TDAMM Workshop, Annapolis, Maryland

# Toward Time-domain and Multi-messenger Science with Supermassive Black Hole Binaries

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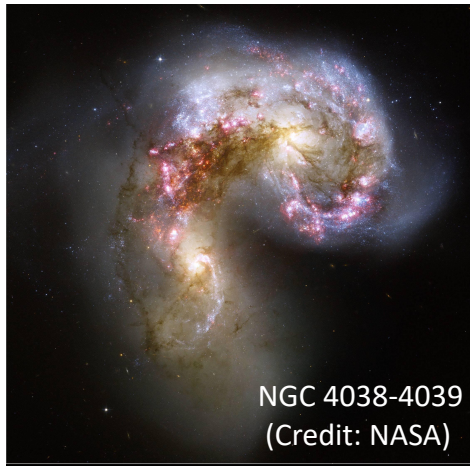
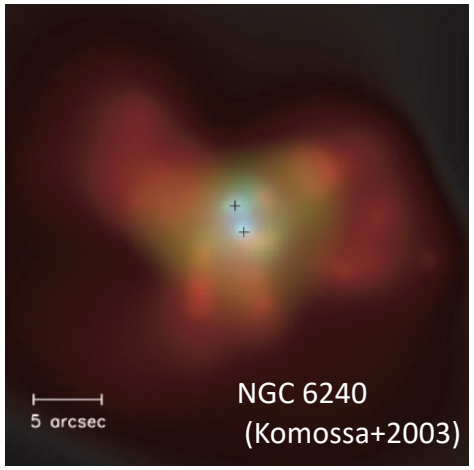
University of Wisconsin – Milwaukee

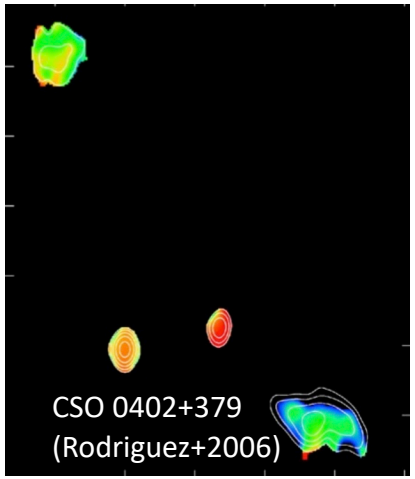
Credit: NASA GSFC/Scott Noble

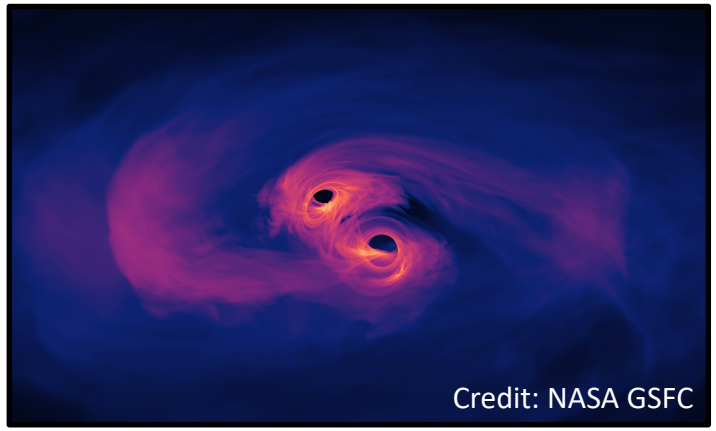
Credit: NANOGrav/Tonia Klein

# A cosmic dance of two supermassive black holes

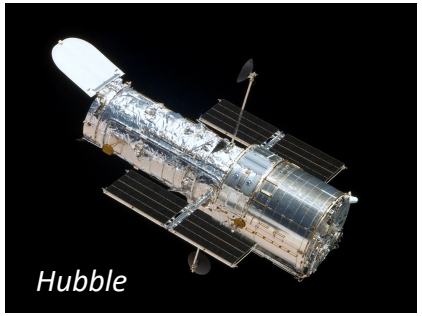


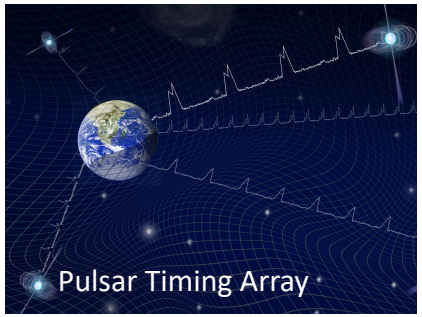



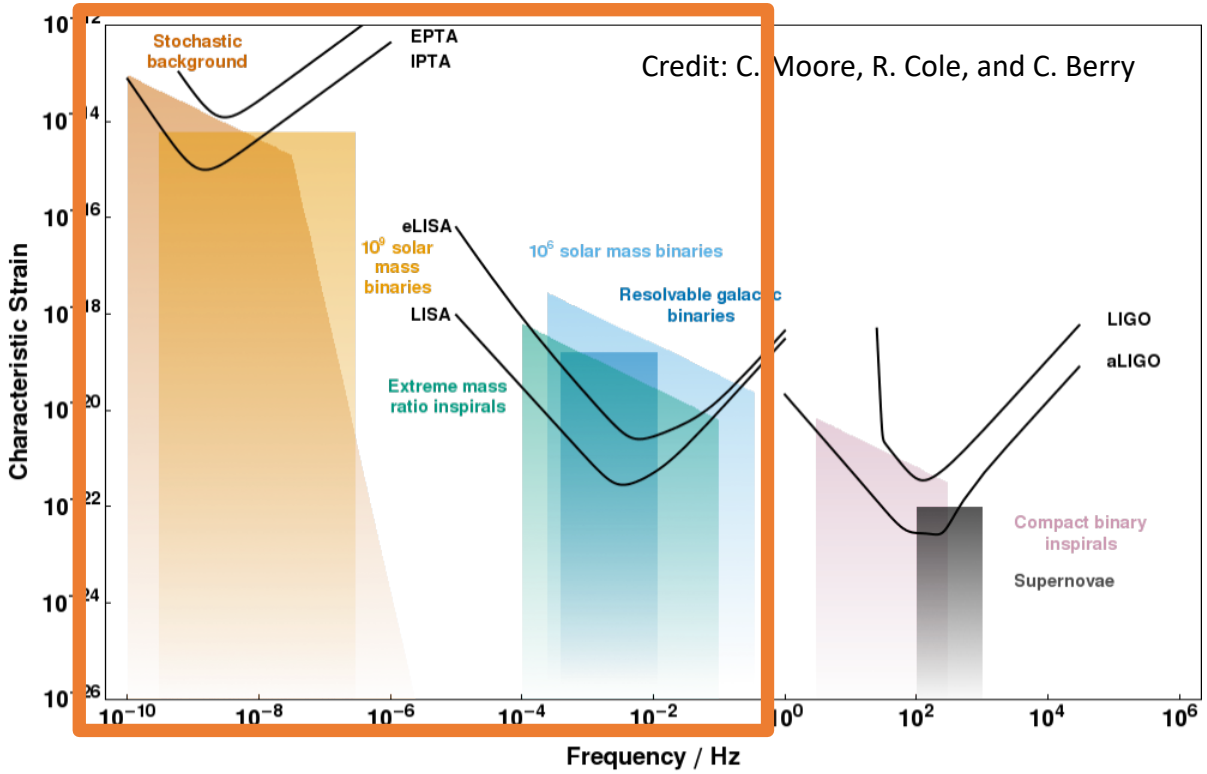

| galaxy merger | dual active galactic nuclei | gravitationally-bound SMBHB | GW-emitting SMBHB |
|---|---|---|---|
| >kpc | hundreds of parsecs – kpc | a few pc – tens of parsecs | milli-pc – centi-pc |





# SMBHBs and Astro 2020

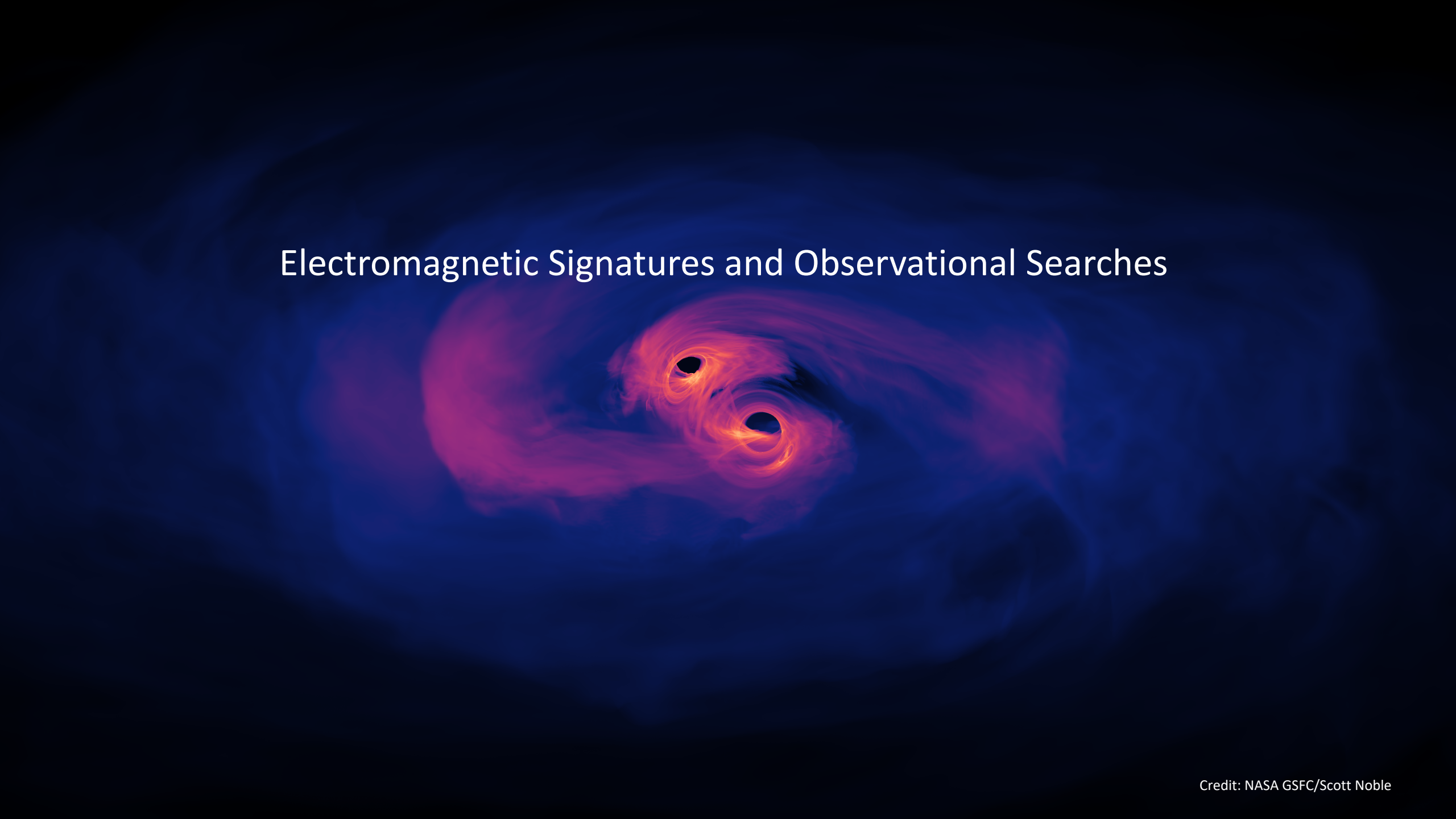
- *"… how SMBHs grow and evolve." (B-DA3)*
- *"Pulsar timing and the space-based interferometer LISA will open up other parts of the gravitational wave spectrum, revealing new sources and new surprises, much as the first X-ray and radio telescopes did." (Box 2.2)*



# Open questions

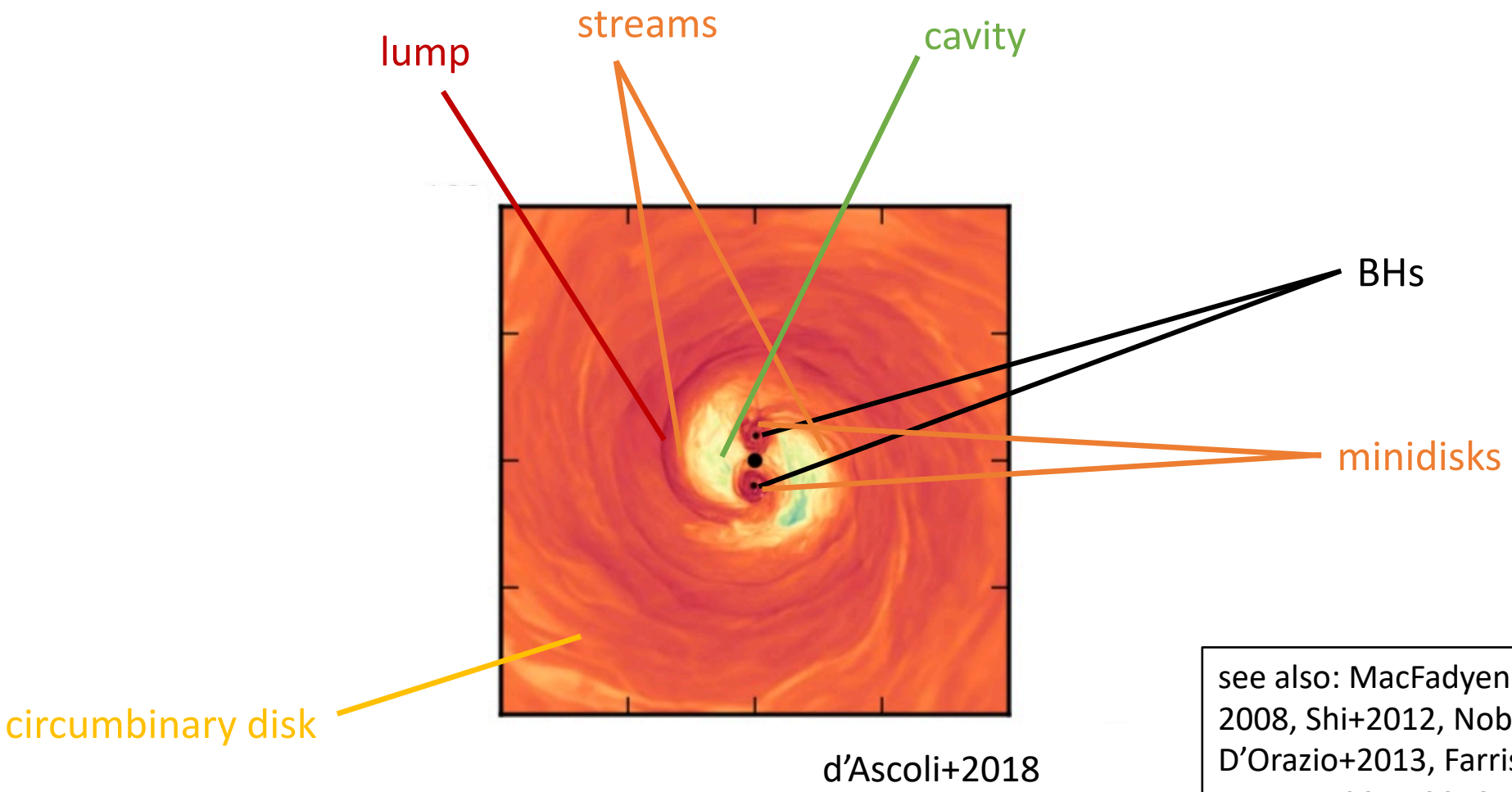
- Do SMBHBs form, and on what timescales?
  - GWs (amplitude of the GW background)
  - EM (single sources; demographics; host galaxy properties) (+ GWs)
- What is the relation between SMBHs and their host galaxies (e.g. M-sigma, environmental coupling)?
  - GWs (amplitude and spectral shape of GWB)
  - EM (+ GWs)
- Do SMBHBs accrete (and emit at AGN luminosities)?
  - GWs (amplitude of GW background)
  - EM (+ GWs)
- Are there unique/unambiguous signatures of SMBHB accretion?
  - EM (+ GWs)

# Electromagnetic Signatures and Observational Searches



Credit: NASA GSFC/Scott Noble

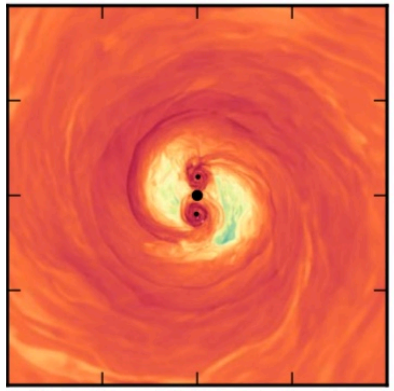
# Anatomy of an SMBHB



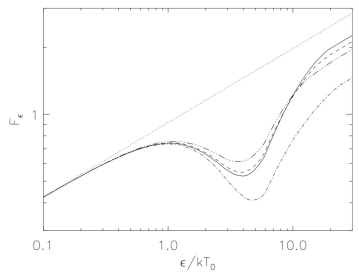

d'Ascoli+2018

see also: MacFadyen & Milosavljevic 2008, Shi+2012, Noble+2012, D'Orazio+2013, Farris+2014, Gold+2014, Bowen+ 2017,2018, Noble+2021, Combi+2022, Gutierrez+2022…)

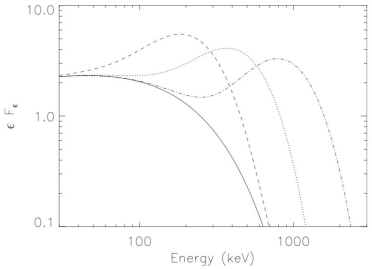
# EM signatures



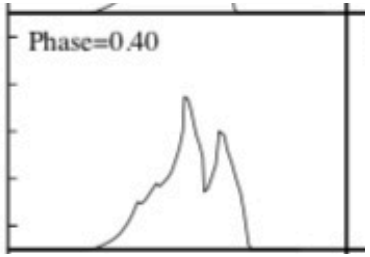
## Spectra




Roedig+2014



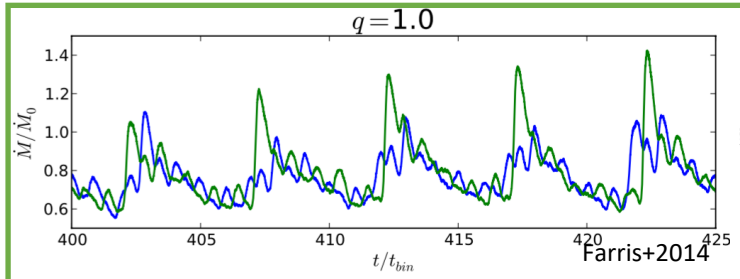

Roedig+2014



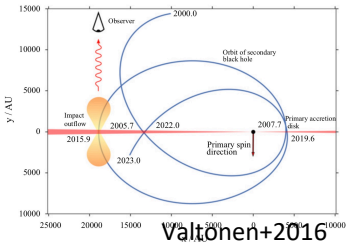

Jovanovic+2013

EM imprint of disk structure

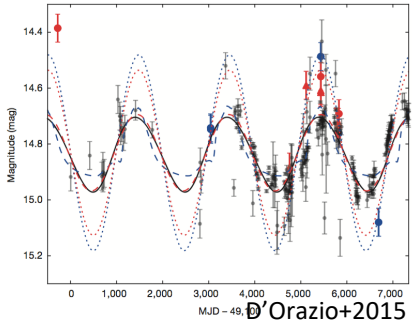
## Variability*



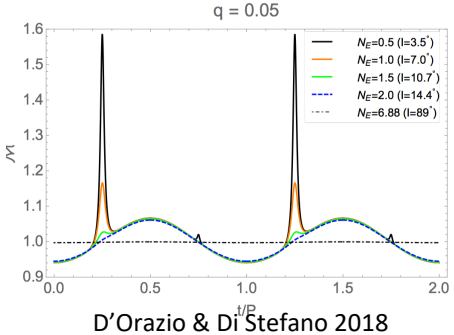

Farris+2014




Valtonen+2016




D'Orazio+2015




D'Orazio & Di Stefano 2018

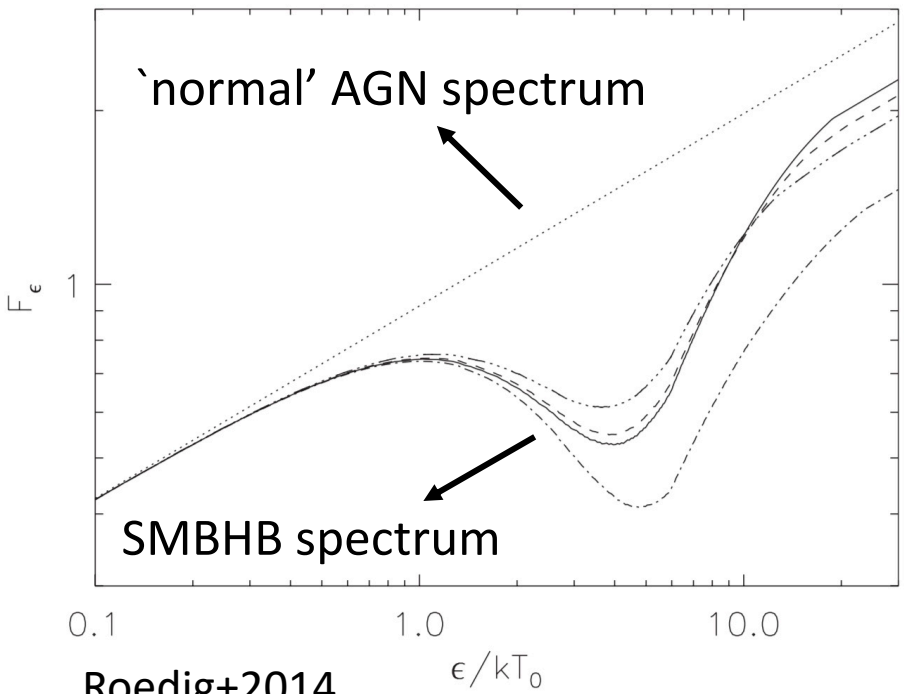
EM imprint of orbital motion

* No circumbinary disk in OJ 287;
also: tidal disruption by an SMBHB (e.g. Ricarte+2014), microlensing (Millon+2022)

# EM signatures – spectra

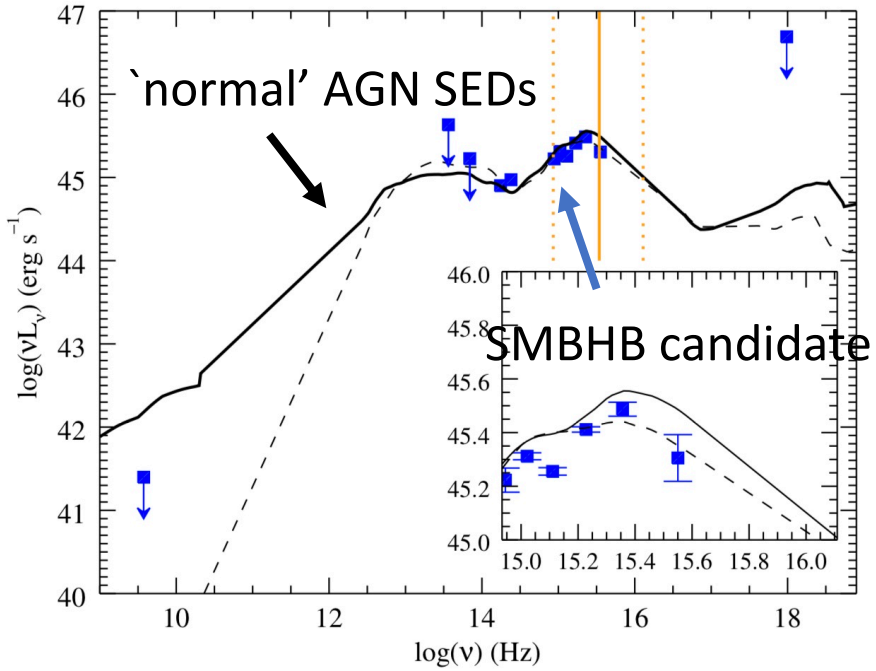
- `Notch' in UV/optical spectral energy distribution

Theory




Roedig+2014
(see also Gültekin & Miller 2012, Farris+2015)

Observations

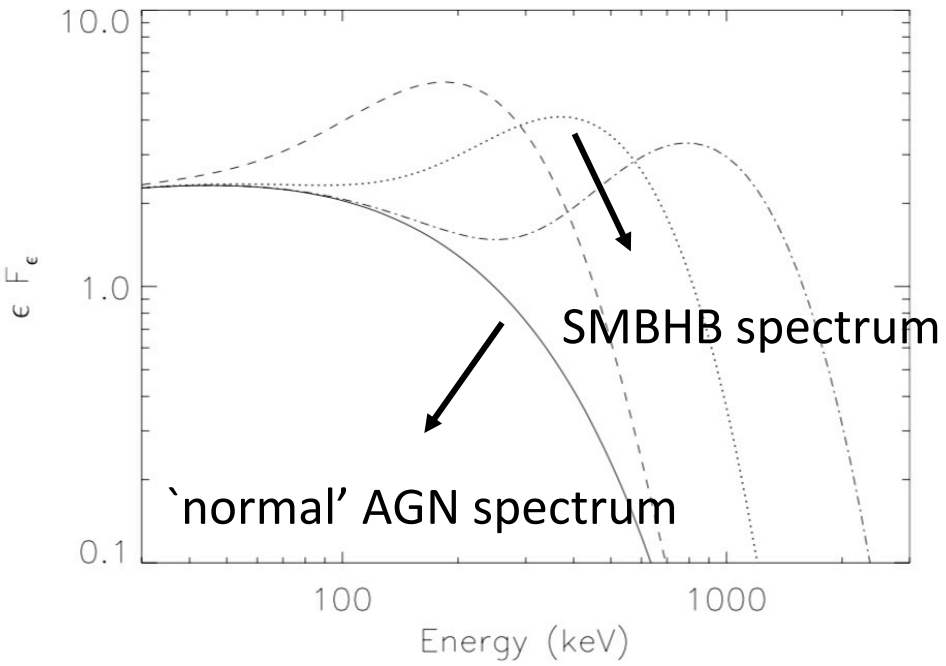



T. Liu+2019
(optical/UV photometry from PS1, SDSS, GALEX; see also Foord+ 2017, 2021)

# EM signatures – spectra

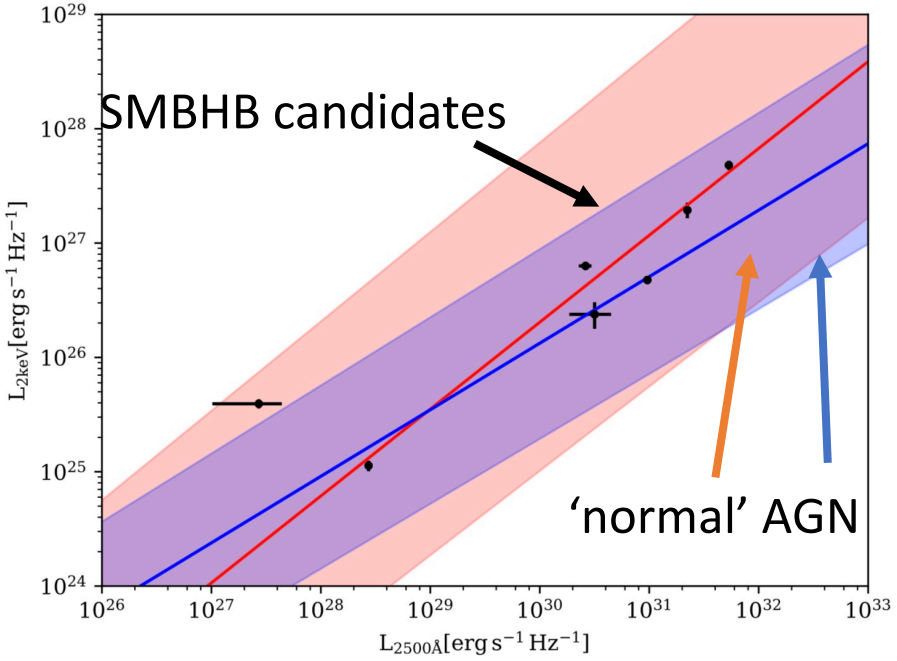
- Excess hard X-ray emission

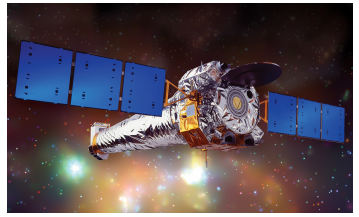
Theory




Roedig+2014
(see also Farris+2015)

Observations



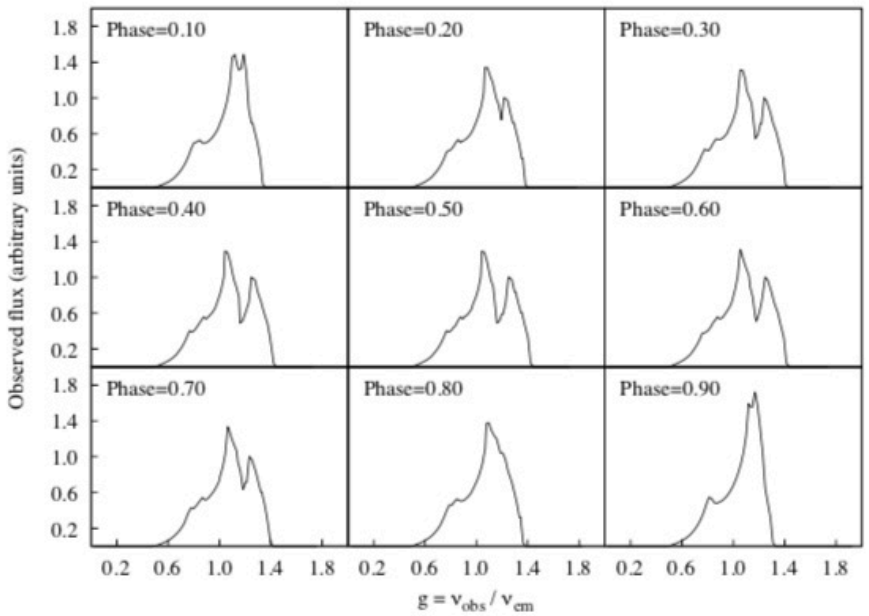



Saade+2020 (archival Chandra)

# EM signatures – spectra

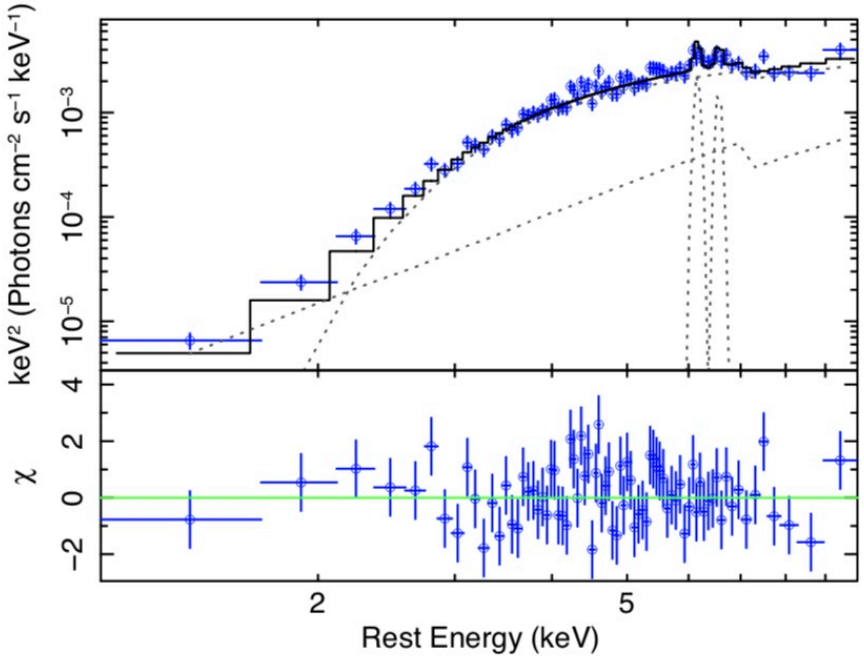
- (Oscillating) double Fe line

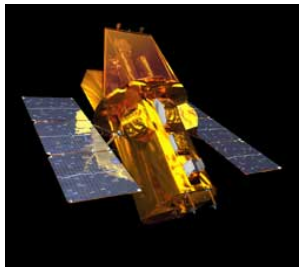
Theory




Jovanovic+2013
(see also e.g. Sesana+2012)

Observations



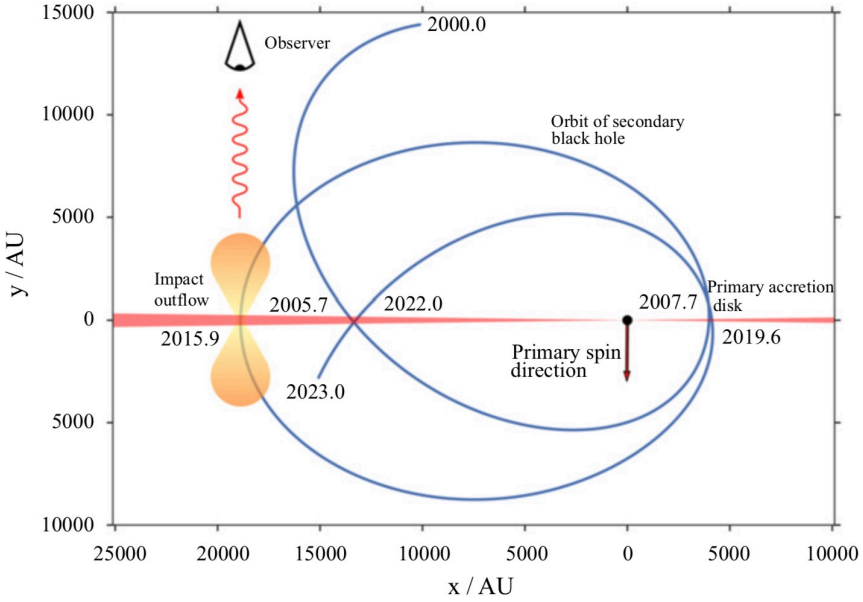



Severgnini+2018 (Swift)

# EM signatures – variability

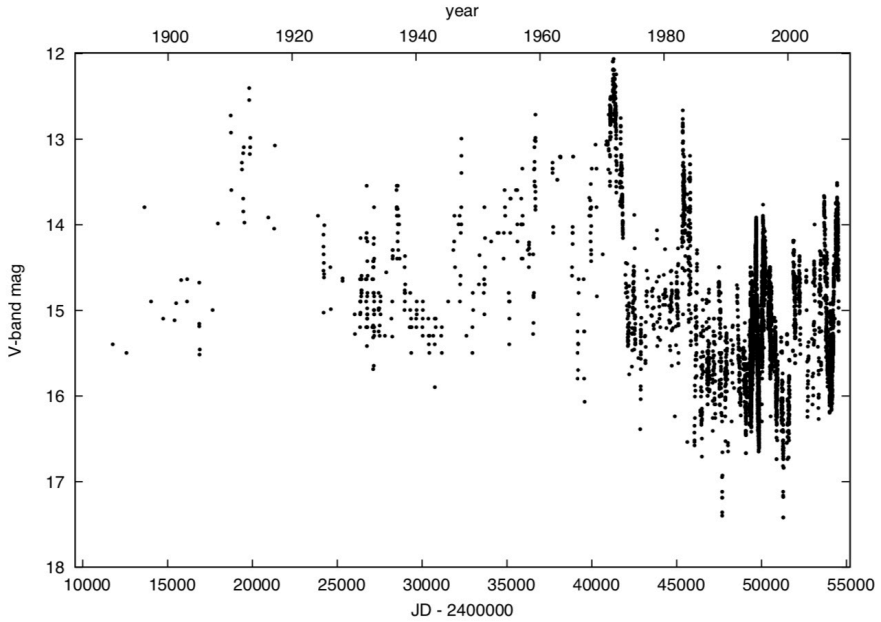
- OJ 287 – ”Rosetta stone” of SMBHBs?

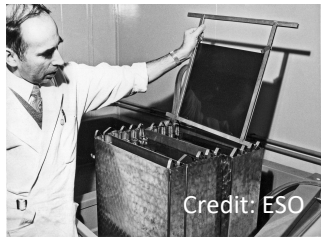
Theory




Valtonen+2016

Observations



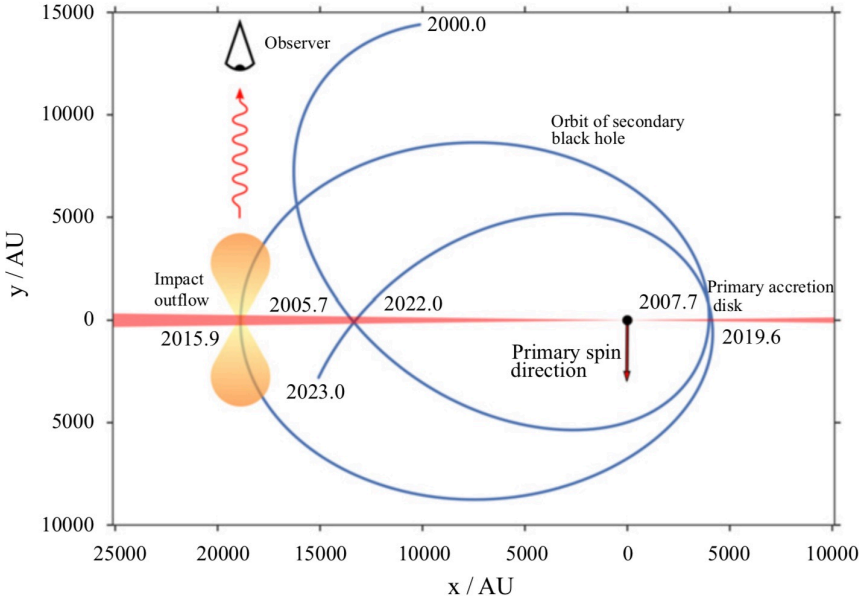

Valtonen+2008b

Predicts: pair of flares due to BH-disk impact

# EM signatures – variability

- OJ 287 – ”Rosetta stone” of SMBHBs?

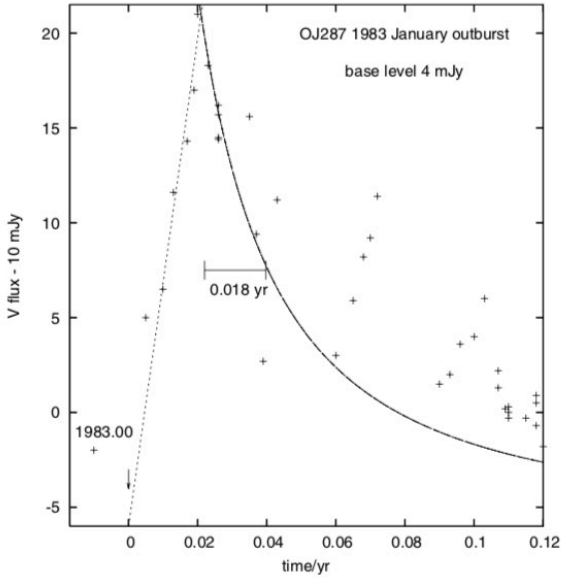
Theory




Valtonen+2016

Predicts: pair of flares due to BH-disk impact

Observations

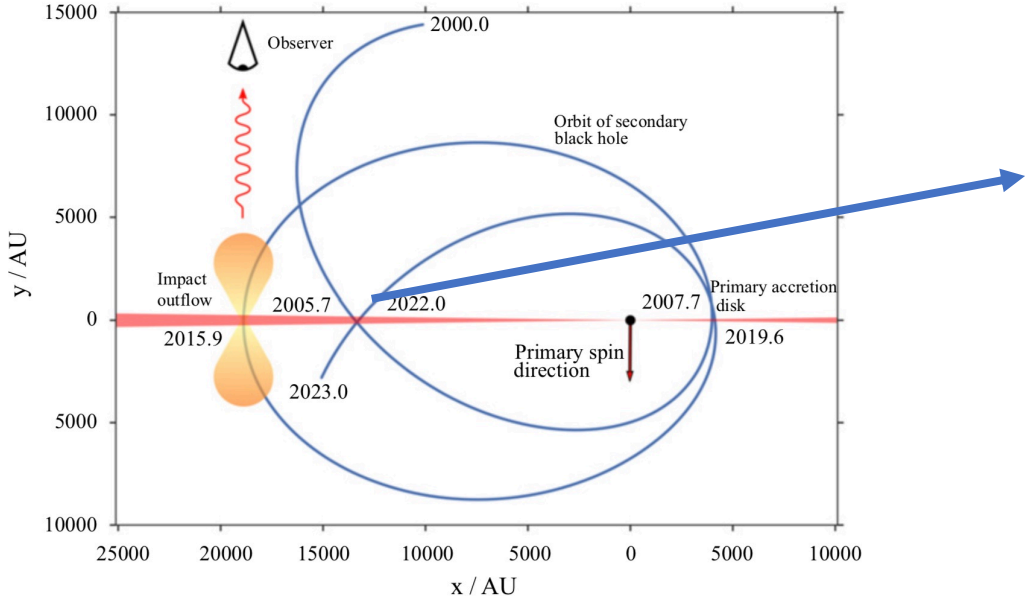



Valtonen+2008a
(outburst in 1983)

# EM signatures – variability

- OJ 287 – ”Rosetta stone” of SMBHBs?

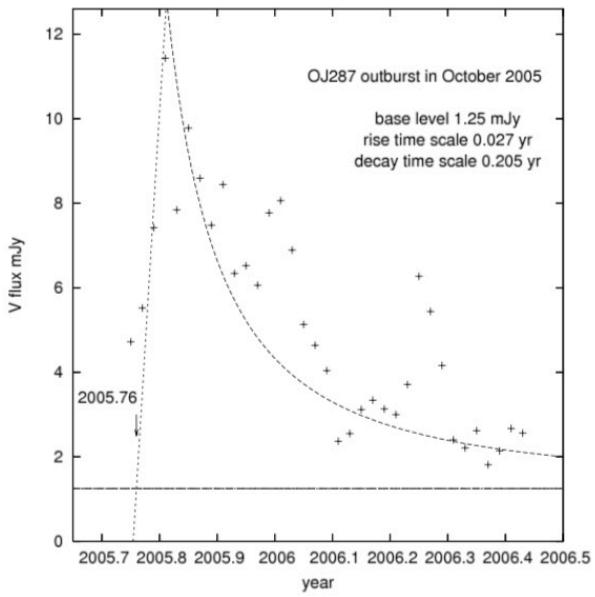
Theory




Valtonen+2016

Predicts: pair of flares due to BH-disk impact

Observations

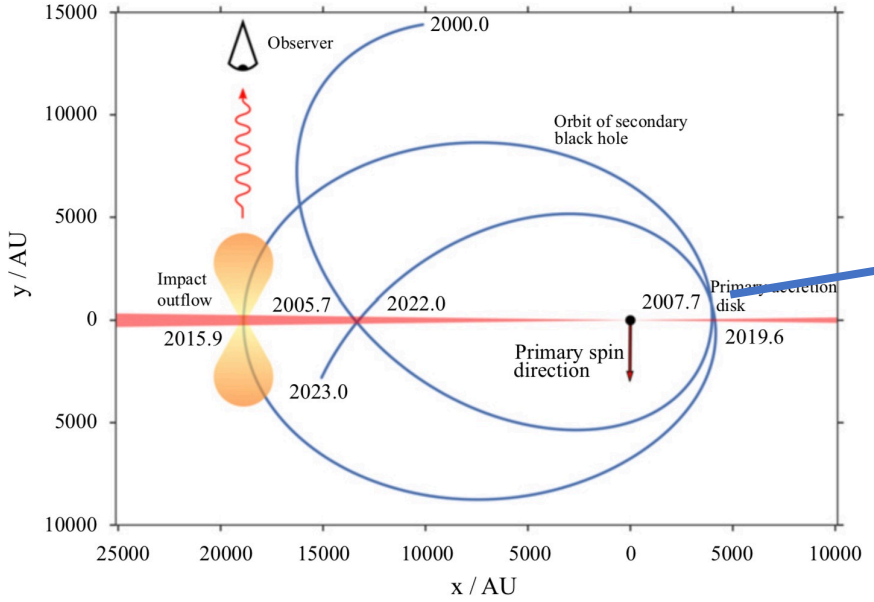



Valtonen+2008a
(outburst in 2005)

# EM signatures – variability

- OJ 287 – ”Rosetta stone” of SMBHBs?

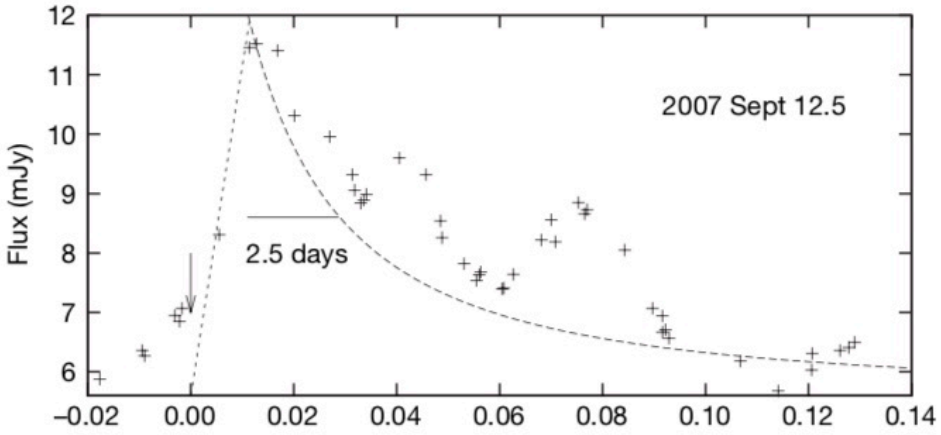
Theory




Valtonen+2016

Predicts: pair of flares due to BH-disk impact

Observations

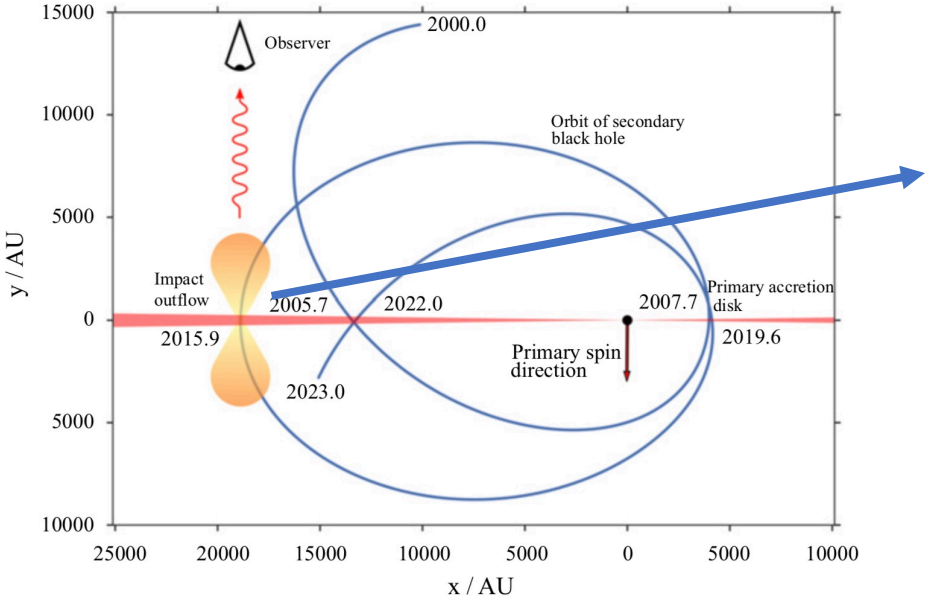



Valtonen+2008b
(outburst in 2007)

# EM signatures – variability

- OJ 287 – ”Rosetta stone” of SMBHBs?

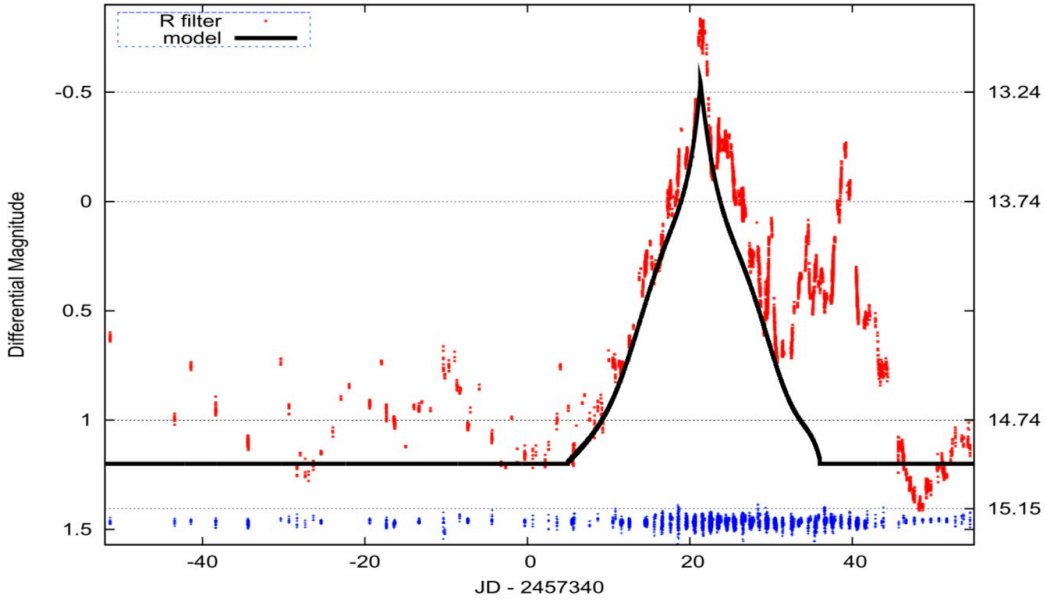
Theory




Valtonen+2016

Predicts: pair of flares due to BH-disk impact

Observations

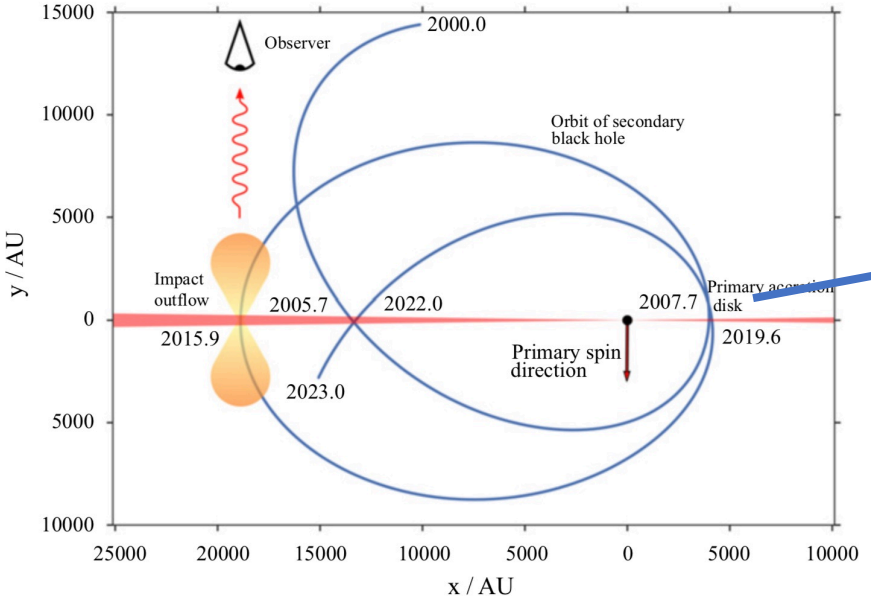



Valtonen+2016
(“centenary flare” in 2015)

# EM signatures – variability

- OJ 287 – ”Rosetta stone” of SMBHBs?

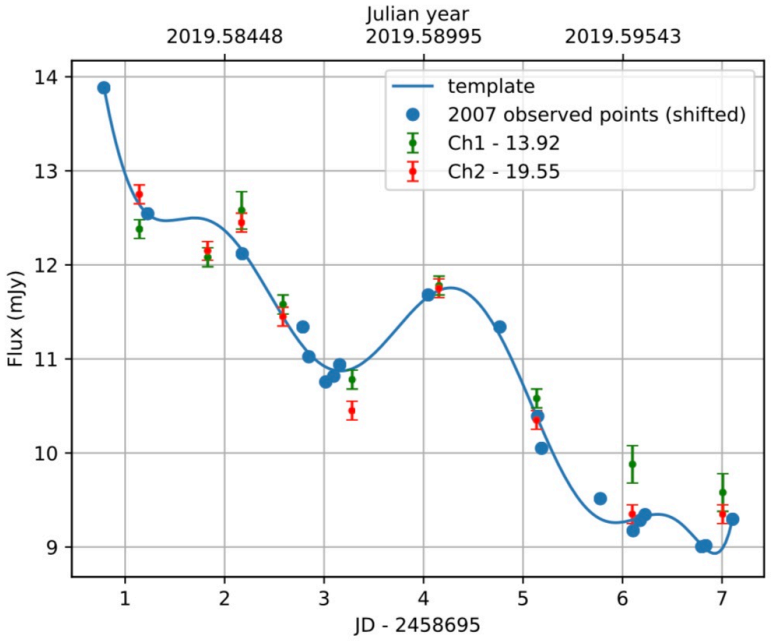
Theory

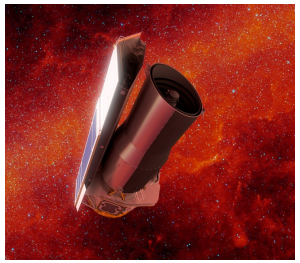



Valtonen+2016

Predicts: pair of flares due to BH-disk impact

Observations



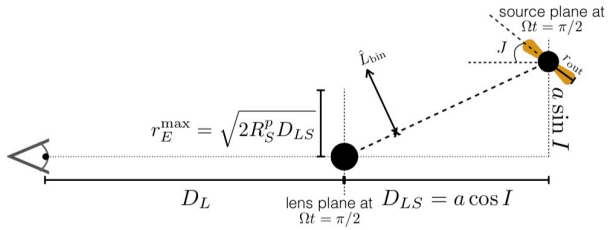



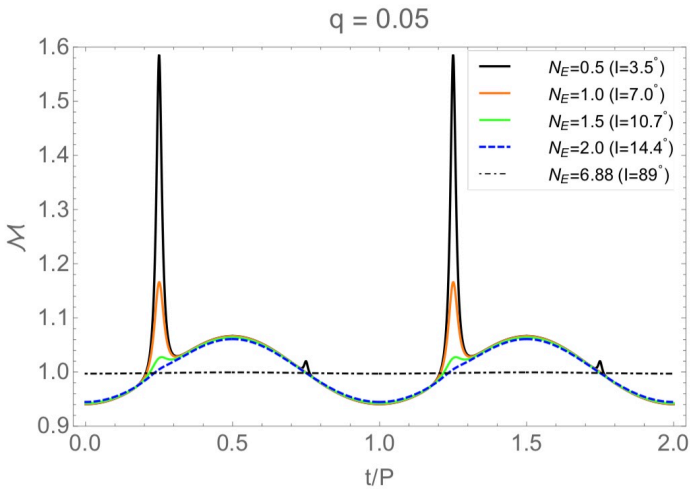
Laine+2020 (Spitzer)
(“Eddington flare” in 2019)

# EM signatures – variability

- Binary self-lensing

Theory

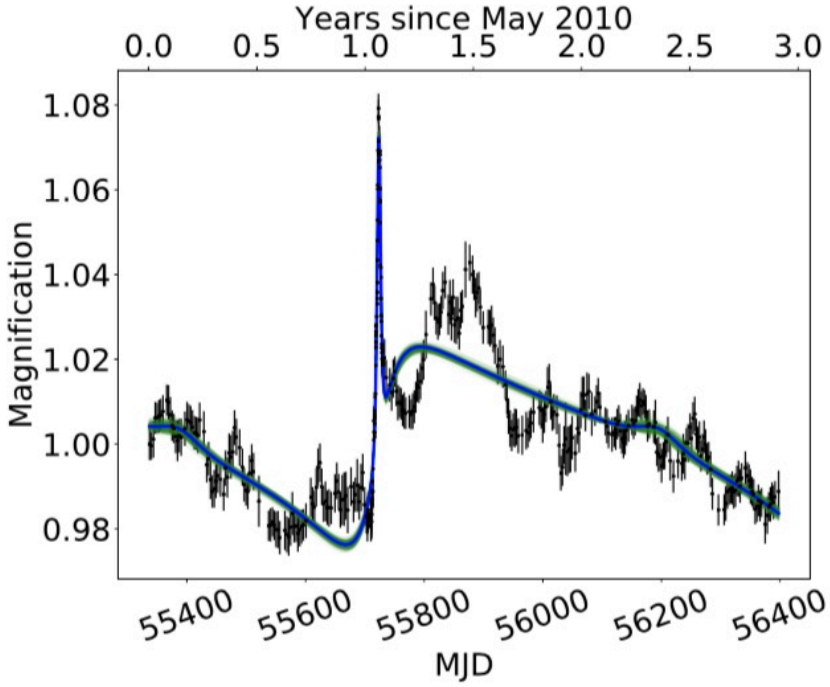


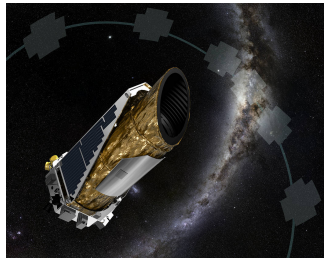




D'Orazio & Di Stefano 2018

Predicts: sharp flares

Observations



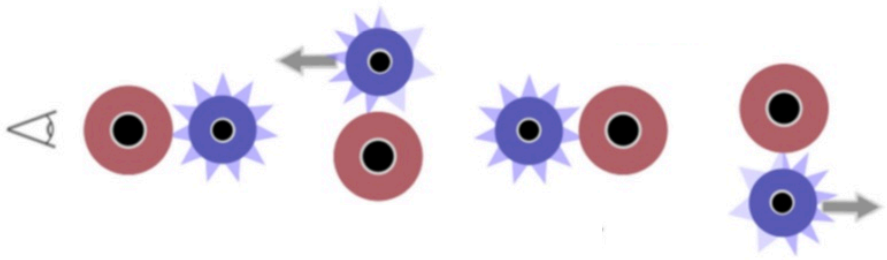



Hu+2020
(Kepler/K2 light curve from Smith+2018a)

# EM signatures – variability

- Relativistic beaming

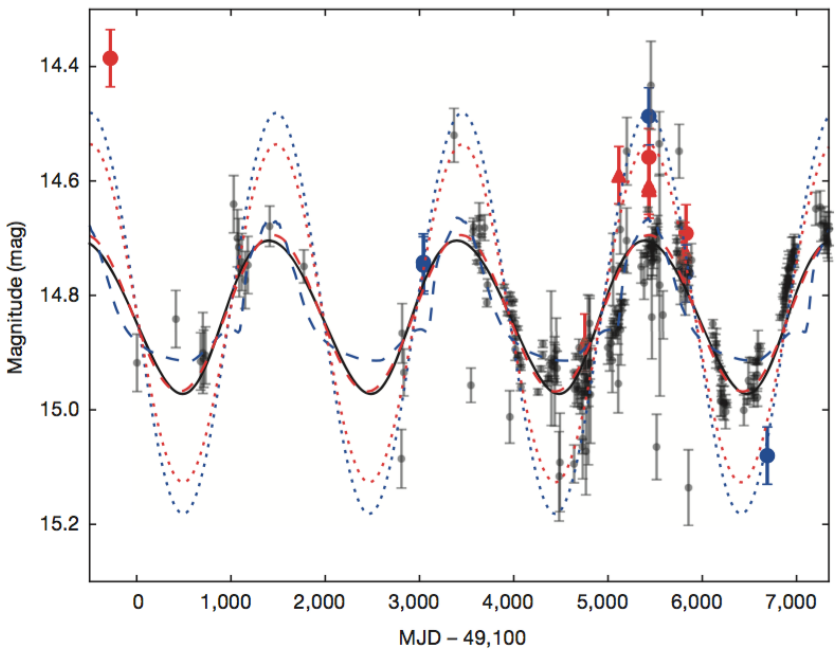
Theory



Credit: Kelley+2018

Predicts: smooth, quasi-sinusoidal light curve profile, UV-optical variability amplitude ratio

Observations

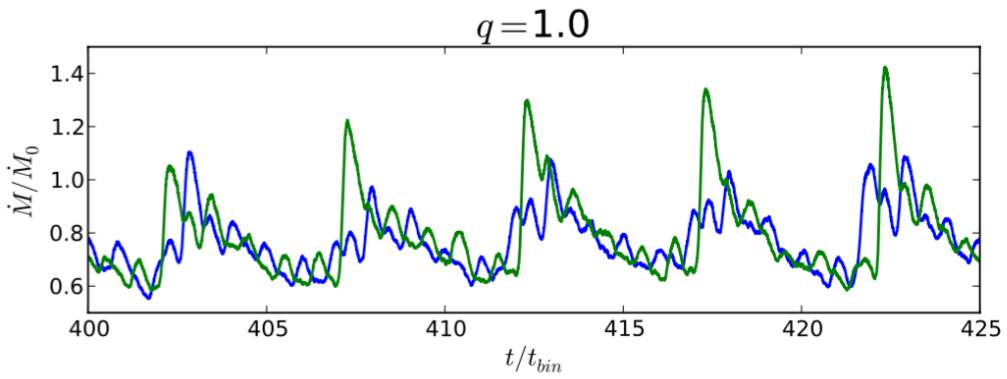


D'Orazio+2015
(CRTS light curve from Graham+2015a, UV light curves from GALEX)

# EM signatures – variability

- Binary-modulated accretion

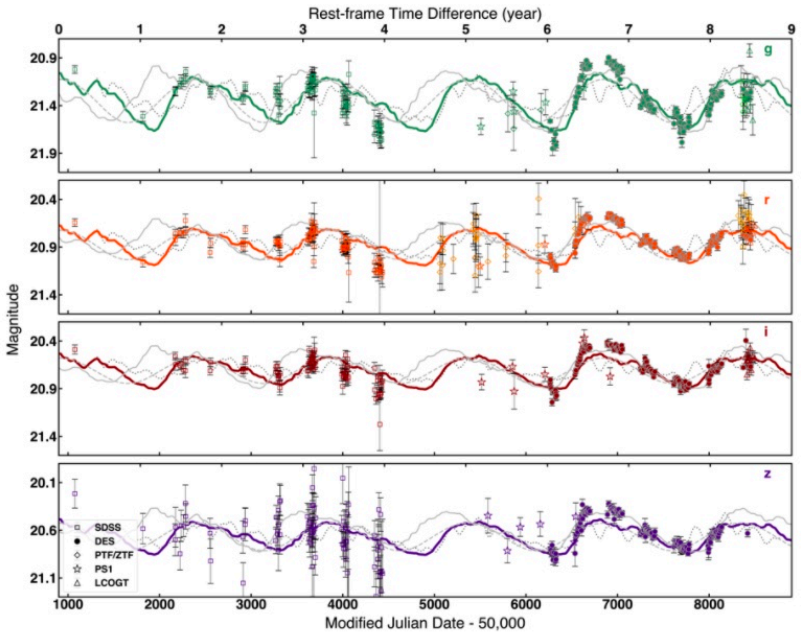
Theory




Farris+2014
(see also Duffell+2020)

Predicts: bursty, `sawtooth' light curve profile

Observations

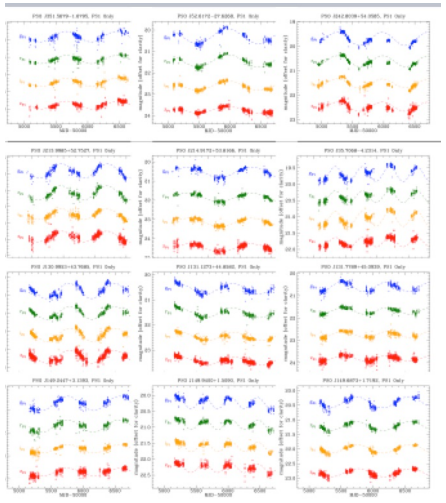


Liao+2020 (DES+SDSS)

# EM signatures – variability

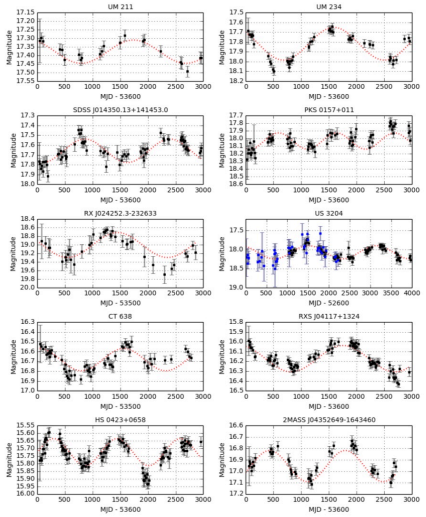
- Systematic searches for periodic AGN – >100 candidates since 2015

Pan-STARRS1
(T. Liu+2015, 2016, 2019)

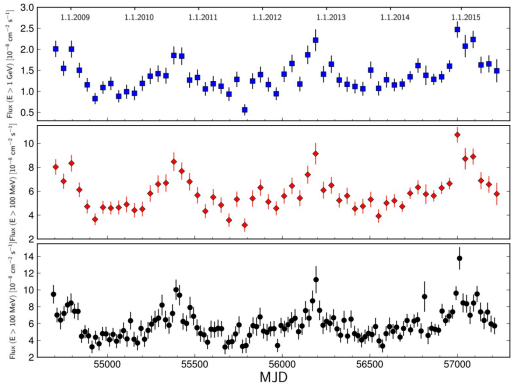


CRTS
(Graham+2015a,2015b)

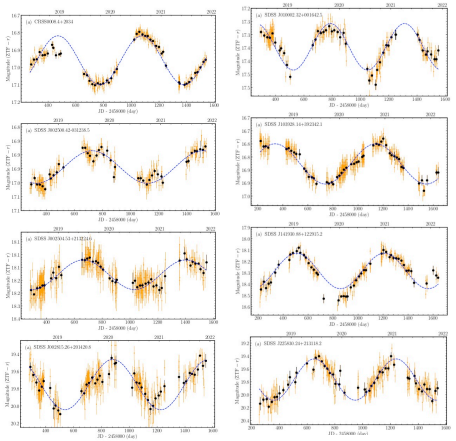
Also: PTF/iPTF (Charisi+2016),
DES+SDSS (Liao+2020,Chen+2020)



Fermi
(Ackermann+2015)

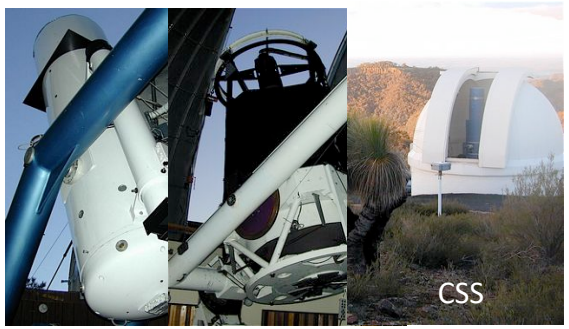


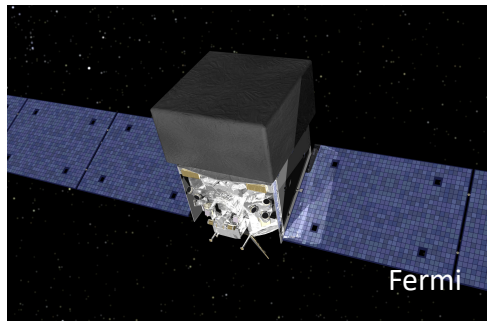

ZTF
(Chen+2022)



VRO LSST
(~2024-2034)

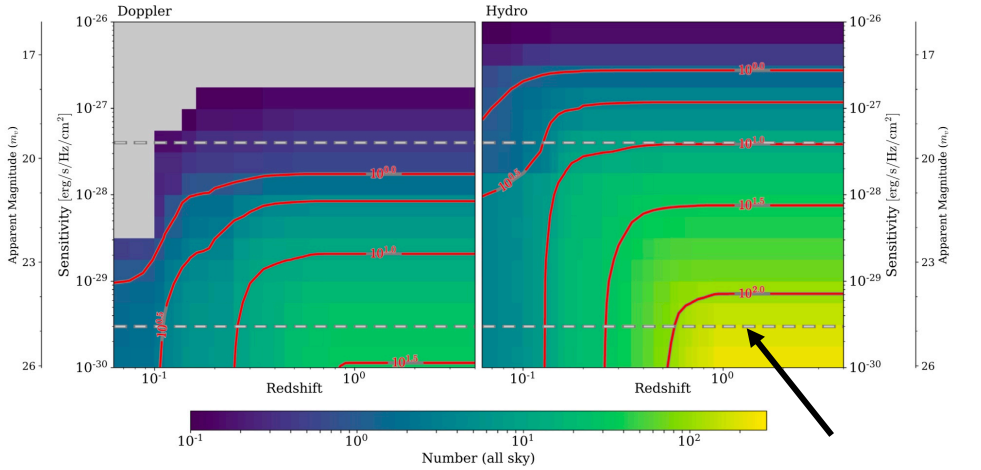
?



# EM signatures – variability

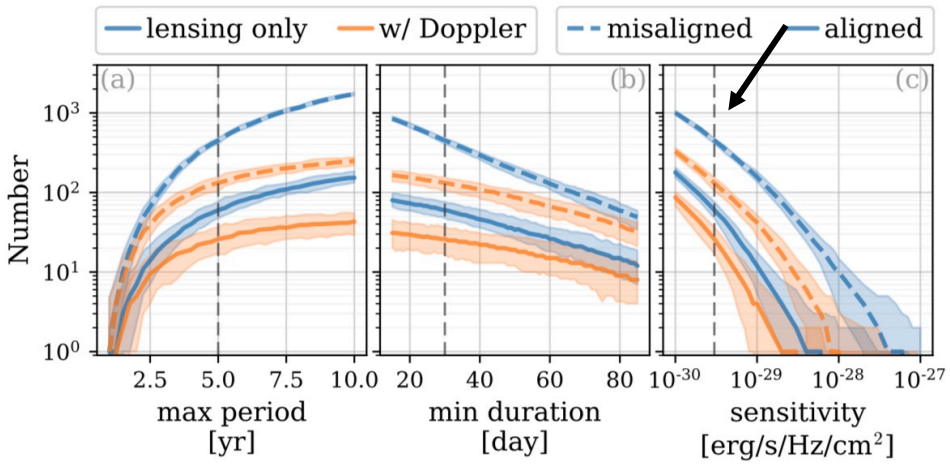
- Number estimates for LSST
  - Modulated accretion – N~40-600
  - Relativistic beaming – N~6–50
  - Self-lensing – N~10–100




Kelley+2019

LSST sensitivity

LSST sensitivity




Kelley+ 2021

# Possible roadmap for SMBHB discovery in the next ~decade (EM)

- Large ground-based time-domain surveys (e.g. LSST) as the discovery engine
  - Systematically search for periodic candidates among >millions of AGN
  - Robust algorithms for identifying (quasi) periodic variability against ‘normal’ AGN variability
  - Modeling light curves (SMBHB theory)

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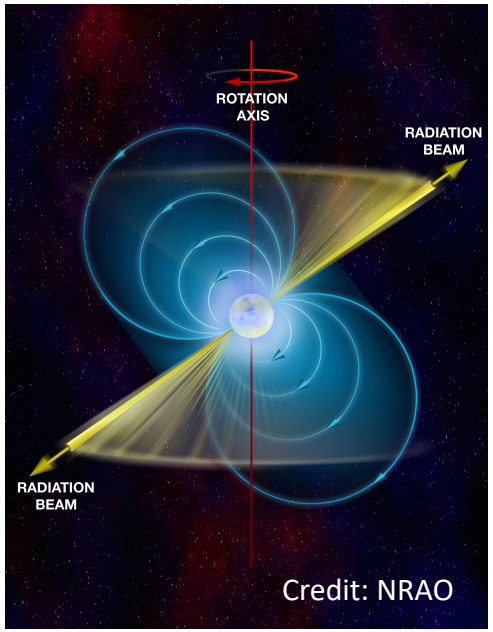
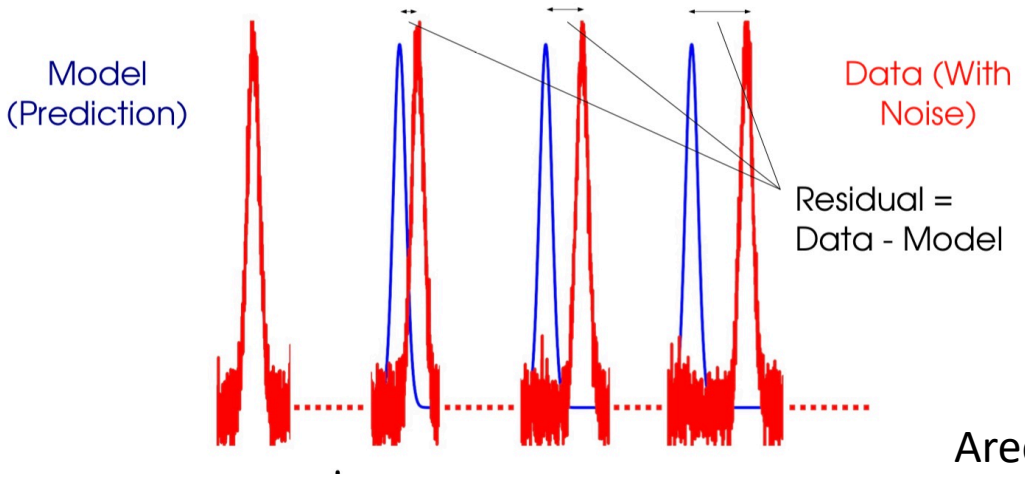
- Invite everyone to the (search) party

# Gravitational-wave and Multi-messenger Searches

Credit: NANOGrav/Tonia Klein

# Pulsar timing array – a Galactic-scale GW detector

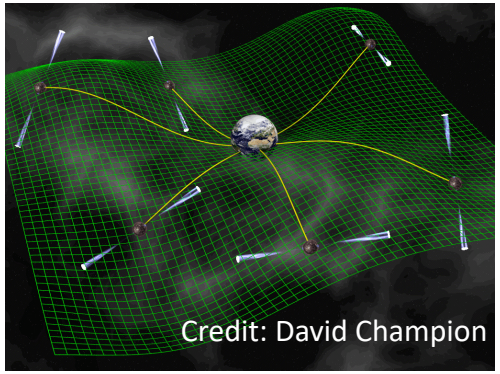



Credit: Ryan Lynch

Green Bank Telescope, West Virginia

Arecibo Observatory, Puerto Rico (–2020)

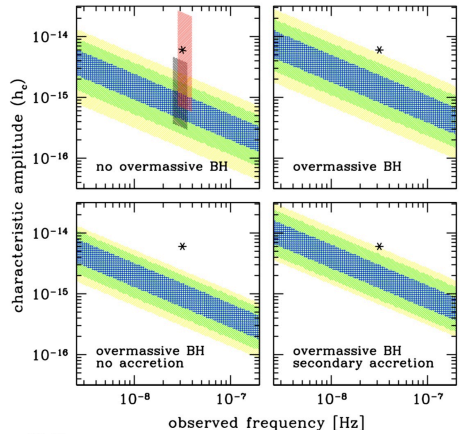


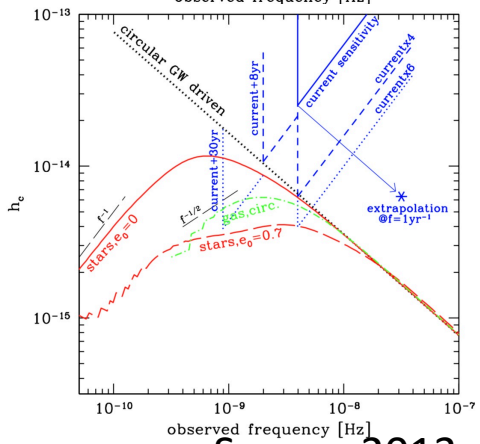

- Timing dozens of millisecond pulsars ~monthly since ~2005
- GW induced residual = data - timing model

# SMBHBs – sirens of low-frequency GWs

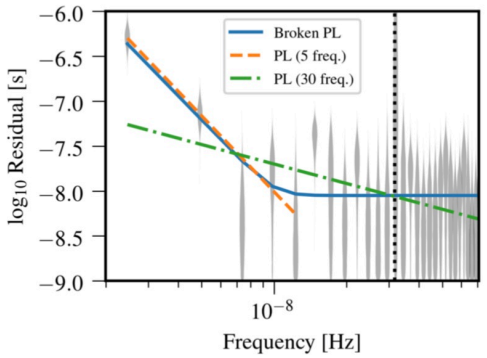
PTAs are expected to detect the GW background in the first half of this decade…

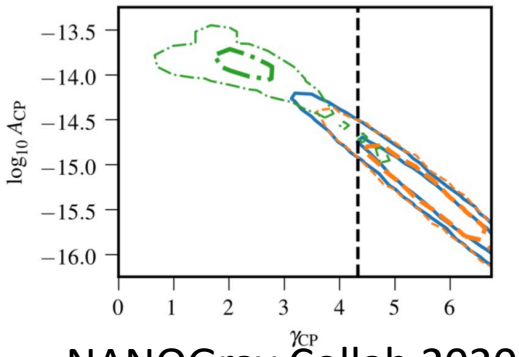
- First hint in 12.5yr dataset?
- 15yr dataset is currently being analyzed
- Detection of a GWB will provide
  - i) direct confirmation of the existence of a population of SMBHBs
  - ii) astrophysical information from the spectral amplitude and shape



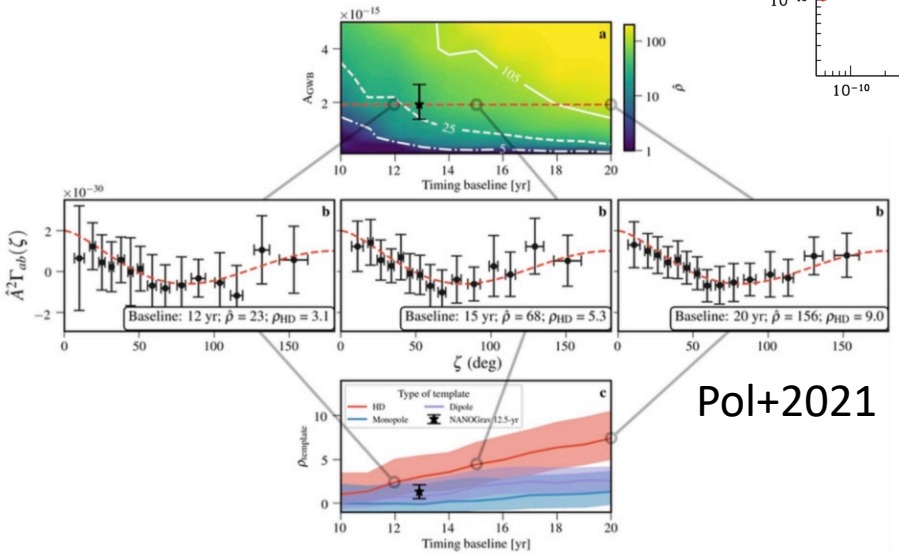




Sesana 2013




NANOGrav Collab 2020

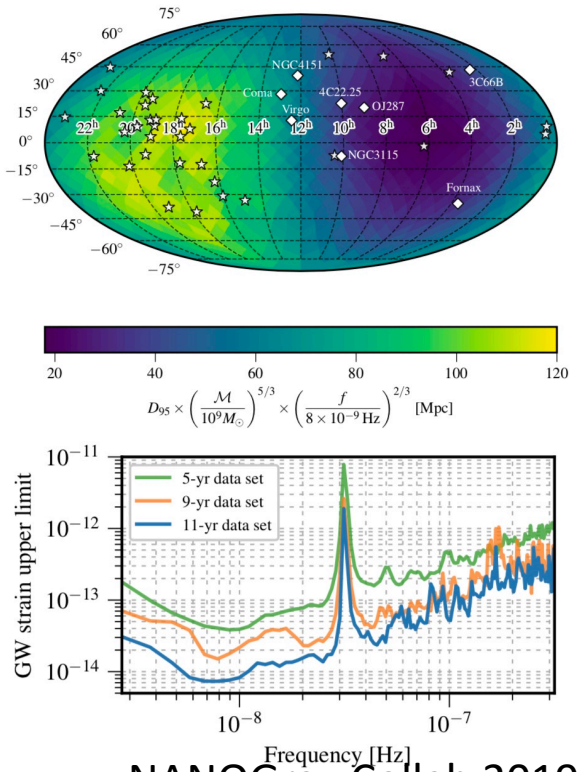



Pol+2021

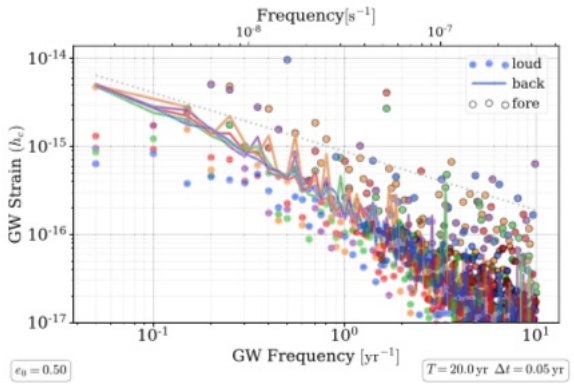
# SMBHBs – sirens of low-frequency GWs

## … and individual sources in the second half

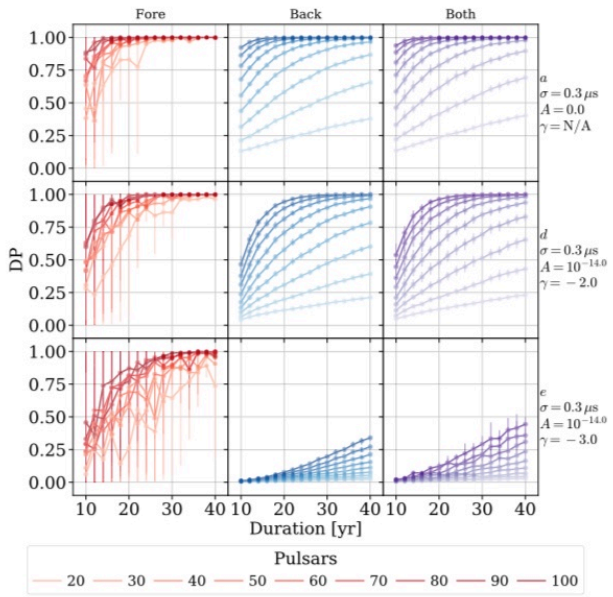
- Tightening constraints on individual SMBHBs
  - CW detection possible with ~20 yr of data




NANOGrav Collab 2019



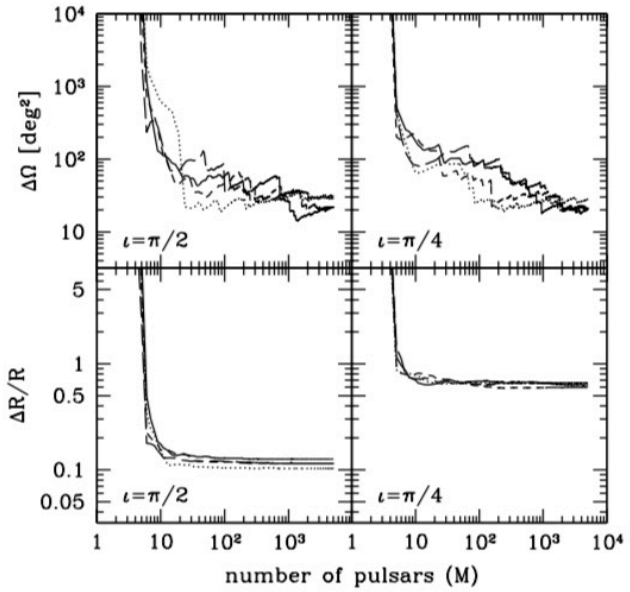

Kelley+2018,
see also Rosado+2015



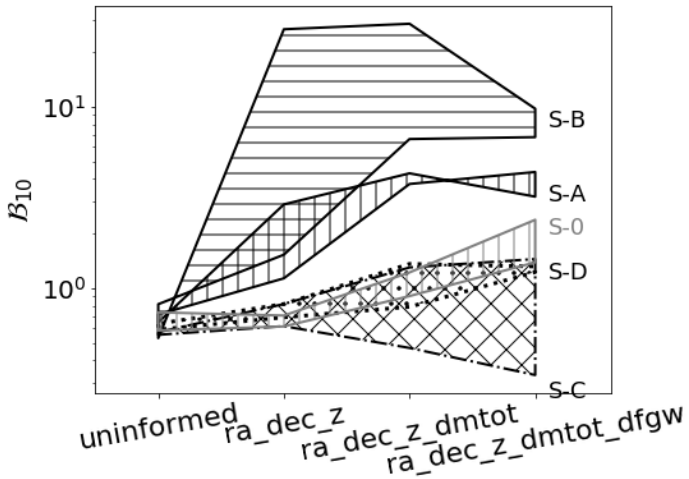
# SMBHBs – sirens of low-frequency GWs

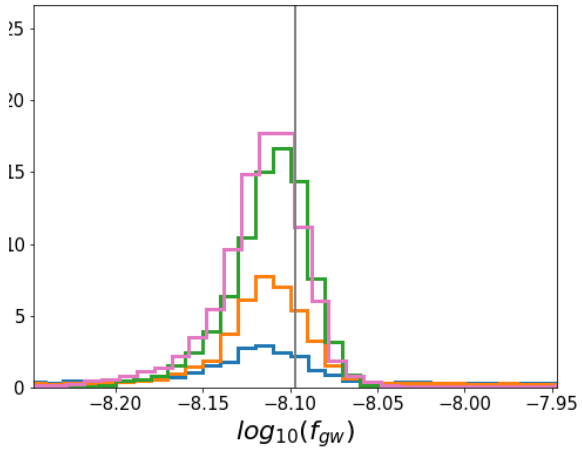
… enabling multi-messenger science with SMBHBs

- PTAs can localize CW sources within ~$10^2$ square deg, constrain GW amplitude within ~a few tens percent, GW frequency within ~ percent (unguided search)
- Targeted searches (known EM candidates) improve both detectability and parameter measurability (factor of a few)



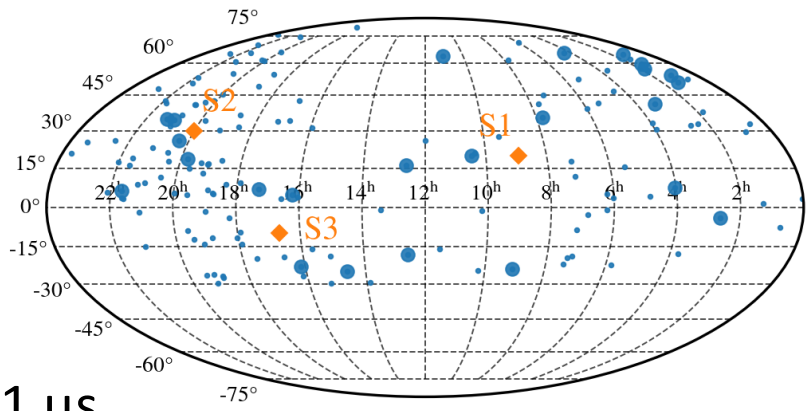

Sesana & Vecchio 2010



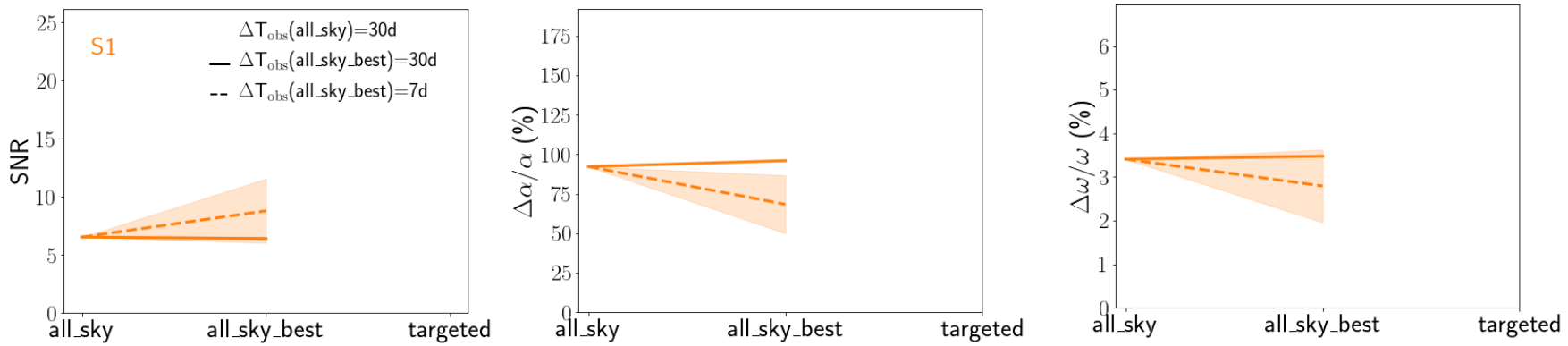

T. Liu & Vigeland 2021

# CW detection prospects




## Individual SMBHB detections

- ~150 MSPs with $\sigma$~500 ns timing precision, or ~20 with $\sigma$ ~60 ns (e.g. DSA-2000)
  - Latest NANOGrav dataset (12.5 yr): ~50 MSPs with $\sigma$ ~1 μs
- Detection of GWs from OJ 287 possible with ~15yr of data
  - Modest SNR (~5)
  - GW constraints on binary parameters less precise than EM (orders of magnitude higher)




T. Liu+ in prep

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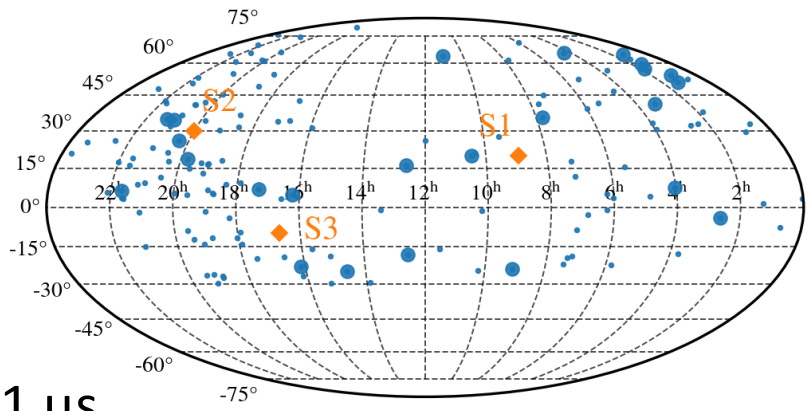


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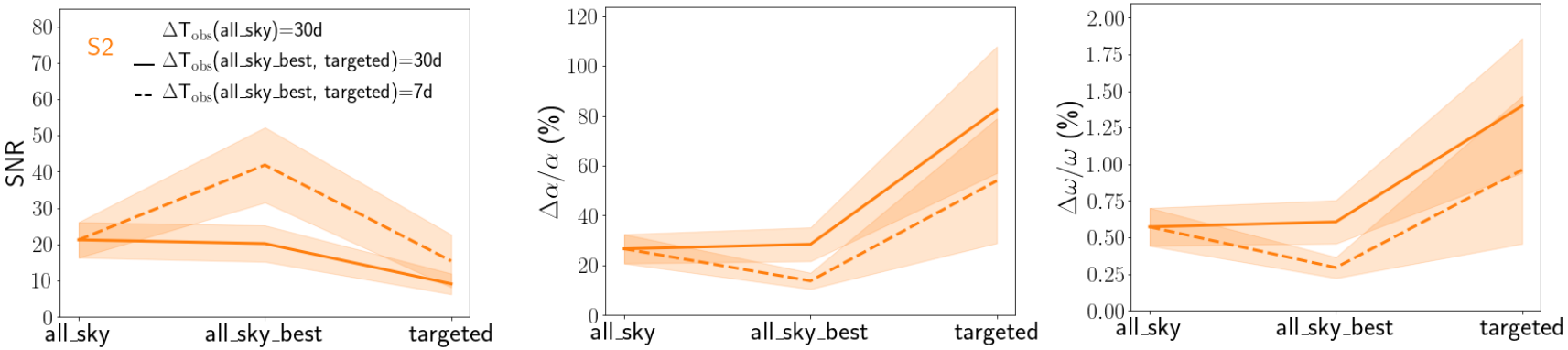
- Detection of GWs from OJ 287 possible with ~15yr of data
  - Modest SNR (~5)
  - GW constraints on binary parameters less precise than EM (orders of magnitude higher)
- For a more typical EM candidate
  - GW measurements are better than EM (factor of a few – orders of magnitude lower)




T. Liu+ in prep

# Possible roadmap for SMBHB discovery in the next ~decade (MMA)

- GW->EM
  - PTAs can localize source within ~a few tens–$10^2$ square degrees
  - Individual SMBHBs most detectable at intermediate frequencies (~0.1-0.3 $yr^{-1}$)
    - GWB louder at low frequencies, fewer single sources at high frequencies, pulsar noise at all frequencies
    - -> Good match to timescales probed by time-domain surveys
  - Need multi-wavelength follow-up
    - Search for optical periodicity in time-domain datasets
    - X-ray follow-up
      - EM counterparts/AGN; post-merger environment; X-ray binary signatures
      - -> Need a large FOV (e.g. Advanced X-ray Imaging Satellite)

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      - -> Need a large FOV (e.g. Advanced X-ray Imaging Satellite)
  - Use EM information to improve GW parameter estimation

# Possible roadmap for SMBHB discovery in the next ~decade (MMA)

- GW->EM(->GW)
- EM->GW
  - ~$10^2$ EM candidates and counting
  - Targeted searches in PTA data
    - Gain a factor of ~ a few in detectability and parameter measurability
  - Precise measurements of binary parameters (esp. frequency)
    - Break degeneracies
    - Joint interpretation of GW+EM observations