

The close environments of accreting black holes: a X-ray spectral-timing view

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DE CATALUNYA
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Why are we interested?

BHs are fundamental engines in our Universe

Observing them is a technological challenge

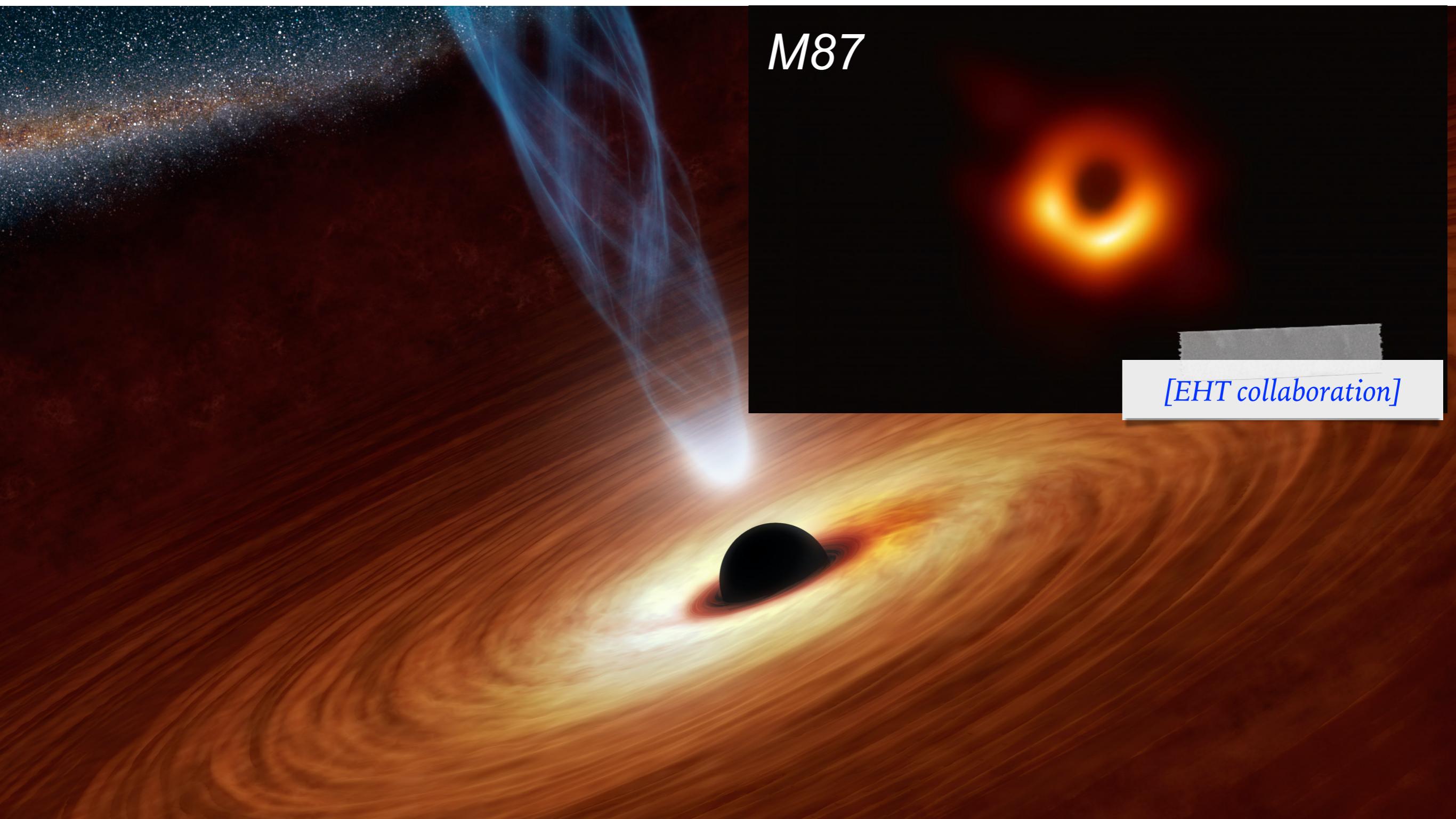
Understanding them is a scientific challenge

Astrophysical BHs



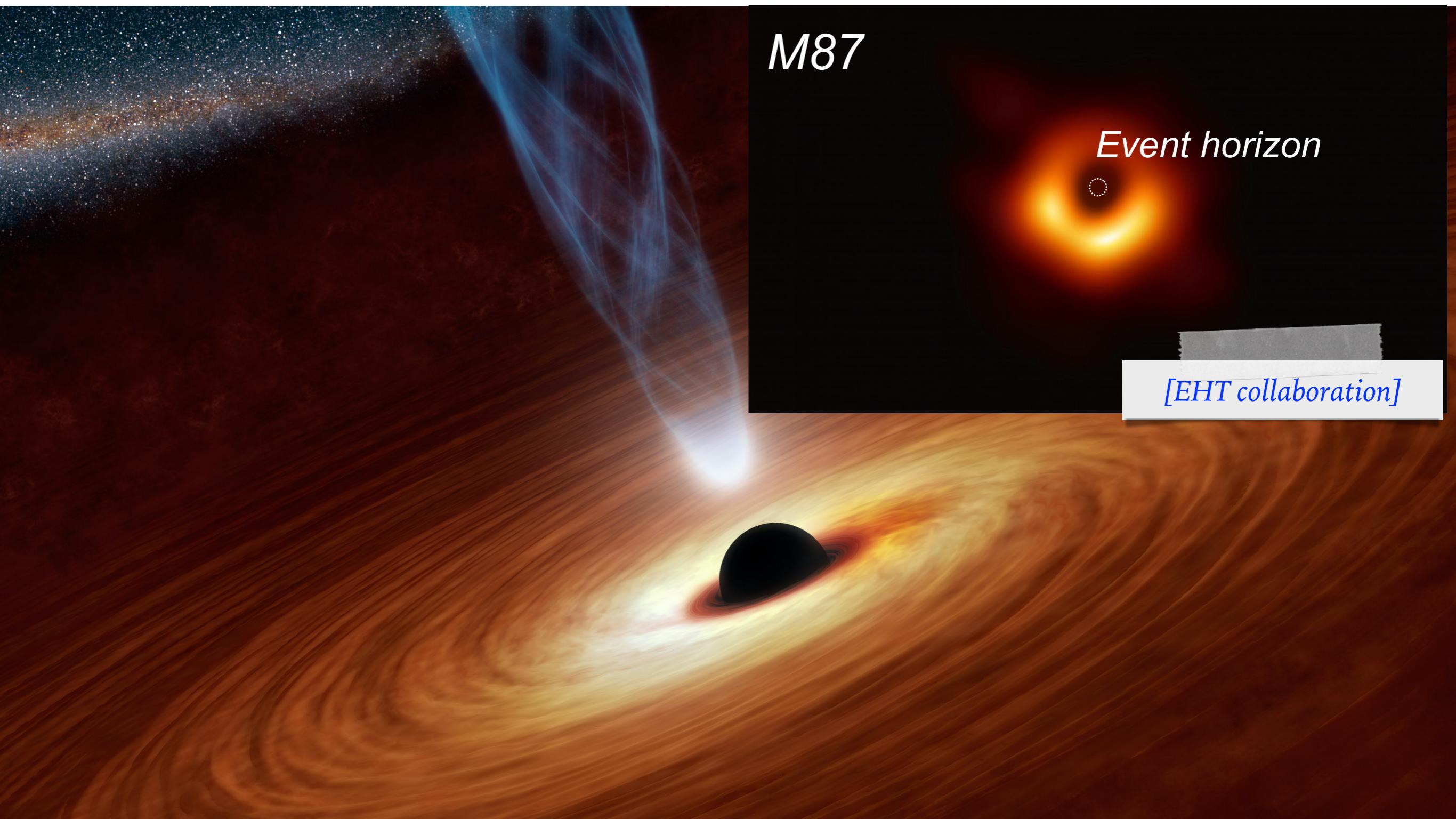
Most efficient mechanism of “persistent” energy production

Astrophysical BHs



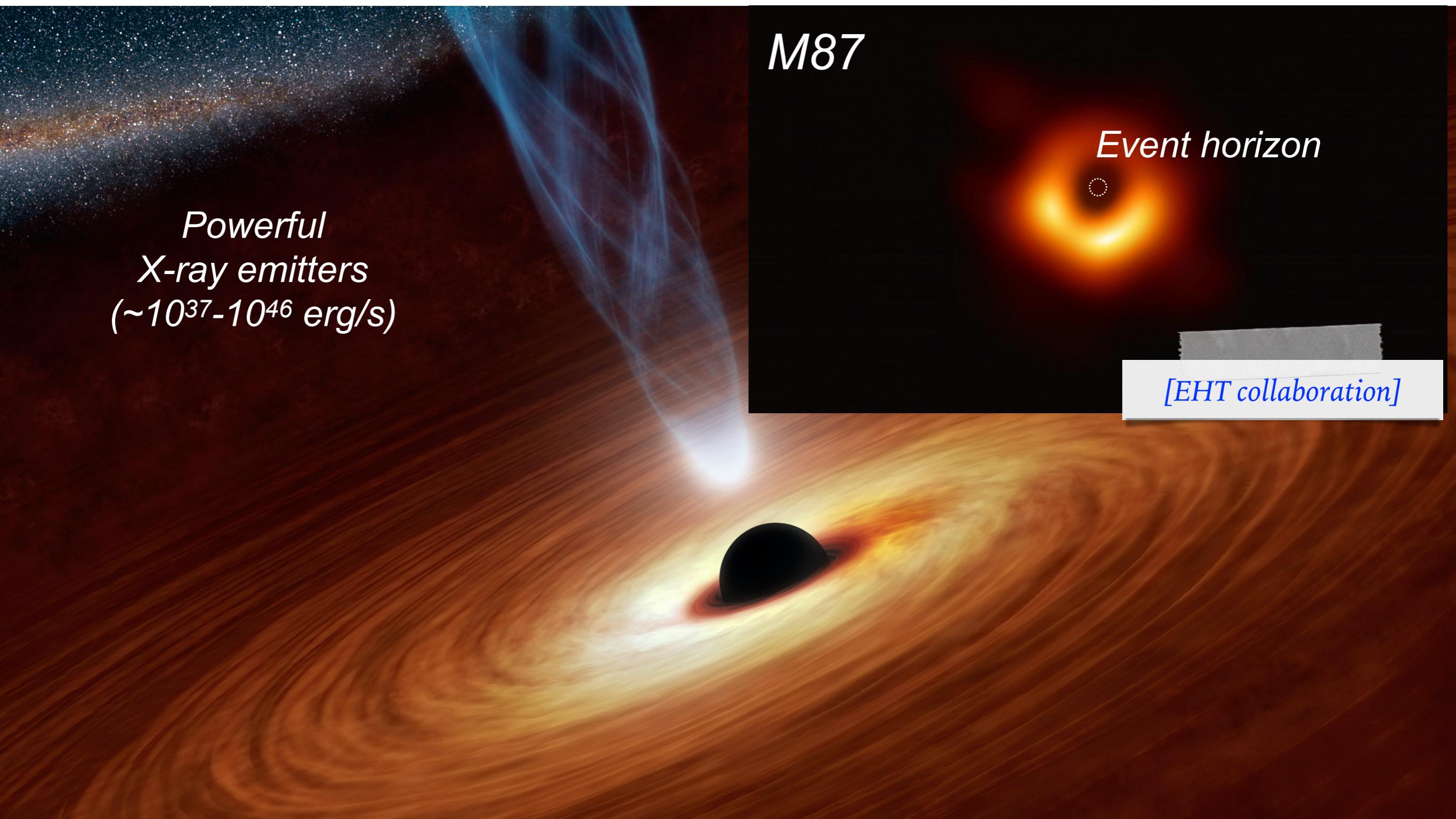
Most efficient mechanism of “persistent” energy production

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Most efficient mechanism of “persistent” energy production

Astrophysical BHs



*Powerful
X-ray emitters
($\sim 10^{37}$ - 10^{46} erg/s)*

M87

Event horizon

[*\[EHT collaboration\]*](#)

Most efficient mechanism of “persistent” energy production

Astrophysical BHs

*Powerful
X-ray emitters
($\sim 10^{37}$ - 10^{46} erg/s)*

*X-ray flux
highly variable
(timescales from
years to $\sim 10^{-3}$ s)*

M87

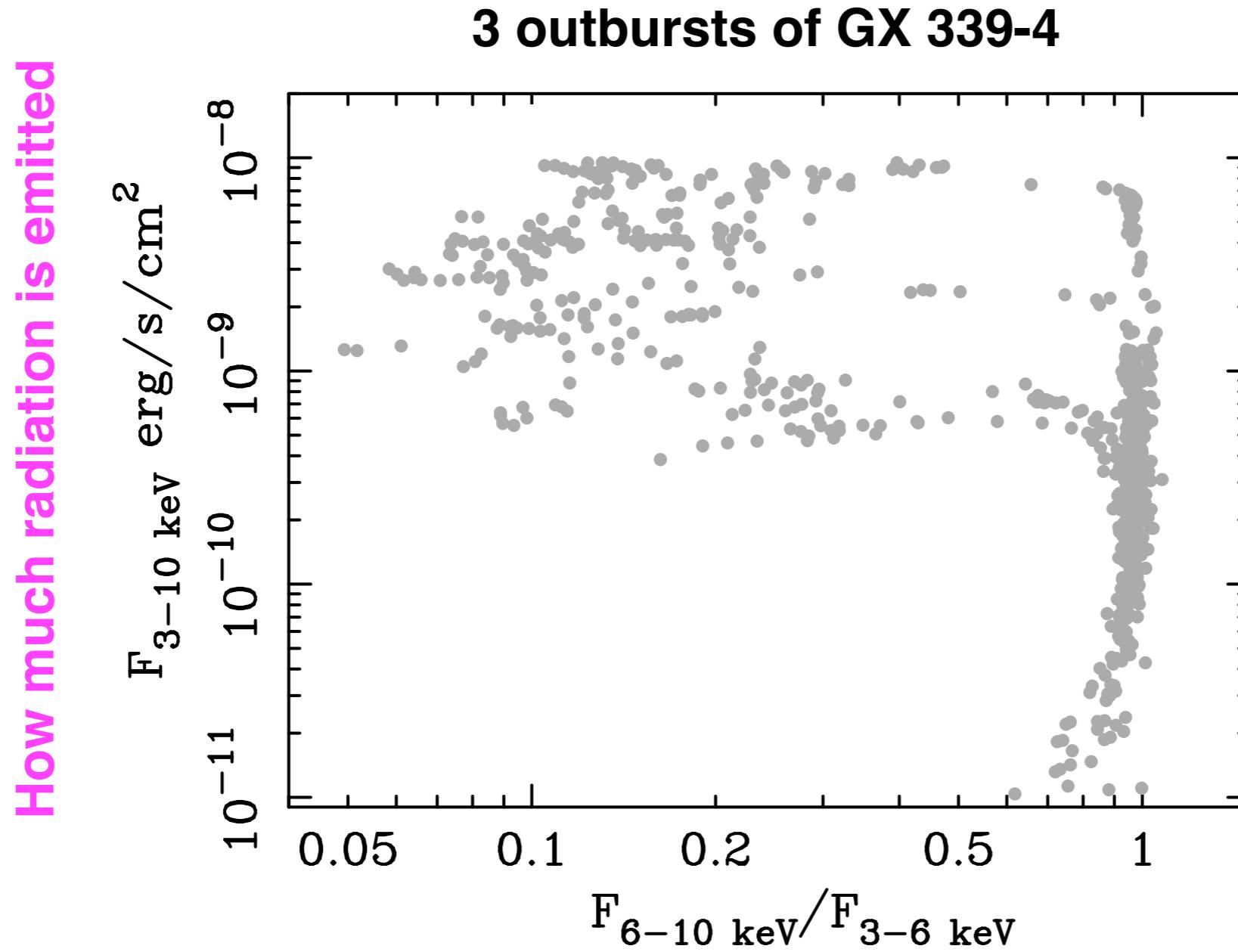
Event horizon

[\[EHT collaboration\]](#)

Most efficient mechanism of “persistent” energy production

BH-accretion: a complex phenomenology

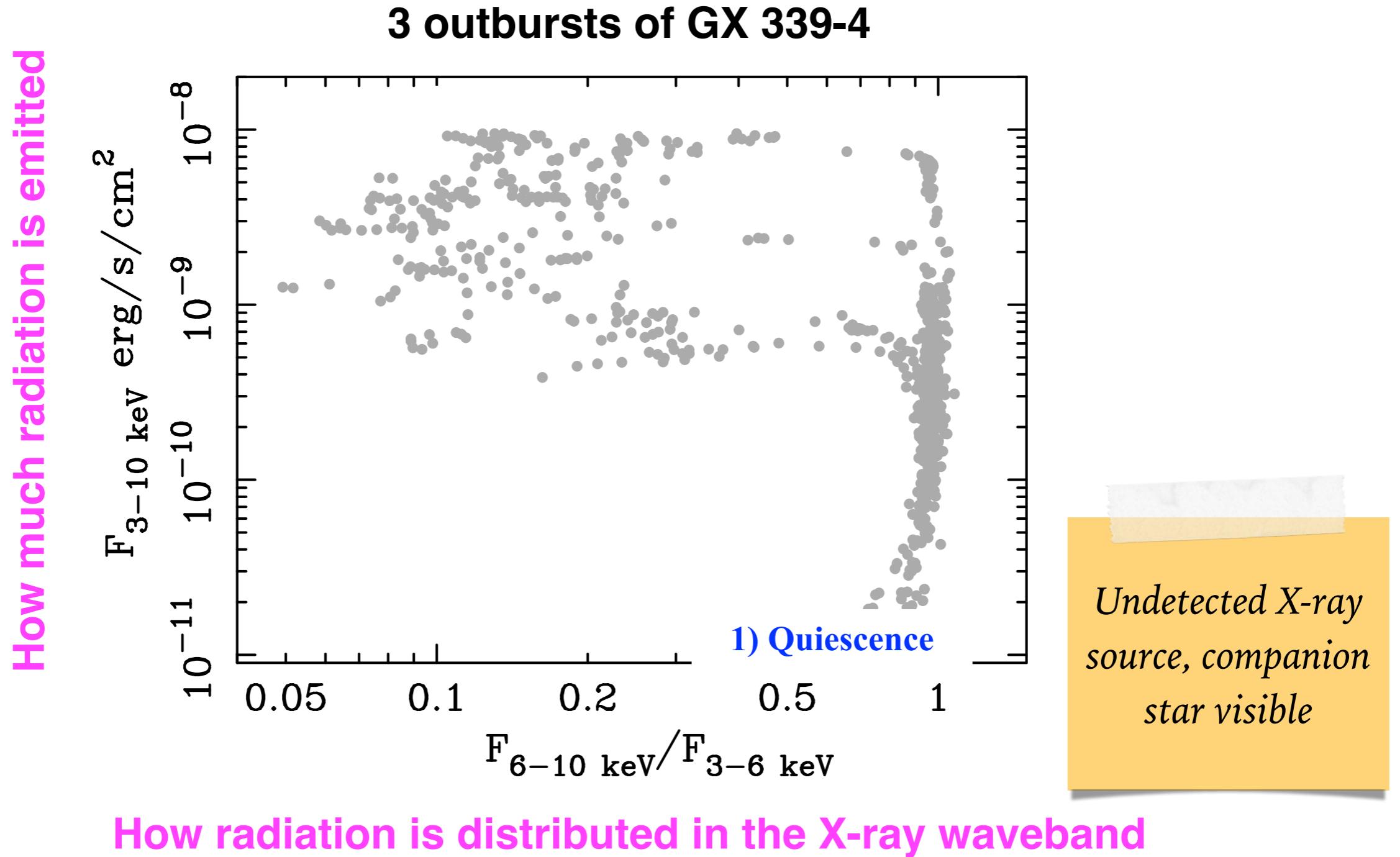
Accretion states in stellar-mass BH binary systems



How radiation is distributed in the X-ray waveband

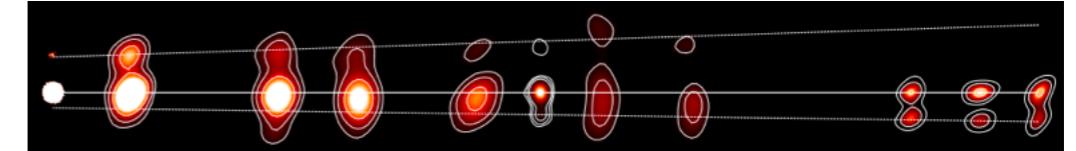
BH-accretion: a complex phenomenology

Accretion states in stellar-mass BH binary systems

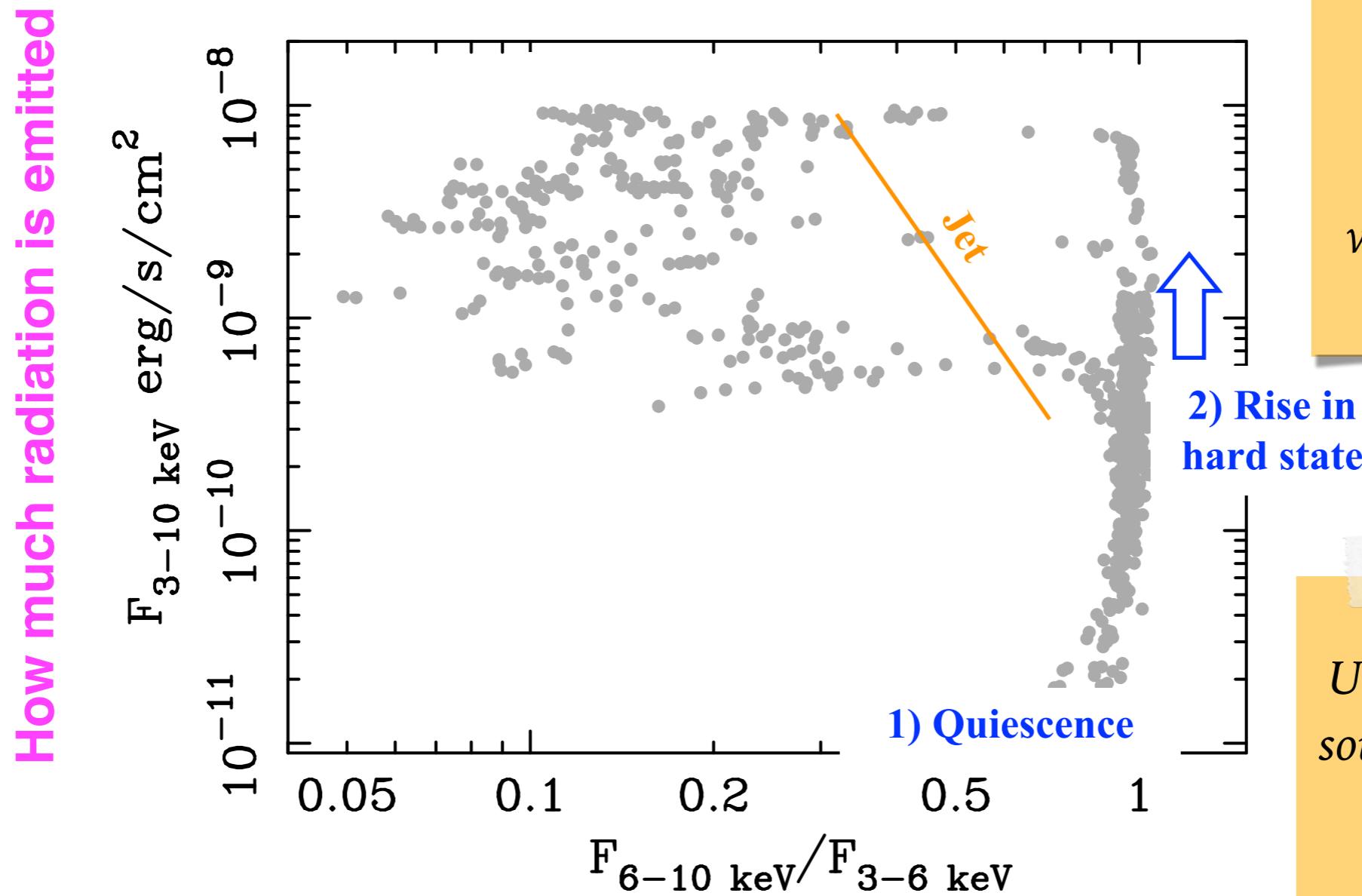


BH-accretion: a complex phenomenology

Accretion states in stellar-mass BH binary systems



3 outbursts of GX 339-4



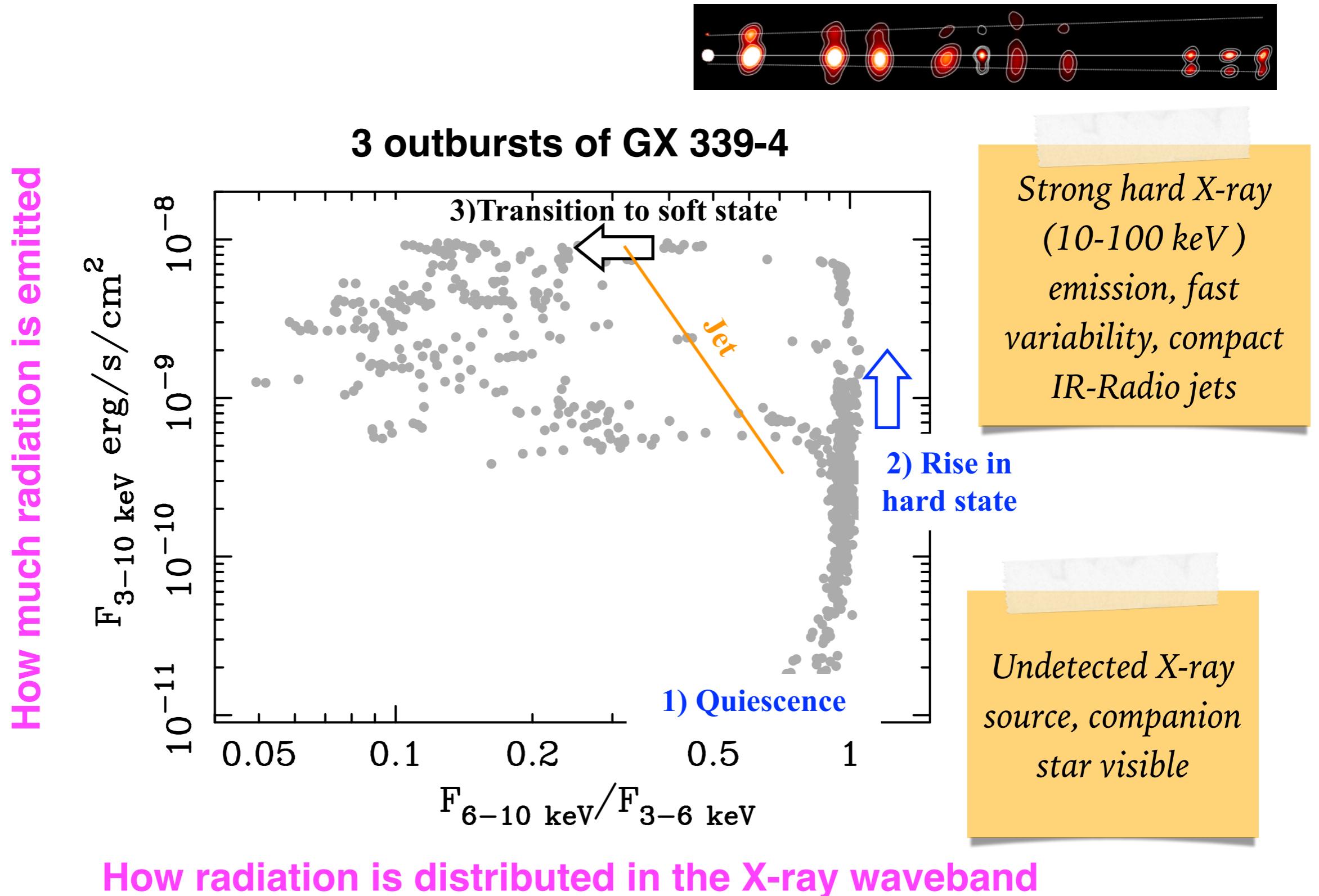
Strong hard X-ray
(10-100 keV)
emission, fast
variability, compact
IR-Radio jets

Undetected X-ray
source, companion
star visible

How radiation is distributed in the X-ray waveband

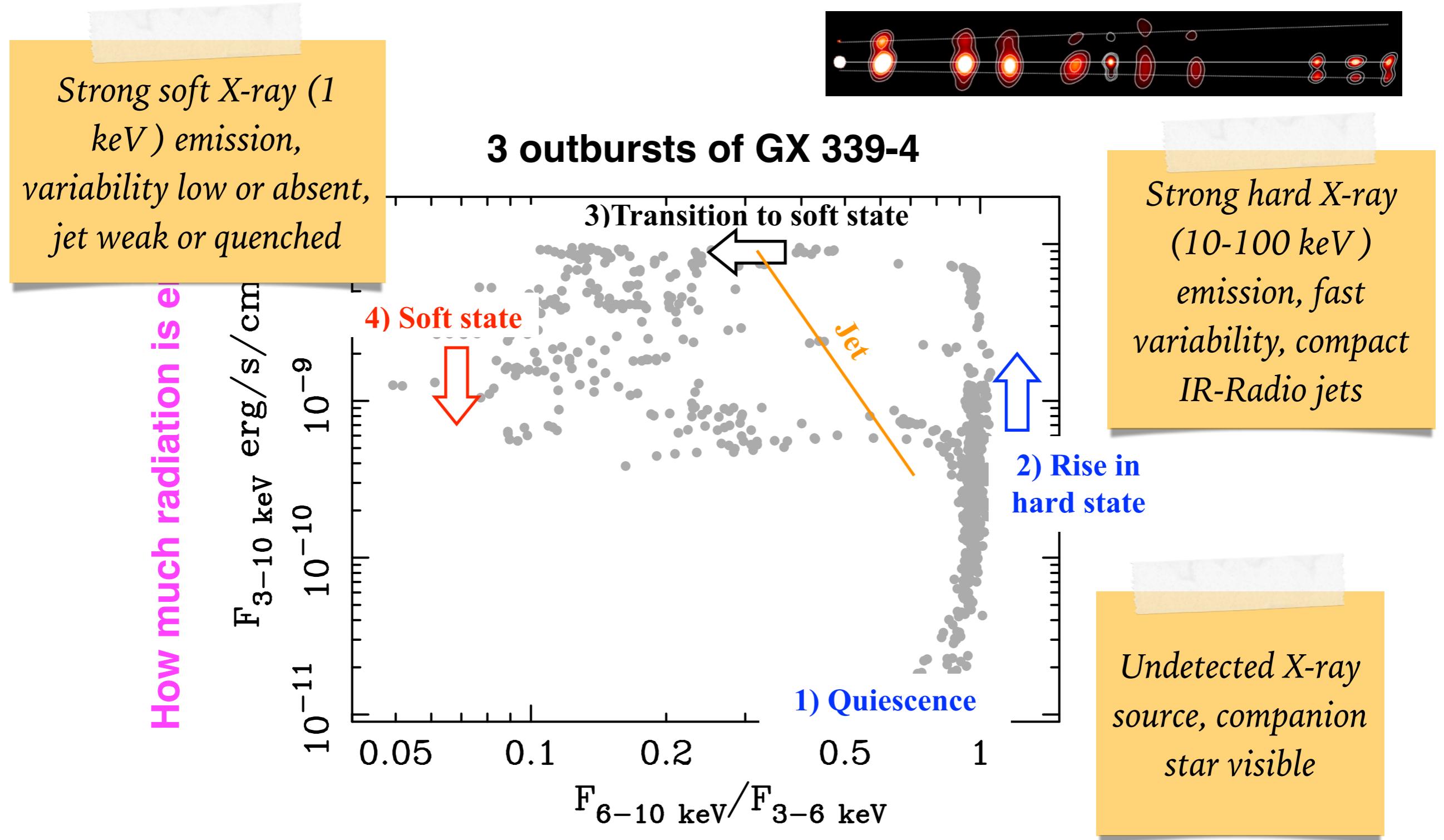
BH-accretion: a complex phenomenology

Accretion states in stellar-mass BH binary systems



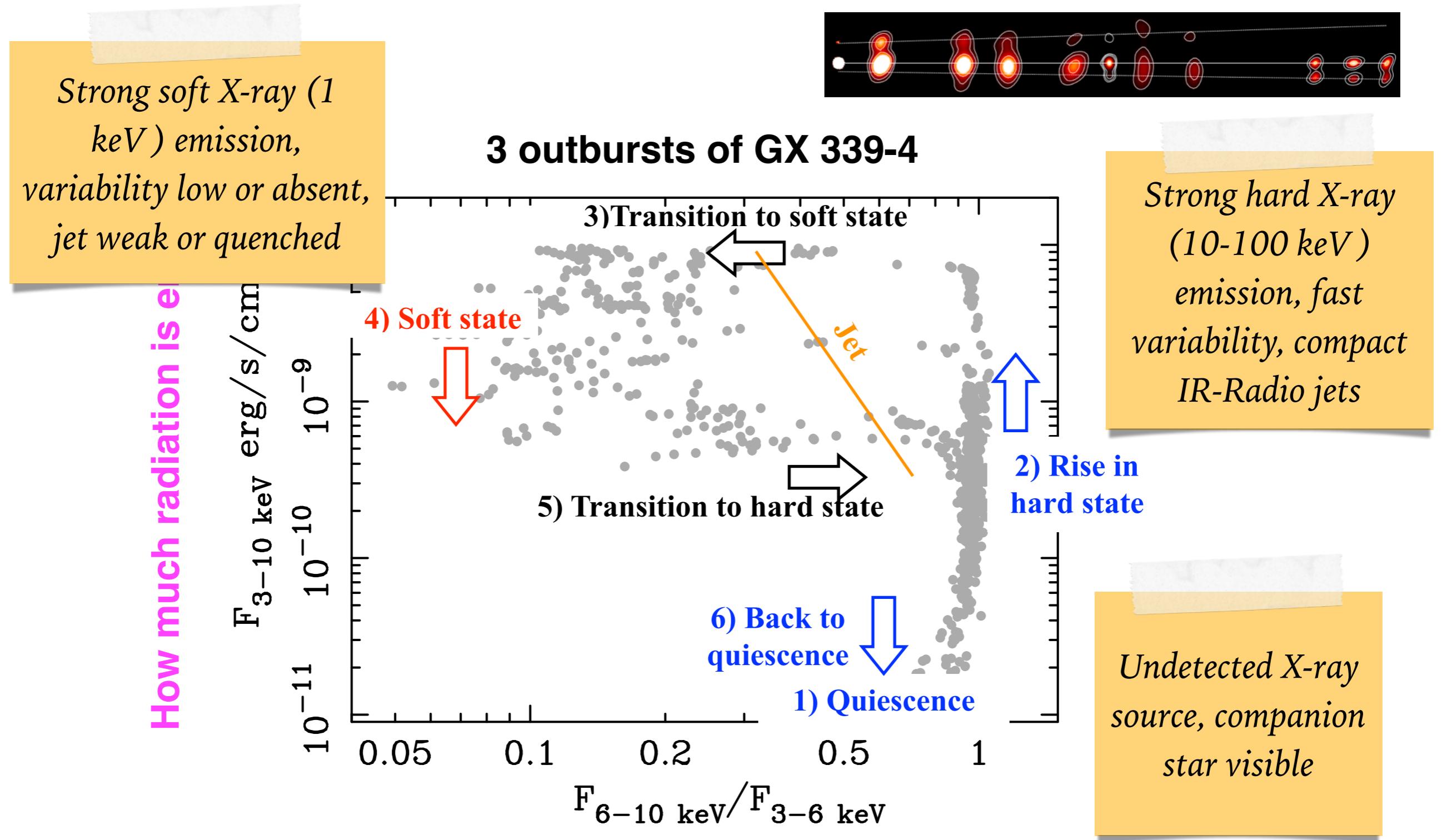
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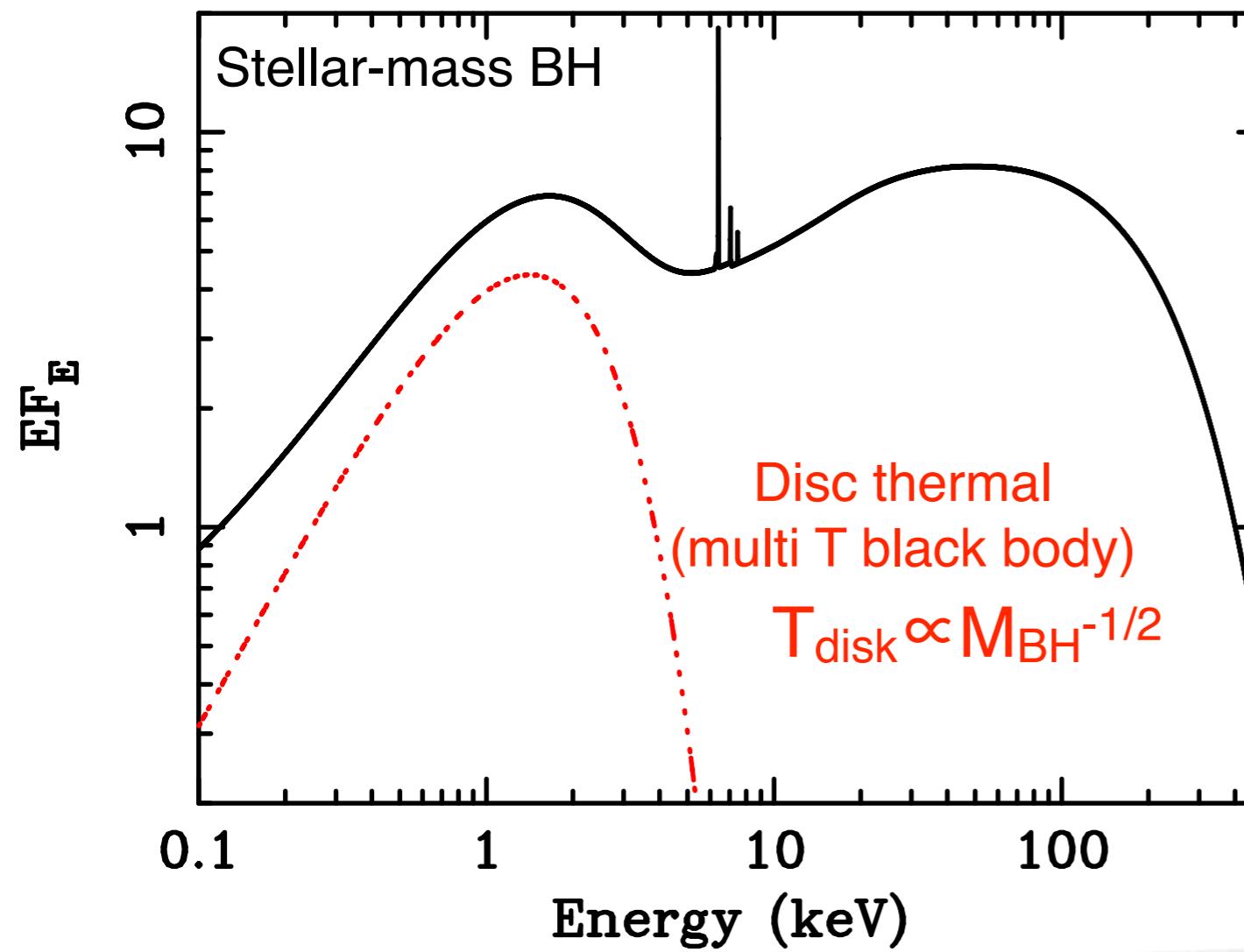
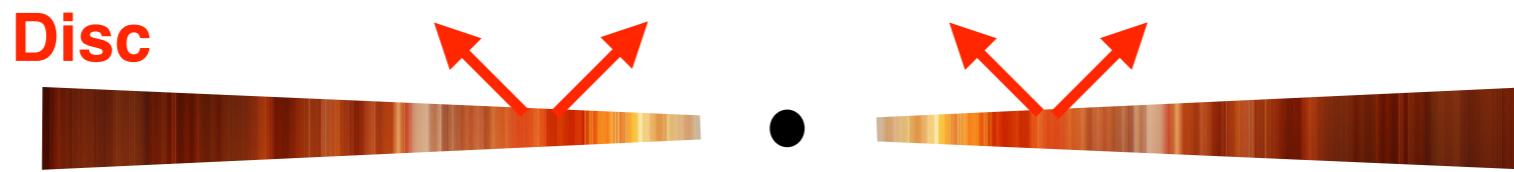
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Accretion states in stellar-mass BH binary systems



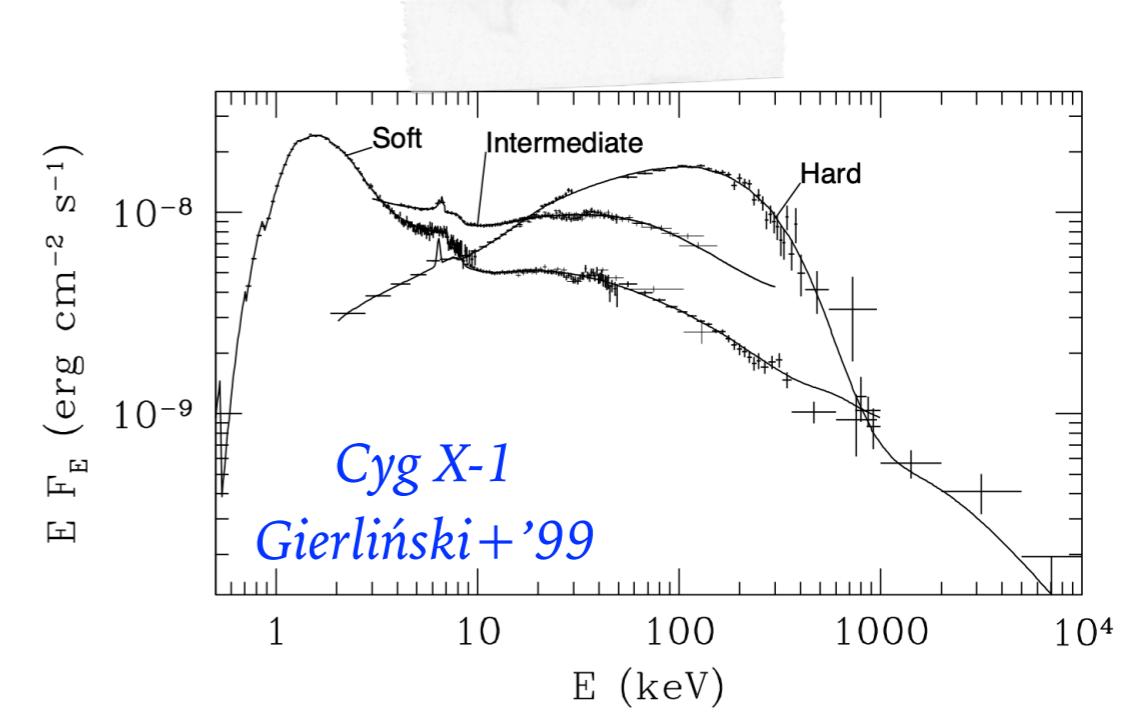
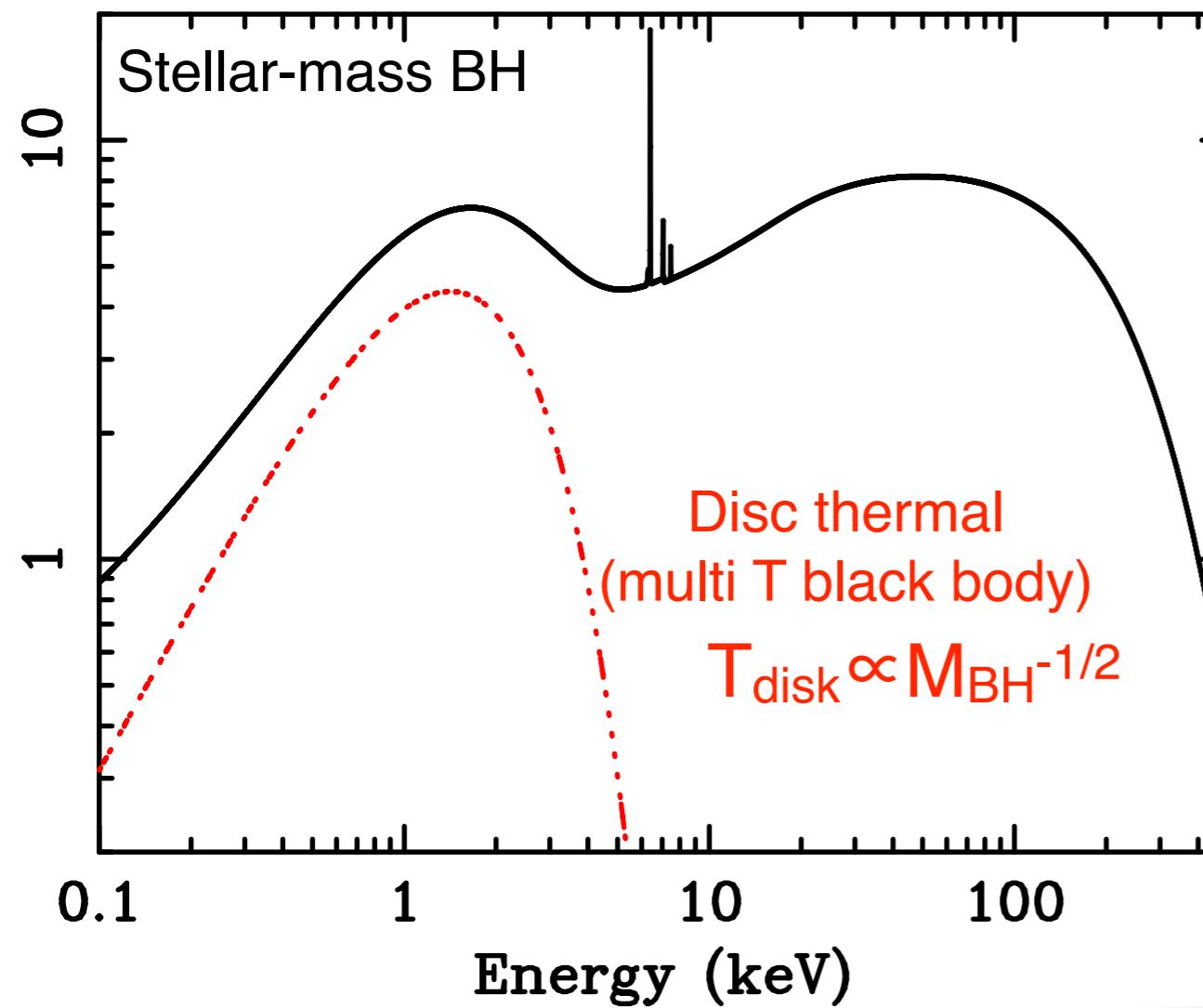
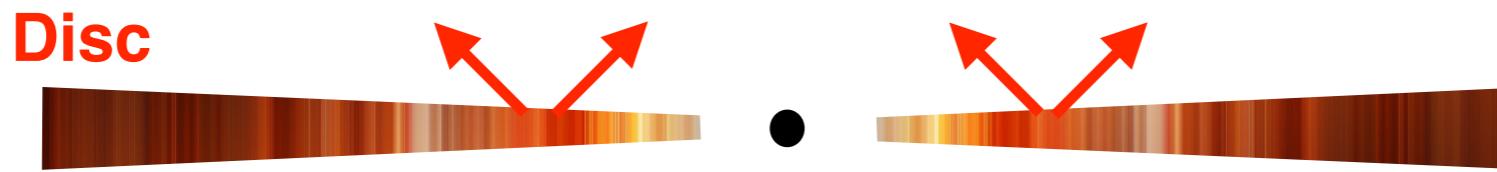
Accretion disc emission

Thermal emission due to dissipation of gravitational energy



Accretion disc emission

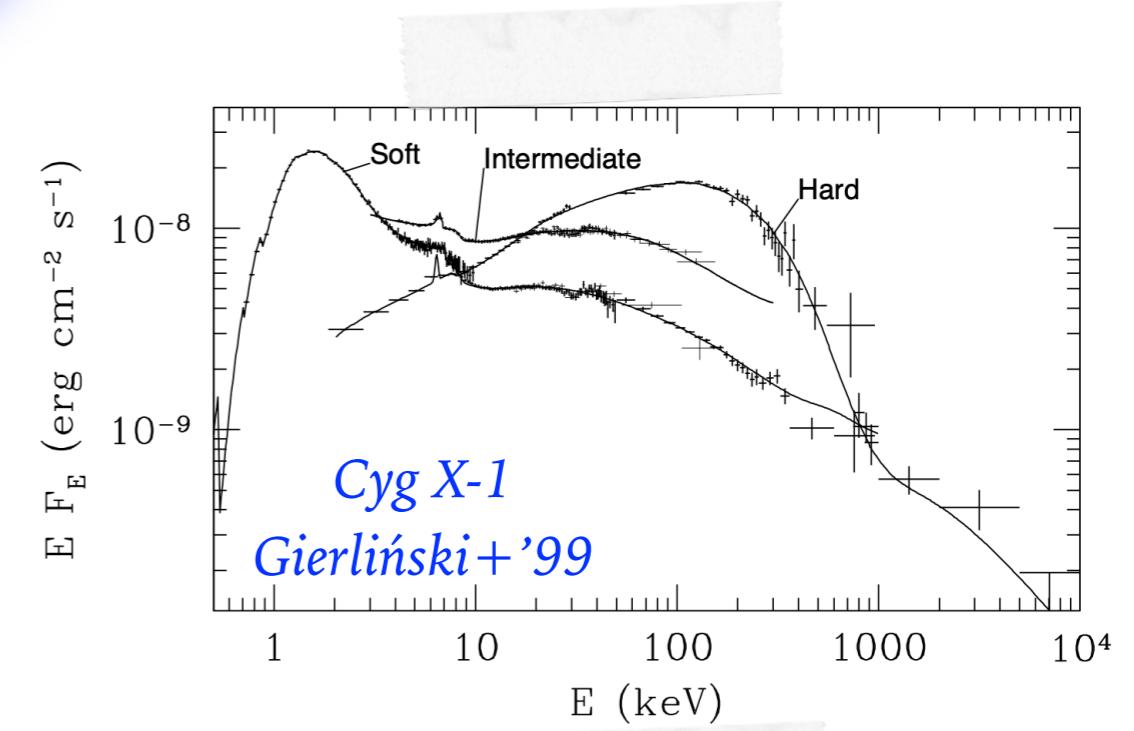
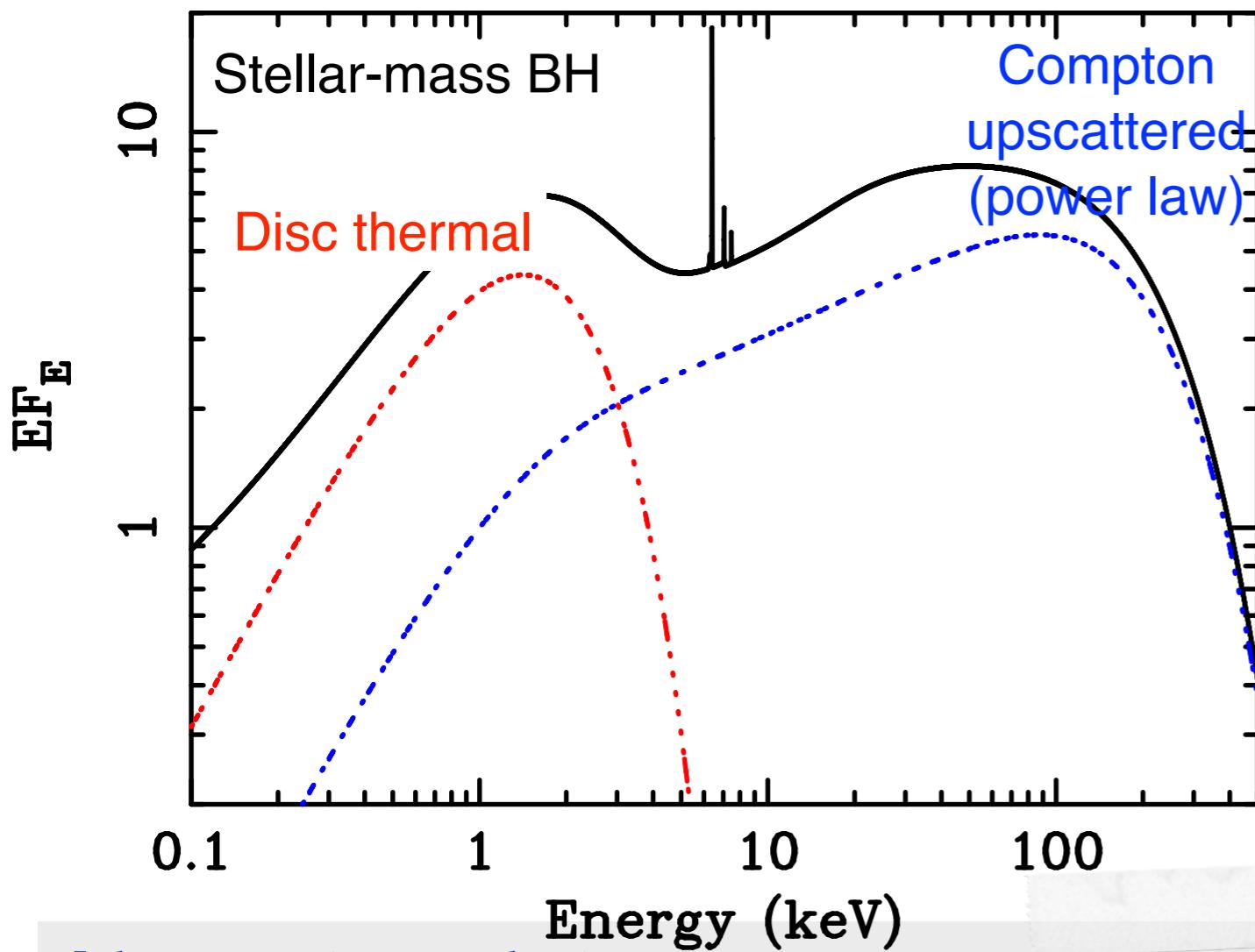
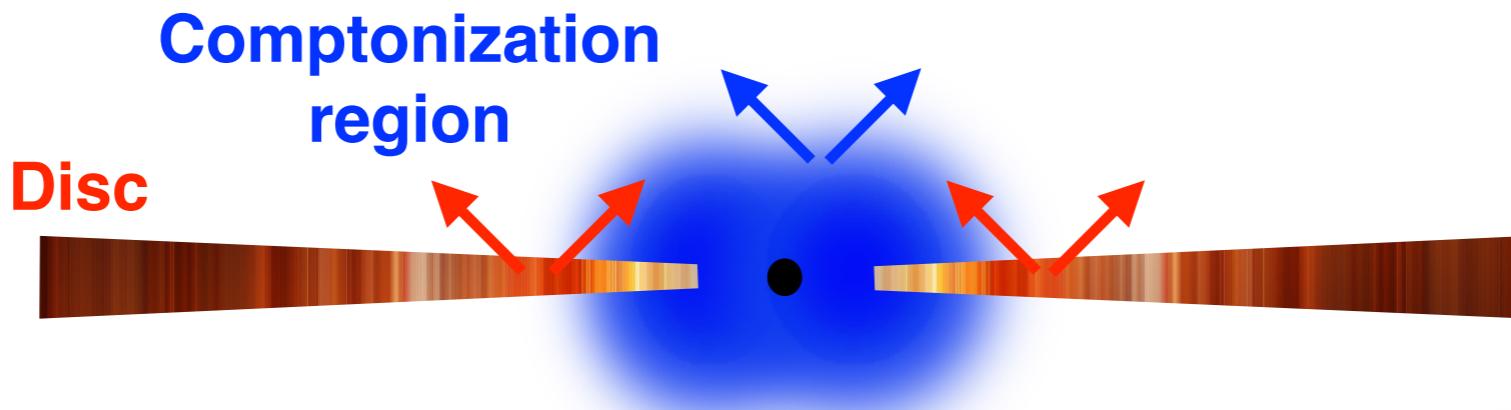
Thermal emission due to dissipation of gravitational energy



Can explain the soft state of BHs

The hard X-ray source

Disc photons get energized in a hot inner plasma (corona, hot flow...)



Needed to explain the hard and intermediate states of BHs

Open questions

What is the nature of the different accretion states?

How are jets launched?

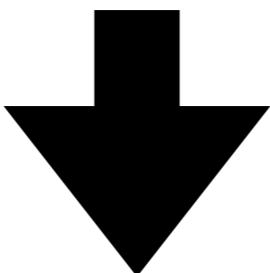
What is the nature of the X-ray source and where is it located?

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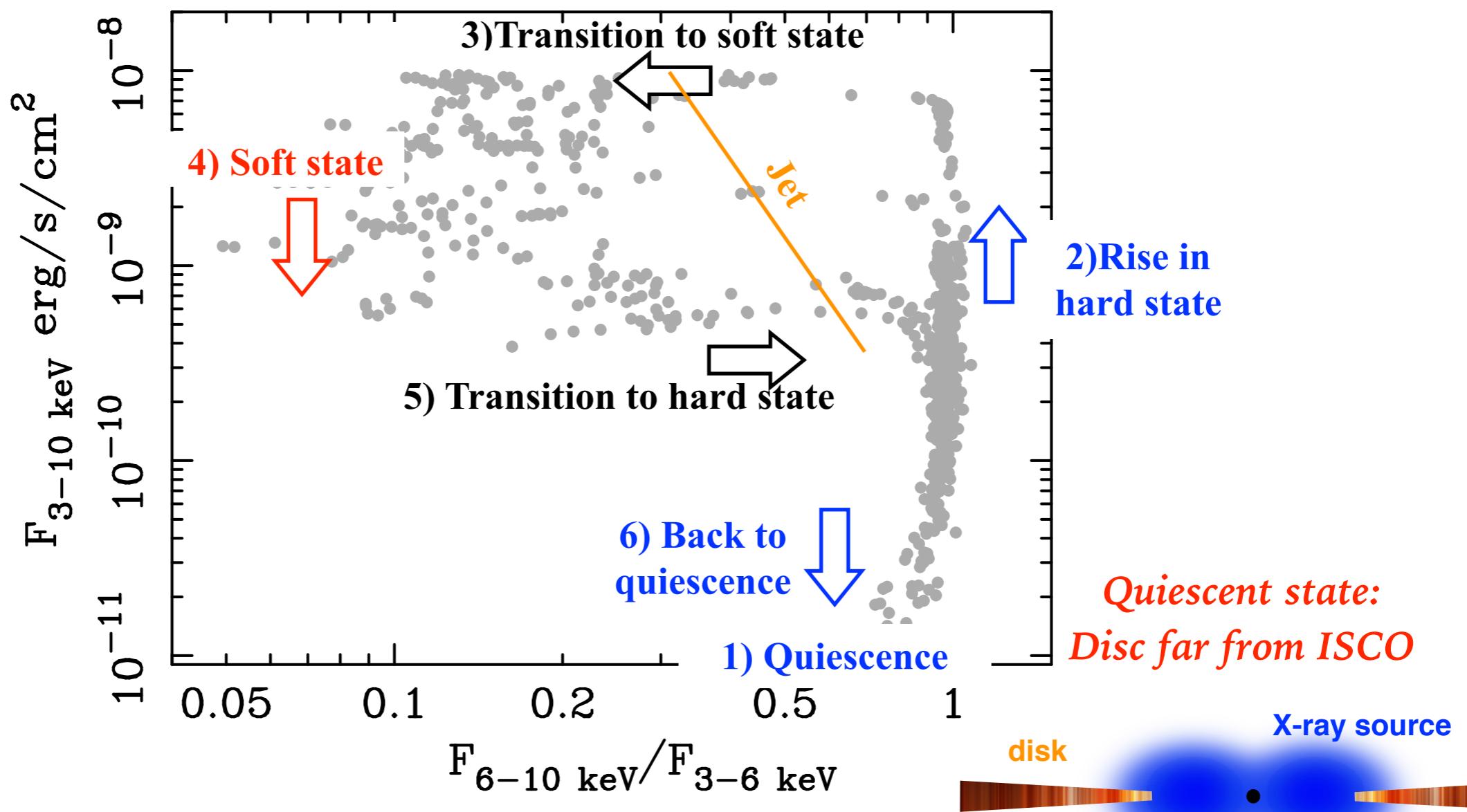
What is the nature of the X-ray source and where is it located?



Inner accretion flow geometry may play an important role

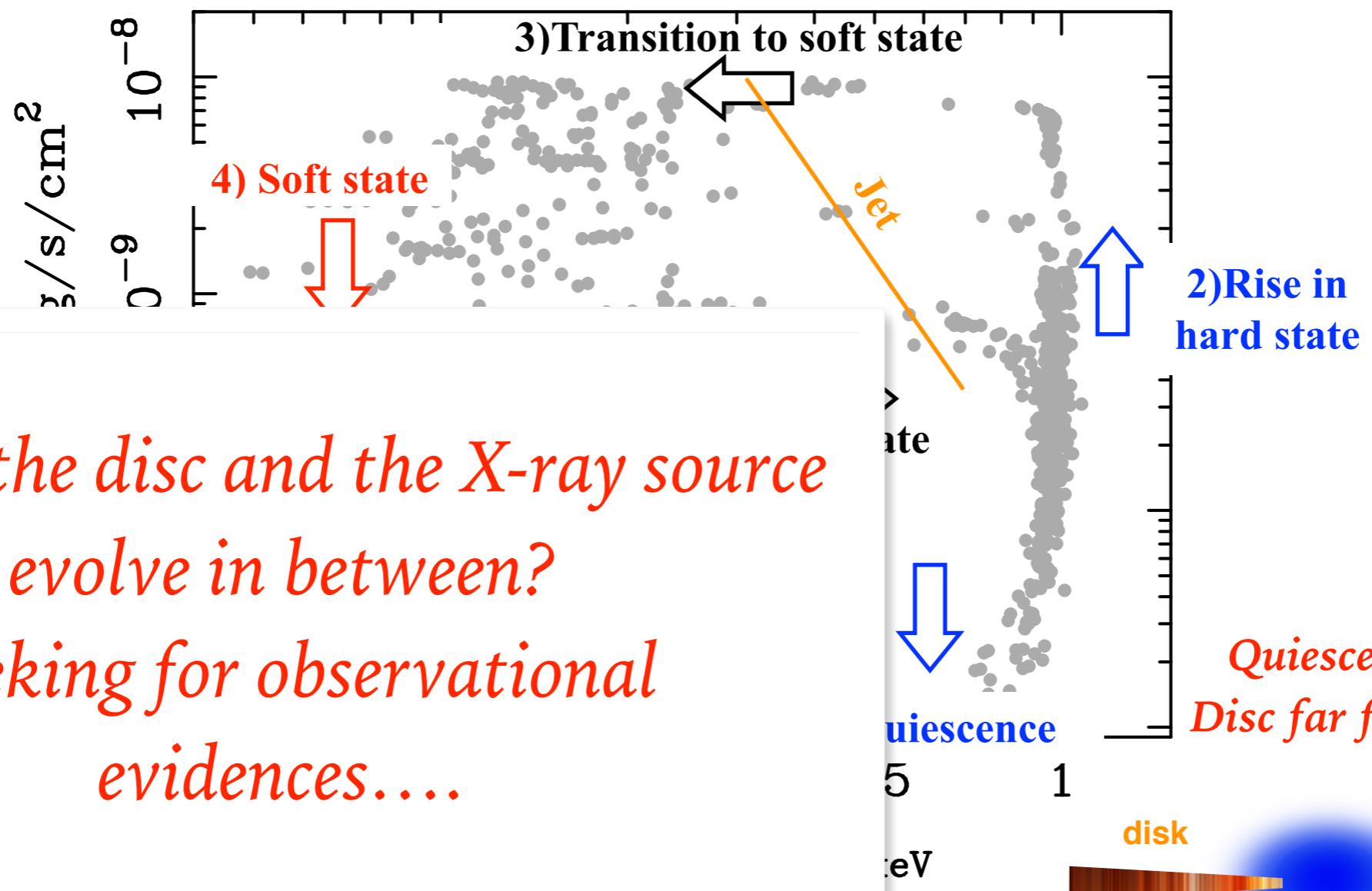
Accretion states: variations of inner flow geometry to explain the outburst evolution of BHs

Soft state: Disc close to ISCO



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Soft state: Disc close to ISCO

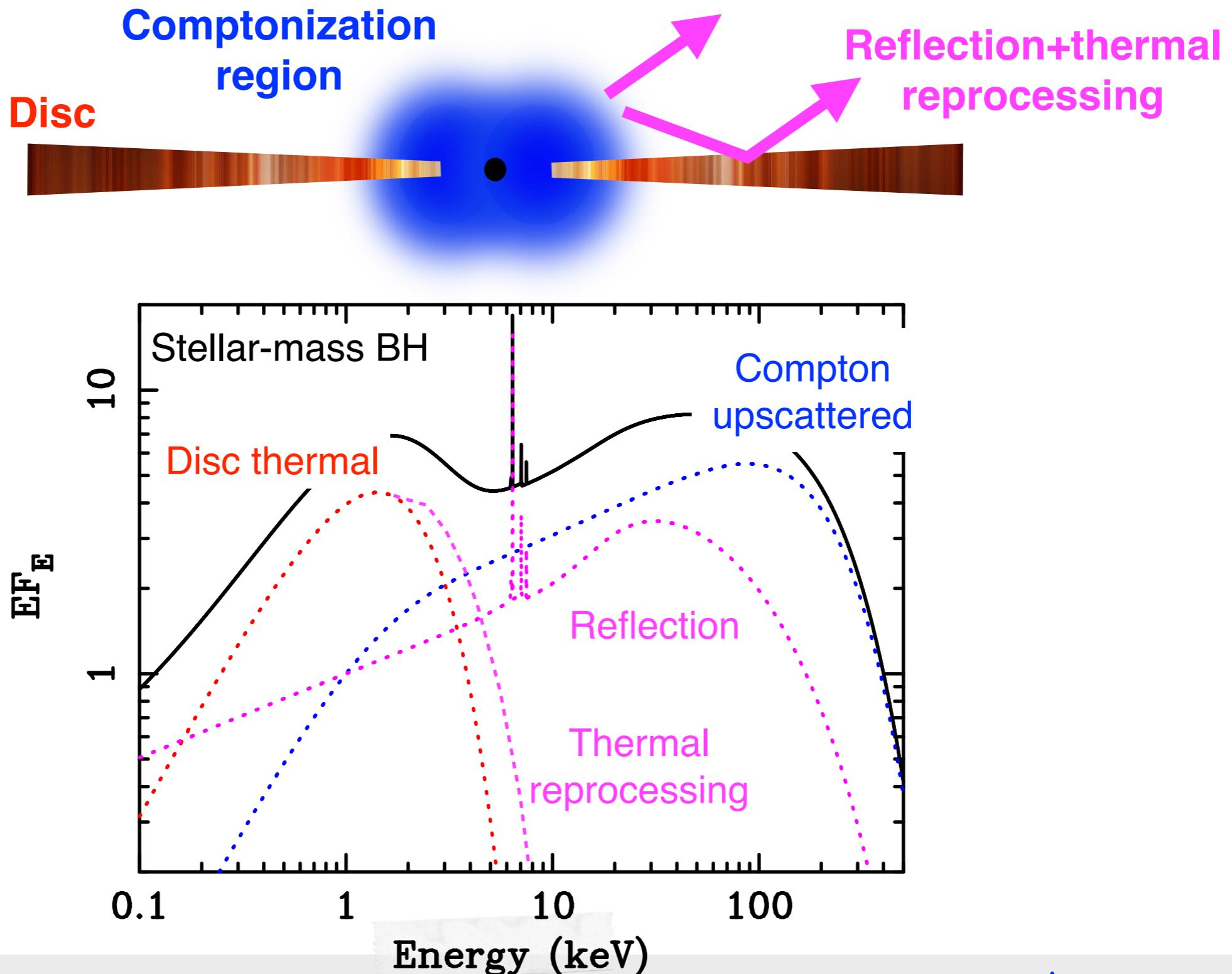


How do the disc and the X-ray source
evolve in between?

Seeking for observational
evidences....

The X-ray spectrum: reprocessing

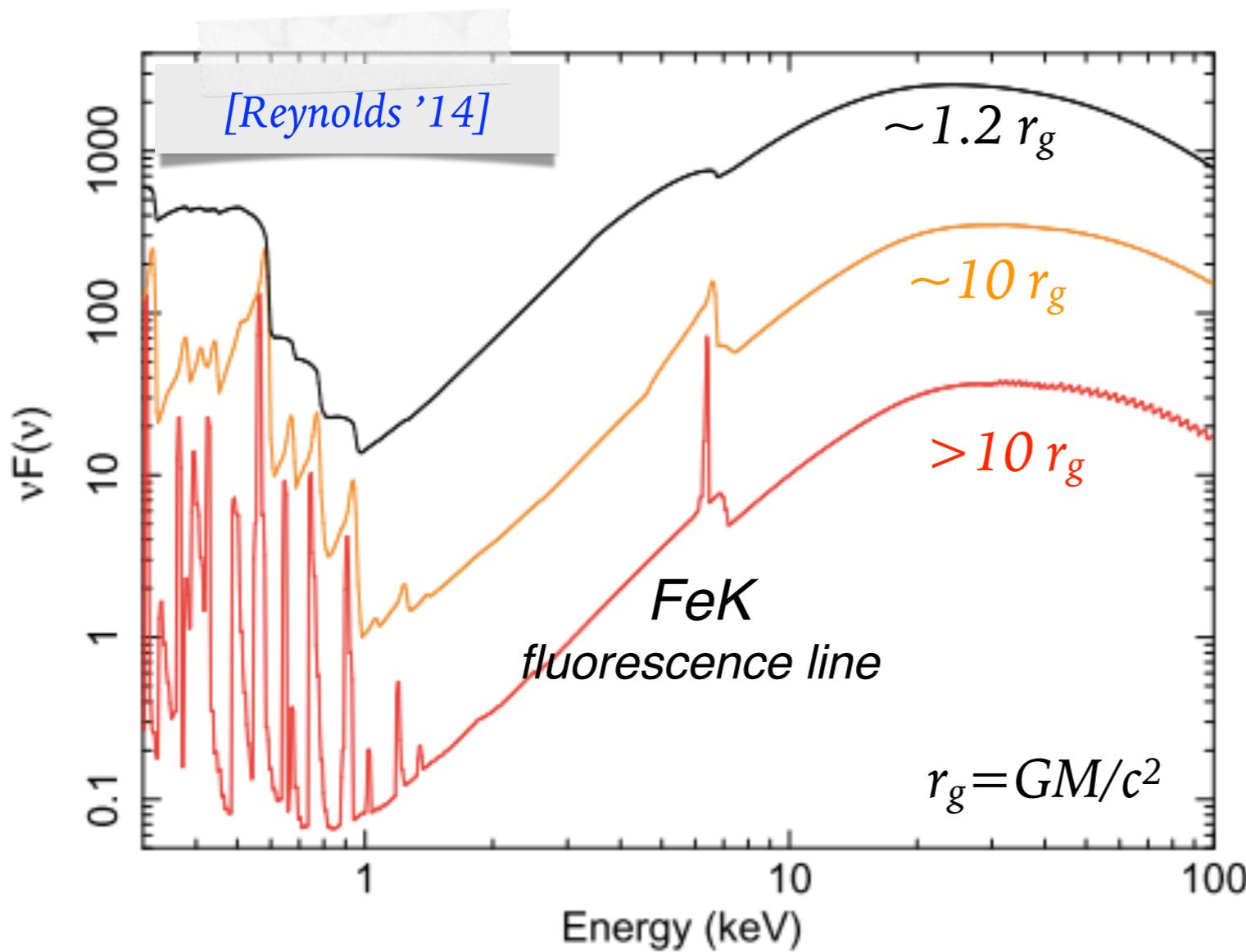
A fraction of hard X-ray photons is reflected+thermally reprocessed in the disk



[Guilbert & Rees '88; Fabian + '89; Matt + '97; Ballantyne + '01; Ross & Fabian '93; Matt + '93; Życki & Czerny '94;
Magdziarz & Zdziarski '95; Nayakshin + '01; Dauser + '16; García + '16; Tomsick + '18]

Relativistic effects in the X-ray spectrum

Relativistic effects create distortions, clearly visible in reflection spectra



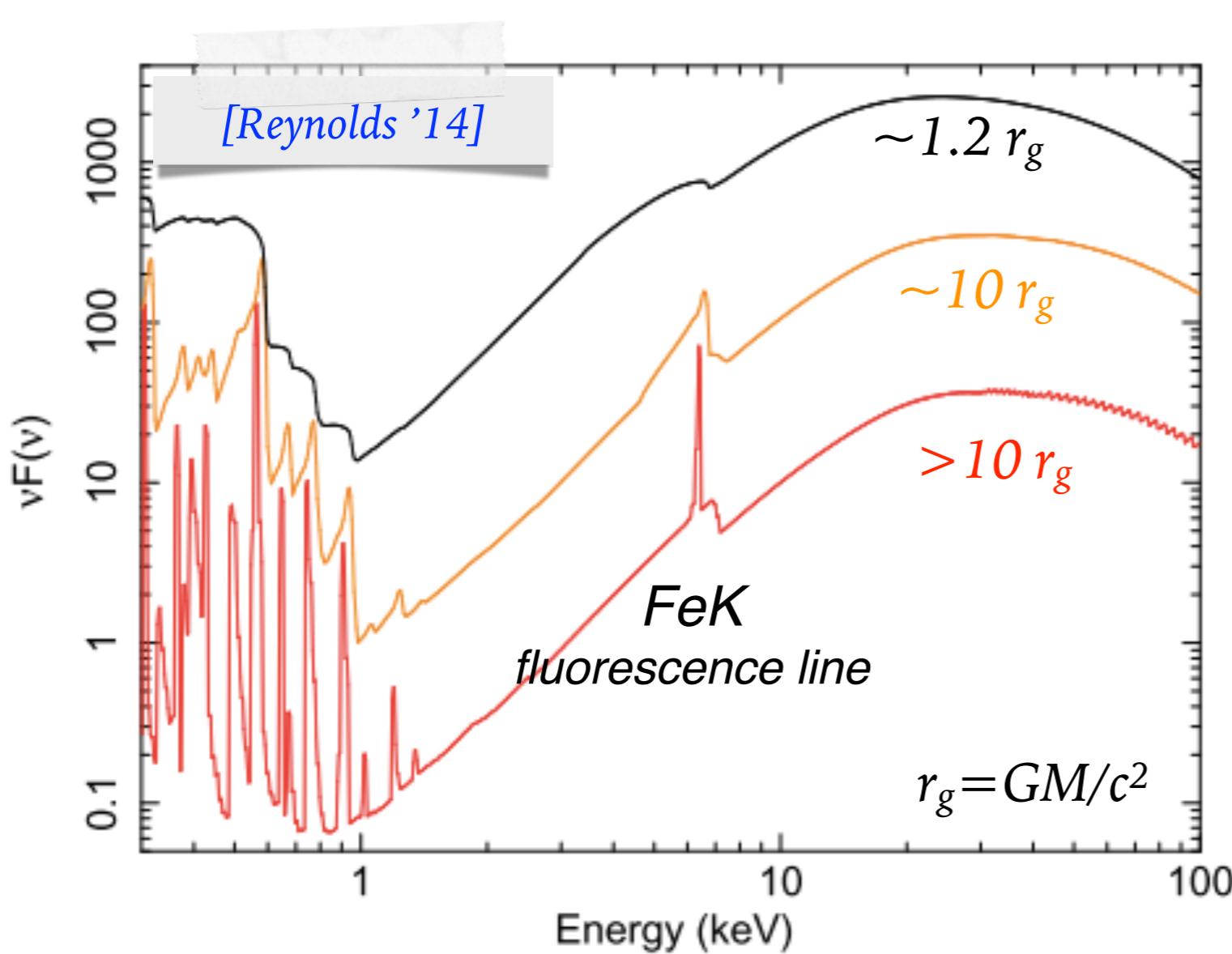
extreme relativity: reflecting material located close to BH



no-relativity: reflecting material far from BH

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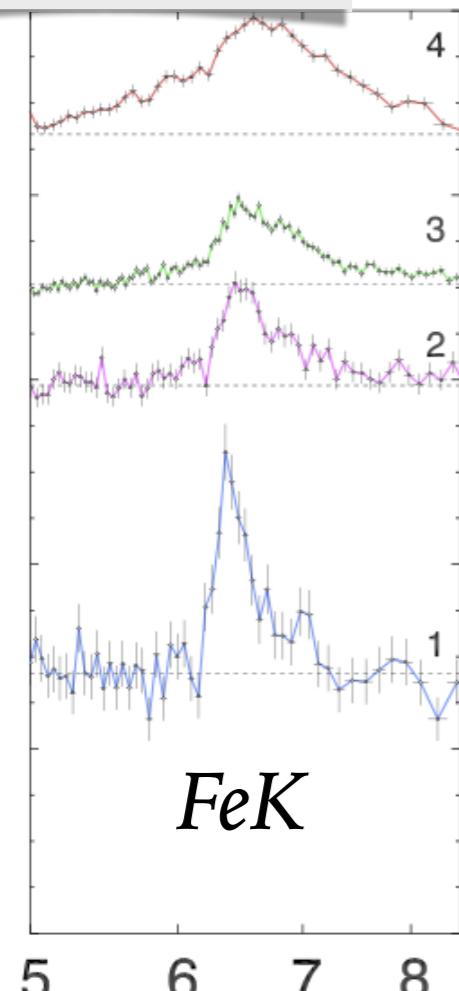
Fitting reflection spectrum allows us to obtain constraints on the inner radius of the accretion disc

Constraints on the inner disc radius in hard state

Powerful method, but not unique solution

[Plant +'15]

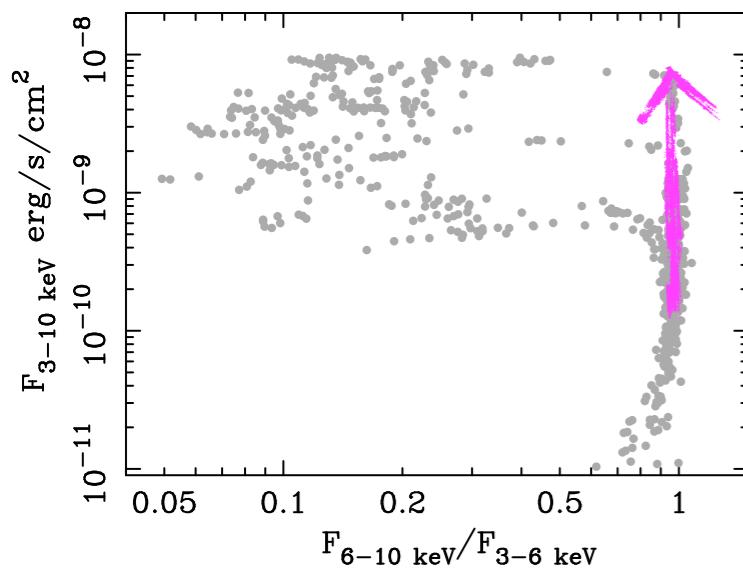
Data / Model



Luminosity
(Hard state)

FeK

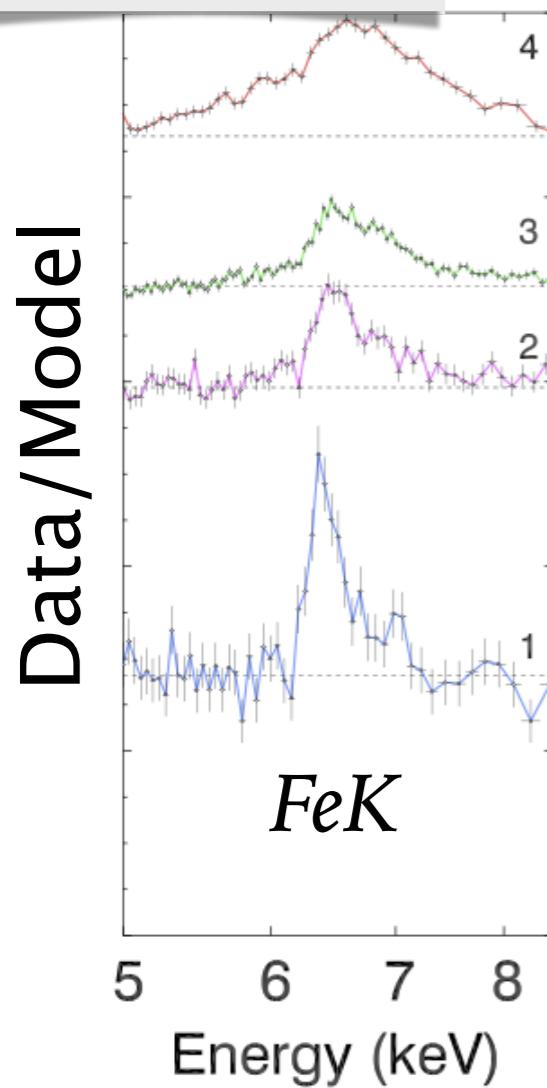
Energy (keV)



Constraints on the inner disc radius in hard state

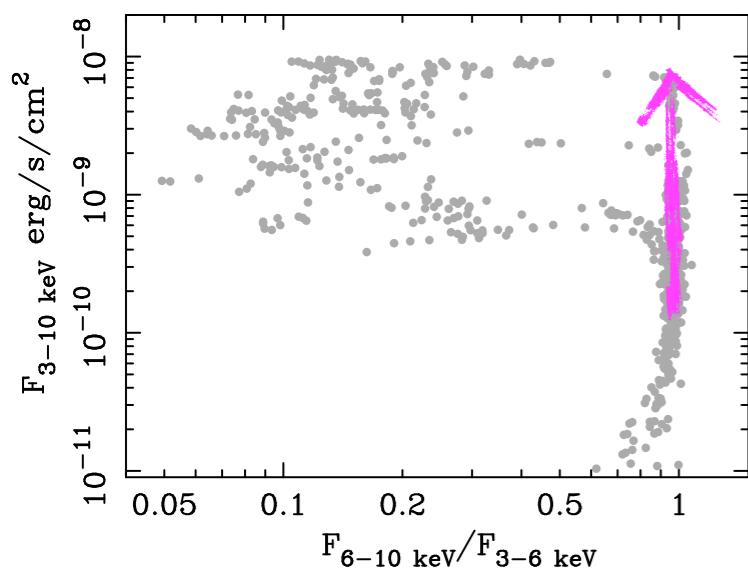
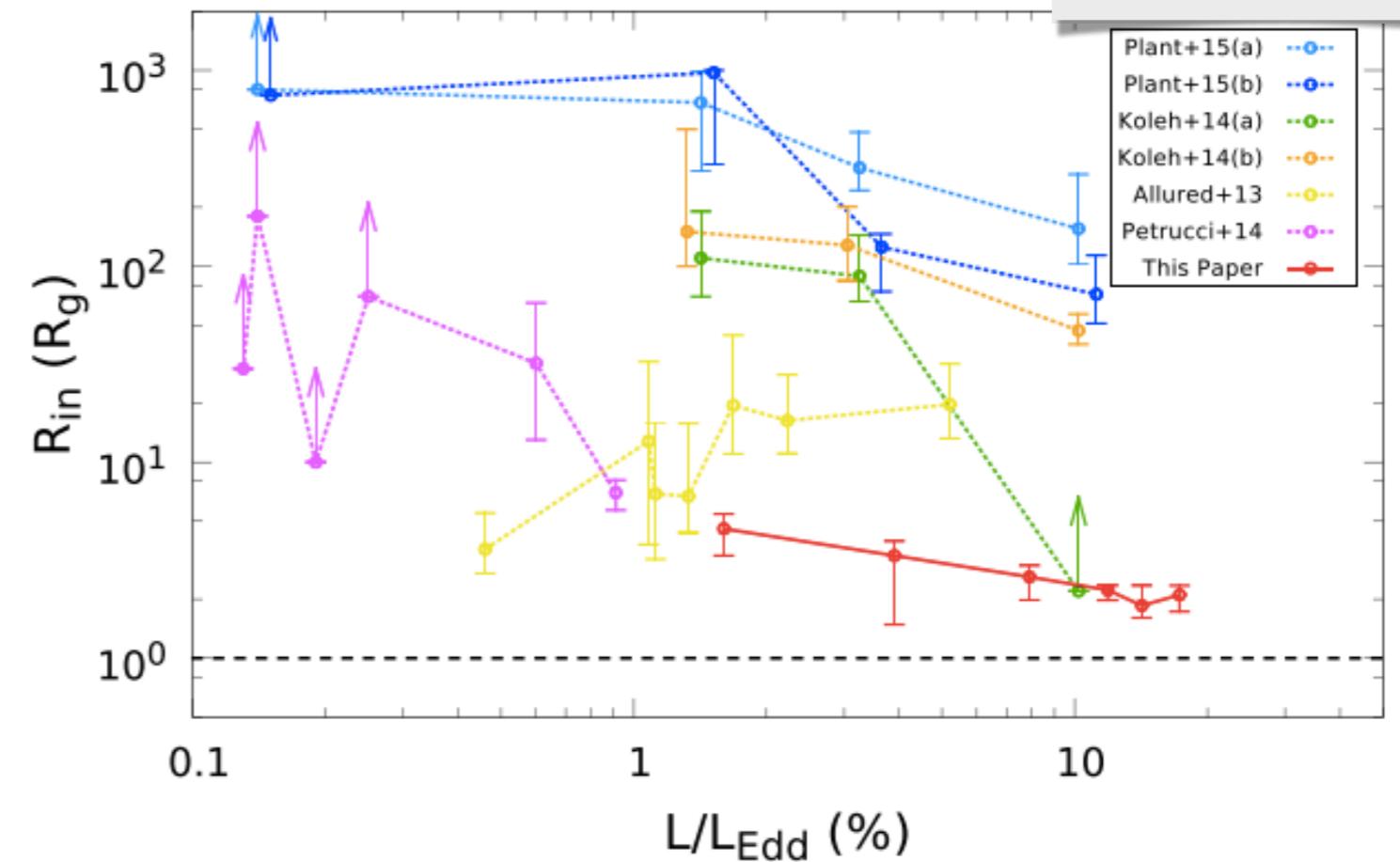
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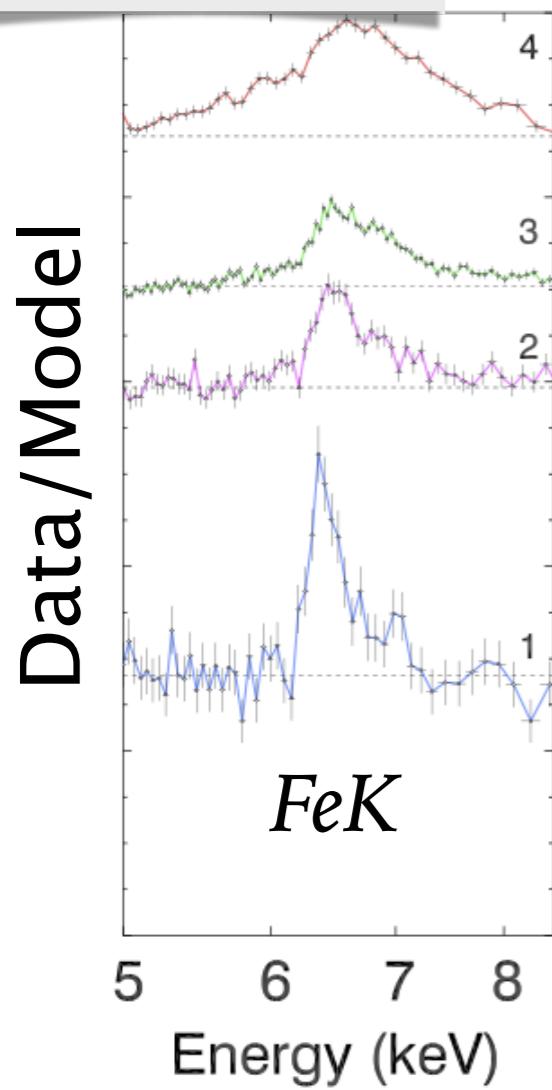
[García +'15]



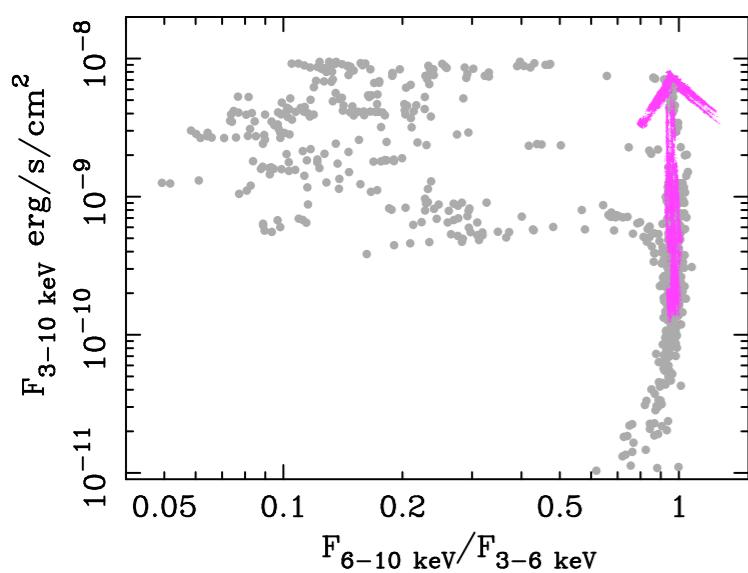
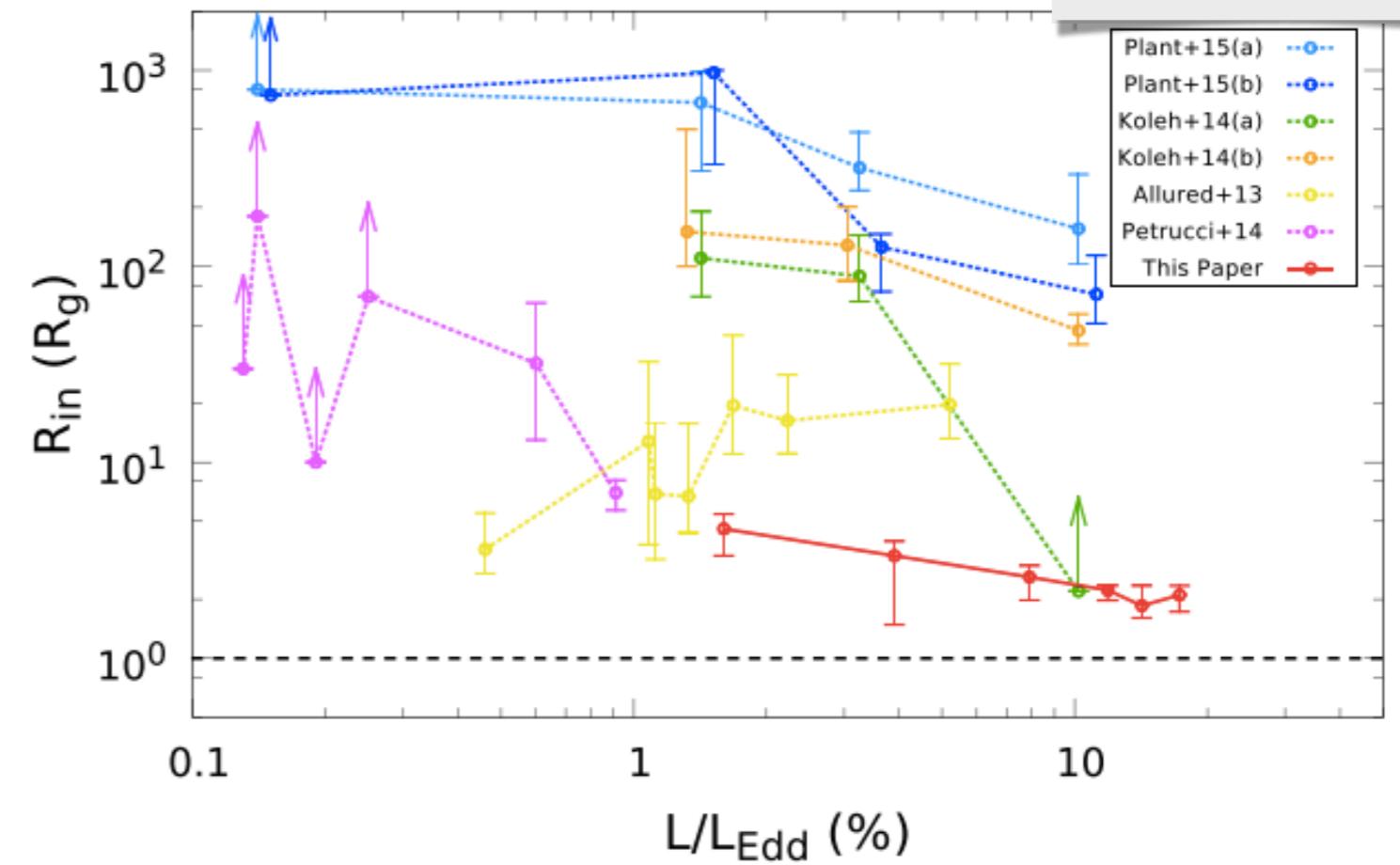
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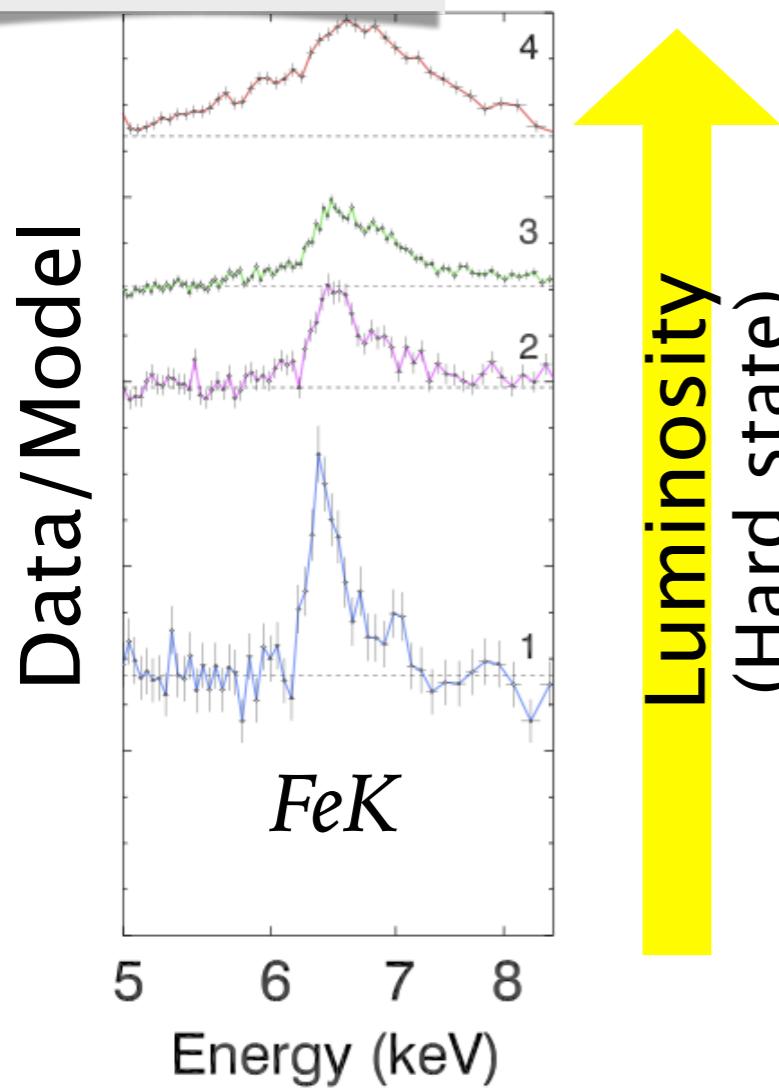


Results span ~ 3
orders of
magnitude!

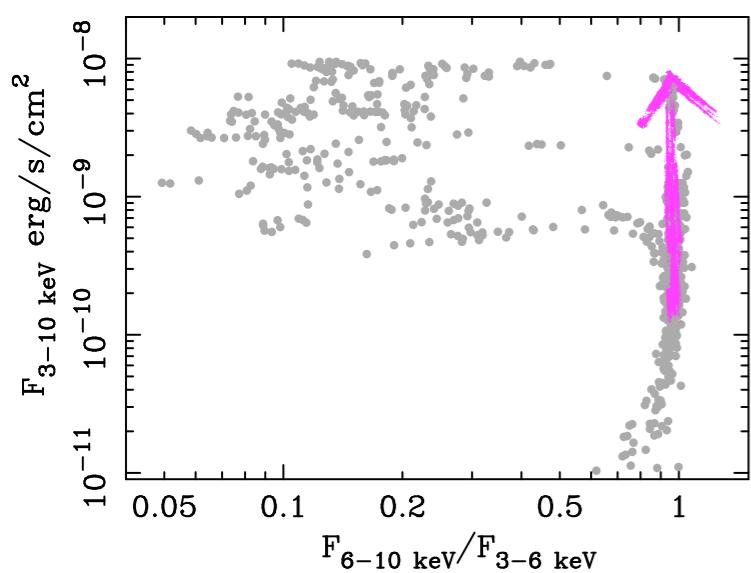
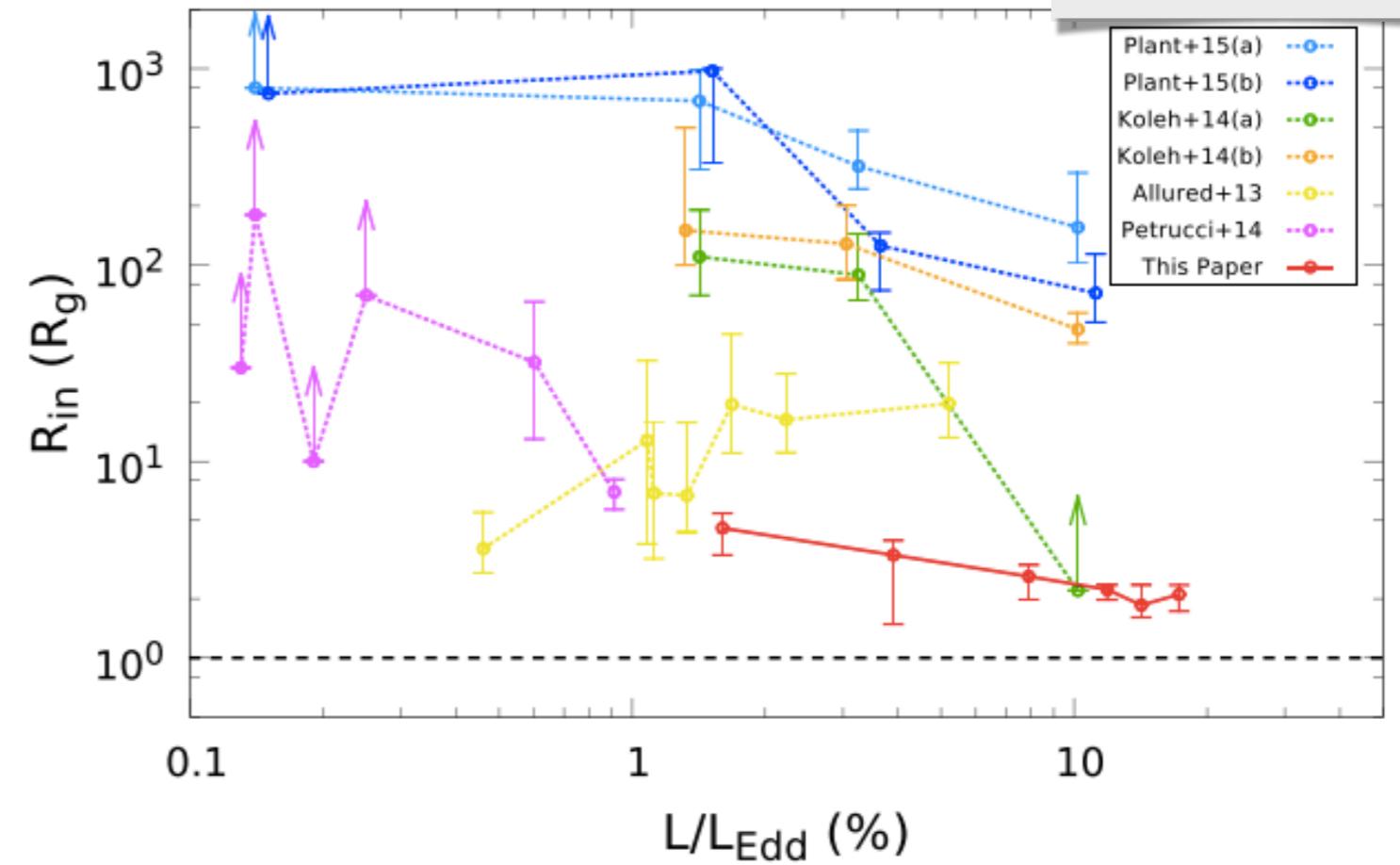
Constraints on the inner disc radius in hard state

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Results span ~ 3 orders of magnitude!

Some estimates suggest the disc reaches close to the ISCO very early in the outburst

Alternative methods to constrain geometry

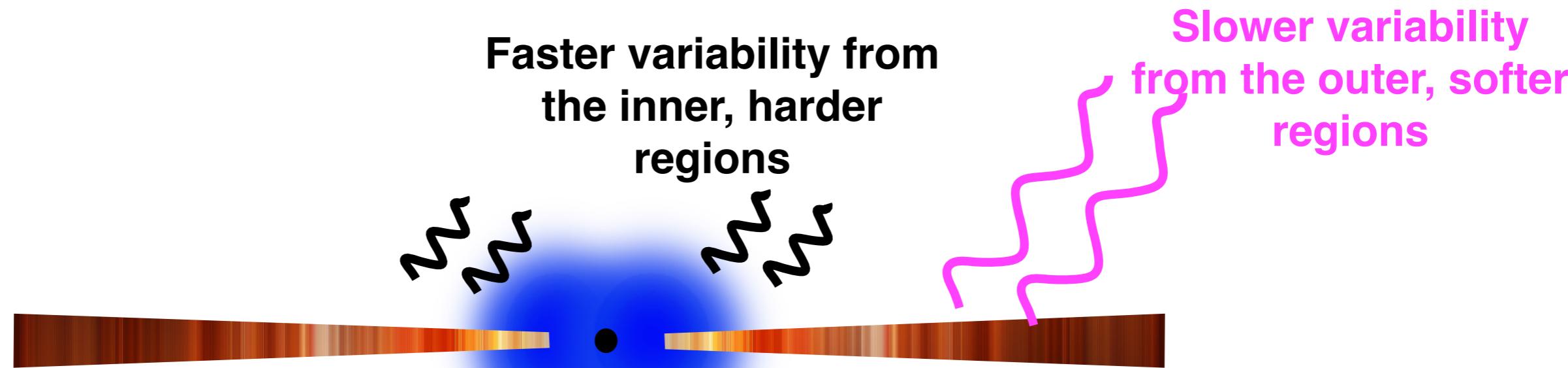
Alternative methods to constrain geometry

X-ray variability

Combined spectral-timing methods can be used to map geometry very close to the BH!

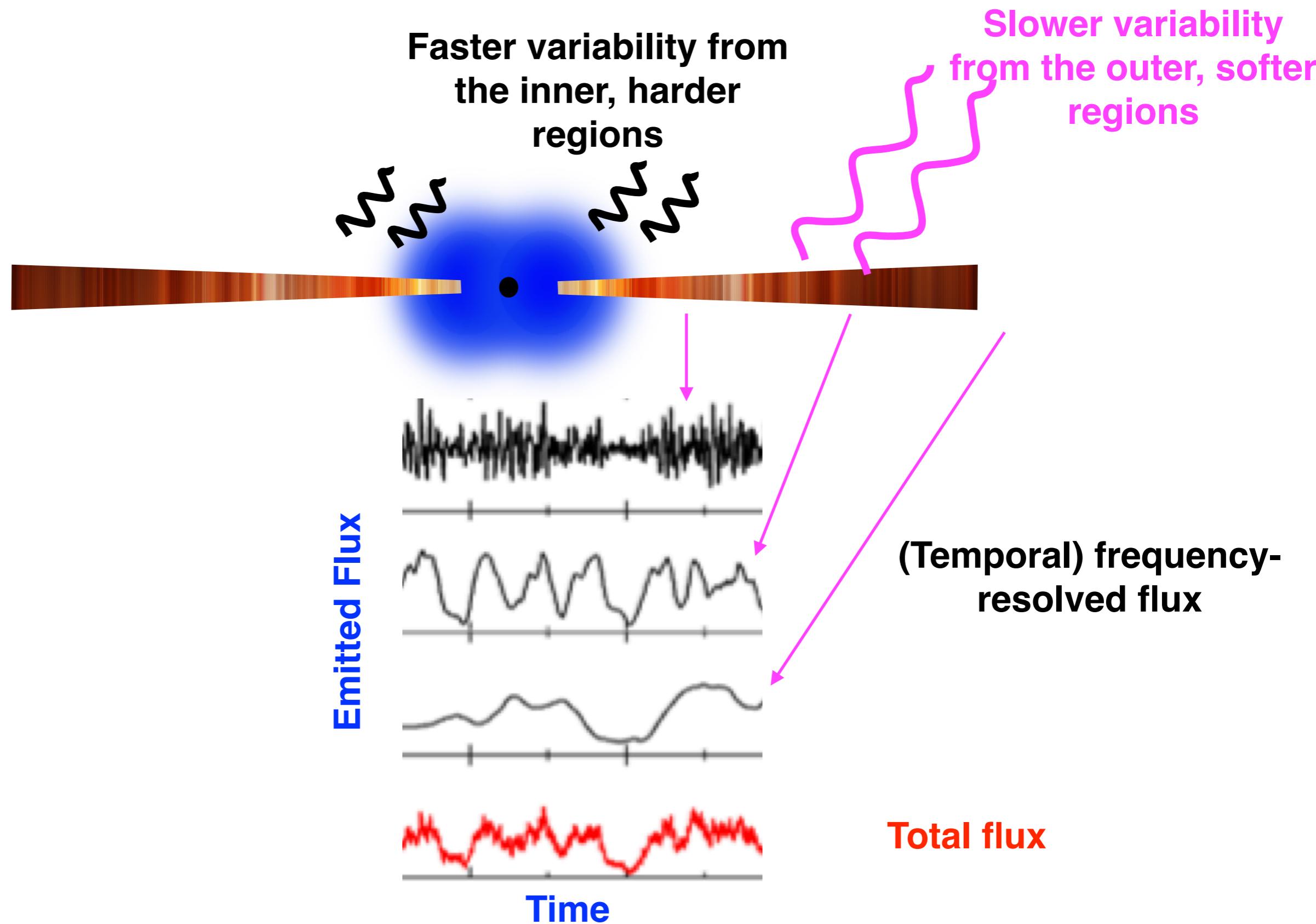
X-ray variability time scales depend on the distance

Allows separating radiation produced at different distances from the BH



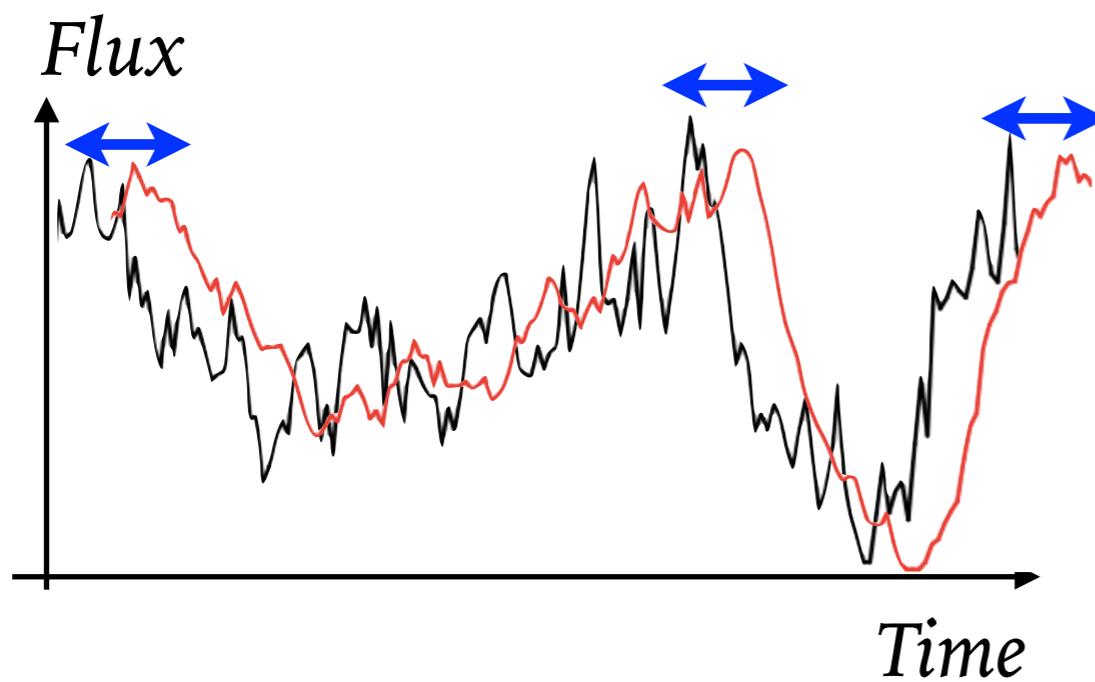
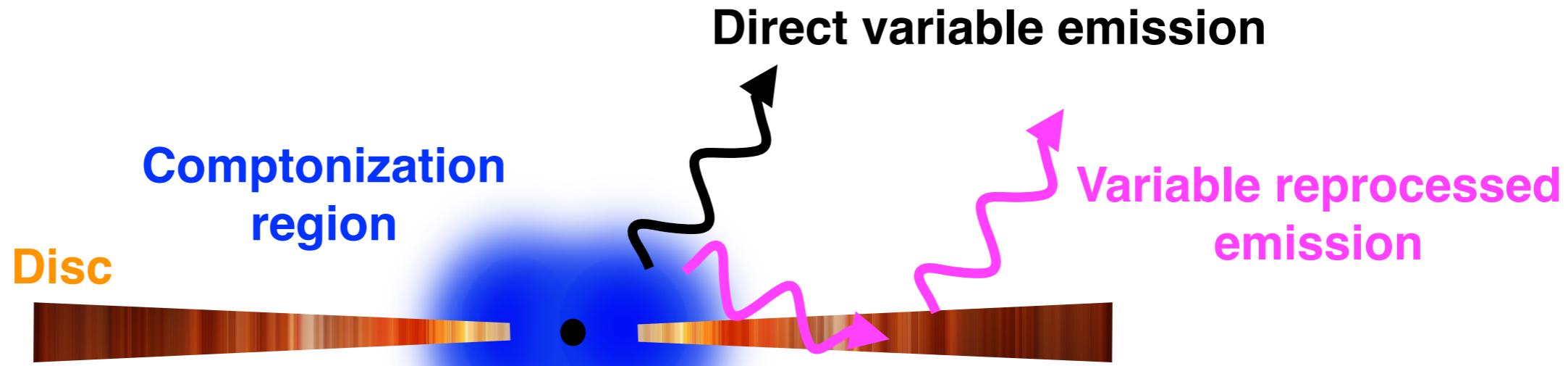
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X-ray reverberation lags

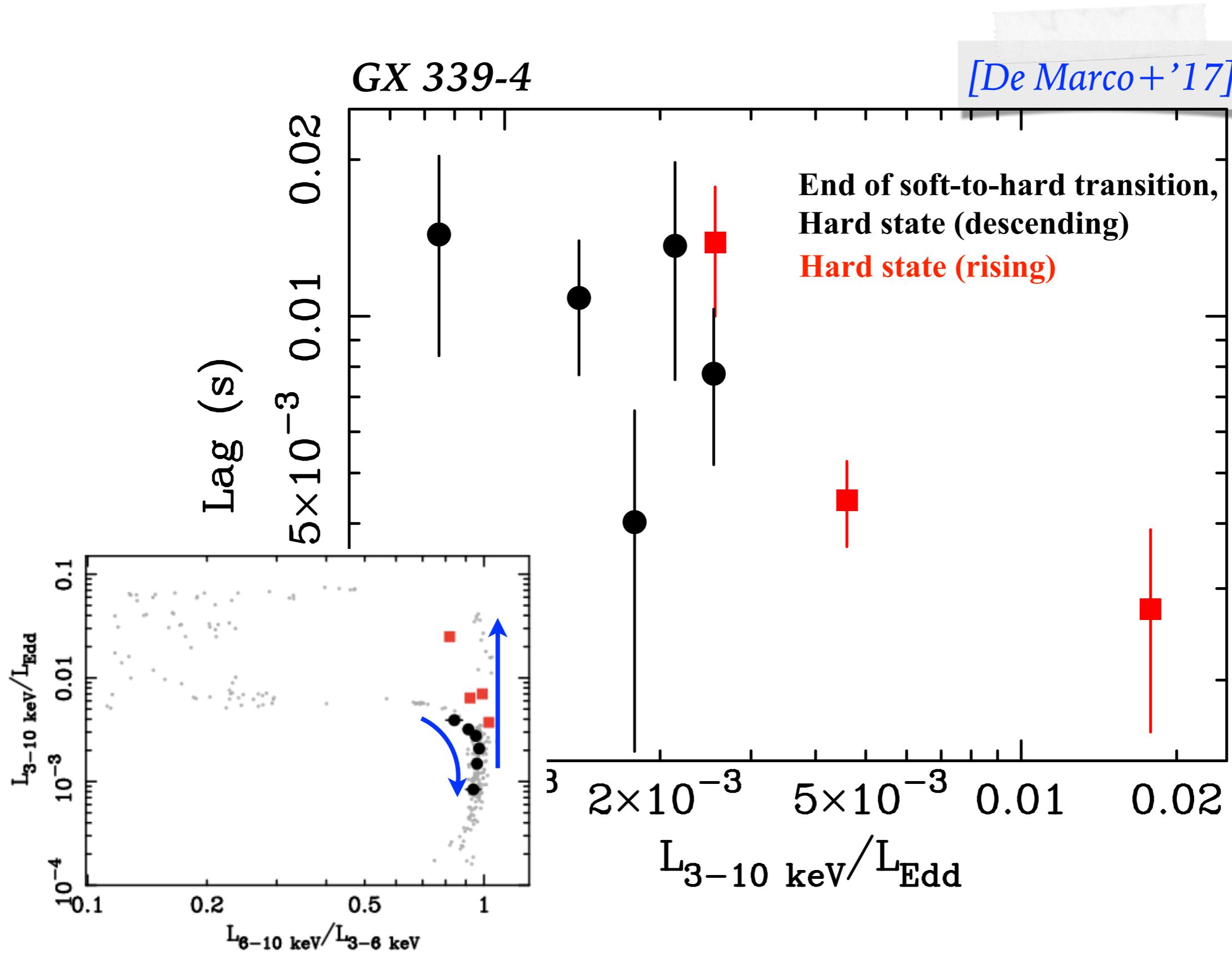
Variable irradiation of the disc produces variable and delayed reprocessed emission



time delays which scale with the distance
between the X-ray source and the disc

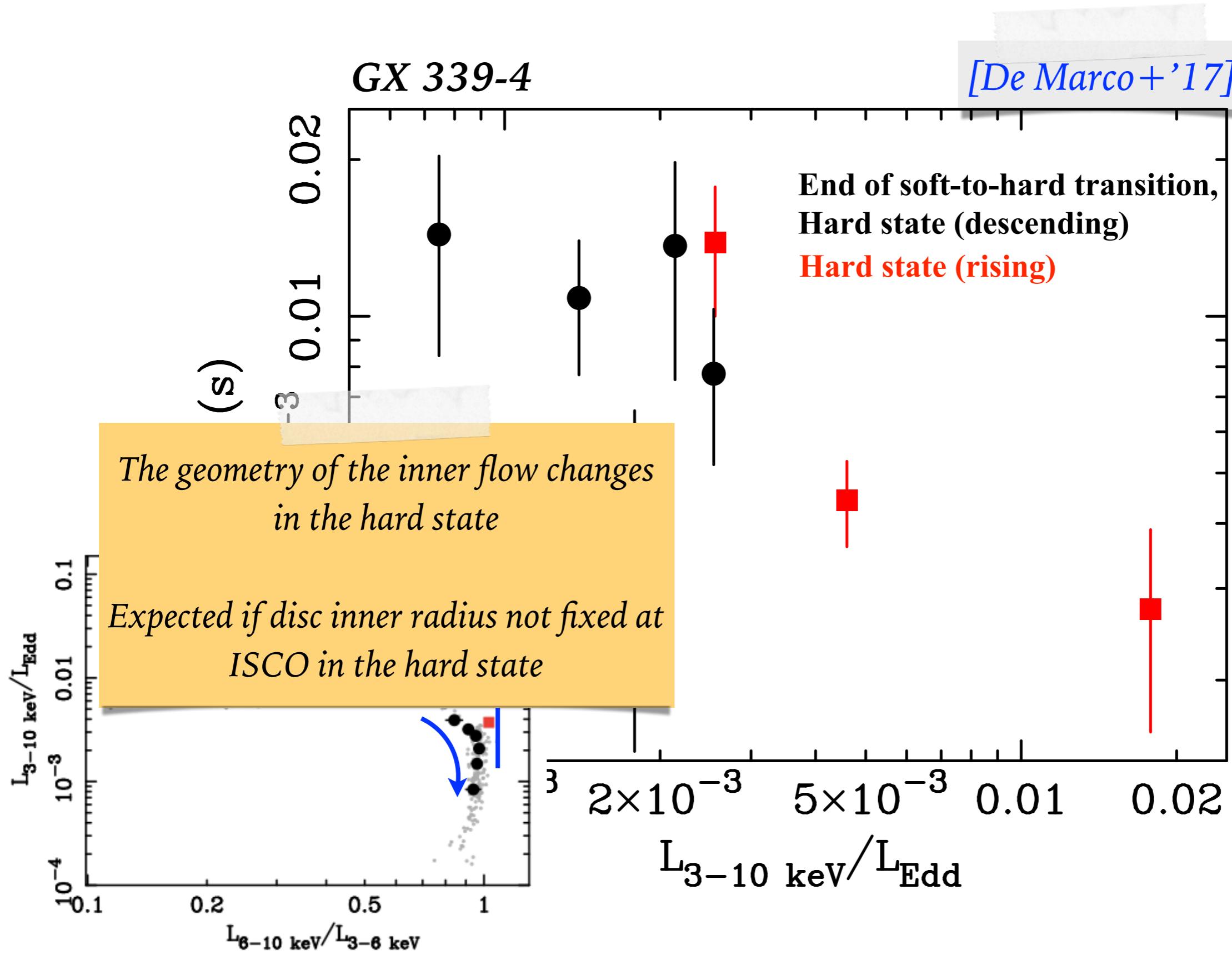
X-ray reverberation during an outburst

Distance mapped by the lag decreases towards luminous hard states



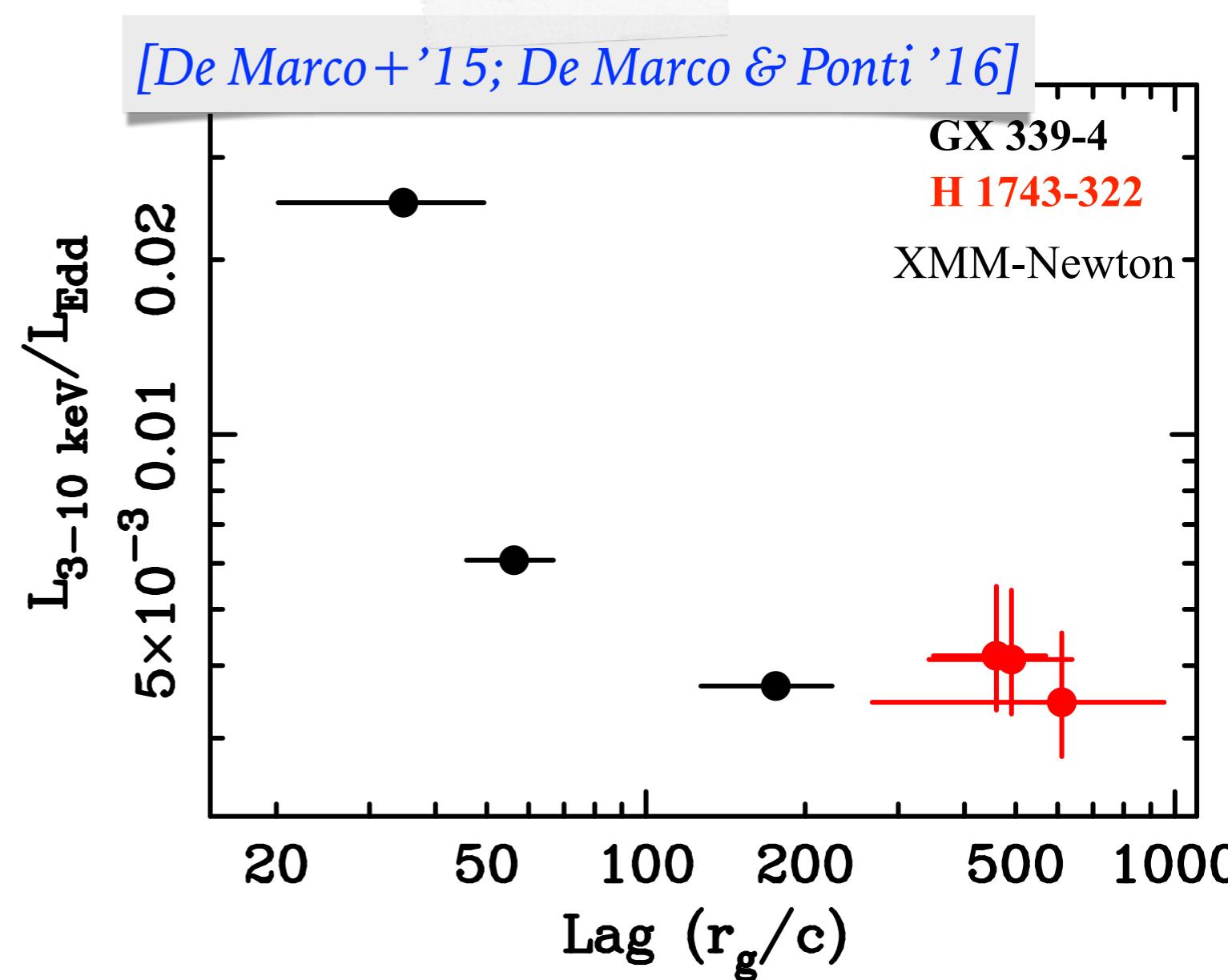
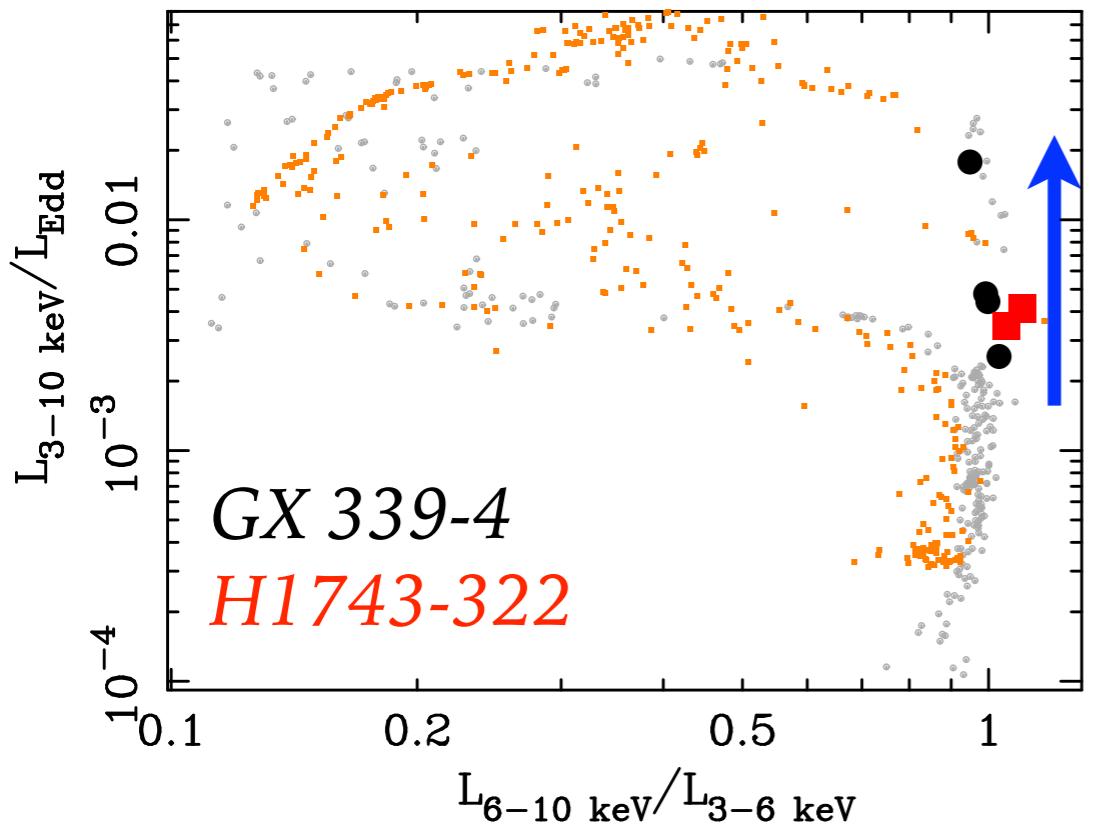
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Evolution of reverberation lag

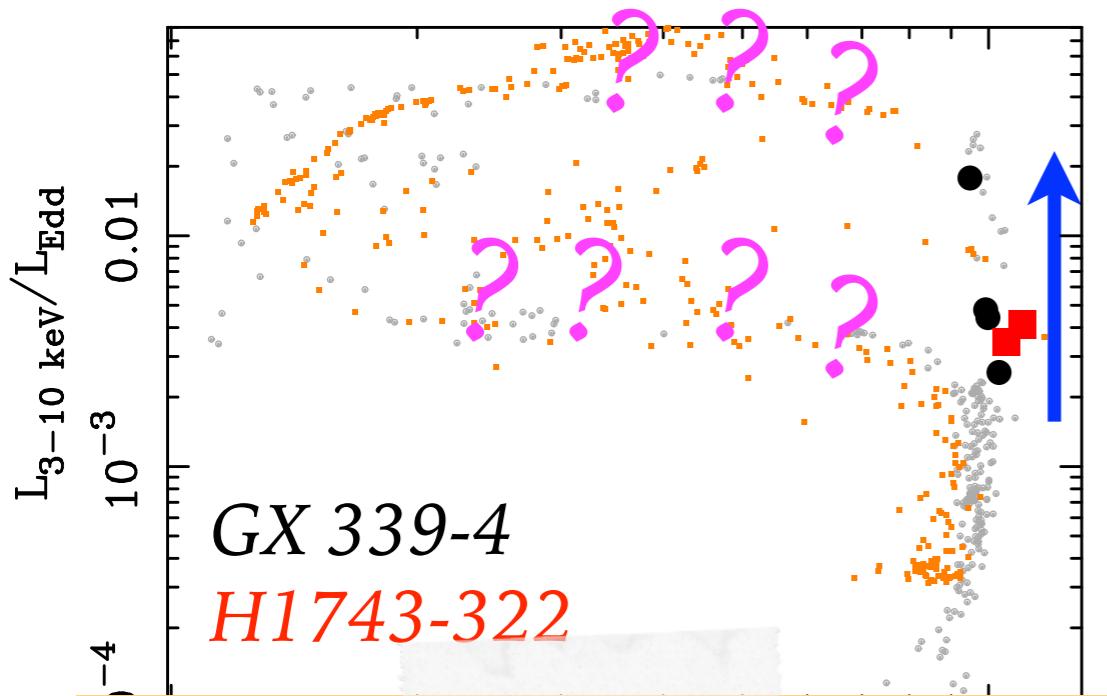
Same behaviour seen in different sources



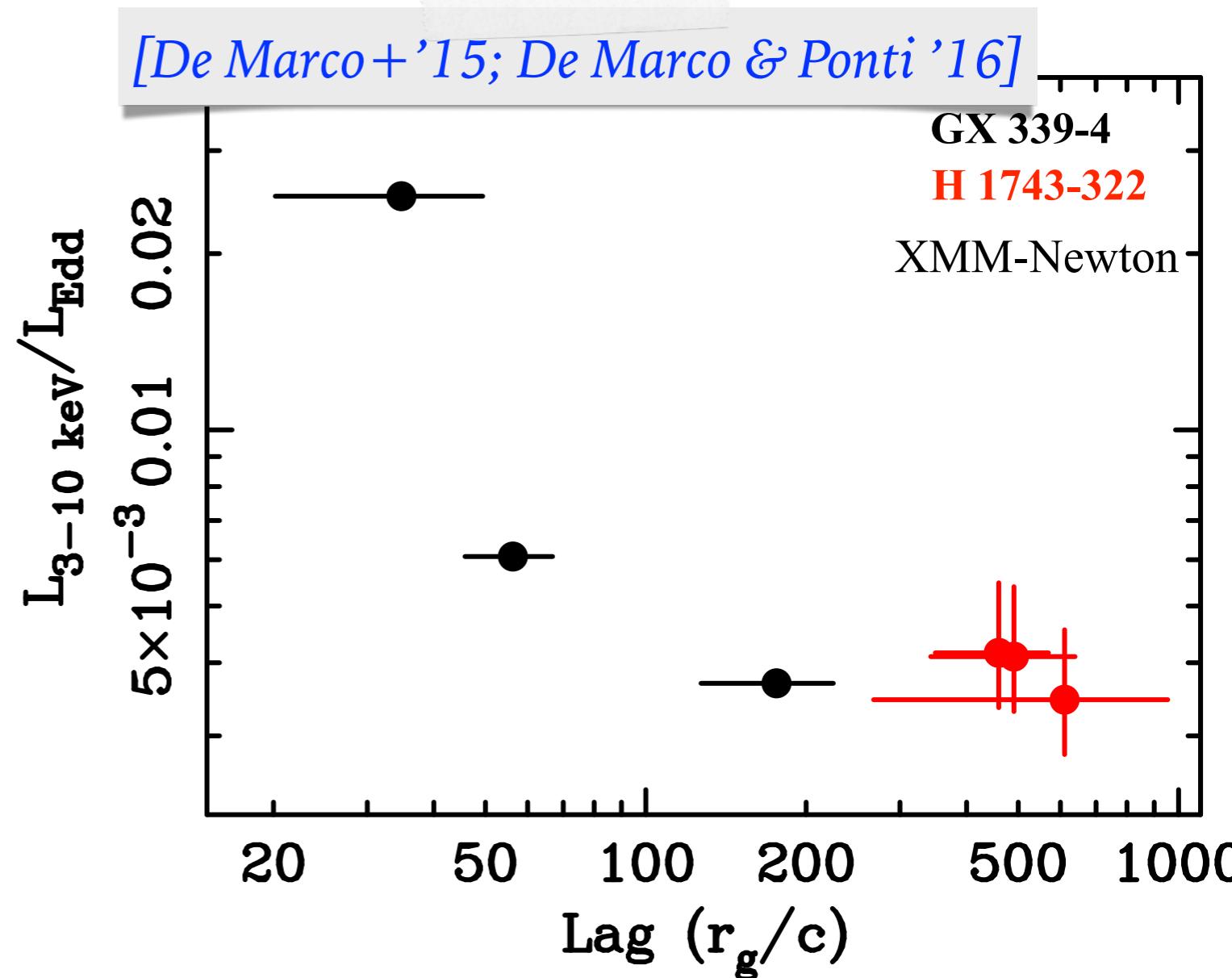
*The reverberation lag decreases as
the source rises in luminosity
throughout the hard state*

Evolution of reverberation lag

Same behaviour seen in different sources



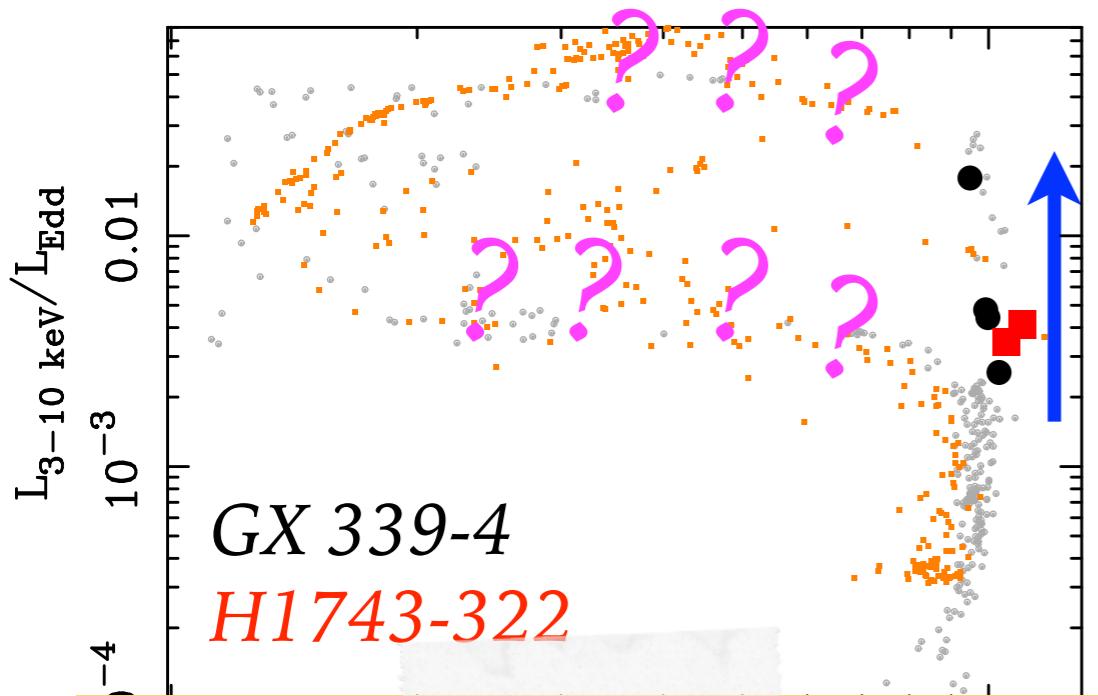
However, data insufficient to map the hard state intensively and to cover the transition...



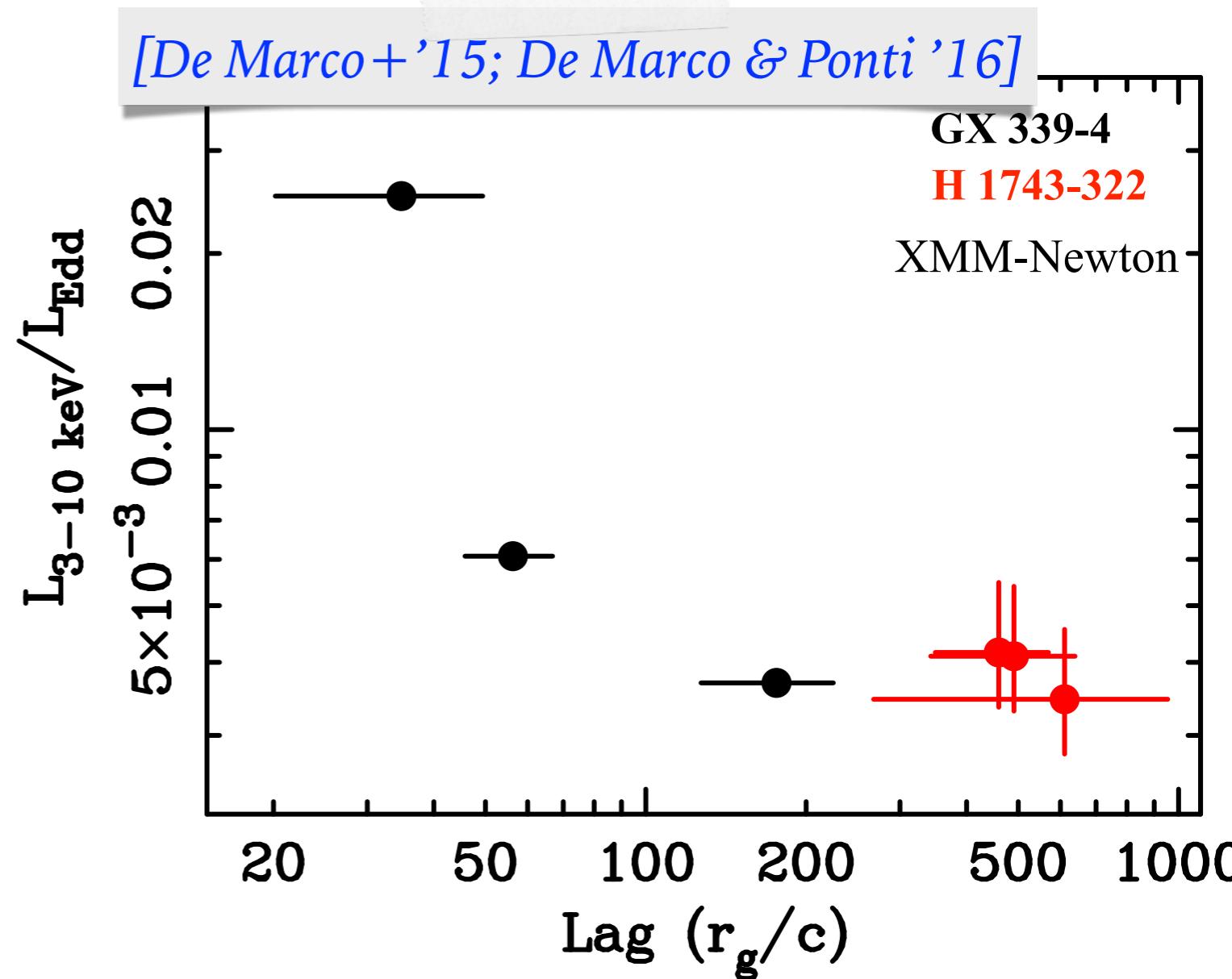
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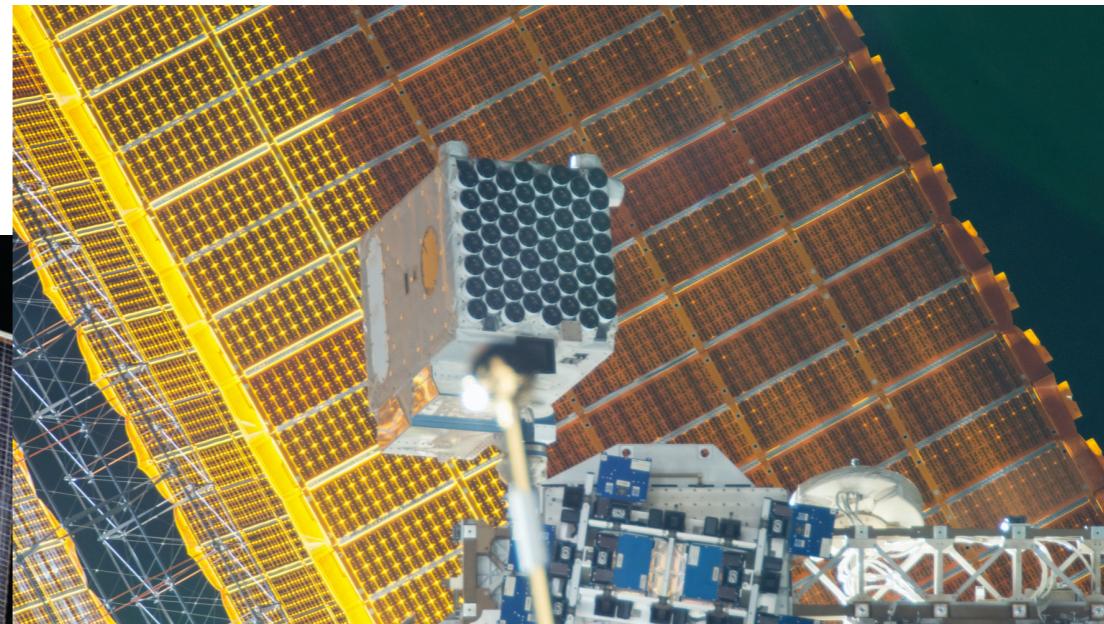
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The reverberation lag decreases as XMM-Newton not designed to perform intensive monitoring and to observe very bright sources

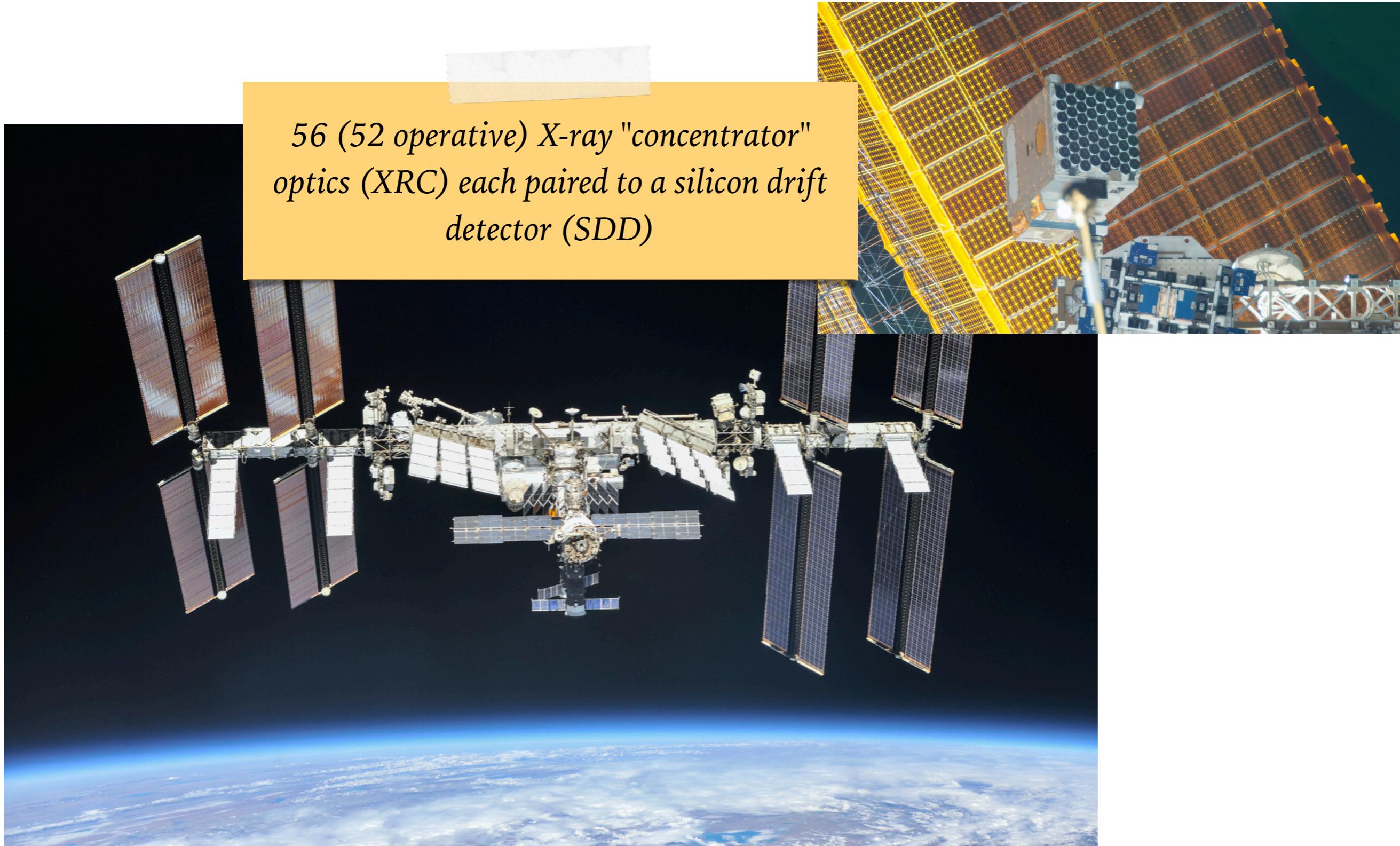
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The Neutron star Interior Composition Explorer (NICER)

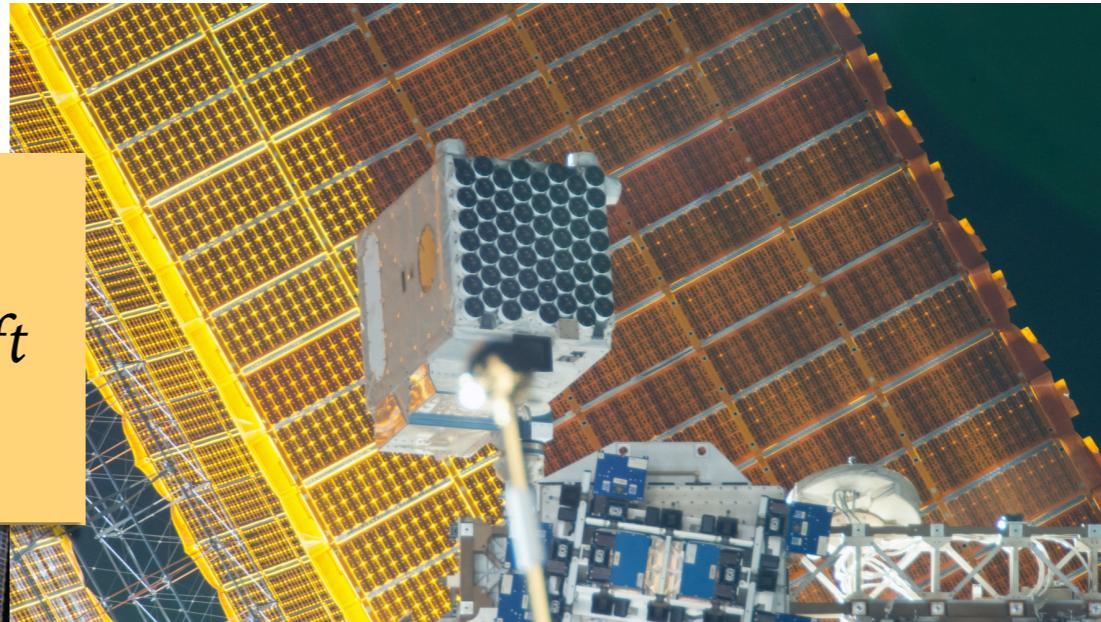
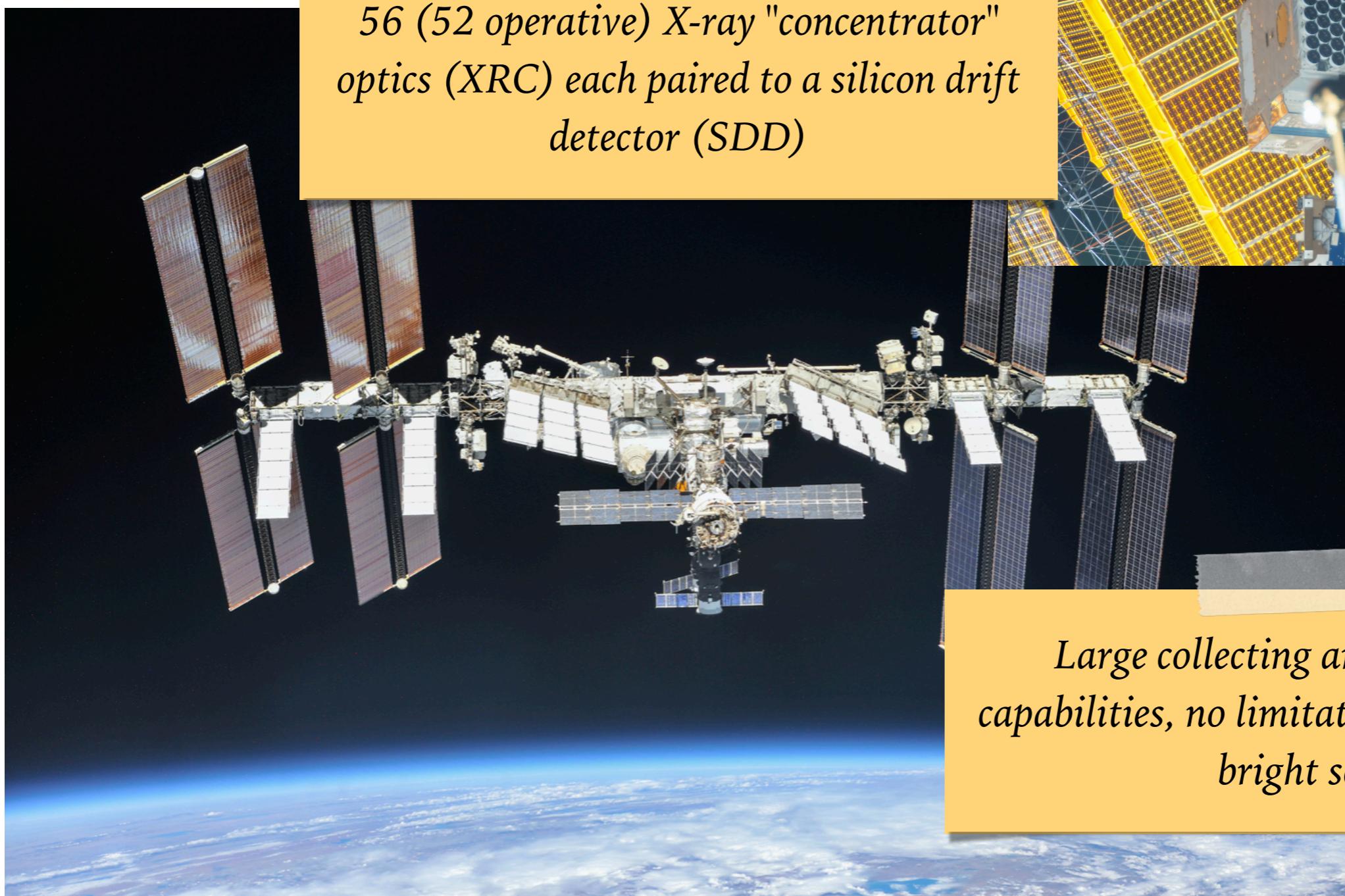


The Neutron star Interior Composition Explorer (NICER)

*56 (52 operative) X-ray "concentrator"
optics (XRC) each paired to a silicon drift
detector (SDD)*



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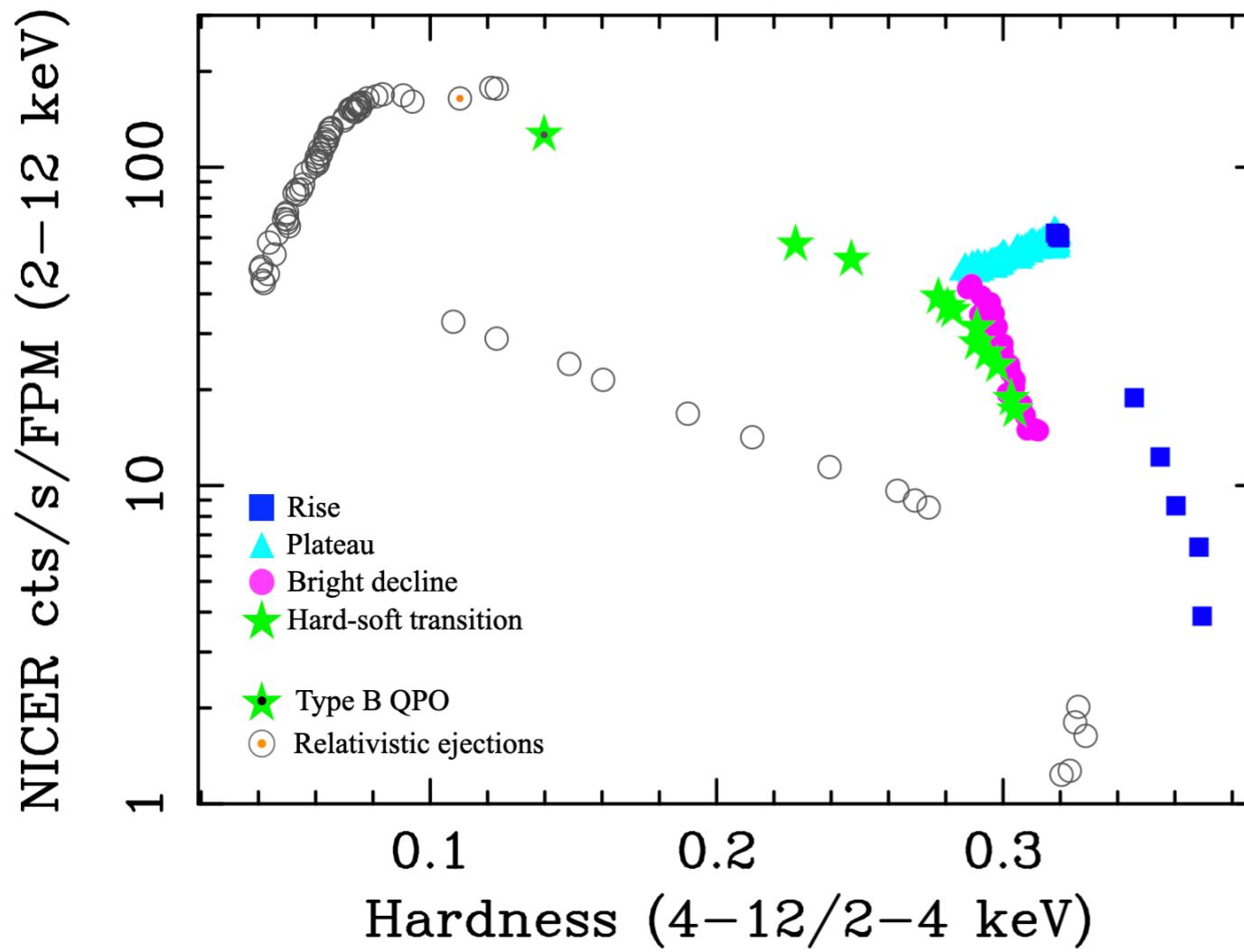
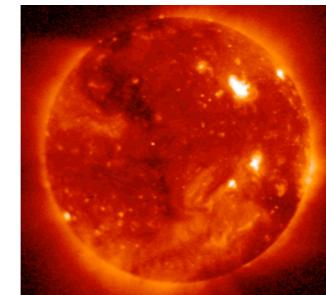


Large collecting area, fast timing capabilities, no limitations to observe very bright source

One of the brightest X-ray binaries ever observed

MAXI J1820+070

*Peak flux ~4 Crab
> Sun at its maximum*

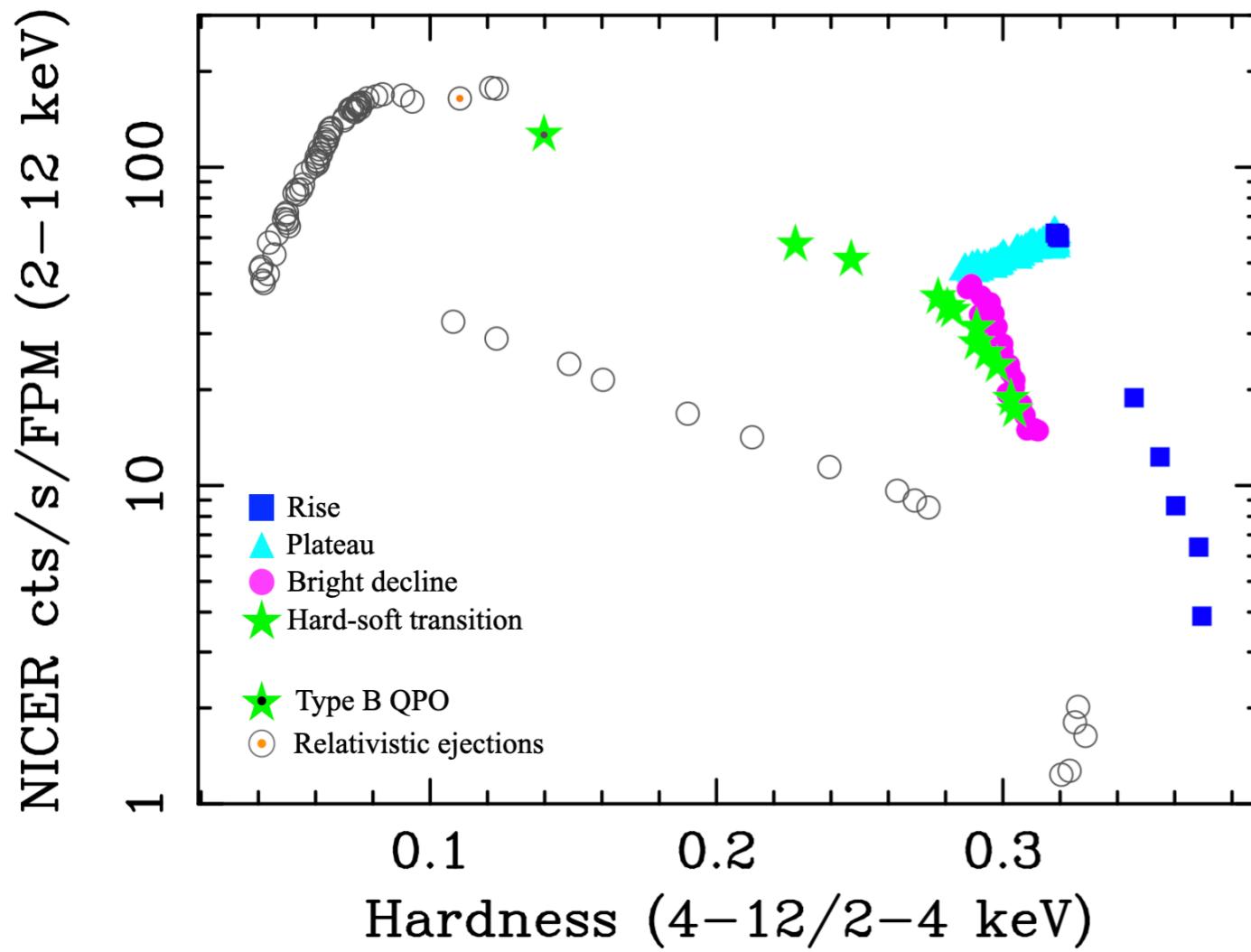
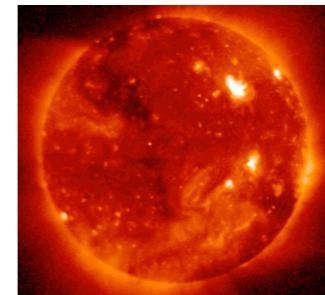


[Kara+'19; Stiele+'19; Bright +'20;
Espinasse+'20; Homan+'20....]

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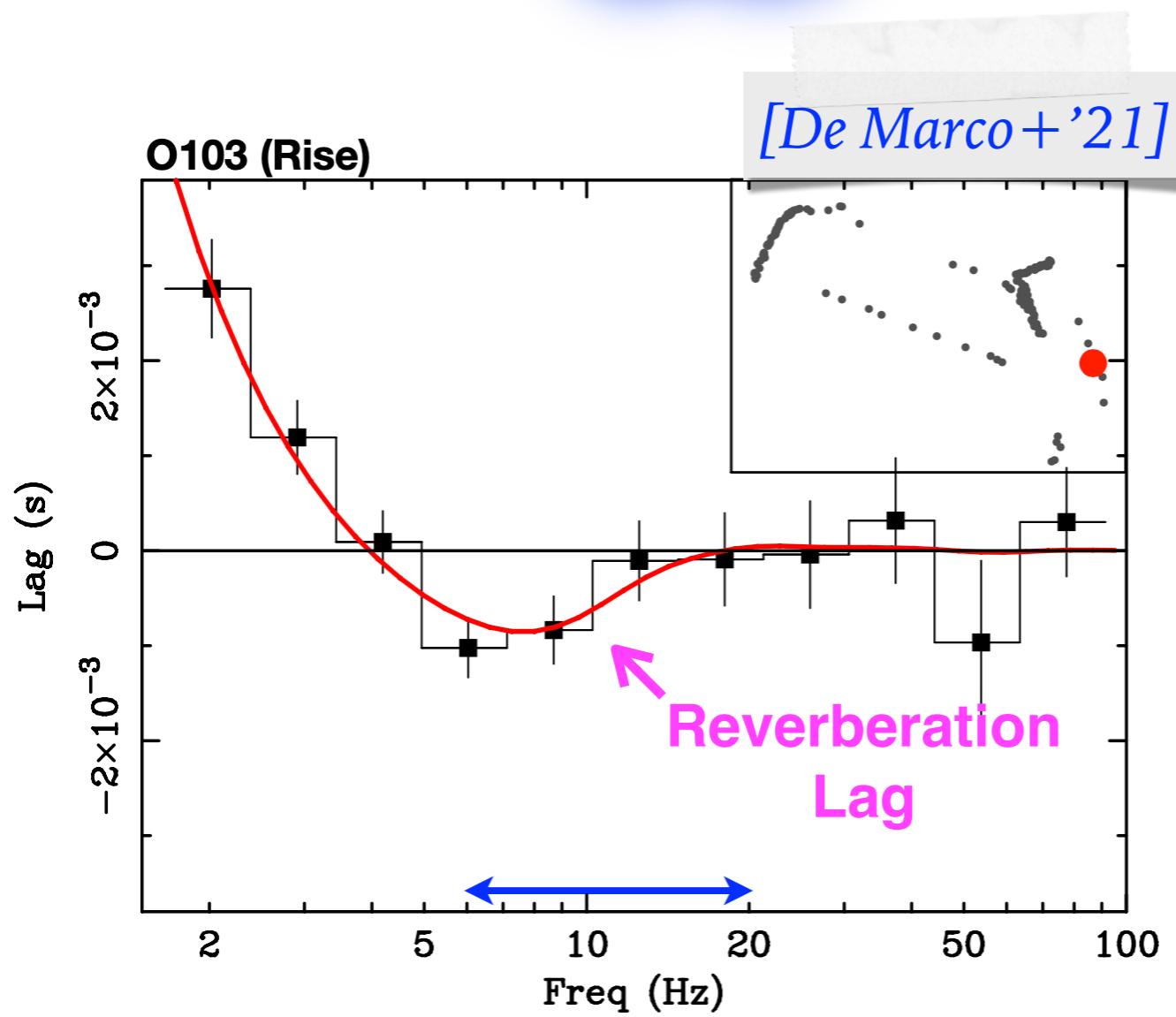
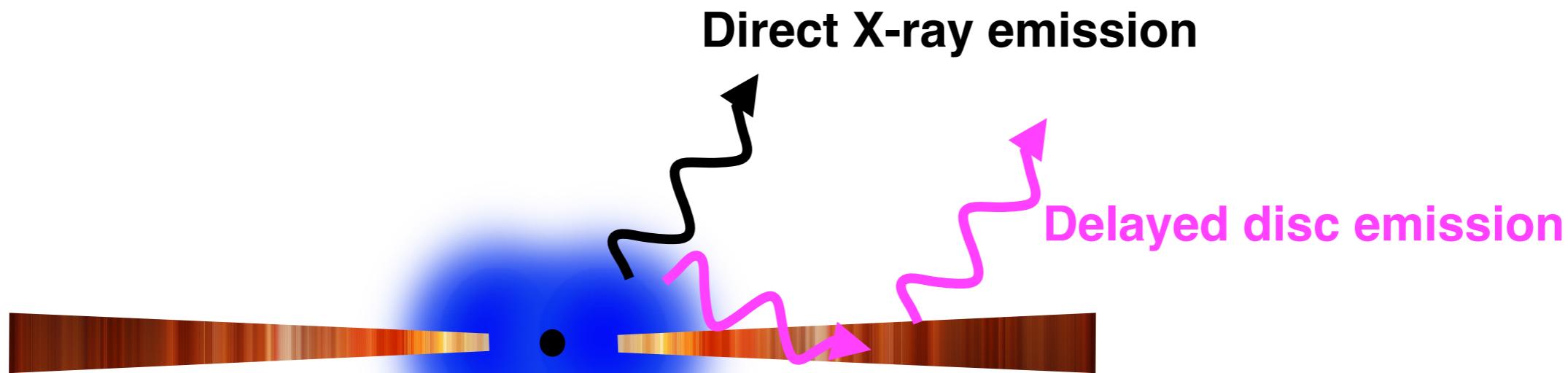
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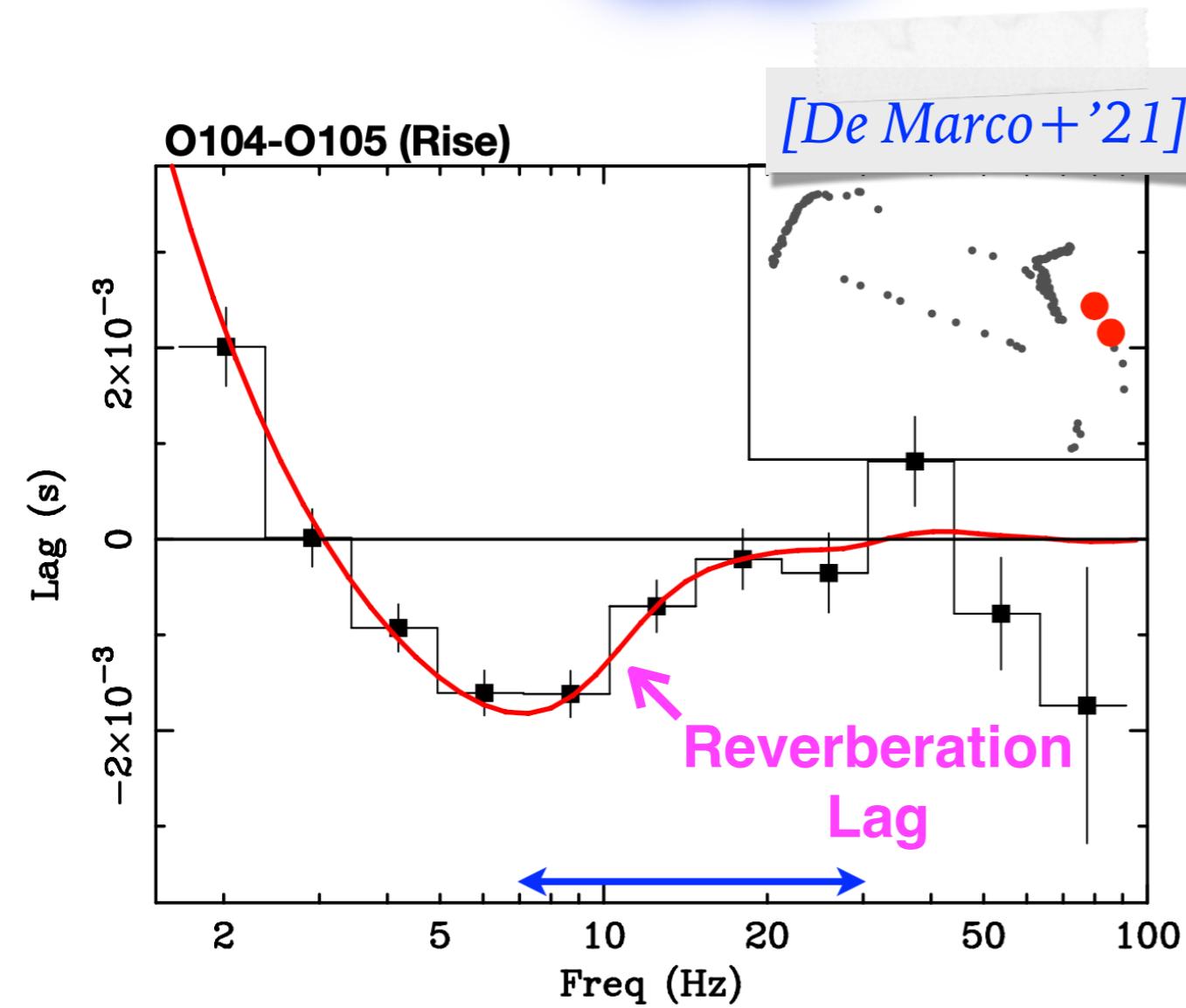
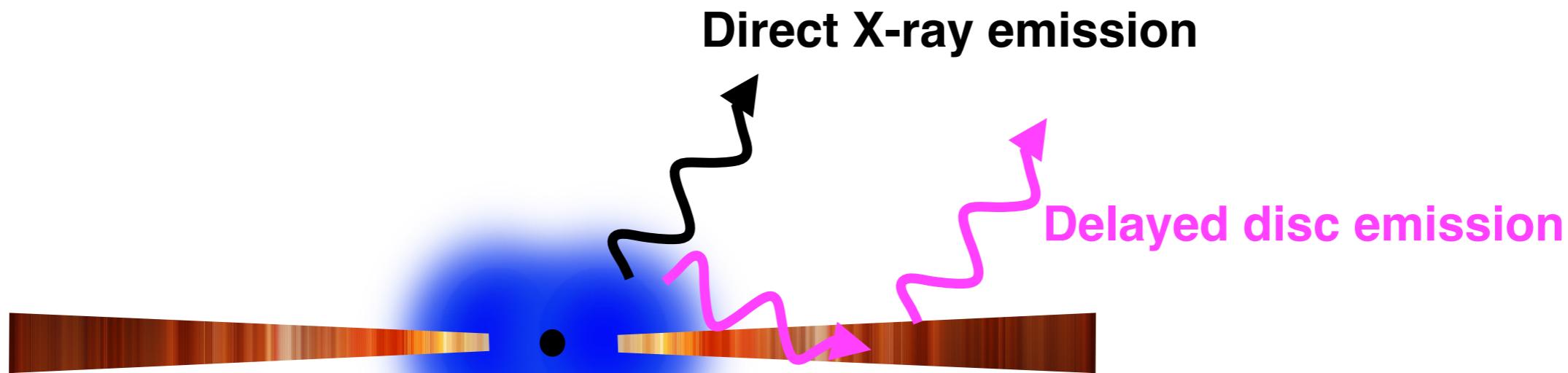
First detailed simultaneous multiwavelength monitoring of hard-to-soft state transition

[Kara+'19; Stiele+'19; Bright +'20;
Espinasse+'20; Homan+'20....]

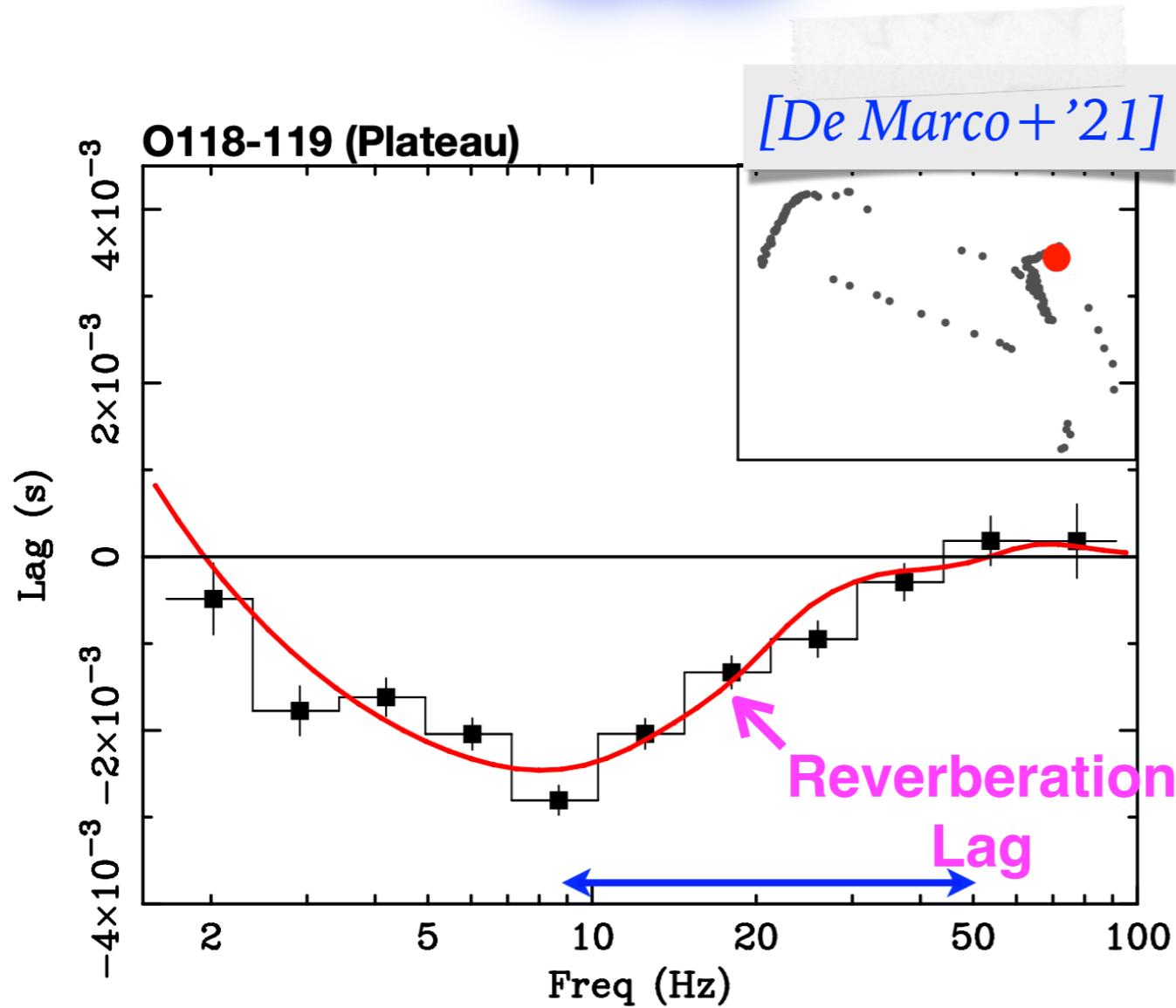
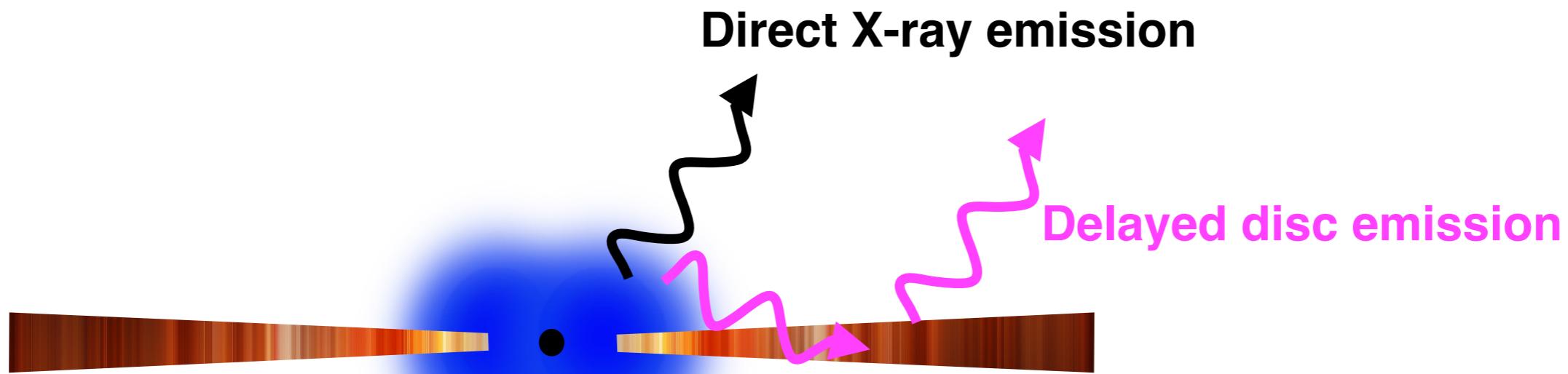
X-ray reverberation



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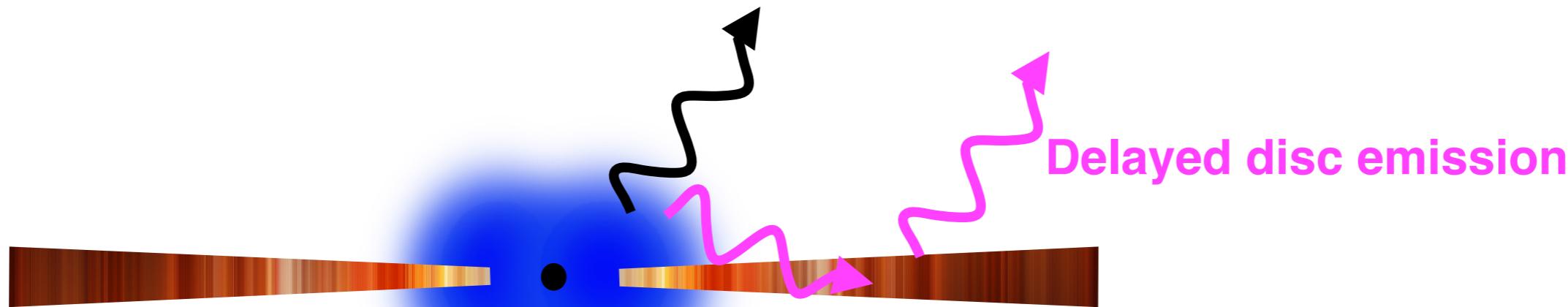


X-ray reverberation

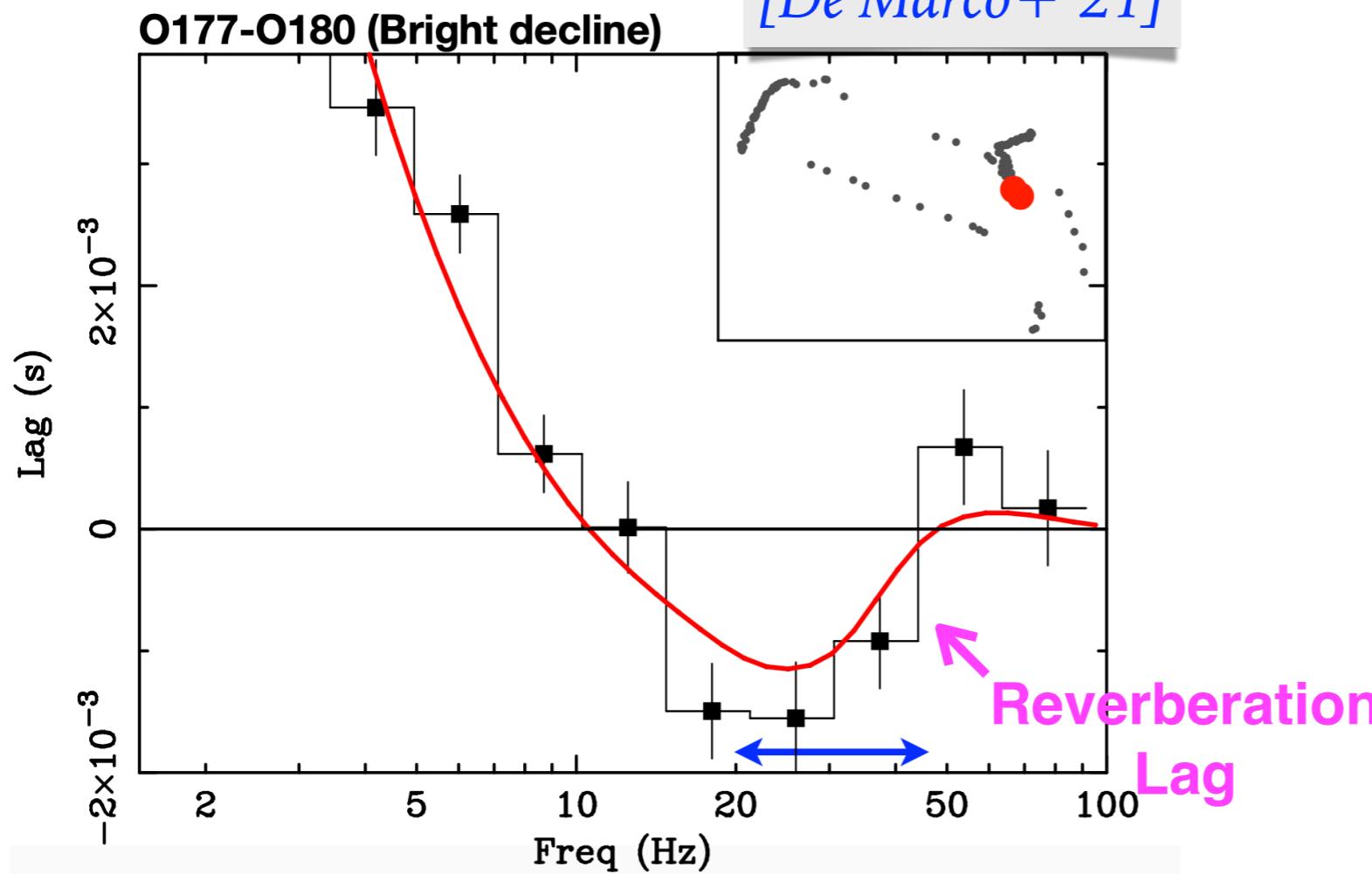


X-ray reverberation

Direct X-ray emission



[De Marco + '21]

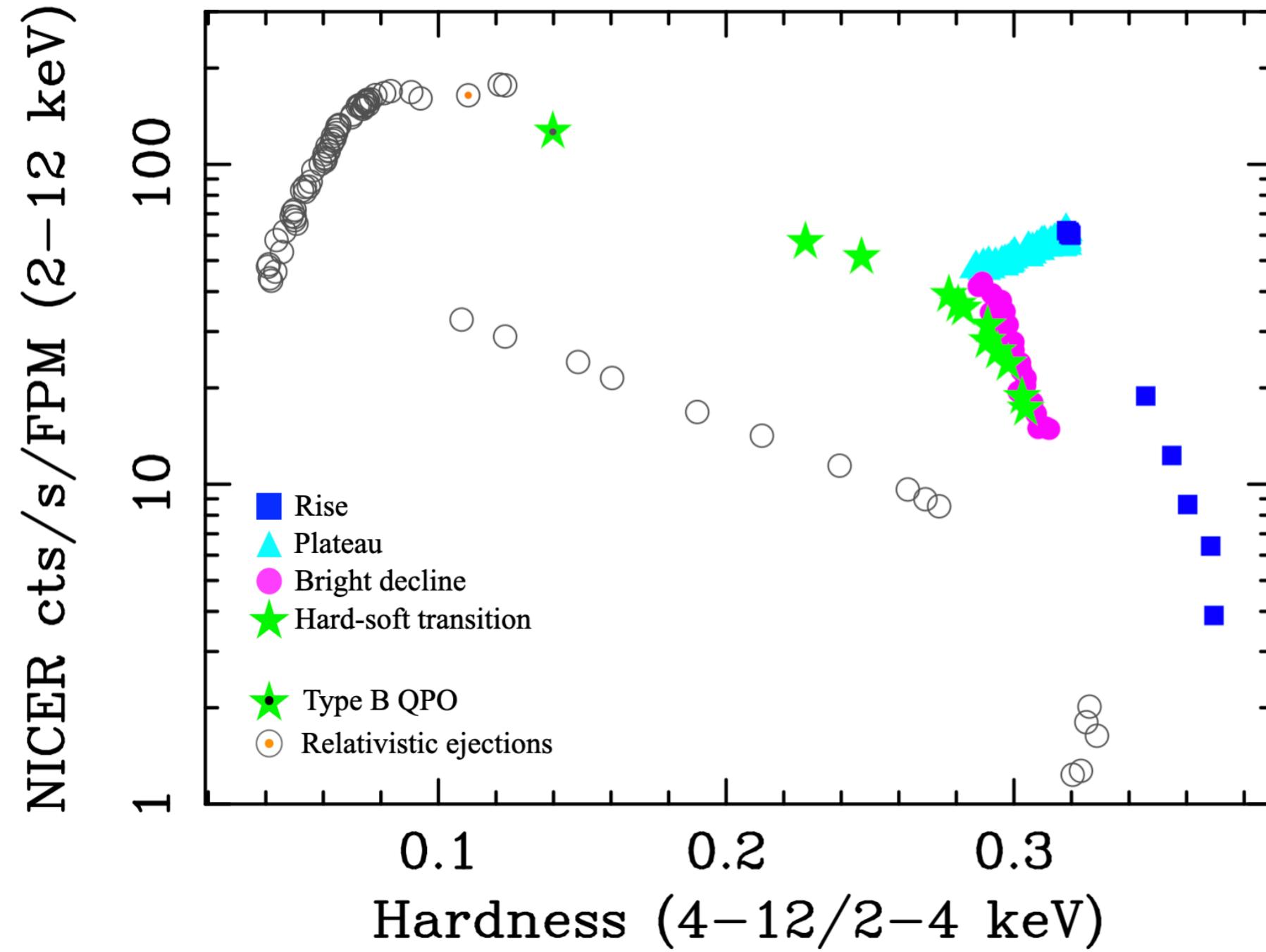


What happens at transition?

The inferred (qualitative) physical picture

Disc approaching the BH throughout the hard state

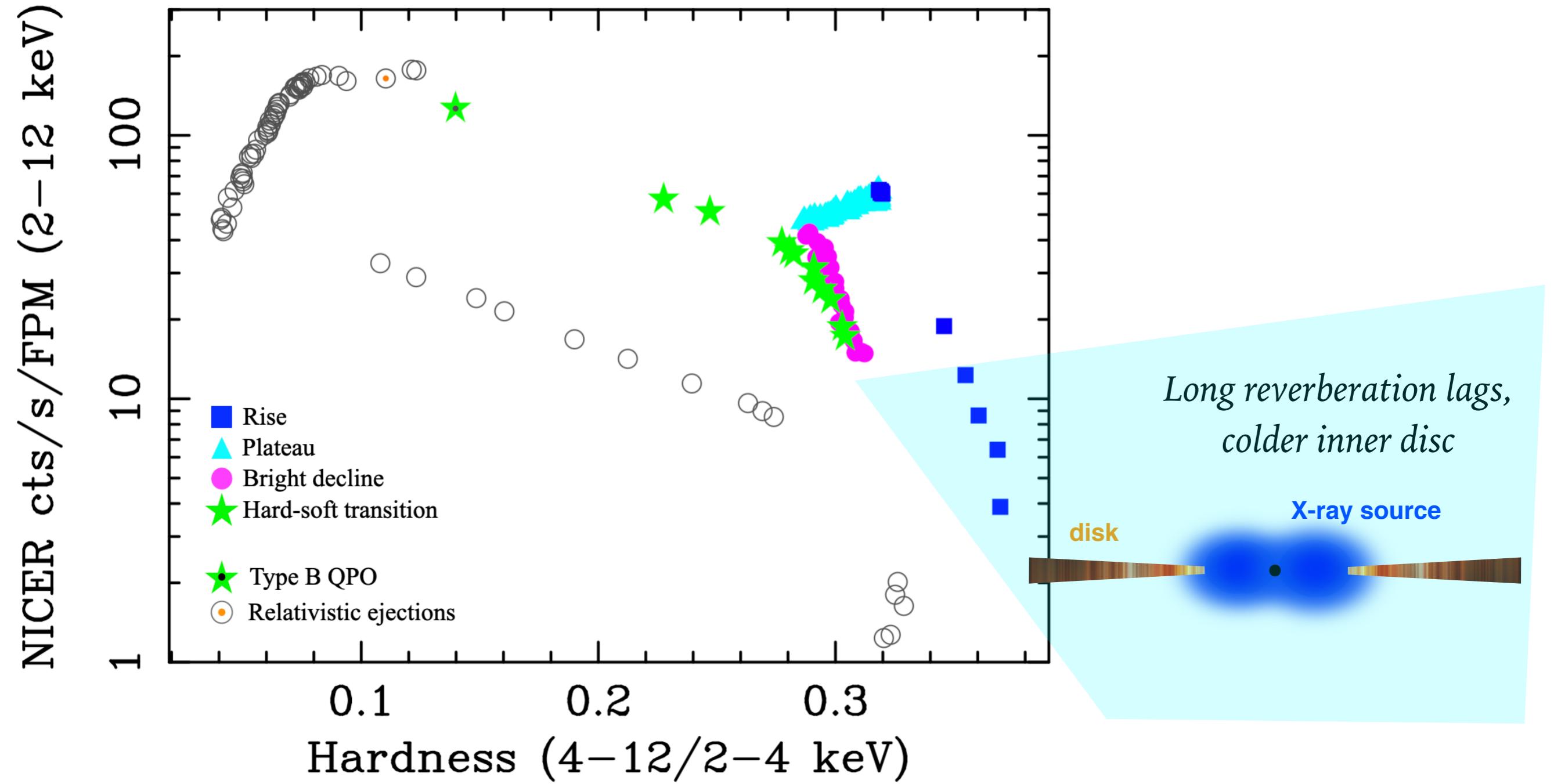
This trend breaks at transition: X-ray source increases in size, disc close to ISCO



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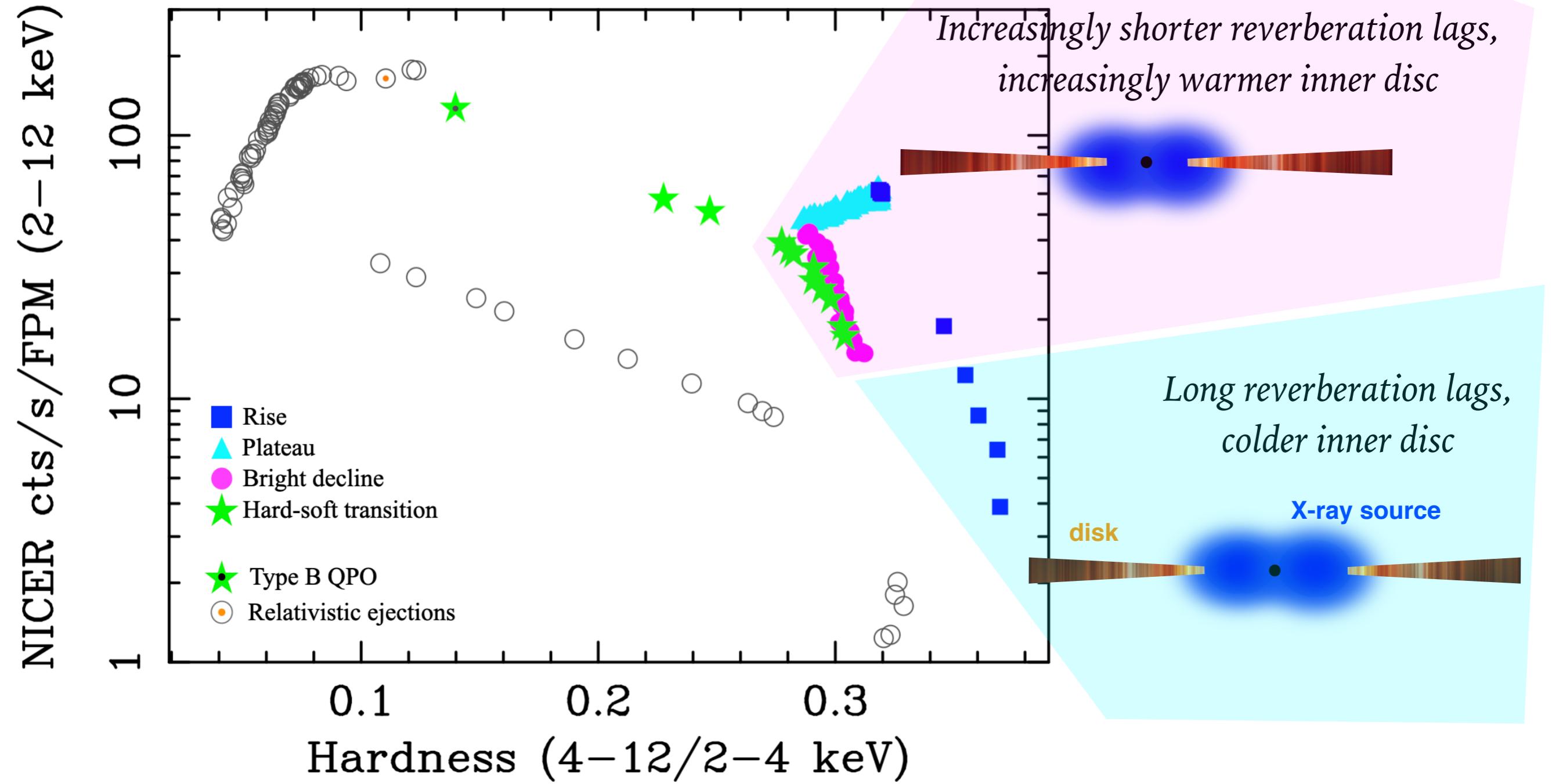
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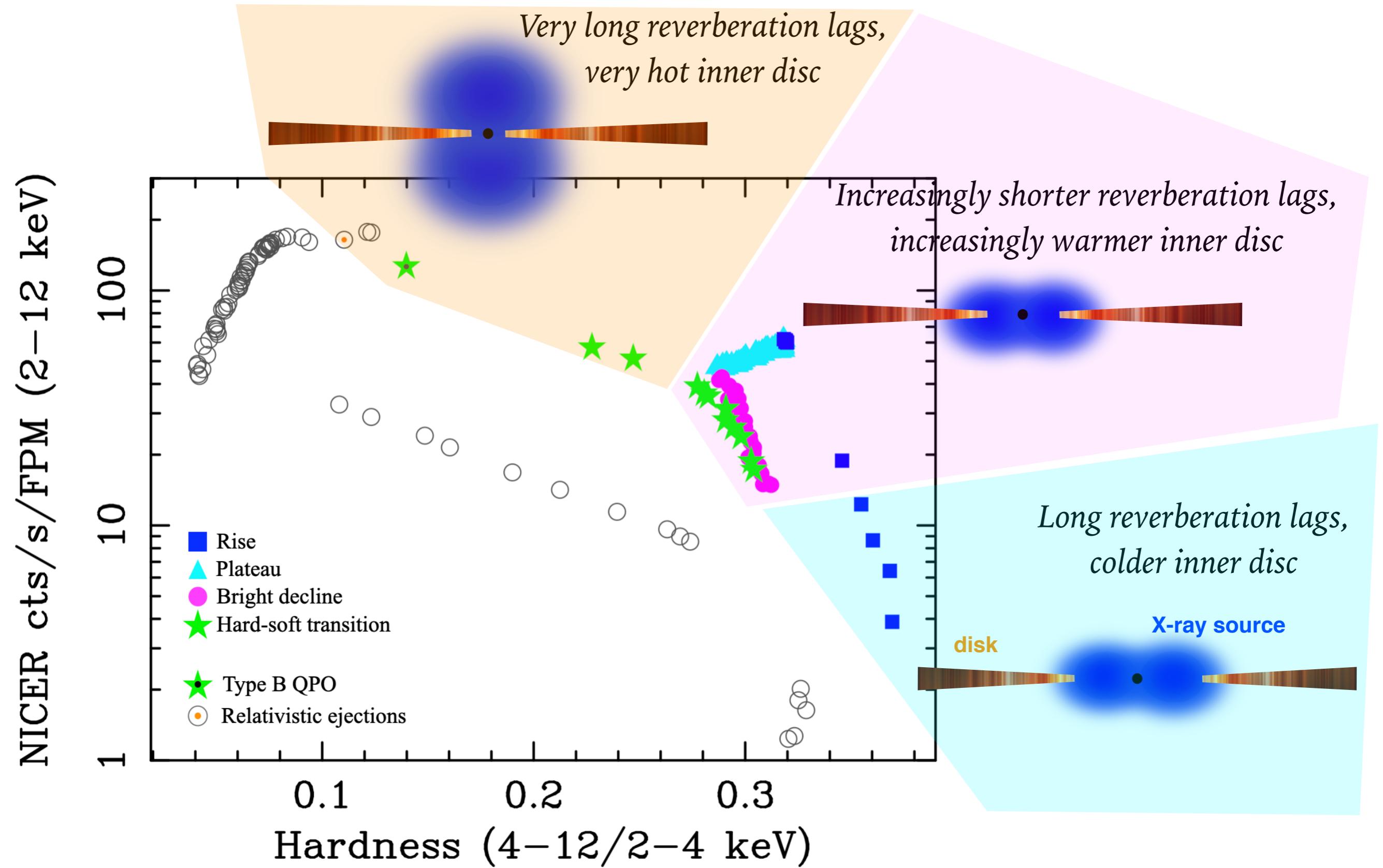
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Conclusions

BHs can be studied using their X-ray spectral and timing information

Combining the spectral and timing information allows us to break degeneracies of standard methods

NICER is making significant inroads for our understanding of stellar-mass BH in binary systems

NICER data of MAXI J1820+070 point to a steady decrease of the inner radius of the accretion disc as the source evolves throughout the hard state, and a major change in the X-ray source geometry right before the transition to the soft state

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Thank you!