The Future of X-rayAstronomy

Keith Arnaud

karnaud@umd.edu

High Energy Astrophysics Science Archive Research Center

University of Maryland College Park
and
NASA's Goddard Space Flight Center

Themes

Politics

Efficient high resolution spectroscopy

Mirrors

Polarimetry

Other missions

Interferometry

Themes

Politics

Efficient high resolution spectroscopy

Mirrors

Polarimetry

Other missions

Interferometry

How do we get a new X-ray astronomy experiment?

A group of scientists and engineers makes a proposal to a national (or international) space agency. This will include a science case and a description of the technology to be used (which should generally be in a mature state).

In principal you can make an unsolicited proposal but in practice space agencies have proposal rounds in the same way that individual missions have observing proposal rounds.

NASA :

Small Explorer (SMEX) and Medium Explorer (MIDEX): every ~2 years alternating Small and Medium, three selected for study for one year from which one is selected for launch.

RXTE, GALEX, NuSTAR, Swift, IXPE

Arcus, a high resolution X-ray spectroscopy mission was a finalist in the latest MIDEX round but was not selected.

Missions of Opportunity (MO): every ~2 years includes balloon programs, ISS instruments and contributions to foreign missions.

Suzaku, Hitomi, NICER, XRISM

Large missions such as HST, Chandra, JWST are not selected by such proposals but are decided as national priorities through the Astronomy Decadal process.

Every ten years a survey is run by the National Academy of Sciences to decide on priorities for both land-based and space-based astronomy.

1960: HST; 1970: VLA; 1980: VLBA; 1990: Chandra and SIRTF; 2000: JWST and ALMA; 2010 WFIRST and LSST.

For the 2020 Decadal Survey NASA has funded studies of four large missions. One of these is Lynx, a successor to Chandra with sub-arcsec imaging and 50 times the area.

In addition NASA has funded small studies of a number of cheaper missions (ie one billion dollars). These include STROBE-X, an X-ray timing and spectroscopy mission; TAP, a multiwavelength mission to study the transient high energy sky; and AXIS, a high resolution X-ray imaging mission.

ESA:

The European Space Agency selects Large (L), Medium (M), and Small (S) missions based on response received to calls for proposals.

Three Large missions are currently under development. One of these is Athena, a super-XMM which improves on previous missions by factor of 20-100 for spectroscopy, 6-10 for imaging surveys, and 3-50 for timing measurements. It is currently scheduled for launch in 2031.

There are currently 4 Medium missions selected to launch in the 2020s. None are for X-ray astronomy. A 5th Medium mission with planned launch in 2032 has three competitors selected, one of which is designed to make multiwavelength observations of transient sources.

There are also 2 Small missions selected but neither is for X-ray astronomy.

Themes

Politics

Efficient high resolution spectroscopy

Mirrors

Polarimetry

Other missions

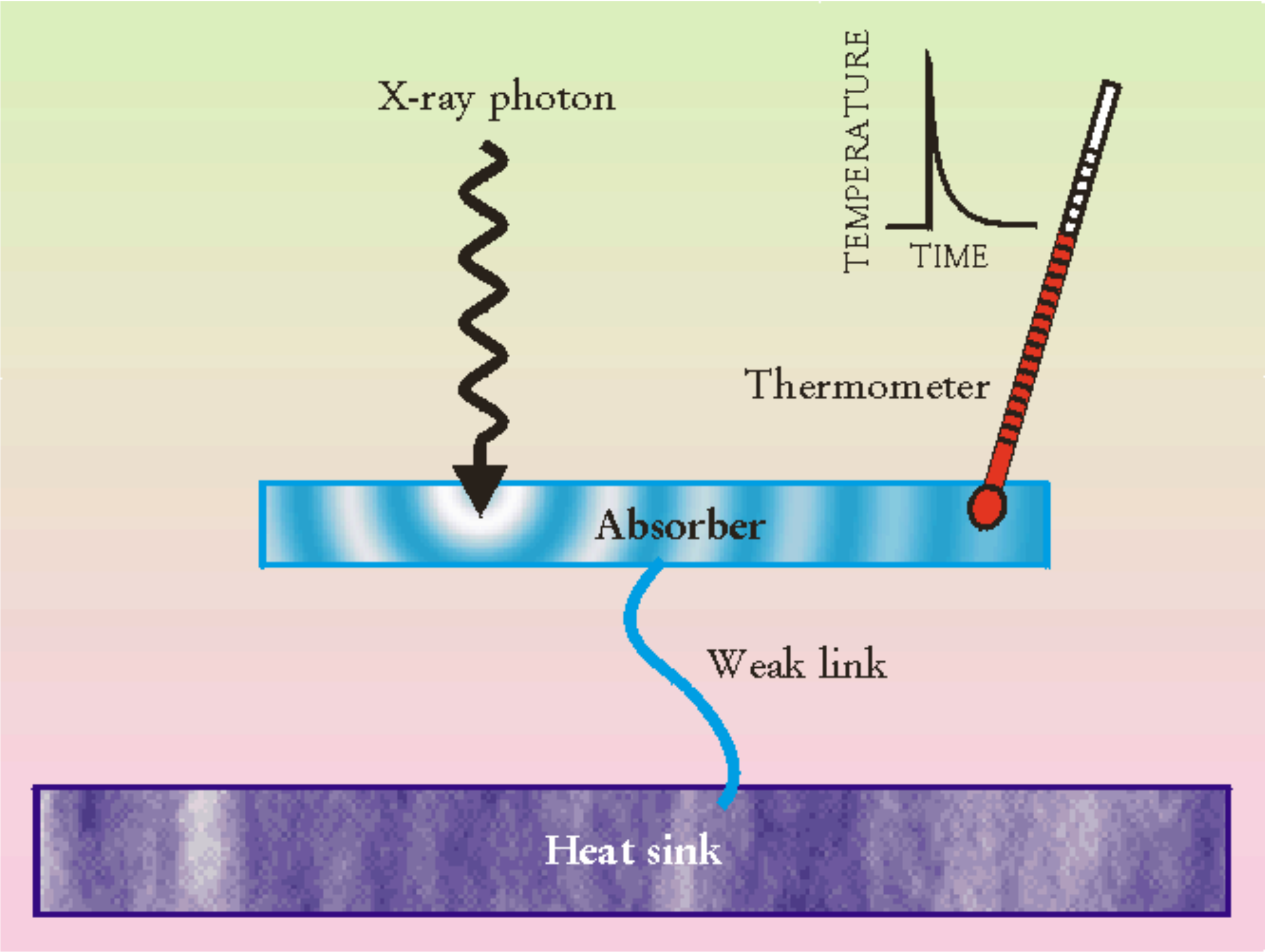
Interferometry

Calorimetry

Most X-ray detectors work by measuring the interaction between X-rays and electrons in atoms. However energetic photons or particles can also be detected by their heat input into a solid. To measure the temperature change due to individual photons or particles requires the detectors to be at very low temperatures (< 0.1 K). This is called microcalorimetry, or occasionally quantum calorimetry, because of its ability to precisely measure energy.

These detectors are now used in dark matter searches, infrared and microwave astronomy in addition to X-ray astronomy.

X-ray calorimetry

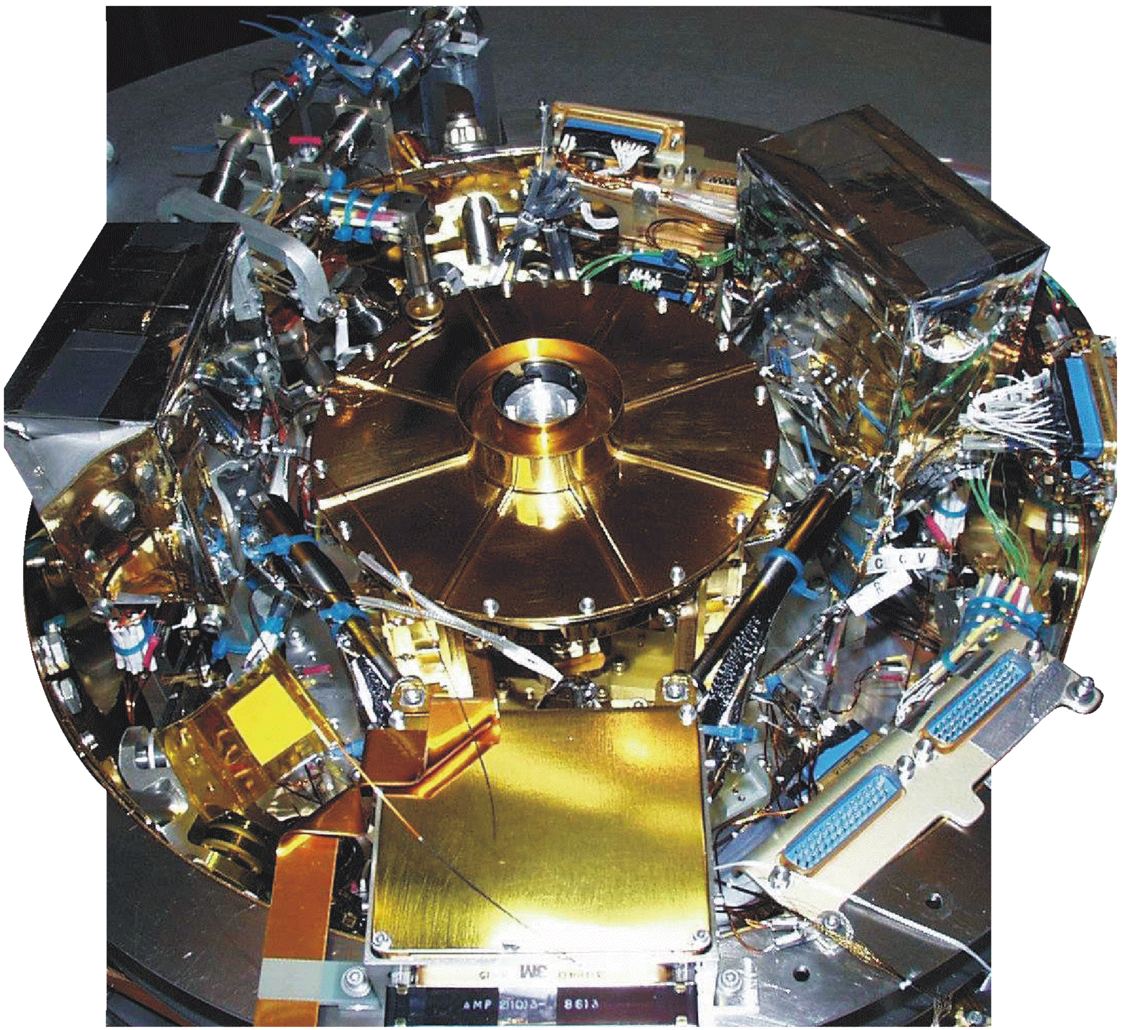


Microcalorimeters vs. Gratings

- Resolutions comparable with gratings. Microcalorimeters win at high energies, gratings at low energies.
- Non-dispersive so :
    - o high efficiency
    - o low background
    - o no problems for extended sources
    - o wide bandpass
- However, microcalorimeters are cryogenic experiments requiring cooling to ~60 mK.

PHYSICS TODAY

AUGUST 1999 PART 1



X RAYS ON ICE

X-rays on Ice

The XRS X-ray microcalorimeter built for Astro-E (the fifth Japanese X-ray astronomy satellite)

Resolution :

9 - 12 eV FWHM

(0.5 - 10 keV)

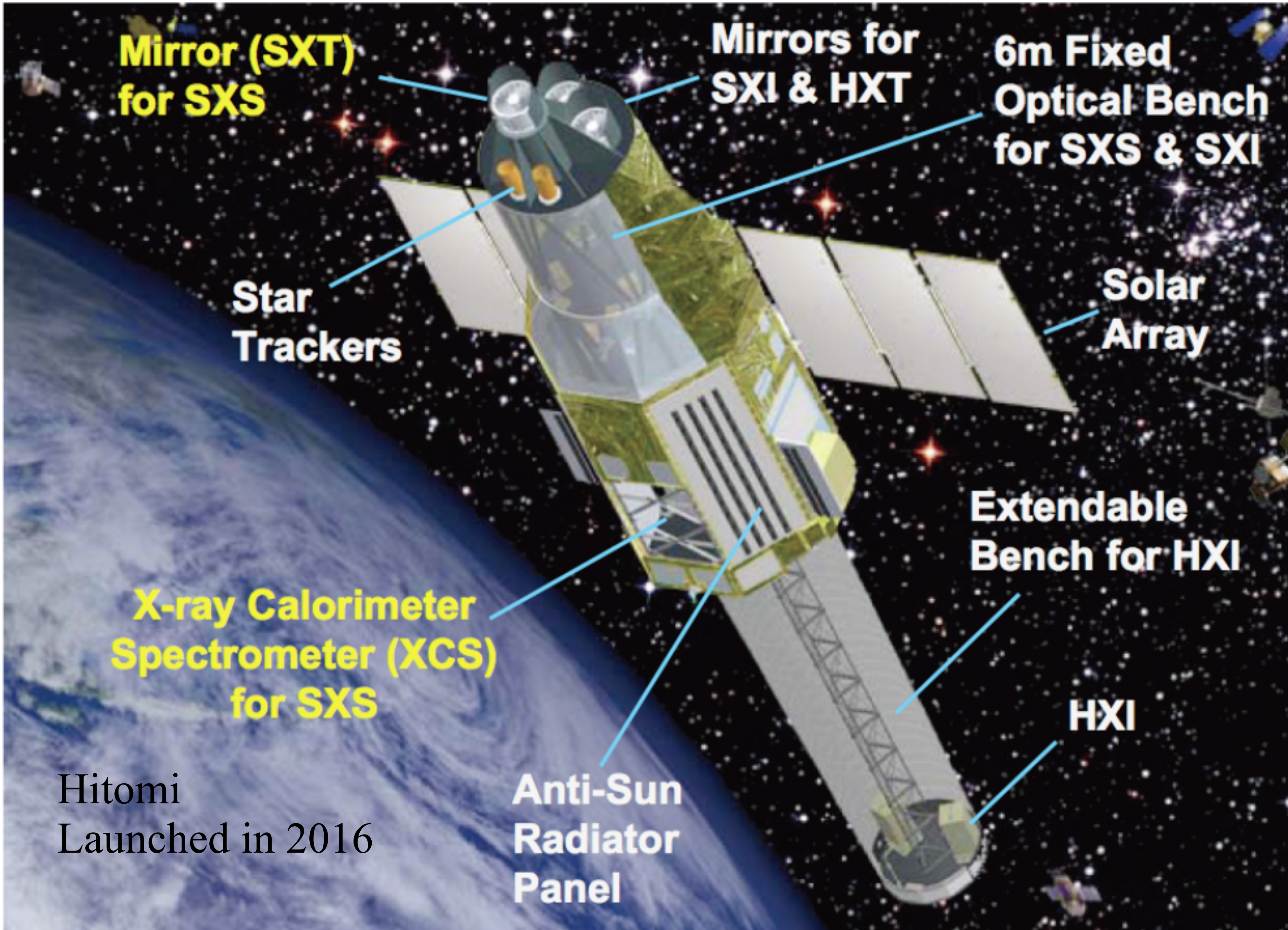
Inserting the He dewar in the Ne dewar

A solid Ne dewar outside a liquid He dewar outside an adiabatic demagnetization refrigerator.

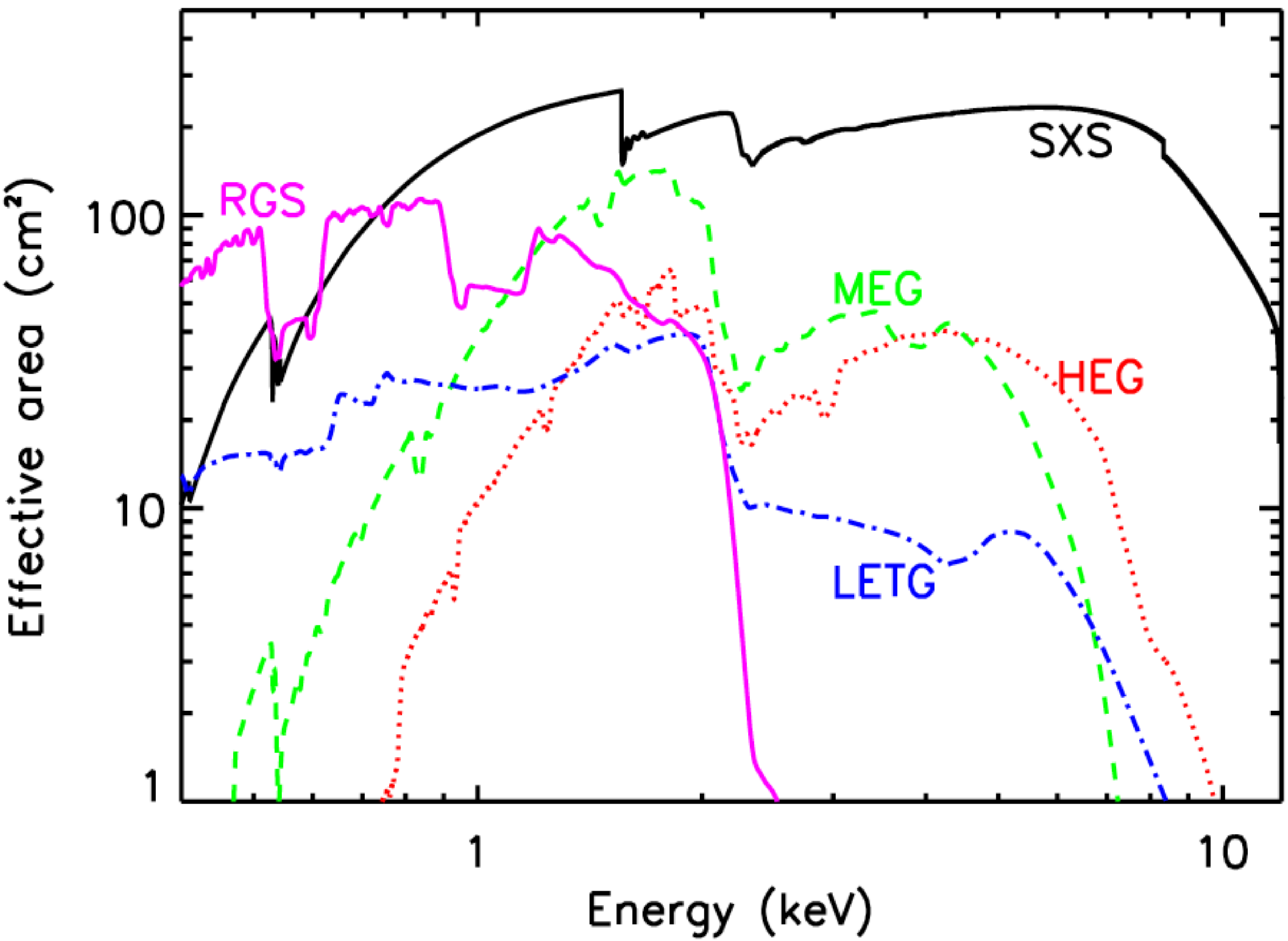
X-ray microcalorimeters have had a frustrating history...

Astro-E	2000	Launch failure
Suzaku	2005	Instrument worked but obtained no astronomical data due to cryogen loss because of a satellite design error
Hitomi	2016	Instrument worked and obtained a few astronomical observations before an operations error led to break-up of the satellite.

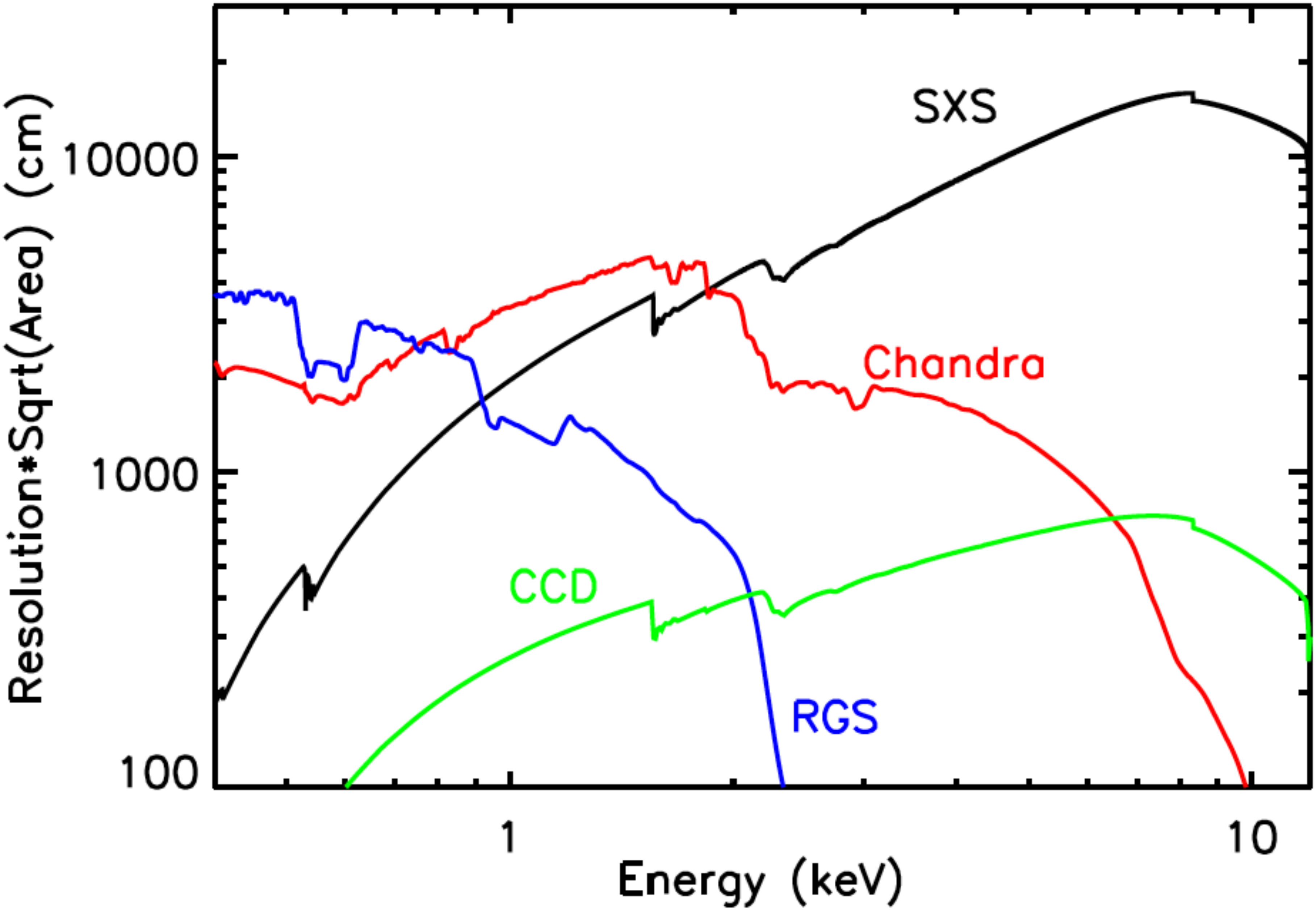
A Hitomi recovery mission (XRISM) launch is planned in early 2022. This will have only the calorimeter and CCD imager.



Hitomi
Launched in 2016

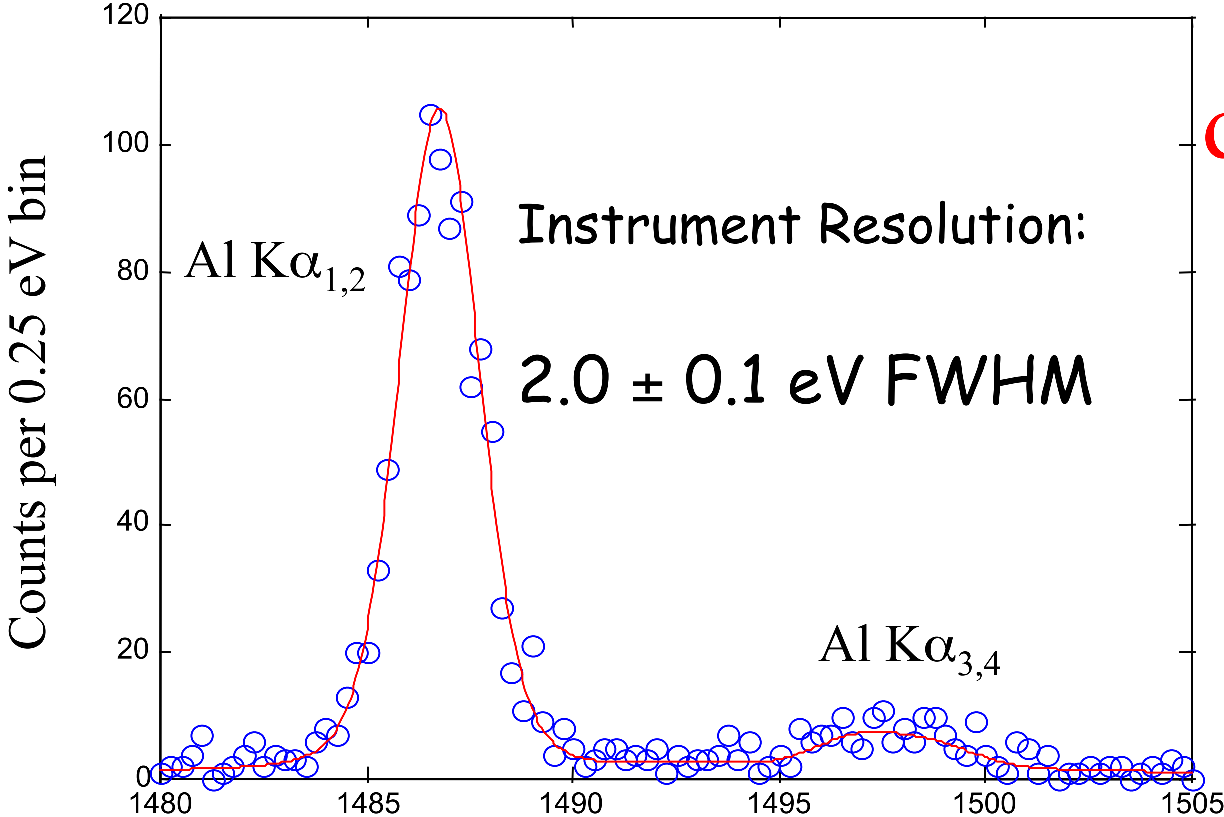


Effective area (cm²)
100
10
1
1
10
Energy (keV)
SXS
RGS
MEG
HEG
LETG

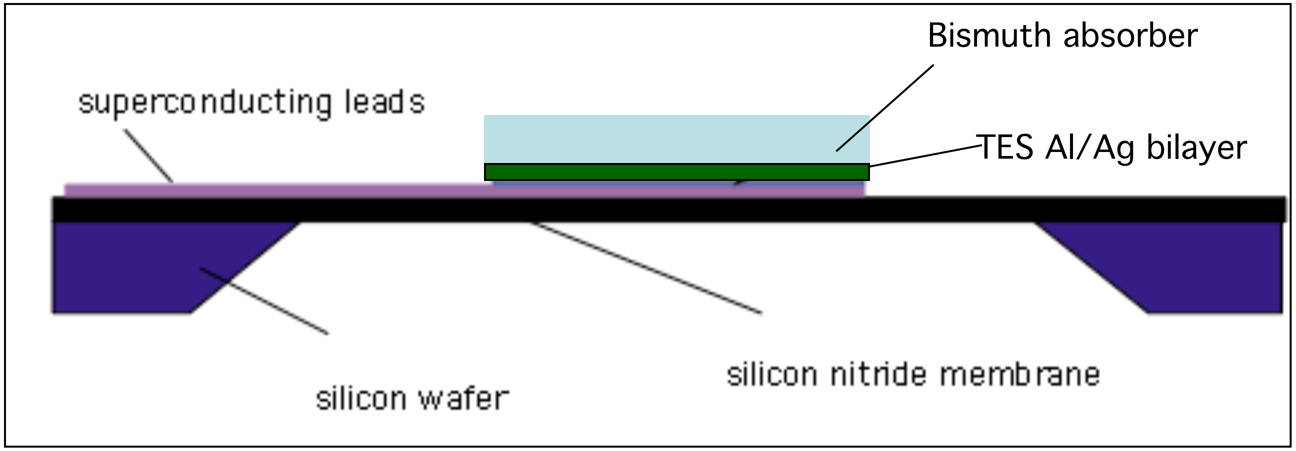


SXS
Chandra
CCD
RGS
10000
1000
100
1
10
Resolution*Sqrt(Area) (cm)
Energy (keV)

Calorimeter development for future missions



450 counts/sec



NIST Boulder Colorado

K. Irwin

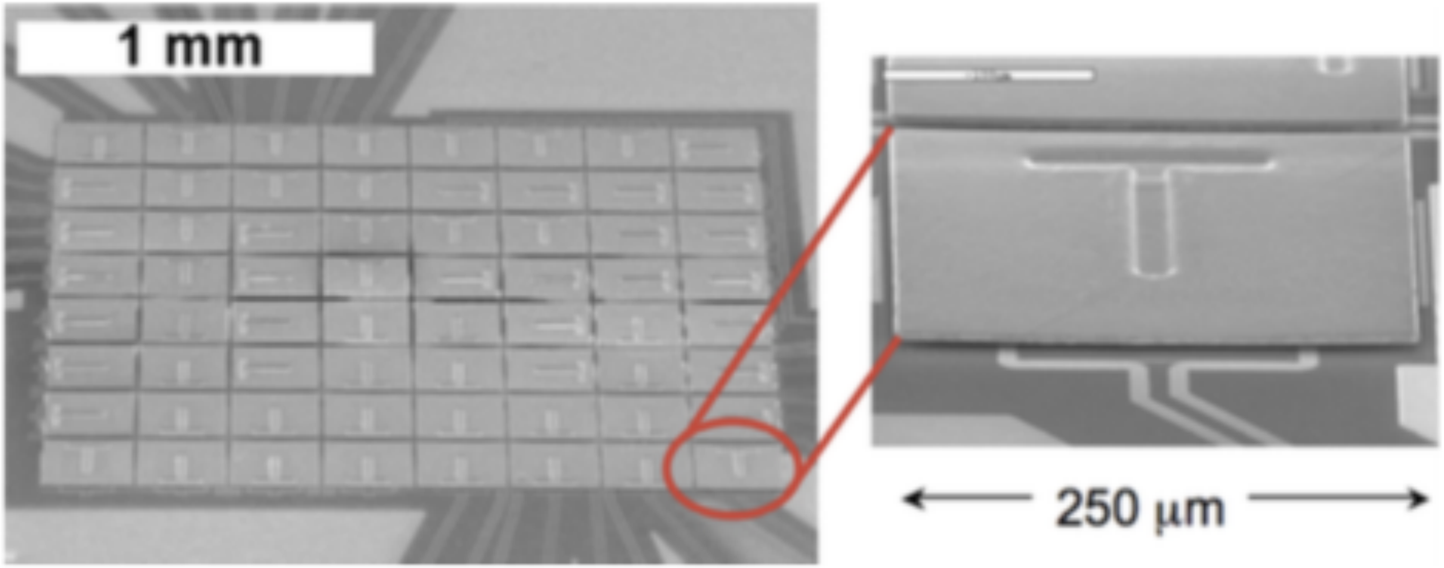


Figure 2. *Electron micrograph of a uniform 8×8-pixel TES array.[6] The closeup view on the right shows an individual pixel with its absorber hanging over the wiring and substrate.*

Current development program is to build larger arrays aiming first for kilopixels and eventually megapixels.

Themes

Politics

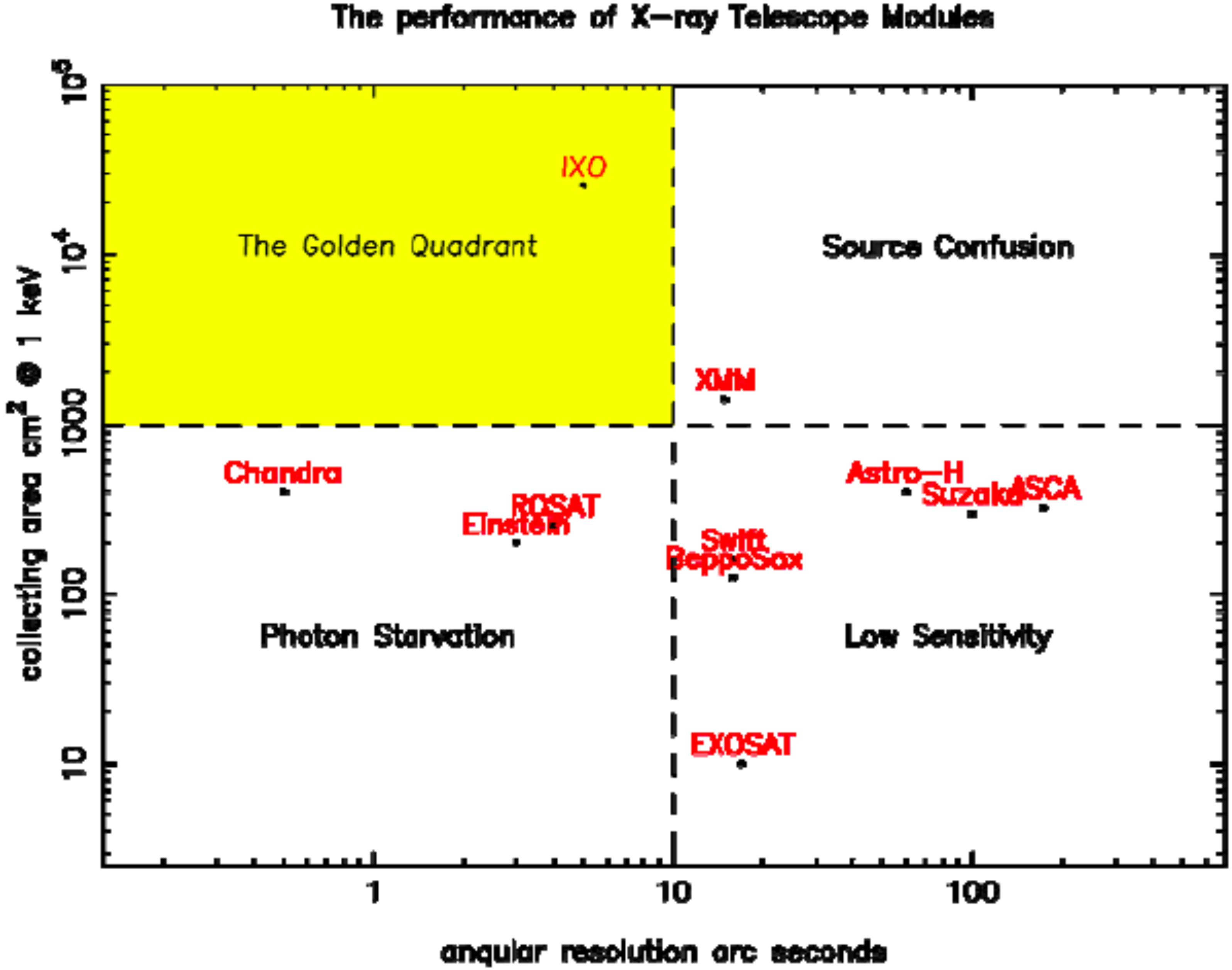
Efficient high resolution spectroscopy

Mirrors

Polarimetry

Other missions

Interferometry



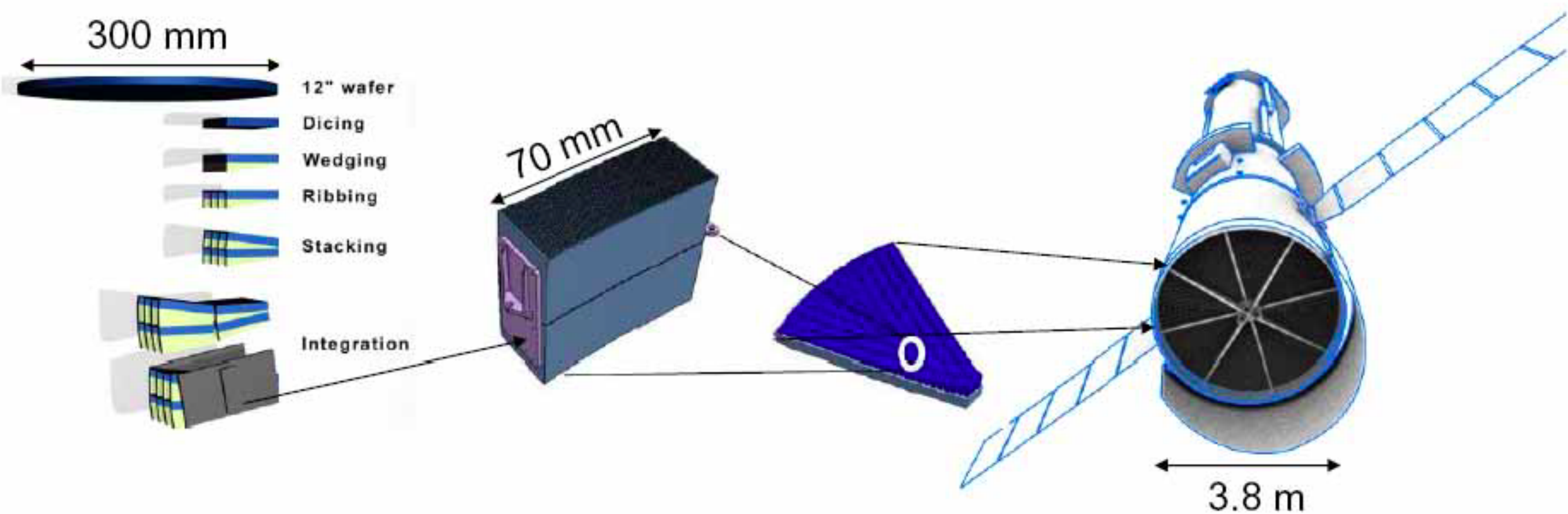
Willingale 2011

The major challenge is building high-quality, lightweight (and cheap) optics.

The Chandra and XMM-Newton mirrors are too heavy and expensive to be made larger.

The Swift/NuSTAR/Hitomi mirrors are lightweight and relatively cheap but their spatial resolution is not good enough.

Silicon pore optics



Based on semiconductor industry standard Si wafers robotically assembled into mirror segments.

Slumped glass optics

Start with high quality commercial glass similar to that used for laptop screens.

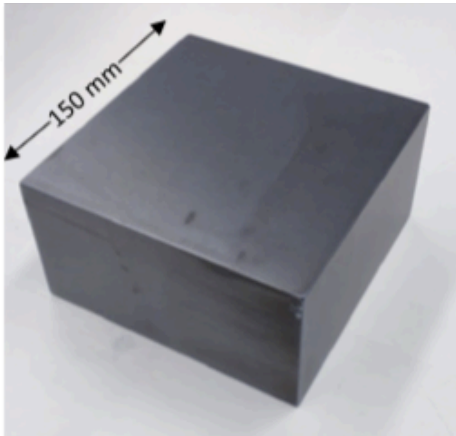
Place on precisely-shaped mold (mandrel) and heat to 600 C in oven. When cooled the glass has the correct mirror shape.

Used for NuSTAR.

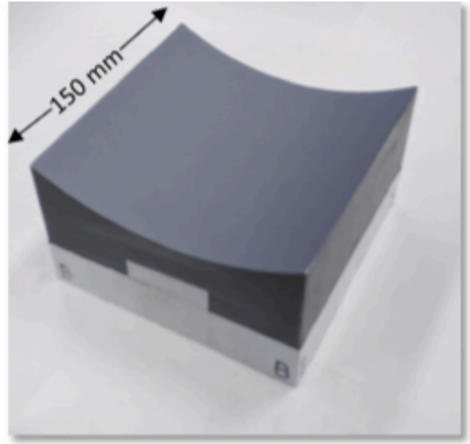
Single-crystal silicon optics

The Goddard mirror group attempted to improve slumped glass optics but realized that they had reached the limit with NuSTAR. To do better they switched to single-crystal silicon.

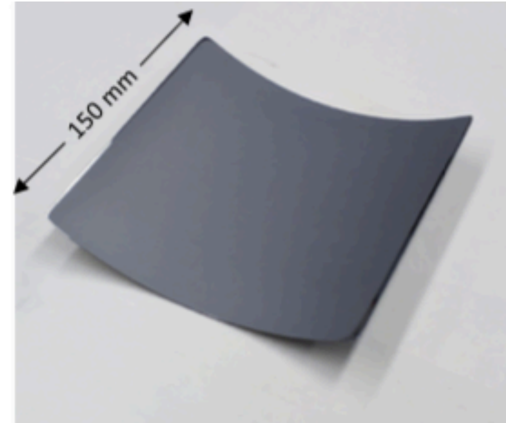
Start with single-crystal silicon block from the semiconductor industry. Cut, grind and machine to get correct shape in block surface. Slice a thin section from the top of the block, polish, and coat with iridium.



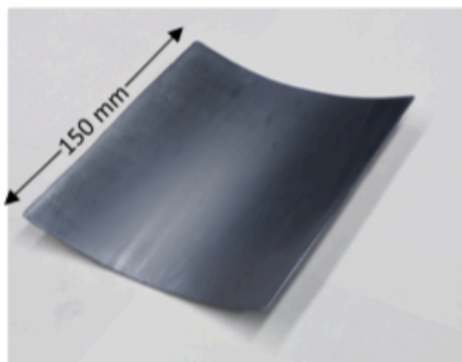
Monocrystalline silicon block



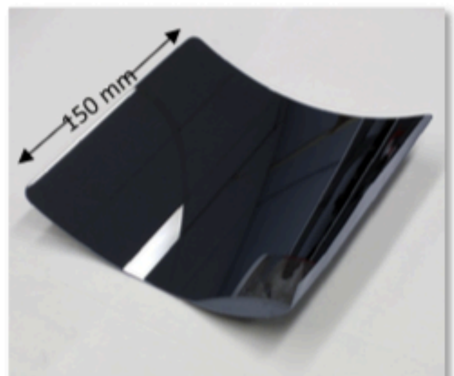
Conical form generated



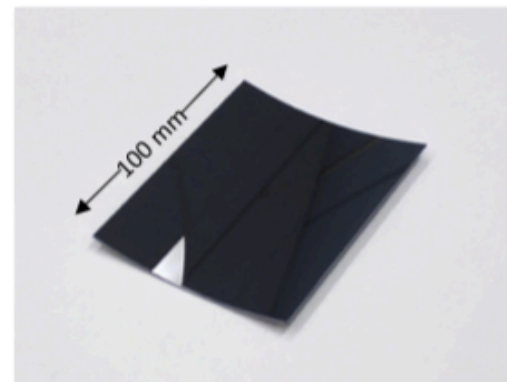
Light-weighted substrate



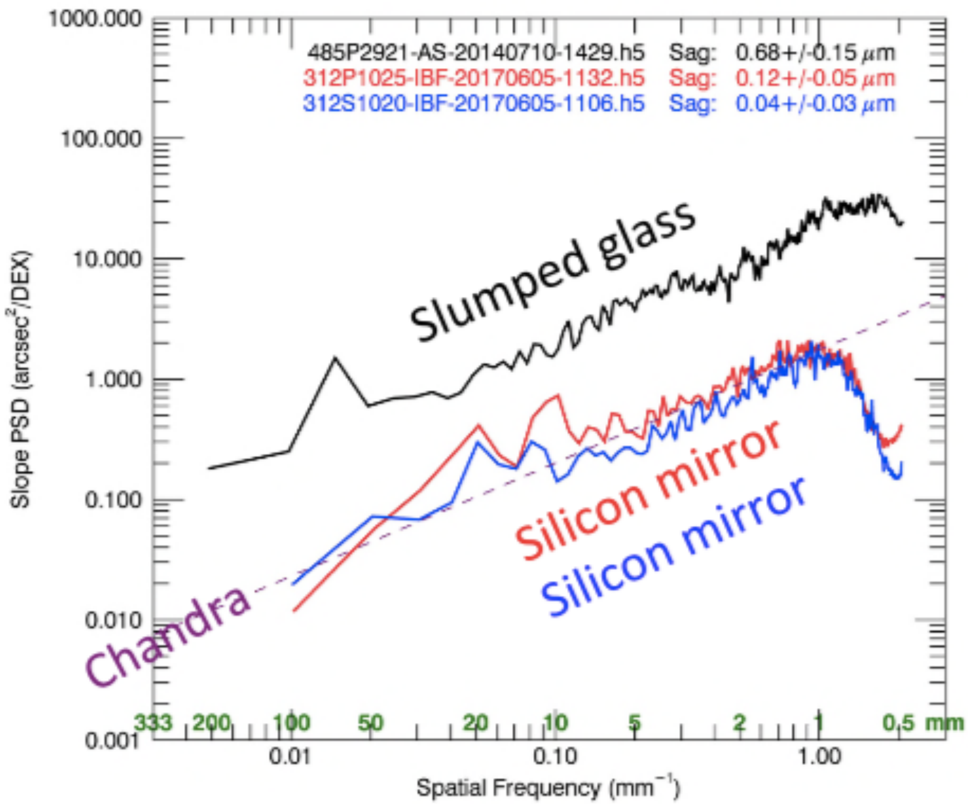
Etched substrate

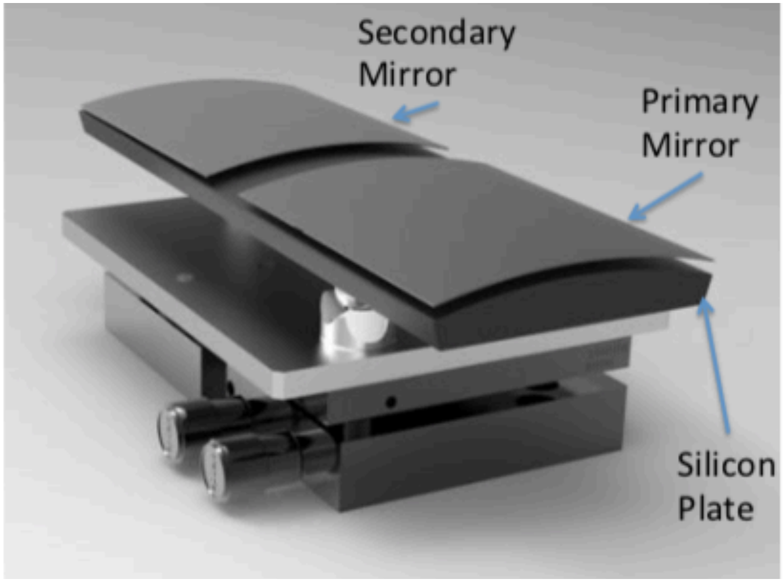


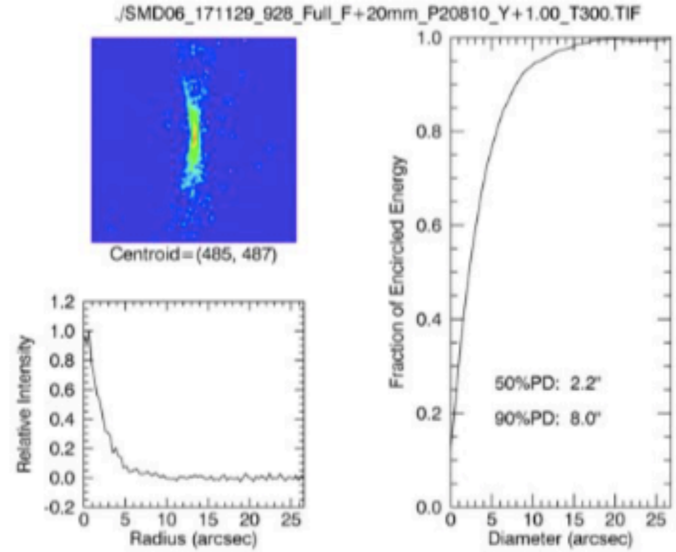
Polished mirror substrate



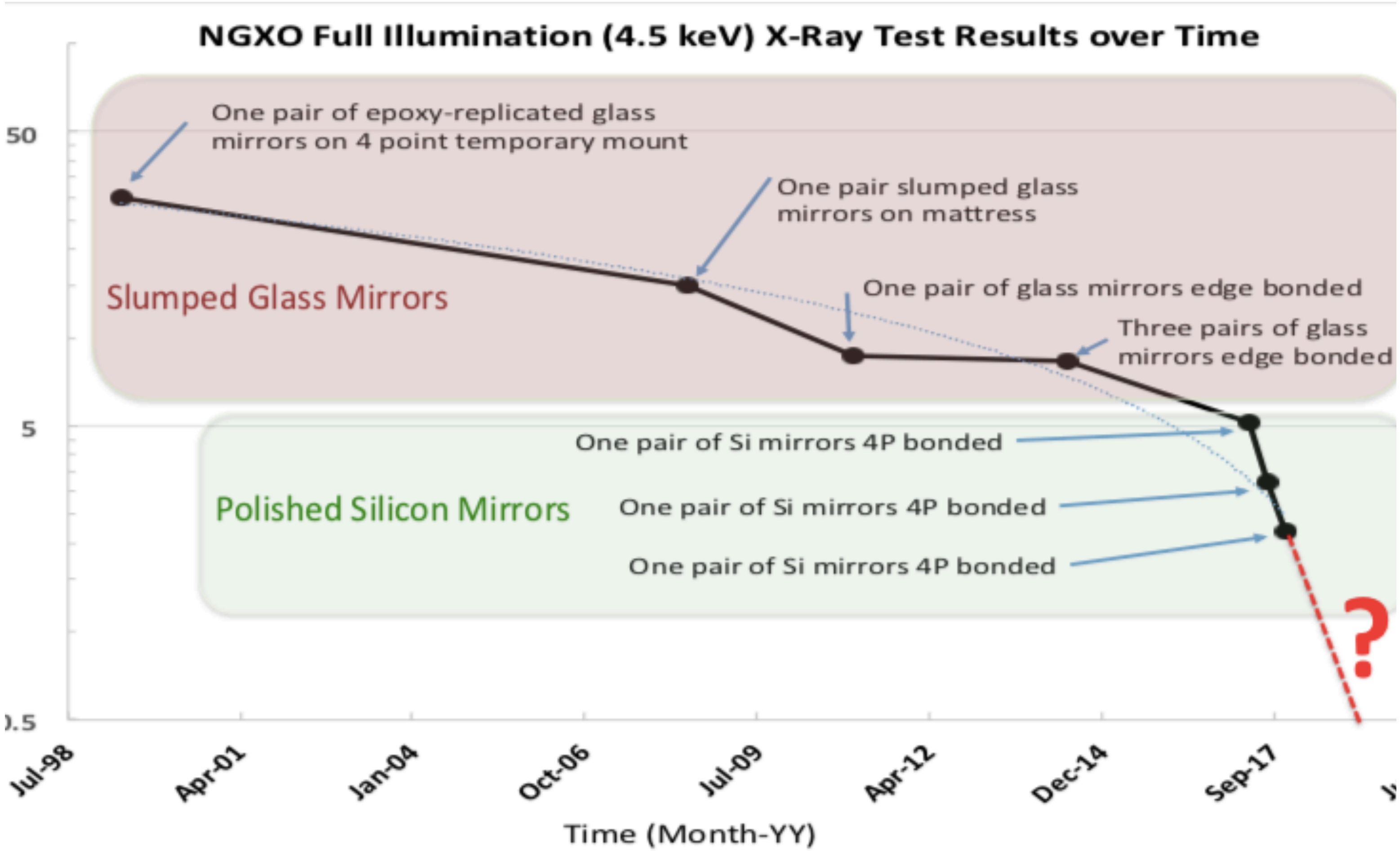
Trimmed mirror substrate


485P2921-AS-20140710-1429.h5 Sag: 0.68+/-0.15 μm
312P1025-IBF-20170605-1132.h5 Sag: 0.12+/-0.05 μm
312S1020-IBF-20170605-1106.h5 Sag: 0.04+/-0.03 μm
Slumped glass
Silicon mirror
Silicon mirror
Chandra
Slope PSD (arcsec²/DEX)
1000.000
100.000
10.000
1.000
0.100
0.010
0.001
333 200 100 50 20 10 5 2 1 0.5 mm
0.01
0.10
1.00
Spatial Frequency (mm⁻¹)





Experimental result with a single pair of mirror shells



Progress over last two decades

Four-point kinematic support

– Locations optimized to minimize gravity distortion and gravity release error.

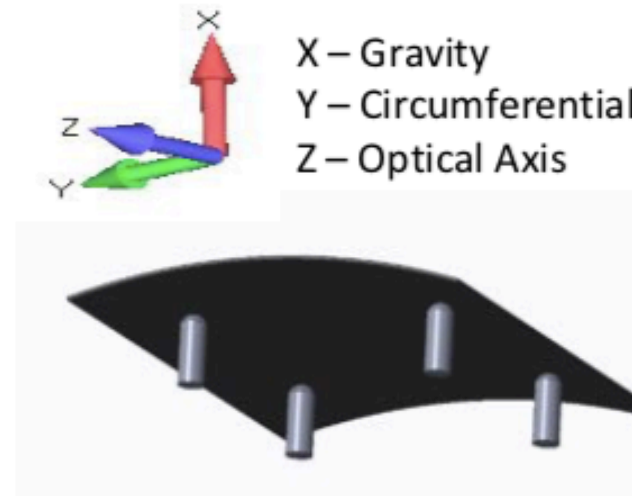
Use nanofabrication technology to make alignment combs (“scaffold”)

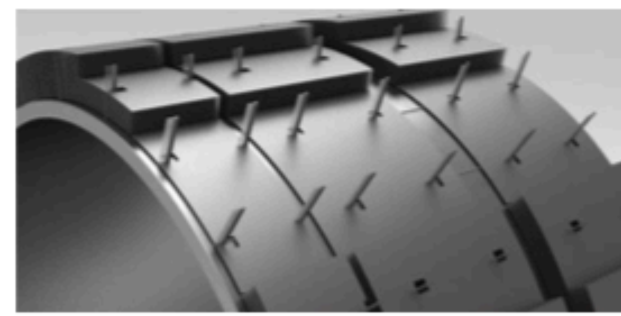
– Deterministic and efficient.

– Highly amendable to robotic operations.

Use acoustics to settle the mirror

– Overcomes static friction and relaxes the mirror.





Fabrication method for full meta-shells

Themes

Politics

Efficient high resolution spectroscopy

Mirrors

Polarimetry

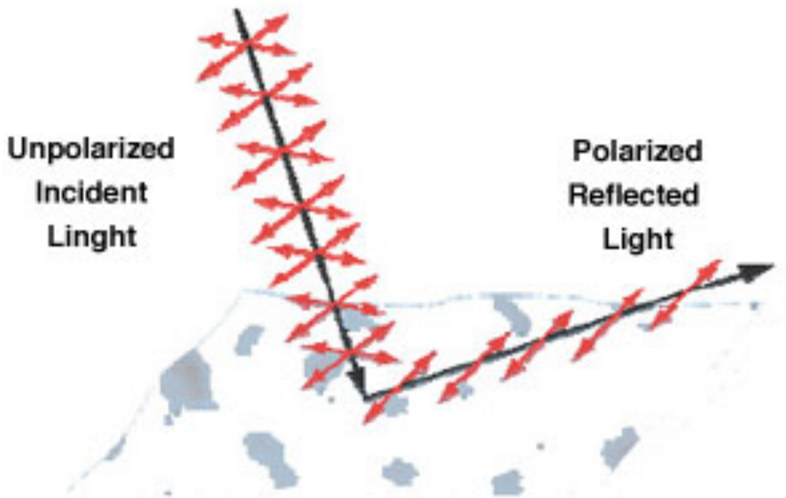
Other missions

Interferometry

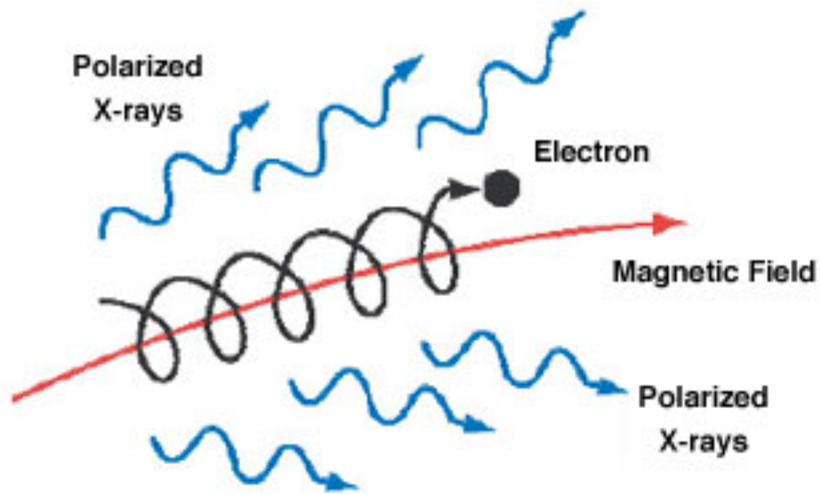
Why X-ray Polarimetry ?

- Because it’s there ! Whenever we look at the Universe in a new way we make unexpected discoveries.

- We expect polarization from X-ray synchrotron sources such as SNR and jets. Also from X-ray reflection in binaries and AGN. Polarization gives 3-D information.



Scattering Induces Polarization



Synchrotron emission in a strong magnetic field

Why X-ray Polarimetry ?

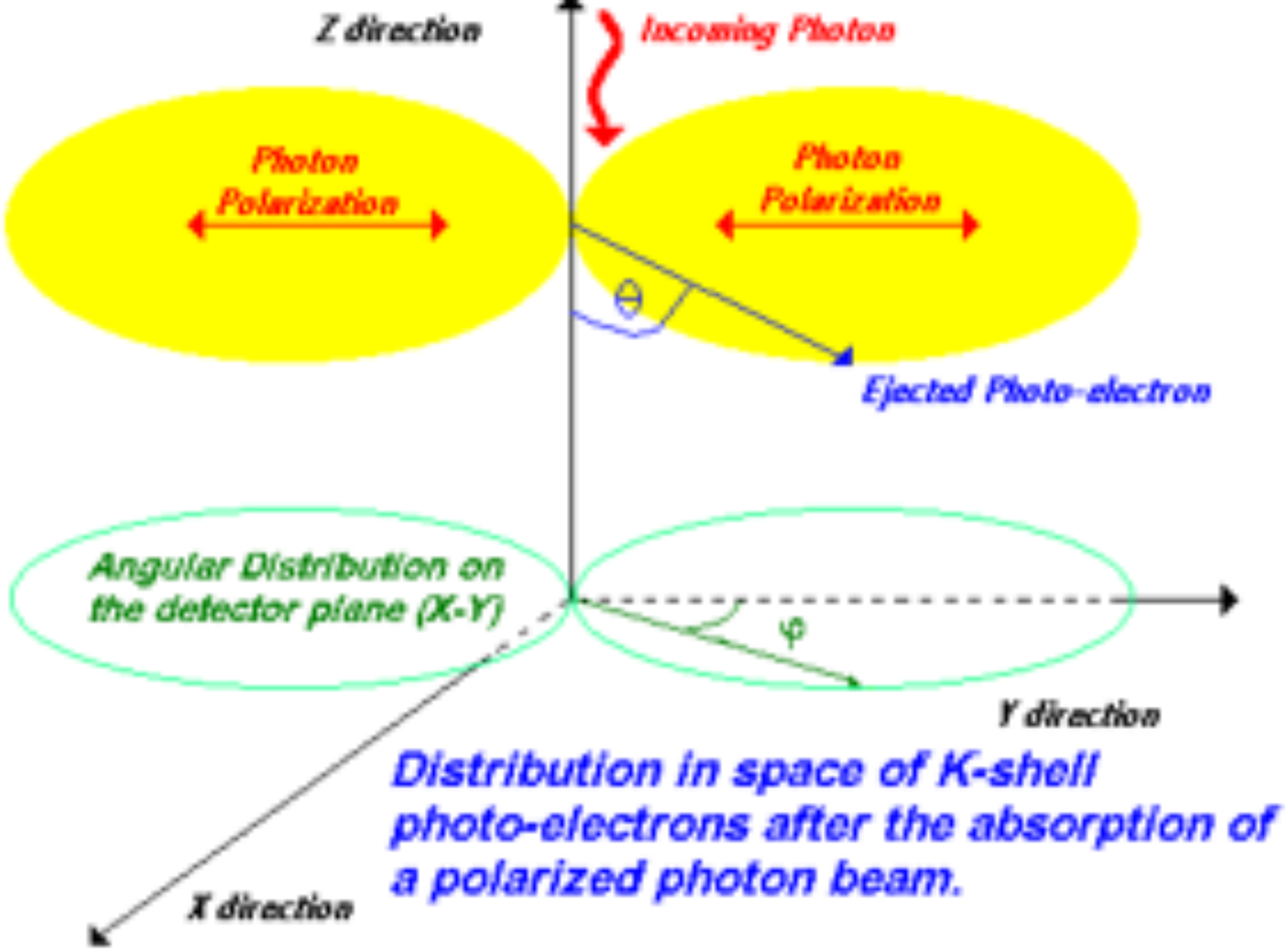
- Because it's there ! Whenever we look at the Universe in a new way we make unexpected discoveries.

We expect polarization from X-ray synchrotron sources such as SNR and jets. Also from X-ray reflection in binaries and AGN. Polarization gives 3-D information.

- There is one detection of X-ray polarization - that of the Crab Nebula.
- No X-ray polarimeter has flown on a satellite since the 1970s. This polarimeter was very inefficient.
- Over the last fifteen years a more efficient polarimeter has been developed.

Consider an X-ray detector consisting of a volume of gas. An X-ray will be detected when it knocks an electron (usually inner shell) out of an atom.

The direction of travel of this electron depends on the polarization of the X-ray.

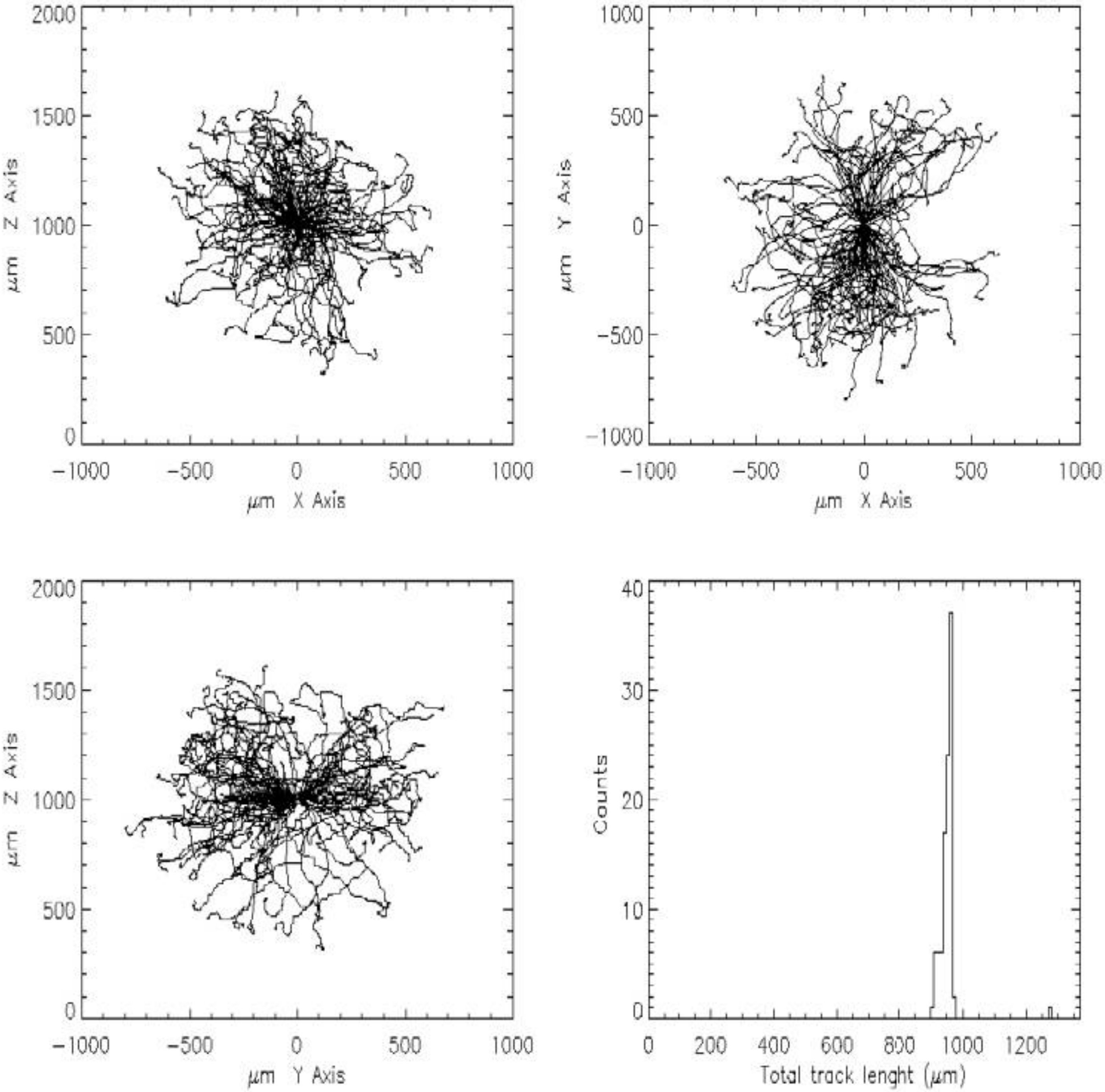


$$\frac{\partial \sigma}{\partial \Omega} = r_0^2 \frac{Z^5}{137^4} \left(\frac{m c^2}{h\nu}\right)^{1/2} \frac{4\sqrt{2}\sin^2(\theta)\cos^2(\phi)}{(1-\beta\cos(\theta))^4}$$

Polarization

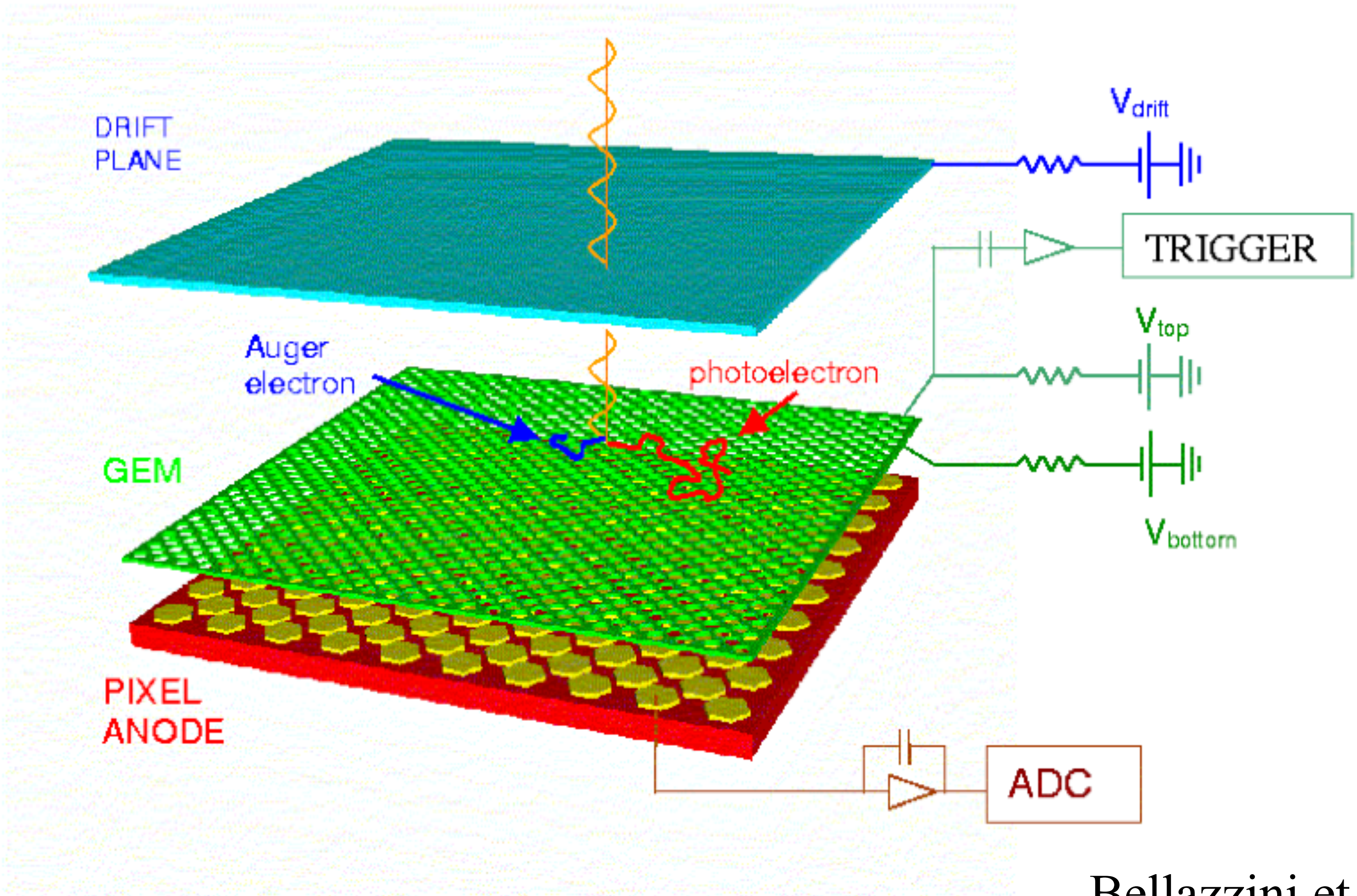
So, if we could measure the direction of the electron we could estimate the polarization angle. However, the electron interacts with other atoms in the gas, losing energy by collisions with atoms and expelling other electrons. Most of the electron energy is lost near the end of the track.

Electron Tracks



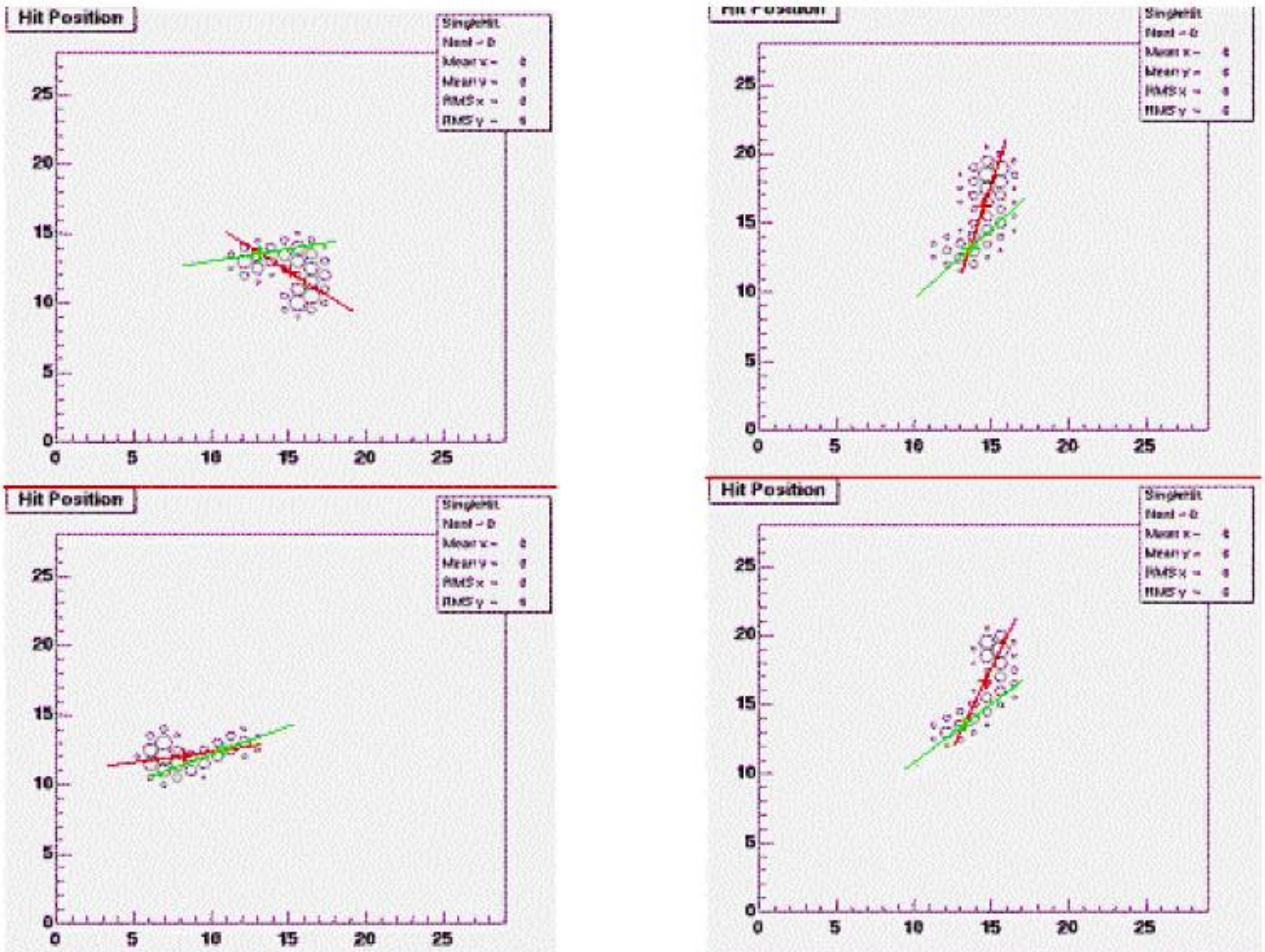
Bellazzini et al.

Microwell detector



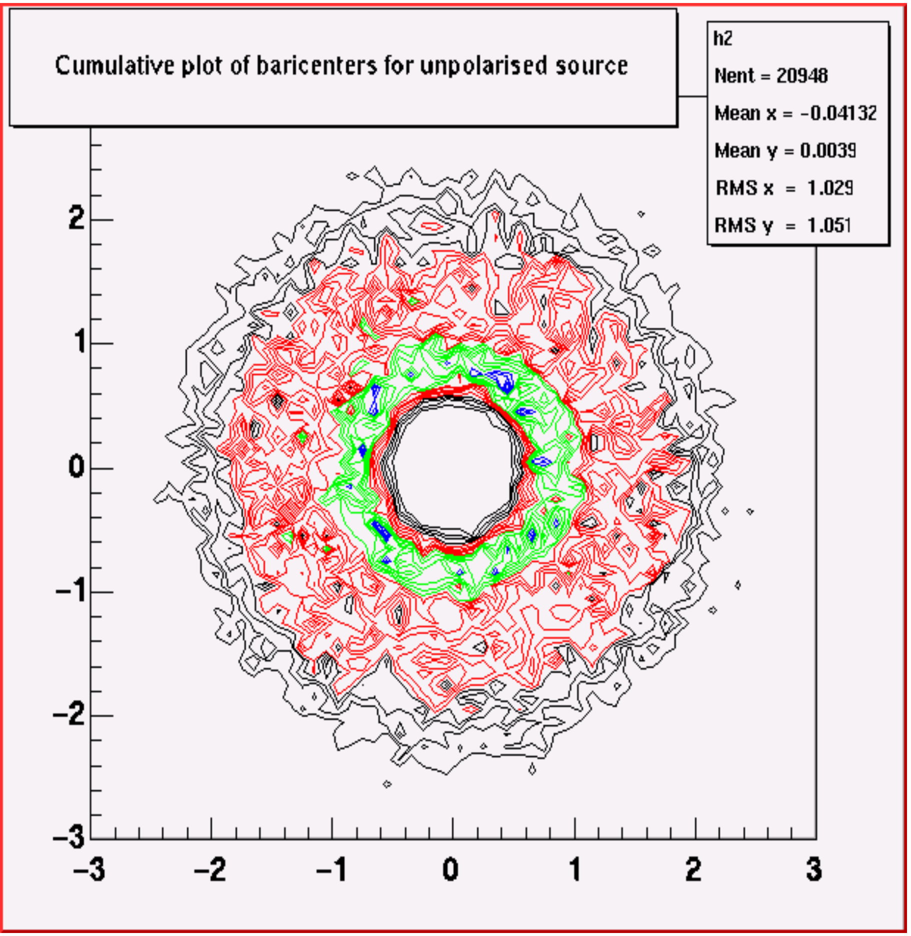
Bellazzini et al.

Bellazzini et al.

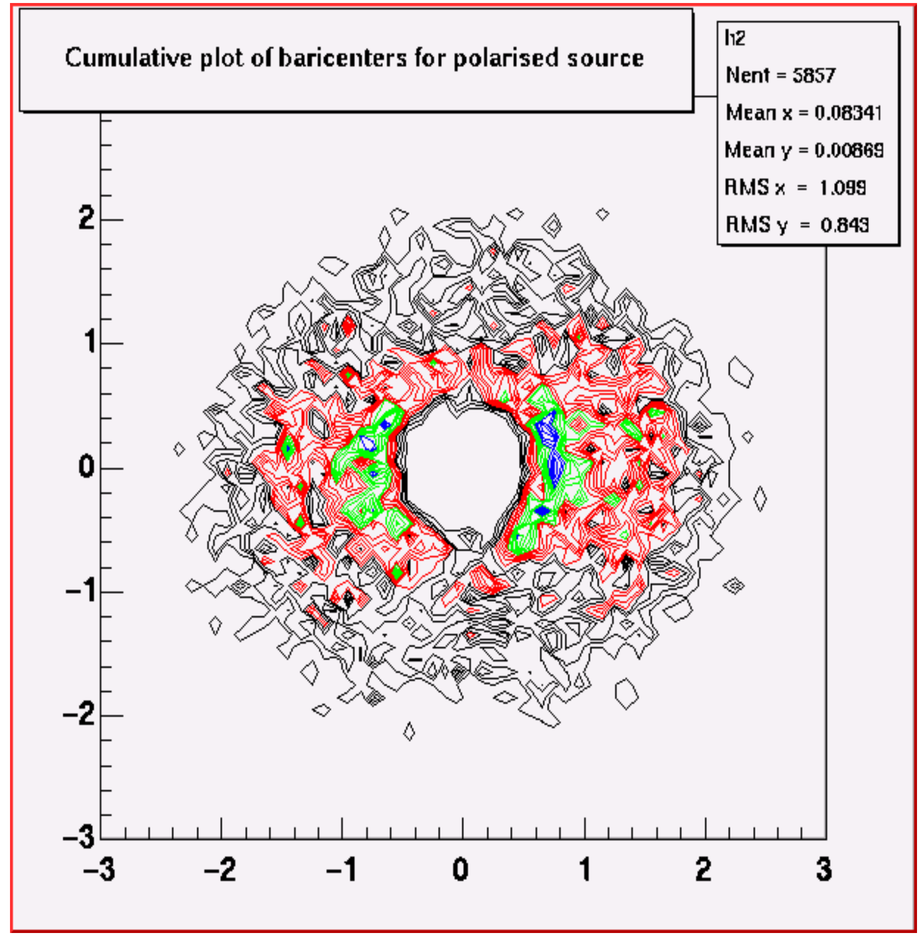


Accumulation of many events

5.9 KeV unpolarized



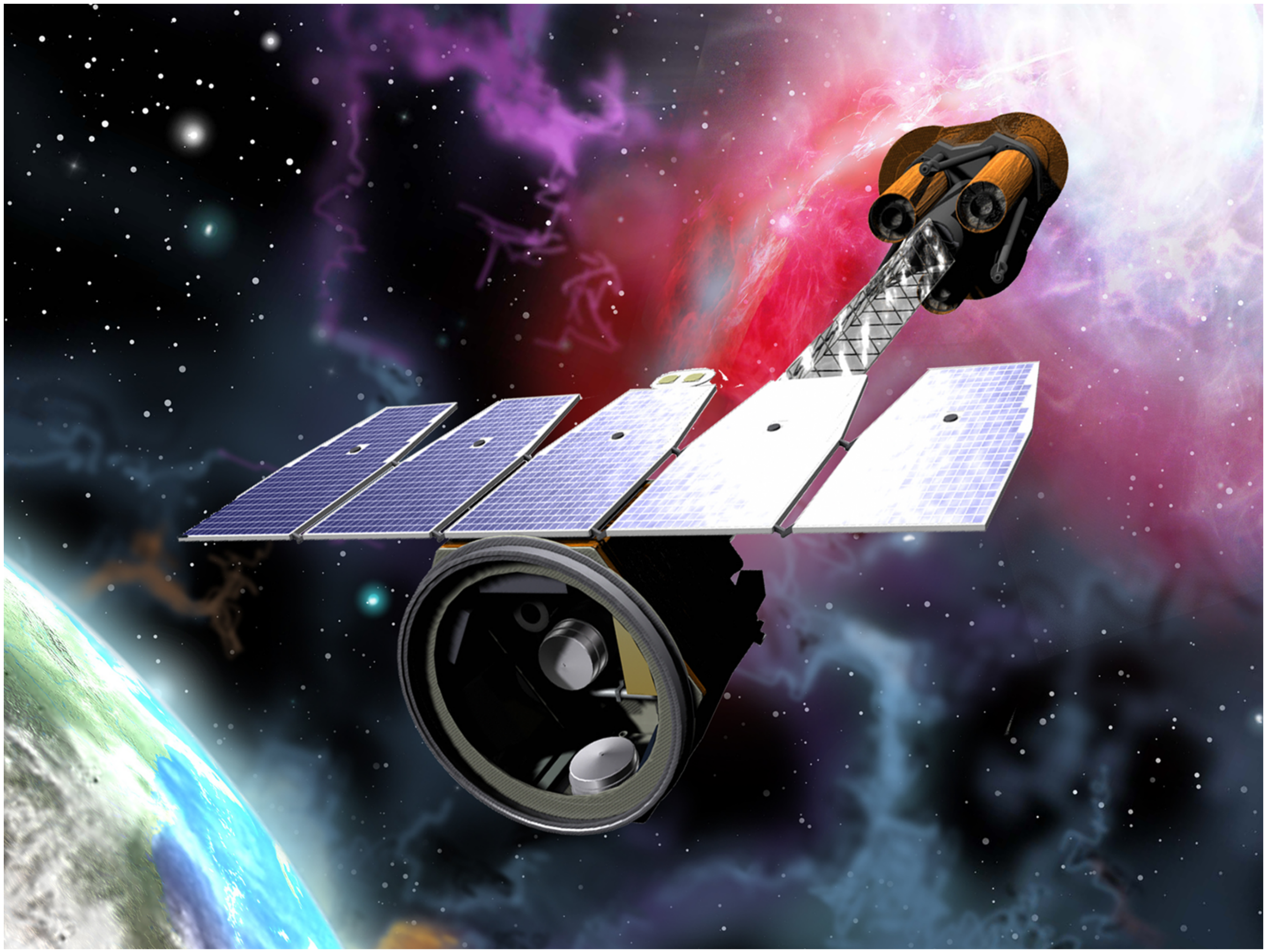
5.4 KeV polarized



Bellazzini et al.

IXPE - Launch in late 2020 on Pegasus

Effective area 690 cm^2, resolution 25 arcsec, FOV 12.9 arcmin



IXPE accomplishes new science with new capabilities

Addresses key questions, providing new scientific results and constraints

- What is the spin of a black hole?
- What are the geometry and magnetic-field strength in magnetars?
- Was our Galactic Center an Active Galactic Nucleus in the recent past?
- What is the magnetic field structure in synchrotron X-ray sources?
- What are the geometries and origins of X-rays from pulsars?

Weisskopf et al.

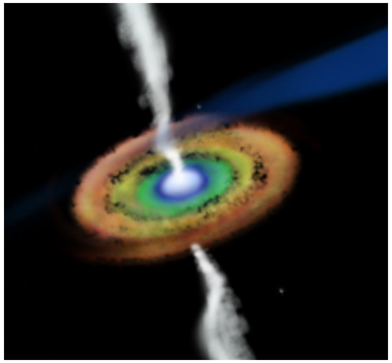
IXPE
Imaging X-Ray Polarimetry Explorer

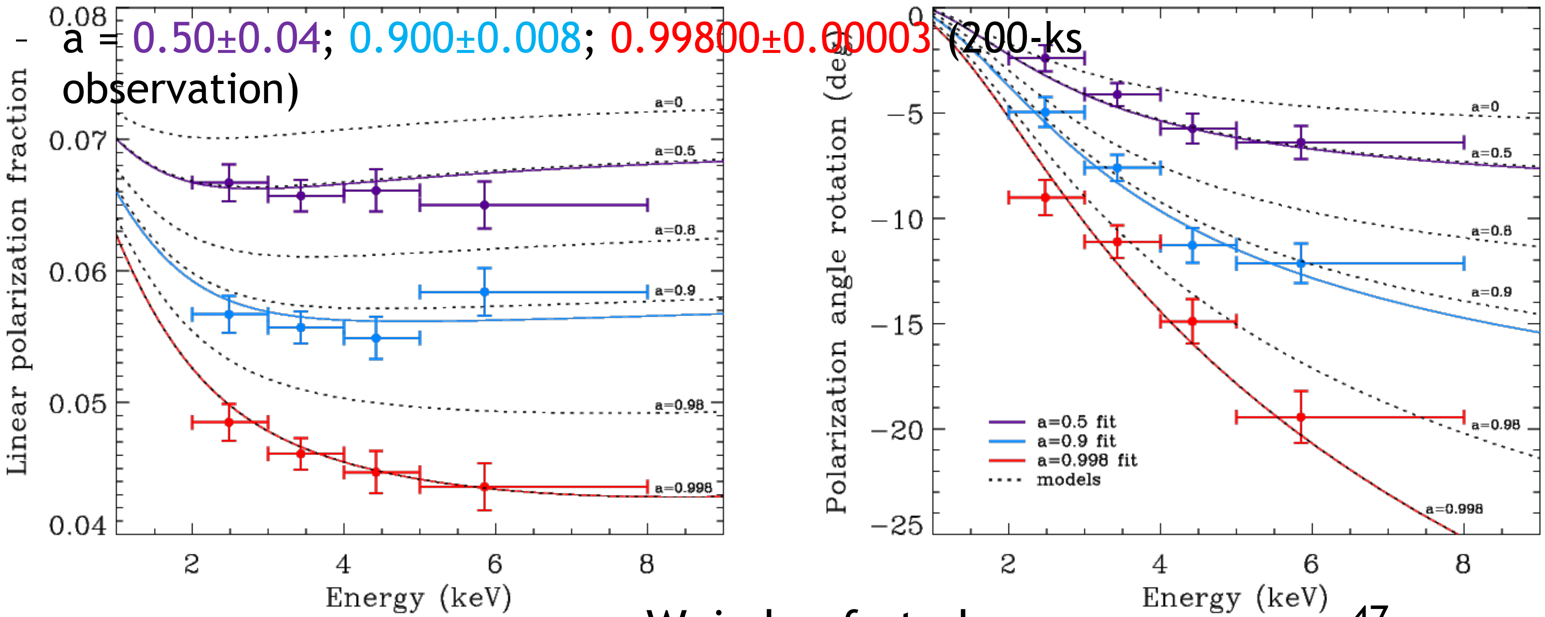
Marshall Space Flight Center

agenzia spaziale italiana

Measure black-hole spin from polarization rotation in twisted space-time: GRX1915+105

- **For a micro-quasar in an accretion-dominated state**
  - Scattering polarizes the thermal disk emission
  - Polarization rotation is greatest for emission from inner disk
    - Inner disk is hotter, producing higher energy X-rays
  - Priors on disk orientation constrain GRX1915+105 model
    - a = 0.50±0.04; 0.900±0.008; 0.99800±0.00003 (200-ks observation)

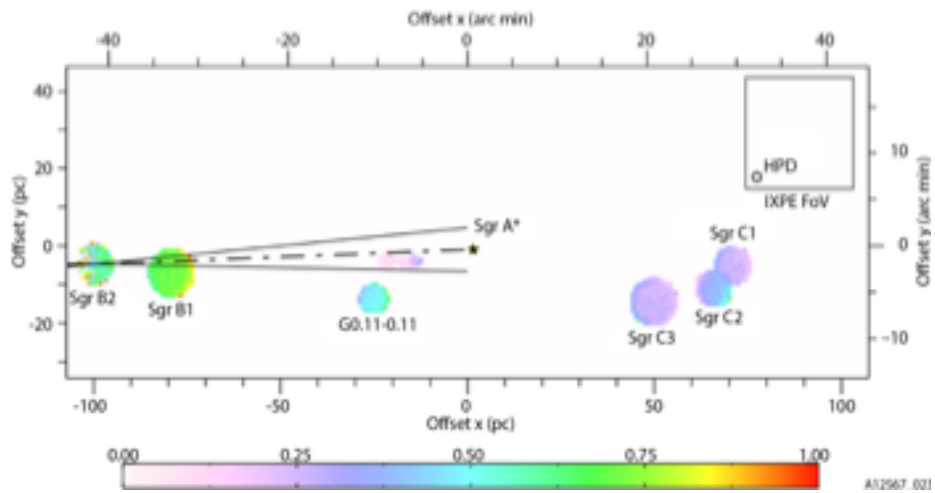


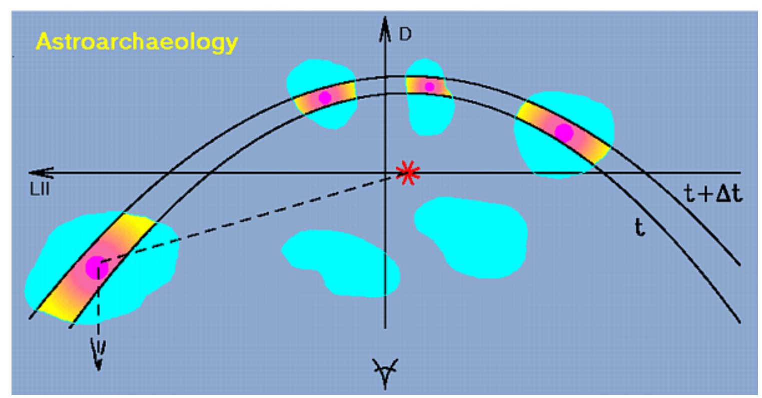


Weisskopf et al.

Was Sgr A* recently 10^6 × more active?

- **Galactic Center molecular clouds (MC) are known X-ray sources**
  - If MCs reflect X-rays from Sgr A* (supermassive black hole in the Galactic center)
    - X-radiation would be *highly polarized* perpendicular to plane of reflection and indicates the direction back to Sgr A*
    - Sgr A* X-ray luminosity was 10^6 larger ≈ 300 years ago
  - If not, still a discovery





Themes

Politics

Efficient high resolution spectroscopy

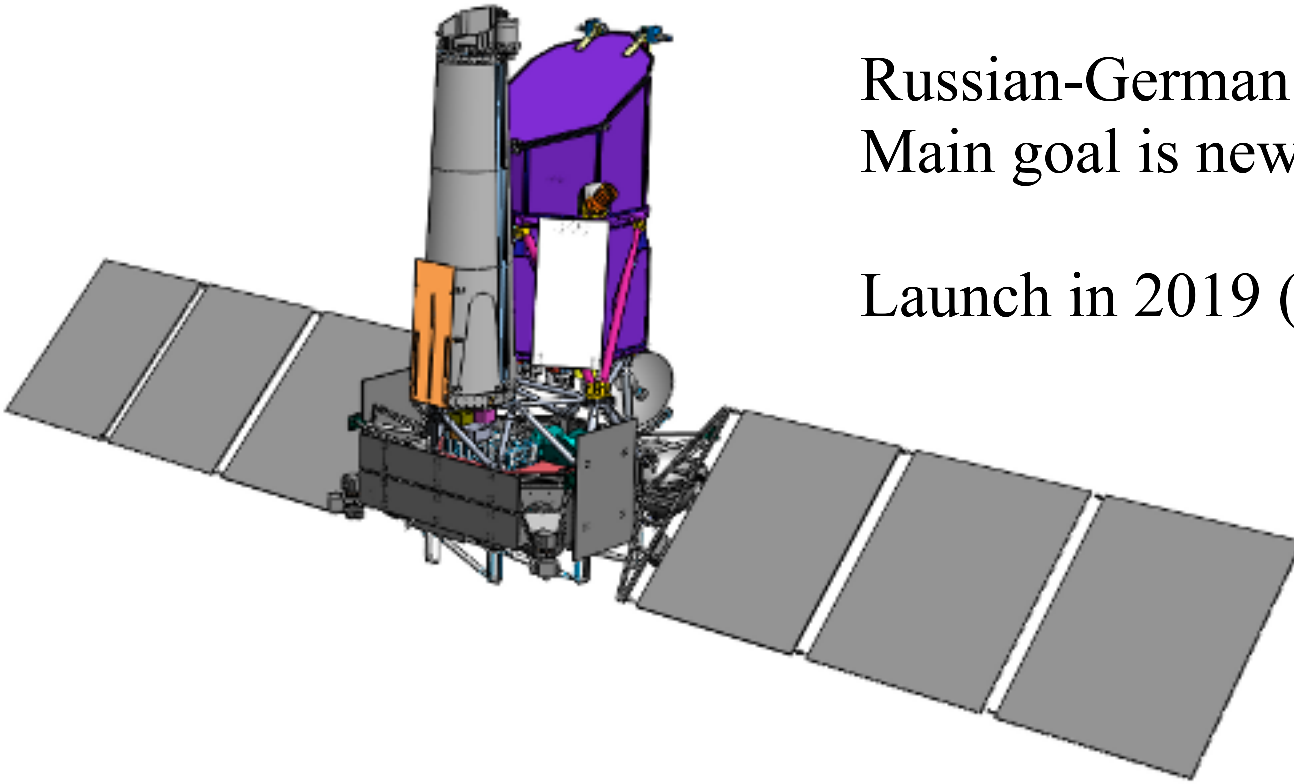
Mirrors

Polarimetry

Other missions

Interferometry

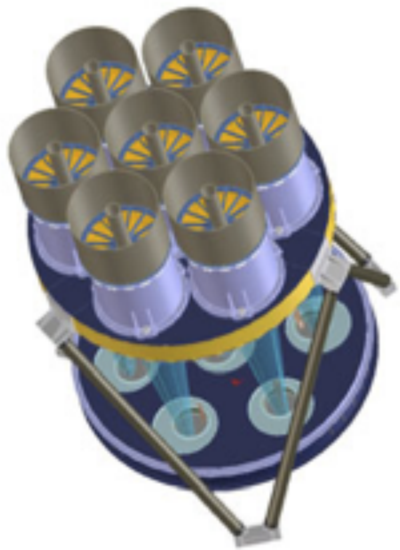
Spectrum-Roentgen-Gamma



Russian-German collaboration.
Main goal is new all-sky survey.

Launch in 2019 (?)

http://hea.iki.rssi.ru/SRG/en/index.php



eROSITA

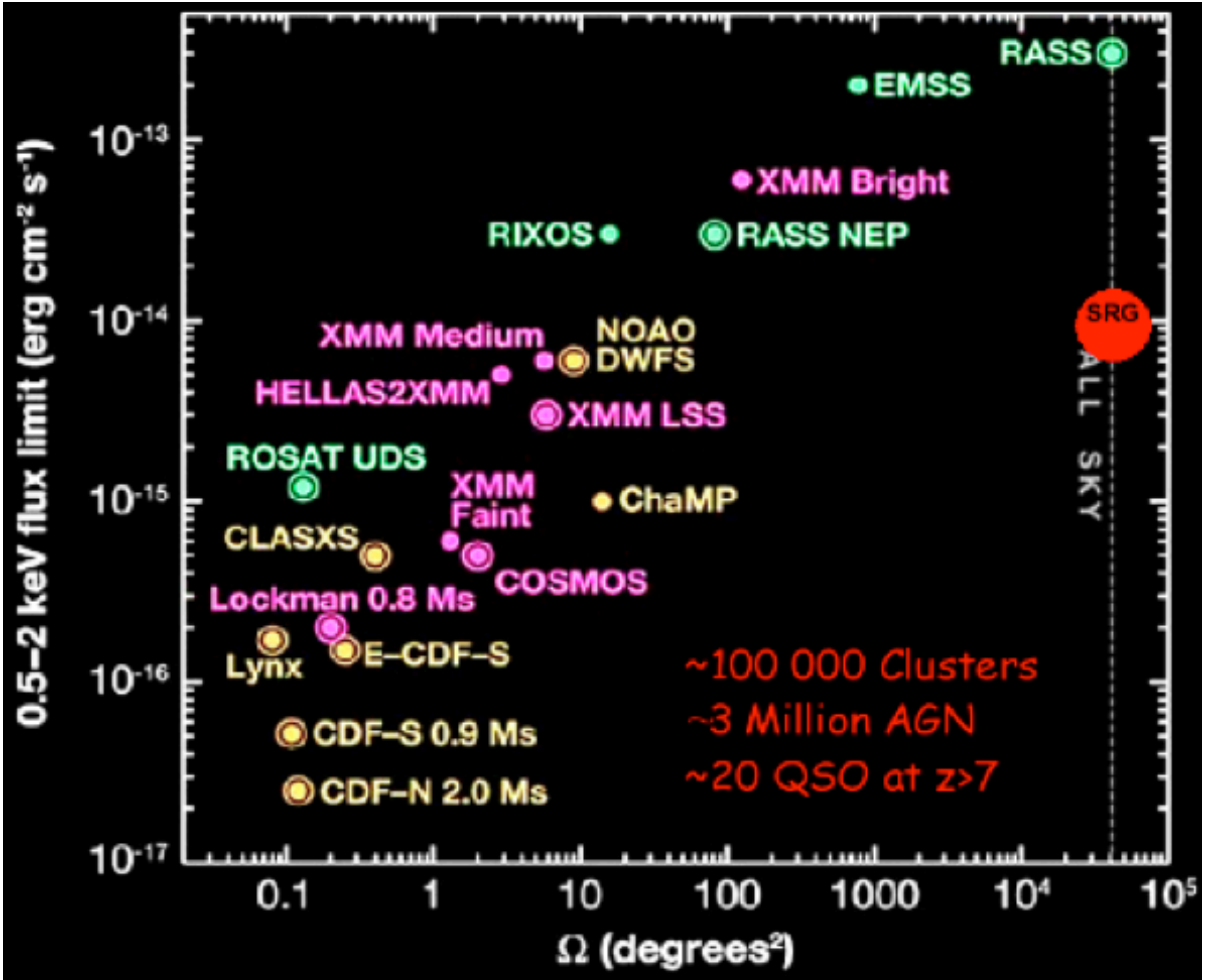
MPE instrument on Spectrum-Roentgen-Gamma

7 identical Wolter-1 telescopes with detector based on EPIC pn technology.

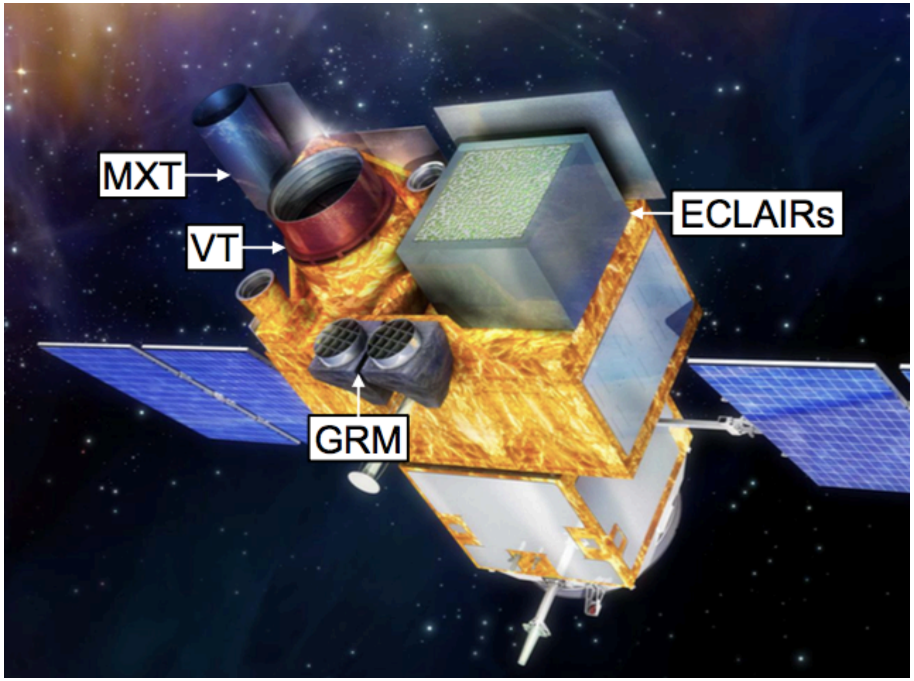
All-sky survey to flux limit 30 times lower than ROSAT All Sky Survey.

Sensitive to 10 keV while ROSAT only up to 2.5 keV.

http://www.mpe.mpg.de/erosita/



0.5–2 keV flux limit (erg cm^{-2} s^{-1})
Ω (degrees^2)
RASS
EMSS
XMM Bright
RIXOS
RASS NEP
SRG
ALL SKY
XMM Medium
NOAO
DWFS
HELLAS2XMM
XMM LSS
ROSAT UDS
XMM
Faint
ChaMP
CLASXS
COSMOS
Lockman 0.8 Ms
Lynx
E–CDF–S
CDF–S 0.9 Ms
CDF–N 2.0 Ms
~100 000 Clusters
~3 Million AGN
~20 QSO at z>7

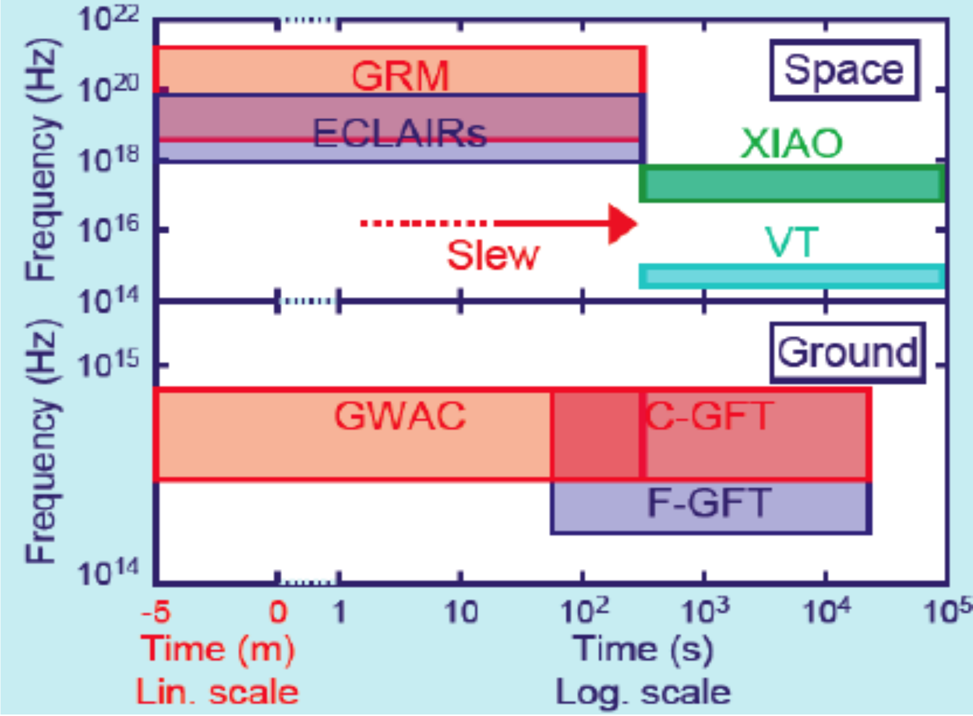


SVOM

Chinese-French GRB astronomy satellite.

Launch in 2021

Wide-field γ-ray instrument to detect GRBs (ECLAIRs). Non-imaging γ-ray detector monitoring the FOV of ECLAIRs (GRM). Narrow-field telescopes for soft X-ray (MXT) and optical (VT).



Themes

Politics

Efficient high resolution spectroscopy

Mirrors

Polarimetry

Other missions

Interferometry

In the first 50 years of X-ray astronomy we increased sensitivity by a factor of 10^9, image resolution by $2.5x10^5$, spectral resolution by 10^4.

How do we keep this progress up for the next 50 years ?

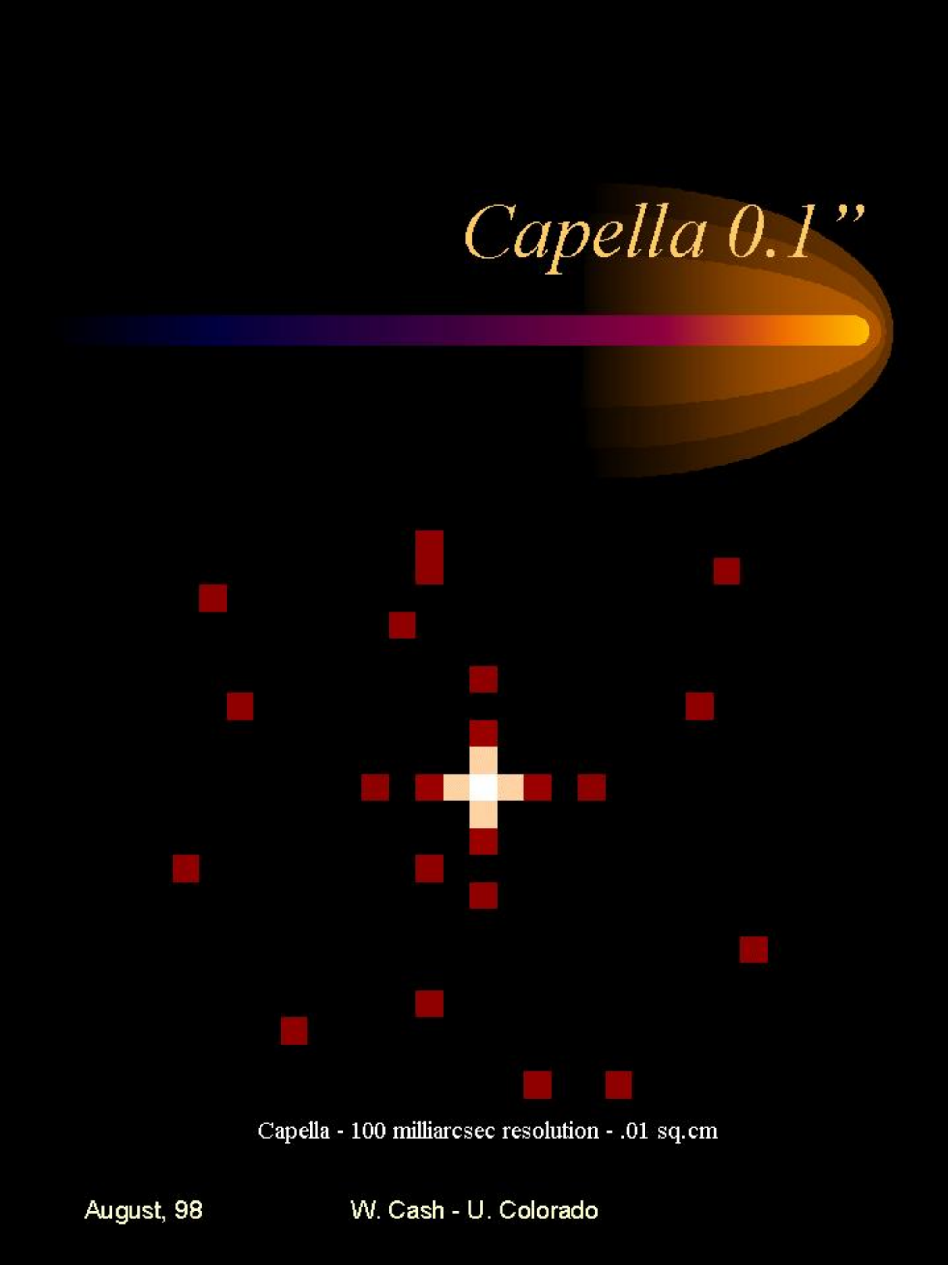
- While astronomical sensitivity has increased by a vast factor imaging resolution has not. HST is only 100 times better than Galileo’s telescope.
- To do better requires interferometry.
- Radio interferometry is well developed but baselines are very long and few sources have high enough surface brightness in the radio band.
- Optical interferometry is coming on line and milliarcsec resolutions should be achievable.

The X-ray band is the natural place for interferometry !

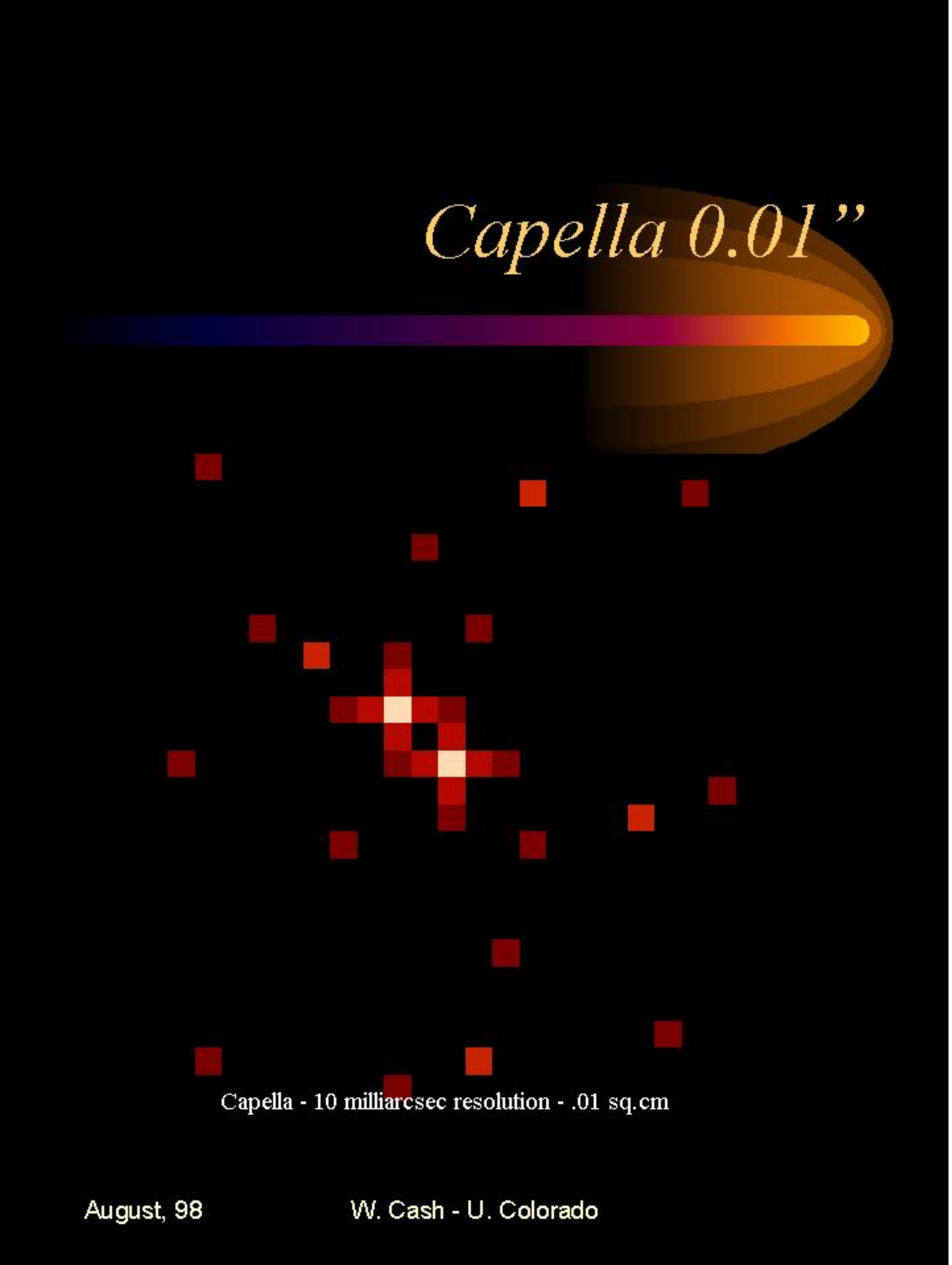
- Microarcsecond resolutions are possible with a baseline of ~10 meters.
- X-ray sources have very high surface brightness on microarcsecond scales.

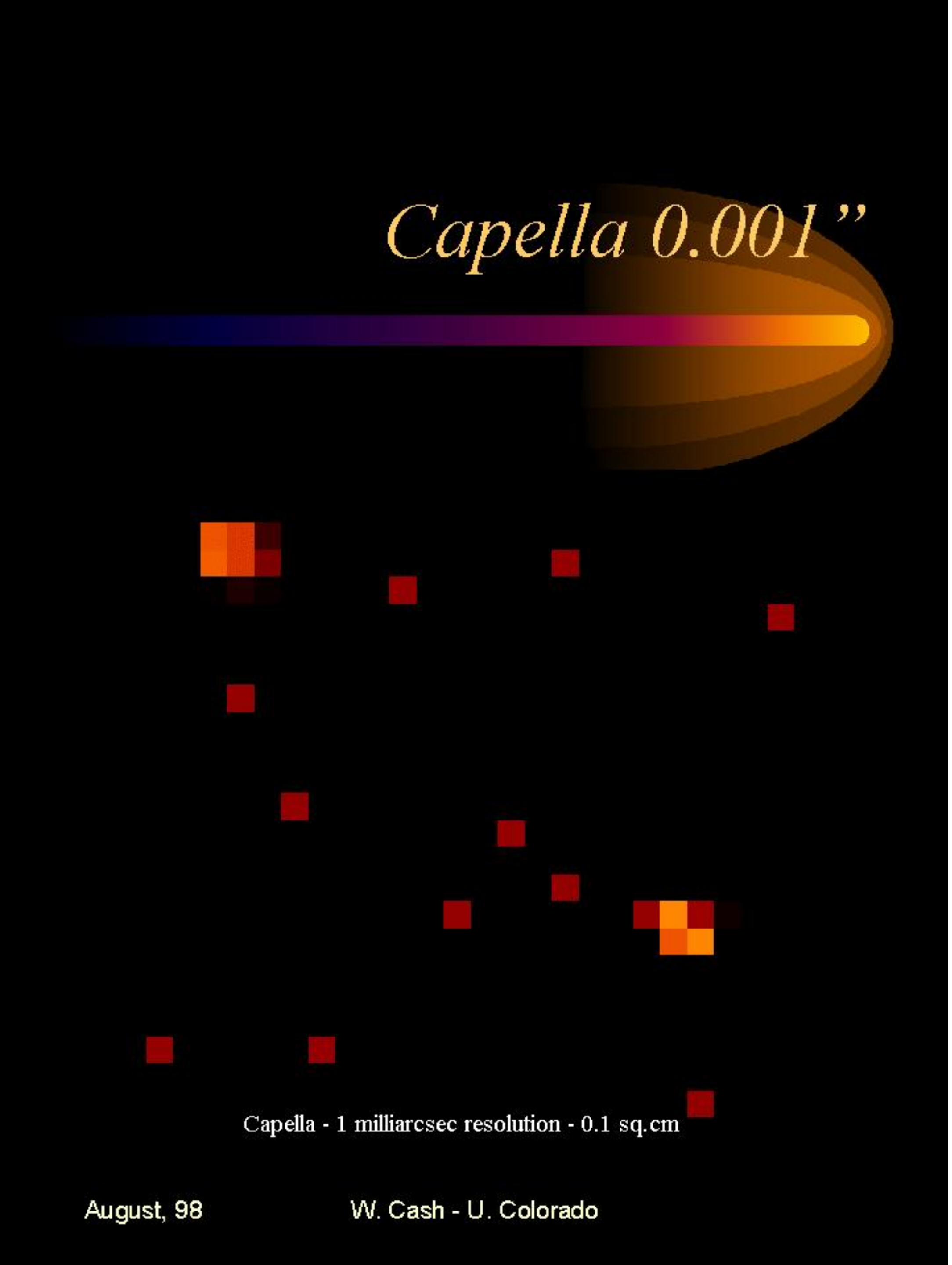
X-ray interferometry allows virtual interstellar travel…

100 milliarcseconds



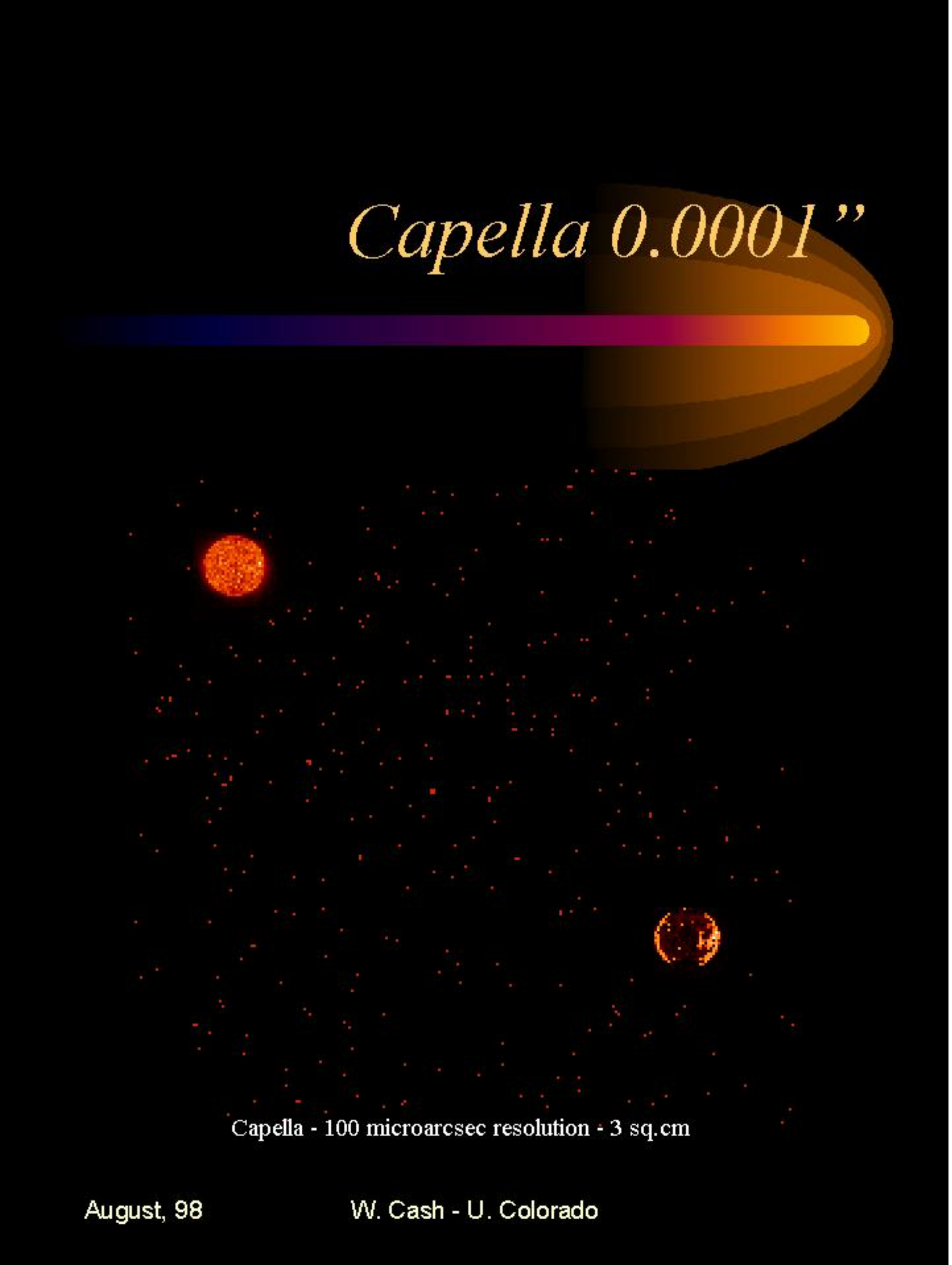
10 milliarcseconds



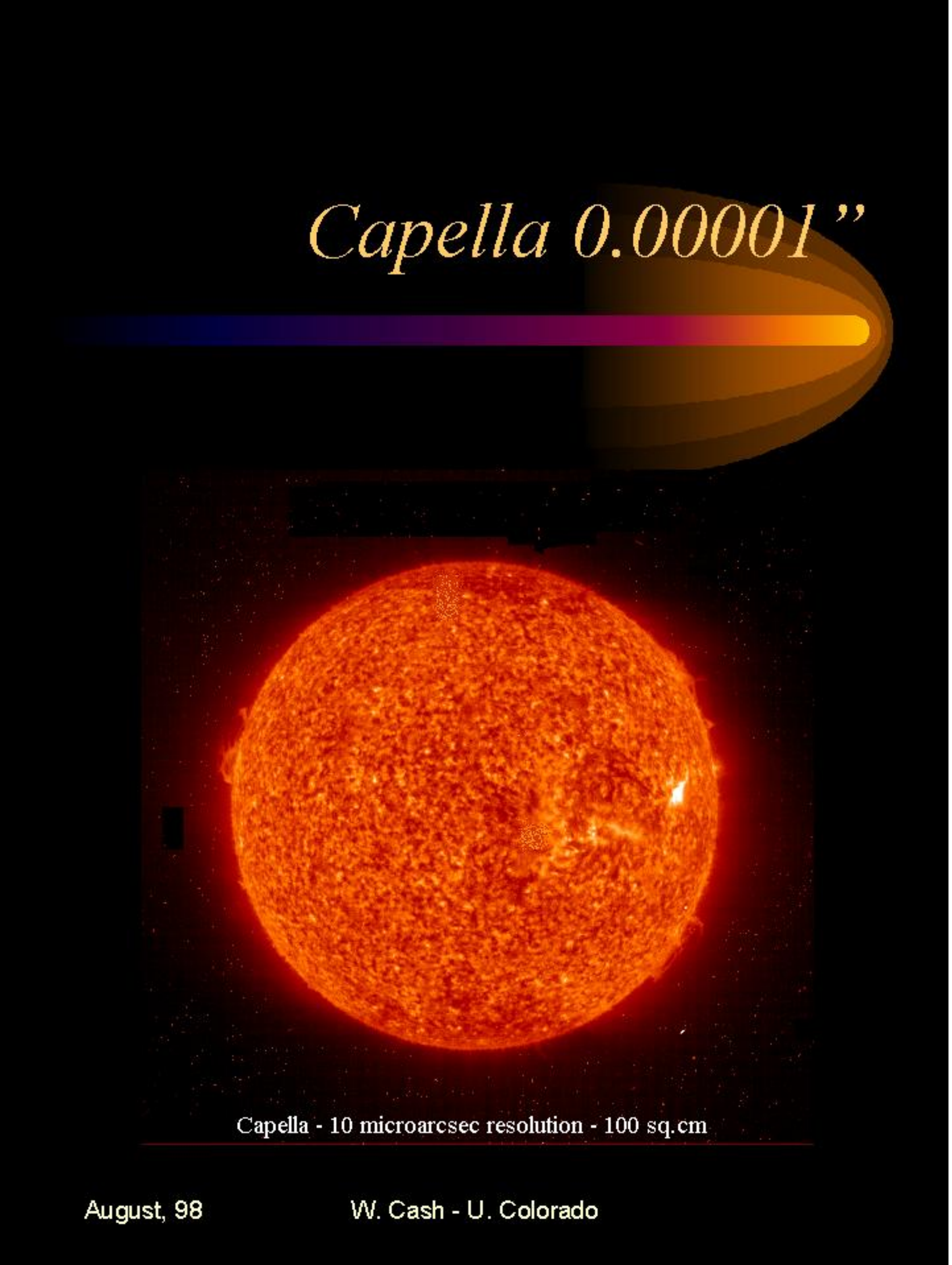


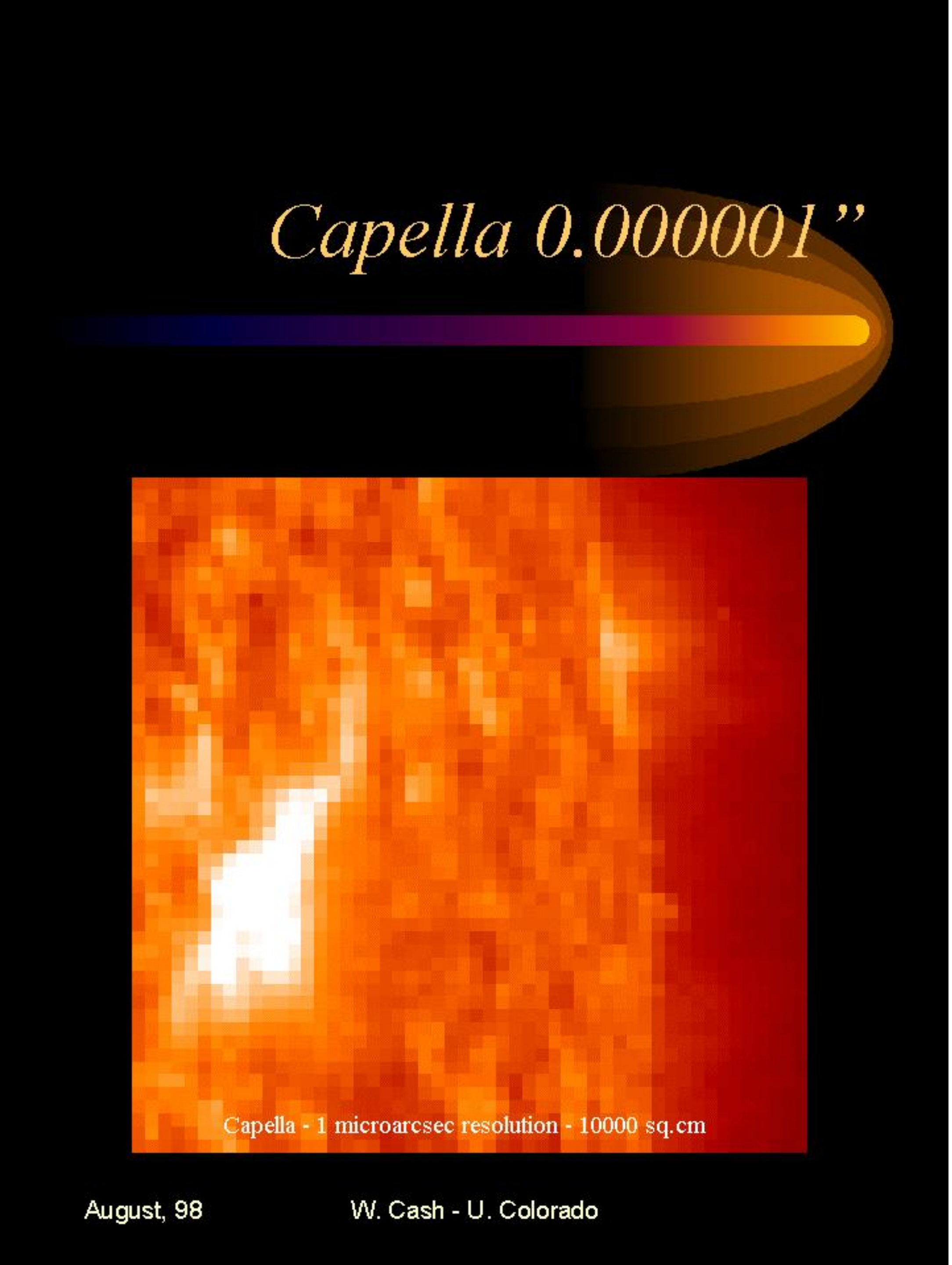
1 milliarcsecond

100 microarcseconds



10 microarcseconds

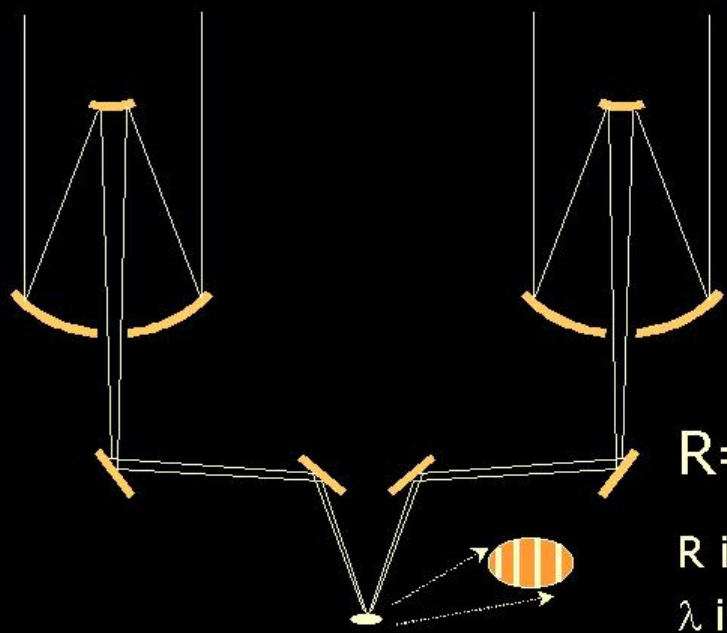




1 microarcsecond

Concept:

Michelson Stellar Interferometer



$R=\lambda/20000D$

R in Arcsec

λ in Angstroms

D in Meters

Grazing Incidence Analog

$R = \lambda / 20000D$

R in Arcsec

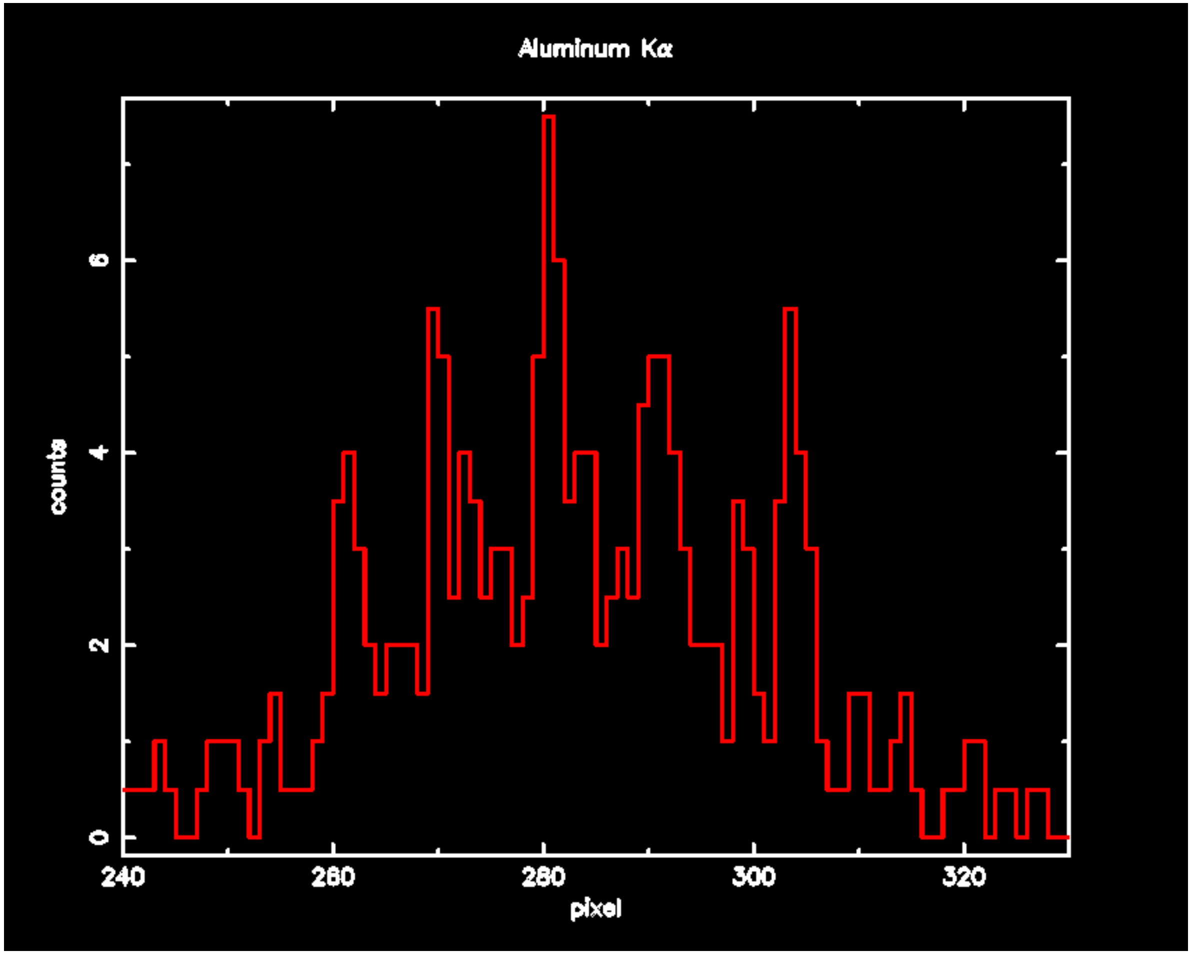
λ in Angstroms

D in Meters

Laboratory test

Fringes at 8.35 Å

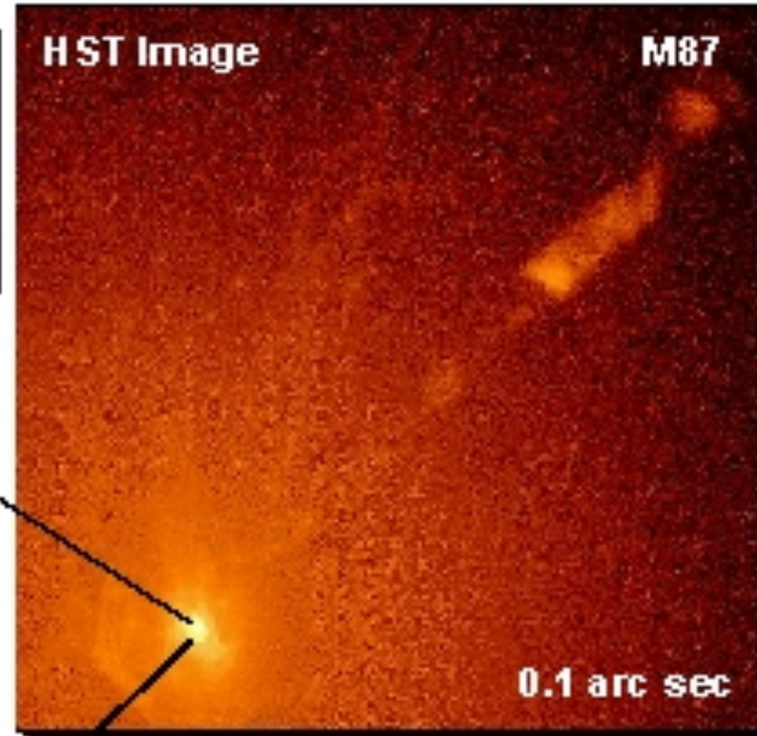
25 November 2002

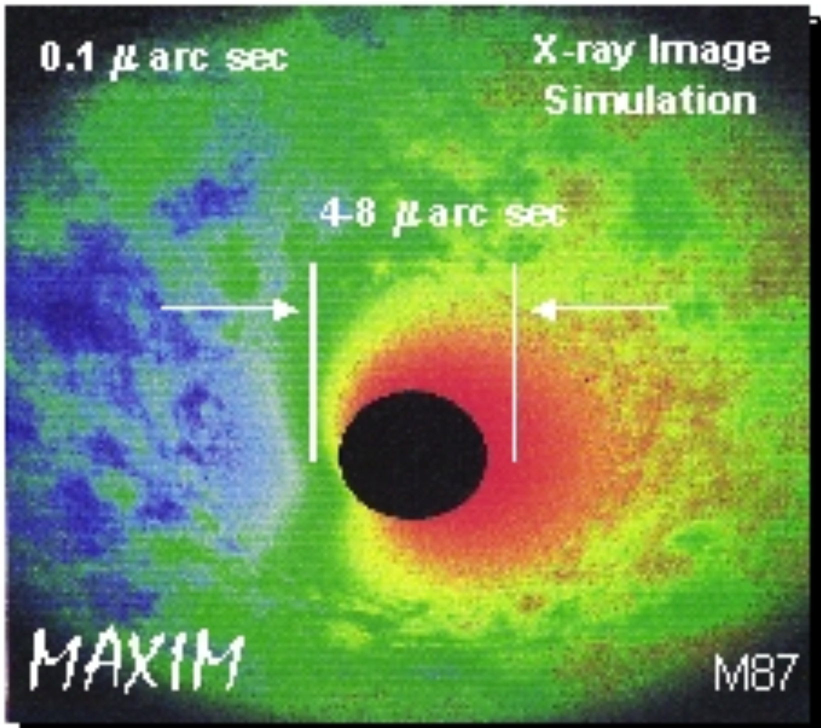


MAXIM Micro Arcsecond X-ray Imaging Mission

Take direct image of a black hole event horizon

- Ultimate journey to visit a black hole
- Fundamental importance to physics
- Will capture the public imagination





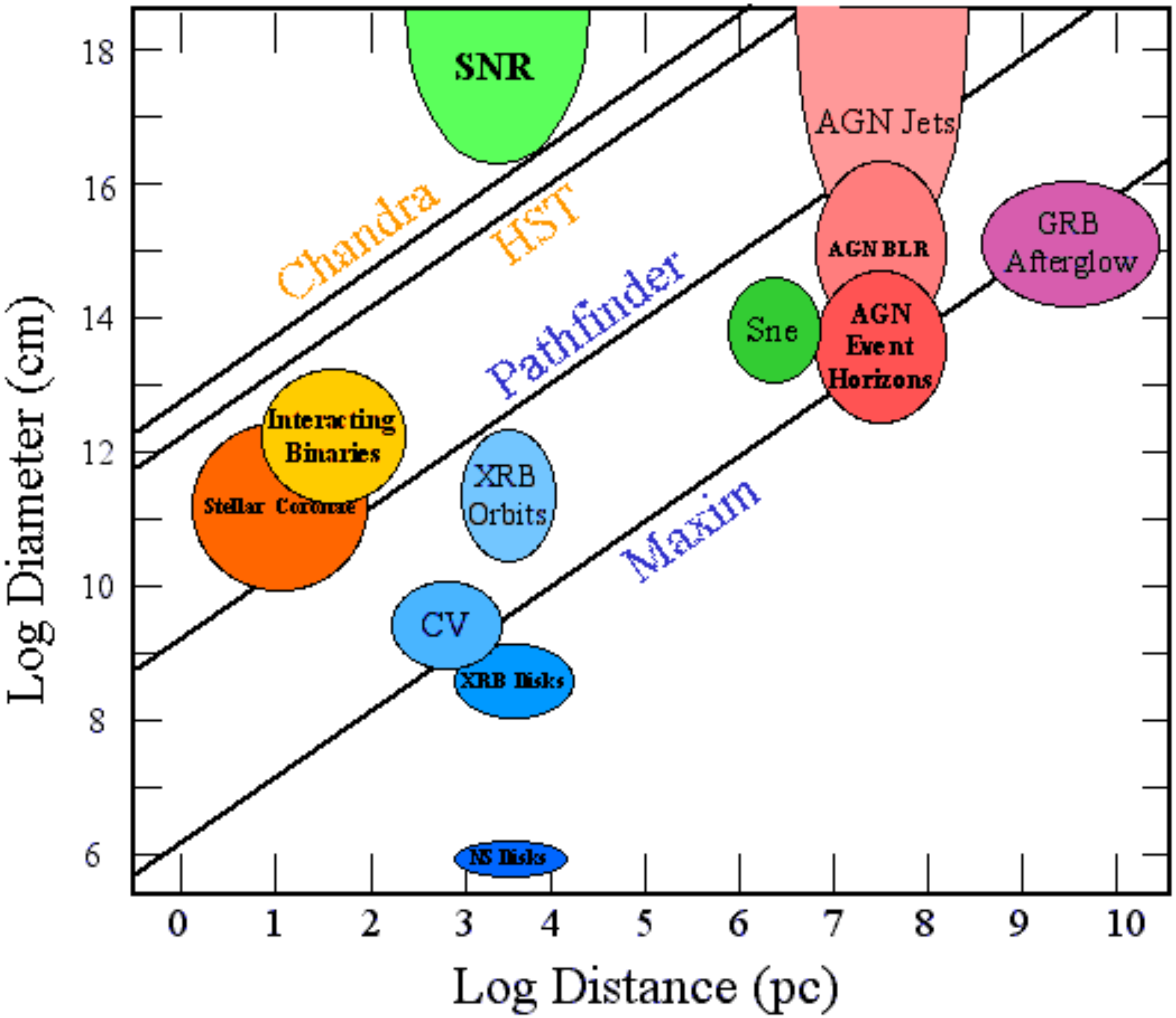
Requires 0.1-1 μ arc second imaging

X-ray interferometry is the best approach

- Baseline of 20 m at 1 Å for 1 μ arc second
- Close to event horizon, energy is emitted in X-rays

http://maxim.gsfc.nasa.gov

Scientific Goals



MAXIM Pathfinder