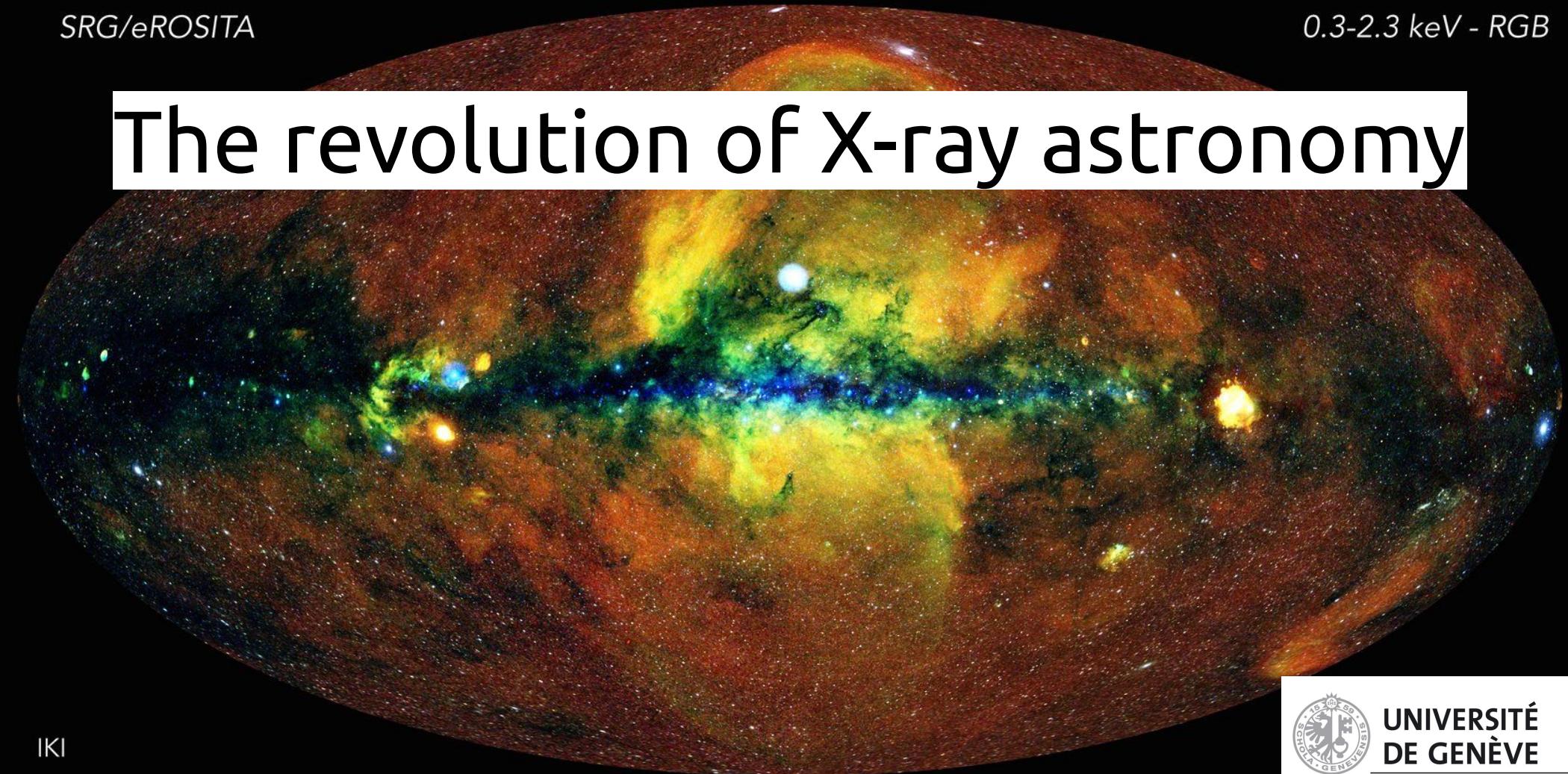


# The revolution of X-ray astronomy



# A history of serendipity

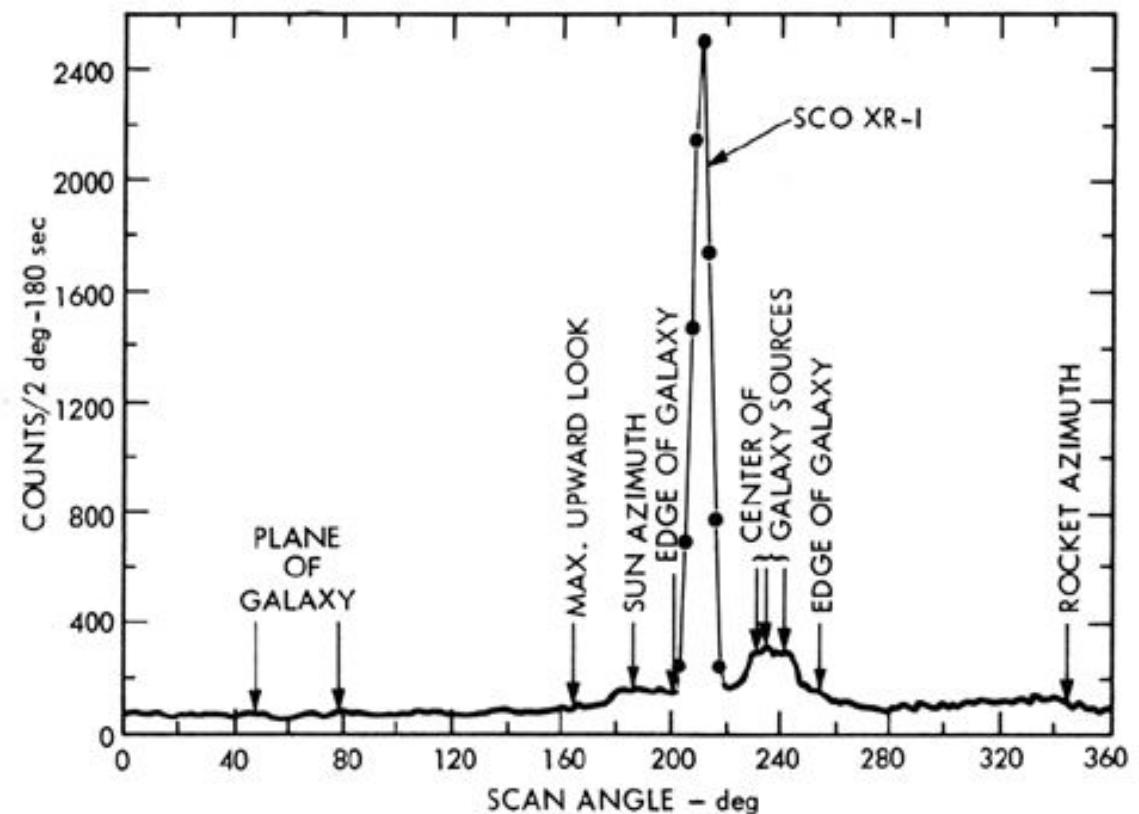


White Sands  
Missile  
Range  
Museum

# The discovery

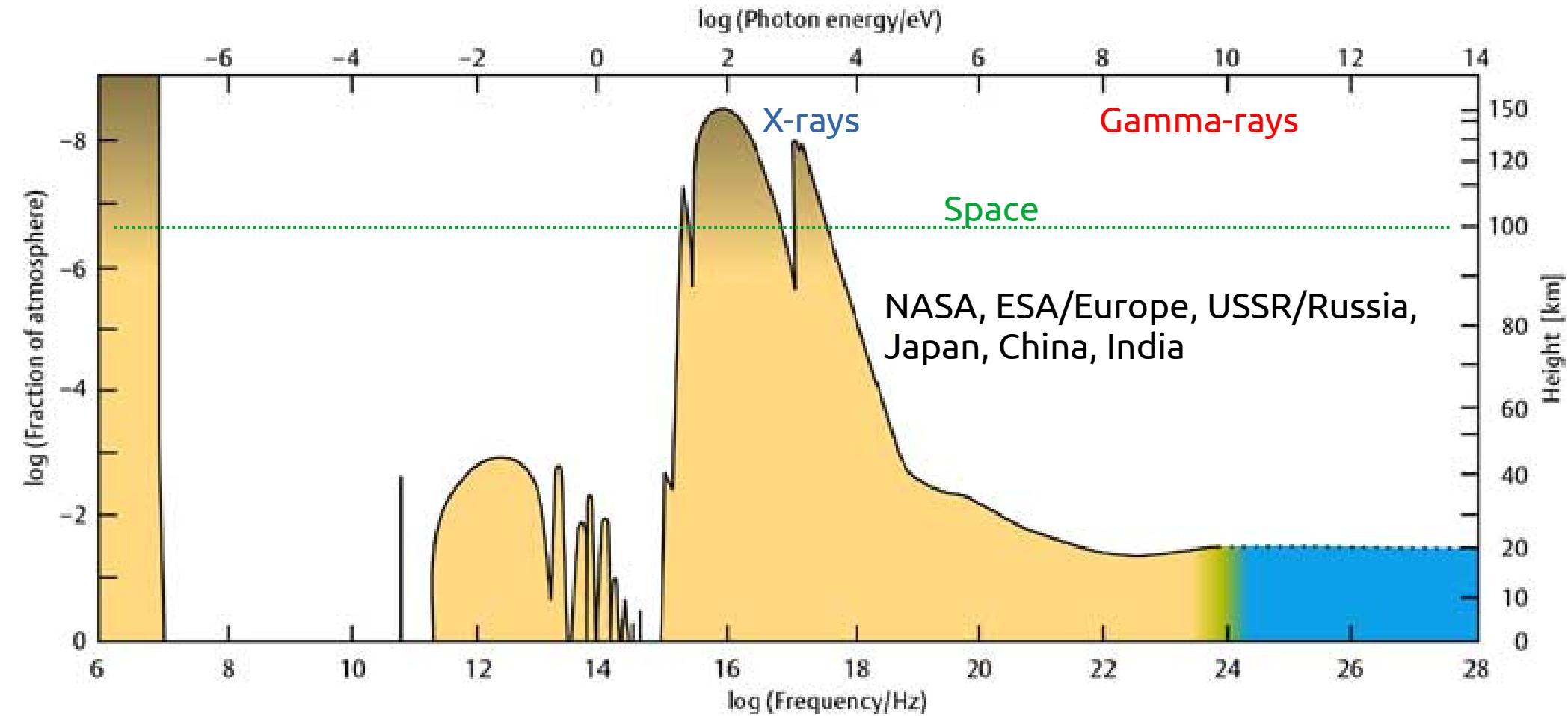


Scanning rocket Aerobee 170, 1962



Riccardo Giacconi, Nobel Prize in Physics 2002

# Why space?

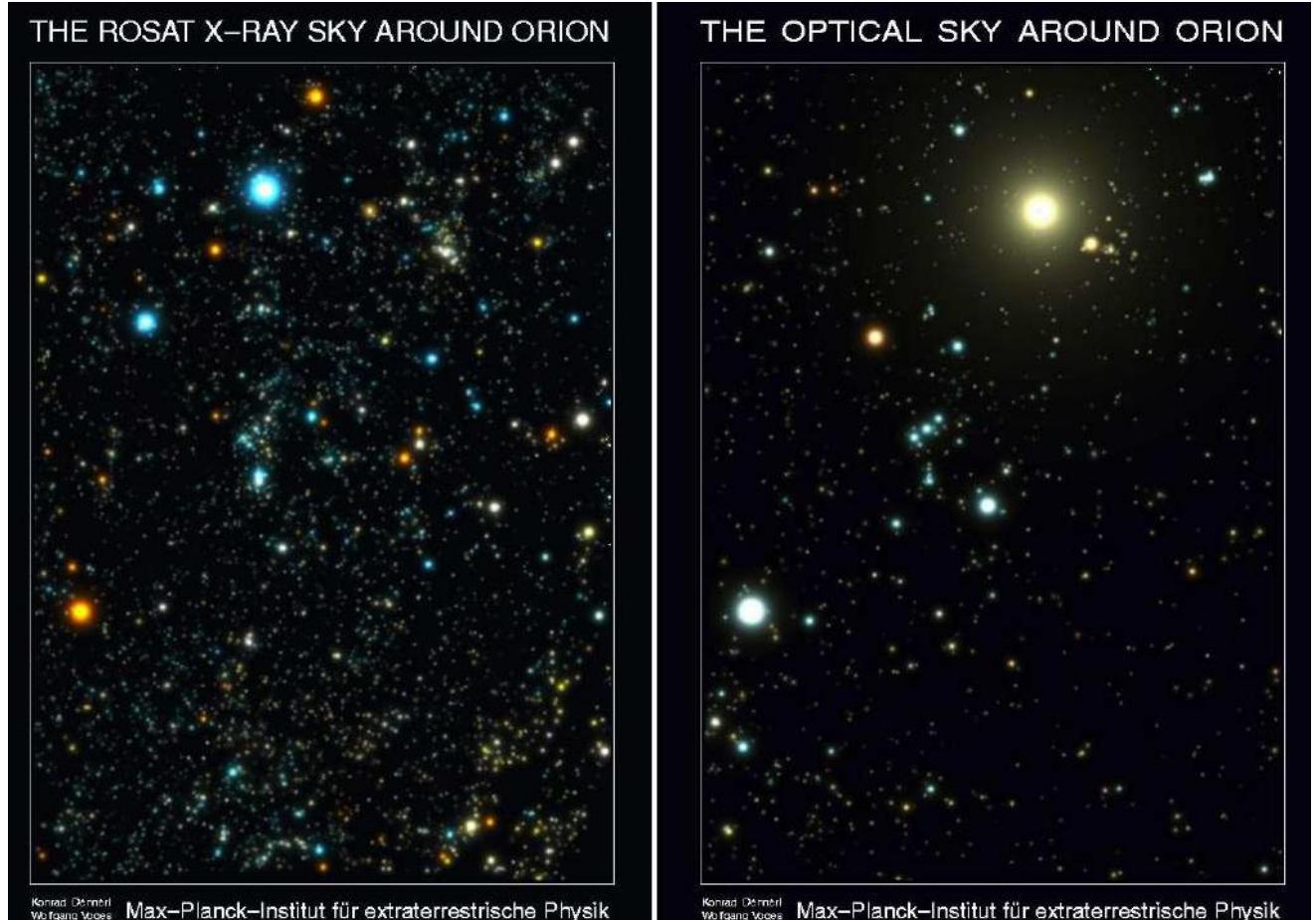




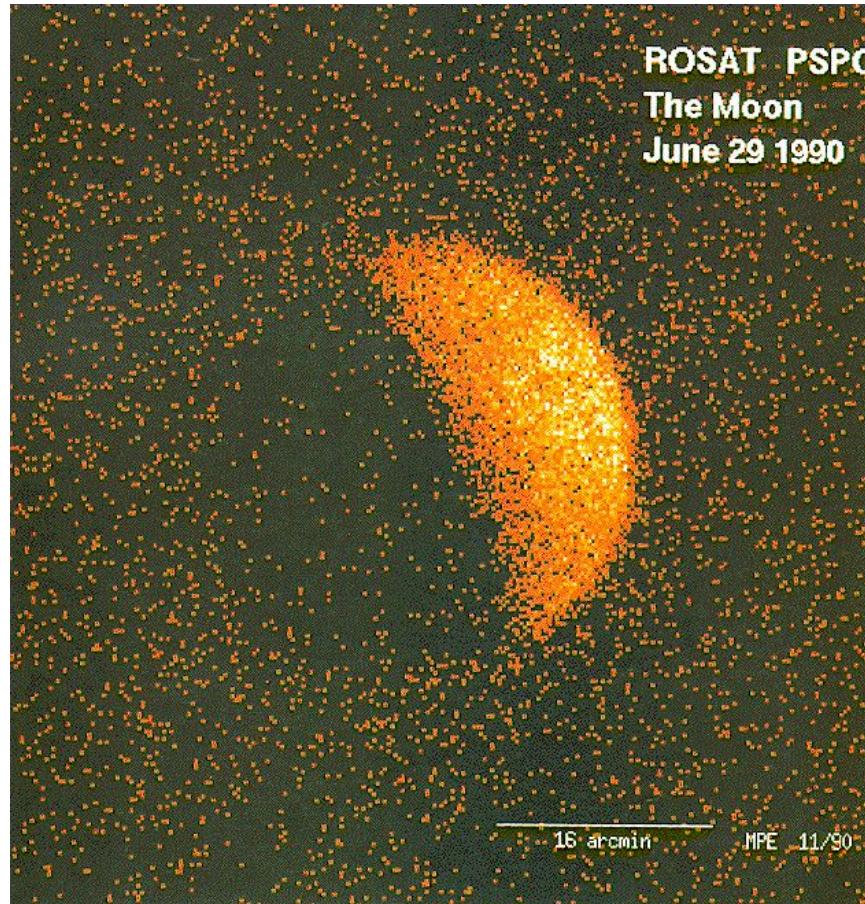
# Why a revolution?



Revealing the  
invisible...



# A lot of sources

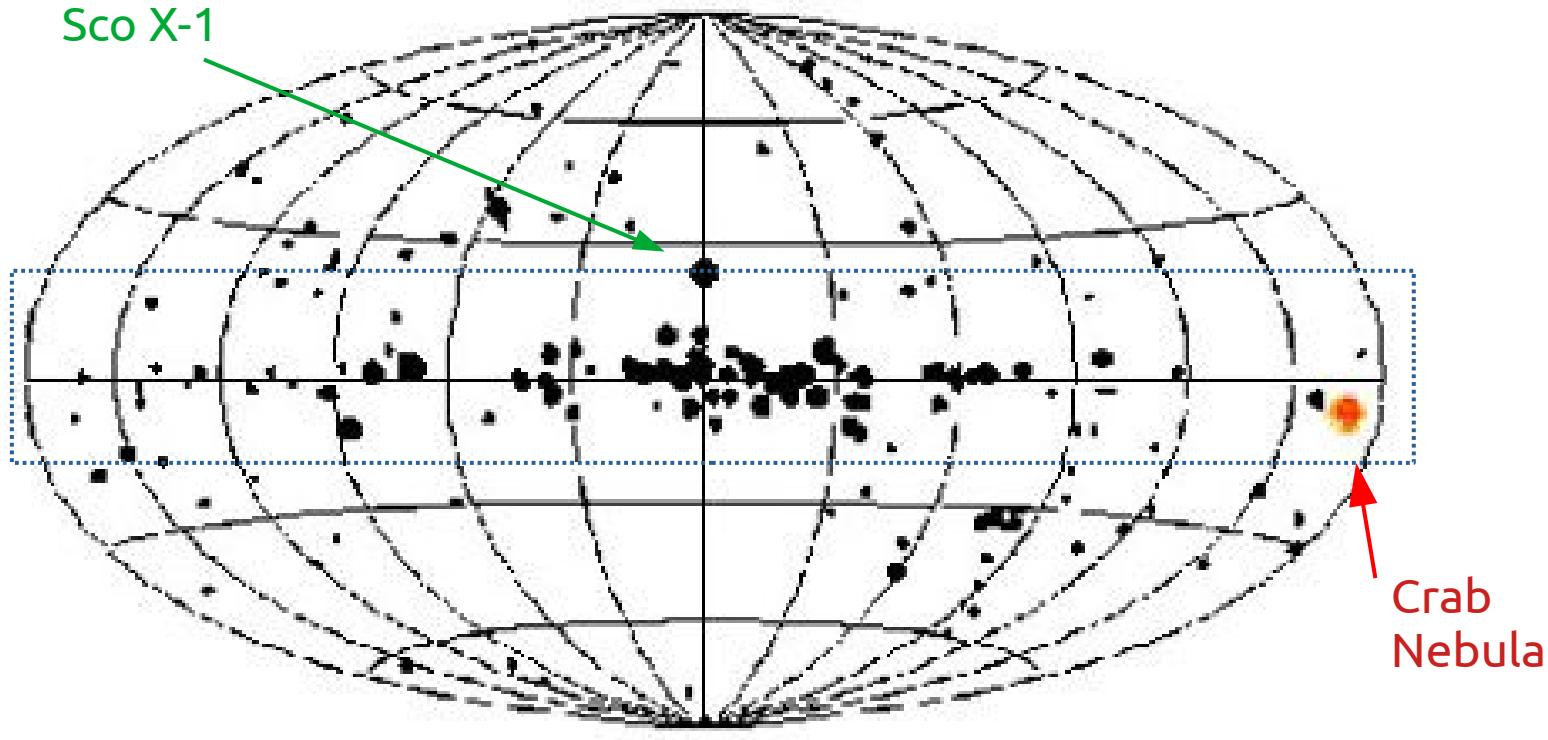


DLR / MPE / ROSAT

# The X-ray sky



Galactic plane



Uhuru (1970-1973): 339 X-ray sources

NASA

# ROSAT ALL-SKY SURVEY Bright Sources

Aitoff Projection  
Galactic II Coordinate System

Galactic plane

Sco X-1

Crab Nebula

wroges 9-Jul-98

Energy range: 0.1 - 2.4 keV

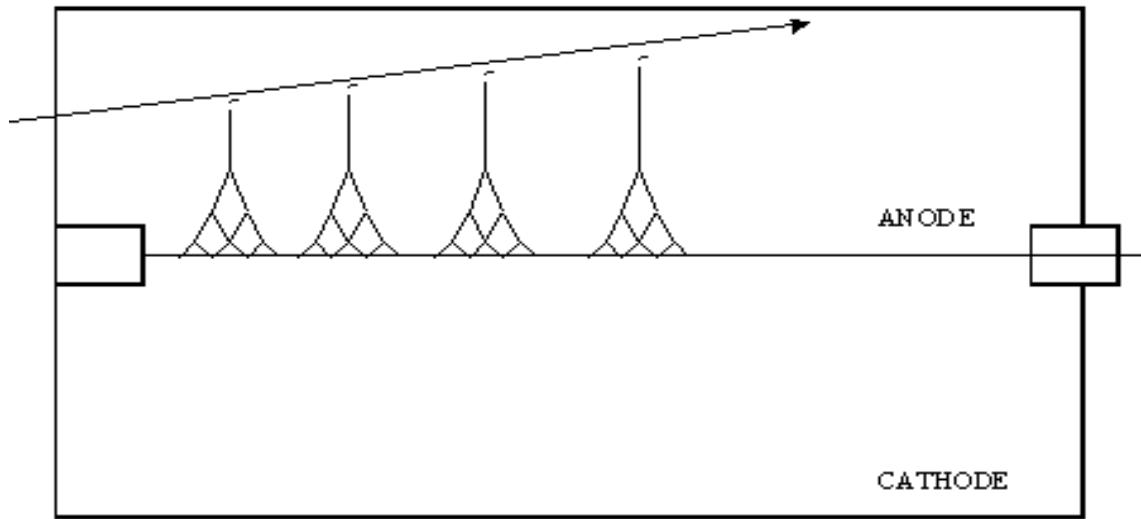
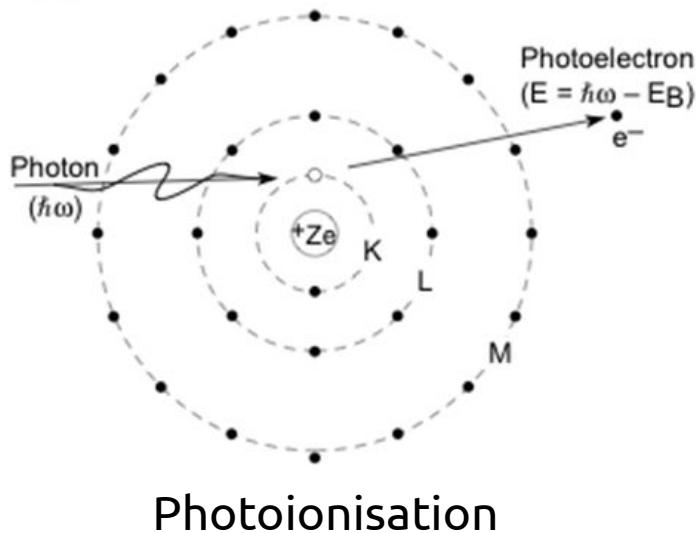
Number of RASS-II sources: 18811

Hardness ratio: -1.0 | -0.4 | -0.2 | 0.2 | 0.6 | 1.0      (soft -> hard : magenta - red - yellow - green - cyan)



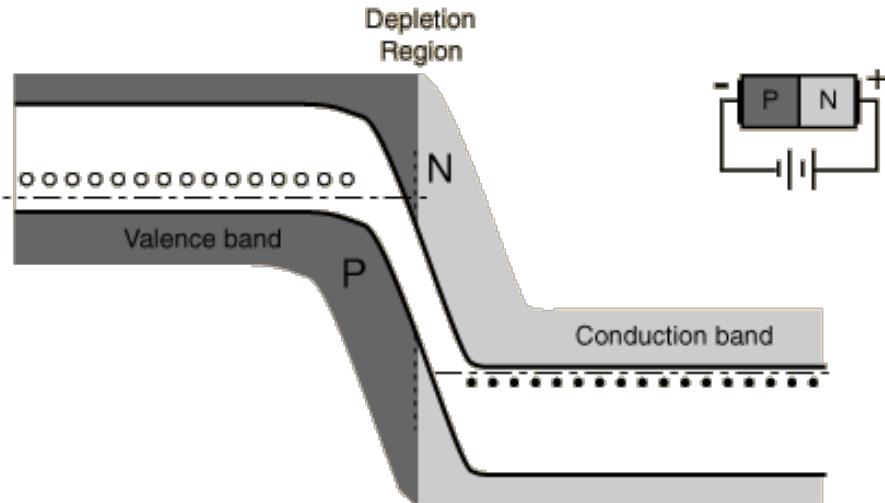
DLR / MPE /  
ROSAT

# Detecting X-rays: Proportional counter

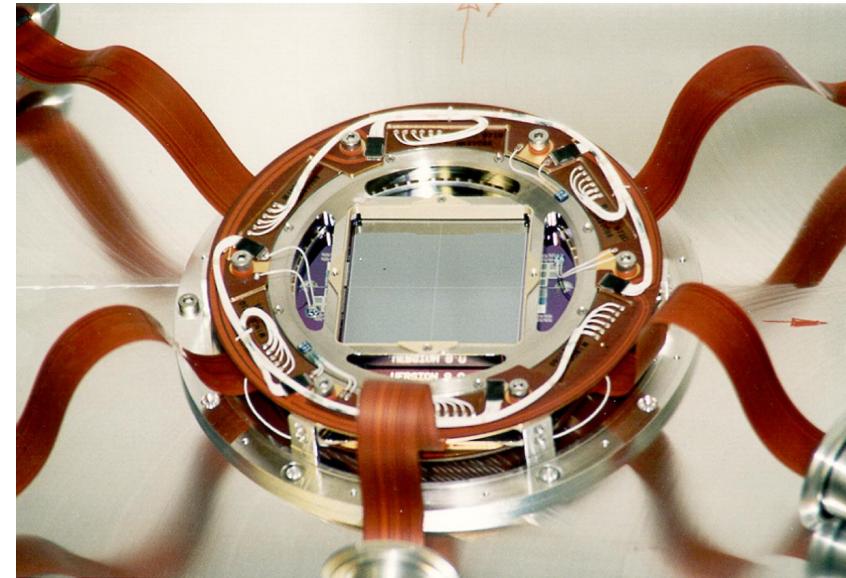


$$E/\Delta E \sim 2$$

# Detecting X-rays: CCDs



Reverse bias p-n junction

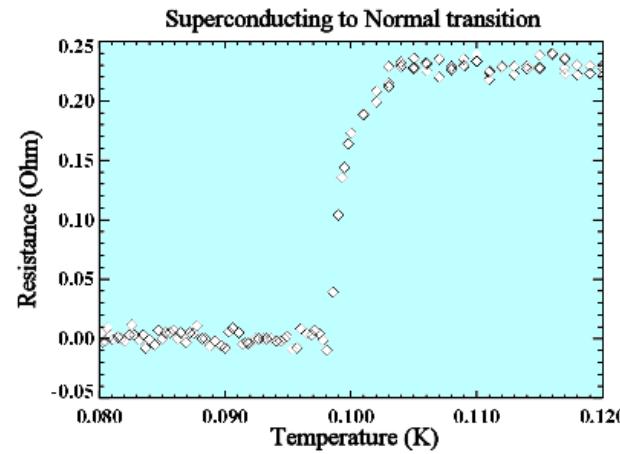
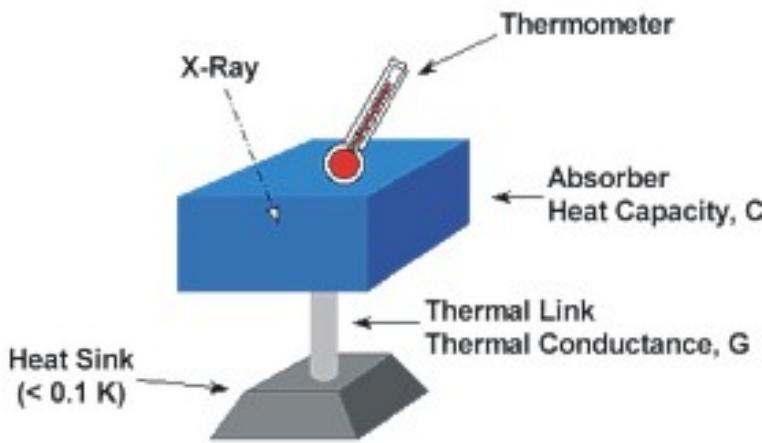


EPIC pn camera (12 CCDs)

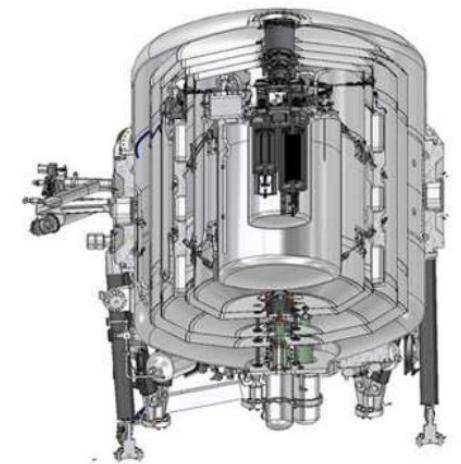
Event per event    $E/\Delta E \sim 10 - 20$

DLR / MPE

# Detecting X-rays: Micro-calorimeters



Transition Edge sensors



Hitomi SXS  
2016

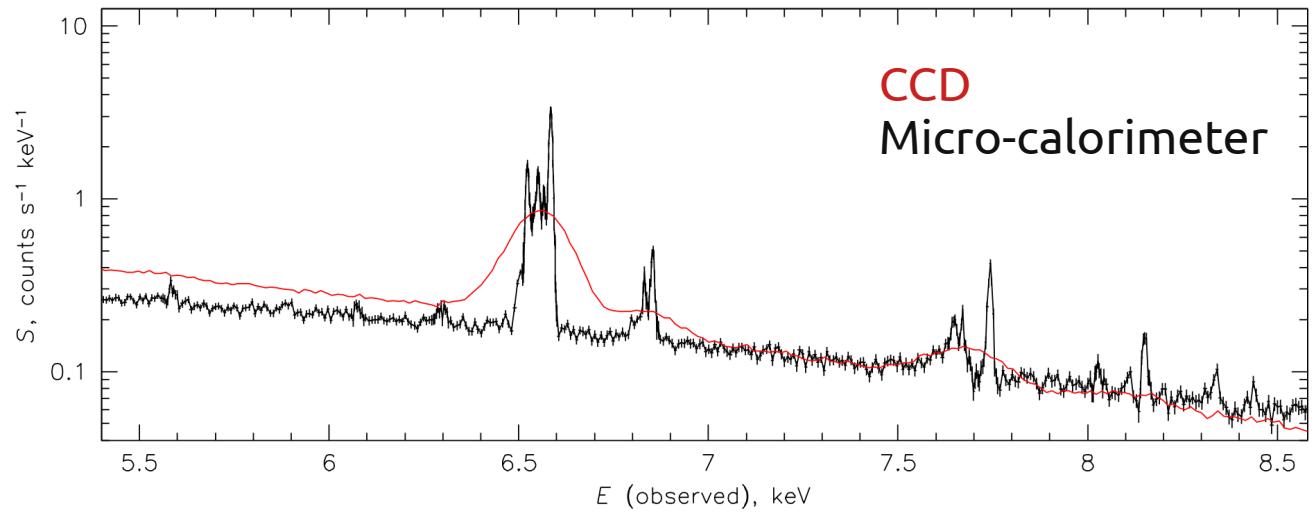
$$E/\Delta E \sim 1000$$

JAXA / NASA / NL / CH / ESA

# Hitomi lone observation

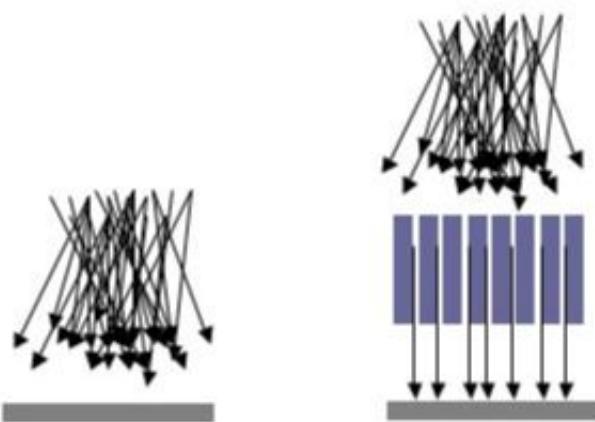


JAXA / NASA / NL / CH / ESA

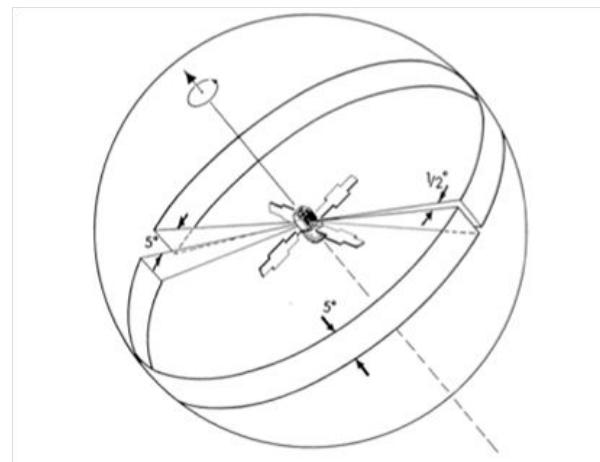


The Hitomi Collaboration, Nature, 2016

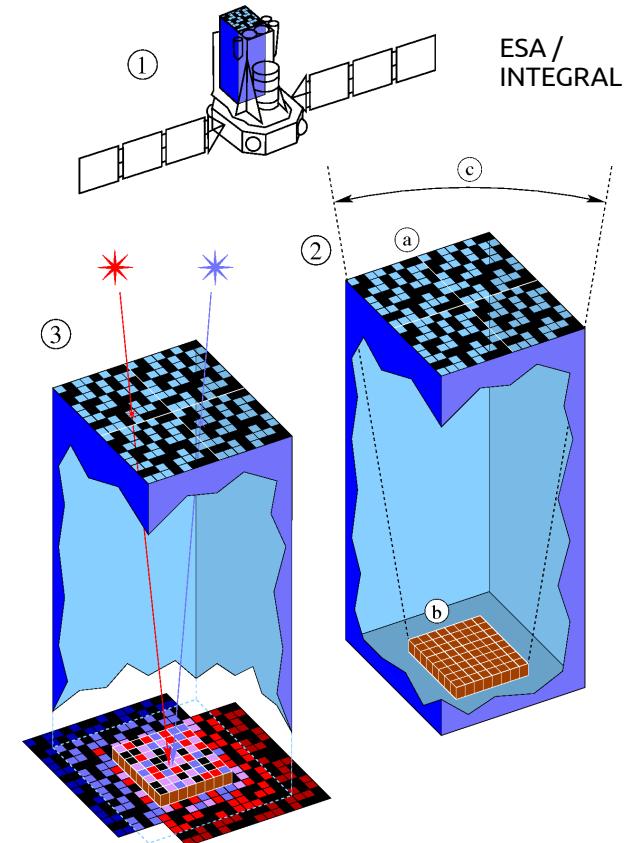
# X-ray telescopes: non-focusing



Collimators



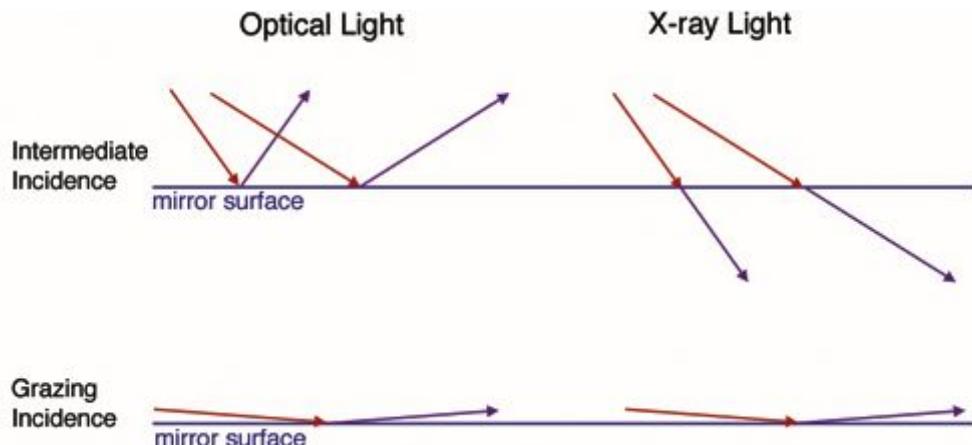
Time modulation



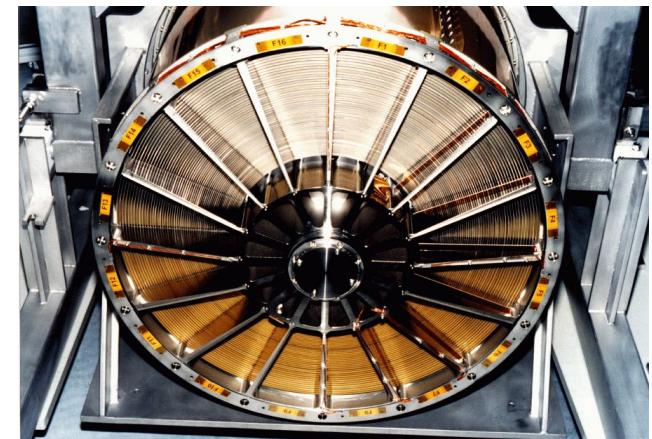
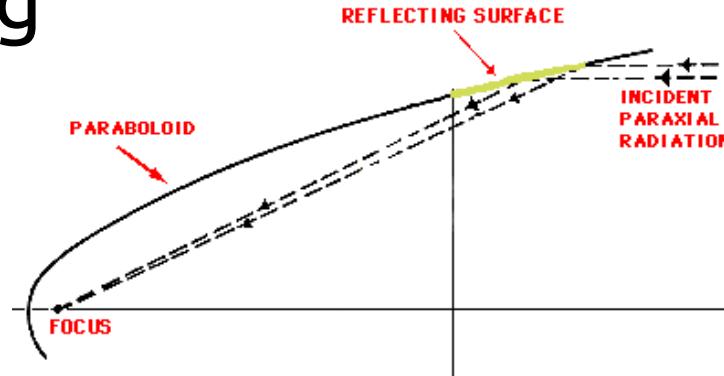
Spatial modulation  
Coded mask

# X-ray telescopes: focusing

(Almost) no X-ray lens, but mirrors...



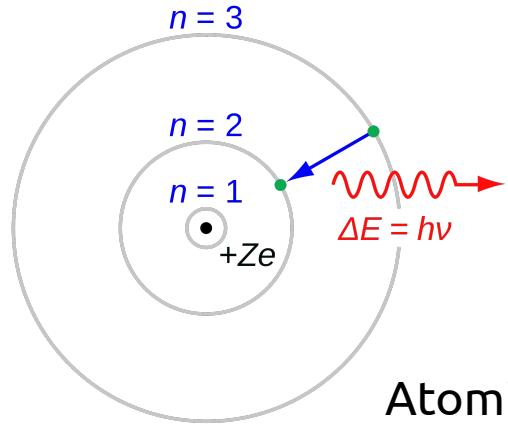
X-ray total reflection possible on metals  $n < 1$



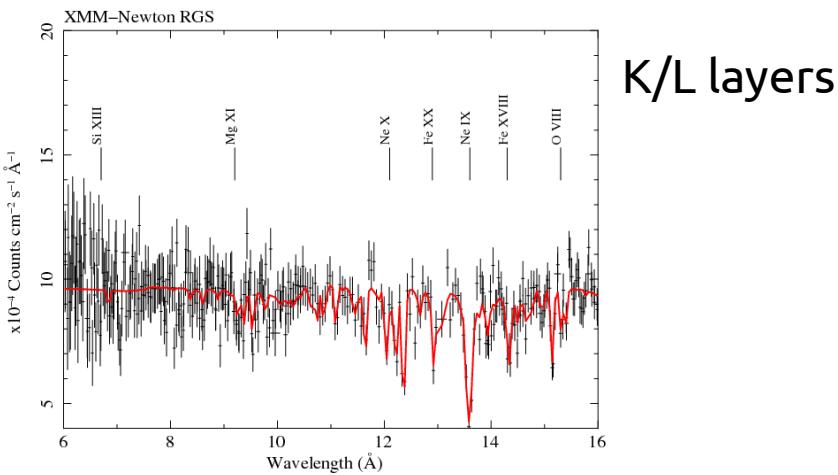
ESA

XMM-Newton replicated mirrors

# Astrophysical processes



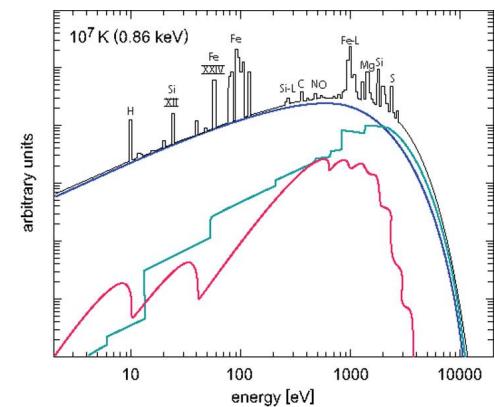
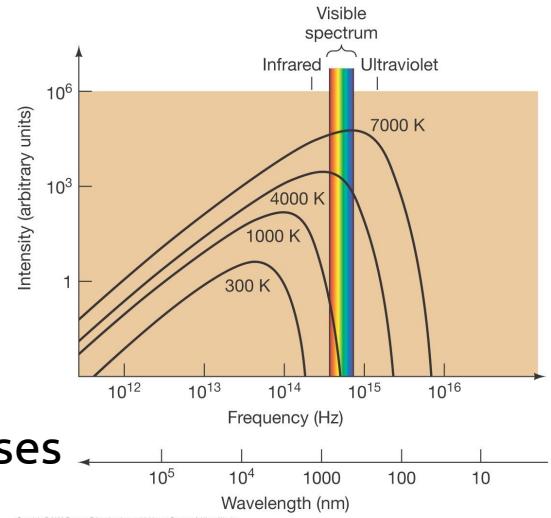
Atomic physics



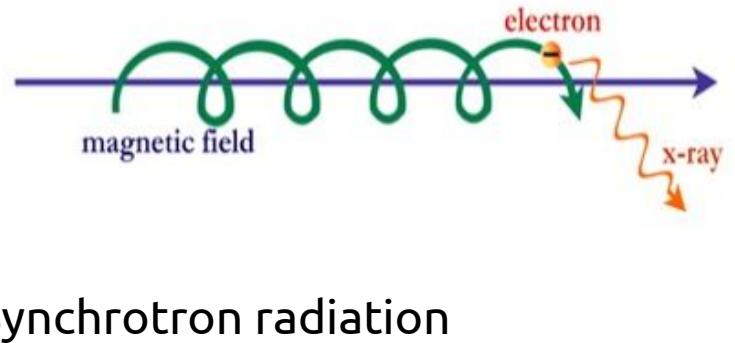
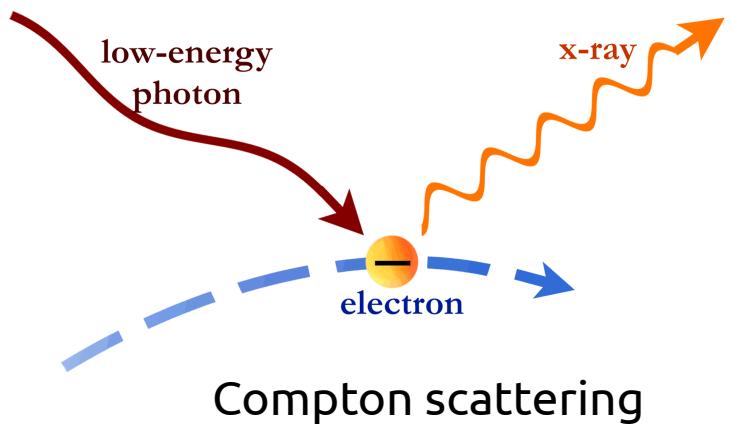
K/L layers

Thermal processes

$T > 10^6 \text{ K}$



# Astrophysical processes



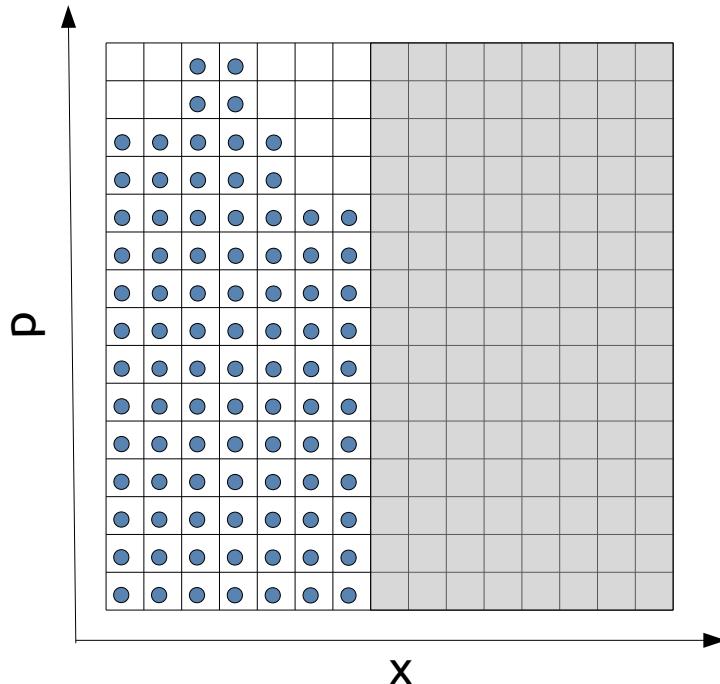
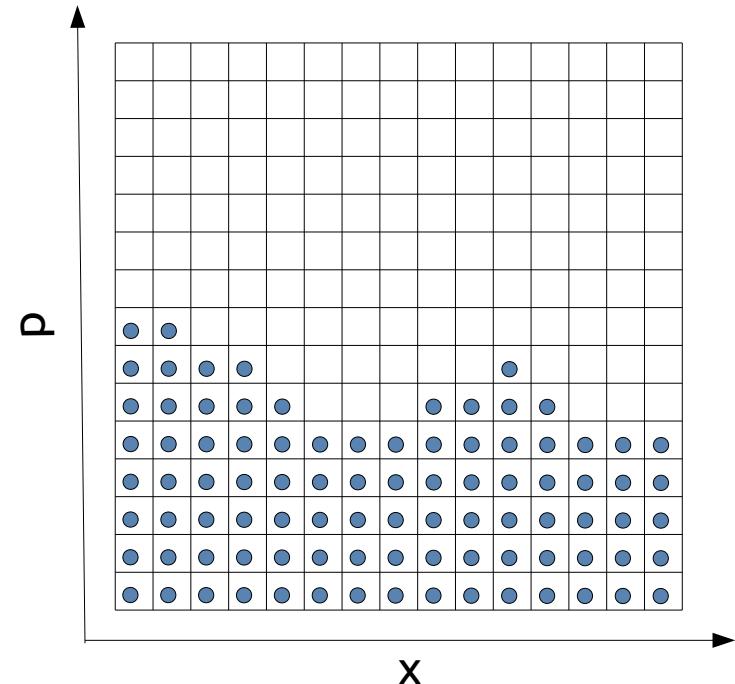
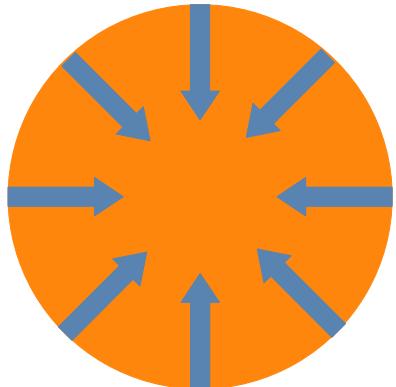
Relativistic particles

$$E_{\phi,\text{out}} \sim \gamma^2 E_{\phi,\text{in}}$$

$$\varepsilon_c \sim \gamma^3$$

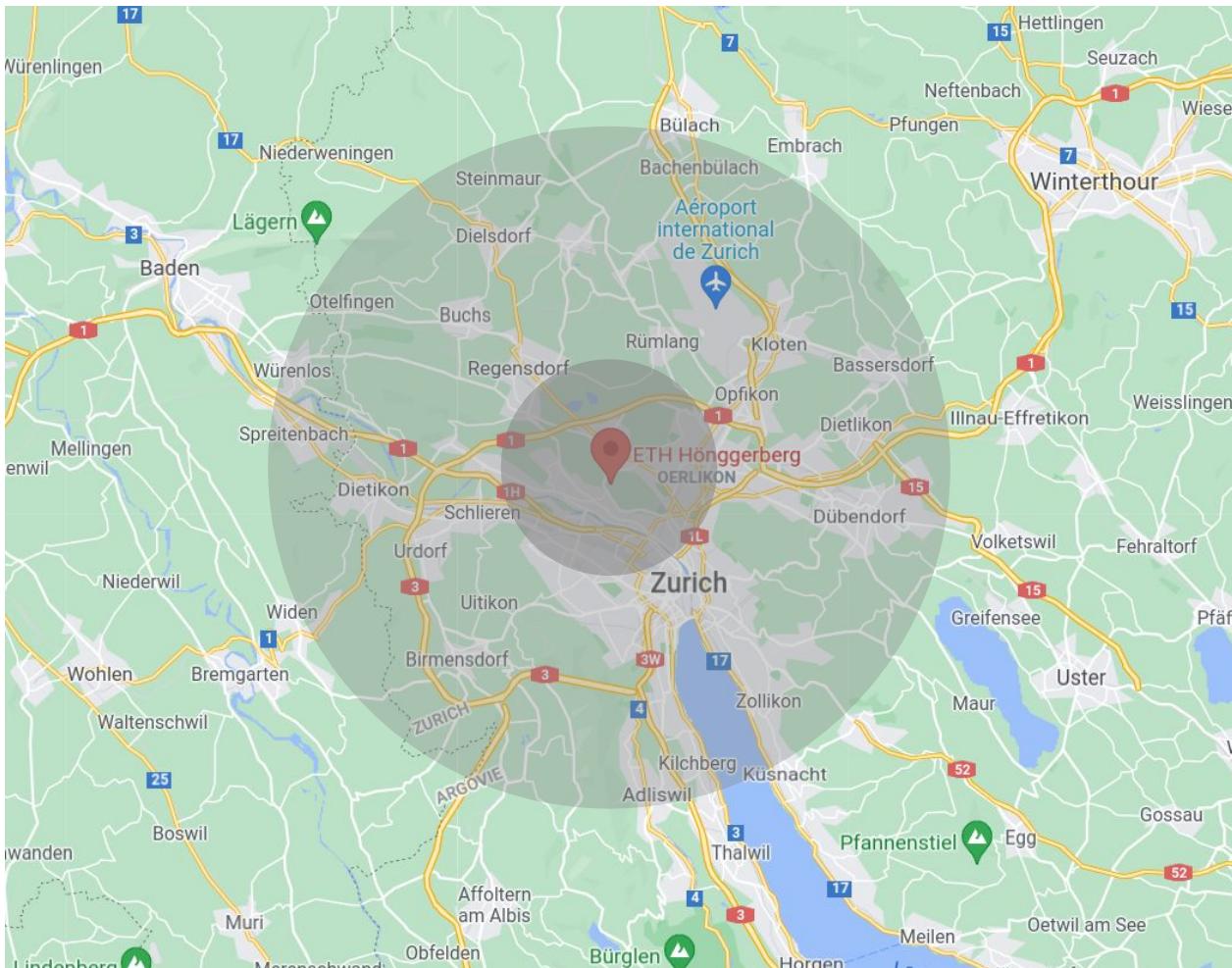
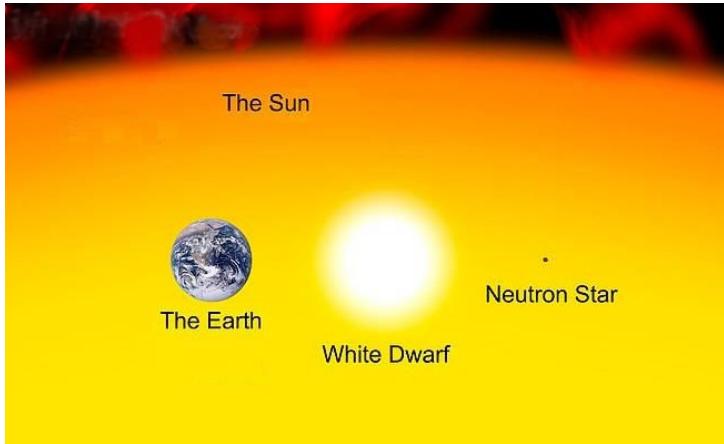
Requires: cosmic accelerators, high energy densities

# Compact objects

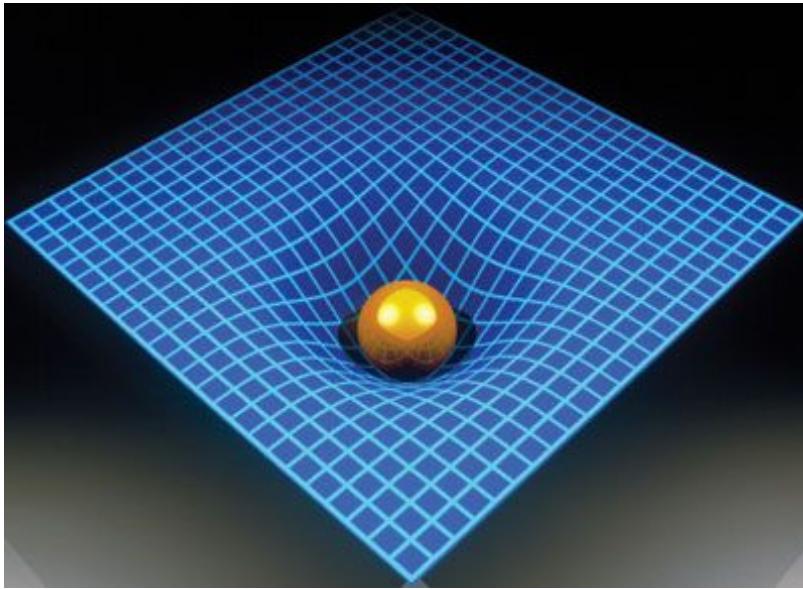


Degeneracy pressure of fermions:  
Electrons → White dwarfs  
Neutrons → Neutron stars

# White dwarfs and neutron stars

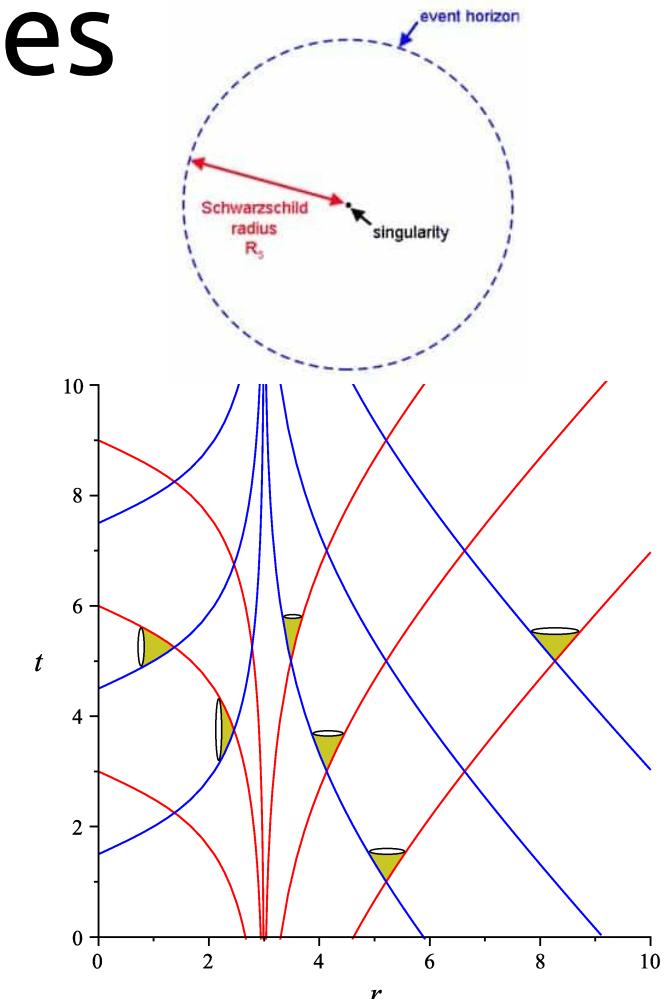


# Black holes



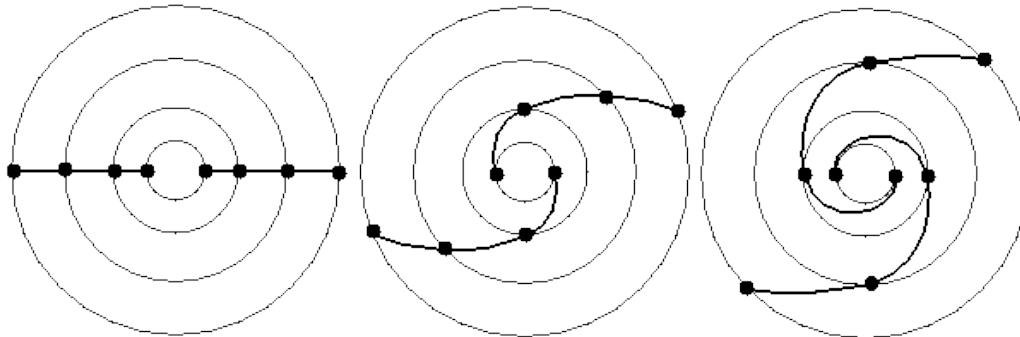
$$v = \sqrt{\frac{2GM}{R}} \rightarrow R_S = \frac{2GM}{c^2}$$

Sun: radius 3 km

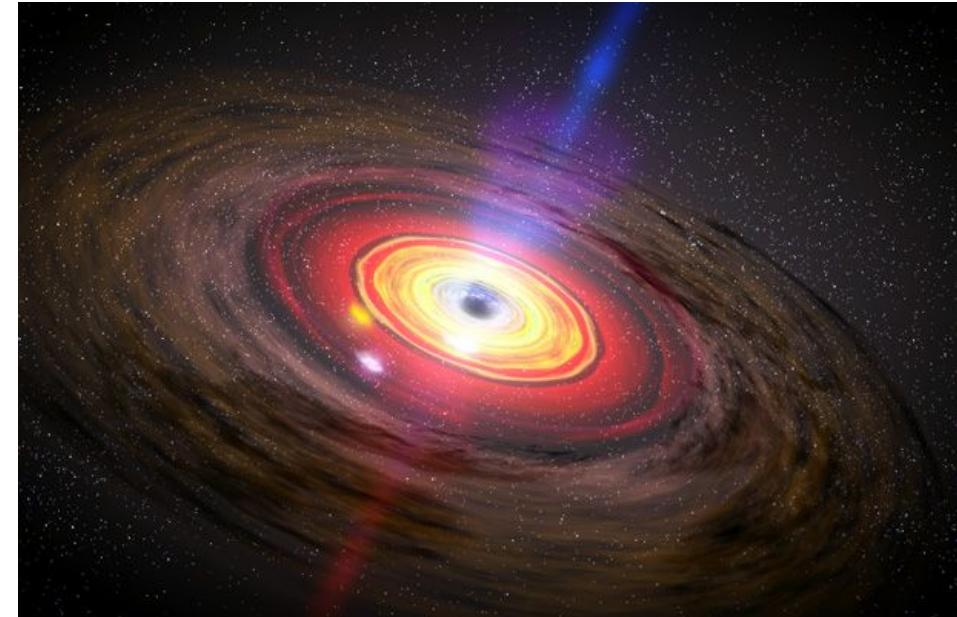


All paths below  $R_s$  lead to the center

# Accretion disks

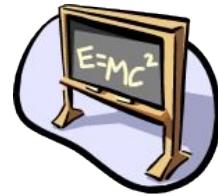


Keplerian rotation



Strong heating due to viscous friction

# Accretion efficiency



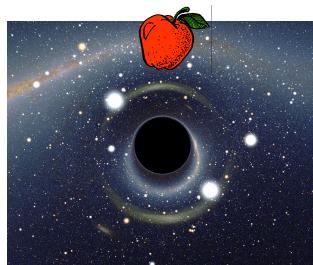
$1 \text{ kg} = 10^{17} \text{ J} = 25 \text{ billion kWh}$



$0.0000001 \text{ \% } (10^{-9})$

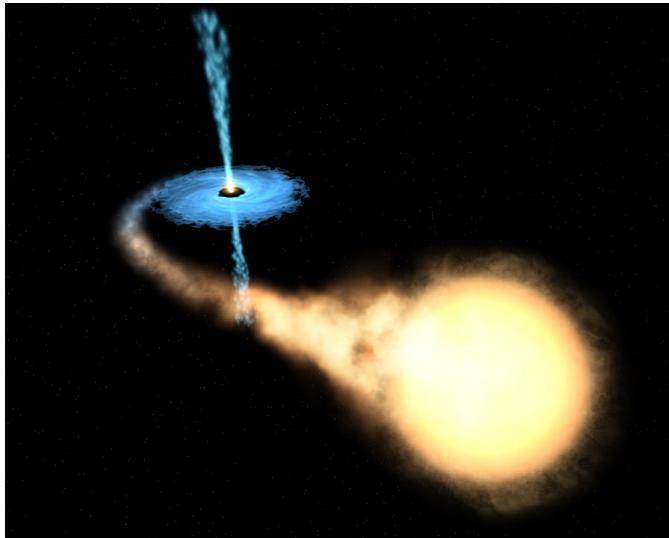


$0.7 \text{ \%}$



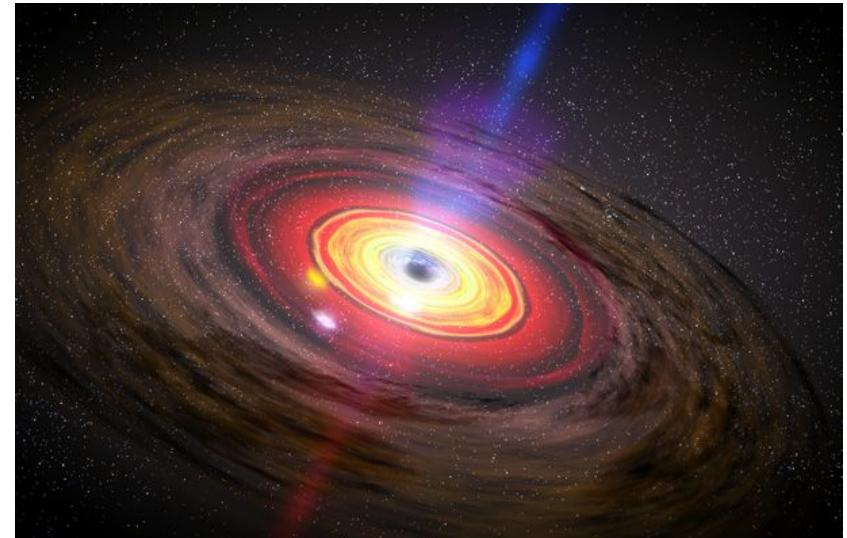
$\rightarrow 40 \text{ \%}$

# Accreting sources



X-ray binaries

Neutron stars  
Stellar-mass black holes



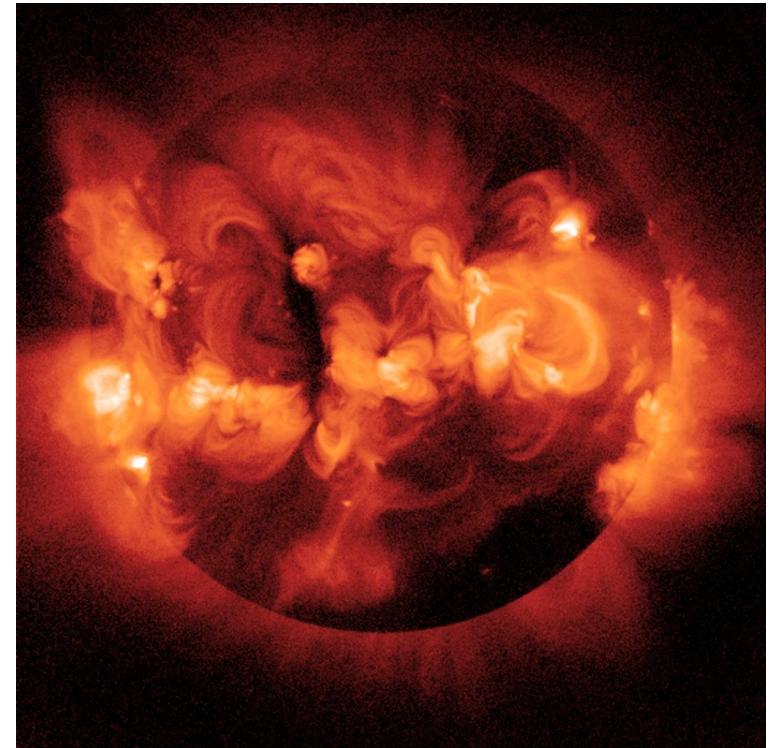
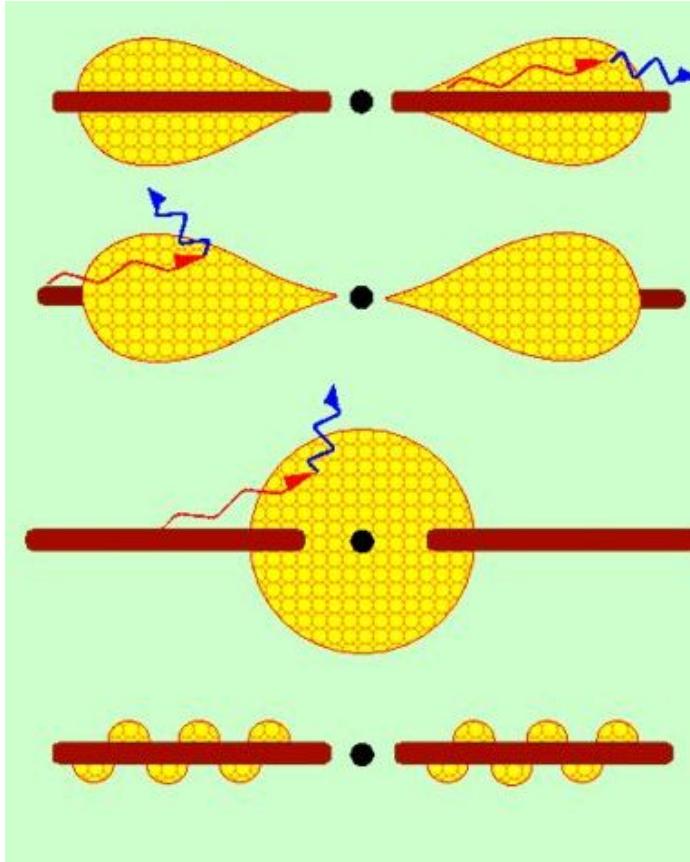
Active galactic nuclei

Supermassive black holes ( $10^{6-9} M_{\odot}$ )  
in the center of all galaxies  
Most luminous steady sources in the Universe  
Milky Way: Nobel Prize in Physics 2020

# X-ray emission from accreting sources

Compton scattering  
in a hot plasma  
 $\sim 10^9$  K

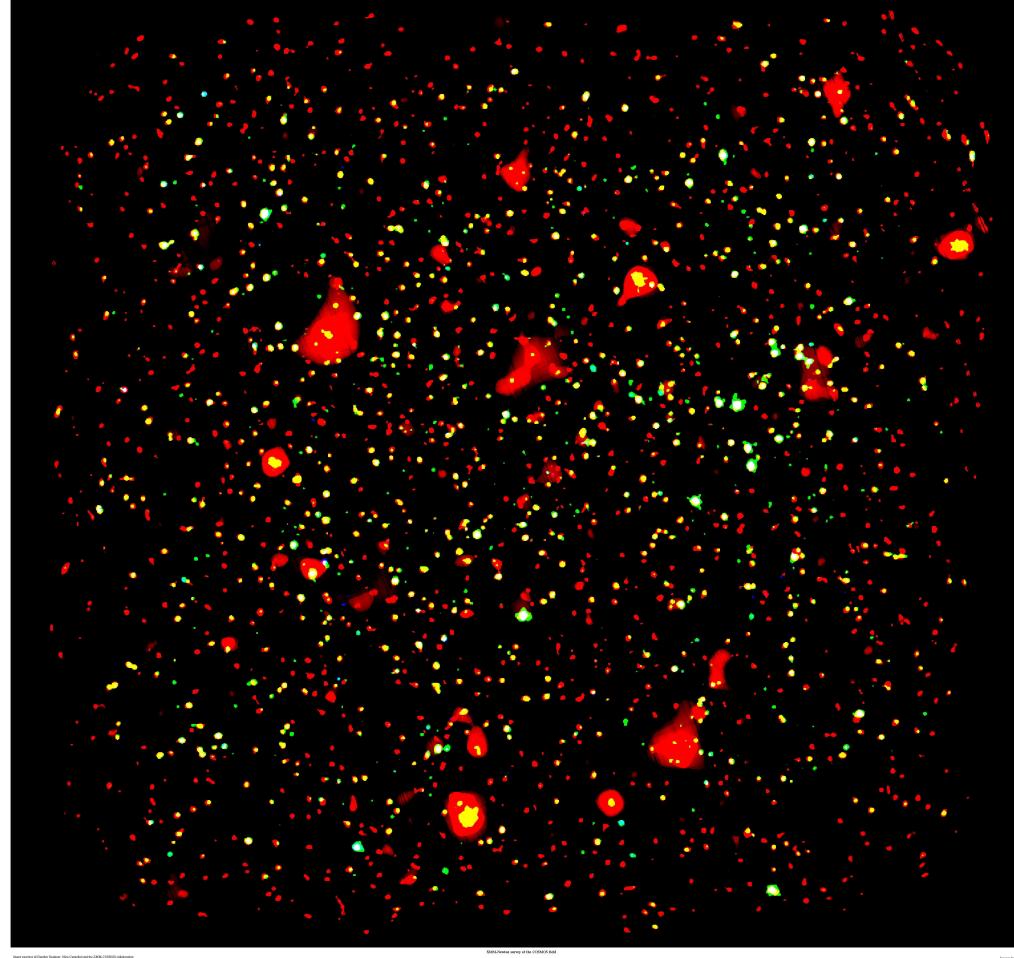
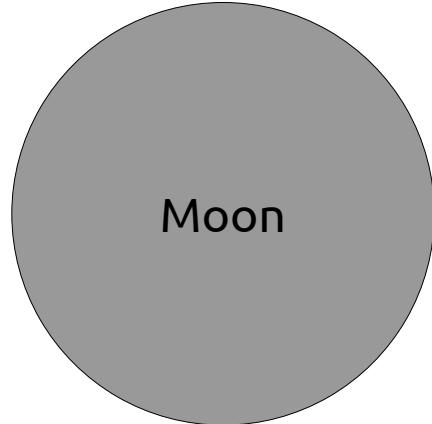
Geometry ?



Solar corona

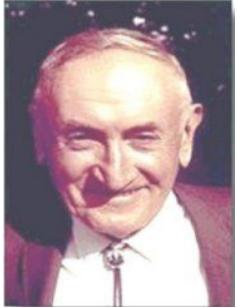
NASA / ESA /  
SOHO

# Tracking supermassive black holes

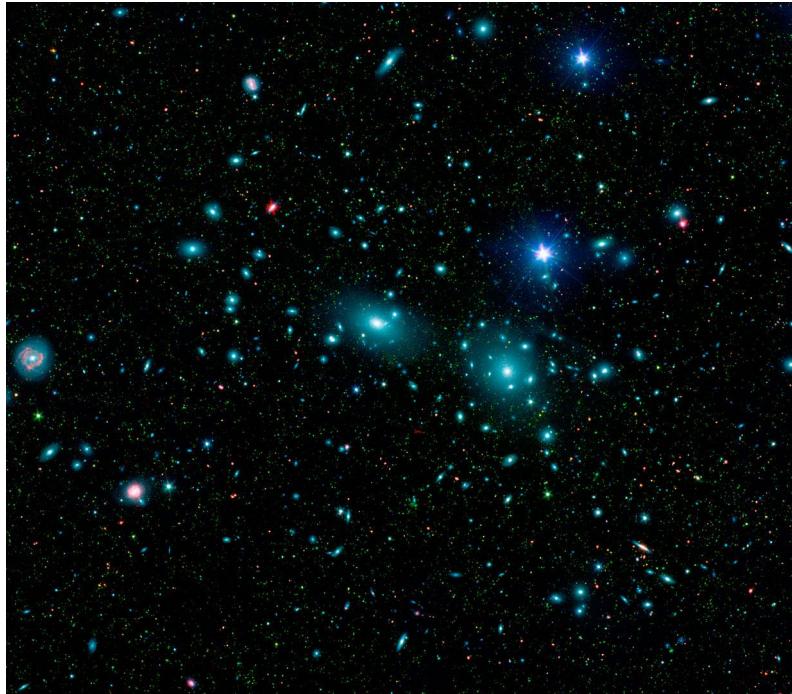


ESA / XMM-Newton

# Clusters of galaxies



Fritz Zwicky  
1933  
Dark matter



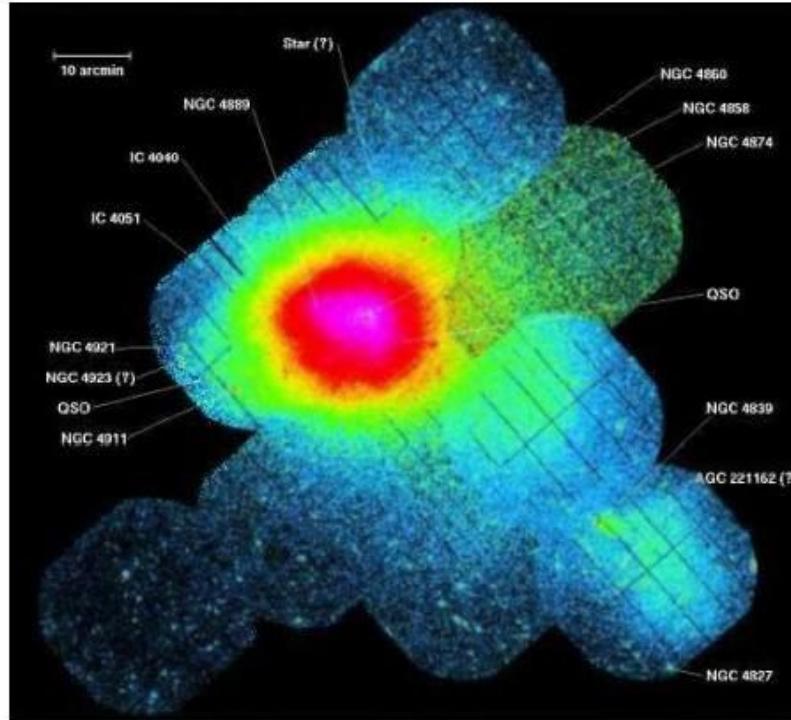
Coma cluster

NASA / JPL-Caltech / L. Jenkins (GSFC)

# Clusters of galaxies



Fritz Zwicky  
1933  
Dark matter

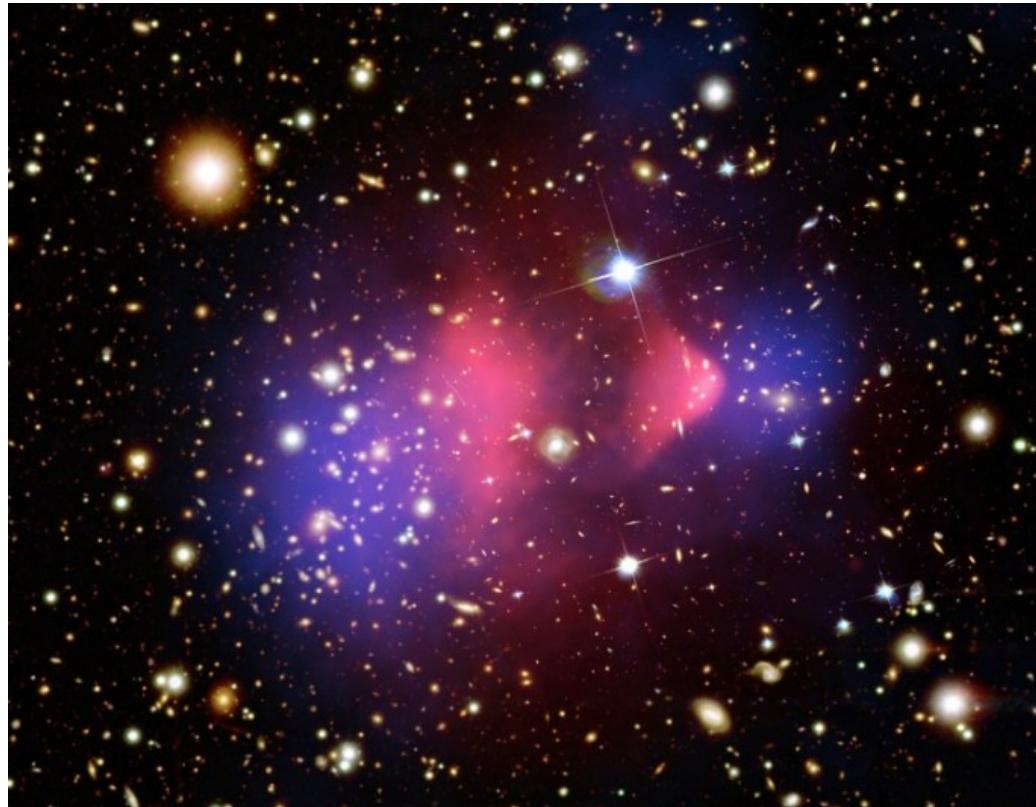


$10^8$  K hot gas  
5-10 times more massive than stars

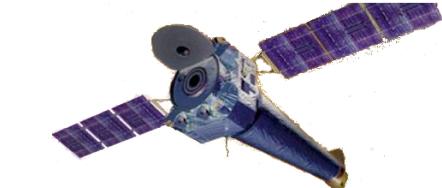


ESA / XMM-Newton

# The Bullet Cluster

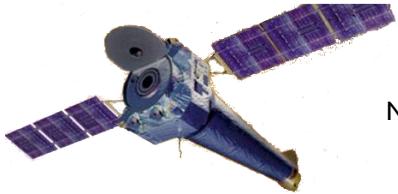
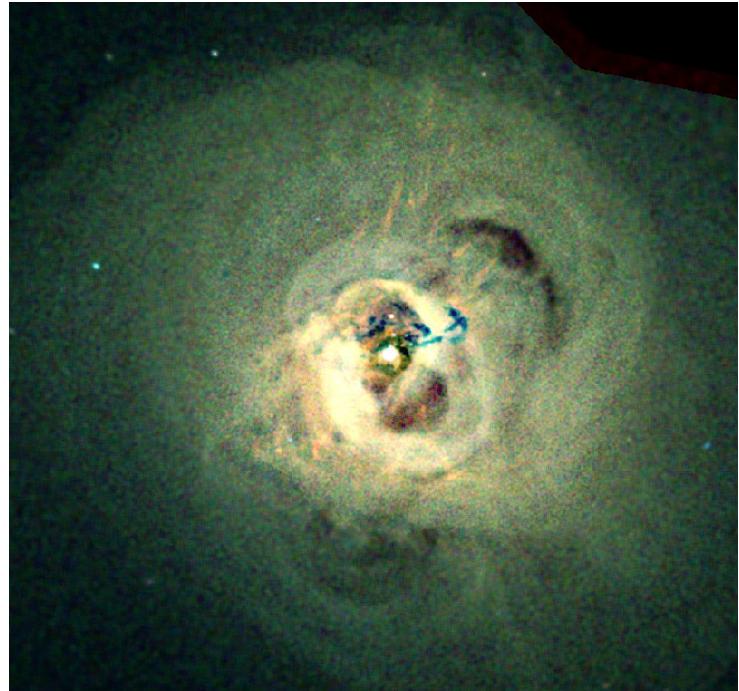


Invisible, collision-less mass  
Dark matter



NASA / CXC / Chandra  
NASA / STScI  
European Southern Observatory

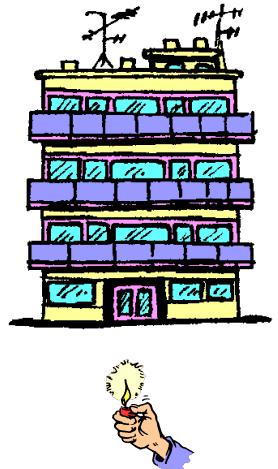
# The Perseus Cluster



NASA / CXC / IoA / A. Fabian

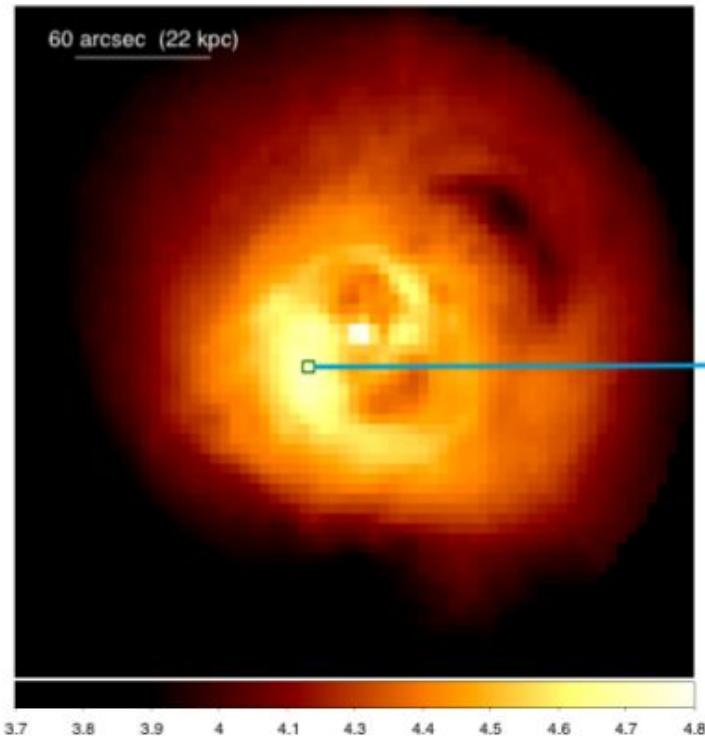


Radio jet of central galaxy

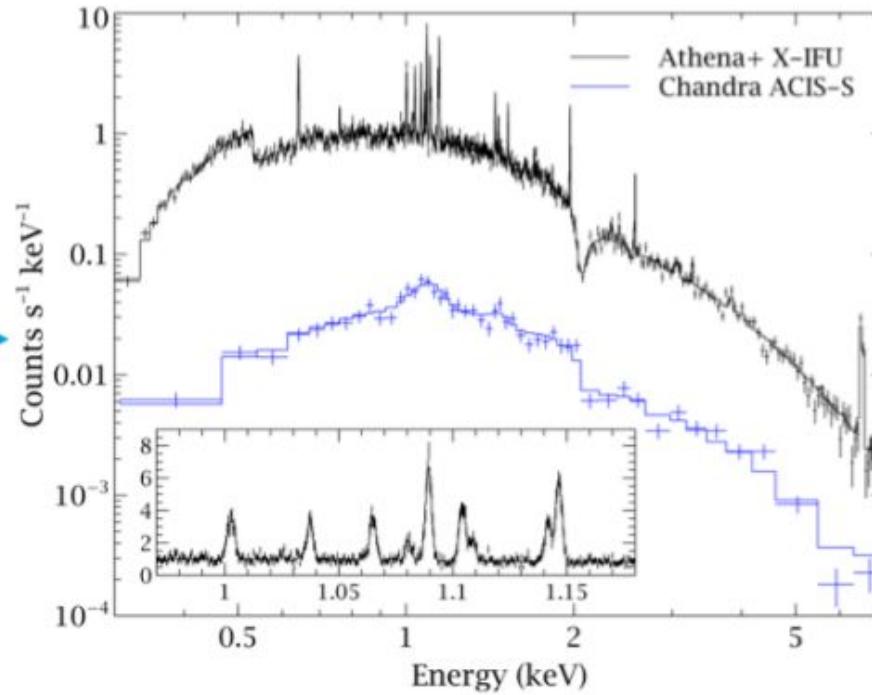


M. Gendron-Marsolais et al.; S. Dagnello,  
NRAO/AUI/NSF; Sloan Digital Sky Survey.

# Athena: The future major X-ray observatory



Launch foreseen in 2034



Strong CH participation is underway