# Fast multiwavelength variability from X-ray binaries


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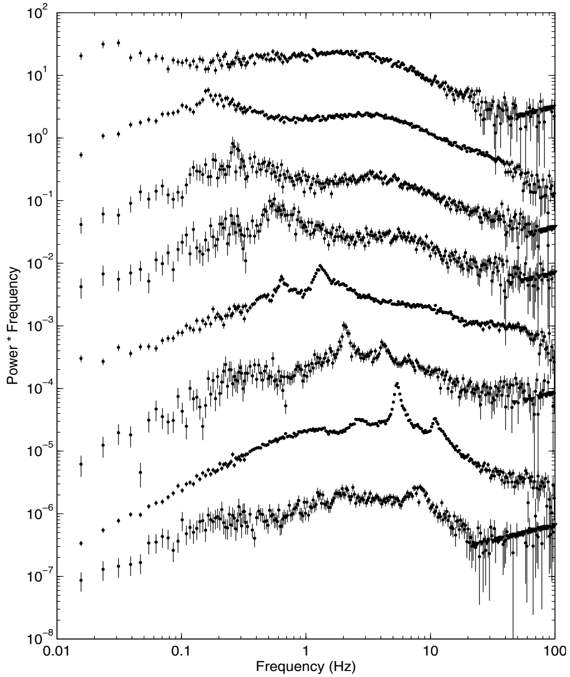
**The many tones of accretion — to the memory of Tomaso Belloni**

Cefalù, 7–11 September 2026 · Session 3.4 — Multiwavelength Variability

# For Tomaso

**I did my PhD with Tomaso on X-ray timing of black-hole transients**

**He taught me to ask ‘‘what is the timescale?’’ before asking ‘‘what is the spectrum’?’**




**This talk is that question,**
**asked outside the X-ray band**

# Where this talk sits in the week

*Deliberately narrow: fast (sub-second to ~minutes), non-thermal, mostly jet-focused*

COMING FROM

**Vincentelli (Tue) —** QPOs, incl. the O-IR ones and their HID evolution

**De Marco (Tue) —** the toolbox - X-ray spectral-timing, lags, reverberation

**Fender (this morning) —** accretion–ejection coupling, the global picture

**Russell (20 min ago) —** MW correlations on longer timescales

**++ many others**

THIS TALK

**The causal regime —** tenths to tens of seconds

**The jet —** lags, stratification, filtering — tested in every band that can see it

**What breaks —** and what we cannot yet measure

COMING NEXT

**Tetarenko (in 45 min) —** rapid mm/radio timing: the same physics, downstream

**Veledina, Baglio (Thu) —** polarimetry — the next observational axis

**Scaringi (Thu) —** CVs — scaling the mass

**++ many others**

# Why fast, and why multiwavelength

*The rare regime where correlation between two bands likely implies causation*

**Spectra tell you what emits.**

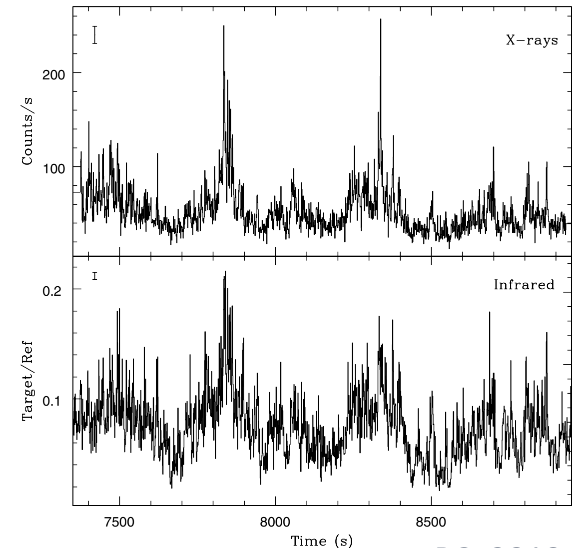
**Fast timing tells you where, and in what order.**

Three things you get for free from a light curve:

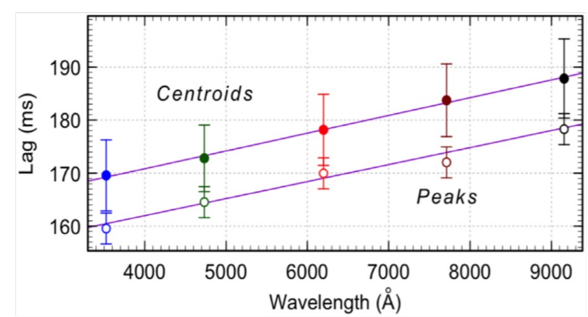
**1. A size limit.** Variability at 100 Hz ⇒ emitting region ≲ 3000 km ≈ $10^2$ RS for a 10 M⊙ BH.

**2. A distance.** A stable lag between two bands is a propagation or light-travel time —it can convert into a physical separation between two emitting zones.

**3. A causal ordering.** Sign of the lag ⇒ which component drives which. Anticorrelation ⇒ a shared, finite energy budget.




*PC+2010*




*Paice+2019*

# The toolbox

*Nothing here is new: the same Fourier machinery Tomas contributed building for X-rays – now applied across 10 decades in* ν

**CCF**

shape, sign, peak lag
→ which component,
how far out

**PSD (per band)**

break frequencies, QPOs
→ characteristic
size scales

**coherence $\gamma^2(f)$**

how much of one band is
linearly predictable from
the other

**lag spectrum $\tau(f)$**

separates reprocessing,
jet and hot flow by
timescale

**rms spectrum**

SED of the VARIABLE flux
→ isolates components
the mean SED cannot

**rms−flux relation**

linear? → multiplicative,
propagating fluctuations

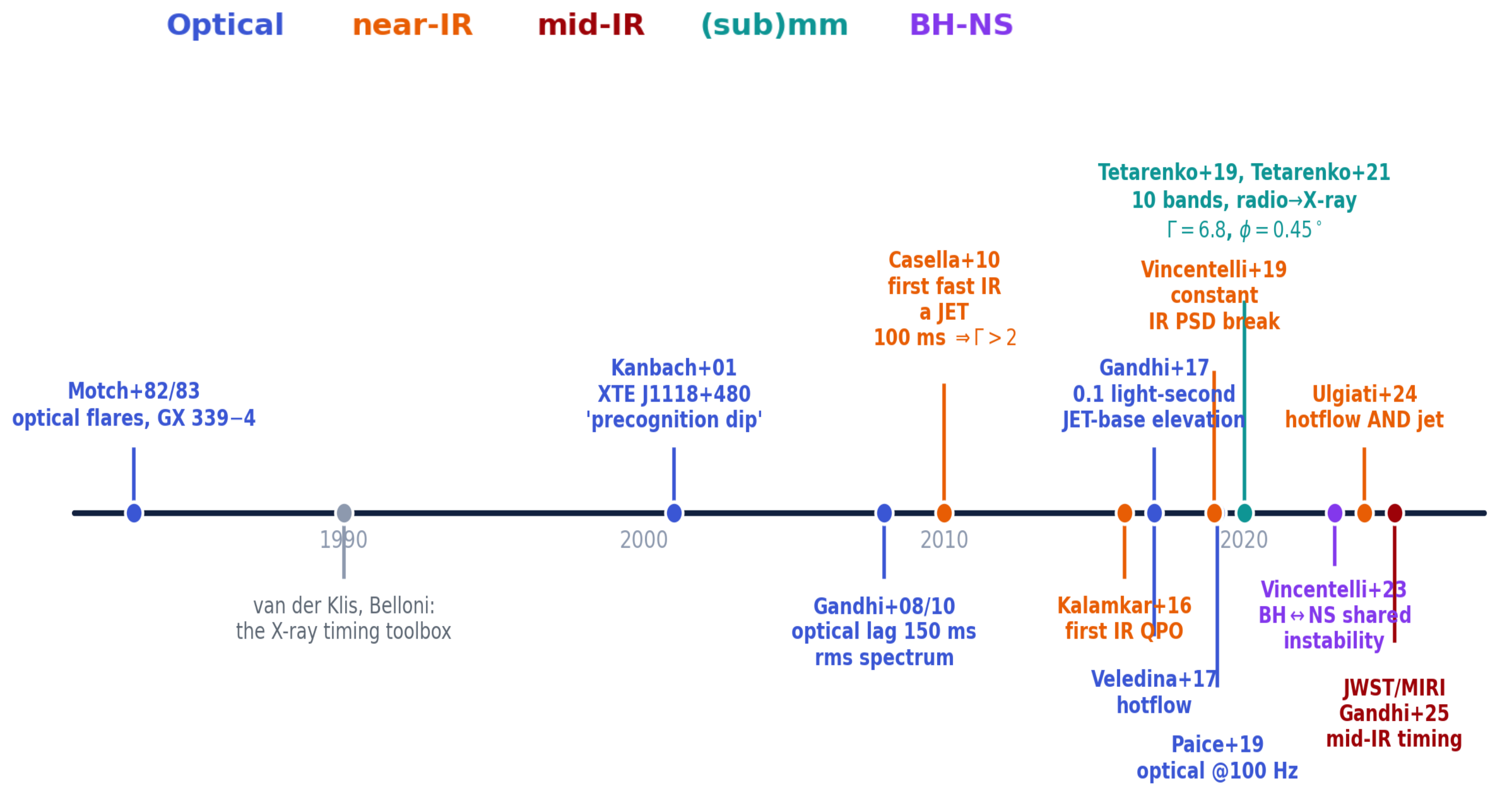
**bispectrum/ higher order**

non-linear coupling
between bands

The main difficulty is **strict simultaneity**

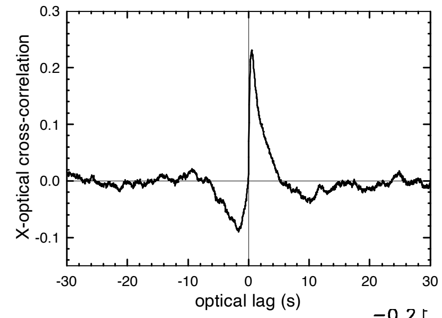
two (or more) oversubscribed facilities agreeing to point at the same object on the same night

# Four decades of fast multi-wavelength variability

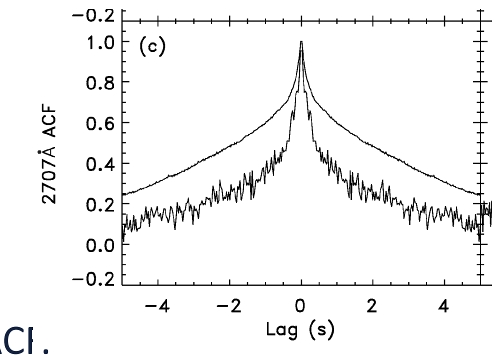


# The prehistory: an optical flicker that should not exist

*Kanbach+2001*




*Hynes+2003*




Textbook expectation
(van Paradijs & McClintock 1994):
optical from an X-ray-irradiated outer disc
⇒ delayed, smeared, positive response.

## Instead:

1. Speed — significant power down to tens of ms. **Size $\lesssim 10^3$ $R_s$**
2. Lag too short — far below the light-crossing time of the outer disc (binary separation in GX 339−4 ≈ 25 light-seconds)
3. Wrong ACF ordering — the X-ray ACF is *broader* than the optical/IR ACF. Reprocessing should smear, not sharpen
4. Anticorrelation — a negative response is not a linear reprocessing transfer function

**So the fast O-IR light is NON-THERMAL**

**Synchrotron from the jet**

*OR*

**Synchrotron from a magnetised hot flow.**

# The founding number: ~100–150 ms

*GX 339-4. Measured within two years of each other, in two different bands*

## Gandhi et al. 2008 (optical, ULTRACAM@VLT)

~150 ms optical lag (hard state)

rms spectrum NOT a single power law X-rays-to-optical: two distinct variable components

Broad anticorrelation dip on ~seconds

## Casella et al. 2010 (near-IR, ISAAC@VLT)

Strong $K_s$/X-ray correlated variability

~100 ms IR lag

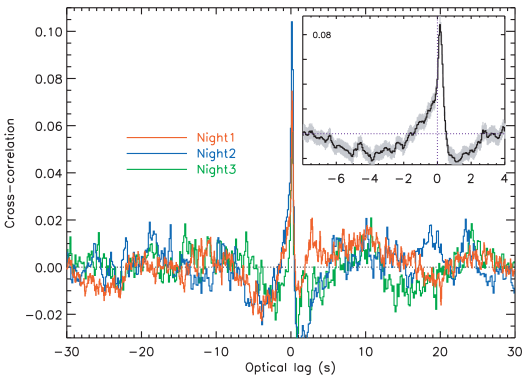
CCF not consistent with reprocessing

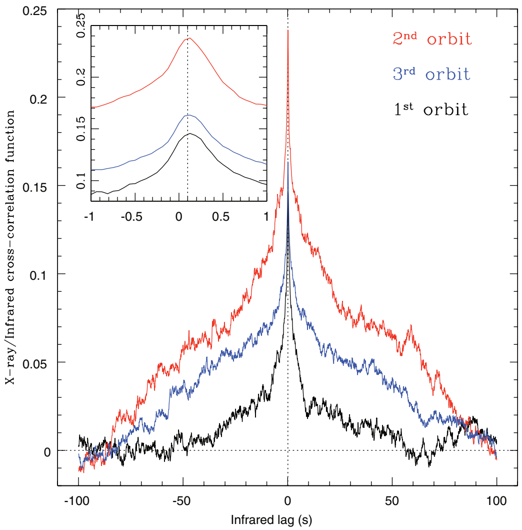
Brightness temperature ~ $2.5 \times 10^6$ K ⇒ **non-thermal**

Positive IR lag → **A JET**

Standard jet assumptions ⇒ $\Gamma > 2$

*Gandhi+2008*



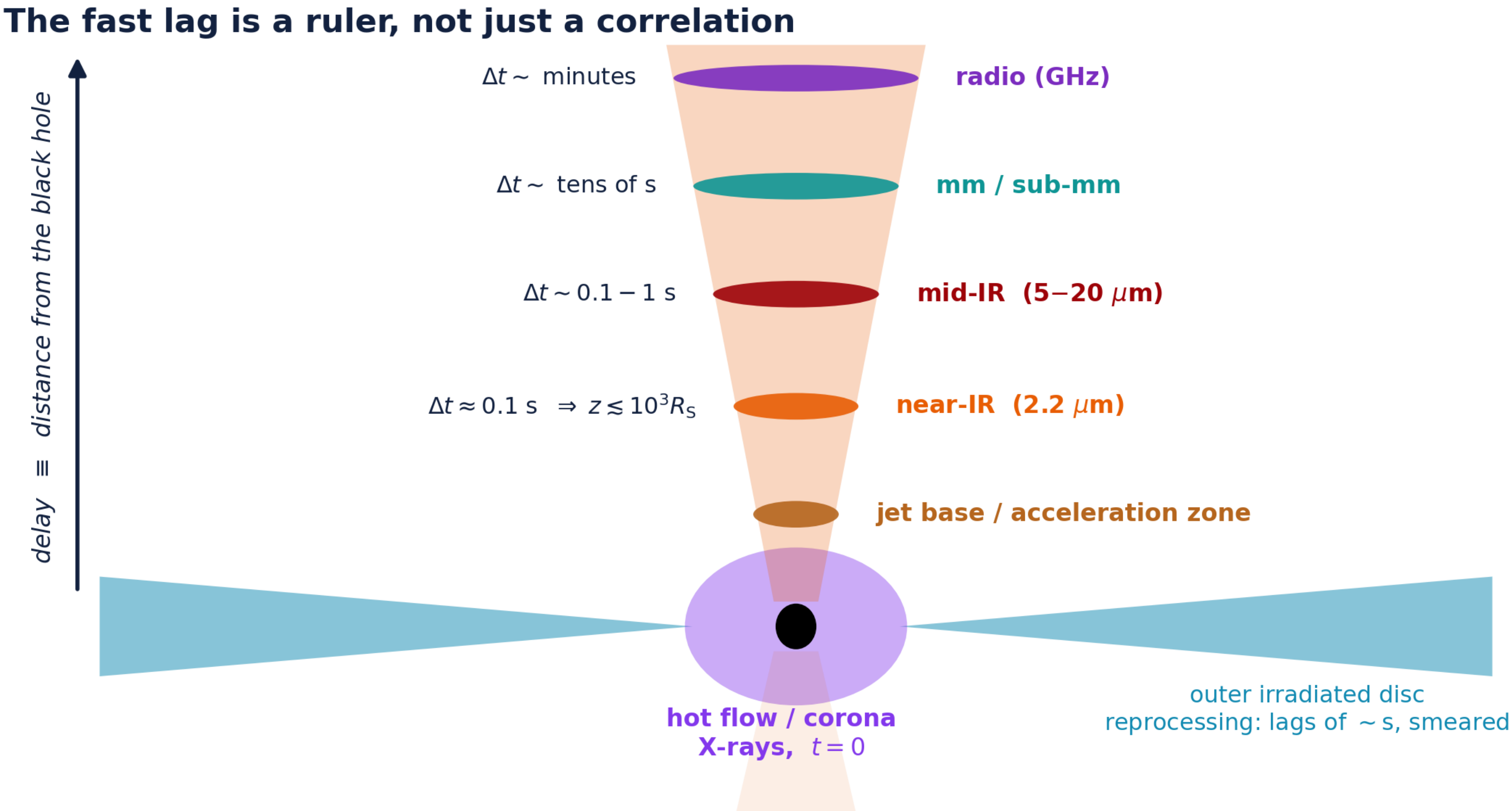

*PC+2010*

**A ~0.1 s O-IR lag to X-rays**

**A travel time from the inflow to the JET**

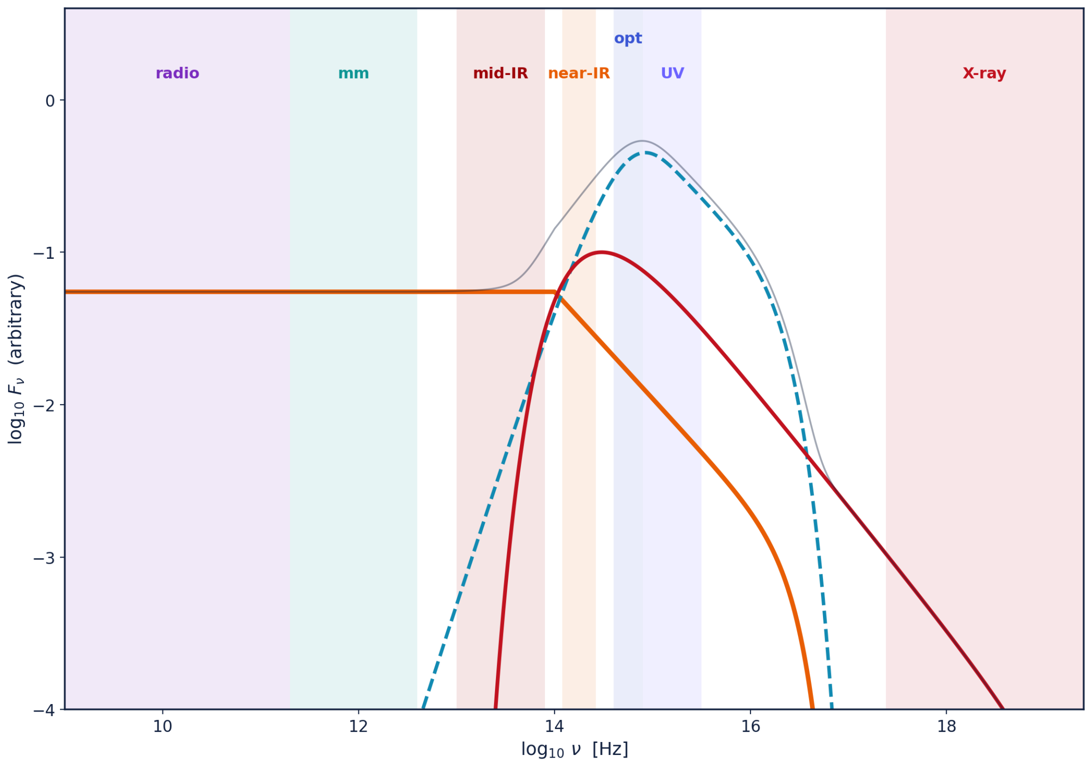
# The delay ladder

*Every band picks out a different distance from the black hole*



# Choosing a band: the trade-offs

*Wavelength is a lever arm — the band follows the question*




**Jet fraction rises to the red**

**Time resolution rises to the blue.**

**Every band buys something and costs something:**

**X-ray —** the reference clock; photon counting to kHz. ***Cost:*** mixes hot flow, disc; unknown geometry

**optical —** ms cadence; multiple bands at once (HiPERCAM). ***Cost:*** three comparable components; absorption

**near-IR —** jet starts dominating; little absorption. ***Cost: (***today) a few Hz Nyquist

**mid-IR —** around the jet break. ***Cost:*** large atmospheric absorption; cadence of sec–min

**mm / radio —** jet dominated. ***Cost:*** strong low-pass filtering; lags of minutes

# The lag as a ruler: 0.1 light-seconds

*V404 Cyg, 2015 — the measurement that closed the argument*

**Gandhi et al. 2017 (optical + radio + X-ray)**

The same optical lag ~0.1 s in another BH

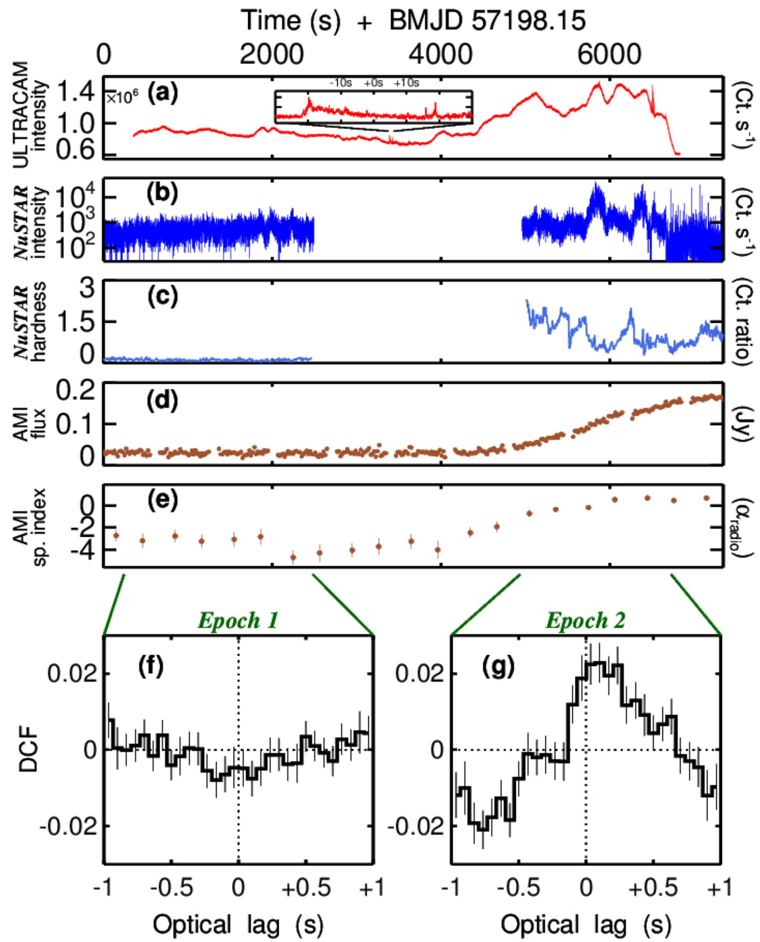
It appears together with a brightening jet

⇒ characteristic elevation $\lesssim 10^3$ $R_s$ for the inner optical emission zone above the BH

Constrains models: the acceleration zone cannot be arbitrarily extended.

**Same ~0.1 s O-IR lag as in GX 339-4**

**$10^3$ $R_s$ similar to blazars: mass-scaling?**




*Gandhi+2017*

# The same delay, in Fourier space (and more)

*Vincentelli,PC+2018*

*Vincentelli et al. 2018 GX 339−4, $K_s$ (Belloni is co-author)*

**First full characterisation of sub-second IR/X-ray variability in an LMXB (w. Tomaso as co-author)**

IR lag ≈ 0.1 s appears at around 1 Hz

A changing slope of the flux–flux relation on 16 s timescales ⇒ A moving jet break?

Properties of RMS–flux relation for jet emission:

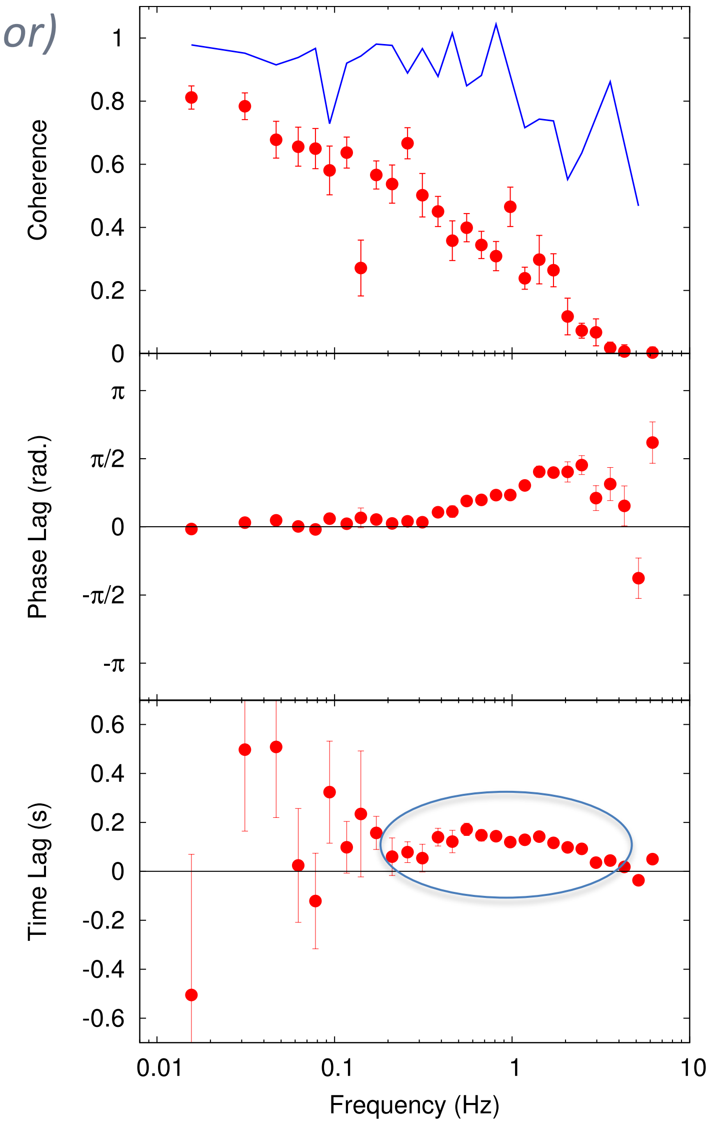
⇒ Non-linear transfer function?

or

⇒ Shock-induced rms-flux relation?

**A new tool at hand:**

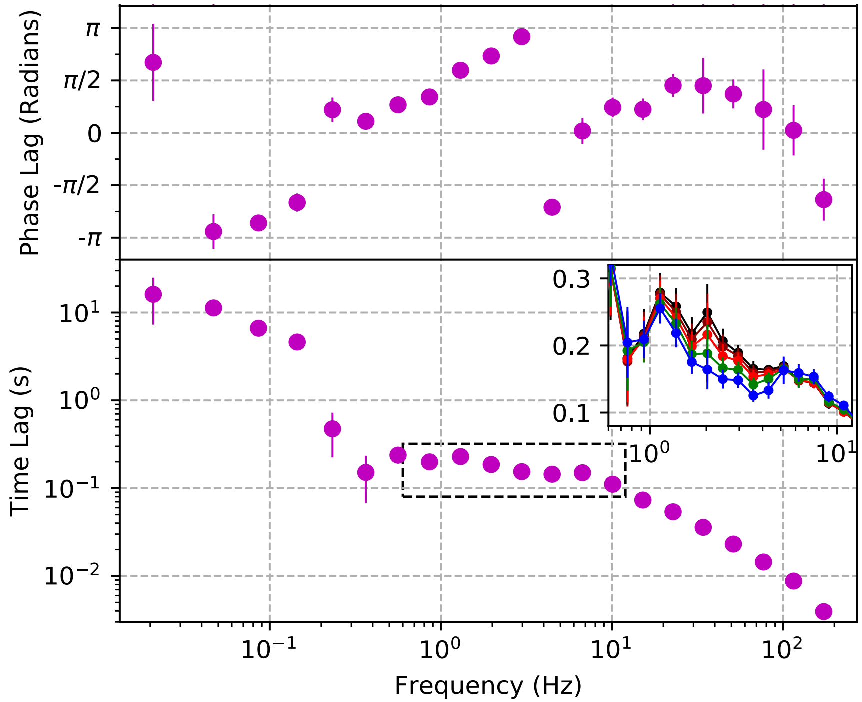
**the JET is being measured**



# The benchmark lag: MAXI J1820+070

*Paice et al. 2019 HiPERCAM@GTC, five optical bands at >100 Hz*

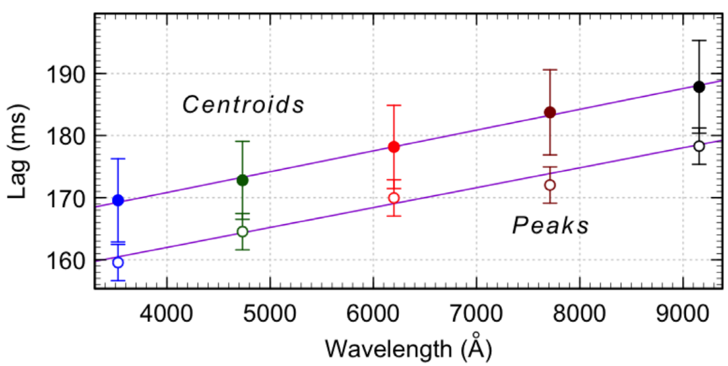
*Paice+2019*




The same optical lag ~165 ms, constant over ~0.3–10 Hz

Lag increases monotonically $u_s \rightarrow z_s$

A separate feature at the lowest frequencies: reprocessing or magnetised hot flow?




**Same lag , different source**

**Well resolved in frequency AND colour**

# The jet as a low-pass filter

*Vincentelli et al. 2019 GX 339−4, $K_s$*

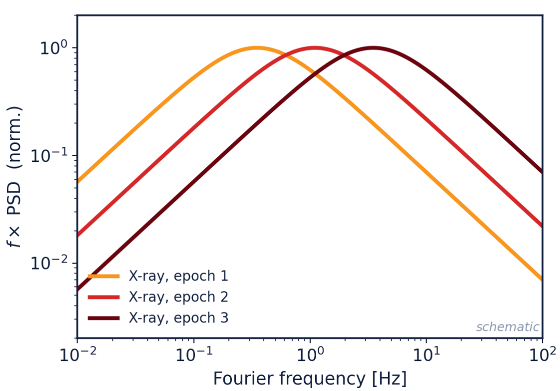
**First multi-epoch fast X-ray/IR campaign on GX 339−4 (2015 decay)**

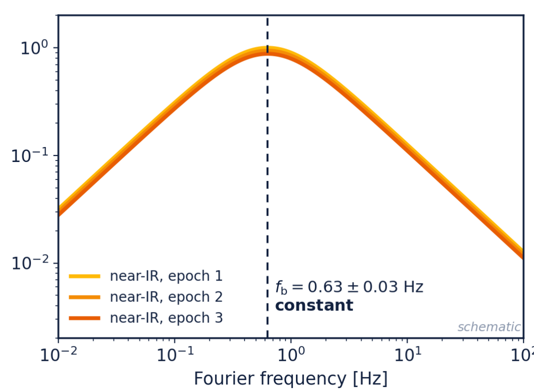
The same ~0.1 s IR lag (‘f course)

The X-ray PSD evolves normally — the break tracks the accretion flow.

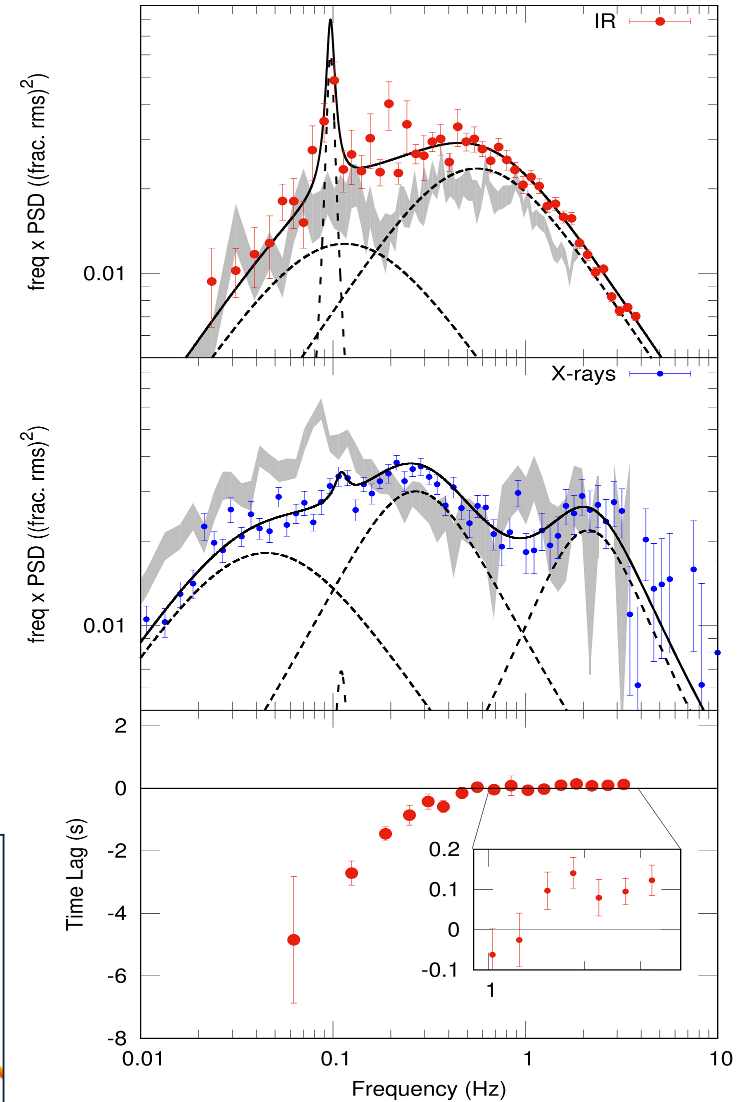
The IR PSD stays there: high-frequency break consistent with being CONSTANT ~0.6 Hz

**The jet imposes its own characteristic timescales**



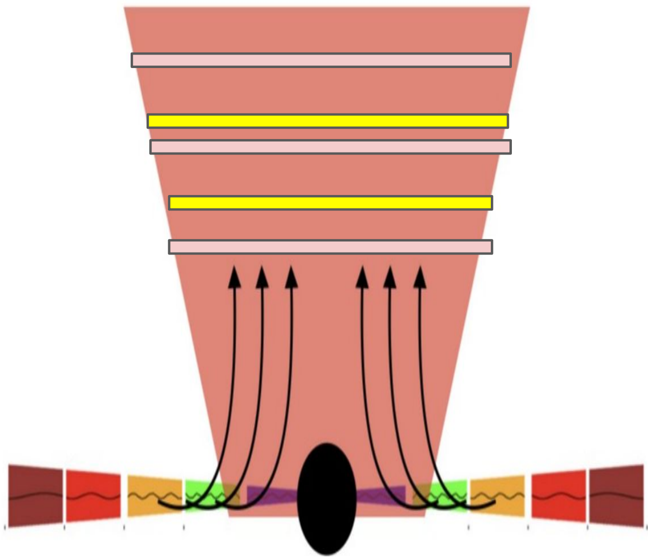




*Vincentelli,PC+2019*



# Model I: internal shocks in the jet

**ISHEM** — Malzac+2013, 2014, 2018

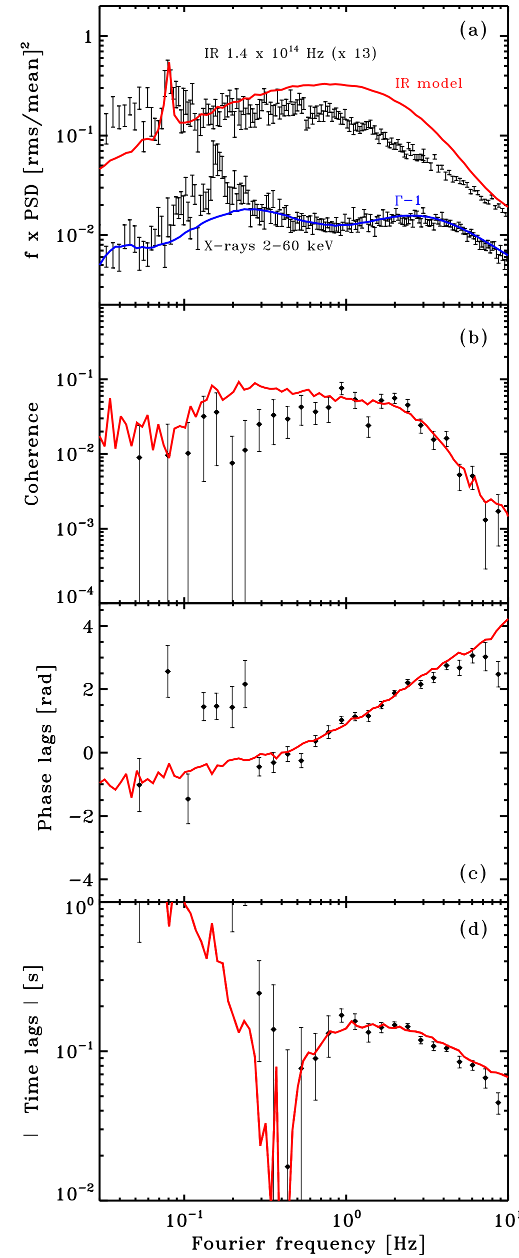


**X-rays from inflow**

**Accretion rate fluctuations enter the jet**

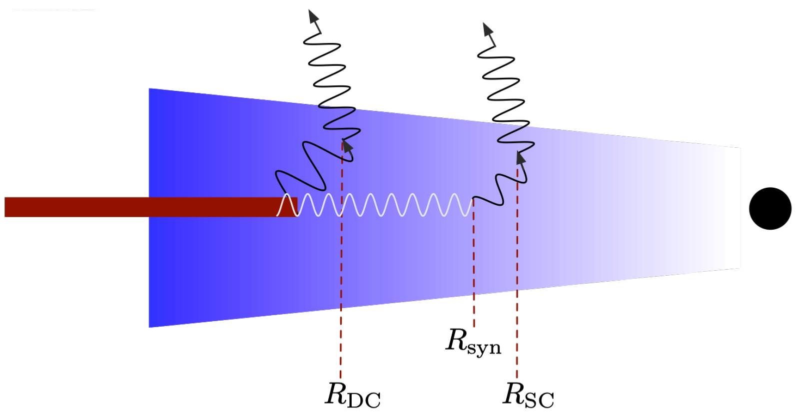
**Differential shell speed ⇒ internal shocks**

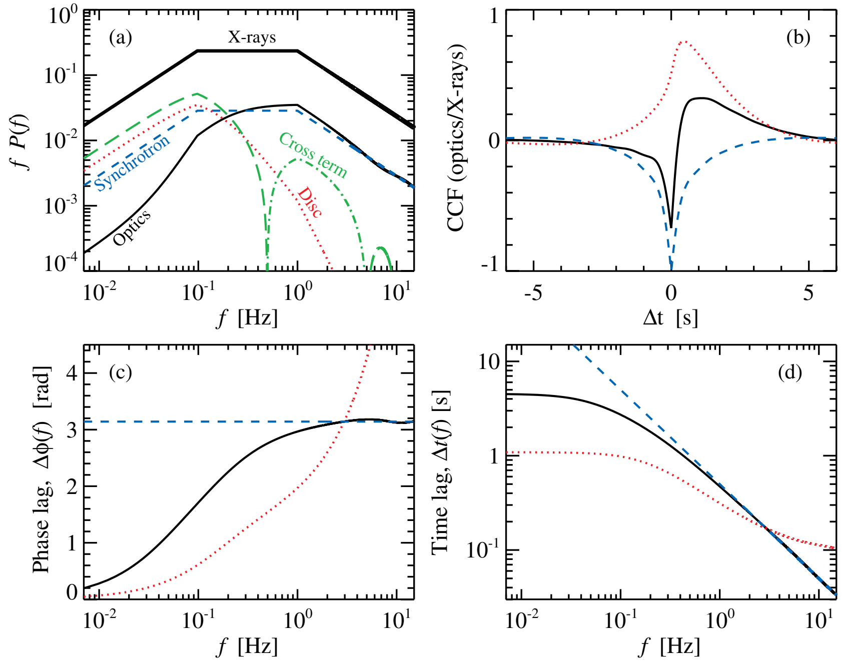
**⇒ Variable synchrotron emission (optical → radio)**



# Model II: the magnetised hot flow

Veledina+ 2011, 2013, 2017




**Accretion rate fluctuations enter a magnetised hot flow**

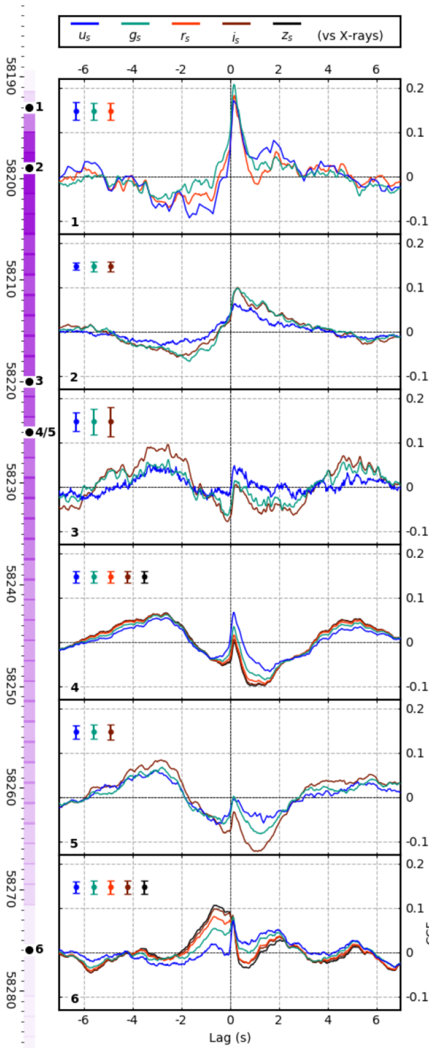
**O-IR synchrotron emission**

**X-rays (self-)Compton emission**

**Turnover expected in the OIR/mid-IR regime**

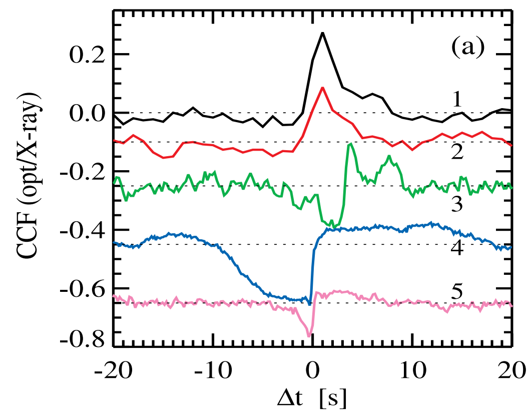
# Doesn’t have to be either/or

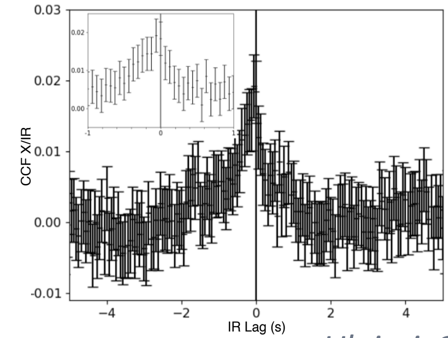
*The same source, at different epochs / Fourier frequencies / wavelengths, shows both*



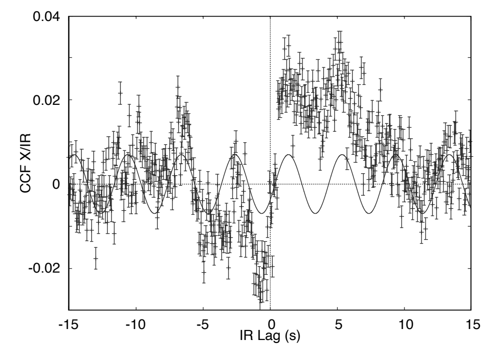

*Paice+2021*

*Veledina+2017*




*Ulgiati+2024*




MAXI J1820 & SWIFT J1753.5

Multiple O-IR epochs, different CCFs

Evolving hot flow AND jet

The question is no longer

***“jet or hot flow?”***

but

**“what sets their relative weight?”**

# Doesn't have to be either/or

*The same source, at different epochs / Fourier frequencies / wavelengths, shows both*

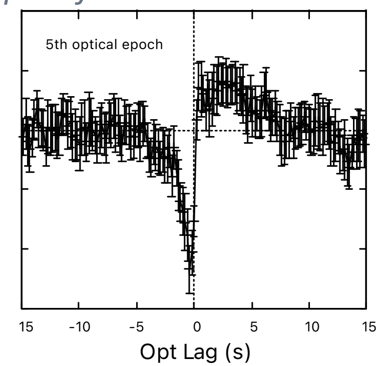
SWIFT J1753.5

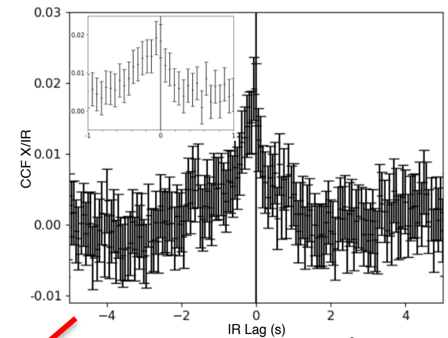
## Opt ≠ NIR

(5 days apart, same flux/state)

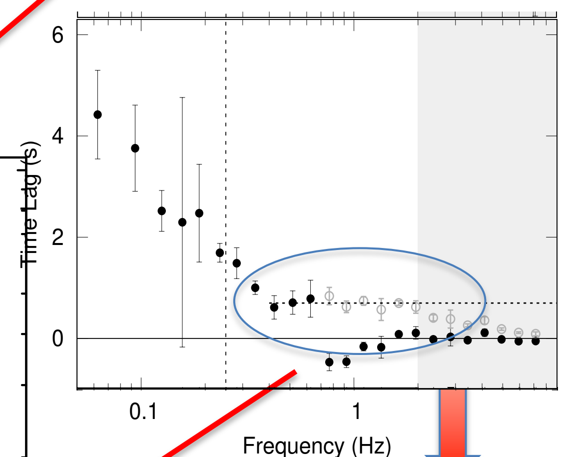
locating the self-absorption break of the hot flow?

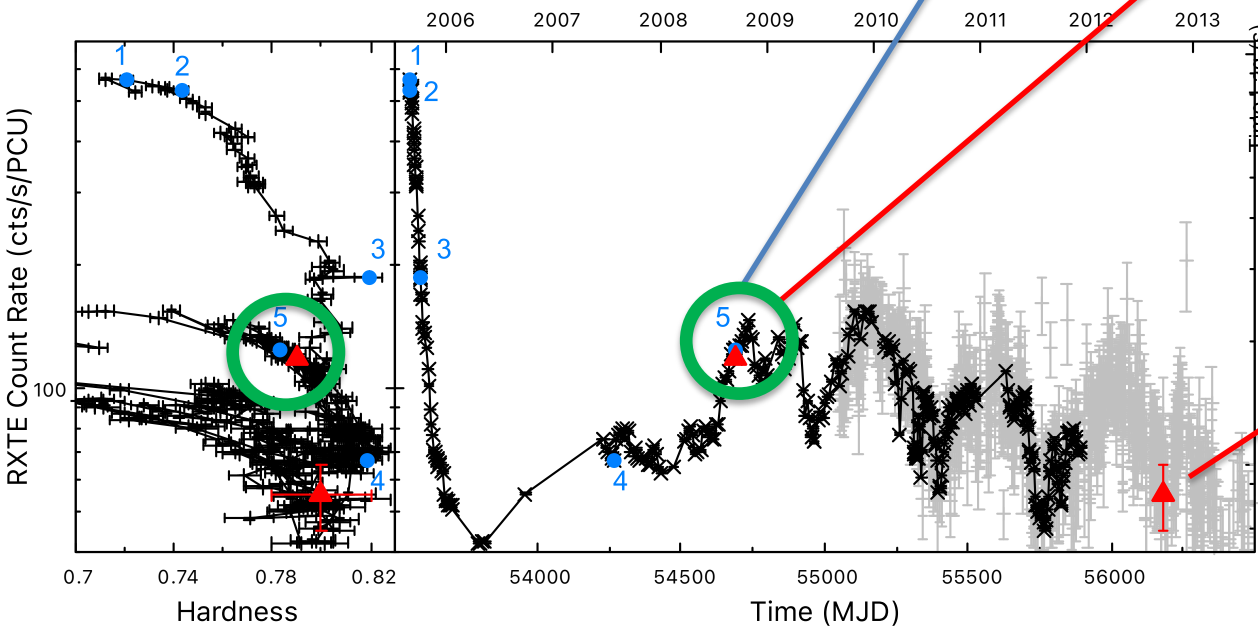
*adapted from Veledina+2017*




*Ulgiati+2024*



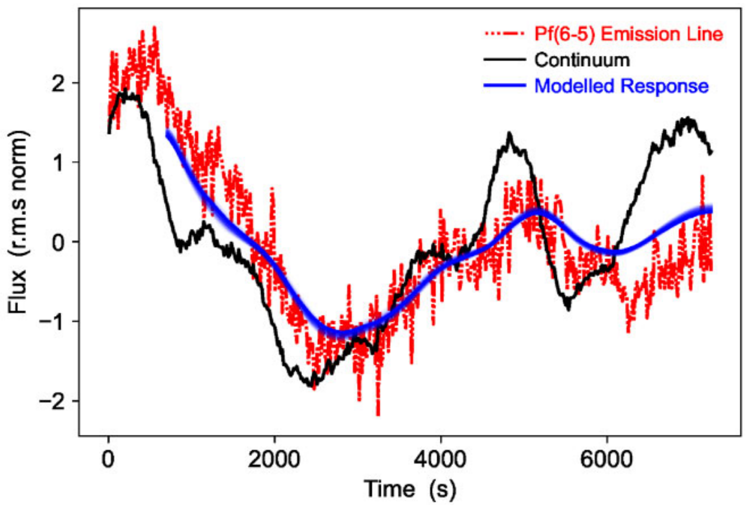




**a jet NIR delay of 0.7 sec**

# A new window: the mid-infrared

*JWST adds what no band had before: time-resolved lines*

*Gandhi+2025*




**Gandhi+2025** — GRS 1915+105 with JWST/MIRI

› The Pfund (6–5) LINE lags the continuum (~150s) — line reverberation, consistent with light travel across the outer disc or with recombination timescales.

**Gandhi+2026,** — GX 339−4 in the SOFT state

› Compact-jet MIR suppressed by ≳300× relative to the hard state — as expected.

› Yet 5–10 μm emission is detected AND variable.

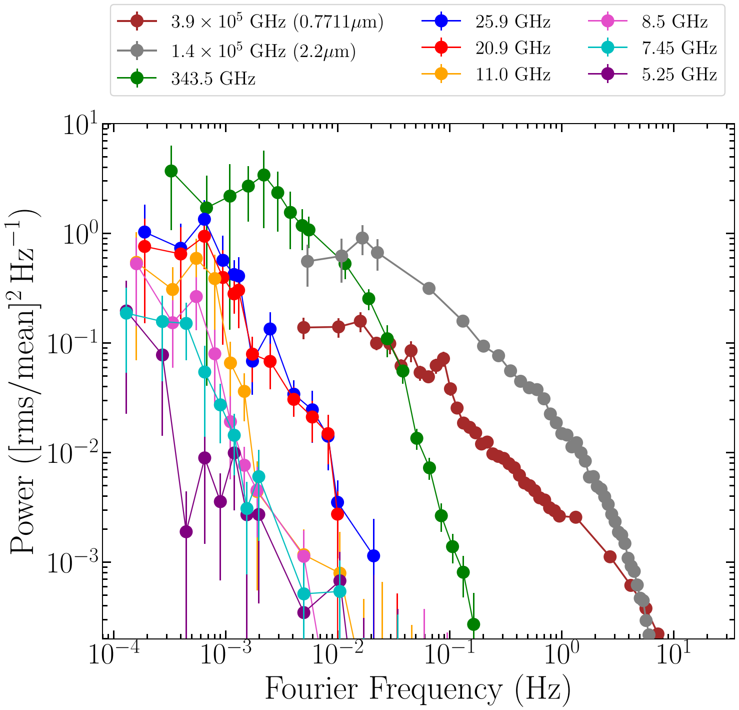
› Best explained by synchrotron from hot flow ⇒ MIR as a probe of the soft-state corona/atmosphere.

**This paper is dedicated to Tomaso's memory.**

**(2025)**

# Ten bands at once

*MAXI J1820+070, 7 hours, hard state: VLA + ALMA + VLT + NTT + NICER + XMM*



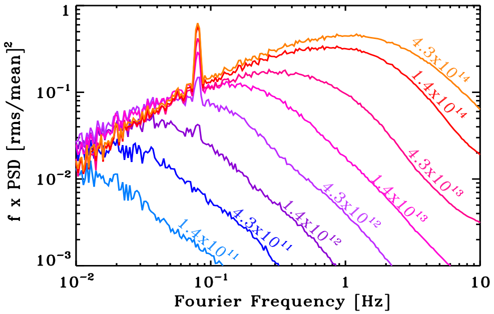

*Tetarenko+21*

Ten electromagnetic bands, strictly simultaneous, radio → X-rays.

Lags from hundreds of ms (X-ray/optical) to minutes (radio/sub-mm) — the delay ladder, measured.

Neat demonstration that the PSD evolves with wavelength.

Jet physics




*Malzac+18*

**More in Alex's talk in 15 minutes**

# The missing half: neutron stars

*4U 1728-34 , 2 hours, hard state, HAWK-I@VLT + XMM + NuSTAR*

*Vincentelli,PC+2023*

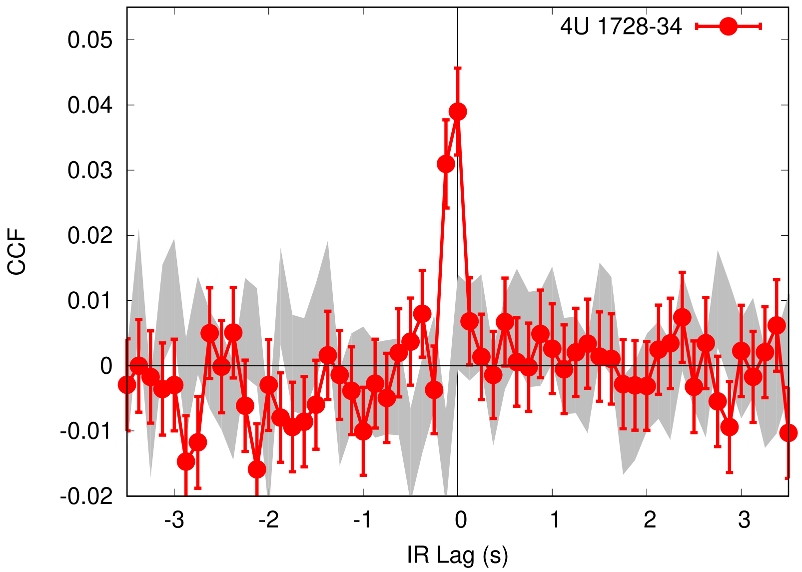
**So far only black holes.**

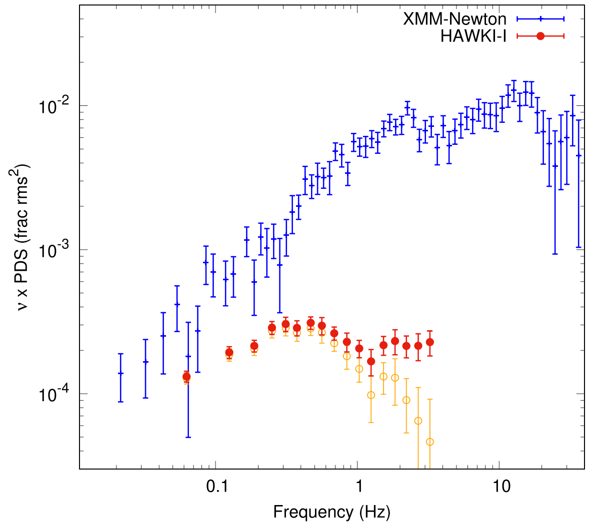
X-rays lead IR by 30-40ms

The lag increases with X-ray energy

A magnetised hot flow?

If a jet lag is present, constrained <60ms
(10ms expected from mass scaling)




**Neutron stars are feasible**
**but challenging**
**(fainter, faster)**

# Where do we stand – What do we need

**Sample size** — ~6 black holes have a proper fast O-IR/X-ray dataset, often single epochs. We are drawing population conclusions from single objects.

**Simultaneity and scheduling** — Transient sources. Oversubscription and rigid scheduling routinely lose them.

**Multi-wavelength** — Multiple O-IR bands are key. More telescopes → more jeopardy.
We need fast instruments instruments with multiple bands from IR to optical

**Time resolution** — Neutron stars need 100–1000 Hz. The optical reaches (tens of) ms, near-IR does not. Southern IR imaging: ~0.125 s.

**Detectors** — Currently read-noise and integration-time limited in O-IR. We need true photon-counting arrays with µs time-tagging and effectively zero read noise. Like X-ray astronomy since the 70s.

*Vincentelli,PC+25 — ESO white paper, "Expanding Horizons: Transforming Astronomy in the 2040s".*

# Coming up: eSiFAP@TNG (4-m class)

Extended SiFAP2@TNG, including:

Instrument PI:

F. Ambrosino (INAF – OA-Roma)

many involved in (and some outside) OA-Roma

Simultaneous opt/nIR photometry (ugriJH filters) at microsecond speed

Aperture photometry with opt/nIR cameras at sub-millisecond speed

Linear fast optical polarimetry
(4 simultaneous Stokes parameters)

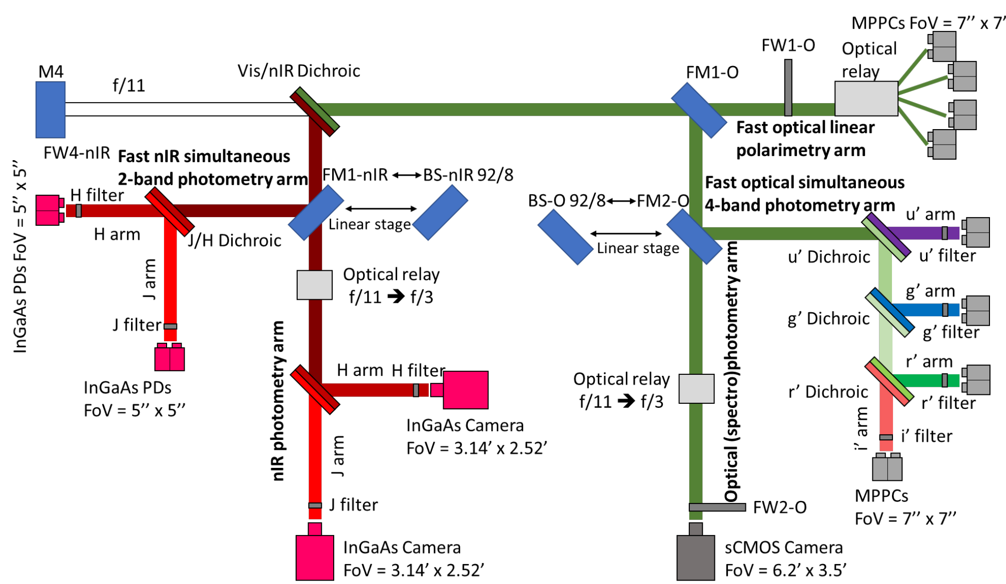
Better than 100ns absolute time accuracy

**Timing/spatial specs for cameras (Vis/nIR)**

- 120 fps full frame, 0.3 e$^-$ read-out noise, int. time 7 us – 1800 s (Vis)
- FoV: 6.2’ x 3.5’ (Vis)
- 600 fps full frame, <20 e$^-$ read-out noise, int. time 100 ns – 1800 s (nIR)
- FoV: 3.14’ x 2.52’ (nIR)

**Timing/spatial specs for fast sensors (Vis/nIR)**

- 5 ps relative time resolution (Vis)
- FoV: 7’’ x 7’’ (Vis)
- 200 ns (TBC) relative time resolution (nIR)
- FoV: 5’’ x 5’’ (nIR)



# Coming up: eSiFAP@TNG (4-m class)

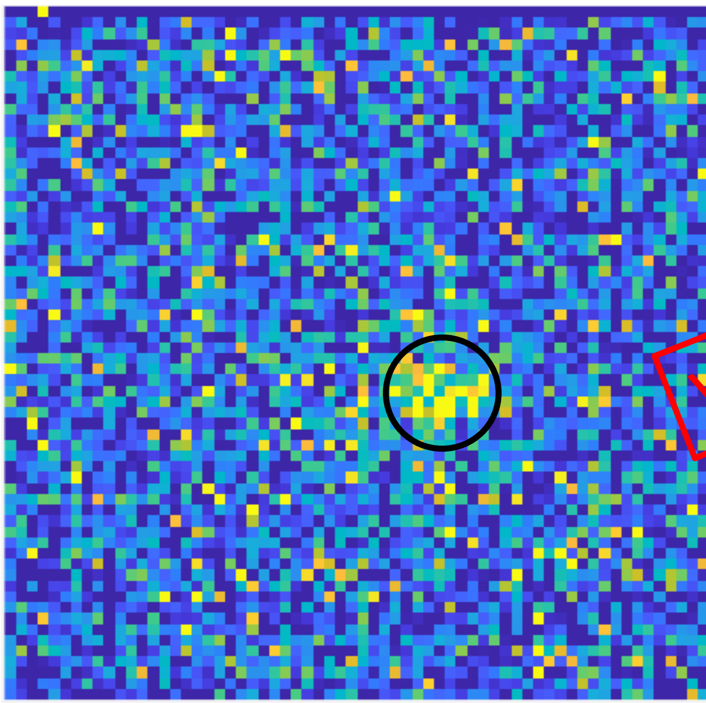
Instrument PI:

F. Ambrosino (INAF – OA-Roma)

many involved in (and some outside) OA-Roma

First tests performed with a sub-system:

- 1 MPPC (80 ns, time tag) + J camera (10 ms)
- April 21st 2026
- Her X-1 (1.24 spin, J ~ 14)



Sum of 2000 J images – 20 seconds total

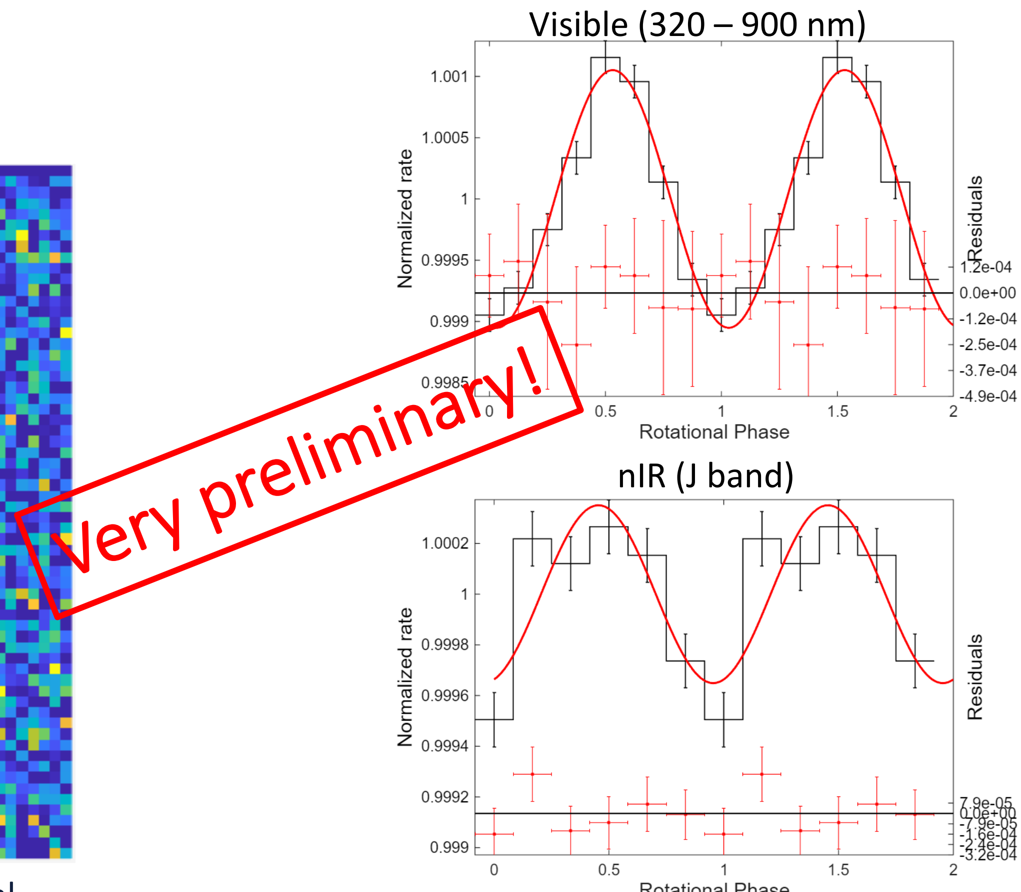


*photo by M. del Santo*

**Tomaso taught a generation of us that a light curve is a measurement, not a picture**

**We are taking that seriously at other wavelengths**

**Grazie**