THE HOT AND ENERGETIC UNIVERSE: XMM-NEWTON, INTEGRAL AND MORE

Xavier Barcons
ESO – European Southern Observatory

With input from:
Norbert Schartel, Erik Kuulkers and many others

- The hot and energetic Universe & high energy astrophysics
- XMM-Newton
  - *The mission*
  - *Science highlights*
  - *The central role of XMM-Newton in Astronomy at large*
- INTEGRAL
  - *The mission*
  - *Science highlights*
- The future: Athena
- Outlook

The hot and energetic Universe

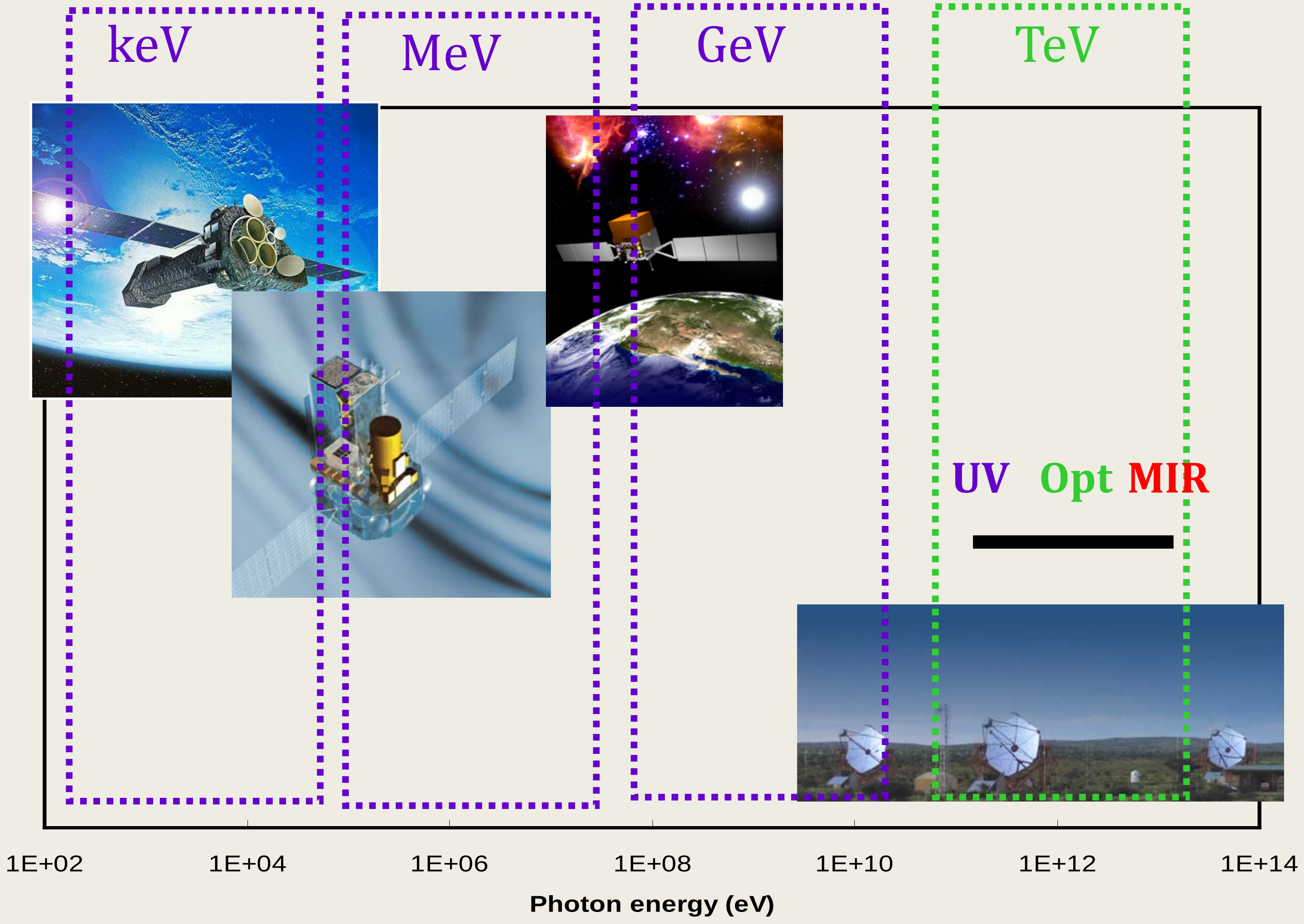
Hot plasmas T> 10^6K

- Intracluster gas (10^7-10^8 K)
- Intergalactic medium (10^5-10^7 K)
- Supernova Remnants (10^6-10^8 K)
- Active coronal stars (10^6-10^7 K)

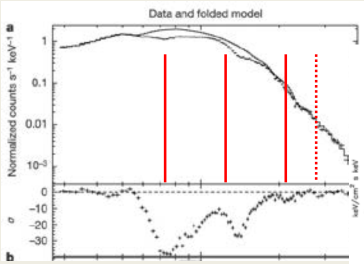
Compact objects

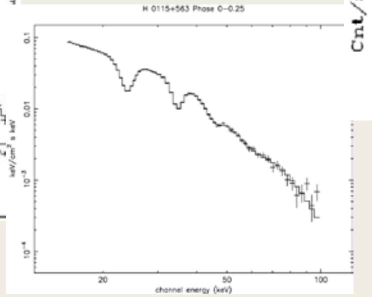
- X-ray binaries
- Black Holes
- Neutron stars & pulsars
- White Dwarfs
- Supermassive Black Holes

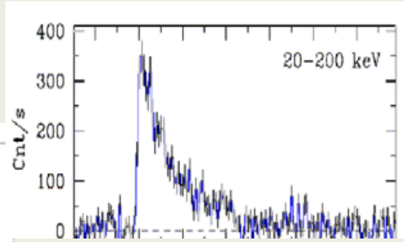
From X-rays to VHE γ-rays

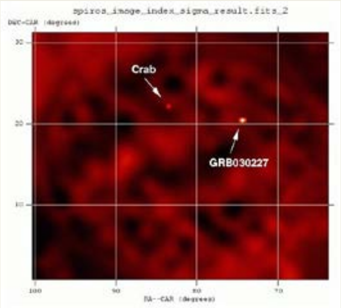


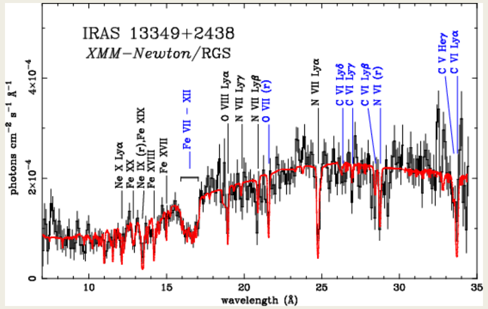
What do we see at high-energies?

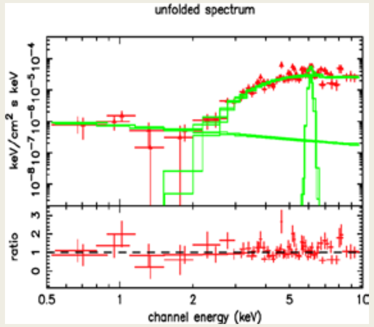


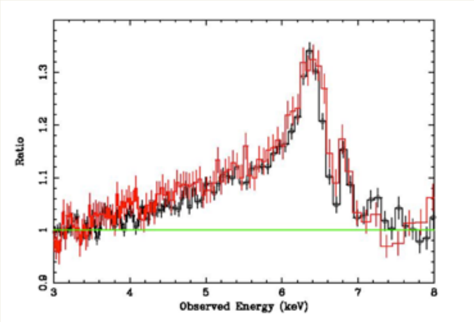


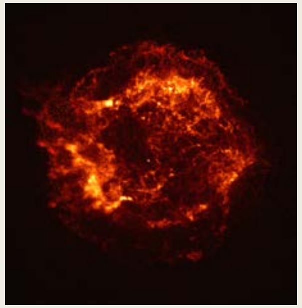


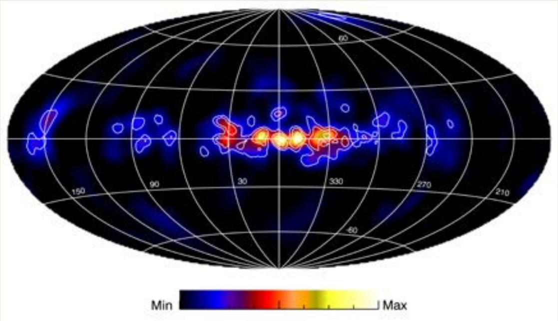


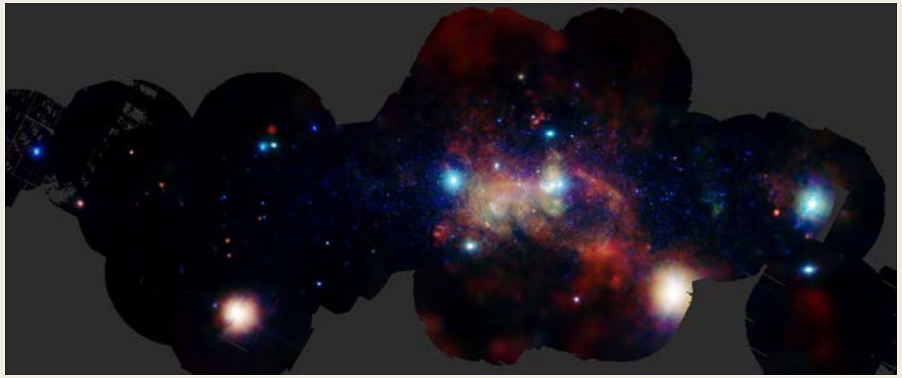


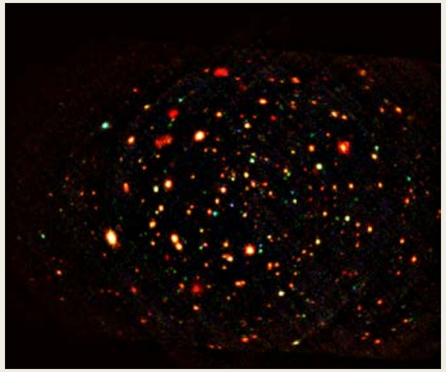






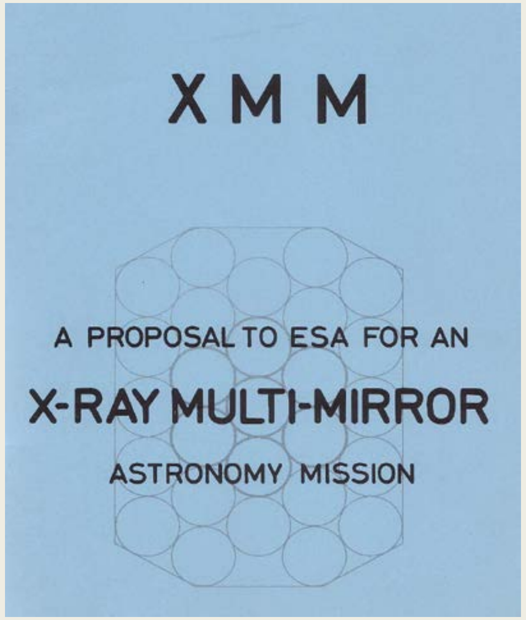






XMM-Newton

- Proposal for an X-ray Multi Mirror (XMM) mission submitted to ESA in 1982 (Bleeker et al)
- Launched on 10 December 1999 from Kourou by Ariane 504
  - *Lots of nervousness, but flawless flight*
- Renamed afterwards to XMM-Newton

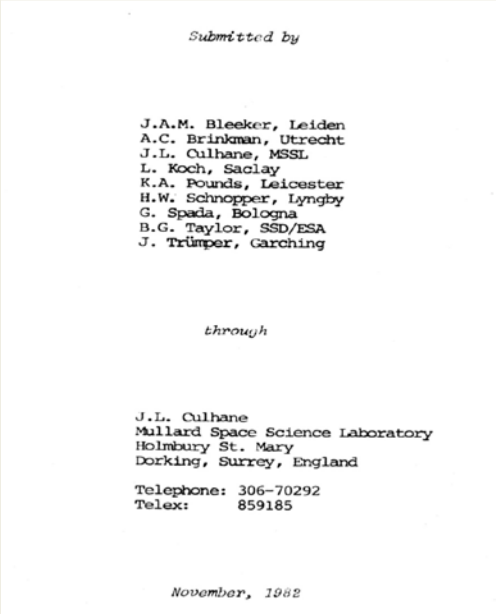


XMM

A PROPOSAL TO ESA FOR AN

X-RAY MULTI-MIRROR

ASTRONOMY MISSION



Submitted by

J.A.M. Bleeker, Leiden
A.C. Brinkman, Utrecht
J.L. Culhane, MSSL
L. Koch, Saclay
K.A. Pounds, Leicester
H.W. Schnopper, Lyngby
G. Spada, Bologna
B.G. Taylor, SSD/ESA
J. Trümper, Garching

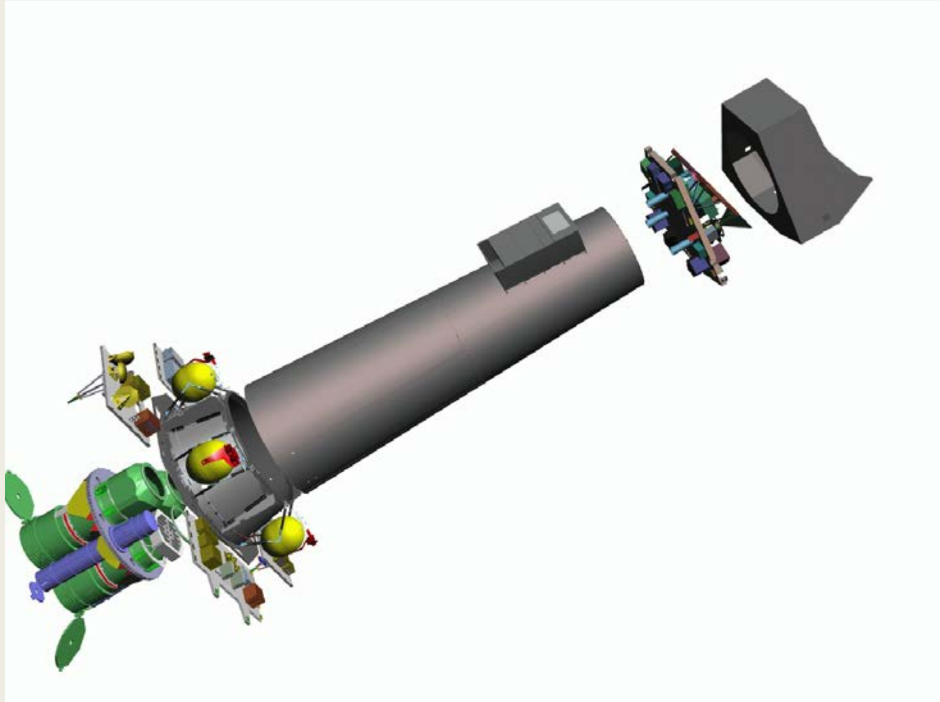
through

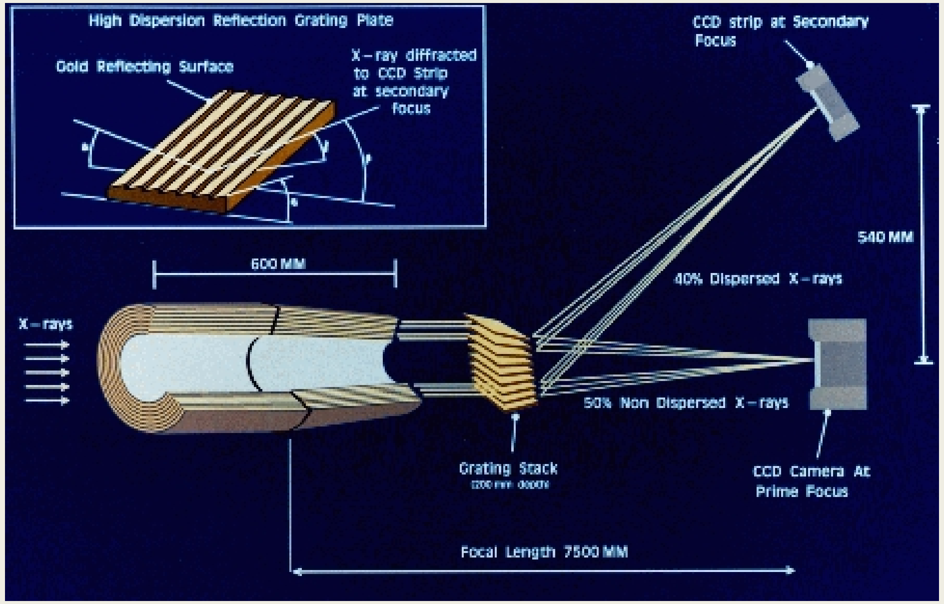
J.L. Culhane
Mullard Space Science Laboratory
Holmbury St. Mary
Dorking, Surrey, England

Telephone: 306-70292
Telex: 859185

November, 1982

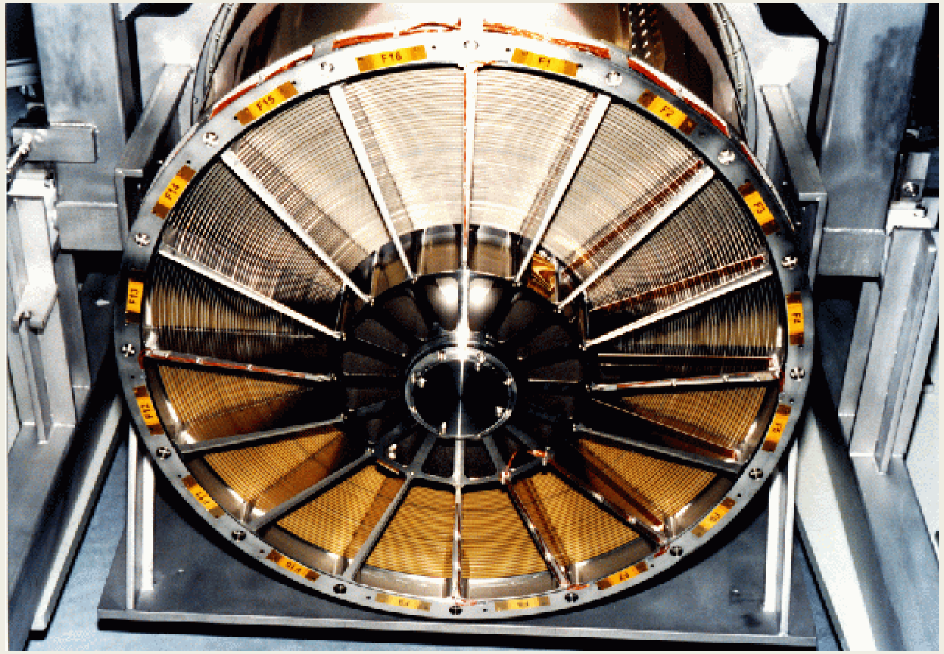
The XMM-Newton payload





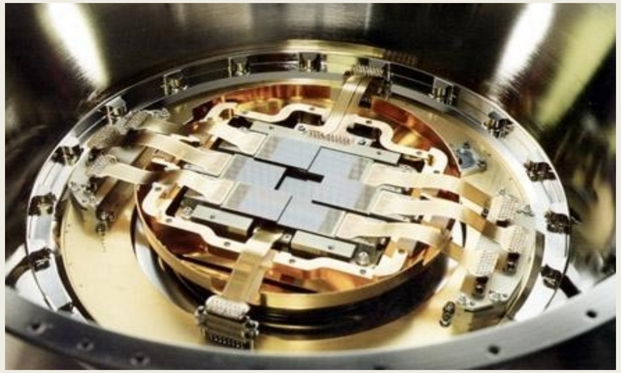
XMM-Newton optics

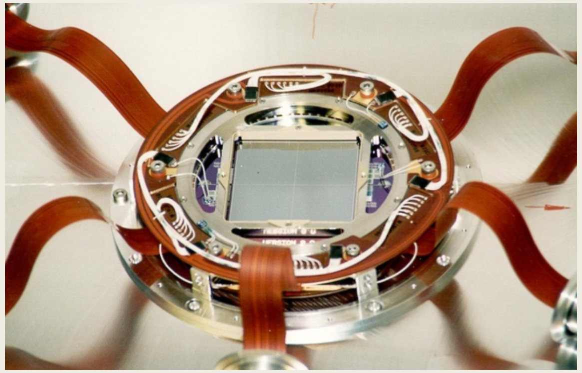
- Three co-aligned X-ray telescopes
- Grazing incidence, FoV at 1 keV about 0.5 deg diameter
- Electroformed Ni substrate, Au coating
- 56 nested couples of mirrors
- Focal length 7.5 m
- Angular resolution: 12-15 arcsec
- Excellent for spectroscopy

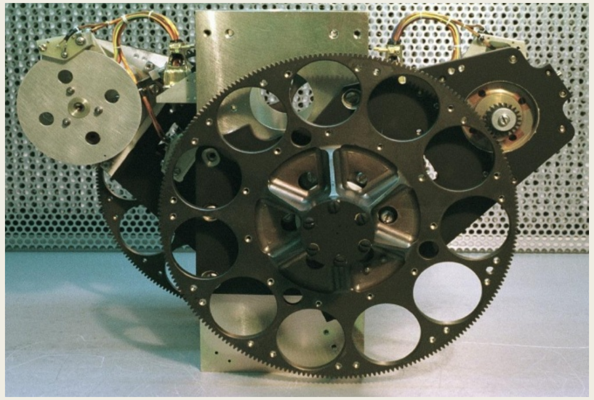


XMM-Newton instruments

- EPIC (2 MOS + 1 pn) imaging spectrometers
  - *Low resolution spectroscopic imaging 0.2-12 keV*
- RGS (2) higher resolution spectroscopy
  - *Dispersive spectroscopy 0.2-3 keV*
- OM Optical/UV monitor
  - *Photon counting imaging 170 – 650 nm*

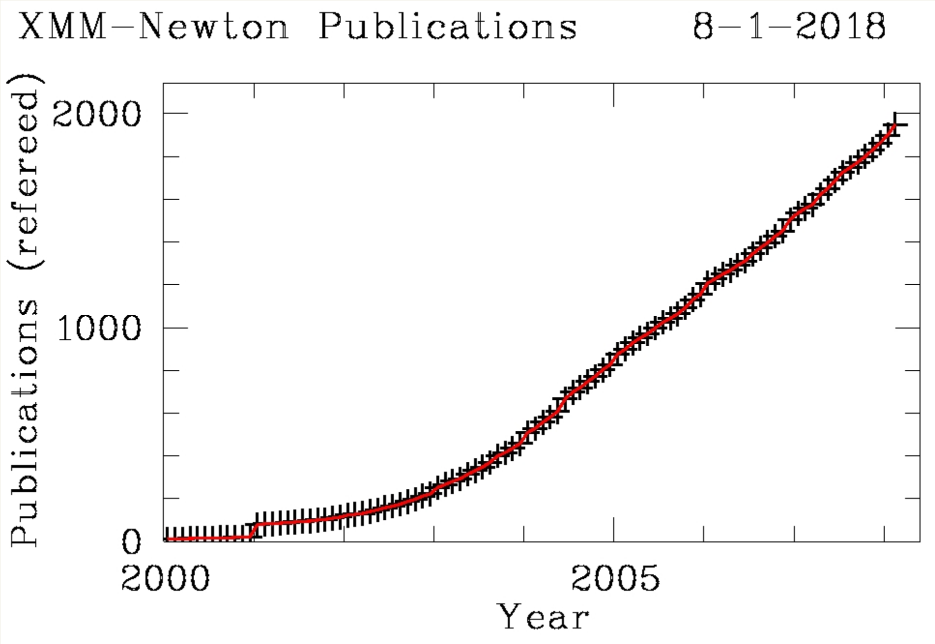


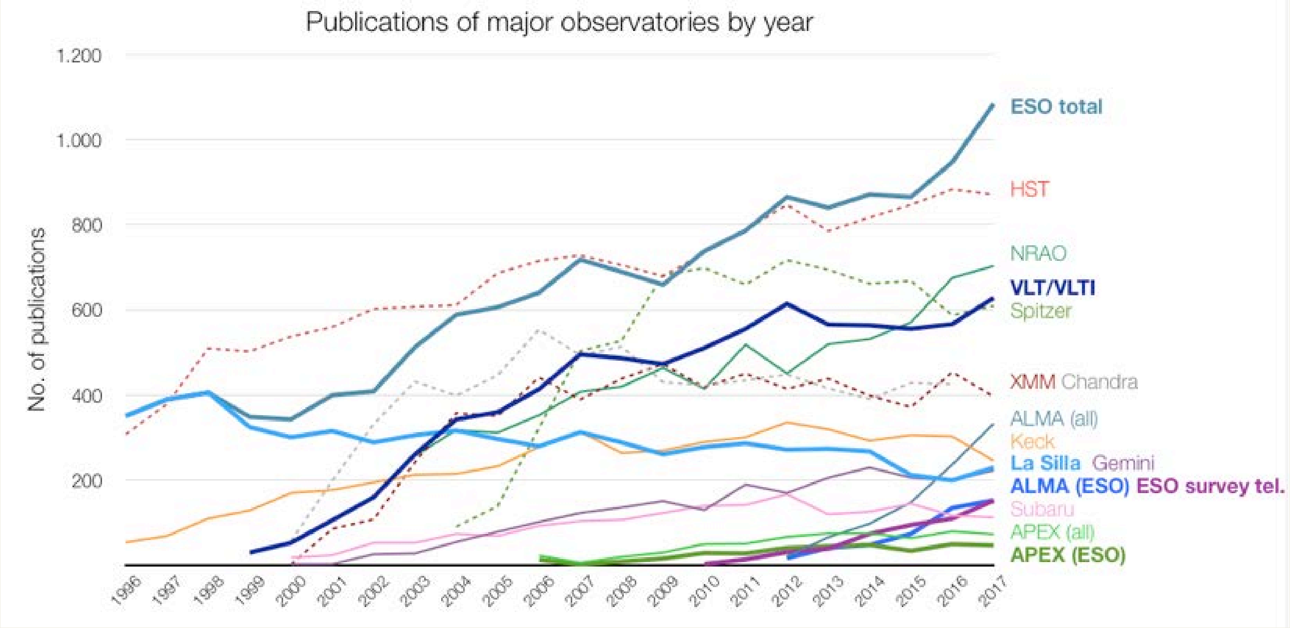




P. Rodríguez/ESA

XMM-Newton science output

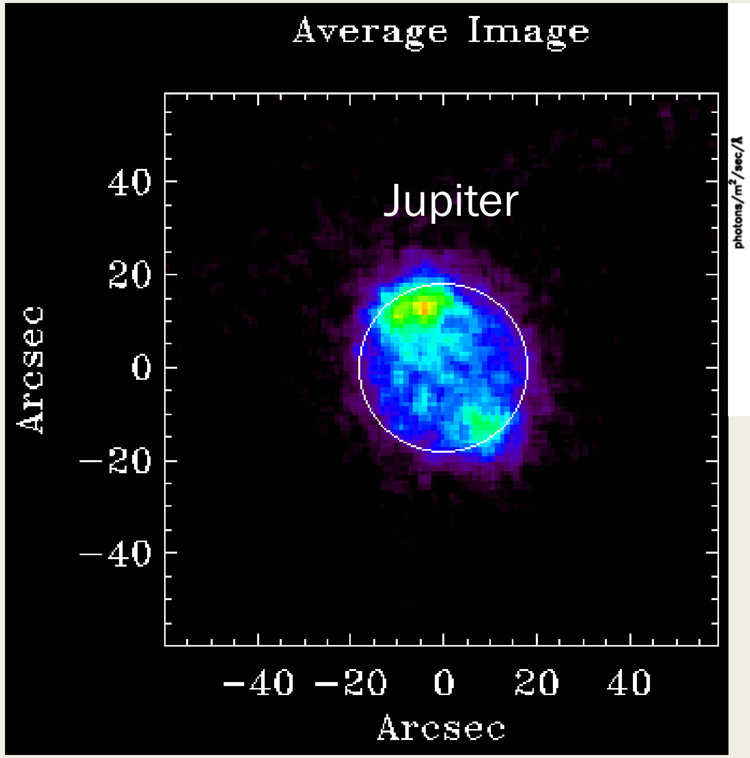


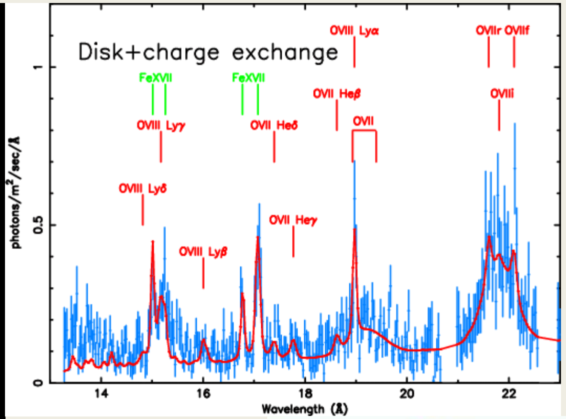


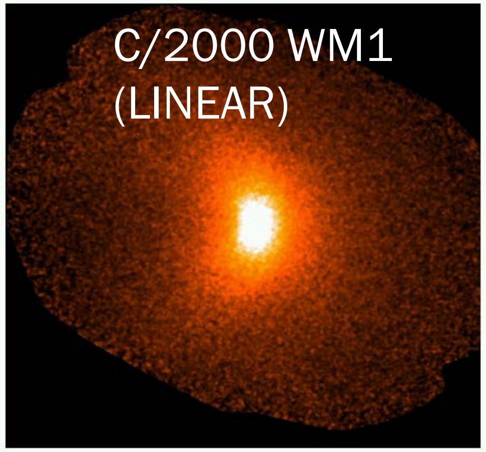
Courtesy N. Schartel/ESA

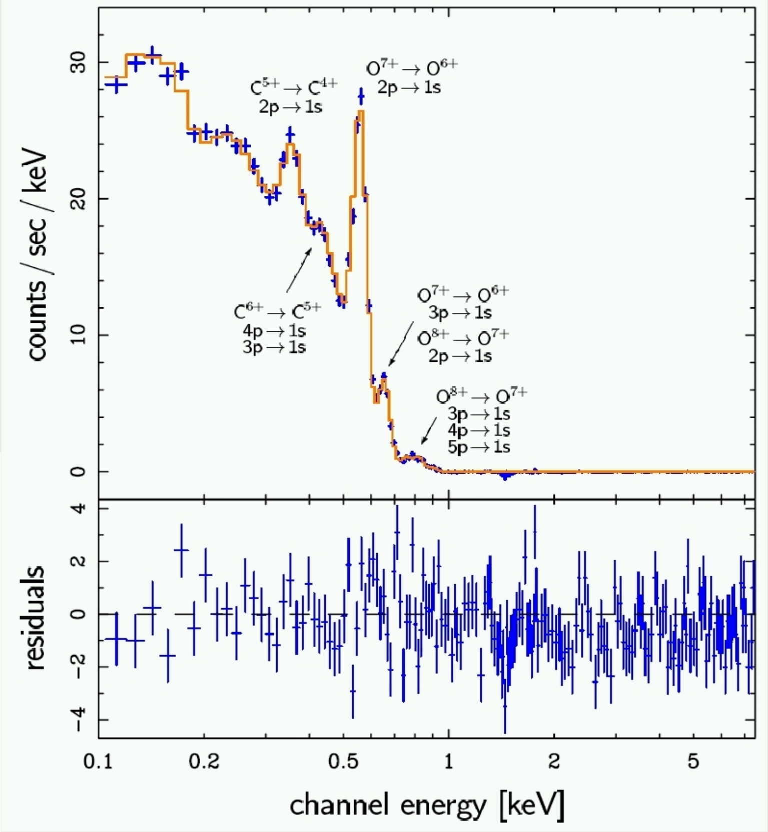
Courtesy Uta Grothkopf/ESO

Solar System:
charge exchange with Solar wind





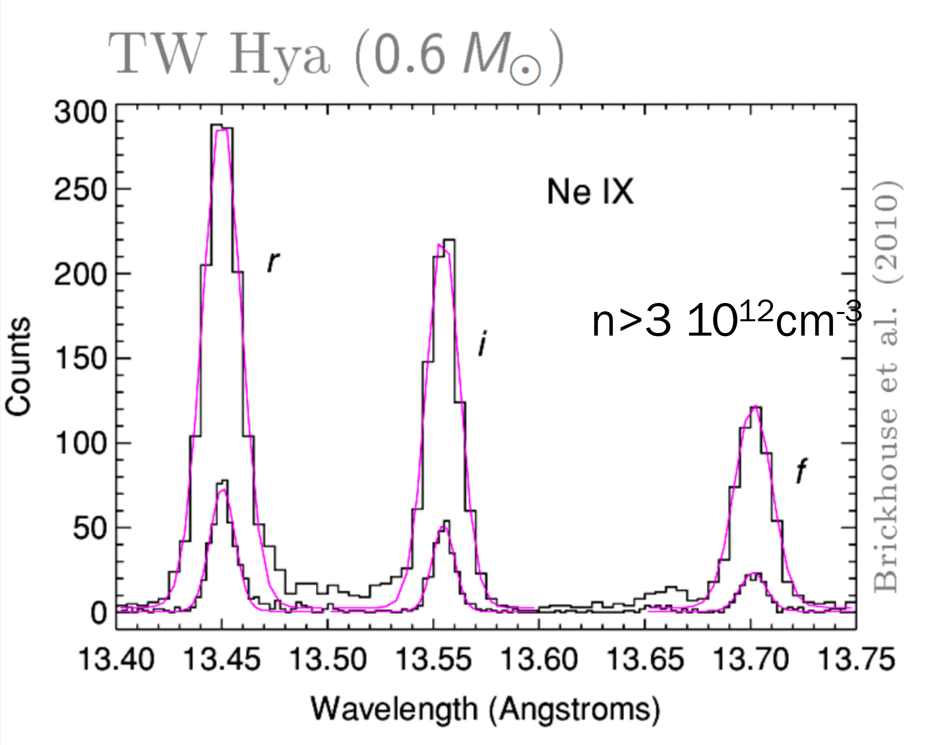


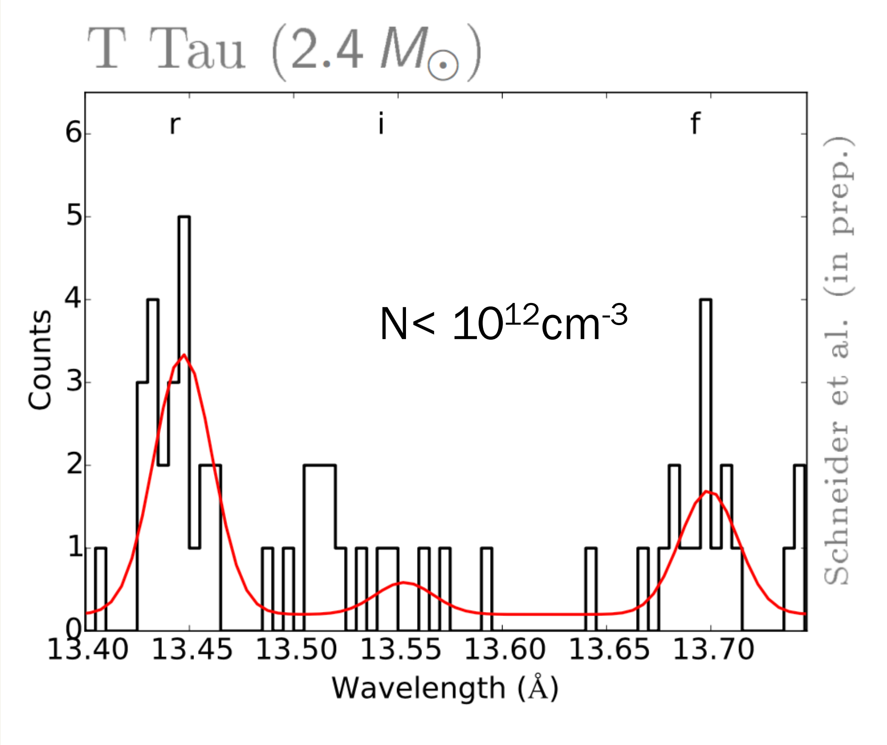


G. Branduardi-Raymont, et al., 2003, A&A 424, 331; 2007, A&A 463, 761 and 2007, PaSS 55, 1126

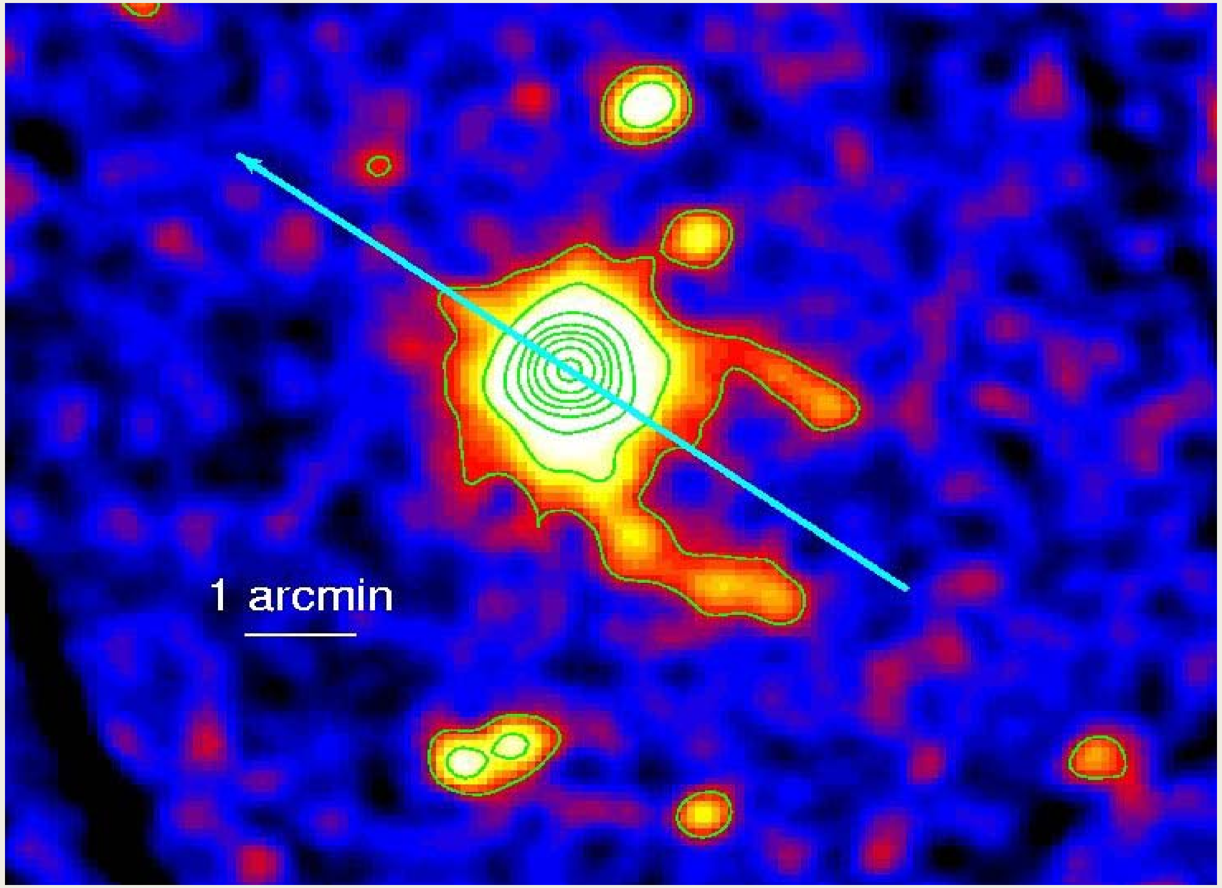
Dennerl, K, et al., 2003, SPIE 4851, 277

Accretion shock signatures in stars: diagnosing gas densities





Geminga's Tails: A Pulsar Bow Shock Probing the Interstellar Medium

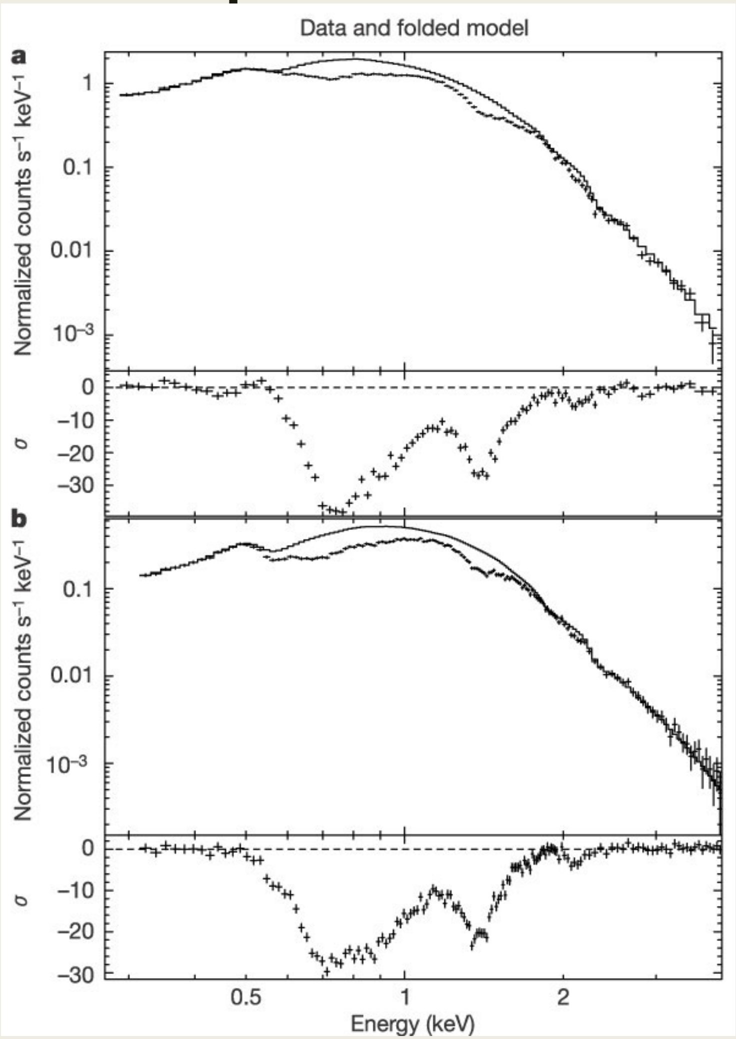


- P. A. Caraveo et al., 2003, Science 301, 1345
- Tails aligned with the object's super-sonic motion
- Electron-synchrotron emission in the bow shock between the pulsar wind and the surrounding medium

➔ Gauge the pulsar electron injection energy and the shock magnetic field

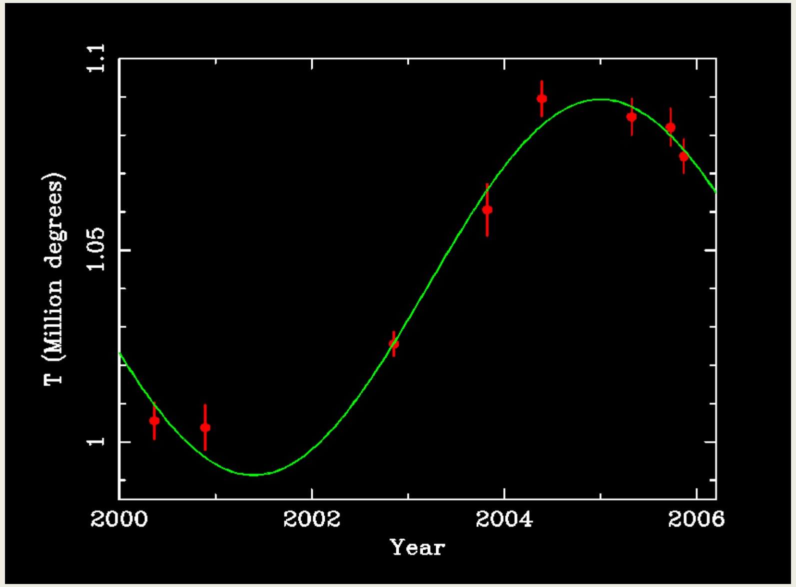
The magnetic field of an isolated neutron star from X-ray cyclotron absorption lines

- Neutron stars exhibit featureless thermal blackbody continua
- A long XMM-Newton/EPIC-pn observation of 1E1207.4-5209, shows absorption features at 0.7, 1.4 and 2.1keV, (2.8keV), harmonics of a cyclotron line.
- Resonant (electron) cyclotron absorption B= 8×10^{10}G.



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

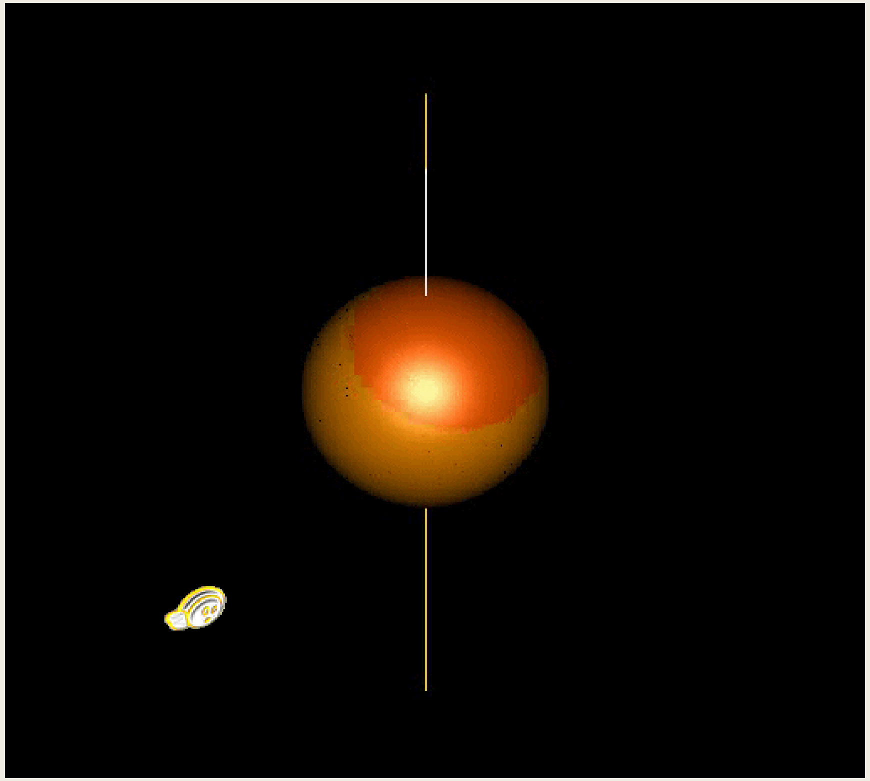
Hot spots in the isolated Neutron Star RX J0720.4-3125



- XMM-Newton spectra over 4.5 years
- Sinusoidal variations in T, size of emitting area, period 7 yrs.

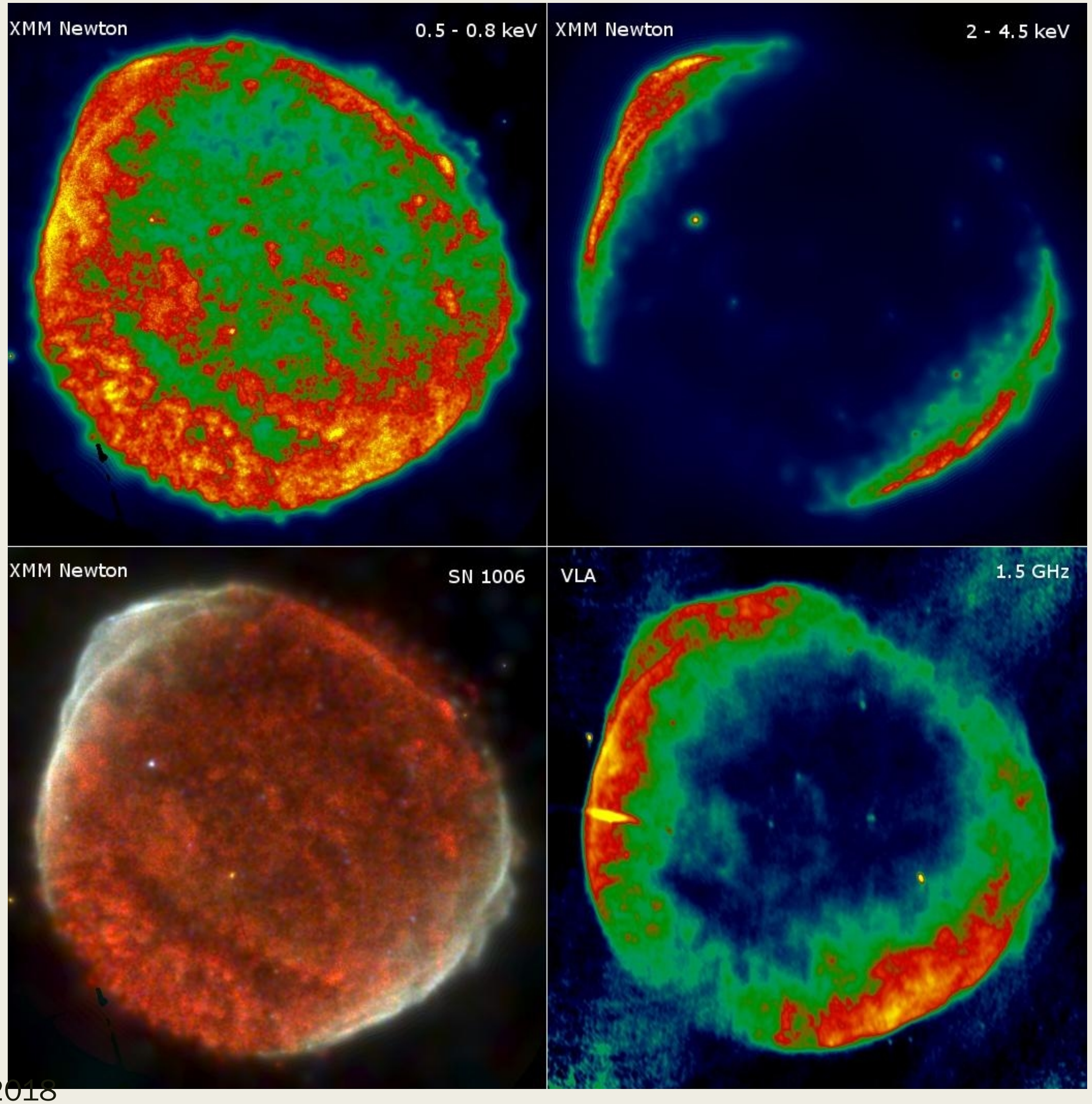
➔ Precession of the neutron star

➔ Two hot spots of different temperature and size, probably not located exactly in antipodal positions



F. Haberl et al., 2006 A&A 451, L17

SN 1006: variations of cosmic-ray acceleration



- R. Rothenflug et al., 2004, A&A 425, 121

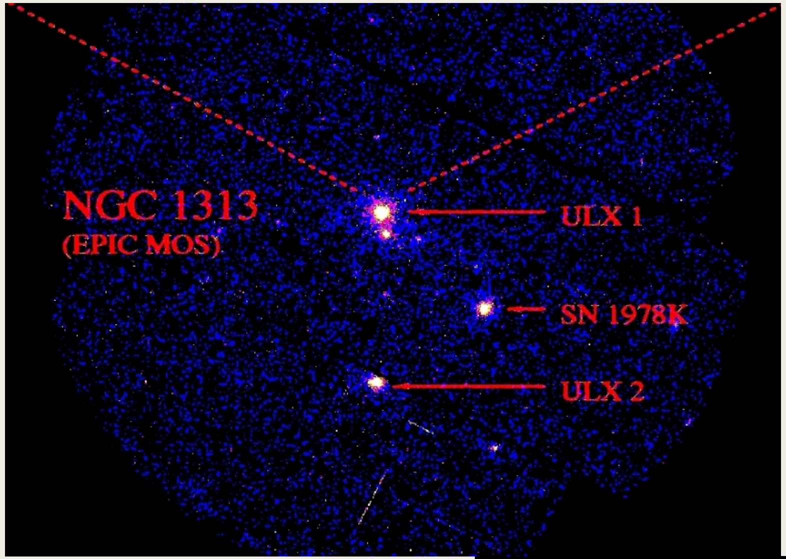
- Prototype of shell supernova remnants

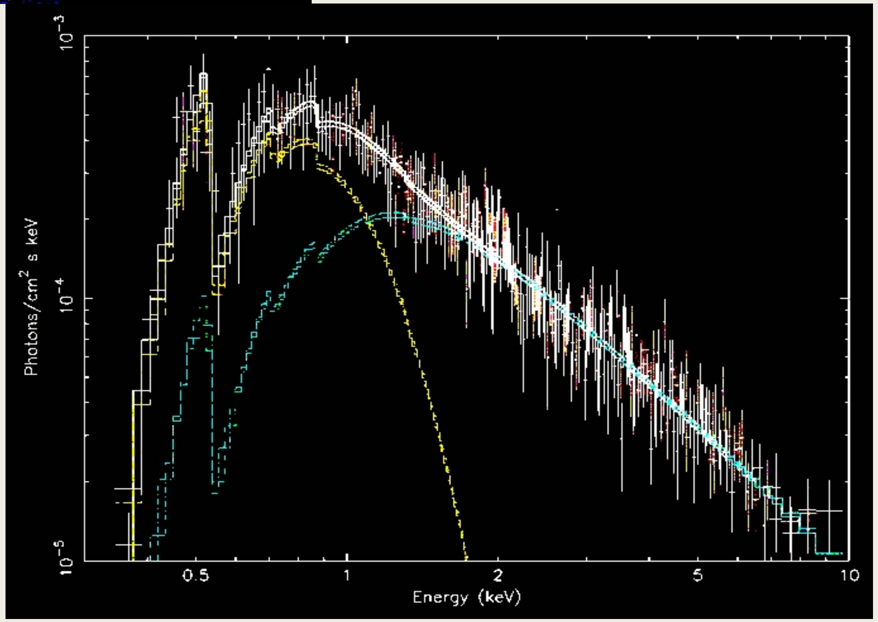
➔ Non-thermal synchrotron emission

➔ The magnetic field is amplified where acceleration is efficient

➔ Relation to the TeV emission

Ultraluminous X-Ray Source in NGC 1313



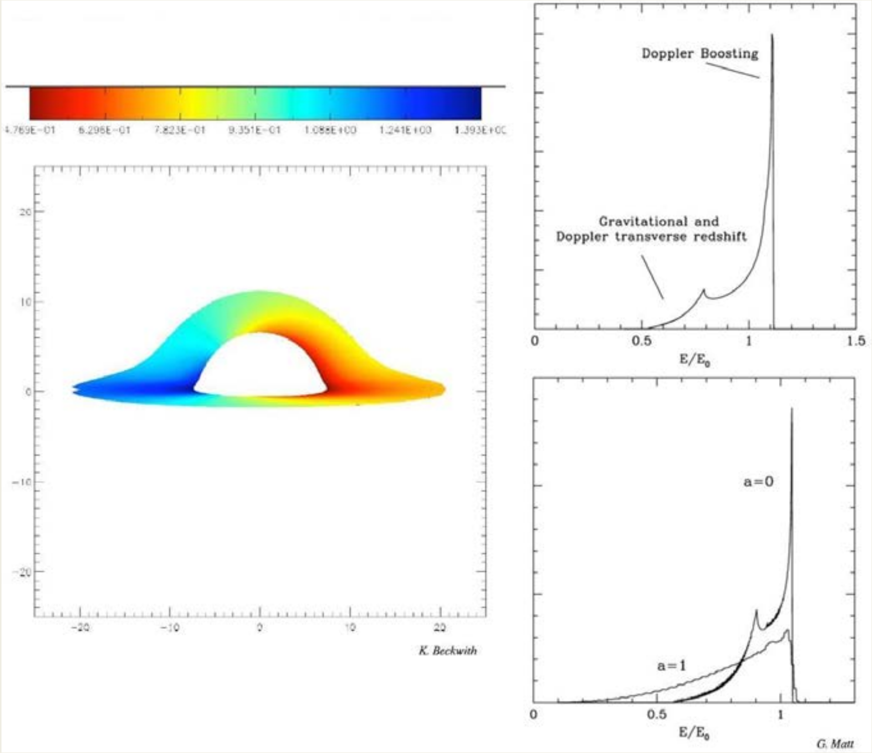


- Cool accretion disk (kT = 150 eV)
- ULX luminosity: 2.0 10^{40} ers/s

➔ BH mass 20-200 $M_{\odot}$

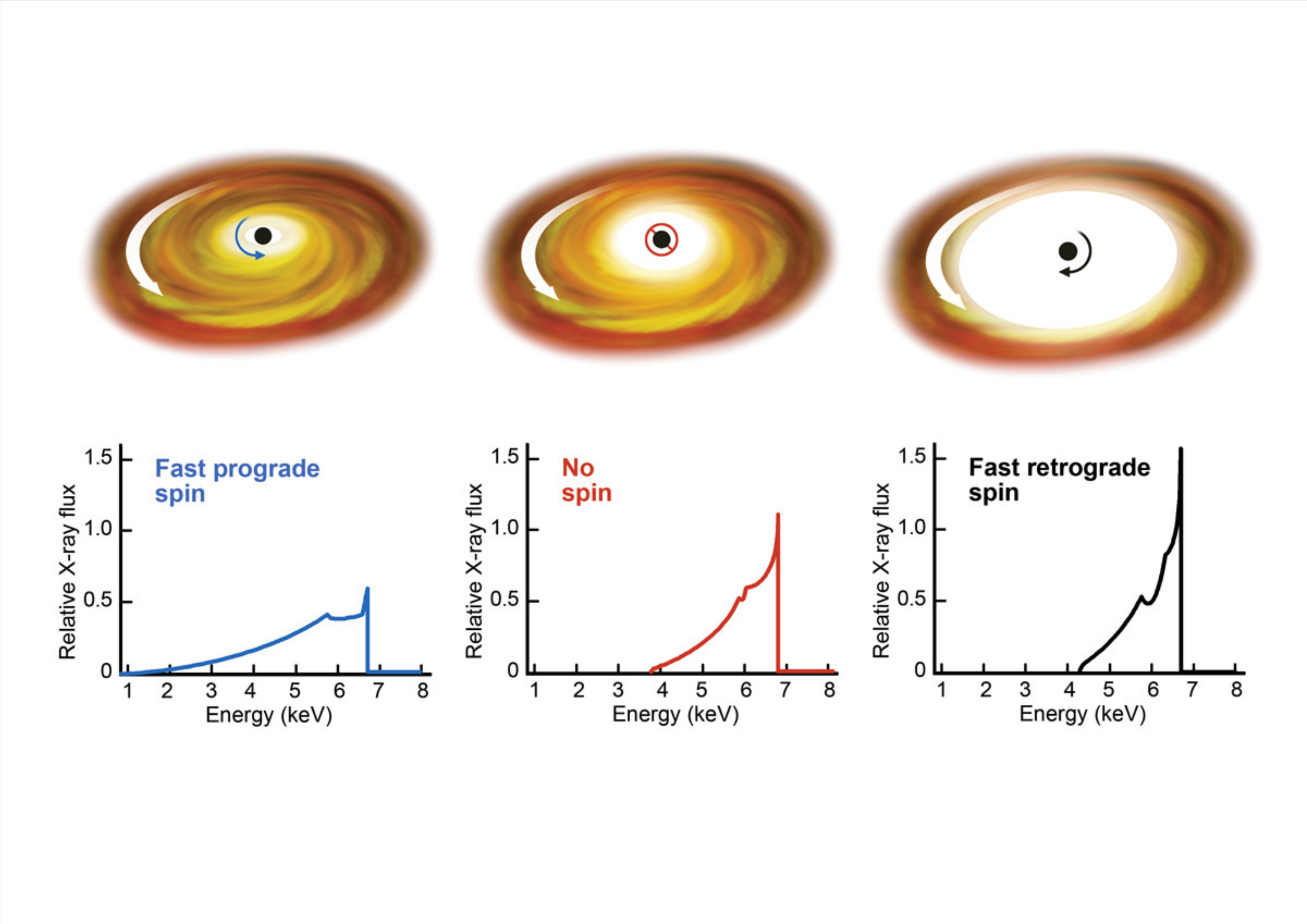
J. M. Miller et al., 2003, ApJ 585, 37

Relativistic effects around Black Holes



- Material orbiting in the vicinity of BH is exposed to strong gravity effects, as predicted by General Relativity
- Emission lines (in particular Fe Kα) from accretion disks are distorted by longitudinal and transverse Doppler effects and gravitational redshift.
- The shape of the emission line depends on the BH spin parameter $a=J/(Mc^2)$

BH spin, Innermost Stable Circular Orbit and Fe line profile

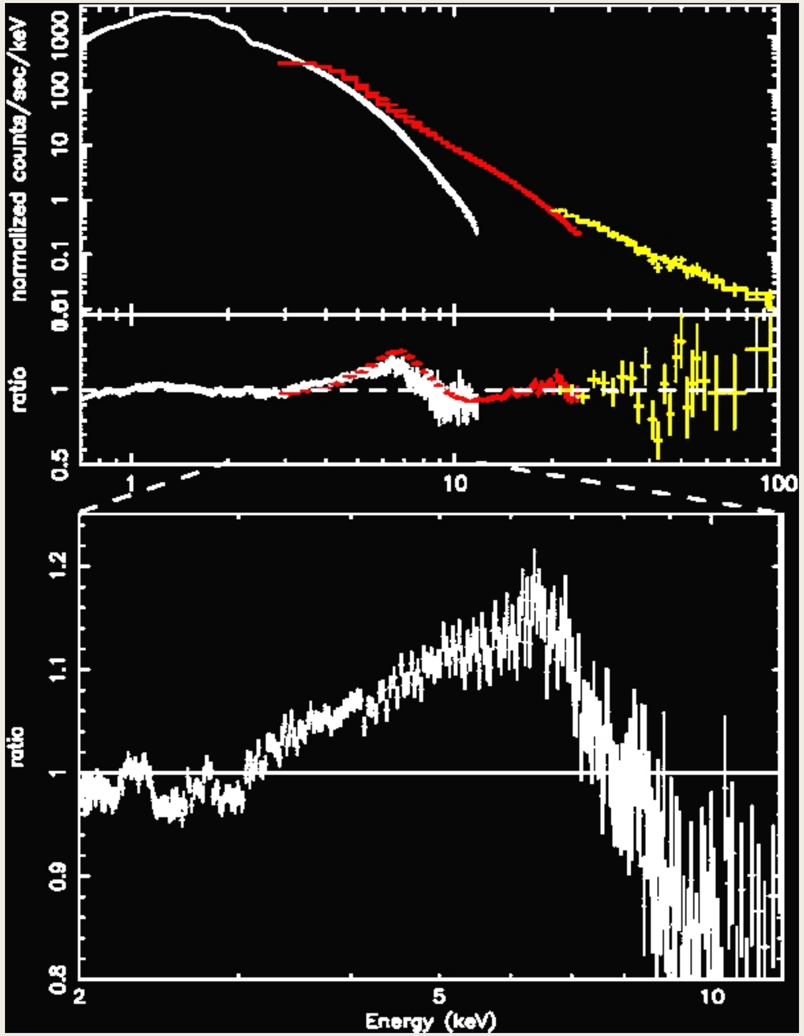


Outburst of the Galactic Black Hole GX 339-4

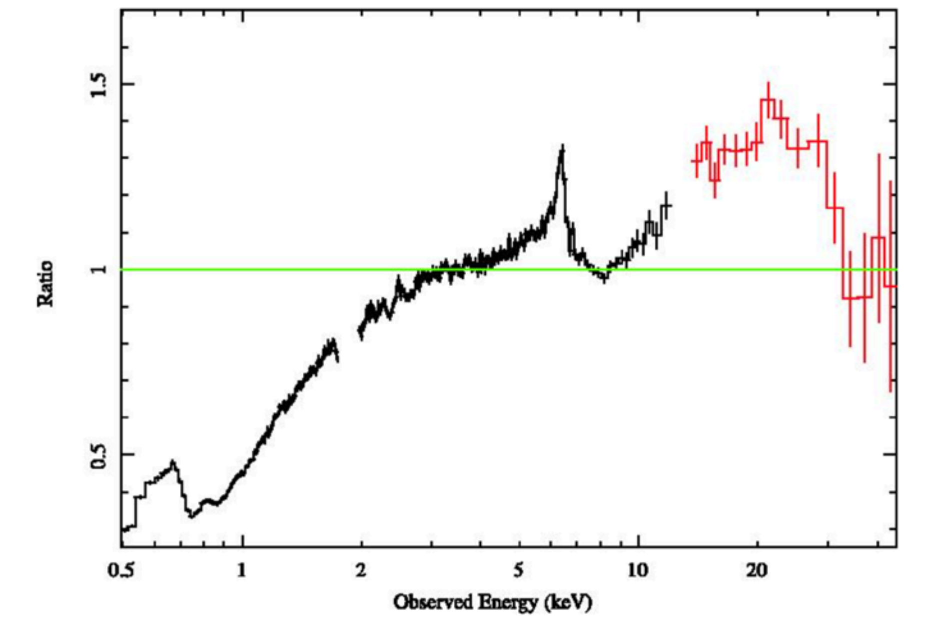
- Extremely skewed, relativistic Fe Kα emission line and ionized disk reflection spectrum
- Inner disk radius is not compatible with a Schwarzschild black hole

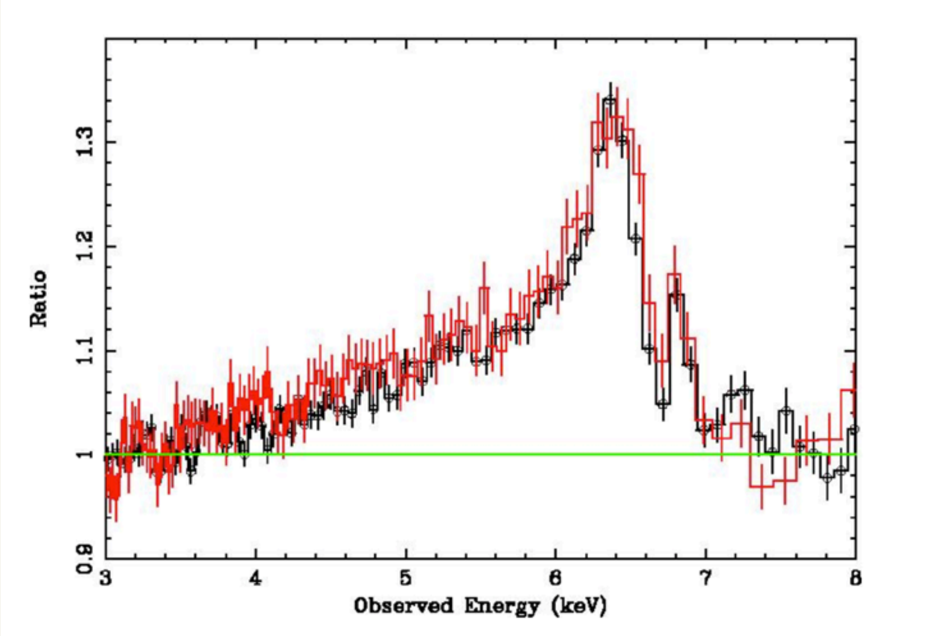
➔ Black hole with a>0.8-0.9 (where rg=GM/C^2 and a=cJ/GM^2)

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

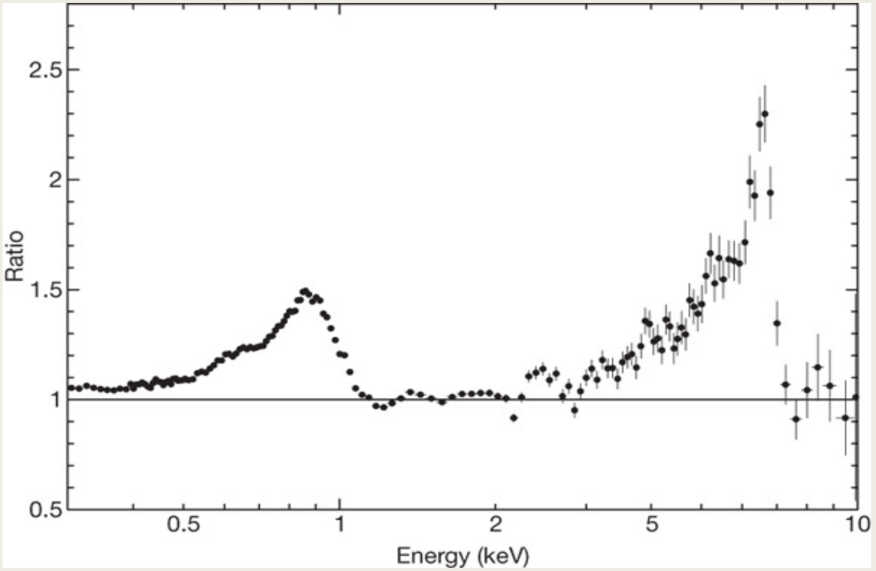


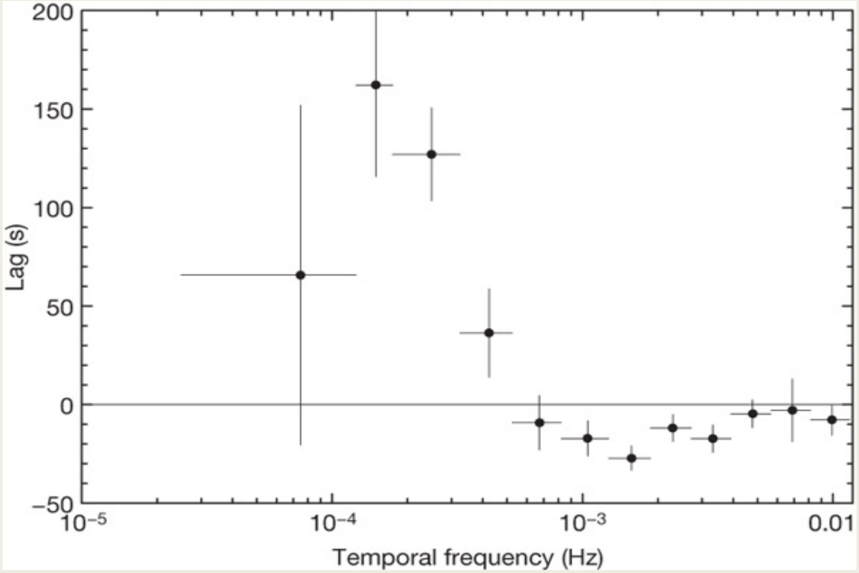
MCG-30-6-15, strong Fe line, high-spin Super-Massive Black Hole





Broad line emission Fe K- and L shell in 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 v > 6 x 10^{-4} Hz*

➔ *Power law changes before refection*

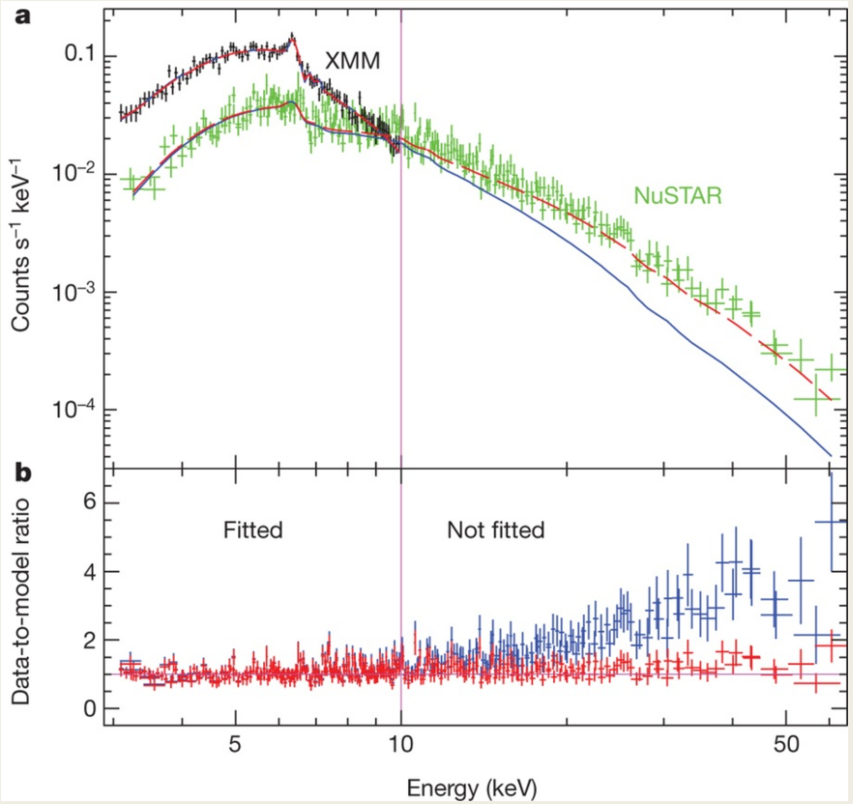
A.C. Fabian, 2009, Nature 459, 540

Relativistic disk reflection, not absorption: NGC1365

➔ 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.

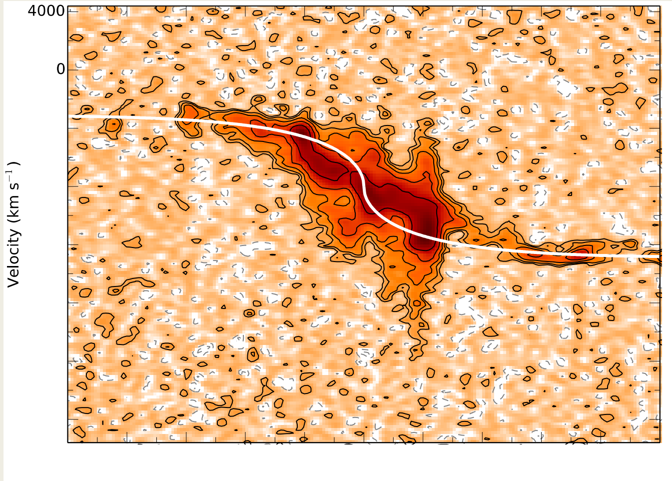
➔ Absorption-dominated models that do not include relativistic disk reflection can be ruled out both statistically and on physical grounds.



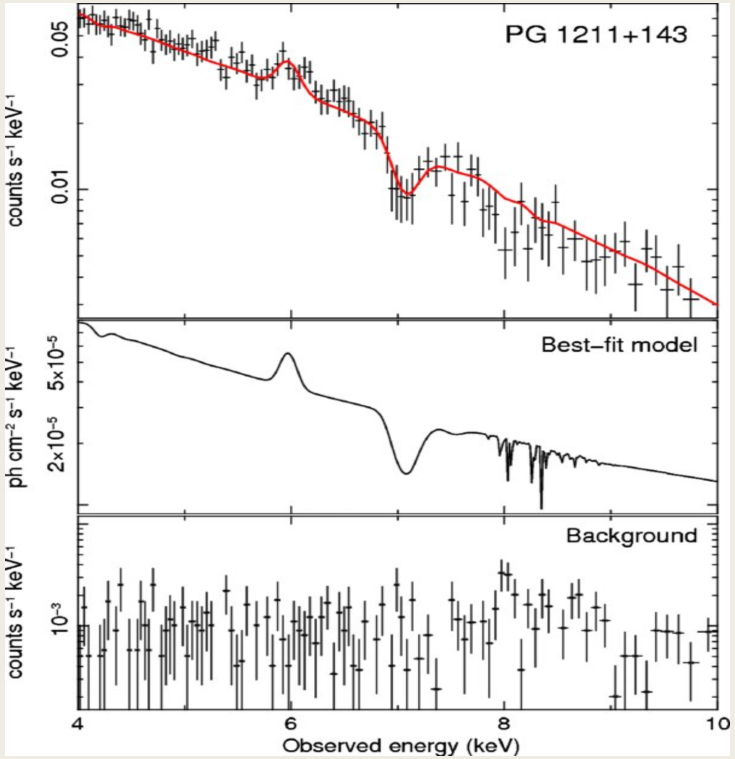
Risaliti G., et al., 2013, Nature 494

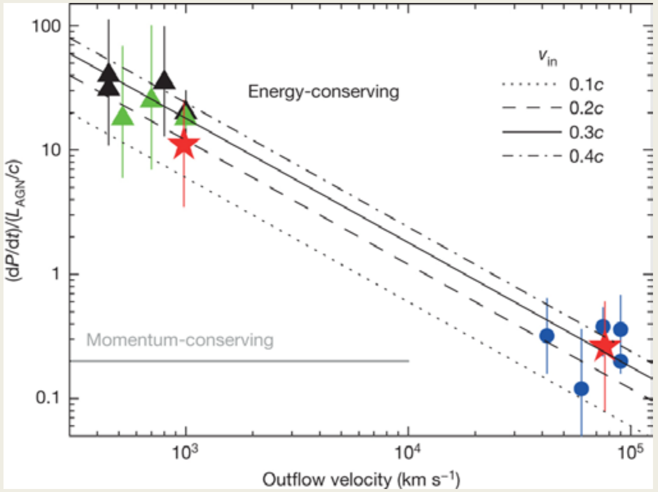
AGN UFOs and molecular outflows

- Molecular outflows routinely found with IRAM-PdB, ALMA and Herschel.
- AGN winds and jets appear to power these molecular outflows in several cases, assuming energy conservation.



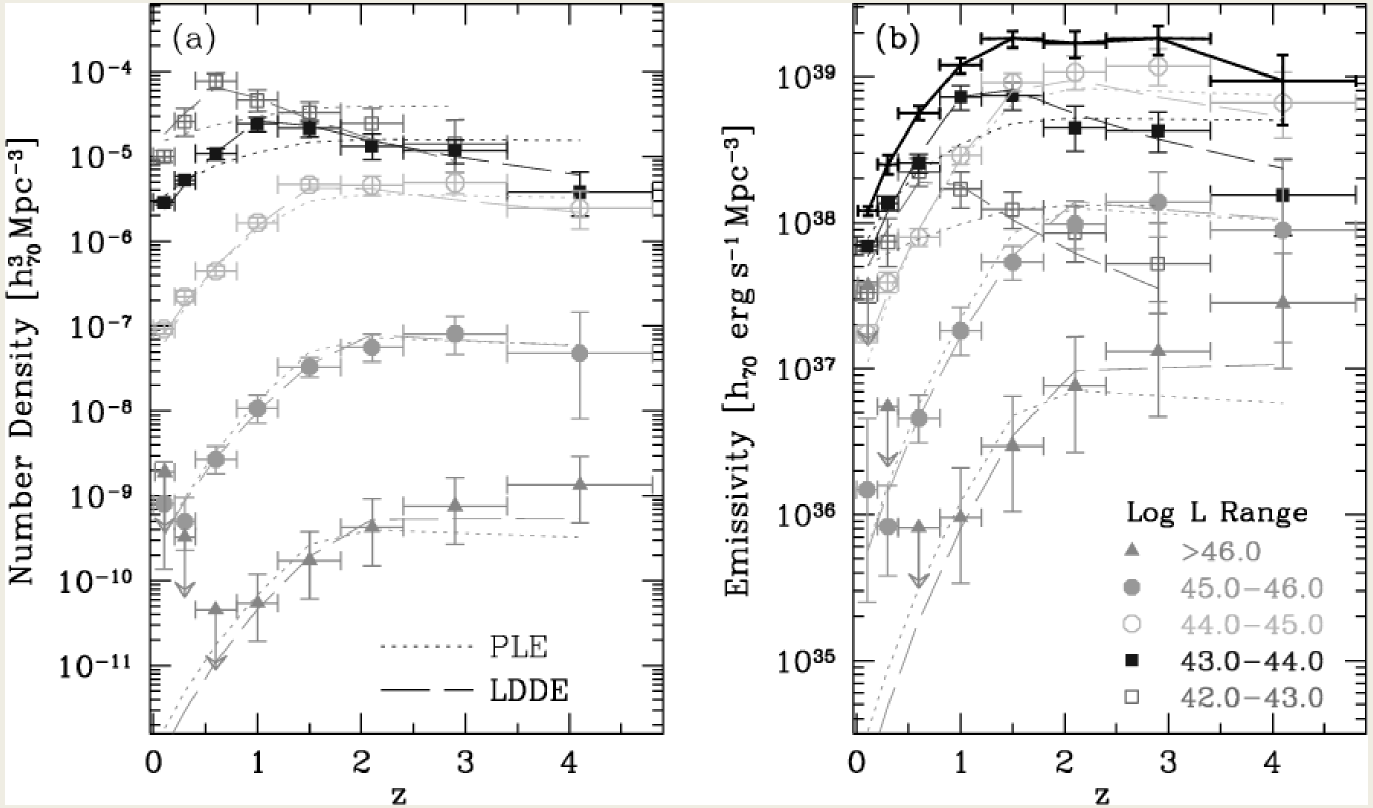
IC5063 CO(2-1)
Morganti et al 2015





IRAS F11119+3257
Tombesi et al 2015

Luminosity-dependent evolution of soft X-ray selected AGN



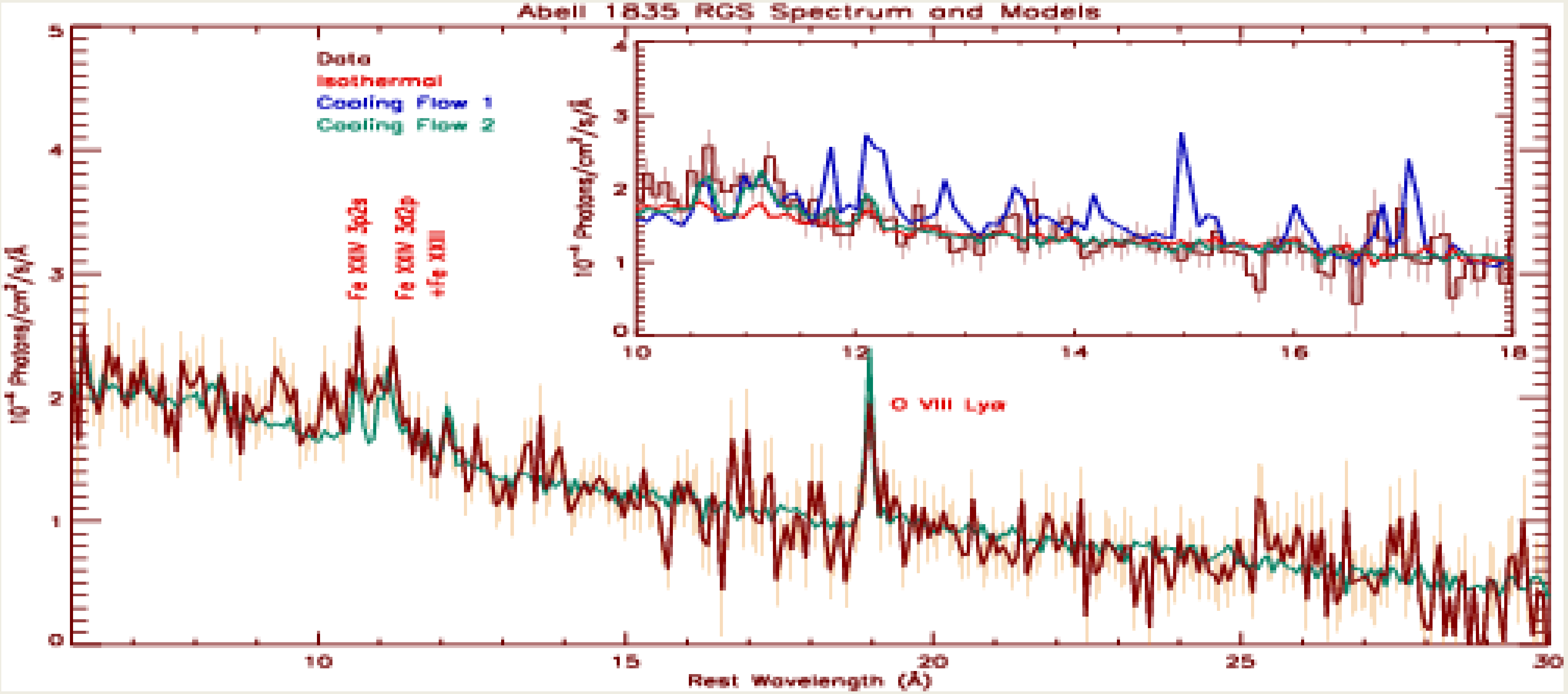
➔ First time reliable space densities for low-luminosity (Seyfert-type) X-ray sources at cosmological redshifts.

➔ The evolutionary behaviour of AGN shows a strong dependence on X-ray luminosity: while the space density of high-luminosity AGN reaches a peak around z~2, the space density of low-luminosity AGNs peaks at redshifts below z=1. This confirms previous ROSAT findings of a luminosity-dependent density evolution.

G. Hasinger, T. Miyaji & M. Schmidt, M., 2005, A&A 441, 417

- total of ~1000 AGN from a variety of ROSAT, XMM-Newton and Chandra surveys

From cooling flows to cooling cores in clusters

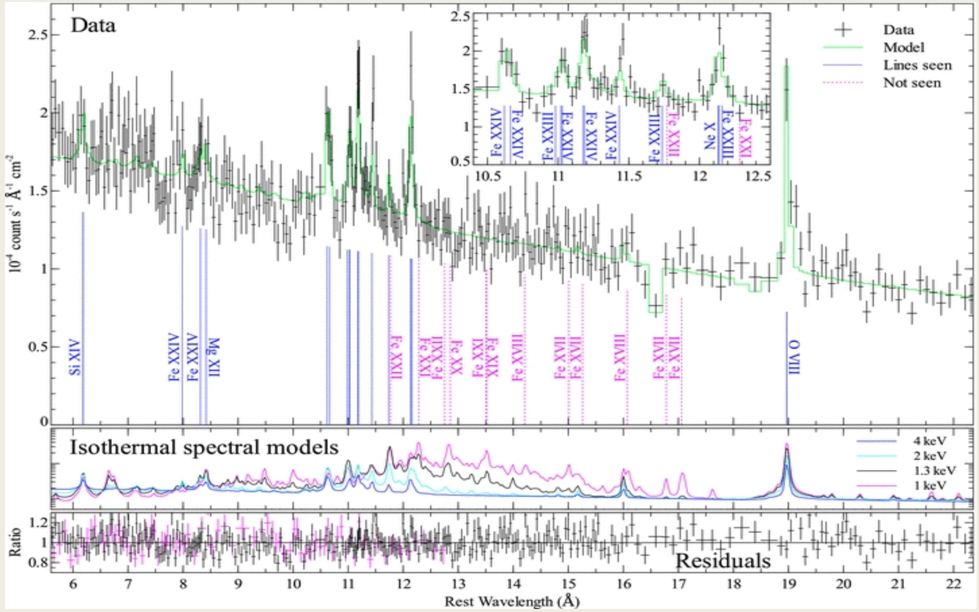


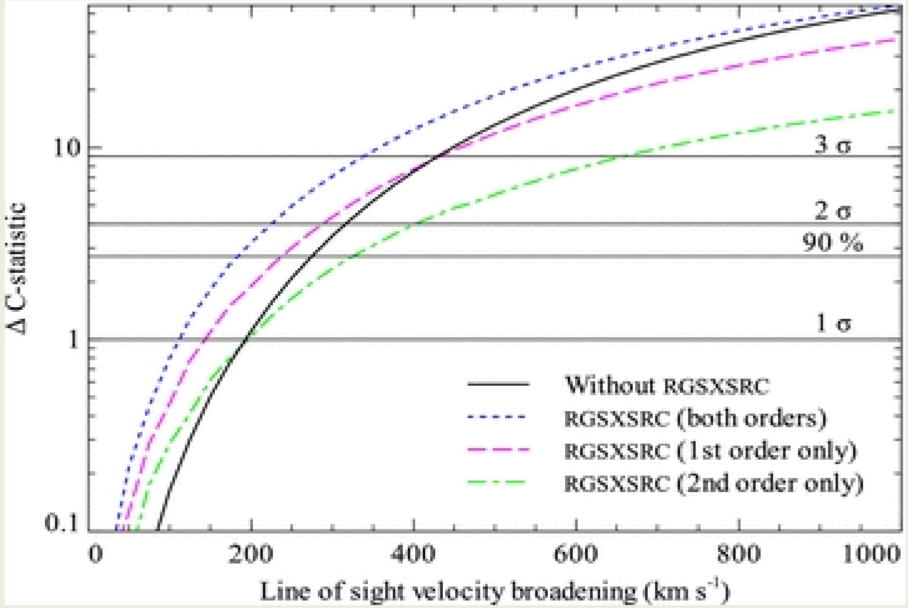
- strong cooling flow missing for low temperatures

➔ heating ➔ AGN feedback

J.R. Peterson, et al., 2001, A&A 365, L104
T. Tamura, et al., 2001, A&A 365, L87
J.S. Kaastra, et al., 2001, A&A 365, L99

Is the intra-cluster gas turbulent?





- Coolest X-ray emitting gas in the cluster occupies a small region (30kpc radius) within the core

➔ 90% - upper limit on non-thermal velocity broadening is 274 km s^{-1}

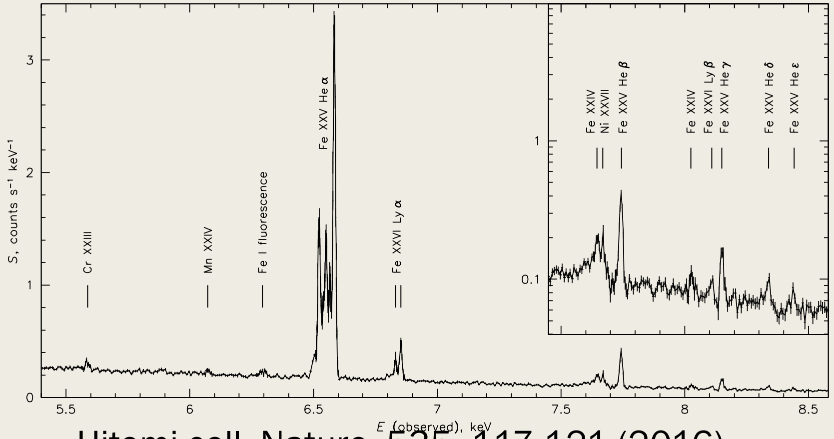
➔ turbulent to thermal energy density < 13%

J.S. Sanders et al., 2010, MNRAS 402, L11

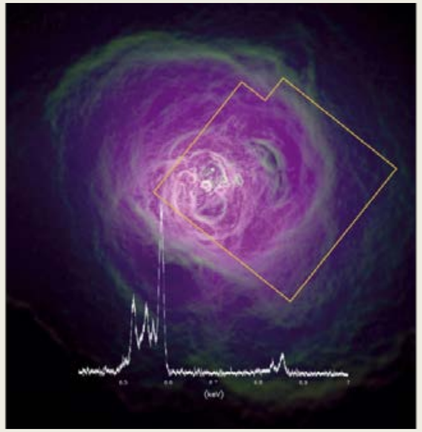
Hitomi (Feb-Mar 2016)

- The JAXA Hitomi satellite was launched in February 2016, with an X-ray calorimeter on board (resolution~5 eV)
  - *Unfortunately, the S/C was lost in March 2016*
  - *But it had taken 275 ks of AMAZING data of the Perseus cluster, above 2 keV.*
- Even at the core of the Perseus cluster, turbulence is very small
- JAXA, along with its international partners, is moving ahead with the “Hitomi recovery mission”, due for launch in 2021/2

Perseus cluster core
Turbulence < 164 km/s



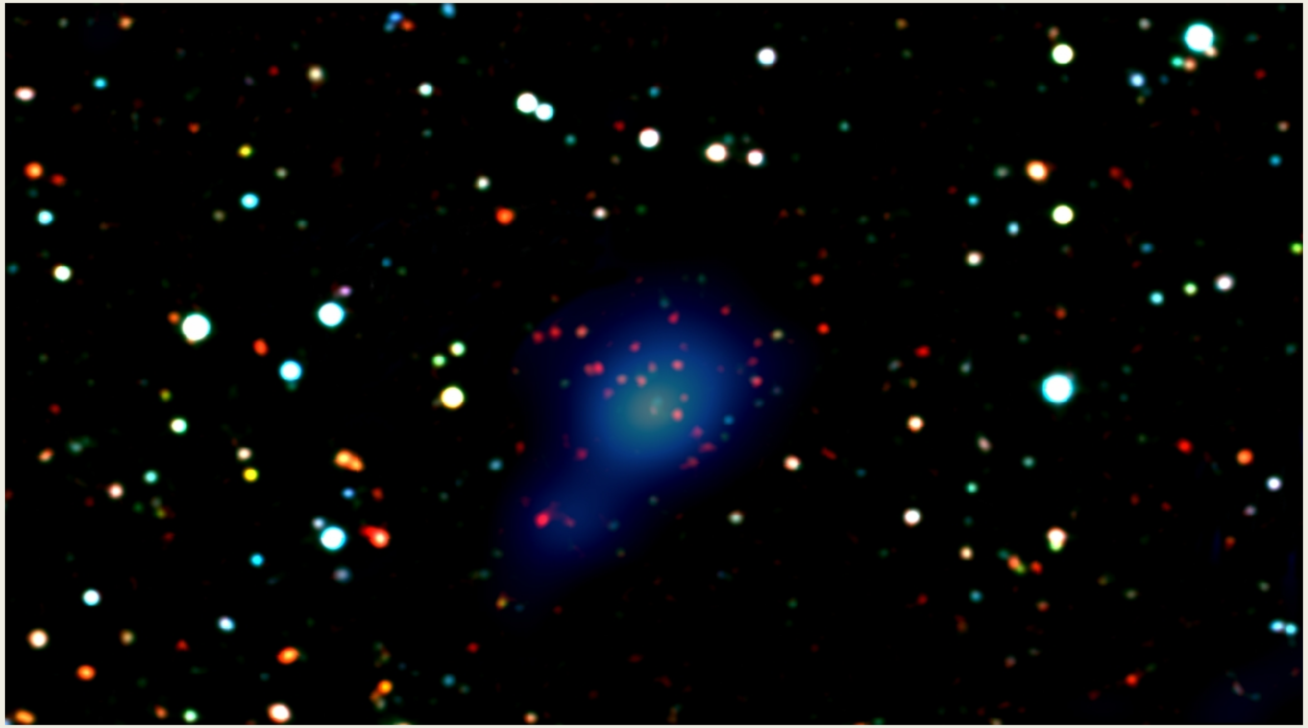
Hitomi coll, Nature, 535, 117-121 (2016)
Courtesy: A.C. Fabian



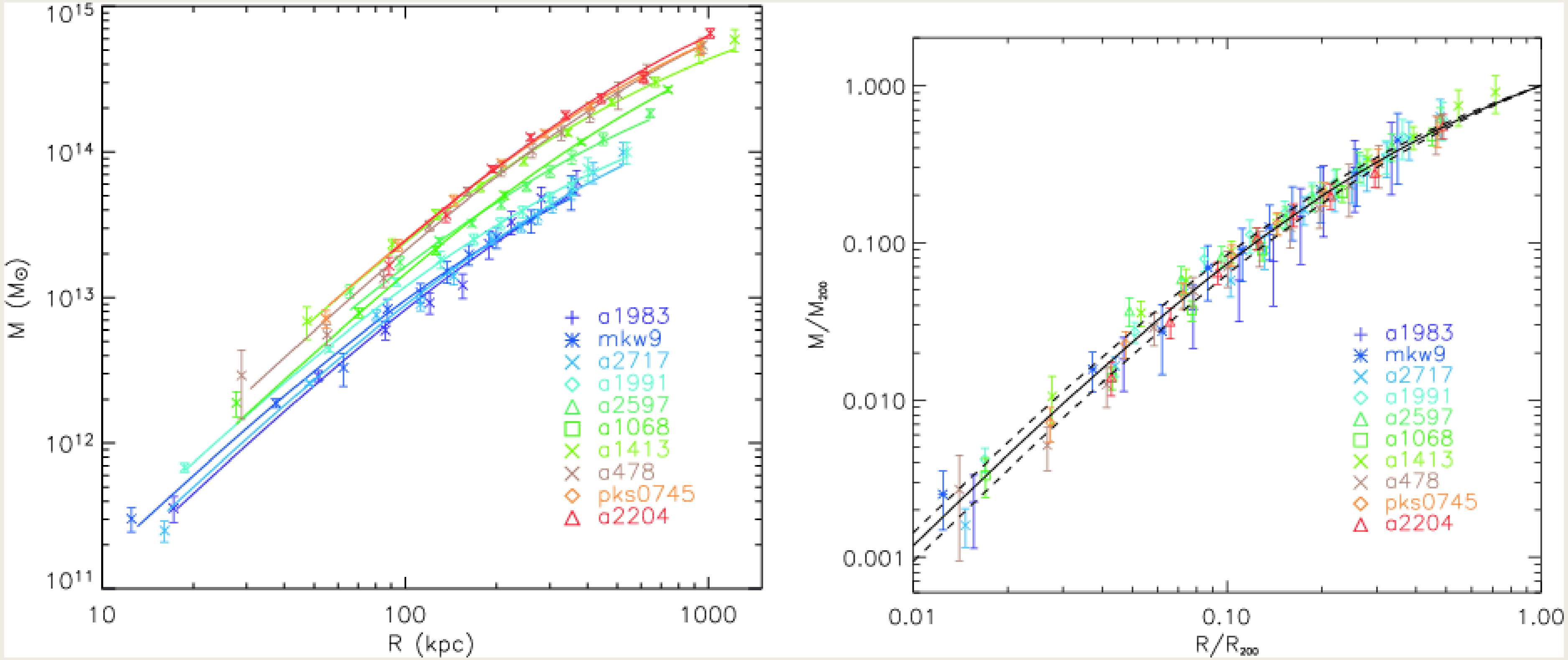
High-z clusters: XMMXCS J2215.9-1738

- Massive galaxy cluster at z=1.45

Stanford et al., 2006 ApJ 646, L13



The universal mass profile of galaxy clusters

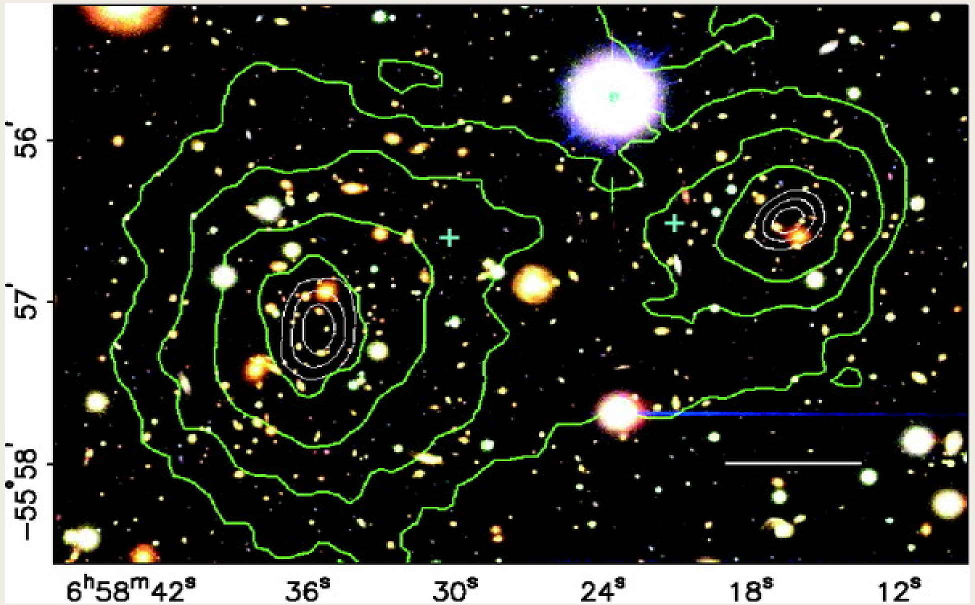


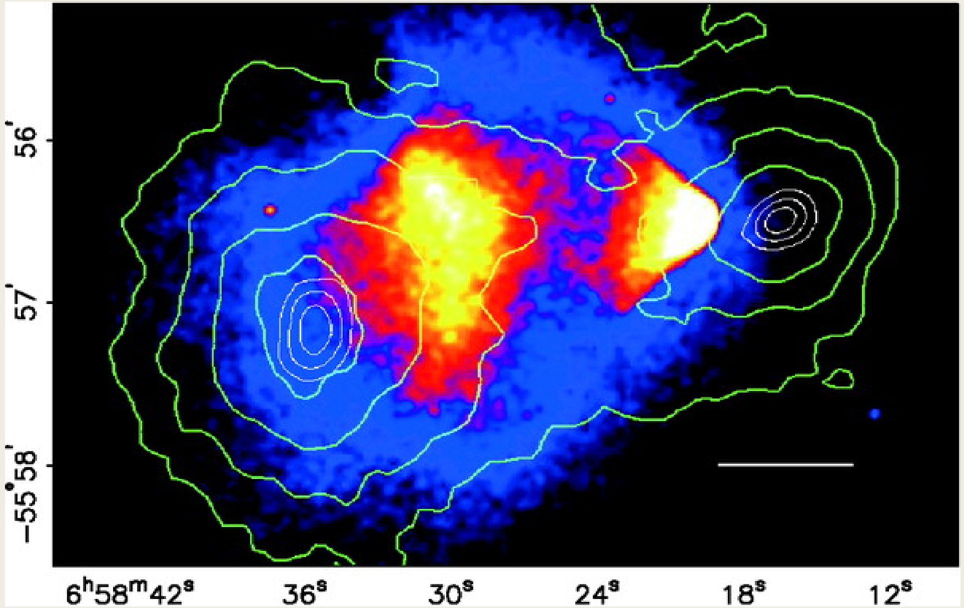
- Integrated mass profiles for a sample of ten nearby (z<~0.15), relaxed galaxy clusters, covering a temperature range of [2-9] keV

➔ NFW profile over 0.01 to 0.5 R_{200}

E. Pointecouteau, M. Arnaud & G.W. Pratt, 2005, A&A 435,1

Bullet cluster: empirical proof of the existence of Dark Matter





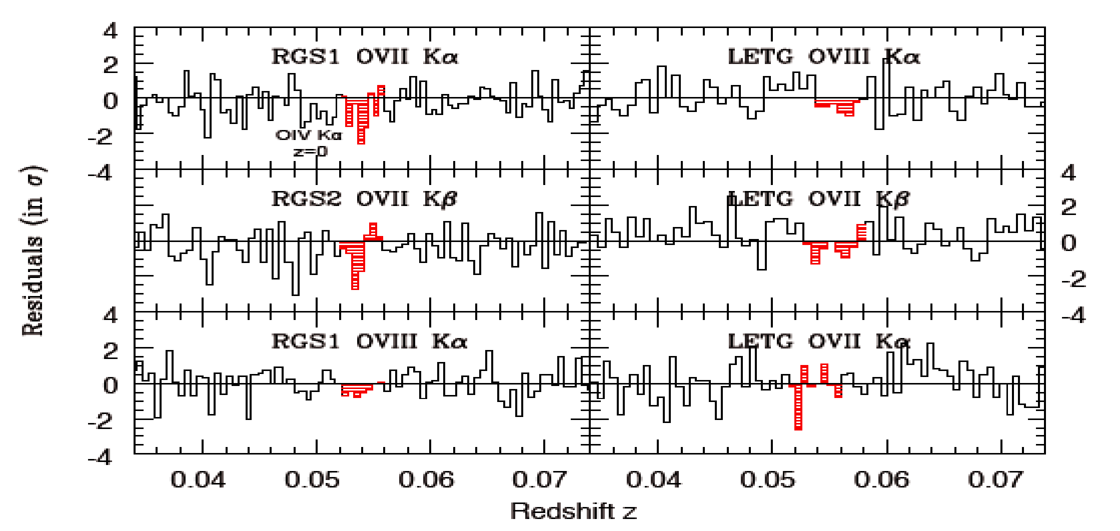
- D. Clowe et al., 2006, ApJ 648, L109
- Weak-lensing observations of cluster merger 1E 0657-558 (z = 0.296)

- **Chandra** X-ray observations

➔ Detection of dark matter, independent of assumptions regarding the nature of the gravitational force law.

Missing baryons in the Warm Hot Intergalactic Medium

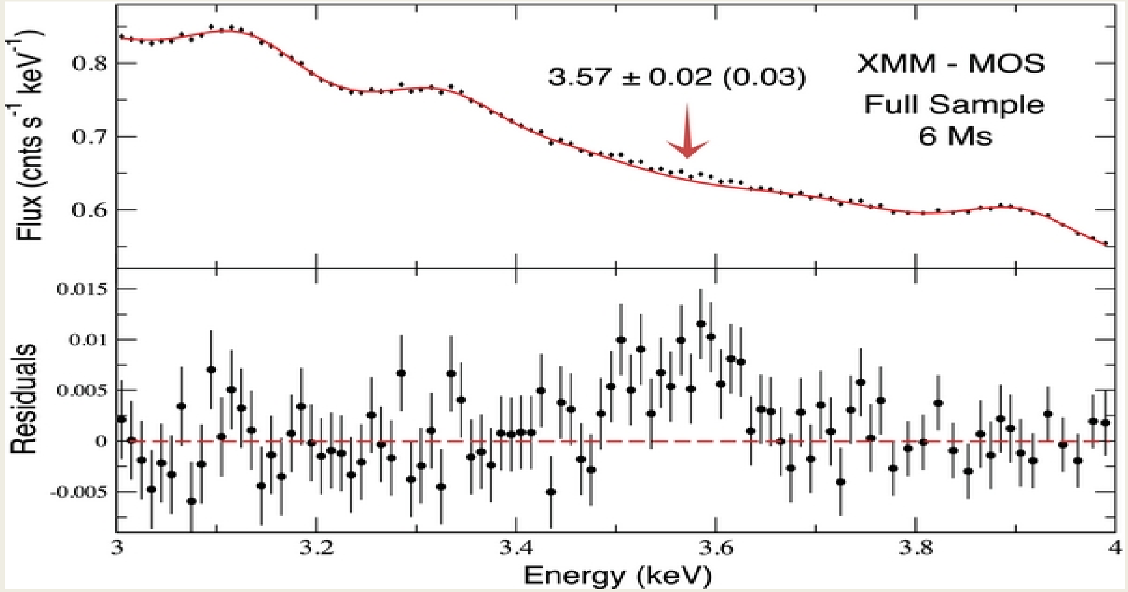
- Tentative detection of 2 WHIM filaments with Chandra against Mrk421 (Nicastro et al 2005, Williams et al 2006).
  - *Contested by Kaastra et al (2006)*
  - *Detections incompatible with XMM-Newton data (Rasmussen et al 2007)*
- Observations of the brightest target in the sky 1ES 1553+113 (z>0.3) with Chandra and on-going XMM-Newton observations revealed 1 + 2 WHIM filaments to ~ 4-6σ significance (Nicastro et al 2013, 2016)
- Some detections likely due to hot galactic halos or outer parts of groups/clusters.



From Nicastro (2016)

The 3.5 keV line: Decay of sterile neutrinos?

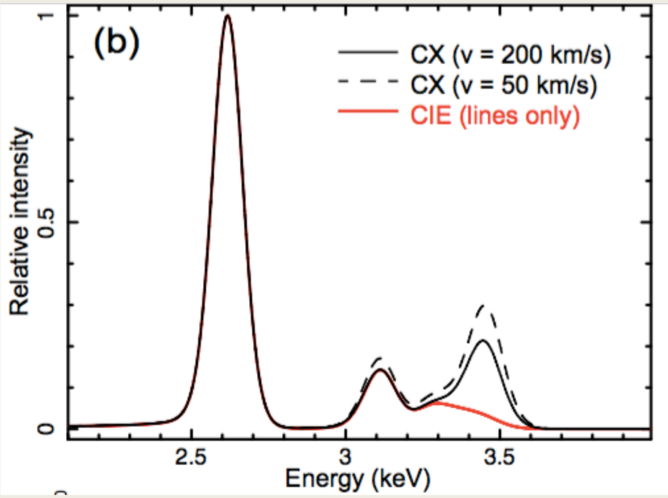
- Bulbul et al (2014) detect a weak emission line at 3.5 keV in the stacked spectrum of 73 galaxy clusters observed with XMM-Newton.
  - *The line is only 1 eV in equivalent width, while the spectral resolution is > 100 eV*
  - *The line is visible in the spectrum of the brighest galaxy cluster (Perseus)*
- Boyarsky et al (2014) reported a similar detection from the Andromeda galaxy
- A number of papers report non-detections: Malyshev et al (2014), Anderson et al. (2015), Tamura et al (2015), Carlson et al (2015), Sekiya et al. (2015).
- Decay of sterile neutrinos with mass ~7.1 keV ?

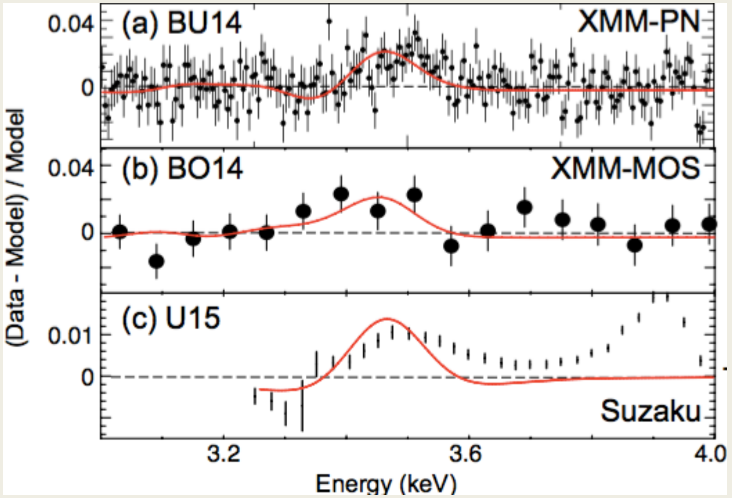


Bulbul et al 2014

If the 3.5 keV line is real, what is it?

- Jeltema & Profumo (2014) proposed to be K XVIII or Cl XVII
  - *But Bulbul et al (2015) argue that the atomic data are incorrect.*
- Gu et al (2016) propose atomic lines from S XVI from n≥9 to the ground state, excited by Charge Exchange from neutral H.
  - *Central AGN could provide the energetic H atoms*
- And, of course, the decay of sterile neutrinos of m=7.1 keV

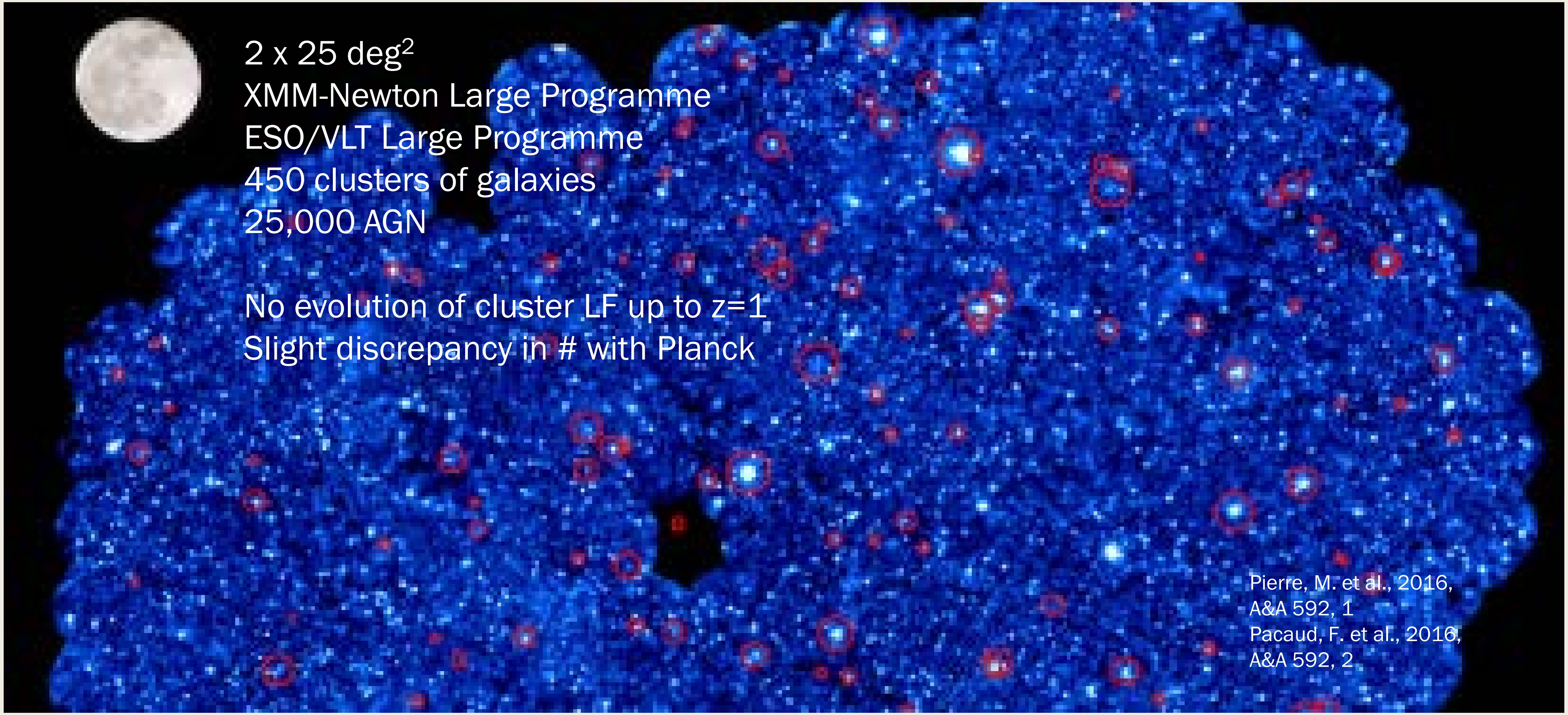




XMM-Newton: a workhorse of European astronomy

- XMM-Newton serves a very large community (about 4000) of European (and international) astronomers.
  – *It is in par with other facilities like ESO's VLT, ALMA, IRAM etc*
- An ESO/ESA VLT/XMM-Newton programme has been running for over a decade
  – *Not heavily subscribed (a few proposals/year), but from the ESO side with a high success rate (0.5 vs average 0.3 for open time)*
  – *Most times used for simultaneous observations, e.g., simultaneous flares in SgrA* in X-rays and in the NIR (Mossoux et al, 2016, A&A, 589, A116)*
  – *Many VLT/XMM-Newton papers are published every year using data obtained independently.*

XMM-Newton(ESA)/VLT(ESO): XXL Survey



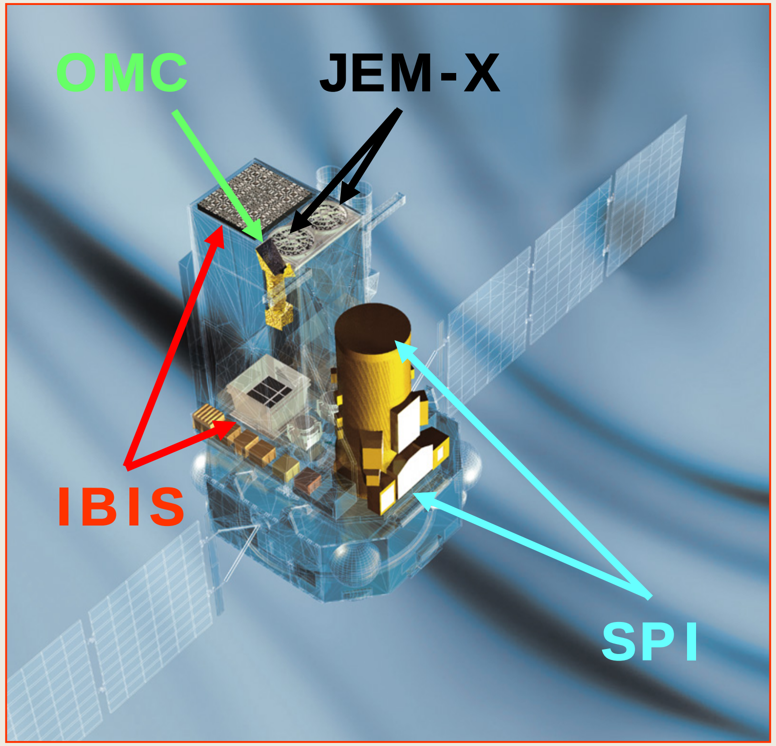
2 x 25 deg^2
XMM-Newton Large Programme
ESO/VLT Large Programme
450 clusters of galaxies
25,000 AGN

No evolution of cluster LF up to z=1
Slight discrepancy in # with Planck

Pierre, M. et al., 2016, A&A 592, 1
Pacaud, F. et al., 2016, A&A 592, 2

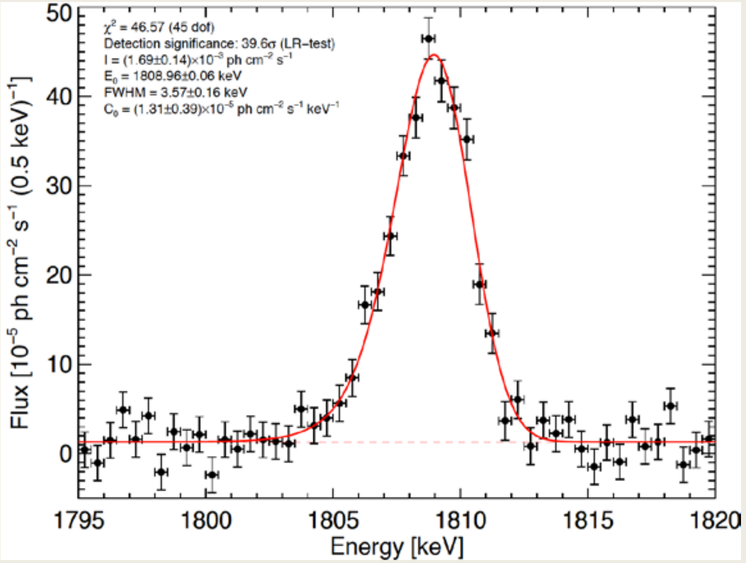
INTEGRAL

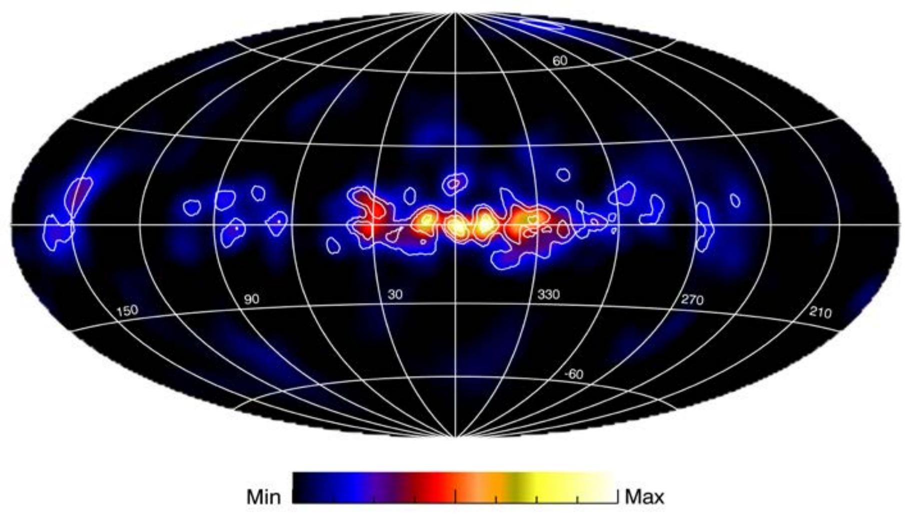
- INTErnational Gamma-Ray Astrophysics Laboratory
- 2nd Medium-Size mission in Horizon 2000
- Launched 17 October 2002 by a Proton launcher from Baikonur
- Instruments:
  - *SPI (Gamma ray spectrometer)*
  - *IBIS (Gamma ray imager)*
  - *JEM-X (X-ray monitor)*
  - *OMC (Optical monitor)*

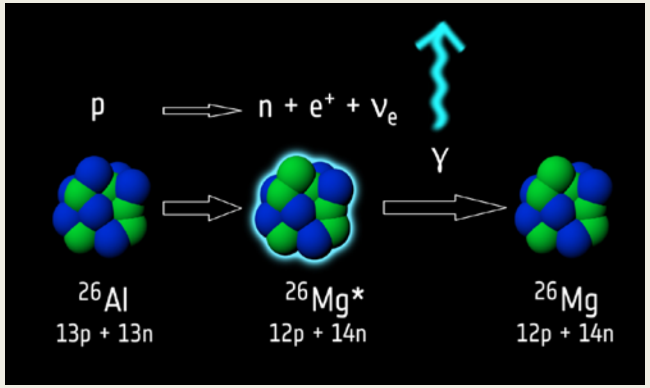


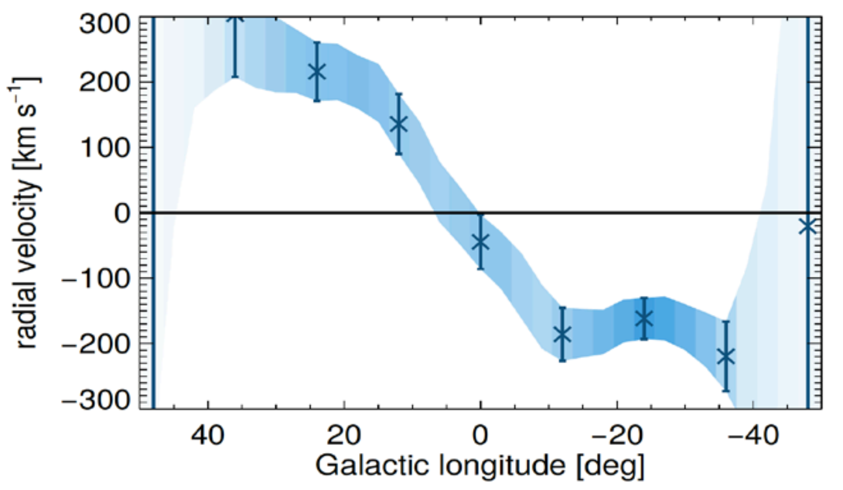
Recent star formation in the Galaxy through the ^{26}Al emission line

^{26}Al $t_{1/2}$ = ~0.7x10^{6} years
produced in massive stars and SNe

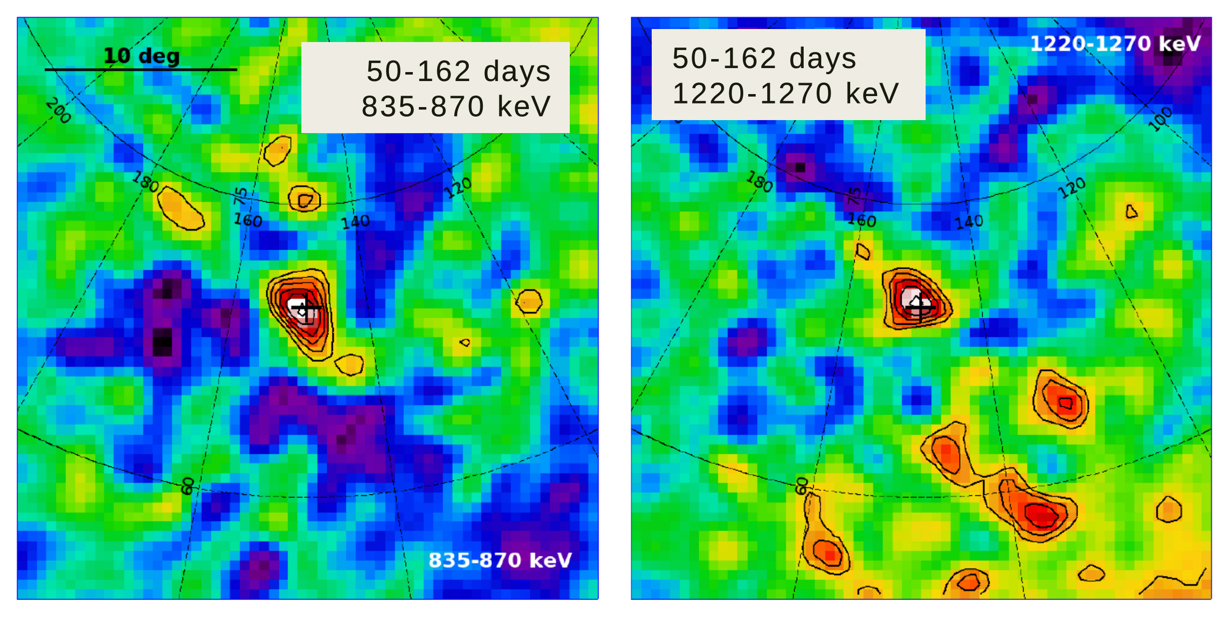


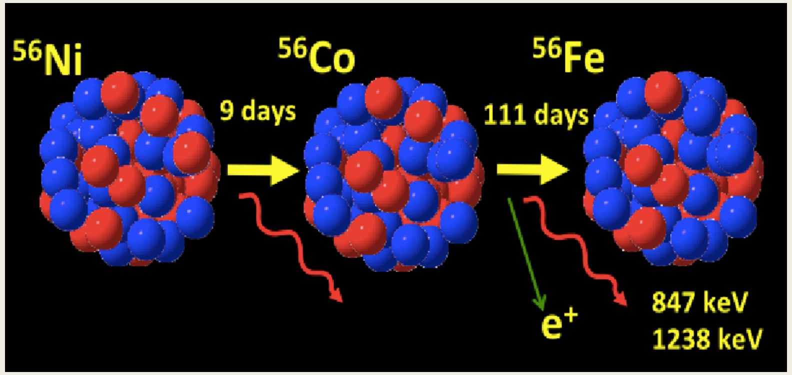






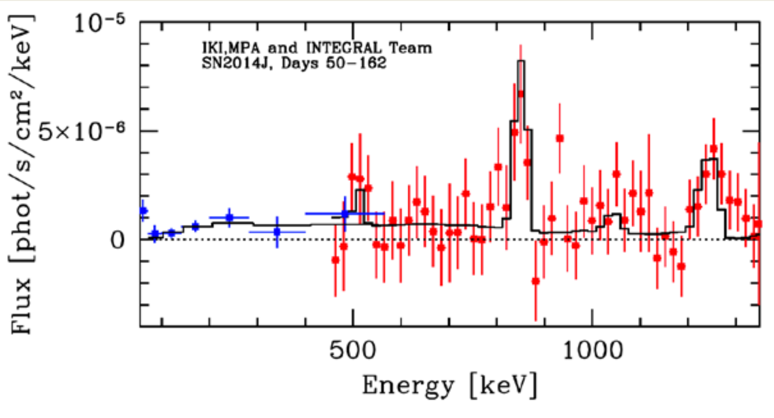
Radioactive decay in Type I SNe



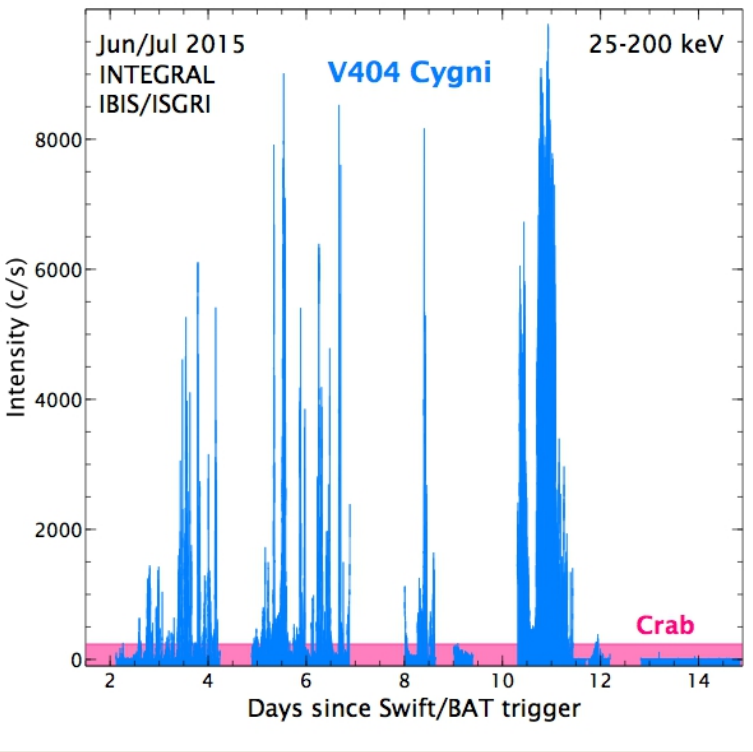


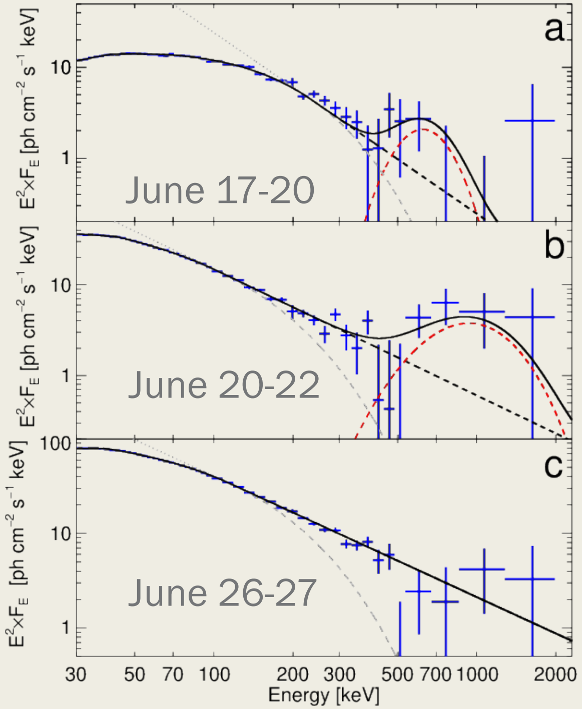
First-ever *direct* detection of radioactive decay of ^{56}Co into ^{56}Fe in a Type Ia supernova: SN2014J in M82

^{56}Co $t_{1/2}$ = ~111 days



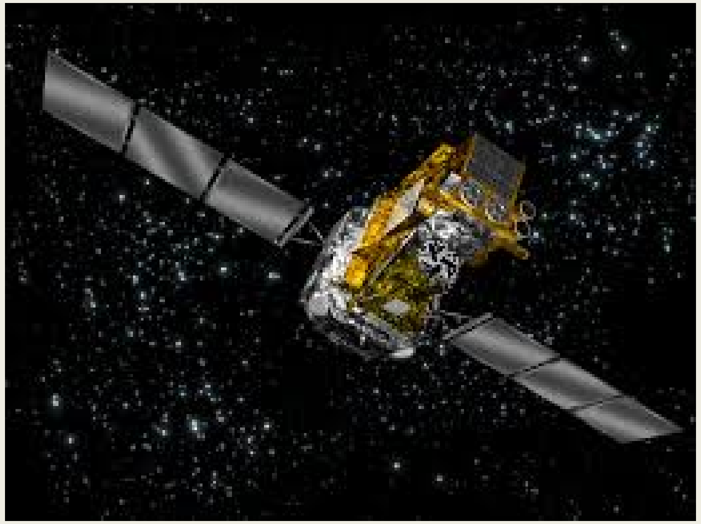
Wake-up of V404 Black Hole 26 years after





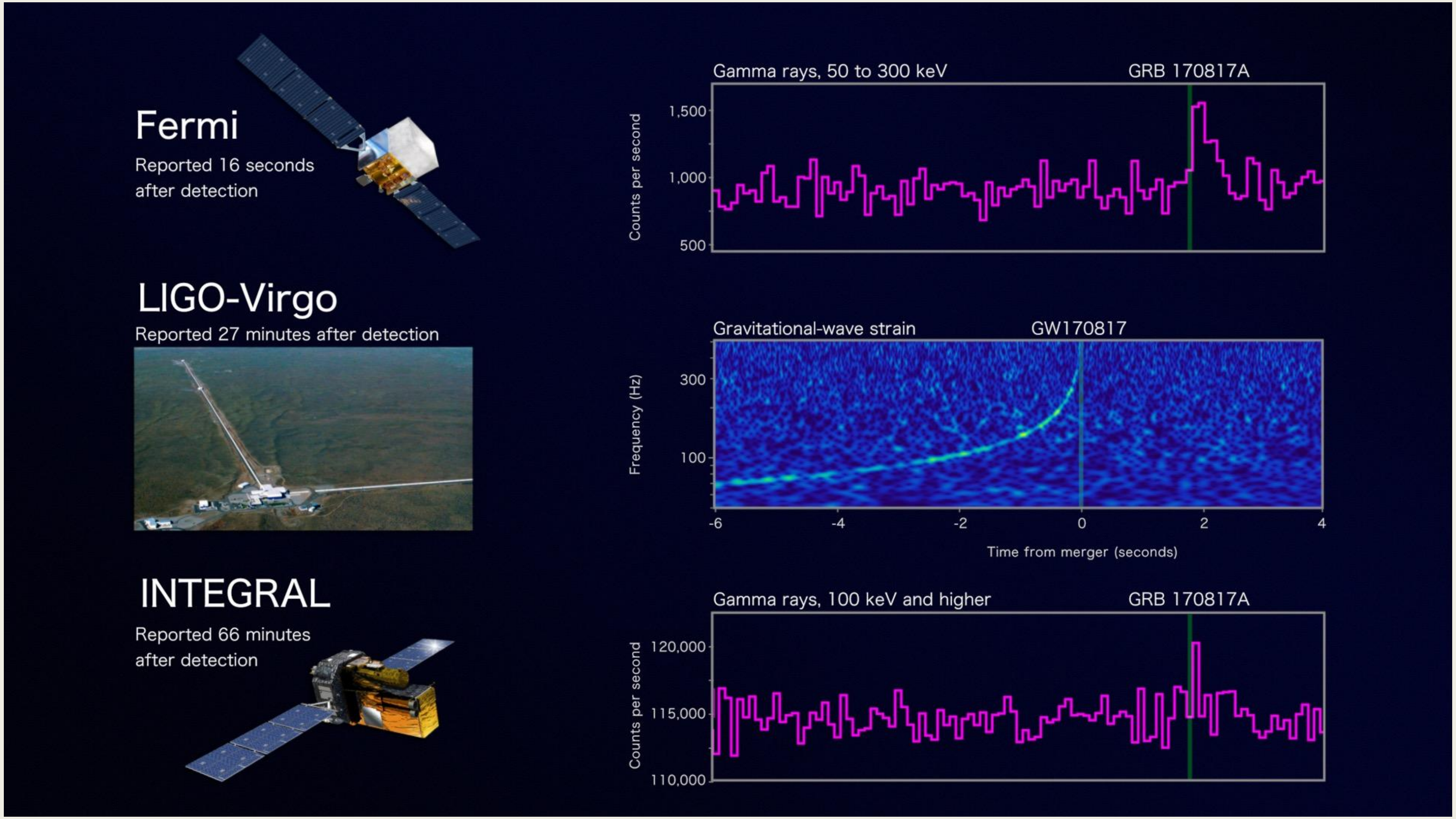
Transient annihilation emission?
Siegert et al 2016

Full sky coverage: detection of transients



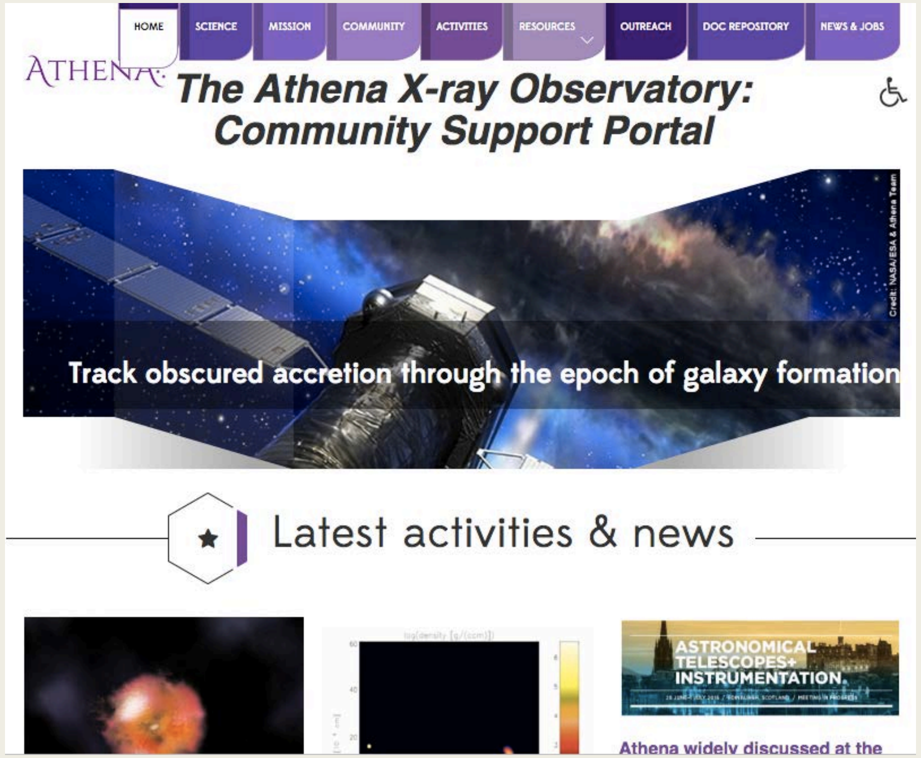
- Shields of SPI & IBIS
  - *SPI/ACS: >75 keV, 50 ms, effective area 1m^2*
  - *IBIS/Veto: 250-2600 keV, 15.6 ms, effective area 0.09 m^2*
- The shields can detect high-energy photons from any direction of the sky
- GRB detections with INTEGRAL so far:
  - *200 GRB per year in SPI/ACS*
  - *5 GRB per year in the large Field of View of IBIS and SPI*

GW170817


Fermi
Reported 16 seconds
after detection
LIGO-Virgo
Reported 27 minutes after detection
INTEGRAL
Reported 66 minutes
after detection
Gamma rays, 50 to 300 keV
GRB 170817A
Counts per second
1,500
1,000
500
Gravitational-wave strain
GW170817
Frequency (Hz)
300
100
-6
-4
-2
0
2
4
Time from merger (seconds)
Gamma rays, 100 keV and higher
GRB 170817A
Counts per second
120,000
115,000
110,000

The future: Athena (Advanced Telescope for High Energy Astrphysics)

- Second Large (L2) mission of ESA Cosmic Vision 2015-2025
- Science theme: The Hot and Energetic Universe
  - *How does ordinary matter assemble in the large-scale structures?*
  - *How do black holes grow and shape galaxies?*
- In addition:
  - *Fast ToO capability to study transient sources*
  - *Observatory science across all corners of Astrophysics*



More info in:
http://www.the-athena-x-ray-observatory.eu

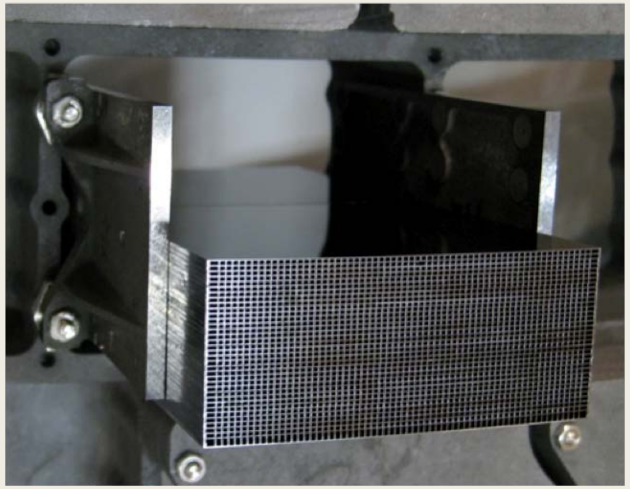
Athena mission concept

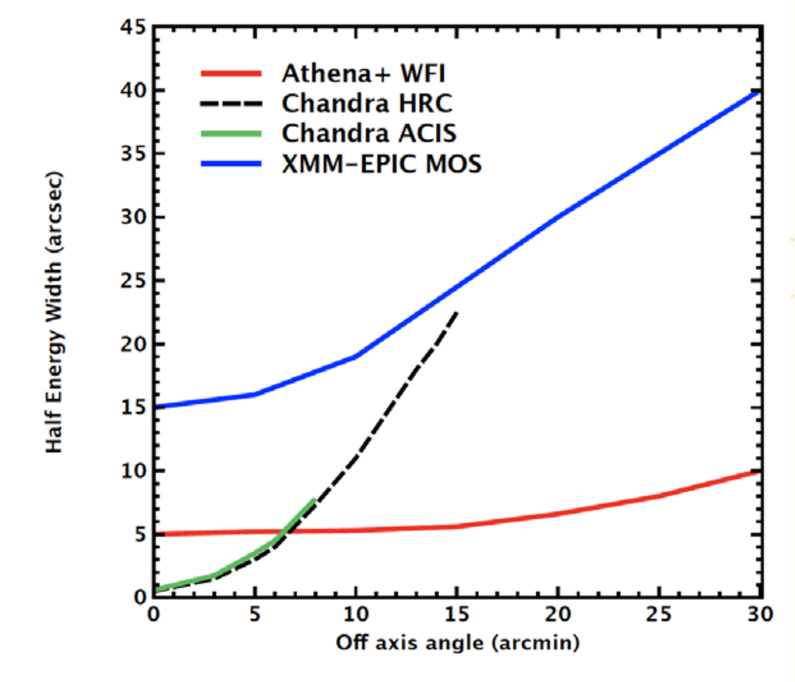
- Single telescope, using Si pore optics. 12m focal length
  - *WFI sensitive imaging & timing*
  - *X-IFU spatially resolved high-resolution spectroscopy*
- Movable mirror assembly to switch between the two instruments
- Launch 2028-2030, Ariane 6.4
- L2 halo orbit (TBC)
- Lifetime > 4 yr

Athena concept, ESA CDF

The Athena X-ray optics

- Athena optics development:
  - *Light-weight Si-pore optics*
  - *Grazing incidence optics, Wolter-I type (paraboloid-hyperboloid), largely with conical approximation*
  - *Vigorous development programme on-going.*
- Performance:
  - *5´´ HEW on-axis*
  - *Graceful degradation off-axis, <10´´ @ 30´*
  - *≥1.4 m^2 effective area @ 1 keV, 0.25 m^2 effective area @ 6 keV*
  - *Limited vignetting at 1 keV*

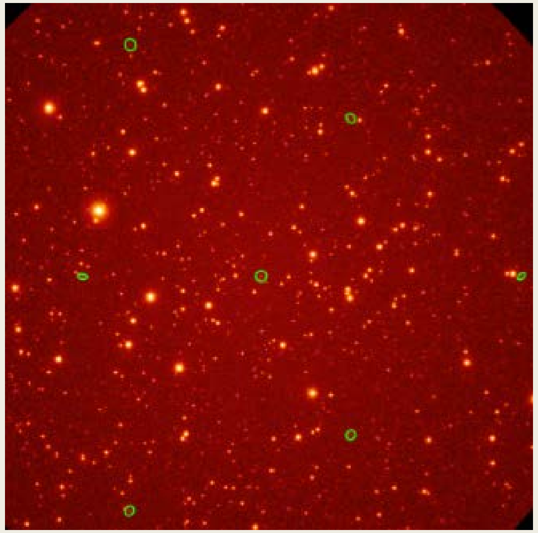


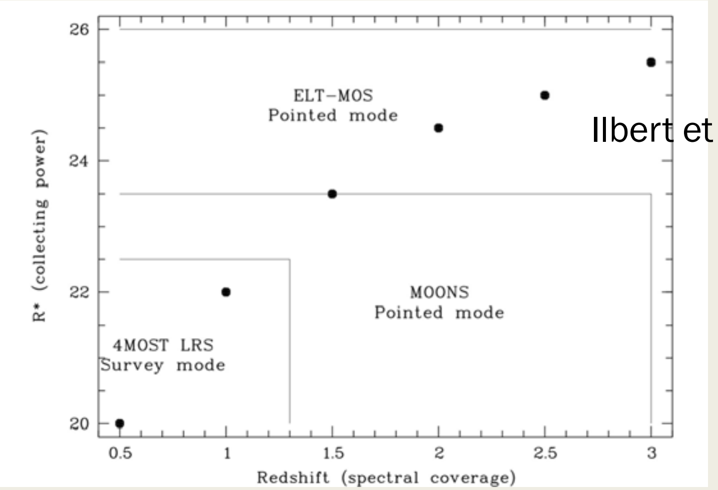


Willingale, Pareschi et al. 2013, arXiV: 1308.6785

Athena. Early galaxy groups and clusters

- Search for early galaxy groups $M > 5 \times 10^{13}$ $M_{\odot}$ at z>2
- Total of ~50 groups in multi-tiered survey lasting for ~1 year





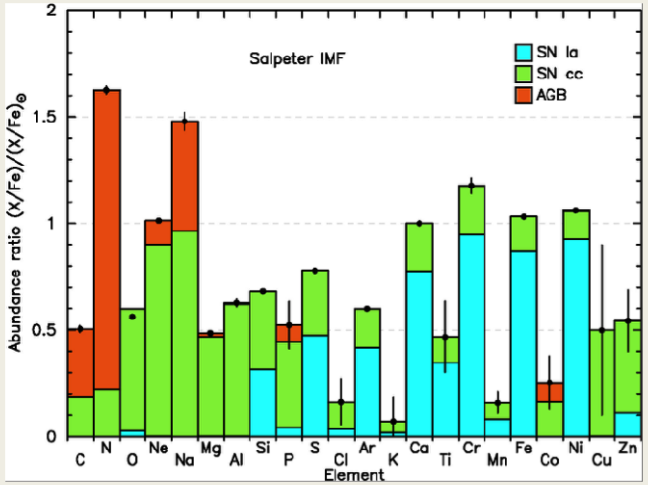
Ilbert et al 2006

- Redshift, galaxy membership
- Galaxy SEDs, stellar masses, morphology (mergers)
- Galaxy metal enrichment
- SFRs, Diffuse Lyα emission shock tracers

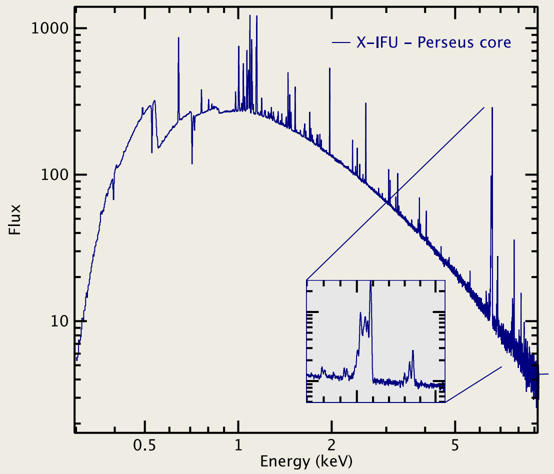
Ettori, Pratt et al. 2013 arXiv1306.2322
Pointecouteau, Reiprich et al. 2013, arXiv: 1306.2319

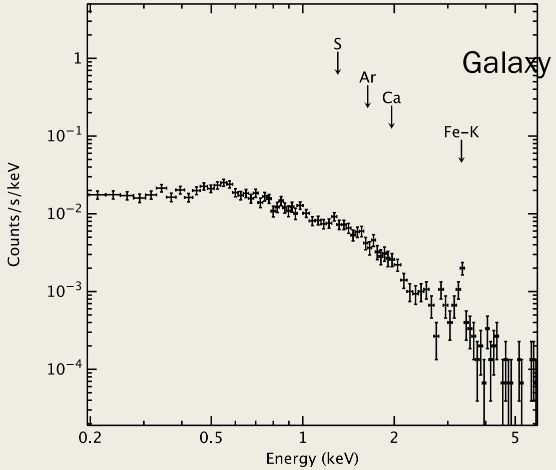
Cluster chemical evolution with Athena

- Clusters of galaxies are closed boxes, all gas is virialised in the DM potential well
- Cosmic chemical evolution best traced by cluster gas
- Constraints on SN types and IMF



[#AthenaNuggets by J. de Plaa](#)



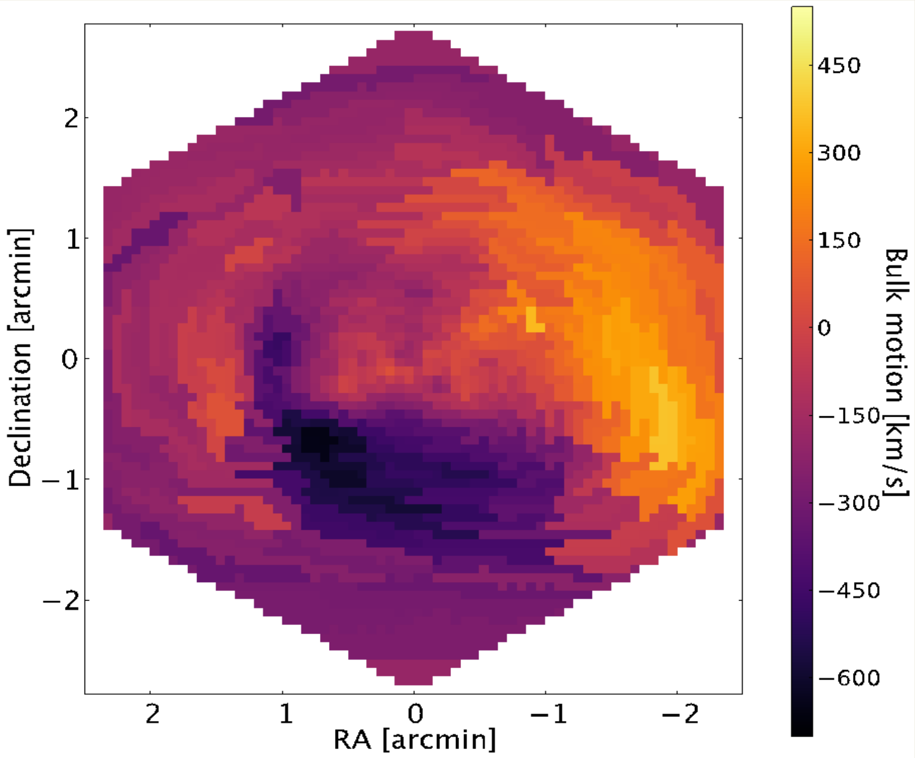


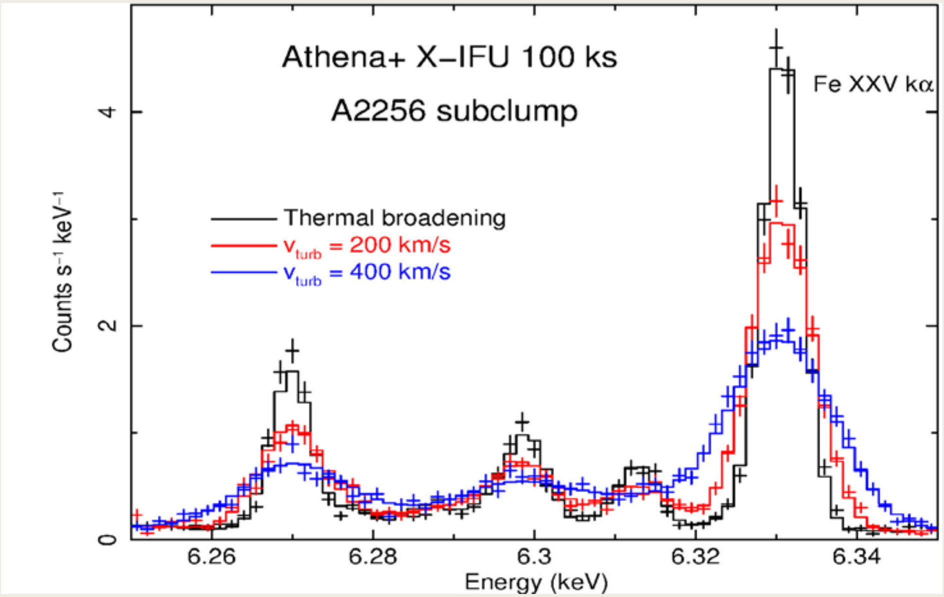
Galaxy group @z=1

Barret et al. 2016, SPIE

Cluster bulk motions & turbulence

Athena will measure gas bulk motions and turbulence down to 20 km/s





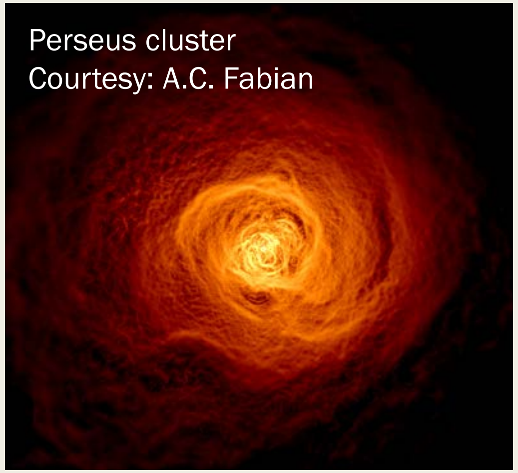
Ettori, Pratt et al. 2013 arXiv1306.2322
Pointecouteau, Reiprich et al. 2013, arXiv: 1306.2319

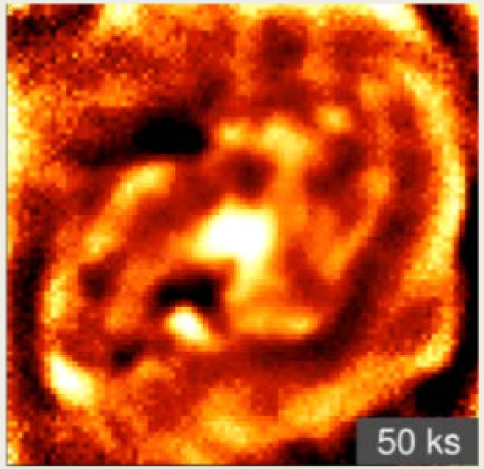
Courtesy: P. Peille, E. Pointecouteau, V. Biffi, E. Rasia, K. Dolag, S. Borgani, J. Wilms

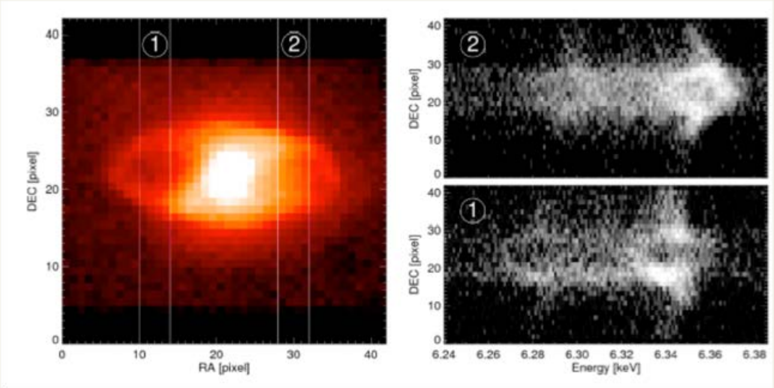
Complementary measurements through 7N (53 GHz) and 57Fe (97 GHz) with ALMA

AGN feedback on cluster scales with Athena

- Dissipation AGN energy into ICM
  - *Energy stored in hot gas around bubbles via bulk motions and turbulence.*
  - *History of radio cluster feedback via ripples.*
  - *AGN jet fuelling vs. cooling through temperature distribution.*
  - *Shock speeds of expanding radio lobes*

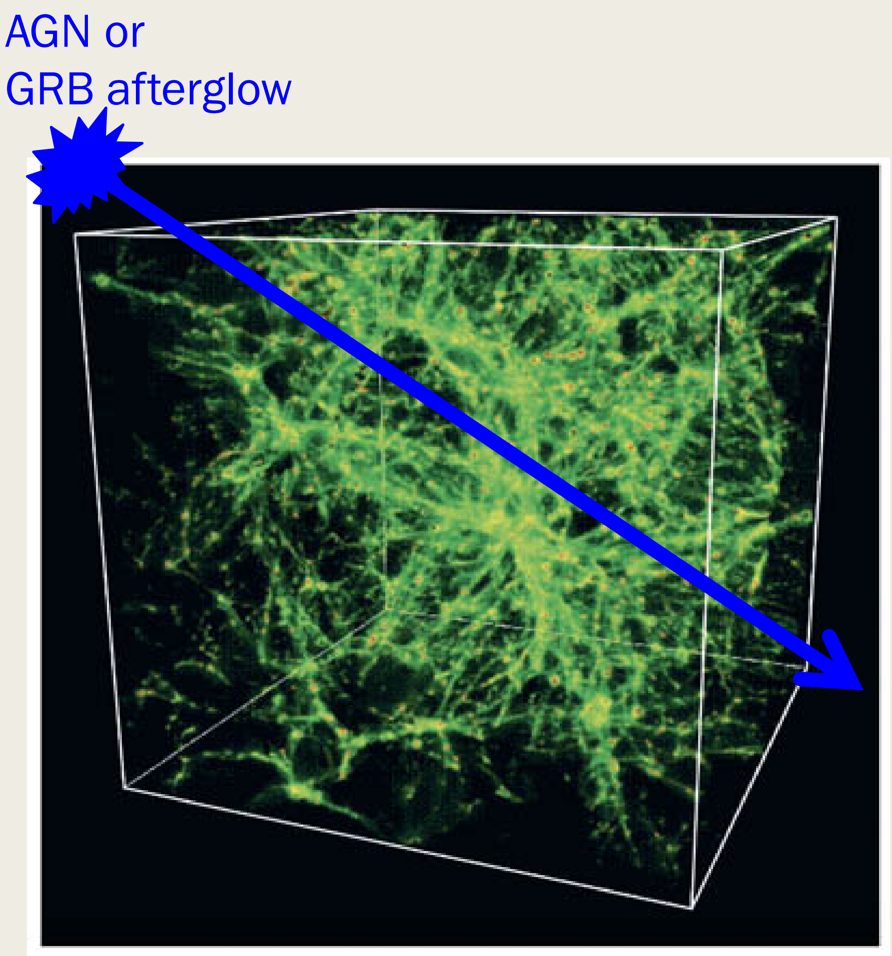

Perseus cluster
Courtesy: A.C. Fabian





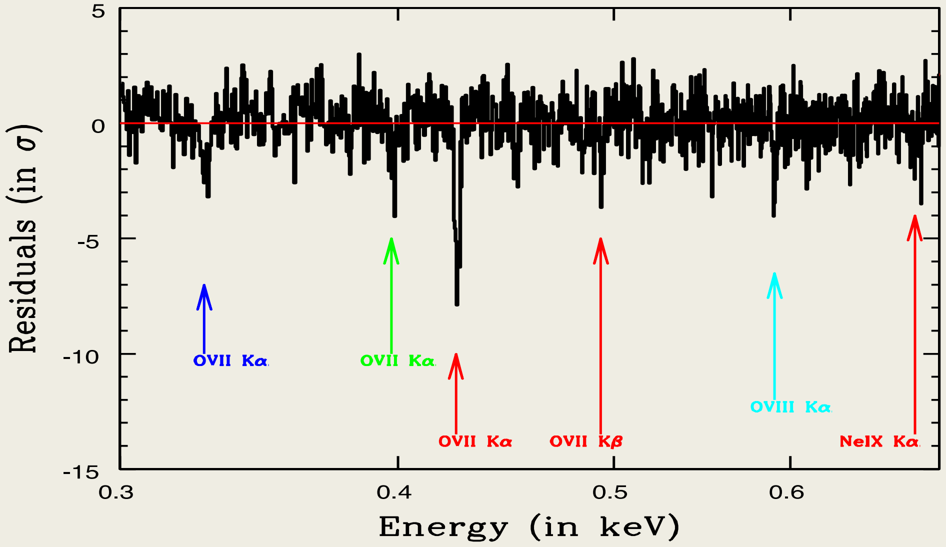
Croston, Sanders et al. 2013 arXiv1306.2323
Simulations by S. Heinz

Characterising the WHIM baryons with Athena



Cen & Ostriker 2006

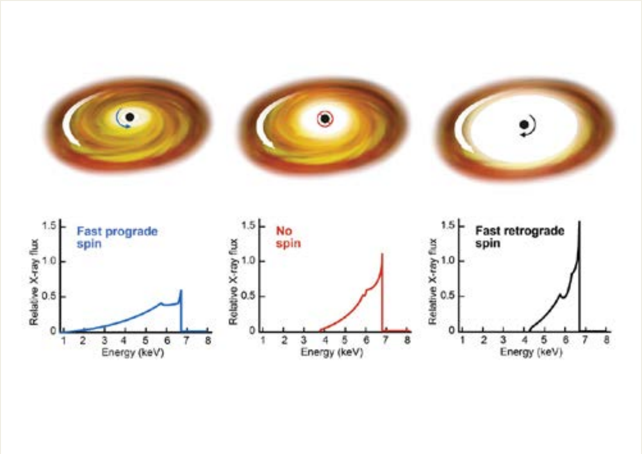
WHIM filaments against a 10% brightest GRB afterglow

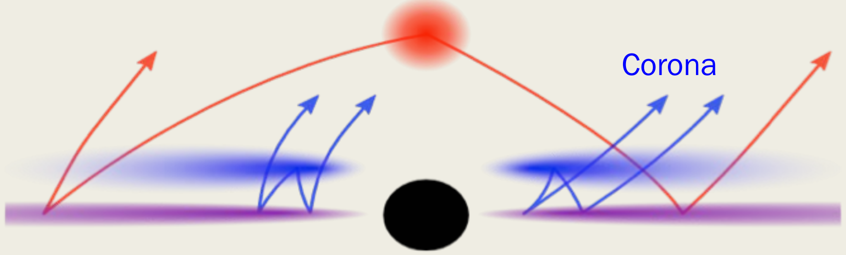


Barret et al. 2016, SPIE
Courtesy: F. Nicastro

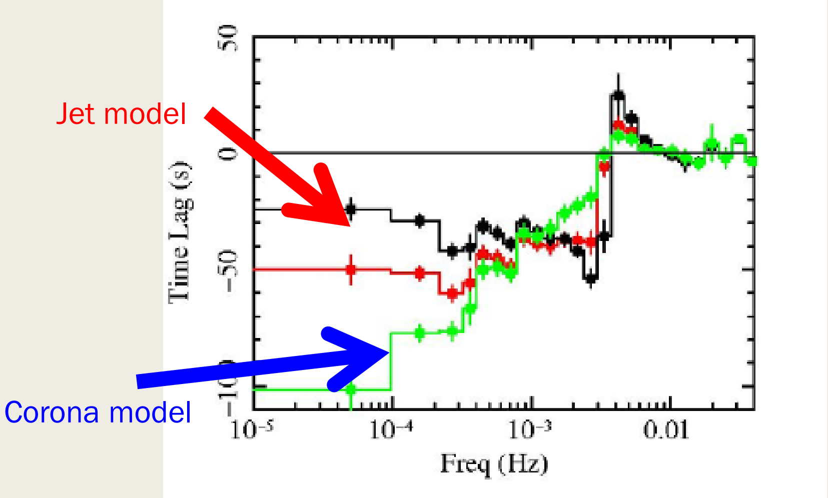
Supermassive Black Hole physics

- Measure SMBH spins through Fe line spectroscopy (unbiased samples)



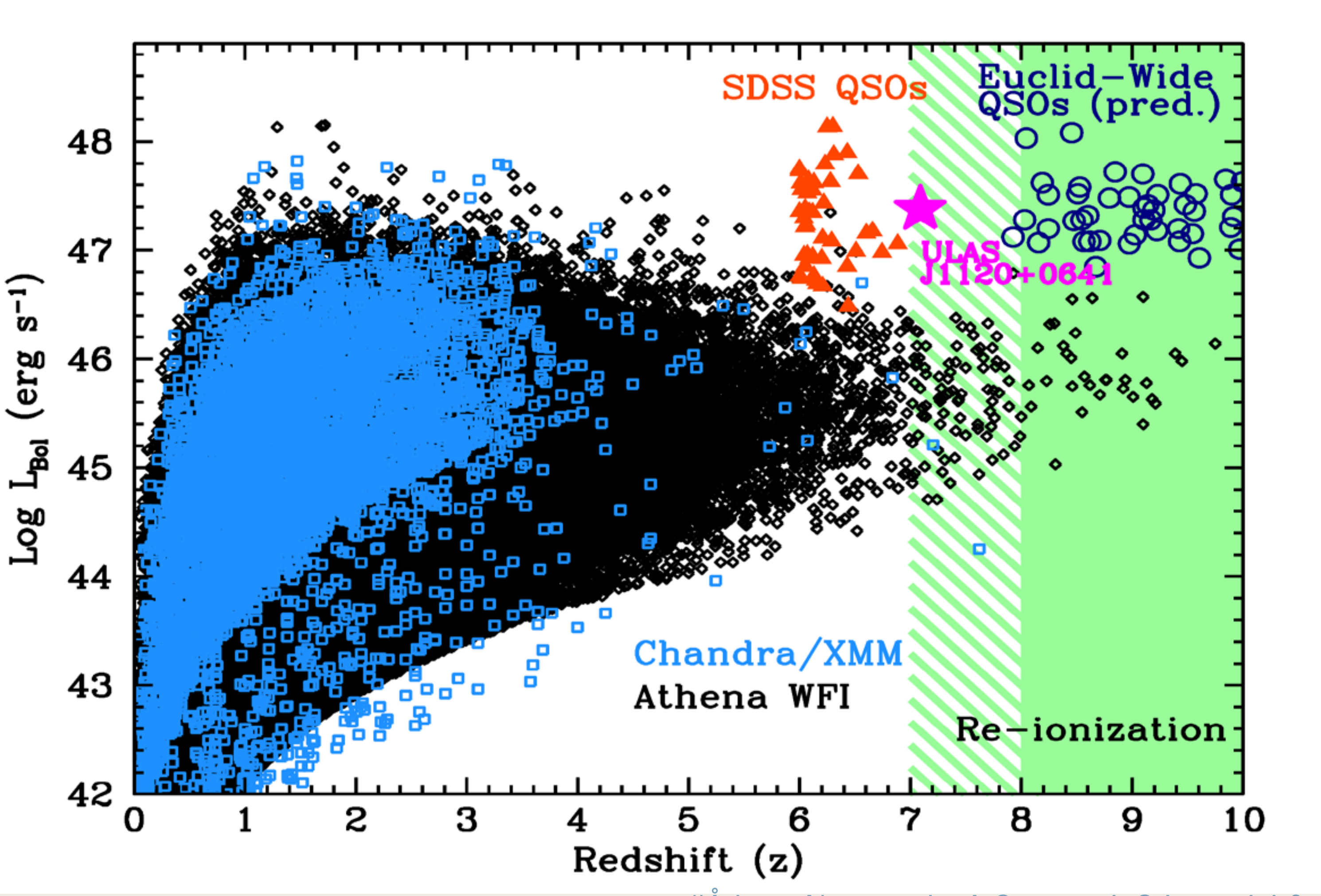


- Accretion geometry and jet/disk relation through reverberation mapping



Dovciak, Matt et al. 2013, arxiv:1306.2331

The history of SMBH growth



#ÅthenaNuggets by A.Comastri, G.Lanzuisi & J.Aird

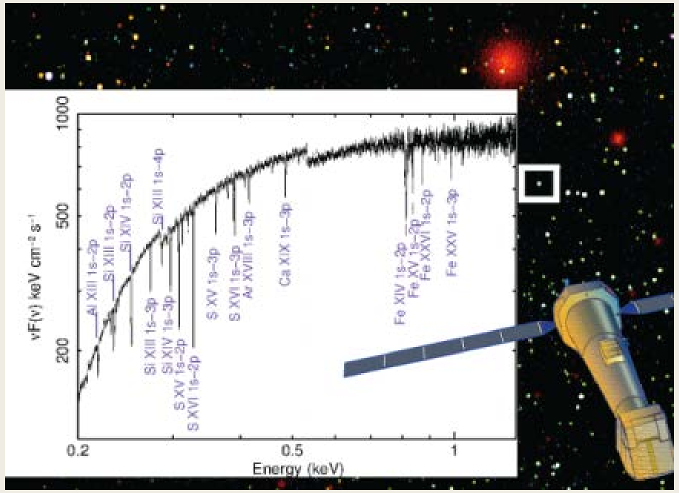
Aird, Comastri et al. 2013 arXiv1306.2325

Only extreme AGN expected in opt/IR surveys

X-rays needed to signpost average AGN

Transient science with Athena

- Observe GRB afterglows at high z (=7-10)
- Obtain (spec or photo) redshifts from the ground, following a GRB alert
  - *Requires RRM and OIR photo/spectroscopic facility*
- Host galaxy ISM metalicity needs:
  - *Athena/X-IFU absorption data for Fe, Si, S, Ca*
  - *OIR spectroscopy for H, O etc*
- Galaxy morphology & spectroscopy at z>7 needs powerful IR imagers and spectrometers (E-ELT)
- OIR polarimetry to provide insight into GRB shock physics



- Athena/WFI will be able to detect ~1000 Tidal Disruption Events every year.
  - *Some of them will be detected early enough for a ground-based follow-up.*

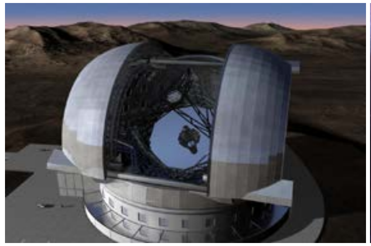
Athena in the framework of the late 2020s

SKA

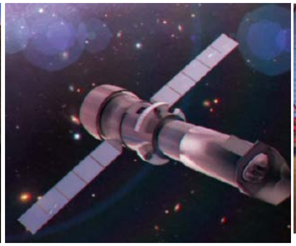
ALMA

JWST

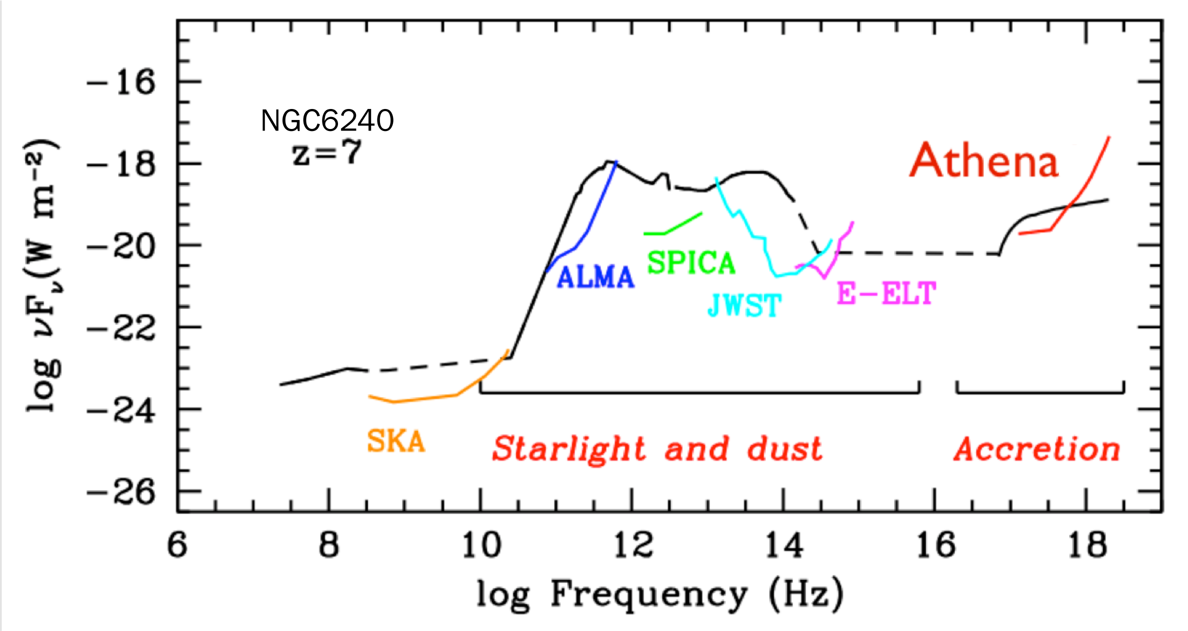
E-ELT



Athena



CTA



Outlook

- Horizon 2000 brought a golden age for high-energy Astrophysics in Europe.
- XMM-Newton has become a workhorse for European X-ray astronomy.
- X-ray observations are nowadays central to many scientific investigations.
- The future is Athena
  - *In synergy with other large observational facilities, including those from ESO (VLT, ELT, ALMA)*