



中国科学院近代物理研究所
Institute of Modern Physics, Chinese Academy of Sciences

用于天体核反应测量的 低气压双层Micromegas-TPC

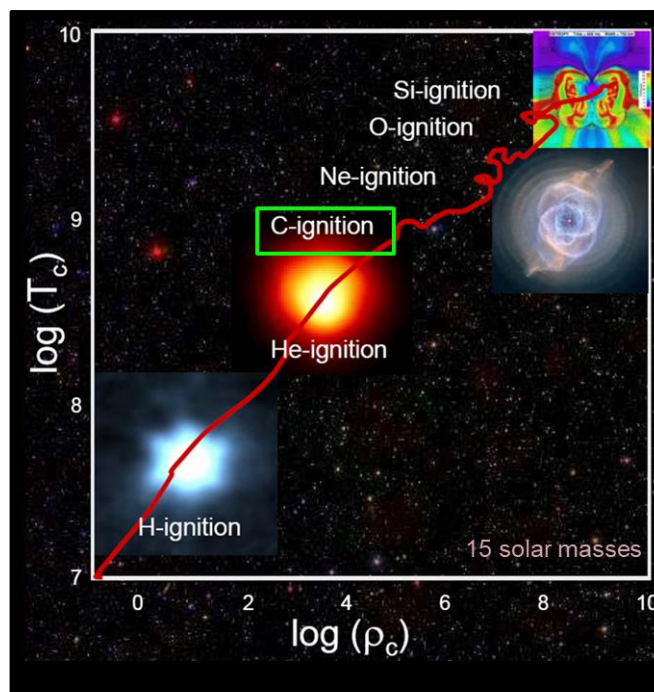
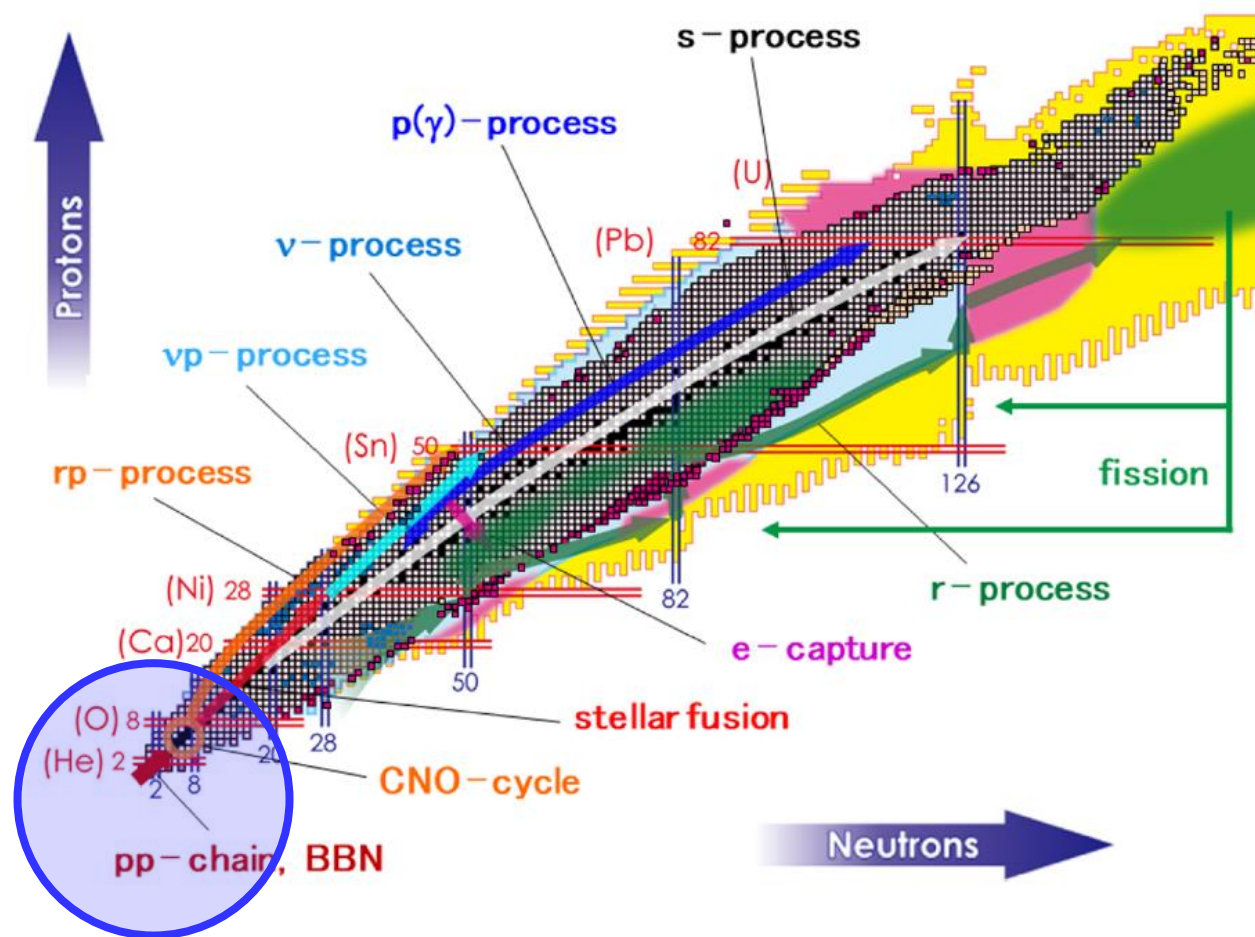
李昀臻，张宁涛
中国科学院近代物理研究所
MATE-TPC合作团队

第十四届全国先进气体探测器研讨会

主要内容

- 研究背景
- Double Micro Megas-TPC的性能
- 天体核反应中低能带电粒子测量
 - $^{12}\text{C}+^{12}\text{C}$ 熔合反应
 - 碳氮氧循环中的(p,a)反应
- 总结与展望

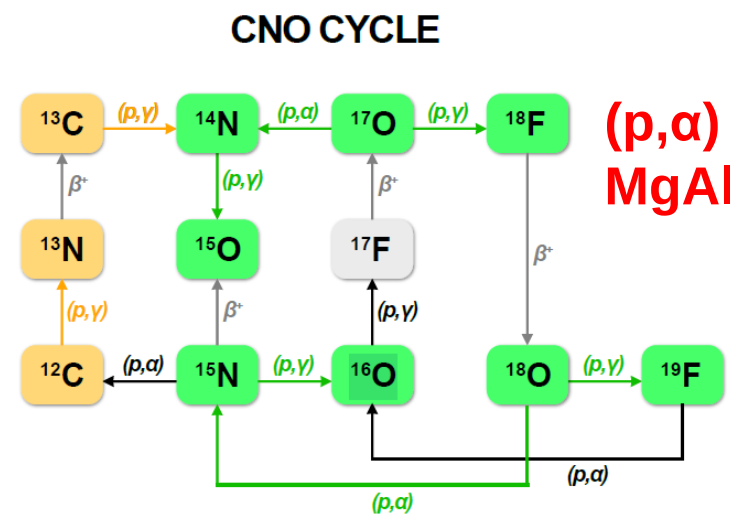
元素核合成：低能核反应（带电粒子出射）



大质量恒星中的
熔合反应: $^{12}\text{C}-^{12}\text{C}$,
 $^{12}\text{C}-^{16}\text{O}$, $^{16}\text{O}-^{16}\text{O}$

Nuclear physics is the key!

"Progress in nuclear astrophysics of east and southeast Asia", AAPPS Bulletin (2021) 31



(p,α) CNO、NeNa、
MgAl循环中的闭合反应

低能核反应直接测量中的实验挑战

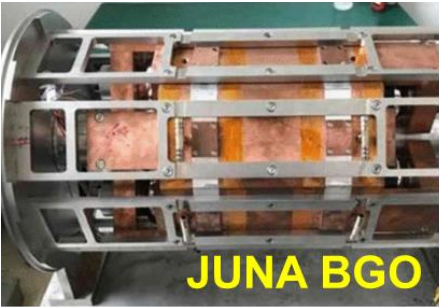
- ✓ 更高的束流强度
- ✓ 更低的本底干扰



测量什么？如何测？



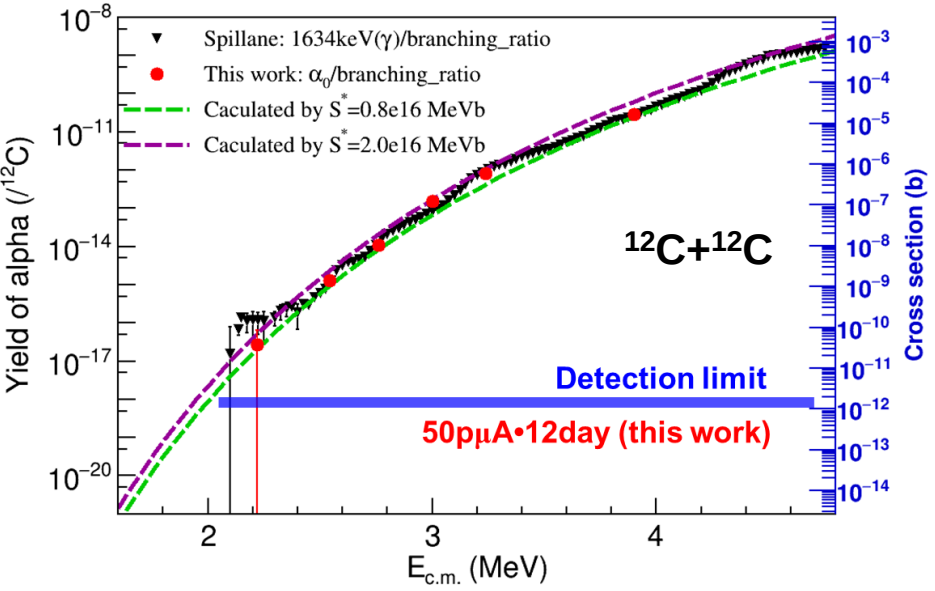
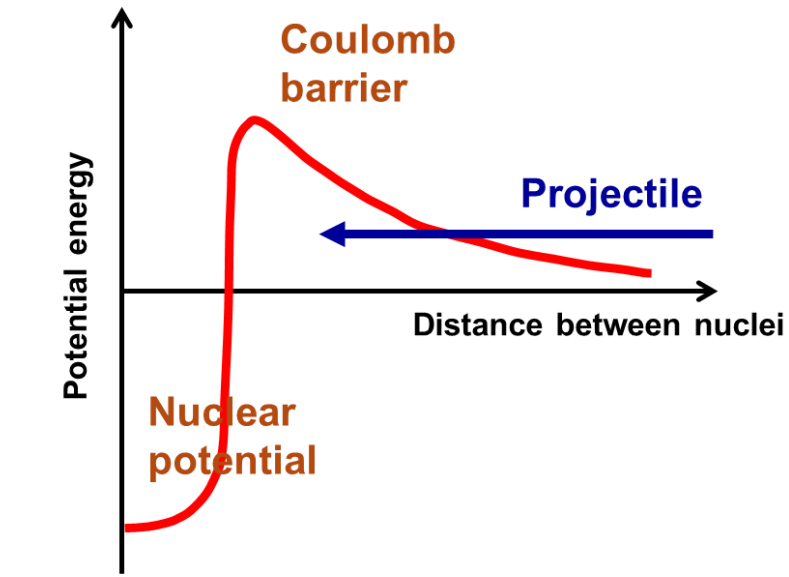
带电
粒子



伽马
射线

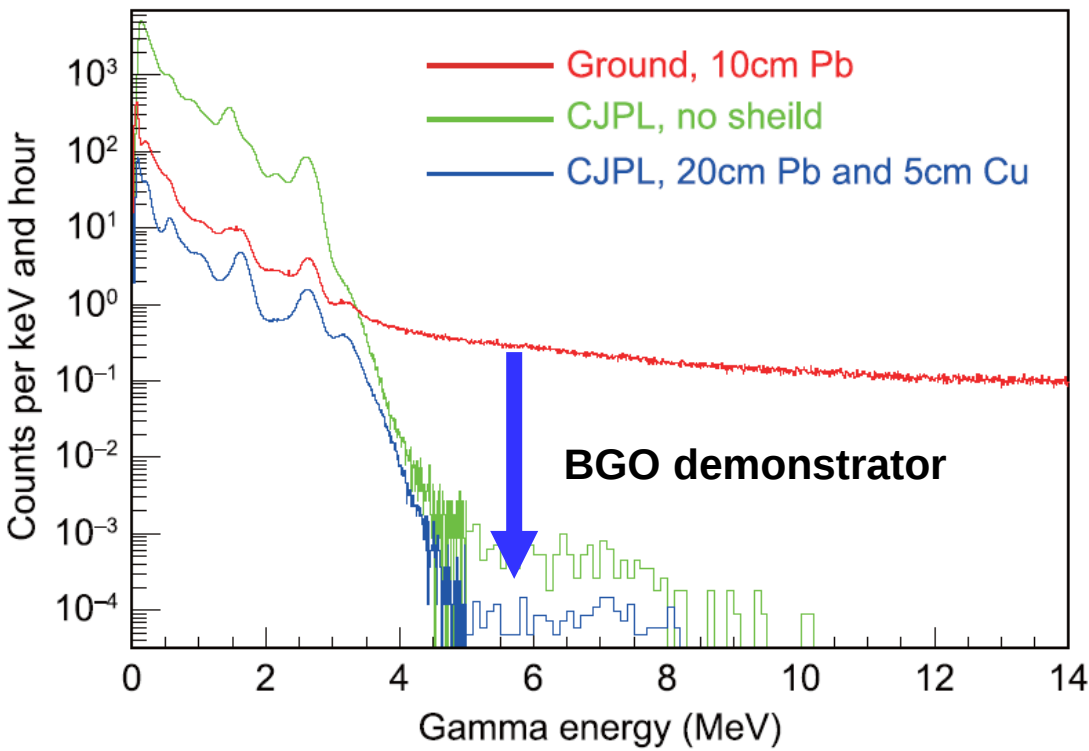


中子

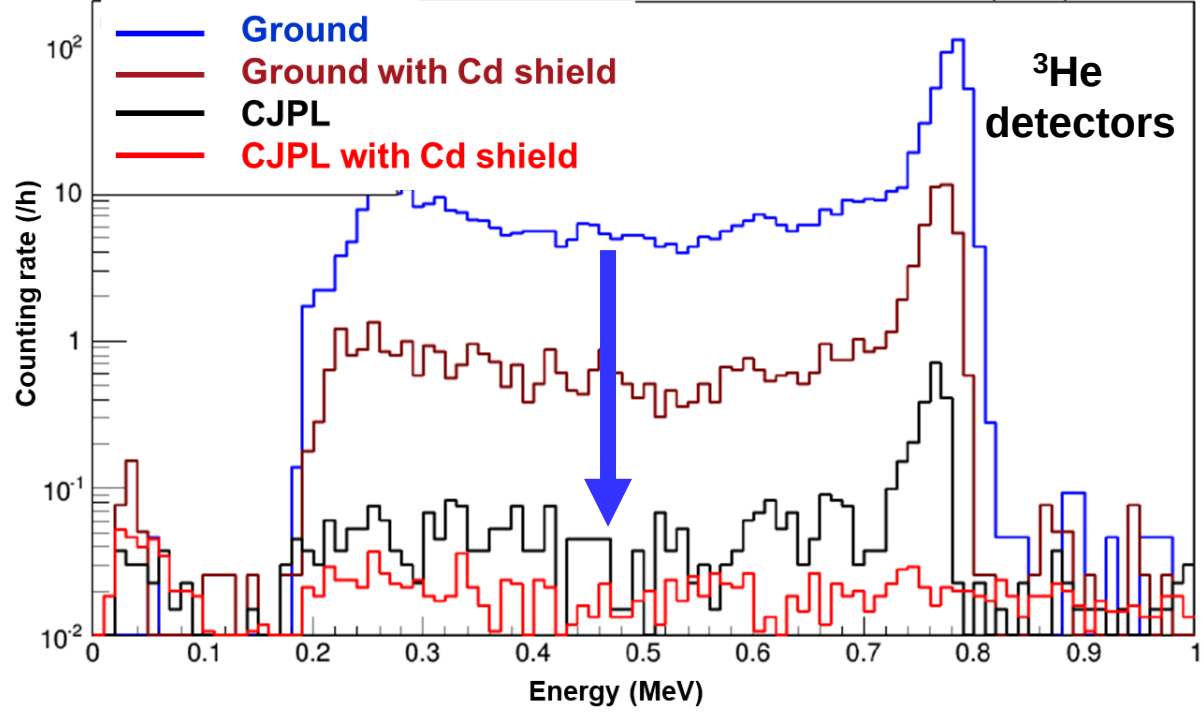


JUNA锦屏地下实验室的伽马和中子本底

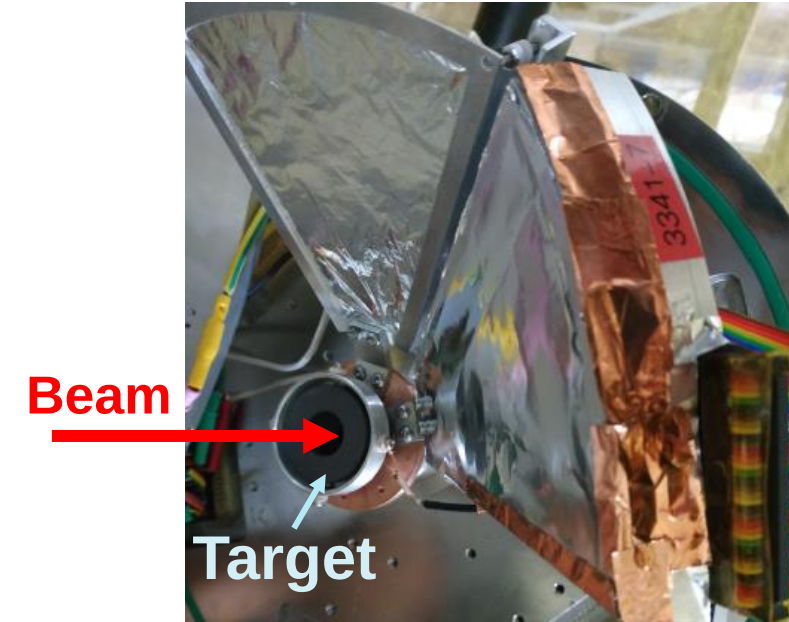
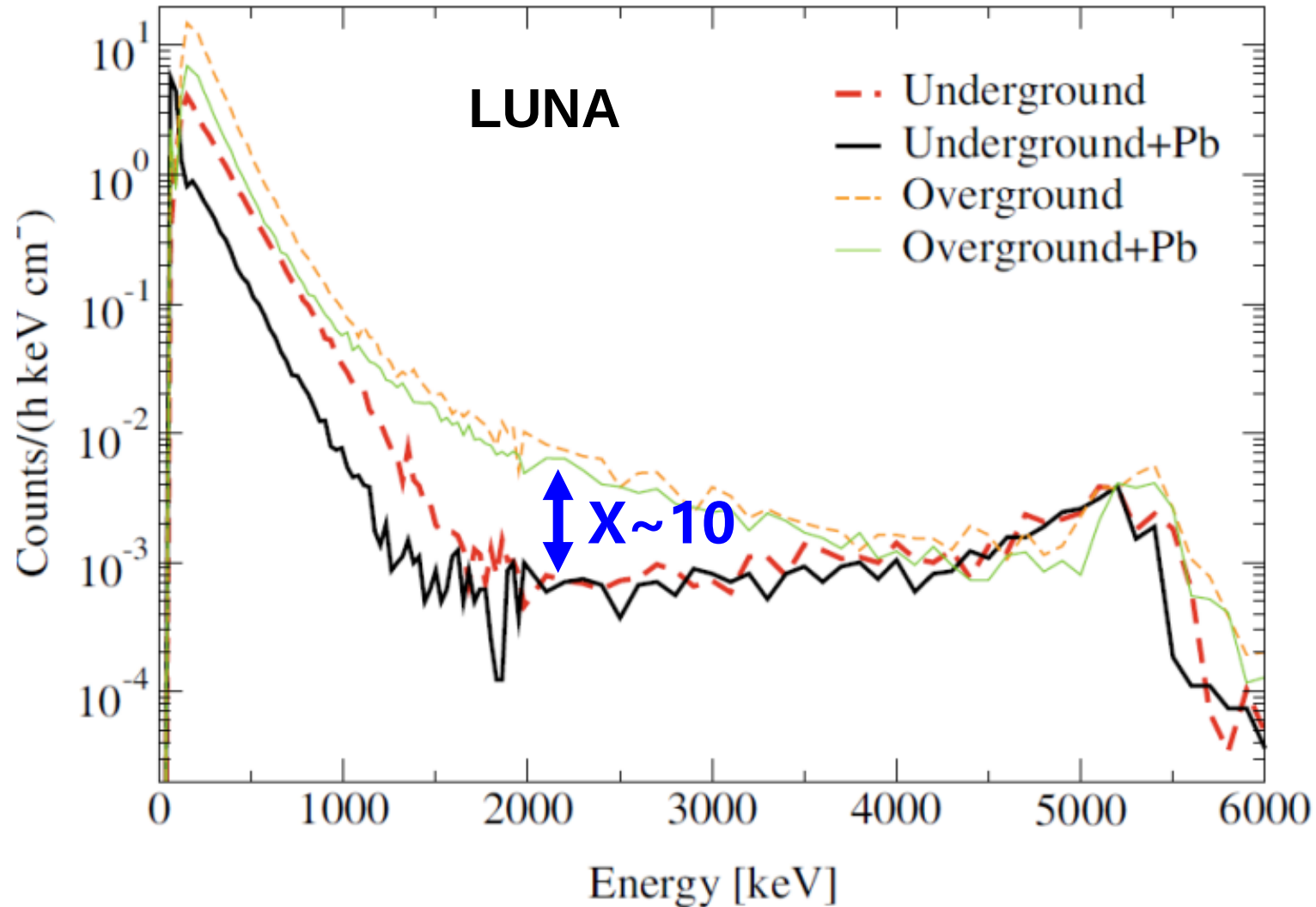
Y. P. Shen et al., *Sci. China-Phys.Mech.Astron.*102022(2017)60



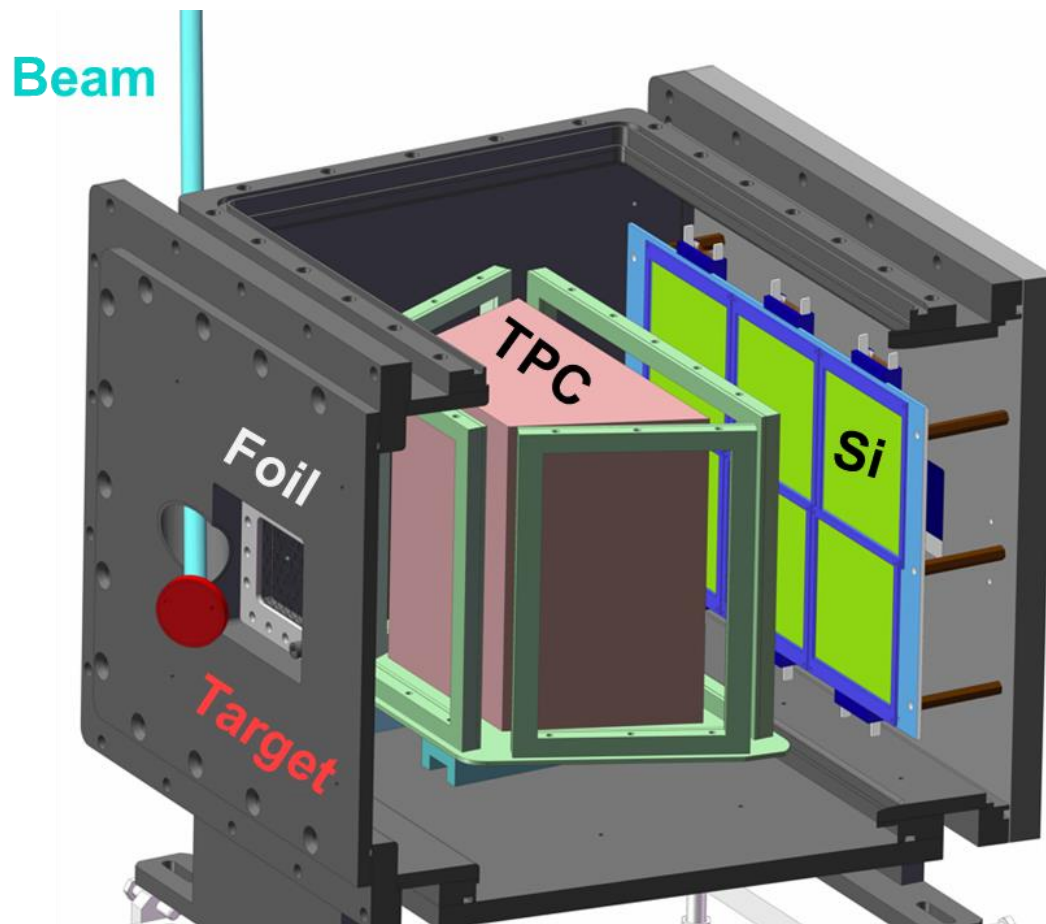
H. Chen's thesis (IMP)



深地实验室的带电粒子本底

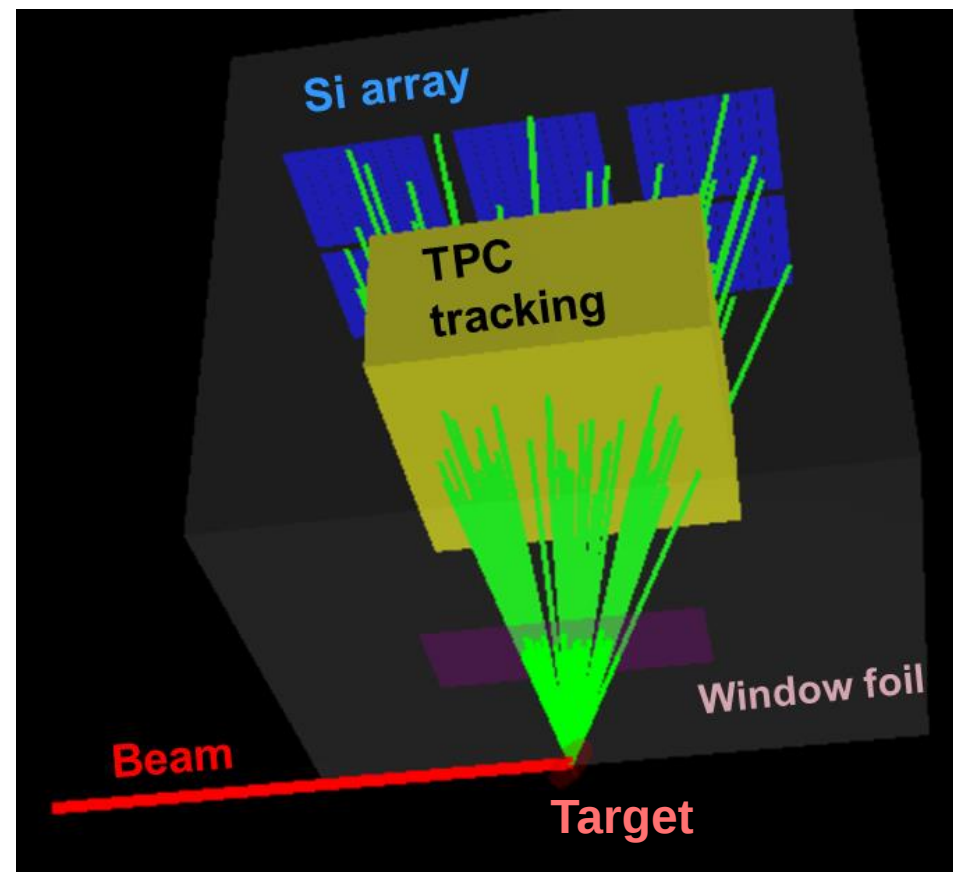


强流束下的TPC：本底压制和轻粒子鉴别



DMM-TPC

α stopped
A few MeV $\rightarrow$ DE-E silicon

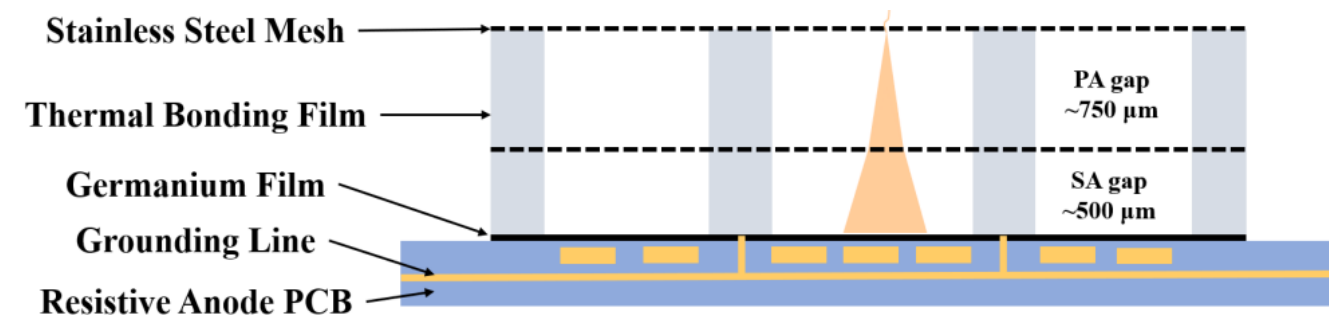


提出强流束TPC概念、建立方法

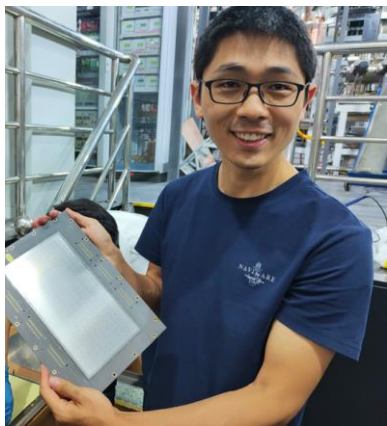
TPC中的Double micro-mesh (DMM)

实验测量对象: 0.5-5 MeV的质子、氦和alpha

实验测量需求: <100 mbar He主气体下工作稳定、低IBF、粒子鉴别



Made by USTC,
University of Science and Technology of China

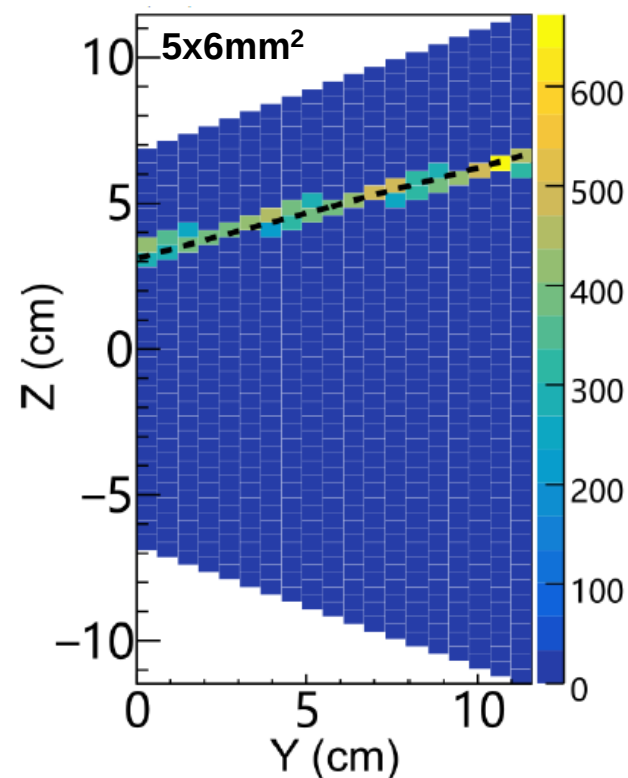


JX Feng, ZY Zhang*(张志永) et al.,
NIMA1031(2022)166595
S Wang et al., Nuclear Science and Techniques
36(2025)143

DMM



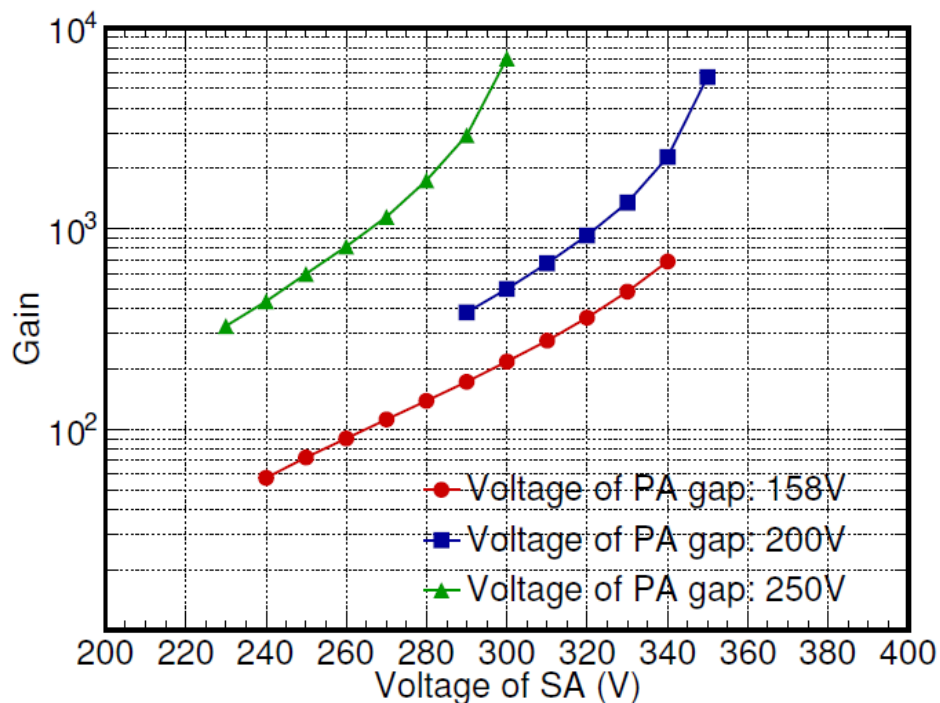
读出平面: 684路



DMM的增益和IBF(Ion back flow)测量

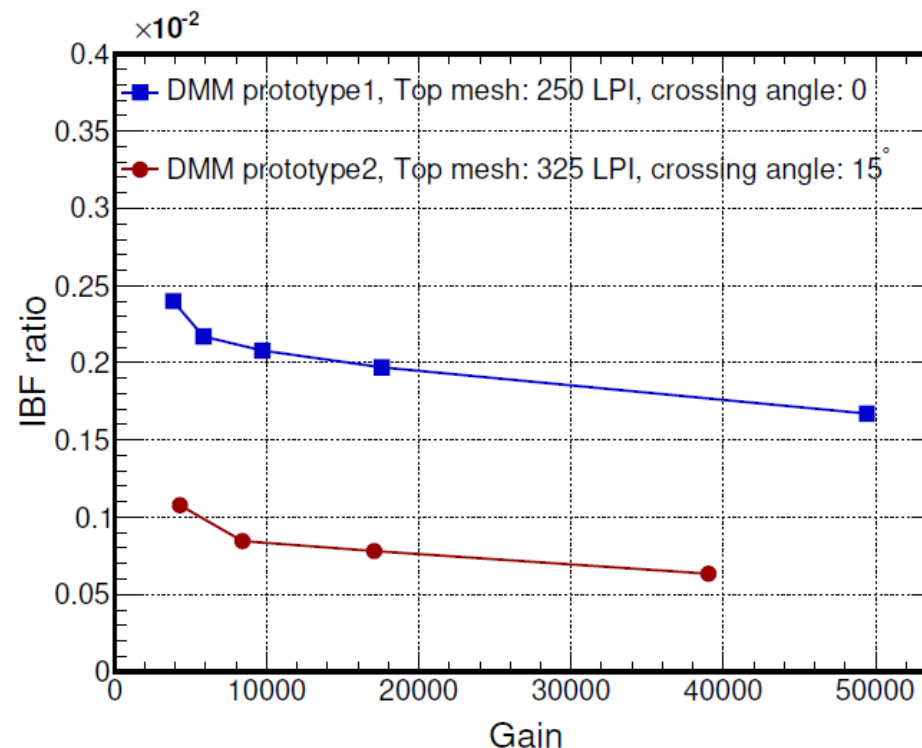
Gain

90%He + 5%CO₂ + 5%Ar at 110 mbar



Ion back flow

50%Kr + 15%CO₂ + 35%Ar at 110 mbar



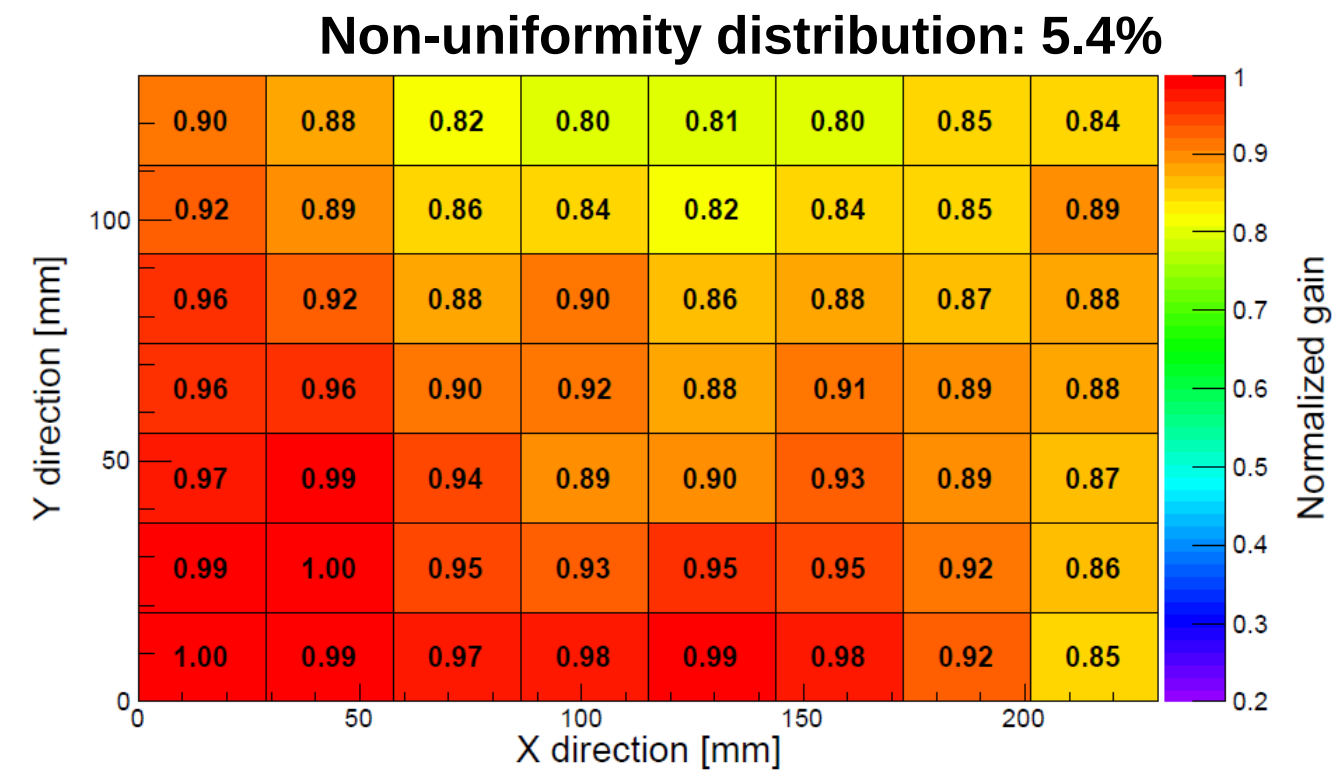
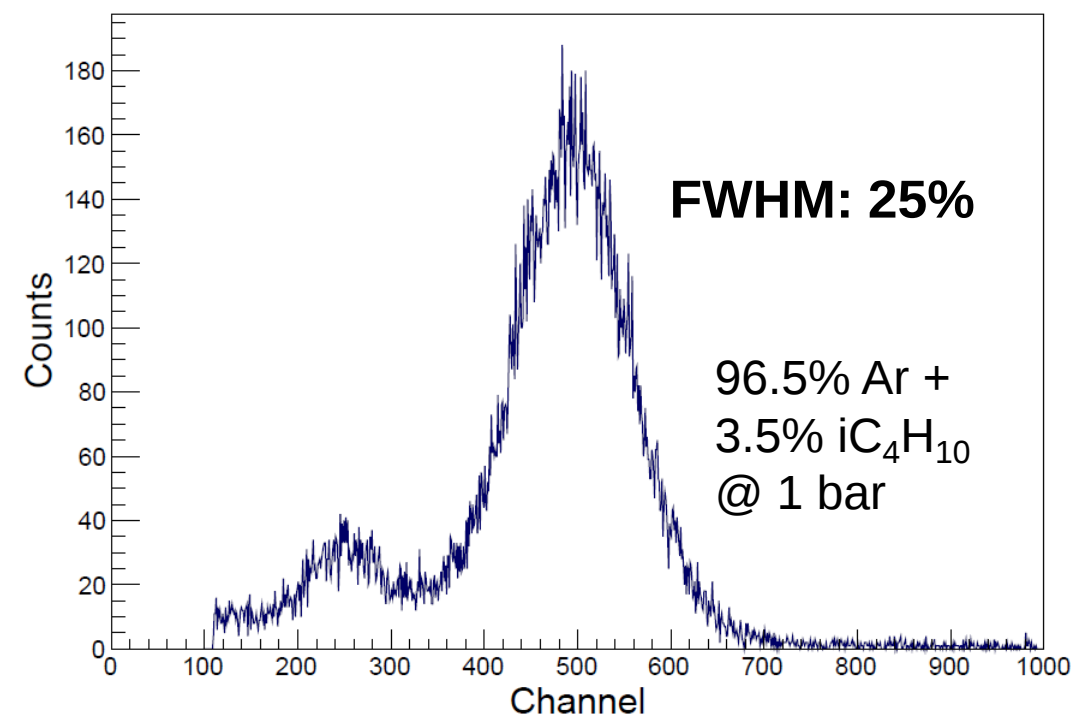
增益的动态可调范围：50~5000

最好的IBF水平：< 1/1000

测试：王硕、王旭、张志永

S. Wang, X. Wang et al., submitted to NIMA (under review)

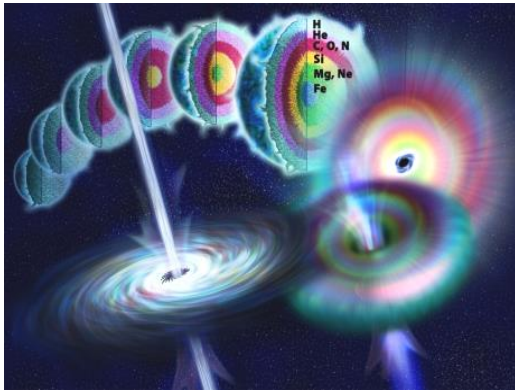
DMM的分辨和增益分布



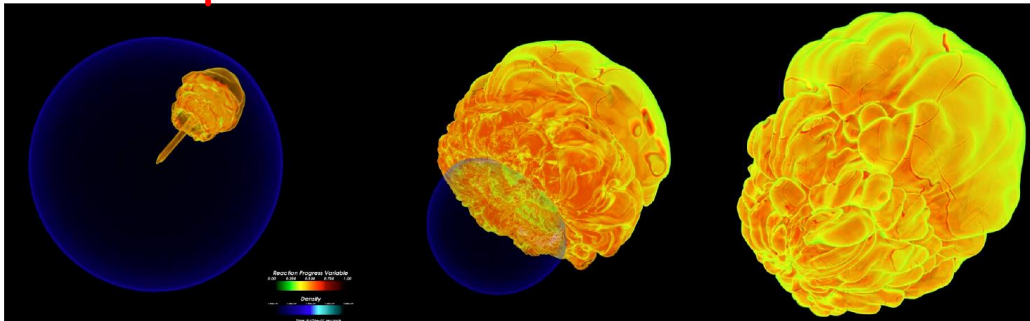
S. Wang, X. Wang et al., submitted to NIMA (under review)

天体物理中的碳碳融合反应

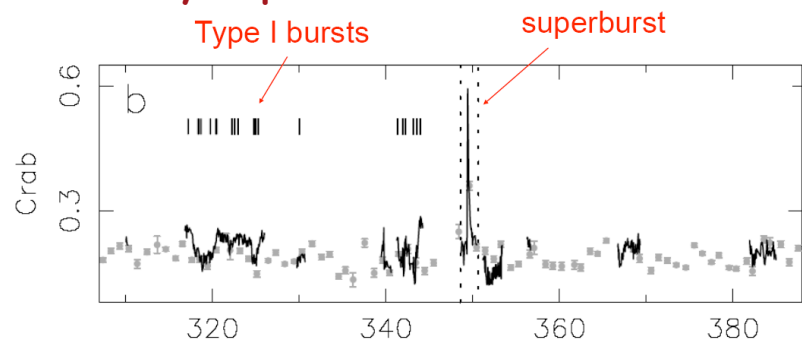
1. Massive star



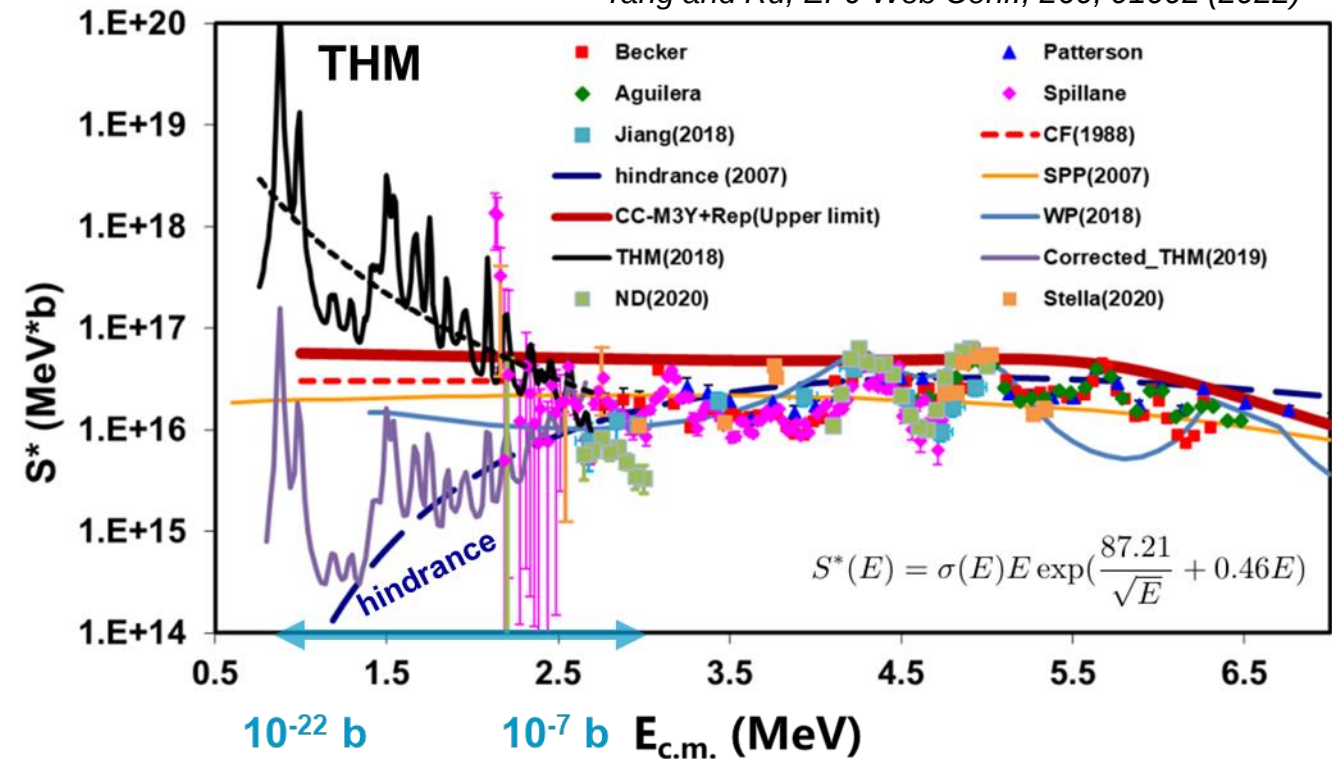
2. Ia supernova



3. X-ray Superburst



Tang and Ru, EPJ Web Conf., 260, 01002 (2022)



- Stellar energy region at 1-3 MeV: ~ 1 pb at $E_{cm}=2$ MeV
- Large discrepancy: up to 3-4 orders of magnitude

基于LEAF平台的碳碳熔合反应直接测量

Low Energy high intensity heavy ion Accelerator Facility (LEAF), IMP, Lanzhou

All-permanent-magnet ECR source

QWR

DTL-2_0.7~1 MeV/u

DTL-1_0.3~0.7 MeV/u

RFQ@ 81.25 MHz_0.5 MeV/u

Superconducting ECR source

70pA on target

Courtesy of Yang Yao

Beam
Target

Foil

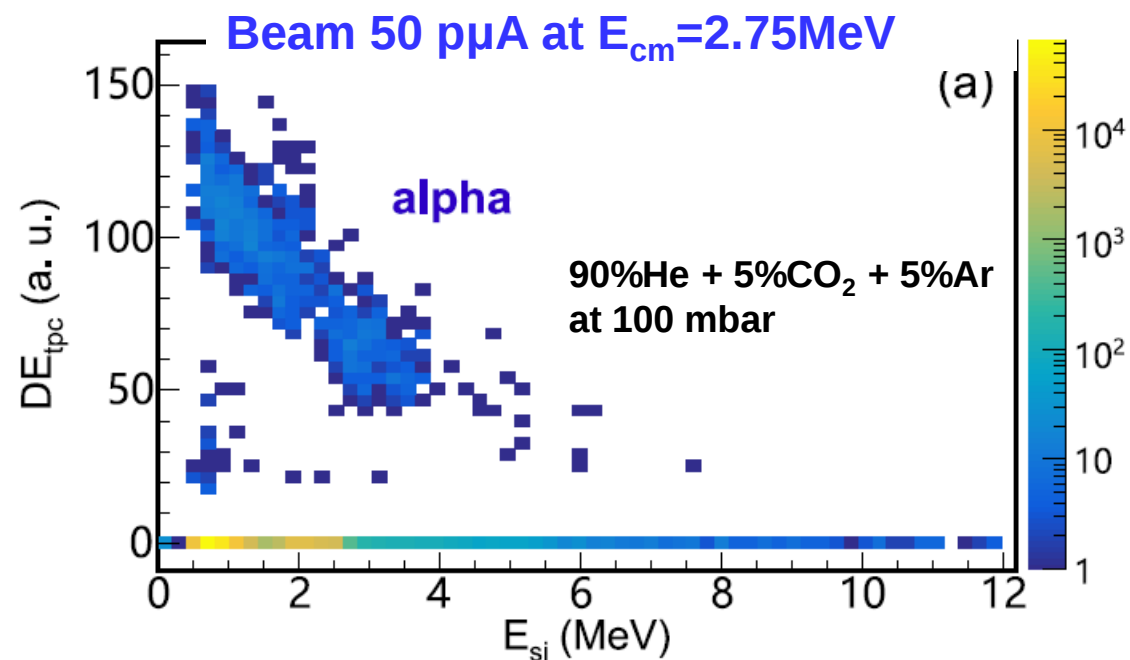
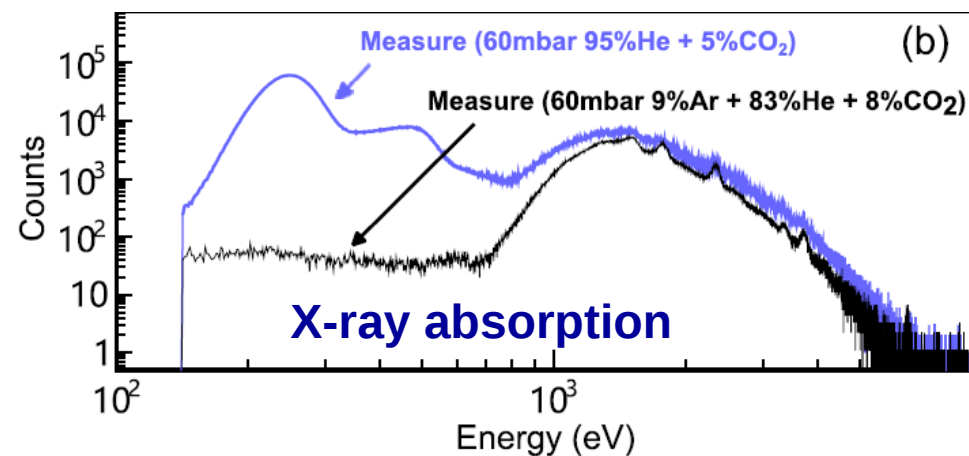
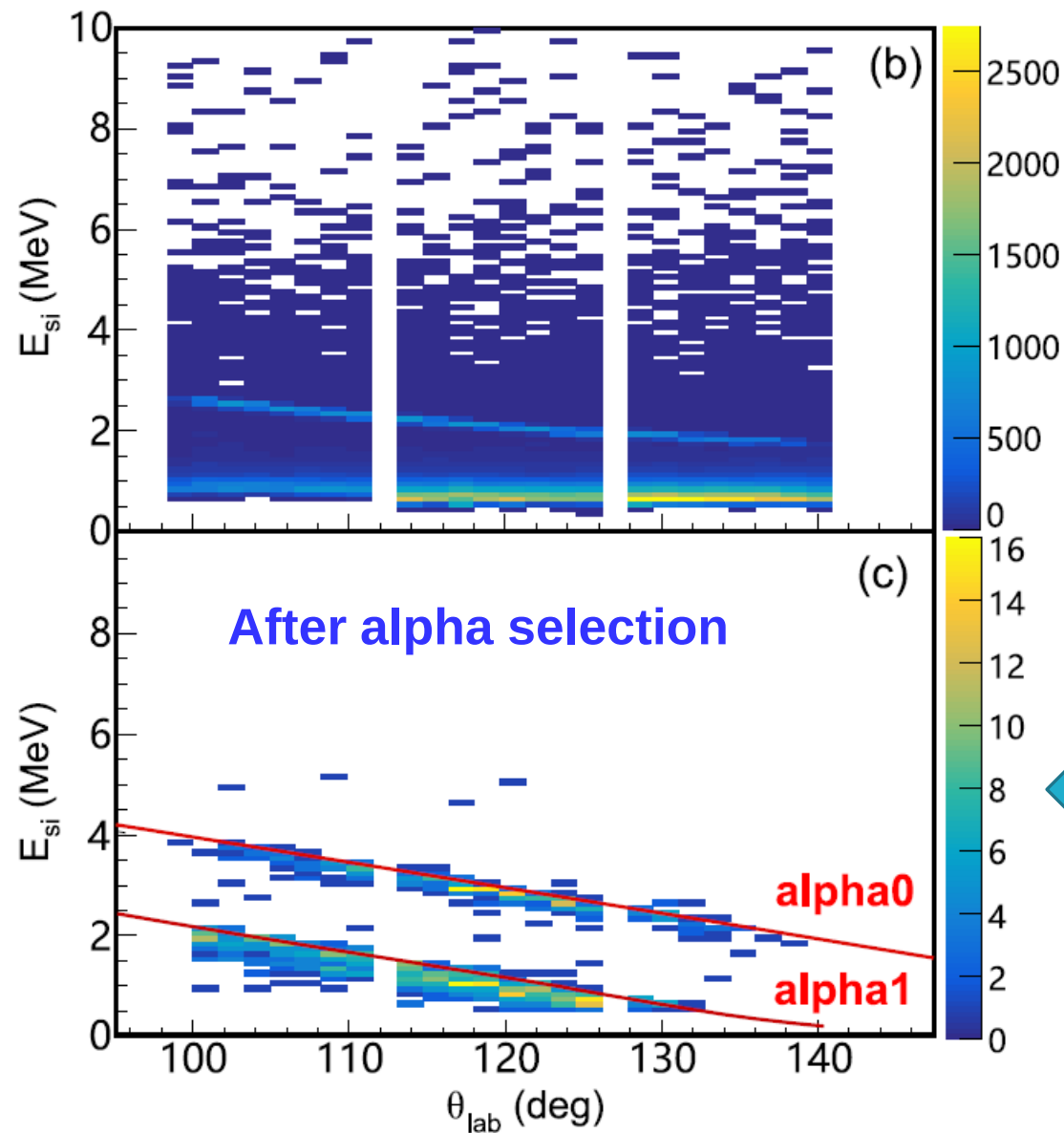
Field cage

TPC

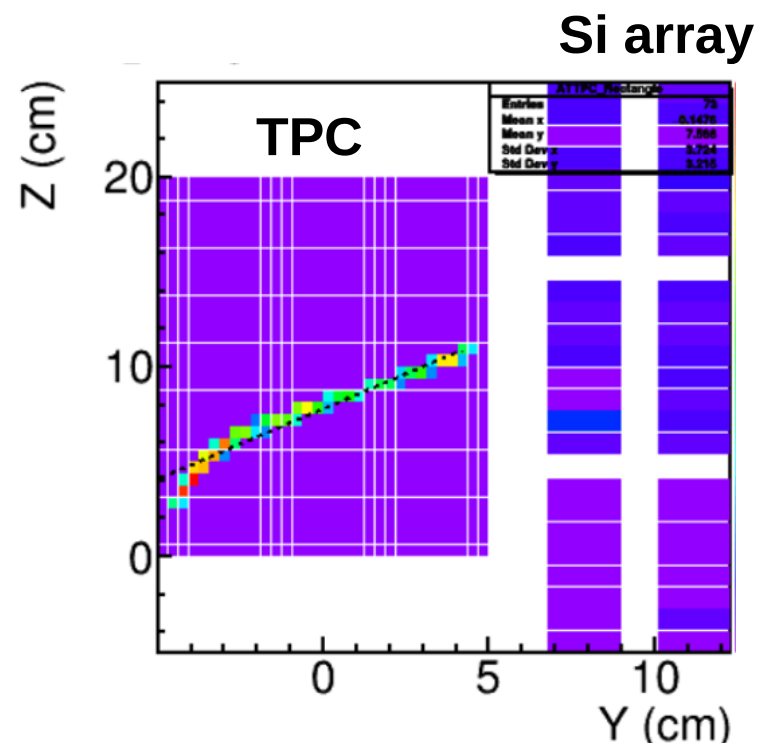
SDD
X-ray

Field cage

alpha测量 $E_{cm}=2.75$ MeV

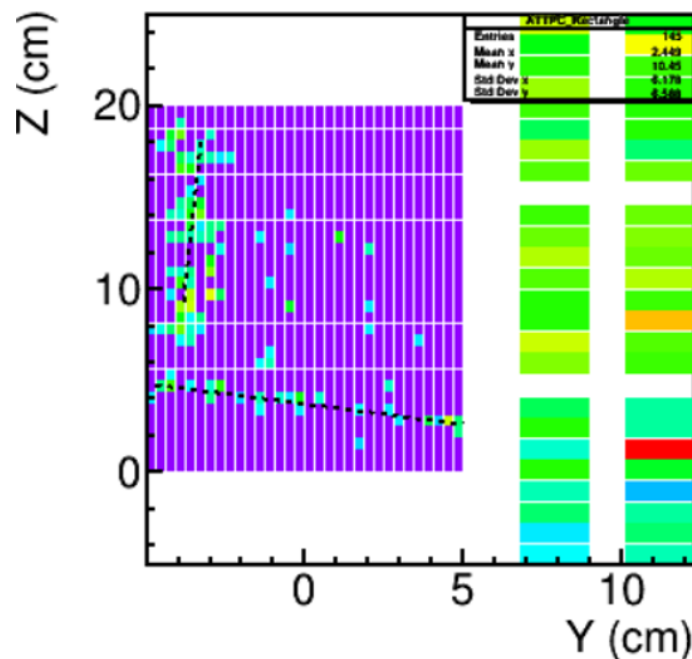


实验中的alpha径迹



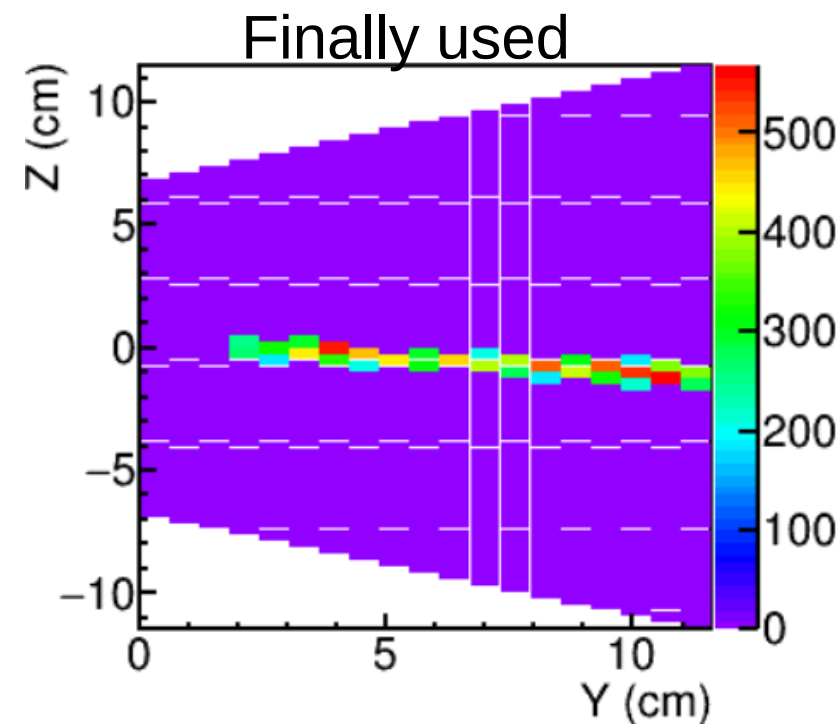
GEM-TPC

- 135-mbar He+5%CO₂
- 30 pμA ¹²C beam



GEM-TPC

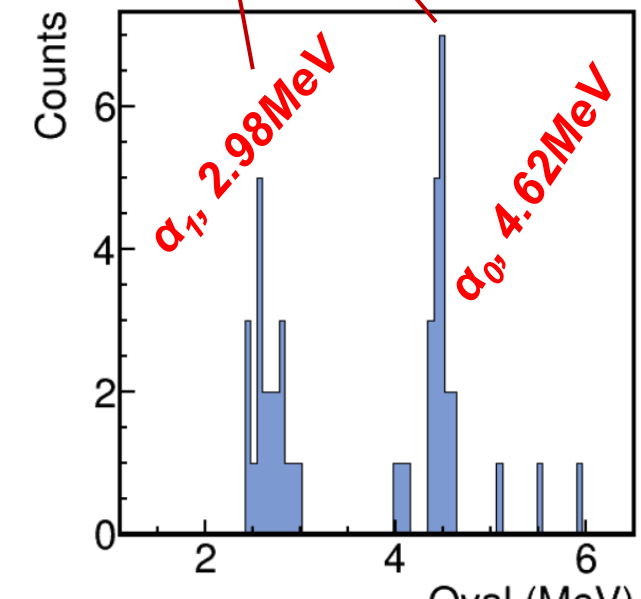
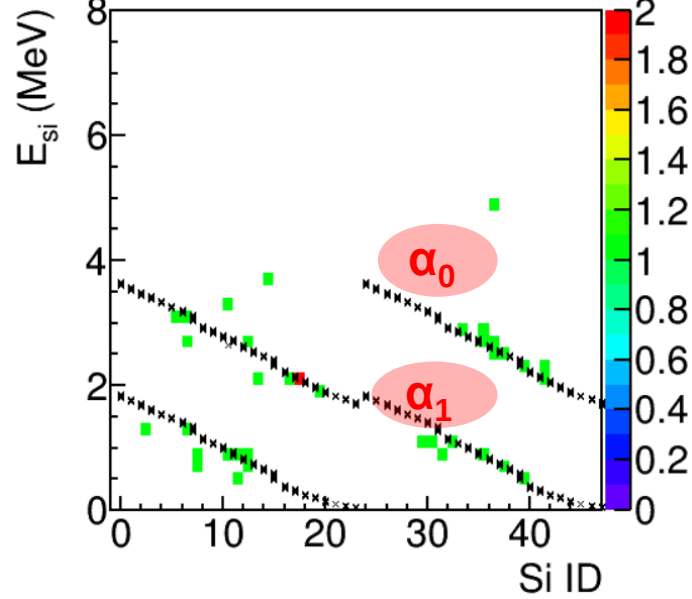
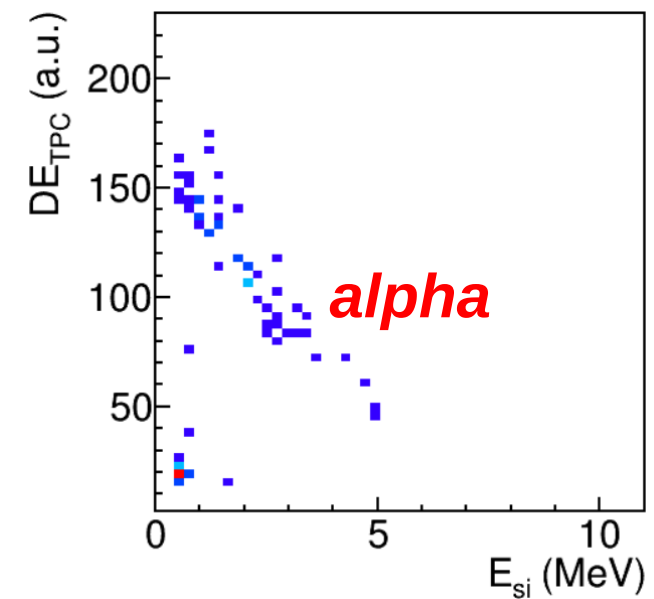
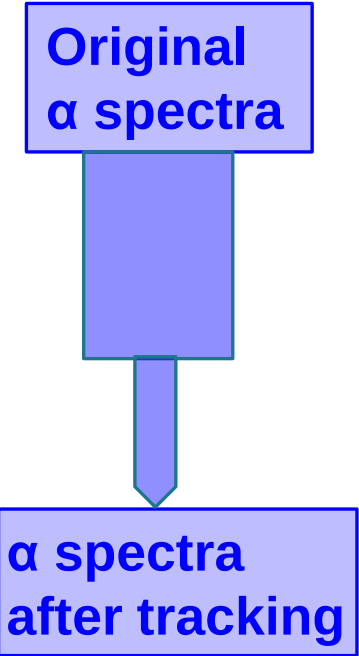
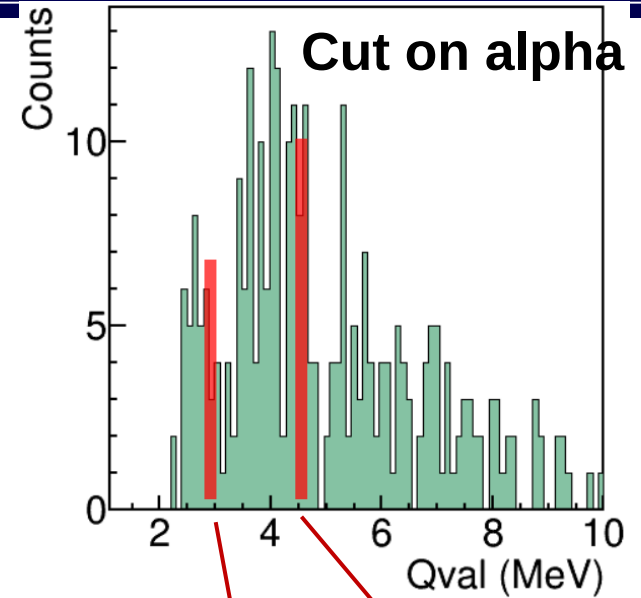
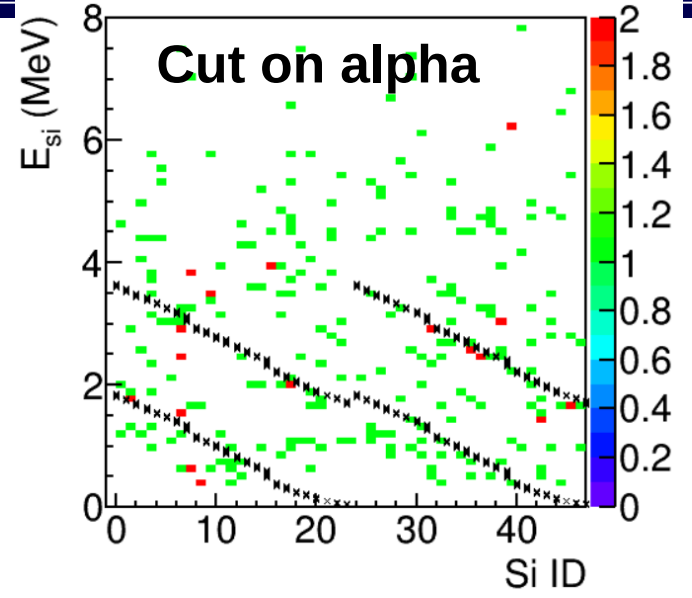
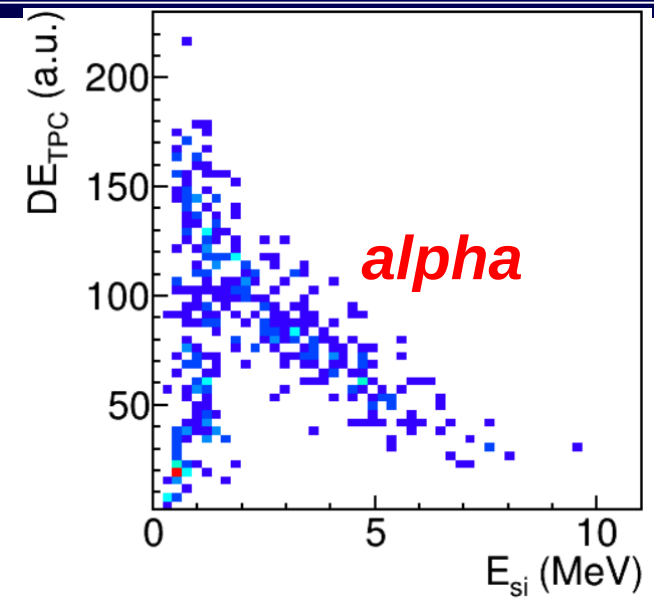
- 90-mbar He+5%CO₂
- 17 pμA ¹²C beam



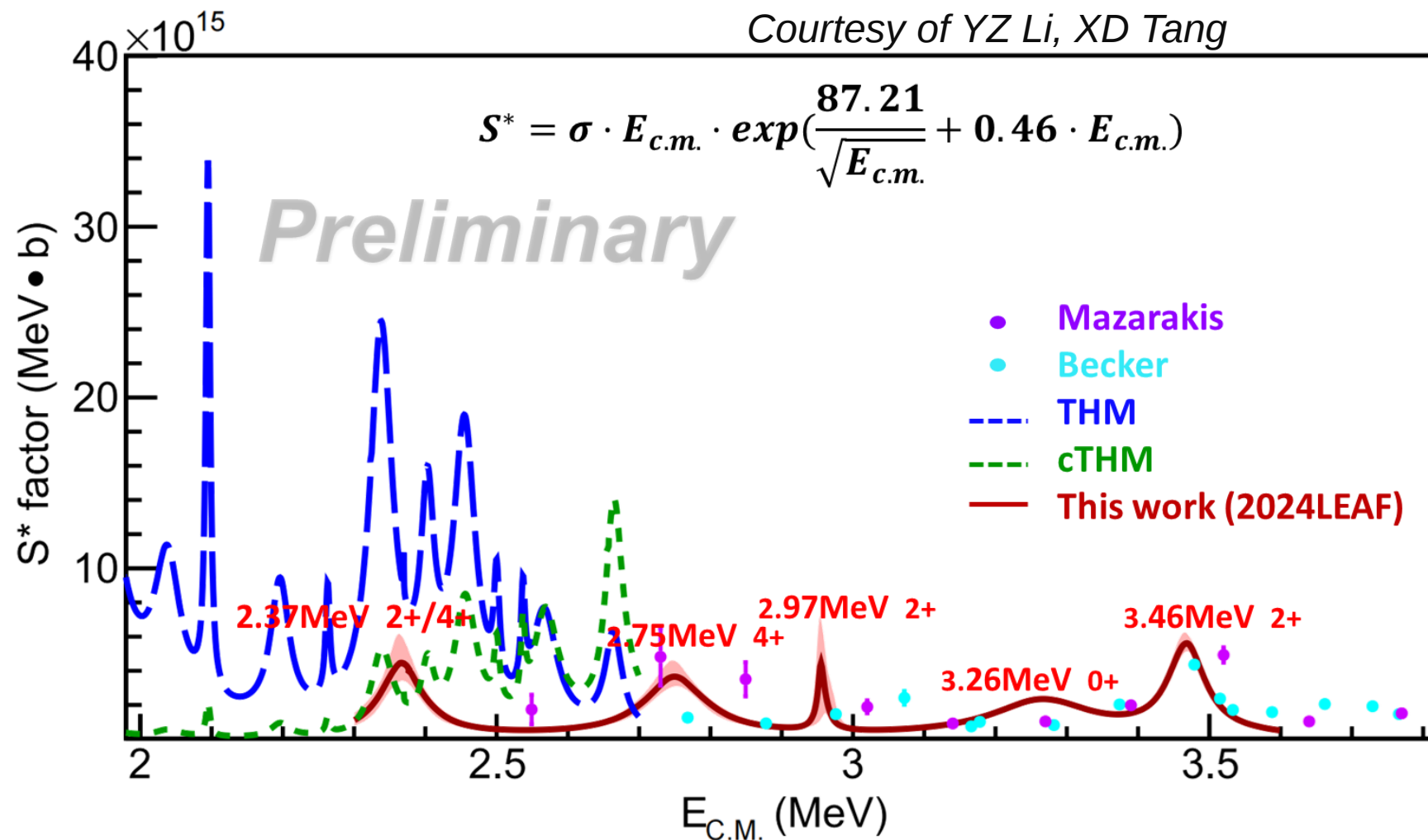
Double Micro Megs -TPC

- 90-mbar He+5%CO₂+5%Ar
- 70 pμA ¹²C beam

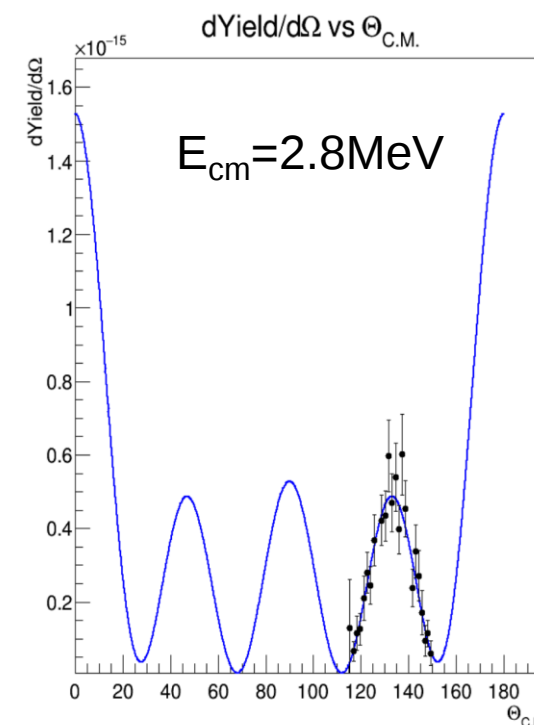
alpha测量 $E_{cm}=2.40$ MeV



初步结果 (α_0 反应道)



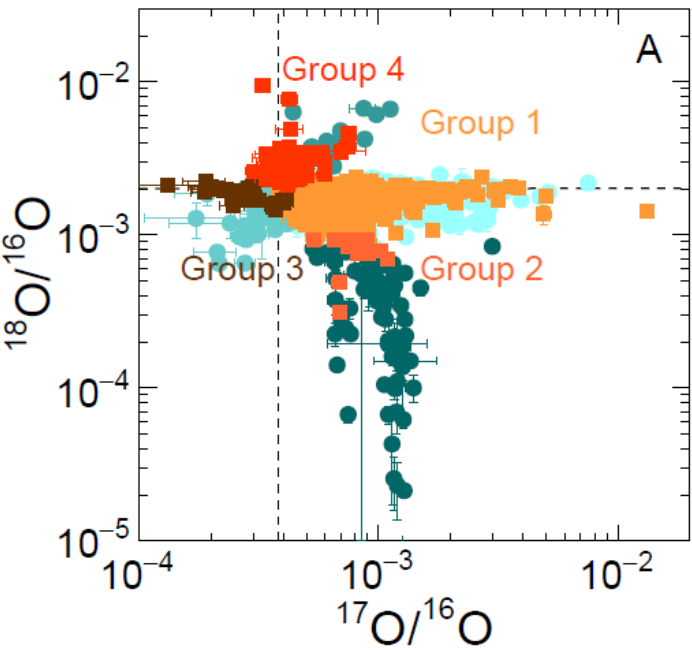
Measurements: $\alpha_{0,1}$, $p_{0,1}$
Ang. dist.: 100-140 $^\circ$ (LAB)



Data analysis: YunZhen Li, Shuo Wang, XiaoDong Tang, ZNT

碳氮氧循环: $^{17,18}\text{O}(p,\alpha)$ 反应的直接测量

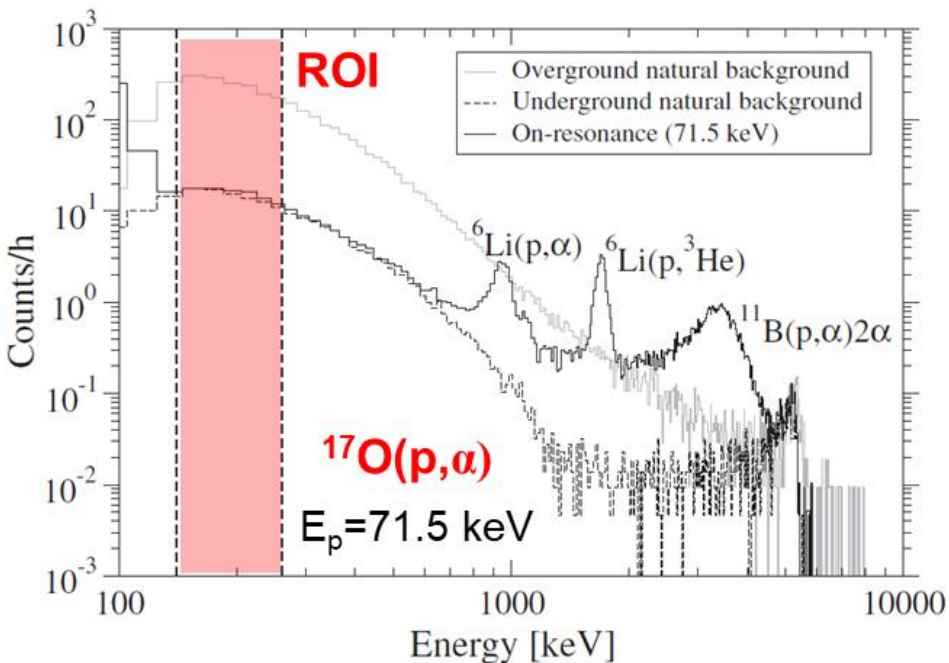
Palmerini et al., Universe 2021, 7, 175



如何理解星体中氧同位素丰度:

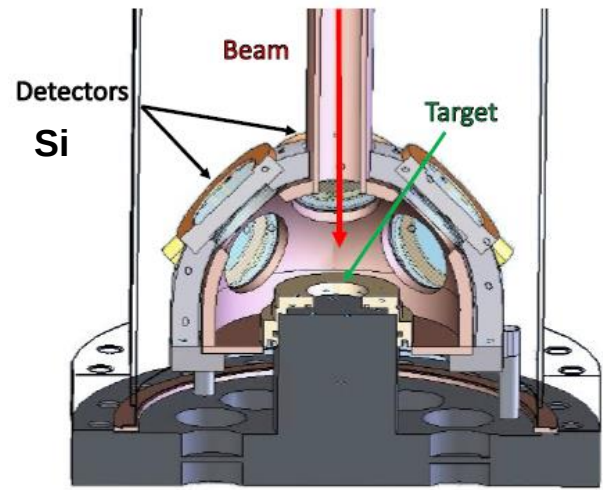
- 产生和破坏反应 (核物理)
- 物质混合过程 (改变演化轨迹)

Bruno et al., PRL 117, 142502 (2016)

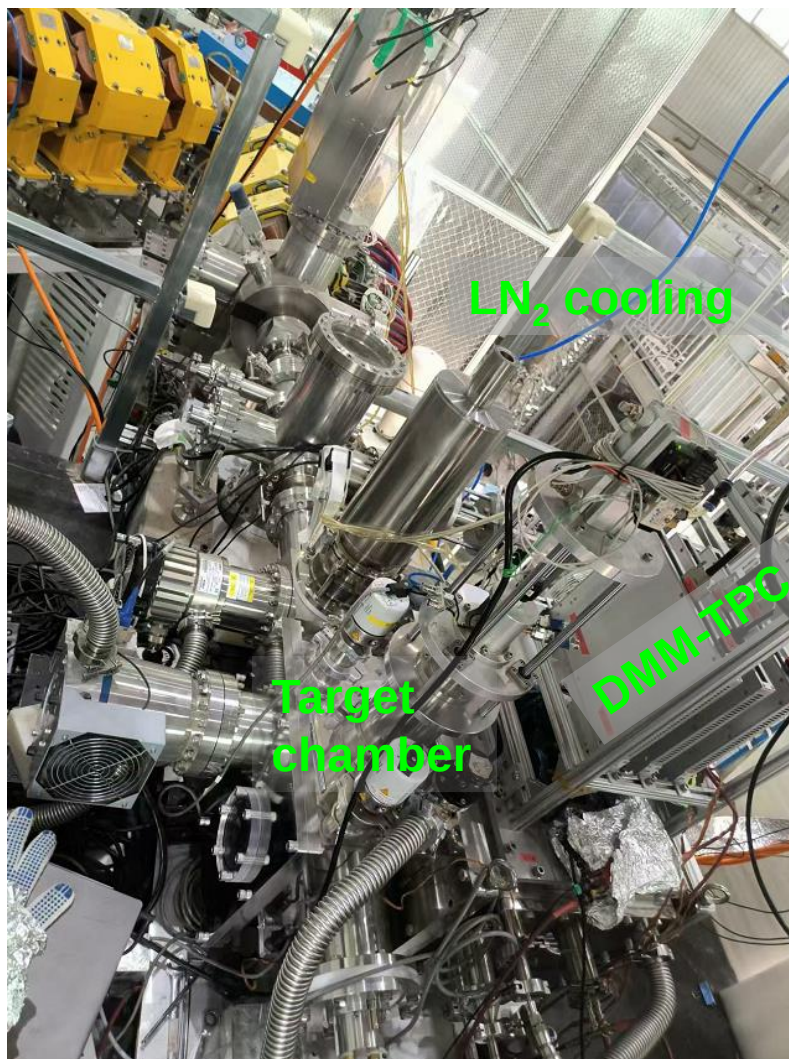


主要的本底成份

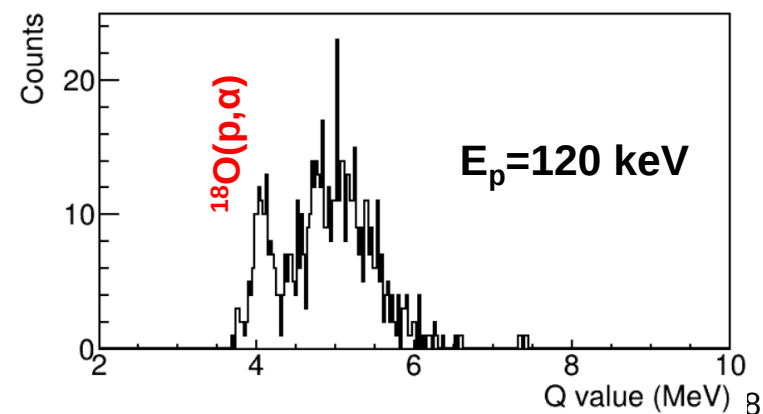
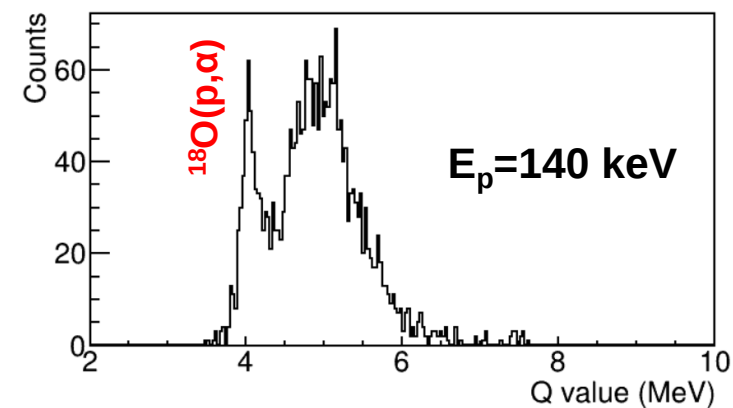
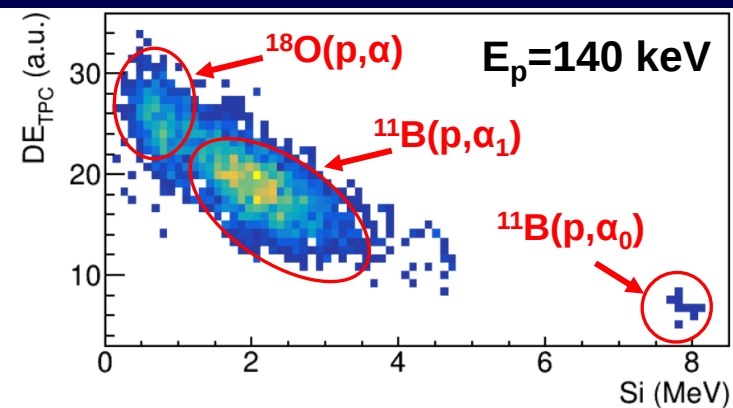
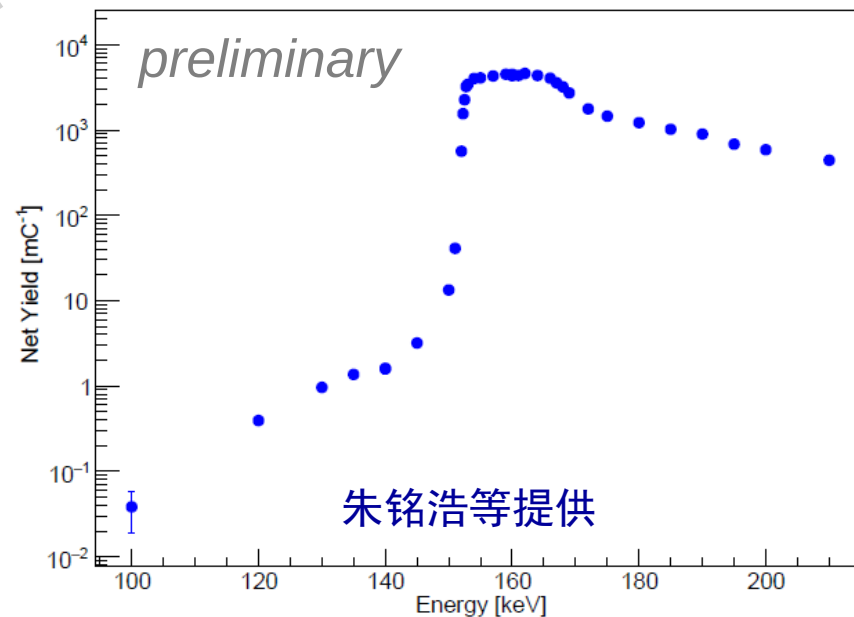
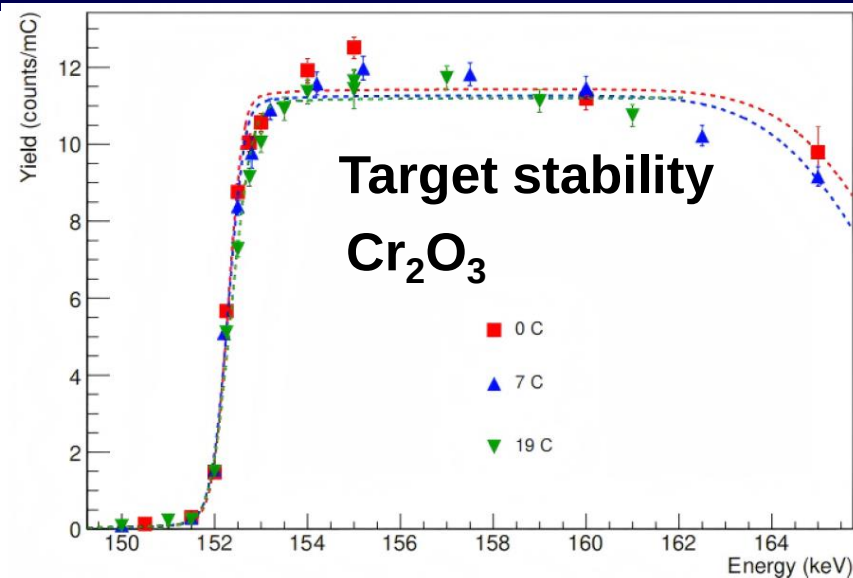
- $^{6}\text{Li}+p$
- $^{11}\text{B}(p,\alpha_{01})$
- Cosmic rays
- Environment radioactivity



$^{18}\text{O}(p,\alpha)$ 反应测量



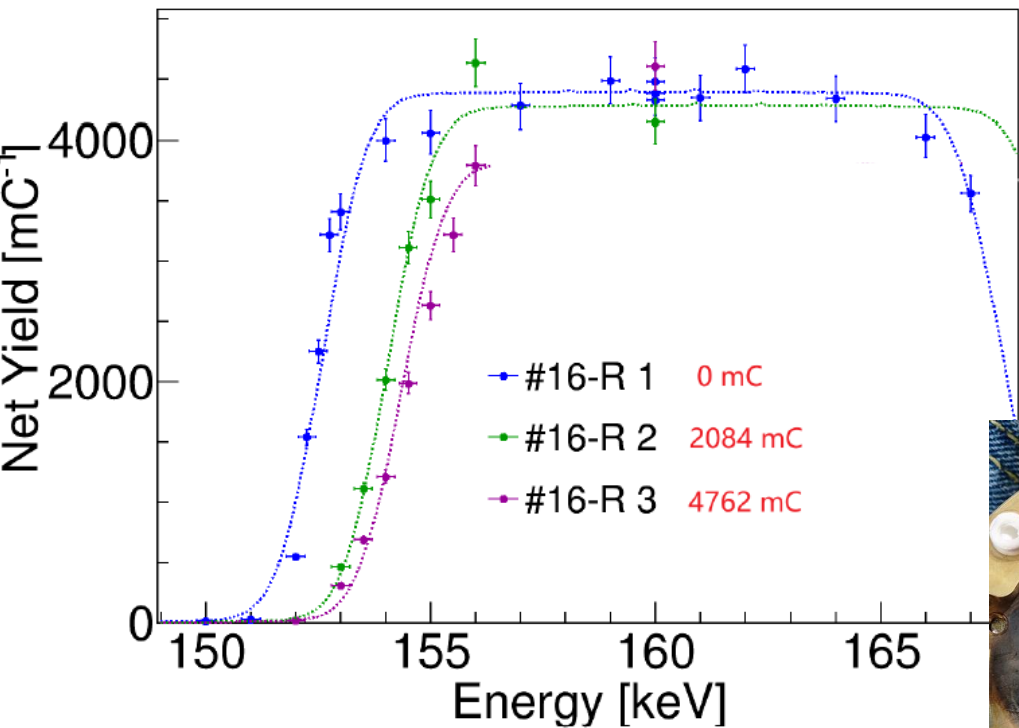
强流质子加速器: 240 kV (近物所),
15 mA



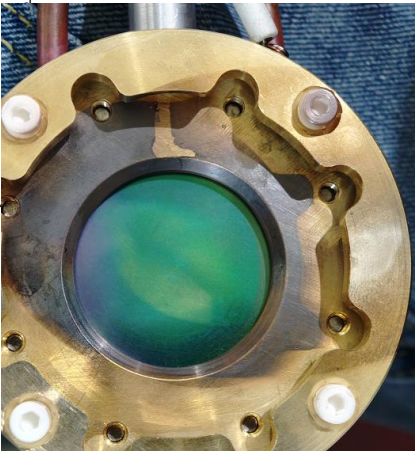
实验中的主要挑战

- ❑ 氧靶中¹¹B杂质
- ❑ 源于TPC工作气体带来的碳沉积

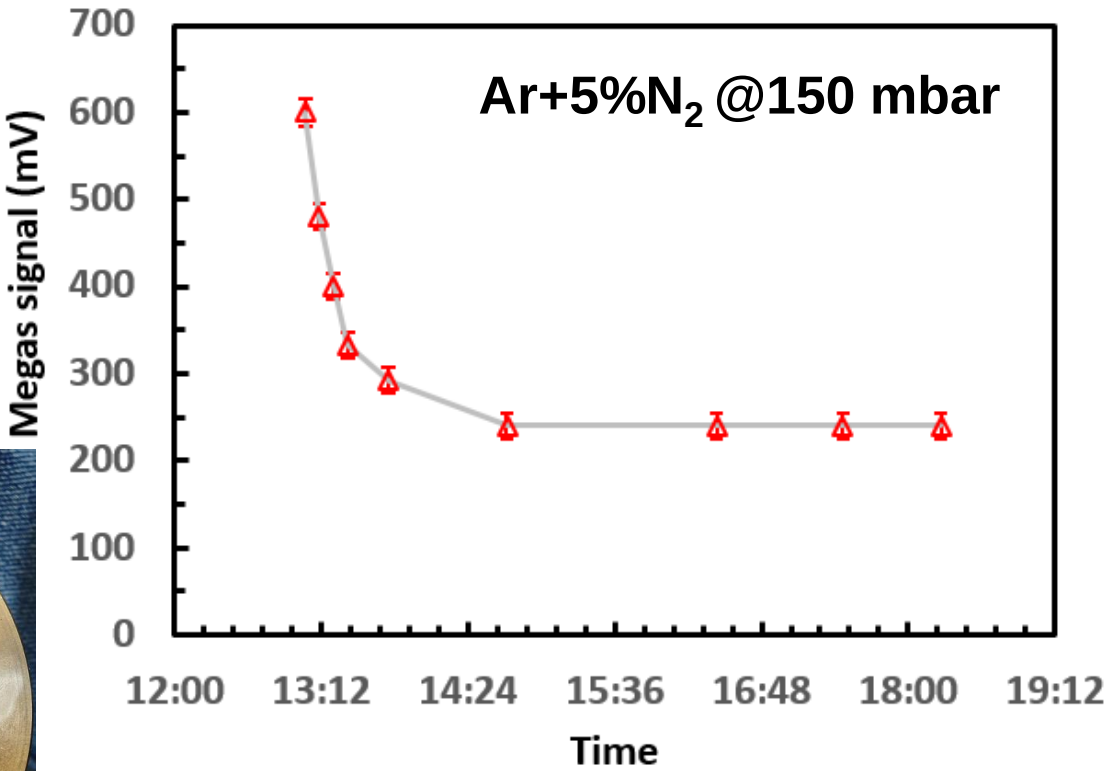
工作气体: He+Ar+CO₂ @ 100 mbar



氧化铬靶



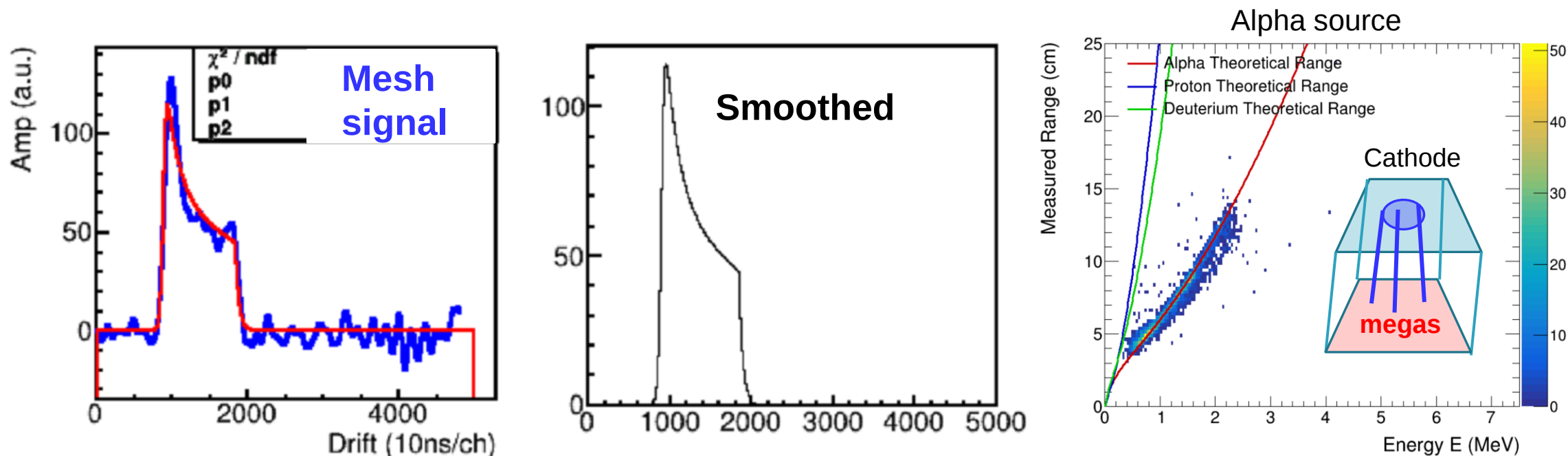
用N₂代替CO₂



朱铭浩等提供

总结和展望

- 和科大团队合作发展了专门用于50-150mbar下的低气压下双层DMM-TPC
- 利用TPC成功开展了 $^{12}\text{C}+^{12}\text{C}$ 在天体能区的反应率测量；推动TPC在100 μA -10mA强流束下的应用
- 发展Bragg-TPC: TPC单举测量、测量100keV-2MeV的低能带电粒子



范翊华等提供

合作团队

MATE: *Multi-purpose Active-target Time projection chamber for nuclear Experiments*

Board: 鲁辰桂、张宁涛、王惠仁、唐晓东

TPC研发负责人: 鲁辰桂、蒲天磊、张宁涛; **Si阵列负责人:** 王惠仁

MATE-TPC团队 (姓氏排列)

高丙水, 李晓斌, 吕冰锋, 马军兵, 茹龙辉, 石福帅, 唐晓东, 王惠仁, 张金龙, 张宁涛, 张志超 (核物理中心)

段利敏, 胡荣江, 鲁辰桂 (气体探测器组)

千奕, 蒲田磊, 赵红赞 (核电子学组)

中国科学院近代物理研究所

所外合作团队

何建军, 李子铭 (北京师范大学)

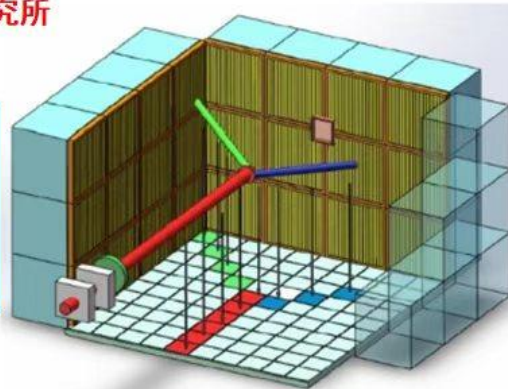
刘承恩, 李奇特, 许金艳 (北京大学)

张志永 (中科大)

陈洁、卢奋华、李晓斌等 (南方科技大学)

国际合作方:

- Ota (Osaka)
- Ahn (CENS, Korea)
- Kaminski (JINR)
- Cwiok (Warsaw)



中国科学院近代物理研究所
Institute of Modern Physics, Chinese Academy of Sciences

