

Direct observation of the Migdal effect induced by neutron bombardment

米格达尔(Migdal)效应的直接观测

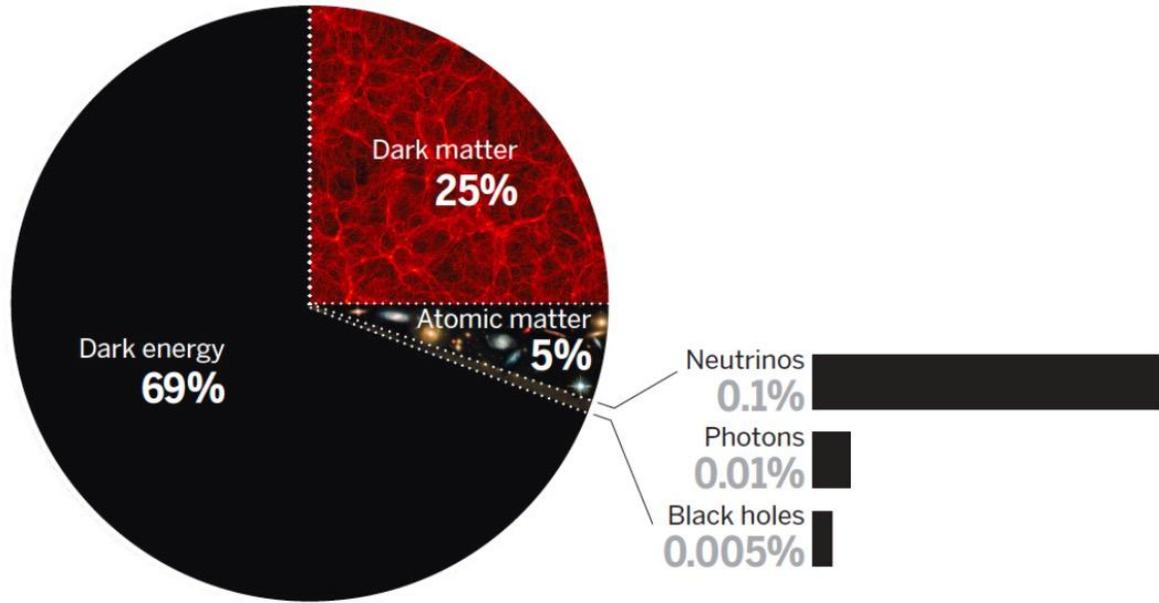


刘倩 (代表 MARVEL 合作组团队)

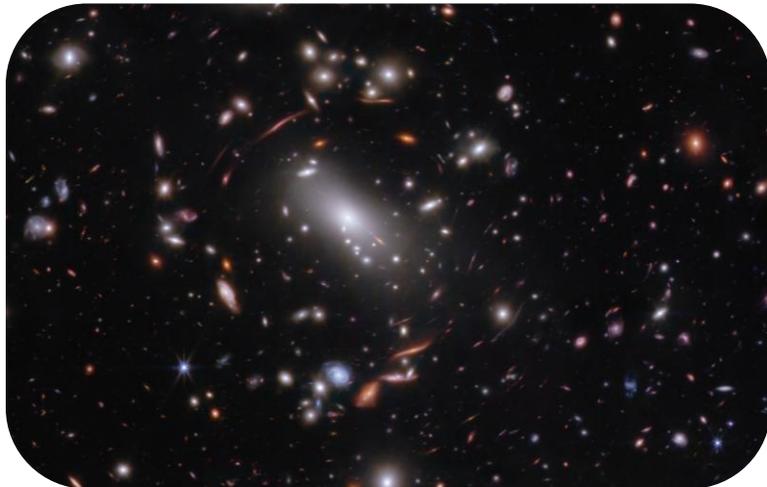
Migdal pRocess Validation by nEutruaL scattering (中性散射中的Migdal过程验证)

中国科学院大学

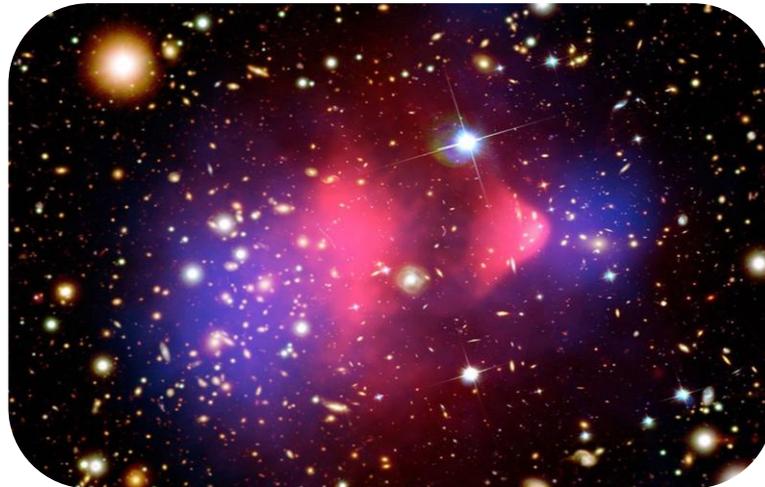




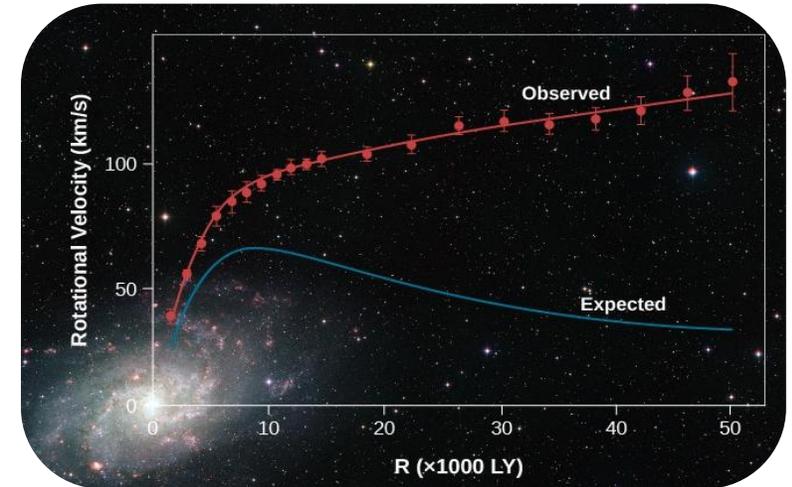
- Dark matter makes up most of the mass in galaxies and galaxy clusters.
- Current evidence comes solely from gravitational interaction.



Gravitational Lens

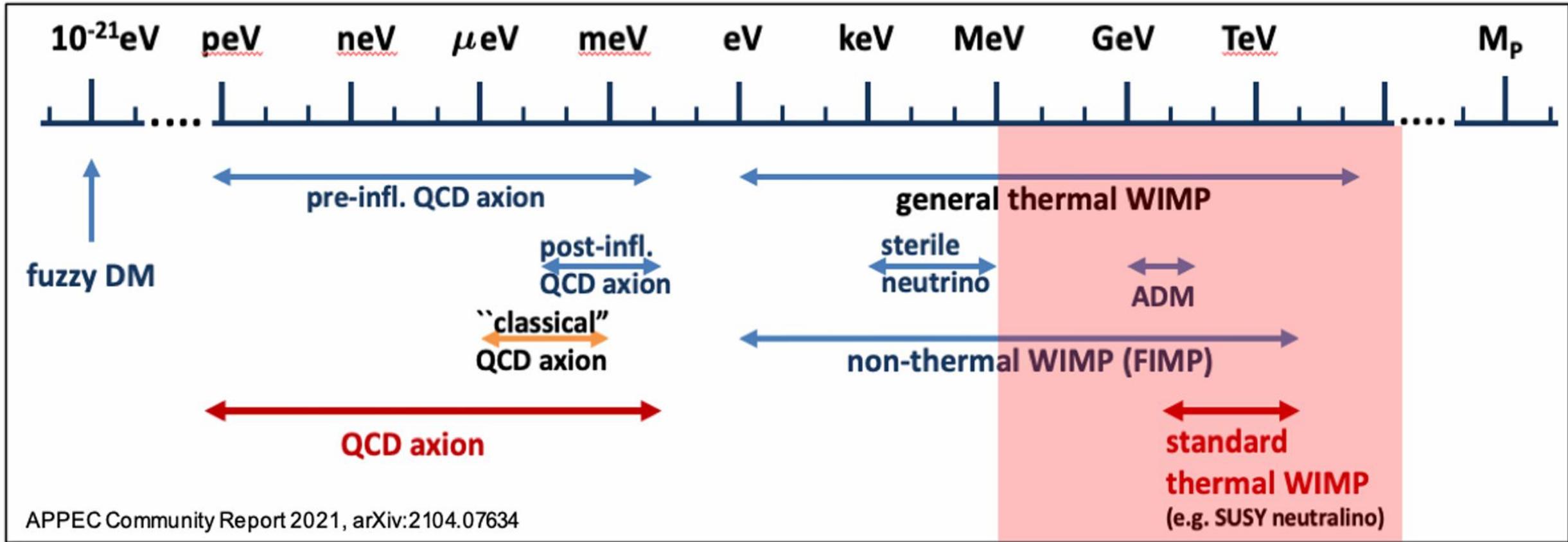


Galaxy mergers



Galactic rotation curve

- Weakly interacting massive particle



Dark matter experiments

- Look for annihilation products of dark matter collisions
- Space and land based telescopes
- Typically look in “boosted” signal area (sun or gravitational well where DM collects)



- * Dark matter scattering with nuclei in target: **billiard ball collision**
- * High mass, low event rate experiments



CDMS

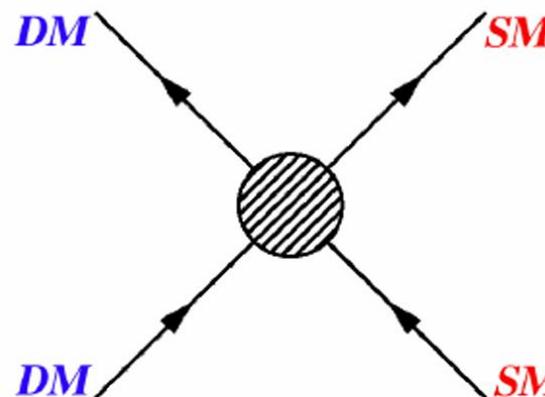


LZ

thermal freeze-out (early Univ.)
indirect detection (now)

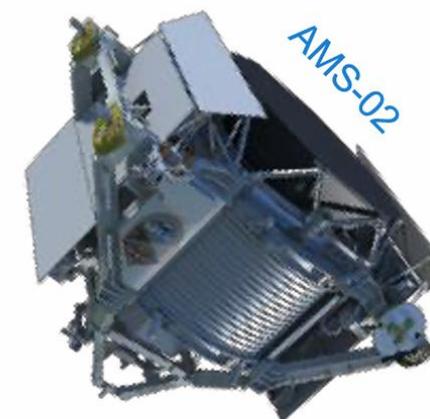


direct detection



production at colliders

- Produce new particles in high energy collisions



CMS/ATLAS



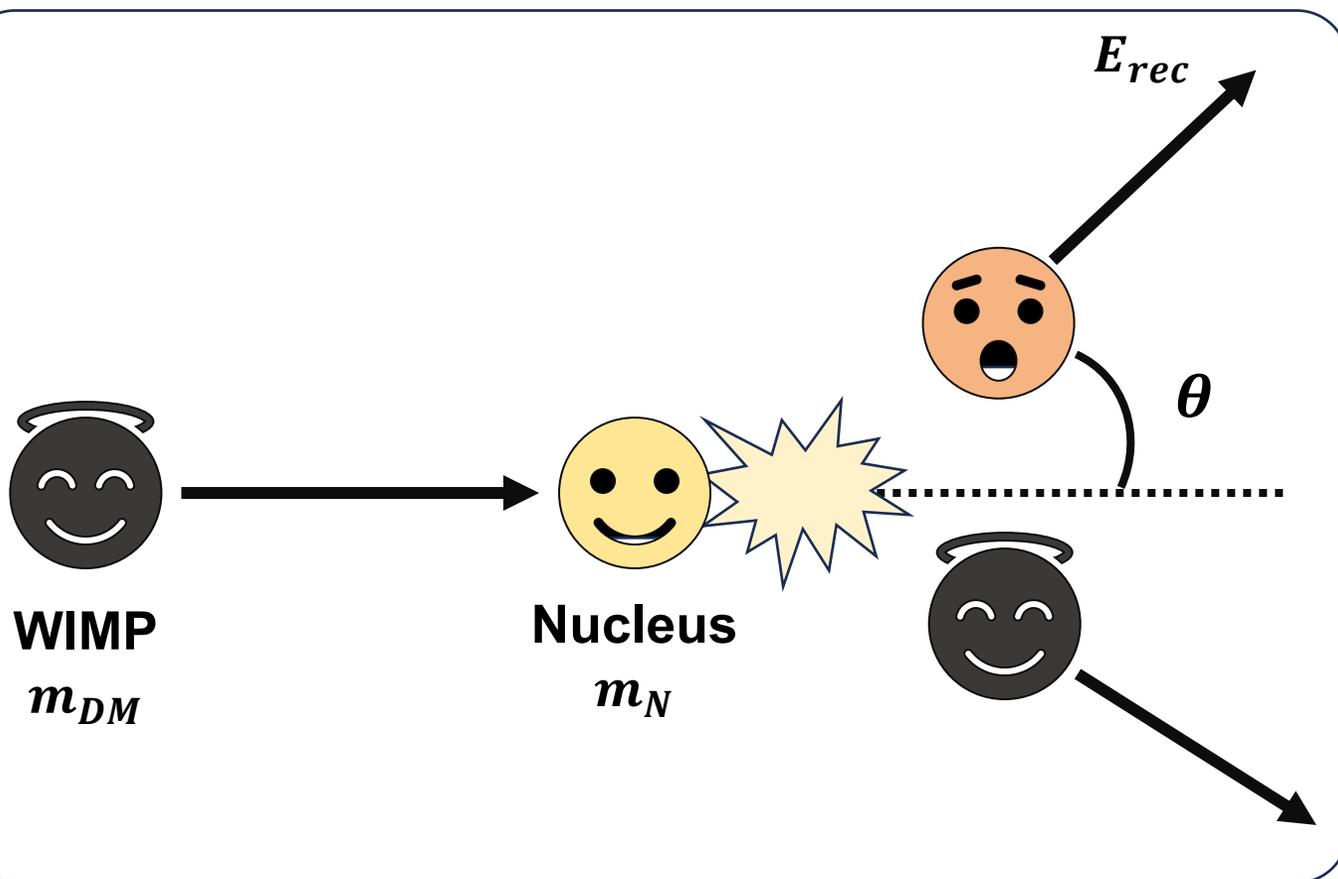
Non-relativistic elastic scattering

$$\mu = \frac{m_{DM} m_N}{m_{DM} + m_N}$$

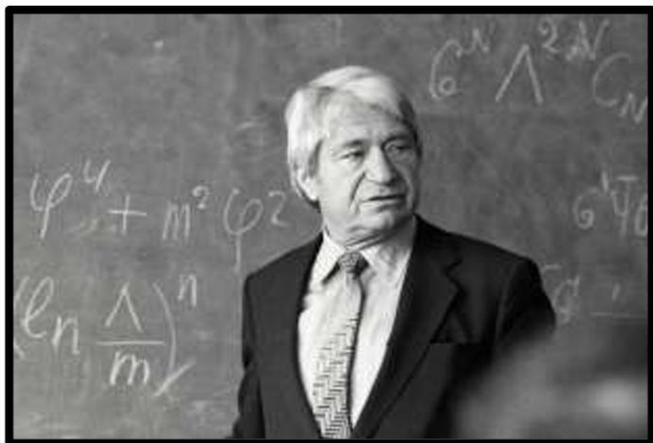
$$E_{rec} = \frac{\mu^2 v^2}{m_N} (1 - \cos\theta) \leq \frac{2\mu^2 v^2}{m_N}$$

$$m_{DM} = 10 \text{ GeV}/c^2; m_N = 131 \text{ GeV}/c^2; v_{DM} = 220 \text{ km/s}$$

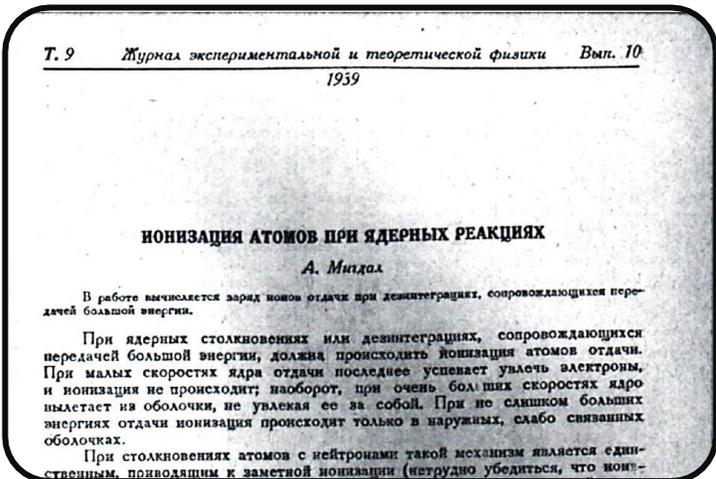
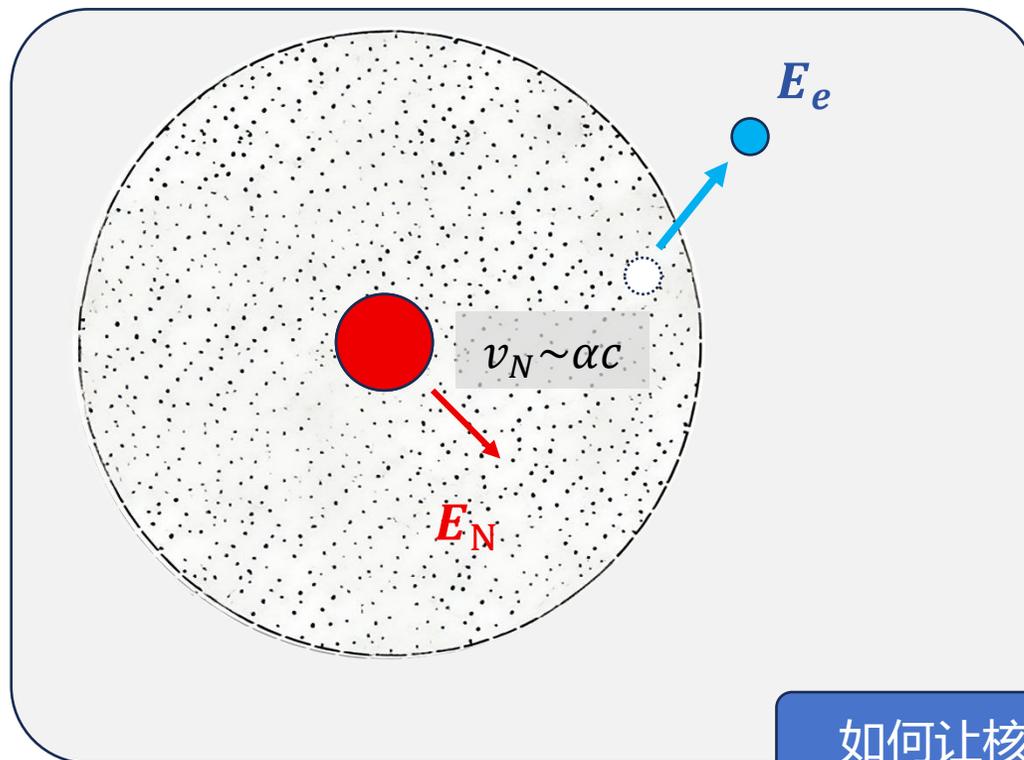
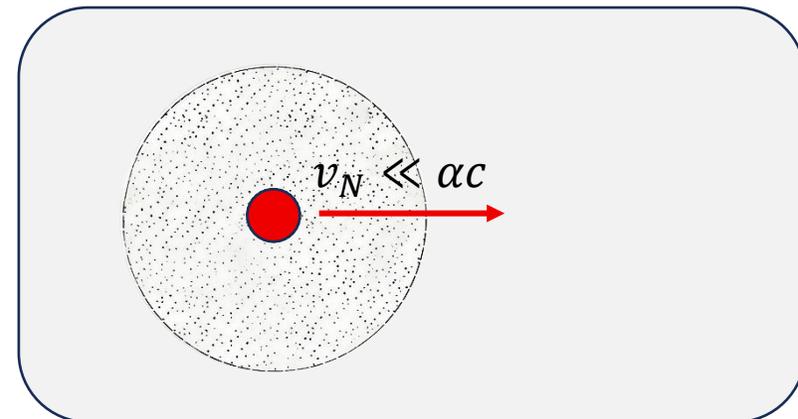
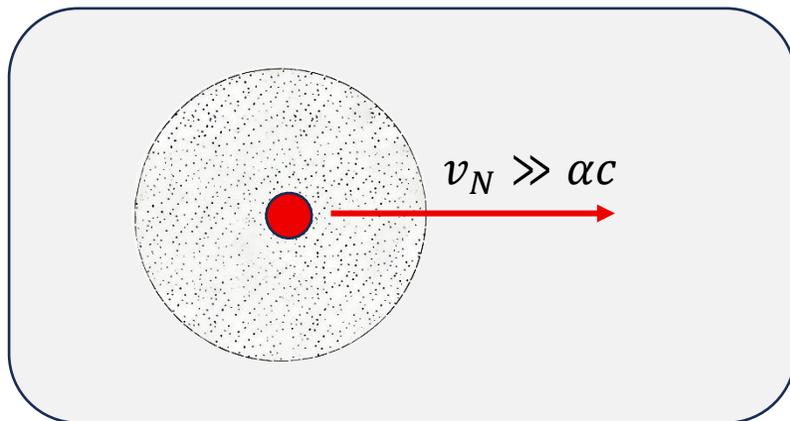
$$E_{rec} \leq 0.7 \text{ keV}_{nr}$$



Exp	threshold
Xenon-1T S1S2	4.9 keVnr (1.4 keVee)
Xenon-1T S2-only	0.7 keVnr (0.186 keVee)
DarkSide50 S1S2	13 keVnr (1.3 keVee)
DarkSide50 S2-only	0.6 keVnr (0.1 keVee)
CDEX:	0.64 keVnr (0.16 keVee)
CRESST-II	0.307 keVnr
SuperCDMS	0.07 KeVee



- 1939年由前苏联科学家Migdal预言

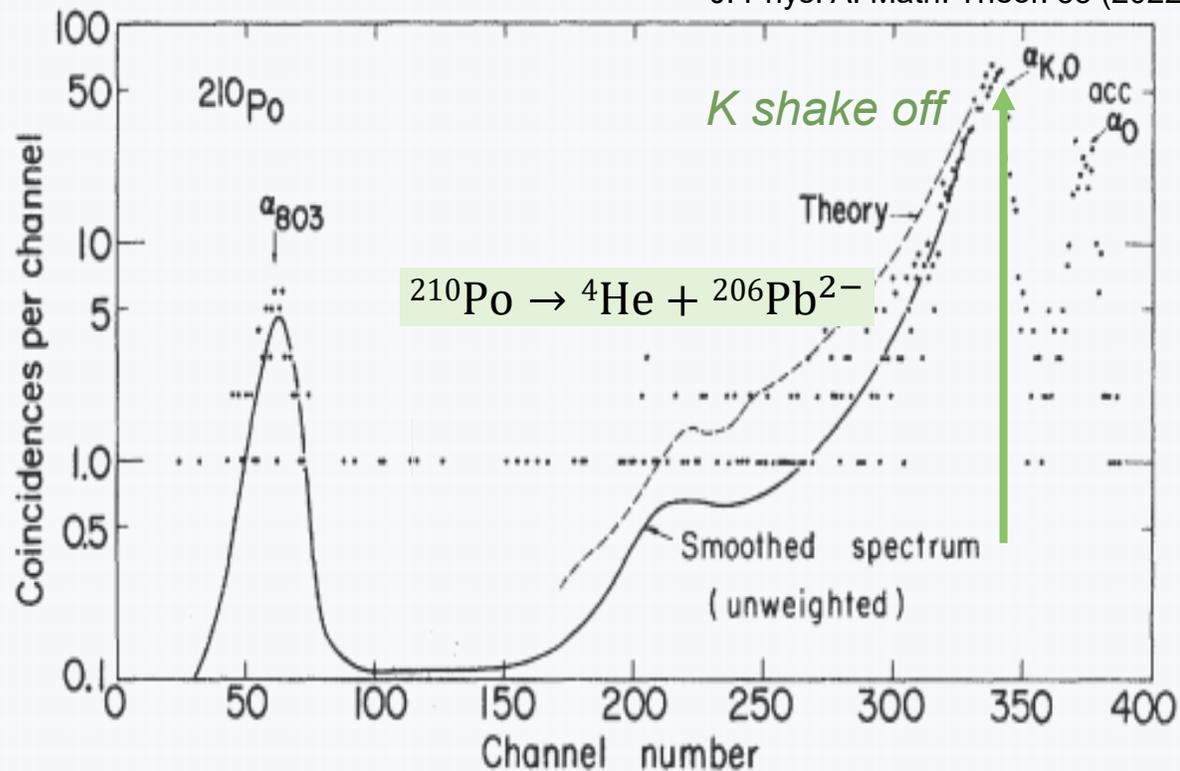


如何让核产生位移?

Migdal效应的间接探测证据

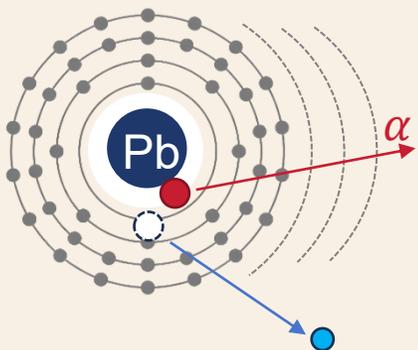
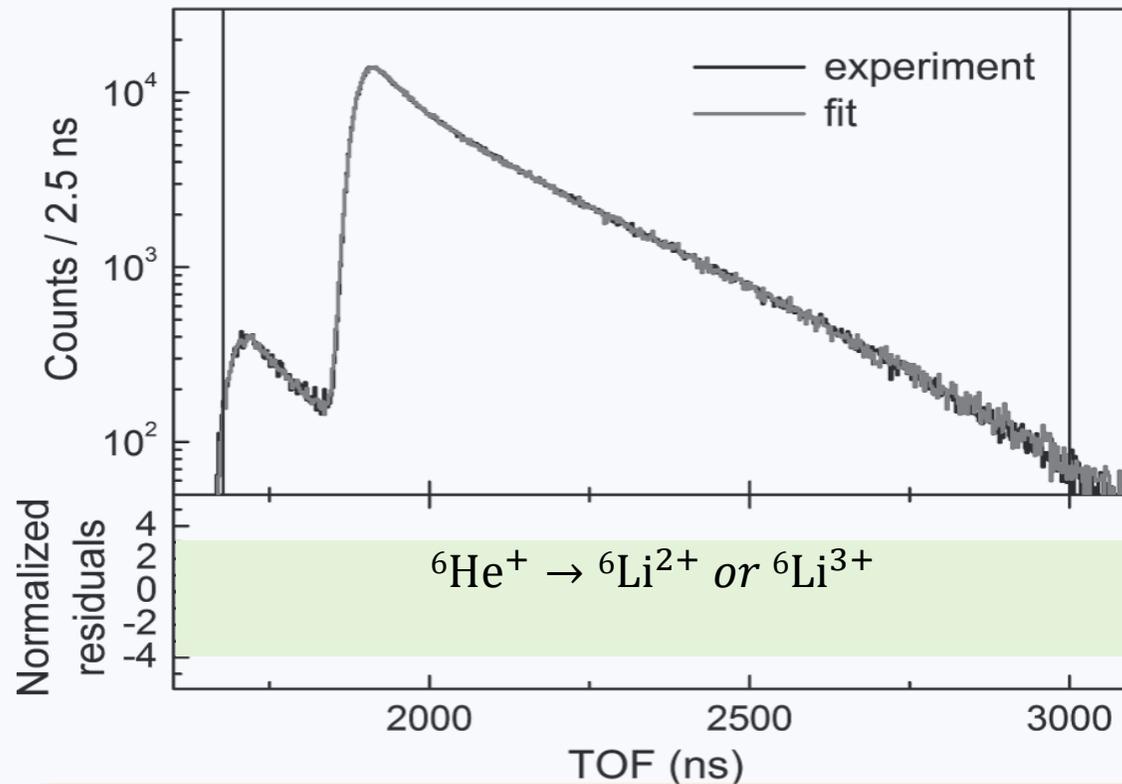
α 衰变

PhysRevC.11.1740 (1975)
J. Phys. A: Math. Theor. 55 (2022)

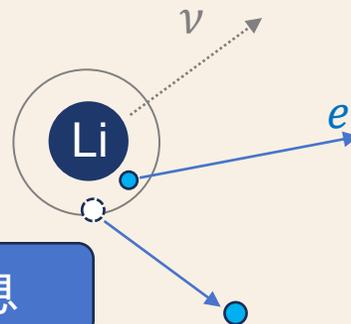


β 衰变

PhysRevLett.108.243201 (2012)



α 电离铅核的k层电子
导致能量降低



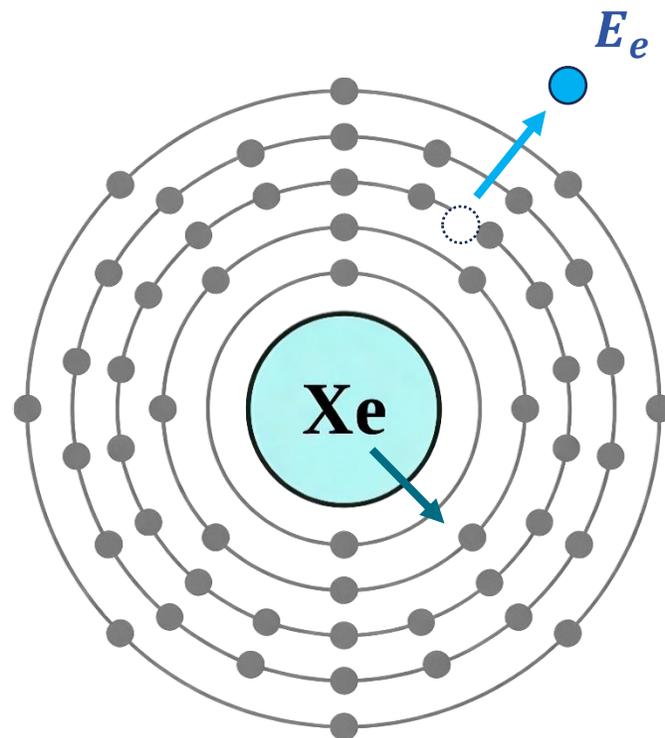
β 衰变中2价锂离子的核
外电子产生3价锂离子

测量的是核子信息

中性粒子碰撞中的Migdal效应

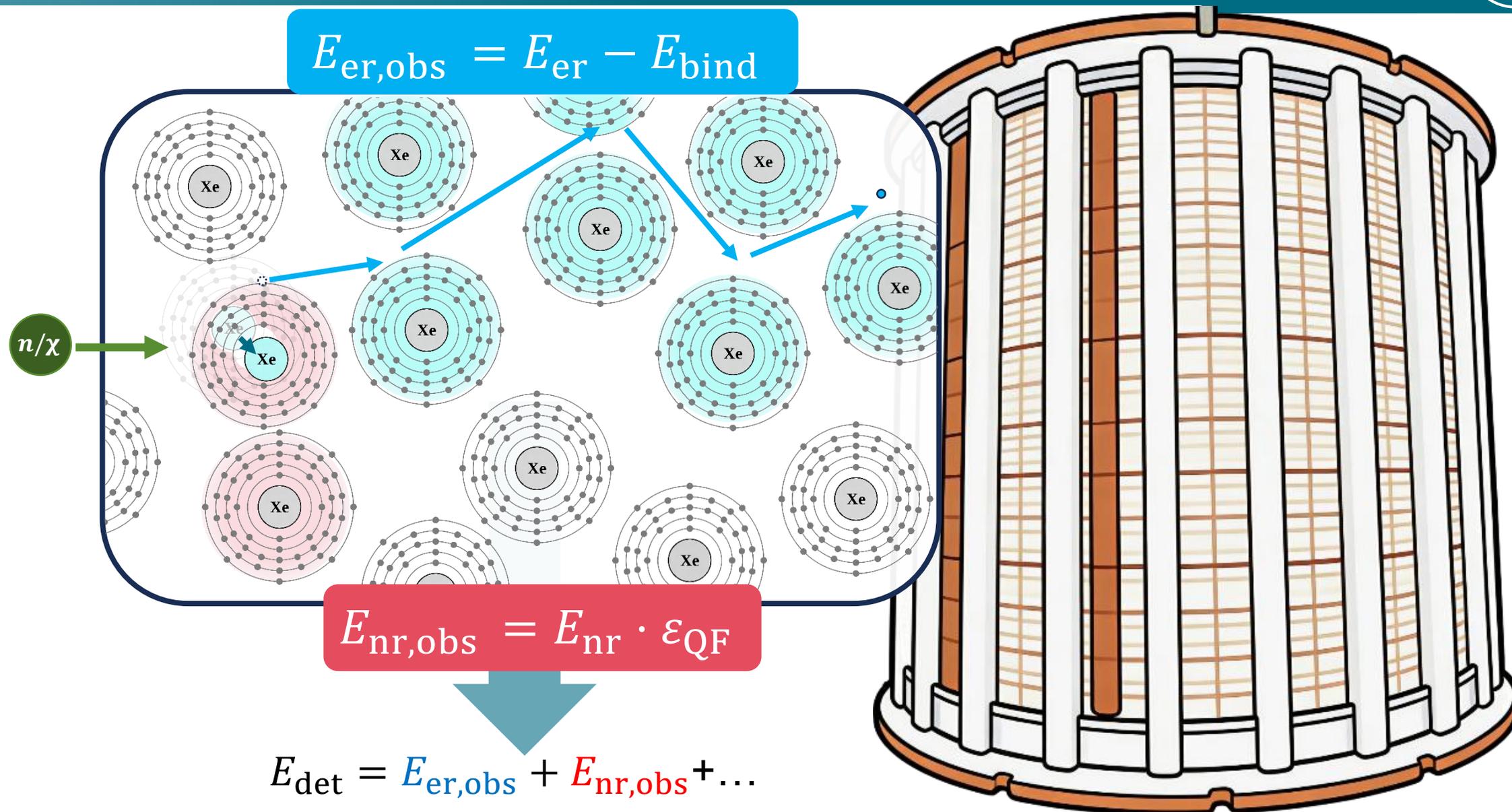


$n/\nu/\chi$

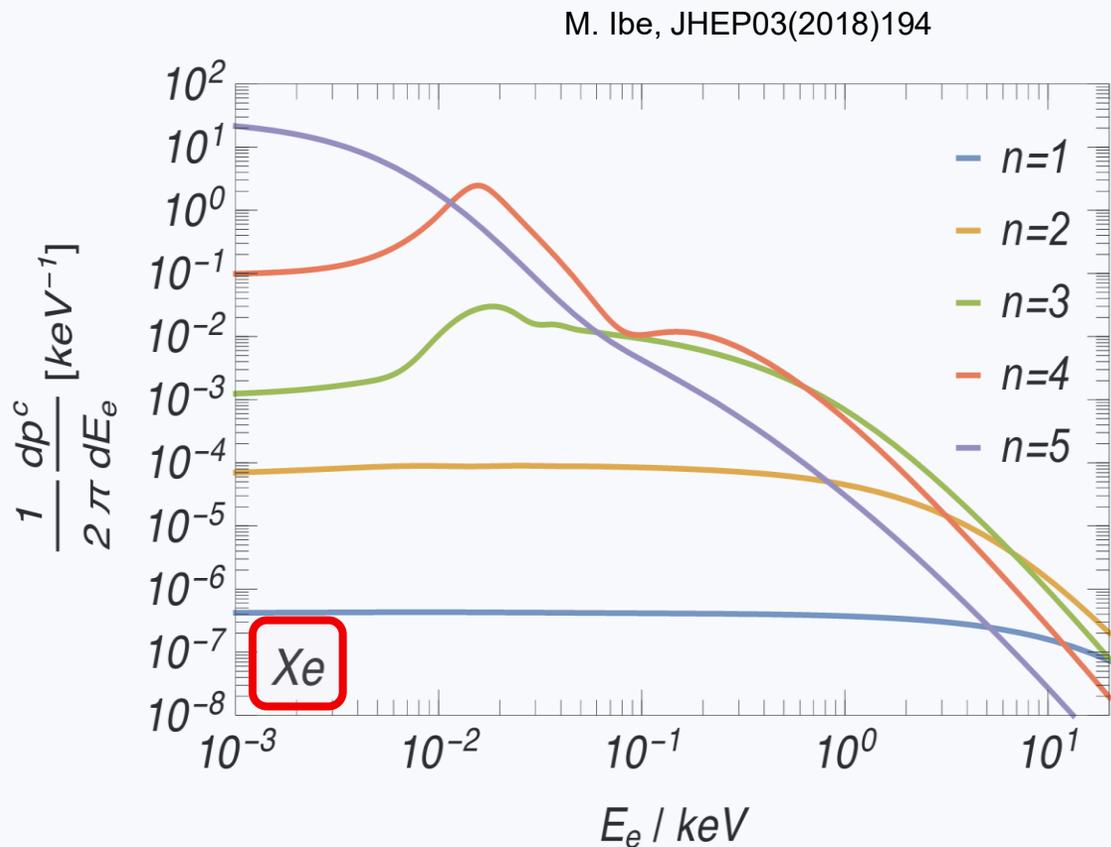


至今已有80余年，仍未有直接观测的证据

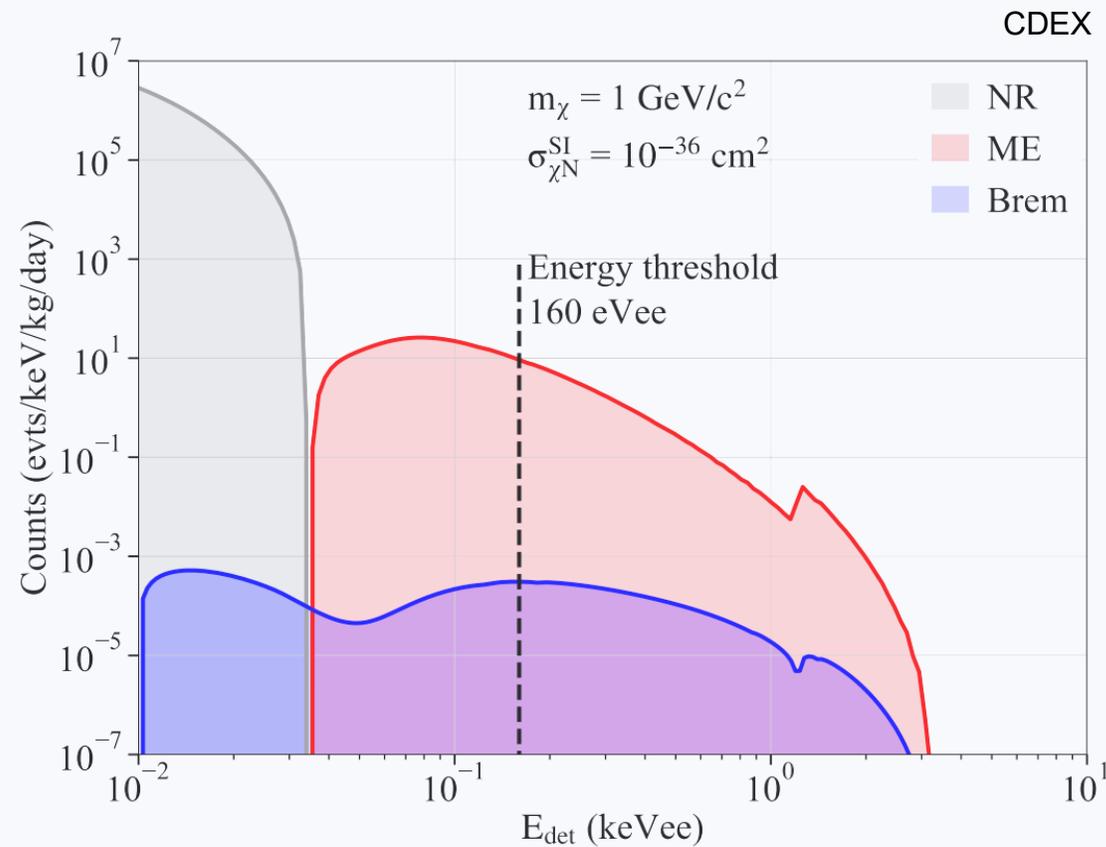
利用Migdal效应直接探测暗物质实验



在低动量转移情况下仍然提供可探测信号!

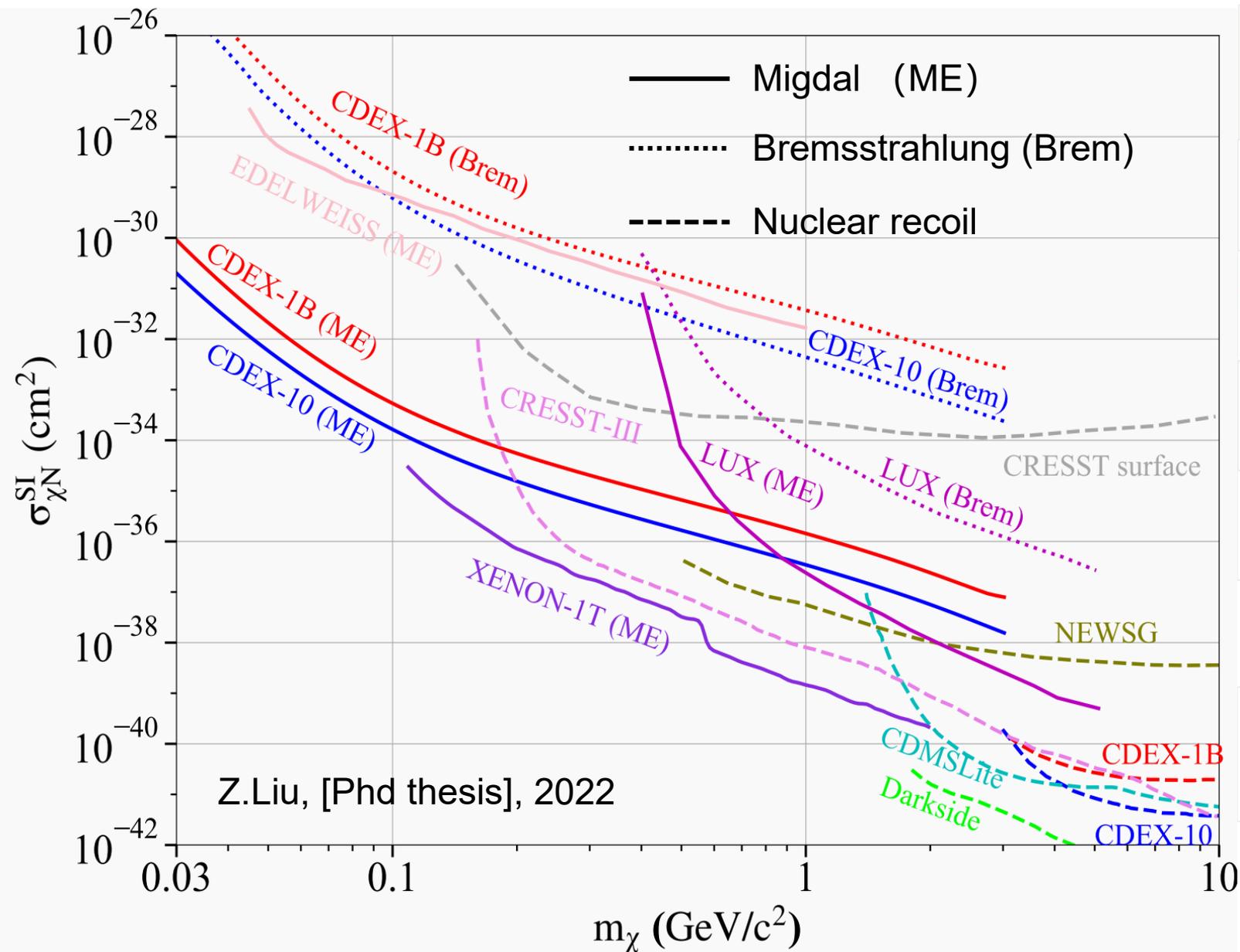


不同轨道均可能产生Migdal电子



Migdal电子沉积能量大于核反冲能量

轻质量暗物质区间的探测限—由Migdal效应主导



Z.Liu, [Phd thesis], 2022

Search for Light Dark Matter Interactions Enhanced by the Migdal Effect or Bremsstrahlung in XENON1T
 XENON Collaboration • E. Aprile (Columbia U.) et al. (Jul 30, 2019)
 Published in: *Phys.Rev.Lett.* 123 (2019) 24, 241803 • e-Print: 1907.12771 [hep-ex]
[pdf](#) [DOI](#) [cite](#) [claim](#) [reference search](#) [329 citations](#)

Search for new physics in low-energy electron recoils from the first LZ exposure
 LZ Collaboration • J. Aalbers (SLAC and Stanford U., Phys. Dept. and KIPAC, Menlo Park) et al. (Jul 28, 2023)
 Published in: *Phys.Rev.D* 108 (2023) 7, 072006 • e-Print: 2307.15753 [hep-ex]
[pdf](#) [links](#) [DOI](#) [cite](#) [datasets](#) [claim](#) [reference search](#) [73 citations](#)

Search for Dark-Matter–Nucleon Interactions with a Dark Mediator in PandaX-4T
 PandaX Collaboration • Di Huang (Shanghai Jiao Tong U.) et al. (Aug 3, 2023)
 Published in: *Phys.Rev.Lett.* 131 (2023) 19, 191002 • e-Print: 2308.01540 [hep-ex]
[pdf](#) [DOI](#) [cite](#) [claim](#) [reference search](#) [51 citations](#)

Results of a Search for Sub-GeV Dark Matter Using 2013 LUX Data
 LUX Collaboration • D.S. Akerib (Case Western Reserve U. and SLAC and KIPAC, Menlo Park) et al. (Nov 27, 2018)
 Published in: *Phys.Rev.Lett.* 122 (2019) 13, 131301 • e-Print: 1811.11241 [astro-ph.CO]
[pdf](#) [DOI](#) [cite](#) [claim](#) [reference search](#) [213 citations](#)

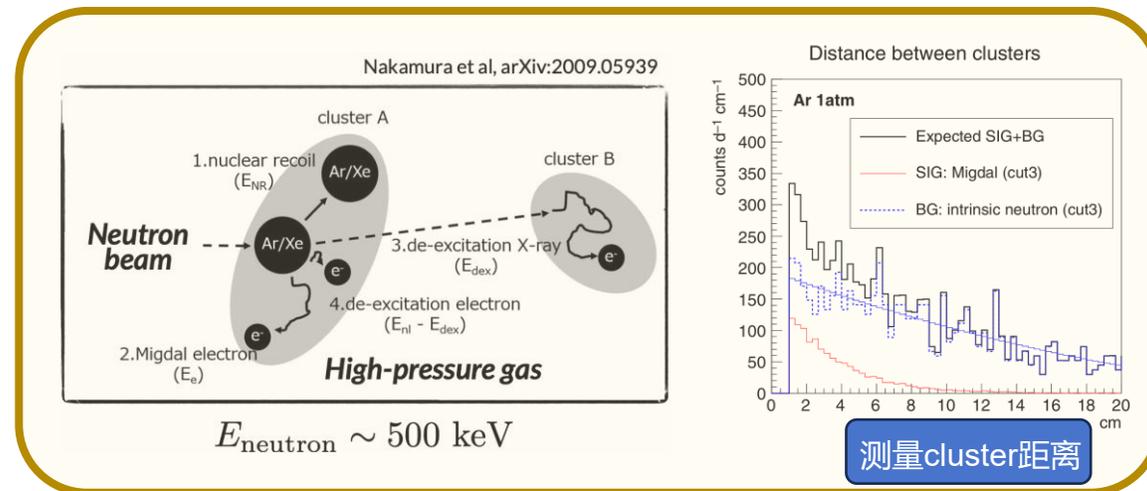
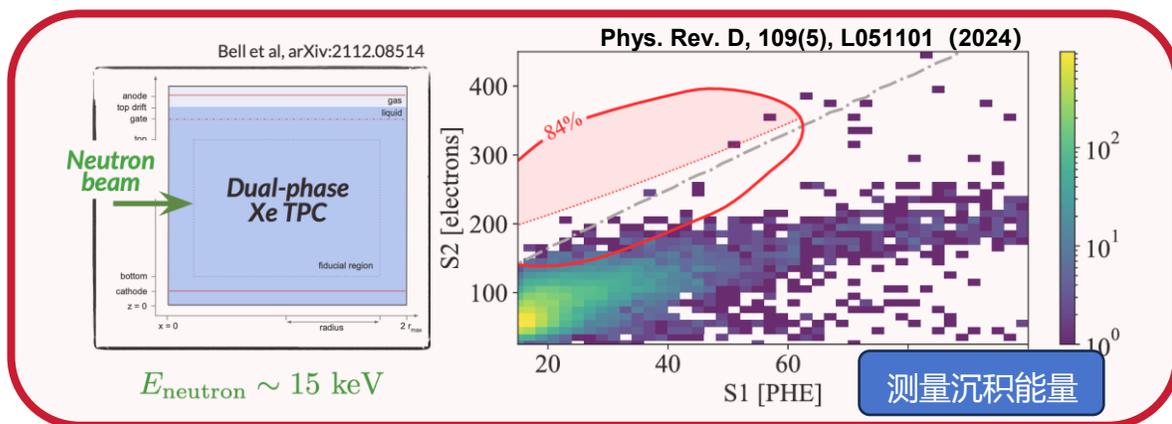
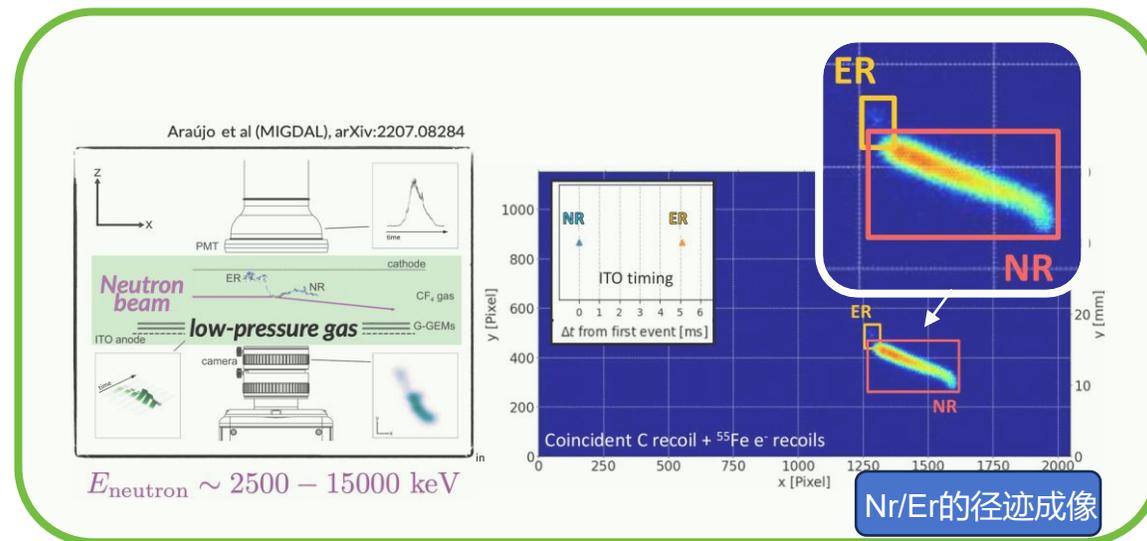
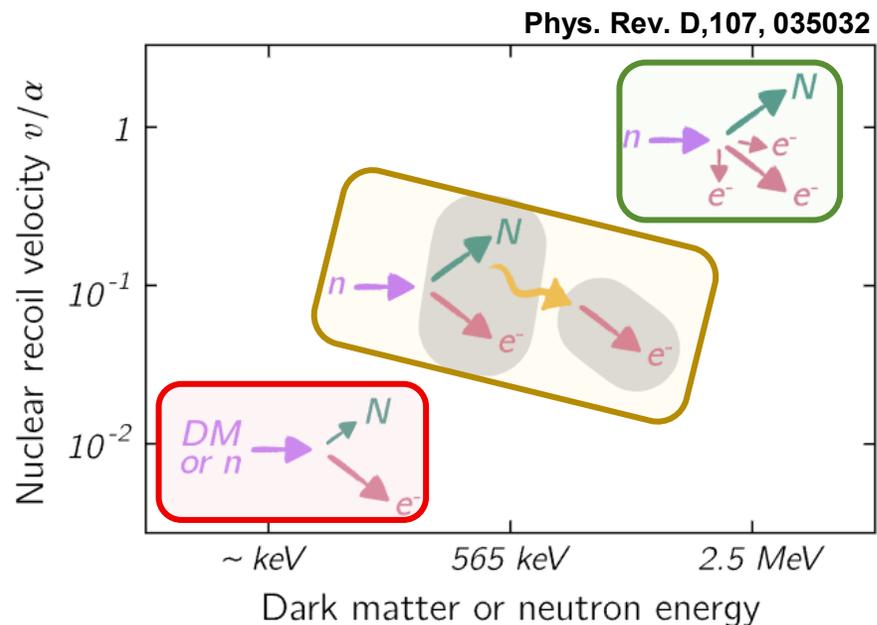
Search for Dark-Matter–Nucleon Interactions via Migdal Effect with DarkSide-50
 DarkSide Collaboration • P. Agnes (Royal Holloway, U. of London) et al. (Jul 25, 2022)
 Published in: *Phys.Rev.Lett.* 130 (2023) 10, 10 • e-Print: 2207.11967 [hep-ex]
[pdf](#) [links](#) [DOI](#) [cite](#) [claim](#) [reference search](#) [107 citations](#)

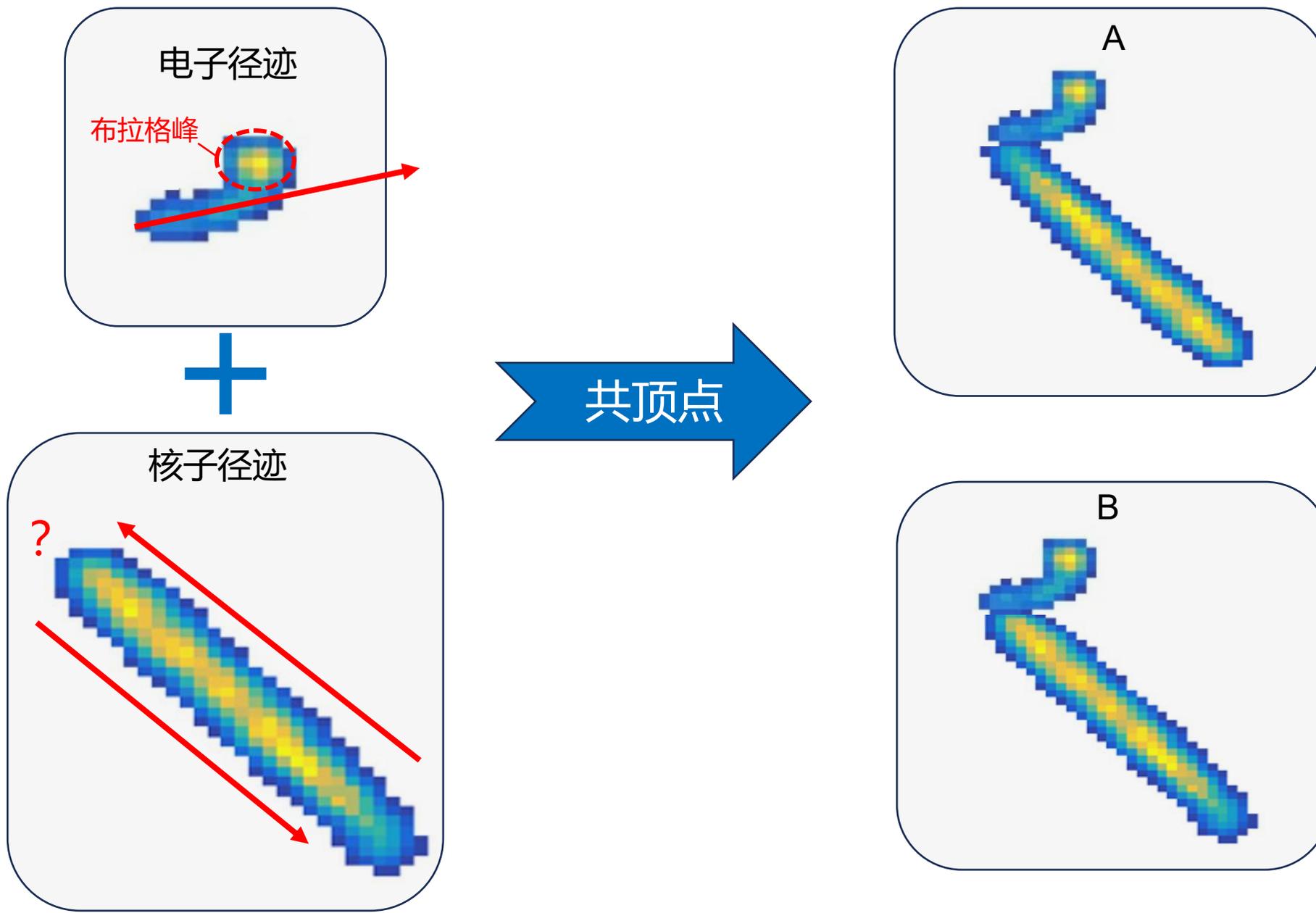
Search for low-mass dark matter via bremsstrahlung radiation and the Migdal effect in SuperCDMS
 SuperCDMS Collaboration • M.F. Albakry (British Columbia U. and TRIUMF) et al. (Feb 17, 2023)
 Published in: *Phys.Rev.D* 107 (2023) 11, 2023 • e-Print: 2302.09115 [hep-ex]
[pdf](#) [links](#) [DOI](#) [cite](#) [claim](#) [reference search](#) [43 citations](#)

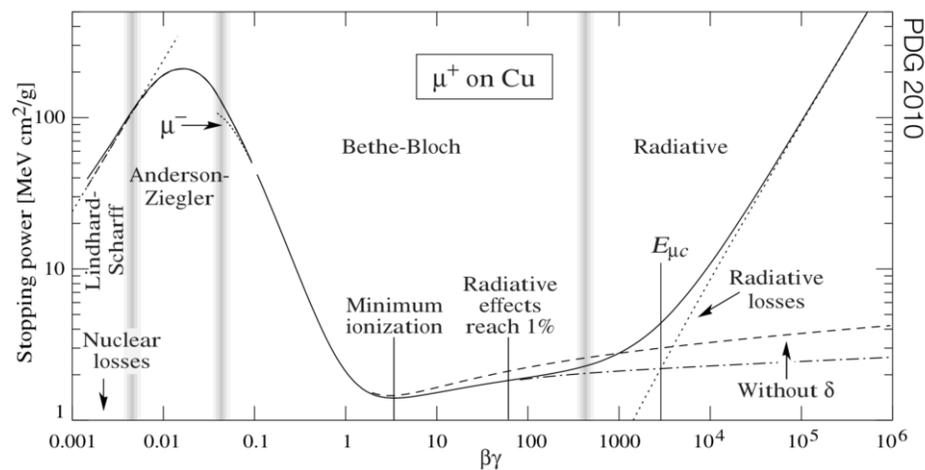
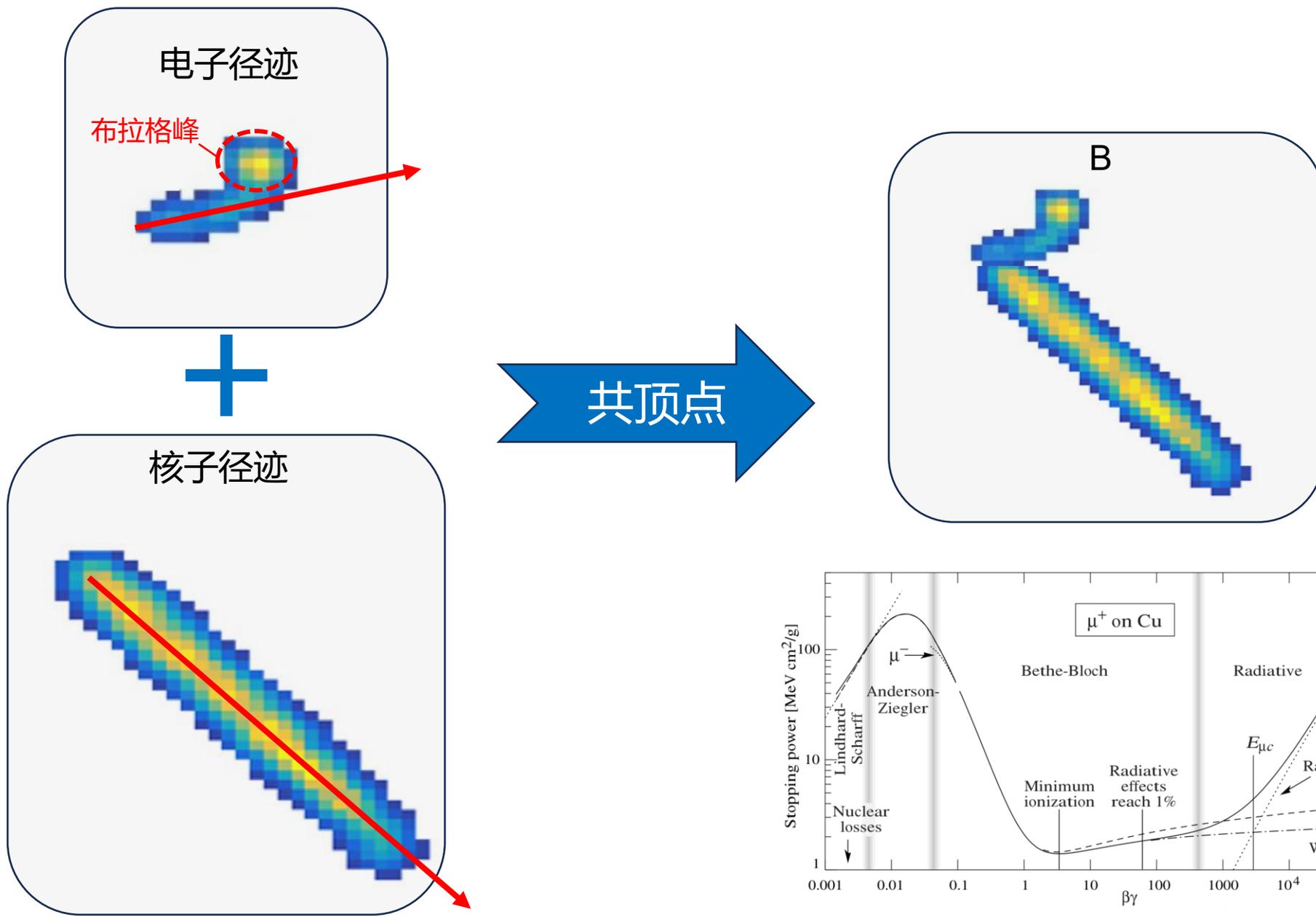
Search for sub-GeV dark matter via the Migdal effect with an EDELWEISS germanium detector with NbSi transition-edge sensors
 EDELWEISS Collaboration • E. Armengaud (IRFU, Saclay) et al. (Mar 8, 2022)
 Published in: *Phys.Rev.D* 106 (2022) 6, 062004 • e-Print: 2203.03993 [astro-ph.GA]
[pdf](#) [DOI](#) [cite](#) [claim](#) [reference search](#) [66 citations](#)

各大暗物质实验：
 XENON/LZ/PandaX/CDEX/DarkSide50/
 SuperCDMS/EDELWEISS/LUX...

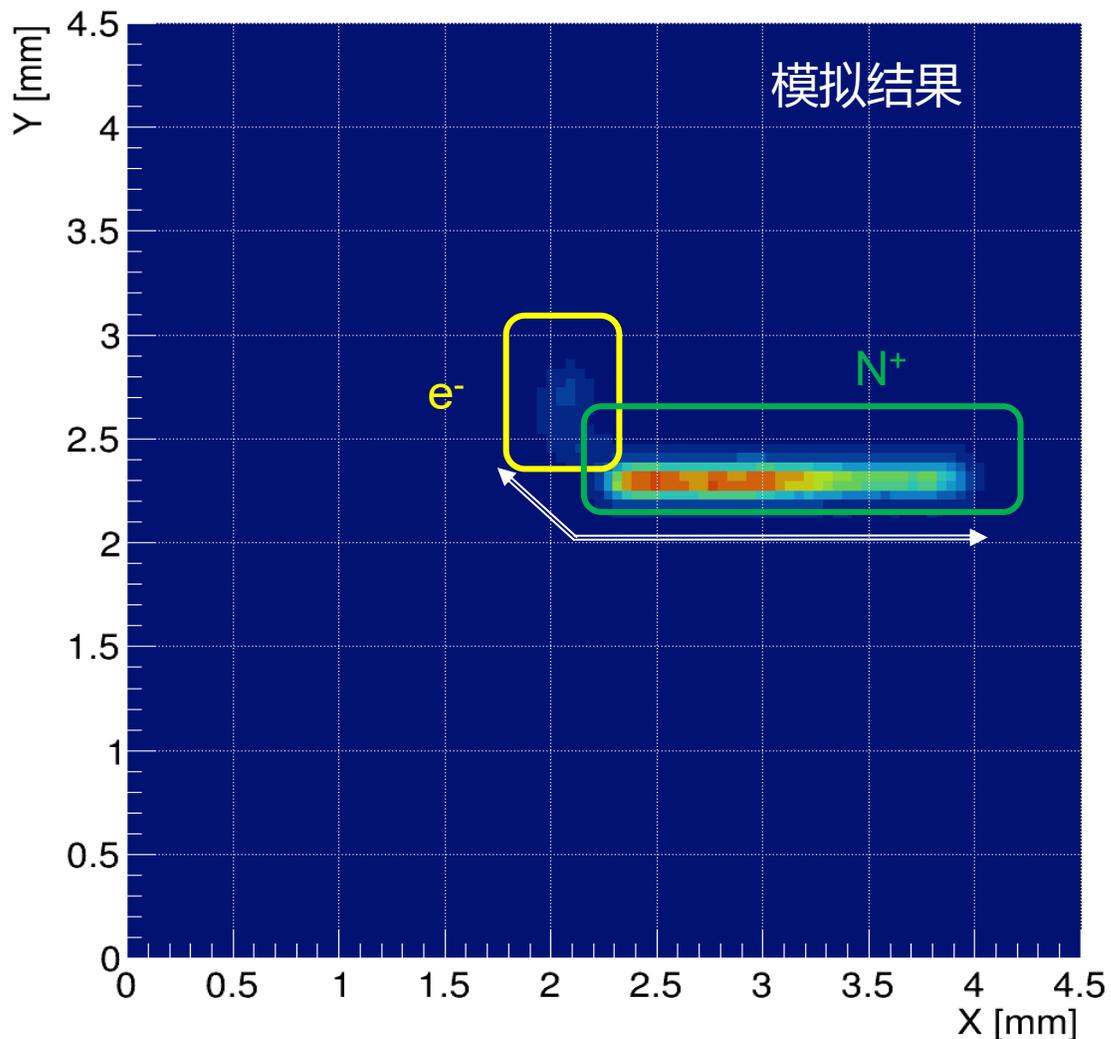
国际上中性粒子Migdal效应实验







ER: 5.9 keV , NR: 300 keV



- 核心挑战:

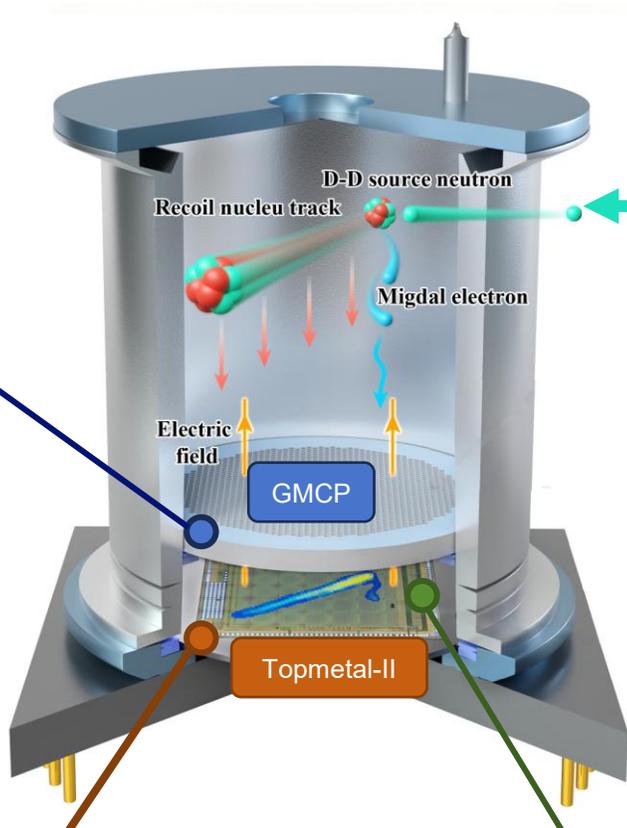
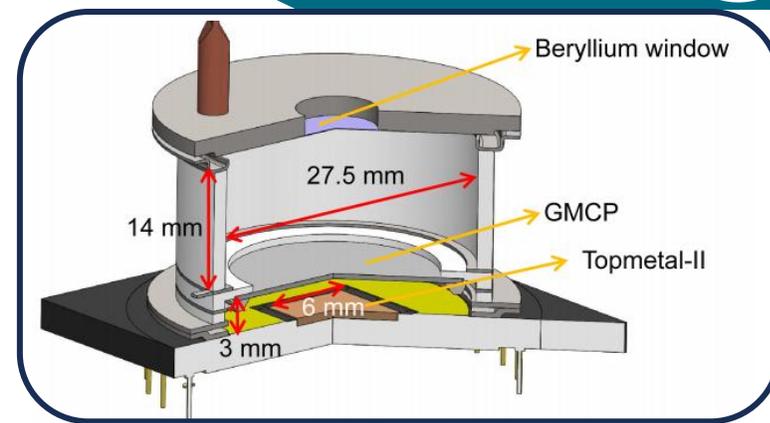
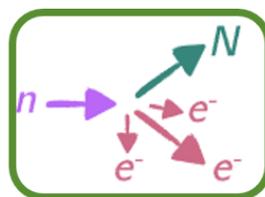
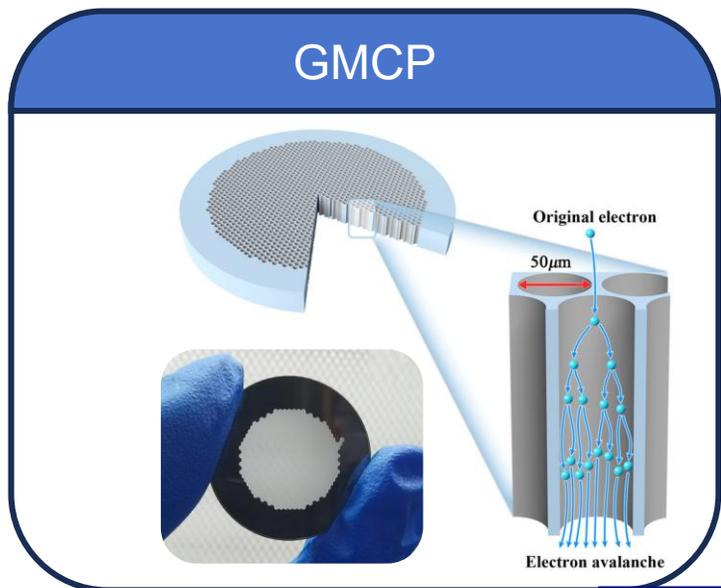
- 信号: 有效信号事例率极低
- 本底: 本底种类繁多, 且实验中存在大量伴生光子本底。

- 探测器性能要求:

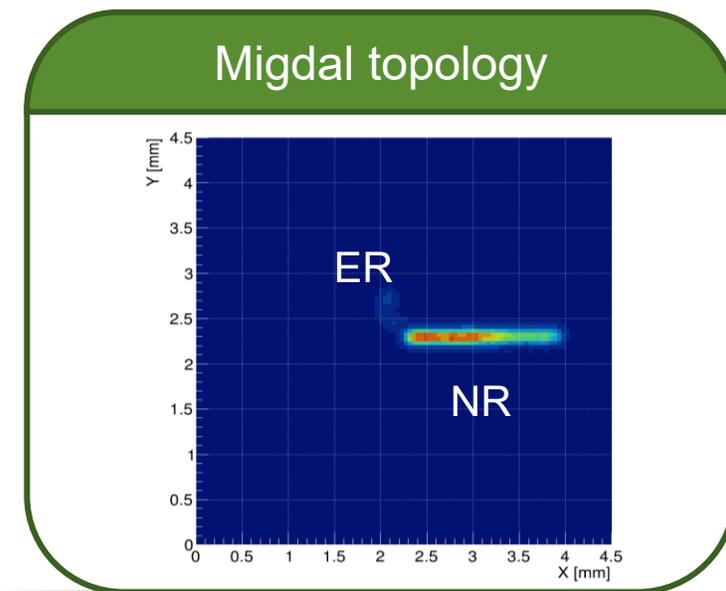
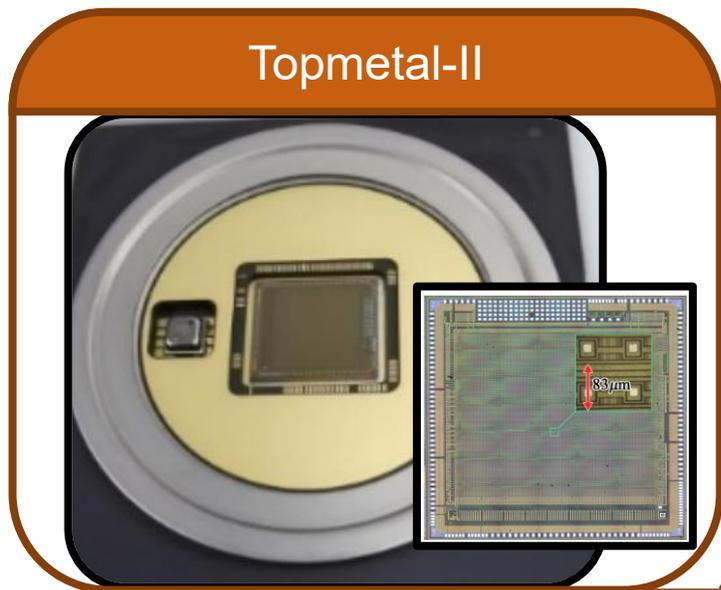
- 能量分辨好: 电子径迹~keV, 核子径迹~百keV, 要求大动态范围
- 空间分辨高: 电子径迹仅数百微米
- 有时间分辨能力: 通过时间关联筛选信号, 压低本底

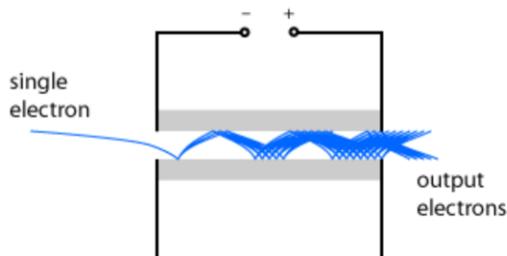
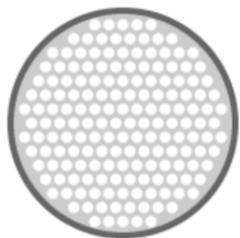
- 解决方案:

- 主动屏蔽: 设计屏蔽体压低本底
- 多维度: 测量中子/光子能谱、开发蒙卡模拟、事例挑选、径迹重建、顶点重建等算法

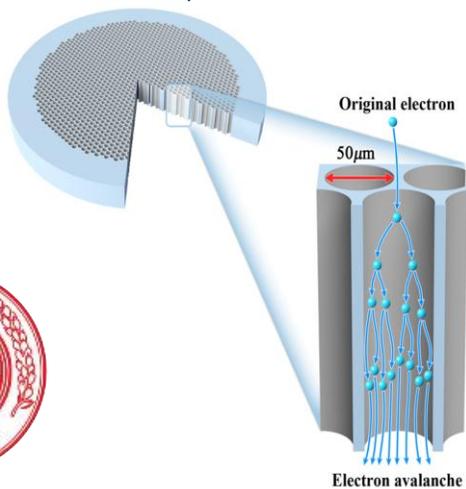


DD neutron source



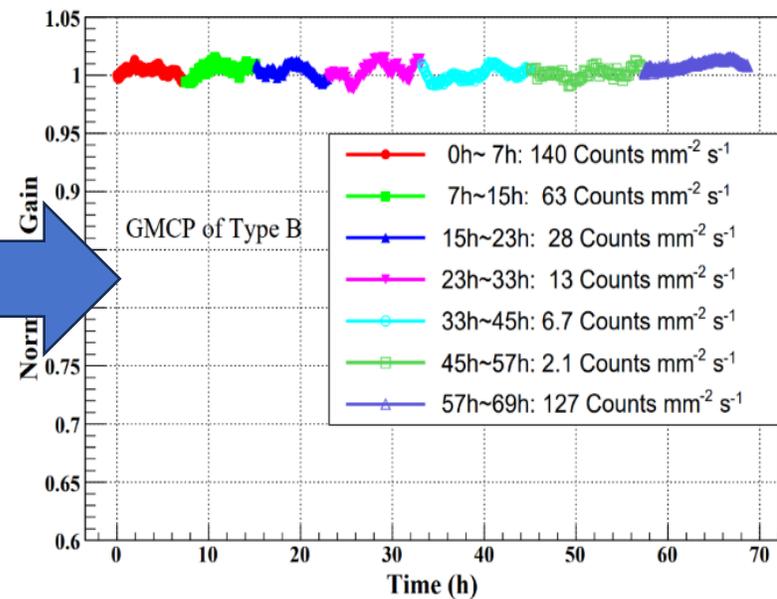
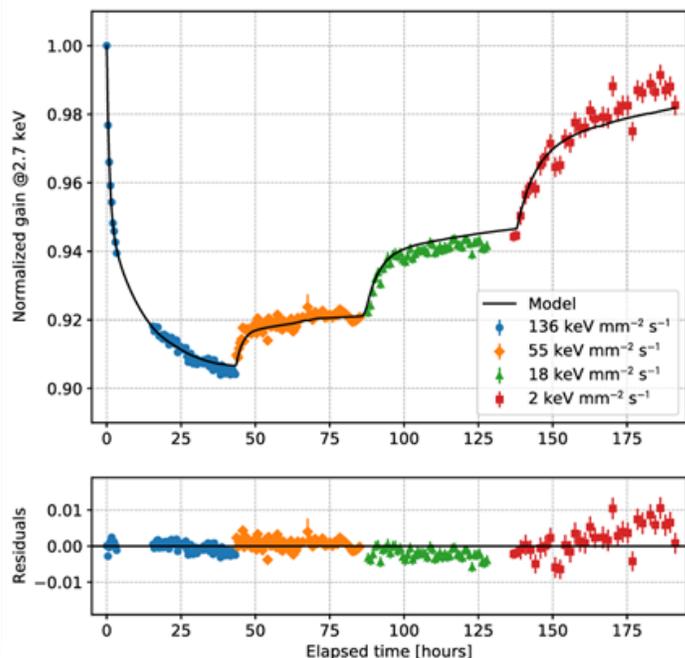


真空器件微通道板 (MCP)



运用于气体探测器 (GMCP)

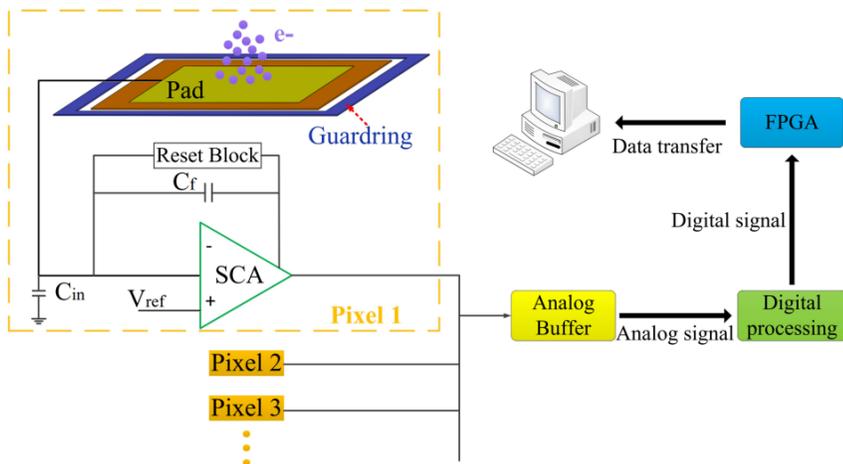
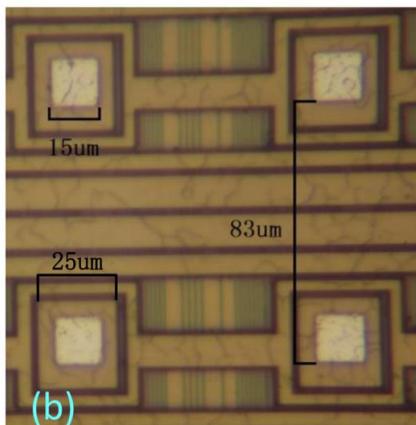
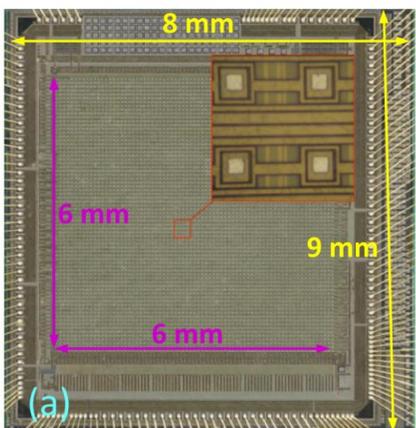
- 微结构气体探测器：GEM/THGEM、MicroMegas...
- 真空器件MCP并**不能直接在气体**下使用！
- 电荷累积在GEM孔内导致增益下降！
- 设计新工艺，在孔内制作阻性材料，释放电荷



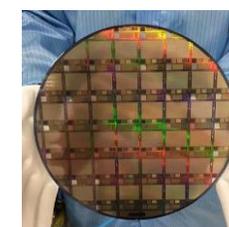
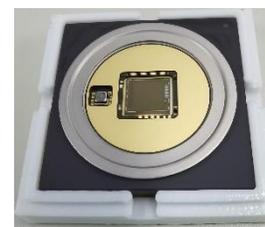
核心器件：像素芯片Topmetal



Topmetal-II

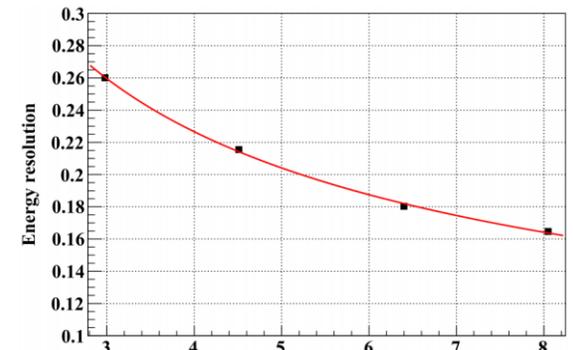
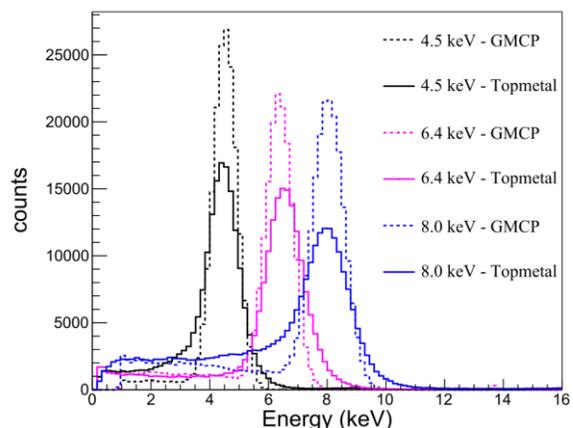


	Topmetal-II ⁻	Topmetal-M1/M2	Topmetal-L
Chip Size /mm ²	6 × 6	18 × 23	17 × 24
Pixel Array	72 × 72	400 × 512	356 × 512
Pixel Size /um ²	83 × 83	45 × 45	45 × 45
ENC	~ 13.4e-	~ 15.4e-	~ 20.0e-
Power Consumption	~ 1W @3.3V	~ 4.3W @3.3V	~ 0.8W @3.3V
Clock	40MHz	5MHz	20MHz
Frame Rate	2.5ms	2.4ms	0.37ms @Sentinel Readout
Readout Mode	Rolling Shutter	Rolling Shutter	Rolling Shutter /Sentinel Readout
Readout Channel	1	16	1



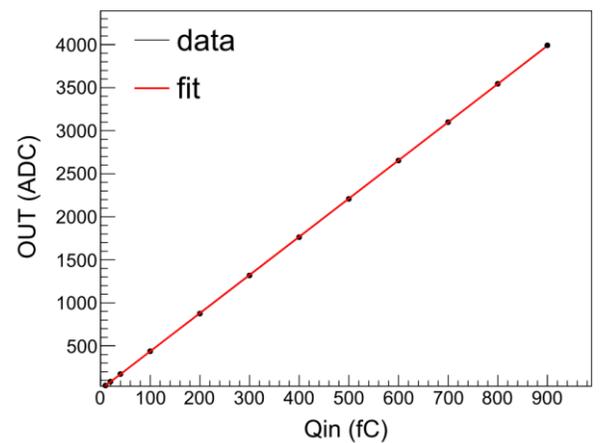
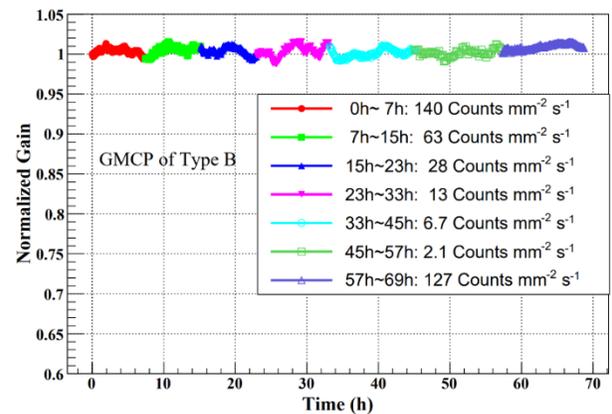
Detector performance

Energy resolution



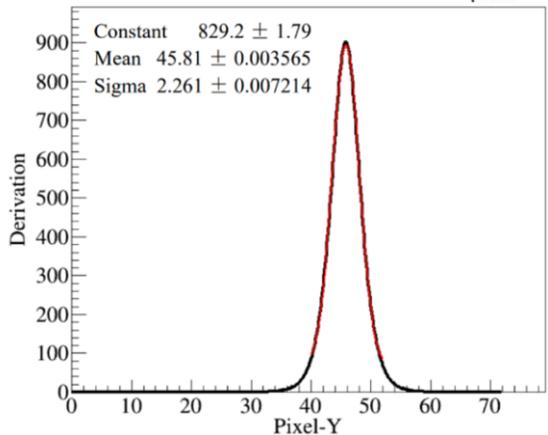
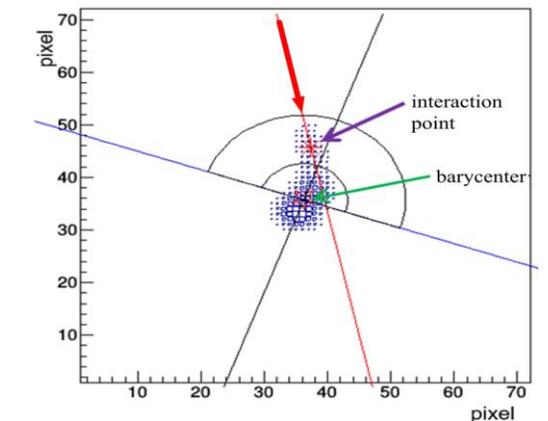
- Good linear energy response
- 20%-30% energy resolution(FWHM)
- Energy resolution follows the relationship $\sim 1/\sqrt{E}$

Dynamic range



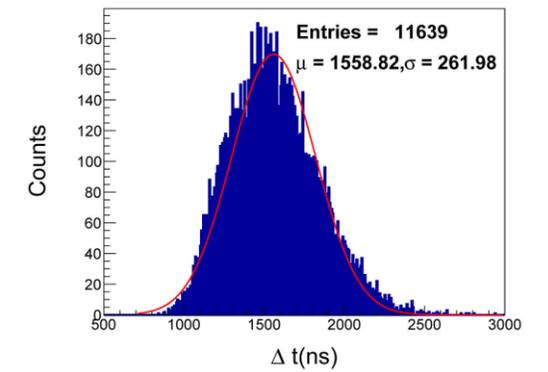
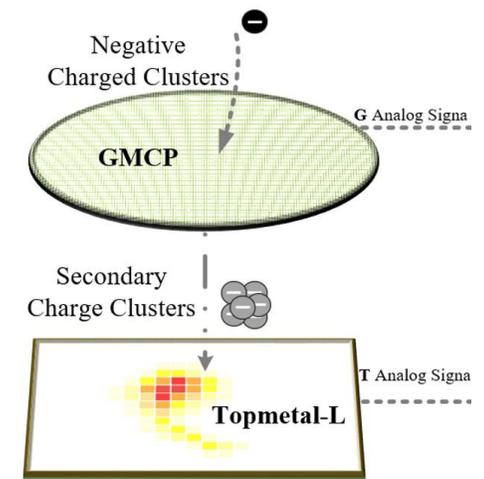
- Stable gain under different count rates(no pile up)
- Good linearity in charge response

Vertex resolution



- $\sim 200 \mu\text{m}$ vertex resolution @ 6.4 keV

Time resolution



- $\sim 262 \mu\text{s}$ time resolution

Scintillator ①

D-D source monitoring



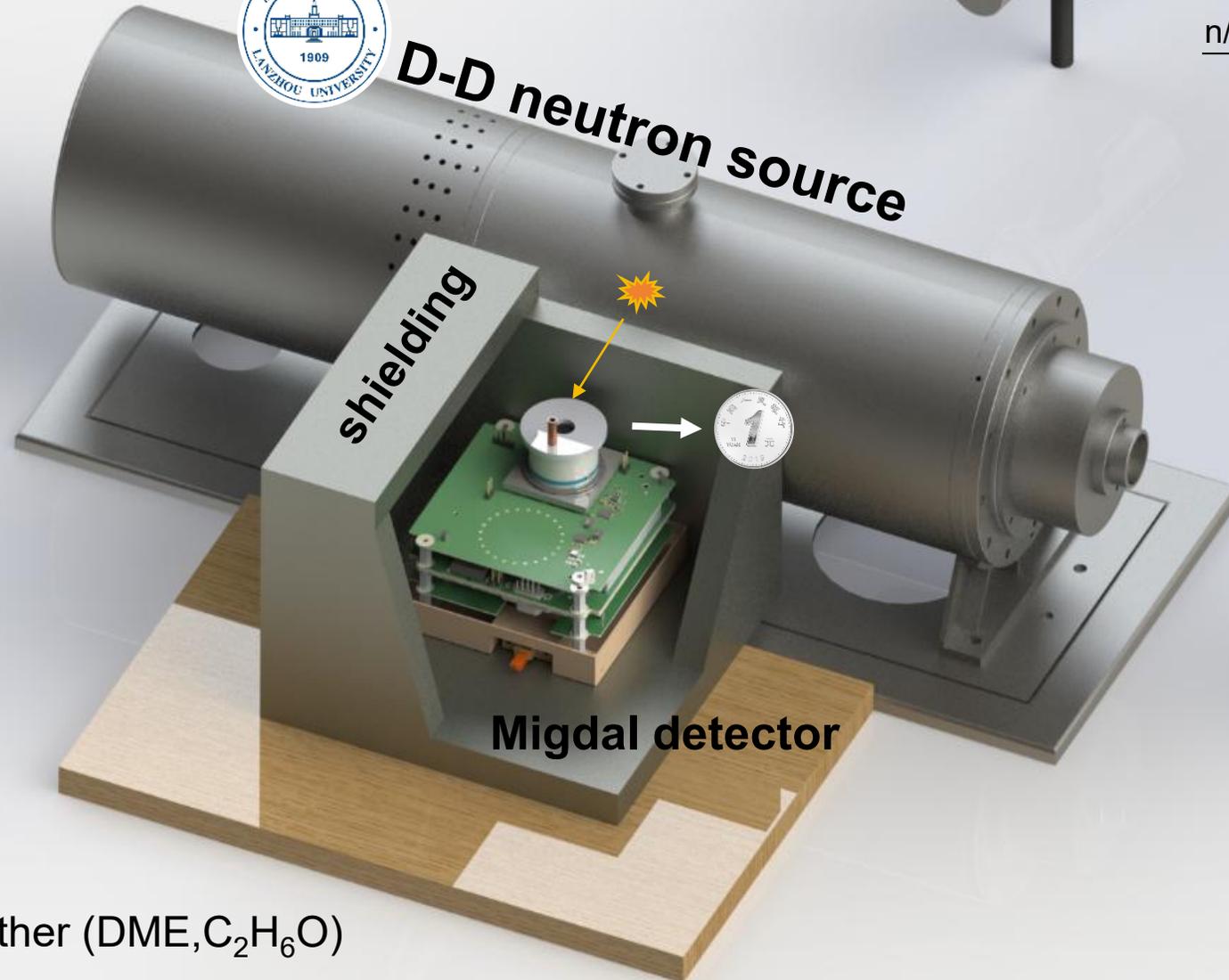
Scintillator ②

n/gamma spectrum meas.



Scintillator ③

D-D source monitoring



D-D neutron source

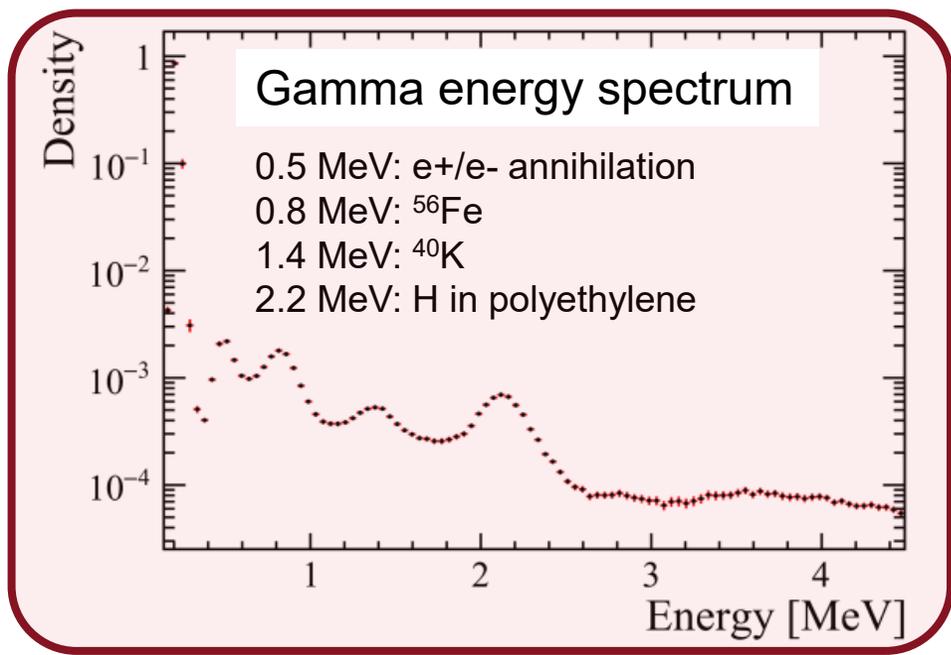
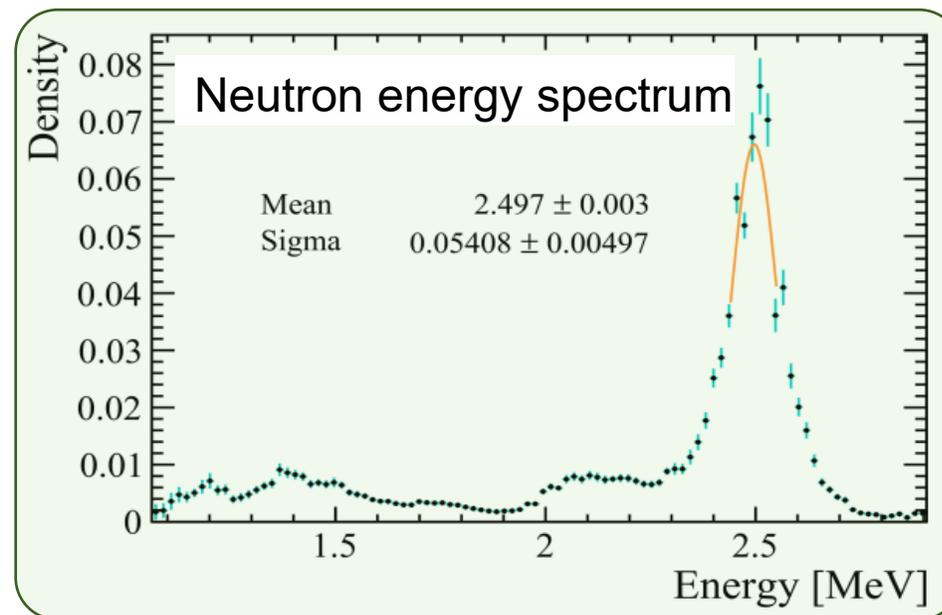
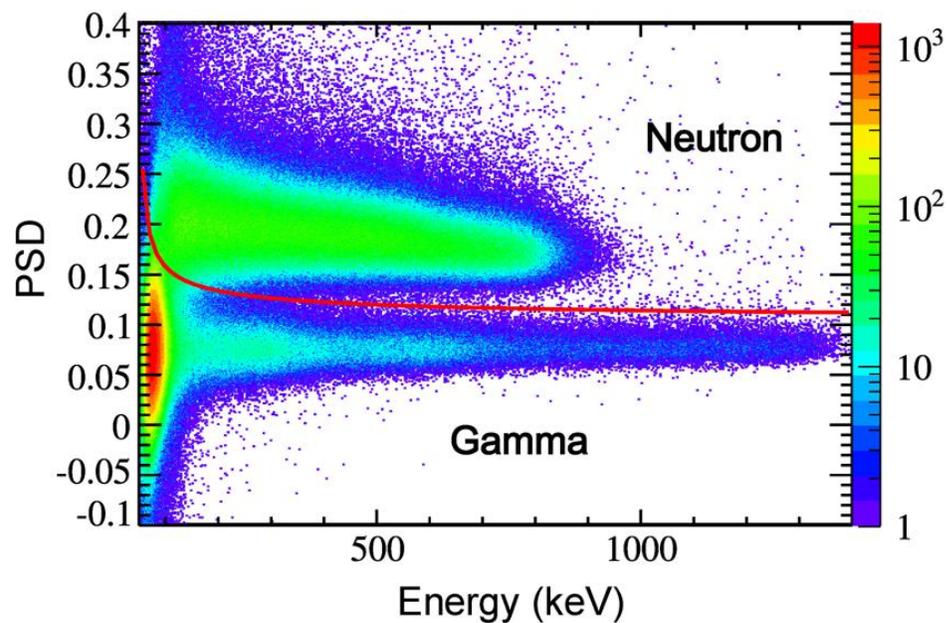
shielding

Migdal detector

Working gas:

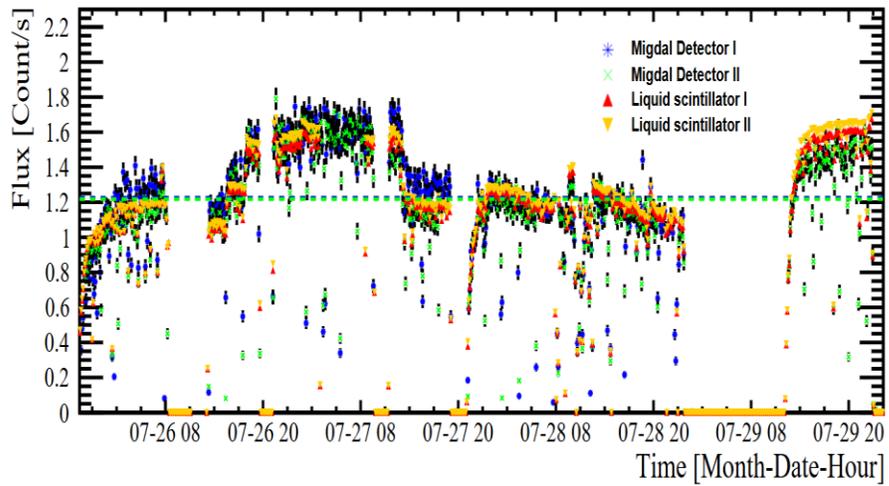
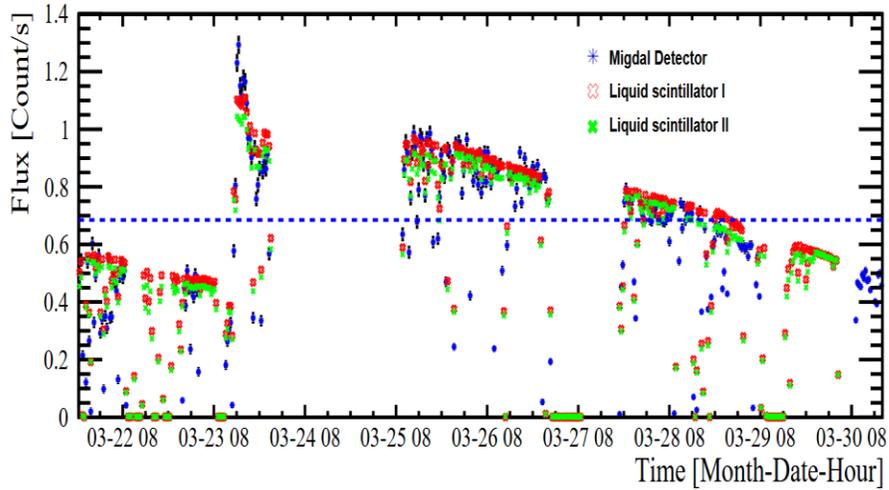
0.8 atm @ ~300 K

40% Helium + Dimethyl ether (DME, C₂H₆O)

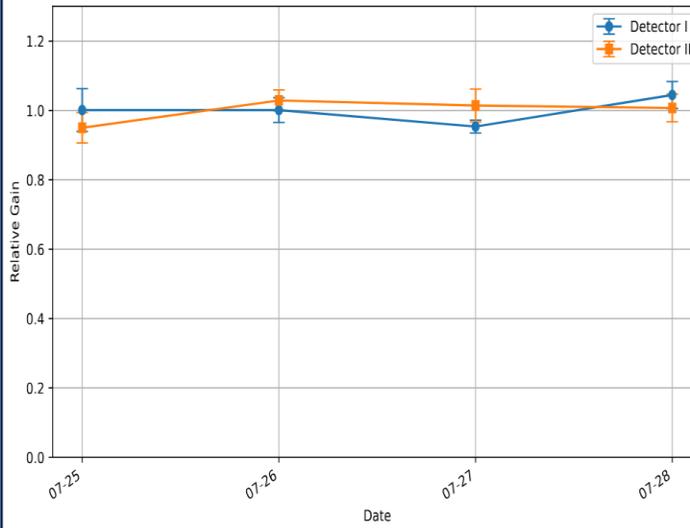
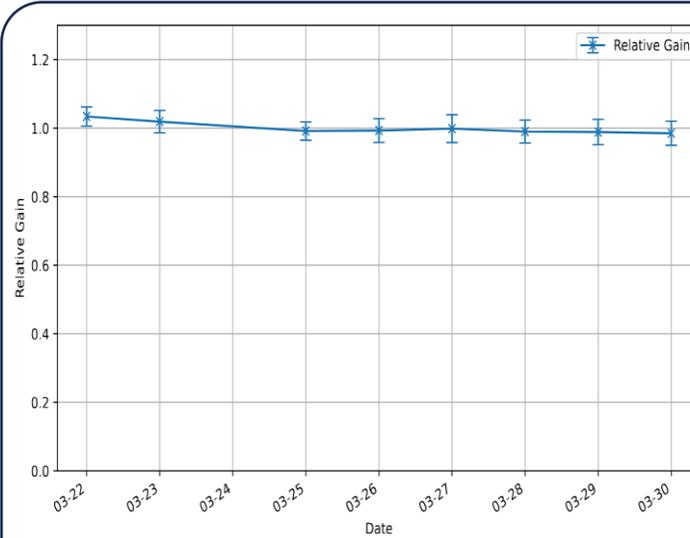


- 采用液闪探测器进行中子/光子能谱测量
- 开发波形分析算法进行中子/光子鉴别
- 根据模拟及标定数据得到液闪探测器的响应矩阵；开发反卷积算法得到中子/光子能谱

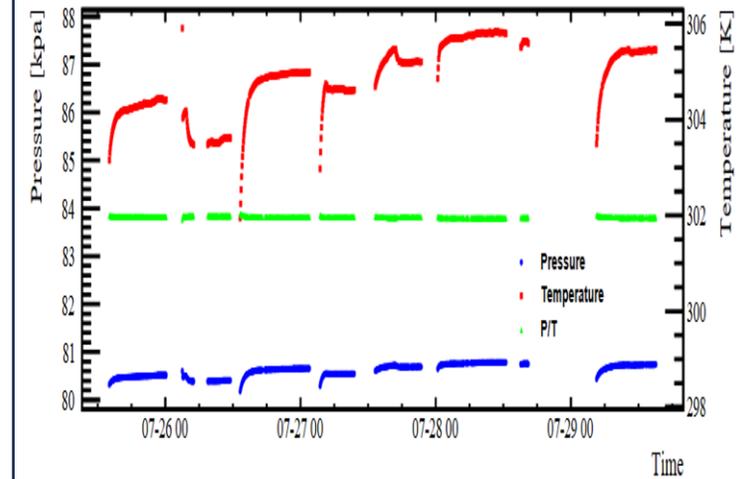
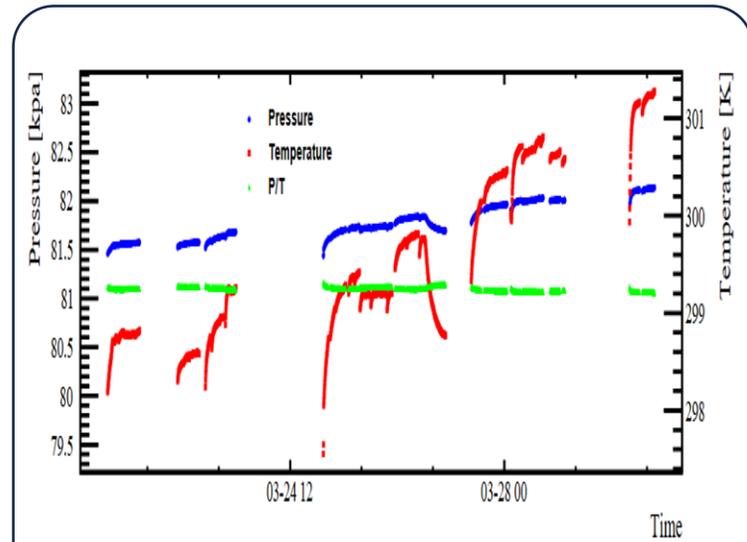
Neutron Flux & Detector performance monitor



- neutron flux monitored by the two LS.

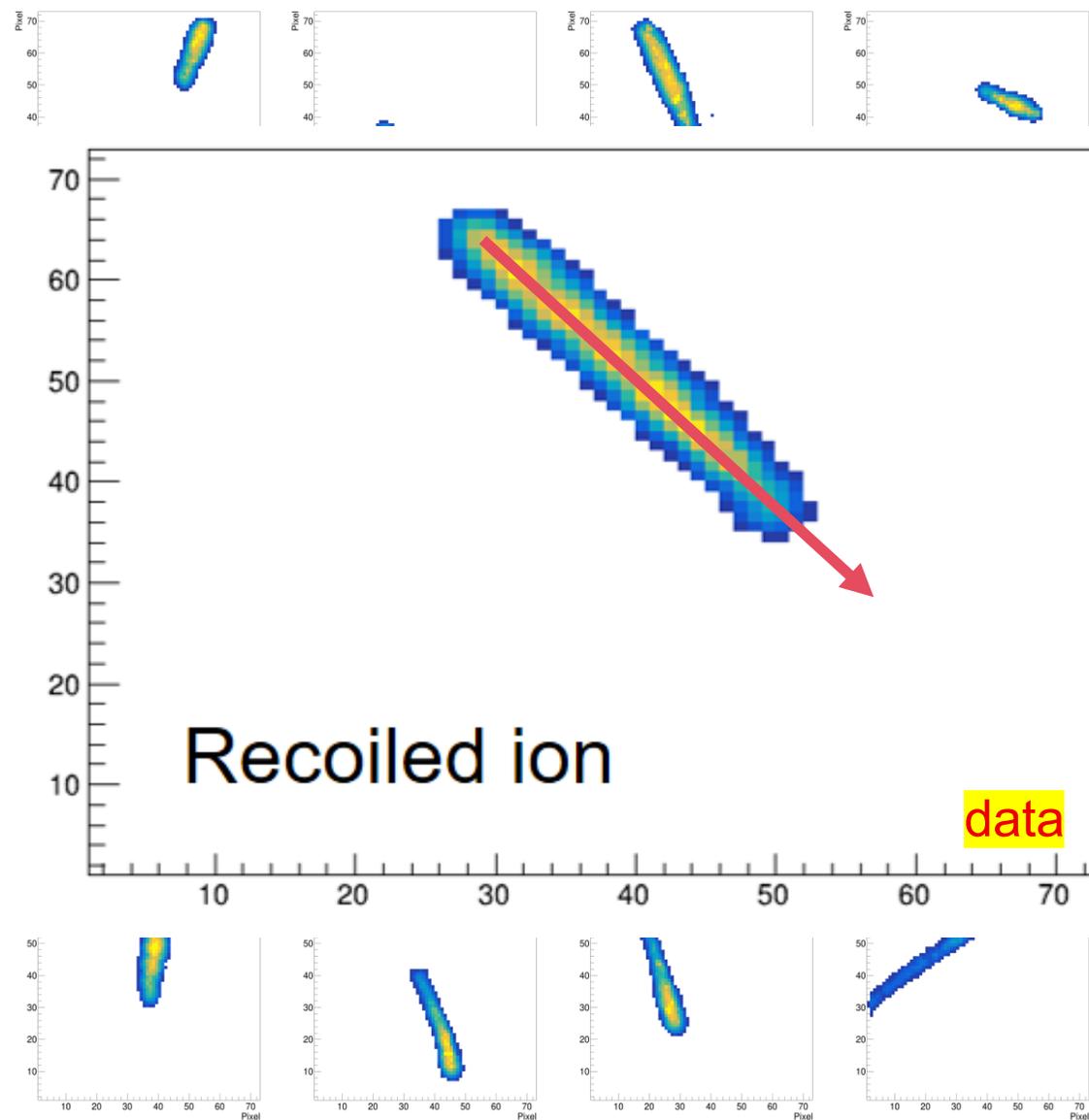
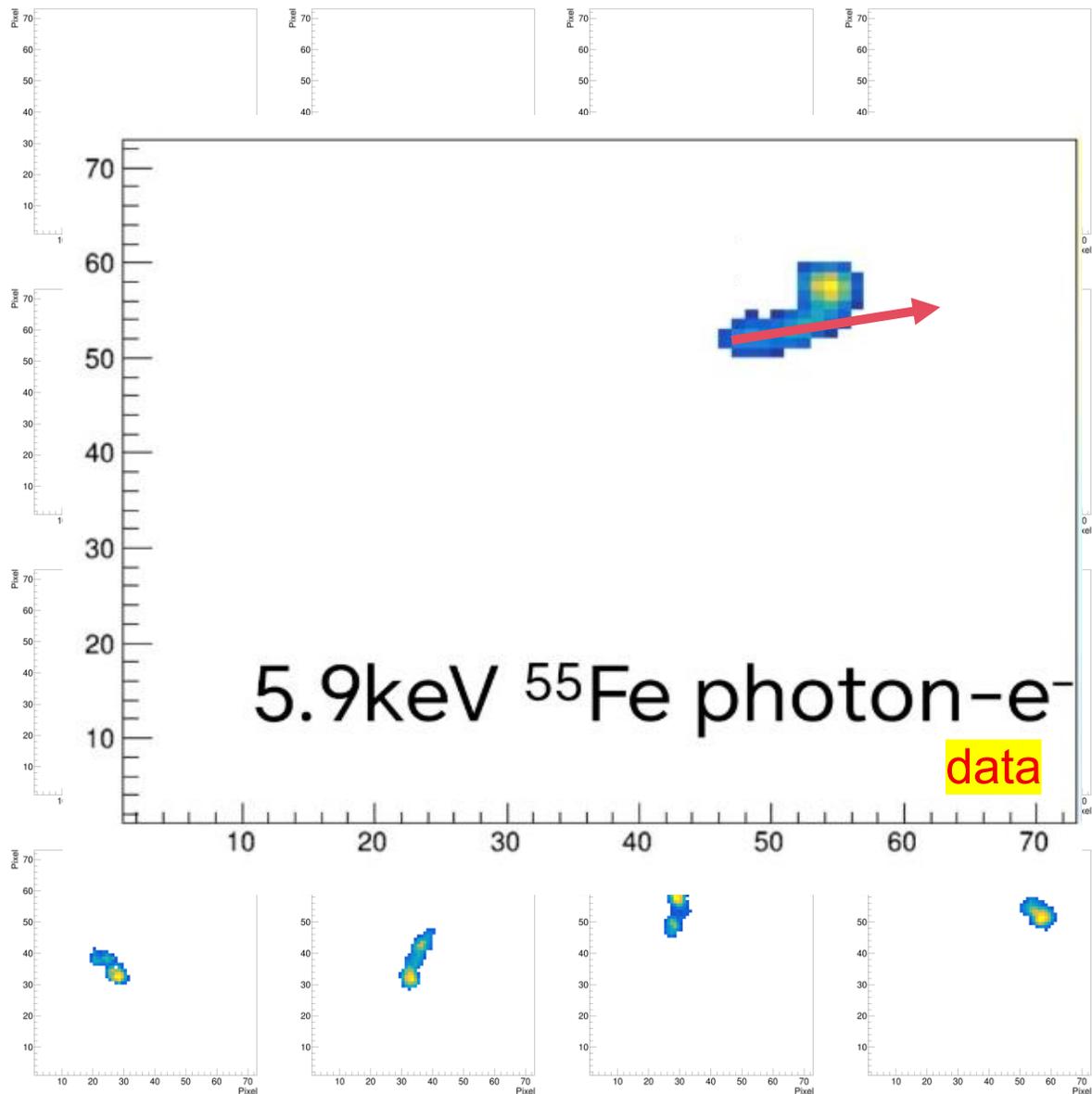


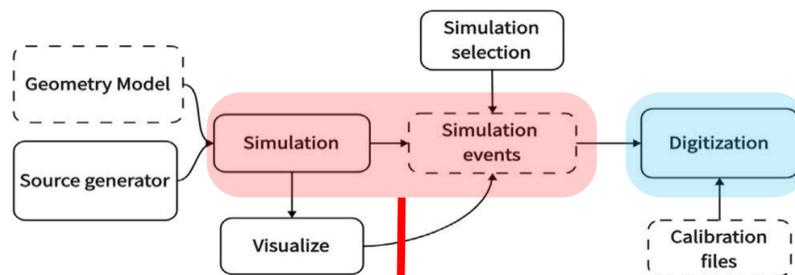
- Gain monitored with an ^{55}Fe .



- T & P are monitored.

电子径迹与反冲核径迹



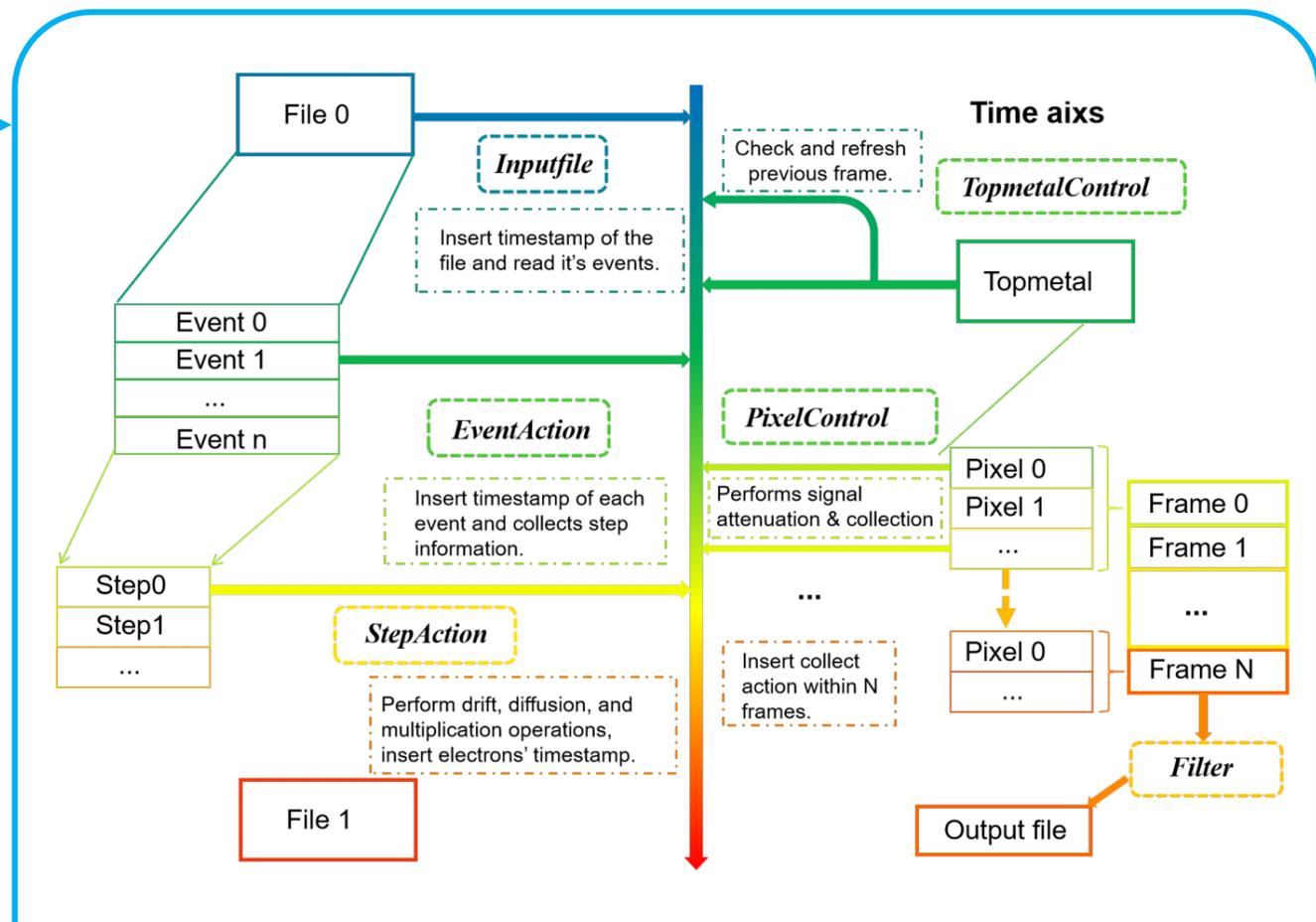


GEANT4
A SIMULATION TOOLKIT

ROOT

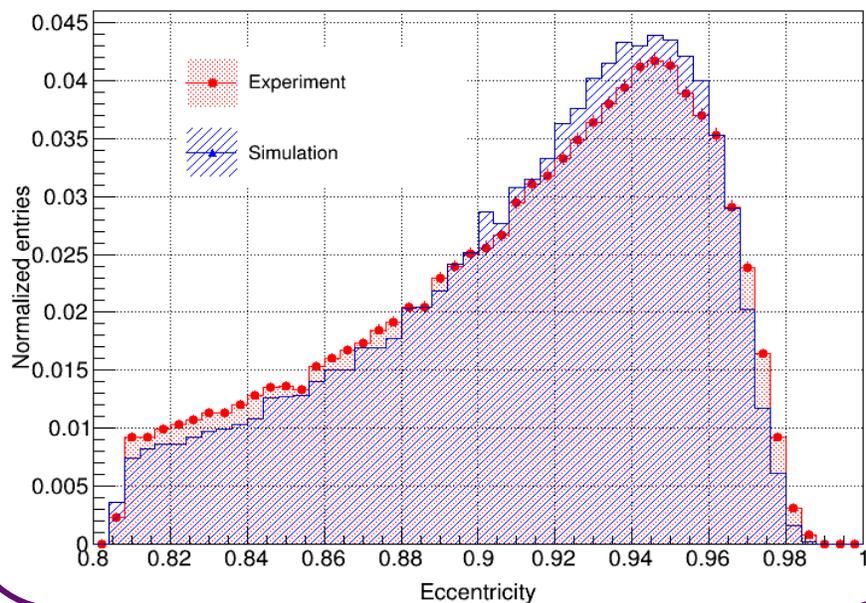
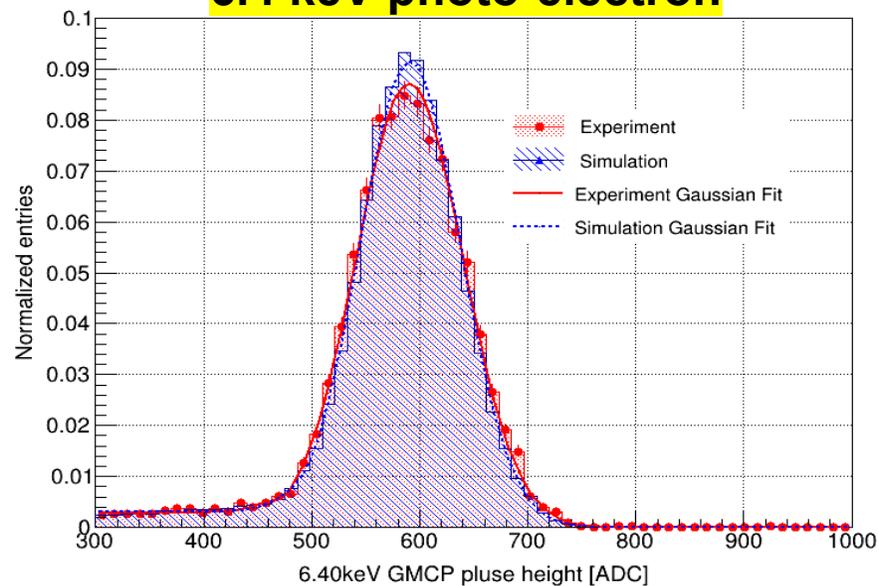
Two images showing detector components: a 3D wireframe model of a detector structure and a 2D image of a detector with a red box highlighting a specific region and a '5 cm' scale bar.

- ✓ 模拟探测器响应
- ✓ 提供MC模拟的truth信息

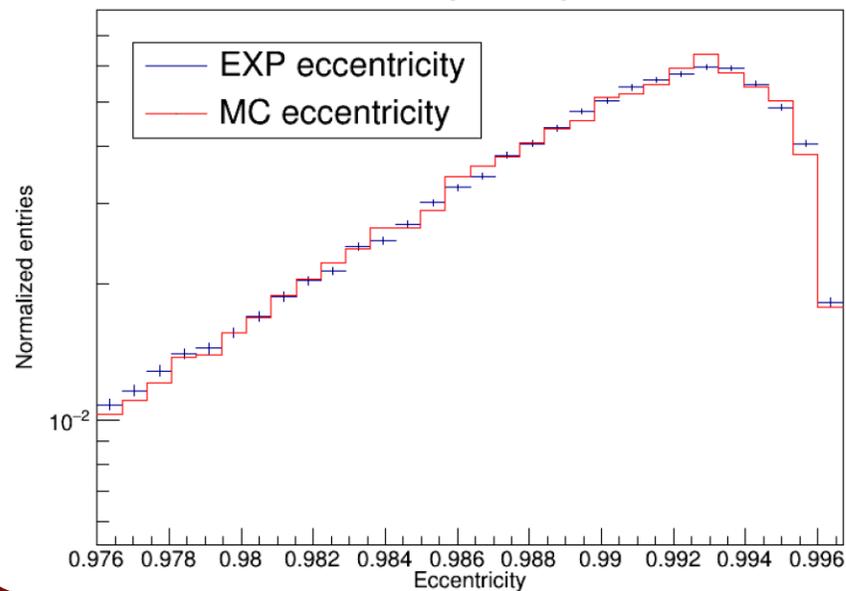
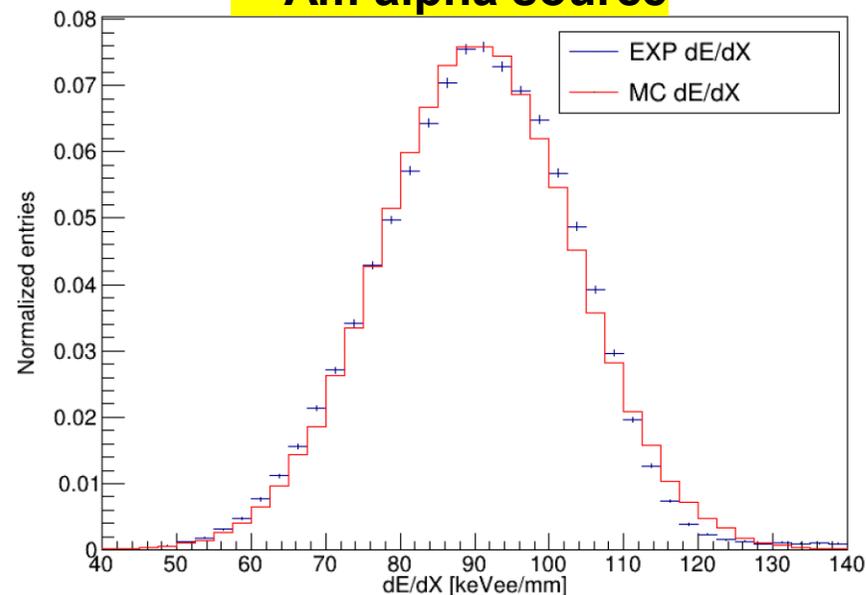


- ✓ 探测器的数字化模拟
- ✓ 模拟电子在探测器中的漂移、倍增及收集过程
- ✓ 模拟电子学对信号的采集及处理过程，并保存为与实验数据完全相同的格式输出

6.4 keV photo-electron



²⁴¹Am alpha source

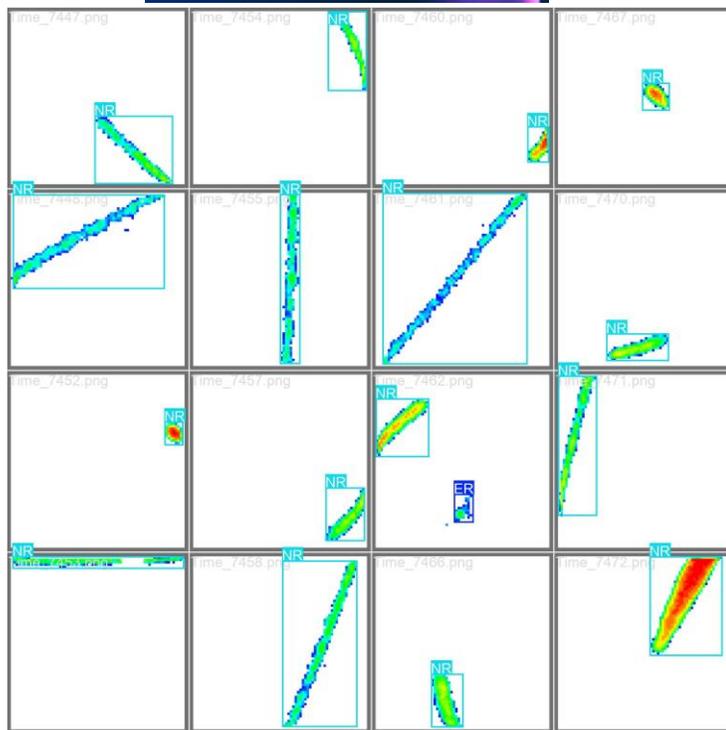




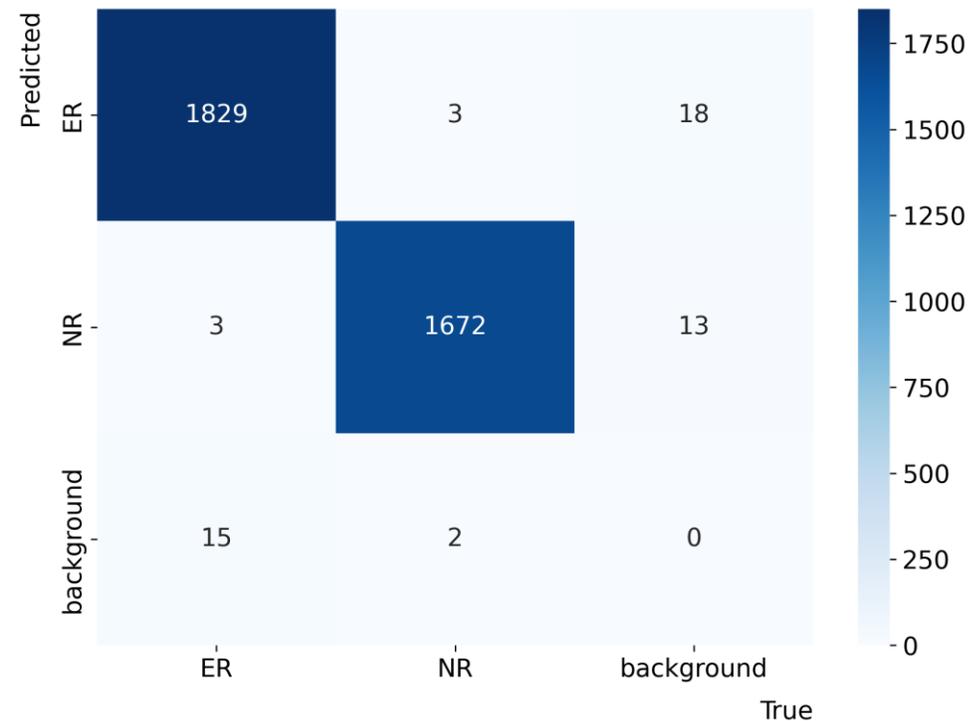
YOLOv8.2

Labeling

Dataset		Train	Valid
Exp	⁵⁵ Fe	3000	1493
	D-D	2994	1354
Sim	ER	1200	301
	NR	1200	301
Total		8394	3449



Training



*1 <https://github.com/ultralytics/ultralytics>



1. Search for the NR vertex through recursive iteration:

$$ADC \cdot \exp(d/d_0)$$

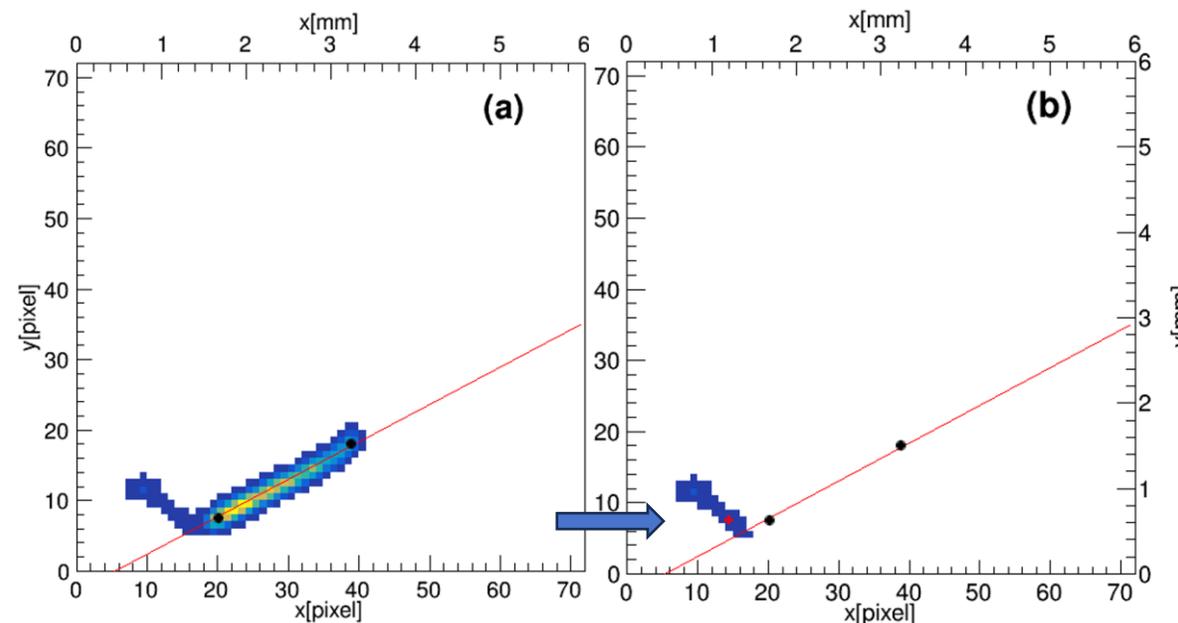
$$(x_0, y_0) \longrightarrow (x_n, y_n)$$

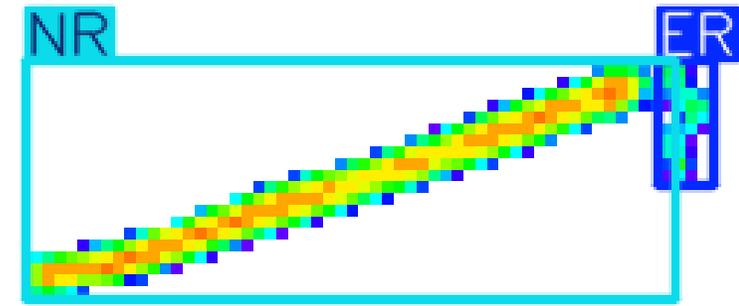
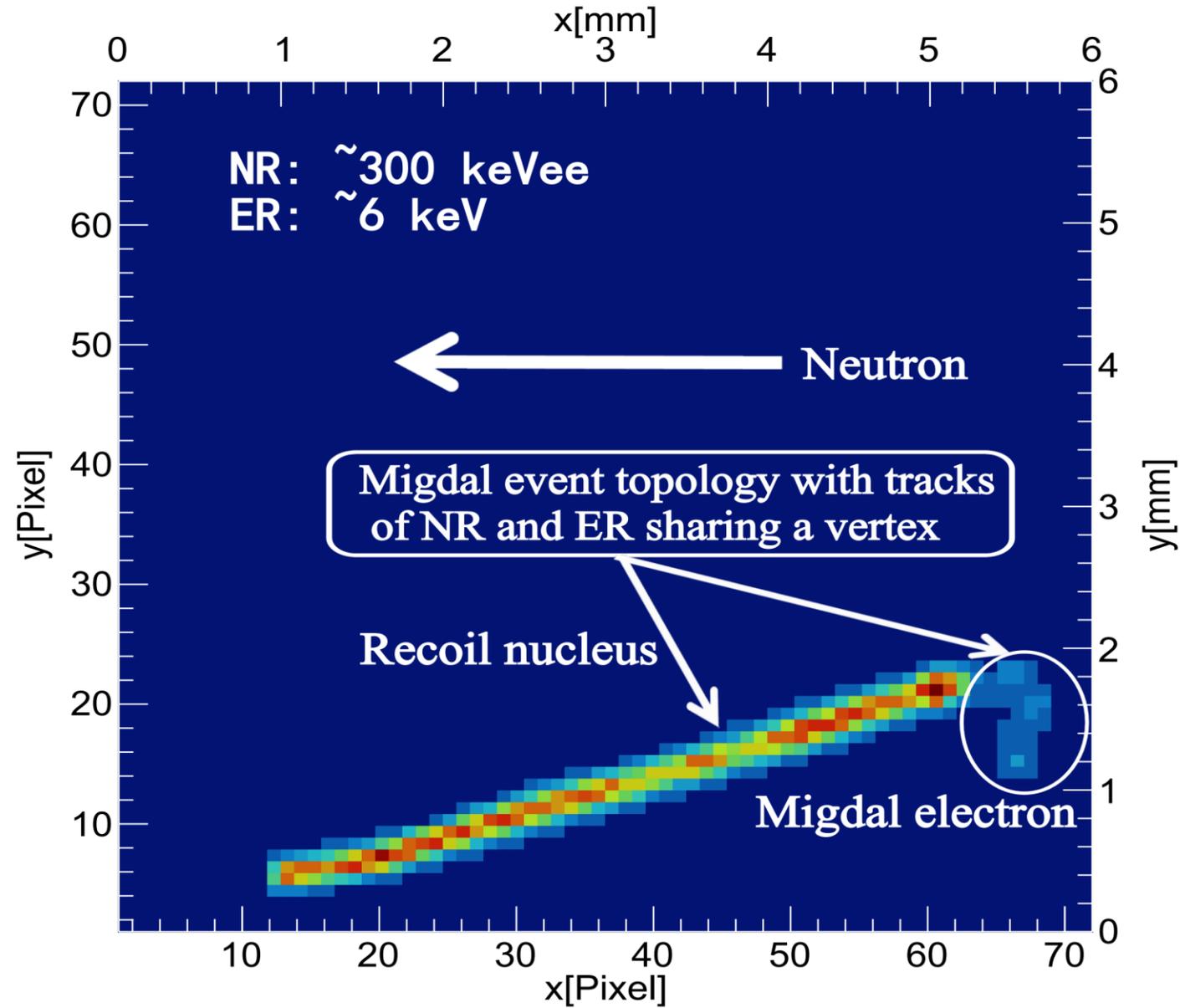
2. Fit the NR(direction, diffusion σ) and subtract it from the image.

3. Search for the electron vertex using **adaptive cutting algorithm**(Nucl. Sci. Tech.doi:10.1007/s41365-021-00903-0).

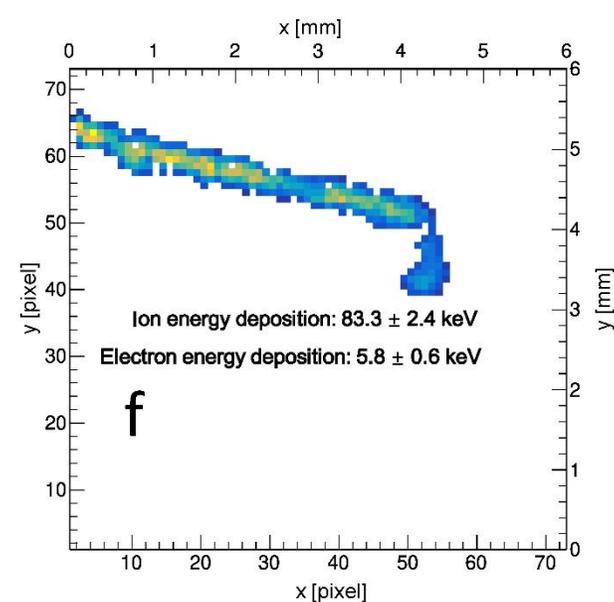
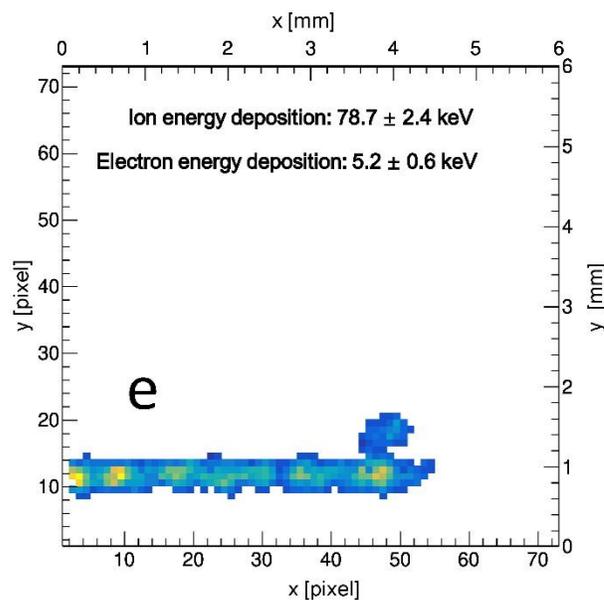
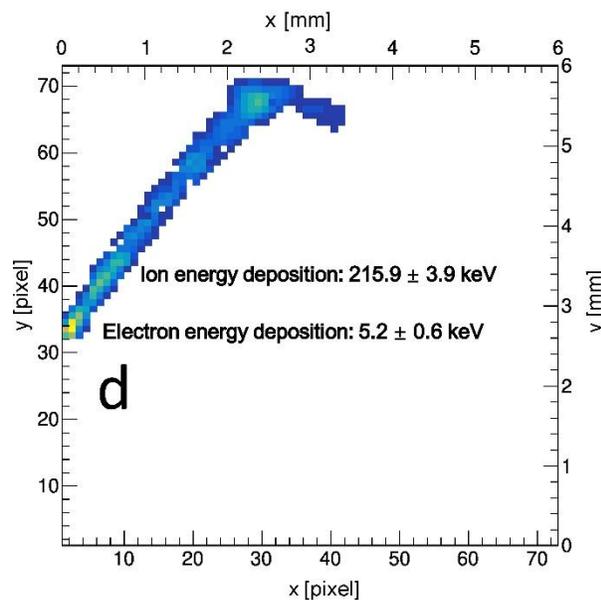
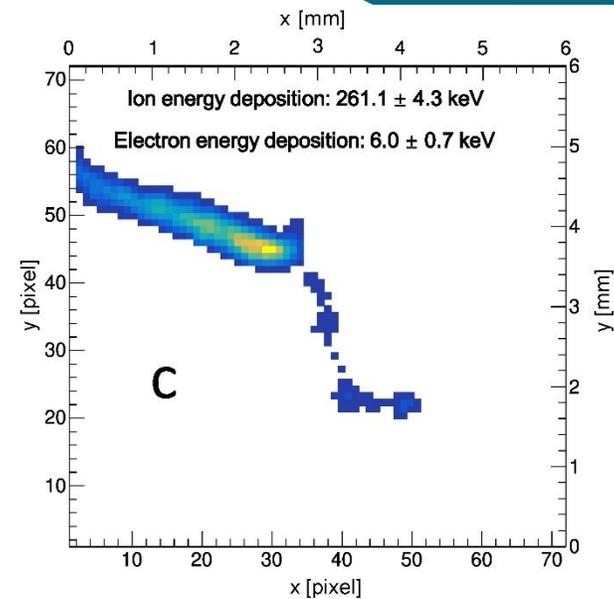
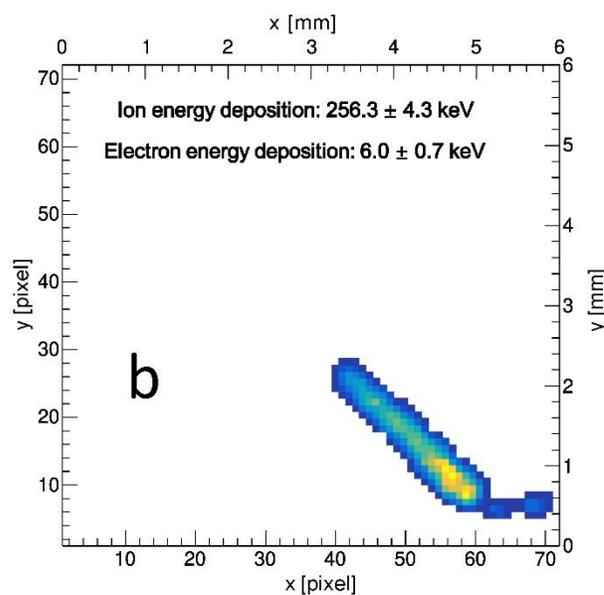
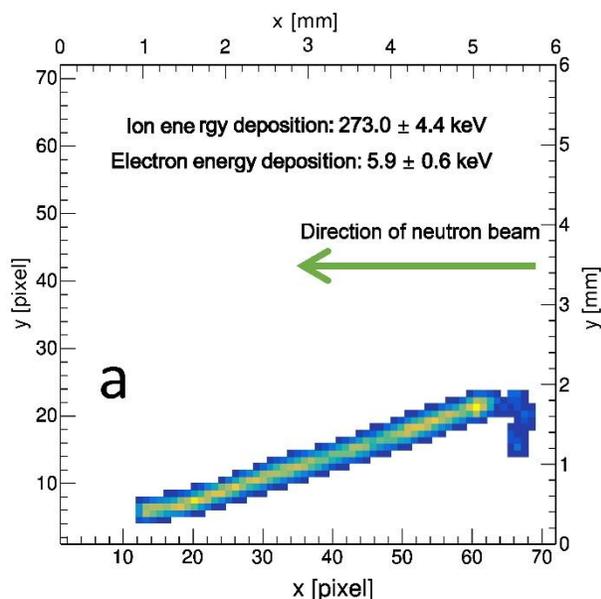
4. Determine whether the electron vertex is adjacent to the nucleon vertex.

$$R = \frac{D - 4\sigma}{L_{ER}}$$

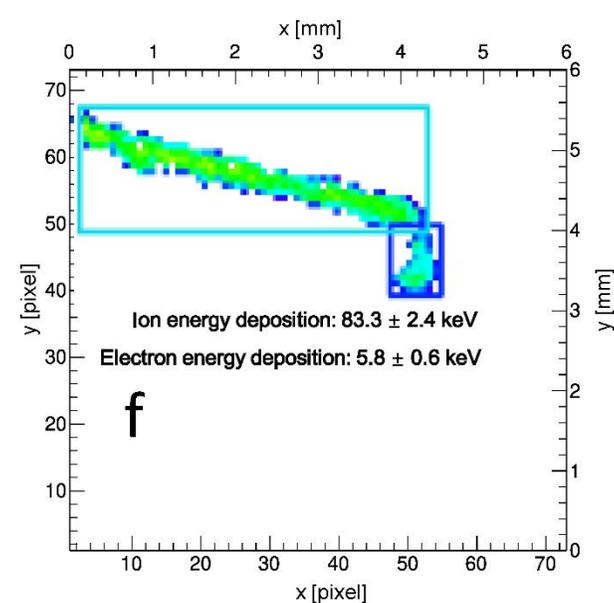
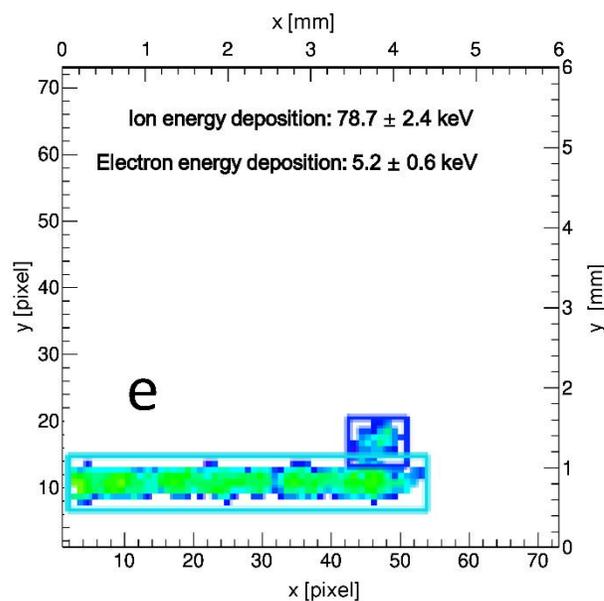
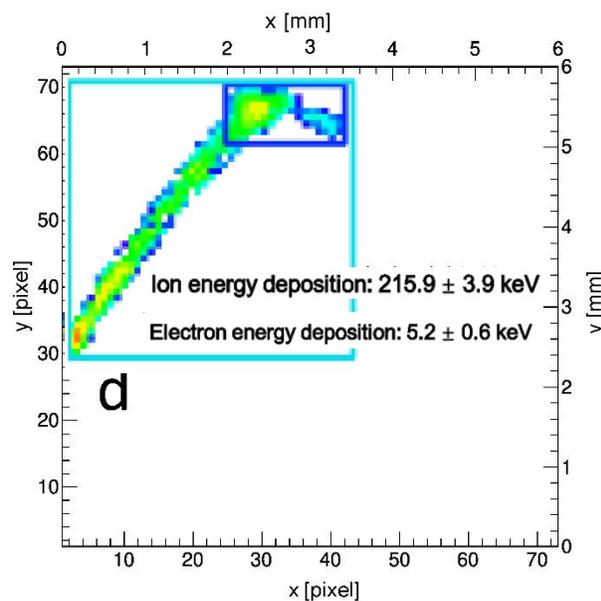
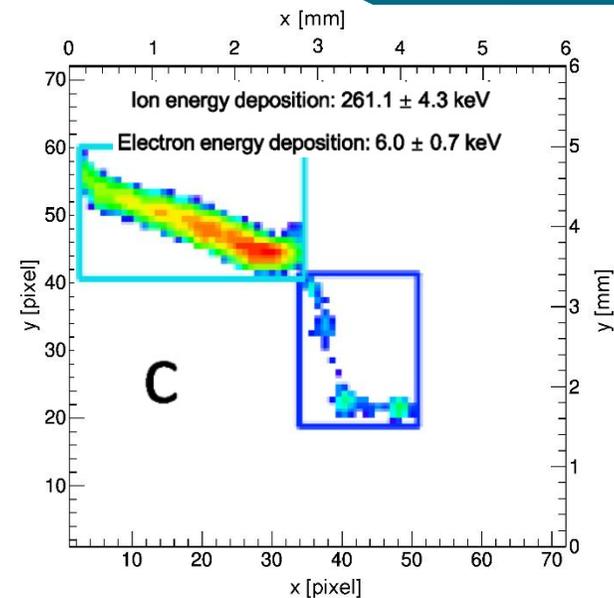
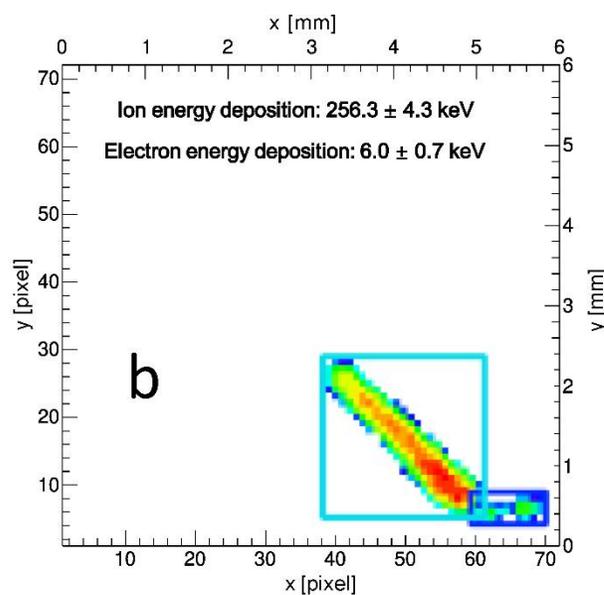
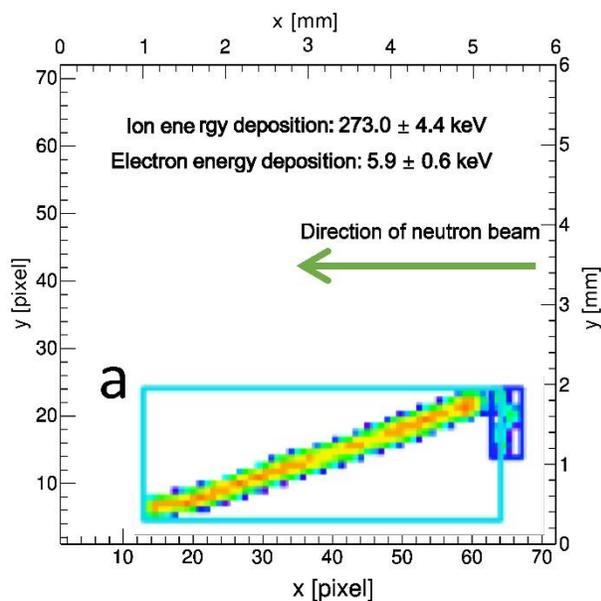




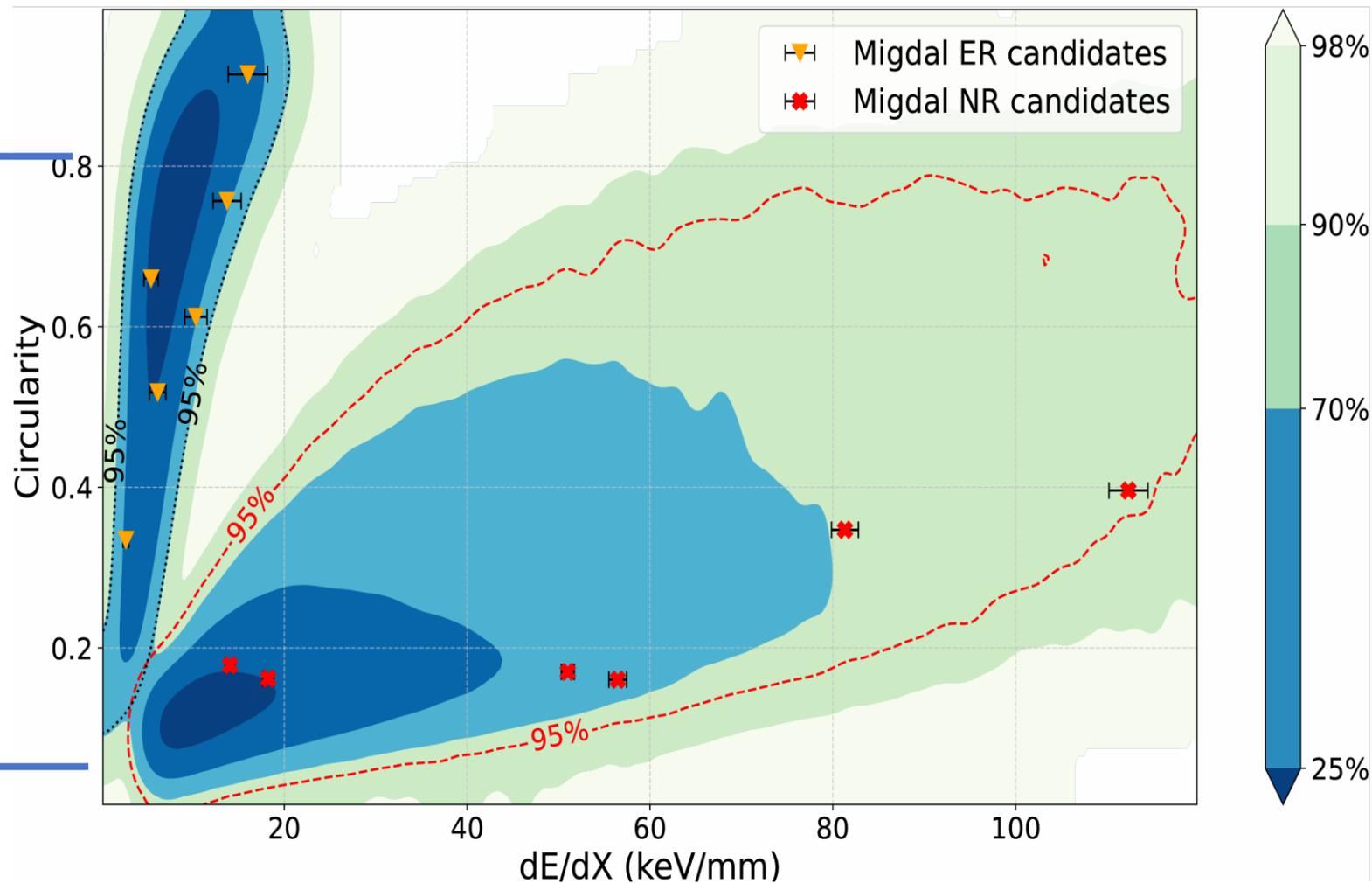
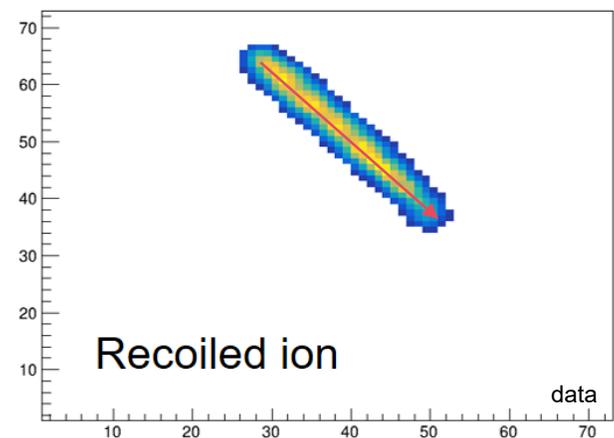
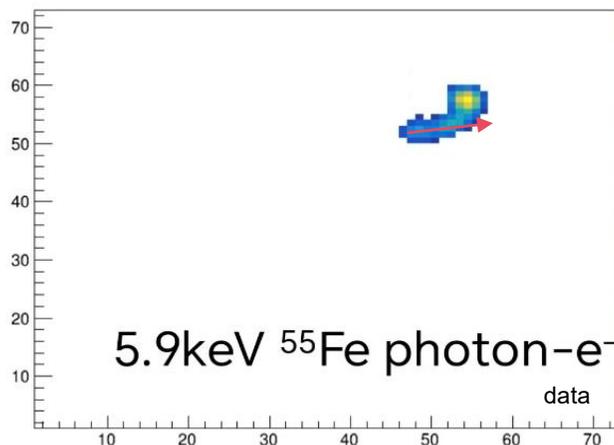
更多的Migdal事例!



全部通过YOLO识别!



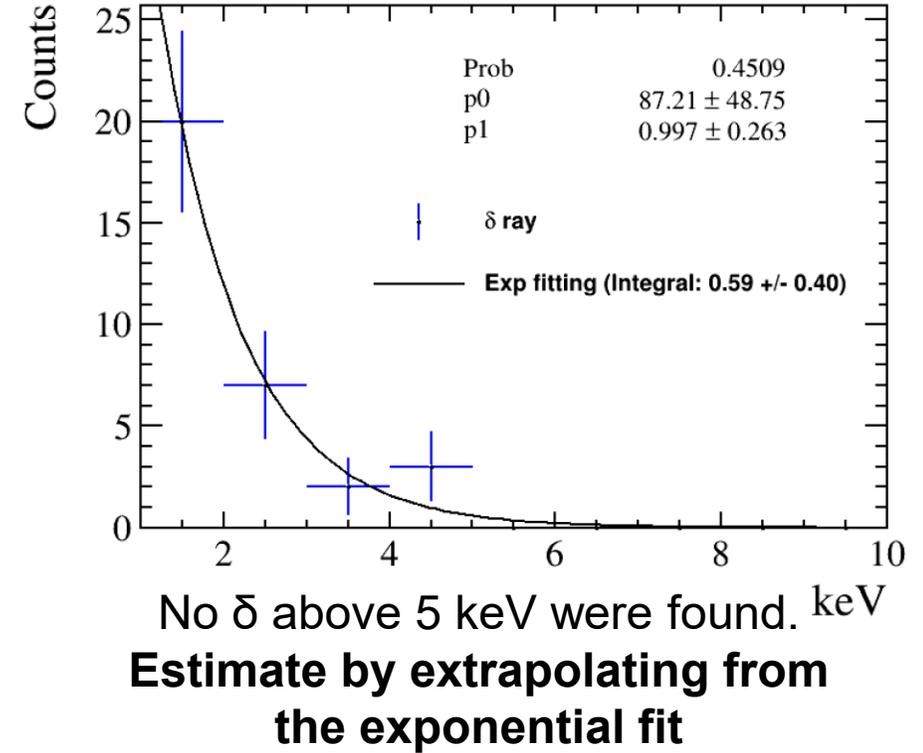
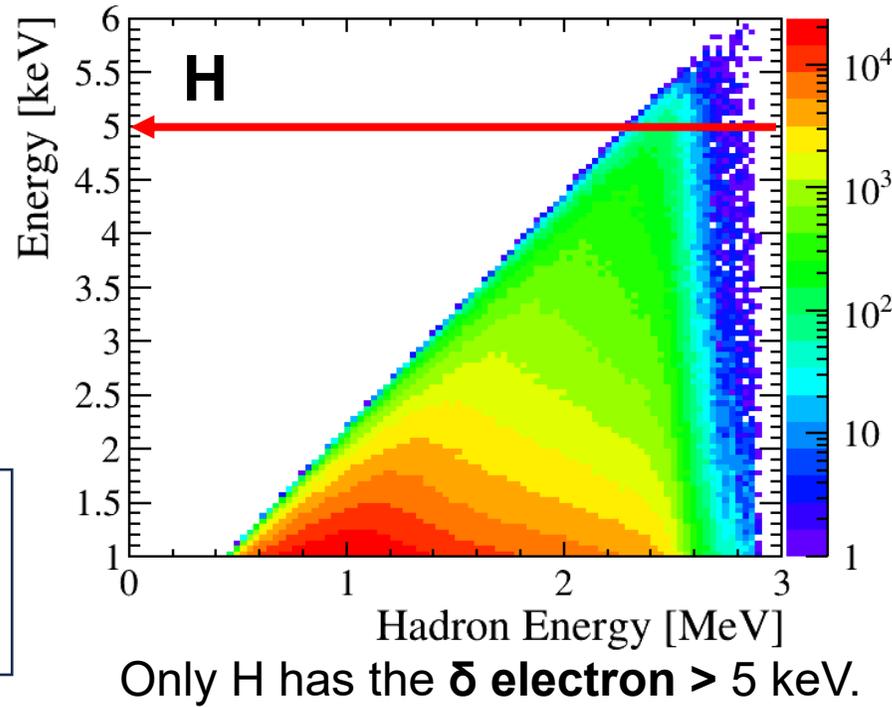
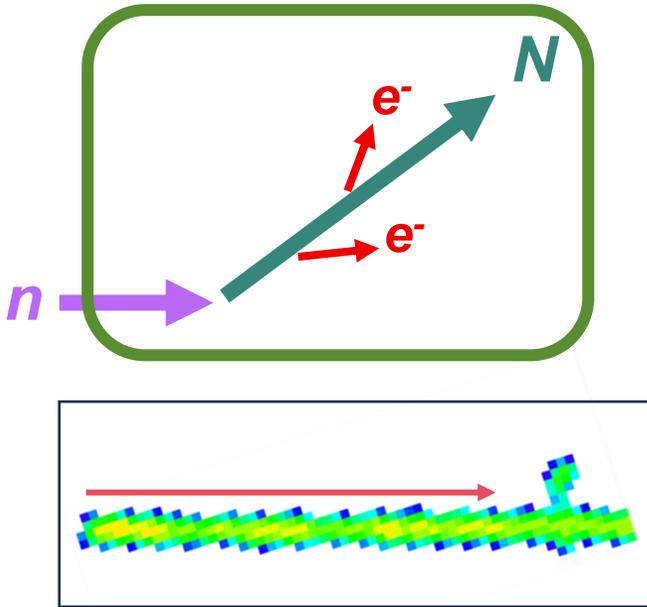
$$5 \text{ keV}_{ee} < E_e < 10 \text{ keV}_{ee}, E_{nr} > 35 \text{ keV}_{ee}$$



Migdal事例中的电子与 ^{55}Fe 源的光电子样本区间一致；核反冲径迹与中子数据中核反冲控制样本一致！

Background Component	Description	Expectation value (5 - 10 keV)	Method
Recoil induced δ ray	δ electron near NR track origin	$0.035 \pm 0.023(\text{stat.}) \pm 0.0068(\text{sys.})$	Data driven
Particle Induced X-ray Emission			
X-ray emission	Photoelectron near NR track origin	0	
Auger electrons	Auger electron near NR track origin	0	
Bremsstrahlung processes			
Quasi-Free Electron (QFEB)	Photoelectron near NR track origin	≈ 0	
Secondary Electron (SEB)	Photoelectron near NR track origin	≈ 0	
Atomic (AB)	Photoelectron near NR track origin	≈ 0	
Nuclear (NB)	Photoelectron near NR track origin	≈ 0	
Random track coincidences	Photo-/Compton electron near NR track	$0.180 \pm 0.022(\text{stat.}) \pm 0.042(\text{sys.})$	Data driven
Muon induced δ ray	δ electron near NR track origin	0.013	MC+Data
Gas radioactivity			
Trace contaminants	Electron from decay near NR track origin	$0.001 \pm 0.00087(\text{sys.})$	Data driven
Neutron activation	Electron from decay near NR track origin	≈ 0	
Secondary nuclear recoil fork	NR track fork near track origin	≈ 0	
Total background		$0.229 \pm 0.032(\text{stat.}) \pm 0.043(\text{sys.})$	

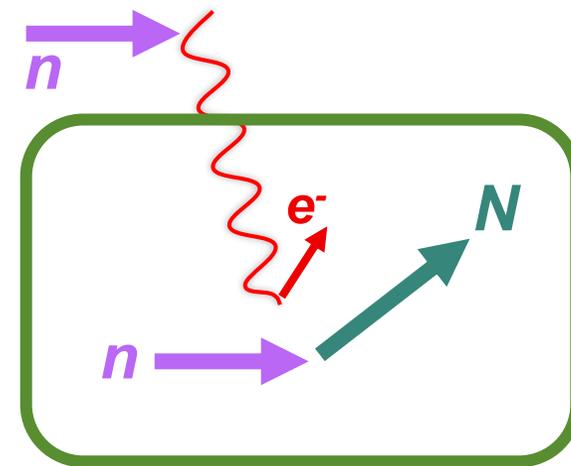
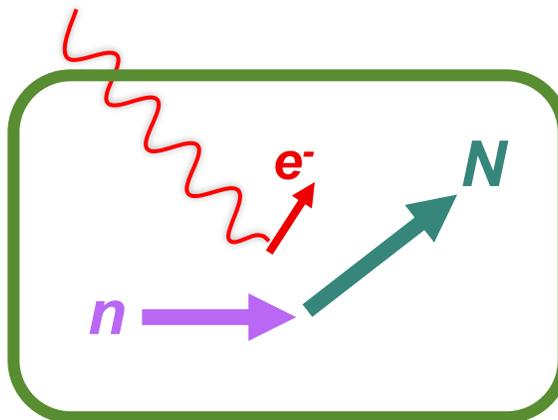
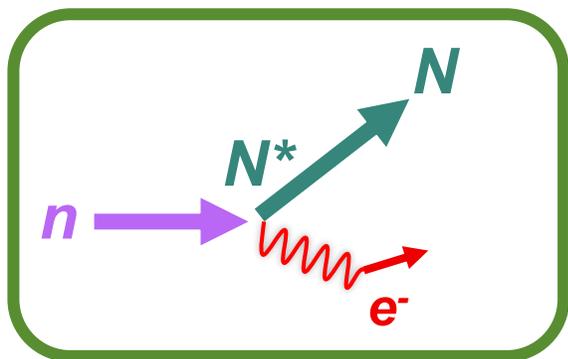
1. Delta电子本底



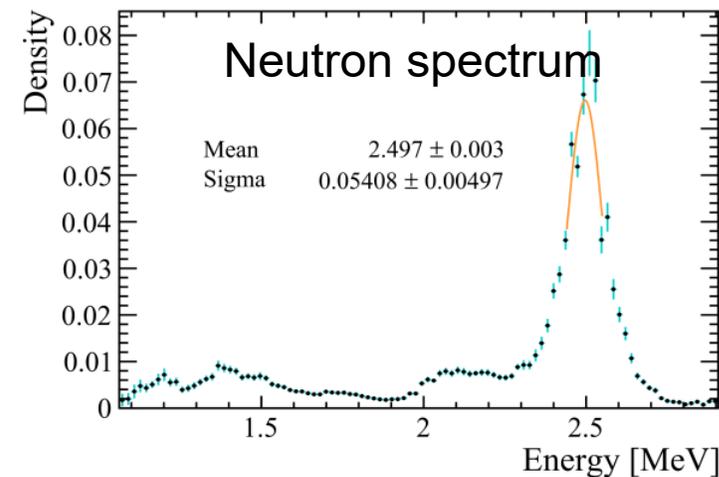
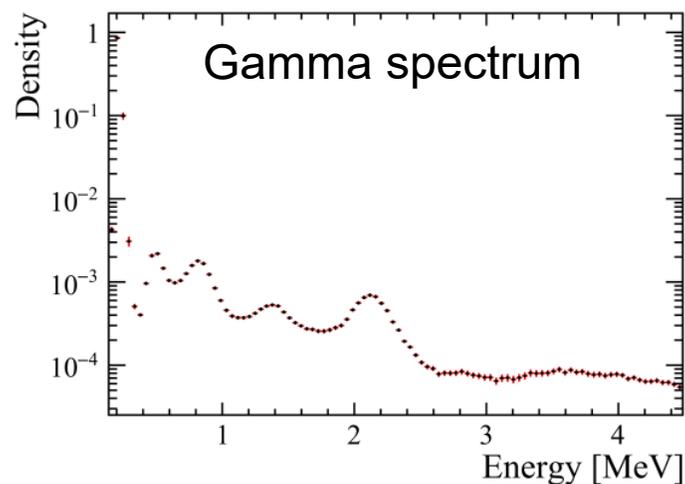
- Consider the selection efficiency for δ -electrons.
- Finally get: 0.035 ± 0.023 (stat.)

2. 偶然符合本底

Method 1: 液闪测得的 n/ γ 能谱代入GEANT4模拟



	NR	Compton e ⁻	photonEle
I	1	4.32×10^{-5}	1.06×10^{-5}
II	1	6.06×10^{-6}	$\sim 3.63 \times 10^{-8}$
III	1	3.11×10^{-6}	7.15×10^{-7}

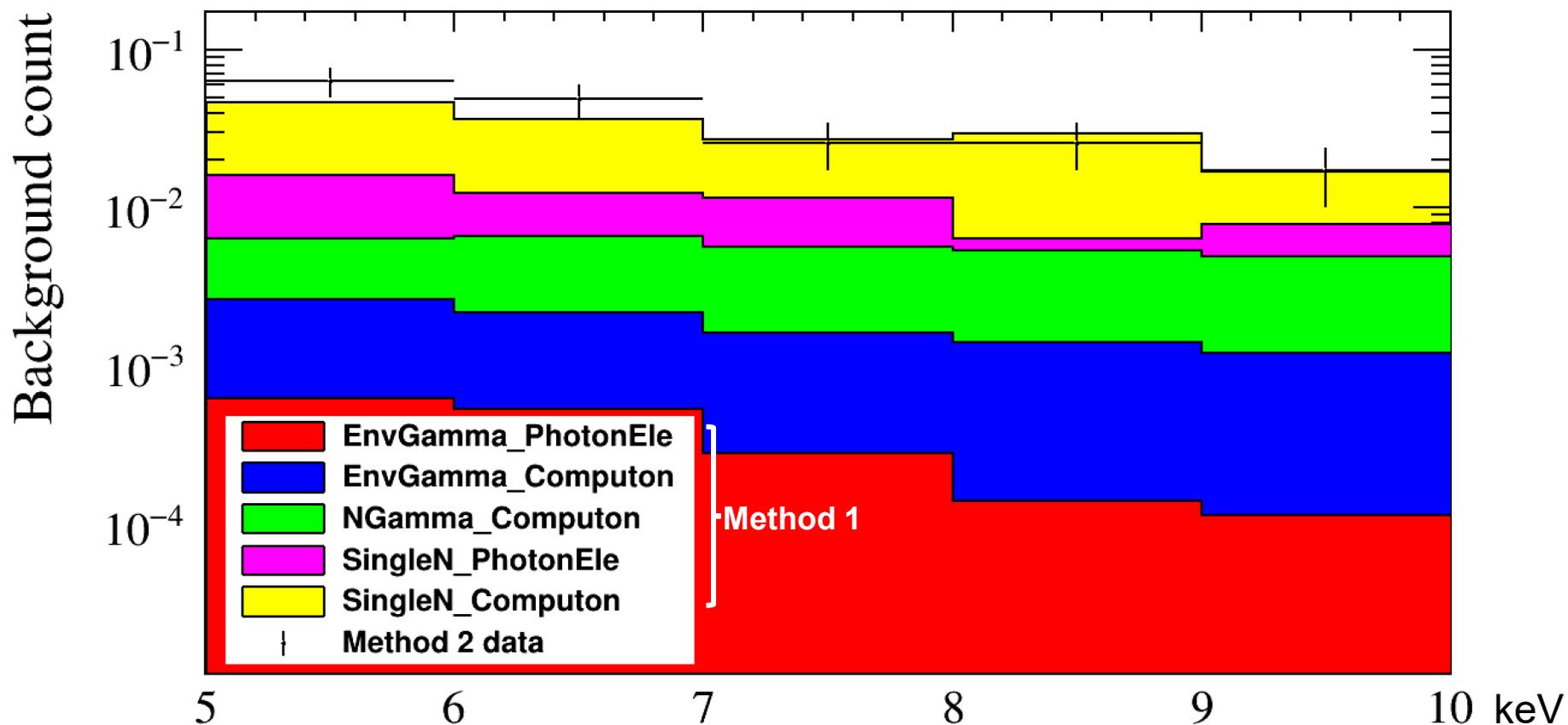


- 三种贡献之和为: 0.16 ± 0.01 (stat.)

2. 偶然符合本底

● Method 2: 数据驱动的方法

- 选取实验数据中的核径迹控制样本与光电子径迹在同一帧上的事例.
- 考虑偶然符合在统一顶点的几率,得到最终本底结果为: $0.180 \pm 0.022(\text{stat.}) \pm 0.042(\text{sys.})$



方法一与方法二的结果在统计误差范围内一致。

- 定义概率密度函数

$$f(x, y|\mu, b) = \frac{(\mu + b)^x}{x!} e^{-(\mu+b)} \cdot \frac{1}{\sqrt{2\pi}\sigma_b} \exp\left(-\frac{(y-b)^2}{2\sigma_b^2}\right)$$

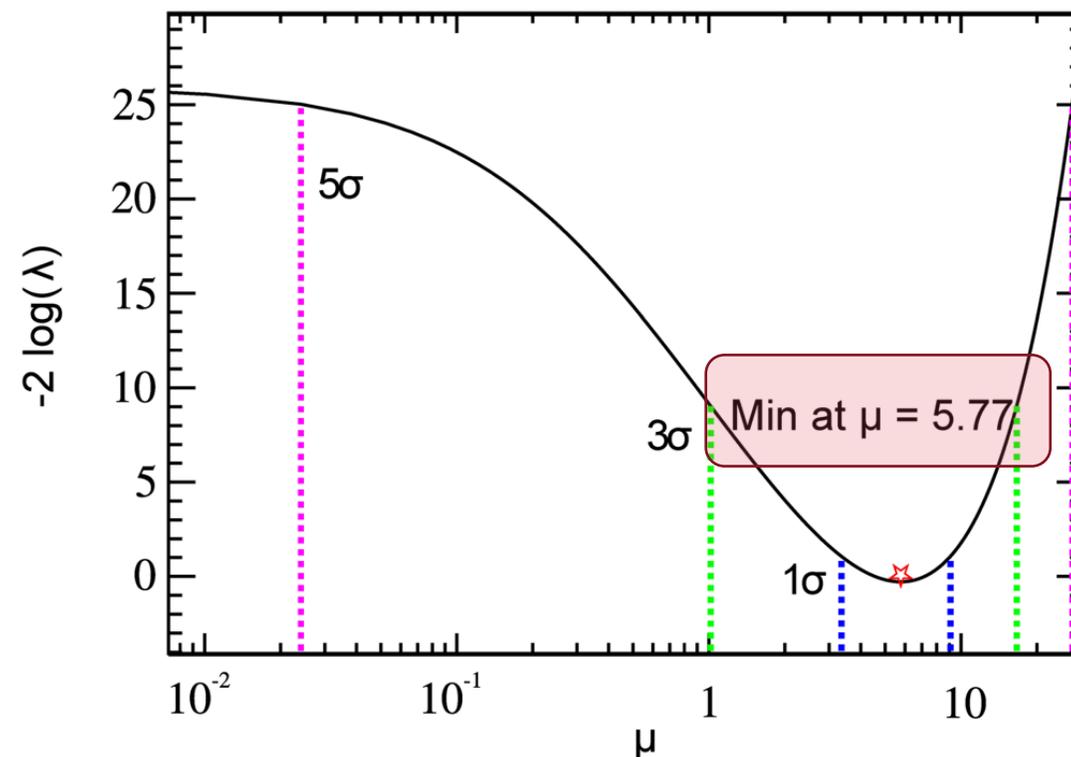
- 构造最大似然函数

$$L(\mu, b|x, y) = \prod_{i=1}^n f(x, y|\mu, b)$$

- 假设检验

- $H_0: \mu = 0$ versus $H_a: \mu \neq 0$

Background: $0.229 \pm 0.032(\text{stat.}) \pm 0.043(\text{sys.})$



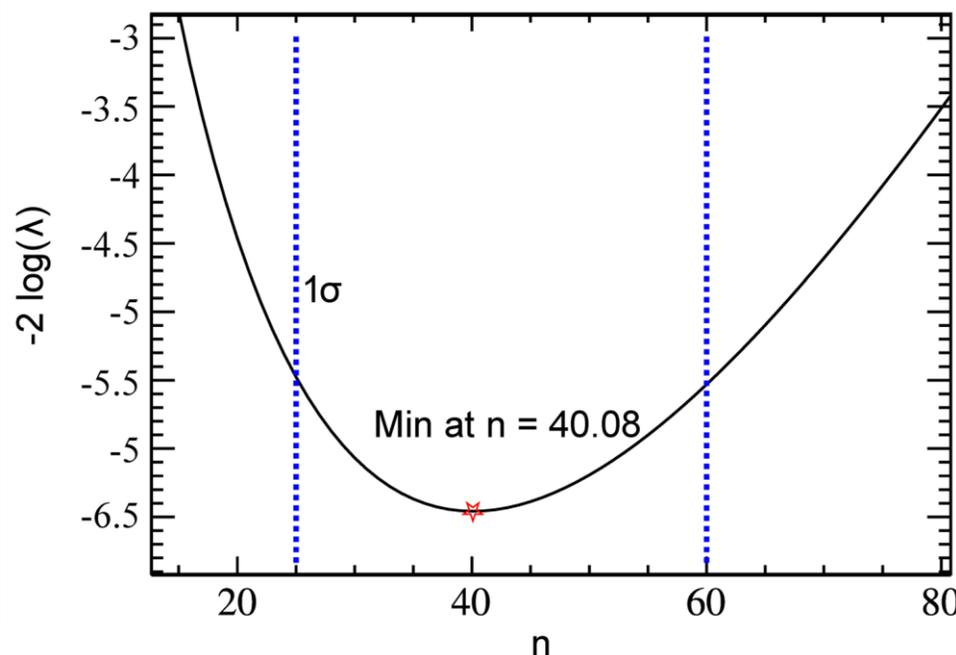
在该本底水平下，观测到5.77个事例达到5 σ

- Migdal过程截面与核反冲截面的比值:

$$P_{\text{Migdal}}(5\text{keV} < \text{ER} < 10\text{keV}, \text{NR} > 35\text{keVee}) = \frac{\left(\frac{n_{\text{obs}}^{\text{ER}} - n_{\text{obs}}^{\text{bg}}}{\varepsilon_{\text{acc}} \varepsilon_{\text{NR}} \varepsilon_{\text{ER}}} \right)}{\left(\frac{n_{\text{tot}}^{\text{NR}}}{\varepsilon_{\text{acc}} \varepsilon_{\text{NR}}} \right)} = \frac{(n_{\text{obs}}^{\text{ER}} - n_{\text{obs}}^{\text{bg}})}{\varepsilon_{\text{ER}} n_{\text{tot}}^{\text{NR}}}$$

- 参数:

	Efficiency/Count	Statistical Error	Systematic Error
Efficiency ε_{ER}	14.4%	$\pm 0.1\%$	$\pm 1.9\%$
$n_{\text{tot}}^{\text{NR}}$	8.17×10^5	± 903	± 35880
$n_{\text{obs}}^{\text{ER}}$	6	± 2.449	
$n_{\text{obs}}^{\text{bg}}$	0.229	± 0.032	± 0.043



- 上下限的计算方式:

$$\Delta P_{\pm} = \sqrt{\left(\frac{n_{\text{min}} - n_{\text{ul/l}}}{n_{\text{min}}} \right)^2 + \left(\frac{n_{\text{tot}}^{\text{NR}} \text{error}}{n_{\text{tot}}^{\text{NR}}} \right)^2} \cdot \frac{n_{\text{min}}}{n_{\text{tot}}^{\text{NR}}}$$

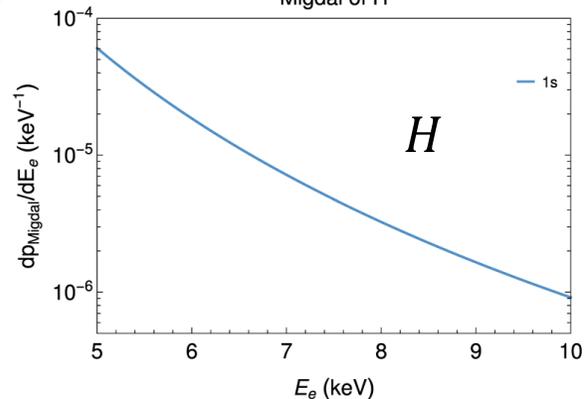
最终结果: $4.91_{-1.87}^{+2.56} \times 10^{-5}$

$$\sum_{nl} \frac{dp^i(nl \rightarrow E_e)}{dE_e}$$

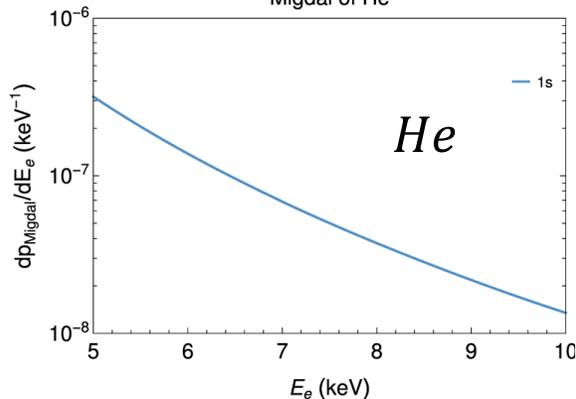
初态为 (n, l) 的电子跃迁到具有 E_e 能量末态的几率。



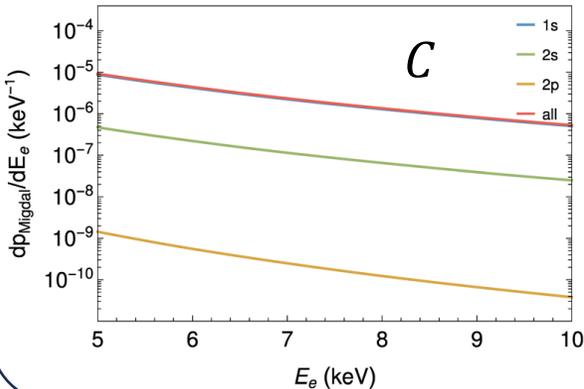
Migdal of H



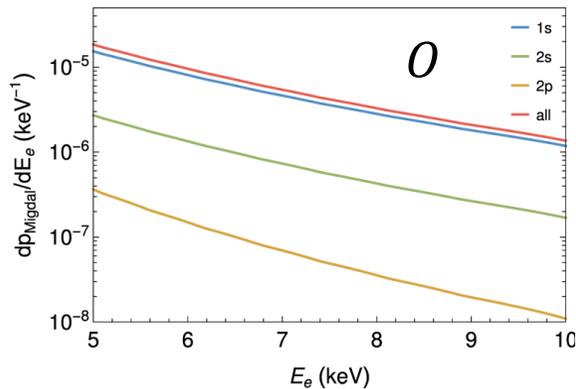
Migdal of He



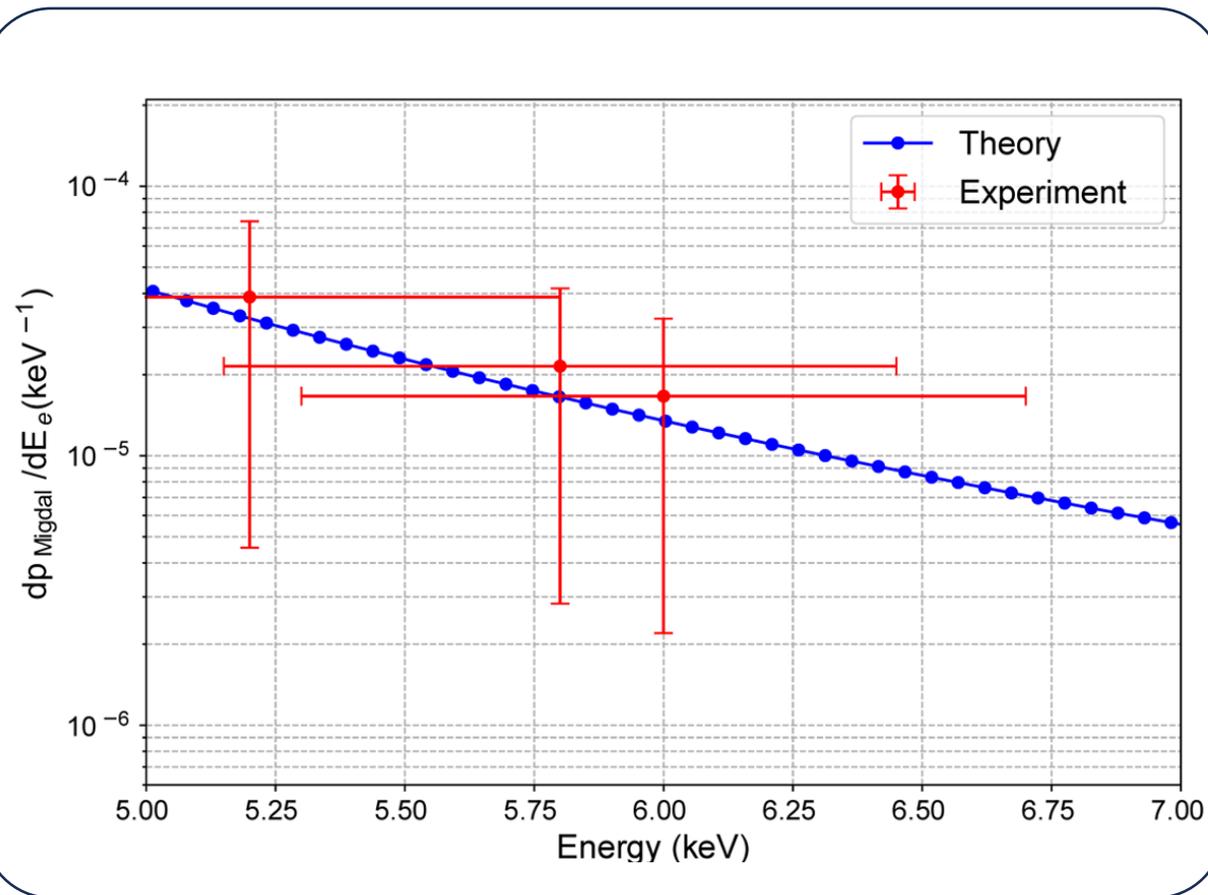
Migdal of C



Migdal of O



每种元素的跃迁几率



总跃迁几率



- 首次直接证实了 1939年利用量子力学预言的Migdal效应，也为轻暗物质探测突破阈值瓶颈提供了关键支撑。
- 自主研发了“微结构气体探测器+像素读出芯片”组合的超灵敏探测装置，相当于可拍摄“单原子释放电子过程”的照相机。
- 正在为第二阶段实验做准备，与暗物质直接探测团队合作，精确测量Migdal效应截面，并针对更多与暗物质实验相关的元素，开展Migdal截面的测量工作。



谢谢!

