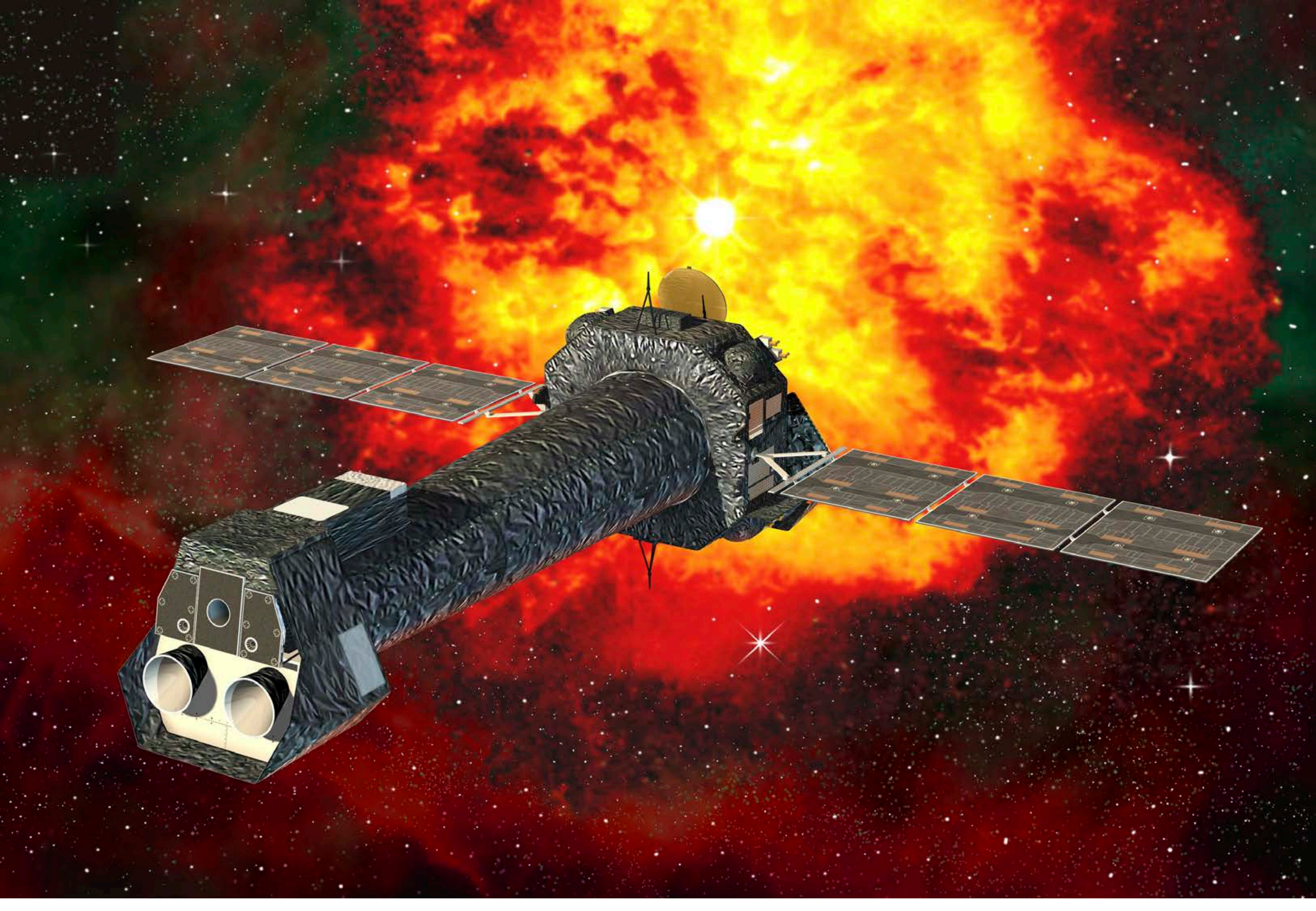
XMM-Newton's impact on Relativistic Astrophysics

The 27th Texas Symposium on Relativistic Astrophysics
Dallas, December 11th, 2013

Norbert Schartel
(XMM-Newton Project Scientist, ESA)

XMM-Newton =

X-ray Multi-mirror Mission

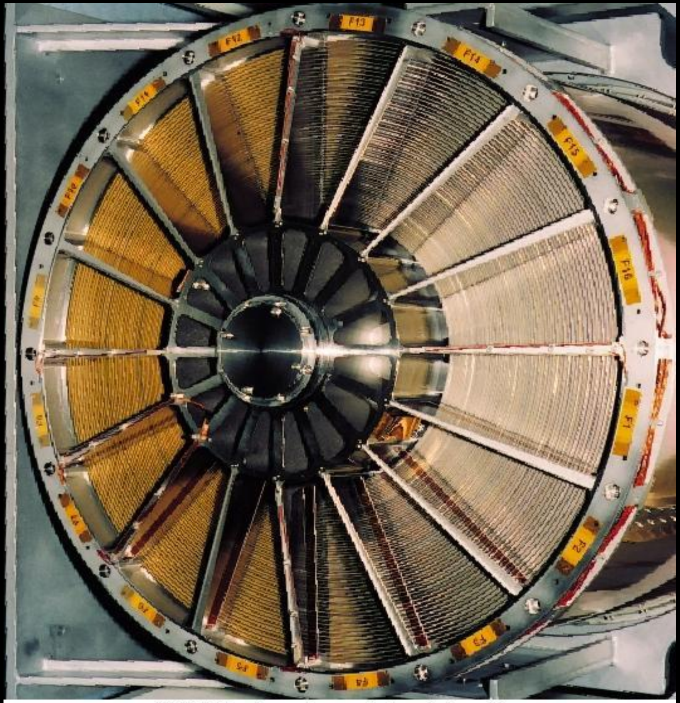


XMM-Newton preparation

Image courtesy of D. Parker

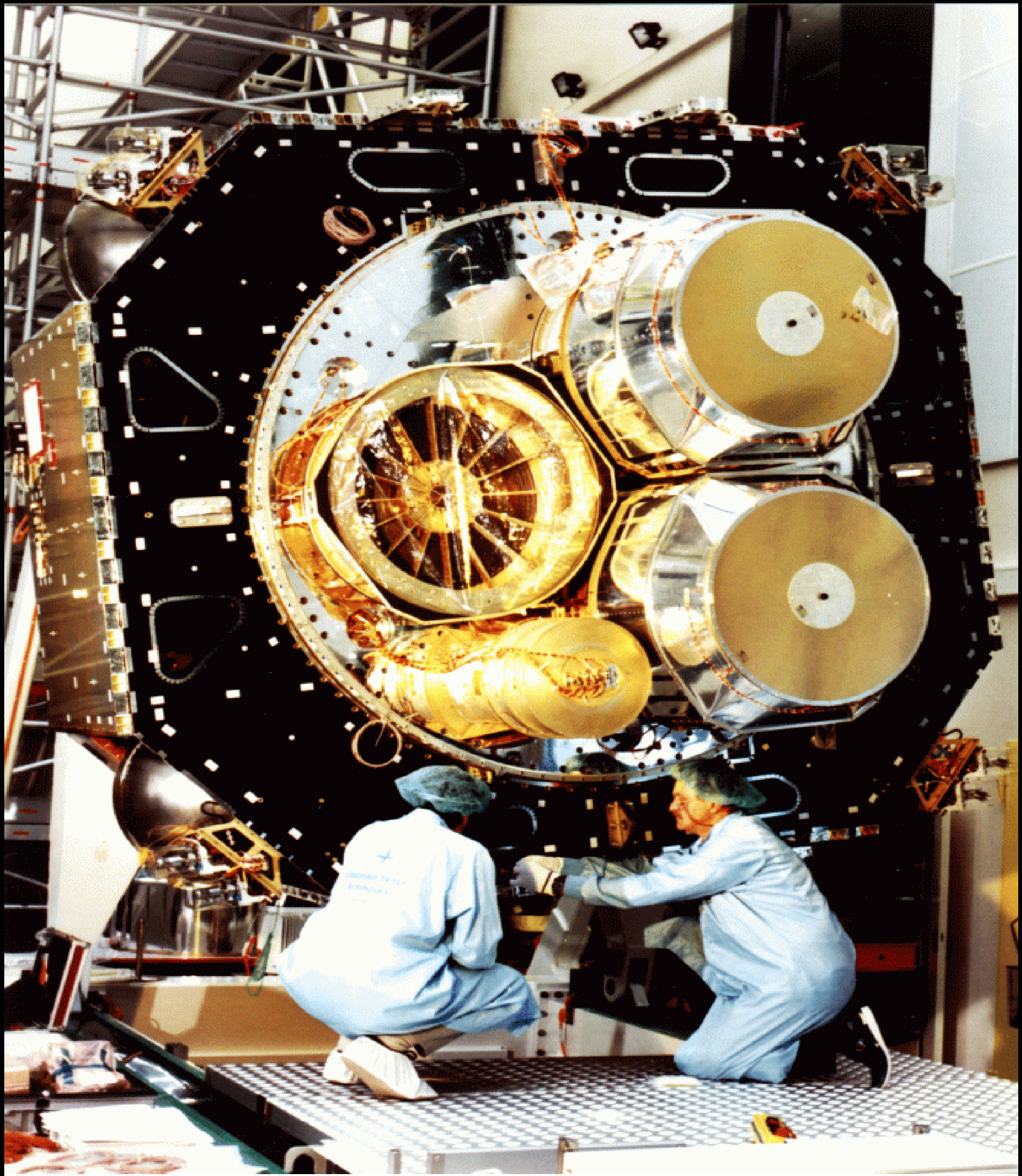
European Space Agency

XMM-Newton has three mirror modules



XMM-Newton mirrors during integration

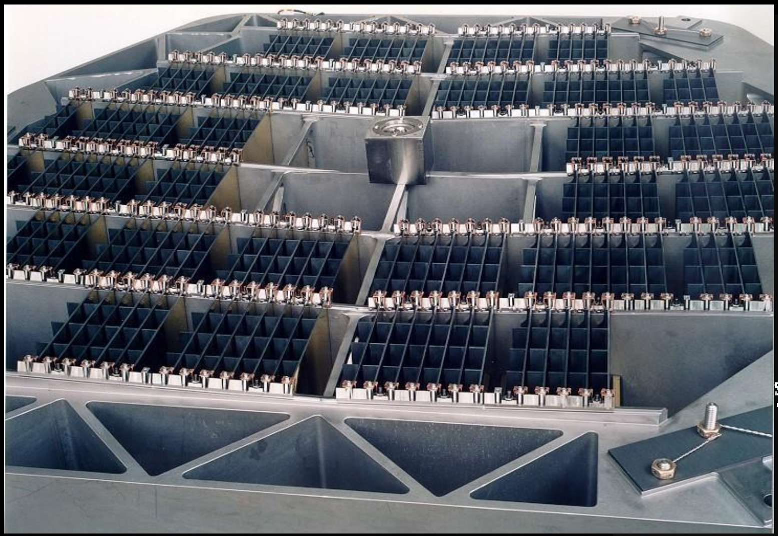
Image courtesy of Dornier Satellitensysteme GmbH — European Space Agency

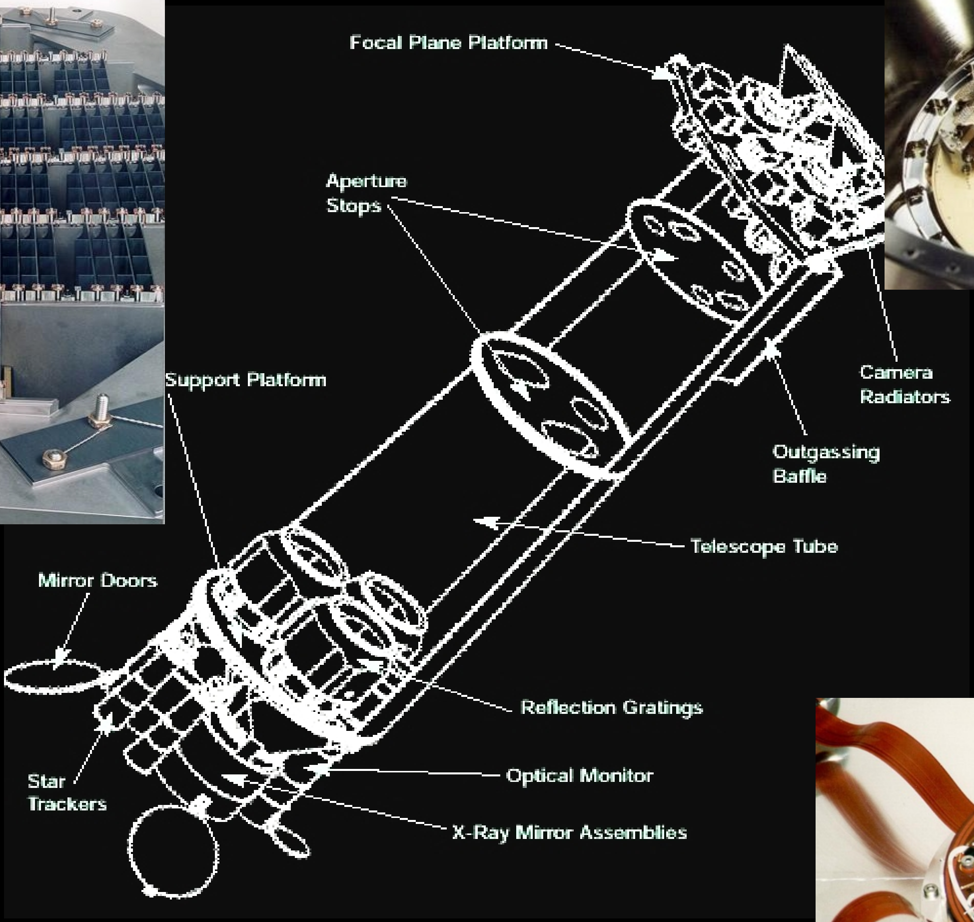


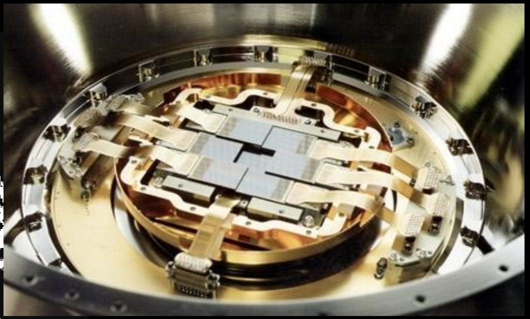
XMM-Newton mirrors during integration

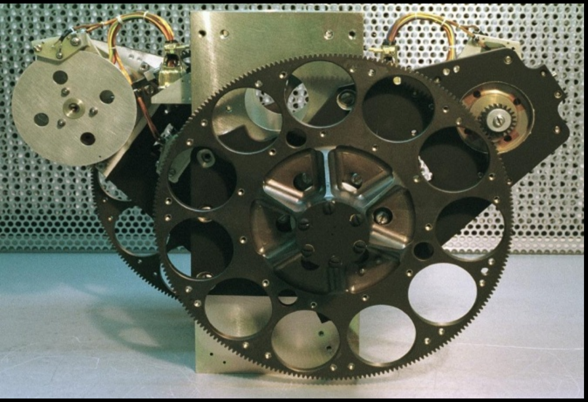
Image courtesy of Dornier Satellitensysteme GmbH — European Space Agency

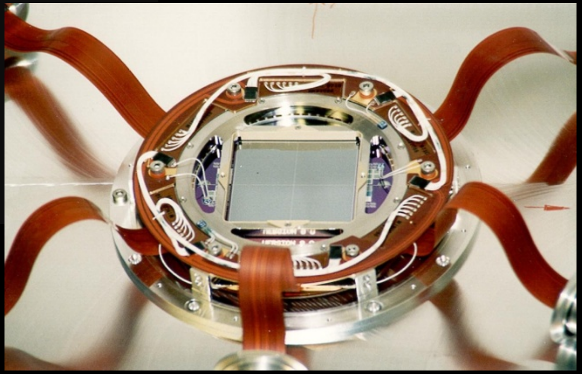
Instruments







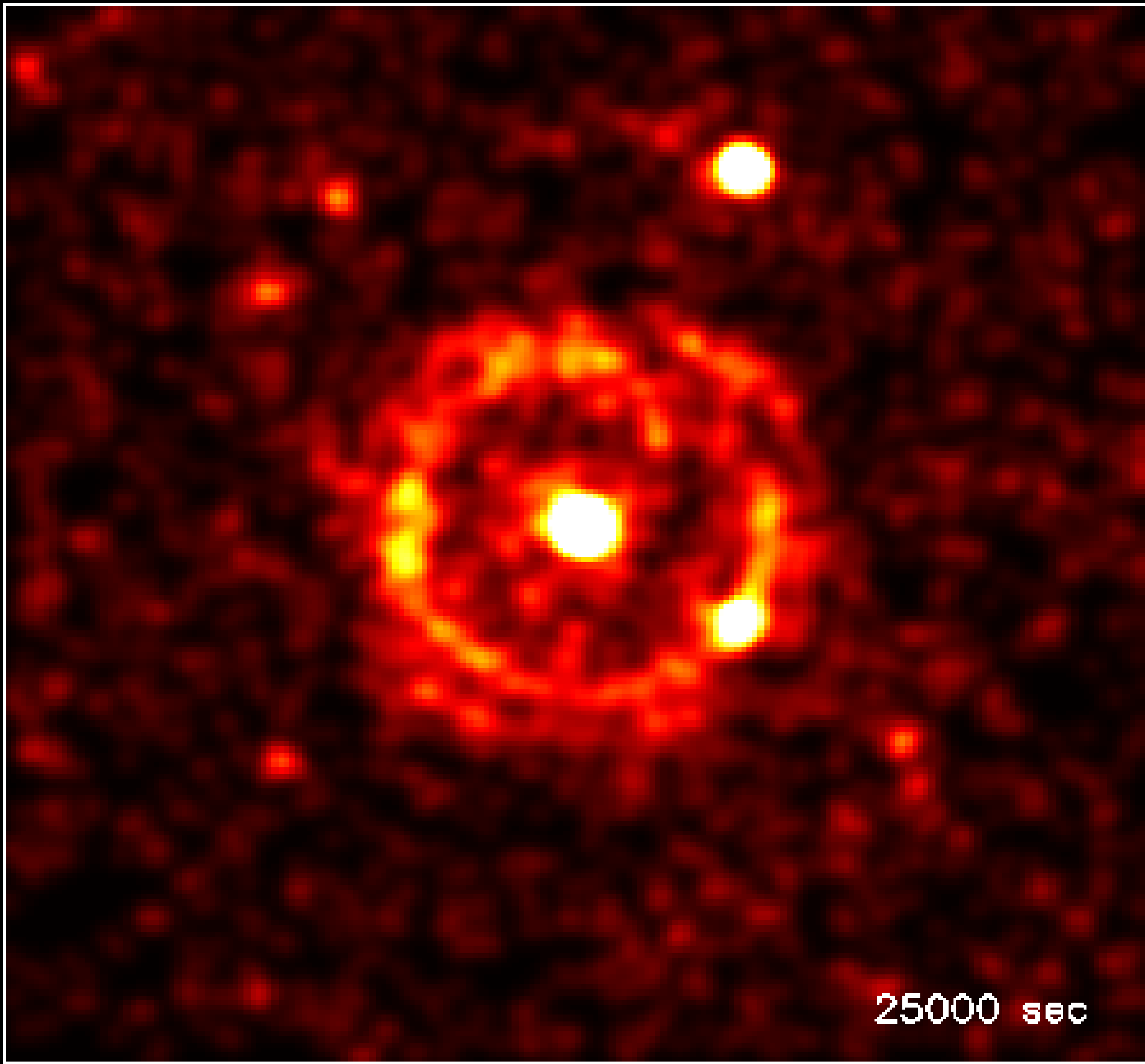




XMM-Newton

- 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)

GRB 031203 XMM–Newton observation



ESA, S. Vaughan (University of Leicester)

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

Neutron Stars

Swings between rotation and accretion power in a binary millisecond pulsar

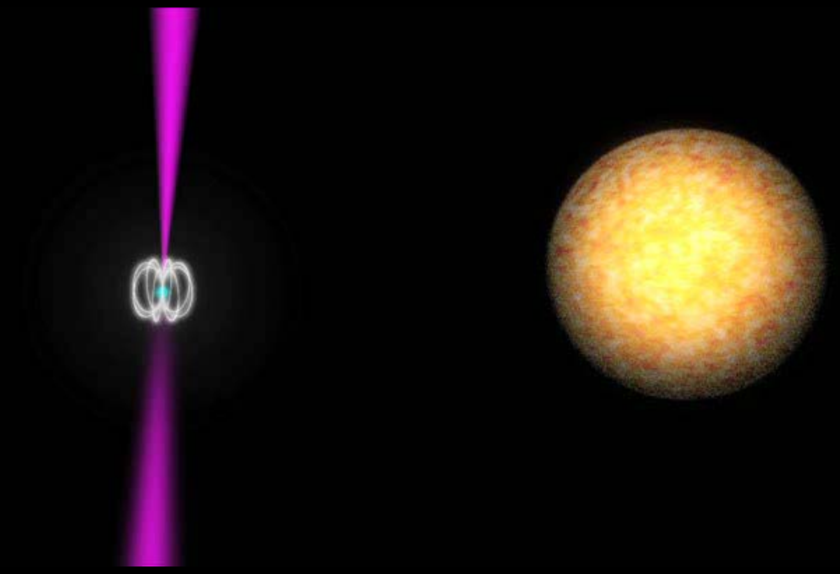
- XMM-Newton, radio and other X-ray satellites observations of X-ray transient IGR J18245–2452, which was first detected by INTEGRAL

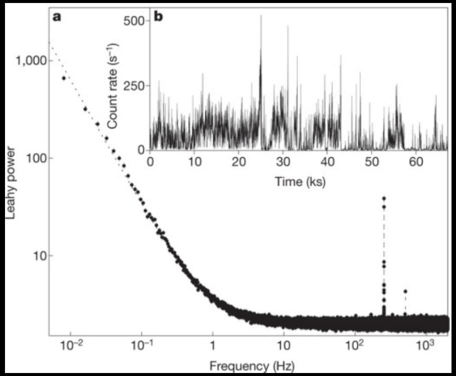
- First observations of accretion-powered, millisecond X-ray pulsations from a neutron star previously seen as a rotation-powered radio pulsar.

- Within a few days after a month-long X-ray outburst, radio pulses were again detected.

➔ evolutionary link between accretion and rotation-powered millisecond pulsars

➔ some systems can swing between the two states on very short timescales





Fourier power spectral density of the 0.5–10-keV X-ray photons obser ved by the EPIC pn camera. The peaks at 254.3 and 508.6 Hz represent the first and second harmonics of the coherent modulation of the X-ray emission of IGR J18245–2452.

Papitto et al., 2013, Nature 501, 517

Synchronous X-ray and Radio Mode Switches: A Rapid Global Transformation of the Pulsar Magnetosphere

Simultaneous observations of PSR B0943+10 with XMM-Newton and GMRT and LOFAR:

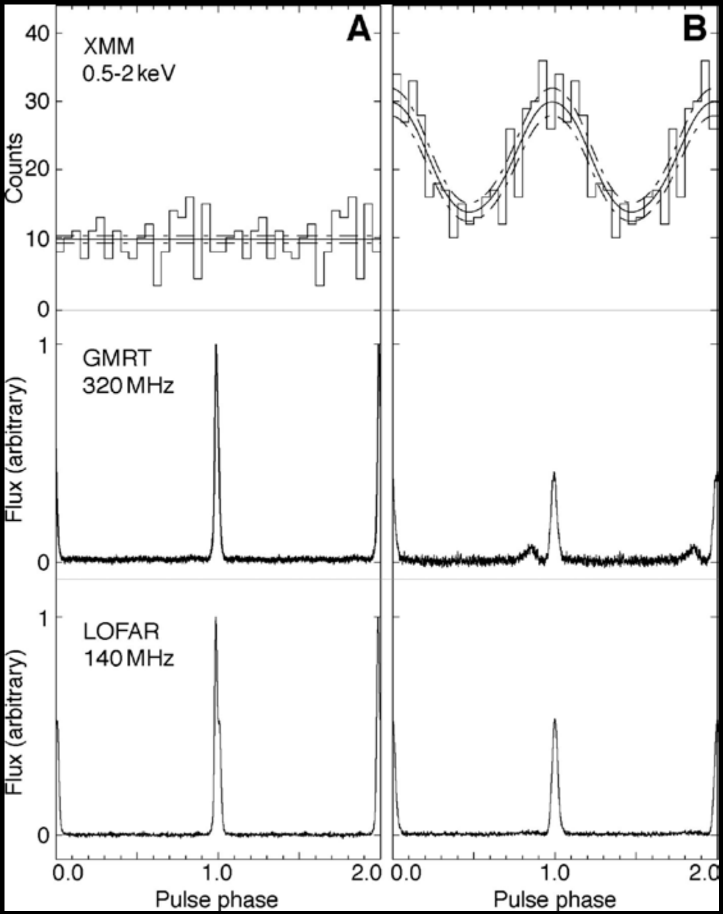
➔ Detection of synchronous switching in the radio and x-ray emission properties

➔ When the pulsar is in a sustained radio-"bright" mode, the x-rays show only an unpulsed, nonthermal component

➔ When the pulsar is in a radio-"quiet" mode, the x-ray luminosity more than doubles and a 100% pulsed thermal component is observed along with the nonthermal component.

➔ Indicates rapid, global changes to the conditions in the magnetosphere, which challenge all proposed pulsar emission theories.

Hermsen, W., et al., 2013 Science 339, 436



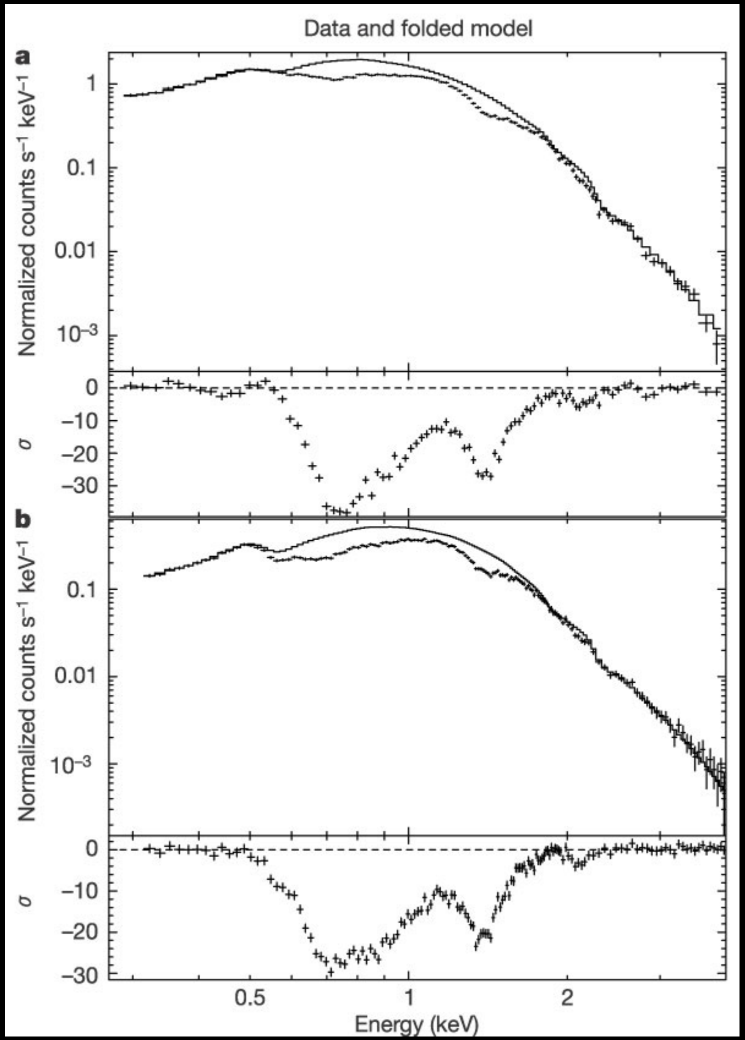
Aligned x-ray and radio pulse profiles of PSR B0943+10 in its B and Q modes. (A) B mode: There is no evidence for a pulsed signal in the B-mode x-ray data, the flat distribution showing constant emission from the pulsar. (B)Q mode: The x-ray profile in the Q mode represents a 6.6s detection on top of a flat constant level

The magnetic field of an isolated neutron star from X-ray cyclotron absorption lines

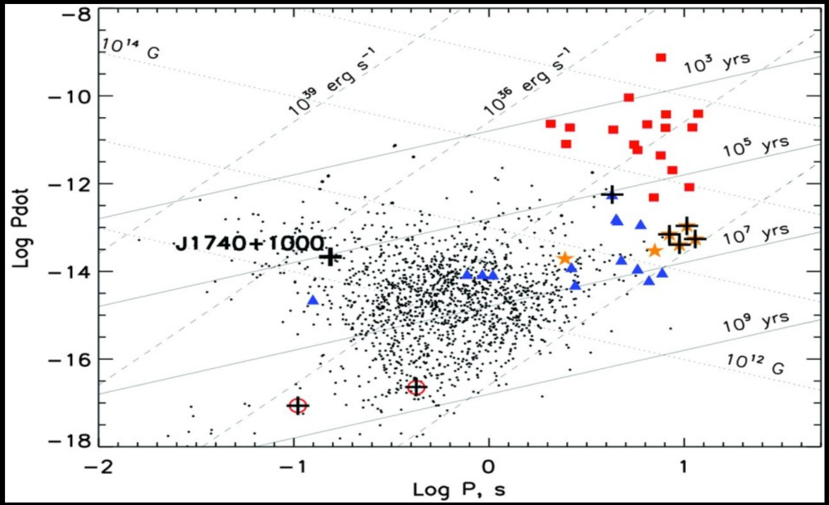
- Features in their X-ray spectra of isolated neutron stars could reveal the presence of atmospheres, or estimation of the strength of their magnetic fields (cyclotron process)
- but almost all isolated neutron star spectra observed so far appear as featureless thermal continua
- the only exception is 1E1207.4-5209, where two deep absorption features have been detected, but with insufficient definition to permit unambiguous interpretation
- EPIC spectra of a long XMM-Newton observation shows three distinct features, regularly spaced at 0.7, 1.4 and 2.1keV, plus a fourth feature of lower significance, at 2.8keV, which vary in phase with the star's rotation.

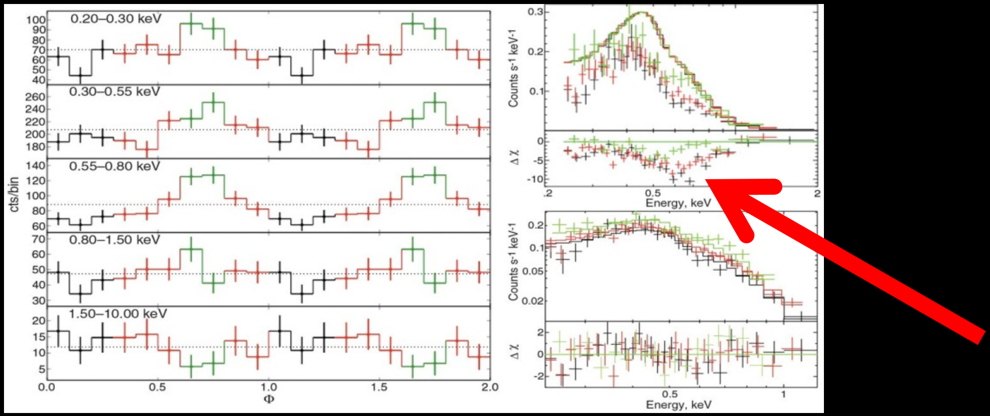
➔ the logical interpretation is that they are features from resonant cyclotron absorption, which allows to calculate a magnetic field strength of 8×10^{10}G, assuming the absorption arises from electrons.

Bignami, G. F., et al., 2003, Nature 423, 725



Absorption Features in the X-ray Spectrum of an Ordinary Radio Pulsar





- Vast majority of known non-accreting neutron stars (NS) are rotation-powered radio and/or γ-ray pulsars
- Their spectra have all been described satisfactorily continuum models, with no spectral lines.

Kargaltsev et al., 2012, Science 337, 946

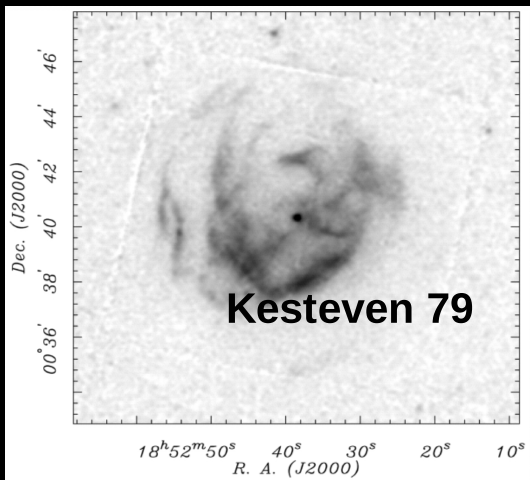
- Spectral features in a handful of exotic NSs were thought to be a manifestation of their unique traits.

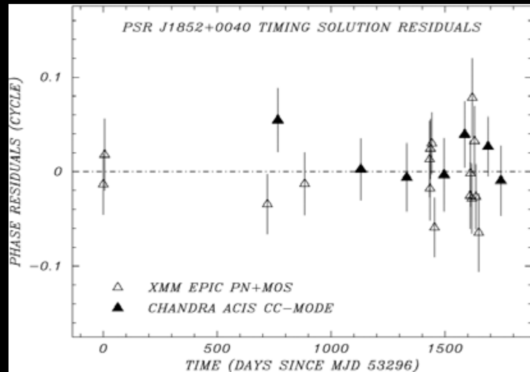
➔ Absorption features in the spectrum of an ordinary rotation-powered radio pulsar, J1740+1000

➔ Bridges the gap between pulsars and more exotic neutron stars

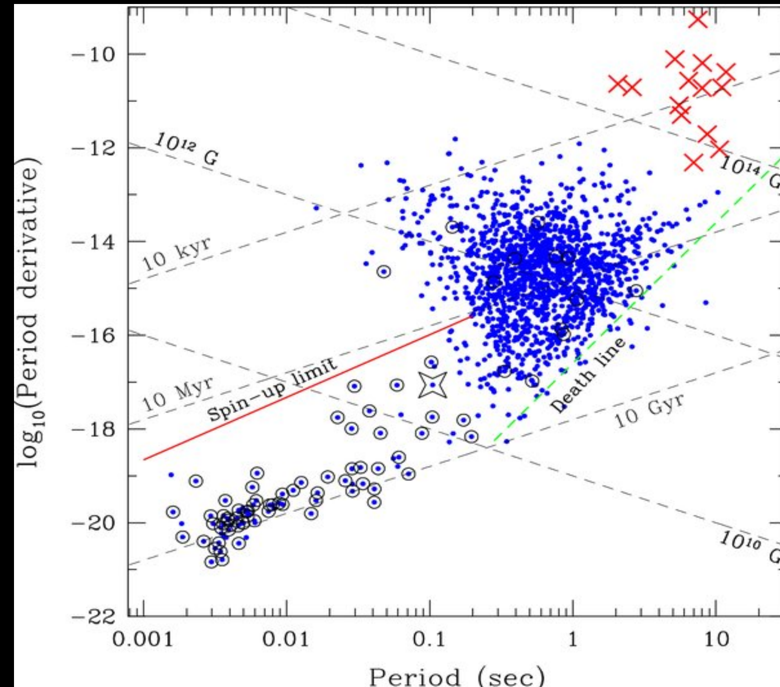
➔ Features are more common in the NS?

Spin-Down Measurement of PSR J1852+0040





Halpern & Gotthelf, 2010, ApJ 709, 436



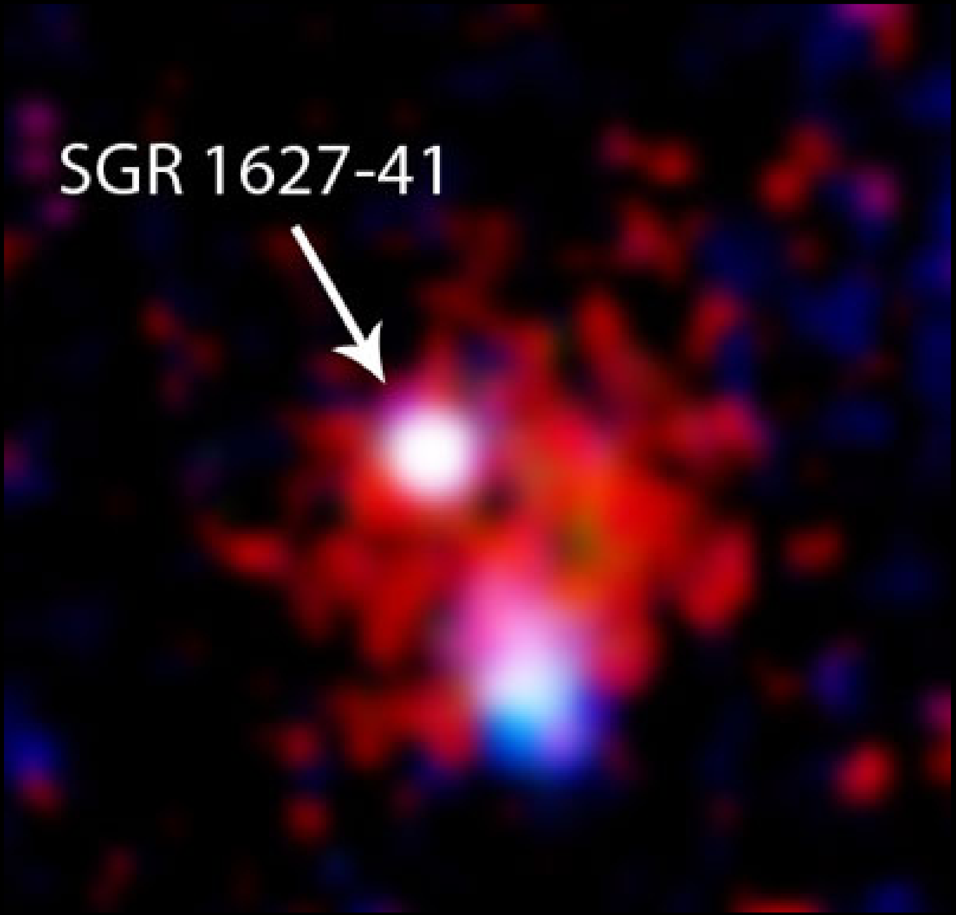
PSR J1852+0040 is Central Compact Object (CCO)

First measurement of the spin-down rate of a CCO:

- ➔ $dP / dt = (8.68 \pm 0.09) \times 10^{-18}$
- ➔ $B_s = 3.1 \times 10^{10}$ G, the smallest ever of a young neutron star and consistent with being a fossil field
- ➔ Strong support for "anti-magnetar"
- ➔ Consistent with low luminosity and lack of magnetospheric activity or synchrotron nebulae

Magnetars

Discovery of 2.6 s pulsations in SGR 1627-41



- The Soft Gamma-ray Repeater SGR 1627-41 reactivated on 2008 May 28 after nearly a decade of quiescence.

➔ XMM-Newton observations on 2008 September 27-28 allowed the detection of pulsations with P = 2.594578(6) s (>6σ confidence, fundamental and the second harmonic)

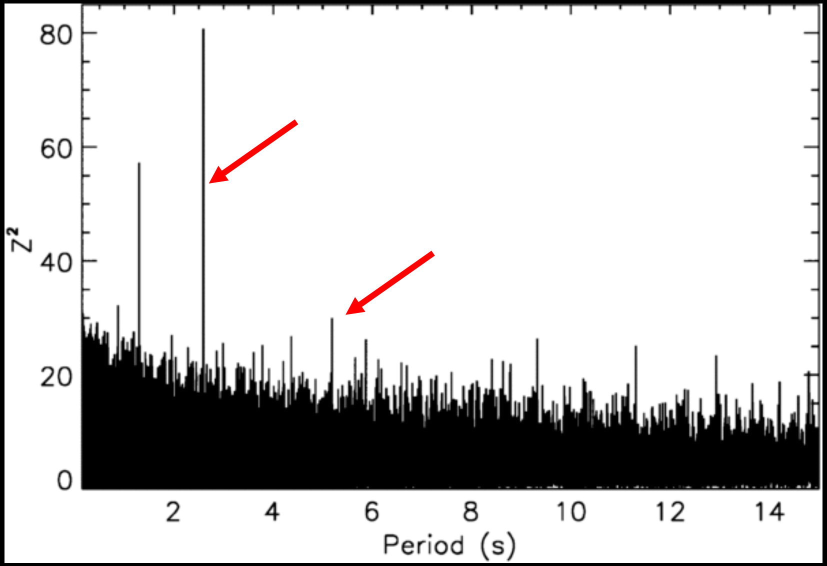
➔ In combination with Chandra data from 2008 June:l

➔ long-term spin-down rate of (1.9+/ 0.4) × 10-11ss^{-1}.

➔ characteristic age of ~2.2 kyr

➔ surface dipole magnetic field strength of ~2 × 10^{14} G.

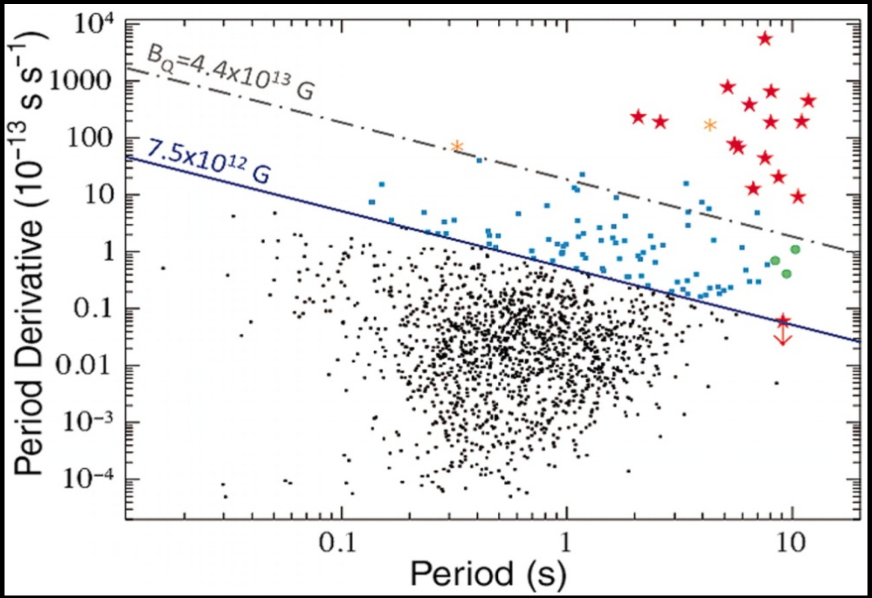
➔ These properties confirm magnetar nature of SGR1627-41

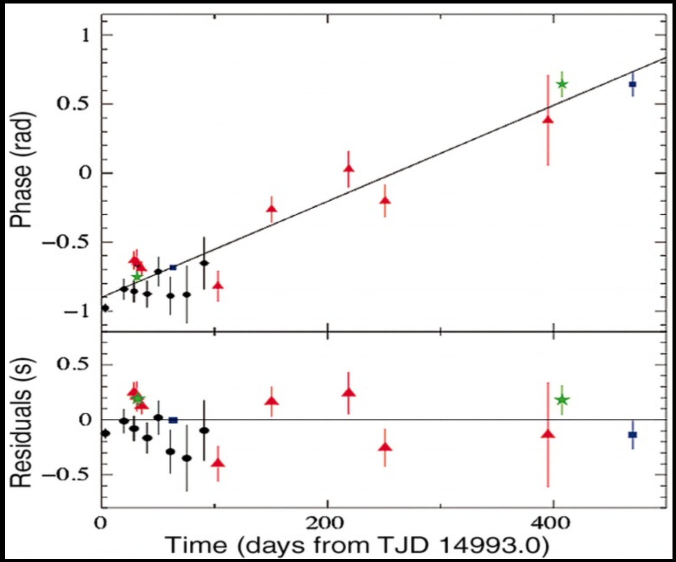


P. Esposito, et al., 2009 ApJ 690, L105 & 2009, MNRAS 399, L44

A Low-Magnetic-Field Soft Gamma Repeater

- Magnetars: neutron stars with extreme magnetic fields, B ~ 10^{14} to 10^{15} gauss, i.e. the binding energy of an electron exceeds its rest mass
- It was generally assumed that Gamma Ray Burst are a characteristics of Magnetars, which consequently were identified with: Anomalous X-Ray Pulsars and Soft Gamma Repeaters (SGR)



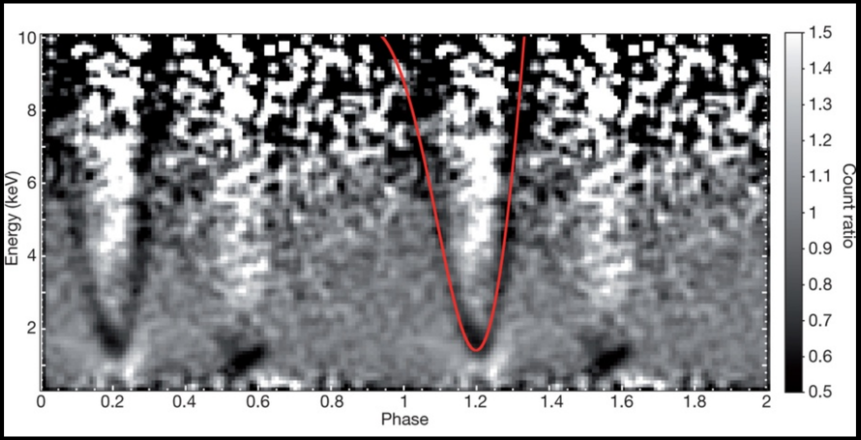


➔ XMM-Newton (& other X-ray observatories) found that SGR 0418+5729 has a magnetic field of < 7.5 × 10^{12} gauss

➔ The emission of a Gamma Ray Burst does not prove a high magnetic field

N. Rea et al., 2010, Science 330, 944

Magnetic multipole field in SGR 0418+5729

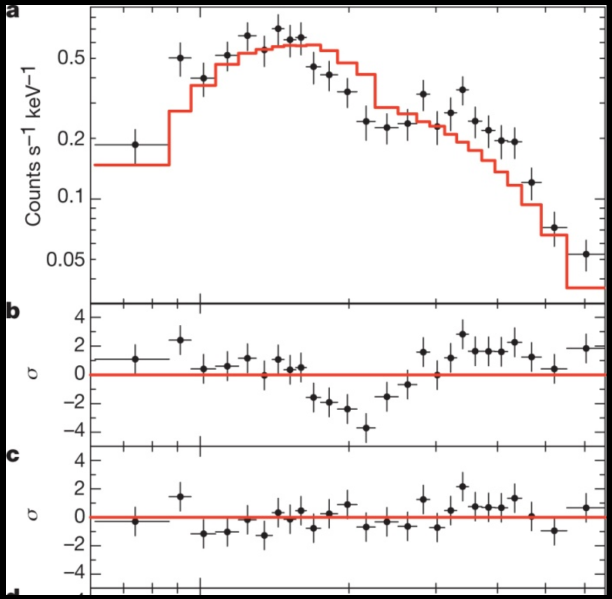


Phase-dependent spectral feature in the EPIC data of SGR 0418+5729.

- Soft-γ-ray repeaters (SGRs) and anomalous X-ray pulsars (AXPs) are neutron stars that sporadically undergo X-ray/γ outbursts
- sources are mainly powered by their own magnetic energy.
- magnetic fields inferred from several observed properties of SGRs and AXPs are greater than those of radio pulsars

- SGR 0418+5729 has a weak dipole magnetic moment of B = 6 × 10 10^{12} G (derived from timing parameters)
- A strong field has been proposed in the stellar interior and in multipole components on the surface
- **X-ray absorption line**
- **which depend strongly on the star's rotational phase**

➔proton cyclotron
➔magnetic field from 2 × 10^{14} G to > 10^{15} G



a: spectrum from phase interval 0.15–0.17 and phase-averaged spectrum in red
b: residuals; c: residuals after adding an absorption line

Tiengo et al., 2013, Nature 500, 312

Black Holes

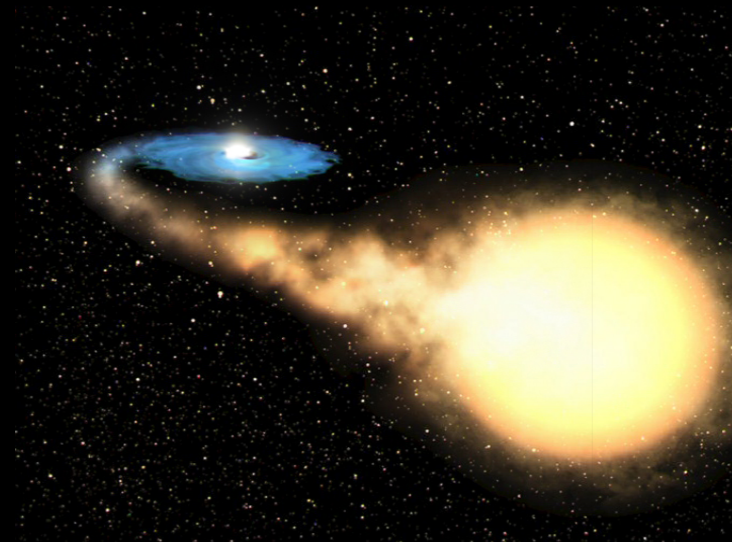
First Black Hole In Globular Star Clusters

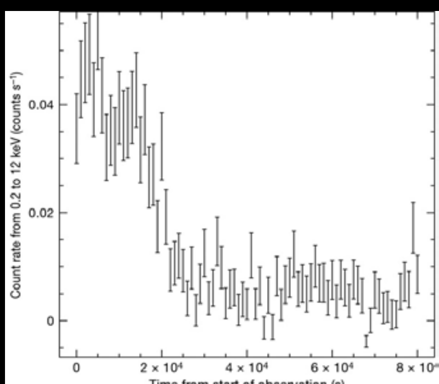
- GCs contain 10^3-10^6 old stars packed within tens of light years

➔ Formation of 10^3 solar mass BH ?

➔Interaction will eject BHs ?

T.J. Maccarone et al., 2007, Nature 445, 183

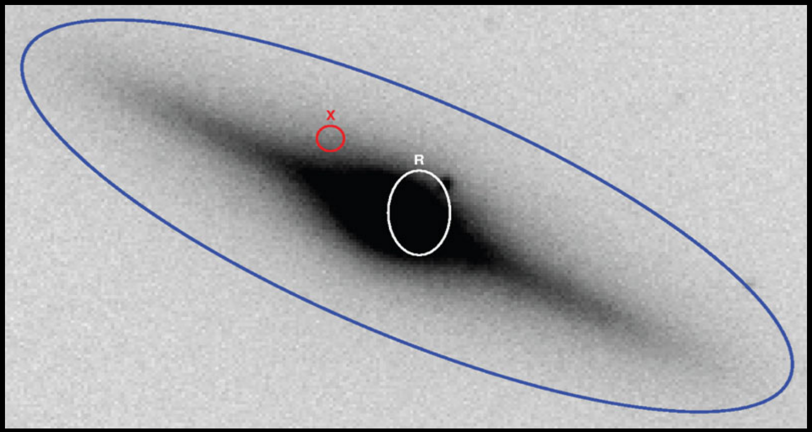


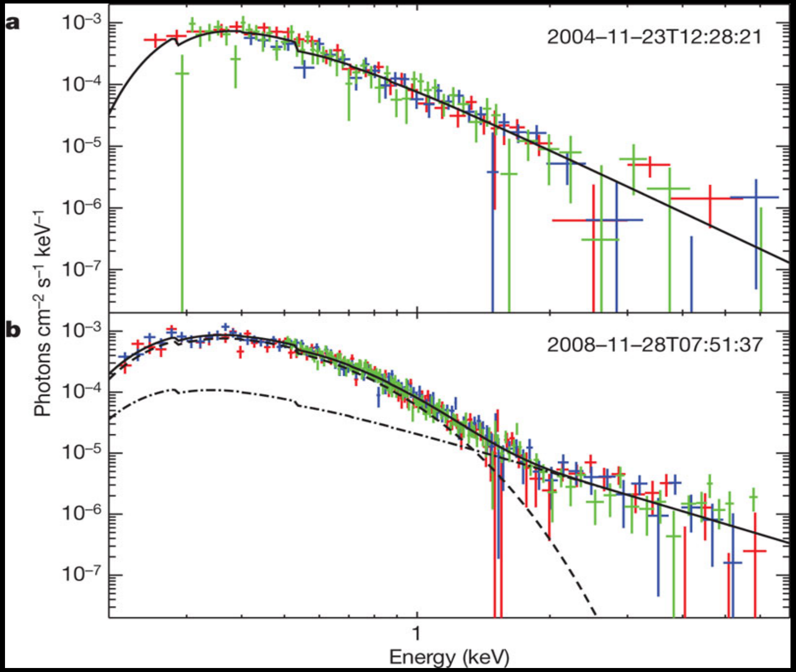


- X-ray source in GC associated with NGC 4472 (in the Virgo cluster)
- X-ray luminosity: 4×10^{39} erg s^{-1}
- Variability excludes composition by several objects

➔ Black hole (15-30 or 400 solar masses)

An Intermediate-Mass Black Hole In ESO 243-49





- 2XMM J011028.1-460421 identified in 2XMM Serendipitous Source catalogue
- Located in the edge-on spiral galaxy ESO 243-49 ➔ distance

S. A. Farrell, et al., 2009, Nature 460, 73

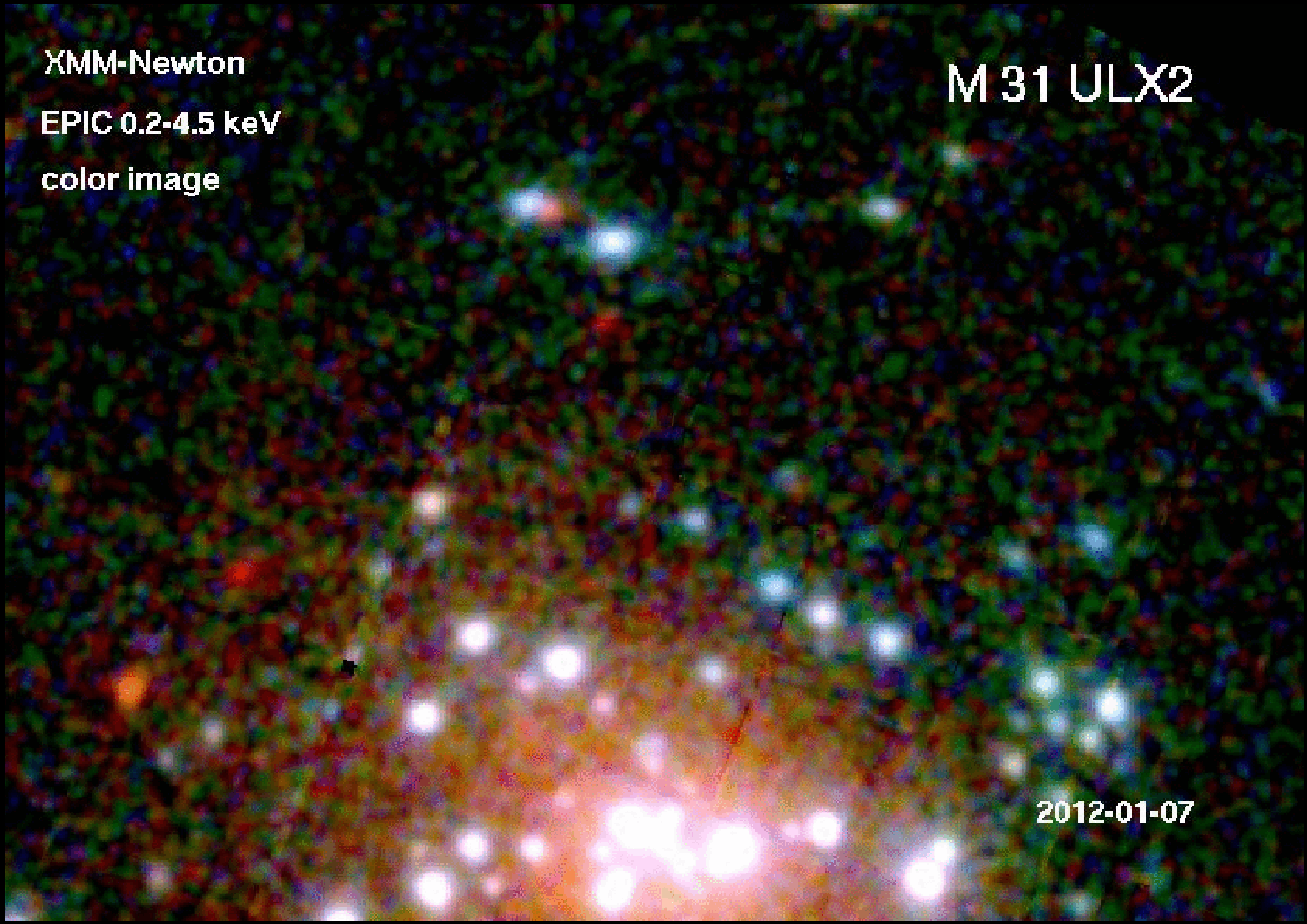
- Variability establishes:

➔ single source

➔ $L = 1.1 \times 10^{42} erg\ s^{-1}$

➔ $m > 500\ M_o$

XMMU J004243.6+412519: A ultraluminous X-ray source discovered in Andromeda

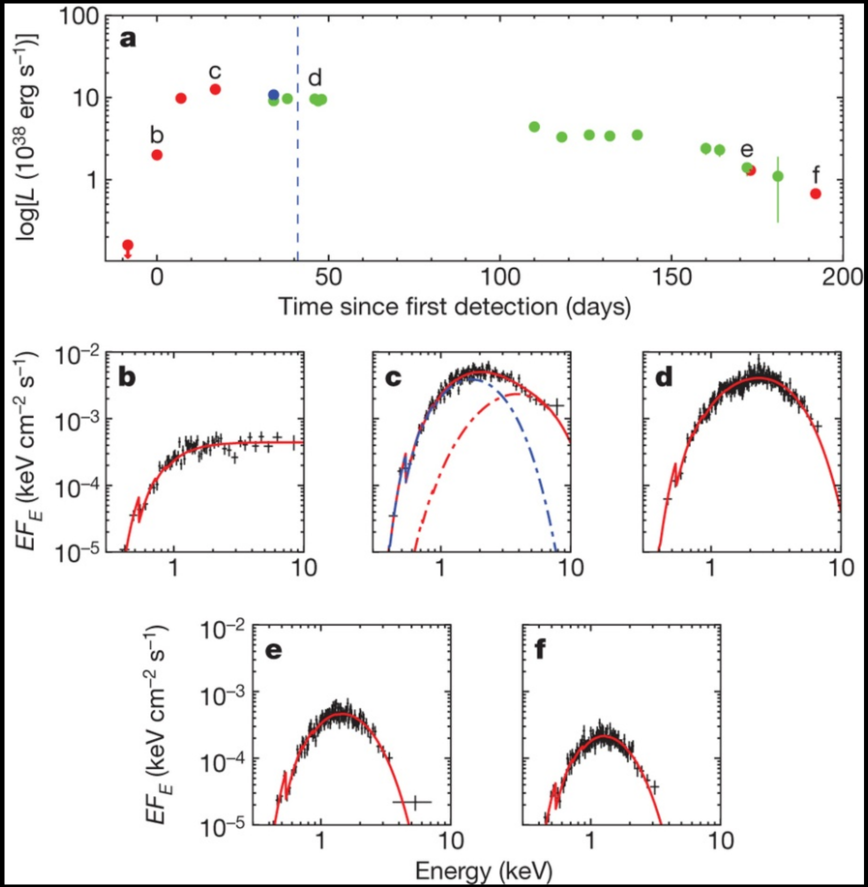


XMMU J004243.6+412519: A ultraluminous X-ray source discovered in Andromeda

- XMM-Newton first detected XMMU J004243.6+412519 on 15 January 2012 at an X-ray luminosity of 2 × 10^{38} erg s^{-1}
- The source's location in an external galaxy allowed the astronomers to probe the emission both from the black hole's accretion disc, at X-ray wavelengths, and from its jets, in radio waves.

➔ These observations revealed, for the first time in an extragalactic stellar-mass black hole, the link between the source's X-ray brightening and the ejection of radio-bright material from the vicinity of the black hole into the jets, indicating an accretion rate close to the black hole's Eddington limit, or even above it.

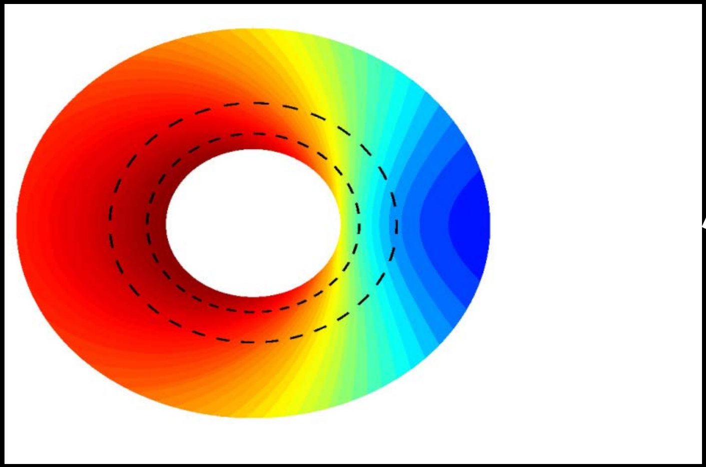
M. Middleton et al., 2013, Nature 493, 187

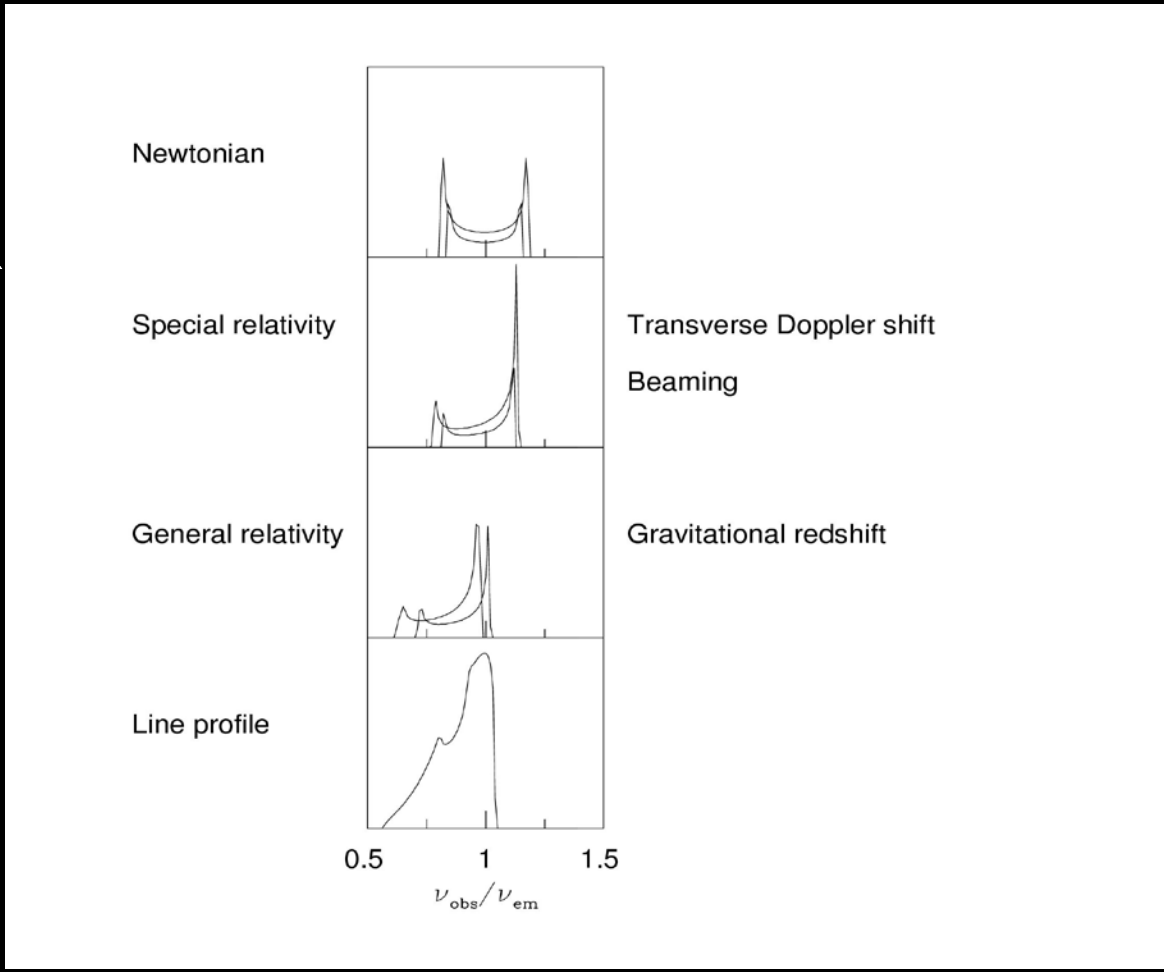


Evolution of the source brightness over ~200 days together with the time of the first VLA detection (blue vertical dashed line). The unabsorbed 0.3-10 keV luminosities are derived from the best-fitting models to the XMM-Newton observations (red), Chandra (blue) and Swift (green)

Spin of Black Holes

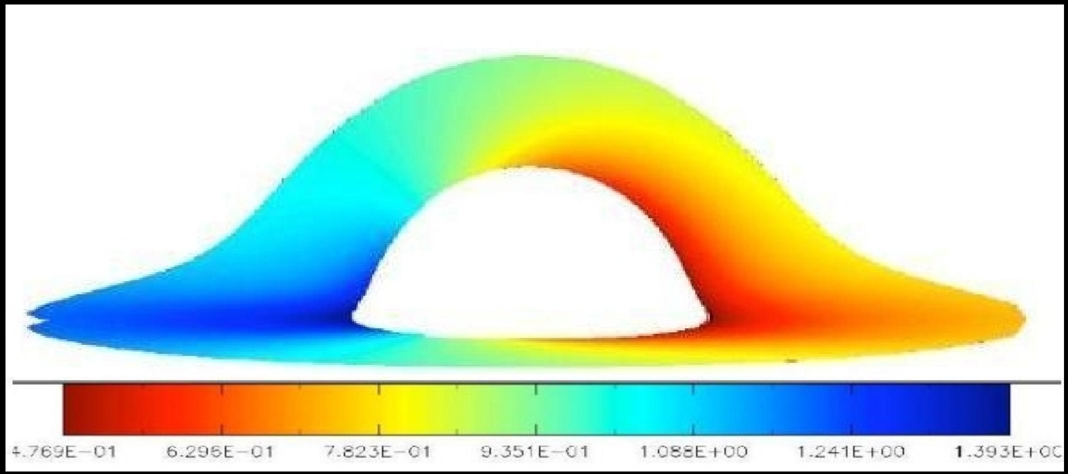
Emission in the Strong Gravitational Field of the Black Hole

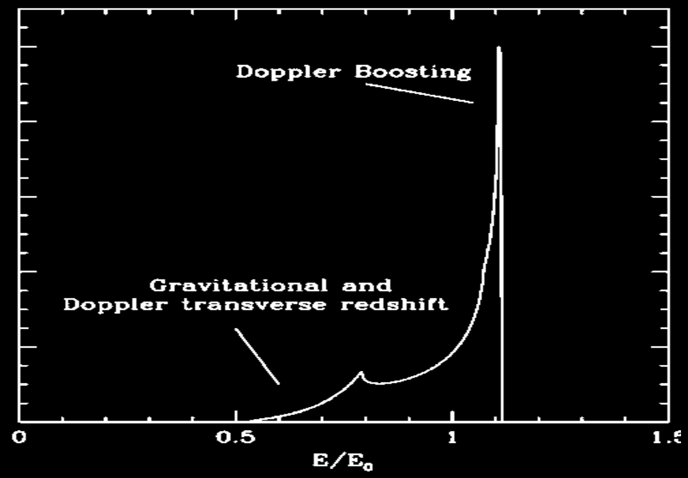


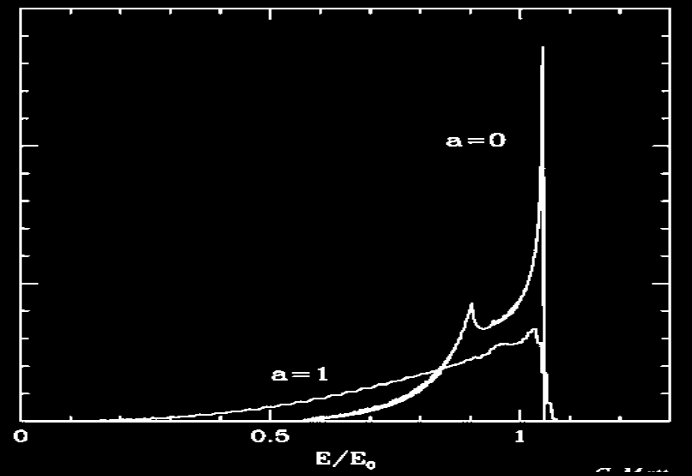


- Fabian et al. (1989); Laor et al (1990); Dovciak et al (2004); K. Beckwith & C. Done, Chris, 2005, MNRAS 359, 1217
- Image courtesy A. Fabian

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

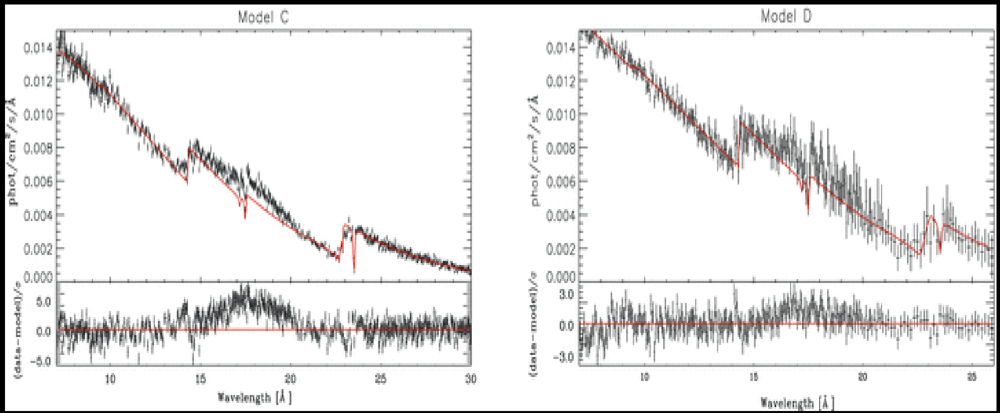






- Image courtesy G. Matt and K. Beckwith
- K. Beckwith & C. Done, Chris, 2005, MNRAS 359, 1217

Broad O VIII Lyα line in the ultracompact X-ray binary 4U 1543-624

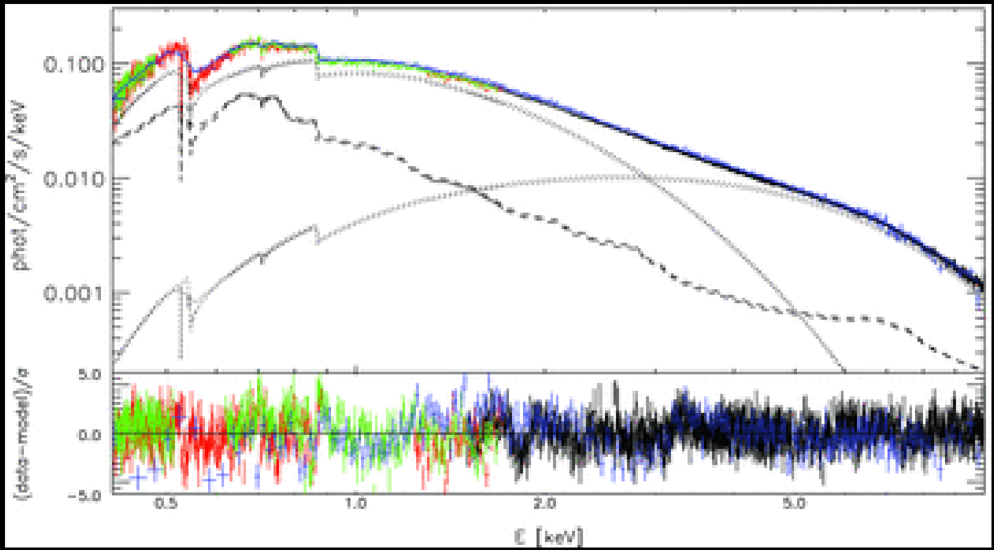


- Discovery of a broad emission feature at ~0.7 keV with the high-resolution spectrographs of the XMM-Newton and Chandra satellites.
- Confirmation of the presence of a weak emission feature at ~6.6 keV

➔ O VIII Lyα and Fe Kα emission caused by X-rays reflected off the accretion disc in the strong gravitational field close to the neutron star

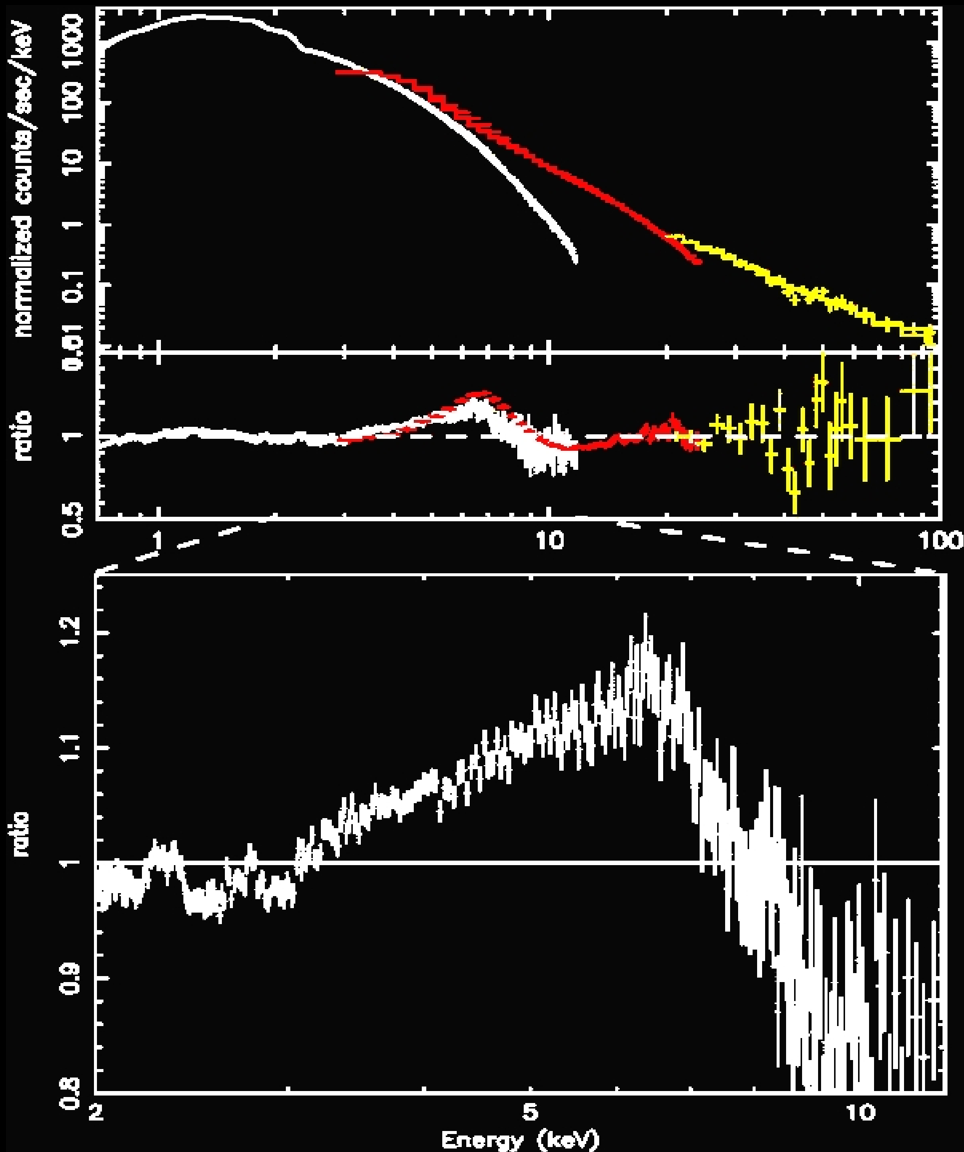
- Ultracompact X-ray binary 4U 1543-624:
  - donor star is a CO or ONe white dwarf
  - transfers oxygen-rich material to the accretor, conceivably a neutron star.

➔ The X-rays reprocessed in the oxygen-rich accretion disc could give a reflection spectrum with O VIII Lyα as the most prominent emission line.



O.K. Madej & P.G. Jonker, 2011, MNRAS 412, L11

Outburst of the Galactic Black Hole GX 339-4

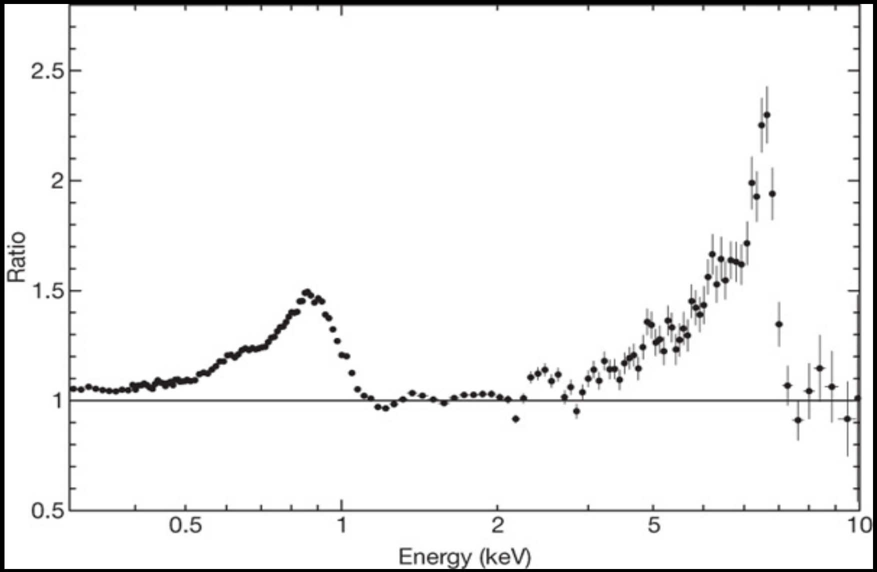


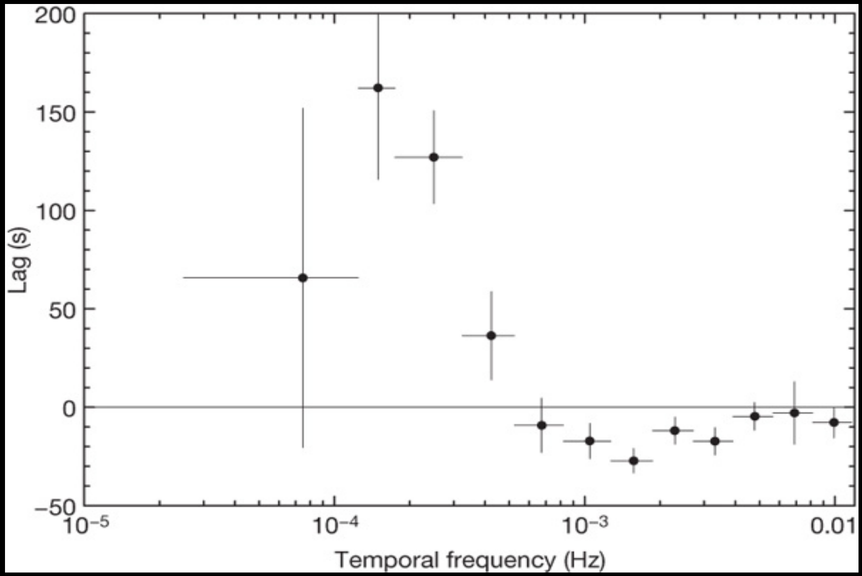
- Extremely skewed, relativistic Fe Kα emission line and ionized disk reflection spectrum
- Inner disk radius is not compatible with a Schwarzschild black hole

➔ Black hole with a>0.8-0.9 (where $r_g=GM/C^2$ and $a=cJ/GM^2$)

J.M Miller et at., 2004, ApJ 606, L131

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

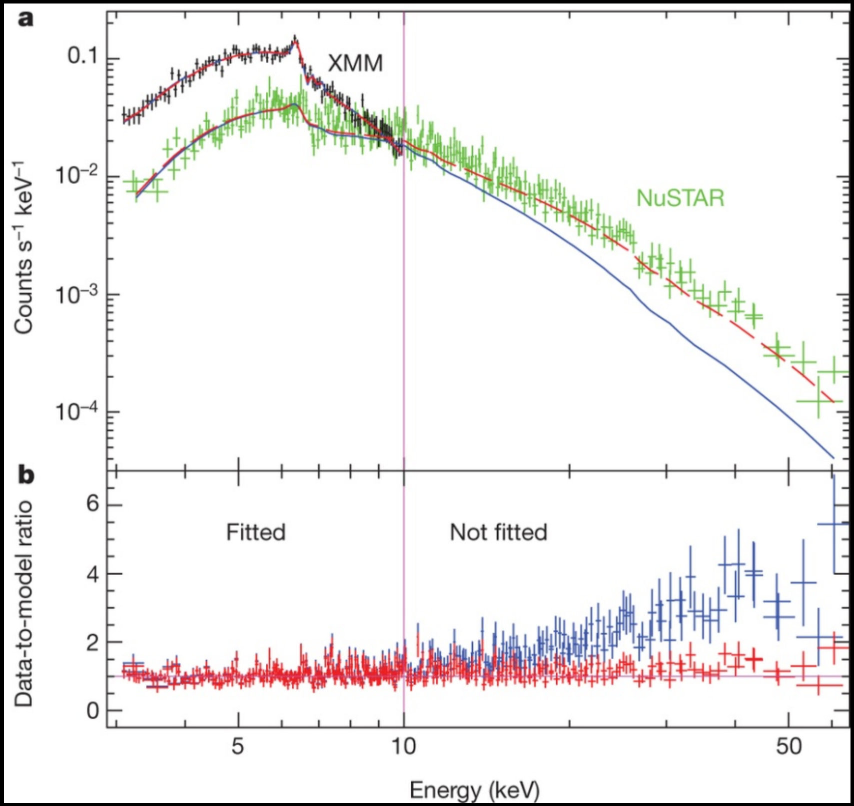
A rapidly spinning supermassive black hole at the centre of NGC1365

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.

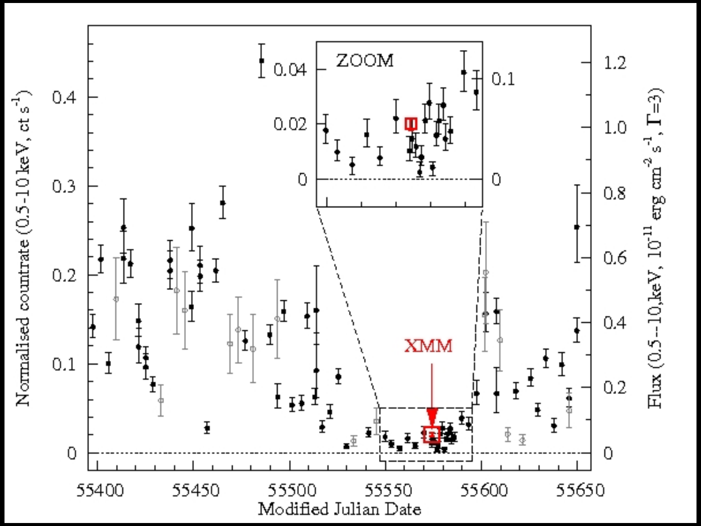
➔ Absorption-dominated models that do not include relativistic disk reflection can be ruled out both statistically and on physical grounds.

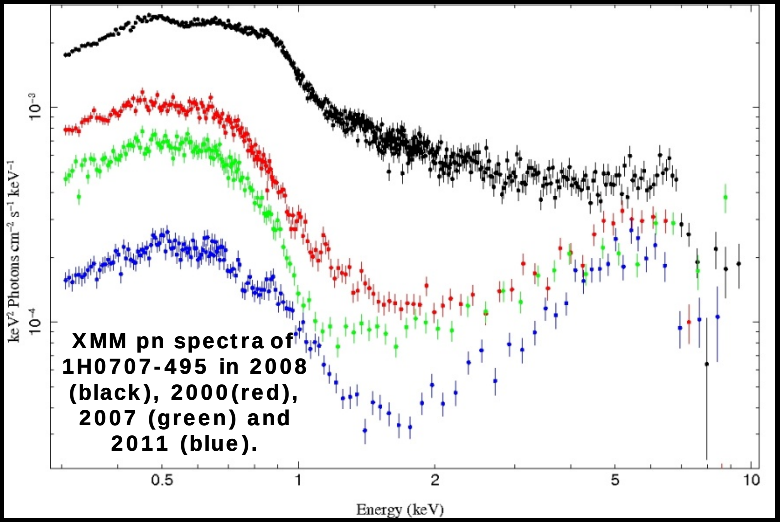


a: XMM-Newton and NuSTAR spectral data and models. The two models contain a relativistic reflection component plus variable partial covering (red), and a double partial covering (blue). Both models have been fitted to the data below 10 keV, and reproduce the lower-energy data well. However, the models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

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

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

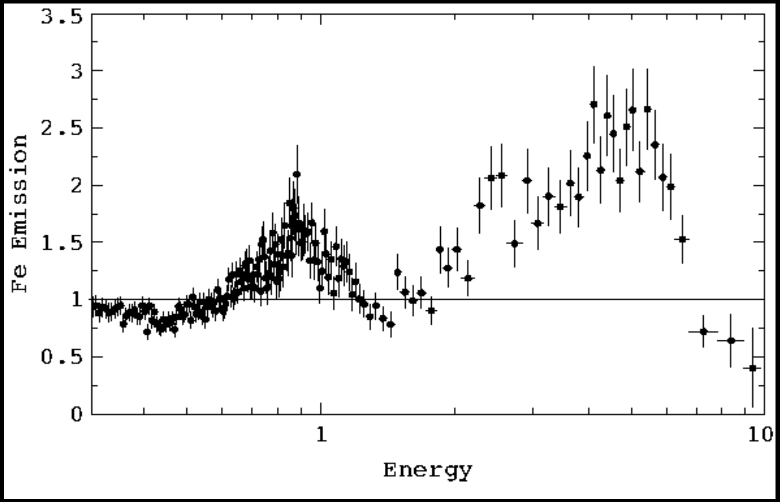




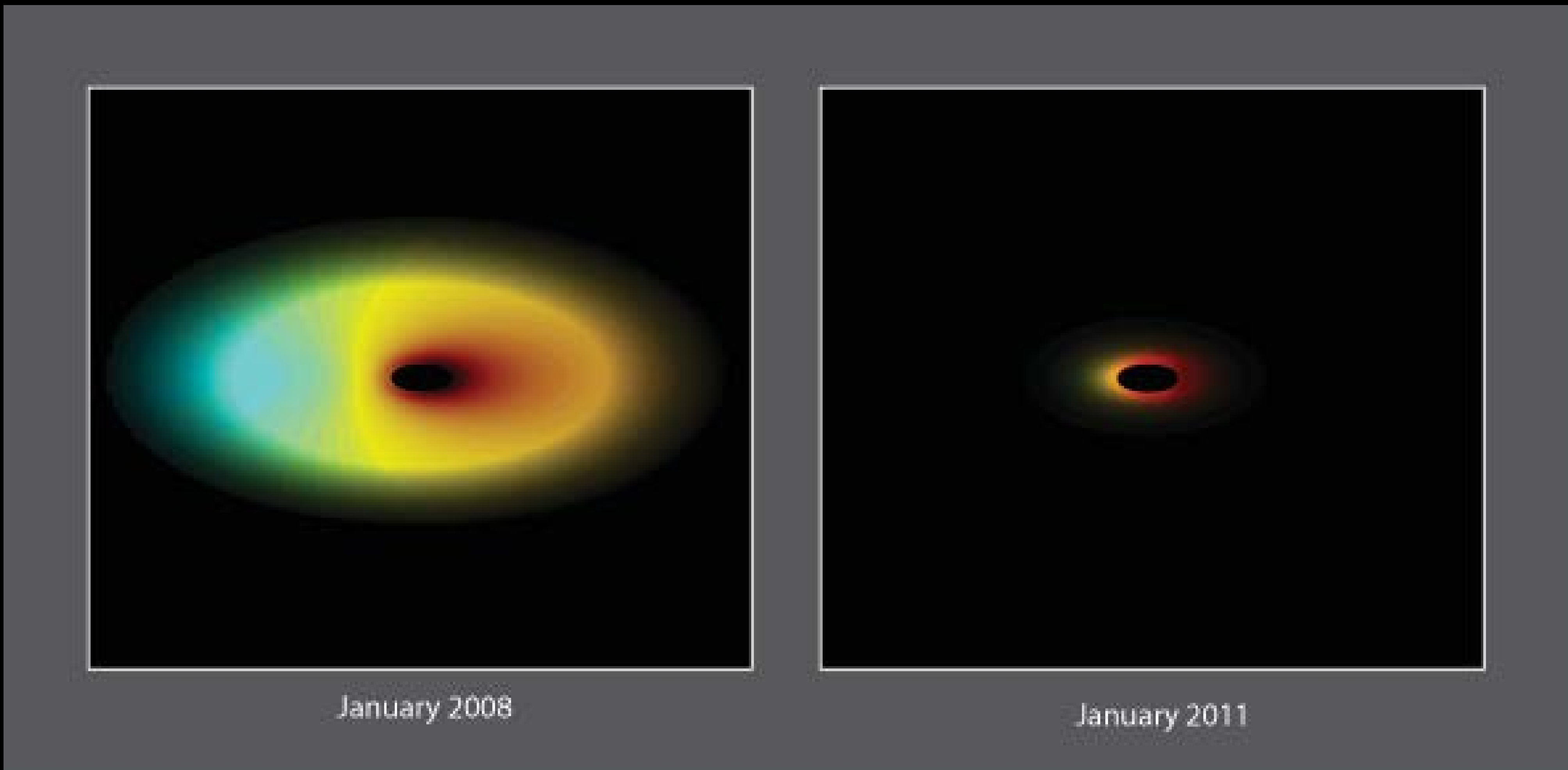
Fabian, A. C. et al., 2012, MNRAS 416, 116

- The Narrow Line Seyfert 1 Galaxy 1H0707-495 was in a low state from 12/2010 to 2/2011 February, 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.



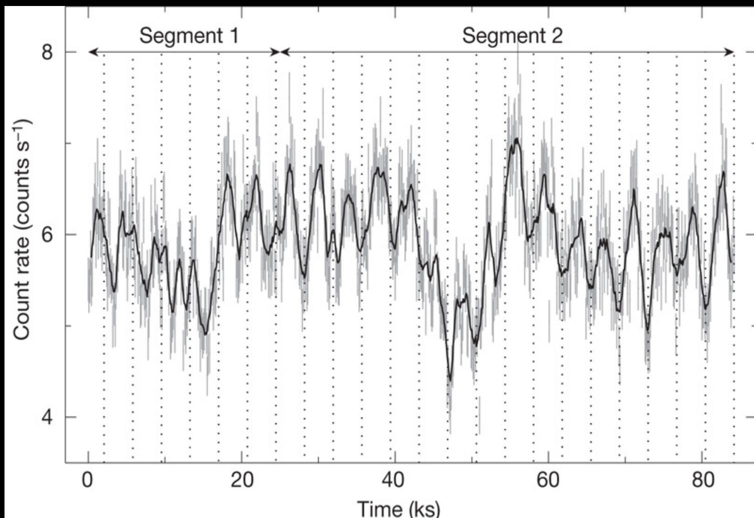
1H0707-495 in low state: An X-ray source within a gravitational radius of the event horizon

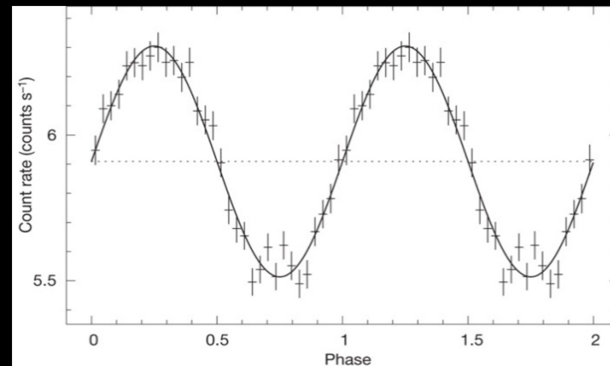


Courtesy Dan Wilkins; A.C. Fabian et al., 2012, MNRAS 419, 116

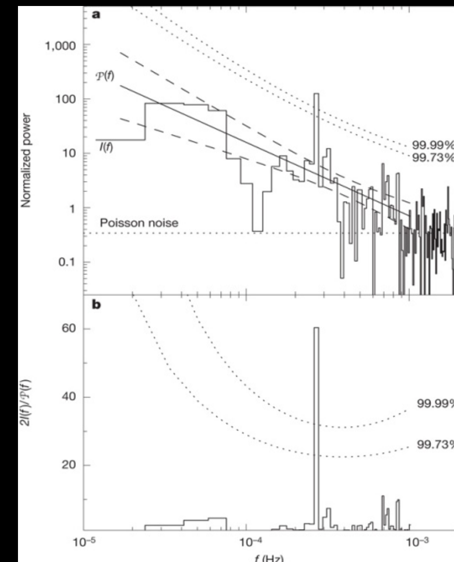
Variability near Black Holes

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: 6.3×10^5 to 3.6×10^7 M_{sun}

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

➔ Provides fundamental length-scale of SMBH system

Microquasars / Galactic Center BH

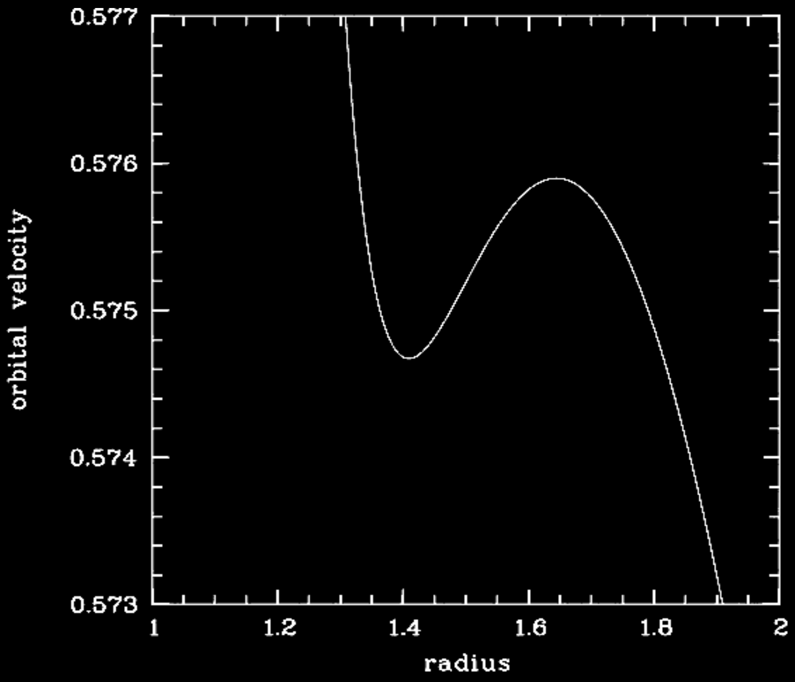
- GRO J1655-40, XTE J1550-564 and GRS 1915+105 show twin high frequency quasi-periodic oscillations with a ratio of 3:2 and/or 3:1
- resonance between vertical and radial epicyclic oscillations and Kepler orbits

➔ 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

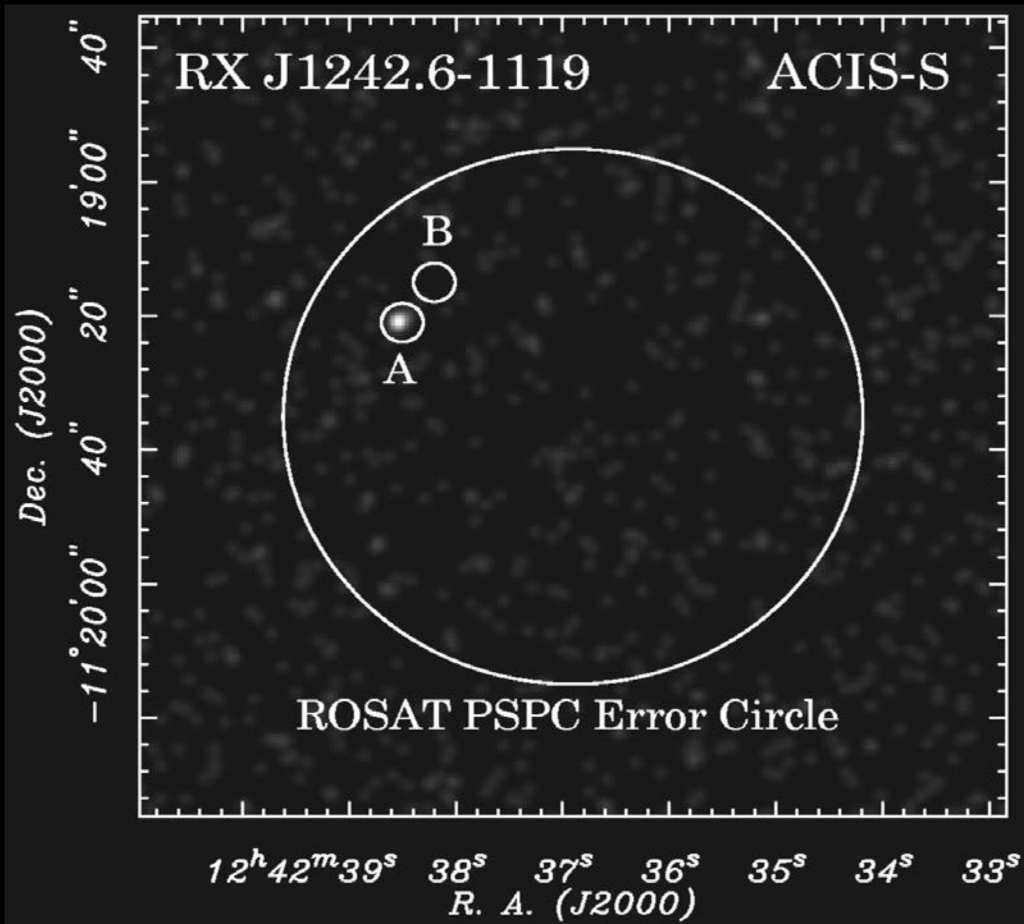
PHYSICAL REVIEW D **71**, 024037 (2005)

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*
[2]*NORDITA, Blegdamsvej 17, DK-2100 Copenhagen, Denmark*
[3]*Theoretical Physics, Göteborg & Chalmers Universities, S-412 96 Göteborg, Sweden*
(Received 12 November 2004; published 28 January 2005)

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

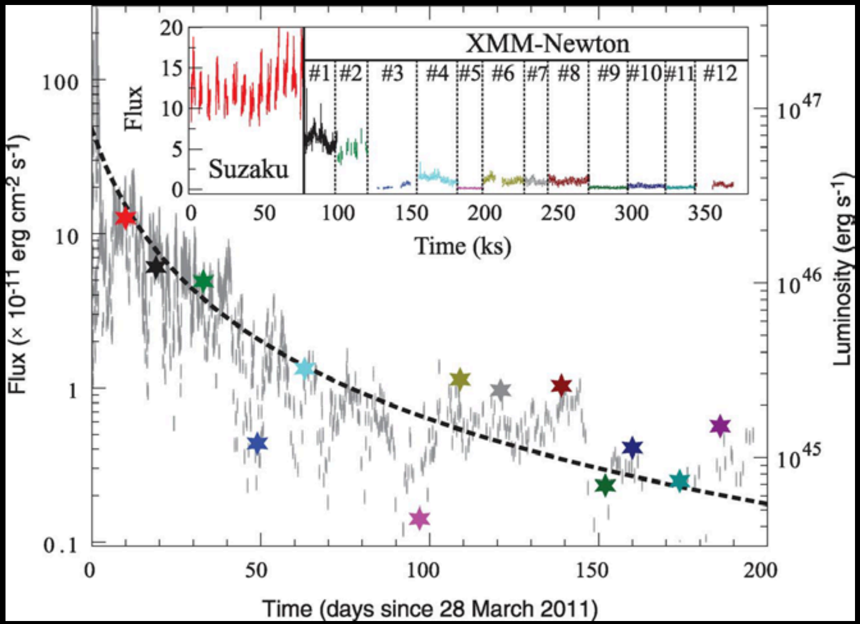


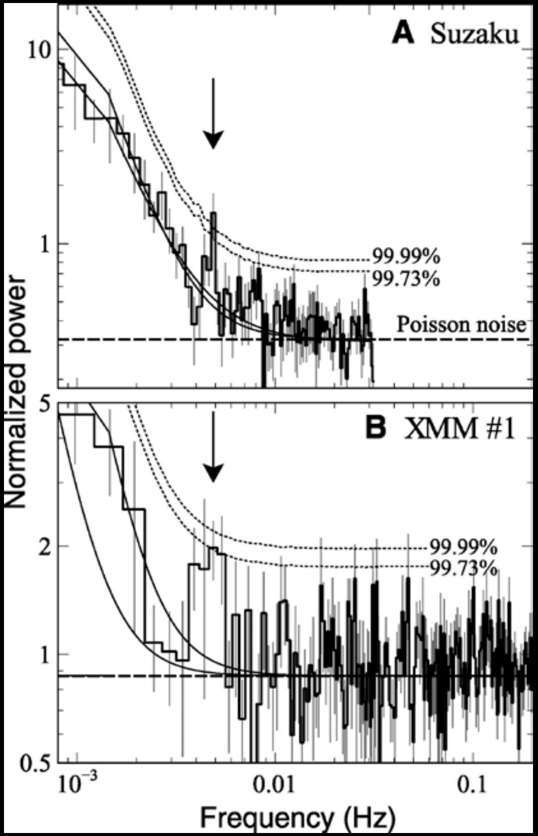
- ROSAT, Chandra and XMM-Newton
- ~200 drop in X-ray luminosity

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

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

Tidal Disruption: Swift J164449.3+573451



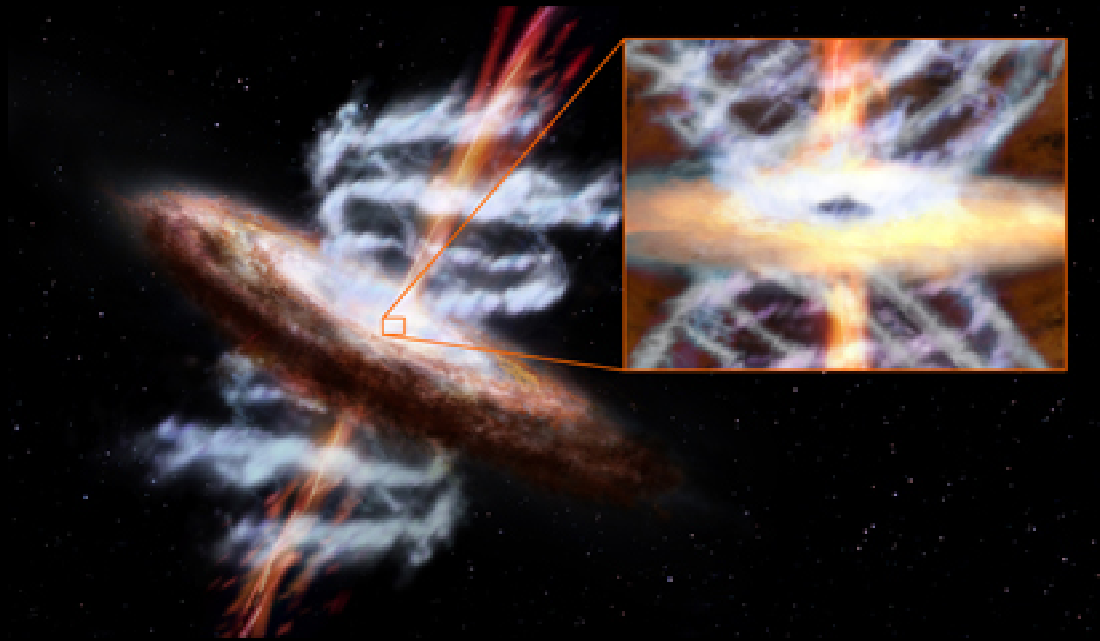


- tidal disruption of a star by a dormant black hole
- bright X-ray flares
- galaxy at redshift z = 0.3534

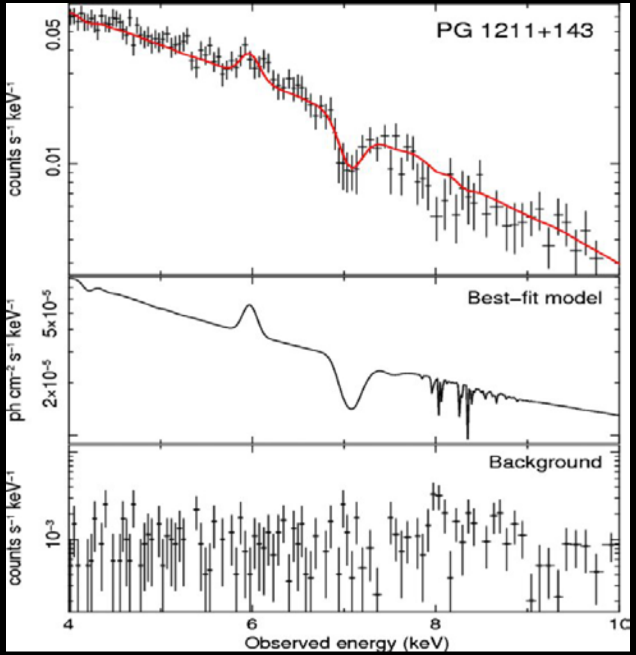
➔ ~200-second x-ray quasi-periodicity

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

Ultra-fast Outflows in Radio-quiet Active Galactic Nuclei



- ➔ Location is in the interval ~0.0003-0.03pc ($\sim10^2$-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: log ξ ~ 3-6 erg s^{-1} cm
- ➔ Column densities are $N_H \sim 10^{22}$-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

What's past is prologue[1]

[1] W. Shakespeare, 1623, The Tempest, Act 2, Scene 1

Reaction Wheels

- Fuel consumption limited the lifetime of XMM-Newton to 2021
- XMM-Newton used only 3 of its 4 reaction wheels
- Experiences with Herschel showed that an operational scenario which uses 4 reaction-wheels reduces the fuel consumption by ~50%

- ➔ A four reaction-wheels operational scenario would allow XMM-Newton science operations up to 2030
- ➔ Successfully Commissioned in October 2013