西湖大學 WESTLAKE UNIVERSITY

SPECTRA暗光子实验

李思根
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第十二届高能物理分会(广州)

Principle

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

考虑暗光子作为暗物质, 存在一个振荡的暗光子背景场

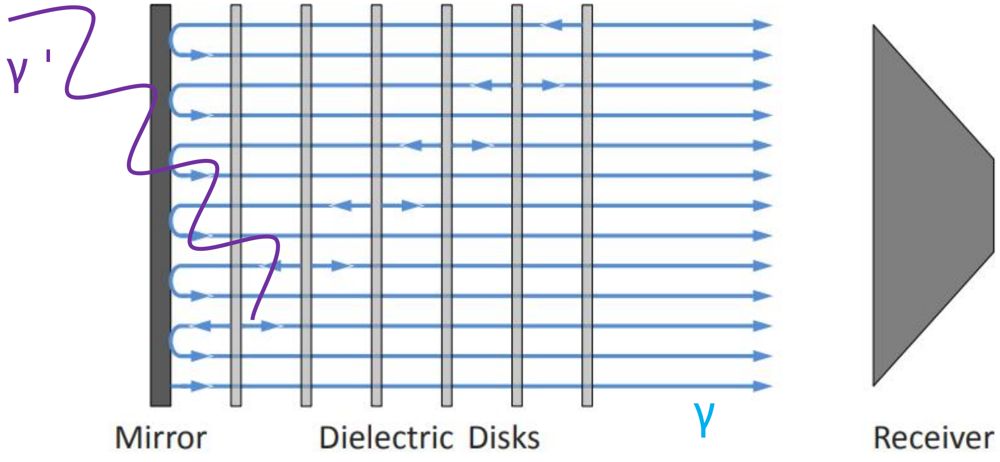
eV质量暗光子 -> 可见光波段

可观测波段探测挑战:

1. 信号共振增强
2. 足够低的光子噪声

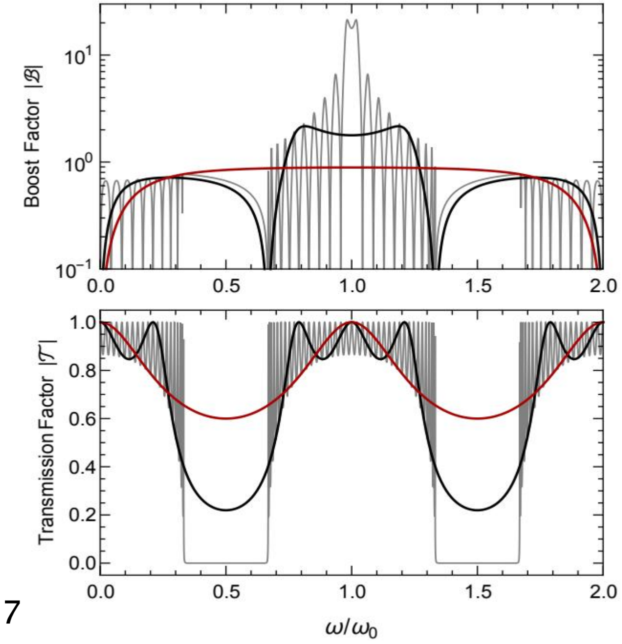
$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0} + \kappa\left(\frac{m_{A'}}{\hbar c}\right)^2 \phi'_{\rm DP},$$
$$\nabla \cdot \mathbf{B} = 0,$$
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t},$$
$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \frac{1}{c^2}\frac{\partial \mathbf{E}}{\partial t} + \kappa\left(\frac{m_{A'}}{\hbar c}\right)^2 \mathbf{A}'_{\rm DP}.$$

麦克斯韦方程组-DP修正



JCAP 1701:061,2017

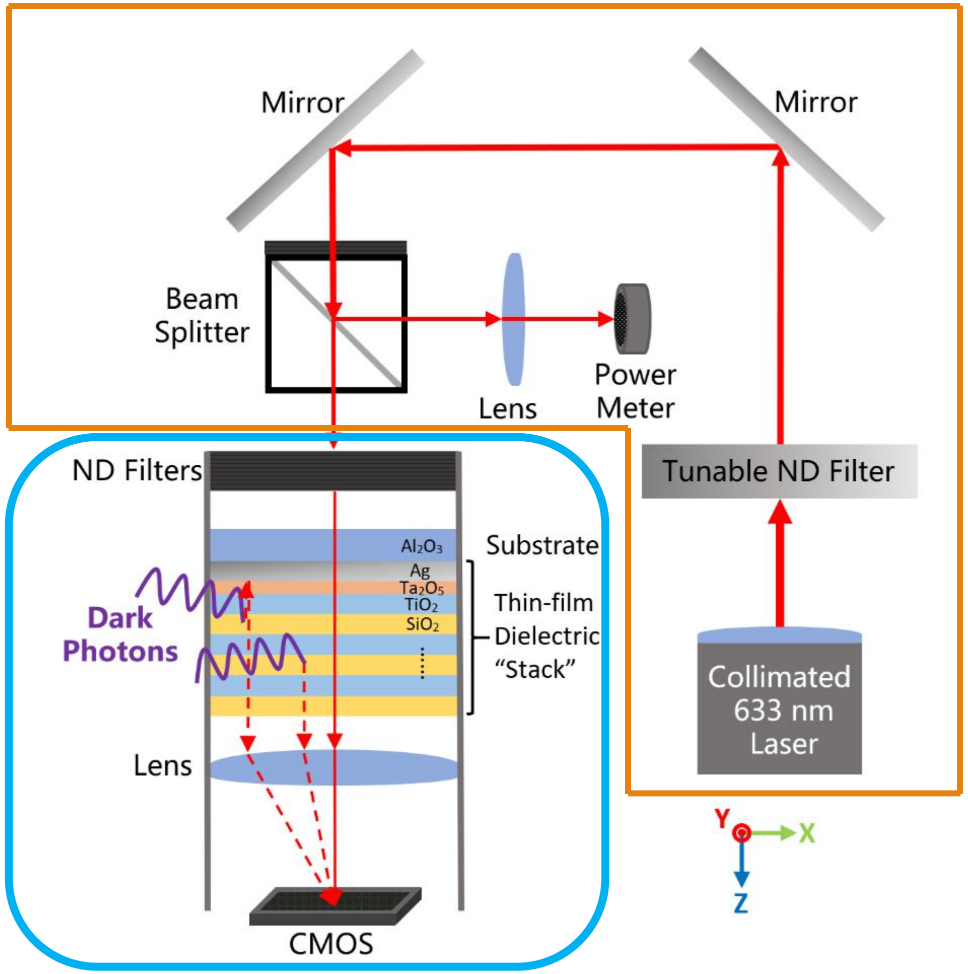
$$\text{Signal rate} \propto \kappa^2 \times |\beta|^2 \times \text{efficiency}$$



N = 1
N = 2
N = 20

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

SPECTRA Prototype



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

主体部分: Haloscope

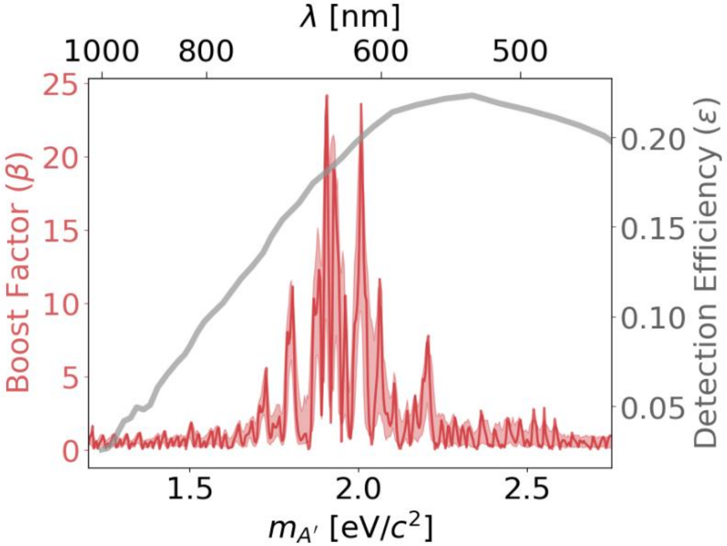
DP到可见光子的转换 (Stack)
信号聚焦 (Lens)
信号探测 (CMOS)

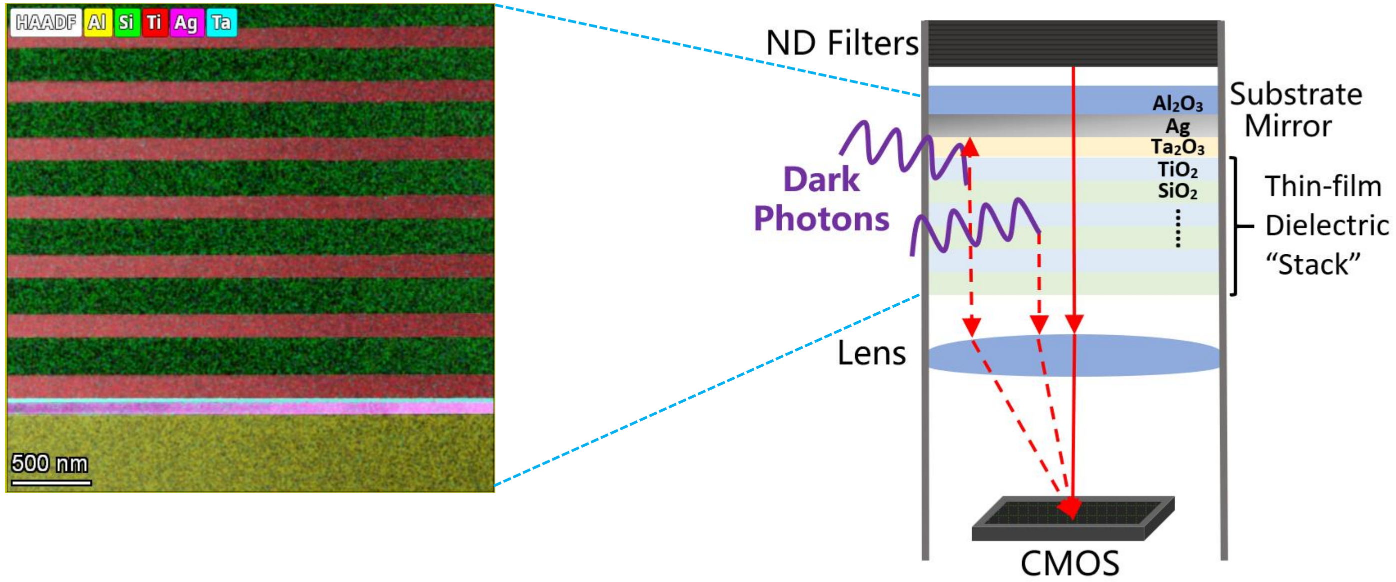
标定部分:

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

Haloscope

Stack: 技术实现: 离子束溅射沉积(IBSD) + TEM表征
尺寸: D = 1-inch (4.9 cm^2), 47 pairs (TiO_2 & SiO_2)



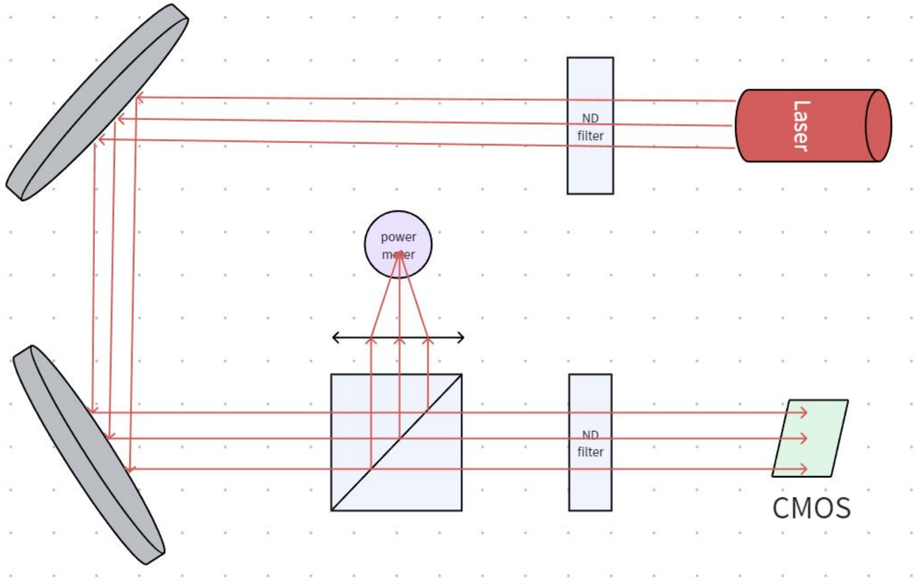


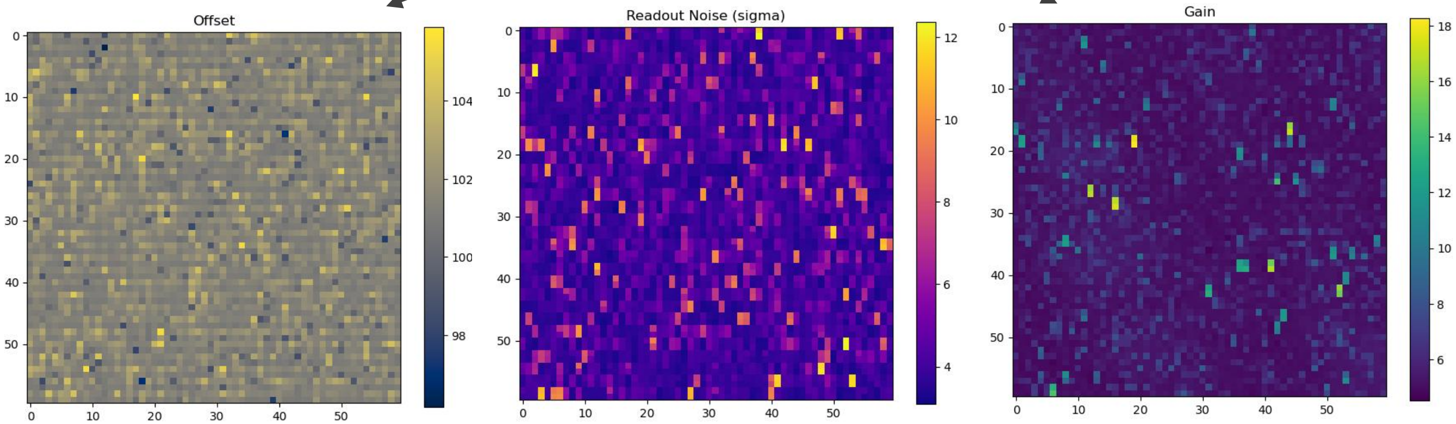
Lens: 接近衍射极限的最佳外形透镜

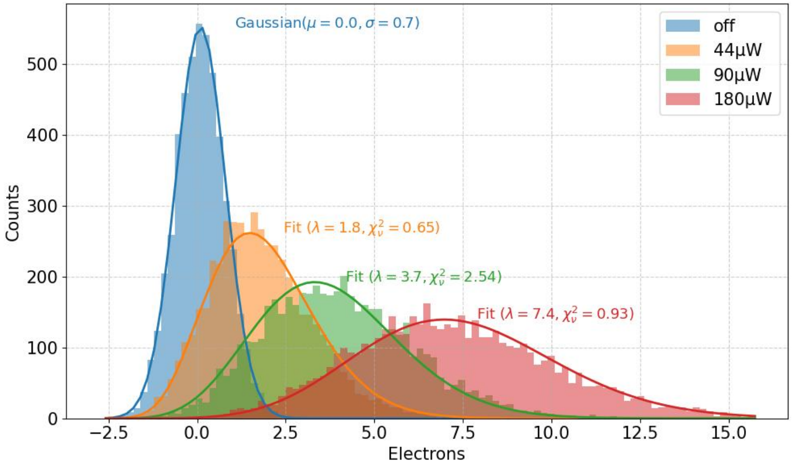
CMOS: 暗计数率~ 10^{-5} e$^-$/s/pixel; 读出噪声 ~ 0.8 e$^-$/frame/pixel
像素尺寸: 3.76*3.76 μm^2; 3000*3000 pixels

Calibration 1: CMOS Parameters

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





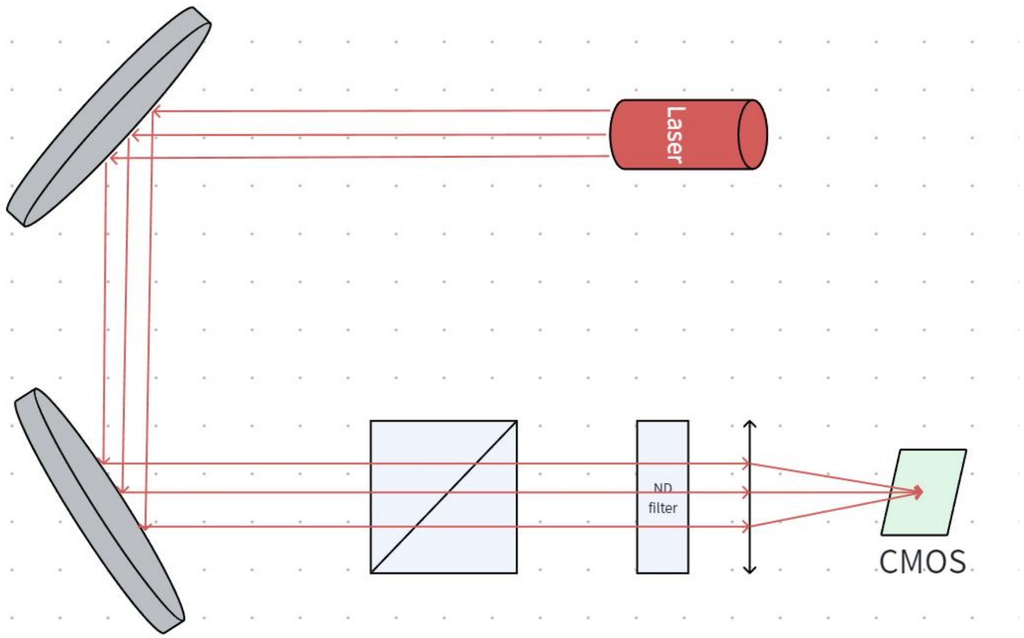


某选定像素的DN统计图示意

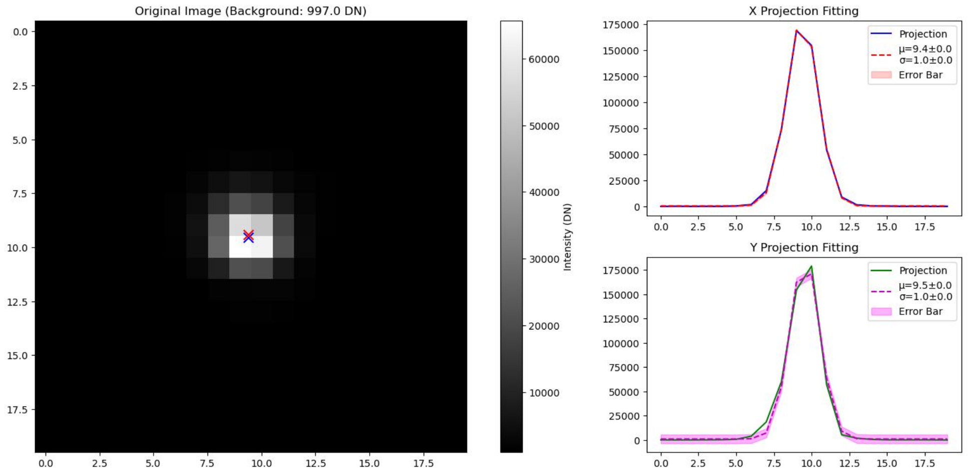
Setup: 1 ms* 5000 帧* 4 组, 分别为0x, 1x, 2x, 4x 激光强度

标定相机参数: offset, readout noise, gain

Calibration 2: Focus

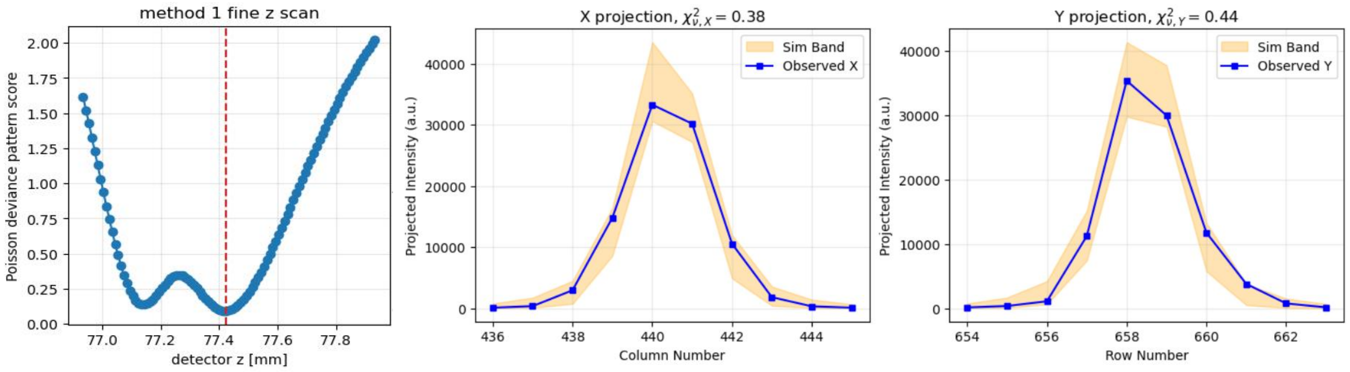


[X, Y]: 二维高斯拟合确定水平位置



Z: LLH确定CMOS与Lens距离以及对应不确定度

确定Pattern变化范围

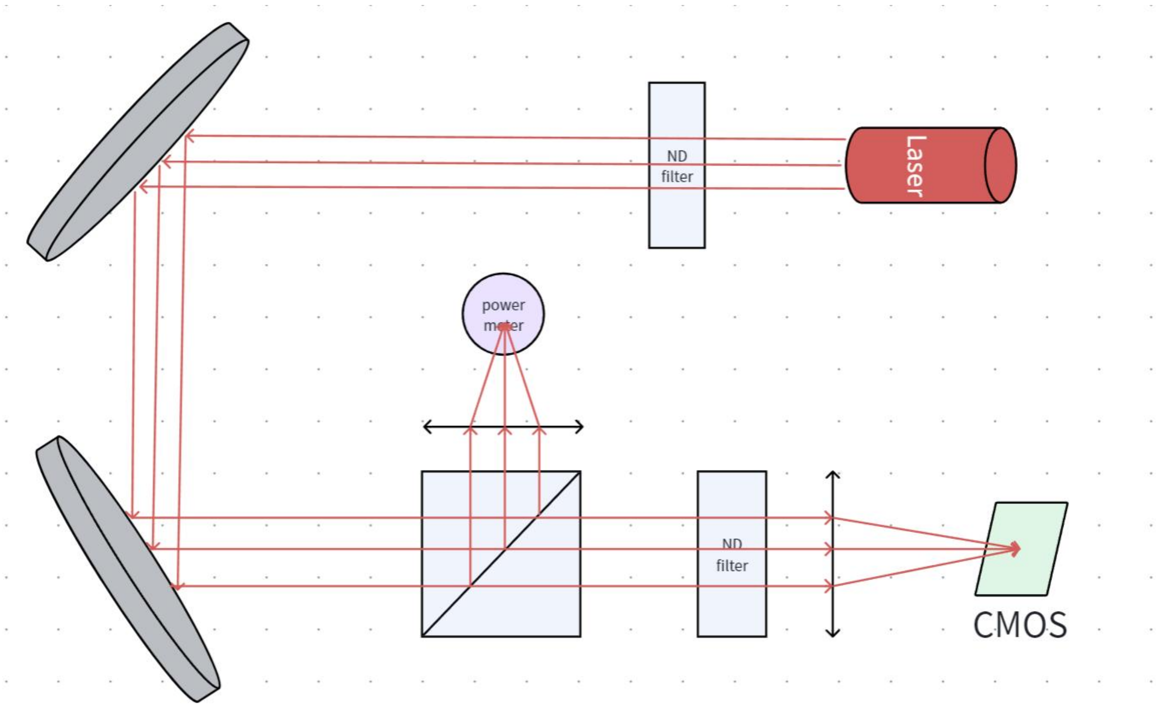


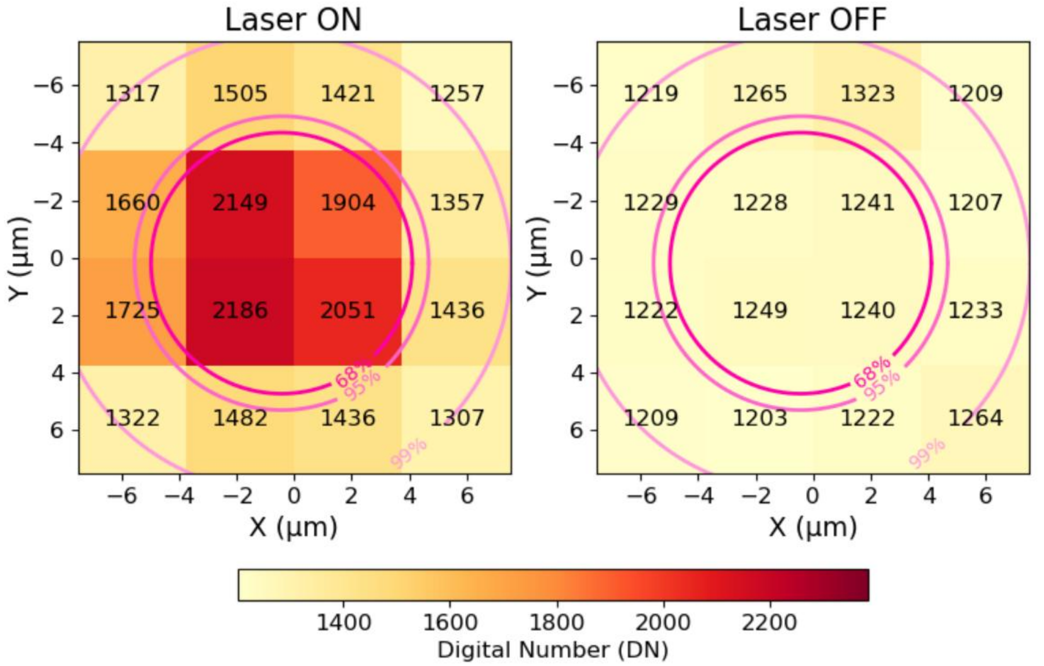
Setup: 1s * 10 帧，较强激光

ROI: [657:661,439:443] pixel matrix

Z distance: $77.42^{+0.06}_{-0.30}$ mm

Calibration 3: Faint Laser





Setup: 1 hour * 12 帧 * 2 组，Laser On/Off

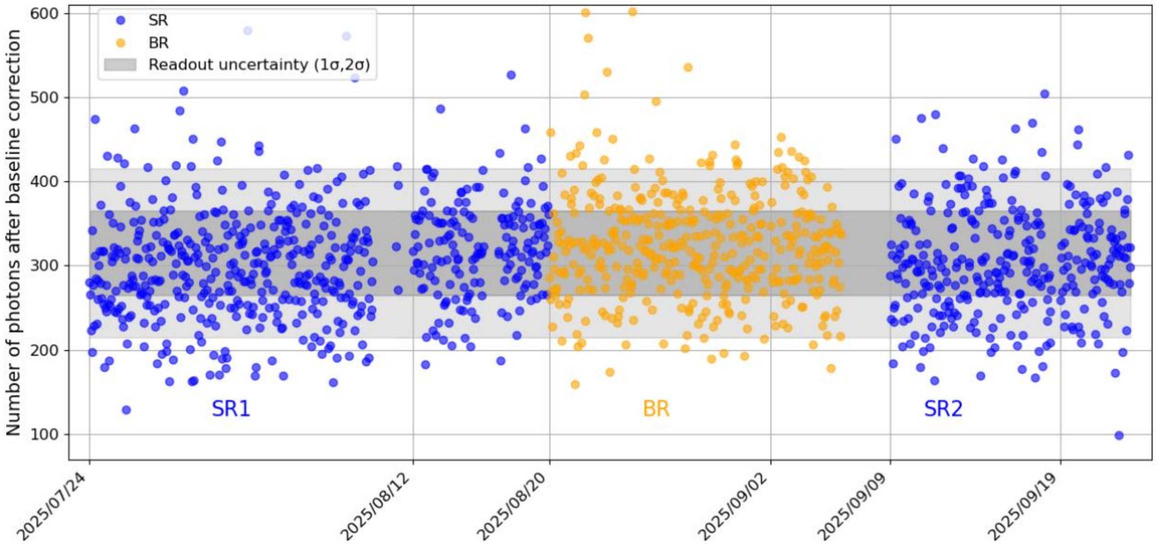
使用微弱激光标定探测器探测能力及效率

标定得到探测效率: 0.413

模拟Pattern收集效率: 0.456

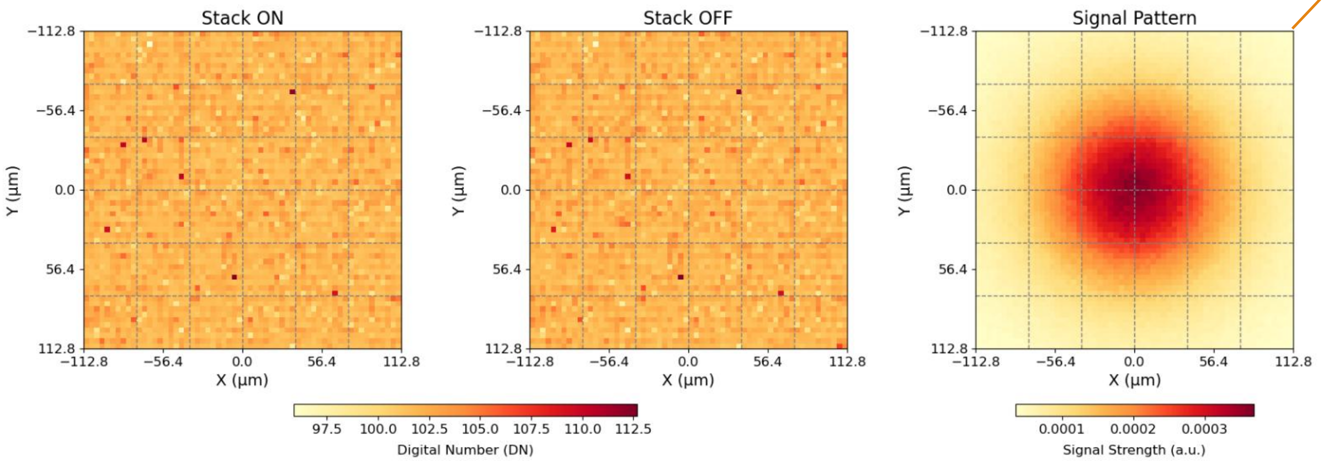
总效率: 0.413*0.456 = 0.188

Science Run & Background Run



	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

$\theta \sim v_{DM}/c \sim 10^{-3}$ ⇨ ROI: 60*60 像素区域



Likelihood:

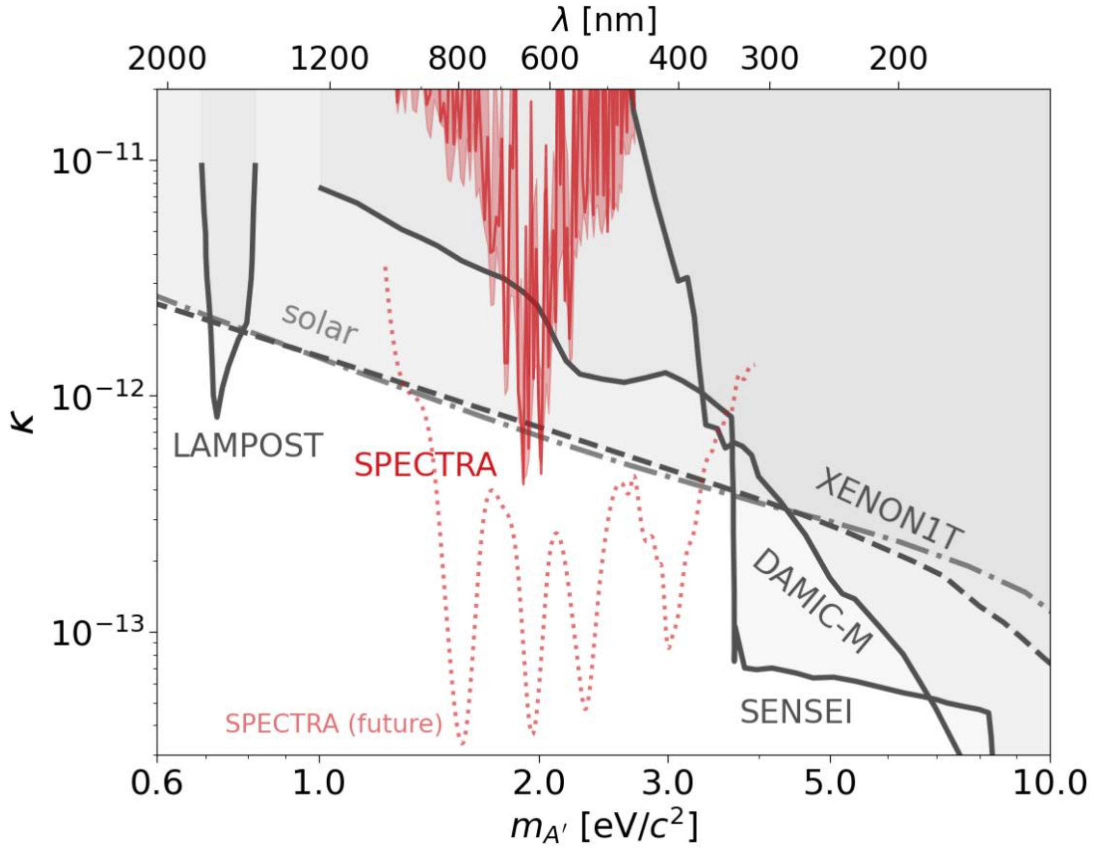
$$\mathcal{L}_m(S,z,\alpha) = \sum_{\lambda_{\rm on}=0}^{\infty} \mathrm{Pois}(\lambda_{\rm on} \mid \mu_{{\rm on},m}) \mathcal{N}(e_{{\rm on},m} \mid \lambda_{\rm on}, \sigma^2_{{\rm on},m}) \times \sum_{\lambda_{\rm off}=0}^{\infty} \mathrm{Pois}(\lambda_{\rm off} \mid \mu_{{\rm off},m}) \mathcal{N}(e_{{\rm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

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

90% 置信区间观测光子数上限N_γ: **1124**

First Result

arXiv:2607.03240



Future:

- **Stack:**
  尺寸升级: (1-inch > 2-inch) √
  多Stack: 增强信号以及谱分析信息
  Chirp-stack: 宽频响应
- **探测器端:**
  降低读出噪声(0.8 > 0.3 e^-) √
  像素尺寸升级: 3.76 > 10 μm
  理想效率QE (~80%)
- **曝光时长:**
  ~3月 Stack On&Off

Thanks

Back Up-Timeline

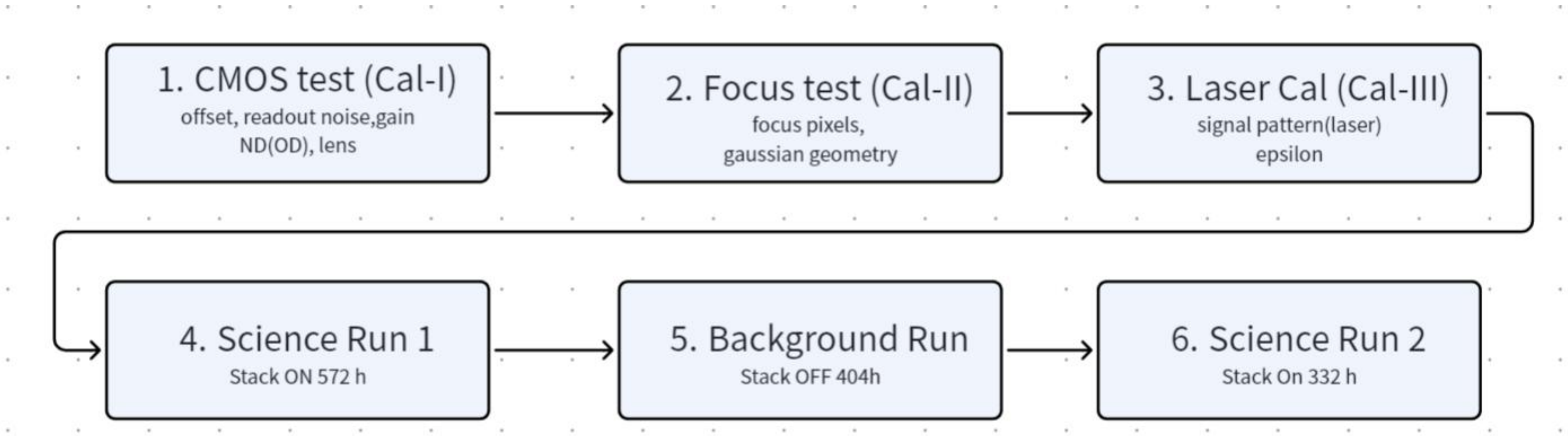


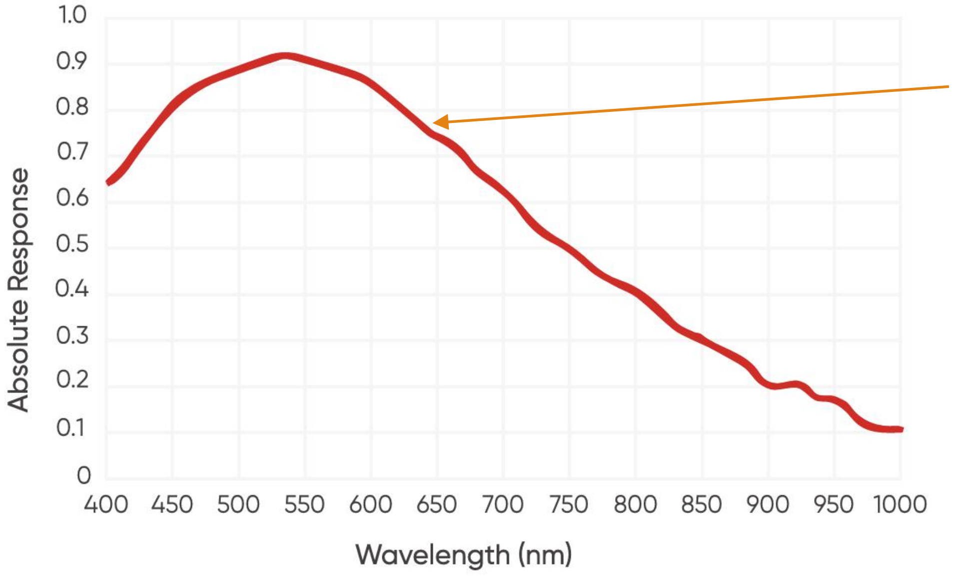
TABLE I. Summary of calibration data sets.

	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, $\sigma_{\rm read}$	focus, geometry	$\epsilon(\omega_0)$, test signal
Used in	DN→ e^- model	template & MC	Eq. (2) norm.

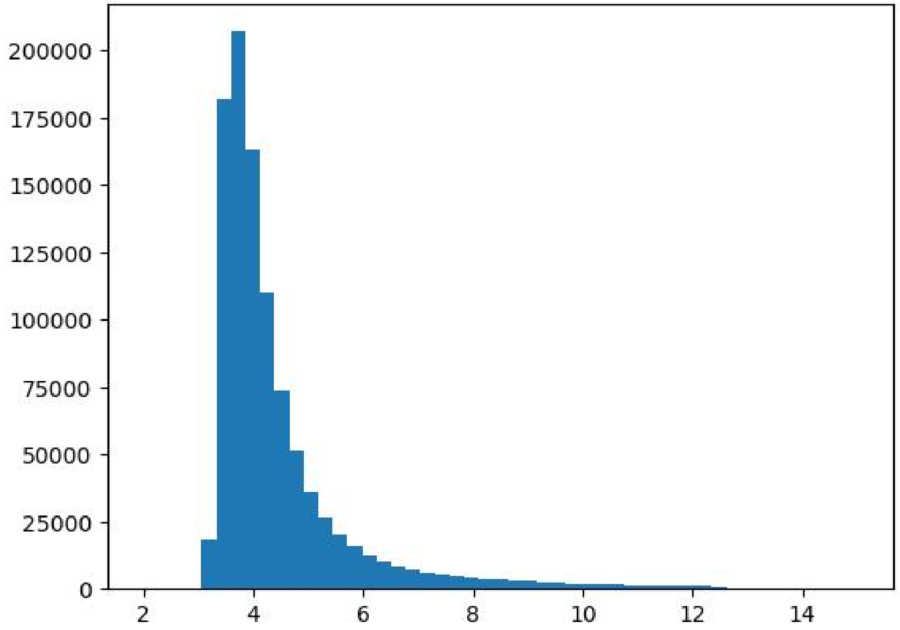
TABLE II. Summary of data sets used in the analysis.

	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

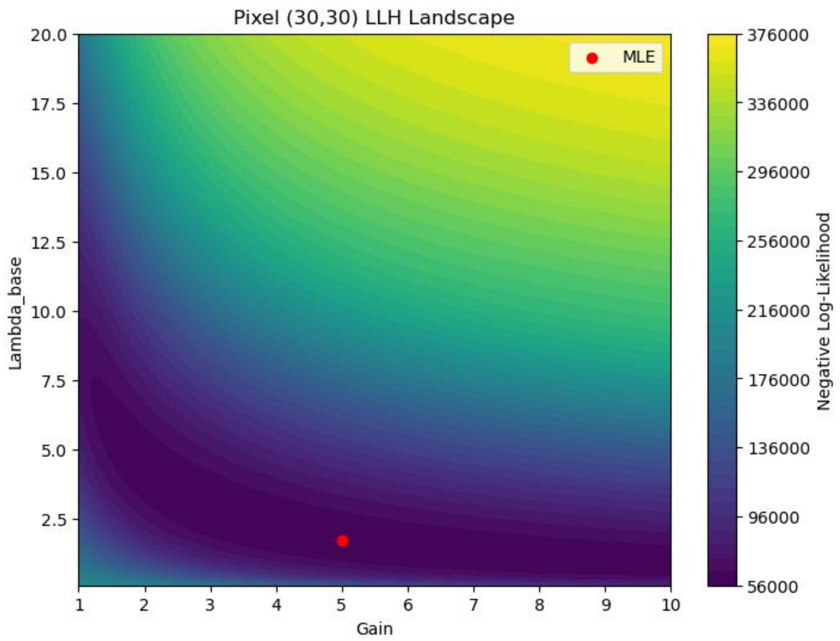


QE from the camera manual

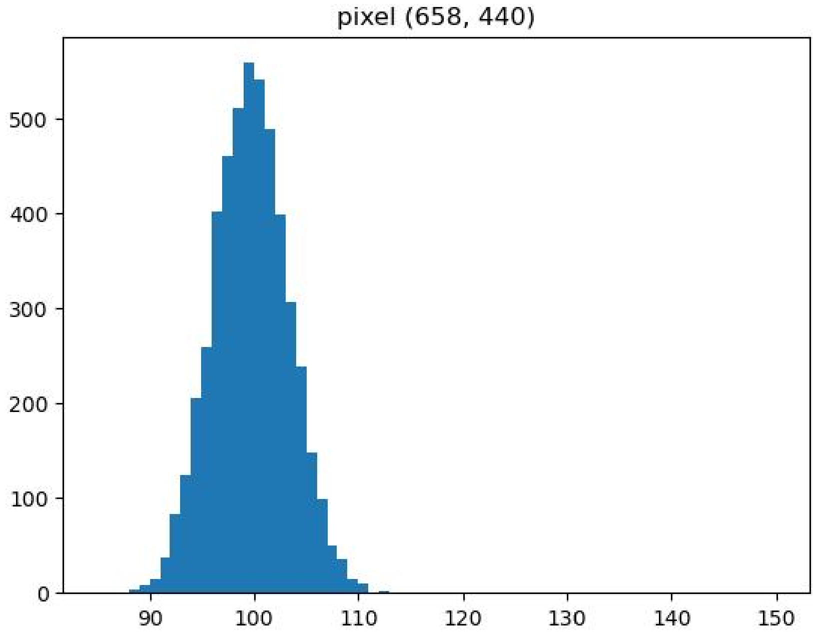


Readout noise(in DN unit) distribution

Back Up-CMOS model

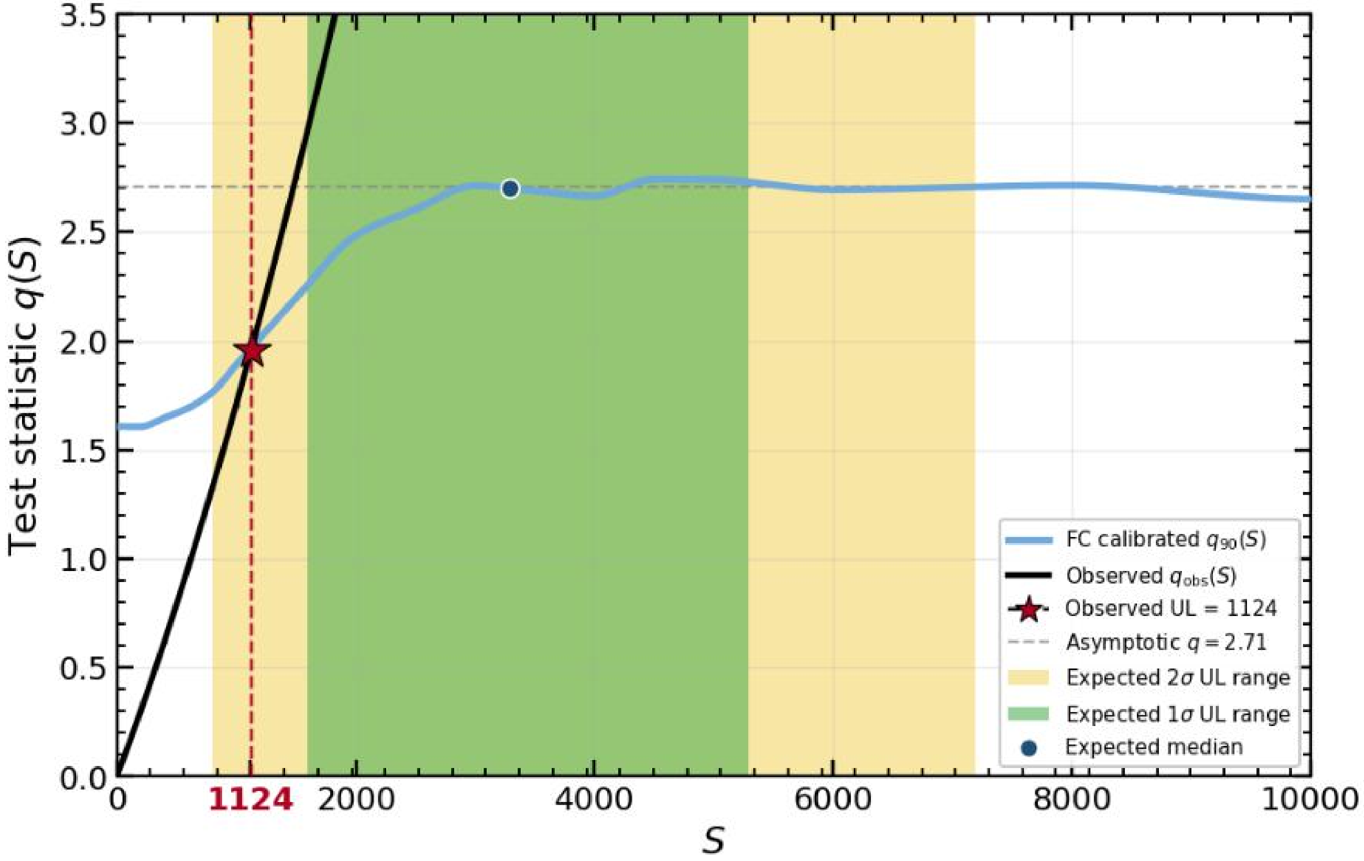


2D likelihood to get gain and lambda(photon number)



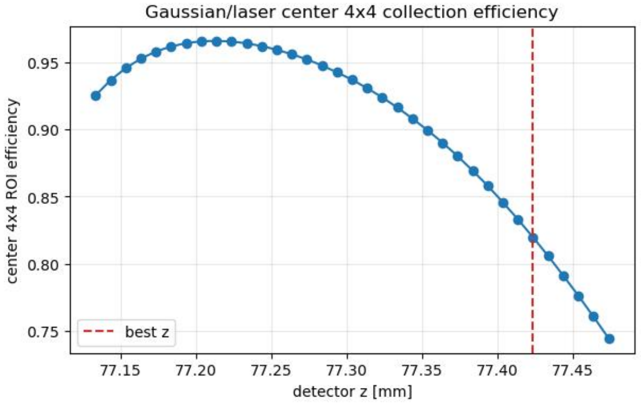
DN distribution for a single pixel with short exposure at dark field

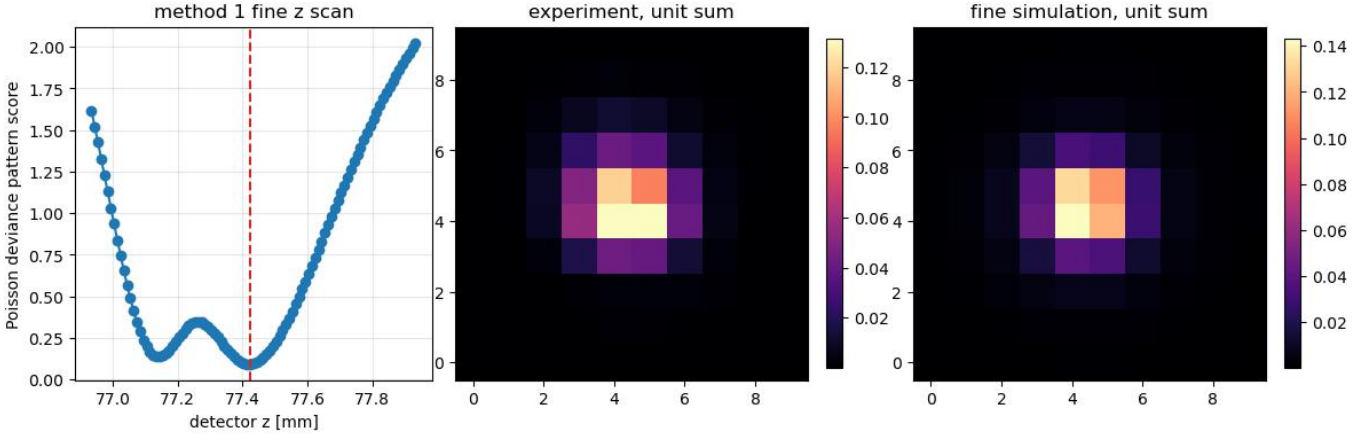
Back Up-Statistic



Back Up-Simulation

Gaussian Laser:





DP Signal: