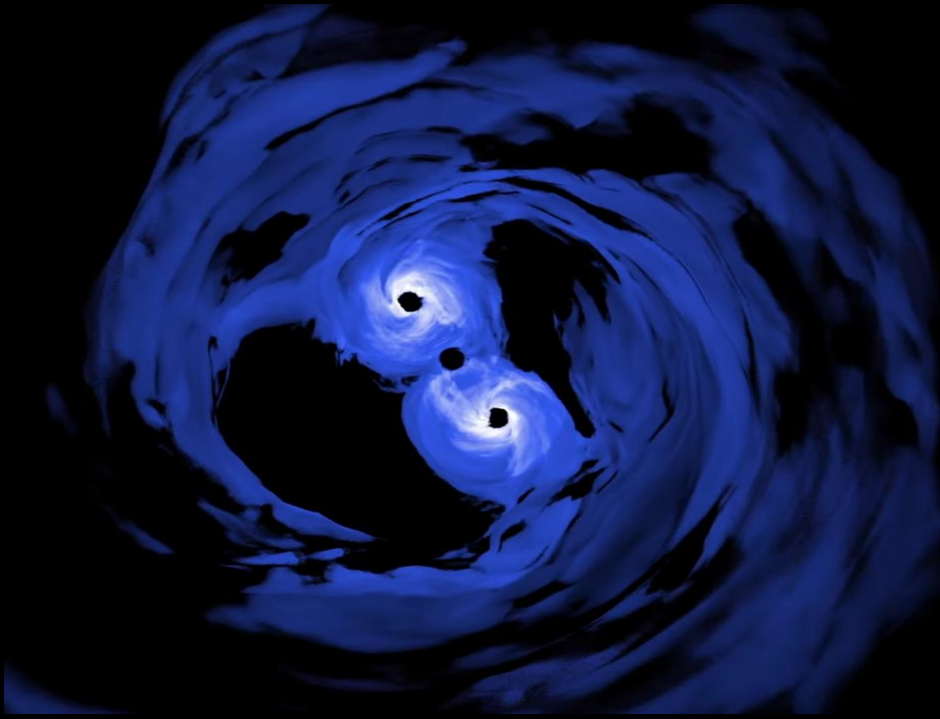


SEARCHING FOR SUPERMASSIVE BLACK HOLE BINARIES WITH SUB-PC SEPARATIONS IN THE HARD X-RAYS

ROBERTO SERAFINELLI

INAF – Osservatorio Astronomico di Brera, Milan, Italy

Collaborators: P. Severgnini, C. Cicone, V. Braito, R. Della Ceca, C. Vignali, F. Ambrosino, M. Dotti, A. Sesana, L. Ballo, V. La Parola, G. Matzeu, A. Zaino

Supermassive Black Holes: Evolution and Environment, Corfu 19-22 June, 2019

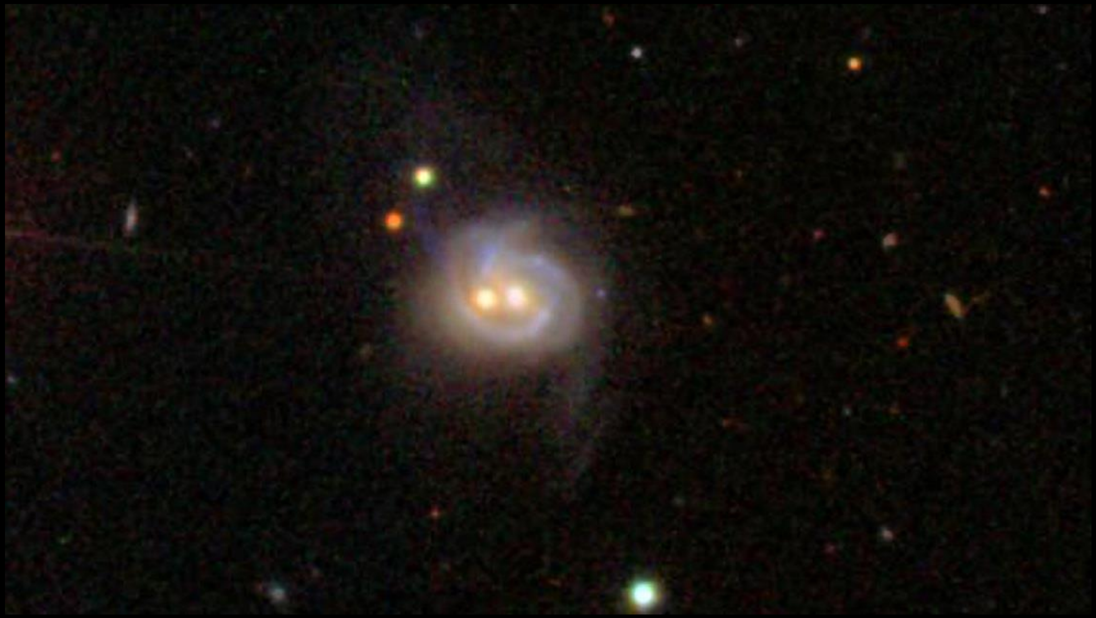
GALAXY MERGERS

- **Galaxy pairs**

Image credit: Hubble Space Telescope

GALAXY MERGERS

- Galaxy pairs
- Dual phase



Muller-Sanchez et al. (2015)

GALAXY MERGERS

- **Galaxy pairs**
- **Dual phase**
- **Orbital phase: may produce continuous GW (Pulsar Timing Array - PTA)**

Image credit: The LIGO/Virgo Collaboration

GALAXY MERGERS

- **Galaxy pairs**
- **Dual phase**
- **Orbital phase: may produce continuous GW (Pulsar Timing Array - PTA)**
- **Coalescence: the two black holes merge producing a single black hole and emitting impulsive GW (LISA)**

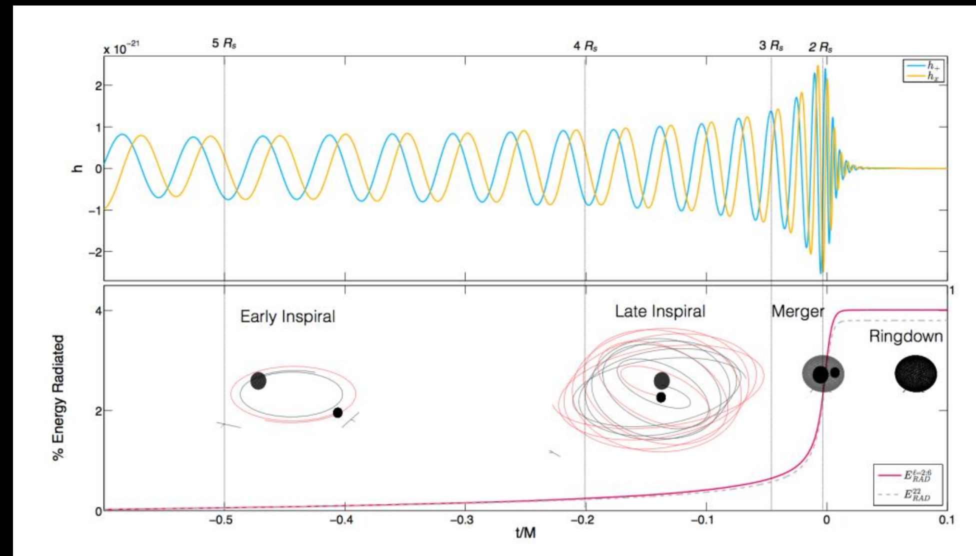
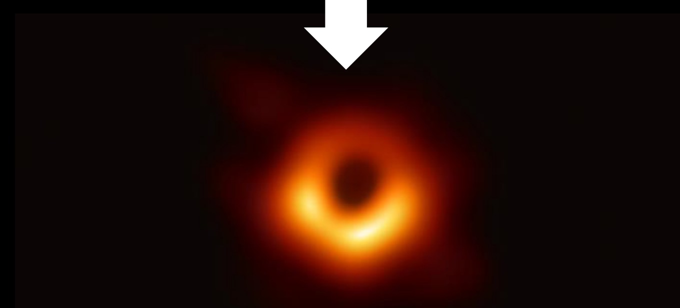


Image credit: Georgia Tech



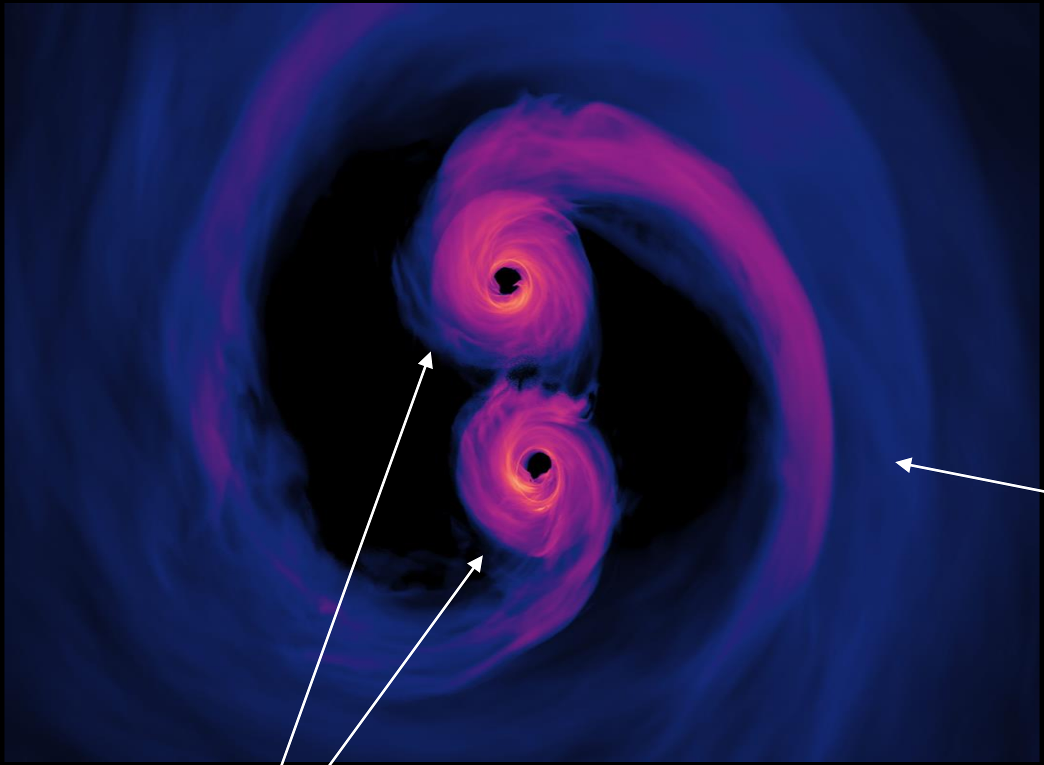
The Event Horizon Telescope Collaboration (2019)

GALAXY MERGERS

- Galaxy pairs
- Dual phase
- **Orbital phase: may produce continuous GW (Pulsar Timing Array - PTA)**
- Coalescence: the two black holes merge producing a single black hole and emitting impulsive GW (LISA)

ORBITAL PHASE

D’Ascoli et al. (2018)



4K-quality video! https://svs.gsfc.nasa.gov/13086

Circumbinary disk

Mainly responsible for optical and IR emission

Mini-disks

Emit in UV/X-rays mainly
Periodically fed by streams of gas

PAST SEARCHES OF SMBHB

Mainly in optical band light curves

Single sources

- **PG 1302-102, $P_0 \sim 60$ months (Graham et al., 2015a)**
- **NGC 5548, $P_0 \sim 180$ months (Bon et al., 2016)**

Catalogues

- **111 candidates in Catalina Real-Time Survey (Graham et al., 2015b)**
- **33 candidates in Palomar Transient Factory (Charisi et al., 2016)**

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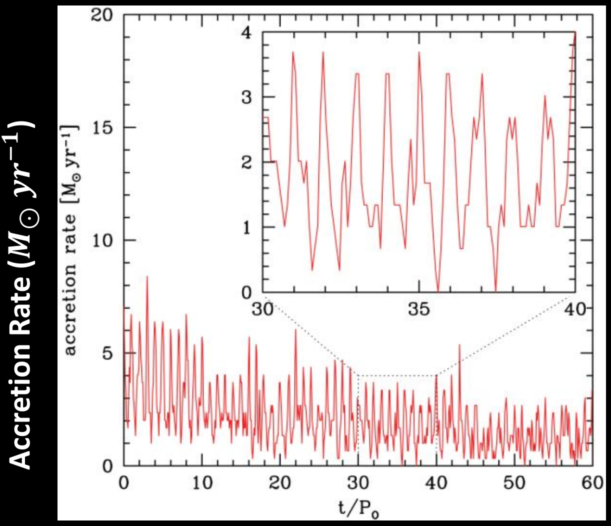
NO PTA SIGNAL DETECTED, TOO MANY SOURCES! (Sesana et al., 2018)

Many false positives

X-RAY TRACES OF SMBHB

Sesana et al. (2012)

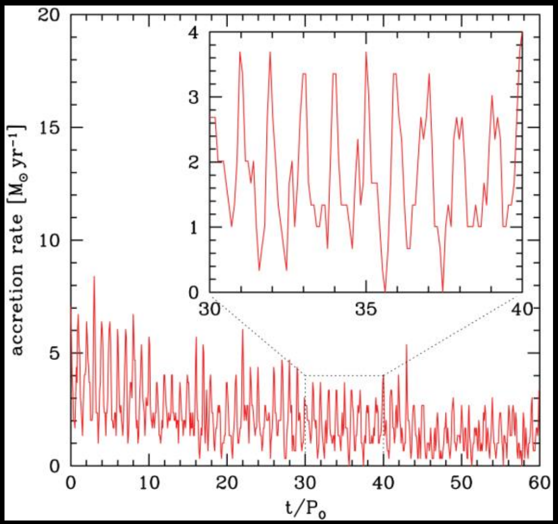


- **Periodicity, due to the modulated feeding from the streams**

X-RAY TRACES OF SMBHB

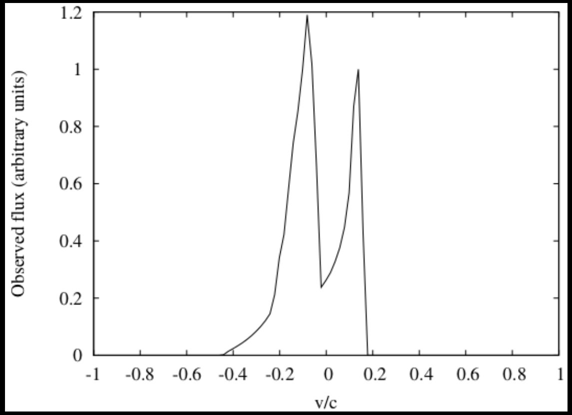
Sesana et al. (2012)

Accretion Rate ($M_\odot\, yr^{-1}$)



Number of periods

- **Periodicity, due to the modulated feeding from the streams**



Popovic et al. (2012)

- **Double Fe Kα line, due to the relative motion of the mini-disks**

MCG+11-11-032

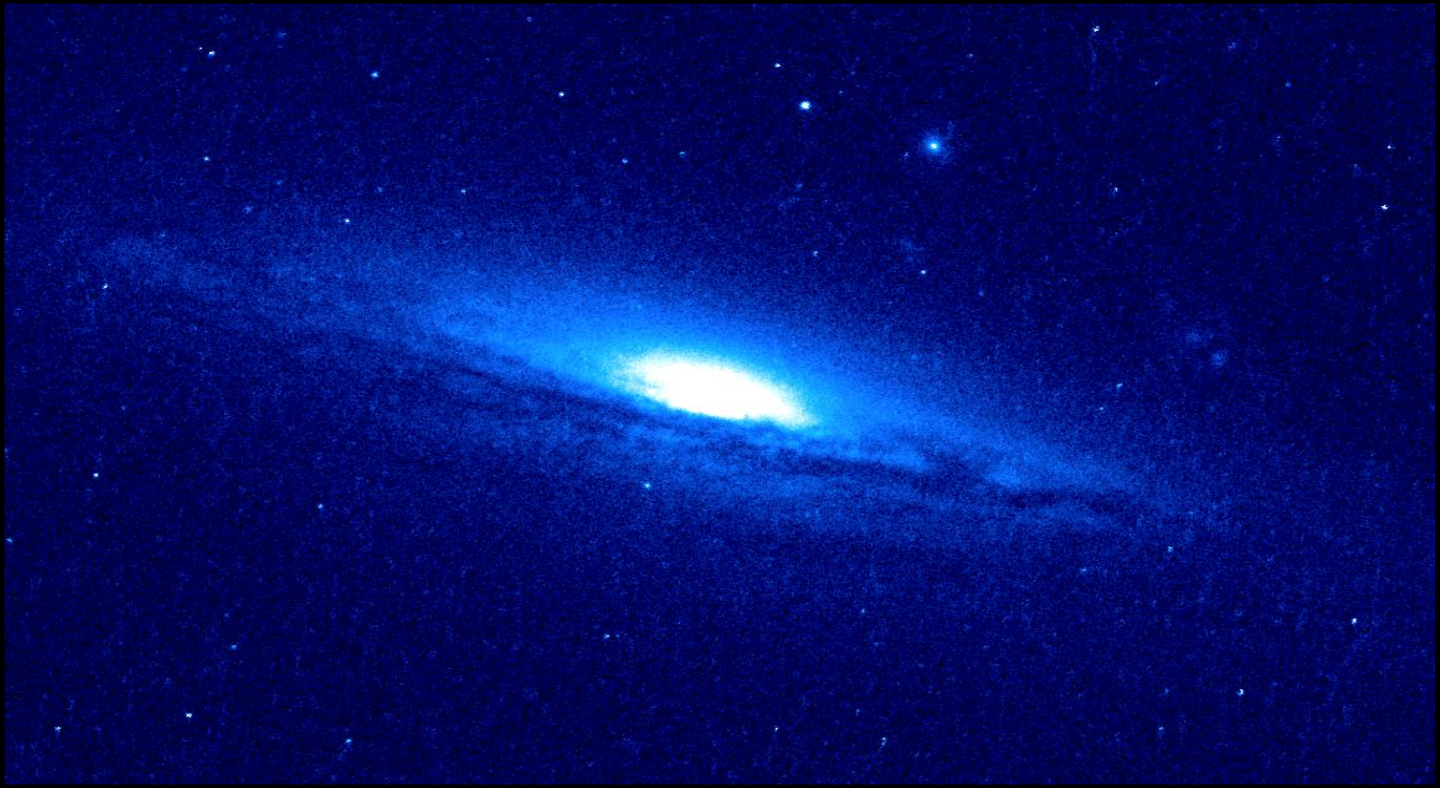


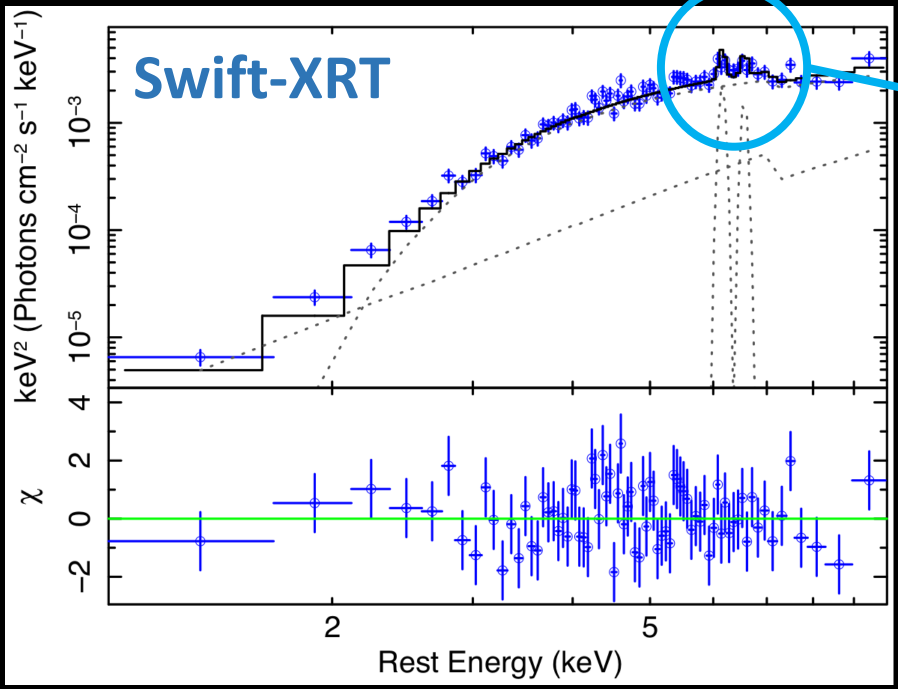
Image credit: Hubble Space Telescope

Seyfert 2 galaxy

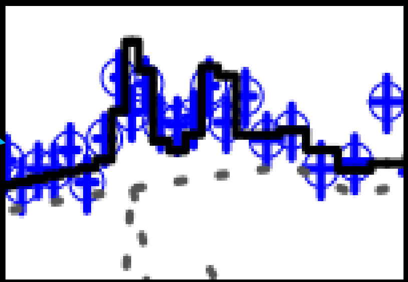
$$\log \frac{M_{BH}}{M_{\odot}} \sim 8.7$$

$$z = 0.036$$

MCG+11-11-032



Severgnini et al. (2018)



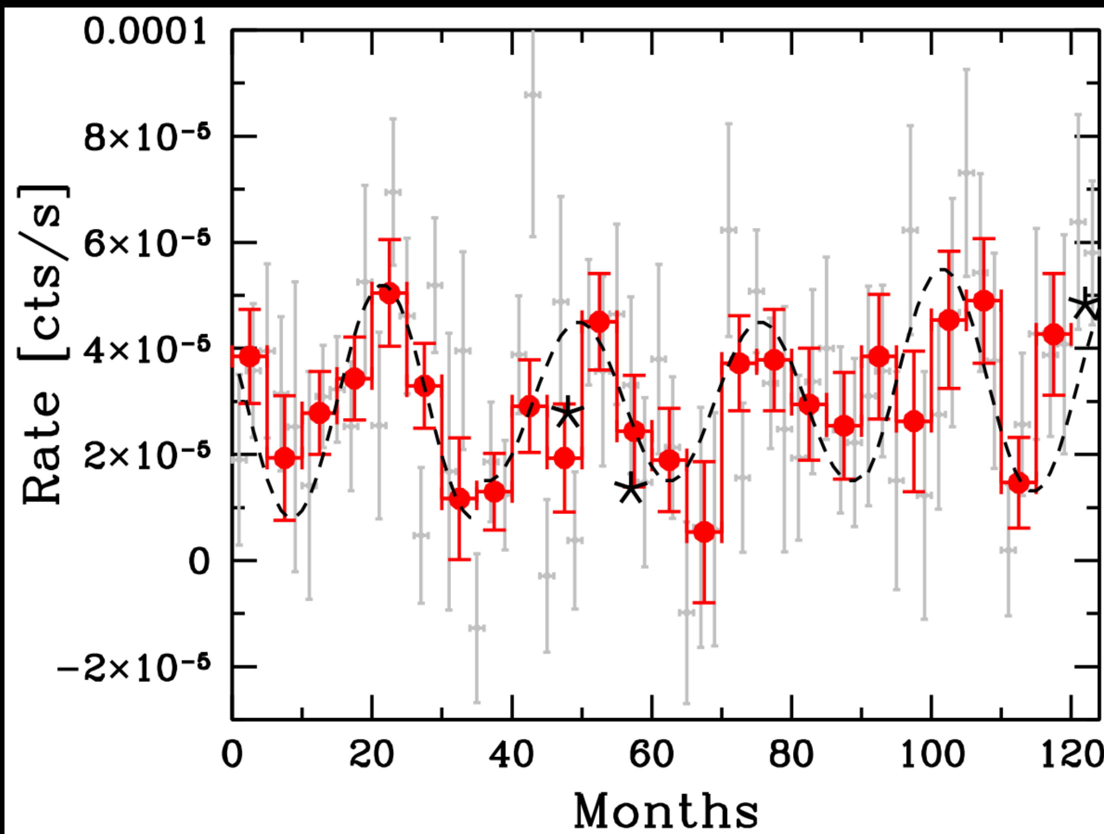
Double Fe Kα line

$E = 6.16 \pm 0.08$ keV (4σ)

$E = 6.56 \pm 0.15$ keV (2σ)

$\Delta v \sim 0.06c$ ➡ If due to orbital motion $P_0 \sim 25$ months

MCG+11-11-032



Severgnini et al. (2018)

Visual inspection of Swift-BAT light curve

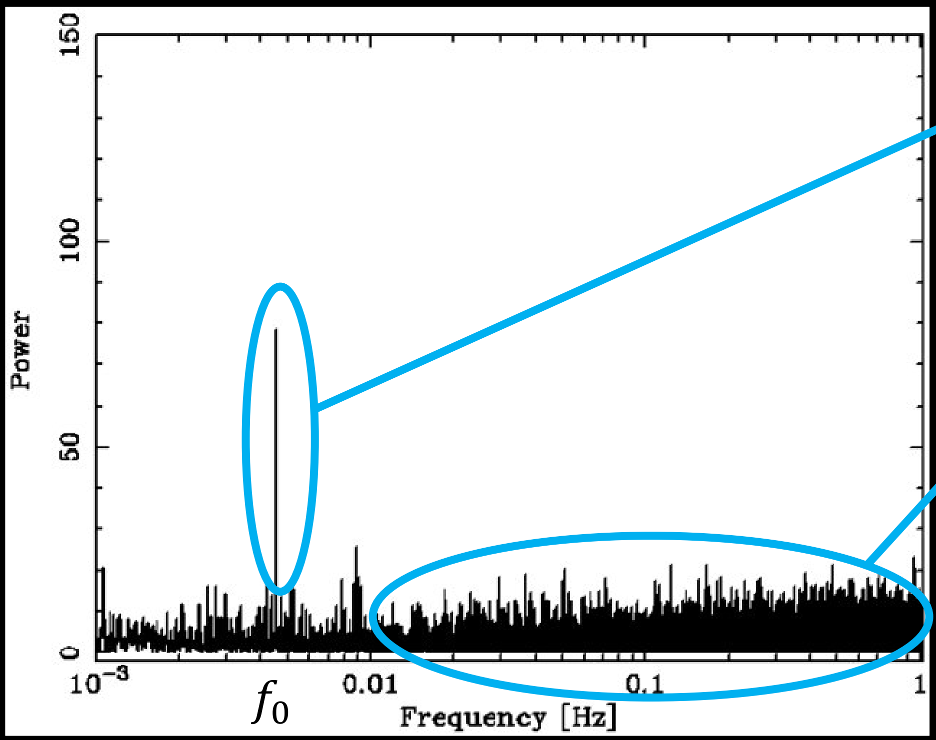
Rebinning data at 4 months shows sinusoidal behavior

...and again

$$P_0 \sim 25 \text{ months}$$

POWER SPECTRUM

Commonly used in pulsar astronomy: radio (e.g., Mickaliger+18), optical (e.g., Ambrosino+17), X-rays (e.g., Israel+16), GW (e.g., Aasi+15)



Torii et al. (1998)

The power spectrum response to sinusoidal function is a Dirac delta-function in $f = f_0$

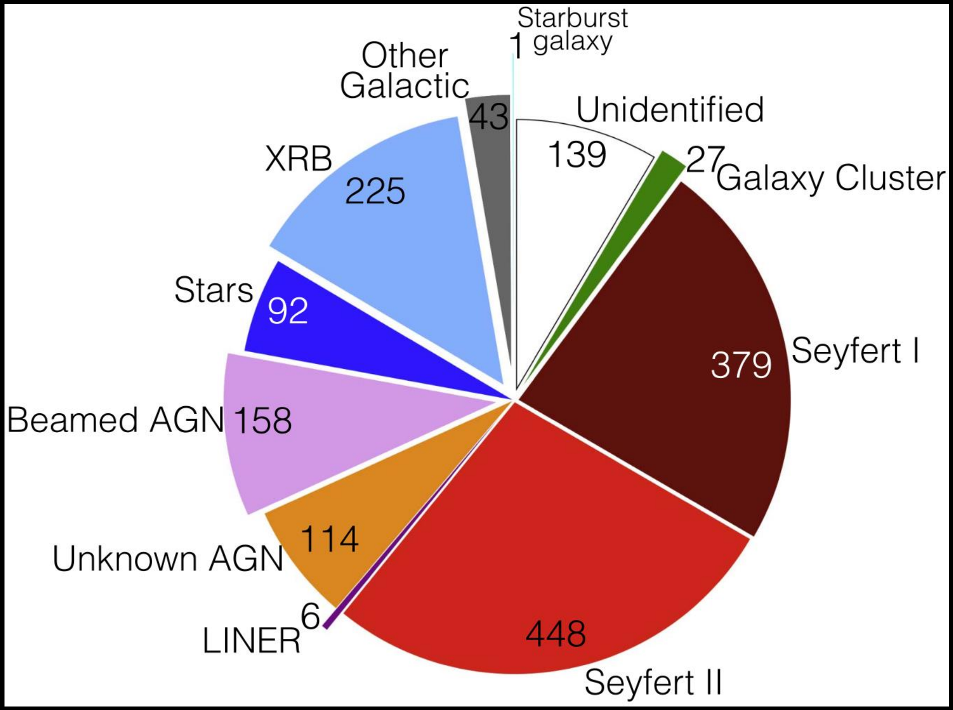
$$P_S \propto \left|\hat{X}\right|^2$$

Noise=non-periodic components of the power spectrum

(other processes)

IDEAL TO FIND PERIODICITIES!

105-month Swift-BAT survey



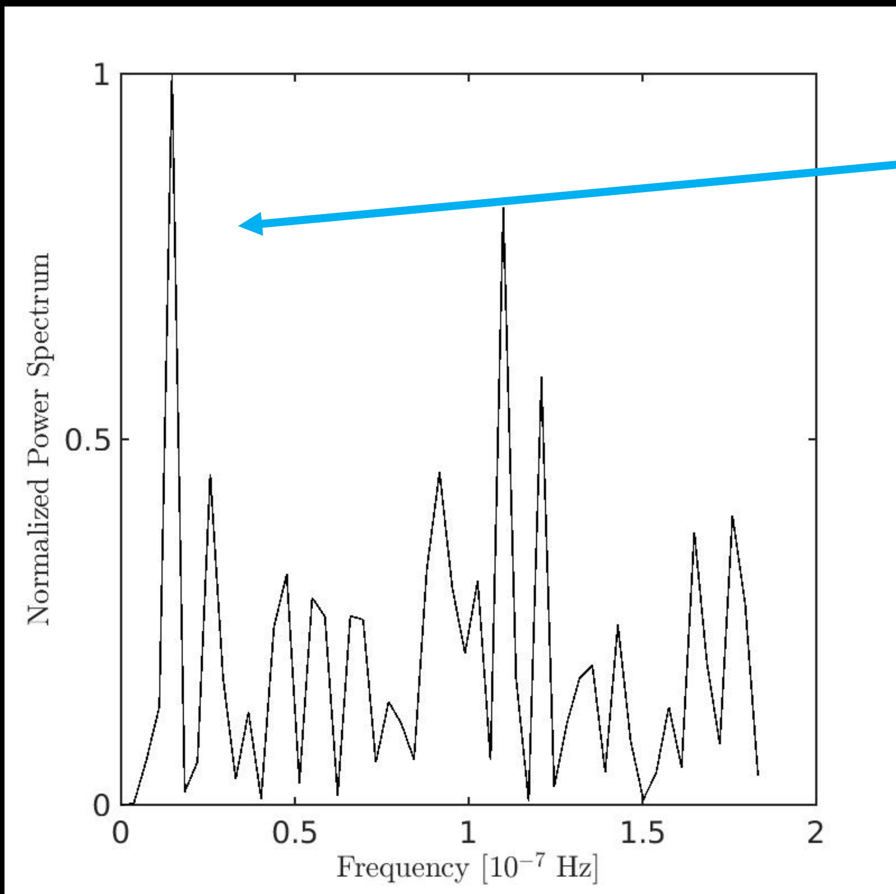
Oh et al. (2018)

- 105-month Swift-BAT hard X-ray survey (Oh et al. 2018)
- 1631 sources: 1105 AGN, 526 other (mostly X-ray binaries)
- Light curves binned at one month
- Hard X-rays are not affected by absorption

Power spectra of BAT light-curves coming up! Stay tuned!

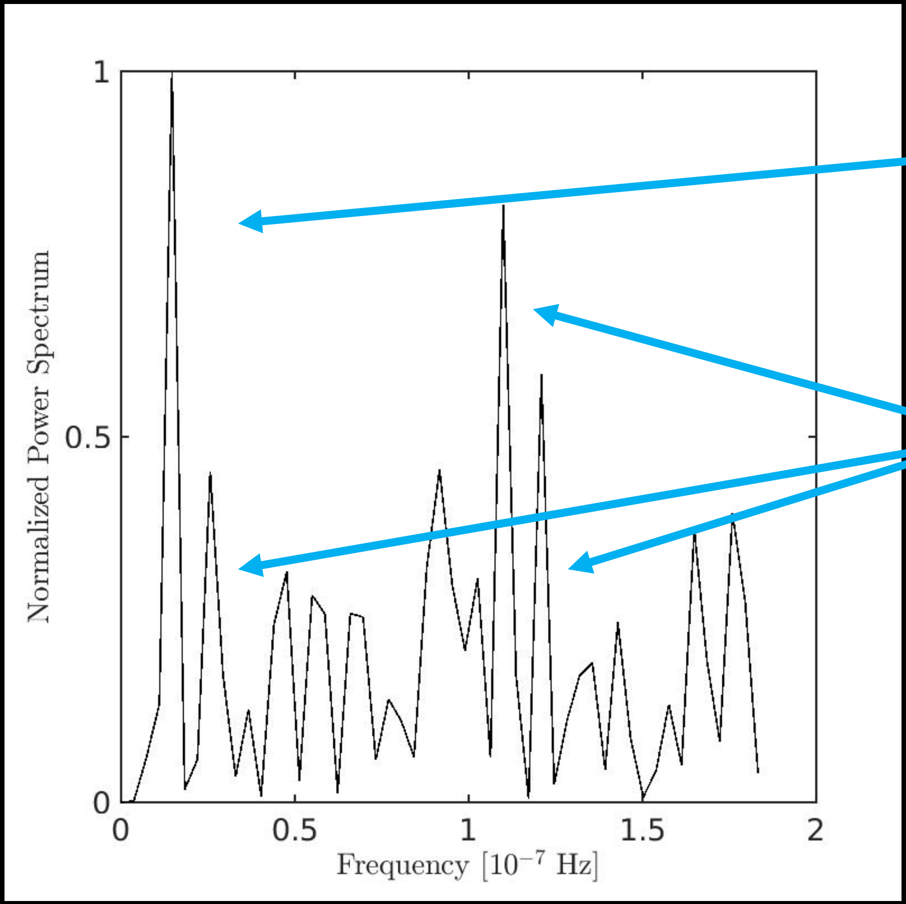
Serafinelli et al. (in preparation)

MCG+11-11-032



Peak at $f_0 = 15 \pm 2$ nHz
$P_0 = 26 \pm 4$ months

MCG+11-11-032



Peak at $f_0 = 15 \pm 2$ nHz
$P_0 = 26 \pm 4$ months

Not very significant, noise is high!

MCG+11-11-032

Noise is not white!

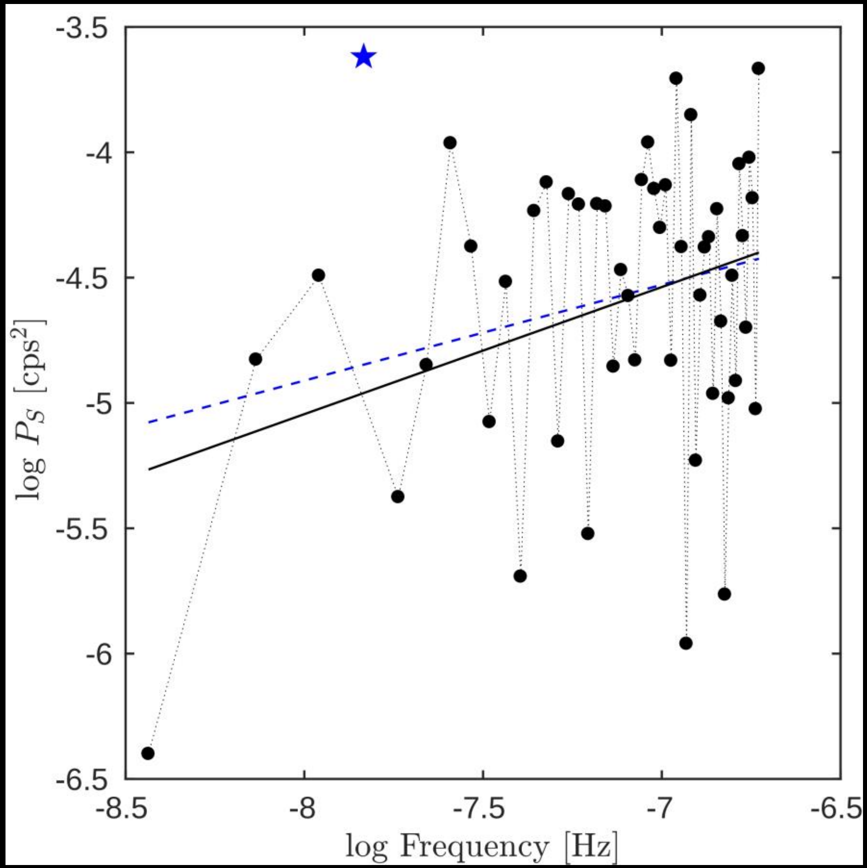
White noise: $P_S \propto f^0$

Colored noise: $P_S \propto f^\alpha$

$\alpha = 0.4 \pm 0.2$ **Including peak (blue)**

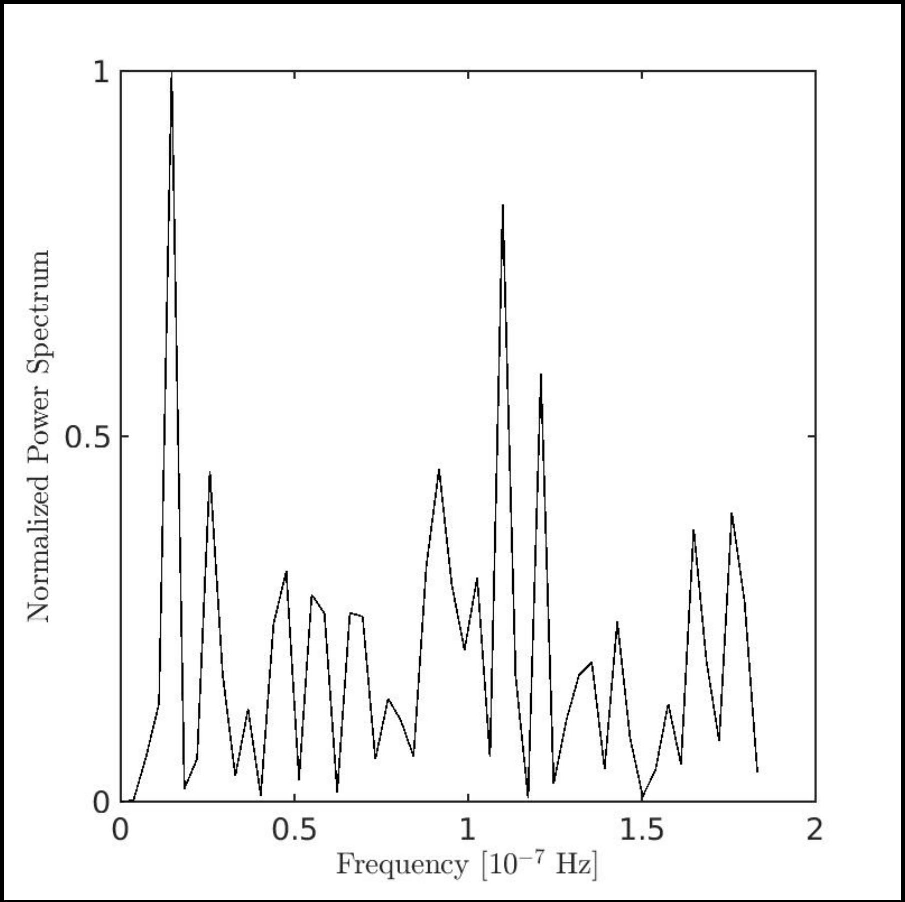
$\alpha = 0.5 \pm 0.2$ **Excluding peak (black)**

We can create a whitening filter that makes noise white (Kasdin 1995)



Serafinelli et al. (submitted)

MCG+11-11-032



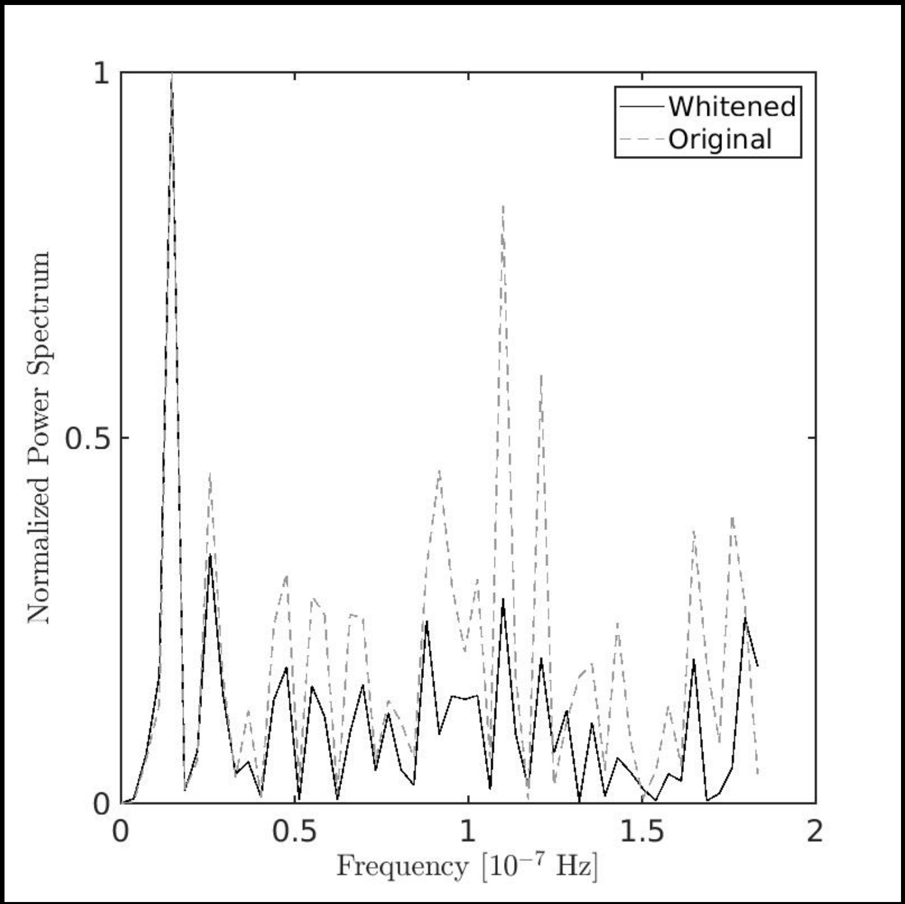
Colored power spectrum

$$P_S \propto \left|\hat{X}(f)\right|^2 \propto f^{\alpha}$$

Colored Fourier Transform

$$\hat{X}(f) \propto f^{\alpha/2}$$

MCG+11-11-032



Serafinelli et al. (submitted)

Filter

$$\hat{H}(f) = f^{-\alpha/2}$$

Whitened Fourier Transform

$$\hat{X}^{(w)}(f) = \hat{H}(f) \times \hat{X}(f) \propto f^0$$

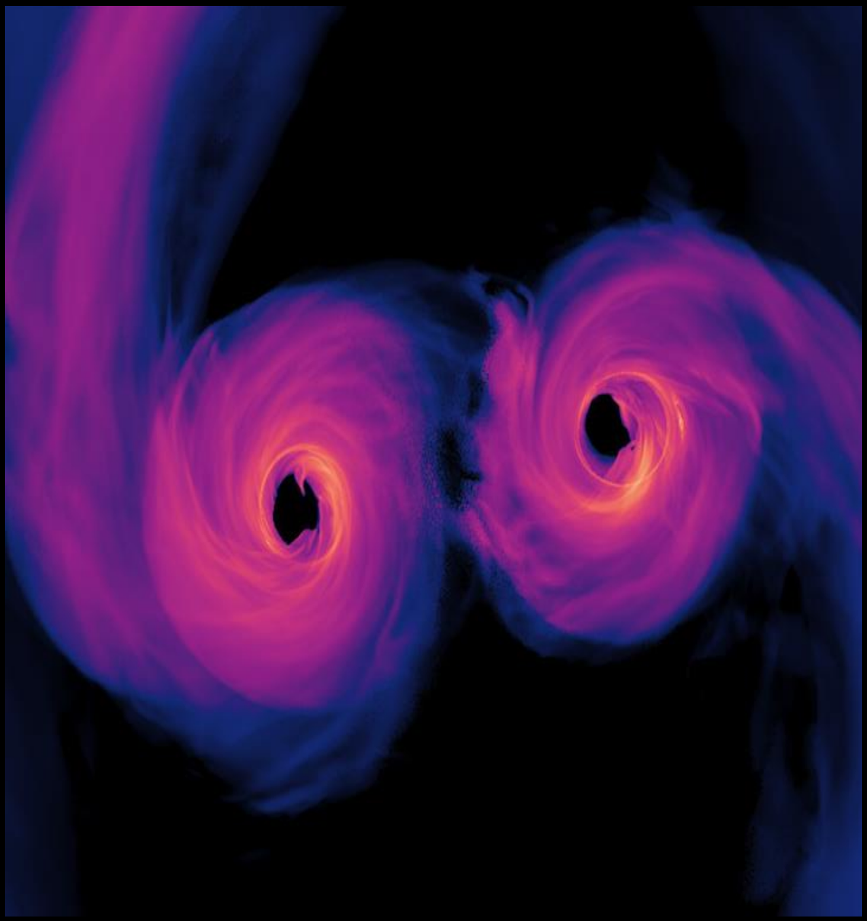
Whitened power spectrum

$$P_S^{(w)} \propto \left|\hat{X}^{(w)}\right|^2 \propto f^0$$

The peak at 15 nHz is still present

NOT A COLORED NOISE FLUCTUATION

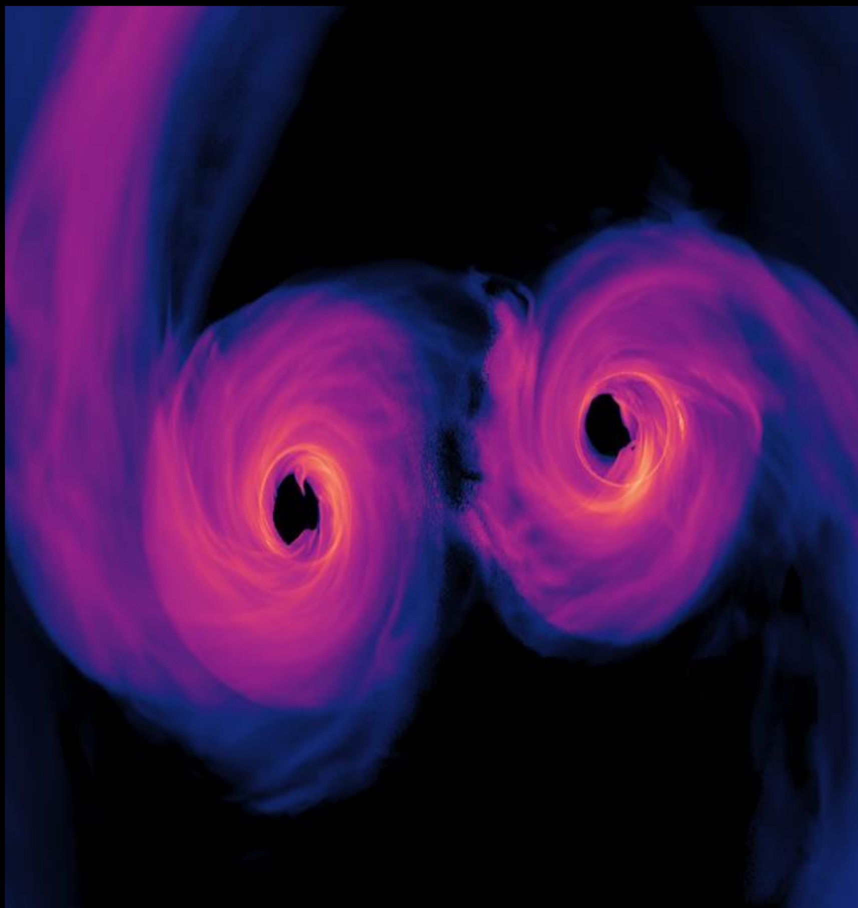
SMBHB HYPOTHESIS



Third Kepler's Law

$$a = \sqrt[3]{\frac{GM_{BH}P_0^2}{4\pi^2}} = 6 \times 10^{-3}\, pc \sim 150\, R_S$$

SMBHB HYPOTHESIS



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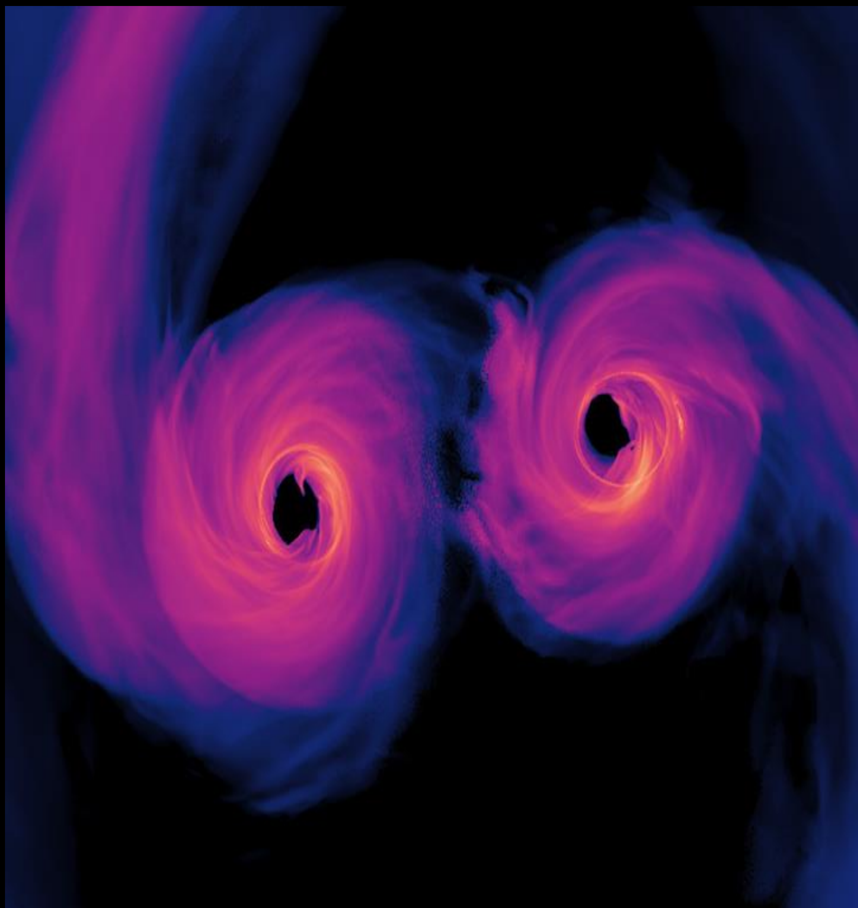
Circular orbit

$$v = 2\pi f_0 a = (0.06 \pm 0.02)c$$

SMBHB HYPOTHESIS



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Circular orbit

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→ **Energy shift of two peaks of Fe Kα lines (Severgnini et al. 2018)**

→ **Assumption of binary system based of light curve periodicity (Serafinelli et al., submitted)**

CONSISTENT!

THE FUTURE?

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Short-term future

- **Find more periodic candidates. BAT catalogue analysis coming up (Serafinelli et al., in prep. STAY TUNED!)**
- **Identify double Fe Kα lines in such candidates. Chandra, XMM and eROSITA spectra to be analyzed**
- **XRISM will be extremely useful**
- **X-ray polarization?**

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- Identify double Fe Kα lines in such candidates. Chandra, XMM and eROSITA spectra to be analyzed
- XRISM will be extremely useful
- X-ray polarization?

Long-term future

- BAT will likely double the duration of available observations. More reliable candidates
- eXTP will carry BAT legacy after its dismissal
- Athena (ESA) and possibly Lynx (NASA) for unprecedented spectroscopic resolutions

SUMMARY

- Double iron Kα emission line feature in Seyfert 2 galaxy MCG+11-11-032
- Energy shift between the Fe lines emission regions leads to relative velocity $\boxed{\Delta \mathrm{v} \sim 6\%\, c}$
- Periodic shape of Swift-BAT light curve $\boxed{(\sim 25 \text{ months})}$

P. Severgnini et al. (2018), MNRAS, 479, 3804

- Power spectrum analysis of 105-Month Swift-BAT light curve
- Power spectrum peak at $\boxed{P_0 = 26 \pm 4 \text{ months}}$ ($f_0 = 15 \pm 2$ nHz)
- Not a colored noise fluctuation
- In the hypothesis of supermassive black hole binary scenario, distance is 6×10^{-3} pc
- Assuming circular orbit the two SMBHs have relative velocity $\boxed{\Delta \mathrm{v} \sim 6\%\, c}$

R. Serafinelli et al., submitted

- More candidates coming up from the Swift-BAT 105-Month hard X-ray survey

R. Serafinelli et al., in prep.