20th Anniversary of XMM-Newton: Supermassive Black Holes

Supermassive Black Holes: Environment and Evolution

20 June 2019

Corfu, Greece

Norbert Schartel

XMM-Newton Proposal

X M M

A PROPOSAL TO ESA FOR AN

X-RAY MULTI-MIRROR

ASTRONOMY MISSION

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November, 1982


00.07

XMM-Newton preparation

Image courtesy of D. Parker

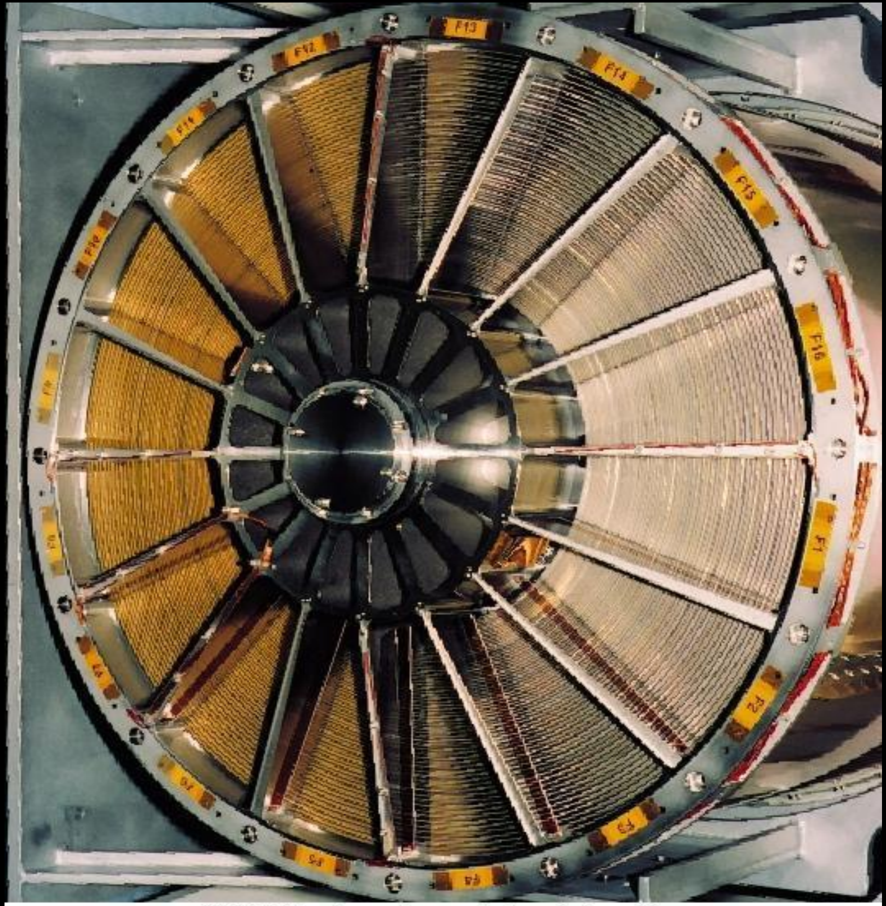
European Space Agency

Mirror Module:

- grazing-incidence Wolter 1 telescopes

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

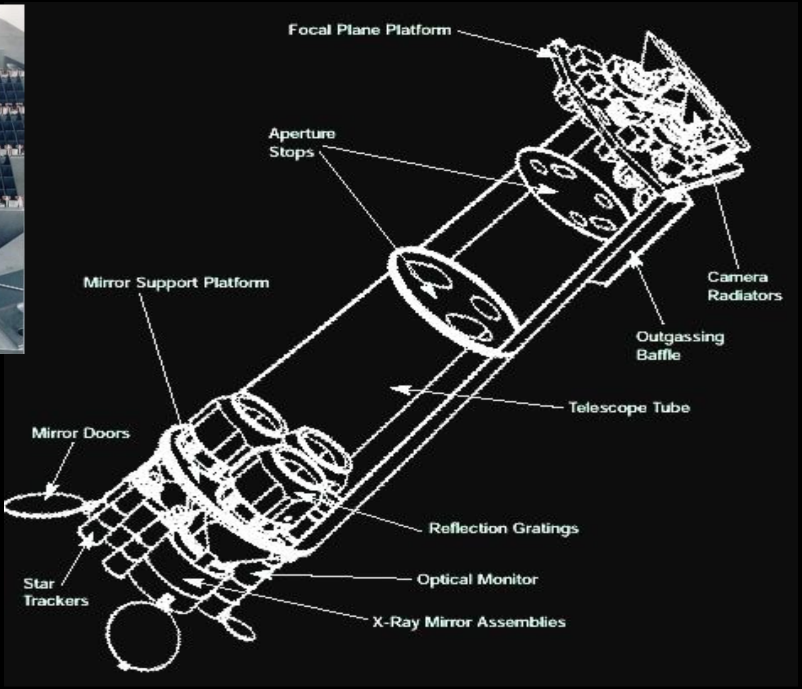
- 58 gold-coated nested mirrors

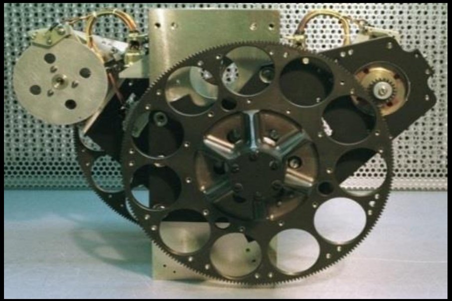


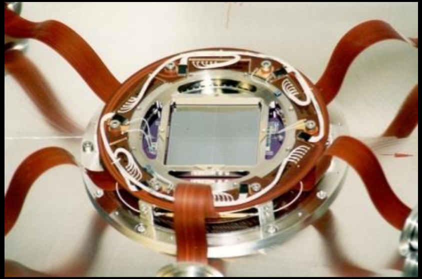
XMM-Newton mirrors during integration

Image courtesy of Dornier Satellitensysteme GmbH   European Space Agency

Instruments



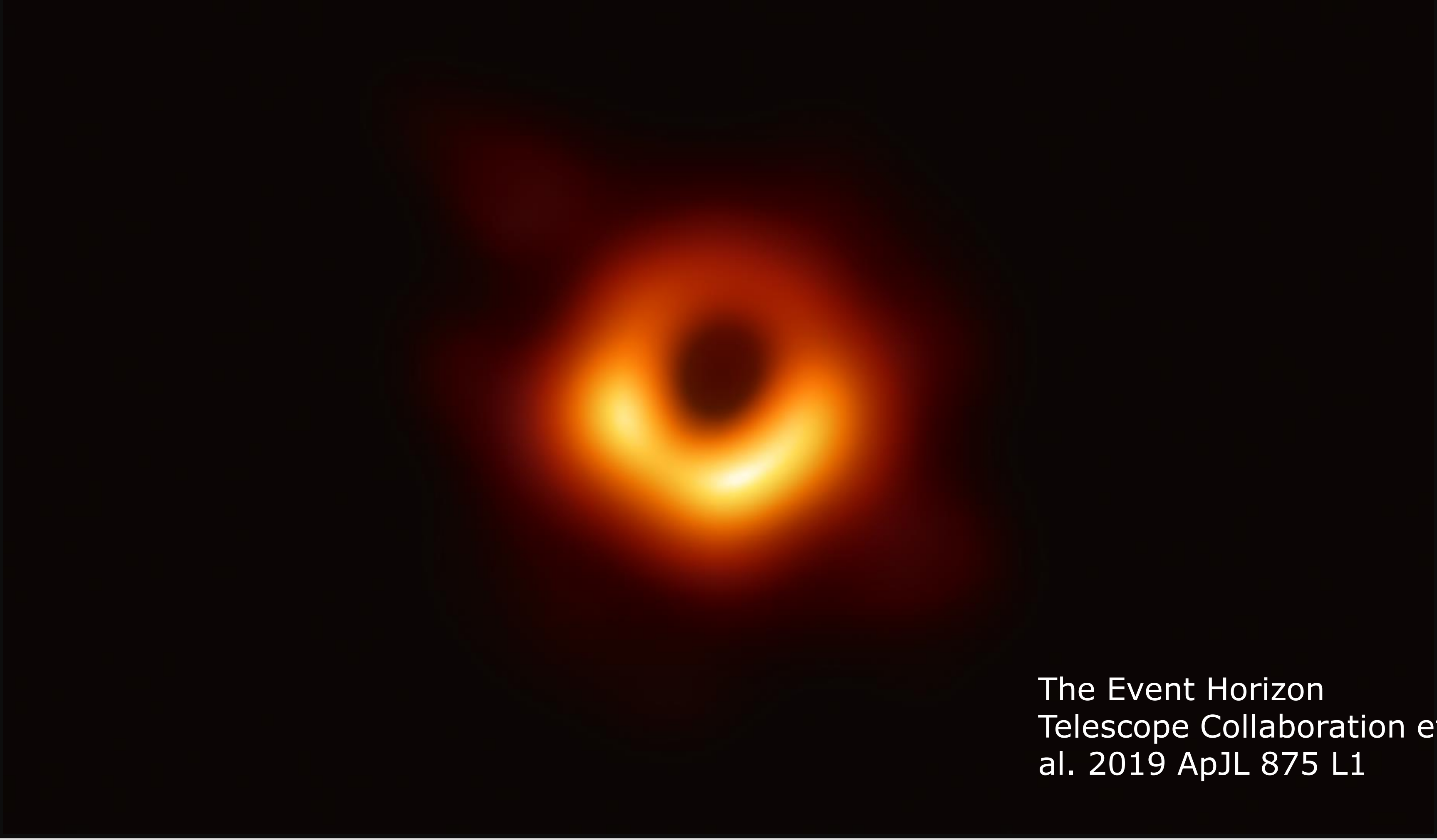




XMM-Newton

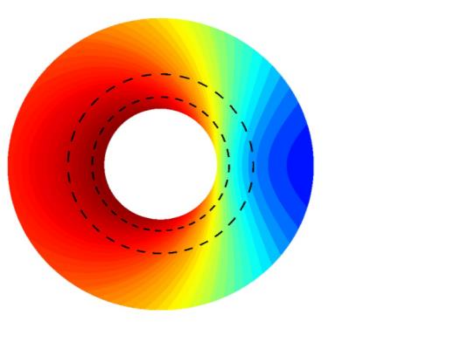
- 3 Mirror Modules / highest effective collecting area ever
- Six simultaneously observing instruments:
  - 3 CCD cameras (one pn and two MOSs)
  - 2 spectrometers (RGS)
  - 1 Optical Monitor (OM)

Supermassive Black Holes



The Event Horizon Telescope Collaboration et al. 2019 ApJL 875 L1

Emission in the Strong Gravitational Field of the Black Hole



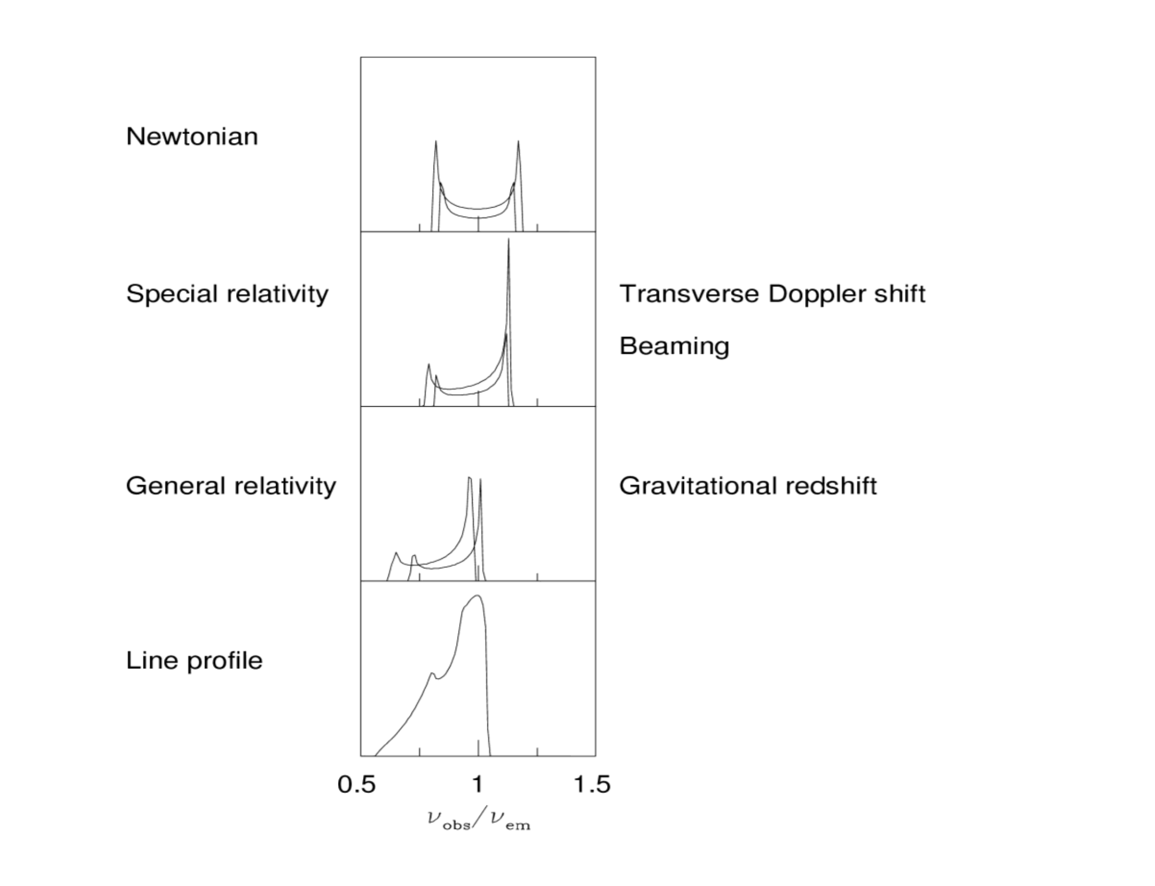
Fabian et al. (1989);

Laor et al. (1990);

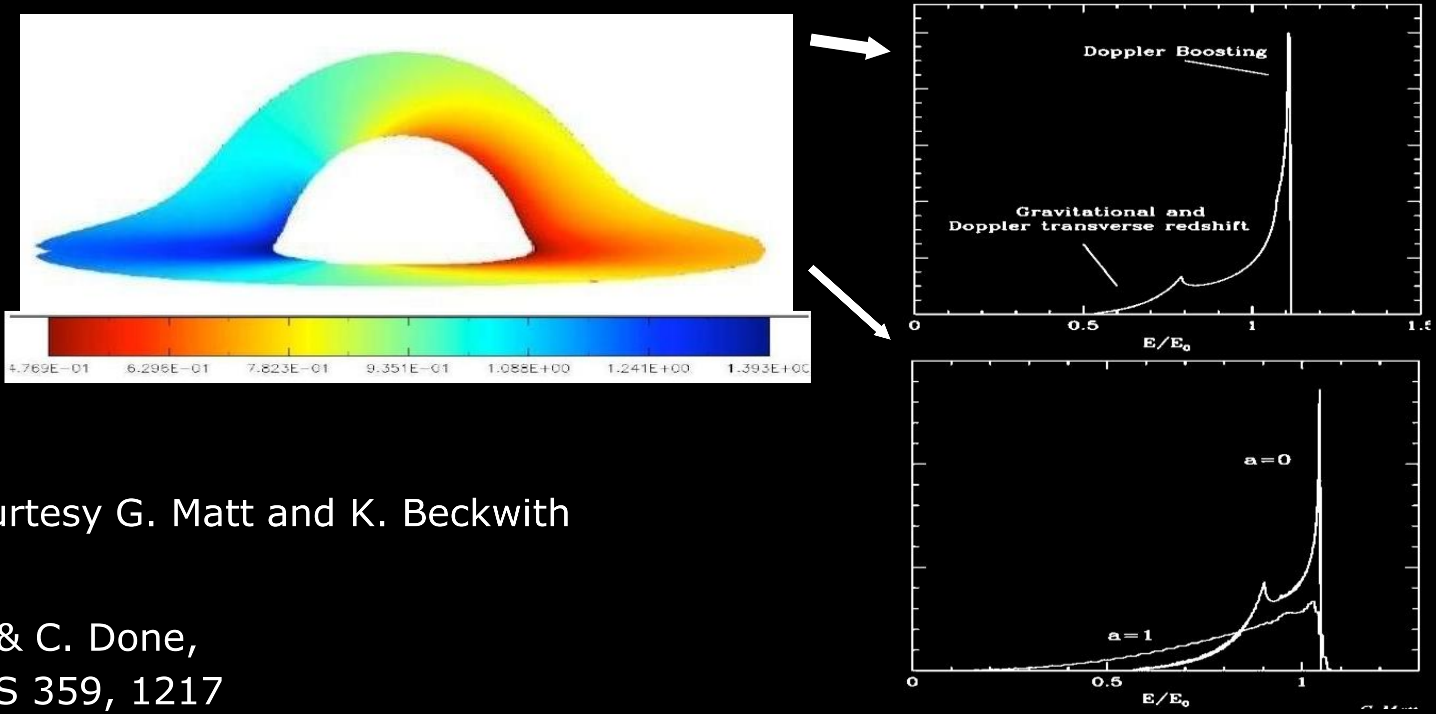
Dovciak et al. (2004);

Beckwith & Done (2005)

- Image courtesy A. Fabian



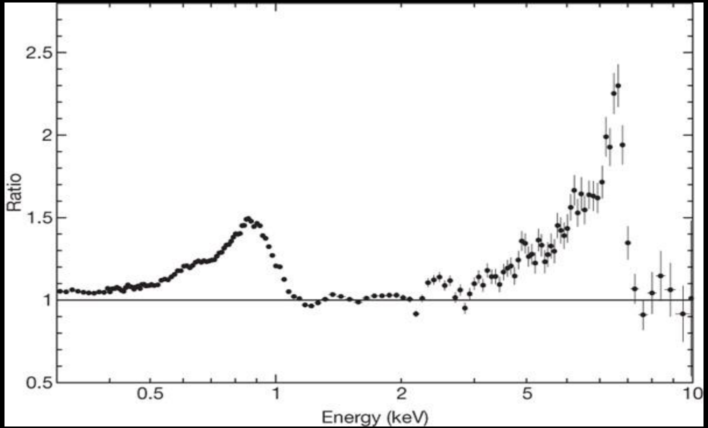
Emission in the Strong Gravitational Field of the (Kerr) Black Hole

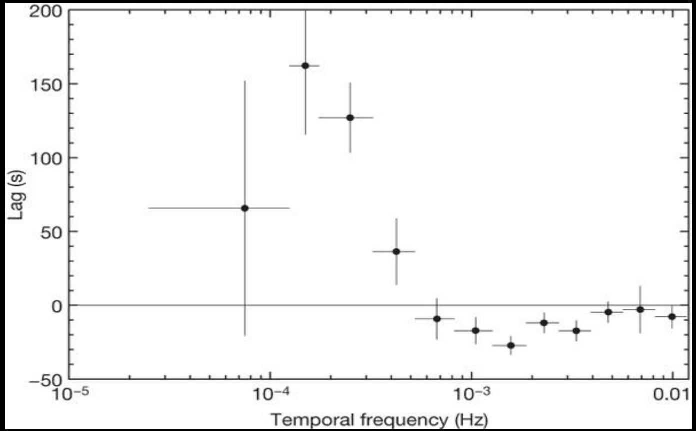


- Image courtesy G. Matt and K. Beckwith

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

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 band flux

➔ Negative lag for ν > 6 x 10^{-4} Hz

➔ Power law changes before refection

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

A rapidly spinning supermassive black hole at the center of NGC1365

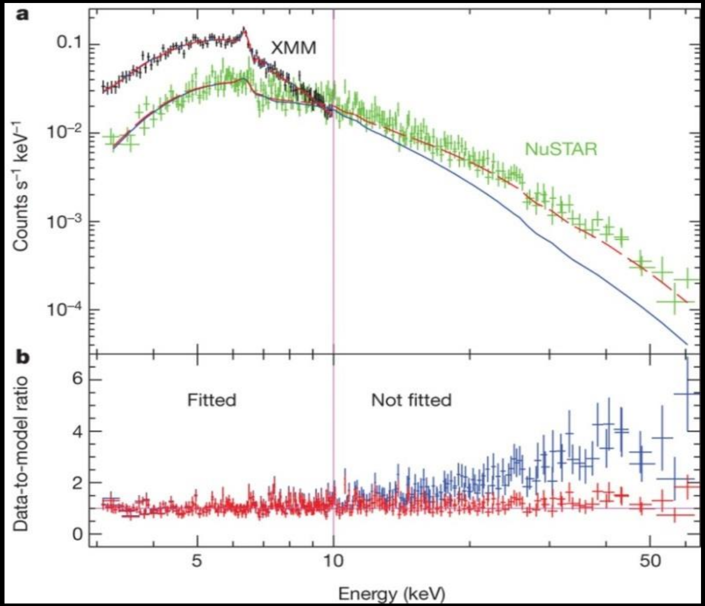
Simultaneous observation of NGC 1365 by XMM-Newton and NuSTAR:

➔ relativistic disk features through broadened Fe-line emission and an associated Compton scattering excess of 10-30 keV

➔ temporal and spectral analyses allows to disentangle continuum changes due to time-variable absorption from reflection, which arises from a region within 2.5 gravitational radii of the rapidly spinning black hole.

➔ Absorption-dominated models that do not include relativistic disk reflection can be ruled out both statistically and on physical grounds.

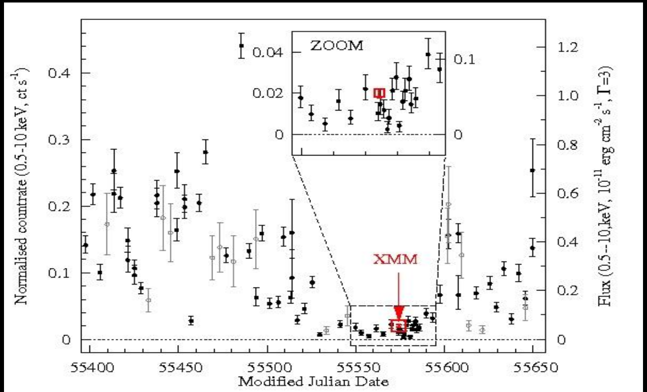
Risaliti G., et al., 2013, Nature 494

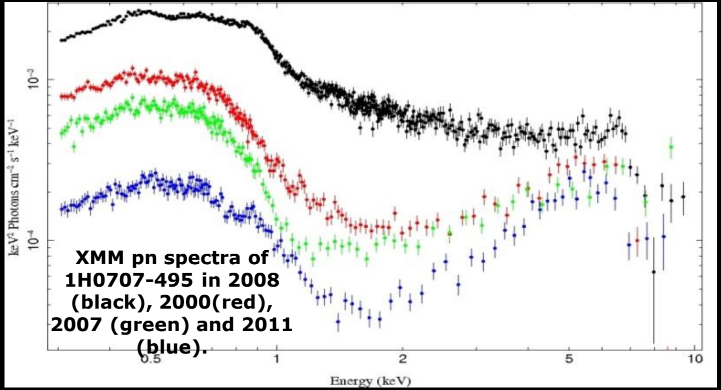


a: XMM-Newton and NuSTAR spectral data and models. The two models contain a relativistic reflection component plus variable partial covering (red), and a double partial covering (blue). Both models have been fitted to the data below 10 keV, and reproduce the lower-energy data well. However, the models strongly deviate at higher energies. b, Data-to-model ratio for the double partial covering (blue) and relativistic reflection plus variable absorber

Variability

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



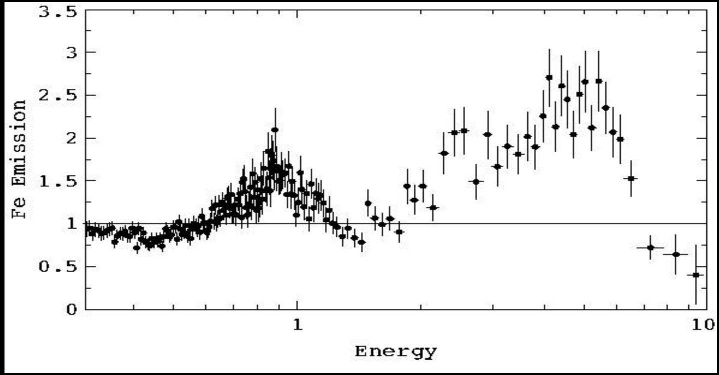


XMM pn spectra of 1H0707-495 in 2008 (black), 2000(red), 2007 (green) and 2011 (blue).

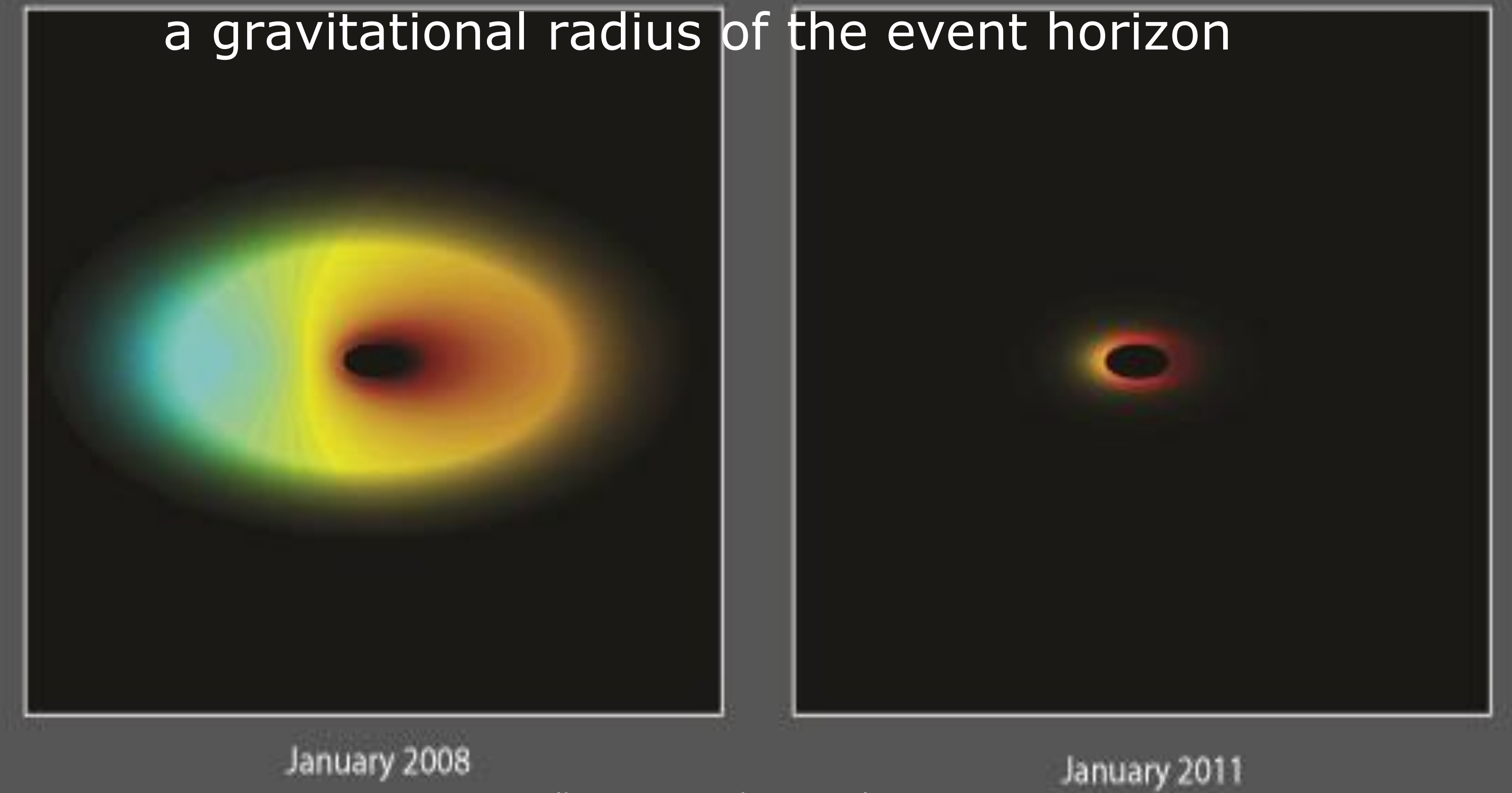
Fabian, A. C. et al., 2012, MNRAS 416, 116

- 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.

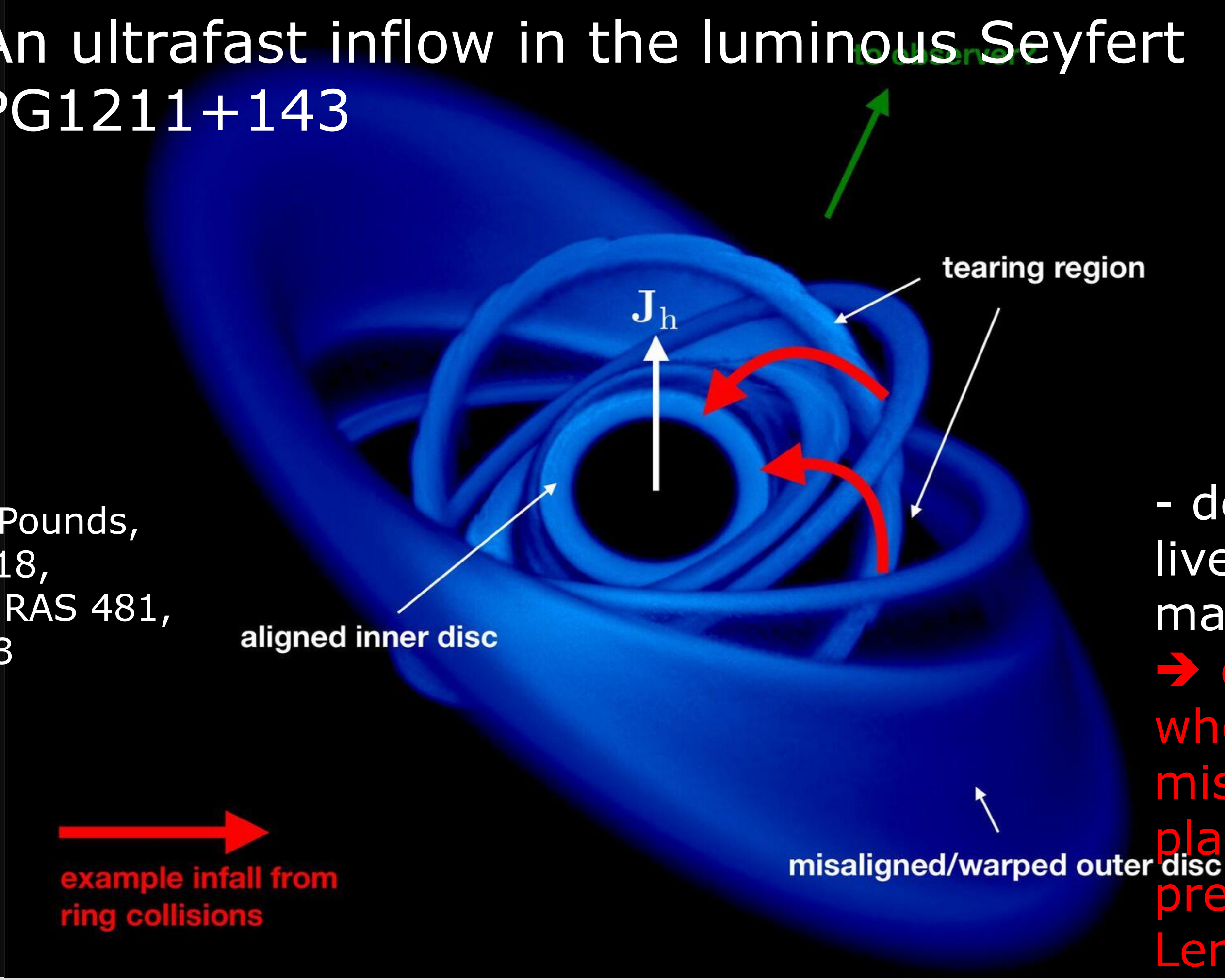


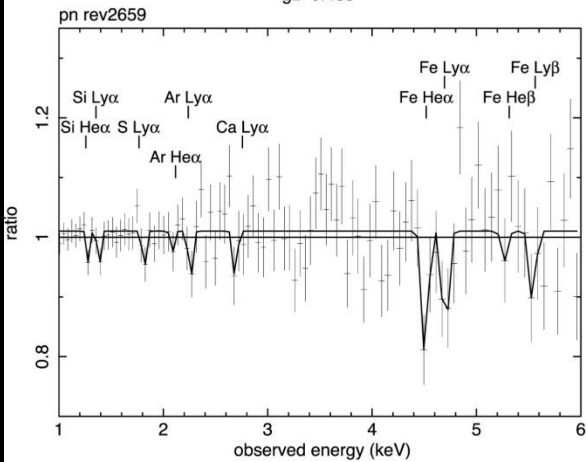
1H0707-495 in low state: An X-ray source within a gravitational radius of the event horizon



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

An ultrafast inflow in the luminous Seyfert PG1211+143





K. Pounds, 2018, MNRAS 481, 183

- detection of a short-lived, ultrafast inflow of matter at v ~ 0.3c

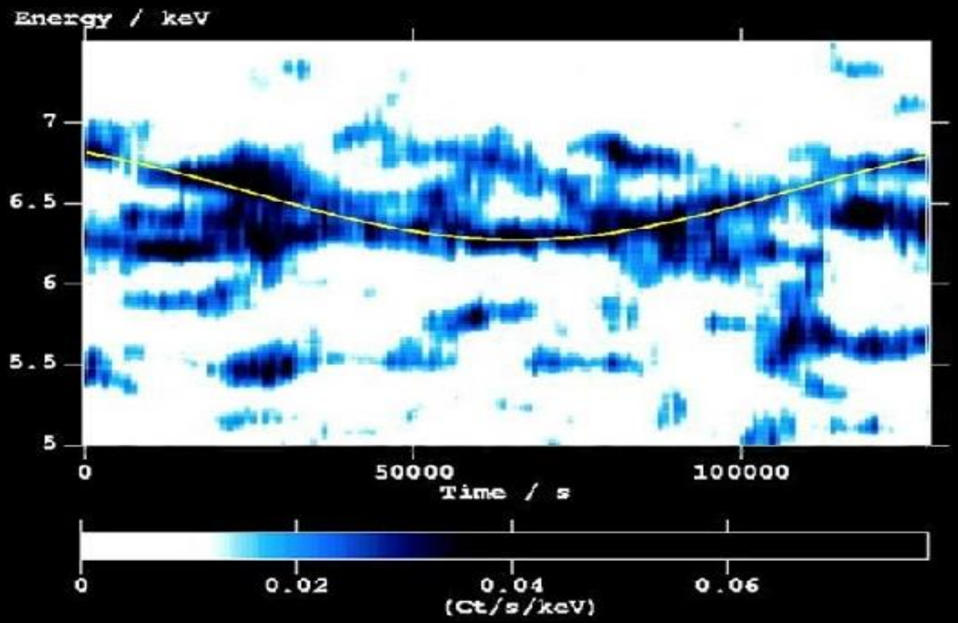
➔ disc tearing, arising when an accretion disc misaligned to the spin plane of the SMBH precesses due to the Lense–Thirring effect

Orbital Motion Close to the Central Black Hole of Mrk 766

- Energy-time plane of EPIC pn data in the 4-8 keV band
- Fe Kα emission shows a variation of photon energy with time consistent with sinusoidal variation

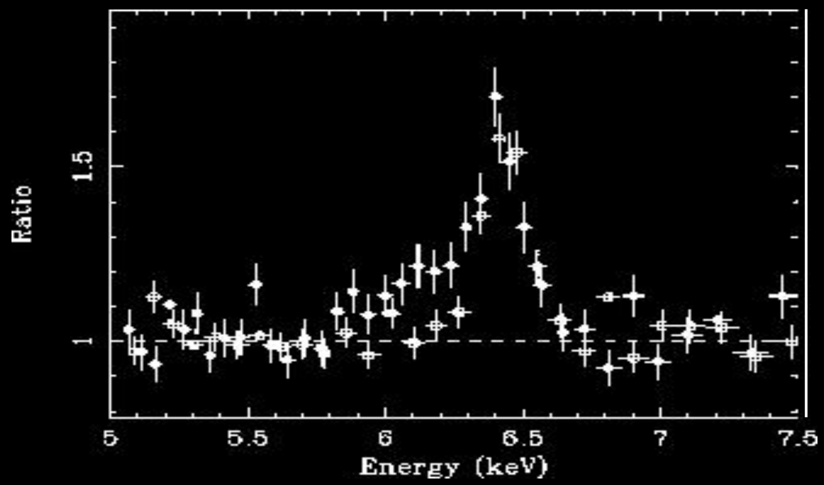
➔ Orbit has a period ~165 ks and a line-of-sight velocity ~13,500 km/s

- $4.9 \times 10^5 < M_{BH} < 4.5 \times 10^7$

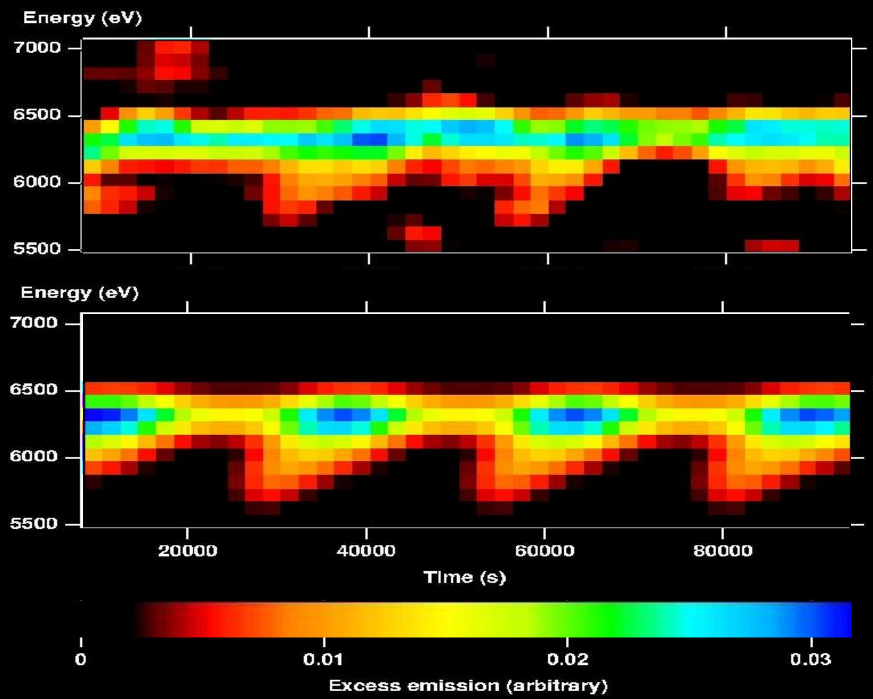


T. J. Turner, et al., 2006, A&A 445, 59

Flux and Energy Modulation of Iron Emission in NGC 3516

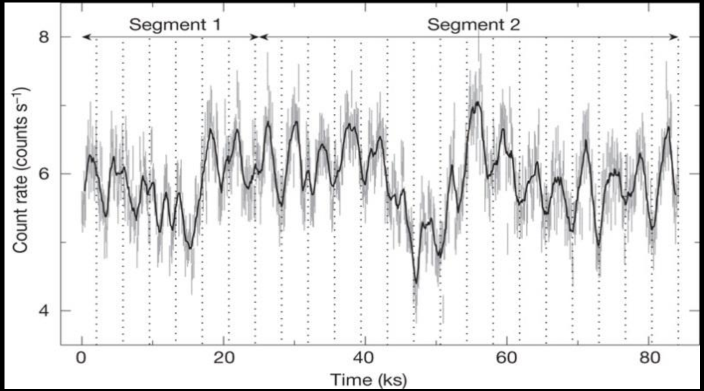


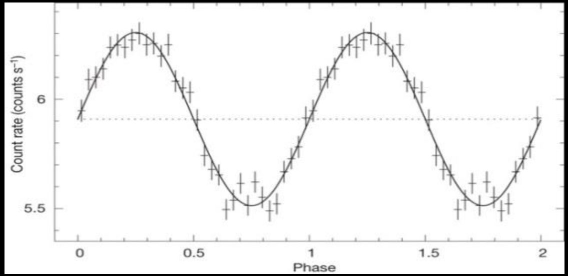
K. Iwasawa, G. Miniutti & A.C. Fabian, 2004, MNRAS 355, 1073



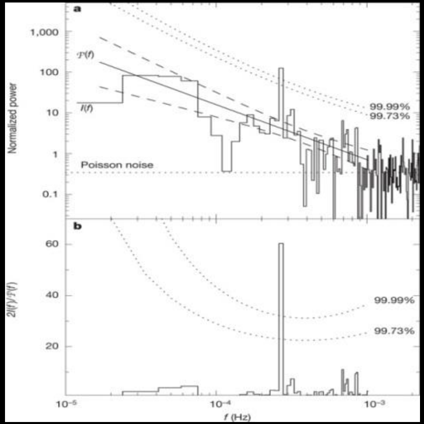
- ➔ "co-rotating" flare at a (3.5-8) r_{Sch}
- ➔ mass of the BH: (1-5) × $10^7 M_o$

First QPO from an AGN





Gierlinski et al., 2008,
Nature 455, 369



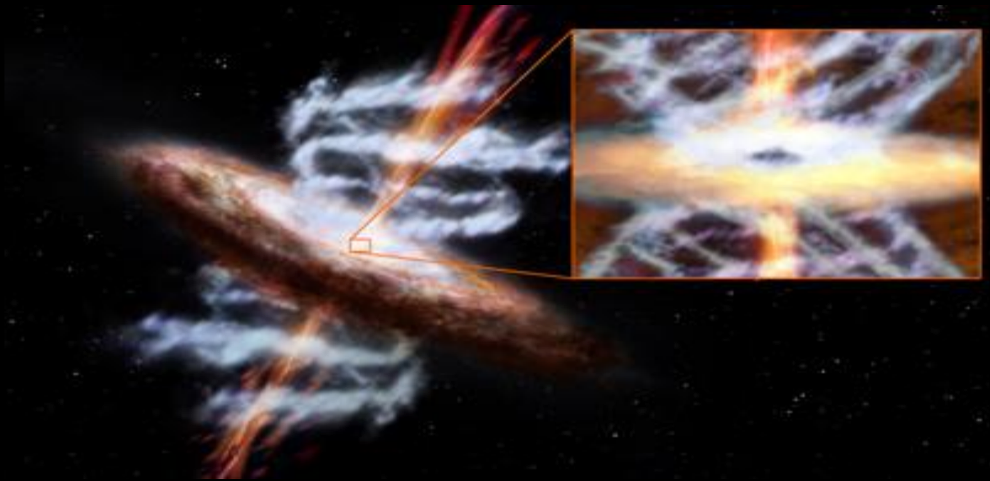
- Since 20 years QPO in X-ray binaries, but never found for AGNs (13y)
- RE J1034+396 nearby (z=0.043) narrow-line Seyfert 1
- Black hole mass: 6.3 x 10^5 to 3.6 x 10^7 M_{sun}

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

➔ Provides fundamental length-scale of SMBH system

Outflows

Ultra-fast Outflows in Radio-quiet Active Galactic Nuclei



➔ Location is in the interval ~0.0003-0.03pc (~10^2-10^4 r_s) from the central black hole

➔ Outflow rates: ~0.01-1 Mo y^{-1} / 5-10% of the accretion rates

➔ Mechanical power ~42.6-44.6 erg s^{-1}

➔ UFOs provide a significant contribution to the AGN cosmological feedback, in agreement with theoretical expectations

- Ultra-fast outflows (UFOs) are detected through blueshifted Fe XXV/XXVI K-shell transitions.
- 42 local radio-quiet AGNs observed with XMM-Newton.

➔ >35% are showing UFOs

➔ v ~ 0.03c -0.3c, mean value of ~0.14c

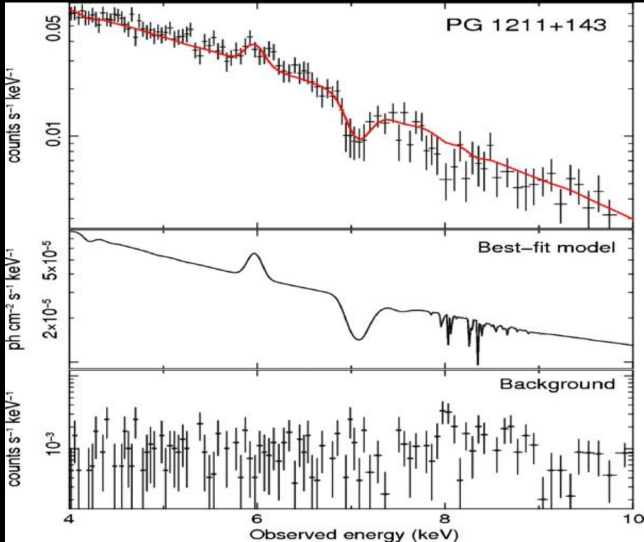
➔ Ionization parameter is very high

➔ Column densities are N_H~10^{22}-10^{24} cm^{-2}

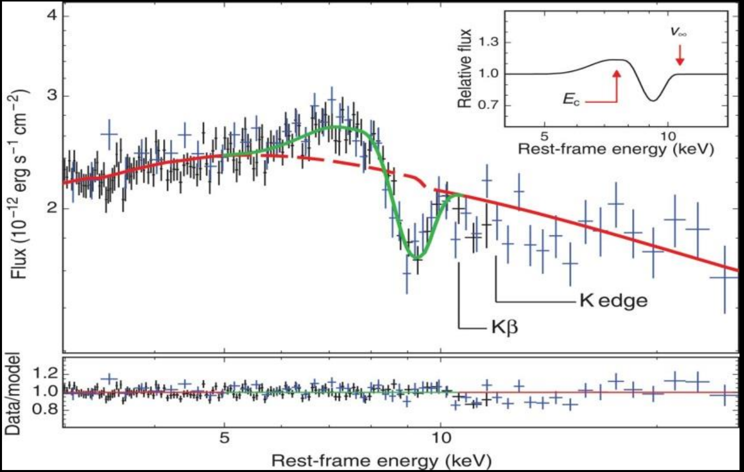
F. Tombesi et al., 2012, MNRAS 422, L1

F. Tombesi, et al., 2011, ApJ 742, 44

F. Tombesi, et al., 2010, A&A 521, 57



Black hole feedback in the luminous quasar PDS 456



XMM-Newton pn data are shown in black and NuSTAR data are shown in blue. The green curve shows a model where the emission and absorption residuals characterizing the Fe-K band are described through a self-consistent P-Cygni profile from a spherically symmetric outflow.

- XMM-Newton and NuSTAR simultaneously observed PDS 456 on four occasions in 2013

- The emission and absorption residuals of the Fe-K band are described through a self-consistent P-Cygni profile

➔ Nearly spherical symmetric outflow of highly ionized gas

➔ This wind is expelled at relativistic speeds from the inner accretion disk

➔ The outflow's kinetic power >10^{46} ergs/s

➔ Enough to provide the feedback required by models of black hole and host galaxy coevolution.

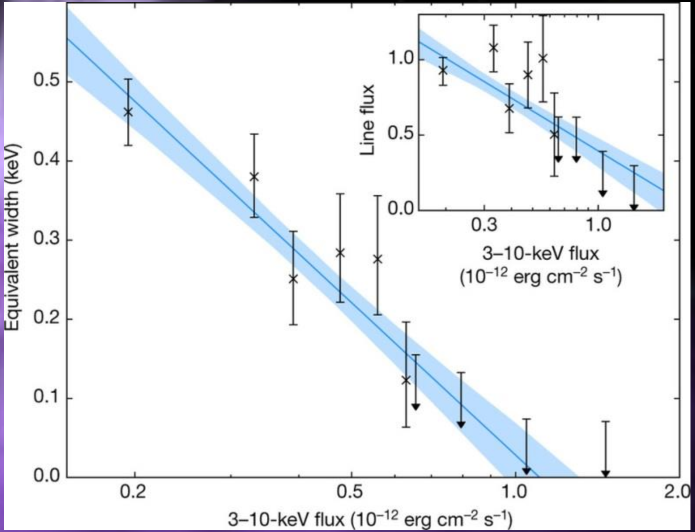
E. Nardini, et al., 2015, Science 347, 860

The response of relativistic outflowing gas to the inner accretion disk of a black hole

Gas outflows from AGNs release huge quantities of energy into the interstellar medium, potentially moderating the growth of their host galaxy.

XMM-Newton observations of the narrow line Seyfert-1 galaxy IRAS 13224-3809:
➔ extreme ultrafast gas flow in the X-ray spectrum
➔ 0.236 ± 0.006 times the speed of light (71,000 km/s)
➔ absorption is strongly anti-correlated with the emission of X-ray

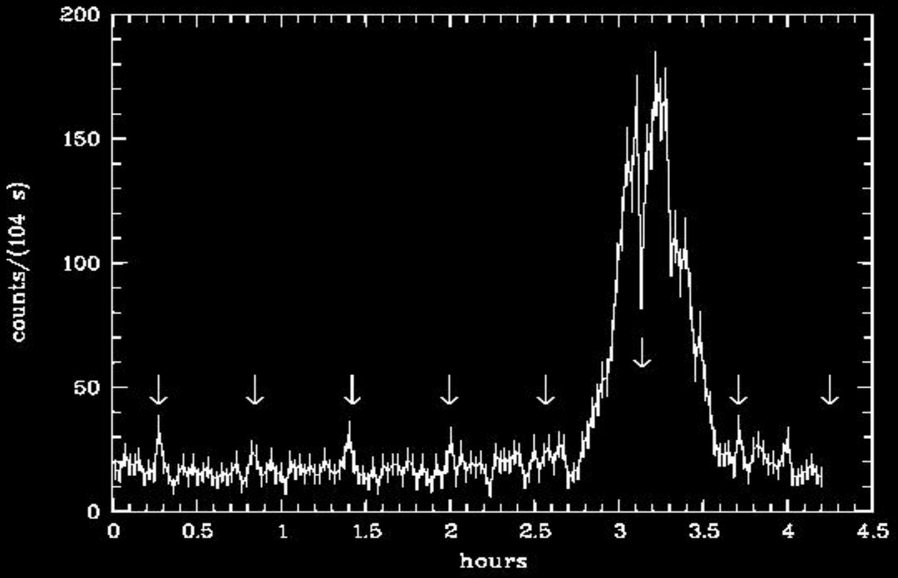
➔ X-ray emission from within a few gravitational radii of the black hole is ionizing the disk wind hundreds of gravitational radii further away as the X-ray flux rises.

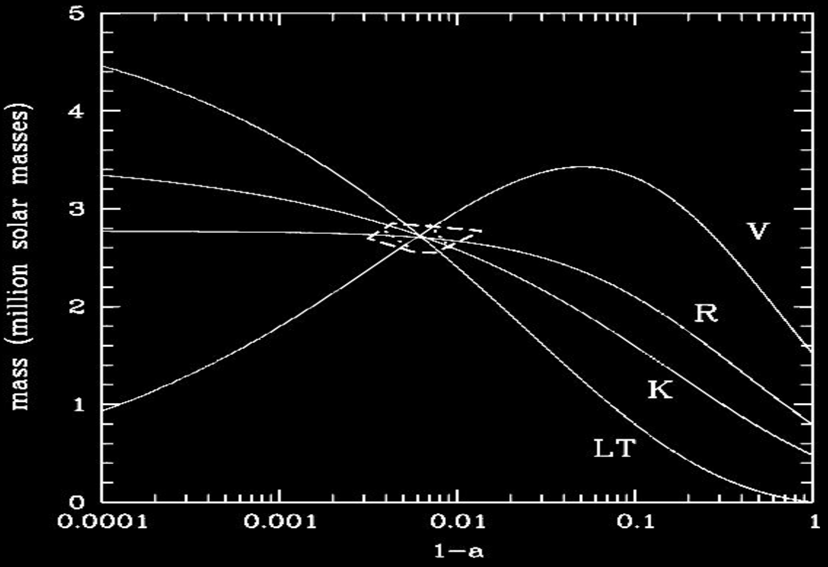


M. L. Parker, et al., 2017
Nature 543, 83

Sgr A*

X-Ray Flare of the Galactic Center BH





B. Aschenbach et al., 2004, A&A 417, 71

-Power density spectrum peaks at periods of 100s, 219s, 700s, 1150s and 2250s

Microquasars / Galactic Center BH

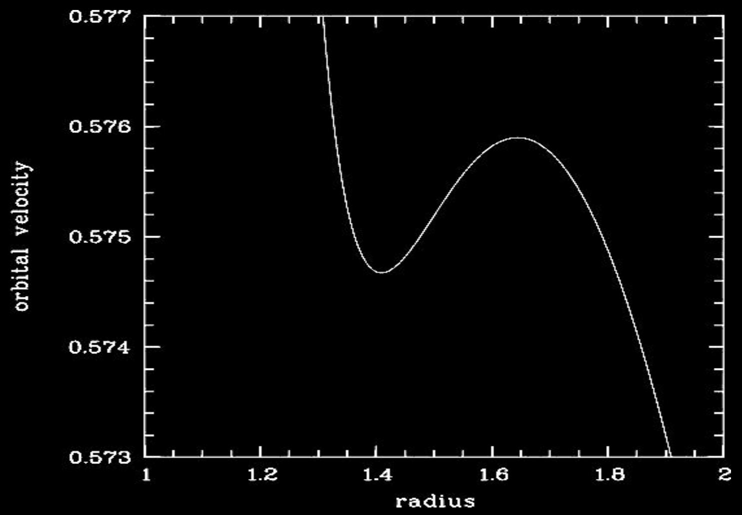
- GRO J1655-40, XTE J1550-564 and GRS 1915+105 show twin high frequency quasi-periodic oscillations with a ratio of 3:2 and/or 3:1
- resonance between vertical and radial epicyclic oscillations and Kepler orbits

➔ New topological structure

➔ Galactic Center BH:

$a = 0.99616$

$M = (3.28 \pm 0.13)\ 10^6 M_\odot$



B. Aschenbach, 2004, A&A 425, 1075

PHYSICAL REVIEW D 71, 024037 (2005)

Aschenbach effect: Unexpected topology changes in the motion of particles and fluids orbiting rapidly rotating Kerr black holes

Zdeněk Stuchlík,[1,2,*] Petr Slaný,[1,2,†] Gabriel Török,[1,2,‡] and Marek A. Abramowicz[1,2,3,§]
[1]*Institute of Physics, Silesian University at Opava, Bezručovo nám. 13, CZ-746 01 Opava, Czech Republic*
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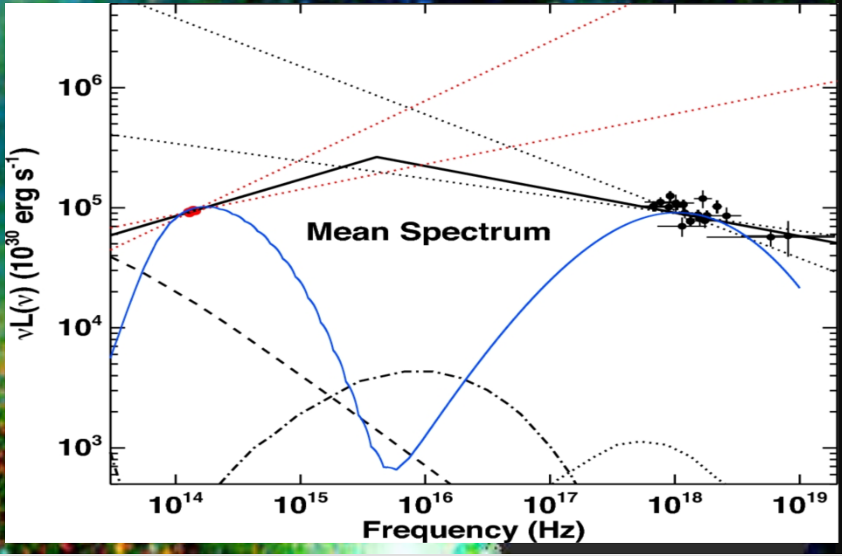
[3]*Theoretical Physics, Göteborg & Chalmers Universities, S-412 96 Göteborg, Sweden*
(Received 12 November 2004; published 28 January 2005)

A powerful flare from Sgr A* confirms the synchrotron nature of the X-ray emission

- multiwavelength monitoring campaign of Sgr A* with XMM–Newton, NuSTAR and SINFONI
- first fully simultaneous observations in near-infrared (NIR) and X-rays of a very bright flare of Sgr A*

Ponti et al., 2017
MNRAS 468, 2447

→ synchrotron emission with a cooling break



The red and black points show the mean NIR and X-ray (XMM–Newton and NuSTAR) emission during a flare. The dotted red and black straight lines show the uncertainties on the determination of the NIR and X-ray power-law slope, respectively. The solid line shows the best-fitting synchrotron with cooling break model.

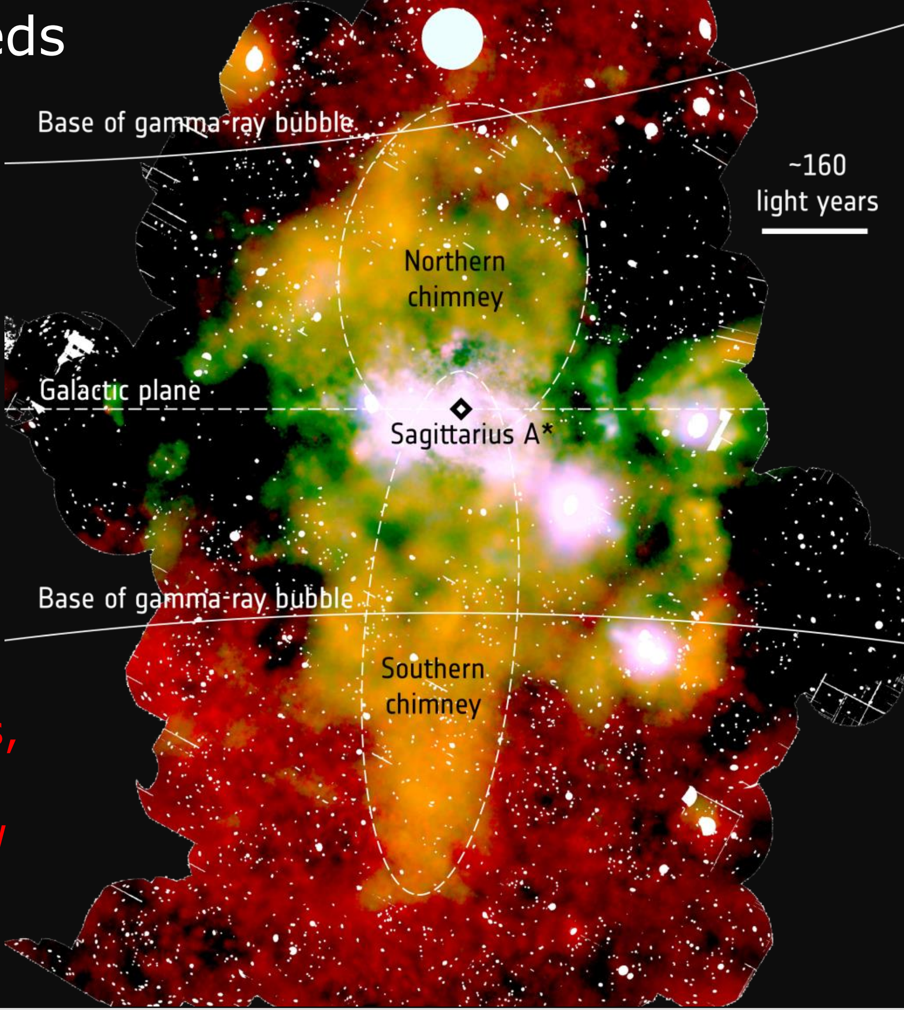
An X-ray chimney extending hundreds of parsecs above and below the Galactic Centre

- γ-ray observations revealed the `Fermi bubble' implying relativistic particles populating huge cavities on both sides of the Galactic plane
- ROSAT X-ray maps show that the edges of these cavities are bright in X-rays

➔ XMM-Newton finds prominent X-ray structures connecting the Galactic Centre to the Fermi bubbles.

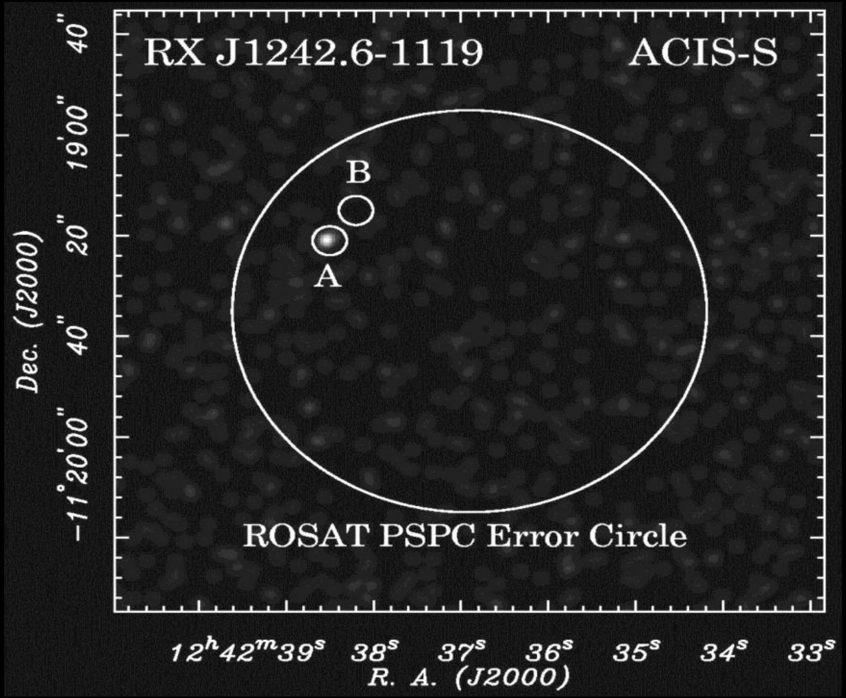
➔ channels through which energy and mass, injected by episodic events at the Galactic Centre, are transported from the central few parsecs to the Fermi bubbles

G. Ponti et al., 2019 Nature567, 347



Tidal Disruption Events

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



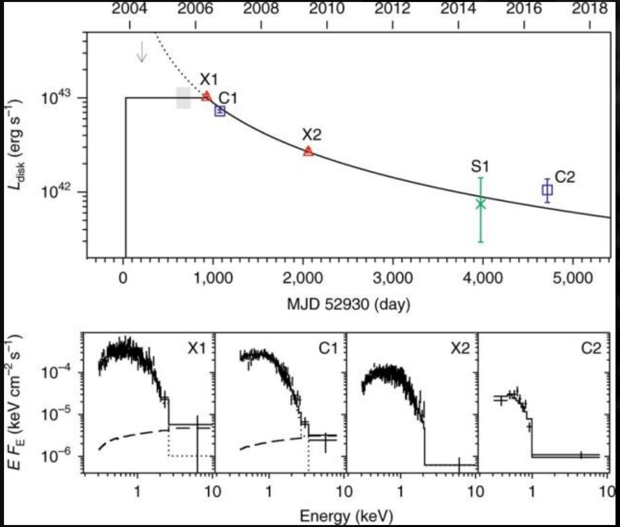
- ROSAT, Chandra and XMM-Newton
- ~200 drop in X-ray luminosity

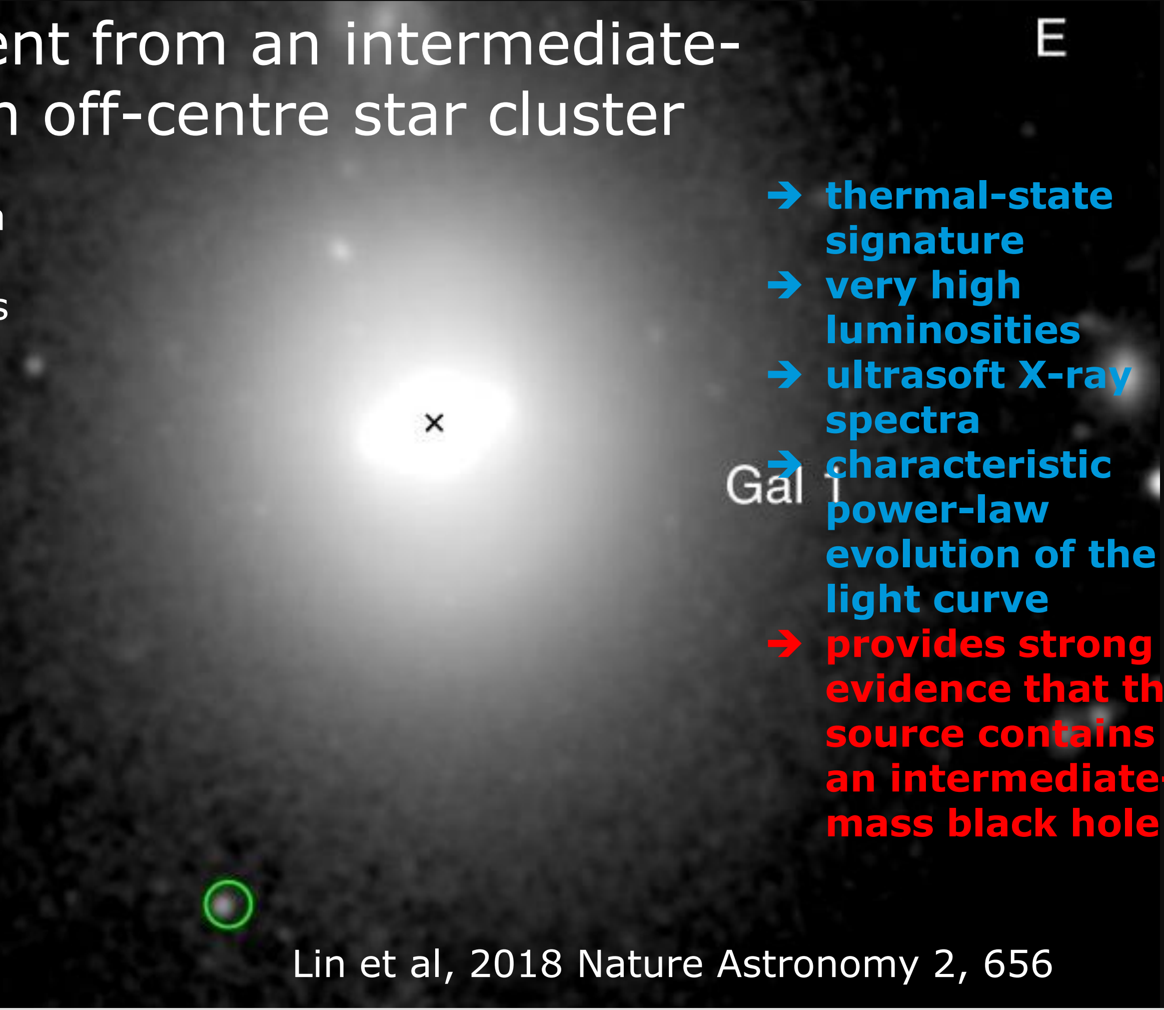
➔ (Partial or complete) tidal disruption of stars captured by the black holes

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

A tidal disruption event from 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

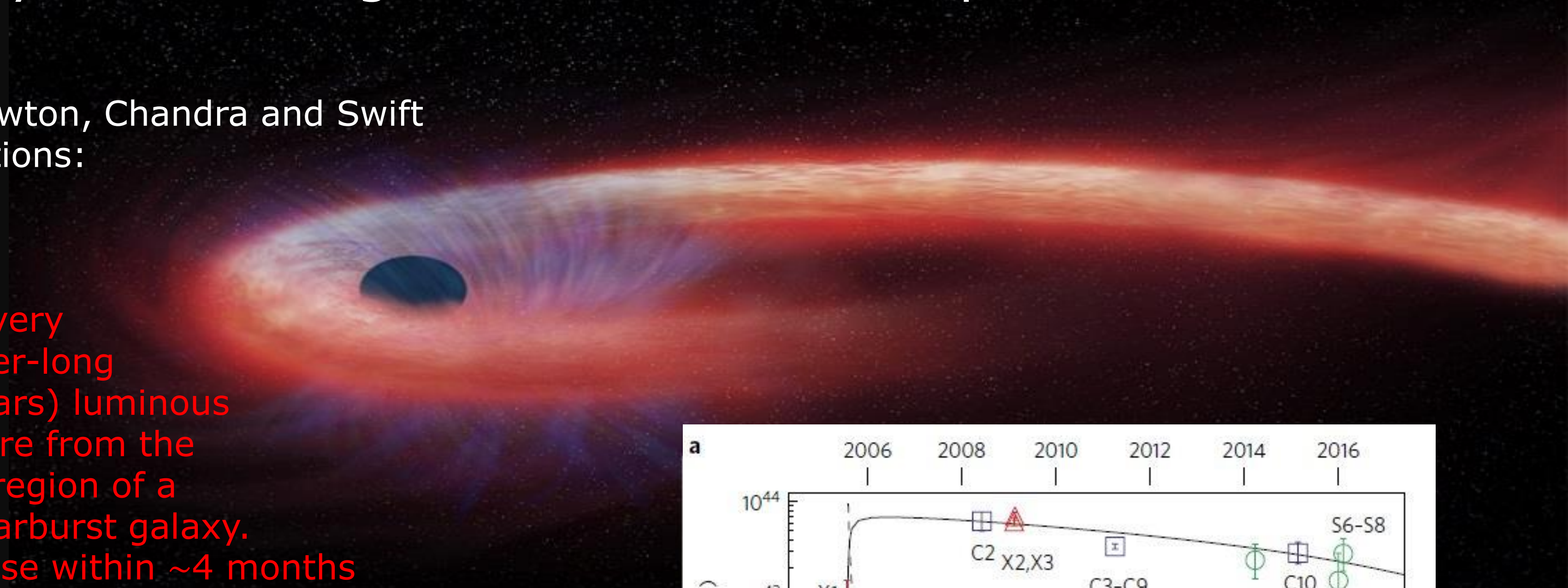




→ **thermal-state signature**
→ **very high luminosities**
→ **ultrasoft X-ray spectra**
→ **characteristic power-law evolution of the light curve**
→ **provides strong evidence that the source contains an intermediate-mass black hole**

Lin et al, 2018 Nature Astronomy 2, 656

A likely decade-long sustained tidal disruption event



XMM-Newton, Chandra and Swift observations:

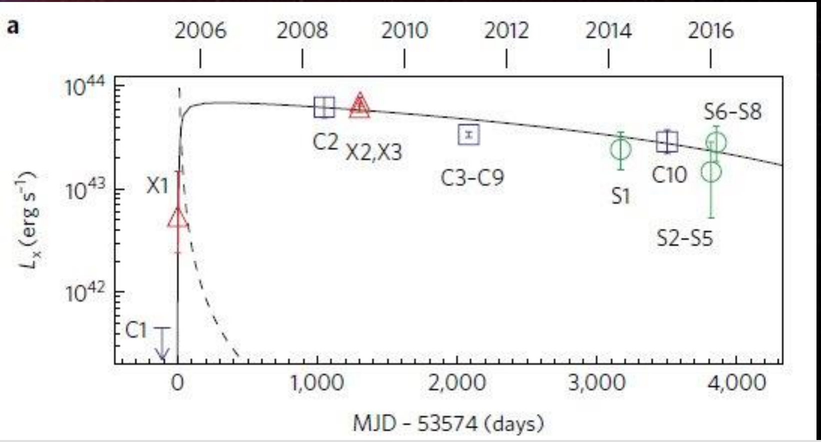
➔ discovery of a super-long (>11 years) luminous X-ray flare from the nuclear region of a dwarf starburst galaxy.

➔ fast rise within ~4 months

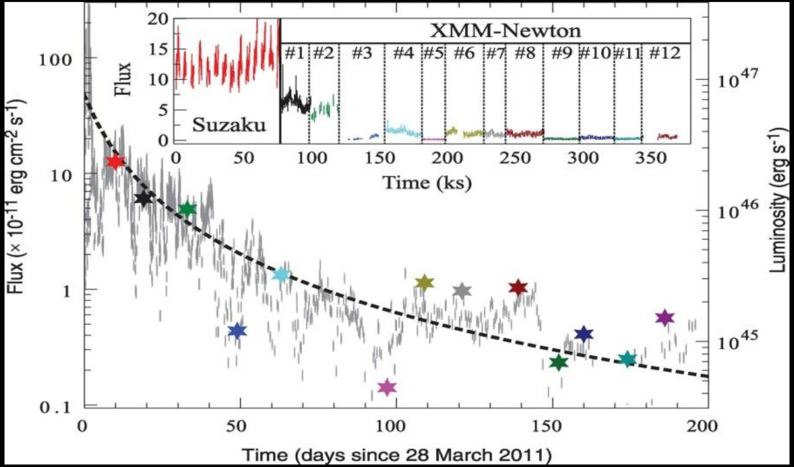
➔ X-ray luminosity persistently high at around the Eddington limit

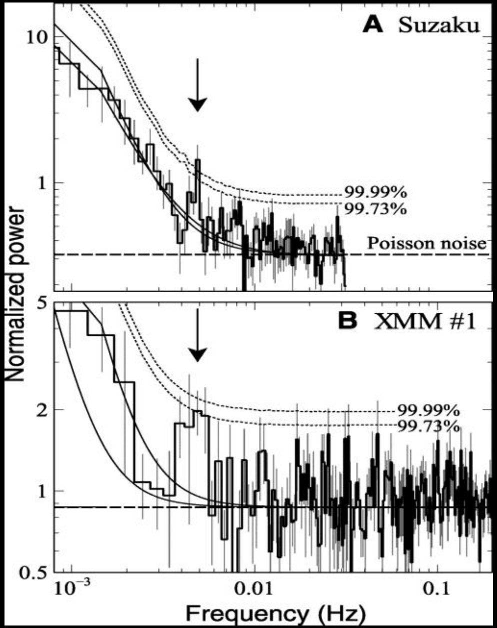
➔ a tidal disruption event

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



Tidal Disruption: Swift J164449.3+573451



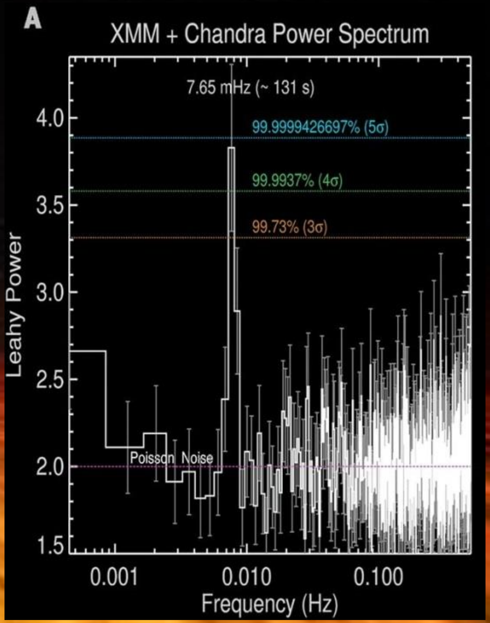


- tidal disruption of a star by a dormant black hole
- bright X-ray flares
- galaxy at redshift z = 0.3534

➔ ~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.

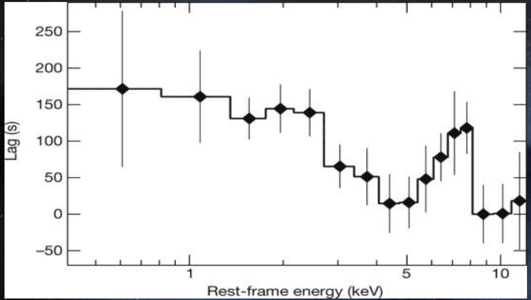
- stellar debris spirals toward the black hole

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

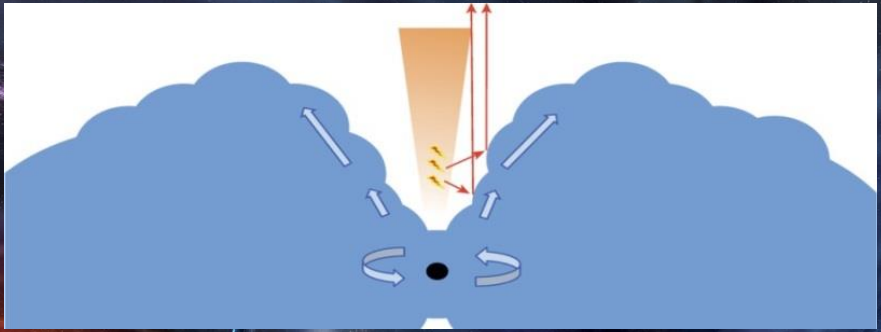
➔ periodicity originates from close to the event horizon and that the black hole is rapidly spinning

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

- XMM-Newton observation of the tidal disruption event ASASSN-14li

- detection of blue-shifted absorption lines of highly ionized atoms

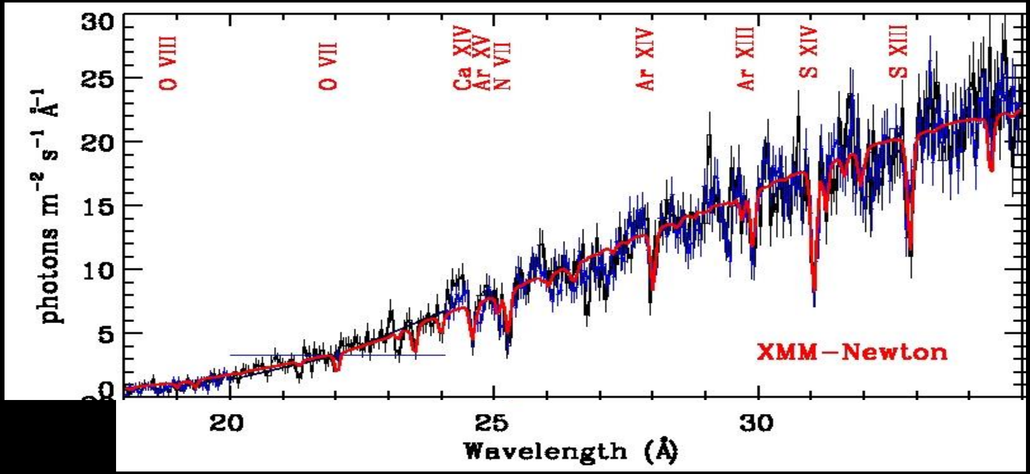
- variability indicates that the gas is close to the black hole

- 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 with a filament of disrupted stellar gas near to the apocenter of an

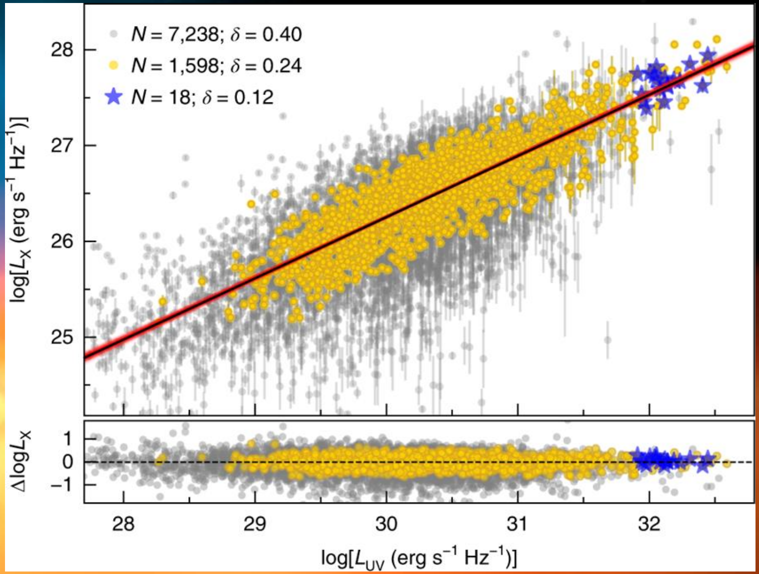


The high-resolution X-ray spectra of ASASSN-14li reveal blue-shifted absorption lines. XMM-Newton spectra from the RGS1 and RGS2 units are shown in black and blue.

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

Distance Scale with Quasars

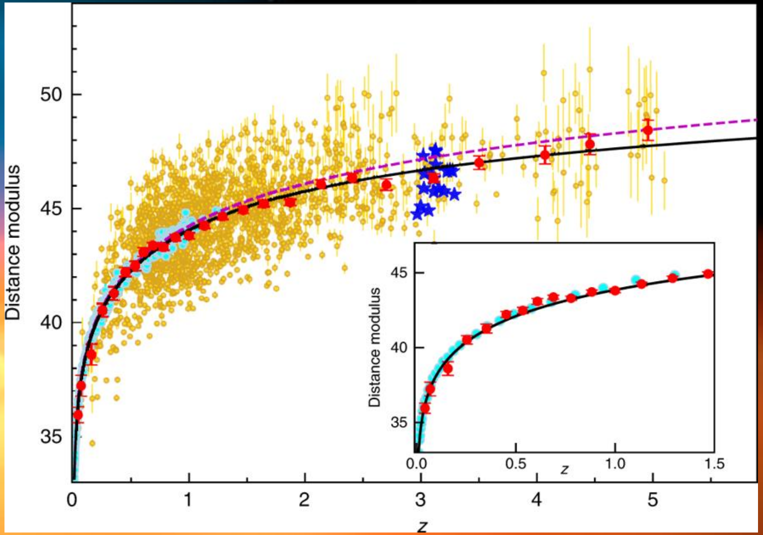
Cosmological Constraints from the Hubble Diagram of Quasars at High Redshifts



- distances estimate based on the X-ray and ultraviolet emission of the quasars

G. Risaliti & E. Lusso, 2019, Nature Astronomy 3, 272

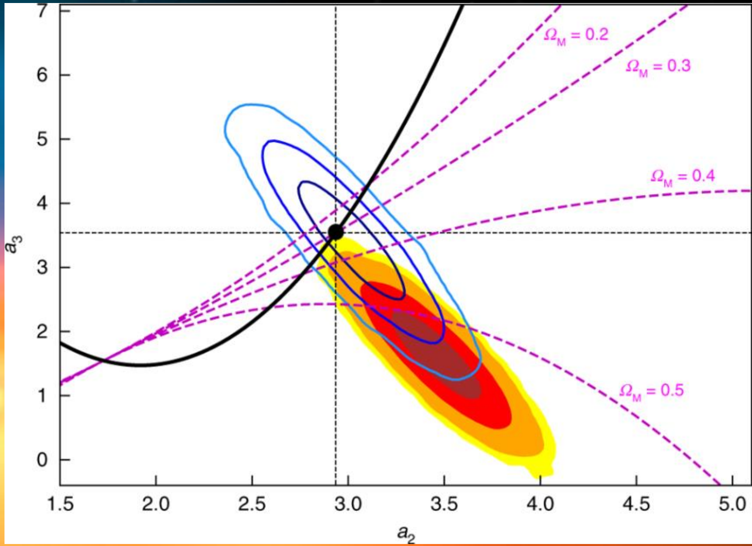
Cosmological Constraints from the Hubble Diagram of Quasars at High Redshifts



- distances estimate based on the X-ray and ultraviolet emission of the quasars
- $z < 1.4$ agreement with supernovae and concordance ΛCDM model

G. Risaliti & E. Lusso, 2019, Nature Astronomy 3, 272

Cosmological Constraints from the Hubble Diagram of Quasars at High Redshifts



- distances estimate based on the X-ray and ultraviolet emission of the quasars
- z < 1.4 agreement with supernovae and concordance ΛCDM model

➔ **z > 1.4 deviations of ~4σ**

➔ **does dark energy density increase with time?**

G. Risaliti & E. Lusso, 2019, Nature Astronomy 3, 272

STATUS OF SPACECRAFT

- **Spacecraft status is very good**
- **All important systems are running on their primary unit, i.e. full redundancy still available.**
- **Currently 42 kg of fuel remain with usage of around 3 kg per year**
- **The solar array is generating around 1790 W and between 800-1350W are used.**
- **All other systems susceptible to wear are in good condition**

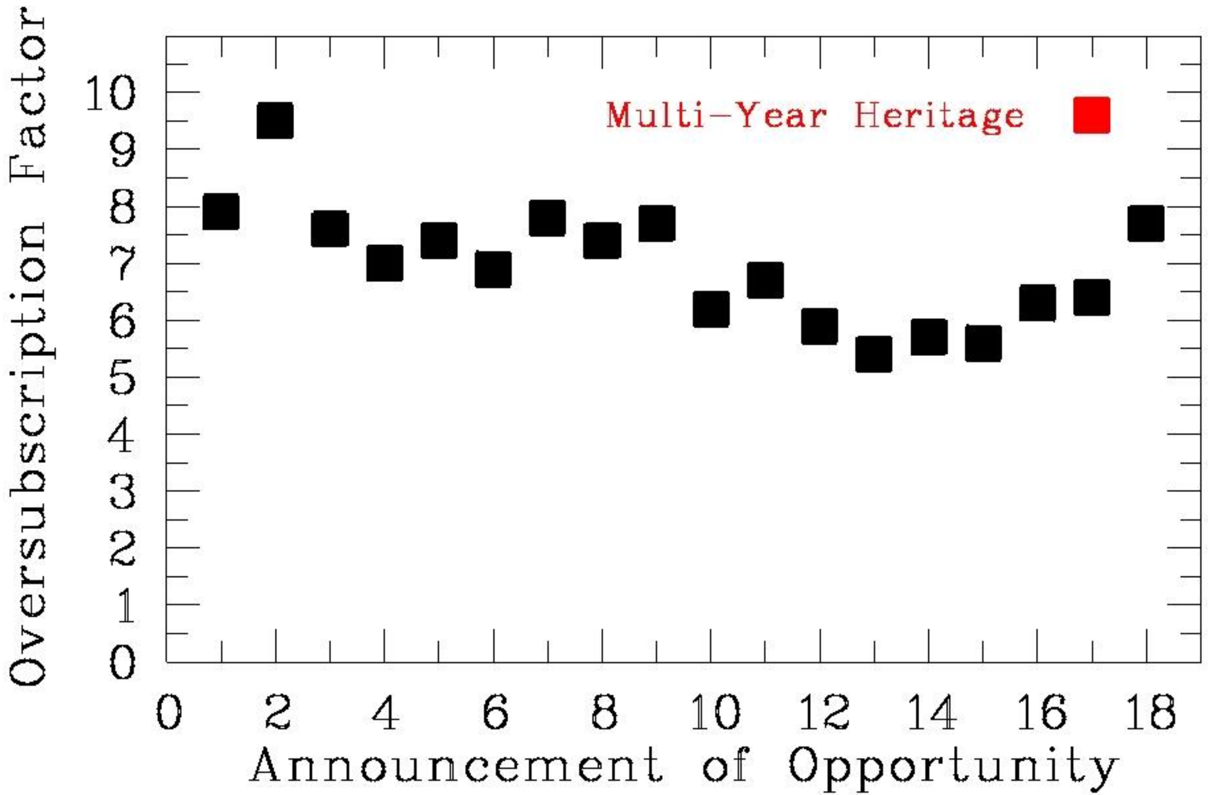
➔ XMM-Newton can well be operational up to 2030/2031

ESA MISSION EXTENSION

- **ESA extensions: Every two years comparing all missions: 2+2 schema:**
  - **2 years operations financed**
  - **4 years planning envelope (indicative extension)**
- **The ESA Science Programme Committee (14 November 2018) unanimously approved operations of XMM-Newton from 1. January 2019 to 31 December 2020.**
- **The ESA Science Programme Committee (14 November 2018) approved the indicative extension of operations of XMM-Newton from 1. January 2021 to 31 December 2022.**

…… + further extensions

FUTURE ESA XMM-NEWTON EXTENSIONS II



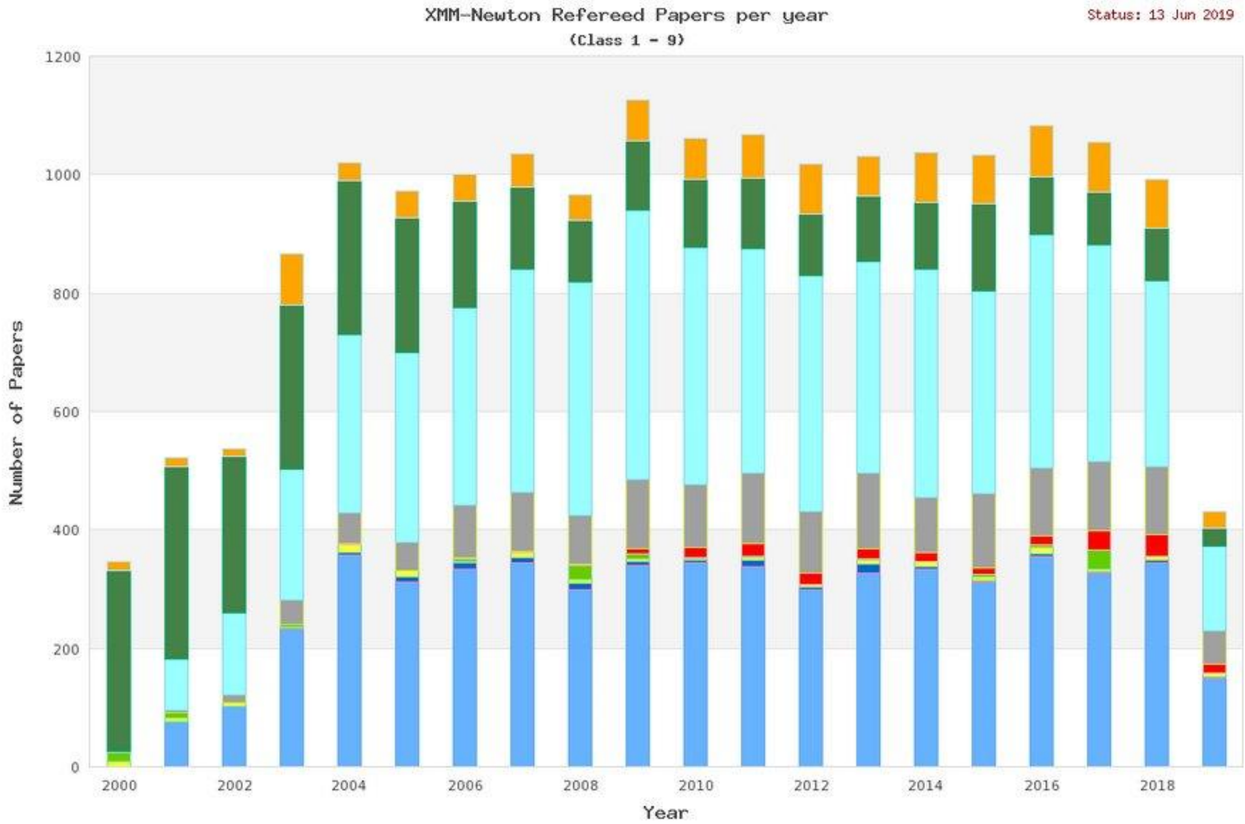
FUTURE ESA XMM-NEWTON EXTENSIONS III

XMM in Name
Mentions XMM
XMM & Citation

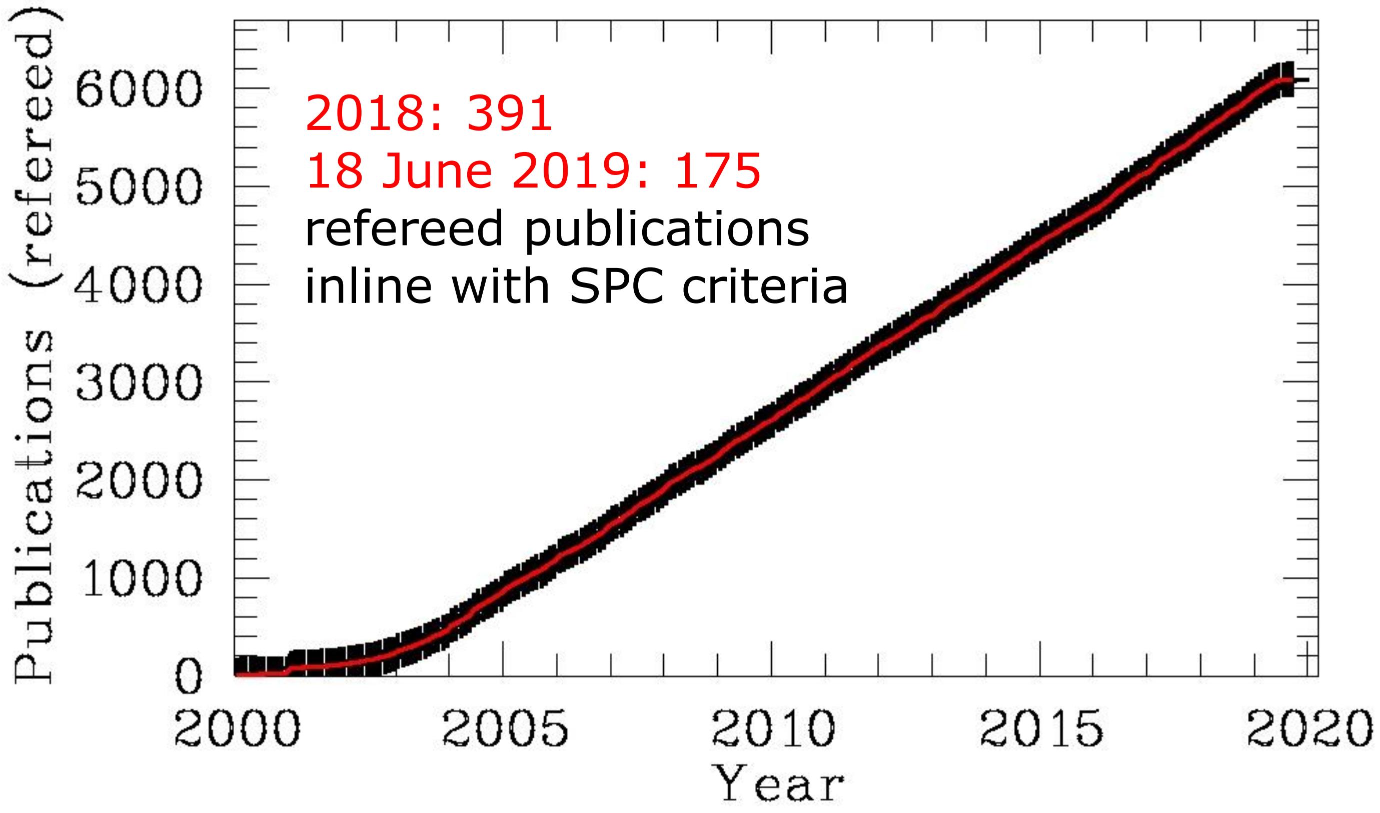
Uses Others

--- SPC ---

Uses Products
Describes
Predicts
Catalogue
Uses Data



FUTURE ESA XMM-NEWTON EXTENSIONS IV



"XMM-Newton the next Decade" Workshop

- **May 2016, ESAC with 148 Participants**
- **Presentations:**

  http://www.cosmos.esa.int/web/xmm-newton/2016-workshop

EVOLUITON OF SCIENTIFIC STRATEGY

Scientific Strategy:

2006: TOO time budget expanded

2007: Workshop XMM-NEWTON THE NEXT DECADE

2007: Users' Group supports large programs

2008: 1st observation of a very large program

2010: ~25% of A&B observing time to large programs

2010: Planck Clusters

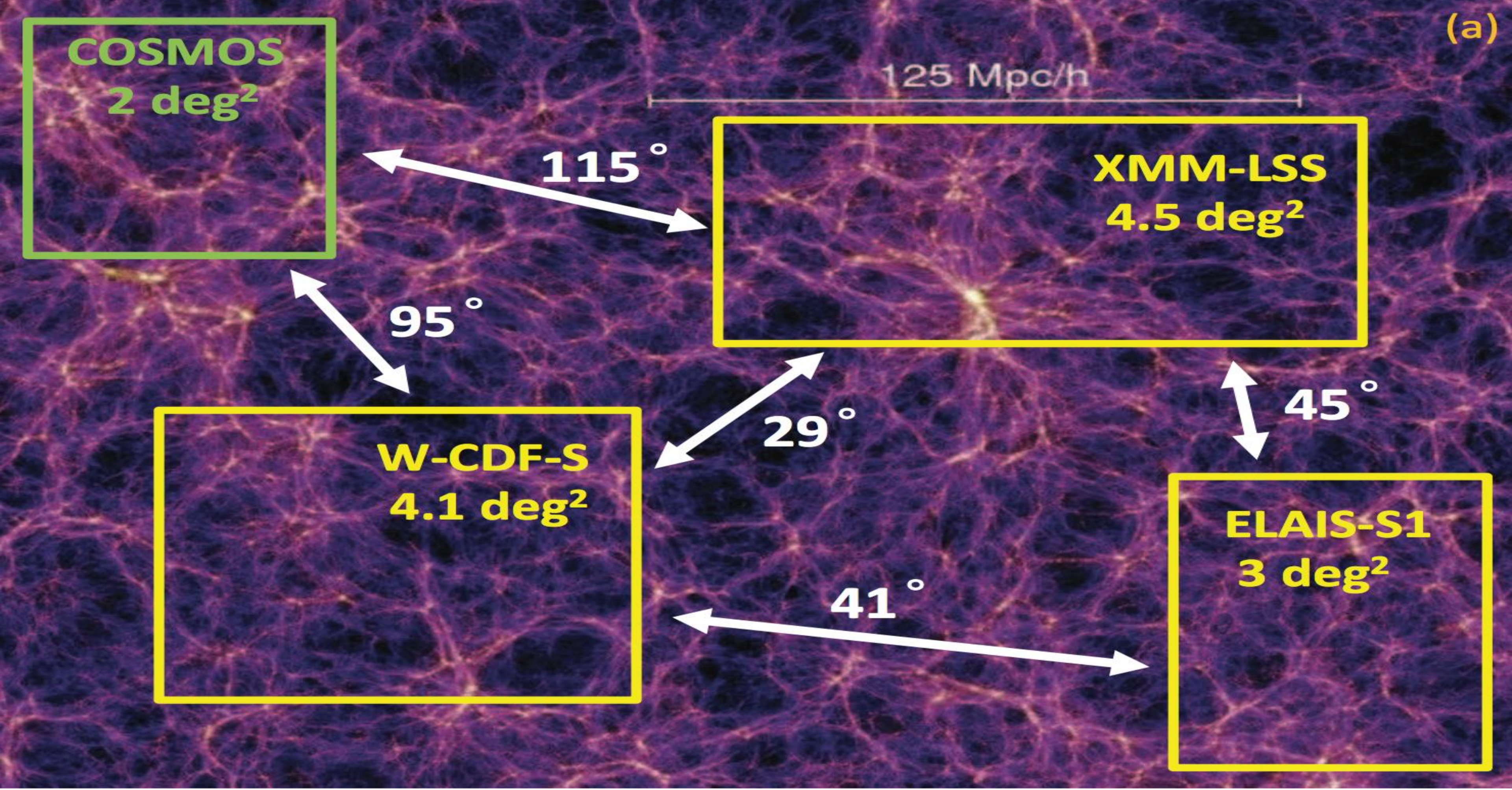
2012: ~45% of A&B observing time to large programs

2013: 1.5 Ms simultaneous with NuSTAR

2016: up to 3.0 Ms simultaneous with NuSTAR

2016: Workshop XMM-NEWTON THE NEXT DECADE (May 2016)

2017 Legacy Programs (~6 Ms over 3 years)


(a)
COSMOS
2 deg²
125 Mpc/h
115°
XMM-LSS
4.5 deg²
95°
29°
45°
W-CDF-S
4.1 deg²
ELAIS-S1
3 deg²
41°

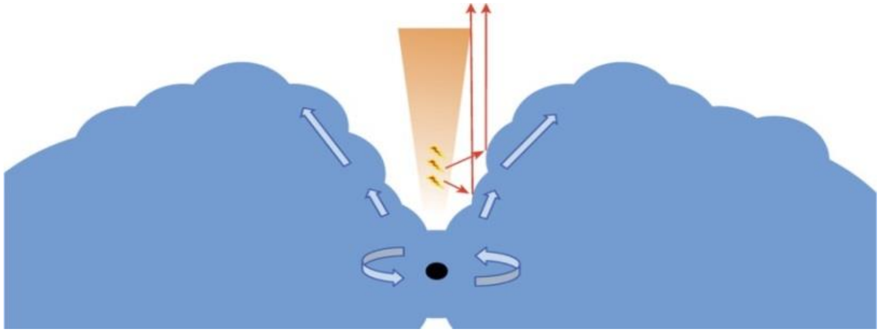
5.0 Ms XMM-SERVS: Pushing Beyond COSMOS

- **AO15: W. Brandt / 48 Obs. / 1.2 Ms : Going Beyond COSMOS with the XMM-SERVS Survey of W-CDF-S, XMM-LSS, and ELAIS-S1**
  - **Very Large Program**
- **AO17: W. Brandt / 78 Obs. / 3.4 Ms Completing and Ensuring Major Impact from the XMM-SERVS Survey**
  - **Multi-Year Heritage Program: Observation in AO17, AO18 & AO19**
- **Science:**
  - **50 ks XMM-Newton depth,**
  - **➔ expect 12,000 AGNs and 760 X-ray groups/clusters.**
  - **➔ SMBH growth across the full range of cosmic environments and SMBH/galaxy connections.**

Active Galactic Nuclei (AGN)

Ultra-deep X-ray reverberation observations of AGNs have a massive untapped potential: geometry of the X-ray remitting corona, returning radiation, jet & wind launching, quasi-periodic-oscillation, disk structure, innermost stable orbit.

Only XMM-Newton has the required effective area to perform such studies (preferably with simultaneous NuSTAR observations)



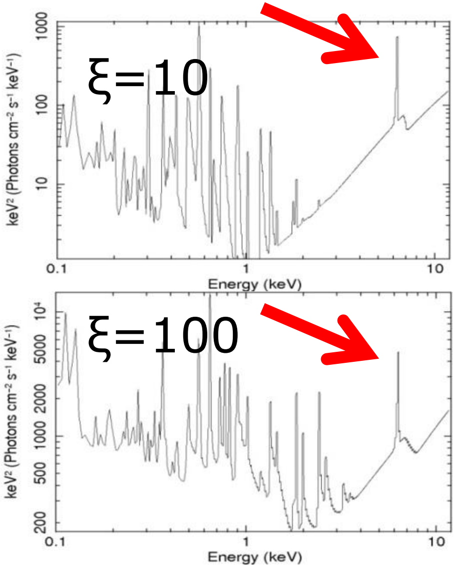
Kara et al., 2016, Nature 535, 388

Large multi-wavelengths monitoring campaigns of AGNs allow to study the physics of the outer disk e.g. the launching of outflows and winds.

XMM Newton is the preferred X-ray facility due to its high throughput and high spectral resolution capacity

Iron Line Studies: A Continuing Success

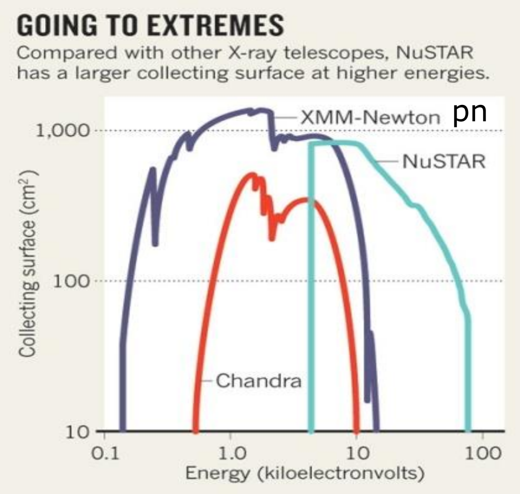
Why is iron so interesting?
- isolated emission line
e.g. reflection spectrum

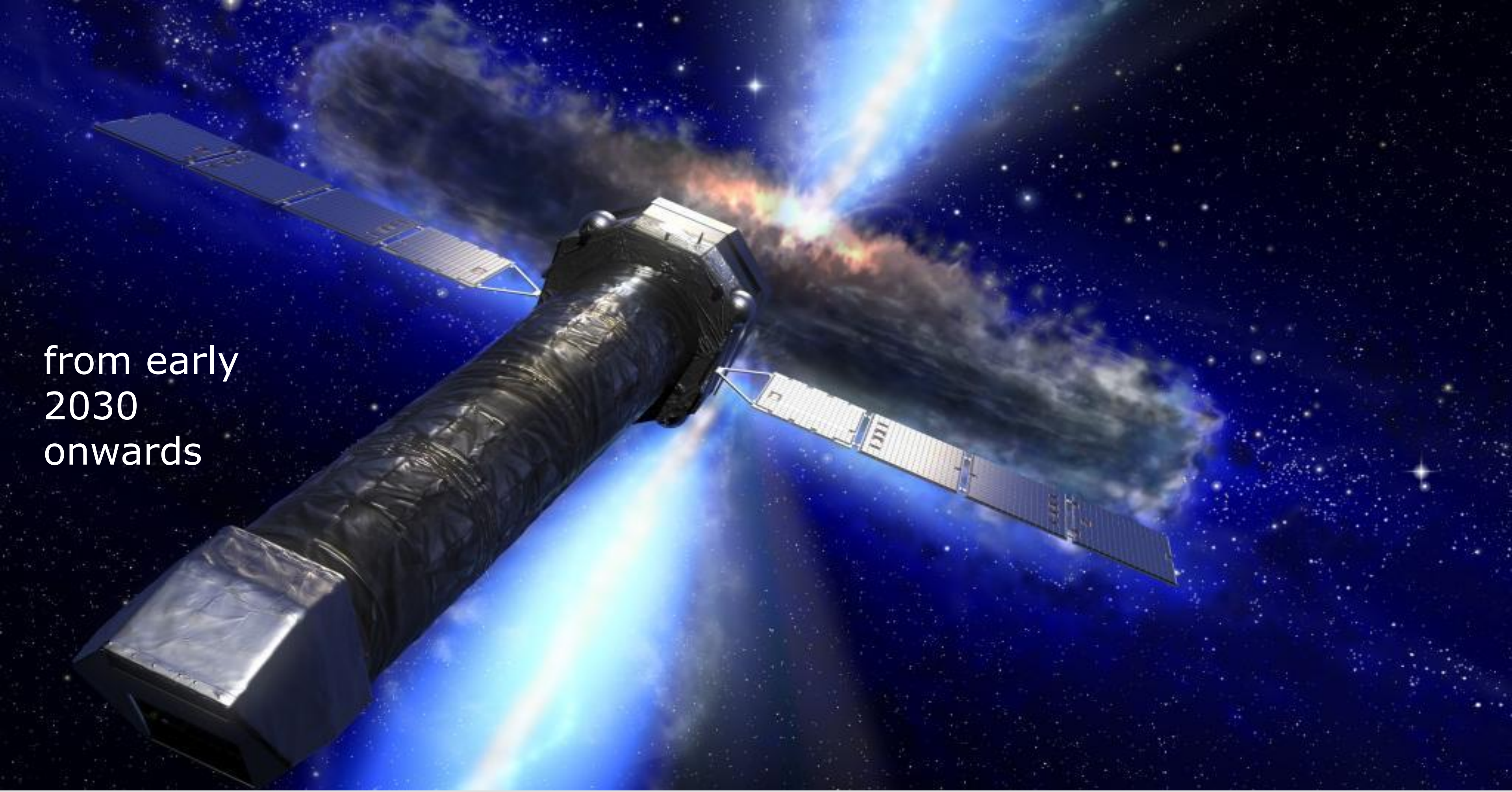


+ high ionization parameter
+ high abundance

- ❑ **Only XMM-Newton has the required high effective area in combination with the ability to make long uninterrupted observations.**
- ❑ **In addition, simultaneous observations with NuSTAR enable an accurate determination of the underlying continuum,- something that cannot be easily achieved by any other combination of satellites, especially for weak sources.**
- ❑ **25% of XMM-Newton high priority time (priority A and B) in AO-17 is being observed simultaneously with NuSTAR**

NuSTAR (Nuclear Spectroscopic Telescope Array, NASA




from early
2030
onwards

Athena

www.the-athena-x-ray-observatory.eu

- Science theme: The Hot and Energetic Universe
  - How does baryonic matter assemble in large-scale structures? How do they evolve from the formation epoch to the present day?
  - How do black holes grow and shape galaxies?
  - Observatory science: 2/3rd (TBC) of the *Athena* nominal operational life allocated through a competitive peer review process
- Single telescope, Silicon Pore Optics technology, 12 m focal length (f.l.), ≥1.4 m^2 @1 keV, 0.25 m^2 @6 keV
- WFI (Active Pixel Sensor Si detector): wide-field (40'x40') spectral-imaging, 120-150 eV @6 keV resolution
- X-IFU (cryogenic imaging spectrometer): 2.5 eV energy resolution (R>2000 @5 keV),
  5' diameter effective field-of-view, ≤5" pixel size
- Performance exceeding by ≥1 order-of-magnitude any existing or planned X-ray missions
  - Area, spatially-resolved high-resolution spectroscopy, weak line sensitivity, survey speed, transient source spectroscopy …
- Mid-Phase A
  - Instrument Preliminary Requirement Reviews passed in 2018/9
  - Next milestone: Mission Formulation Review (Q3/2019)
  - Adoption Q3/2021. Launch early 2030s

courtesy Matteo Guainazzi