Multi-Wavelength Timing Properties (Observations)

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IUCAA

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Science & Technology Facilities Council

Farewell:

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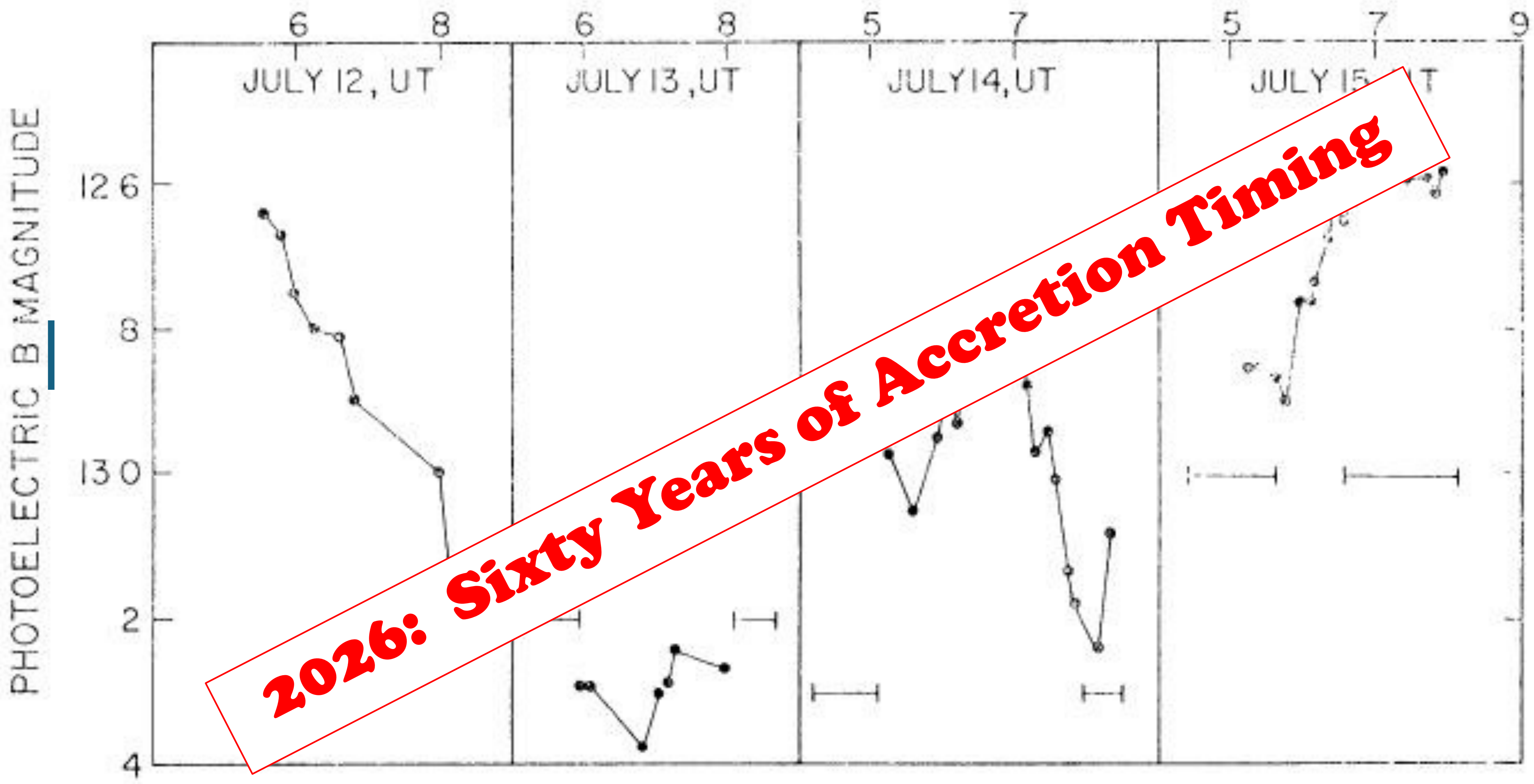
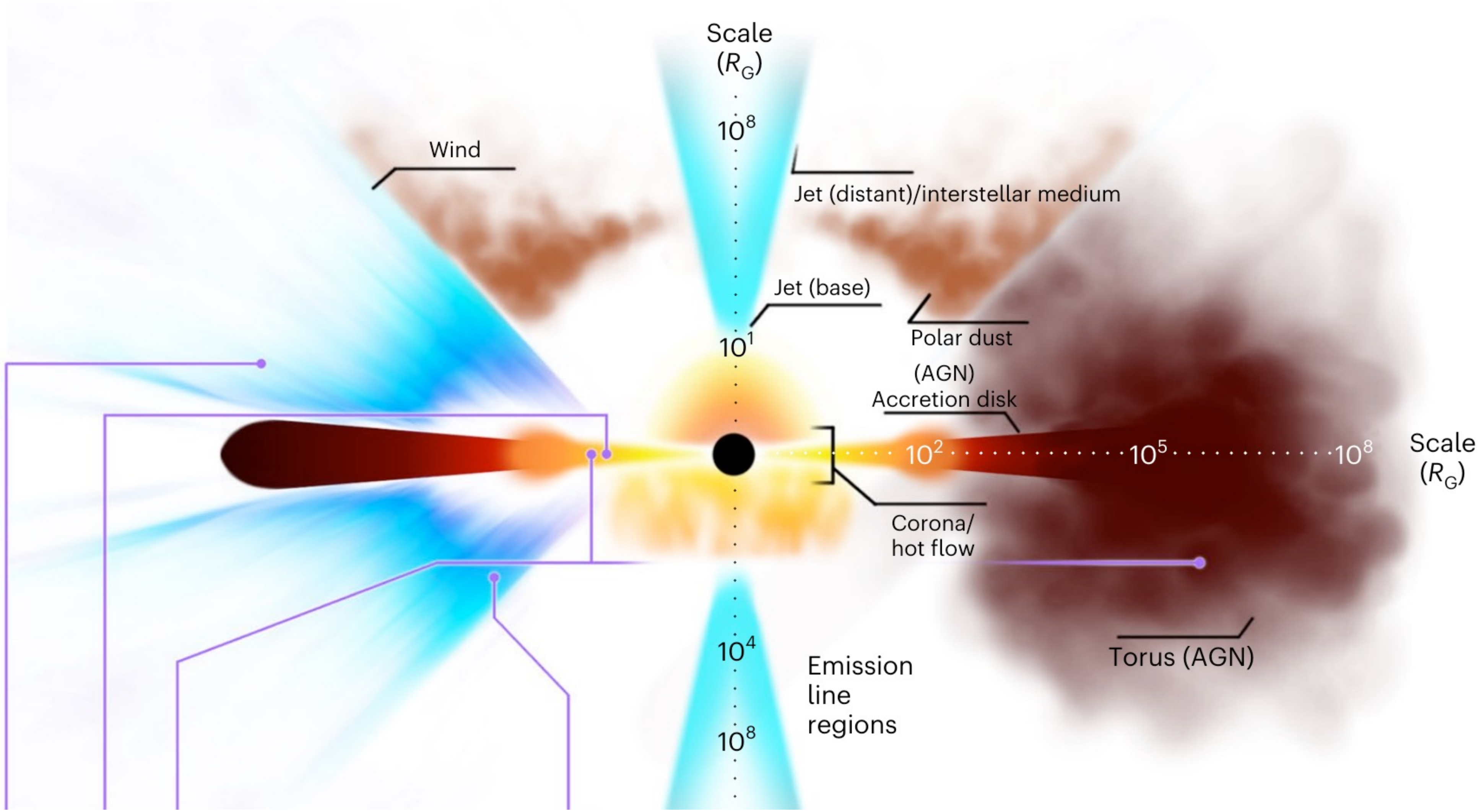
Tomaso Belloni

Name the source



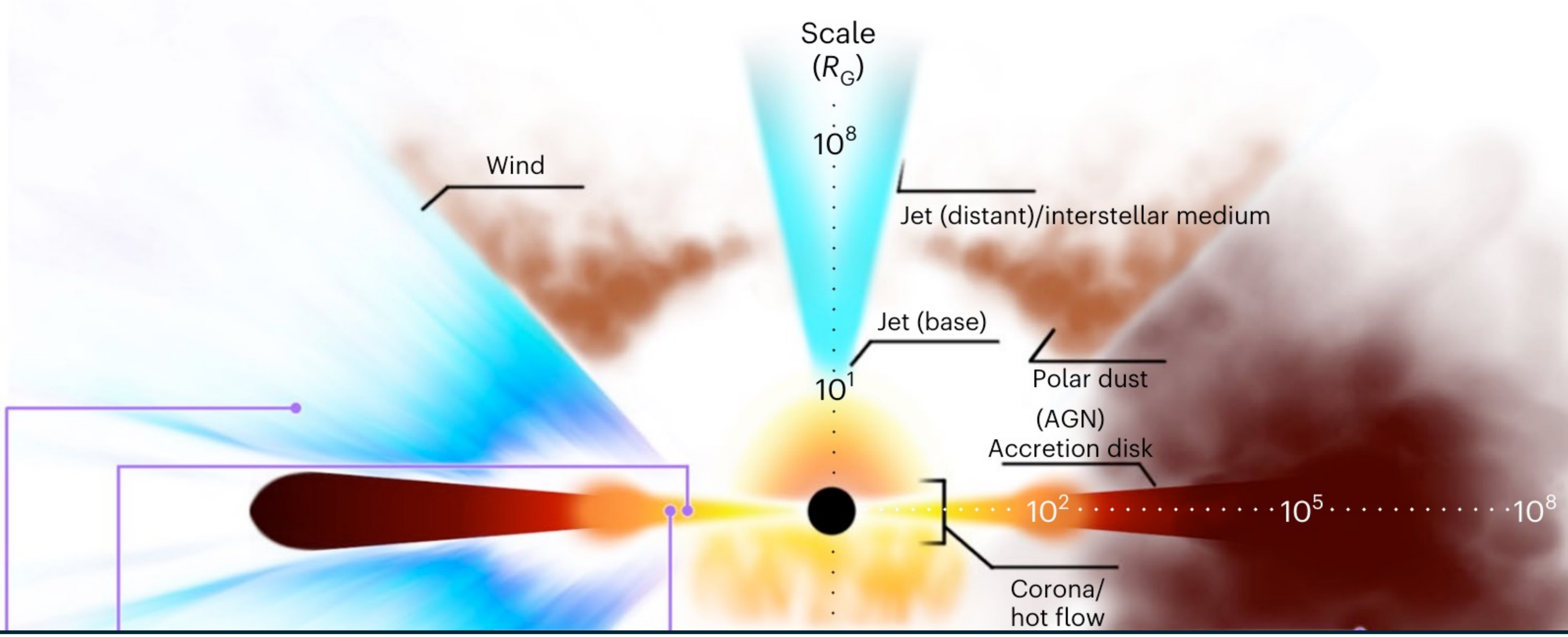
(Sandage et al. 1966)

Timing constrains geometry and causal relationships



(Gandhi et al. 2022)

Timing constrains geometry and causal relationships



Disc timescales:

$$t_{\text{light-cross}} < t_{\text{dyn}} \sim t_z \sim \alpha t_{\text{th}} \sim v t_{\text{ejec}} \sim \alpha (\text{H/R})^2 t_{\text{visc}}$$

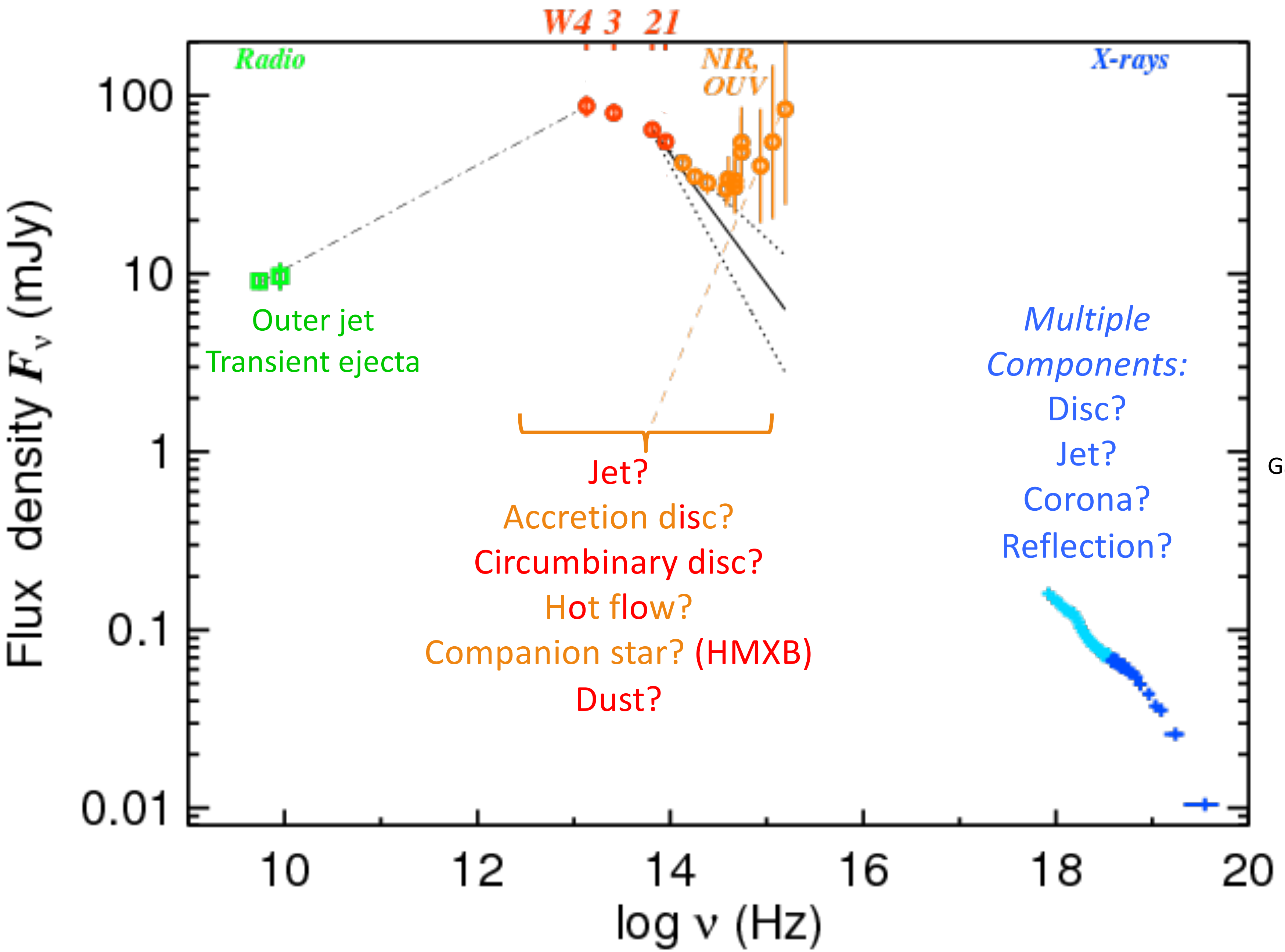
ms ~ few seconds

seconds ~ days

days ~ months

(e.g. Frank, King & Raine)

Timing provides key discriminating power

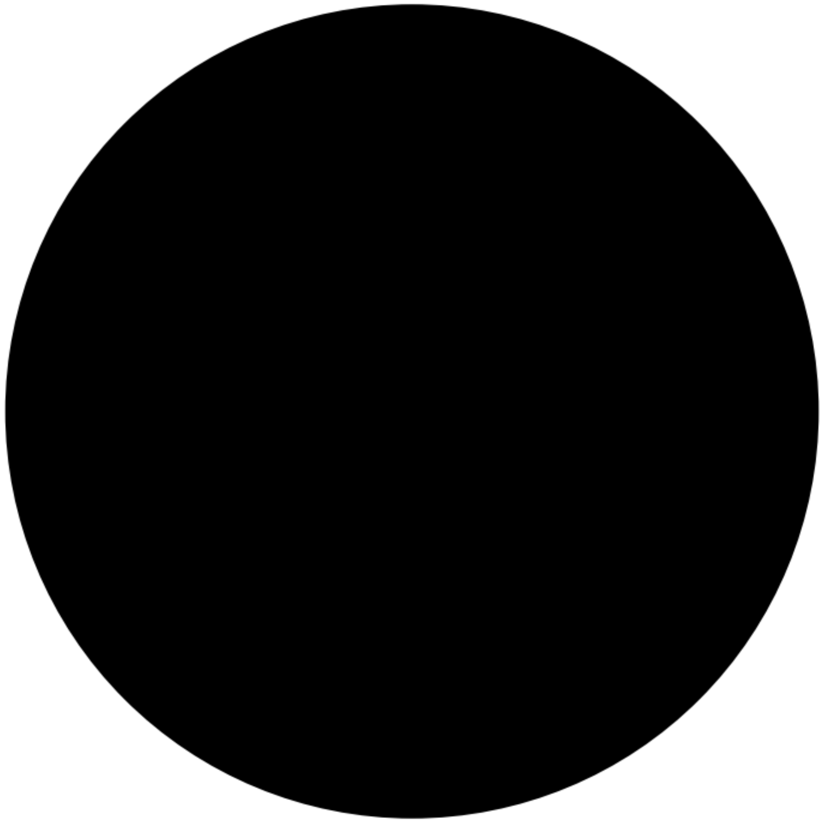


+
Gamma-rays
...

GX 339-4: 2010 hard state

In-situ experiments with a (new) microquasar??

- ‘Planet IX’ – a primordial BH and the first MQ created by humanity?



(Scholtz & Unwin 2020)

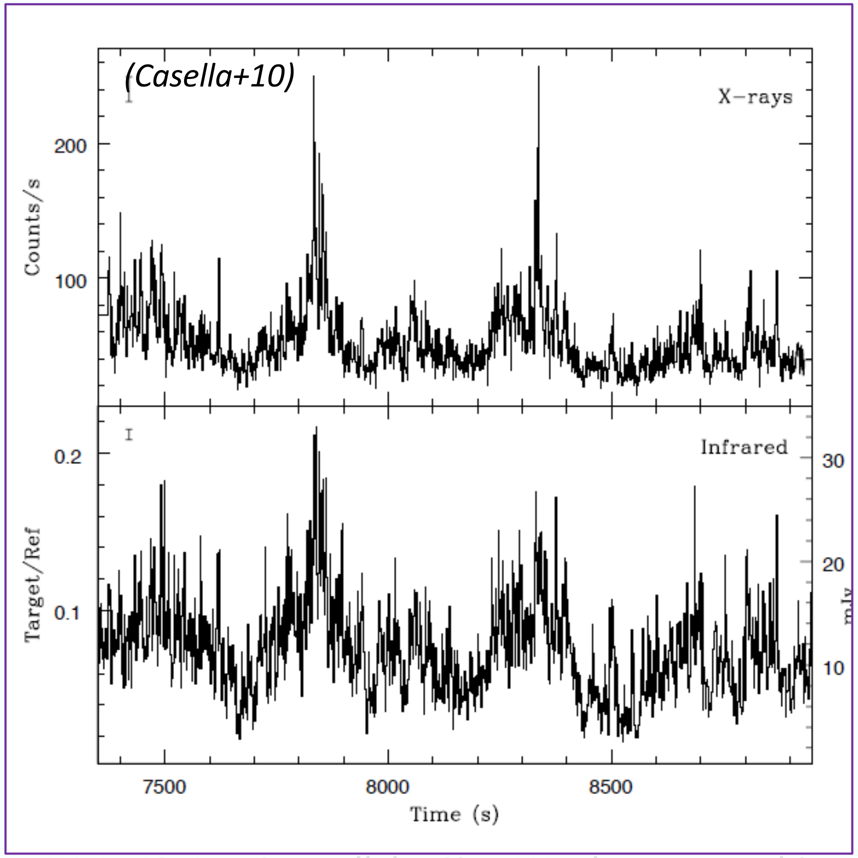
FIG. 1. Exact scale (1:1) illustration of a $5M_{\oplus}$ PBH. Note that a $10M_{\oplus}$ PBH is roughly the size of a ten pin bowling ball.

Multi-Wavelength Timing Properties (Observations)

- **Disentangling multiple components using timing**
  - Review and Hard State Inner Jets
  - New: Extending this to Quiescence and the Soft State

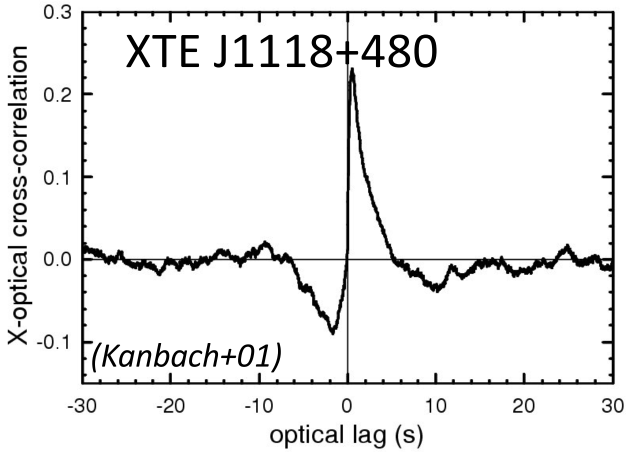
- **New parameter space for expanding the census of XRBs**
  - How can we bring out the next transformational advances in the field?

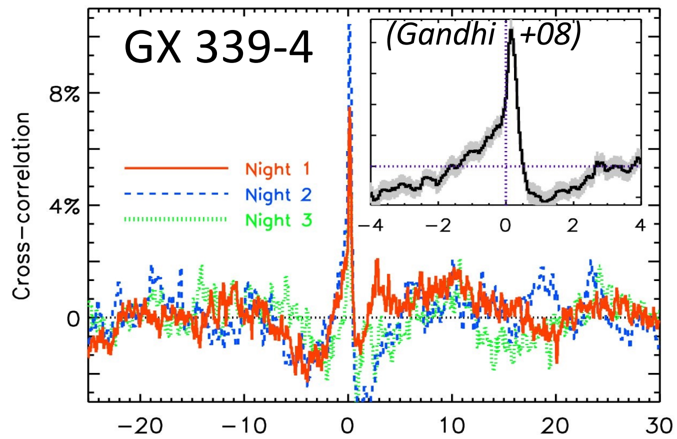
Fast timing signatures in joint BH OIR/X-ray light curves

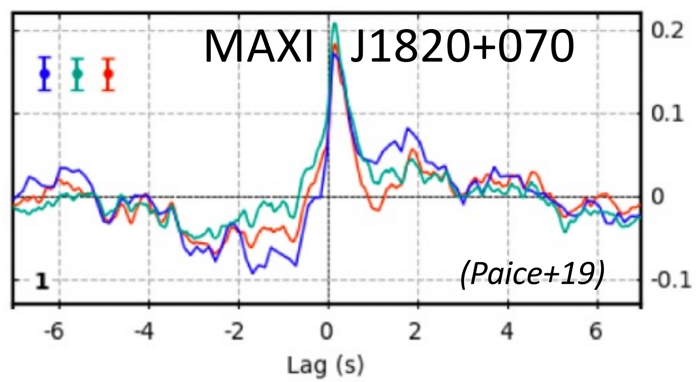


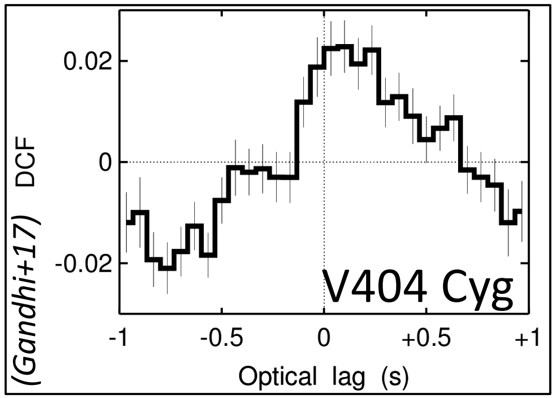
4U 1543-475 See talk by Sian Woahene-Demehin

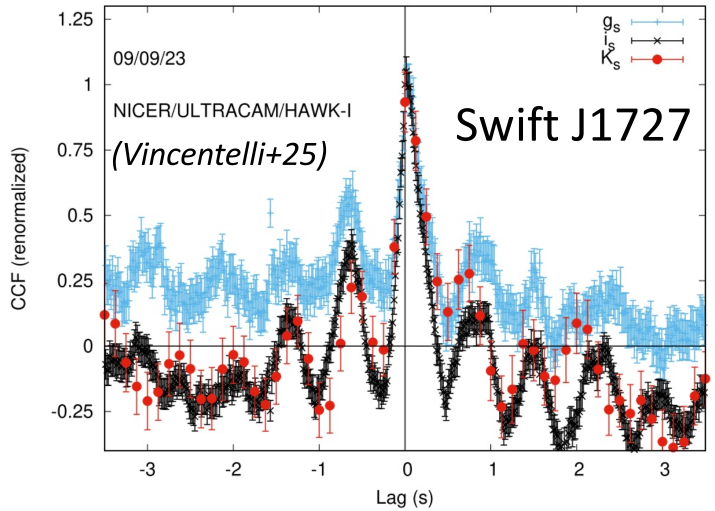
Fast timing signatures in joint BH OIR/X-ray light curves

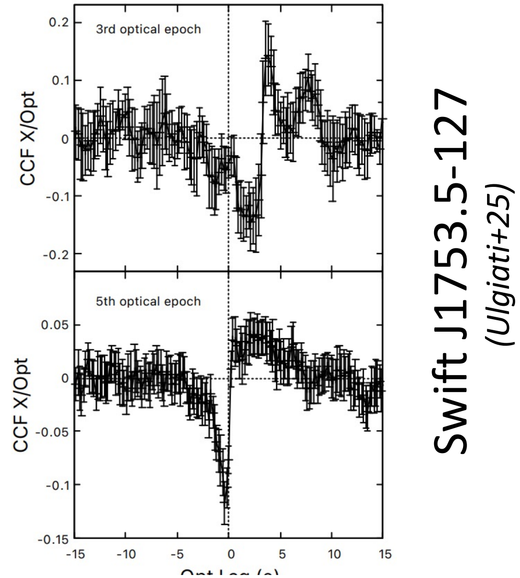


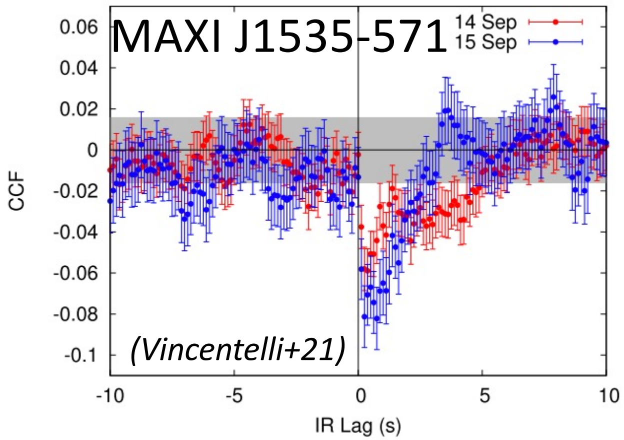


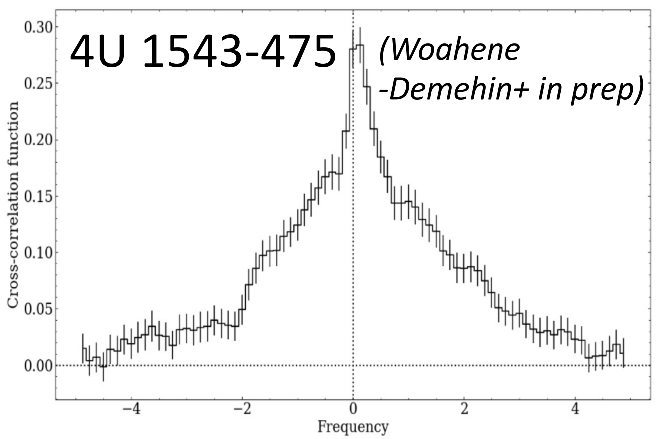


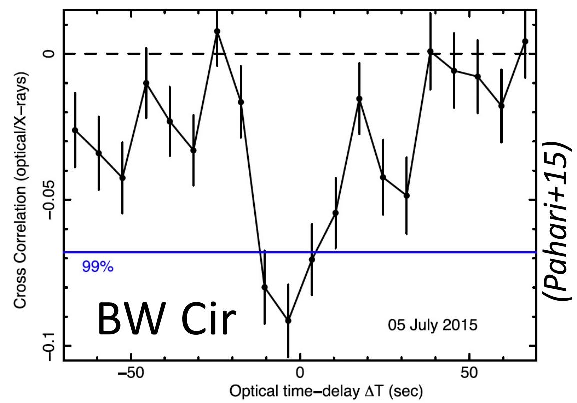












Optical/X-ray coherence and lags

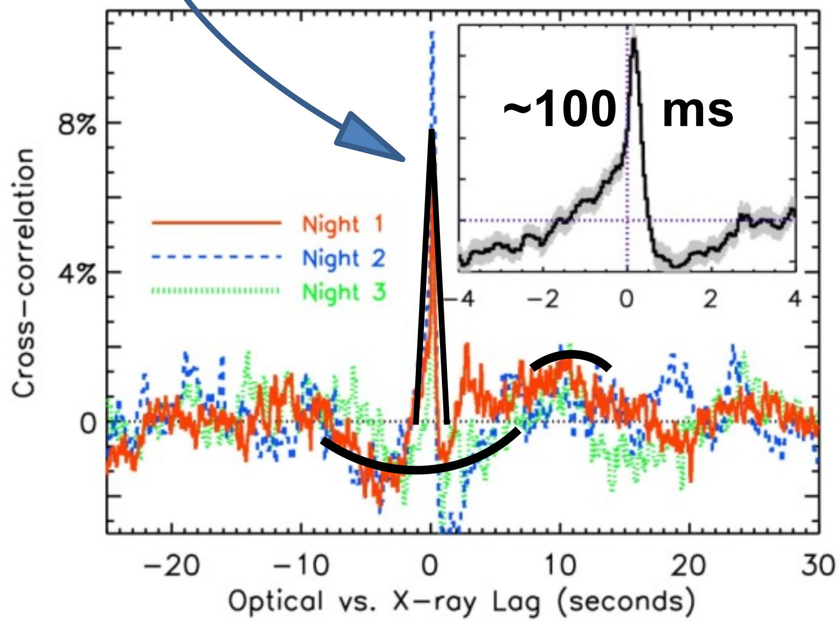
$$\text{Coherence} = \frac{|\langle X^* O\rangle|^2}{\langle|X^2|\rangle\langle|O^2|\rangle}$$

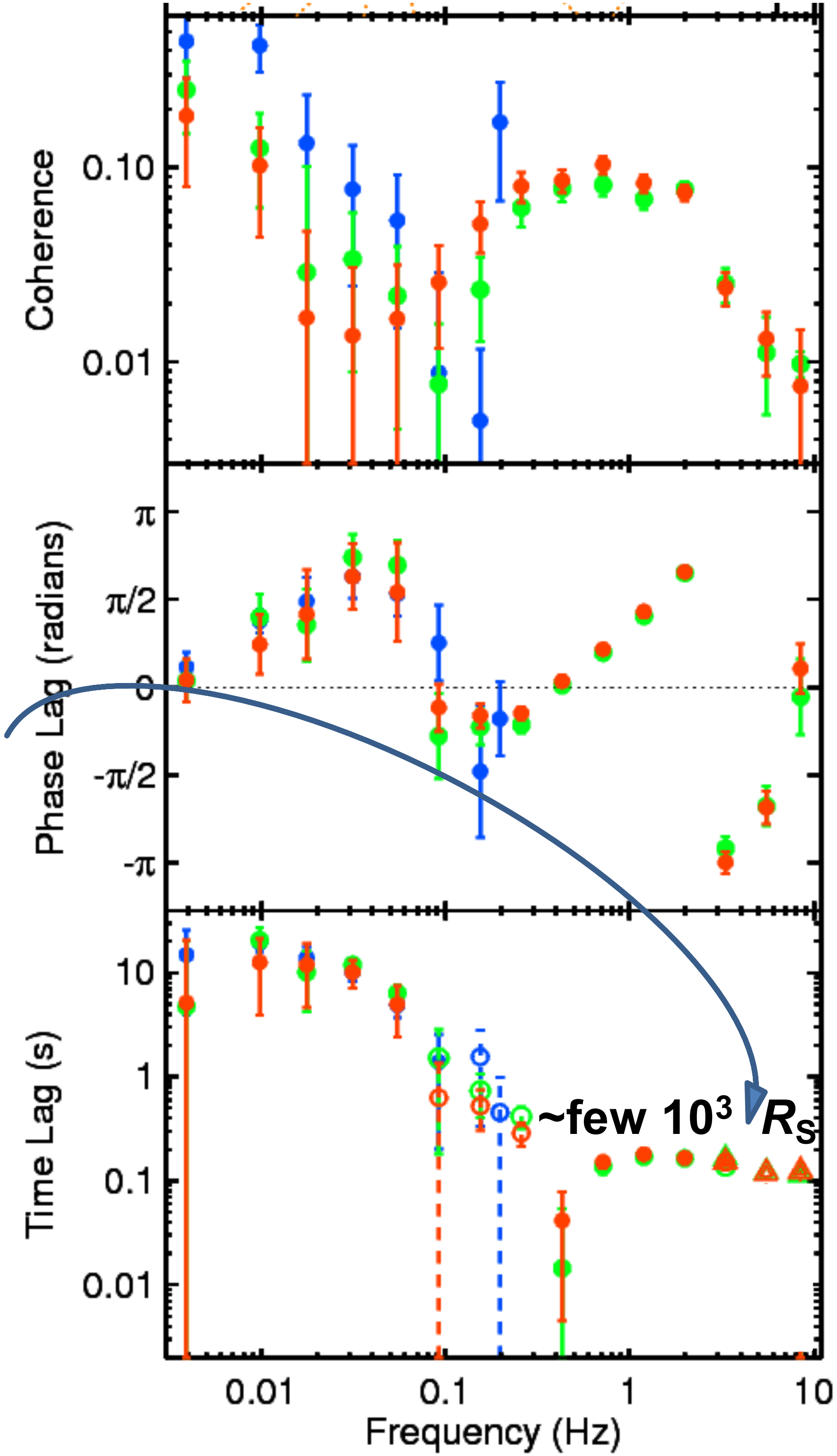
$$\text{Phase lag} = \arg(X^* O)$$

$$\text{Time lag} = \frac{\text{Phase lag}}{2\pi f}$$

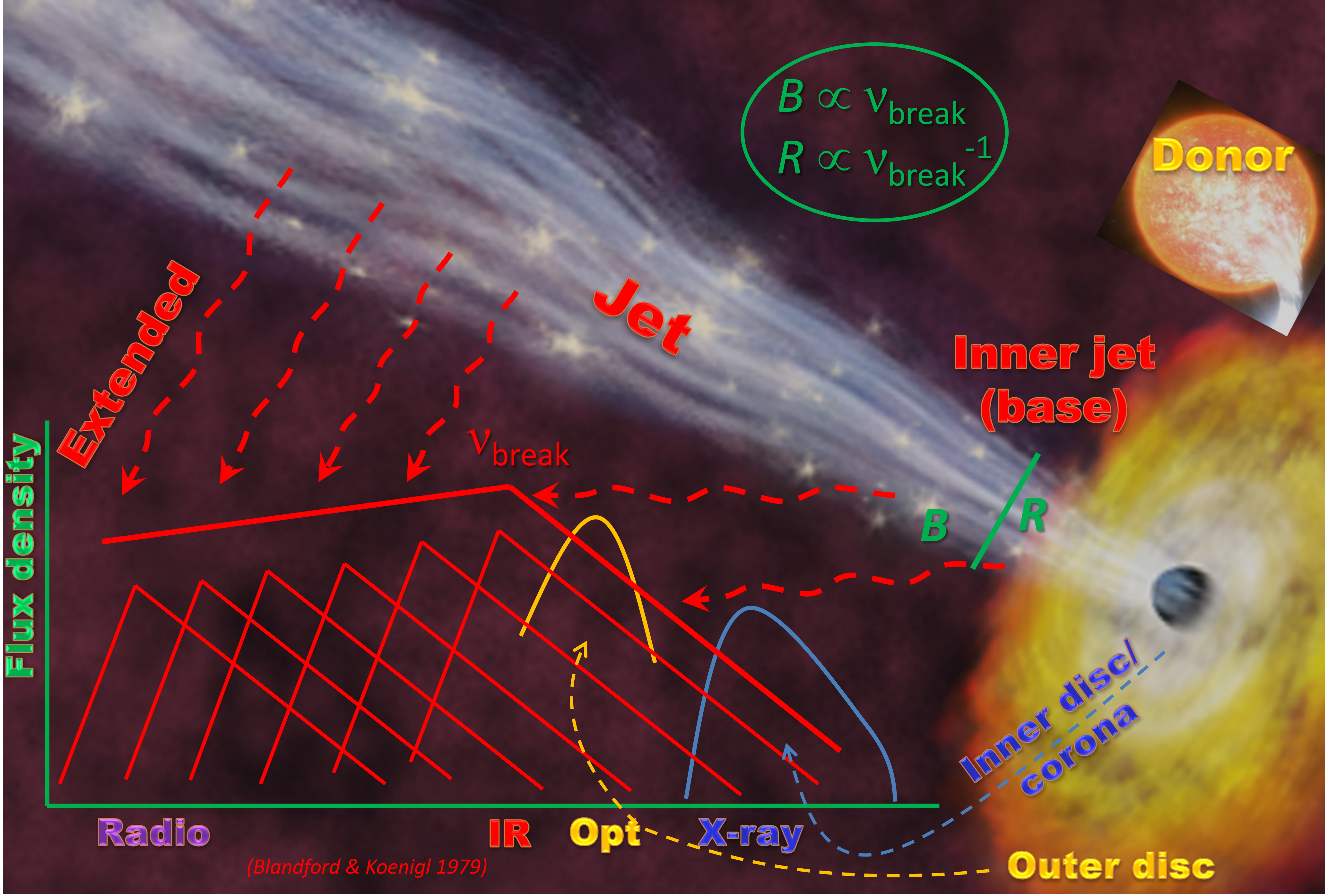
GX 339-4
(Gandhi+ 2010)

Fast component

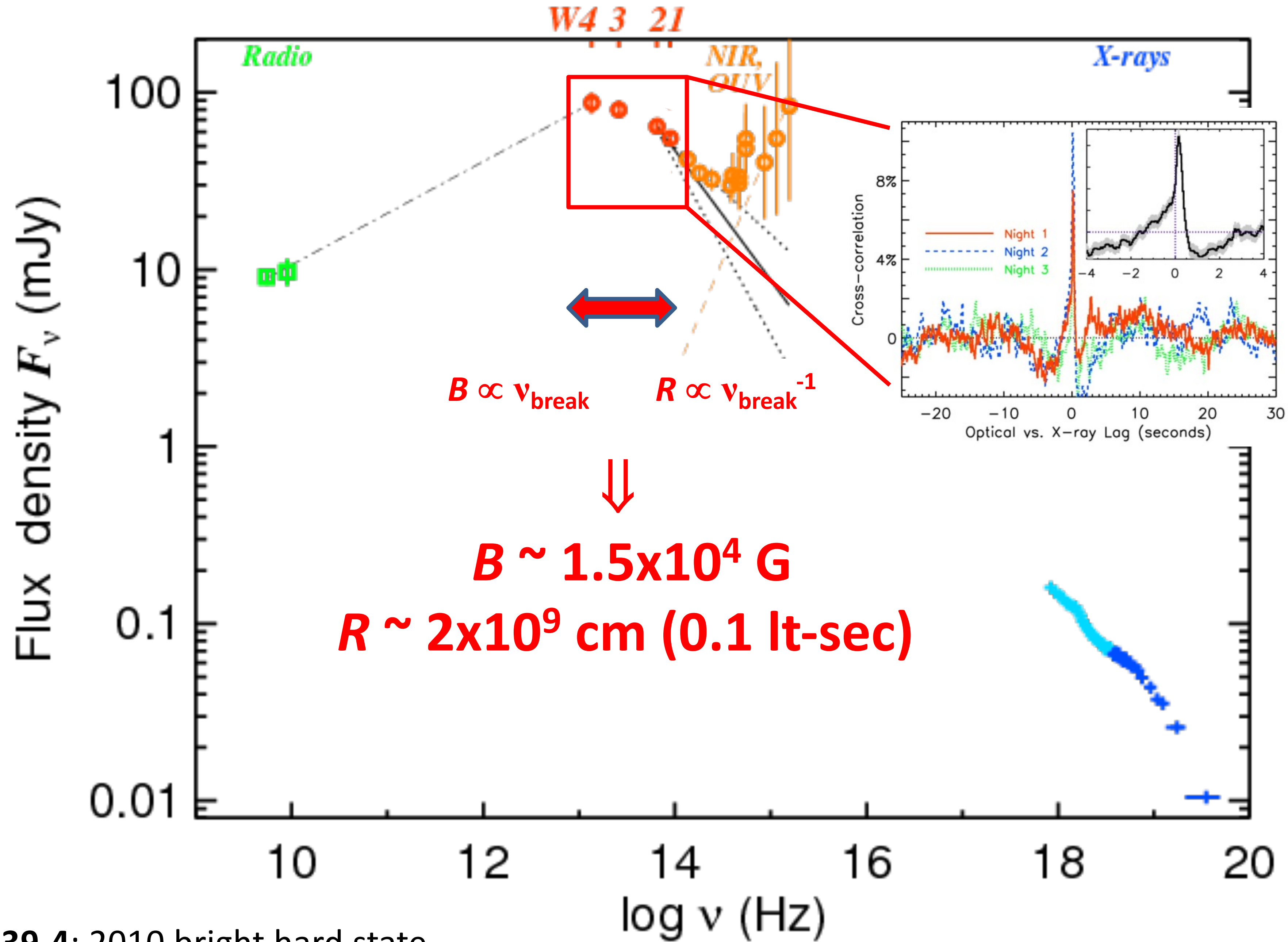




Synchrotron break constrains inner jet



Fast timing and Spectral break are self-consistent



B $\propto \nu_{break}$ *R* $\propto \nu_{break}^{-1}$

$\Downarrow$

B ~ 1.5x10^4 G

R ~ 2x10^9 cm (0.1 lt-sec)

Corbel et al. 2002, Gandhi et al. 2011,D. Russell et al. 2013, T. Russell et al. 2014, Tetarenko et al. 2020, 2021, Echiburu-Trujillo+24…

GX 339-4: 2010 bright hard state

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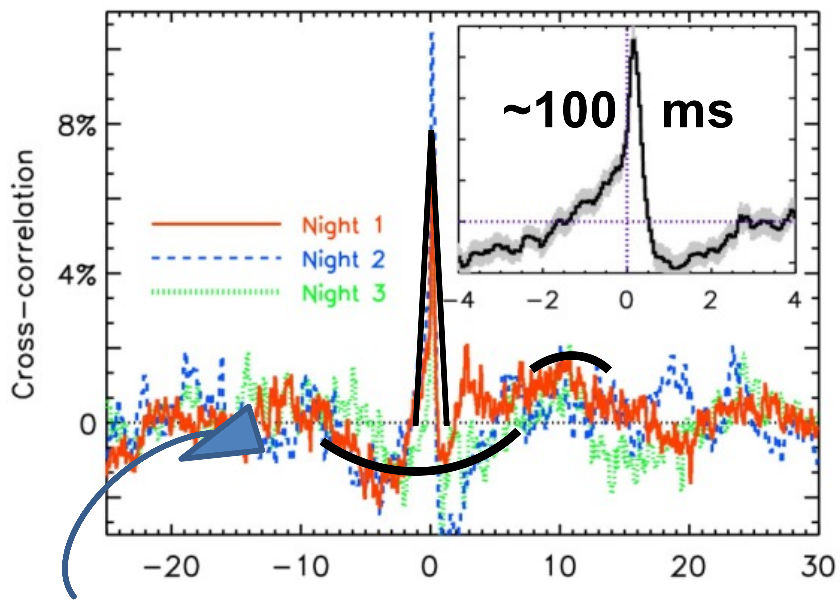

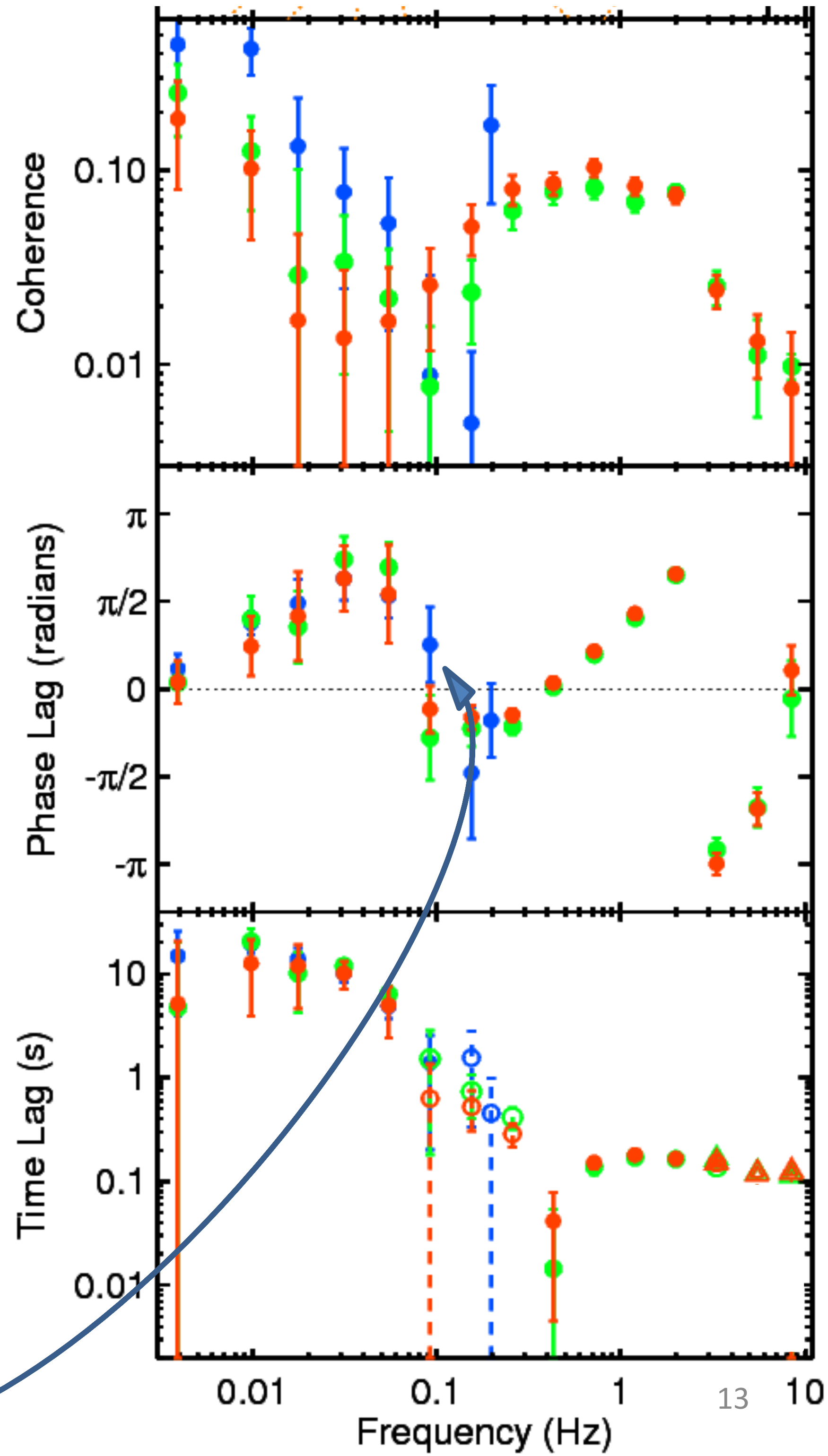

Intermediate anti-corr. component

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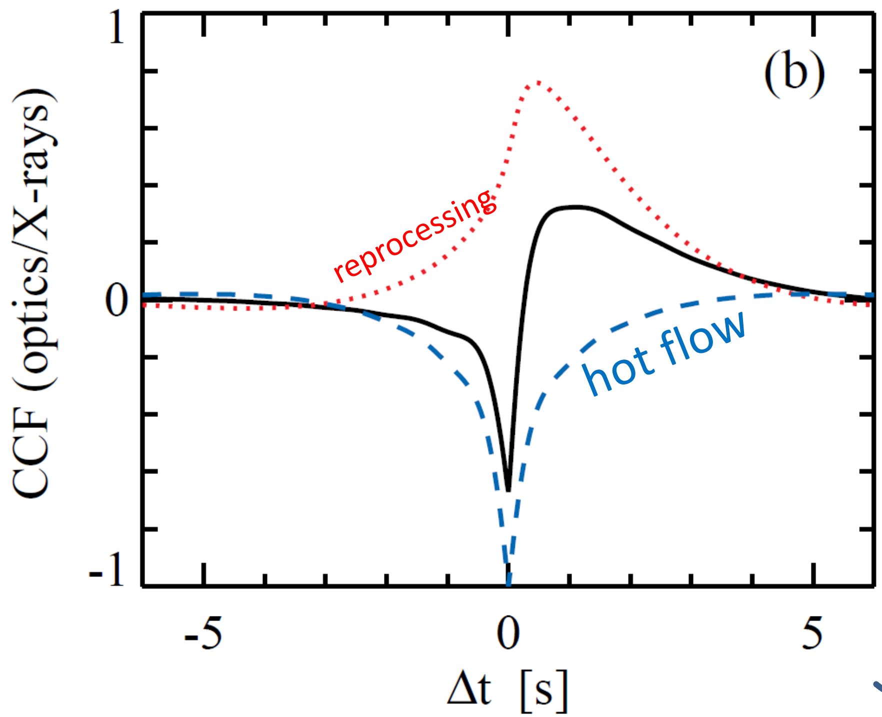
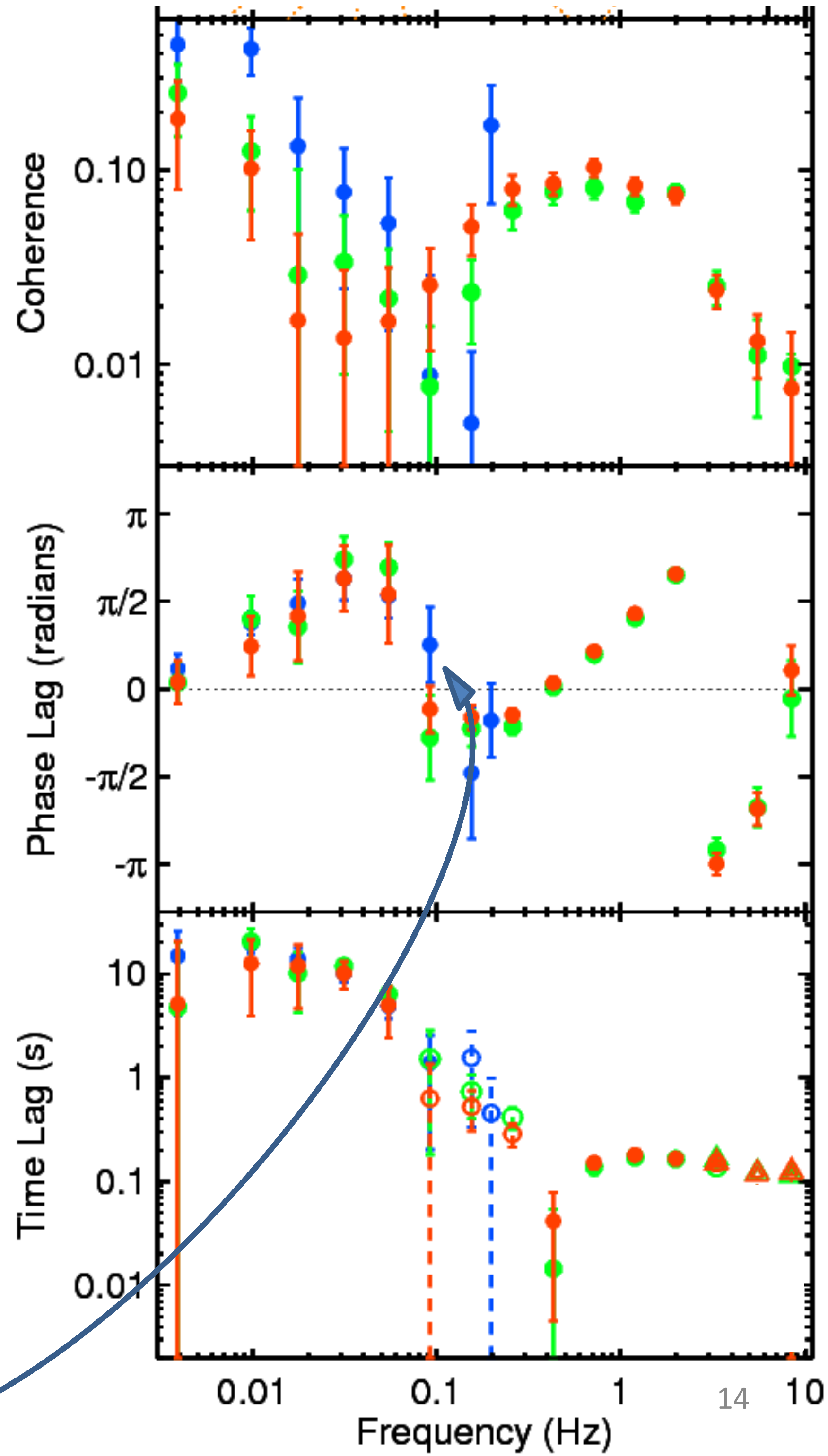
Veledina+11:
Synchrotron Self-Compton Hot Flow





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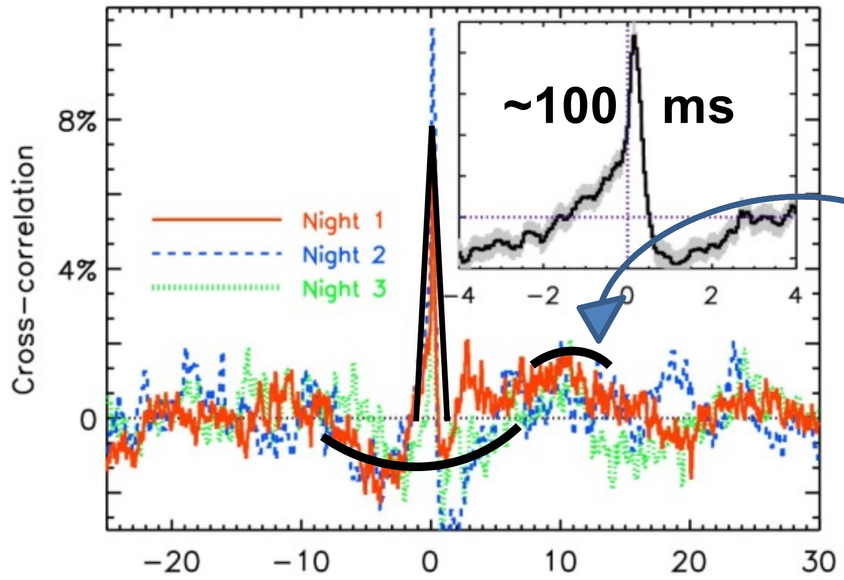
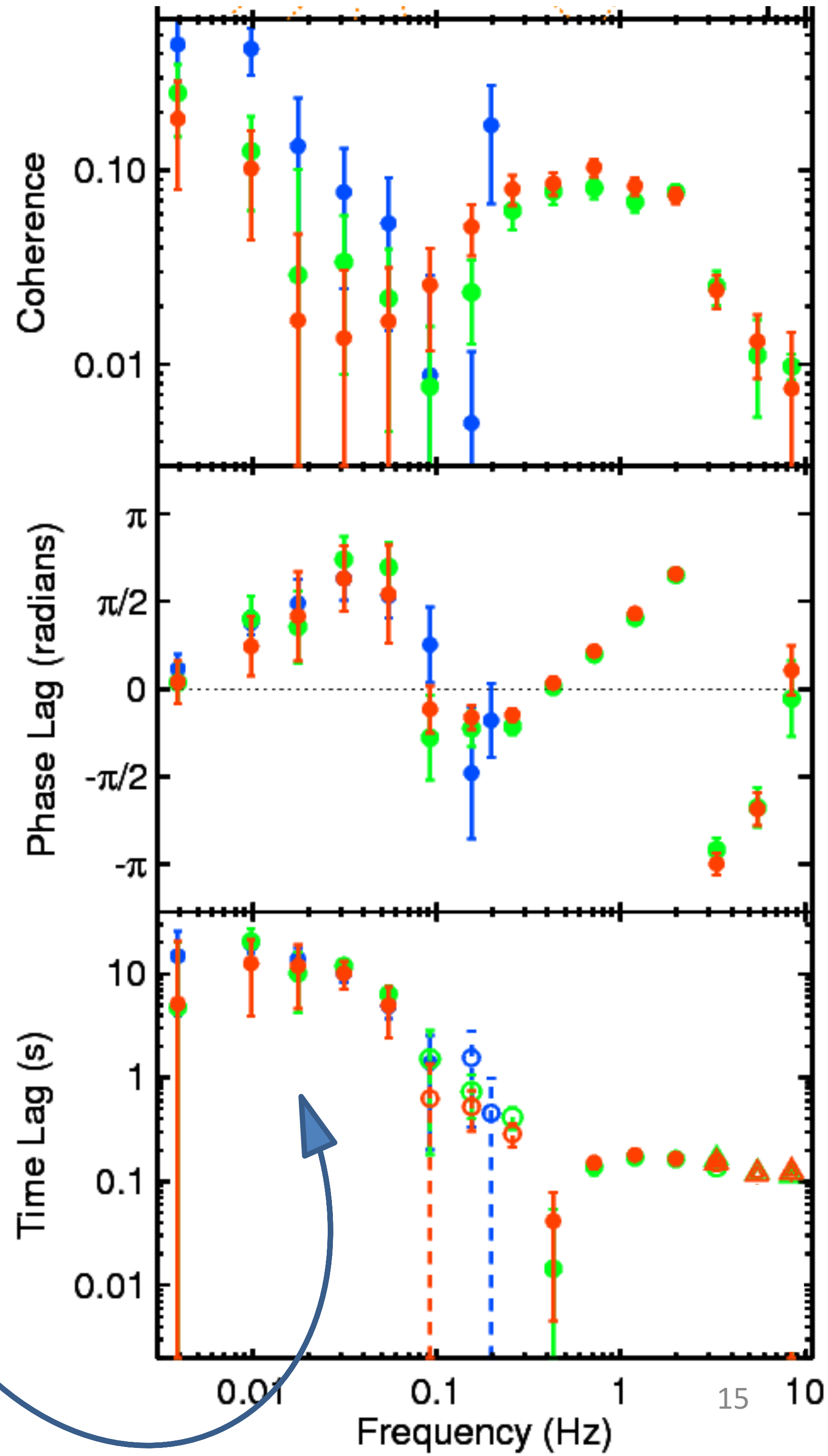
GX 339-4
(Gandhi+ 2010)

Fast component



Slow

Intermediate negative component



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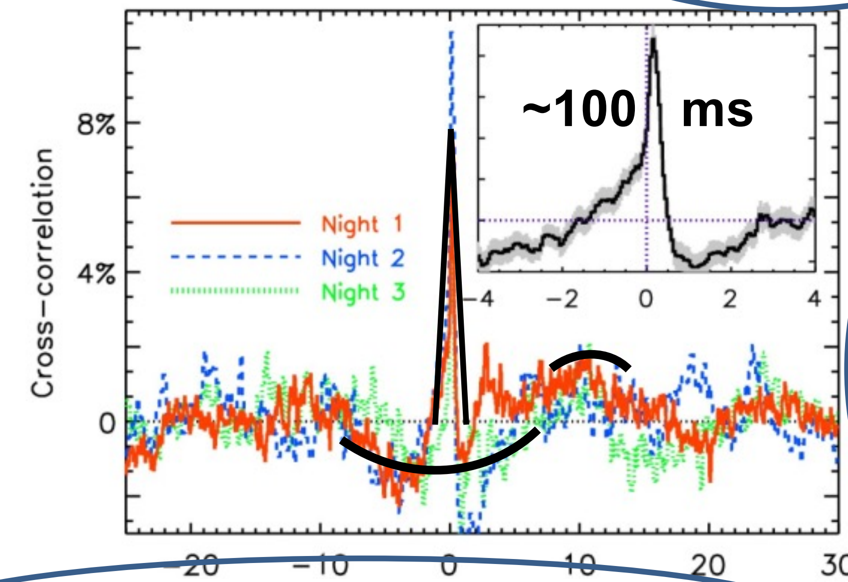
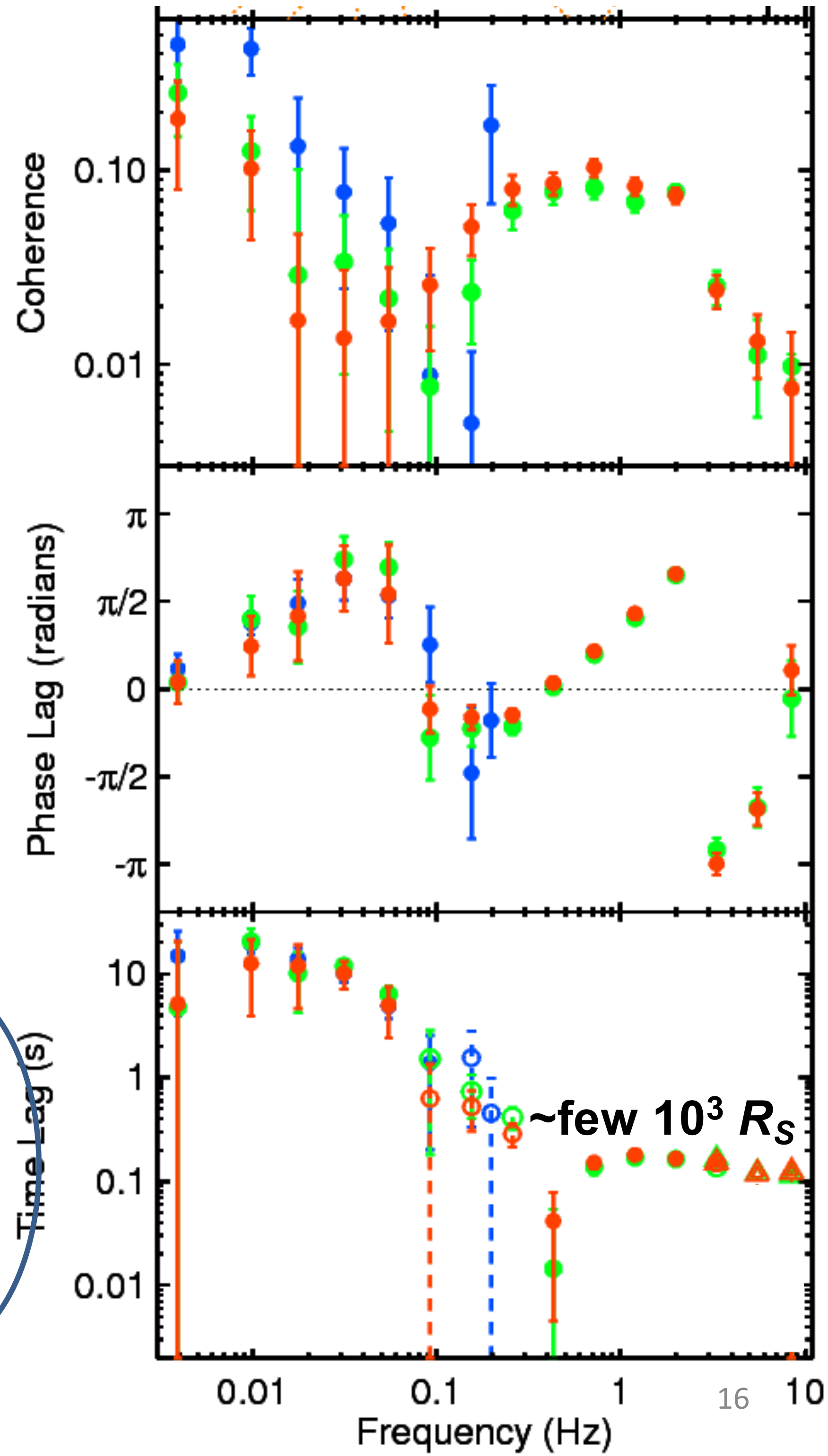
GX 339-4
(Gandhi+ 2010)

Jet $\Rightarrow$ Fast component

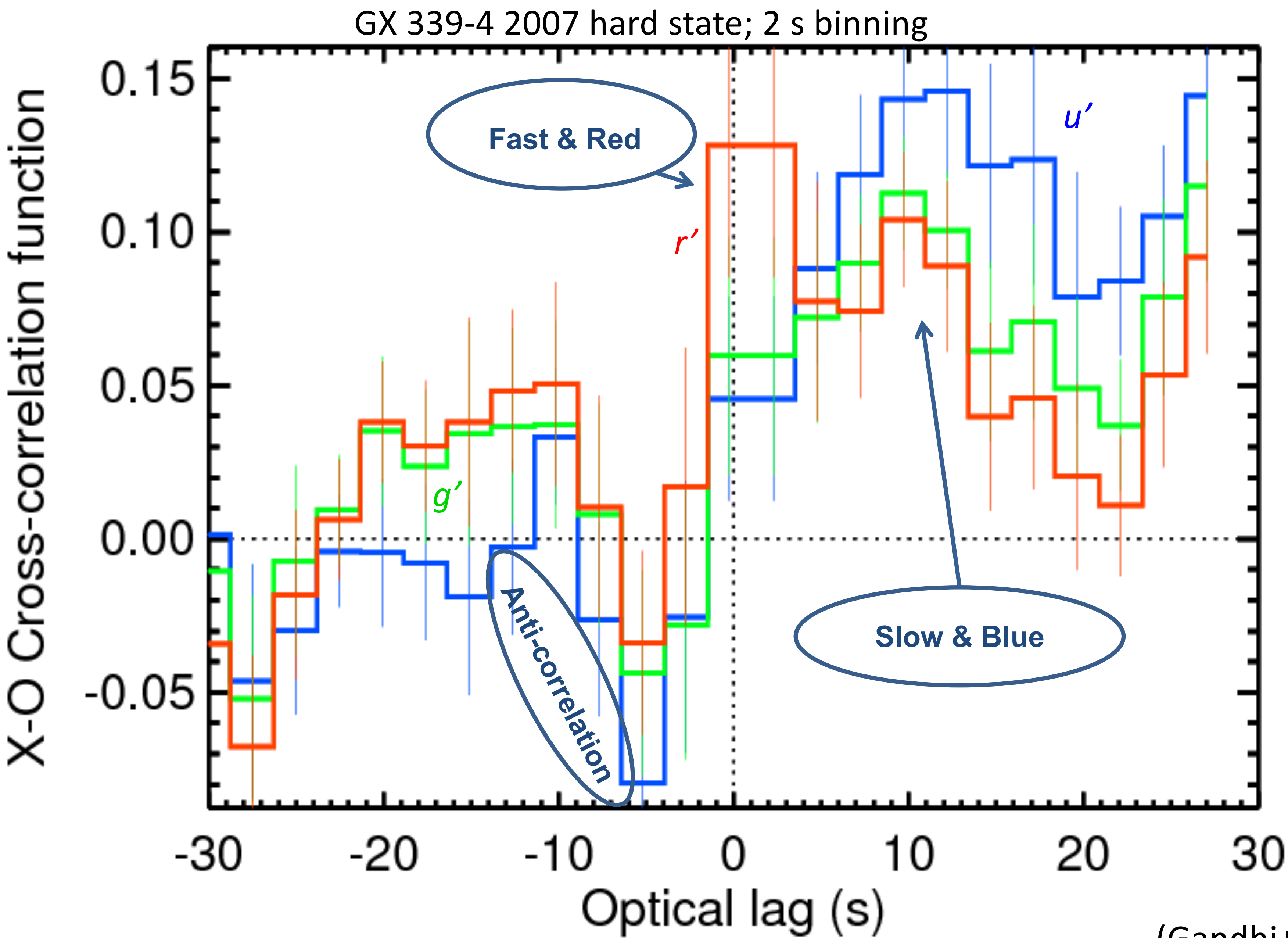


Slow $\Rightarrow$ reprocessing

Hot flow $\Rightarrow$ Negative component

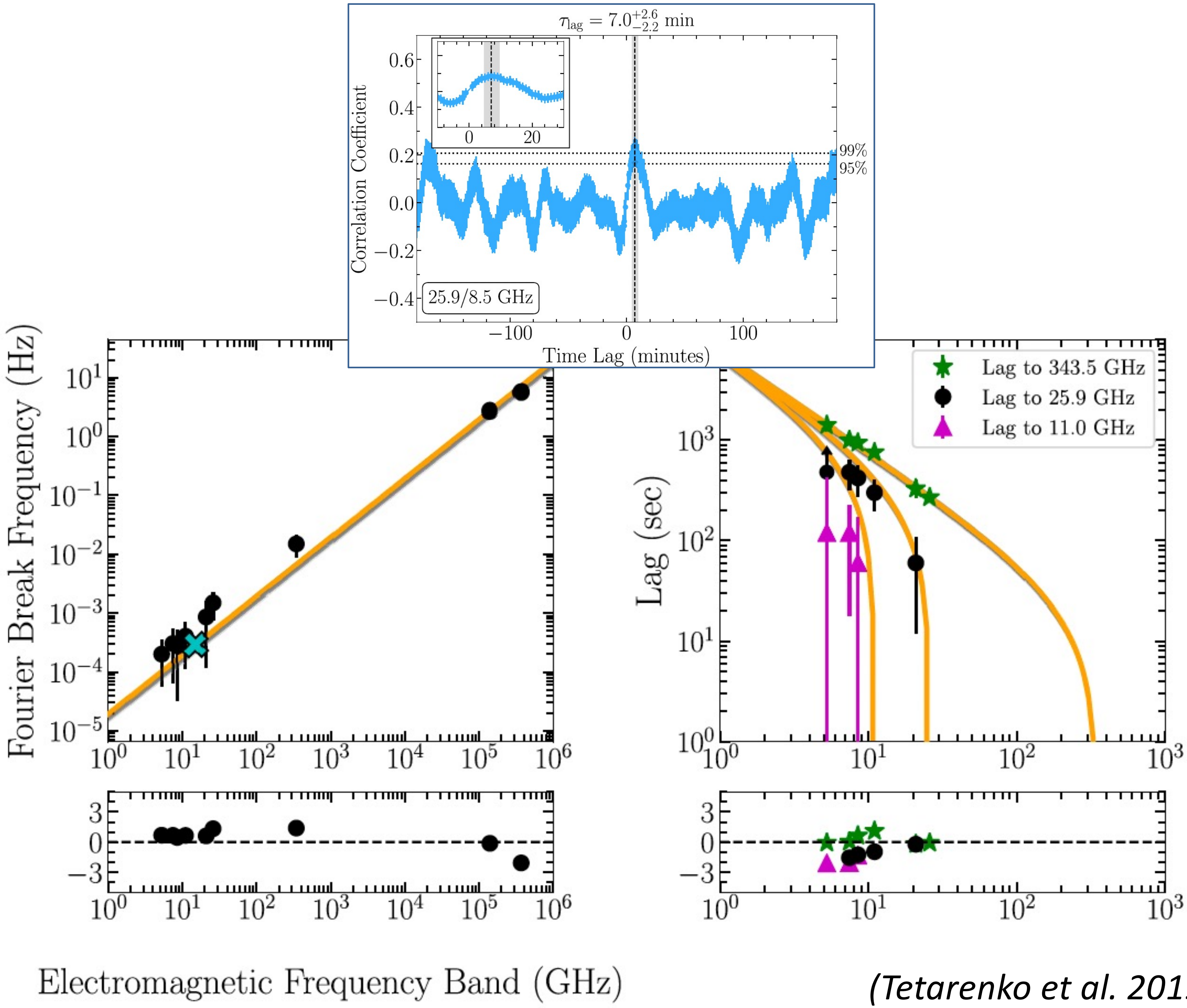


Separating timing with spectral colour



(Gandhi+ 2010)

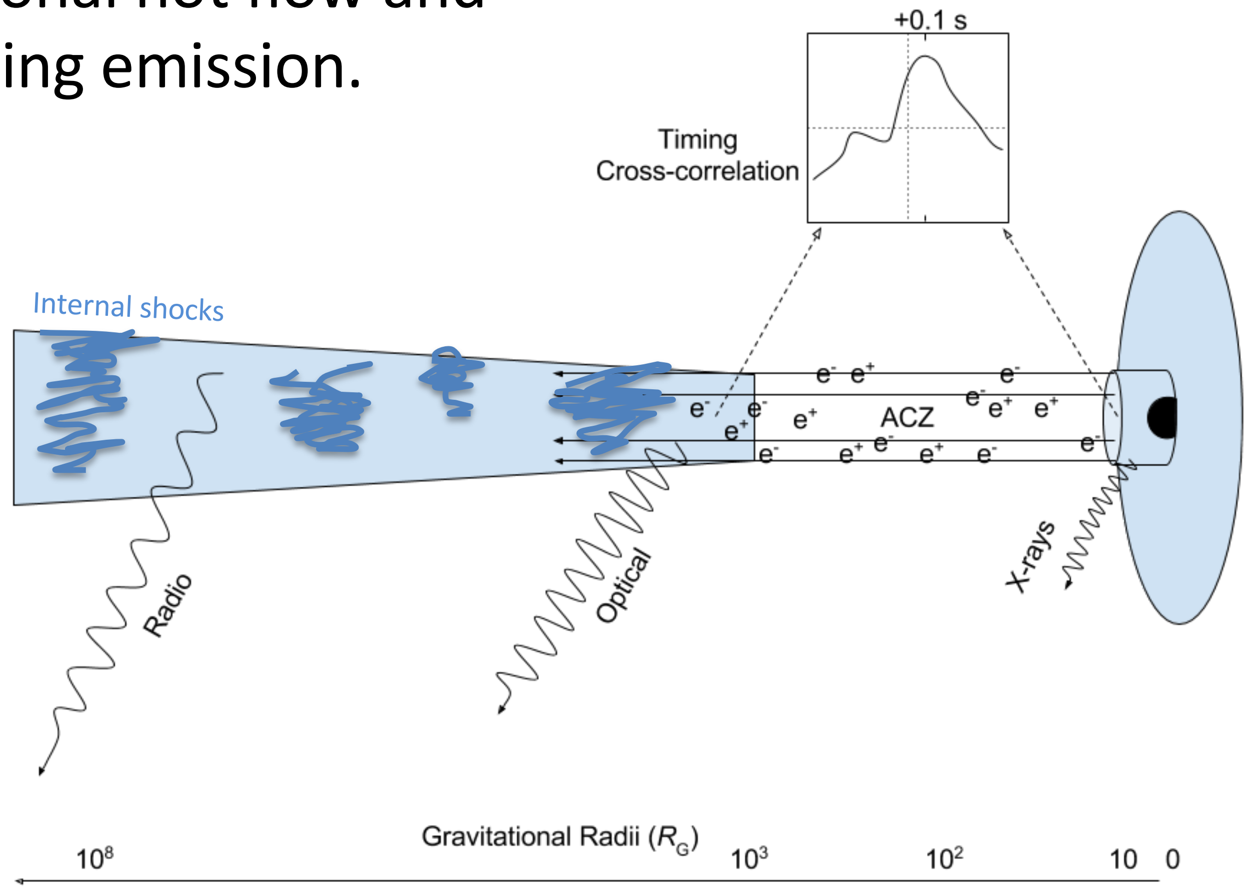
Separating timing with spectral colour



(Tetarenko et al. 2019, 2021)

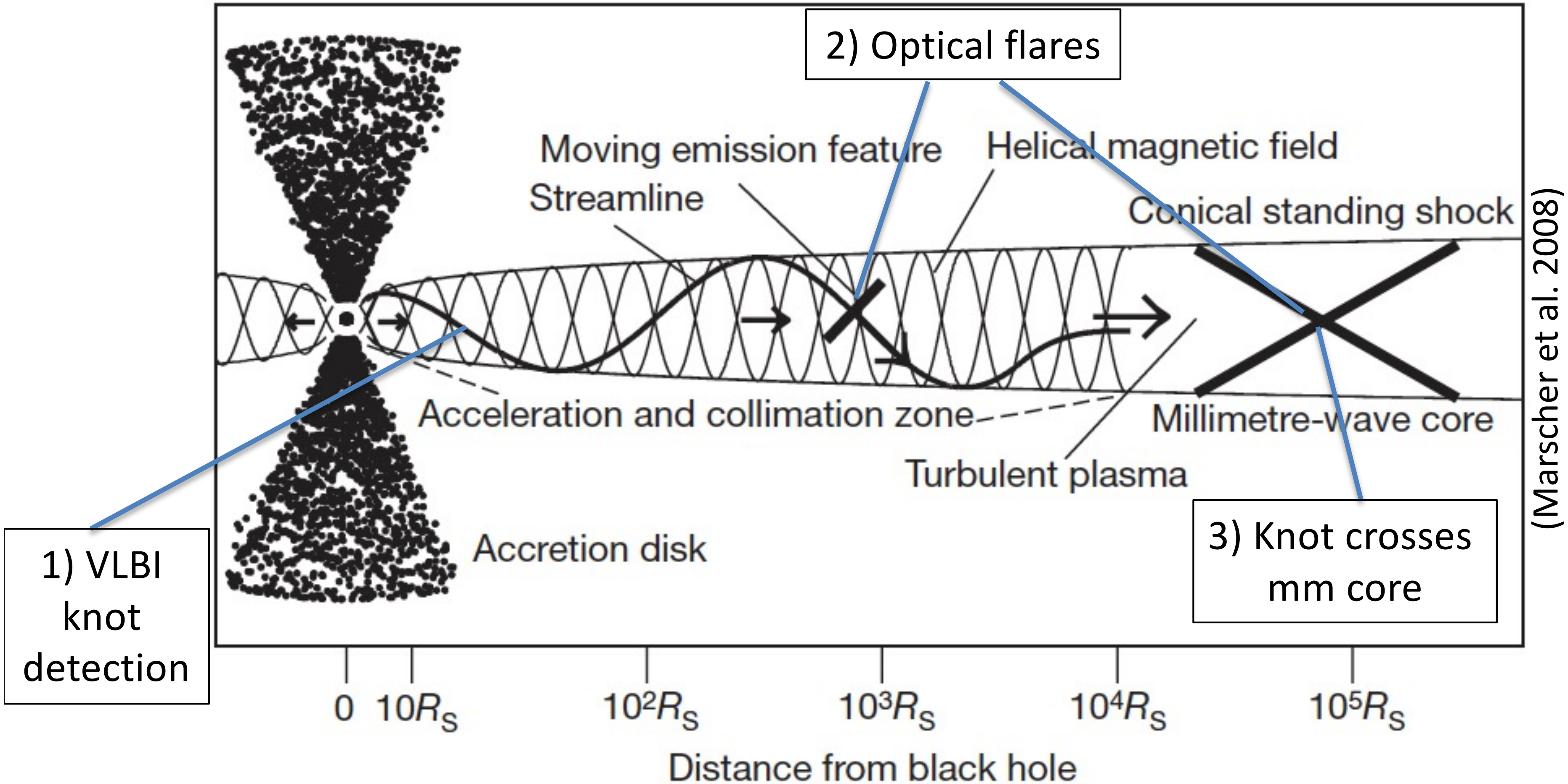
Hard-State Inner-Jet/Disc Connection

- Multiwavelength emission from compact jet responding to X-ray core feeding.
- Poynting flux dominated near the base. Radiative jet base elevated ~$10^{3\text{-}4}$ R_G above compact object where B ~ 10^4 G.
- Additional coronal hot flow and disc reprocessing emission.



(Gandhi et al. 2017)

Consistent with internal shock model and with AGN observations



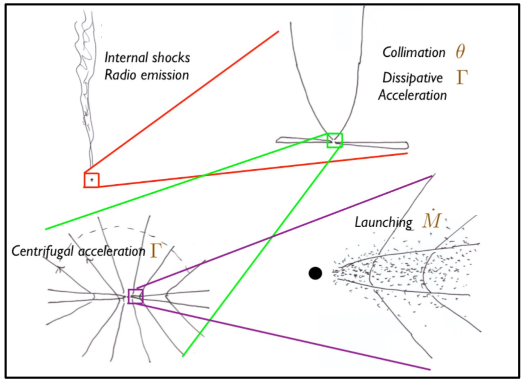
Time delays

ACZ crossing of ~10^4 R_S.

Internal shock modelling: Malzac 13, 14.

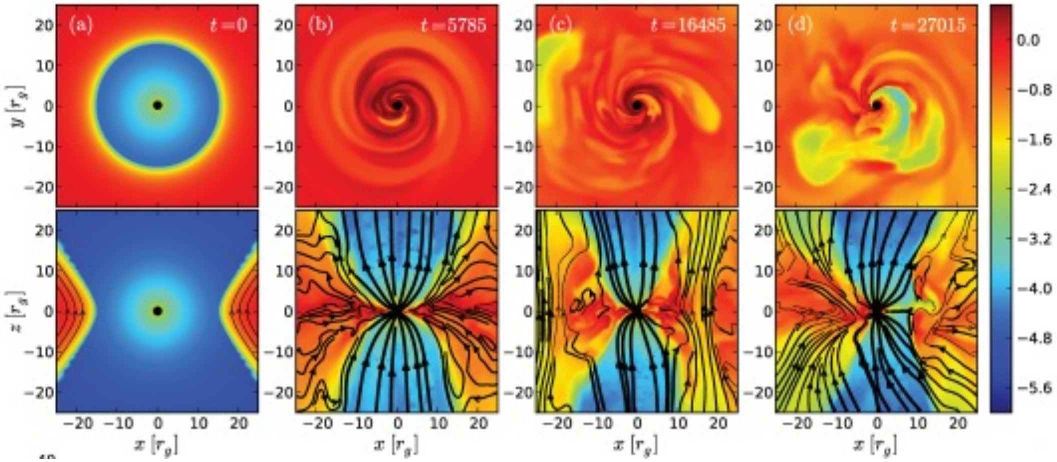
Other models: JED-SAD (Ferreira 97; Marcel+18), Poynting-Robertson Cosmic Battery (Nylafis+).

MHD jet acceleration and collimation



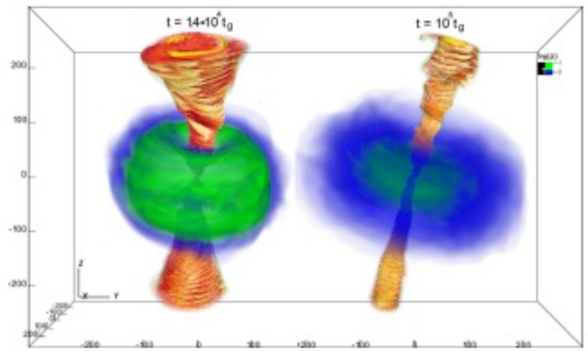
(Spruit 2008)

- ➢ Substantial advancements in MHD models.
- ➢ Next step: Incorporate radiative transport and variability.



(Tchekhovskoy+2011)

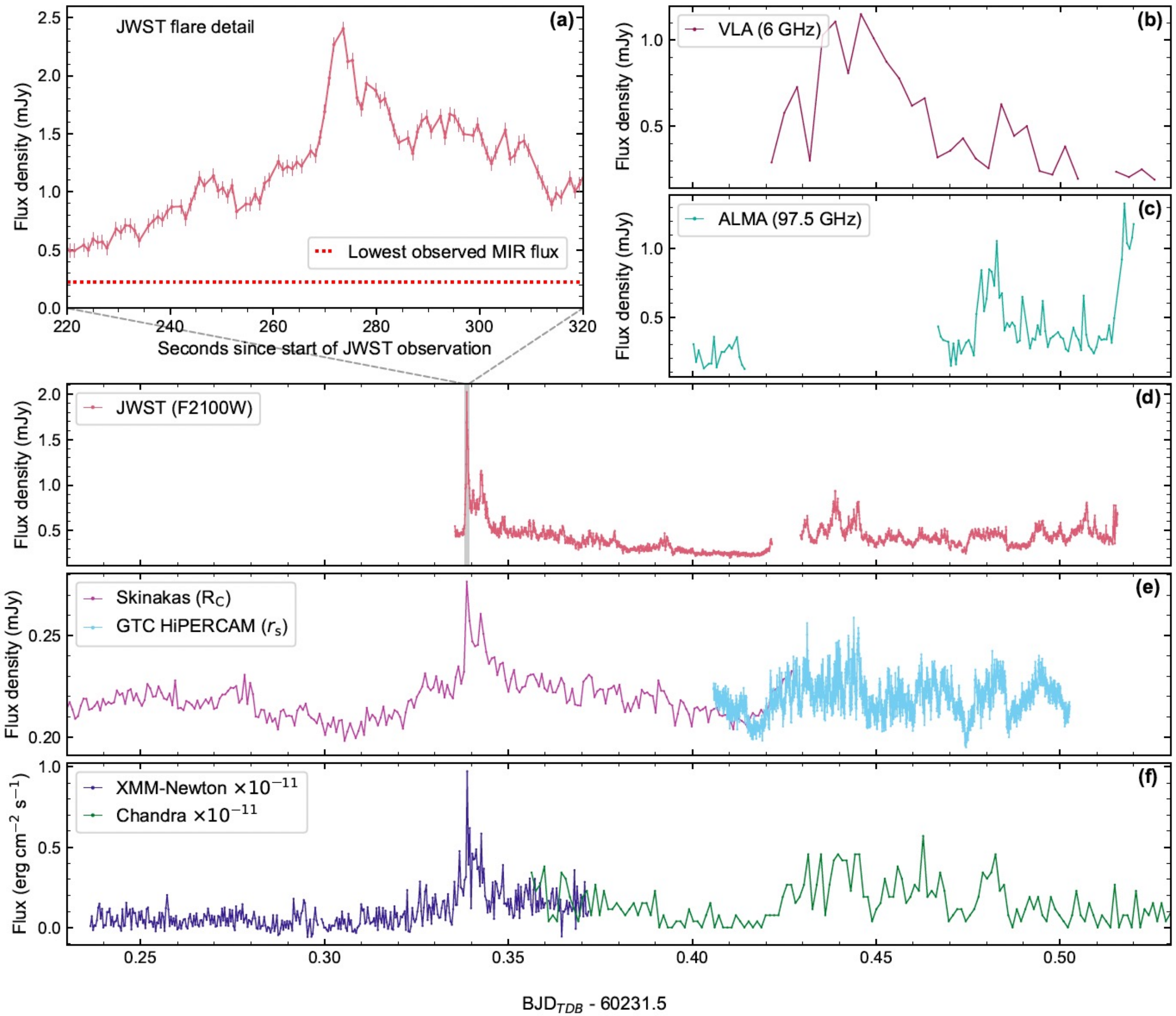
(Liska+2018)



- ➢ Multiwavelength timing constrains boundary conditions and critical flow points/surfaces.

How does the ‘inner jet’ behave in other states?

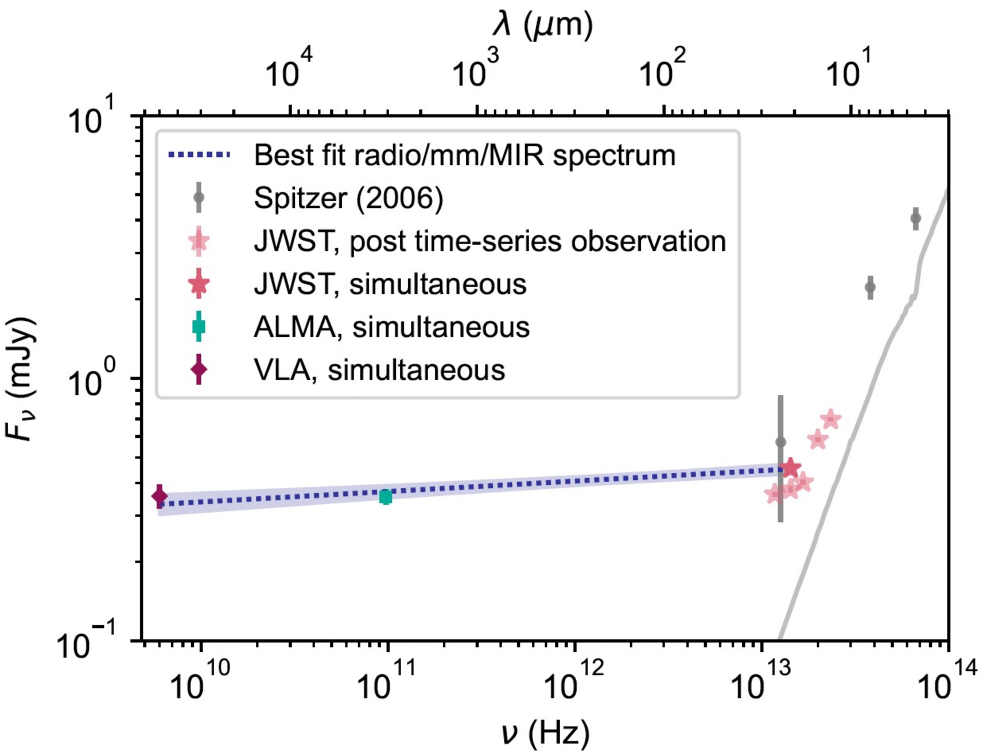
- V404 Cyg in quiescence at $L / L_{\mathrm{Edd}} \sim (2\text{-}5) \times 10^{-7}$
- Strong simultaneous multwl. variations $\Longrightarrow$ Synchrotron.

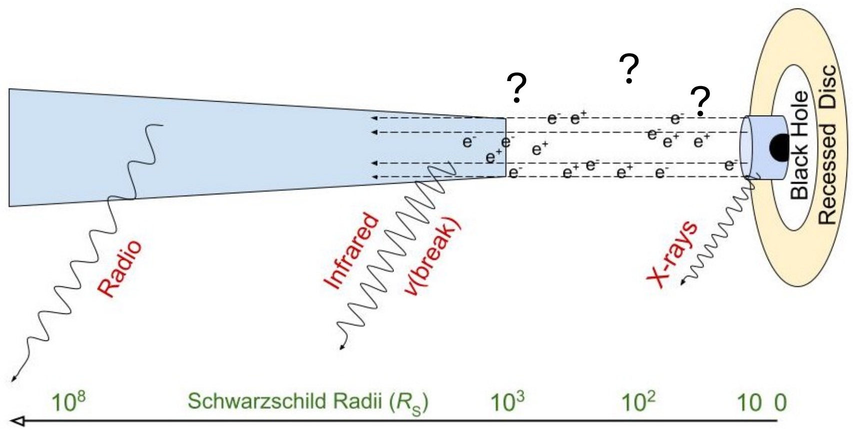


(Borowski et al. 2025)

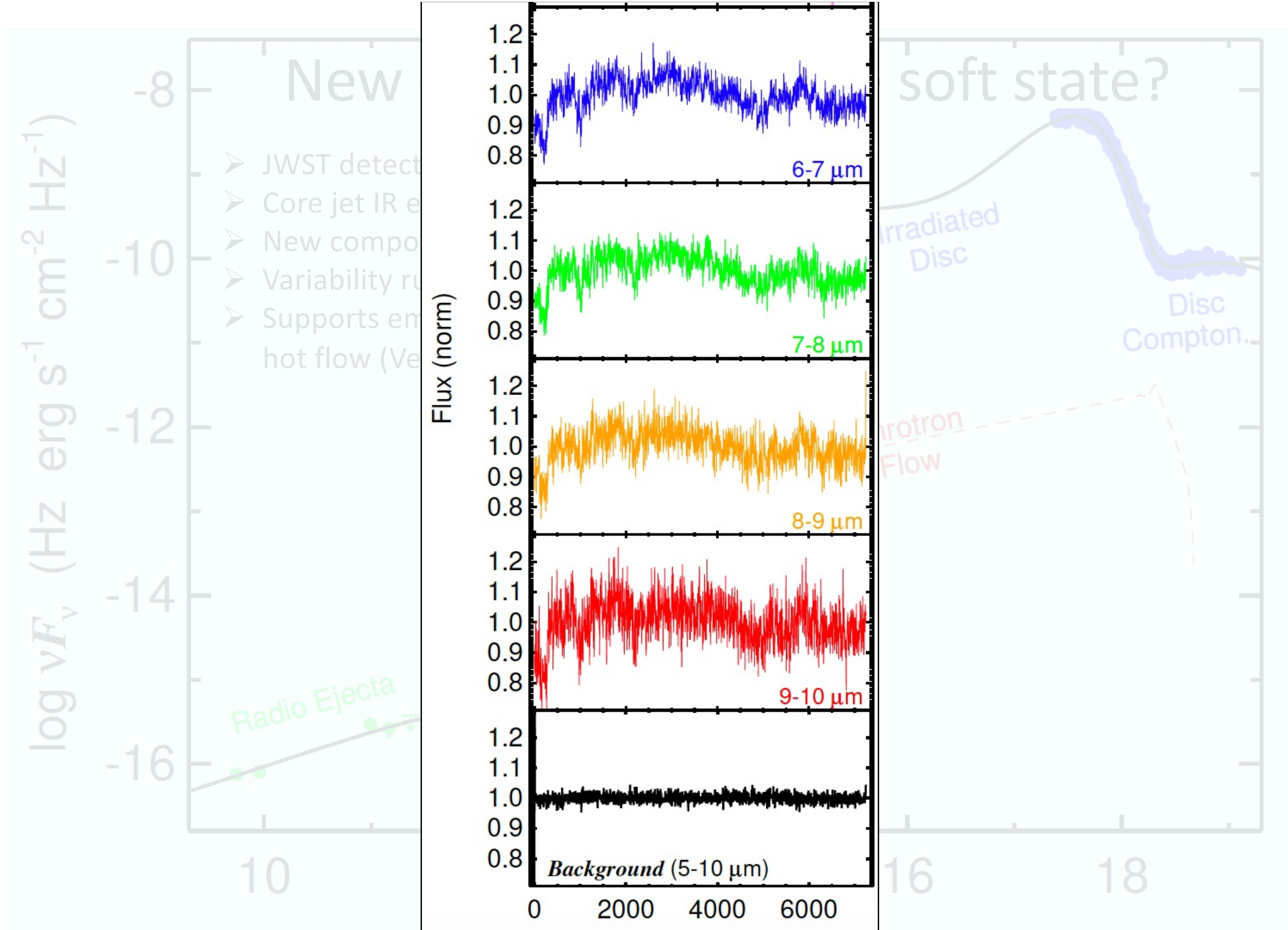
Jet persists into Quiescence

- Flat spectrum + variability $\Longrightarrow$ very similar B field or much smaller jet opening angle….
- Scales remain to be quantified.
- How does this relate to sources like M87 and Sgr A*?



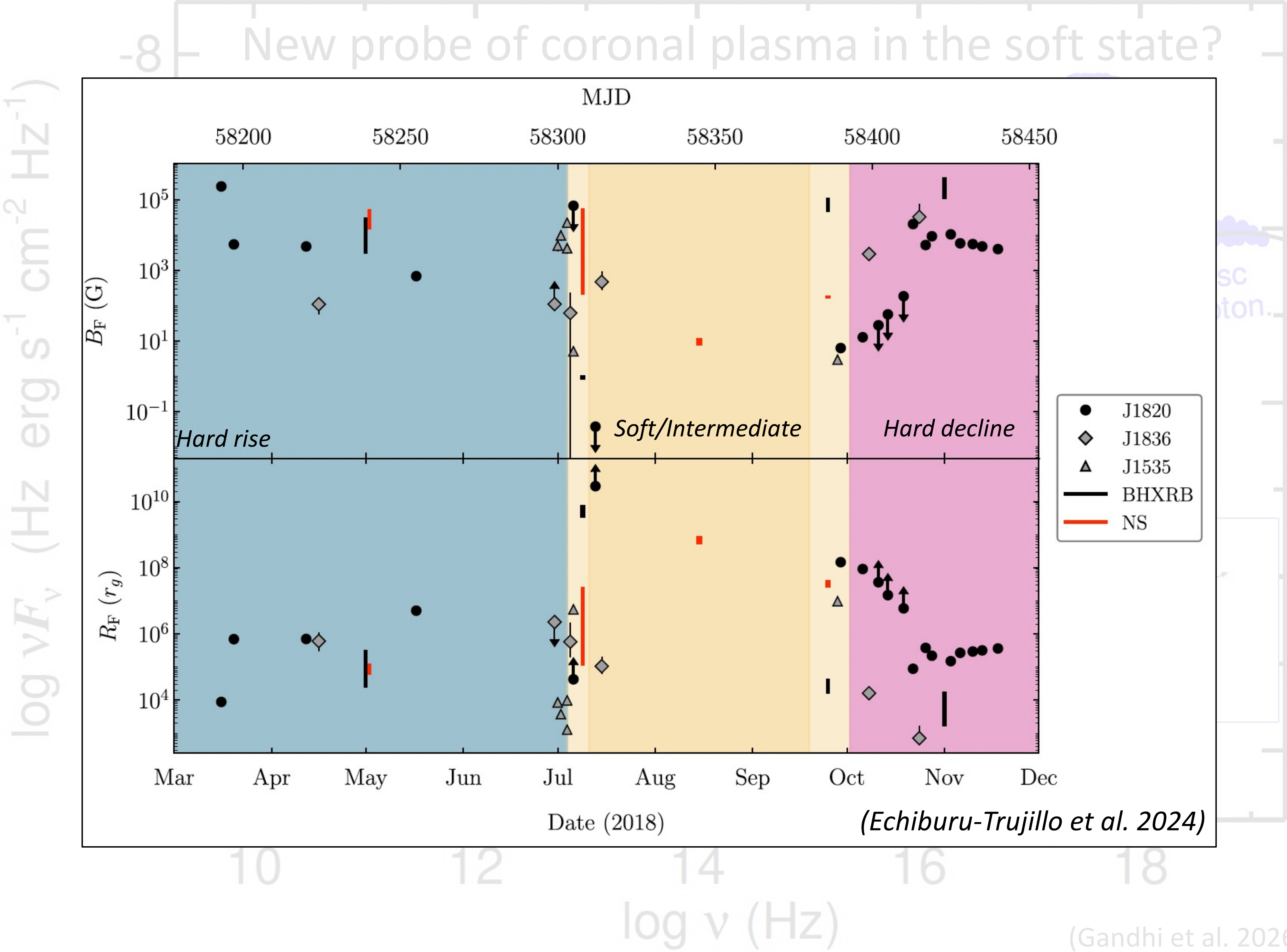


(Borowski et al. 2025)



(Gandhi et al. 2026)

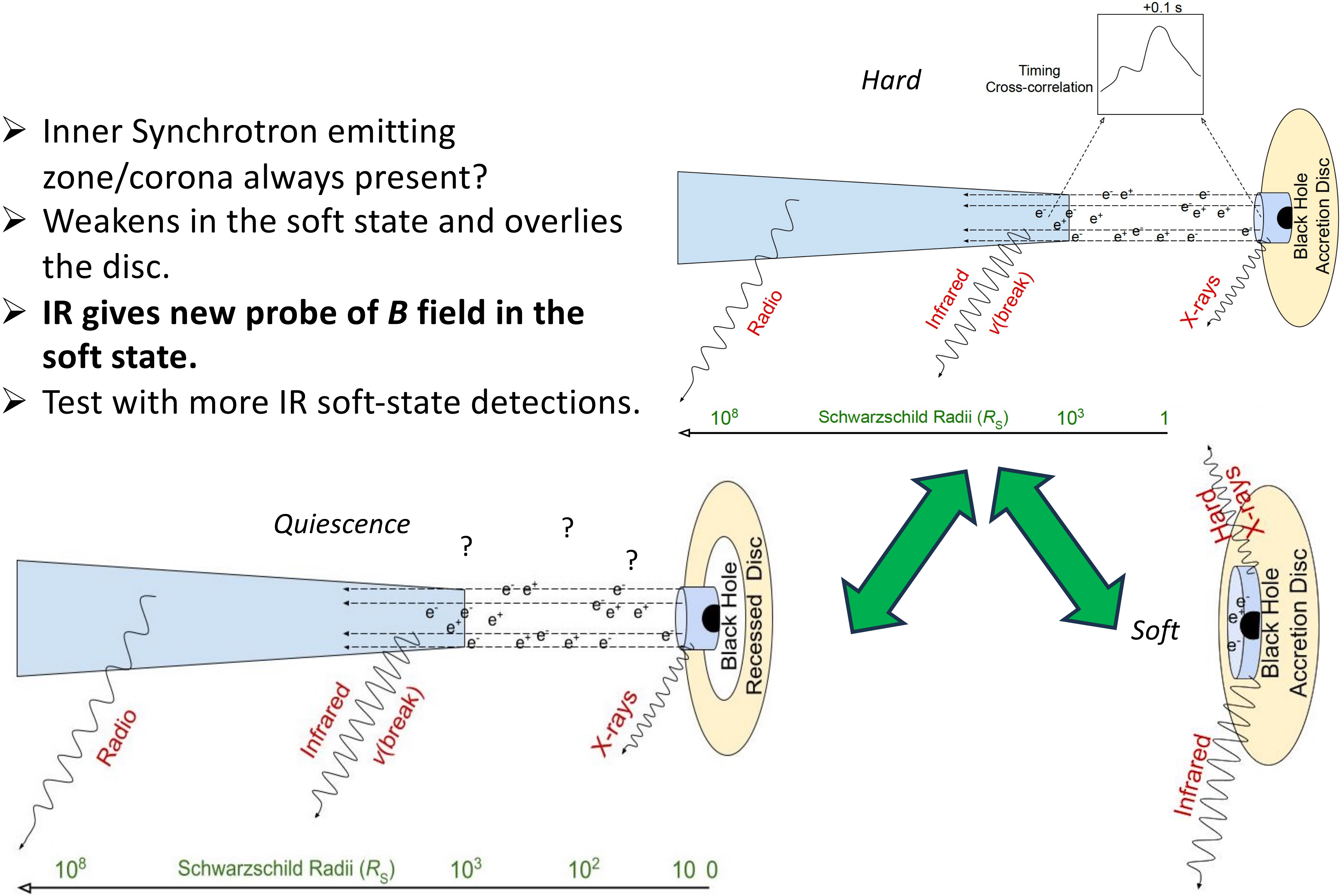
New probe of coronal plasma in the soft state?



(Gandhi et al. 2026)

‘Jet base’ evolution across states

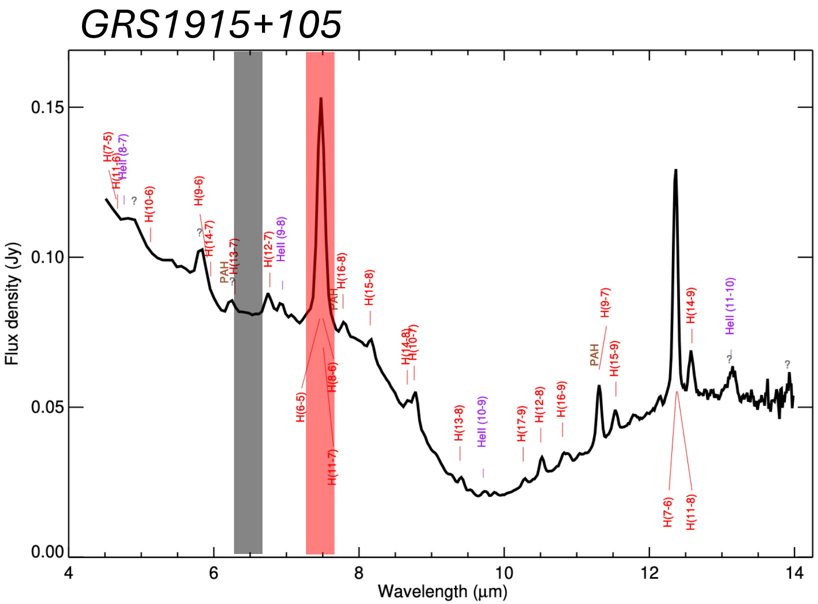
- ➢ Inner Synchrotron emitting zone/corona always present?
- ➢ Weakens in the soft state and overlies the disc.
- ➢ **IR gives new probe of *B* field in the soft state.**
- ➢ Test with more IR soft-state detections.

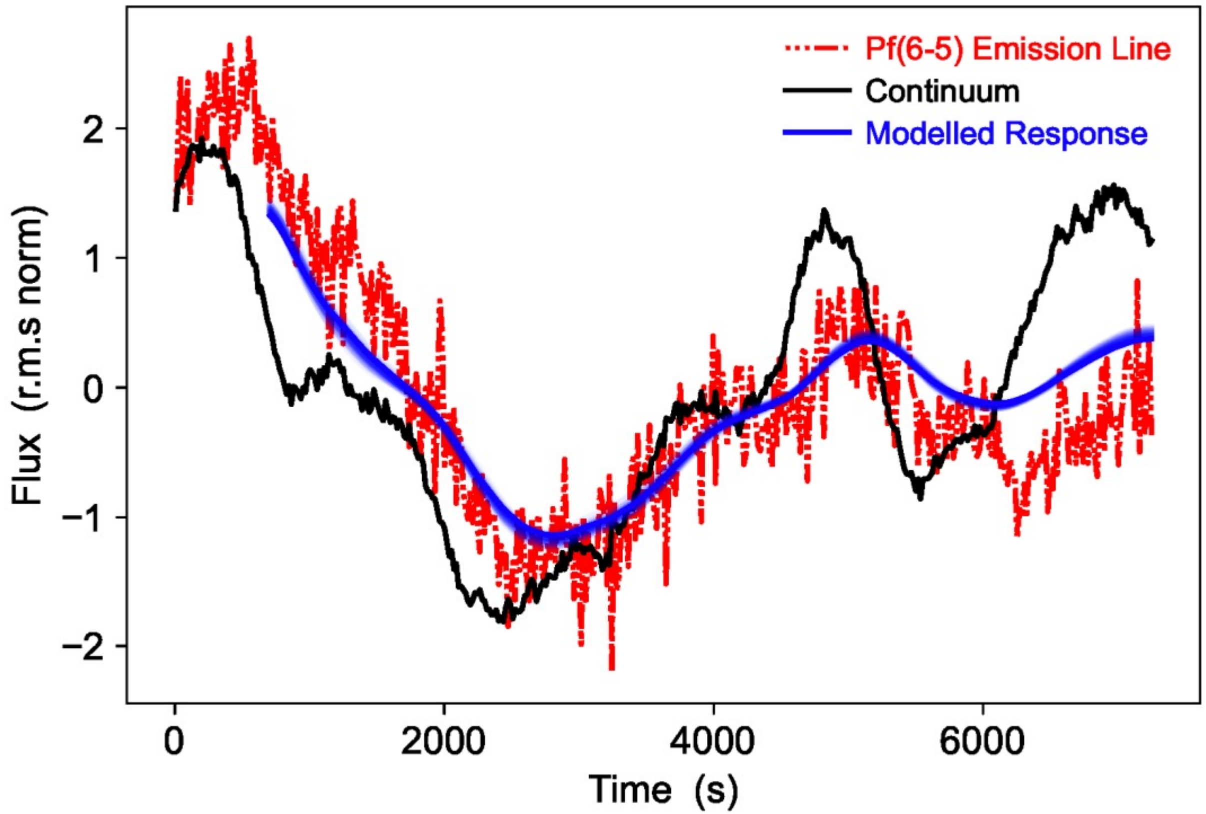


X-ray Binaries with JWST: Status so far

Source	Observation	Goal
GRS 1915+105	Cycle 1 ToO (MIRI LRS TSO)	Cause of the new 'obscured state'? MIRI LRS TSO. ⟹ *Gandhi et al. (2025)*
GX 339-4	Cycle 1 ToO (MIRI LRS TSO)	Origin on multiwavelength variability? MIRI LRS TSO. Guiding failure. Re-observed in soft state. ⟹ *New synchrotron component*
4U 0142+61	Cycle 1 (NIRCAM+MIRI)	Discs in magnetars? MIRI+NIRCAM. ⟹ *Hare et al. (2024)*
V404 Cyg	Cycle 2 quiescence (MIRI imaging)	Origin of quiescent flickering? MIRI Imaging. ⟹ *Quiescent Jet* *Borowski et al. (2025)*
A 0620-00	Cycle 2 quiescence (NIRCAM+MIRI imaging)	Origin of quiescent emission? MIRI LRS+Imaging ⟹ *Quiescent Wind* *Zuo et al. (2025)*
XTE J1118+480	Cycle 2 quiescence (NIRCAM+MIRI imaging)	Origin of quiescent emission? MIRI LRS+Imaging

IR Emission Line Reverberation



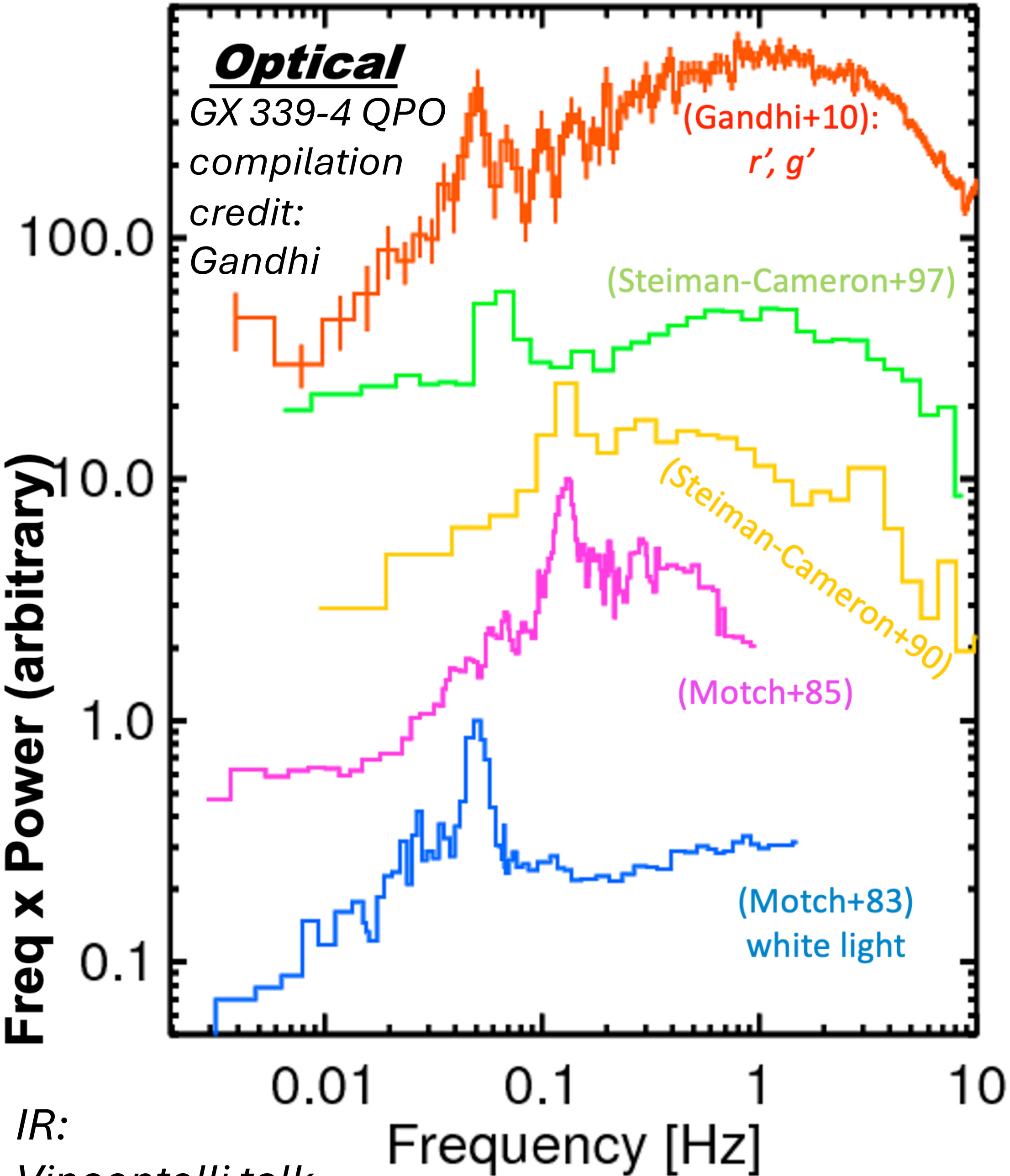


- ➢Spectral-timing shows clear MIR variability.
- ➢Emission line response follows continuum with ~few x100 s delay.

- ➢First O/IR reverberation in an XRB.
- ➢Constrains location of extended emission-line zone.

(Gandhi et al. 2025)

Quasi Periodic Oscillations (OIR); only real ones



IR: Vincentelli talk

Lense–Thirring (solid-body) precession: Misaligned inner hot flow/corona/jet precession (e.g. Ingram et al. 2009).

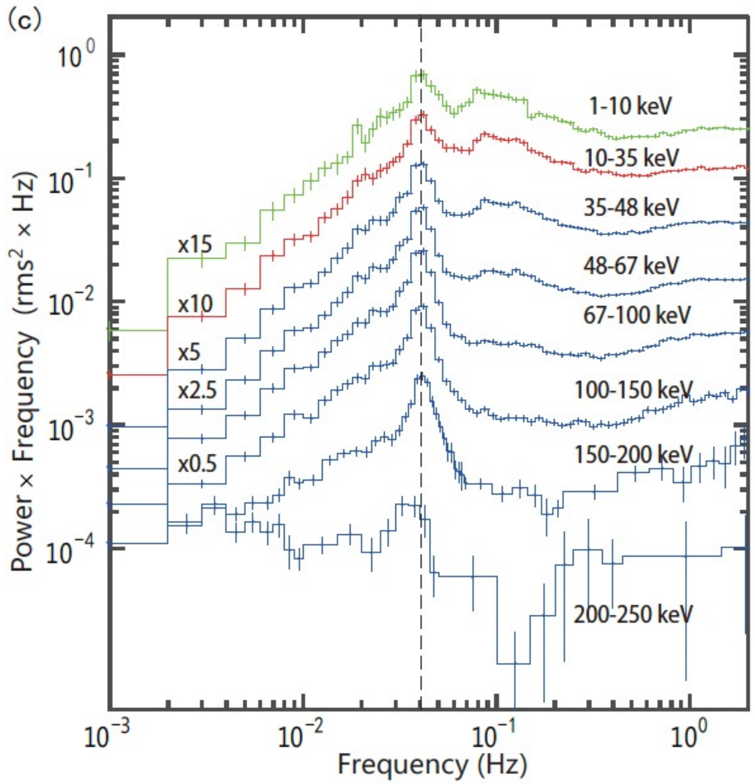
Relativistic epicyclic resonance: Radial/vertical epicyclic mode coupling near ISCO (e.g. Kluzniak & Abramowicz 2001; Török et al. 2005).

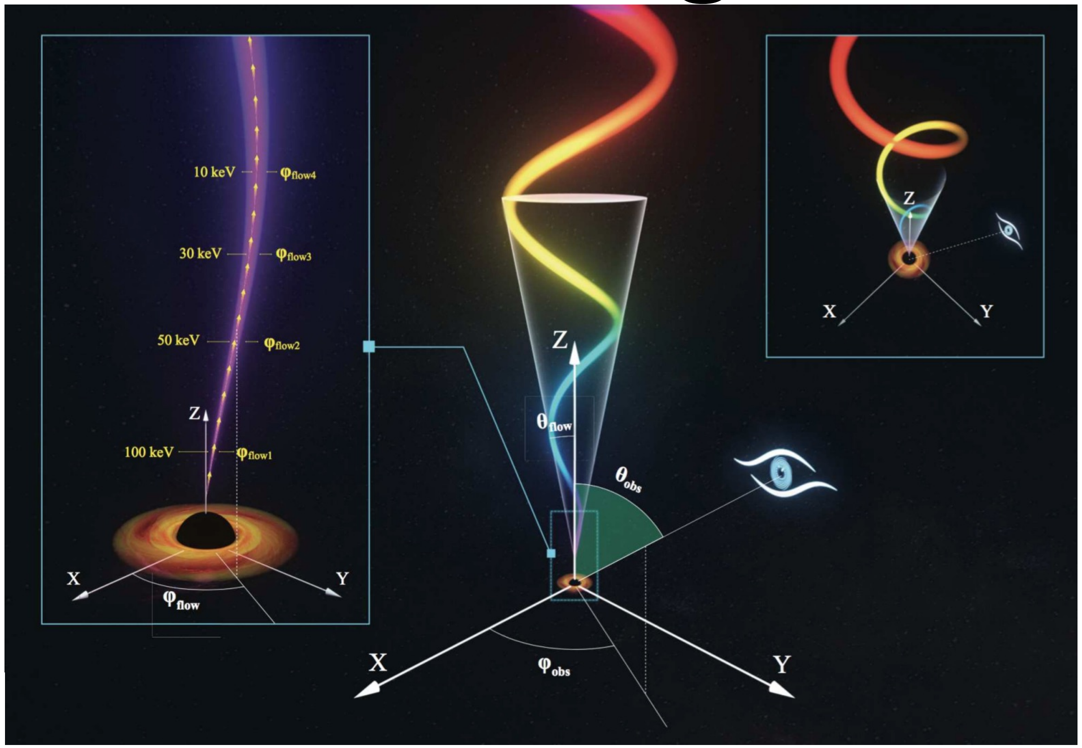
Accretion–Ejection Instability (AEI): Global MHD spiral/Rossby mode in a magnetised inner disk extracting energy into the corona/jet (e.g. Tagger & Pellat 1999).

Warp/irradiation-driven precession: Bardeen-Petterson alignment or radiation-driven global disk warps induce nodal/jet precession (Bardeen & Petterson 1975; Pringle 1996).

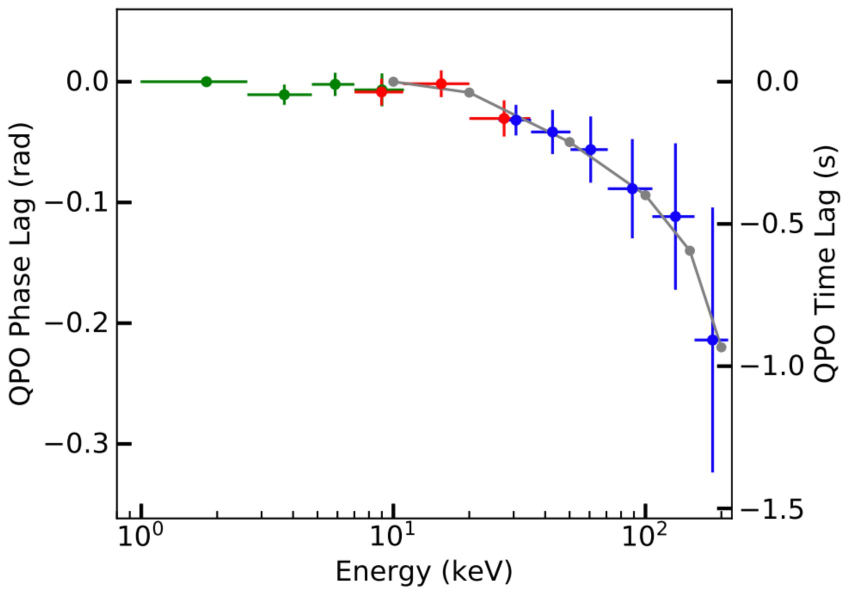
Not all models can apply to MWL QPOs.

Precessing Jet?





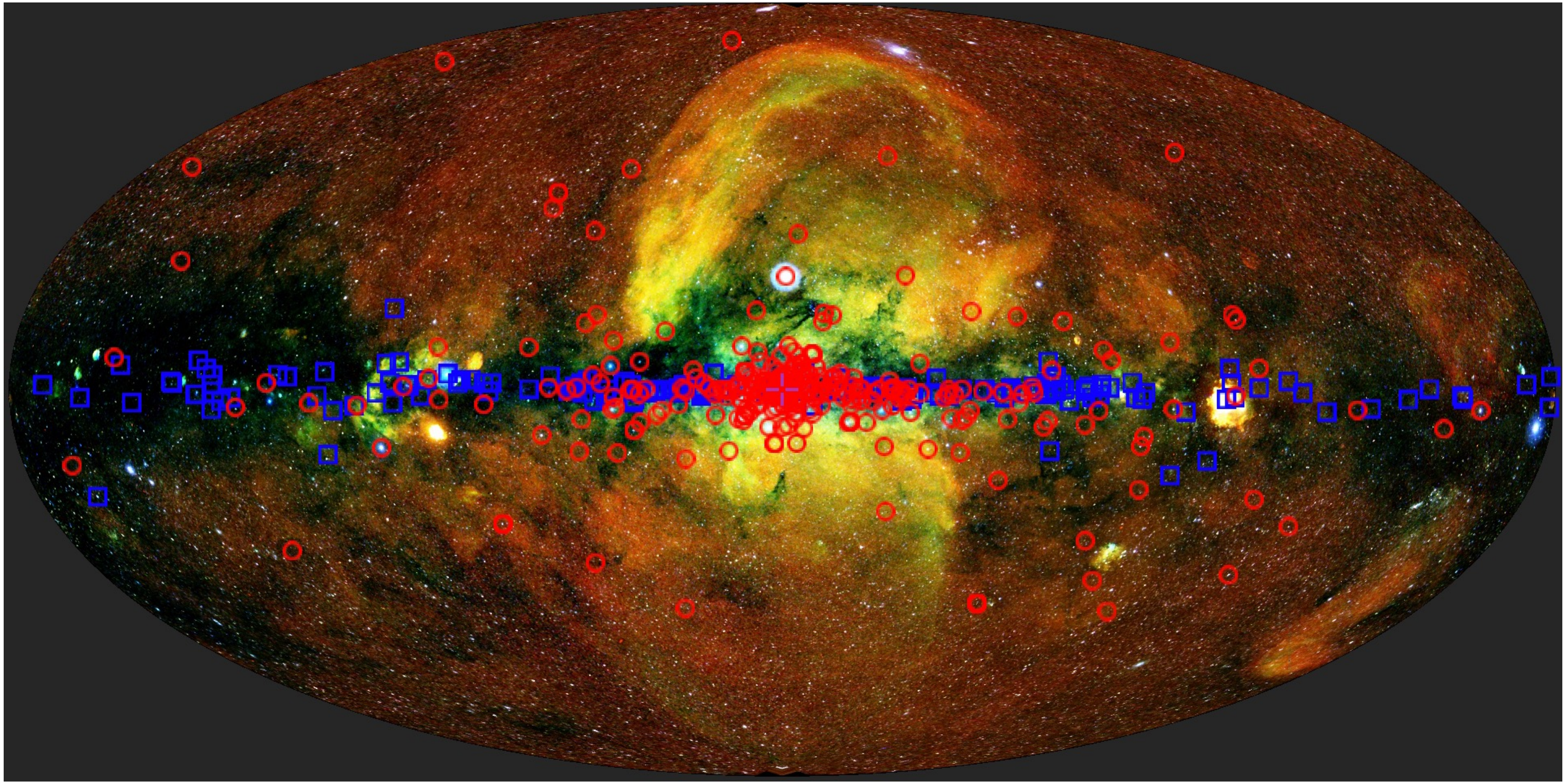
Ma et al. (2021): HXMT



- Very long QPO soft lag in MAXI J1820+070.
- Interpreted as Lense-Thirring precession of a twisted jet.
- Matches optical QPO frequency.
- Need to test with O/X QPO phase lags.

New Parameter Space with upcoming sky surveys

- Enhance the census of XRBs (in quiescence) with LSST, SKA, CTA, ...
- Test Disk Instability Model (cf. Lasota et al., Russell et al., XB-NEWS).
- Measure orbital periods of quiescent systems (Johnson et al. 2019).



Summary and Community-driven efforts

- Timing is the key to constraining geometry and causal physics.

- Multiwavelength coordinated campaigns are critically important, but difficult to organise. Proactively collaborate.

- Advocate for timing exploitation in *all* facilities. Use such meetings to drive community consensus.

- Proactively support your mission of interest.
  We need to scale up collecting area.

- Software: Still a bit of an entry barrier for people who don’t work on timing analysis. Create software that makes this seamless, especially for multiwavelength analysis.

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