Direct observation of the Migdal effect induced by neutron bombardment

米格达尔(Migdal)效应的直接观测

Nature **649**, 580 (2026)

MARVEL

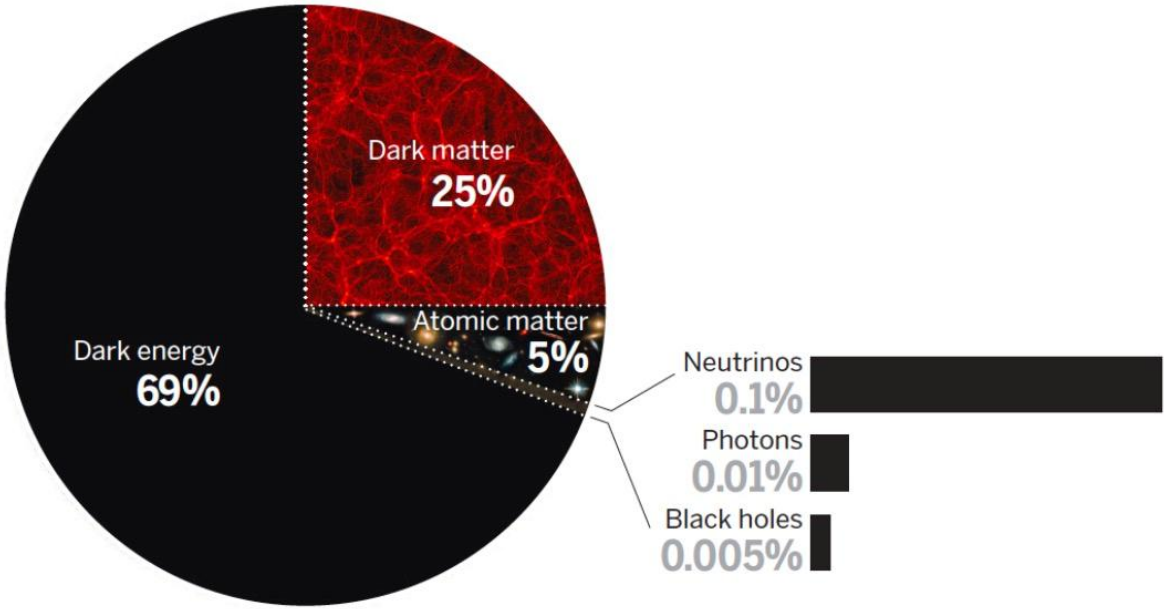
刘　倩

(代表 **MARVEL** 合作组团队)

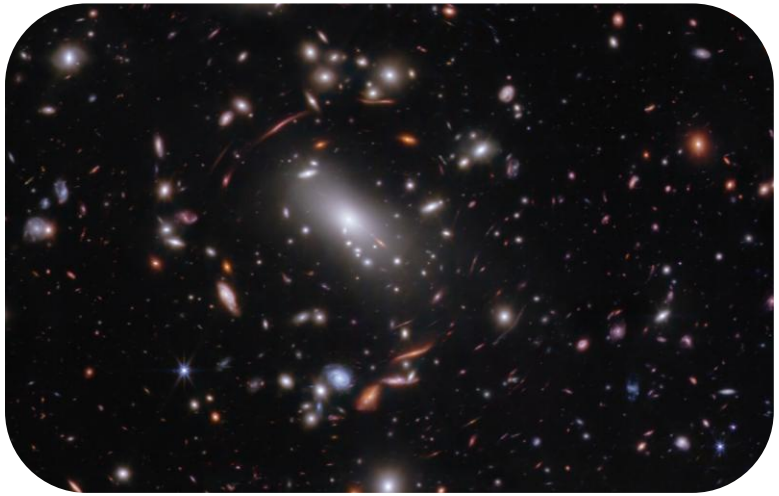
MigdAl pRocess Validation by nEutruaL scattering (中性散射中的Migdal过程验证)

中国科学院大学

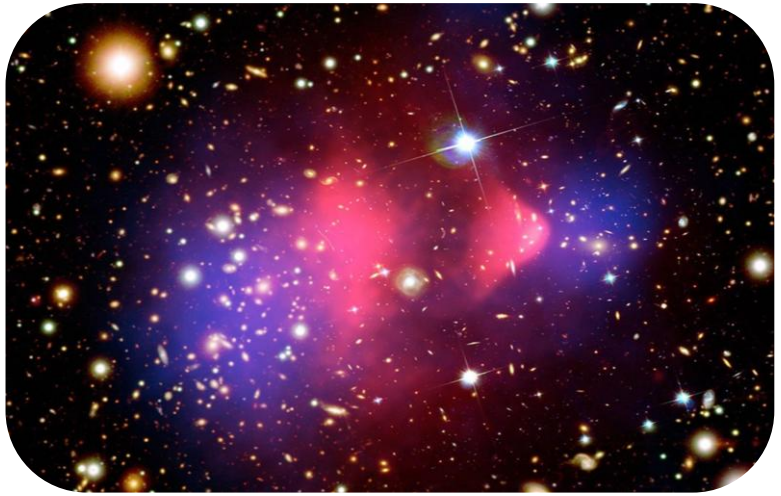
Dark matter



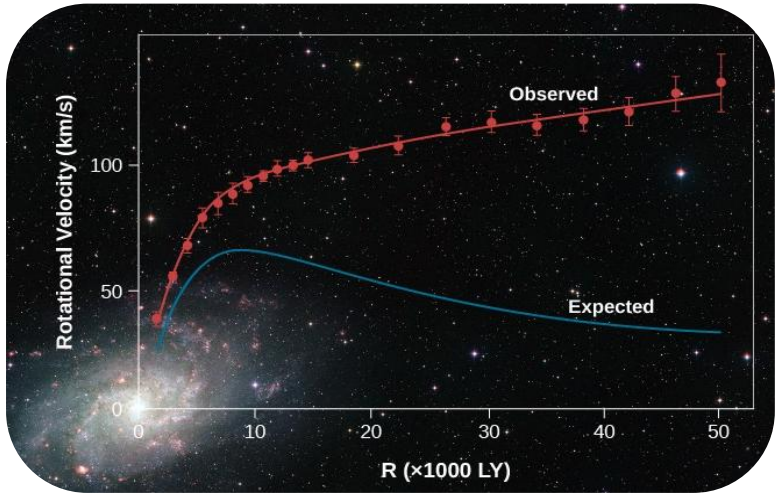
- Dark matter makes up most of the mass in galaxies and galaxy clusters.
- Current evidence comes solely from gravitational interaction.



Gravitational Lens

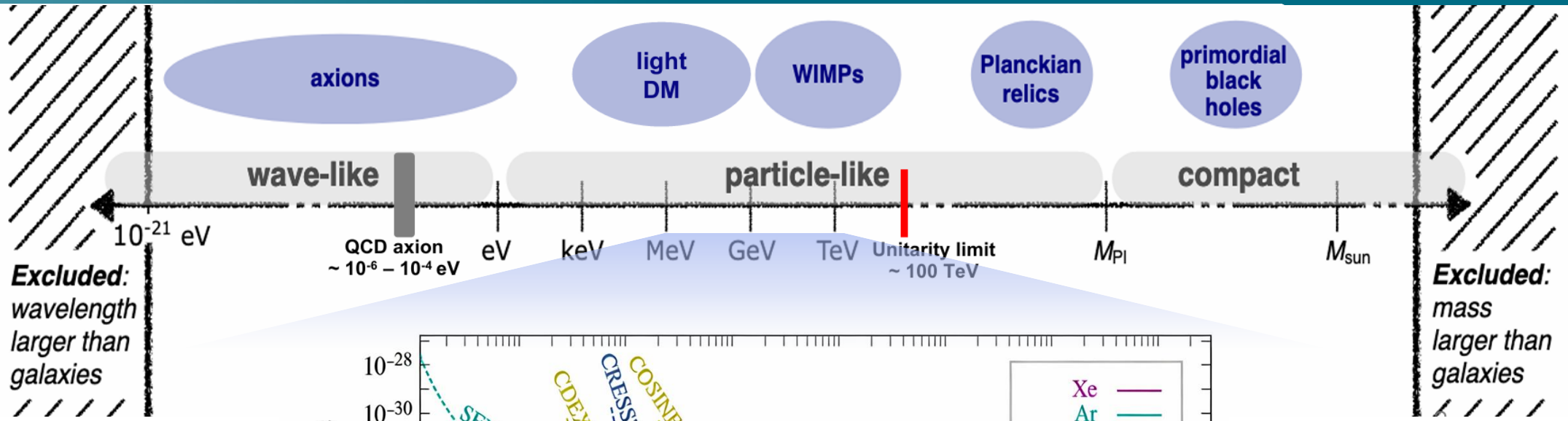


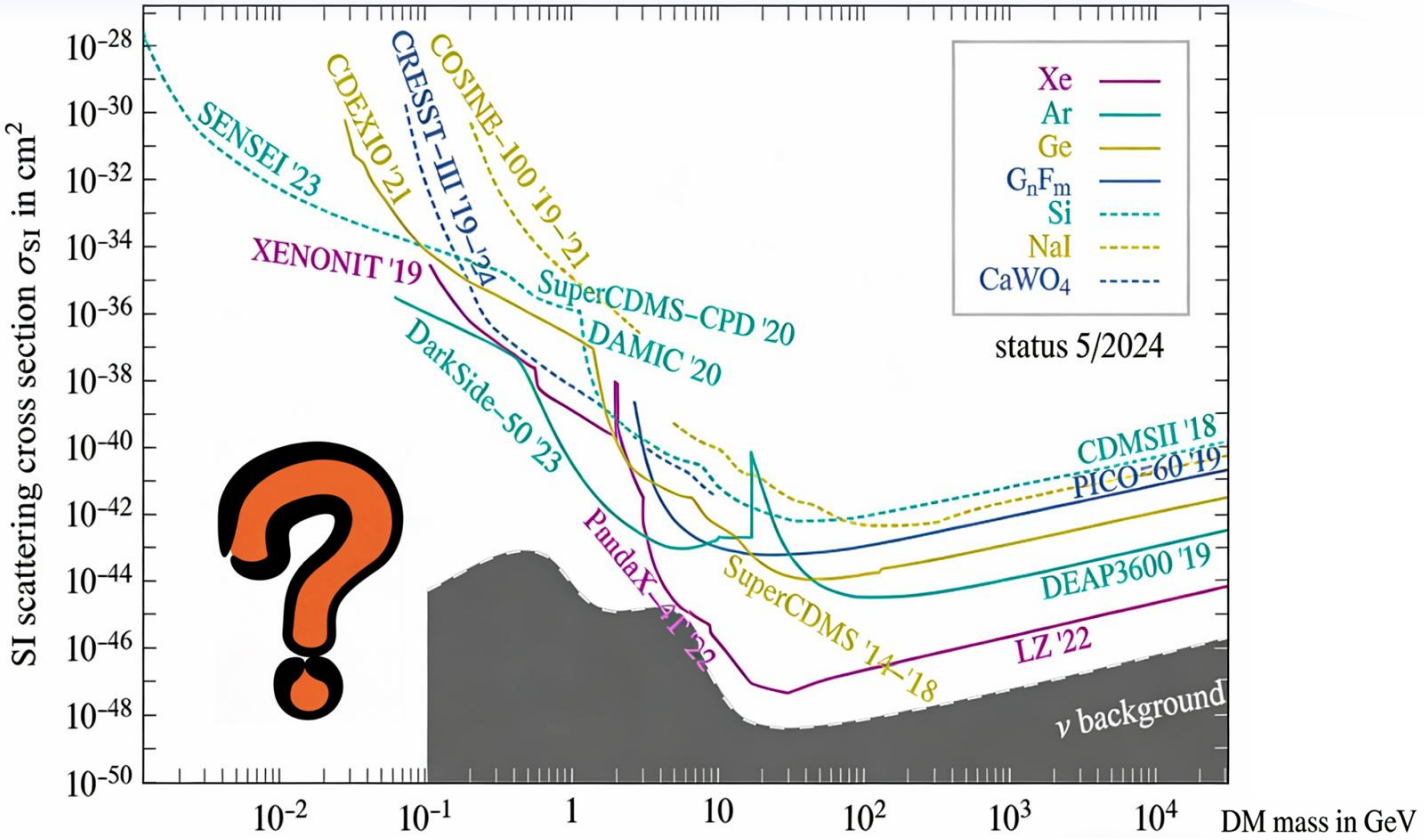
Galaxy mergers



Galactic rotation curve

WIMP


axions
light DM
WIMPs
Planckian relics
primordial black holes
wave-like
particle-like
compact
10^{-21} eV
QCD axion
~ 10^{-6} – 10^{-4} eV
eV
keV
MeV
GeV
TeV
Unitarity limit
~ 100 TeV
M_{Pl}
M_{sun}
Excluded: wavelength larger than galaxies
Excluded: mass larger than galaxies

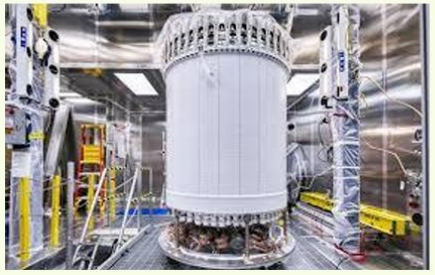

SI scattering cross section σ_{SI} in cm^2
DM mass in GeV
Xe
Ar
Ge
G_nF_m
Si
NaI
$CaWO_4$
status 5/2024
SENSEI '23
CDEX10 '21
CRESST-III '19–'24
COSINE-100 '19–'21
XENONIT '19
SuperCDMS-CPD '20
DAMIC '20
DarkSide-50 '23
PandaX-4T '22
SuperCDMS '14–'18
LZ '22
DEAP3600 '19
PICO-60 '19
CDMSII '18
ν background

Dark matter experiments

WIMP dark matter searches, PIC-2025

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

CDMS

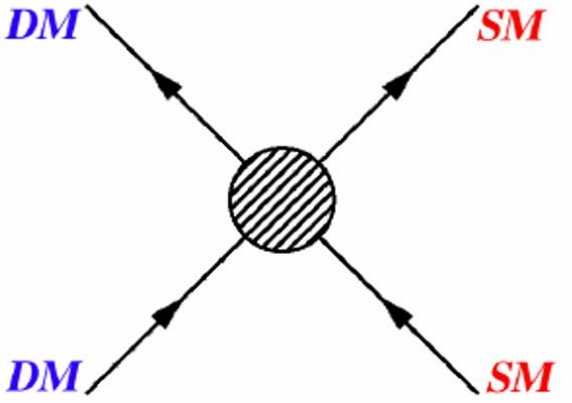


LZ

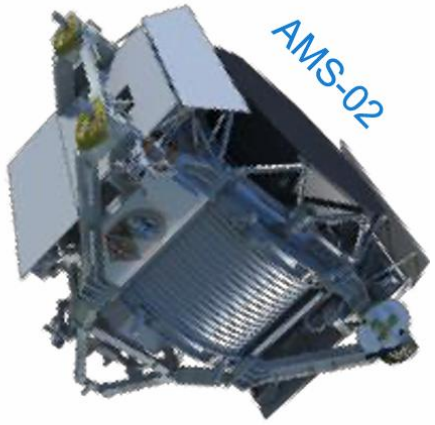
direct detection

- 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)

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



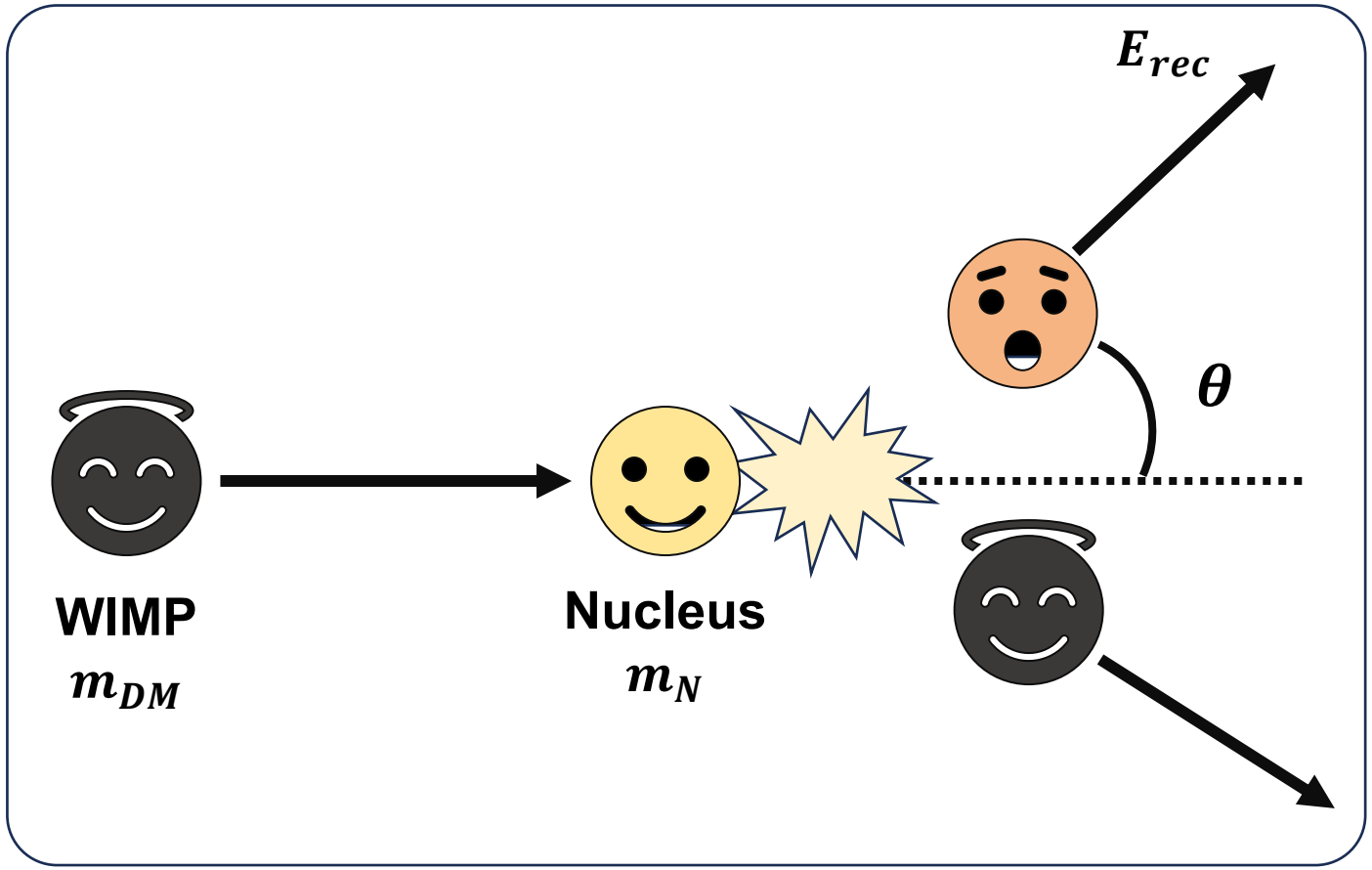
production at colliders



CMS/ATLAS

- Produce new particles in high energy collisions

DM-nucleus elastic scattering



Non-relativistic elastic scattering

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

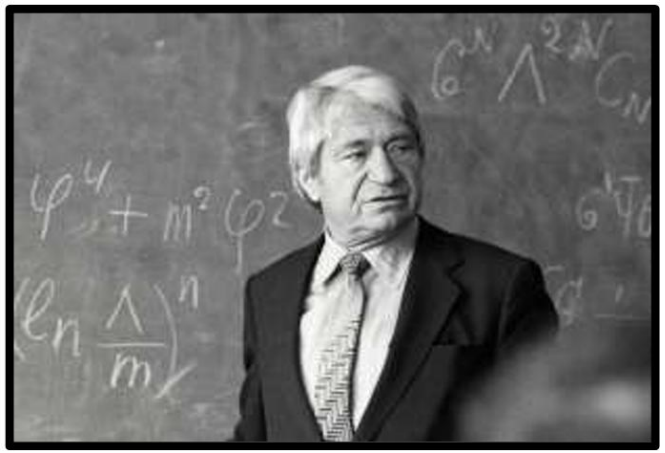
$$E_{rec} = \frac{\mu^2 v^2}{m_N}(1 - \cos\theta) \leq \frac{2\mu^2 v^2}{m_N}$$

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

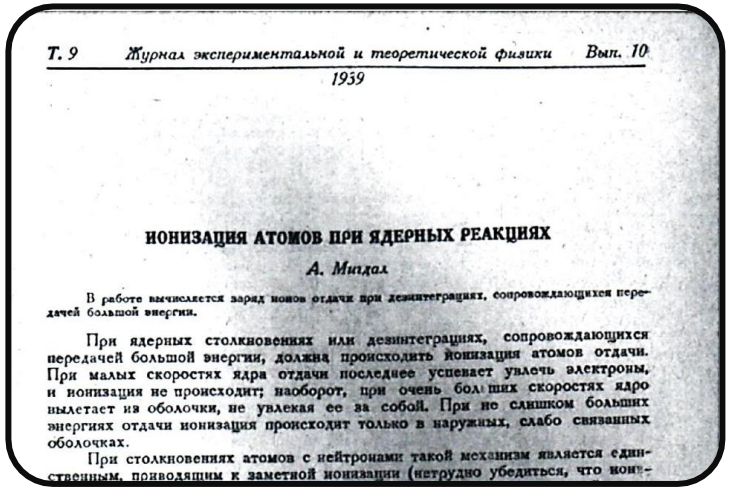
$E_{rec} \leq 0.7$ keV$_{\mathrm{nr}}$

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

Migdal效应



- 1939年由前苏联科学家Migdal预言



Т. 9 Журнал экспериментальной и теоретической физики Вып. 10
1939

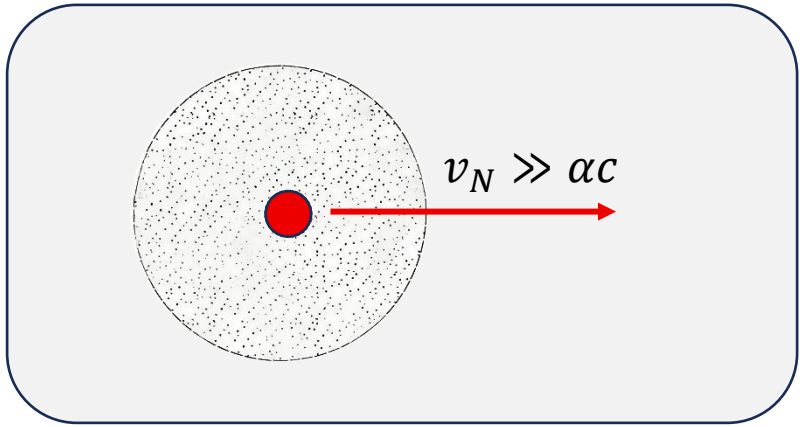
ИОНИЗАЦИЯ АТОМОВ ПРИ ЯДЕРНЫХ РЕАКЦИЯХ

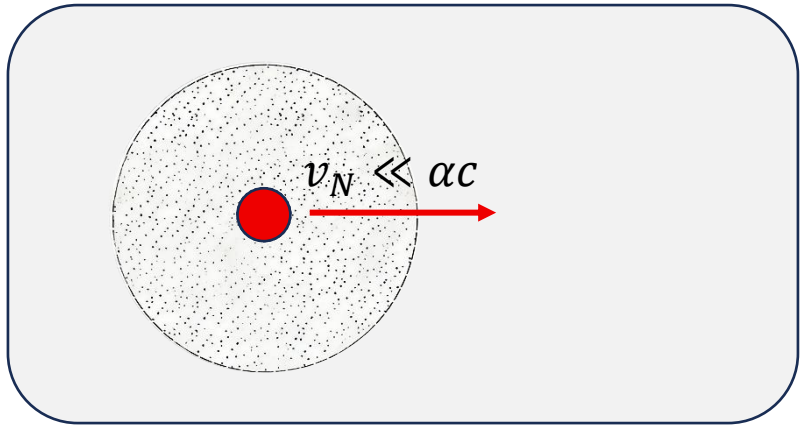
А. Мигдал

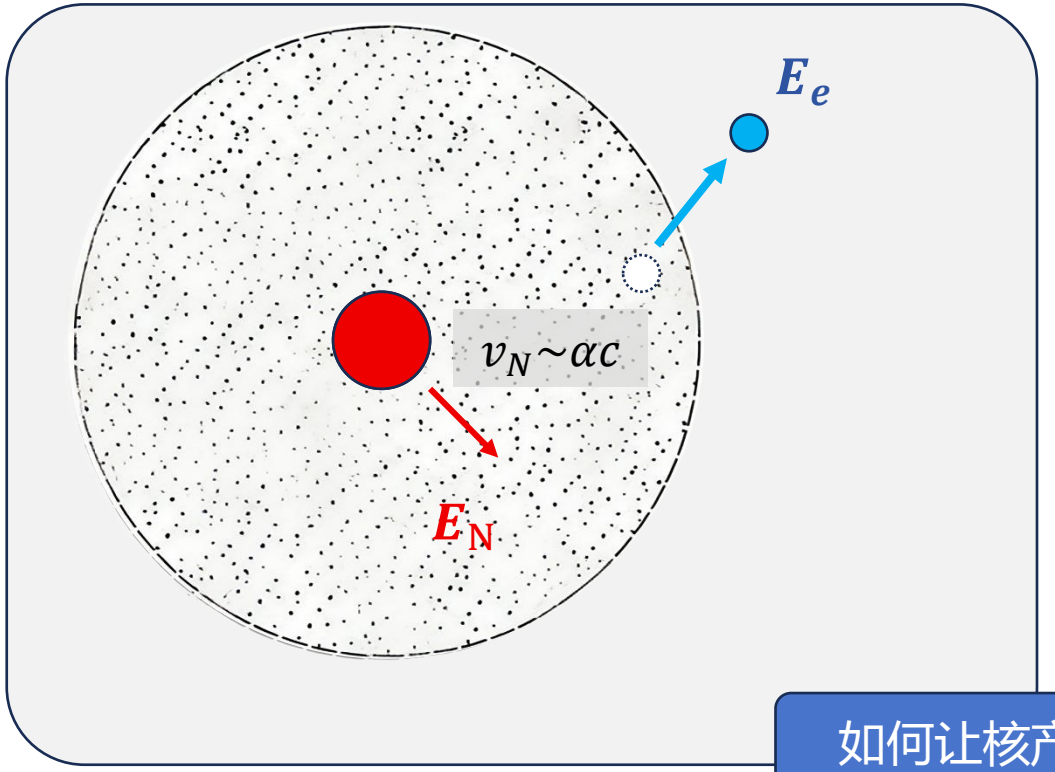
В работе вычисляется заряд ионов отдачи при дезинтеграциях, сопровождающихся передачей большой энергии.

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-





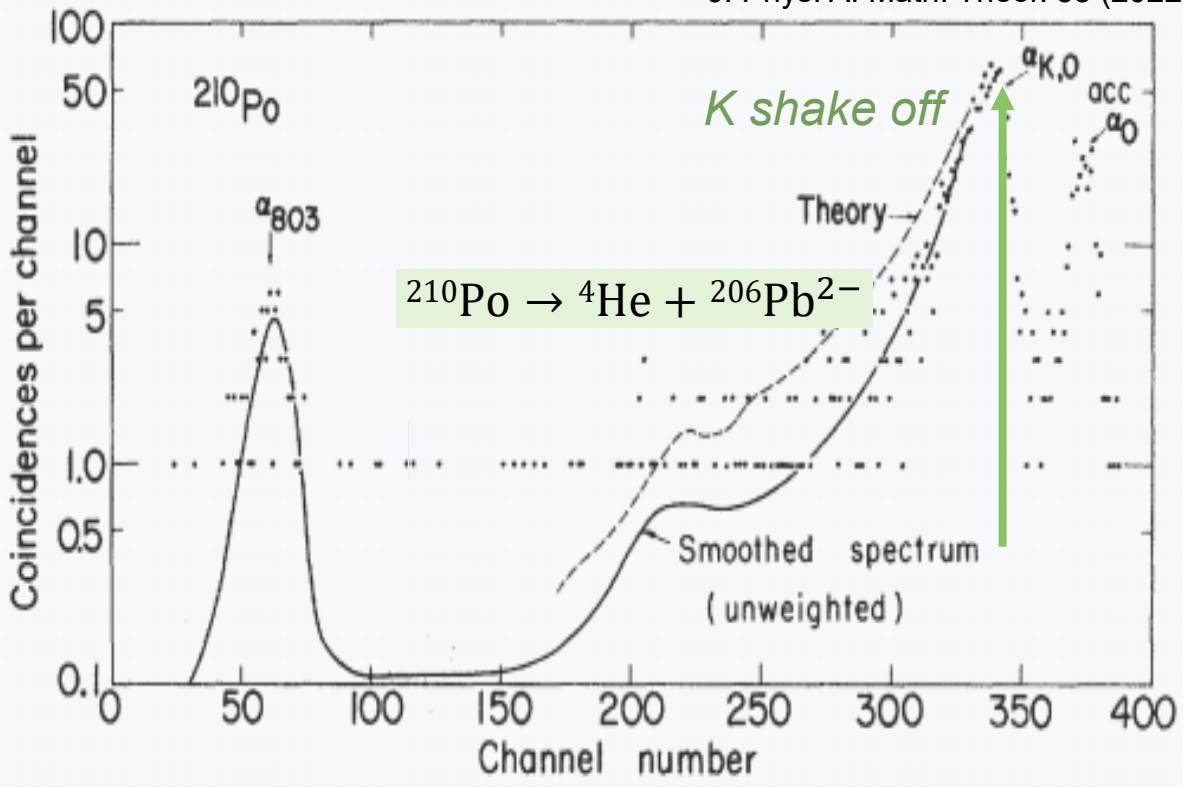


如何让核产生位移?

Migdal效应的间接探测证据

α 衰变

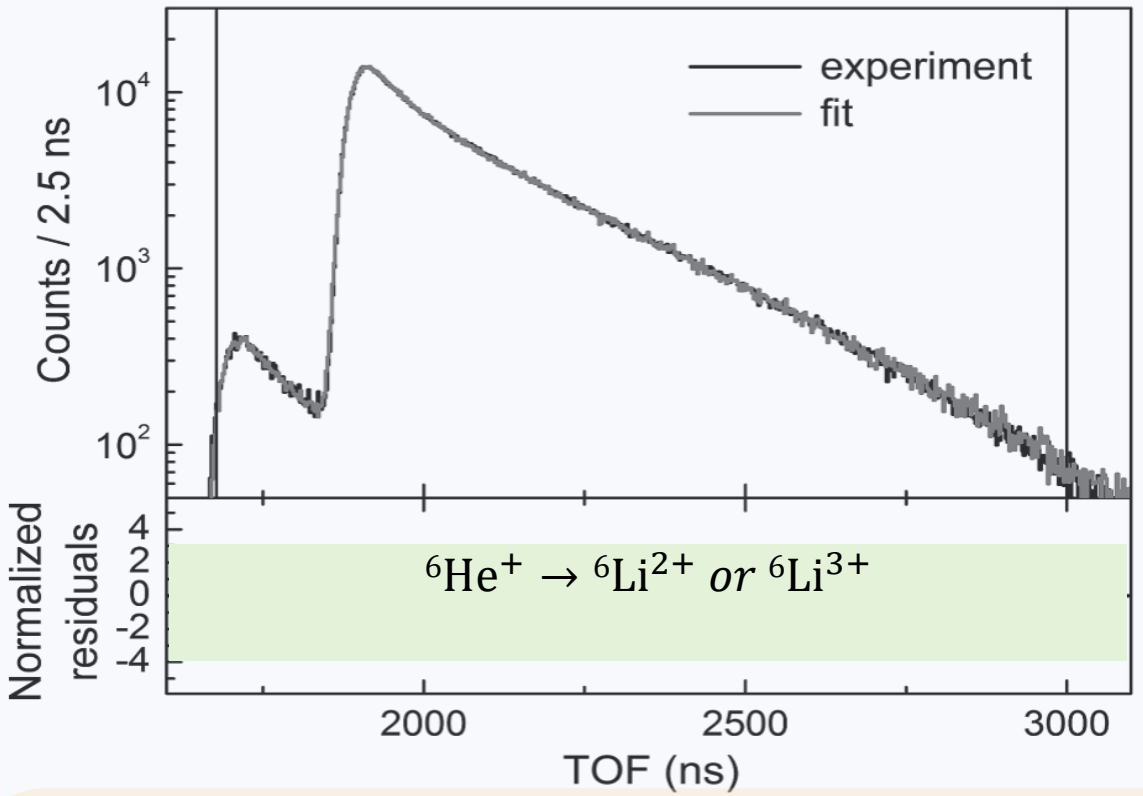
PhysRevC.11.1740 (1975)
J. Phys. A: Math. Theor. 55 (2022)



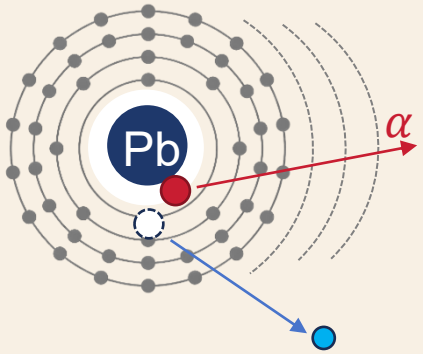
$^{210}\mathrm{Po} \rightarrow {}^{4}\mathrm{He} + {}^{206}\mathrm{Pb}^{2-}$

β 衰变

PhysRevLett.108.243201 (2012)

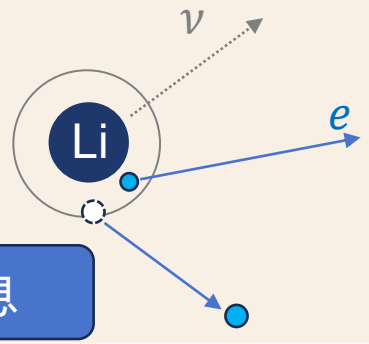


$^{6}\mathrm{He}^{+} \rightarrow {}^{6}\mathrm{Li}^{2+}\ or\ {}^{6}\mathrm{Li}^{3+}$



α电离铅核的k层电子

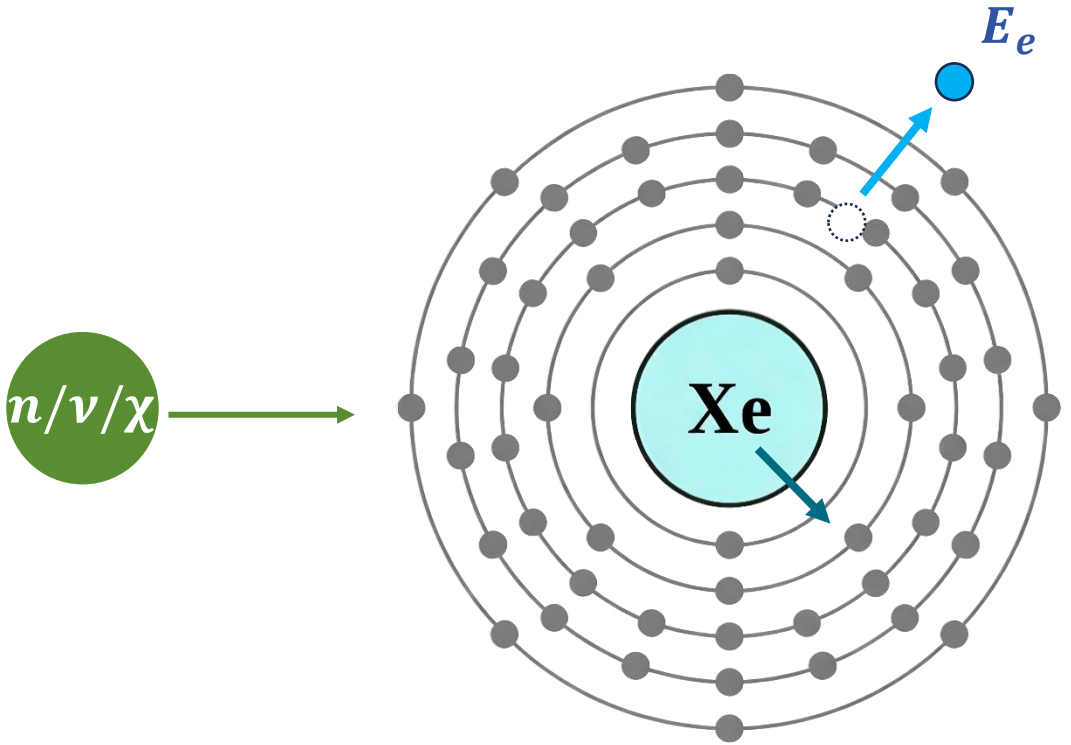
导致能量降低



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

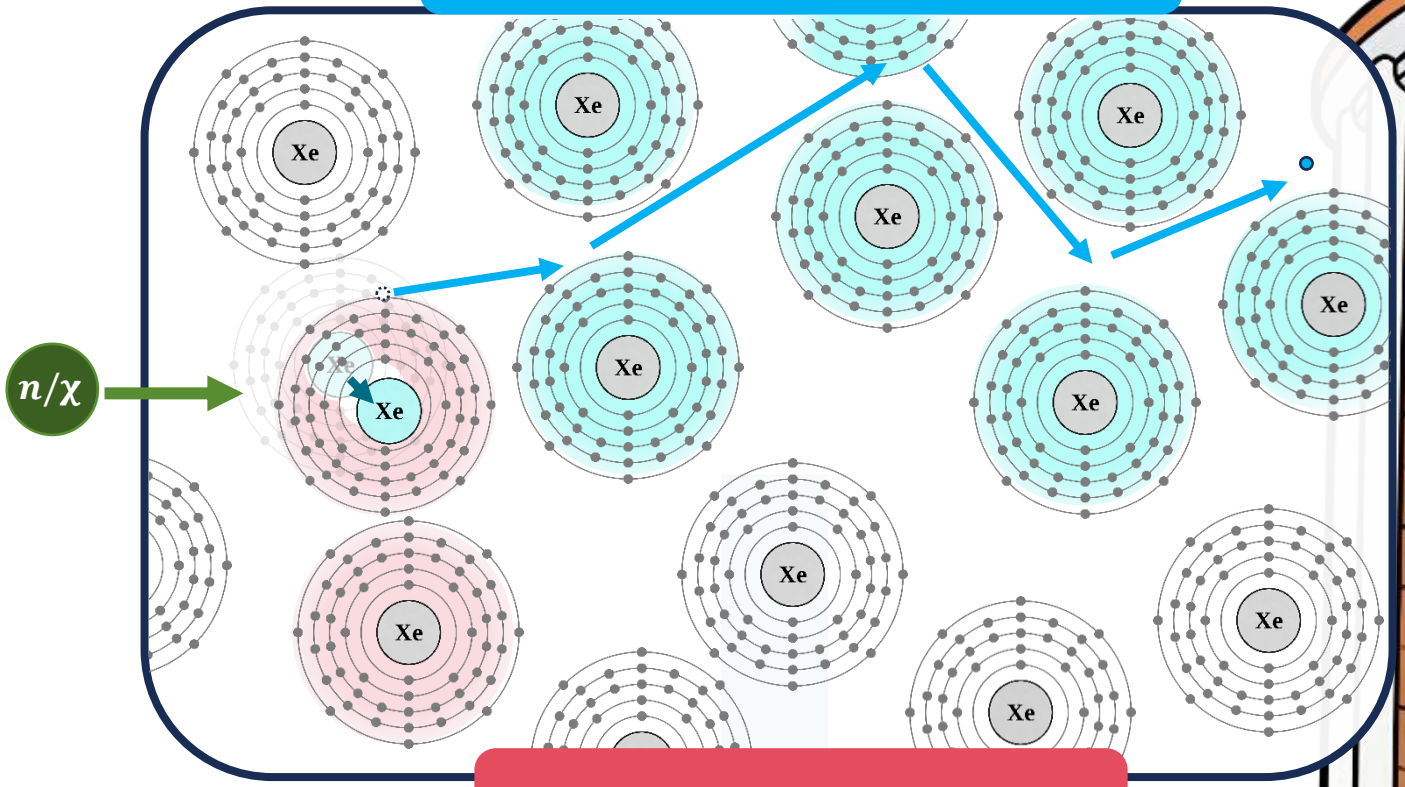
中性粒子碰撞中的Migdal效应



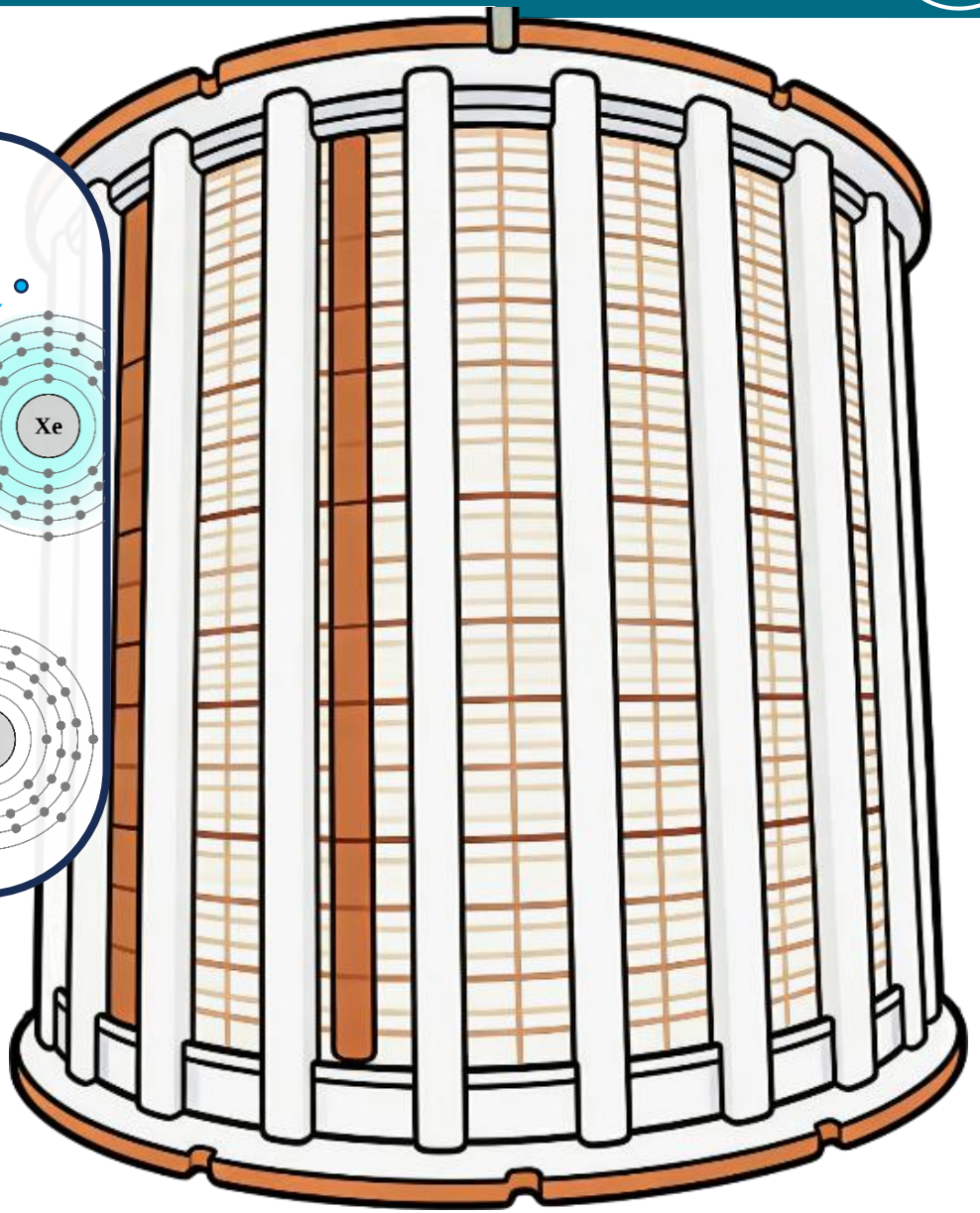
至今已有80余年，仍未有直接观测的证据

利用Migdal效应直接探测暗物质实验

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



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

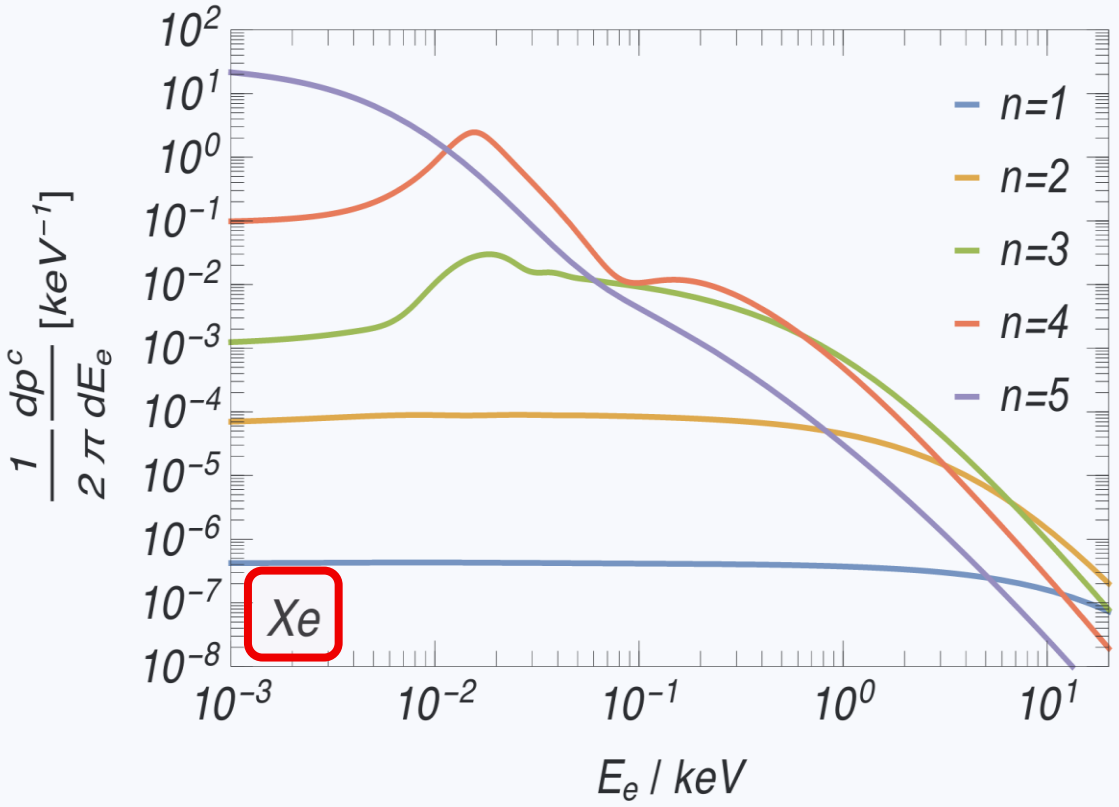


$$E_{\mathrm{det}} = E_{\mathrm{er,obs}} + E_{\mathrm{nr,obs}} + \ldots$$

在低动量转移情况下仍然提供可探测信号！

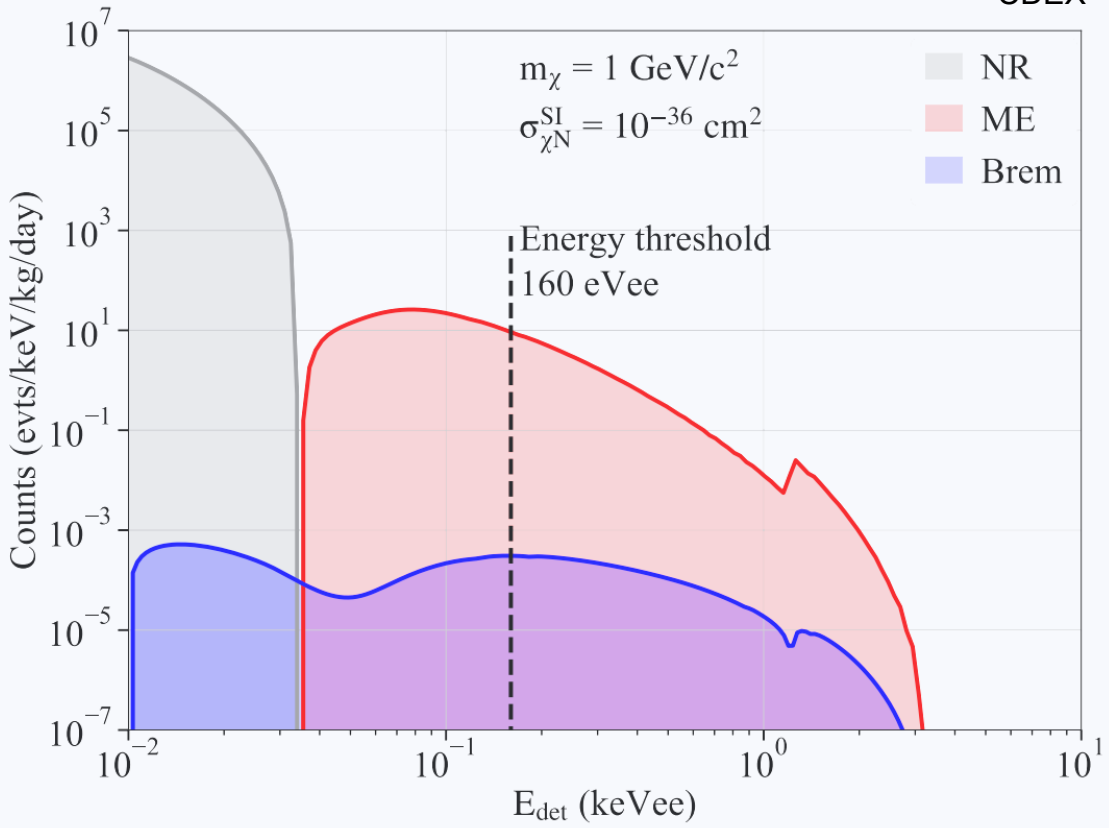
Migdal效应的特点

M. Ibe, JHEP03(2018)194



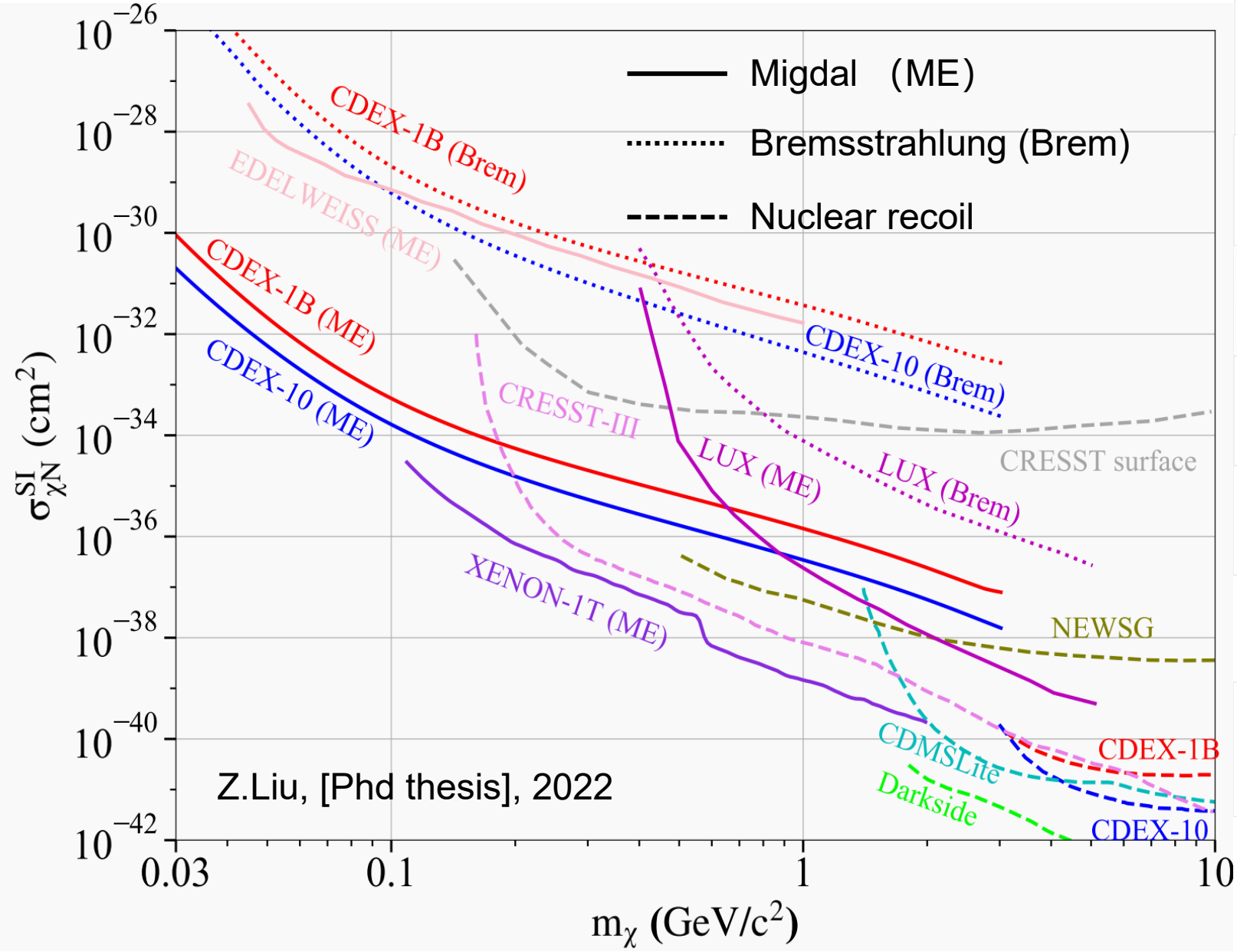
不同轨道均可能产生Migdal电子

CDEX



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



Search for Light Dark Matter Interactions Enhanced by the Migdal Effect or Bremsstrahlung in XENON1T #1
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 #1
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 #1
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 #1
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 #1
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

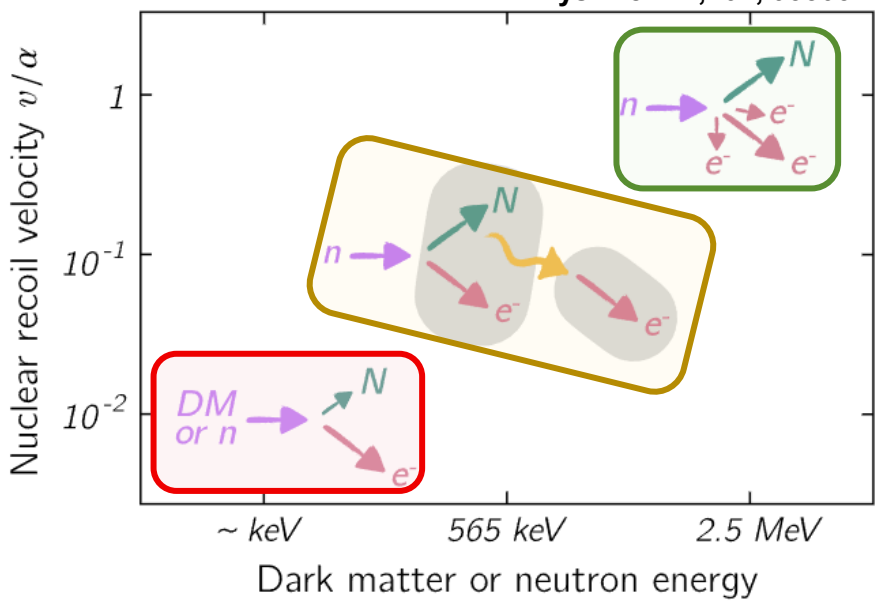
Search for low-mass dark matter via bremsstrahlung radiation and the Migdal effect in SuperCDMS #1
SuperCDMS Collaboration • M.F. Albakry (British Columbia U. and TRIUMF) et al. (Feb 17, 2023)
Published in: *Phys.Rev.D* 107 (2023) 11, 2023 • e-Print: 2302.09115 [hep-ex]
pdf links DOI cite claim reference search 43 citations

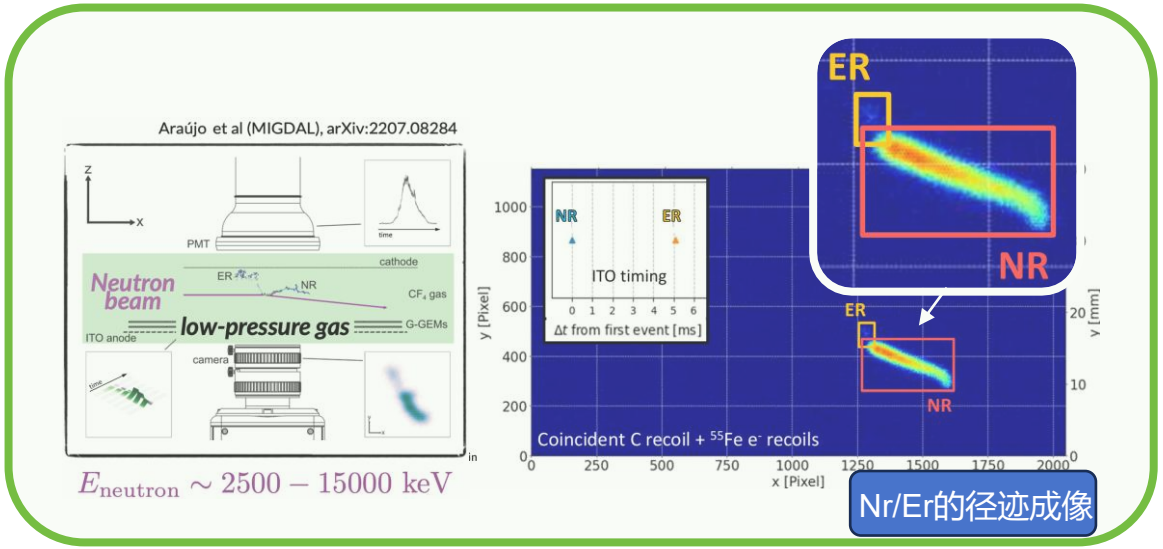
Search for sub-GeV dark matter via the Migdal effect with an EDELWEISS germanium detector with NbSi transition-edge sensors #2
EDELWEISS Collaboration • E. Armengaud (IRFU, Saclay) et al. (Mar 8, 2022)
Published in: *Phys.Rev.D* 106 (2022) 6, 062004 • e-Print: 2203.03993 [astro-ph.GA]
pdf DOI cite claim reference search 66 citations

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

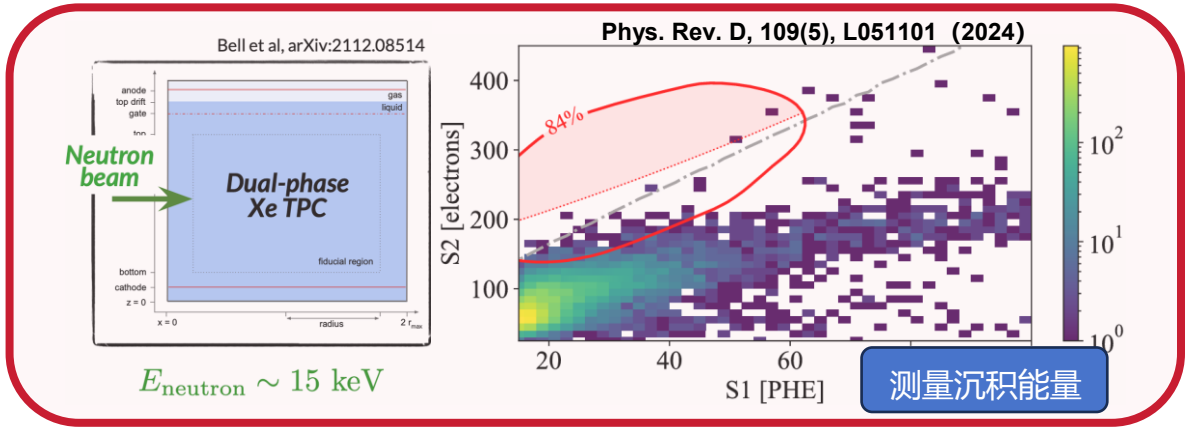
国际上中性粒子Migdal效应实验

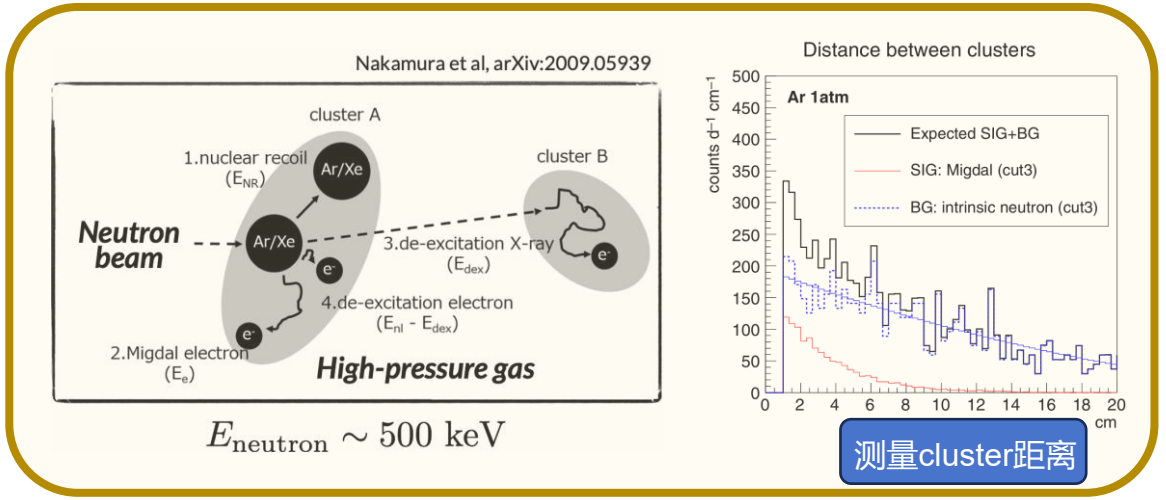
Phys. Rev. D,107, 035032



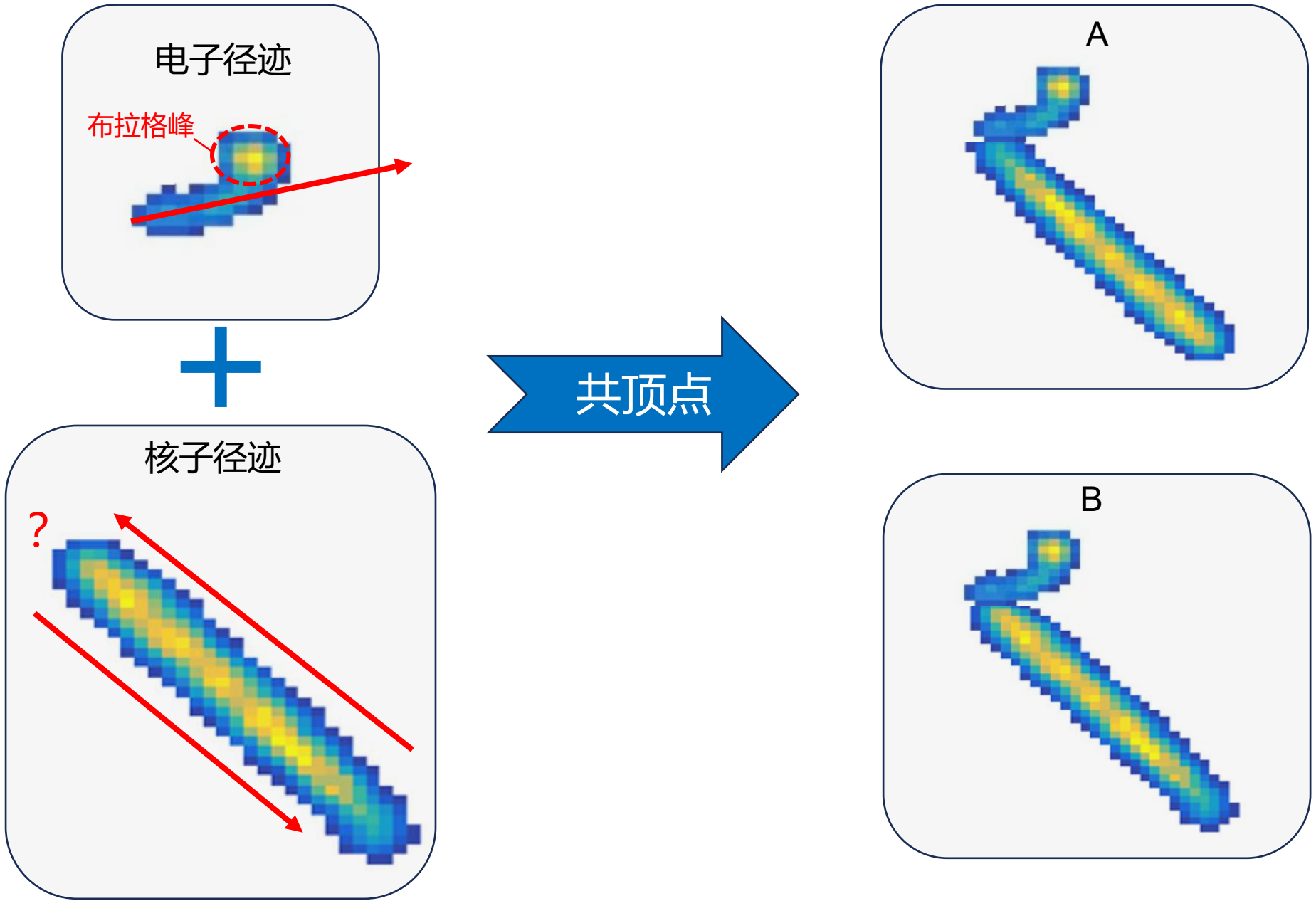


Phys. Rev. D, 109(5), L051101 (2024)

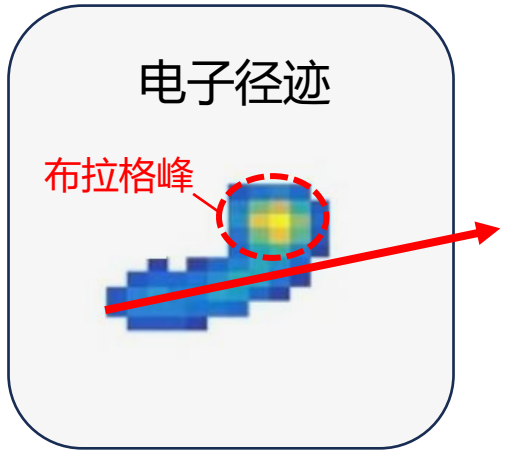


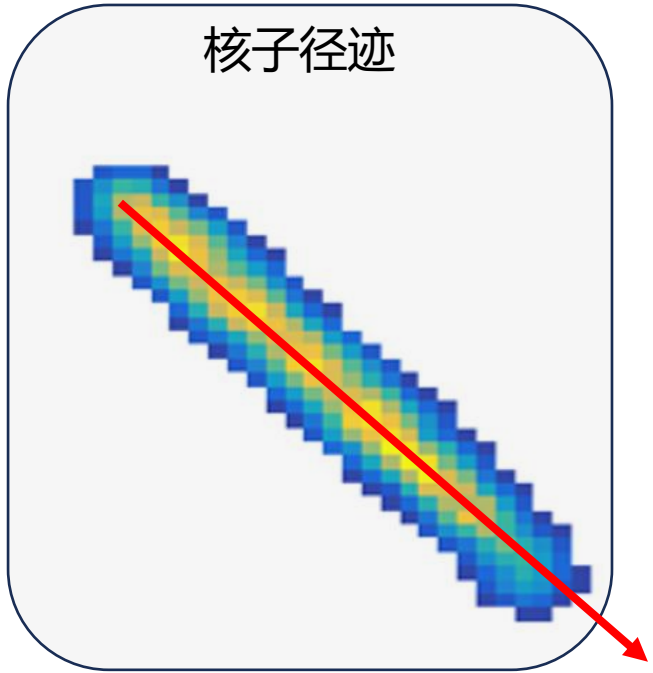


Migdal事例的特征

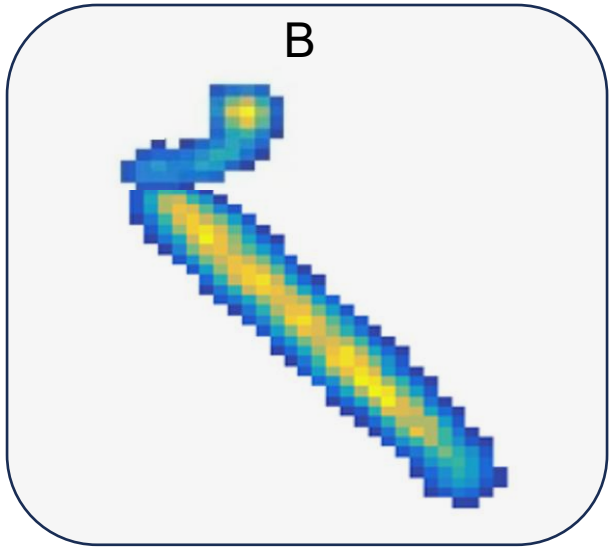


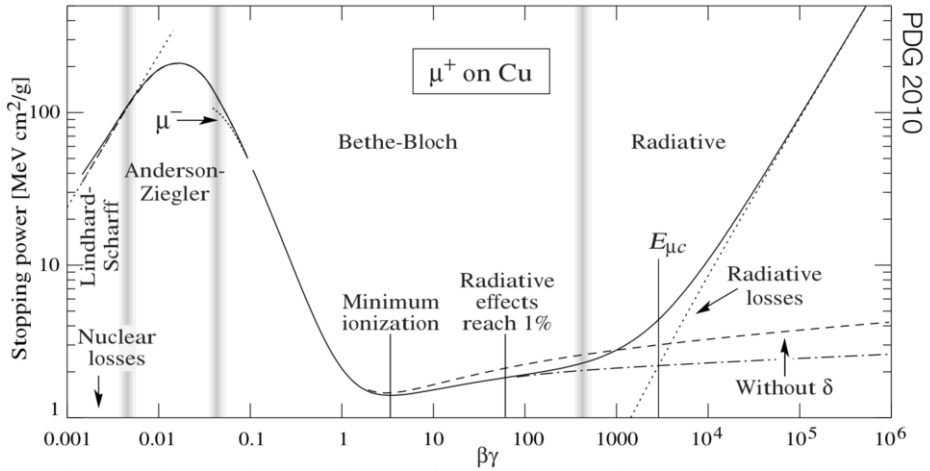
Migdal事例的特征



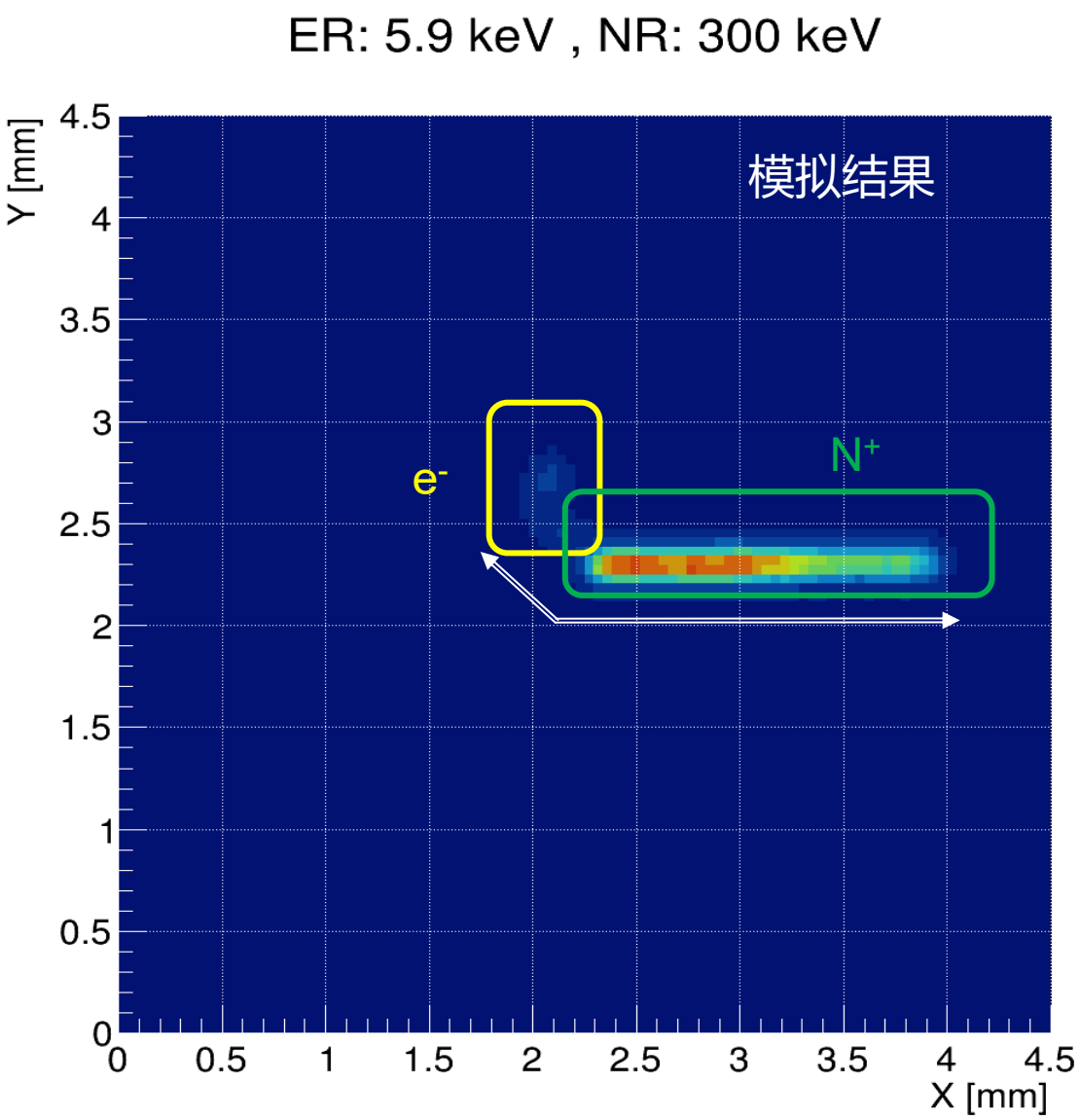


共顶点





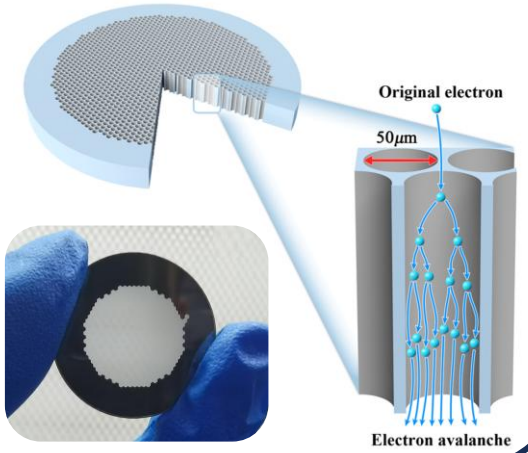
对探测器的要求

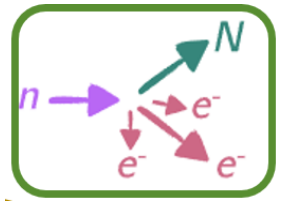


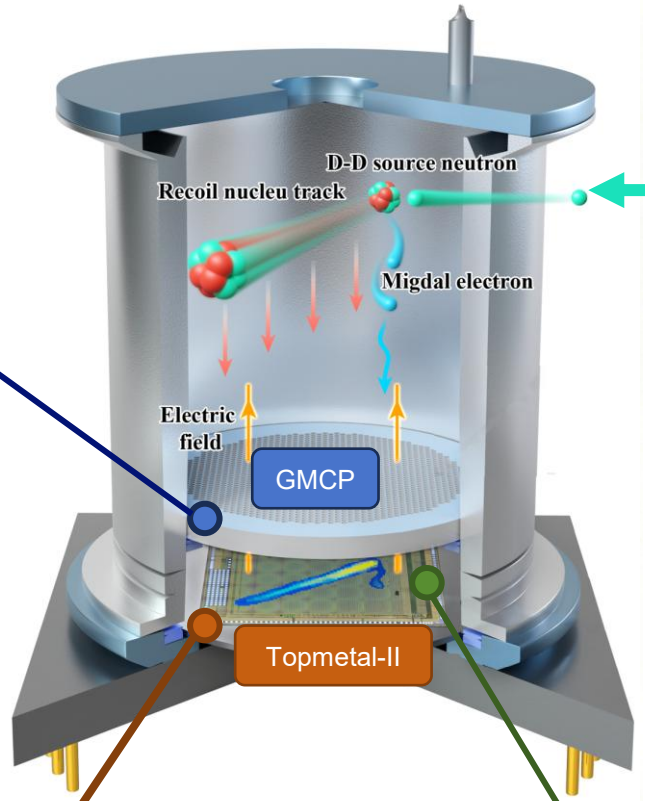
- 核心挑战:
  - 信号：有效信号事例率极低
  - 本底：本底种类繁杂，且实验中存在大量伴生光子本底。
- 探测器性能要求:
  - 能量分辨好：电子径迹~keV，核子径迹~百keV，要求大动态范围
  - 空间分辨高：电子径迹仅数百微米
  - 有时间分辨能力：通过时间关联筛选信号，压低本底
- 解决方案:
  - 主动屏蔽：设计屏蔽体压低本底
  - 多维度：测量中子/光子能谱、开发蒙卡模拟、事例挑选、径迹重建、顶点重建等算法

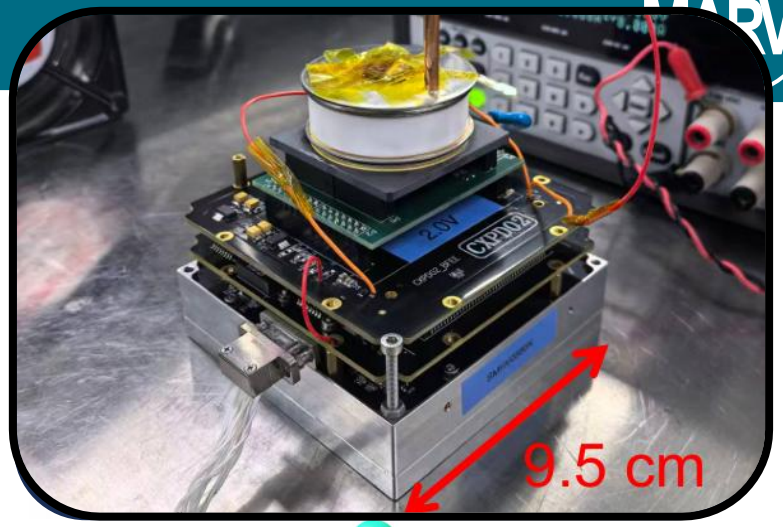
MARVEL 实验装置示意

GMCP



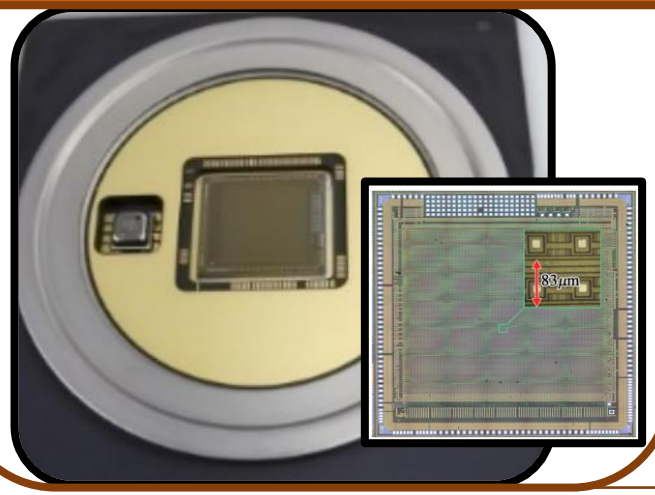




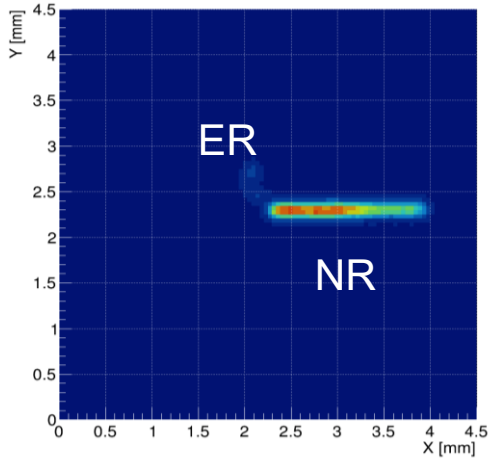


DD neutron source

Topmetal-II



Migdal topology

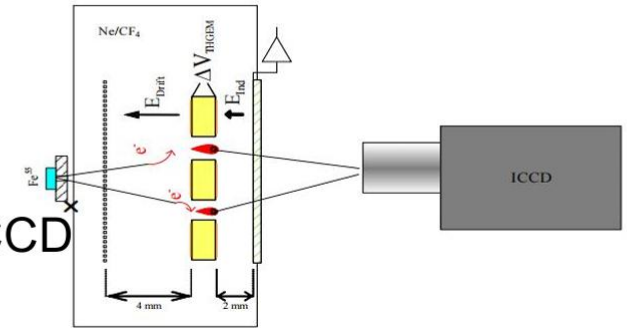


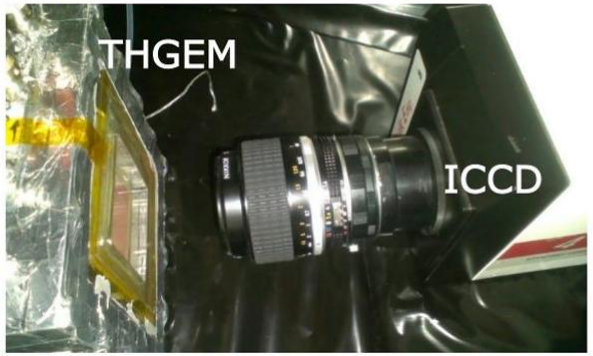
Development of the detector design

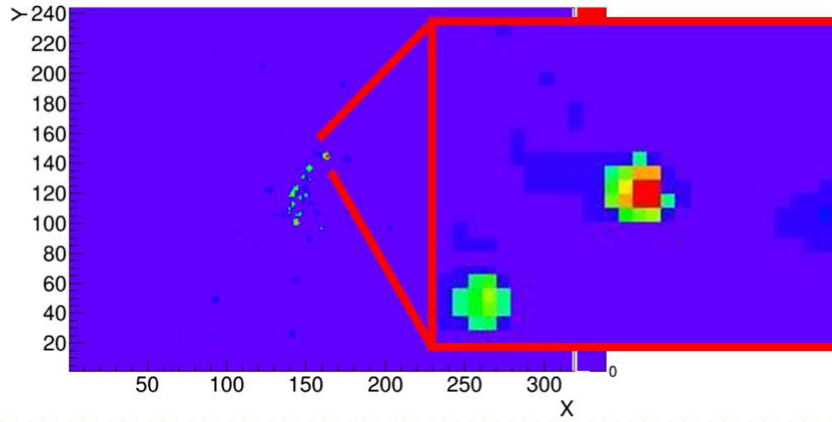
10.1088/1748-0221/13/06/P06011

2015-2018

THGEM/Mesh+CCD

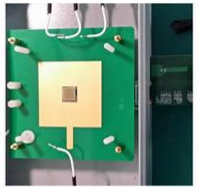


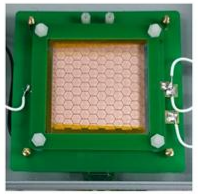


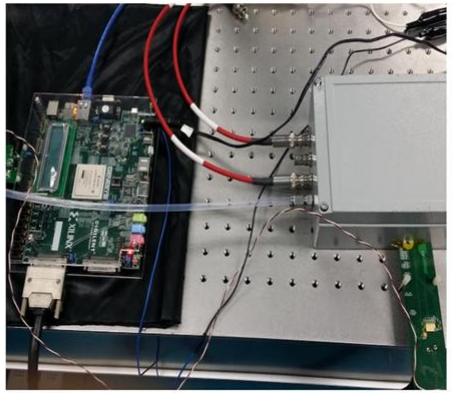


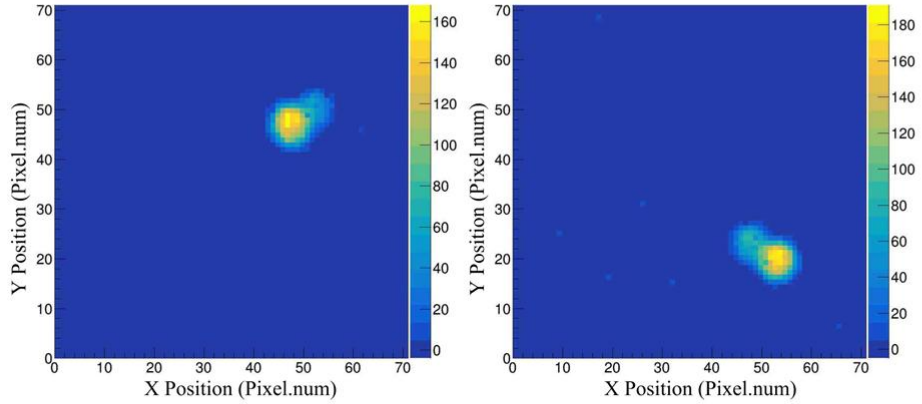
2019-2020

THGEM+Topmetal



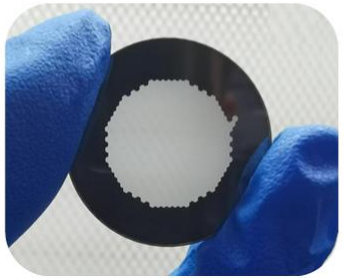


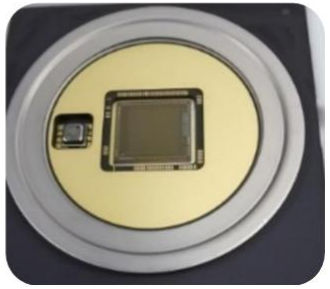


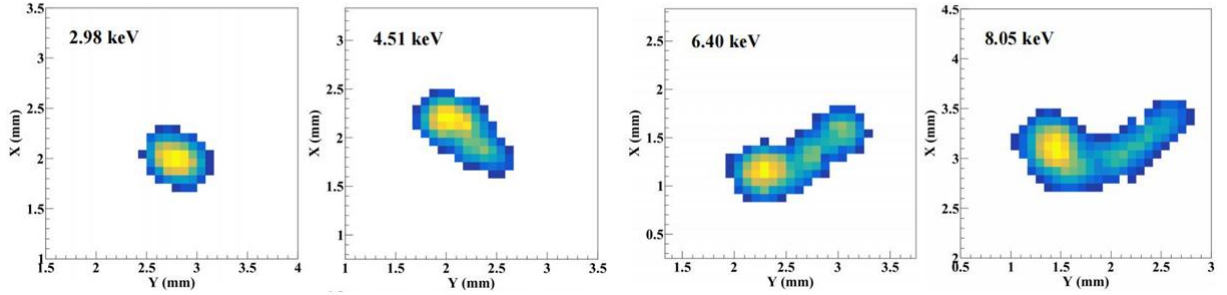


2021-now

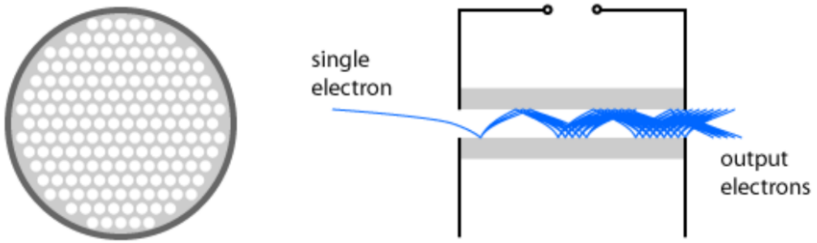
GMCP+Topmetal





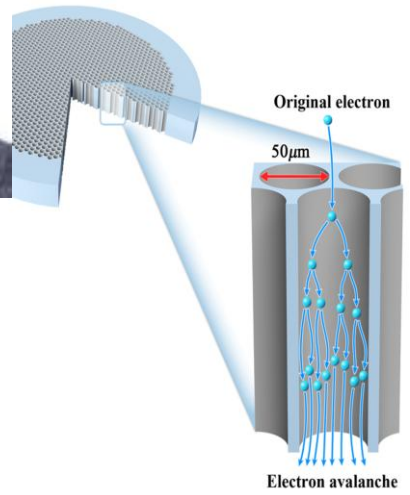


核心器件：GMCP



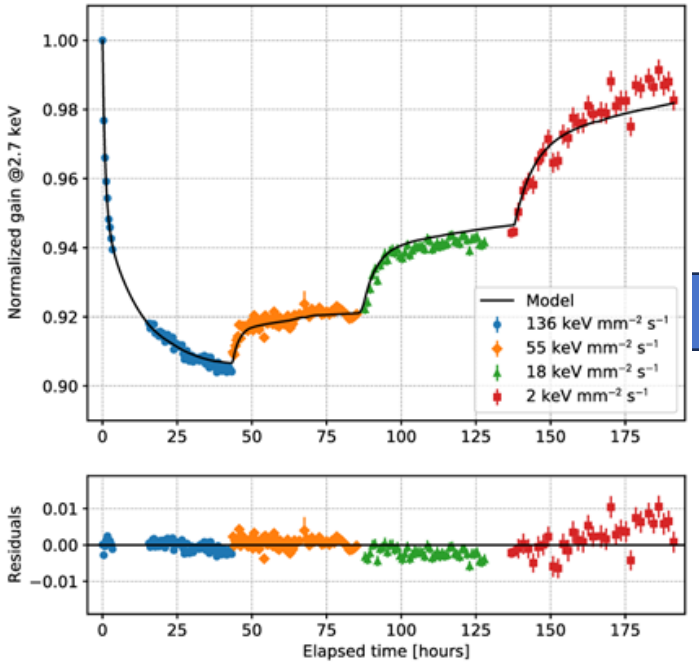
真空器件微通道板（MCP）

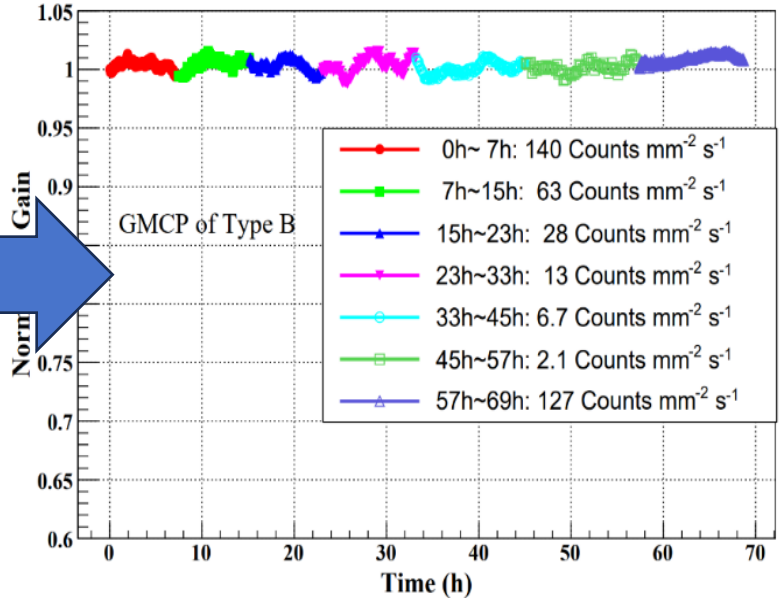
刘宏邦



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

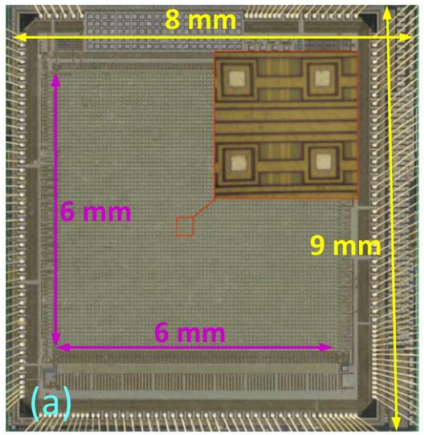


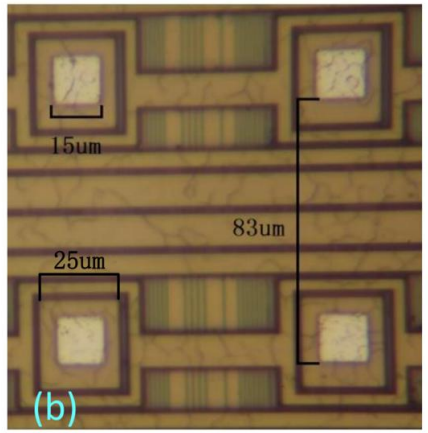


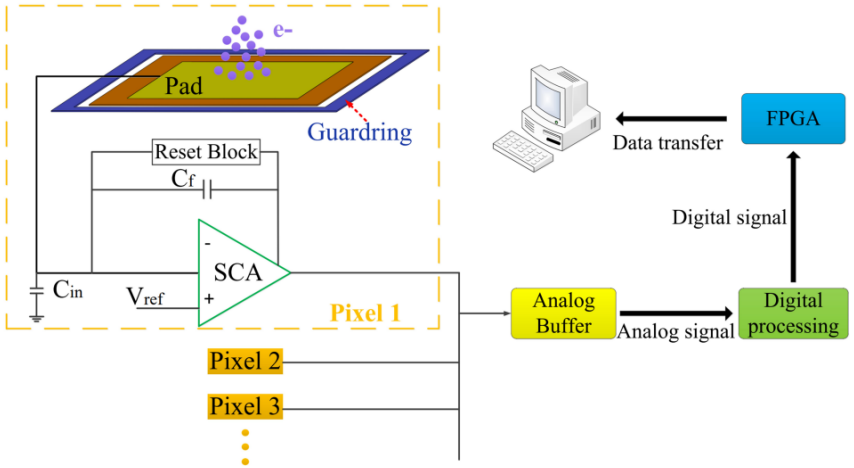
核心器件：像素芯片Topmetal

孙向明

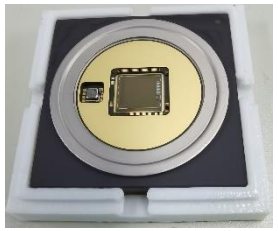
Topmetal-II

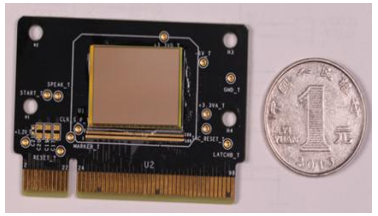


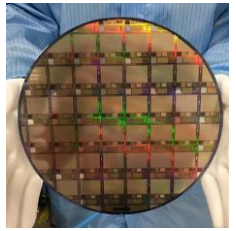




	Topmetal-II⁻	Topmetal-M1/M2	Topmetal-L
Chip Size /mm²	6 × 6	18 × 23	17 × 24
Pixel Array	72 × 72	400 × 512	356 × 512
Pixel Size /um²	83 × 83	45 × 45	45 × 45
ENC	~ 13.4e-	~ 15.4e-	~ 20.0e-
Power Consumption	~ 1W @3.3V	~ 4.3W @3.3V	**~ 0.8W @3.3V**
Clock	40MHz	5MHz	20MHz
Frame Rate	2.5ms	2.4ms	0.37ms @Sentinel Readout
Readout Mode	Rolling Shutter	Rolling Shutter	Rolling Shutter **/Sentinel Readout**
Readout Channel	1	16	1

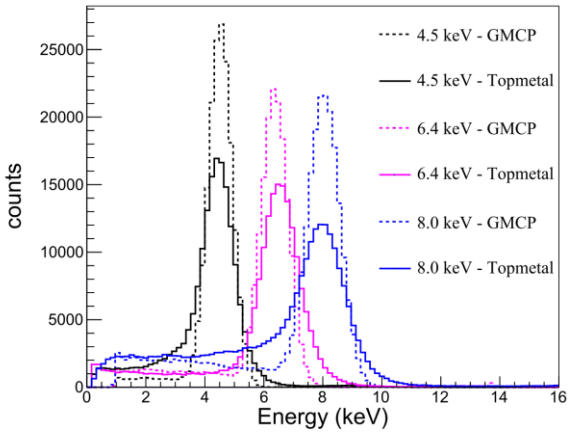


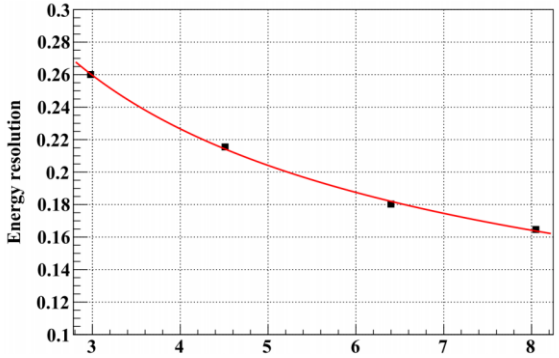




Detector performance

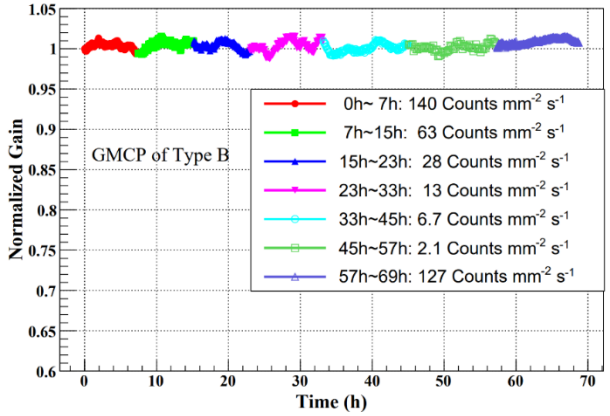
Energy resolution

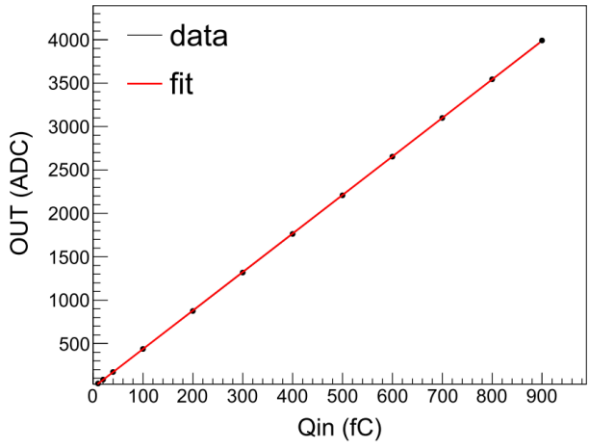




- Good linear energy response
- 20%-30% energy resolution(FWHM)
- Energy resolution follows the relationship ~ $1/\sqrt{E}$

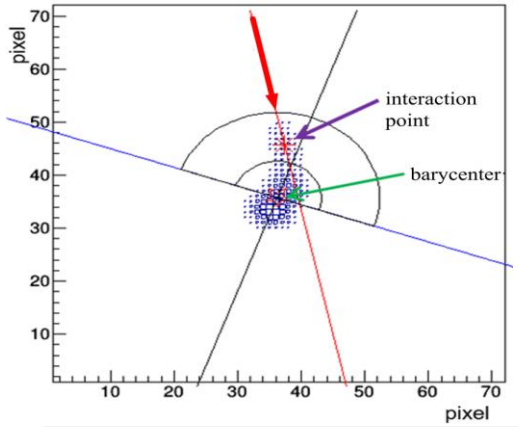
Dynamic range

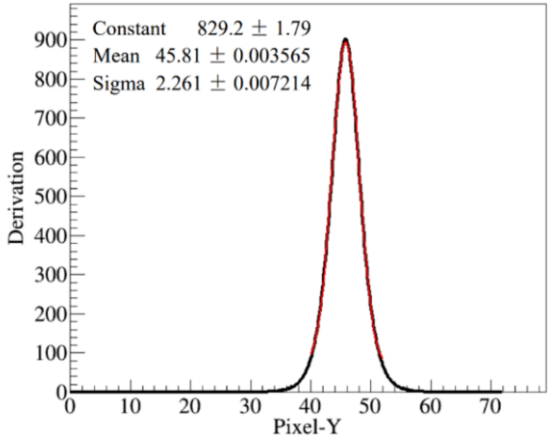




- Stable gain under different count rates(no pile up)
- Good linearity in charge response

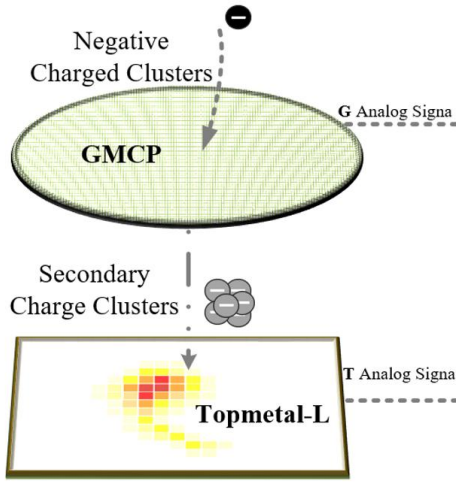
Vertex resolution

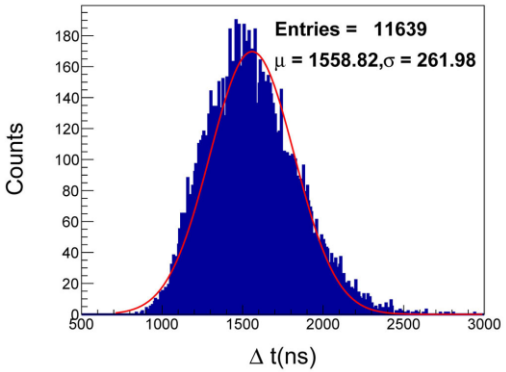




- ~200 μm vertex resolution @ 6.4 keV

Time resolution





- ~262 μs 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

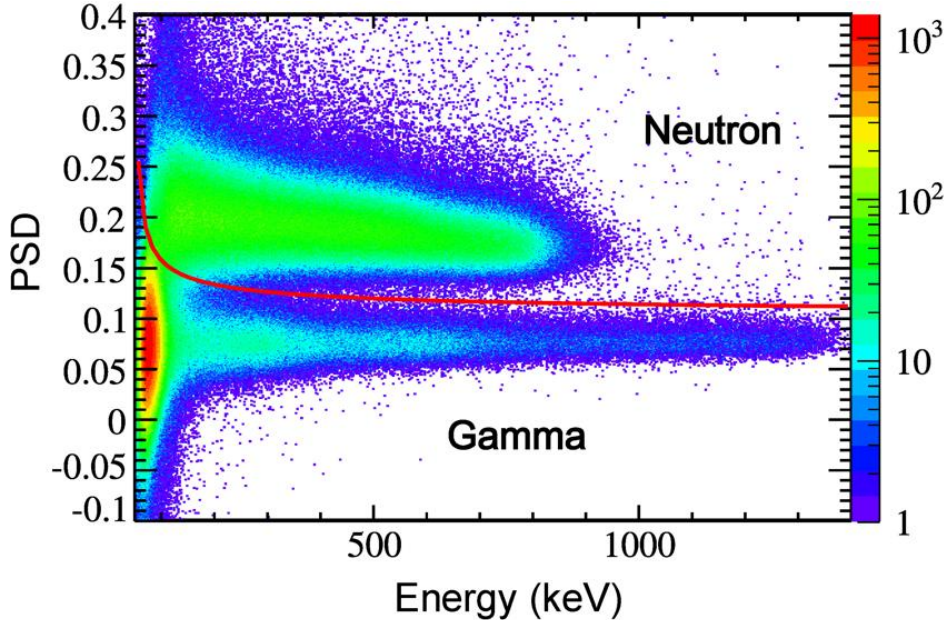
Migdal detector

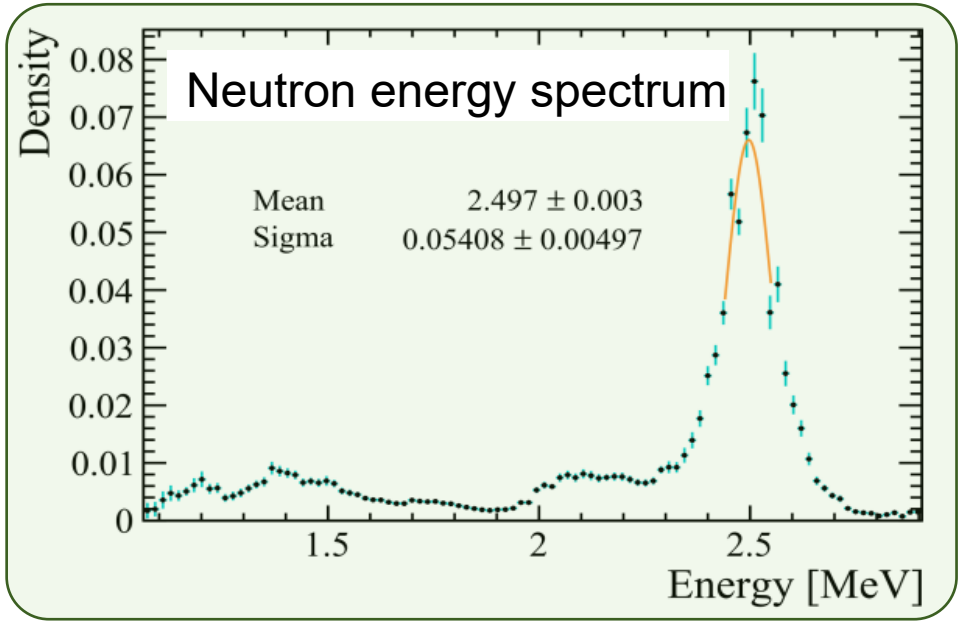
Working gas:

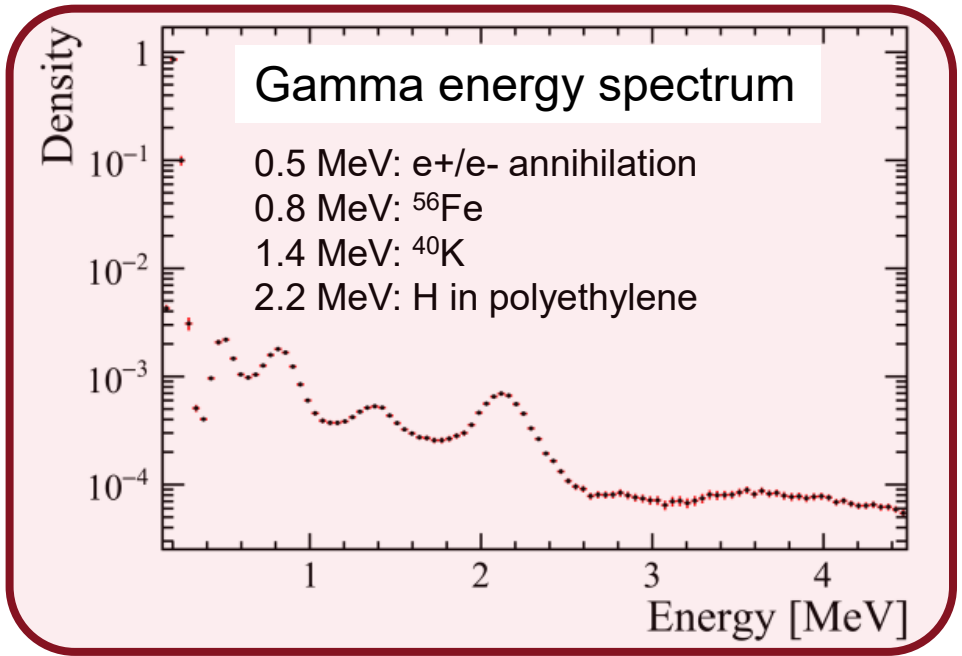
0.8 atm @ ~300 K

40% Helium + Dimethyl ether (DME, C_2H_6O)

中子/光子能谱测量

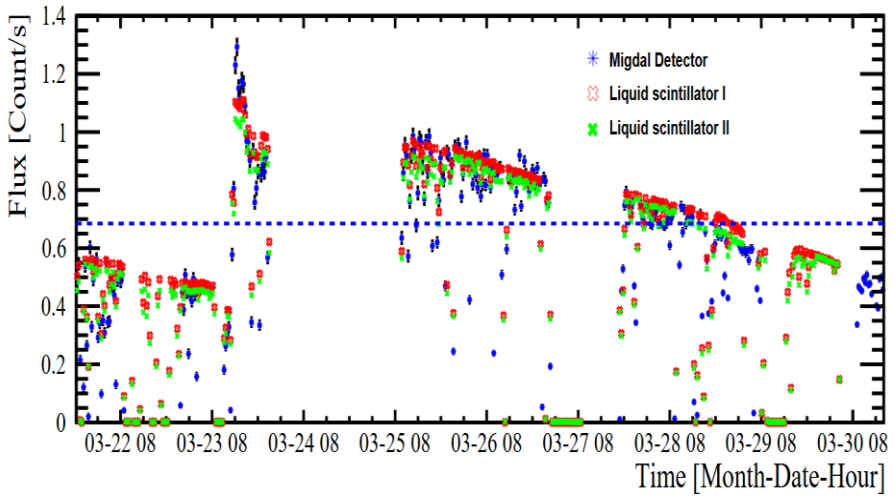


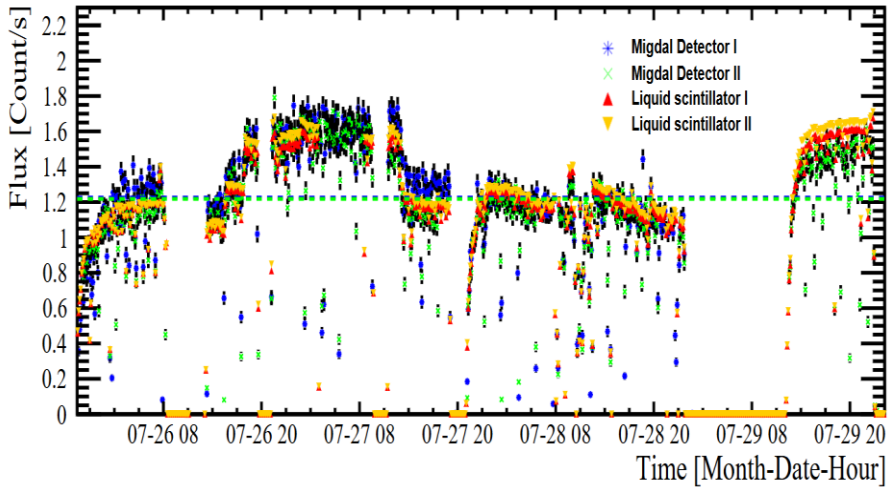




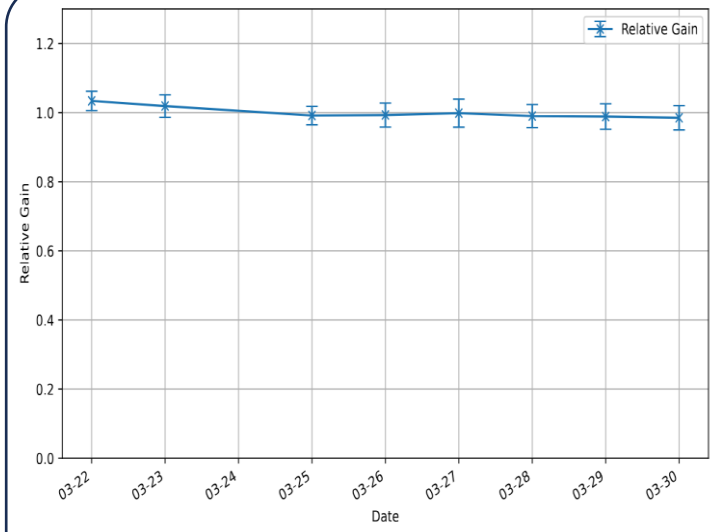
- 采用液闪探测器进行中子/光子能谱测量
- 开发波形分析算法进行中子/光子鉴别
- 根据模拟及标定数据得到液闪探测器的响应矩阵；开发反卷积算法得到中子/光子能谱

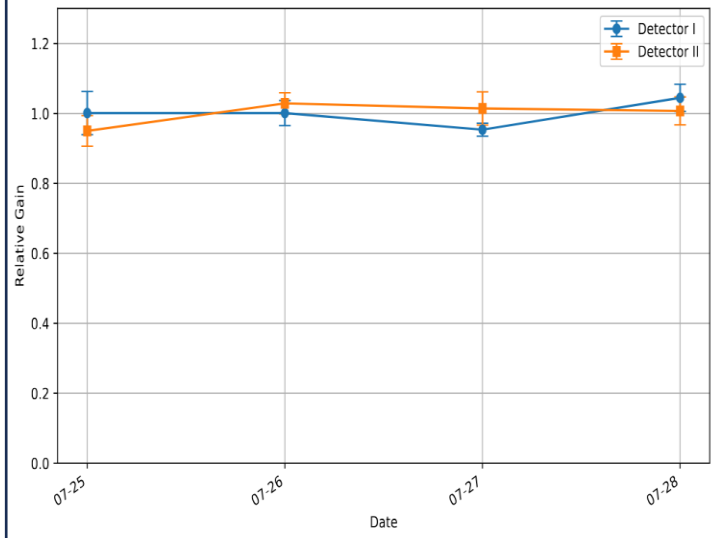
Neutron Flux & Detector performance monitor



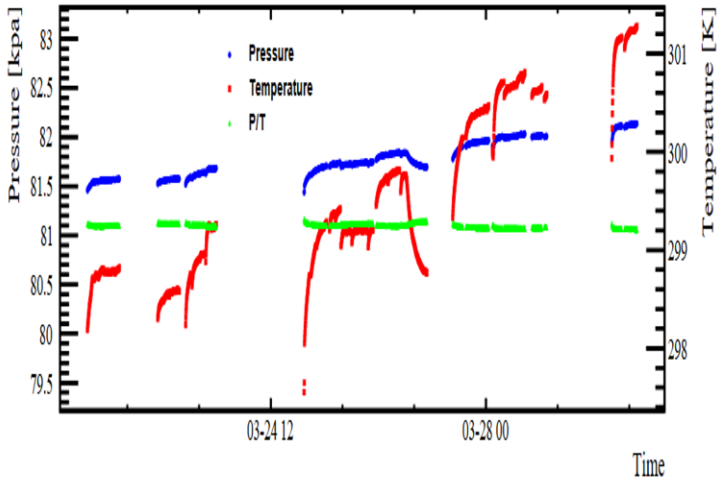


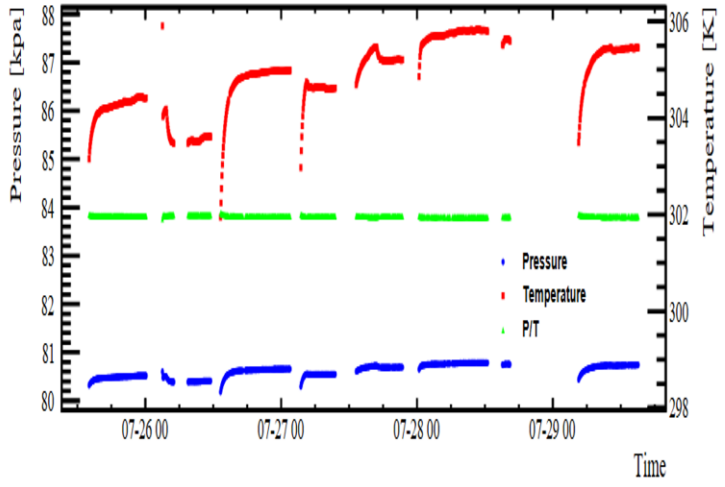
- neutron flux monitored by the two LS.





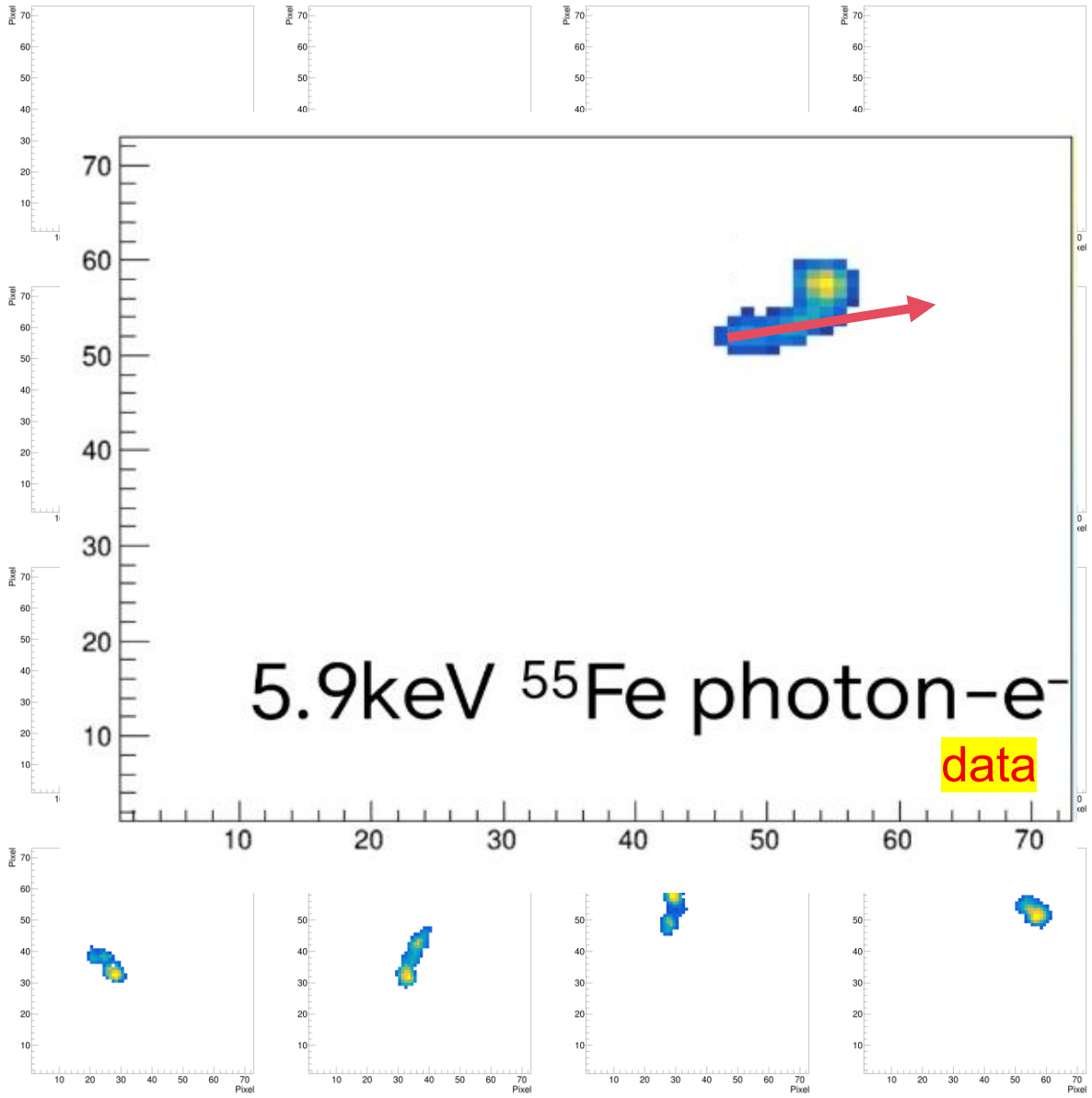
- Gain monitored with an ^{55}Fe.

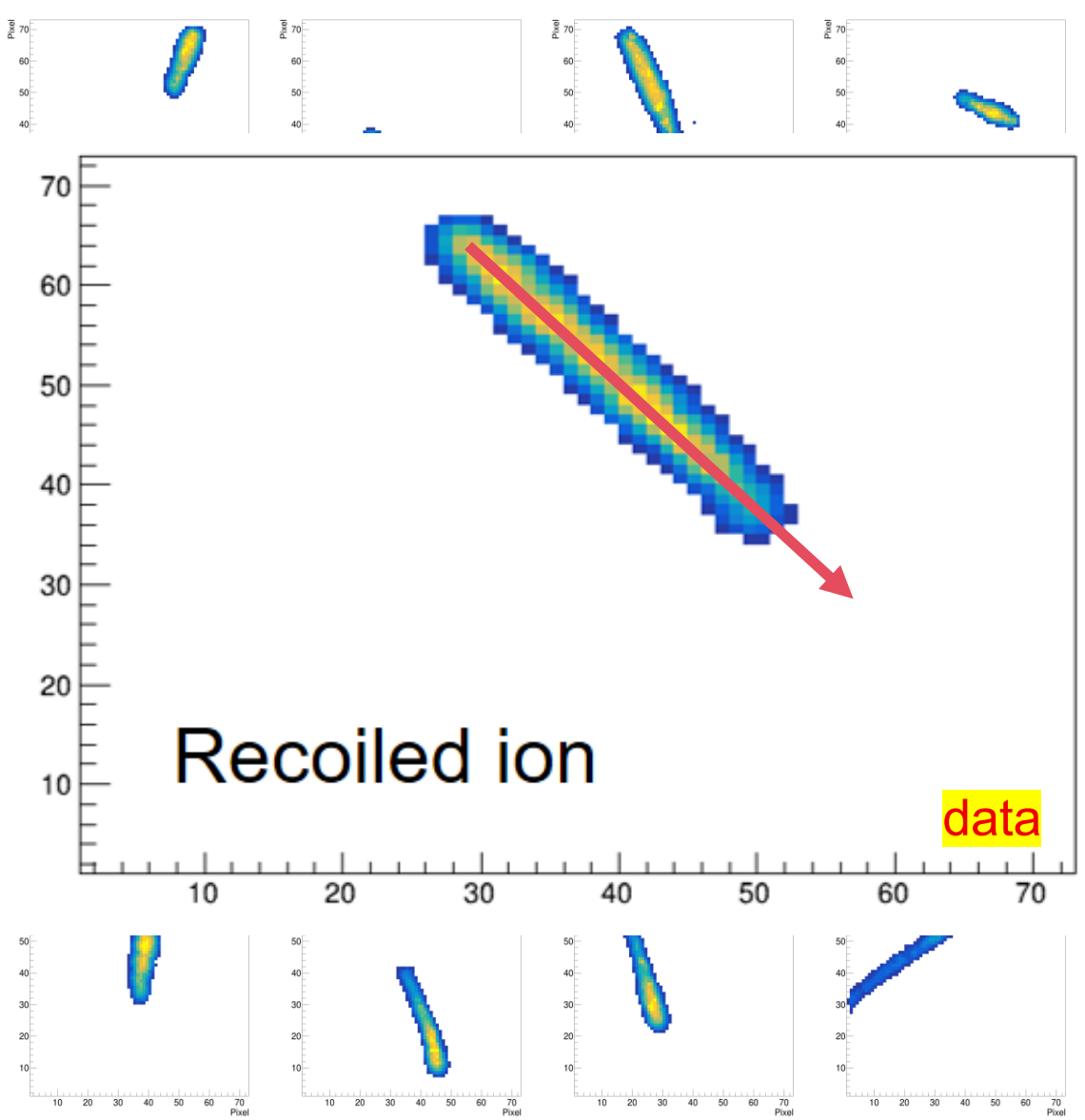




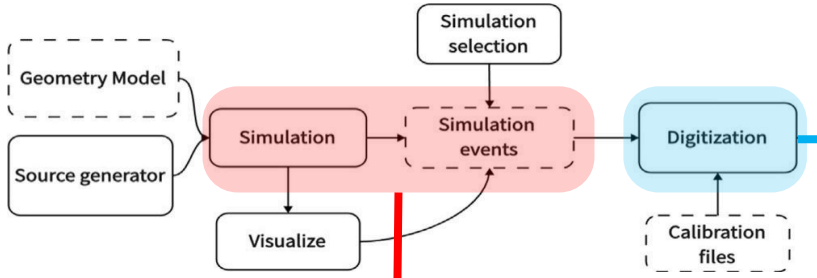
- T & P are monitored.

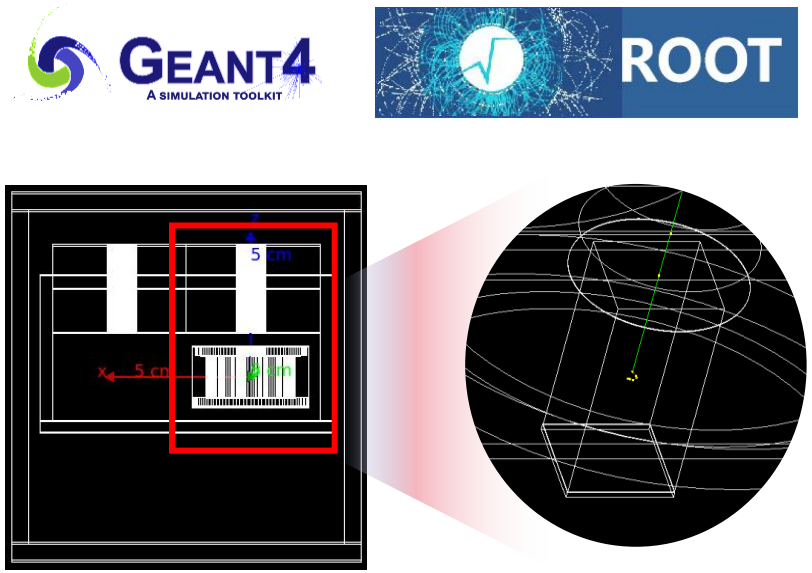
电子径迹与反冲核径迹



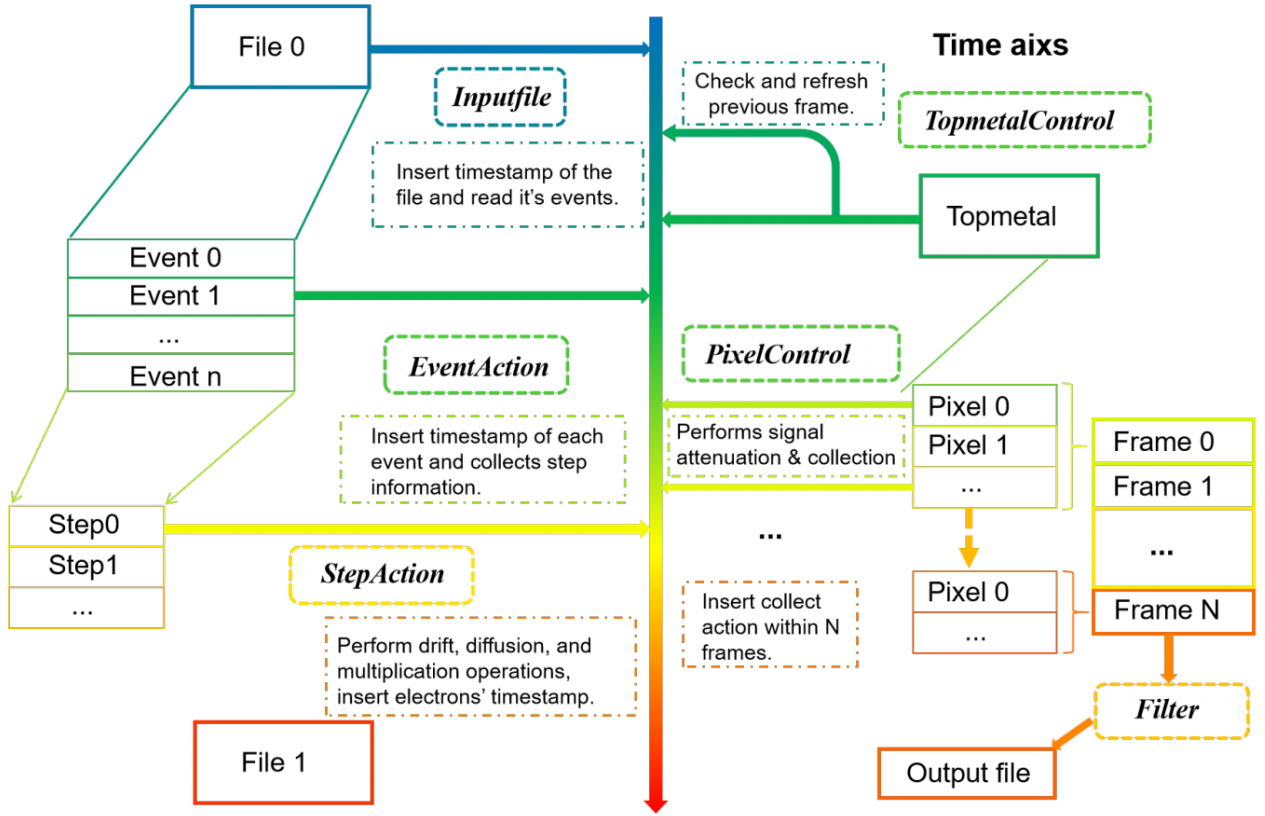


软件模拟框架





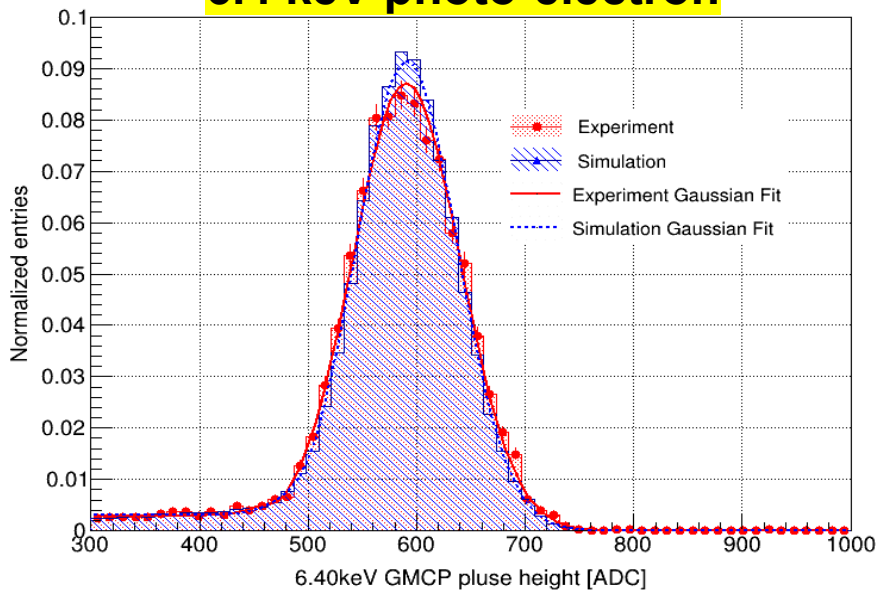
- ✓ 模拟探测器响应
- ✓ 提供MC模拟的truth信息

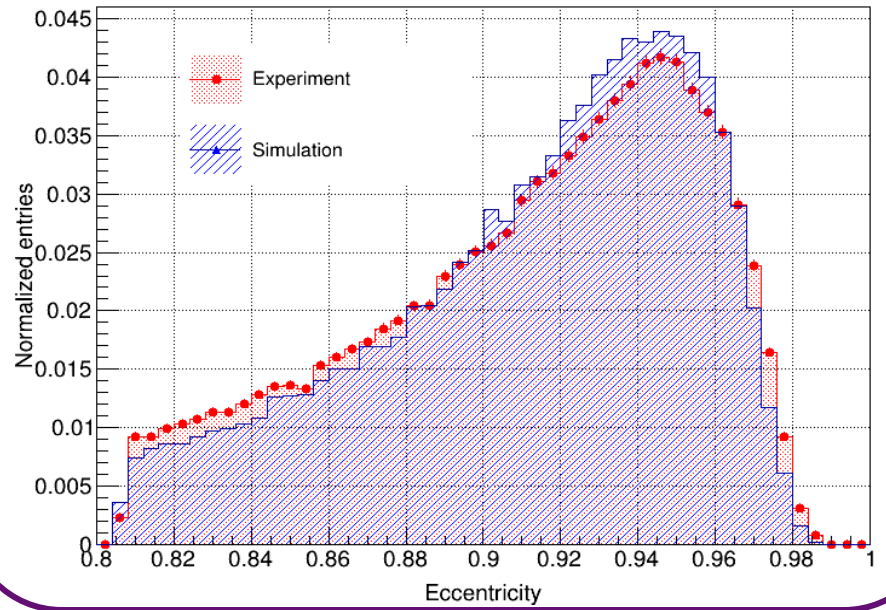


- ✓ 探测器的数字化模拟
- ✓ 模拟电子在探测器中的漂移、倍增及收集过程
- ✓ 模拟电子学对信号的采集及处理过程，并保存为与实验数据完全相同的格式输出

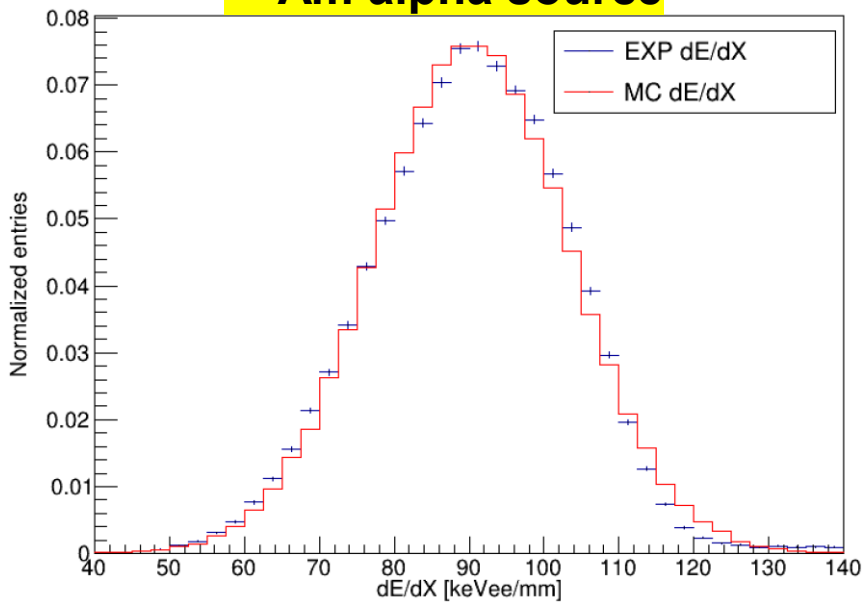
实验与模拟的一致性检验

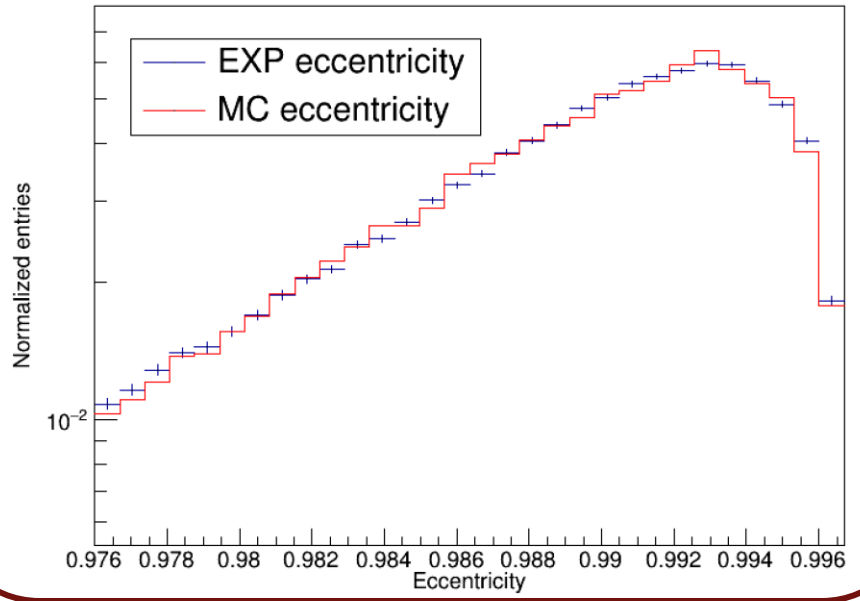
6.4 keV photo-electron





^{241}Am alpha source





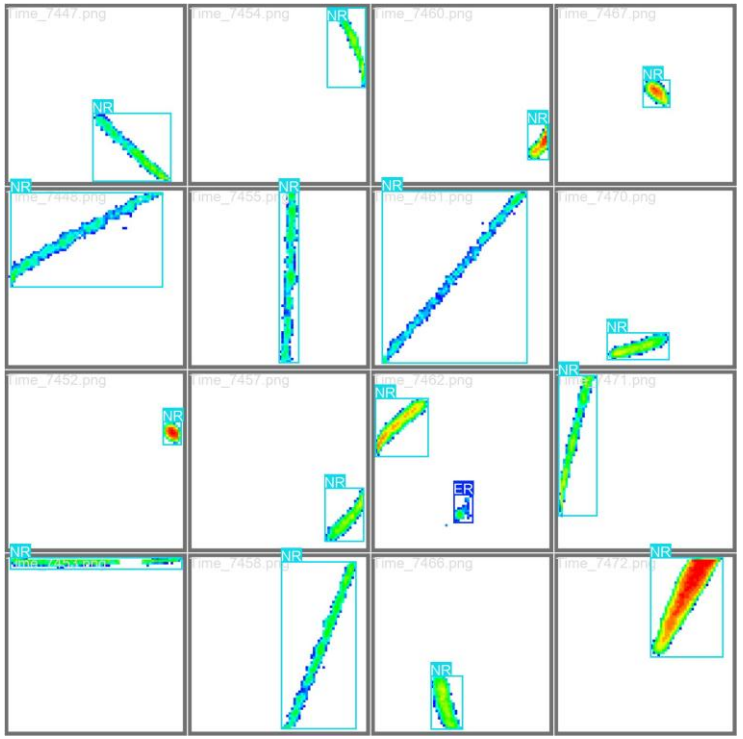
事例挑选

Data → YOLO*1 preselection → NR reconstruction → ER reconstruction → Vertex cut

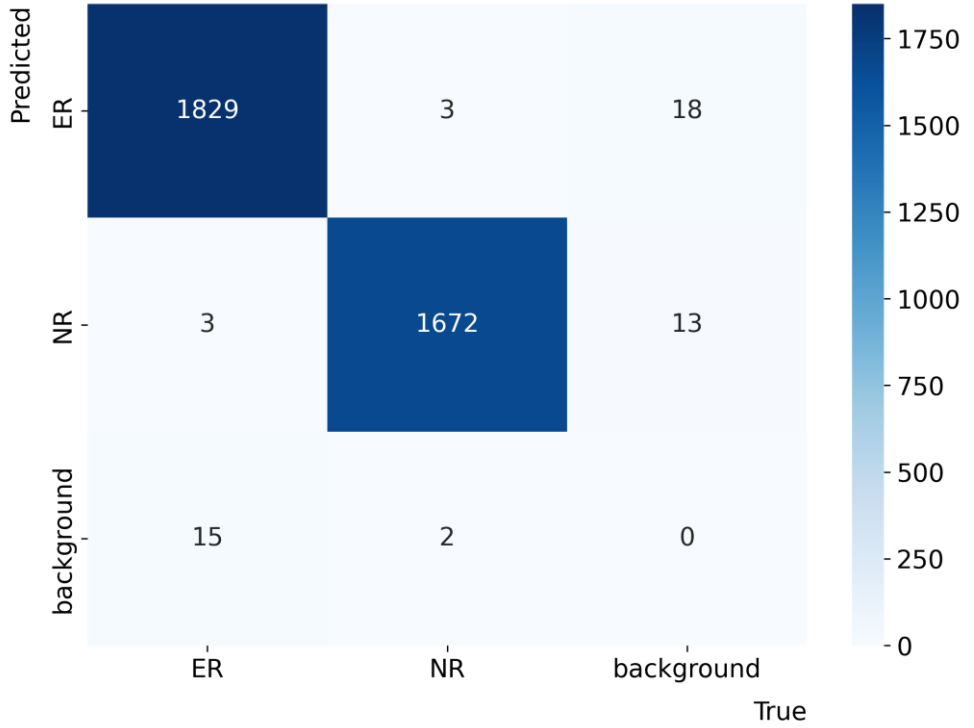
Labeling

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

YOLOv8.2



Training



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

事例重建

Data → YOLO*1 preselection → NR reconstruction → ER reconstruction → Vertex cut

1. Search for the NR vertex through recursive iteration:

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

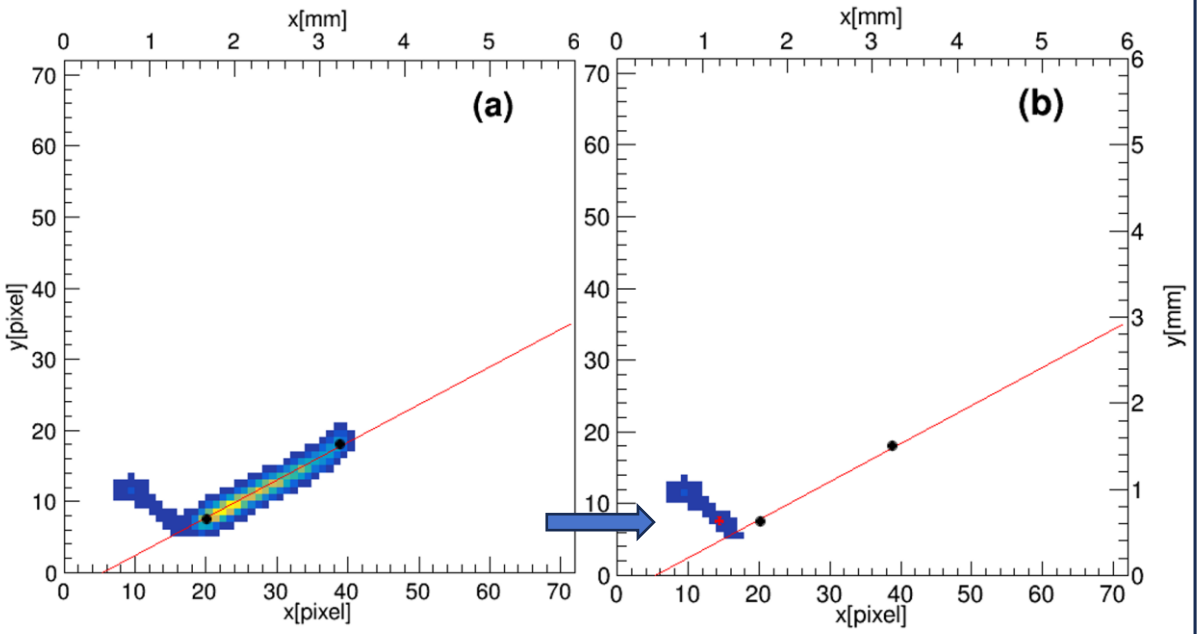
$$(x_0,y_0) \longrightarrow (x_n,y_n)$$

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

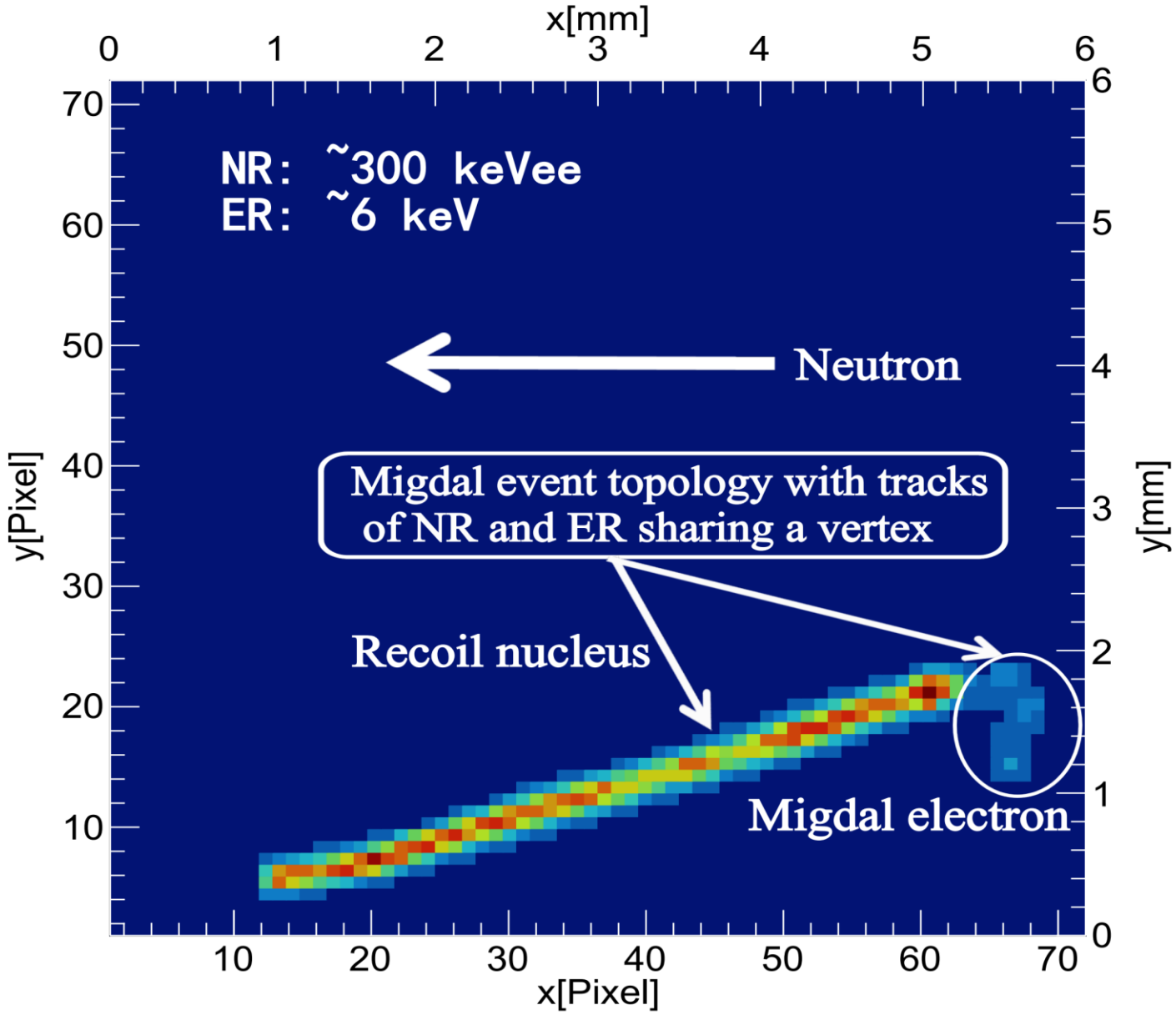
3. Search for the electron vertex using **adaptive cutting algorithm**(Nucl. Sci. Tech.doi:10.1007/s41365-021-00903-0).

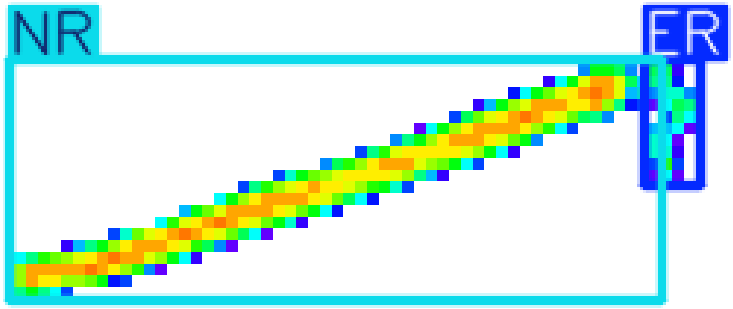
4. Determine whether the electron vertex is adjacent to the nucleon vertex.

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

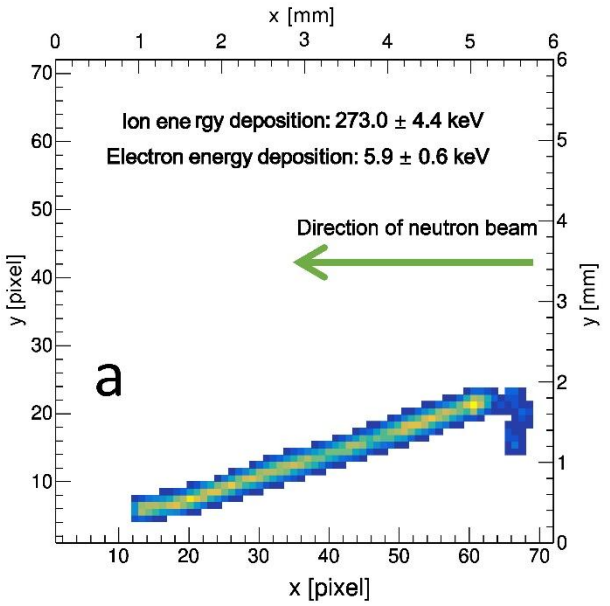


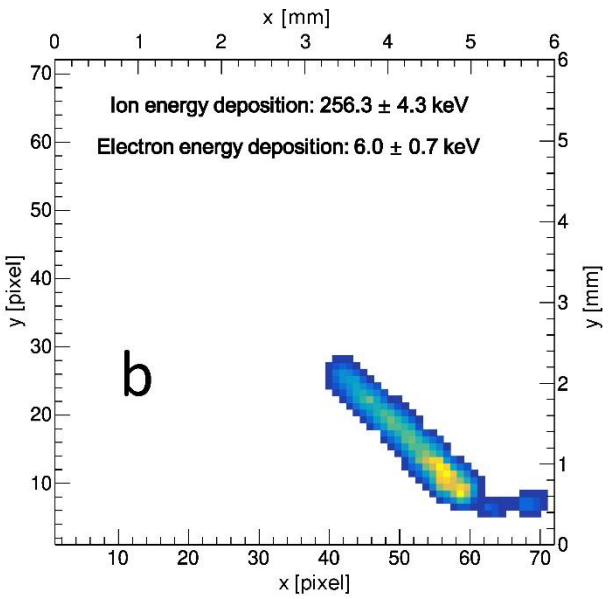
Migdal 事例

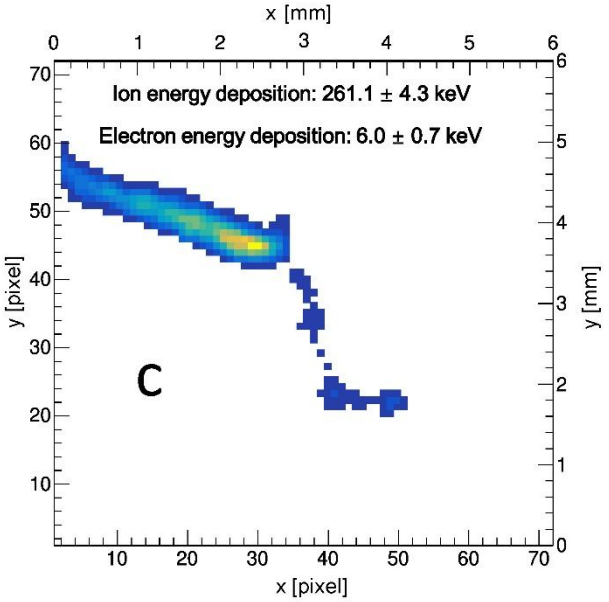

x[mm]
0
1
2
3
4
5
6
y[Pixel]
10
20
30
40
50
60
70
y[mm]
0
1
2
3
4
5
6
NR: ~300 keVee
ER: ~6 keV
Neutron
Migdal event topology with tracks of NR and ER sharing a vertex
Recoil nucleus
Migdal electron
x[Pixel]

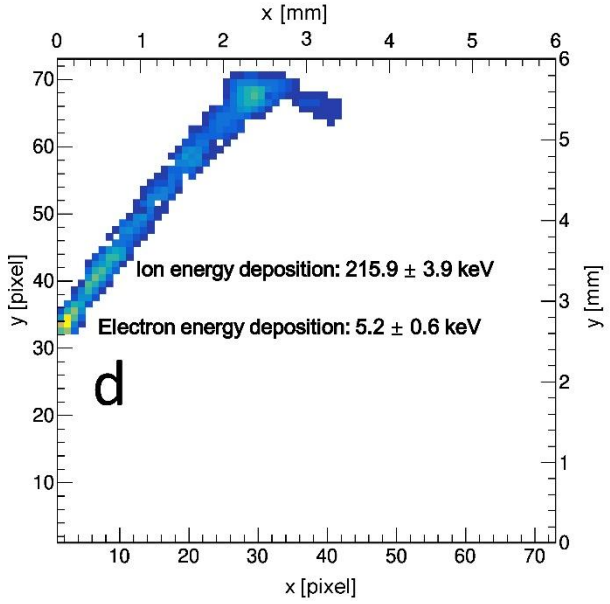

NR
ER

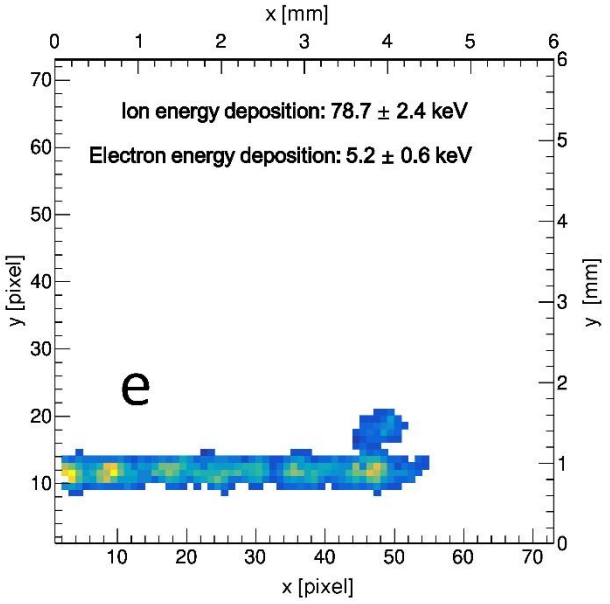
更多的Migdal事例！

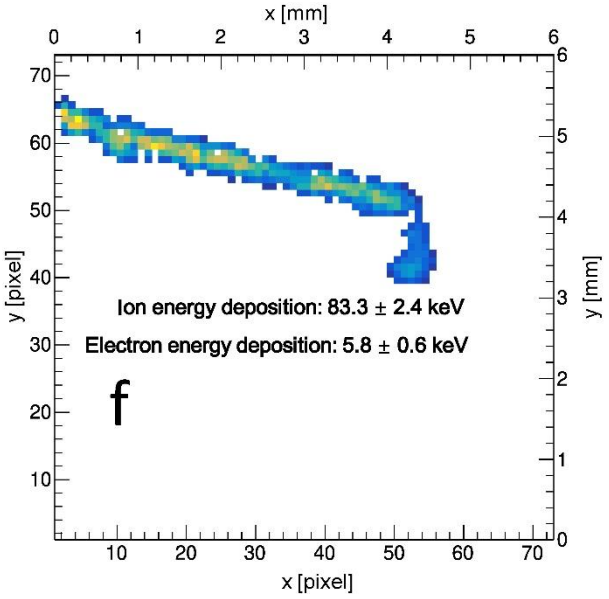




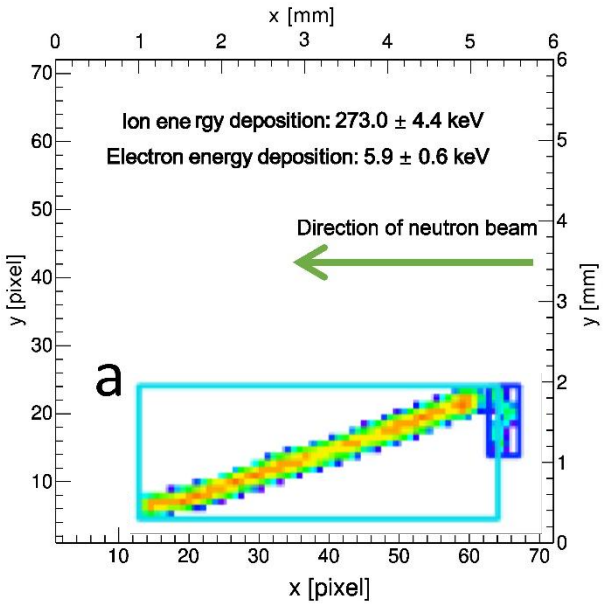


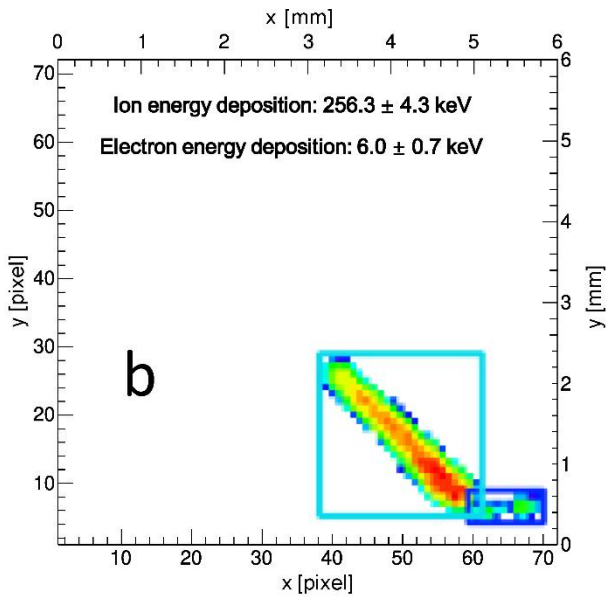


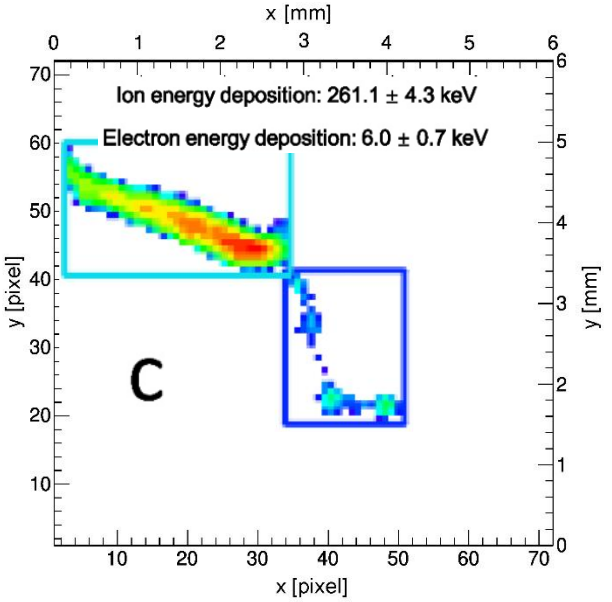


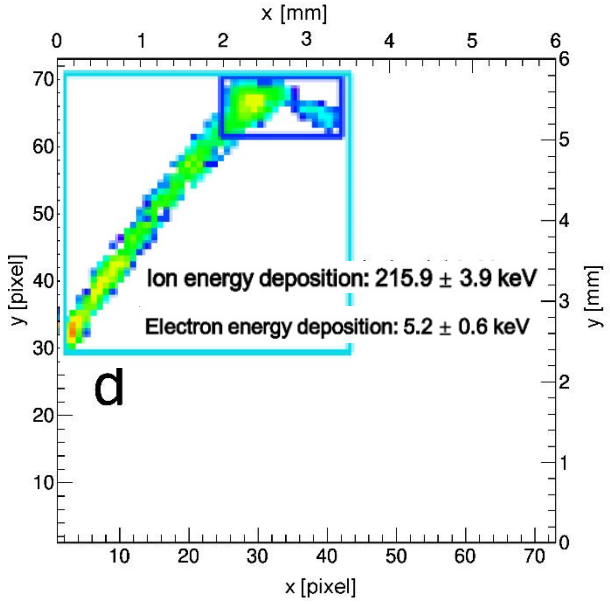


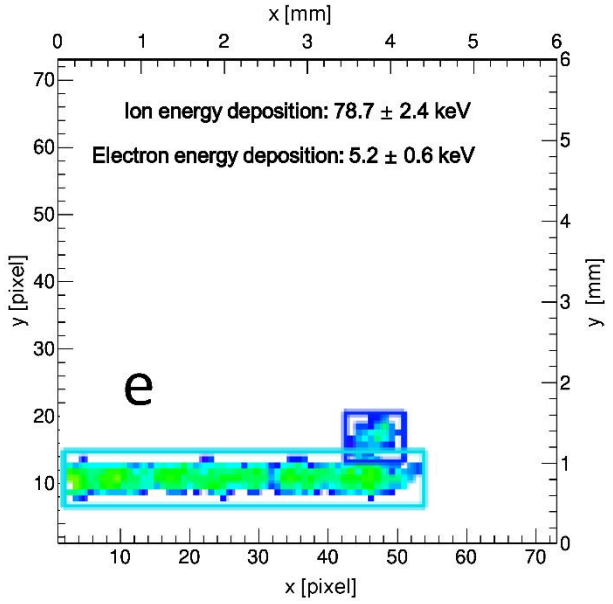
全部通过YOLO识别！

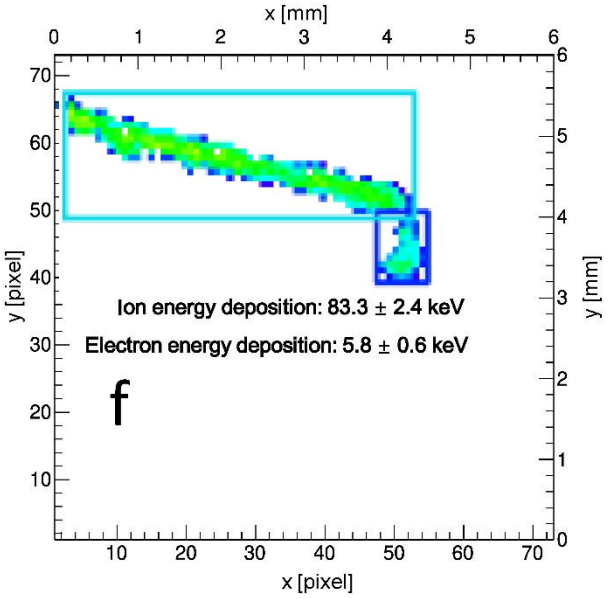

x [mm]
Ion ene rgy deposition: 273.0 ± 4.4 keV
Electron energy deposition: 5.9 ± 0.6 keV
Direction of neutron beam
a
x [pixel]
y [pixel]
y [mm]


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]

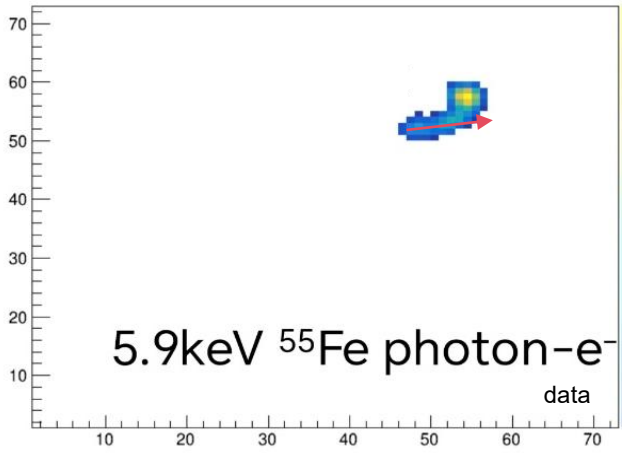

x [mm]
Ion energy deposition: 215.9 ± 3.9 keV
Electron energy deposition: 5.2 ± 0.6 keV
d
x [pixel]
y [pixel]
y [mm]

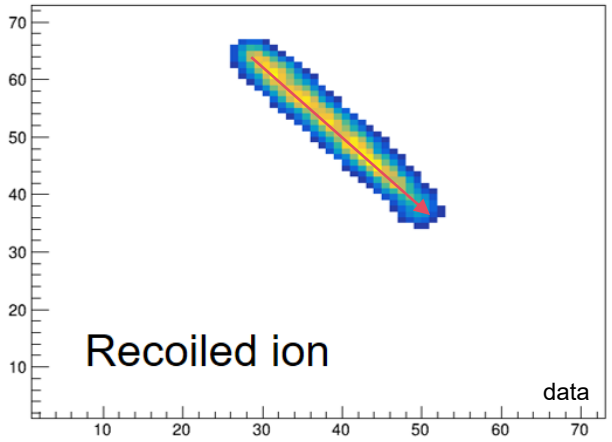

x [mm]
Ion energy deposition: 78.7 ± 2.4 keV
Electron energy deposition: 5.2 ± 0.6 keV
e
x [pixel]
y [pixel]
y [mm]

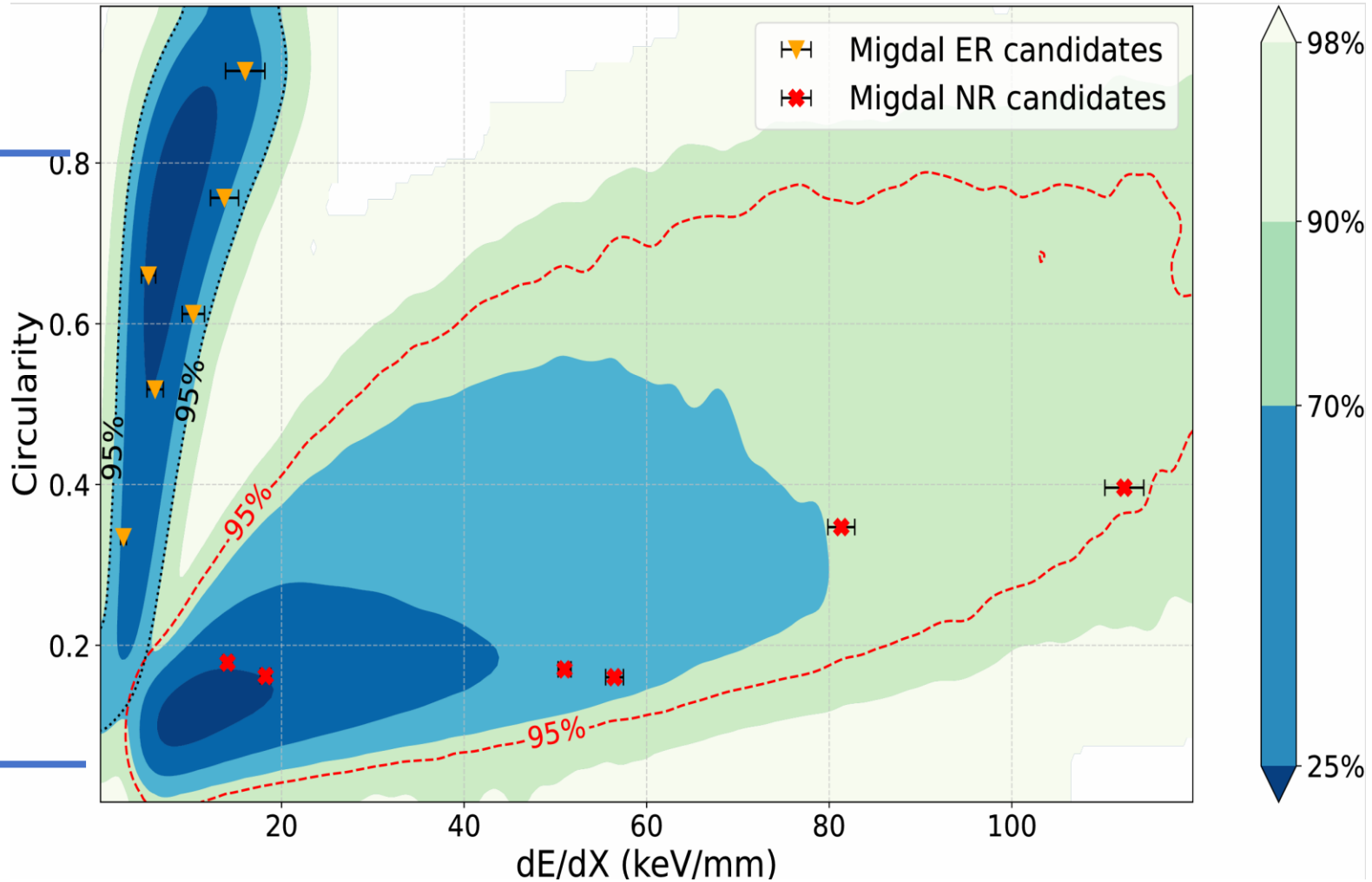

x [mm]
Ion energy deposition: 83.3 ± 2.4 keV
Electron energy deposition: 5.8 ± 0.6 keV
f
x [pixel]
y [pixel]
y [mm]

电子与核子径迹

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





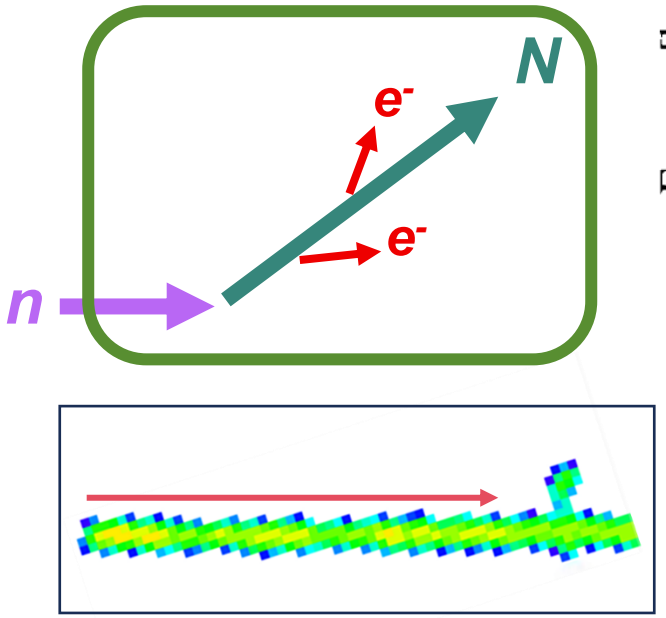


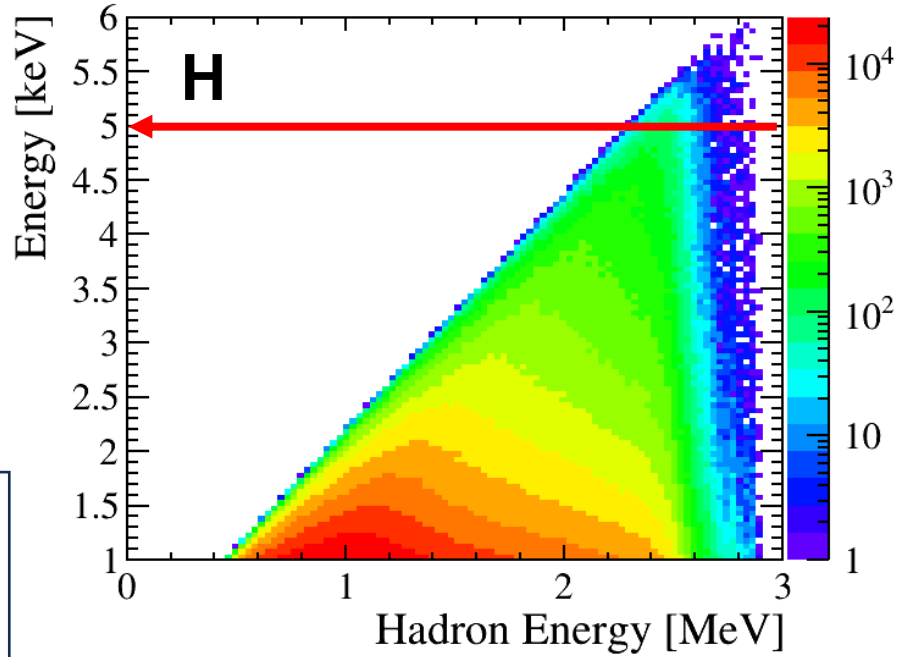
Migdal事例中的电子与^{55}Fe源的光电子样本区间一致；核反冲径迹与中子数据中核反冲控制样本一致！

本底估计

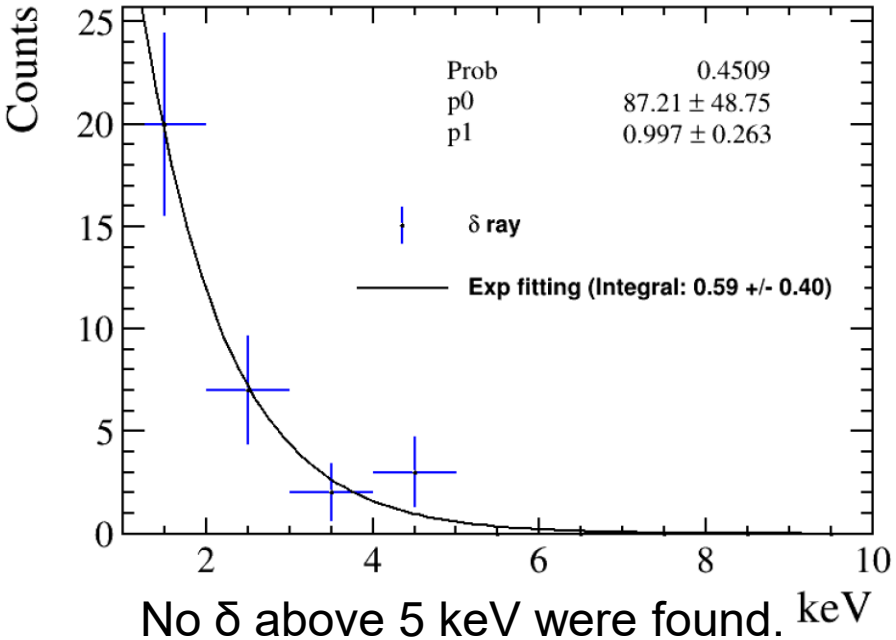
Background Component	Description	Expectation value (5 - 10 keV)	Method
Recoil induced δ ray	δ electron near NR track origin	0.035±0.023(stat.)±0.0068(sys.)	Data driven
Particle Induced X-ray Emission			
X-ray emission	Photoelectron near NR track origin	0	
Auger electrons	Auger electron near NR track 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±0.022(stat.)±0.042(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±0.00087(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±0.032(stat.)±0.043(sys.)	

1. Delta电子本底





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



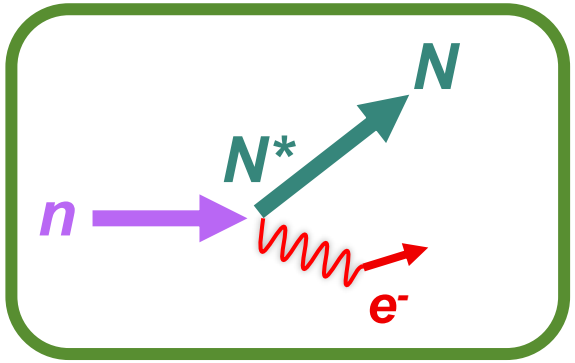
No δ above 5 keV were found.

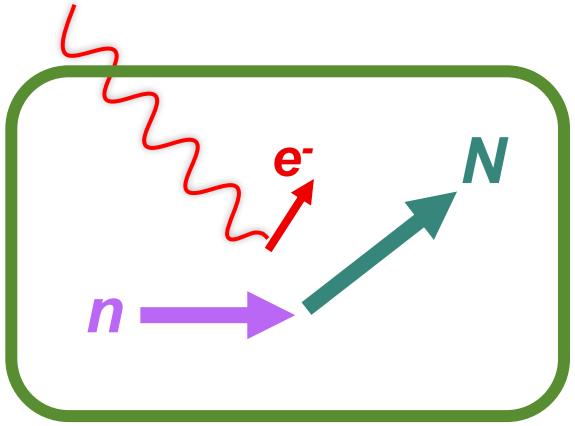
Estimate by extrapolating from the exponential fit

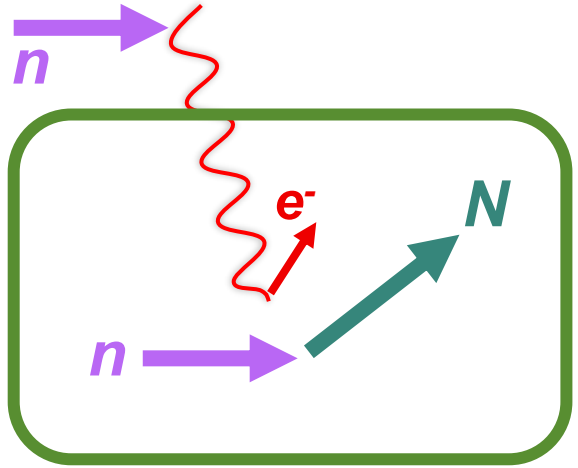
- Consider the selection efficiency for δ-electrons.
- **Finally get: 0.035±0.023(stat.)**

2. 偶然符合本底

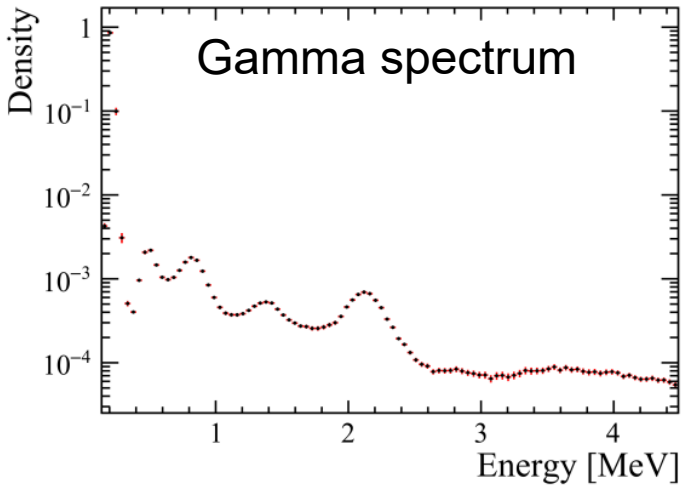
Method 1: 液闪测得的 n/γ 能谱代入GEANT4模拟

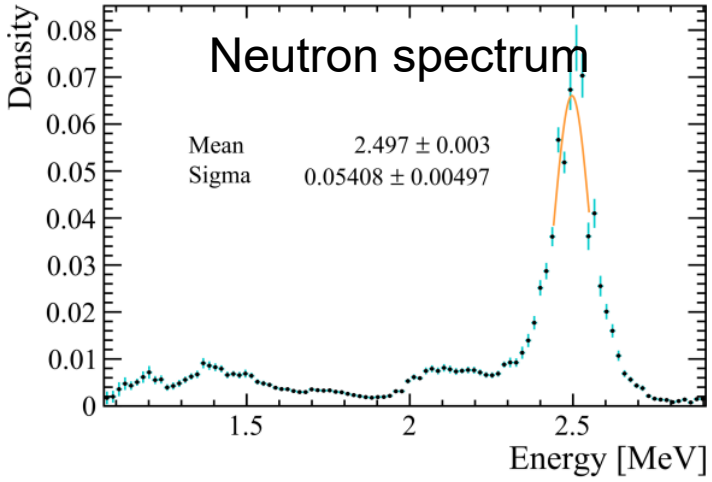






	NR	Compton e⁻	photonEle
I	1	4.32×10^{-5}	1.06×10^{-5}
II	1	6.06×10^{-6}	$\sim 3.63 \times 10^{-8}$
III	1	3.11×10^{-6}	7.15×10^{-7}

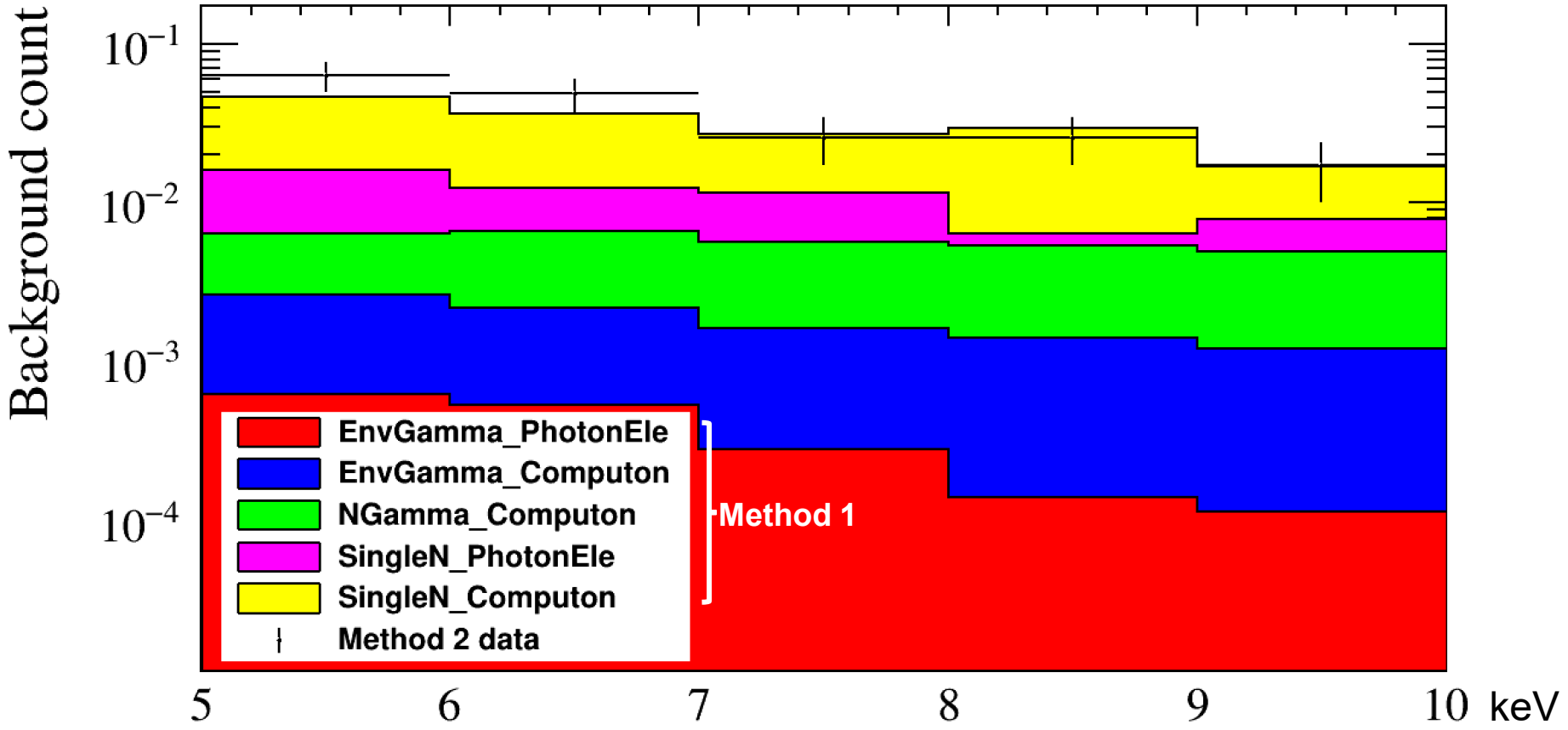




- **三种贡献之和为: 0.16±0.01(stat.)**

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±0.022(stat.)±0.042(sys.)**



方法一与方法二的结果在统计误差范围内一致。

显著度

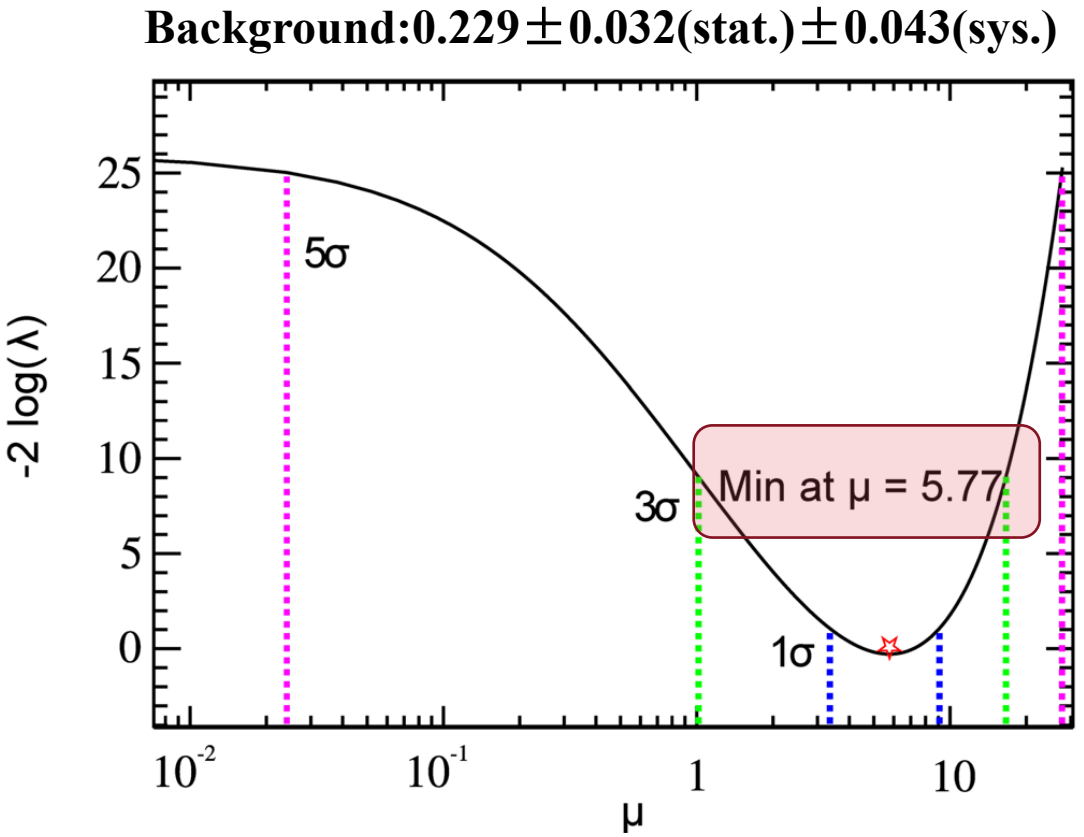
- 定义概率密度函数

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

- 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 $H_a:\mu\neq 0$



在该本底水平下，观测到5.77个事例达到5σ

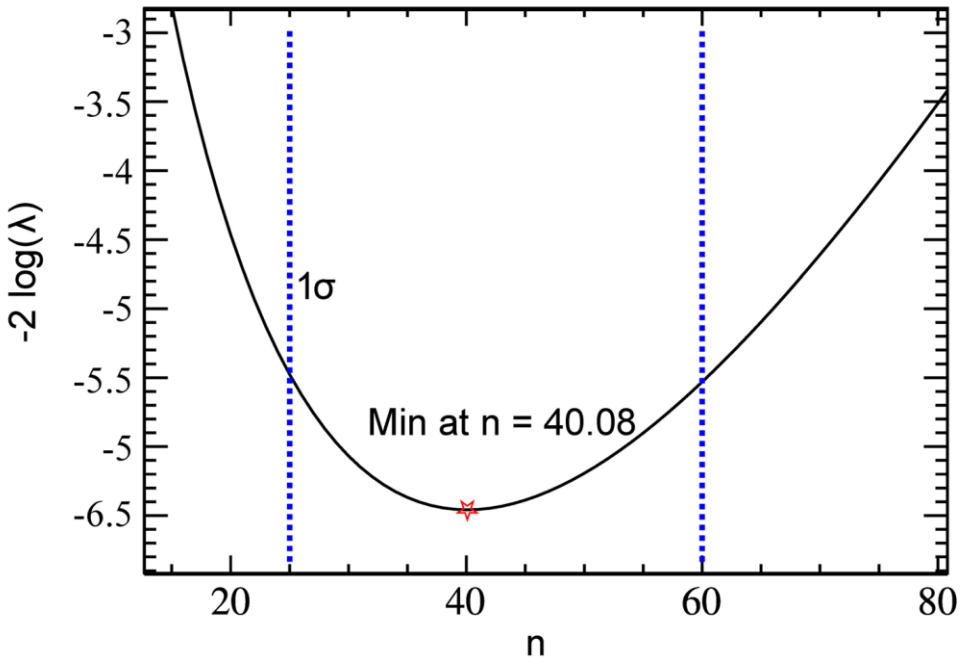
相对截面计算

- Migdal过程截面与核反冲截面的比值:

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

- 参数:

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



- 上下限的计算方式:

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

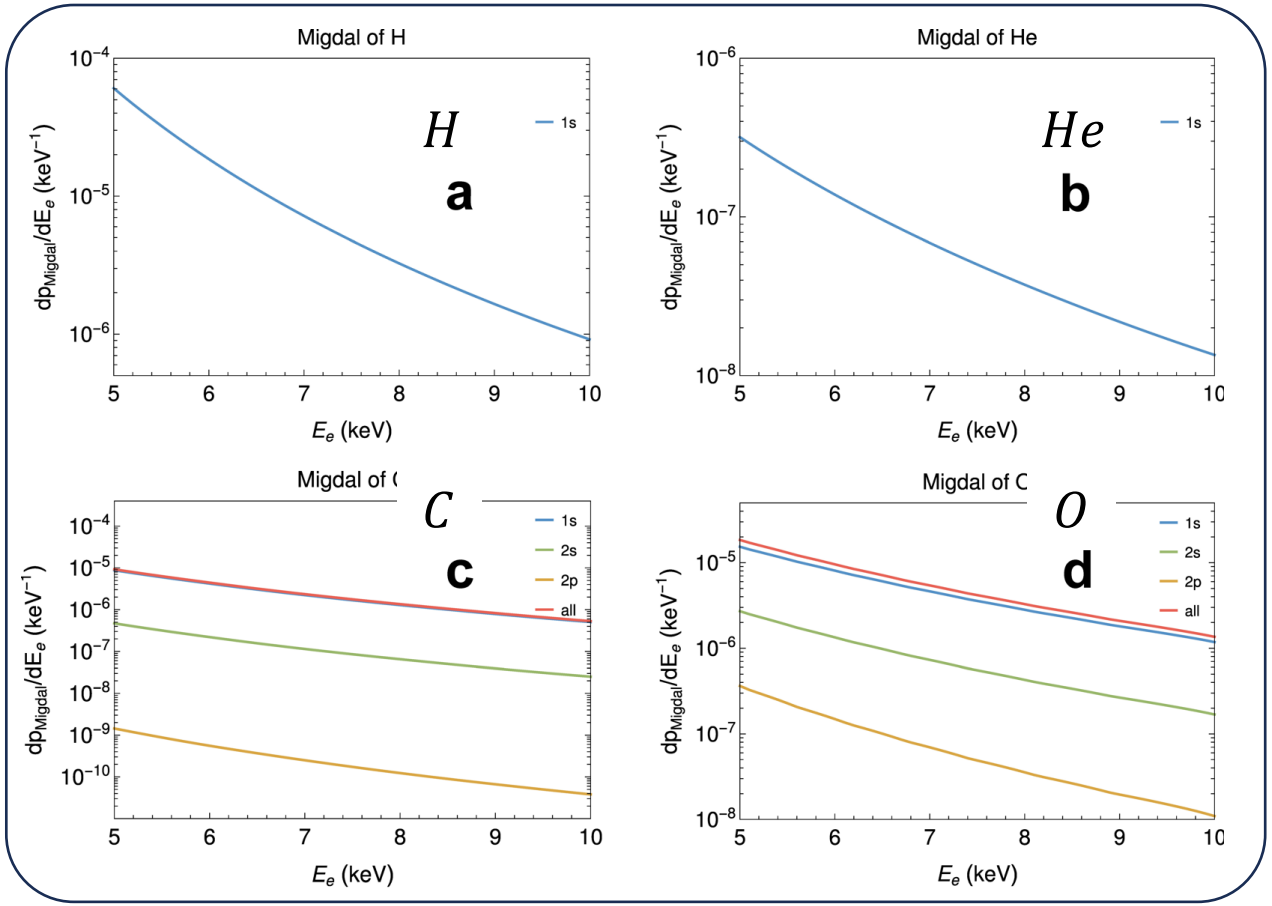
最终结果: $4.91^{+2.56}_{-1.87} \times 10^{-5}$

总跃迁几率

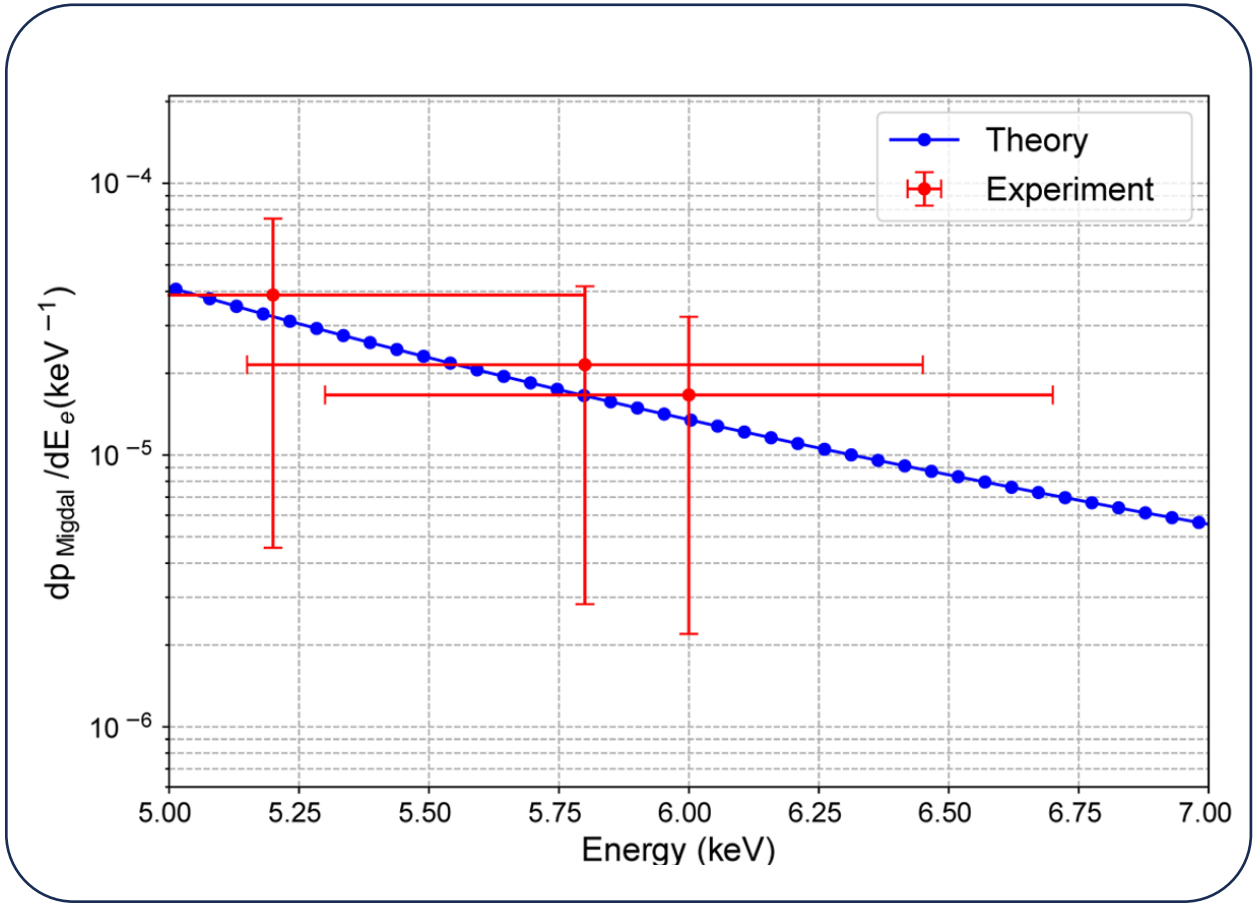
$$\sum_{nl} \frac{dp^i(nl \to E_e)}{dE_e}$$

初态为 (n,l) 的电子跃迁到具有 E_e 能量末态的几率.

武雷　　祝斌



每种元素的跃迁几率



总跃迁几率

总结

- 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。
- 中国科学院大学、广西大学、华中师范大学、兰州大学的相关核心教师，均具备 BESIII、LHCb 等对撞机实验的科研工作经验。参与工作的多名研究生亦依托对撞机实验完成学业与科研训练。
- 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！