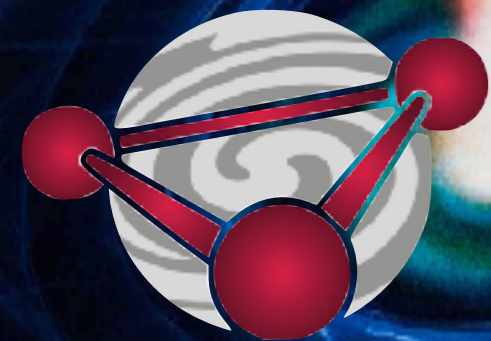


MULTI-MESSENGER OBSERVATIONS OF SUPERMASSIVE BH BINARIES



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VANDERBILT UNIVERSITY
→ **WASHINGTON STATE UNIVERSITY**

14th SCSLSA
Bajina Basta, June 21 2023

SUPERMASSIVE BLACK HOLES



M31: NASA

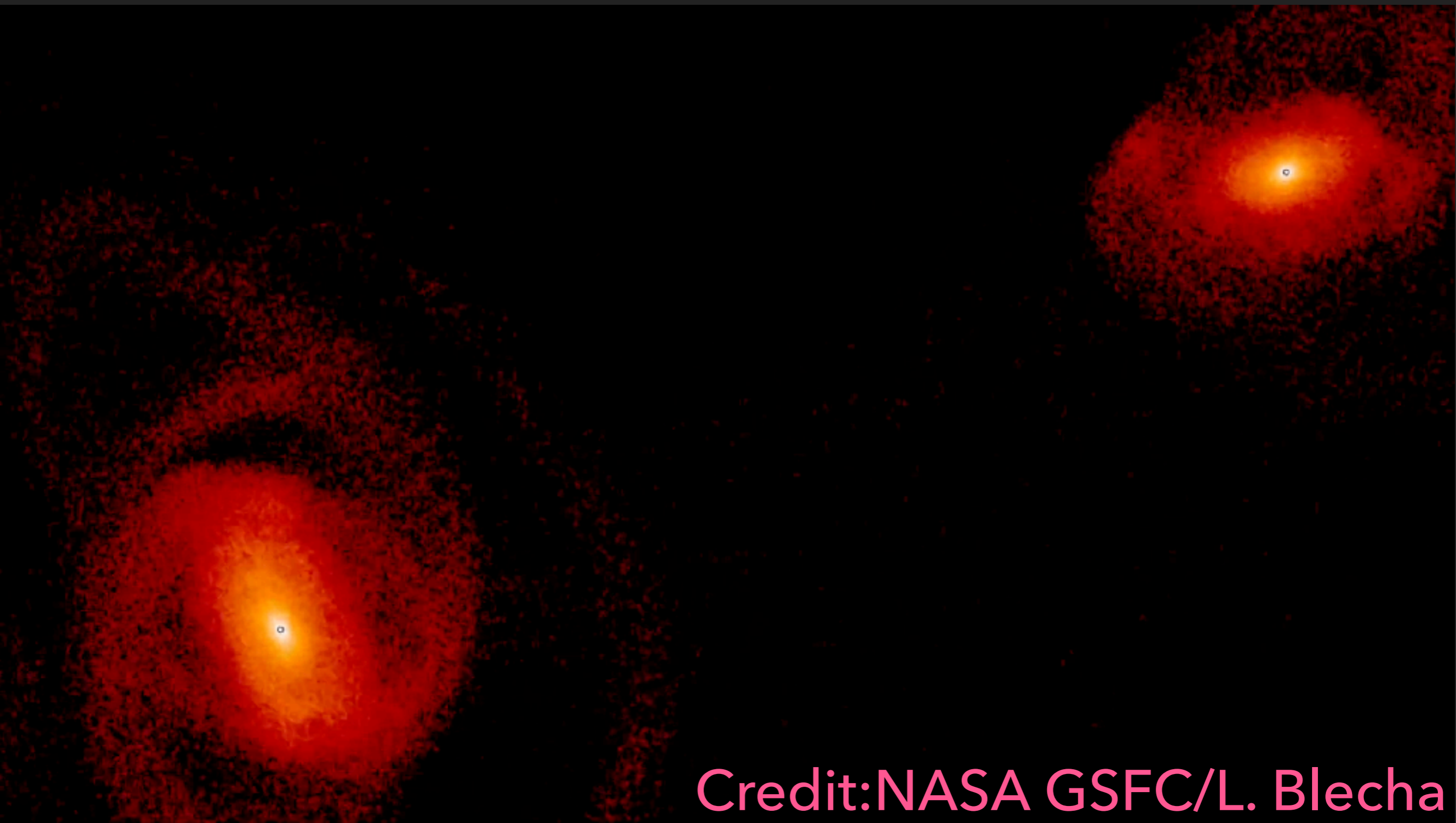
SUPERMASSIVE BLACK HOLES



M87: Event Horizon
Telescope 2019

Every massive galaxy has a
Supermassive BHs with mass
 $10^5 - 10^{10} M_{\text{sol}}$

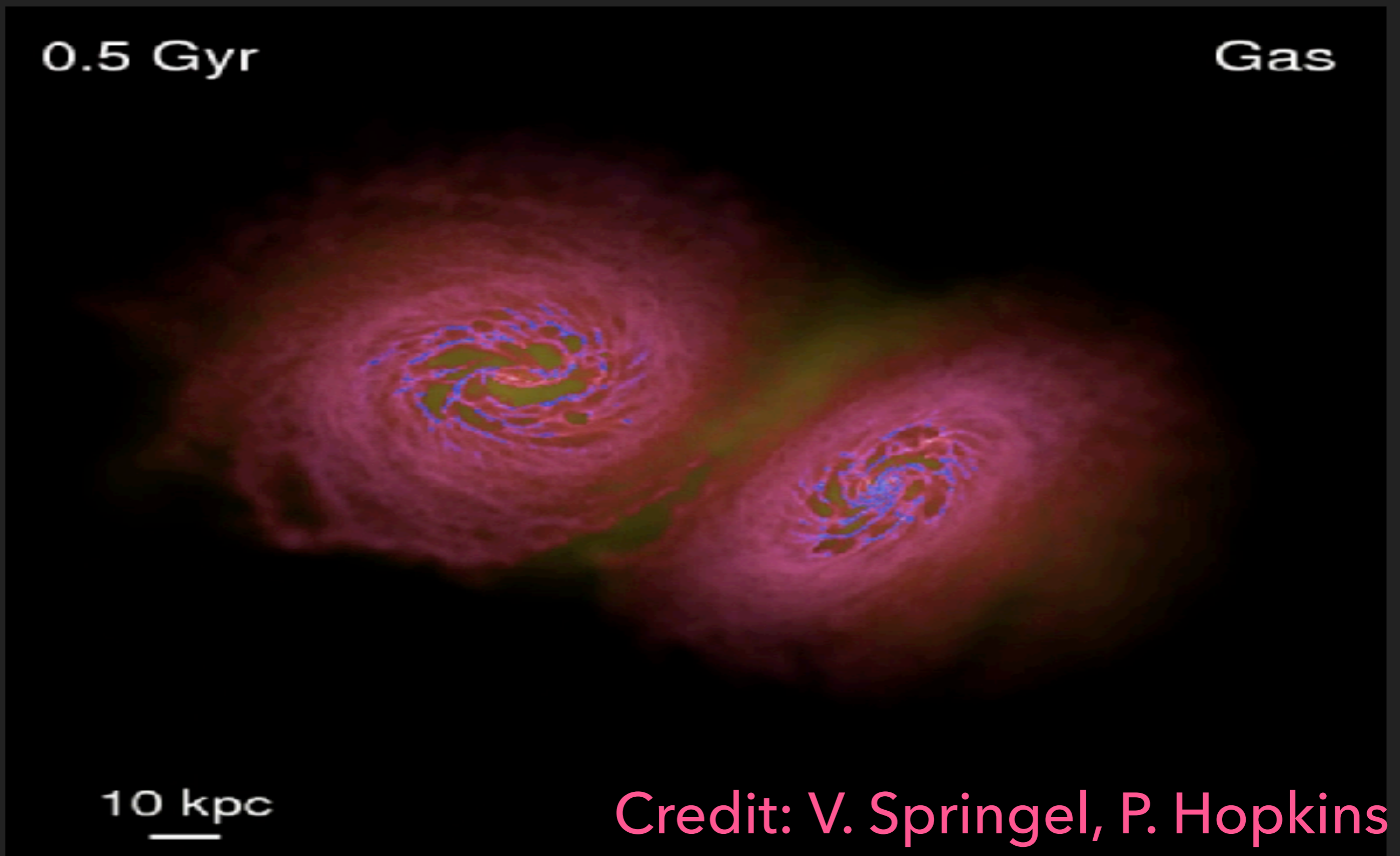
GALAXY MERGERS



Credit: NASA GSFC/L. Blecha

- ▶ SMBHBs should be fairly common.

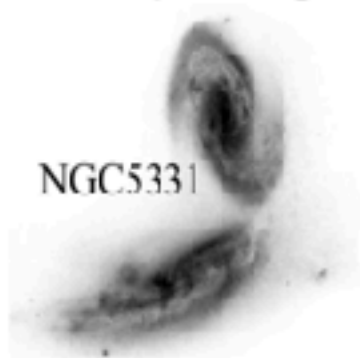
GALAXY MERGERS



- ▶ Binaries form in gas-rich environments.

BINARY EVOLUTION

Galaxy Merger



NGC 5331

Dynamical friction drives massive objects to central positions

Stellar Core Merger



NGC 17

Dynamical friction less efficient as SMBHs form a binary.

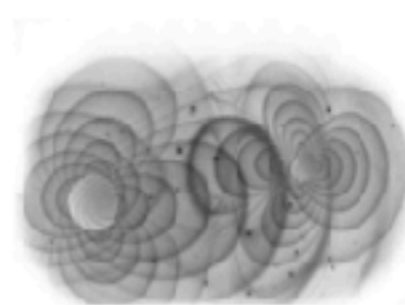
Binary Formation



4C 37.11

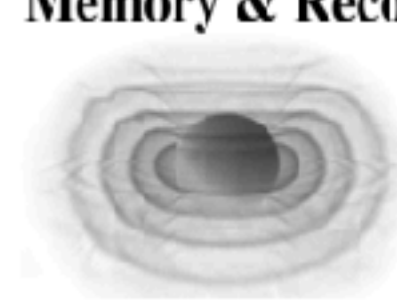
Stellar and gas interactions dominate binary formation

Continuous GWs



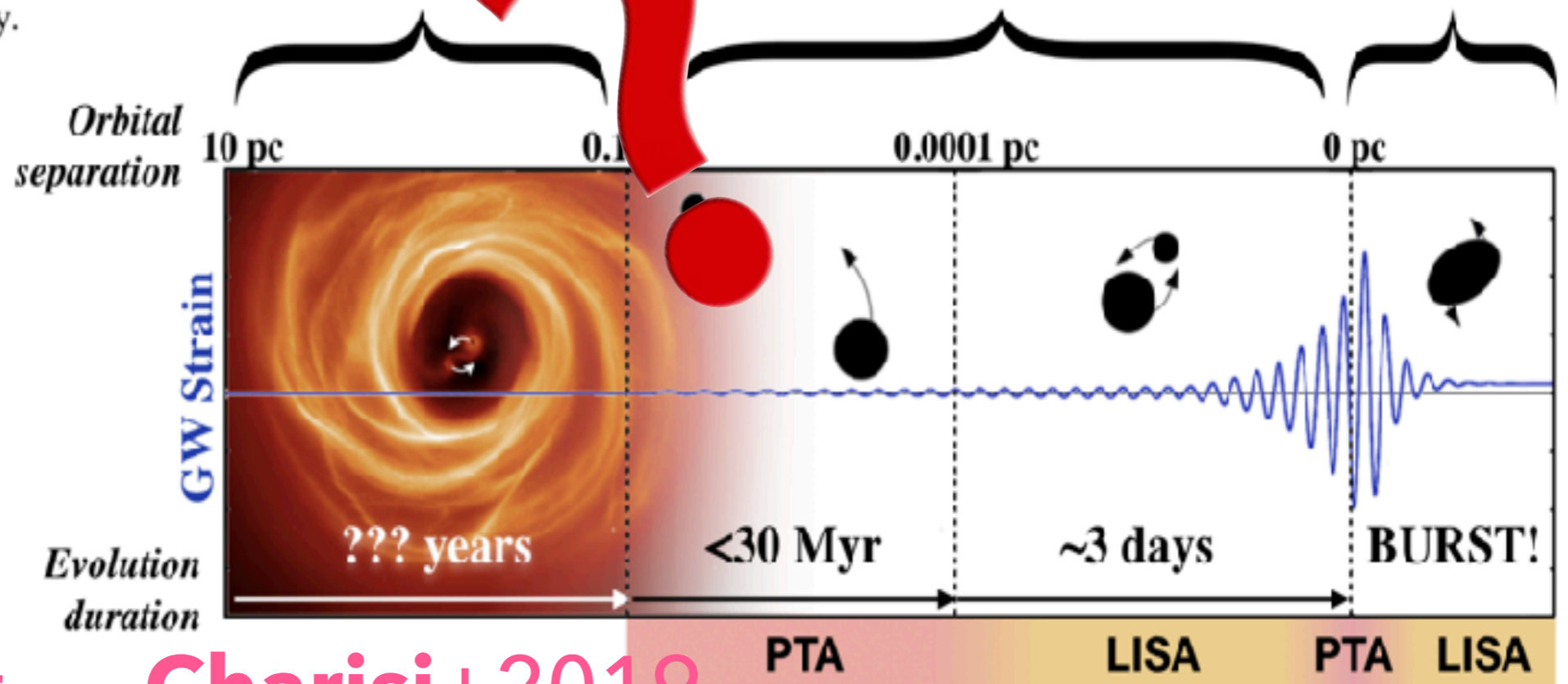
Gravitational radiation provides efficient inspiral. Circumbinary disk may track shrinking orbit.

Coalescence, Memory & Recoil



Post-coalescence system may experience gravitational recoil.

The Lifecycle of Binary Supermassive Black Holes

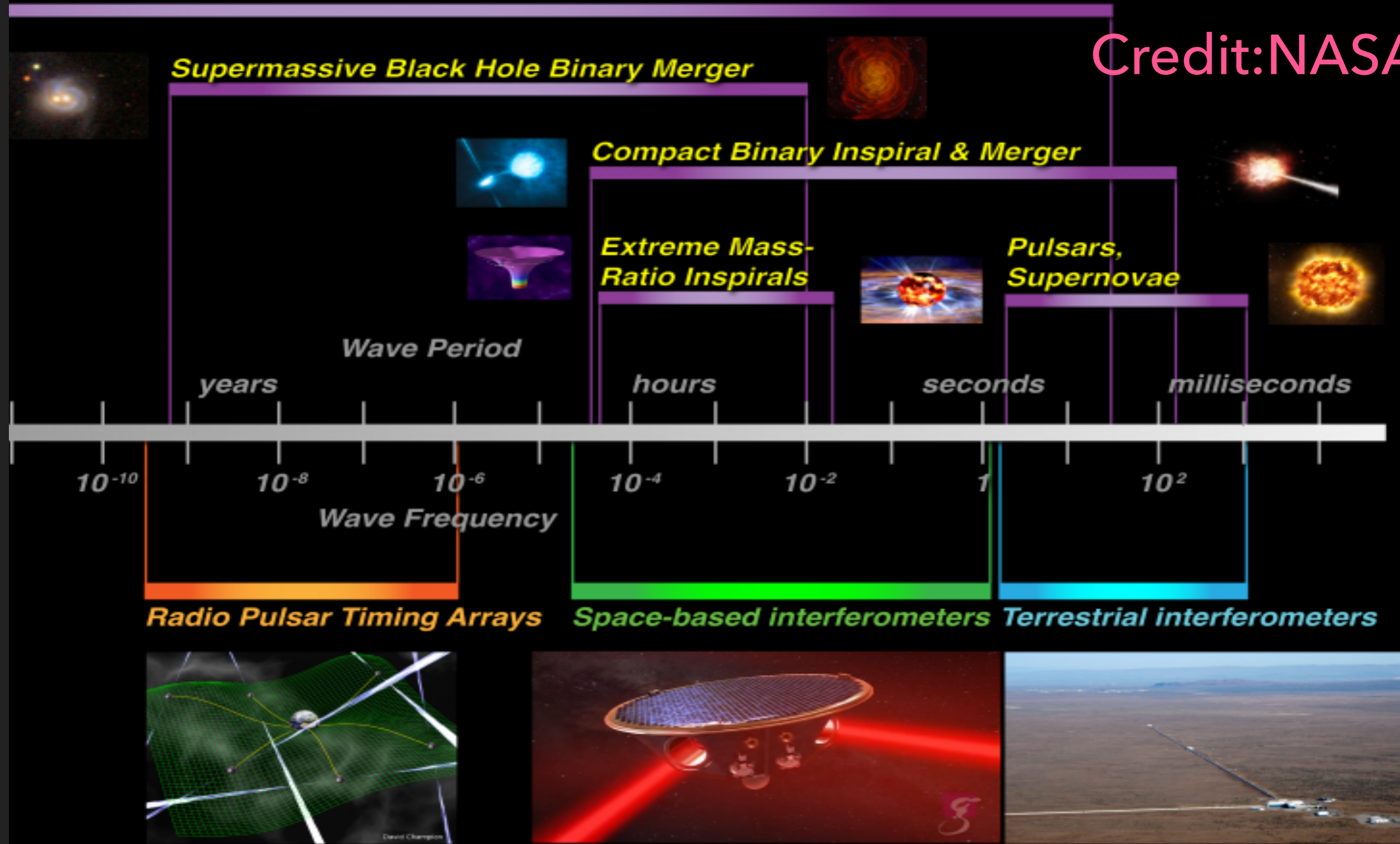


Burke-Spolador, incl. Charisi+2019

► SMBHBs important for galaxy evolution.

GRAVITATIONAL WAVE SPECTRUM

Credit: NASA



▶ SMBHBs most promising sources of low-frequency GWs.

SUPERMASSIVE BLACK HOLE BINARIES



- ▶ How do binaries form and evolve?
- ▶ What are the EM signatures of binaries?
- ▶ How do galaxies form and evolve?
- ▶ How do black holes grow, evolve, form?
- ▶ Is general relativity correct?
- ▶ Can binaries be used as cosmological probes?

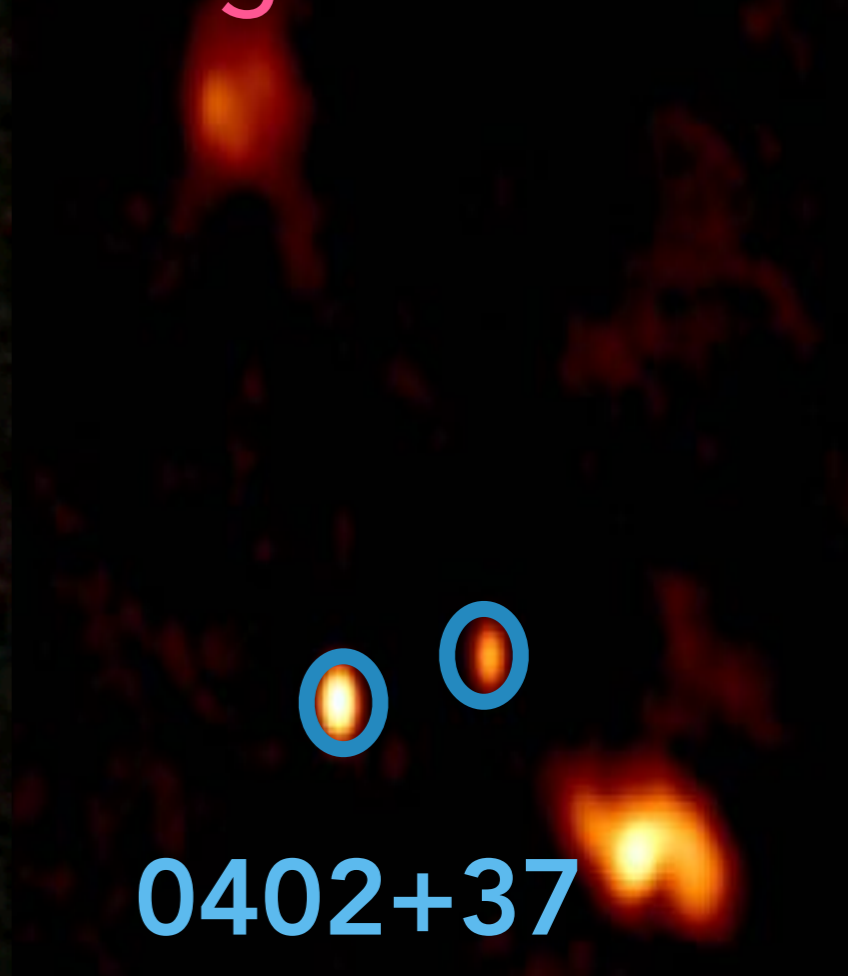
EM SEARCHES FOR BINARIES

EM OBSERVATIONS

Hudson+2006

Koss+2012

Rodriguez+2006



Arp 273

Mrk 739

0402+37

>30 kpc

3.4 kpc

7.3 pc

mega-parsec

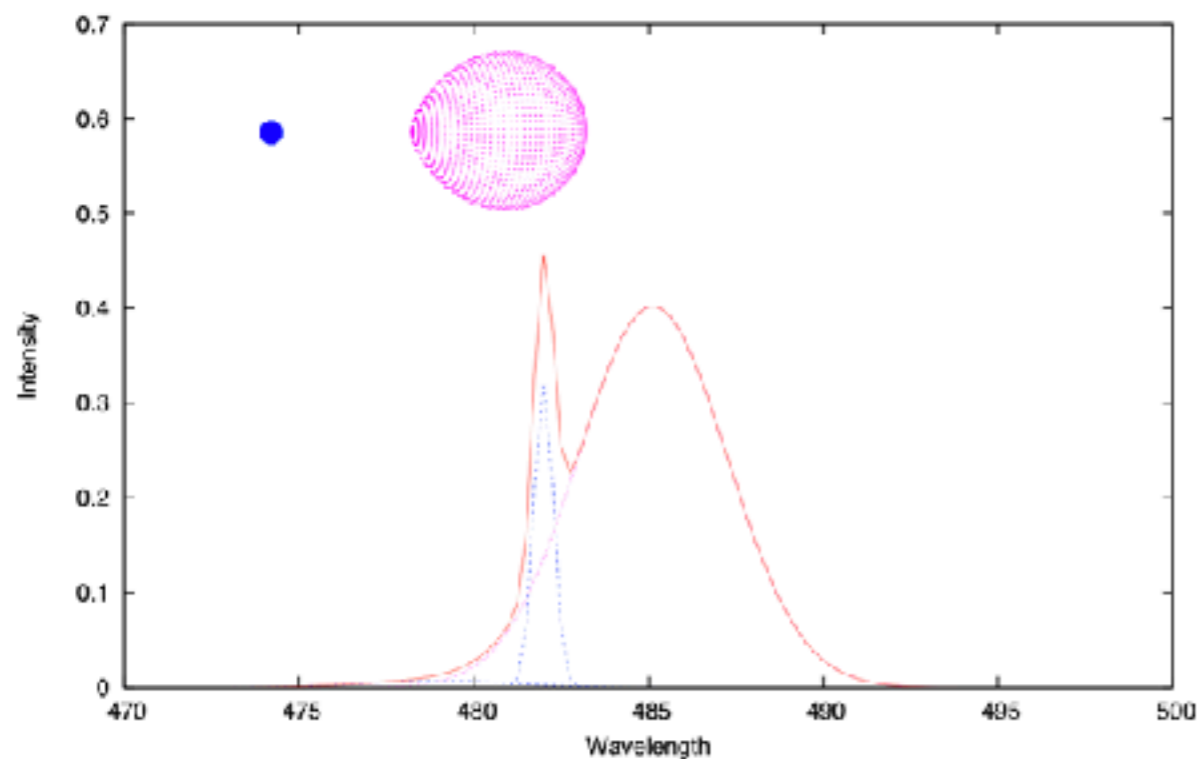
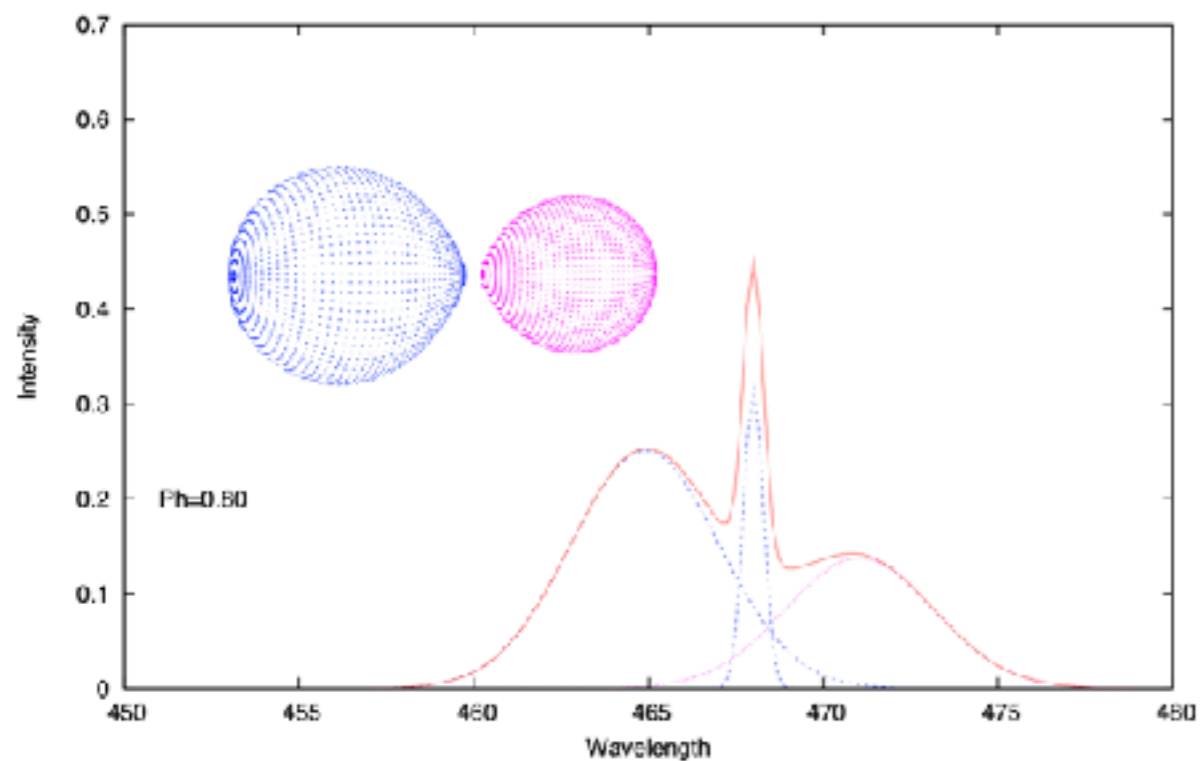
kilo-parsec

parsec

???

See review: De Rosa, incl. Charisi+2019

QUASARS WITH ATYPICAL BROAD LINES



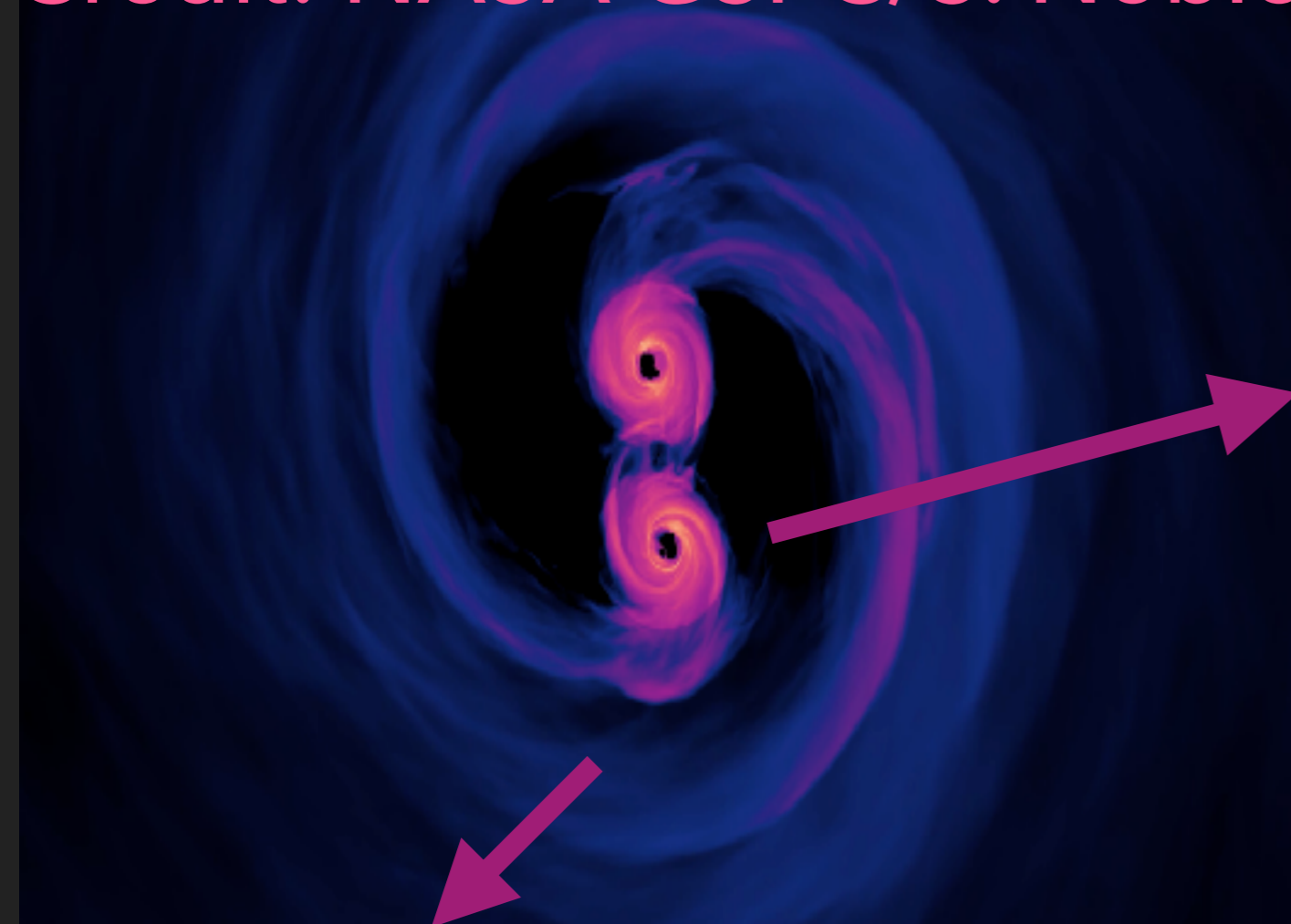
- ▶ Hundreds of candidates detected in SDSS.
- ▶ Signature is not unique.
- ▶ Long-term monitoring is required.

QUASARS WITH PERIODIC VARIABILITY

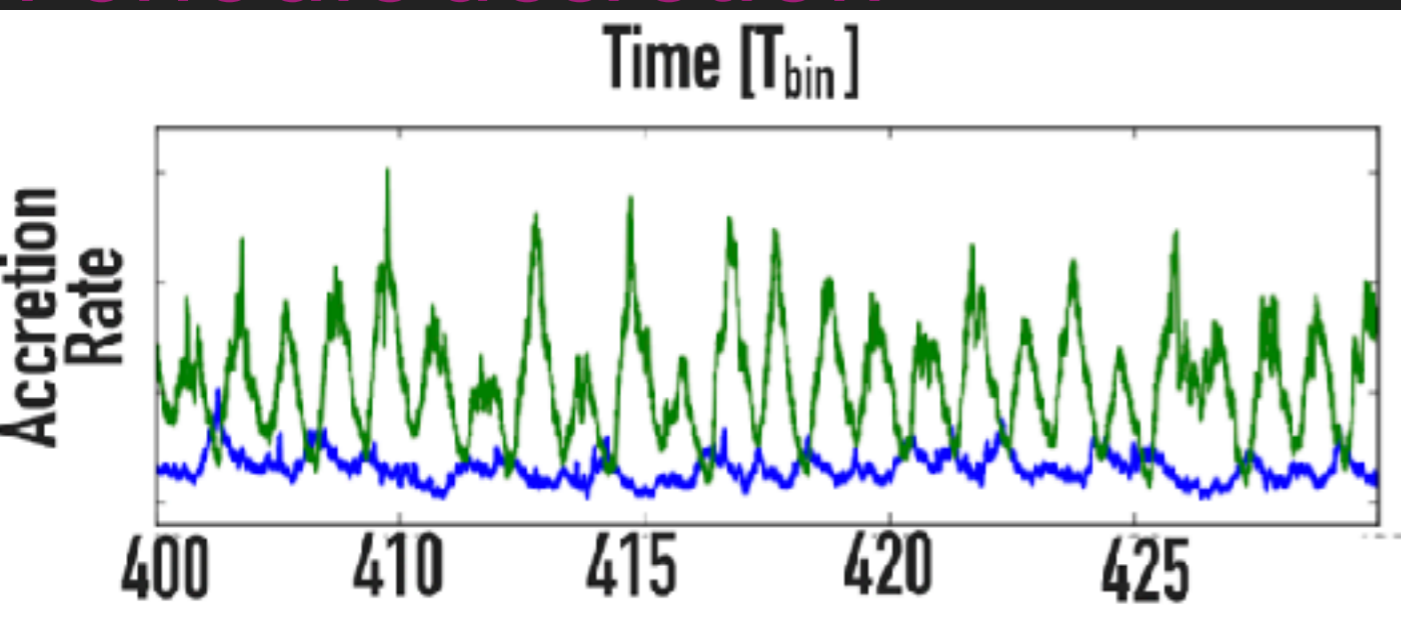
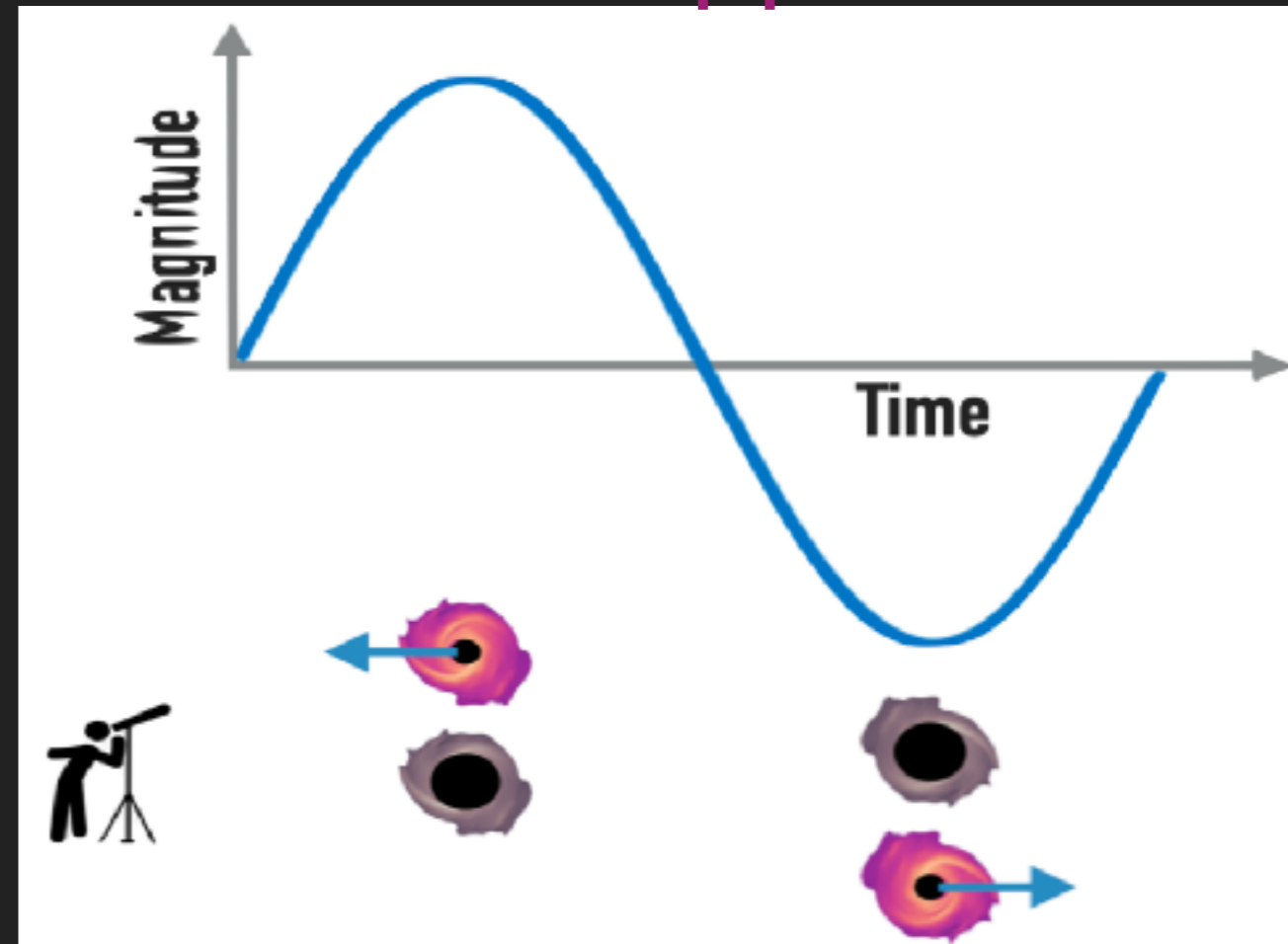
Credit: NASA GSFC/S. Noble

- ▶ Bright quasar-like emission.
- ▶ Periodic variability.

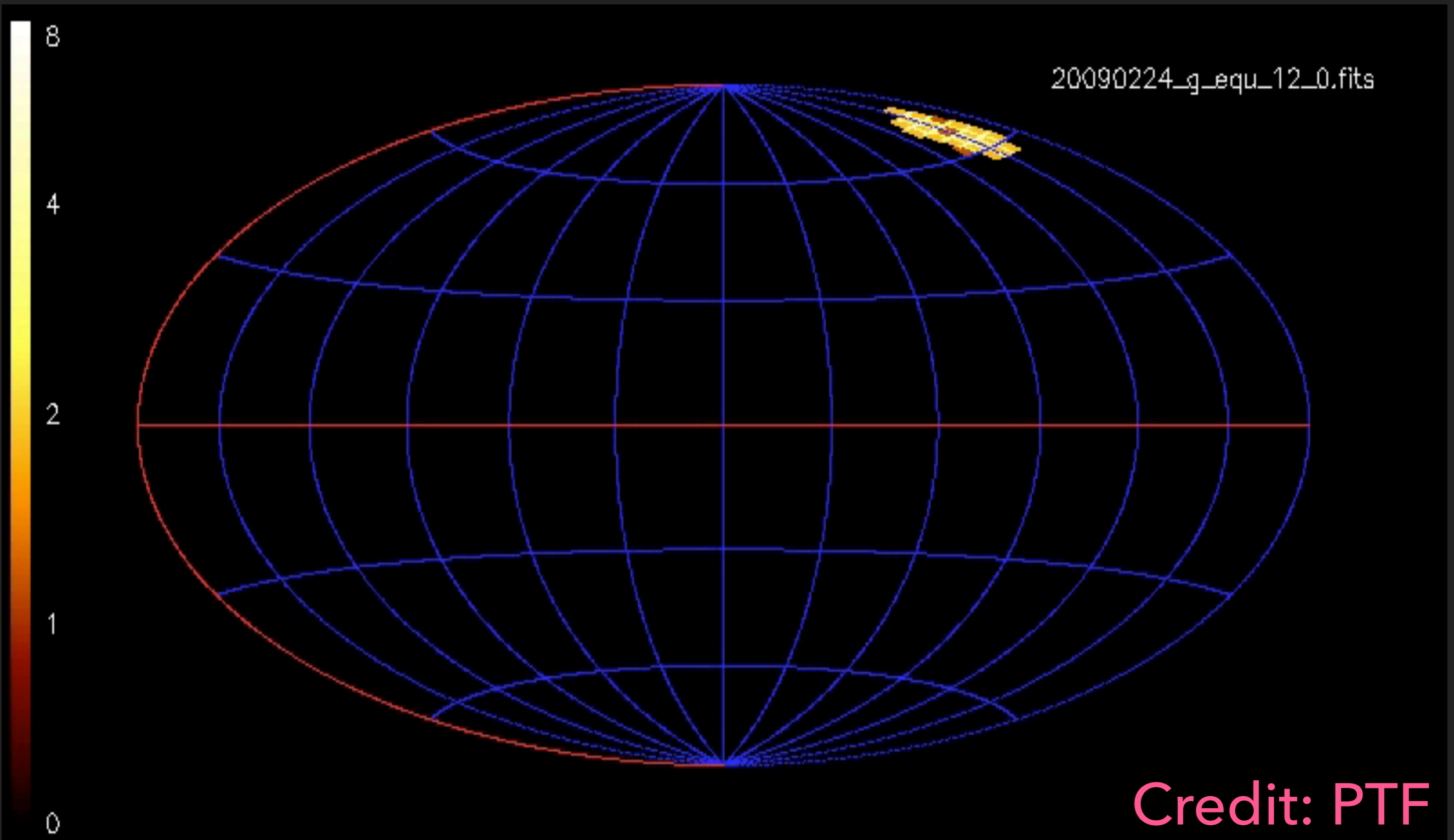
Relativistic Doppler boost



Periodic accretion

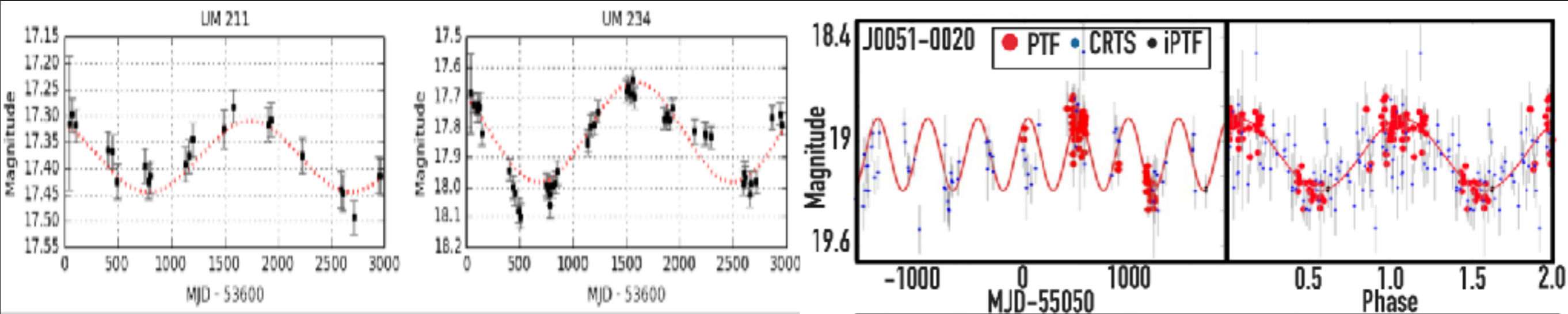


TIME DOMAIN SURVEYS

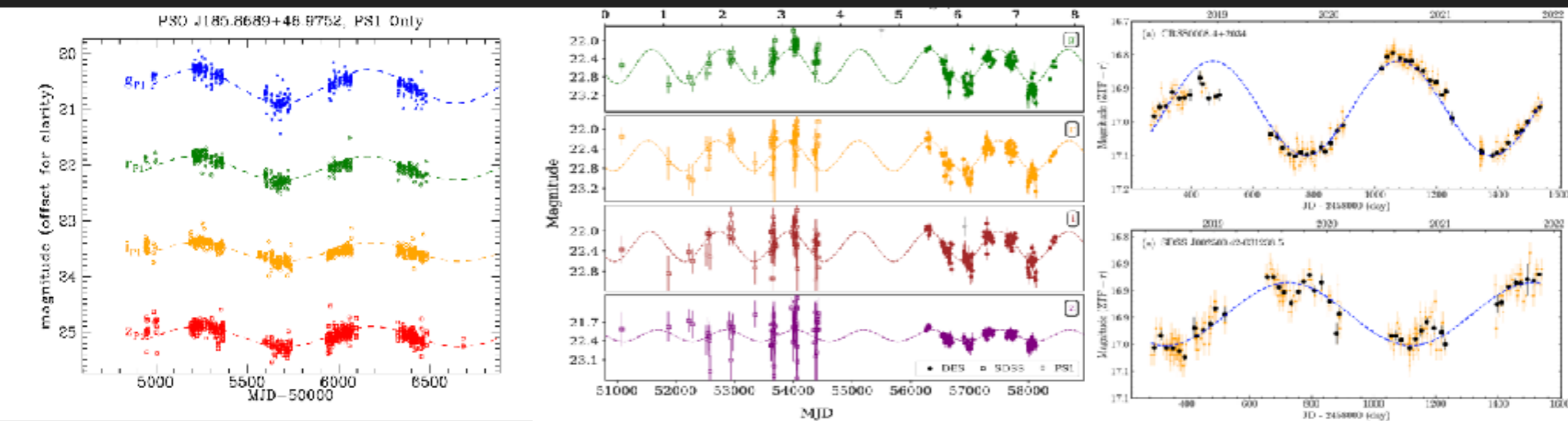


- ▶ Time-domain surveys provided large samples of quasars for the first systematic searches.

SYSTEMATIC SEARCHES



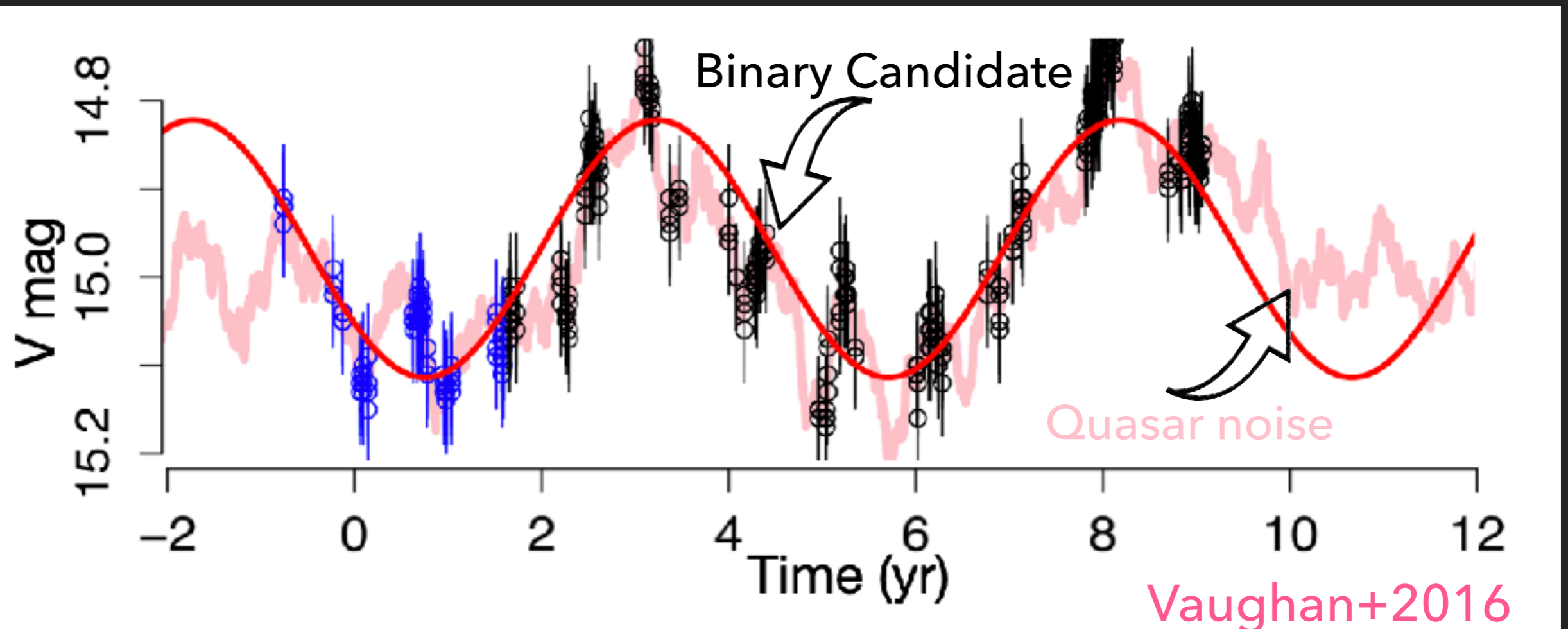
► CRTS: 111 of 245,000 [Graham+2015](#) ► PTF: 33 of 35,000 [Charisi+2016](#)



► PanSTARRS: 1 of 9,000 [Liu+2019](#) ► DES: 5 of 625 [Chen+2020](#) ► ZTF: 117 of 144000 [Chen+2022](#)

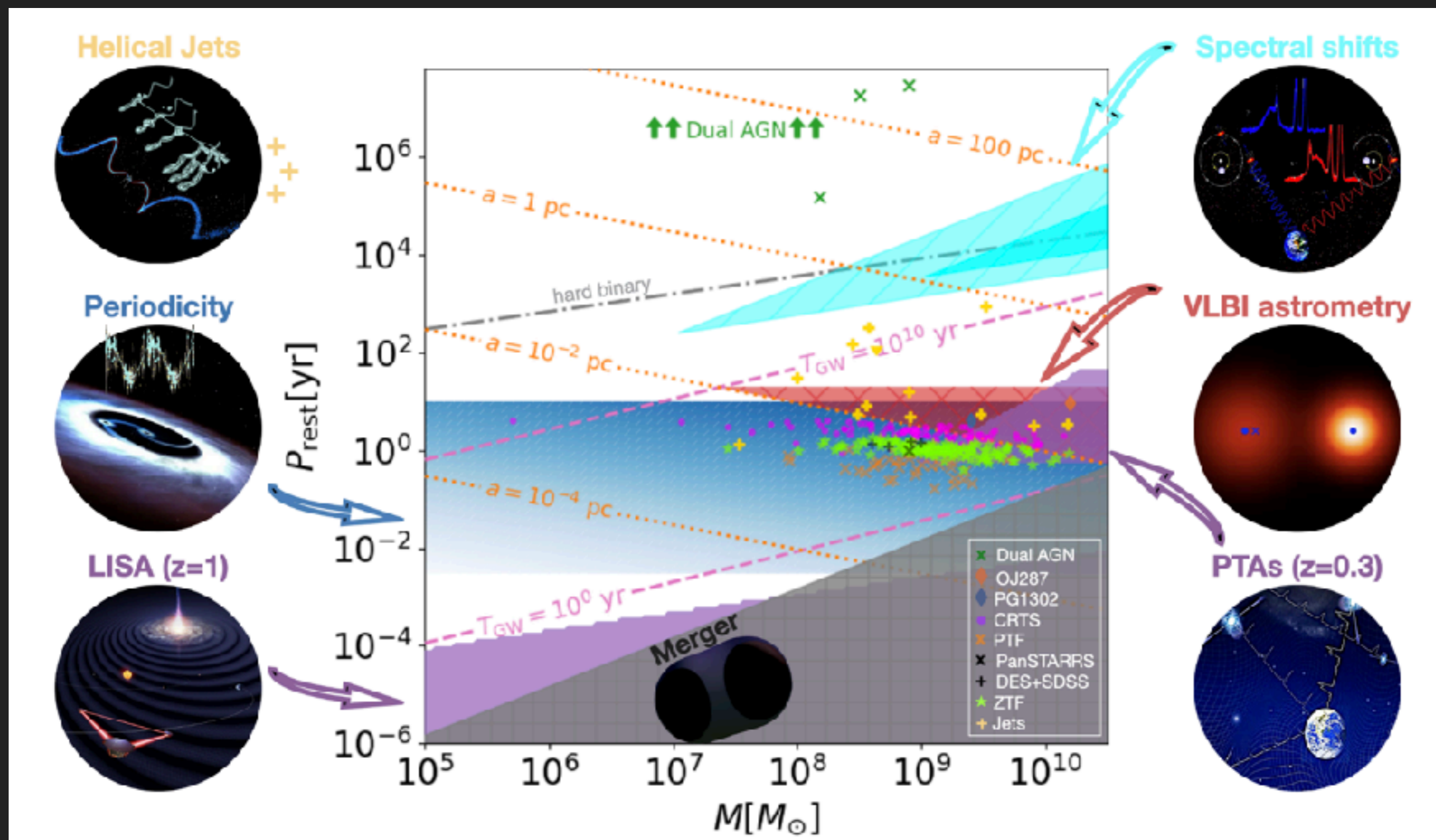
~250 Candidate Supermassive Black Holes.

QUASAR PERIODICITY OR STOCHASTIC NOISE?



- ▶ Stochastic variability mimics periodicity.
- ▶ Significant contamination with false positives.
- ▶ Long-term monitoring is required OR additional signatures.

ADDITIONAL SIGNATURES



See review: **D’Orazio, Charisi+2023**

- ▶ Several candidates show multiple signatures.
- ▶ Challenging to distinguish them from quasar variability

THE FUTURE IS BRIGHT!

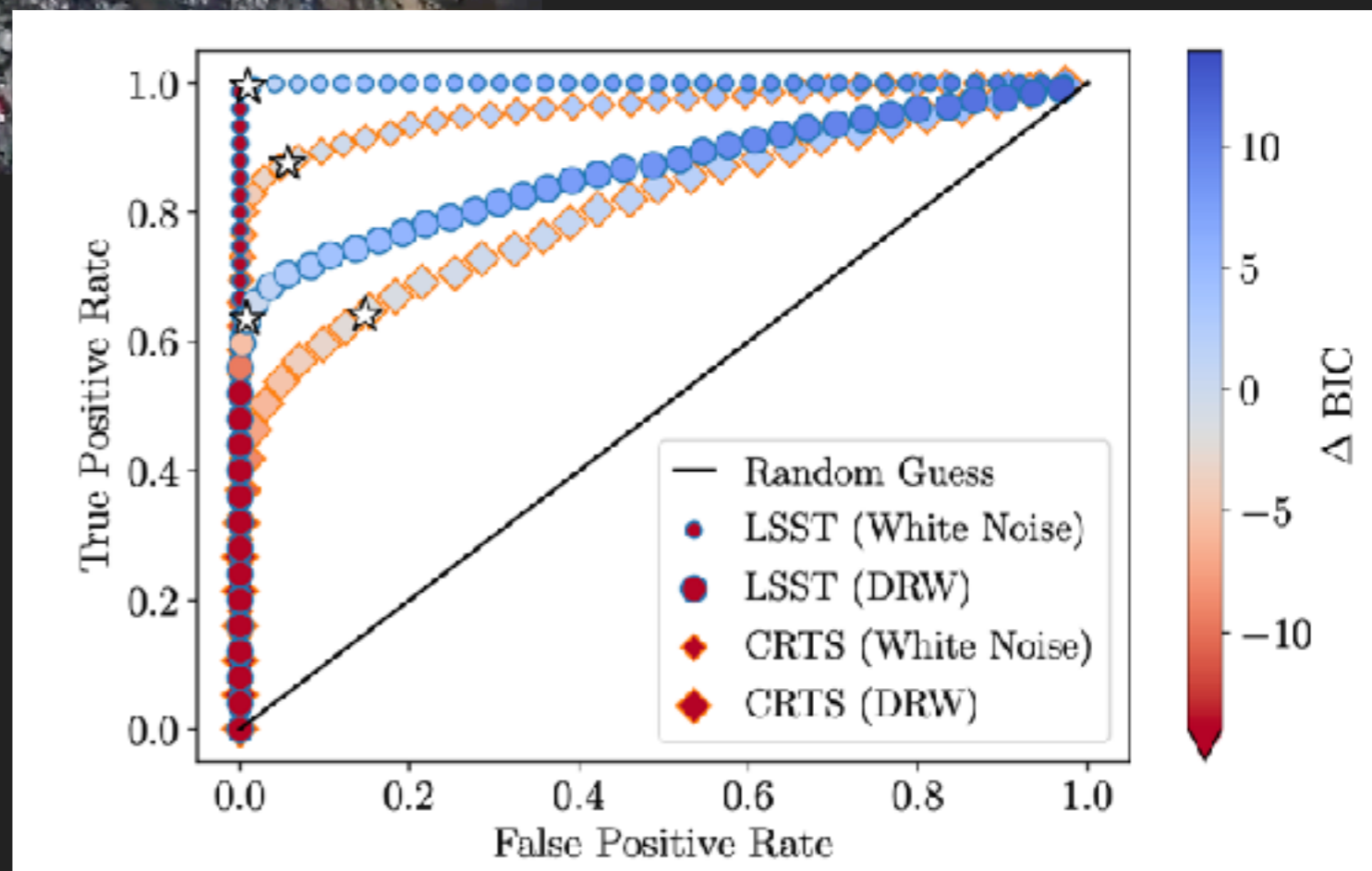


- ▶ 20-100 million quasars
- ▶ High-quality data
- ▶ First data release in 2025

Legacy Survey of Space & Time (LSST)
Rubin Observatory

Very reliable binary
candidates due to
quality of LSST data.

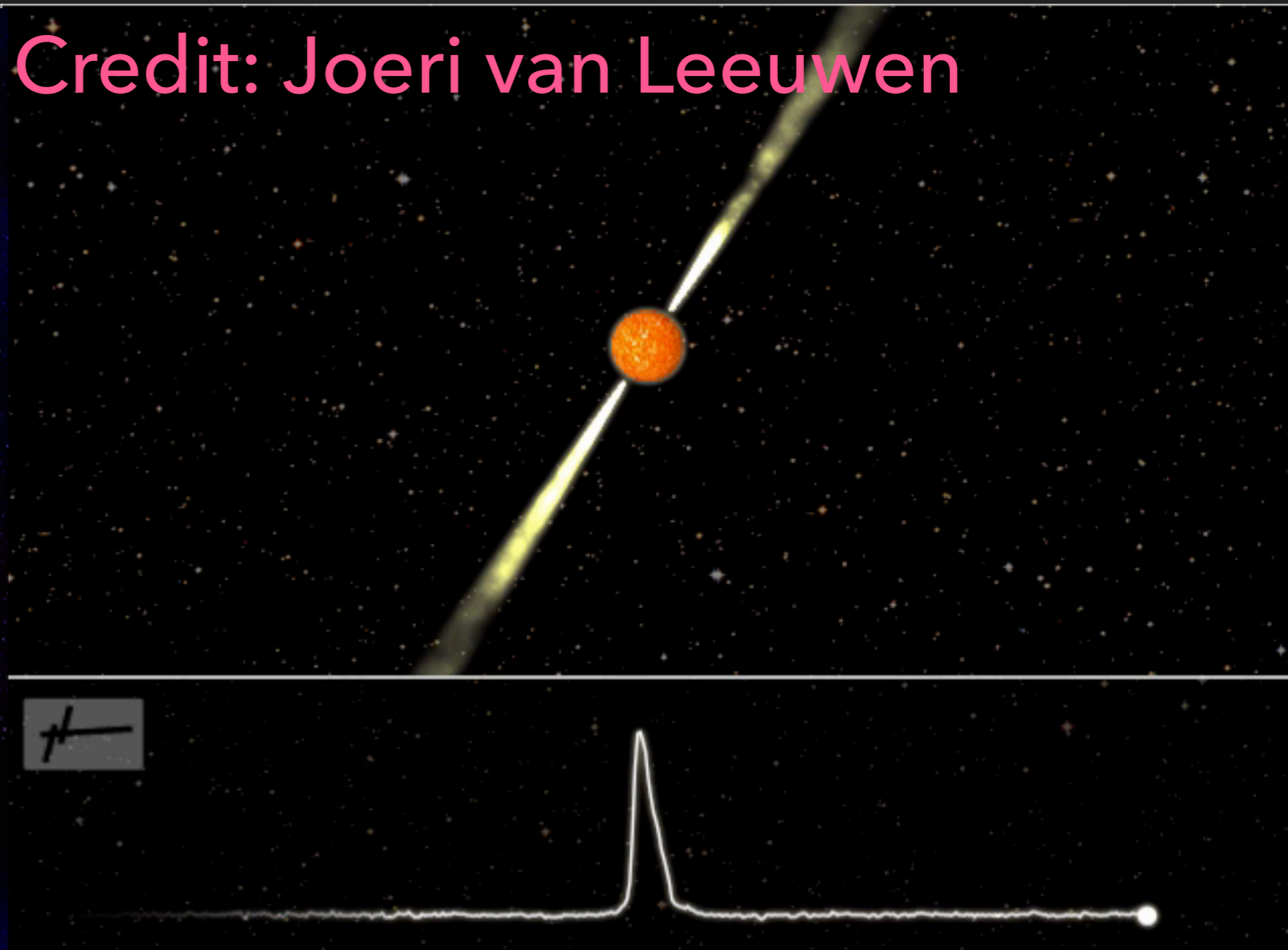
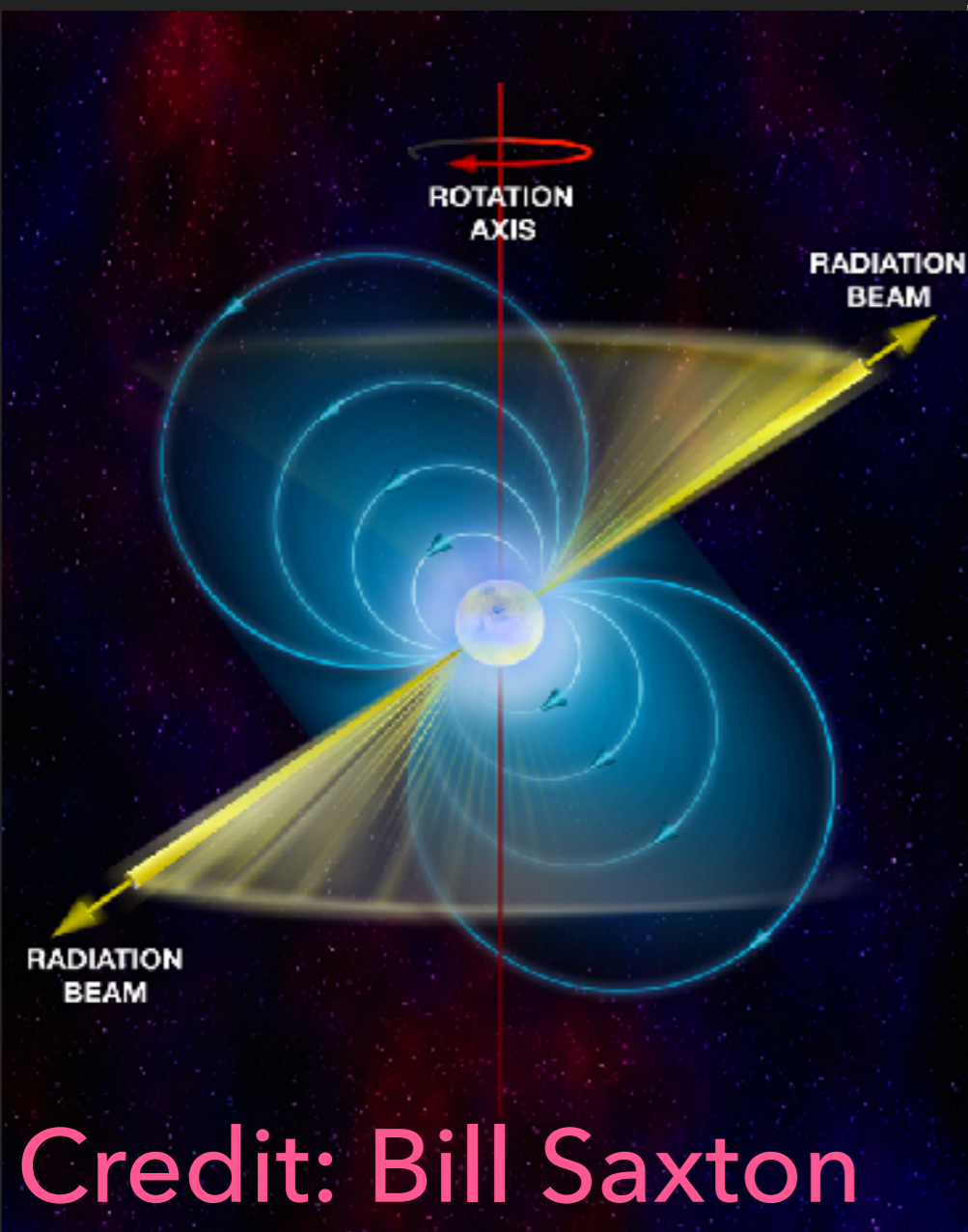
Witt, Charisi+2022



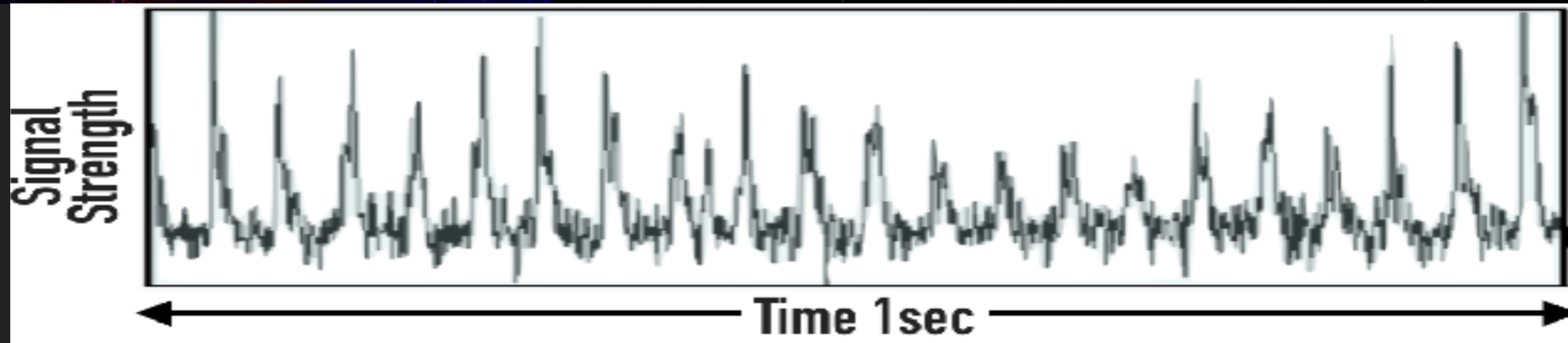
GRAVITATIONAL WAVES PULSAR TIMING ARRAYS

MILLISECOND PULSARS

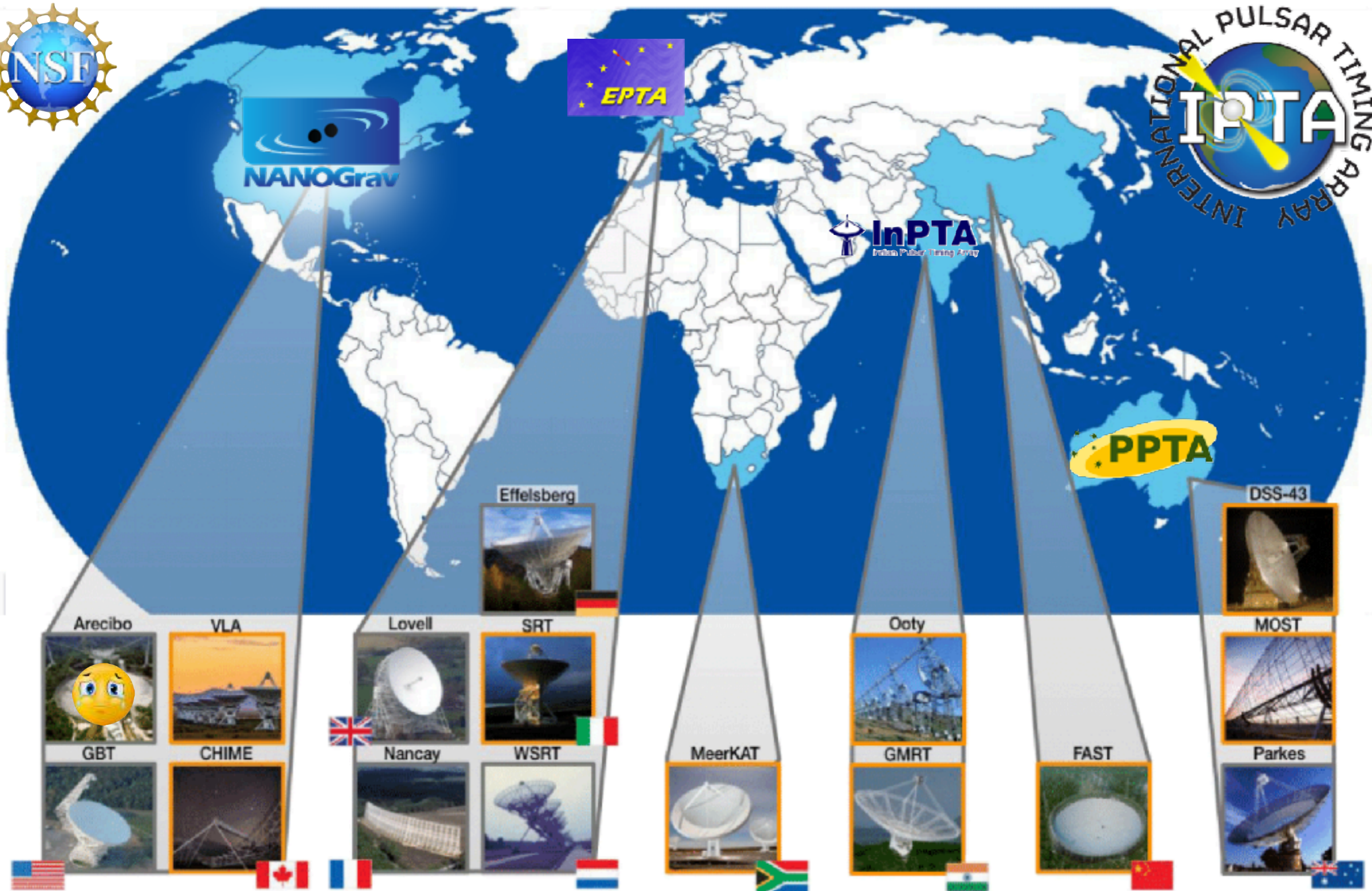
Credit: Joeri van Leeuwen



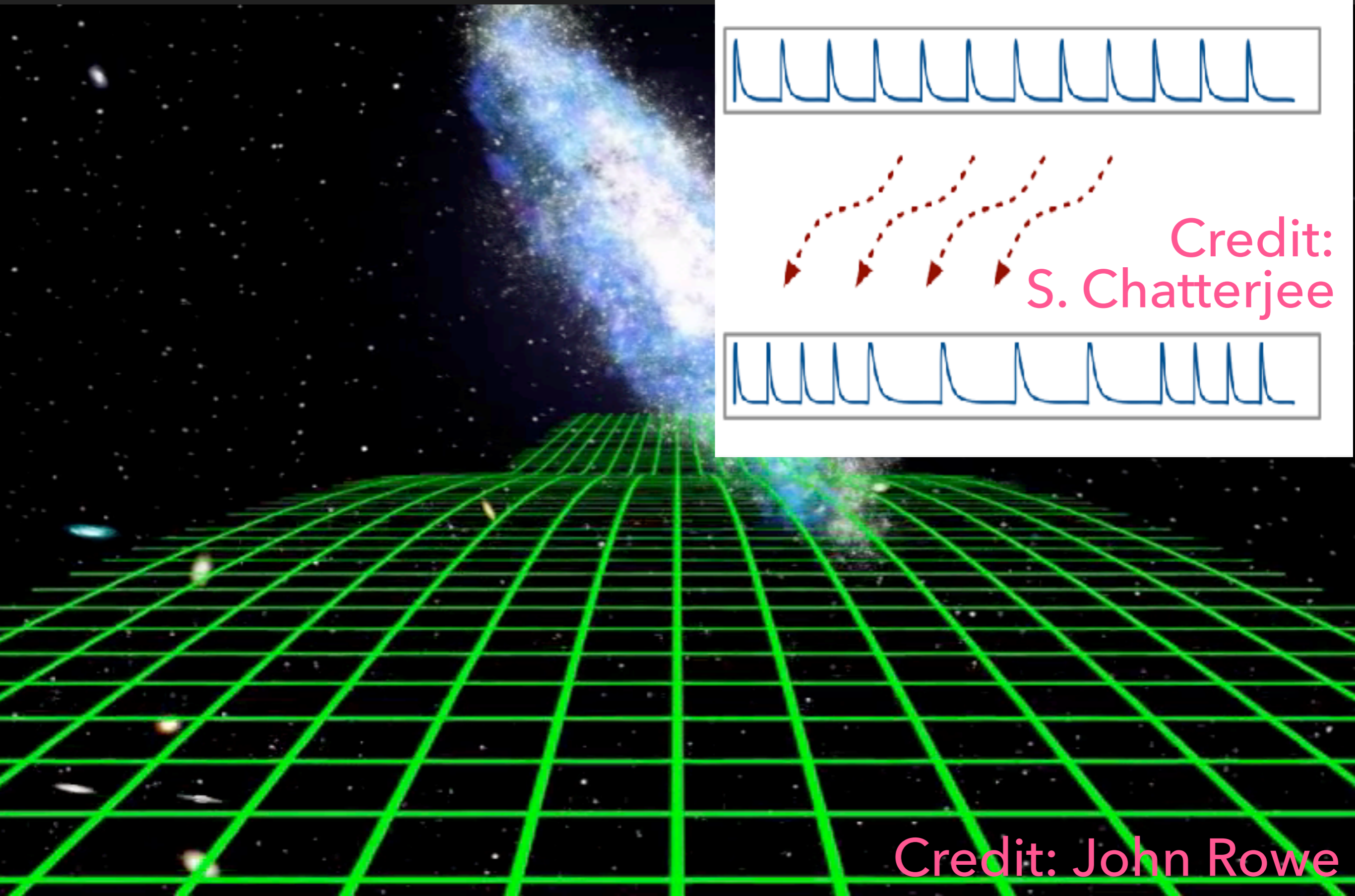
Credit: Bill Saxton



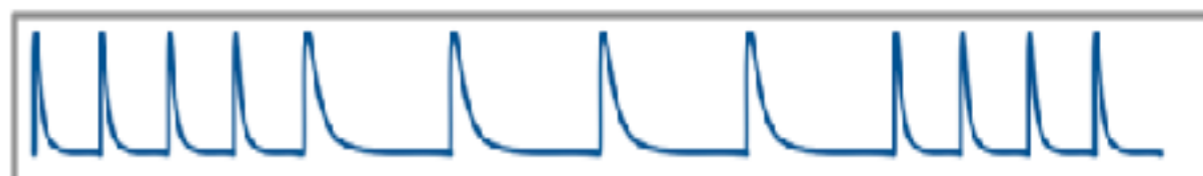
INTERNATIONAL COLLABORATION



PULSAR TIMING ARRAYS

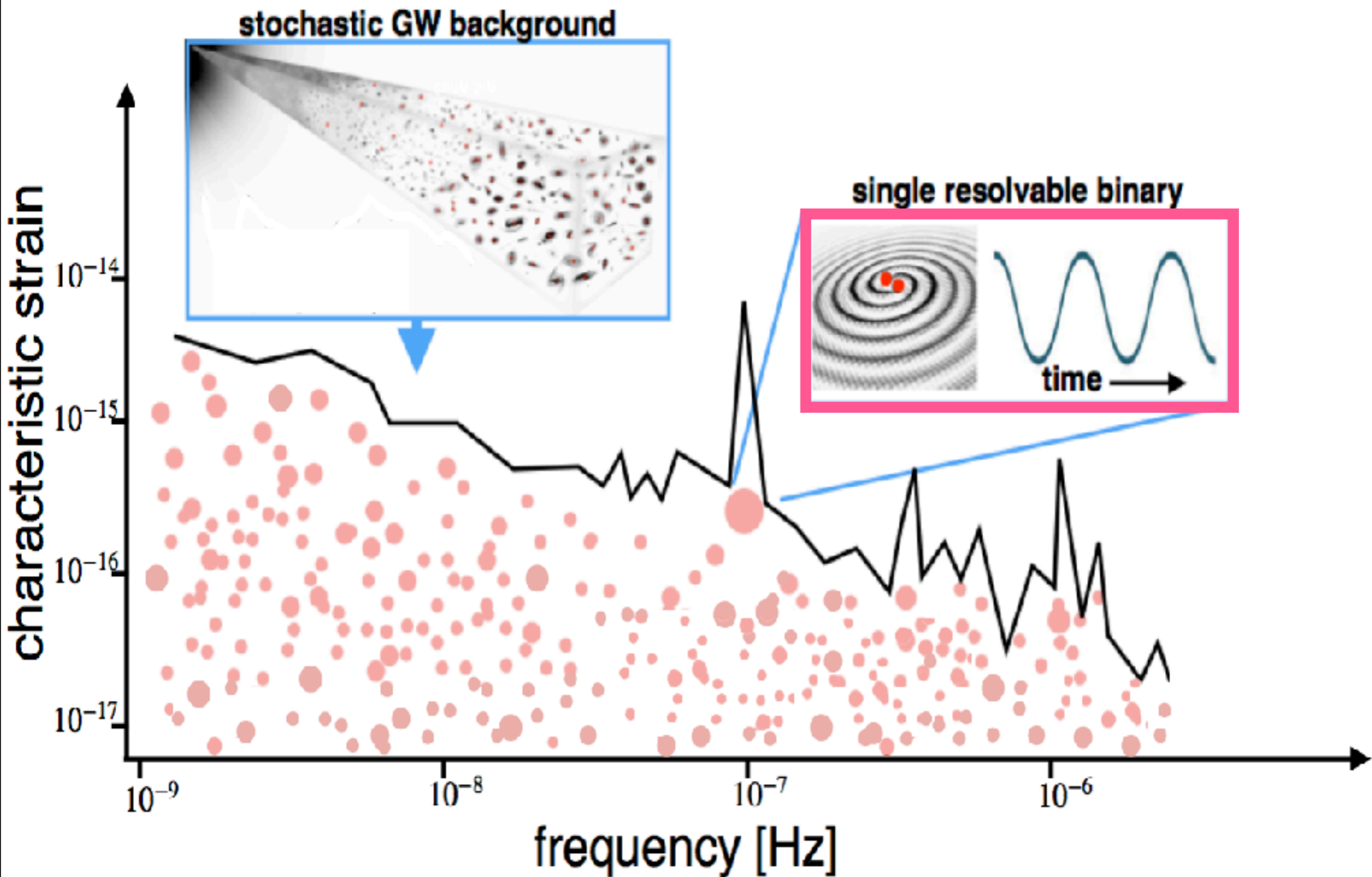


Credit:
S. Chatterjee

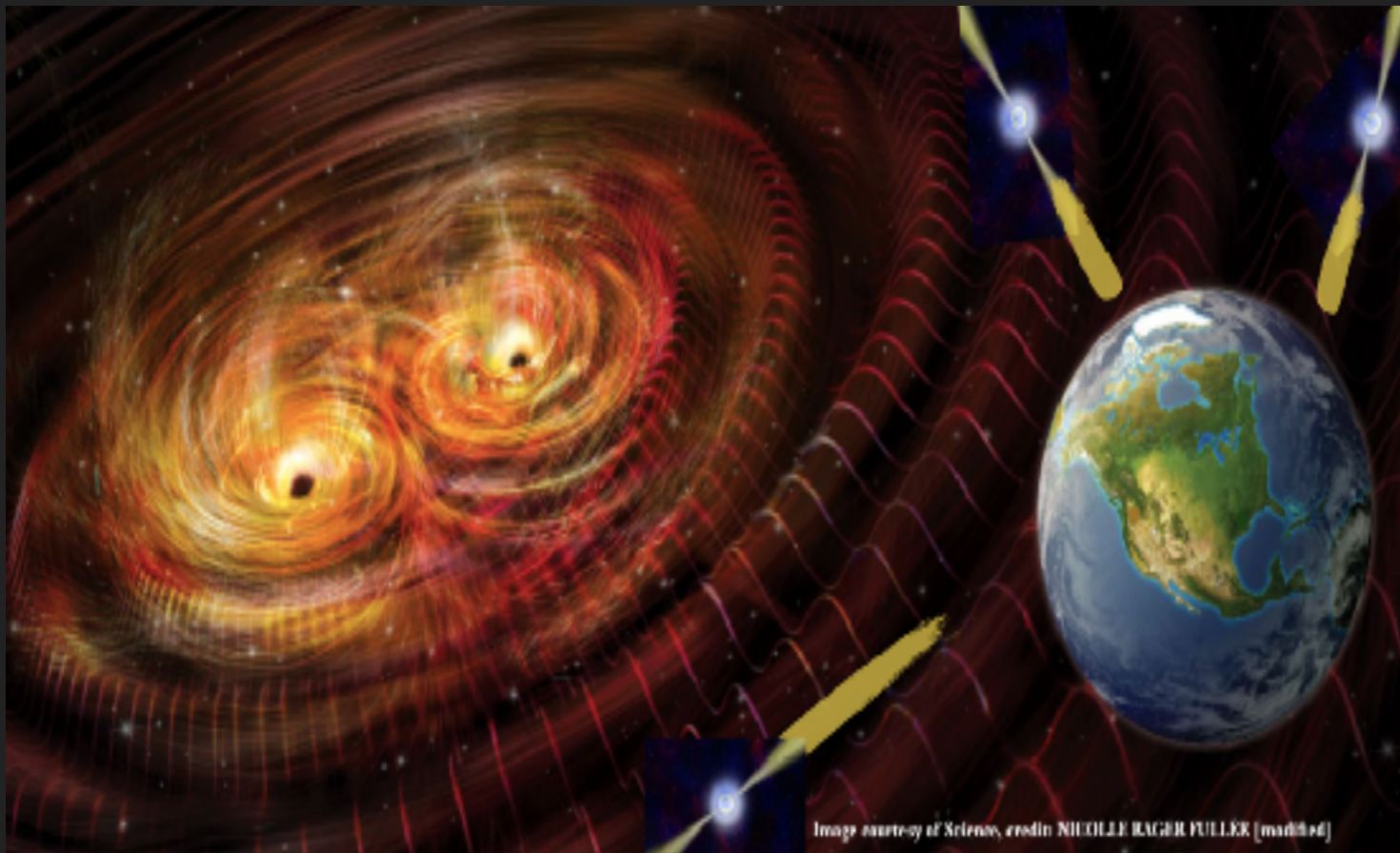


Credit: John Rowe

INDIVIDUALLY RESOLVED BINARIES



MULTI-MESSENGER OBSERVATIONS

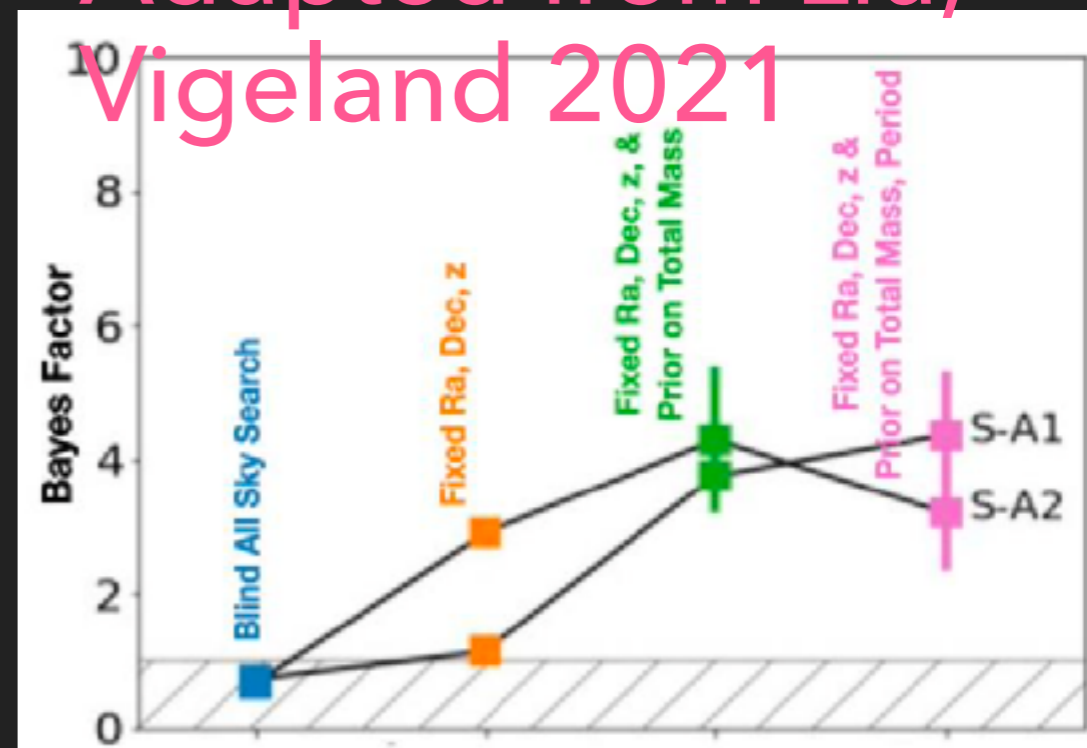


- ▶ GWs probe dynamics.
- ▶ EM obs. probe interaction with gas.
- ▶ Multi-messenger obs. provide the most complete picture.

- ▶ EM information boosts PTA detection sensitivity.
- ▶ Improves PTA limits by an order of magnitude.

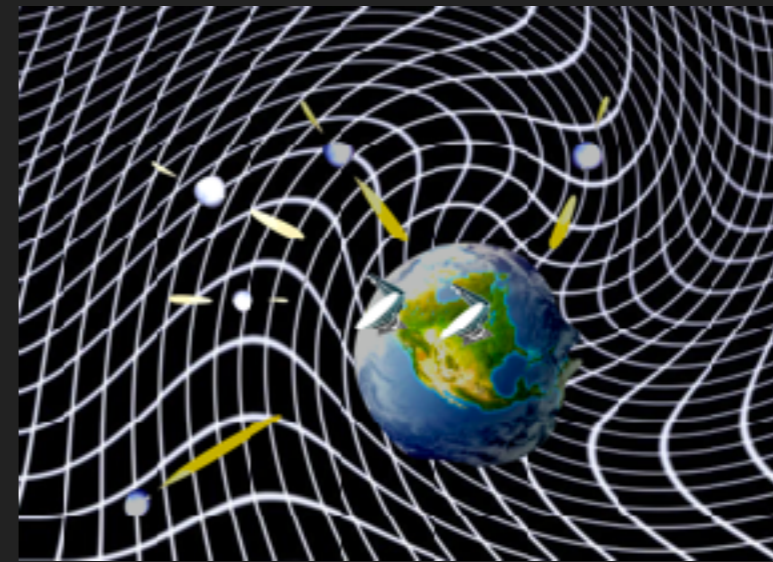
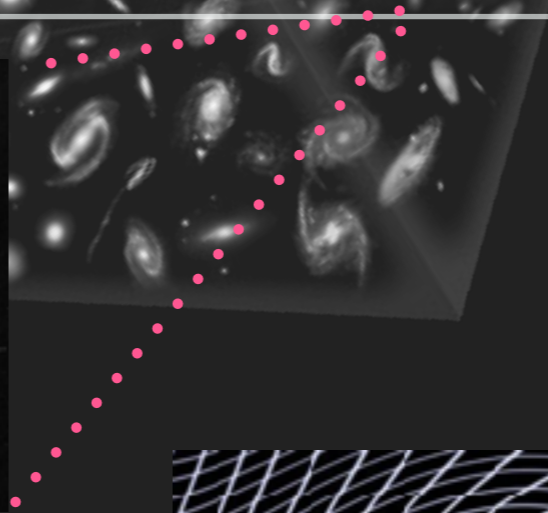
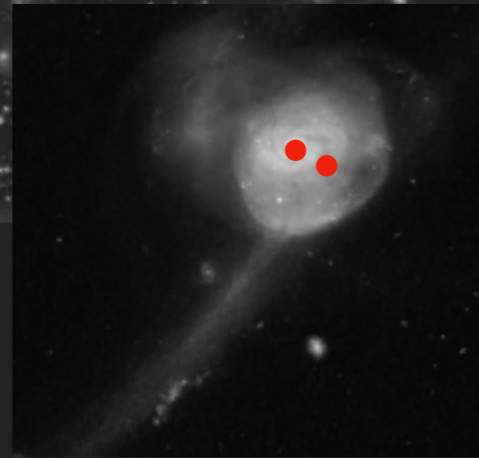
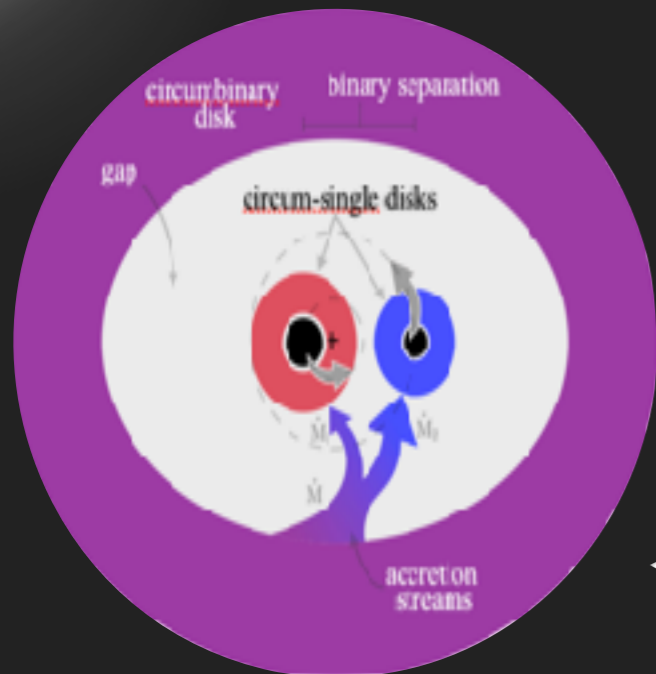
Arzoumanian+2020_{incl.} Charisi

Adapted from Liu, Vigeland 2021

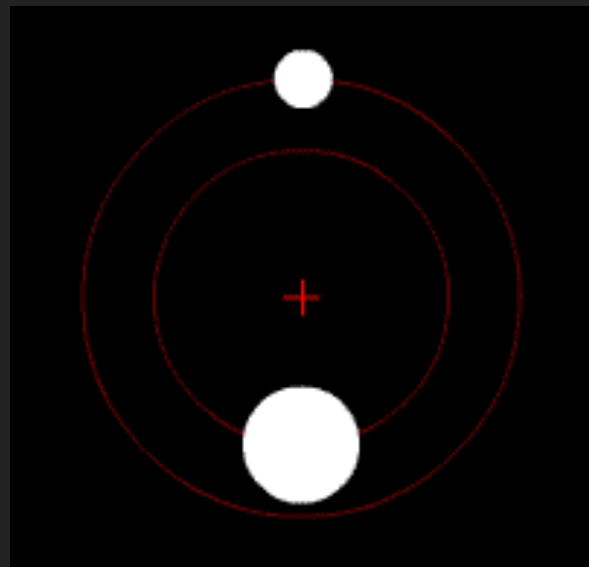


CONNECTIONS WITH ORBITAL DYNAMICS

Charisi+2022

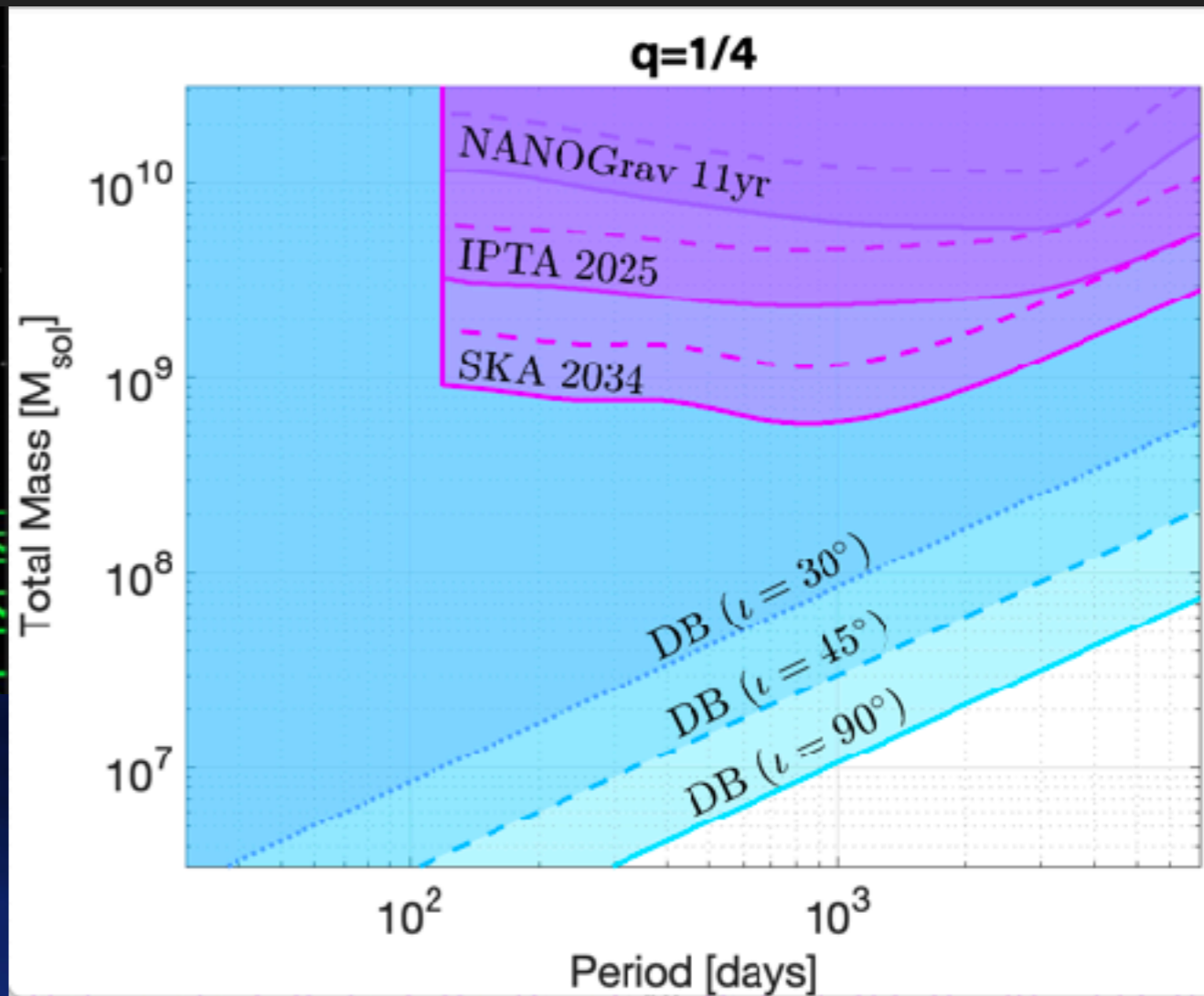
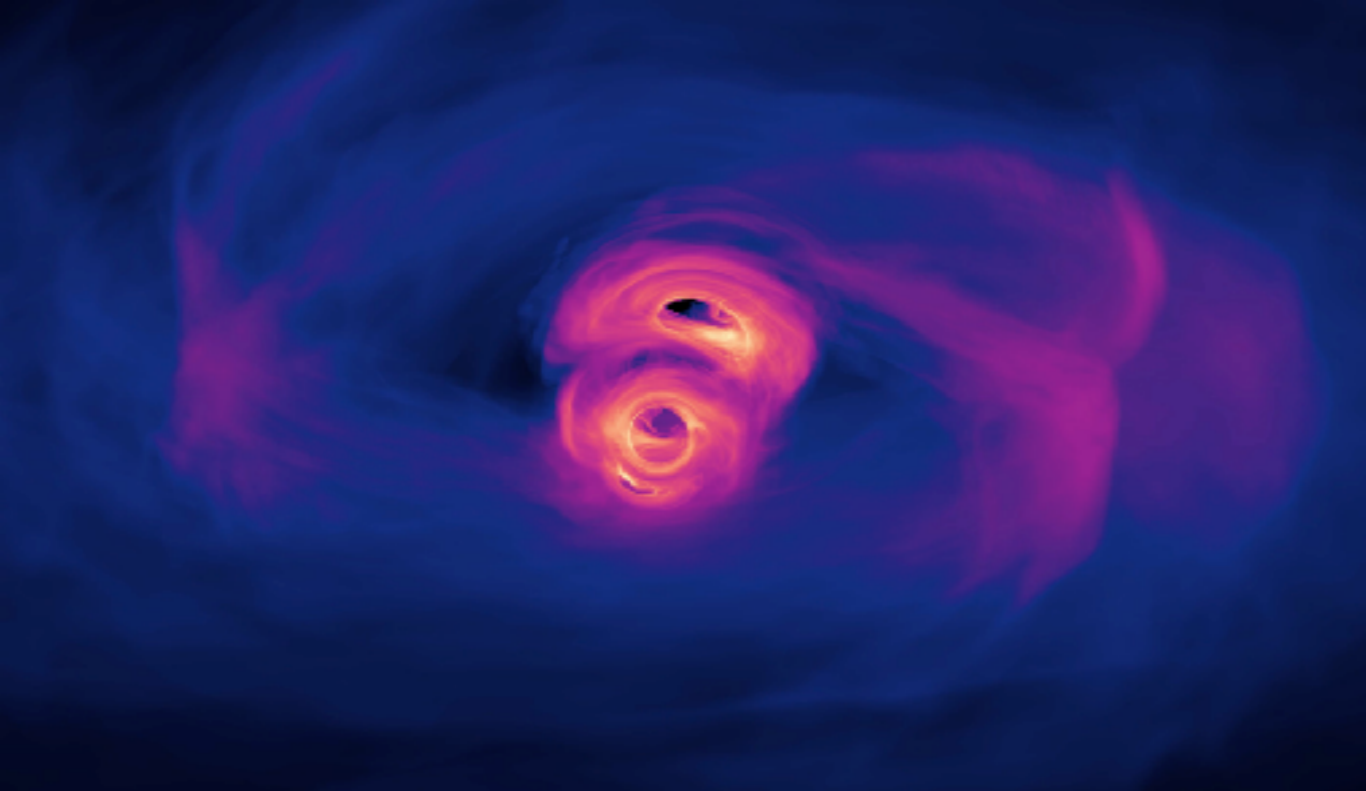
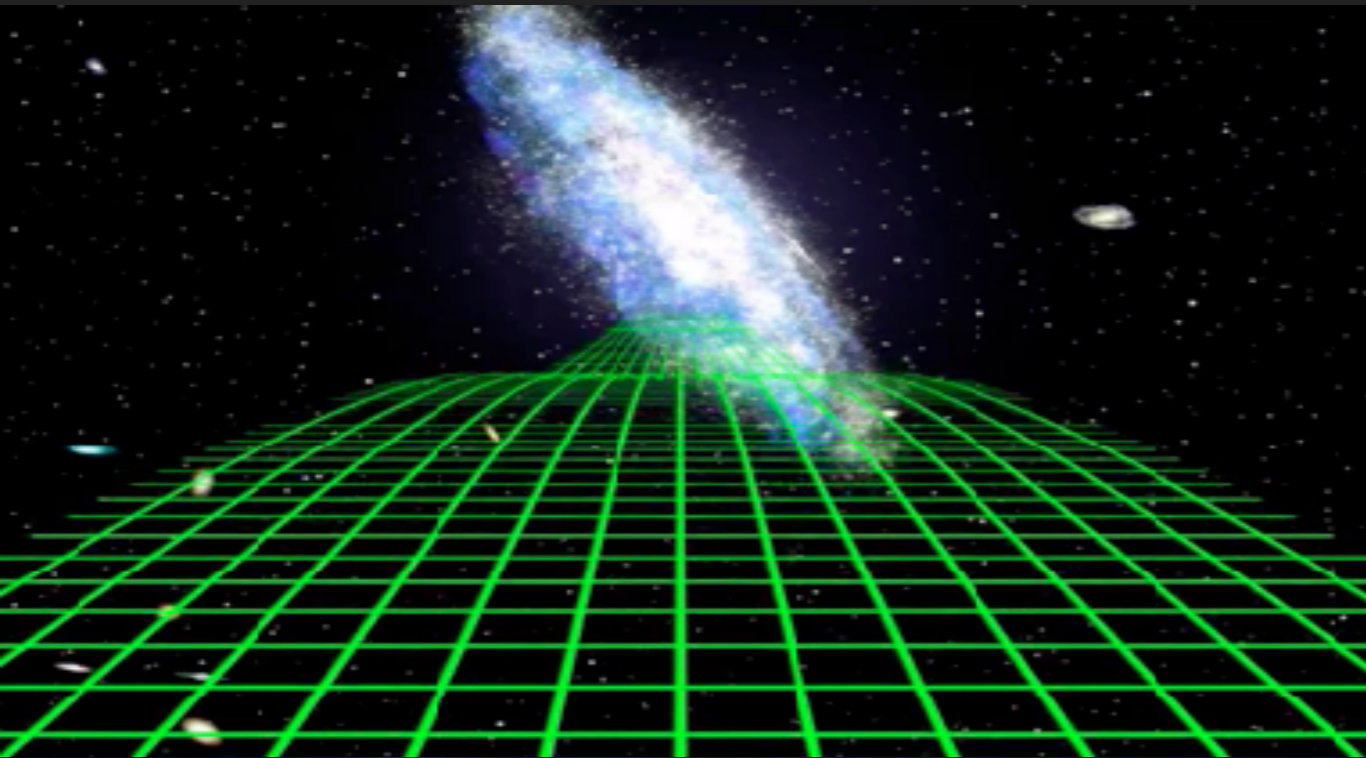


▶ PTAs and EM surveys probe the same binaries



Model	Period	Phase	Amplitude
Circular ($q > 0.4$) Periodic Accretion	😊	☹️	☹️
Circular ($q < 0.4$) Periodic Accretion	😊	☹️	☹️
Circular Doppler Boost	😊	😊	😊

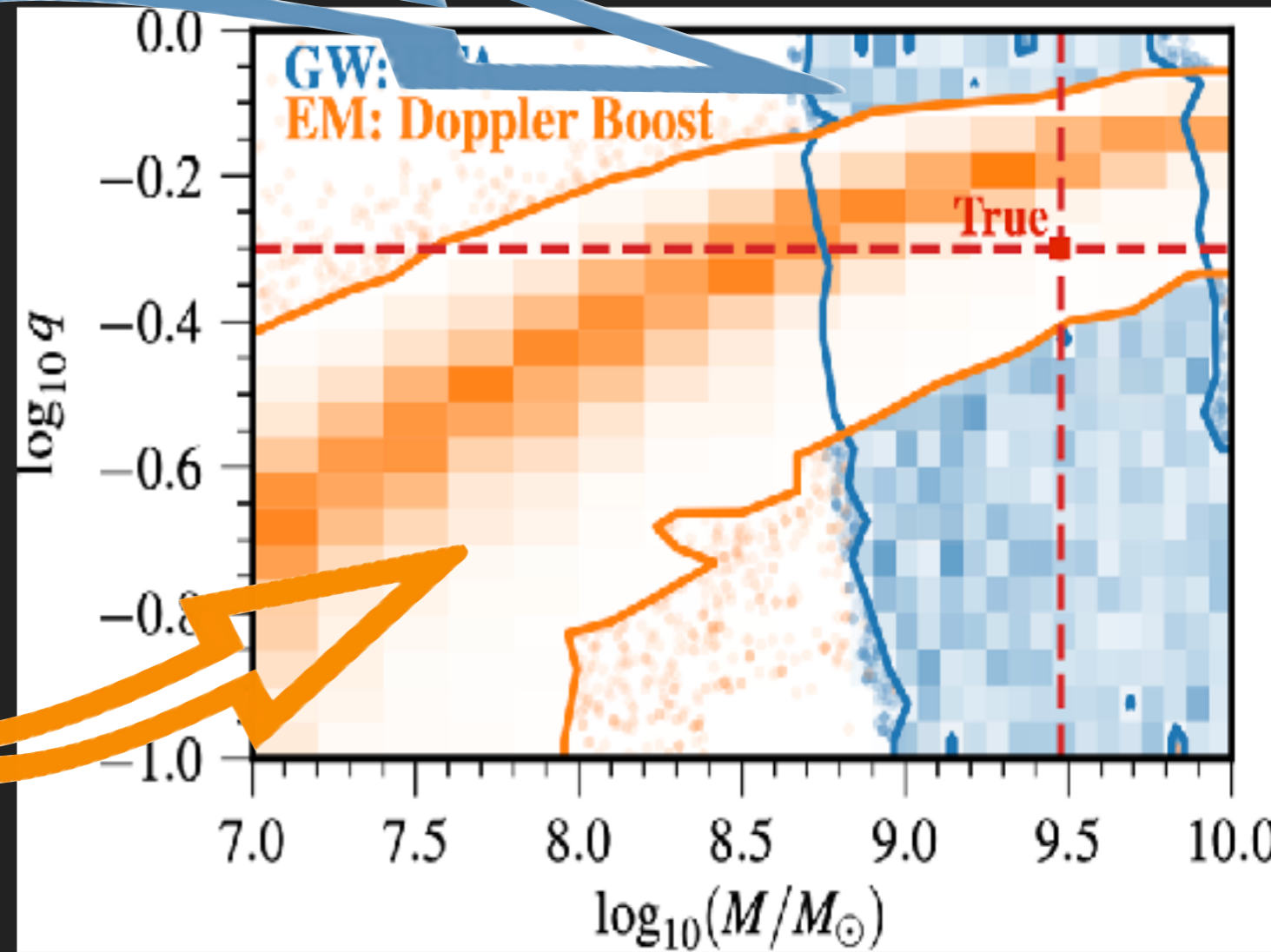
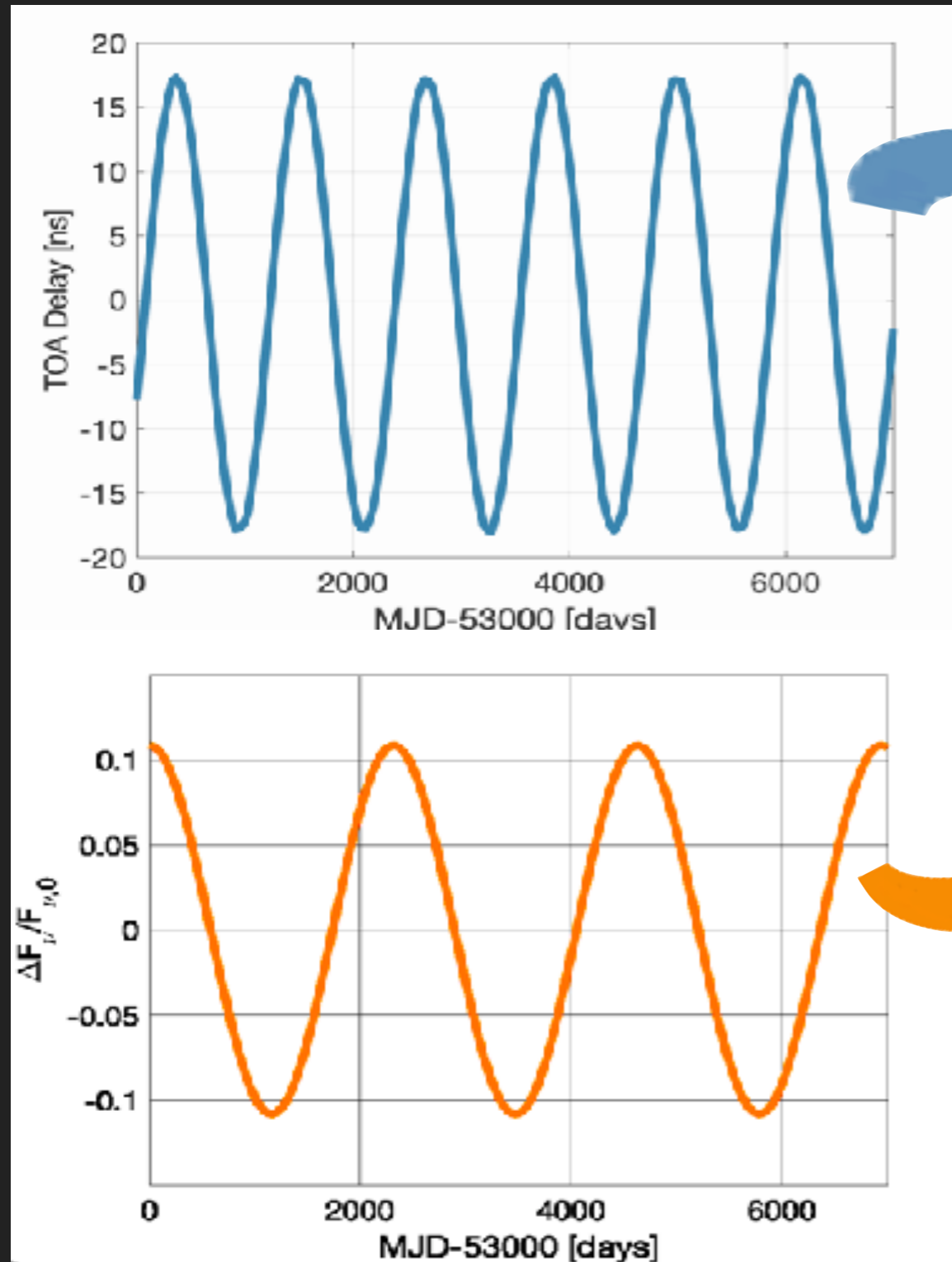
MULTI-MESSENGER OBSERVATIONS



- ▶ Significant overlap in parameter space.

Charisi+2022

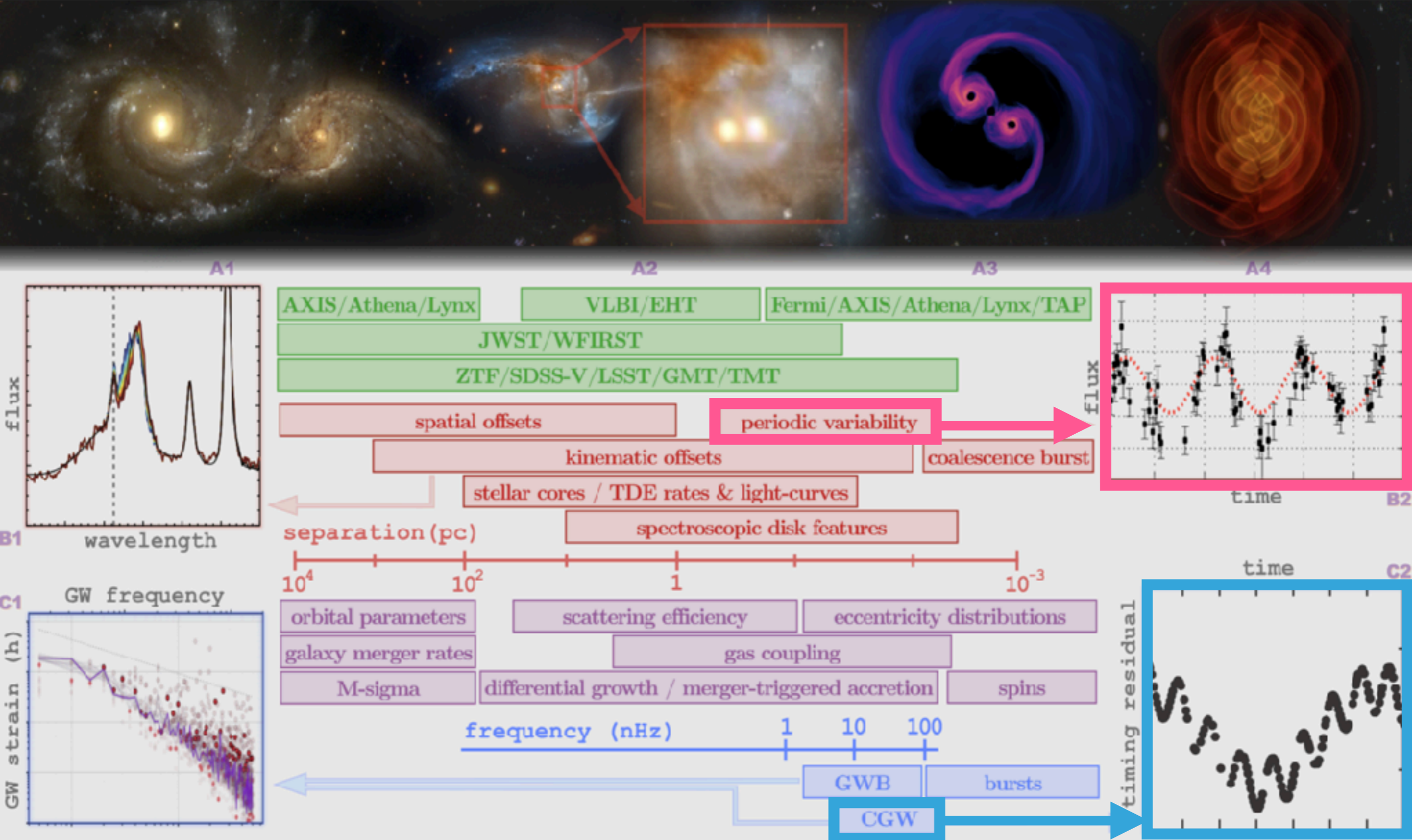
MULTI-MESSENGER OBSERVATIONS



Charisi+in prep

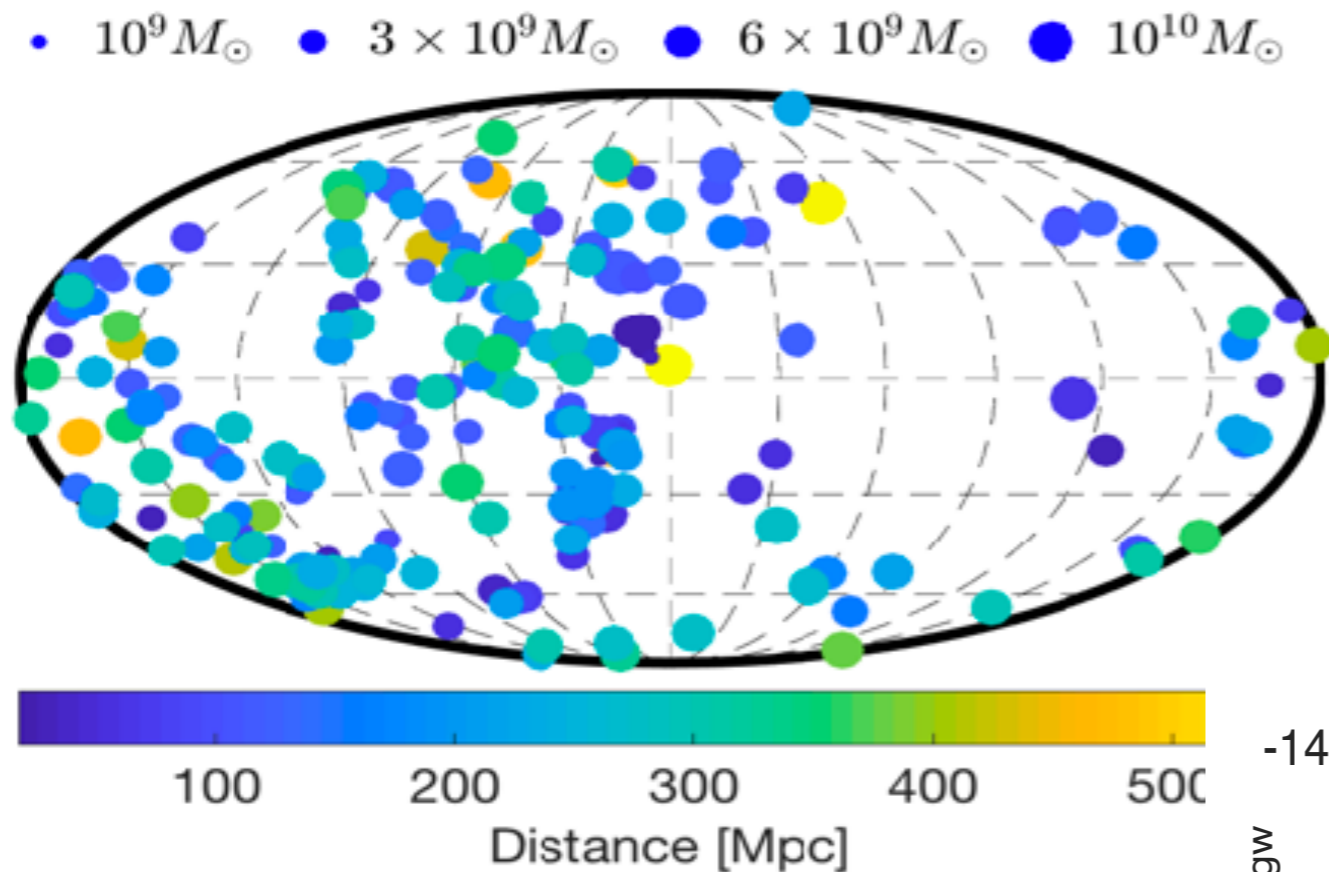
- Pipeline to jointly analyze EM+GW data.

MORE MULTI-MESSENGER SIGNATURES



Kelley, Charisi+2019

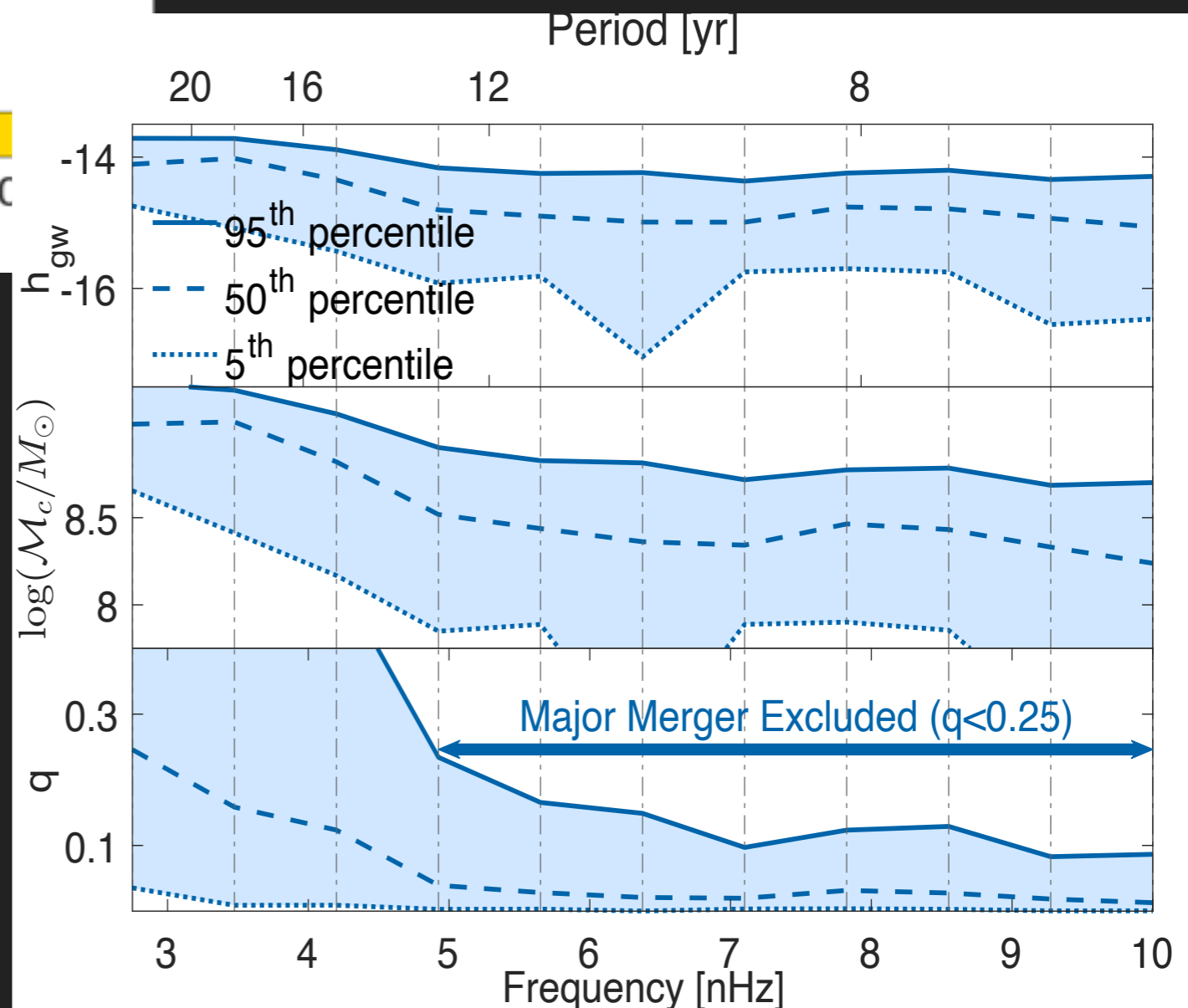
CONSTRAINTS ON LOCAL GALAXIES



▶ ~200 galaxies within NANOGrav volume.

▶ Constraints on mass ratio comparable to Milky Way.

Arzoumanian+2021
(*led by Charisi)



SUMMARY

- ▶ SMBHBs produce bright EM emission.
- ▶ ~250 candidates identified as quasars with periodic variability.
- ▶ More and more reliable candidates expected in LSST.
- ▶ SMBHBs are strong sources of GWs.
- ▶ PTAs and time-domain surveys probe the same population of binaries.
- ▶ Multi-messenger observations are possible for a variety of binaries.