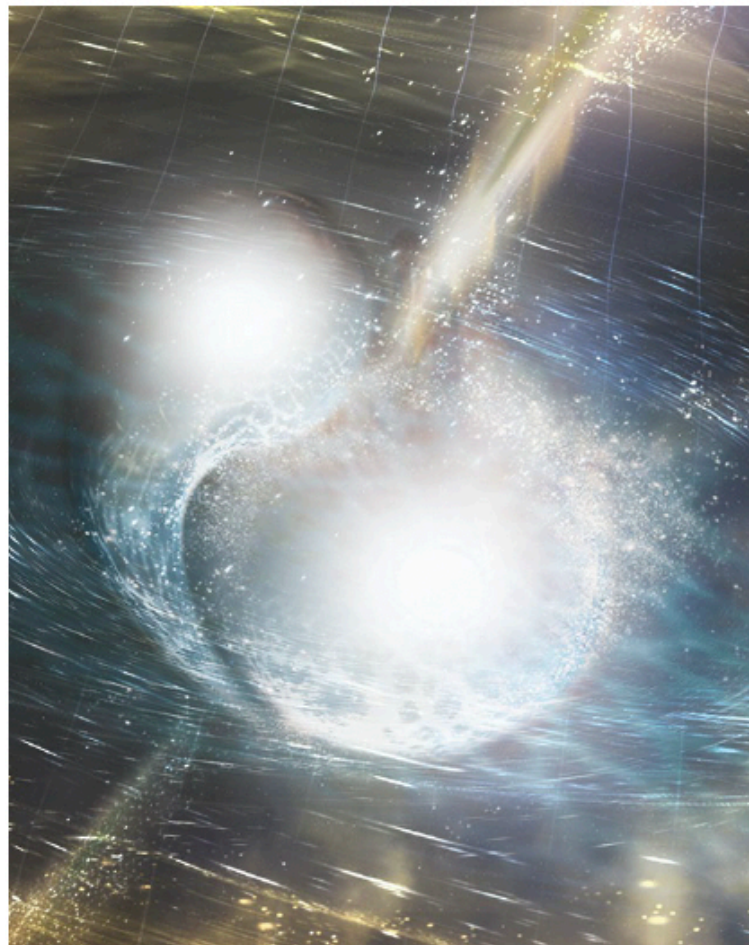
Discovery space for the coming decade: multi-messenger and time domains
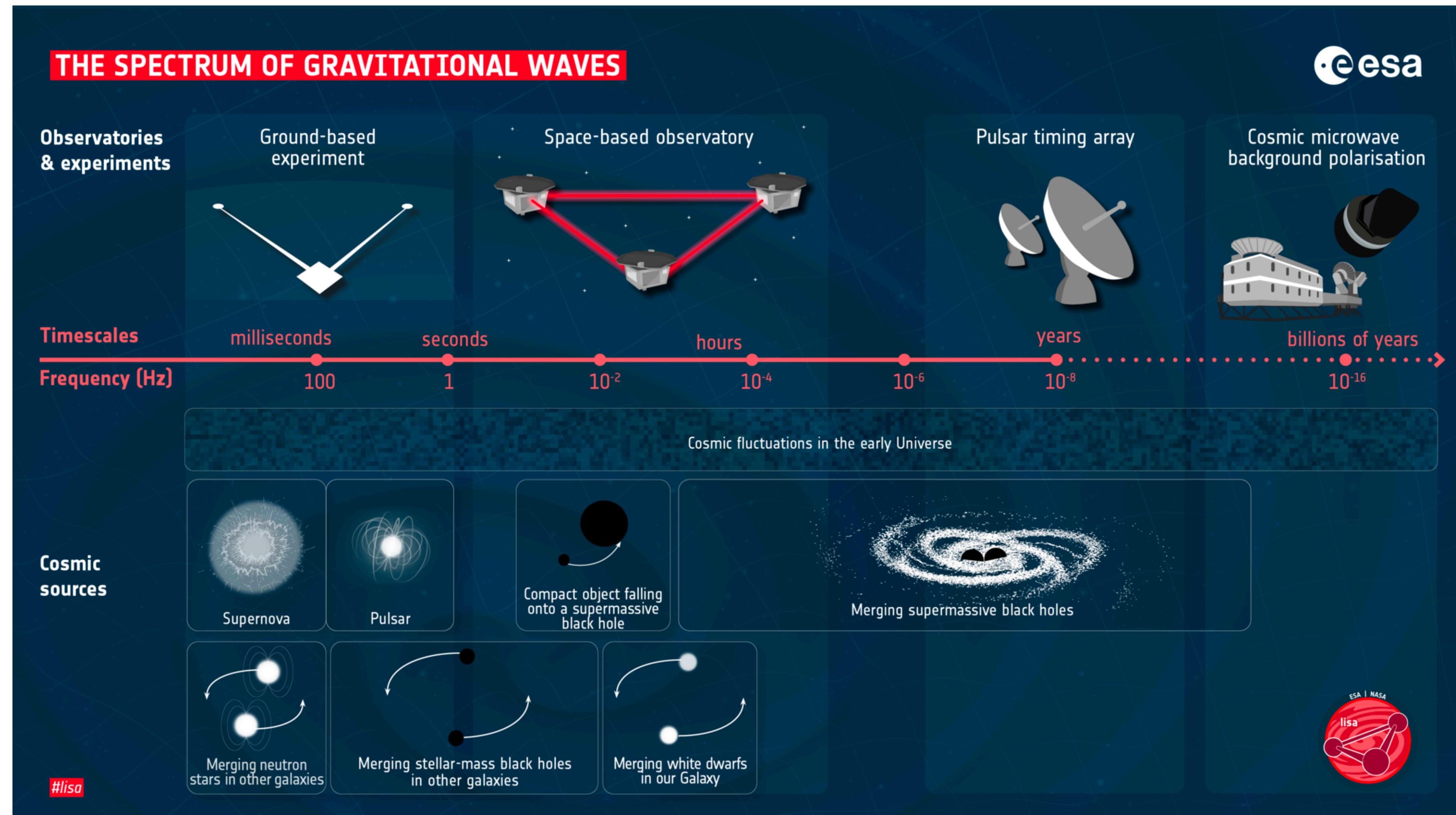
Synergy between GW and EM facilities

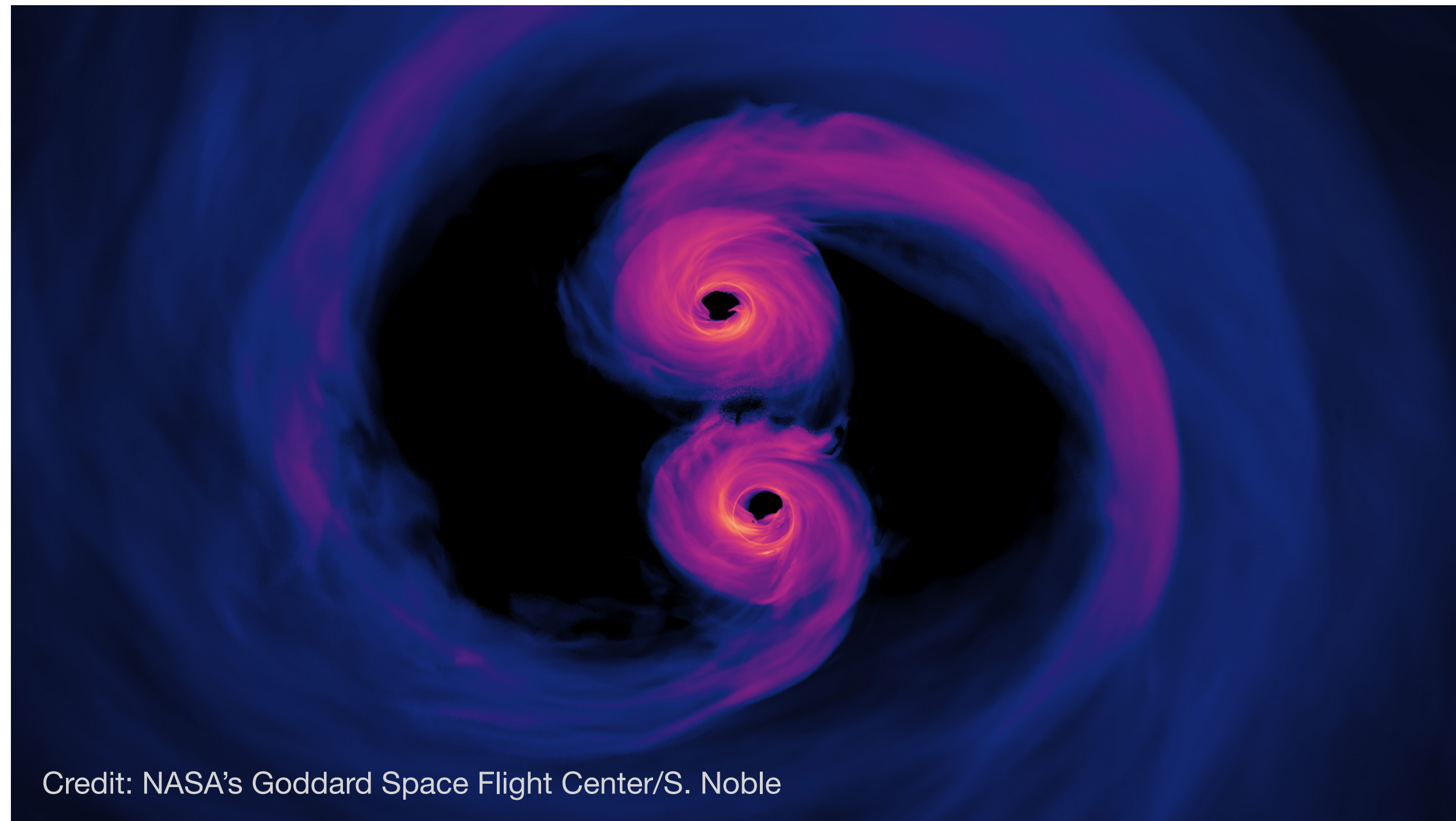**Major differences between LISA and LIGO BBH observations:**

- **Coalescing MBHs expected in gas-rich environments: EM signals expected**
- **LISA designed to detect inspiraling MBHs in "slow motion": provide forewarnings to EM and particle detectors for MMA**

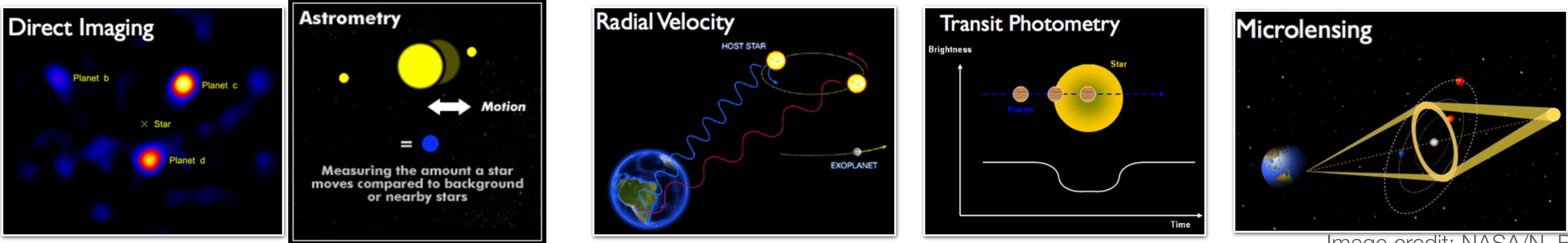Credit: NASA's Goddard Space Flight Center/S. Noble

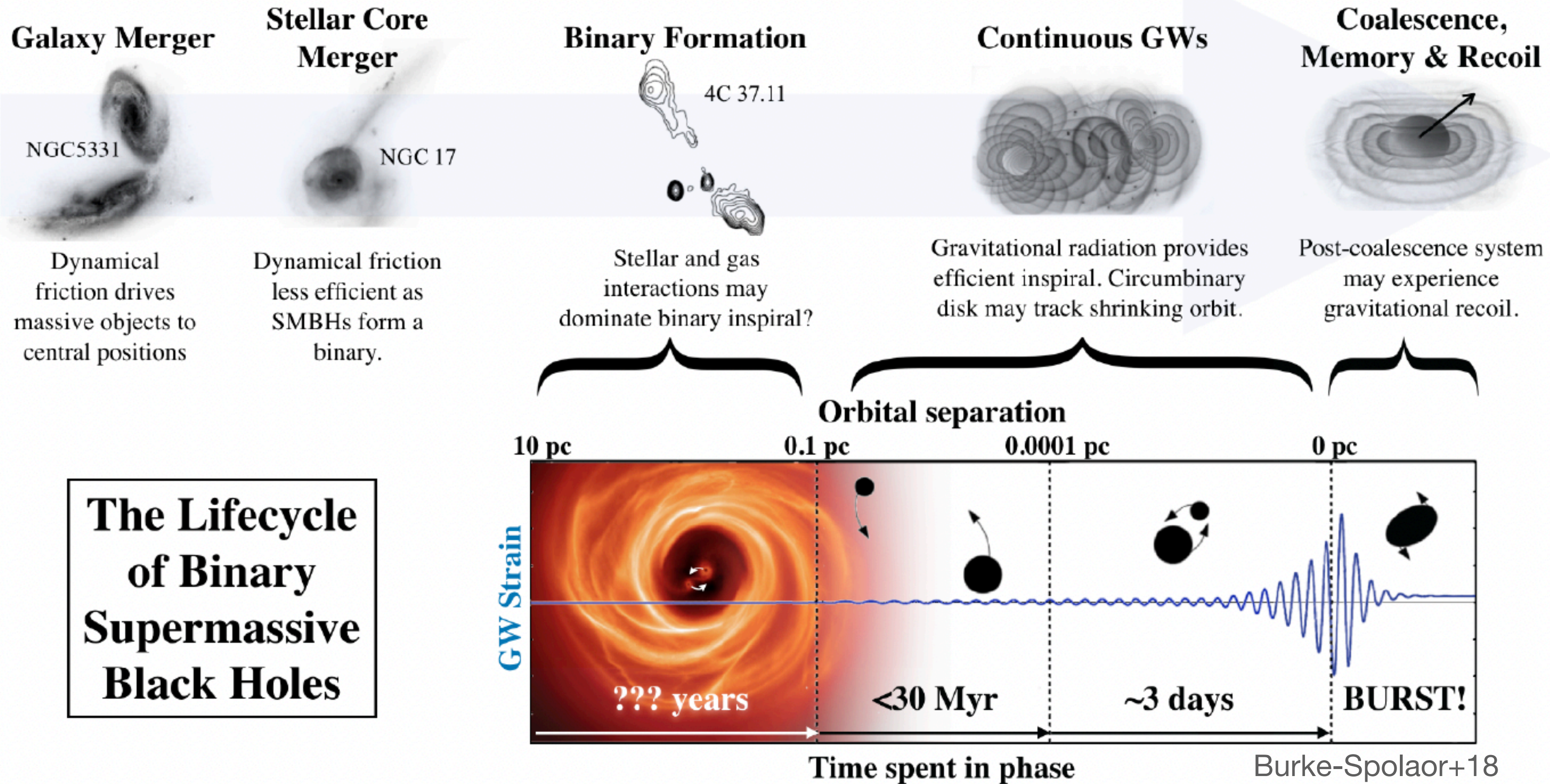**EM observations help LISA localize sources and measure redshifts**

- **Efficient EM observations and data analysis tools needed for realizing the full discovery potential in the multi-messenger and time domains**

EM Searches of Dual/Binary MBHs: Analogy with Exoplanets

Direct Imaging — Planet b, Planet c, × Star, Planet d

Astrometry — Motion, = (blue dot). Measuring the amount a star moves compared to background or nearby stars

Radial Velocity — HOST STAR, EXOPLANET

Transit Photometry — Brightness, Planet, Star, Time

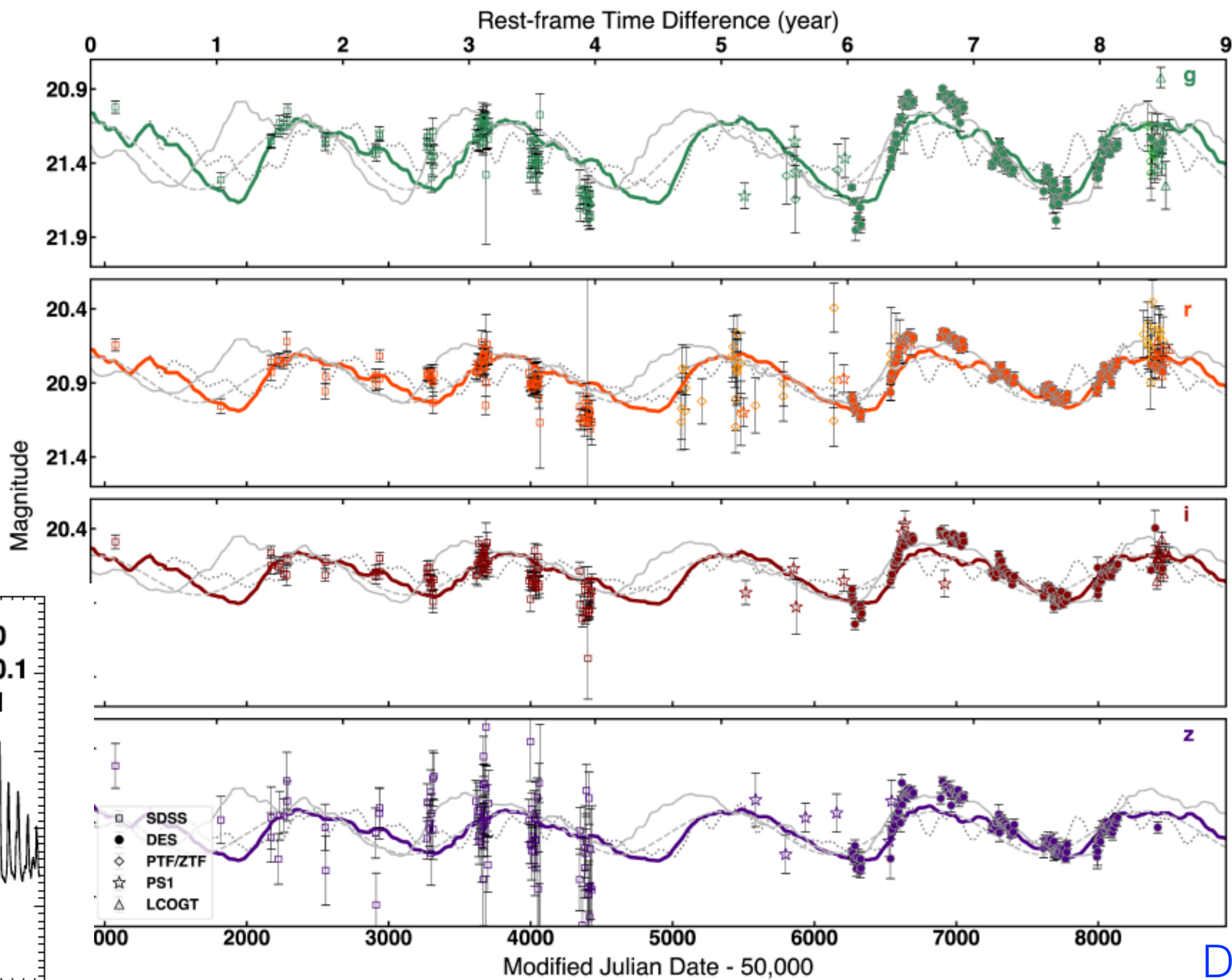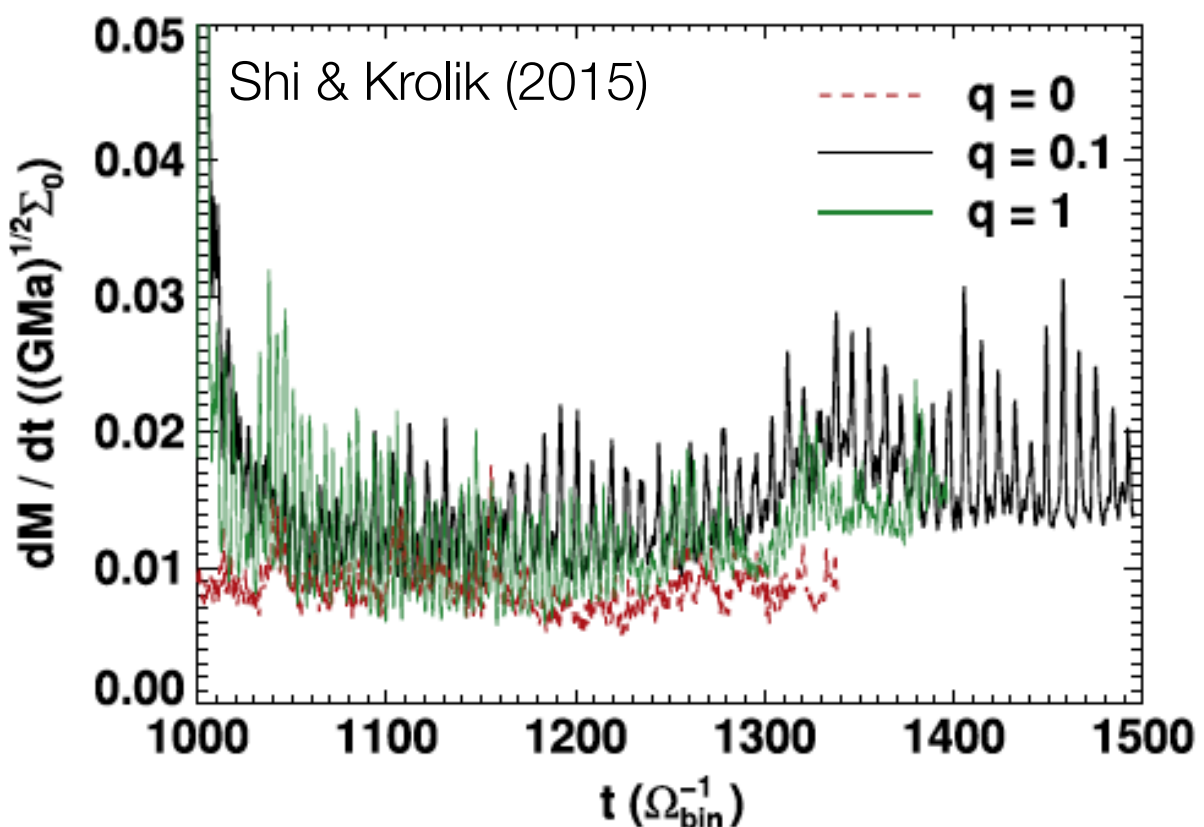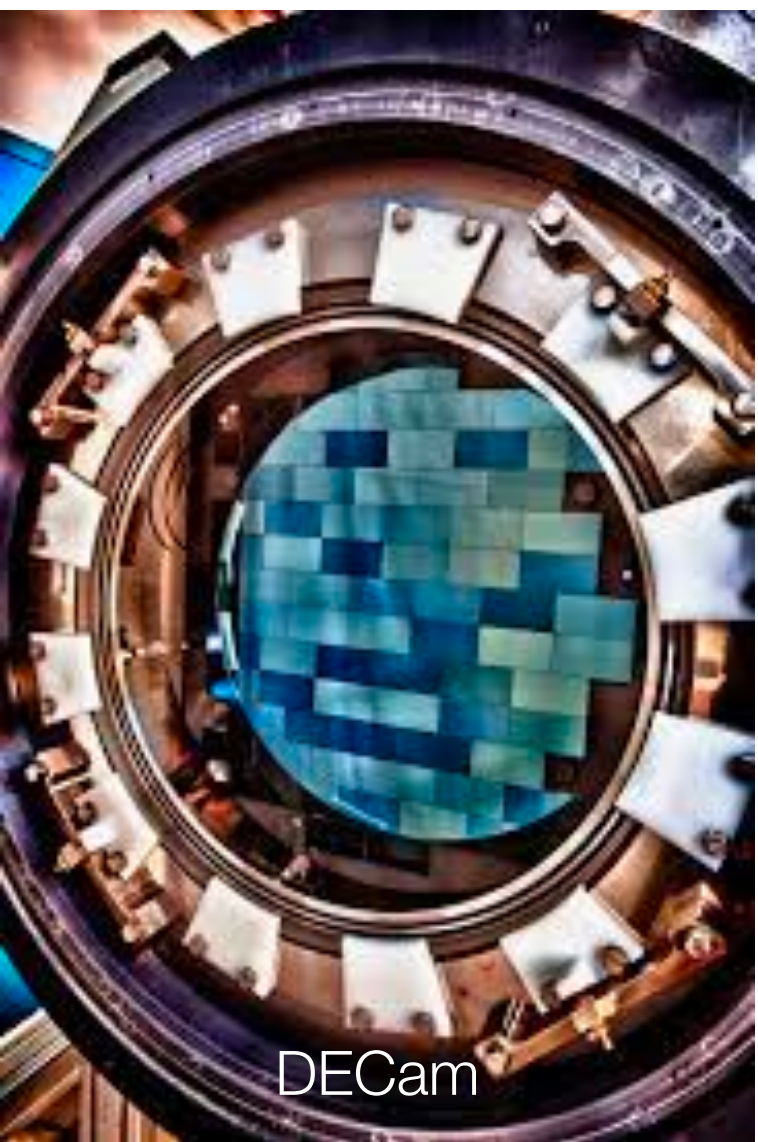Microlensing

Image credit: NASA/N. Batalha

A multi-scale interdisciplinary problem: connecting cosmology, galaxy evolution, dynamics, accretion disk physics, GRMHD, and multi-messenger astronomy

Galaxy Merger — NGC5331 — Dynamical friction drives massive objects to central positions

Stellar Core Merger — NGC 17 — Dynamical friction less efficient as SMBHs form a binary.

Binary Formation — 4C 37.11 — Stellar and gas interactions may dominate binary inspiral?

Continuous GWs — Gravitational radiation provides efficient inspiral. Circumbinary disk may track shrinking orbit.

Coalescence, Memory & Recoil — Post-coalescence system may experience gravitational recoil.

The Lifecycle of Binary Supermassive Black Holes

Orbital separation

10 pc   0.1 pc   0.0001 pc   0 pc

GW Strain

??? years   <30 Myr   ~3 days   BURST!

Time spent in phase

Burke-Spolaor+18

Frequency and Abundance of Binary sUpermassive bLack holes from Optical Variability Surveys (FABULOVS)

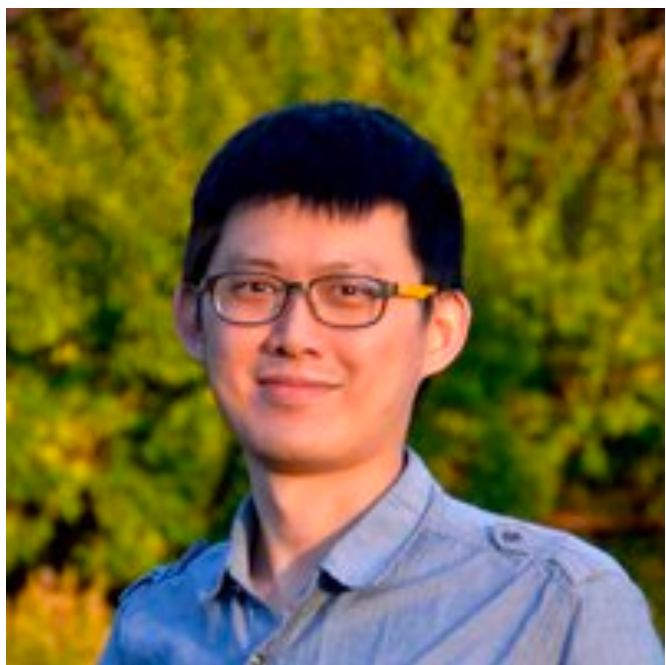- **Candidate Milli-pc MBBHs from Periodic Light Curves w/ SDSS+DES+DECam Long-Term Monitoring**

DECam

Shi & Krolik (2015)

Rest-frame Time Difference (year)

SDSS (98—07)   DES (12—19)

1. Continued monitoring to test red noise (DECam Long-term Programs)
Zhuang et al. in prep

2. Multi-wavelength follow-ups (VLA, XMM, NuSTAR) to test origins
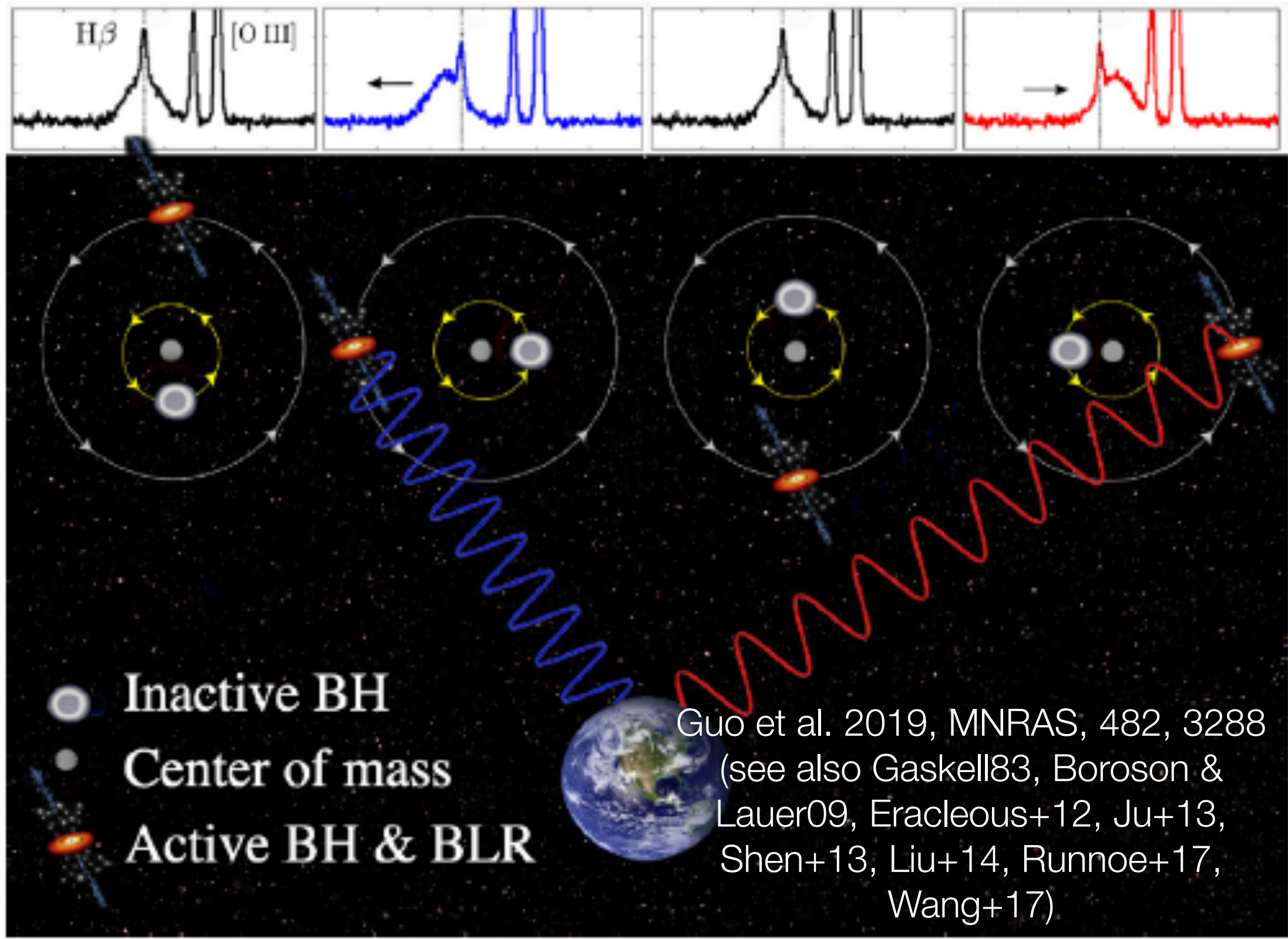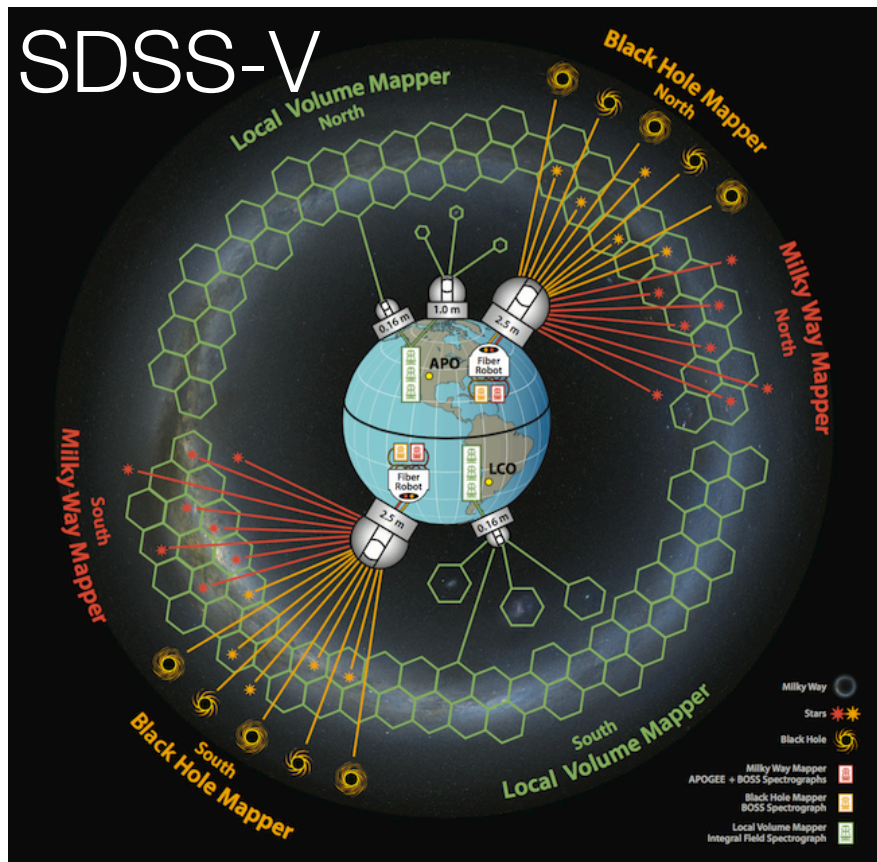Chen+21b, Foord+22

Dr. Tony Chen (JHU)

Dr. Mingyang Zhuang

LSST
DECam (19-24)(24+)

Liao et al. 2021, MNRAS, 500, 4025 (see also Chen+20)

Frequency and Abundance of Binary sUpermassive bLack holes from Optical Variability Surveys (FABULOVS)

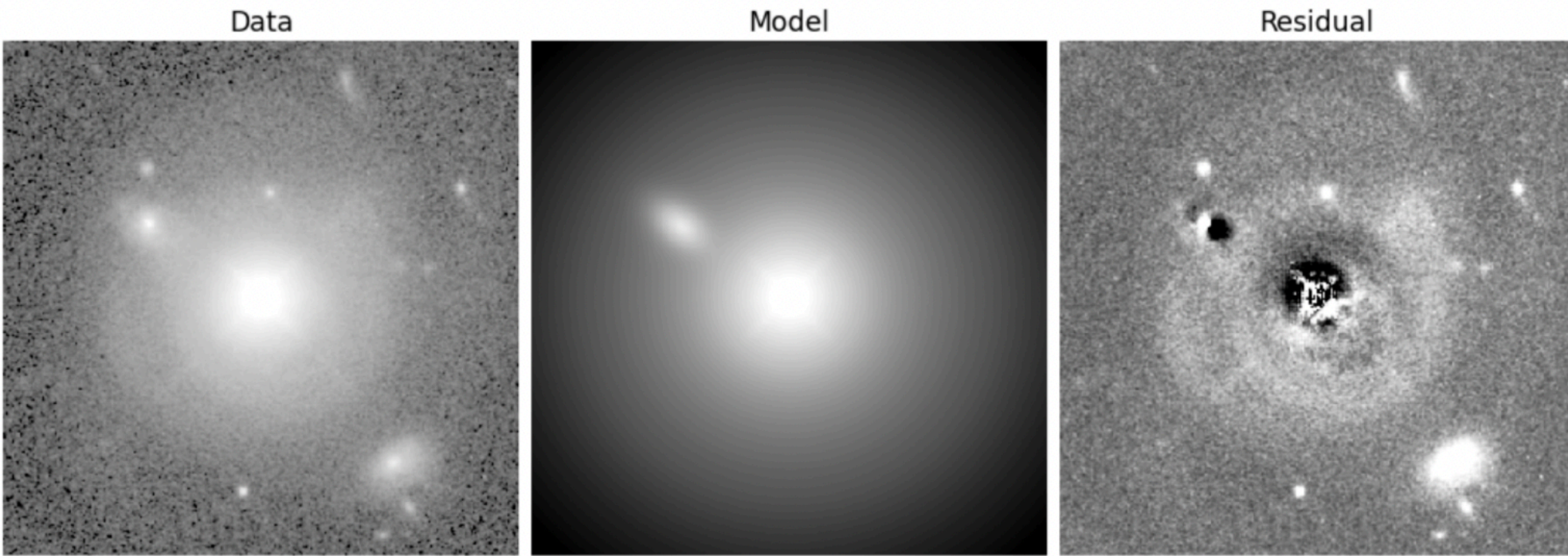- **Candidate Sub-pc MBBHs from Radial Velocities w/ SDSS Muti-Epoch Spectroscopy**

Dr. Hengxiao Guo (SHAO)

Liam Nolan

HST Imaging: Complementary Test of the Binary Hypothesis

Guo et al. 2019, MNRAS, 482, 3288 (see also Gaskell83, Boroson & Lauer09, Eracleous+12, Ju+13, Shen+13, Liu+14, Runnoe+17, Wang+17)

Inactive BH
Center of mass
Active BH & BLR
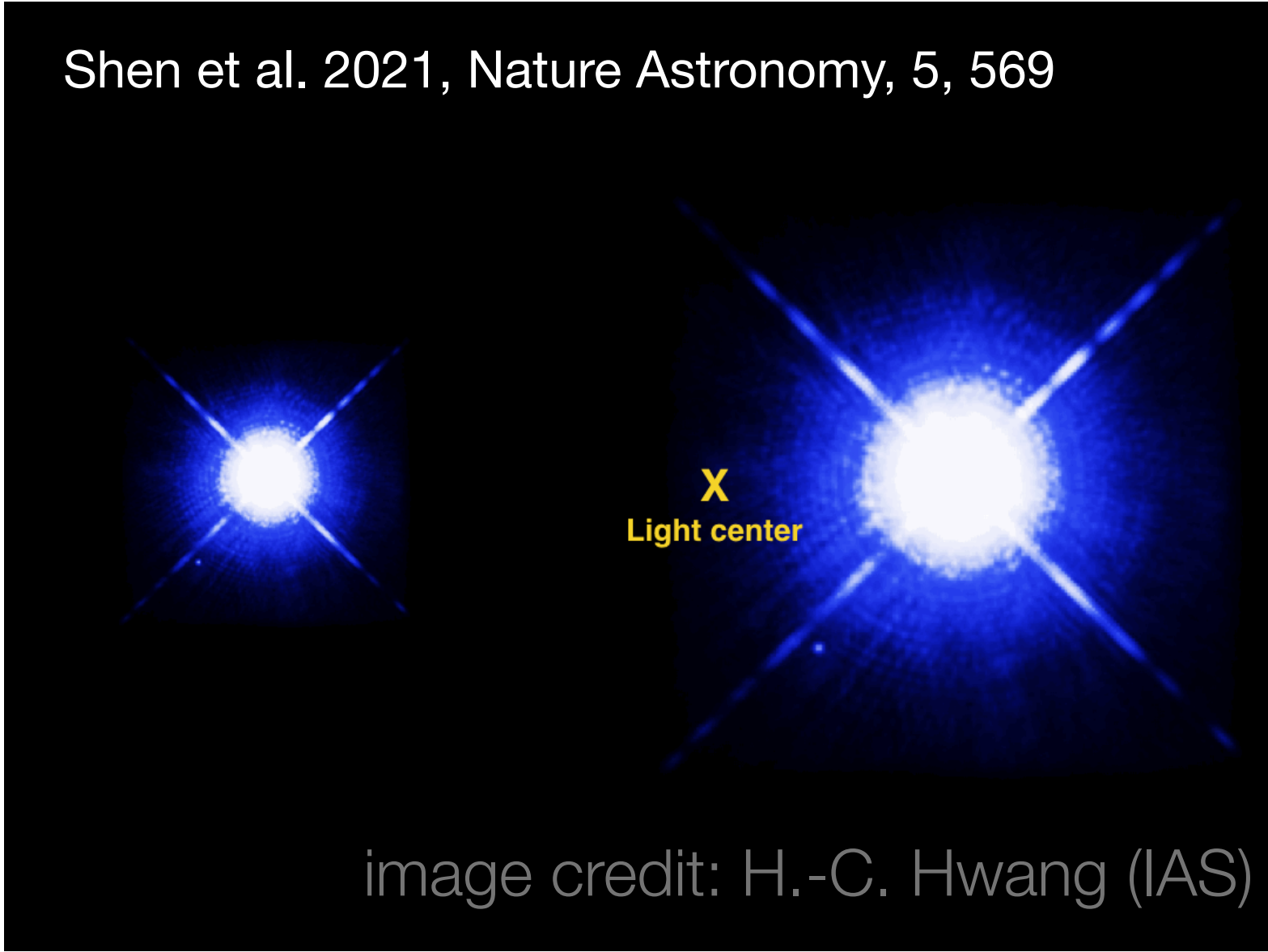
Data   Model   Residual

Nolan et al. in prep

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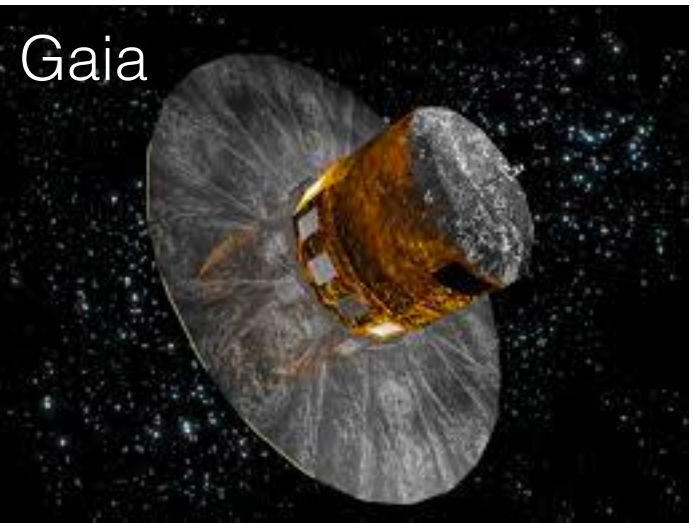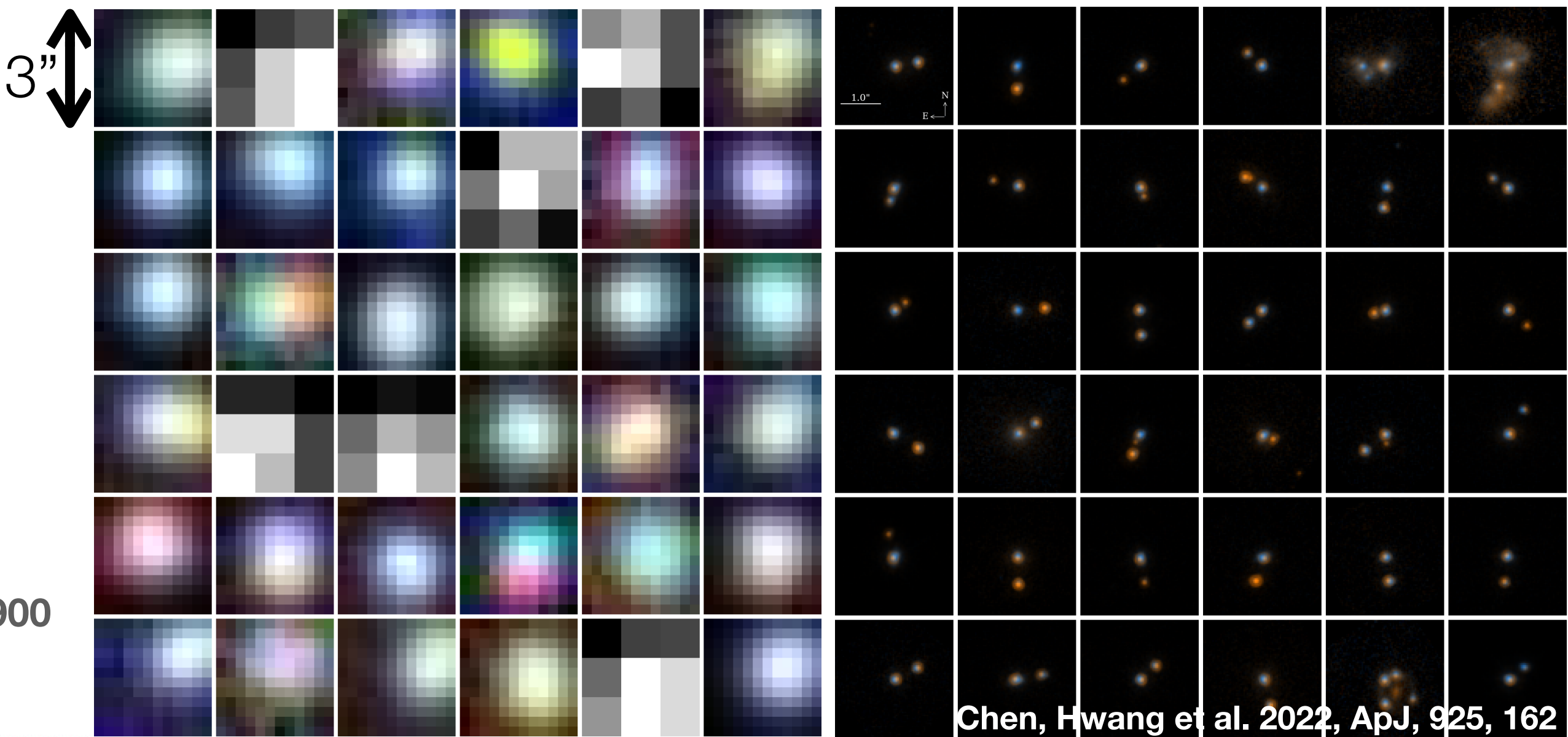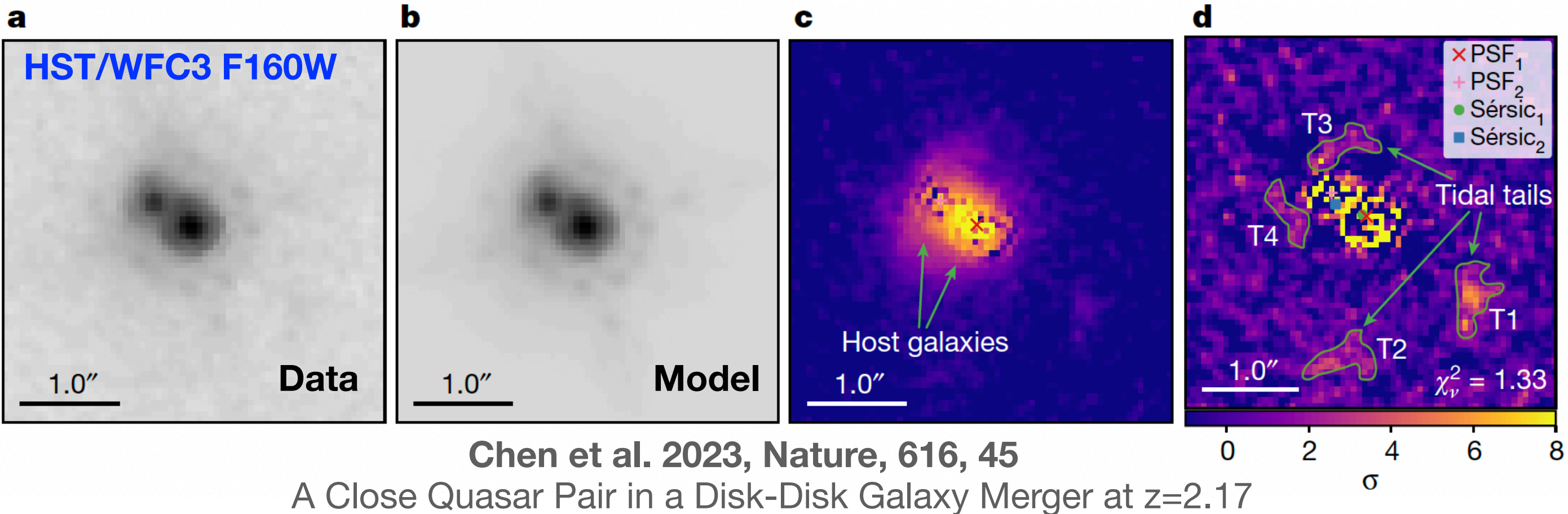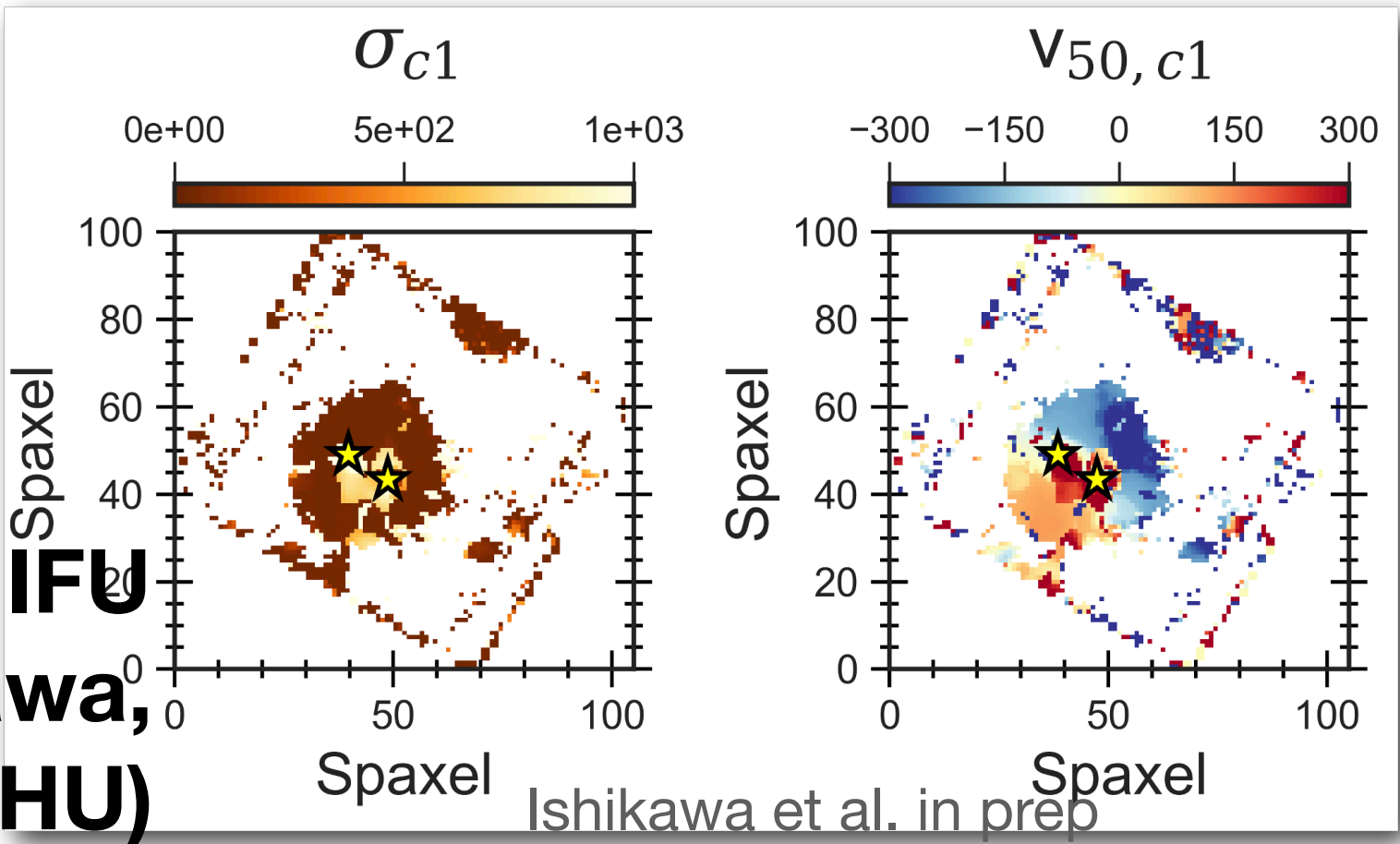## Discover sub-arcsec dual/lensed quasars at cosmic noon

Dr. Tony Chen

Shen et al. 2021, Nature Astronomy, 5, 569

X
Light center

image credit: H.-C. Hwang (IAS)

Dr. Hsiang-Chih Hwang (IAS)

HST SNAP 15900 (PI Hwang)

3"

Chen, Hwang et al. 2022, ApJ, 925, 162

Gaia

JWST NIRSpec IFU
PIs: Yuzo Ishikawa,
N. Zakamska (JHU)

σ_{c1}

$V_{50,c1}$

Spaxel

Ishikawa et al. in prep

a HST/WFC3 F160W **b** **c** **d**

Data

Model

Host galaxies

PSF₁ ×PSF₁
+PSF₂
●Sérsic₁
■Sérsic₂

T3

T4

Tidal tails

T2

T1

$\chi_\nu^2 = 1.33$

σ

Chen et al. 2023, Nature, 616, 45
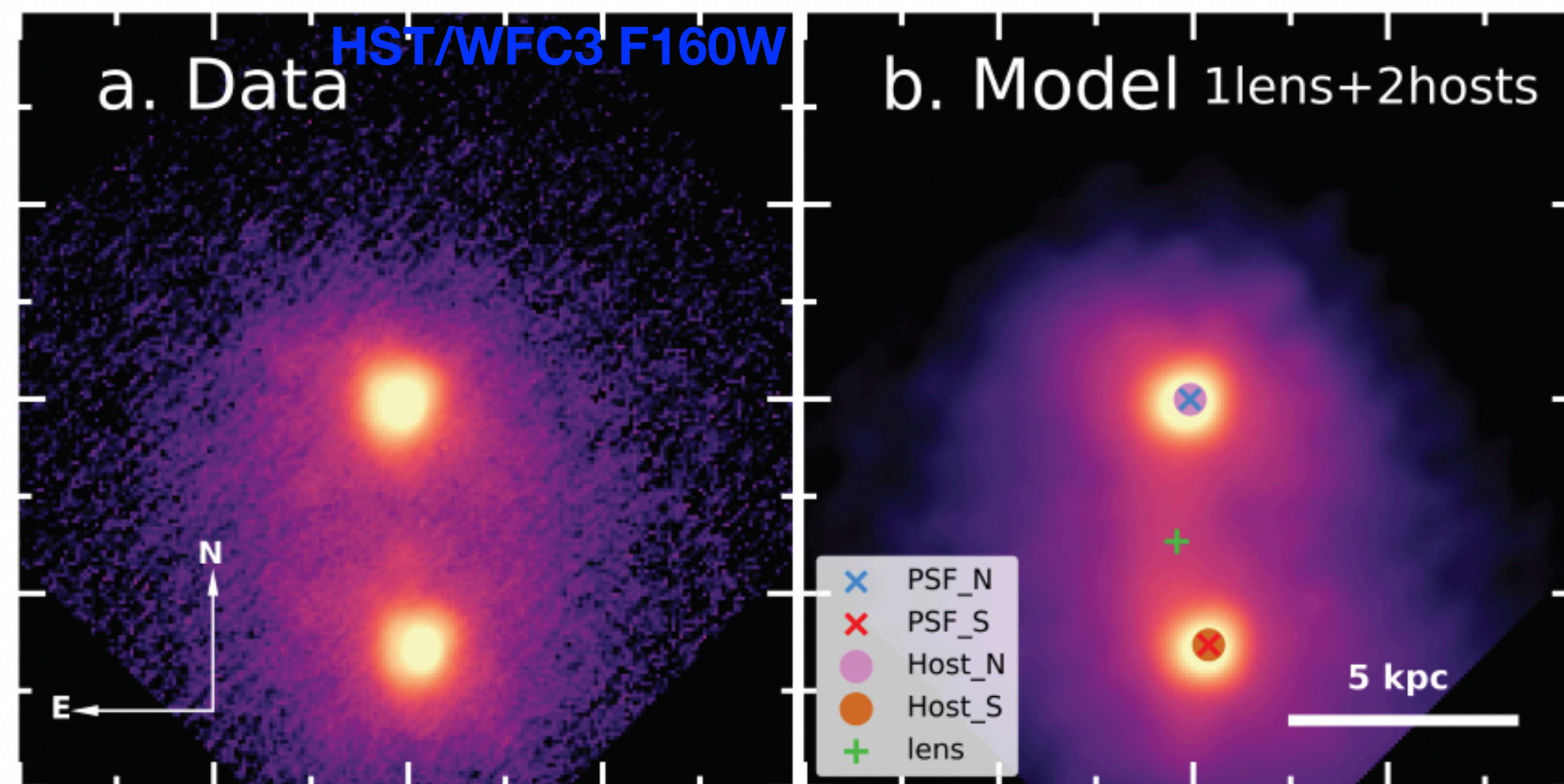A Close Quasar Pair in a Disk-Disk Galaxy Merger at z=2.17

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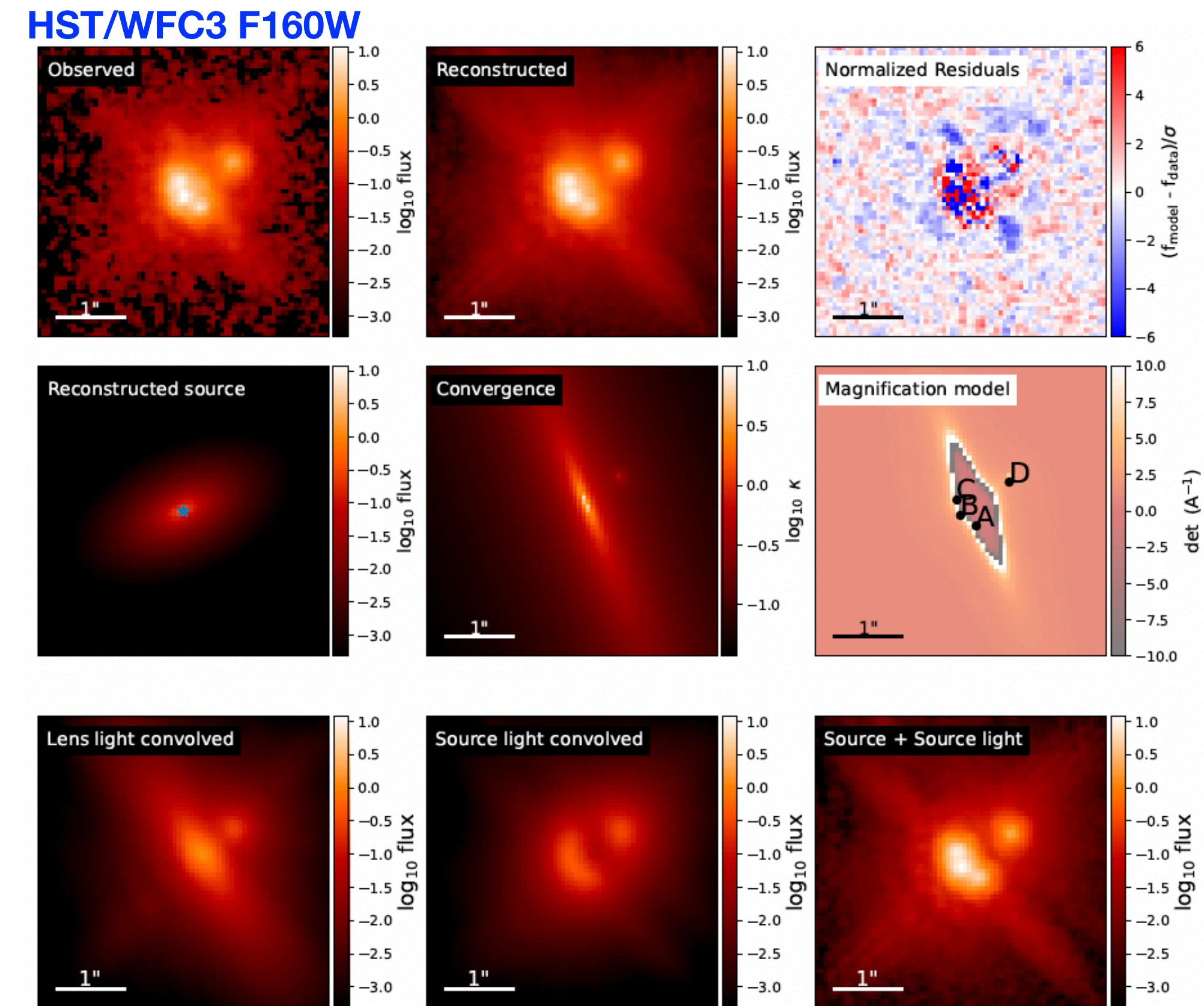

Dr. Arran Gross

Gross et al. (2023) ApJ, 956, 117

VODKA: SDSS J0823 at z=1.81: A Likely Lensed Quasar

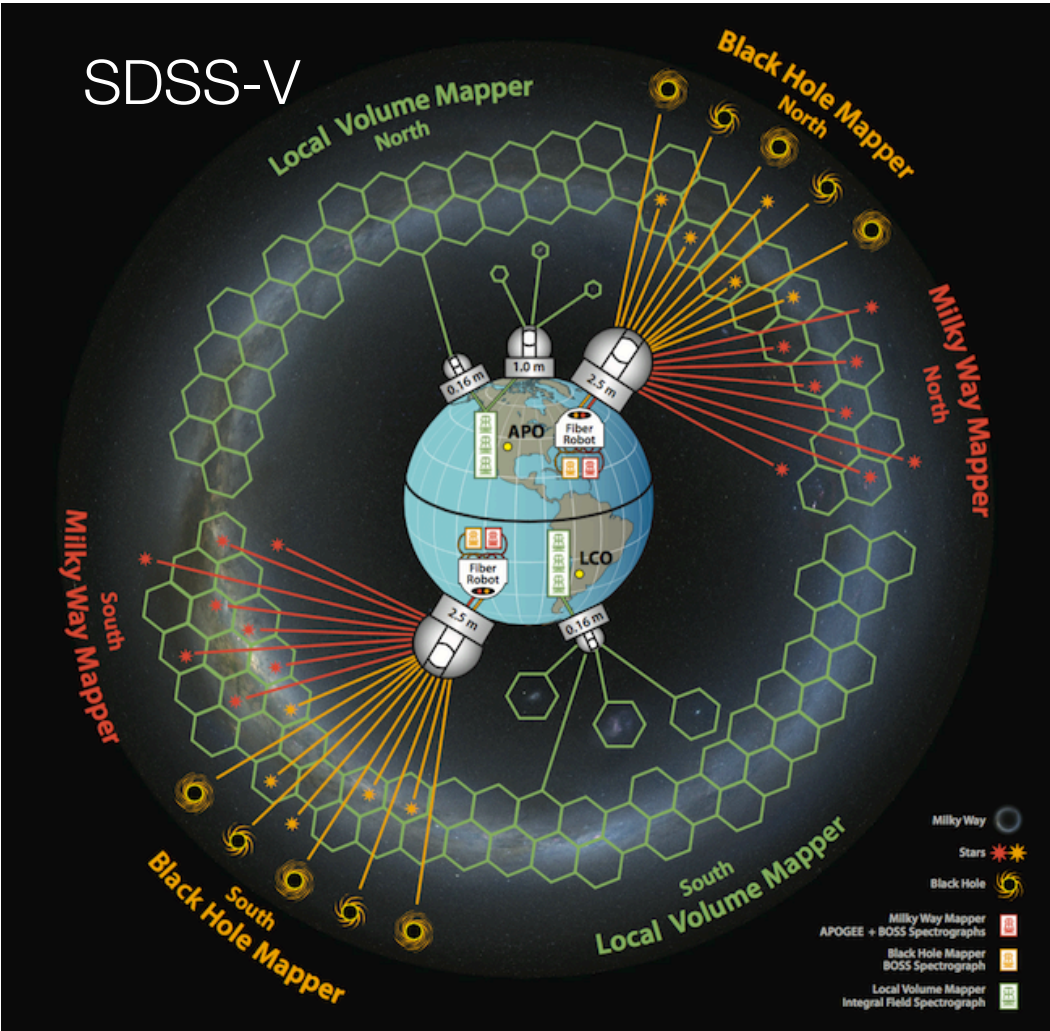**Surprisingly nontrivial to distinguish dual and lensed quasars: high-resolution deep IR imaging is key**
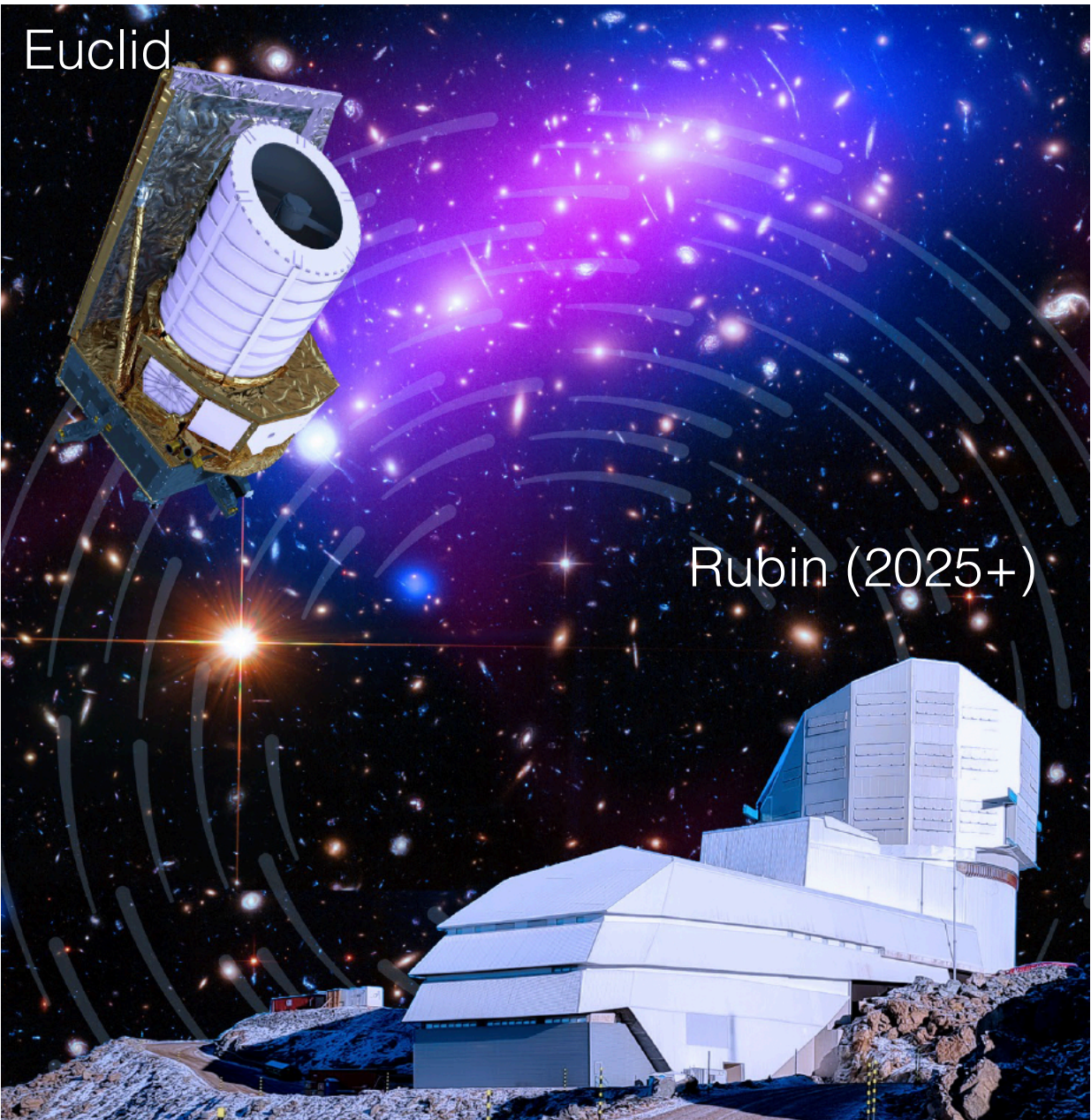

Dr. Junyao Li

Li et al. (2023) ApJL, 955, 16

VODKA: SDSS J1608+2716: A Subarcsecond Quadruply Lensed Quasar at z = 2.575

Looking Forward & Takeaways

Rubin, Euclid, and Roman will revolutionize the field in synergy w/ PTA & LISA

SDSS-V

Euclid

Rubin (2025+)

Roman (2027+)

Dual/lensed/offset MBHs, IMBHs from high-resolution deep photometry & variability

Roman Core Community Survey White Papers
Dual: Shen et al. (2023), arXiv:2306.15527
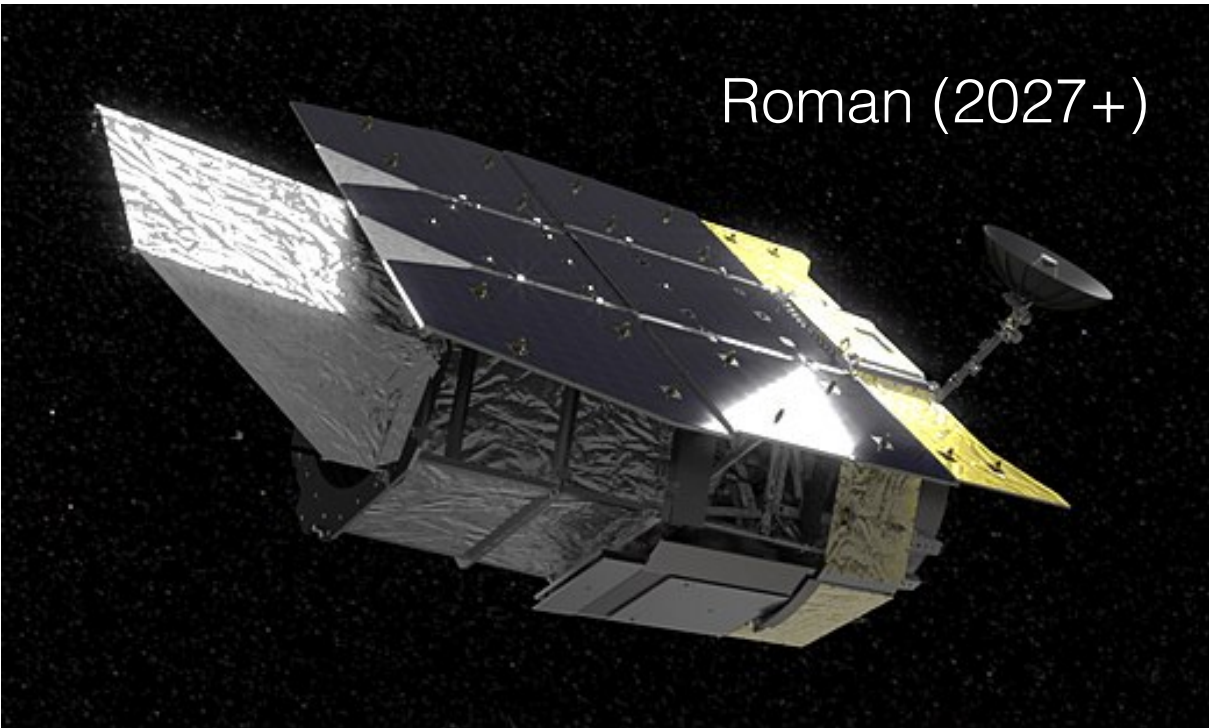Binary: Haiman et al. (2023), arXiv:2306.14990

Sub-pc binary MBH candidates from long-term spectroscopic monitoring

Milli-pc binary MBH/ IMBH candidates from periodic variables/ transients (also partial TDEs, EMRIs)

ASASSN-14ko, Payne+21