



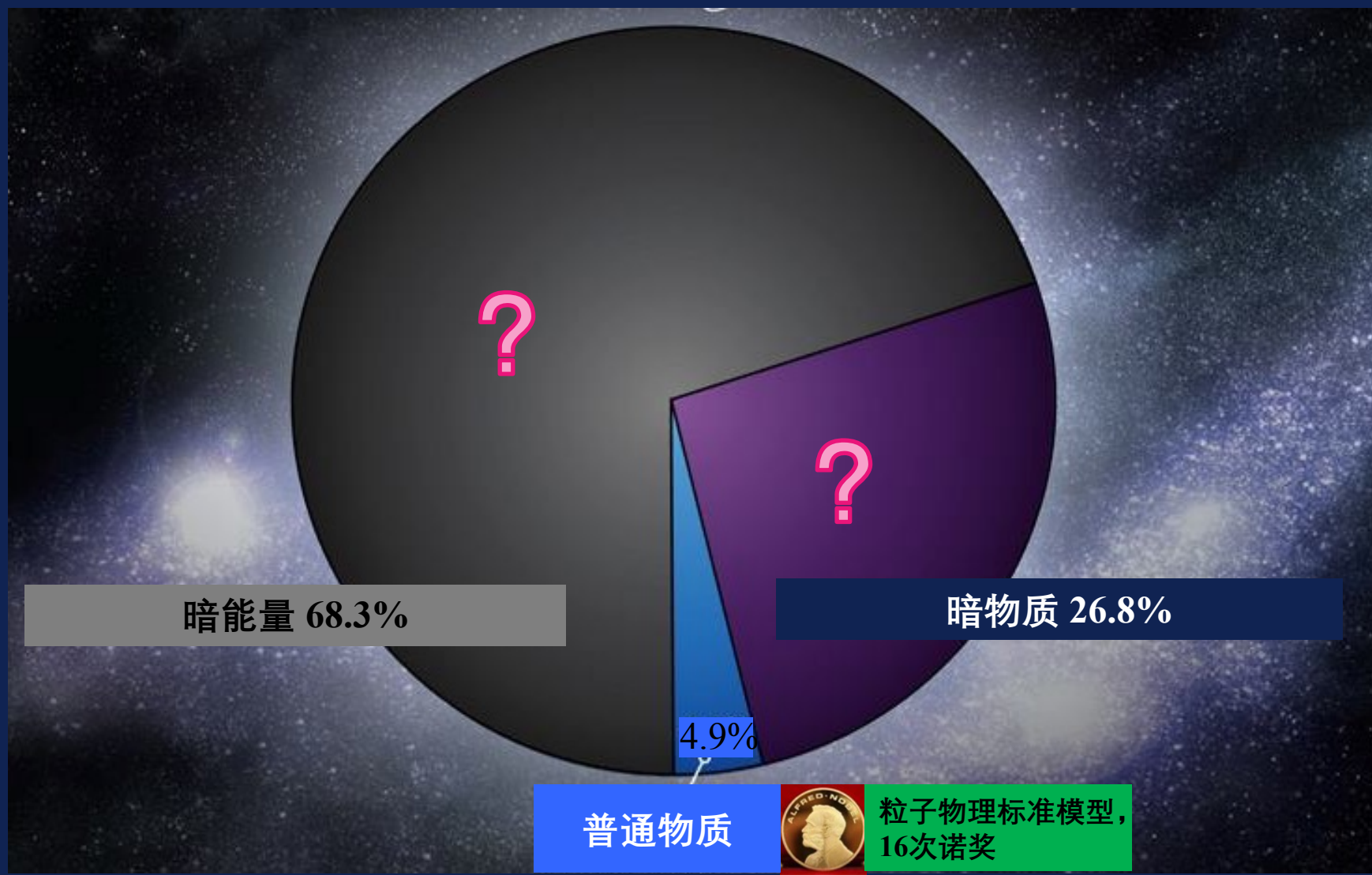
# 暗物质直接探测：PandaX 实验

周宁

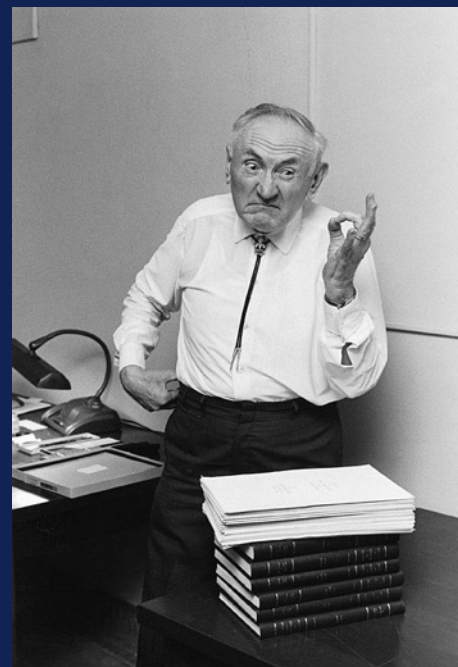
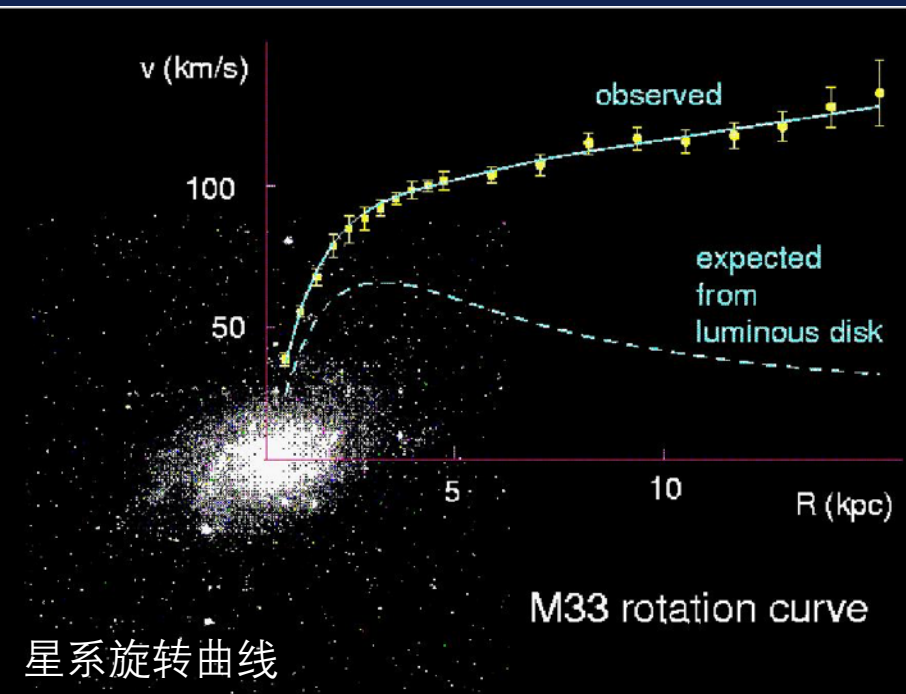
WHEPS 2016-07-31

# 暗物质问题

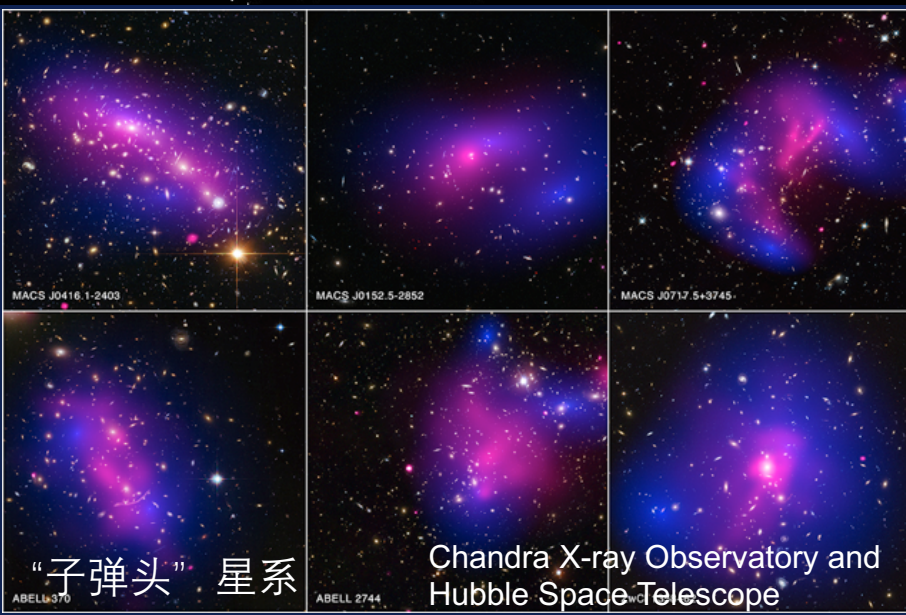
- 在实验室发现暗物质并研究暗物质的本质会在根本上改变我们对基本粒子和相互作用的理解



# 暗物质的证据



Fritz Zwicky  
(1933)

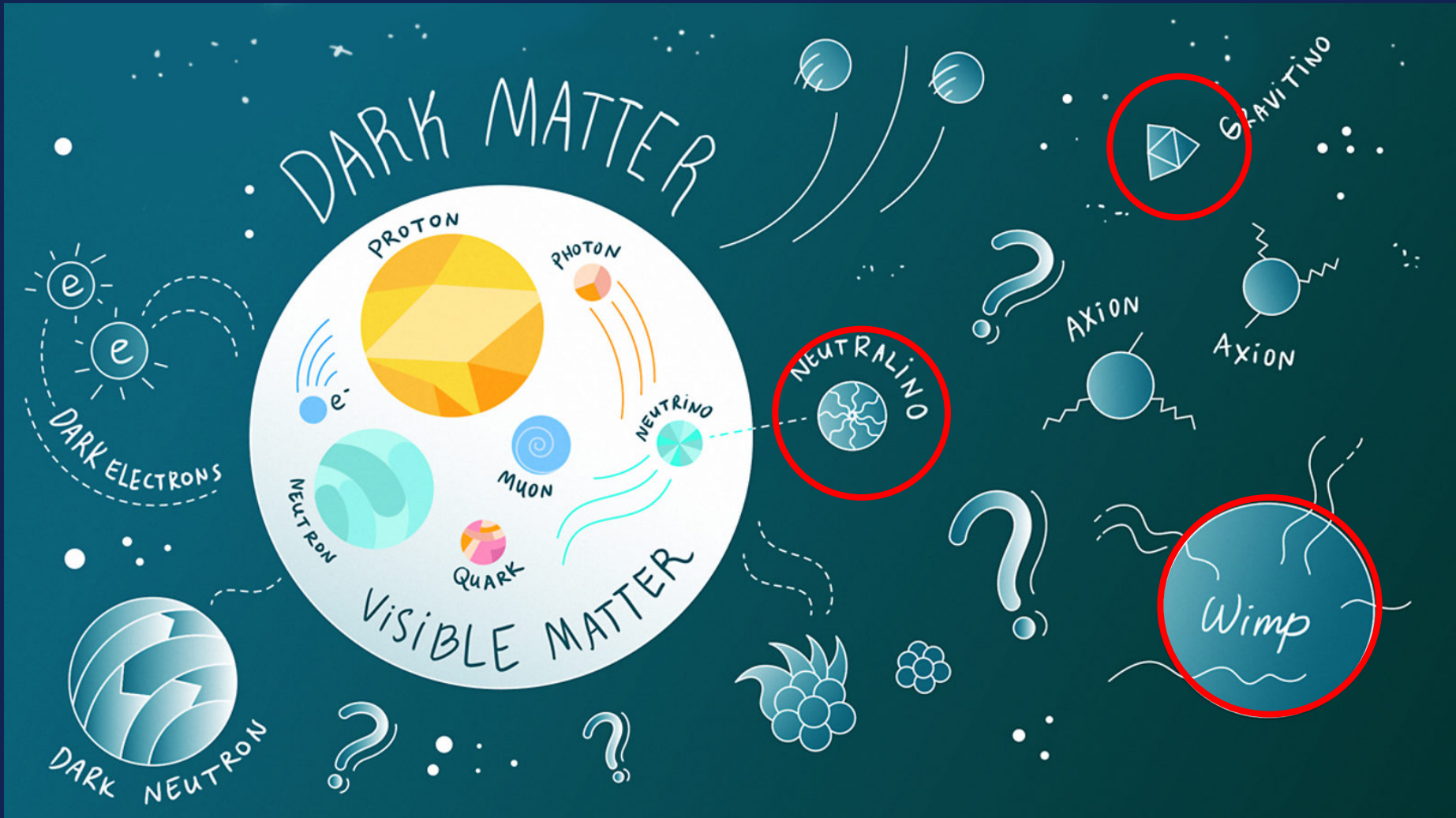


Vera Rubin  
(1970's)



# 暗物质是什么？

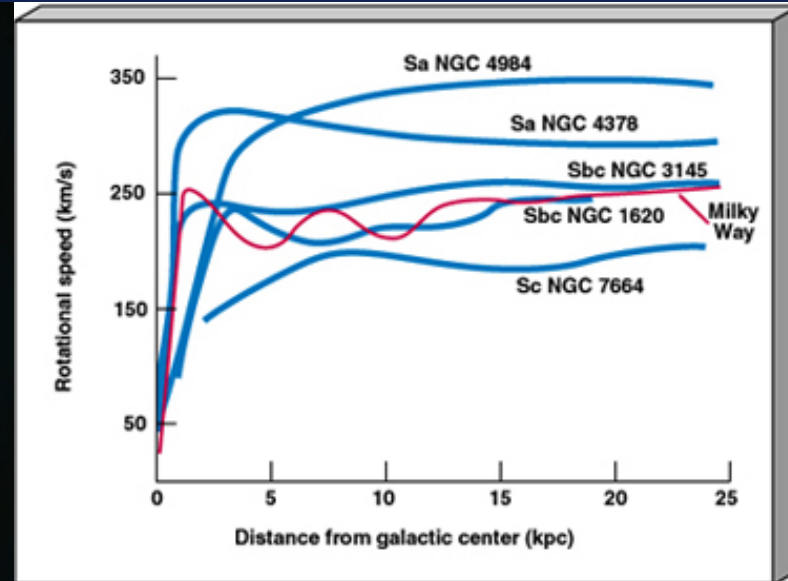
- 暗物质候选：有弱相互作用的大质量粒子（WIMP）





# 我们周围的暗物质

- 在太阳系附近，暗物质密度  $0.3(0.1) \text{ GeV/cm}^3$
- 暗物质麦克斯韦速度分布（方均根  $220 \text{ km/s}$ ）
- 一秒大概10万个暗物质粒子( $100 \text{ GeV}$ ) 穿过指甲



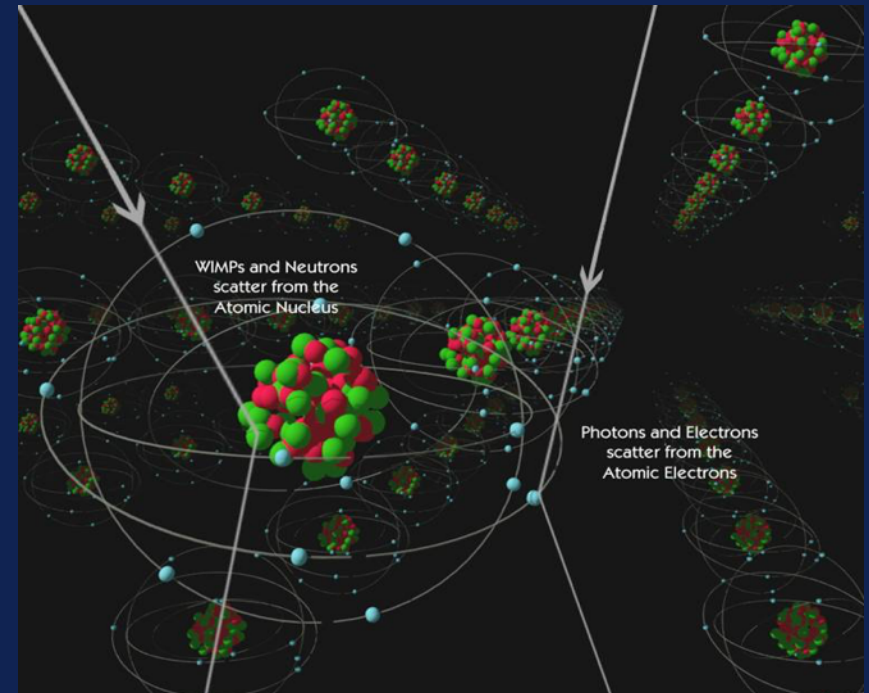
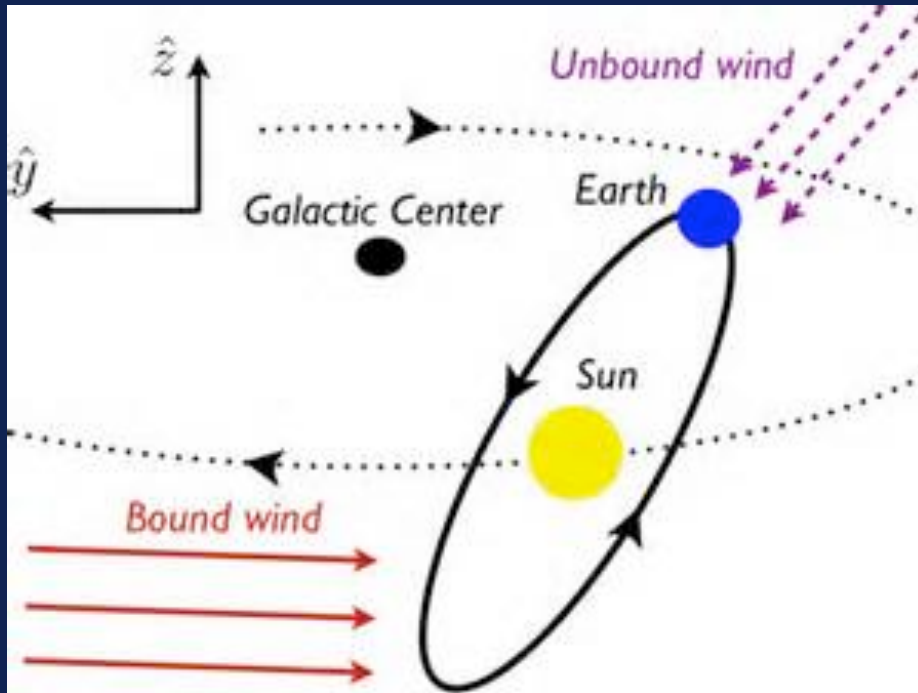
银河系暗物质晕

# 暗物质直接探测

- Goodman & Witten, 1985

太阳系附近暗物质相对于地球有一定速度

暗物质粒子入射打在探测器原子核，通过测量原子核的反冲信号来确定暗物质的存在



# 暗物质直接探测

- 但是，暗物质和普通物质的反应截面极低！
  - 一吨质量探测器观察一年，反冲能量在10keV以下的事例不超过20个
- 暗物质信号很容易被其他已知粒子信号（本底）覆盖
  - 宇宙线
  - 辐射（岩石，探测器材料，空气等）
- 于是我们
  - 深地实验室—屏蔽宇宙线本底
  - 提高材料纯度—降低辐射
  - 增加探测器质量—提高信号产生事例
  - 降低探测能量阈值—提高信号采集事例



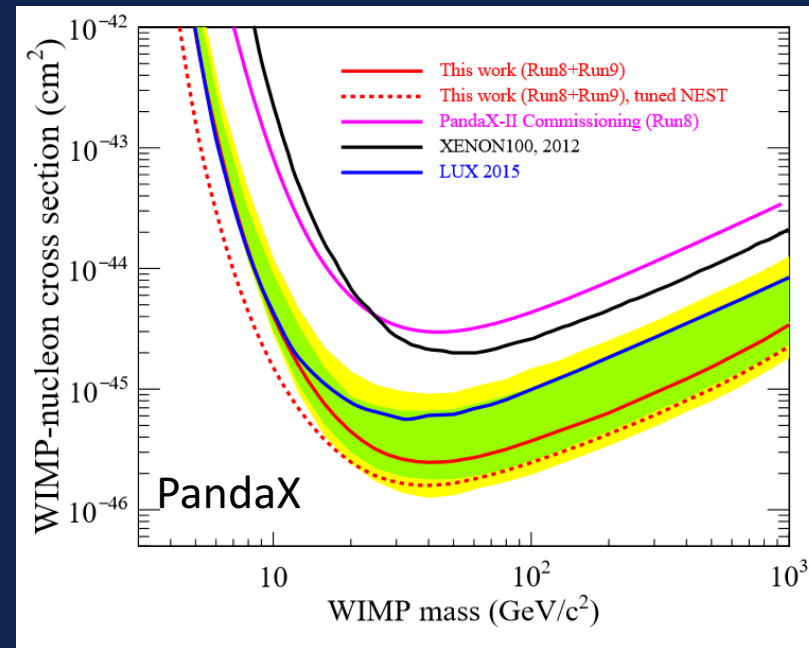
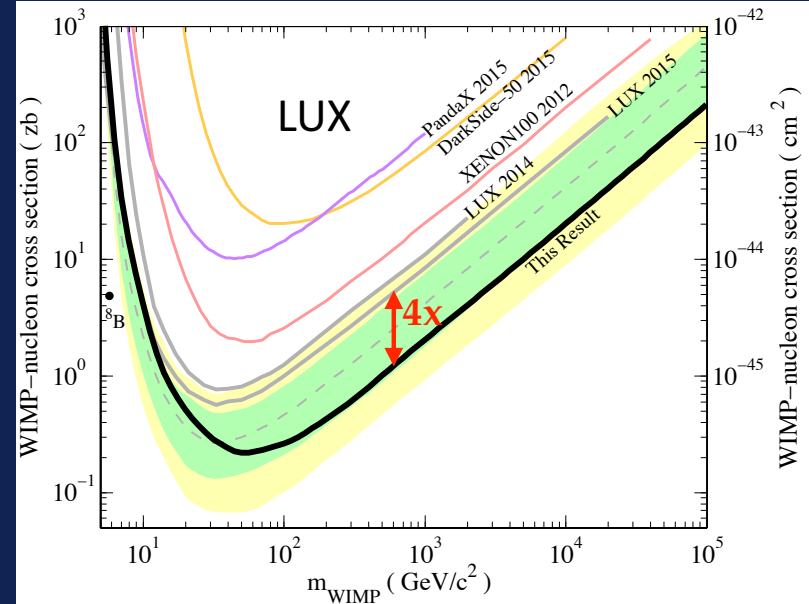
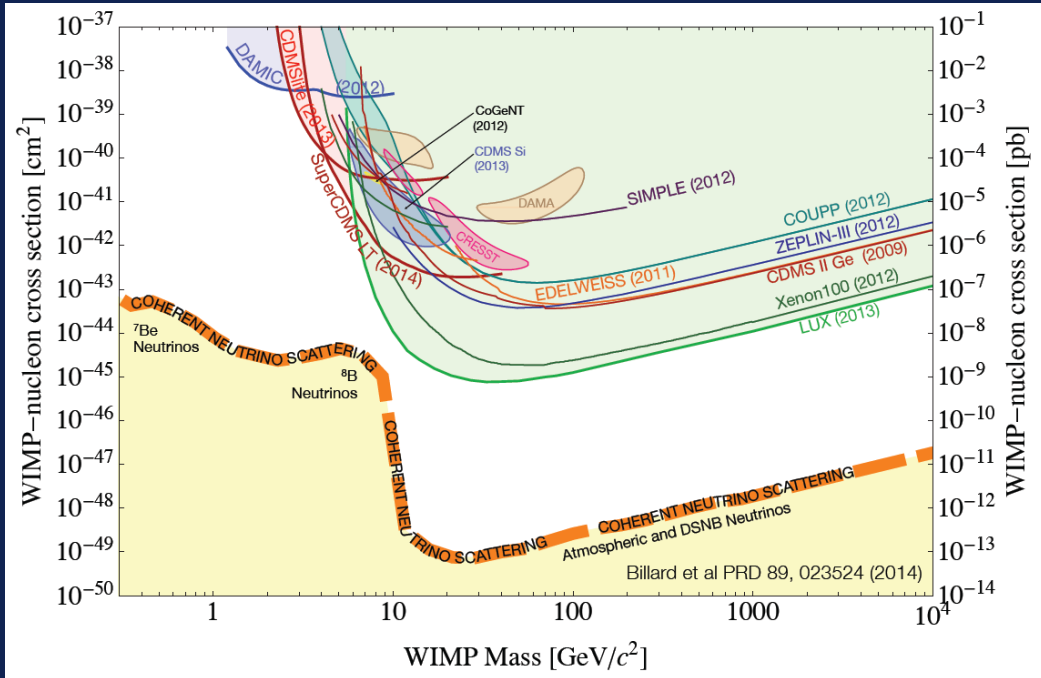


# 暗物质直接探测



# 目前进展

- IDM 2016 暗物质大会
- 中国PandaX和美国LUX实验公布最新结果



# PandaX 实验

- 2016年7月21日，PandaX实验公布了3.3万吨.天的实验结果





# 四川锦屏山

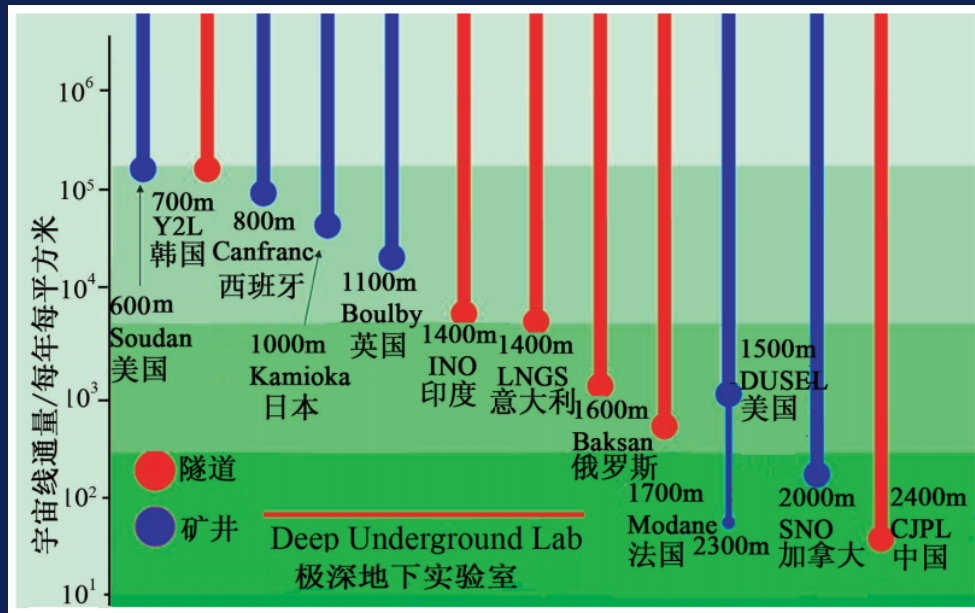
- 距离西昌240公里





# 中国锦屏地下实验室 (CJPL)

- CJPL - China Jinping Underground Laboratory
- 世界上屏蔽最深的实验室，水平方向进出



# PandaX 实验

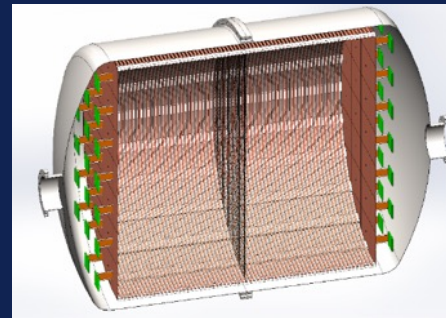
PandaX = Particle and Astrophysical Xenon Experiments



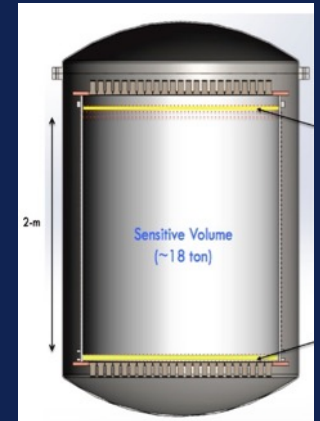
Phase I: 120 kg  
DM  
2009-2014



Phase II: 500  
kg DM  
2014-2017



Phase III: 200 kg  
to 1 ton  $^{136}\text{Xe}$   
0vDBD  
2016-2020



Phase IV: 3-40  
ton DM  
2016-2025



# PandaX 合作组

- 2009年成立，大约50人
  - 上海交通大学，北京大学，山东大学，上海应用物理研究所，中国科学技术大学，中国原子能研究所，中山大学，雅砻江水电开发公司，Maryland University, University of Michigan



# PandaX 实验装置



新浪图片

# 暗物质和靶核碰撞截面

- WIMP粒子与单个核子自旋无关散射截面  $\sigma = \sigma_0 F^2(q)$

$$\sigma_0 = \frac{4\mu_T^2}{\pi} (Zf_p + (A-Z)f_n)^2$$

- 每公斤靶质量，散射事例率

$$dR = \frac{N_A}{A} \sigma v dn$$

$$dn = \frac{n_0}{k} f(v, v_e) d^3v$$

$$dR = \frac{1}{k} \frac{N_A}{A} \frac{\rho_\chi}{M_\chi} \sigma v f(v, v_e) d^3v$$

- 假设暗物质的速度服从麦克斯韦分布

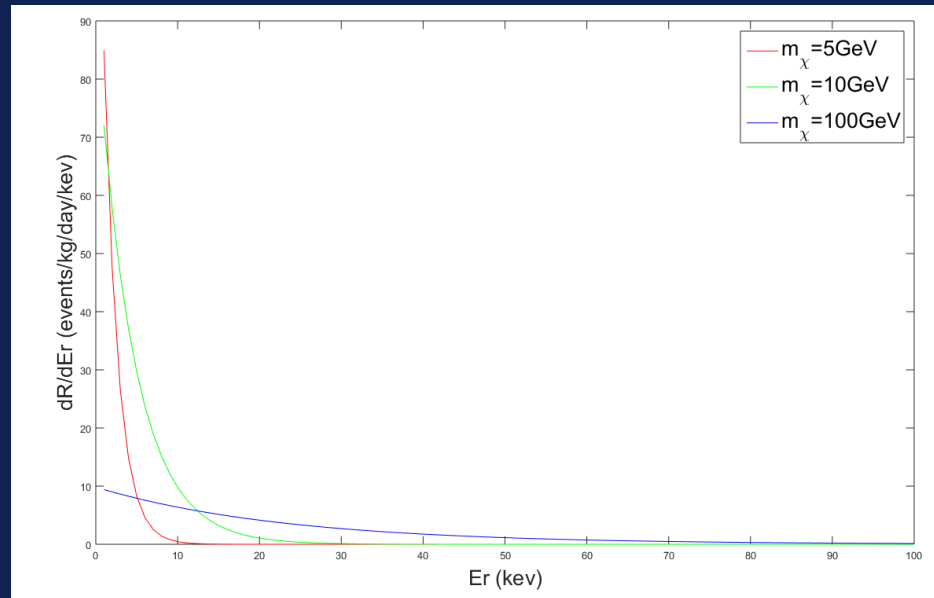
$$f(v, v_e) = e^{-(v+v_e)^2/v_0^2}$$

- 本地暗物质质量密度

$$\rho_\chi = 0.3 \text{ GeVc}^{-2} \text{cm}^{-3}$$

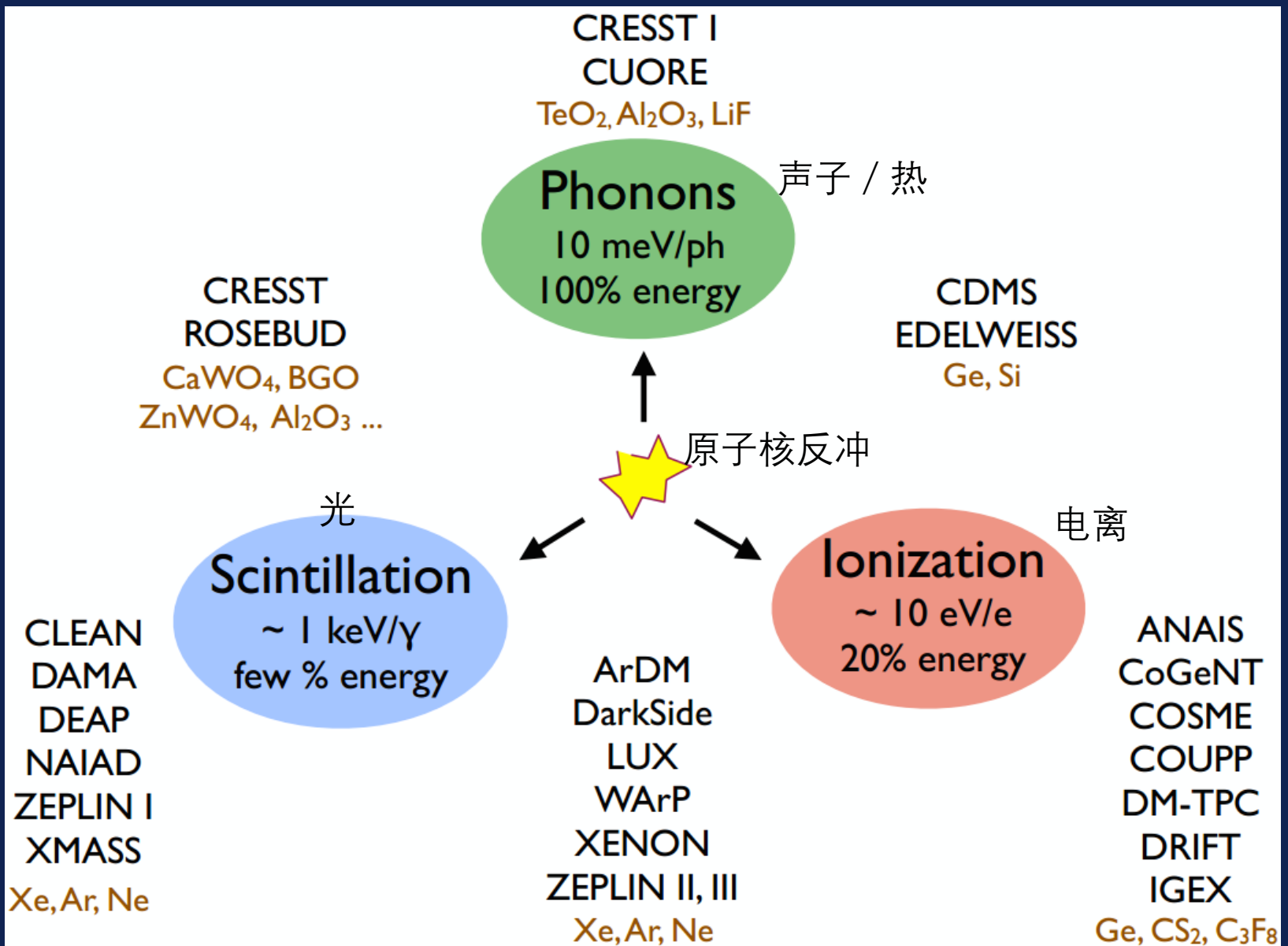
$$v_0 = 220 \text{ km/s}$$

- 暗物质碰撞靶核反冲能谱



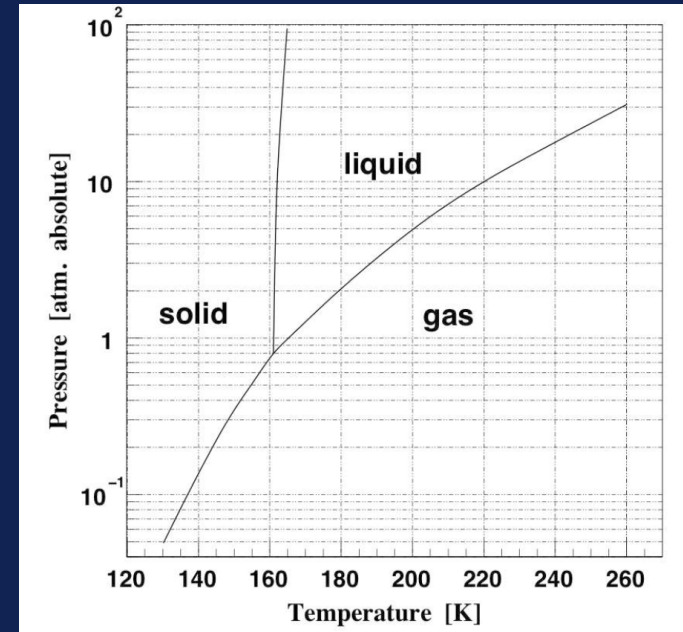


# 探测器原理



# 液氙性质

- 大气中含量低—成本相对其他惰性气体高
- 高沸点—易于液化



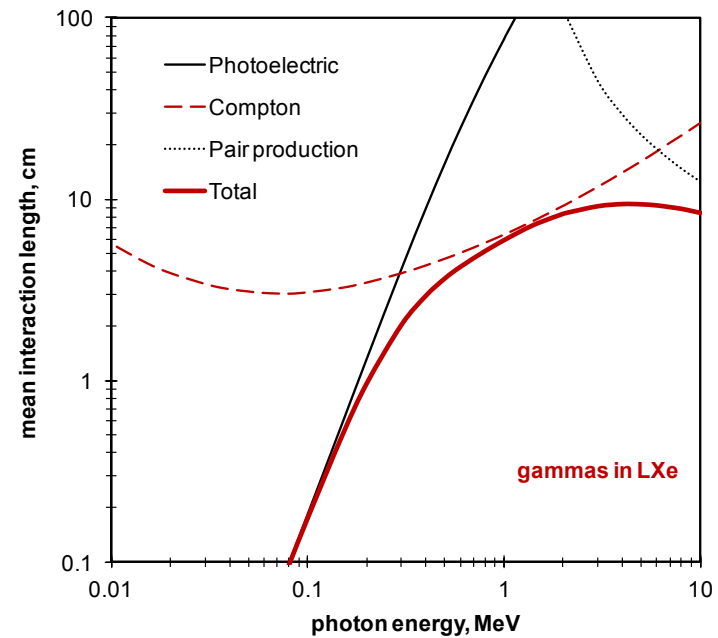
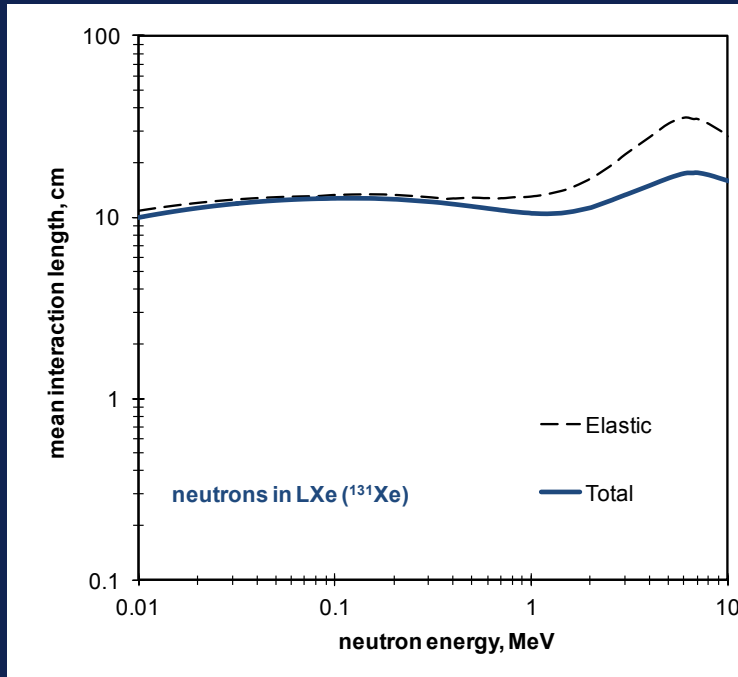
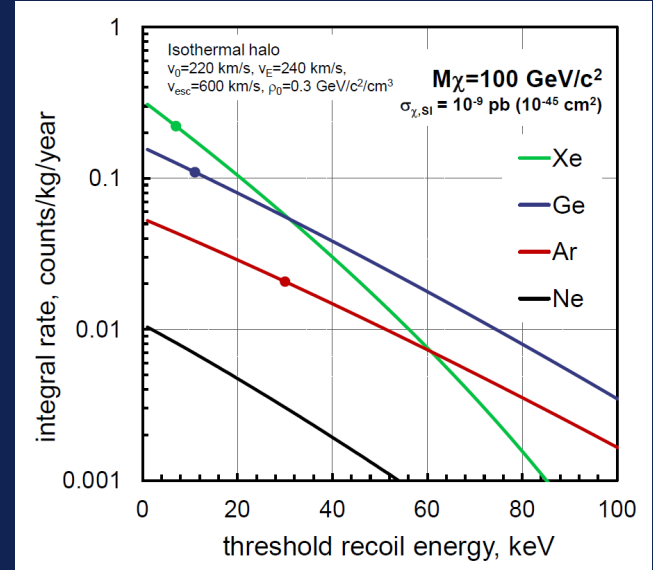
性质	氦 (He)	氖 (Ne)	氩 (Ar)	氪 (Kr)	氙 (Xe)	氡 (Rn)
原子序数 (Z)	2	10	18	36	54	86
平均摩尔质量	4.0	20.2	39.9	83.8	131.3	222
熔点 ( $T_m$ , 标准大气压)	-	24.5 K	83.4 K	115.6 K	161.4 K	202 K
沸点 ( $T_b$ , 标准大气压)	4.2 K	27.2 K	87.2 K	121.2 K	165.2 K	211.3 K
三相点温度 ( $T_t$ )	2.2 K	24.6 K	83.8 K	115.8 K	161.3 K	202 K
三相点压强 ( $P_t$ )	0.05 atm	0.43 atm	0.68 atm	0.72 atm	0.78 atm	0.69 atm
气体密度 (标况)	0.18	0.90	1.78	3.71	5.85	9.97
液体密度, g/cm <sup>3</sup>	1.25	1.21	1.39	2.42	3.06	4.40
固体密度, g/cm <sup>3</sup>	-	1.44	1.62	2.83	3.54	-
相对介电常数 $\epsilon_r$	1.06	1.53	1.50	1.66	1.95	-
大气中丰度 (ppm, 体积)	5.2	18.2	9340	1.1	0.09	-
市场价格, 美元/立方米	22.3-44.9	2.7-8.5	60-120	400-500	4000-5000	-

气体密度是指 0 °C, 标准大气压的条件下

# 液氙性质

- 大原子序数, 较高密度

- 高事例率
- 自屏蔽效应





# 液氙性质

- 不同自旋稳定同位素

氙 (Xenon)	$^{124}\text{Xe}$ (0.09%), $^{126}\text{Xe}$ (0.09%), $^{128}\text{Xe}$ (1.92%) $^{129}\text{Xe}$ (26.44%), $^{130}\text{Xe}$ (4.08%), $^{131}\text{Xe}$ (21.18%) $^{132}\text{Xe}$ (26.89%), $^{134}\text{Xe}$ (10.44%), $^{136}\text{Xe}$ (8.87%)
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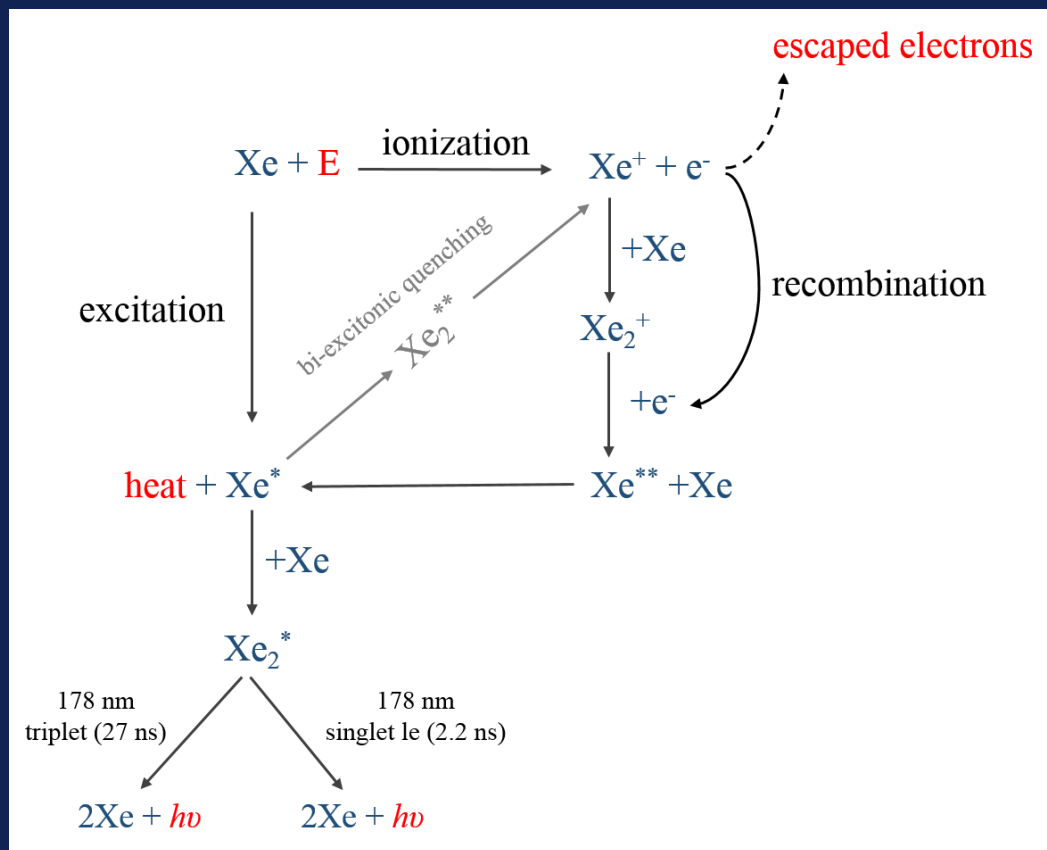
- Xe129: 1/2
- Xe131: 3/2
  
- 既能探测自旋无关暗物质散射，
- 又能探测自旋相关

# 氙光电效应

- 液氙中能量沉积：闪烁光子，电离电子
  - 暗物质信号，中子，X射线
- 受激发原子，电子-离子对
  - 形成“二聚体”：178nm 真空紫外光
  - 电离电子

$$E_{dep} = W \times (N_i + N_{ex})$$

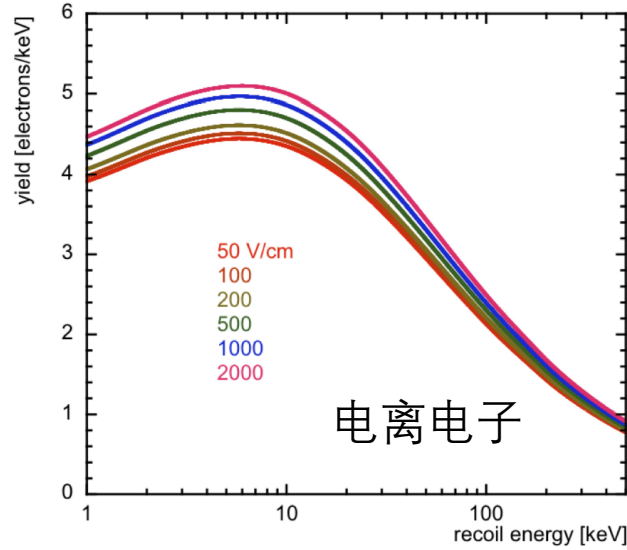
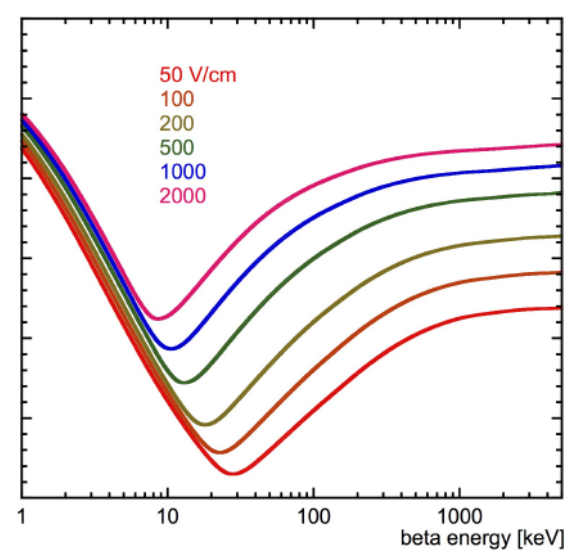
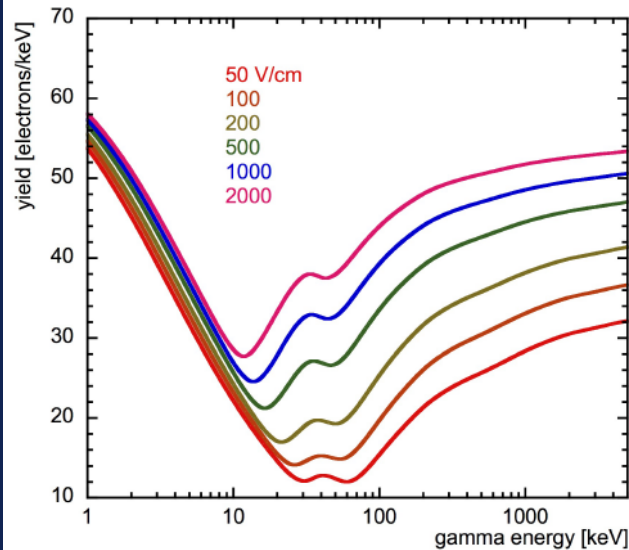
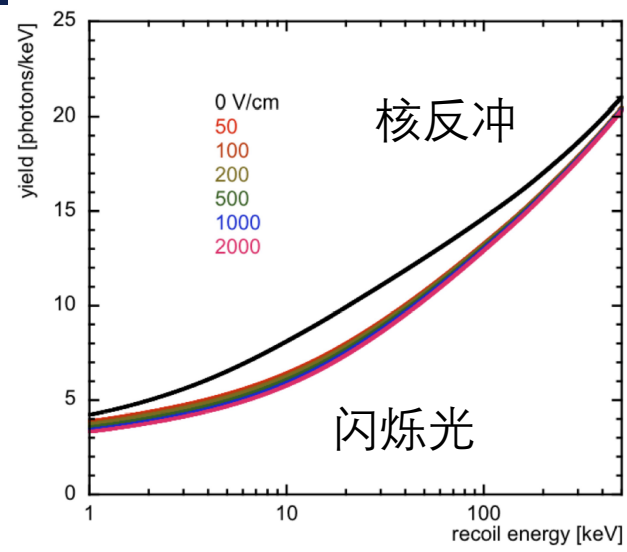
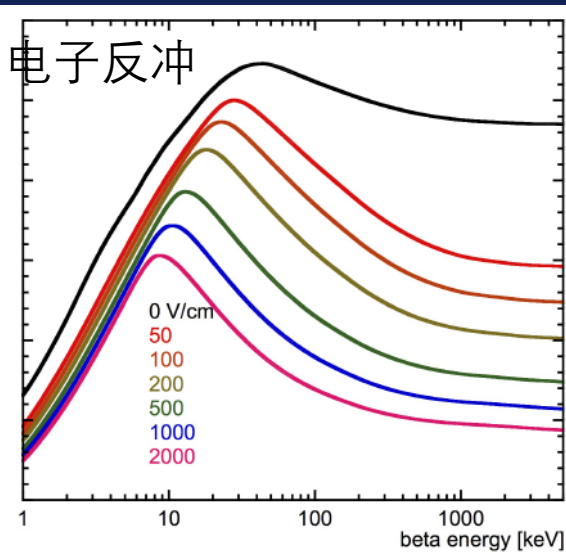
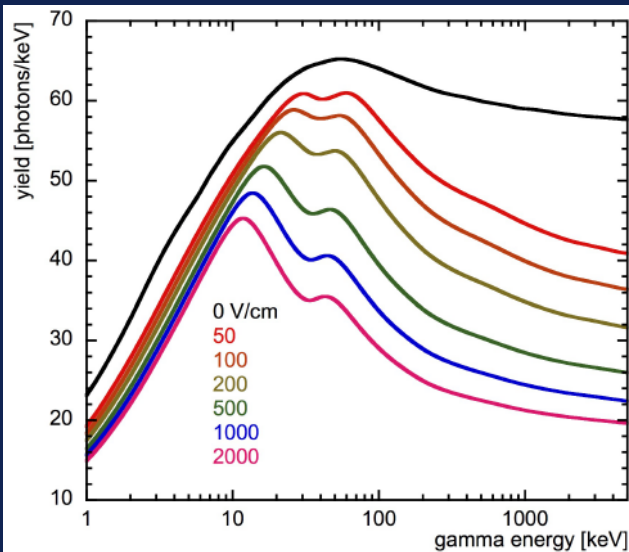
$W \sim 13.7\text{eV}$ , 高光电产额



# 氙光电效应

闪烁光和电离电子产额 (NEST模拟)

核反冲和电子反冲不同的相对产额





# 电离电子

- 外加电场

- 抑制电子离子重结合
- 采集电离电子

- 电子在外场中漂移

- 漂移速度  $\sim 2\text{mm}/\mu\text{s}$
- 扩散效应
- 电子寿命 (被杂质吸收)

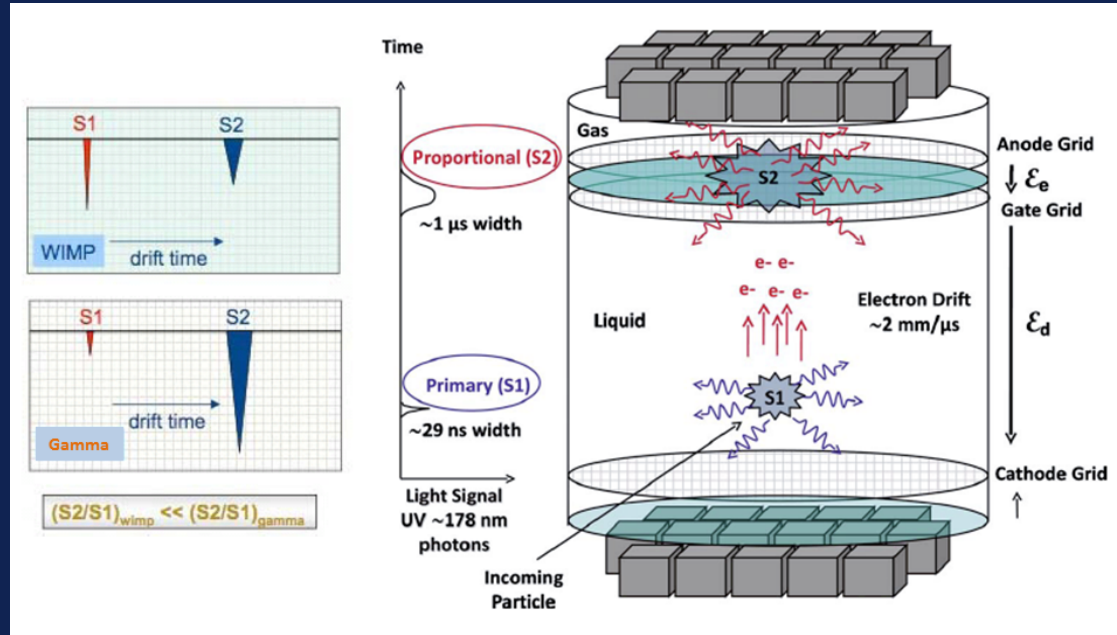
$$N_e(t) = N_e(0)e^{t/\tau}$$

- 提供信号背景鉴别

- 完整采集反冲能量

- 提供散射位置信息

- 由于电荷传感器噪音，很难直接读取电离电子



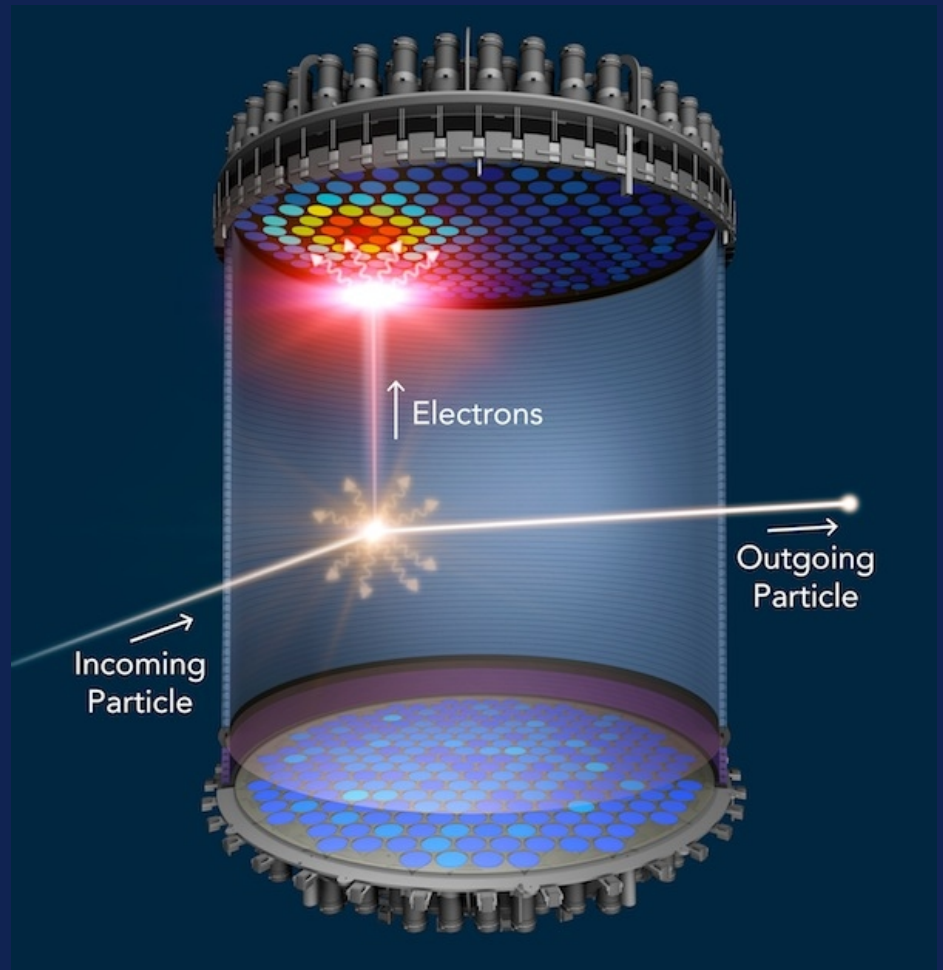
# 电致发光

- 电子在电场作用下在气态惰性气体穿行
- 通过非弹性散射引起惰性气体原子激发
- 退激发发出闪烁光
- 控制电场—正比闪烁光
- 放大电离电子信号

$$\frac{dN_{\text{ph}}}{dx} = \alpha \left( \frac{E_g}{p} - \beta \right) p$$

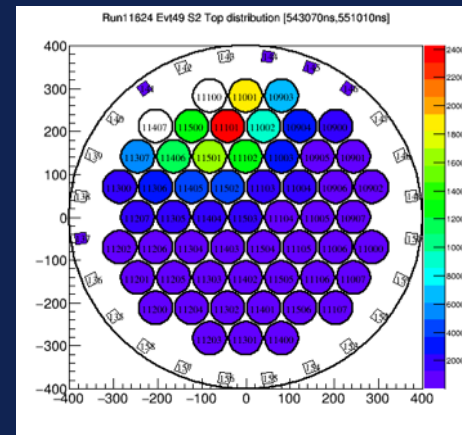
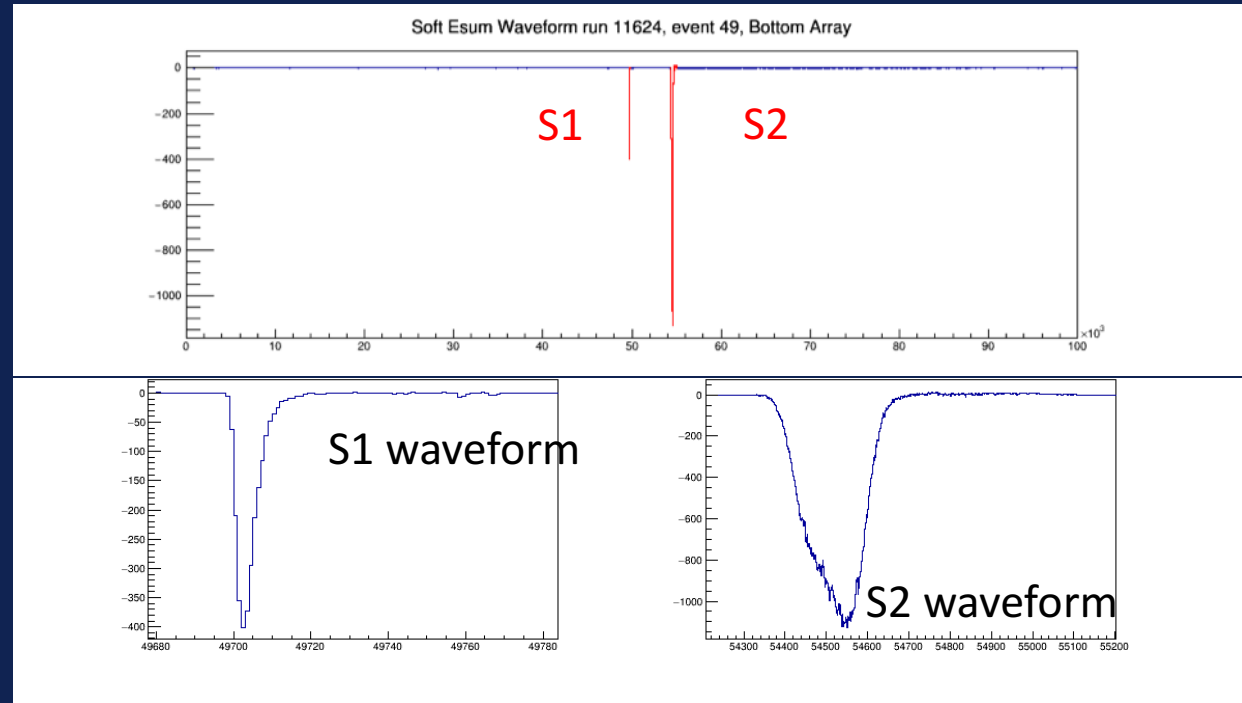
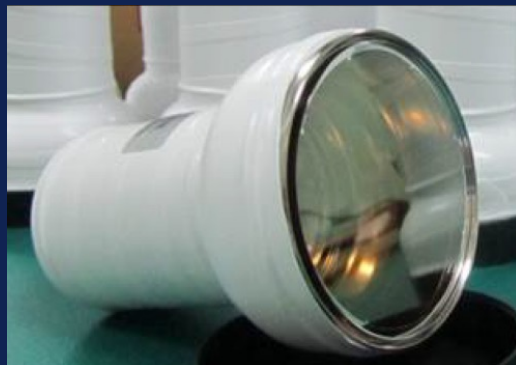
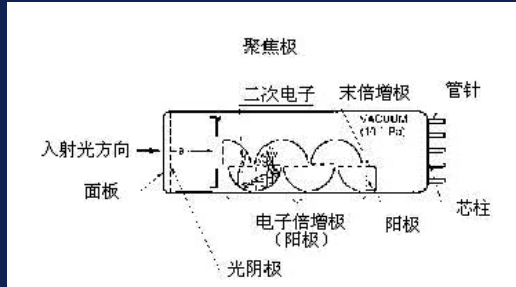
$$\alpha = 70 \text{ photon/kV}$$

$$\beta = 1 \text{ kV / cm / atm}$$



# 光电管倍增管

- 收集光子，放大信号
- 位置和能量重建

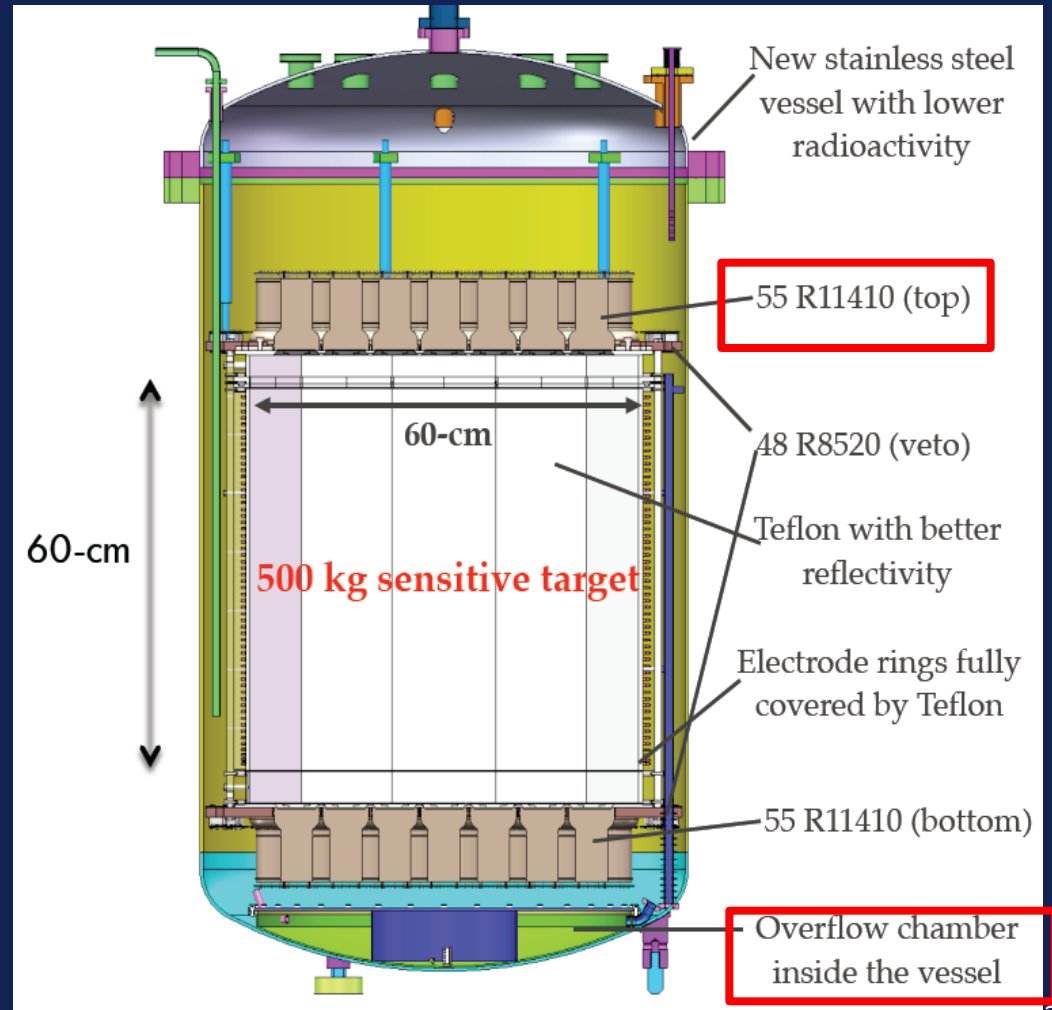




# 气液两相型氙探测

## 实验构成

- 屏蔽体
- 外罐真空容器，内罐压力容器
- 探测器：时间投影室
- 氙气提纯系统
- 液氙制冷及存储系统
- 电子学系统



First delivery of PandaX equipment to Jinping lab,  
Aug. 16, 2012



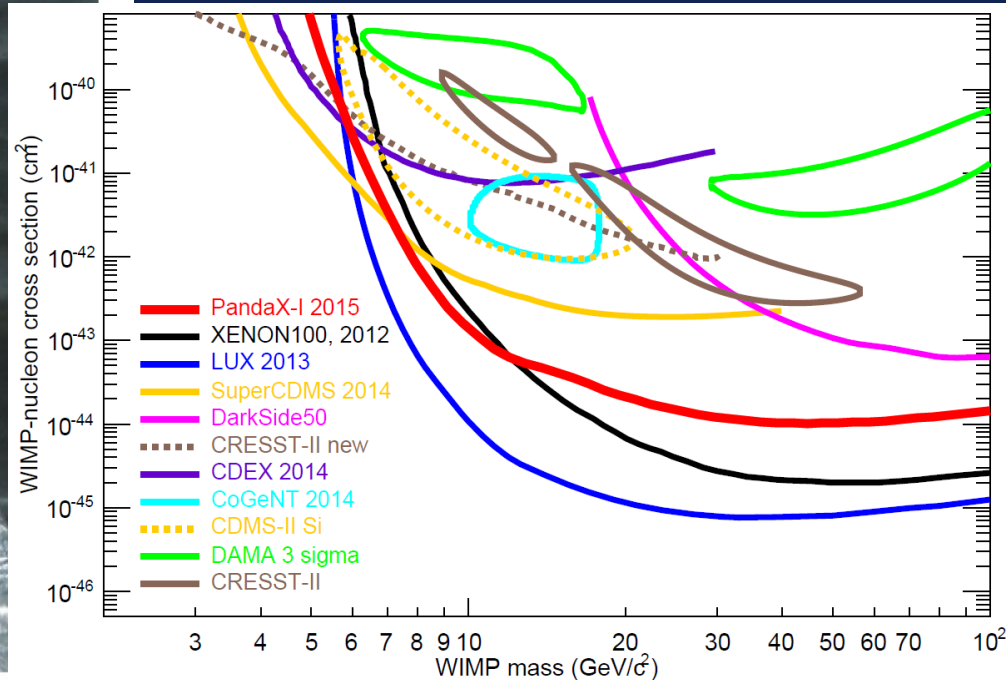


# PandaX 一期实验

- 120公斤液氙
- ❑ Completed in **Oct. 2014**, with 54.0 x 80.1 kg-day exposure
- ❑ Data strongly disfavor **all** previously reported claims
- ❑ Competitive upper limits for low mass WIMP in xenon experiments

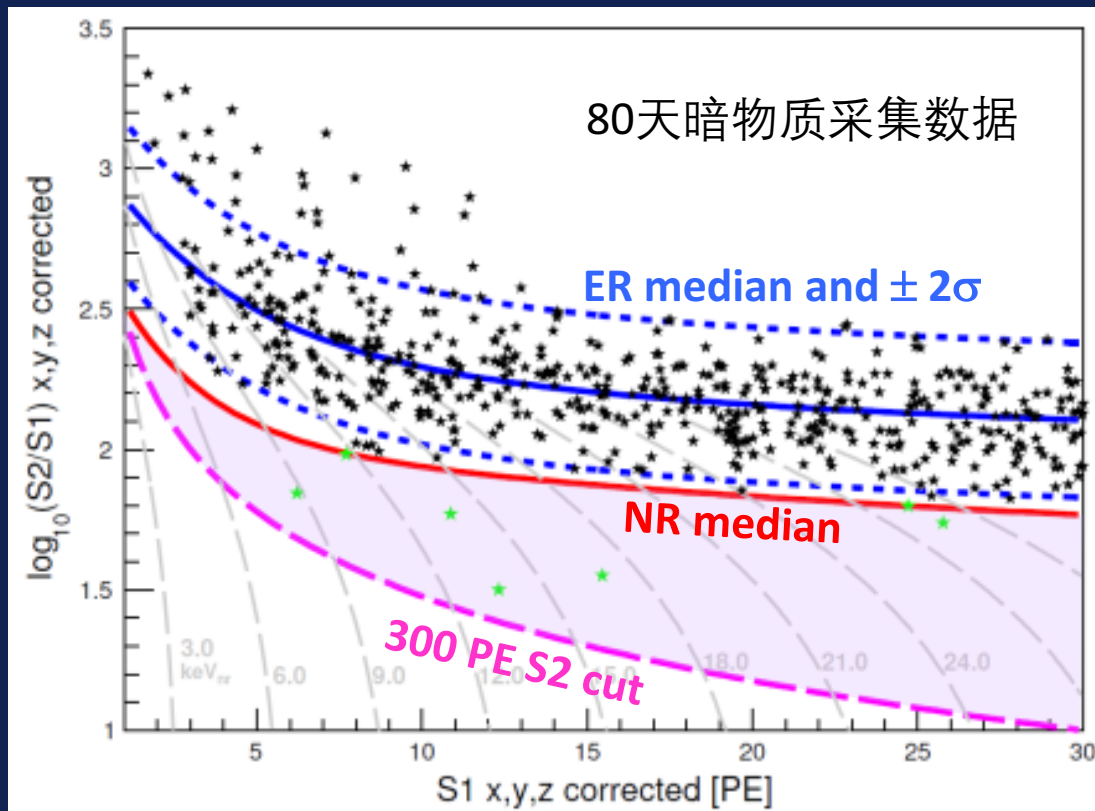
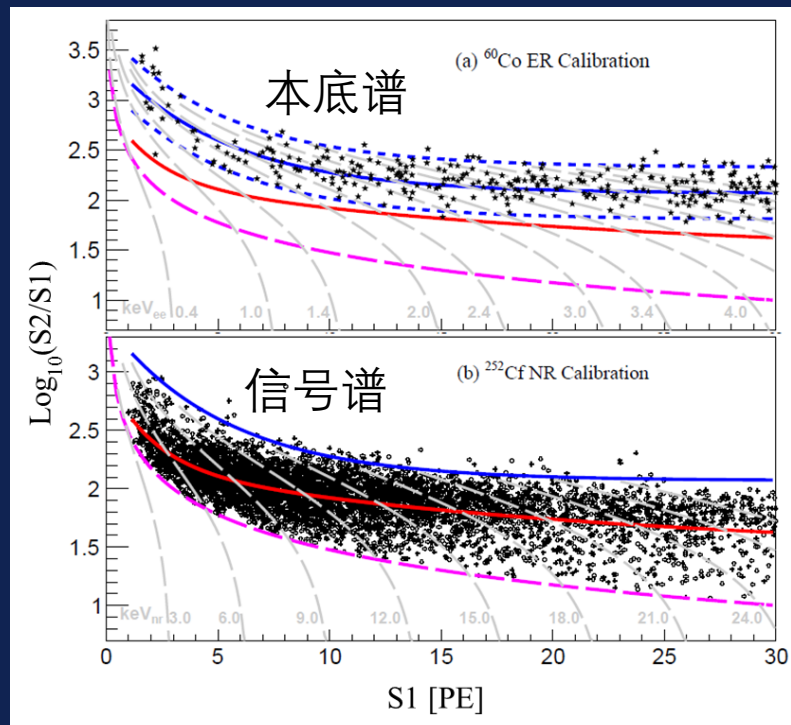


Phys. Rev. D **92**, 052004(2015)



# 探测器响应

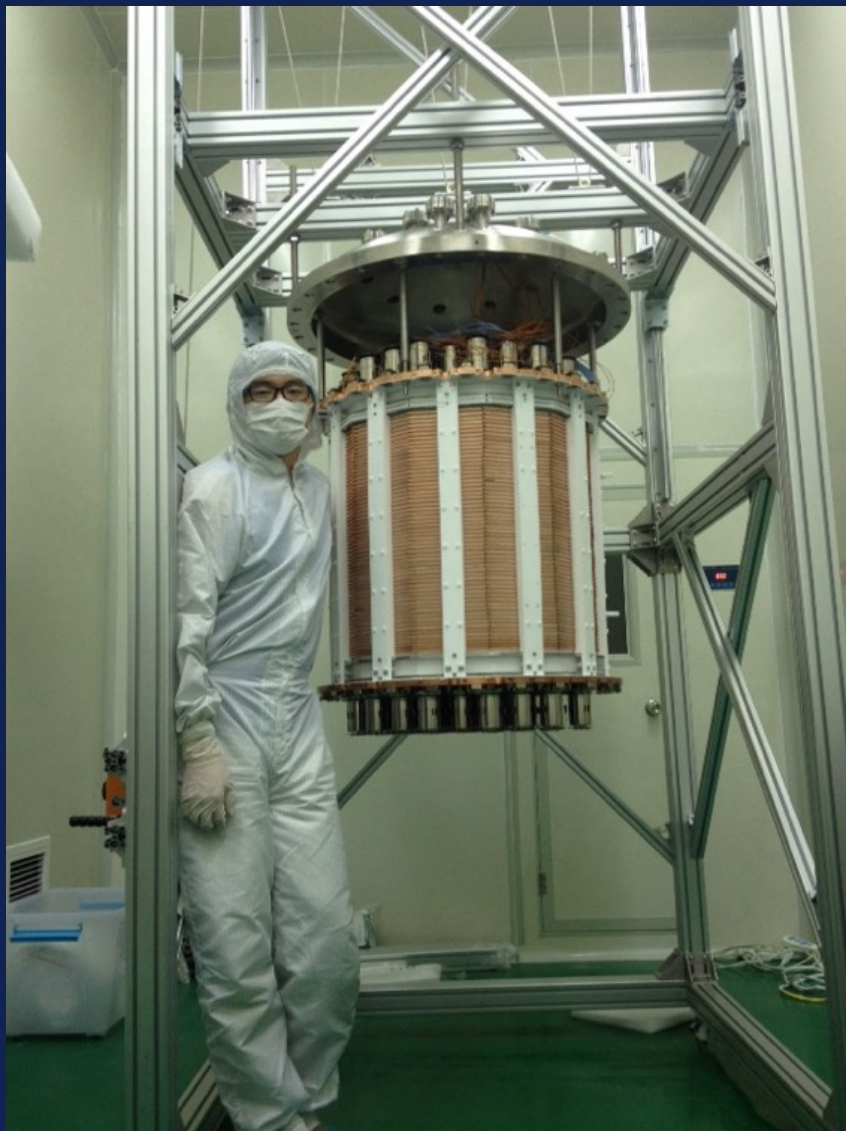
- 用不同放射源刻度探测器：
  - 信号和背景的分布谱





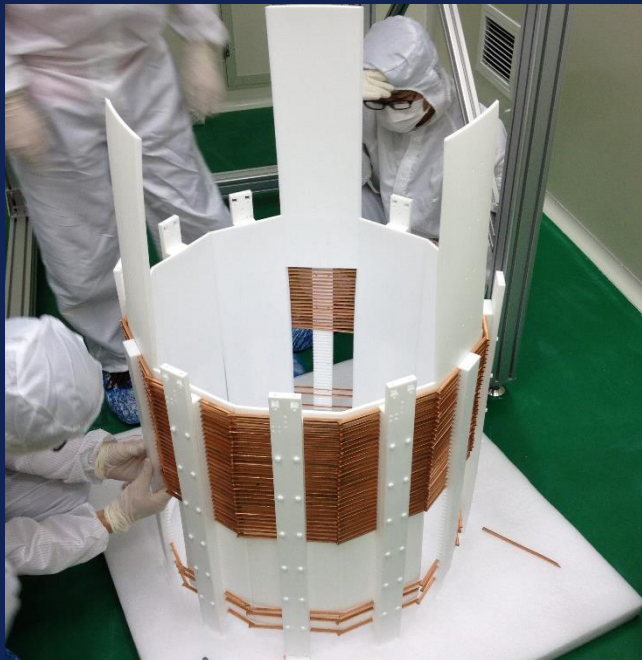
# PandaX 二期实验

- 500公斤液氙



- ▣ 特种不锈钢内罐
- ▣ 60cm时间投影室和新电极
- ▣ 更多 3" PMTs 和设计改进
- ▣ 独立的外层反符合系统

# PandaX 二期实验组装

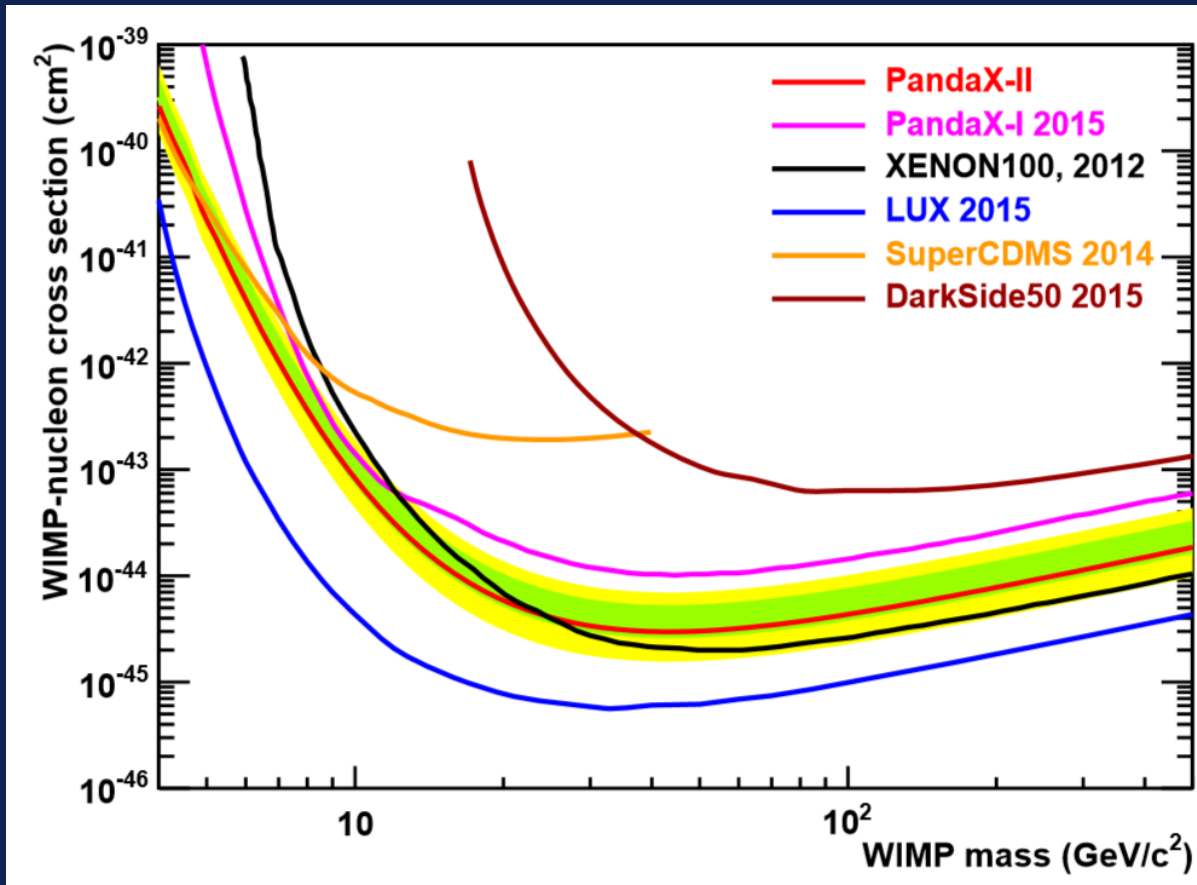


## 二期运行

- We had a series of engineering runs in 2015, fixing various problems as we were testing all the components of the setup
- Commissioning run (Run 8): Nov. 22 – Dec. 14 (19.1 live-day x 306 kg FV) but with high Kr background (Phys. Rev. D. 39, 122009 (2016))
- After a Kr distillation campaign, the detector was refilled. Physics data taking started in Mar. 2016 (Run 9)

# 二期初步结果 (Run8)

Phys. Rev. D. 39, 122009 (2016)



Simple counting analysis based on an expected background of 3.2(0.7) evts and 2 observed evts

Sizable (x2) difference of using original NEST or tuned NEST to predict DM distribution due to DM acceptance, but within  $1\sigma$  band

Low mass: competitive with SuperCDMS; high mass: similar exclusion limit as XENON100 225-day

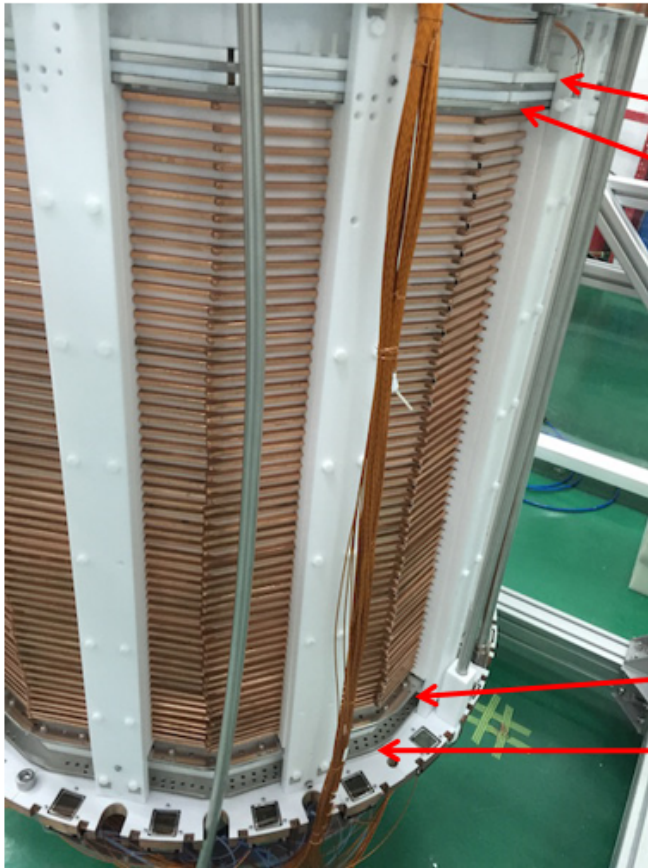


# 二期 Run9

Items	Status in Run 9
Krypton level	Reduced by x10
Exposure	Increased x4 (79.6 vs 19.1 day)
ER calibration	Now have tritium calibration
NR calibration	Statistics x6
Analysis	Improved position reconstruction
Background	Accidental background suppressed more than x2 using BDT

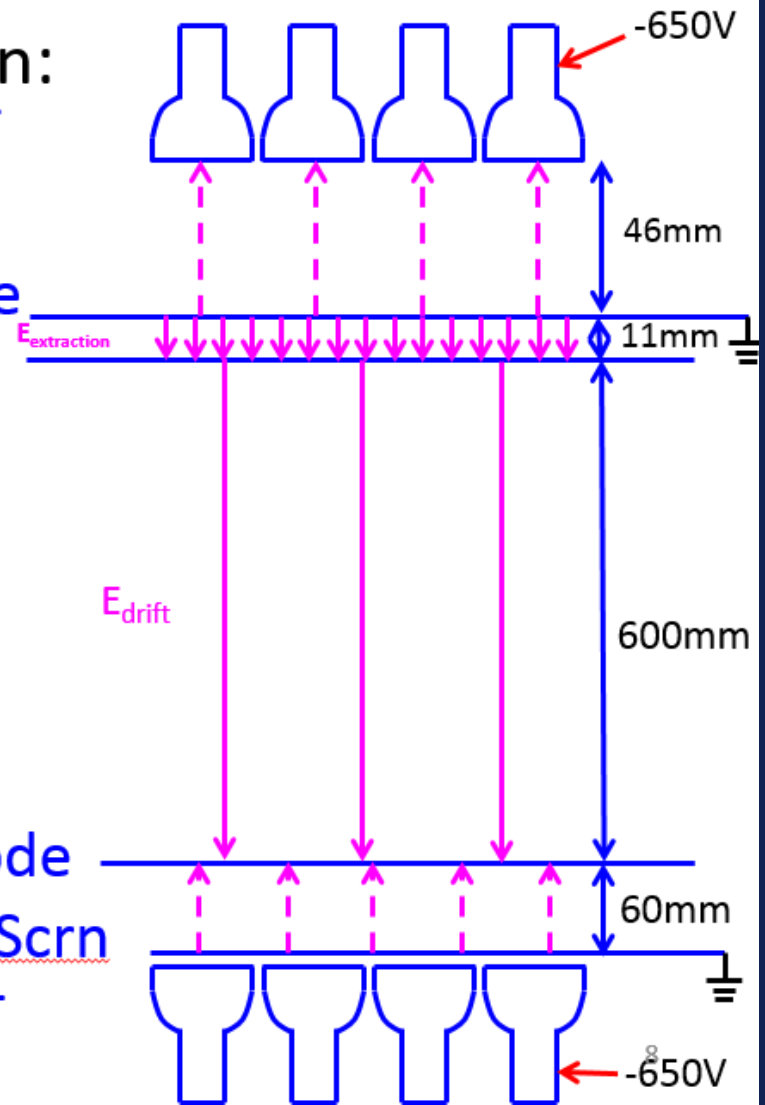
# 电场设置

Field Configuration:  
TPMT



Anode  
Gate

Cathode  
Bttm Scrn  
BPMT



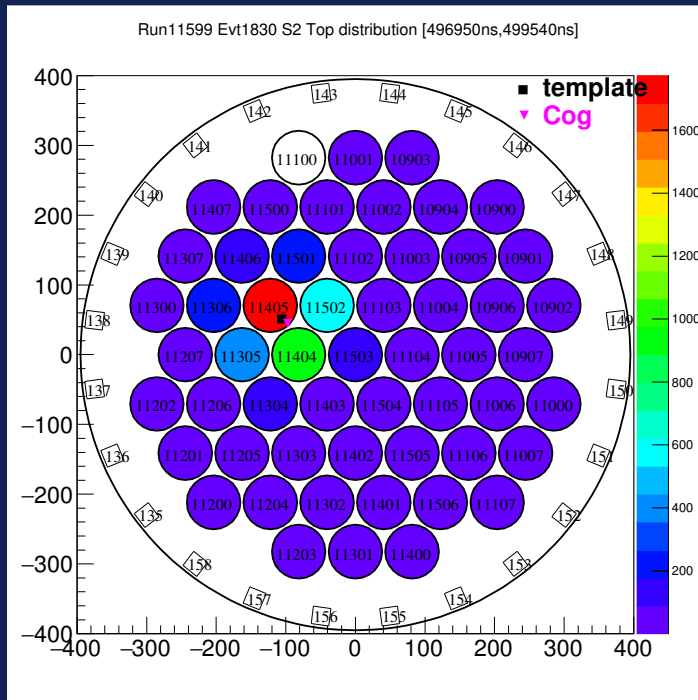
# 不同电场设置数据

Condition	live time (day)	$E_{\text{drift}}$ (V/cm)	$E_{\text{extract}}$ (kV/cm)
1	7.76	397.3	4.56
2	6.82	394.3	4.86
3	1.17	391.9	5.01
4	63.85	399.3	4.56

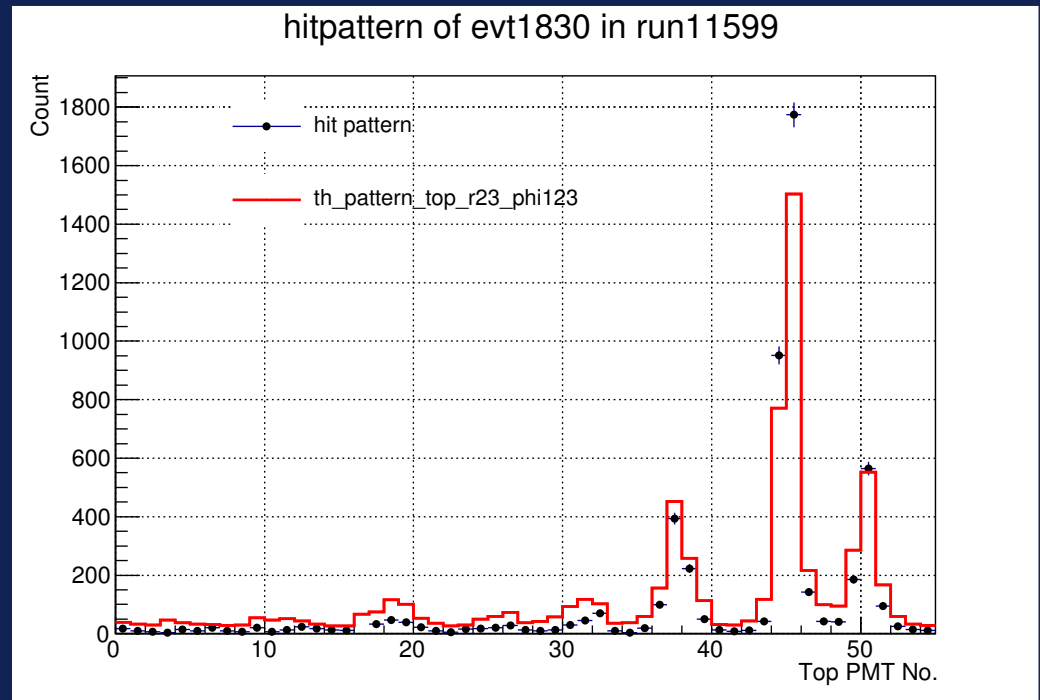
Mar. 9-Jun 30, in total 79.6 live-day of under slightly different conditions (optimization of drift and extraction fields).

# 信号位置重建

- Z—方向
  - S1, S2 信号时间差
- XY—平面
  - 重心法
  - Template method



(a) Distribution vs. PMT location.



(b) 1-d distribution in (a), data and MC overlaid



# 信号位置重建

# 信号能量重建

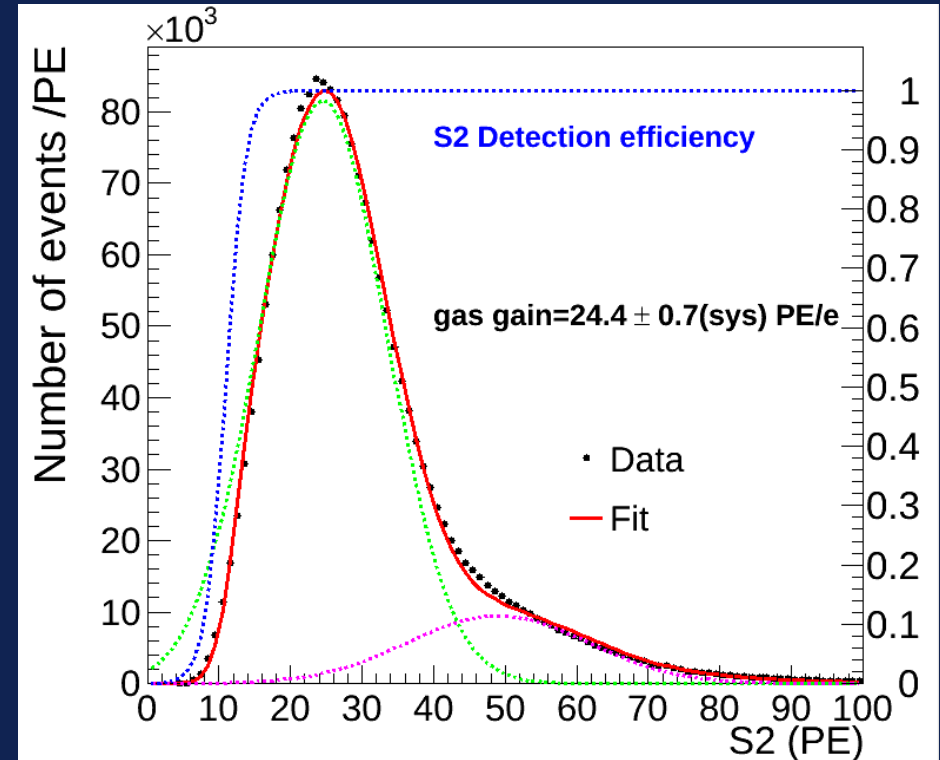
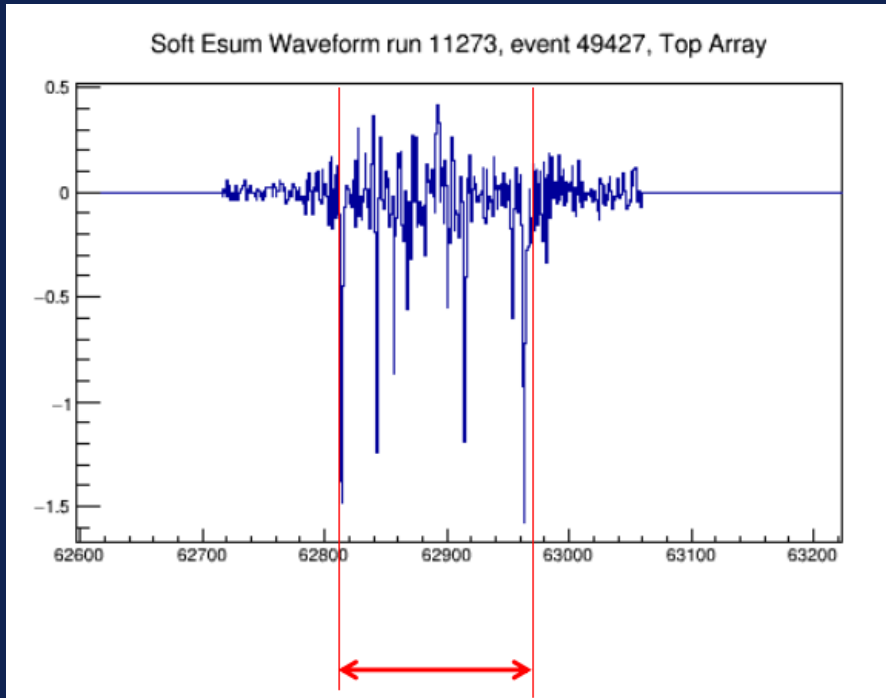
- 每个事例，对应电子等同能量

$$E_{ee} = W \times \left( \frac{S1}{PDE} + \frac{S2}{EEE \times SEG} \right),$$

- $W=13.7$  eV 平均产生一个电子或者光子所需能量
- PDE : 光子探测效率
- EEE : 电离电子萃取效率
- SEG : 单电子信号率PE/e

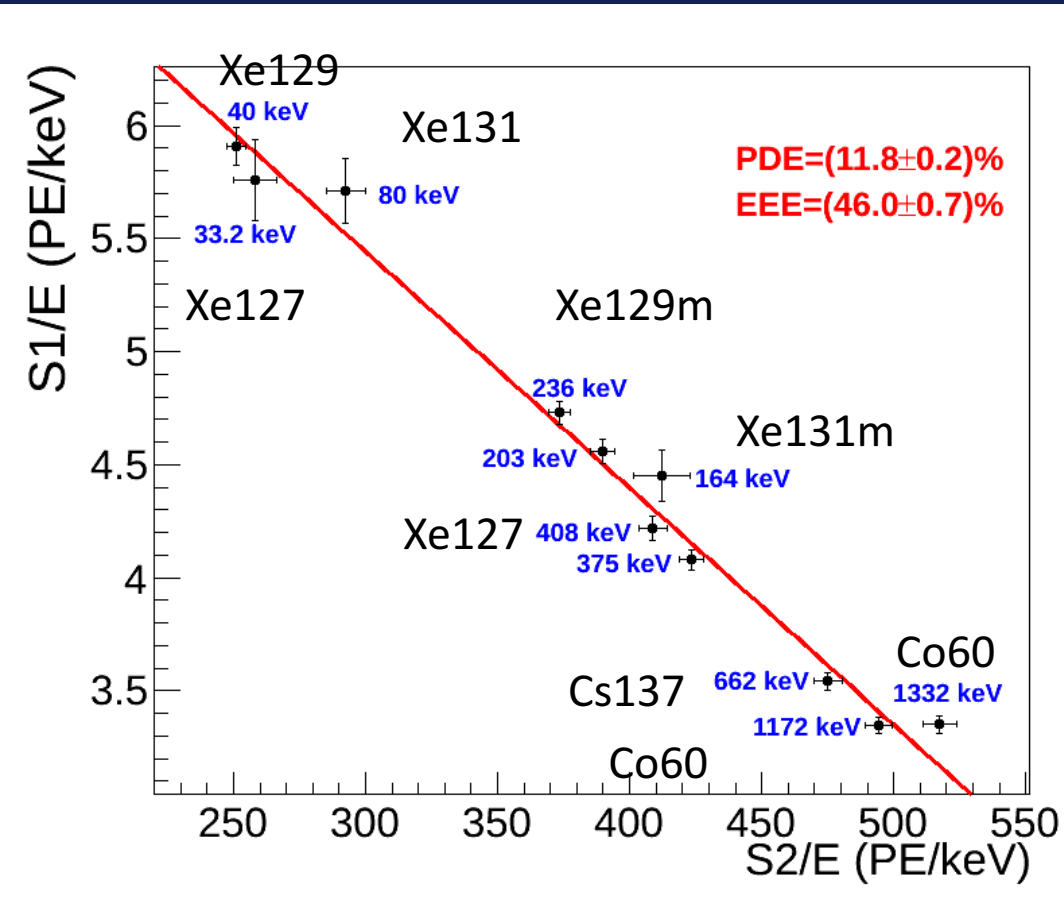
# 单电子信号率

- 单电子信号



- Identify smallest S2 in the data
- Varying selection method and fits to study systematic uncertainty  
 $\Rightarrow 24.4 \pm 0.7$  PE/e

# 电子光子效率估计

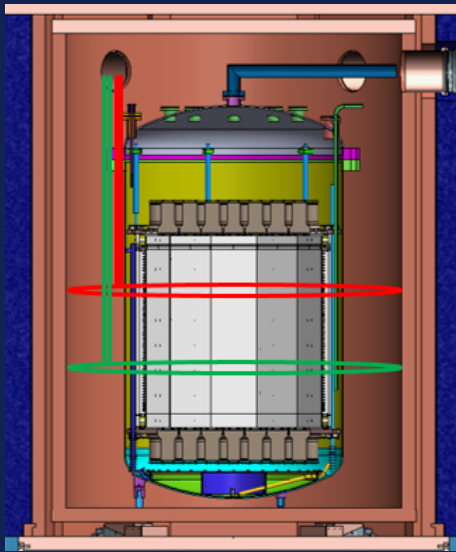


- Gaussian fits to all ER peaks in data
- Uncertainty on each data point estimated using energy nonlinearity
- Linear fit in  $S1/E$  vs  $S2/E$  to extract PDE and EEE

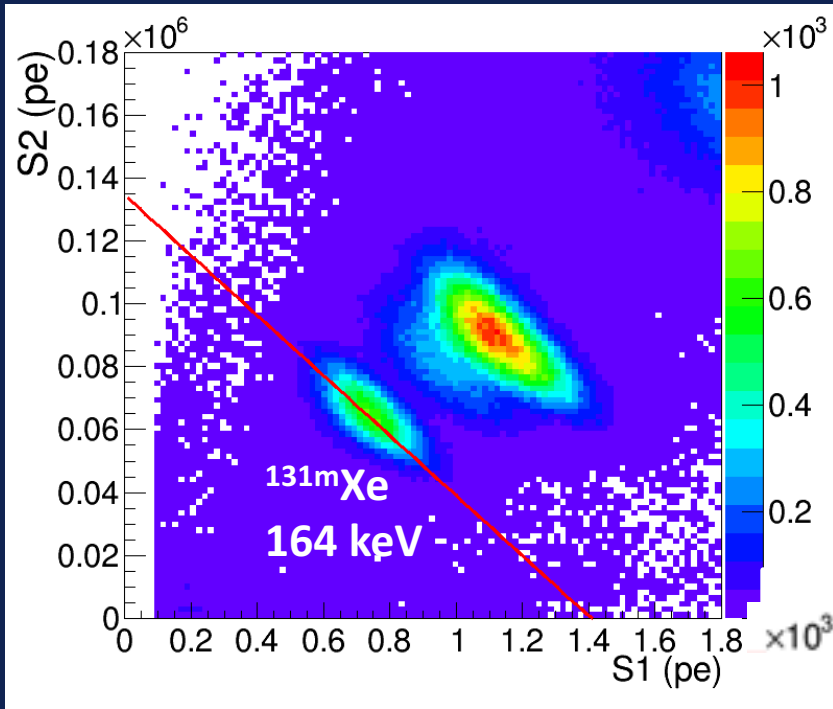


# 探测器性能研究和刻度

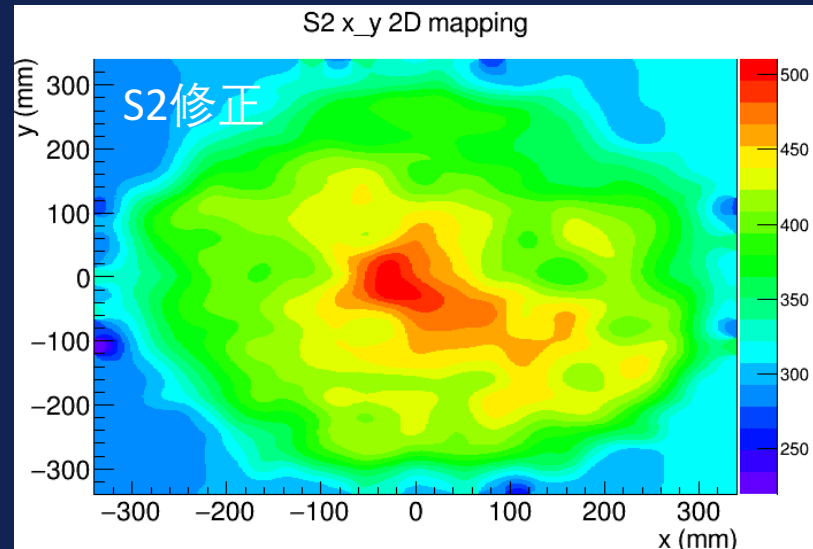
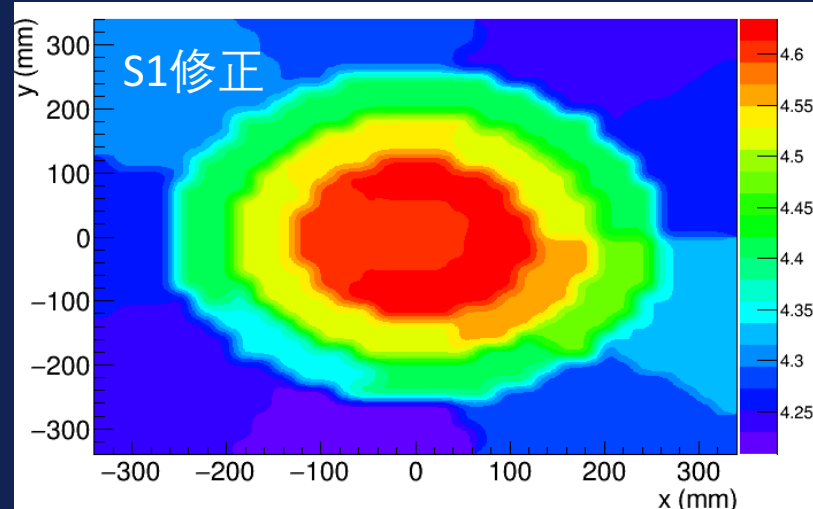
- Internal/external ER peaks:
  - Detector uniformity corrections
  - Light/charge collection parameters
- Low rate AmBe neutron source:
  - ⇒ Simulate DM NR signal
- CH<sub>3</sub>T injection: tritium beta decays
  - ⇒ Simulate ER background



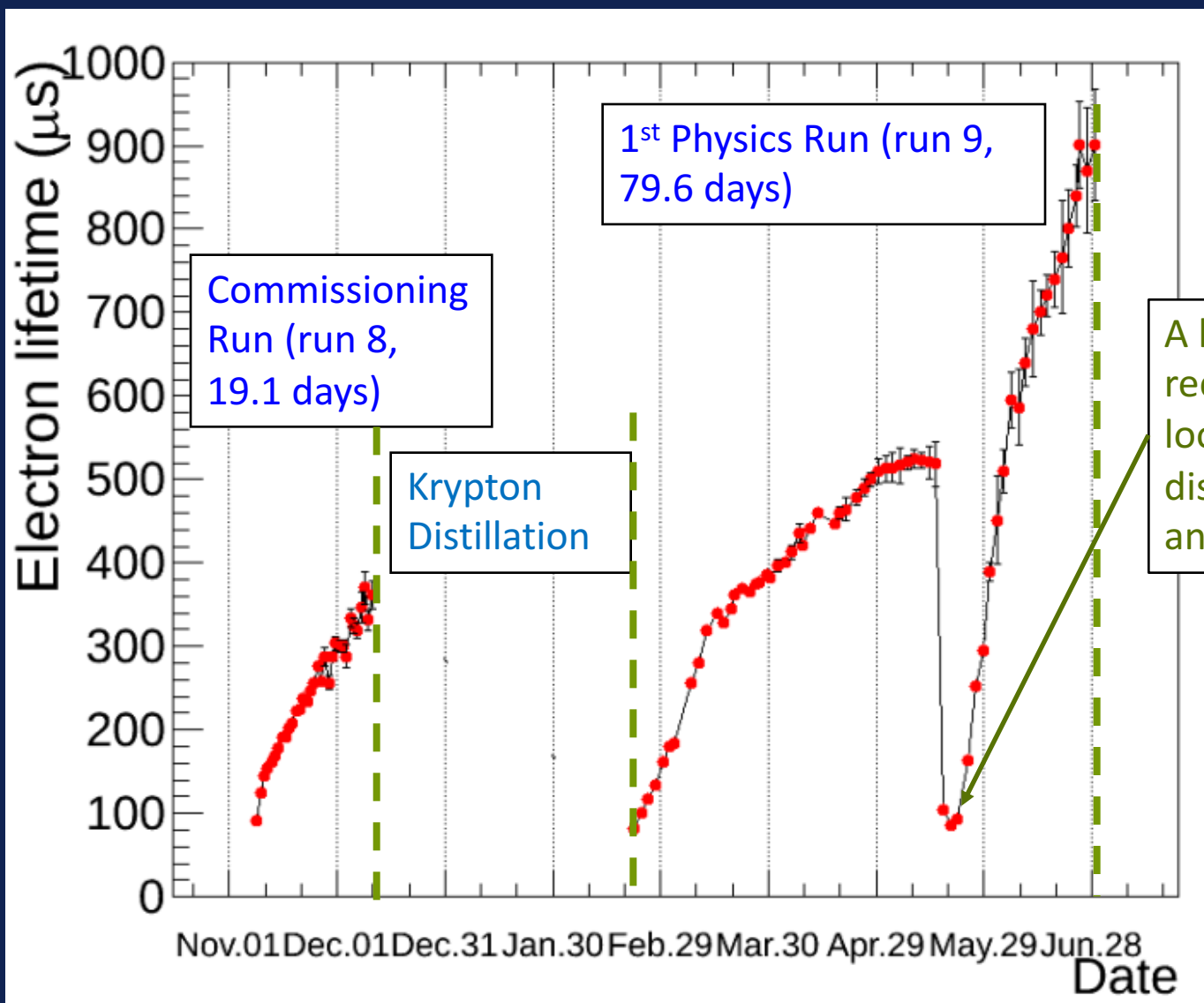
# 探测器均匀性刻度修正



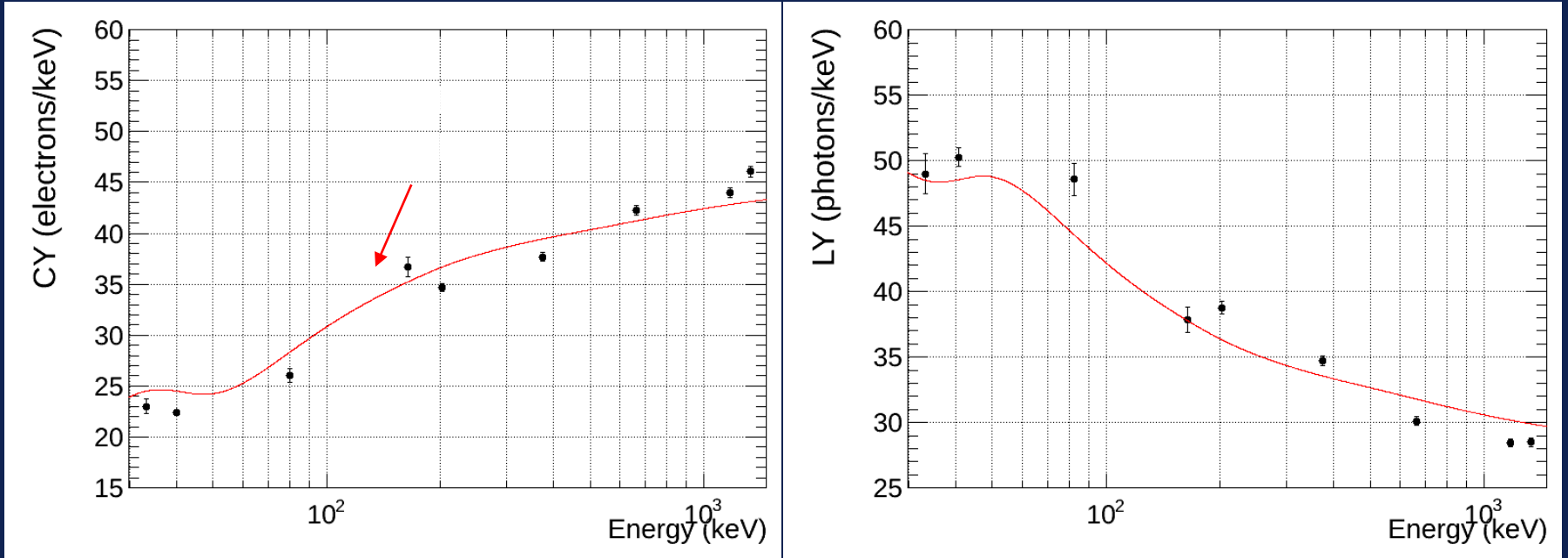
- LY: PE/keV @ 164 keV vs. horizontal position
- CY: PE/keV @ 164 keV vs horizontal position
- Vertical non-uniformity corrected by electron lifetime



# 电子寿命随时间变化

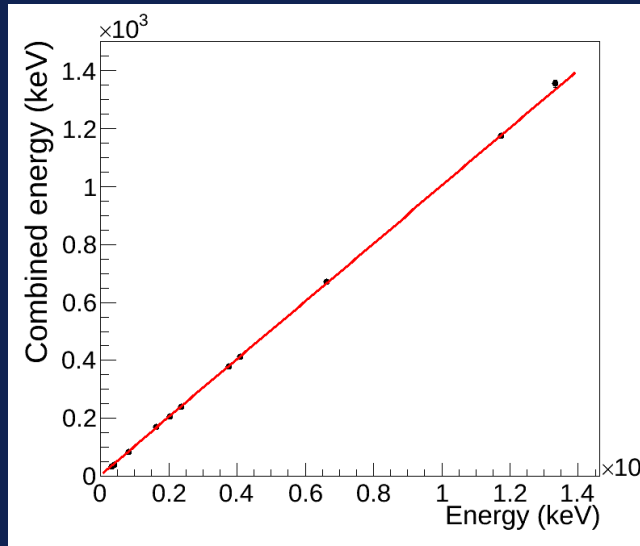
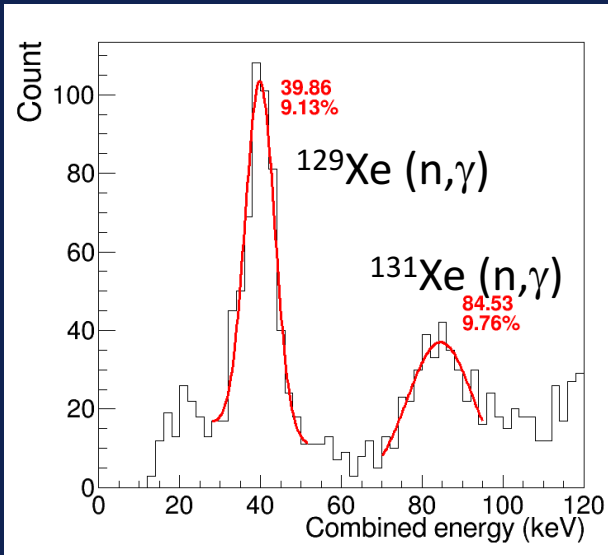


# 光电产额和NEST模拟对比

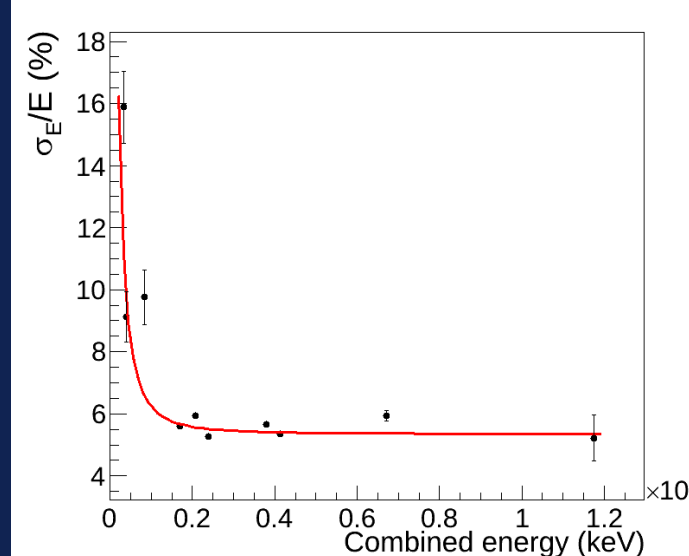
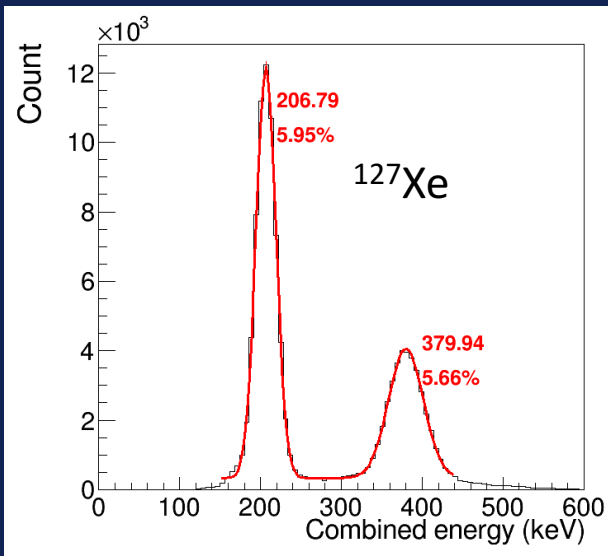


- Reasonable agreement observed between NEST ER model and values extracted from our data

# 能量线性关系和分辨率



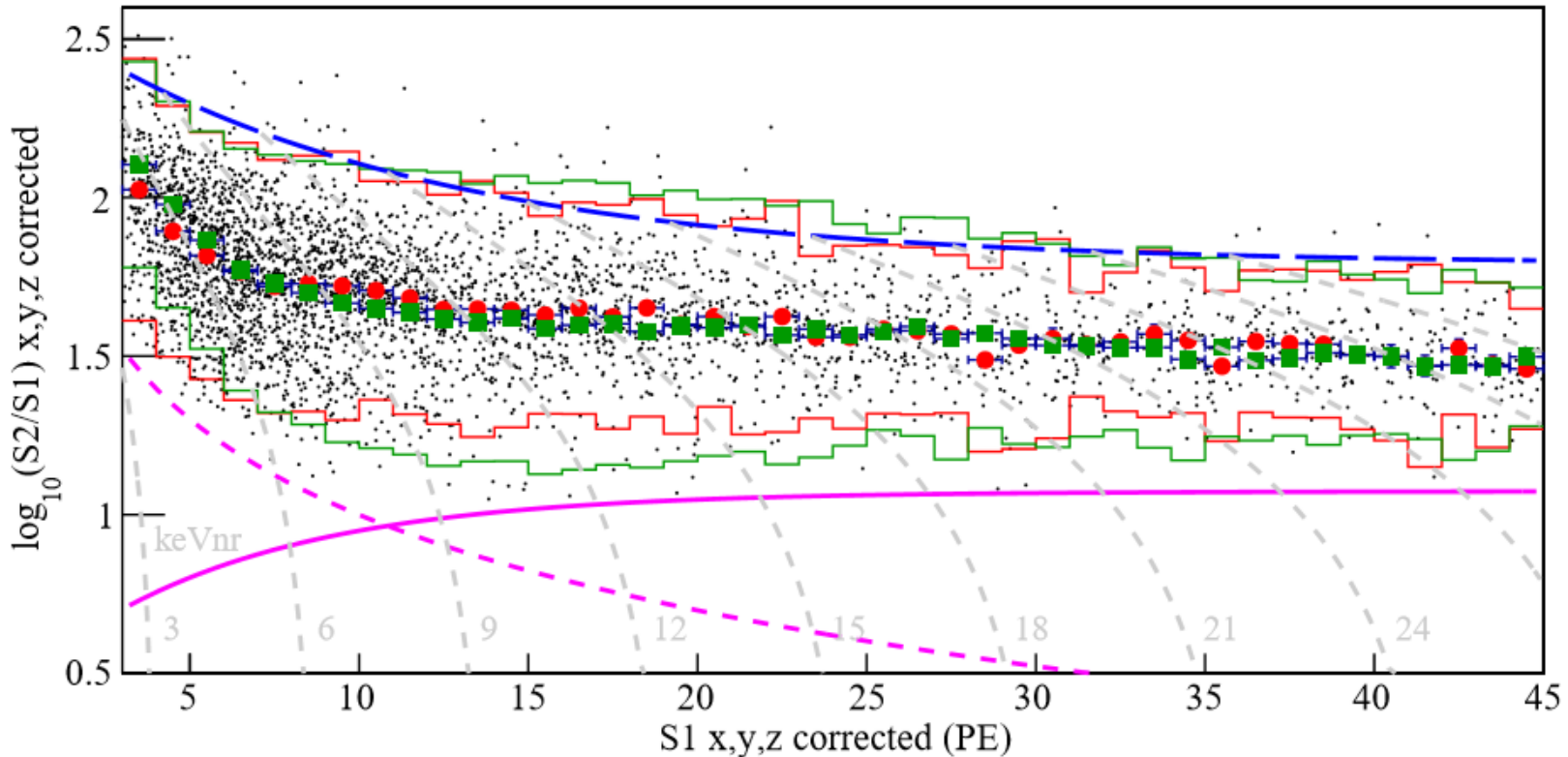
< 2%  
nonlinearity  
achieved for  
[33, 1332] keV



Resolution  
approaching  
5% @ high  
energy

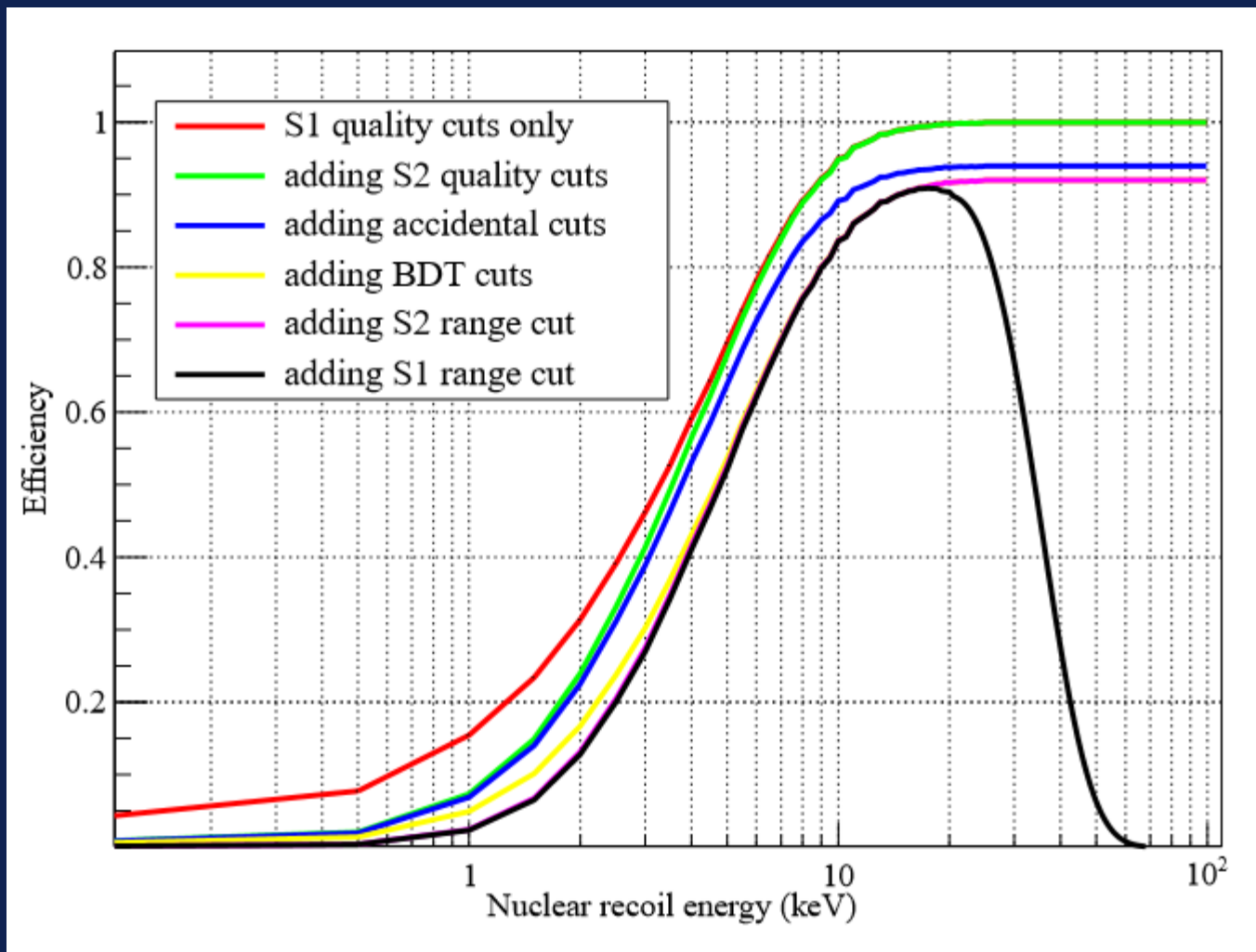


# 核反冲信号刻度



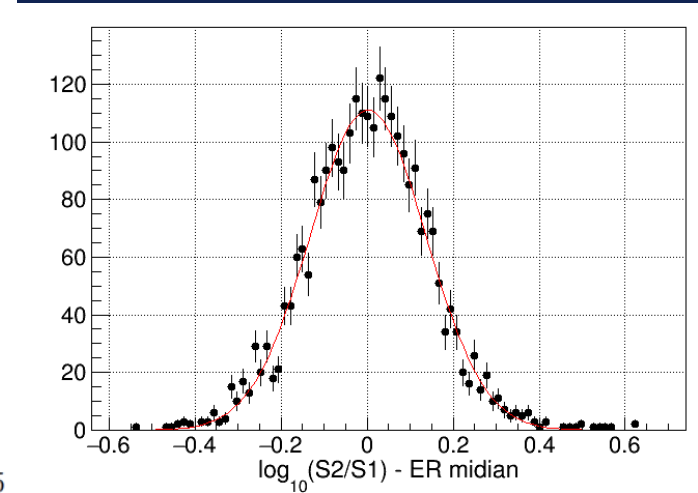
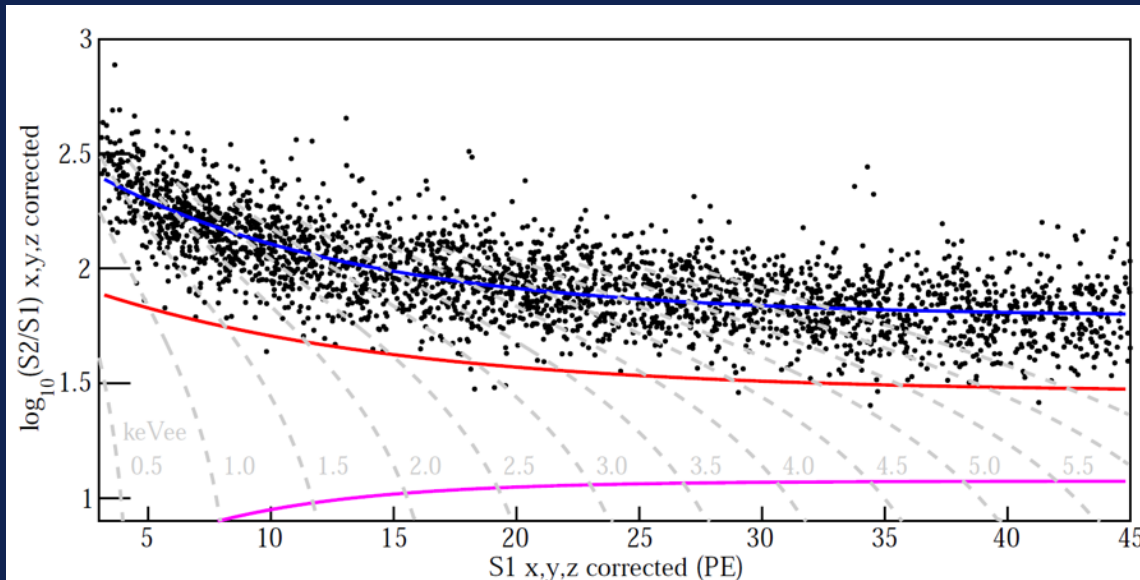
- 162.4 hours of AmBe data taken, with  $\sim 3400$  low energy single scatter NR events collected
- NR median curve and NR detection efficiency determined

# 核反冲信号效率



# 电子反冲刻度

- 氚化甲烷（短寿命，注入探测器内部均匀分布）



- ▣ 18.0 hours of tritium data taken, with  $\sim 2800$  low energy ER events collected
- ▣ 9 events leaked below NR median,  $(0.32 \pm 0.11)\%$
- ▣ Consistent with Gaussian expectation

# 背景研究

Like before, ER and accidental background identified in the data

- ER background

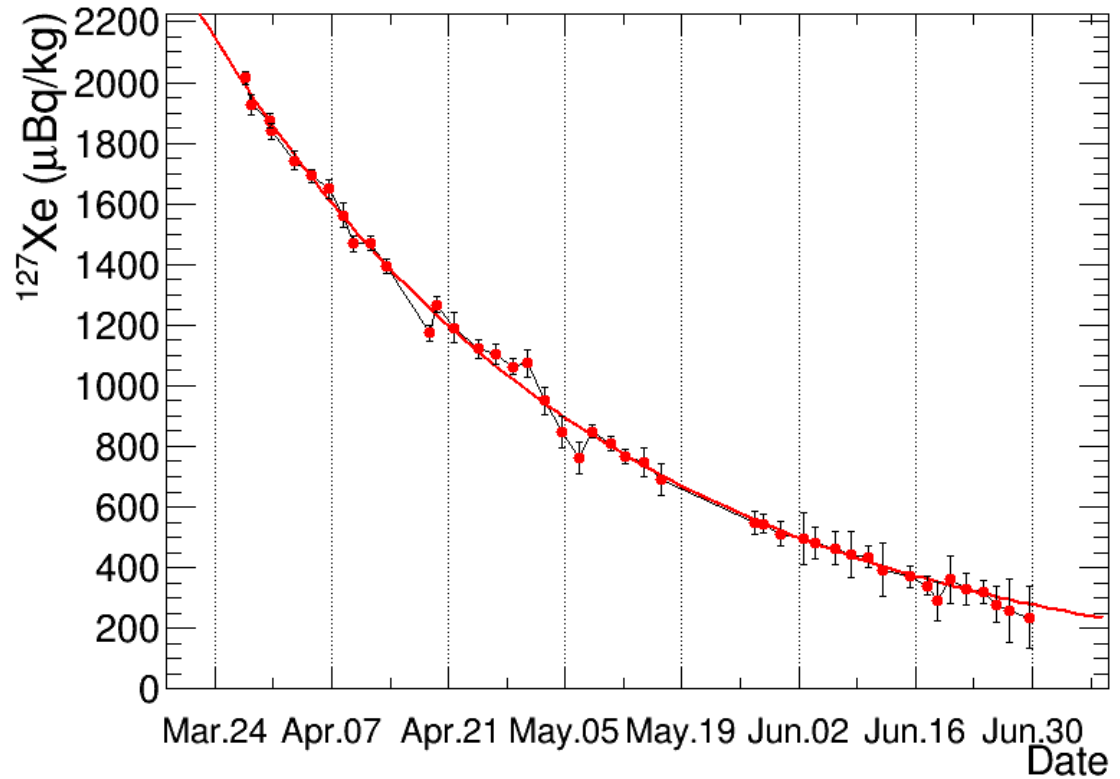
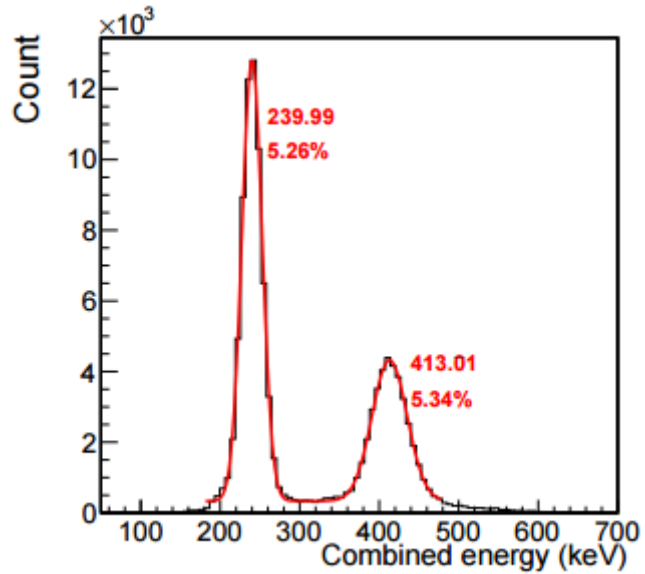
- $^{127}\text{Xe}$  (due to surface exposure of xenon during distillation)

- $^{85}\text{Kr}$  (suppressed by a factor 10)

- Others

- Accidental background (determined by data)

# Xe127

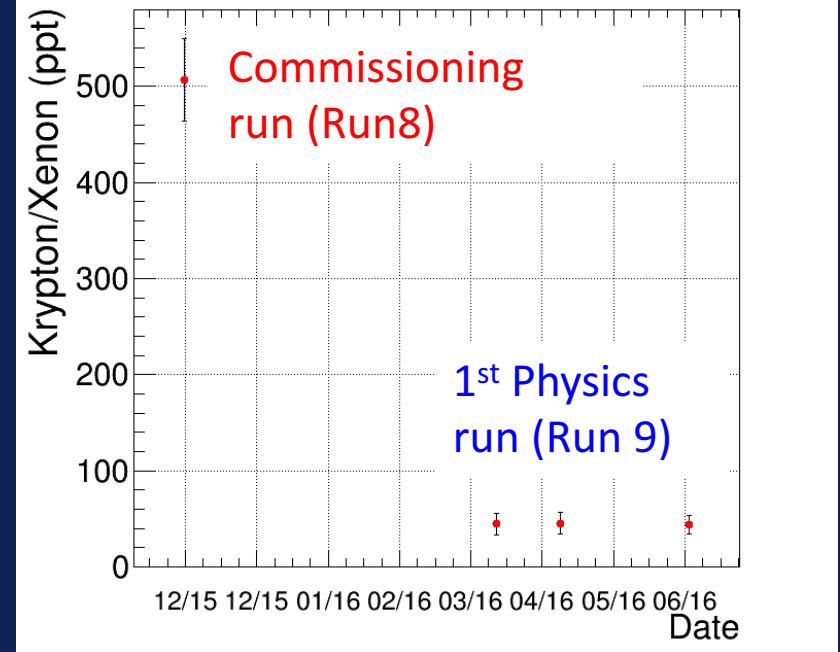
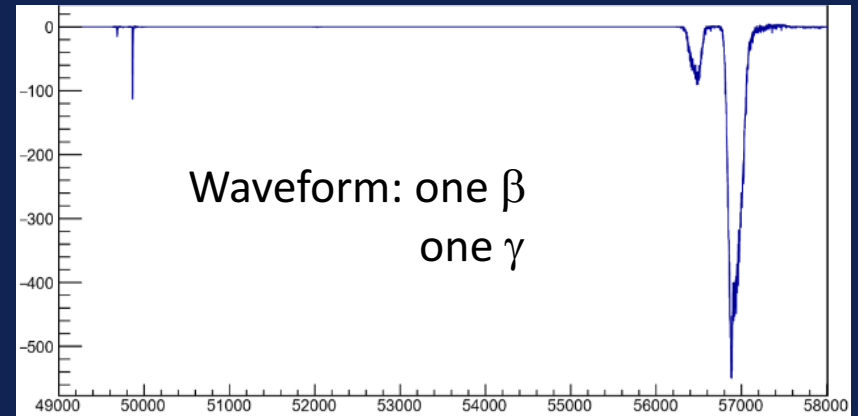
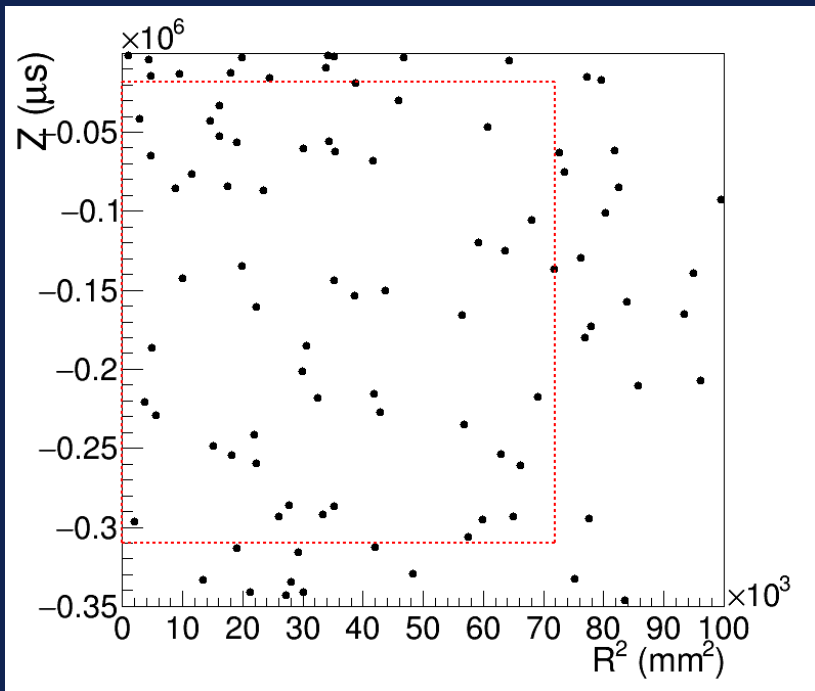


Rate of  $^{127}\text{Xe}$  estimated by fitting the 408 keV (375 keV+33.2 keV) peak



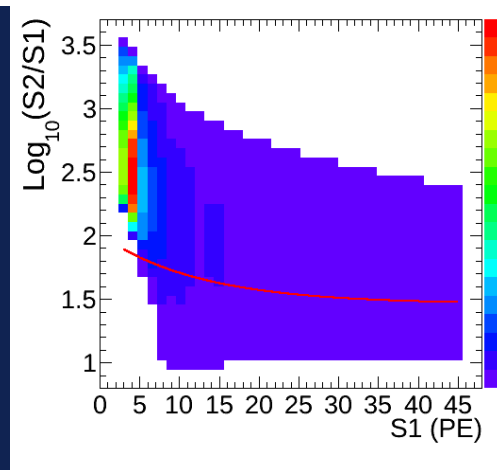
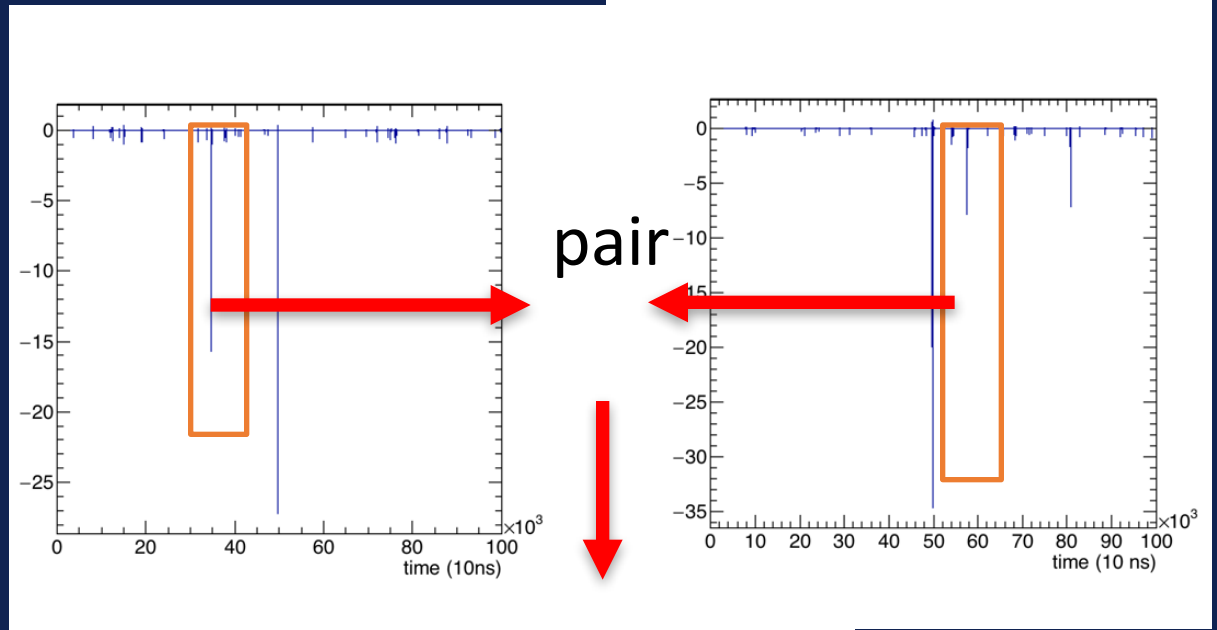
# Kr85

- Estimated from delayed  $\beta$ - $\gamma$  coincidence analysis
- Uniformly distributed
- Significantly reduced after distillation

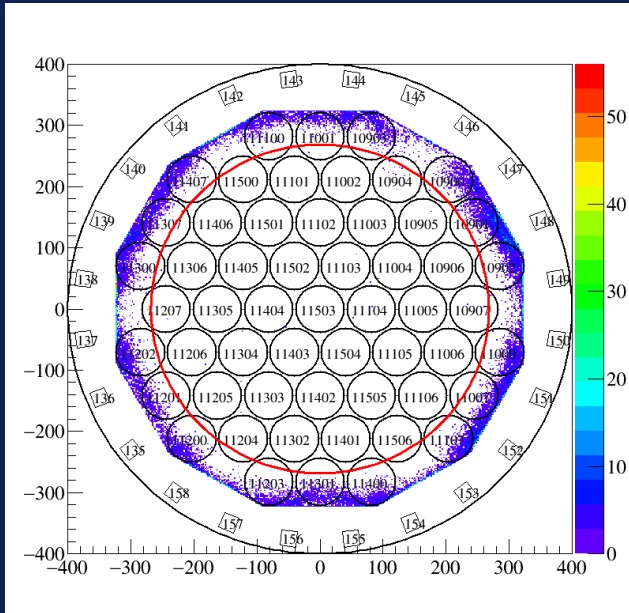


# 偶然背景

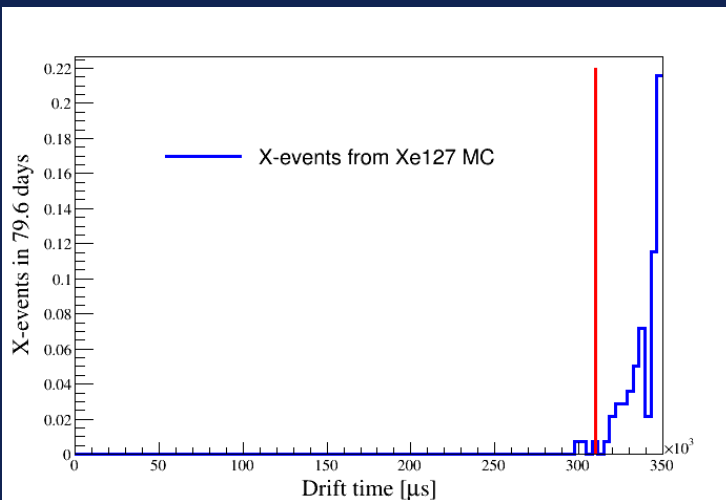
Isolated S1 and S2 were selected and randomly paired to simulate accidental events



# 信号区域确定



- Horizontal cut determined by distribution of events with S1 between [45, 200] PE and suppressed S2
- Vertical cut: Upper boundary consistent with the previous analysis; Lower boundary determined by X-events from  $^{127}\text{Xe}$  MC



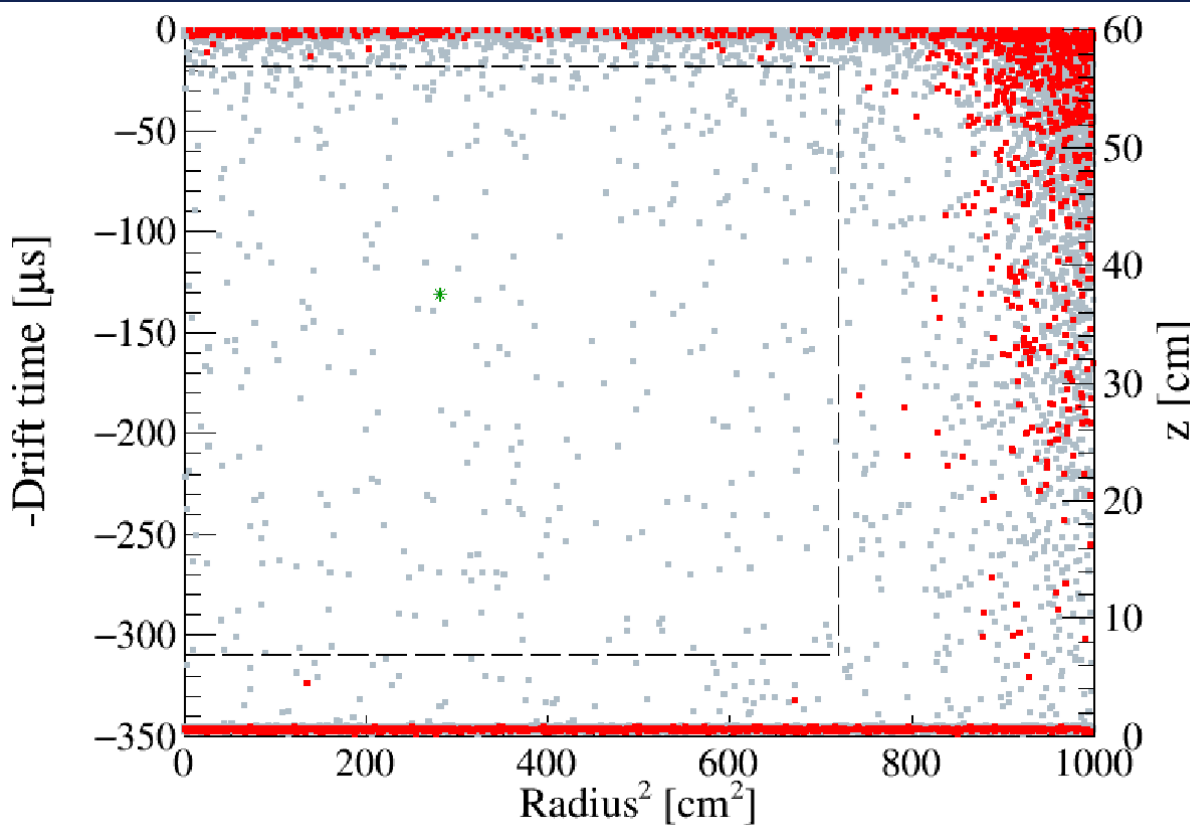
- FV in Run 9 with 328.9 kg
- S1 cut: [3, 45] PE & S2 cut [100 raw, 10000] PE: consistent with previous analysis

# 最终选择事例

Gray: all

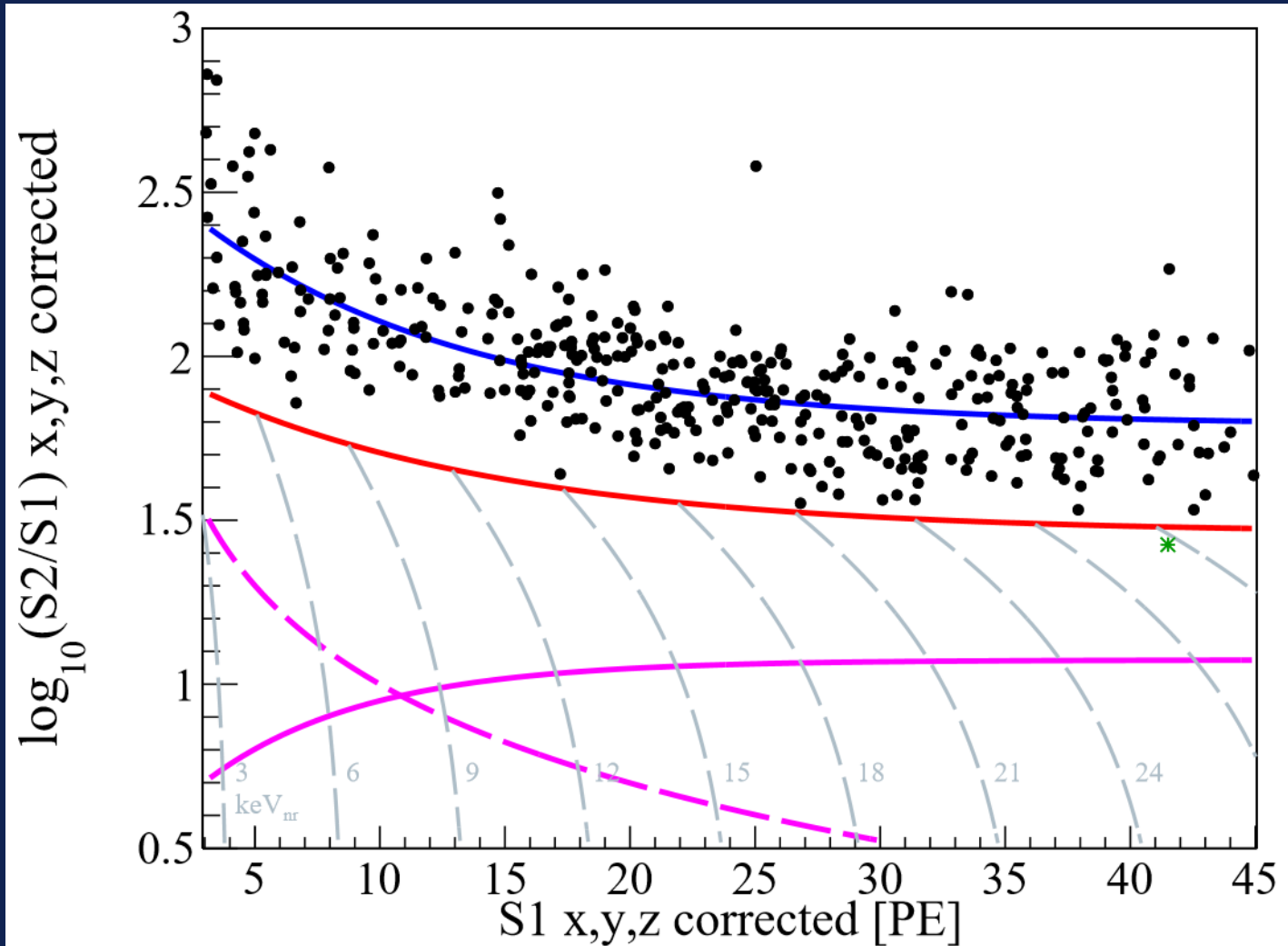
Red: below NR median

Green: below NR median and in FV



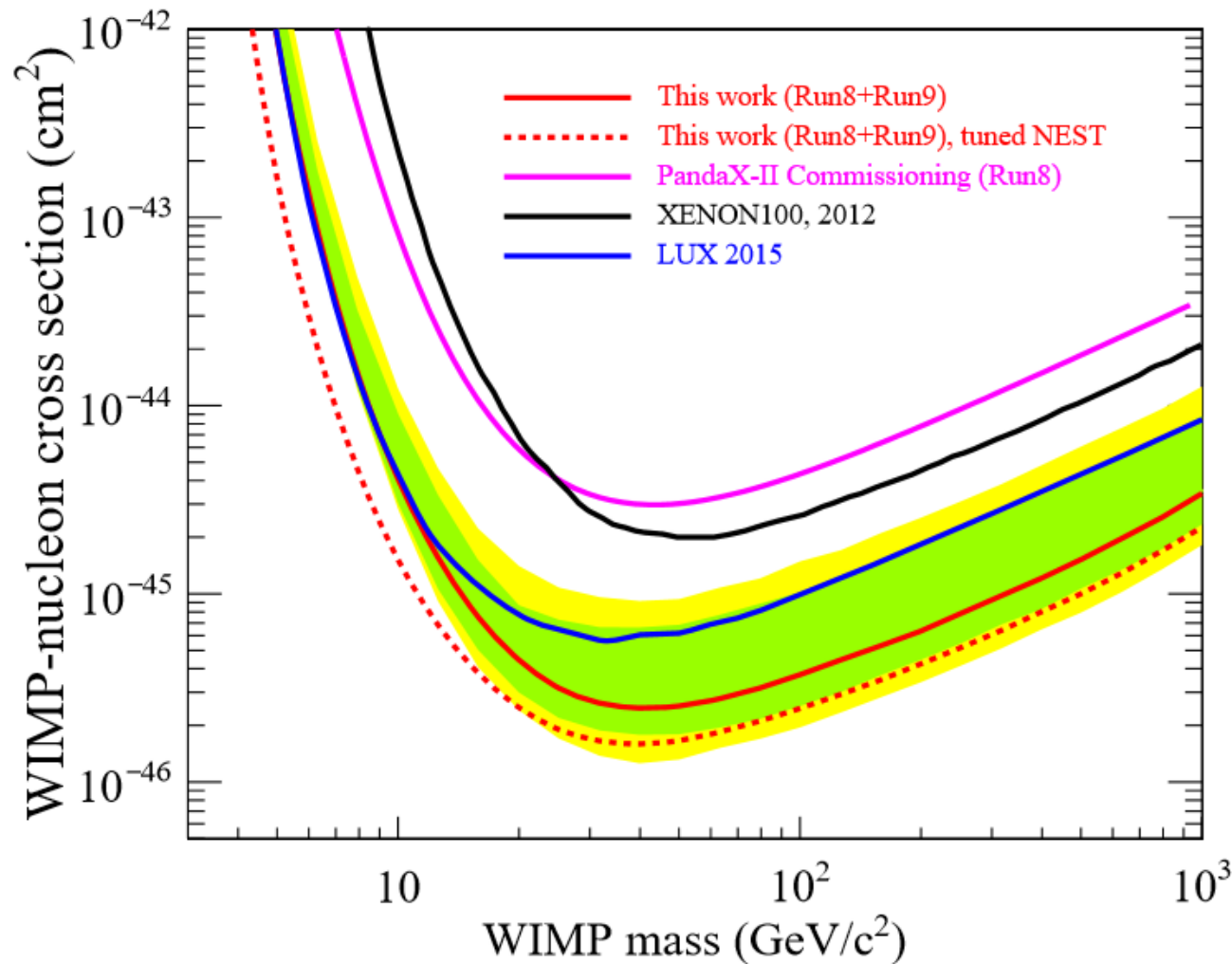
- 389 total candidates found in the FV
- 1 below NR median
- Outside FV, edge events more likely to lose electrons, leading to S2 suppression

# 最终选择事例 (Run9)





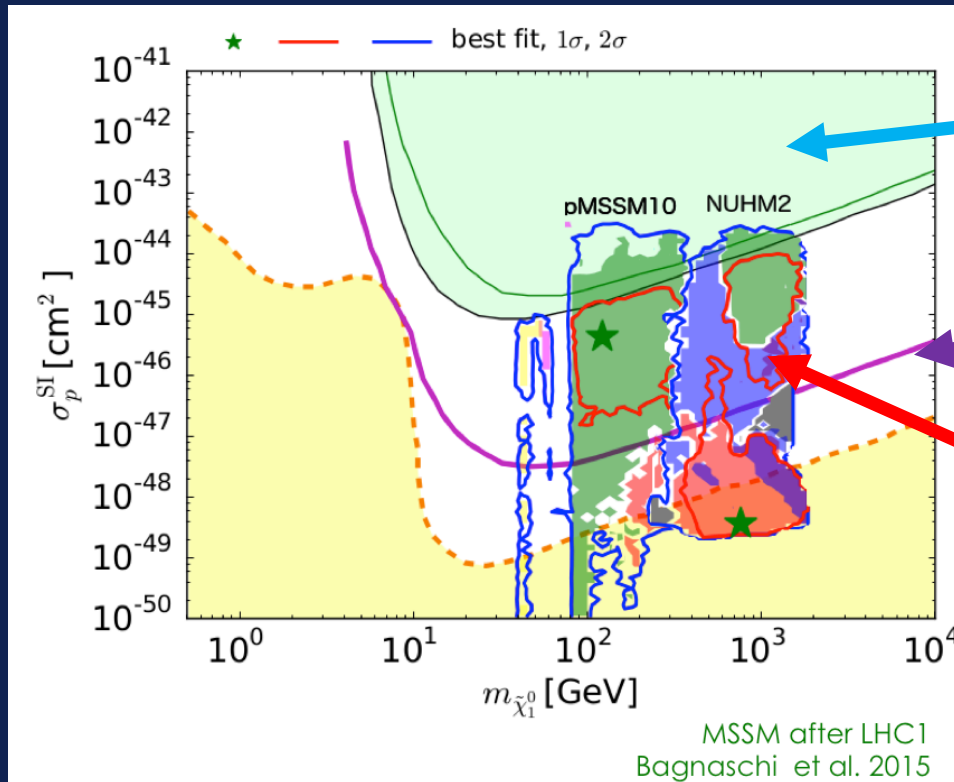
# 结果



Minimum upper limit for isoscalar SI elastic cross section at  $2.5 \times 10^{-46} \text{ cm}^2$ , more than a factor of 2 improvement compared to the LUX 2015 results

# 中国PandaX-xT计划

- 2016-2020 : 4 吨液氙 (灵敏区) , 计划2018年建成运行
- 率先探索未知信号区域, 并和未来美国LZ 7吨实验 (2020) 相互验证
- 为进一步30吨级终极暗物质实验做技术研发储备
- 



目前直接探测排除区域

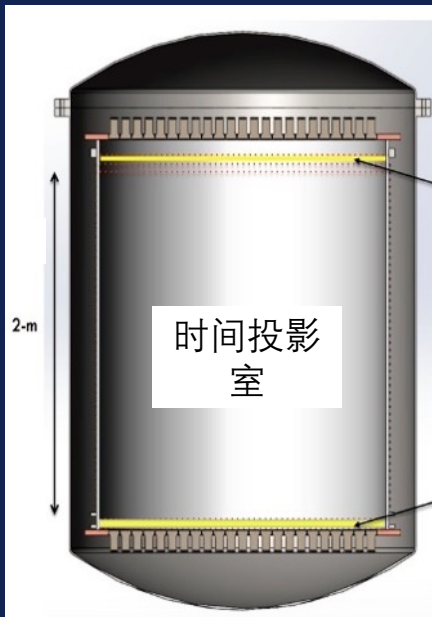
PandaX-xT灵敏区

理论预测信号区域

# 4吨级暗物质实验设计

## 整体实验布局示意图

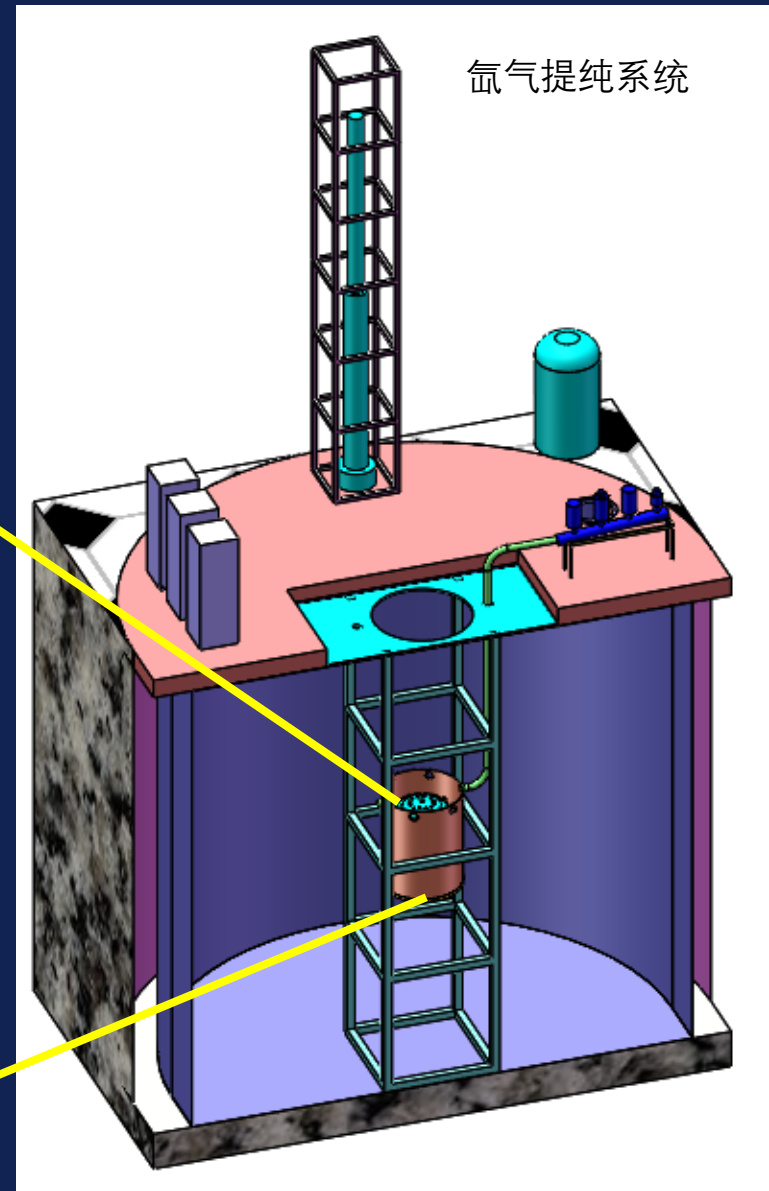
- 13米深纯水屏蔽体
- 外罐真空容器，内罐压力容器
- 探测器：时间投影室
- 氙气提纯系统
- 液氙制冷及存储系统
- 电子学系统



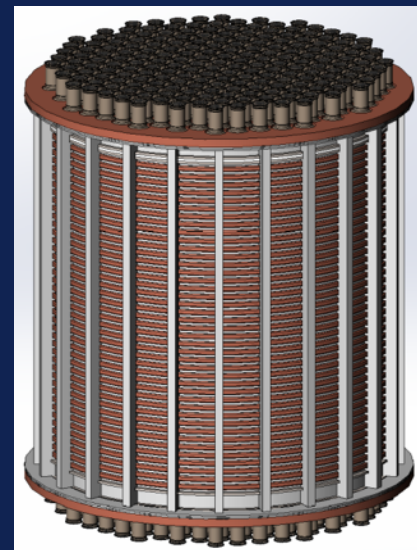
内罐压力容器



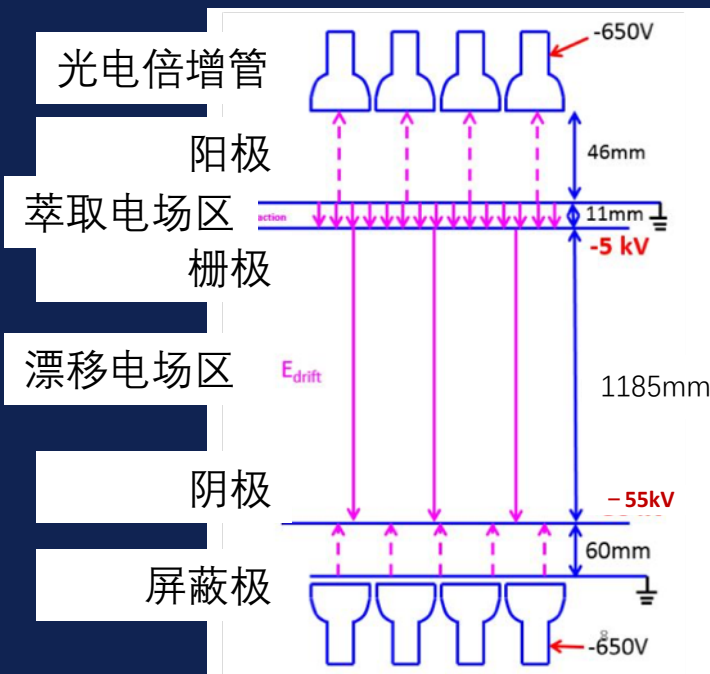
外罐真空容器



# 探测器主体部分设计

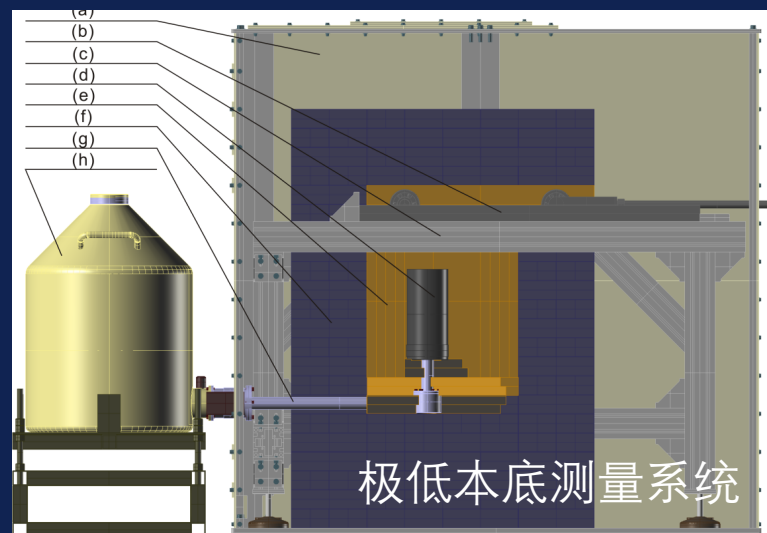
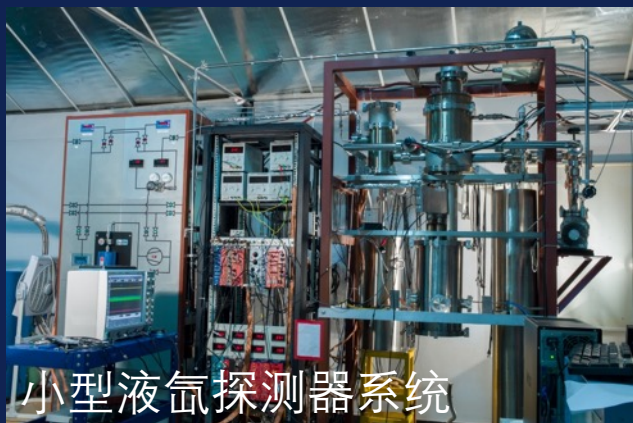


- 圆柱形时间投影室探测器
  - 有效直径：1185mm，高度：1185mm
  - 液氙（灵敏区）：5.5吨（4吨）
- 电极：屏蔽极，阴极，栅极，阳极
  - 网状结构
  - 漂移电场：400 伏/厘米
  - 萃取电场：6000 伏/厘米
  - 60个整形环确保探测器内部匀强电场
- 光电倍增管：低本底3吋
  - 上下各约200个紧密排列
- 特氟龙反射板：包围探测器内壁
  - 确保光子采集效率



# 其他系统

- 本底测量系统，制冷系统，屏蔽系统，氙提纯系统，电子学系统等





# 小结

- 我们在中国推进暗物质直接探测，跻身世界领先行列。
- 计划发展终极暗物质探测器

