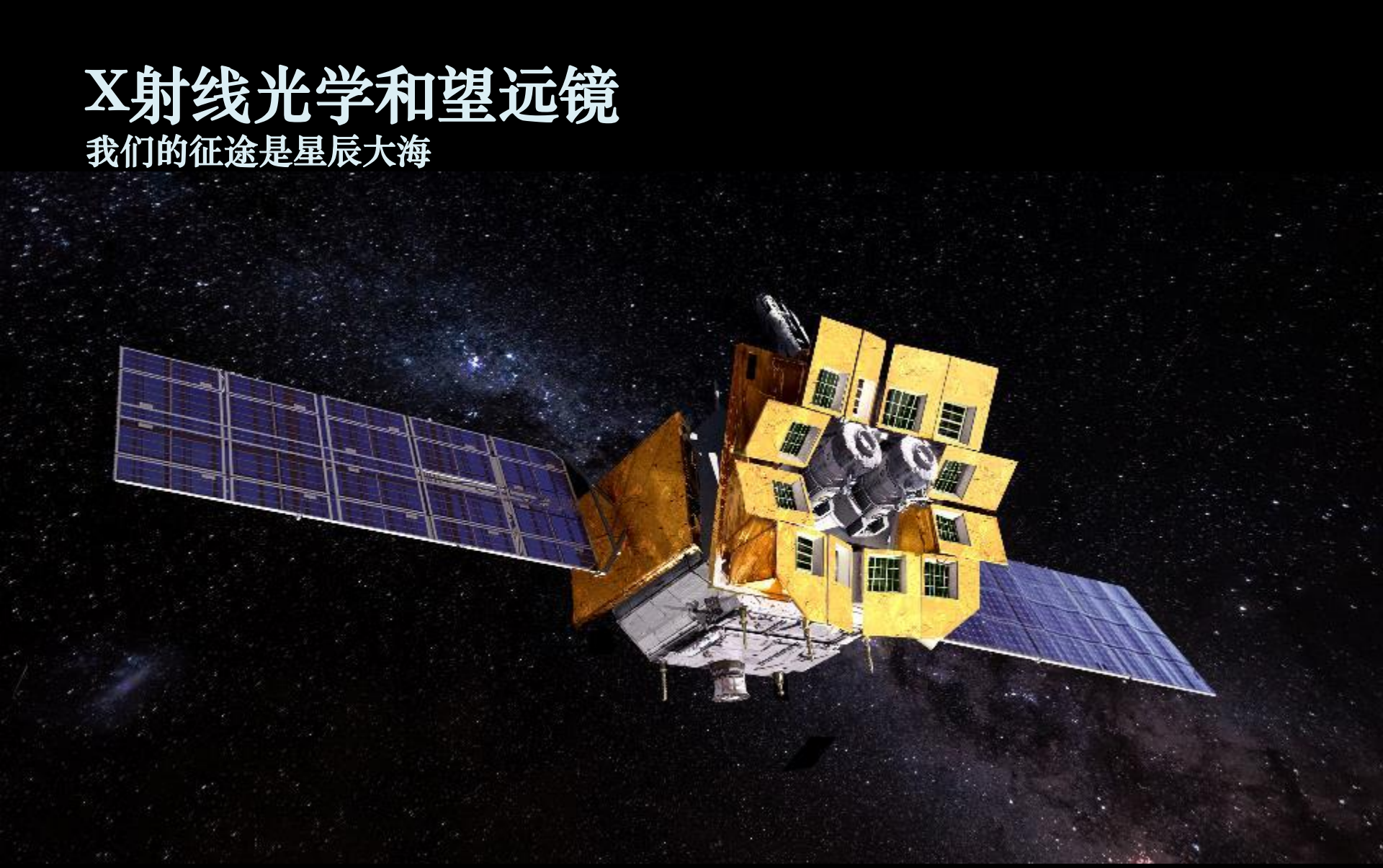
X射线光学和望远镜

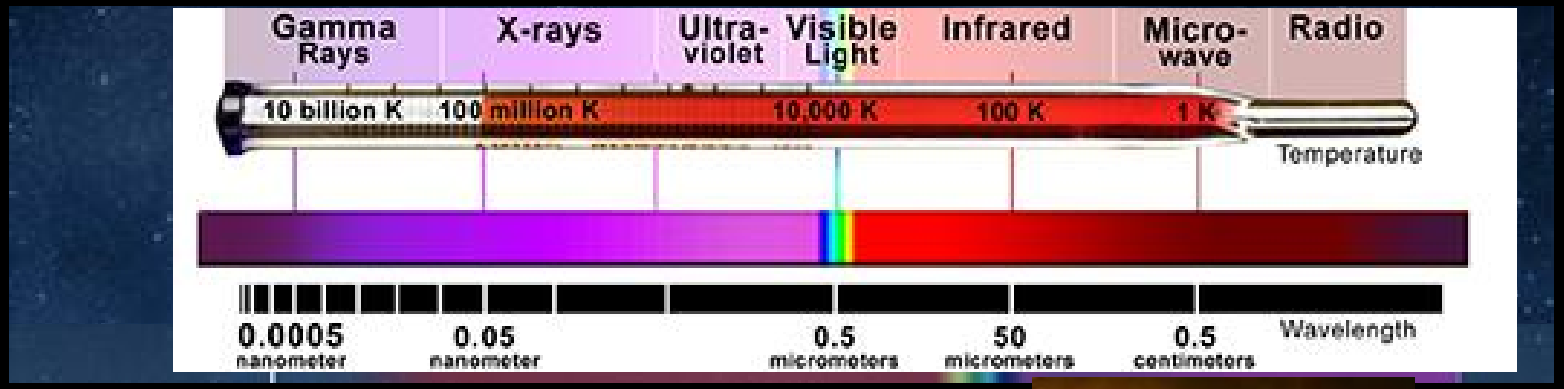
我们的征途是星辰大海

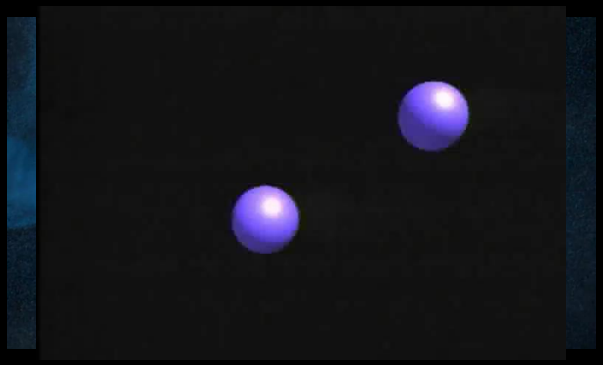


爱因斯坦探针卫星WXT载荷团队

国家天文台 张臣

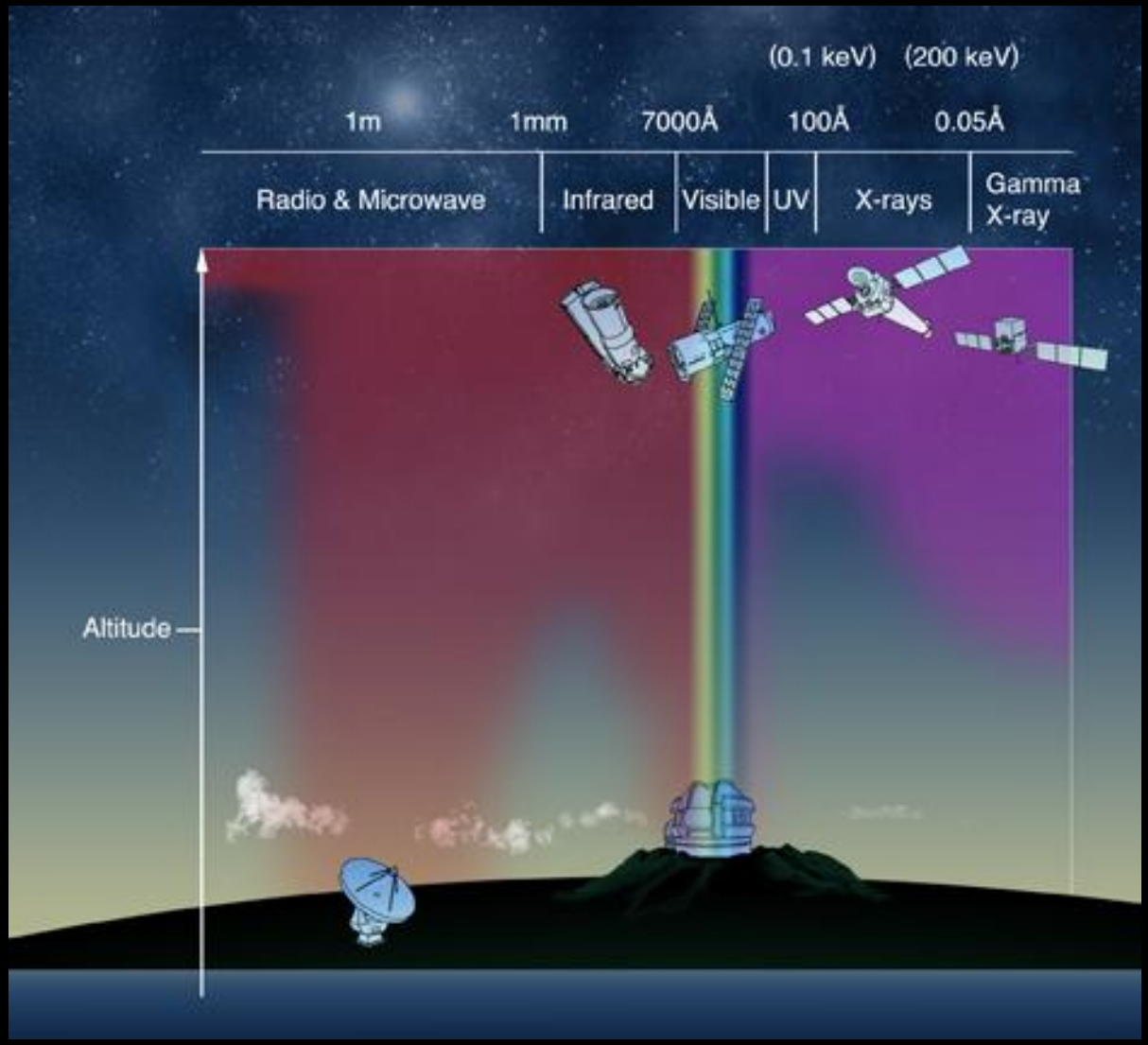
高能光子





改变方向很困难，以至于稍不注意就被吸收了

X射线望远镜：空间和真空

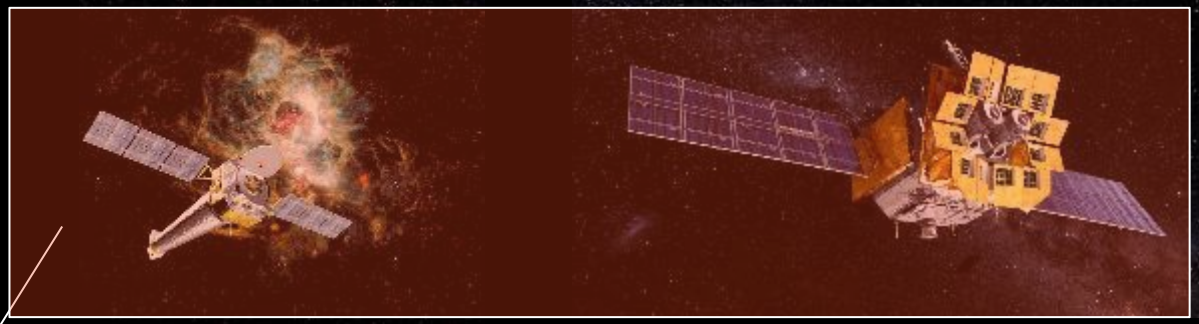


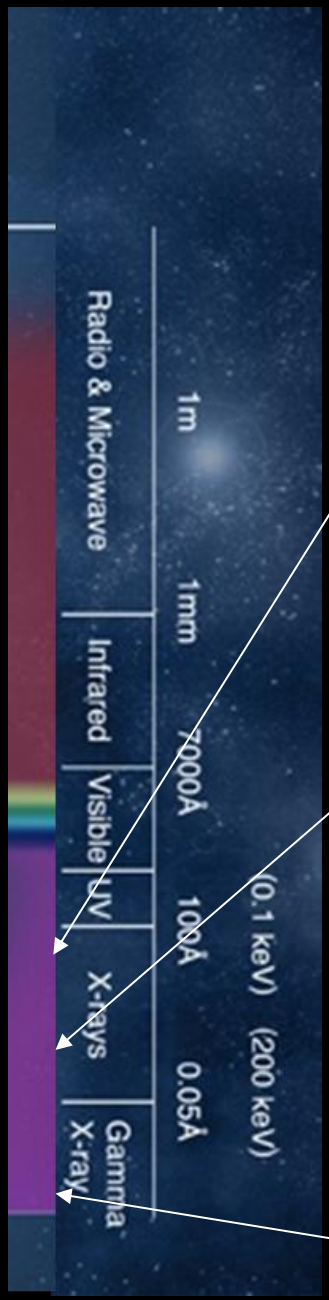
高能所100 m测试设备

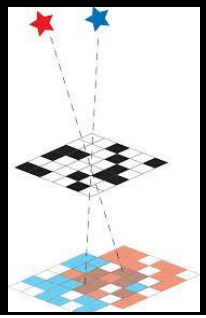
X射线望远镜，成像？成像！

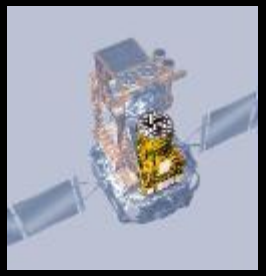
光子方向矢量测量

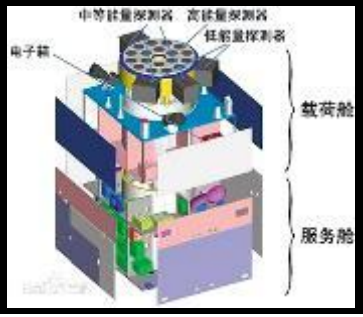
直接成像



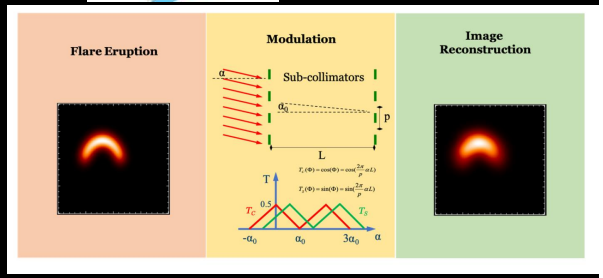


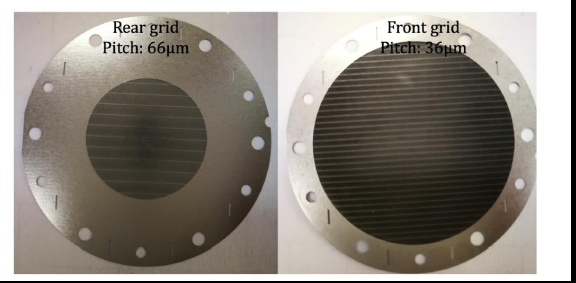






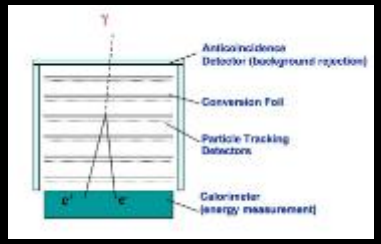
空间调制

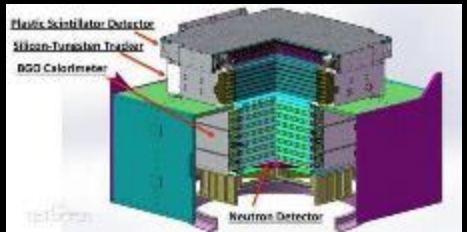




时间、傅里叶分量

非直接成像





径迹反解

认识一下真实的数据

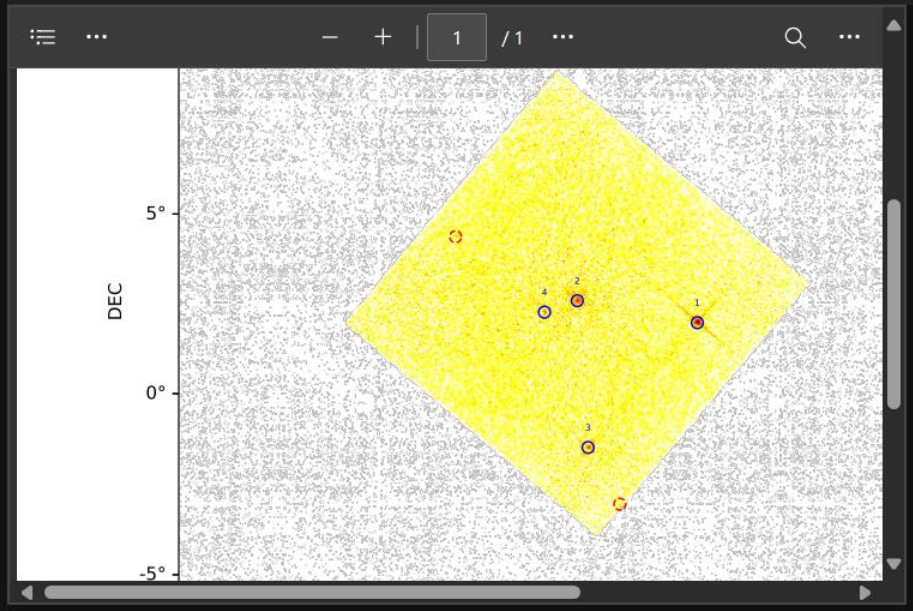
ep08500000058wxt11s1 v7

RA, Dec	187.616, 2.012
RA (HMS), Dec (DMS)	12h30m28.0s , +02d00m44.2s
Galactic l, b	290.736, 64.386
1 σ Pos Err (arcmin)	0.232
Exposure Time (s)	24838
Observation Start (UTC)	2024-04-10 12:35:55
Net Rate	0.02039278
Estimated Flux (erg/cm^2/s)	4.08e-11
Counts	506.51584
Background Counts	6.405128
Significance	31.42956
Source Detected Number	148 WXT
Observation Number	57 WXT, 6 FXT

Open an issue in Redmine

Issues of related observation

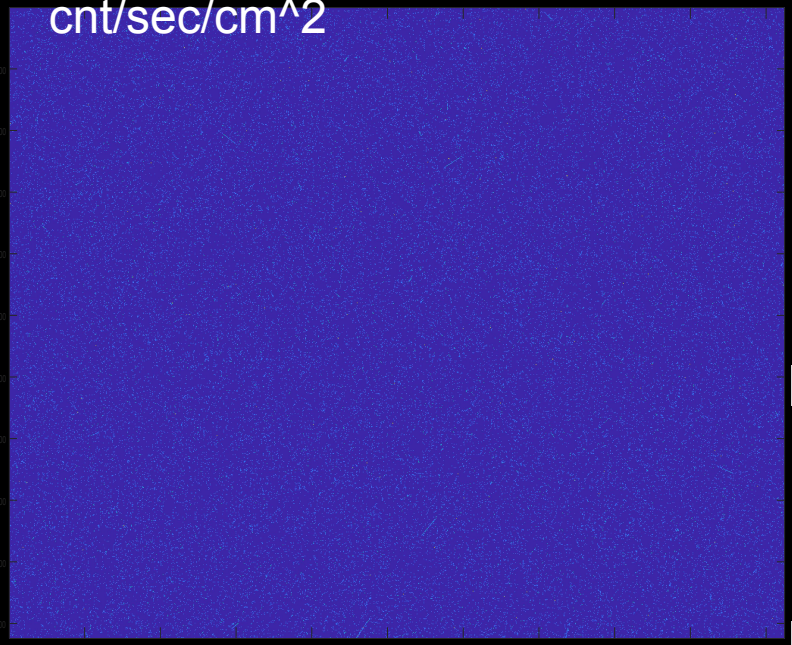
Source QuickLook



Show image in DS9 | Download level1 data | Download Level2-3 Data

认识一下本底

地面 宇宙线 0.04 cnt/sec/cm^2



宇宙线+弥漫X射线本底+各种反照+弥漫的结构

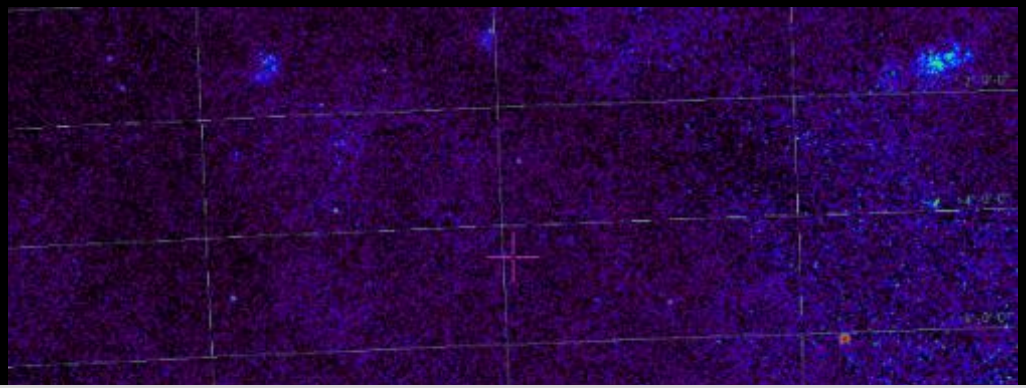
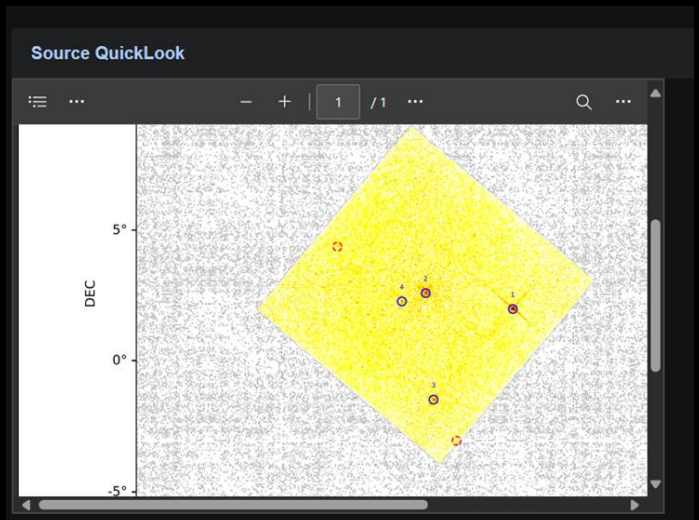


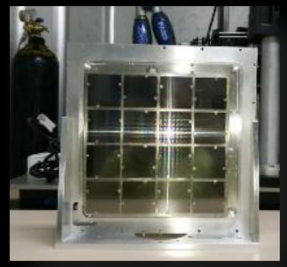
表 1. 根据轨道号 06800002000 至 06800003000 的数据，得到的 LEIA 本底计数率表。

cmos	Count rates in different energy ranges (cts/sec/cm^2)					-
	0.5-4 keV	0.5-1 keV	1-2 keV	2-3 keV	3-4 keV	orbits available
13	0.31	0.07	0.07	0.07	0.06	660
14	0.31	0.07	0.08	0.07	0.07	618
15	0.32	0.09	0.10	0.09	0.09	479
16	0.36	0.08	0.09	0.08	0.08	546

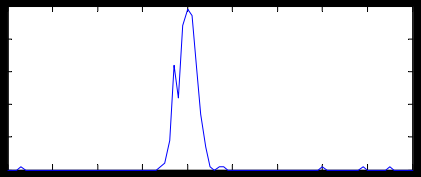
25k*36*0.31=27000本底计数
506个源光子



聚焦成像，灵敏度第一选择

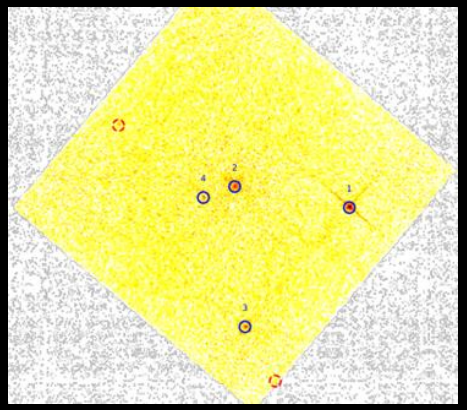


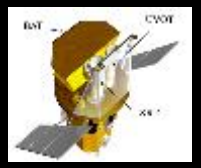
Aperture size

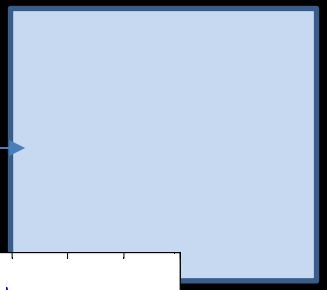


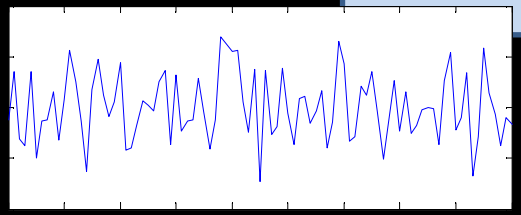
Focusing

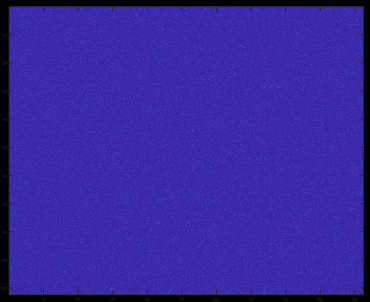
Detector size

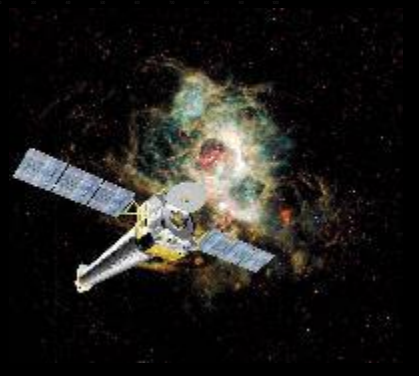




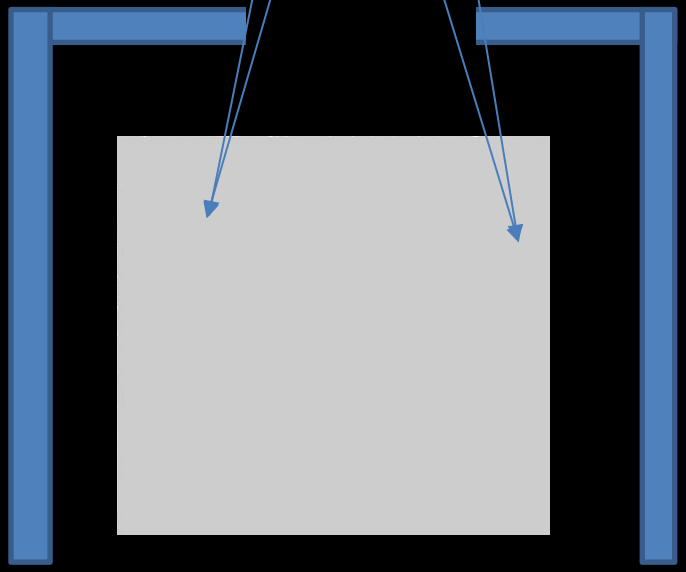


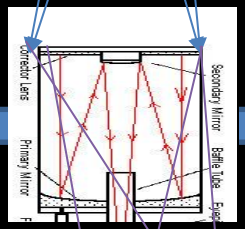


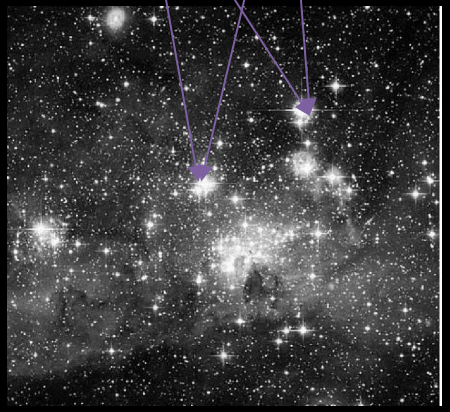




何为成像




Corrector Lens
Secondary Mirror
Primary Mirror
Baffle Tube



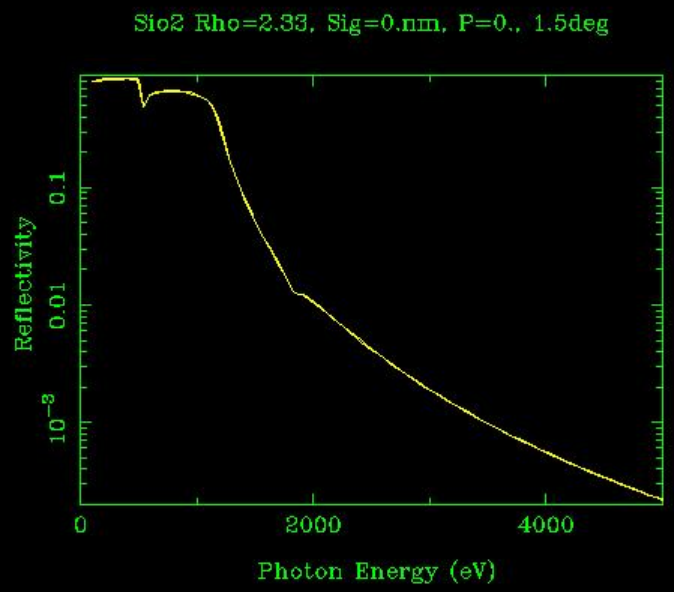
X射线反射式光学系统：X射线在光滑物质表面的反射原理

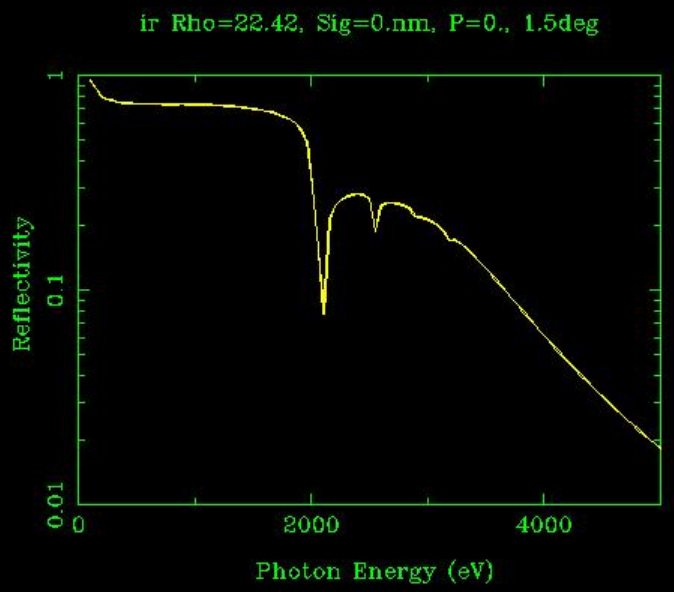
基本假设，高能X射线作用下，固体物质可以视为固定的正离子和自由电子的组合。（物质最外层电子的结合能几个eV）

- X射线在物质表面的反射：宏观电动力学的解释
- 物质被近似为一团自由电子
- 使用Maxwell方程组，考虑自由电子电流项：**折射率小于1，但是小的有限**，X射线光子的相速度超过了光速!
- 可以使用Fresnel定理计算反射和折射强度

$$n = 1 - \delta - \mathrm{i}\beta; \qquad \text{with} \quad \delta = \frac{\lambda^2}{2\pi} r_e \rho,$$

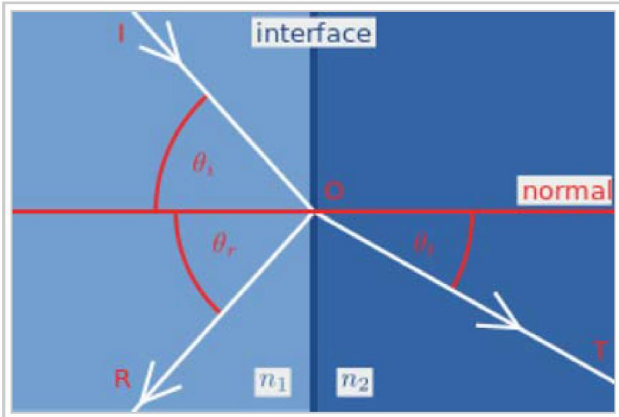
X射线光子的反射效率



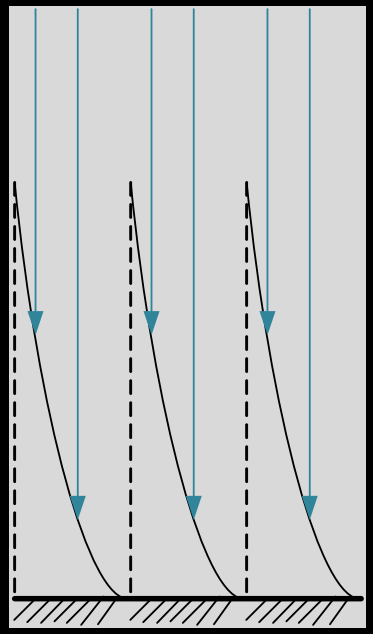


单层膜系统，在4 keV以上就近乎不可用了

在X射线光学反射系统中，临界角是一个非常小的量，也就是说X射线光子的偏折是一个非常难得事情，需要良好的设计反射角的分配

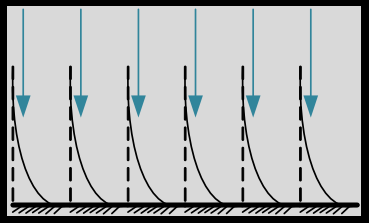


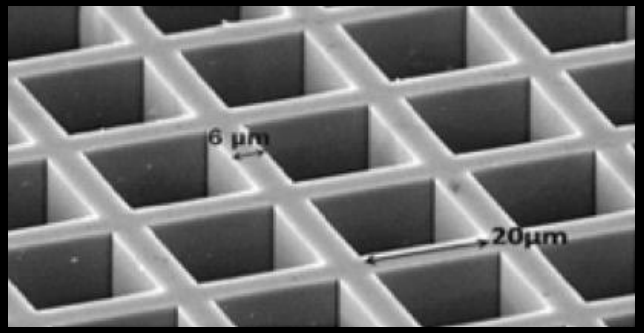
Variables used in the Fresnel equations.



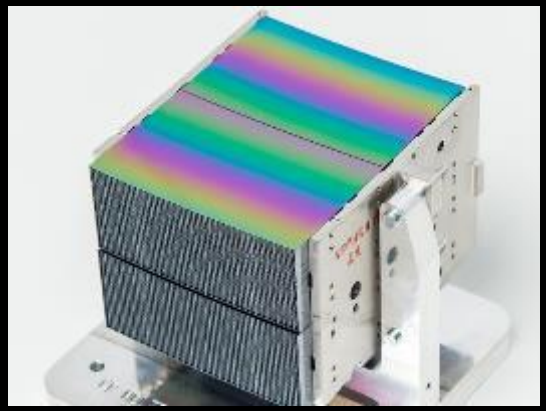
~200 mm间距一个
>10 mm壁厚
~1000 mm高度
~10亿一片

~6 mm间距一个
~1 mm壁厚



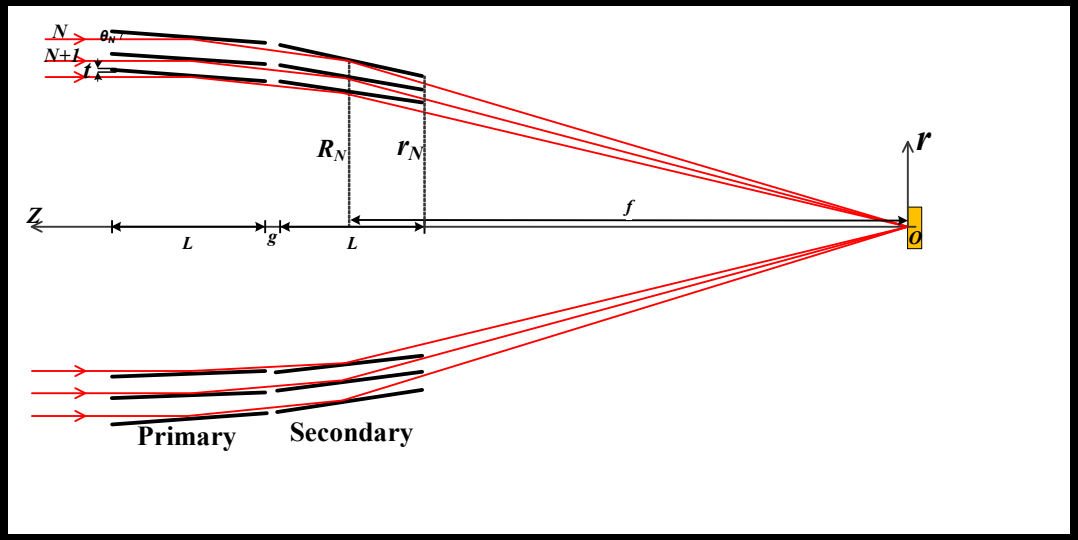


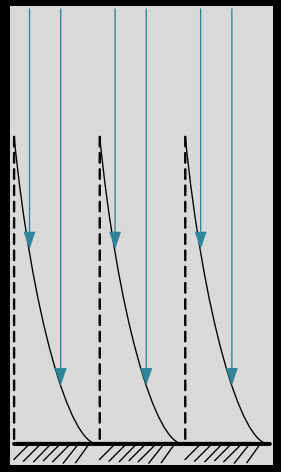
~0.04 mm间距一个
~0.008 mm壁厚
~2 mm高度
~10万一片



X射线光学：制作，布置和优化X射线的反射面的学科

X射线望远镜的口径、焦距有效面积的关系



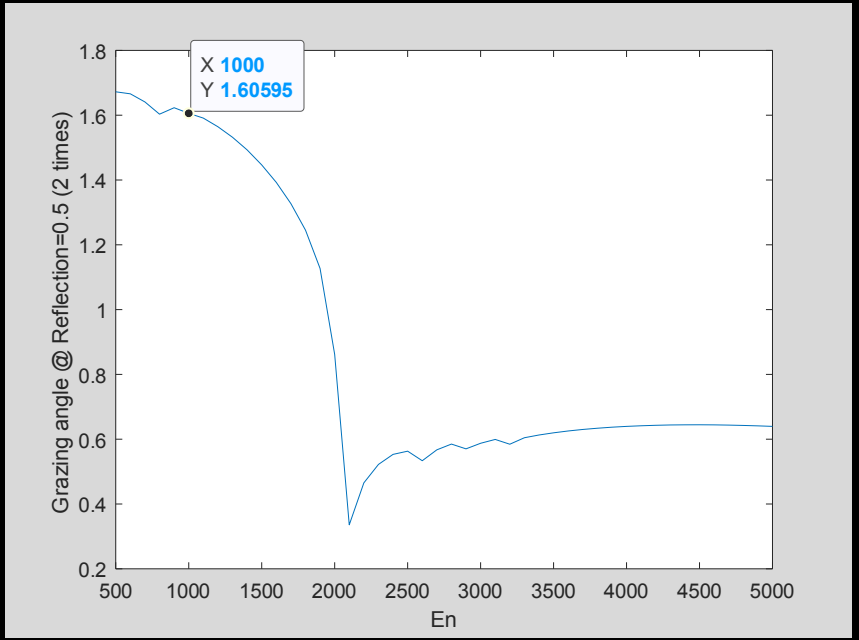


Wolter-I:

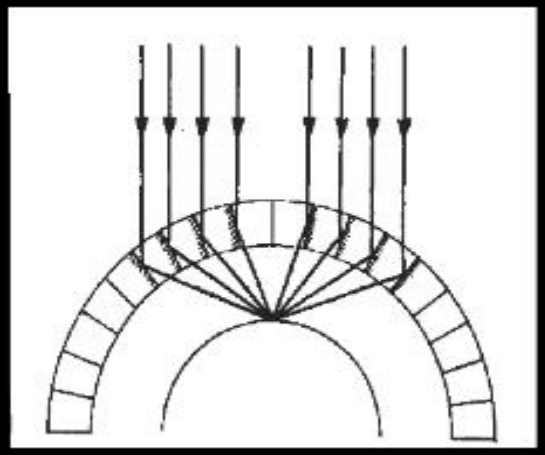
Grazing incidence angle: $\theta_R = \frac{R}{4f}$

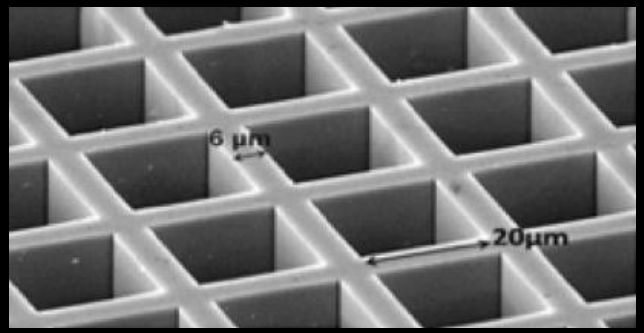
$$A = \theta_c * 4f$$

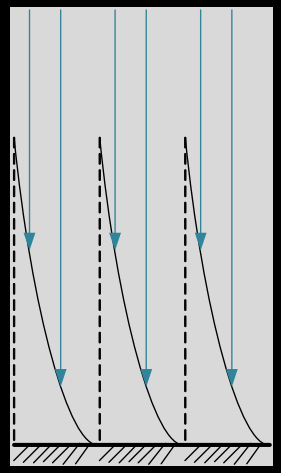
FXT，1 keV 1.6度反射角设计
计算得到最大口径：357.4 mm
实际最大反射面口径 358 mm



X射线望远镜的口径、焦距有效面积的关系





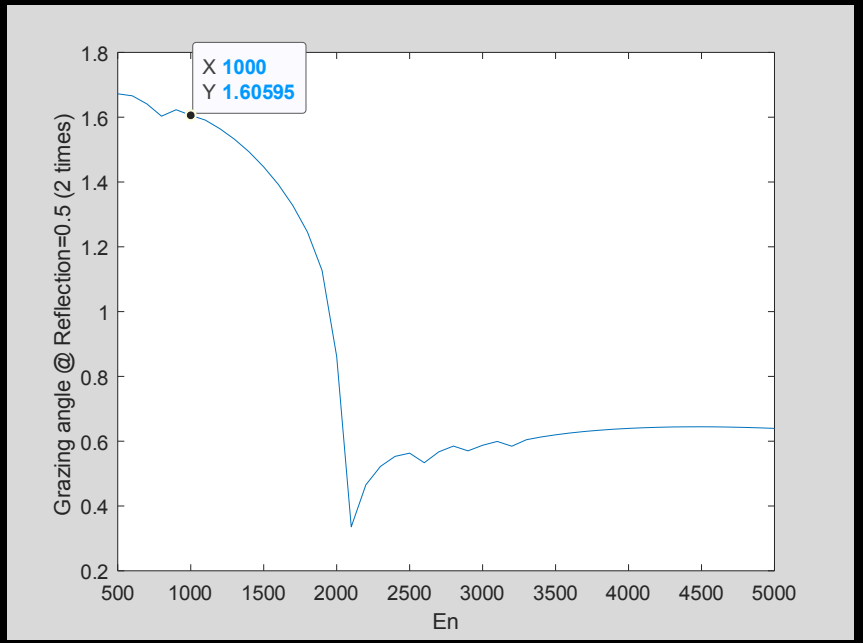


Lobster-Eye

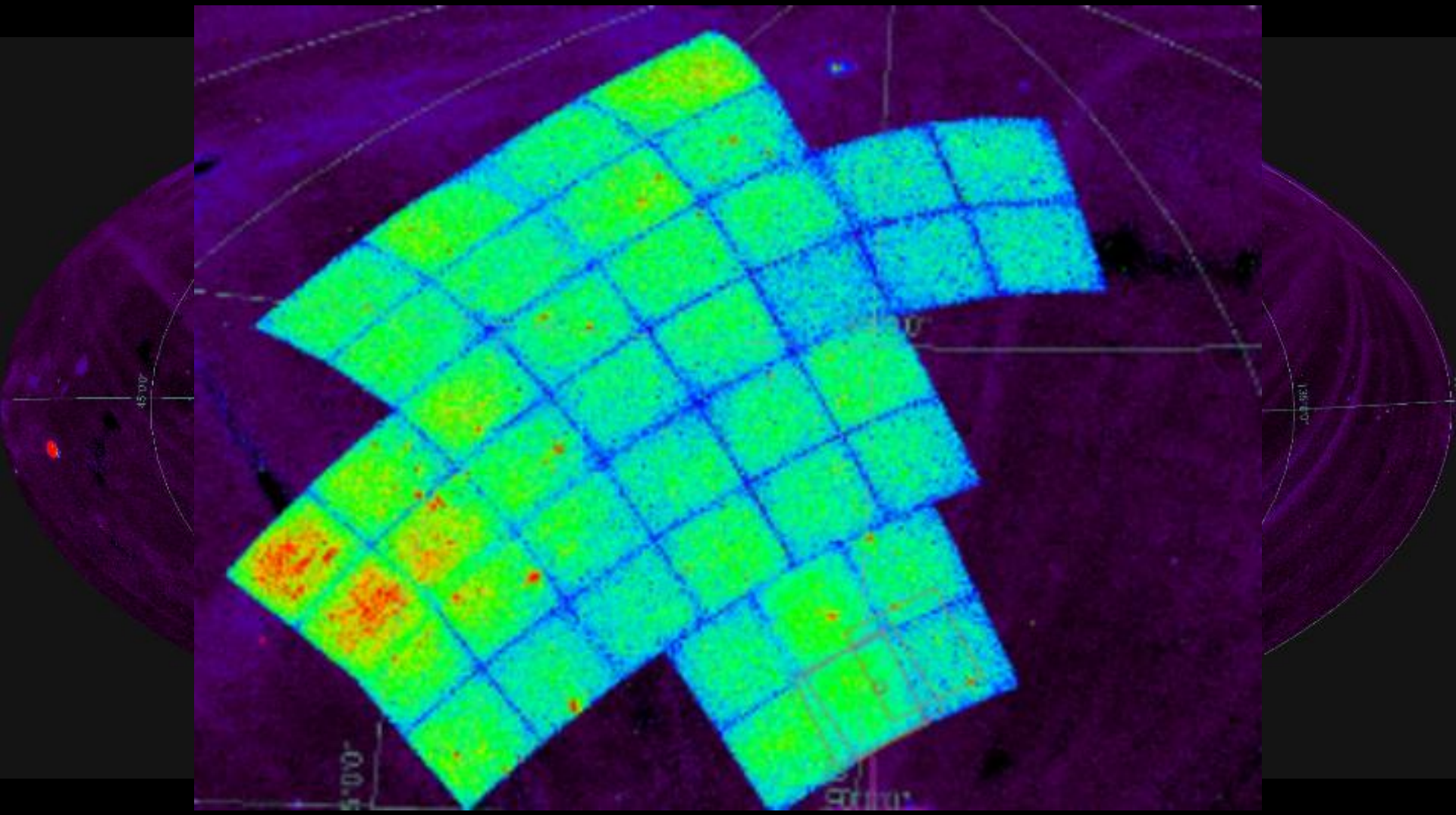
Grazing incidence angle: $\theta_R = \frac{R}{2f}$

$$A = \theta_c * 2f$$

WXT，1 keV 1.6度反射角计算
计算得到反射范围：42*42 mm
约一个镜片大小!



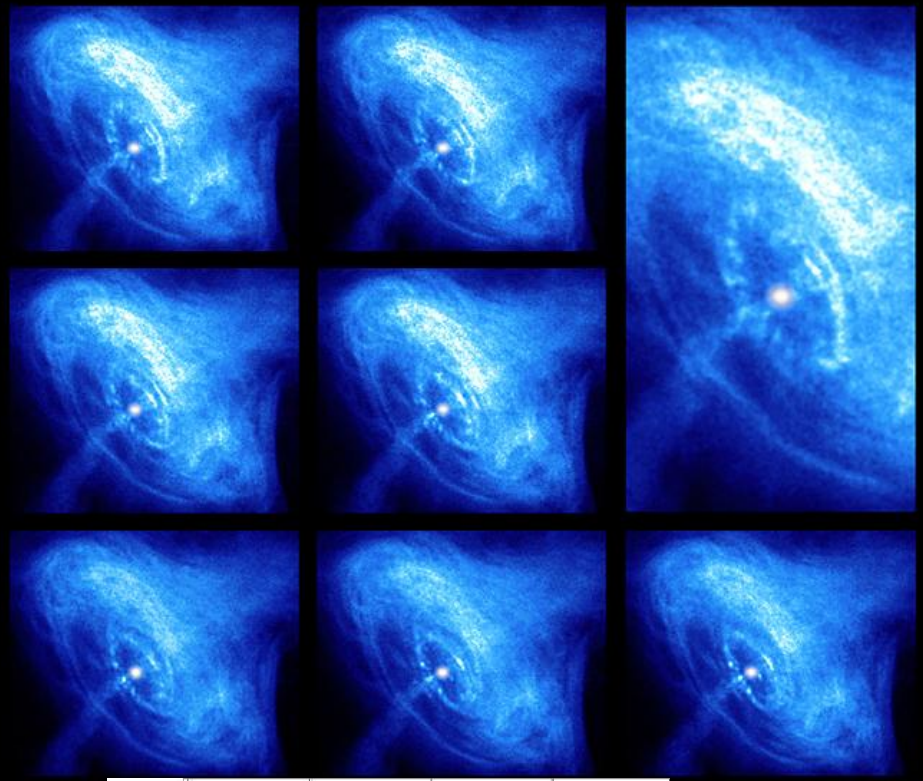
视场和发现

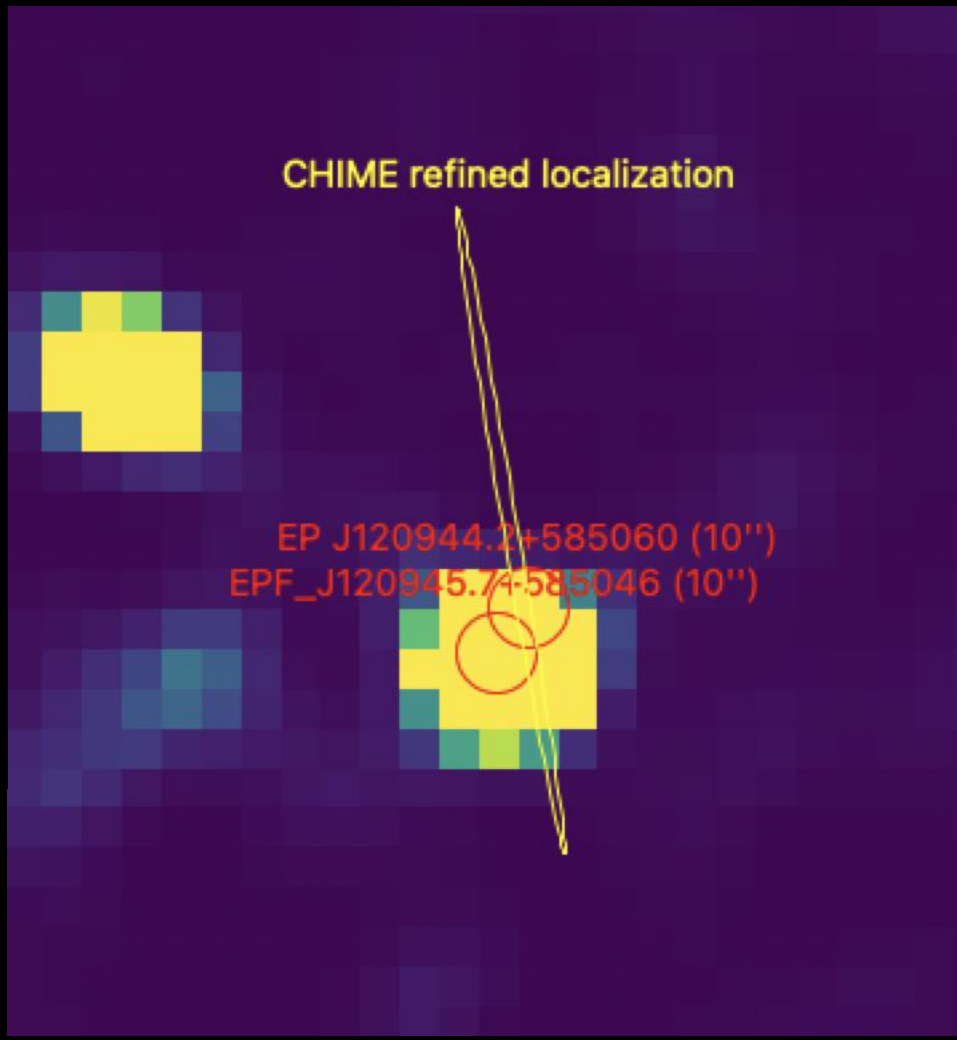


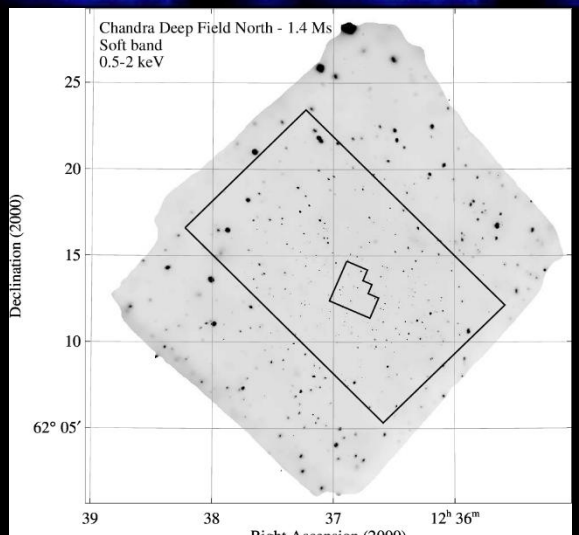
X射线望远镜：鱼和熊掌、几乎一颗卫星一套技术

名称	主要性能指标	光学类型	材料	质量	研制技术
Chandra (1999)	角分辨率：0.5arcsec 有效面积：800cm^2@1keV 直径：1.2m 焦距：10m	Wolter-I型 4对整壳反射镜	Zerodur玻璃，1.6~2.4 cm厚	总：955 kg 面积重量比：~0.5cm^2/kg	精确测量与标准研磨和抛光技术相结合
Suzaku (2005)	角分辨率：~120arcsec 有效面积：0.225m^2@1keV	Wolter-I型几何圆锥形近似； 4个175层,1个168层。6944镜段	环氧树脂和铝； 0.18mm厚	总：19.3kg 面积重量比：~20cm^2/kg	薄箔弯曲
NuStar (2012？)	角分辨率：~52 arcsec 有效面积：0.15m^2@1.5keV 层半径：51-191mm 焦距：10.15m 视场：12角分*12角分	Wolter-I型几何圆锥形近似； 133层，1276镜段	Schott D263玻璃、F131，石墨复合材料;钛芯轴； 多层膜； 0.21mm厚	总：37 kg(单个) 面积重量比：	热弯玻璃 (圆柱-圆锥)
XMM-Newton (1999)	角分辨率：~10 arcsec 有效面积：0.15m^2@1.5keV 直径：0.7m*3个 焦距：7.5m	Wolter-I型 58层*3个	镍；0.47 -1.07 mm厚	总：500 kg 面积重量比：~3cm^2/kg	精密芯轴的化学镀基复制
eROSITA (2019) EP FXT	角分辨率：~24arcsec 有效面积：340cm^2@1keV 直径：erosita 0.36m*7个 FXT 2个 焦距：1.6m	Wolter-I型 54层	镍；0.2-0.6 mm厚；300mm长		精密芯轴的化学镀基复制
EP WXT	角分辨率：~300 arcsec 有效面积：3 cm^2@1keV 焦距：0.375 m	Lobster-eye	玻璃基地		精密刻蚀技术

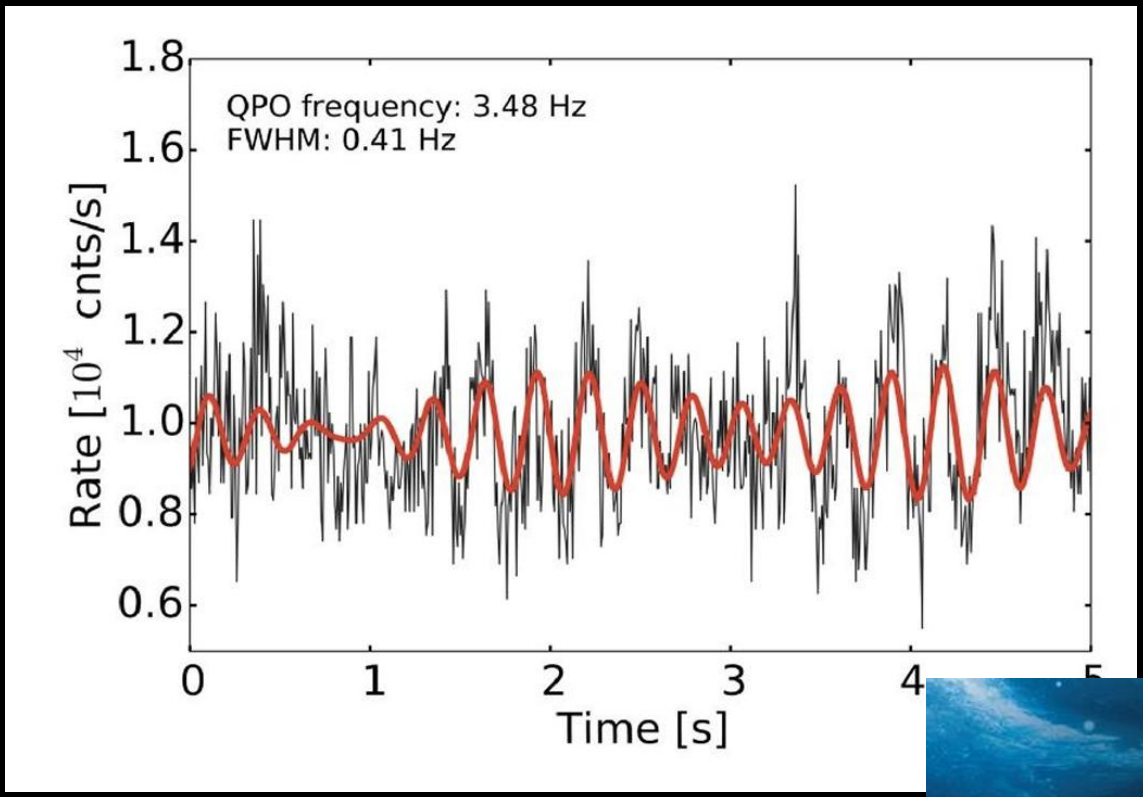
角分辨率：好的图像，好的定位和极高的灵敏度







有效面积：偏向亮源的时变和能谱研究



探测器的能力：极致的能量分辨率

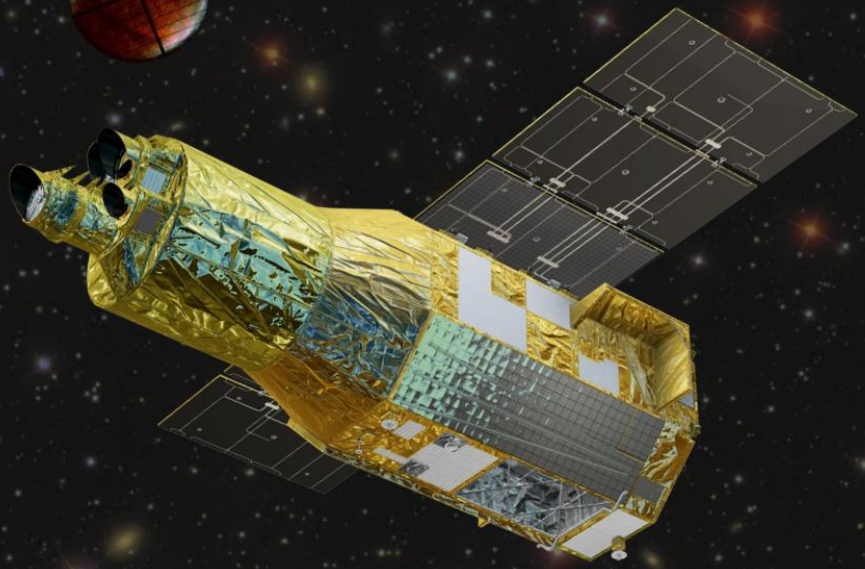
XRISM

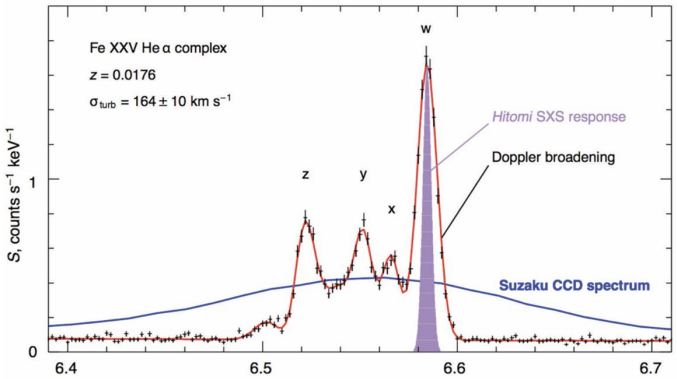
International Conference 2025

- sponsored by the JSPS core-to-core program -

Opening a New Era of the Dynamic Universe

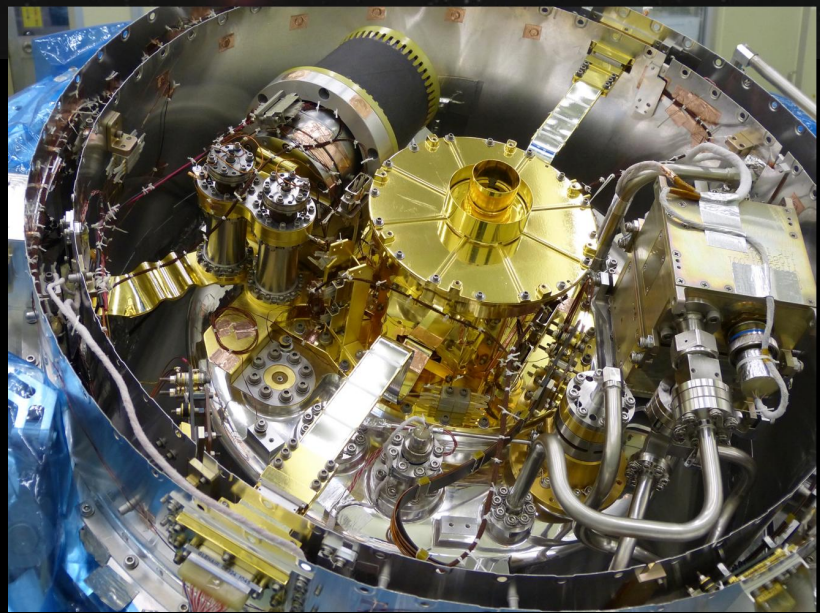
October 20-24, 2025, Kyoto, Japan



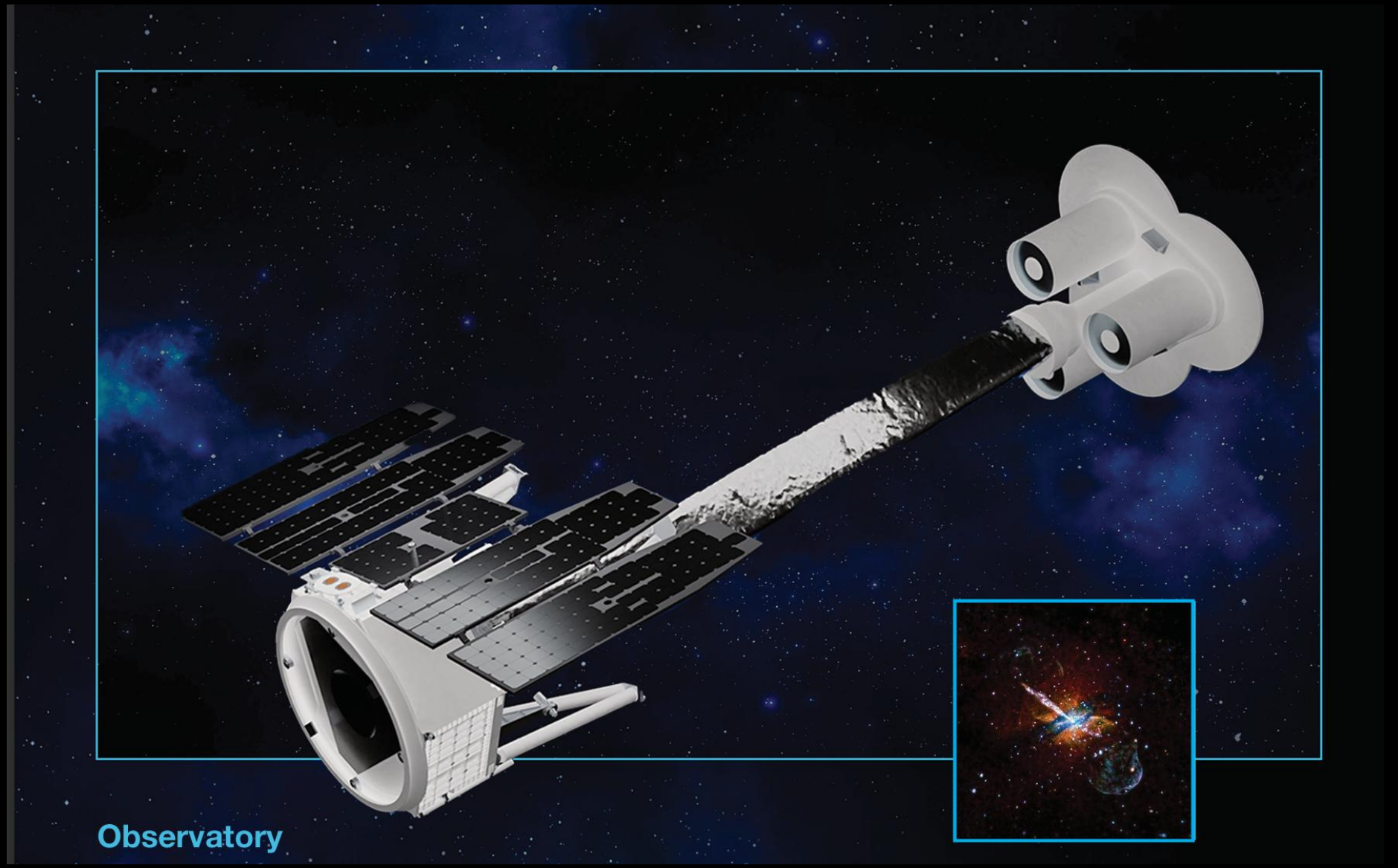


The Hitomi spectrum of the Perseus Cluster, showing the power of microcalorimeter X-ray spectroscopy. The previous best X-ray spectrum of this object is the Suzaku spectrum, shown in blue.

Parameter	Requirement	Goal
Energy Resolution	7 eV (FWHM)	5.0 eV
Energy Scale Accuracy	± 2 eV	± 0.5 eV
Residual Background	2 x 10^{-3} counts/s/keV	< 1 x 10^{-3} counts/s/keV
Field of View	2.9 x 2.9 arcmin	same, by design
Angular Resolution	1.7 arcmin (HPD)	1.2 arcmin
Effective Area (1 keV)	> 160 cm^2	250 cm^2
Effective Area (6 keV)	> 210 cm^2	312 cm^2
Cryogen-mode Lifetime	3 years	4+ years
Operational Efficiency	> 90%	> 98%

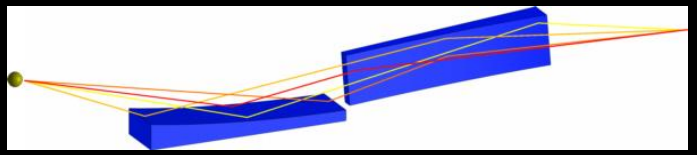


探测器的能力：偏振，新的窗口



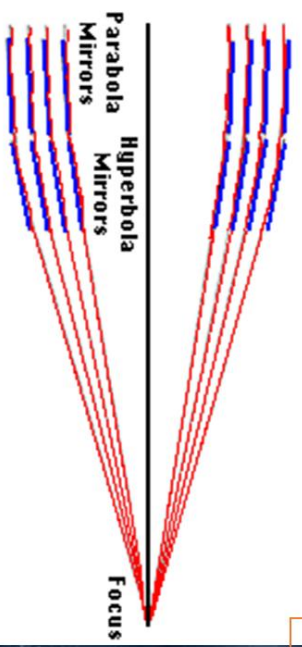
天文X射线望远镜：成年人不做选择行么？

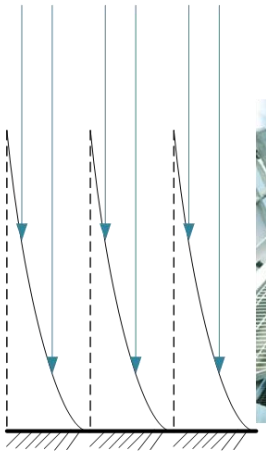
名称	主要性能指标	光学类型	材料	质量	研制技术
Chandra (1999)	角分辨率：0.5arcsec 有效面积：800cm²@1keV 直径：1.2m 焦距：10m	Wolter-I型 4对整壳反射镜	Zerodur玻璃， 1.6~2.4 cm厚	总：955 kg 面积重量比： ~0.5cm²/kg	精确测量与标准研磨和抛光技术相结合
Suzaku (2005)	角分辨率：~120arcsec 有效面积：0.225m²@1keV	Wolter-I型几何圆锥形近似； 4个175层,1个168层。6944镜段	环氧树脂和铝； 0.18mm厚	总：19.3kg 面积重量比： ~20cm²/kg	薄箔弯曲
NuStar (2012？)	角分辨率：~52 arcsec 有效面积：0.15m²@1.5keV 层半径：51-191mm 焦距：10.15m 视场：12角分*12角分	Wolter-I型几何圆锥形近似； 133层，1276镜段	Schott D263玻璃、F131，石墨复合材料;钛芯轴； 多层膜； 0.21mm厚	总：37 kg(单个) 面积重量比：	热弯玻璃 (圆柱-圆锥)
XMM-Newton (1999)	角分辨率：~10 arcsec 有效面积：0.15m²@1.5keV 直径：0.7m*3个 焦距：7.5m	Wolter-I型 58层*3个	镍；0.47 -1.07 mm厚	总：500 kg 面积重量比： ~3cm²/kg	精密芯轴的化学镀基复制
eROSITA (2019) EP FXT	角分辨率：~24arcsec 有效面积：340cm²@1keV 直径：erosita 0.36m*7个 FXT 2个 焦距：1.6m	Wolter-I型 54层	镍；0.2-0.6 mm厚；300mm长		精密芯轴的化学镀基复制
EP WXT	角分辨率：~300 arcsec 有效面积：3 cm²@1keV 焦距：0.375 m	Lobster-eye	玻璃基地		精密刻蚀技术

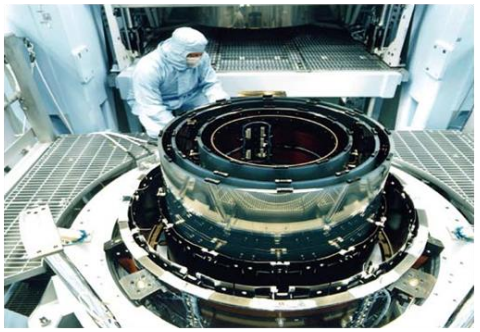


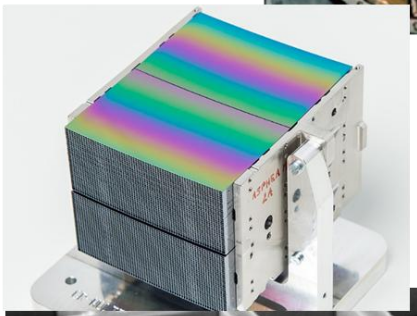
不得不做的选择

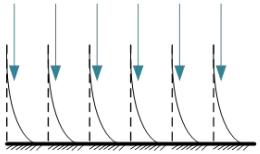
X射线光学！！

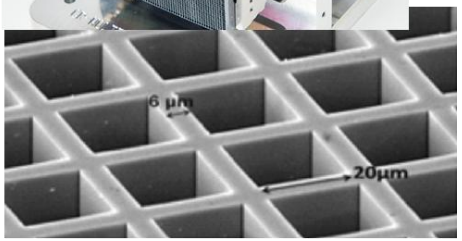


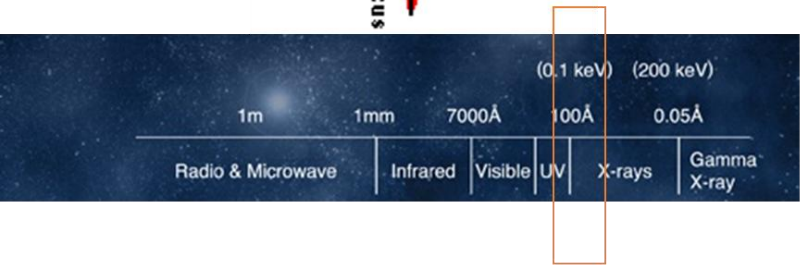






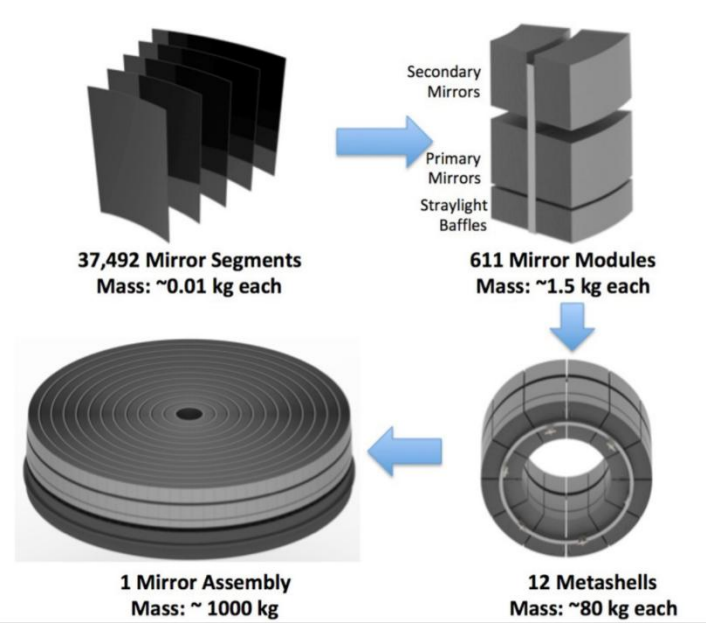


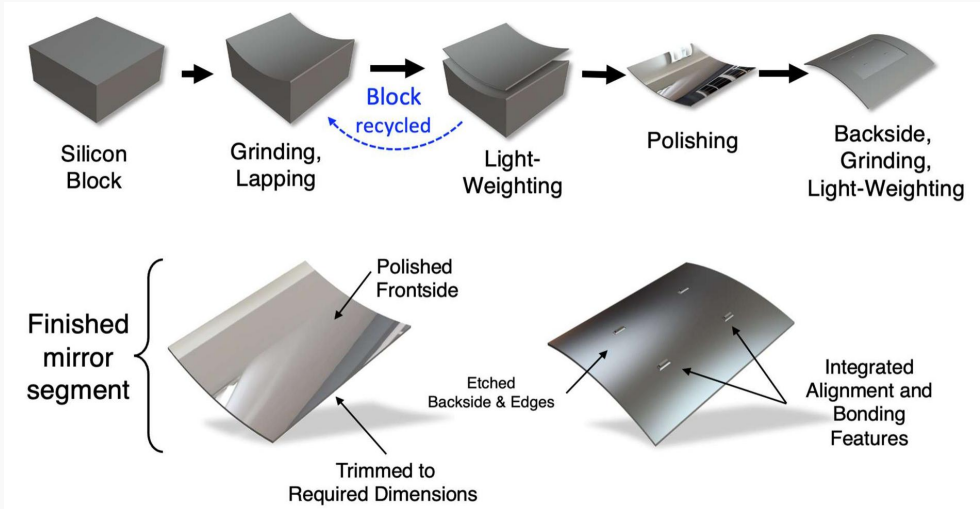


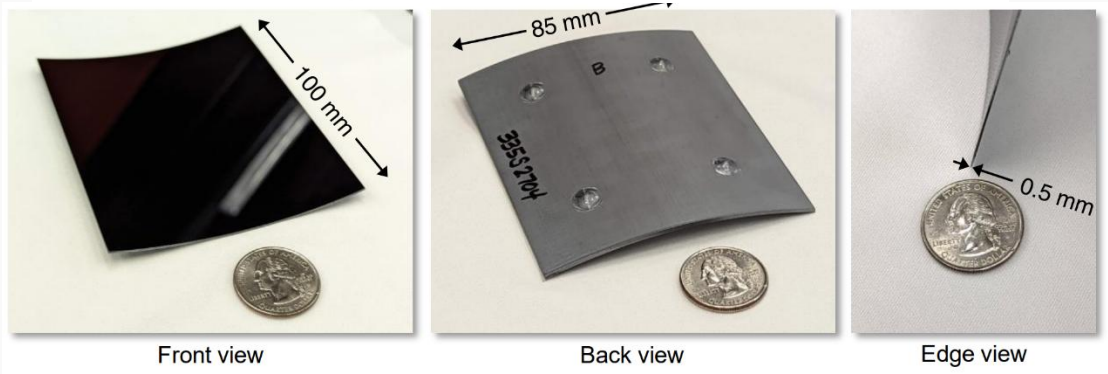


微孔X射线光学（MPO），紧凑型X射线光学

单晶硅超壳光学器件(Silicon Meta-shell Optics)



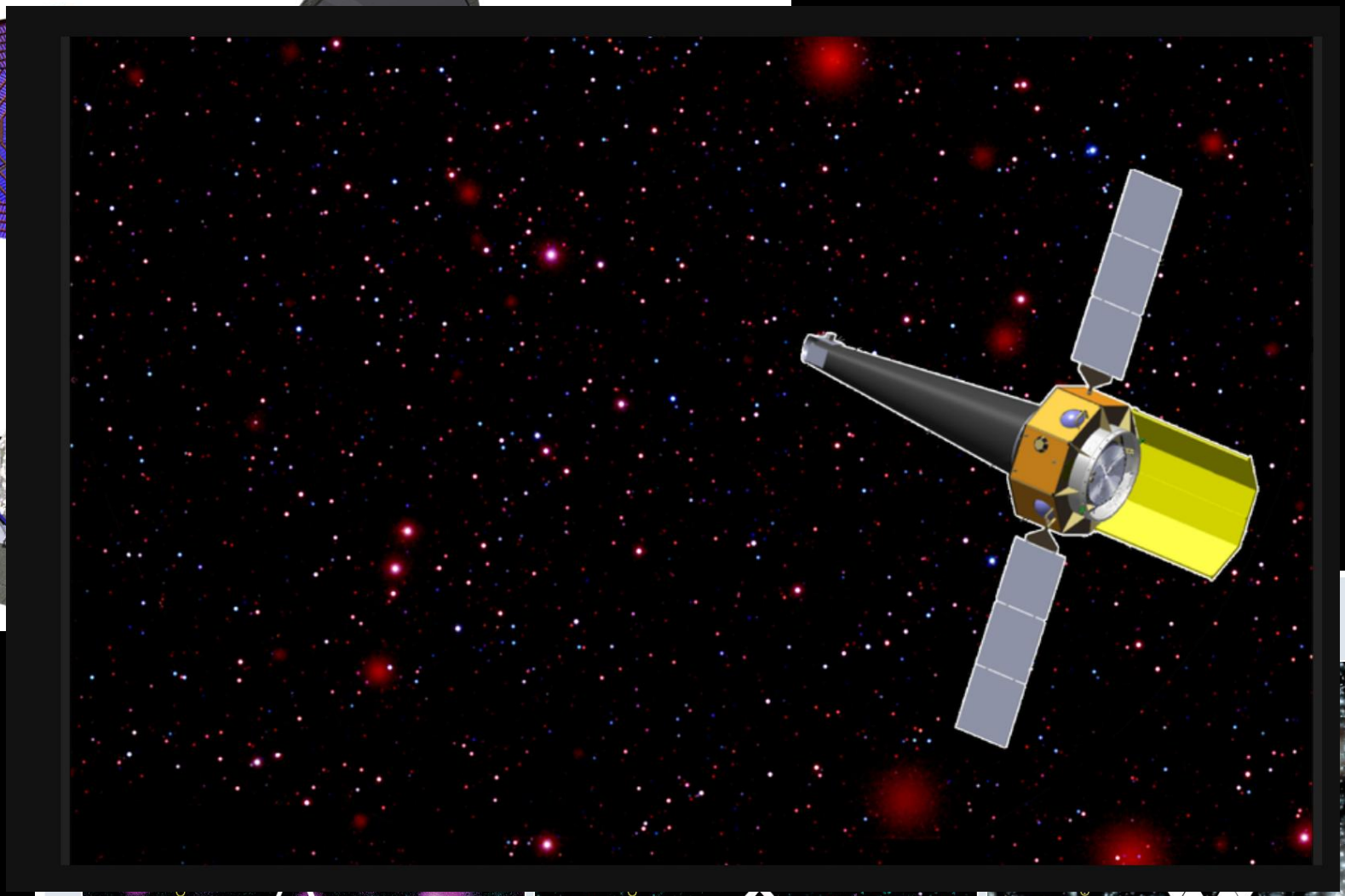


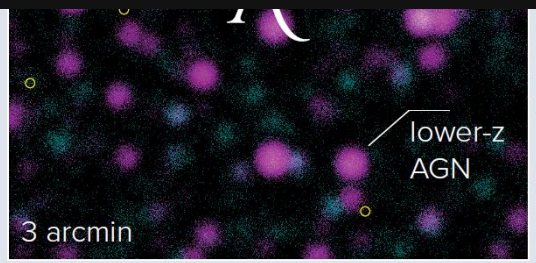


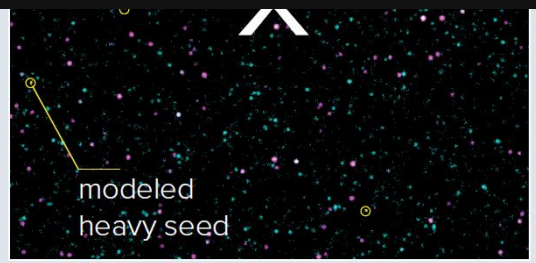
戈达德太空飞行中心 2011
(Goddard Space Flight Center)

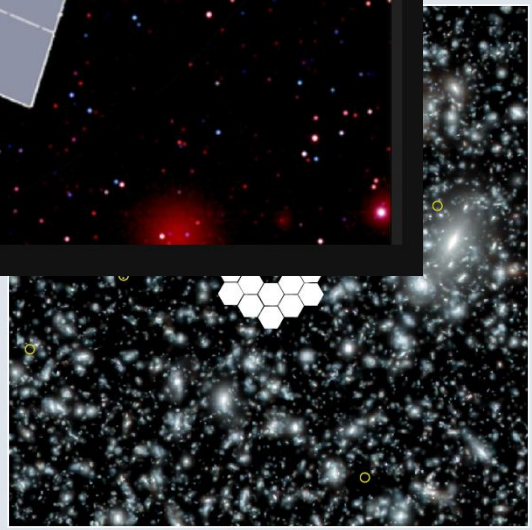
2023年10月 单基板：0.4；单对：0.82角秒HPD；多对：2~3角秒HPD

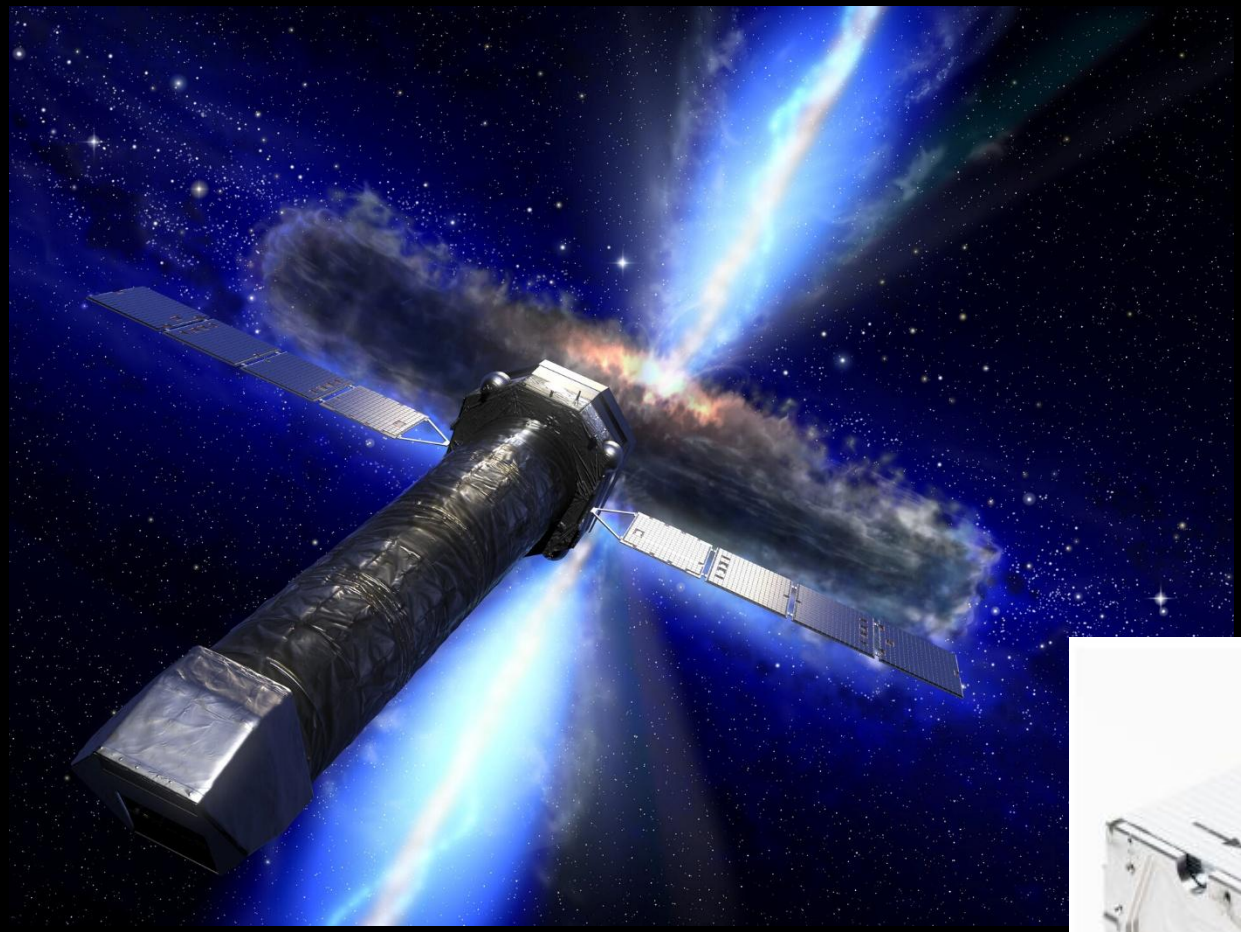
单晶硅：无内应力、2.33 g/ cm3,更硬、高导热性、热膨胀系数低




lower-z
AGN
3 arcmin


modeled
heavy seed





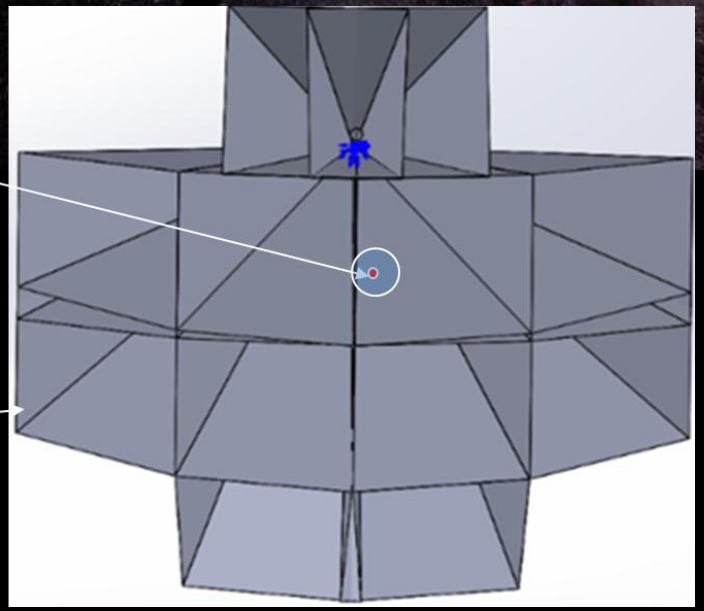
- ESA 2030年的 NewATHENA 任务
  - 2005年，硅孔光学器件SPO
  - 直径2米，反射镜492个SPO
  - Wolter-Schwartzschild设计
  - 12米,9角秒HPD,1.1m²@1keV

eXTP：国人的解决方案

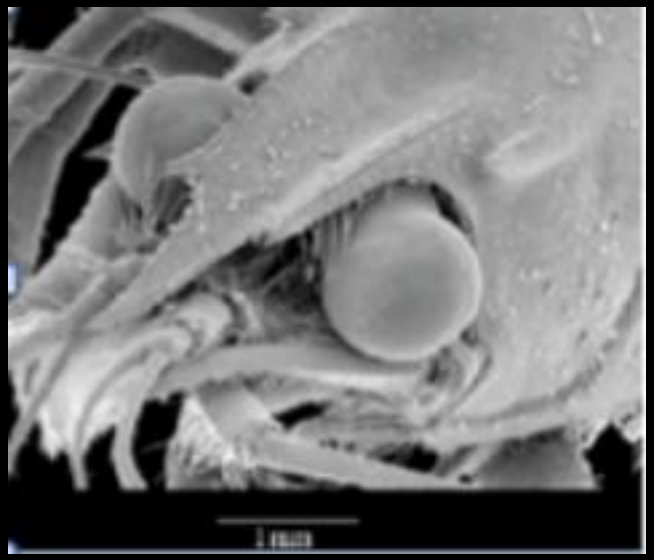
在有限资源情况下，根据科学目标做的最佳的取舍

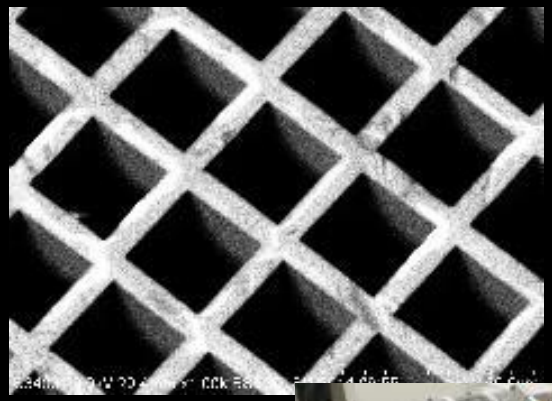
小视场深入研究和精确定位

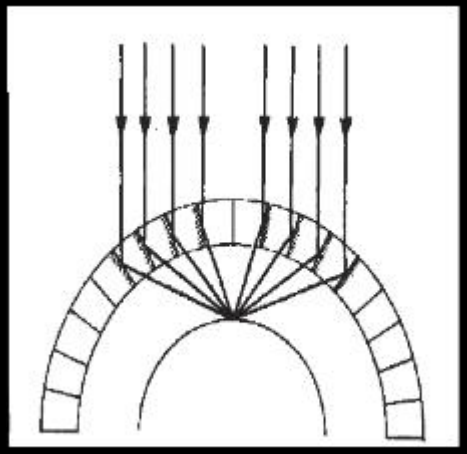
大视场发现随机事件：直线光学（准直）->聚焦，灵敏度的飞跃

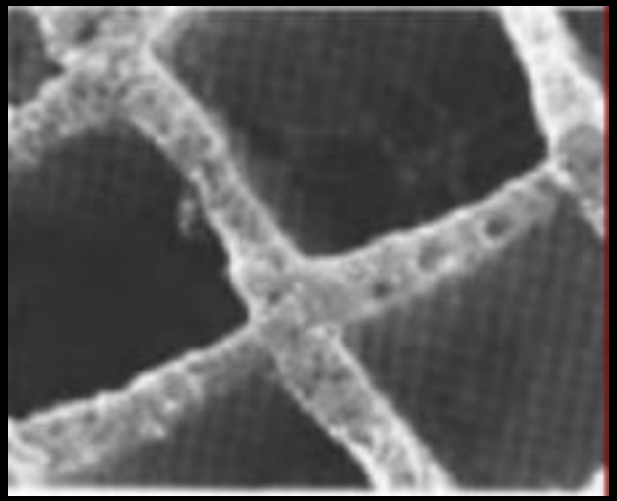


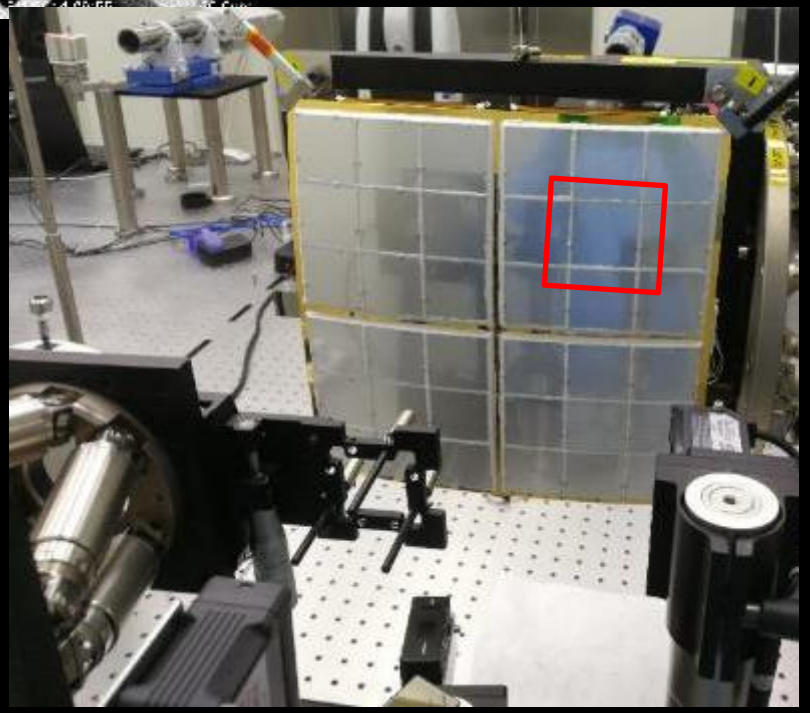
龙虾眼光学：以宽视场为核心的光学



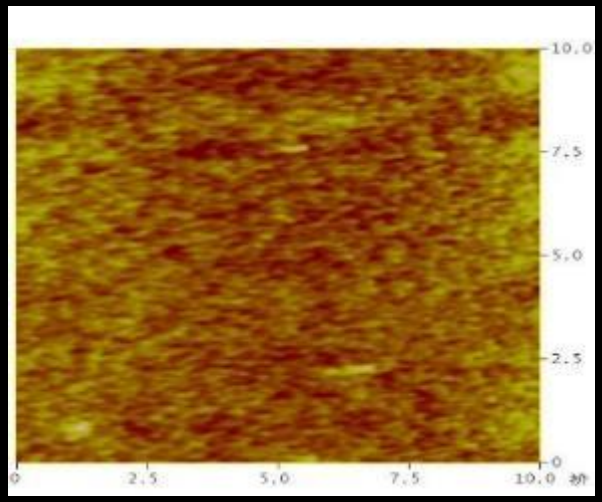


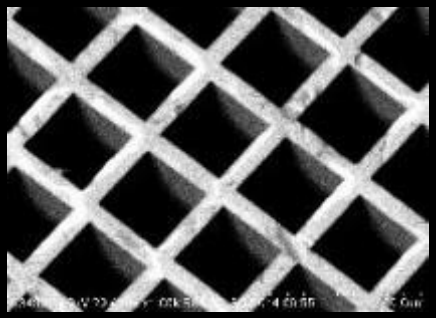


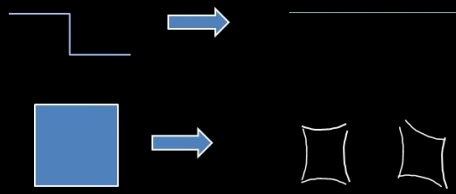




制作一个镜片

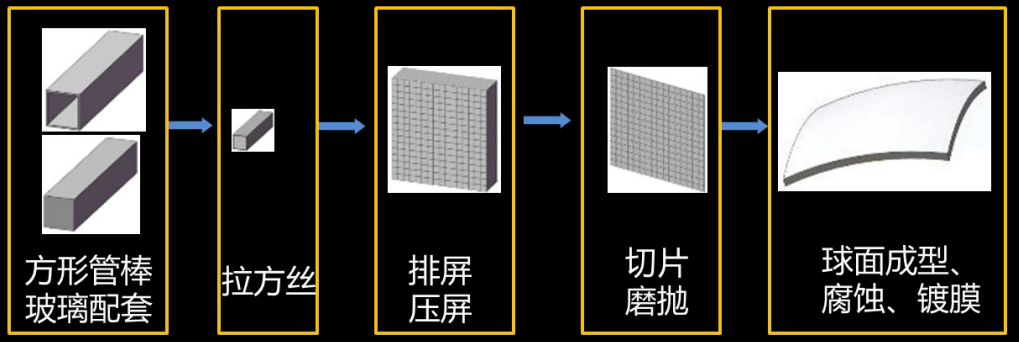






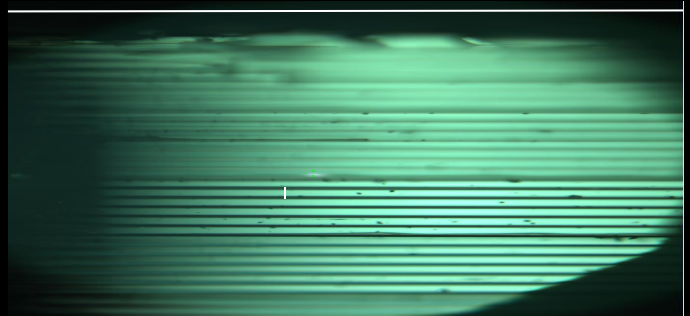
变形过程中
自然变好

变形过程中
结构畸变



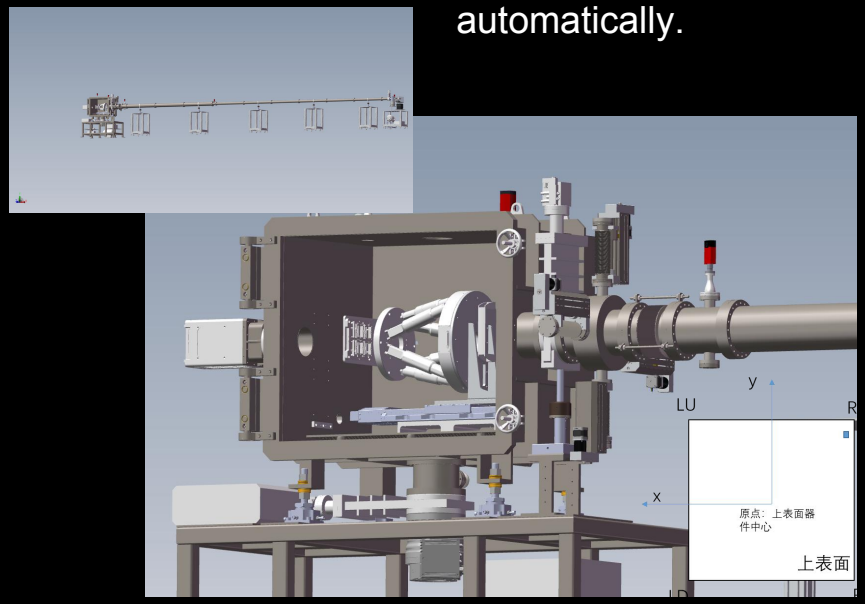
方形单丝　方形复丝　方形屏段　MPO平板　MPO

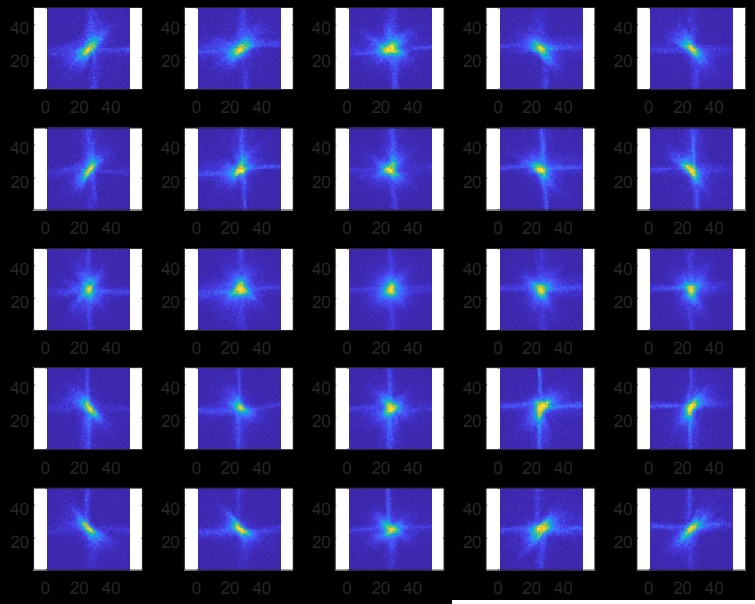
所有工艺均需高精度控制！

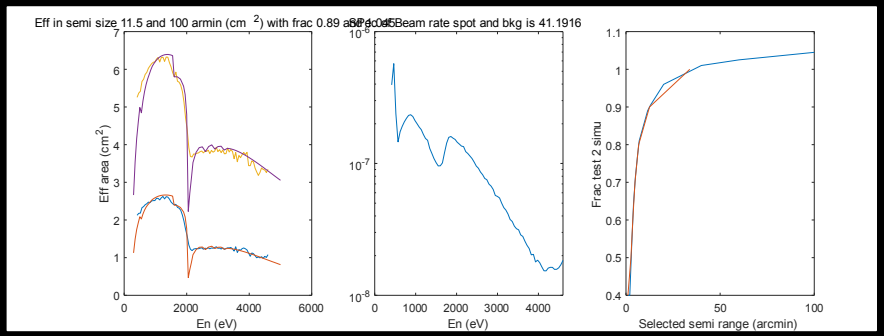


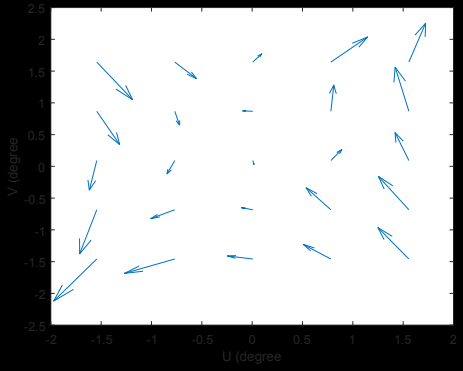
MPO Chip qualification facility

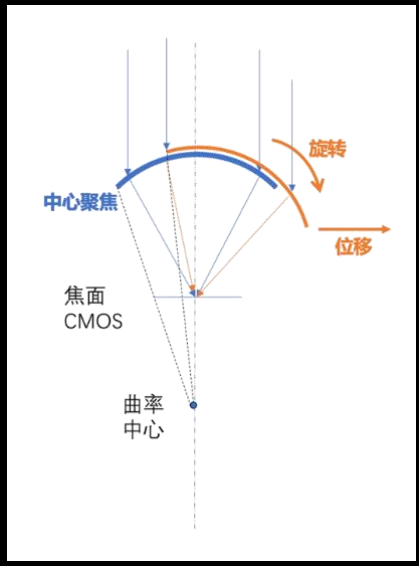
Designed for batch production.
~15 m long, almost fully automatically.



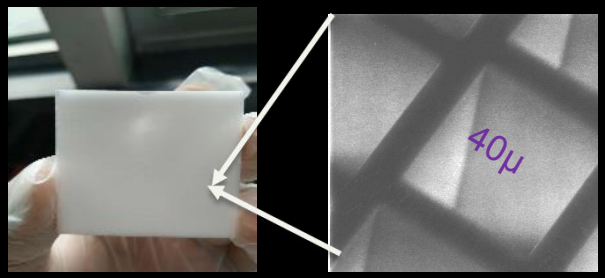


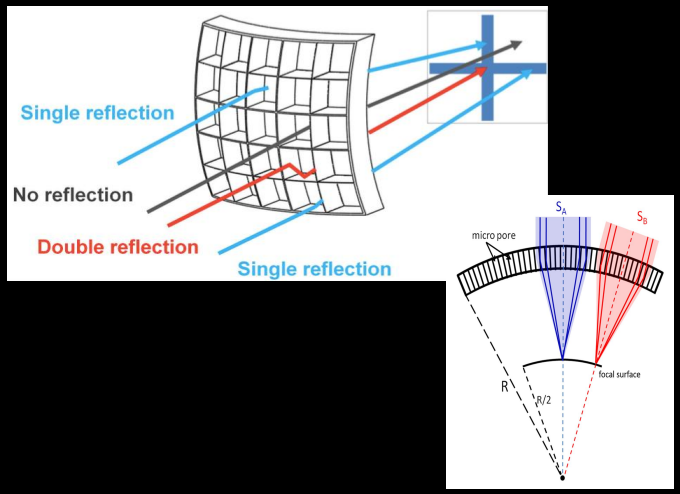


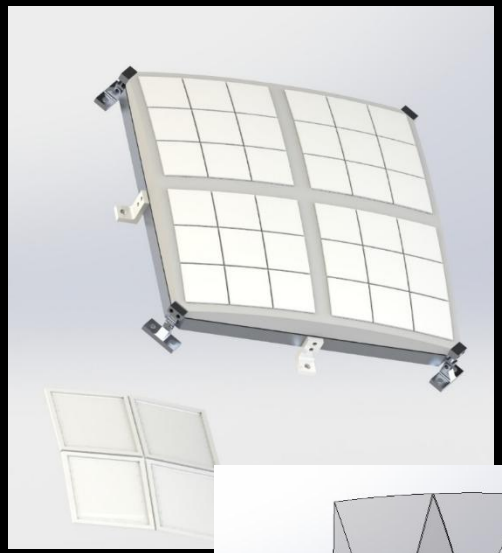


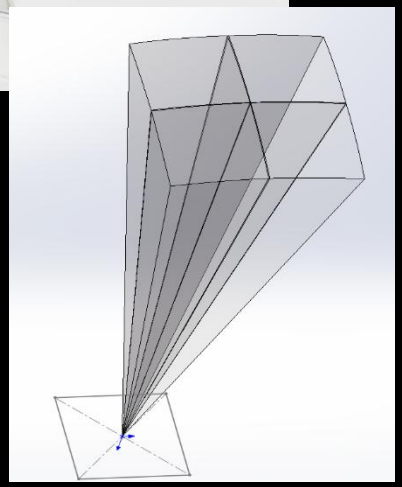


FOV configuration

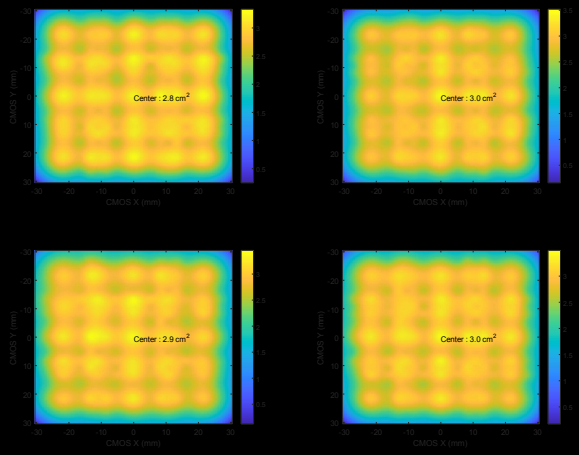








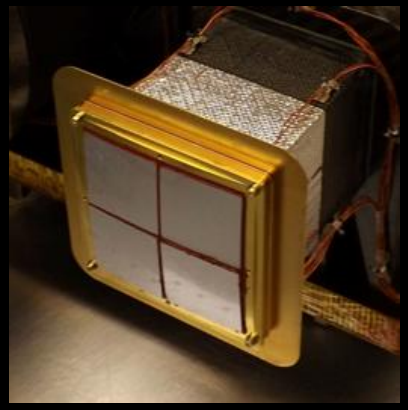
- 12 modules: ~330 sq. degree each
- 48 sub-modules: ~85 sq. degree each
- 432 MPO chips: 42.5*42.5*2.5 mm^3, 40 mum channel with 48 mum pitch
- 48 CMOS sensors: 4 k*4 k pixel array with 15 mum pixel size
- Vignetting in sub-module level

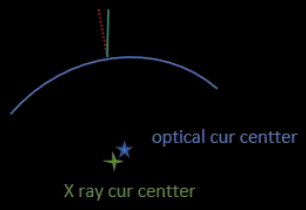


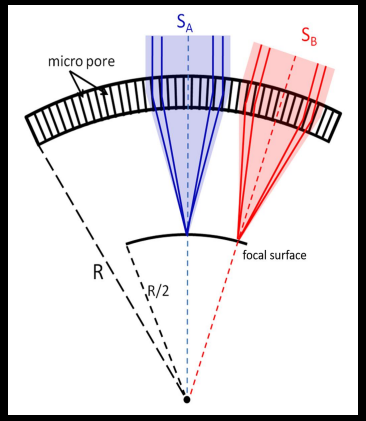
- 4 sub-modules in one module due to ceramic package of the CMOS sensors.

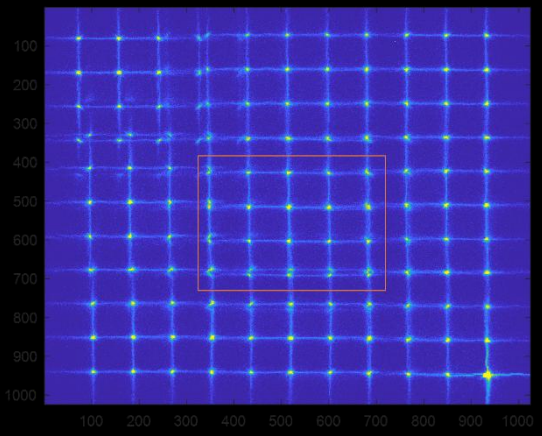
How to mount the chips on the frame

- Direct glue
- uniform bias angle of the chips?

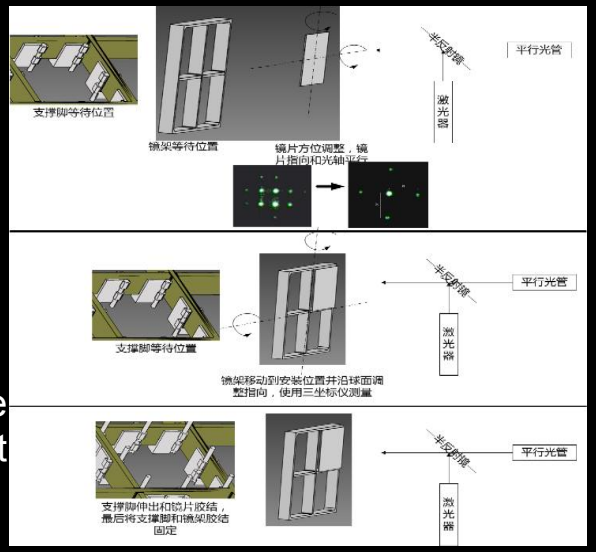






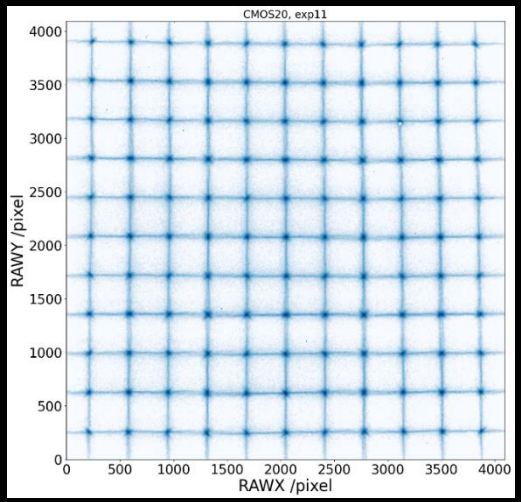


Adjust each chip based on there parameters and then glue.



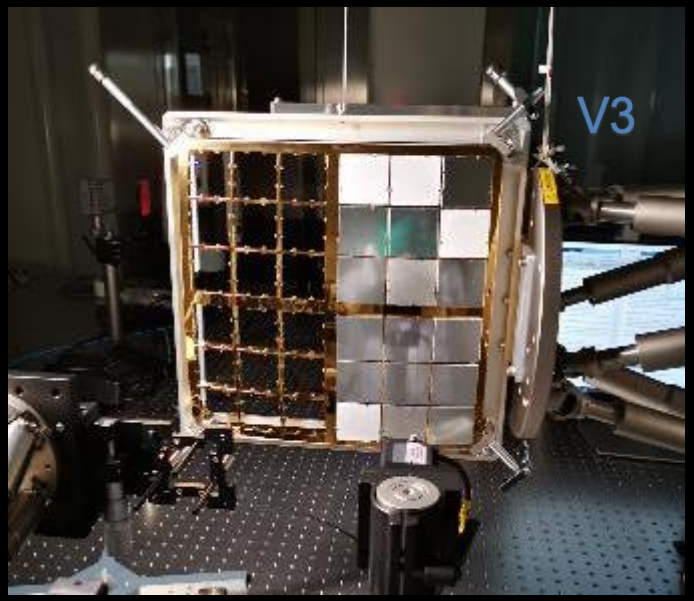
Bias angles do varies a lot
0~5 arcmin

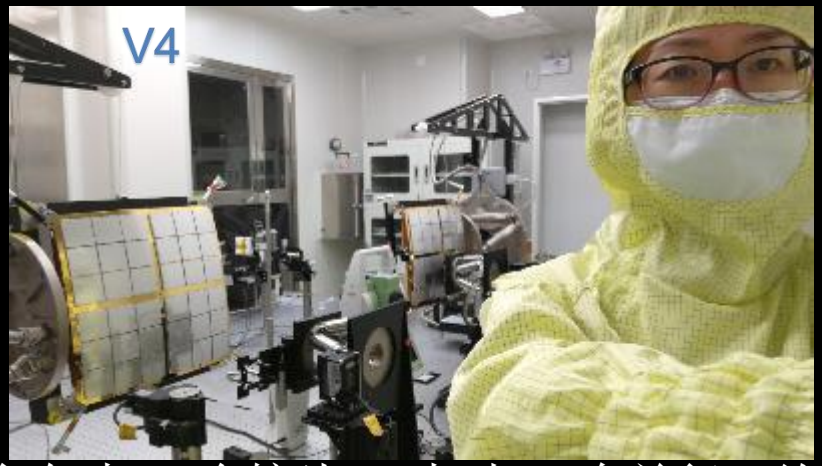
A large amount of work to measure all bias angles for all the chips!



制作一个组件

手动：1个镜片高度紧张的3小时*468天



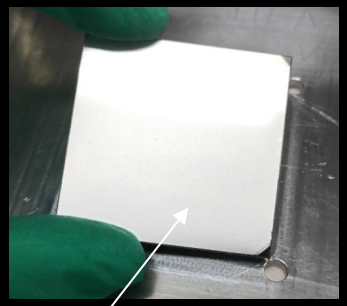


全自动：1个镜片0.5小时，2套并行，约234天安装时间

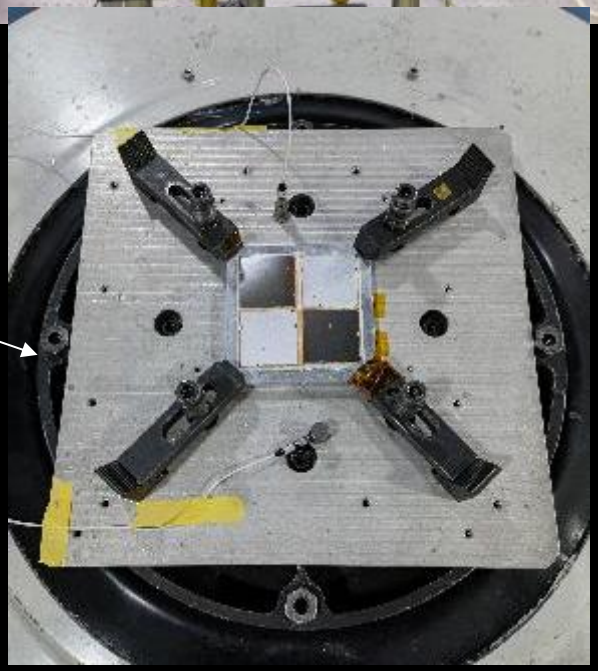
正样12+1套：468个MPO器件的高质量安装需求

航天是个苦差事

无应力装调
角秒精度

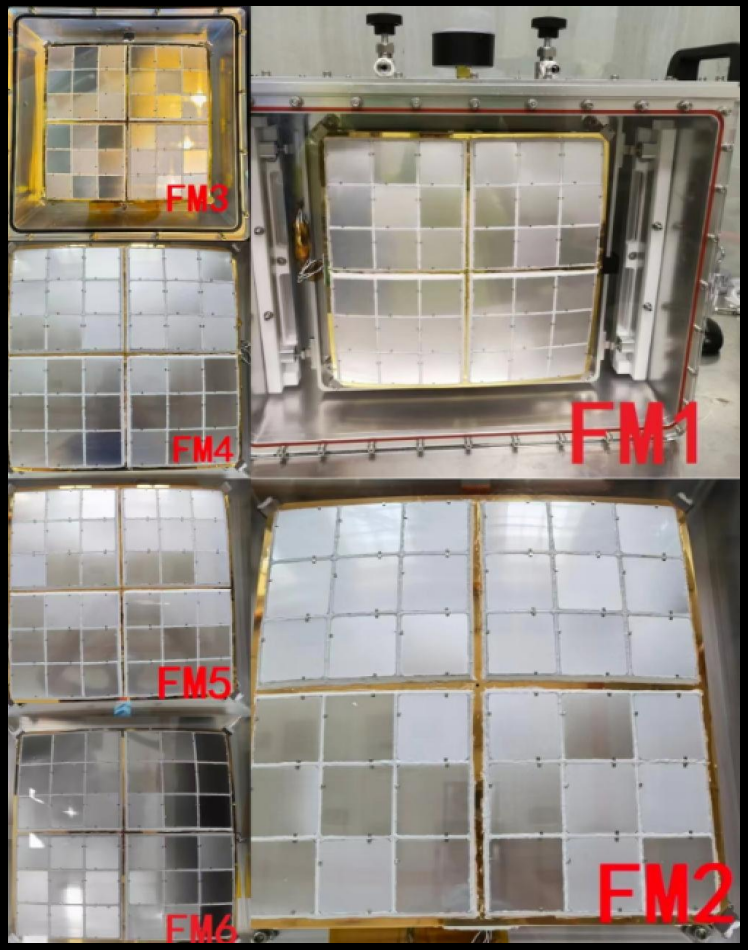


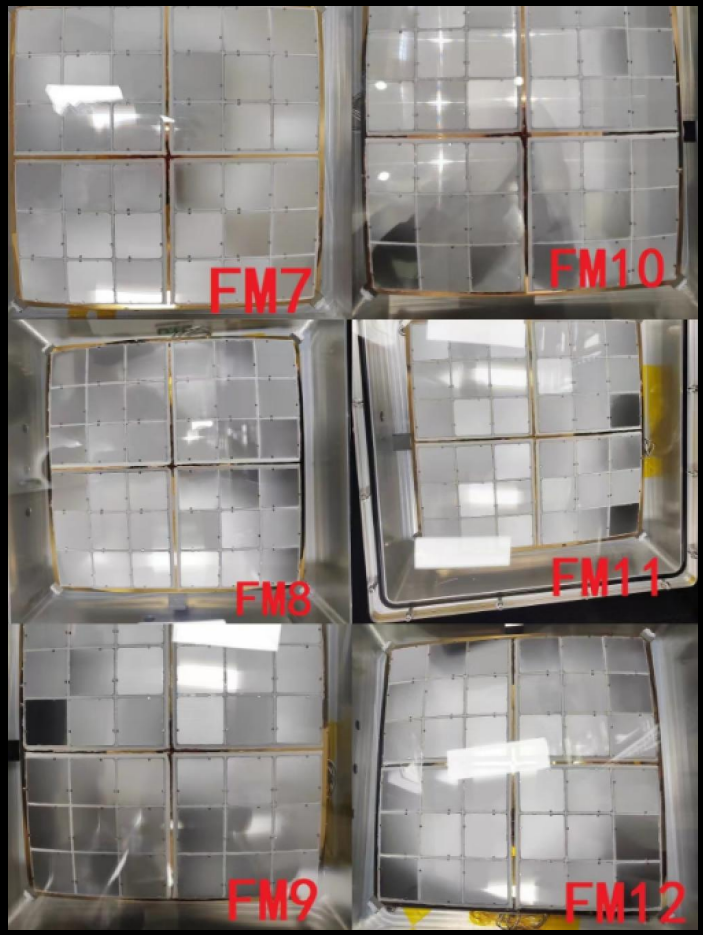
抗住野蛮的振动



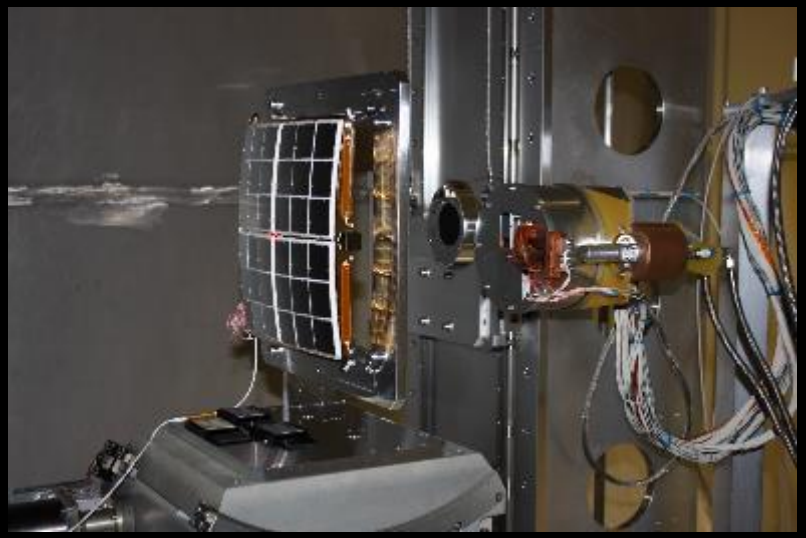
我已经变形
了……（弹性）

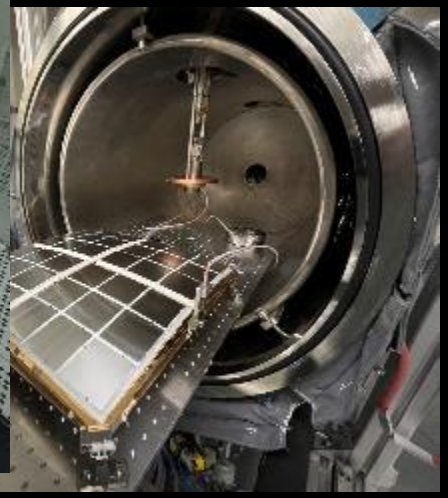
真空X射线测试<->大气可见光装调基准
的传递

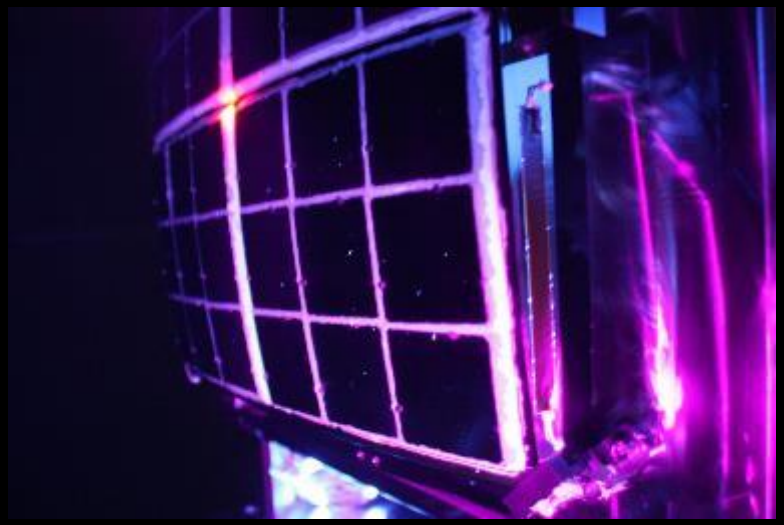

FM3
FM4
FM1
FM5
FM2
FM6


FM7
FM10
FM8
FM11
FM9
FM12


EXIT

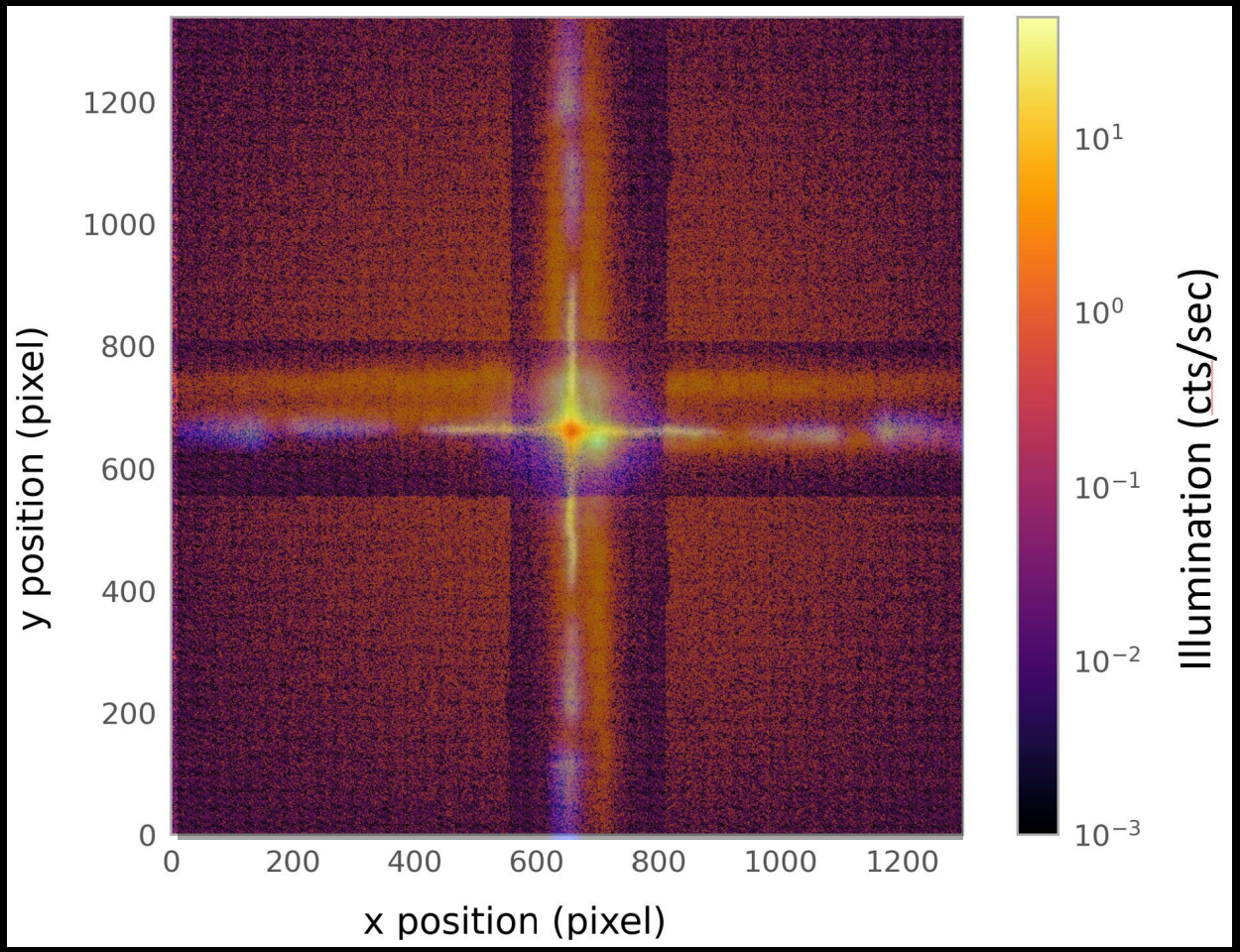






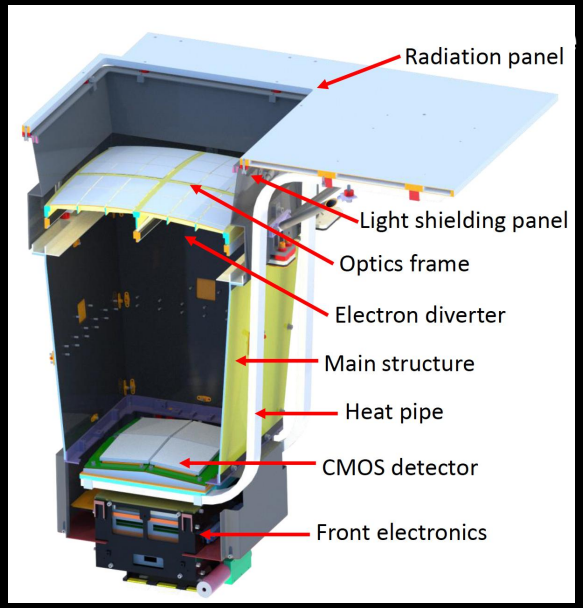
EP的龙虾眼怎么样

VS



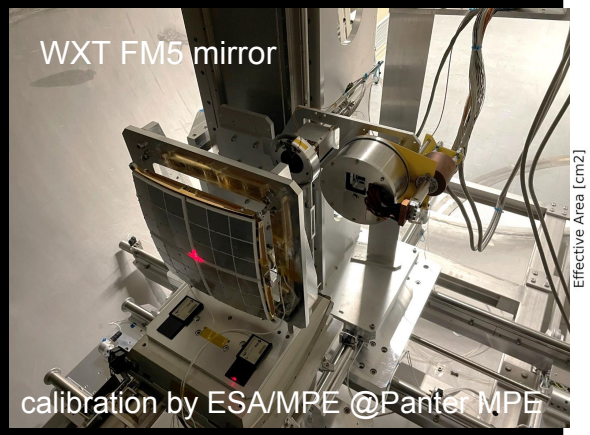
Wide-field X-ray Telescope (WXT)

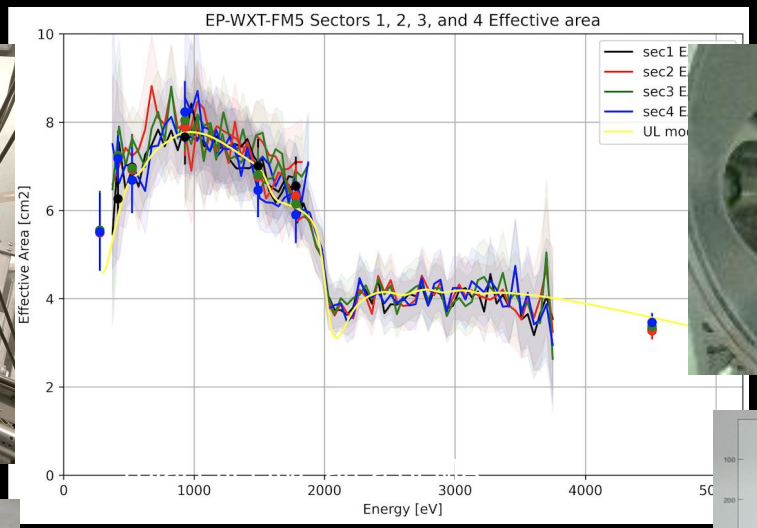
WXT

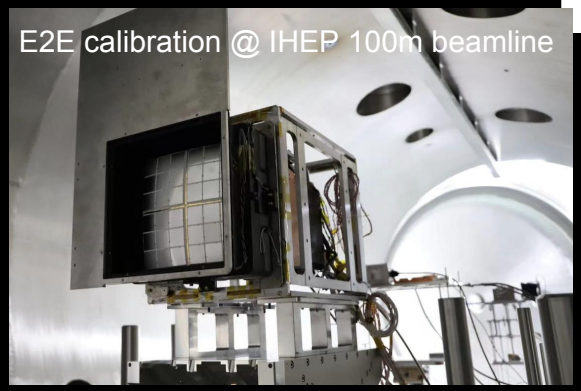


Weight 17kg

Flight model

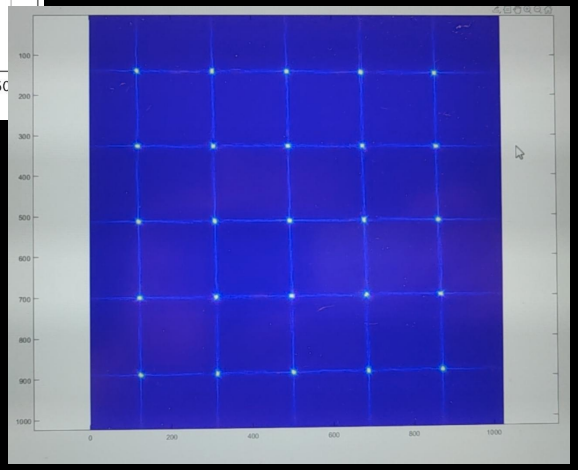






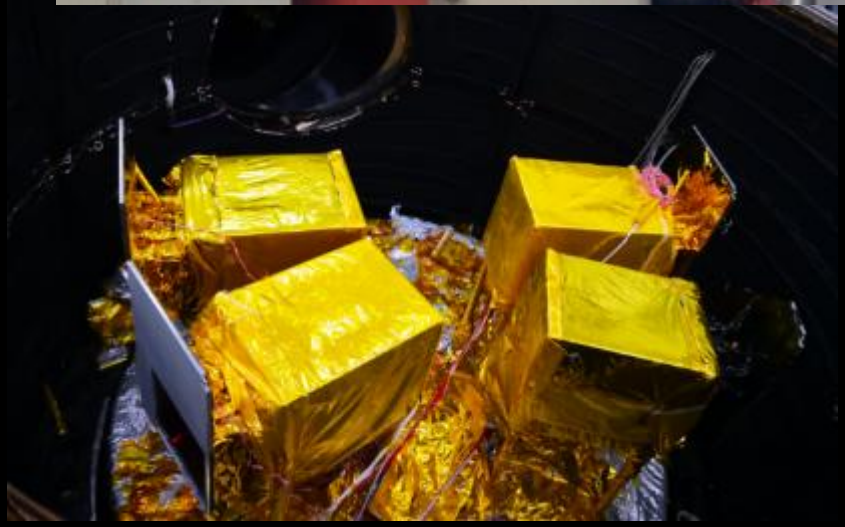
Credit: V. Burwitz (MPE)

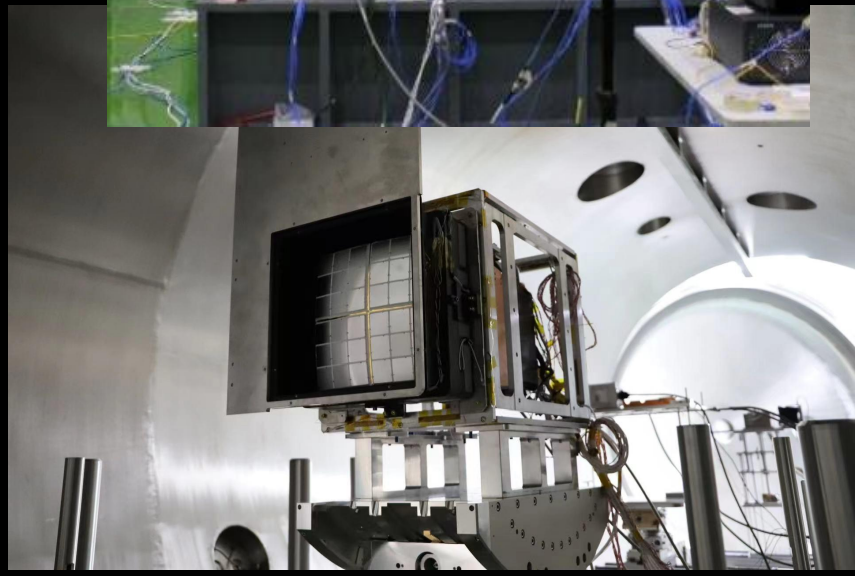
¼ FoV (9 deg x 9 deg)
of one module (FM)



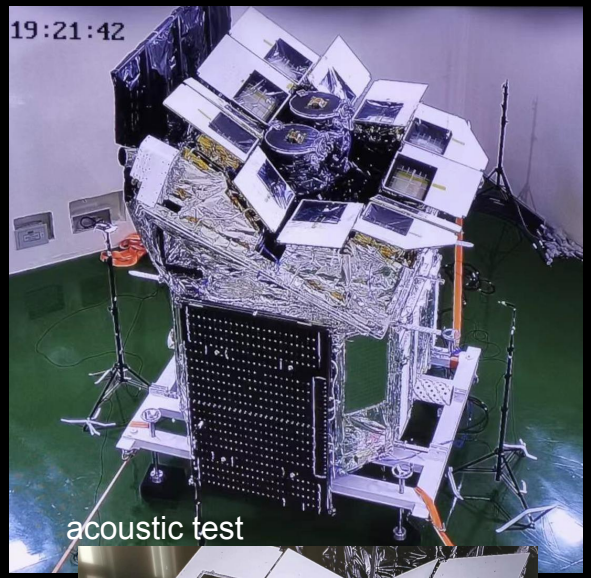
PSF scaning in 25 directions

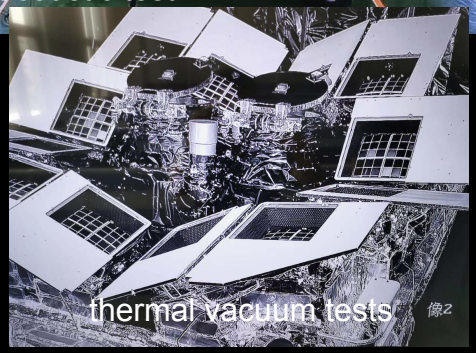
漫漫飞天路





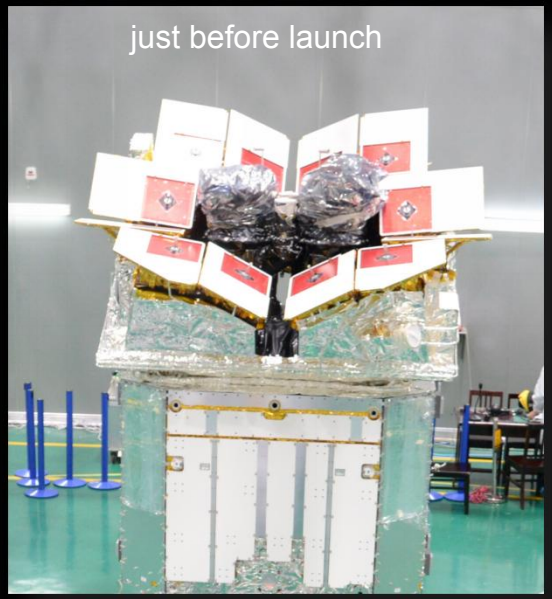
EP satellite





S/C developed @ MicroSat/CAS, Integration & tests

Satellite weight	1430 kg
Power	1150 W
Dimension	3.418(H) × 2.591(D) × 10.309(W) meters




西昌卫星发射中心

我们的征途是星辰大海