

“X射线天文学60周年及中国X射线天文研究”研讨会
时域与多信使天文学时代的X射线天文研究
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国内X射线Wolter-I 聚焦望远镜研制进展

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- 王波, 王浪平, 王殿龙, 丁飞, 廖秋岩 (哈工大)
- 盛立志, 强鹏飞 (西光所)
- 李连升, 石永强, 黎月明 (502所)
- Peter Friedrich, Vadim Burwitz (MPE)

报告内容

- X射线聚焦技术
- Wolter型聚焦镜简介
- 国内Wolter型聚焦镜研制
- EP-FXT及eXTP聚焦镜研制进展
- 总结与展望

一、X射线聚焦技术

掠入射角

- $\alpha_t = 5.6 \lambda \rho^{1/2} \sim 1^\circ$

表面粗糙度

- $\sim 0.5 \text{ nm}$

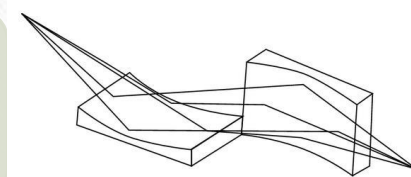
面形精度

- $\sim 1 \mu\text{m}$

常用的X射线聚焦技术

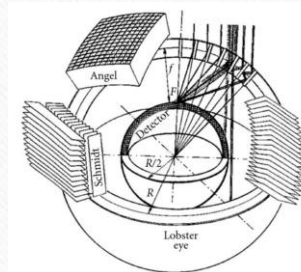
Kirkpartrick-Baez

- 1948年
- 面积大，分辨好



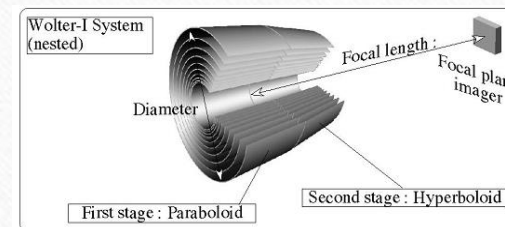
Lobster-eye

- 1975年 (Schmidt), 1979年 (Angel)
- 视场大



Wolter

- 1952年
- 面积大，分辨好，广泛应用



二、Wolter型聚焦镜简介

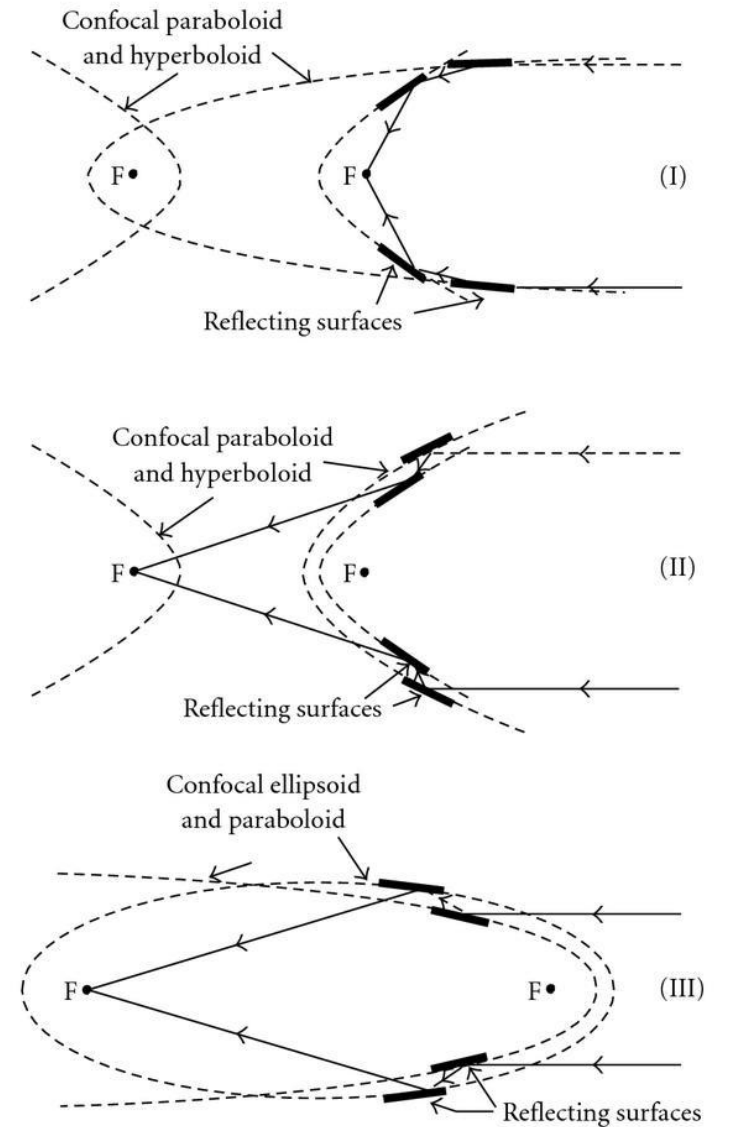
- 1952年 H. Wolter发表X射线显微镜3种聚焦方法 (70周年)
- 1960年 Giacconi和Rossi提出嵌套式Wolter-I聚焦镜结构天文应用
- 1963年 Wolter型望远镜搭载探空火箭获得太阳X射线图像 (电铸镍镜片; 角分辨好于1 arcmin)
- 1978年 使用Wolter-I聚焦镜的HEAO-B (爱因斯坦)卫星发射, 获巨大成功

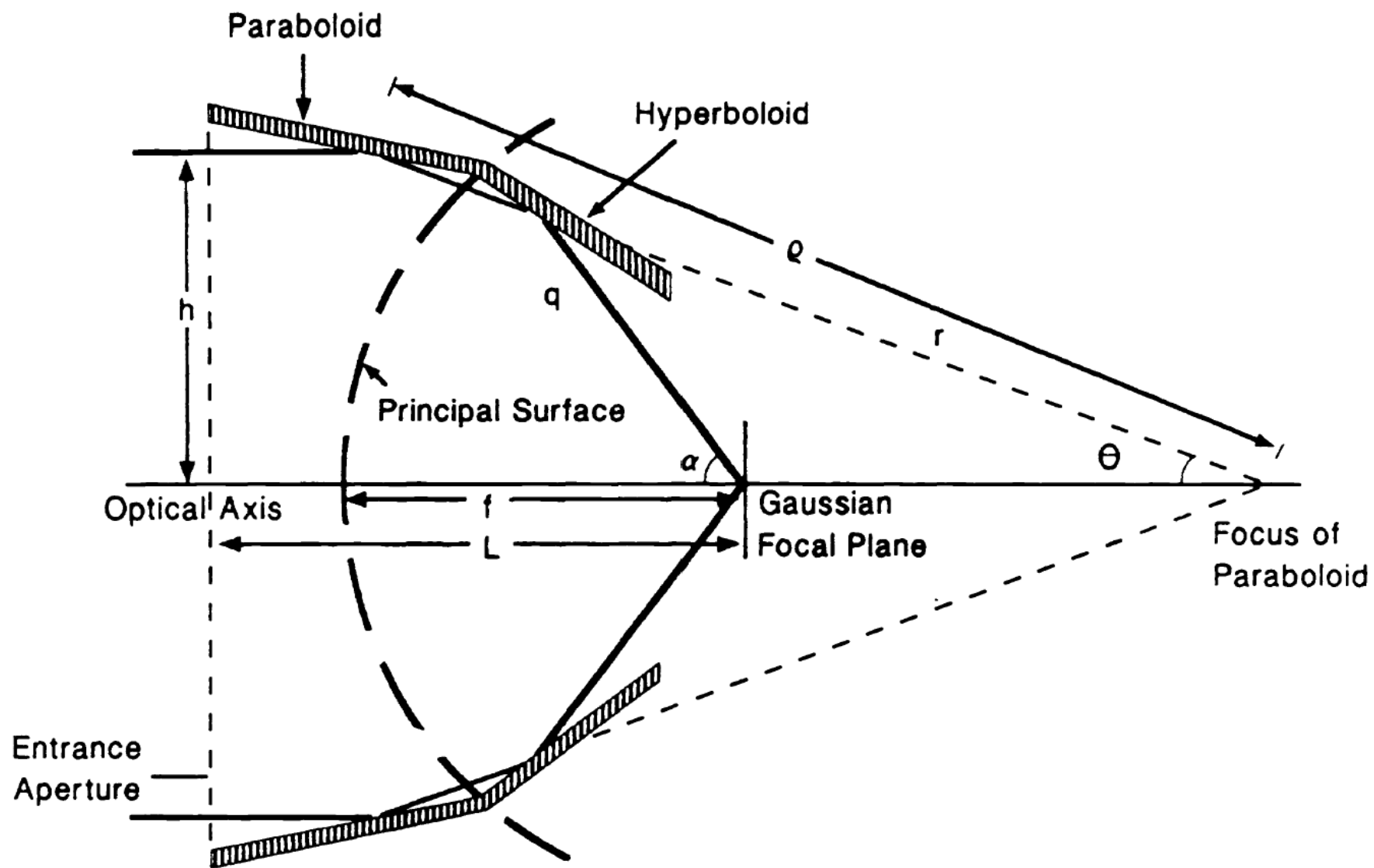


Hans Wolter
(1911-1978)

Wolter聚焦镜的三种设计

- 掠入射使单片聚焦镜不符合Abbe正弦条件，无法成像
- Wolter提出采用两片聚焦镜：第一段为旋转抛物面；第二段为旋转双曲面或旋转椭球面
- Wolter指出可通过增加双曲面的个数来增大望远镜口径，总镜子数需为偶数
- Wolter进而提出严格满足Abbe正弦条件的Wolter-Schwarzschild望远镜





Wolter-I聚焦镜示意图

Overview of X-ray Optics

4-Shells Glass Optics

HEAO-2 NASA 1978

EXOSAT ESA 1982

ROSAT 1990

1980

Electroforming Replication

Swift NASA 2004

Suzaku JAXA 2005

2000

Lobster Eye

IXPE NASA 2021

SVOM CHN&FRA 2023

Einstein Probe China 2023

eXTP China 2027

2020

2030

Electroforming Replication

ASCA JAXA 1993

BeppoSAX ESA 1996

Chandra NASA 1999

XMM-Newton ESA 1999

1990

Slumped Glass Optics

NuSTAR NASA 2012

ASTROSAT India 2015

XPNAV-1 China 2016

NICER NASA 2017

SRG eROSITA Germany 2019

2010

Silicon Pore Optics

Micro Slot Optics

Athena ESA 203?

Lynx NASA 203?

HUBS China 203?

2030

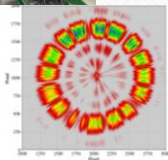
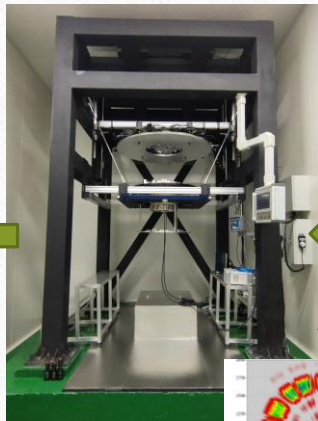
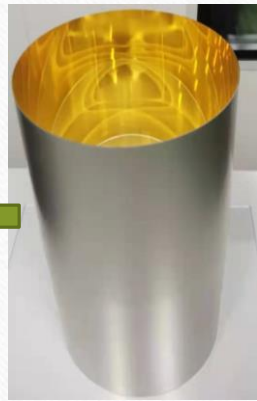
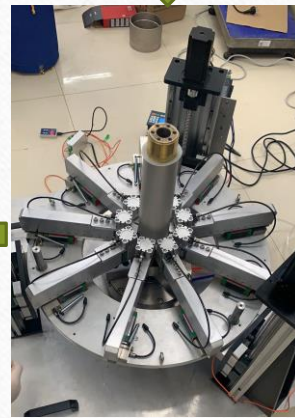
三、国内Wolter型聚焦镜研制

- 脉冲星应用
- X射线天文
- 热弯玻璃（同济大学，502，513，空间中心，西光所）
- 电铸镍（高能所，哈工大，西光所，502，长光所）



蒋筑英
(1938-1982)

电铸镍聚焦镜片制造 (高能所、哈工大、西光所)



热弯玻璃聚焦镜片制造（北京控制工程研究所）



模具加工

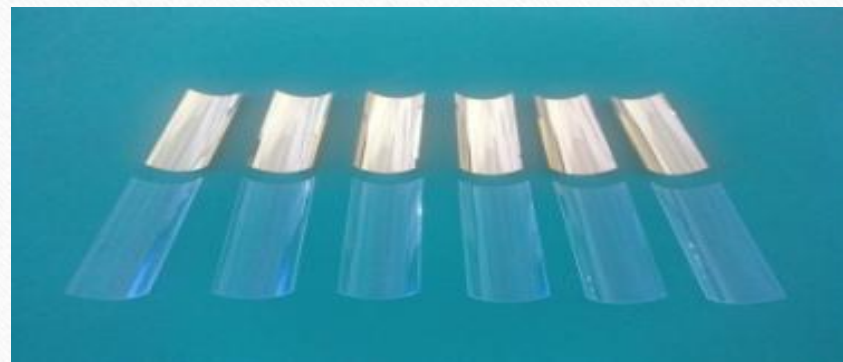
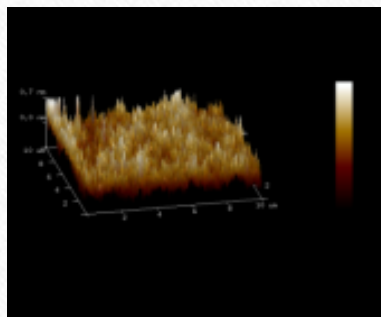
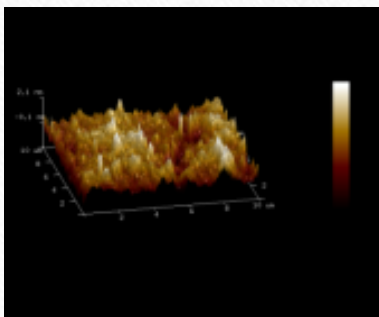


玻璃热弯



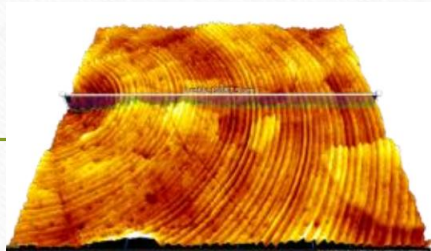
镜片检测

粗糙度测试（热弯前、后）



模具测量

✓ 波纹度和粗糙度

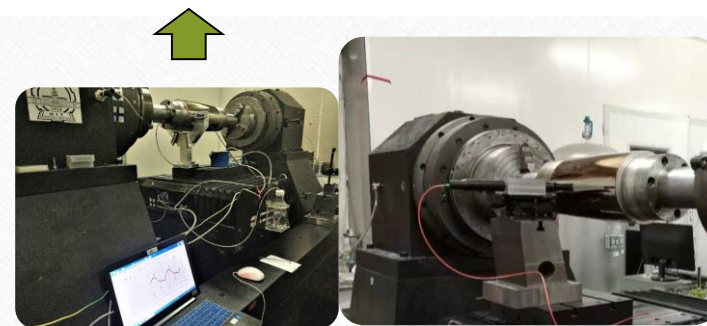
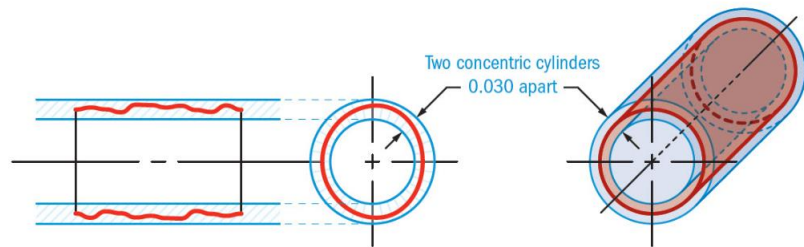


原子力显微镜



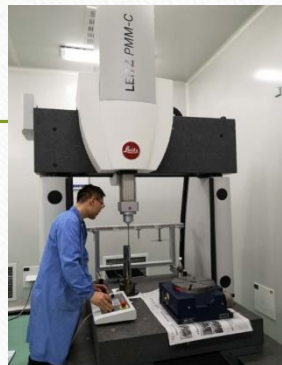
白光干涉仪

✓ 面形误差

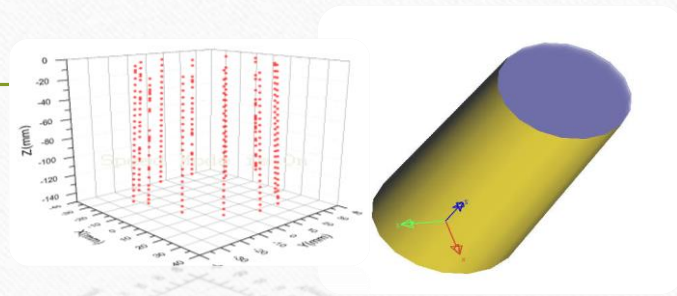


在线白光检测

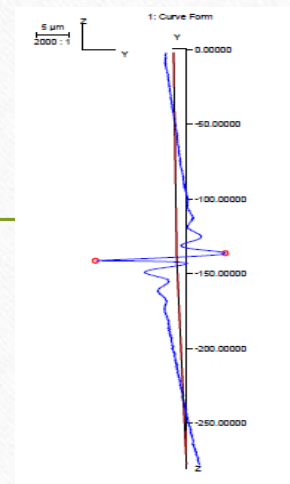
面形测试



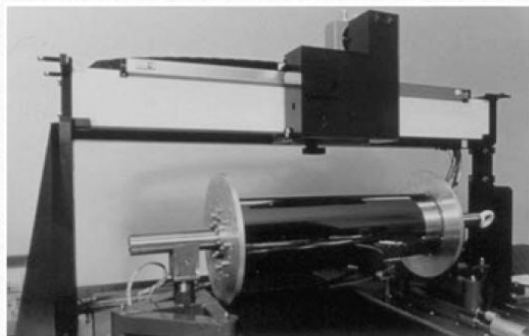
三坐标测量仪



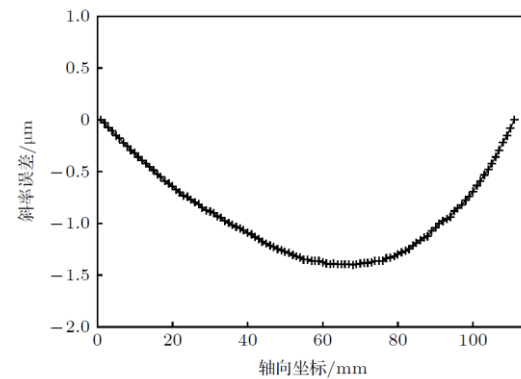
三坐标测量结果及拟合面型



三坐标测量残差

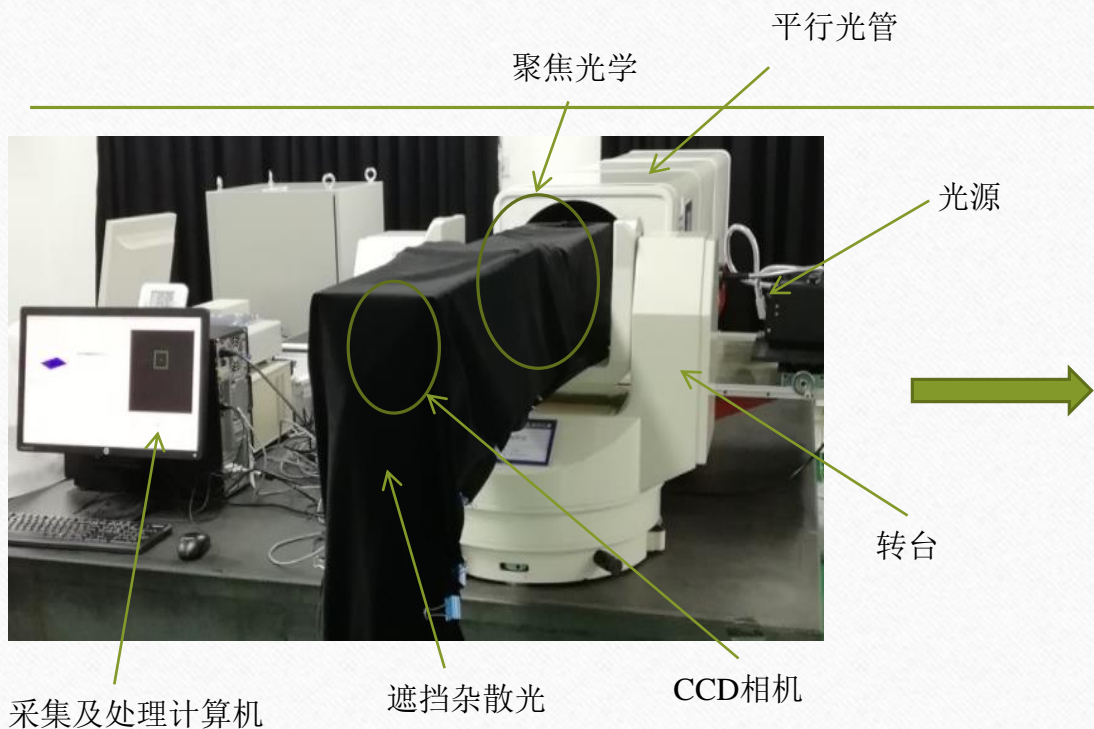


长程轮廓仪 (LTP)

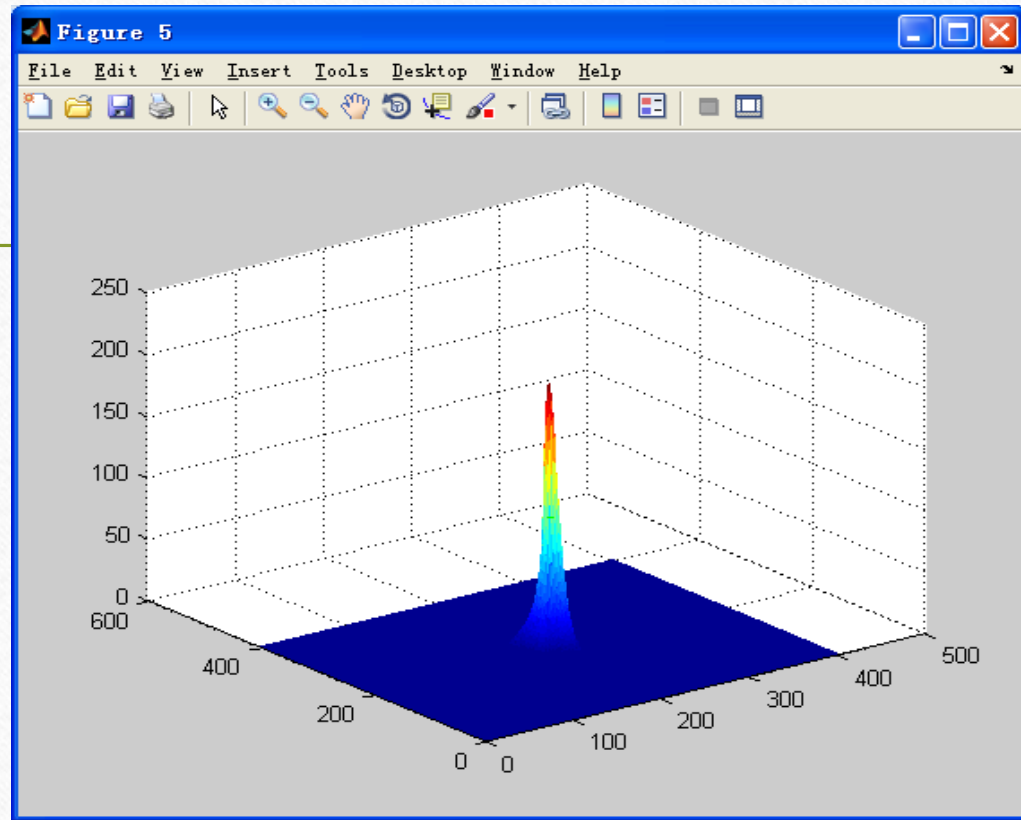


斜率误差均方根值0.42um

聚焦镜检测装置

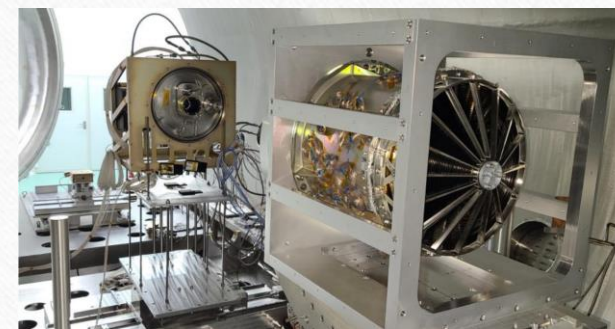


角分辨率测试系统 (502所)



实测的角分辨率达到15" (FWHM)

X射线聚焦镜测试装置



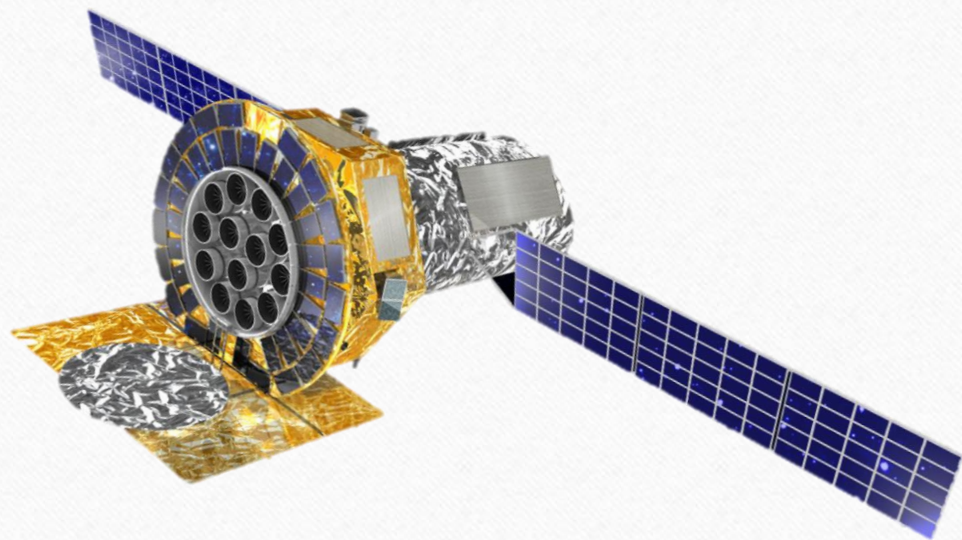
高能所100mX射线标定装置



北京控制工程研究所30米X射线测试装置



四、EP-FXT及eXTP聚焦镜研制进展



聚焦镜性能比较

	eXTP		EP-FXT
	SFA	PFA	
Number of Mirror Modules	9	4	2
Number of mirror shells	45		54
Focal length	5.25 m		1.6 m
Envelope	≤600 mm (Diameter)		≤420 mm (Diameter)
Effective area on axis	≥820 cm ² @ 2 keV ≥550 cm ² @ 6 keV		≥300 cm ² @ 1.25 keV
Energy range	0.3~10 keV		0.3~10 keV
Field of View	>12'		1°
Angular resolution (HPD)	<30" (15")		2' (30")
Mass budget	≤100 kg		≤50 kg
Working temperature	20±1 °C		20±1 °C

遮阳翻转机构
Deployable structure

星敏
Star Sensor

棱镜
Prism

遮阳保护盖
Thermal cover

遮光筒
Thermal baffle

聚焦镜组件
The Mirror Assembly

电子偏转器
The Electron deflector

支撑结构
FXT Interface structure

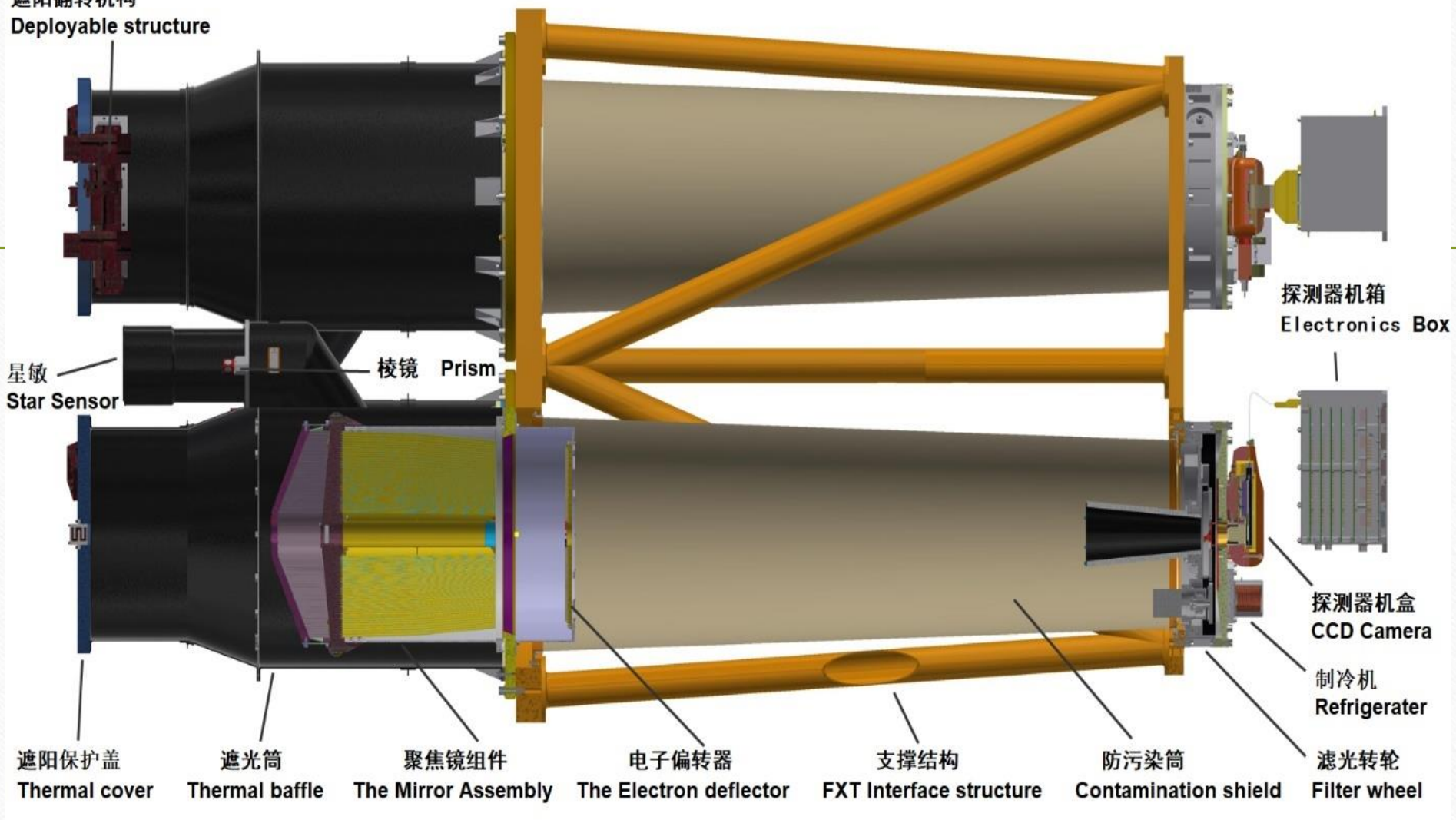
防污染筒
Contamination shield

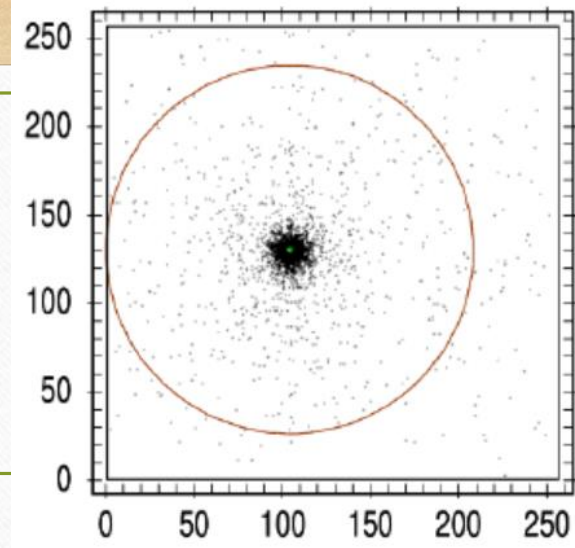
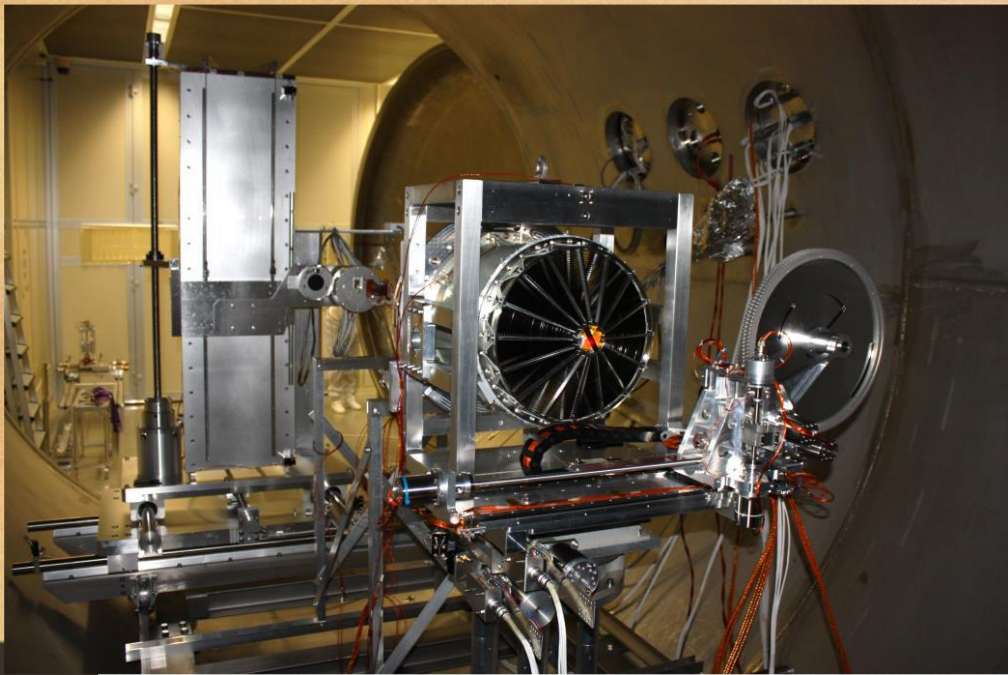
探测器机箱
Electronics Box

探测器机盒
CCD Camera

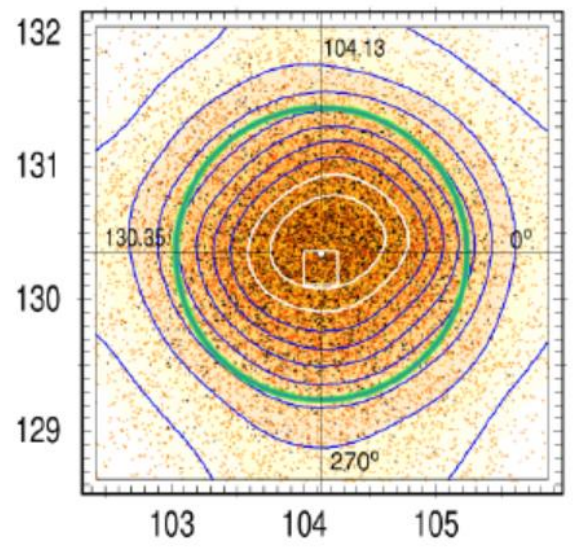
制冷机
Refrigerater

滤光转轮
Filter wheel

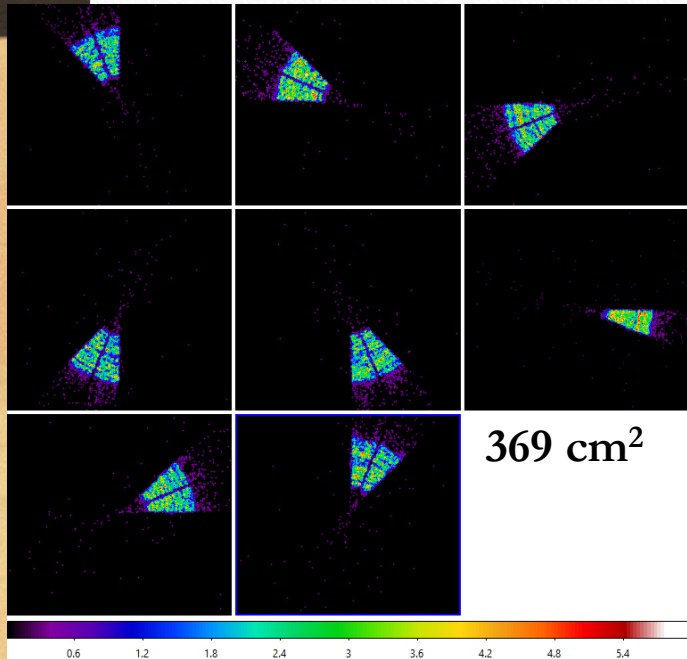




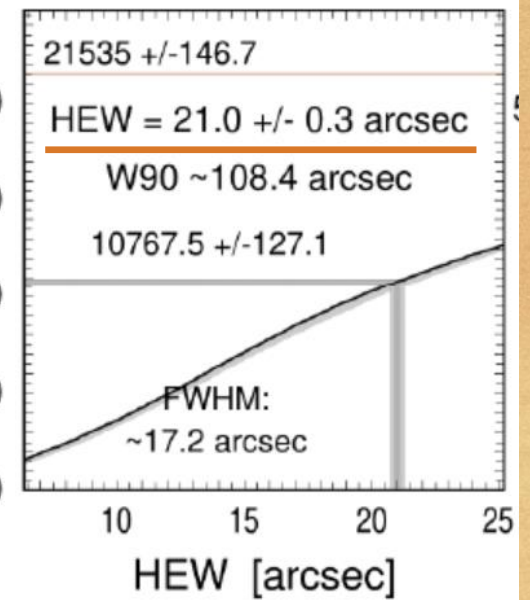
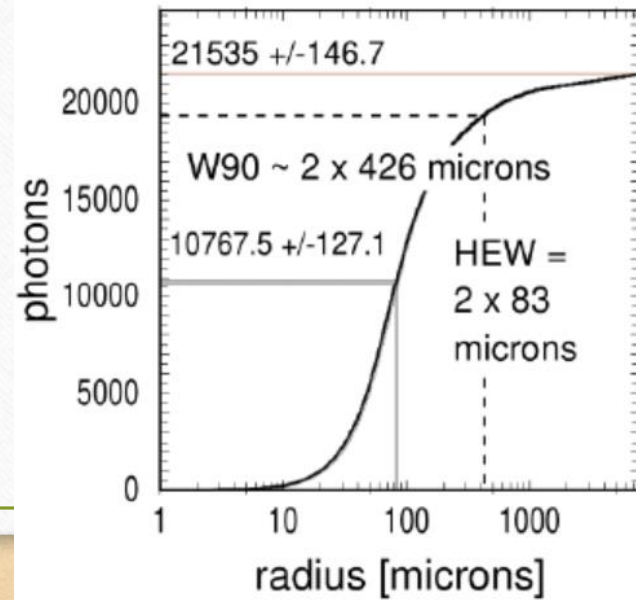
full CCD image (telescope frame)
reference frame: HK210722_001.fits



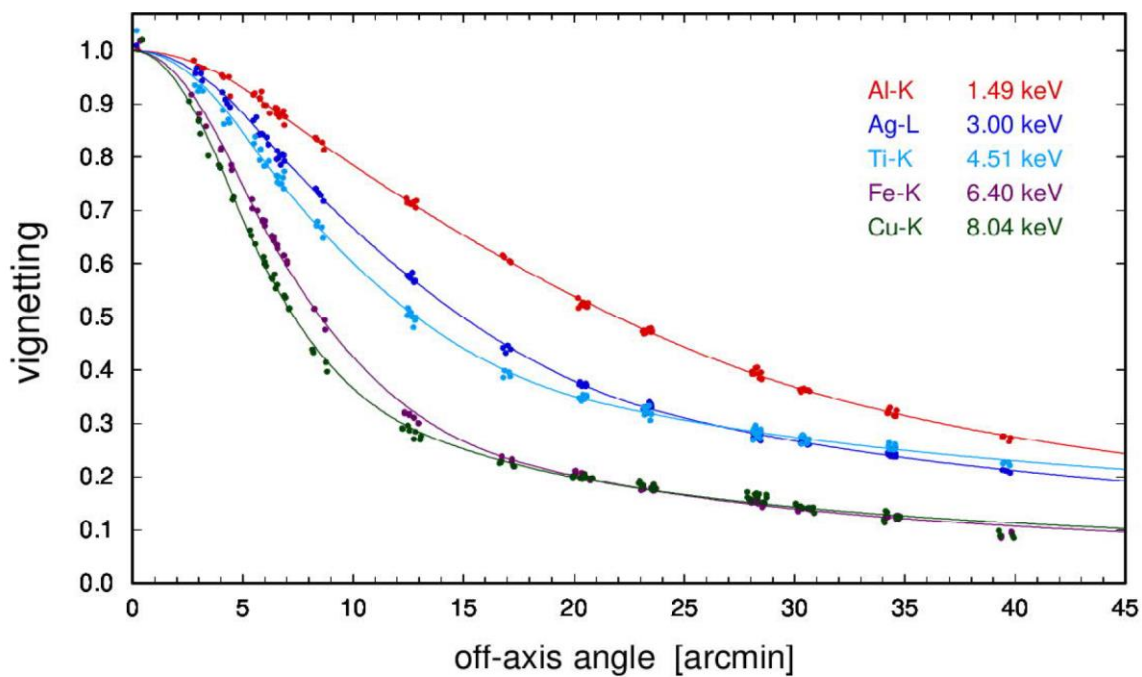
zoomed region (telescope frame)
HEW center: 104.13 130.35



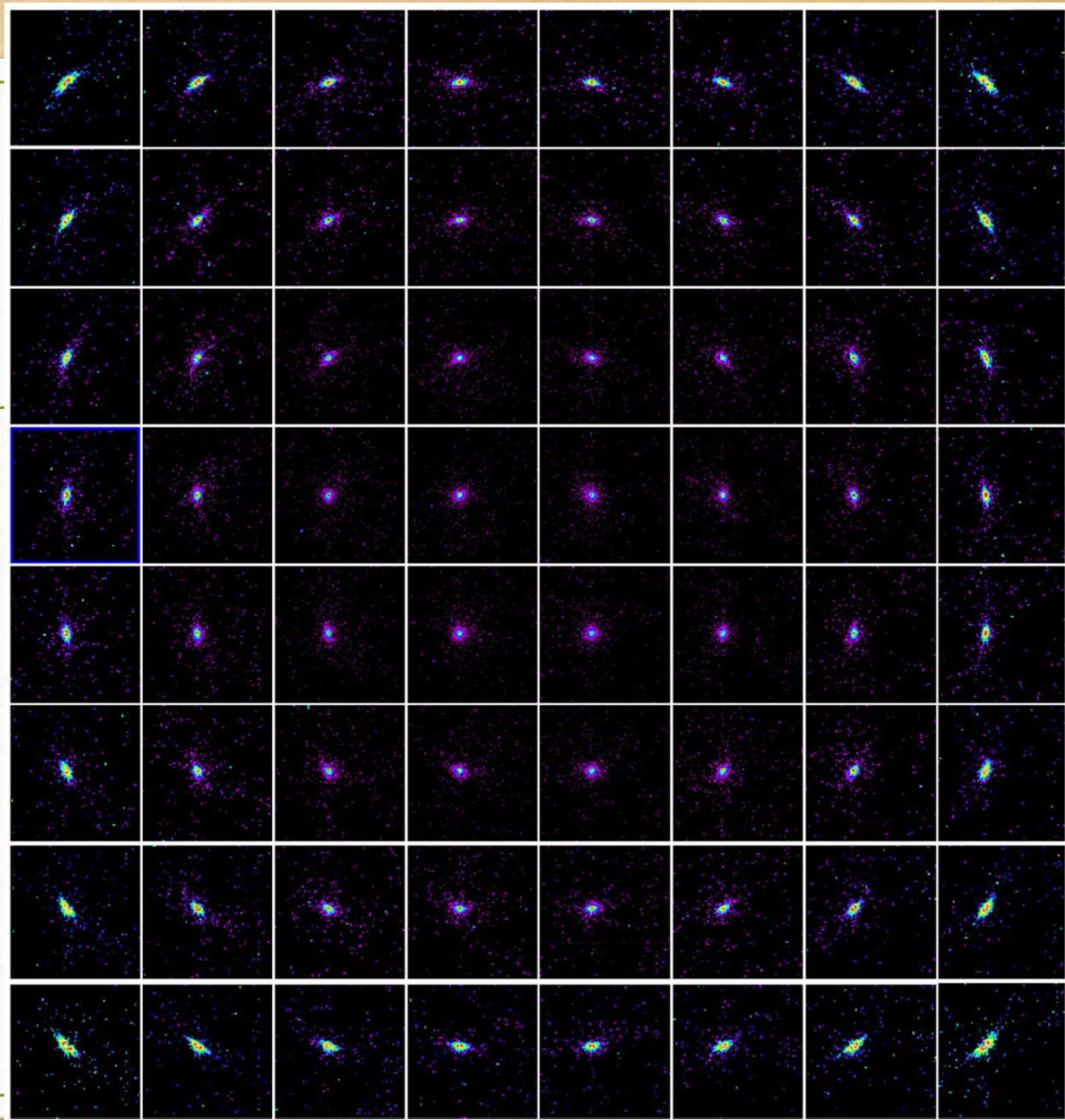
FXT ESA
QM测试



ESA 聚焦镜FM标定



Vignetting标定

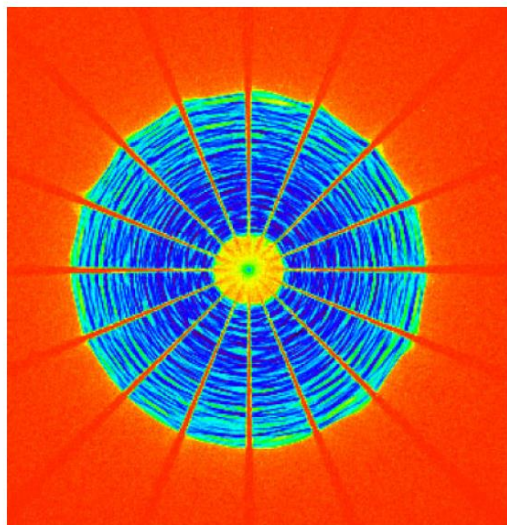


PSF标定: 每方块 8*8 arcmin; AL

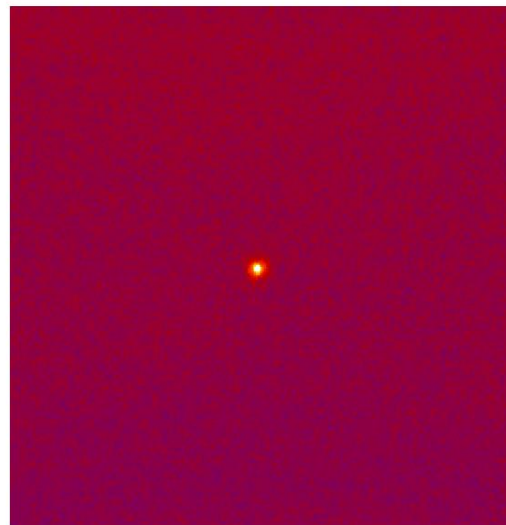
FXT聚焦镜进展

EP-FXT-MA-CAL PANTER
PSF Measurements

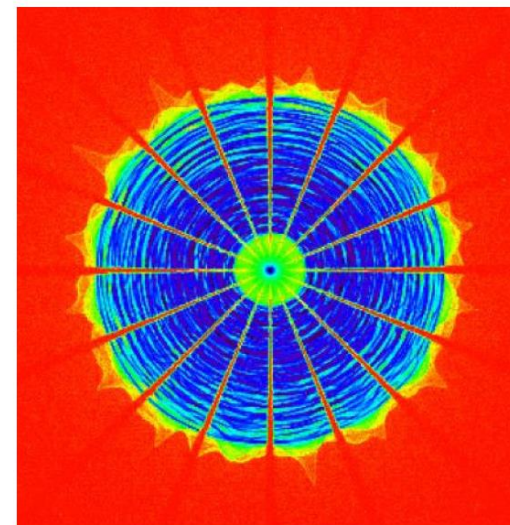
Intrafocal



In Focus

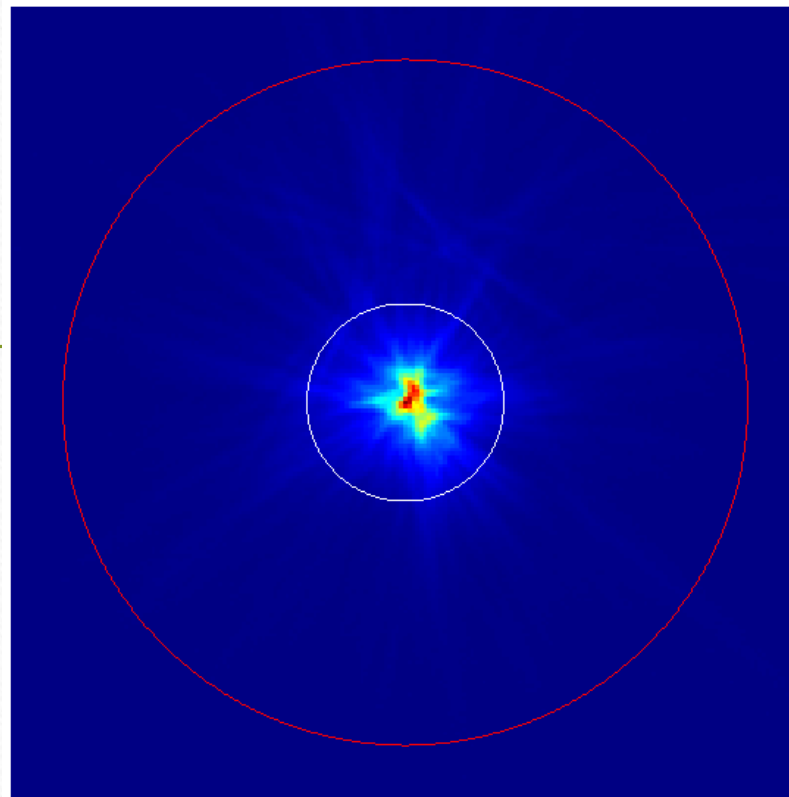
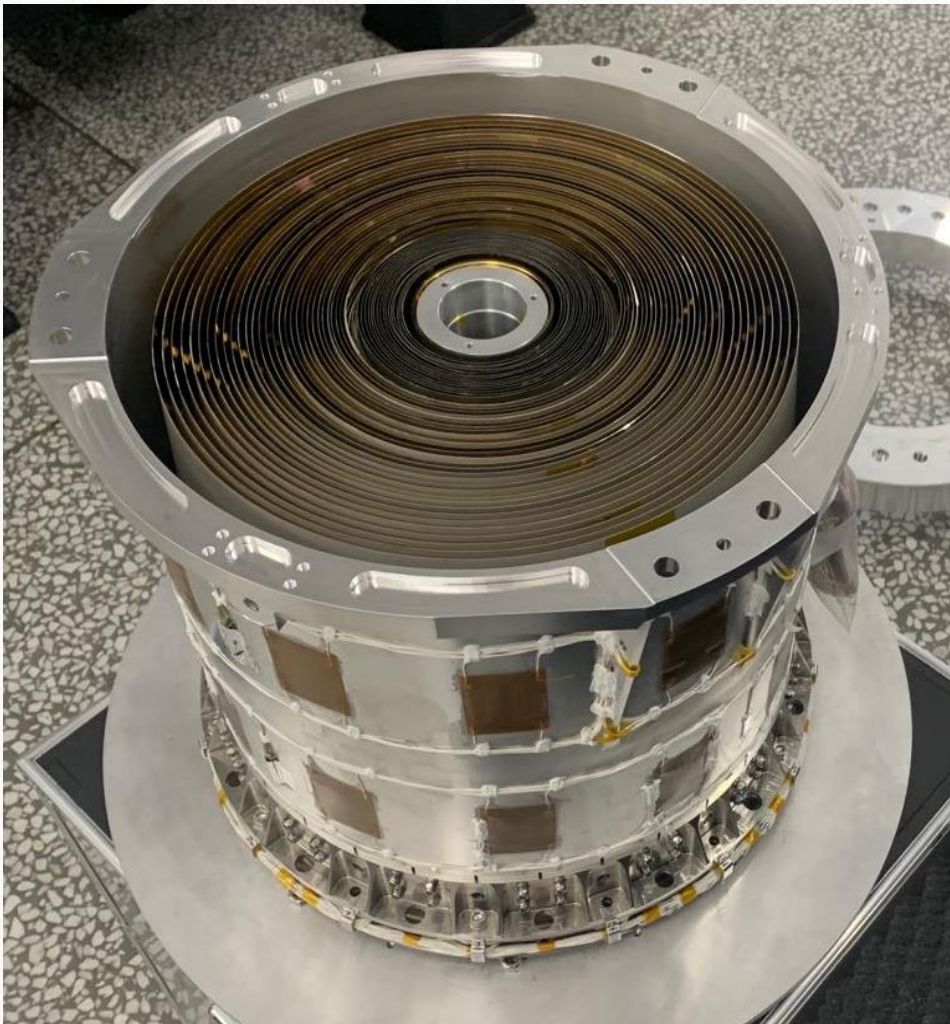


Extrafocal



Transition	Energy [keV]	HEW [arcsec]	FWHM [arcsec]	W90 [arcsec]	PSF Images	
					Full detector	Zoomed
C-K	0.277	21.9 ± 0.3	16.9	93.6		
Al-K	1.495	21.9 ± 0.3	16.2	107.5		
Cu-K	8.040	25.3 ± 0.4	16.0	350.2		

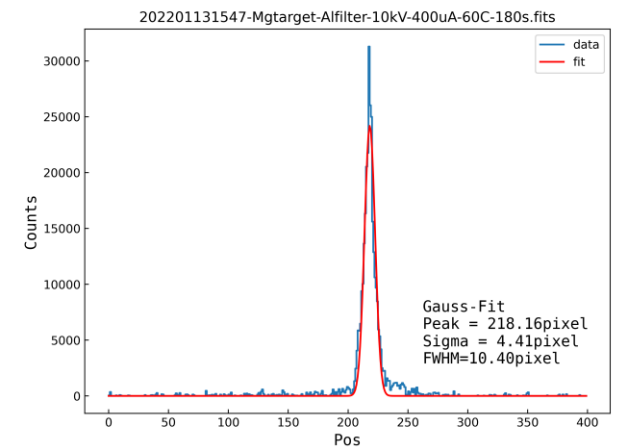
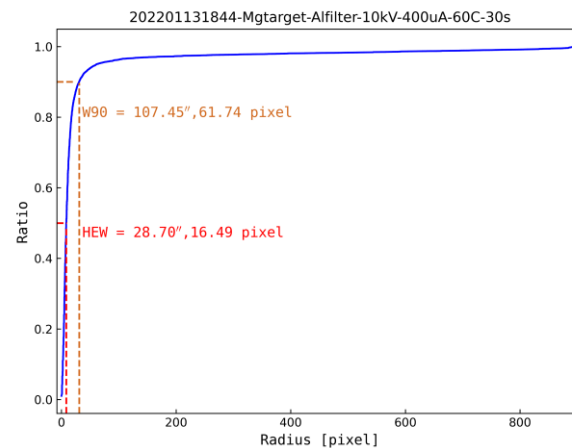
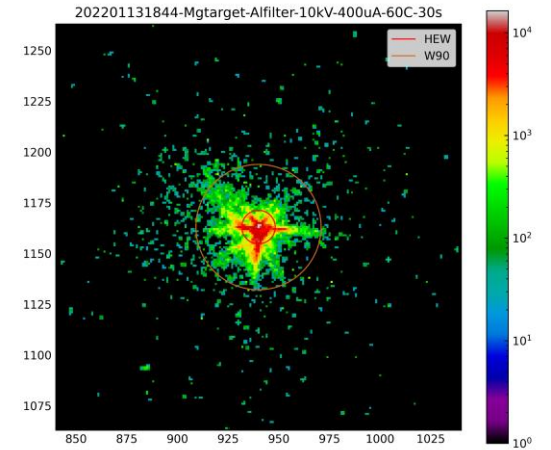
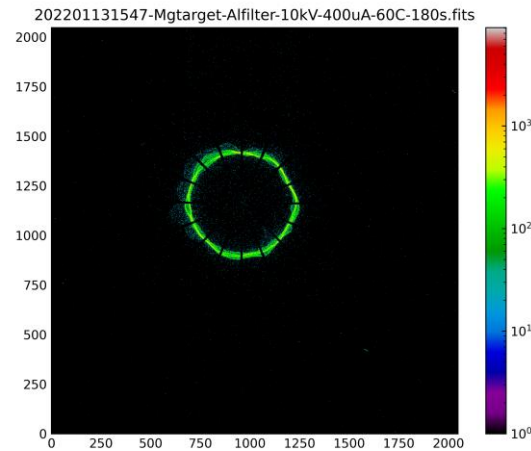
ESA 聚焦镜FM已在Panter完成测试, 性能良好

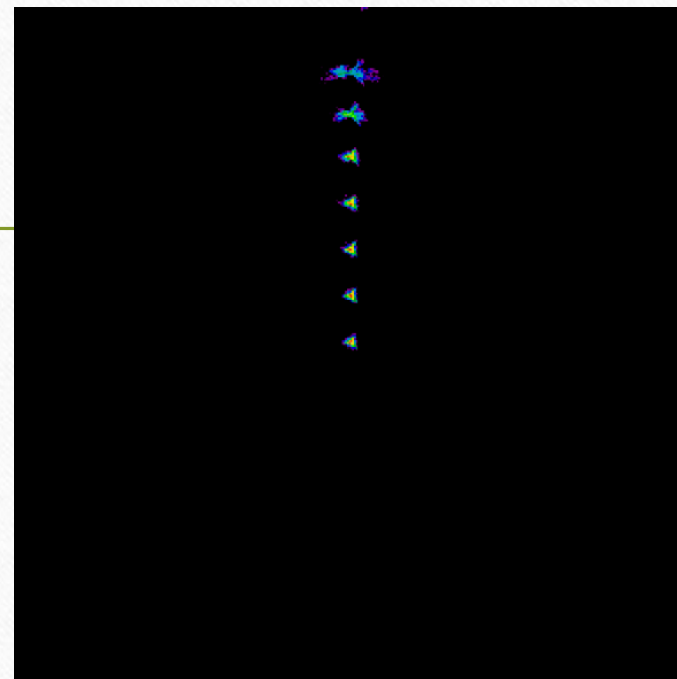
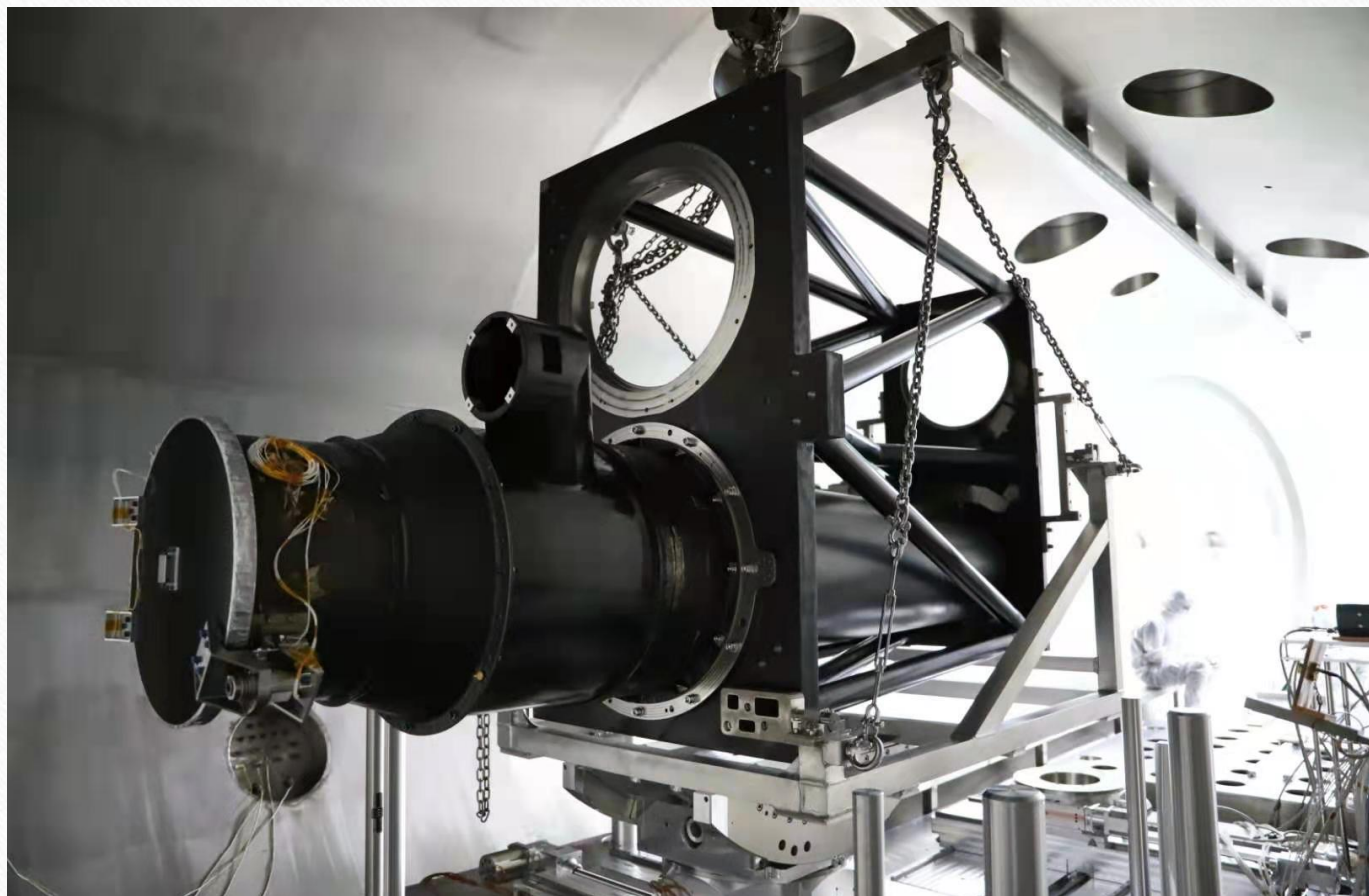


国产FXT聚焦镜鉴定件；
光学组HPD：77"

X-ray Test of the New Mirror Shells

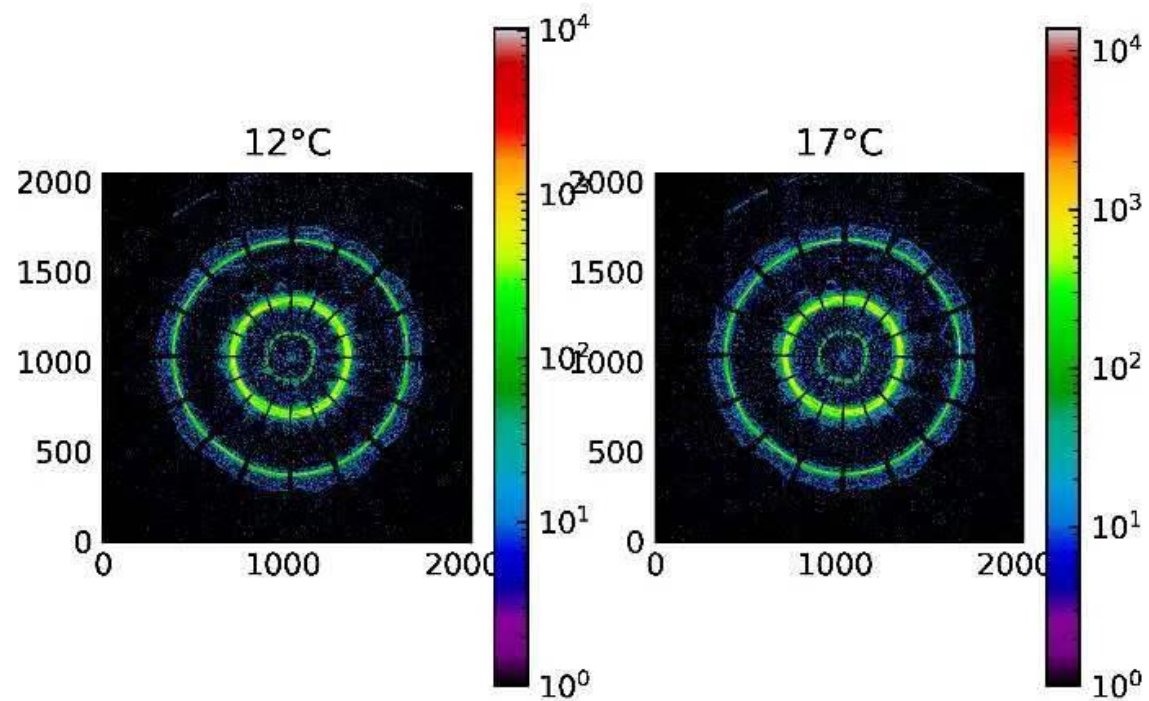
- A new No.18 mirror shell is developed recently, the HPD in X-ray test is 28.7 arcsecs.
- The effective area is about 10% different from the theoretical value.



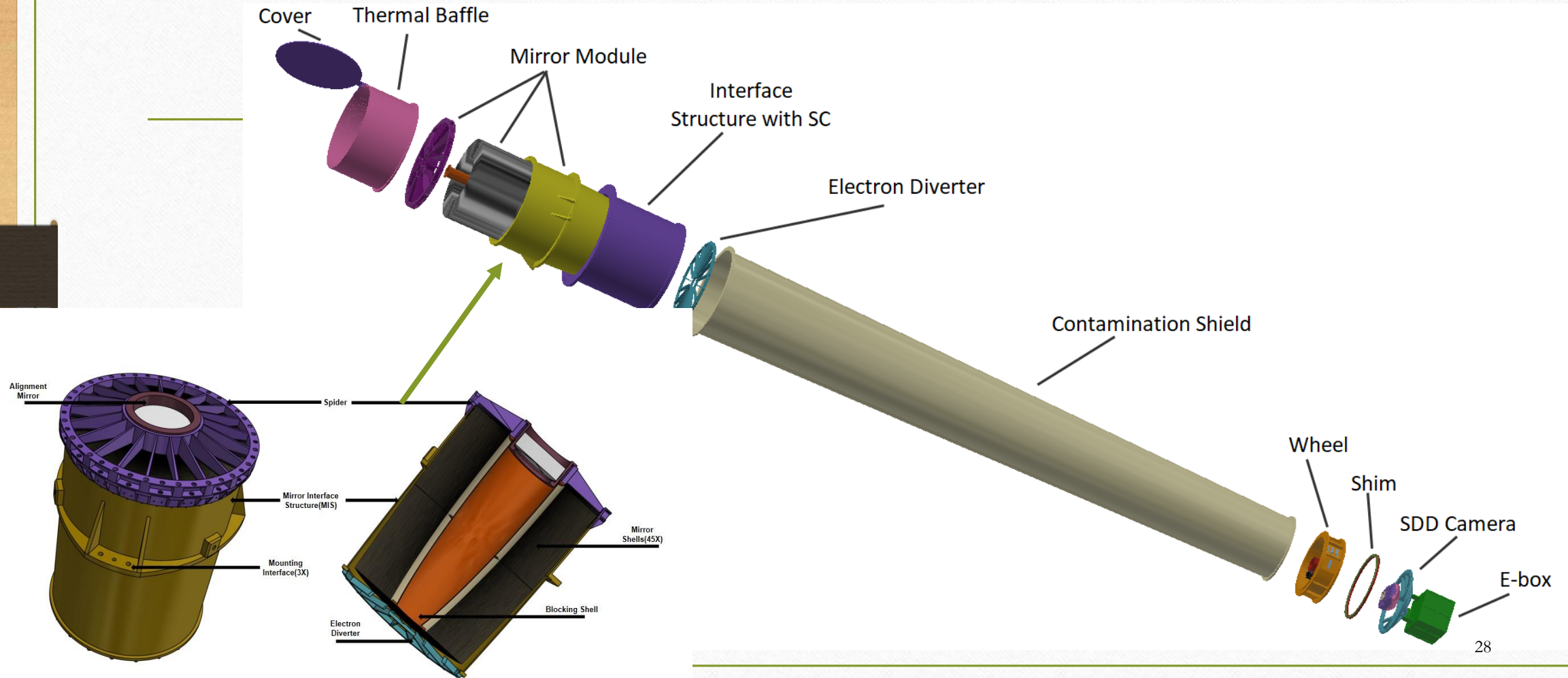


望远镜级端对端测试

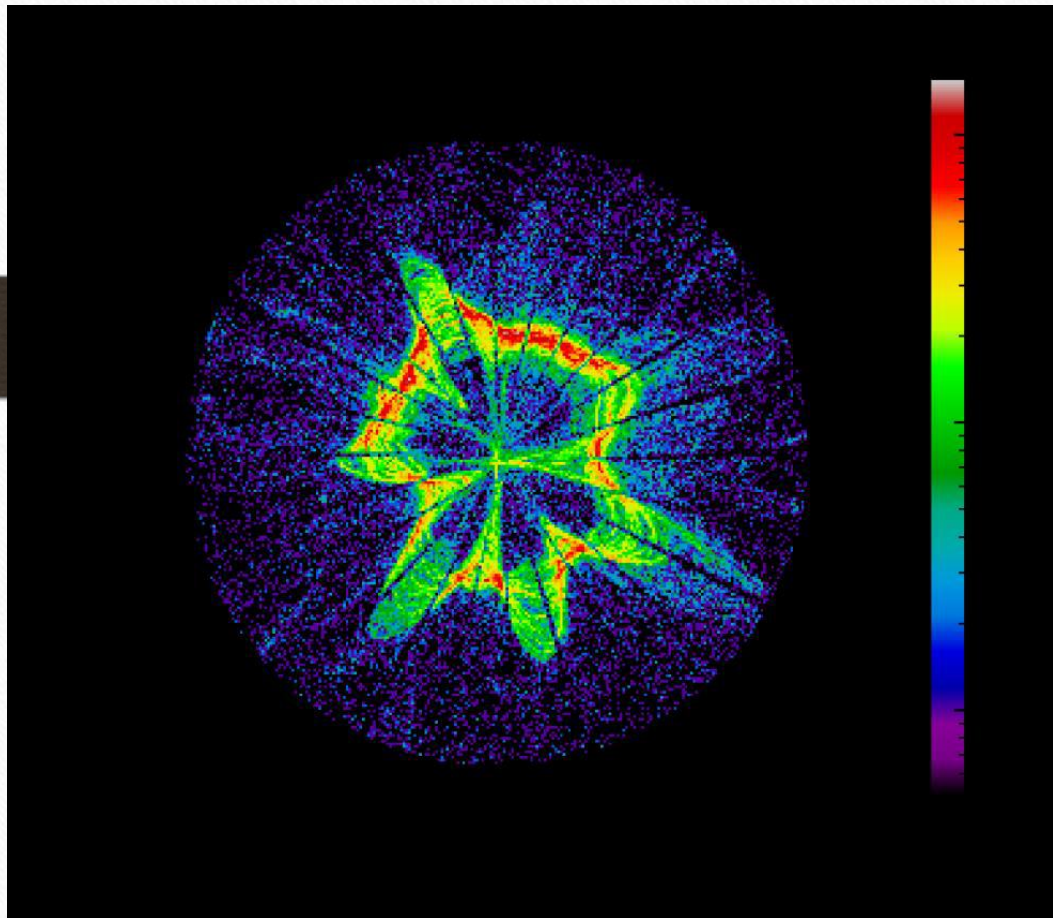
聚焦镜热光试验



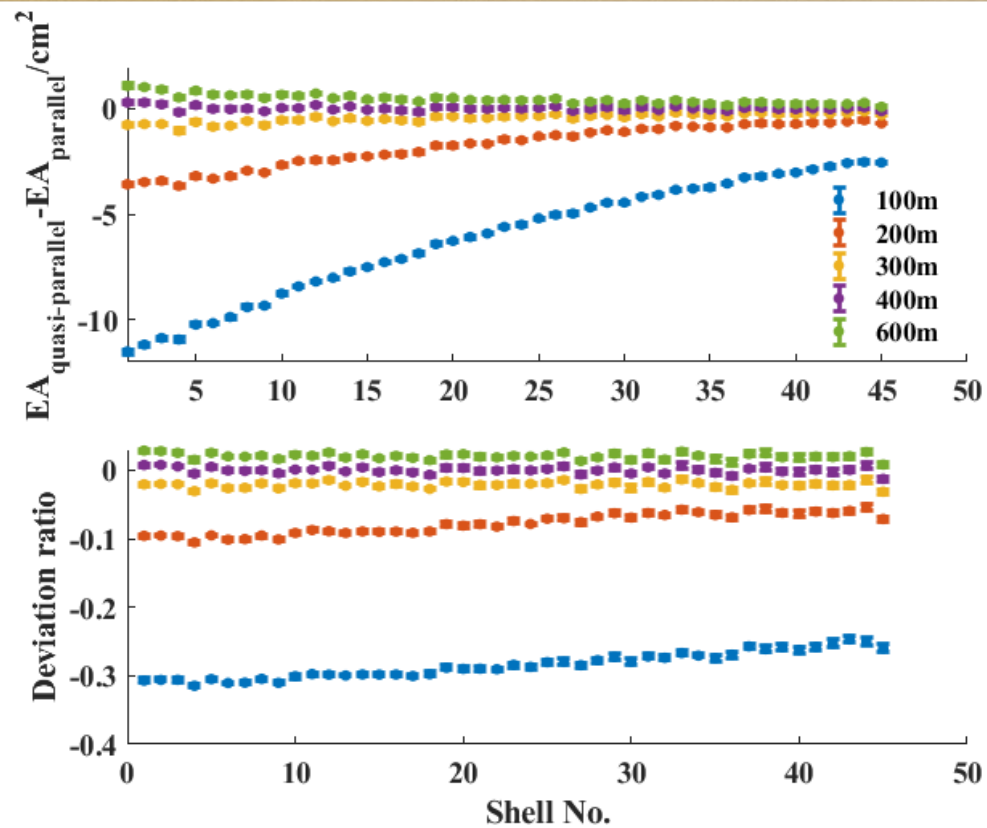
Configuration of X-ray Telescope of eXTP



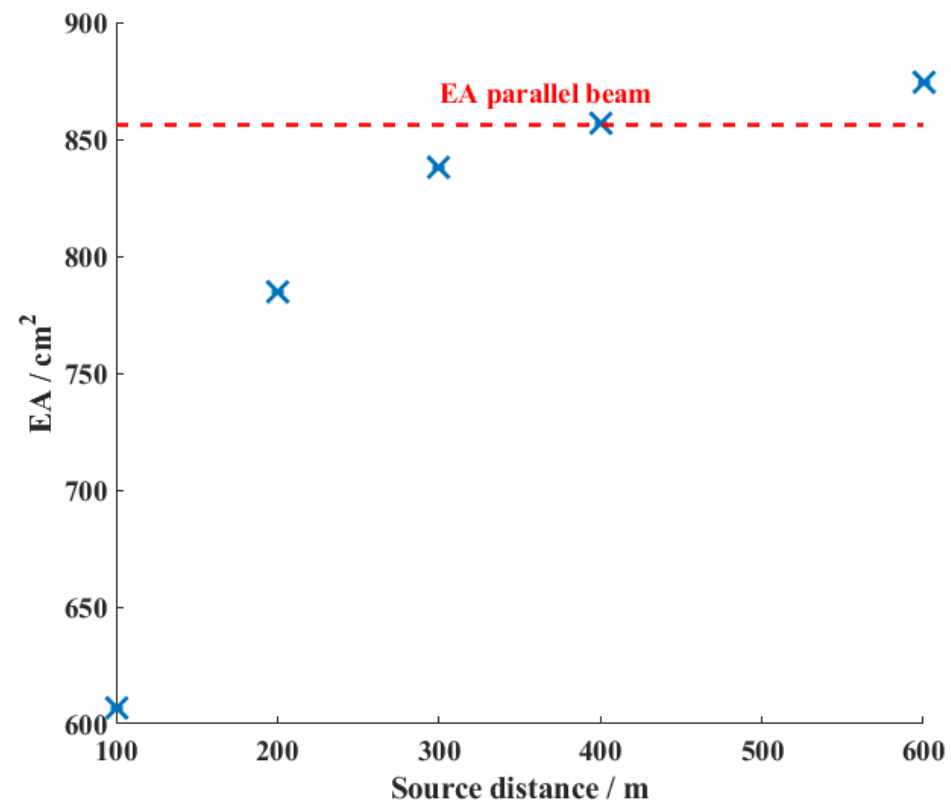
eXTP 45号镜片测试



能量 (keV)	HPD (角秒)	W90 (角秒)
1.49	30.8	157
4.51	33.9	168
8.05	39.1	184



EA deviation of different distance source @1.49 keV



EA of different distance source @1.49 keV

- 全面而高效地测试标定长焦望远镜
- 实现面阵型聚焦镜的端对端测试
- 我们可能需要更长的束线。

五、总结与展望

- Wolter型望远镜是X射线天文应用最多的望远镜
- 国内有多家单位对各类Wolter型望远镜开展研究
- X射线标定测试装置非常重要
- 增进交流，促进合作
- 未来超大X射线聚焦镜（SPO、大阵列）？超长标定测试束线？



流派的形成是藝術（技術）成熟的標志

谢谢!