Future X-ray instruments relevant to CTAO science

Credit: IRAP, CNES, ESA & ACO

Matteo Guainazzi

NewAthena & XRISM ESA Project Scientist

“We all were sea-swallow'd, though some cast again
(And by that destiny) to perform an act
Whereof what's past is prologue what to come,
In yours and my discharge.”

William Shakespeare, “The Tempest”

Outline

Piro et al., 2022, Exp. Astr., 54, 23

1. Fundamentals of X-rays/γ-ray synergies
2. Science cases
   - SNR
   - AGN
   - GRB
3. Synergies with:
   - NewAthena [and XRISM]
   - THESEUS [and *Einstein Probe*]

Chapter on CTAO and ν written by: M. Ahlers, A. Coleiro, E. de Oña Wilhelmi, J. Vink, P. Padovani.

Athena

Multi-messenger-*Athena* Synergy White Paper

Multi-messenger-*Athena* Synergy Team

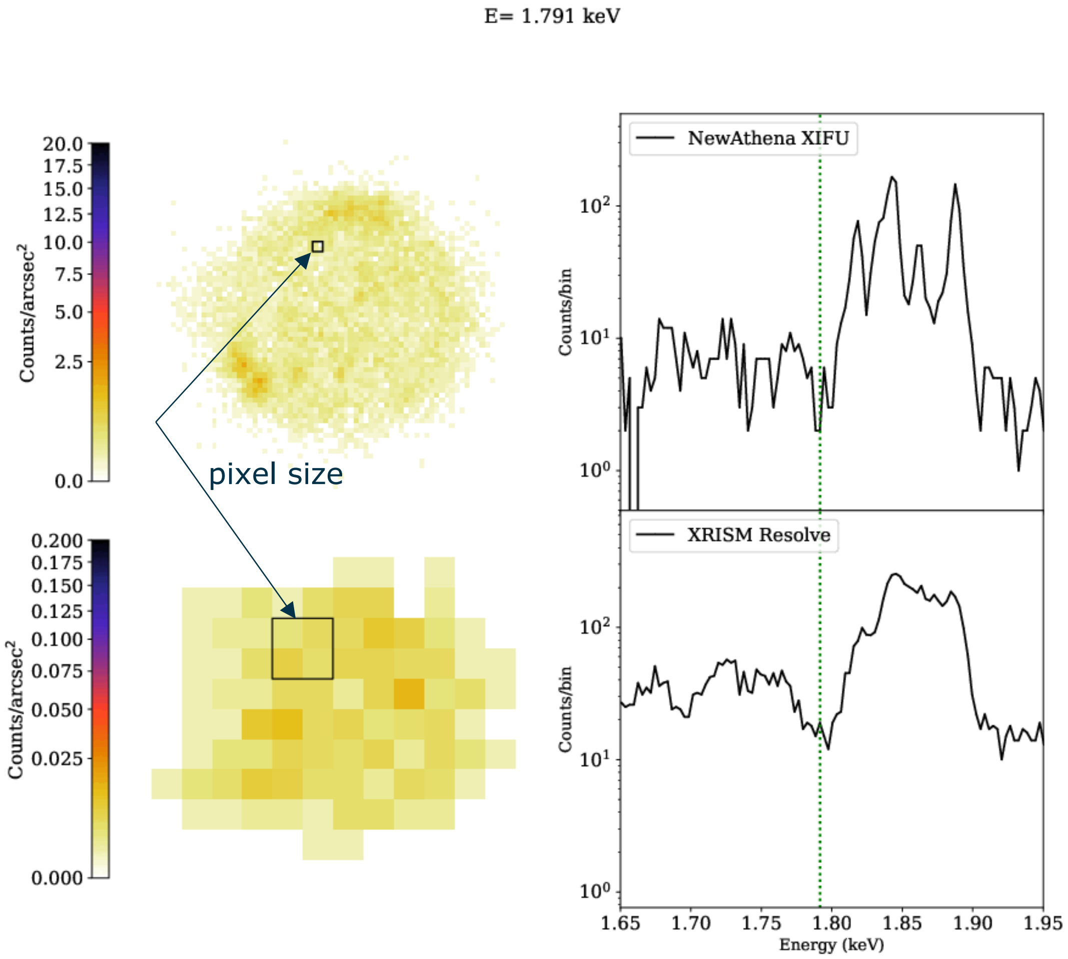
General principles of X-ray/γ-ray synergies

- **Synchrotron-emitting leptons (e^-)**
  - Probing (fast) acceleration conditions "on the act"
  - Identify sources of inverse Compton up-scattering (up to the γ-ray regime)
  - Complete the Cosmic Ray energy budget
  - Help disentangling (in principle) hadronic from leptonic γ-ray emission
    - Synchrotron brightness $\approx n_e U_B$
    - γ-ray brightness $\approx n_e U_R$
    - Assuming single-zone leptonic emission → B → verify leptonic hypothesis
  - Determination (with radio) of the spectral index of electronic population
    - → intrinsic γ-ray spectral index → Extra-galactic Background Light estimate
- **Thermal emission associated with regions of particle accelleration**
  - X-rays warrants higher-spatial resolution
  - Mapping of local plasma and radiation energy densities

Integral field unit capabilities in X-rays

Credit: F. Acero (CEA) & C. Kirsch (FAU)

Cassiopea A (X-ray bright SNR)



cf. H. Nakajima's talk

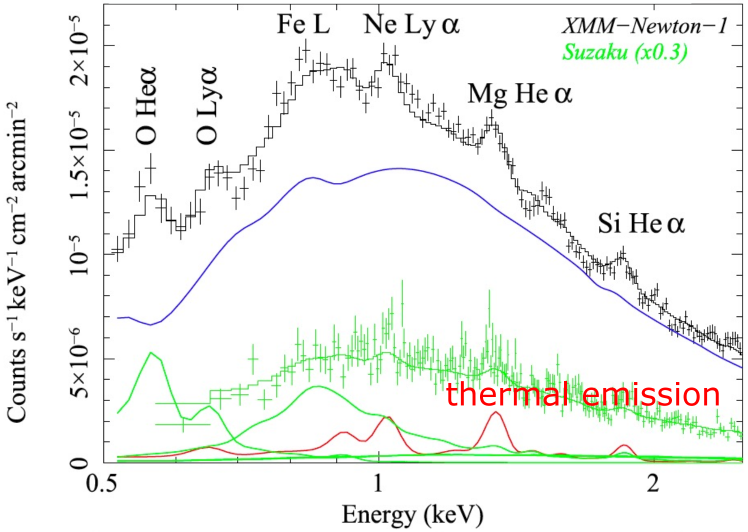
XRISM *Resolve*
ΔE≤5 eV*
35 pixels, 30" side
Operational (2023-)

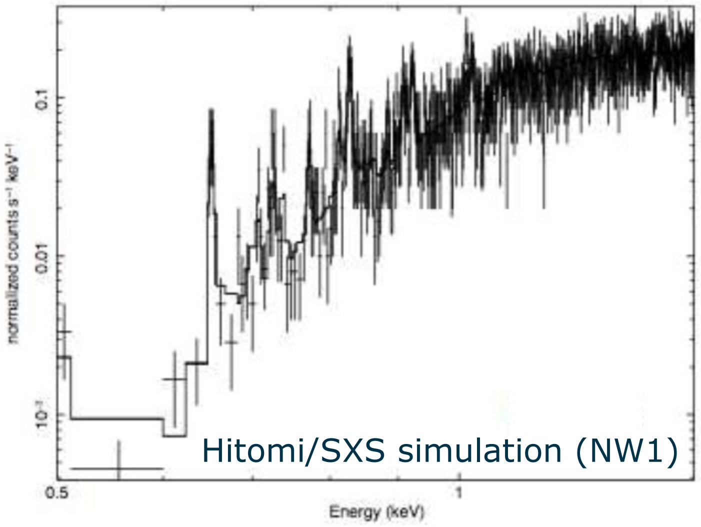
NewAthena X-IFU
ΔE≤4 eV
~1500 pixels, 5" side
Launch ~2037

*7 eV (requirement) shown

Thermal emission in SNR synchrotron-dominated regions

Katsuda et al., 2015, ApJ, 814, 29; Hughes et al., 2014, arXiv:1412.1169



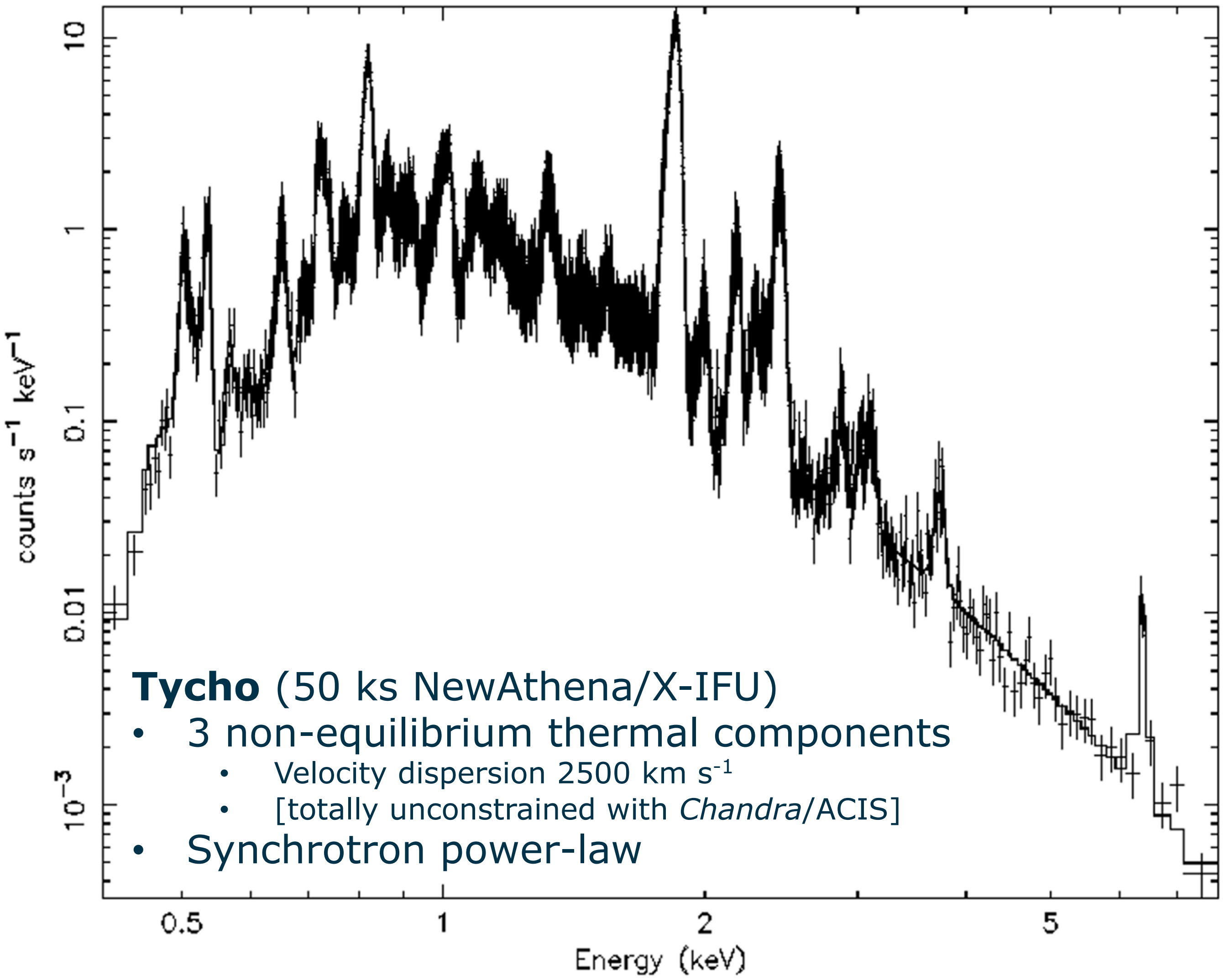


- Detecting thermal emission in synchrotron-dominated SNR regions is hard with CCD resolution
  - In the example: RXJ1713.7-3946
- Lack of density estimation prevents constraining the hadronic contribution to the γ-ray emission
- **Spatially-resolved, high resolving power is crucial**
  - [Note: *Hitomi*/SXS is the same technology as XRISM/*Resolve*]
- Enables measurements of density and composition of the SNR as a function of position
- Mapping of young SNR (*e.g.*, SN1006, Tycho,) in the observation plans of XRISM and *Athena*

Ion temperature and CR accelleration efficiency

Credit: L. Godinaud, A. Decourchelle, F. Acero (CEA)

Vink et al., 2010, ApJ, 722, 1727



Tycho (50 ks NewAthena/X-IFU)

- 3 non-equilibrium thermal components
  - Velocity dispersion 2500 km s^{-1}
  - [totally unconstrained with *Chandra*/ACIS]
- Synchrotron power-law

- Line profiles contraints thermal Doppler broadening → T_{ion}
- Likely to dominate at the SNR edges
- Link to CR accelleration efficiency in shocks:

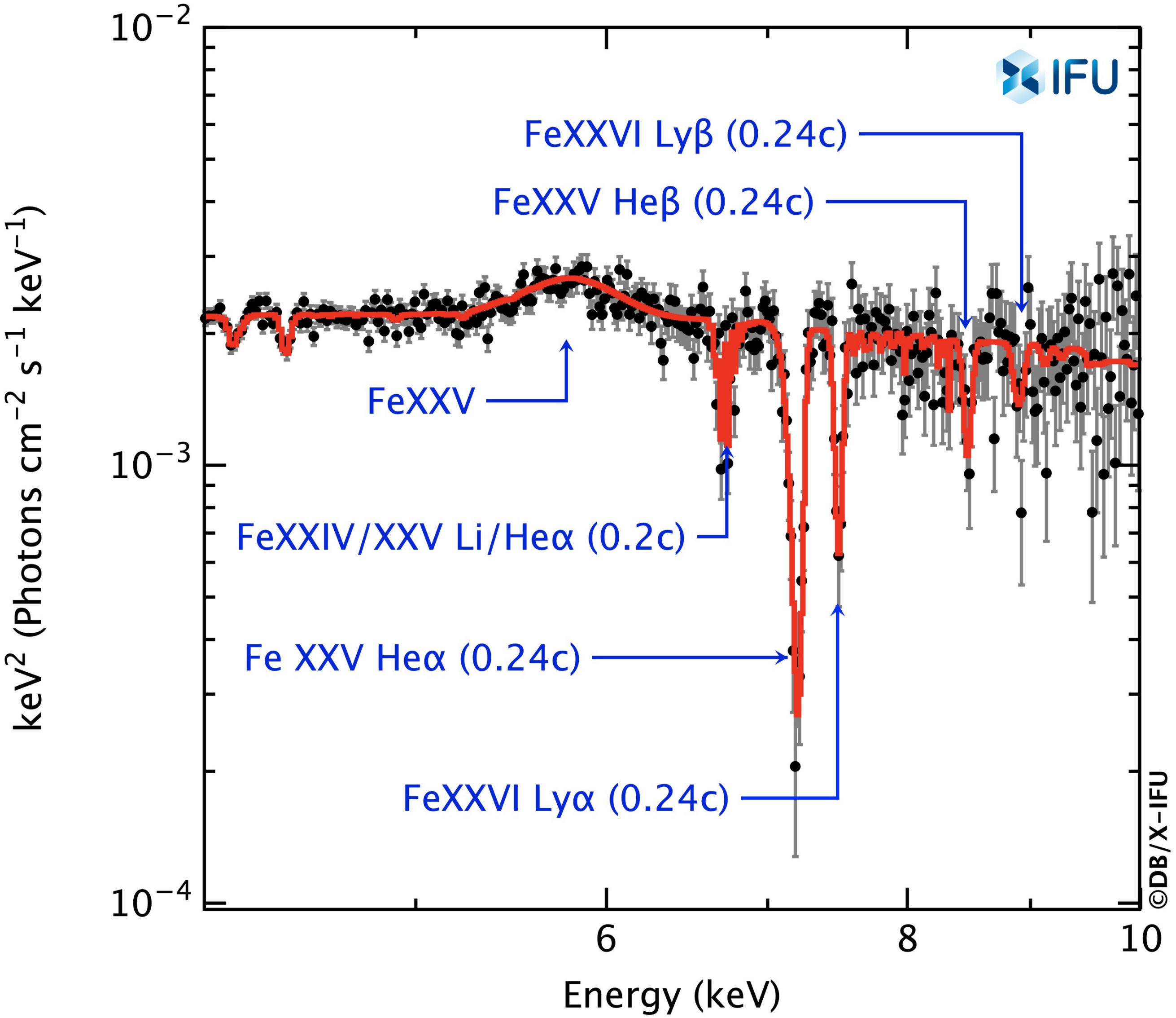
$$k_B T_2 = \frac{1}{\chi_{12}}\left(1 - \frac{1}{\chi_{12}}\right)\mu m_p V_s^2 = \frac{3}{16}\mu m_p V_s^2$$

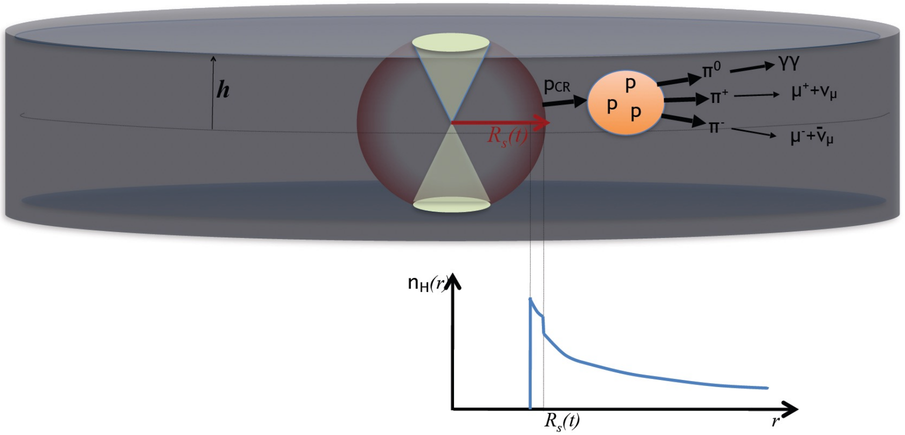
- Requires knowledge of shock velocities, measured by *Chandra* in many young SNRs
- Probably only NewAthena science

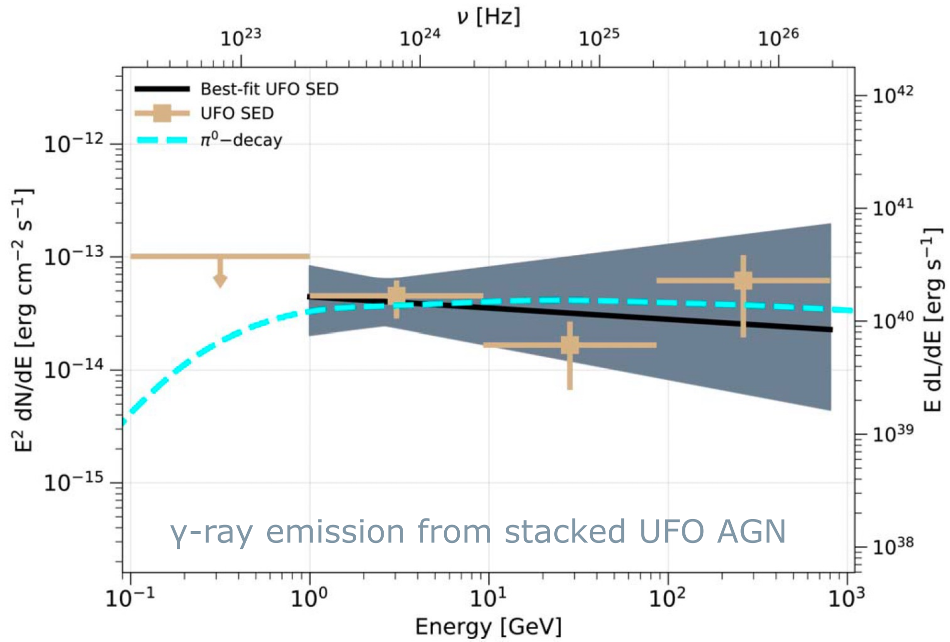
Ultra-Fast Outflows (UFOs) in AGN

Credit: X-IFU Consortium

Lamastra et al., 2017, A&A, 607, 18; Aiello et al., 2021, ApJ, 921, 144



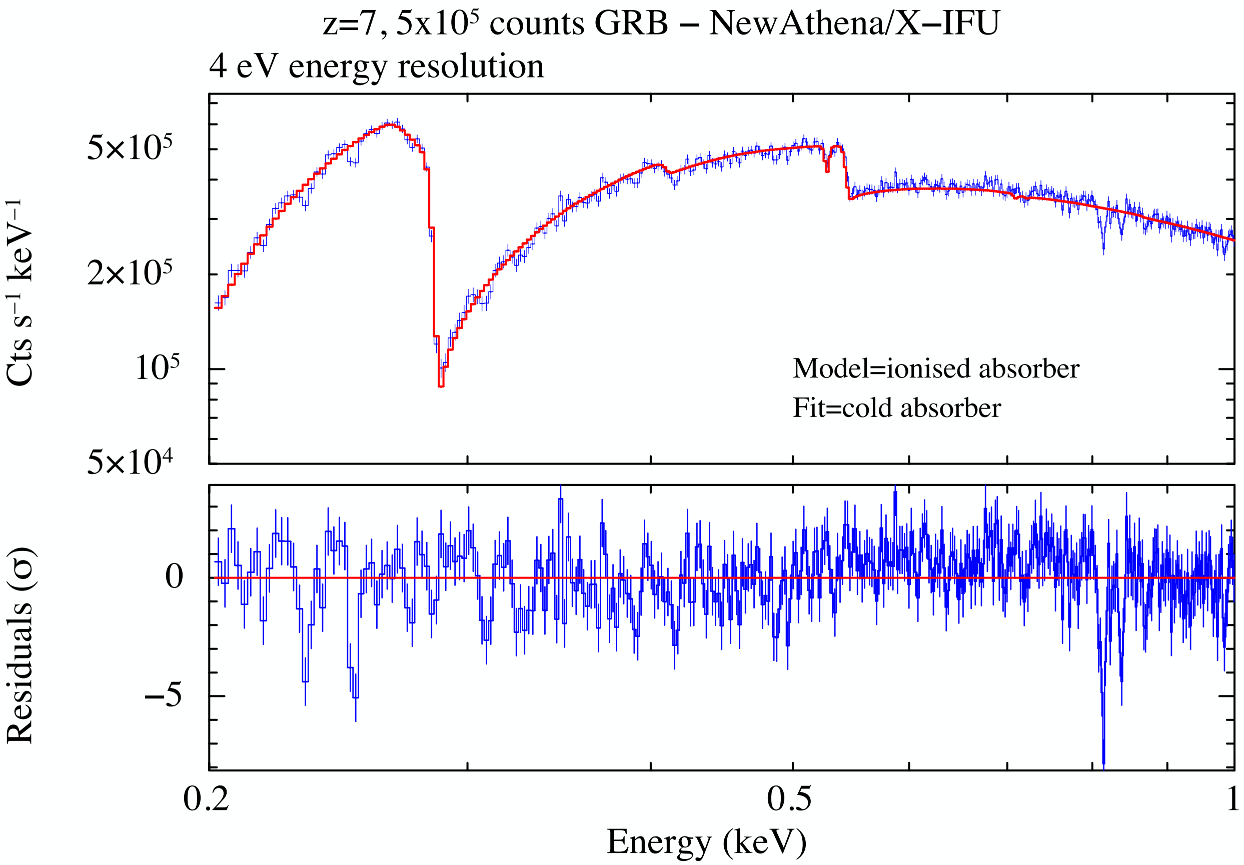




Long GRBs

Credit: A. Thakur, L. Piro (IAPS), M. Guainazzi (ESA)

- Candidates for extragalactic CR
- Prompt emission:
  - X-rays: relativistic leptons
  - γ-rays: shocks in jets
- Afterglows: jet interaction with the circum-/interstellar medium
- X-ray absorption lines → close GRB environment:
  - First generation of stars
  - Generation of the first BH
  - dissemination of the first metals
- X-ray non-thermal component → constrain emission mechamisms



Other sources for NewAthena/CTAO synergies

Piro et al., 2022, Exp. Astr, 54, 23

- ”Superbubbles” in star forming regions
- Nearby (<10 Mpc) supernovae
- Pulsar Wind Nebulae
- Starburst galaxies
- Accretion shocks in clusters of galaxies


Athena

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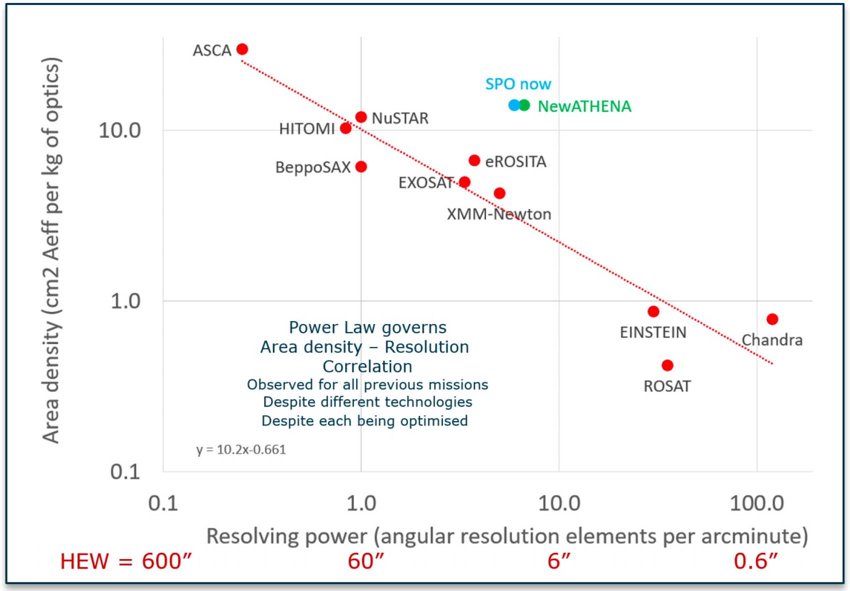
NewAthena: three key science-enabling innovations

Bavdaz et al. 2023, SPIE, 1267902-1

Credit: D. Barret (IRAP)

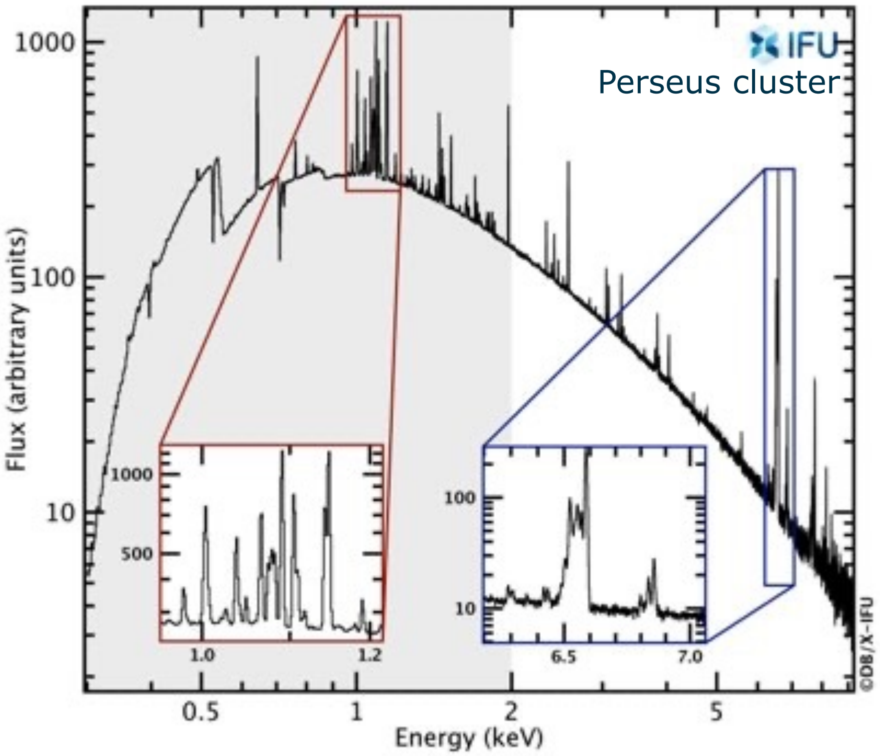
Credit: A. Rau (MPE)

The largest space-qualified X-ray mirror for astronomy



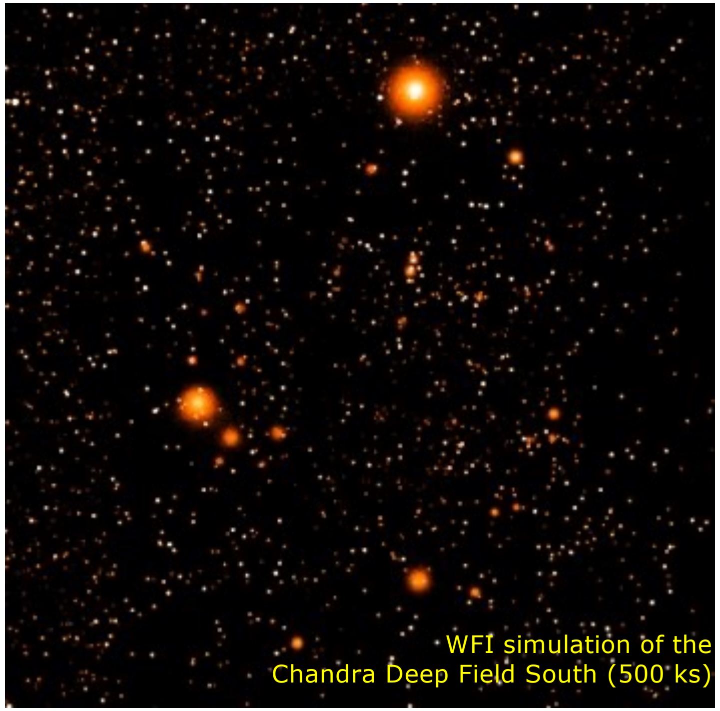
X-ray telescope based on Silicon Pore Optics technology (ESA), 9” HEW, 1.0 m^2 area @1 keV

Unprecedented spectroscopic capabilities



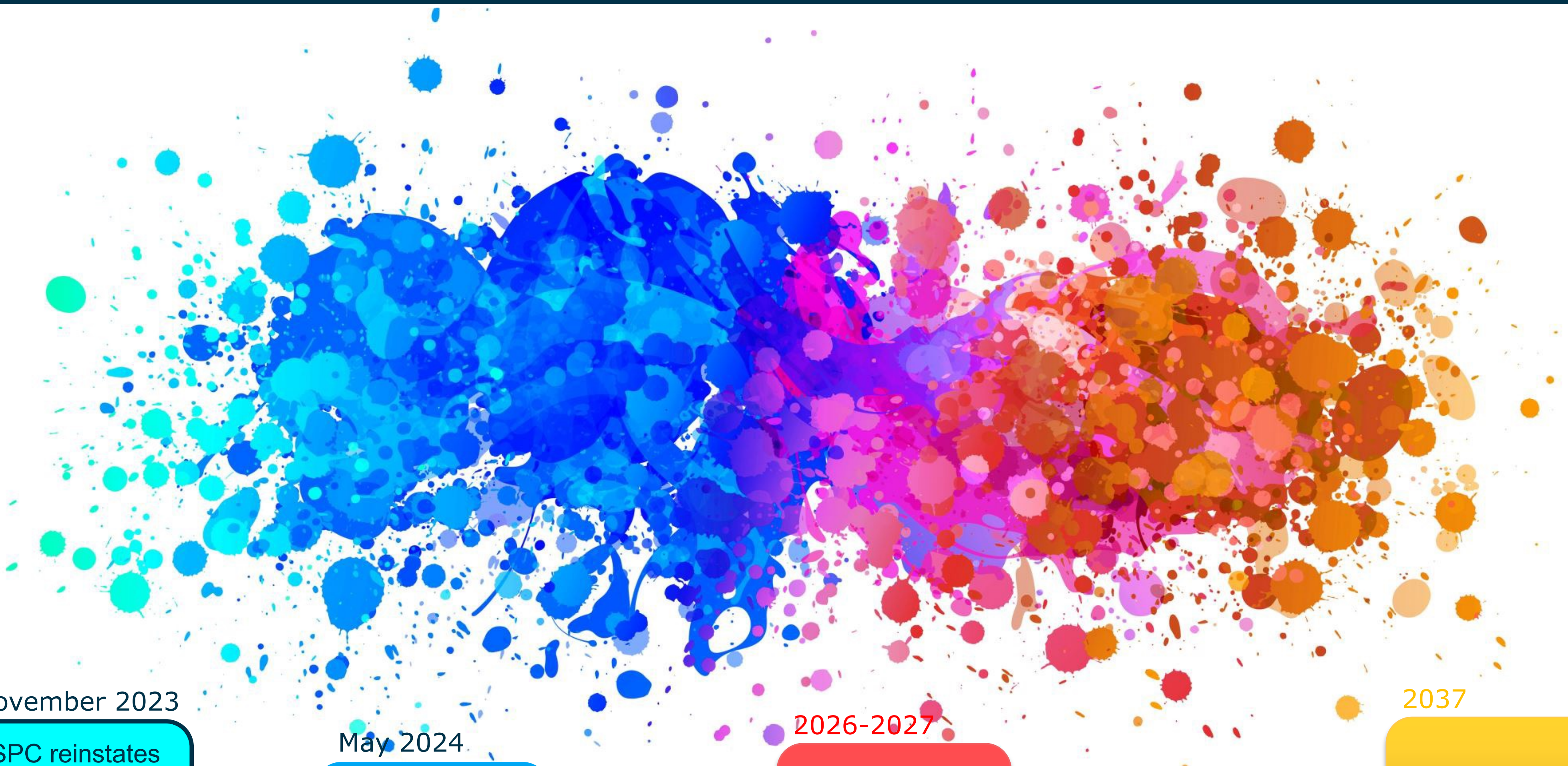
X-Ray Integral Field Unit (X-IFU) (CNES/IRAP-led), ≤4 eV energy resolution over >1500 pixels, ~5” each (4’ effective diameter FoV)

The fastest sky X-ray survey machine



Wide Field Instrument (WFI) (MPE-led), DEPFET sensor, <170 eV resolution @7 keV, 40’x40’ FoV

NewAthena status (diagram created by AI, not in scale)



November 2023

SPC reinstates the mission in the Science Program

May 2024

Start of industrial Phase A

2026-2027

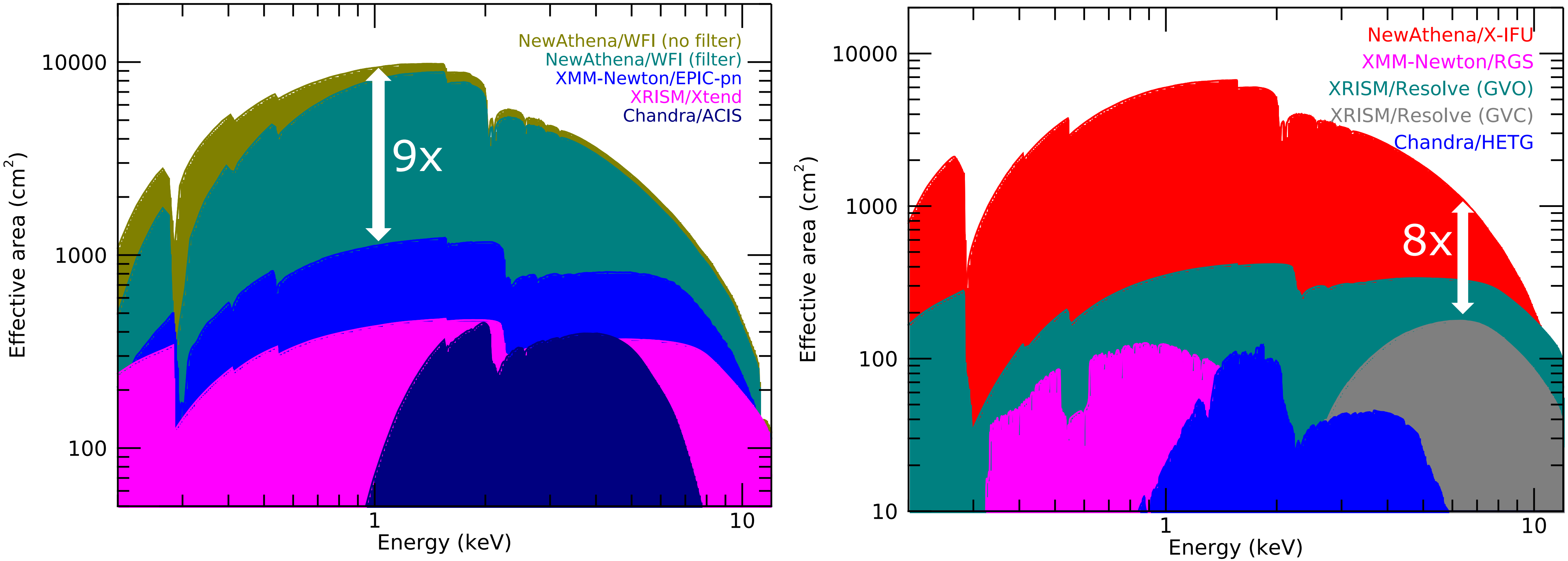
Adoption

2037

Launch

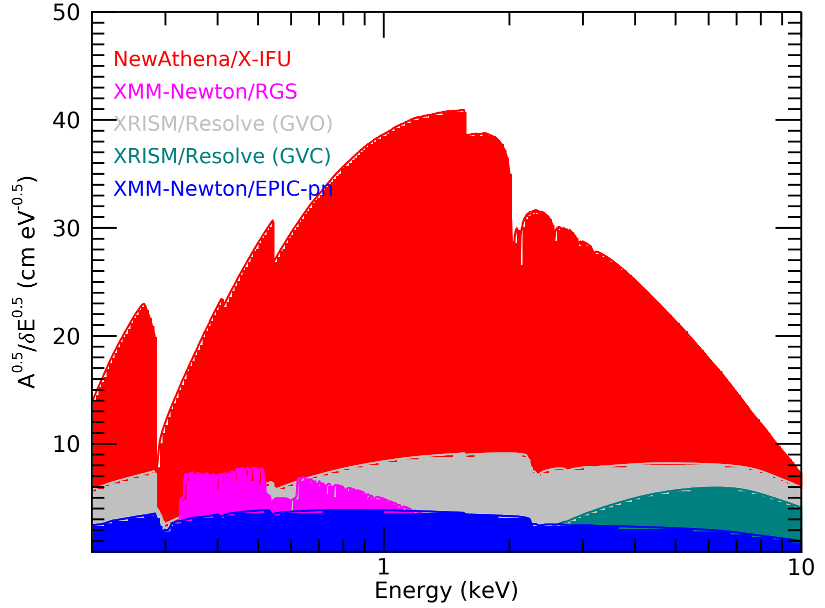
A large mirror area mission

Comparison with commensurate operational X-ray observatories

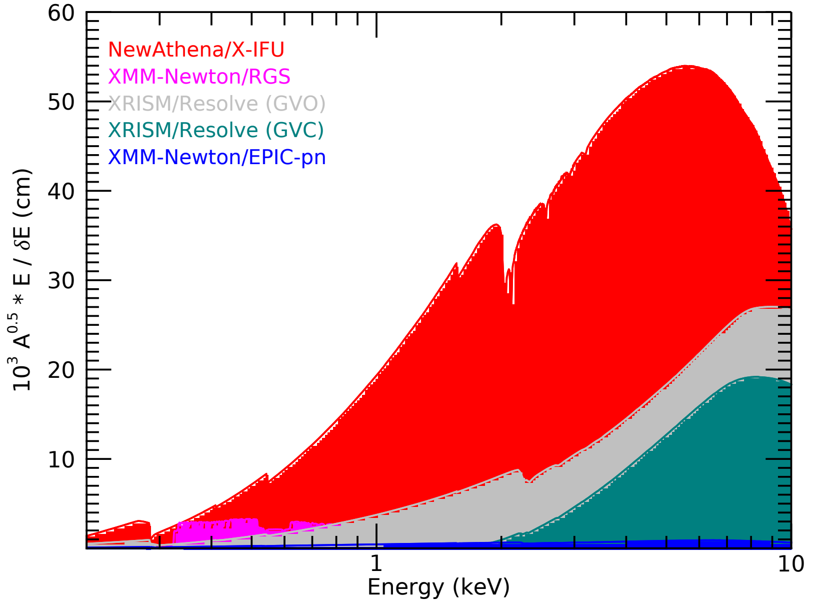


X-IFU spectroscopic capabilities in context

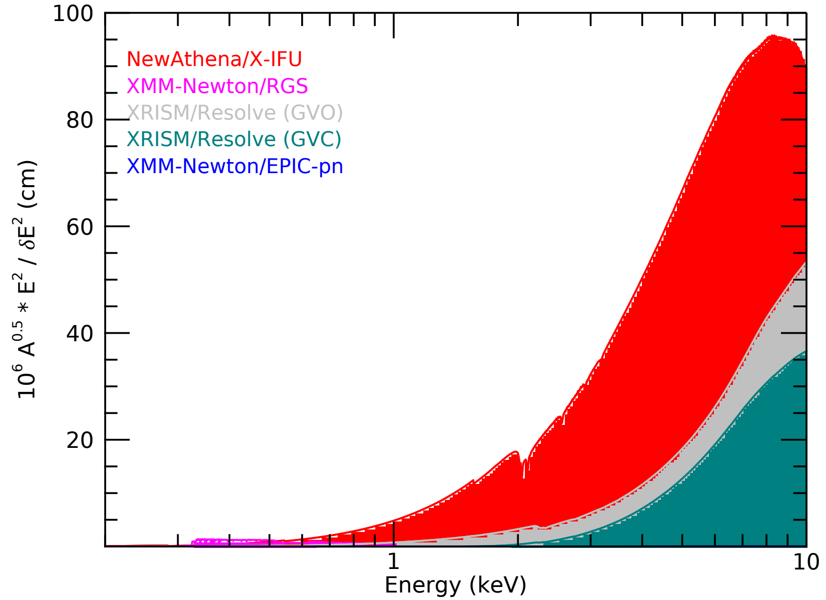
Detection weak lines



Velocity strong lines



Broadening strong lines



Detection
Velocity
Broadening

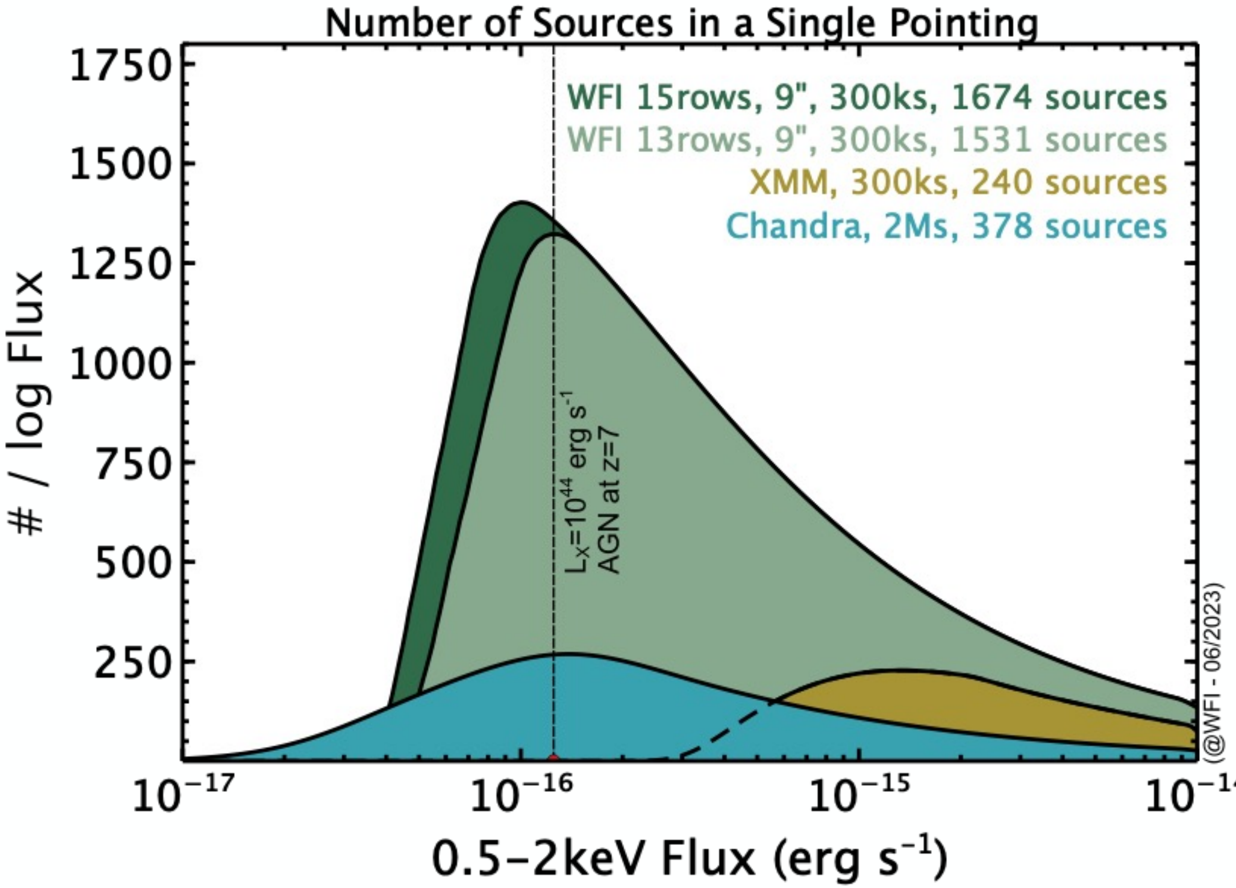
FoM	Strong line	Weak line
M_l	6.1	6.8
M_v	7.5	8.4
M_σ	9.1	10.2

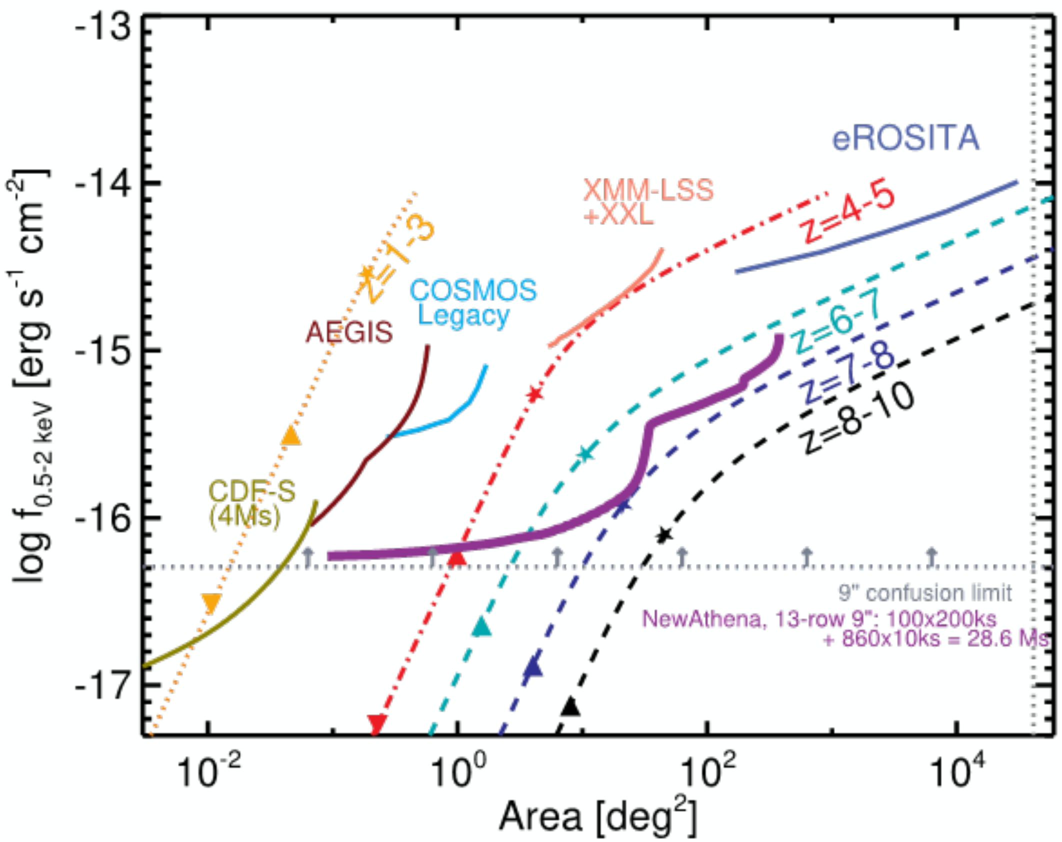
Energy-weighted 2-9 keV ratio between X-IFU and *Resolve* FoMs

NewAthena X-ray survey performance (WFI)

Credit: A. Rau (MPE), J. Aird (UoE)

Credit: J. Aird (UoE)





Hint: the NewAthena/WFI grasp exceeds that of eROSITA by a factor ~2

Einstein Probe (operational)

Credit: CAS

- China/CAS-led mission with participation by ESA and MPE
- Combination of wide-field (~1.1 sr) and narrow ("follow-up" telescopes in the soft X-ray band
- Rapid downlink and uplnk capabilities
- Science pillars:
  - Soft X-ray transients
  - Transient flares from quiescent super-massive black holes
  - Multi-messenger astrophysics
- Launch: **January 2024**: 3-years nominal operations

THESEUS (M7 candidate)

Credit: ESA

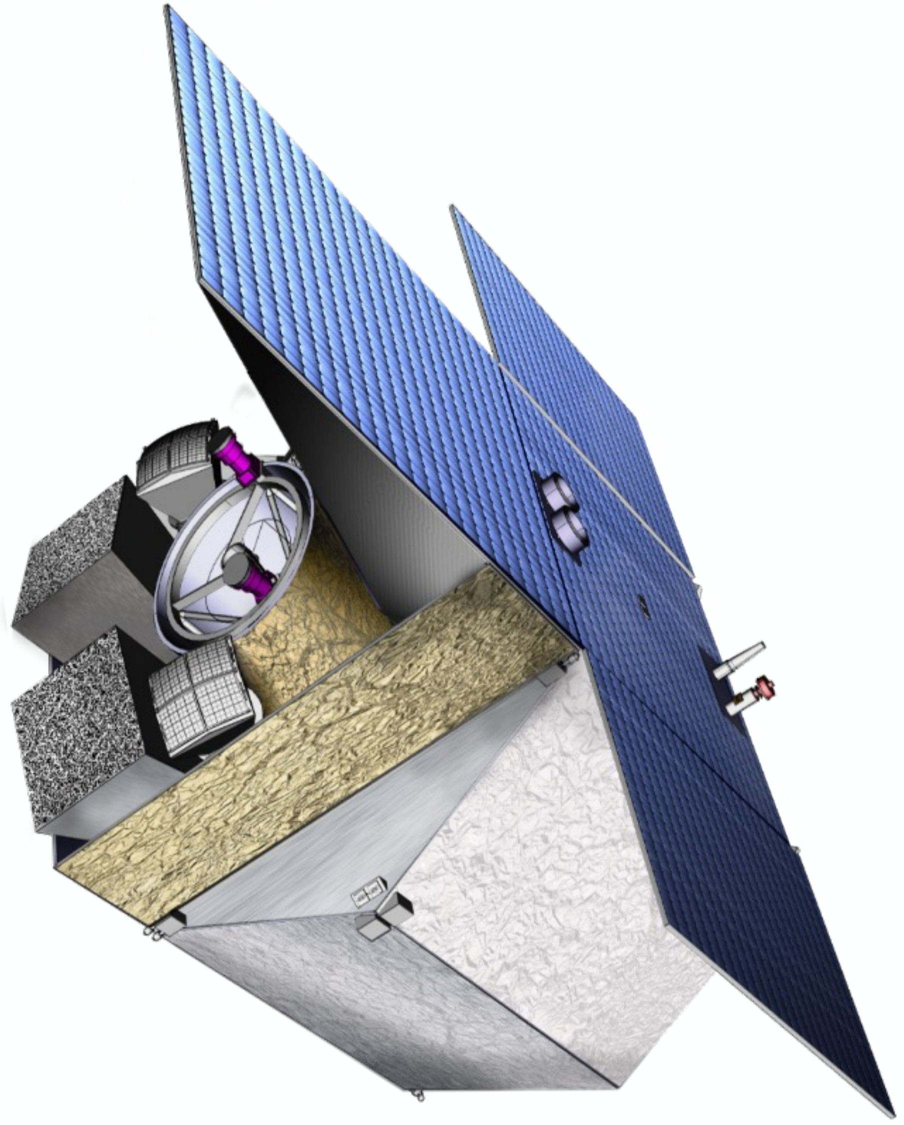
- Candidate ESA mission for the “M7”-slot
  - Three missions in competition

- Payload:
  - Wide-field monitors 0.3 keV to ~20 MeV
    - Broad field-of-view (~sr)
    - Arcminute-level source localization
  - 70-cm class IR telescope

- Autonomous repointing capabilities (≤10 mins.)

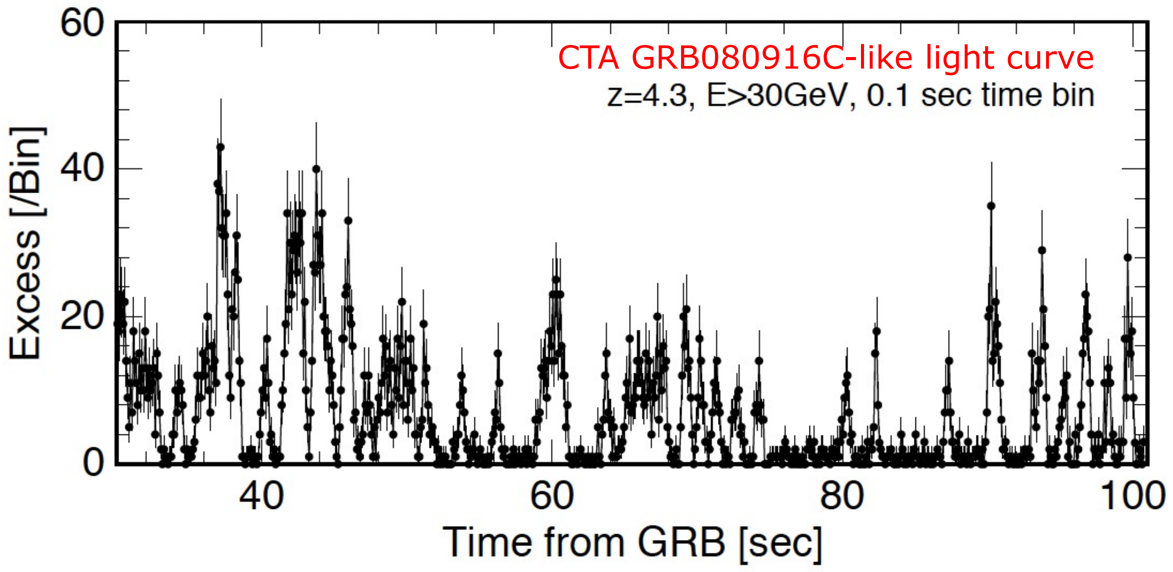
- Science pillars:
  - Early Universe GRBs
  - Multi-messenger astrophysics
  - The transient X-ray sky

- **Selection ~2026, launch ≤2037**



THESEUS/CTAO synergies

Bernardini et al., 2018, Mem.S.A.It., 75, 282



External trigger, accurate location and *z* for GRBs, TDEs, supernova breakouts, XRBs, AGN flares, multi-messenger transients

CTAO THESEUS-triggered GRB detection rate **5-10 GRB/site/year**

Broad-band characterization of high-energy transients in the CTAO Key Science Projects

… more in the poster by L. Amati

Take-home message

Aharonian et al., 2007, ApJ, 2007, 661, 236

Whatever your favourite CTAO science question:

Multi-messenger astrophysics

Nature of relativistic particle populations

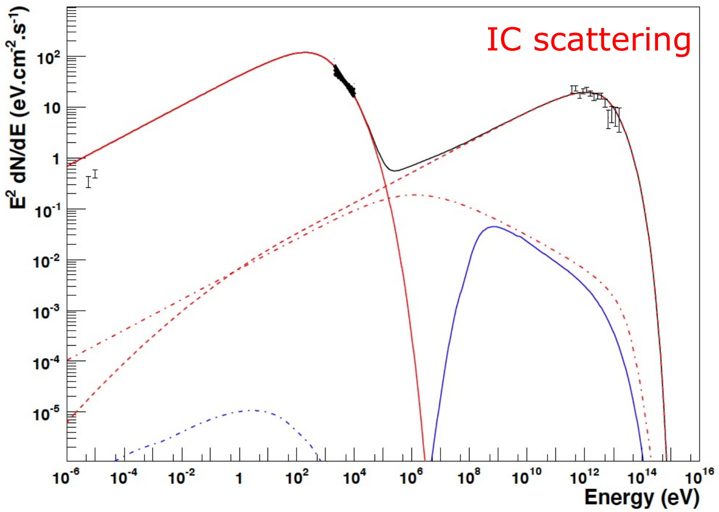
Particle accelleration and their environment

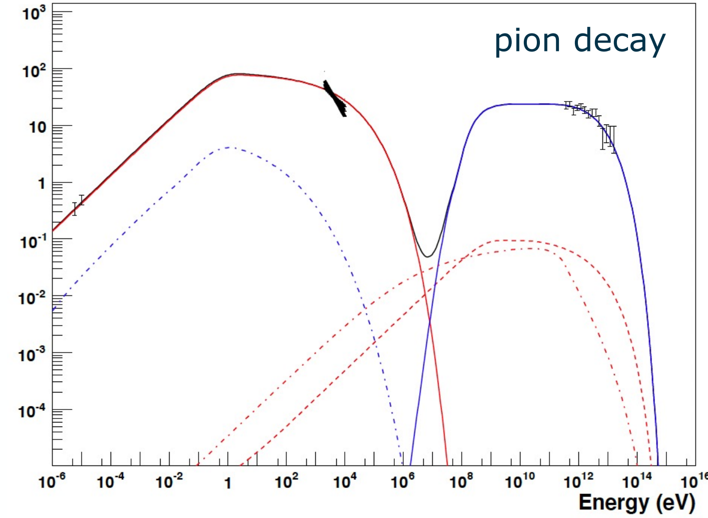
EBL

Origin of cosmic rays

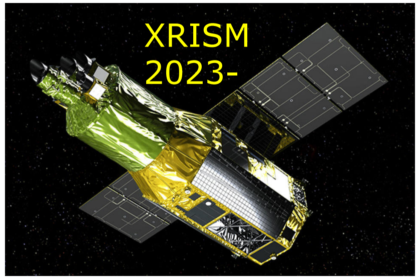
Interaction of outflows, jets and blast waves on the ISM

SNR RXJ0852.0-4622

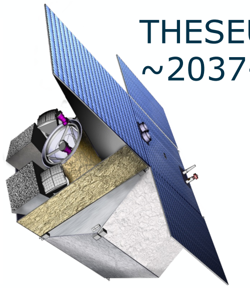




X-rays probe environment, enable broad-band coverage, provide accurate triggers and space-resolved measurements.



Einstein probe
2024-



THESEUS
~2037-

… not to forget eXTP, and a (possible) X-ray NASA probes

XRISM and NewAthena scientific performance

Parameter	XRISM performance	*Athena* requirement
Spectrometer	***Resolve* (Gate Valve Closed)**	**X-IFU**
Total effective area at 7keV	0.012 m^2	0.09 m^2
Total effective area at 1 keV	0	0.52 m^2
Energy resolution at 7keV	5 eV	4 eV
Field of View (diameter)	3 arc mins	4 arc mins
Pixel Size	30 arc secs	5 arc secs
Background (2-7 keV)	10^{-3} ph $cm^{-2}s^{-1}keV^{-1}$	$5x10^{-3}$ ph $cm^{-2}s^{-1}keV^{-1}$
Imager	***Xtend***	**WFI**
Effective area at 1 keV	0.03 m^2	0.86 m^2
Field of view (side)	38x38 arcmins	40x40 arc mins
Background (2-10 keV)	$2x10^{-5}$ ph $cm^{-2}s^{-1}keV^{-1}$	$8x10^{-3}$ ph $cm^{-2}s^{-1}keV^{-1}$
Optics angular resolution on-axis @ 1 keV	1.3 arc mins	5 arc secs
ToO Response time	≤72 hours	≤12 hours