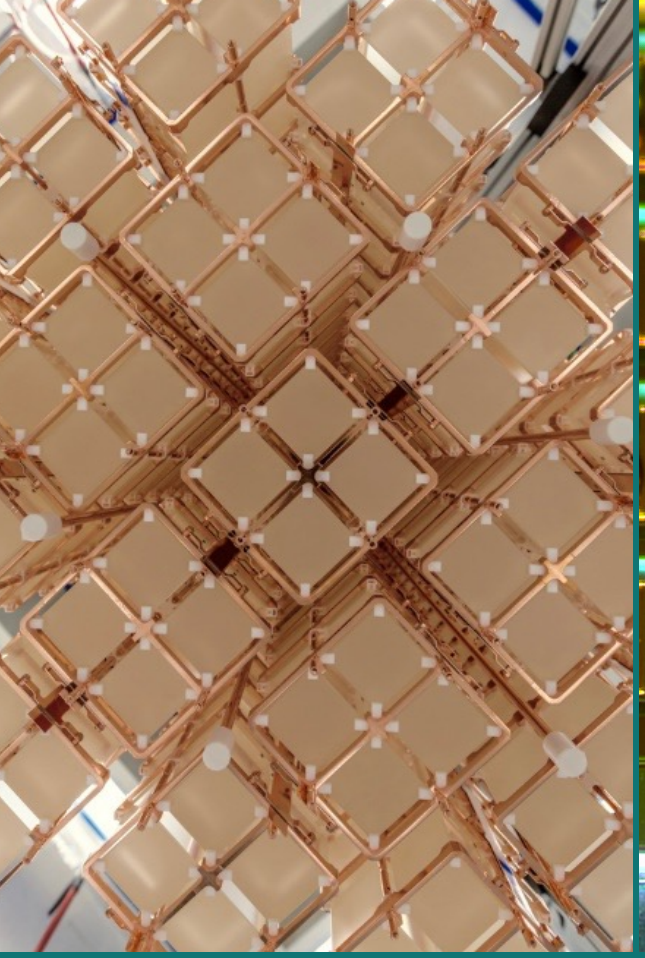
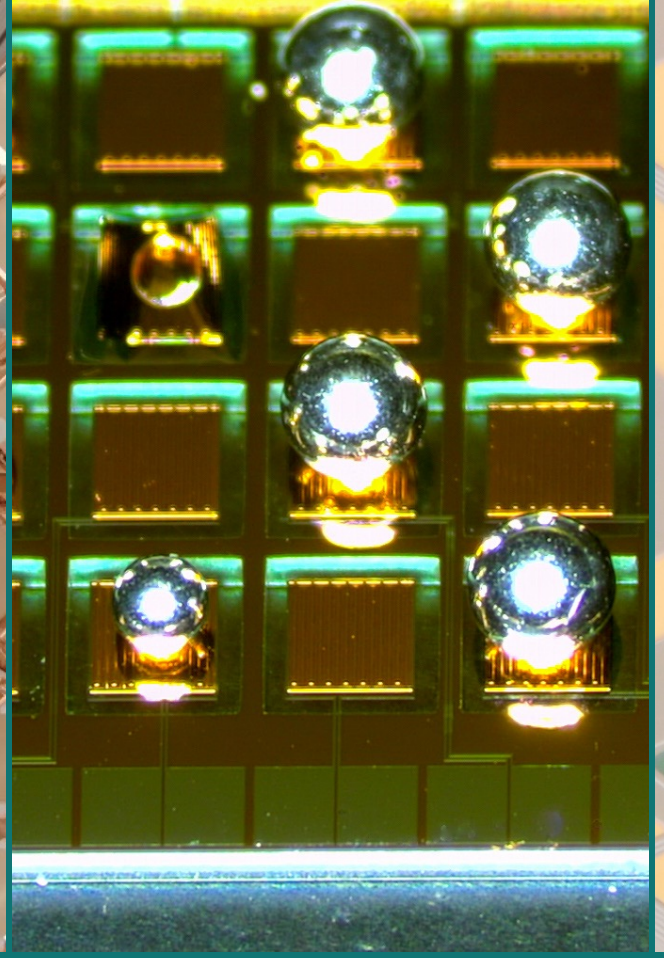
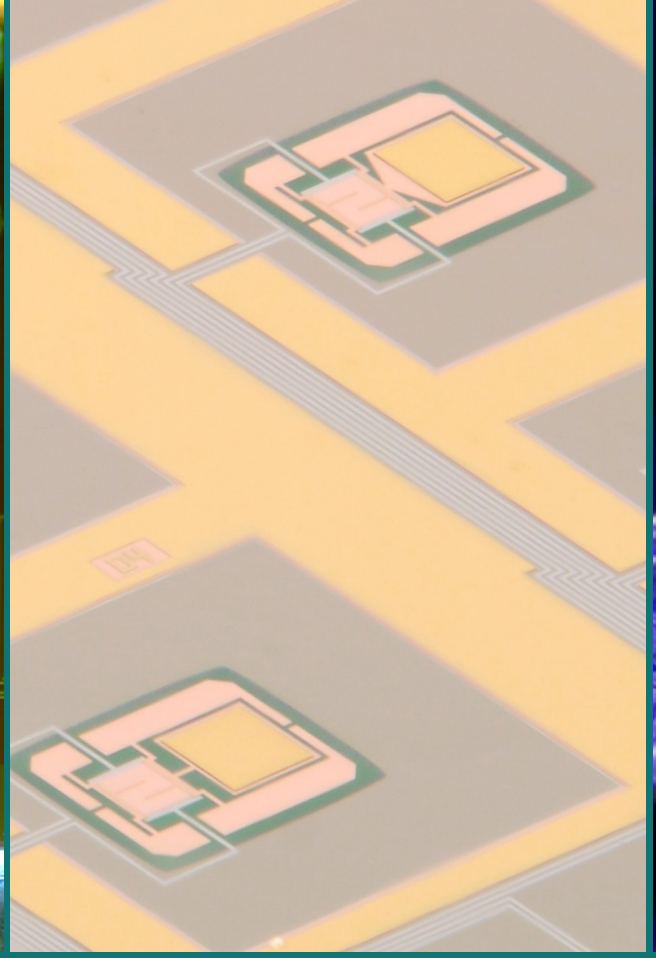
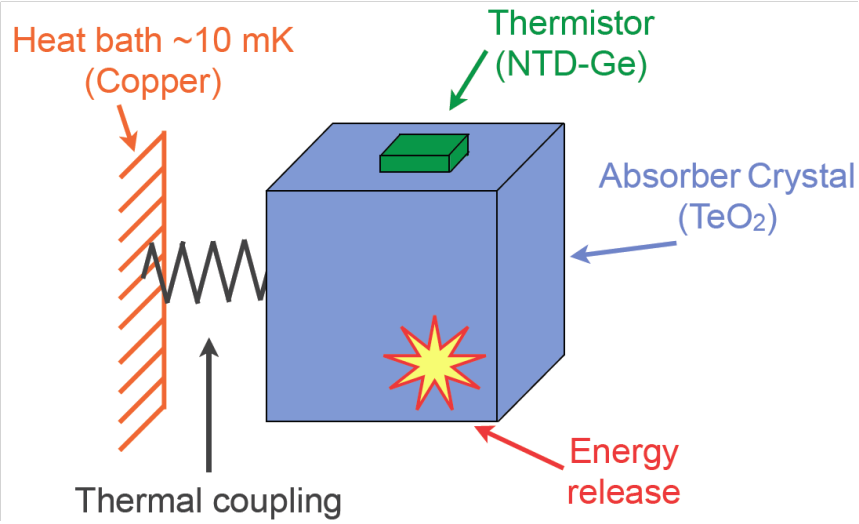




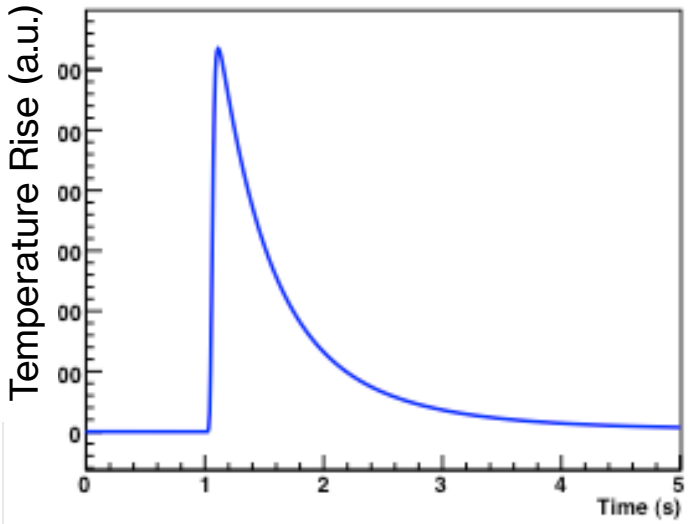

低温量热器技术在粒子与核物理中的应用

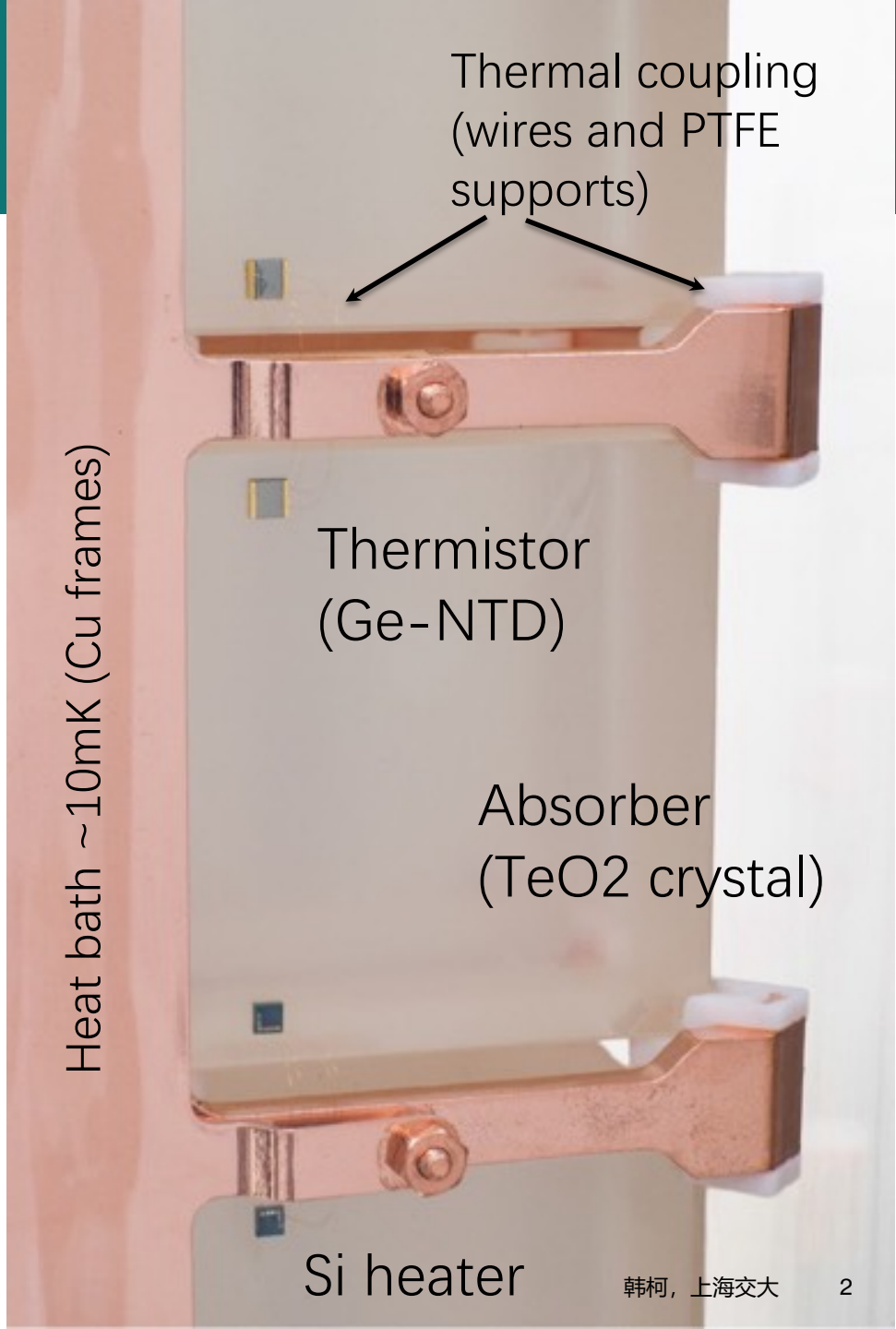
韩 柯　上海交通大学

低温量热器 Bolometers

- **通过温度变化来测量能量**
- **mK级别低温→小的比热容**
- **声子能量极小→极高的内秉分辨率**

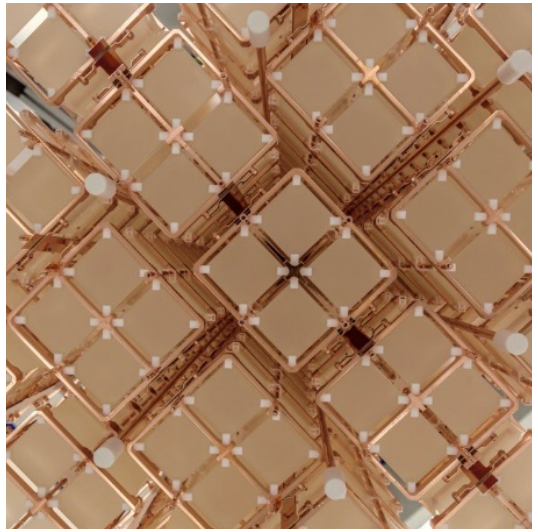




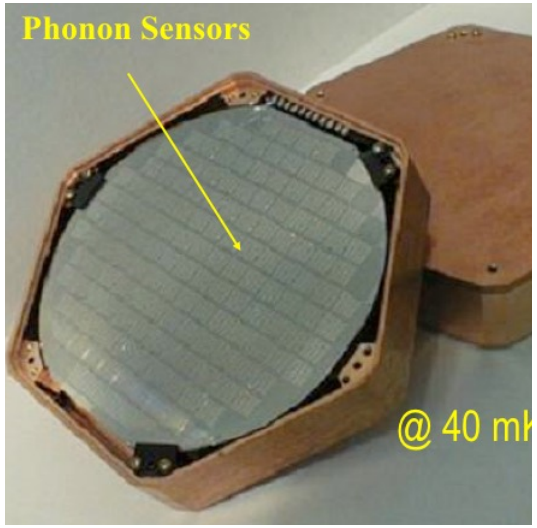


用途广泛的灵敏探测技术

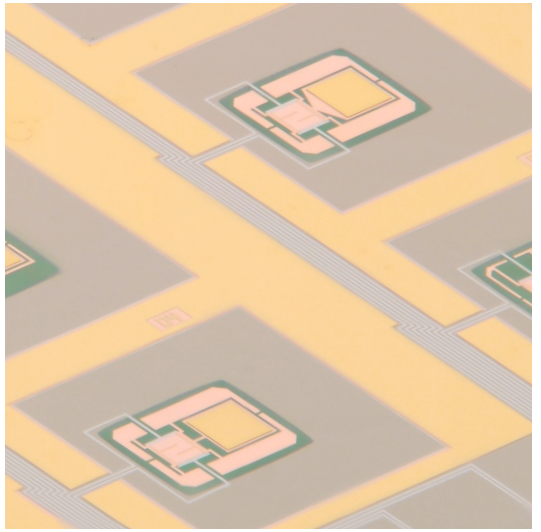
- 千克量级吸收体 → $0\nu\beta\beta$ searches
  - CUORE, CUPID，AMoRE
- 克量级吸收体→ Dark Matter，neutrino mass
  - CDMS，CRESST，HOLMES，ECHO
- 毫克量级吸收体→ 宇宙学应用
  - SPT，Planck，CMB S4
- Sterile neutrino search, coherent neutrino scattering, etc
- X、gamma光谱



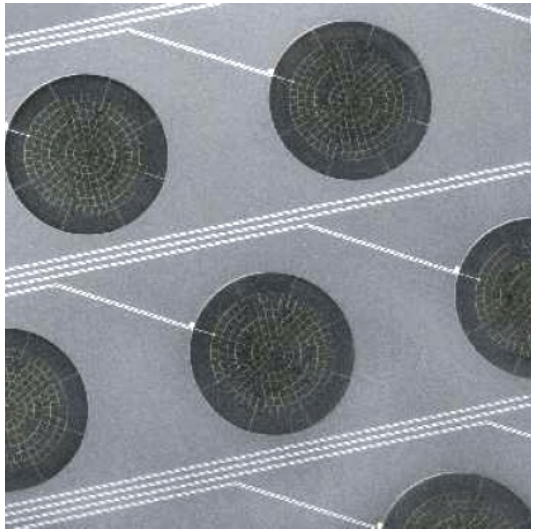
CUORE



CDMS



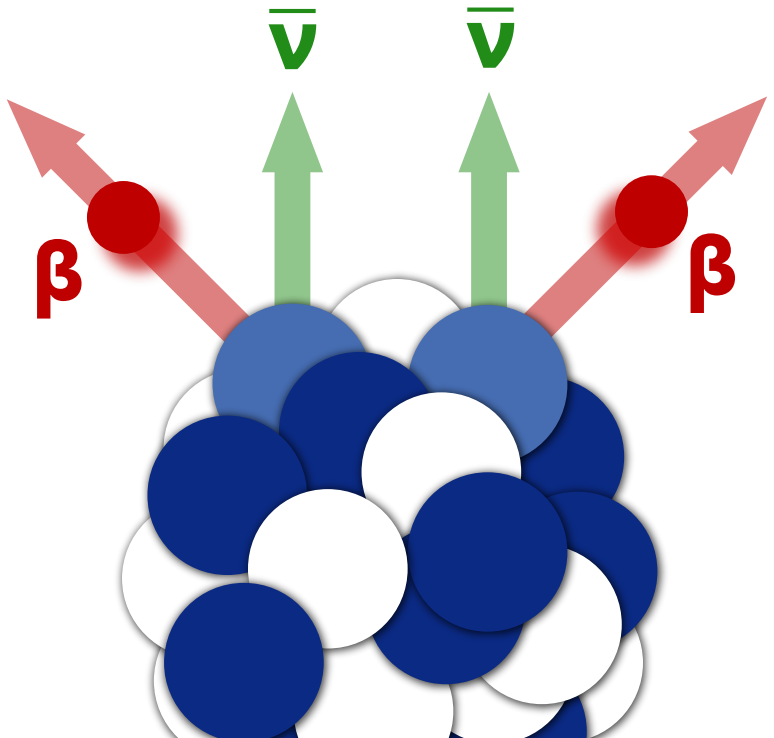
HOLMES

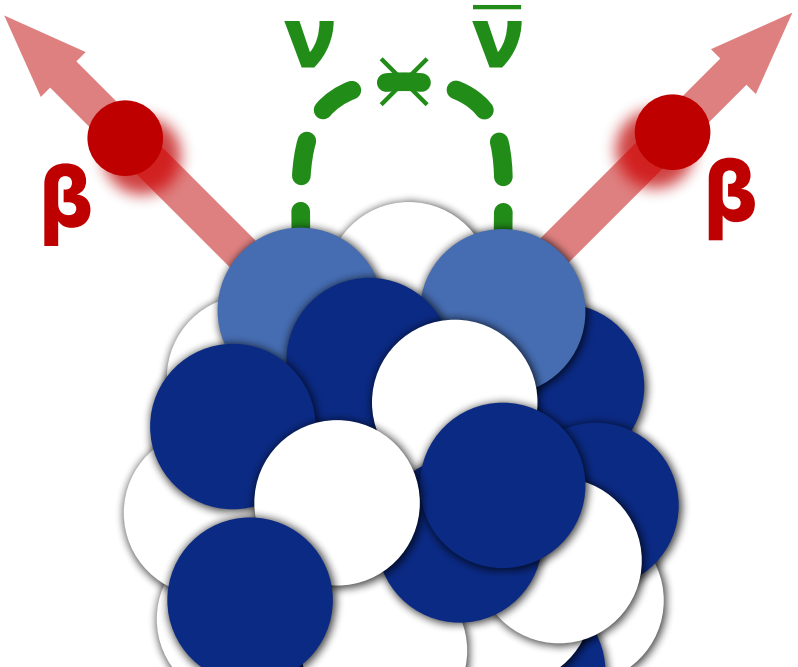


SPT

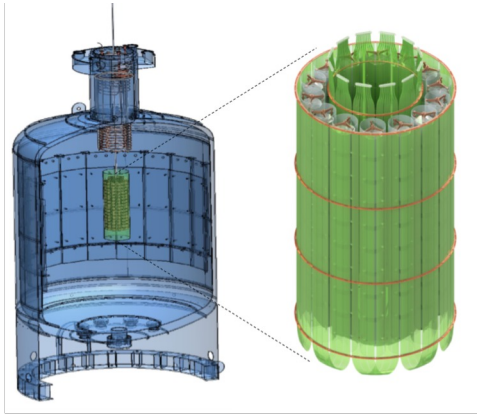
无中微子双贝塔衰变

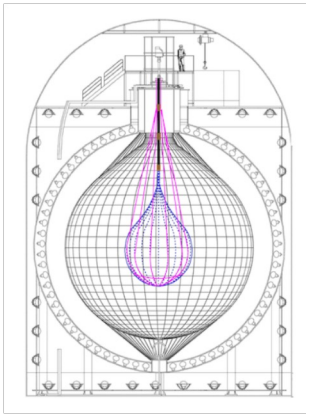
- 寻找马约拉纳中微子， 探索中微子质量起源
- 破坏轻子数守恒，对于宇宙早期正反物质不对称性给出可能解释
- 例子：$^{136}Xe \rightarrow {}^{136}Ba + 2e^{-}(+2\bar{\nu})$

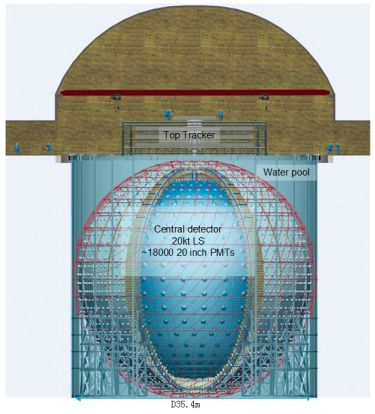




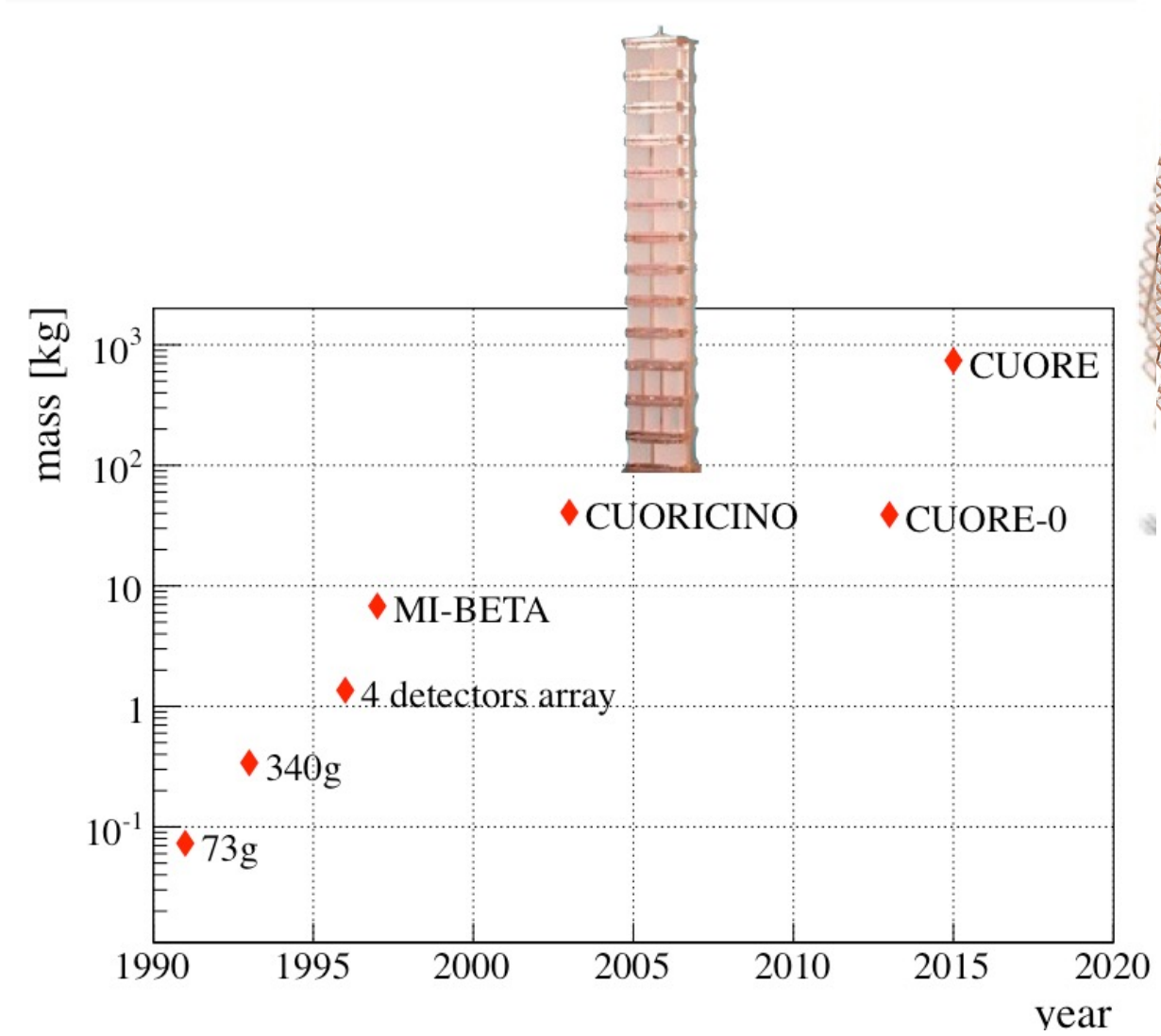
Solid state detector arrays	Gas/liquid detectors
CUORE/CUPID	KamLAND-ZEN
LEGEND	nEXO
CDEX	PandaX
CUPID-CJPL	NvDEX
	JUNO-0νββ

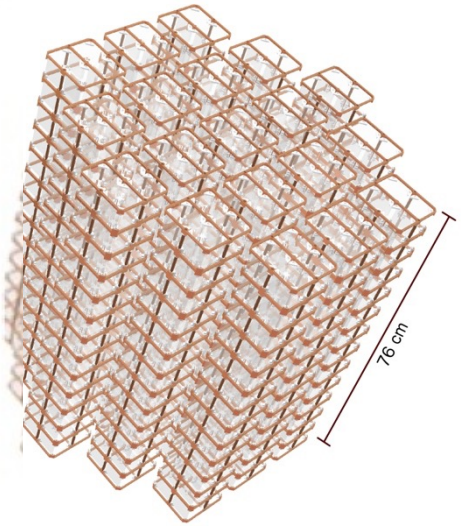


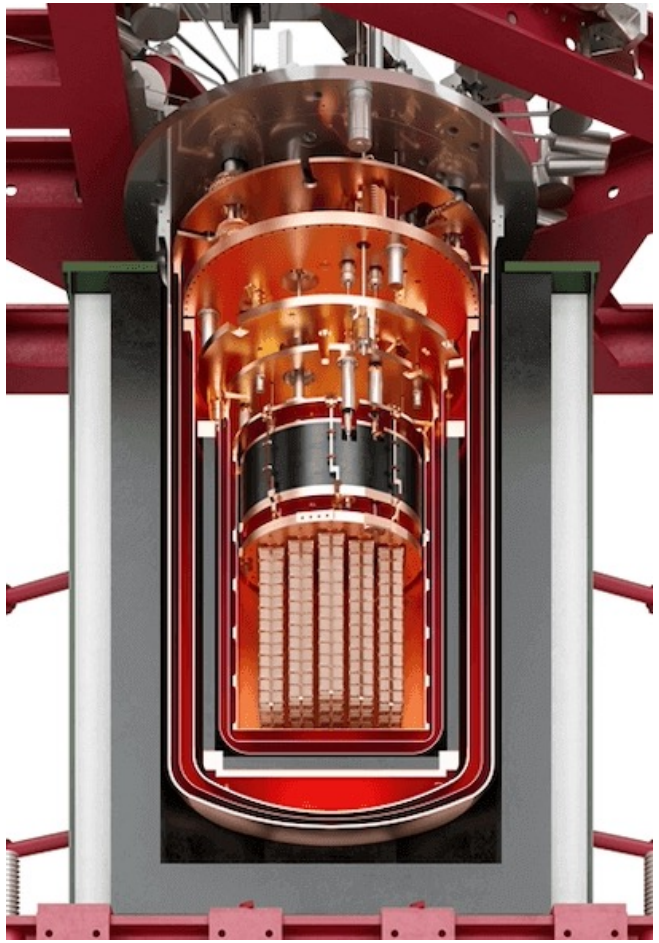




CUORE/CUPID



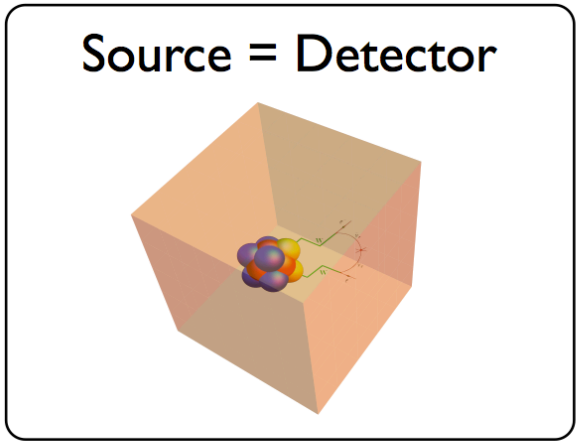


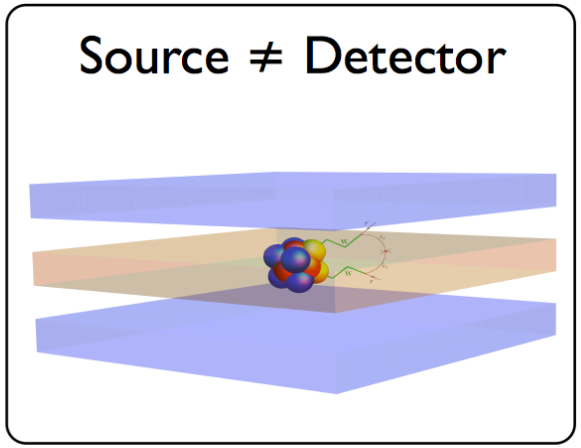


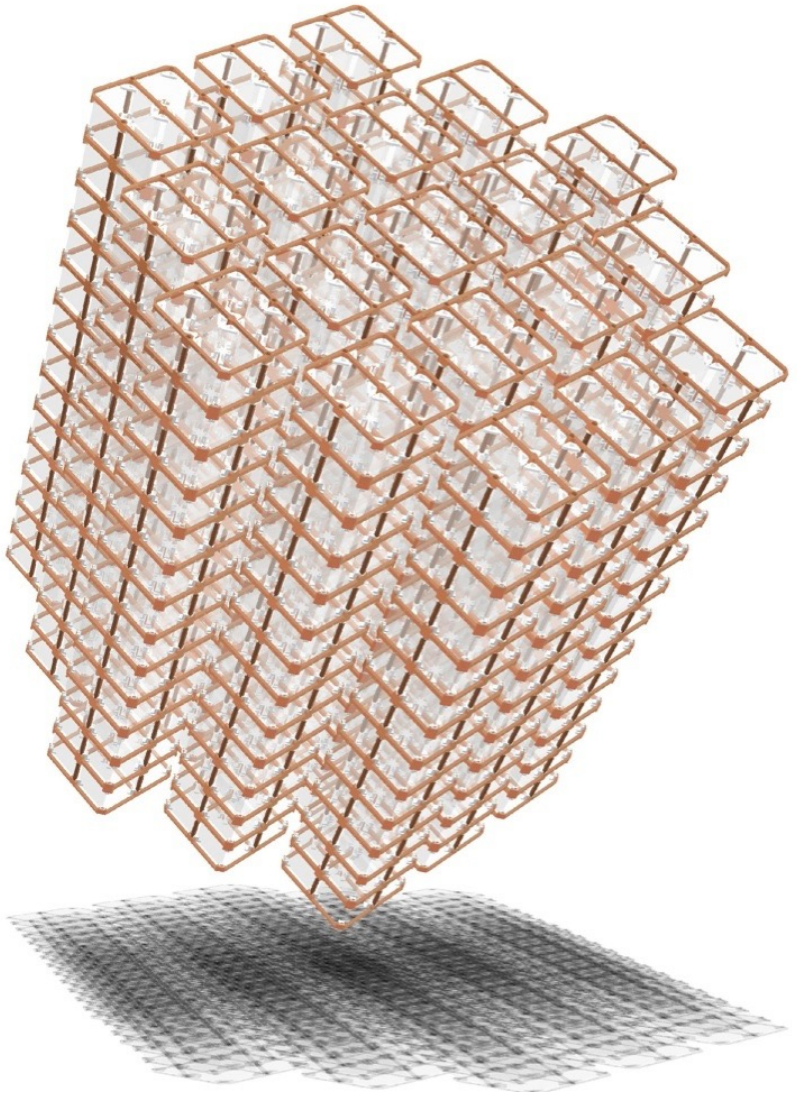
未来 CUPID

CUORE 无中微子双贝塔衰变实验

- 寻找 ^{130}Te 的无中微子双贝塔衰变
- 988 TeO_2 晶体组成量能计阵列
  - 晶体质量741 kg; 206 kg ^{130}Te







CUORE 无中微子双贝塔衰变实验

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  - 晶体质量741 kg; 206 kg ^{130}Te
- 世界上最大的稀释制冷机，把整个阵列冷却到10mK

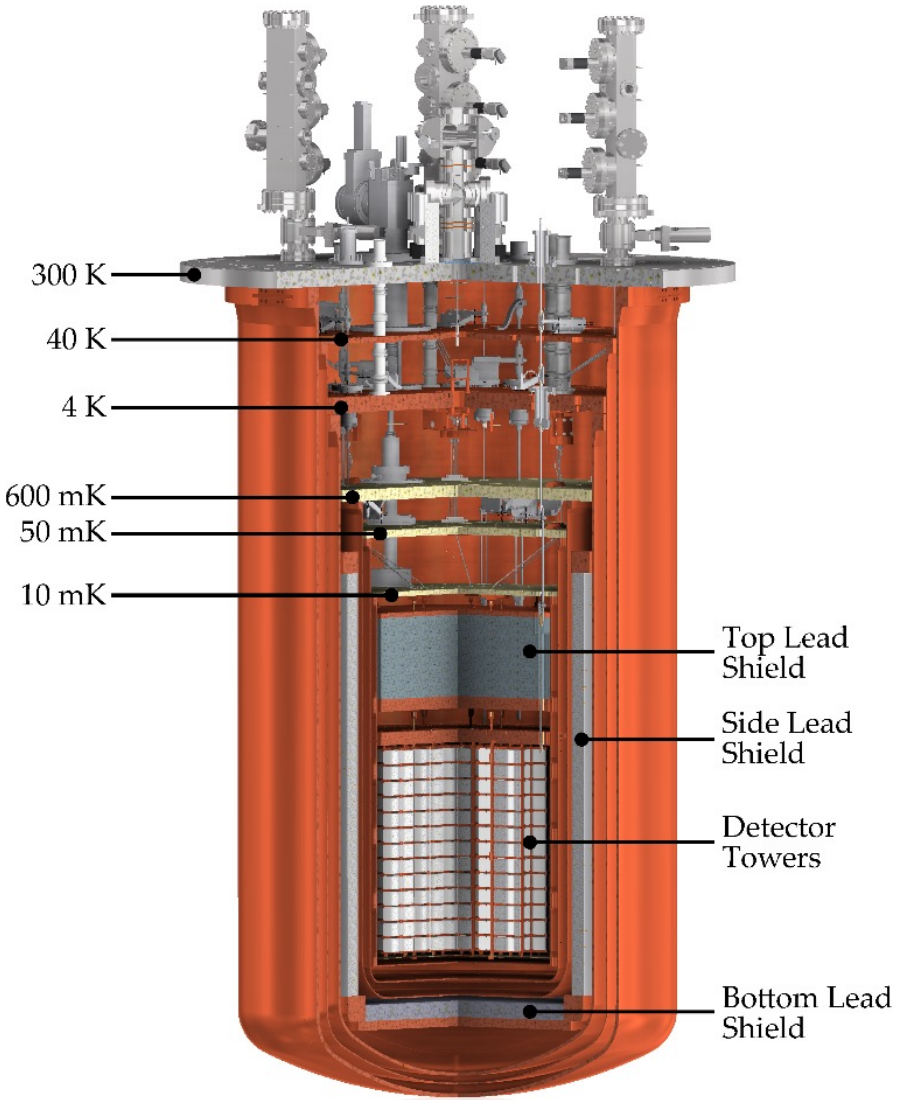
October 29, 2014

HUFF POST SCIENCE

Scientists Create Coldest Cubic Meter In The Universe, Claim New World Record

The Huffington Post | By Jacqueline Howard

Posted: 10/27/2014 9:31 am EDT | Updated: 10/27/2014 9:59 am EDT



CUORE 无中微子双贝塔衰变实验

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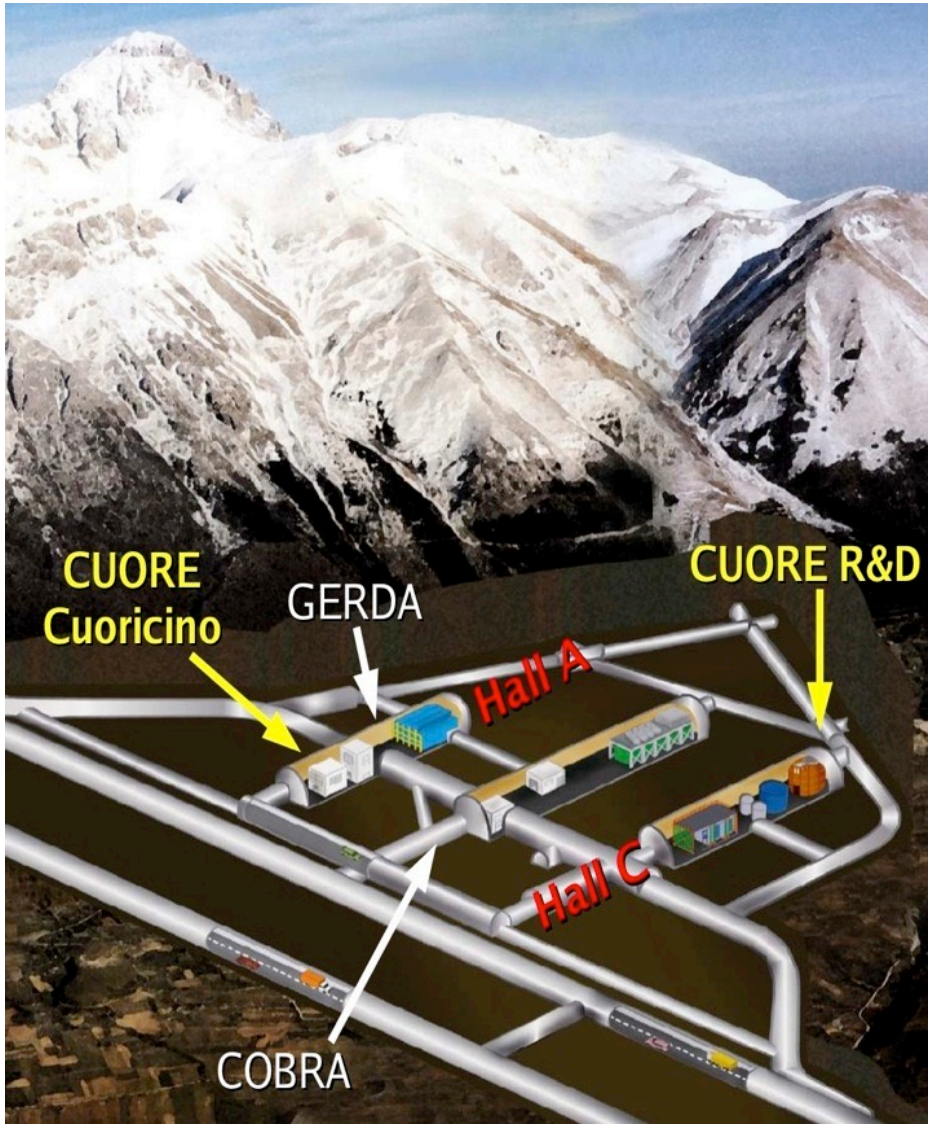
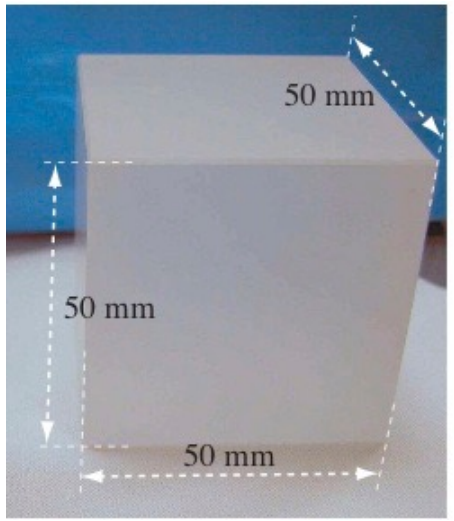
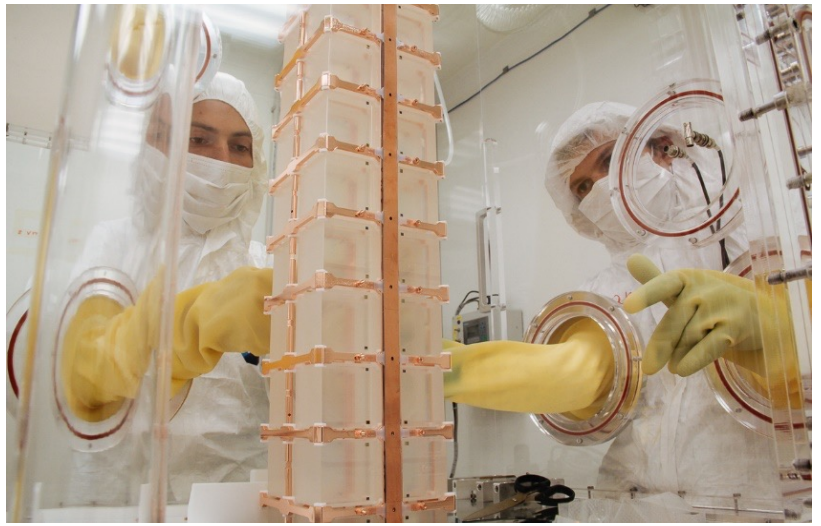
  - 晶体质量741 kg; 206 kg ^{130}Te
- 世界上最大的稀释制冷机，把整个阵列冷却到10mK
- 意大利格兰沙索地下实验室Gran Sasso underground lab (LNGS)
  - 大约1400米的埋深
- 2017年初开始取数

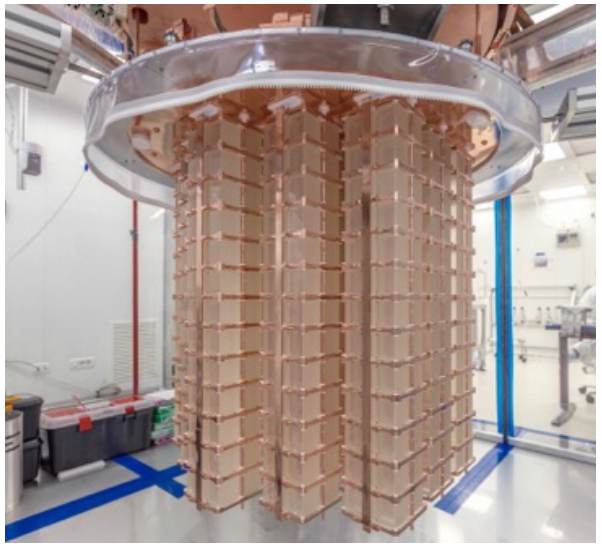


CUORE 二氧化碲（TeO_2）晶体

- 5x5x5 cm^3, 750g
  - 相对经济的最大晶体
- ΔT = 0.1 mK/MeV at 10 mK
- 0νββ要求:低本底radio-pure
- Survives the heat cycling
  - ✓TeO2
  - x Te
- 硅酸盐所生产

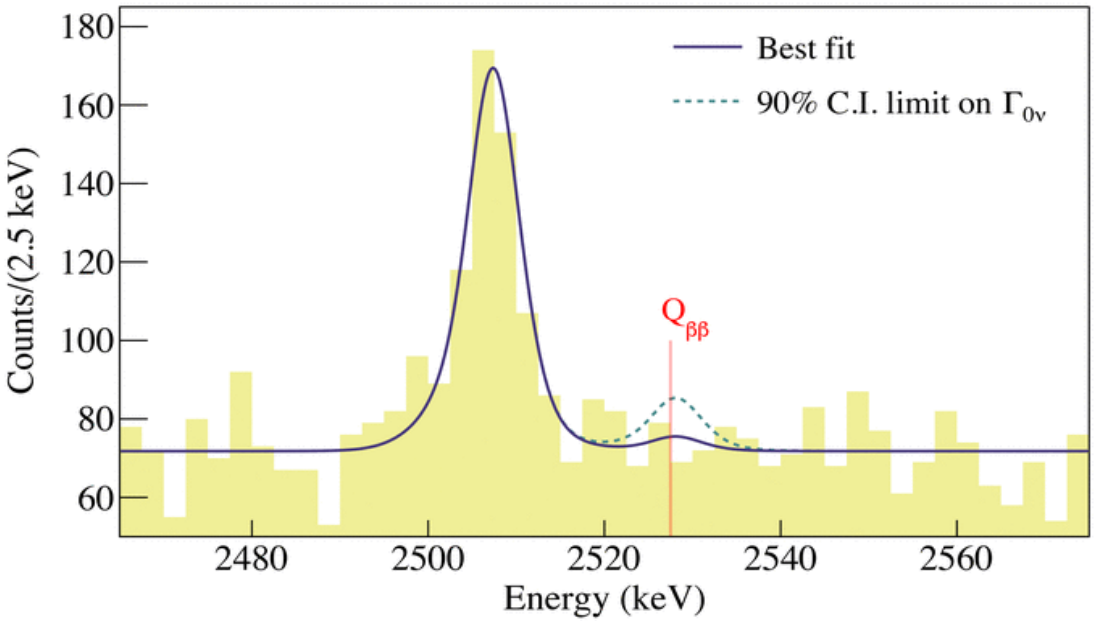


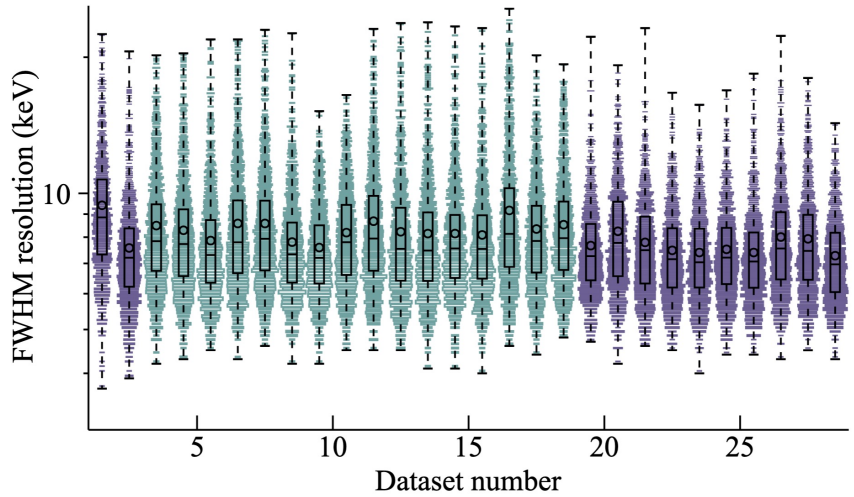


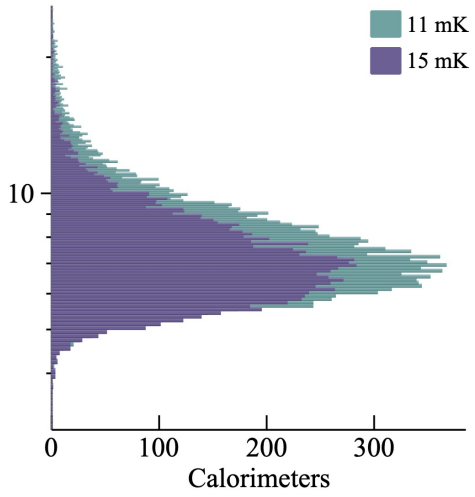


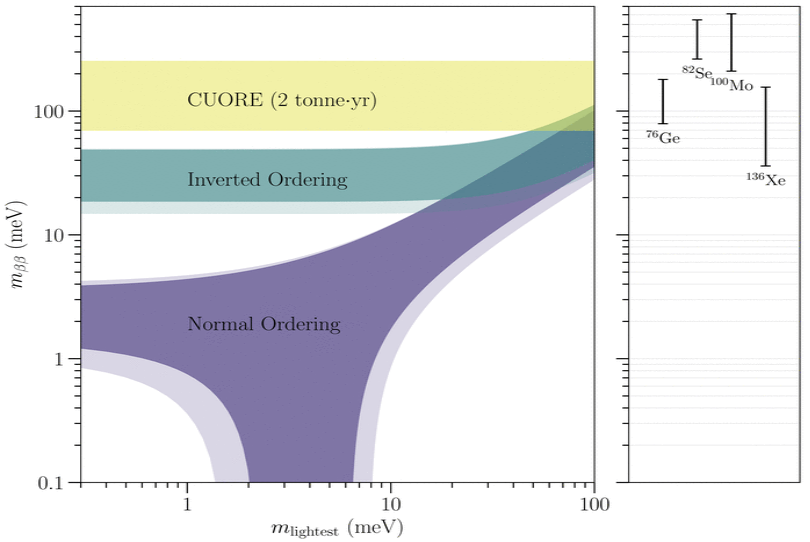
CUORE 稳定运行近十年

- 能量分辨率稳定在 7 keV (at 2.6 MeV)
- 屡次刷新130Te 最好结果
- 最新2吨年数据发表在Science
- DOI: (10.1126/science.adp6474)



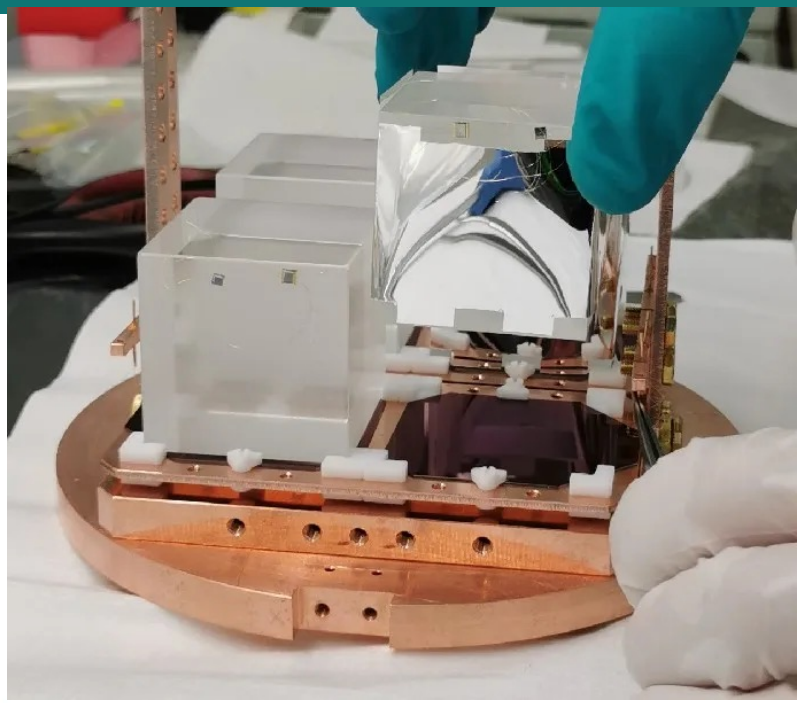




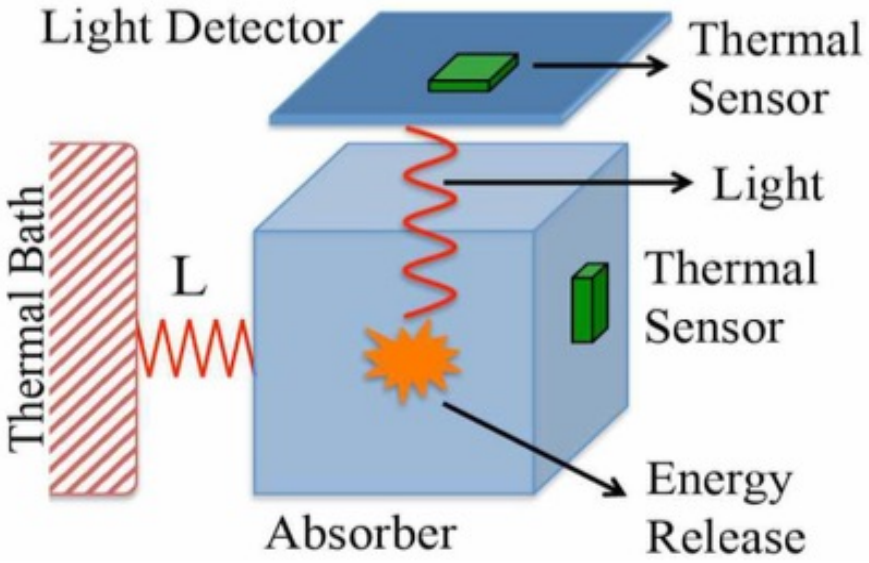


CUPID - CUORE Upgrade with Particle ID

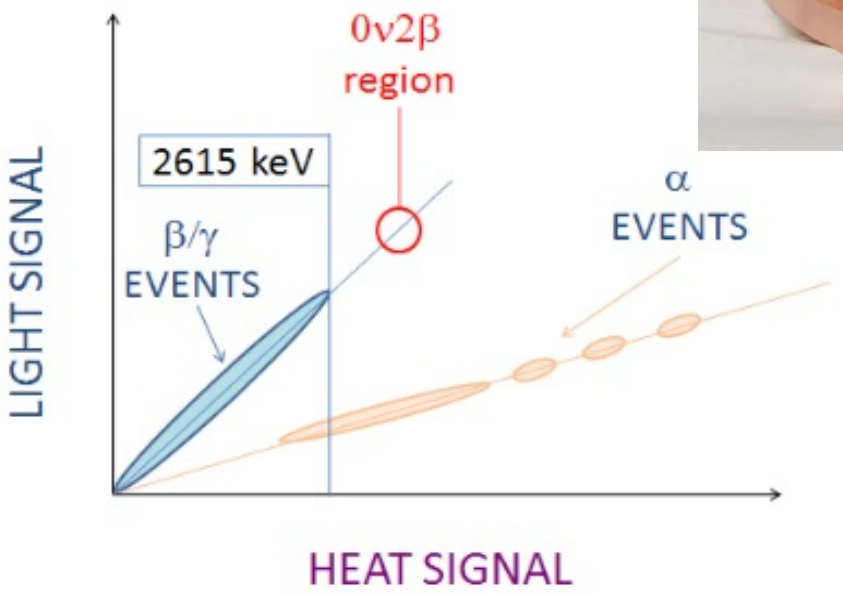
- 富集^{100}Mo的钼酸锂（LMO）晶体
- 光读出→本底粒子鉴别



Scintillating Bolometer

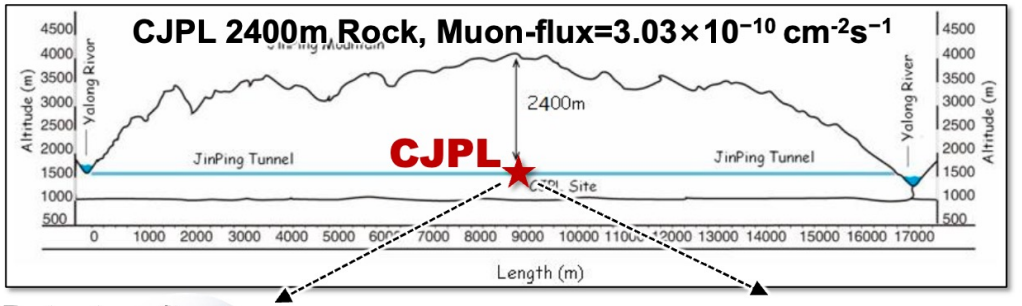


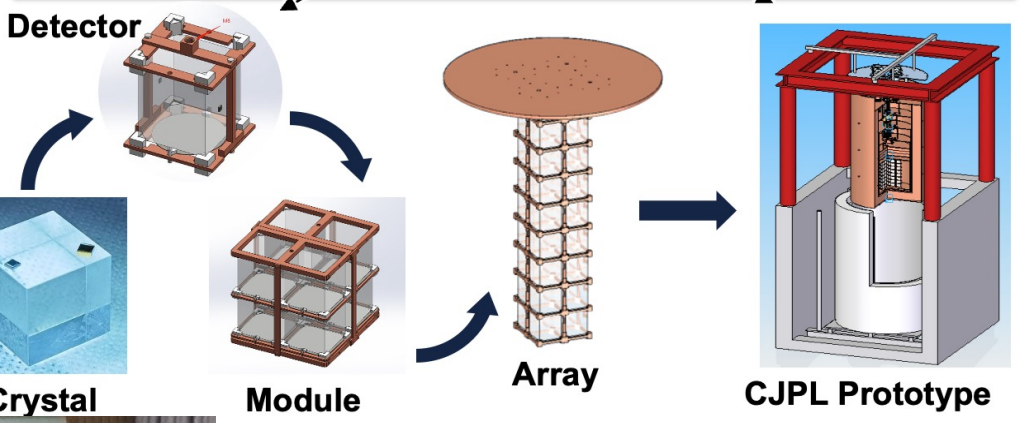
Particle Identification



CUPID-CJPL

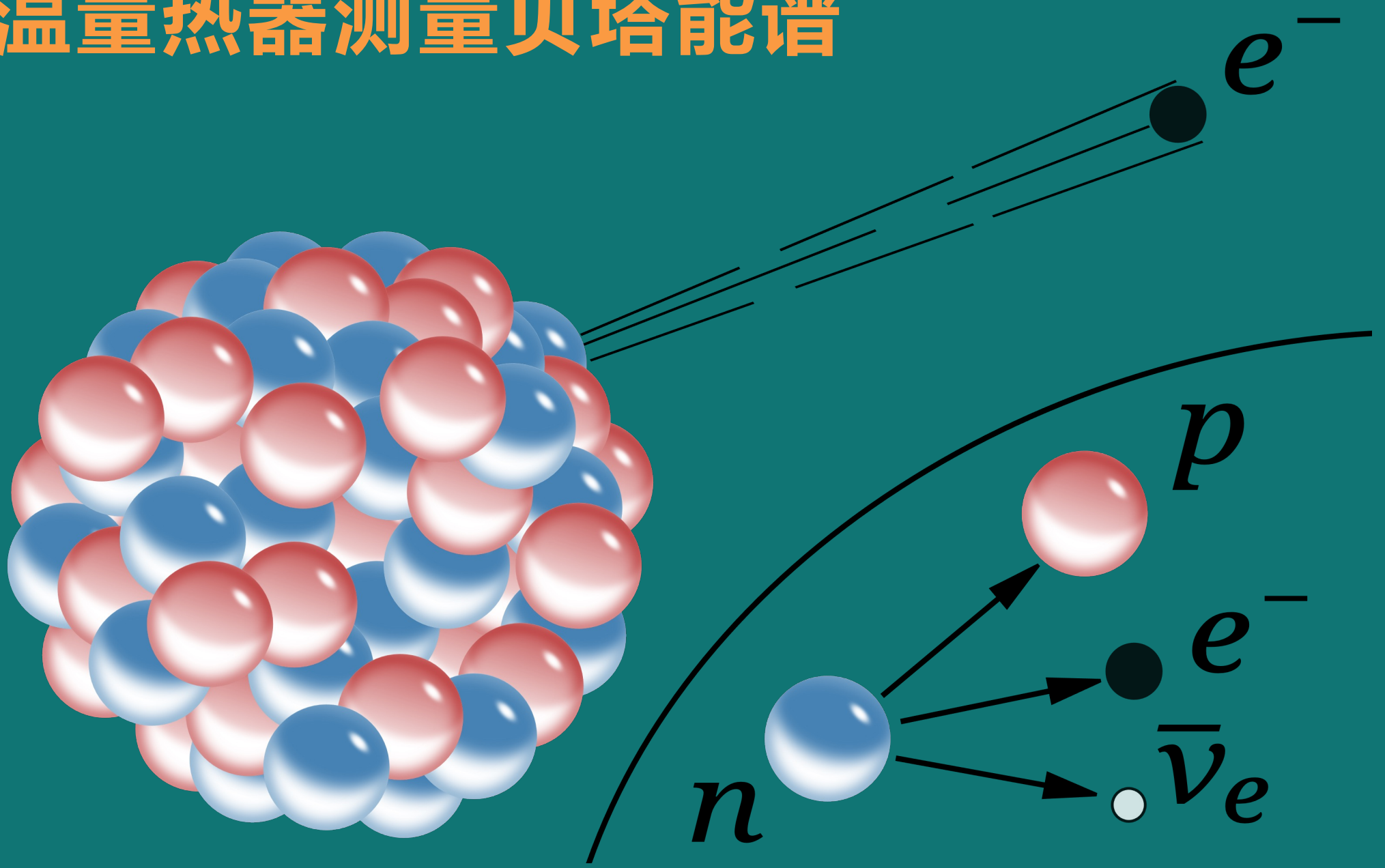
- 发展国内的低温闪烁量热器技术
- 开展无中微子双贝塔衰变实验预研
- 基金委重大科学基础设施CJPL集成项目



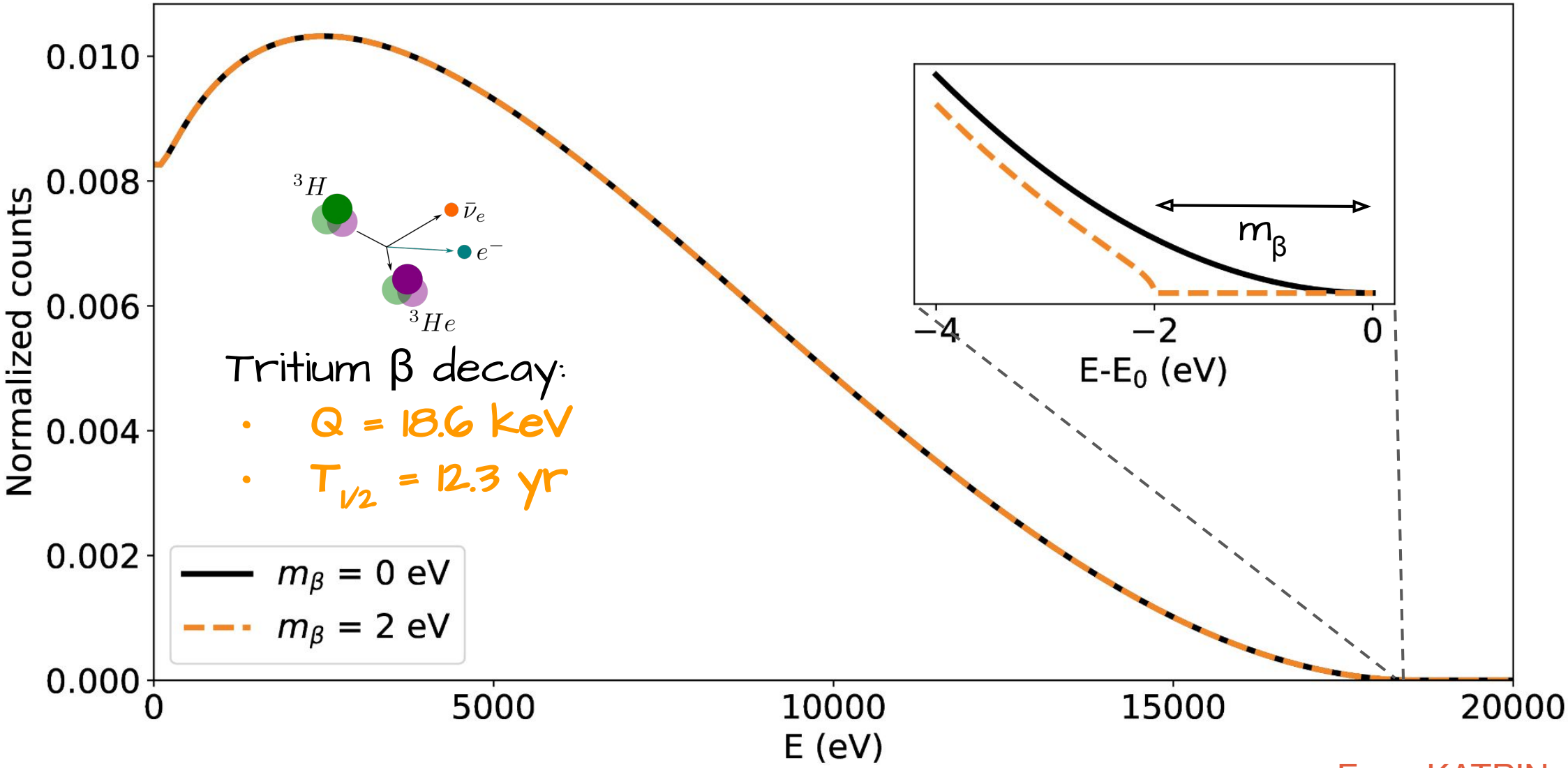


清华 + 复旦 +
科大 + 上交

低温量热器测量贝塔能谱

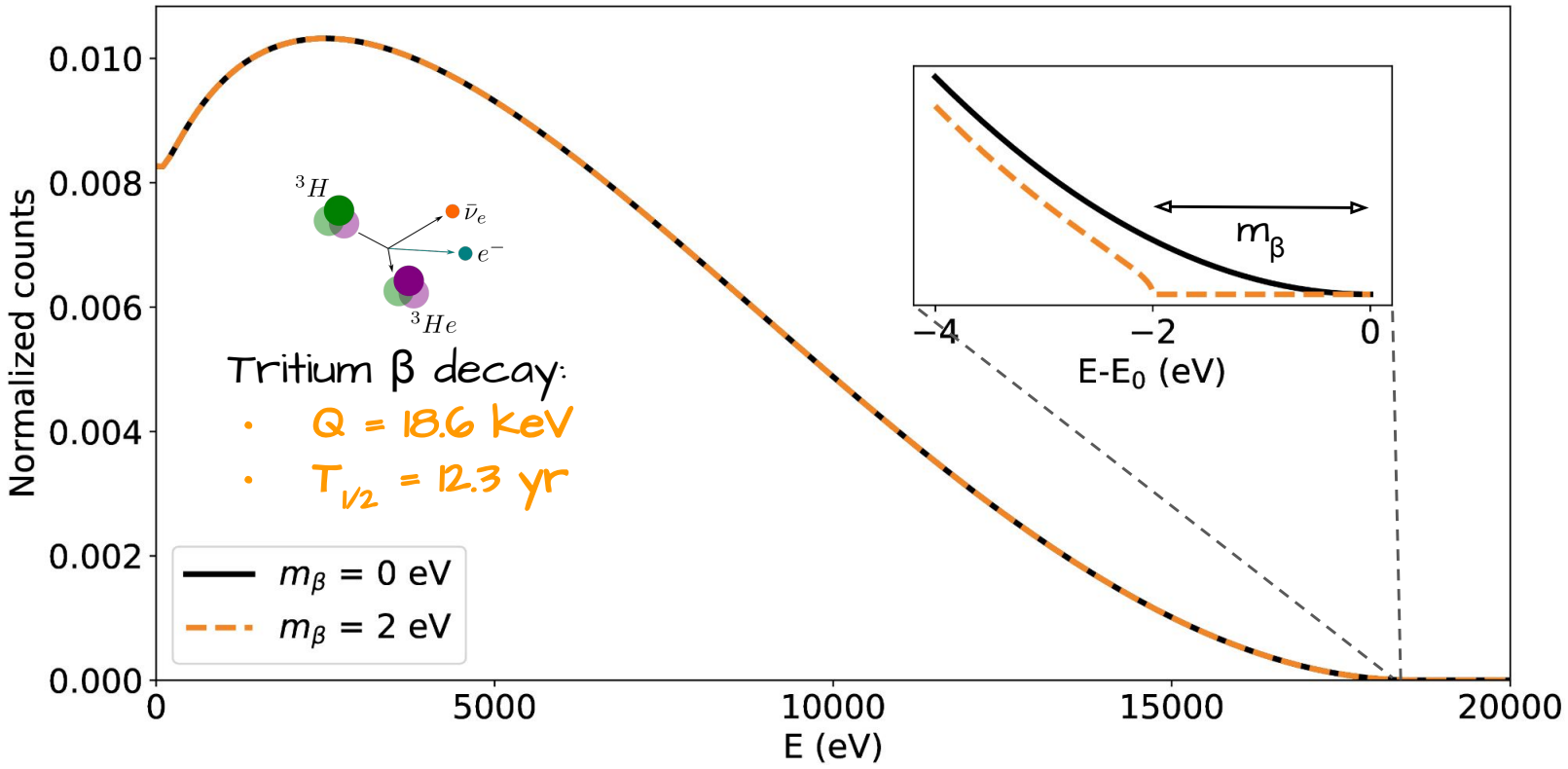


最简单：氚 β spectrum



From KATRIN

理论计算：氚 β spectrum



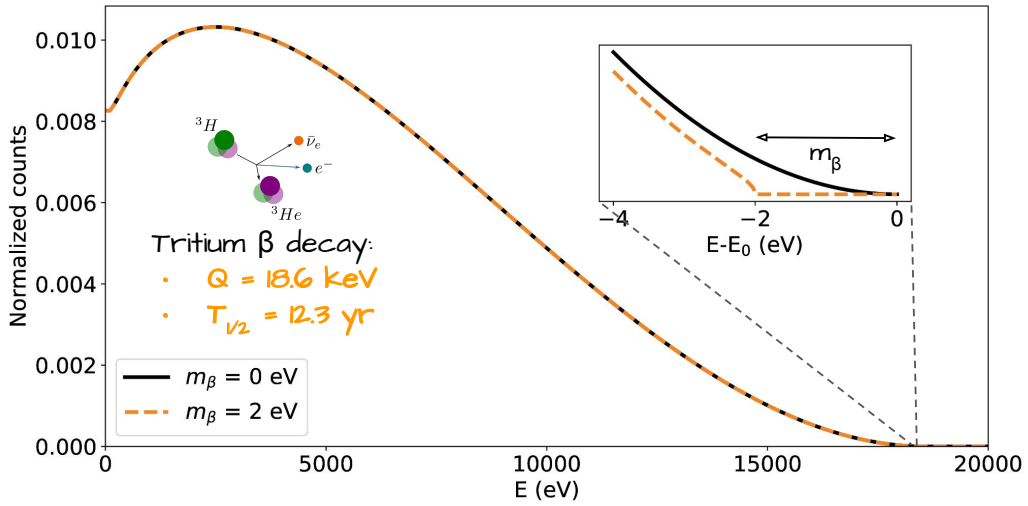
- Initial and final state
- V-A
- Fermi screening correction
- Weak magnetism current
- Recoiled Coulomb potential
- Finite nuclear size correction
- Radiative correction
- Atomic Quantum Effect (AQE):
  - Exchange of β and e^-

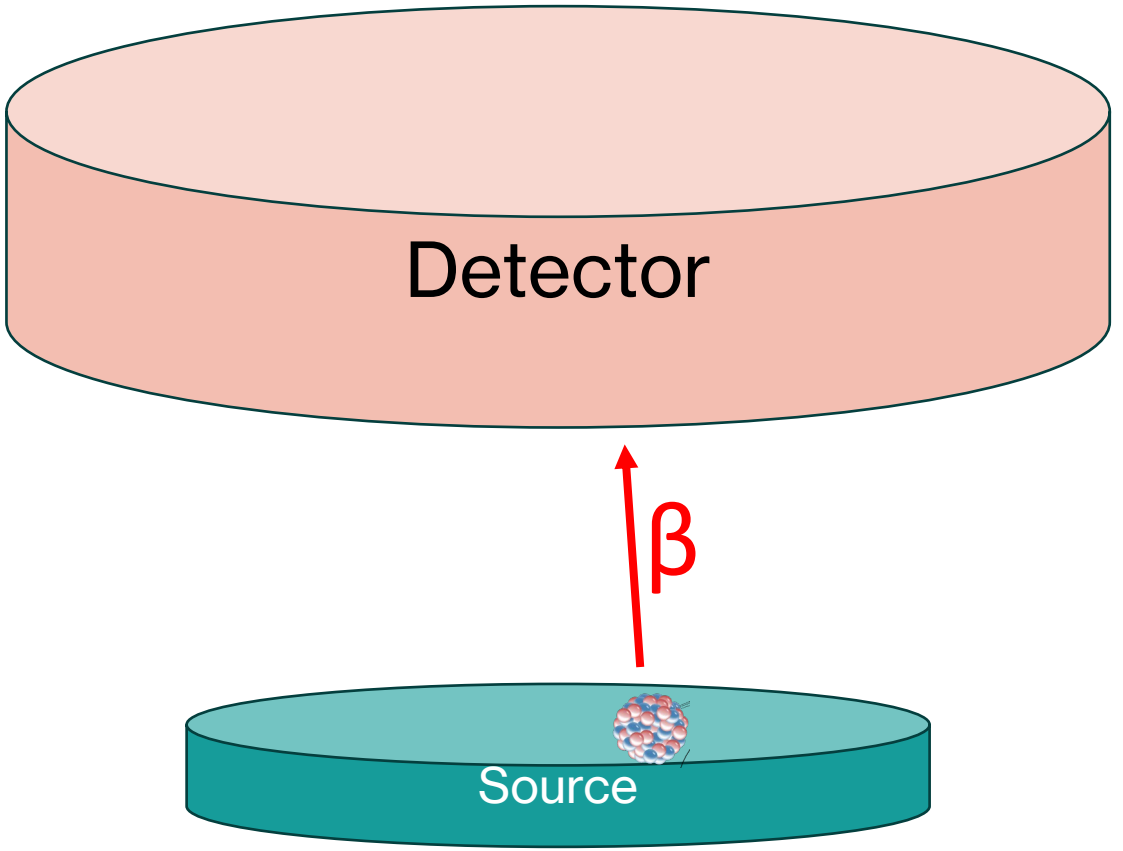
From KATRIN

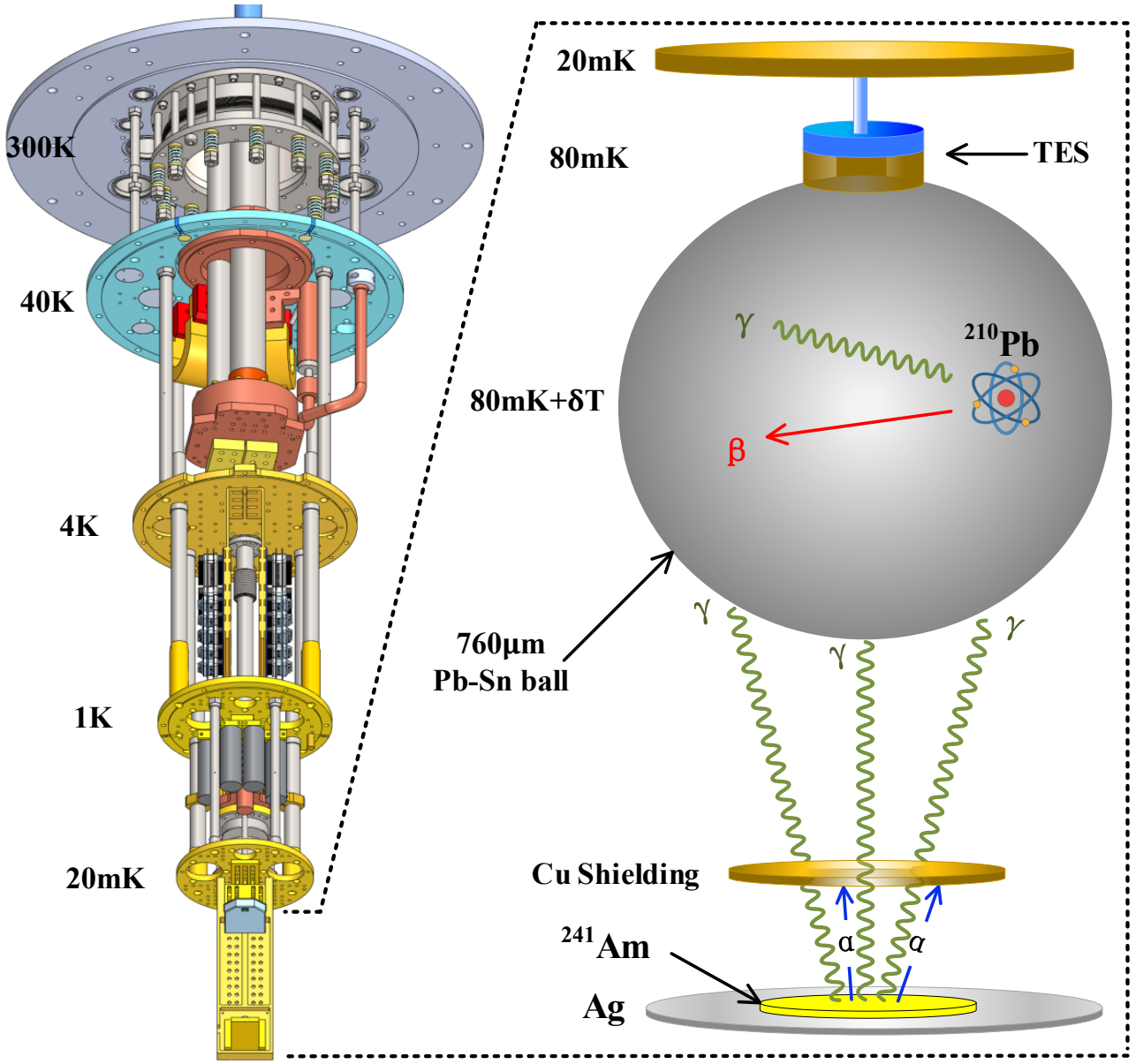
精密 β 能谱测量很有挑战

1. 电子从源中放出后，立即损失能量
2. 探测器阈值效应
3. 能量响应模型
4. 本底信号

- **完整精确β能谱尚未测量**



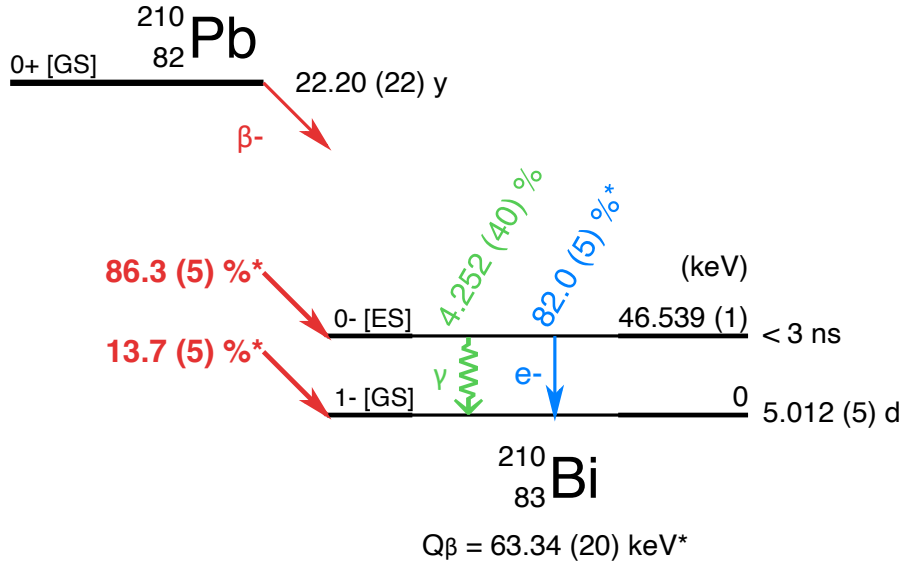




Shuo Zhang, Hao-Ran Liu, Ke Han, Xavier Mougeot, Paul-Antoine Hervieux, *et al.* Arxiv:2509.26390

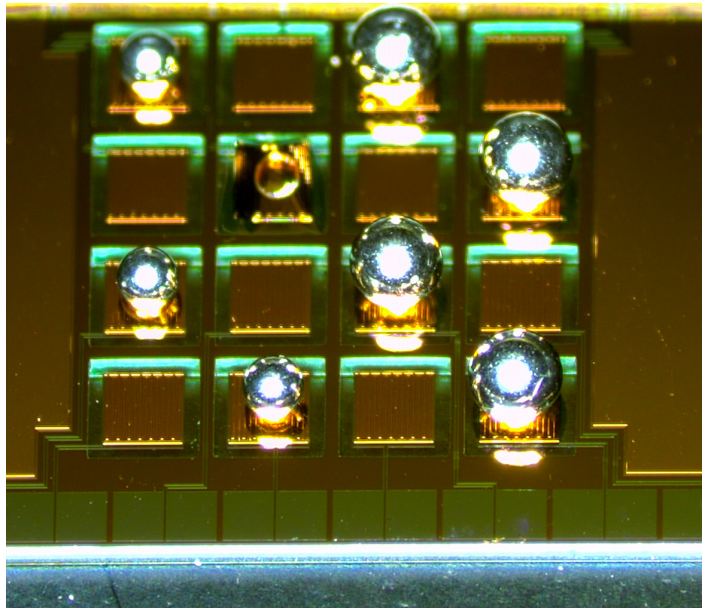
源 = 低温量热器

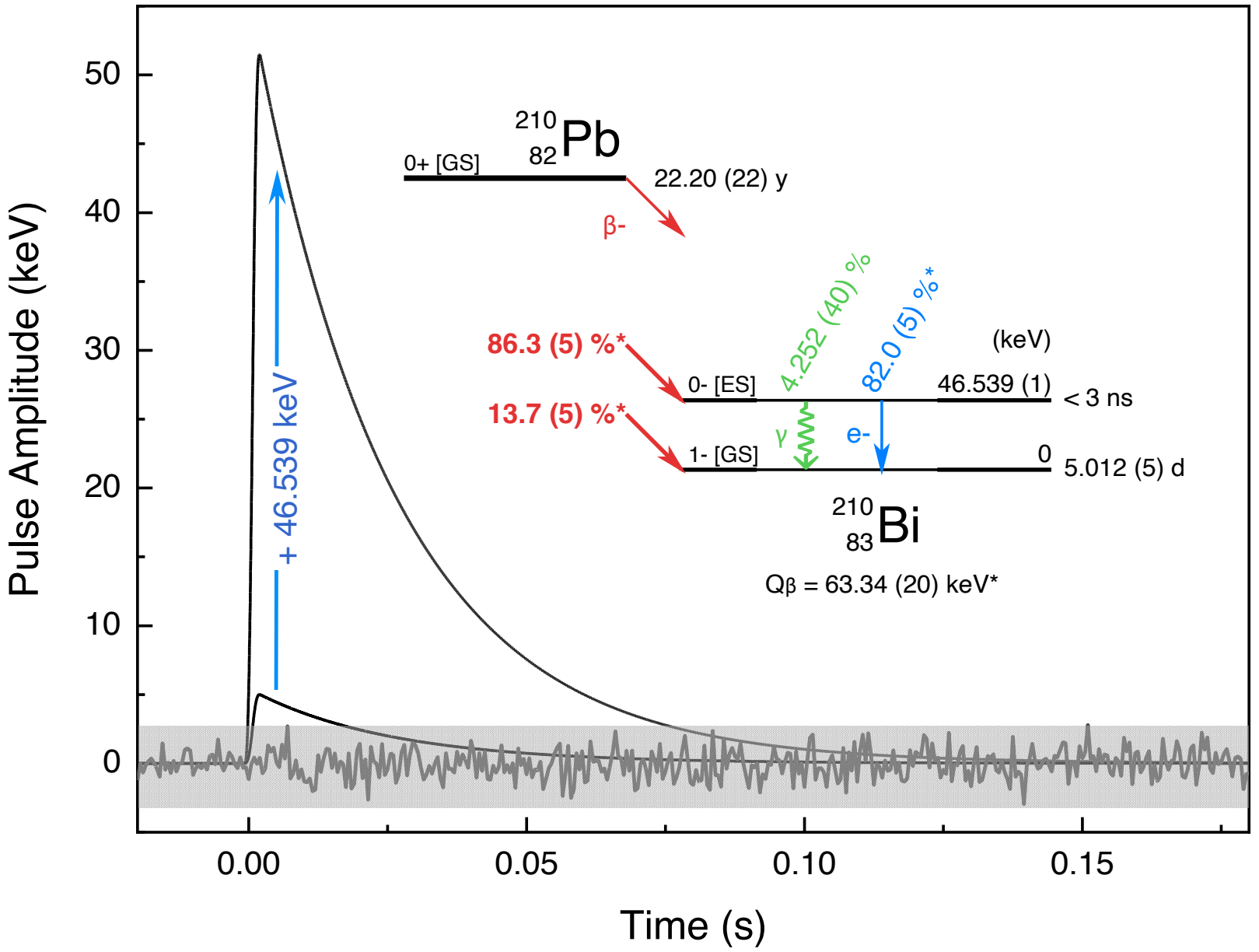
😀 所有能量沉积到探测器中



γ coincidence summing

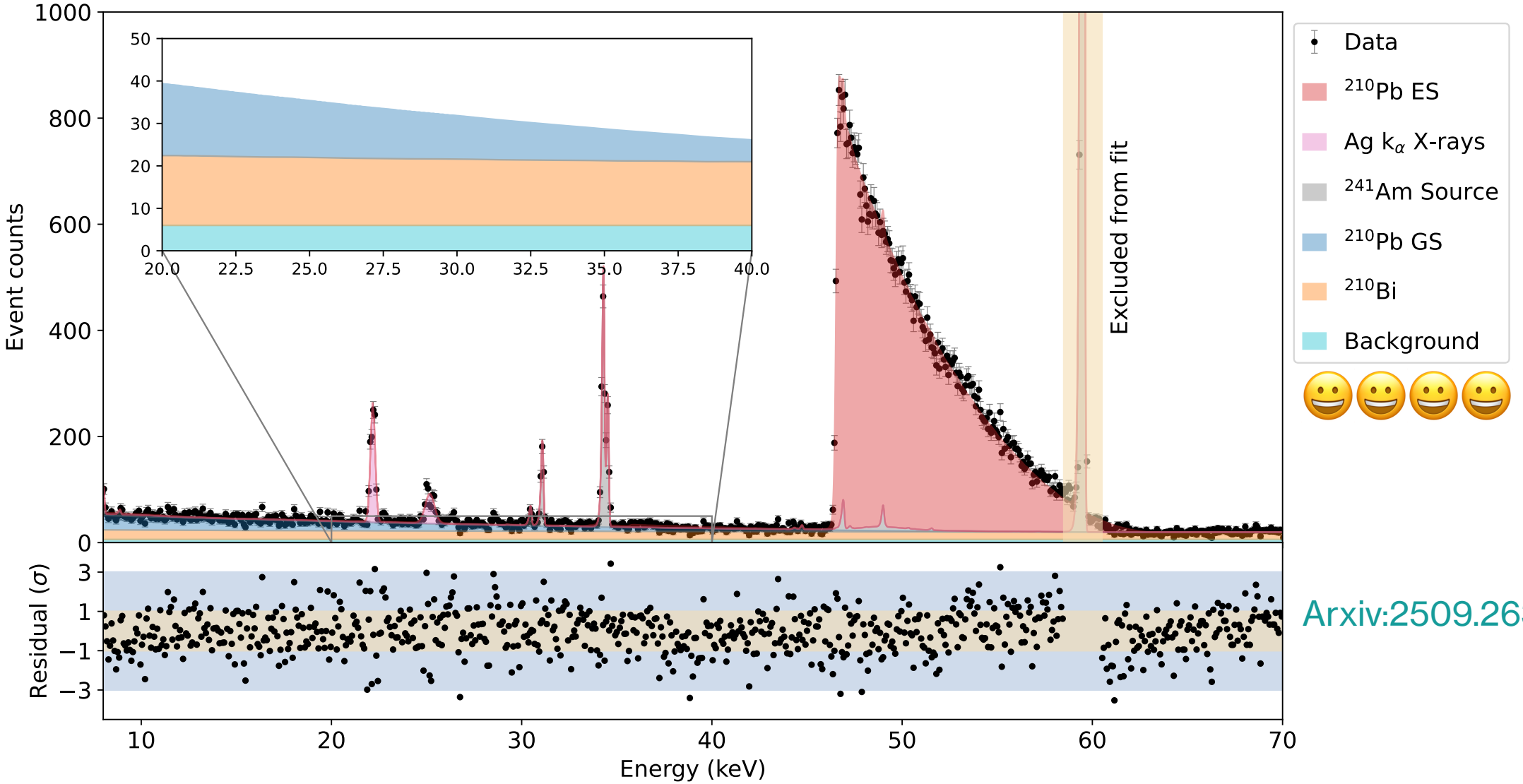
😀😀 无阈值 β 测量





Arxiv:2509.26390

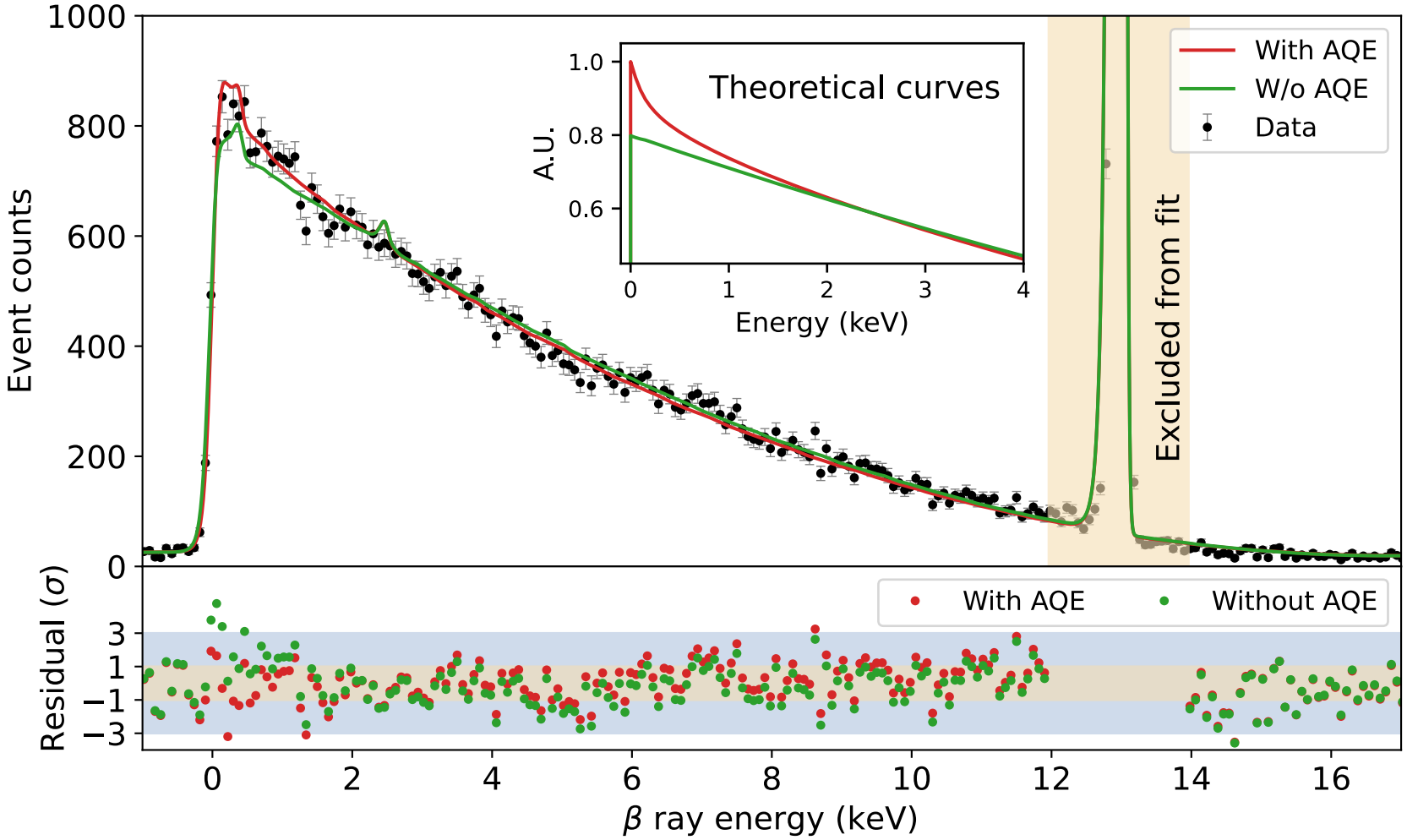
😀😀😀 多个单能峰用于能量标定



😀😀😀😀

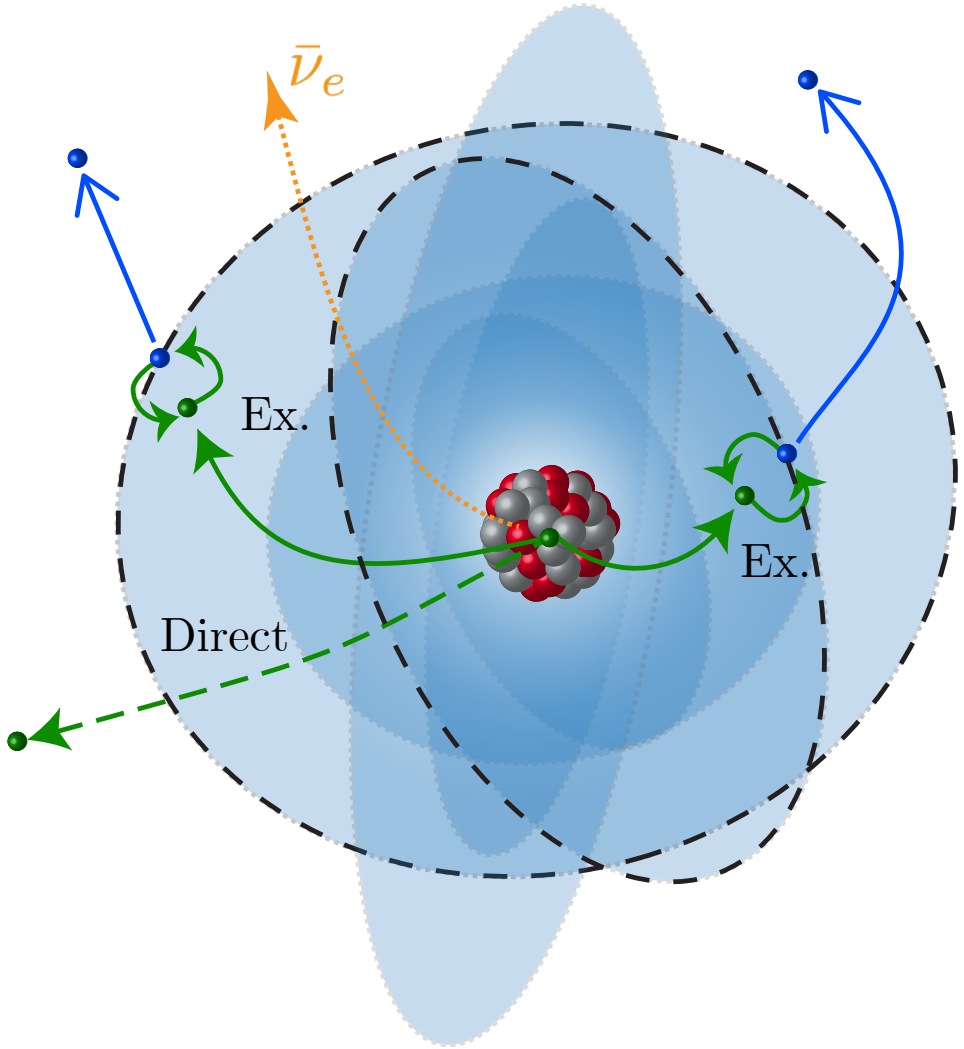
Arxiv:2509.26390

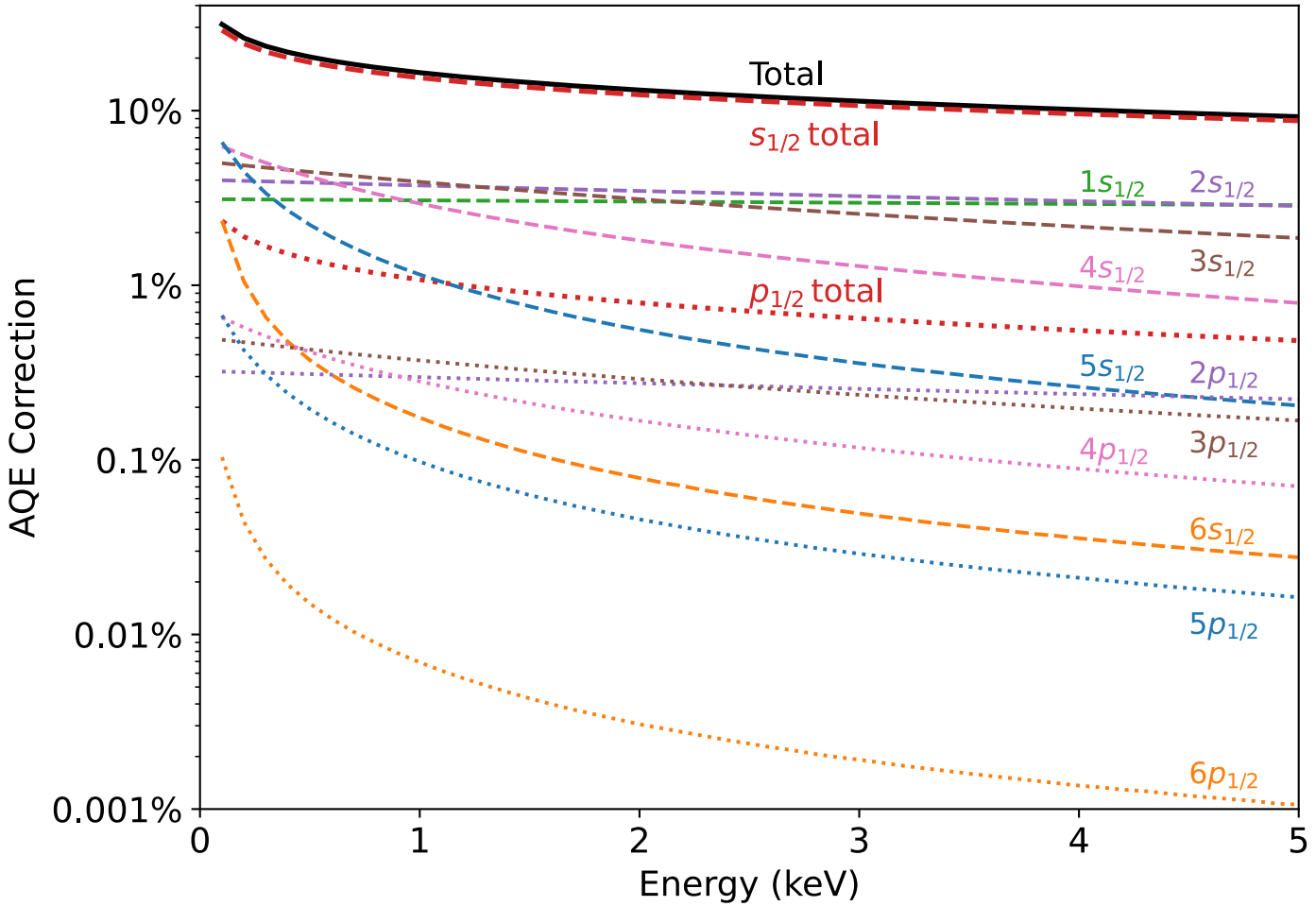
首个从 0 keV 开始测量的完整精确 β 能谱



Arxiv:2509.26390

AQE: 所有电子轨道都贡献低能 β





Atomic Quantum Effect (AQE)

Arxiv:2509.26390

^{210}Pb is a lucky choice, and the “only” candidate

Reasonable halflife

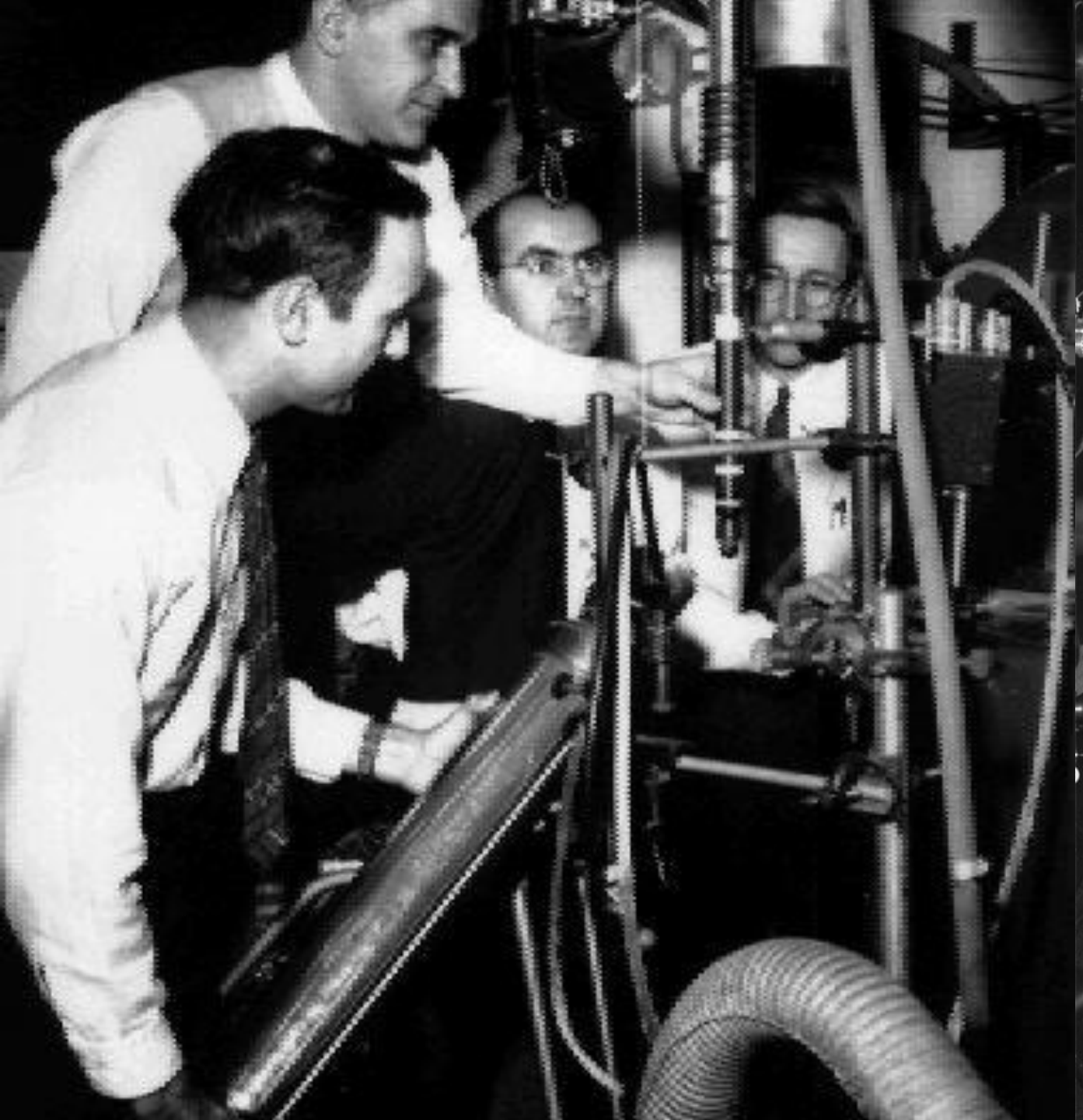
Relatively simple decay scheme

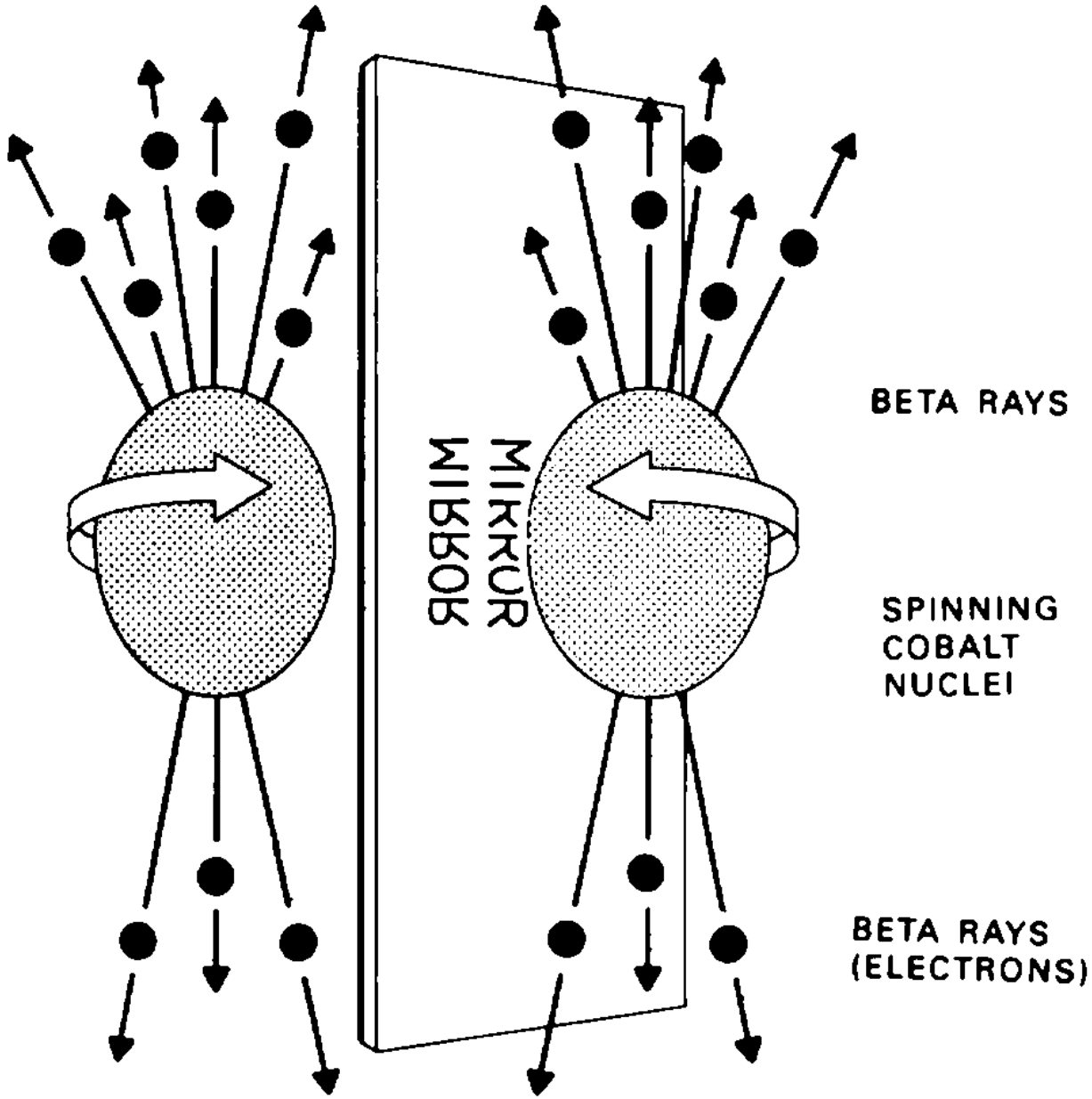
Right β and γ energies

“Accidental” exposure

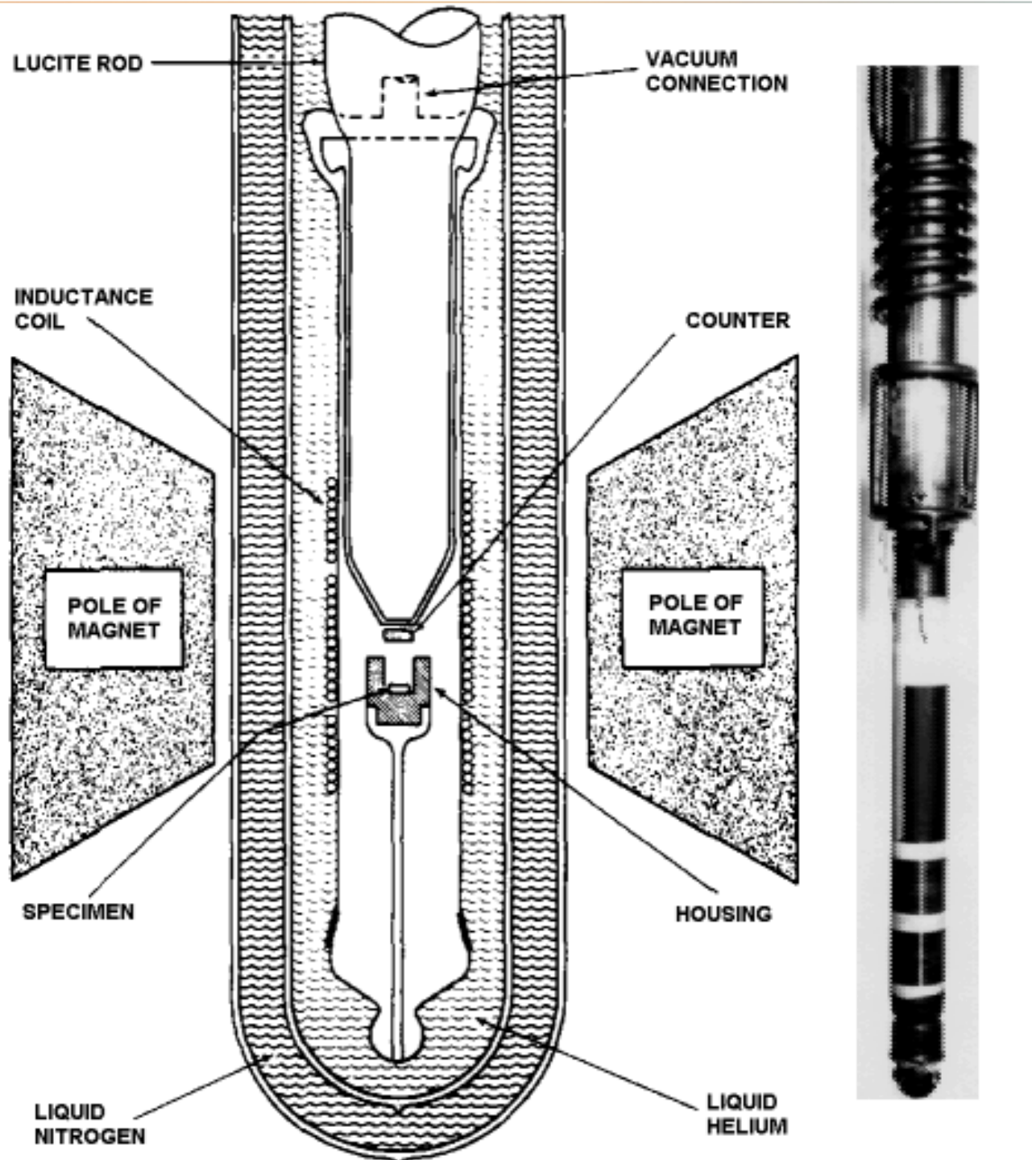
总结

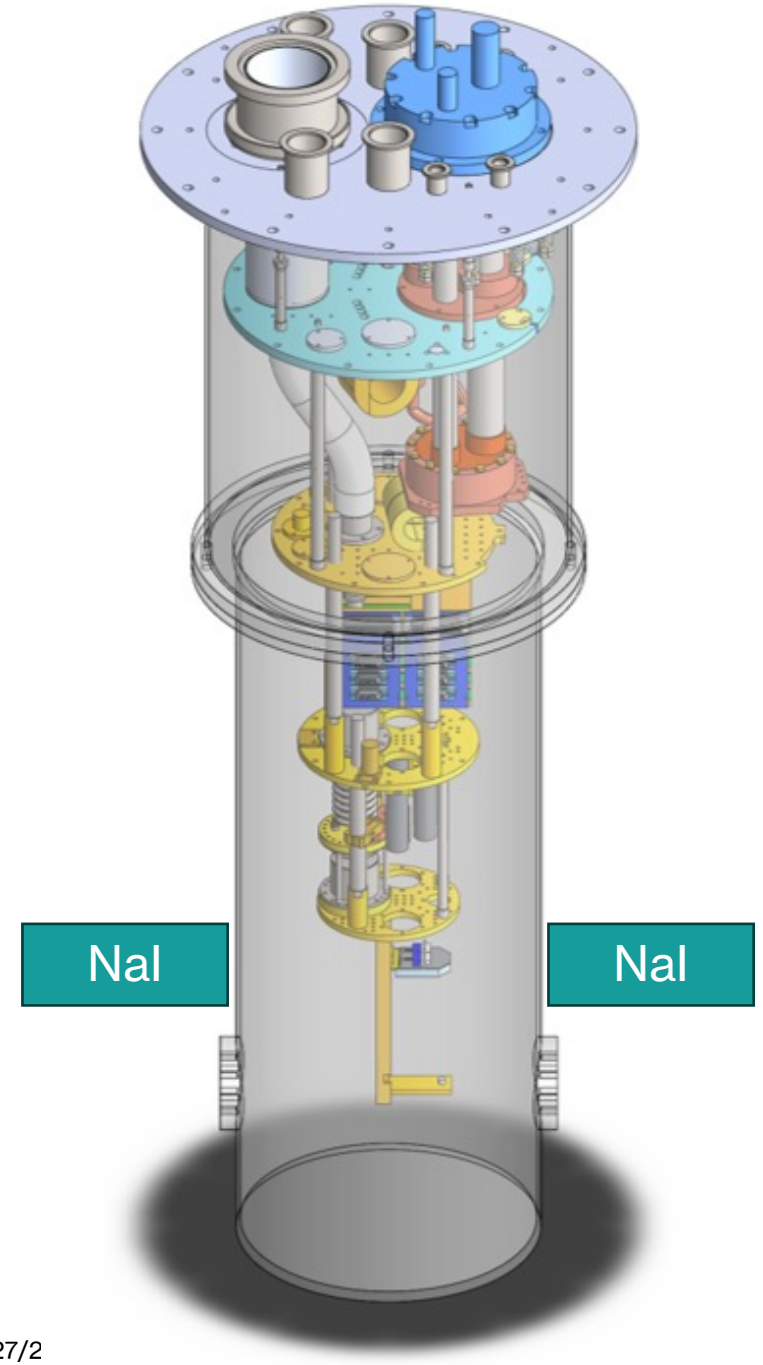
1. 低温量热器是一项广泛应用的精密探测技术
2. CUORE/CUPID 实验持续推动低温量热器技术在无中微子双贝塔衰变中的应用
3. 基于 TES 量热器，精确测量 β 能谱
4. 广阔的粒子物理与核物理应用场景

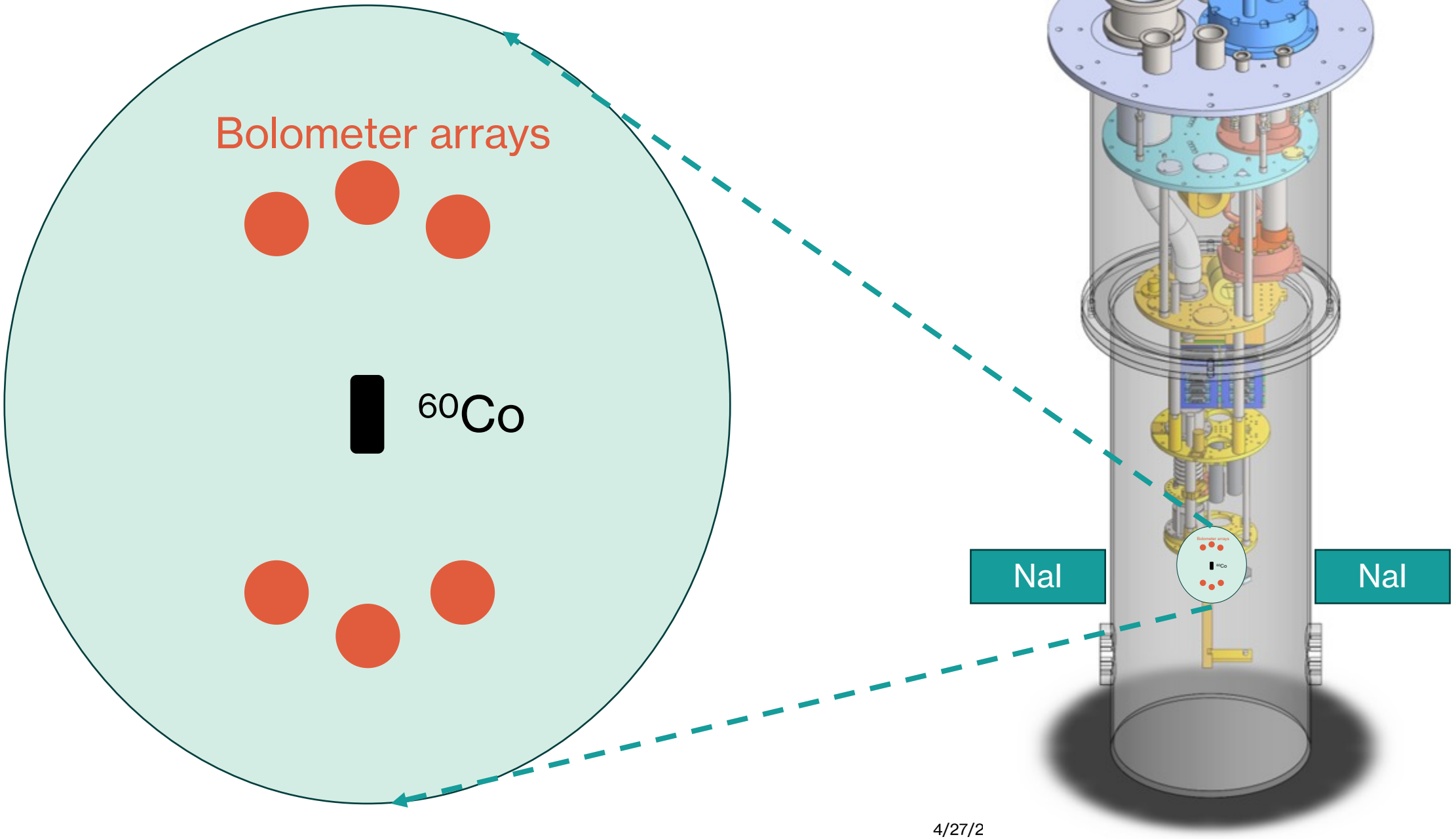




Beta anistropy

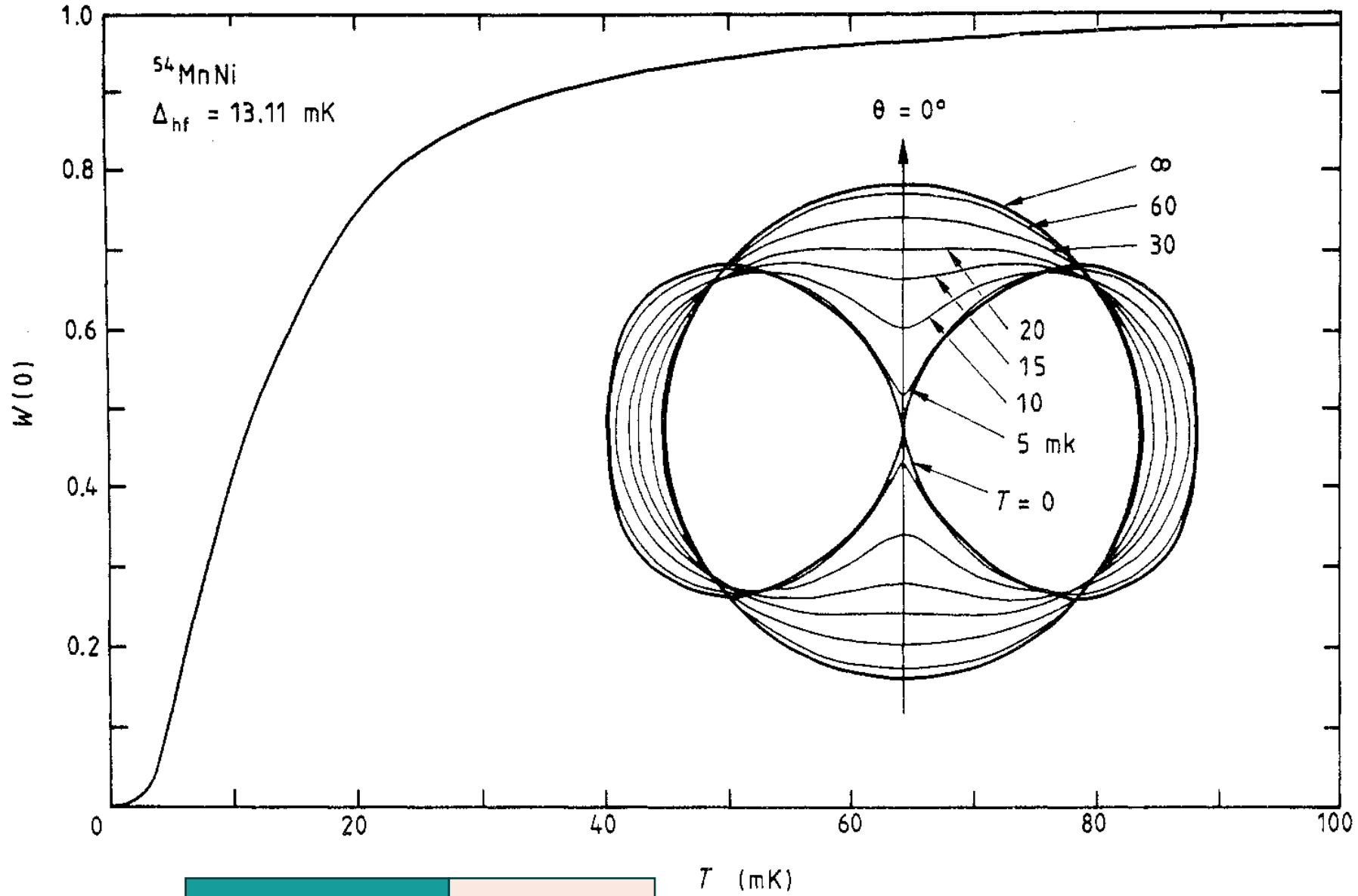

LUCITE ROD
VACUUM CONNECTION
INDUCTANCE COIL
COUNTER
POLE OF MAGNET
POLE OF MAGNET
SPECIMEN
HOUSING
LIQUID NITROGEN
LIQUID HELIUM


NaI
NaI


Bolometer arrays
^{60}Co
NaI
NaI

PMT

NaI

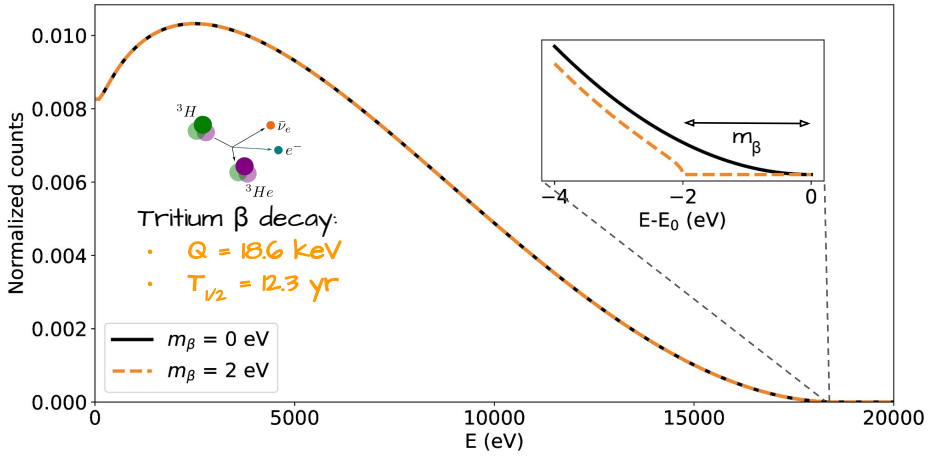


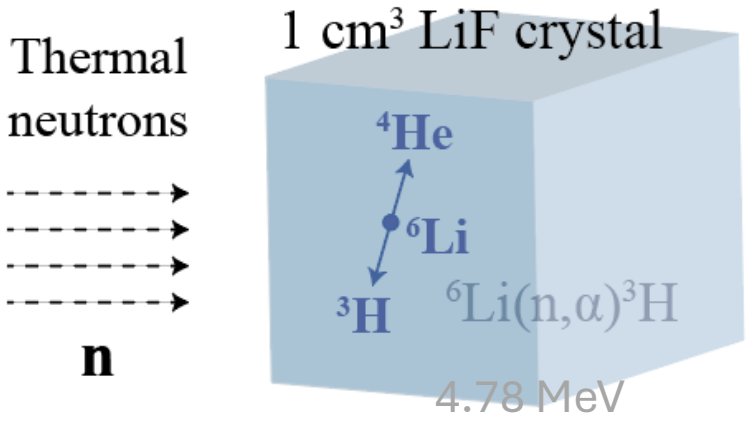
^{60}Co

NaI PMT

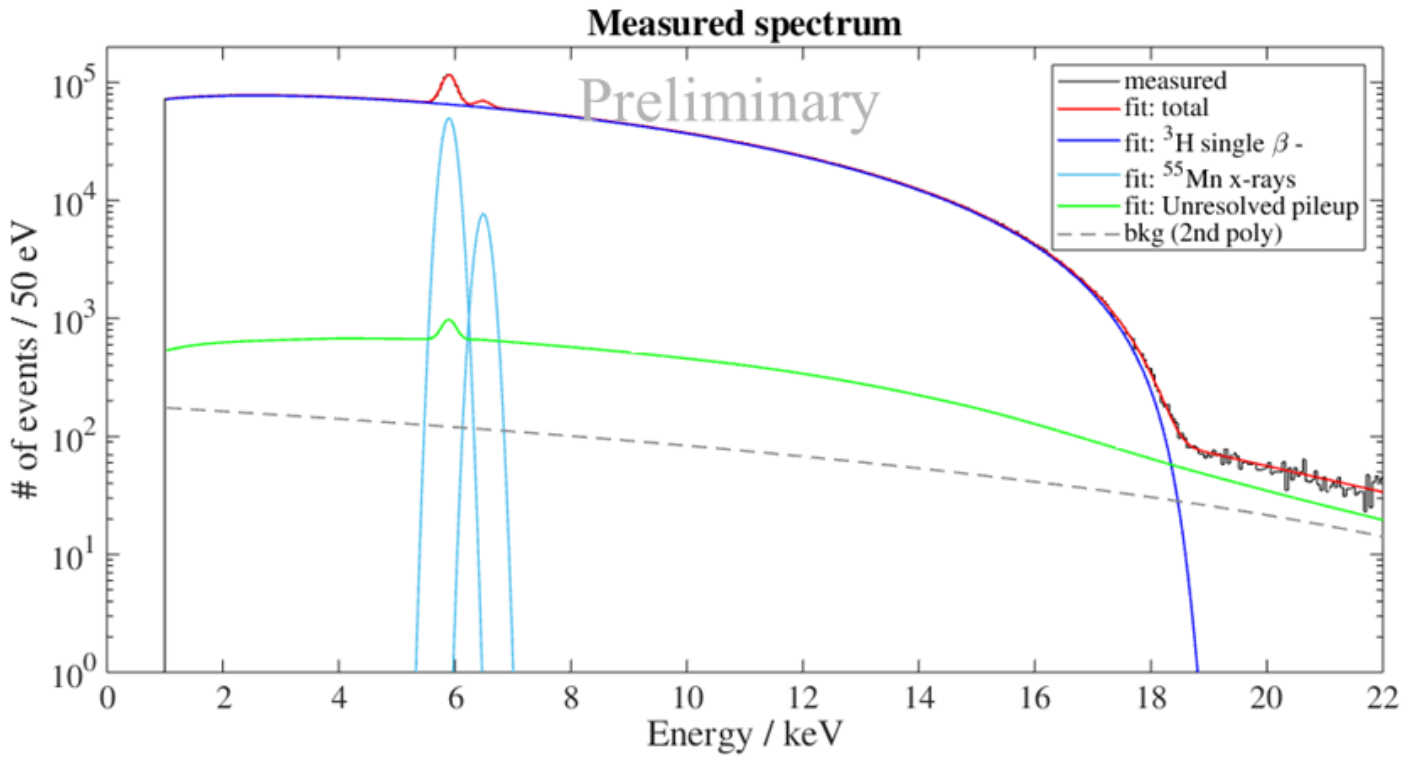
Fatterns for a typical gamma-ray angular distribu-
t relative to the quantisation axis; corresponding temperatures in mK are indicated. The main curve shows the gamma-ray anisotropy at $\theta = 0°$ as a function of temperature (after Marshak 1983).

实验测量：氚 β spectrum





From LiFE-SNS



1 keV 以上测量能谱