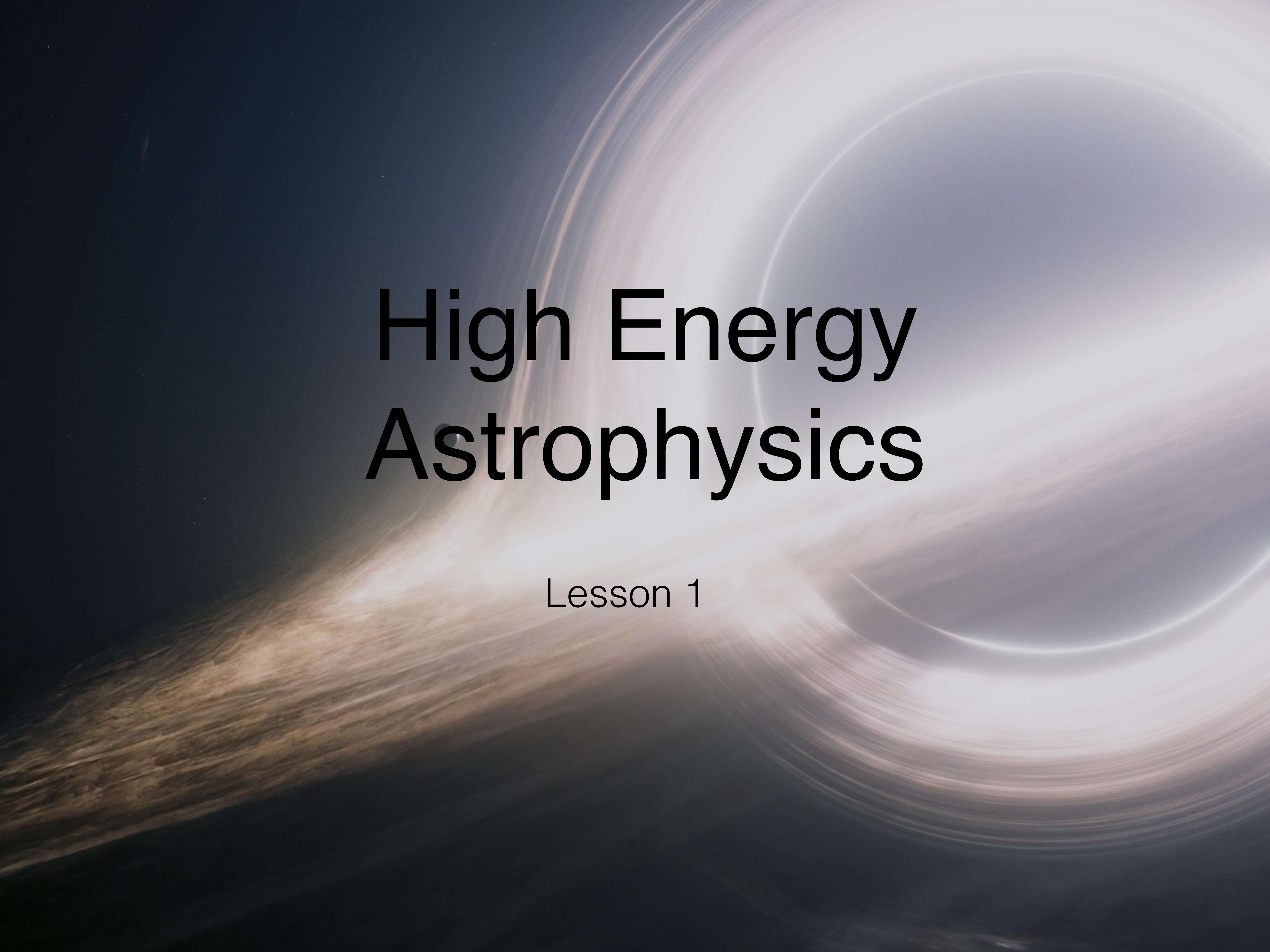


High Energy Astrophysics

Lesson 1

Goal:

- To provide an overview of observational High Energy Astrophysics

Literature:

- *S. Rosswog, M. Brüggen: "Introduction to High-Energy Astrophysics" (Cambr. 2007)*
- *P. Schneider: "Extragalactic Astronomy and Cosmology" (2015)*
- *Seward & Charles: Exploring the X-ray Universe*
- M.Longair: "High-Energy Astrophysics" I,II, III (Cambridge Univ. Press: 2011)
- F. Melia: "High Energy Astrophysics" (Princeton U.P. 2009)
- Werner & Mernier: Hot atmospheres of galaxies, groups, and clusters of galaxies

Requirements:

- Home assignment with a brief presentation (topic to be determined in October) 40%

- Oral exam 60%

Lecture Overview

- Introduction: What is high-energy astrophysics? Telescopes and detectors for high-energy astrophysics
- Supernovae and supernova remnants
- Gamma ray bursts
- Neutron stars, pulsars, X-ray binaries (TBD)
- Active galactic nuclei
- Clusters of galaxies and the large scale structure of the Universe
- Your lectures!
- (Additional lecture/exercises on X-ray data analysis)

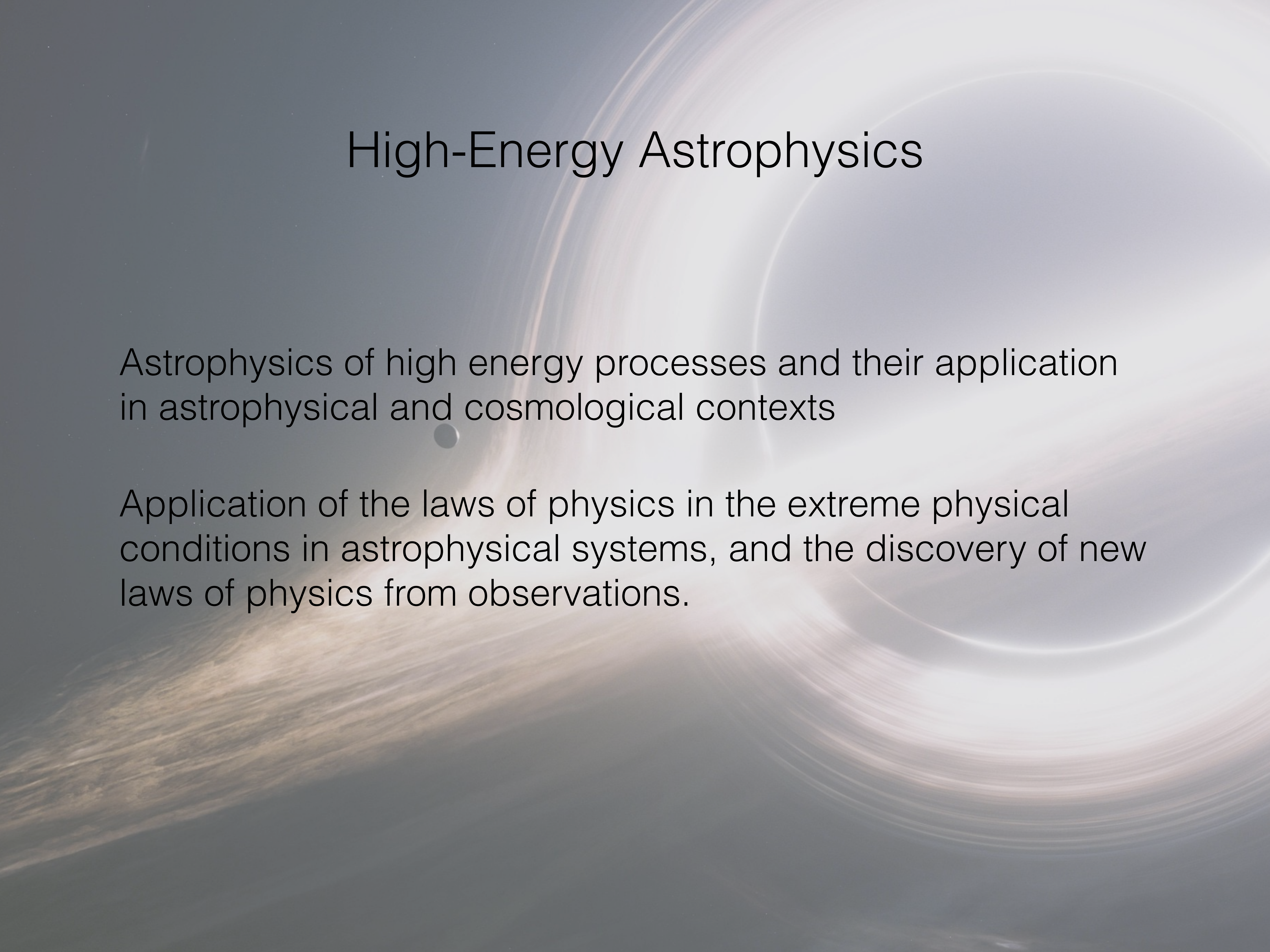
About YOU

- Science Interests?
- Expectations?
- Wishes?
- Concerns?
- Previous Courses and Lectures?
- Plans?

Today:

What is high-energy astrophysics?

Telescopes and detectors for high-energy astrophysics

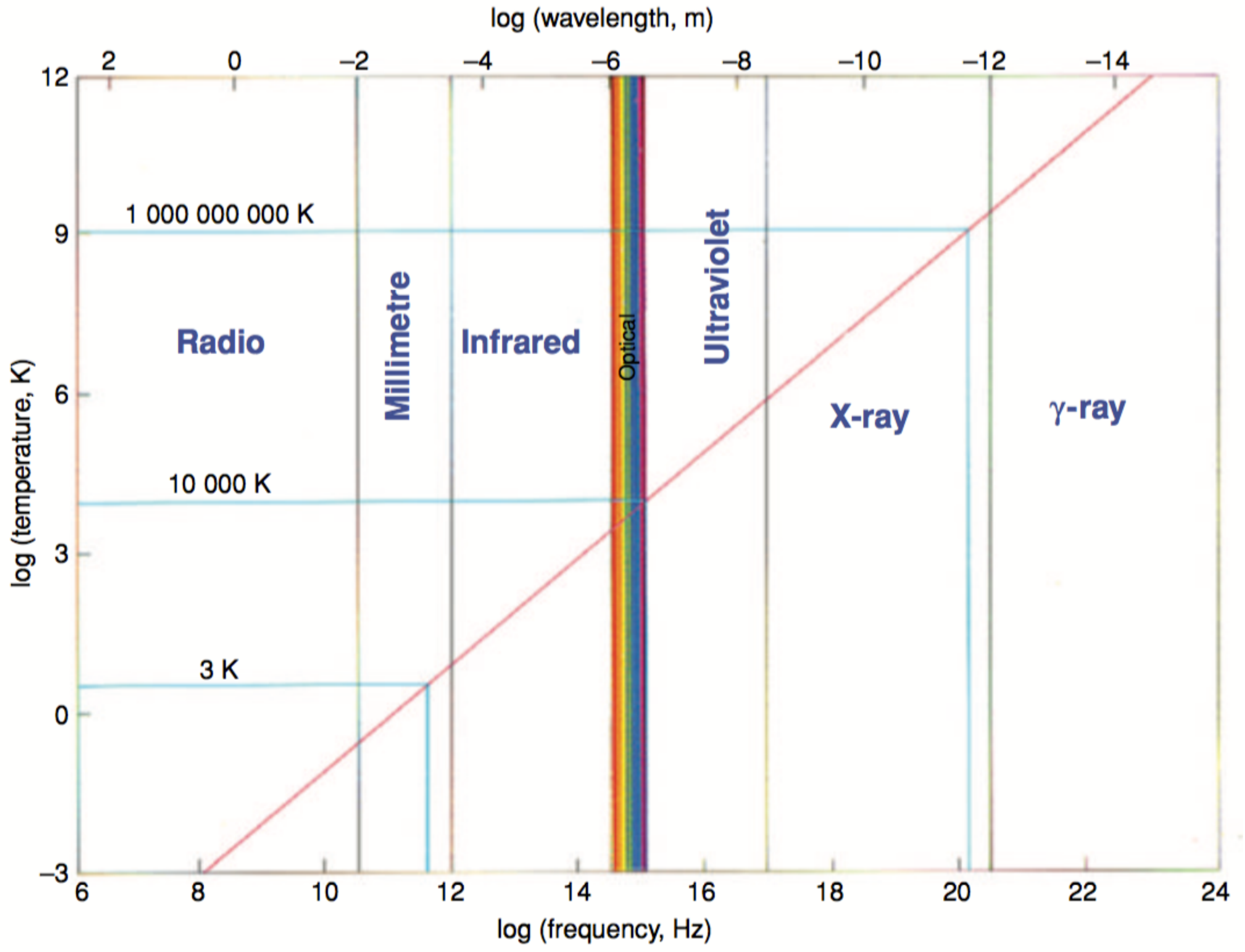


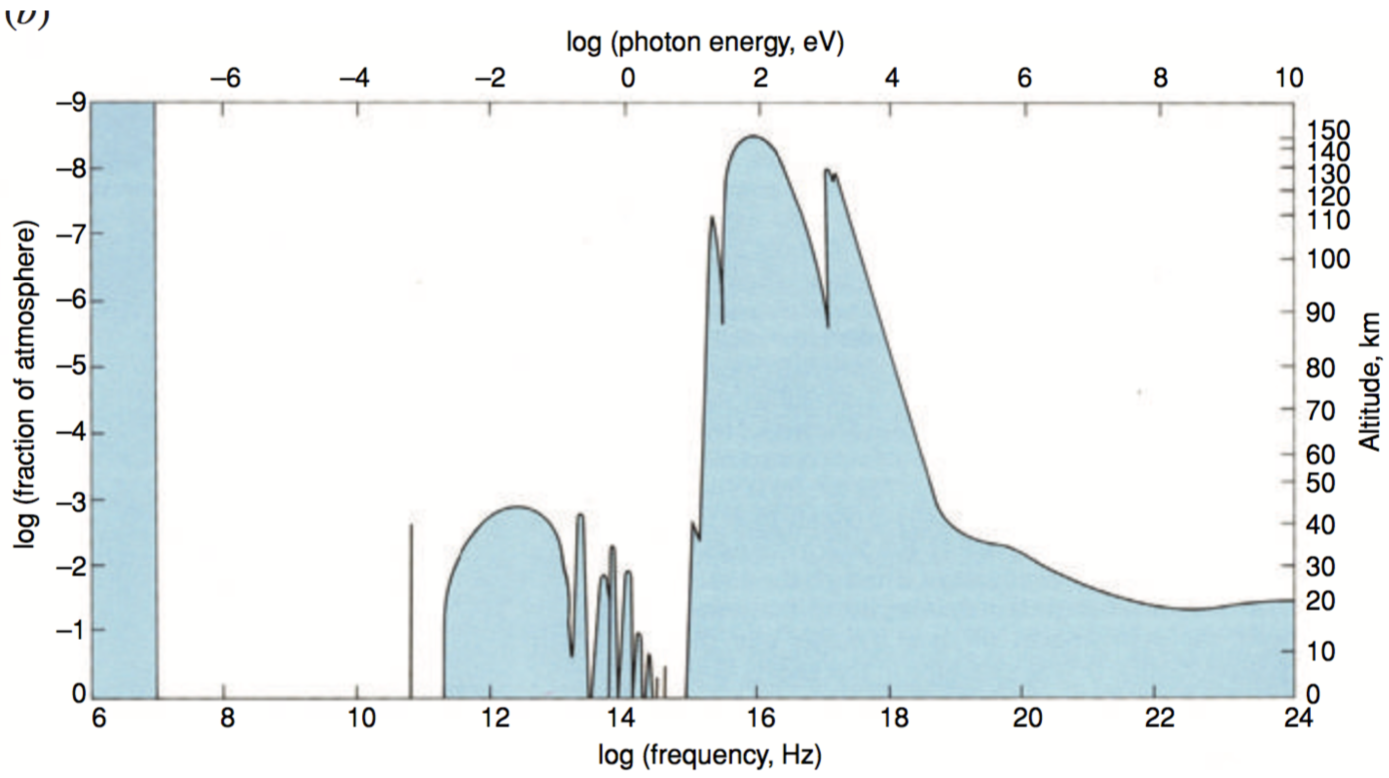
High-Energy Astrophysics

Astrophysics of high energy processes and their application in astrophysical and cosmological contexts

Application of the laws of physics in the extreme physical conditions in astrophysical systems, and the discovery of new laws of physics from observations.

Messengers of high-energy phenomena





Observations in different wavebands can be thought of as providing different temperature maps of the Universe according to Wiens displacement law:

$$\nu_{\max} = 10^{11}(T/\mathrm{K})\mathrm{Hz};\ \lambda_{\max}T = 3\times10^{6}\ \mathrm{nm\ K}$$

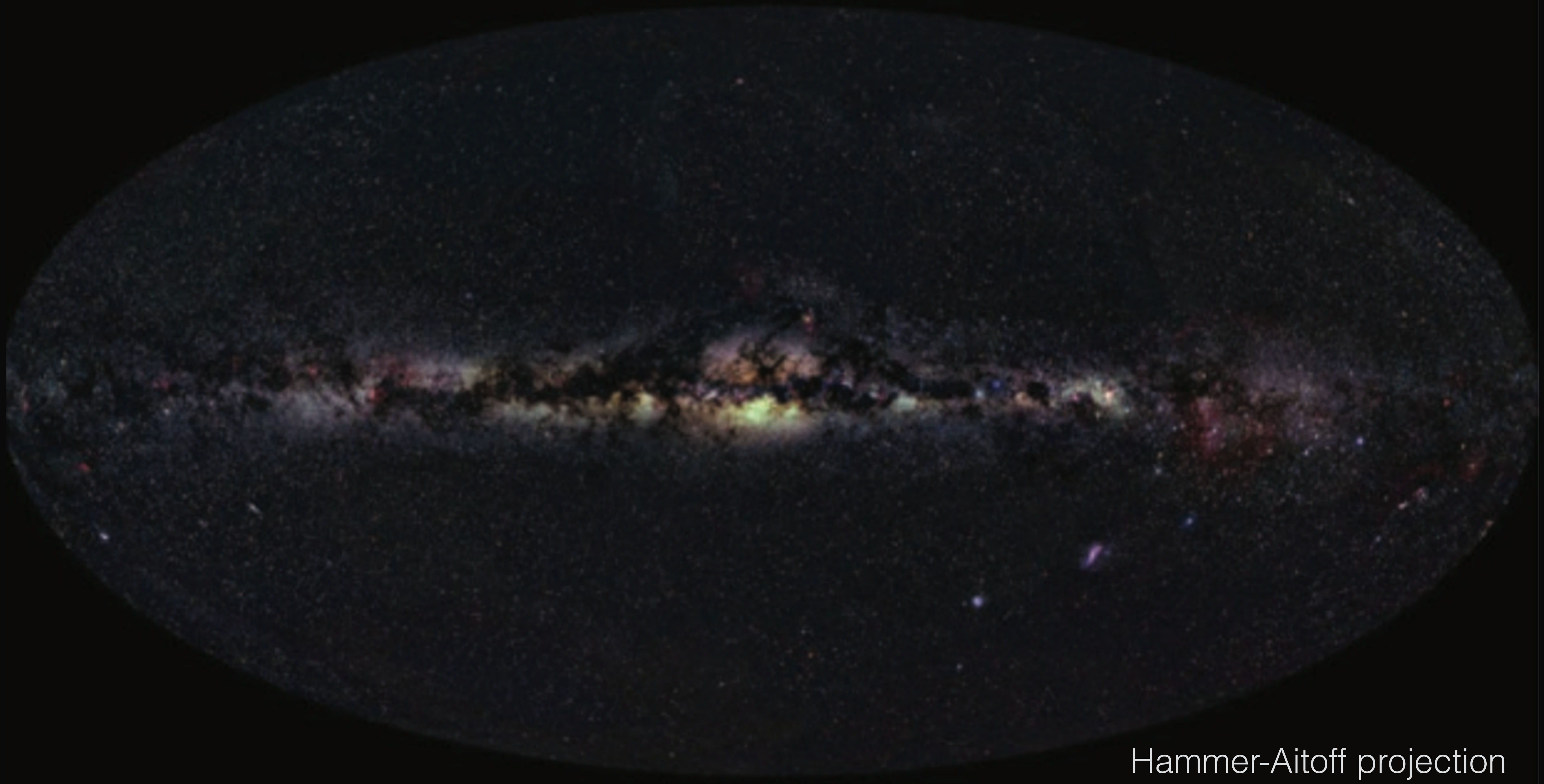
photon energy $E=h\nu$ expressed in electron volts (visible light 2–3 eV)

$T=E/k_b$ thermal 0.5–10 keV X-rays trace temperatures 5 x 10^6–10^8 K; 10 MeV ~ 10^{10} K; 10 eV ~ 10^5 K

In non-thermal sources - where emitting particles that don't have a Maxwellian energy distribution - the effective temperature of the emitting particles can far exceed these temperatures. Such are e.g. radio sources, quasars, X-ray and Gamma-ray sources with emitting ultra-relativistic electrons.

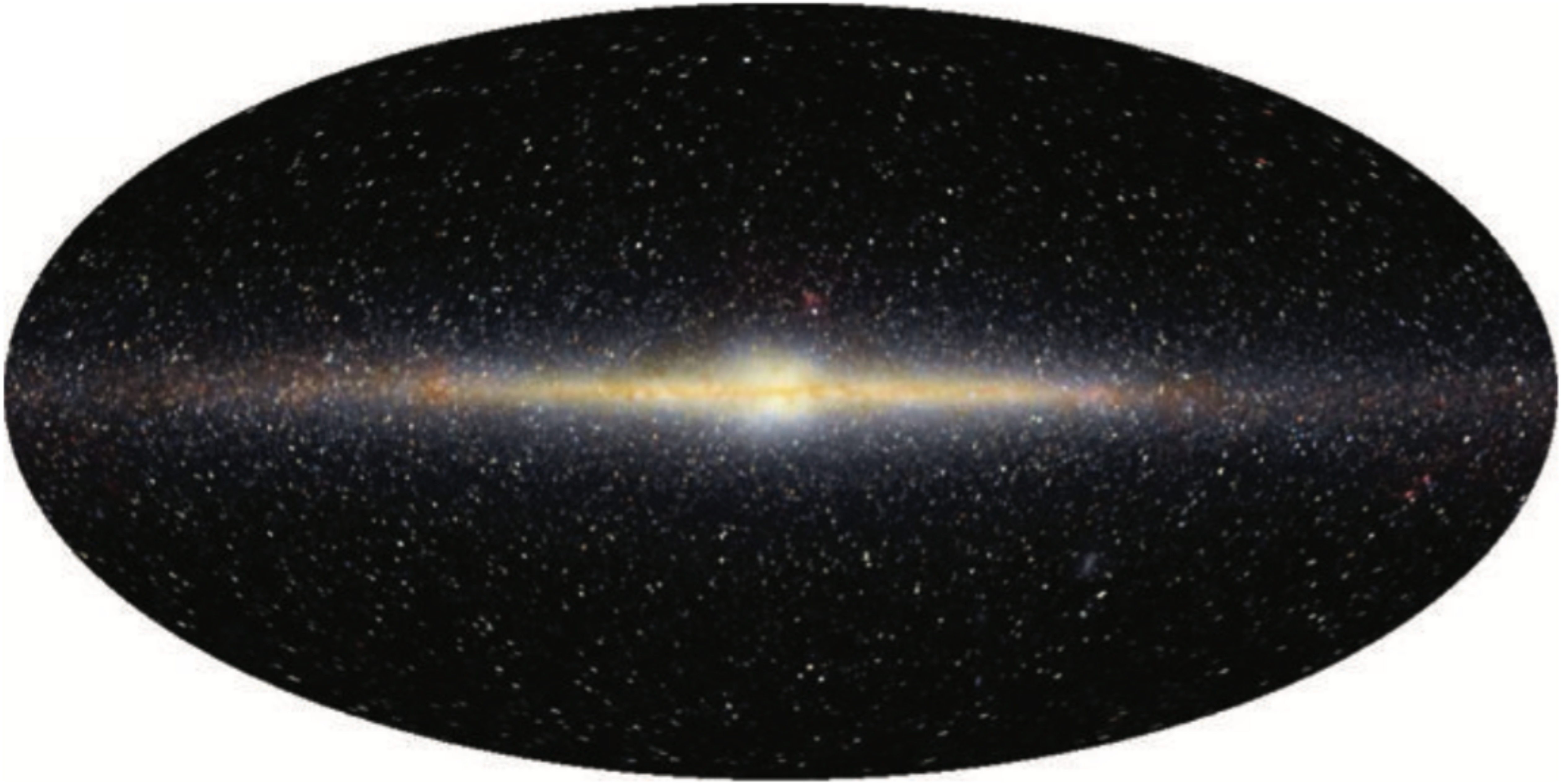
Other messengers include cosmic rays and gravitational waves

Optical waveband

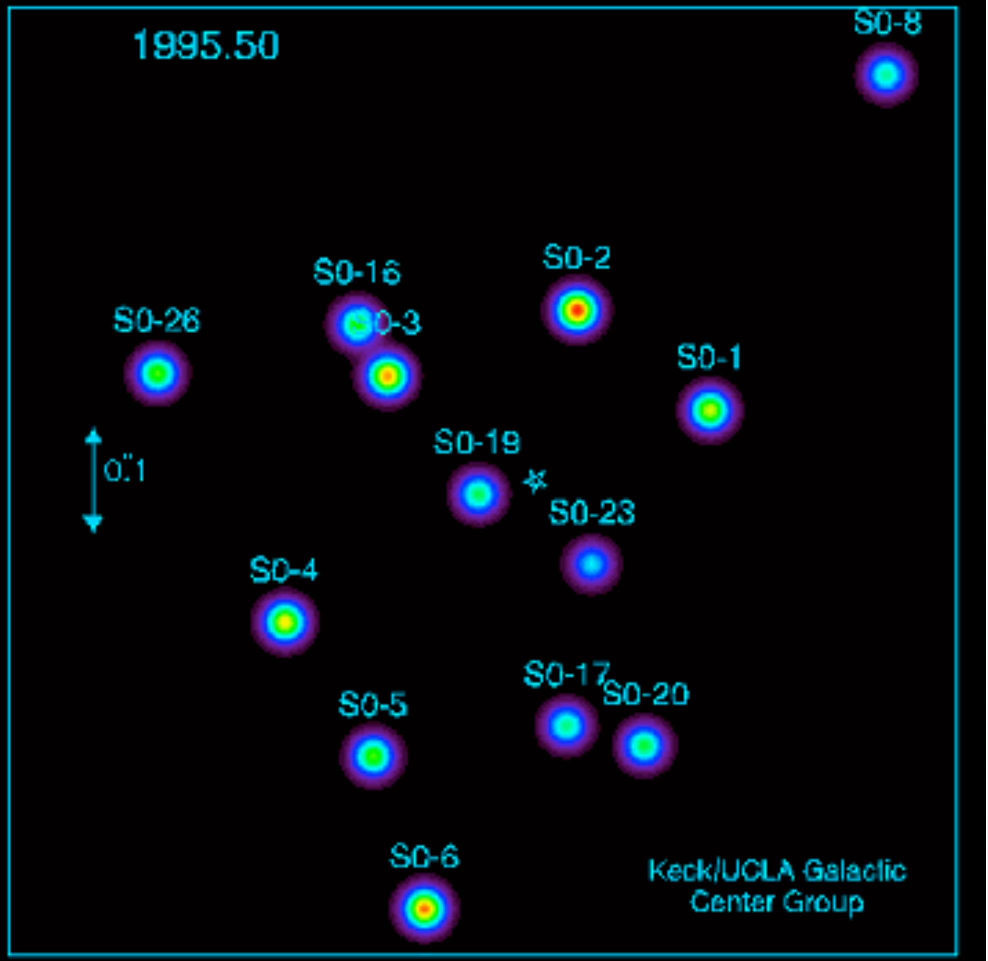

Hammer-Aitoff projection

- The Universe in the optical waveband is almost entirely the integrated light of stars
- Significant fraction of baryons locked up in stars with photosphere $T \sim 3000$—10,000 K emitting in optical waveband
- Disadvantage is extinction by dust grains
- Many high energy astrophysical objects are faint in optical

Near-infrared waveband



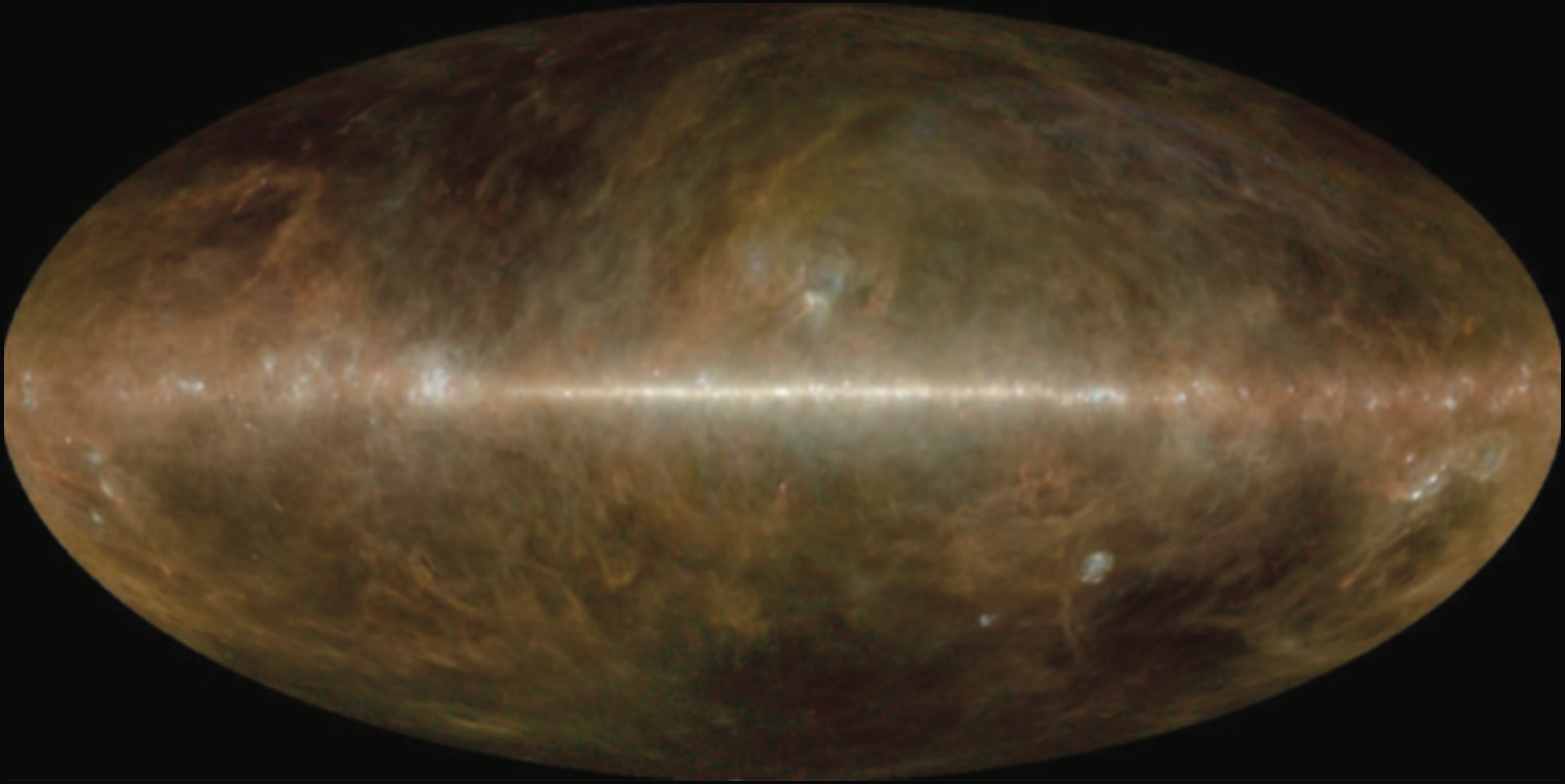
- Dust extinction a strong function of wavelength $I = I_0\ e^{-\alpha r}$ where α proportional to λ^{-1}
- Because of reduced extinction the Galaxy is clearly seen



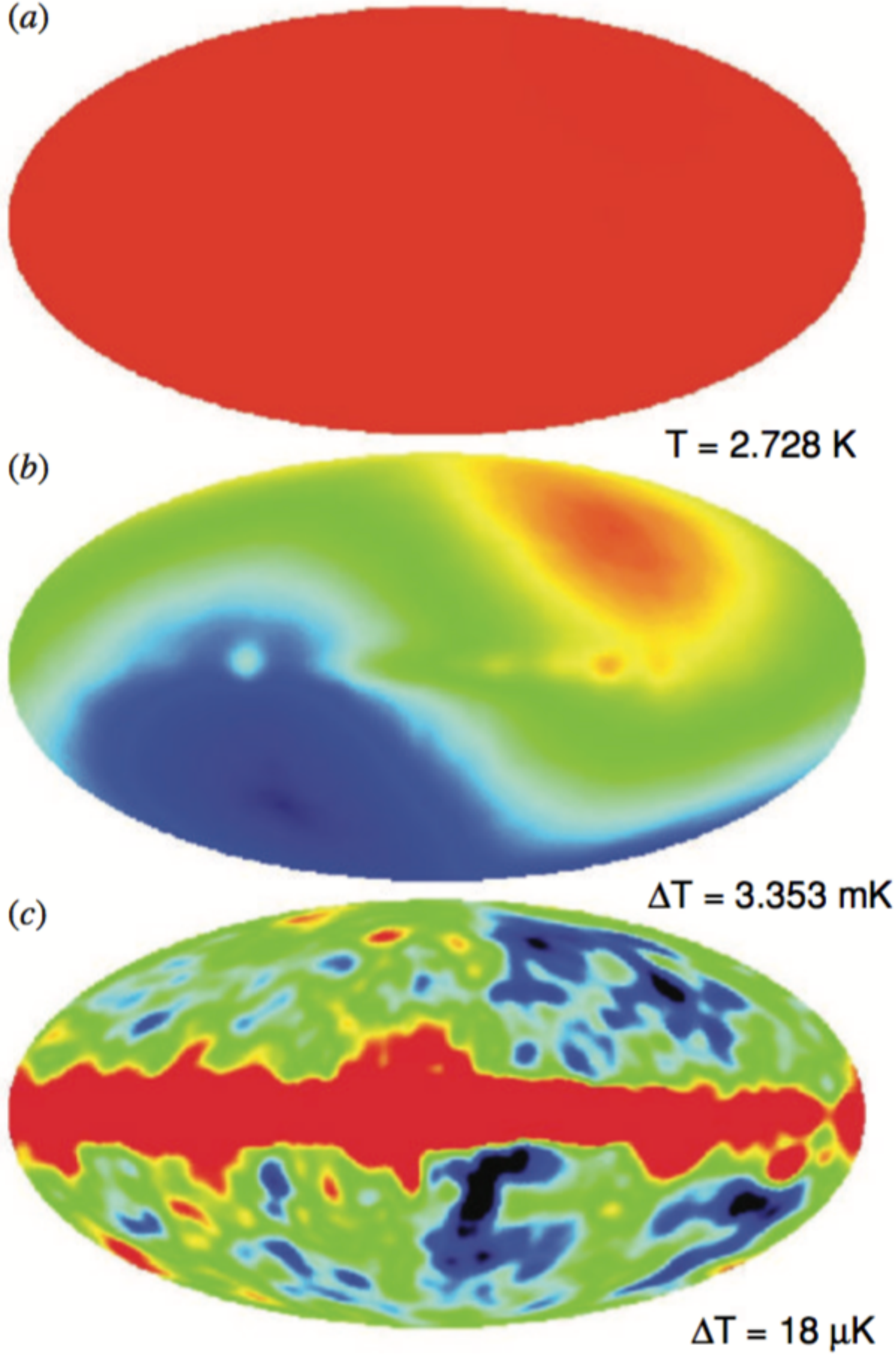

© Yuri Beletsky

- Adaptive optics in the near-infrared allows almost diffraction limited imaging
- These observations provide evidence of a $4x10^6$ solar mass black hole in the Galactic center

Far-infrared waveband



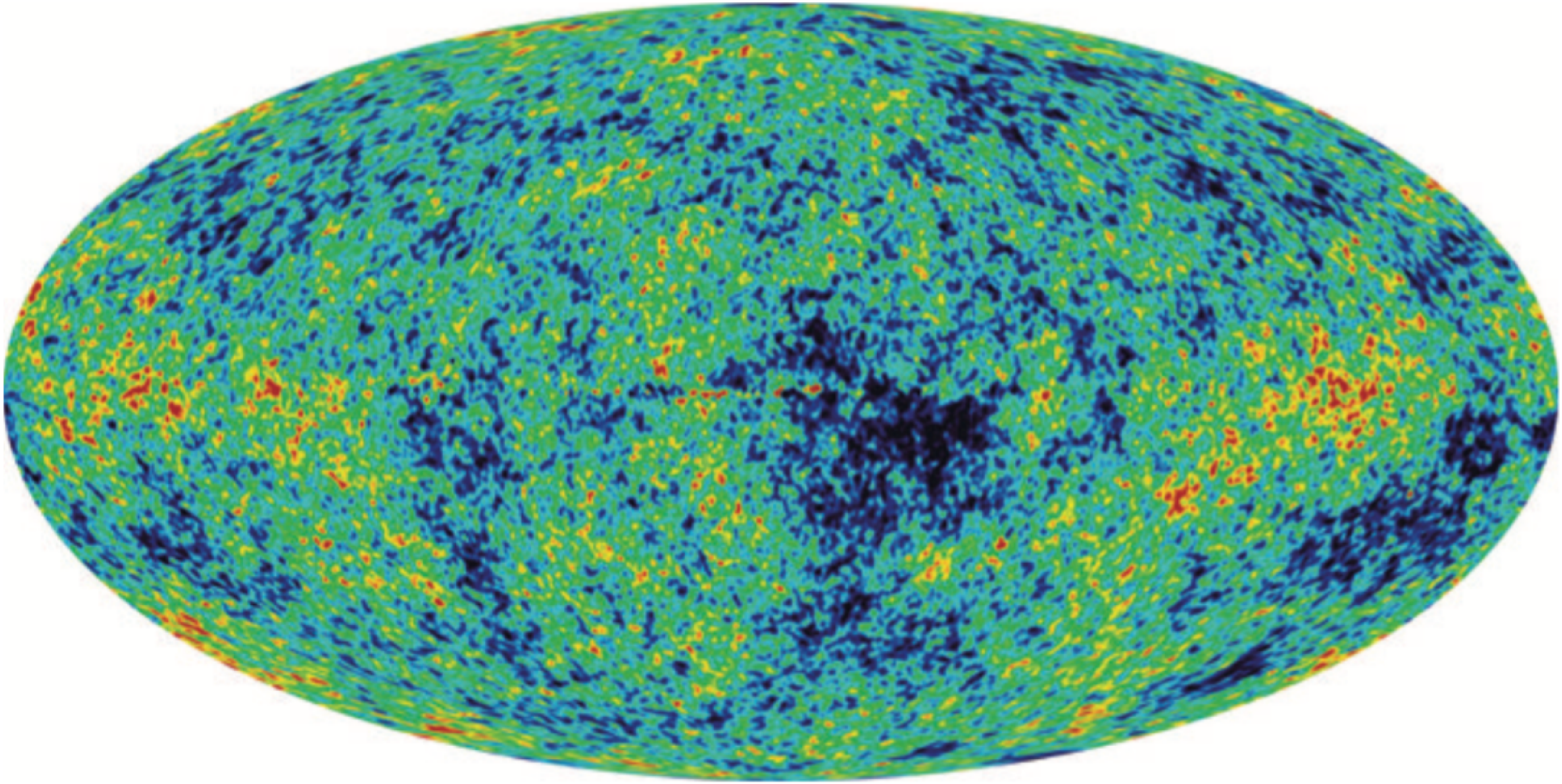
- Emission of dust grains
- Indicates active regions of star-formation and accretion
- Mid- and far-infrared require airborne or space observatories and are thermal background limited



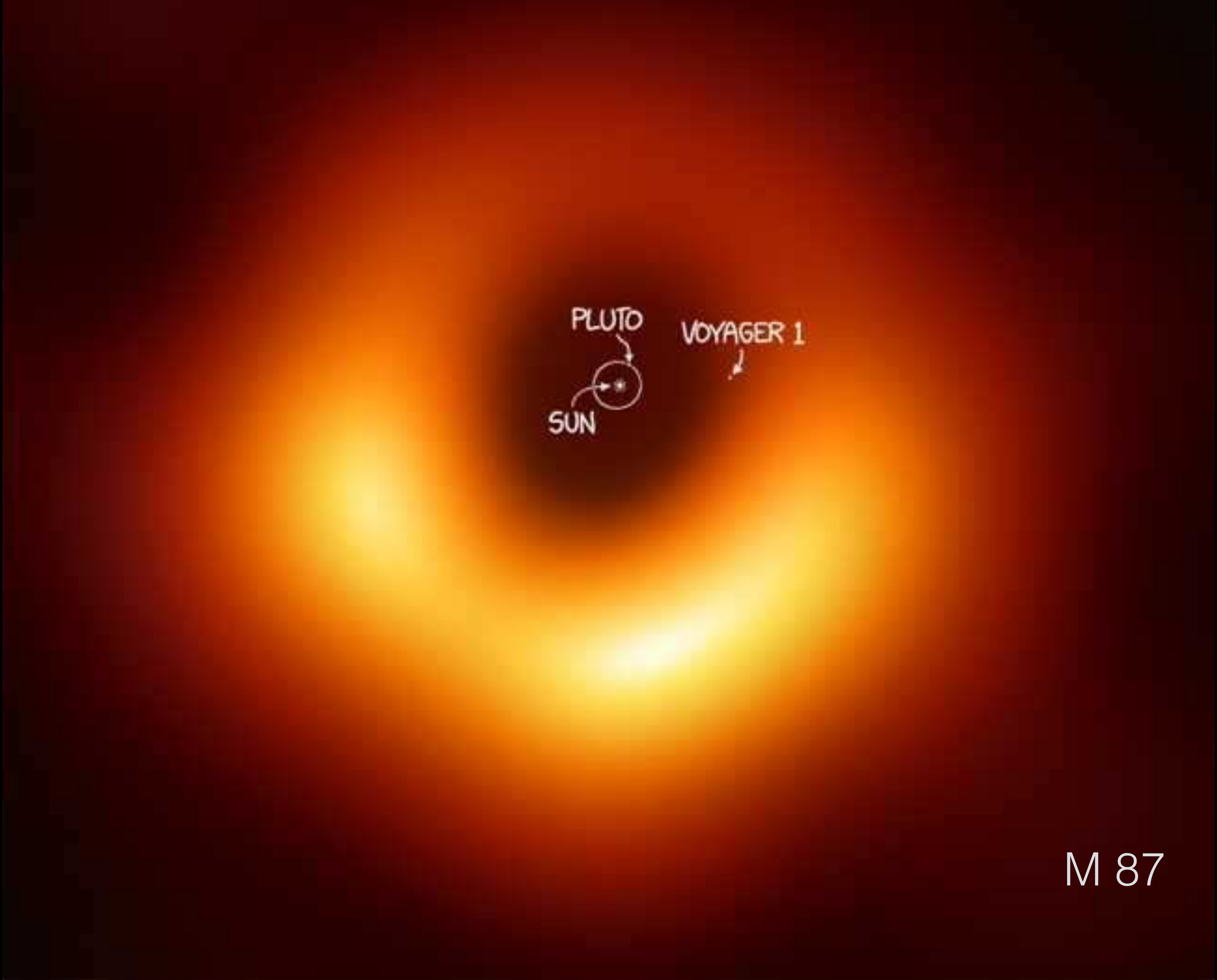
Millimeter & sub-millimeter

- dominated by the cosmic microwave background radiation
- extraordinarily uniform with a perfect black body spectrum at *T*~2.728 K
- at the sensitivity level of 1/1000 large scale anisotropy of dipolar form is observed (due to the Solar systems motion through isotropic radiation field at 350 km/s)
- at the 1/100,000 sensitivity the dust emission of the Galactic plane is intense (also bright star-forming sub-millimeter galaxies)
- away from the Galactic plane fluctuations of cosmological origin

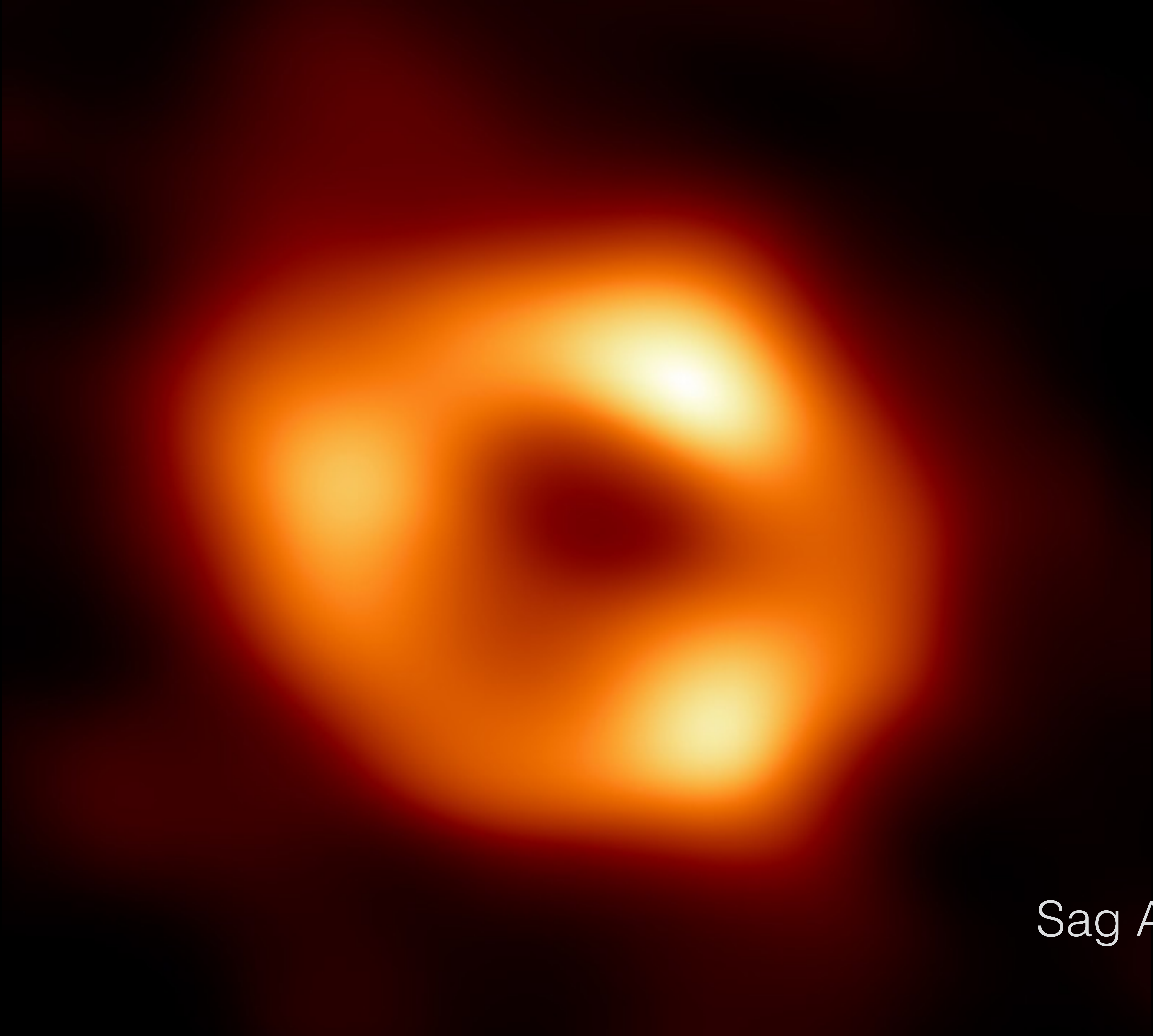
Cosmic microwave background radiation from Planck



- fluctuations of cosmological origin
- the CMB provides a radiation background for observations of clusters of galaxies (the so called Sunyaev-Zeldovic effect) and for interaction of high energy particles

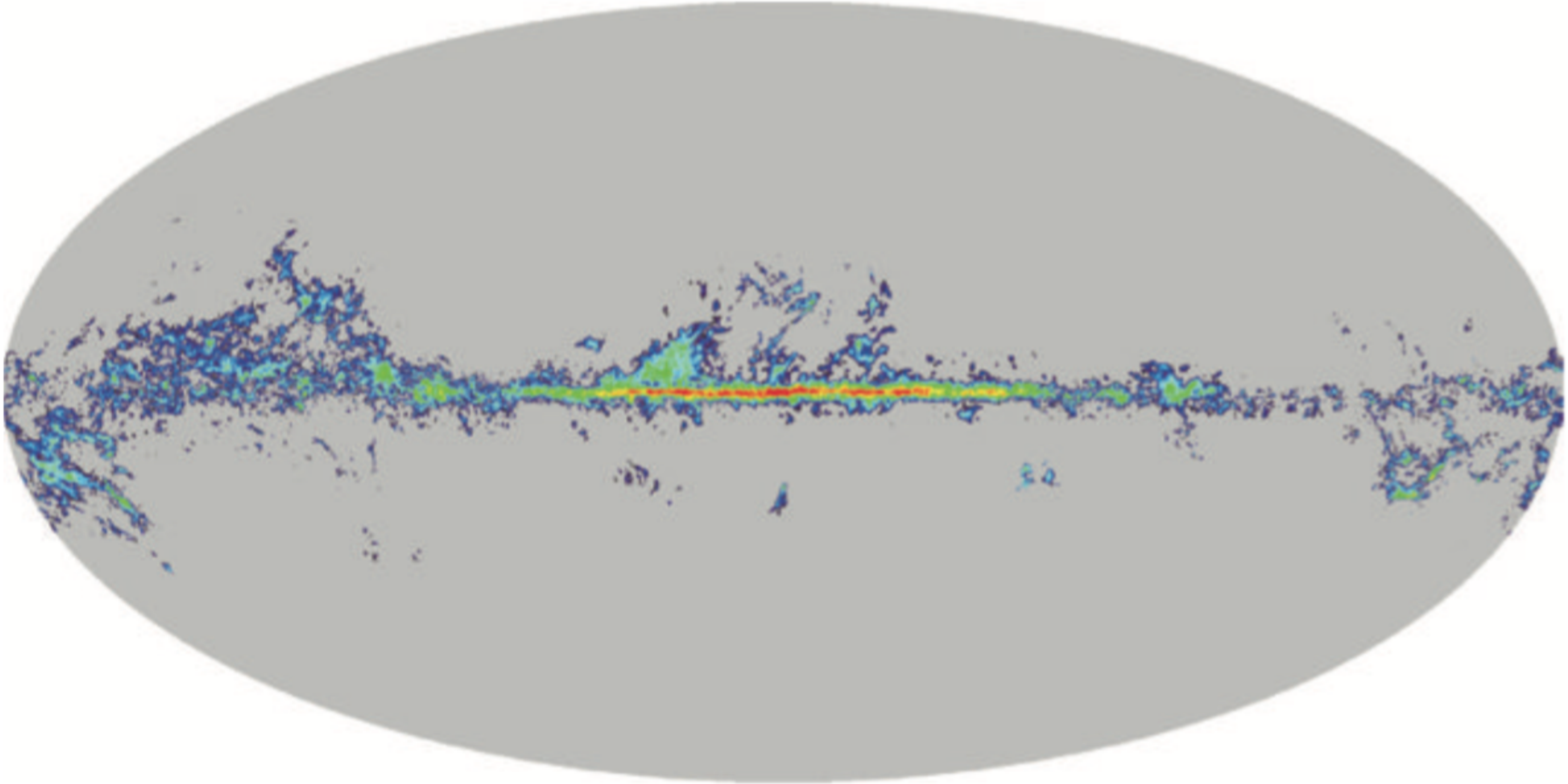


M 87



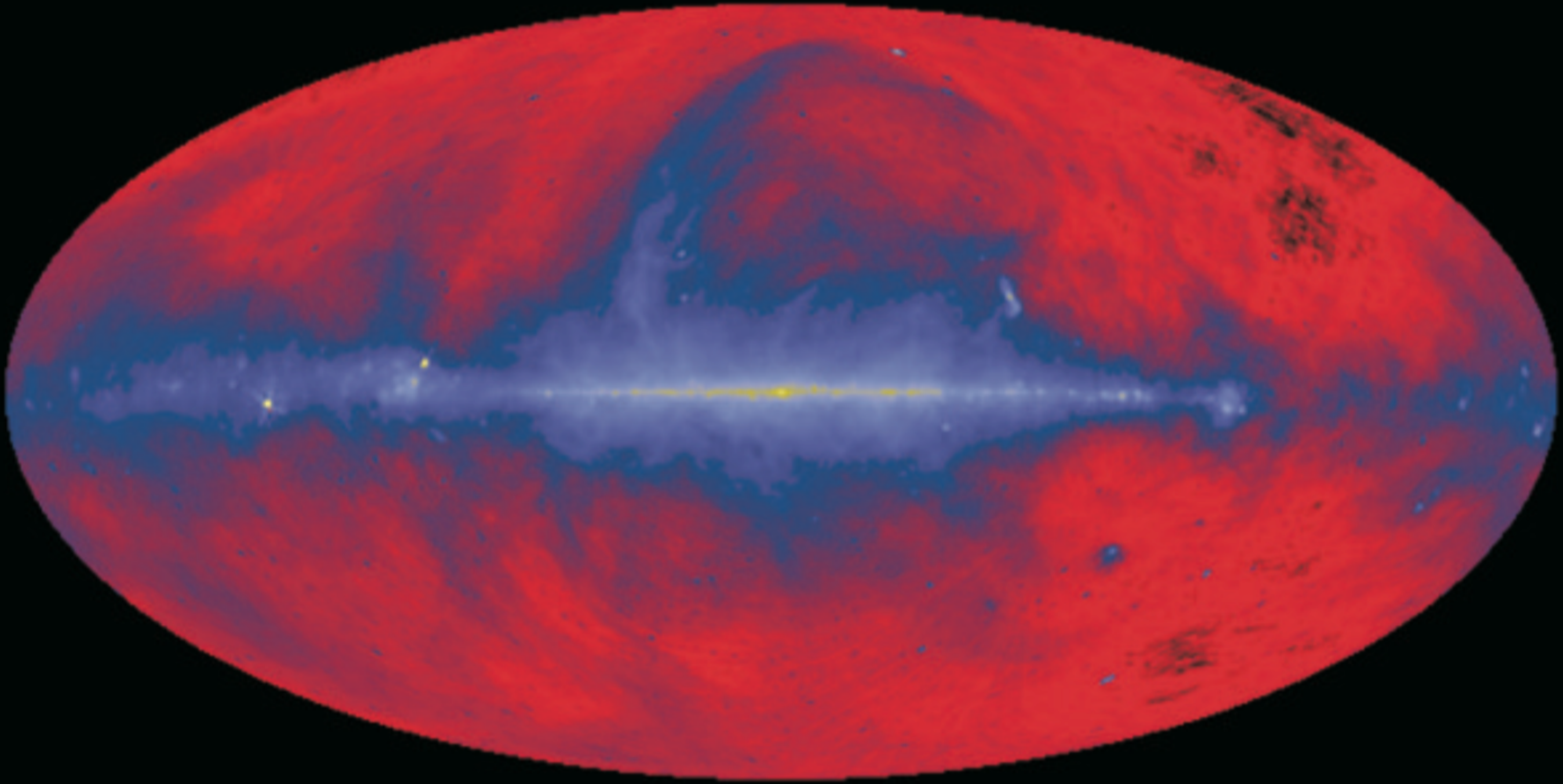
Sag A*

CO emission of molecular gas



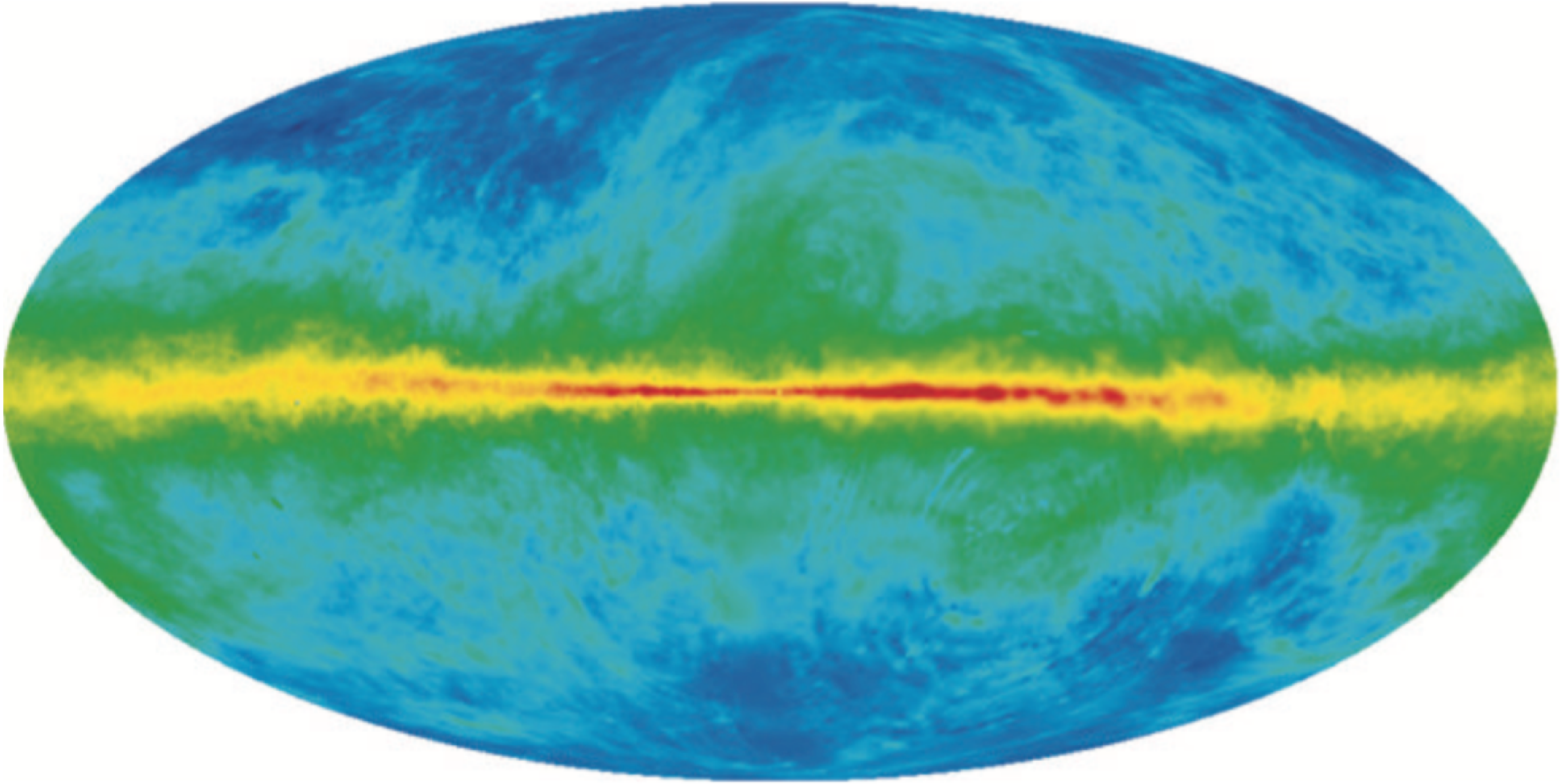
- the most common molecular line emission (strong electric dipole moment)
- regions of starformation

synchrotron radiation at 408MHz



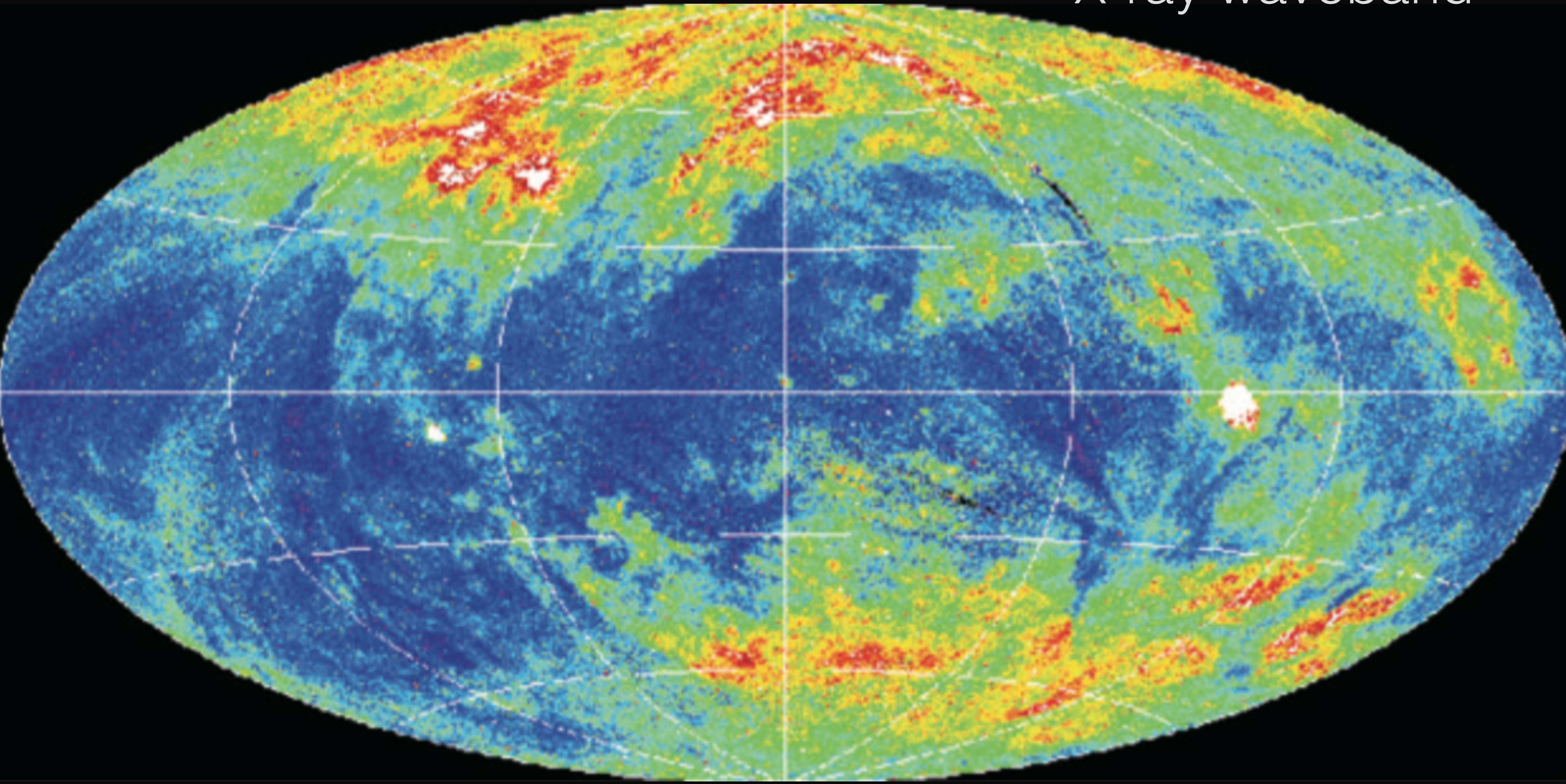
- tracing relativistic electrons interacting with magnetic fields
- especially important for studies of the physics of active galactic nuclei

21 cm line of neutral hydrogen

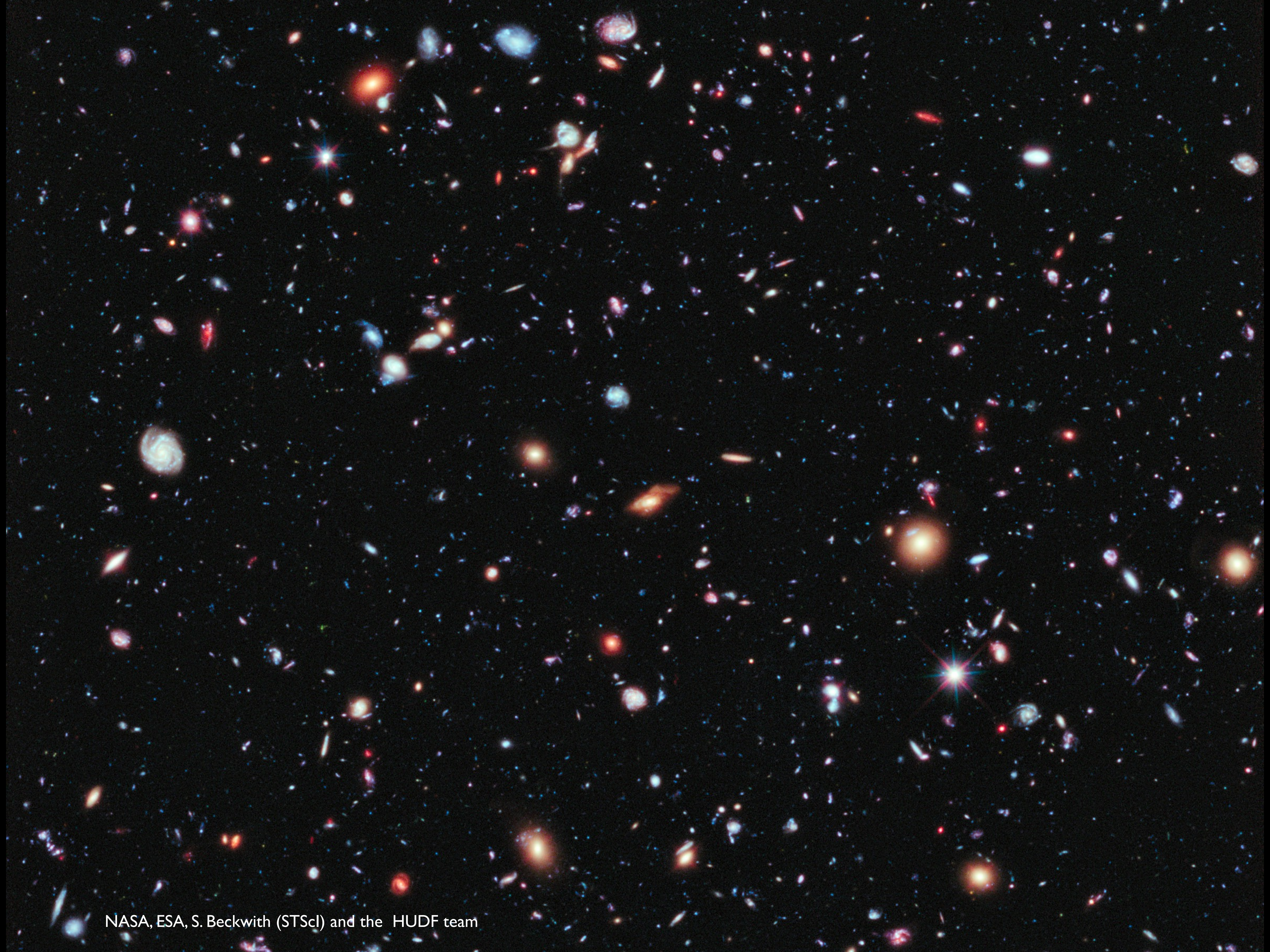


- neutral hydrogen emits 21 cm radiation due to the small change in energy when the relative spins of electrons and protons change (probability once in 12 million years)
- also molecular emission - small molecules (like CO) emit in the millimeter, larger linear molecules in the radio

X-ray waveband

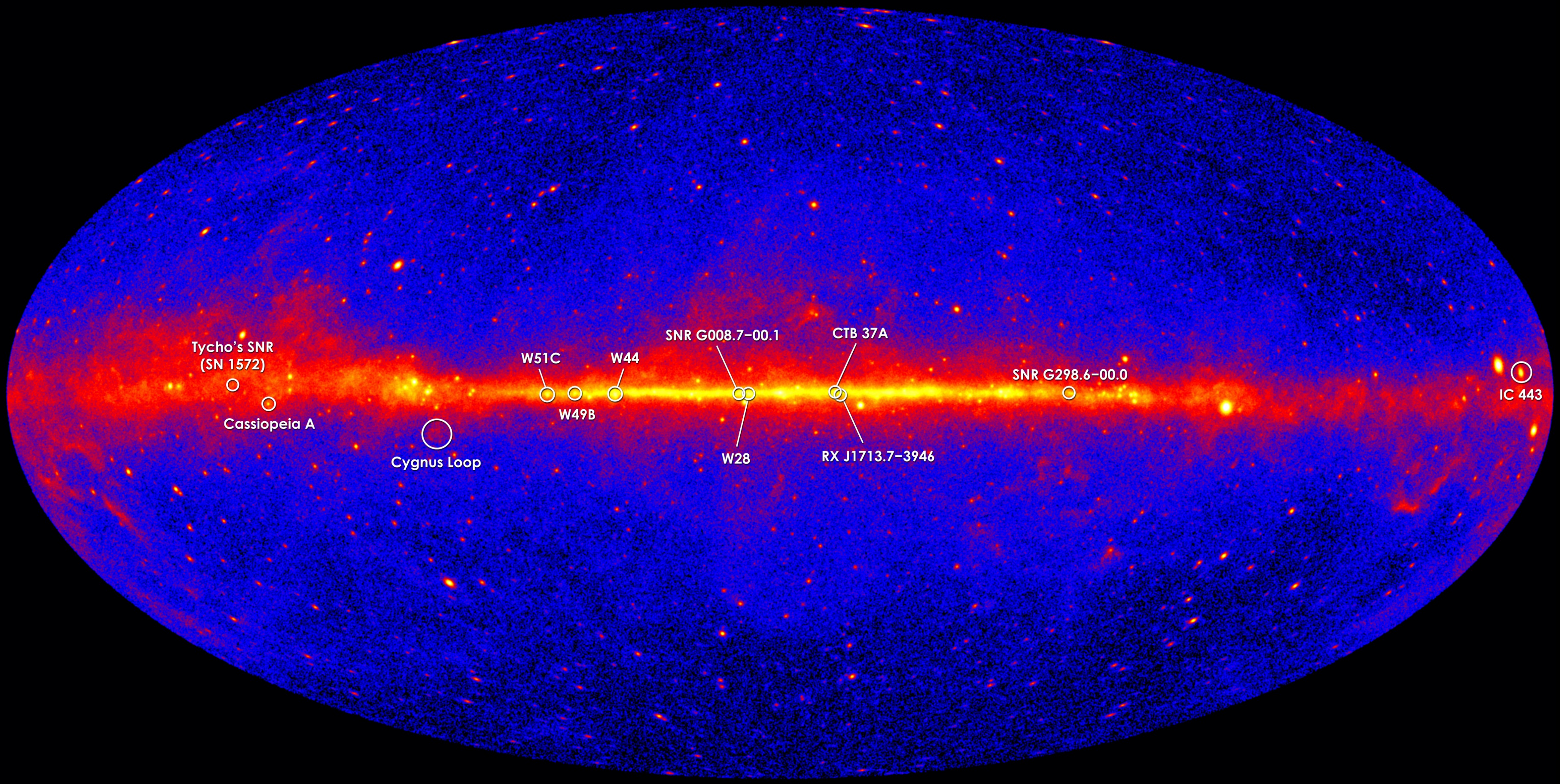


- X-ray binaries powered by accretion onto white dwarfs, neutron stars and black holes; stellar coronae; supernova remnants; galaxy clusters; AGN; diffuse Galactic emission
- The soft X-ray emission anticorrelates with the distribution of HI because of photoelectric absorption by interstellar gas



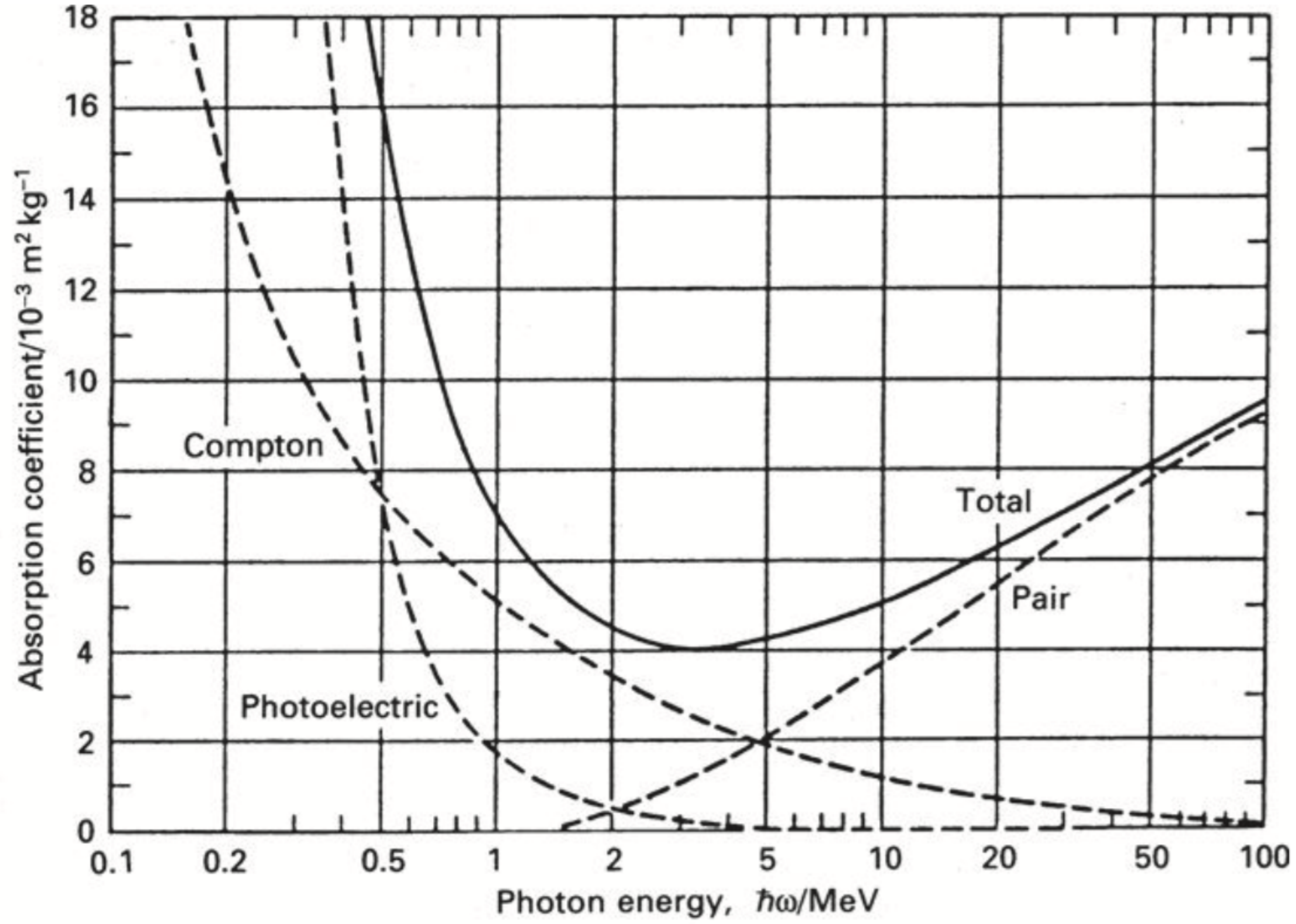
NASA, ESA, S. Beckwith (STScI) and the HUDF team

Gamma-ray sky E>1 GeV



Supernova remnants

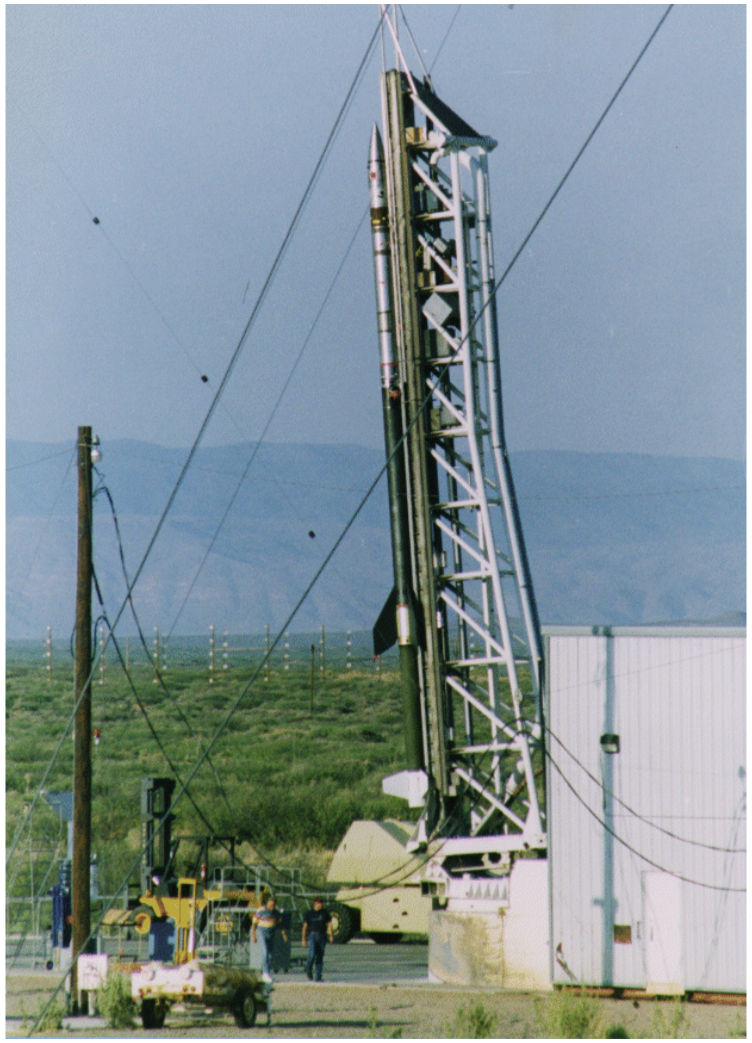
Interaction of high energy photons with matter



If a photon has a larger energy than $2m_ec^2$, then in a field of a nucleus it can decay into an electron positron pair

Geiger-Muller counters
Proportional counters
Scintillator detectors
Charge-Coupled Devices (CCDs)
Calorimeters

The X-ray Universe was discovered using sounding rockets



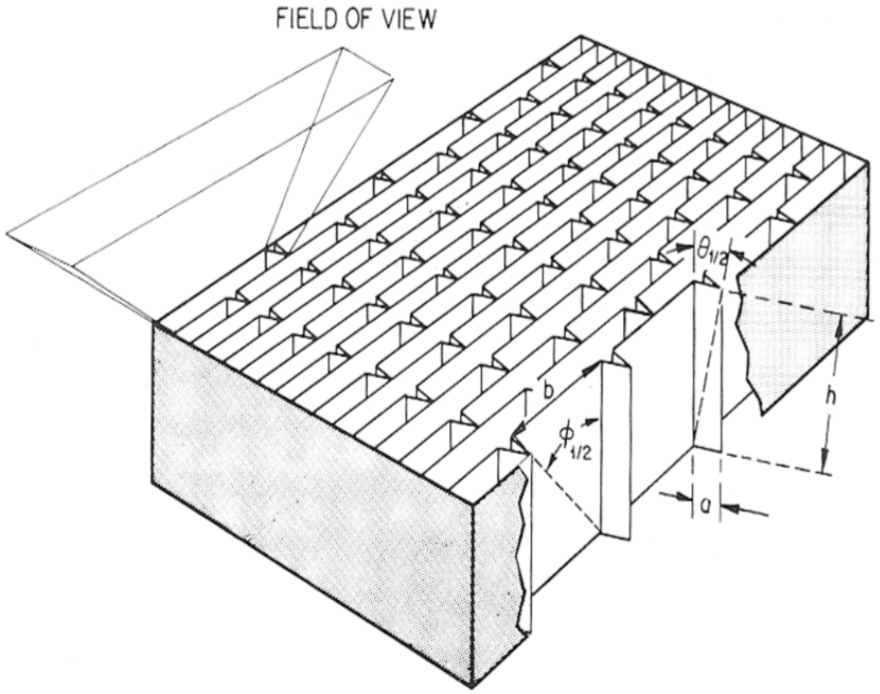
Friedmann et al. 1949 at Naval Research Lab (NRL) discovers X-ray emission from the Sun

Realisation that the Sun would not be detectable at stellar distances…

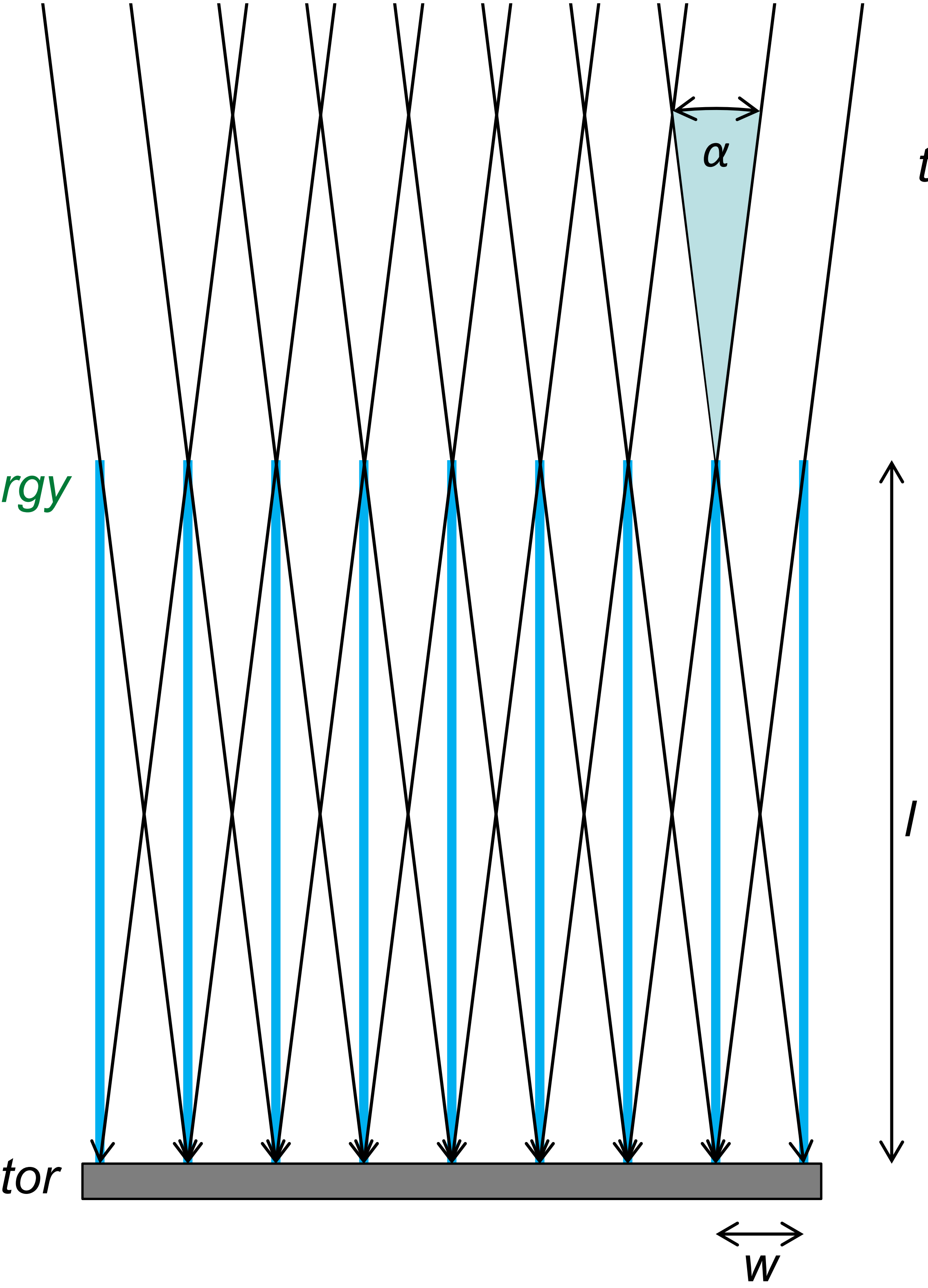
In 1962, Riccardo Giacconi et al. Search for X-rays from the Moon and discover the X-ray source Sco X-1. Turns out that while for the Sun $L_X=10^{-6}{}_{Opt}$, for Sco X-1 $L_X=10^9 L_X^{Sun}$

Rockets typically spend only ~5 min over 100 km!

Collimators



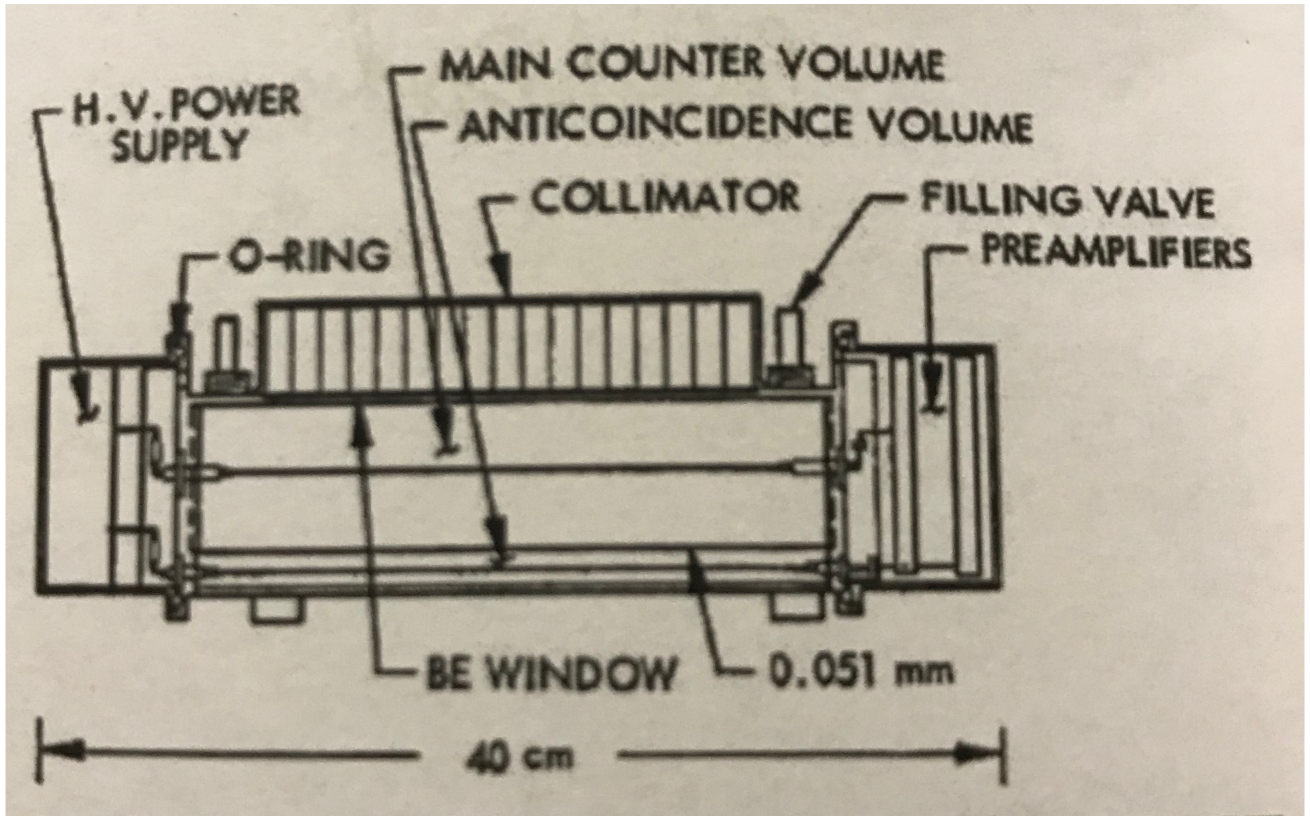
- *simple*
- *independent from photon energy*
- *very low spatial resolution*
- *high background*



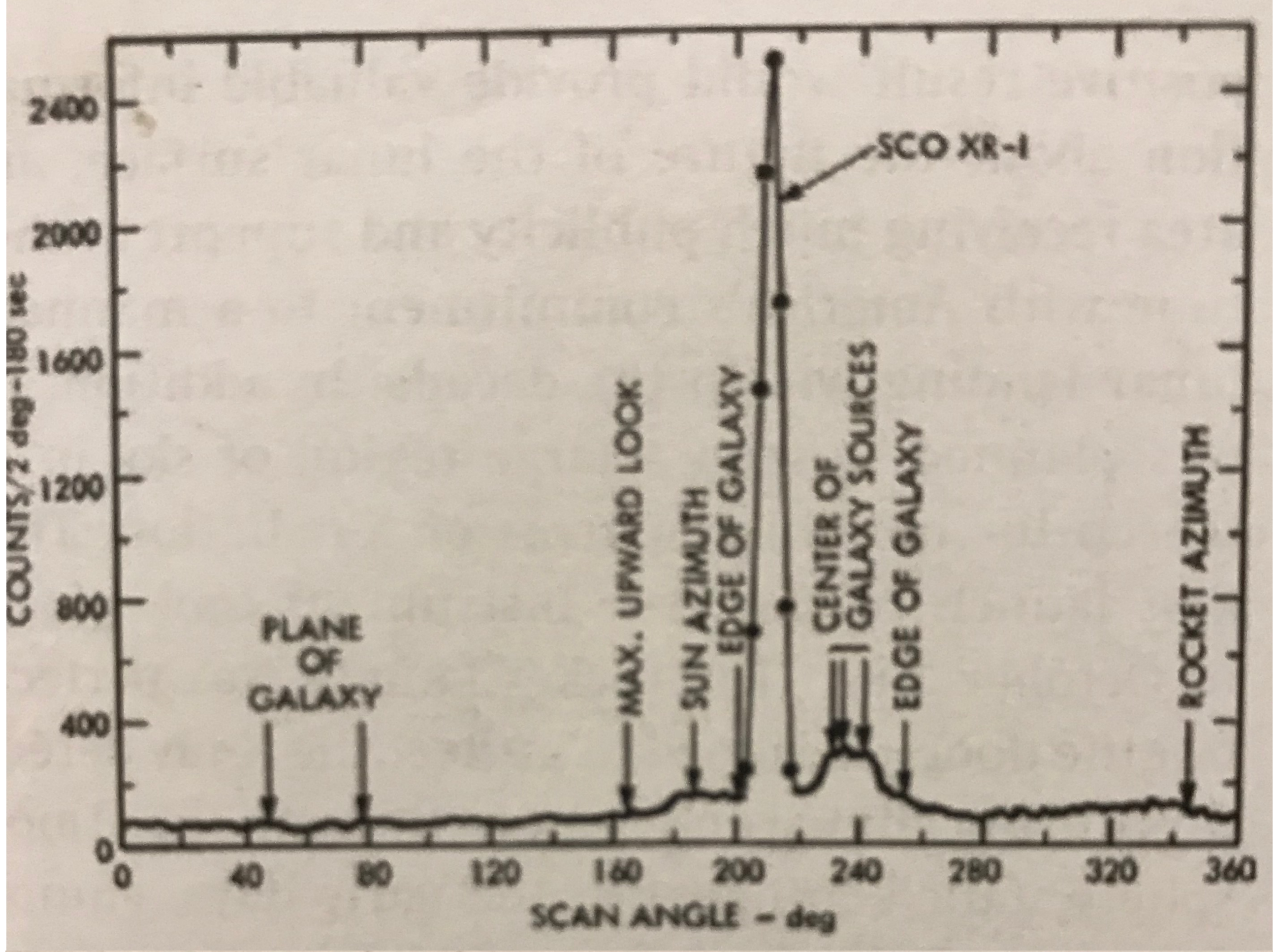
angular resolution:

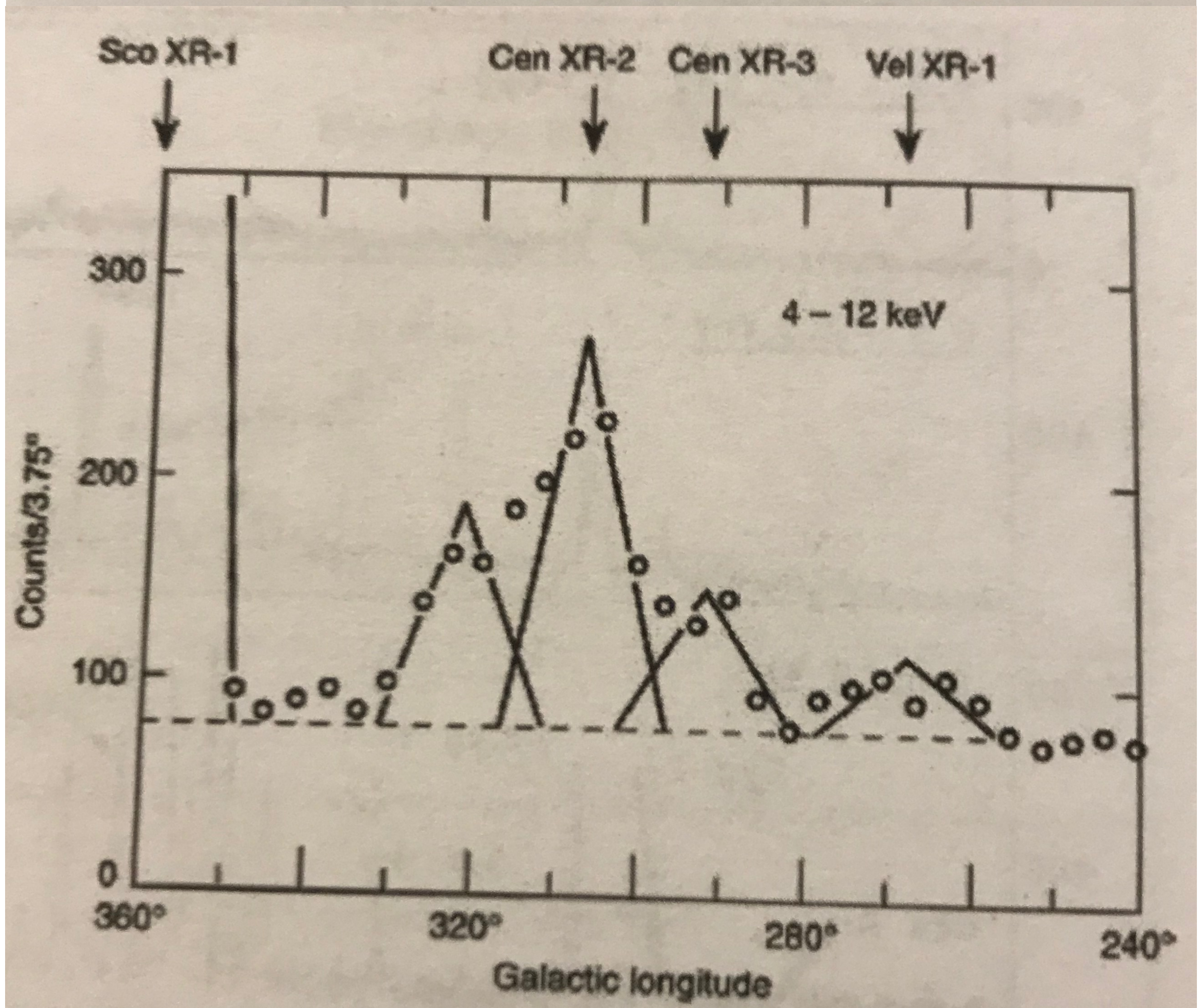
$\tan \alpha/2 = w / (2\ l)$

$\tan \alpha \approx w / l$ *(for small α)*



Proportional counter used on early sounding rocket observations



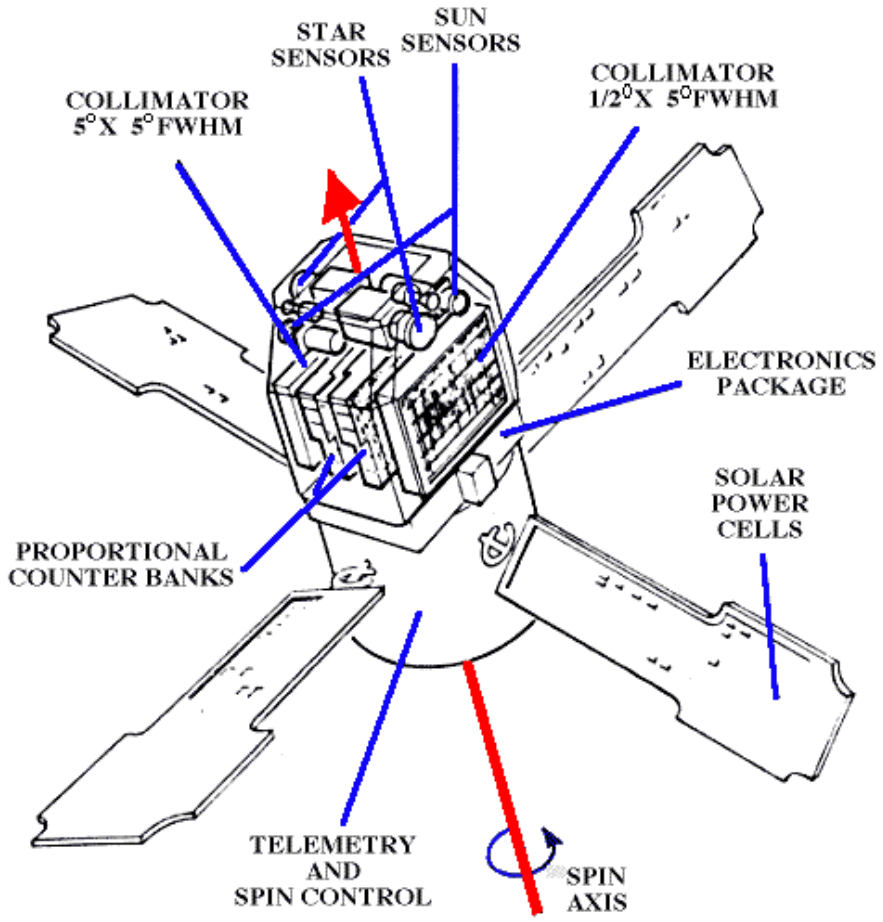


Uhuru - The first X-ray satellite

12 December 1970:
UHURU (“Freedom in Swahili)
launched from Kenia

Angular resolution of 0.52 degrees

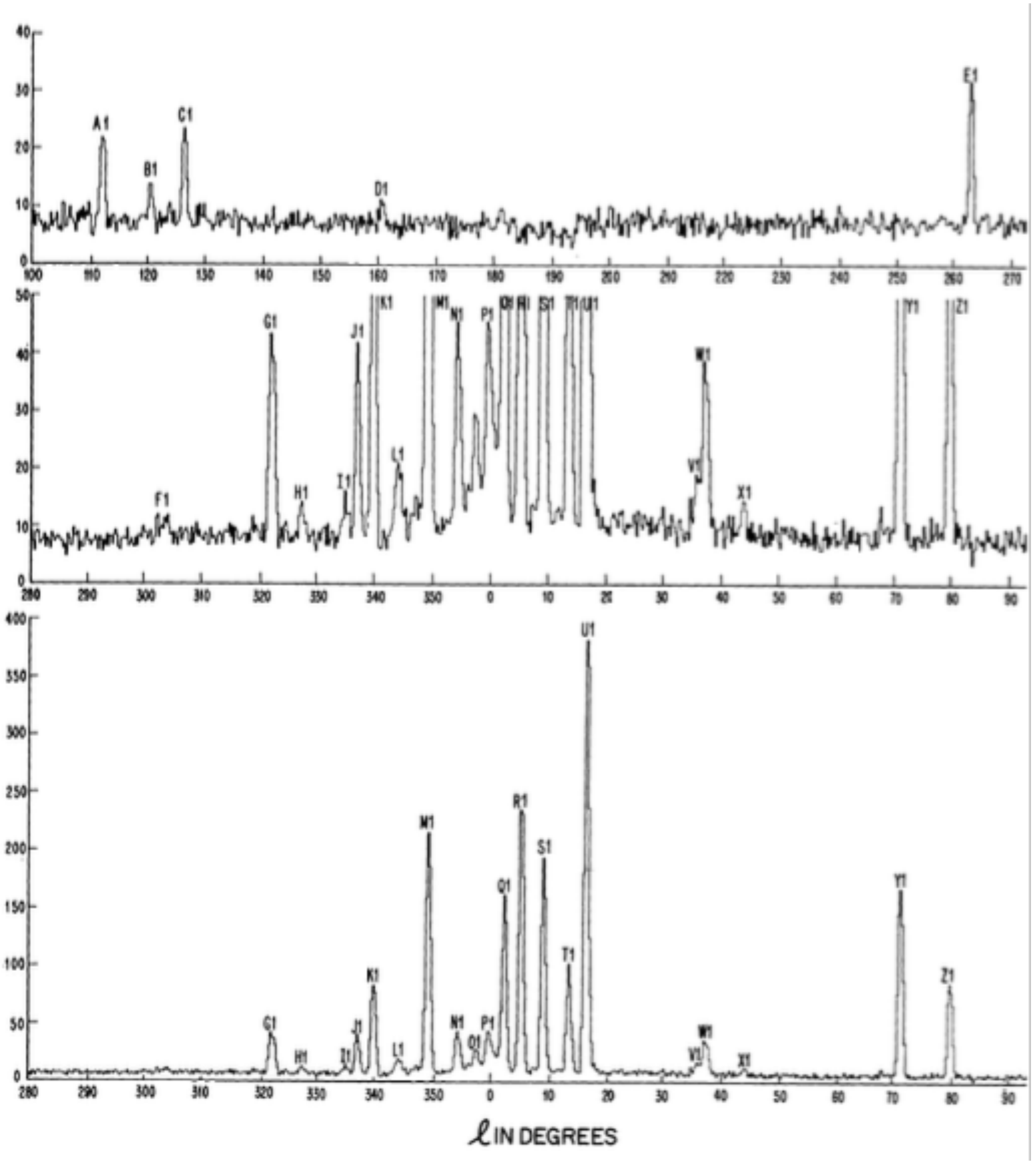
Uhuru - The first X-ray satellite



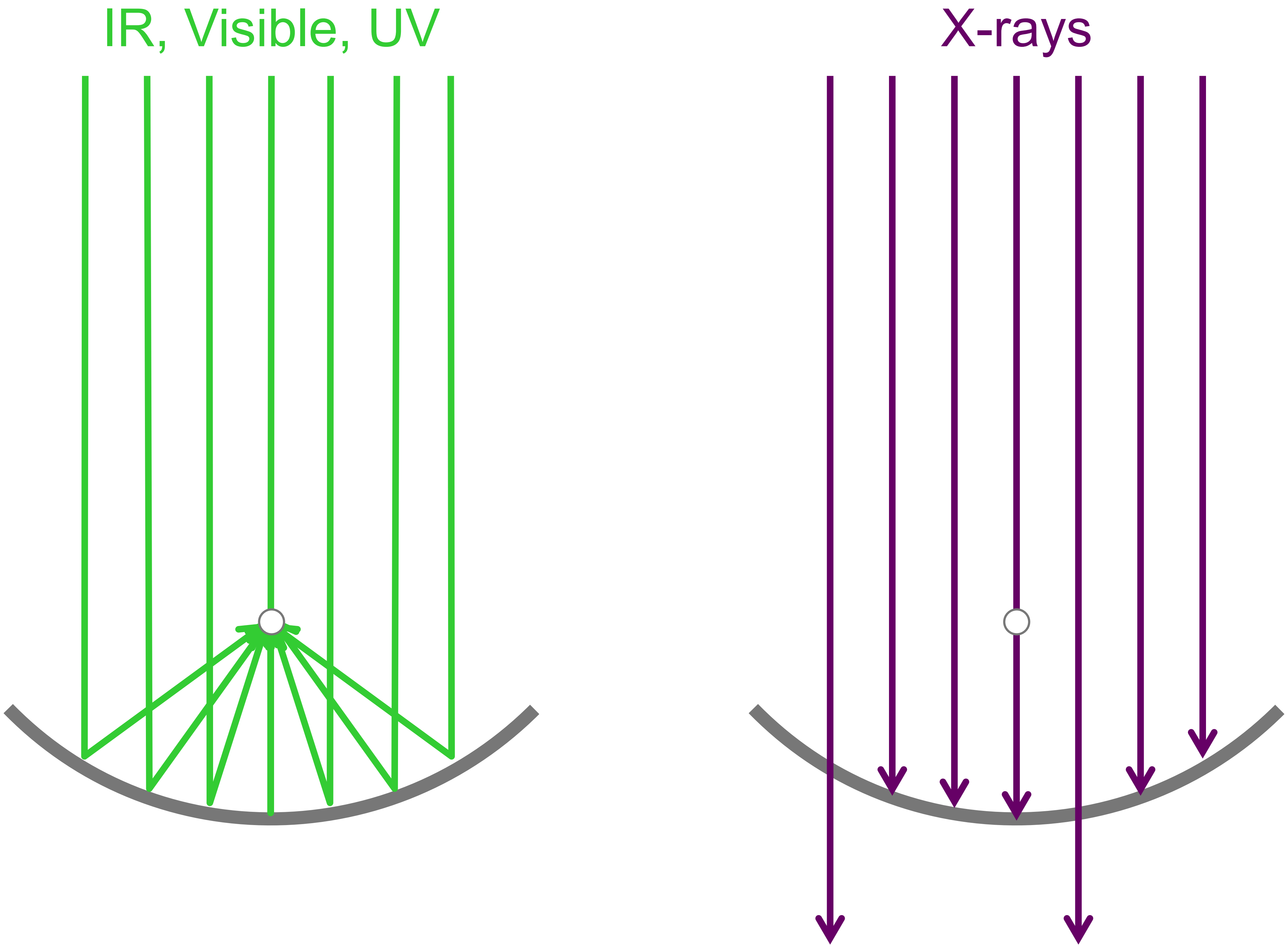
Identification of Cygnus X-1, the first strong candidate for an astrophysical black hole

Discovery of the pulsing accretion-powered binary X-Ray sources such as Cen X-3, Vela X-1, and Her X-1

Uhuru all sky catalog catalog of 339 objects in the 2—6 keV band



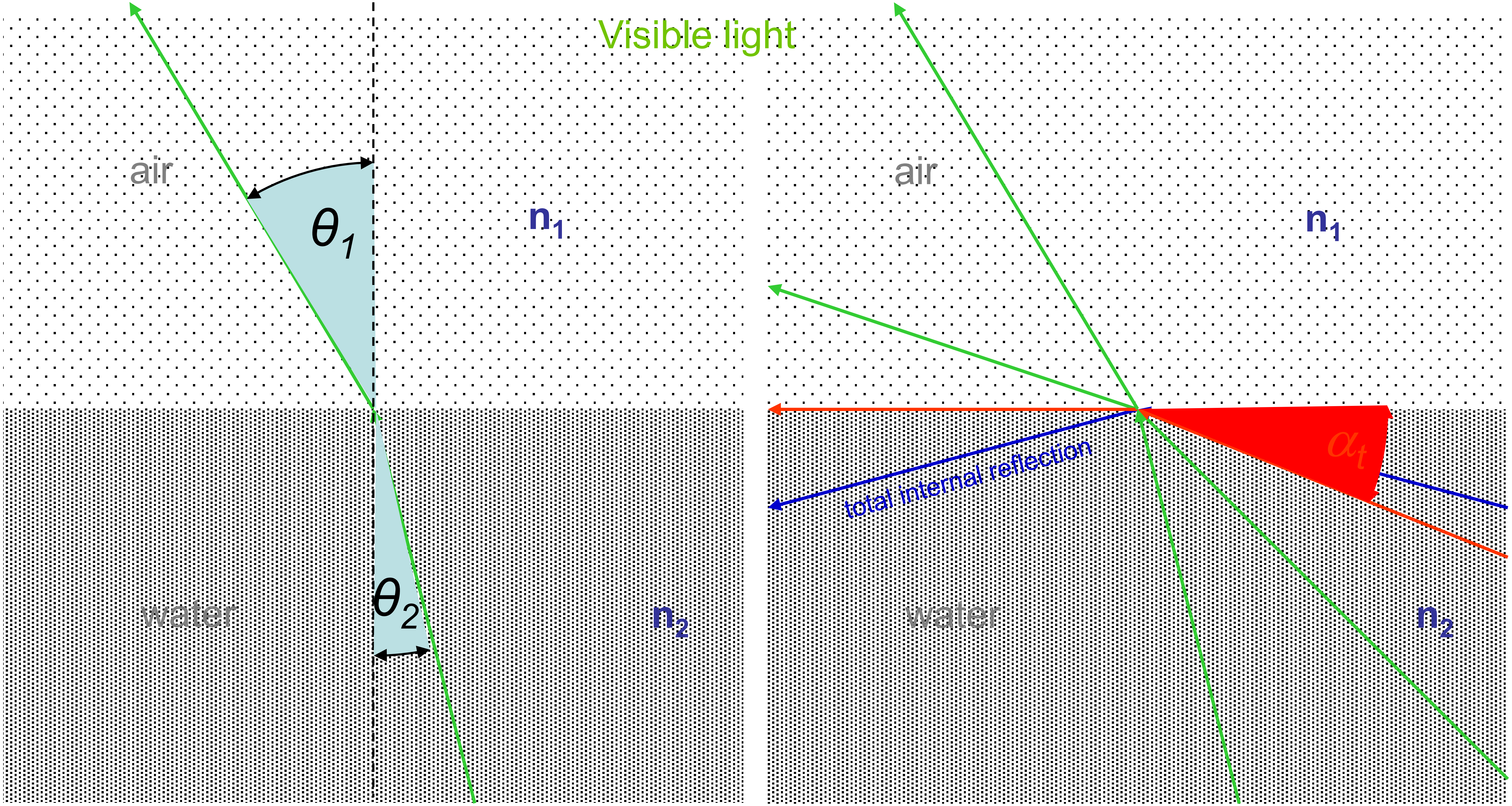
Reflection and Absorption



Index of Refraction and Total Internal Reflection

Snell's law: $n_1 \sin \theta_1 = n_2 \sin \theta_2$

$\rightarrow \cos \alpha_t = n_1 / n_2$



Index of Refraction and Grazing Angle

Complex refractive index *n*:

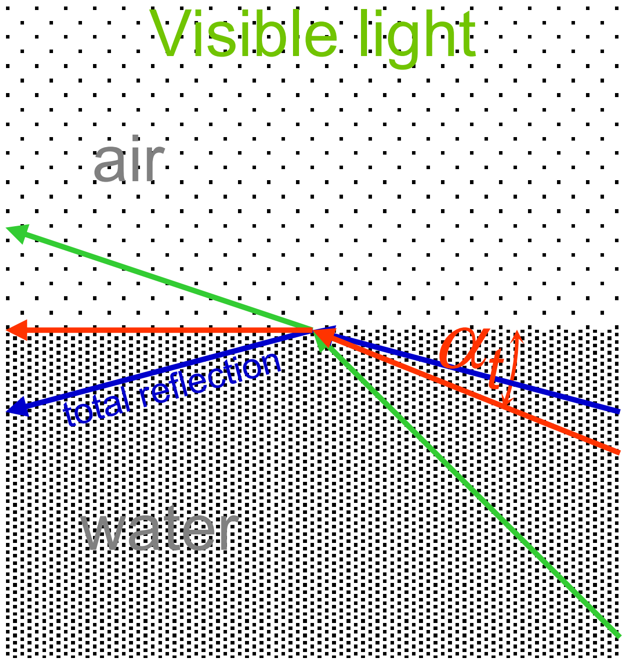
$$\mathbf{n = \underbrace{1 - \overset{\text{phase change}}{\delta}}_{\substack{\textit{slightly less than 1} \\ \textit{for X-rays in matter} \\ \textit{exactly 1 in vacuum}}} - i\overset{\text{absorption}}{\beta}}$$

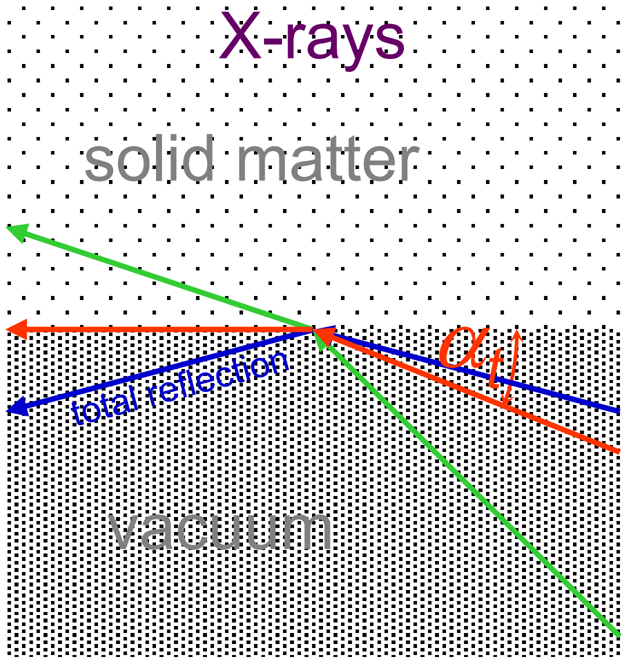
$$\delta = \frac{r_e}{2\pi}\,\frac{N_0\,\rho}{A}\,Z\,\lambda^2$$

Critical grazing angle α_t:

$$\mathbf{\cos\alpha_t = 1 - \delta} \quad \textbf{\textit{(Snell's law)}}$$

for $\delta << 1$: $\alpha_t = \sqrt{2\,\delta}$





from theoretical atomic physics:

$$\delta \sim E^{-2} \qquad \delta \sim Z$$

$$\underbrace{\rightarrow \alpha_t \sim E^{-1} \qquad \alpha_t \sim \sqrt{Z}}$$

for practical use:

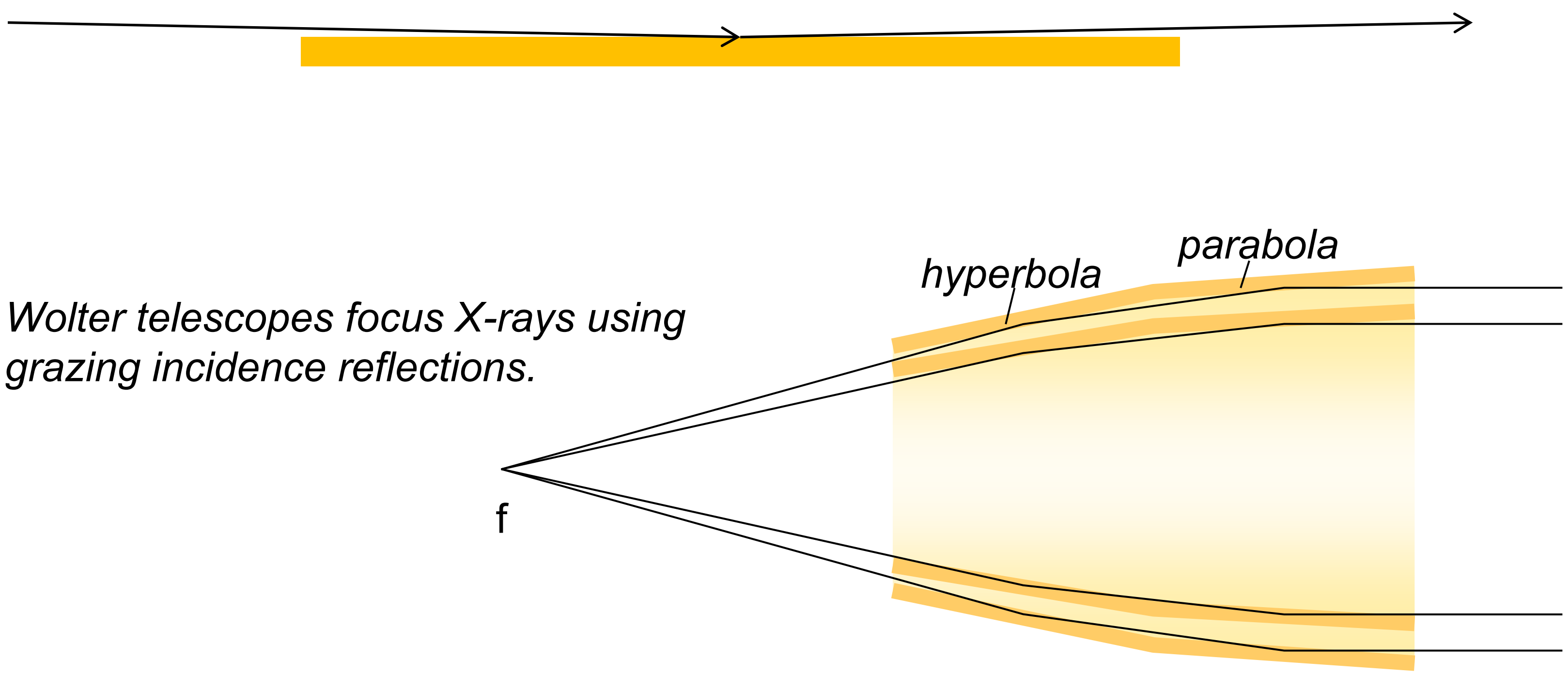
$$\alpha_t \approx 69\,\sqrt{\rho}\,/\,E$$

α_t in arc minutes

E in keV

ρ in g/cm^3

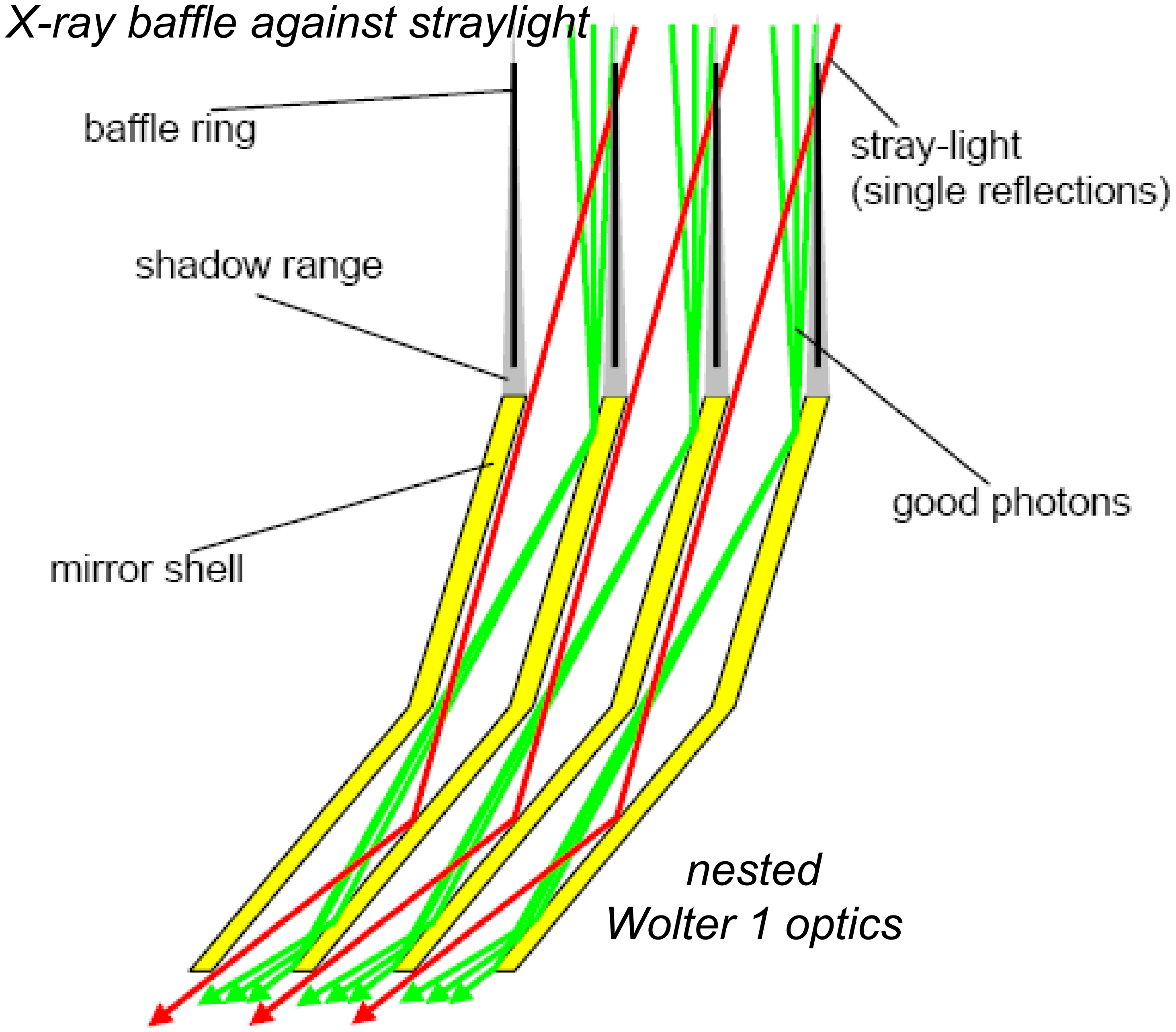
The Wolter Type I telescope



Wolter telescopes focus X-rays using grazing incidence reflections.

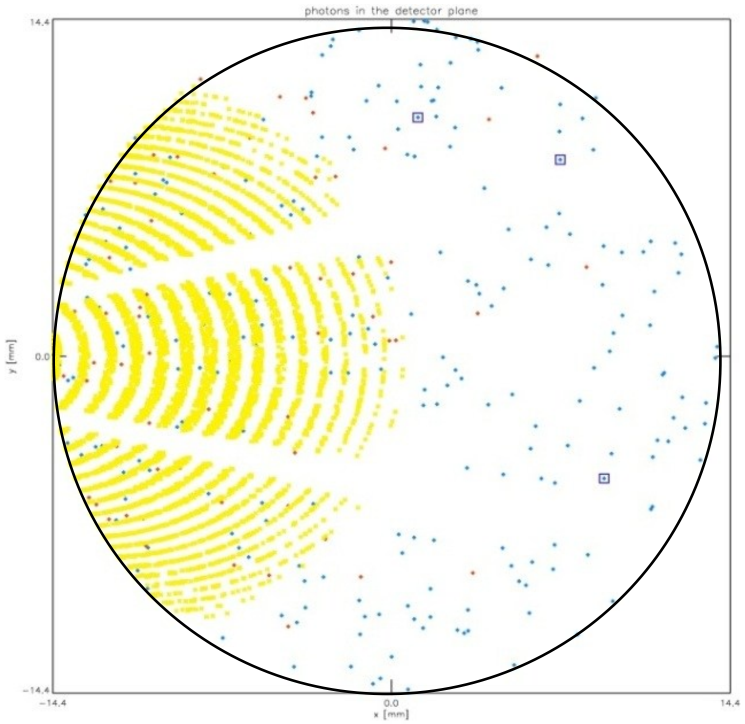
- achieve the best 2D resolution
- collect or “gather” weak fluxes of photons
- concentrate the photons on a small region of the detector to minimize the detector background
- these mirrors are compact
- Used first time on the Einstein observatory

Straylight: Single Reflections (and how to prevent them)

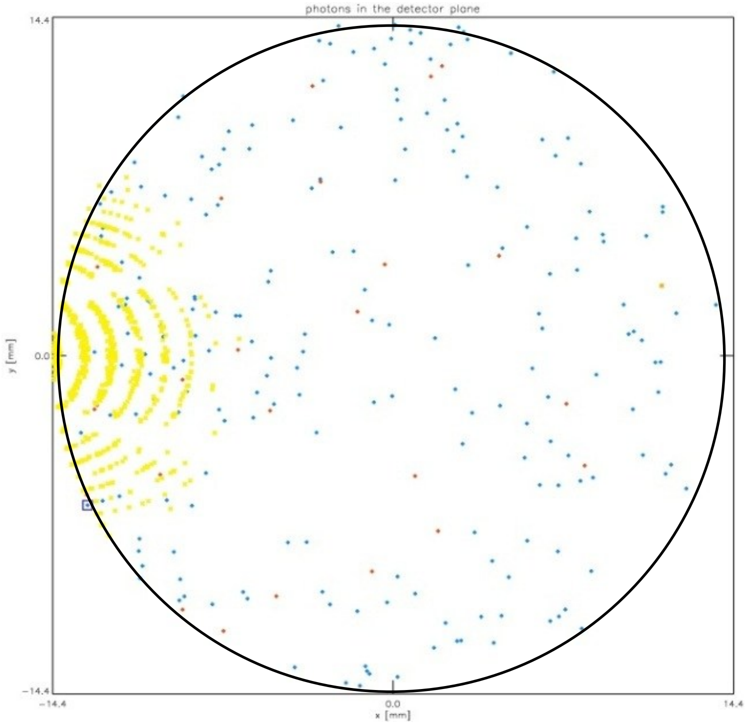


source 1° off-axis

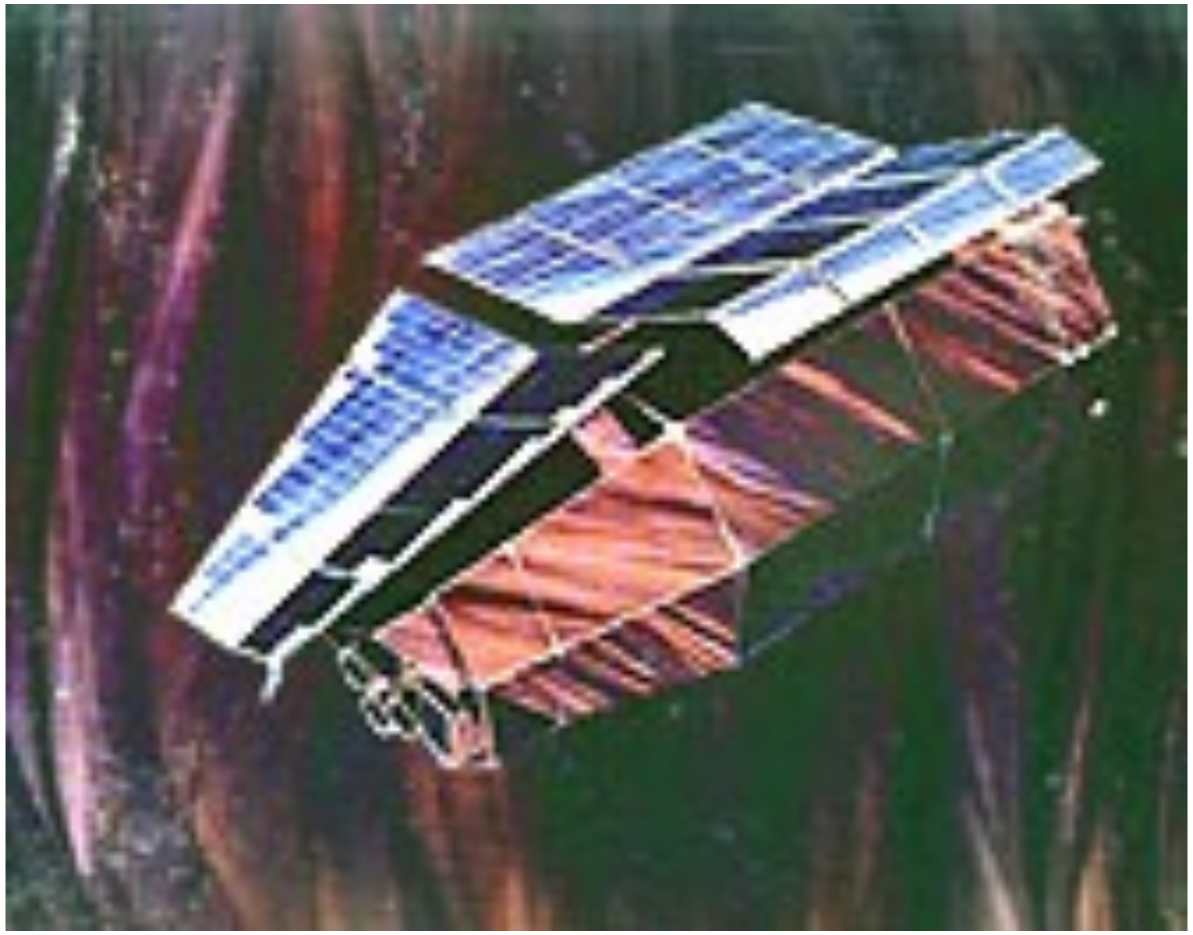
without baffle



with baffle



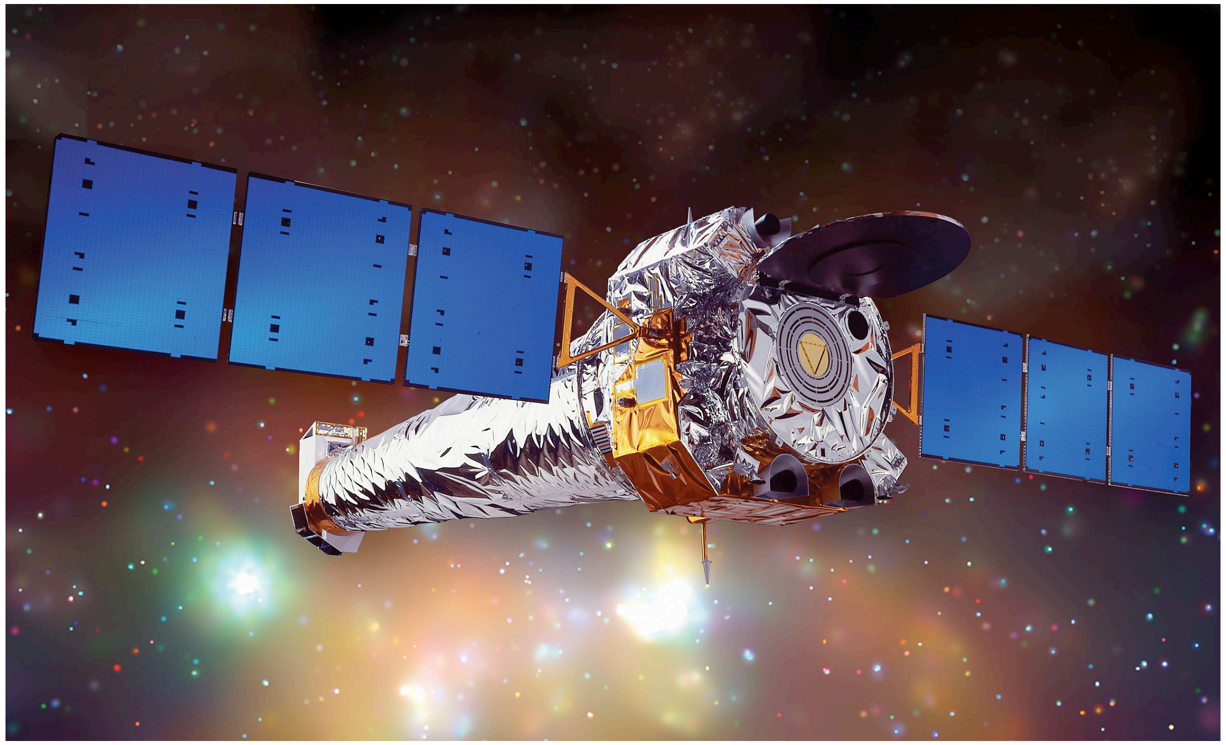
The first X-ray imaging telescope



1978 Nov - 1981 April
NASA's Einstein X-ray Observatory

0.2 - 20 keV
θ=2 arcsec
First X-ray spectra
Coronae of stars
Supernova remnants
Resolved extragalactic sources

Riccardo Giacconi received the Nobel Prize in Physics in 2002 for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources



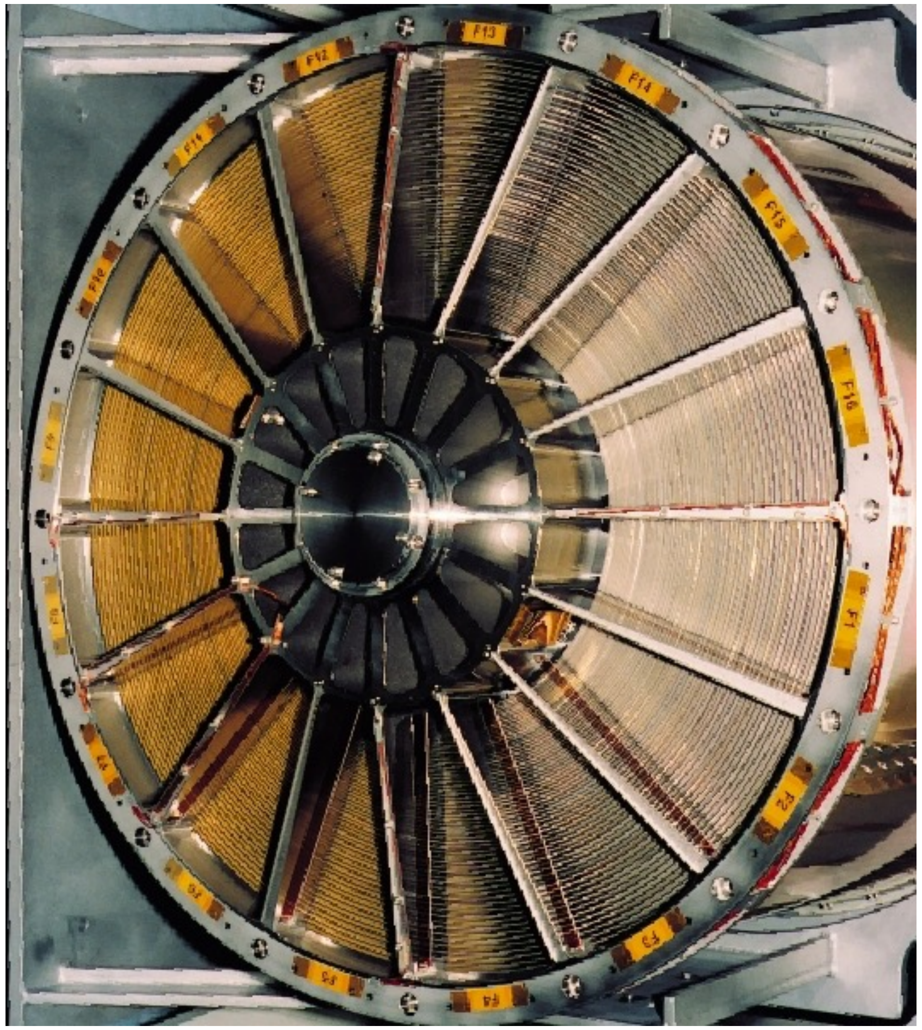
Chandra
(NASA)

XMM-Newton
(ESA)

Sensitivity:
555 cm^2 @1 keV
Spatial resolution:0.2 arcsec
Launched in:
1999

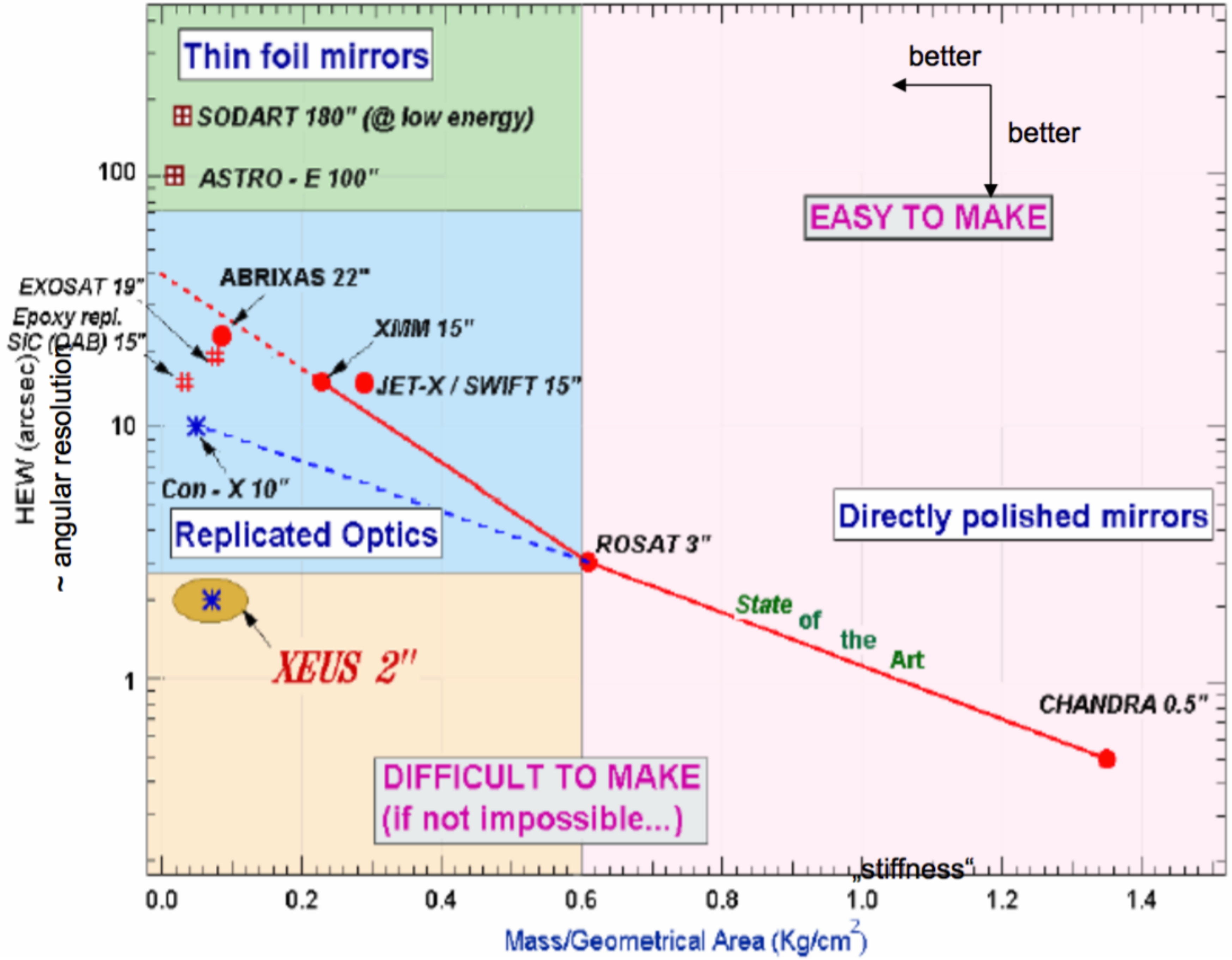
Sensitivity:
4650 cm^2 @1 keV
Spatial resolution:
6 arcsec
Launched in:
1999

Chandra mirror

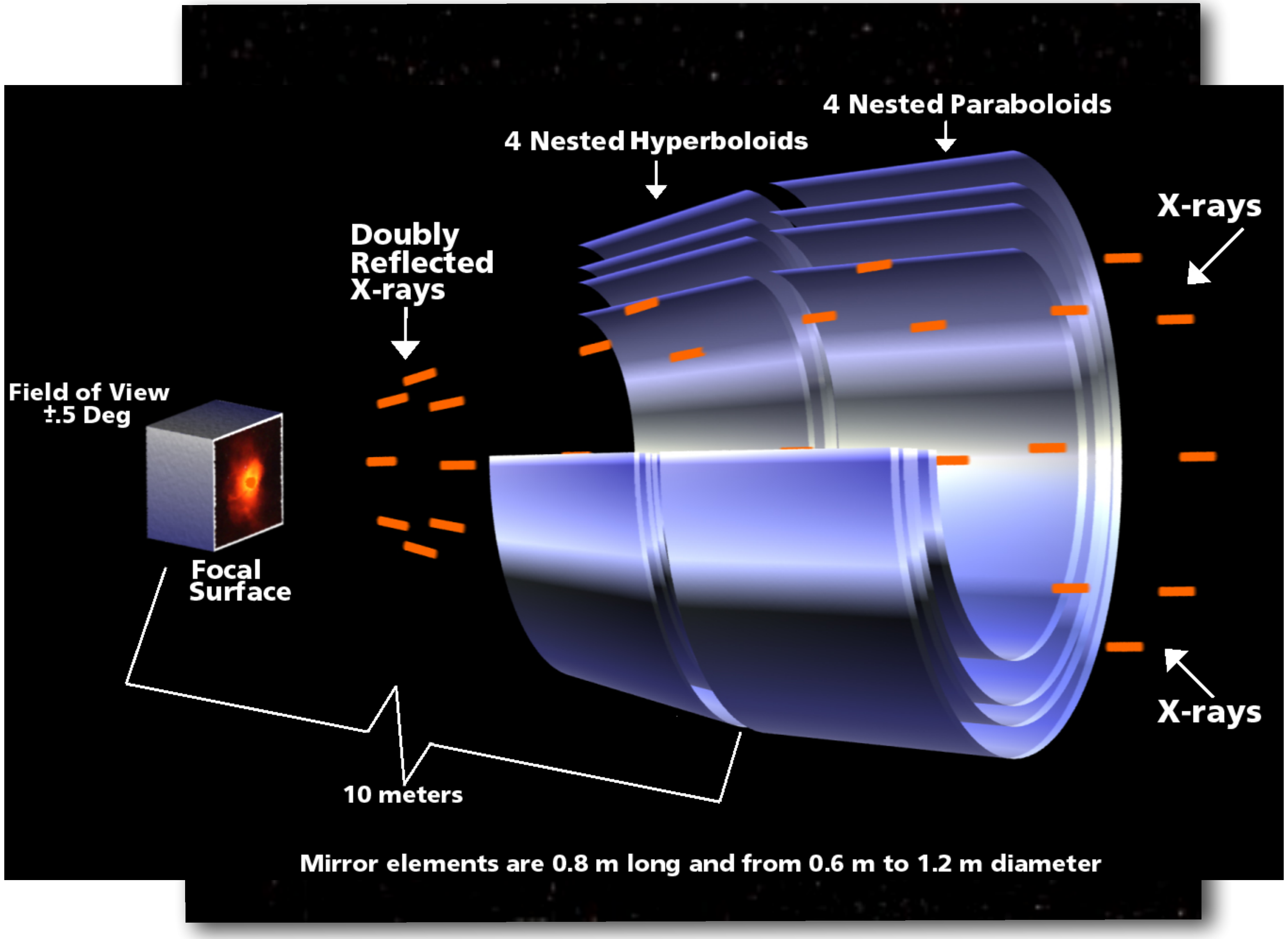


XMM-Newton mirror

			X-ray Telescope Mirrors			
	Einstein	**EXOSAT**	**ROSAT**	**BBXRT/ASCA**	**Chandra**	**XMM**
Mirror Characteristic						
aperture diameter	58 cm	28 cm	83 cm	40 cm	1.2 m	70 cm
mirrors	4 nested	2 nested	4 nested	118 nested	4 nested	58 nested
geometric area (cm2)	350	80	1140	1400	1100	6000
grazing angle (arcmin)	40-70	90-110	83-135	21-45	27-51	18-40
focal length (m)	3.45	1.09	2.4	3.8	10	7.5
mirror coating	Ni	Au	Au	Au	Ir	Au
highest energy focused (keV)	5	2	2	12	10	10
on axis resolution (arcsec)	4	18	4	75	0.5	20



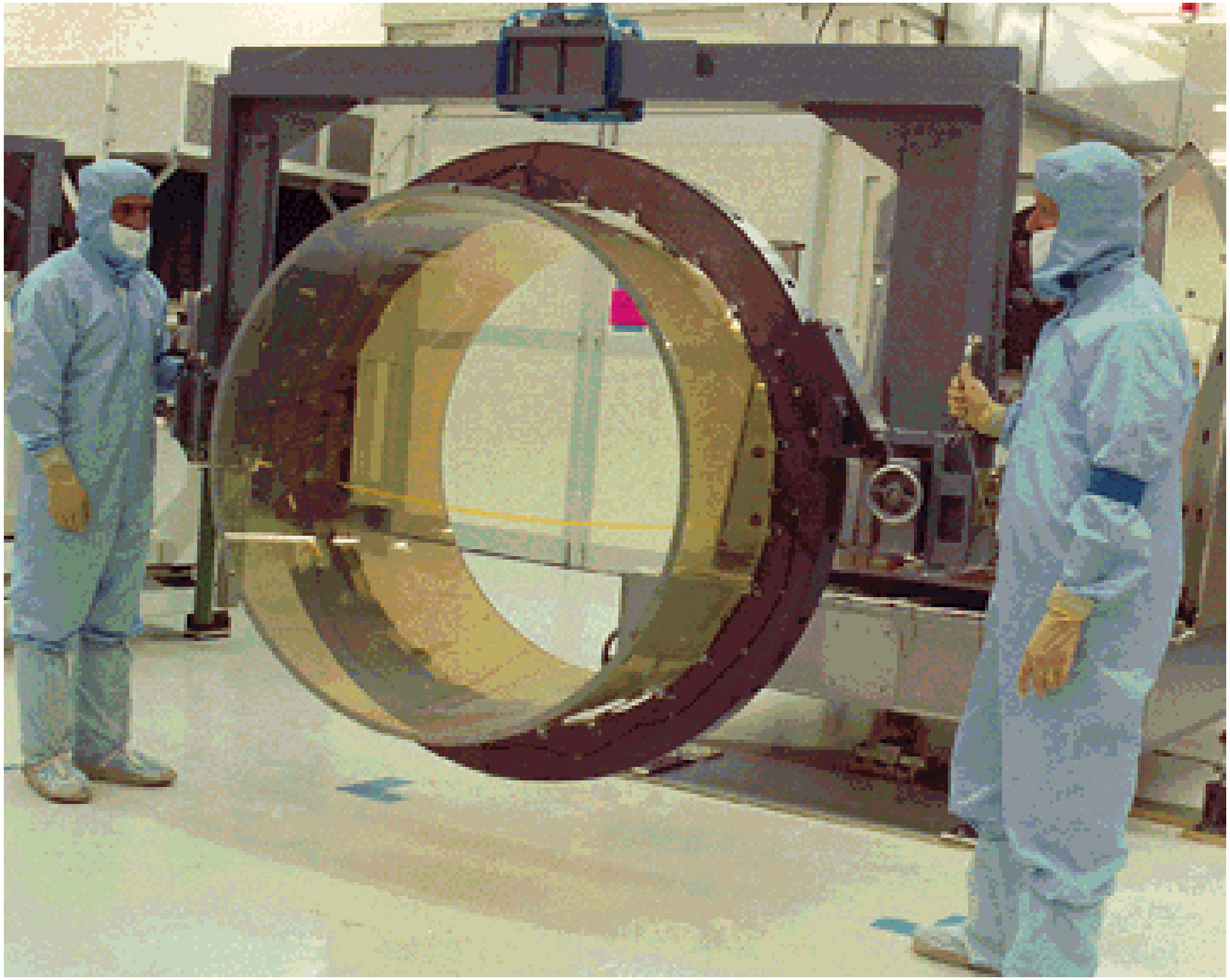
The Chandra X-ray Observatory



Mirror elements are 0.8 m long and from 0.6 m to 1.2 m diameter

- Chandra launched in 1999
- at an elliptical orbit with apogee at r ~ 135,000 km and perigee at r ~ 14,000 km
- Massive mirrors with extremely high angular resolution of 1 arcsec
- Four shells with a thickness of 2–3 cm
- made of Zerodur (glass with zero expansion coefficient)
- effective area of 800 and 400 cm^2 @ 0.25 and 5 keV respectively
- focal length 10 meters
- max. diameter 1.2 m
- coated with Ir
- challenging manufacturing

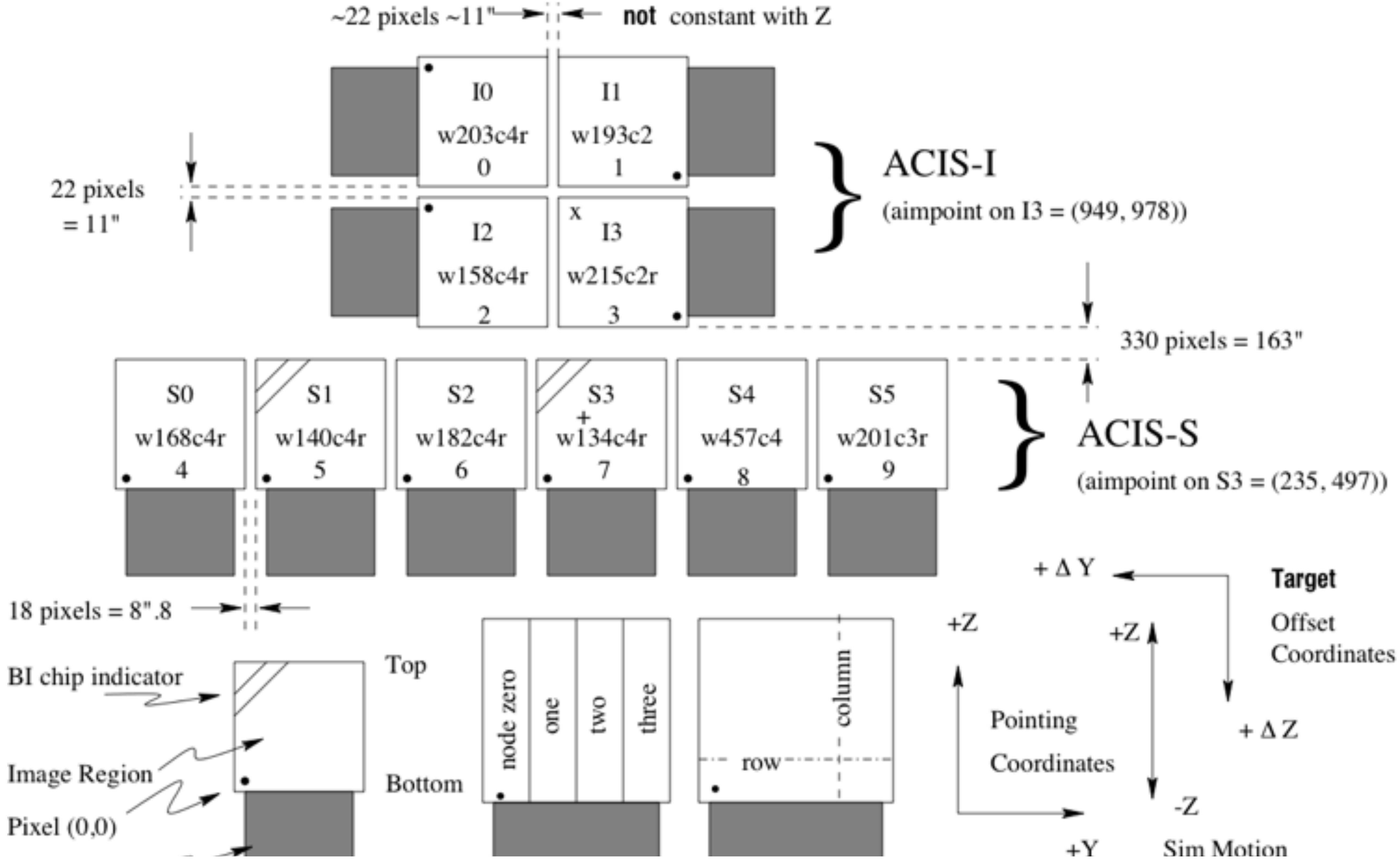
X-Ray Mirrors made of polished Zerodur: Chandra



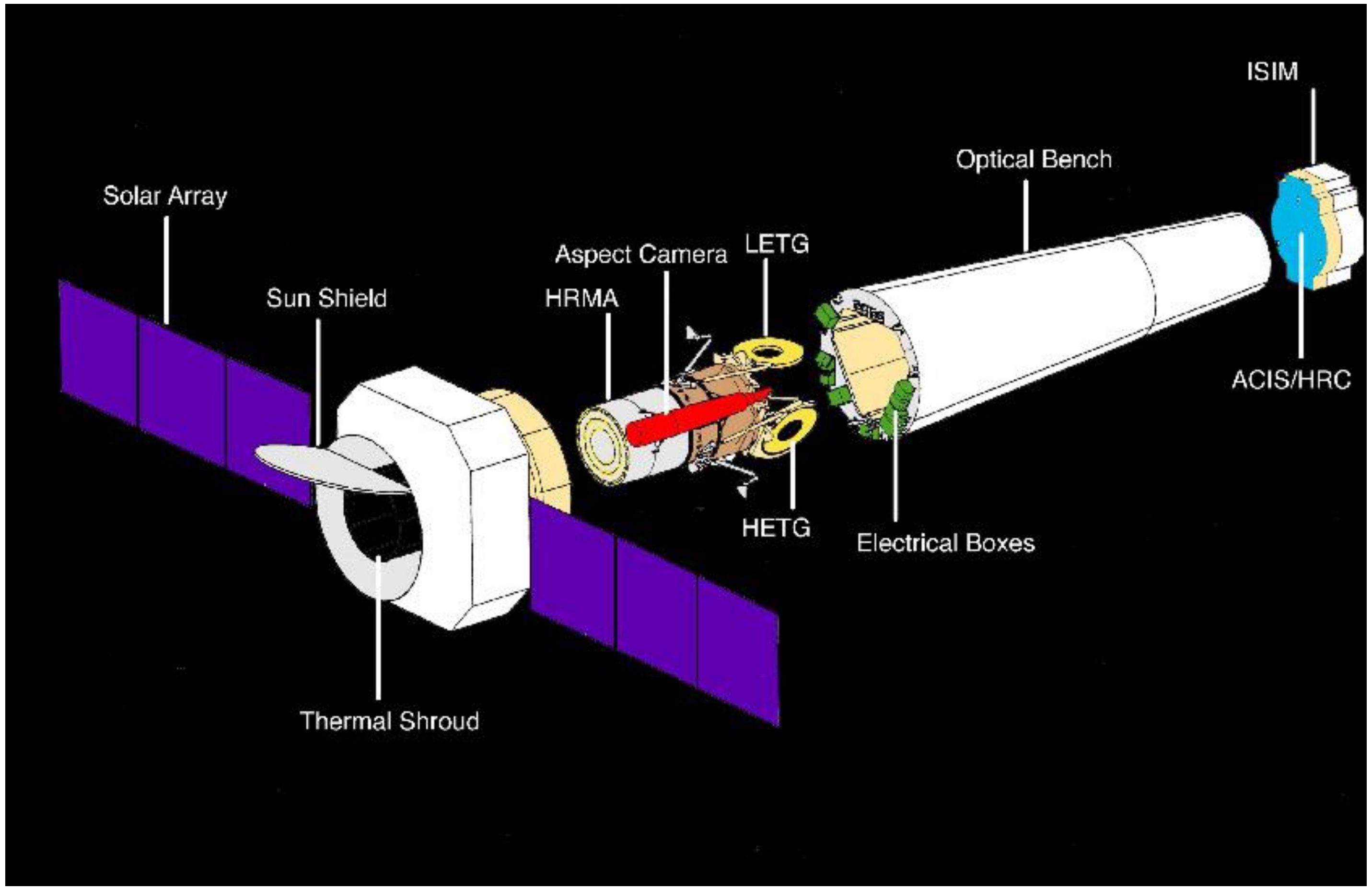
Chandra X-ray mirror (1 of 4)

Chandra’s Advanced CCD Imaging Spectrometer made of ten 1024 × 1024 pixel (8.3 × 8.3 arcmin) CCDs

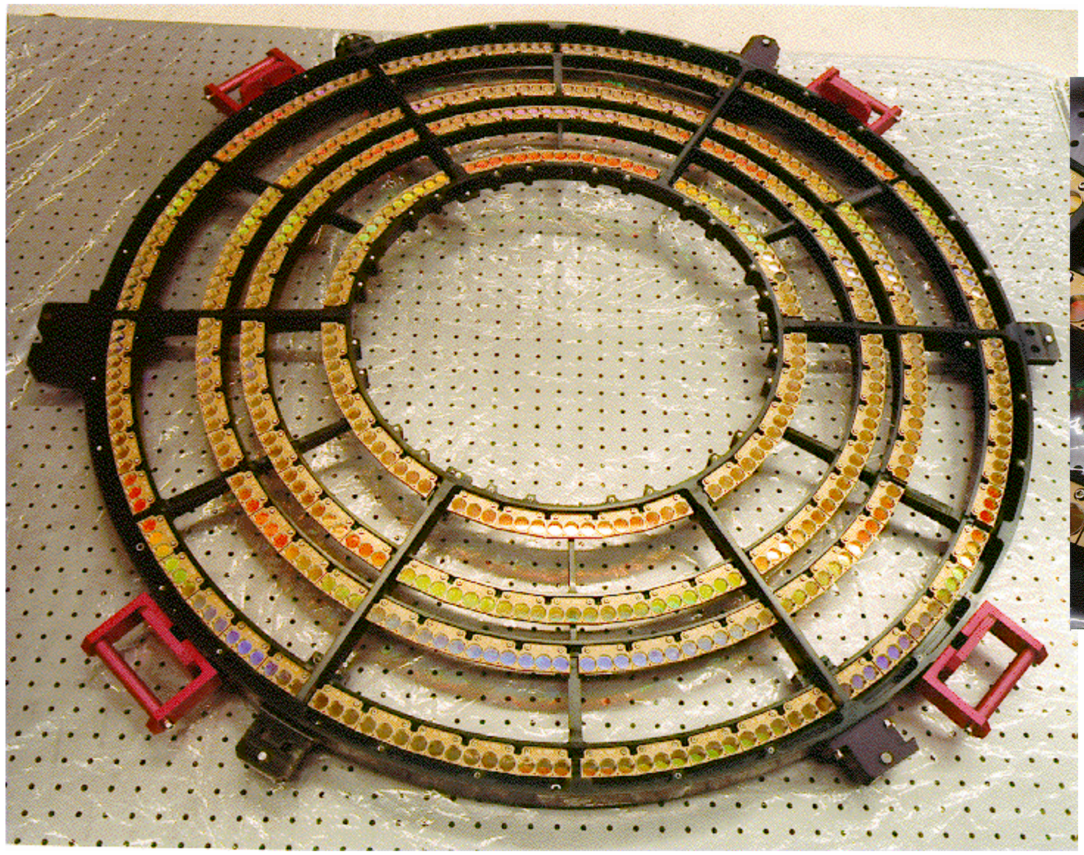
0.5 arcsec on axis spatial resolution
~150 eV spectral resolution

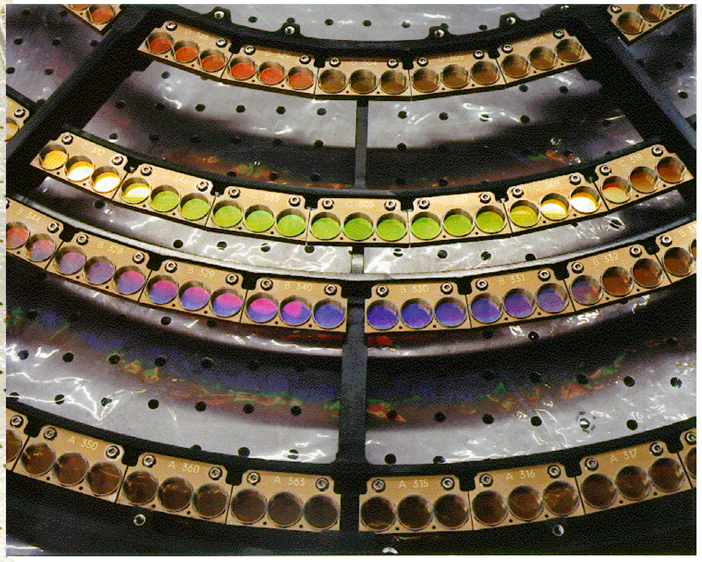


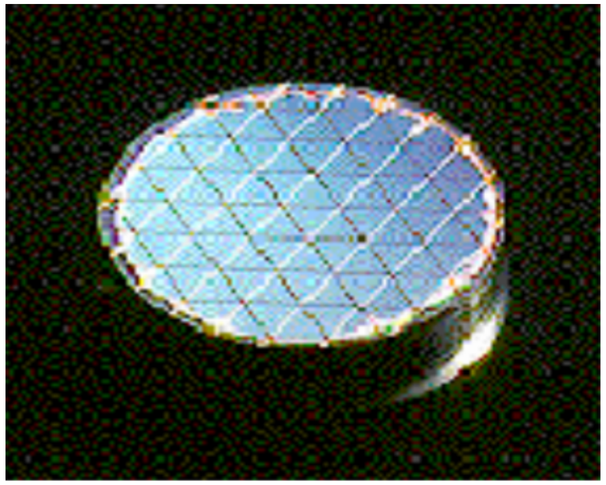
Chandra transmission grating spectrometers

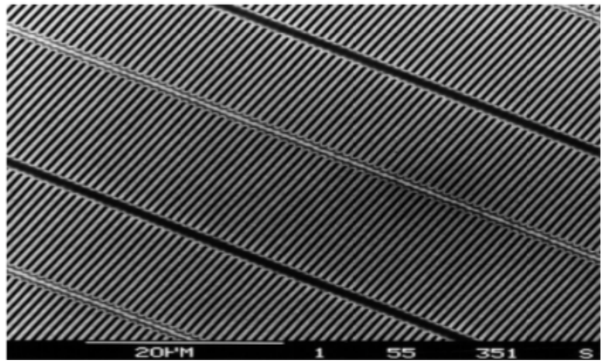


- gratings made of free standing gold wires
- Diameter of each grating facet 1.6cm
- 540 single grating facets mounted on a ring shaped frame
- spectral resolution of 40—2000

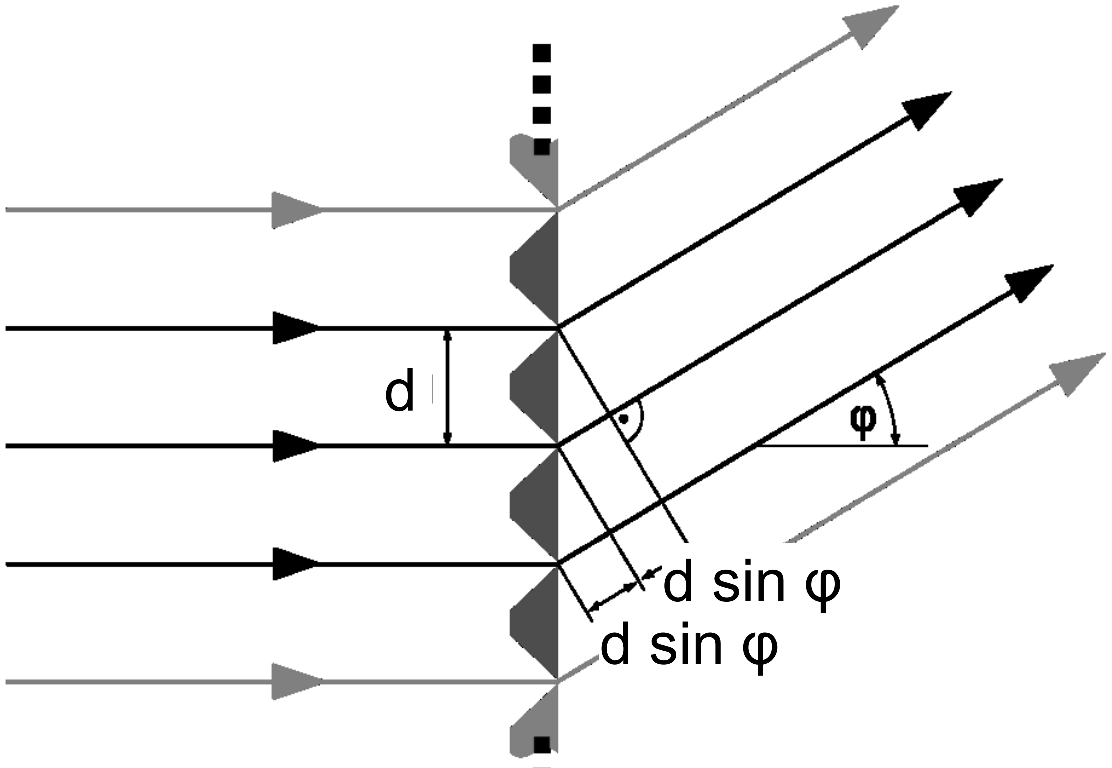






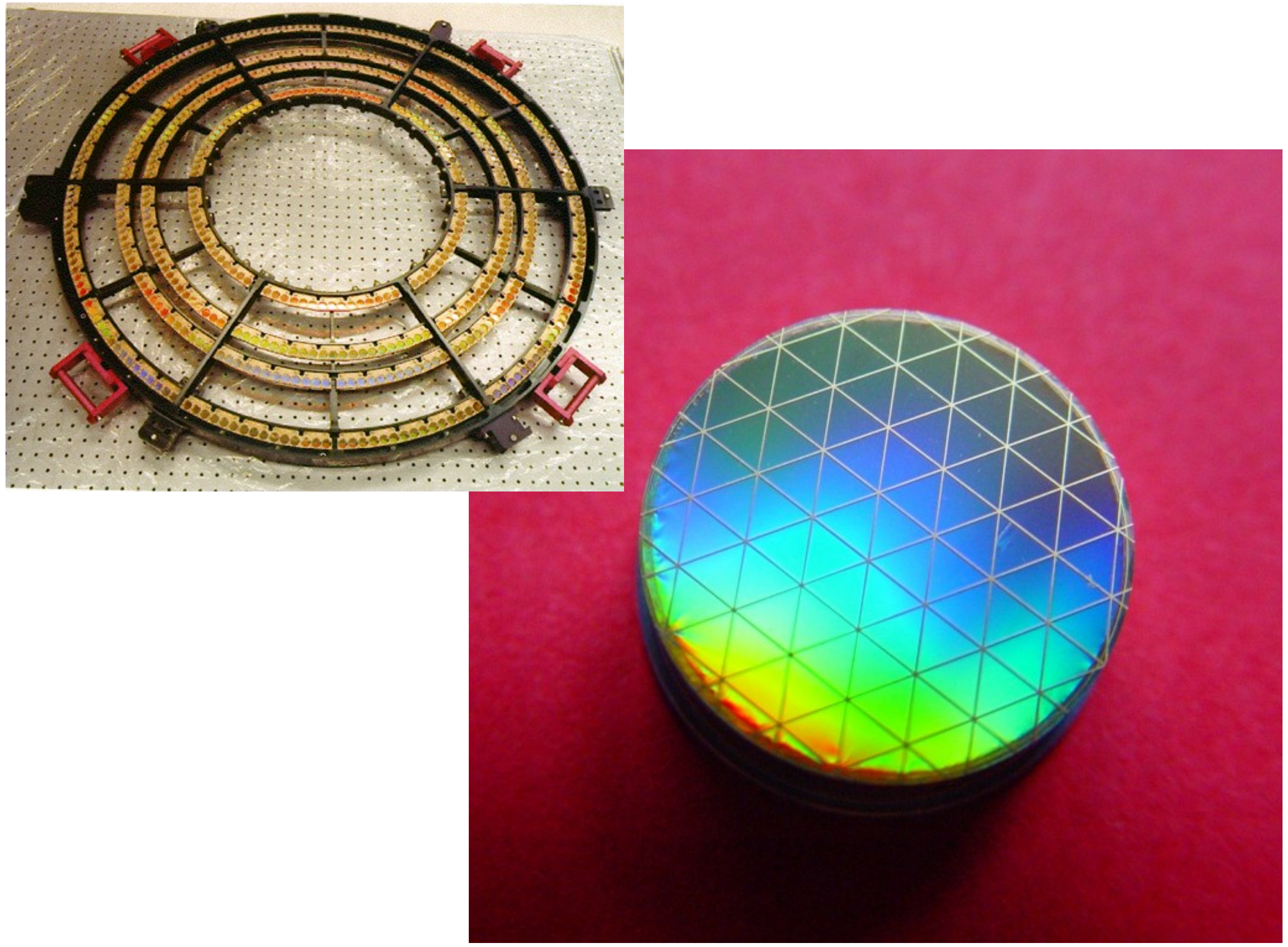


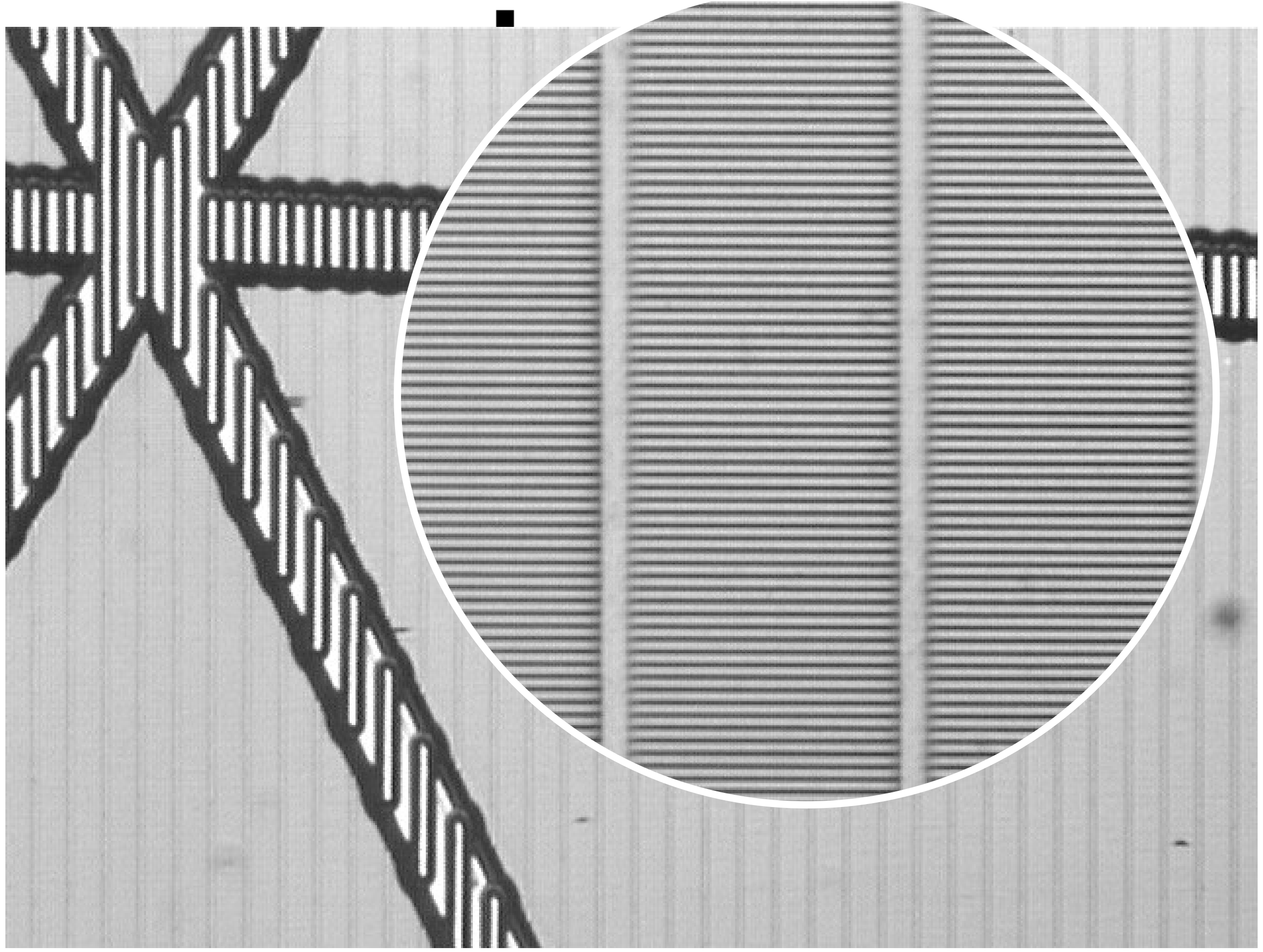
2.5. Gratings



Gratings

n λ = d sin (φ)

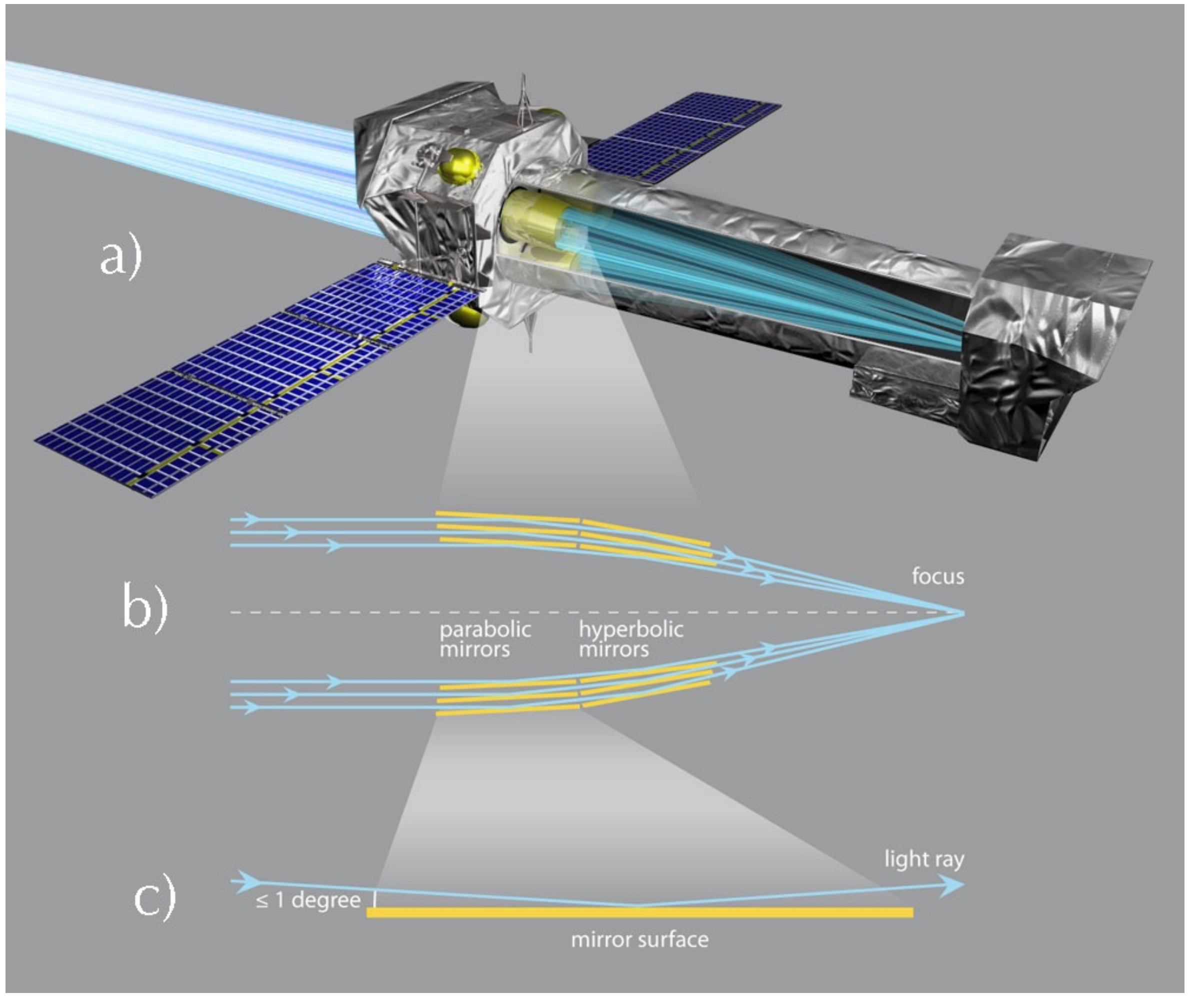


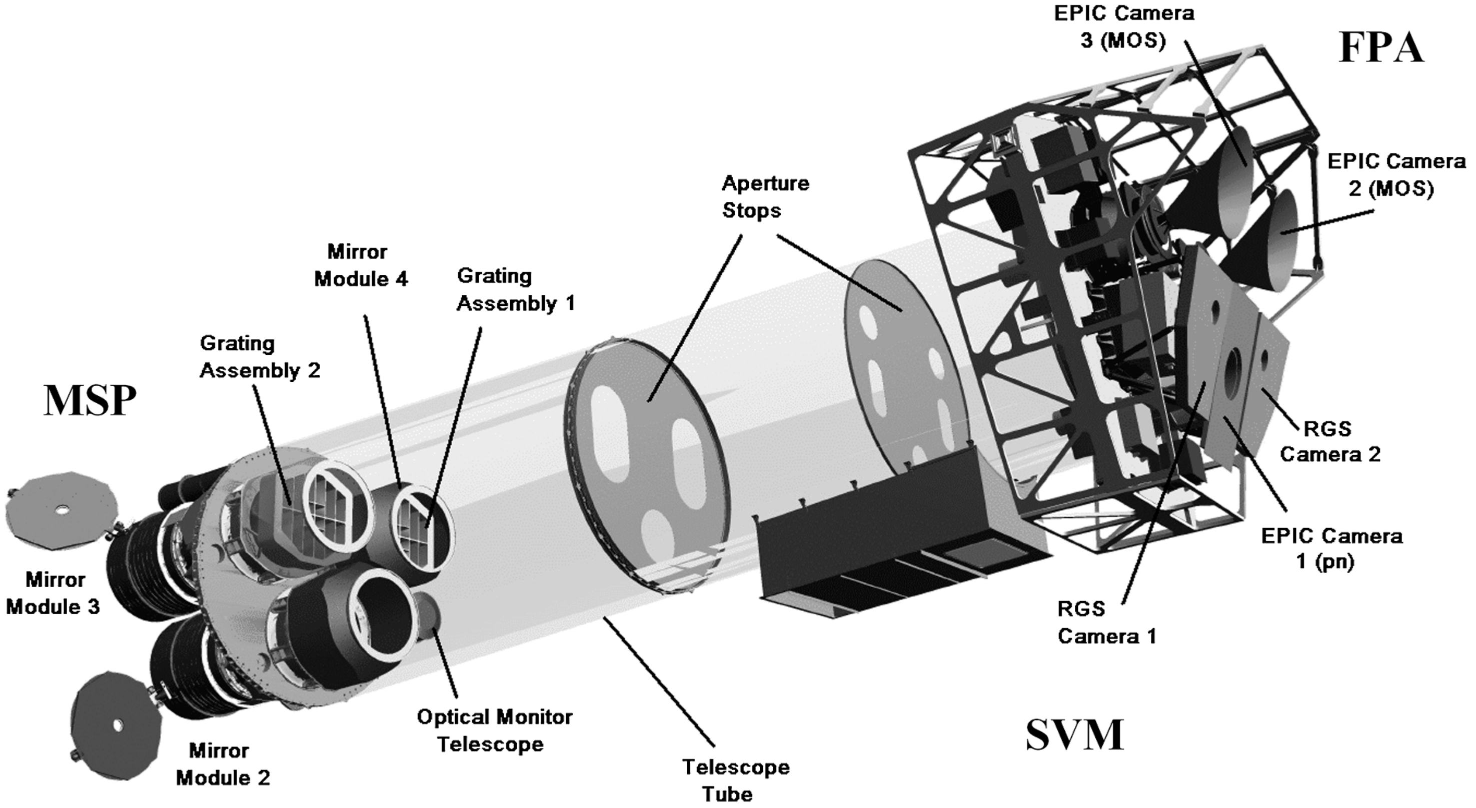


The XMM-Newton X-ray Observatory

- XMM launched in 1999
- at an elliptical orbit with apogee at r ~ 113,000 km and perigee at r ~ 5,600 km
- Three telescopes on board
- each made of 58 mirror shells
- shell thickness 0.5 and 1mm
- effective ara @ 1keV 1475 cm^2
- spatial resolution ~6–15 arcsec
- focal length 7.5 m
- max diameter 70 cm

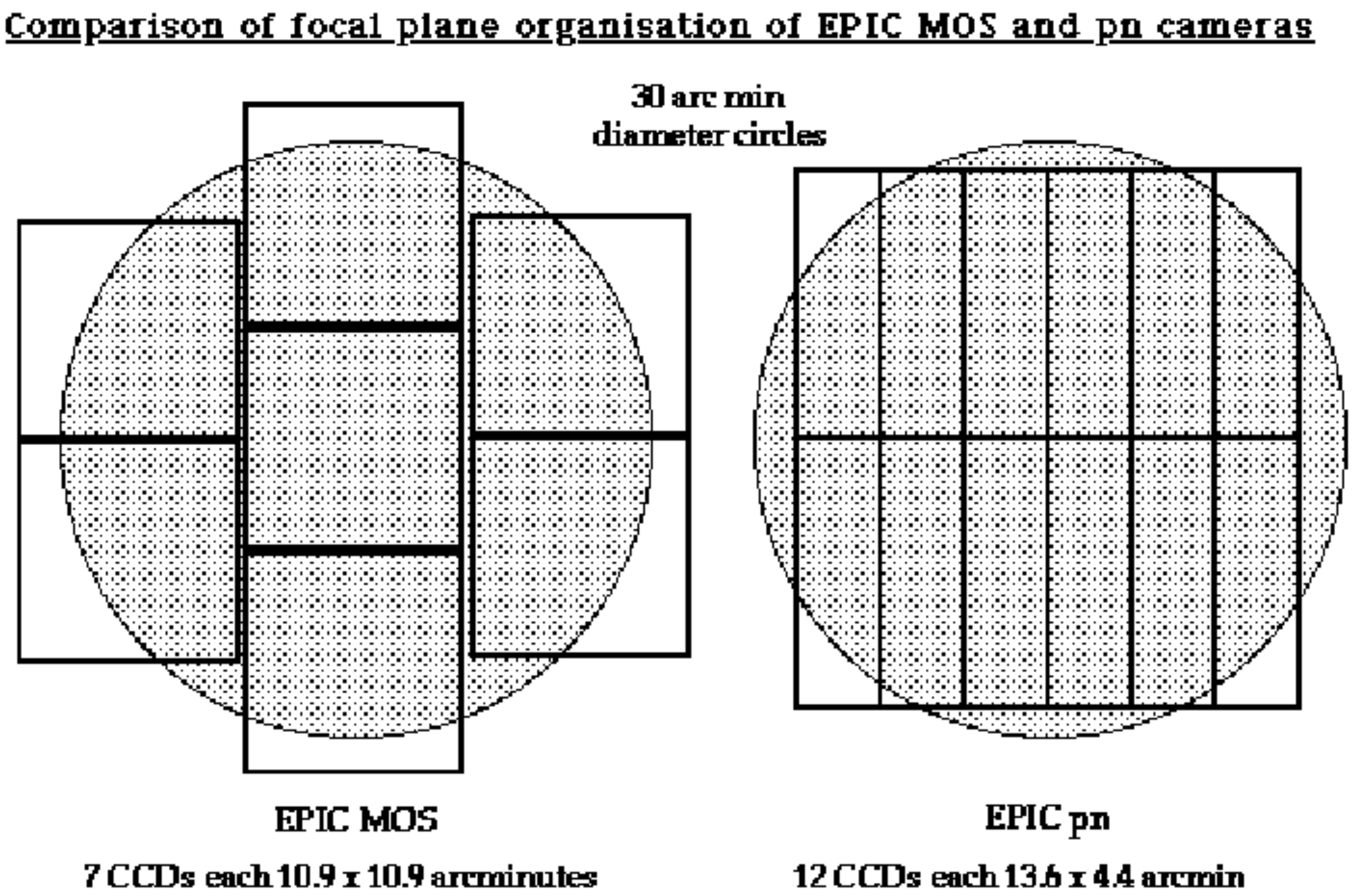
The XMM-Newton X-ray Observatory

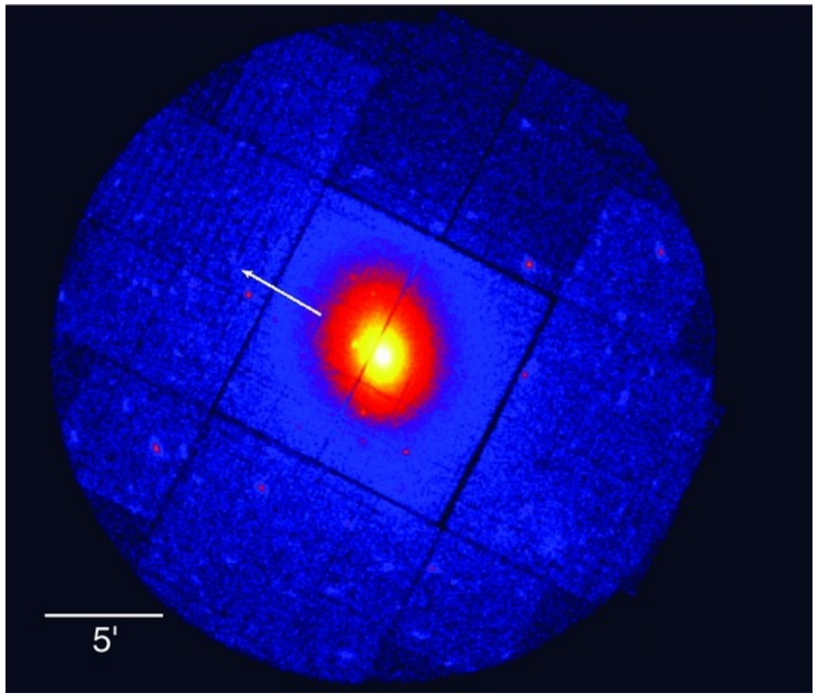




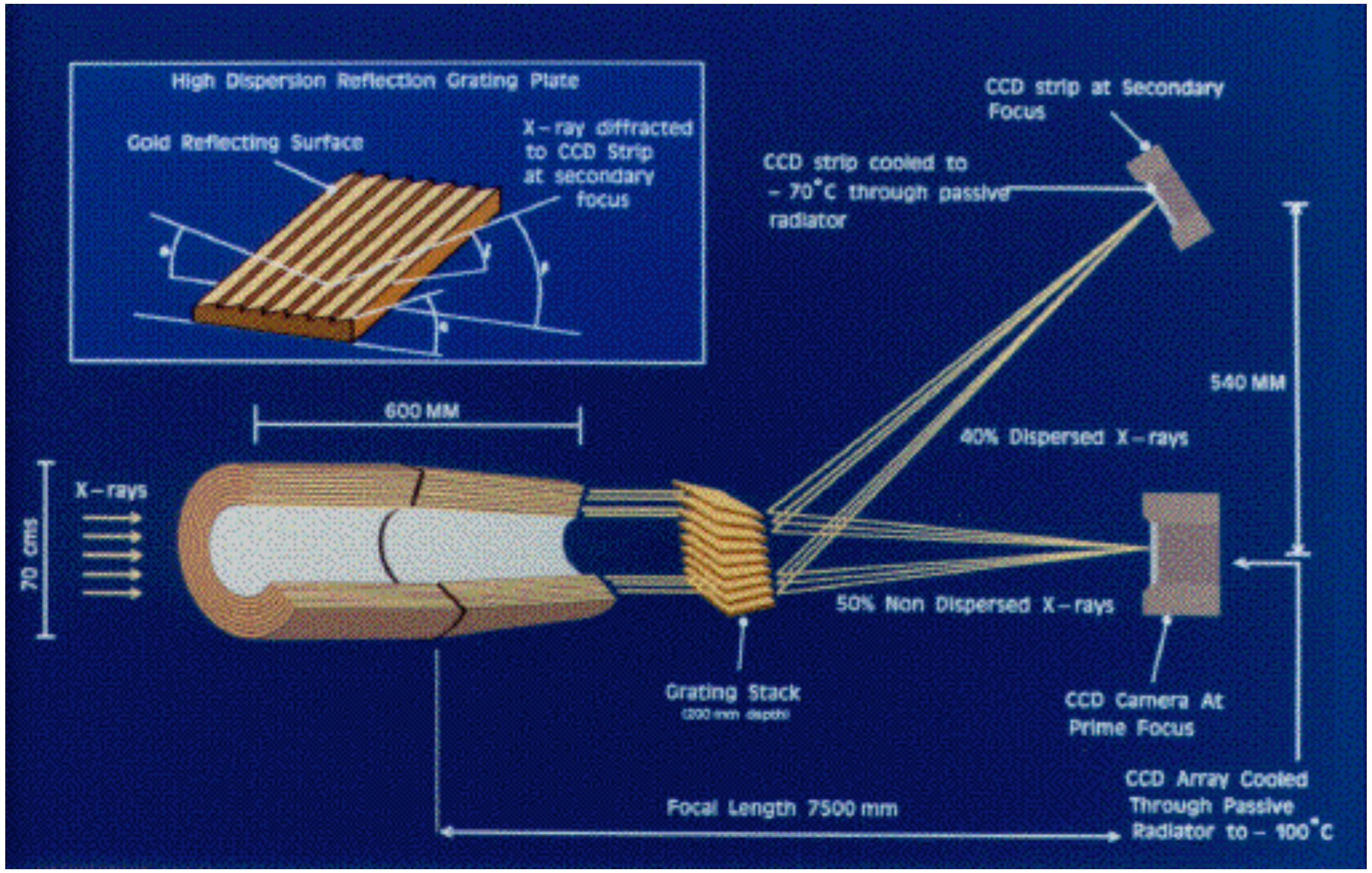
- three imaging CCD detectors (MOS1, MOS2, pn)
- two grating spectrometers (RGS1, RGS2) with corresponding CCDs

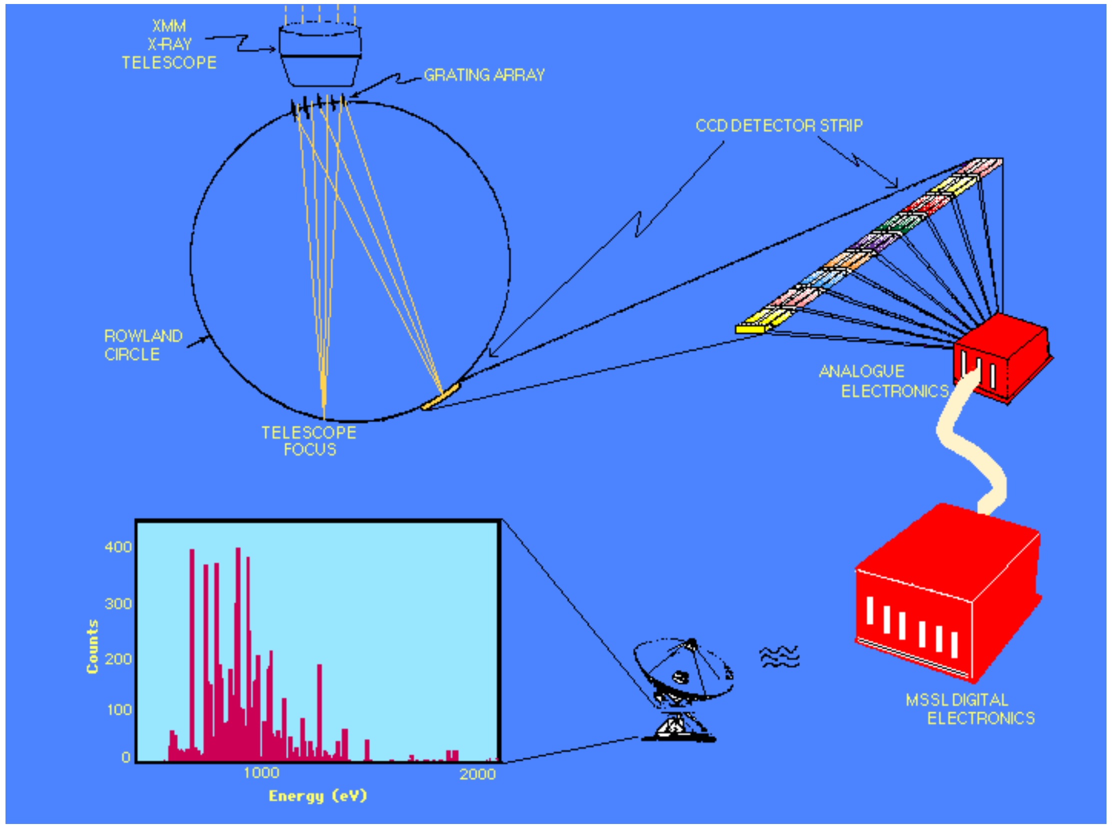
European Photon Imaging Camera (EPIC)

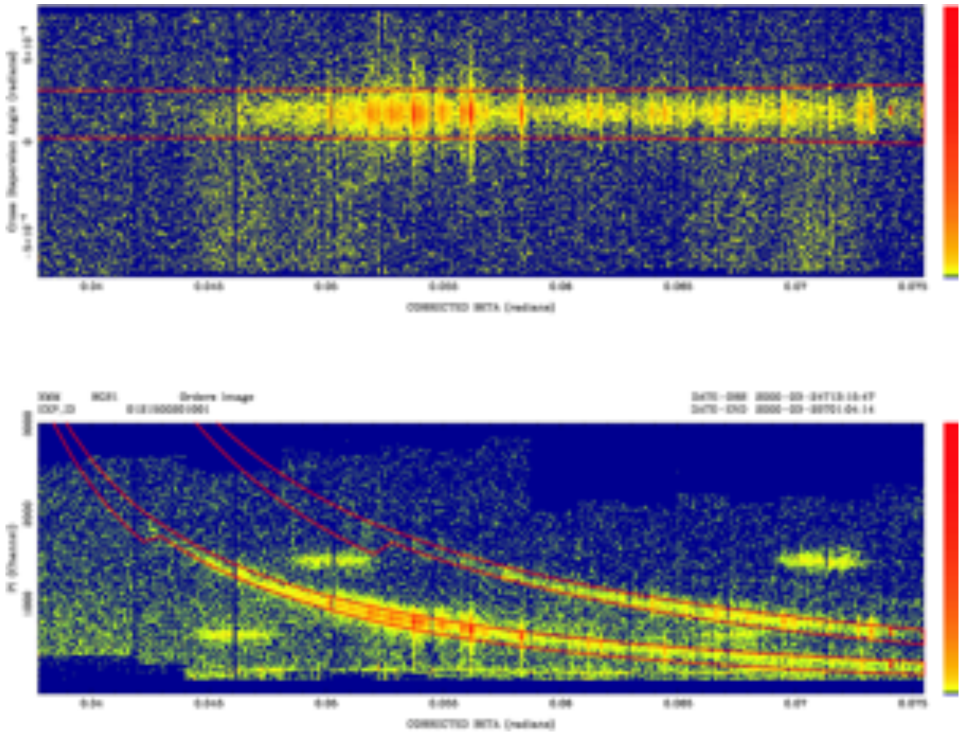


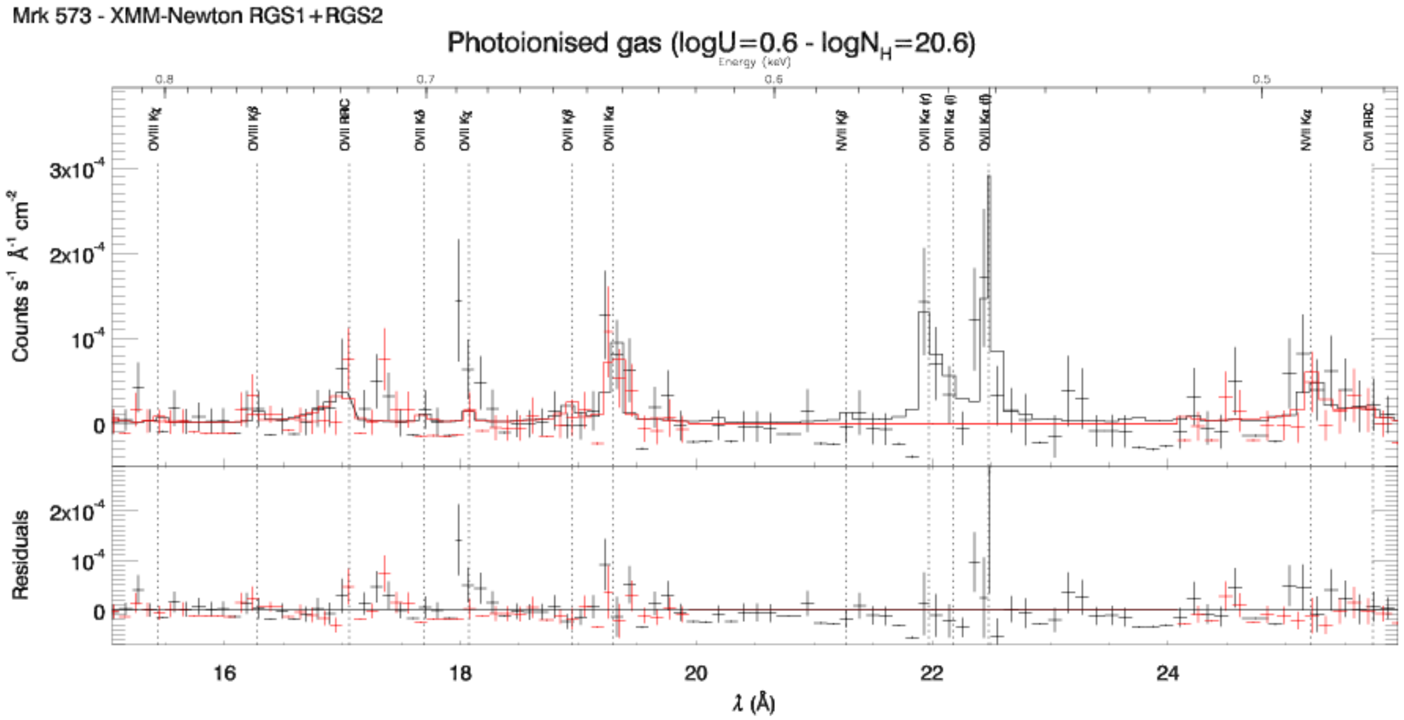


- Two arrays of 7 Metal-Oxide-Silicon CCDs (0.1—10 keV band)
- One array of 12 back illuminated pn CCDs (0.1—15 keV band)
- E/DE =20—50
- Diameter of the field of view 30 arcmin

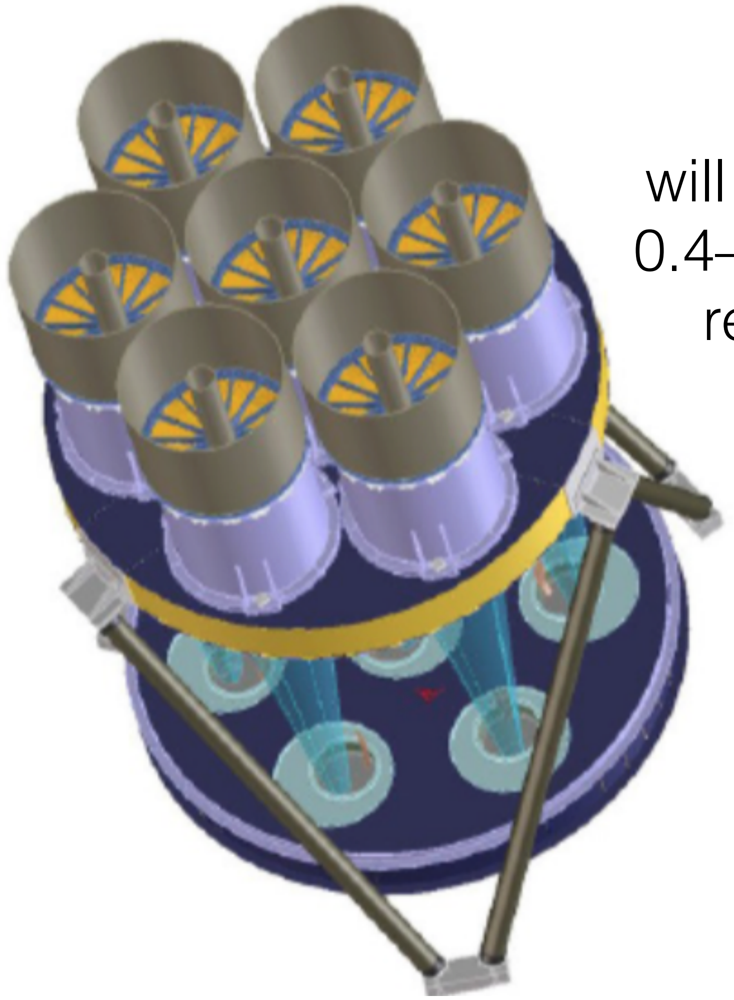

High Dispersion Reflection Grating Plate
Gold Reflecting Surface
X-ray diffracted to CCD Strip at secondary focus
CCD strip at Secondary Focus
CCD strip cooled to - 70°C through passive radiator
600 MM
540 MM
70 cms
X-rays
40% Dispersed X-rays
50% Non Dispersed X-rays
Grating Stack
(200 mm depth)
CCD Camera At Prime Focus
CCD Array Cooled Through Passive Radiator to - 100°C
Focal Length 7500 mm


XMM X-RAY TELESCOPE
GRATING ARRAY
CCD DETECTOR STRIP
ROWLAND CIRCLE
TELESCOPE FOCUS
ANALOGUE ELECTRONICS
MSSL DIGITAL ELECTRONICS
Counts
400
300
200
100
0
1000
2000
Energy (eV)



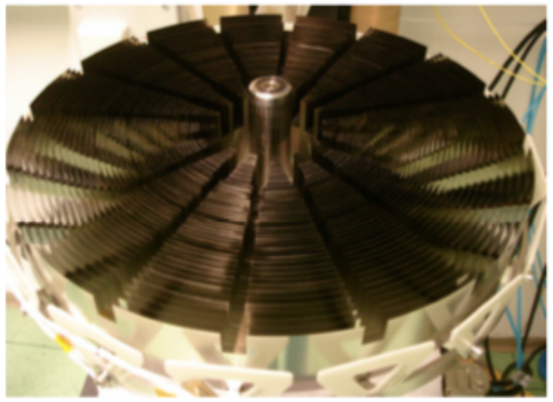

Mrk 573 - XMM-Newton RGS1+RGS2
Photoionised gas (logU=0.6 - logN_H=20.6)
Energy (keV)
0.8
0.7
0.6
0.5
OVIII Kγ
OVIII Kβ
OVII RRC
OVII Kδ
OVII Kγ
OVII Kβ
OVIII Kα
NVII Kβ
OVII Kα (r)
OVII Kα (i)
OVII Kα (f)
NVII Kα
CVI RRC
Counts s^-1 Å^-1 cm^-2
3x10^-4
2x10^-4
10^-4
0
Residuals
2x10^-4
10^-4
0
16
18
20
22
24
λ (Å)

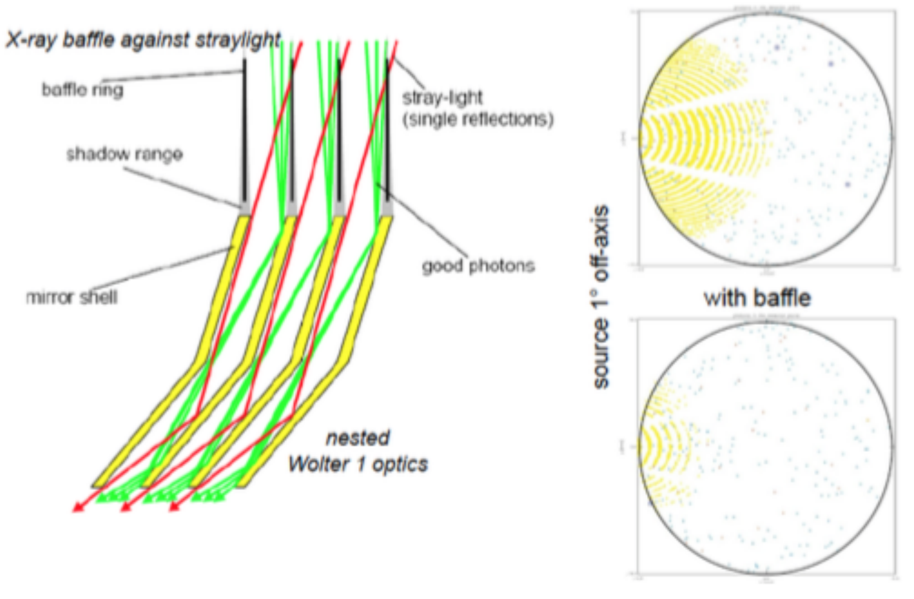
eRosita on Spectrum-Roentgen-Gamma



7 telescopes each made of
54 nested mirror shells

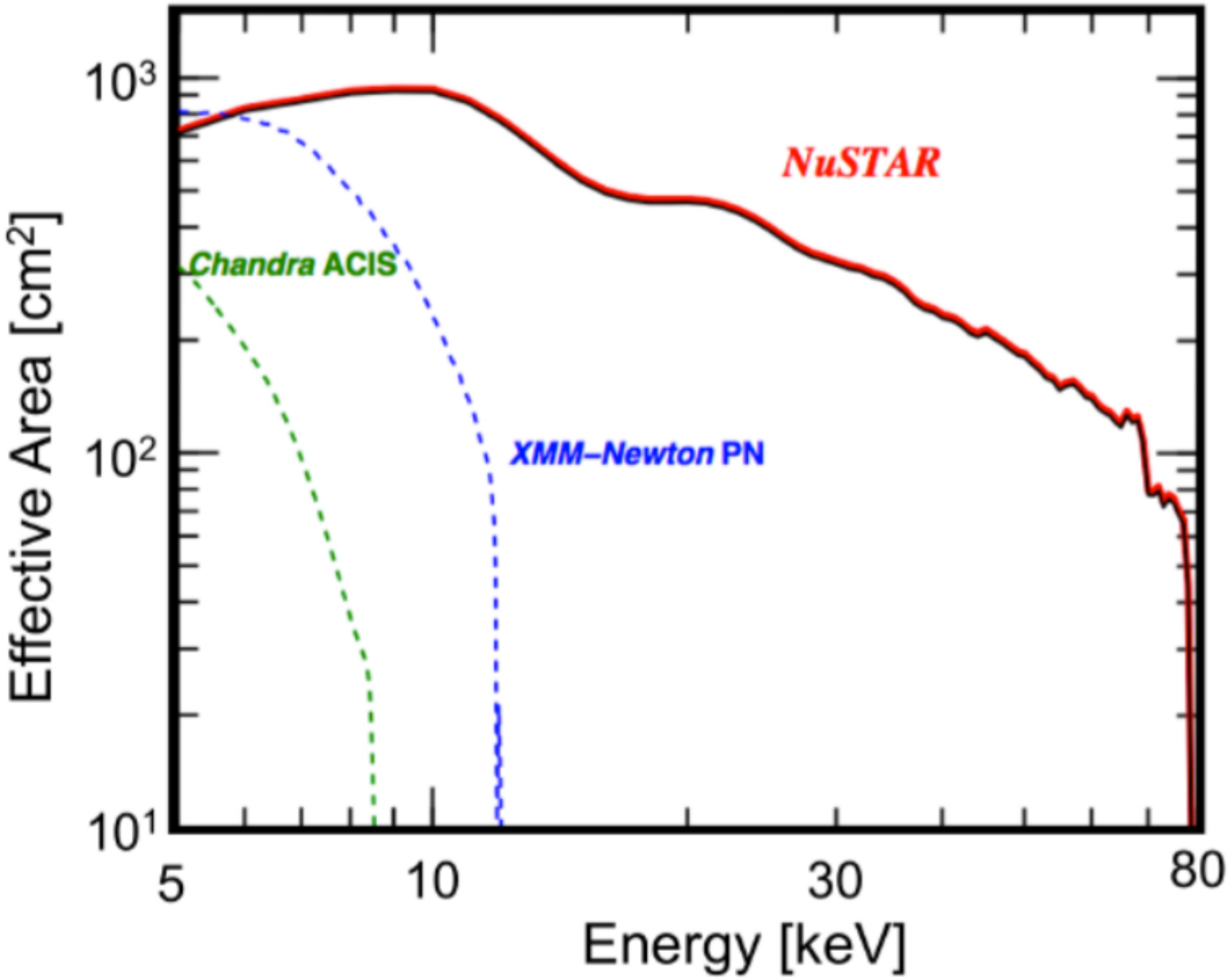
will survey the whole sky in the
0.4—10 keV band at the spatial
resolution of XMM-Newton





- detect the hot intergalactic medium of 50-100 thousand galaxy clusters
- detect up to 3 Million new, distant active galactic nuclei
- study the physics of galactic X-ray emitting pre-main sequence stars, supernova remnants and X-ray binaries.

Nustar - the first hard X-ray telescope



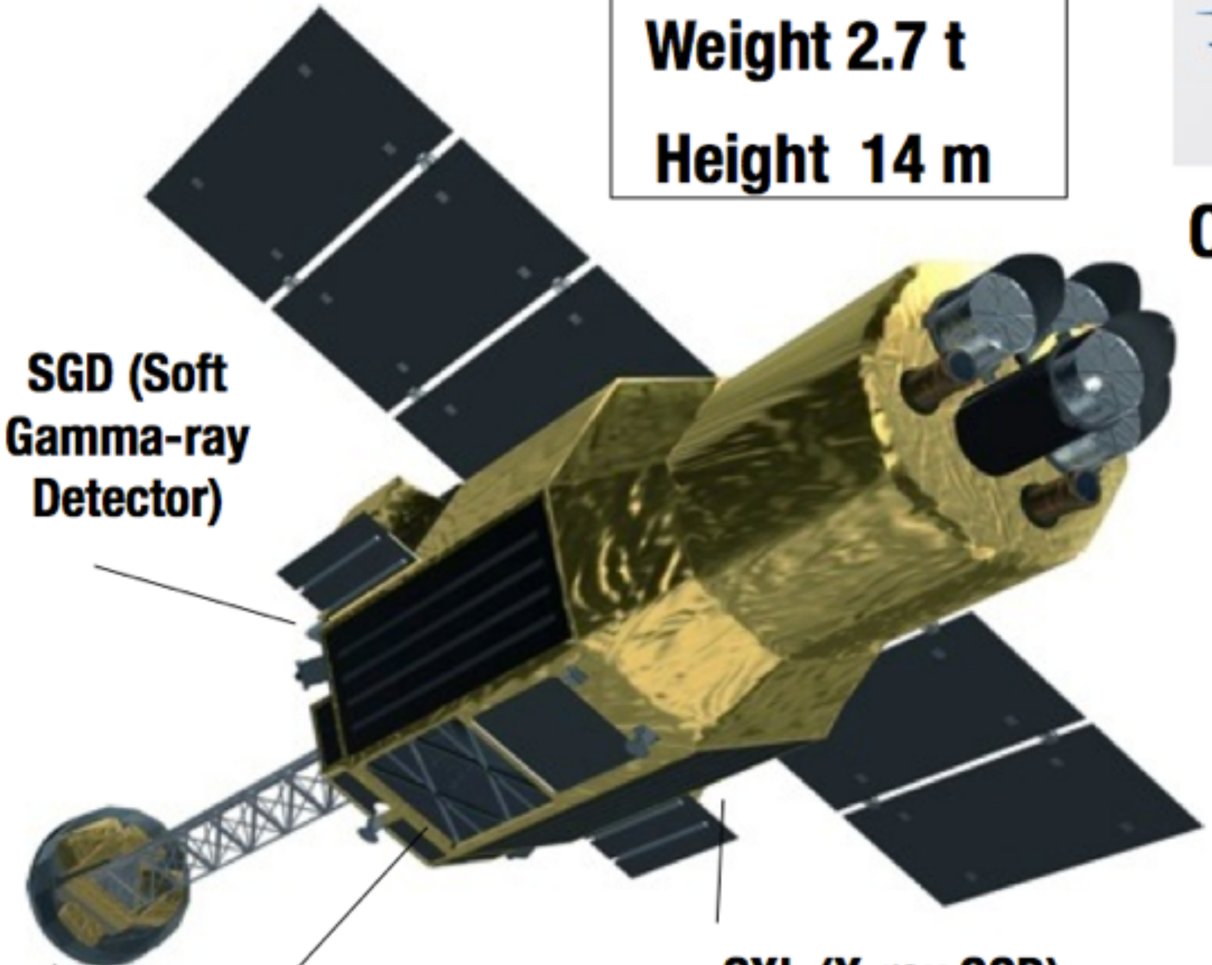
- Optics with 130 Nested multilayer shells: W/SiC and Pt/SiC
- Up to 80 keV
- 10 meter focal length
- 40 arcsec spatial resolution

The Astro-H X-ray Observatory

ASTRO-H is an international X-ray observatory, which is the 6th in the series of the X-ray observatories from Japan. More than 160 scientists from Japan/US/Europe/ Canada.

Launch 2015
Weight 2.7 t
Height 14 m

Orbit Altitude: 550km, Inclination: ~31 degrees



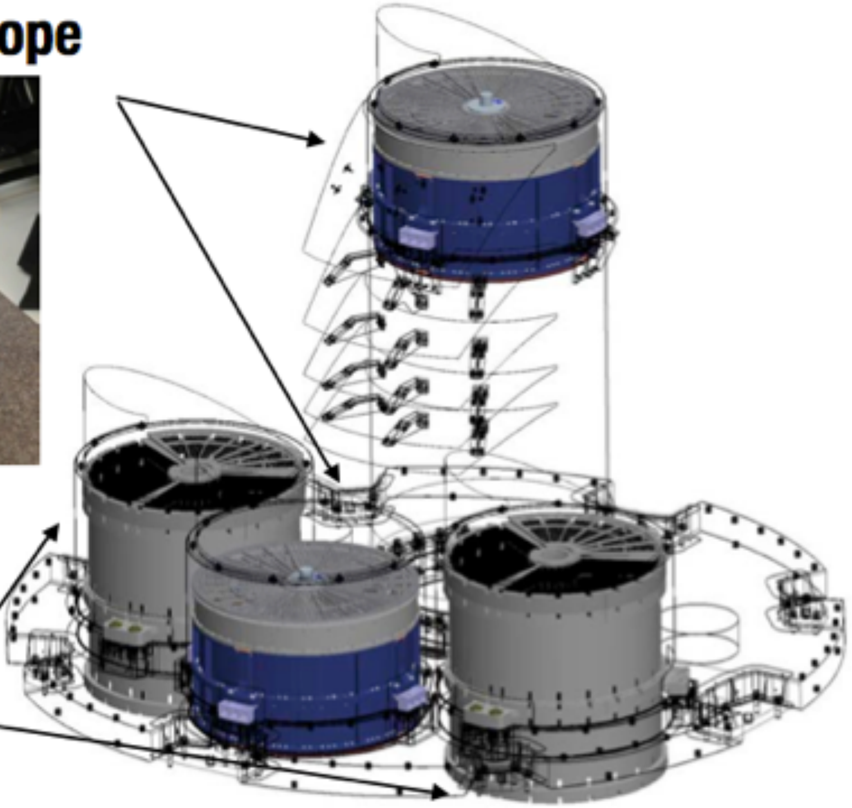
SGD (Soft Gamma-ray Detector)

SXI (X-ray CCD)

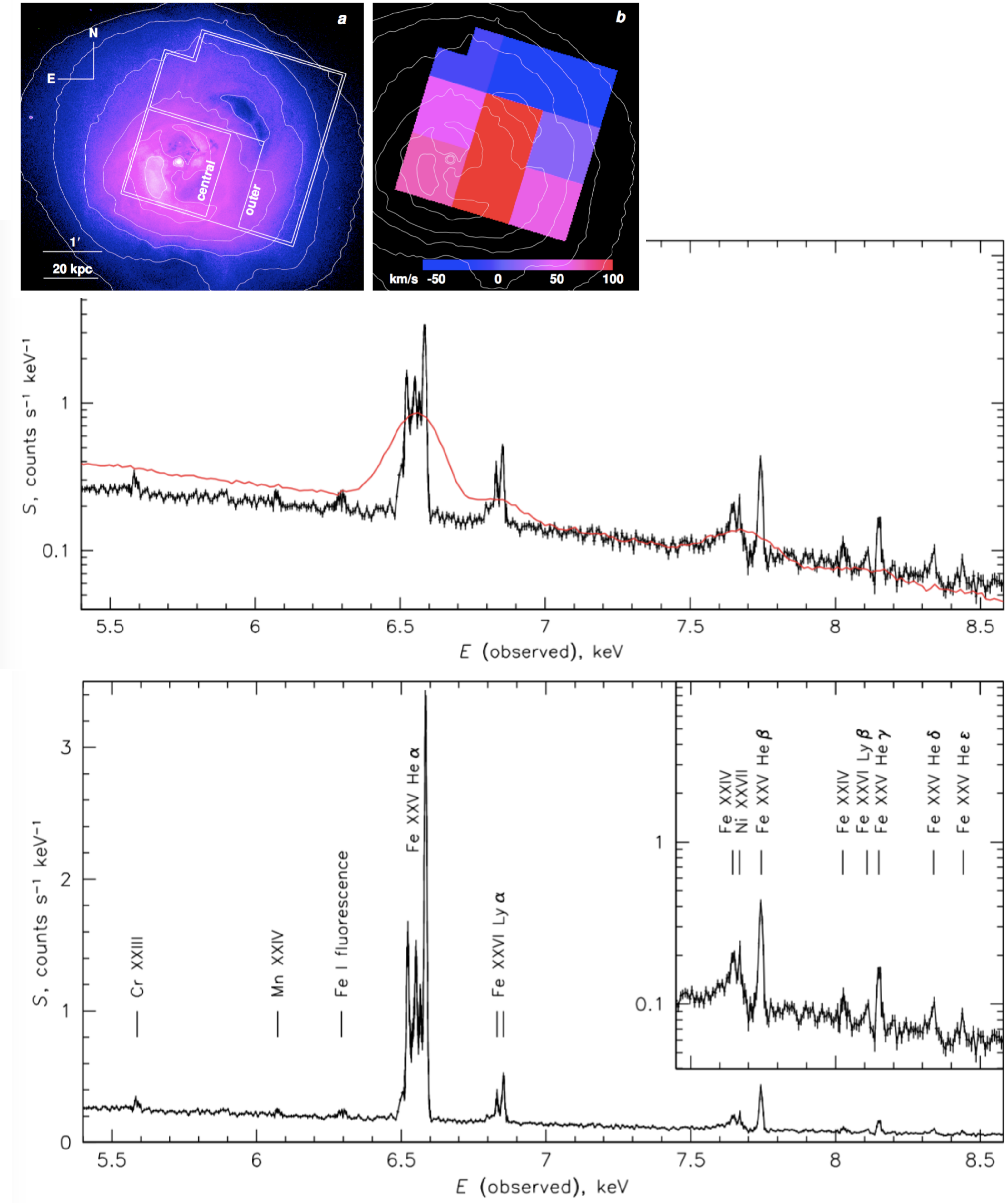
SXS (Micro Calorimeter)

HXI (Hard X-ray Imager)

Soft X-ray Telescope

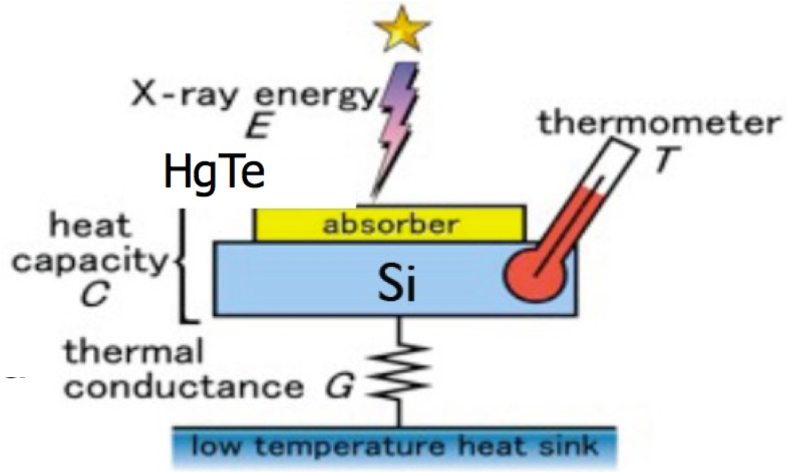


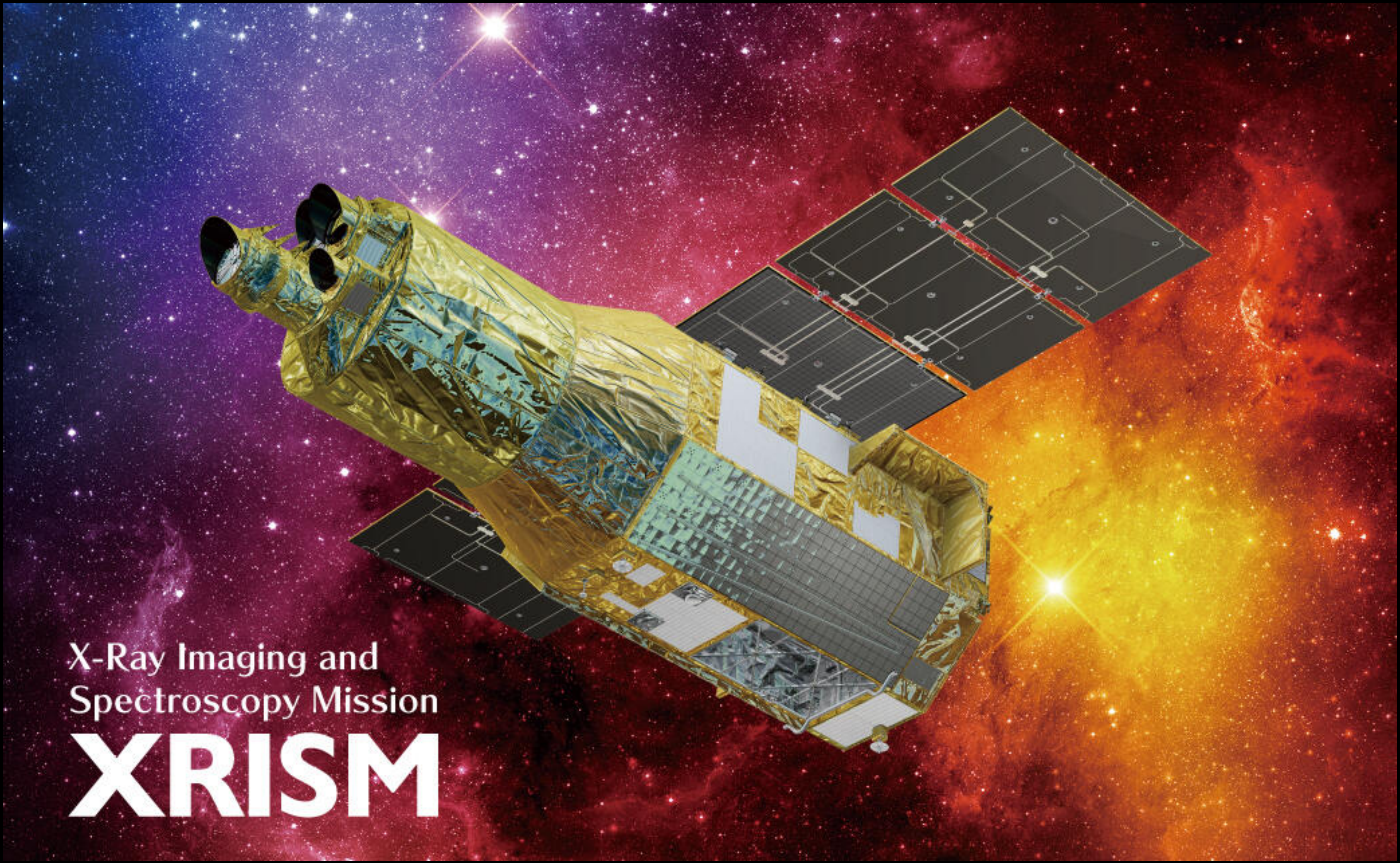
Hard X-ray Telescope



- SXS is an X-ray microcalorimeter array of 6x6 pixels at the focus of the Soft X-ray Telescope, which is capable of high-resolution spectroscopy and limited imaging of 3'x3' field of view in the soft X-ray (0.3-12 keV) band

- The microcalorimeter detector measures the temperature rise upon each incident X-ray photon, achieving an ~5eV energy resolution.

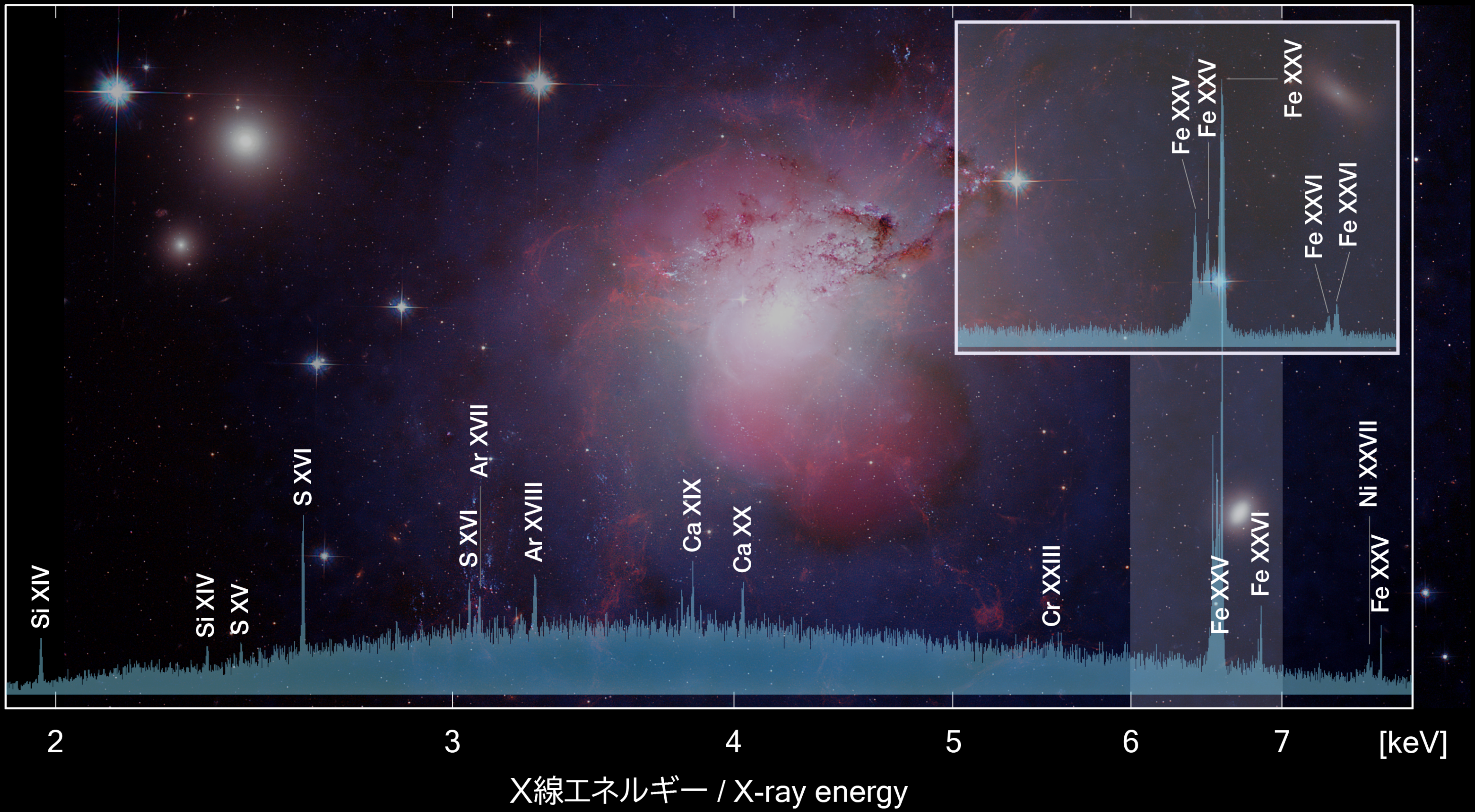




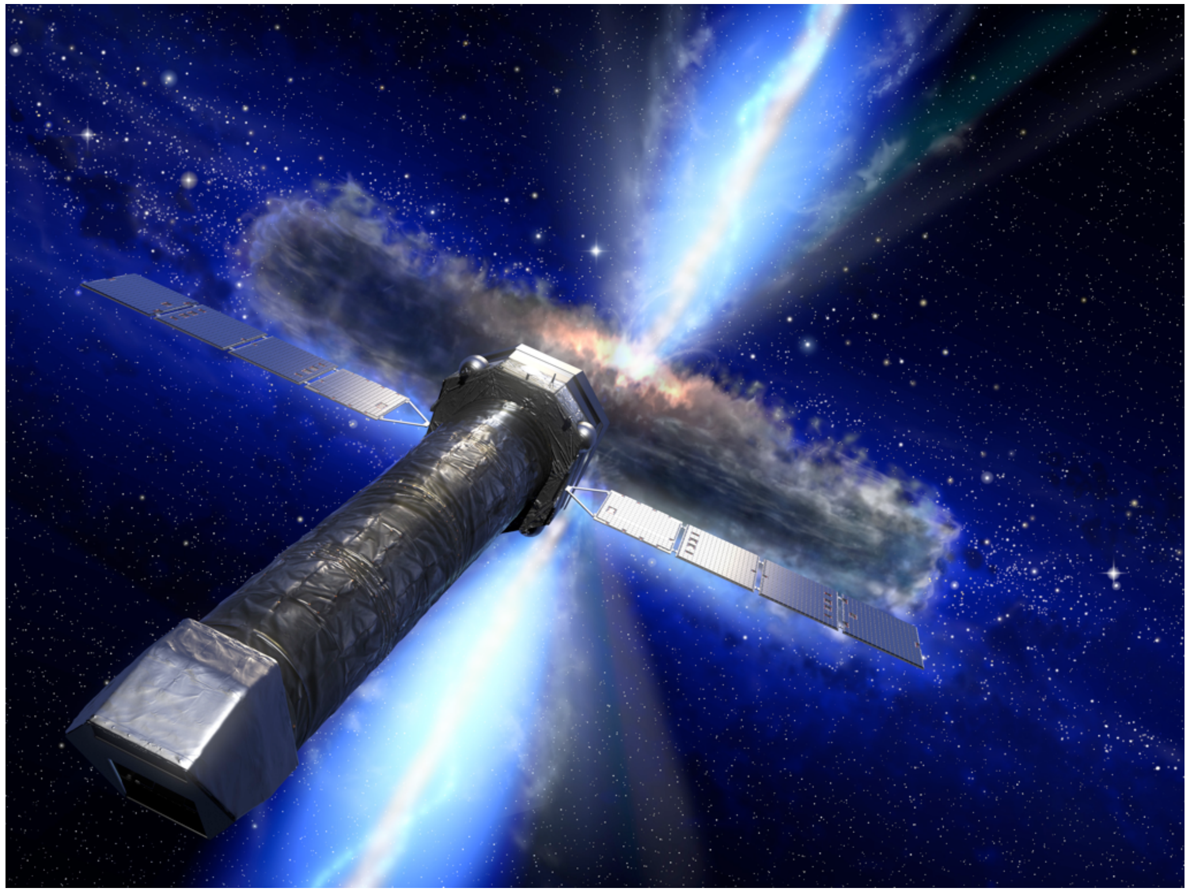
X-Ray Imaging and
Spectroscopy Mission

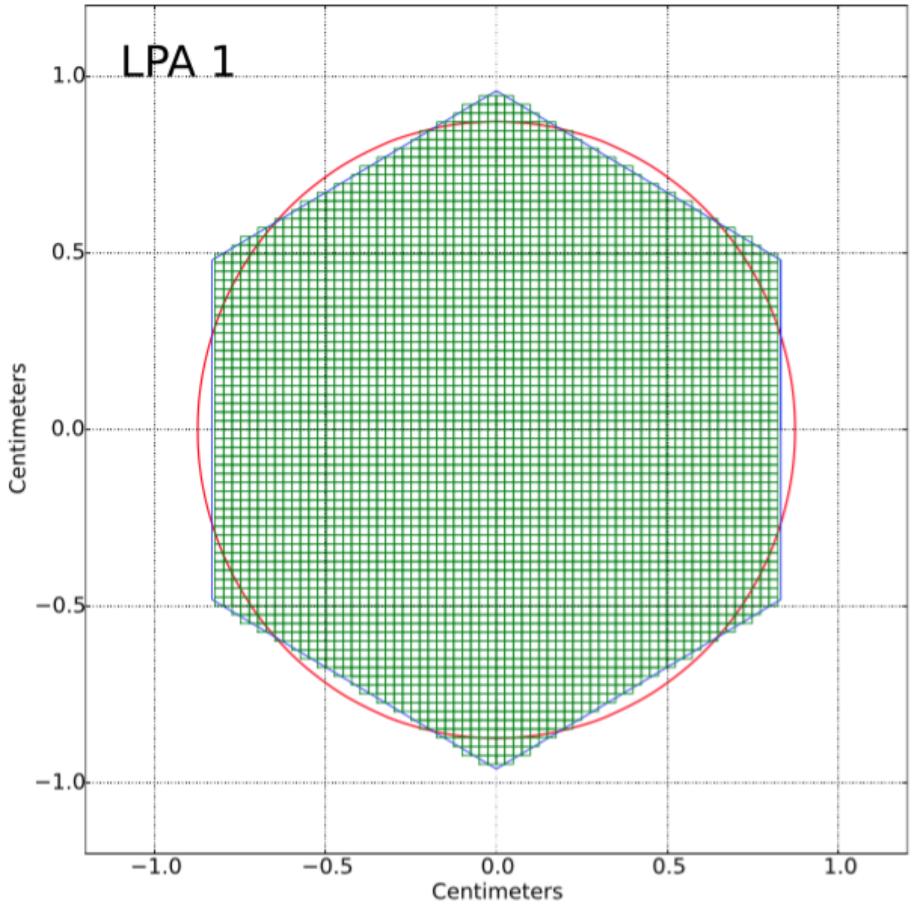
XRISM

X-ray Spectrum of Perseus Galaxy Cluster Measured by XRISM Resolve

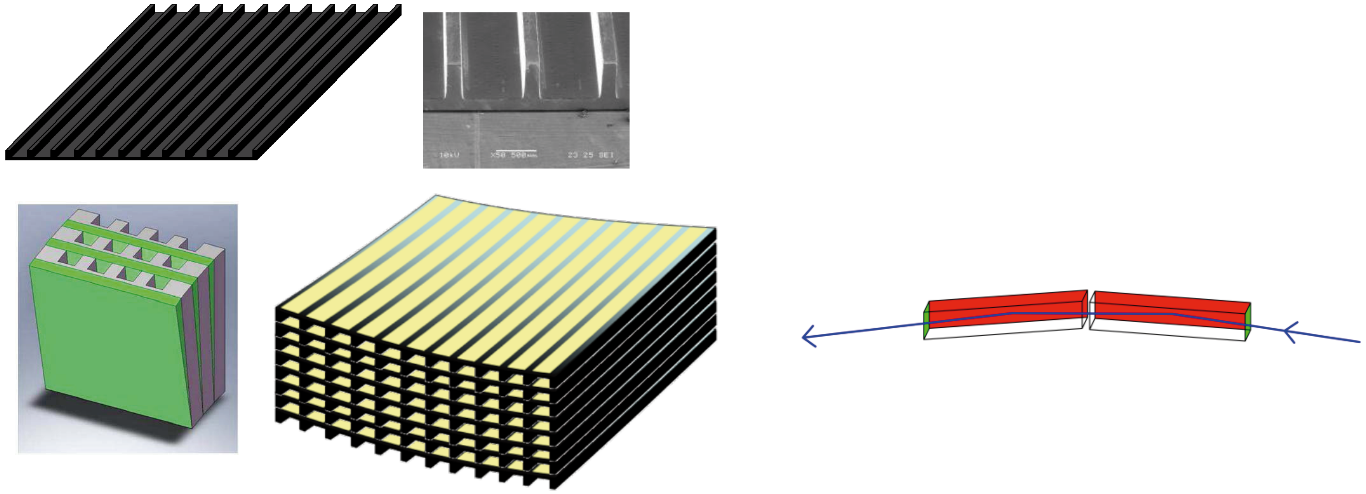


The *Athena* X-ray observatory



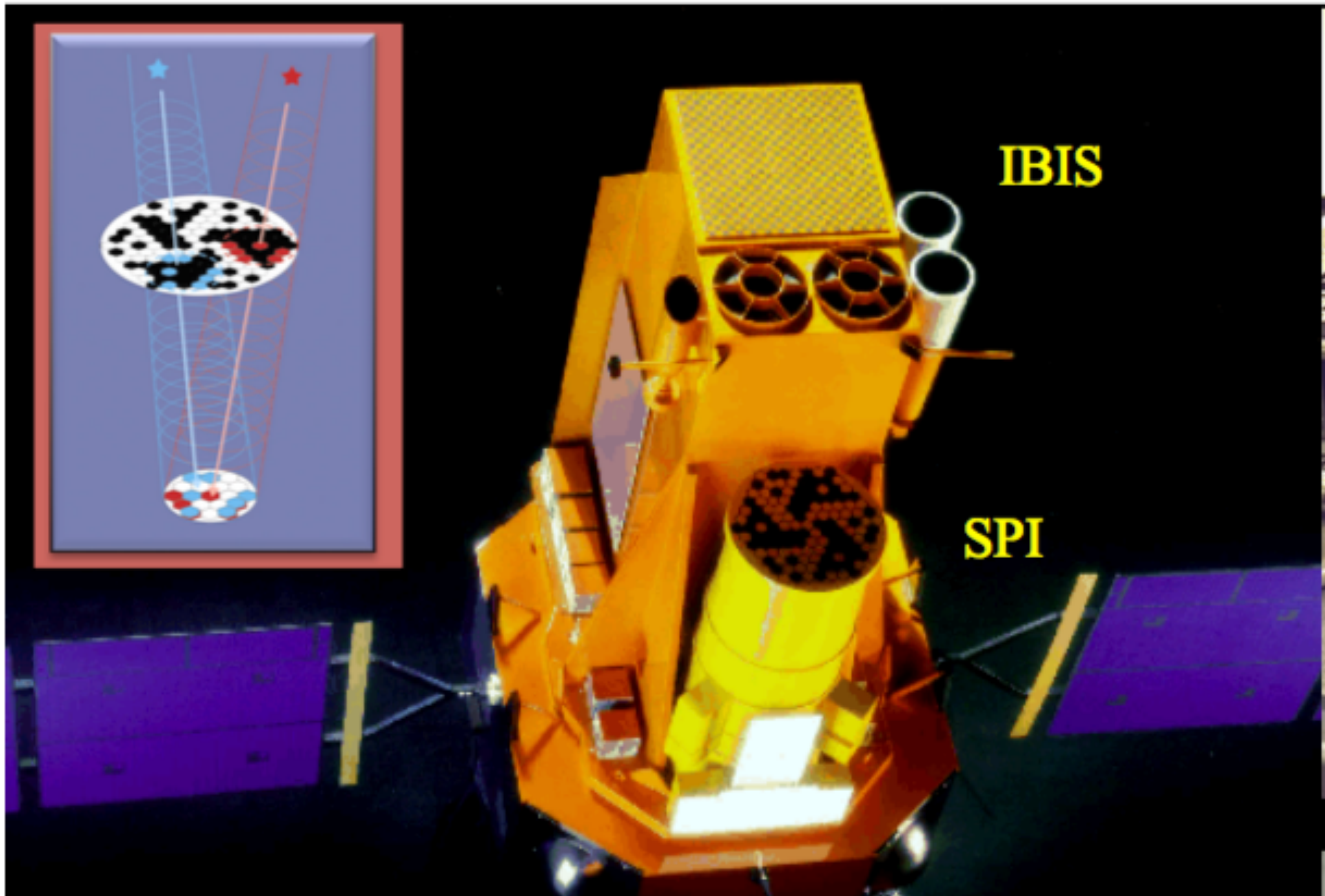


Silicon pore optics

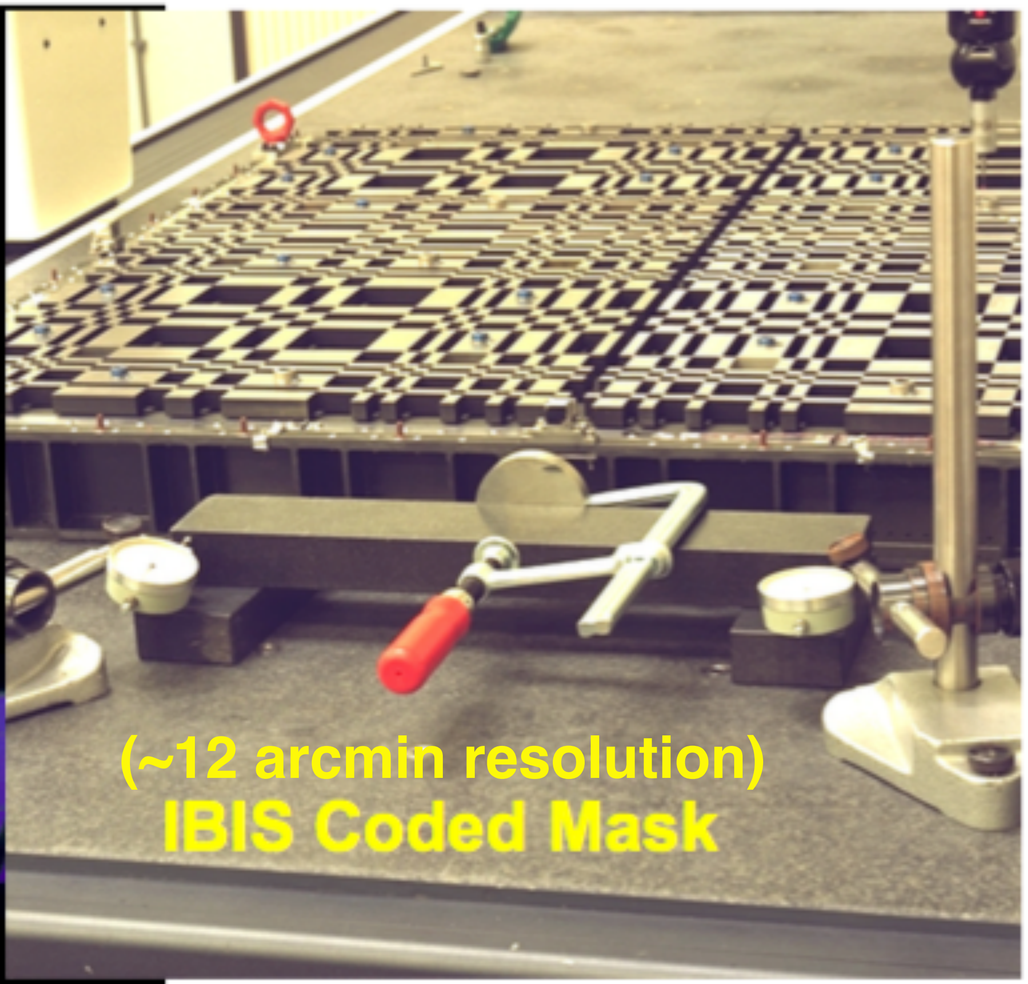


Energy range	0.2-12 keV
Energy resolution:	~2 eV
Field of View	5’ (diameter) (3840 TES)
Effective area @ 0.3 keV	1500 cm2
Effective area @ 1.0 keV	15000 cm2
Effective area @ 7.0 keV	1600 cm2
Time resolution	10 μs

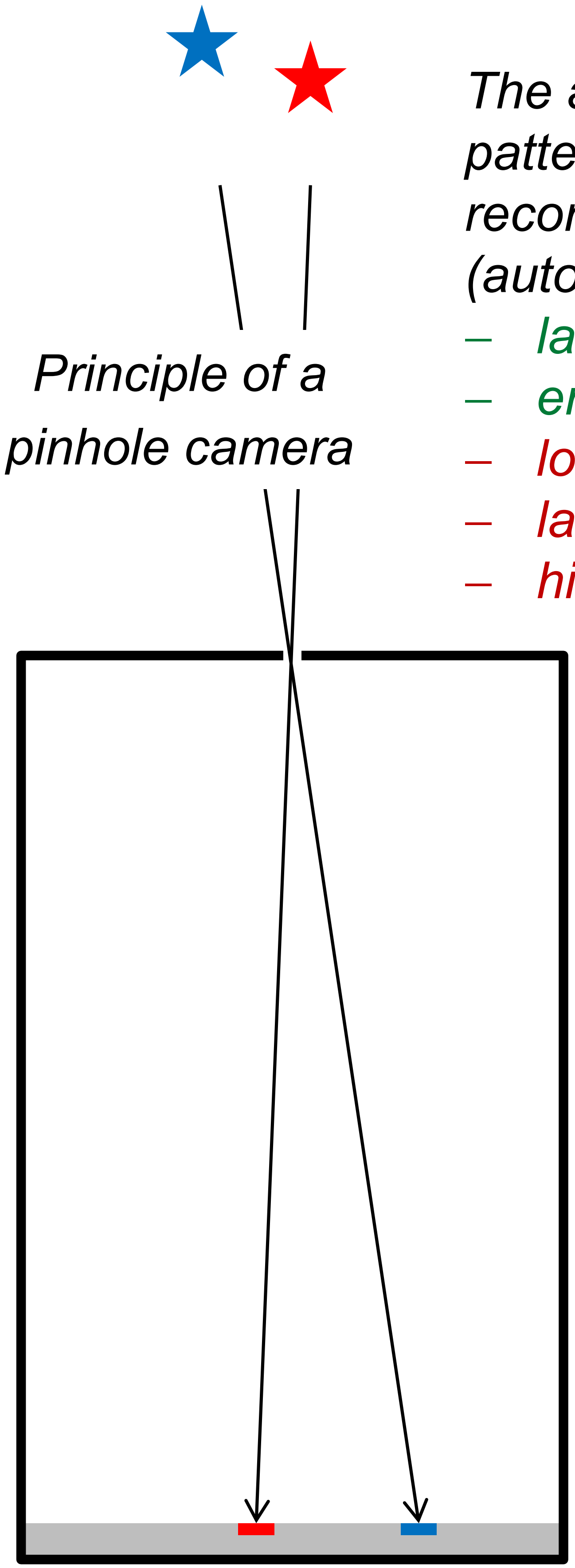
The Integral (soft) Gamma-Ray observatory



15 keV—10 MeV

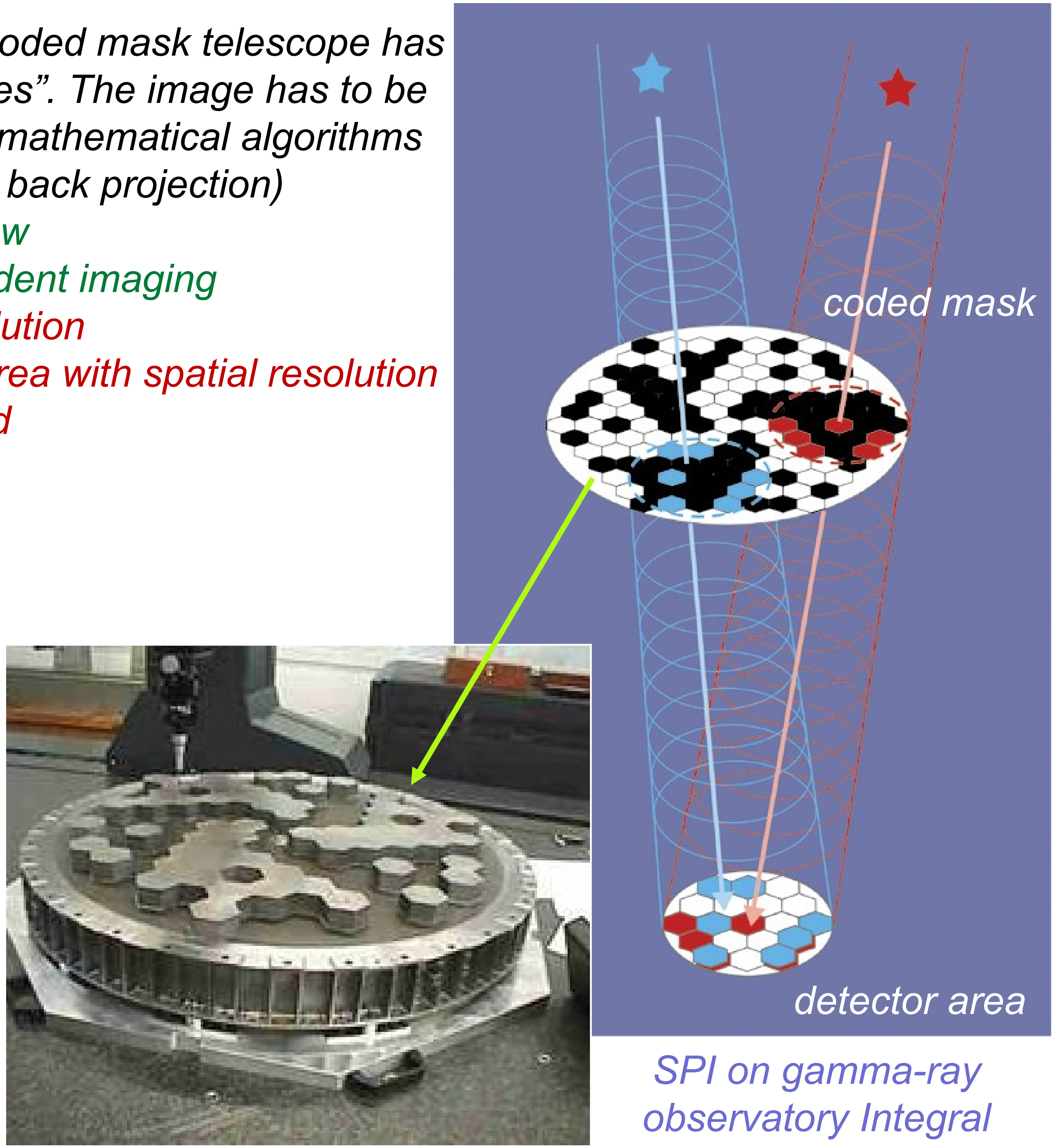


Coded Mask Telescopes



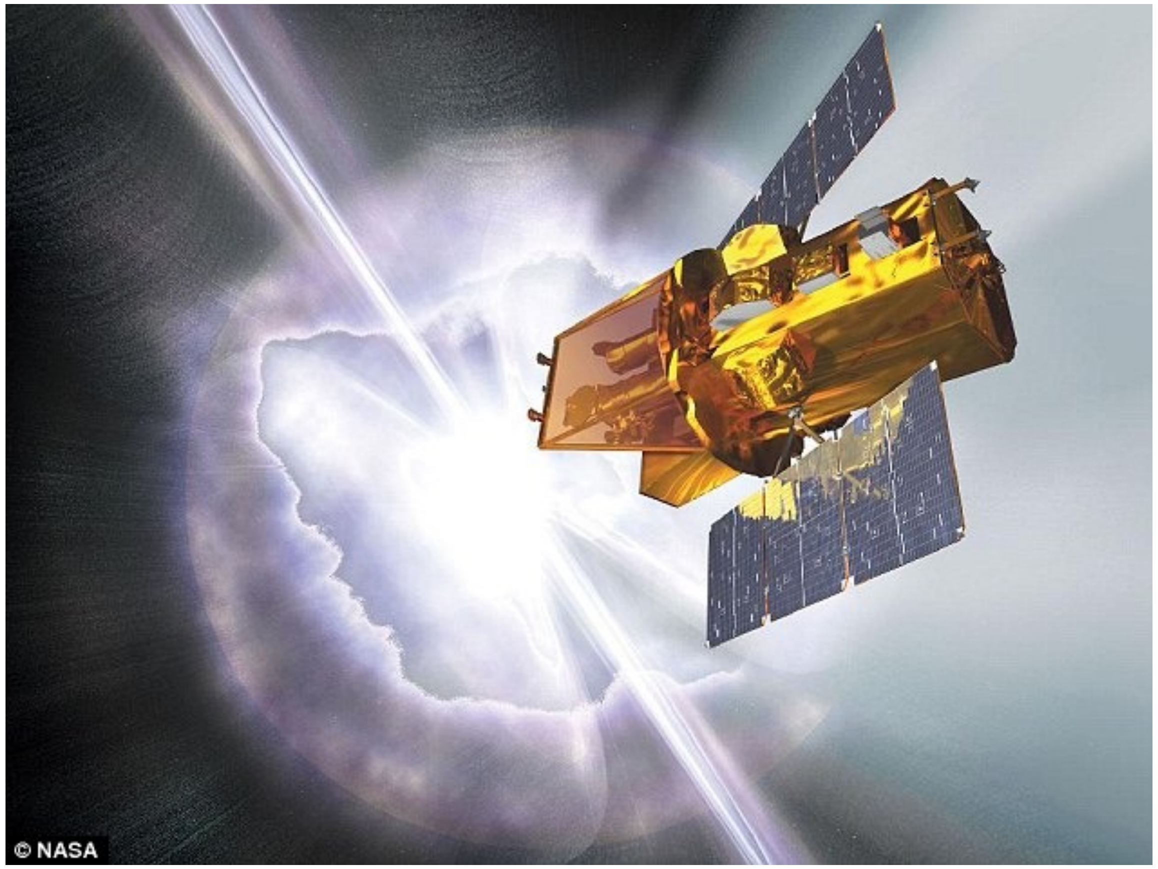
The aperture of a coded mask telescope has patterns of “pin holes”. The image has to be reconstructed with mathematical algorithms (auto correlation or back projection)

- *large field-of-view*
- *energy independent imaging*
- *low spatial resolution*
- *large detector area with spatial resolution*
- *high background*

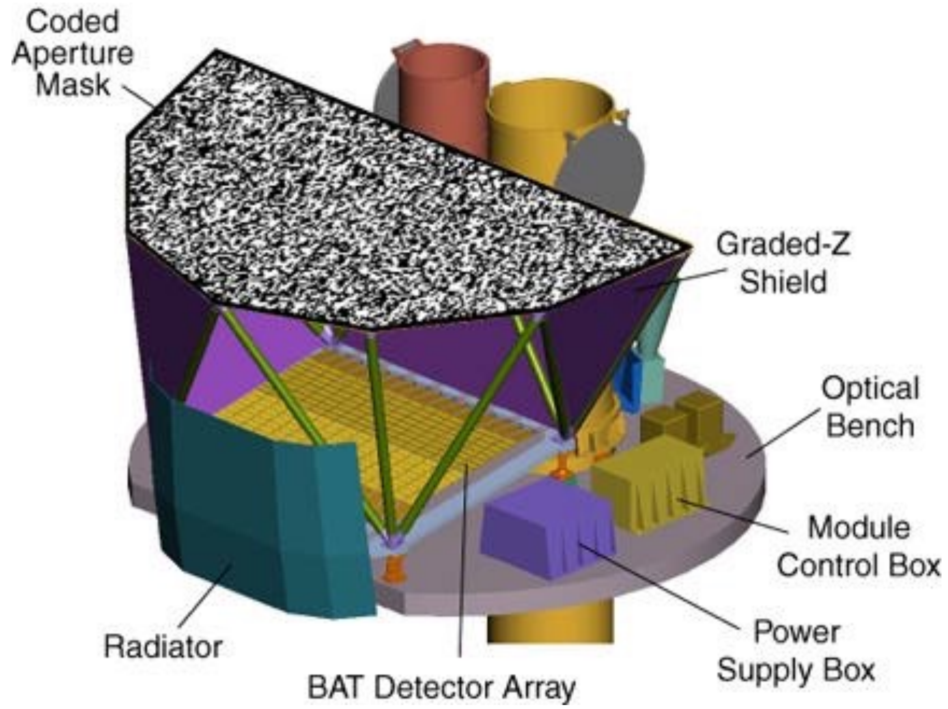


SPI on gamma-ray observatory Integral

Swift Gamma-Ray Burst Mission



© NASA

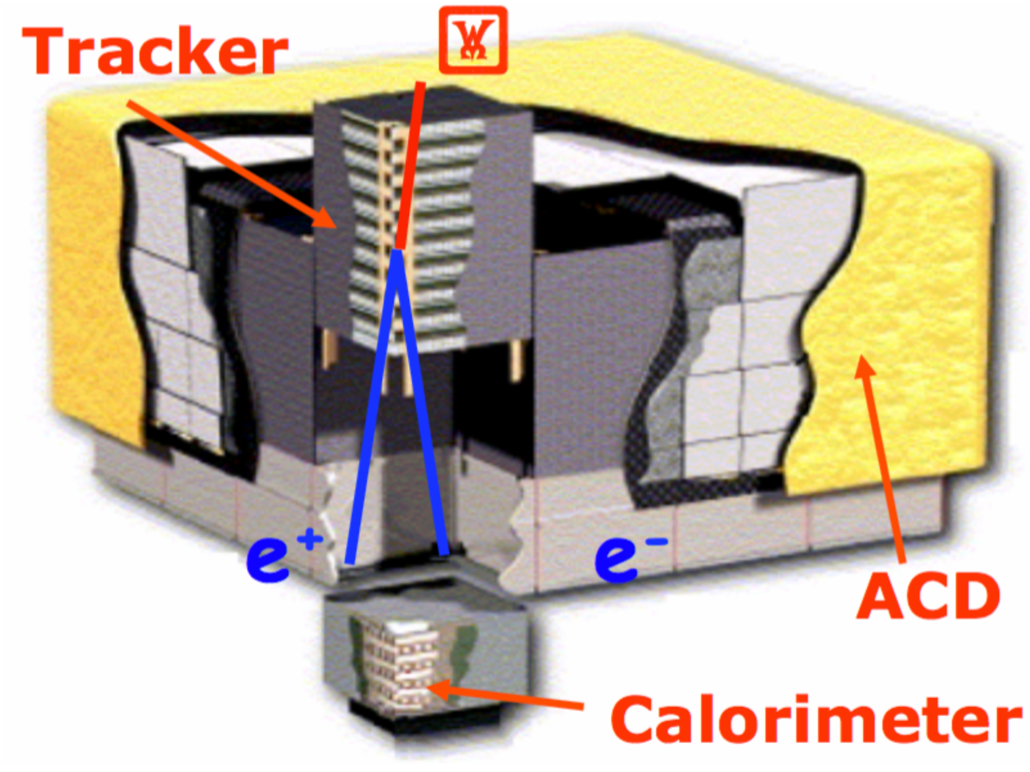


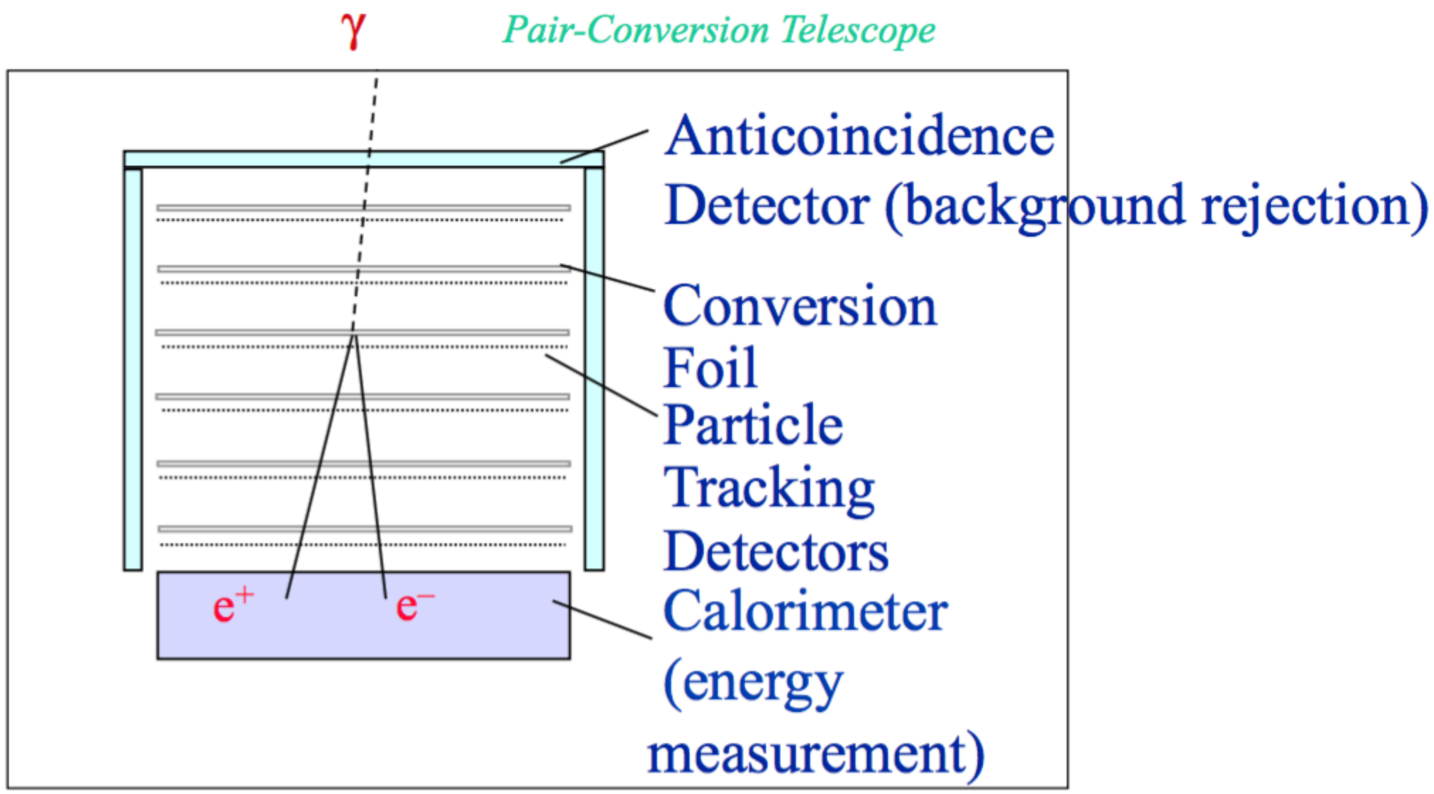
- **Burst Alert Telescope** (Energy range: 15–150 keV) coded-aperture mask of 52,000 randomly placed 5 mm lead tiles. Covers over one steradian fully coded, three steradians partially coded. Locates the position of each event with an accuracy of 1 to 4 arc-minutes within 15 seconds.

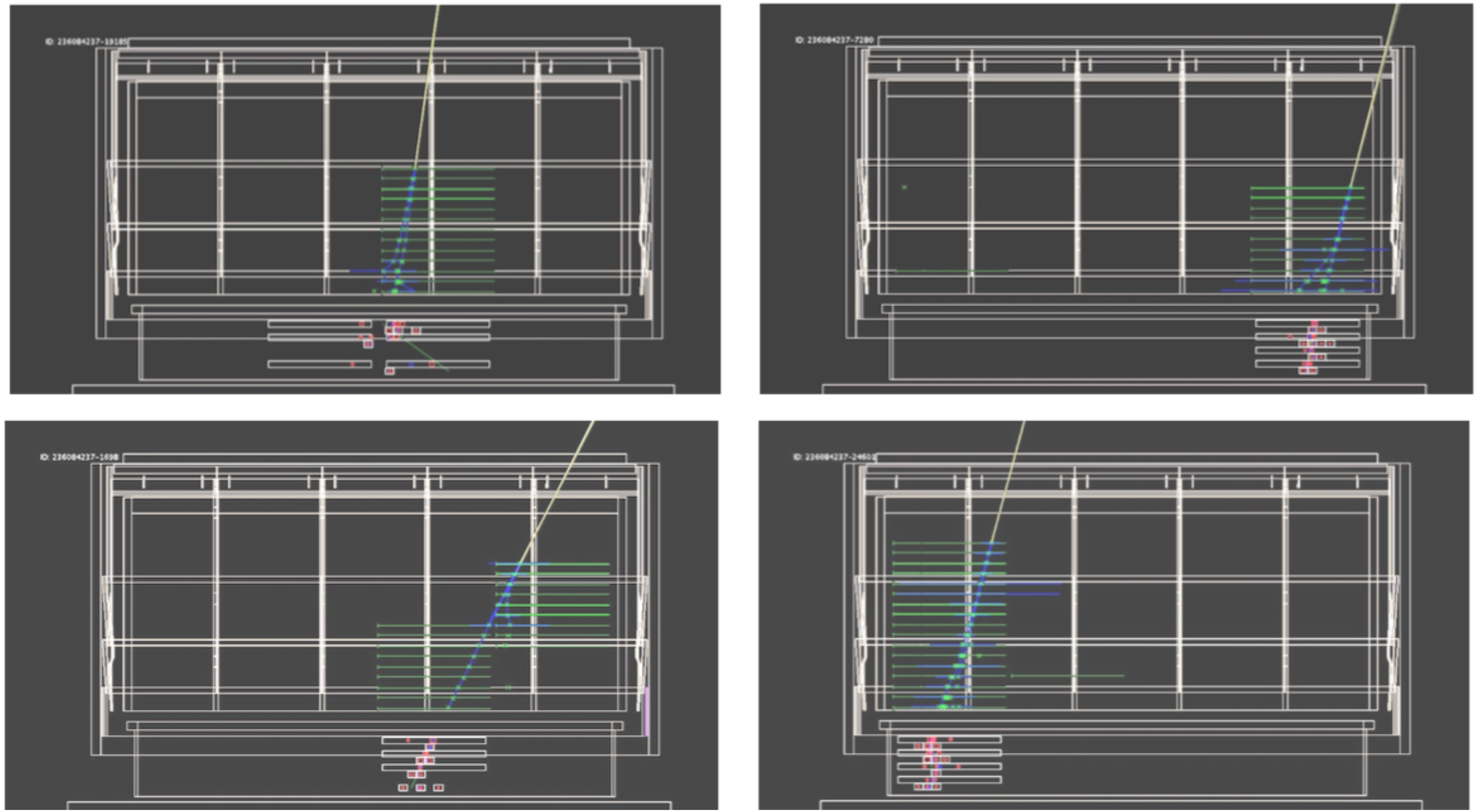
- **X-ray Telescope** MOS CCD behind 12 nested Wolter type I X-ray mirrors take images and spectra of the X-ray afterglow

- **Ultraviolet/Optical Telescope** Measures the light-curve of the optical/UV afterglow

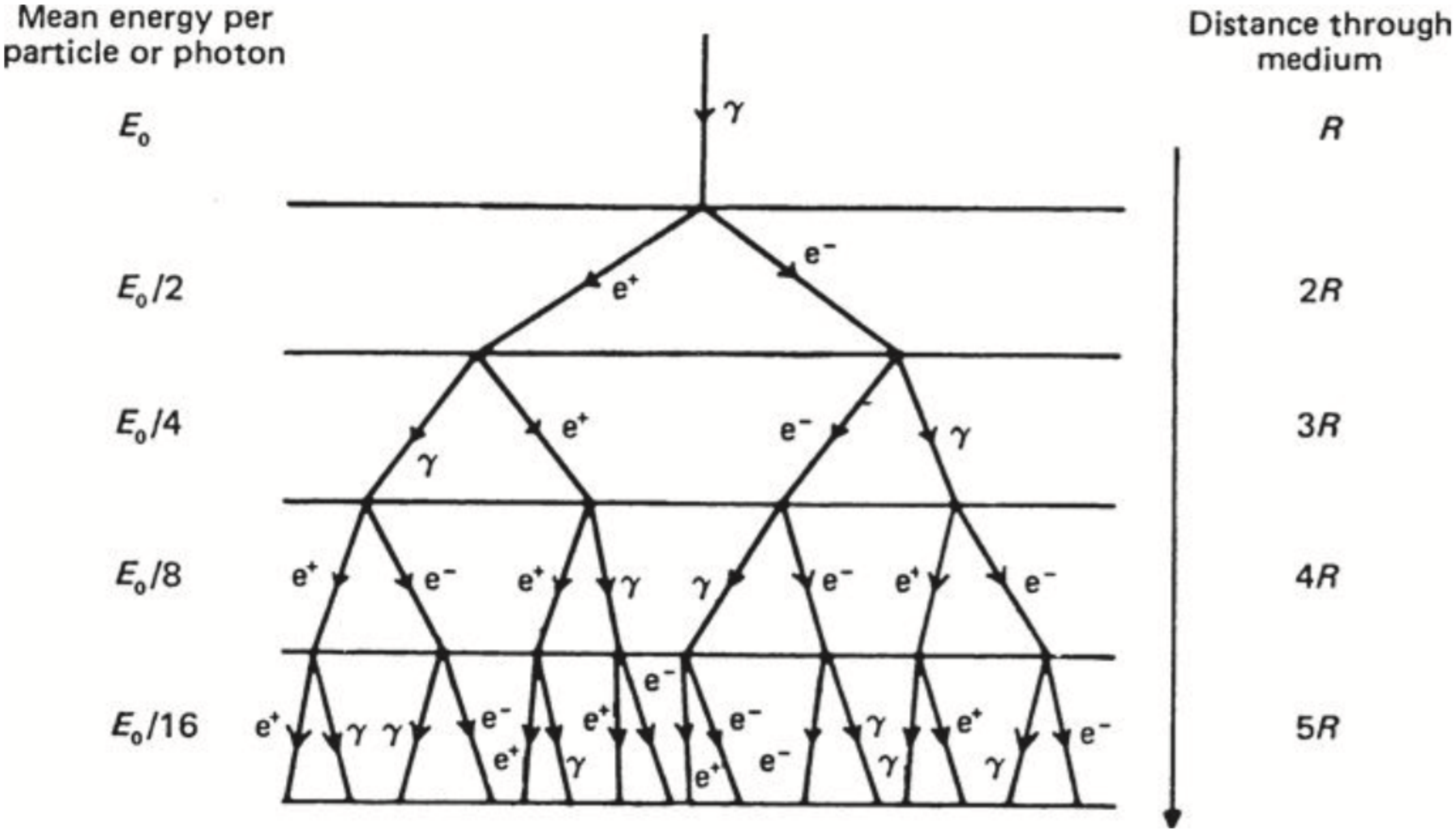
Fermi gamma-ray observatory

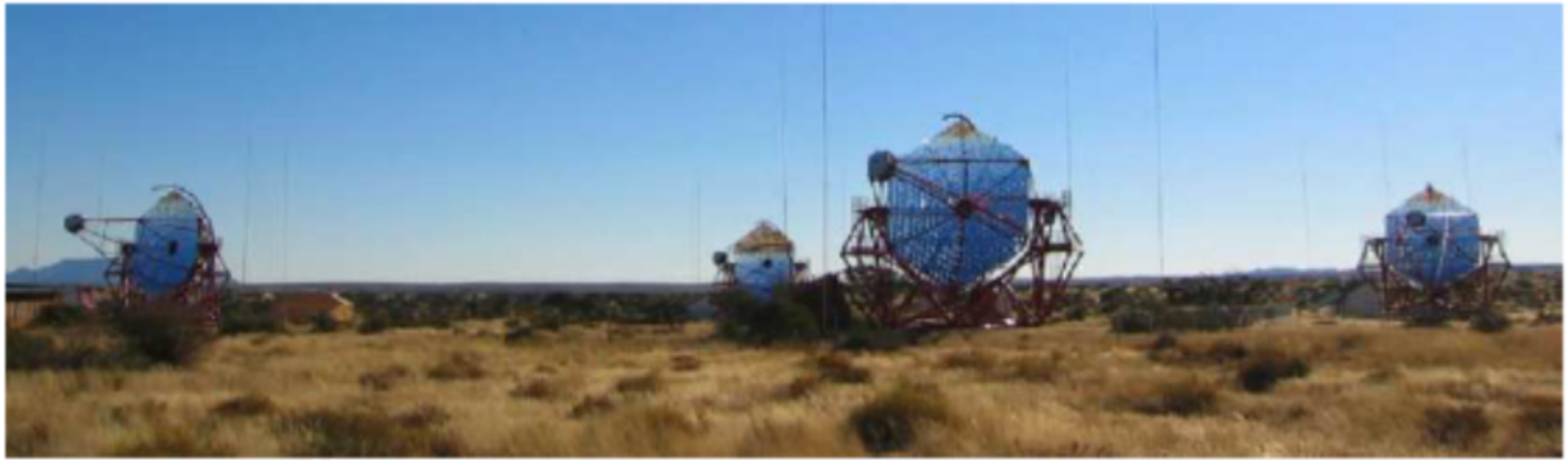






After distance nR, the number of (photons + electrons + positrons) is 2^n and their average energy is $E_0/2^n$.



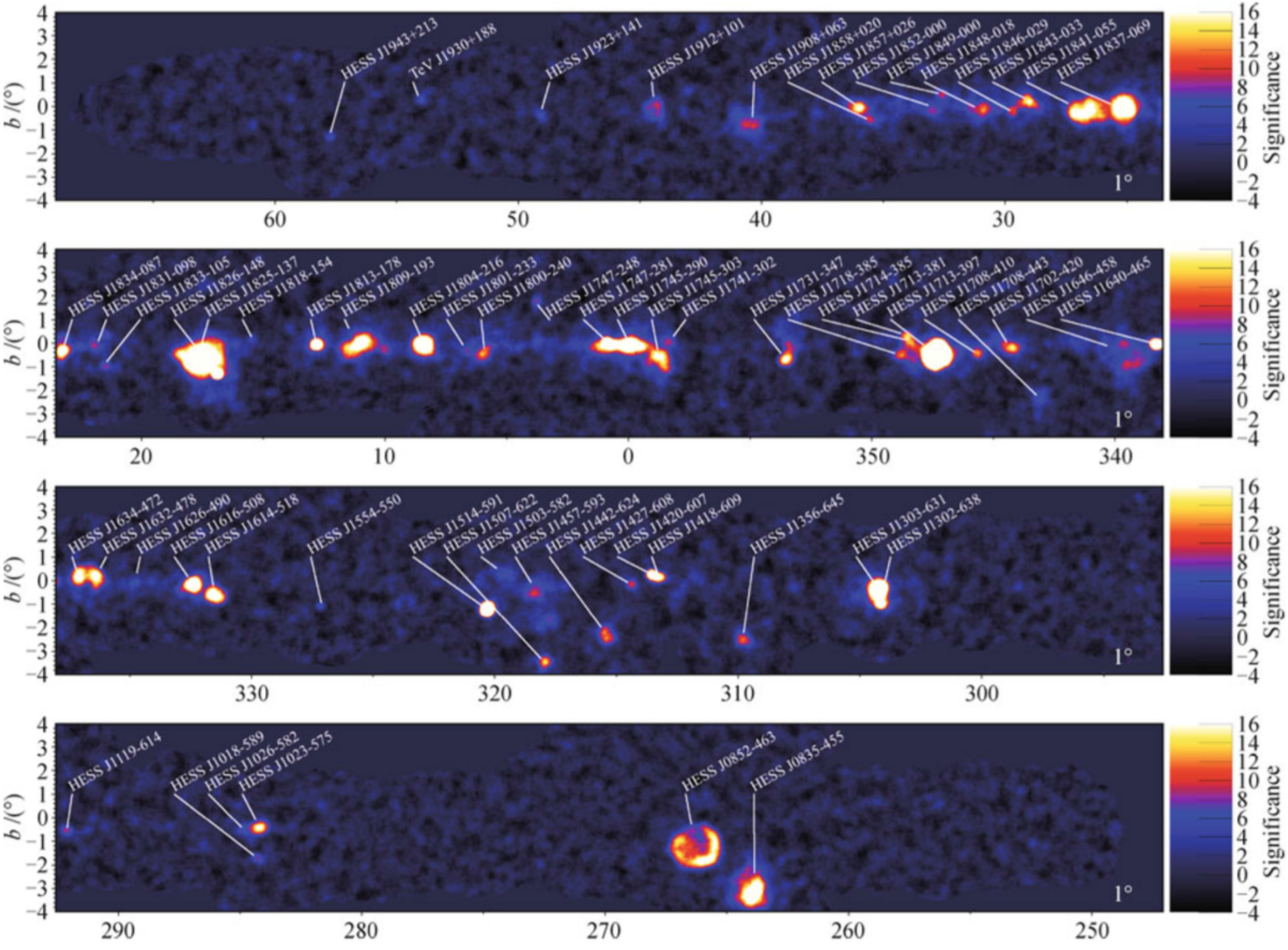


H.E.S.S.

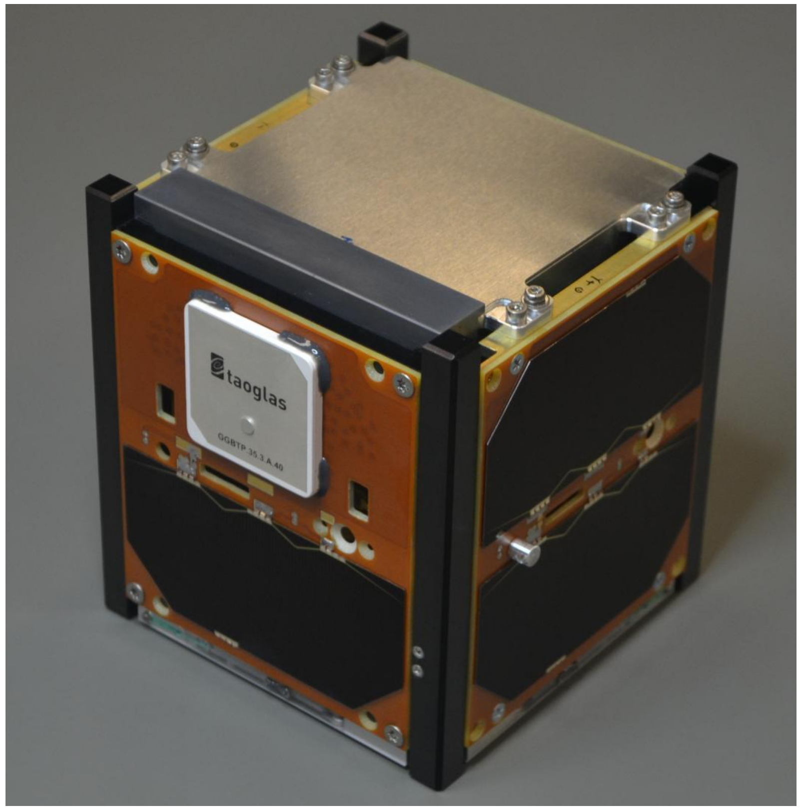
MAGIC

VERITAS

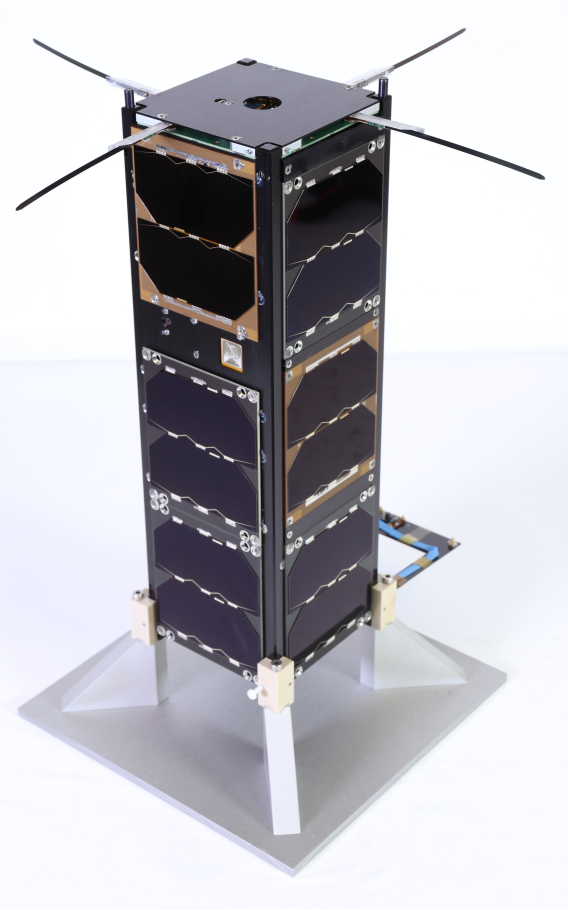
The TeV sky from HESS



CubeSats for High-Energy Astrophysics



GRBAlpha
Launched in March 2021
~155 transients

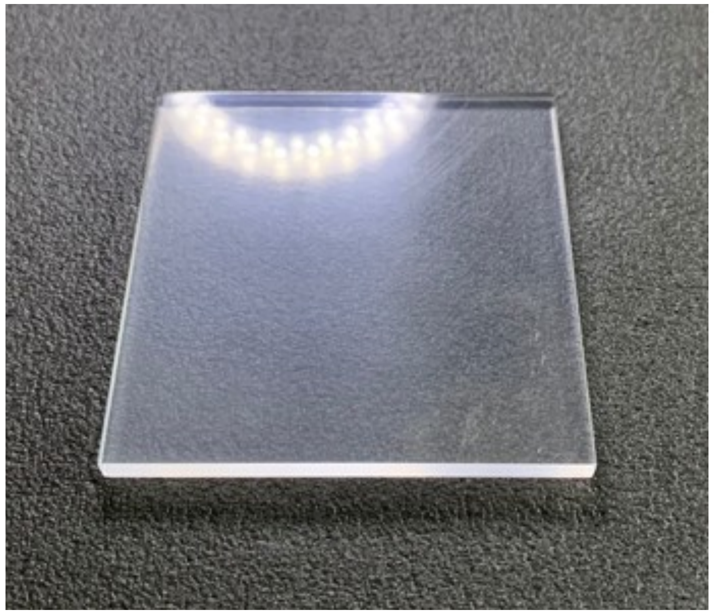


VZLUSAT-2
Launched in January 2022
~100 transients

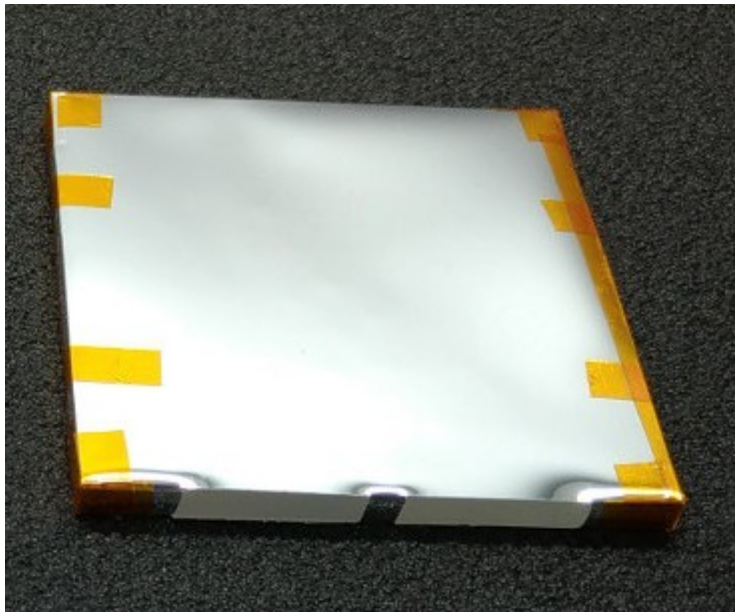
GRBBeta
Launched in July 2024
~1st two weeks after launch!

GRBAlpha detector

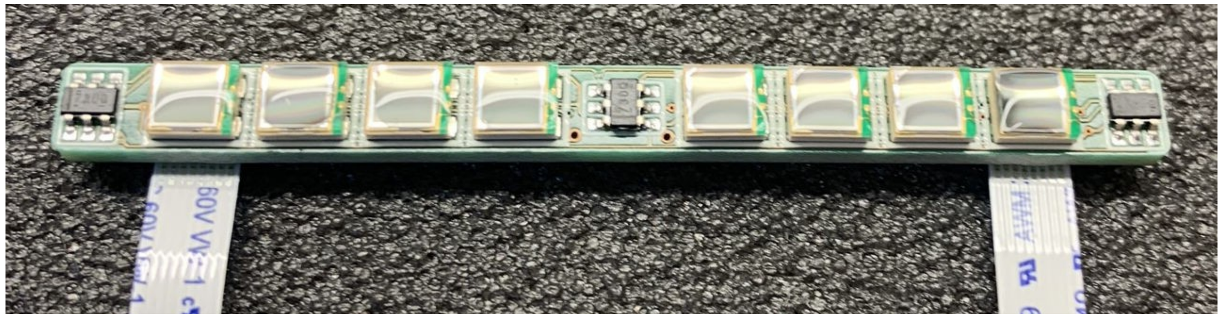
Pál+ 2020



CsI(Tl) scintillator

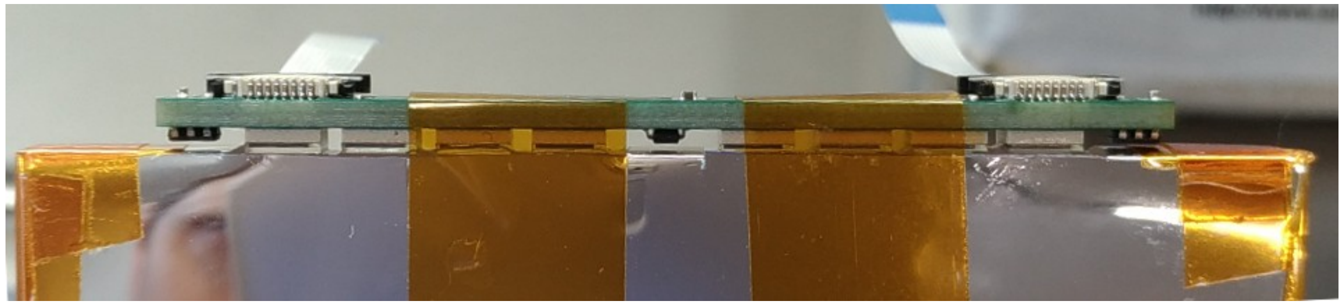


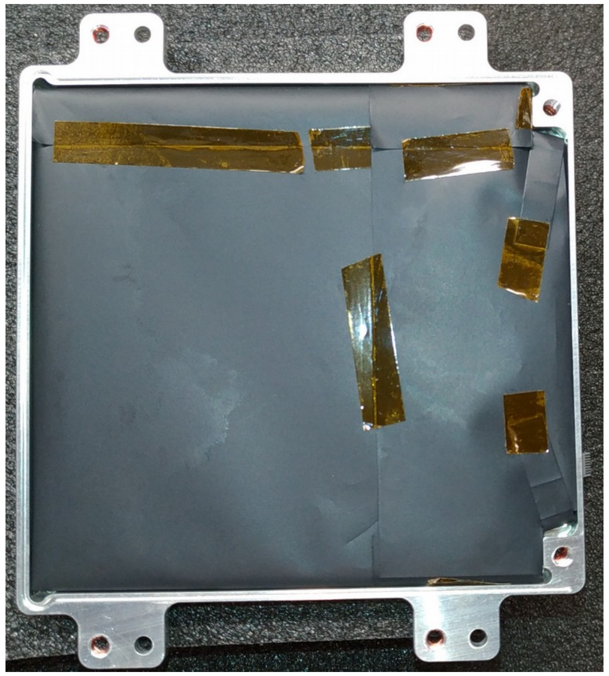
Wrapped in Enhanced Specular Reflector (ESR)



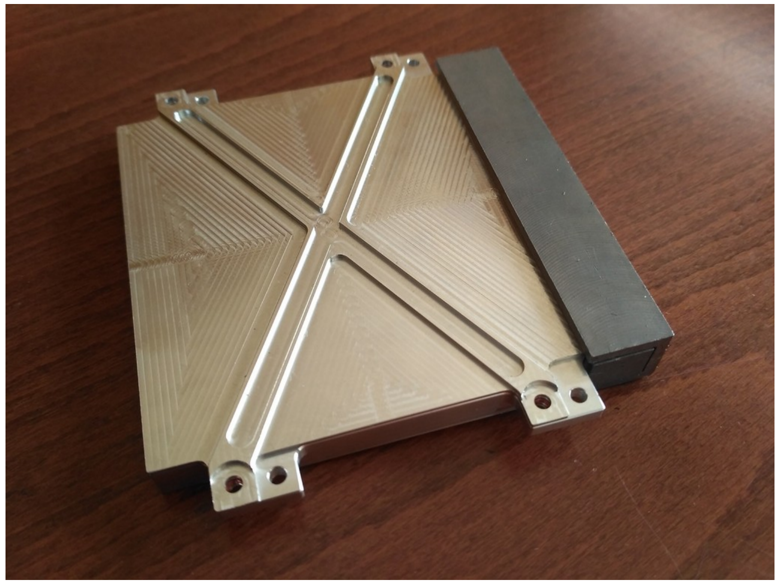
2 readout channels of 4 MPPCs (S13360-3050 PE) by Hamamatsu

GRBAlpha detector

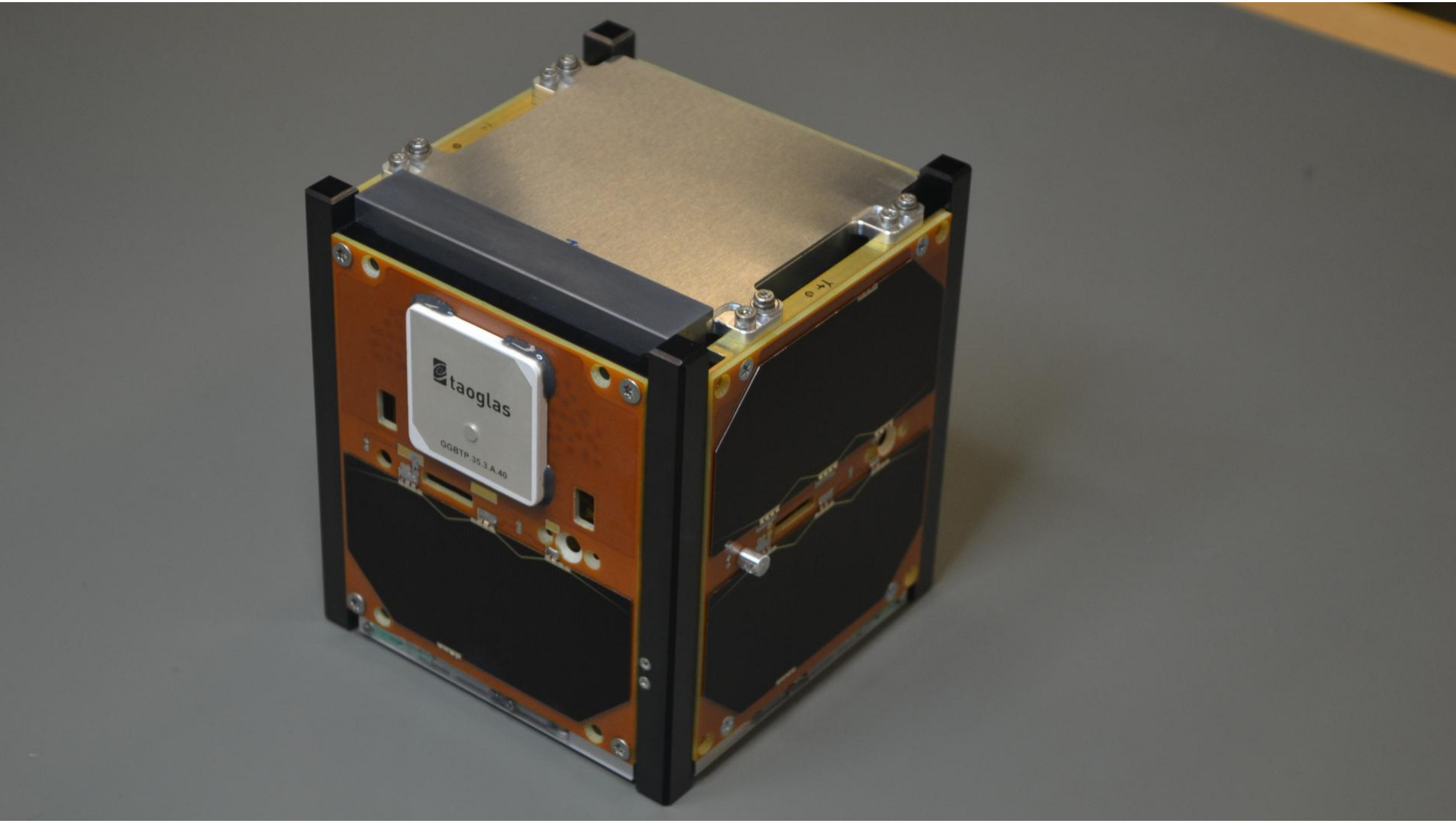


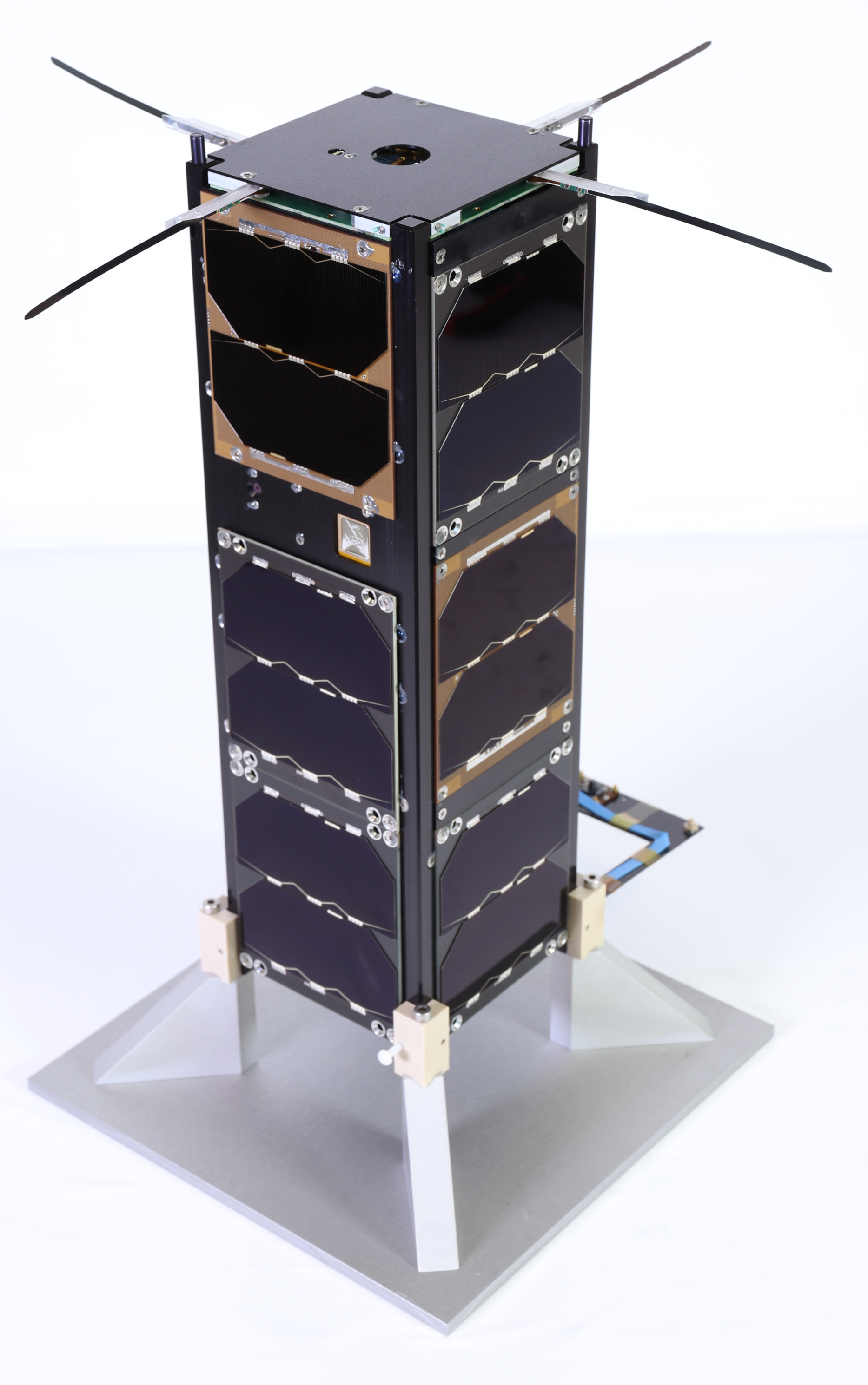


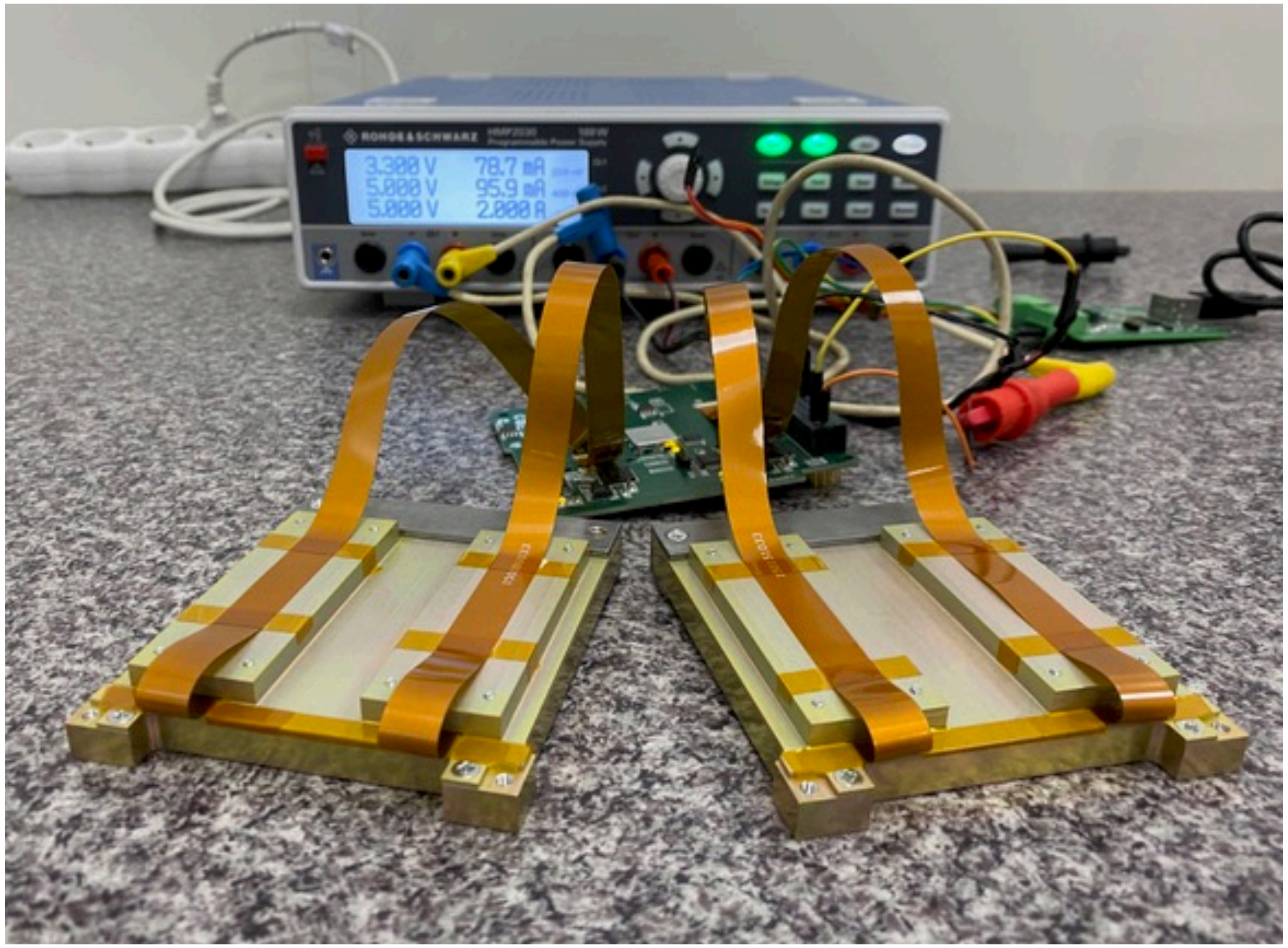
DuPont Tedlar TCC15BL3 wrapping



Assembled detector with Pb-Sb alloy to reduce MPPC degradation by protons


taoglas
GGBTP.35.3.A.40





ROHDE&SCHWARZ
HMP2030
3.300 V 78.7 mA
5.000 V 95.9 mA
5.000 V 2.000 A