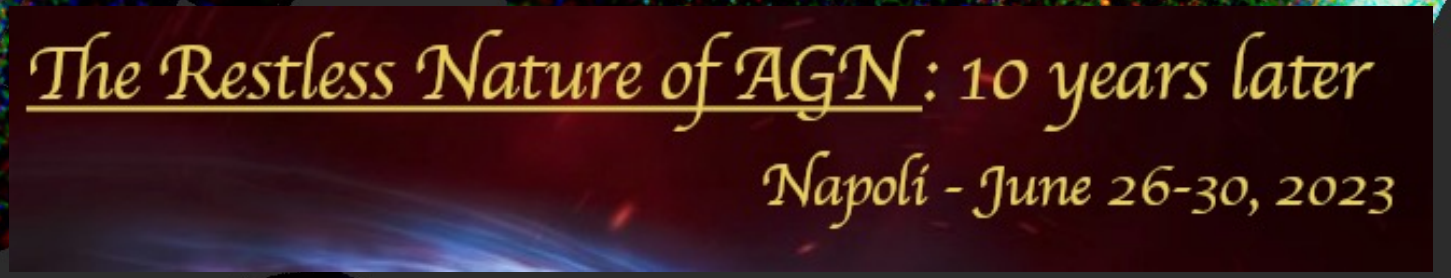
XMM-Newton Highlights of Black Hole Variability



Norbert Schartel

06/06/2023

XMM-Newton preparation

Image courtesy of D. Parker

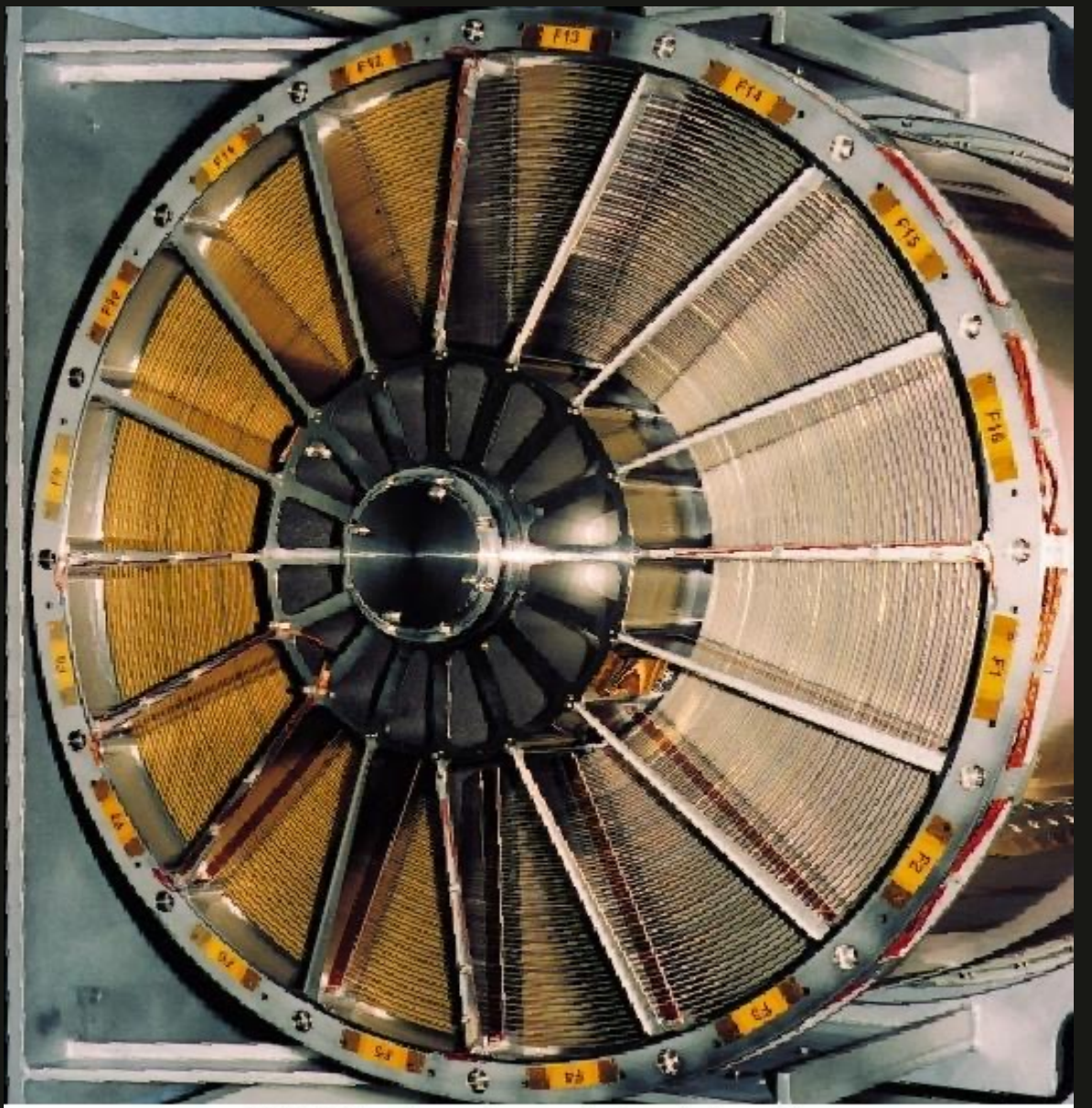
European Space Agency

Mirror Module:

- grazing-incidence Wolter 1 telescopes

- each mirror shell consists of a paraboloid and an associated hyperboloid

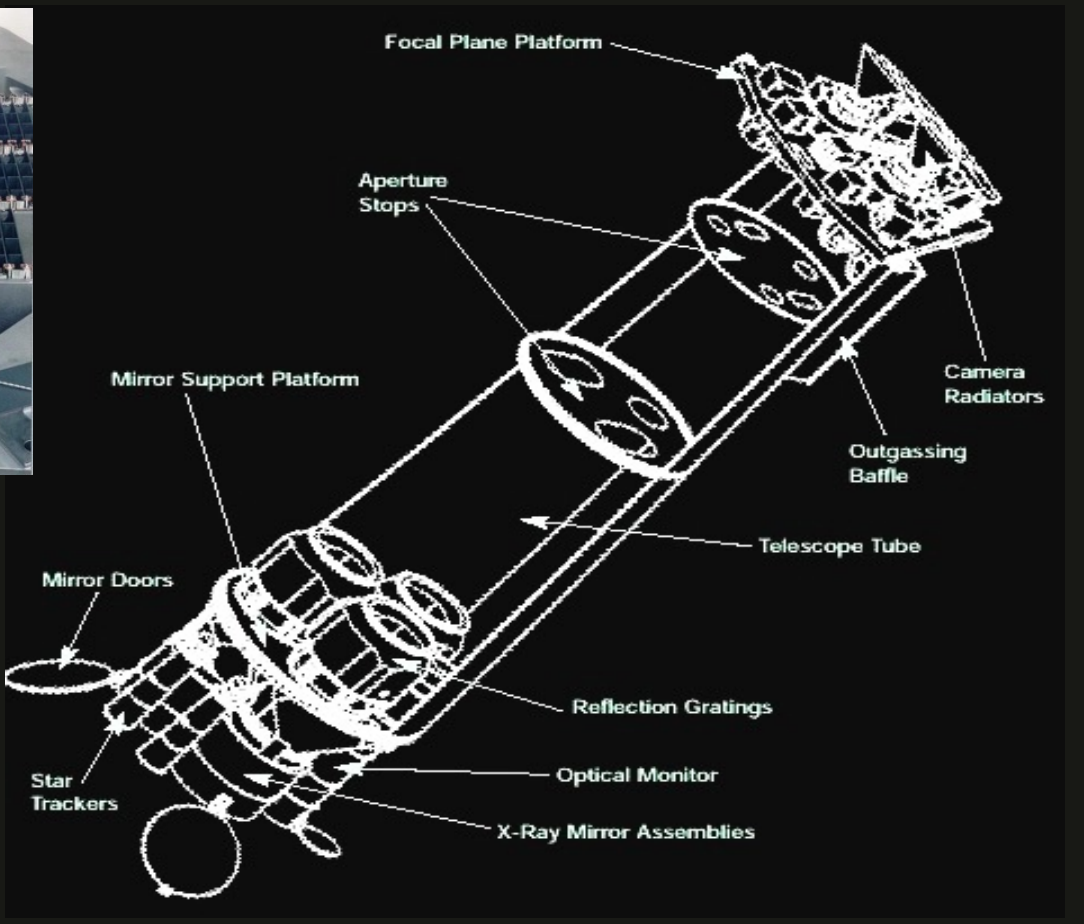
- 58 gold-coated nested mirrors

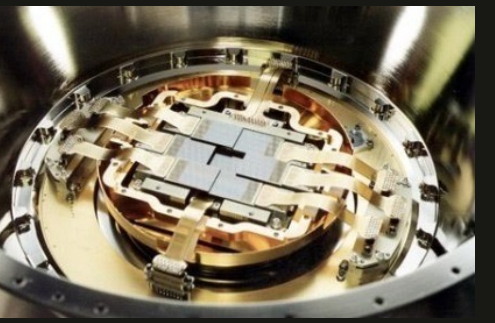


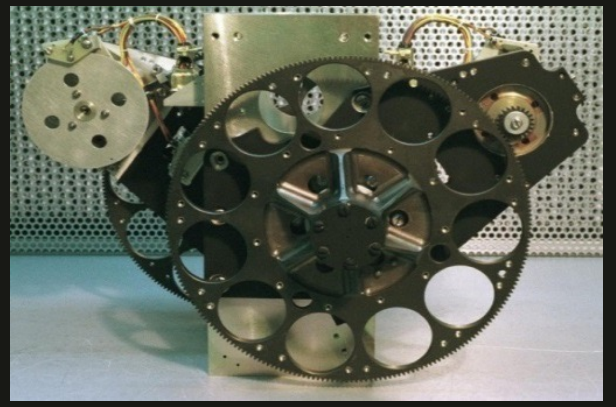
XMM-Newton mirrors during integration

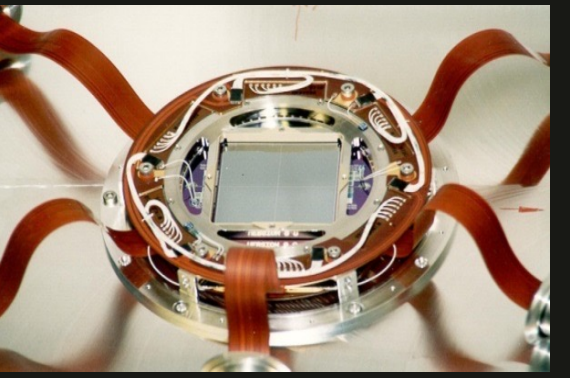
Image courtesy of Dornier Satellitensysteme GmbH European Space Agency

Instruments



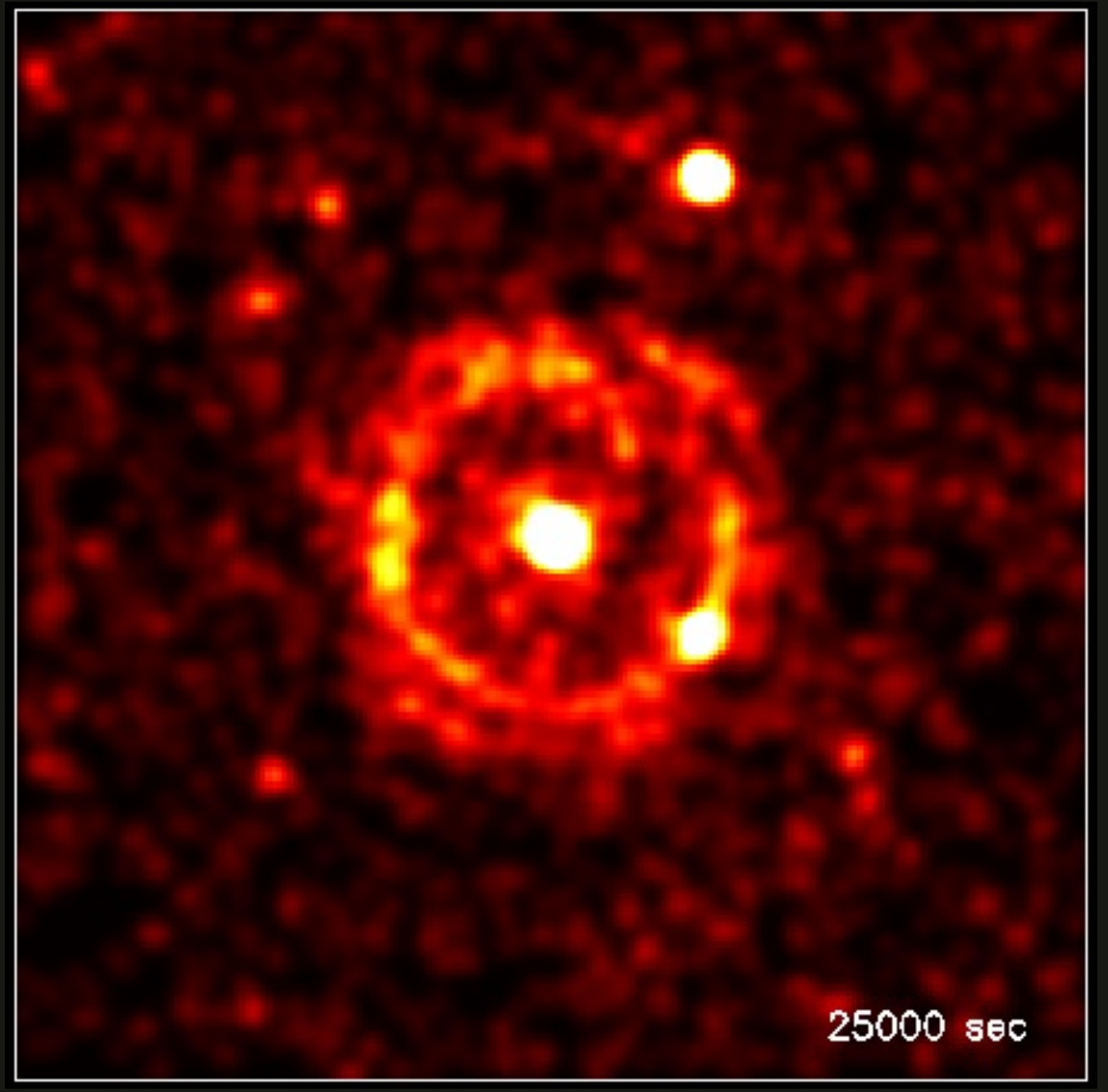






XMM-Newton

- 3 Mirror Modules / highest effective collecting area ever
- Six simultaneously observing instruments:
    - 3 CCD cameras (one pn and two MOSs)
    - 2 spectrometers (RGS)
    - 1 Optical Monitor (OM)



S. Vaughan et al., 2004, ApJ 603, L5

➔ Discovery of an evolving dust-scattered X-ray halo

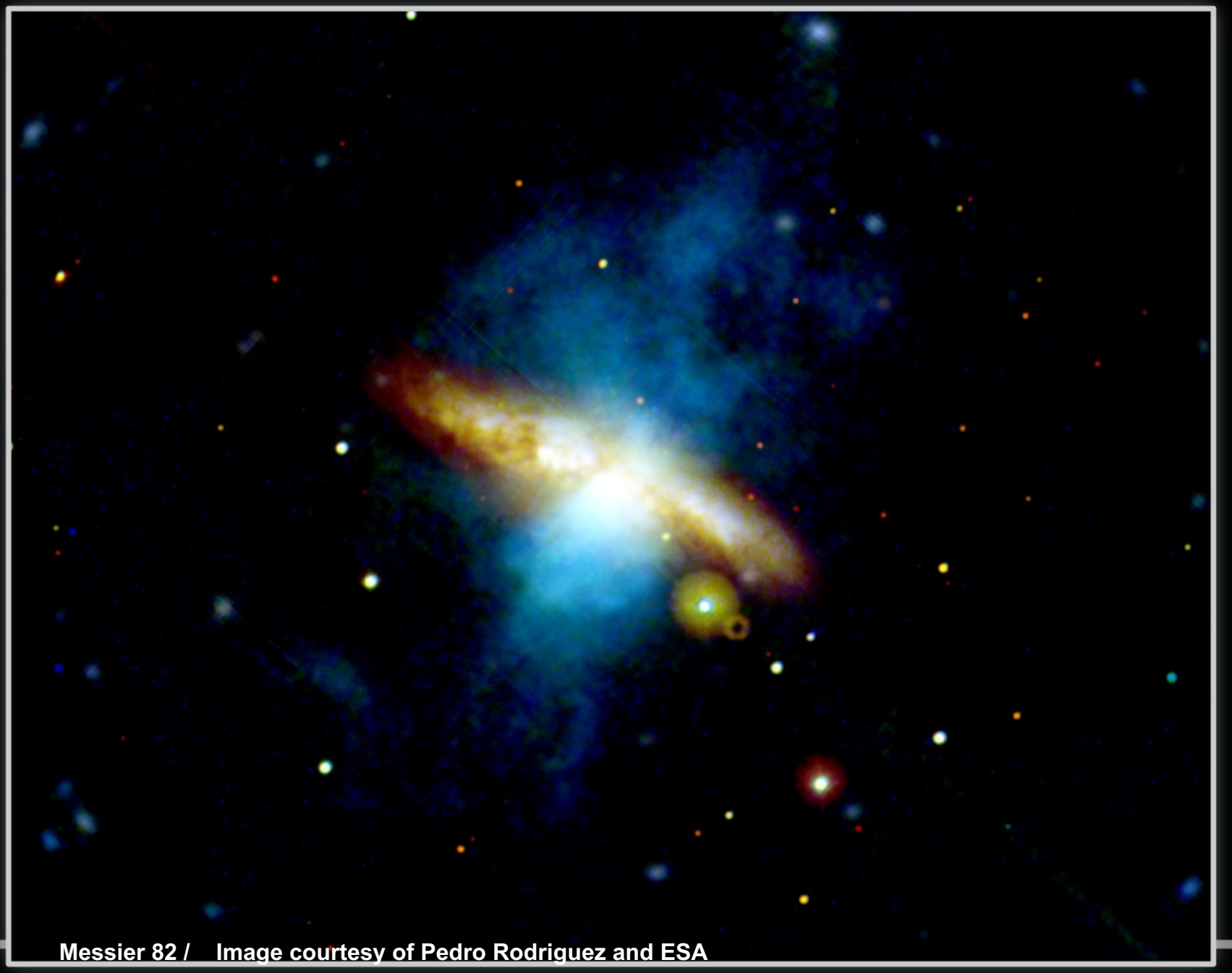
➔ Will allow highly accurate distance determina-tions to the dust

Optical and UV

V+B
(540nm, 434 nm)

U+UVW1
(348nm, 294nm)

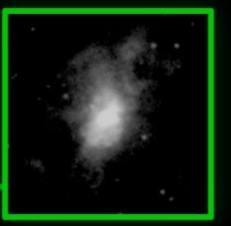
UVM2+UVW2
(234nm, 218nm)



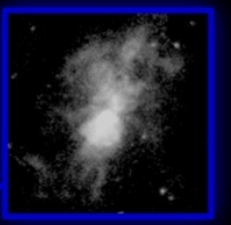
Messier 82 / Image courtesy of Pedro Rodriguez and ESA

X-Ray

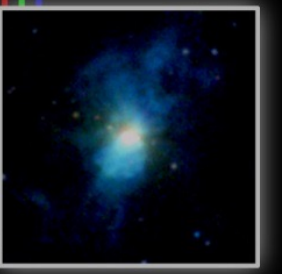
1.2-7.0keV



0.7-1.2keV



0.3-0.7keV



Second Nature Review!

- Nature published a review highlighting the scientific results based on XMM-Newton and Chandra observations achieved during the second decade after satellite launch.
- The article resumes a previous Nature for the fist decade.

➢ The two reviews in Nature underline the high scientific impact of the two missions as recognized by the general scientific community.

Vol 462|24/31 December 2009|doi:10.1038/nature08690 nature

REVIEWS

The first decade of science with Chandra and XMM-Newton

Maria Santos-Lleo[1], Norbert Schartel[1], Harvey Tananbaum[2], Wallace Tucker[2] & Martin C. Weisskopf[3]

NASA's Chandra X-ray Observatory and the ESA's X-ray Multi-Mirror Mission (XMM-Newton) made their first observations ten years ago. The complementary capabilities of these observatories allow us to make high-resolution images

Review

X-ray astronomy comes of age

https://doi.org/10.1038/s41586-022-04481-y

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Accepted: 28 January 2022

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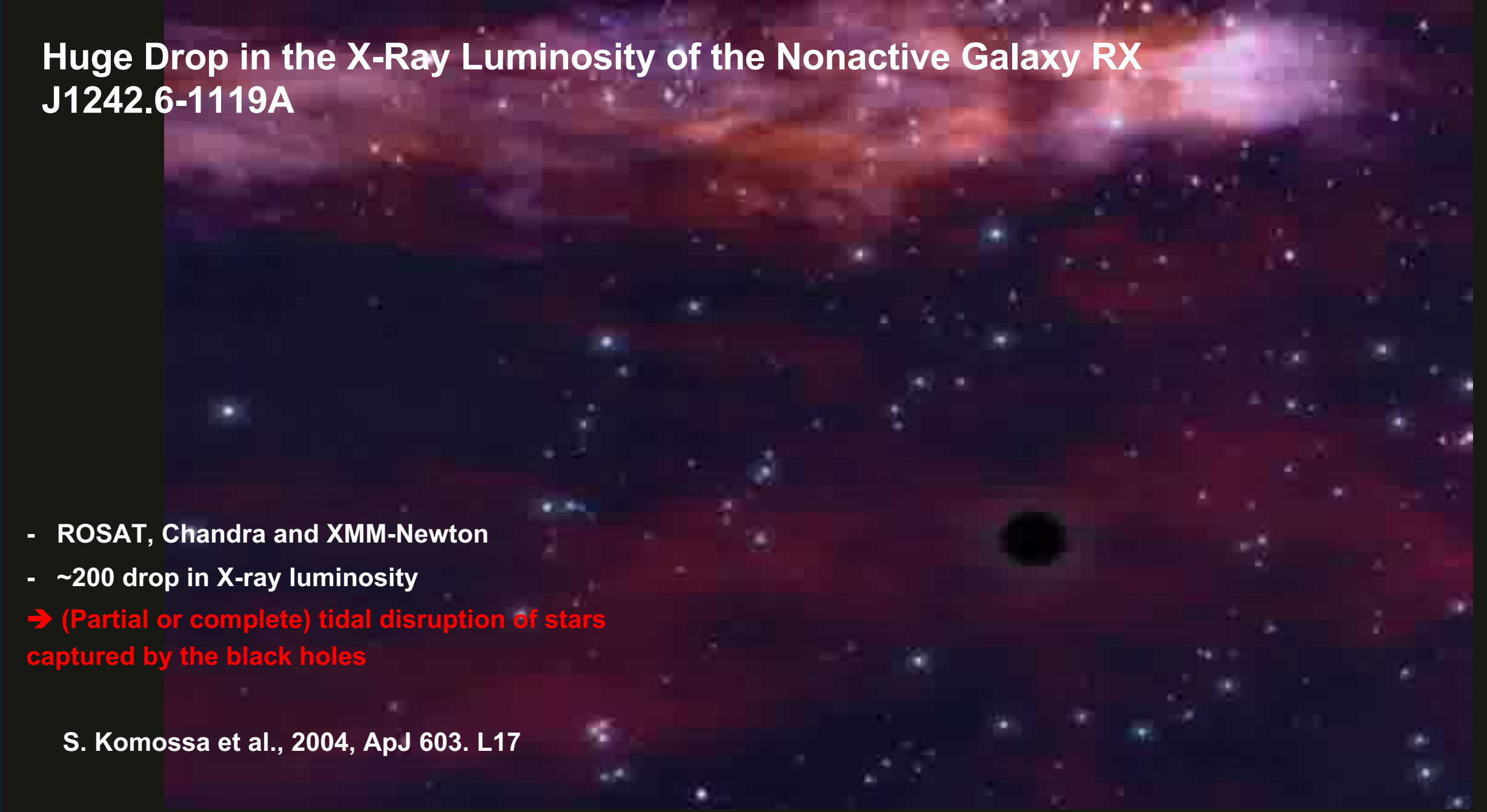
Belinda J. Wilkes[1,2]✉, Wallace Tucker[1], Norbert Schartel[3] & Maria Santos-Lleo[3]

The Chandra X-ray Observatory (Chandra) and the X-ray Multi-Mirror Mission (XMM-Newton) continue to expand the frontiers of knowledge about high-energy processes in the Universe. These groundbreaking observatories lead an X-ray

Tidal Disruption Events

Huge Drop in the X-Ray Luminosity of the Nonactive Galaxy RX J1242.6-1119A



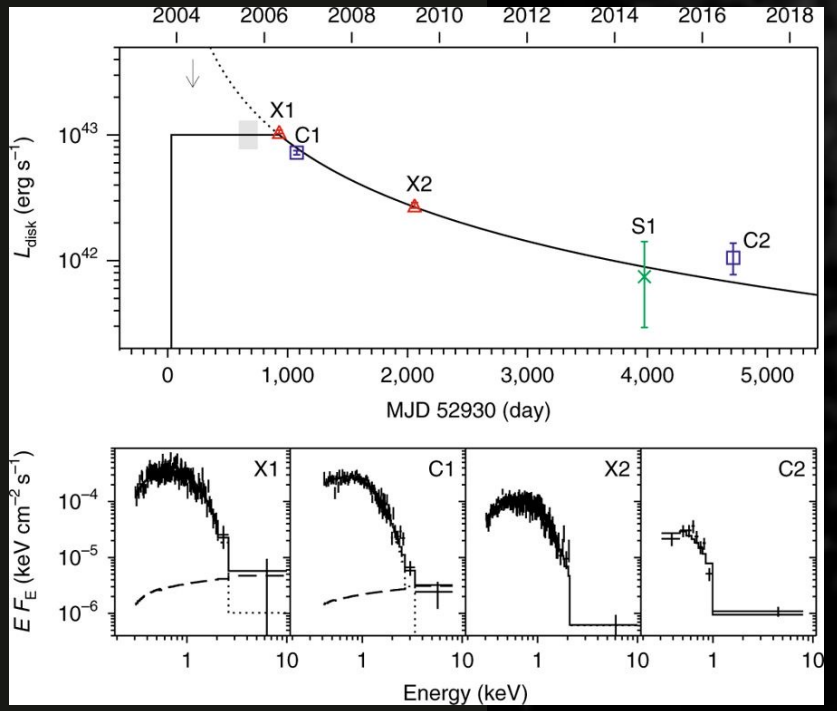
- ROSAT, Chandra and XMM-Newton
- ~200 drop in X-ray luminosity

➔ (Partial or complete) tidal disruption of stars captured by the black holes

S. Komossa et al., 2004, ApJ 603. L17

A tidal disruption event rom an intermediate-mass black hole in an off-centre star cluster

- luminous X-ray outburst from a massive star cluster
- luminosity peaked at 10^{43} erg/s and decayed systematically over 10 years



E

Gal 1

- ➔ thermal-state signature
- ➔ very high luminosities
- ➔ ultrasoft X-ray spectra
- ➔ characteristic power-law evolution of the light curve
- ➔ provides strong evidence that the source contains an intermediate-mass black hole

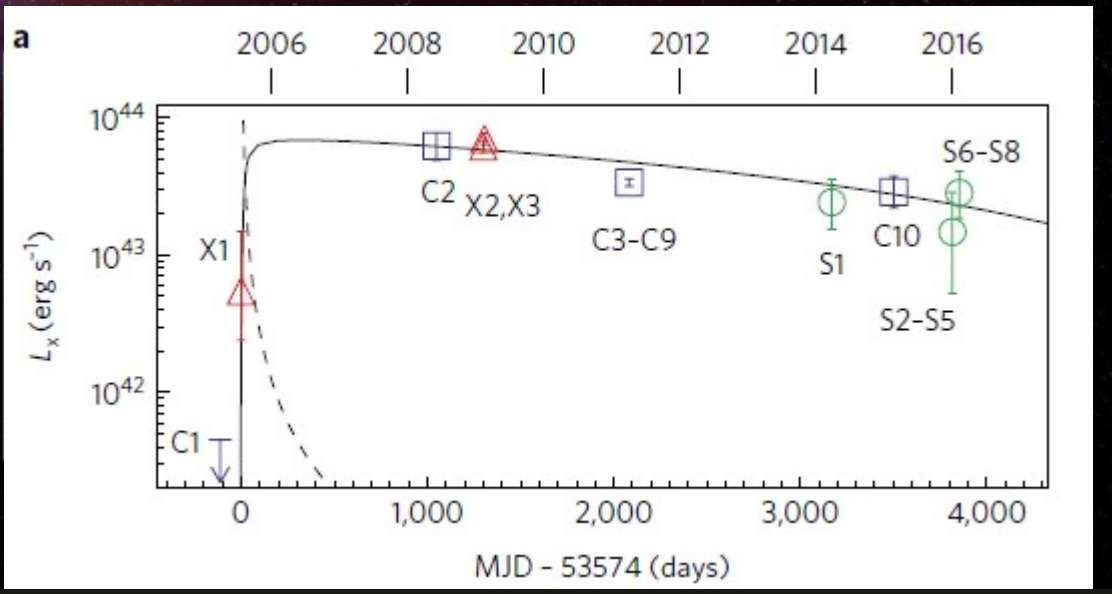
Lin et al, 2018 Nature Astronomy 2, 656

A likely decade-long sustained tidal disruption event

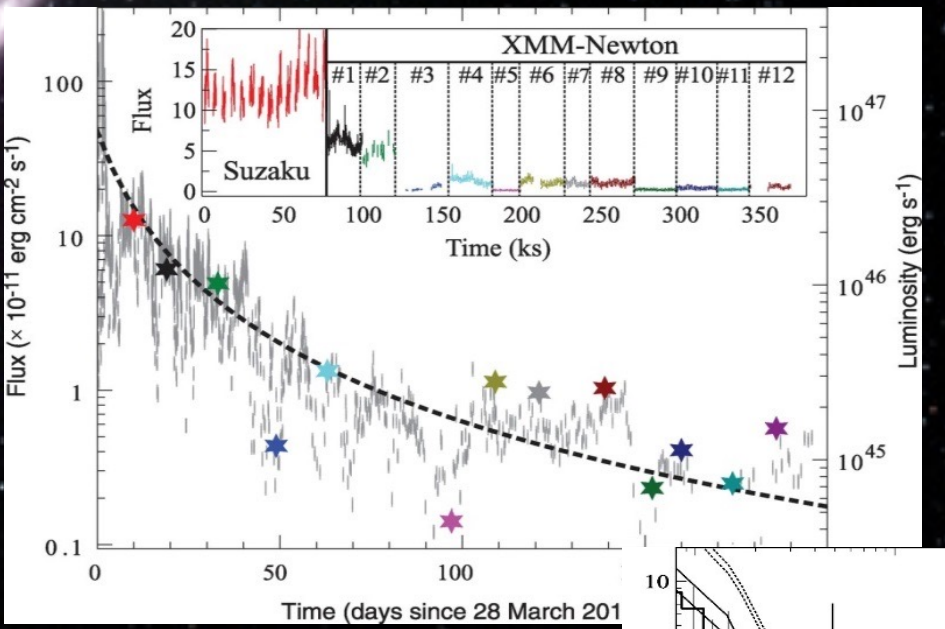
XMM-Newton, Chandra and Swift observations:

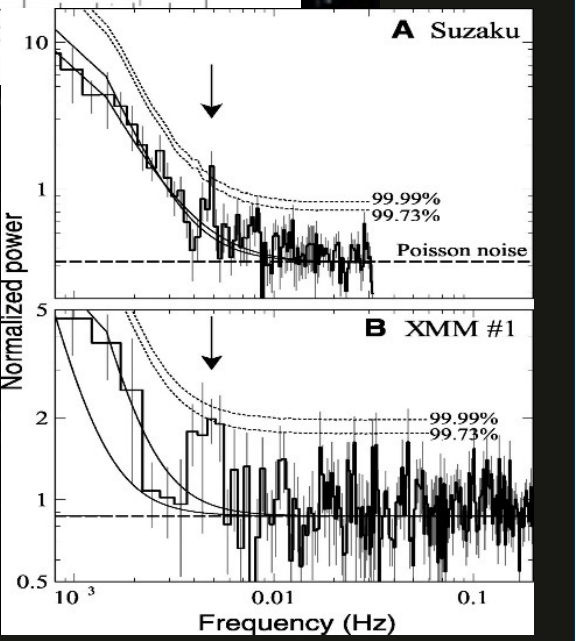
➔ discovery of a super-long (>11 years) luminous X-ray flare from the nuclear region of a dwarf starburst galaxy.
➔ fast rise within ~4 months
➔ X-ray luminosity persistently high at around the Eddington limit
➔ a tidal disruption event

D. Lin et al., 2017 Nature Astronomy, 1, 33



Tidal Disruption: Swift J164449.3+573451



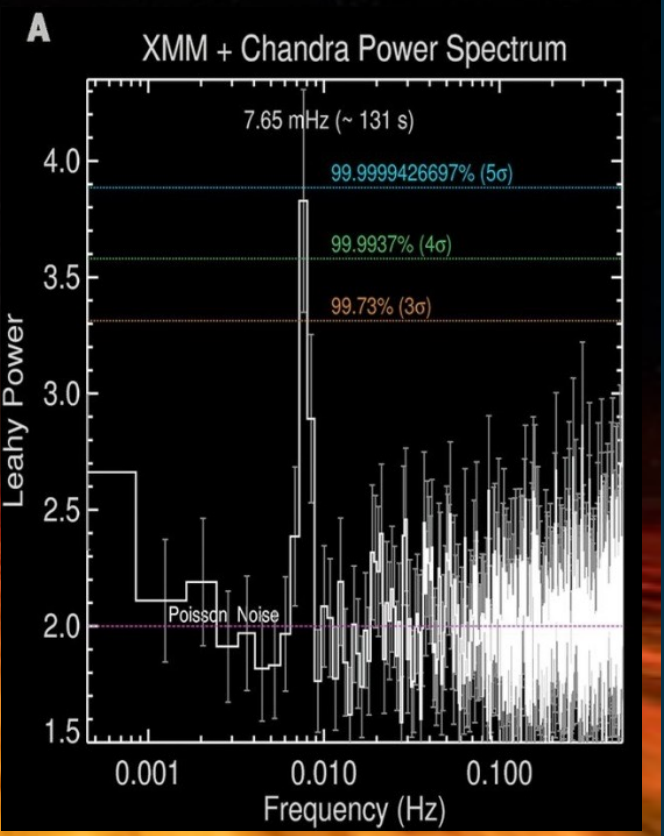


- tidal disruption of a star by a dormant black hole
- bright X-ray flares
- galaxy at redshift z = 0.3534

➔ ~200-second x-ray quasi-periodicity

R.C. Reis et al., 2012, Science, 337, 949

Quasi-Periodic Oscillations after a Star is Disrupted by a Massive Black Hole



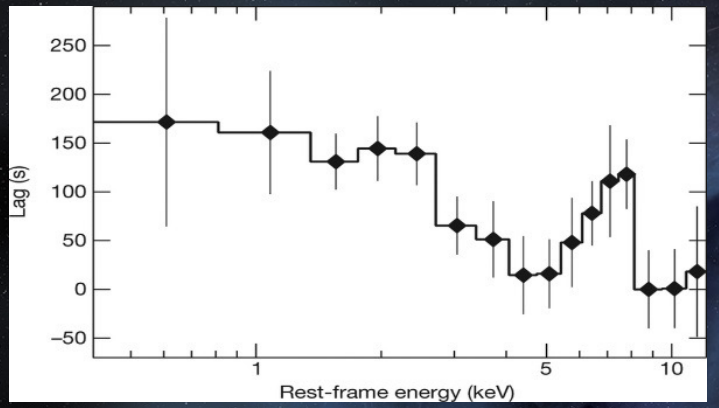
- tidal forces close to black holes can rip apart stars that come too close to them.
- stellar debris spirals toward the black hole

➔ stable 131-second x-ray quasi-periodic oscillation from the tidal disruption event ASASSN-14li

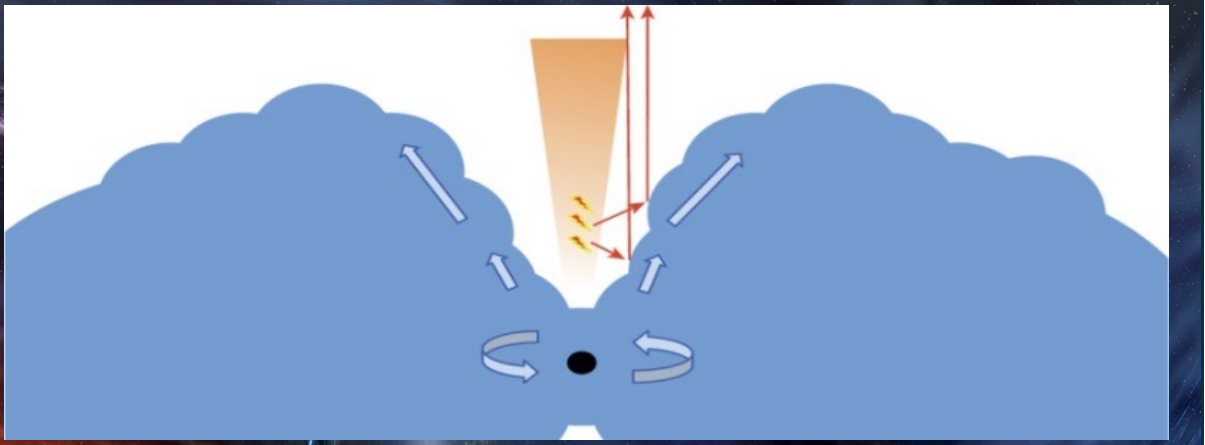
➔ periodicity originates from close to the event horizon and that the black hole is rapidly spinning

D. R. Pasham, et al., 2019, Science 363, 531

Relativistic Reverberation in the Accretion Flow of a Tidal Disruption event



The emission from ~4–5 keV and 8–13 keV (continuum) vary first, and the iron line from ~7–8 keV responds ~100 s later.



Swift J1644+57 is a super-Eddington accreting source, with a thick disk (blue) and a relativistic radio jet (orange). The blue arrows represent the dynamics in the disk: the accretion flow rotates around the central black hole and the walls of the funnel are outflowing at ~0.1c–0.5c.

Swift J1644+57 tidal disruption event

- relativistic jet pointed in line of sight

Kara et al., 2016, Nature 535, 388

➔ Reverberation arising from gravitationally redshifted iron Kα photons reflected off the inner accretion flow

➔ Accretion rate of 100 times the Eddington limit

➔ X-rays do not arise from the relativistic jet

Flows of X-ray gas reveal the disruption of a star by a massive black hole

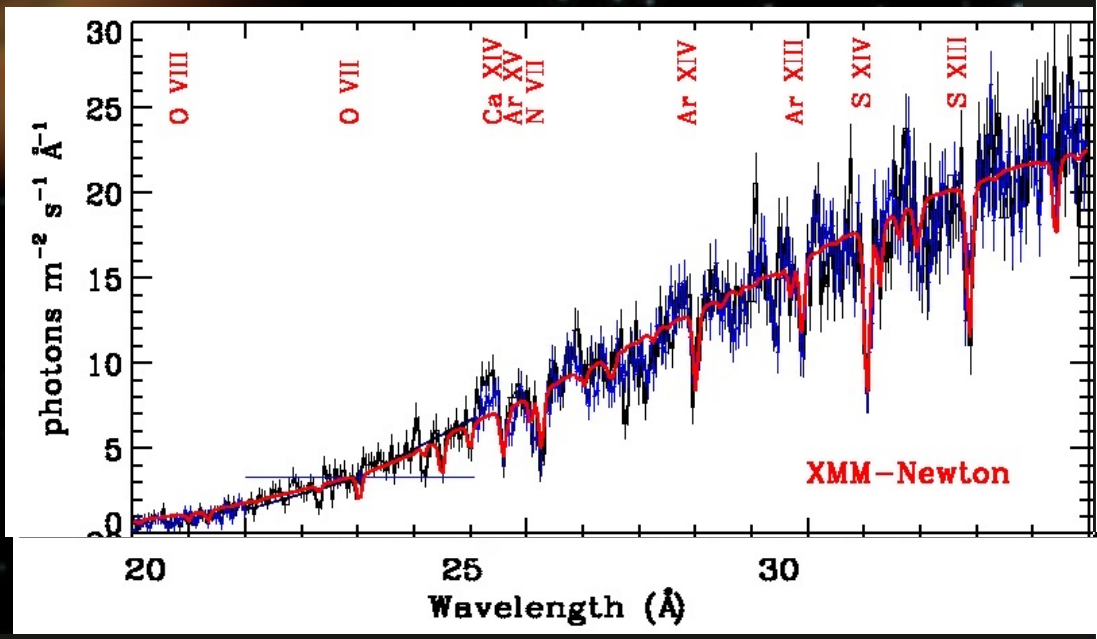
J.M. Miller et al., 2015, Nature 526, 542

- tidal disruption event ASASSN-14li
- detection of blue-shifted absorption lines of highly ionized atoms
- variability indicates that the gas is close to the black hole
- narrow line widths indicate a low volume filling factor
- outflow speeds are below the escape speed from the radius set by variability

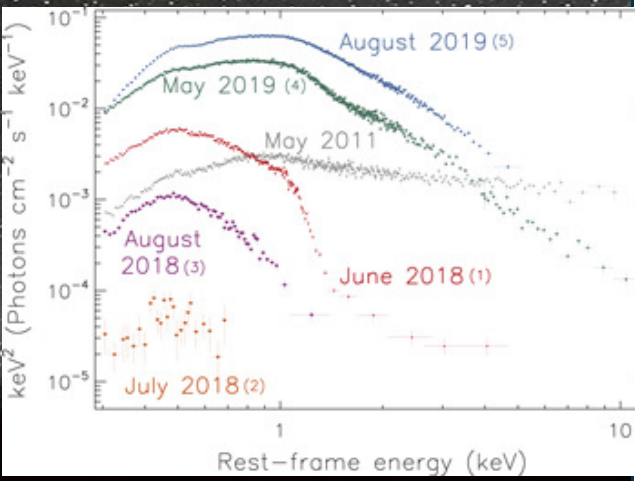
➔ rotating wind from the inner region of a nascent accretion disk, or

➔ a filament of disrupted stellar gas near to the apocenter of an elliptical orbit

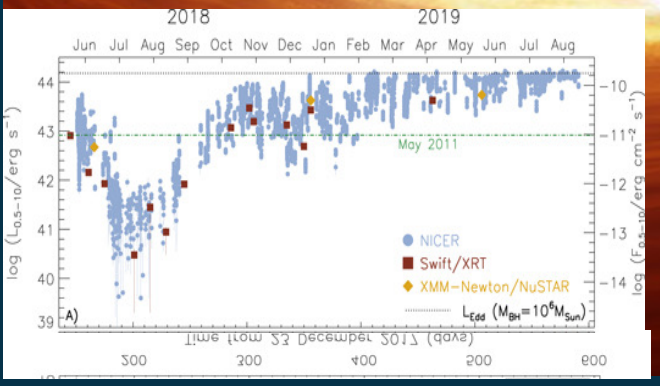
The high-resolution (RGS1 & RGS2) X-ray spectra of ASASSN-14li reveal blue-shifted absorption lines.



Destruction and Recreation of the X-Ray Corona in a Changing-look AGN 1ES 1927+65



Ricci et al. 2020, ApJ 898, L1

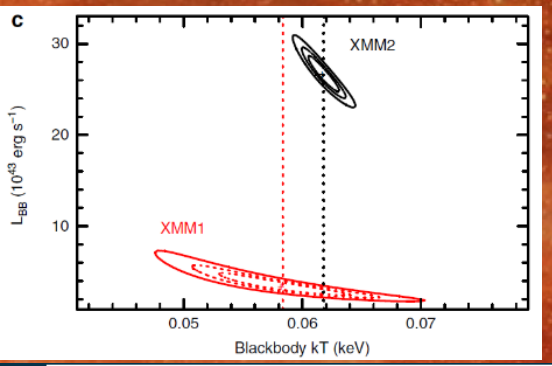


- after optical/ultraviolet outburst the power-law component disappeared
➔ corona was destroyed
- increase in luminosity to levels exceeding the pre-outburst level ≳300 days
➔ X-ray corona is recreated

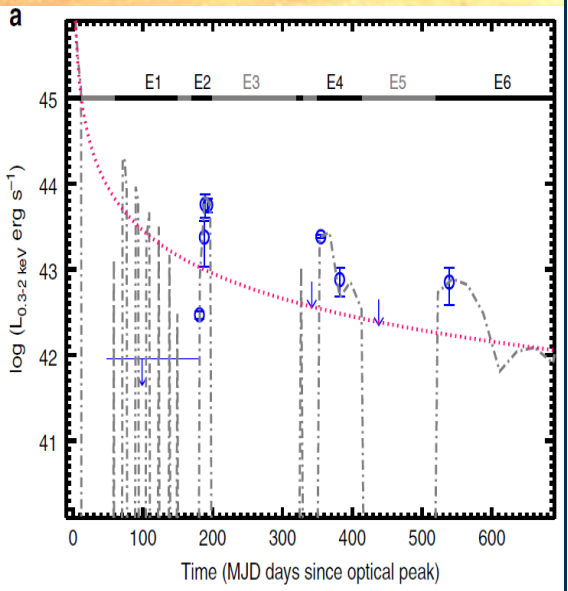
X-Ray Flares from the Tidal Disruption Event by a Candidate Supermassive Black Hole (SMBH) Binary

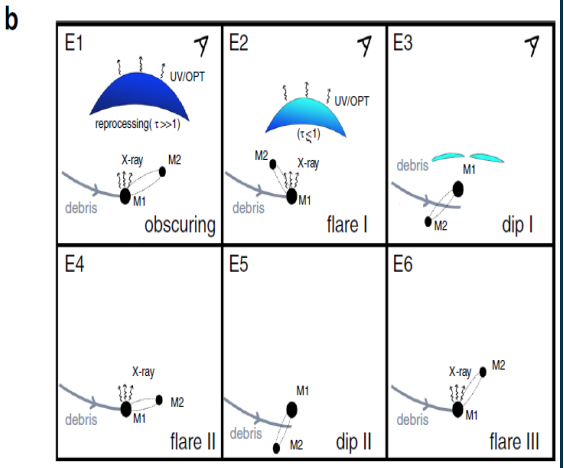
TDE OGLE16aaa:
- delayed X-ray brightening around 140 days after the optical TDE
- several flux dips during the decay phase.
- unusual for standard TDEs

X. Shu et al., 2020,
Nature Communications
11, 5876



➔ SMBH binary or patchy obscuration
➔ reprocessing is important in the TDE early evolution
➔ X-ray observations are promising in revealing SMBH binaries





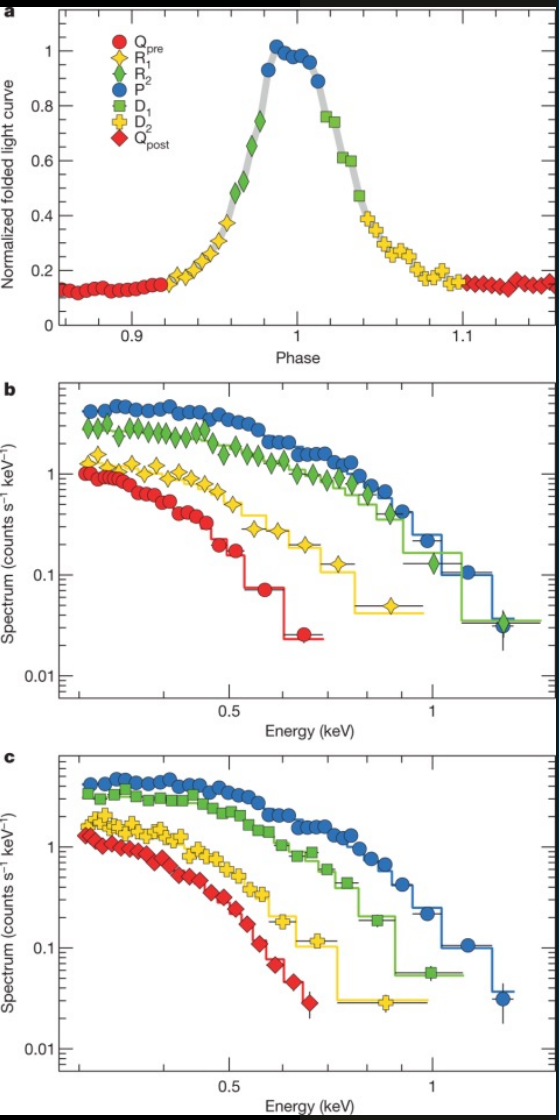
Nine-hour X-ray quasi-periodic eruptions from a low-mass black hole galactic nucleus

Seyfert 2 galaxy GSN 069

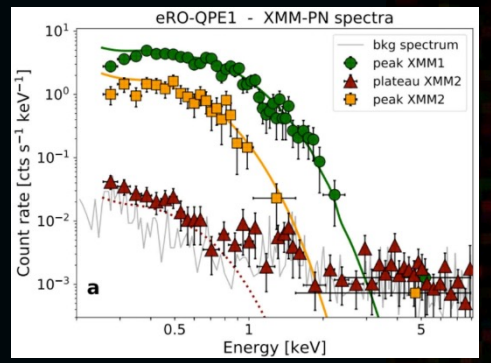
z = 0.0189

$M_{BH} \approx 2 \times 10^6 M_\odot$

Miniutti et al., 2019, Nature 573, 381



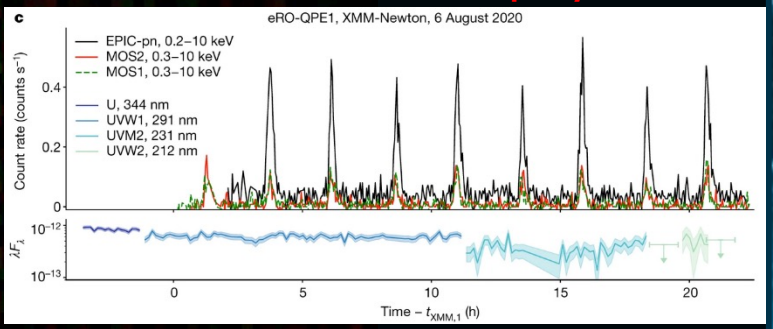
Quasi-Periodic Eruptions from Quiescent Galaxies



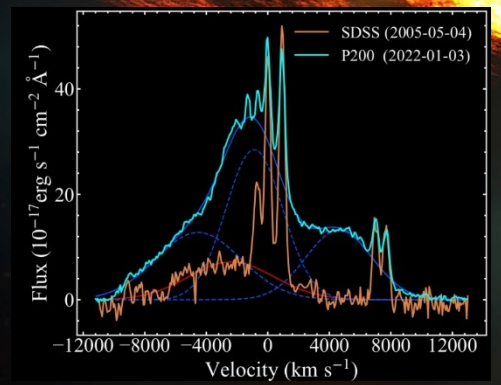
- 2 sources detected by SRG/eROSITA
- Characterization with XMM-Newton and NICER
- Quasi-Periodic Eruptions (QPEs)
- No pre-existing active nuclei, i.e. quiescent galaxies
- Inconsistent with accretion disk instabilities.
- QPEs likely driven by an orbiting compact object.
- Secondary object is much smaller than the main body

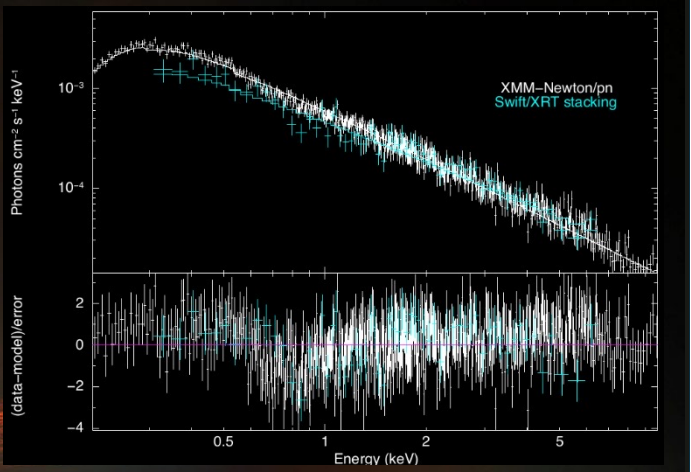
R. Arcodia et al. (2021, Nature 592, 704)

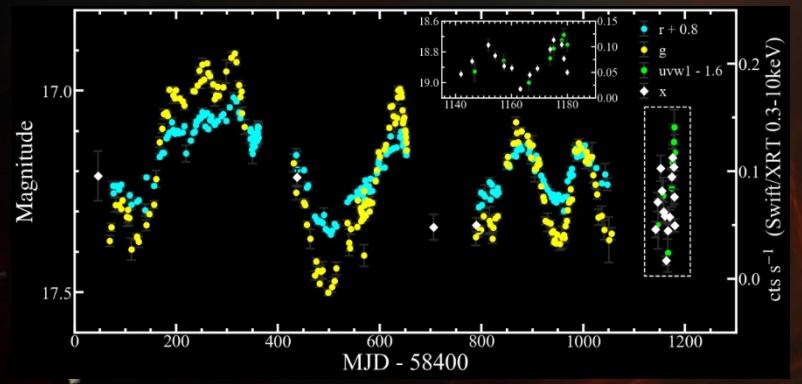
QPEs are viable candidates for the electromagnetic counterparts of extreme mass ratio inspirals with considerable implications for multi-messenger astrophysics.



Imminent Merger of a Supermassive Black Hole Binary







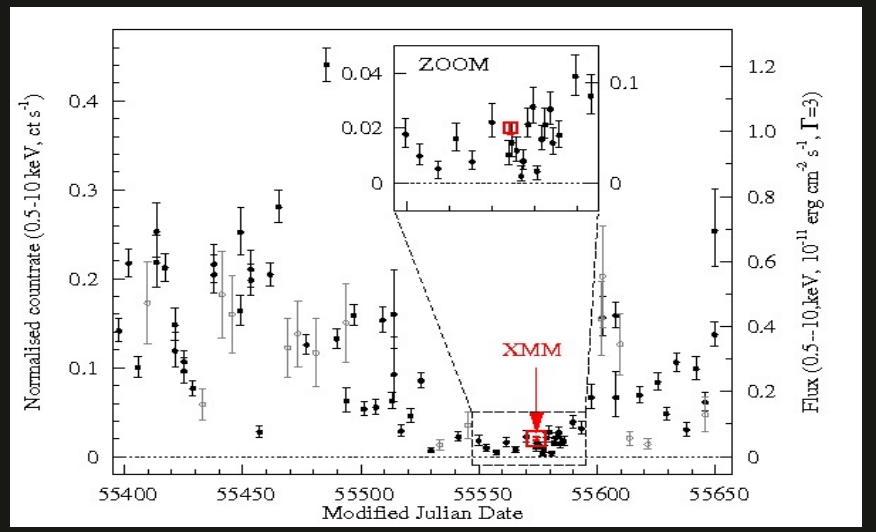
Jiang et al. (2022, arxiv: 2201.1163)

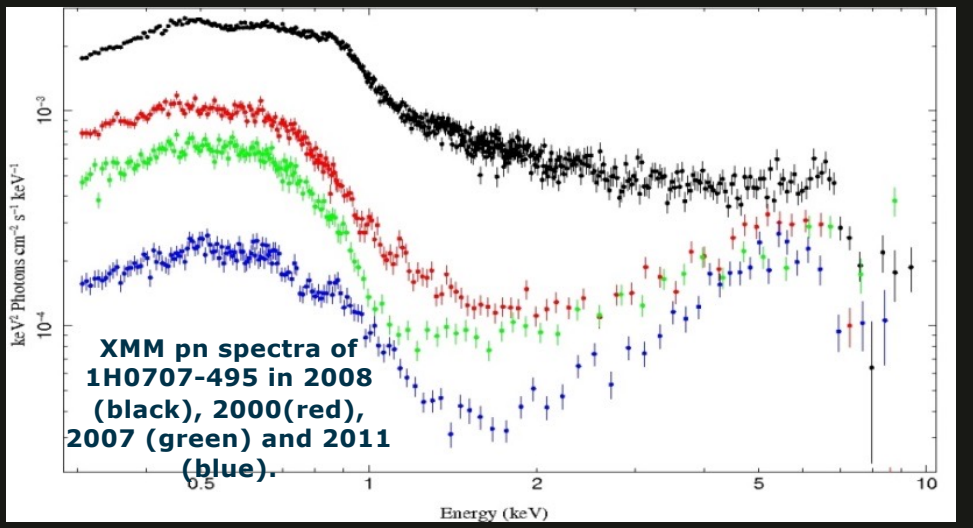
➔ X-ray: two-component absorber, one is outflowing and the other is inflowing with velocity > 0.1c

➔ disk crossings at small separations of the SMBH binary

Supermassive Black Holes - AGN Variability

1H0707-495 in low state: An X-ray source within a gravitational radius of the event horizon

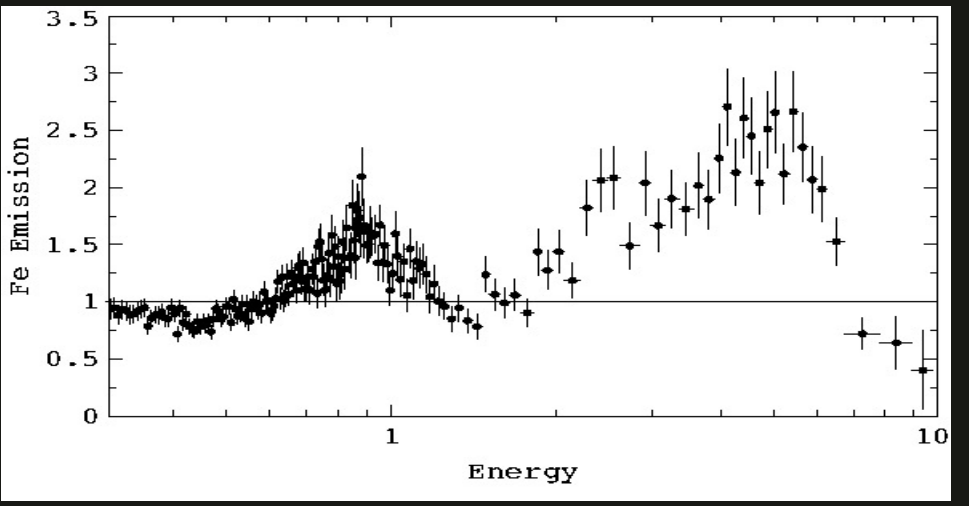




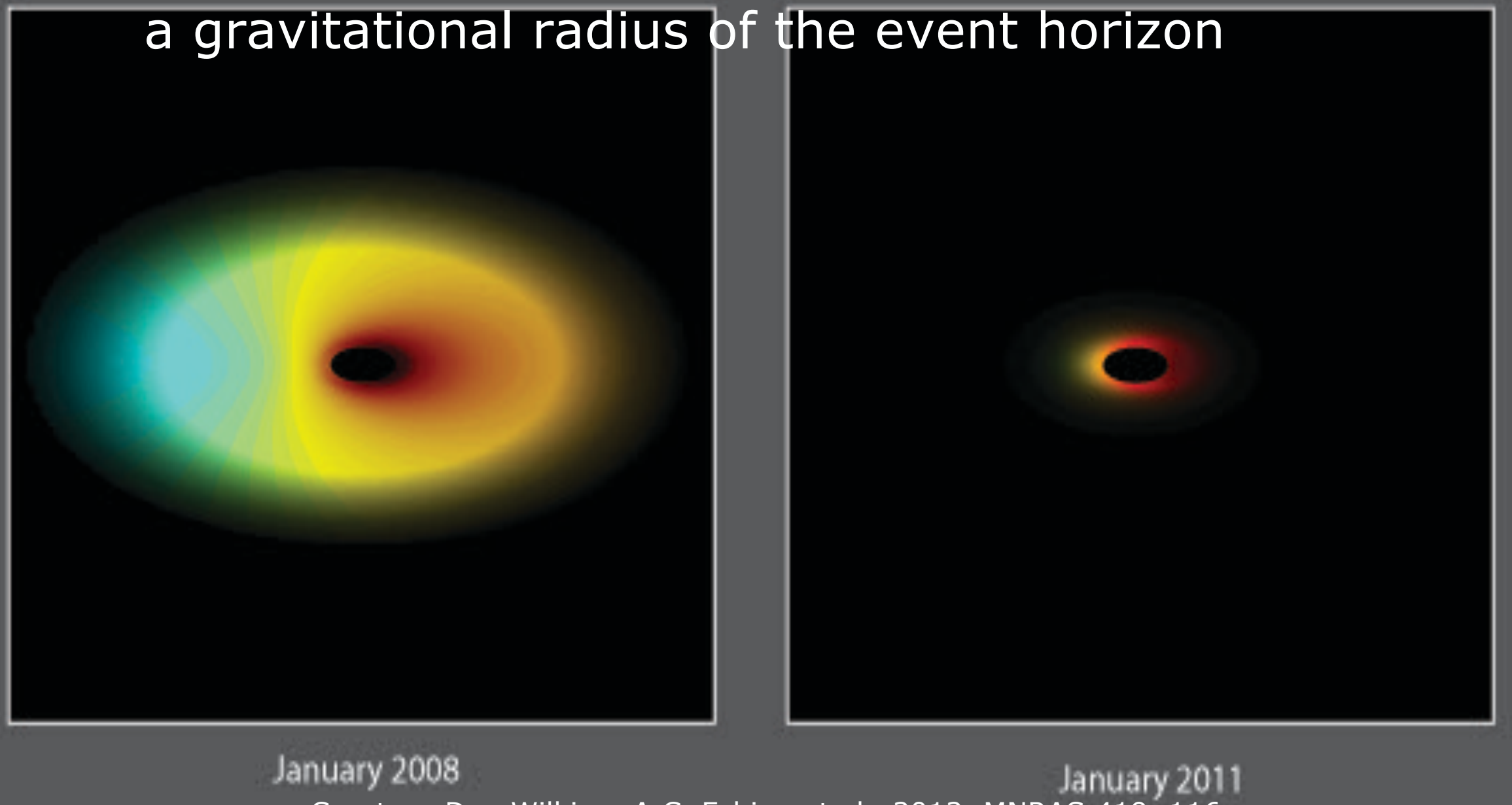
Fabian, A. C. et al., 2012, MNRAS 416, 116

- The Narrow Line Seyfert 1 Galaxy 1H0707-495 was in a low state from 12/2010 to 2/2011, discovered by monitoring of Swift
- 100 ks XMM-Newton observation of the low state: flux has dropped by a factor of 10 in the soft band, and a factor of 2 at 5 keV, compared with a long observation in 2008
- The spectrum is well fit by a relativistically-blurred reflection spectrum

➔ The irradiating source must lie within 1 gravitational radius of the event horizon of the black hole, which spins rapidly.



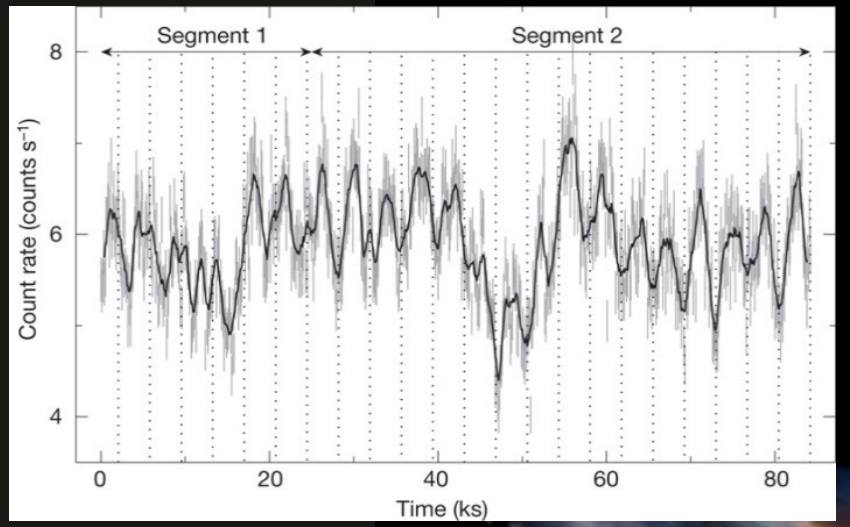
1H0707-495 in low state: An X-ray source within a gravitational radius of the event horizon

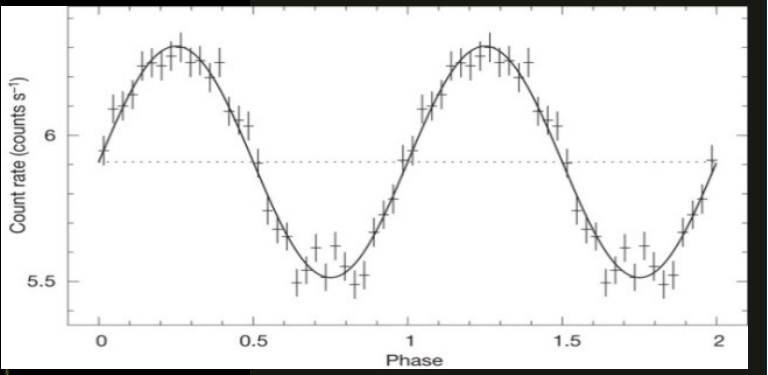


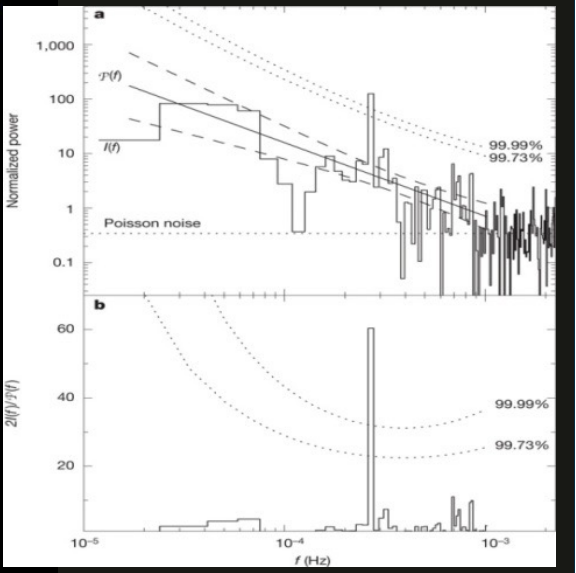
Courtesy Dan Wilkins; A.C. Fabian et al., 2012, MNRAS 419, 116

First QPO from an AGN

Gierlinski et al., 2008, Nature 455, 369







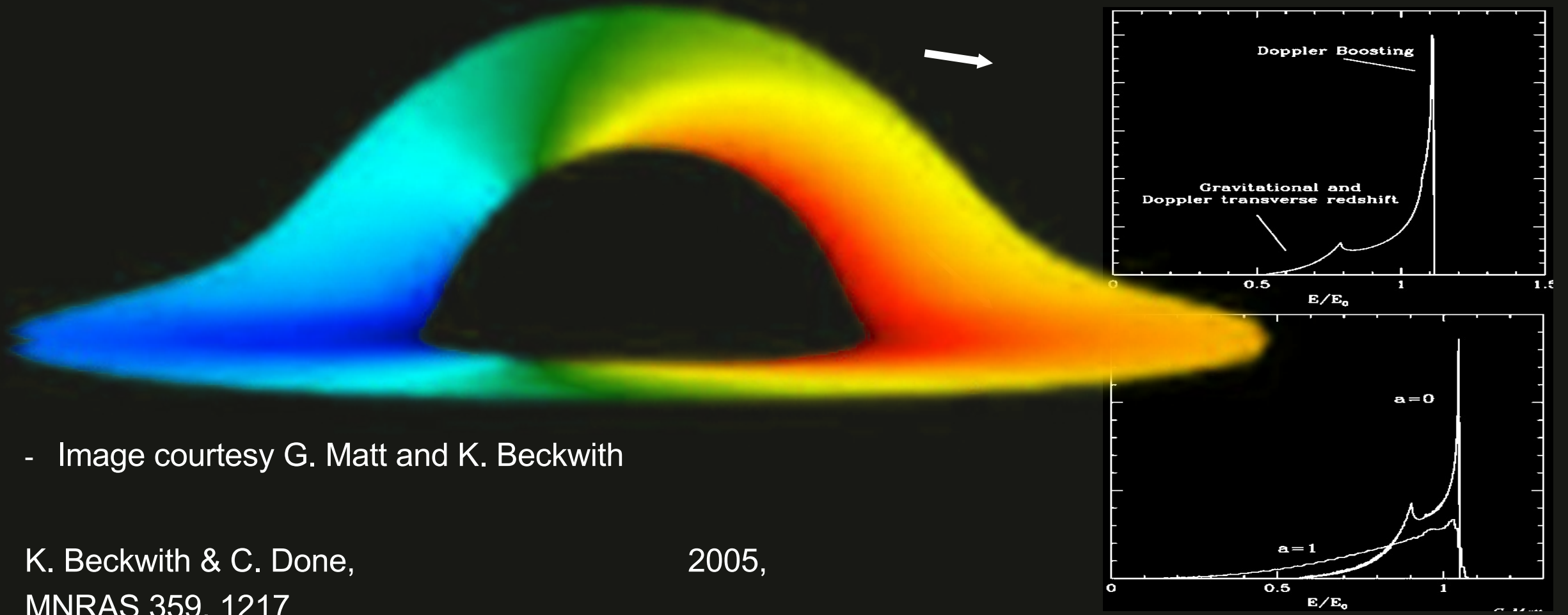
- Since 20 years QPO in X-ray binaries, but never found for AGNs (13y)
- RE J1034+396 nearby (z=0.043) narrow-line Seyfert 1
- Black hole mass: 6.3 x 10^5 to 3.6 x 10^7 M_{sun}

➔ XMM-Newton detection of a ~ 1 hour quasi periodic oscillation (QPO)

➔ Provides fundamental length-scale of SMBH system

Black Holes / General Relativity

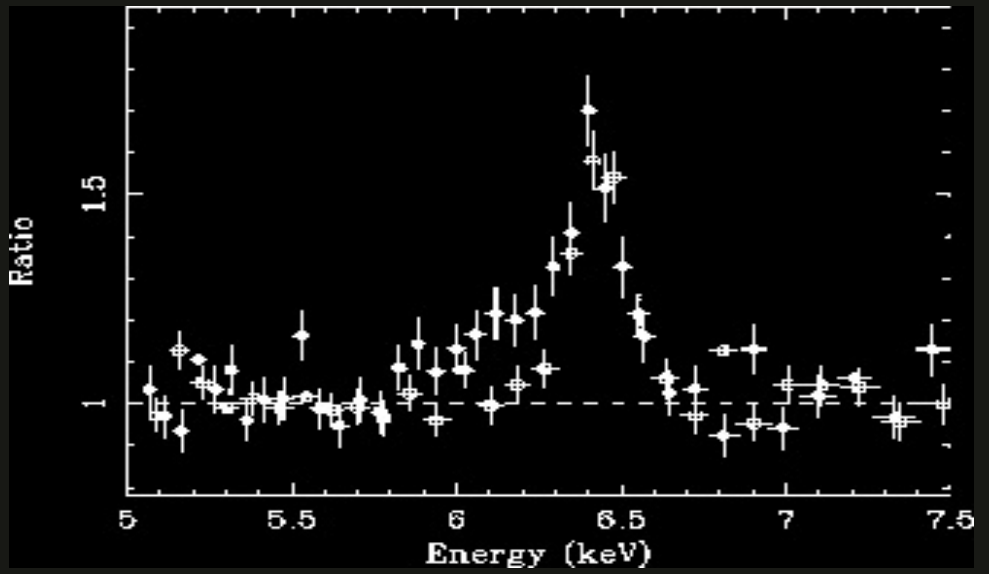
Emission in the Strong Gravitational Field of the (Kerr) Black Hole

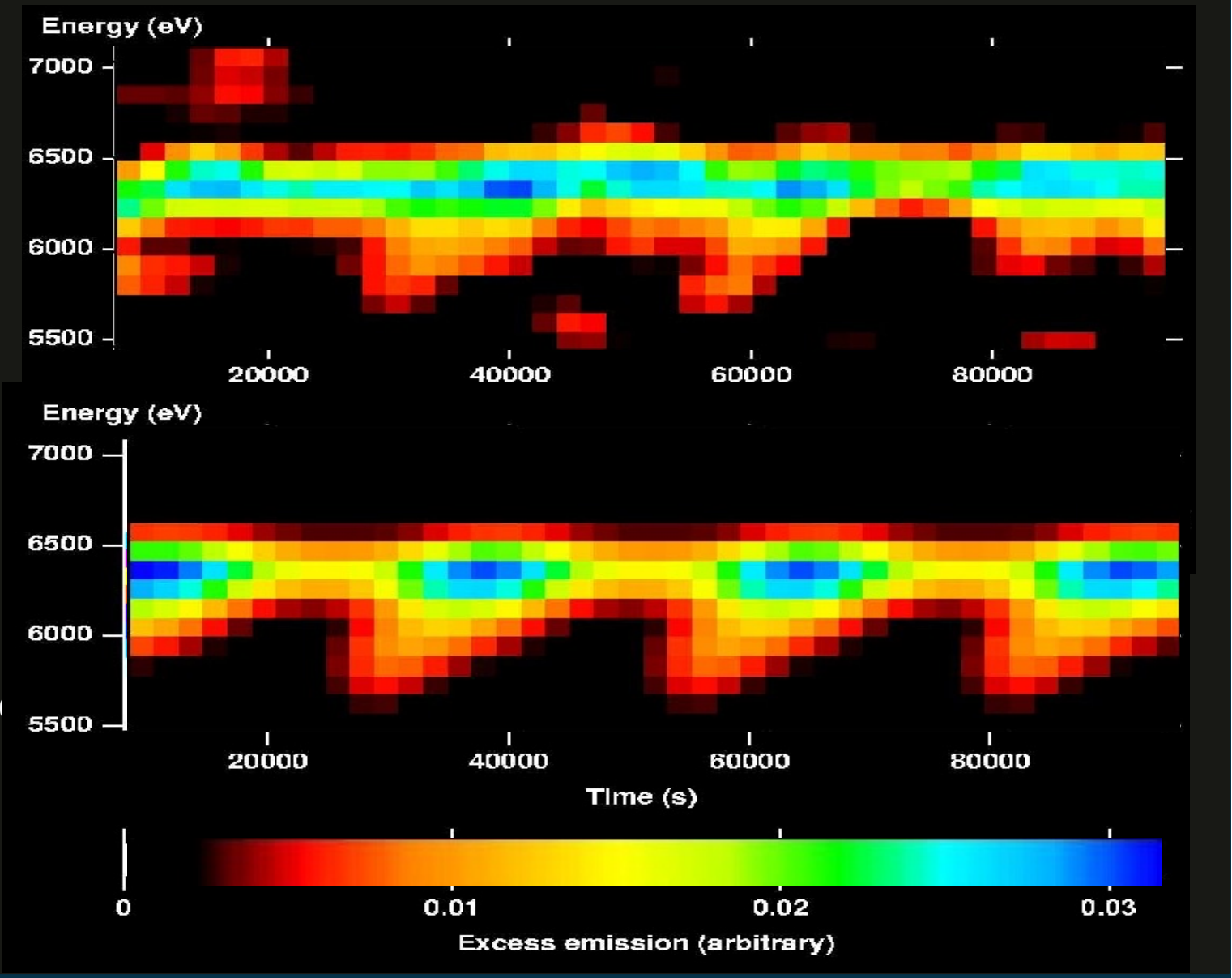


- Image courtesy G. Matt and K. Beckwith

K. Beckwith & C. Done, 2005,
MNRAS 359, 1217

Flux and Energy Modulation of Iron Emission in NGC 3516



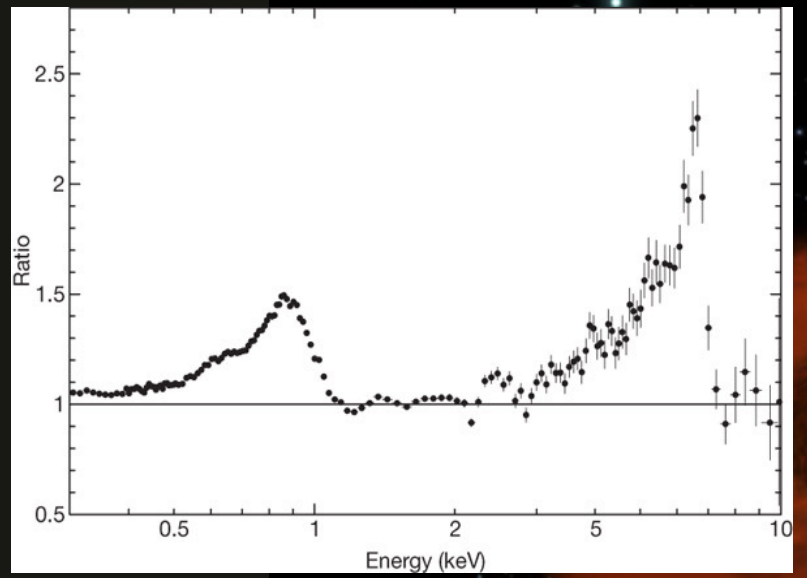


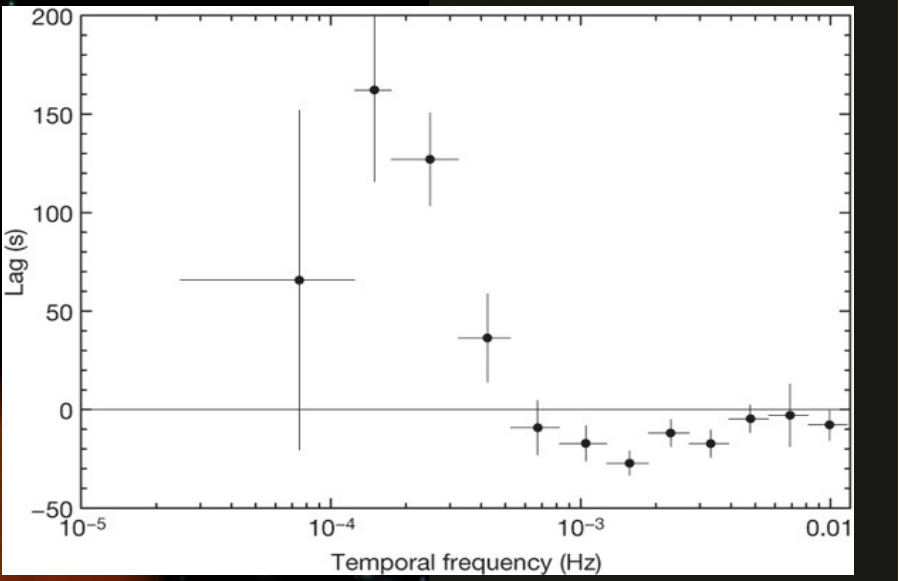
K. Iwasawa, G. Miniutti & A.C. Fabian, 2004, MNRAS 355, 1

➔ "co-rotating" flare at a (3.5-8) r_{Sch}

➔ mass of the BH: (1-5) × $10^7 M_o$

Broad line emission from iron K- and L shell transitions in the active galaxy 1H 0707-495





Broad Iron K & L emission lines :

- Line ratio (photons) 1:20
- Emitted between 1.3 and 400 r_g
- Emissivity index 4
- BH spin rate a > 0.98

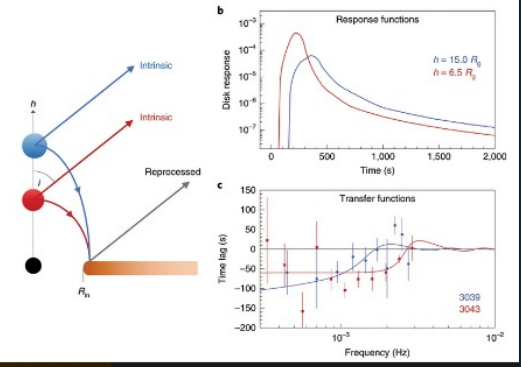
➔ Frequency-dependent lags between the 1
4 kev band flux and the 0.1 – 1 keV ba
flux

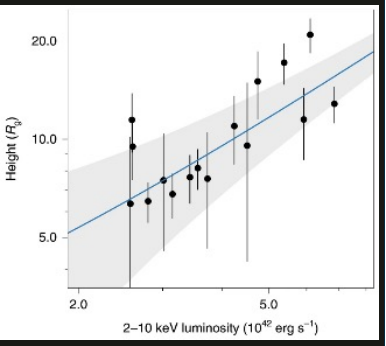
➔ Negative lag for $\nu > 6 \times 10^{-4}$ Hz ➔ Pow
law changes before refection

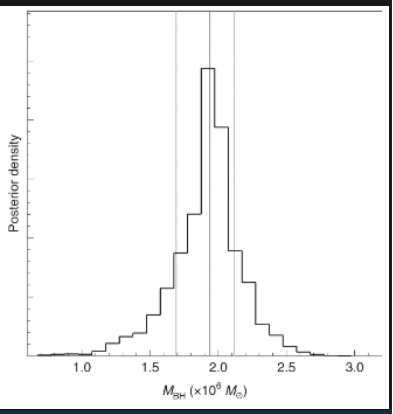
A.C. Fabian, 2009, Nature 459, 540

Dynamic Black Hole Corona in an AGN through X-ray Reverberation Mapping

Alston et al., 2020, Nature Astronomy 4, 597







X-ray reverberation based on a long XMM-Newton observation of the IRAS 13224−3809

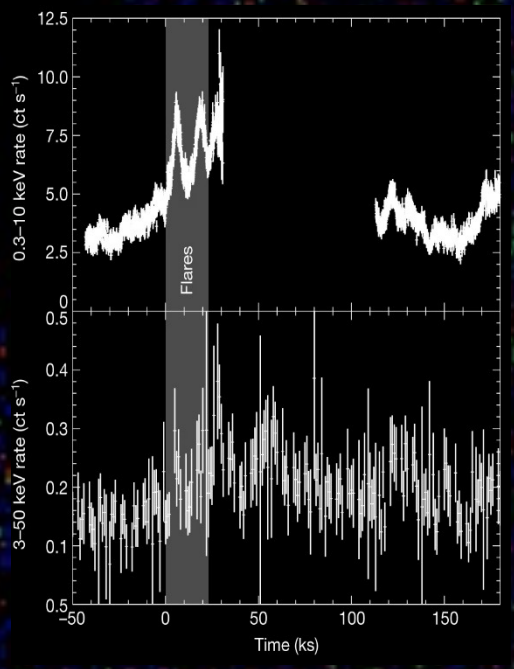
➔ X-ray corona increases with increasing luminosity

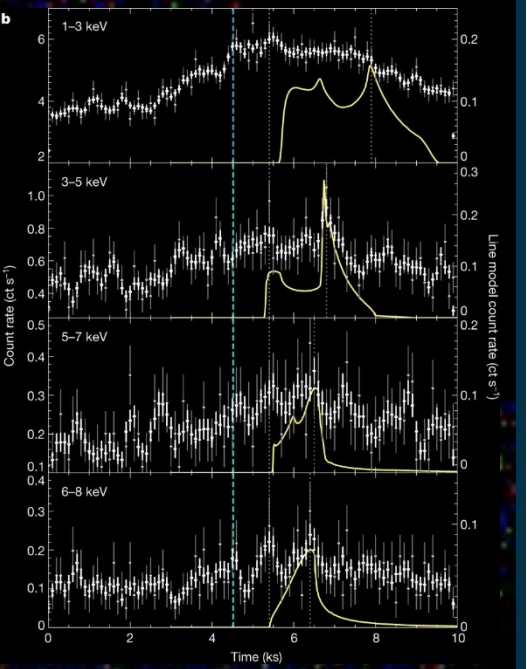
➔ break inherent degeneracy between black hole mass, inner disk radius and height of corona

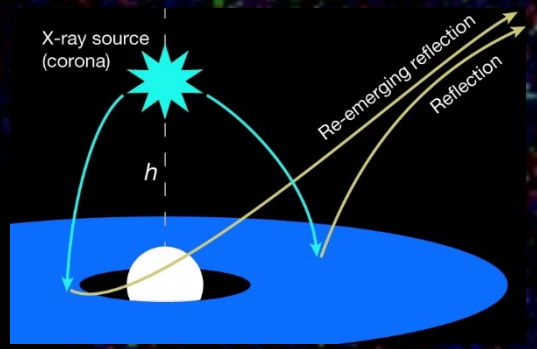
➔ $M_{BH} = 1.9 \pm 0.2 \times 10^6\ M_\odot$

➔ spin value a = 0.97

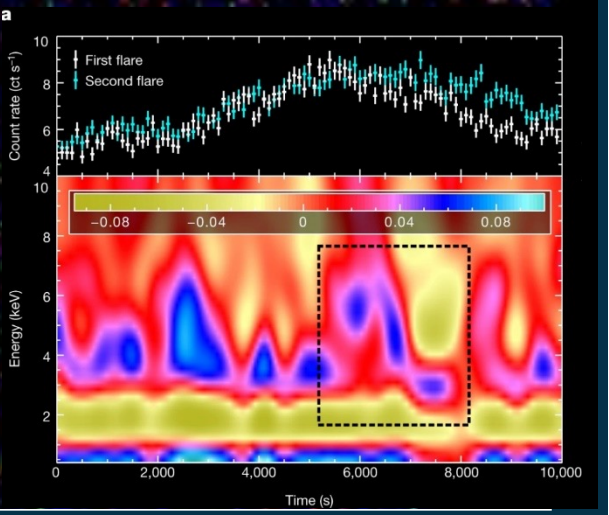
Light bending and X-ray echoes from behind a supermassive black hole 1Zw1







D. Wilkins et al., 2021,
Nature 595, 657



Thank you very much !