WESTLAKE UNIVERSITY 西湖大學

SPECTRA室温暗光子探测实验

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2026年7月21日
2026年紫金山暗物质研讨会（乌鲁木齐）

Motivation

暗光子作为暗物质的一种候选模型，可以看作是震荡的背景场

暗光子A′ 与普通光子动力学耦合： $\kappa F_{\mu\nu} F'^{\mu\nu}$

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0} + \kappa \left(\frac{m_{A'}}{\hbar c}\right)^2 \phi'_{\mathrm{DP}},$$

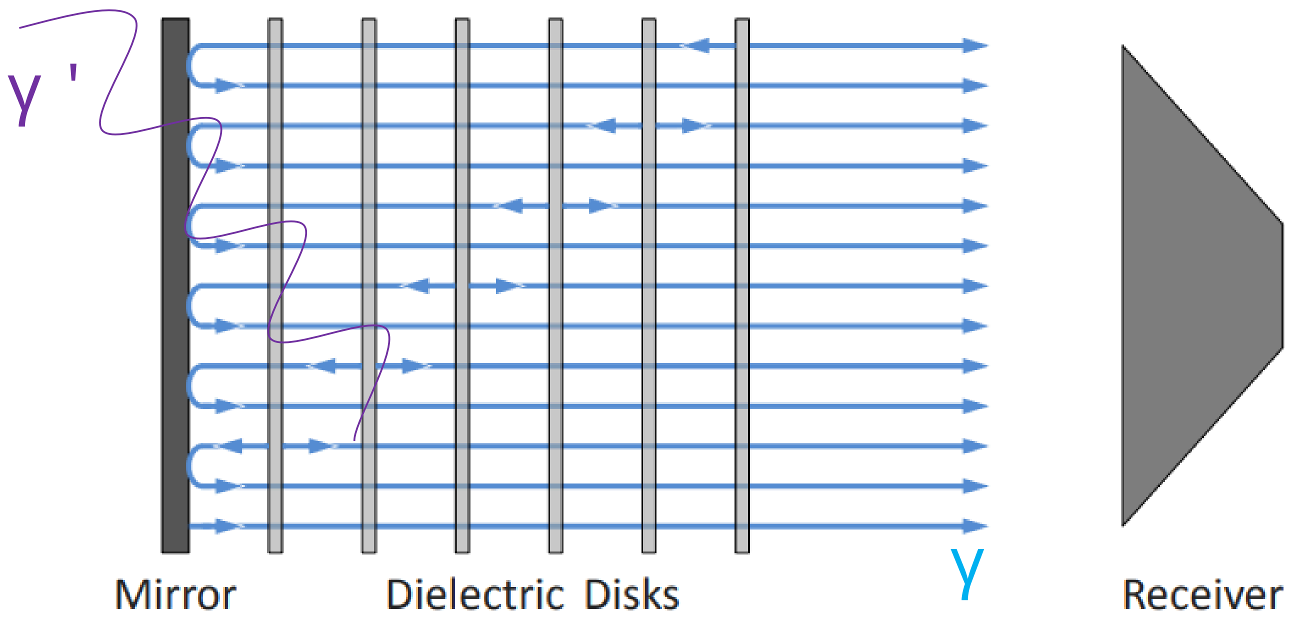
$$\nabla \cdot \mathbf{B} = 0,$$

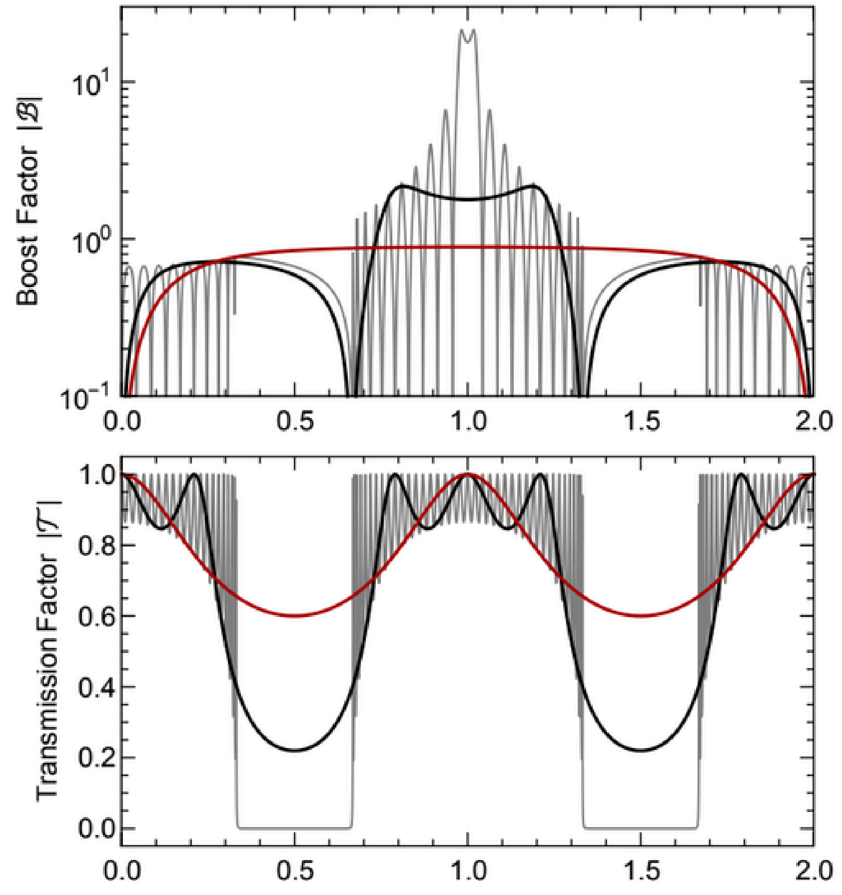
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t},$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \frac{1}{c^2}\frac{\partial \mathbf{E}}{\partial t} + \kappa \left(\frac{m_{A'}}{\hbar c}\right)^2 \mathbf{A}'_{\mathrm{DP}}.$$

暗光子修正的 Maxwell 方程

arXiv:2110.02875 [hep-ph]





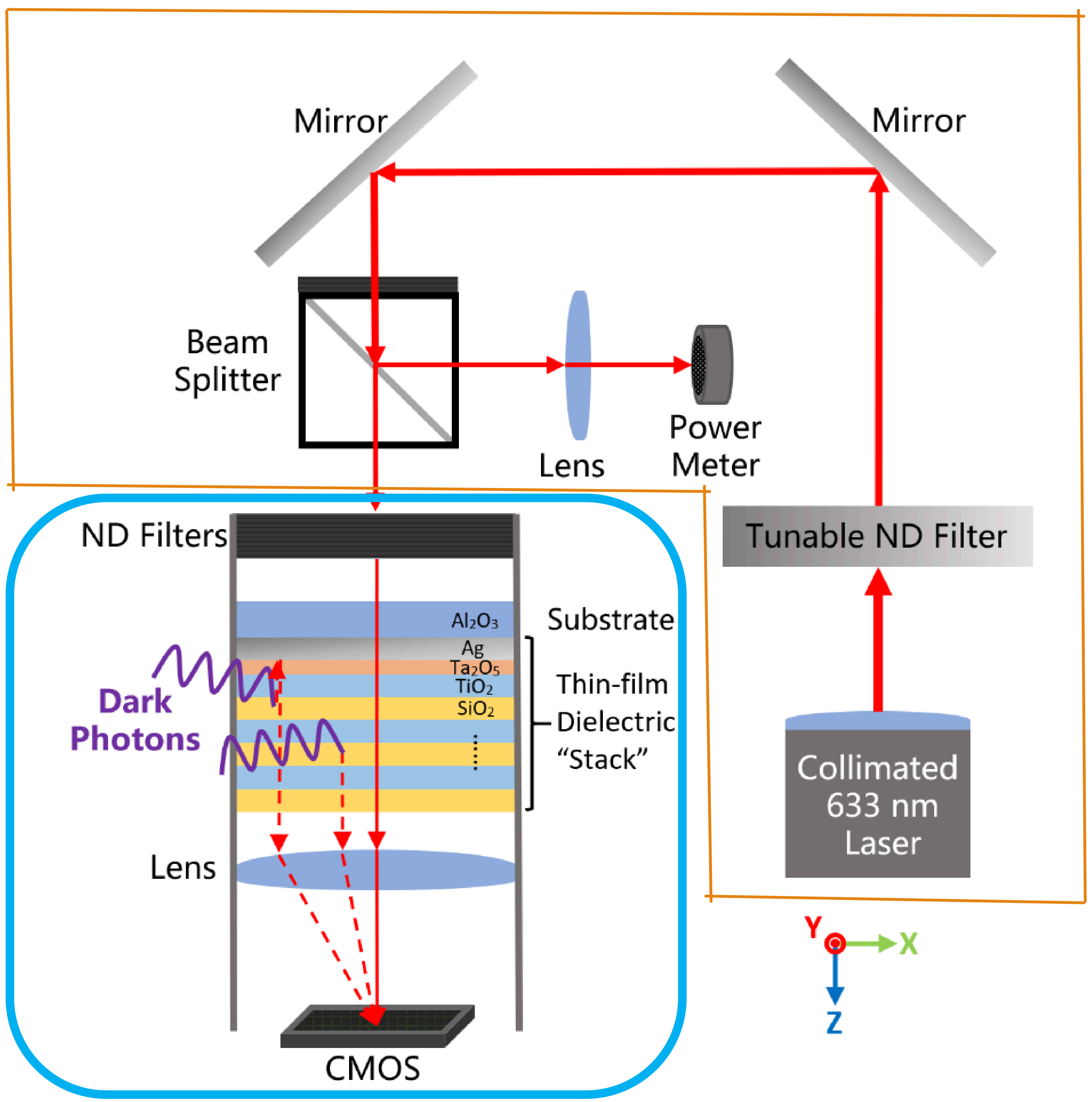
$$\omega \simeq \frac{\pi}{n_i d_i}$$

N = 1
N = 2
N = 20

Signal rate $\propto \kappa^2 \times |\beta|^2 \times$ efficiency

arXiv:1612.07057 [hep-ph]

SPECTRA Prototype



Spatially-resolved Photon Emission Conversion with Transmission Reflector Arrays (SPECTRA)

主体部分: Haloscope

- 暗光子到可见光子的转换 (Stack)
- 信号聚焦 (Lens)
- 信号接受 (CMOS)

标定部分: Calibration

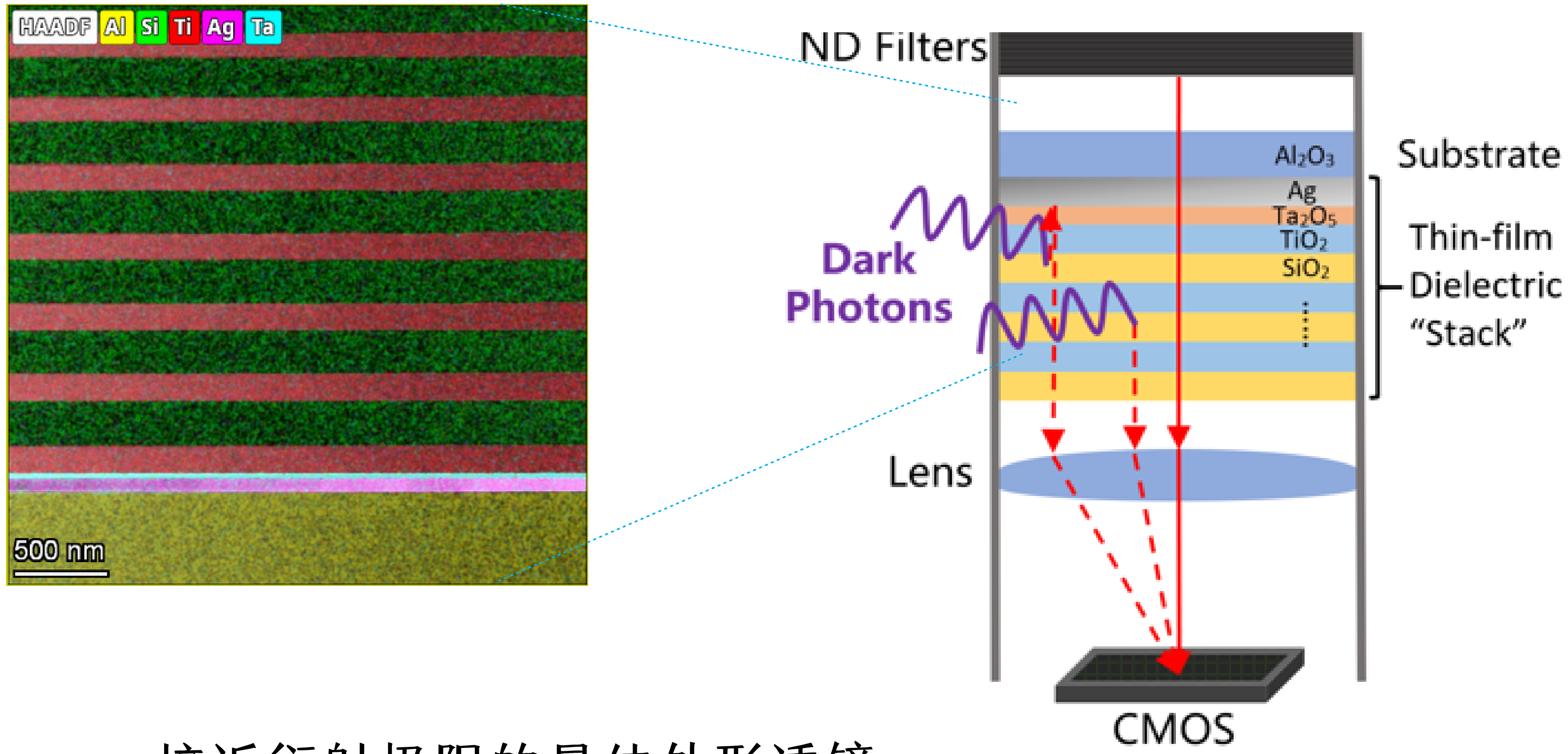
- 聚焦位置 (光模拟Pattern信息)
- 光学效率 (仪器效率，信号收集效率)

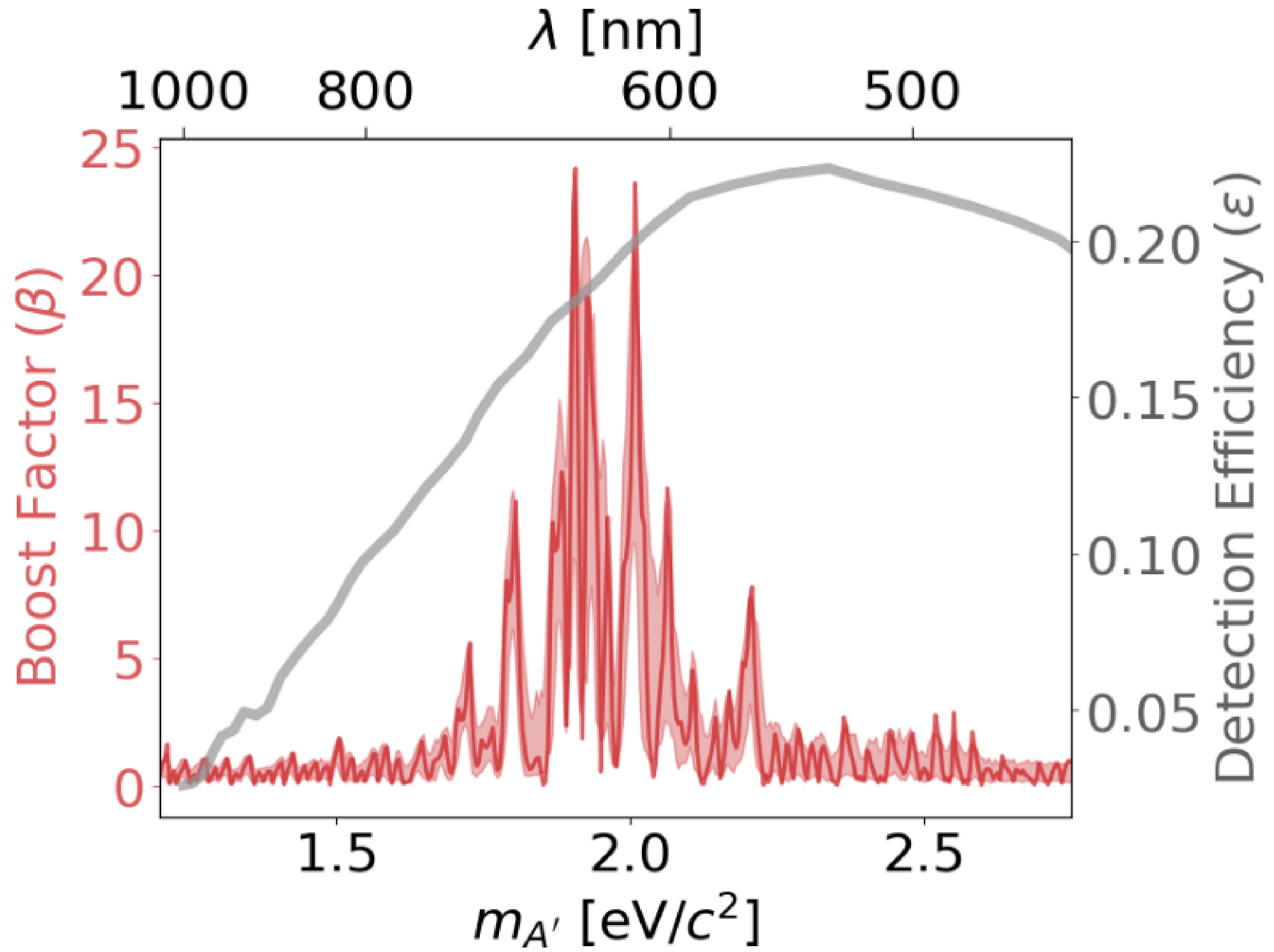
arXiv:2607.03240 [hep-ex]

Haloscope

Stack:

- 技术实现：离子束溅射沉积 (IBD) + TEM 表征
- 尺寸：直径为一英寸（2.54cm）的圆柱体，47 pairs (TiO_2 & SiO_2)

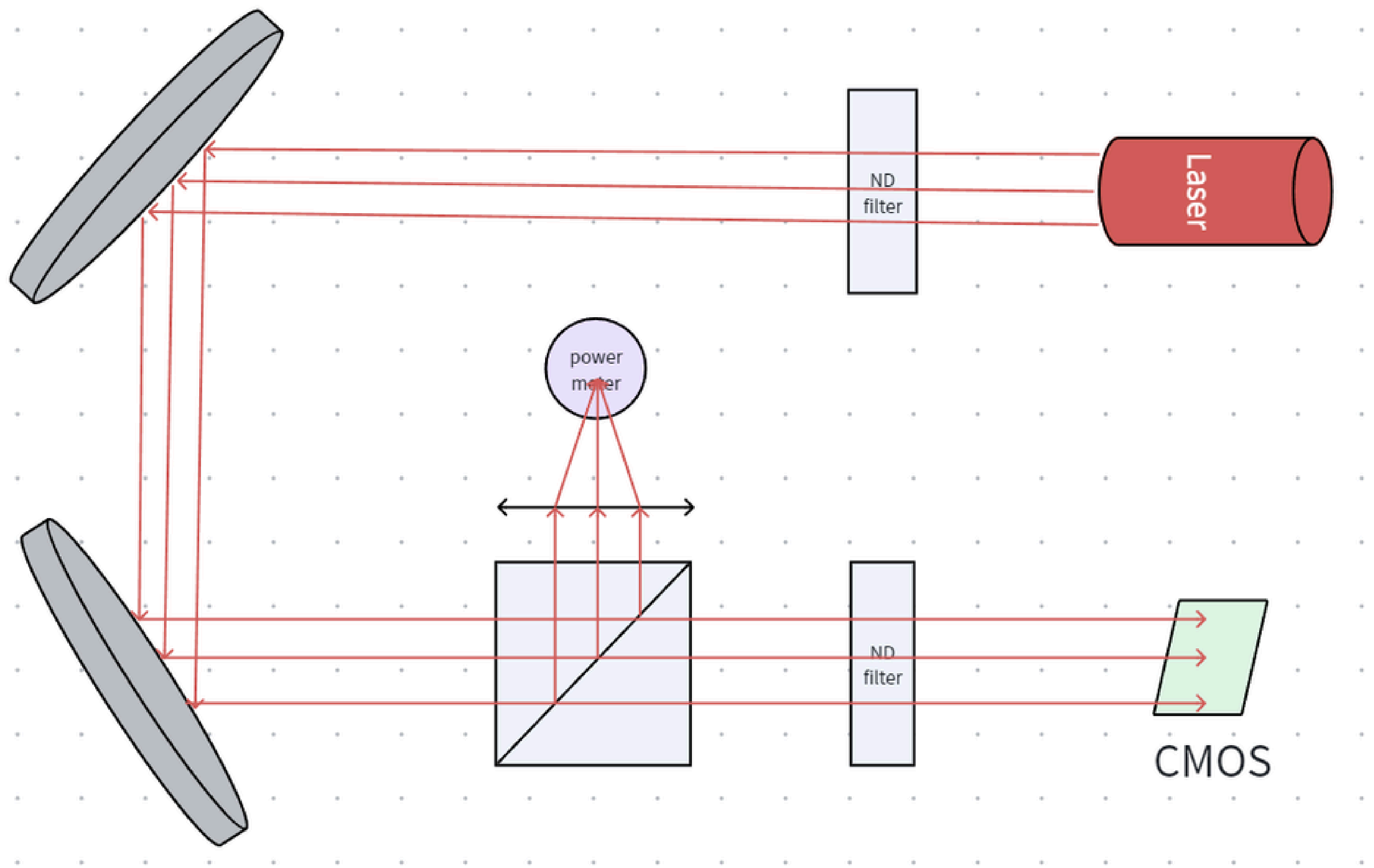




Lens: 接近衍射极限的最佳外形透镜

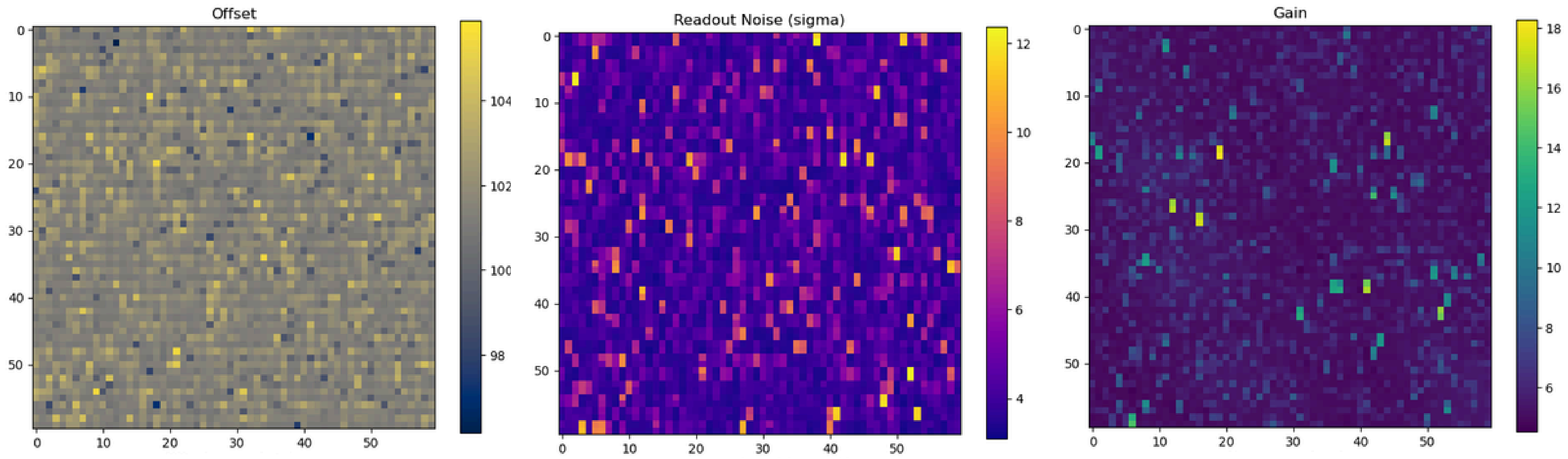
CMOS:
- 暗计数率~ 10^{-5} e^{-}/s/pixel， 读出噪声 ~ 0.8 e^{-}/frame/pixel
- 像素尺寸：3.76 x 3.76 μm^2， 3000 x 3000 pixels

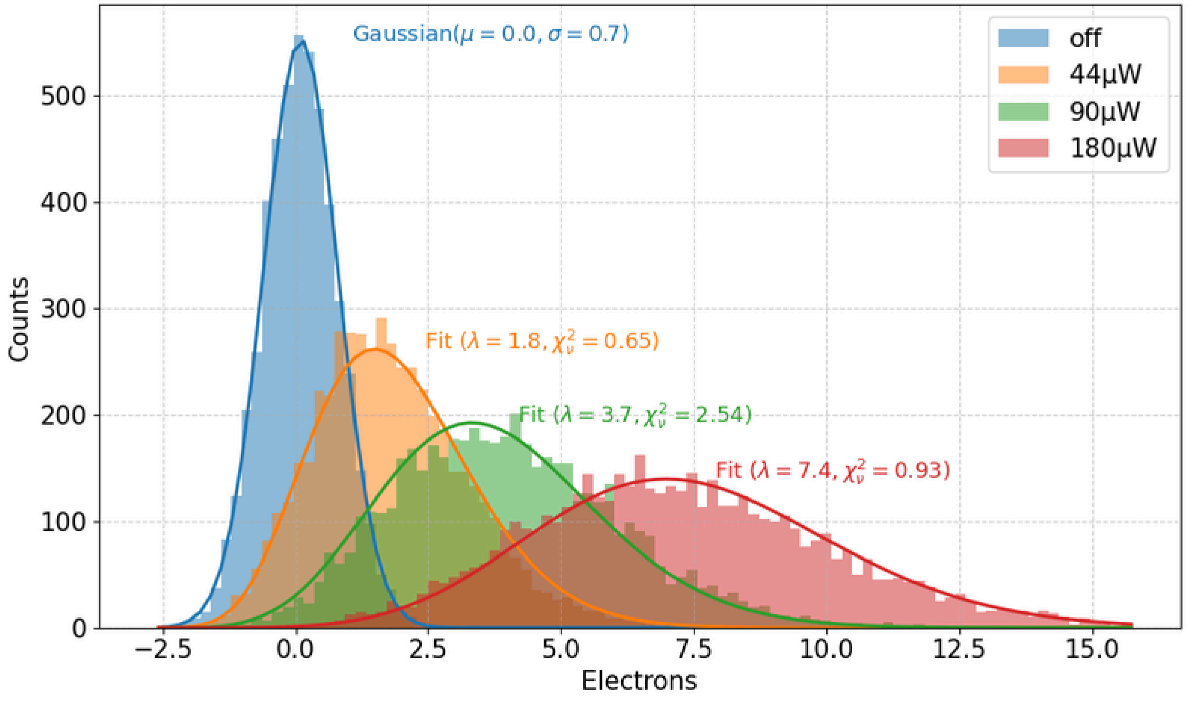
Calibration 1: CMOS Parameters



$$DN = \mathcal{N}(N_0, \sigma_{\text{read}}) + g \cdot \text{Pois}(\lambda)$$

Offset N_0 | Readout Noise σ_{read} | Gain g



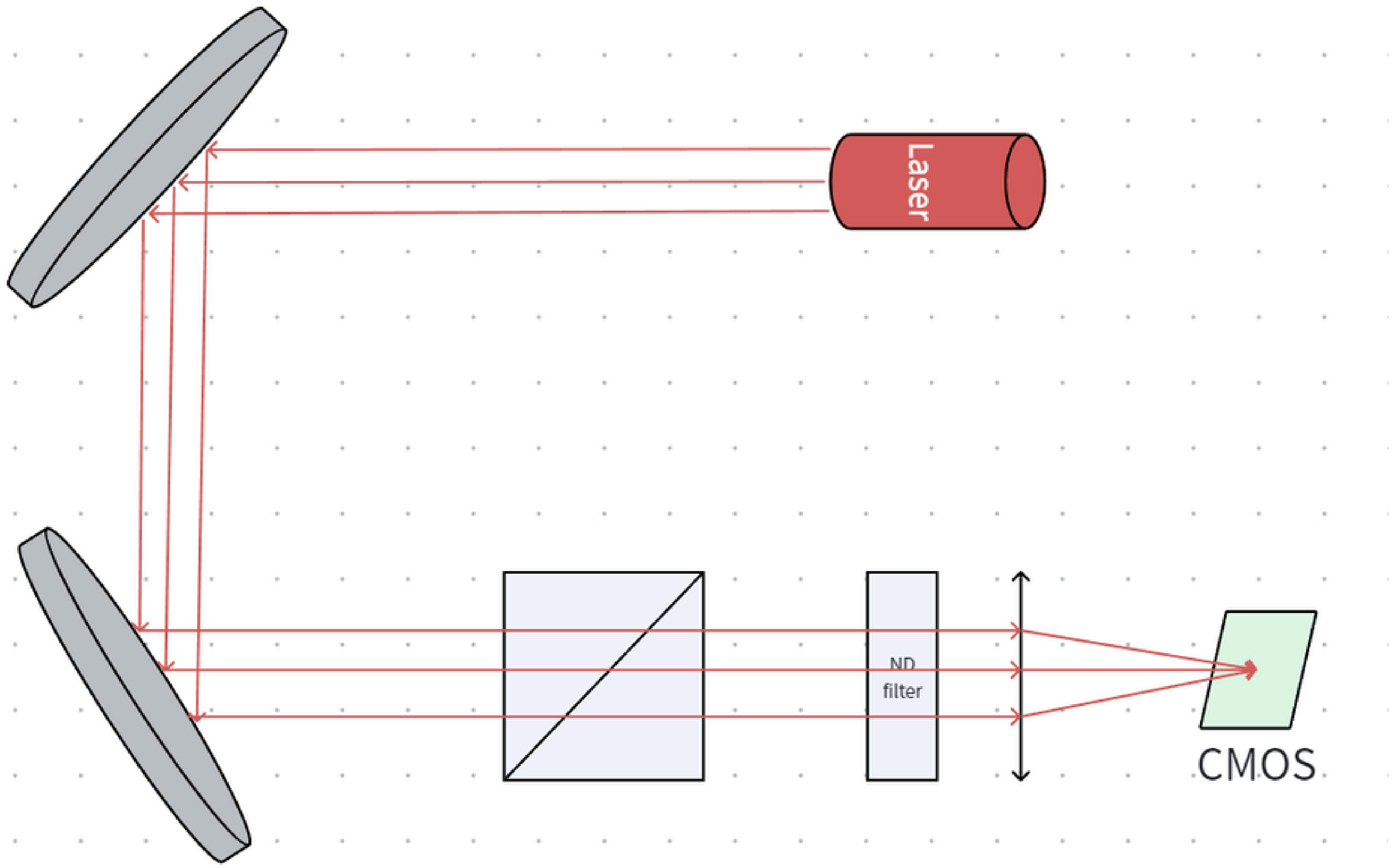


Setup: 1 ms x 5000 帧 x 4 组，分别为 0x, 1x, 2x, 4x 激光强度

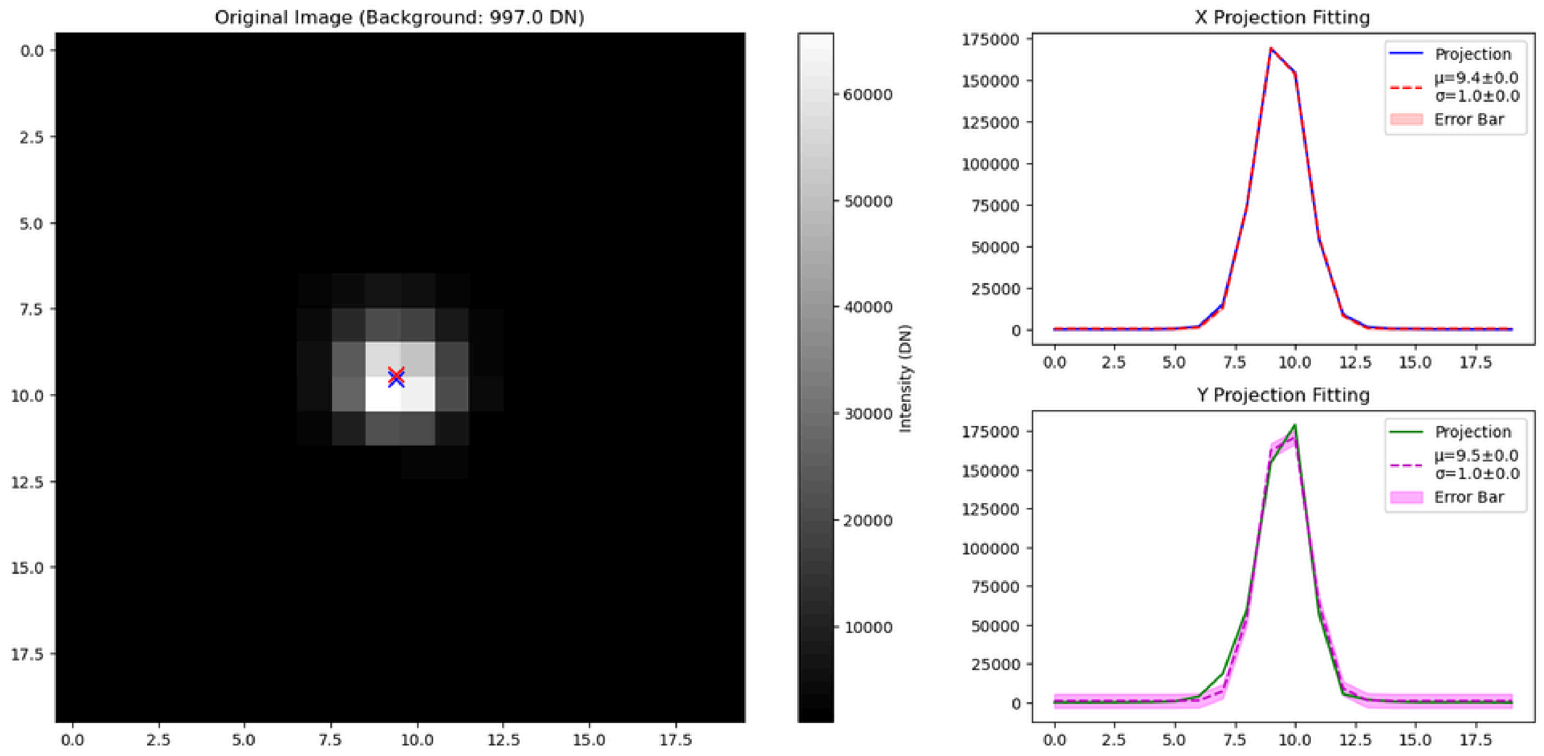
标定CMOS像素参数：Offset, Readout Noise, Gain

Calibration 2: Focus Position

Setup: 1s x 10 帧， 较强激光

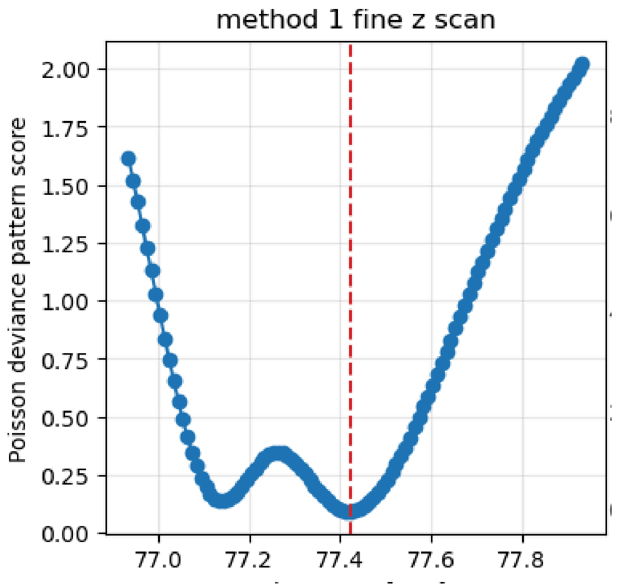


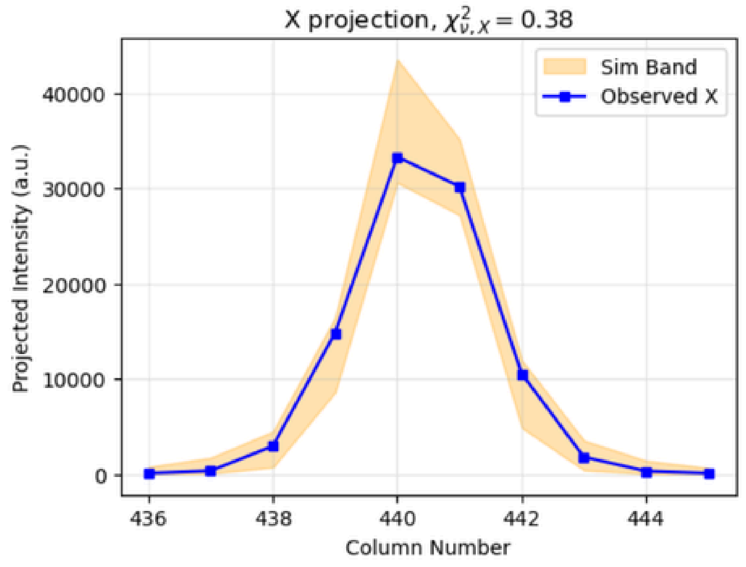
二维高斯拟合确定水平位置 (X, Y)

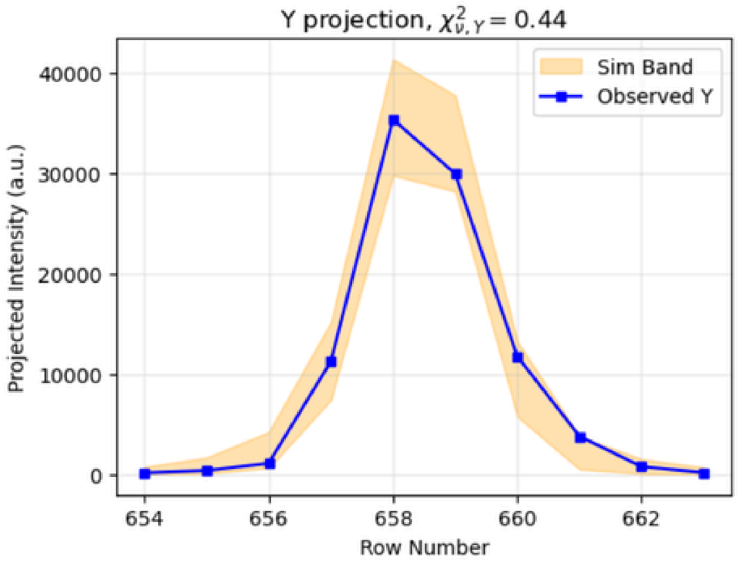


通过调整光模拟中Z方向的距离来拟合标定数据

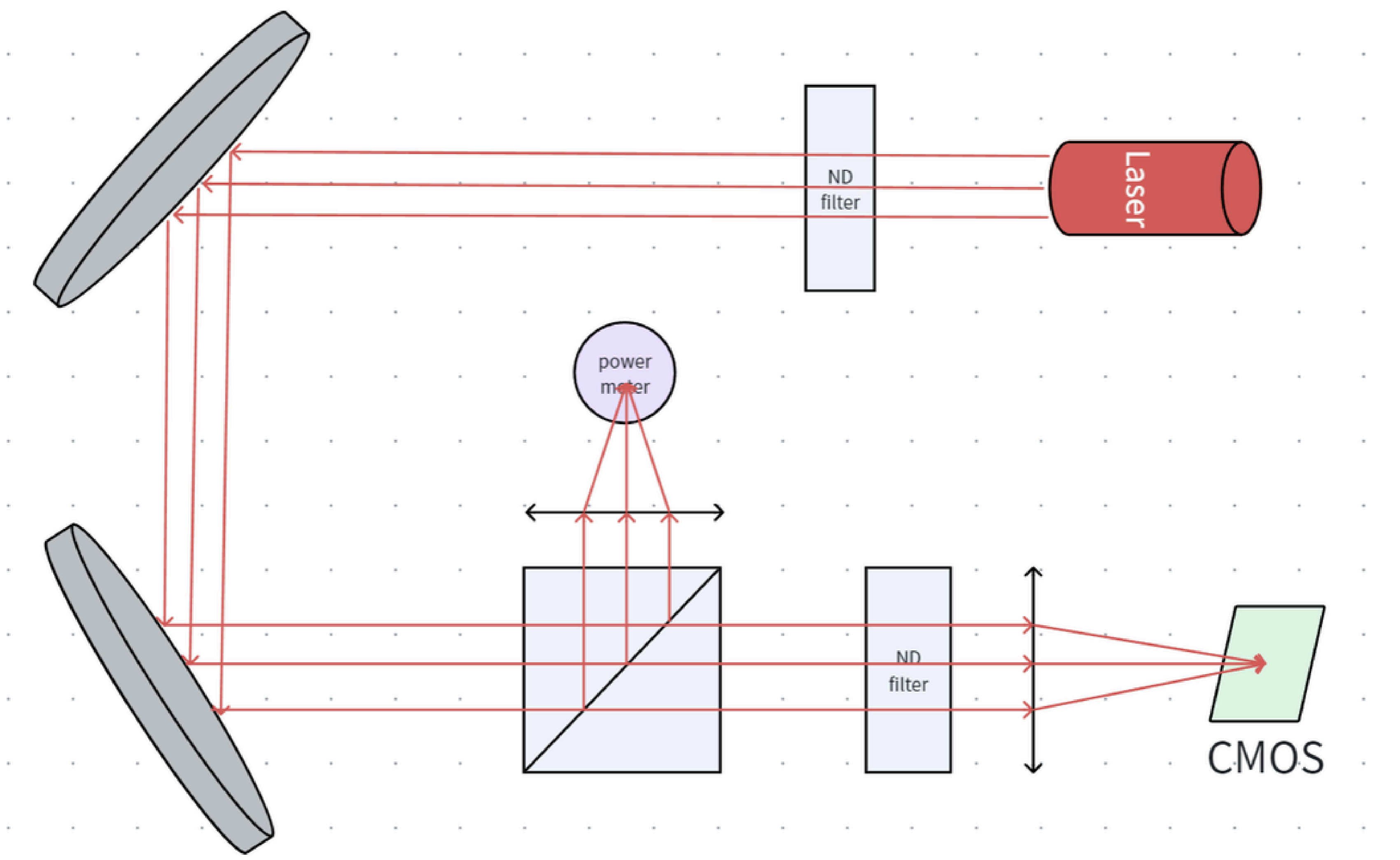
而确定Z方向上限制范围 $77.42^{+0.06}_{-0.3}\ mm$

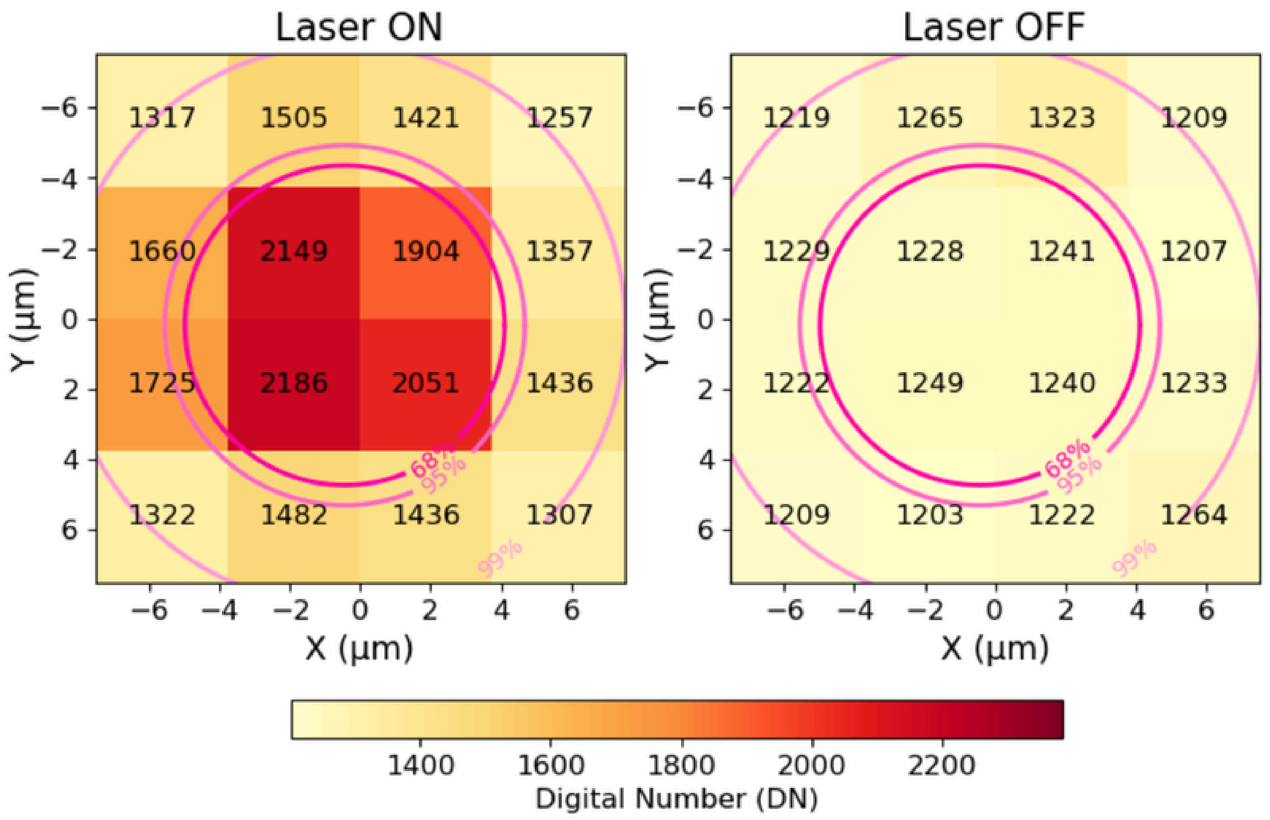




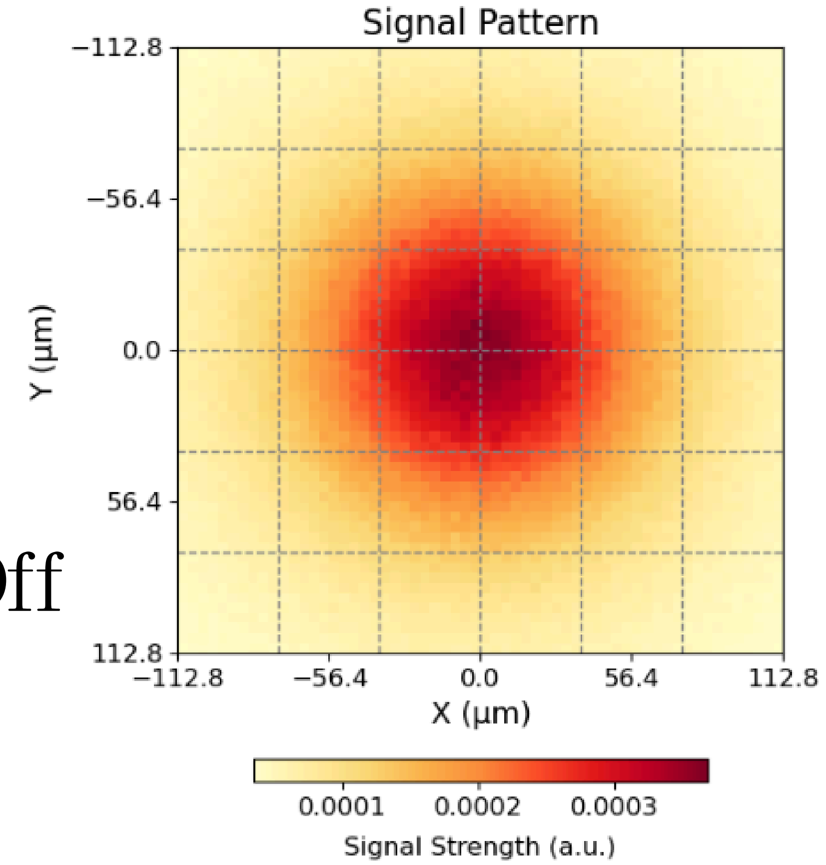


Calibration 3: Faint Laser Validation





标定得到系统探测效率：0.413



10^{-3} rad 发散角

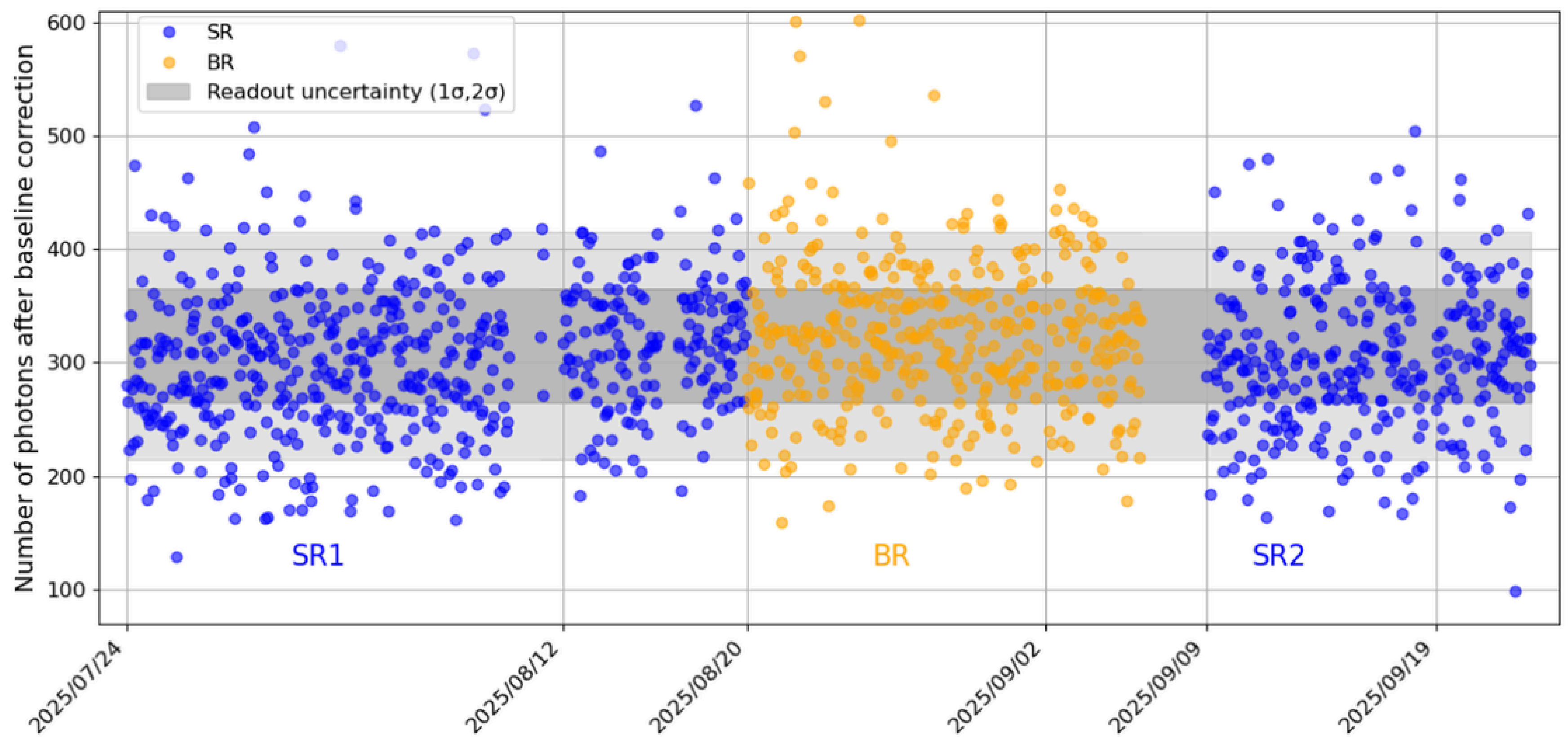
暗光子信号Pattern收集效率 ： 0.456

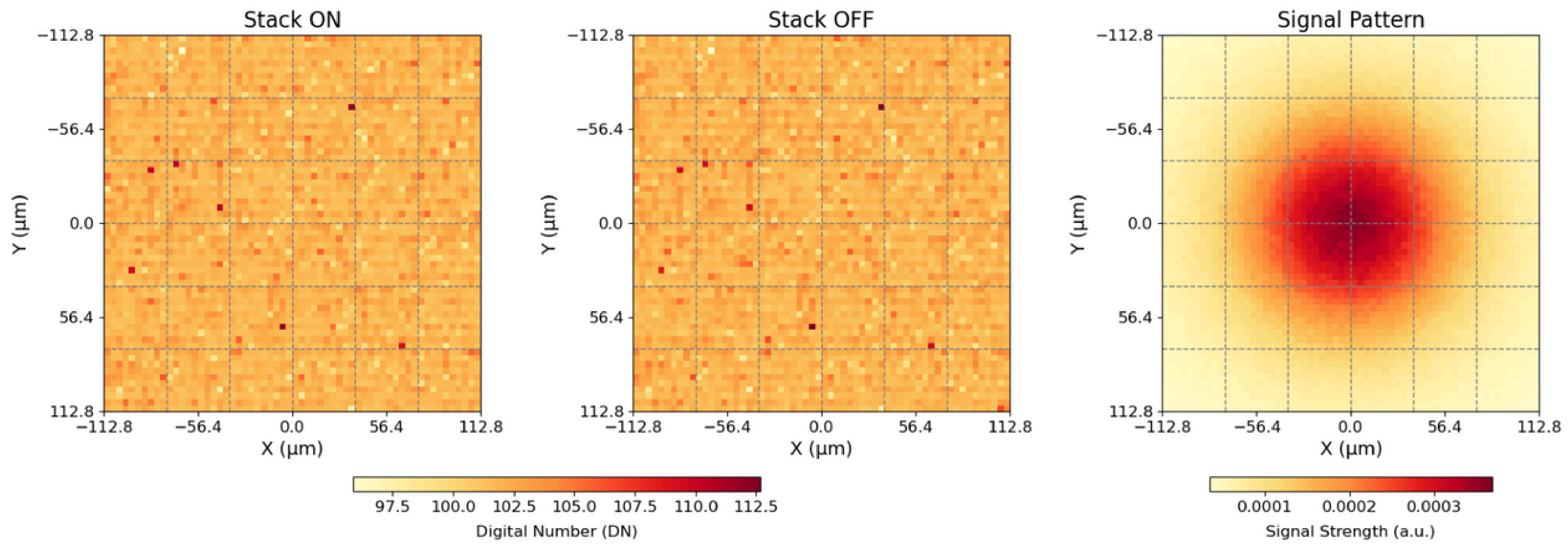
Setup: 1 hour x 12 x 2 组, 微弱激光 On / Off

使用微弱激光标定探测器系统的探测效率

总效率：0.413 x 0.456 = 0.188

Science Run & Background Run





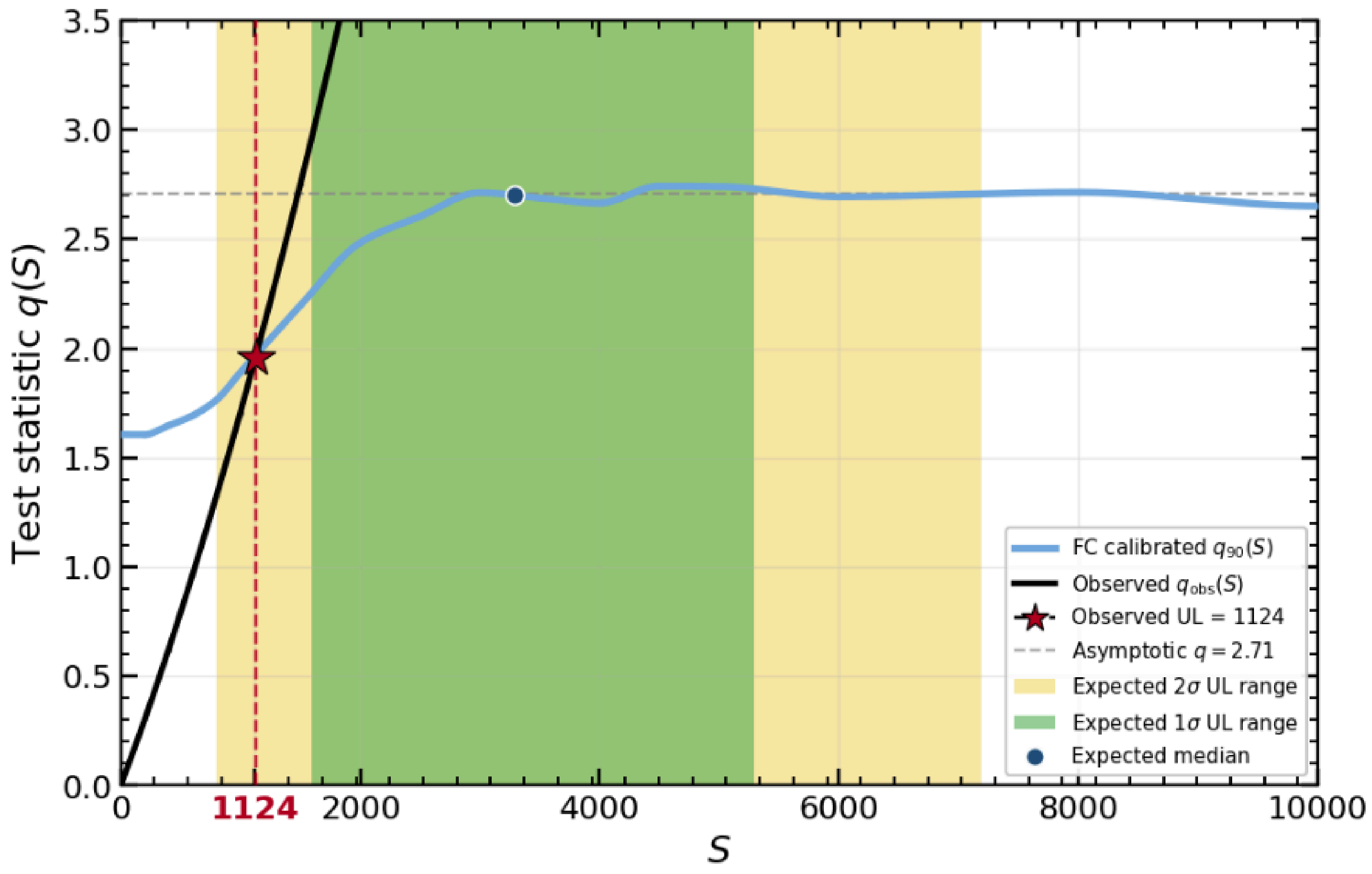
- ROI：60 x 60 像素区域
- Science Run：904 小时, 3600 s 一帧

  2025/07/24 – 2025/08/20 &

  2025/09/08 –2025/09/18
- Background Run：404 小时 , 3600 s 一帧

  2025/08/20 – 2025/09/06

Statistical Inference



基于 36 个宏像素的似然函数

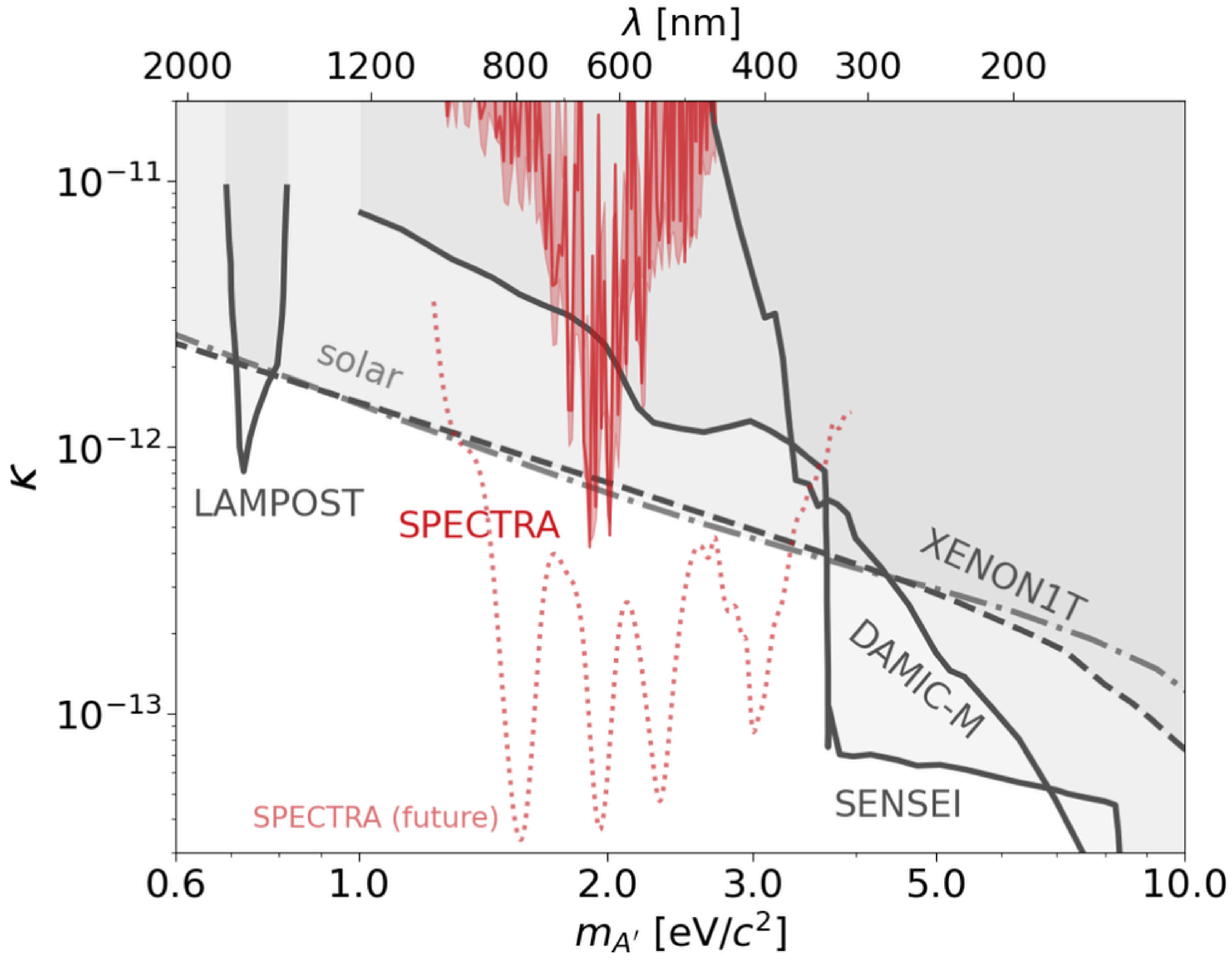
$$\mathcal{L}_m(S,z,\alpha) = \sum_{\lambda_{\rm on}=0}^{\infty} \mathrm{Pois}(\lambda_{\rm on} \mid \mu_{{\rm on},m})\,\mathcal{N}(e_{{\rm on},m} \mid \lambda_{\rm on}, \sigma^2_{{\rm on},m}) \times \sum_{\lambda_{\rm off}=0}^{\infty} \mathrm{Pois}(\lambda_{\rm off} \mid \mu_{{\rm off},m})\,\mathcal{N}(e_{{\rm off},m} \mid \lambda_{\rm off}, \sigma^2_{{\rm off},m})$$

$$\mathcal{L}(S,z,\alpha) = \prod_{m=1}^{36} \mathcal{L}_m(S,z,\alpha)$$

Feldman - Cousins 方法

- 对每个信号强度 S 生成 20,000 组 Toy-MCs，构建 90% 置信水平临界值。
- 生成 50,000 组仅背景 Toy-MCs，得到预期上限及其置信带。

Result & Outlook



$$N_\gamma = 19 \cdot \frac{\rho}{0.4\,\mathrm{GeV/cm^3}} \frac{2\,\mathrm{eV}}{m_{A'}} \left(\frac{\kappa}{10^{-12}}\right)^2 \frac{S}{4.9\,\mathrm{cm}^2} \cdot \epsilon\beta^2 \langle\cos^2\theta\rangle,$$

升级计划：

- 采用多个 2 英寸 stack 或啁啾 stack，提高信号转换强度并拓展暗光子质量覆盖范围。
- 延长单帧曝光时间，降低读出噪声对搜索灵敏度的影响。
- 将更多像素纳入统计推断，提高 ROI 信号收集效率和信号背景判别能力。

谢谢！

Thank you!

Back Up-Timeline

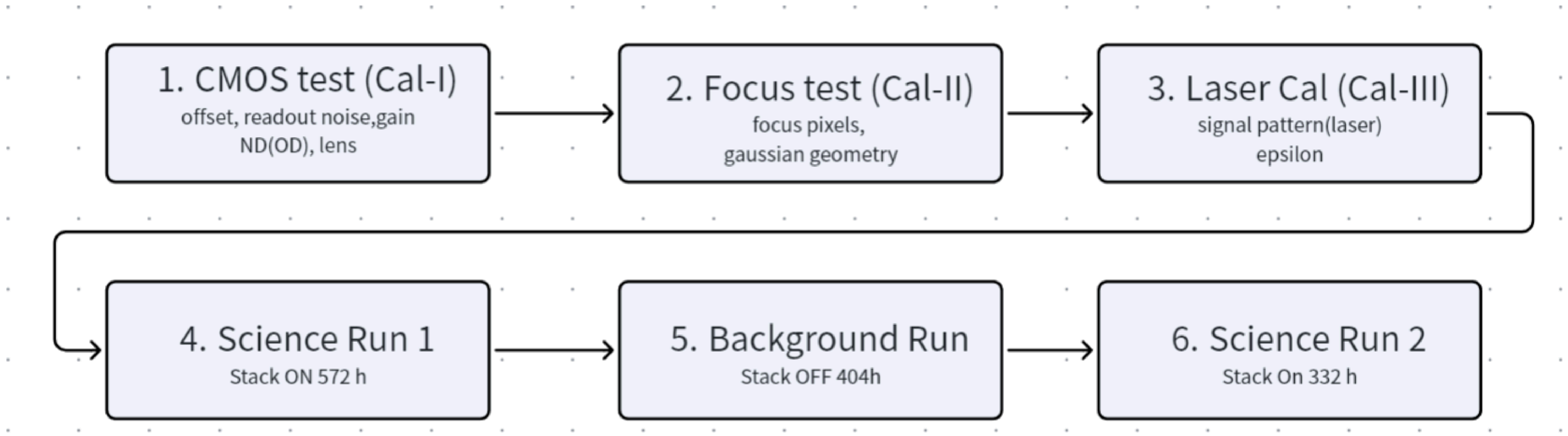


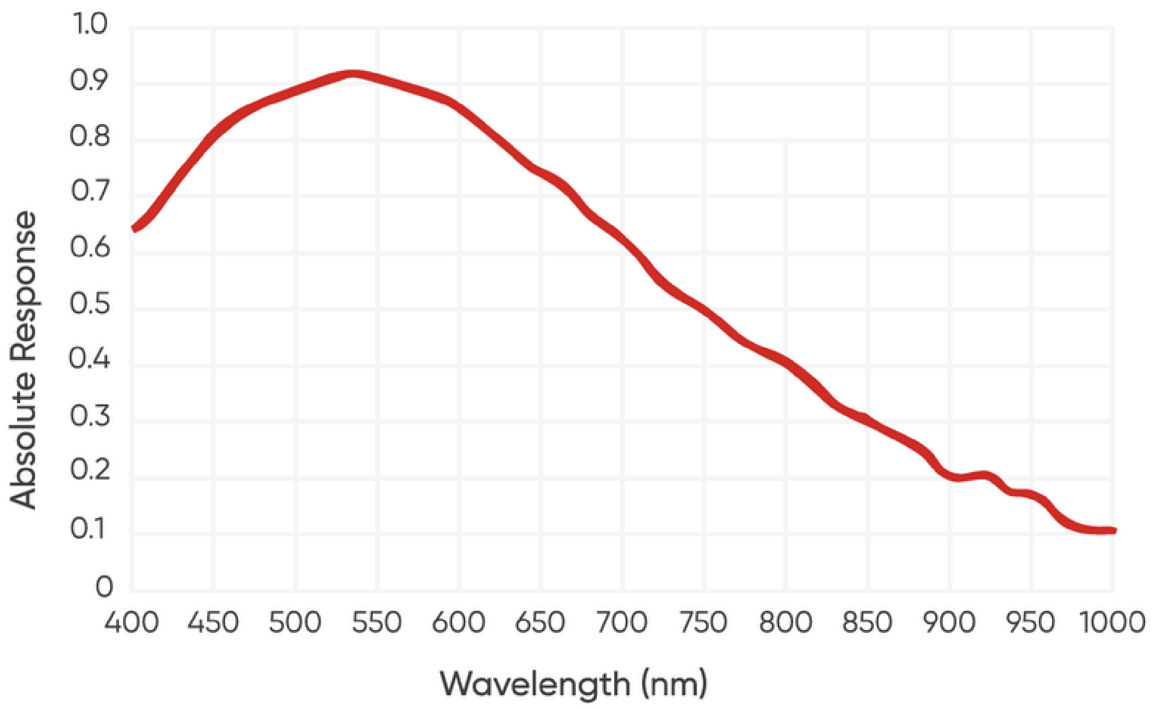
TABLE I. Summary of calibration data sets.

	Cal-I	**Cal-II**	**Cal-III**
Duration	1 ms×5000×4 mult.	1 s×10	>24 h
Optics	ND-only	ND+Stack+Lens	ND+Stack+Lens
Atten.	Tunable	Moderate	>16 OD
Output	gain/offset, σ_{read}	focus, geometry	$\epsilon(\omega_0)$, test signal
Used in	DN→ e^- model	template & MC	Eq. (2) norm.

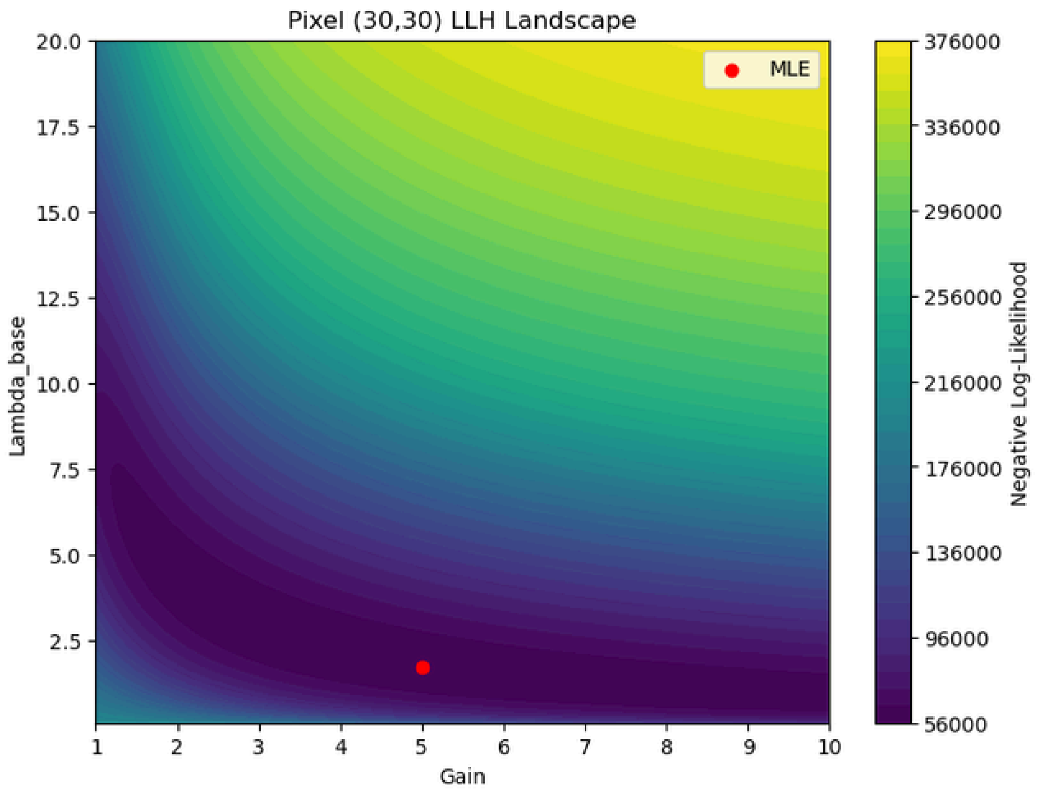
TABLE II. Summary of data sets used in the analysis.

	SR1	**BR**	**SR2**
Configuration	Stack on	Stack off	Stack on
Period (2025)	Jul. 24–Aug. 20	Aug. 20–Sep. 6	Sep. 8–Sep. 18
Exposure	572 h	404 h	332 h
Frame time	3600 s	3600 s	3600 s
Purpose	DPDM Search	Noise constraint	DPDM Search

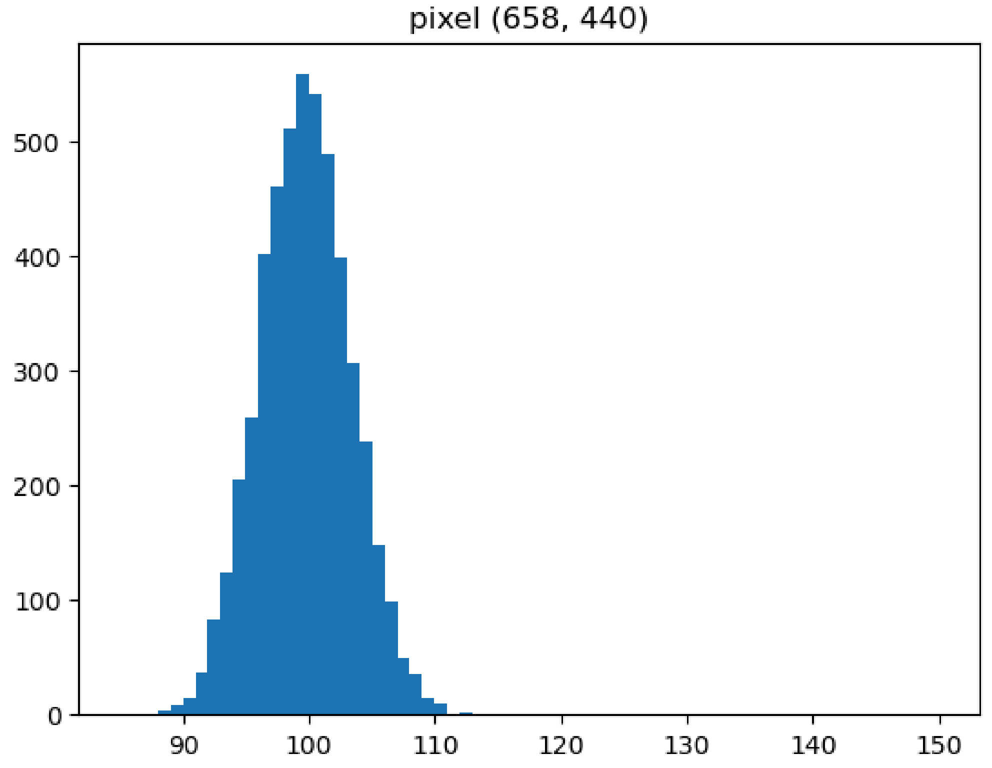
Back Up-CMOS



第三方测量的量子效率（QE）参数



激光标定中2D 似然函数拟合得到Gain和探测到的光子数



短曝光中单像素的数值分布

Back Up-Statistic

$$N_\gamma = 19 \cdot \frac{\rho}{0.4\,\mathrm{GeV/cm^3}} \frac{2\,\mathrm{eV}}{m_{A'}} \left(\frac{\kappa}{10^{-12}}\right)^2 \frac{S}{4.9\,\mathrm{cm}^2} \cdot \epsilon\beta^2 \langle \cos^2\theta \rangle,$$

$$e_{\mathrm{on},m} = \sum_{i\in\mathcal{P}_m} \frac{DN_i^{\mathrm{on}} - F_{\mathrm{on}} N_{0,i}}{g_i},$$

$$e_{\mathrm{off},m} = \sum_{i\in\mathcal{P}_m} \frac{DN_i^{\mathrm{off}} - F_{\mathrm{off}} N_{0,i}}{g_i}.$$

$$\mu_{\mathrm{on},m}(S,z,\alpha) = S\,\epsilon(z)\,p_m(z) + \frac{F_{\mathrm{on}}}{F_{\mathrm{off}}}\alpha B_m + F_{\mathrm{on}}\,\hat{\delta}_{\mathrm{DN}} \sum_{i\in\mathcal{P}_m} \frac{1}{g_i},$$

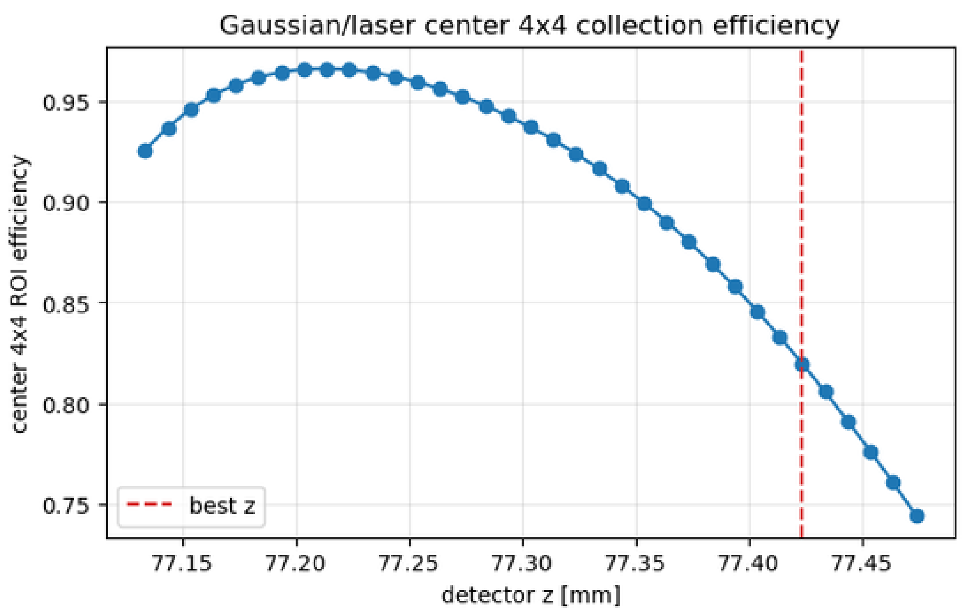
$$\mu_{\mathrm{off},m}(\alpha) = \alpha B_m.$$

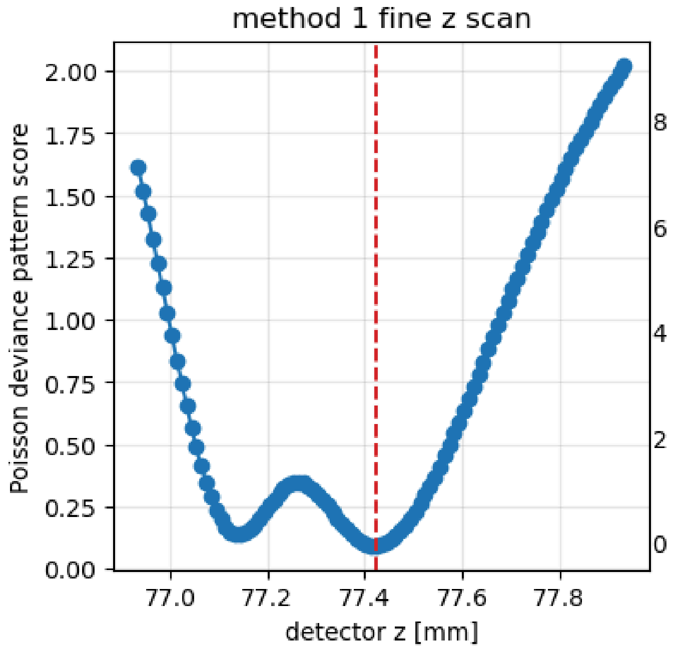
$$\sigma^2_{\mathrm{on},m} = F_{\mathrm{on}} \sum_{i\in\mathcal{P}_m} \sigma^2_{\mathrm{read},i},$$

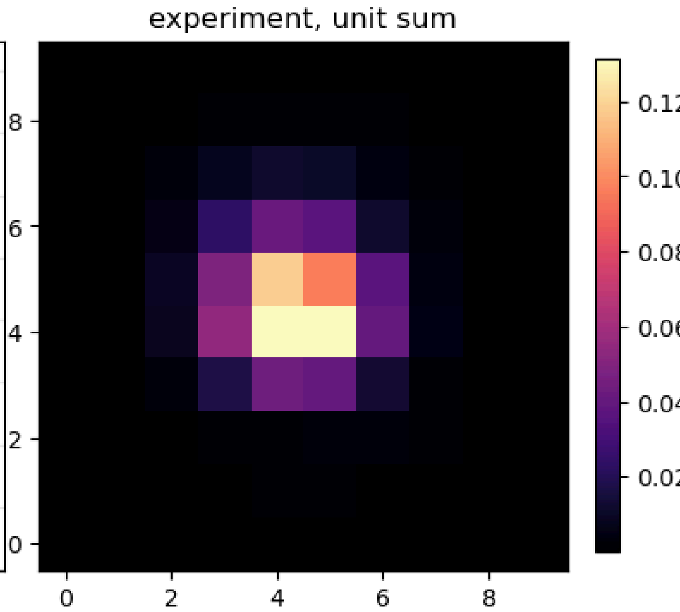
$$\sigma^2_{\mathrm{off},m} = F_{\mathrm{off}} \sum_{i\in\mathcal{P}_m} \sigma^2_{\mathrm{read},i}.$$

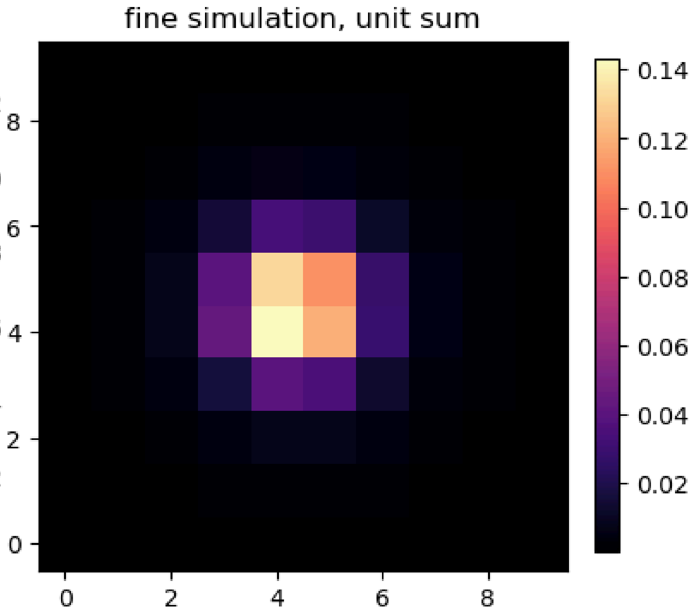
Back Up-Simulation

高斯激光









暗光子信号