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ASFAE ASTROFÍSICA Y FÍSICA DE ALTAS ENERGÍAS

Technological development and preparation for scientific exploitation of Athena XIFU

ASFAE/2022/02 project

Jessica Planelles Villalva

Graciela Sanjurjo Ferrín

Universidad de Alicante

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BRIEF HISTORY OF X-RAY ASTROPHYSICS:
X-ray astrophysics provided a completely new image of the universe.

In 1948, X-rays were observed for the first time with the detection of X-ray emission from the hot solar corona.

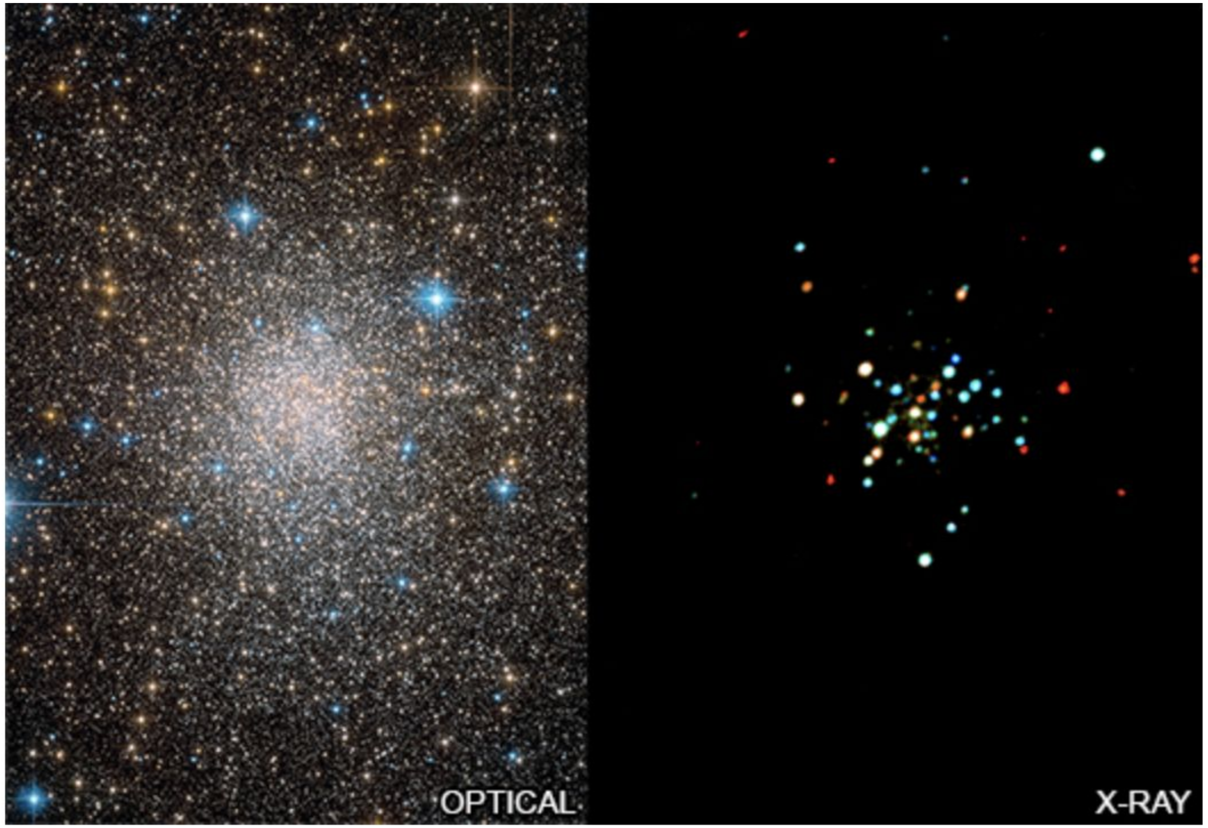
In 1962, the first source of X-rays outside our Solar System was discovered:

Riccardo Giacconi (awarded the Nobel Prize in Physics in 2002 for the discovery) detected X-rays from Scorpius X-1 using an X-ray detector aboard a sounding rocket.

In 1999, the two most prominent missions in the history of X-ray astronomy were launched: NASA's Chandra X-ray Observatory and ESA's XMM-Newton.

2023-XRISM

2038-ATHENA's X-ray Integral Field Unit (XIFU)



Terzan 5

Credit: X-ray: NASA/CXC/Univ. of Amsterdam/N.Degenaar, et al.; Optical: NASA, ESO/F.Ferraro

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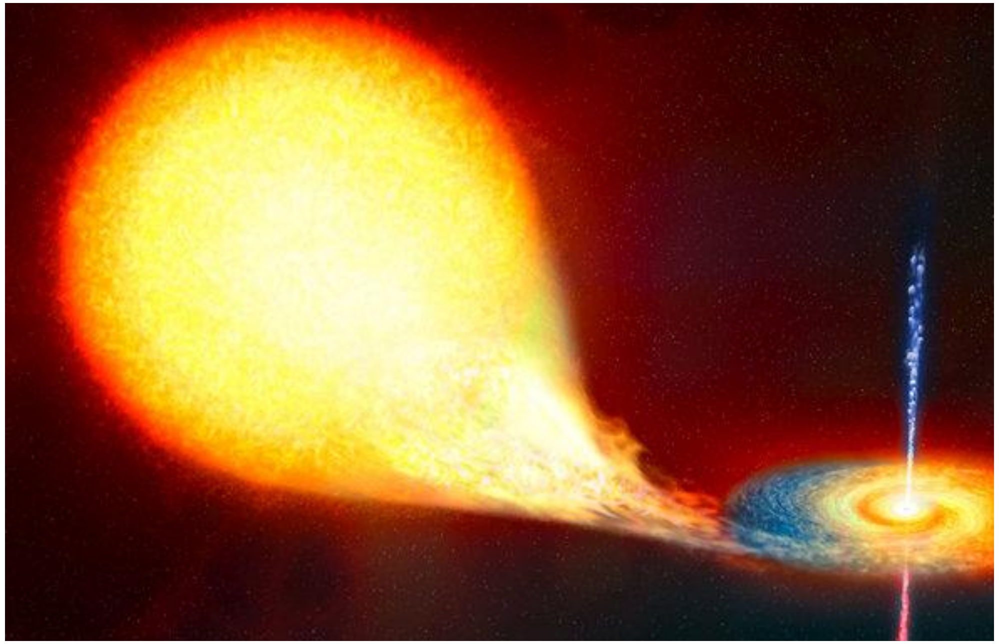
HIGH MASS X-RAY BINARIES AND ACCRETION



Donor or companion: massive star of stellar type 0 or B

Compact object: black hole, neutron star and white dwarft.

X ray radiation is produced when the donnor's matter is accreted by the compact object.

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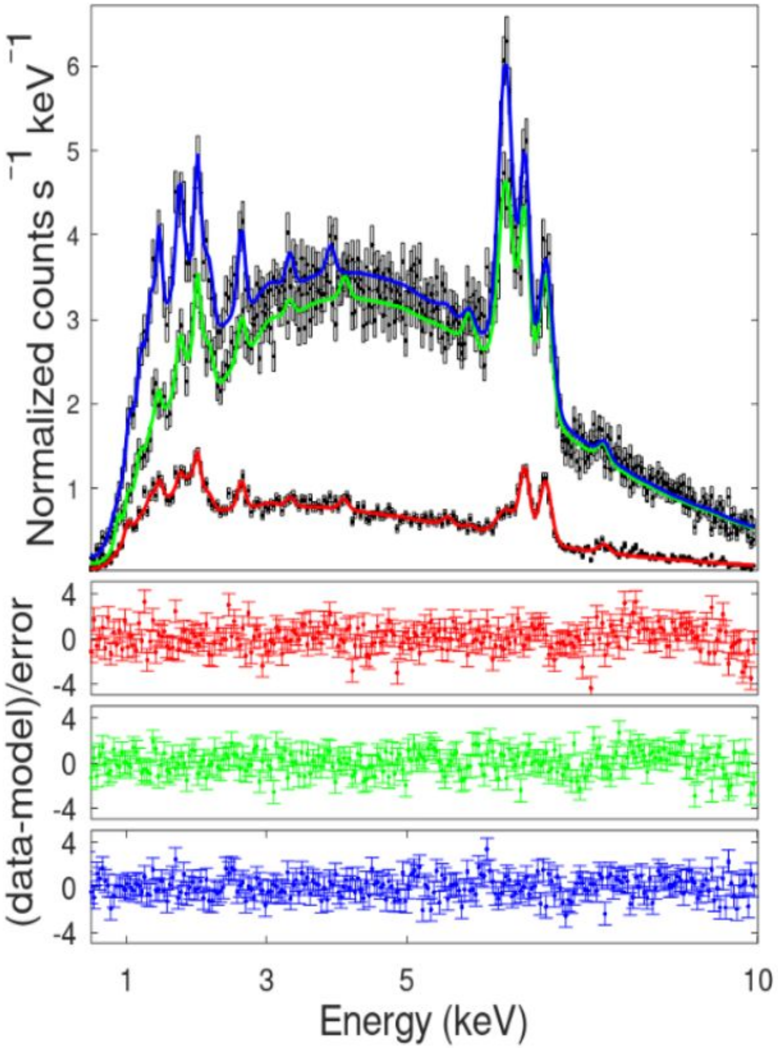
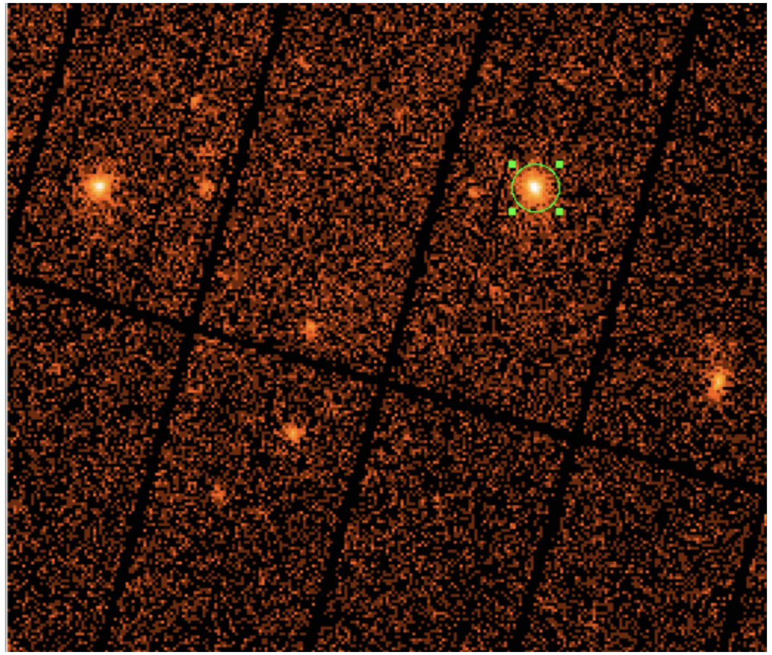
SCIENTIFIC PRODUCTS USED FOR THE ANALYSIS: SPECTRA

- **Absorption:** Of radiation, especially at low energies by matter that absorbs it.

- **Continuum:** Compton, bremsstrahlung, or synchrotron.

- **Emission lines:** an element or molecule is in an excited state and returns to its initial state by emitting a photon.





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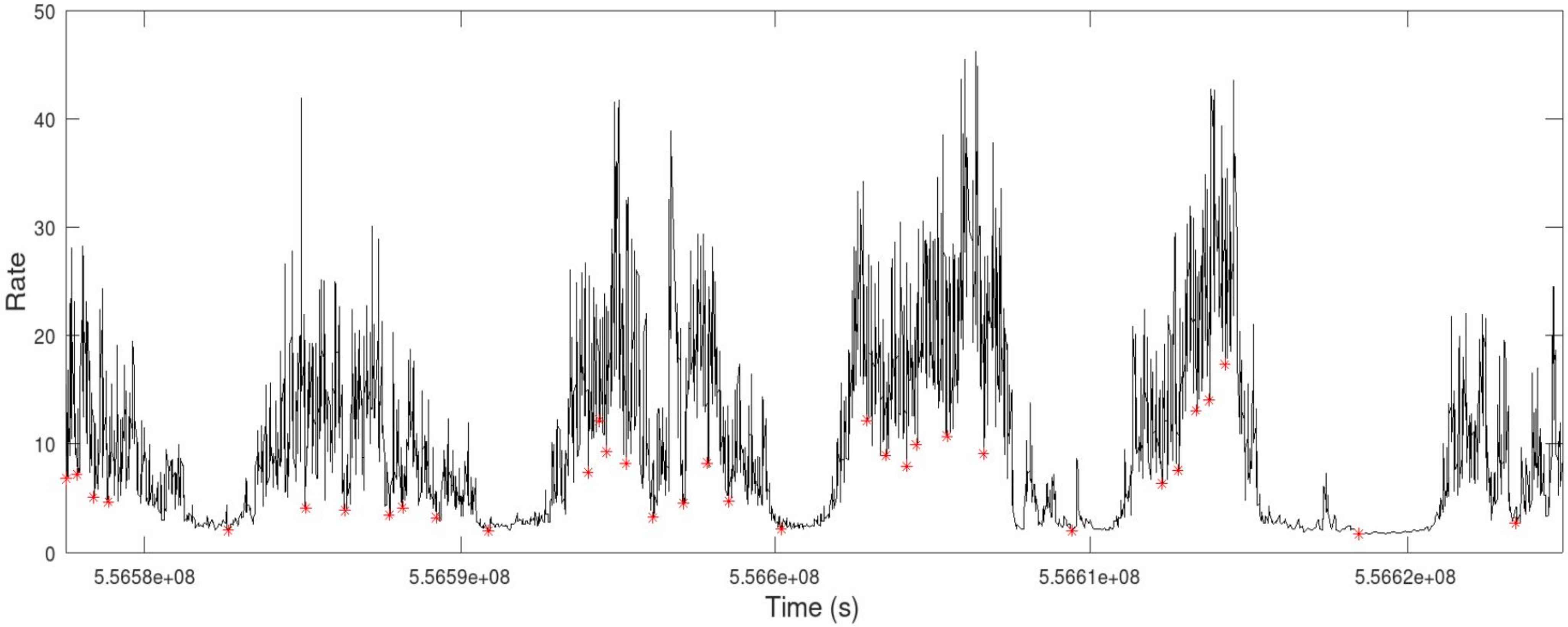
SCIENTIFIC PRODUCTS USED FOR THE ANALYSIS: LIGHT CURVES

The radiation ordered in chronological order.
Can also be divided in energy ranges -> color ratio analysis



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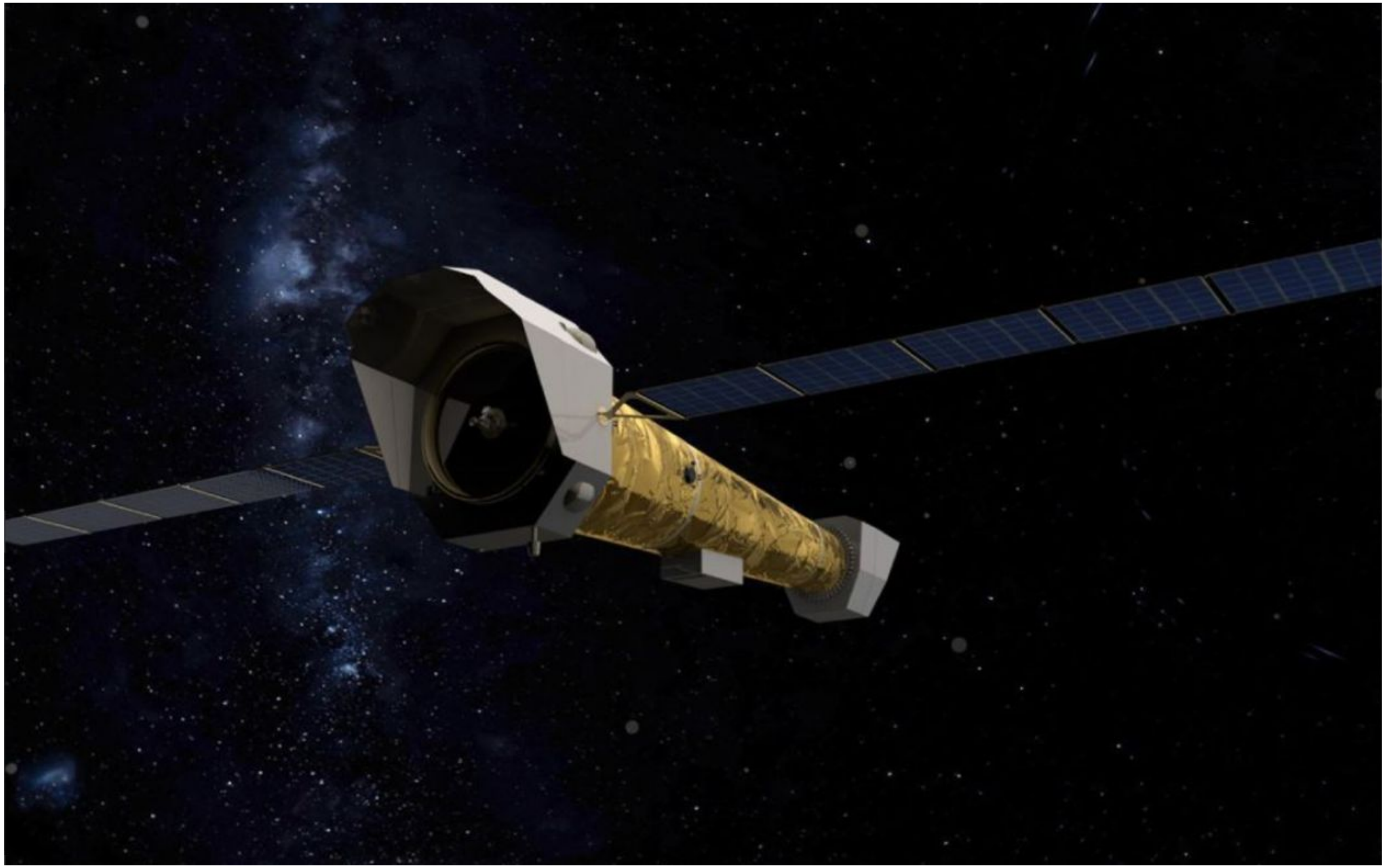
The Athena X-ray Integral Field Unit: X-IFU

- Instrument of the future space telescope of the European Space Agency, Athena (Advanced Telescope for High Energy Astrophysics).
- X-IFU is an X-ray spectrometer designed to capture the universe in high spectral resolution.
- High spectral resolution + high-quality images.
- Launch : 2037
- It will address the scientific theme of the Hot and Energetic Universe.



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Exploring the Hot and Energetic Universe with X-IFU:

- How does accretion work on supermassive black holes?
- What causes violent emissions from supermassive black holes and what impact do they have on the cosmological evolution of galaxies?
- How is gravitational energy directed in large structures toward mass velocity and turbulence?
- How does feedback from supermassive black holes in clusters affect intracluster gas?
- High-Mass X-ray Binaries (HMXBs) provide a unique window into the study of extreme phenomena in the cosmos, such as intense gravitational fields, high-energy accretion processes, and the dynamics of powerful stellar winds.
- X-IFU will explore these shock regions in detail, revealing the physics of interactions between stellar winds and accreting matter.
- We will be able to put new limits on the equation of state for dense matter in neutron stars.
- Contribution to Multi-Messenger Astrophysics:
  X-IFU will facilitate X-ray observations that correlate with other signals, such as gravitational waves and neutrinos, for example thanks that HMXBs are the sources of the GW.

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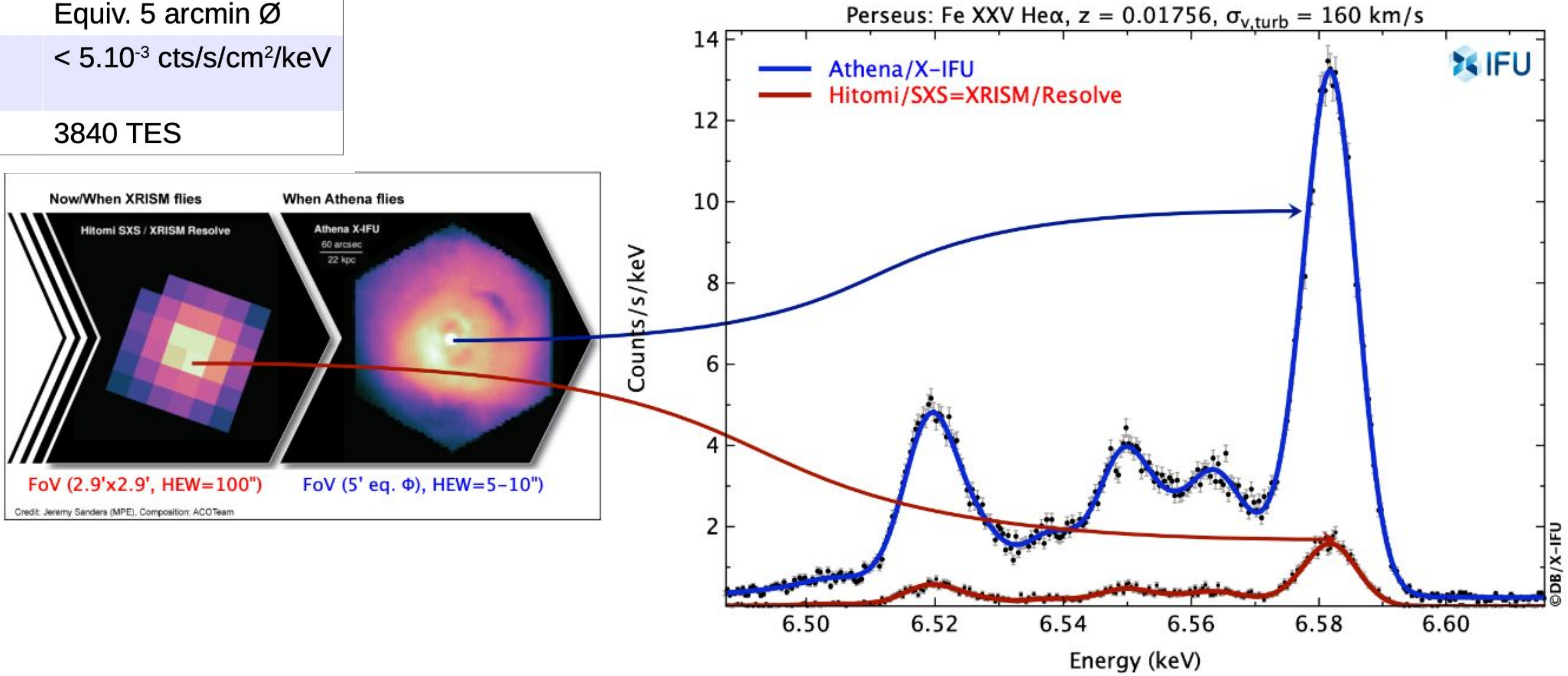
Supremacy over all X-ray telescopes: gain in spectral resolution

X-IFU	
Spectral resolution	2.5 eV (E<7 keV)
Energy range	0.2-12 keV
Pixel size	~ 5”
Field-of-view	Hexagon Equiv. 5 arcmin Ø
Non X-ray background	< 5.10^{-3} cts/s/cm^2/keV
Detector	3840 TES



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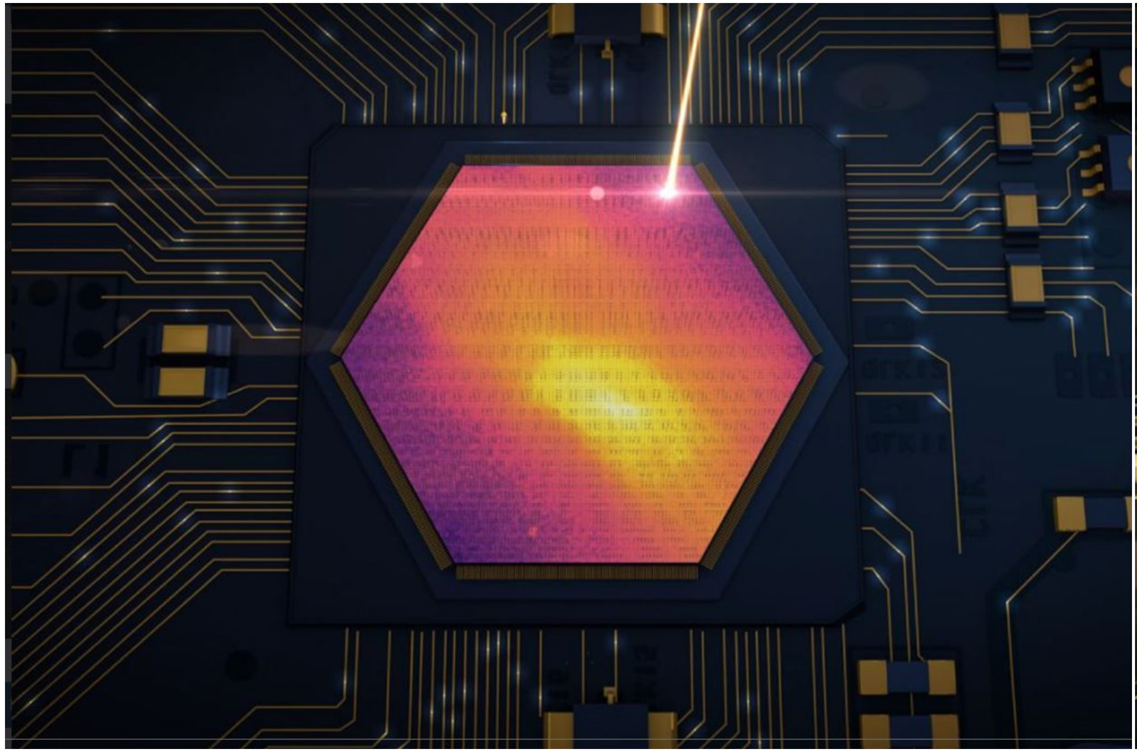
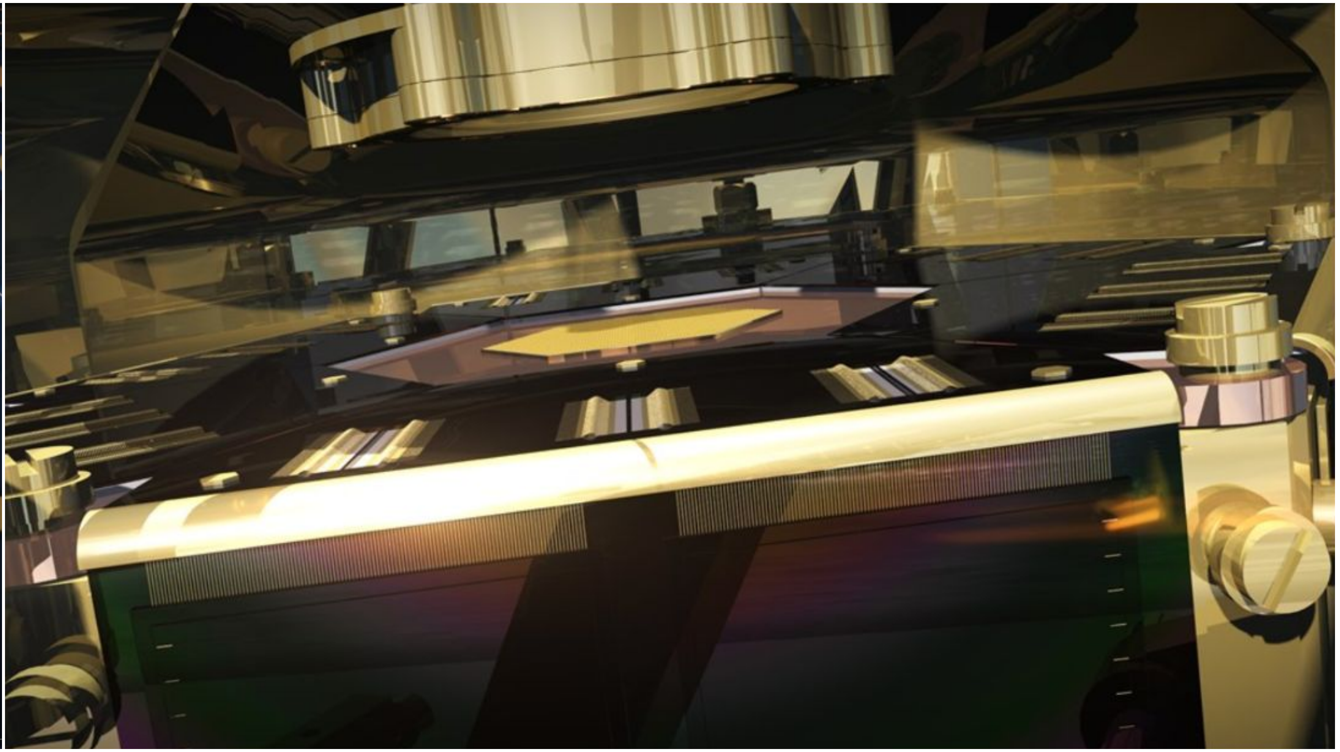
Thousands of microcalorimeters

- The instrument uses microcalorimeters, highly sensitive heat sensors.
- They are cooled to almost absolute zero (-273.1°C / 50mK) to increase their sensitivity.
- The measured temperature is converted into an electrical signal using superconducting thermometers.
- This signals are analyzed individually to estimate the energy of each X-ray photon.





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TES (Transmission Edge Sensors)

- TES are thin superconducting thermistors that operate in the transition region between superconducting and normal states.

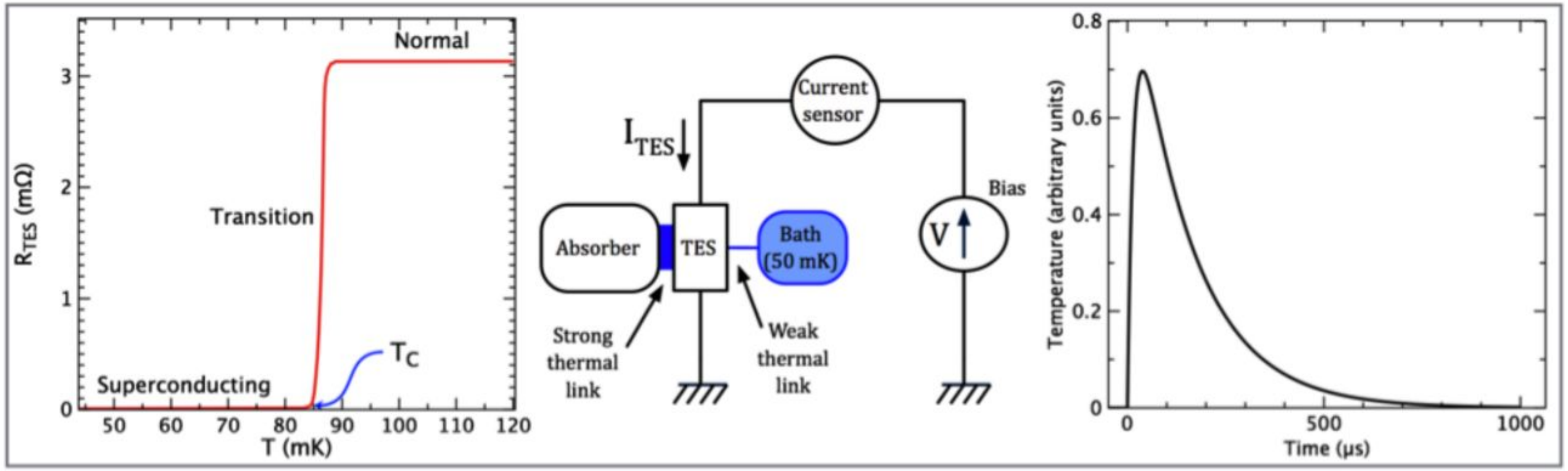
- The absorption of a photon increases the temperature of the TES and, therefore, the resistance of the TES.

- Each X-ray photon generates a current pulse, the intensity varies depending on its energy, used to measure precisely the energy and arrival time of the photon.

- Measures are used to reduce the background effects of particles, such as the Cryogenic Anticocidence (CryoAC) detector.

X-IFU – Principle

X-IFU-pixels are single *Transition Edge Sensors*, operated at 50 mK
$\Rightarrow$ **measure temperature increase** of photon hitting the pixel



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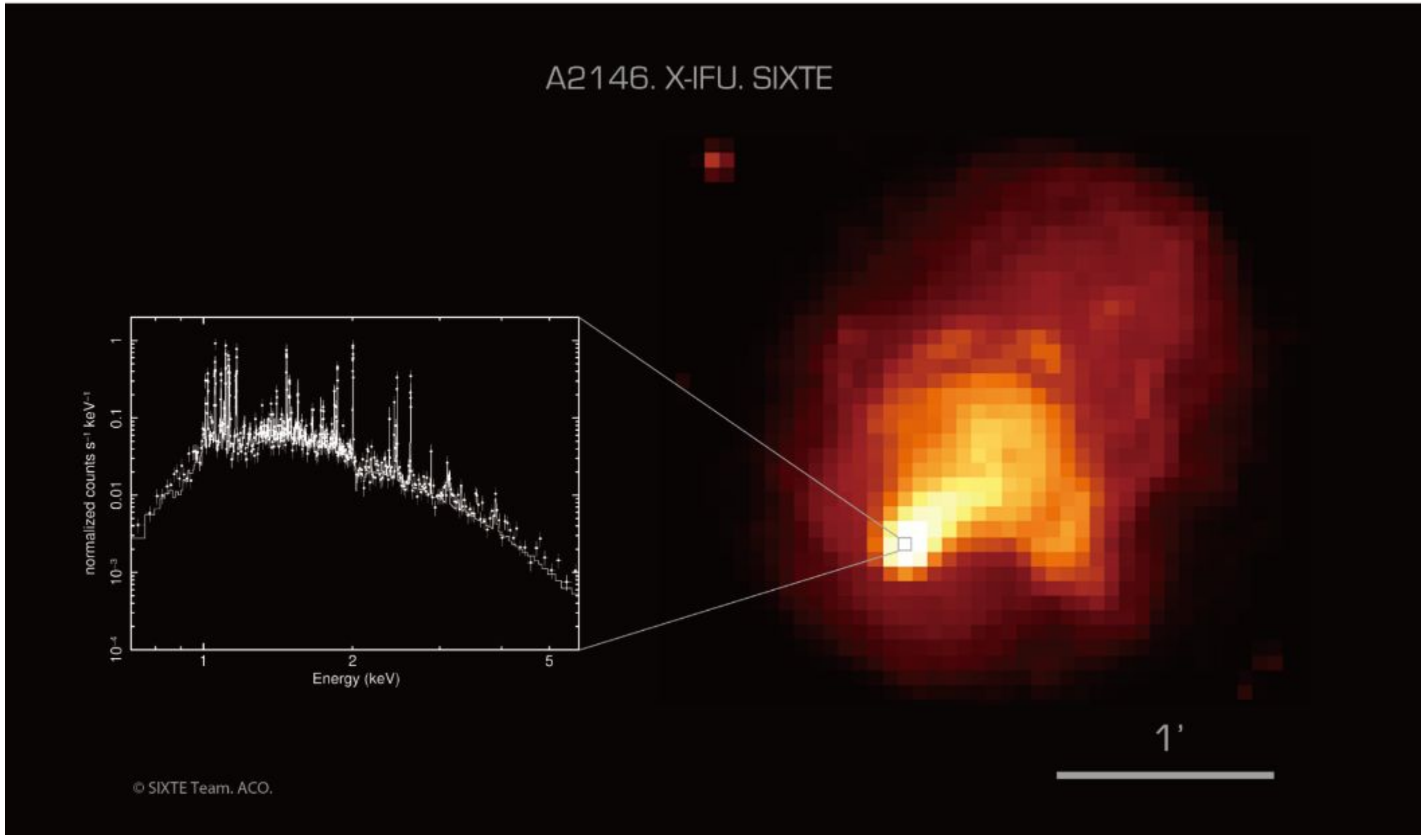
Developing the X-IFU simulator

- SIXTE is a Monte Carlo simulation software package for generic X-ray astronomical instrumentation.
- We simulate sources that from in a flexible input file called SIMPUT.
- Once defined the source, we use SIXTE to produce a sample of photons that are propagated through the optics.
- SIXTE contains modules for various types of detectors, being able to perform simulations with TES.
- We implement the characteristic effects of these detectors, we analyze how the observations will be like for this new instrument.



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Advances in TES:

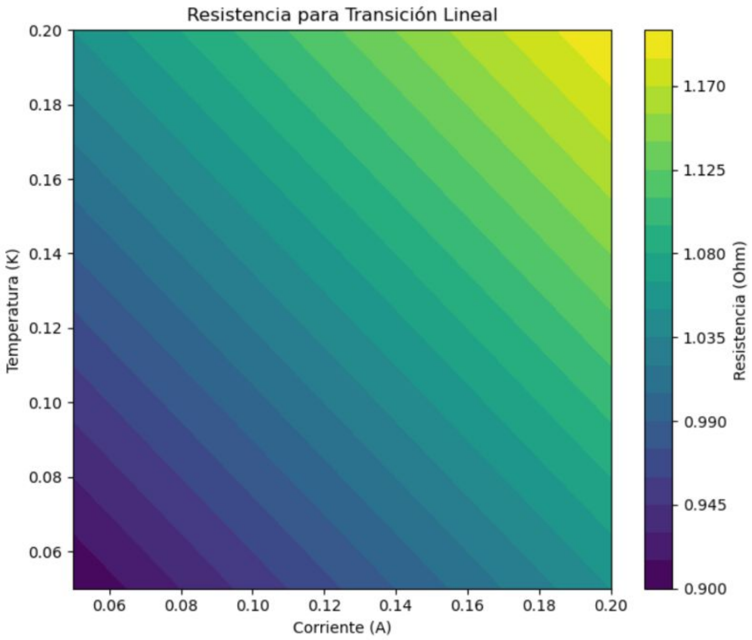
- We've made a significant progress in the design and operation of the TES.
- We are addressing technological challenges of operating near absolute zero and refine the measurement of changes in energy
- Looking for the best response in the TES:

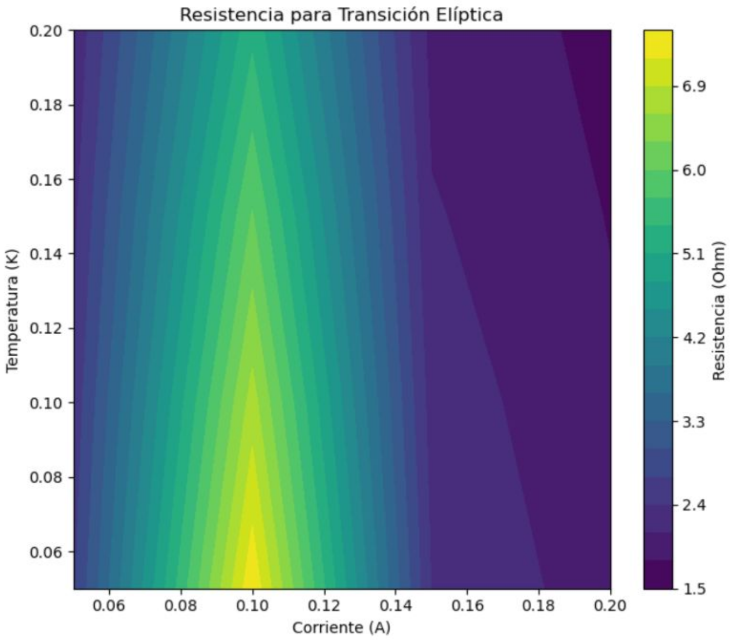
Traditional Linear Model:

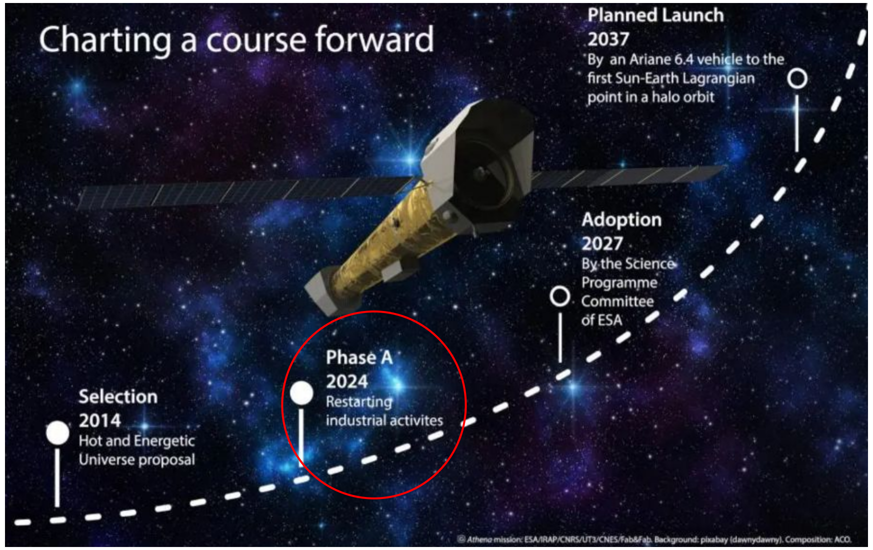
- The relationship between the resistance of the TES and its temperature is linear near the transition point between the superconducting state and the normal state.
- It does not fully capture the complex dynamics under conditions of energy fluctuations.

Transition to an Elliptical Model :

- It represents a more precise description of the TES resistance as a function of temperature and current intensity.
- It considers an elliptical geometry to fit better, allowing a more detailed characterization of the TES response. Increasing the energy precision of the detected photon.







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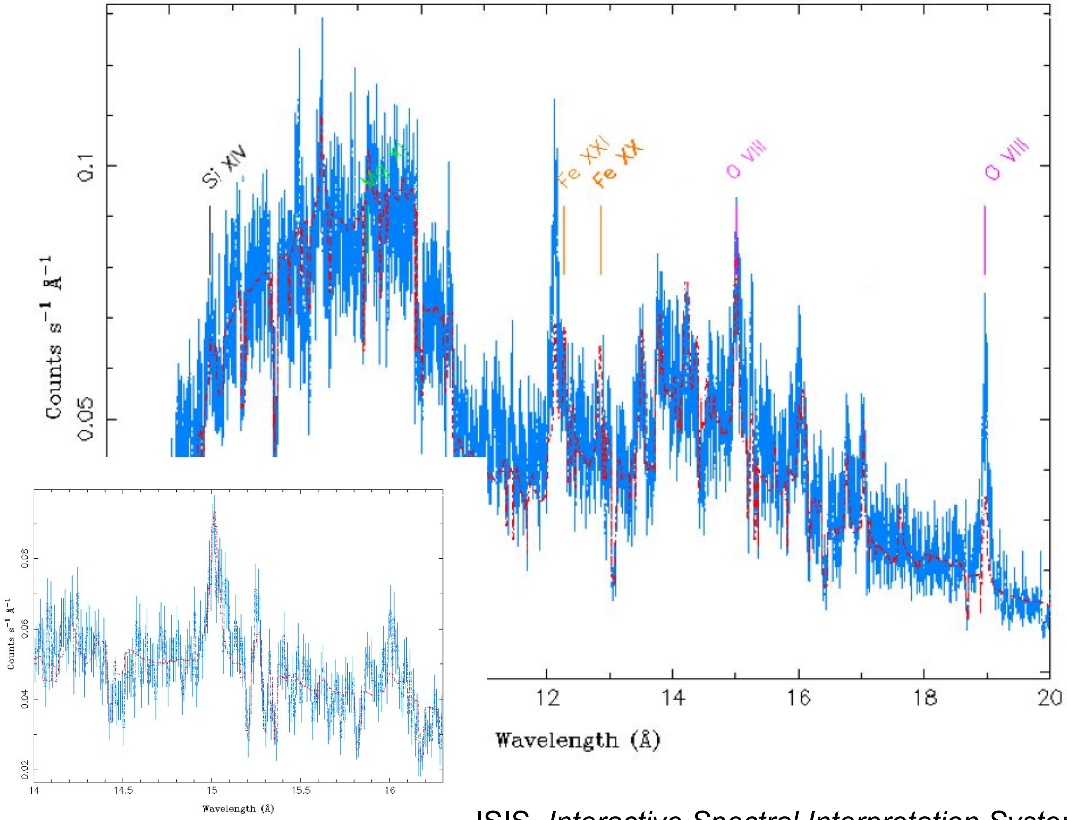
X-IFU science: simulating spectra with SIXTE

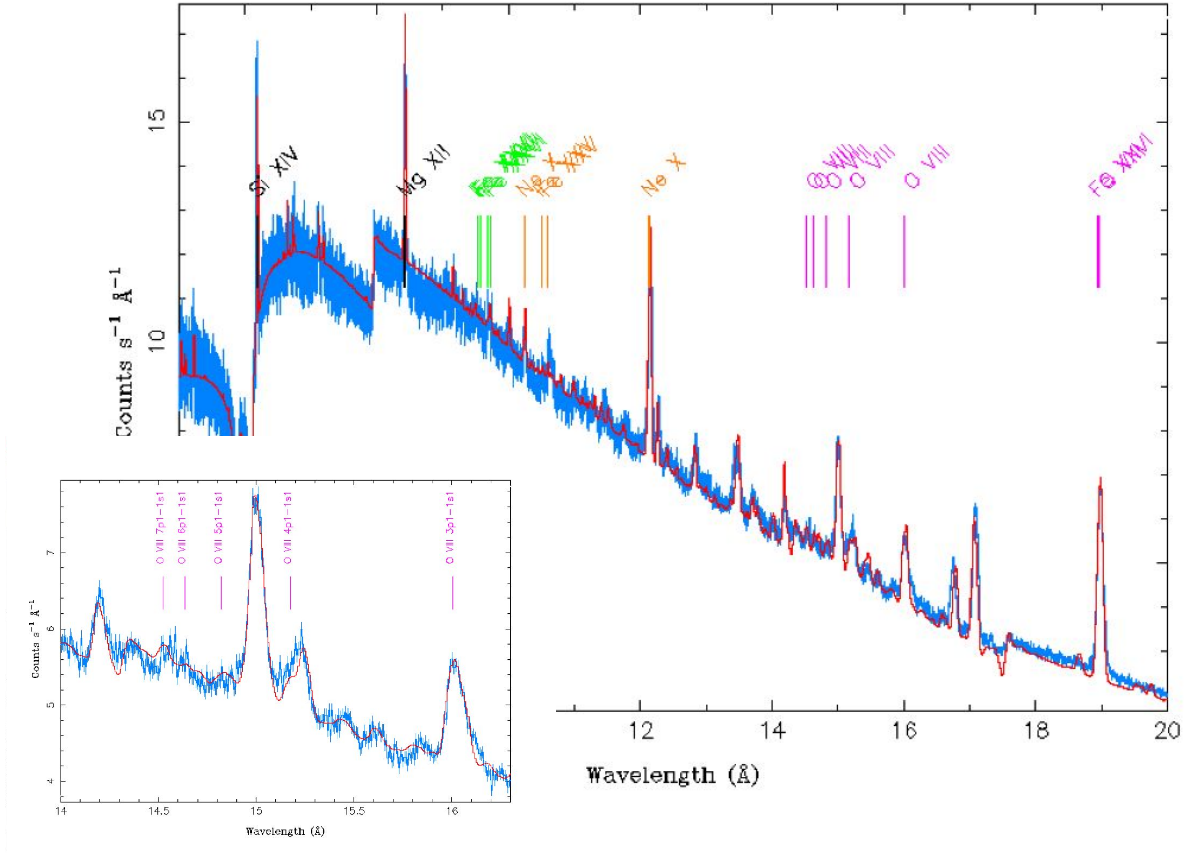
X-IFU will detect weak emission/absorption lines, measuring the physical properties of hot plasmas in HMXB: velocity, turbulence, abundances, ionization, density, temperature, broadening and chemical composition can be calculated.

Spectra with RGS (XMM-Newton)



ISIS, *Interactive Spectral Interpretation System*
ATOMDB

Spectra simulated with X-IFU



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NEXT CHALLENGES

- New analysis that we were not able to perform before.
- Our current methods of analysis and modeling might get obsolete.
- A forest of emission lines: 3 parameters per line and new resolution.

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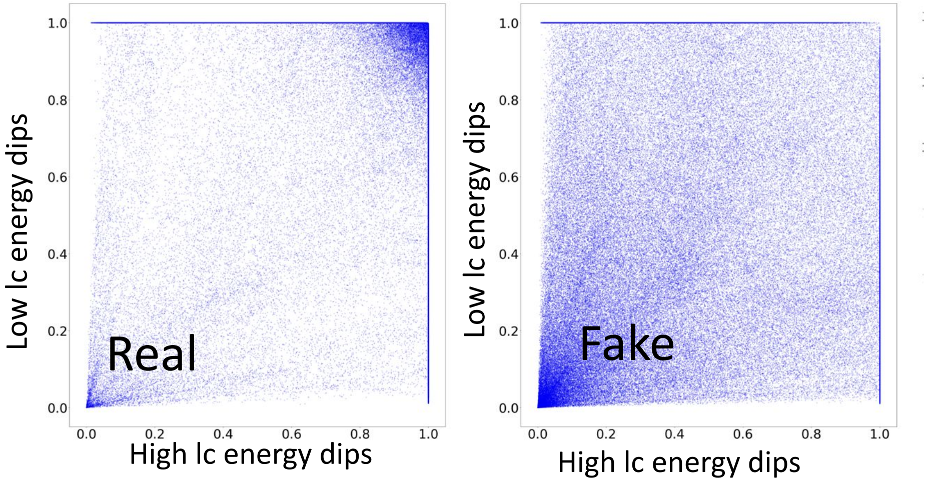
Dips in Light Curves with Gaussian Mixture

Dip overlap in high and low energy range LC



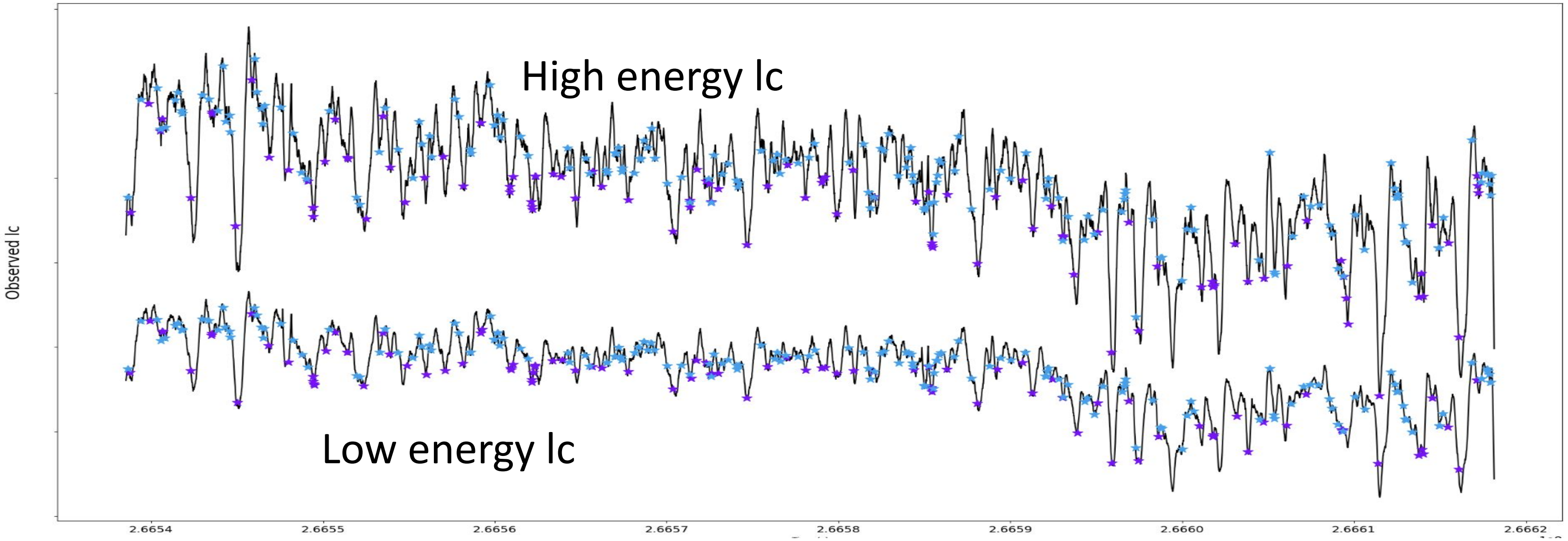
The objective is to distinguish dips in the light curves that are caused by astrophysical phenomena.

1- Generate a similar noise light curves (fake).

2- Detect dips in the high and low energy light curve, both real and fake. A dip candidate must overlap.

3- Apply some filters.

4- Group the data using Gaussian Mixture and discard all groups that contain dips.



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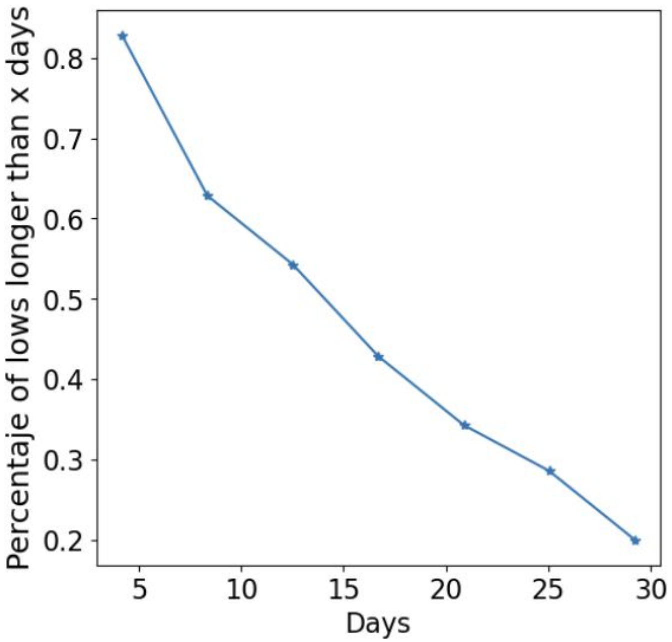
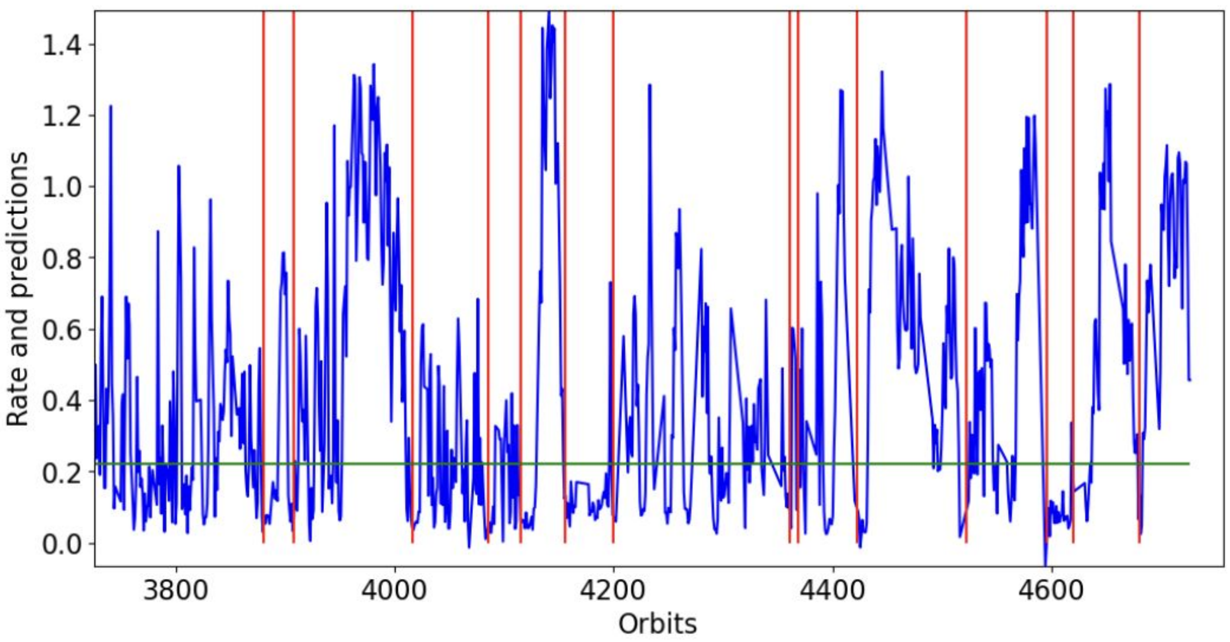
Long low emission state triggers in MAXI with random forest

Tool for TOo with trigger proposals. The goal is observing sources during periods of low emission:

- Study the processes involved in state changes.
- Obtain observations of higher quality.

Cen X-3 MAXI LC. Each point represents a Cen X3 orbit flux (out of eclipse)





Cen X3 example: Percentage of duration exceeding 10 days: 71% compared to 56% if we only wait for a low count rate.

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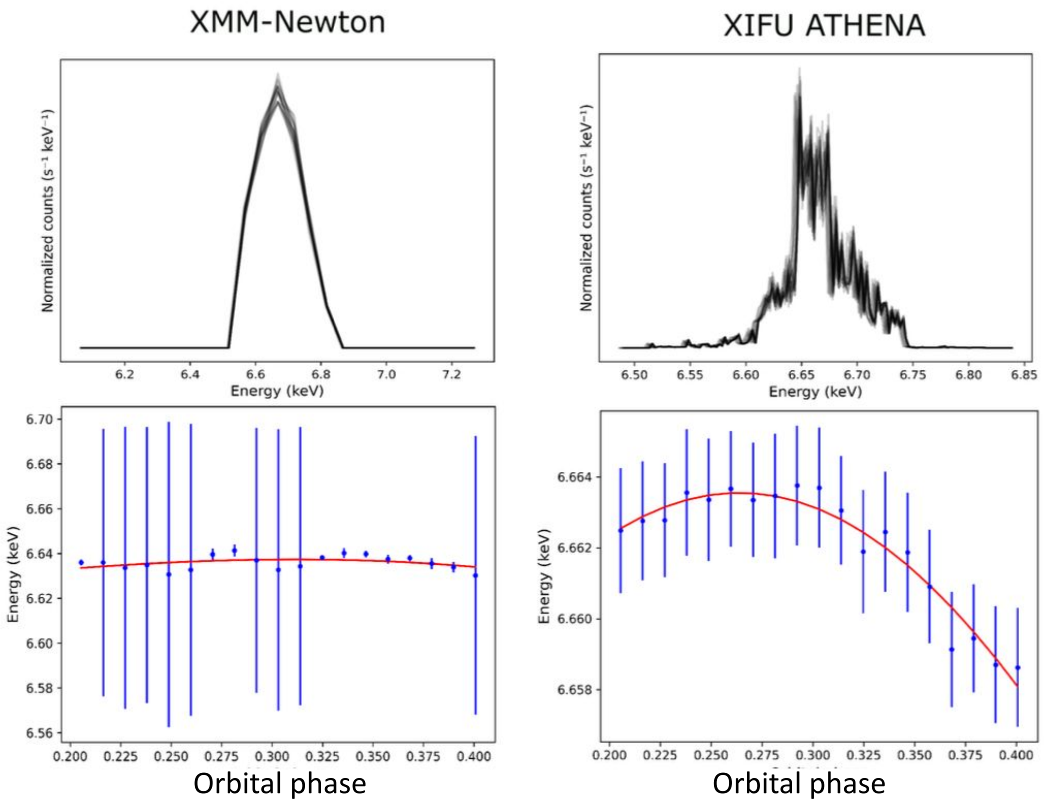
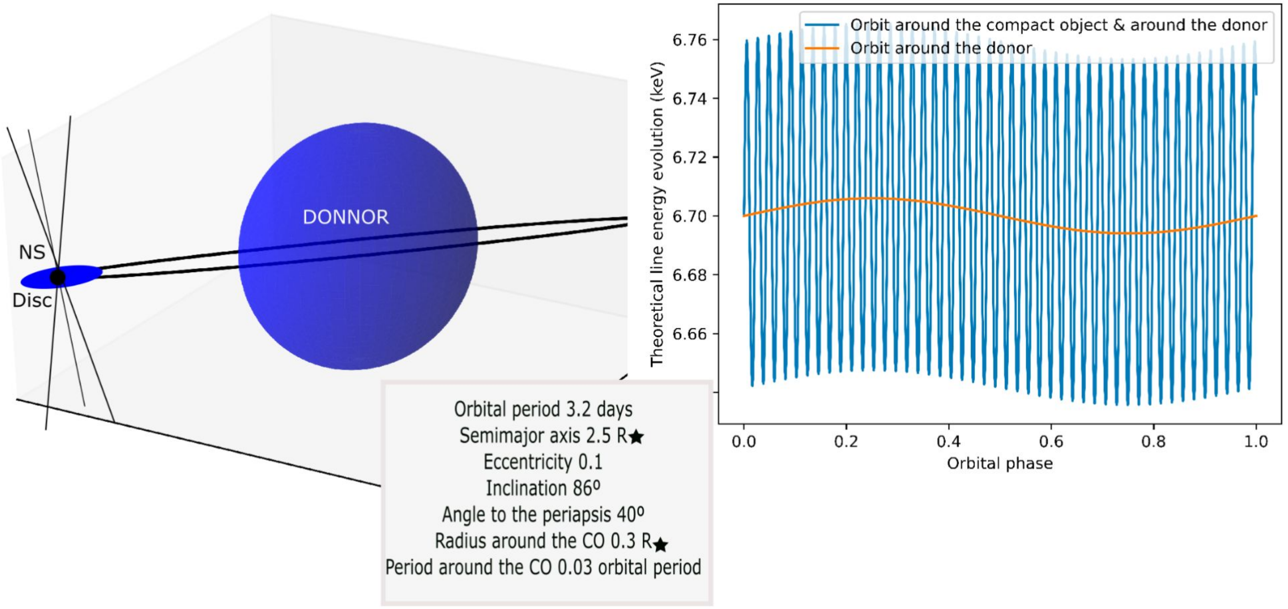
Doppler in High Resolution X-Ray





	System	*XMM*	*XIFU*
Distance to barycenter (R*)	2.2	2.8±0.3	2.8±0.6
Orbital period (d)	3.2	3.1 ± 0.1	3.4 ± 0.1
Eccentricity	0.1	0.2 ± 0.06	0.04 ± 0.05
Angle to the periapsis	40	29± 12	46±8
Inclination	86	89 ± 4	89 ± 8
χ^2		0.2	0.9

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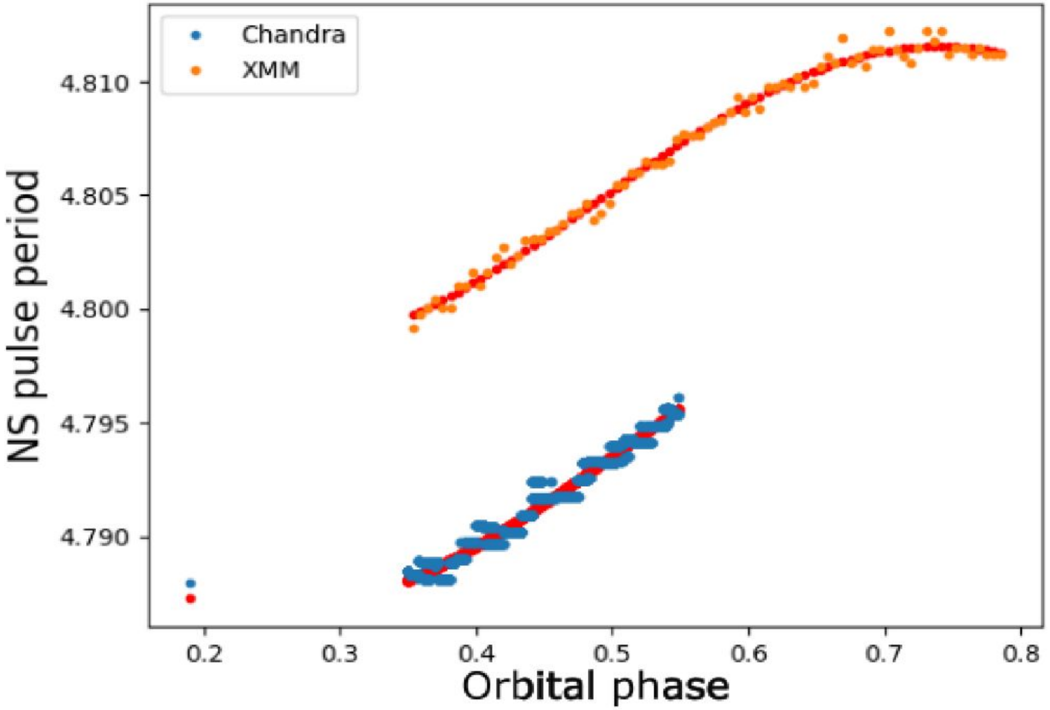
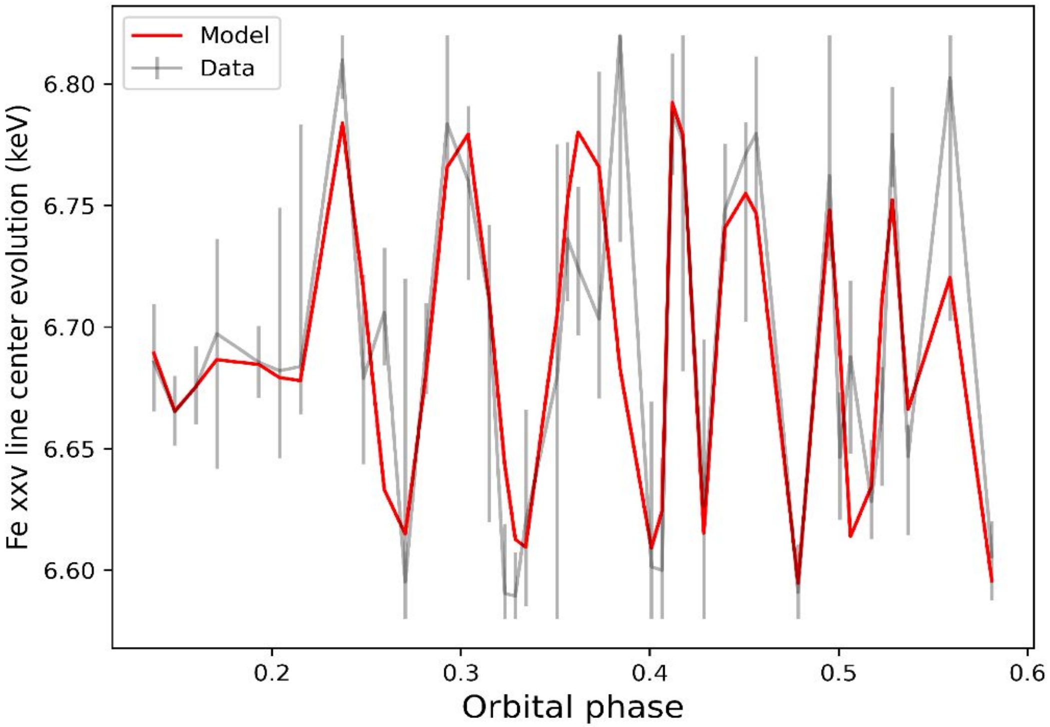
Doppler in XMM and Chandra

Doppler shift of the NS pulse caused by its motion around the orbit.



Doppler shift of the center of an emission line that might be consistent with a complex movement of the emitting plasma within the system.



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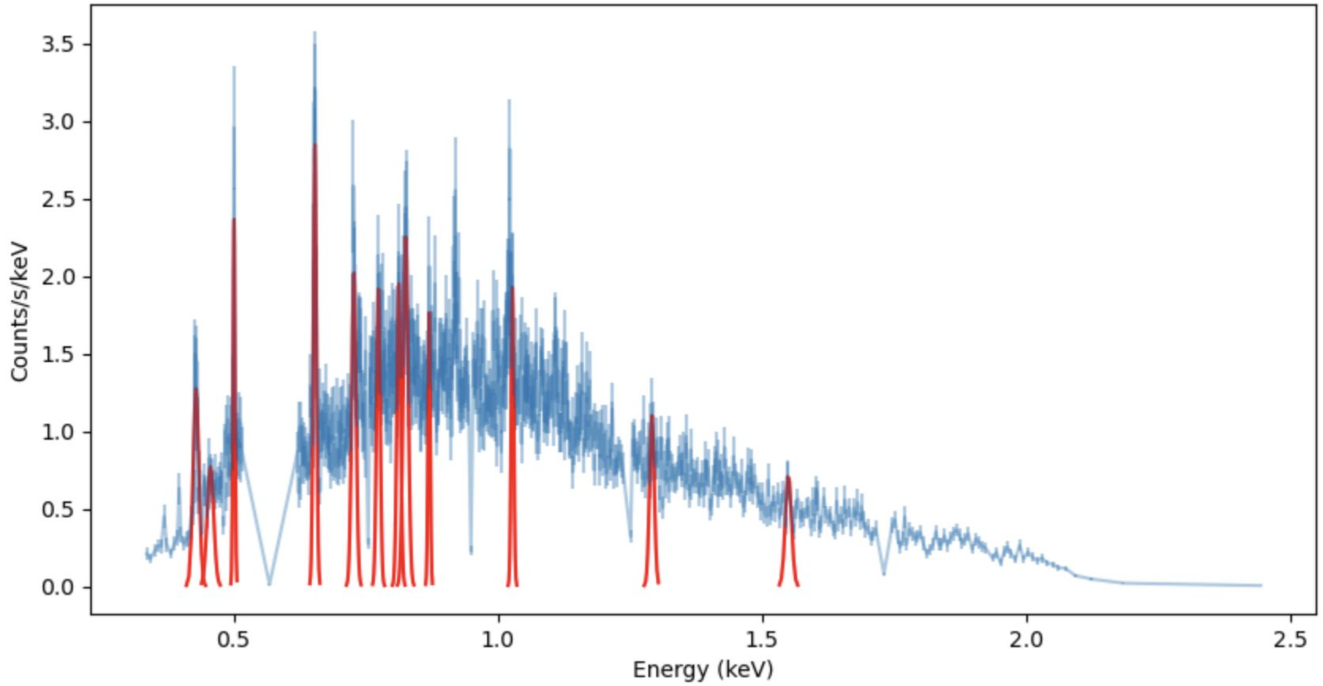
Automatic emission line detector.



Faster analysis

amplitude	center	sigma	eamplitude	ecenter	esigma	rsq
1.27601	0.42881	0.00549	0.11234	0.00077	0.00083	0.72497
0.76989	0.45608	0.00613	0.03812	0.00054	0.00088	0.86193
2.36943	0.50072	0.00191	0.20106	0.00023	0.00026	0.82850
2.85327	0.65370	0.00299	0.15257	0.00020	0.00025	0.84355
2.02689	0.72753	0.00419	0.13423	0.00040	0.00056	0.68581
1.91548	0.77386	0.00341	0.10594	0.00027	0.00053	0.73923
1.95577	0.81245	0.00355	0.06031	0.00016	0.00027	0.91388
2.25227	0.82557	0.00468	0.10869	0.00035	0.00056	0.72943
1.80683	0.86992	0.00206	0.33903	0.00059	0.00115	0.47060
1.92577	1.02758	0.00244	0.16070	0.00033	0.00061	0.70544
1.09959	1.29143	0.00442	0.13936	0.00073	0.00142	0.58797
0.71487	1.54979	0.00579	0.05208	0.00058	0.00086	0.87240

We are working on:

- Identification of emission lines
- Calculation of ratios in triplets -> Plasma temperatures/electronic densities
- Ionization parameters

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jessica.planelles@ua.es graciela.sanjurjo@ua.es

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