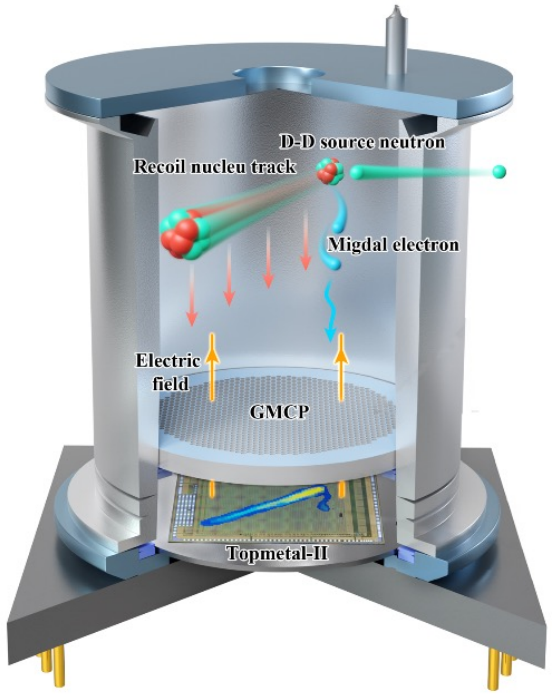
中子-原子核散射中的Migdal效应直接观测



郑阳恒

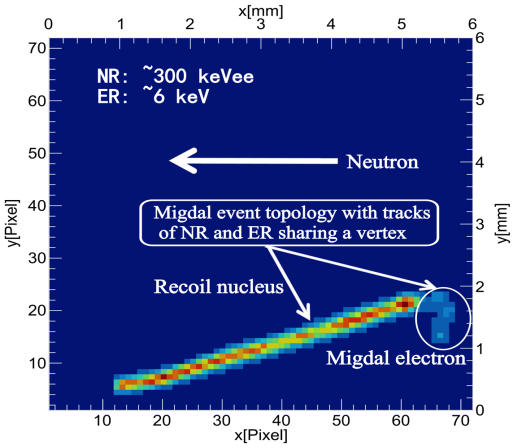
中国科学院大学

代表MARVEL 实验合作组

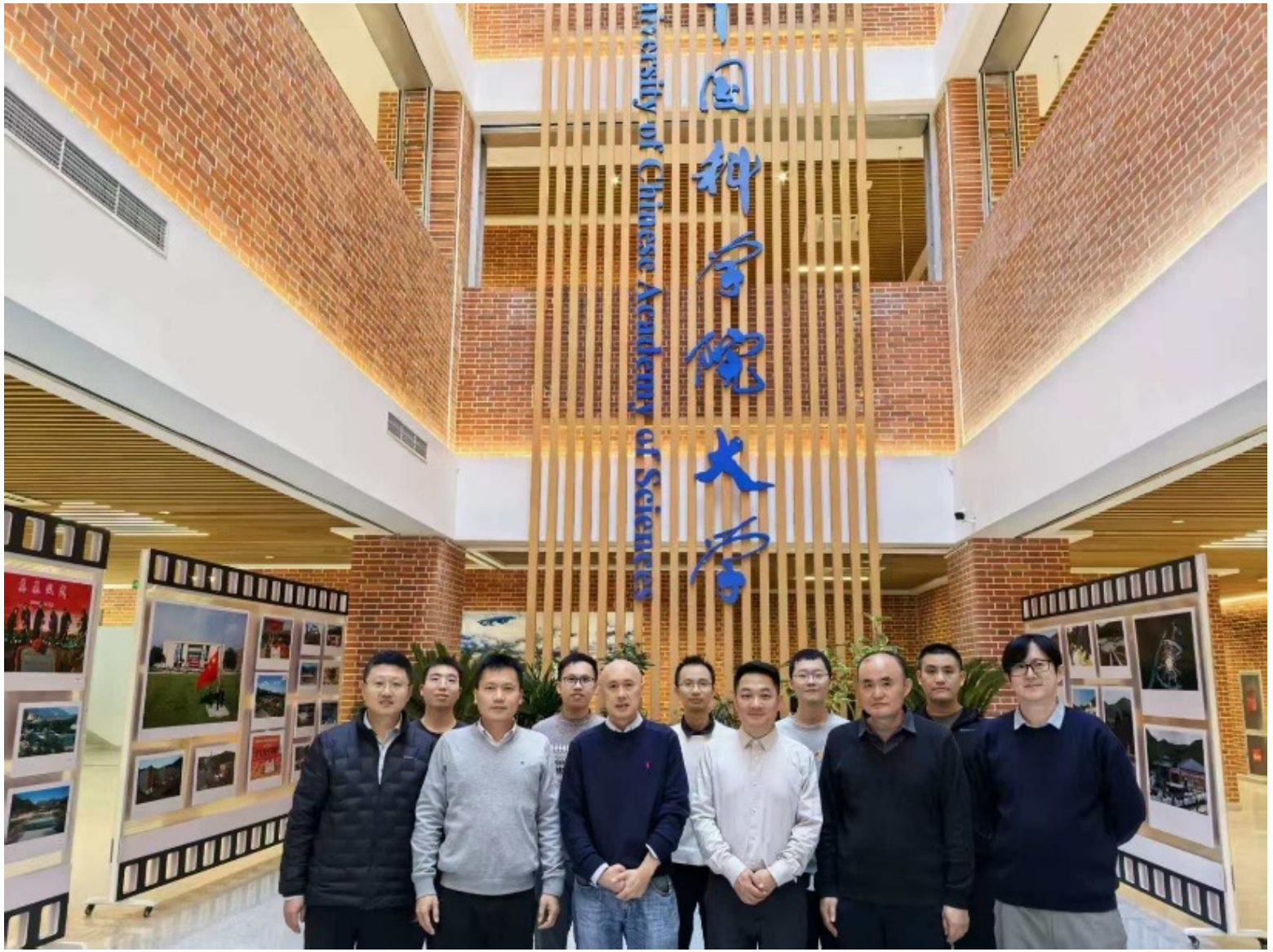
(MigdAl pRocess Validation by nEutruaL scattering)

高能与低能核物理交叉学术研讨会

华东师范大学，2026年5月16日

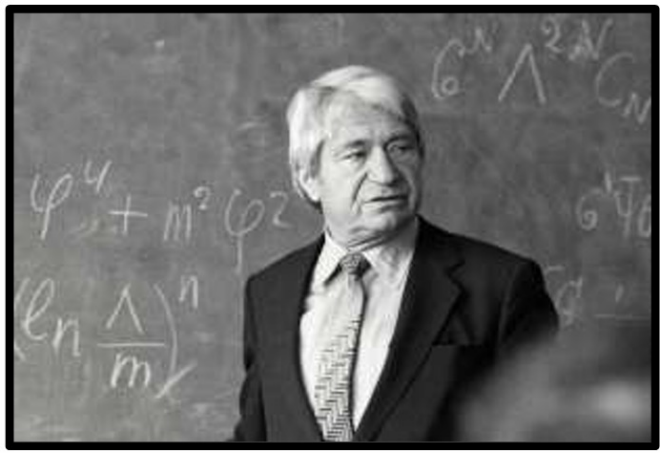


MARVEL实验合作组



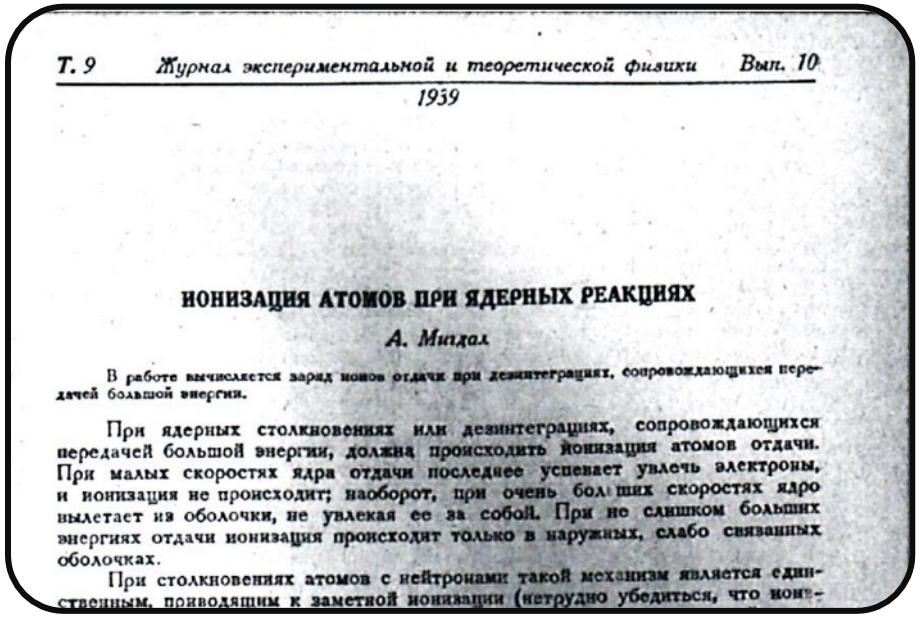
- University of Chinese Academy of Sciences (UCAS)
- Guangxi University (GXU)
- Central China Normal University (CCNU)
- Lanzhou University (LZU)
- Nanjing Normal University (NNU)
- Yantai University (YTU)

Migdal 效应（理论）– 电子的抖出



Consider a rapid intranuclear process (e.g. α decay or fission) that abruptly changes Coulomb potential. The atomic electrons instantaneously experience the new potential; some electrons cannot adjust to the new potential well immediately, and are therefore excited or ejected.

最早由Arkady Migdal于 1939 至 1940 年间提出



Т. 9 Журнал экспериментальной и теоретической физики Вып. 10

1939

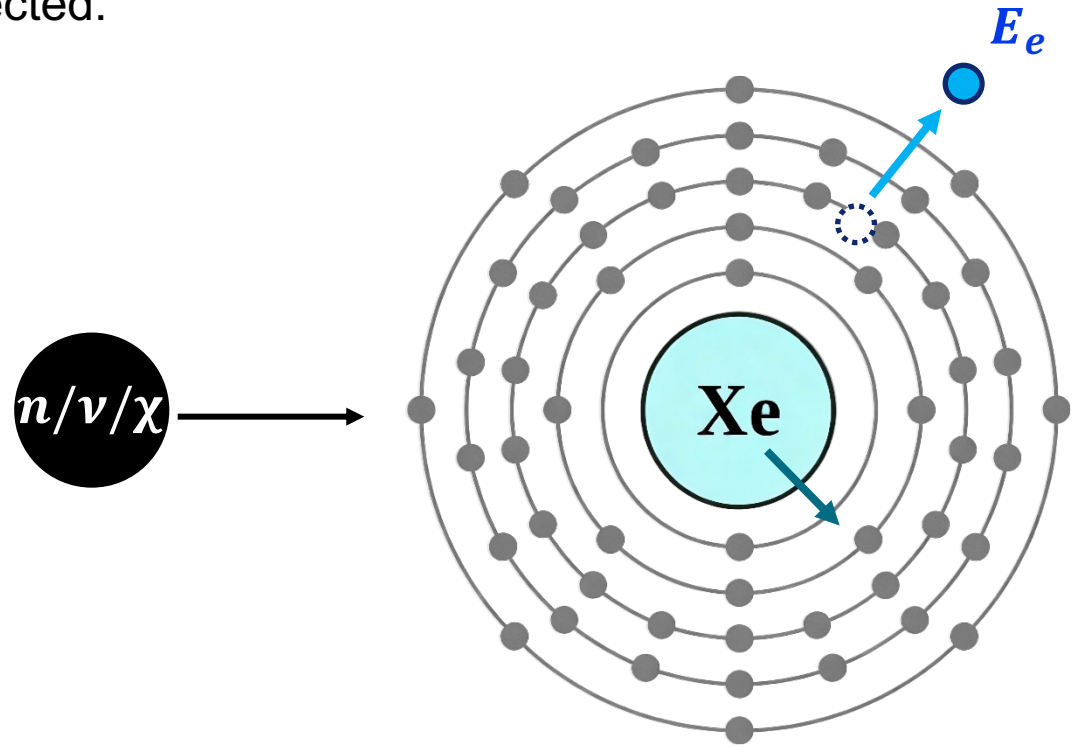
ИОНИЗАЦИЯ АТОМОВ ПРИ ЯДЕРНЫХ РЕАКЦИЯХ

А. Мигдал

В работе вычисляется заряд ионов отдачи при дезинтеграциях, сопровождающихся передачей большой энергии.

При ядерных столкновениях или дезинтеграциях, сопровождающихся передачей большой энергии, должна происходить ионизация атомов отдачи. При малых скоростях ядра отдачи последнее успевает увлечь электроны, и ионизация не происходит; наоборот, при очень больших скоростях ядро вылетает из оболочки, не увлекая ее за собой. При не слишком больших энергиях отдачи ионизация происходит только в наружных, слабо связанных оболочках.

При столкновениях атомов с нейтронами такой механизм является единственным, приводящим к заметной ионизации (нетрудно убедиться, что ион-



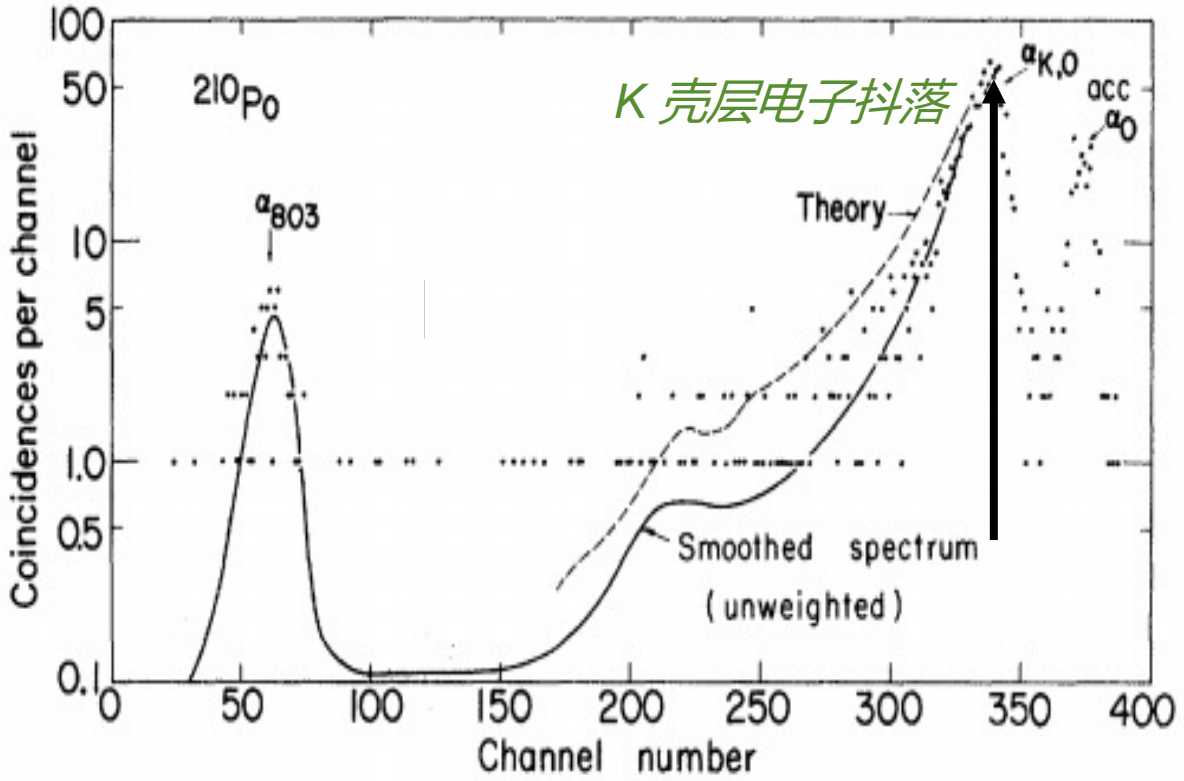
自1939年提出至今80余年，Migdal电子从未被直接观测到！

难点：需要研发能拍摄“单原子释放电子过程”的超敏感探测器，和创新的实验方法。

Migdal 效应的间接观测

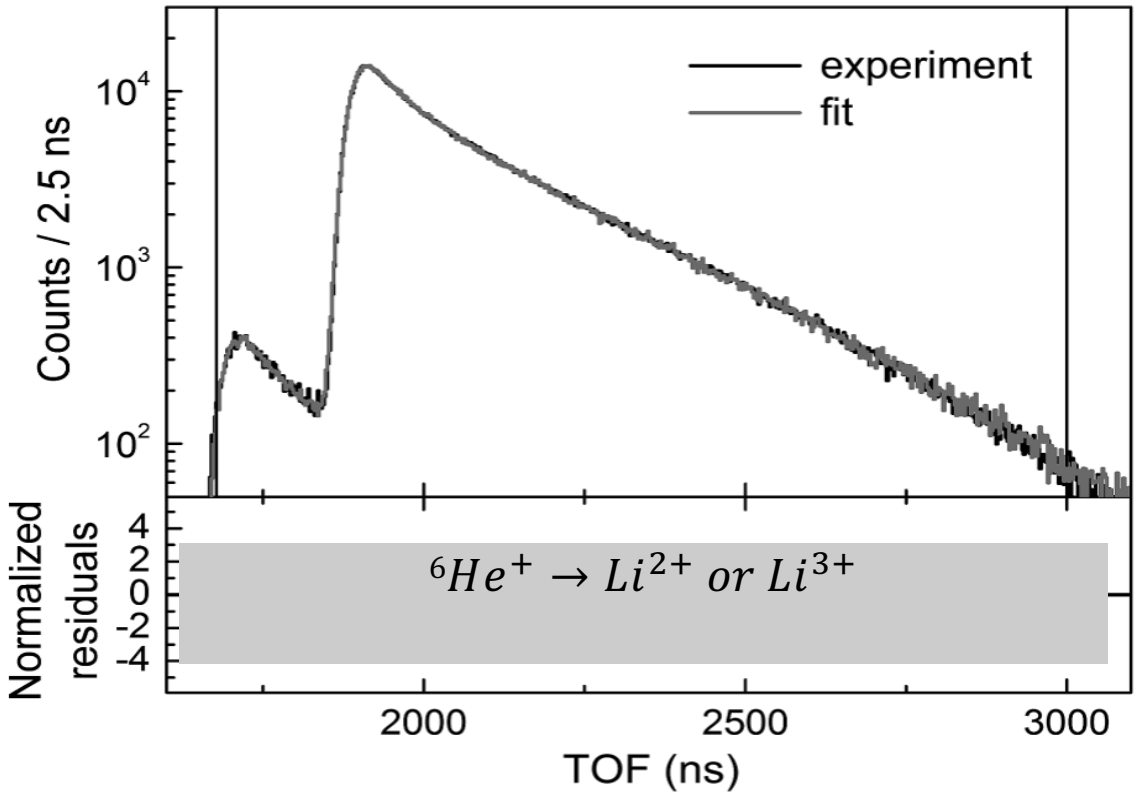
α 衰变中的Migal效应（1975）

PhysRevC.11.1740



β 衰变的Migdal效应（2012）

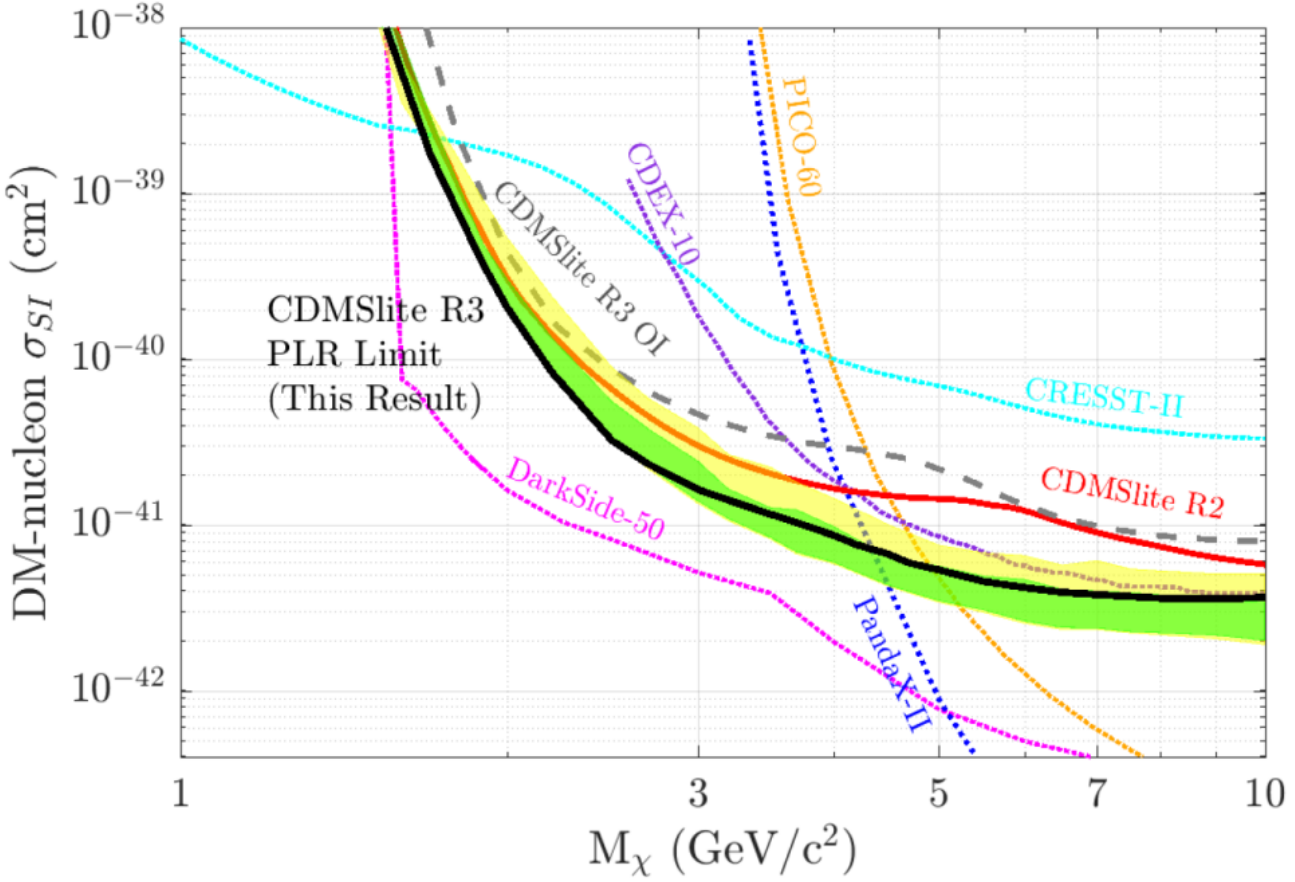
PhysRevLett.108.243201



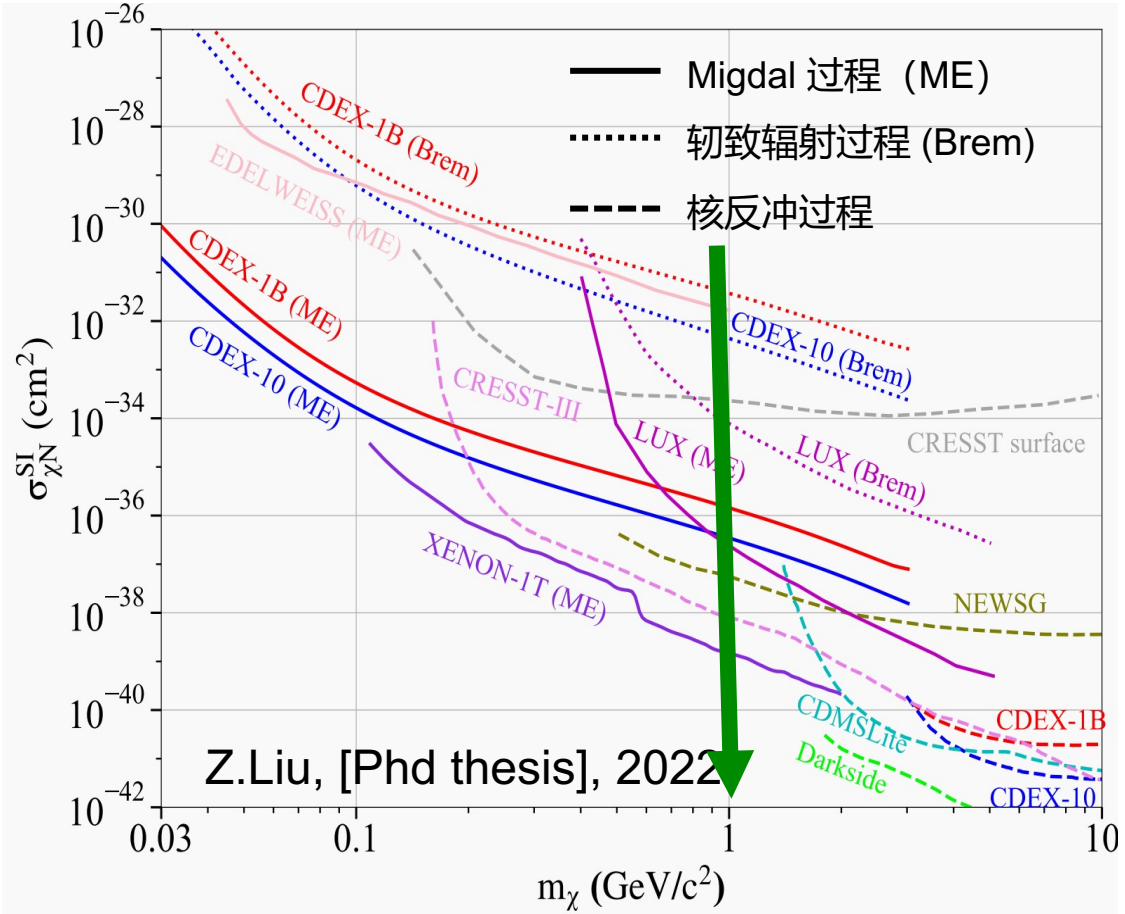
Migdal效应于 20 世纪 70 年代起在放射性衰变过程中被间接观测到

Migdal效应在亚 GeV 量级暗物质探测中的影响

SuperCDMS, PRD 99, 062001 (2019)

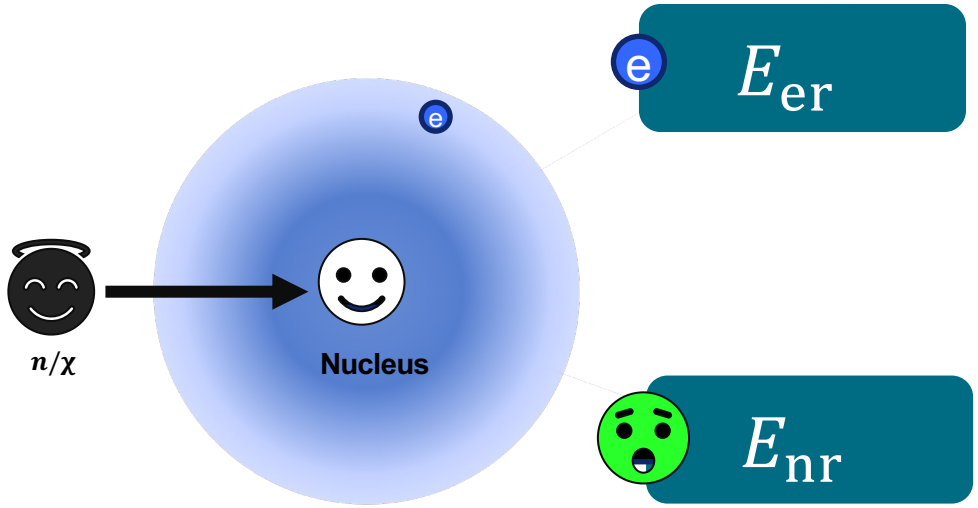


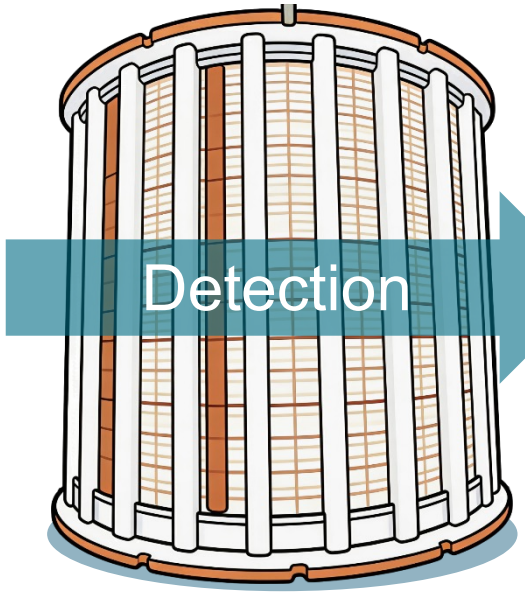
2018年以前，没有引入Migdal效应的上限



引入Migdal效应（理论）对暗物质直接探测的影响：PLB 606, 313–322 (2005)；NPB 727, 406–420 (2005)；PLB 639, 218–222 (2006)；JHEP018,194(2018)

Migdal效应的反冲电子探测（Migdal电子）



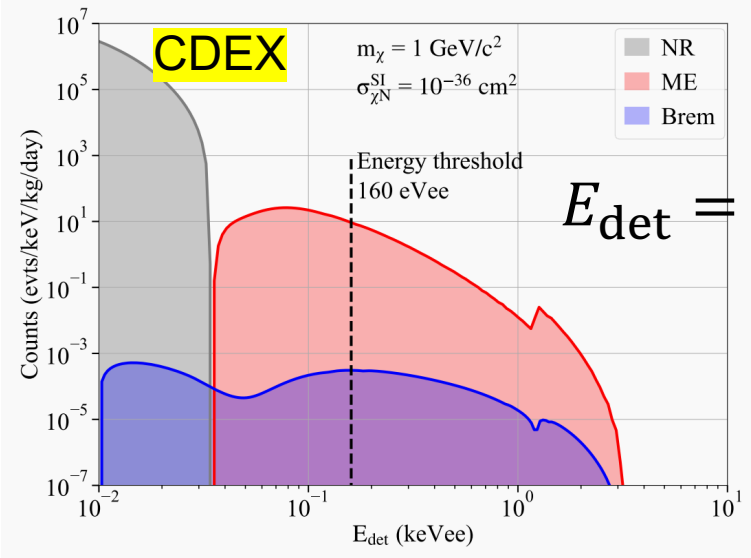


$$E_{er,obs} = E_{er} - E_{bind}$$

$$+$$

$$E_{nr,obs} = E_{nr} \cdot \varepsilon_{QF}$$

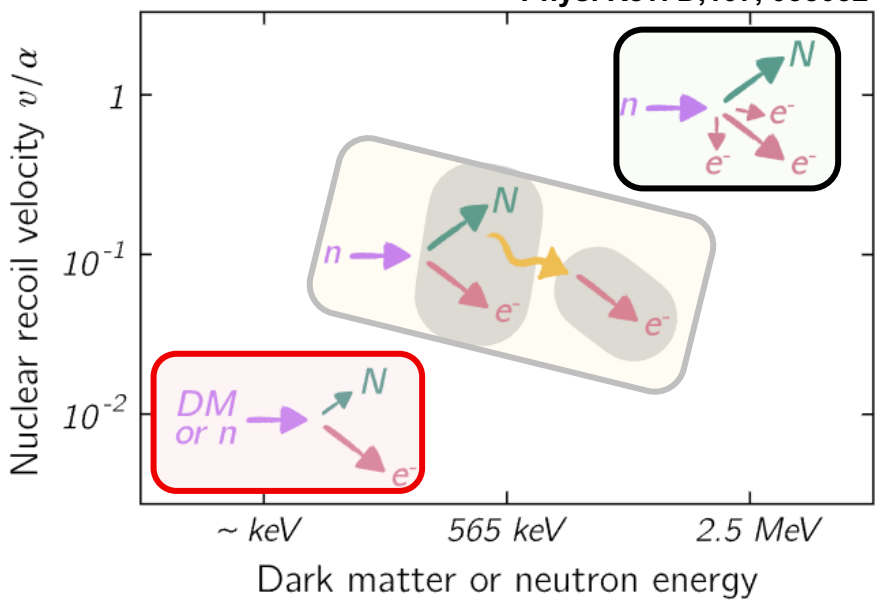
The Migdal electron aids in searching for nuclear recoils below the threshold in direct DM experiments.

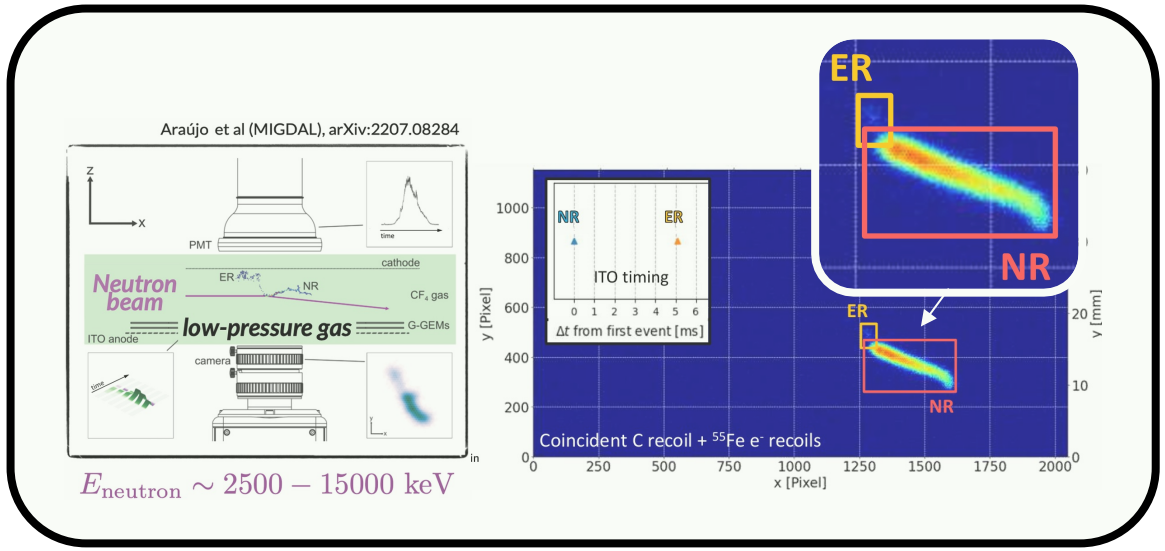


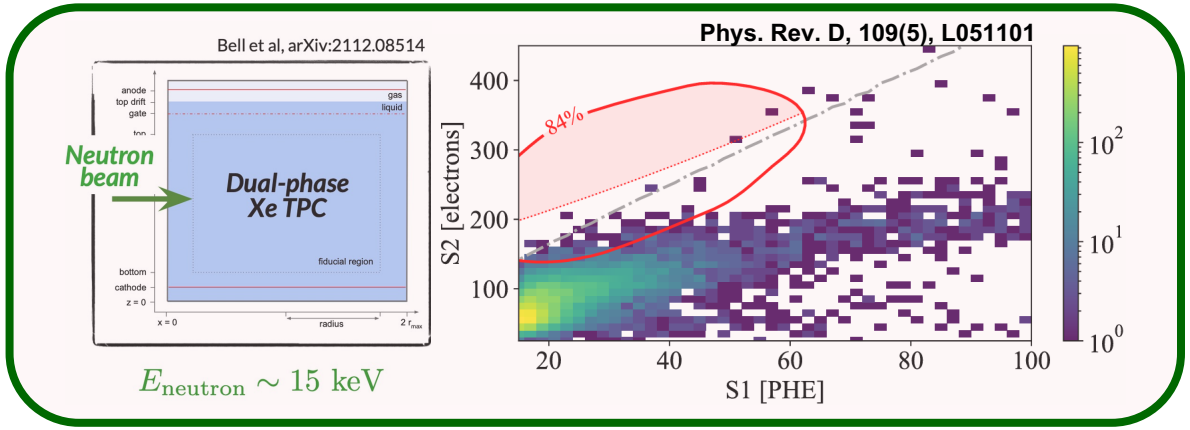
$$E_{det} = E_{er,obs} + E_{nr,obs} + \cdots$$

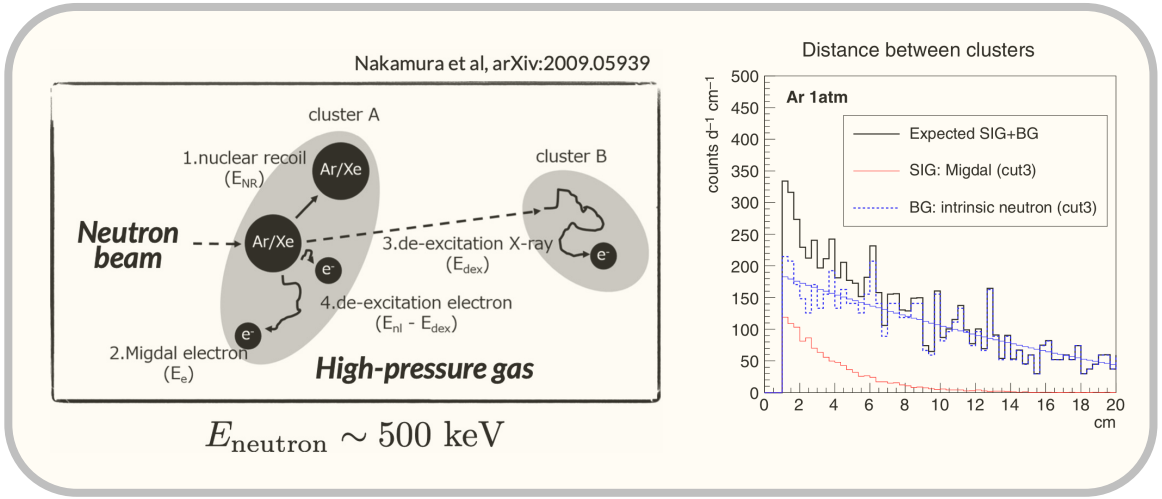
Migdal效应直接观测实验

Phys. Rev. D,107, 035032

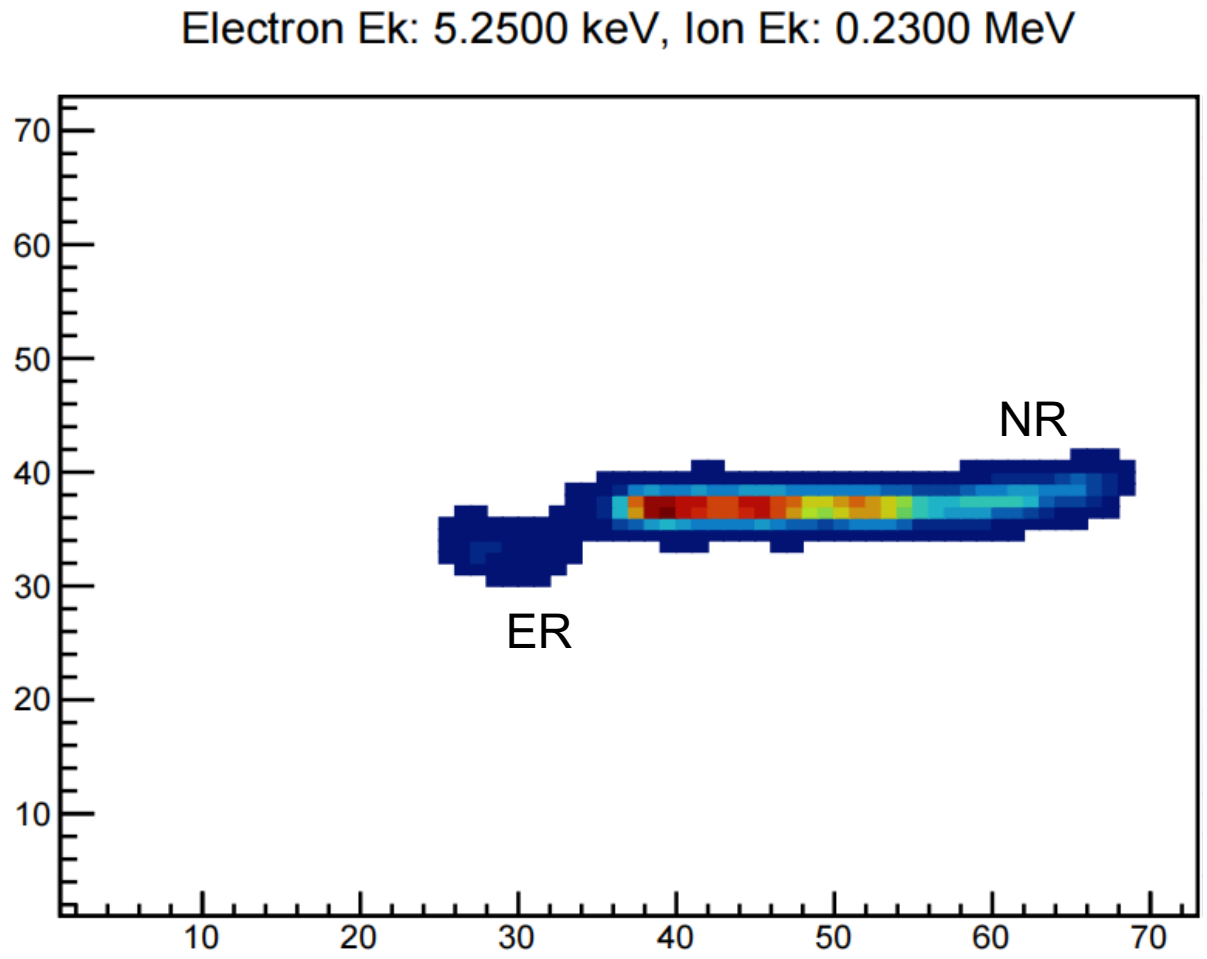








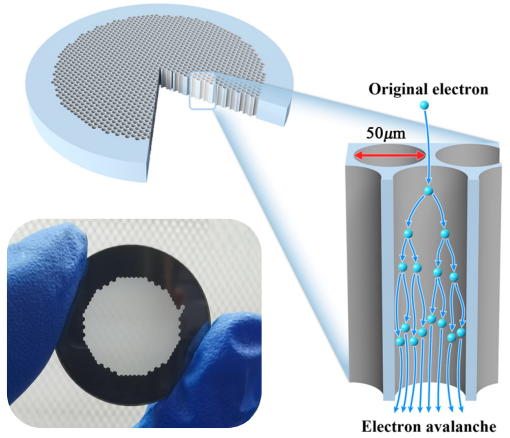
Migdal效应的信号拓扑结构和探测器需求

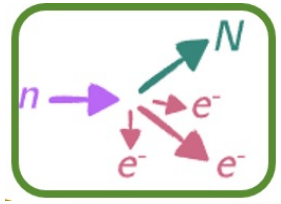


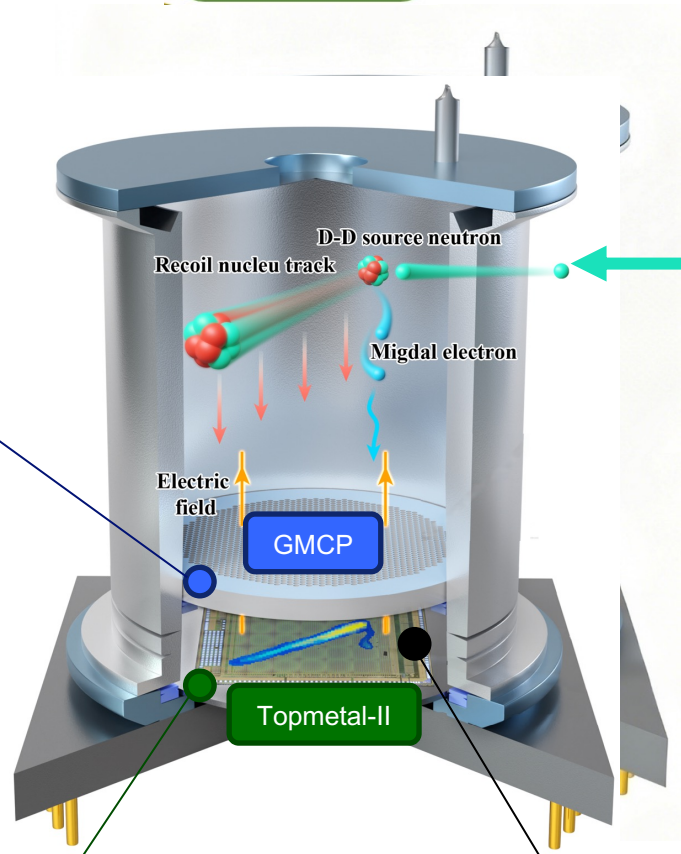
- 电子~keV，核子~百keV
  - 好的能量分辨
  - 大的动态范围
- 电子与核子共顶点
  - 好的顶点分辨
- 本底背景剔除
  - 好的位置分辨
  - 好的时间分辨

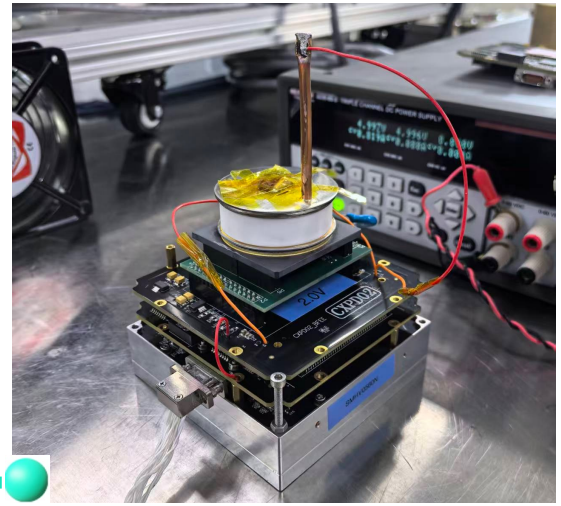
MARVEL探测器（GMCP + Topmetal读出）

GMCP



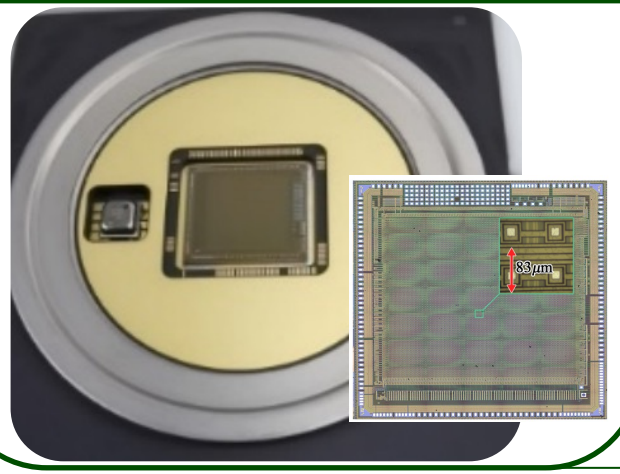




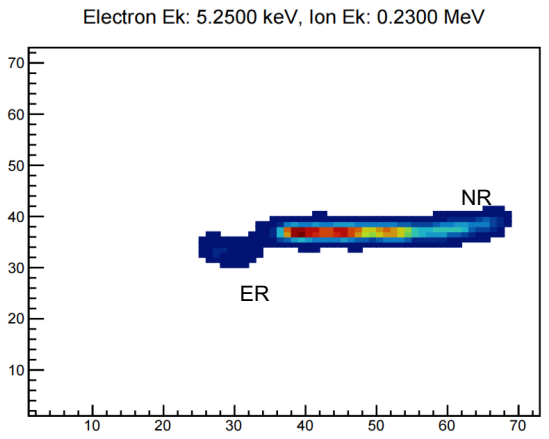


氘氘中子源

Topmetal-II



Migdal 拓扑结构

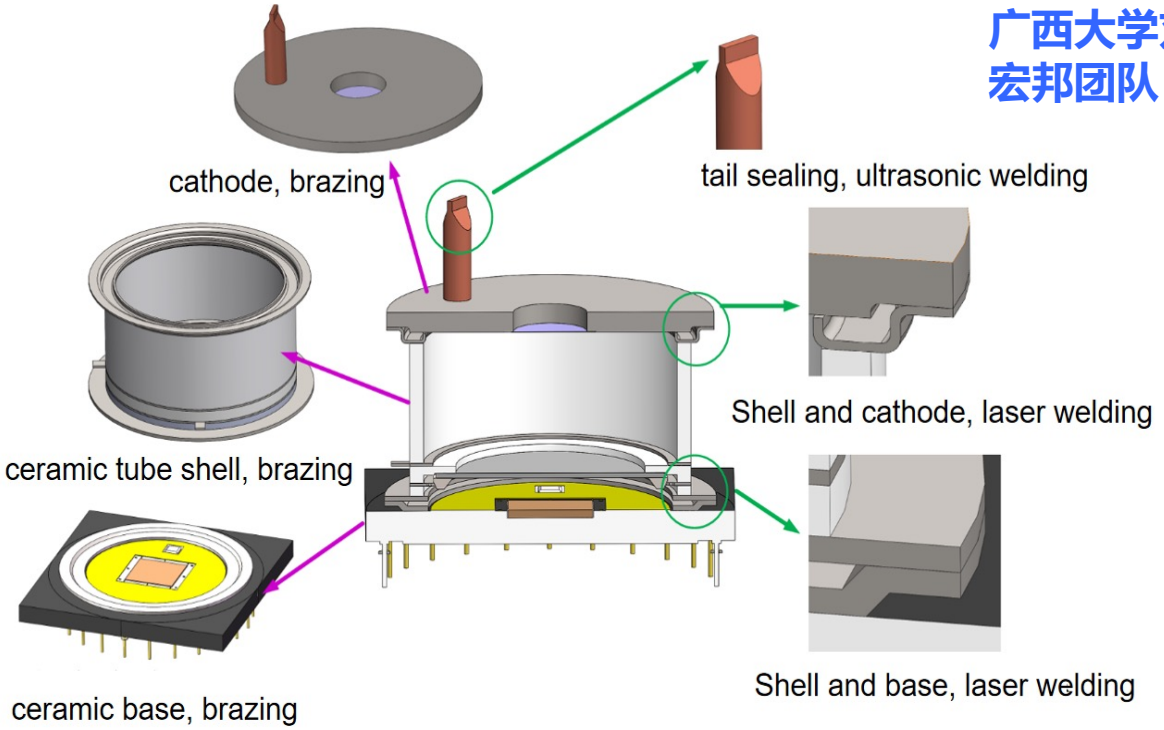


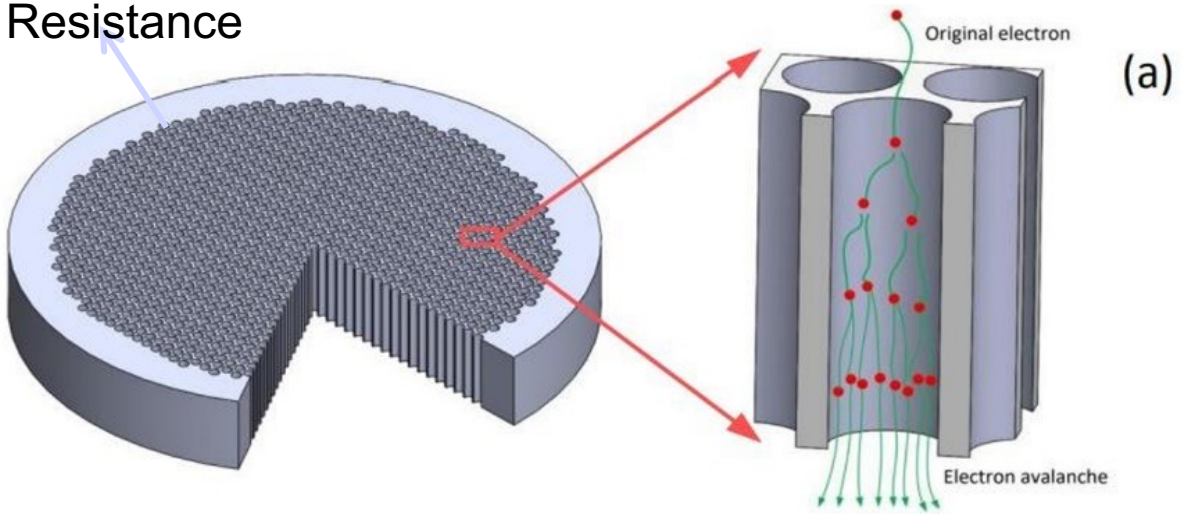
Gas Macro-Channel Plate (GMCP)

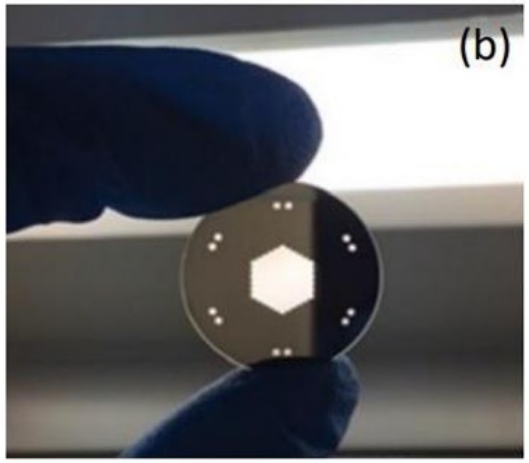
- 最初为空间软X射线偏振探测实验设计
- 低气体泄露率与低材料放气率
- 抑制电荷堆积效应

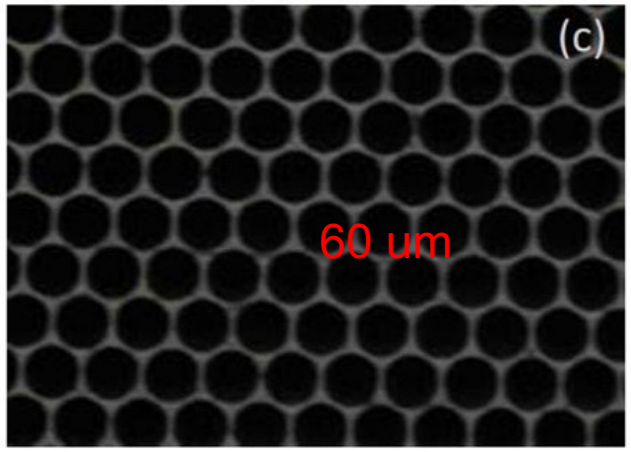


广西大学刘宏邦团队





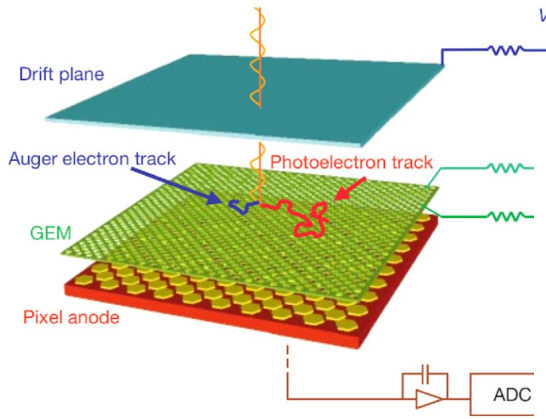




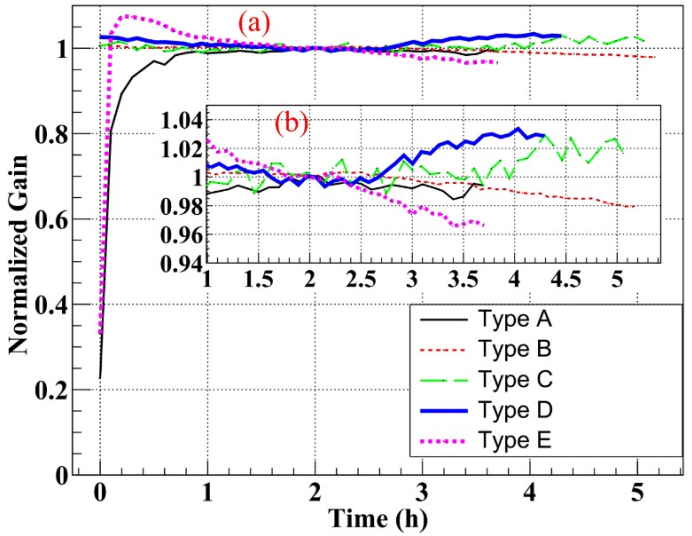
气体微通道板（GMCP），运用于气体探测器

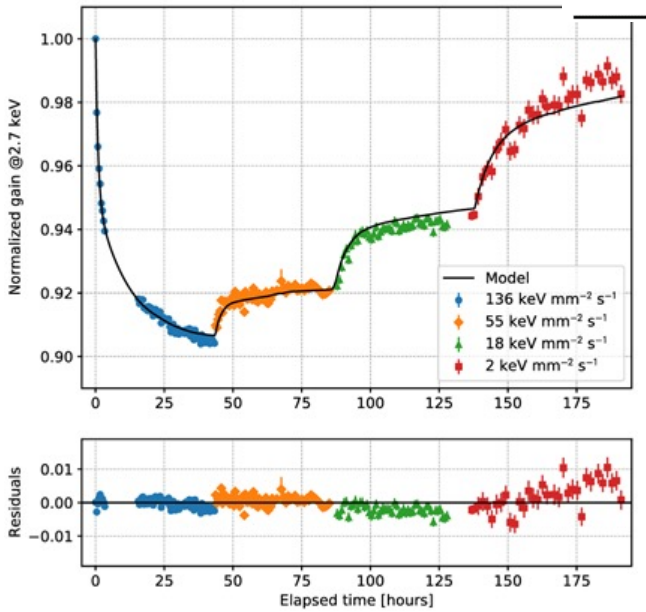
Leak rate: ~7.6^{-11} Torr·L/s

GMCP的电荷堆积效应及消除



	Type A	Type B	Type C	Type D	Type E
Hole diameter	50 μm	50 μm	50 μm	60 μm	30 μm
Thickness	400 μm	400 μm	300 μm	300 μm	300 μm
Hole pitch	60 μm	60 μm	60 μm	80 μm	40 μm
GMCP resistance	∞	5 GΩ	3 GΩ	5 GΩ	∞
Hydrogen reduction	Without	With	With	With	Without

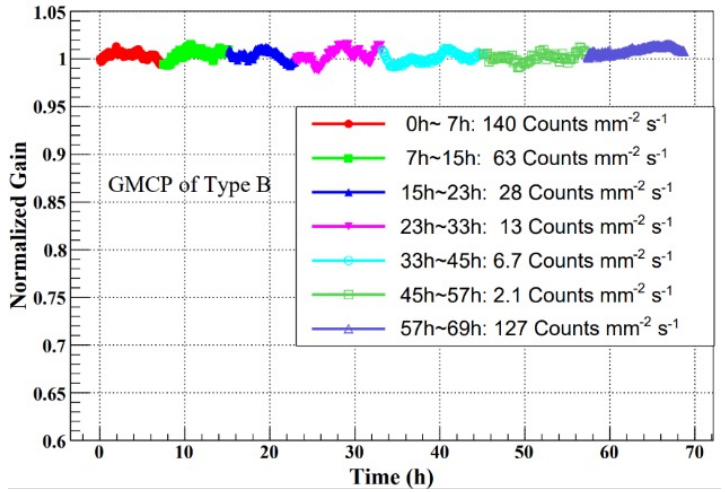




原因：　电荷累积在GEM孔内

消除方案：阻性材料，释放电荷

实现：　GMCP通过氢还原，孔内形成导电层，具有体电阻特性



不同计数率下的稳定性

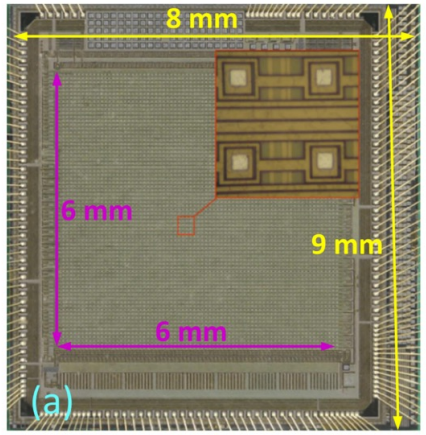
GEM探测器增益随X射线流量变化

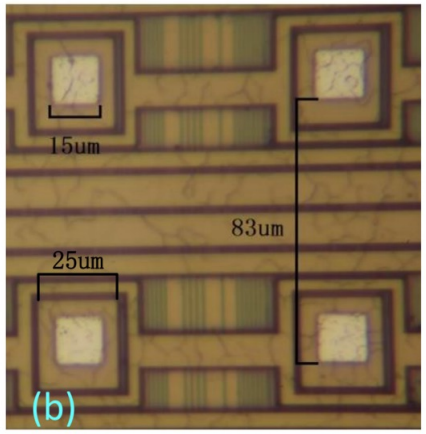
核心器件：Topmetal像素芯片

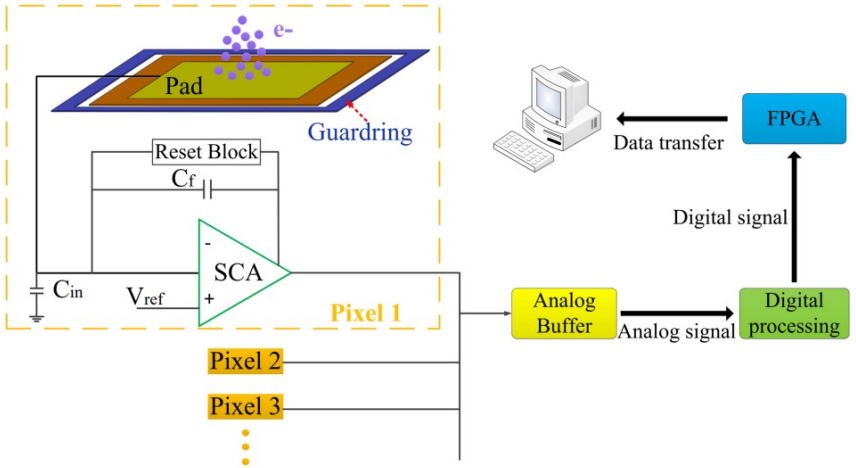
Topmetal-II



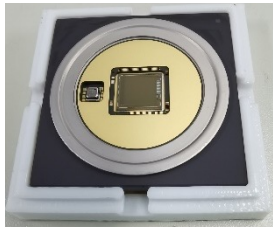
华中师大孙向明团队

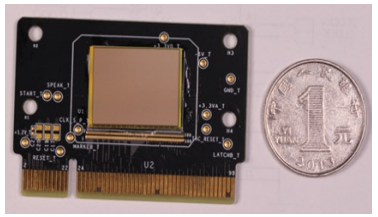


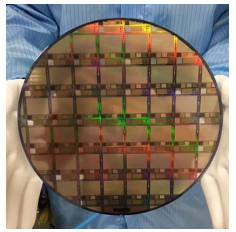




	Topmetal-II⁻	Topmetal-M1/M2	Topmetal-L
Chip Size /mm²	6 × 6	18 × 23	17 × 24
Pixel Array	72 × 72	400 × 512	356 × 512
Pixel Size /um²	83 × 83	45 × 45	45 × 45
Pixel Electrode / um²	15 × 15	10 × 20	26 × 26
ENC	~ 13.4e-	~ 15.4e-	~ 20.0e-
Power Consumption	~ 1W @3.3V	~ 4.3W @3.3V	**~ 0.8W @3.3V**
Clock	40MHz	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

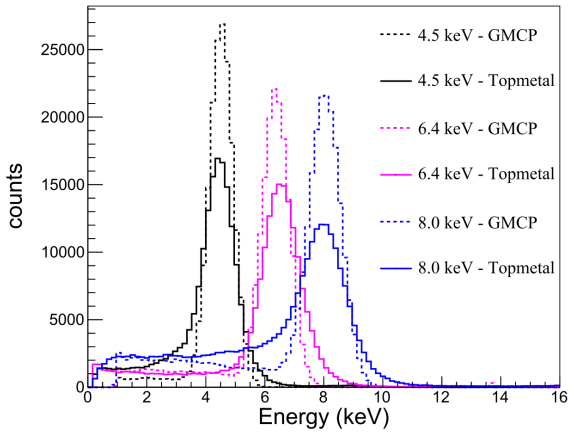


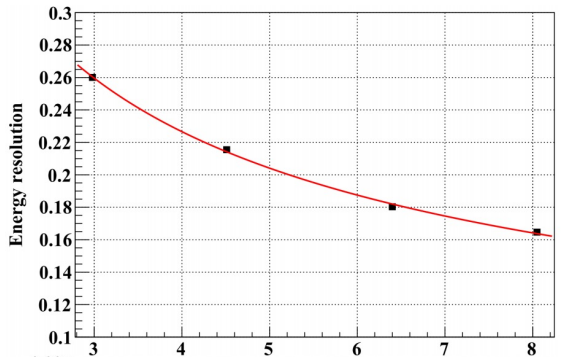




探测器性能

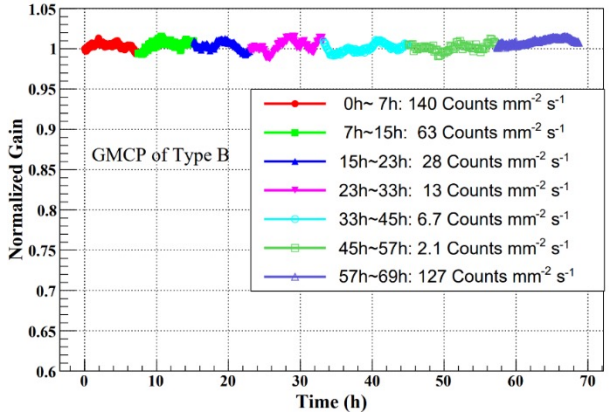
Energy resolution

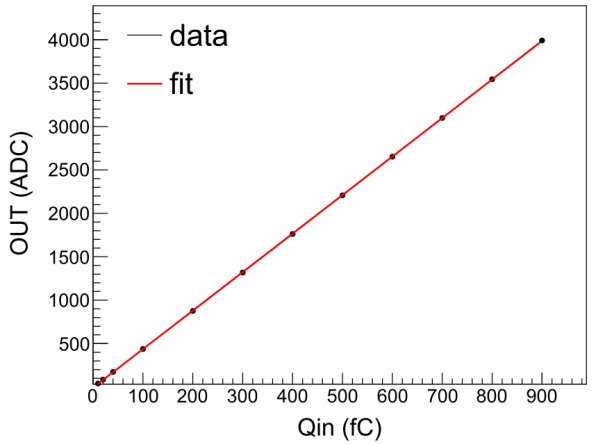




- Good linear energy response
- 20%-30% energy resolution(FWHM)
- Energy resolution follows the relationship ~ $1/\sqrt{E}$

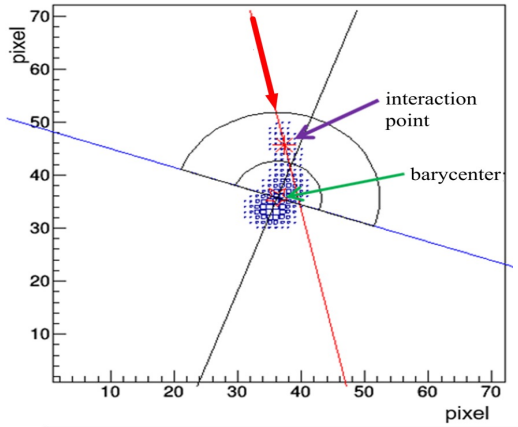
Dynamic range

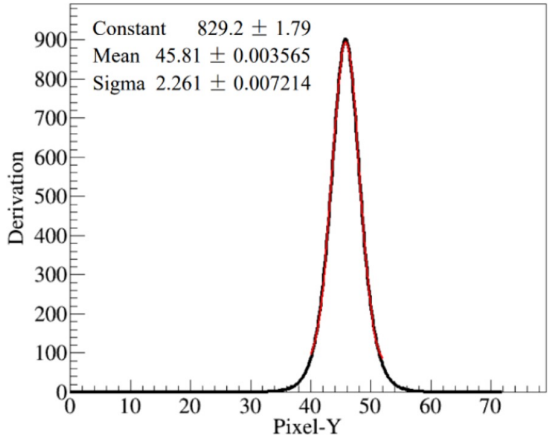




- Stable gain under different count rates(no pile up)
- Good linearity in charge response

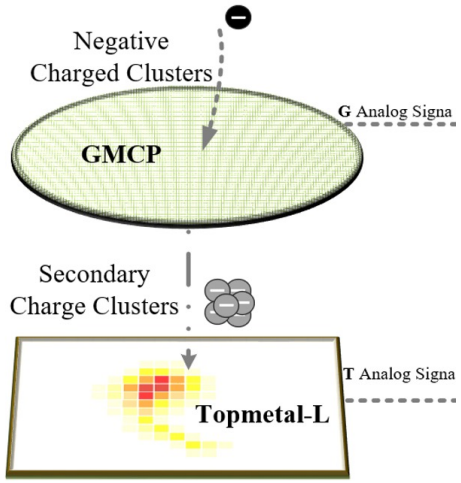
Vertex resolution

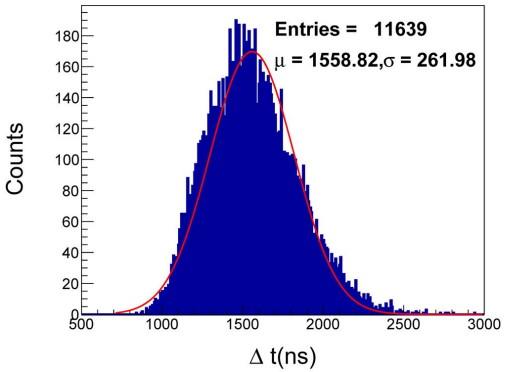




- ~200 μm vertex resolution @ 6.4 keV

Time resolution





- ~262 ns time resolution

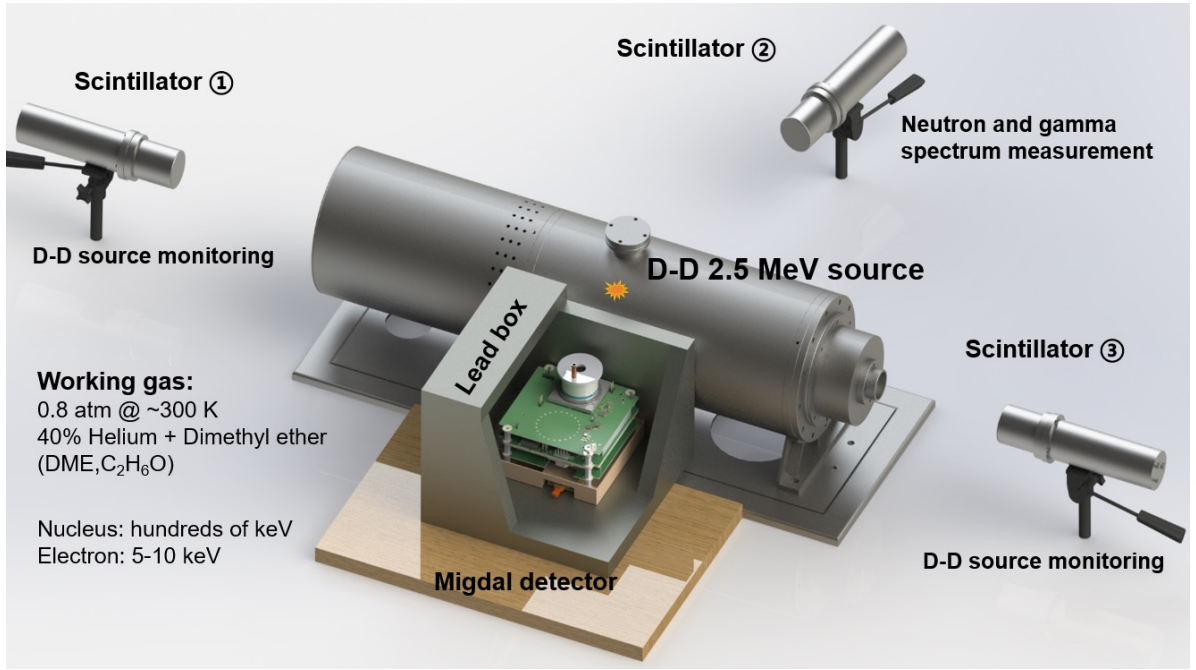
实验设计、数据采集与物理分析团队

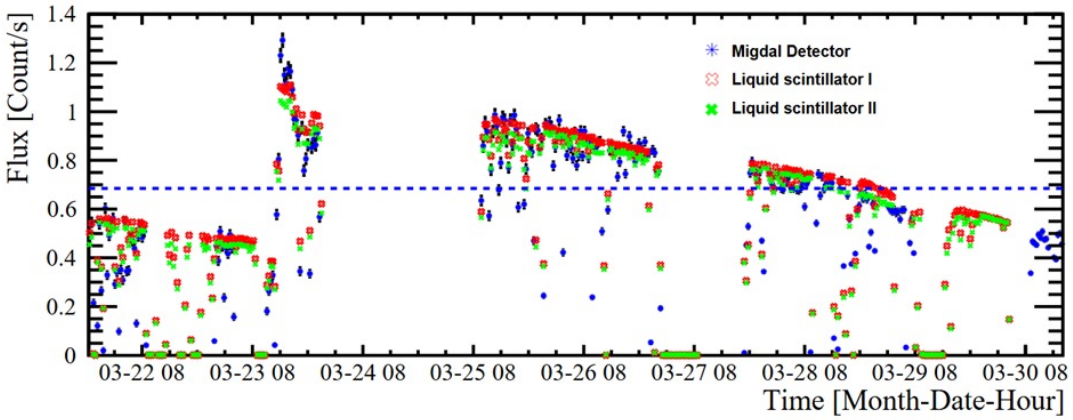


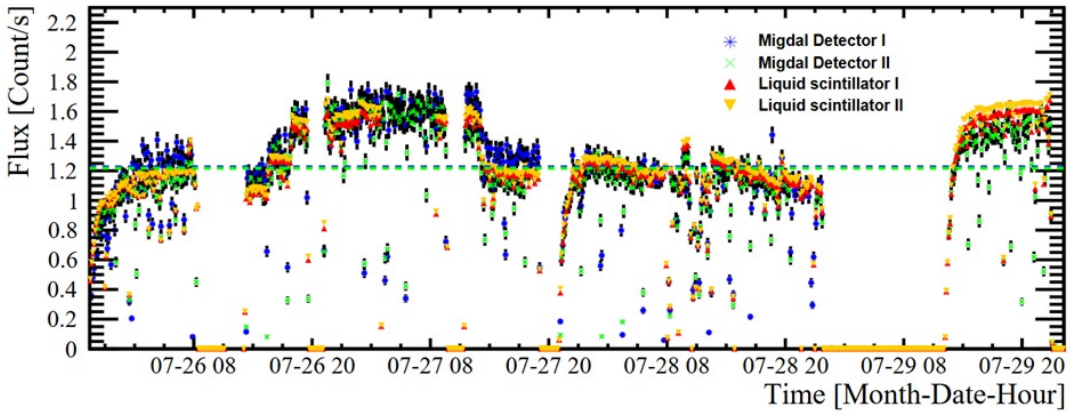
刘倩和他的小伙伴们（易涤凡，马瑞廷、黄文谦、
苏晨光，景新媚、孔令全，左杰，余运林晨，陈石）

- 第一作者易涤凡、重要贡献者苏晨光，孔令全，左杰、余运林晨均为国科大本博贯通培养的博士生
- 均在二年级结束的暑假开展前沿科研实践工作（刘倩和郑阳恒联合指导）。
- 教学相长
  - 郑阳恒讲授《原子物理学》
  - 刘倩讲授《粒子与辐射探测技术》

中子束流实验现场

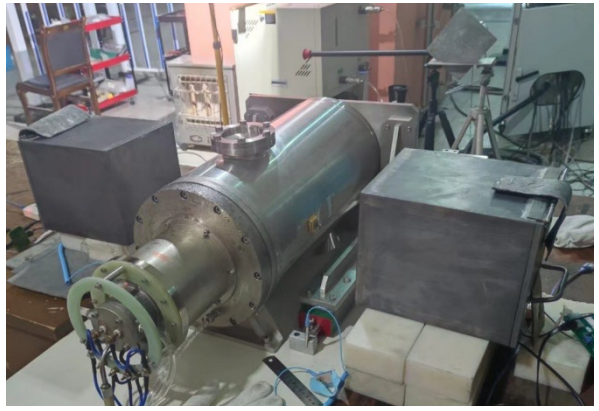






探测器现场计数率情况

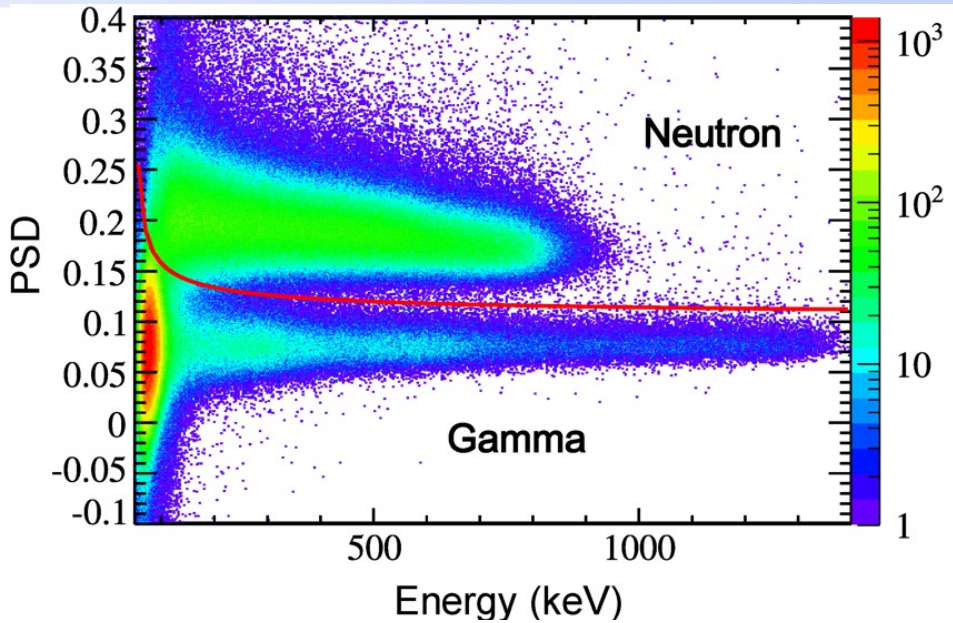


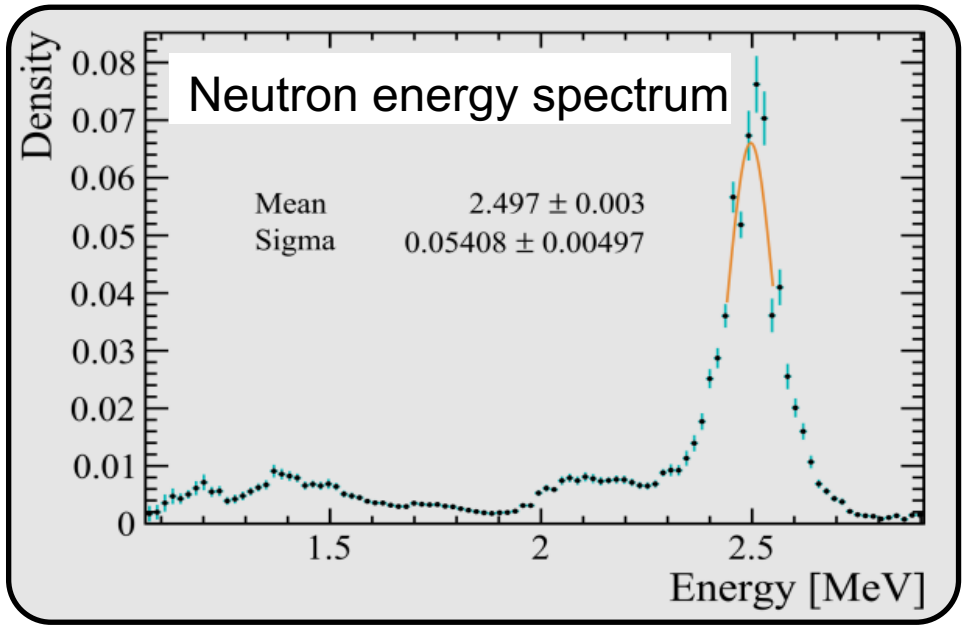


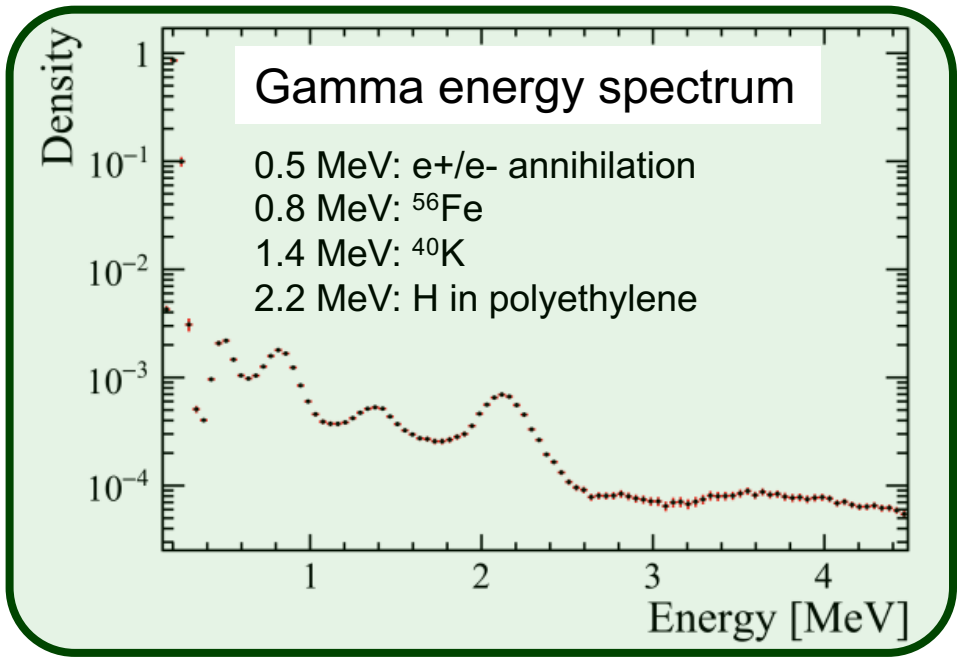


姚泽恩团队提供氘-氘聚变反应加速器中子源

Neutron/Gamma energy spectrum (液闪)

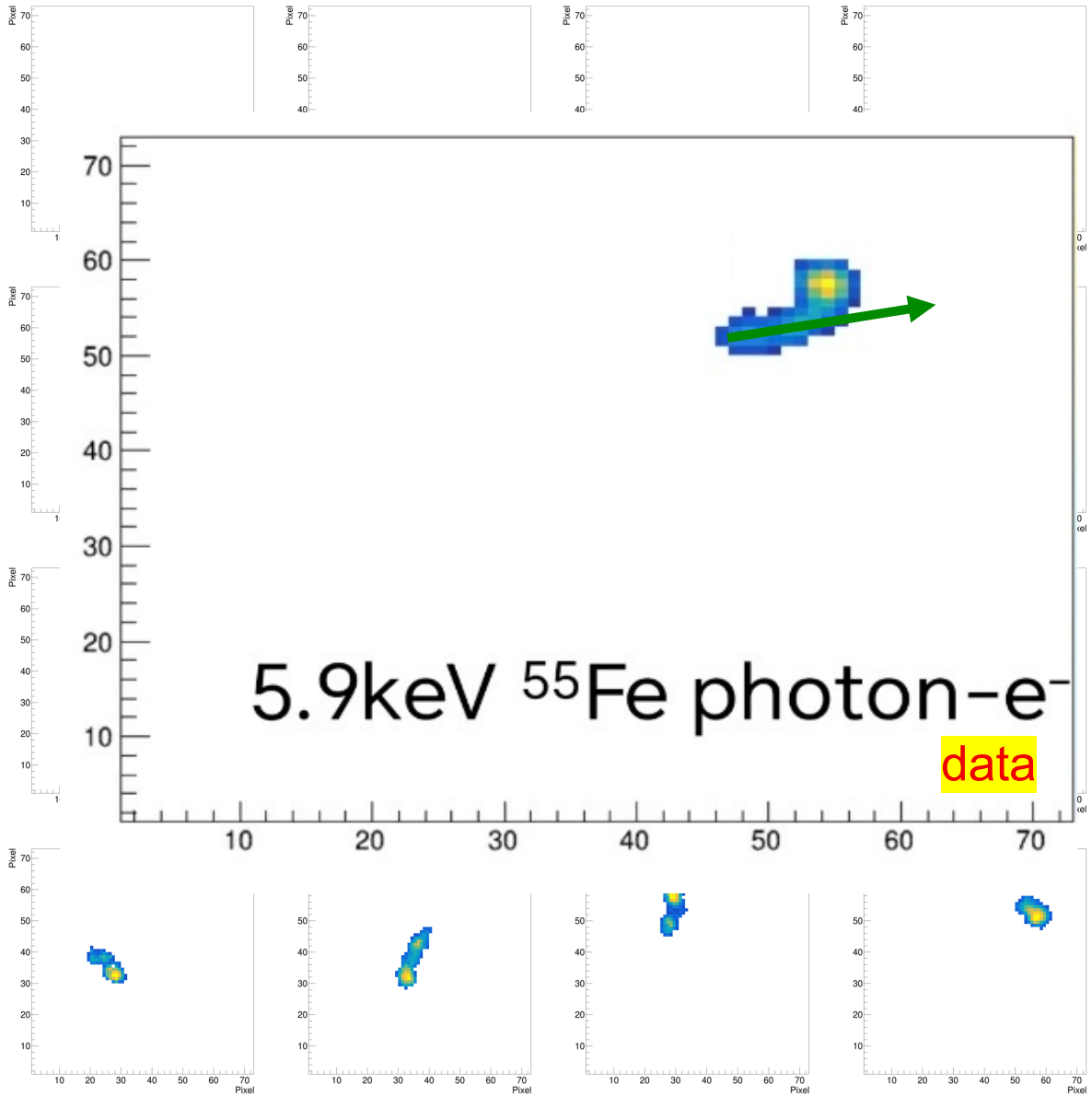


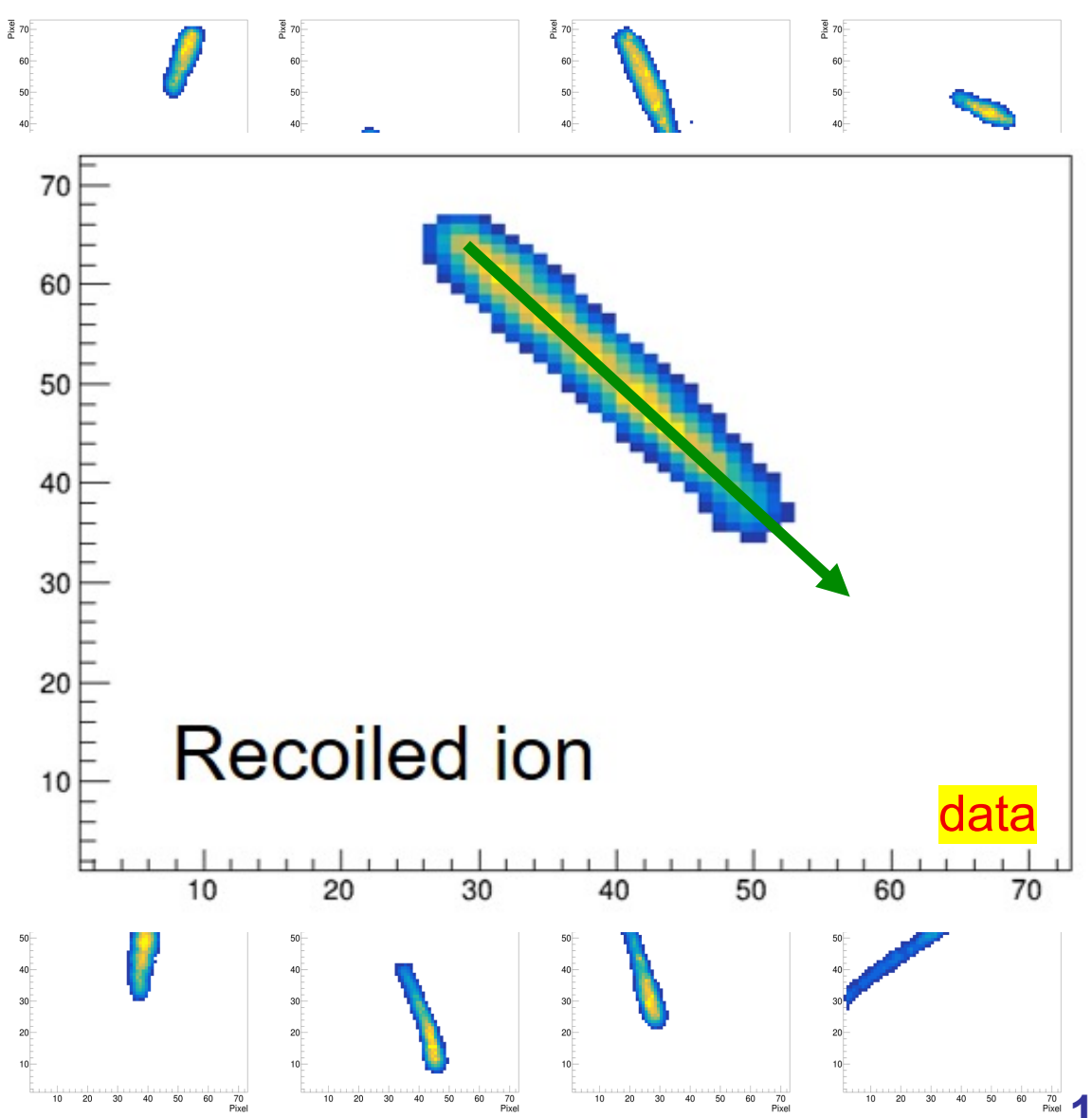




- Distinguishing neutrons from gammas using Pulse Shape Discrimination (PSD)
- Obtaining energy spectra via unfolding: using the response matrix of the LS, which is validated through calibration and simulation

Electron & ion tracks



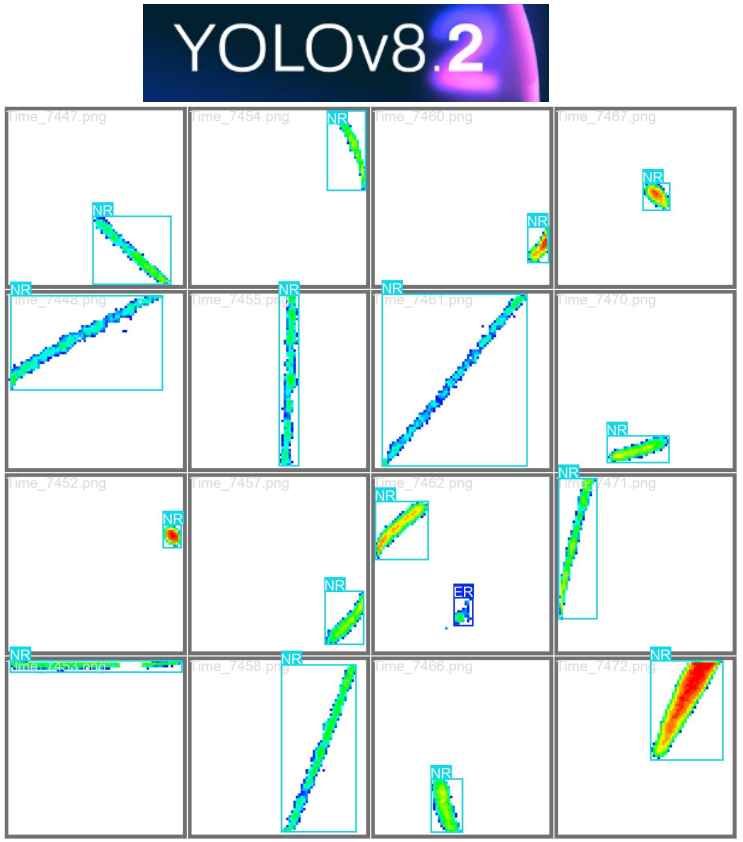


Event selection

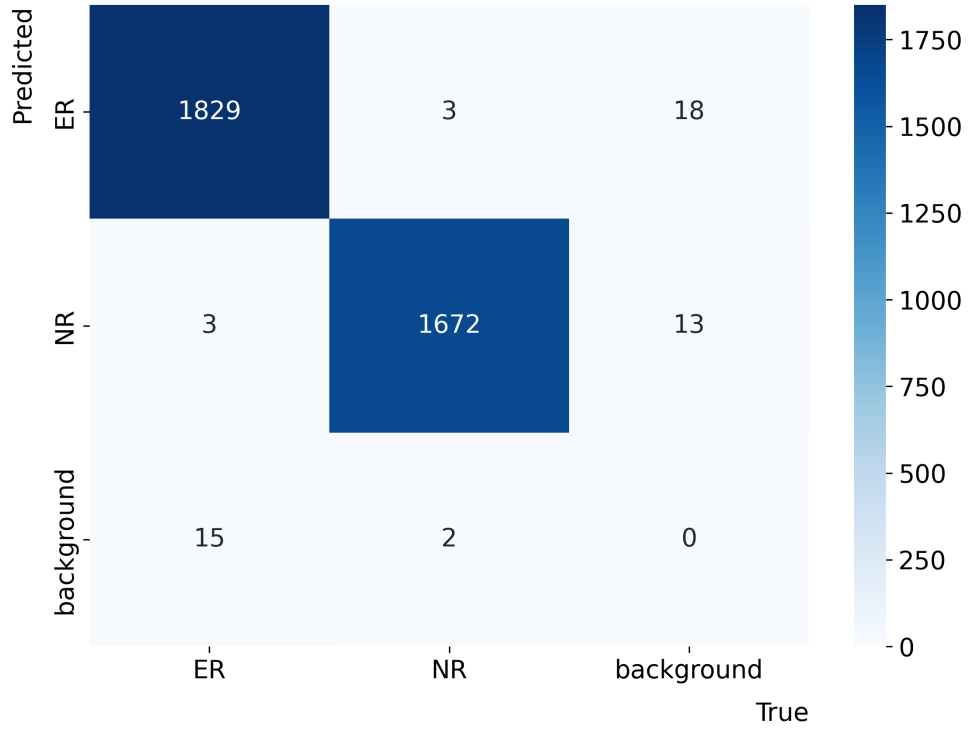


Labeling

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

Event selection



1. Search for the NR vertex through recursive iteration:

$$\mathrm{ADC}\cdot exp\,(\,d/d_0)$$

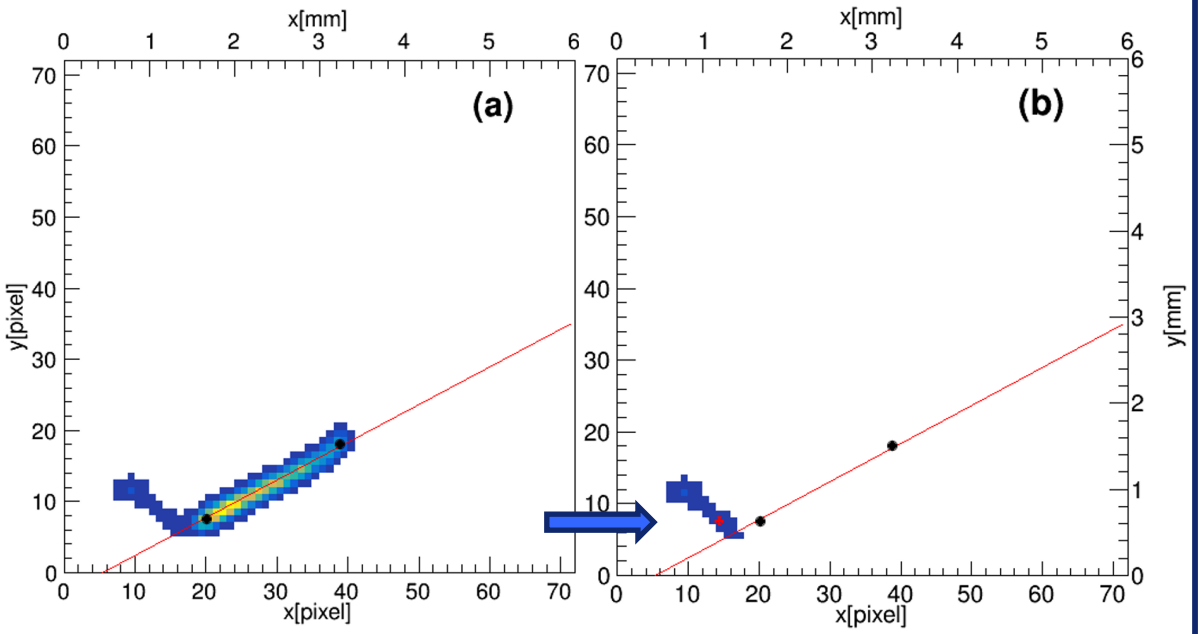
$$(x_0,y_0) \longrightarrow (x_n,y_n)$$

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

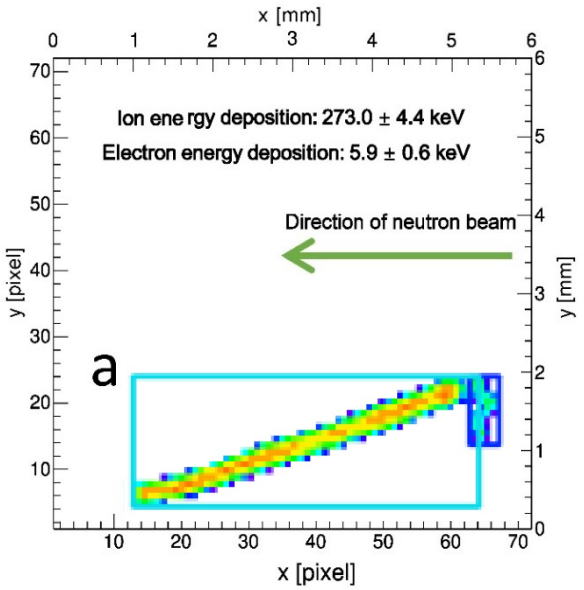
3. Search for the electron vertex using **adaptive cutting algorithm**(Nucl. Sci. Tech.doi:10.1007/s41365-021-00903-0).

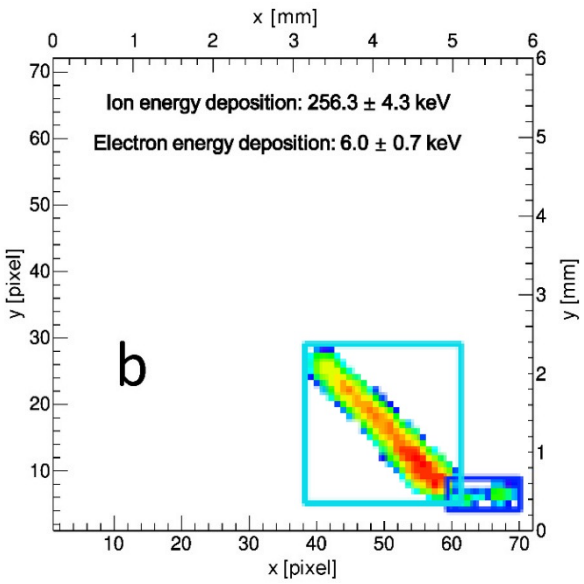
4. Determine whether the electron vertex is adjacent to the nucleon vertex.

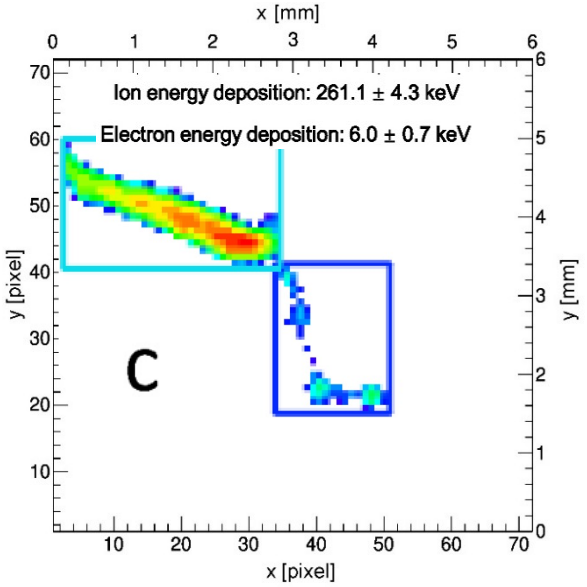
$$R = \frac{D - 4\sigma}{L_{\mathrm{ER}}}$$

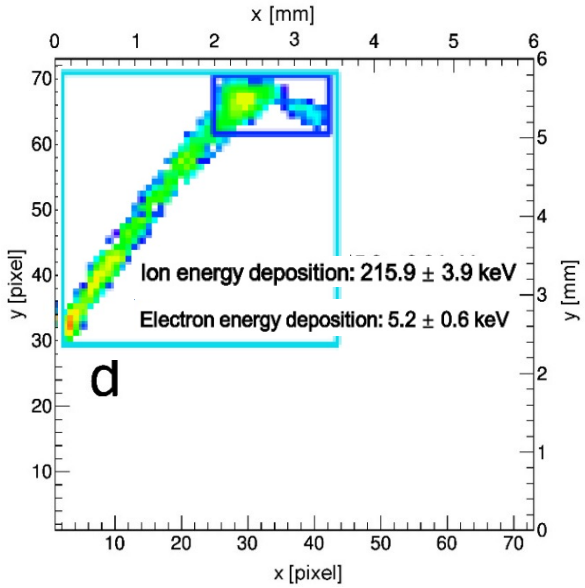


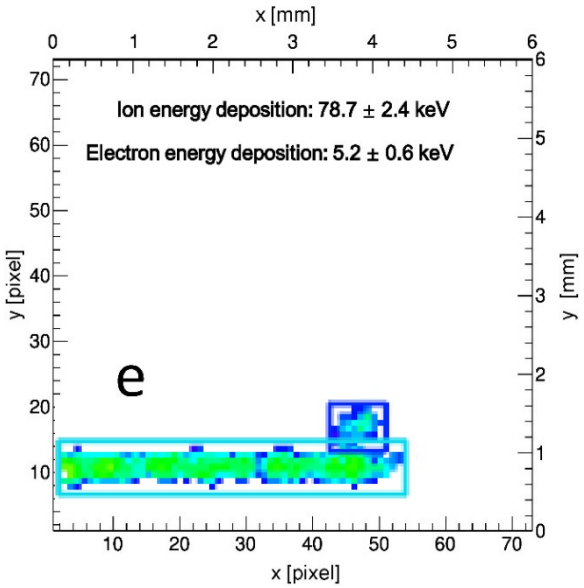
Migdal candidates和AI算法识别（YOLO）

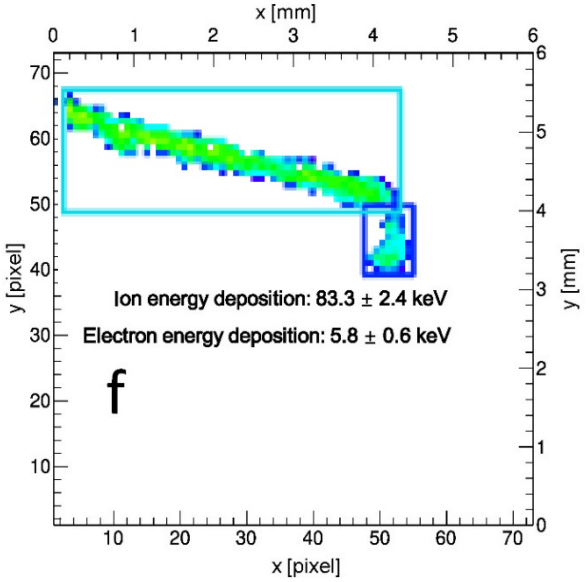










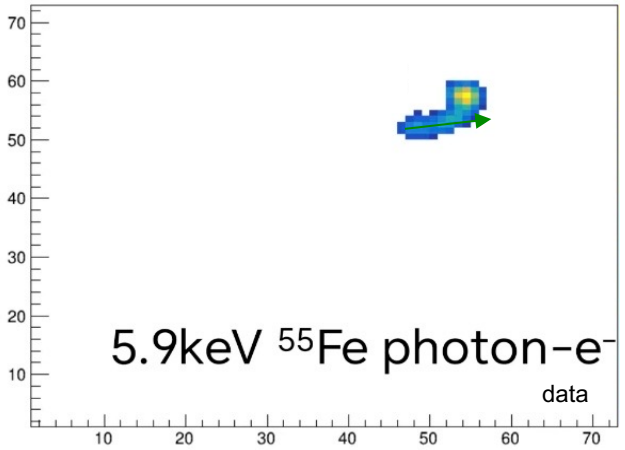


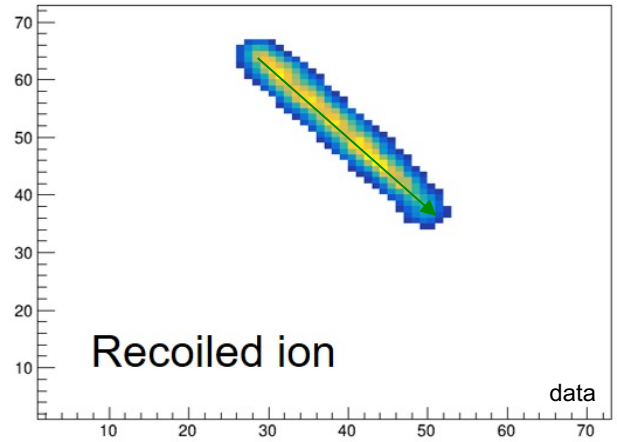
通过约150小时的数据采集，从81.7万个候选事件中，精准筛选出6个符合米Migdal效应特征的事例，以超过 **5σ** 统计显著性实现了Migdal效应直接观测。

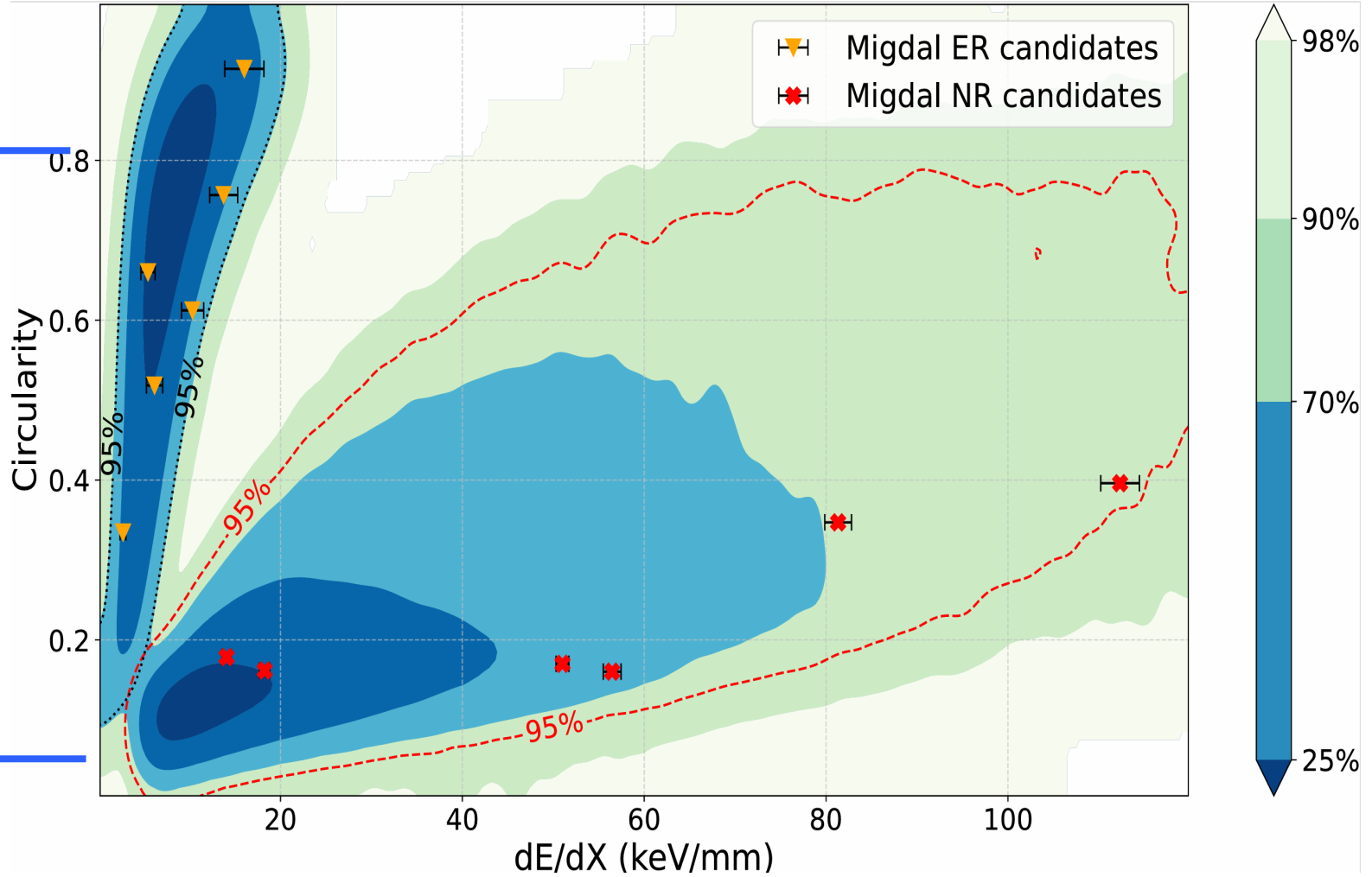
(Nature 649(2026)580)

Electron & ion tracks

$5\ keV_{ee} < Ee < 10\ keV_{ee}, E_{nr} > 35 keV_{ee}$





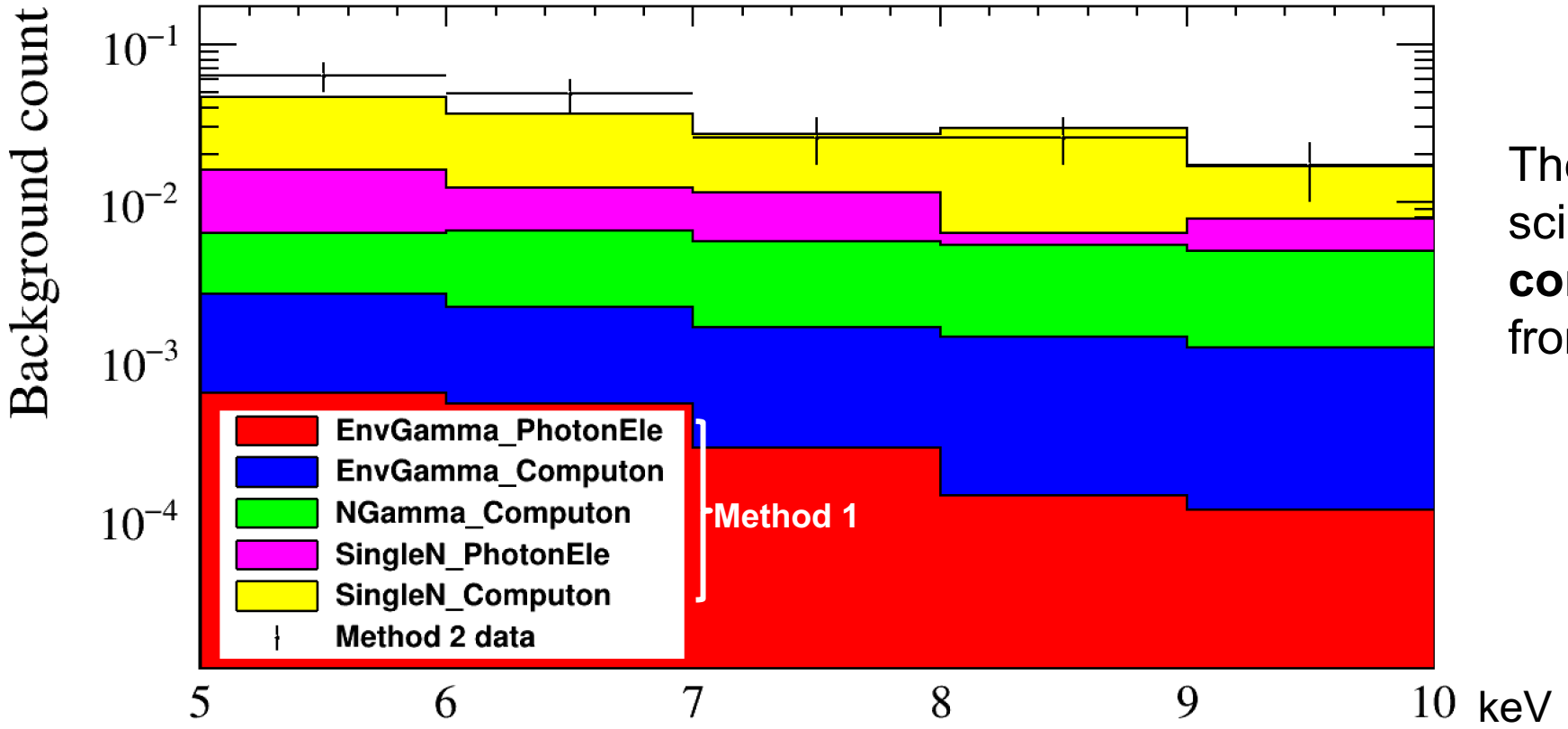


物理分析难点与挑战：本底估算

本底成分	描述	期望值(5 - 10 keV)	方法
反冲诱导 δ 电子发射	核反冲径迹起点附近的δ电子	0.035±0.023(stat.)±0.0068(sys.)	数据驱动
粒子诱导 X 射线发射			
X射线发射	核反冲径迹起点附近的光电子	0	
俄歇电子	核反冲径迹起点附近的俄歇电子	0	
韧致辐射过程			
库仑场散射辐射	核反冲径迹起点附近的光电子	≈ 0	
二次电子辐射	核反冲径迹起点附近的光电子	≈ 0	
激发 / RI 辐射	核反冲径迹起点附近的光电子	≈ 0	
直接散射辐射	核反冲径迹起点附近的光电子	≈ 0	
径迹的偶然符合	核反冲径迹起点附近的光电子/康普顿电子	0.180±0.022(stat.)±0.042(sys.)	数据驱动
宇宙线缪子诱导 δ 电子发射	核反冲径迹起点附近的光电子	0.013	蒙特卡洛模拟
气体放射性			
痕量污染物	核反冲径迹起点附近衰变产生的电子	0.001±0.00087(sys.)	数据驱动
中子活化	中子活化原子核后的衰变过程	≈ 0	
次级核反冲分叉	核反冲径迹起点附近的径迹分叉	≈ 0	
总本底计数		0.229±0.032(stat.)±0.043(sys.)	

径迹的偶然符合

- **Method 2: Estimated from Data**
  - **Get the number of electron tracks within the 5-10 keV energy range that appear in the same frame as the nucleon tracks.**
  - **Considering the accidental coincidence of NR and ER with a vertex selection efficiency,**
  - **the final expected background value is 0.180±0.022(stat.)±0.042(sys.)**

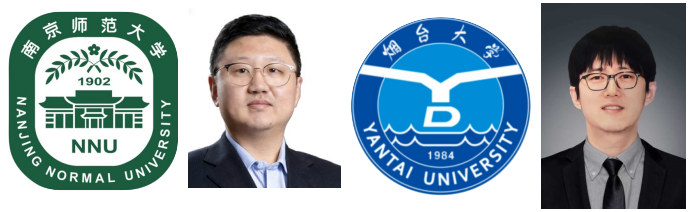


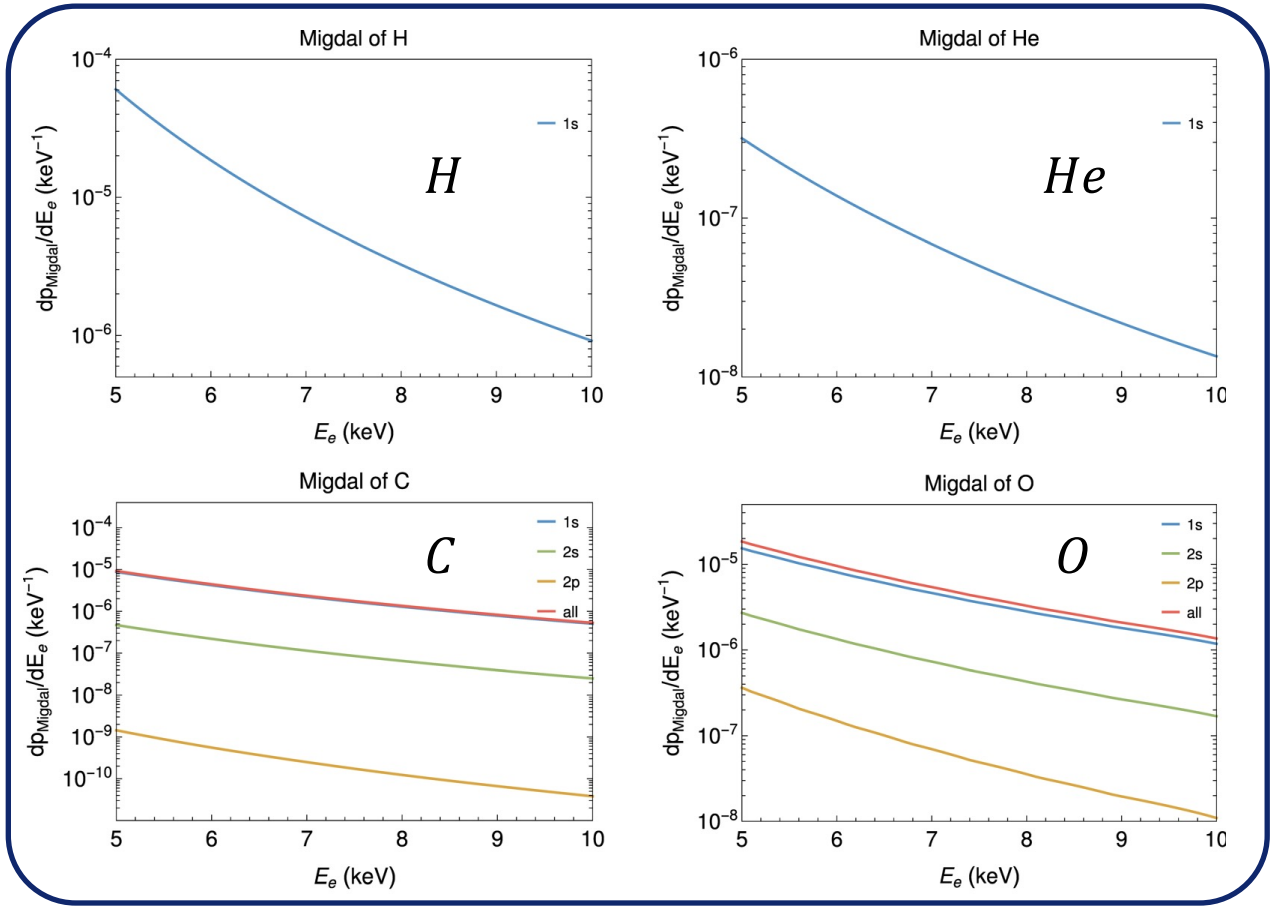
The results from the liquid scintillation + GEANT4 are **consistent** with the data obtained from the Migdal detector.

理论计算：总Migdal效应跃迁概率

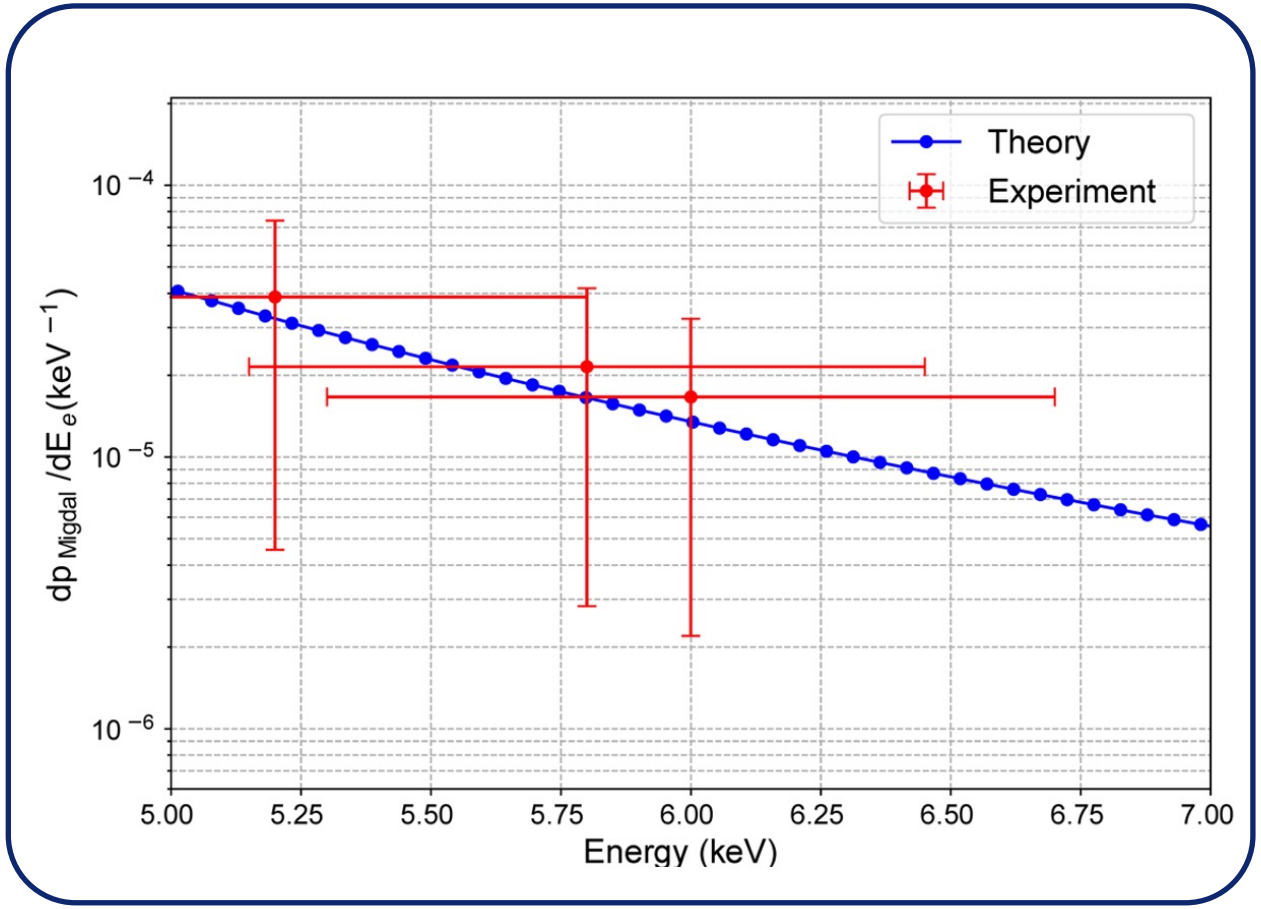
$$\sum_{nl} \frac{dp^i(nl \to E_e)}{dE_e}$$

The transition probability for ionization of an electron from an initial state (n, l) to a final state with energy E_e.



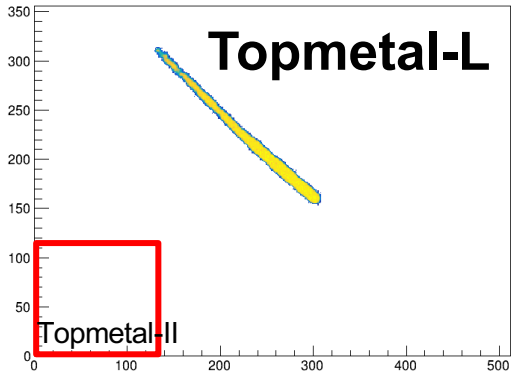


Transition probability of each element

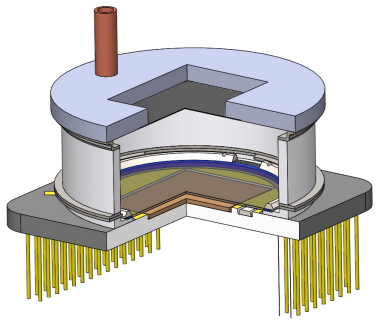


Total Transition probability

探测器升级计划

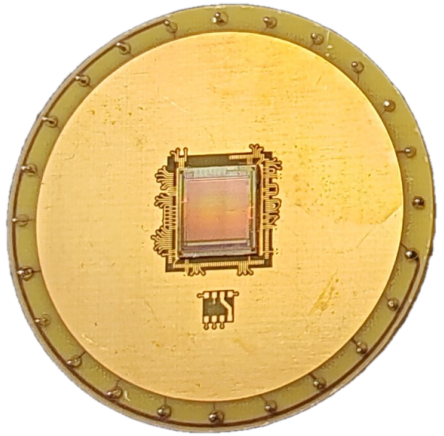


Topmetal-L结构示意



探测器结构示意

新型大面积微通道板像素探测器研制

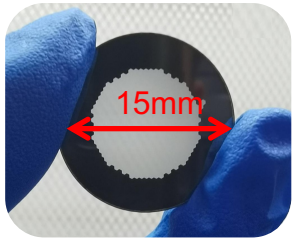


Topmetal-II

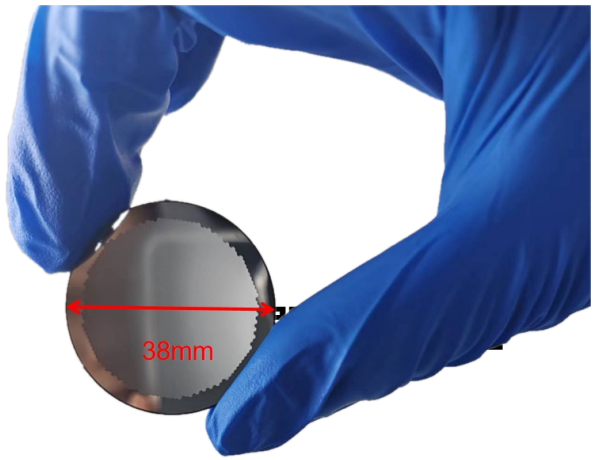


Topmetal-L

- 基于Topmetal-L像素芯片，完成大面积气体微通道像素探测器(GMPD)研制。探测器面积3.6 cm²，比之前的有效面积大了10倍, 功耗小于1 W 。



气体微通道板 (GMCP)



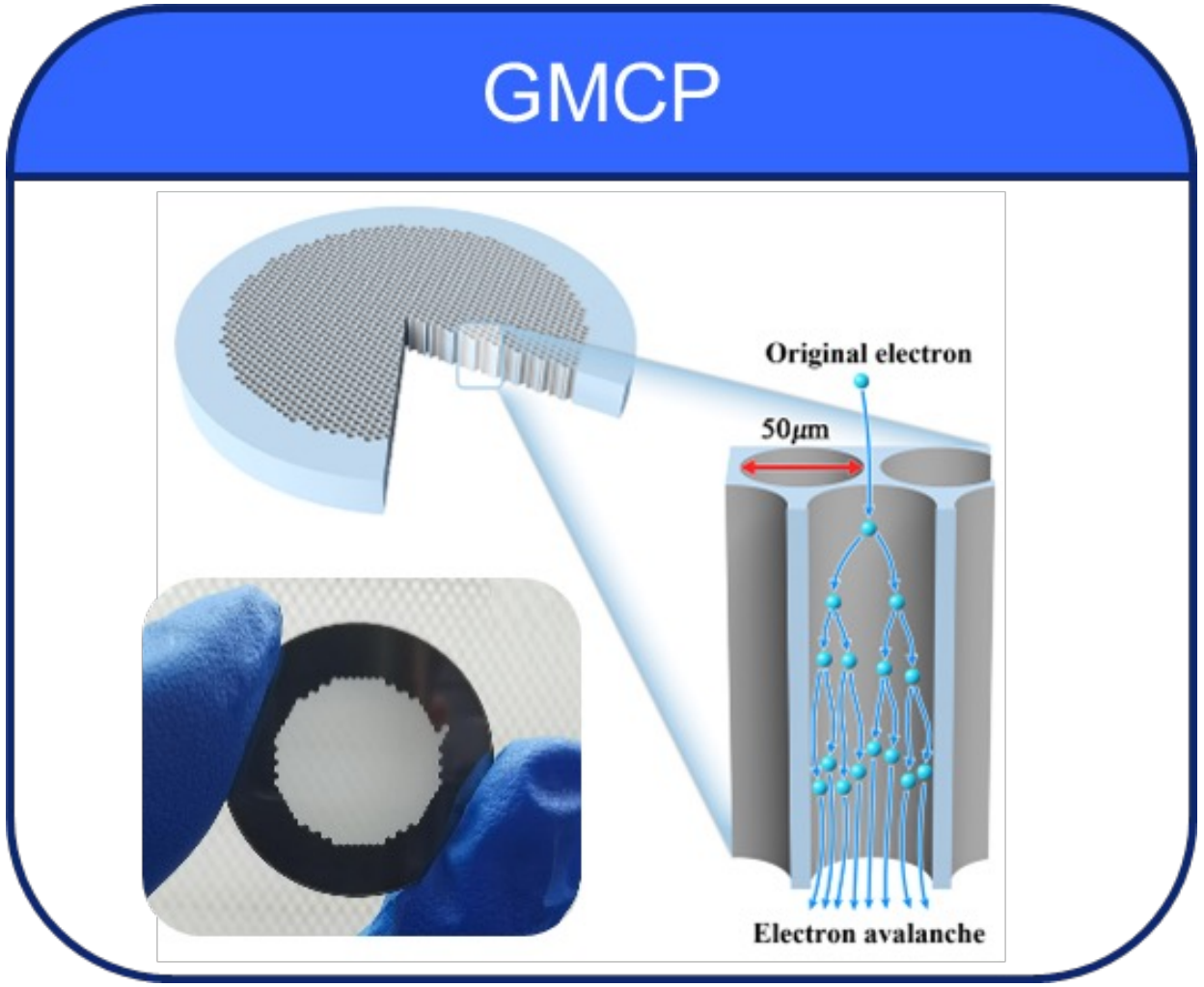
Larger GMCP

总结与展望

- 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。在核反冲能量超过35 keVee、电子反冲能量范围为5–10 keV的条件下，截面的比值为：$4.9^{+2.6}_{-1.9}\times10^{-5}$
- 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。
- 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。
- 未来考虑采用3D 成像TPC探测器

谢谢关注！

先进微结构探测器：气体微通道板GMCP



可用于天文观测空间软X射线偏振

广西大学团队

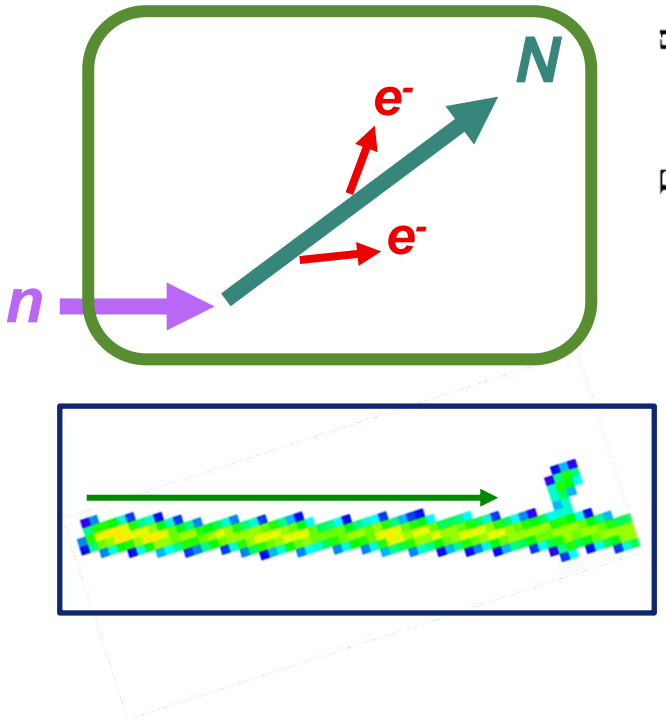

梁恩维

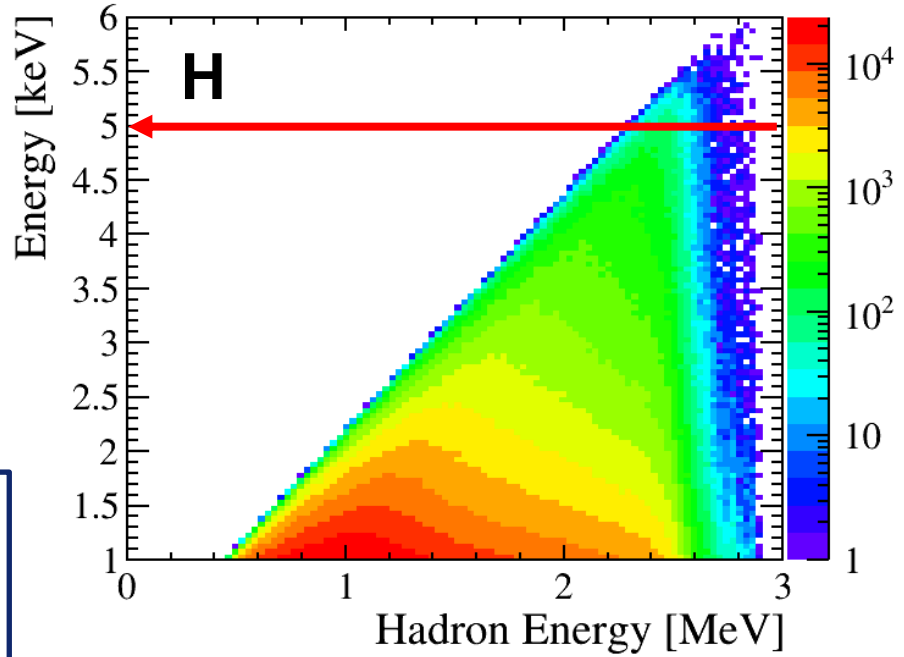

刘宏邦


封焕波

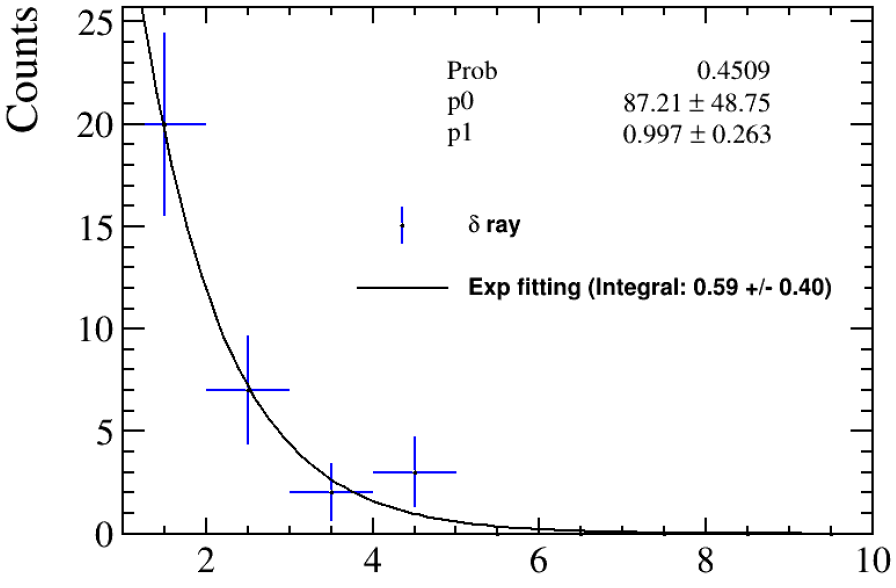
- 在广西自治区、广西相对论天体物理重点实验室的全力支持下，广西大学物理学院提供了建造和测试“相机”的平台，也为天体物理研究的X射线偏振探测和穿越辐射探测提供了关键技术支撑。
- 国科大学生易涤凡（文章第一作者）和左杰均在该实验平台上联合培养。

反冲诱导δ电子发射





Only H has the **δ electron >** 5 keV.



No δ above 5 keV were found.
Estimate by extrapolating from the exponential fit

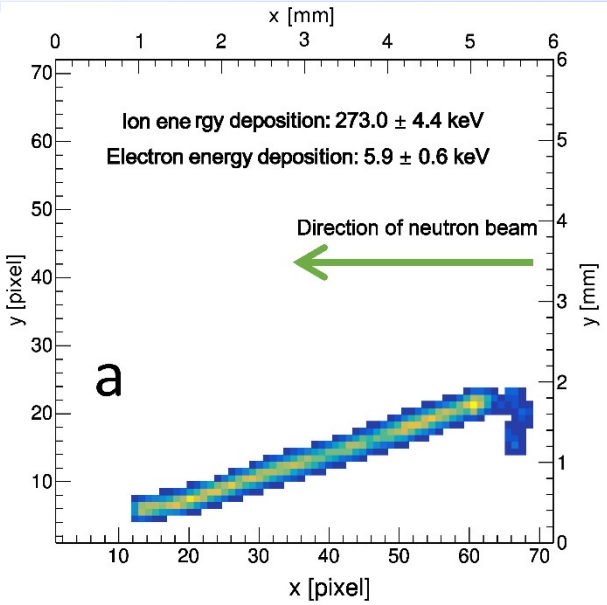
- **Consider the selection efficiency for δ-electrons.**
- **Finally get: 0.035±0.023(stat.)**

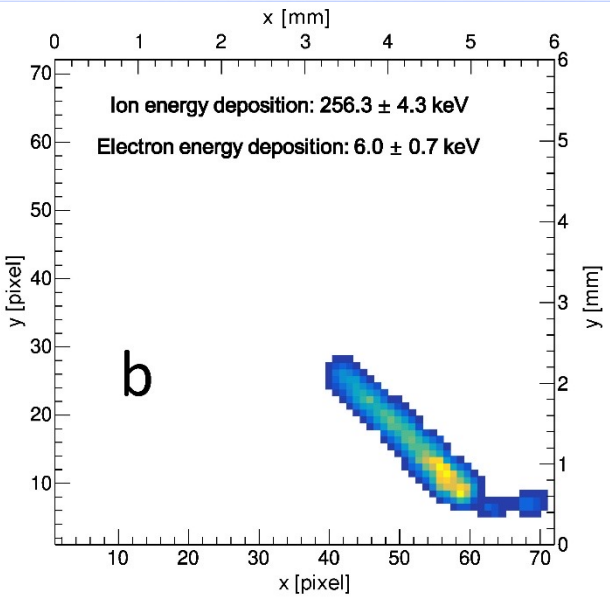
宇宙线缪子诱导δ电子发射

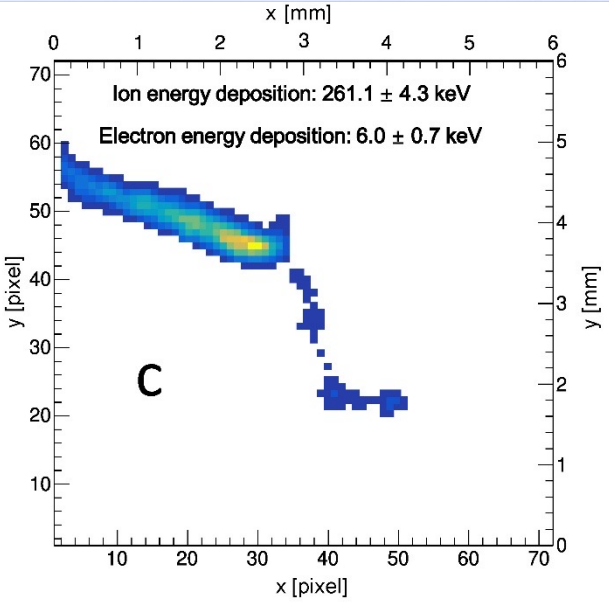
- **Adopt Local Cosmic Muon Flux Measurement Results**
  - **The local cosmic muon flux measurement(Liu,G.,et al, 2024) in Lanzhou is used for estimation.**
- **Set Nuclear Recoil Rate Benchmark and Calculate δ-ray Ratio**
  - **Set the nuclear recoil rate of the D-D neutron source as 1.4 event per second, and in the 5-10 keV energy range, considering the detector's energy resolution, calculate the ratio of δ-ray production to nuclear recoil as 1.85×10-5.**
- **Considering random track coincidence**
- **Include detector's muon exclusion efficiency**

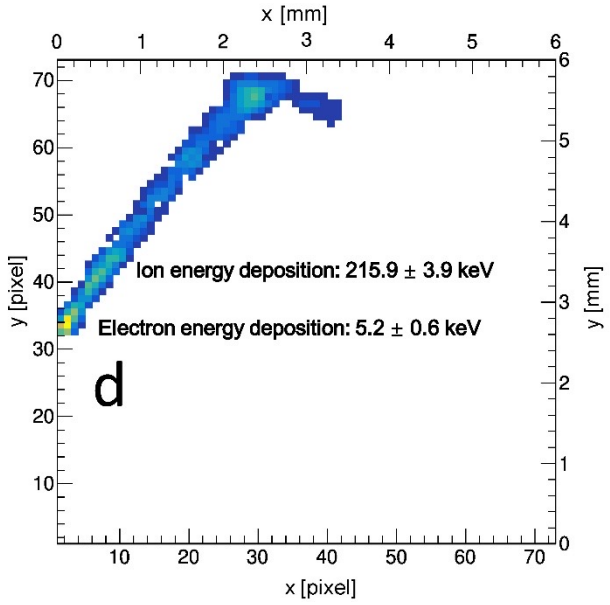
Normalize to the number of experimental data points and determine that δ-rays contribute 0.013 events.

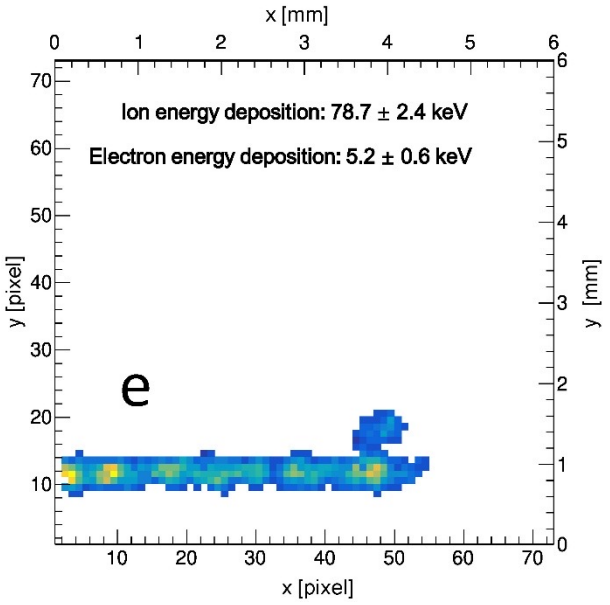
And more!

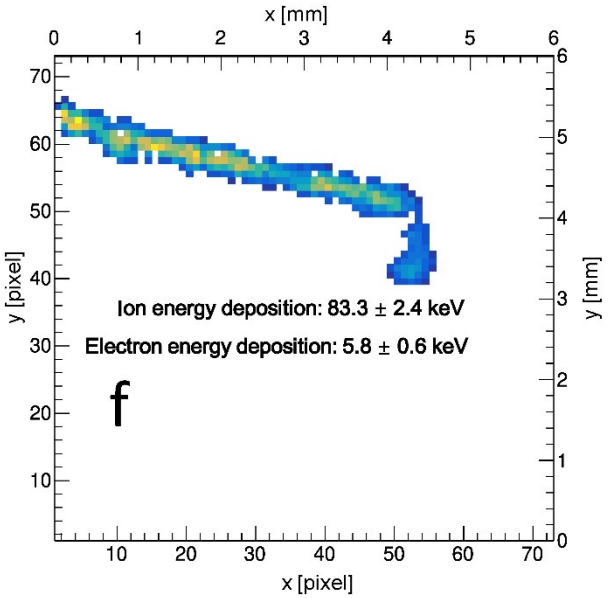

x [mm]
Ion ene rgy deposition: 273.0 ± 4.4 keV
Electron energy deposition: 5.9 ± 0.6 keV
Direction of neutron beam
a
x [pixel]
y [pixel]
y [mm]


x [mm]
Ion energy deposition: 256.3 ± 4.3 keV
Electron energy deposition: 6.0 ± 0.7 keV
b
x [pixel]
y [pixel]
y [mm]

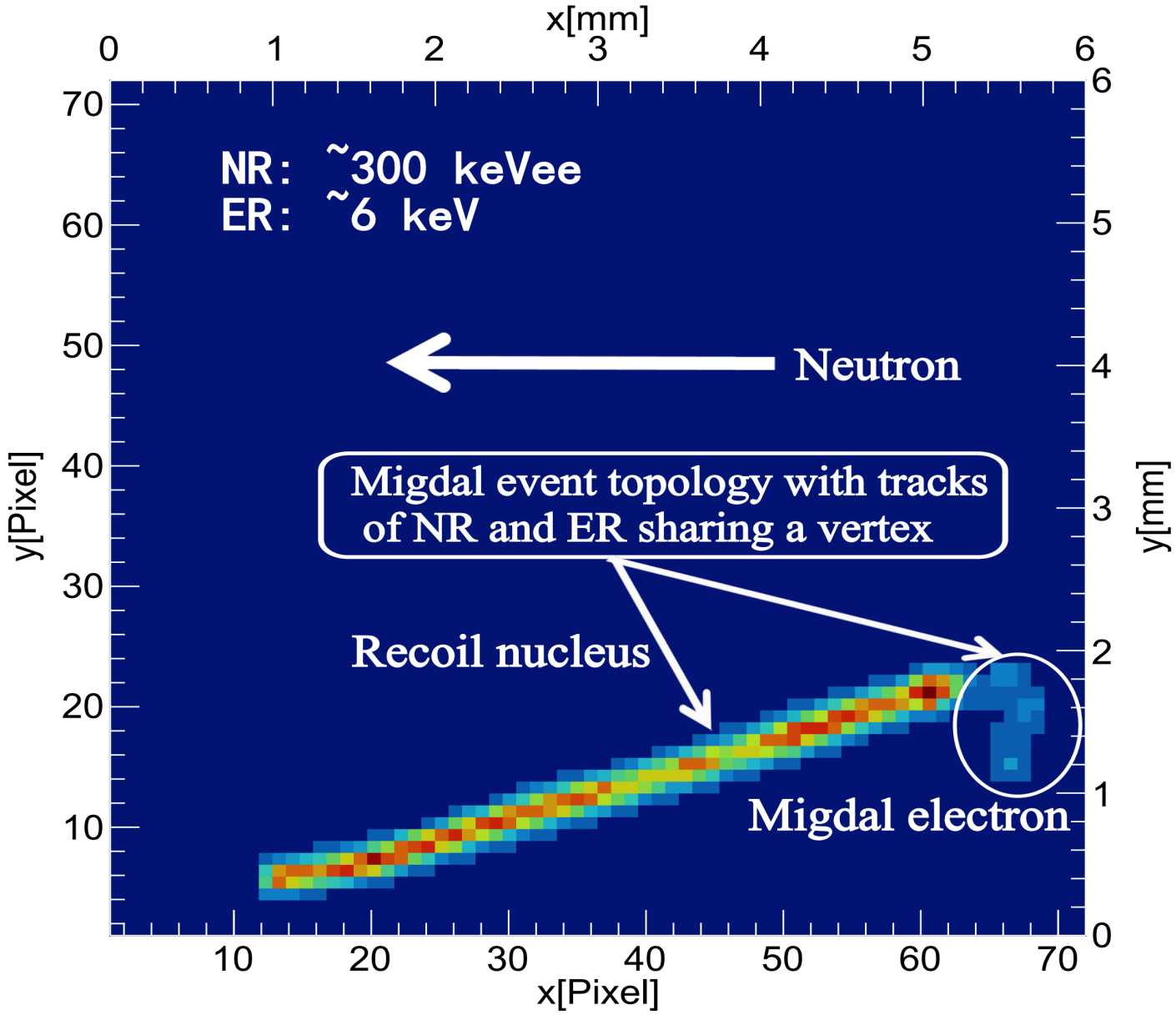

x [mm]
Ion energy deposition: 261.1 ± 4.3 keV
Electron energy deposition: 6.0 ± 0.7 keV
c
x [pixel]
y [pixel]
y [mm]

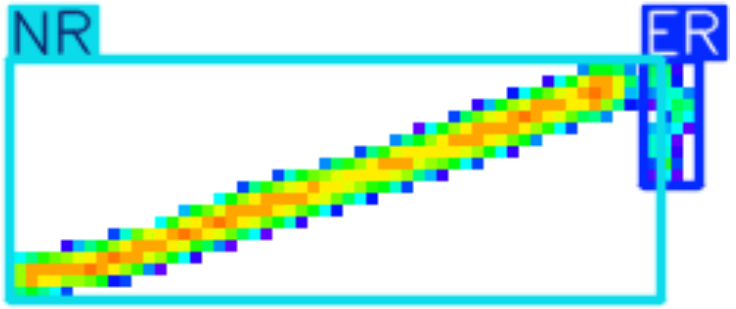

x [mm]
Ion energy deposition: 215.9 ± 3.9 keV
Electron energy deposition: 5.2 ± 0.6 keV
d
x [pixel]
y [pixel]
y [mm]


x [mm]
Ion energy deposition: 78.7 ± 2.4 keV
Electron energy deposition: 5.2 ± 0.6 keV
e
x [pixel]
y [pixel]
y [mm]


x [mm]
Ion energy deposition: 83.3 ± 2.4 keV
Electron energy deposition: 5.8 ± 0.6 keV
f
x [pixel]
y [pixel]
y [mm]

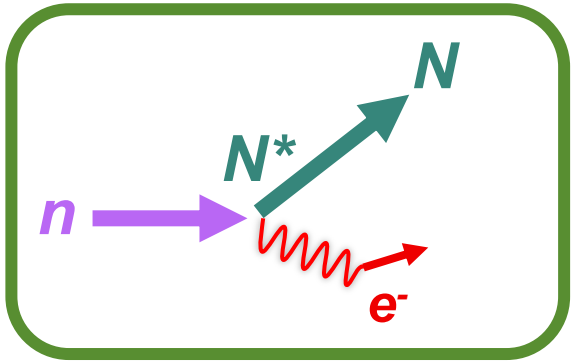
The Migdal candidate!

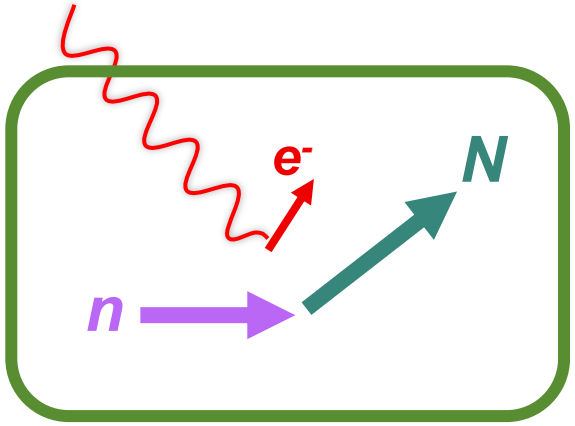


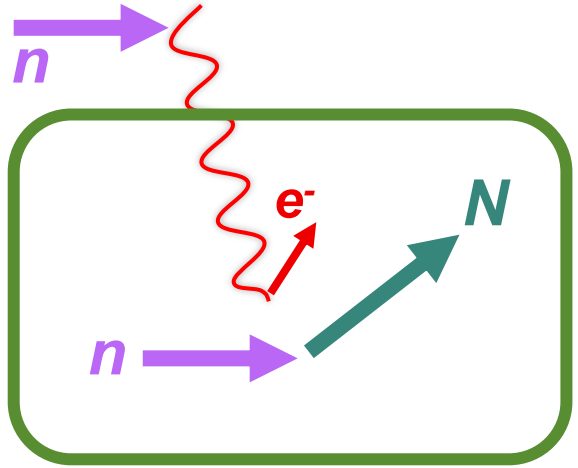


径迹的偶然符合

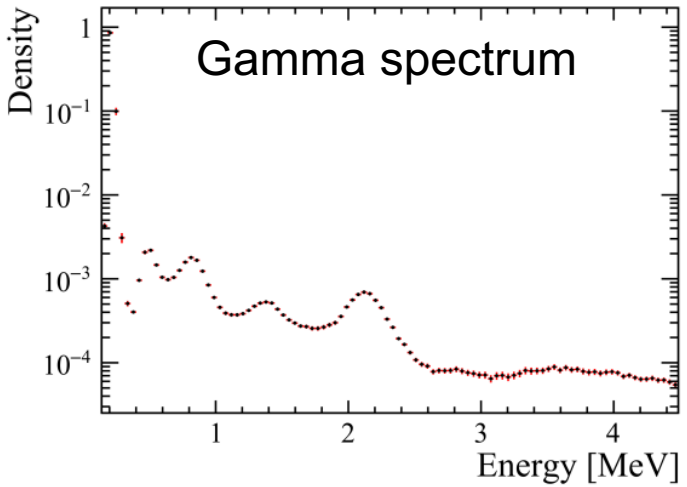
Method 1: n/γ spectrum measured by LS + GEANT4

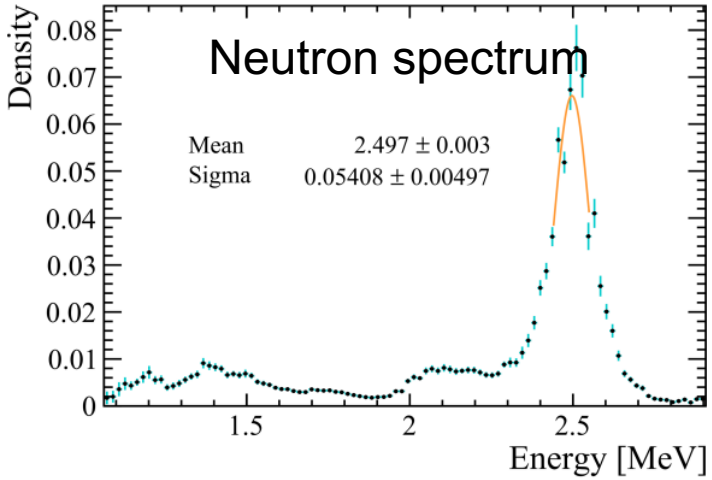






	NR	Compton e⁻	photonEle
I	1	4.32×10^{-5}	1.06×10^{-5}
II	1	6.06×10^{-6}	$\sim3.63\times10^{-8}$
III	1	3.11×10^{-6}	7.15×10^{-7}





- **The expected background contribution of the 3 components in total is: 0.16±0.01(stat.)**

Topmetal特点

超低噪声

13.9 e^- (ENC等效噪声电荷)

世界最低水平之一，微弱信号精确探测的基石

核心技术原理

- 直接电荷收集：避免硅体内传输，消除主要噪声源
- 优化CSA：差分架构+高阻工艺，有效抑制环境干扰

大动态范围

0~14,000 e^-/1.1V

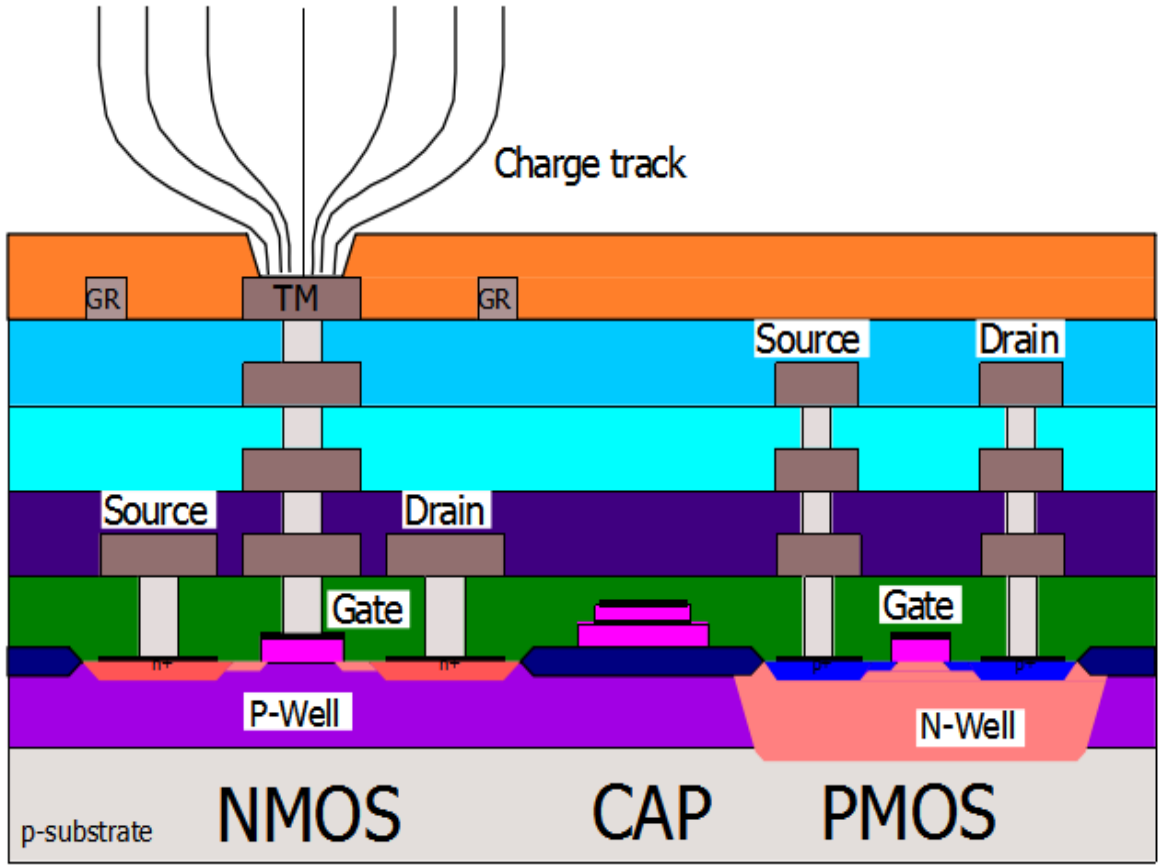
宽输入电荷范围与高输出电压动态区间

核心技术原理

- 高转换增益：极小反馈电容，精准捕捉微弱信号
- 宽线性区：CSA在全量程保持线性，确保能量准确

Topmetal技术概念

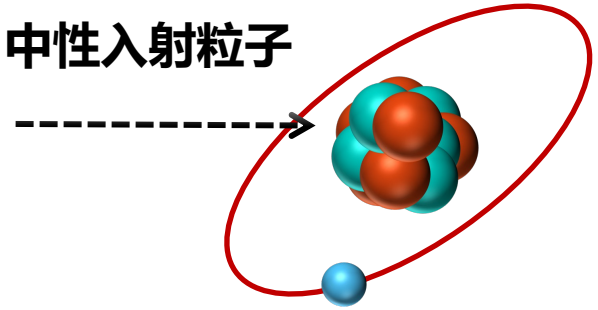
- Topmetal技术是一种高空间分辨、低噪声直接电荷探测技术，采用CMOS集成电路工艺制造高精度像素探测器。摒弃传统半导体内部电荷收集方式，首创设计的顶层金属（Topmetal）开窗像素结构直接收集自由电荷，收集的电荷在“节点”处引起电位变化，经源极跟随器和行/列多路复用器进行模拟读出，还可通过阈值鉴别器等转化为数字值，并形成电荷云分布的二维图像，实现高空间分辨成像。

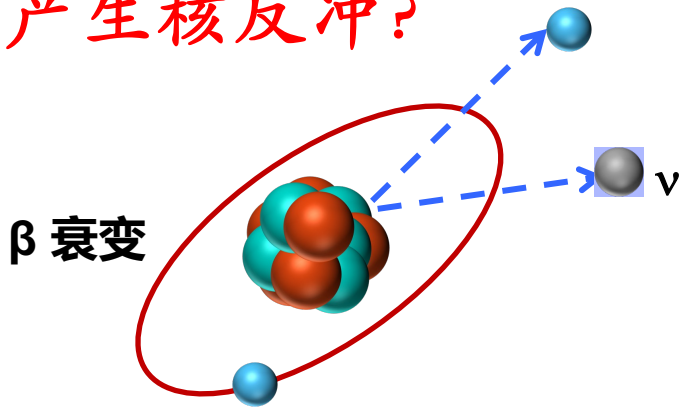


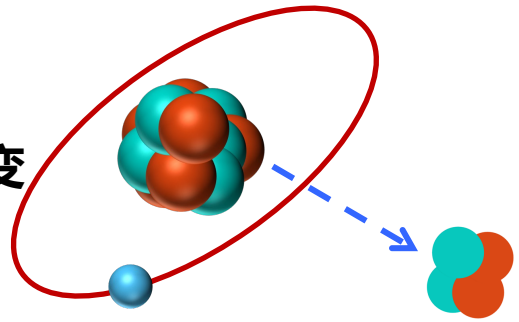
Topmetal原理图

原子在核反冲过程中的物理图像

怎么产生核反冲？

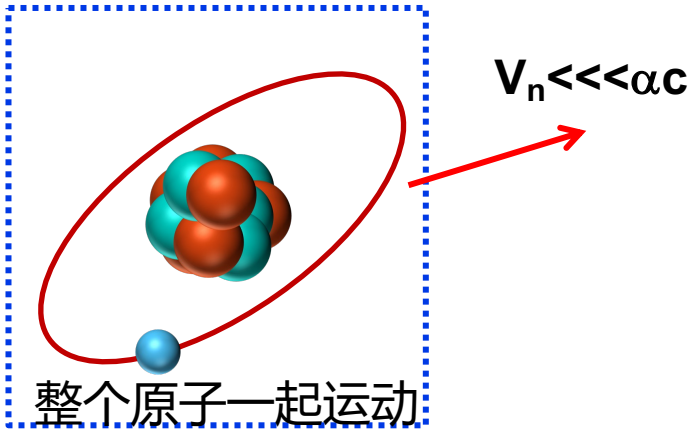




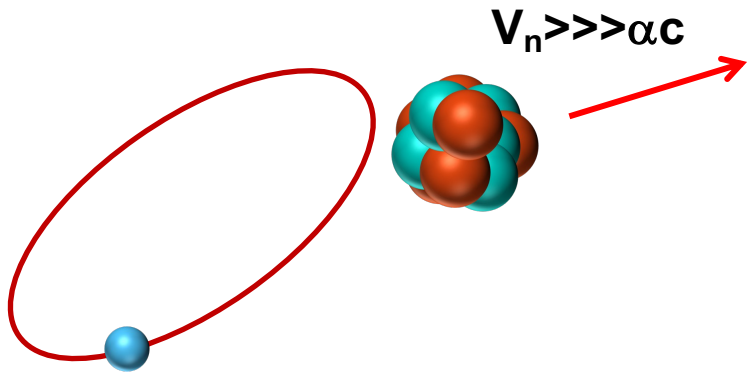


核反冲后会发生什么？ $\alpha = 1/137$

1. 较低能量转移

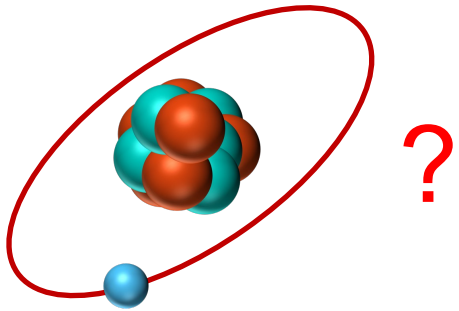


2. 较高能量转移



3. 中等能量转移

$V_n \sim \alpha c$



Topmetal系列像素芯片

自2012年以来，项目团队成功研制了Topmetal一系列芯片，涵盖不同像素间距（40~83μm）、阵列规模（6*64~400*512）及芯片尺寸（6*8~18*23mm²），拥有了完整自主知识产权。

