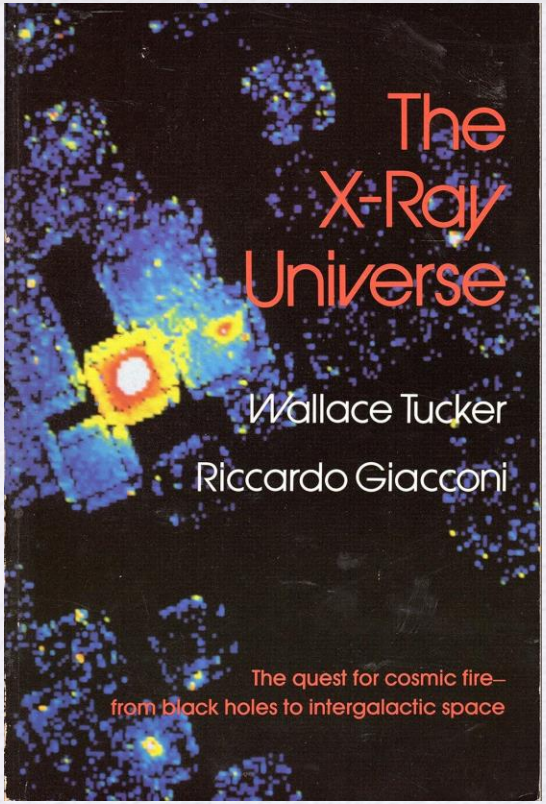
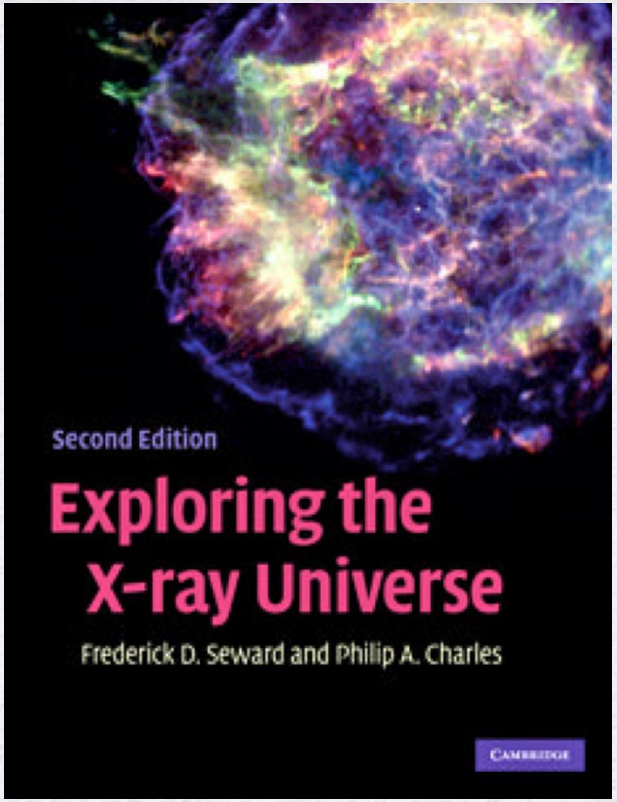
X射线天文学简介

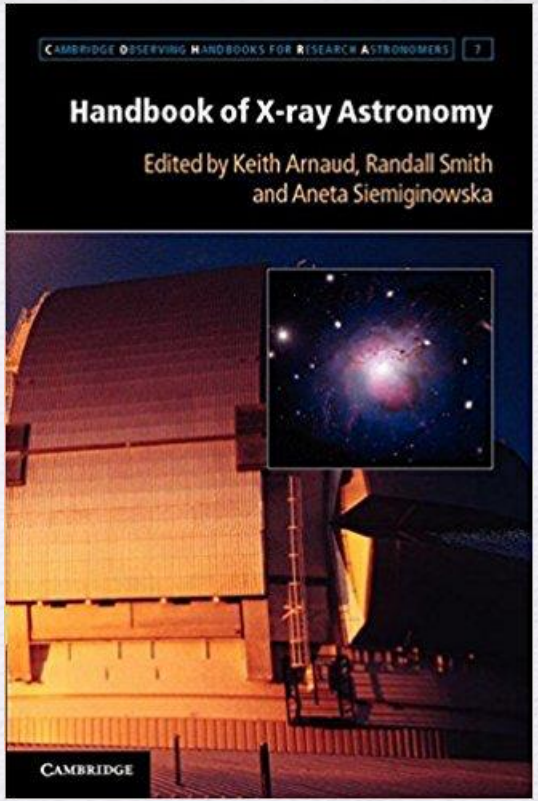
袁为民

天体物理不可或缺的重要组成部分
空间科学的主力方向之一
实验科学、技术与理论驱动、昂贵、大团队协作/项目

参考书


The X-Ray Universe
Wallace Tucker
Riccardo Giacconi
The quest for cosmic fire–
from black holes to intergalactic space


Second Edition
Exploring the X-ray Universe
Frederick D. Seward and Philip A. Charles
CAMBRIDGE


CAMBRIDGE OBSERVING HANDBOOKS FOR RESEARCH ASTRONOMERS
7
Handbook of X-ray Astronomy
Edited by Keith Arnaud, Randall Smith
and Aneta Siemiginowska
CAMBRIDGE

2021： X-ray discovery 获诺奖 120 周年；
2022 X-ray 天文学诞生 60 周年，X-ray 天体 发现获诺奖 20 周年

作为宇宙信使的X射线

原创 袁为民 中国物理学会期刊网 2021-08-18 10:00

收录于话题
#X射线专题 4个 >

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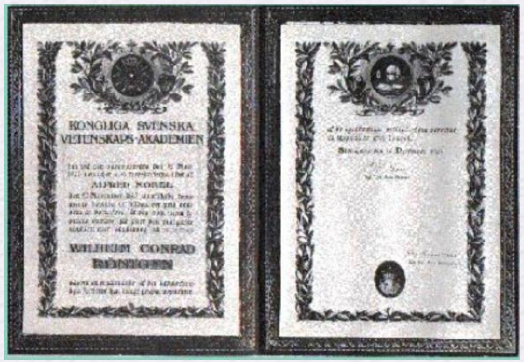
本文选自《物理》2021年第8期

高级科普文章

The discovery of X-rays in 1895

Wilhelm Röntgen's image of Anna Bertha Röntgen's hand. Image credit: Wellcome Library, London.

吸收概率∝Z^3



Roentgen's 1901 Nobel Price in Physics (first ever)

Wilhelm C. Roentgen 伦琴

伦琴在检测他的阴极射线管（电子枪）时发现了X射线（伦琴射线）。
偶然性（或机遇）在科学发展中往往起着重要的作用。
机遇总是偏爱那些有准备的人。

伦琴与X射线的发现

原创 曹则贤 中国物理学会期刊网 2021-08-13 10:00

收录于话题 #X射线专题 4个 >

作者：曹则贤(中国科学院物理研究所)

本文选自《物理》2021年第8期

X-ray & γ-ray 量级和单位

- 更多表现为粒子性 Photon -- 光子
- 辐射频率：ν
- 光子能量：

$$E = h\upsilon = hc/\lambda \qquad h = 6.625 \square 10^{-27} ergs$$ Planck's const

$$E = kT \qquad k = 1.38 \square 10^{-16} ergK^{-1}$$ Boltzmann's

T – temperature　　Wien displacement law, peak　　$h\nu = 2.82kT_{bb}$

- 单位：*electron-volts (eV)*

1 eV = 1.6x10^{-12} erg

- 转换
  - 光子波长-能量
  - 光子能量-温度

$$E = 12.4/\lambda(A) \quad (\text{keV})$$
$$E = 8.62 \square 10^{-5} T \quad (\text{eV})$$
$$T = 1.16 \square 10^{4} E \quad (\text{K})$$

1 eV = 1.16x10^{4} K
1 keV ~ 10^{7} K

物理量单位：cm . g . S 制

高能电磁波段

Photon	EUV	X-ray	Gamma-ray
能量	13.6 – 100 eV	0.1 – 200 keV	200keV-10^{15}eV (PeV)
频率 (Hz)	3.3E15 – 2.4E16	2.4E16 – 4.8E19	> 4.8E19
波长 (A)	911 - 124	124 - 0.062	< 0.062
温度(K)	1.6E5 - 1.16E6	1.16E6 – 2.3E9	> 2.3E9

高能波段展示的是 Hot & energetic universe !

X-ray 是宇宙中一种很自然的辐射

刘碧芳讲座

超新星激波

m_p - proton mass

- 抛射物速度 V> 5,000km/s; 气体热能量 $E \sim \frac{1}{2} m_p V^2 \sim kT$
- $T > 10^8$ k ~10keV

星系和星系团：气体速度弥散~恒星/星系速度弥散ΔV

- 星系： star ΔV > 100km/s; $T > 3 \times 10^6$ k ~0.3 keV
- 星系团：galaxy ΔV > 1000km/s; $T > 3 \times 10^7$ k ~3 keV

引力束缚系统的维里温度：

$$kT = \alpha \frac{GMm_p}{R}$$

M/R: compactness (势井深度)

- 星系团：$M \sim 10^{15} M_{sun}$ $R \sim 2Mpc$ → $T \sim 10^{7\text{-}8}$ k
- 恒星： $M \sim 1\, M_{sun}$, $R \sim 1\, R_{sun}$ → $T \sim 4 \times 10^6$ k (soft X-ray !) 日冕温度

X-ray 的性质

- 粒子性
- 一定的穿透性
- 与物质相互作用

  - 光电吸收（photoelectric absorption）

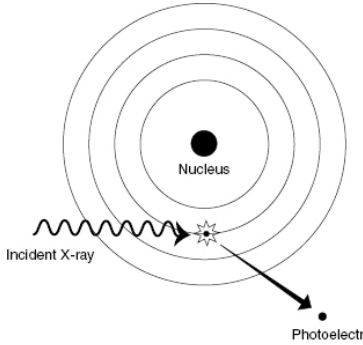
    E = 13.6eV - ~60 keV

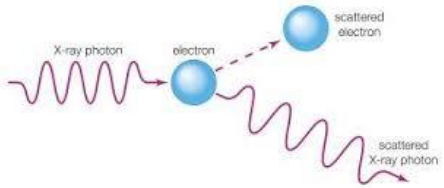
  - 电子散射（Compton scattering）

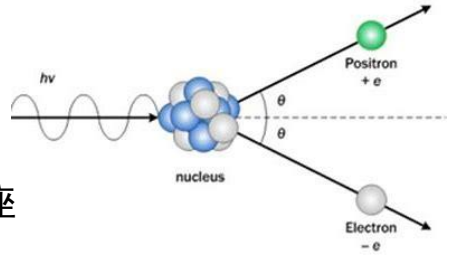
    60 keV < E < ~ 10MeV

  - 产生正负电子对（pair production）

    E > 1.02MeV (主导 > 5-10 MeV）



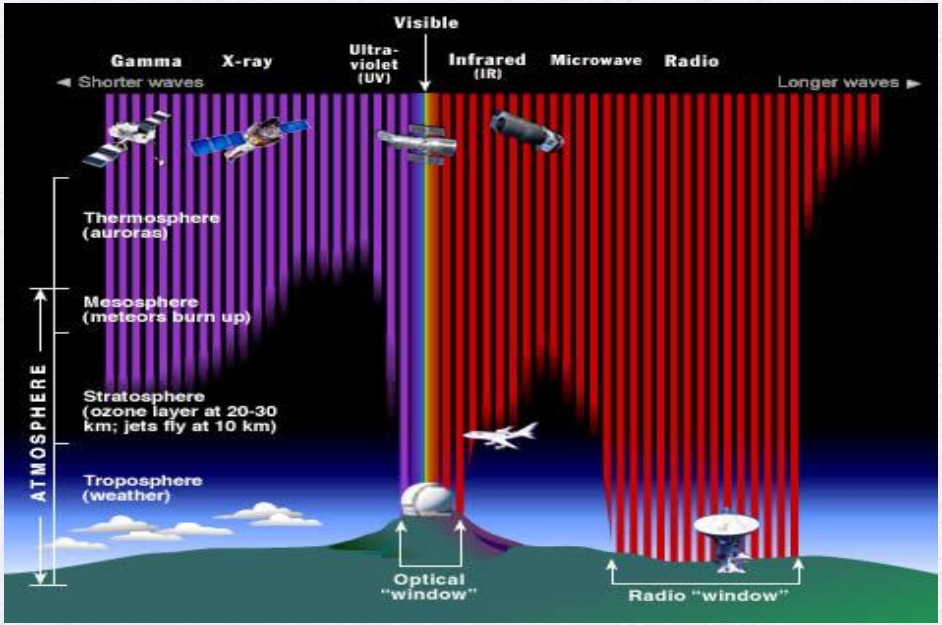


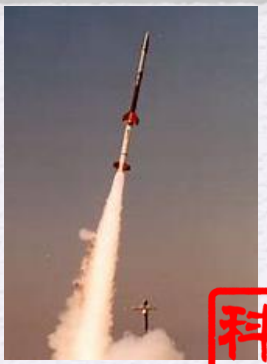


高能探测器正是运用了这些原理

cosmic X-rays cannot reach the ground

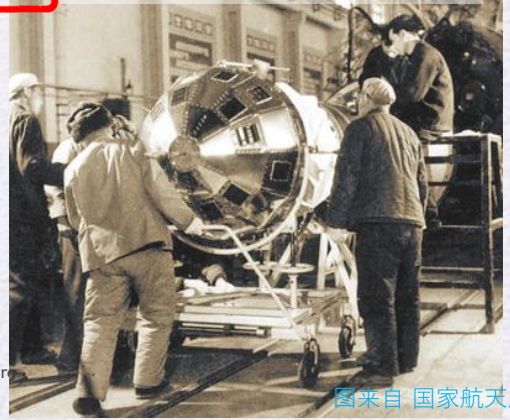
Atmospheric transmission to EM radiations





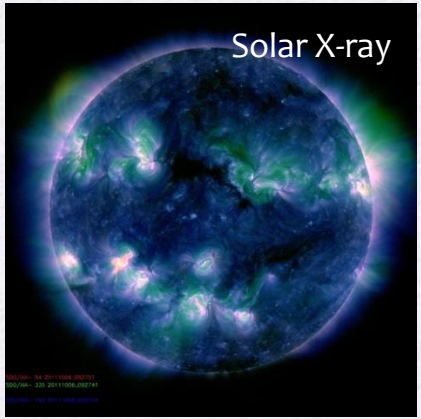
Pictures from NASA
https://science.nasa.gov/missions/explor

东方红一号卫星 1970. 4. 24



来自太阳的X-ray辐射

V-2 rockets 1949年太阳被探测到为 X 射线源
天空中唯一 X 射线源，直到 1962




Dr. Friedman with Aerobee rocket.

探测器：
Geiger计数器

X-ray 来自于Solar corona： $kT \sim 10^6$ k

光度为光学总光度的百万分之一

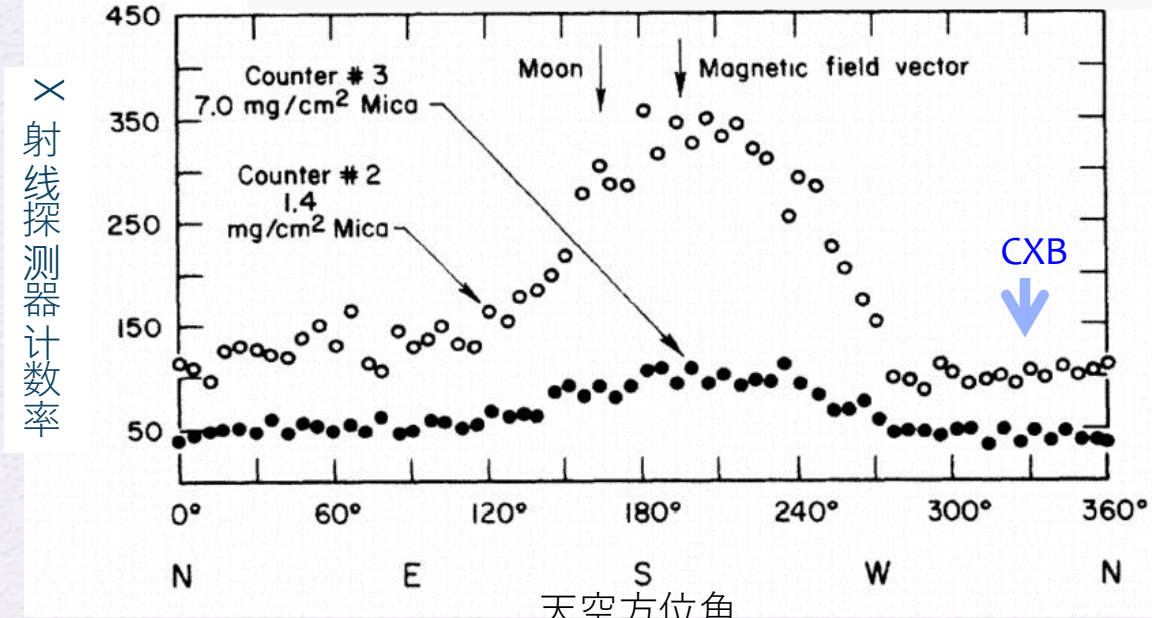
预期其它恒星的 X 射线不可能被当时的仪器探测到

开启探索宇宙的新窗口 - X 射线 (1962)

R. Giacconi
(1931-2018)

2002 诺贝尔物理学奖

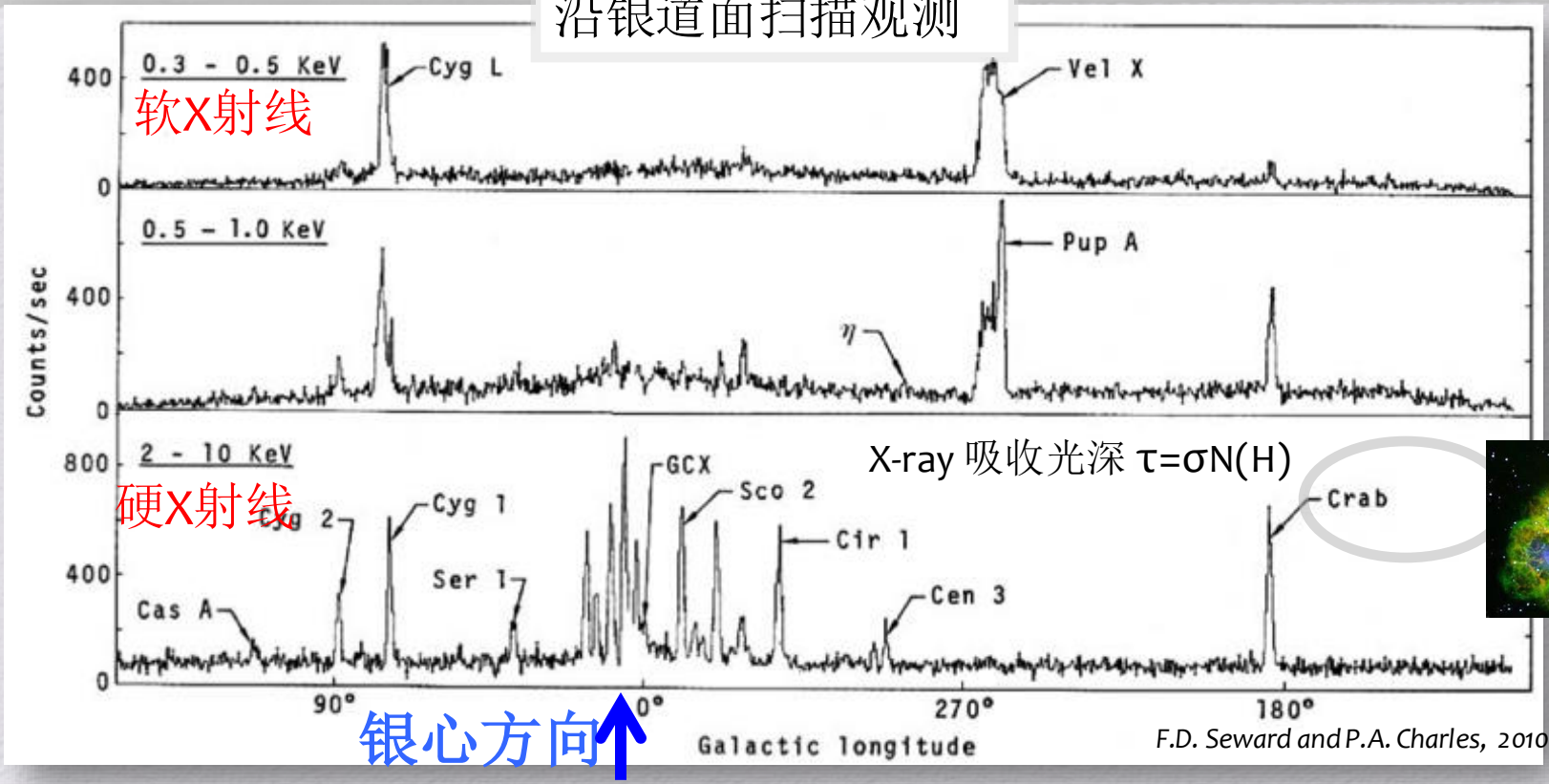
首次发现宇宙X射线源天蝎座X-1



'Observing Sco X-1 was the reward nature offered to scientists willing to gamble on a long shot'. --- R. Hirsch <*Glimpsing an Invisible Universe*>

more X-ray sources discovered in the 1960's

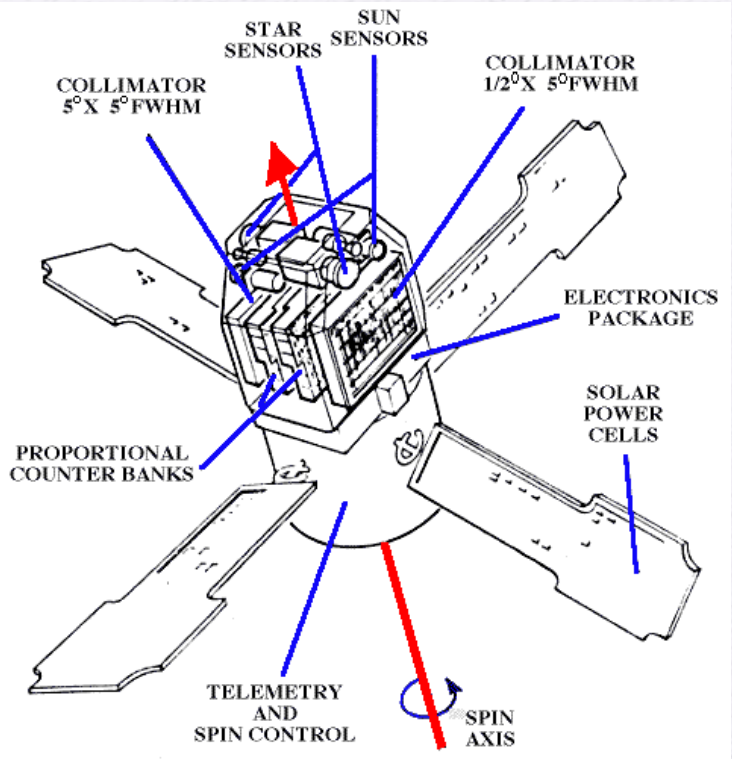
沿银道面扫描观测



X-ray 吸收光深 $\tau=\sigma N(H)$

F.D. Seward and P.A. Charles, 2010

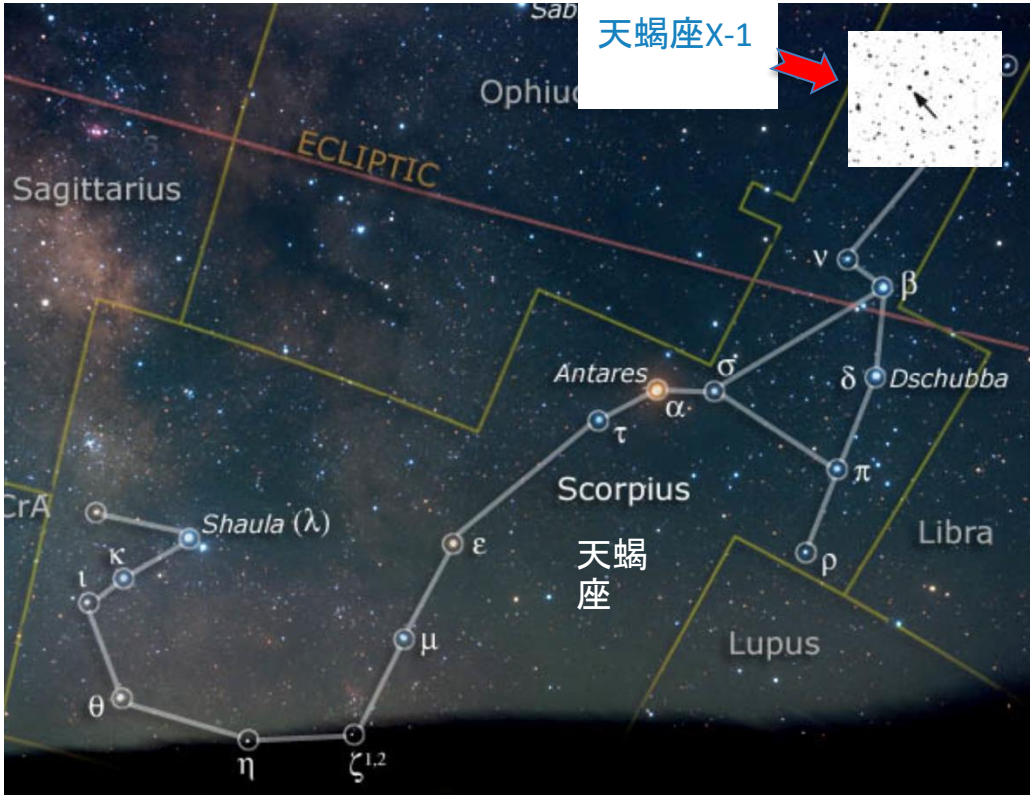
X 射线观测的突破: Uhuru 卫星

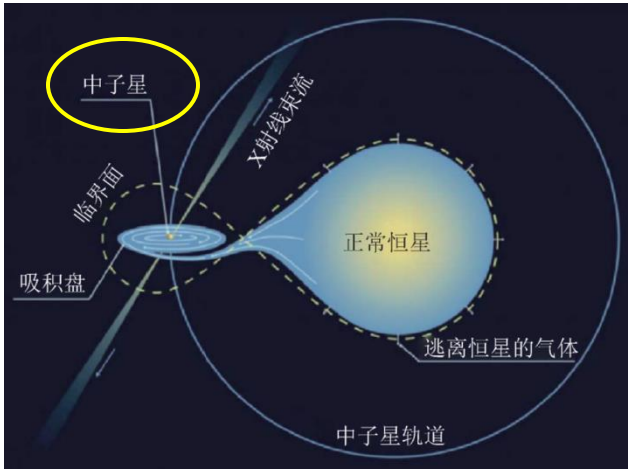


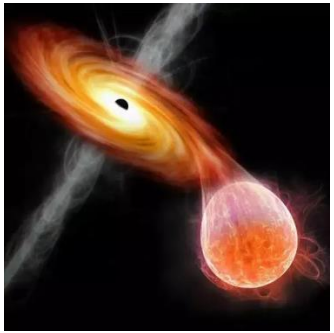
1970 第一颗X射线天文卫星. NASA

Bruno Rossi

神秘的天蝎座X-1：中子星 X-ray 双星





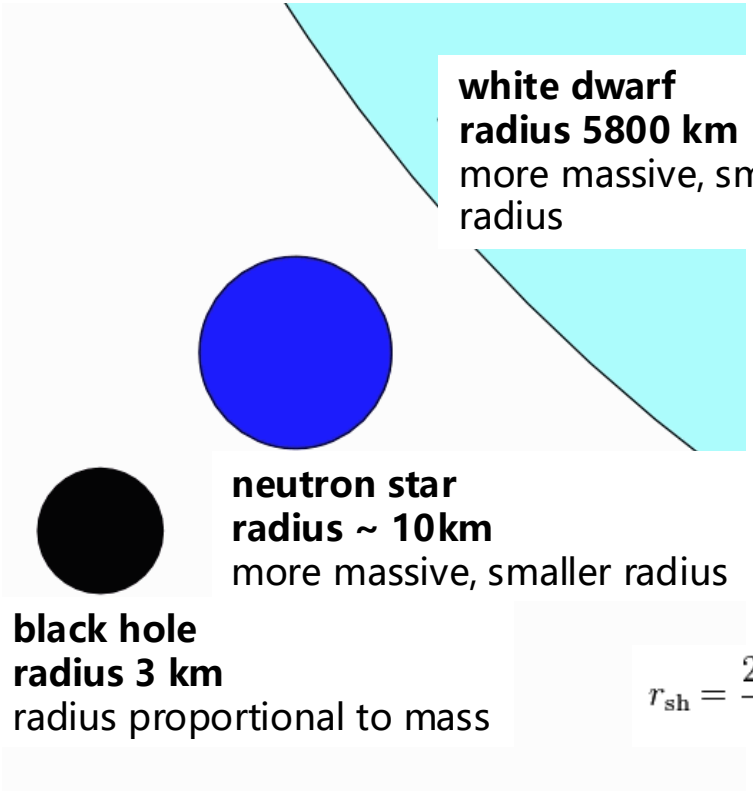


吸积释放引力能

袁峰讲座

compact objects: white dwarf, neutron stars & black holes

1 solar mass



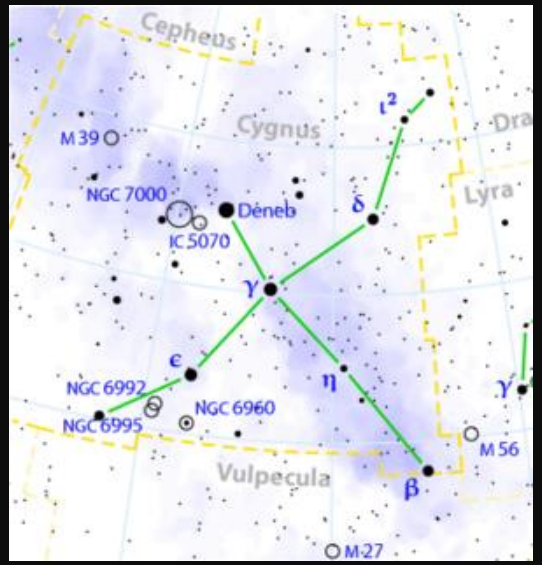
white dwarf
radius 5800 km
more massive, smaller radius

neutron star
radius ~ 10km
more massive, smaller radius

black hole
radius 3 km
radius proportional to mass

$$r_{\rm sh} = \frac{2GM}{c^2} \approx 2.95\,\frac{M}{M_{\rm Sun}}\ {\rm km},$$

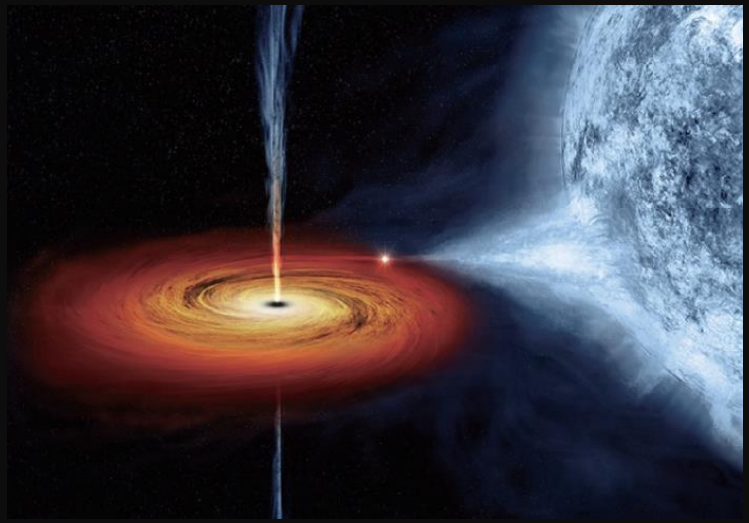
Black hole X-ray binary : stellar mass black hole



Cyg X-1

mass ~ 20 M_sun

compact objects with mass > 3 M_sun have to be black holes



space-time singularity

celestial object in the universe

energy source: gravity potential energy

matter is heated to 10^6-10^7 k in the process of falling on black hole, and emits X-rays

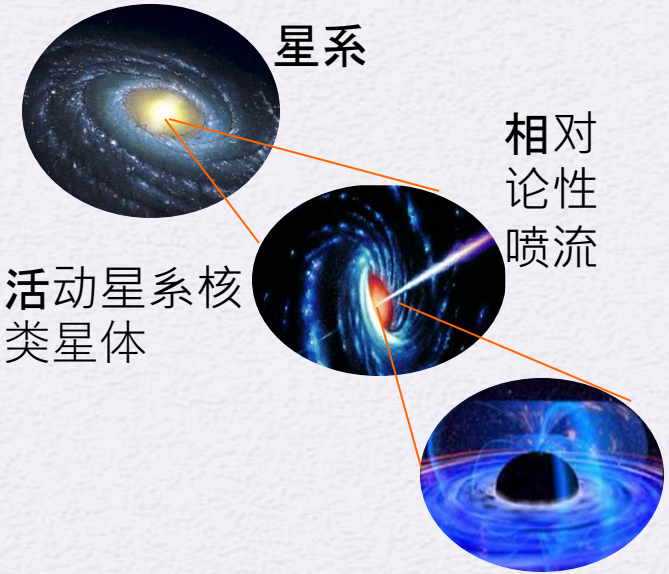
陶炼讲座

活动星系核：活动的超大质量黑洞

强 X 射线源 $10^{42\text{-}47}$ erg/s

质量=$10^{5\text{-}9}$ $M_{\odot}$的黑洞可以产生观测到的辐射功率

黑洞吸积盘—引力能转换为辐射能的发动机

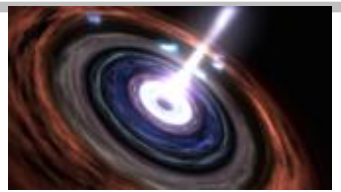


金驰川讲座，袁峰讲座

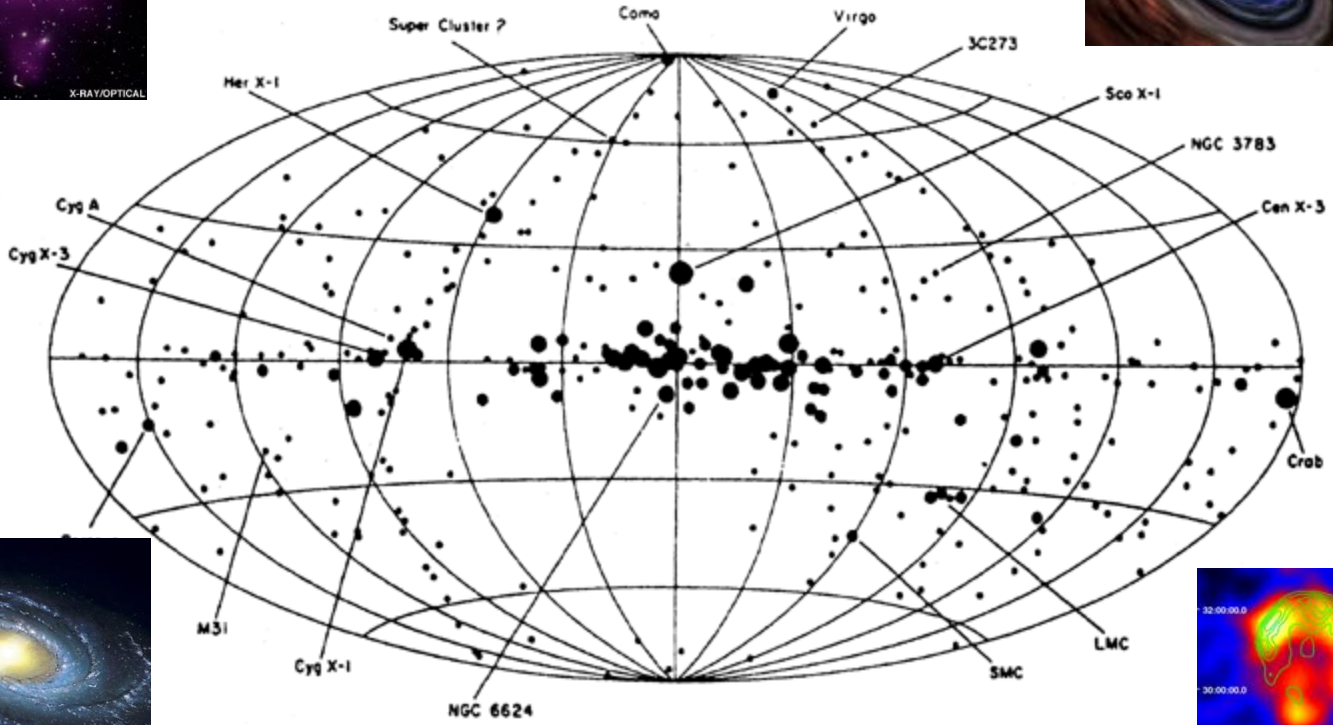
Milestones & X-ray missions since 1962

- 1962- 1970火箭和气球实验
  - Soc X-1, Crab Nebular, bright X-ray binaries, etc.
  - 1st extragalactic source: M87 (active galaxy)
  - Cluster of galaxies (Coma cluster)
- 1970s Uhuru : 1st X-ray 天文卫星 , HEAO-I, Ariel-V, …
- 1978 Einstein 卫星： 1st X-ray telescope
- 1980s: EXOSAT, Ginga, …
- 1990 ROSAT: 1st 深度X射线全天巡天(1.8 万亮源, >10万暗源)
- 1990s: ASCA （first CCD）, Beppo-SAX, RXTE, …
- 1999- 大型X射线天文台 Chandra, XMM-Newton
- 2000- Swift, Suzaku, MAXI, AstroSAT, NuSTARS, NICER, HXMT-慧眼, eROSITA, IXPE, XRISM, EP

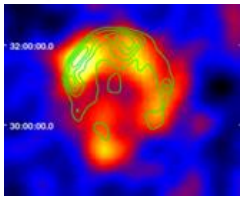
首个 X 射线全天巡天结果：Uhuru 卫星

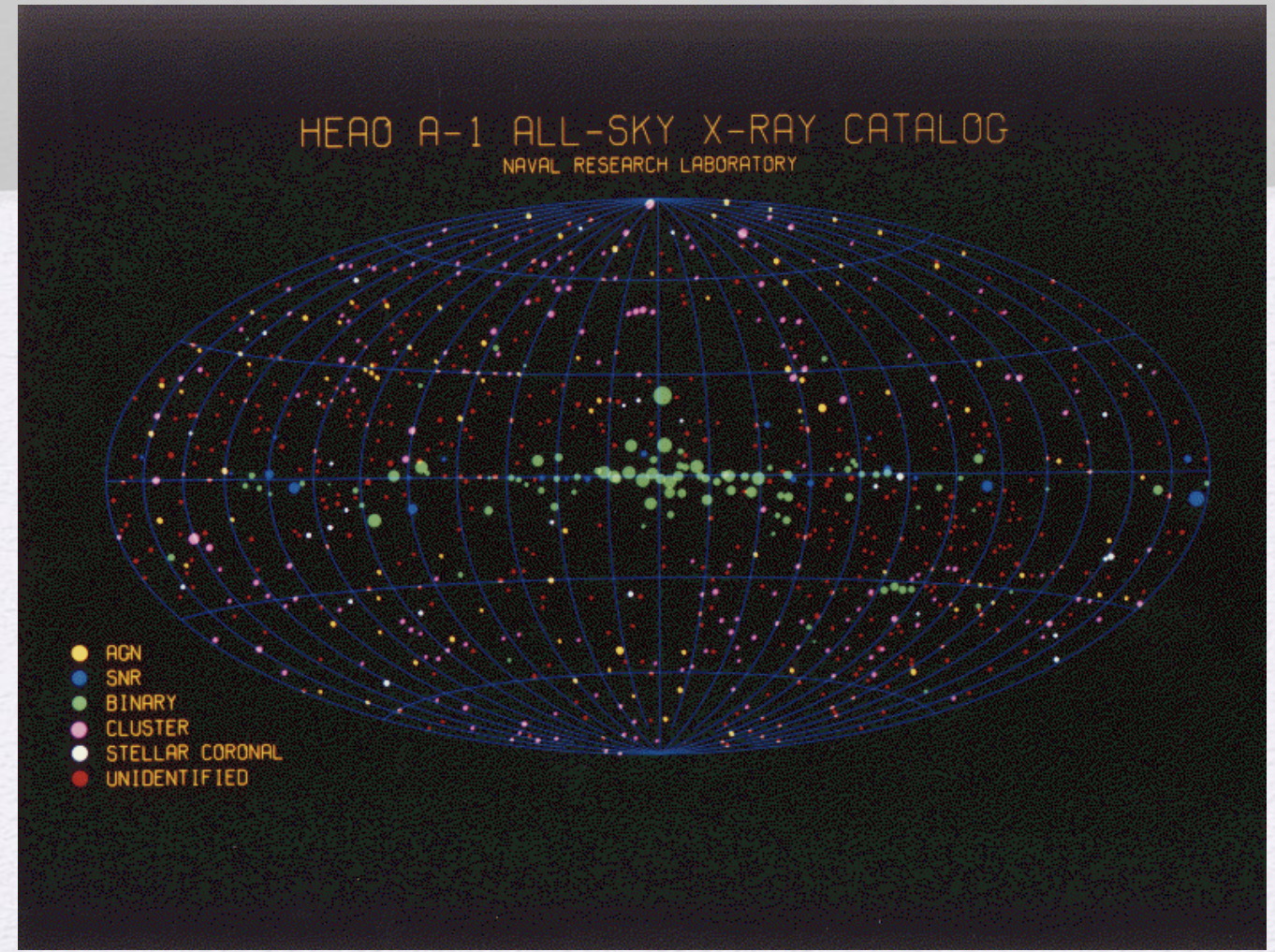


4U catalogue: 339 X 射线源



n et al. 1978




HEAO A-1 ALL-SKY X-RAY CATALOG
NAVAL RESEARCH LABORATORY
AGN
SNR
BINARY
CLUSTER
STELLAR CORONAL
UNIDENTIFIED

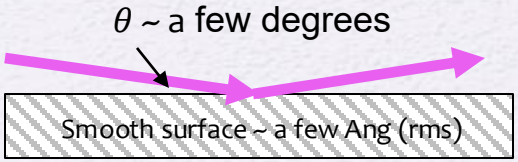
第一台 X 射线望远镜：Einstein Observatory (HEAO-II)

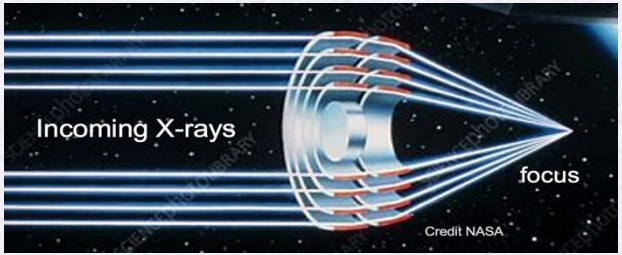
- X-ray reflection by grazing incidence
- Higher reflectivity for lower-E X-rays

Frist: Einstein Observatory (NASA) 1978-1981

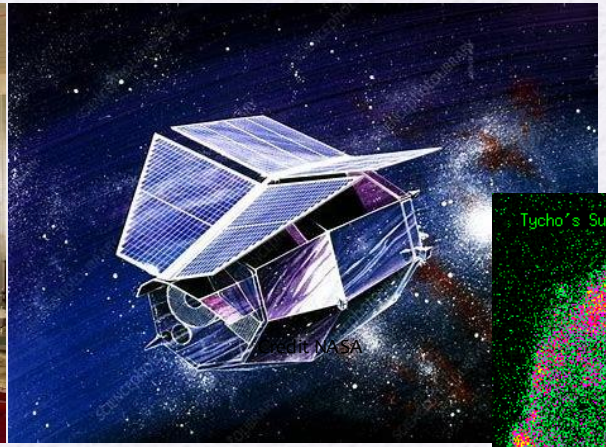
100 x more sensitive than Uhuru

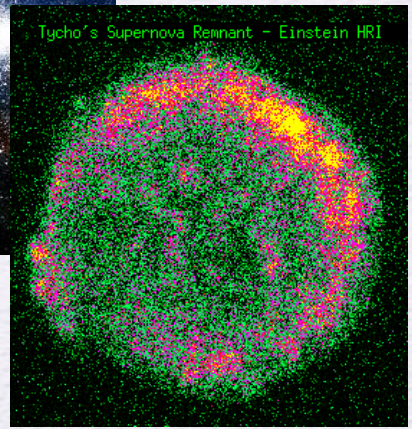
Revolutionzied X-ray astronomy





Wolter-I optics

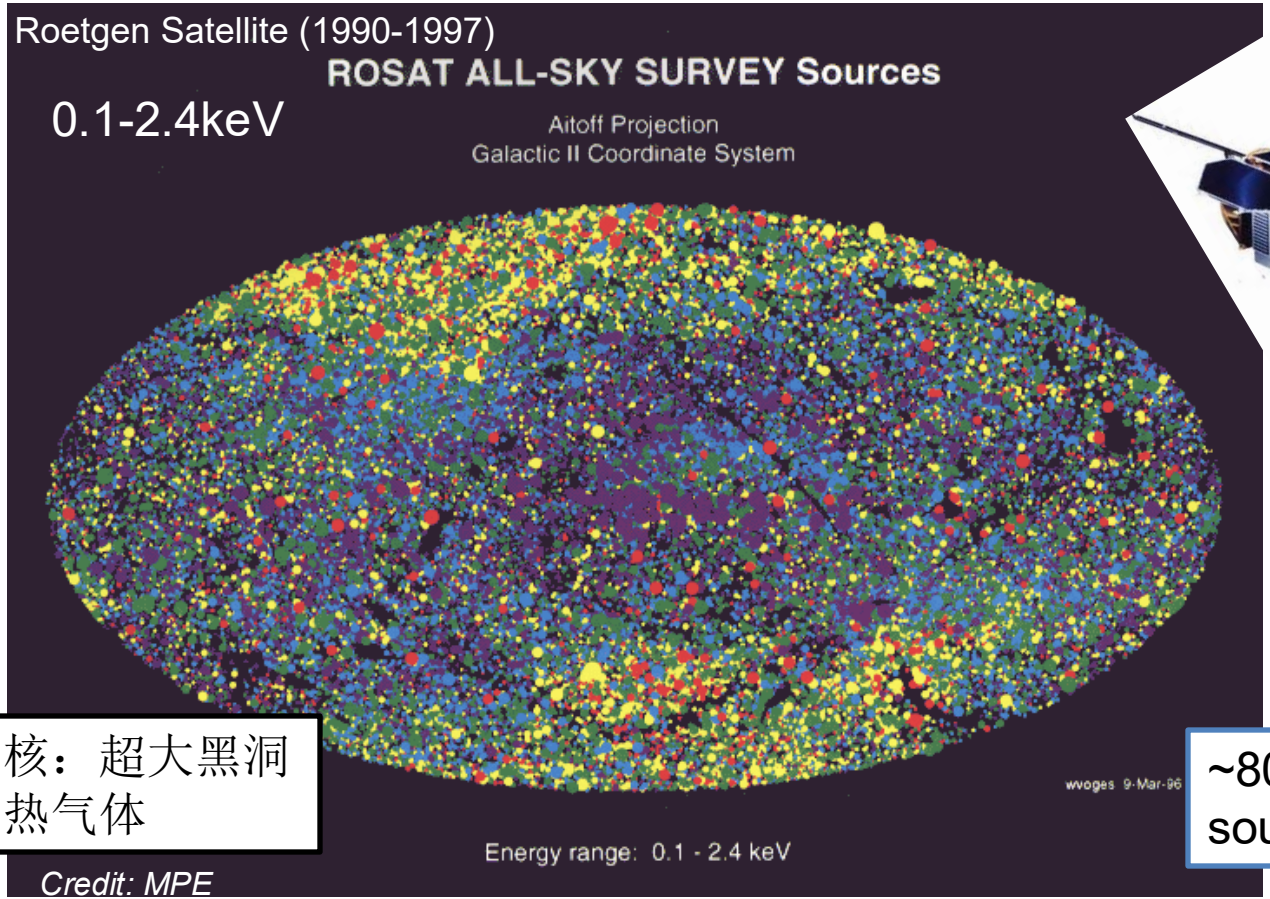




XMM-Newton, Chandra, NuSTAR, eROSITA…

EP-FXT

ROSAT：首个深度软X射线全天巡天



RoetgenSatellite
(1990-1997)

活动星系核：超大黑洞
星系团：热气体

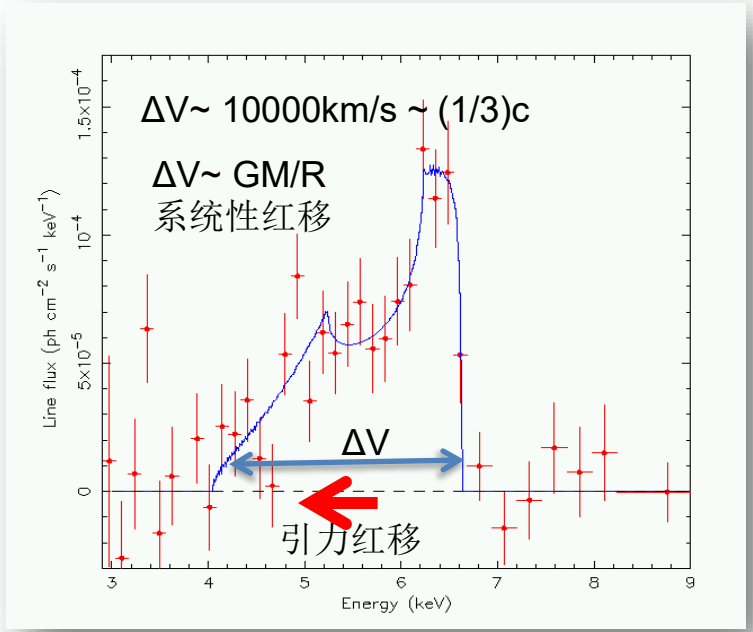
~80,000
sources

ASCA 卫星： 首次使用 X射线 CCD

ASCA (JAXA/ISAS) 1994-2001
First X-ray satellite using CCD

spectral resolution ΔE/E~ 10%

SMBH和吸积盘的观测证据：X 射线 宽Fe 线



黑洞
自旋测量

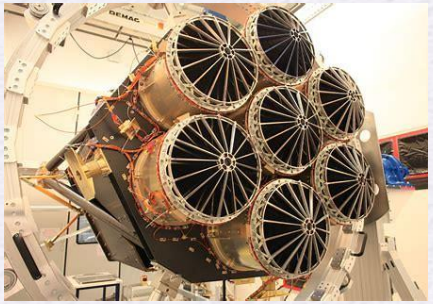
“Gravitationally redshifted emission implying an accretion disk and massive black hole in the active galaxy MCG-6-30-15”

Tanaka + (1995)

Current X-ray astronomy satellites

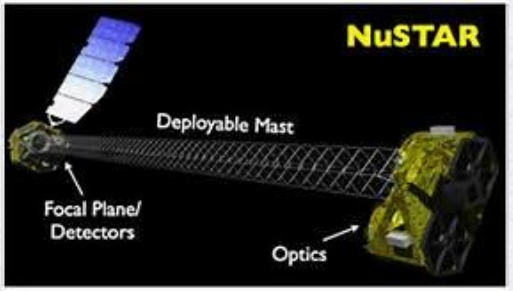
Chandra （NASA ） 0.5” 角分辨

XMM-Newton （ESA） 大面积



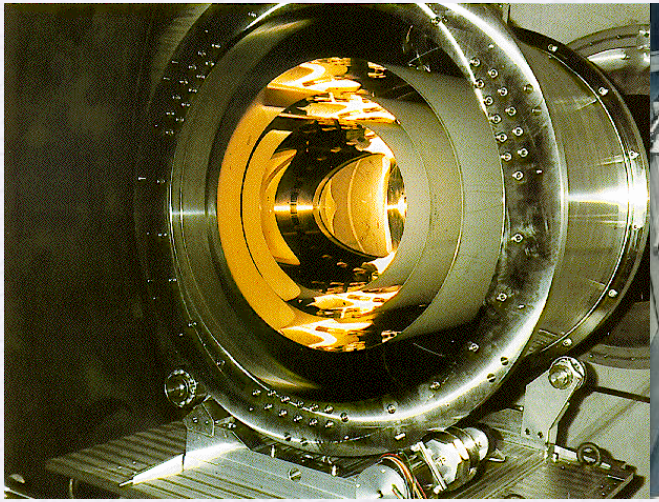
eROSITA （MPE） high grasp

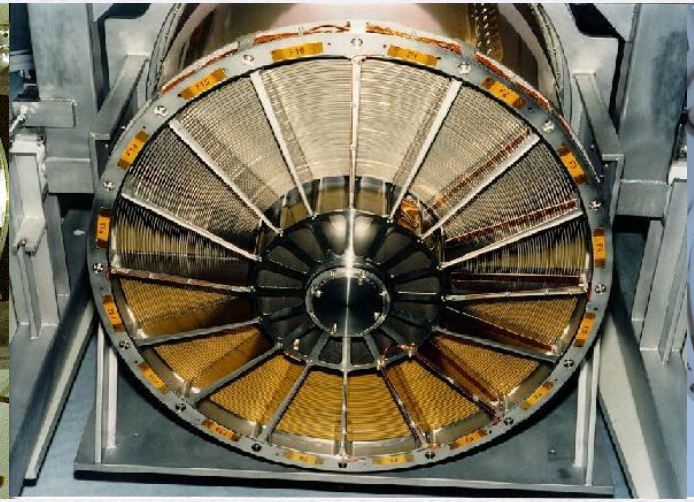
快速机动后随观测



（NASA ） 3-79keV

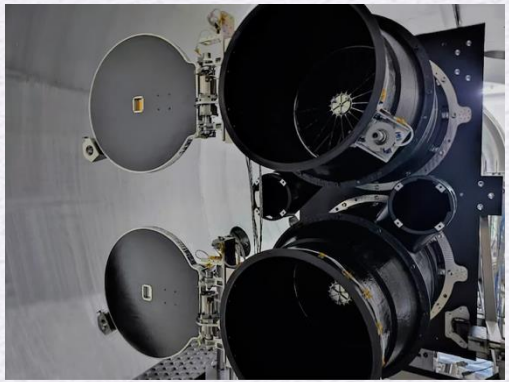
XRISM （JAXA/NASA）
high energy resolution 3 eV





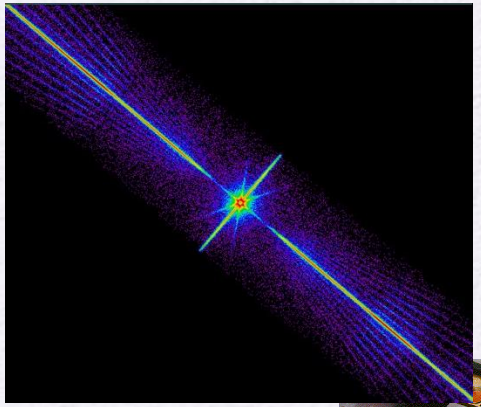
Chandra (NASA)

XMM-Newton (ESA)

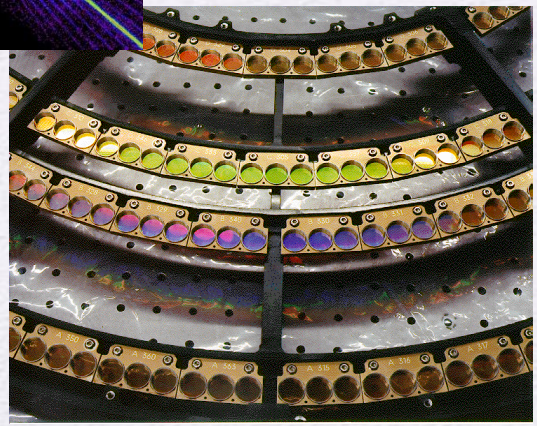


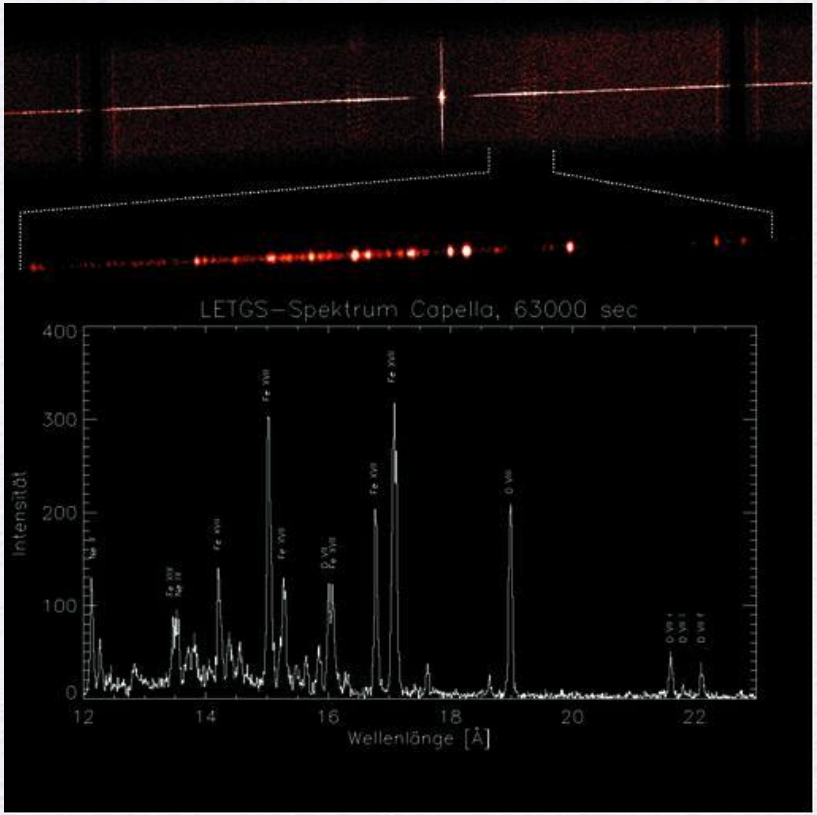
EP-FXT@ (CAS)

X-ray 高分辨光谱观测：分光光谱仪



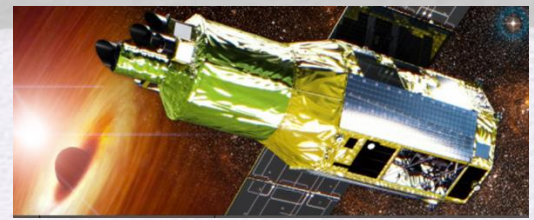
Chandra/LETGS

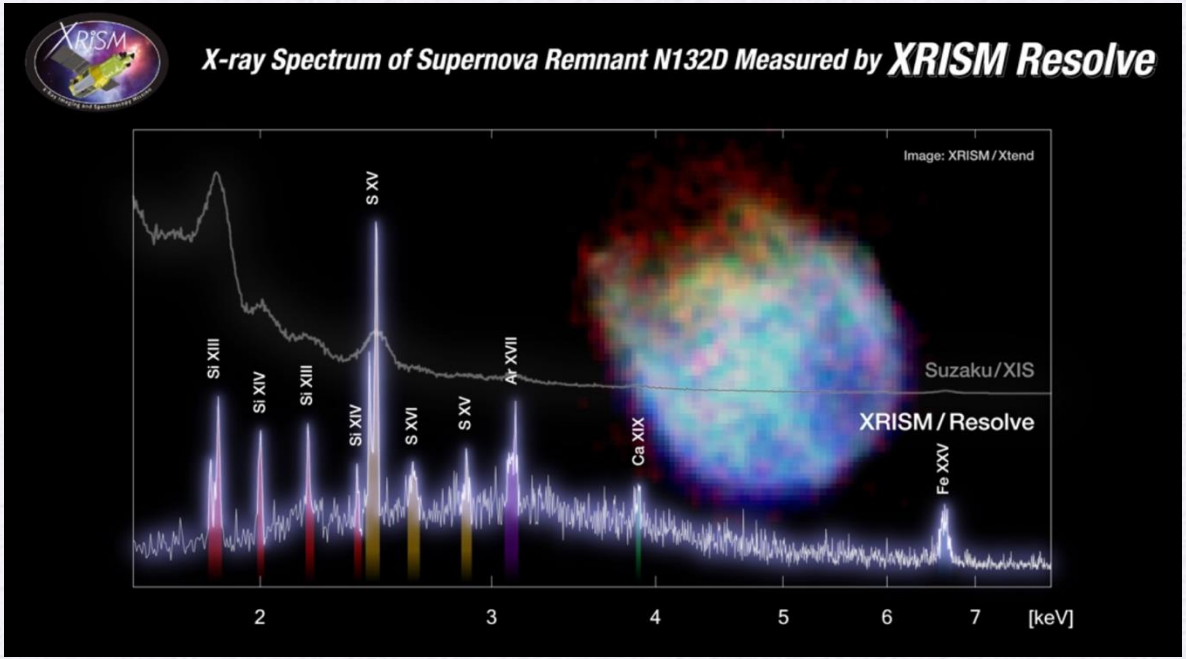




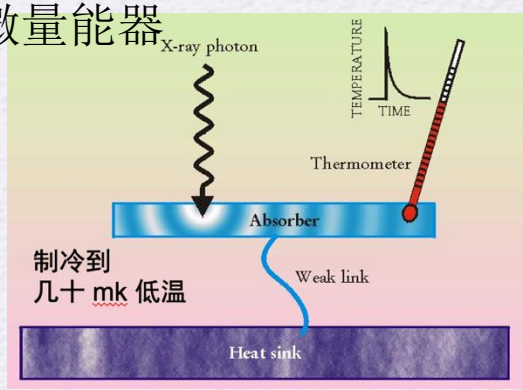
XRISM (JAXA)

2023-



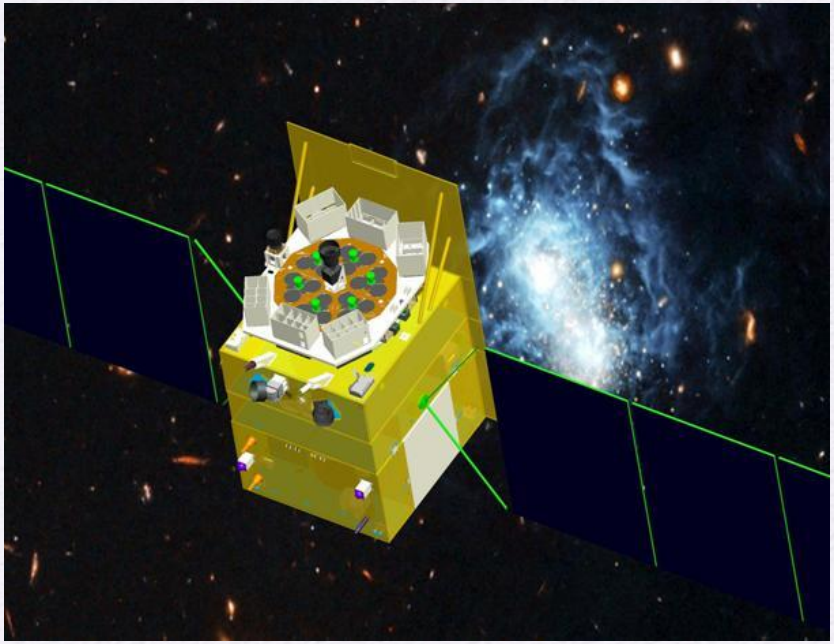


微量能器



energy resolution
< 5eV

中国首颗 X 射线天文 卫星慧眼-HXMT



宽能段、大有效面积、高时间分辨率

详见宋黎明报告

2017-6-15 酒泉

天体辐射信息的获取

- X 射线观测：单光子探测；测量光子的

探测器记录：计数率、 能量、时间、位置、电子云径迹

- 天体信息： 辐射强度、光谱、光变、位置（图像）、偏振

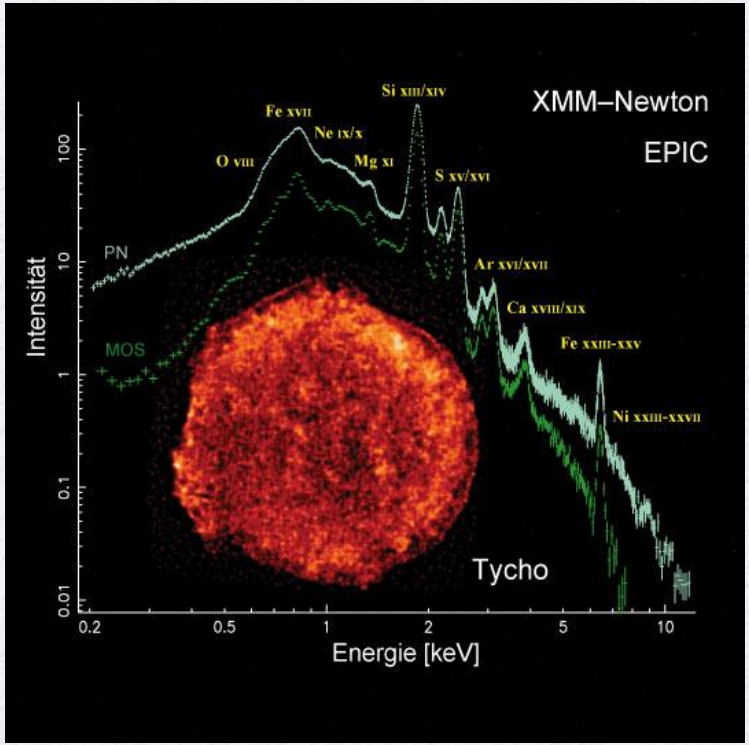
以上物理量可以从探测到的大量光子信息中提取获得

张文达、潘海武 讲座

What do we get from X-ray observations?

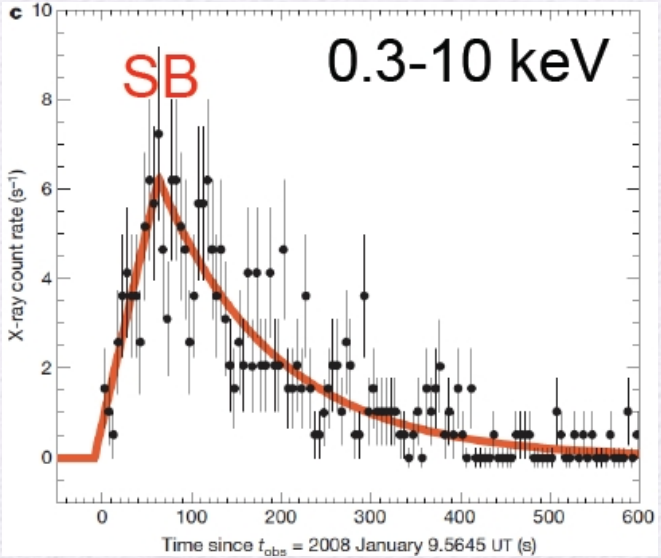
X-ray image

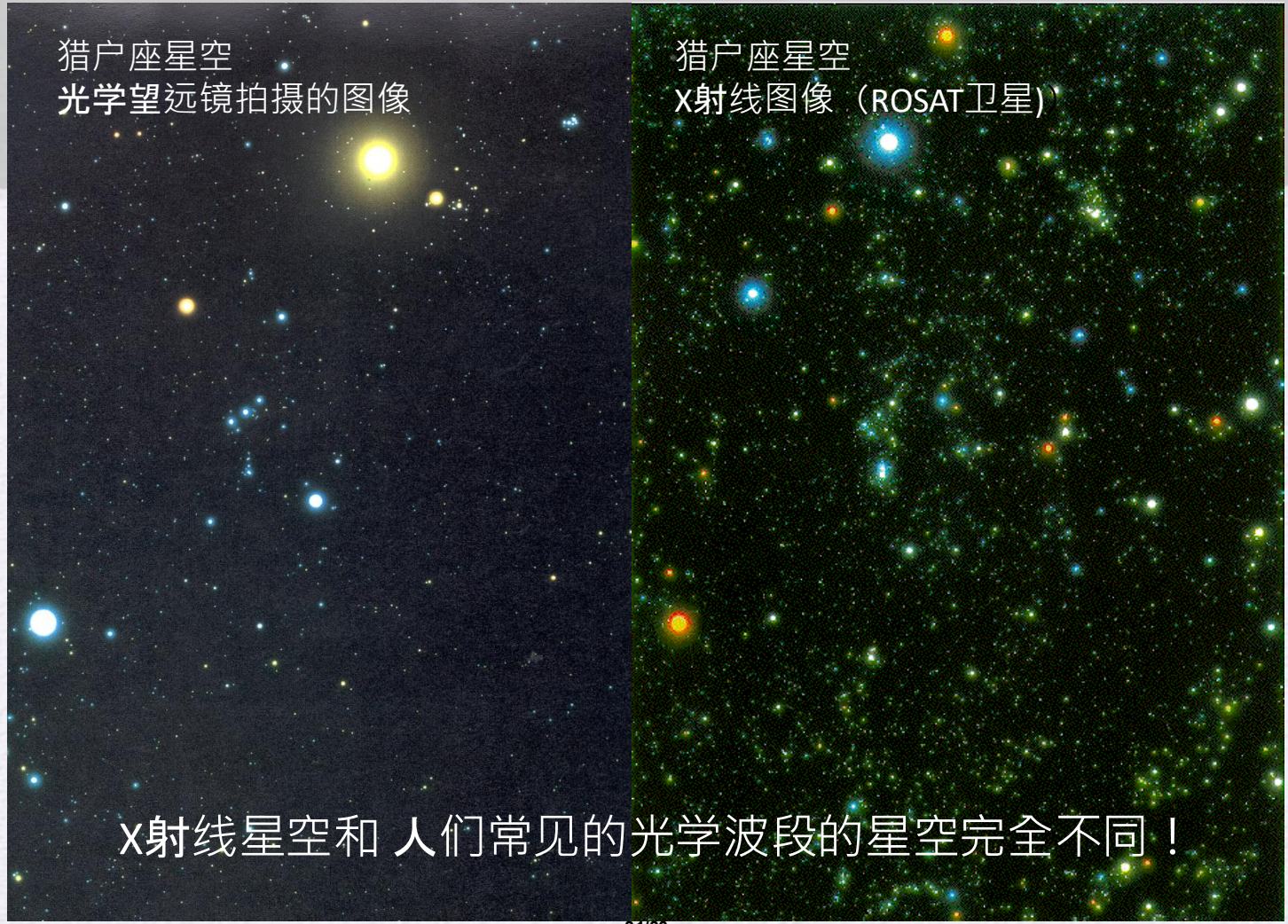
X-ray spectrum



Get all three in one X-ray photon detection!

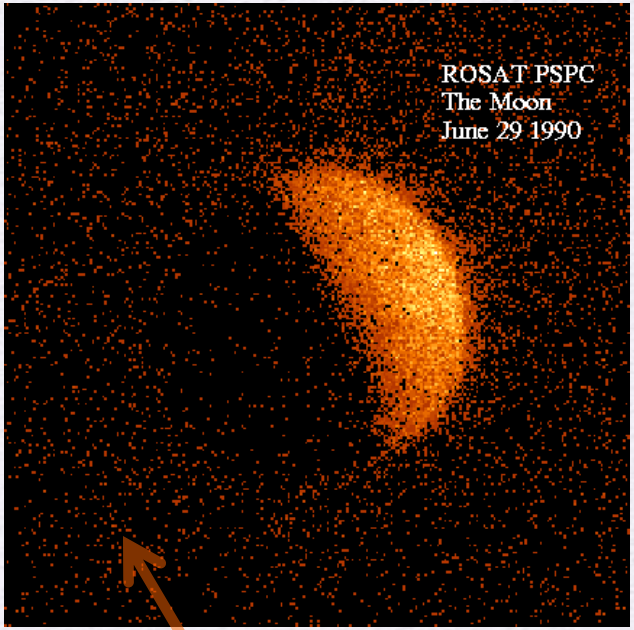
X-ray lightcurve



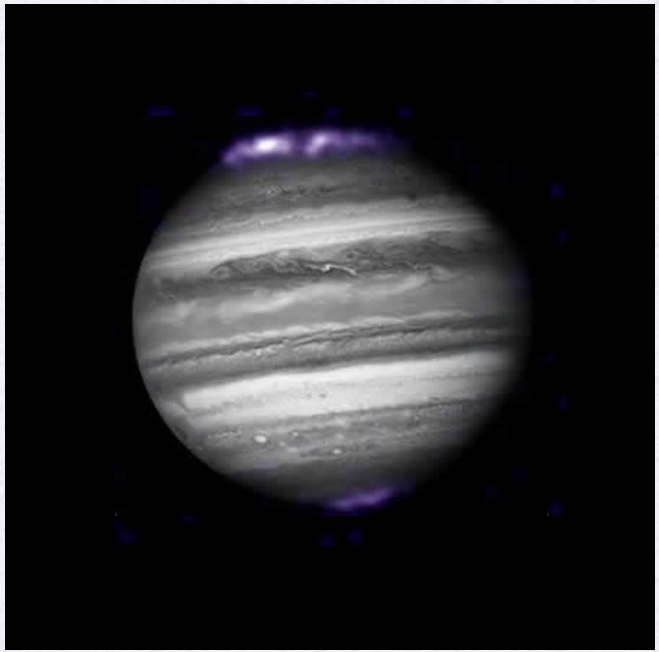

猎户座星空
光学望远镜拍摄的图像
猎户座星空
X射线图像（ROSAT卫星）
X射线星空和 人们常见的光学波段的星空完全不同！

credit: MPE

X-rays from objects in solar system

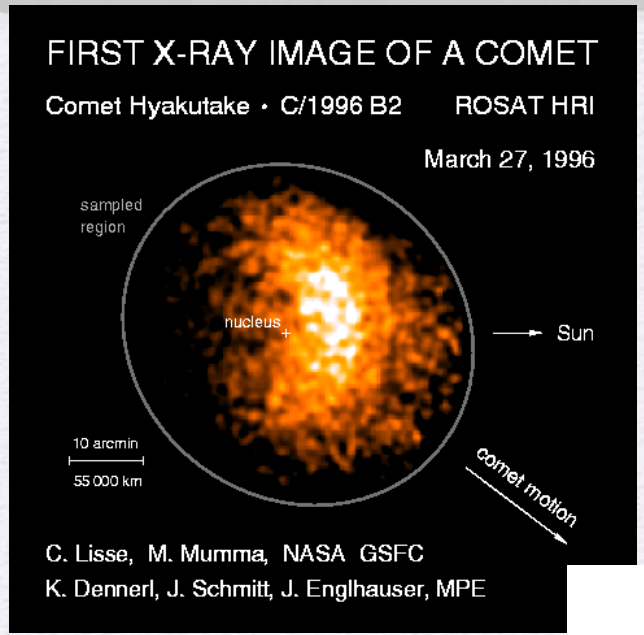


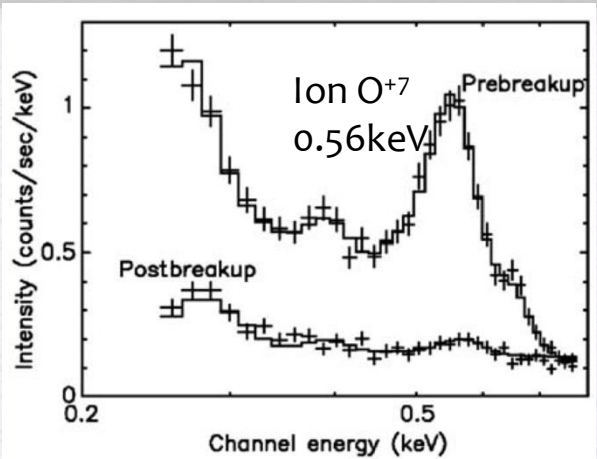
宇宙X射线背景辐射



木星

X-rays from comets

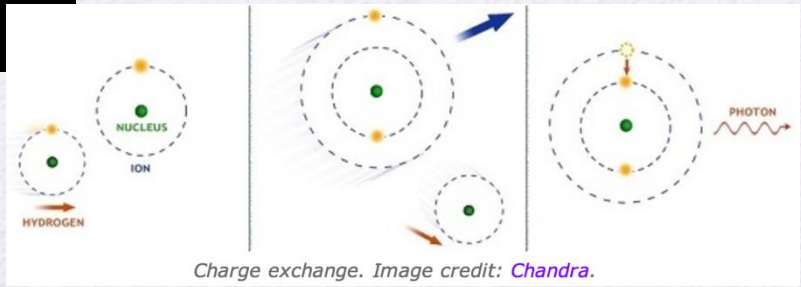




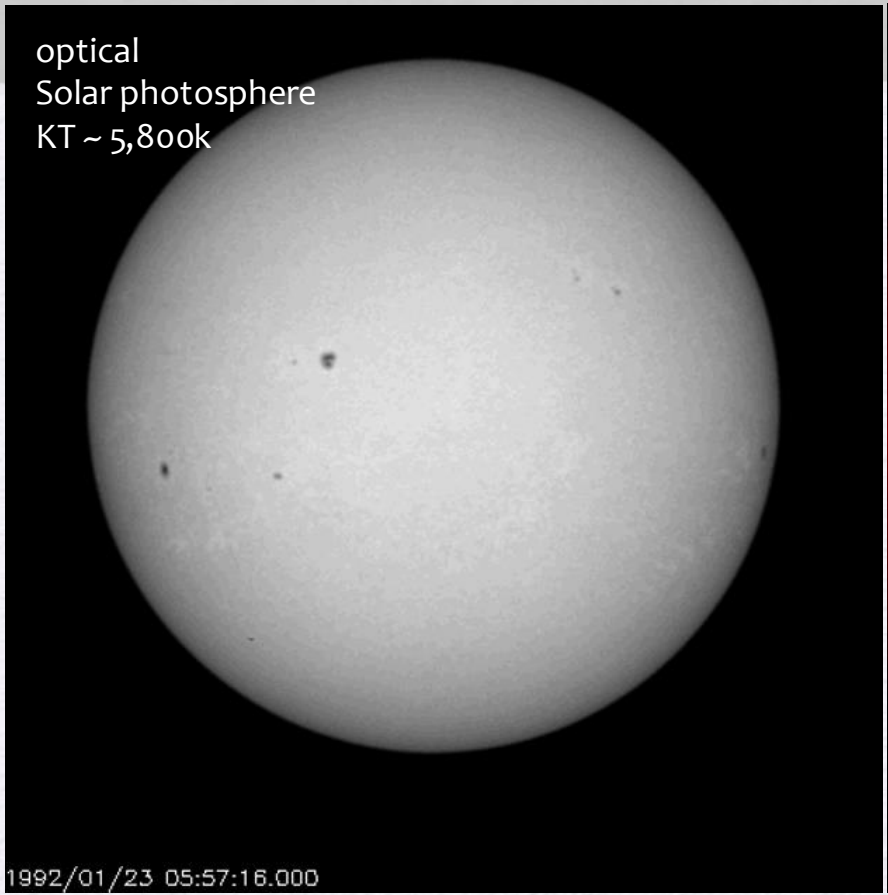
Chandra ASIS

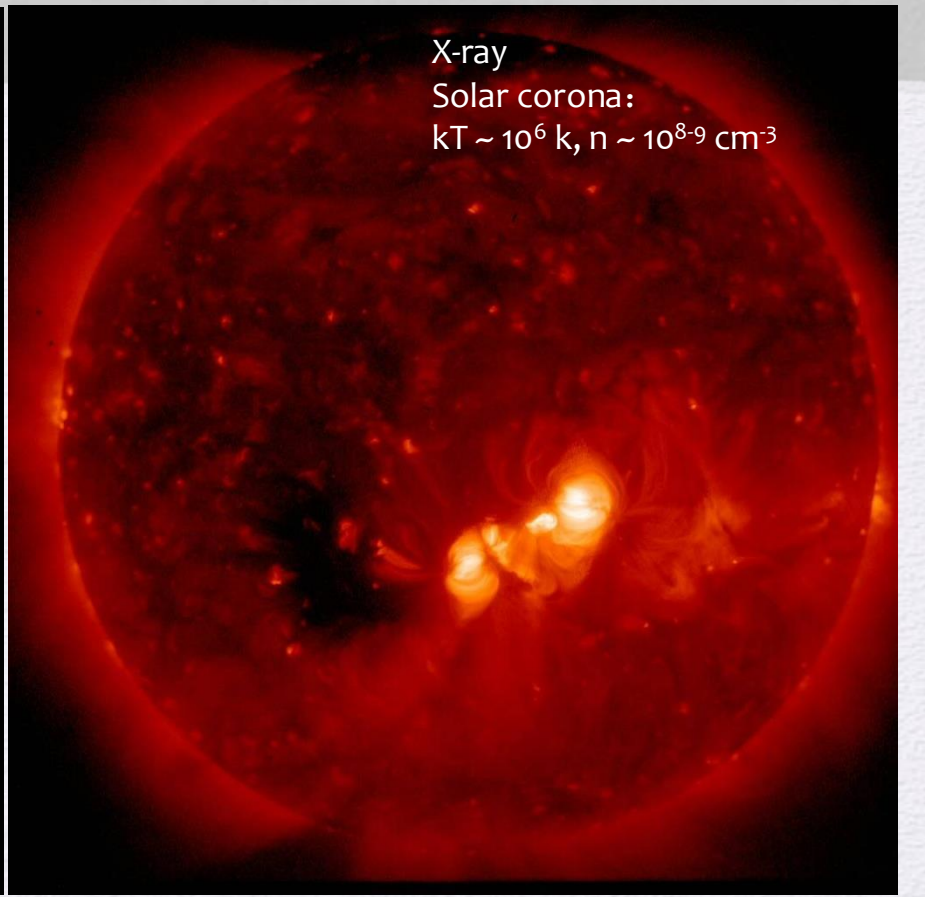
Lisse et al. 2001

Charge-exchange emission

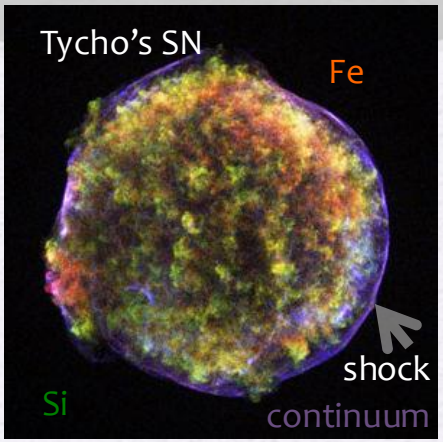


The sun/stars seen in optical and X-ray

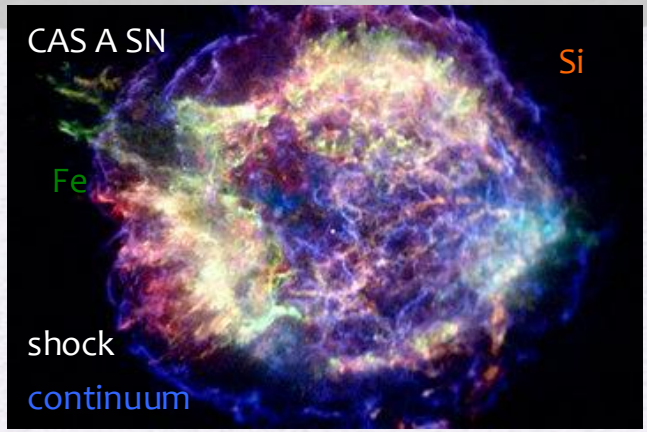


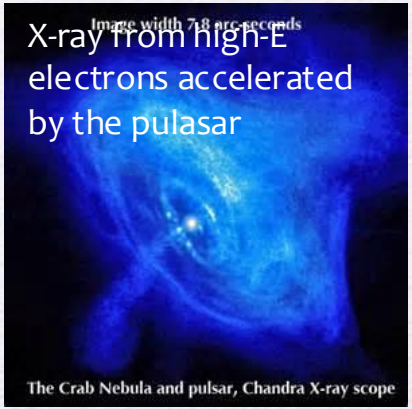


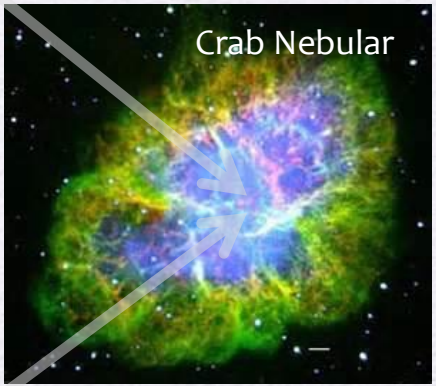
Supernova remnants in X-rays

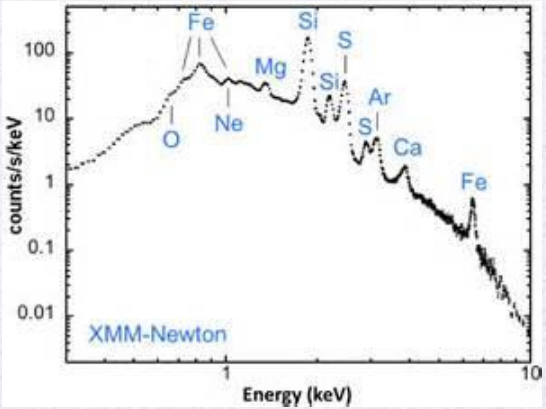


激波加速
高能粒子
→ 宇宙
线





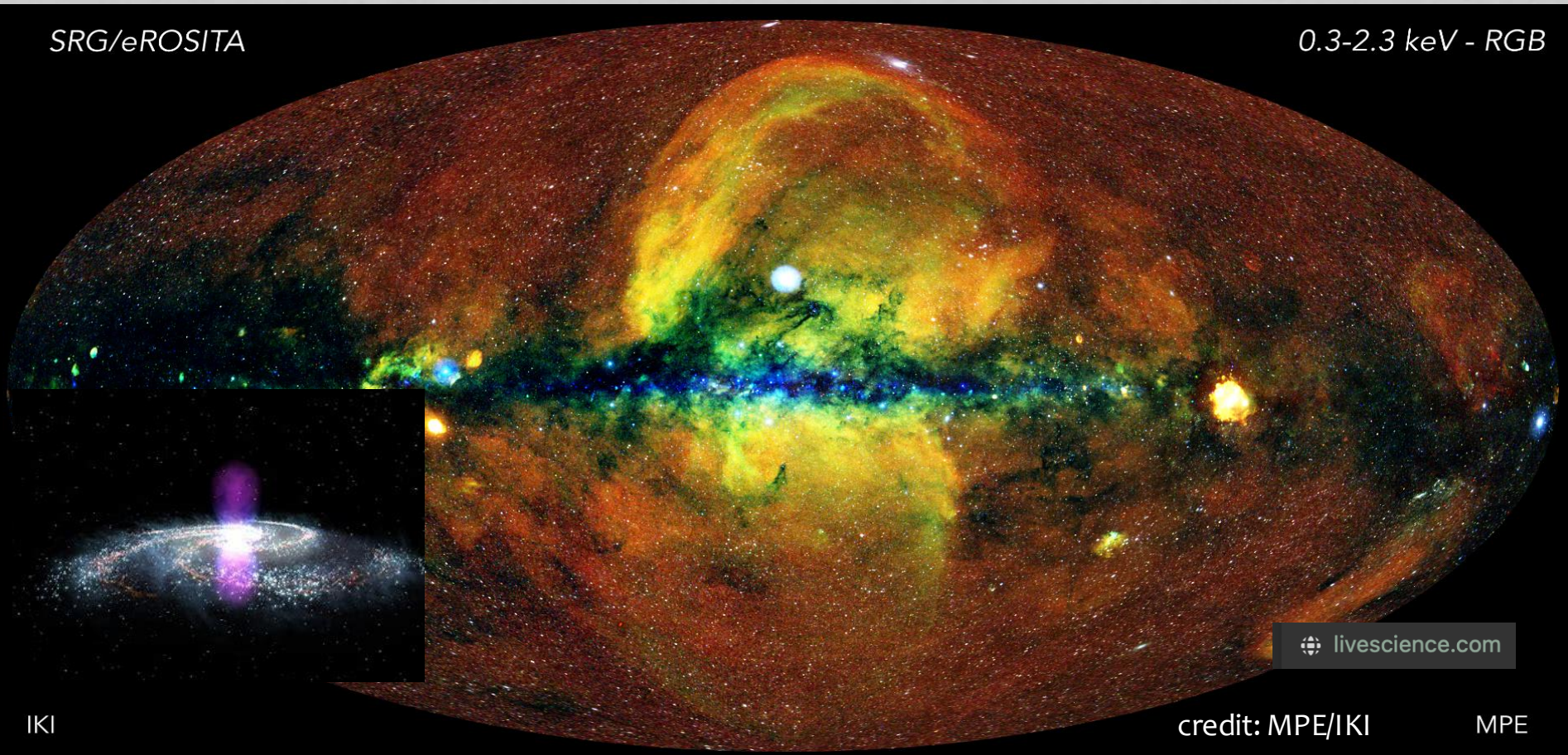




X-ray image of the Galactic center

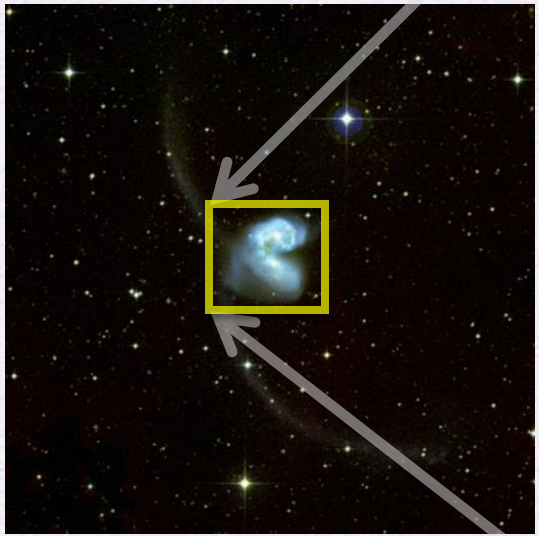
D. Q. Wang et al. 2002 Credit: NASA/CXO/Chandra

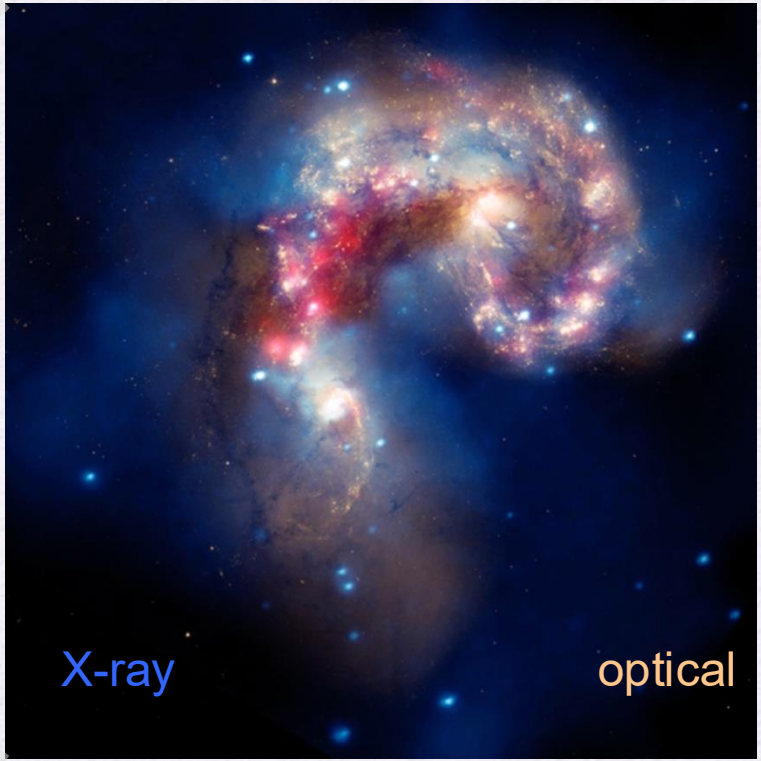
eROSITA X-ray bubble



草帽星系

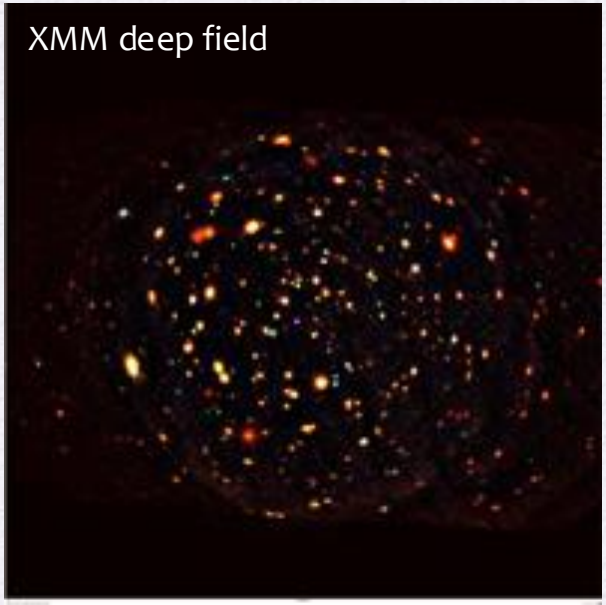
星系大碰撞：触角星系



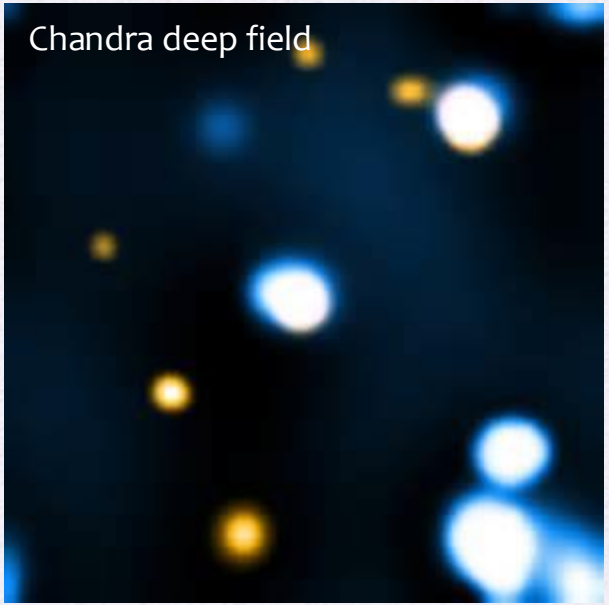


Credit: NASA/CXO/Chandra

Long-standing mystery of cosmic X-ray background solved



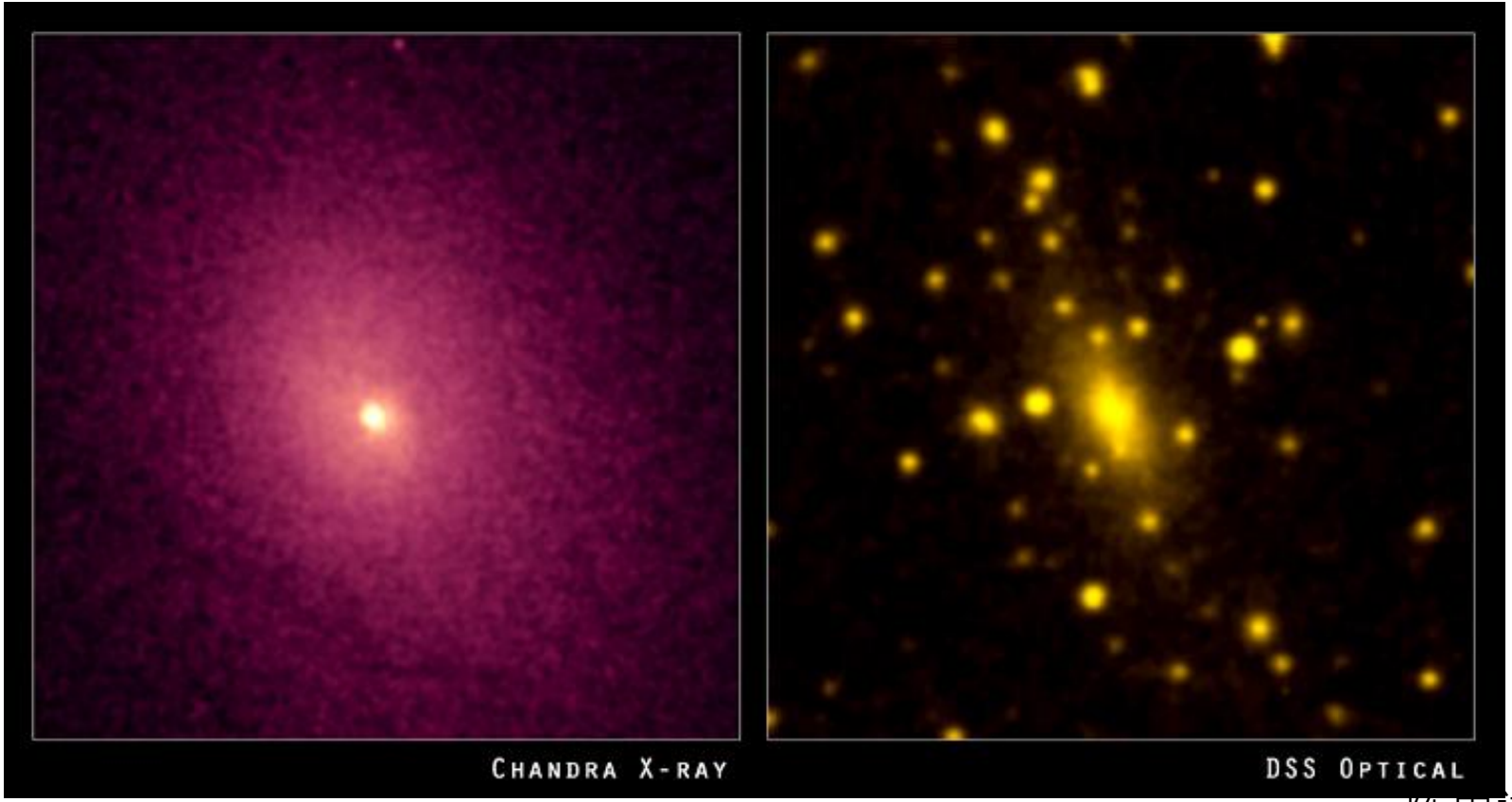
Hasinger et al.



Alexander et al.

CXB X-ray radiation is (almost) resolved into discrete X-ray sources: active galaxies and galaxies → black hole accretion energy

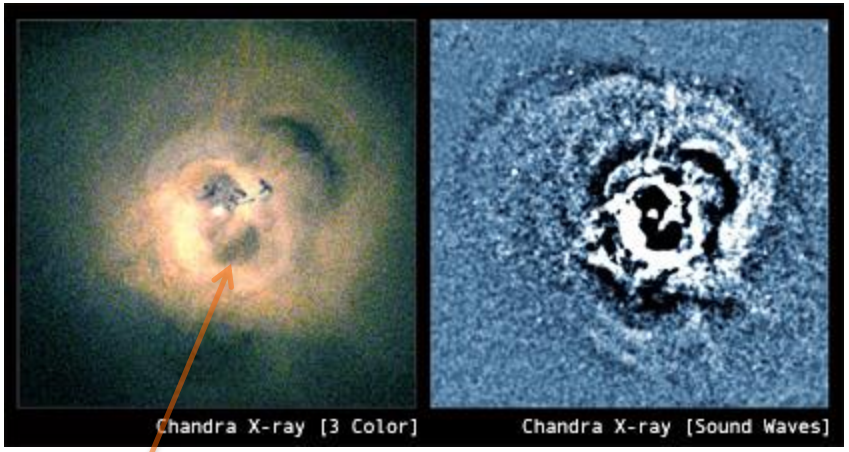
A cluster of galaxies seen in X-ray and optical

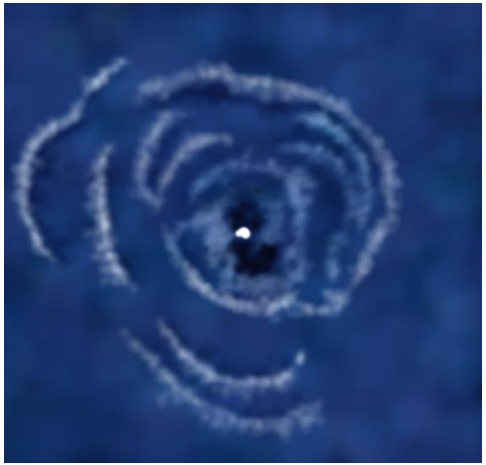


AGN heating/feedback

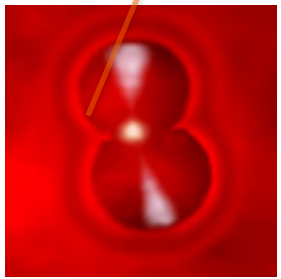
气泡向外传播形成的ICM气体声波的波纹

Perseus cluster





Credit: NASA/CXO/Chandra

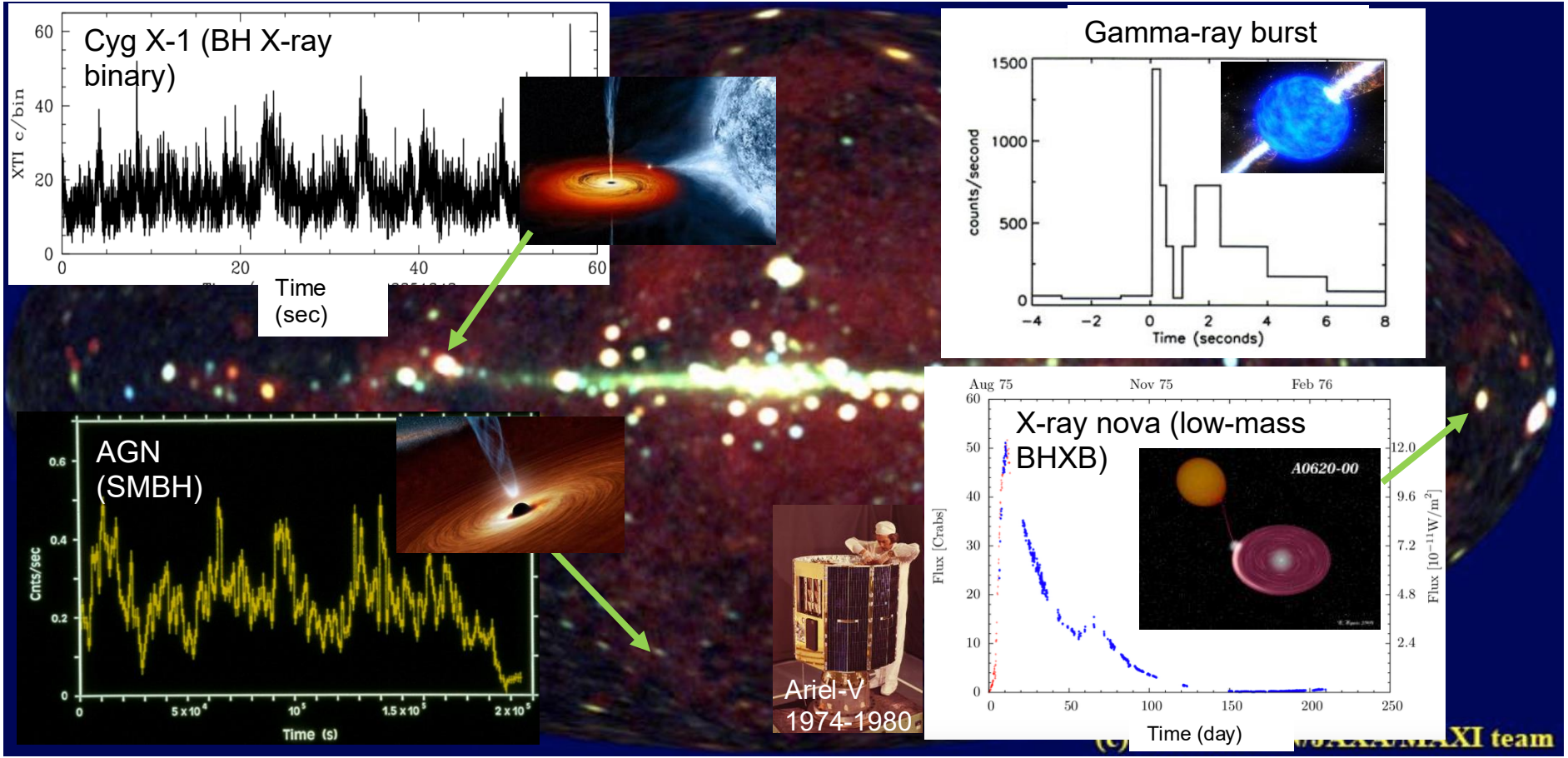


Energy feedback from central AGN/SMBH

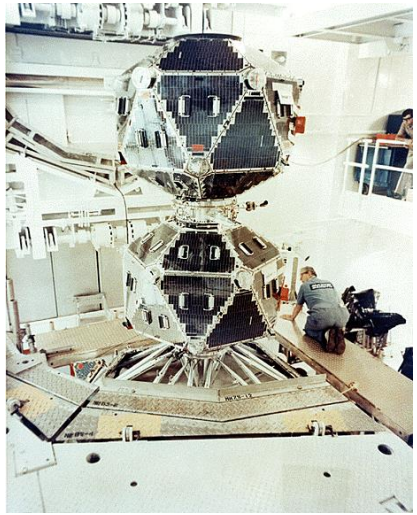
Sound speed ~10^3km/s → 气泡间隔10^7 年！

Fabian 2006

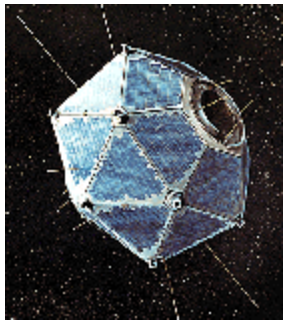
X 射线的天空充满剧烈变化和暂现源



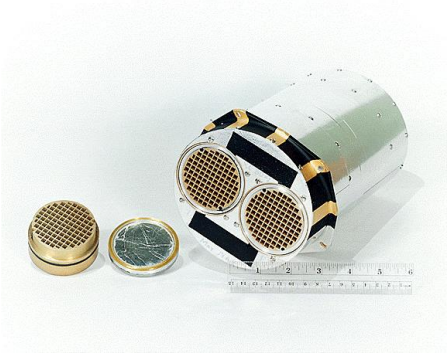
伽玛暴的发现

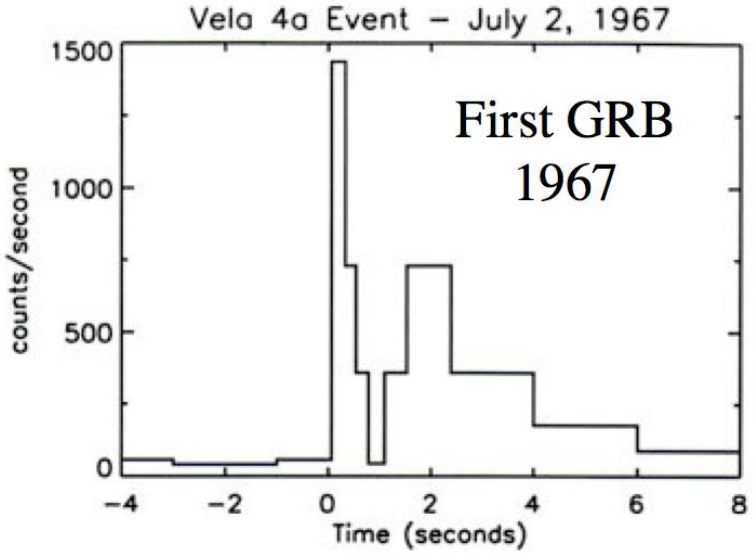


Vela-5A/B 1969-1979



碘化鈉晶体闪烁探测器
3-12keV

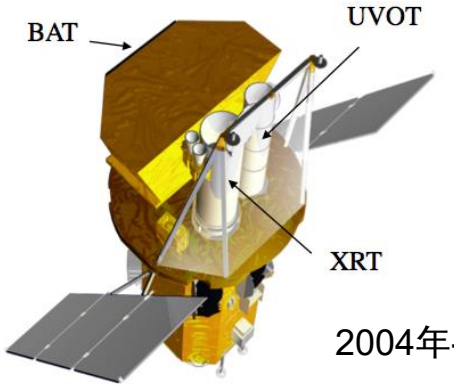




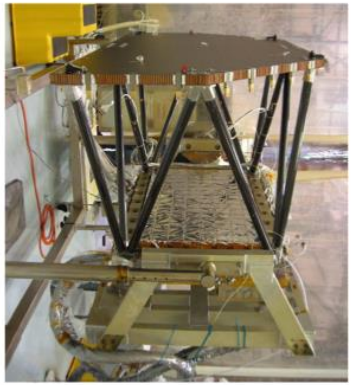
Klebesadel, Strong & Olson 1973

吴雪峰 讲座

伽玛暴卫星Swift



2004年--



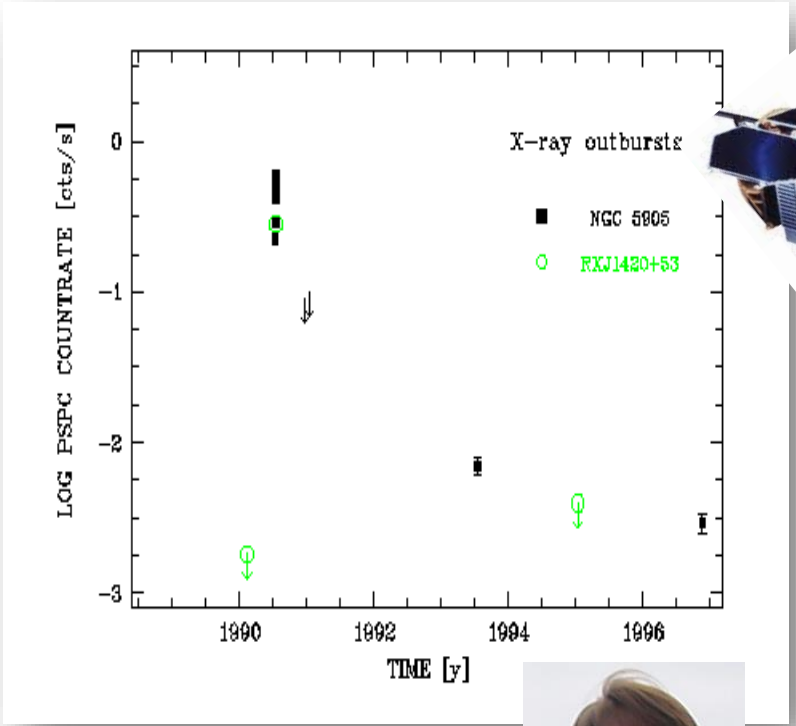
- BAT
  - coded mask +
  - CdZnTe 探测器 5000cm2
  - FoV: 2 sr
  - 13-300keV
- XRT: 0.3-10keV
- UVOT: optical/UV

> 1000 伽玛暴， 最高红移8.3

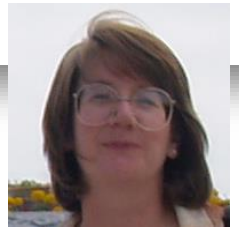
平均每周3.3个触发

- 1.8 伽玛暴
- 1.0 其它暂现源

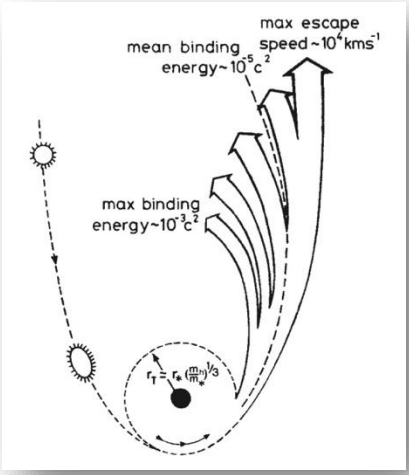
黑洞潮汐瓦解恒星事件 Tidal disruption event (TDE)



NGC 5905
(Komossa et al. 2001)



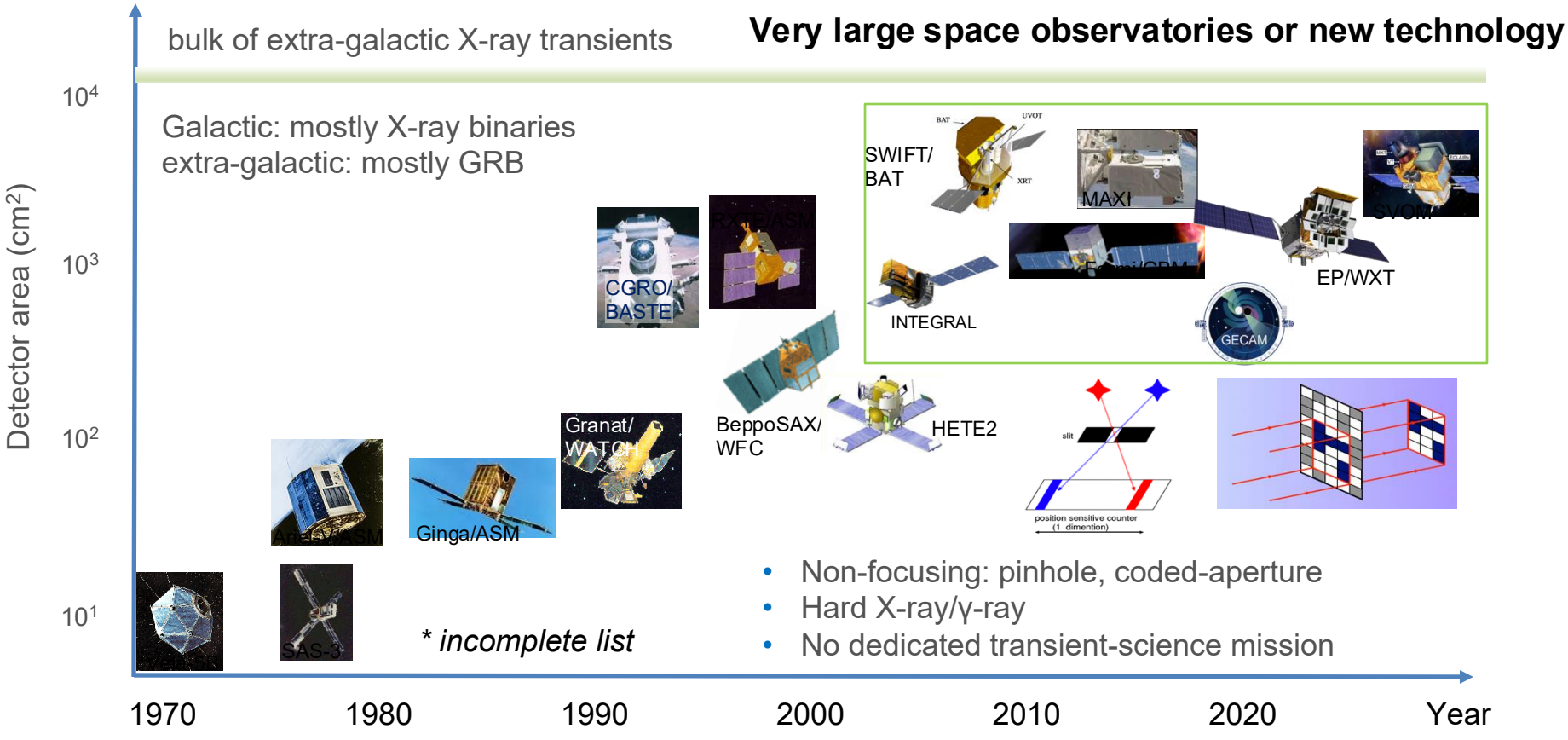
ROSAT



Rees 1988

暂现的
黑洞吸积盘

X射线/伽马射线宽视场监视器的发展

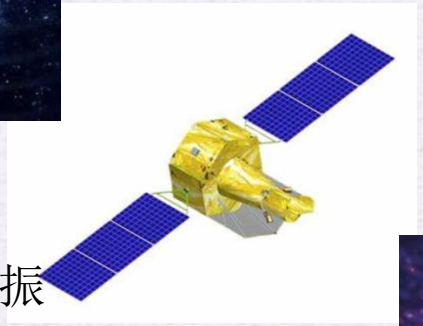


天关- Einstein Probe (EP) 2024-1

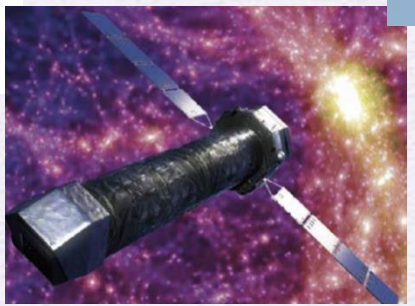
刘元讲座

未来

eXTP (CAS)
大面积+时标+偏振



HUBS (CSA)
高光谱分辨率



Athena+ (ESA)
大面积+高光谱分辨率

YXAM 2030's, 2040's

Your X-ray Astronomy Mission