What are the three most essential performances in cosmic X-ray measurements?

Ideally, we would like to measure the X-ray photon energy, arrival direction, and arrival time.

However, we may not directly measure the X-ray photon energy ,arrival direction and arrival time.

What we detect is electric signals from X-ray detectors, and the detector resolution is limited.

X-ray → detector → observe

1. Better spatial resolution → Good image
2. Better spectral resolution → Good spectra
3. Better timing resolution → Precise timing study

How can we design X-ray instruments to maximize the sensitivity (= signal to noise ratio)?
The larger the effective area, the more X-ray photons are collected. → Signals increased

Better to reduce the background noise (mostly electric particles [protons, electrons] in orbit).
The particle background is proportional to the dimension of detector.

Focus X-rays using X-ray mirror into a small detector pixel (CCD, microchanel plate etc)

Chandra is most sensitive ~200 cm² (~1 keV) → 1 CCD pixel

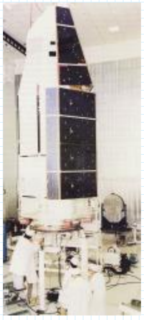
X-ray astronomy started in 1962, but the first X-ray imaging satellite using mirrors, Einsten, was launched in 1978. Why it was so difficult to make X-ray mirrors? Give two reasons.

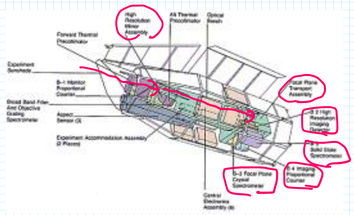
$\lambda \approx 1 Å \sim 10^{-8}$

1. mirror has to be smooth ~Å
2. X-rays are difficult to reflect

https://chandra.harvard.edu/resources/animations/mirror_comparison_sm_2017.mov
Explanation of the principle of X-ray mirror

https://heasarc.gsfc.nasa.gov/Images/heao2/heao2_prepflight.gif





Einstein

It was the first X-ray mission to use focusing optics with imaging detectors with an angular resolution of a few arcseconds, a field-of-view of tens of arcminutes. The sensitivity was several 100 times greater than any previous X-ray astronomy mission.
<https://heasarc.gsfc.nasa.gov/docs/einstein/heao2_about.html#instrument>

Einsten and ROSAT (1991) can image up to < 2 keV. X-ray imaging above > 2 keV was made possible with ASCA X-ray Telescope for the first time. ASCA is much smaller, lighter and cheaper than Einstein or ROSAT. Why this was made possible? What was the trade-off?

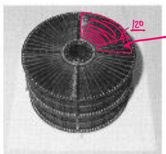
ASCA ~10 keV

https://darts.isas.jaxa.jp/astro/asca/

ASCA

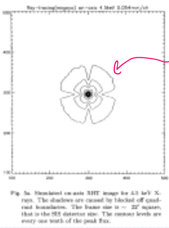
http://cdsads.u-strasbg.fr/pdf/1995PASJ...47..105S

https://doi.org/10.1364/AO.34.004848



Aluminum foil → thin, light, cheap, easy to fabricate → large effective area, nest many foils

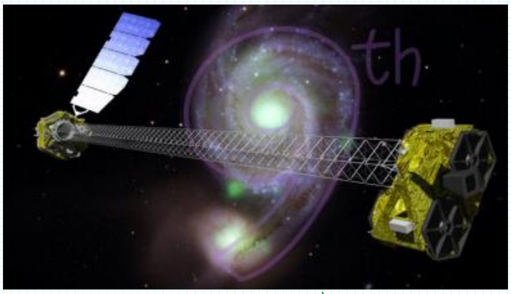
<https://ui.adsabs.harvard.edu/abs/1995PASJ...47..105S/abstract>



X-ray point source
PSF
Point Spread Function

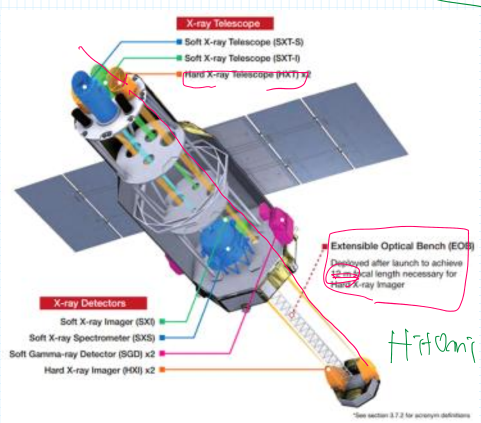
NuSTAR and Hitomi/HXI are the first satellites which can focus hard X-rays up to ~70 keV. How this was possible?

https://www.nustar.caltech.edu/news/126



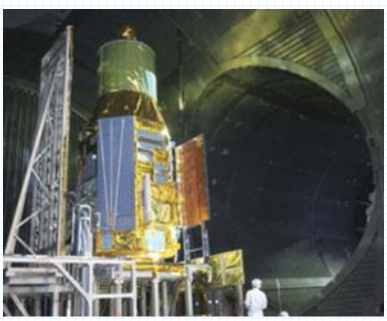
NuSTAR

https://global.jaxa.jp/projects/sas/astro_h/instruments.html



Hitomi

https://global.jaxa.jp/projects/sat/astro_h/topics.html



In 2023, what would be the best satellites/instruments for the following observations?

active or planned missions

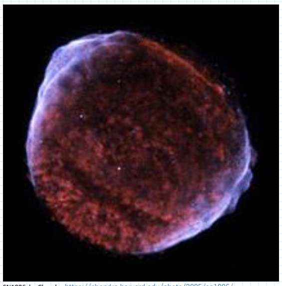
- Best X-ray imaging and sensitivity with the highest angular resolution in 0.5 - 10 keV

Chandra!

https://chandra.harvard.edu/photo/2019/tycho/

Tycho SNR by Chandra

RGB

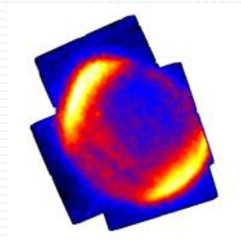


SN1006 by Chandra https://chandra.harvard.edu/photo/2005/sn1006/

https://heasarc.gsfc.nasa.gov/docs/asca/gallery/sn1006.html

The first hard X-ray image of SN1006 by ASCA

around 1994



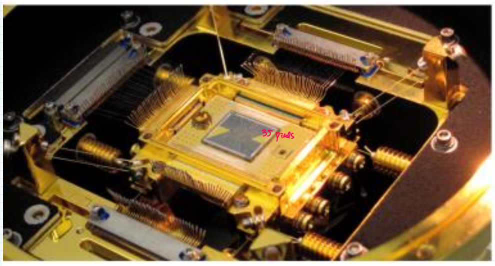
https://chandra.harvard.edu/graphics/resources/illustrations/craftOptBench45-72.jpg

https://chandra.harvard.edu/resources/ppt/telescope.html

- High resolution spectroscopy in the iron K-band (6-7 keV)

XRISM!!

XRISM white paper



X-ray microcalorimeter

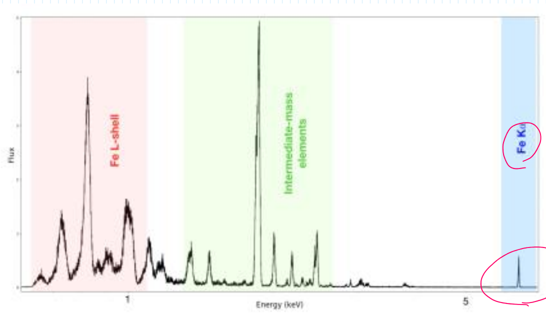


Figure 17: A sample spectrum that one might expect from a young Type Ia SNR, such as Tycho or Kepler's SNR. Lines from various elements or groups are highlighted. Lines are broadened due to the extremely high temperatures that result from gas being shocked by a 5,000 km s^{-1} shock wave. *XRISM* will resolve the widths of these lines in SNRs, leading to a direct measurement of the plasma temperature.

- High resolution spectroscopy at ~ 1keV for diffuse sources (e.g., supernova remnants, clusters of galaxies).

XRISM!!

- High resolution spectroscopy at ~ 1keV for point sources (e.g., stars, X-ray binaries)

Grating!!

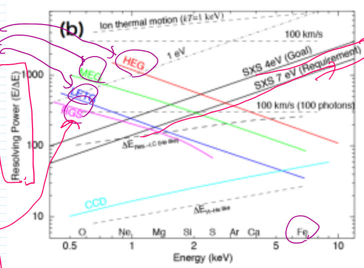
Chandra grating

XMM grating

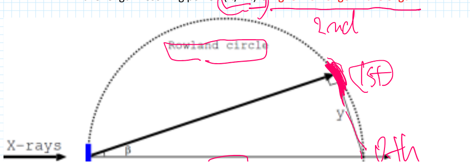
https://pos.sissa.it/306/046/pdf (Ishida 2017)

For microcalorimeter, ΔE is constant (determined by accuracy of the temperature measurement), so the resolving power (E/ΔE) is higher for higher energies

→ ASTRO-H (Hitomi) ⟷ XRISM

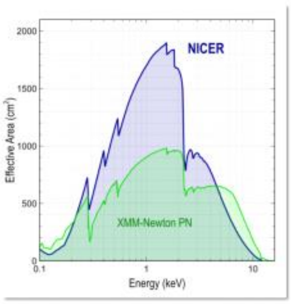


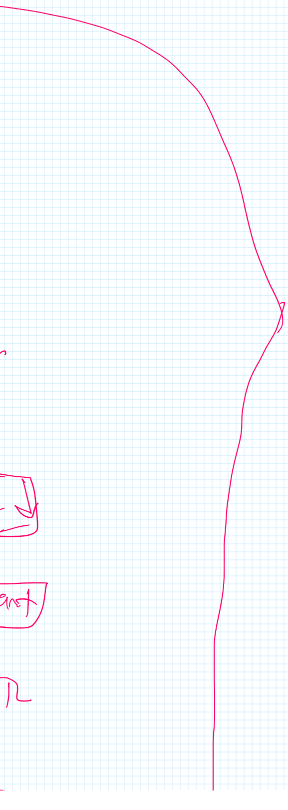
For grating, spectral resolving power (E/ΔE) is higher for lower-energies
= wave-length resolving power (λ/Δλ) is higher for longer-wavelength



- Very fast timing study (<< 1msec) for bright X-ray sources

- **Bandpass:** 0.2-12 keV
- **Effective area:**
  - >2000 cm^2 @ 1.5 keV
  - 600 cm^2 @ 6 keV
  - *2x XMM-Newton for soft X-ray timing*
- **Energy resolution:**
  - 85 eV @ 1keV,
  - 137 eV @ 6 keV
  - *Similar to XMM and Chandra*
- **Time-tagging resolution:**
  - <300 nsec (absolute)
  - *~25x better than RXTE*





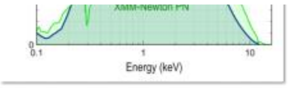
Similar to XMM and Chandra

- **Time-tagging resolution:**

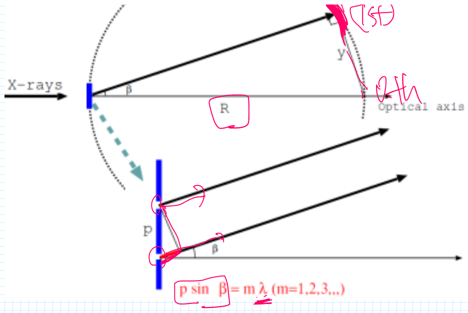
  <300 nsec (absolute)

  ~25x better than RXTE
  ~100-1000x better than XMM

- **Spatial resolution:** 5 arcmin diam. non-imaging FOV

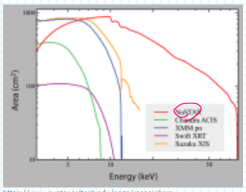


https://heasarc.gsfc.nasa.gov/docs/nicer/nicer_about.html



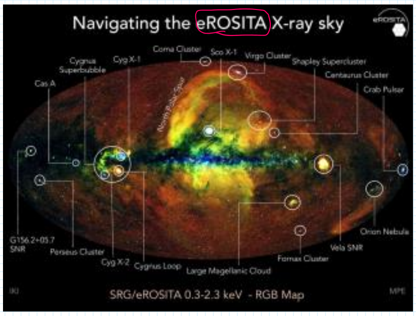
Δλ is determined by the position accuracy (Δy), not dependent on λ.

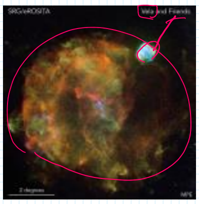
- Hard X-ray imaging above > 10 keV NuSTAR!



https://www.nustar.caltech.edu/page/researchers

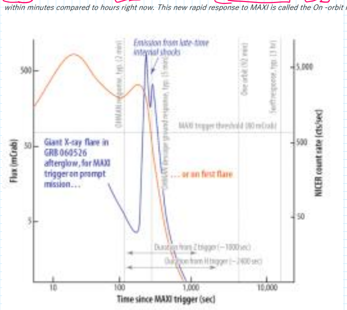
- Most sensitive all-sky X-ray image in 0.5 - 10 keV (no fast detection needed)





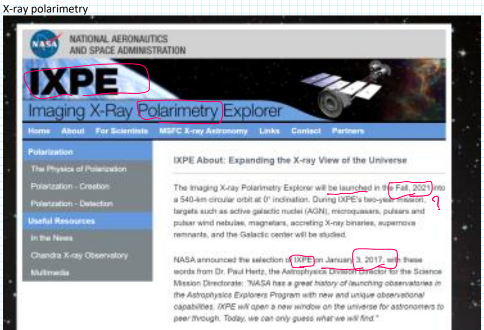
- Monitor all-sky in X-rays, discover bright X-ray transients and immediate follow-up X-ray observations OHMAN!

NICER will react to triggers from MAXI in an automatic way using a laptop computer on the ISS, in order to follow up on new t ransients within minutes compared to hours right now. This new rapid response to MAXI is called the On -orbit Hookup of MAXI and NICER or "OHMAN"



<https://heasarc.gsfc.nasa.gov/docs/nicer/science_nuggets/20190725.html>

- X-ray polarimetry


NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

IXPE

Imaging X-Ray Polarimetry Explorer

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Polarization
The Physics of Polarization
Polarization - Creation
Polarization - Detection
Useful Resources
In the News
Chandra X-ray Observatory
Multimedia

IXPE About: Expanding the X-ray View of the Universe

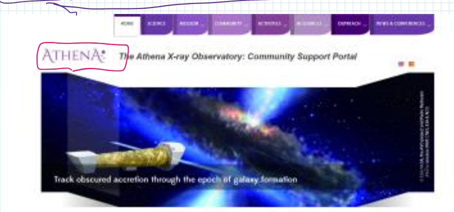
The Imaging X-ray Polarimetry Explorer will be launched in the Fall, 2021 into a 540-km circular orbit at 0° inclination. During IXPE's two-year mission, targets such as active galactic nuclei (AGN), microquasars, pulsars and pulsar wind nebulae, magnetars, accreting X-ray binaries, supernova remnants, and the Galactic center will be studied.

NASA announced the selection of IXPE on January 3, 2017, with these words from Dr. Paul Hertz, the Astrophysics Division Director for the Science Mission Directorate: *"NASA has a great history of launching observatories in the Astrophysics Explorers Program with new and unique observational capabilities. IXPE will open a new window on the universe for astronomers to peer through. Today, we can only guess what we will find."*

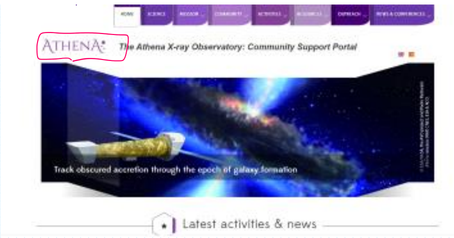
https://ixpe.msfc.nasa.gov/about/

In early 2030's, which X-ray astronomy satellite will be operating? What will be the main instrument? How will be the performance?

https://www.the-athena-x-ray-observatory.eu/

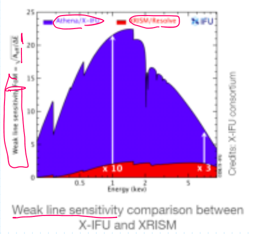


approved!!
ESA
L-mission

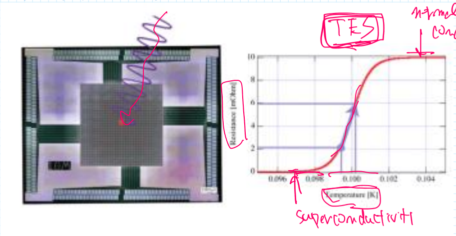


approved!!
ESA
L-mission
M-mission

Much larger effective area



https://www.the-athena-x-ray-observatory.eu/11-news/555-athenanuggets-balancing-on-the-edge-detecting-x-rays-with-transition-edge-sensors.html



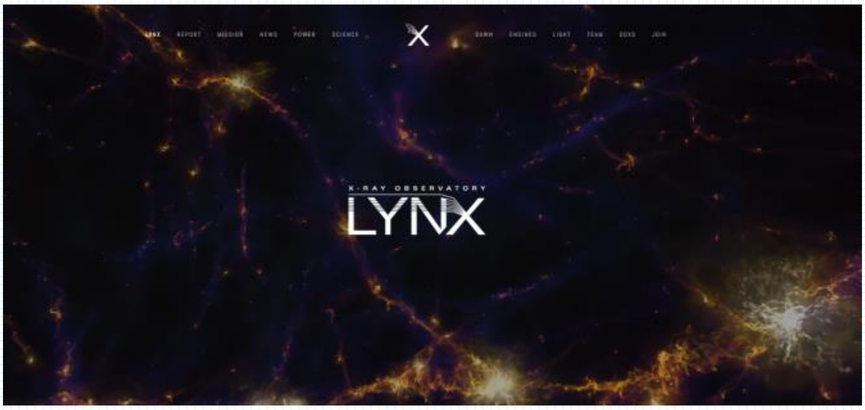
Pixelization of microcalorimeter X-IFU, unveiling the secrets of the hot and energetic Universe

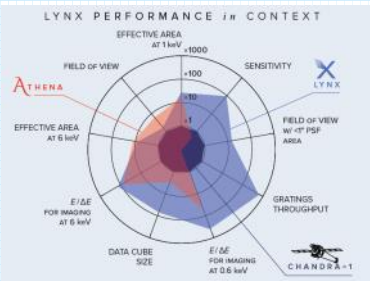
Transition Edge Sensor (TES) → Utilize the "edge" of the super-conductivity and normal conductivity
Extremely senstive to the temperature change → better energy resolution

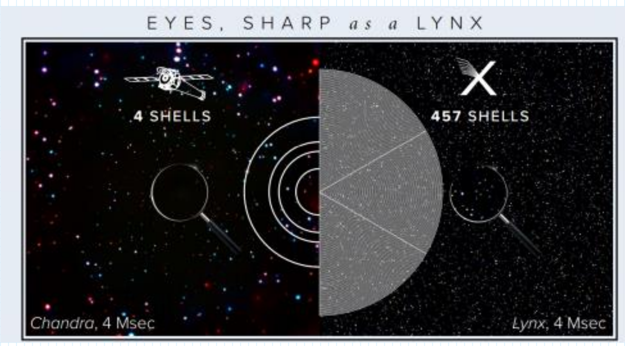
In early 2040's, which X-ray astronomy satellite is expected to be launched? What would be the performance?

not approved

https://www.lynxobservatory.com/







Plan your missions in 2050's !!