基于劳厄衍射的空间硬X/软γ射线聚焦技术

姜维春

第三届地下和空间粒子物理与宇宙物理前沿问题研讨会

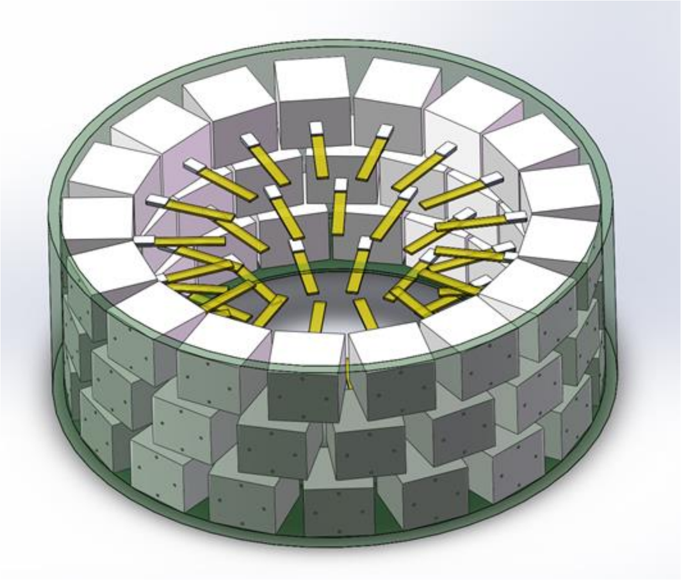
西昌，2024-05-09

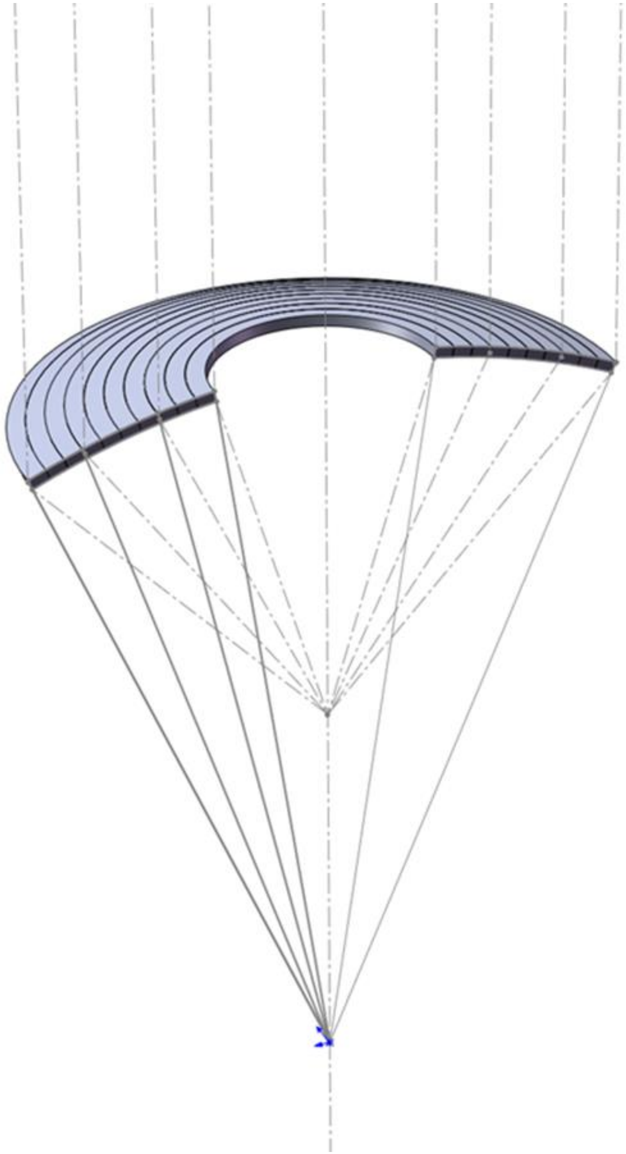
中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

中国科学院粒子天体物理重点实验室
KEY LABORATORY OF PARTICLE ASTROPHYSICS, CAS

汇报提纲

1. 科学目标
2. 劳厄光学原理及发展现状
3. 劳厄光学关键技术
4. 项目发展规划
5. 总结





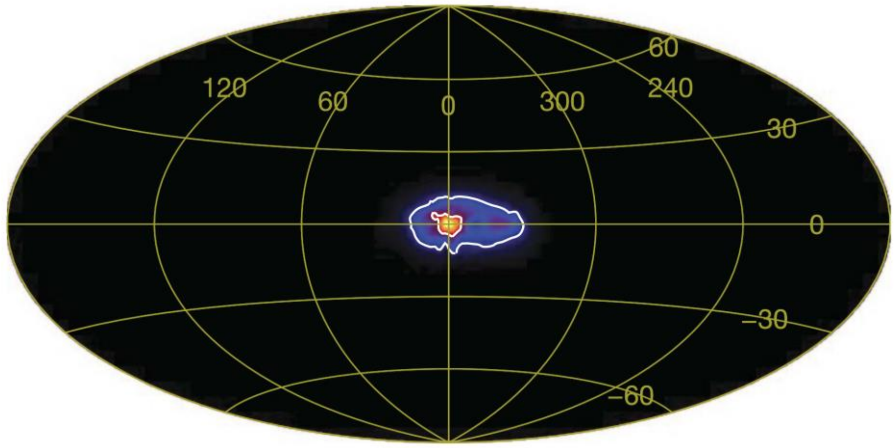
科学目标

硬X射线和软伽马射线天文学是天体物理和粒子天体物理学研究的关键窗口。

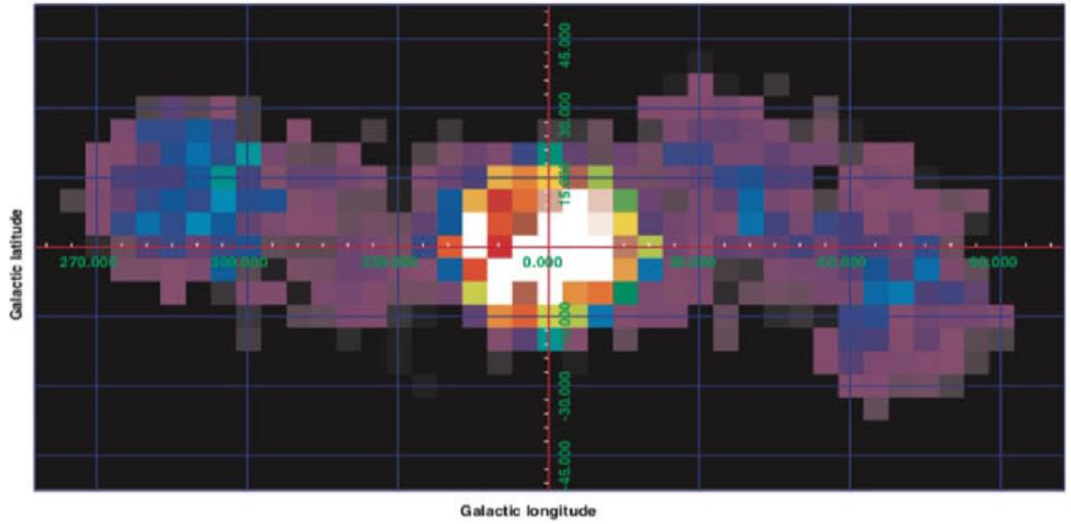
- 银河系中心区域511 keV正电子湮灭线及其起源
- 高能天体瞬变现象
  - 千新星演化
  - 伽马暴（GRB）瞬时辐射机制和磁场的作用
  - 伽马暴余辉的硬X射线能谱和偏振
  - 低光度伽马暴、快速蓝光瞬变、快速射电暴、软伽马复现源
  - Ia型超新星爆发和核塌缩产生的核谱线
- 依靠其高灵敏度和宽能区的优势实现更多未知高能瞬变现象的发现和研究

科学目标—origin of the positron annihilation line

- The Positron Puzzle：
- The 511 keV γ-ray emission from the galactic center region may fully or partially originate from the annihilation of positrons from dark matter particles with electrons from the interstellar medium. Alternatively, the positrons could be created by astrophysical sources, involving exclusively standard model physics.



（Weidenspointner, G.,2008）



（Bouchet, L.，2009）

Sky map of the 511 keV positron annihilation line found with the INTEGRAL SPI telescope

Scientific goals—origin of the positron annihilation line

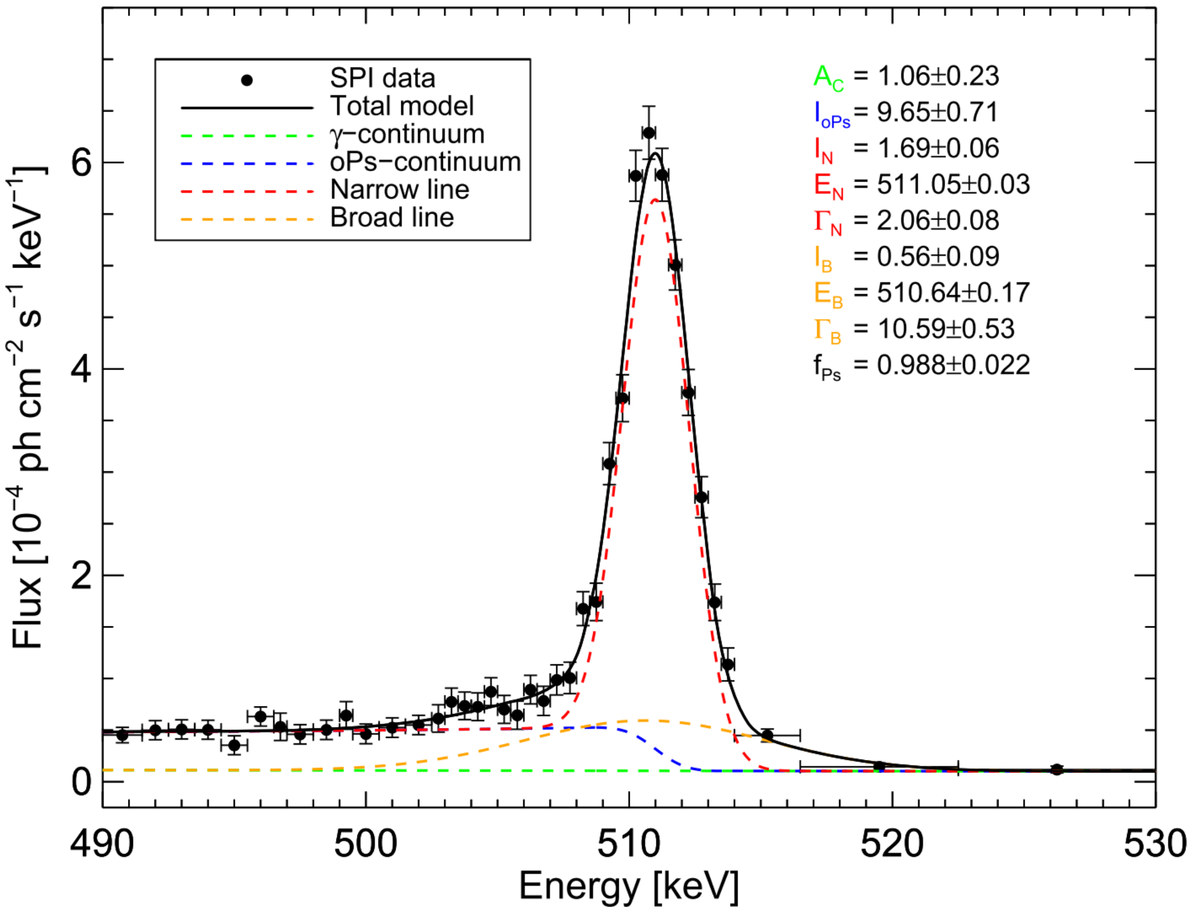
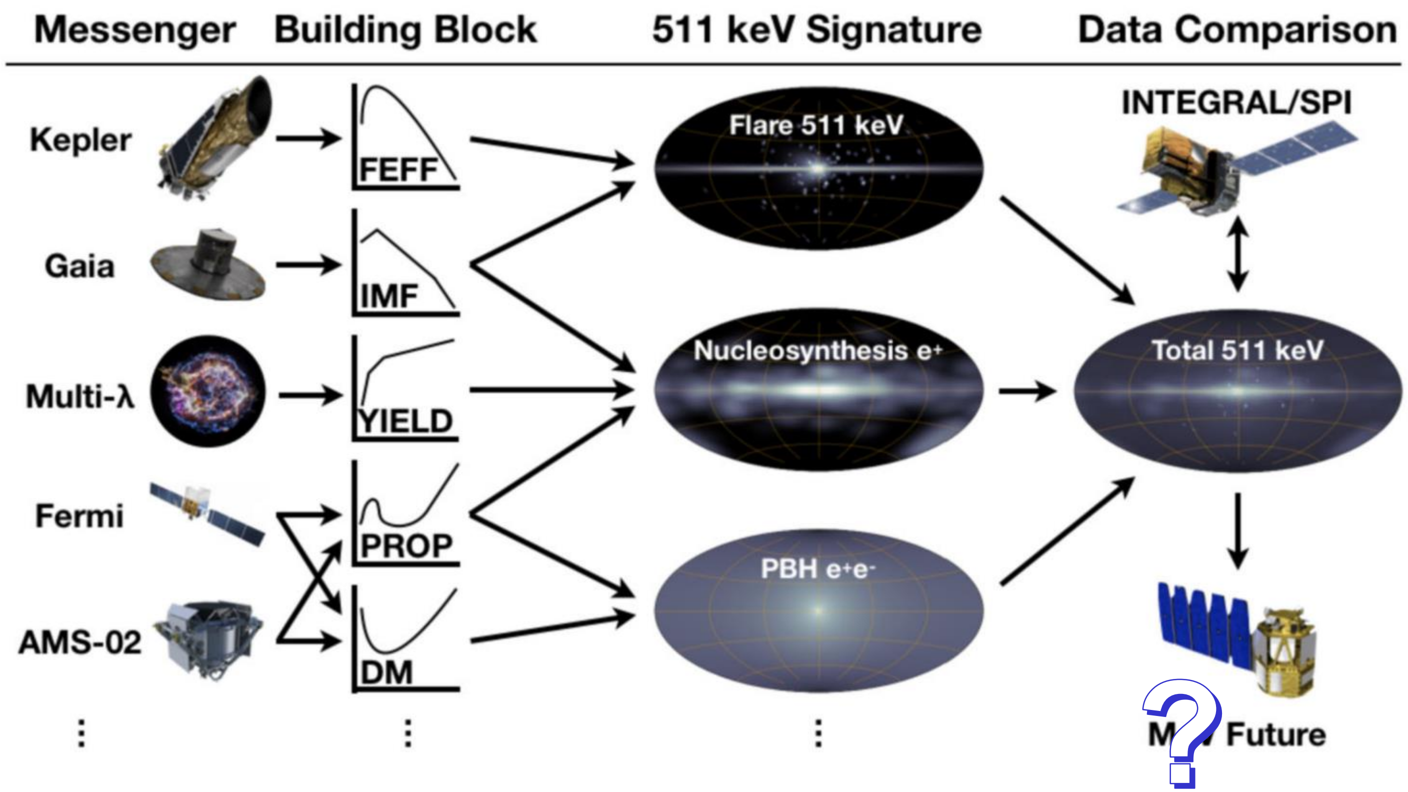


Fig. 2 INTEGRAL/SPI spectrum of the entire Galaxy, decomposed into a narrow and a broad line, in addition to the ortho-Ps continuum and the Galactic diffuse continuum (Siegert et al. 2019a)

Scientific goals—origin of the positron annihilation line

- The Positron Puzzle：
- High angular resolution
- High energy resolution



（Thomas Siegert，2023）

千新星演化

- 按照并合后数小时、数天、数年...的时间尺寸研究超新星演化；
- 需要高灵敏度的观测仪器

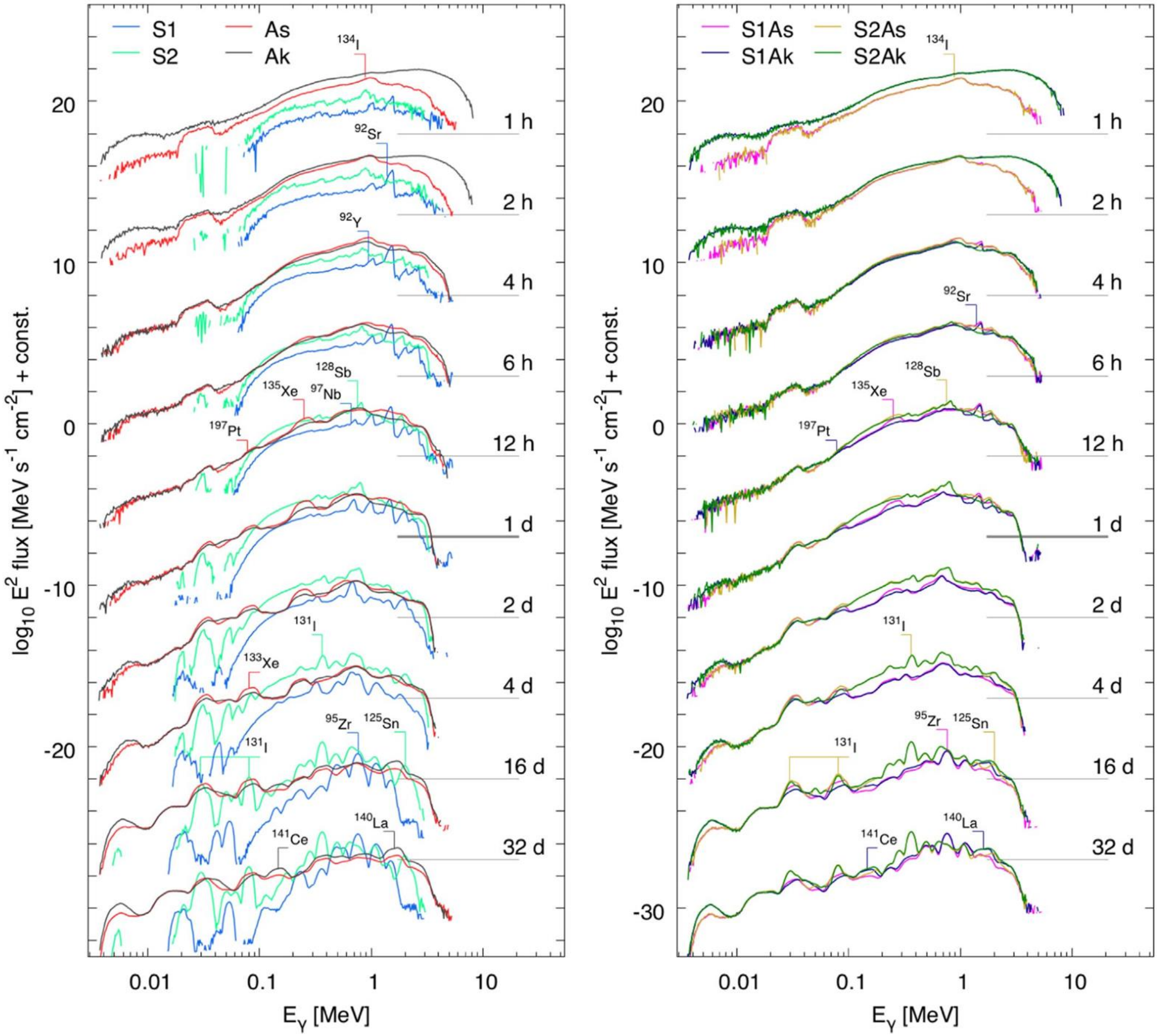


Figure 4. Evolution of synthetic spectra of one-component (left) and two-component (right) sources, as seen from the distance of 3 Mpc. For clarity, the spectra are offset by multiples of 3 dex in log space, up or down from zero-offset spectrum at 1 day. The offsets are indicated by horizontal lines. Some of the features in one-component spectra are labeled with isotopes which are producing the features (see Table 2).

（Korobkin et al. 2022）

千新星演化

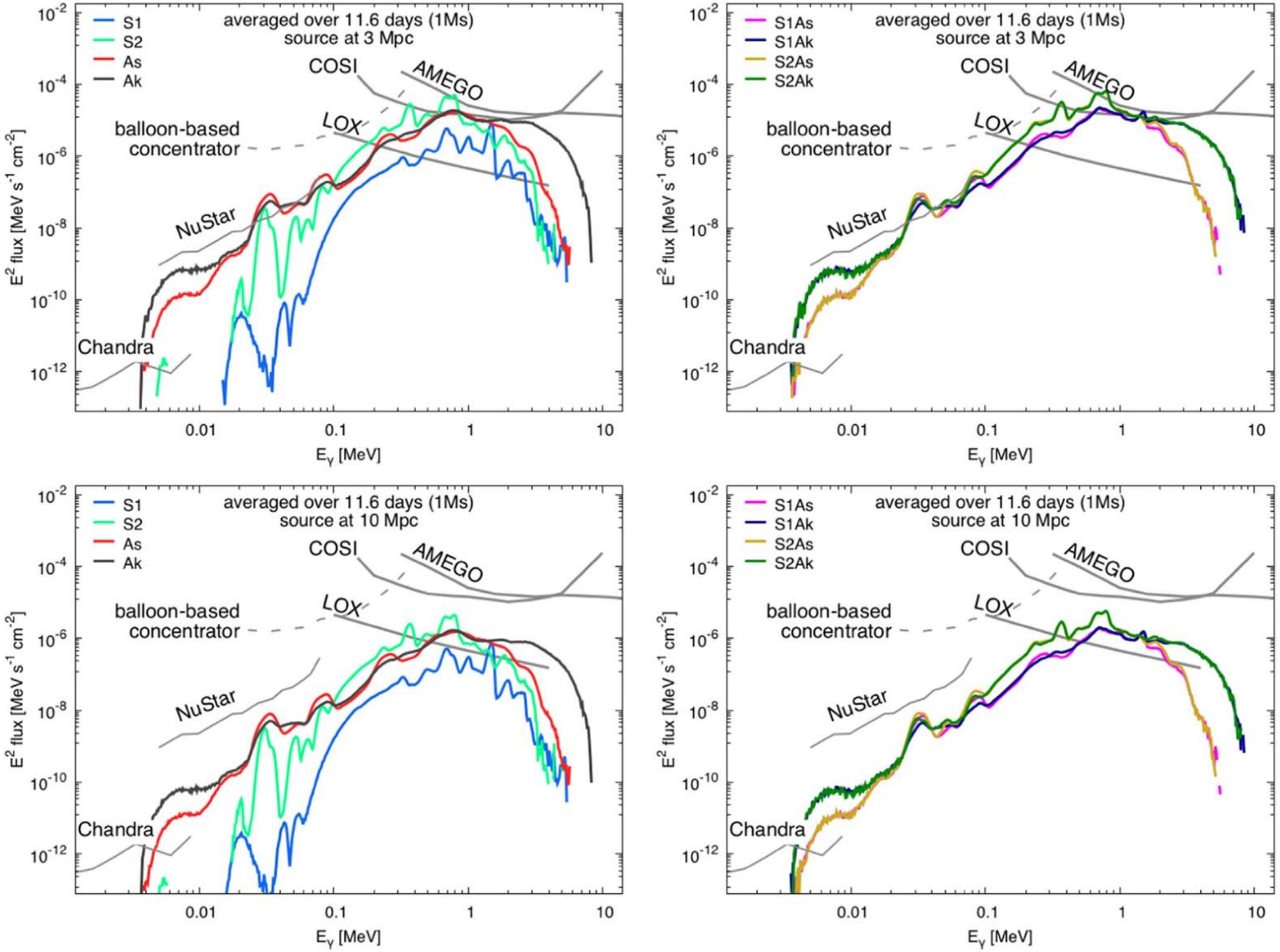
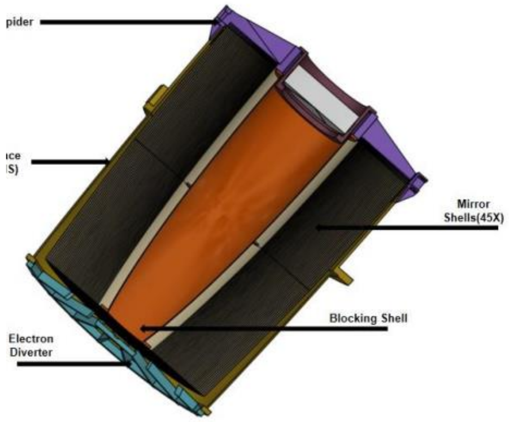
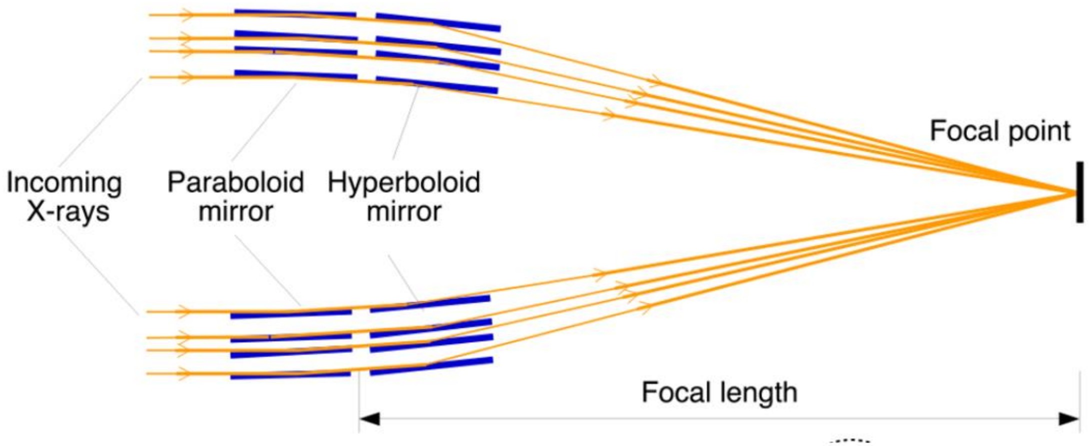


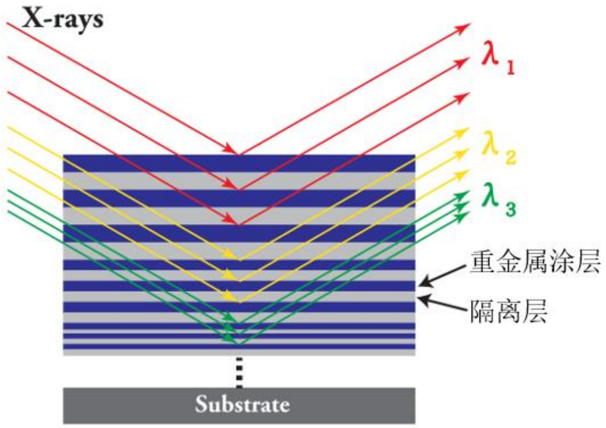
Figure 10. Synthetic spectra of one-component (left column) and two-component (right column) sources at distance 3 Mpc (top row) and 10 Mpc (bottom row), integrated over the first 1Ms (11.6 days).

（Korobkin et al. 2022）

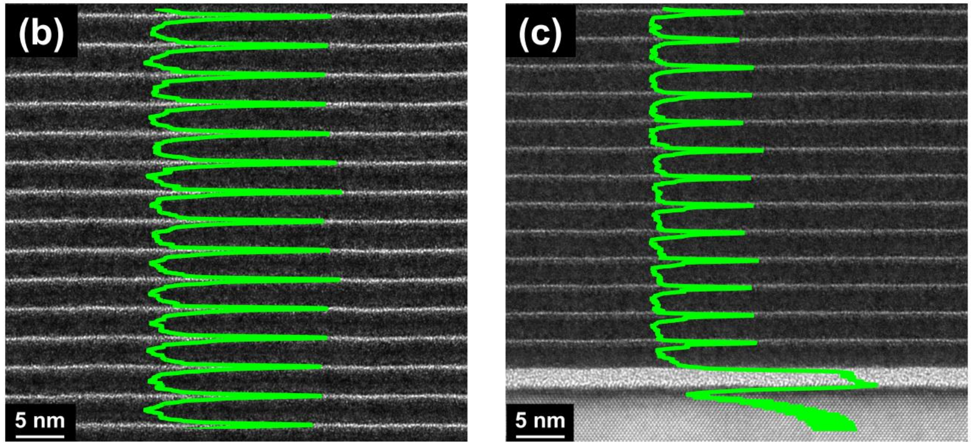
Wolter I 型X射线光学（<80keV）



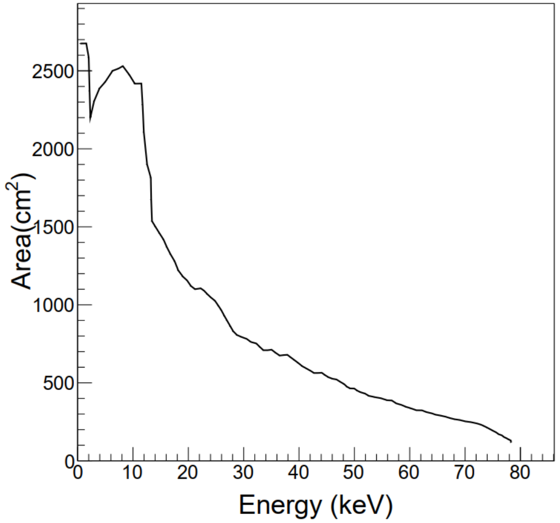




能段	10~60keV
Effiency Aera	>2000cm2@10keV, >300cm2@60keV
Angular Resolution	<=30arcsec@30keV
Focal length	30米
Outer/Inner Diameter	47.2cm/22.2cm



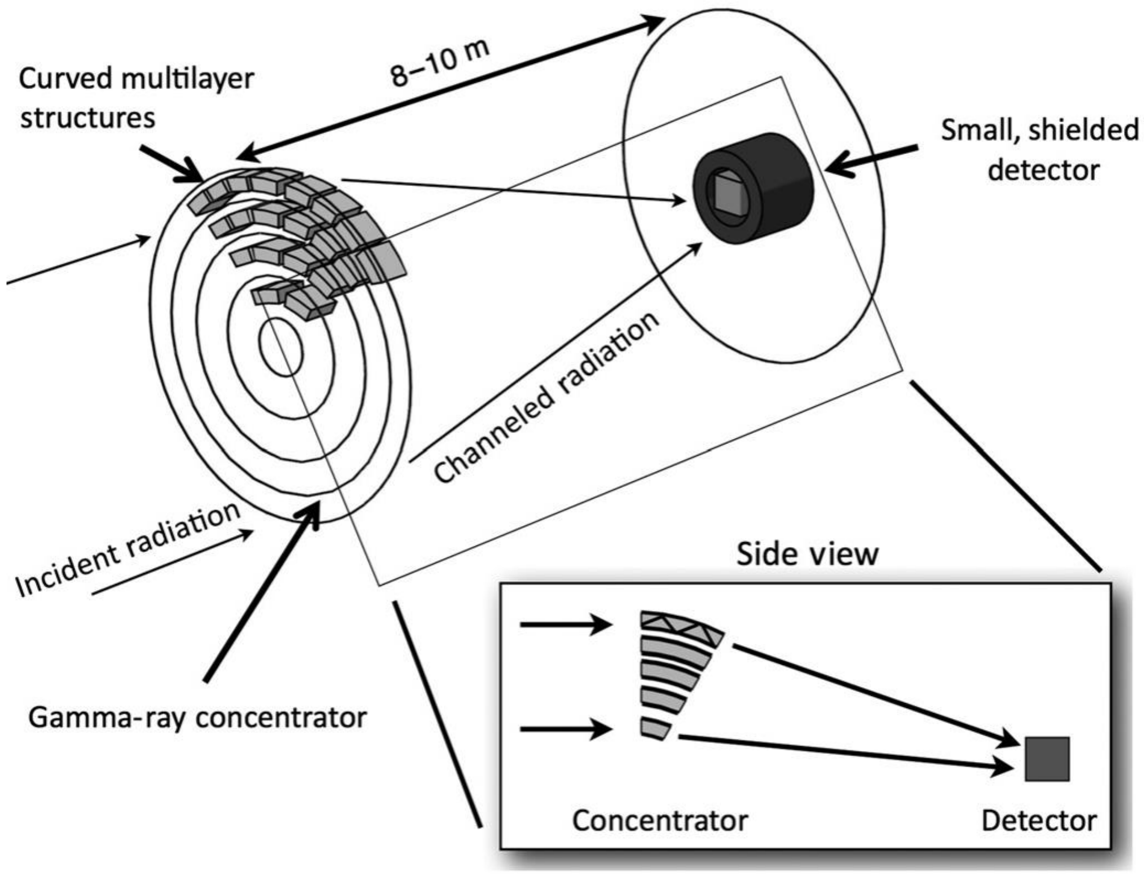
（C. BURCKLEN, 2019）

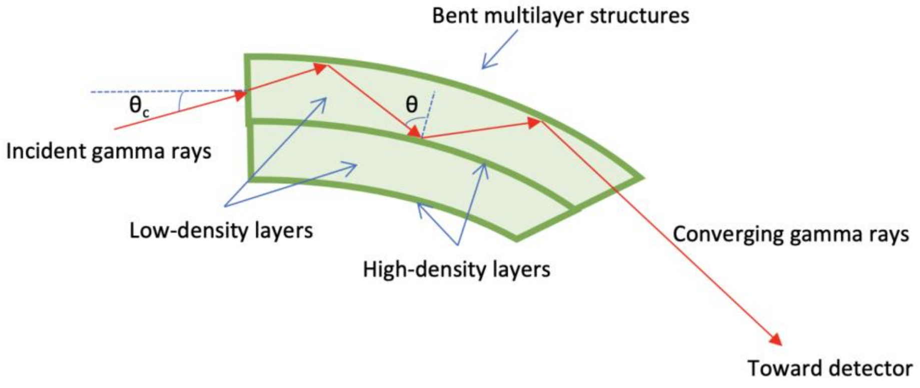


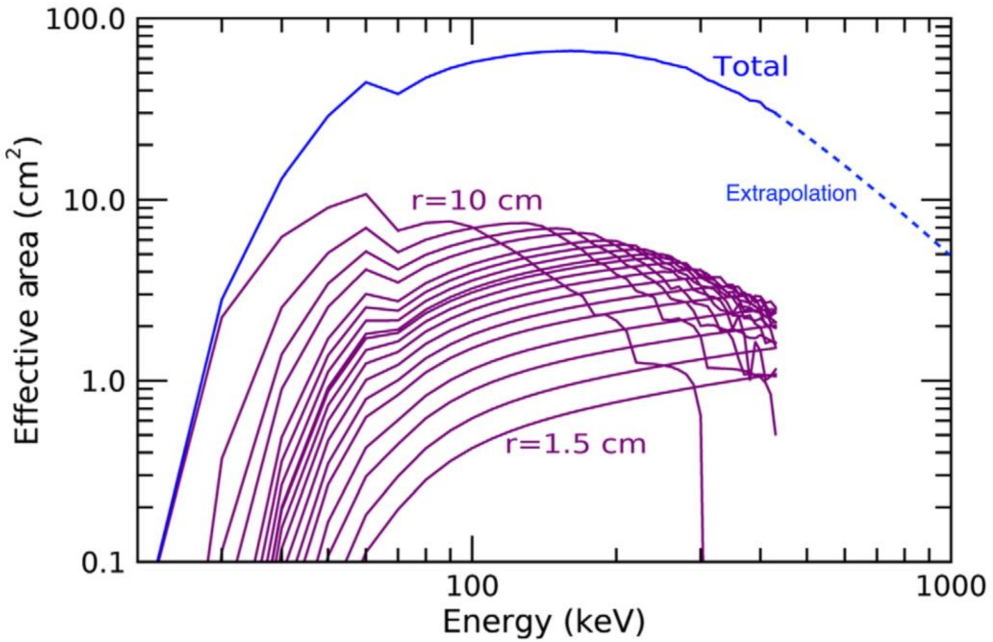
gradient graded multilayer film process

Pt/C,W/Si

通道光学聚焦技术（400keV）





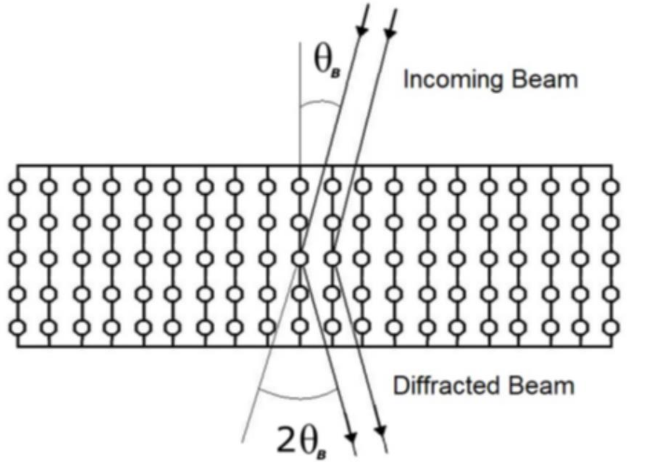


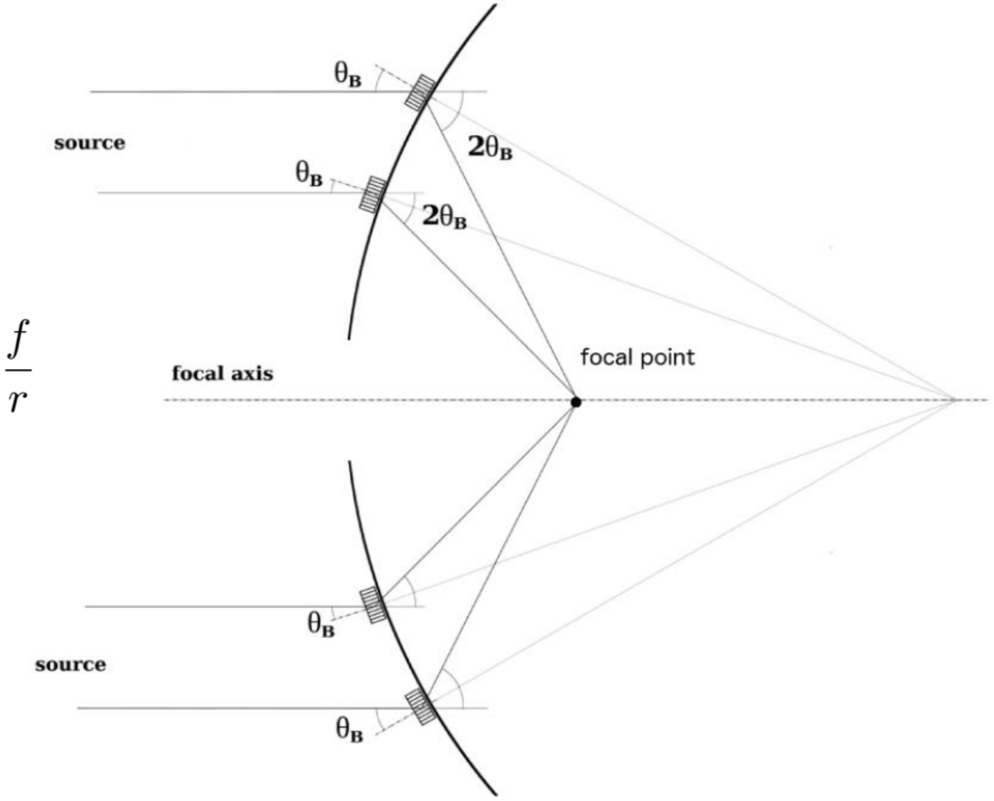
Laue聚焦镜（80~700keV，200keV~2MeV）

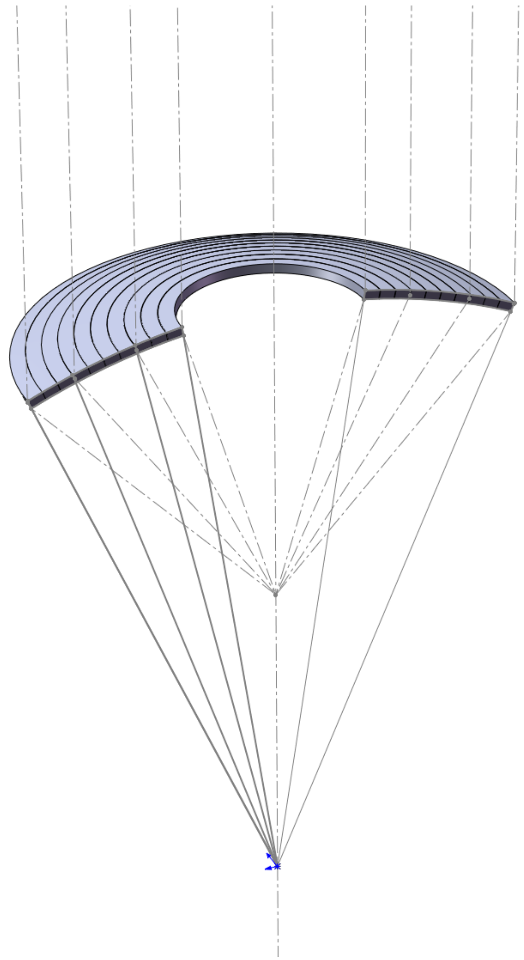
- 衍射聚焦的原理

$$2d_{hkl}\sin\theta_B = n\frac{hc}{E}$$

$$E = \frac{hc}{2d_{hkl}\sin\left[\frac{1}{2}\arctan\left(\frac{r}{f}\right)\right]} \sim \frac{hc}{d_{hkl}}\frac{f}{r}$$



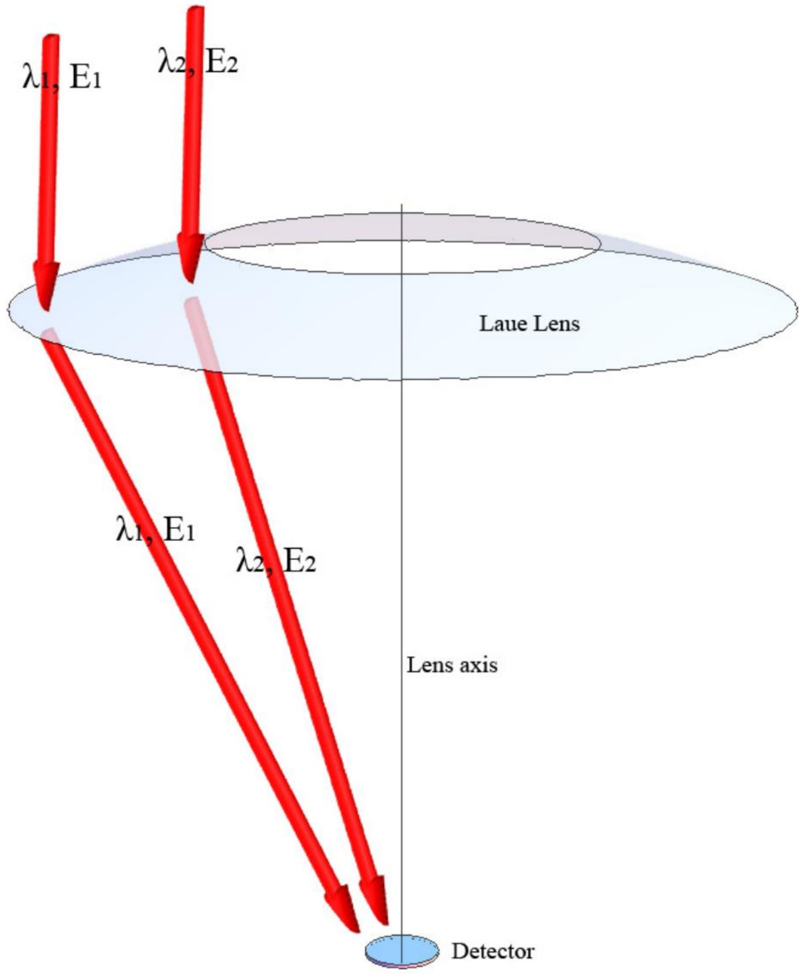


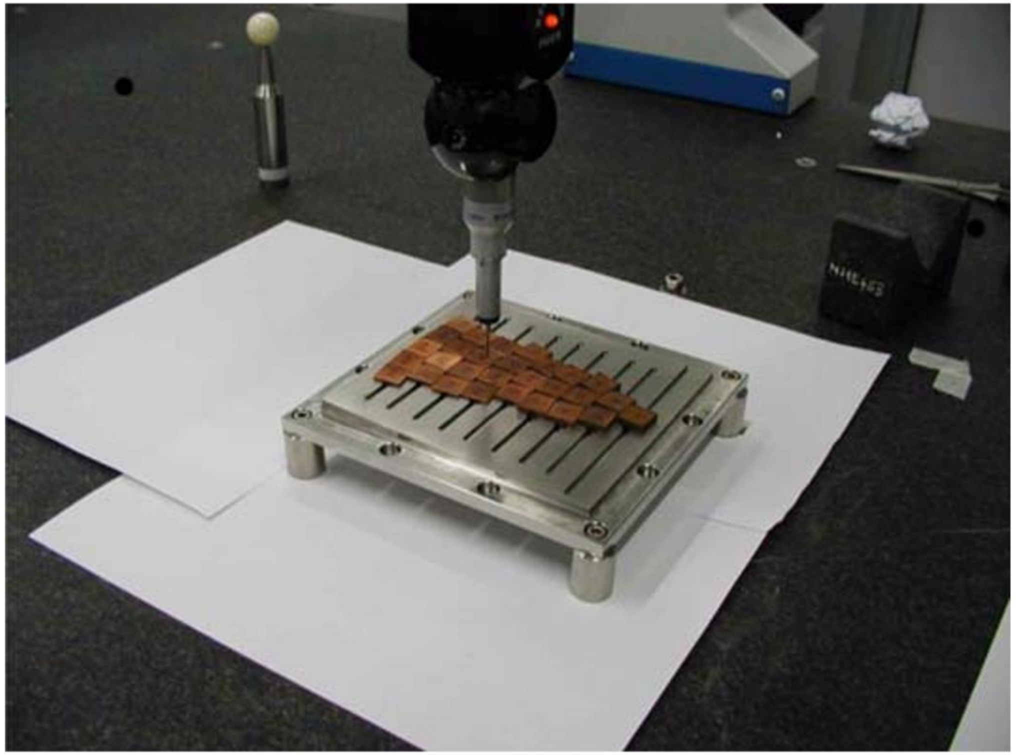


Laue聚焦镜原理图

（Lisa Ferro, 2022）

早期平面晶体Laue透镜



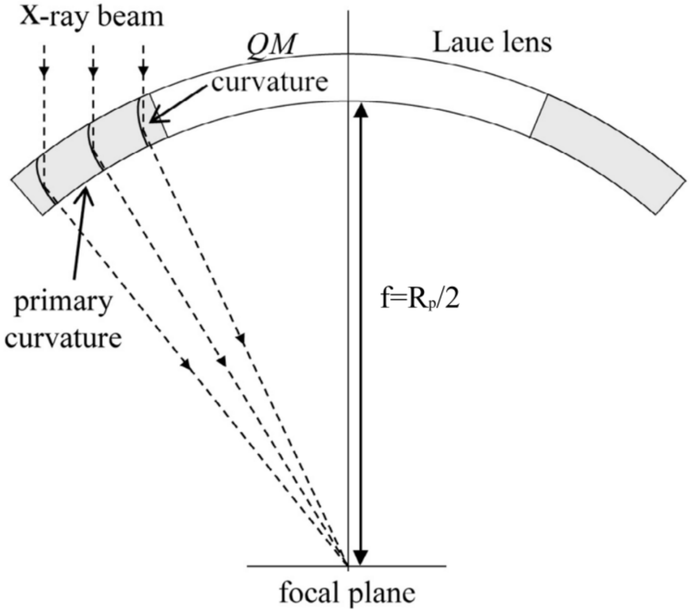


CLAIRE-首个劳厄透镜

- 2001年6月14日首飞
- 窄带劳厄透镜，气球项目
- 45厘米之间的钛架，安装8环576块晶体
- 有效面积 64cm^2@170keV
- 指向Crab，在72分钟有效观测时间内得到33个170keV的光子

弯曲晶体的优势

- 单个晶片具有聚焦能力，可以获得更好的角分辨率；
- 弯曲晶体衍射效率可以大于50%，而平面晶体的理论上限是50%；
- 有利于拓展能量范围。



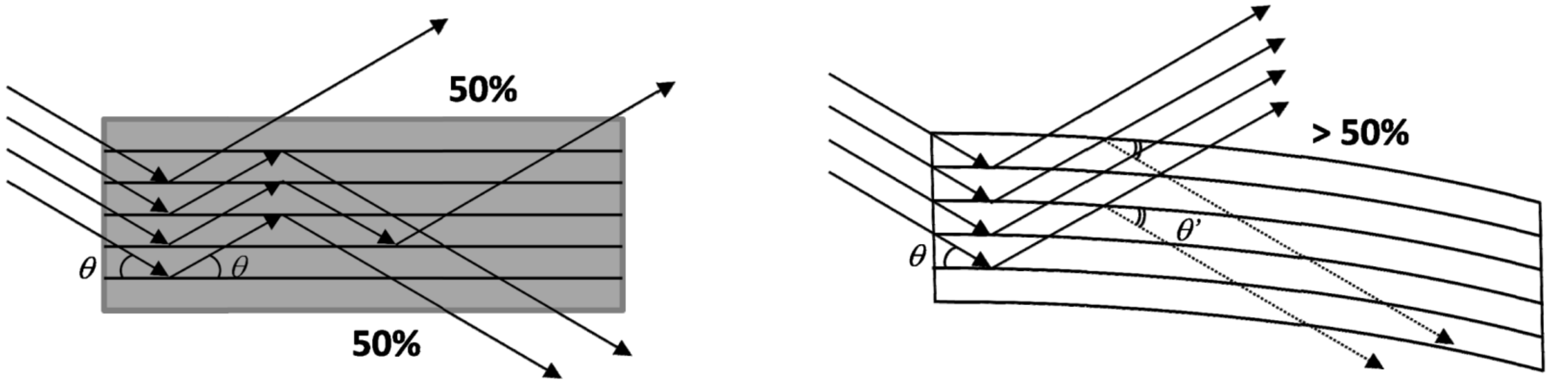
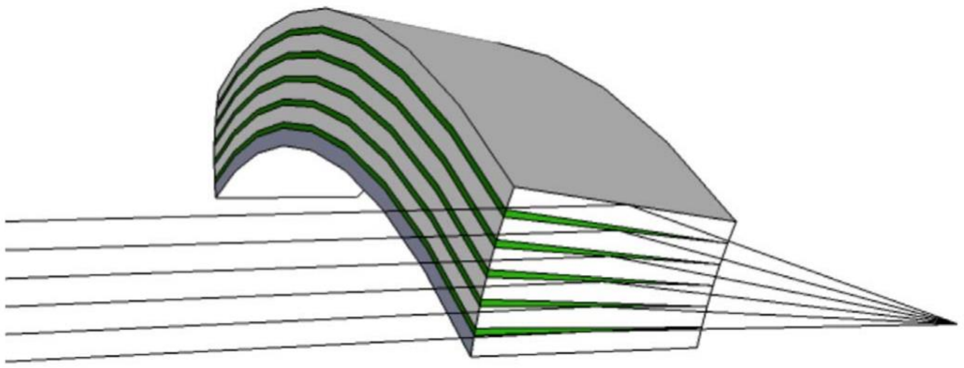
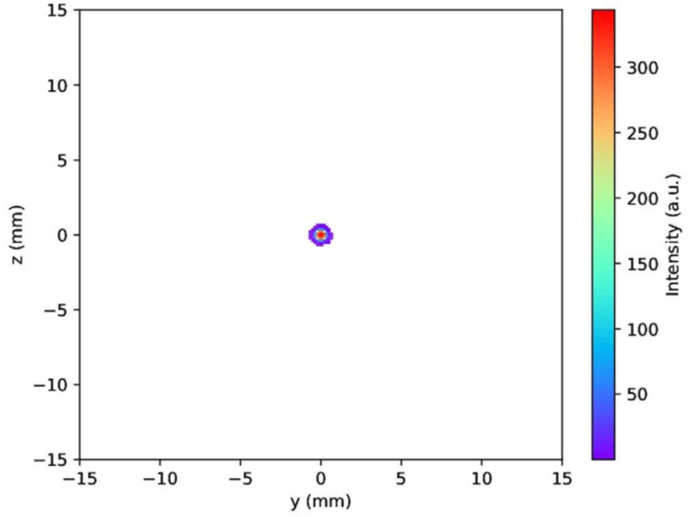


Figure 10: flat crystal planes (left) versus curved crystal planes (right). The curvature along this axis reduces nultiple reflections within the crystal, improving the reflectivity which in a flat crystal is limited to 50% due to multiple reflections. Additionally this curvature and widens the energy bandpass of the crystal.

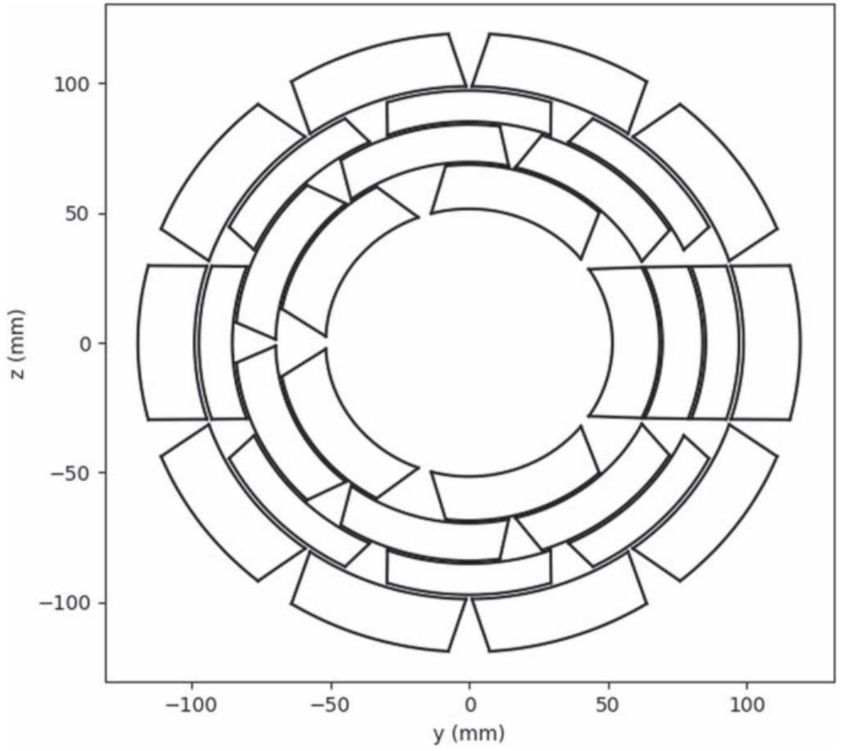
Laue透镜—曲面晶片

- 曲面晶片组装方式
  - 便于小口径透镜
  - 不利于能区扩展
  - 理论上两维聚焦
  - 仿真结果只能到200keV



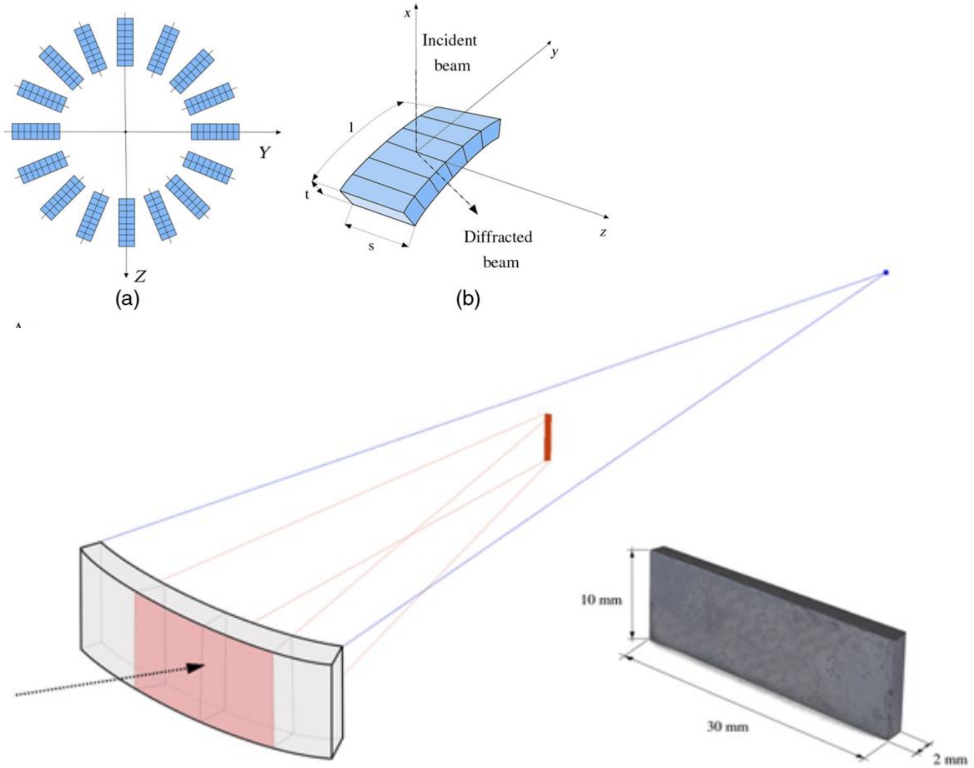


X-ray profile at the focal point for a simulated source diameter of 2 mm.

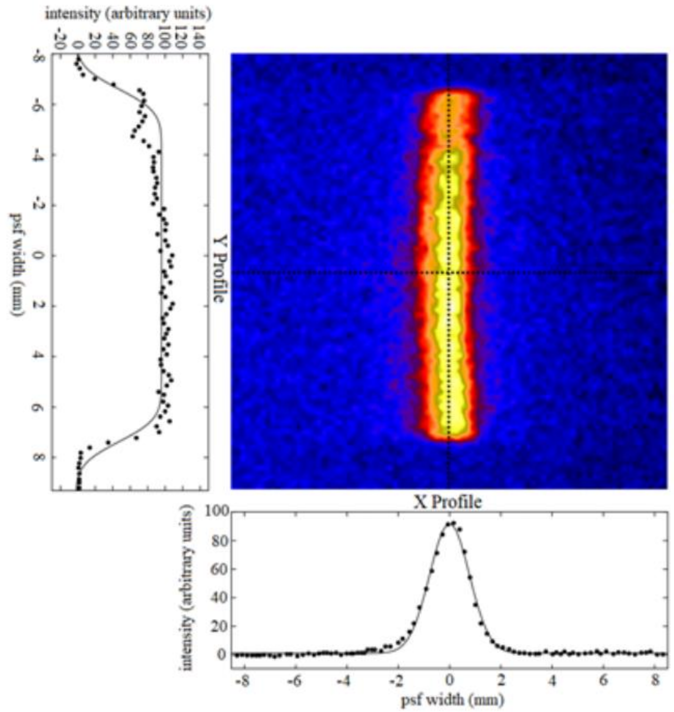


UC Berkeley configuration

Laue聚焦镜

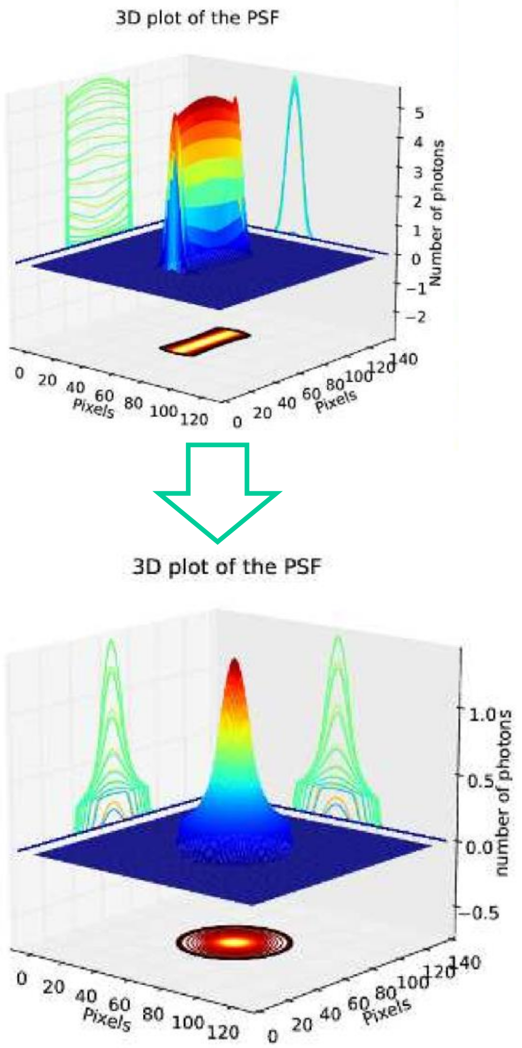


Ferrara configuration



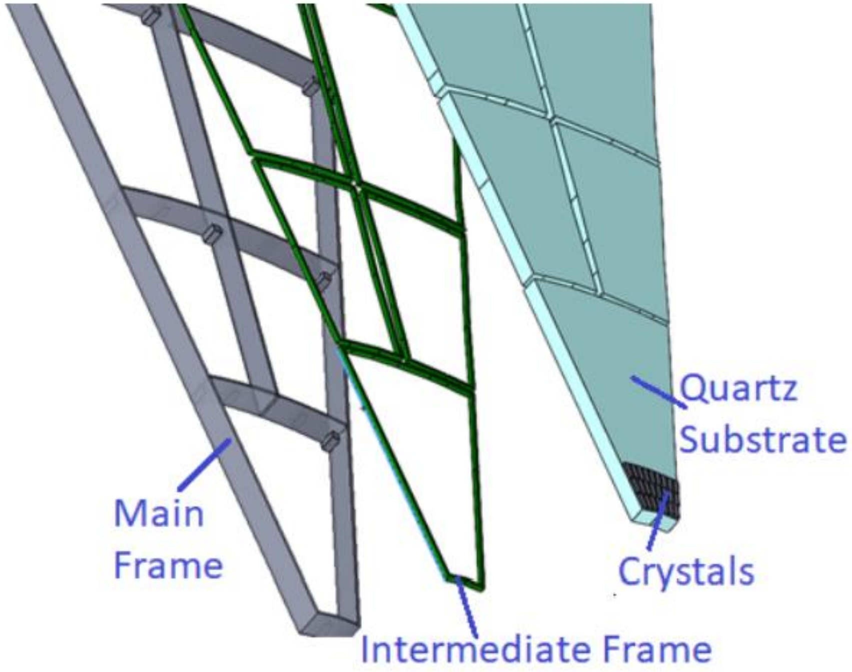
Laue聚焦镜的拼装

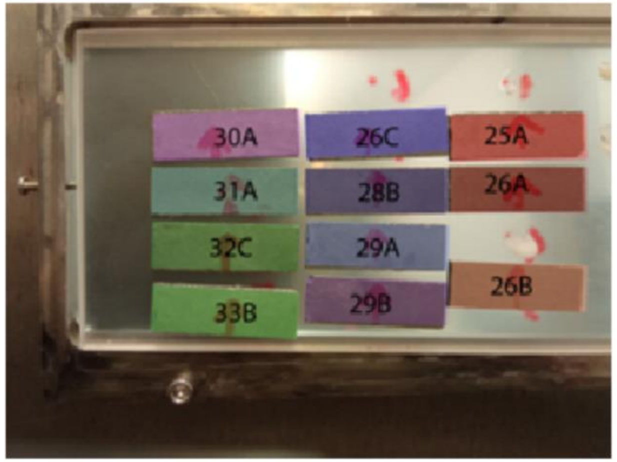
（Lisa Ferro, 2022）

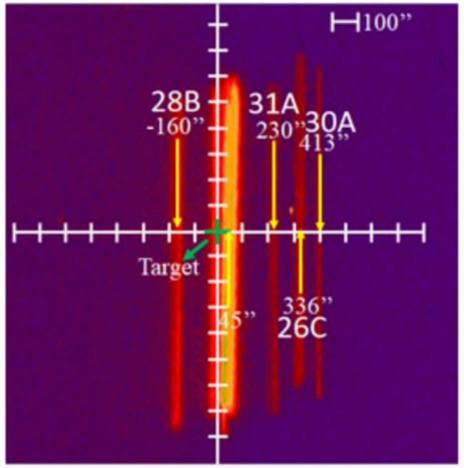


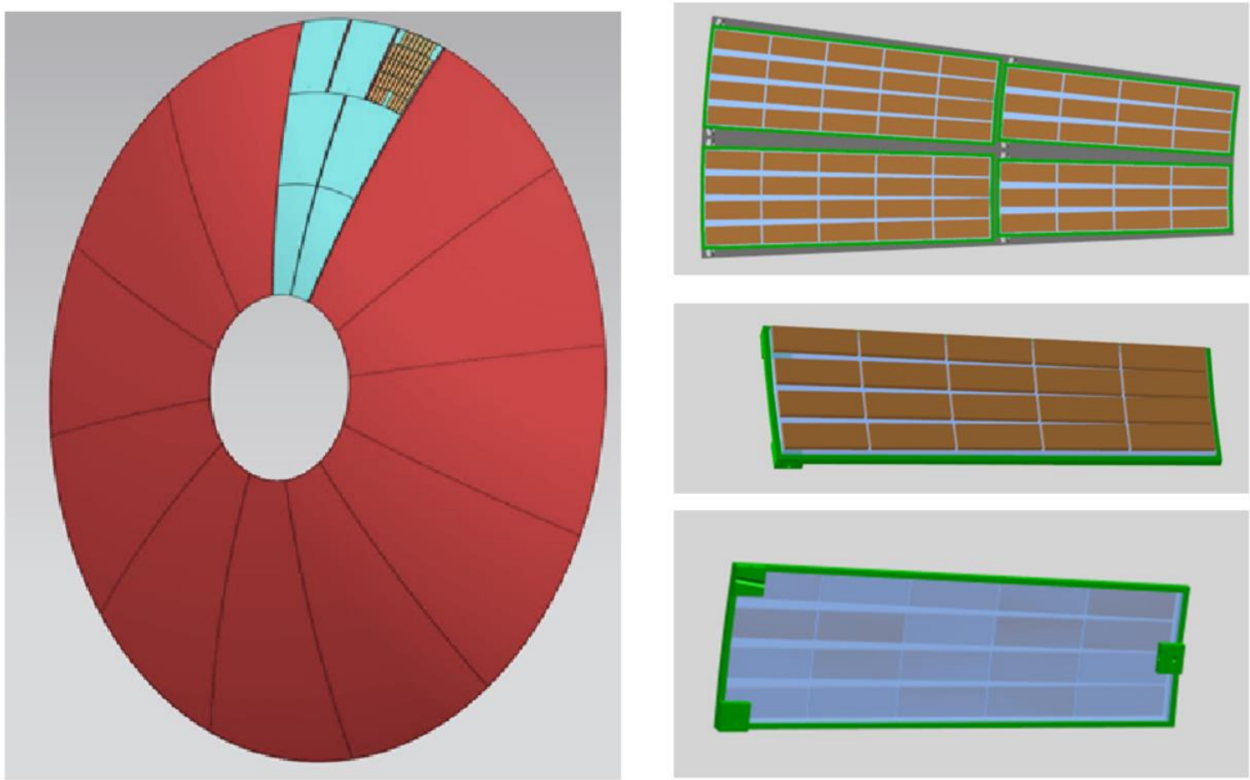
（V. Valsan, 2013）

Laue聚焦镜—高精度组装





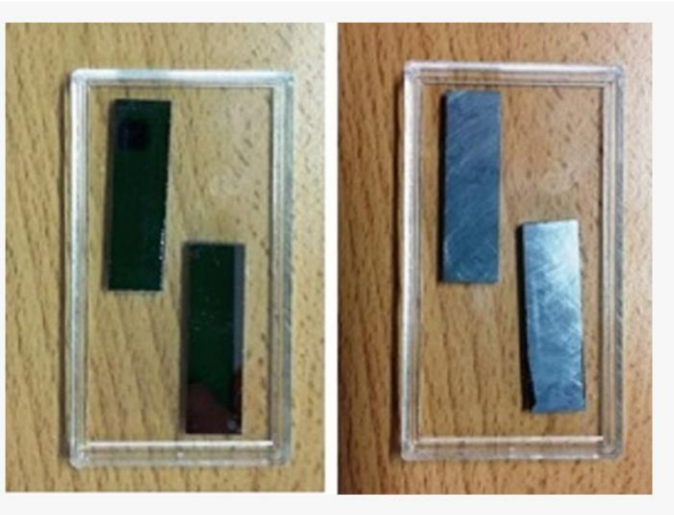




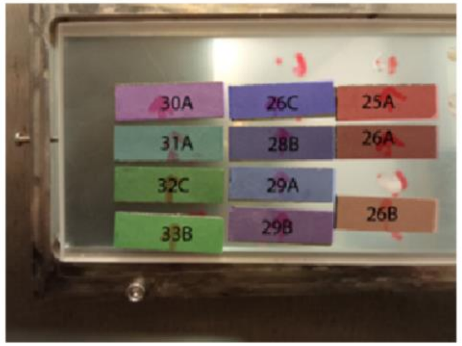
Laue聚焦镜的拼装

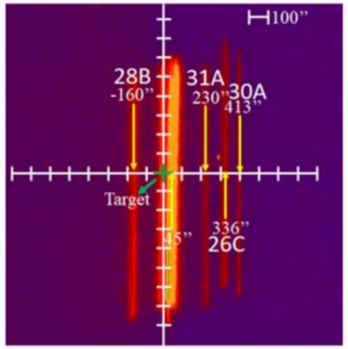
（Lisa Ferro, 2022）

关键技术

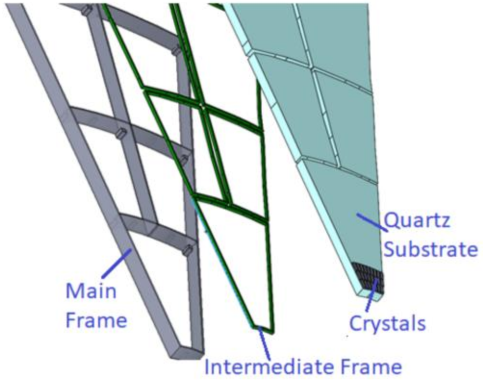


- 高精度高一致性劳厄弯晶技术
- 高精度劳厄晶片粘接技术



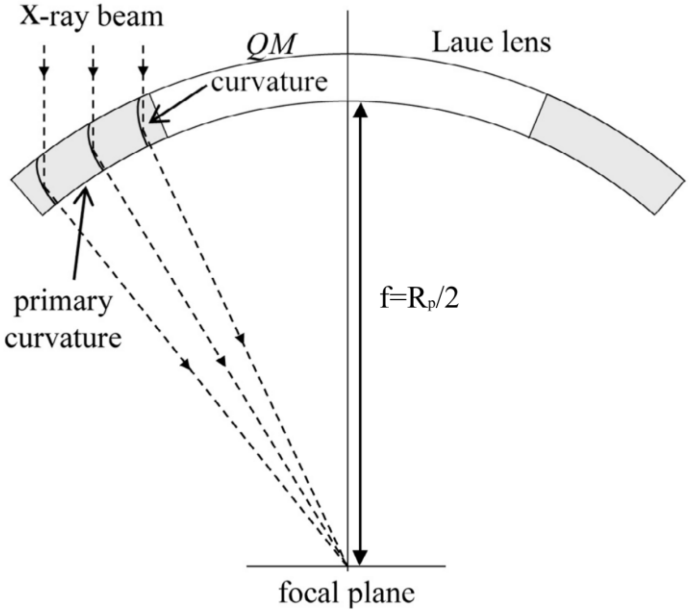


- 高精度劳厄透镜组装技术



劳厄晶片—自保持弯曲晶片

- 柱面晶片： 尺寸1cm×3cm×2mm，曲率半径30±1.5m（对应端点1μm误差）。
- 曲面晶片：焦距15±0.75m。
- 弯曲晶体：聚焦、连续能区、衍射效率超过50%。
- 研究如何产生二次曲率，及其对衍射效率和聚焦的影响。
- 研究外力撤销后，晶片形状随时间的恢复情况，随温度的变化情况等。



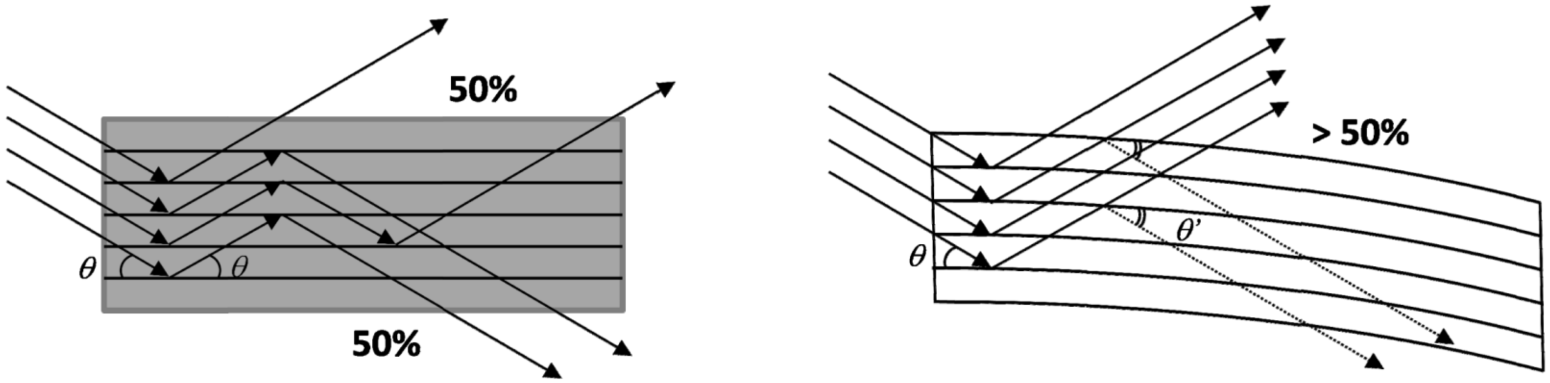
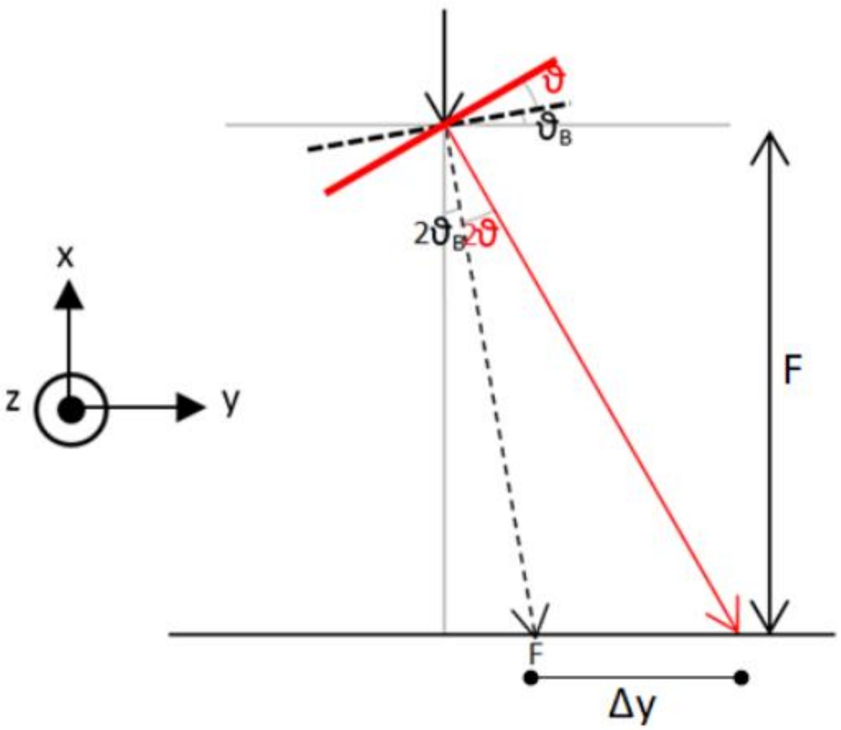
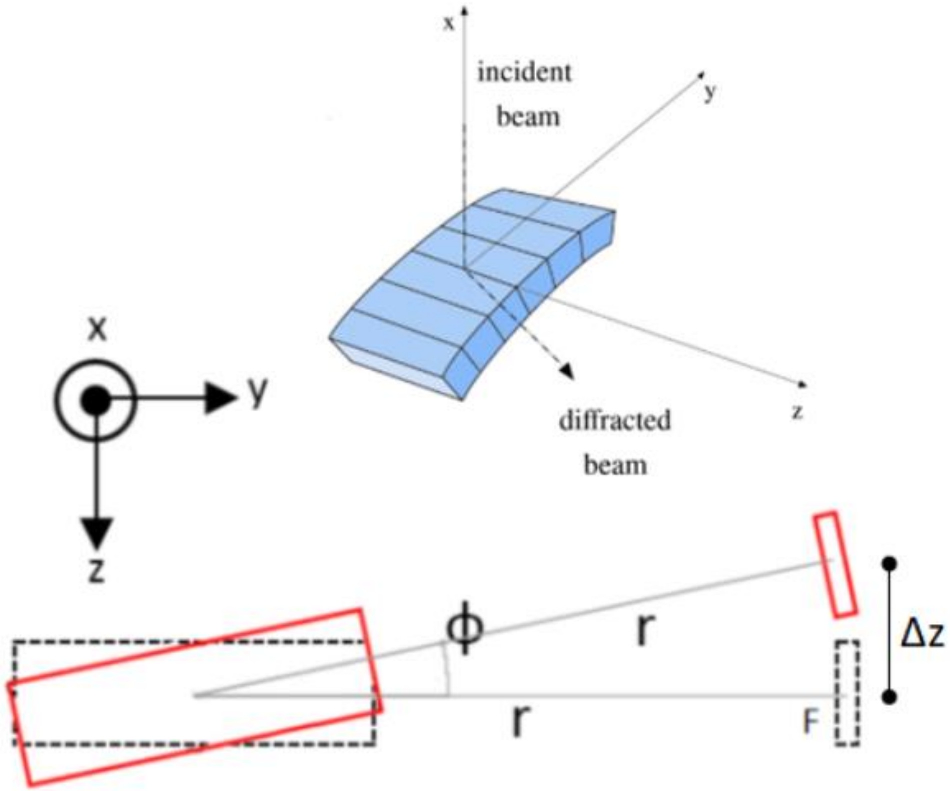


Figure 10: flat crystal planes (left) versus curved crystal planes (right). The curvature along this axis reduces nultiple reflections within the crystal, improving the reflectivity which in a flat crystal is limited to 50% due to multiple reflections. Additionally this curvature and widens the energy bandpass of the crystal.

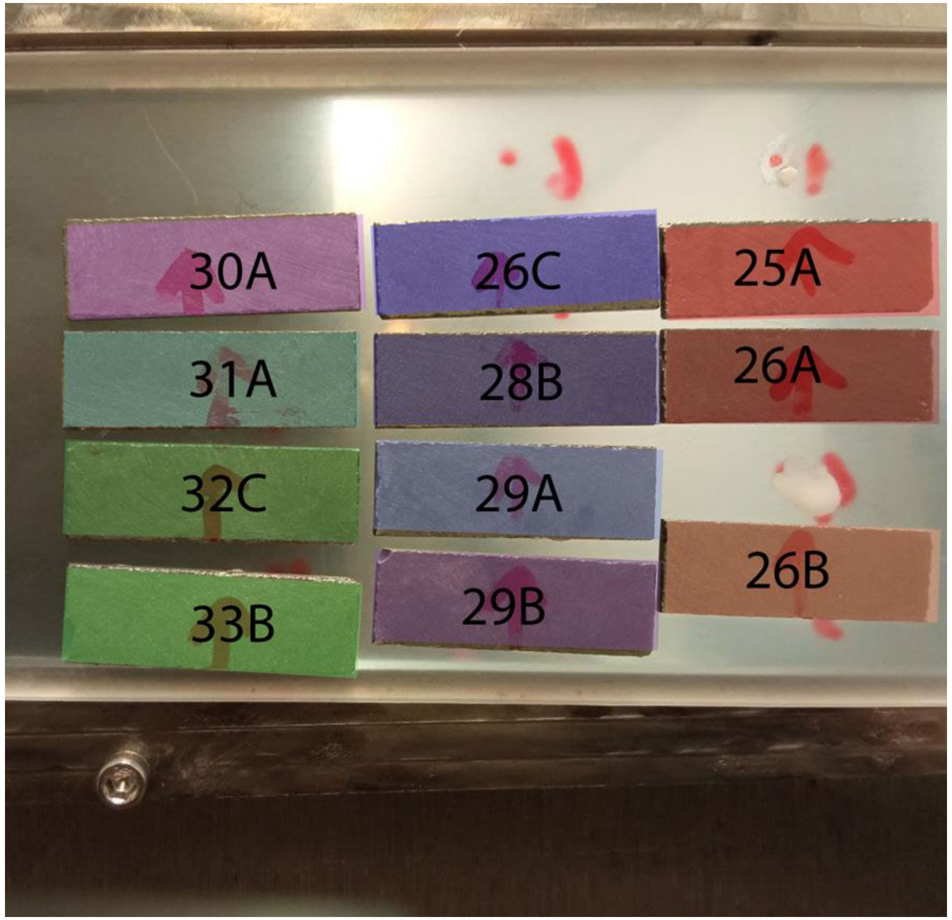
劳厄晶片的高精度粘接

- 俯仰角和方位角两个方向的精度要求均为10″。
- 认为粘接过程和劳厄透镜组装过程的误差的是随机的，每一步的误差不超过7″。





自保持弯晶



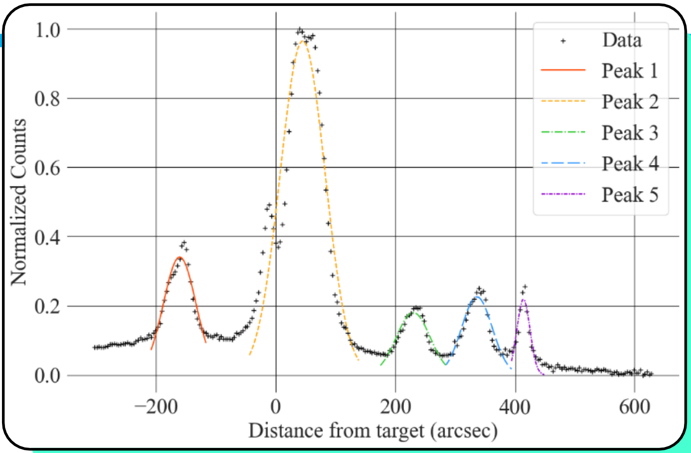
Crystal ID	Curvature Radius (m)	Thickness (μm)
25A	40.0 ± 0.4	1700 ± 5
26A	39 ± 1	1717 ± 5
26B	37.8 ± 0.3	1775 ± 5
26C	38.8 ± 0.8	1744 ± 5
28B	40.62 ± 0.04	1775 ± 5
29A	39.08 ± 0.01	1732 ± 5
29B	38.4 ± 0.9	1749 ± 5
30A	38.1 ± 0.6	1676 ± 5
31A	40.6 ± 0.1	1745 ± 5
32C	40.7 ± 0.7	1731 ± 5
33B	40.8 ± 0.3	1678 ± 5

Ferro+2024, JATIS

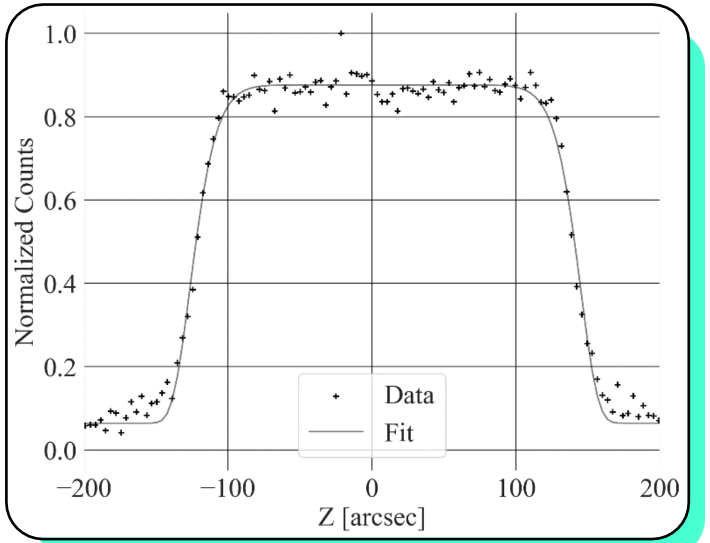
晶体高精度安装

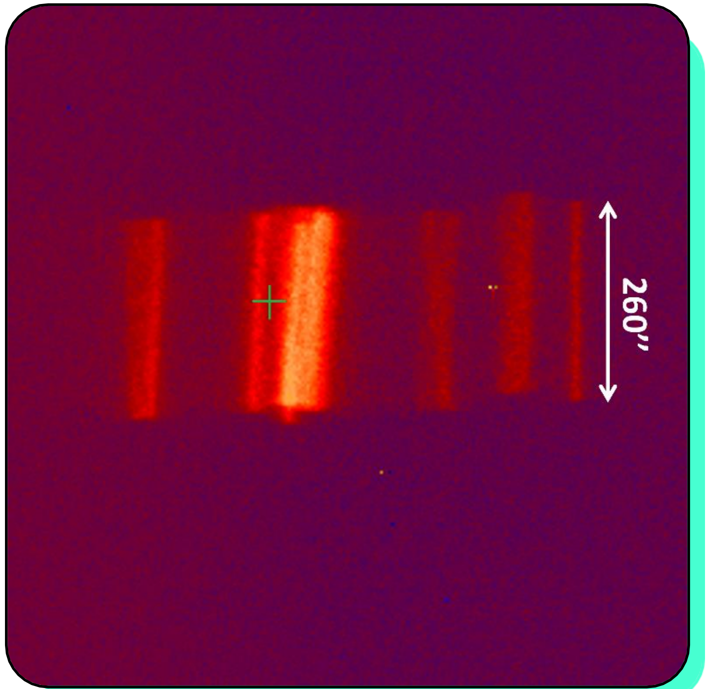
- 目前国际最好水平
  仍然不能满足要求。

Center: 45 ± 1 asec
FWHM: 88 ± 3 asec



Center: 9.2 ± 0.3 asec
Amplitude: 267 ± 7 asec

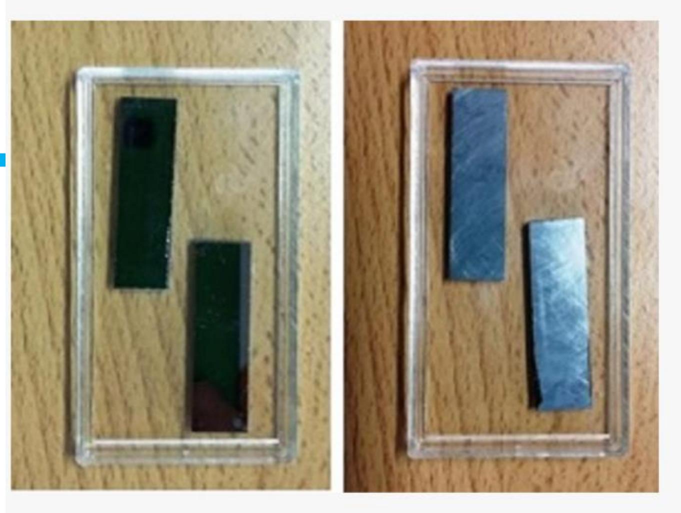




Ferro+2024, JATIS

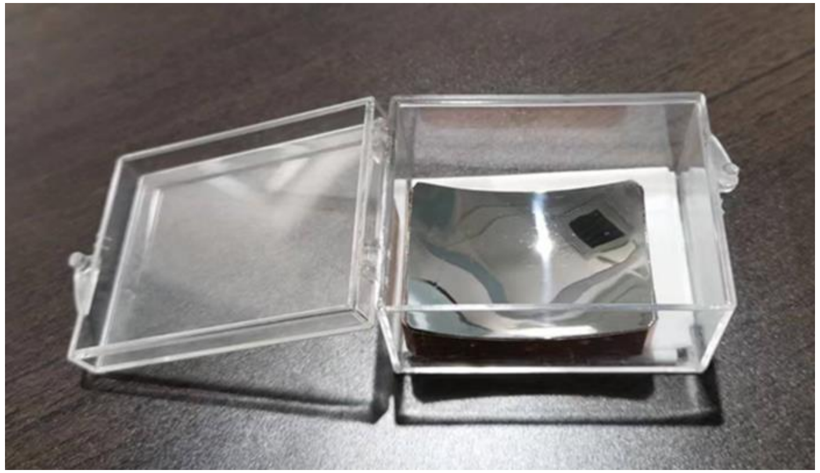
自保持弯晶加工

- 有损弯曲



- 阳极键合

- 无损弯曲



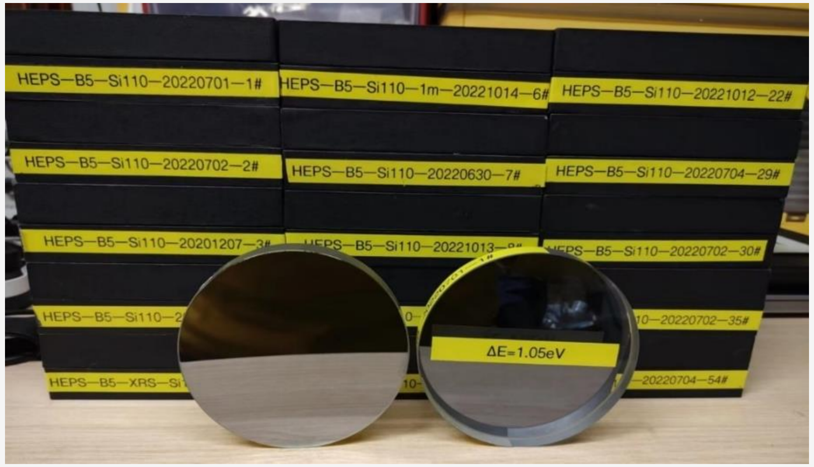
高能所多学科中心阳极键合技术工作基础

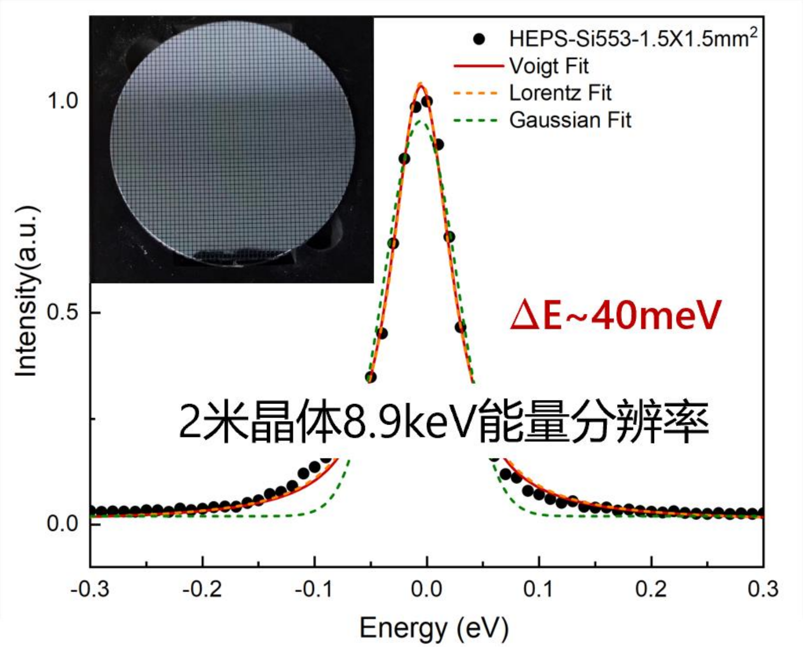
B5团队依托高能所HEPS工程项目牵引，先后：

- 突破：无界面孔洞、高质量**硅、锗**球面阳极键合技术**（国内领先）**
- 优化：扇形开槽应力释放技术；
- 创新：基于多孔陶瓷的真空吸附分析晶体技术**（国际先进）**
- 自主研制球弯、条带和平切像素型多种类型分析晶体；
- 极限能量分辨突破了50meV；
- 曲率半径涵盖0.5-2米；
- 入选了中科院自主仪器产品目录，成果转化>90万；
- 产品用于：SSRF, HEPS 等先进同步辐射及实验室光源。
- 代表性文章：

  J. Appl. Cryst. (2023). 56 (中科院1区，IF=6.1)

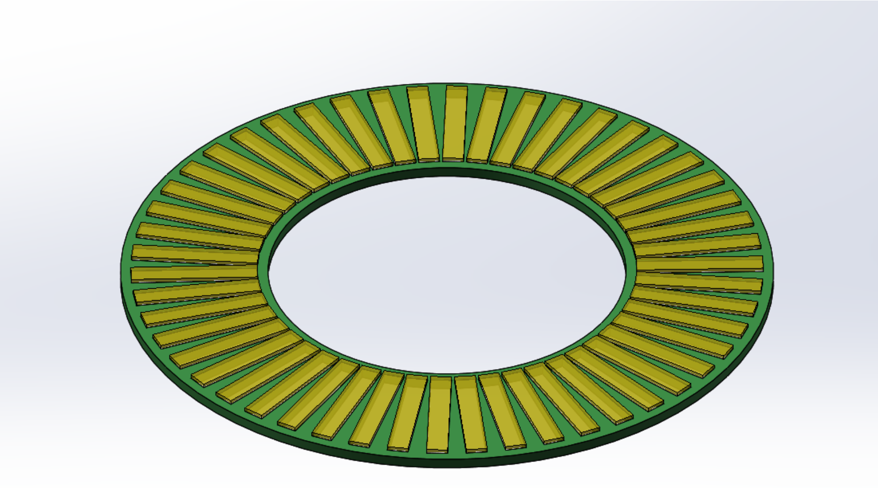
  Rev. Sci. Instrum. 94, 023102 (2023)
- 专利：实用及发明专利合计**5项**；

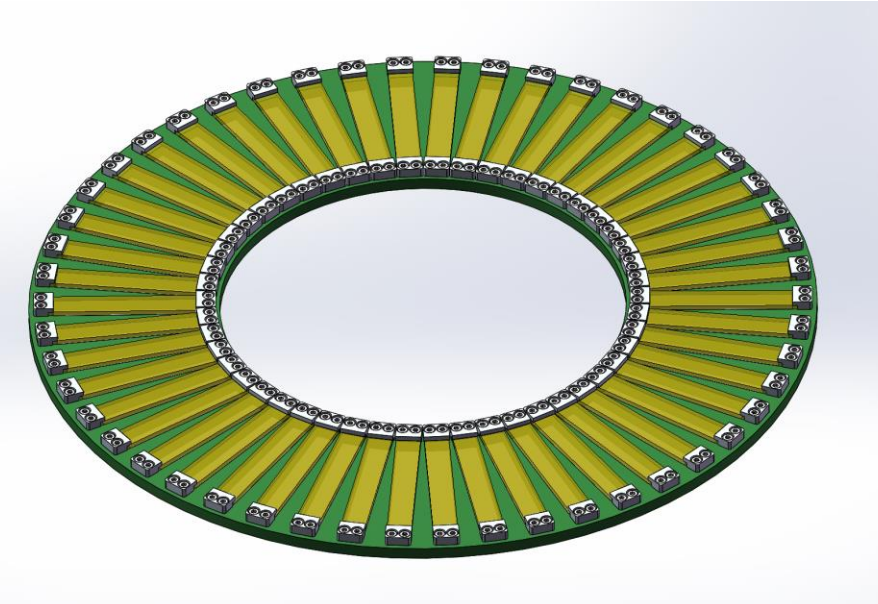




实现511窄带劳厄透镜的方法

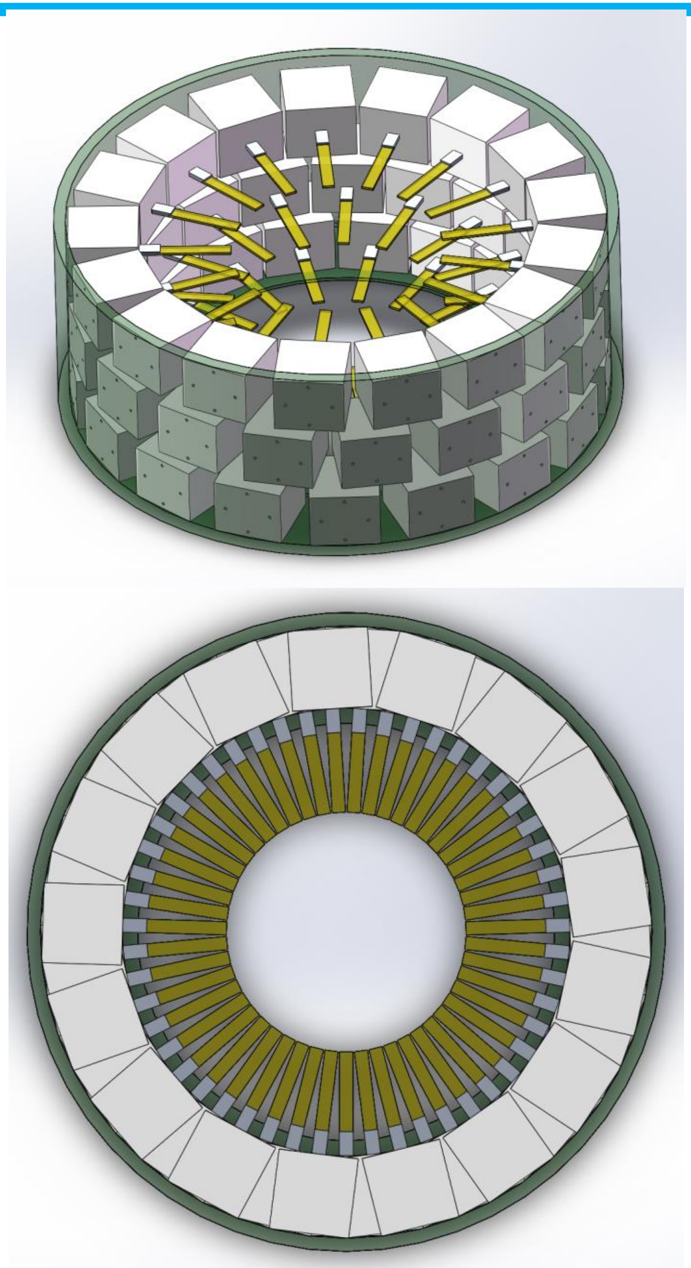
- 自适应调节方法
- 直接键合法
- 弯晶粘接法
- 机械固定法

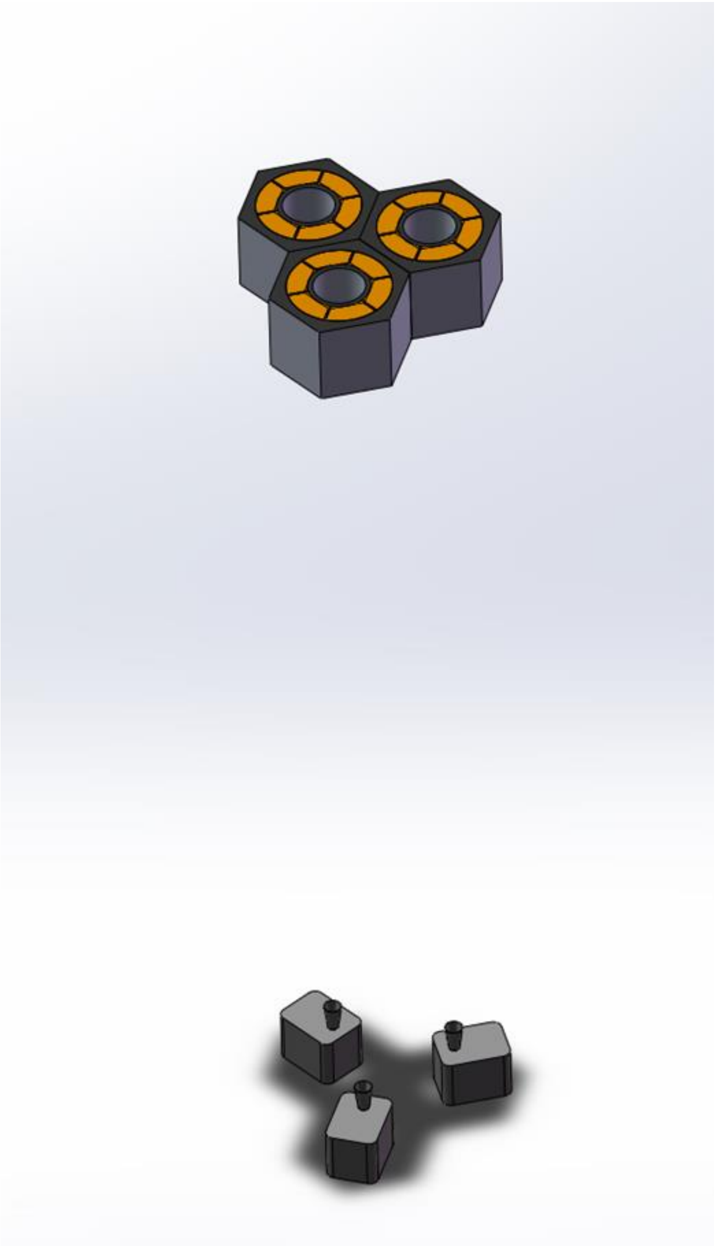




实现511窄带劳厄透镜的方法

- 调节机构尺寸：50×50× 60 mm^3
- 分辨率 1 arcsec
- 重复定位精度 10 arcsec
- 动态范围 1~2°
- 第一层与第三层间隔120mm。
- 基线方案以落实合作单位。
- 扩展功能：扫描扩展视场
- 在轨校准：在轨光学测量系统，或者利用天体源校准 太阳？或者 ？？

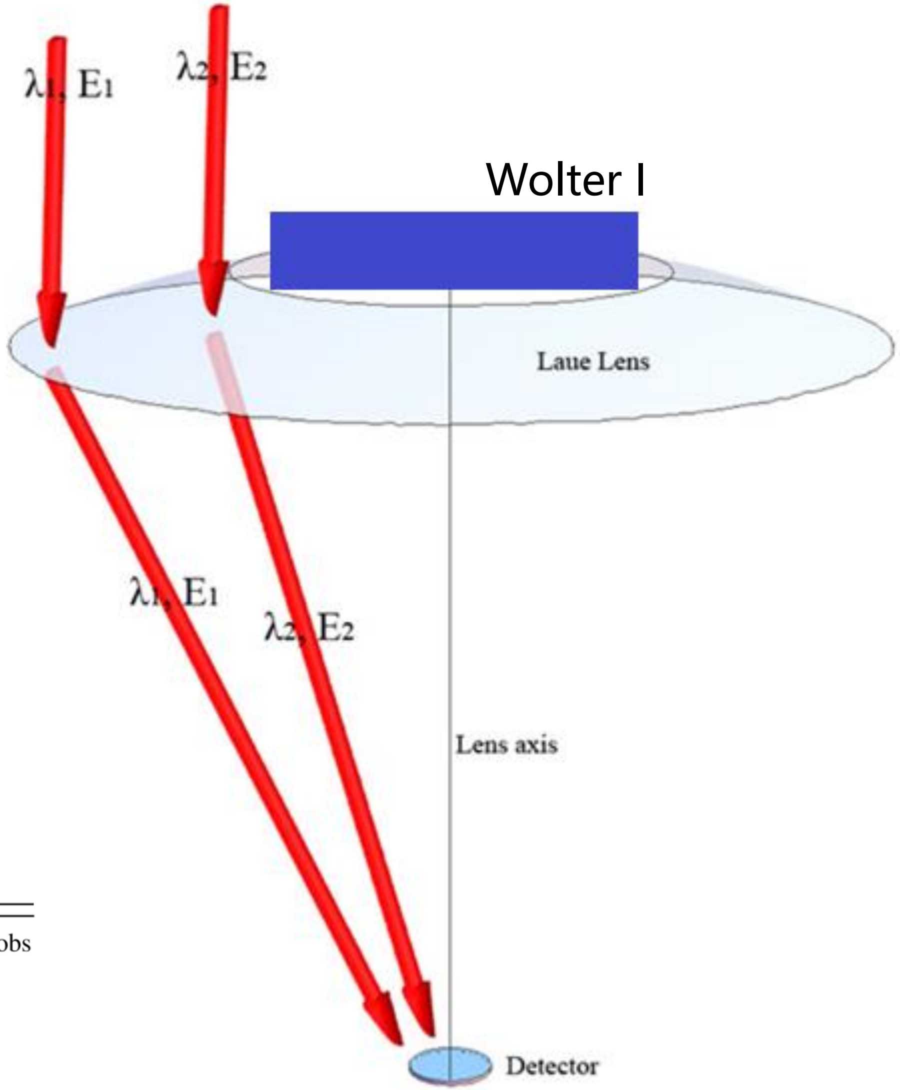




Laue Focusing Telescope

Scientific Motivation: Develop a space-based focusing telescope for high energy astrophysics.

Energy range: 50-900keV (10~900keV with Wolter I).
Angular resolution: 30 arcsec(HPD).
Energy resolution: < 0.045%@511keV (TES)
Sensitivity: the expected increase is by a factor of at least 10–100 with respect to IBIS onboard Integral.
Scientific capability: Imaging, spectroscopy, polarimetry and timing.



$$I^{\min}(E) = n_\sigma \frac{\sqrt{B(E)}\sqrt{A_d}}{\eta_d(E) f_\epsilon A_{\text{eff}} \sqrt{\Delta E}\sqrt{T_{\text{obs}}}}$$

$$I_L^{\min}(E_l) = 1.31 n_\sigma \frac{\sqrt{[2B(E_l)A_d + I_c(E_l)\eta_d f_\epsilon A_{\text{eff}}]\Delta E}}{\eta_d f_\epsilon A_{\text{eff}}\sqrt{T_{\text{obs}}}}$$

511keV Laue Focusing Telescope (近期)

Scientific Motivation： Develop a space-based focusing telescope for positron puzzle.

Energy range： 450-550keV

Effective Area: >400cm^2@511keV

Angular resolution： 1 arcmin(HPD)

Field of view： ~4 arcmin

Energy resolution： ＜0.1%@511keV （TES）

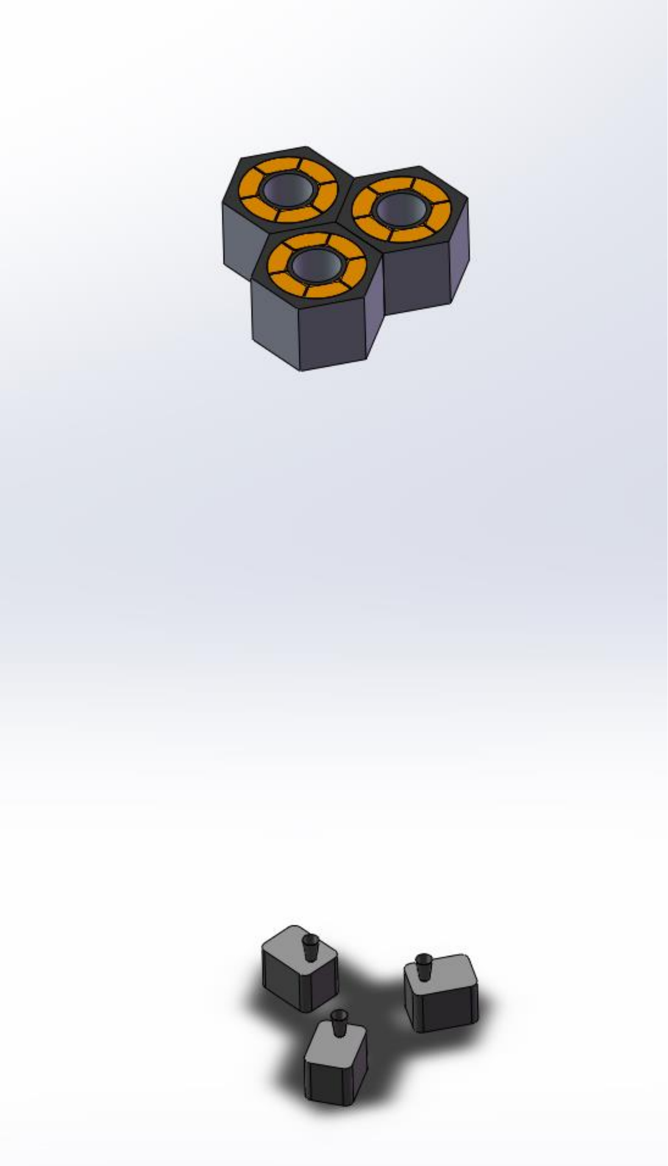
Line Sensitivity： the expected increase is by a factor of 12 with respect to SPI onboard Integral.

Laue focusing telescope:

Laue Mirror Ge （111） Laue Lens

Focal length： ~15m

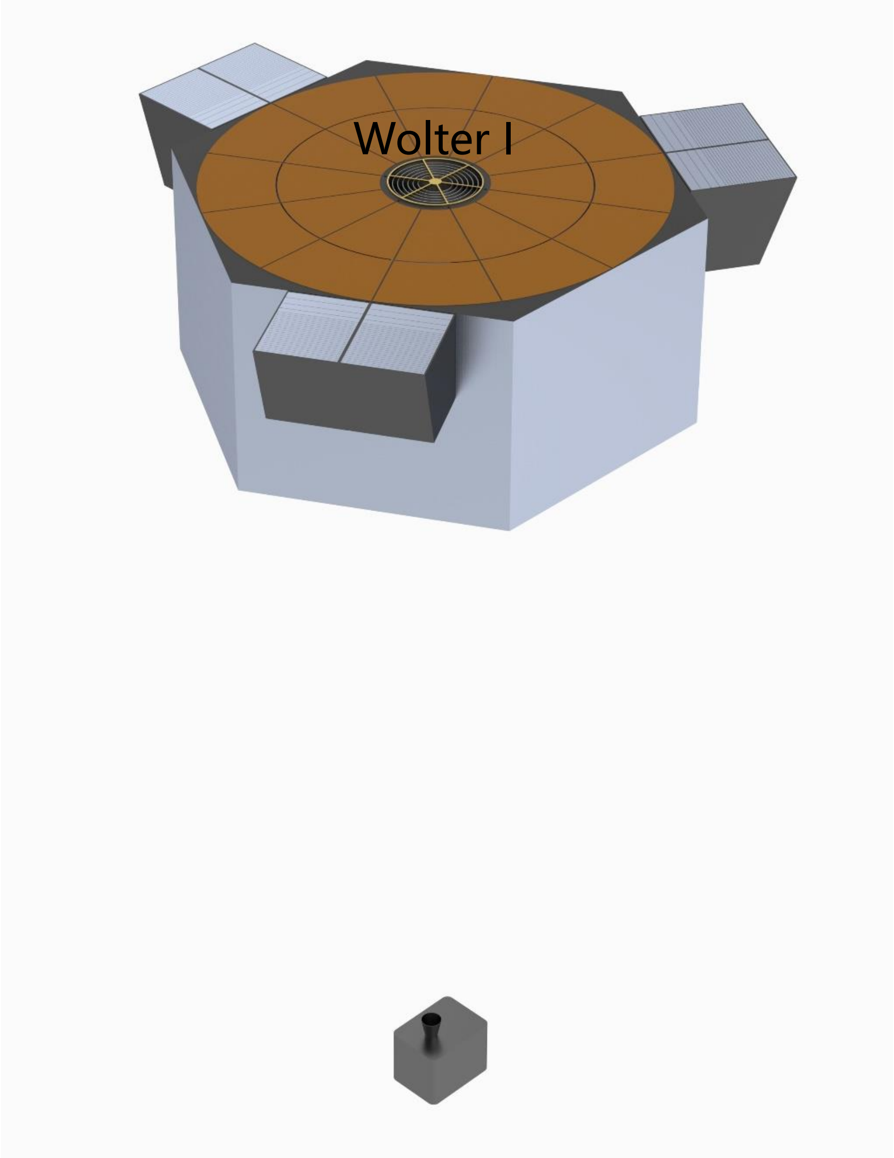
Laue Lens diameter： ~30 cm for each



Scientific capability： spectroscopy, polarimetry and timing.

X ray and soft gamma ray Focusing Telescope (中期)

- Laue focusing telescope
  - Laue Mirror + Wolter I Mirror (from WXPT)
    - Ge（111）Laue Lens + Si （or nickel)
    - Focal length：~30m
    - Laue Lens diameter：~3m
    - Wolter I Mirror diameter: ~30 cm
  - Focal plane detector（Pixeled，100μm）
  - TES
    - 0.08%@511keV
- Wide field monitor (WFM)
  - coded aperture
  - point source localization capability:1 arcmin
  - Energy range: 10keV~2MeV
  - GAGG+SiPM



X ray and soft gamma ray Focusing Telescope (中期)

Scientific Motivation： Develop a space-based focusing telescope for high energy astrophysics.

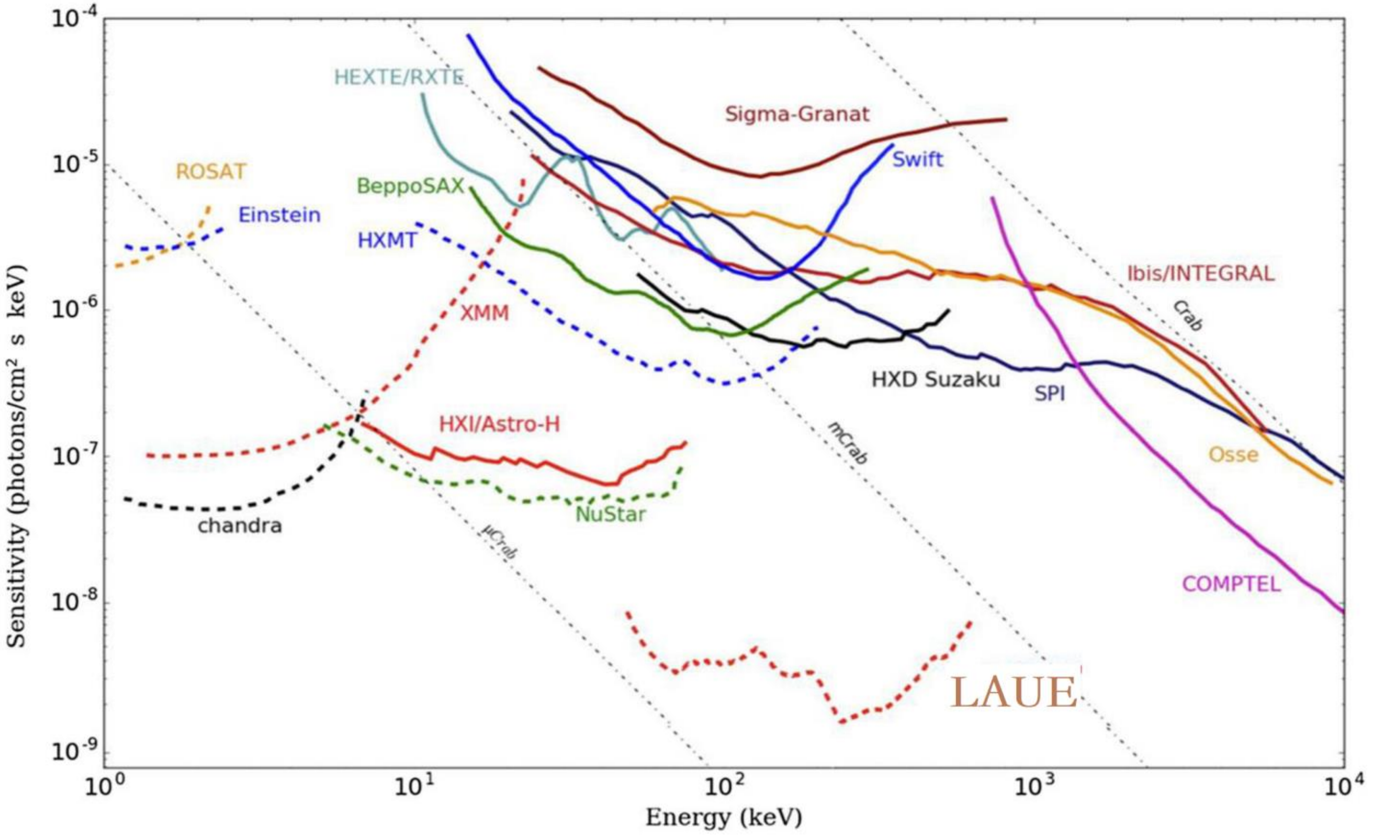
Energy range： 50-900keV (10~900keV with Wolter I).

Angular resolution： 30 arcsec(HPD).

Energy resolution： ＜0.08%@511keV （TES）

Sensitivity： the expected increase is by a factor of at least 10–100 with respect to IBIS onboard Integral.

Scientific capability： spectroscopy, polarimetry and timing.

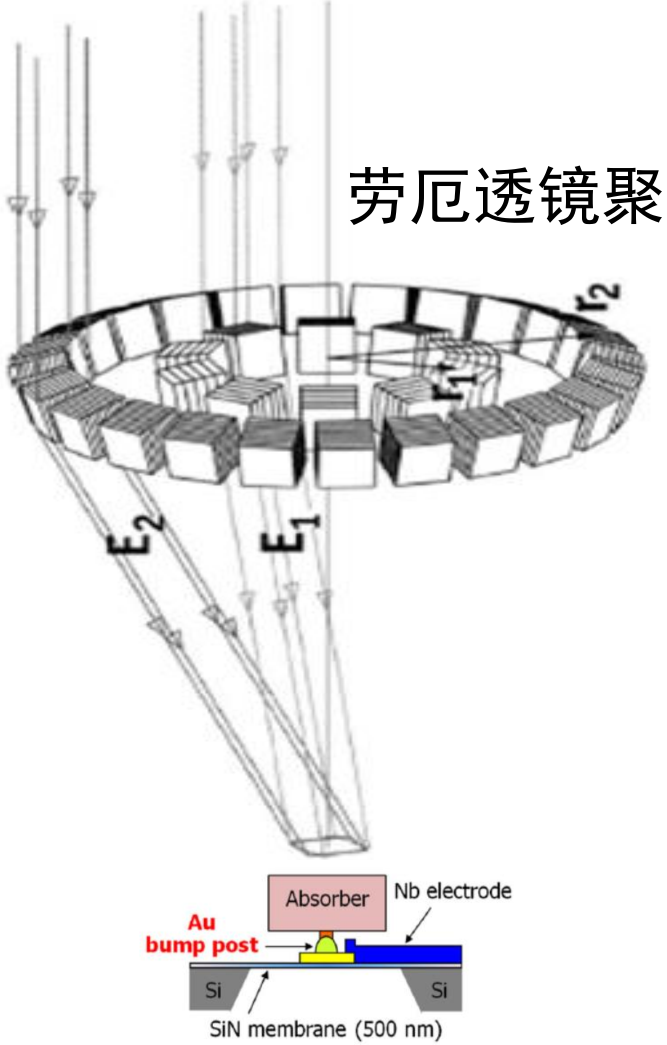


空间天文项目灵敏度对比

（Enrico Virgilli，2022）

核天体物理探针计划（远期）

FIONA (Focusing Imager Of Nuclear Astrophysics)



劳厄透镜聚焦

Energy band: 0.2~2MeV
Effective area: 100~1000cm^2
Angular res: ≤1 arcmin(focus)
Energy res: ≤ 0.07%@662keV
FOV: 0.5° *0.5° (focus)

Line Sensitivity: 100 × COSI （2025发射，HPGe）

（Farzane Shirazi，2022）

总结与展望

- 本项目将研制一种基于Laue透镜的空间硬X和软γ射线聚焦技术。
- 首先完成511keV劳厄透镜样机的研制。
- 基于劳厄聚焦技术，我们进行了空间项目的近期、中期和远期规划，将实空间硬X和软γ射线现高灵敏度聚焦观测。

谢谢！