XMM-Newton: Scientific Strategy and Prospects

XMM-Newton survey legacy for Athena and beyond
26-29 February 2024
Toulouse, France

Norbert Schartel

26/03/2024

Mission Extension

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- Mission extension scheme is changed from 2 + 2 years to 3 + 3 years
- plus 1 year to synchronize the mission extensions with the minister meetings

- XMM-Newton:
  - Approved for 2023 and 2026
  - Tentative approval for 2027 – 2029

Mission Extensions force an evaluation of the performed science and formulation of new scientific goals for the next years

ESA/SPC(2023)5,REV.1
Paris, 4 April 2023
(Original: English)

EUROPEAN SPACE AGENCY

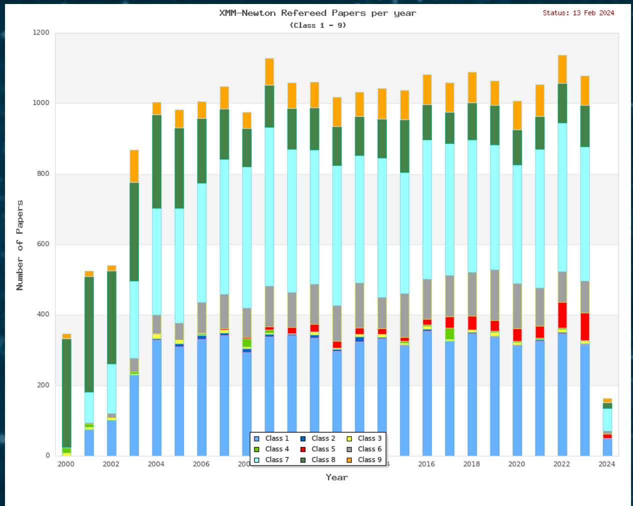
SCIENCE PROGRAMME COMMITTEE

Extensions of mission operations for the period 2023–2029

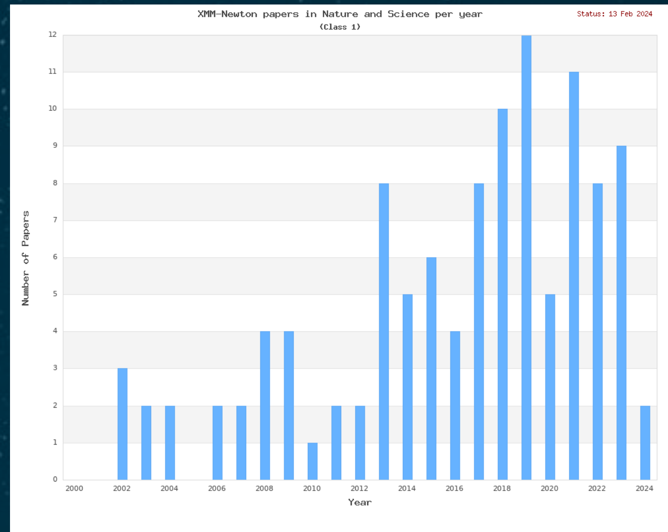
Summary

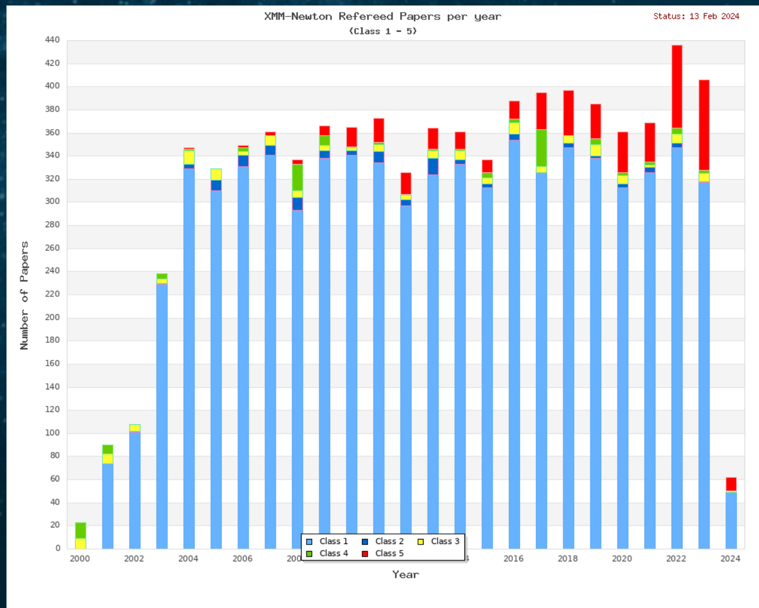
This paper proposes the extension of the operations of scientifically productive missions in orbit. Confirmation of the operations of seven missions (Gaia, Hinode*[1], HST*, IRIS*, SOHO*, XMM-Newton and CHEOPS*) for 2023–2026 is proposed, together with indicative extension of the operations of five missions (Hinode*, HST*, IRIS*, XMM-Newton and CHEOPS*) for 2027–2029.

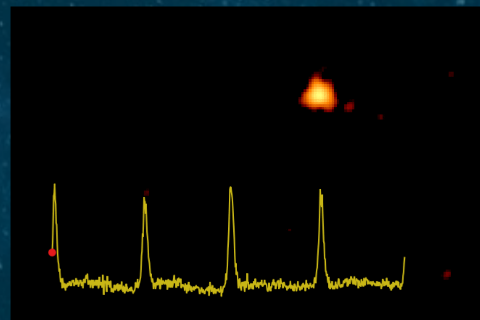
Aim: Maximizing the Scientific Output



ideally transformative / disruptive science







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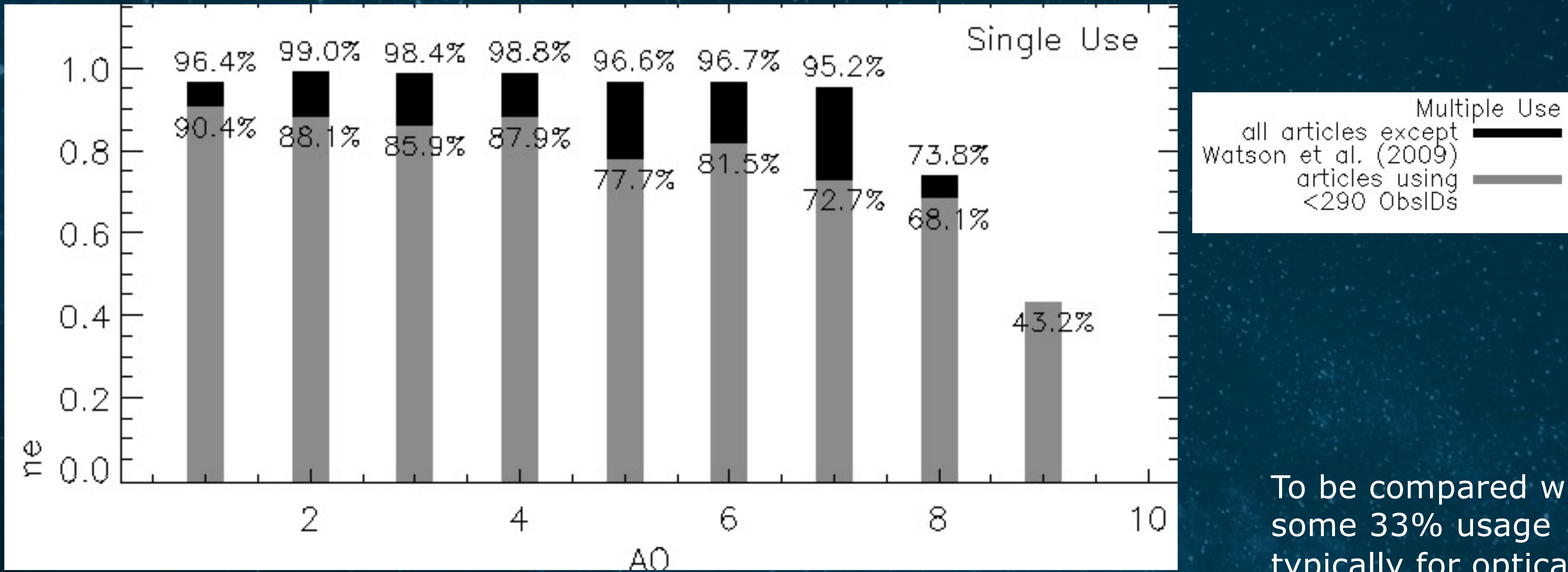
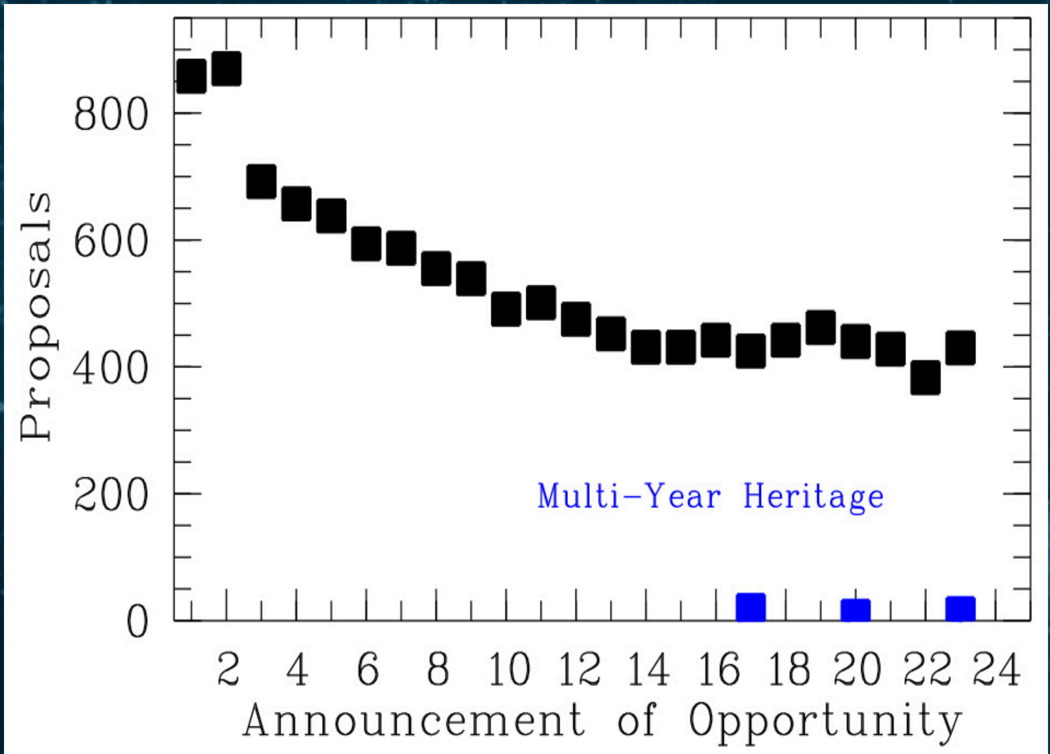
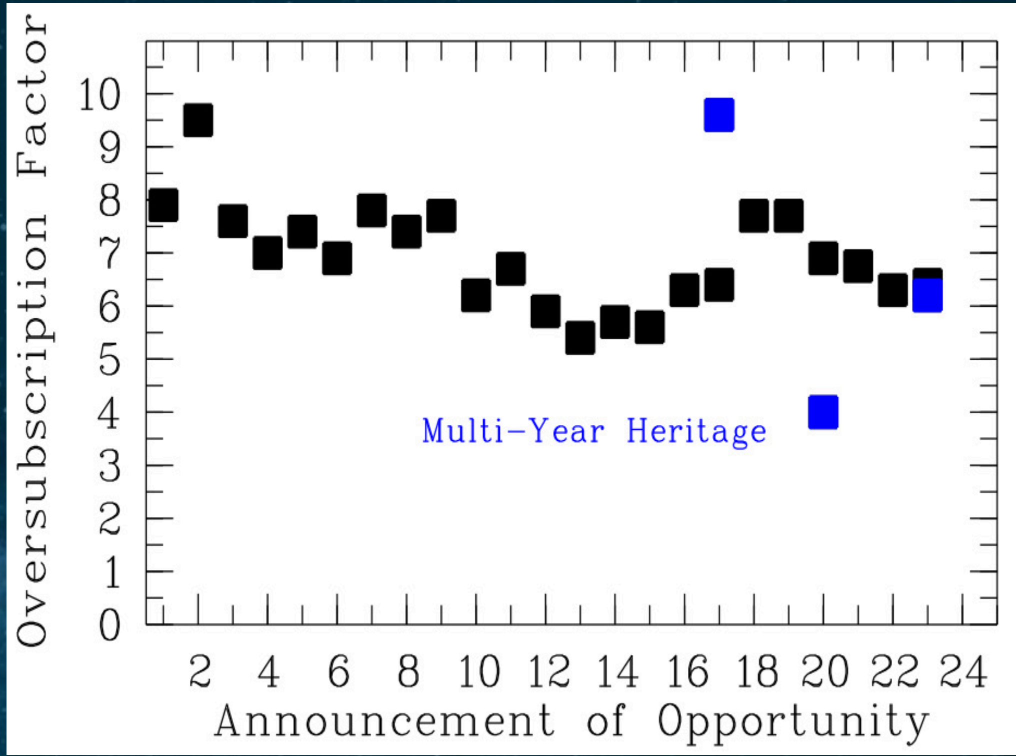


Ness et al., 2014, AN 335, 210

To be compared with some 33% usage typically for optical large optical observatories

XMM-Newton Peer Review





Discovery Space I

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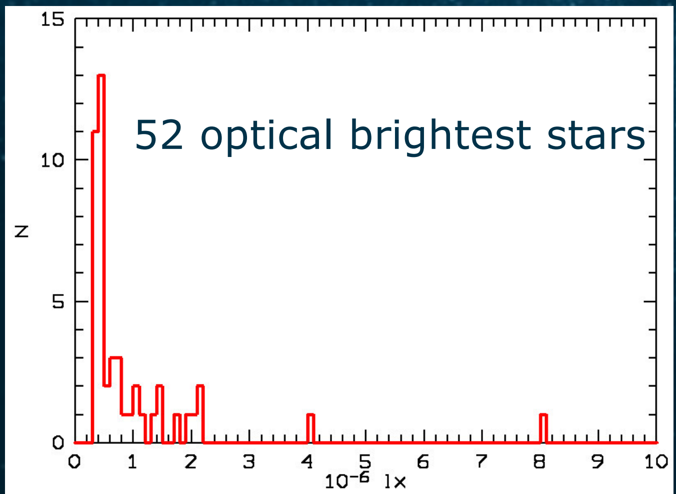
Quality of spectra:

- Quality of spectra is given by their number of photons (photon counting)
- Poisson Statistics -> Signal / noise ~ (exposure time)^2 / S/N ~ T^2
- Factor two in S/N: 10ks -> 40ks -> 160 ks -> 540 ks
  to be compared with time per panel (400 ks and 800 ks for some 50 proposal)
- Similar for surveys -> S/N ~ (area)^2 ~ T^2

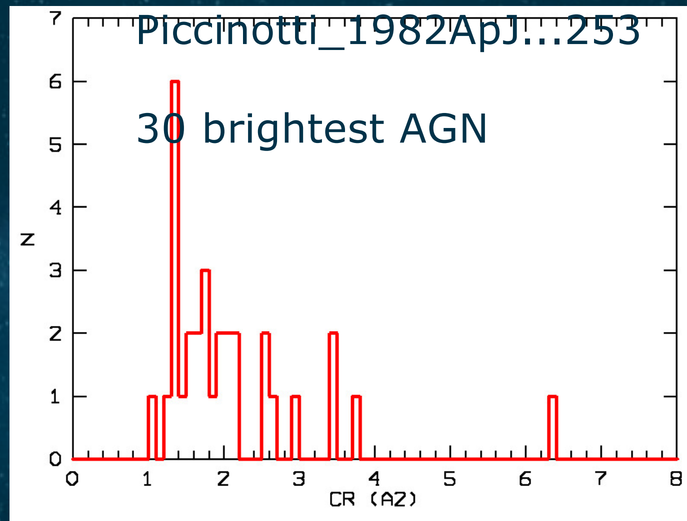
Discovery Space II

Other sources:

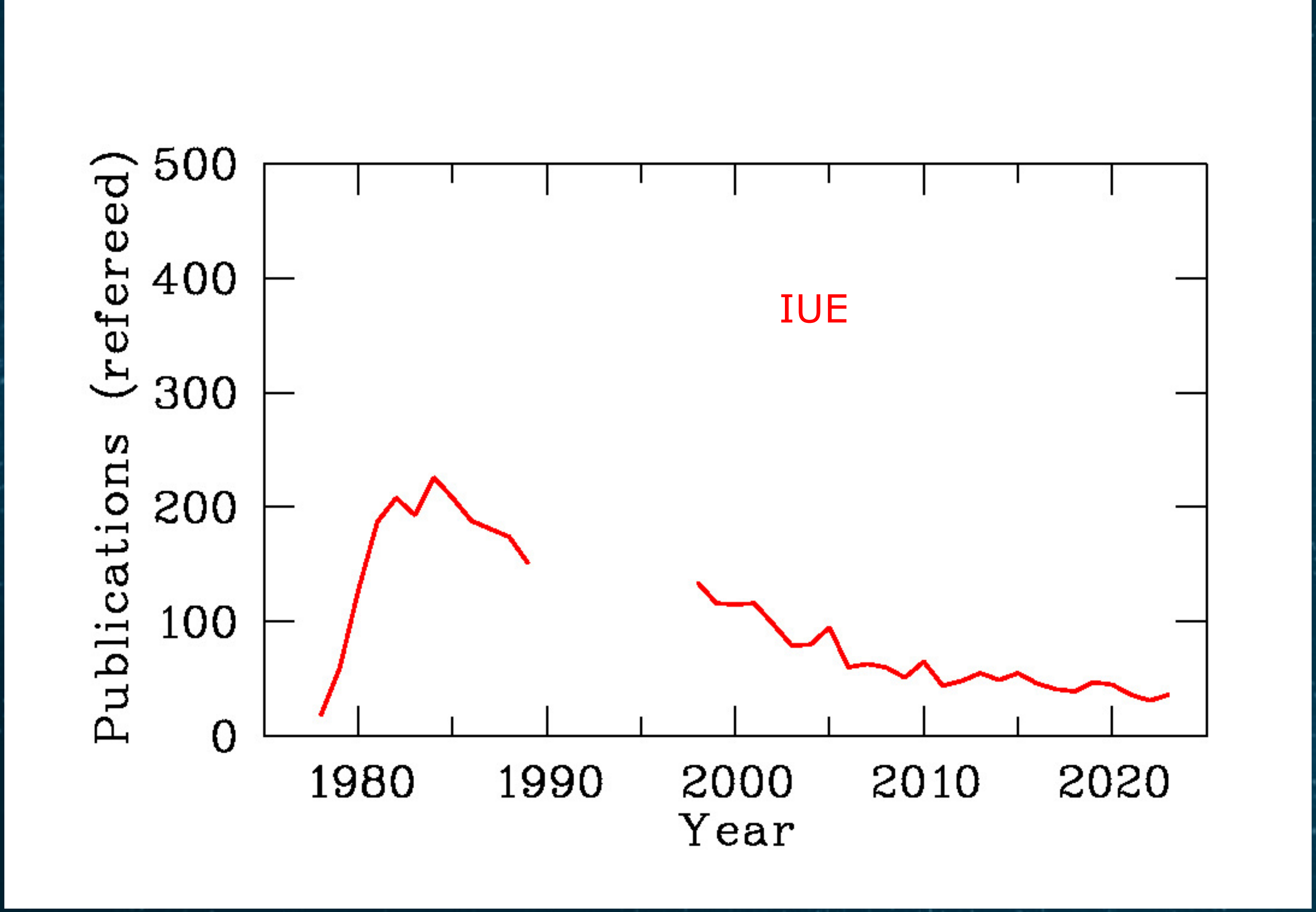
- Distribution of sources in sky
- Weaker sources need easily a factor 5 (and more) more exposures time obtain a spectra with comparable S/N
- There are only few sources which allow to obtain good spectra



- Less and less duplications within the reviews process
- After 7 - 10 years a new facility has explored its discovery space



Publications



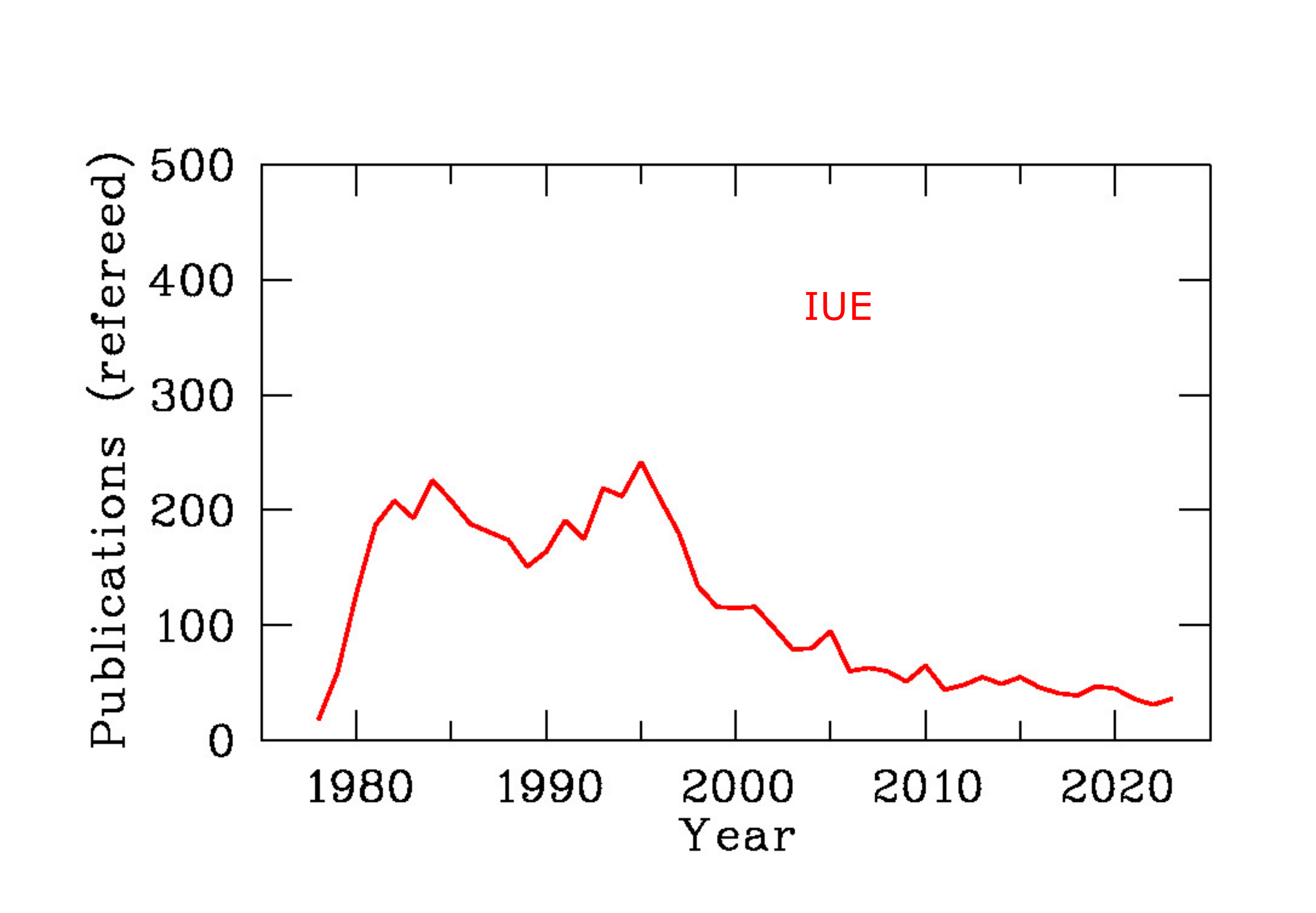
IUE:
International
UV Explorer

First spectral
facility for UV
energy range

What to do?

- New instrumentation:
  - VLT -> VLTI (e.g. Gravitas)
  - Quite limited for current spacecraft generation (but see, HST and Schartel, 2012, AN 33, 209)
  - For XMM-Newton there is some 40% S/N potential from cross-calibration of the instruments
- Teaching:
  - Overlap of research and education
  - High student numbers and shortage of institute own facilities in Europe
  - Problematic for mission extensions and justification of operational costs of space missions
- Change of science goal
  - E.g. use as survey facility
  - XMM-Newton in very inefficient for observation of large areas
- Expanding scientific discovery space
  - Way XMM-Newton was going
  - Development out of small start points

Publications



Expanding Scientific Discovery Space

- Large programs:
  - Allows exploration the discovery space of the next generation of missions
  - Rules and OTAC procedures were several times adapted to the changing requirements
- Two types of large programs:
  - Large programs: >300 ks
    - Large program have the same oversubscription than “normal” programs
    - Typically, some 45% of the A and B priority time goes to large programs
    - Science:
      - Long observations to study variability (e.g. spin and mass of SMBH)
      - Deep spectra of weak objects (e.g. WHIMs)
      - Various samples
  - Multi-Year Heritage Programs: > 2 Ms
    - Offered every 3 year and performed over 3 years
    - Science:
      - Extragalactic survey (4.5 Ms)
      - Galactic center region survey (4.0 Ms)
      - Samples of Planck clusters and high redshift (z>6) quasars
      - Highest redshift quasars
      - Euclid field

Evolution of Large and Multi-Year-Heritage Programmes

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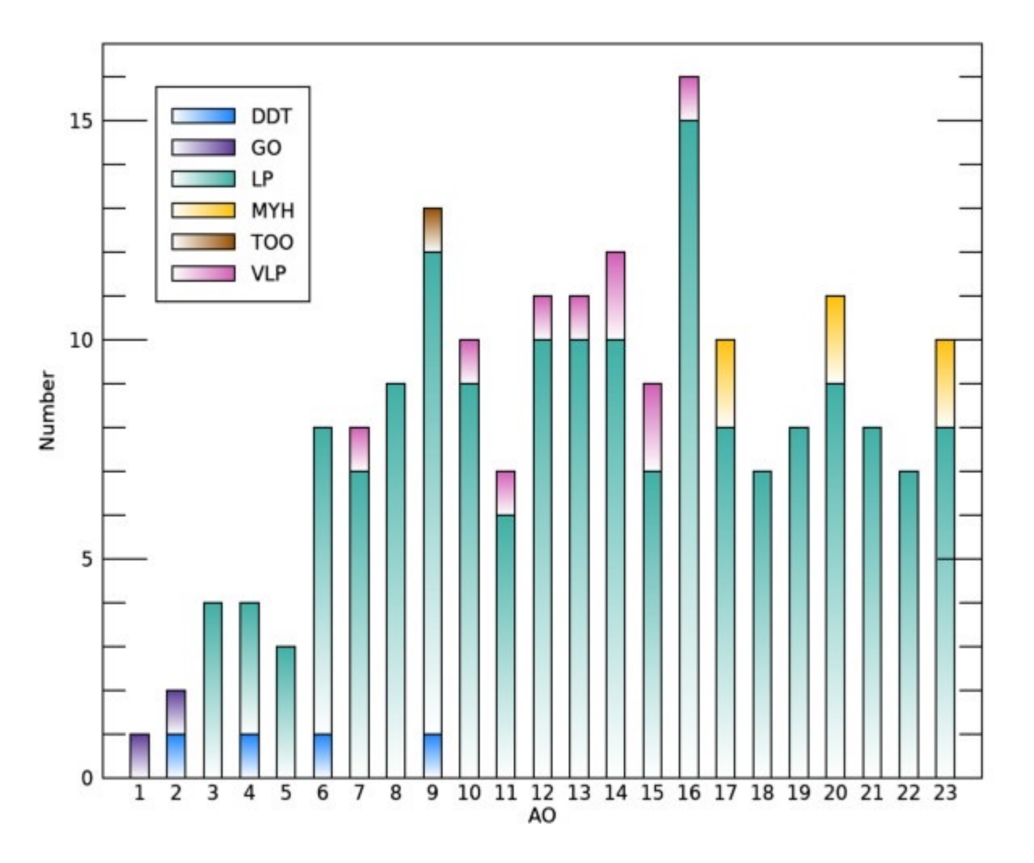
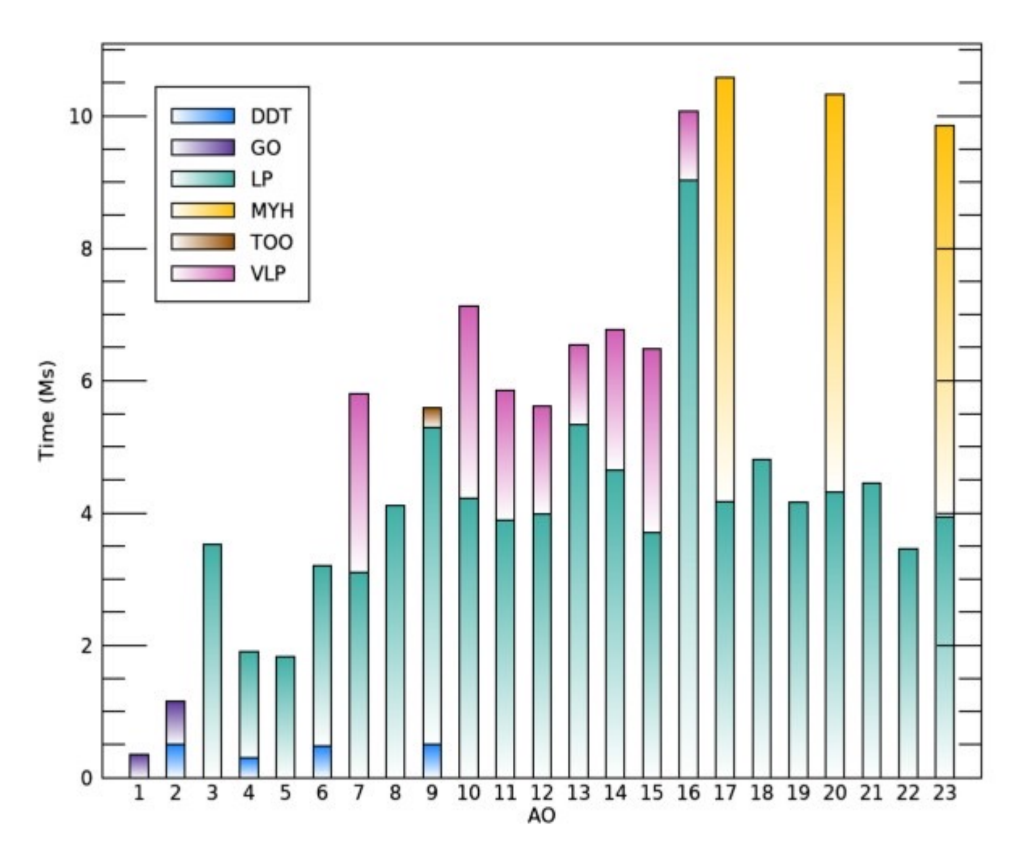


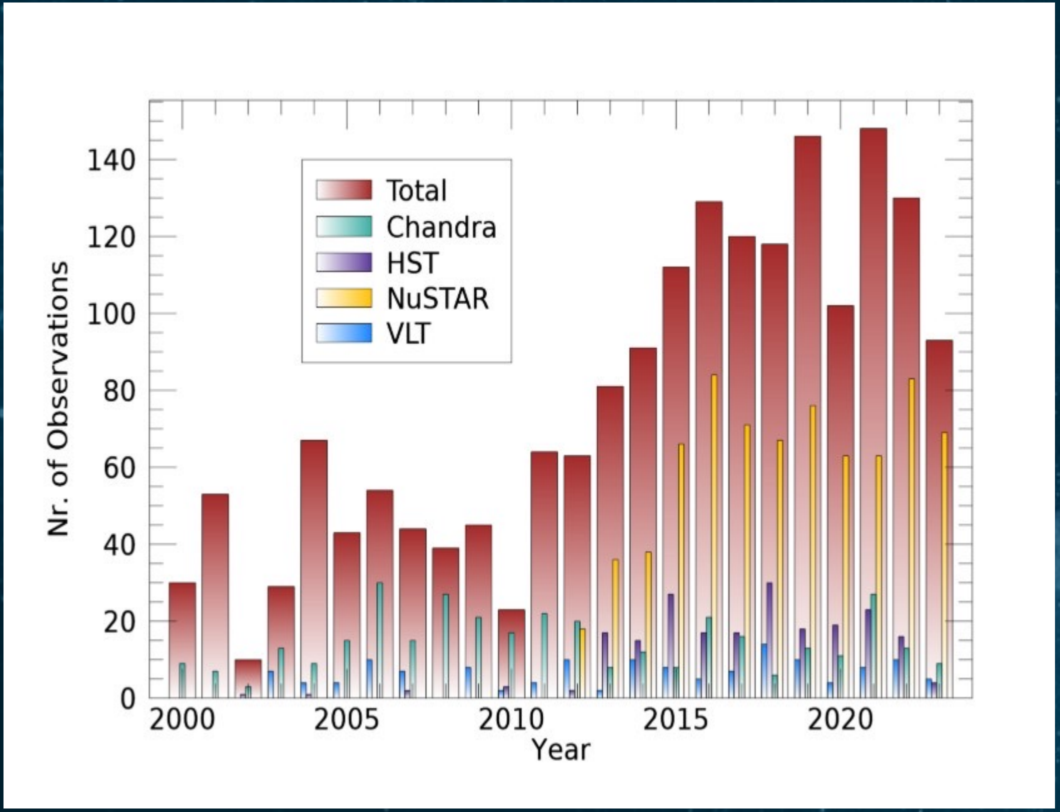


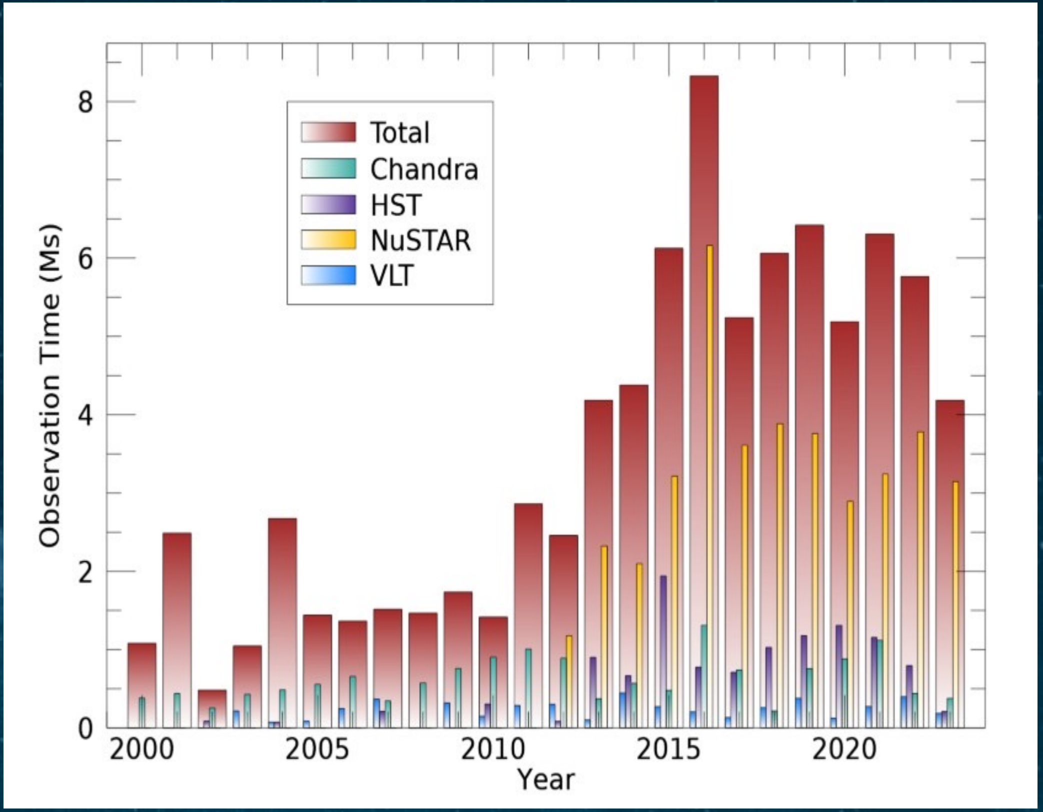
Courtesy: Pedro Rodriguez

Expanding scientific discovery space

- Joint Programs
  - From Radio to TeV:
  - NRAO, JWST, VLT/I, HST, Swift, Chandra, NuSTAR, Integral, H.E.S.S., MAGIC
- Most successful, if two facilities allows to address the same science:
  - Planck: Sunyaev–Zeldovich effect for Clusters of Galaxies (does not require coordinated observations)
  - HST: absorbing winds and outflow in AGN and binaries (coordinated and simultaneous observations)
  - NuSTAR: use the 6.4 keV iron line as diagnostics for compact objects (simultaneous observations)
  - H.E.S.S & MAGIC: identification and mechanism of TeV emitters (partly simultaneous observations)

Evolution of Coordinated Observations



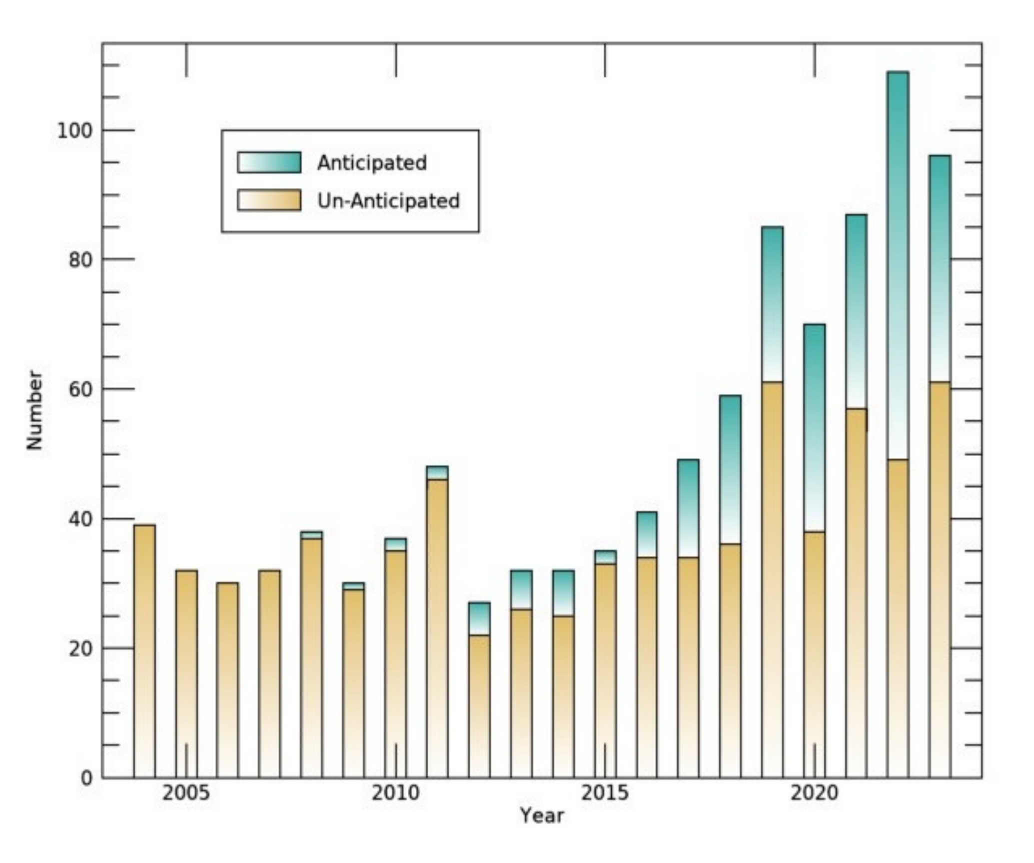


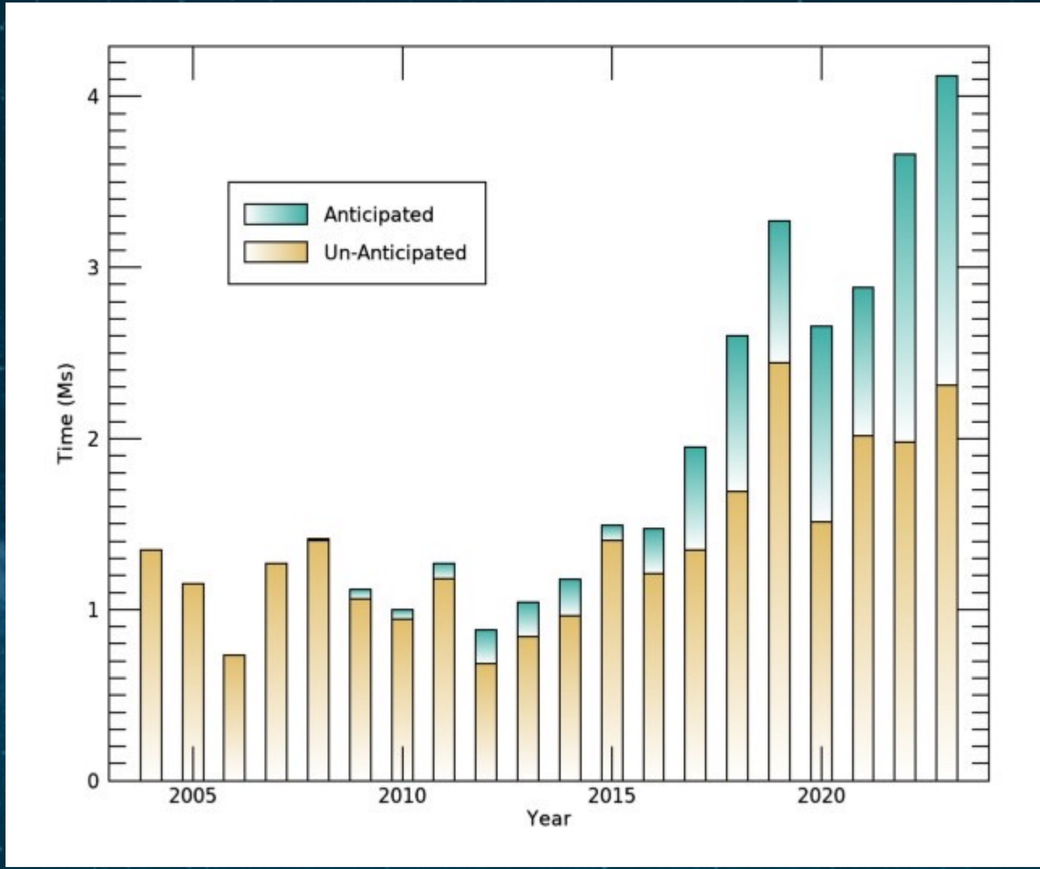
Courtesy: Pedro Rodriguez

Expanding scientific discovery space

- Targets of Opportunity (TOO)
  - Were not foreseen during planning and development of XMM-Newton (4 weeks scheduling in advance)
  - AO1: Only triggered observation (anticipated TOOs with coordinates)
  - D/SCI agreed on unanticipated TOOs answering a question during press-conference in the context of launch of satellite
  - Anticipated TOOs
  - Change of rules, i.e. OTAC chairpersons asked to recommend on TOOs
  - It is important to have the procedures in place in time
  - Supported by the increasing weight of time-domain area search
  - Beppo Sax, (GRB), Swift, eROSITA, …… optical surveys (ZTF, AT) …. Einstein … LSST

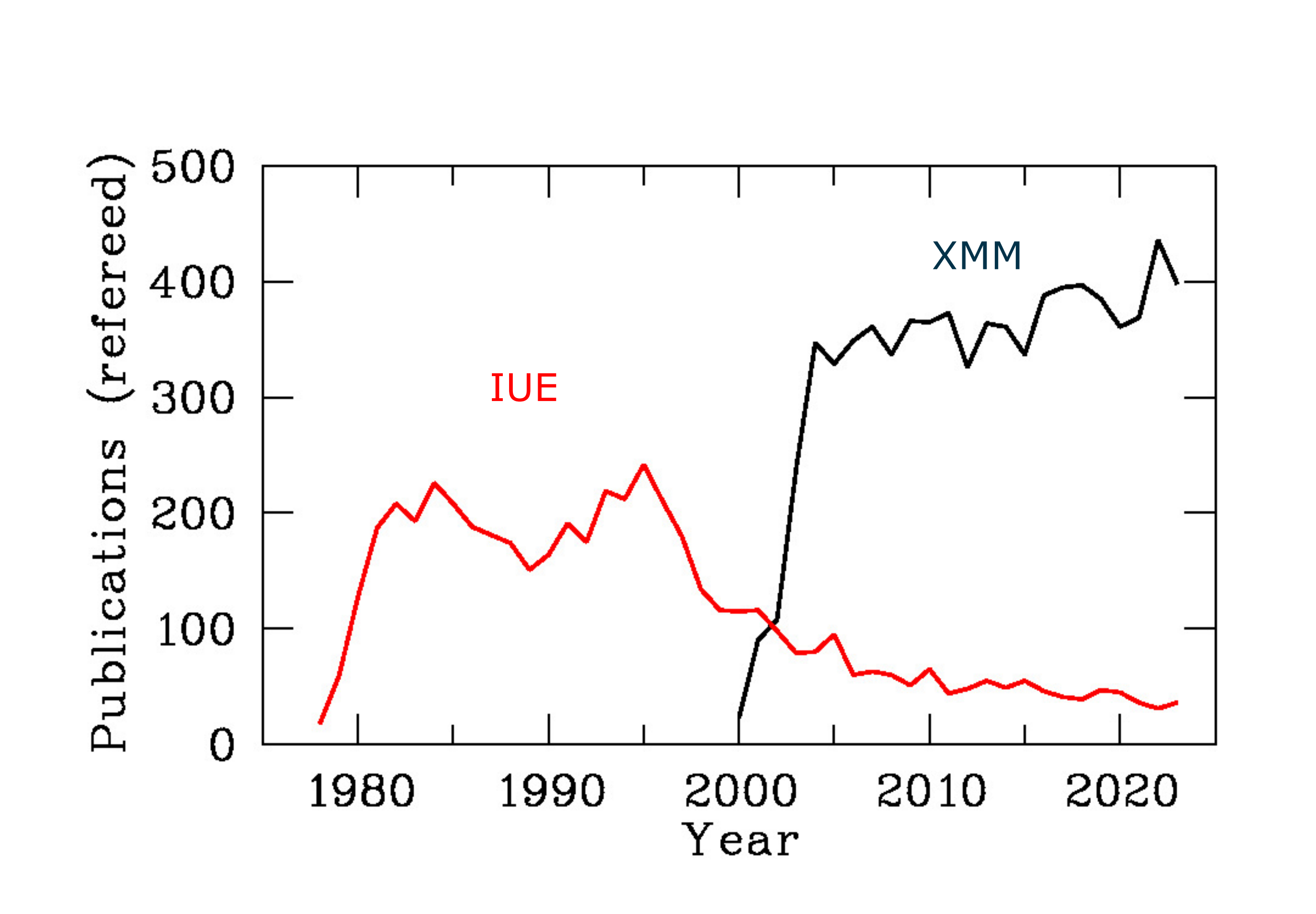
Evolution of TOOs





Courtesy: Pedro Rodriguez & Lucia Ballo

Publications

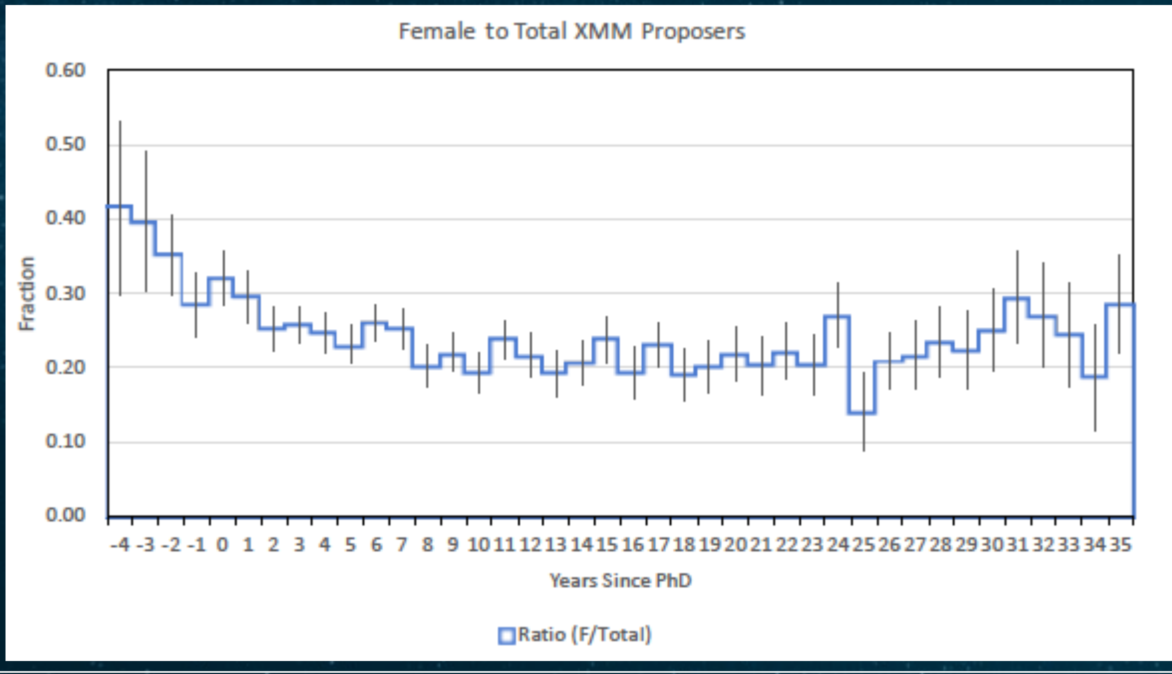


XMM-Newton Peer Review

4 XMM-Newton Observing Time Proposals

A. N. Parmar[1,2], N. Schartel[3] and M. Santos-Lleó[3]

Should be at astoph now



Aims of the XMM-Newton Peer Review

- ❑ Distribution of observing ➔ Maximize the publication of high impact results
- ❑ Deep trust in comumnity about the process and fairness
- ❑ Establishing a program which is convincing for community and ensucres the flow of publications
- ❑ Establishing a program which is convincing for funding structure (mission extenstions every 3 yeas)
- ❑ Including the comunuty in the observatory process / establishing wide support for the mission
- ❑ Building and connecting the community (small countires & new member states)

- ❑ Peer Review of XMM-Newton should not be “burden”
- ❑ Peer Review of XMM-Newotn is a postive scientific event withing the yearly cycle

Some Background:

- AO1 (1999) Classical set-up:
  - One panel per scientific category (7 scientific categories)
  - Between 5 and 9 panel members
  - All conflicts in the panel ("solved" by conflicted panel member leaves the room)
  - Special: Panel meetings on different dates (due to manpower constraints)
  - Special: Panel members from almost all member states of ESA (← D/SCI)

→ Review experience: brightest light and darkest shadows → change of set-up

- AO2 15 panels most with 3 panel members only → change of current set-up
- Later input from personal experiences
  - Chandra & NuSTAR
  - Chairpersons meeting (large program discussion)
  - ESO from comments

→ Adjustments of set-up

Lessons from AO1/AO2: Distributed, Isolated Panels

- Distributed, isolated panels:
  - 2 or more panels per scientific category
    - ➔ No (major) conflicts of interest
  - Each panel consists of 5 panel members from different countries of home institutes
    - ➔ No bias from communities
  - Each panel meets on different dates & places
    - ➔ No bias from other panel members
  - The Panel members do not know the members of the other panels
    - ➔ No bias from other panel members
  - Each panel has a defined and fixed budget of observing time which it allocates
    - ➔ No bias from own research interest
  - Panel members from every ESA member state
  - Majority of panel members selected form PIs & CoIs of previous AOs

Distributed, Isolated Panels

- Outcome:
    - Sufficient high number of proposals:
        - to identify the really best proposals
        - to consider small areas
    - Sufficient expertise and discussions to identify (hidden) feasibility issues
    - Gender statistics equals outcome for double-anonymous (1.10±0.05 for A&B&C,)
    - The relative success rate changes from AO to AO
    - High acceptance rate of young proposers (~37% (for people before PhD) equals double-anonymous 1st time proposers)
    - No bias of against age (years after PhD)
    - No language bias (Acceptance rates: UK: 43.1%, IT: 44.3%, DE: 42.5, FR: 48.0)
    - Keeps original new ideas connected with name of PI
    - Promotes recognition of young scientists

XMM-Newton Peer Review

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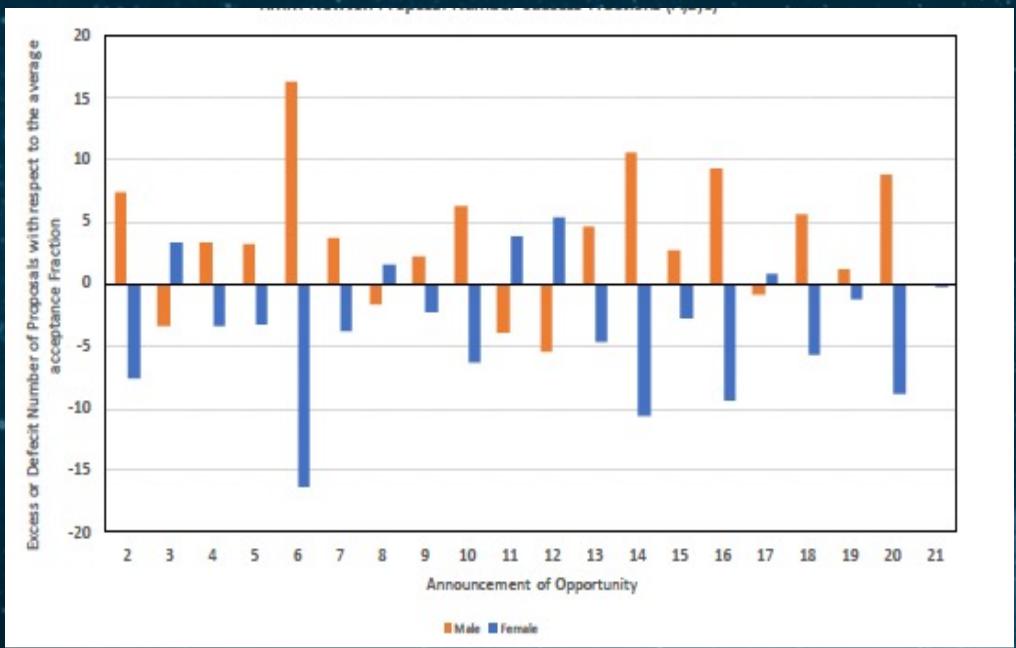

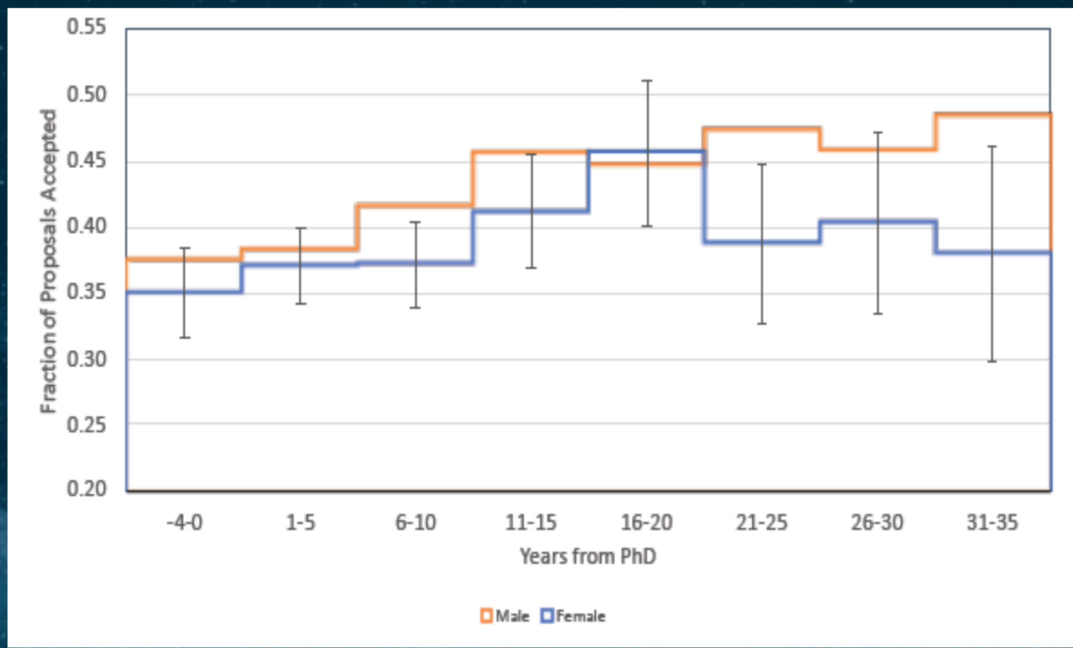

84 Parmar et al.

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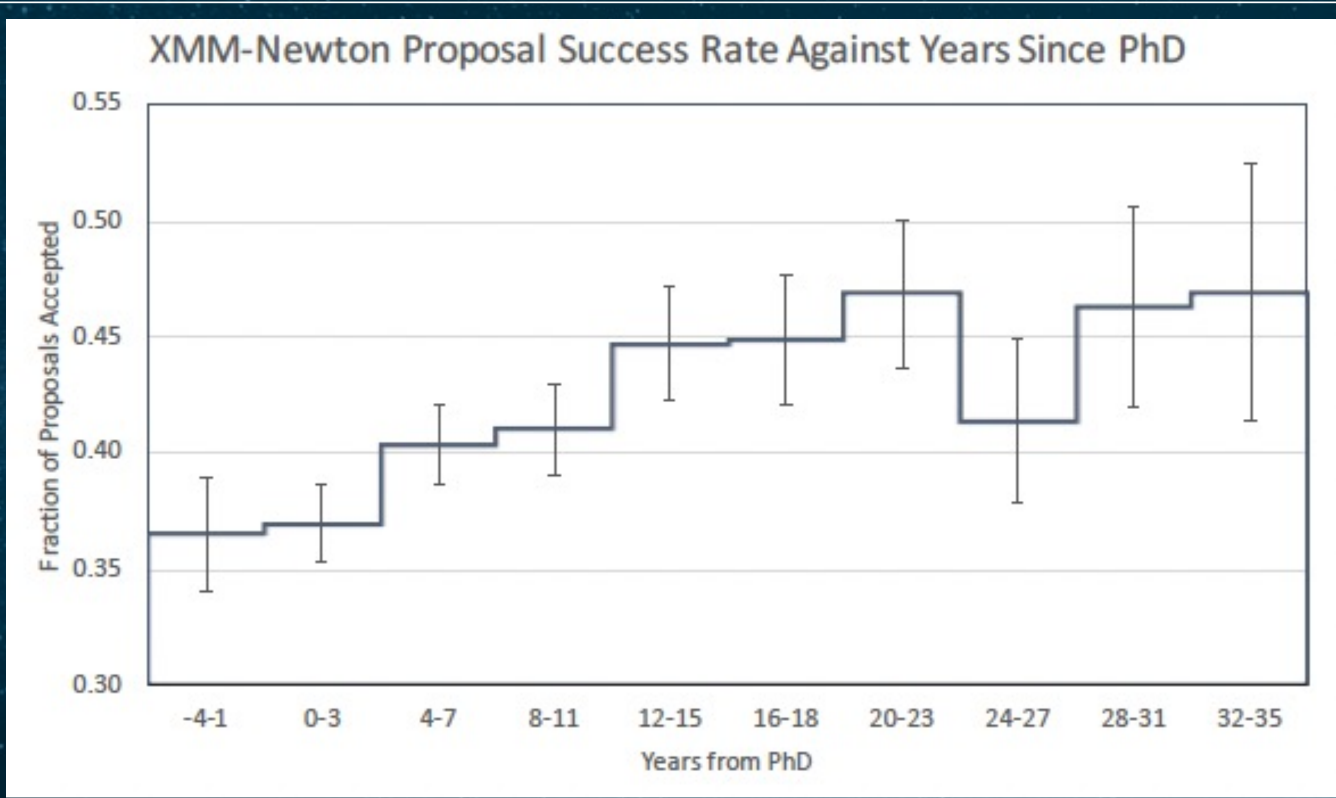
XMM-Newton Peer Review



84 Parmar et al.

4 XMM-Newton Observing Time Proposals

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XMM-Newton Peer Review

Priority	Parameter	Proposal PI All	Male	Female
	Proposals Submitted	10,579	7997	2582
A,B,C	Number Accepted	4287	3316	971
	Percentage Accepted	40.5%	41.5	37.7
	Ratio Male/Female		1.100	
A,B	Number Accepted	2467	1929	538
	Percentage Accepted	23.3	24.1	20.9
	Ratio Male/Female		1.155	
	Time Requested (s)	1.97×10^9	1.49×10^9	4.81×10^8
A,B,C	Time Accepted (s)	4.82×10^8	3.68×10^8	1.14×10^8
	Percentage Time Accepted	24.4%	24.7%	23.6%
	Ratio Male/Female		1.045	
A,B	Time Accepted(s)	2.78×10^8	2.17×10^8	6.08×10^7
	Percentage Time Accepted	14.1%	14.6%	12.6%
	Ratio Male/Female		1.154	
	Overall Male/Female Difference		5–15%	

HST: 1.09 after double annonympurs

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4 XMM-Newton Observing Time Proposals

A. N. Parmar[1,2], N. Schartel[3] and M. Santos-Lleó[3]

XMM-Newton User Model

- The user model assumes a small research group as typically found in European universities. All permanent staff have significant teaching duties that, during certain periods of the year, allow very limited time for research. In addition, the research group may contain non-permanent full-time researchers (e.g. post-doc), post-grad students and other students, the numbers of which can fluctuate and may have other responsibilities. It is recognised that the combined teaching and research environment, even in small research groups, can often generate new ideas and hypotheses, sometimes of a transformational nature, that lead to subsequent XMM-Newton programs.
- In many ESA member states, an accepted XMM-Newton proposal ensures funds for a post-doc or a Ph.D. position. Experience shows that a 1-year proprietary period is the minimum required within most PhDs, and is often too short to get results published, which is relevant especially in the case of high-interest data.
- Based on experience early in the mission, a proprietary period of 0.5-year is generally granted for unanticipated TOOs so as:
    1. to allow publication in high-profile journals, e.g. Nature and Science;
    2. to avoid hasty and poor detection claims in circulars.

XMM-Newton User Model

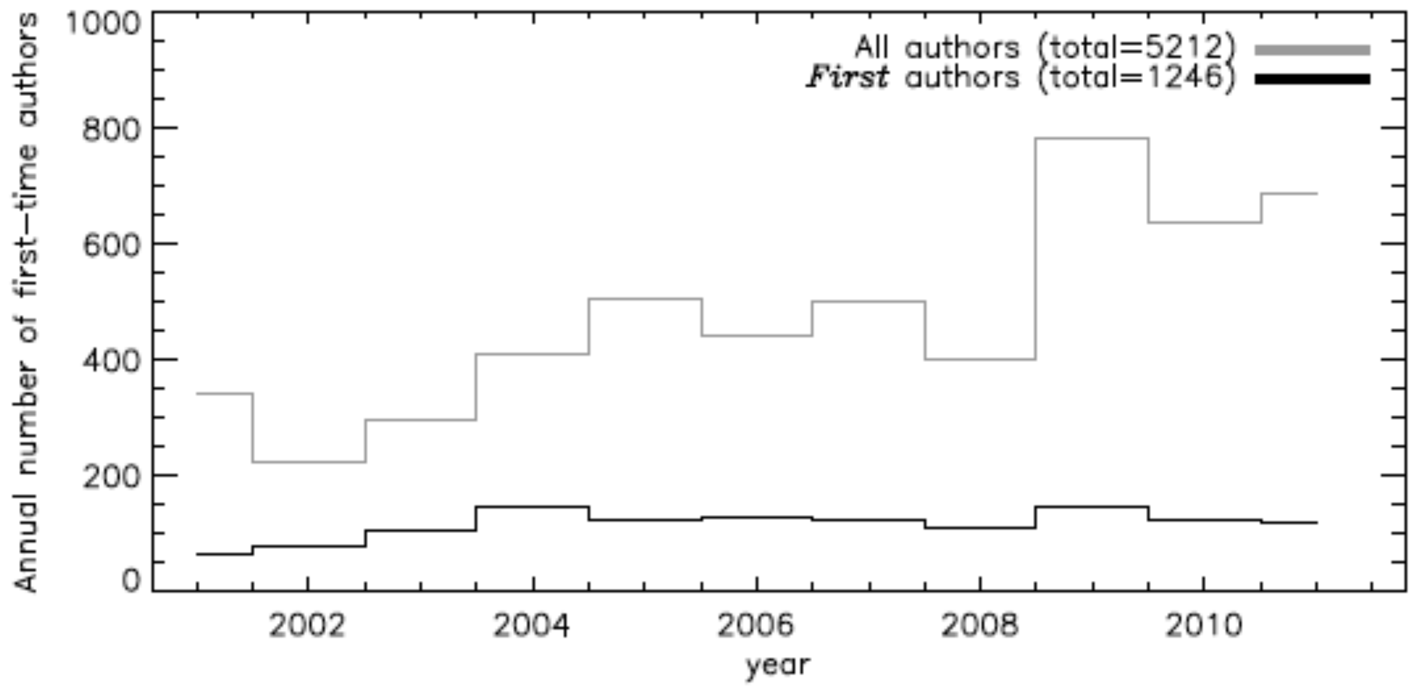


Fig. 2 Evolution with time of new authors (grey) and new *first* authors (black) publishing a refereed paper which directly uses XMM-*Newton* data.

Astron. Nachr. / AN 335, No. 2, 210 – 220 (2014) / **DOI** 10.1002/asna.201312001

XMM-*Newton* publication statistics

J.-U. Ness[1,⋆], A.N. Parmar[2], L.A. Valencic[3,4], R. Smith[5], N. Loiseau[1], A. Salama[1⋆⋆], M. Ehle[1], and N. Schartel[6]

Data Rights

The aim of defined proprietary periods is to give Principal Investigators (PI, compare XMM-Newton user model), a fair and reasonable opportunity to publish their XMM-Newton data in a refereed journal.

This covers both normal proposals and unanticipated Target of Opportunity (TOO) notifications.

At the same time, the rules ensure that data are made available to the worldwide scientific community in a timely manner.

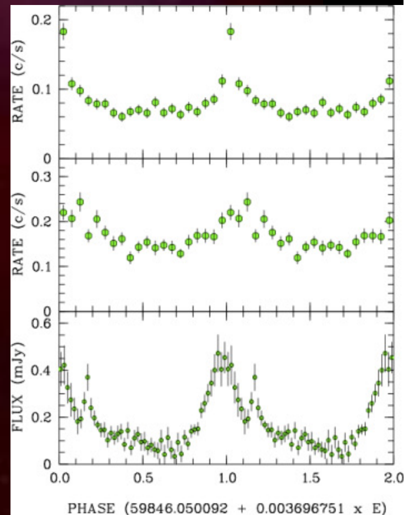
Some Science Highlights

A 5.3-min-period pulsing white dwarf in a binary

- detected with eROSITA
- coincident with a G=17.1 stellar Gaia-source
- dedicated XMM-Newton observation
- simultaneous pulsations with a period of 319s at X-ray and UV

➔ second white-dwarf pulsar
➔ spin-down of rapidly rotating white dwarf provides enough energy to power the pulses
➔ exact driving mechanism is not fully understood

Schwope et al., 2023, A&A 674, L9
Pelisoli et al., 2023, Nature Astronomy 7, 931

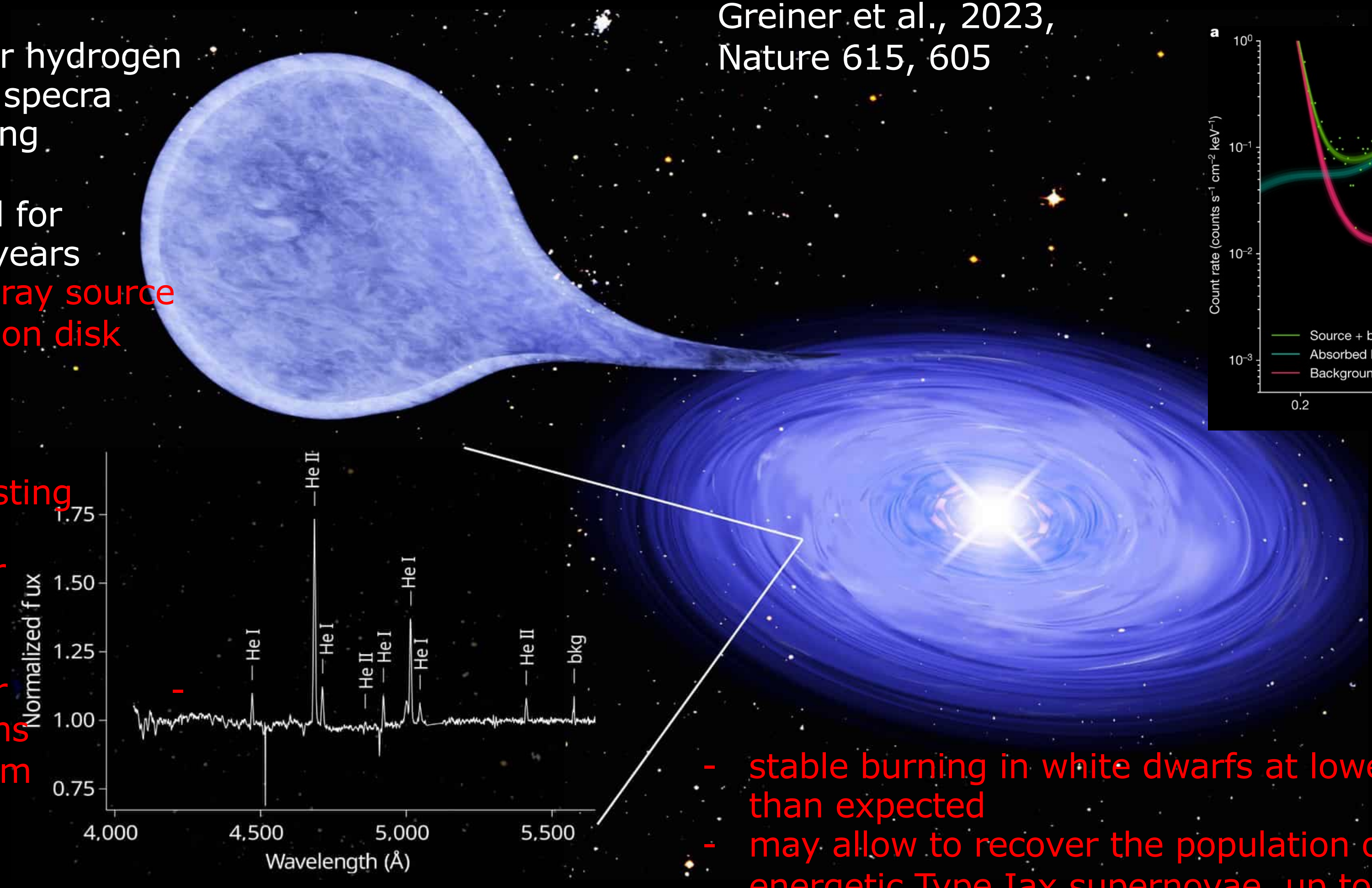


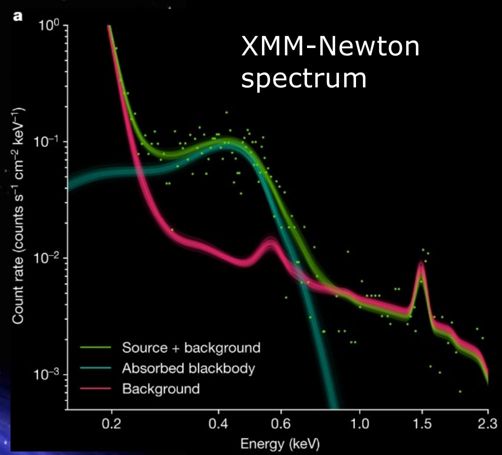
EPIC-pn X-ray, OM/UVM2 & ULTRACAM g-band light curves folded over the spin phase

A helium-burning white dwarf binary as a supersoft X-ray source

Greiner et al., 2023, Nature 615, 605

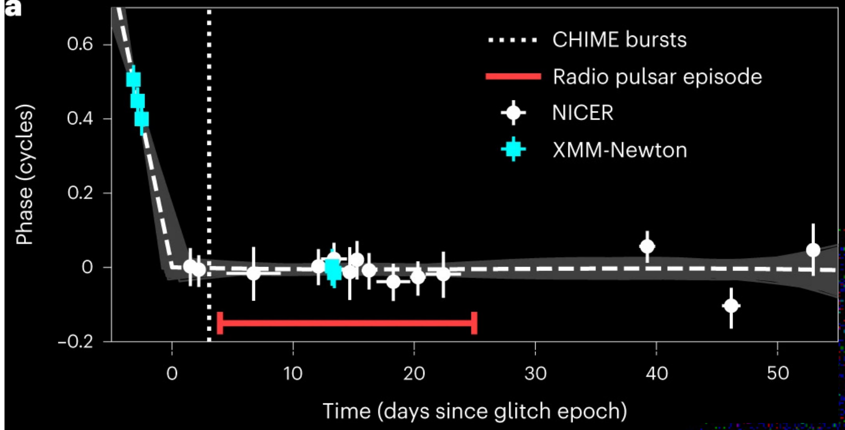
- no evidence for hydrogen in Type Ia SN specra
- Helium-accreting WD have been predicted for more than 30 years
- ➔Supersoft X-ray source with an accretion disk whose optical spectrum is dominated by helium, suggesting a hydrogen-free donor star
- ➔ pathways towards Chandrasekhar mass explosions based on helium accretion





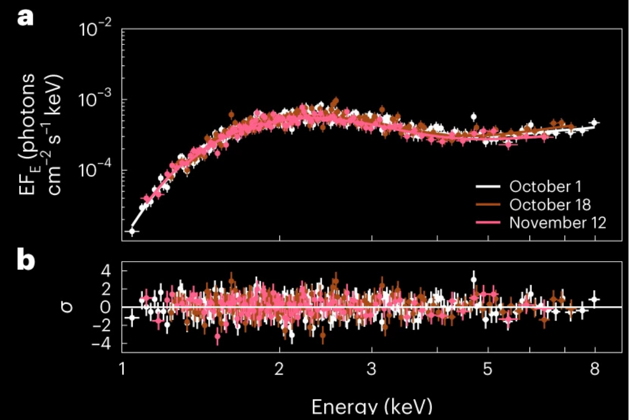
- stable burning in white dwarfs at lower accretion rates than expected
- may allow to recover the population of the sub-energetic Type Iax supernovae, up to 30% of all SN Ia

Magnetar spin-down glitch clearing the way for FRB-like bursts and a pulsed radio episode



Phase residuals, in rotational cycles.
Dashed line is the best-fit timing model which includes a spin-down glitch

XMM-Newton spectra before and after glich

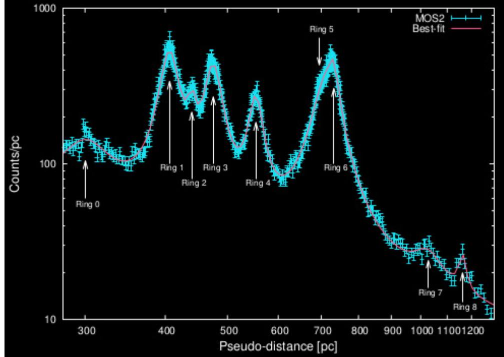


- large spin-down glitch event from SGR 1935+2154 on 5 October 2020
- no change to X-ray behaviour, nor X-ray bursting
- subsequent days, 3 FRB-like radio bursts and month-long episode of pulsed radio emission
- ➔ rarity of spin-down glitches and radio signals from magnetars: their approximate synchronicity suggests an association

Younes et al., 2023, Nature Astronomy 7, 339

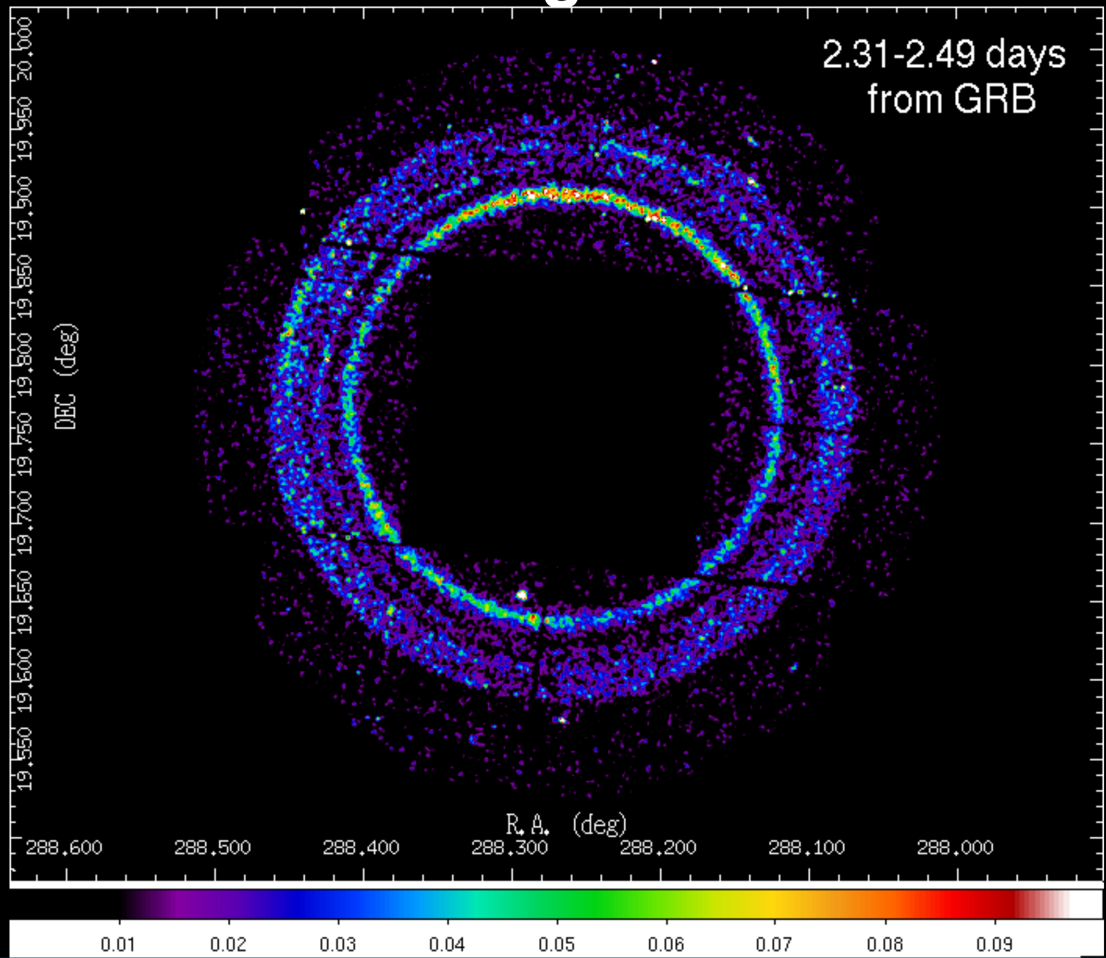
Explanaiton: impulsive crustal plasma shedding close to the magnetic pole generates a wind that combs out magnetic field lines, rapidly reducing the star’s angular momentum while temporarily altering the magnetospheric field geometry to permit the pair creation needed to precipitate radio emission

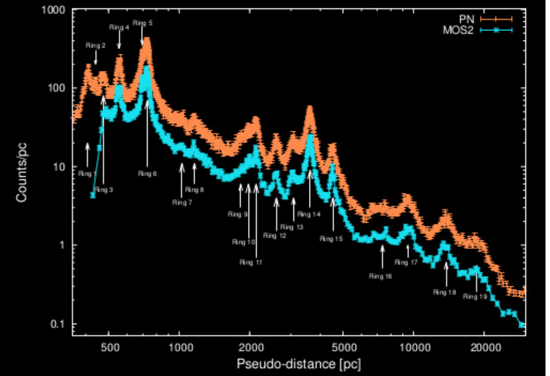
The power of the rings: the GRB 221009A soft X-ray emission from its dust-scattering halo



GRB 221009A is the brightest gamma-ray burst (GRB) ever detected

➔ 20 expanding X-ray rings produced by scattering in Galactic dust clouds at distances ranging from 0.3 to 18.6 kpc

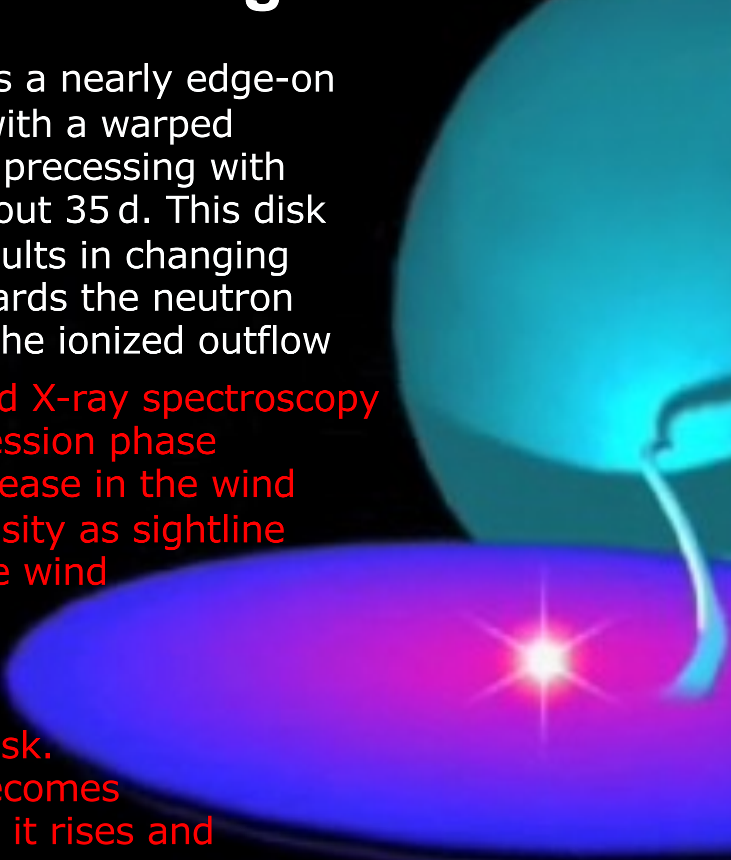




➔ reconstrucion of spectrum of the GRB prompt emission as an absorbed power law with photon index 1-1.4

Tiengo et al., 2023, arXiv:2302.11518v1

Vertical wind structure in Her X1 X-ray binary revealed by a precessing accretion disk



Hercules X-1 is a nearly edge-on X-ray binary with a warped accretion disk precessing with a period of about 35 d. This disk precession results in changing sightlines towards the neutron star, through the ionized outflow

- time-resolved X-ray spectroscopy over the precession phase

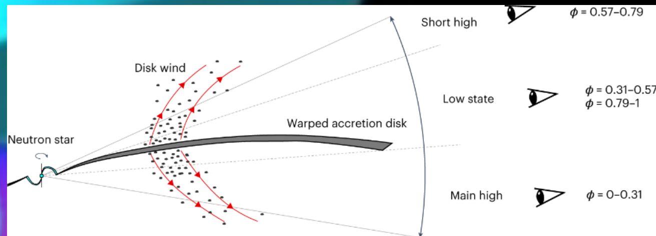
➔ strong decrease in the wind column density as sightline samples the wind at greater heights above the accretion disk.

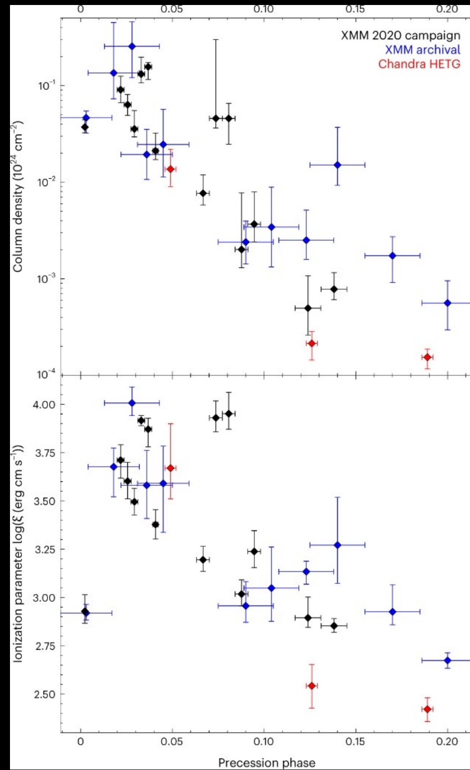
➔ the wind becomes clumpier as it rises and expands away from the neutron star

➔ two-dimensional map of wind properties

➔ measurement of the vertical structure

➔ allows direct comparisons with three-dimensional global simulations to reveal the outflow launching mechanism.



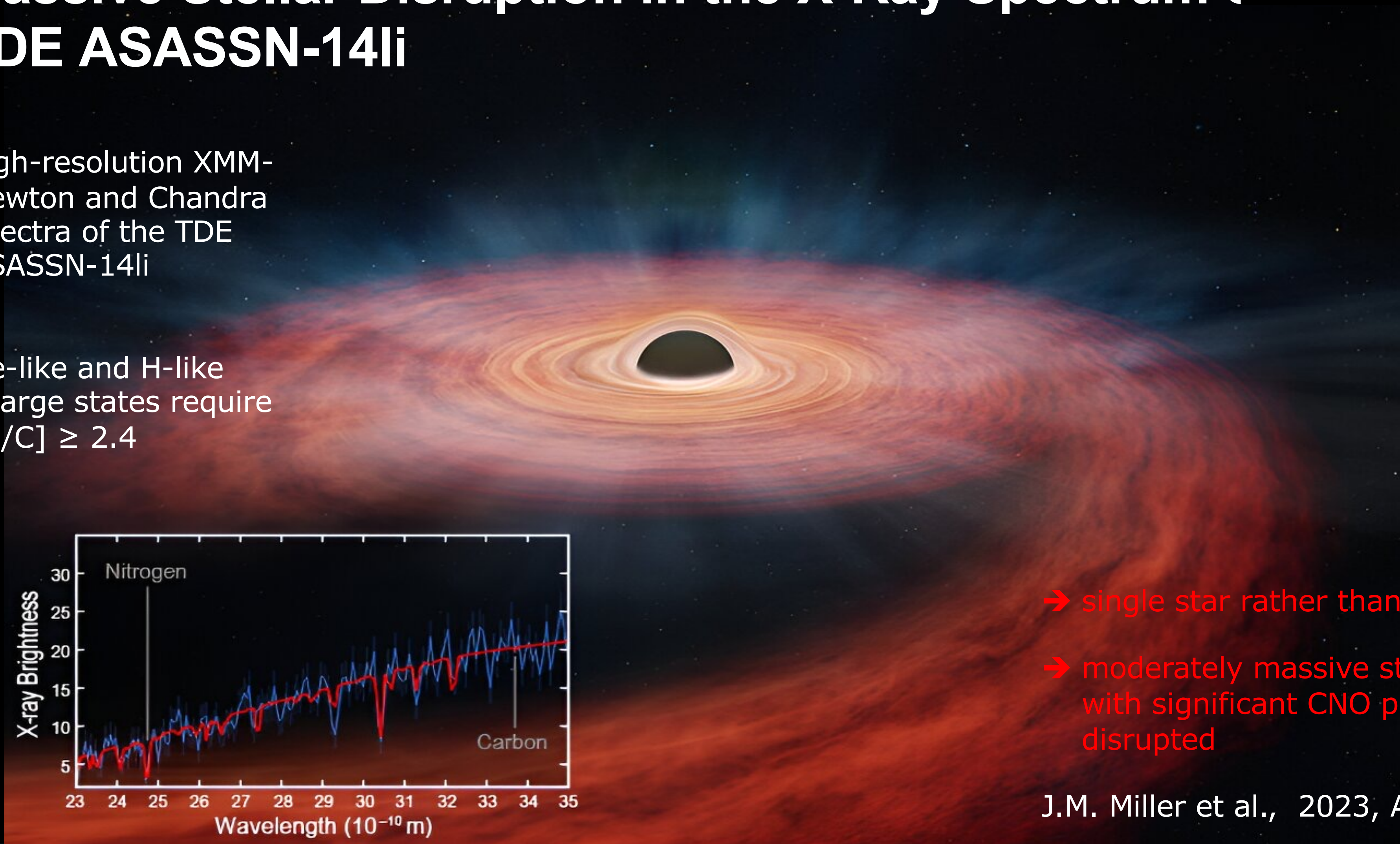


P. Kosec et al., 2023, Nature Astronomy 7, 715

Massive Stellar Disruption in the X-Ray Spectrum TDE ASASSN-14li

- high-resolution XMM-Newton and Chandra spectra of the TDE ASASSN-14li

- He-like and H-like charge states require [N/C] ≥ 2.4



➔ single star rather than AGN accretion

➔ moderately massive star ($M \gtrsim 3$ M) with significant CNO processing was disrupted

J.M. Miller et al., 2023, ApJL 953 L23

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

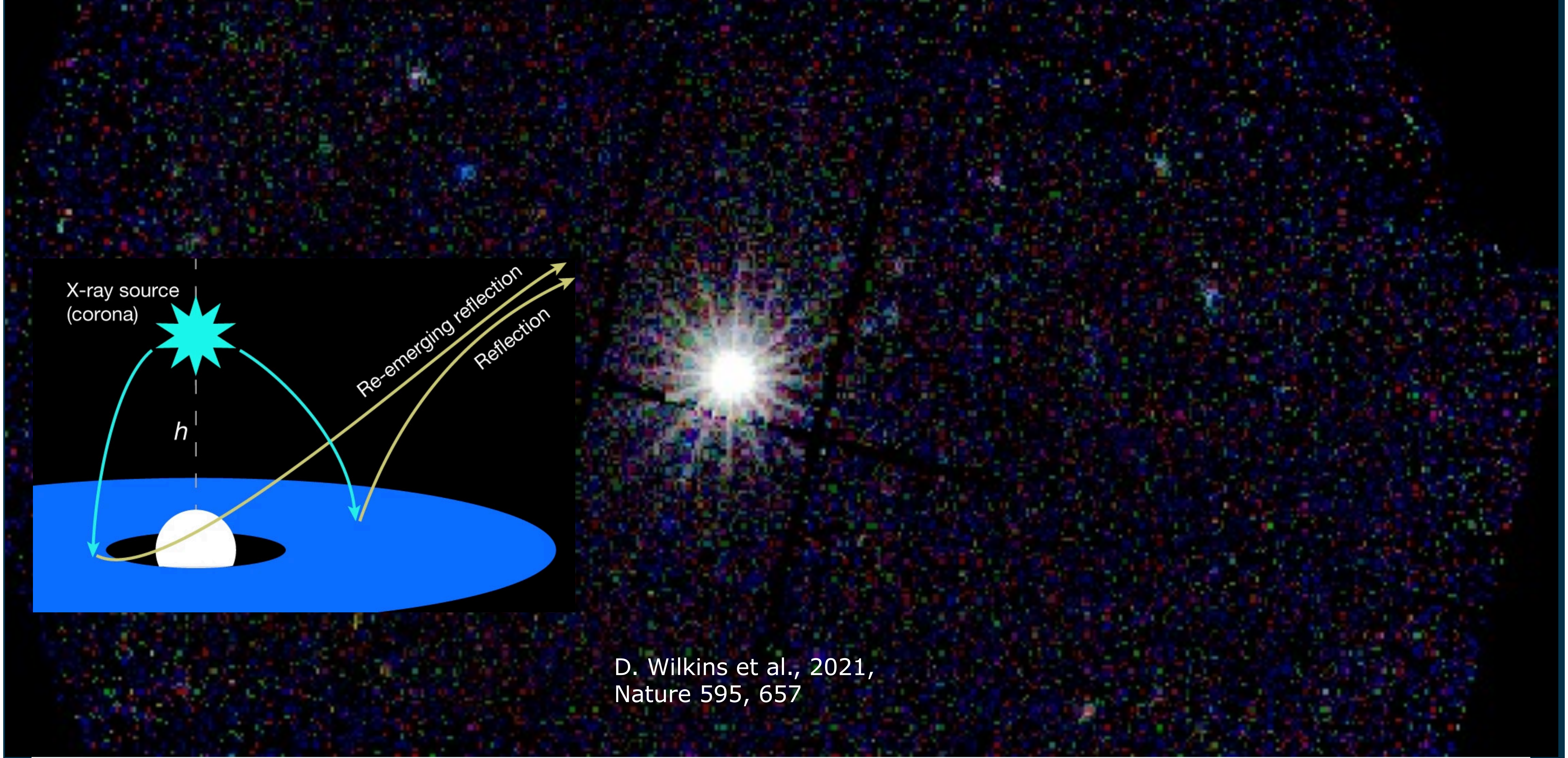
Alston et al. 2020, Nature Astronomy 4, 597

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

➔ X-ray corona increases with increasing luminosity

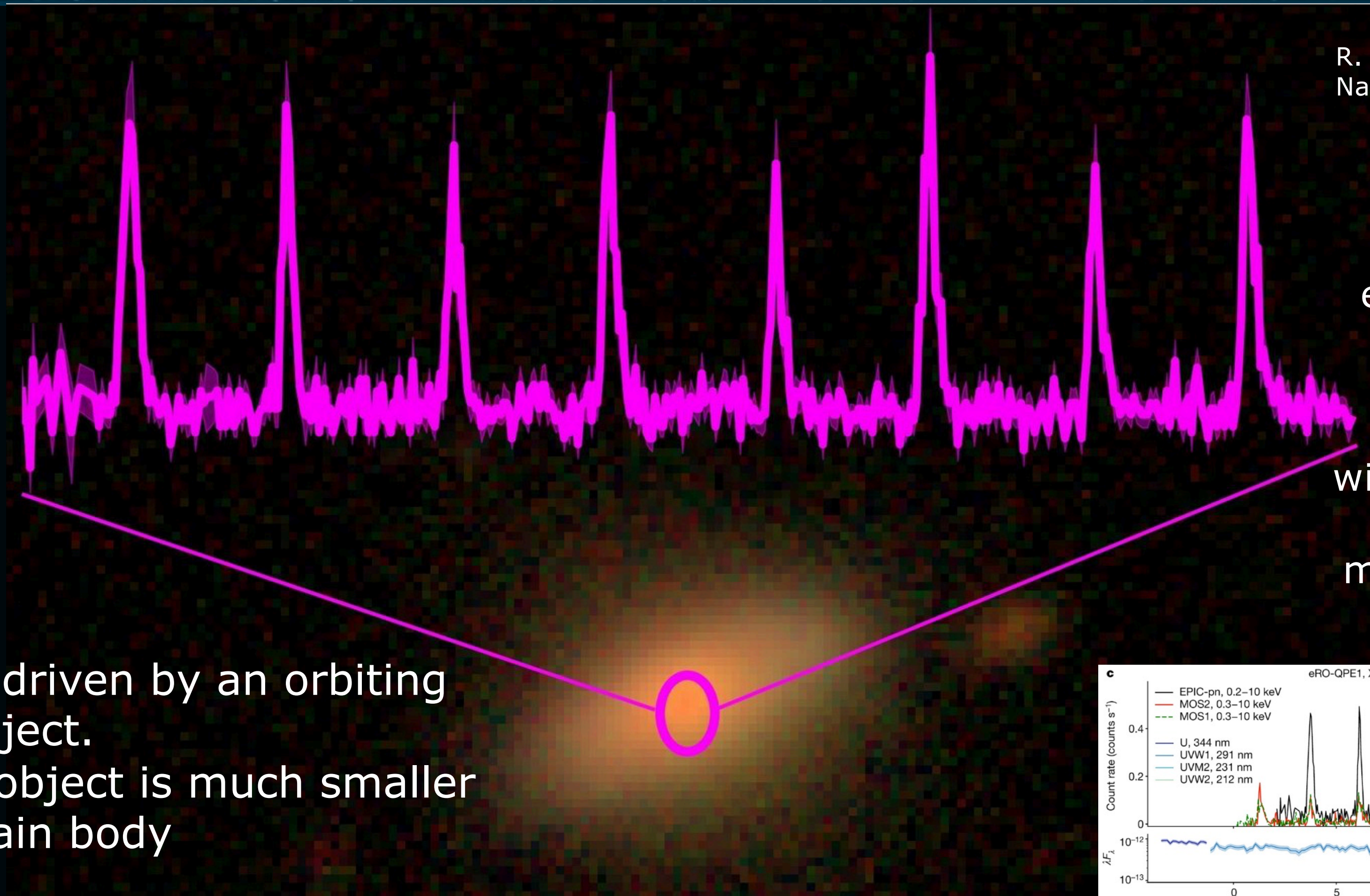
➔ break inherent degeneracy between black hole mass, inner disk radius and height of corona

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



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

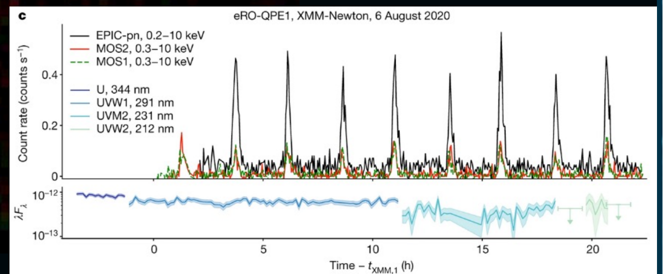
Quasi-Periodic Eruptions from Quiescent Galaxies



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

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

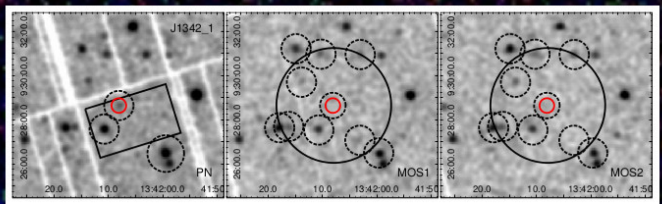
- QPEs likely driven by an orbiting compact object.
- Secondary object is much smaller than the main body



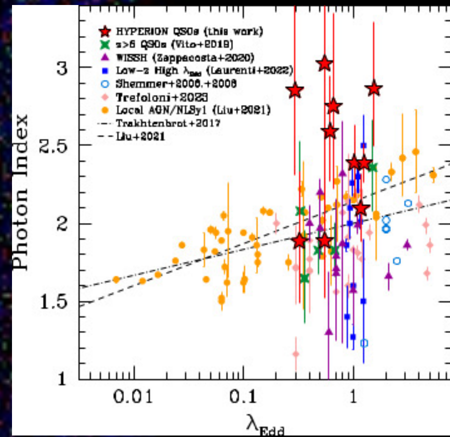
Hyperluminous Quasars at the Epoch of Reionization

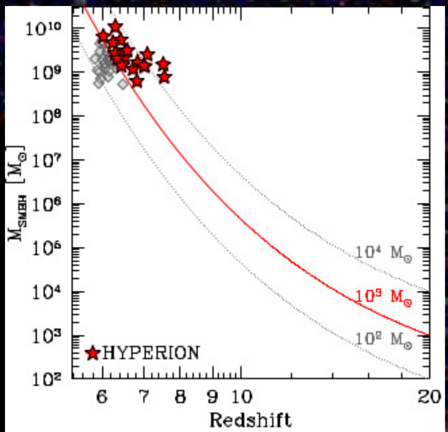
esa

10 luminous quasars (QSOs) at the epoch of reionization (z > 6) powered by well-grown supermassive black holes (SMBHs) with masses 10^9 M_{solar}

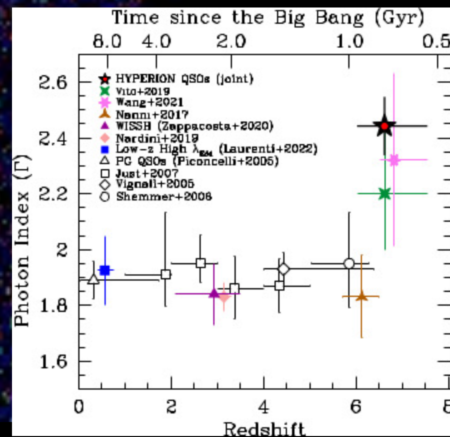


Zappacosta et al. (2023, A&A 678, 201)



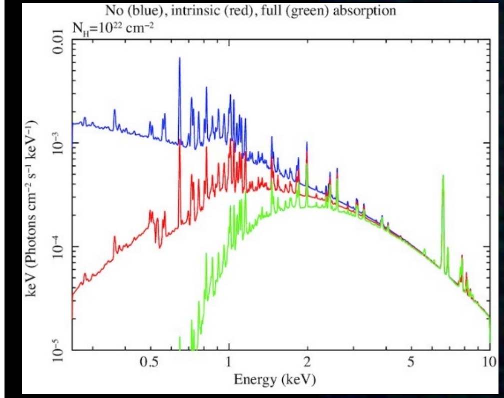


➔ steep average X-ray photon index (Γ ≈ 2.4 ± 0.1)
➔ average index inconsistent (≥4σ) with the canonical value
➔ suggesting genuine redshift evolution



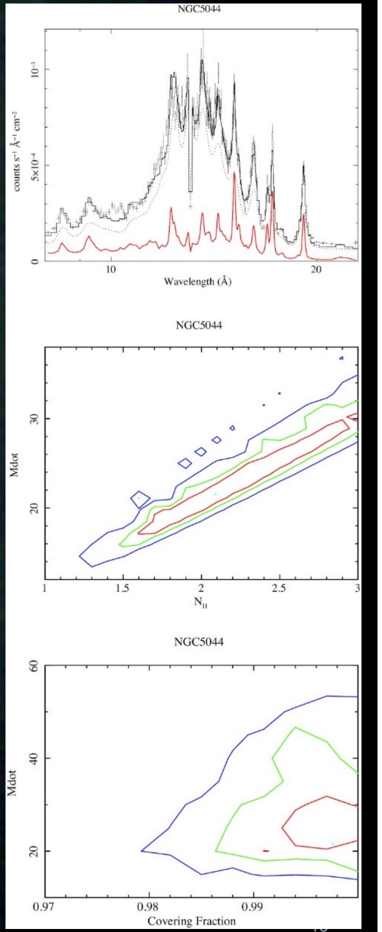
Hidden cooling flows in clusters of galaxies

- radiative cooling time of the hot gas at the centres of cool cores in clusters of galaxies drops down to 10 Myr
- observed mass cooling rate of such gas is very low, suggesting that AGN feedback is very tightly balanced or that the soft X-ray emission from cooling is somehow hidden
- XMM-Newton Reflection Grating Spectrometer spectra
- + intrinsic absorption model in which the cooling and coolest gas are closely interleaved to search for hidden cooling flows



➔ mass cooling rates of 5−40M_0/yr for the normal clusters, 1000 M_0/y or more for the extreme clusters, and 1−2M_0/yr for the elliptical galaxies

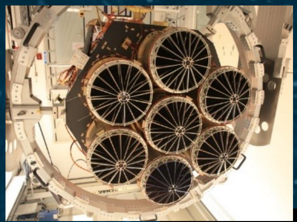
Fabian et al., 2022, MNRAS 515, 3336
Fabian et al., 2023, MNRAS 521, 1794
Fabian et al., 2023, MNRAS 524, 716F

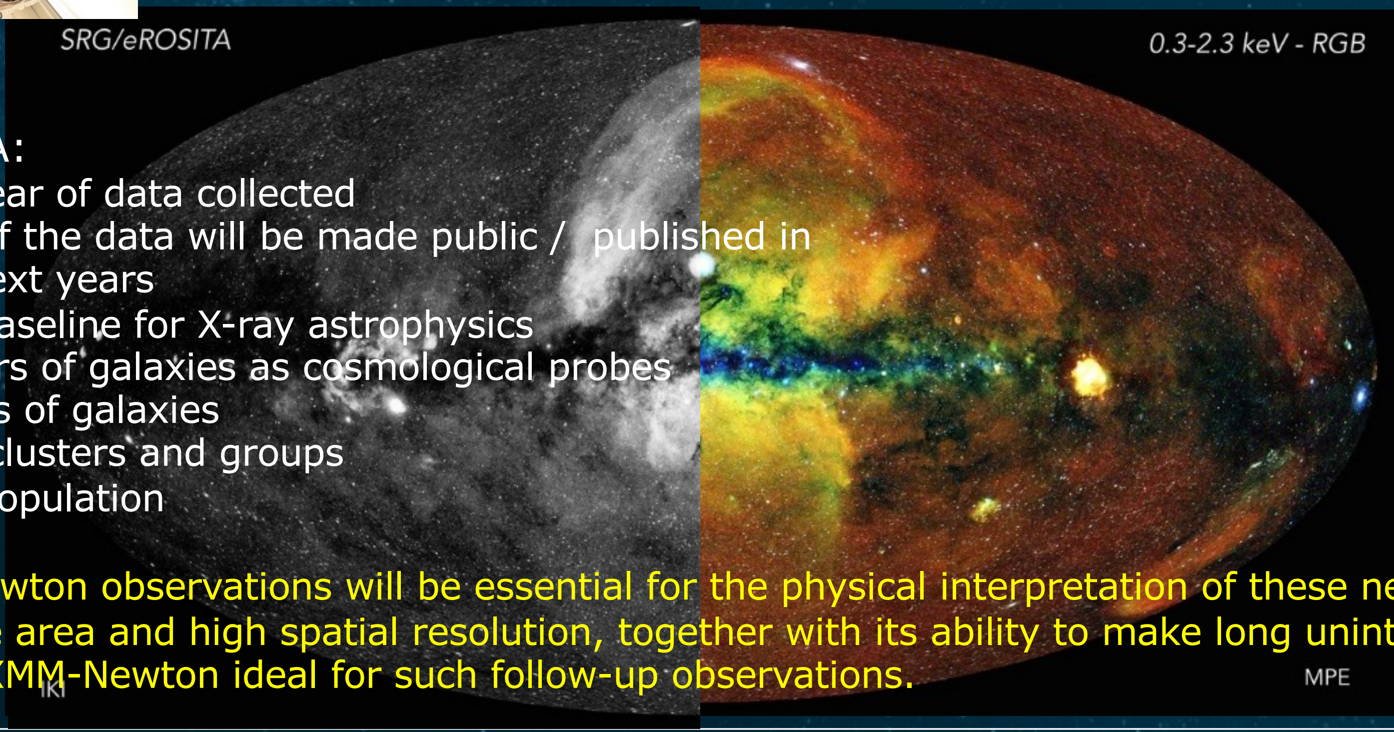


Scientific Potential of Mission Extension

A Revolution in the X-ray Sky

	ROSAT Survey	eROSITA Survey
Coverage	1 times (0.5 year)	5 times (2.5 years)
Grasp	1	2
Spatial resolution	1	~2–3 (conservative)
		~ 20 – 30 times deeper





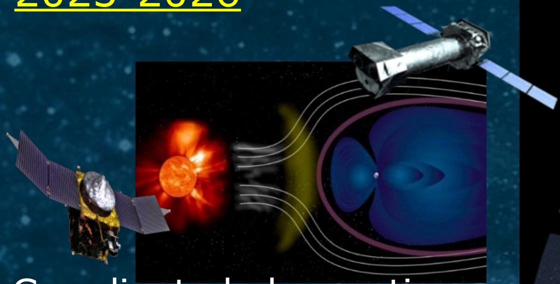
eROSITA:
- ❑ 2.5 year of data collected
- ❑ Half of the data will be made public / published in the next years
- ➔ New baseline for X-ray astrophysics
- ➔ Clusters of galaxies as cosmological probes
- ➔ Groups of galaxies
- ➔ Early clusters and groups
- ➔ AGN population

Einstein Probe (2023):
- ❑ first high-sensitivity transient monitor in the soft X-ray sky
- ➔ New baseline for X-ray transients
- ➔ Bursting binaries and AGNs
- ➔ Tidal disruption events
- ➔ GW counterparts?

XMM-Newton observations will be essential for the physical interpretation of these new sources. The large effective area and high spatial resolution, together with its ability to make long uninterrupted observations, makes XMM-Newton ideal for such follow-up observations.

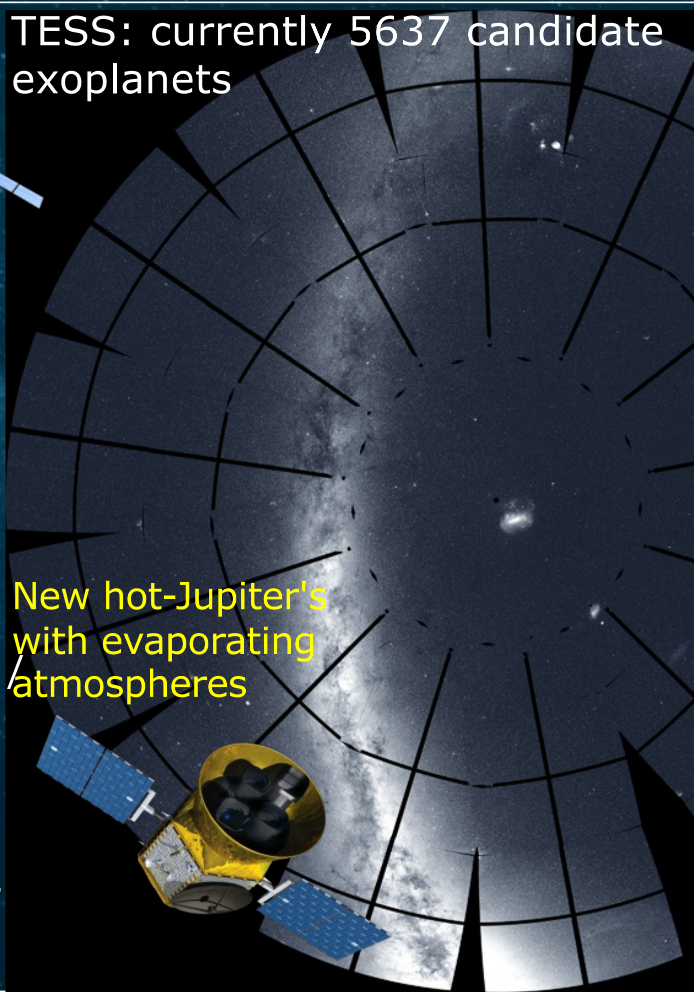
Life-Cycle of Planets and Stars

solar maximum in 2023-2026



Coordinated observations of SMILE (launch in 2024) and XMM-Newton

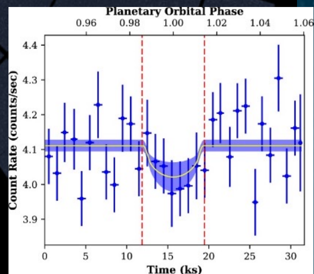
3 Nature / Science articles based on XMM-Newton - Juno



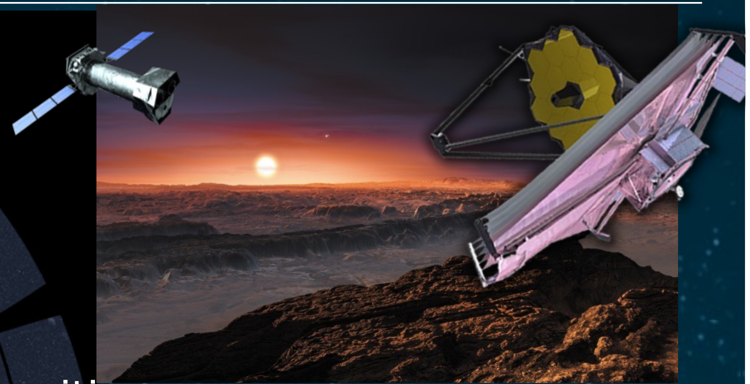
TESS: currently 5637 candidate exoplanets

New hot-Jupiter's with evaporating atmospheres

Major opportunities will come from Plato (2027) & ELT (2027).

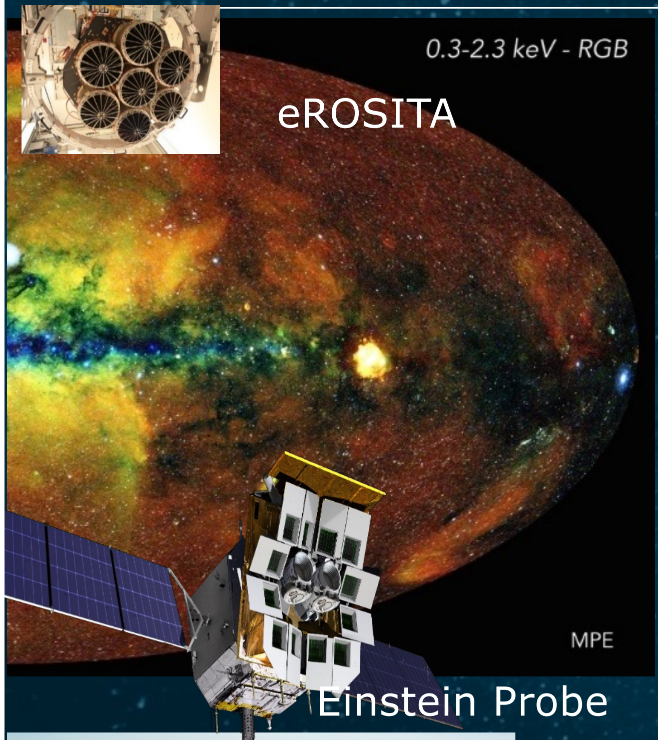


WASP-80 OM UV light curve (King 2018)



UV/X-ray irradiation of the host star directly affects the question of exoplanet habitability: major driver of photochemistry, upper atmospheric heating, atmospheric mass loss and evaporation. JWST/XMM-Newton observations are particularly promising in order to understand the chemistry of exoplanet atmospheres.

Isolated and Binary Compact Objects & their Evolution



With its high throughput and fast timing capability, XMM-Newton has a central role in the study of Galactic Compact Objects.

<u>Transients:</u>

➔ unique potential to uncover physics of entire classes of objects to what governs their evolution

➔ Interplay of accretion state, launching of winds and jets

<u>Ultraluminous X-ray Pulsars (ULXP):</u>

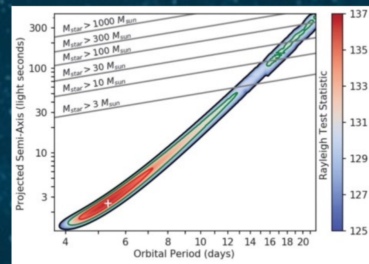
➔ high resolution spectra to study in detail the winds providing in-sights into the physical processes

<u>BH and NS statistics:</u>

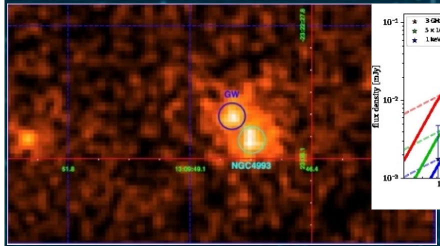
➔ Known are only the tip of the iceberg (LIGO/VIGO)

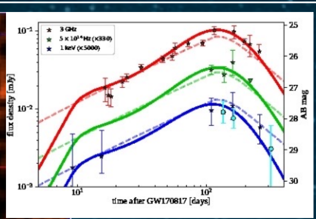
XMM-Newton's outstanding record:

- low magnetic field magnetar (Rea 2010, Science 330; Tiengo 2013 Nature)
- Transitional MSP (Papitto 2013, Nature)
- ULX (Pinto, 2016, Nature; Israel, 2017, Science)



Gravitational Wave (GW) Events, Neutrino Events and Sources emitting at Highest Energies

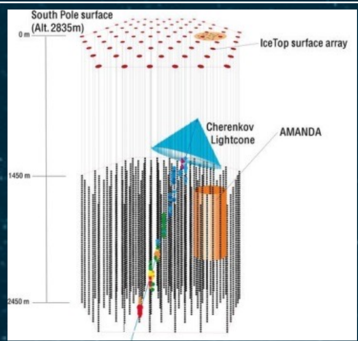




Only XMM-Newton and Chandra have the sensitivity to detect X-ray counterparts of NS-NS merger

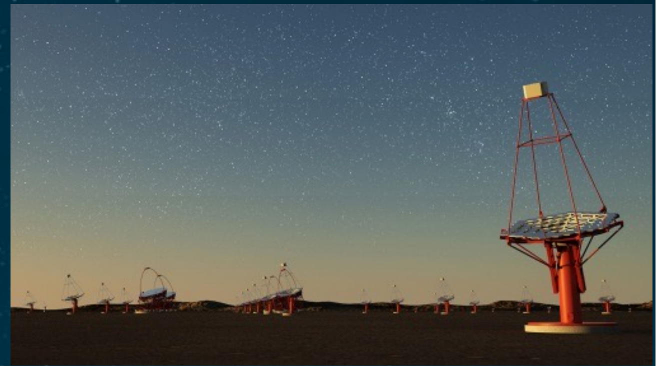
- ➔Year-long X-ray light-curves are required to unveil the bust/jet emission
- ➔Rapid TOOs to search for hyper-massive NS shortly after merger
- ➔Increased sensitivity of GW observatories implies that future GE events will be more distant and even fainter

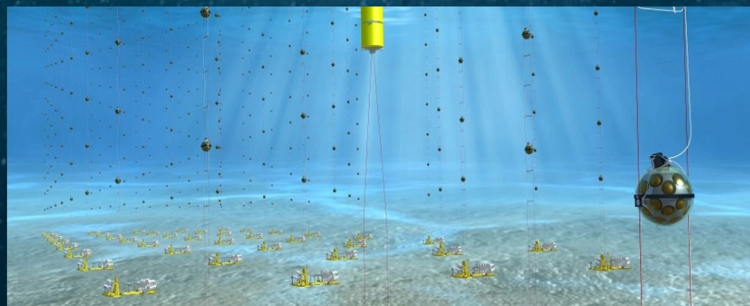
Run 4: 2023   Run 5: 2026 & 2027



As BL-Lac and jet-breakthrough in tidal disruption events, are rare, albeit strong X-ray sources

XMM-Newton is the facility of choice for future identifications due to its sensitivity in combination with large field of view





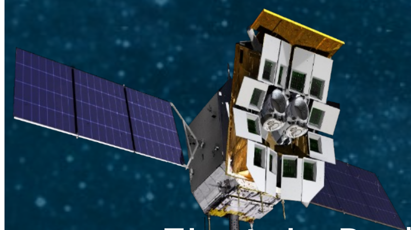
New Gamma-ray sources from H.E.S.S., MAGIC, VERITAS and CTA (from 2025) in the GeV to TeV energy range

XMM-Newton is of fundamental importance for the study of new γ and TeV-ray sources

Active Galactic Nuclei (AGN) and Tidal Disruption Events (TDEs)

eROSITA

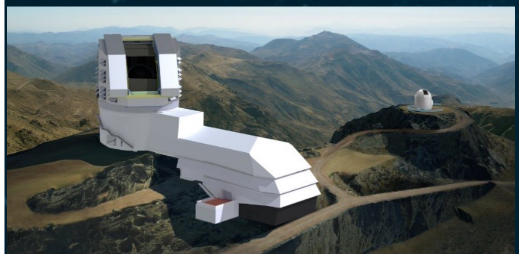
100000s of new, X-ray emitting AGNs



Einstein Probe

Revolution for TDE

Vera C. Rubin Observatory



Ultradeep X-ray reverberation mapping of AGNs have a massive untapped potential: geometry of the X-ray emitting corona, innermost stable orbit, SMBH mass and spin, disk-structure & quasi-periodic-oscillation

Event Horizon Telescope (EHT), Gravity, ELT (2027) and their update

Only XMM-Newton has the required effective area to perform such studies (further enhanced when observed simultaneously with NuSTAR)

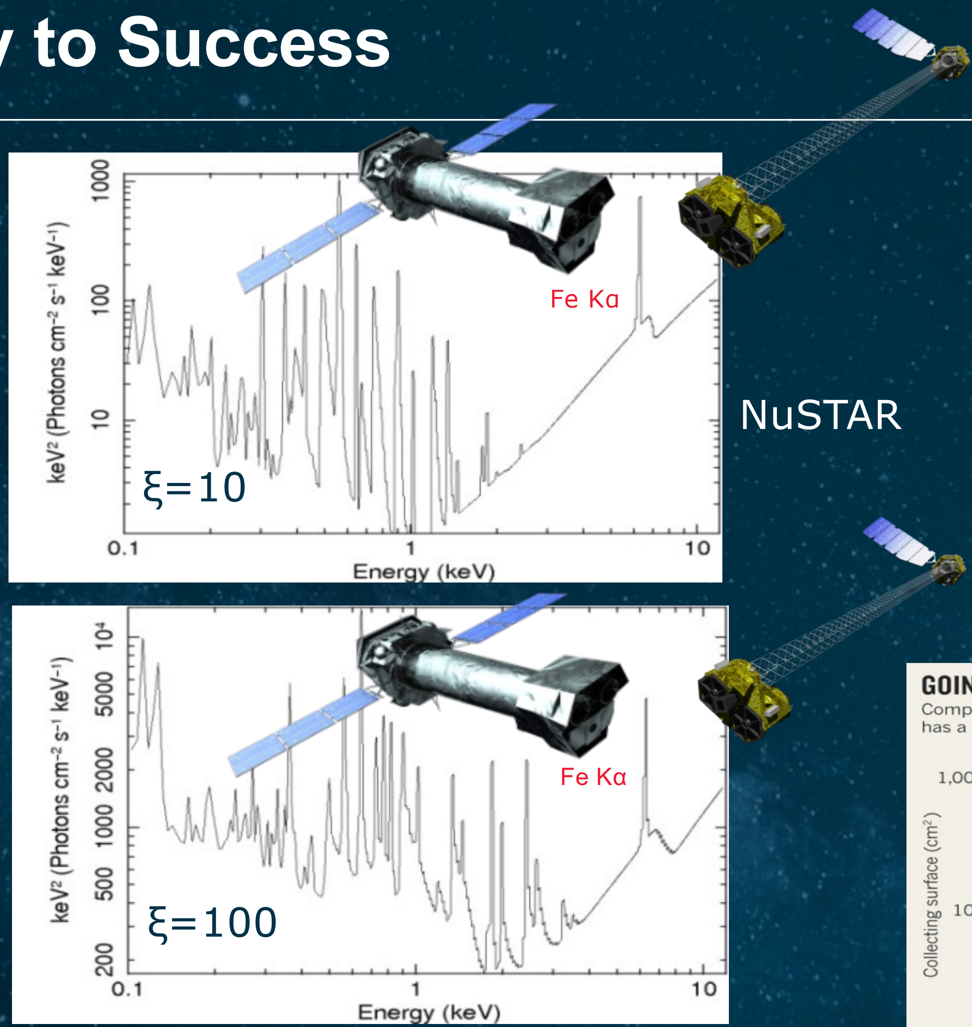
AGNs allow to study the physics of the outer disk e.g. the launching of outflows, winds and jets

Iron (Fe Kα): the Key to Success

Only XMM-Newton has the required high effective area in combination with the ability to make long uninterrupted observations.

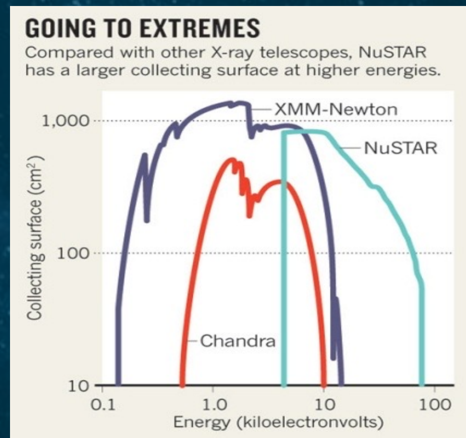
❑In addition, simultaneous observations with NuSTAR enable an accurate determination of the underlying continuum something that cannot be easily achieved by any other combination of satellites, especially for weak sources.

❑ Typically 20% of XMM-Newton high priority time (priority A and B) is being observed simultaneously with NuSTAR



Fe Kα:

- ❑ High abundance
- ❑ High emissivity
- ❑ High energy
- ❑ Line is isolated

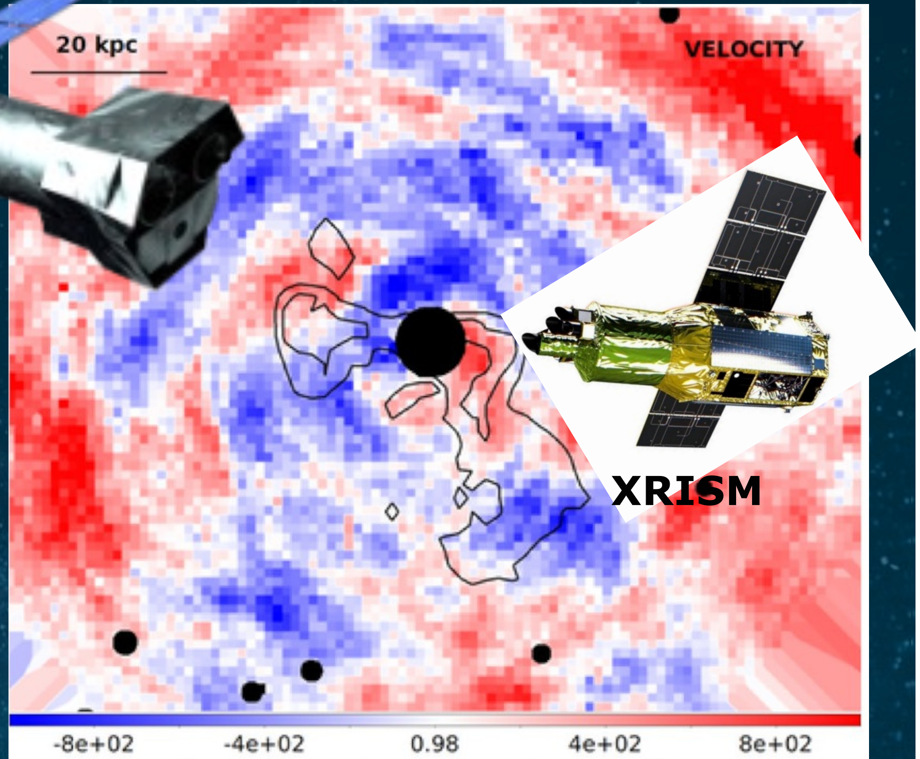


Galaxies and Clusters of Galaxies (CG)

esa

XMM-Newton is best suited to study the CG detected by

- ❑ eROSITA
- ❑ Euclid (2023)
- ❑ CG at high redshift
- ❑ proto-clusters at z~2
- ❑ follow-up of Euclid-weak lensing selected system
- ❑ thermodynamic properties (in combination with Sunyaev-Zeldo'vich experiments (SZE)
- ❑ shock conditions in radio relics (in combination with SKA & its pathfinders)

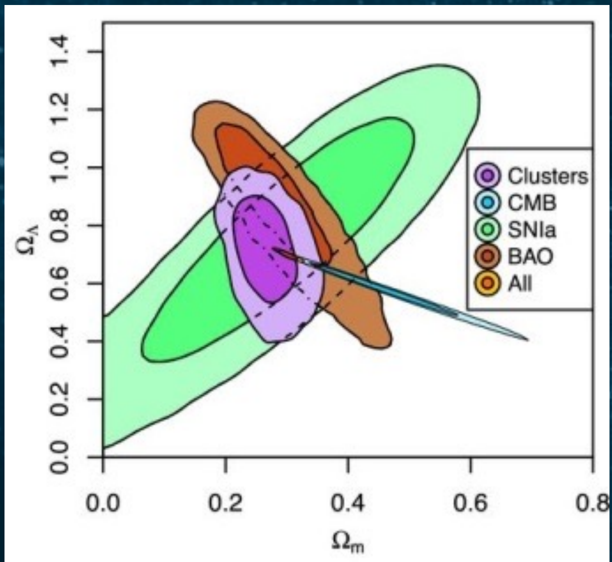


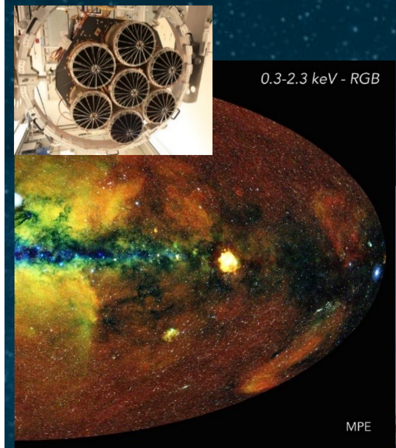
XMM-Newton is the most sensitive instrument for the detection of weak extended sources.

XMM-Newton pn velocity structure of Virgo CG (Ganuzzi, 2022, MNRAS 511, 45) reaching $\Delta v \sim 100 \mathrm{km\ s}^{-1}$

Tests of Cosmological Models

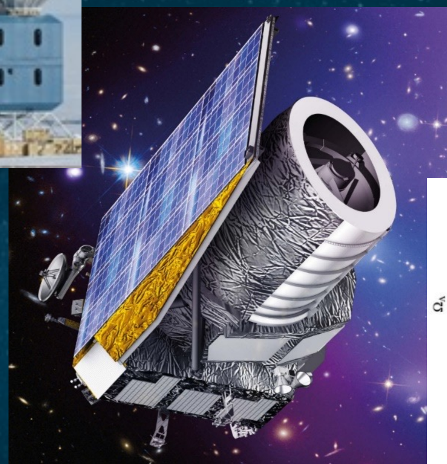
The tightest constraints on the cosmological parameters are only obtained by combining results based on super-novae, cosmic microwave background and clusters of galaxies



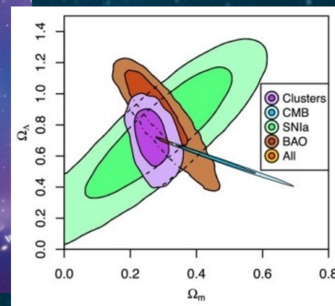


eROSITA

SZ (e.g. South Pole Telescope)



Euclid



XMM-Newton is vital to define precisely the CG structure. The XMM-Newton follow-up in combination with strong and weak, will lead to significantly tighter constraints on the CPs and shed light on a possible anisotropy of the cosmological structure

Hyperluminous Quasars at the Epch of Reionization