The Axion Dark Matter eXperiment:
From Current Sensitivity to Next-Generation Improvements

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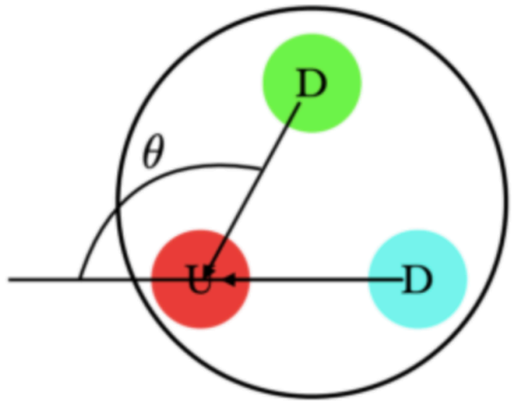
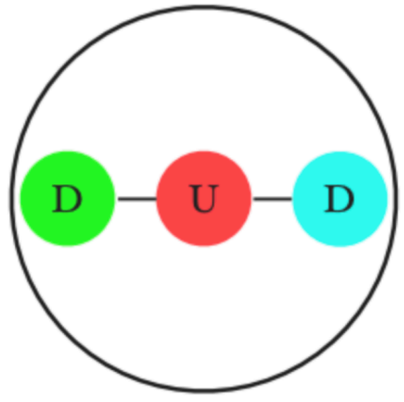
强相互作用CP破缺问题



- 量子色动力学（QCD）的拉式量中自然产生破坏CP对称性项
- $\mathscr{L} = \theta \frac{g^2}{32\pi^2} F_a^{\mu\nu} \tilde{F}^a_{\mu\nu}$
- 但强相互作用的测量均显示QCD是CP守恒的，例如: 中子电偶极矩测量对θ产生极强限制 $\theta < 5 \times 10^{-11}$ (来自PSI的结果)



C. Abel et al., Phys. Rev. Lett. 124, 081803 (2020)

Credit to Anson Hook, arXiv:1812.02669

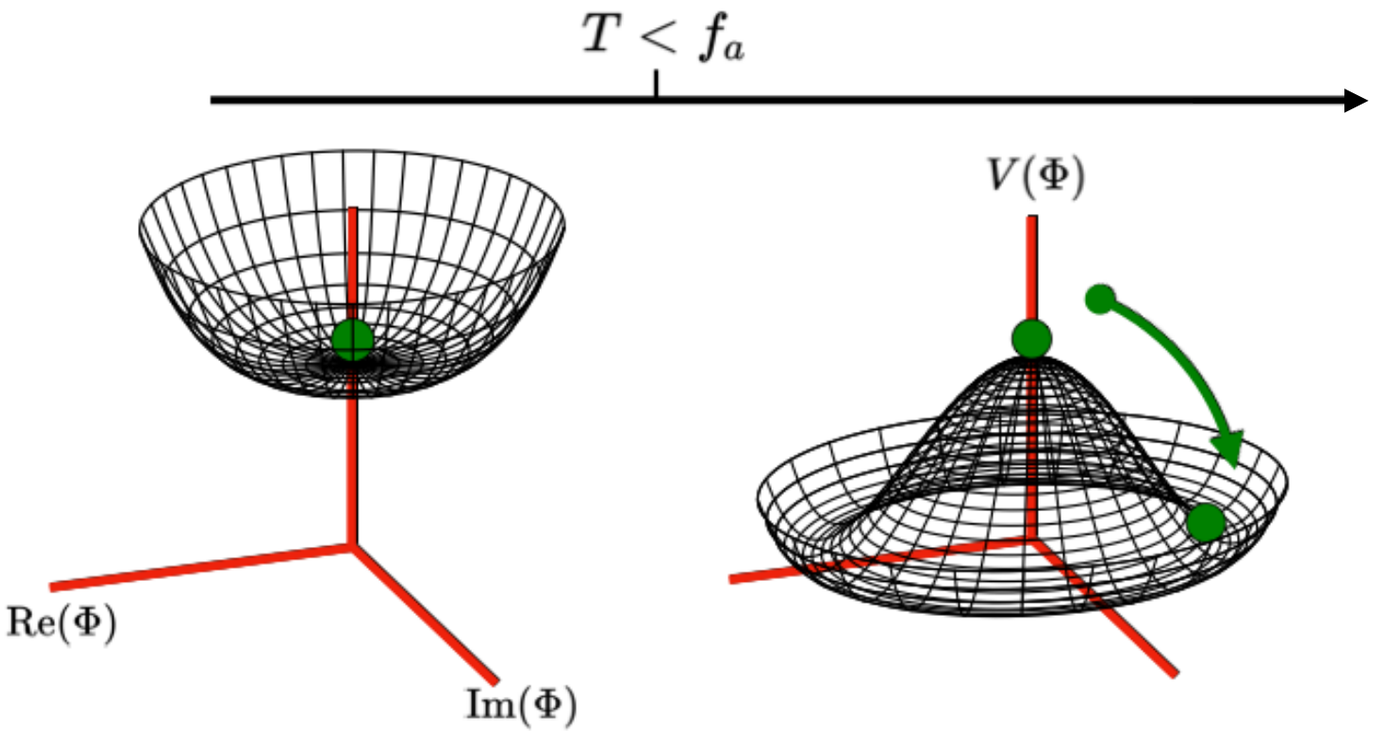
Peccei-Quinn（PQ）机制

- Roberto Peccei 和 Helen Quinn 提出：一个超出标准模型的对称性$U_{\mathrm{PQ}}(1)$，可使θ在低能区等效趋于0

  R. D. Peccei and Helen R. Quinn, Phys. Rev. Lett. 38, 1440 (1977)

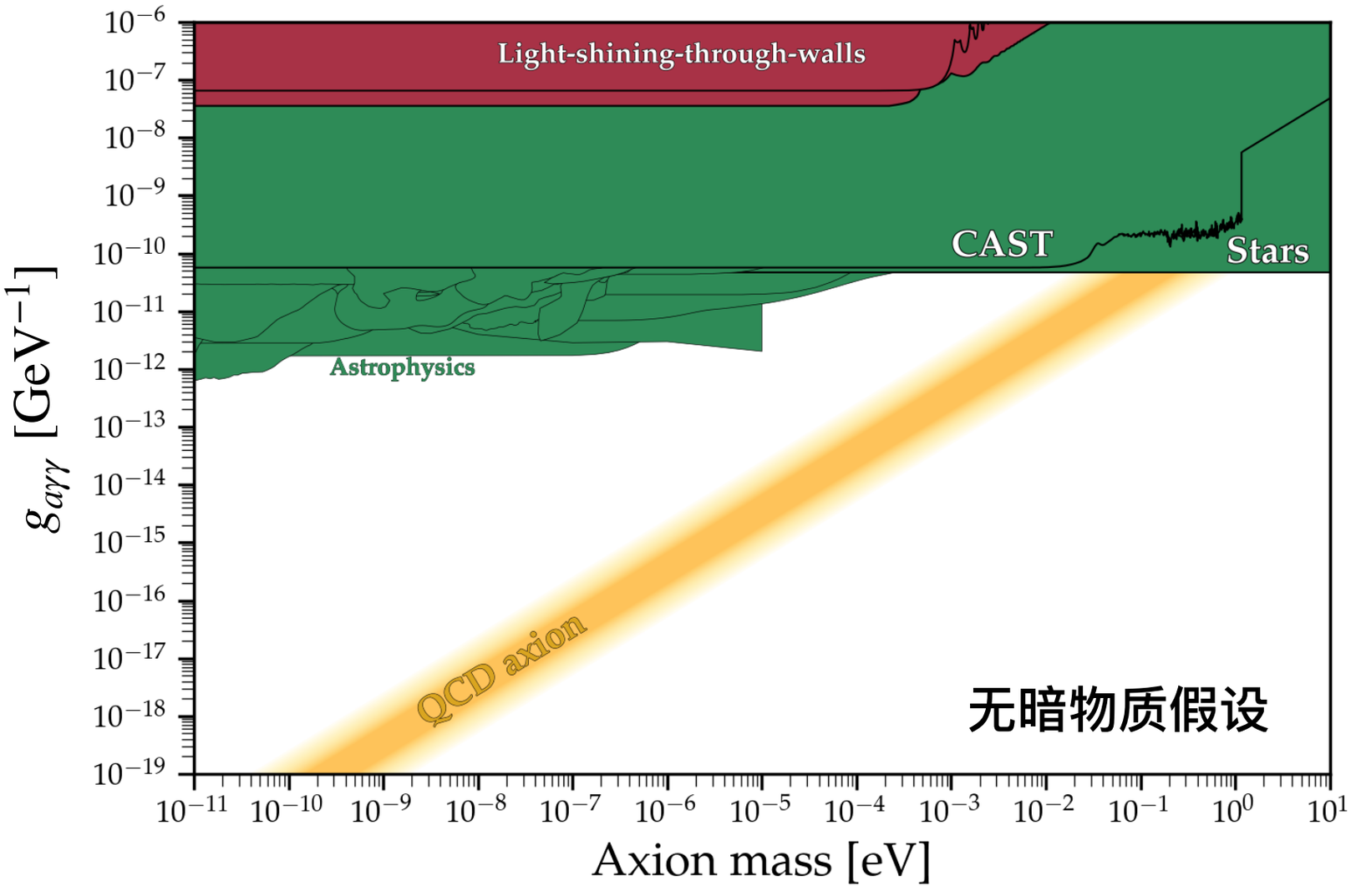
- Frank Wilczek和Steve Weinberg提出：在$U_{\mathrm{PQ}}(1)$自发破缺后，会产生一个Pseudo Nambu Goldstone 玻色子，被命名为轴子（Axion）

  F. Wilczek, Phys. Rev. Lett. 40, 279 (1978)　　*Steven Weinberg, Phys. Rev. Lett. 40, 223 (1978)*



轴子能标

- 轴子质量与$U_{\mathrm{PQ}}(1)$ 自发对称破缺能标f_a的关系$m_a = \dfrac{m_\pi f_\pi}{f_a}\dfrac{\sqrt{m_u m_d}}{m_u + m_d} \approx 5.7\ \mu\mathrm{eV}\dfrac{10^{12}\ \mathrm{GeV}}{f_a}$
  - $f_a \gtrsim 10^9$ GeV, $m_a \lesssim 10$ meV
  - 轴子与光子的耦合常数：$g_{a\gamma\gamma} \propto m_a$



- 光照穿墙实验
- 天文观测
- 太阳轴子

两个轴子基准模型

di Cortona, G.G. et al. JHEP 01 (2016) 034.

	Kim–Shifman–Vainshtein–Zakharov	Dine–Fischler–Srednicki–Zhitnitsky
树级 轴子与标准模型费米子耦合	0	非0
E/N	0	8/3

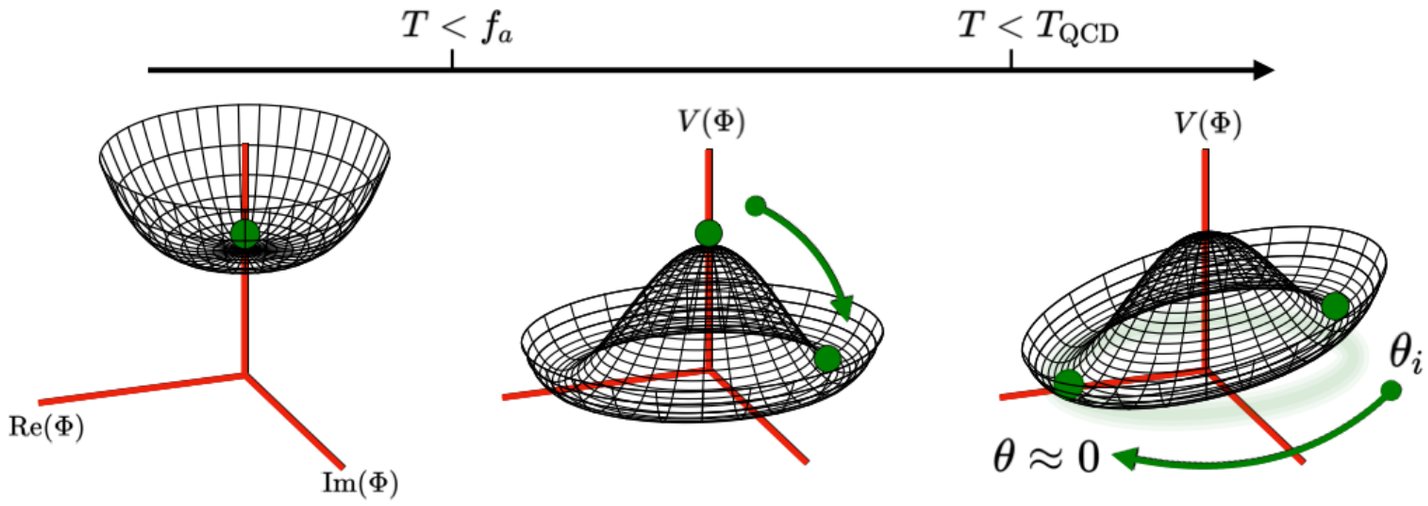
$g_\gamma = (E/N - 1.92)/2$: KSVZ, -0.97 DFSZ, 0.36

$$g_{a\gamma\gamma} = \alpha g_\gamma / \pi f_a$$

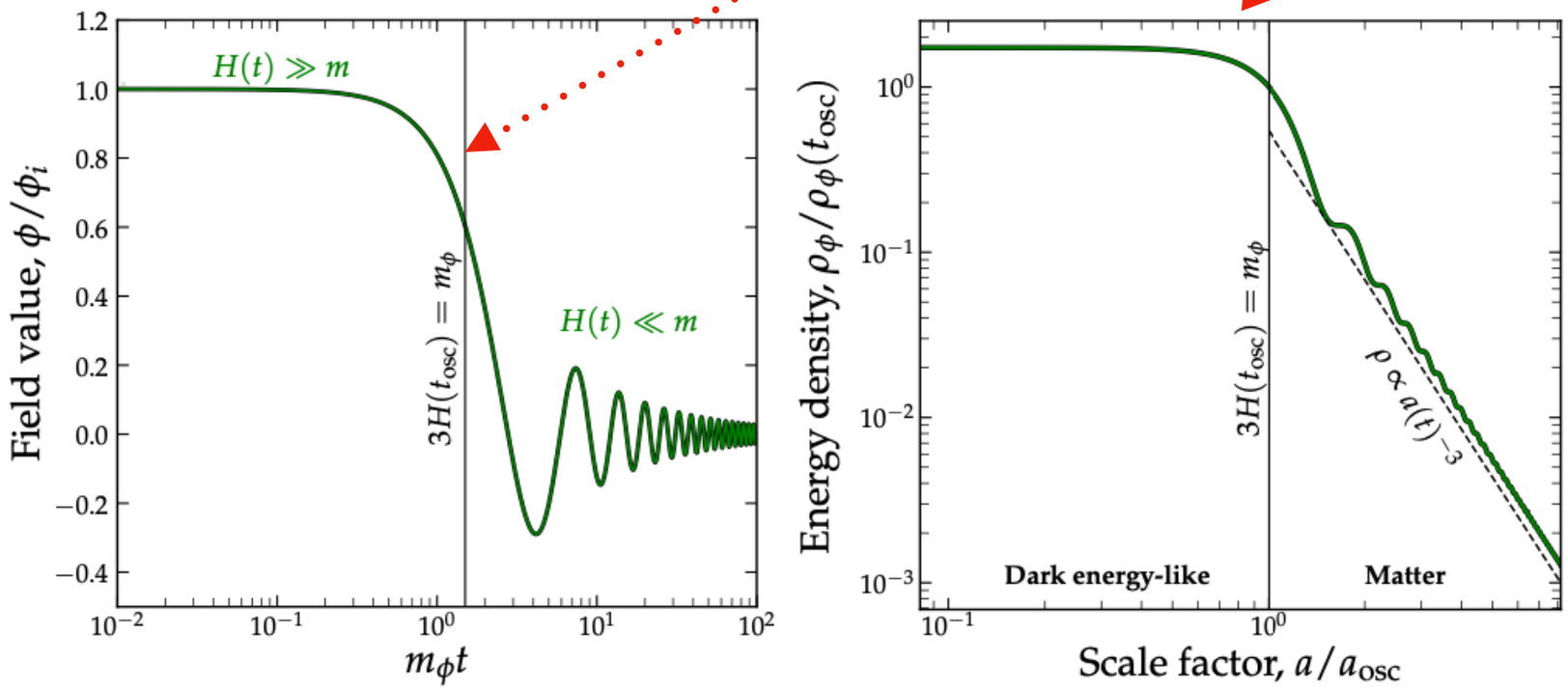
在轴子-费米子耦合探测中， *DFSZ* g_{ae} 更容易探测

轴子暗物质的宇宙模型

- 在QCD相变后，$T_{\rm univ} < T_{\rm QCD}$
  - θ等效趋近于0
  - 轴子密度符合冷暗物质的运动方程



$$T_{\rm univ} = T_{\rm QCD} \approx 200\ \text{MeV}$$



Plots from Ciaran A. J. O'Hare, PoS COSMICWISPers (2024) 040

轴子暗物质的来源

- Misalignment production (错位生成):
  - Pre-inflation (宇宙暴涨前)：θ_i 与m_a共同作用
  - Post-inflation (宇宙暴涨后)： $< \theta_i^2 > = \frac{\pi^2}{3}$
- Topological defect decays 拓扑缺陷产生
  - 只贡献于宇宙暴涨后的情况
- 若为宇宙暴涨后产生，基于 $\Omega_{\rm DM} h^2 = 0.12$, **可预测轴子质量**
  - $m_a \sim 1\ \mu\text{eV}$ to $1\ \text{meV}$ （误差来源：有限温度核物理，宇宙学， 轴子能谱等）

轴子与标准模型粒子

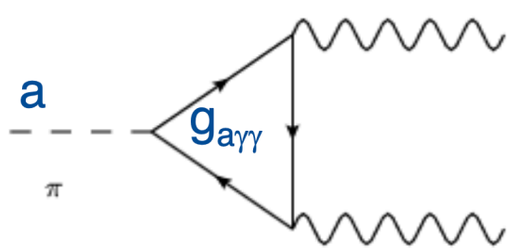
$$\mathscr{L} = -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} - \frac{i}{2} g_d a \tilde{N} \sigma_{\mu\nu} \gamma_5 N F_{\mu\nu} + g_{aNN} (\partial_\mu) \tilde{N} \gamma^\mu \gamma_5 N + g_{aee} (\partial_\mu) \tilde{e} \gamma^\mu \gamma_5 e$$

轴子-双光子耦合项

轴子-核子电偶极矩耦合项

轴子-原子核轴矢矩的耦合

轴子与电子轴矢量流的耦合



- 成熟的技术
- 适合引入量子技术

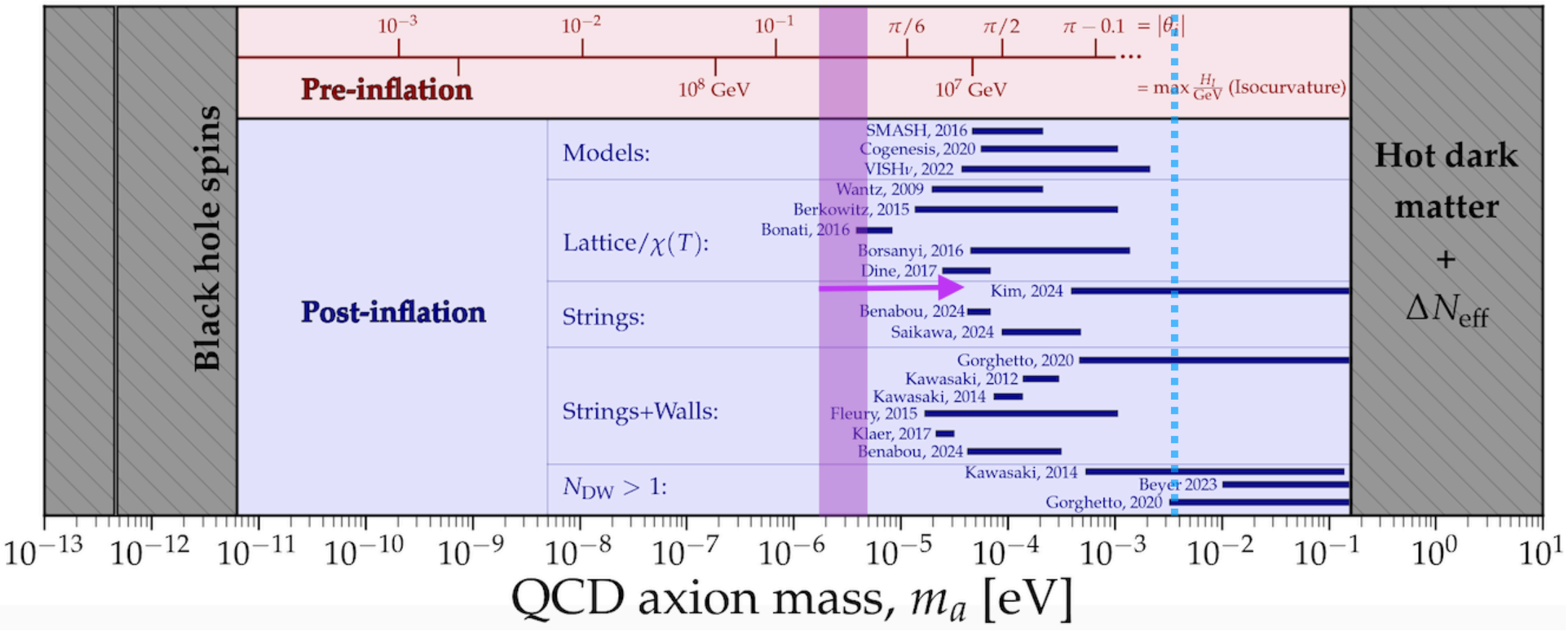
- 在探索灵敏度的阶段

Peter W. Graham and Surjeet Rajendran, Phys.Rev. D88 (2013) 035023

类波暗物质

- 根据太阳系的暗物质密度，当质量 $\ll 10$ eV, 基态布局数 $N \approx \frac{\rho_{\rm DM}}{m}\lambda_{\rm dB}^3 \gg 1$

ADMX 达到基准模型灵敏度的参数区间



Plots from Ciaran A. J. O'Hare, PoS COSMICWISPers (2024) 040

宏观二能级系统
在轴子探测中的应用

Probing dark matter axions using the hyperfine structure splitting of hydrogen atoms

Qiaoli Yang*, Shiqin Dong

Department of Physics and Siyuan Laboratory, Jinan University, Guangzhou 510632, China

$|j_i, 0> \rightarrow |j_f, 1>$ transitions. The event rate is then

$$NR = N\frac{\pi}{f_a^2 m_a}\left(\frac{v}{\delta v}\right)^2 \rho_{\mathrm{CDM}} \tag{17}$$

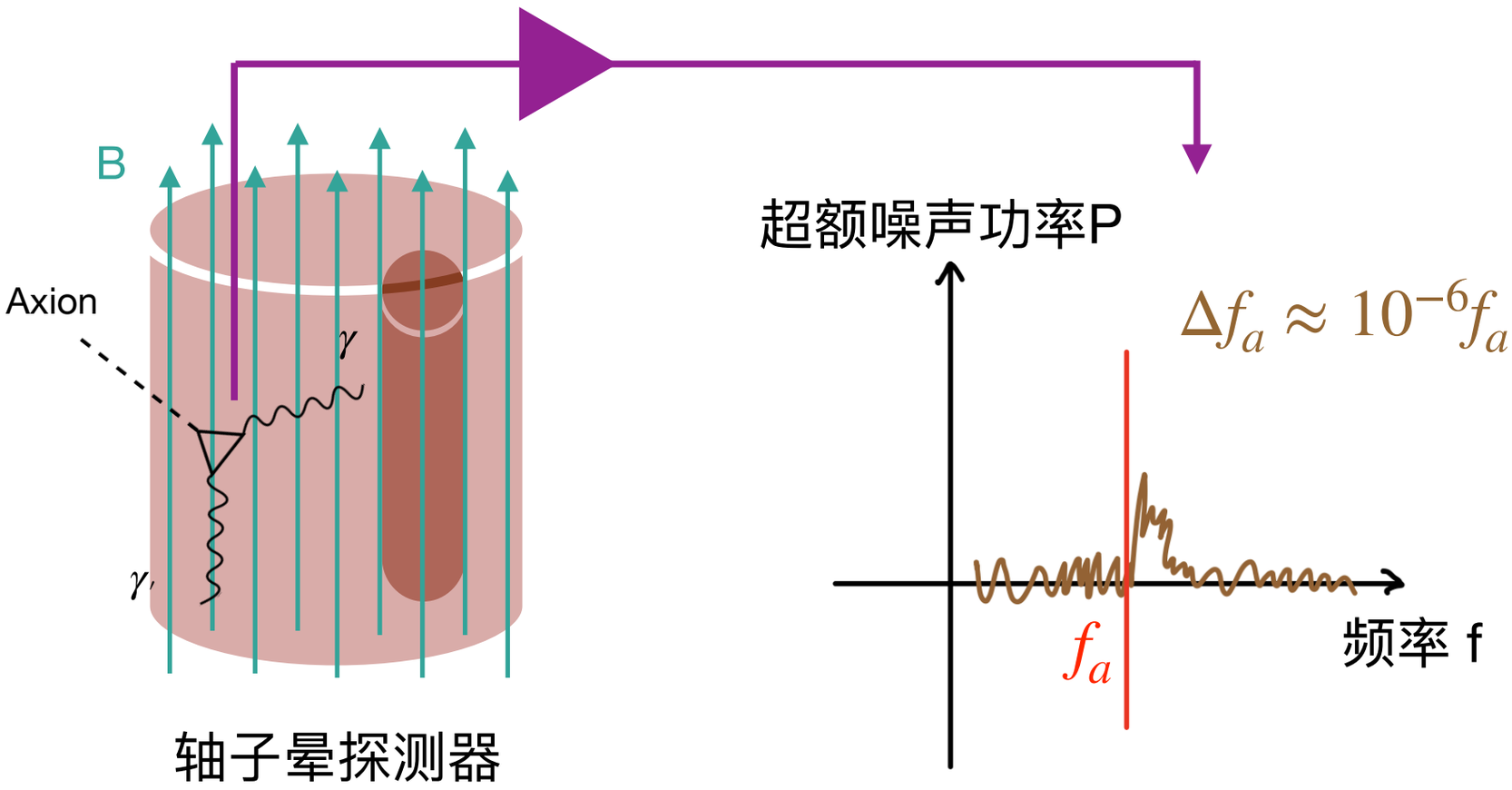
$$= N \times 3.7 \times 10^{-25}\left(\frac{v}{\delta v}\right)^2\left(\frac{t}{\mathrm{s}}\right)\left(\frac{m_a}{10^{-5}\mathrm{eV}}\right)^{-1}\left(\frac{f_a}{10^{11}\ \mathrm{GeV}}\right)^{-2}.$$

For $\delta v \sim 10^{-3}$c, $m_a \sim 10^{-5}$ eV, $f_a \sim 10^{11}$ GeV, and $N \sim 1$mole, the event rate is 2.0 s^{-1}. If $\delta v \sim 10^{-7}$c [34], only 10^{-8} mole atoms

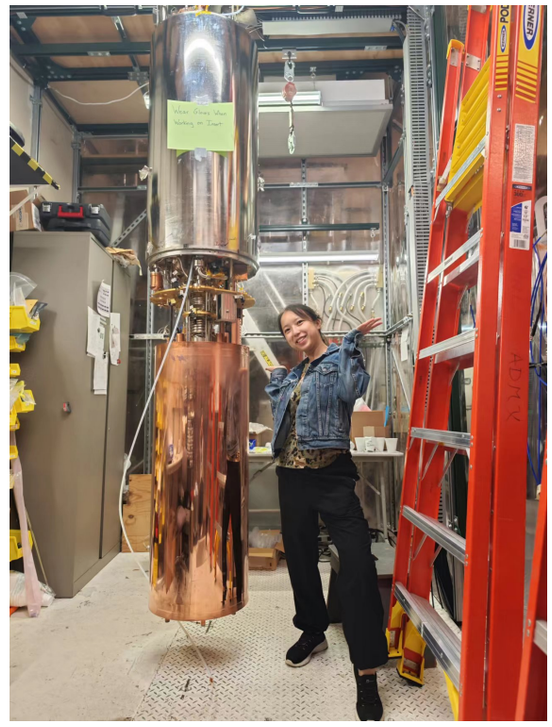
Axion Dark Matter eXperiment

Sikivie晕探测器

Pierree Sikivie PRL 51:1415 (1983)



轴子晕探测器

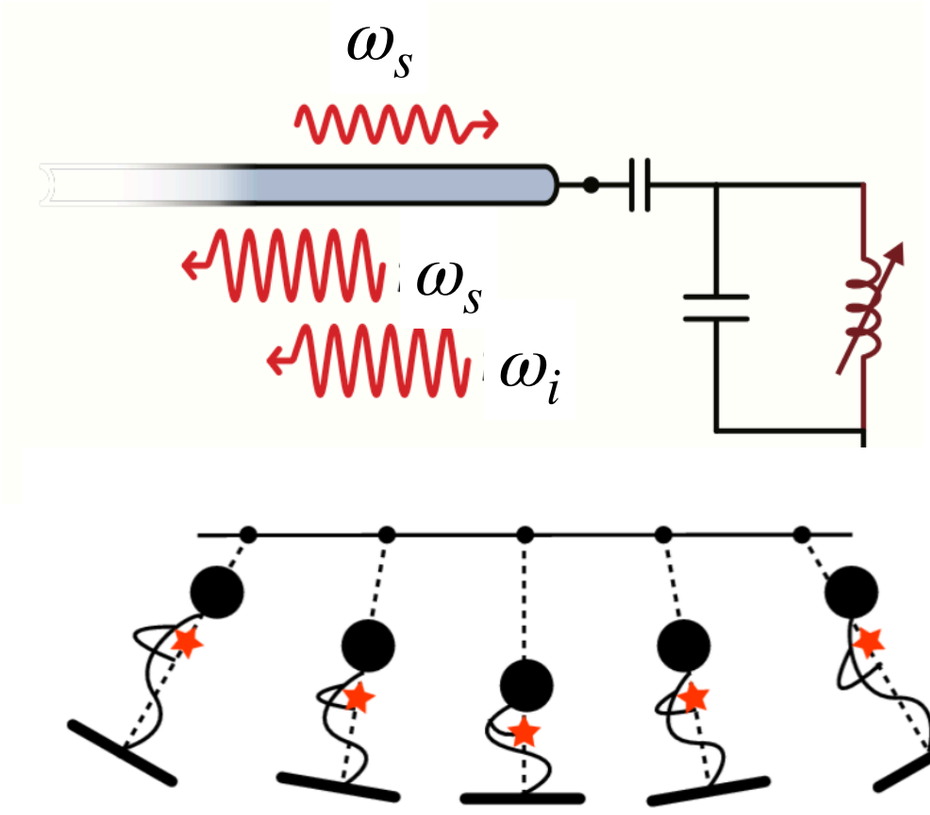


地点：华盛顿大学

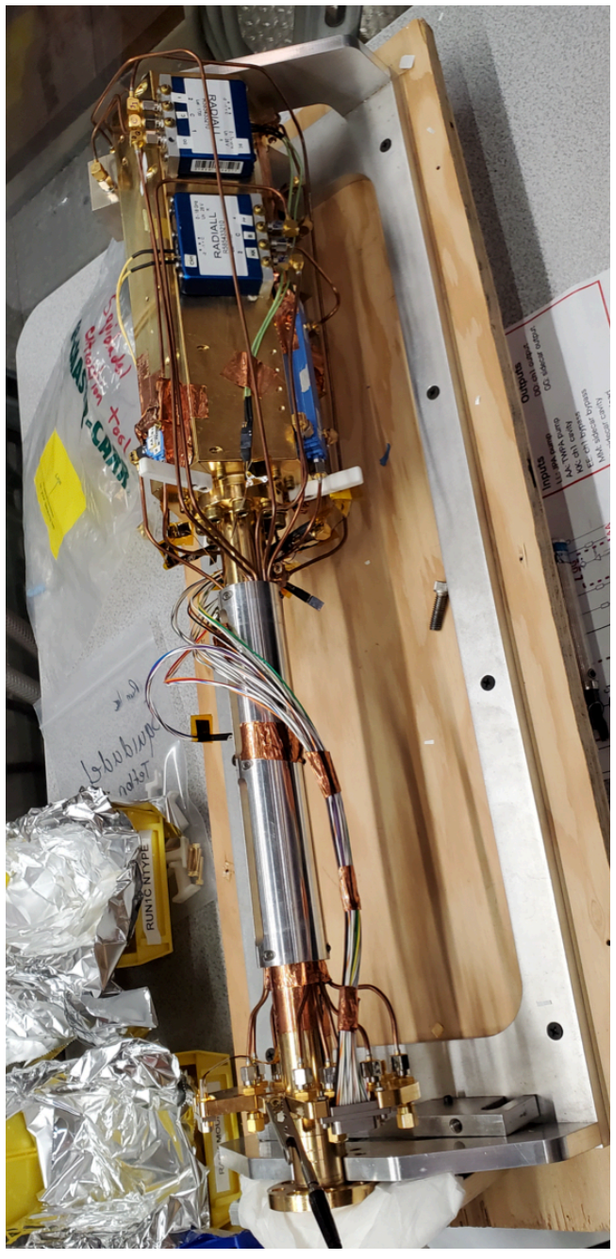
- 冷暗物质: $m_a \approx hf, Q_a \sim 10^6, \mathcal{O}(1)\text{GHz}$
- $\delta P_{\text{bkg}} \propto T_{\text{thermal}} + T_{\text{receiver}}$

量子放大器

- Josephson parametric amplifier (JPA) 约瑟夫森参量放大器: 由能量守恒而引入的闲频（idler frequency） $\omega_{\mathrm{p}} = \omega_{\mathrm{s}} + \omega_{\mathrm{i}}$



$$L_0 + \delta L \cos(2\pi\omega_p t + \phi_p)$$



约瑟夫森结



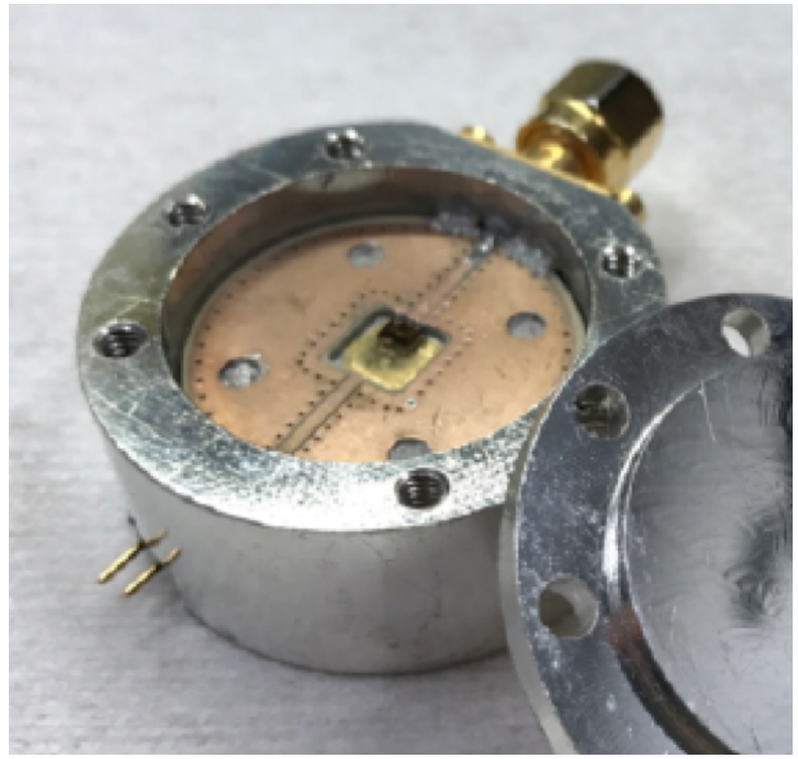
John Clarke　　John M. Martinis　　Michel H. Devoret

2025年诺贝尔物理学奖获得者

1984-1985年，约瑟夫森结的宏观量子效应在John Clarke 的领导下被系统研究，奠定了超导量子领域。

John Clarke 也是将超导量子干涉仪带入轴子物理探测领域的先驱（至今为ADMX合作者）。

- Josephson junction (约瑟夫森结)的宏观量子隧穿效应
  - 例：Al-Al_2O_3-Al
- $$L_J = \frac{\Phi_0}{2\pi I_c \cos\phi} = L_J = \frac{\Phi_0}{2\pi\sqrt{1-(I_{\text{bias}}/I_c)^2}}$$
  - ϕ：结两侧超导波函数的相位差
  - $\Phi_0 = h/2e$：磁通量子



JPA provided by
Siddiq Group at UC Berkeley

标准量子极限

- 针对不同设计而计算出的理论最低噪声

$$P = \hbar\omega b\frac{(\hat{X}^2 + \hat{P}^2)}{2}$$

$$\geq \hbar\omega b(n_{\text{th}} + 1/2)$$

$$n_{\text{th}} = \frac{1}{e^{\hbar\omega/k_BT} - 1}$$

噪声受温度限制

$$T \gg \hbar\omega/k_B \qquad P \geq k_BT$$

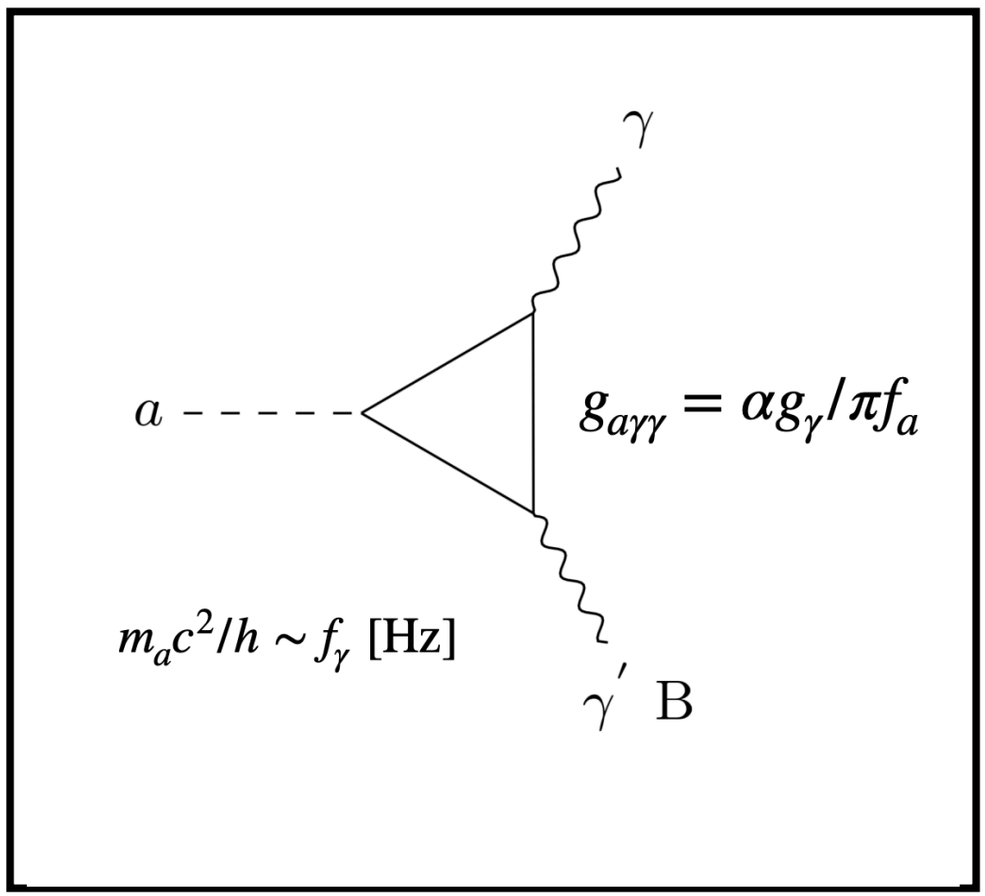
噪声受量子限制

$$T \ll \hbar\omega/k_B \qquad P \geq \hbar\omega/2$$

- 以ADMX 读出为例子 (50mK @ 1GHz):
  腔膜本身 1/2 $\hbar\omega_s$ + JPA 闲频膜 1/2 $\hbar\omega_s$

信号强度

$$P_a = 2 \times 10^{-23}\ \mathrm{W} \times \left(\frac{g_\gamma}{0.36}\right)^2 \left(\frac{\rho}{0.45\ \mathrm{GeV/cm^3}}\right) \left(\frac{f_a}{1.3\ \mathrm{GHz}}\right)$$



与轴子本质相关的特性

- g_γ: 模型相关无量纲参数(KSVZ:-0.97, DFSZ: 0.36)
- ρ: 局域暗物质能量密度
- $f_a \approx m_a/h$: 轴子/光子频率

$$\times \left(\frac{B_0}{7.68\ \mathrm{T}}\right)^2 \left(\frac{V}{107\ l}\right) \left(\frac{Q_L}{25{,}000}\right) \left(\frac{C_{010}}{0.34}\right)$$

与实验环境相关因素

- B_0: 磁场强度
- V: 共振腔体积
- C_{010}: 形式因子
- Q_L: 有载品质因素

信噪比

信号: $P_a = 3.5 \times 10^{-23}$ W $\longleftrightarrow$ 40 photons/s

$$E = hf_a$$

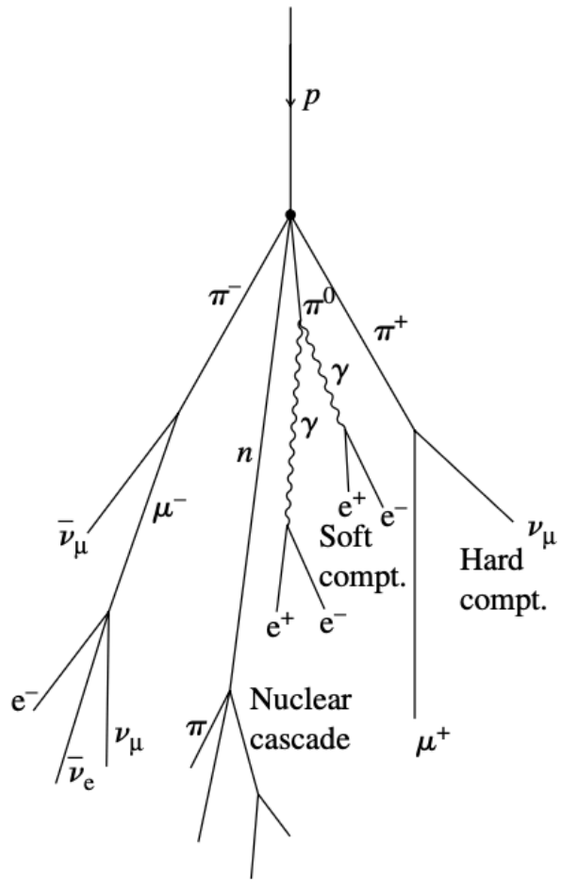
噪声: $\delta P_{\text{bkg}} = k_B T_{\text{sys}} b / \sqrt{bt} = k_B T_{\text{sys}} \sqrt{b/t}$

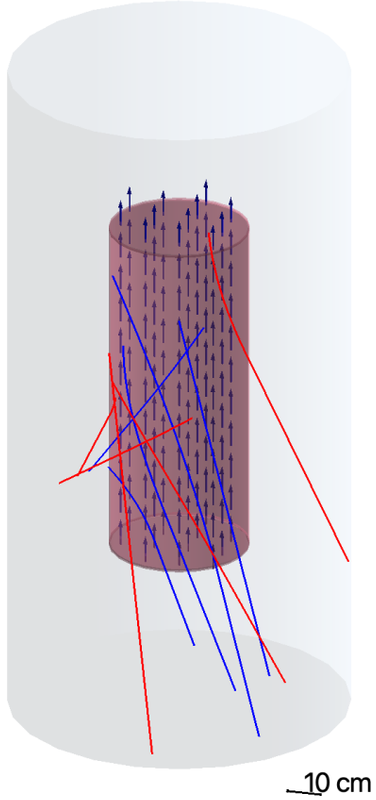
- k_B: 玻尔兹曼常数 [J/K]
- T_{sys}: 系统噪声温度 [K]
- b: 噪声积分带宽 [Hz]
- t: 积分时间 [s]

Signal to noise ratio (SNR)信噪比: $\text{SNR} = \dfrac{P_a}{\delta P_{bkg}}$

物理事例噪声?

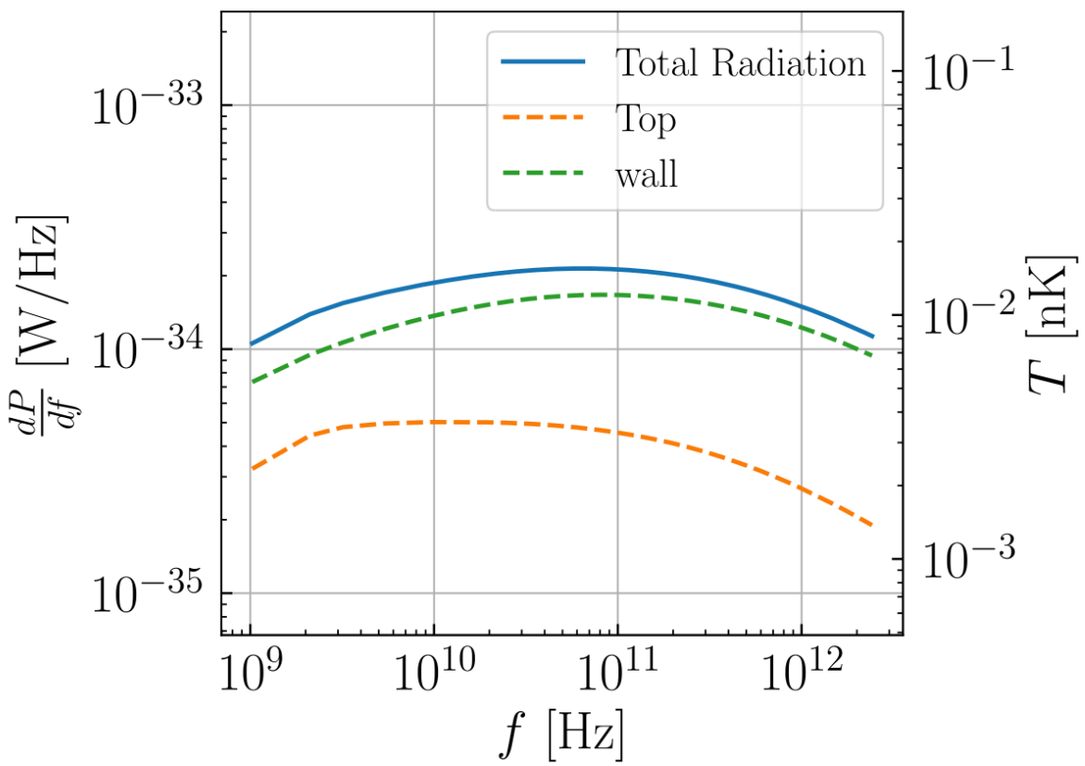
- α, β, γ粒子会沉积过高能量
- 宇宙缪子在强磁场中的光子辐射能量分布在 μeV - meV



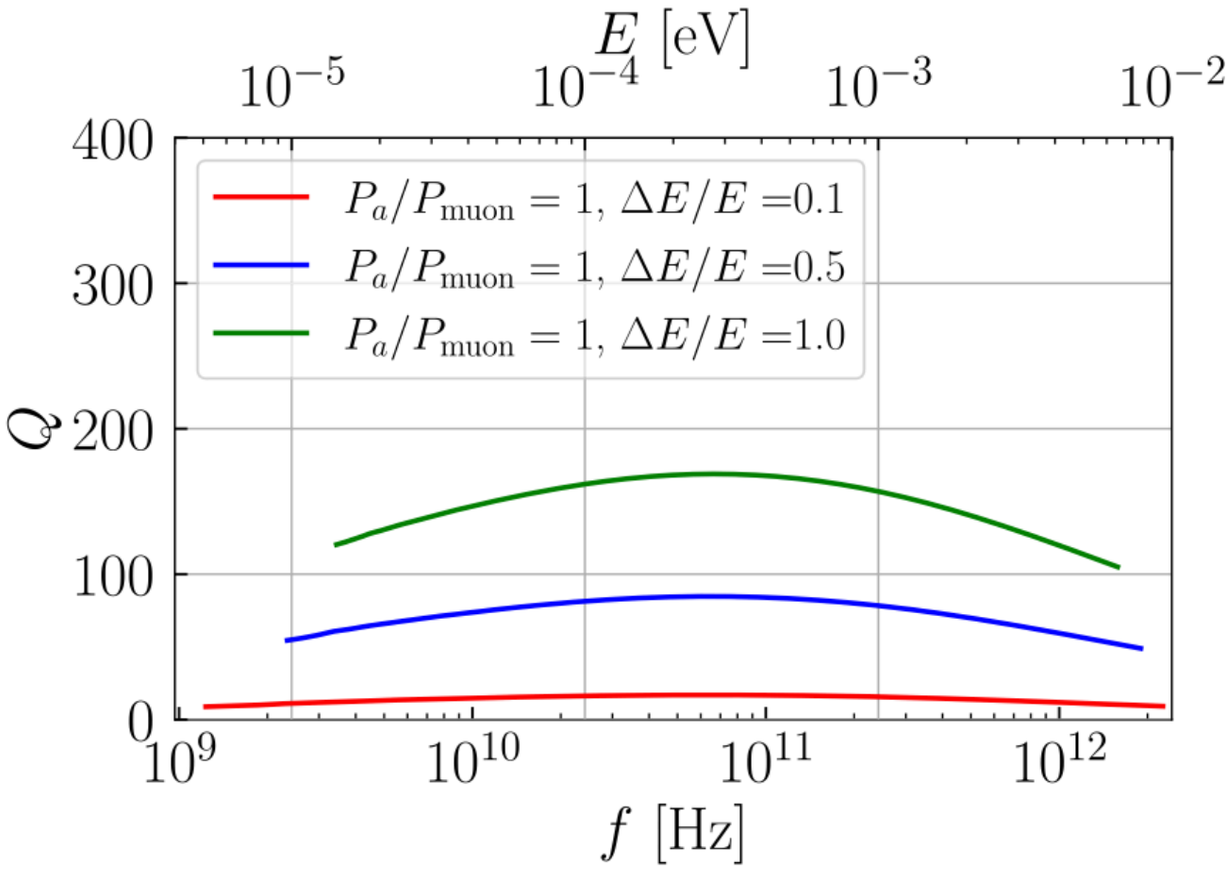


GEANT4 simulation + analytical radiation calculation

对 ADMX一类共振实验贡献很小

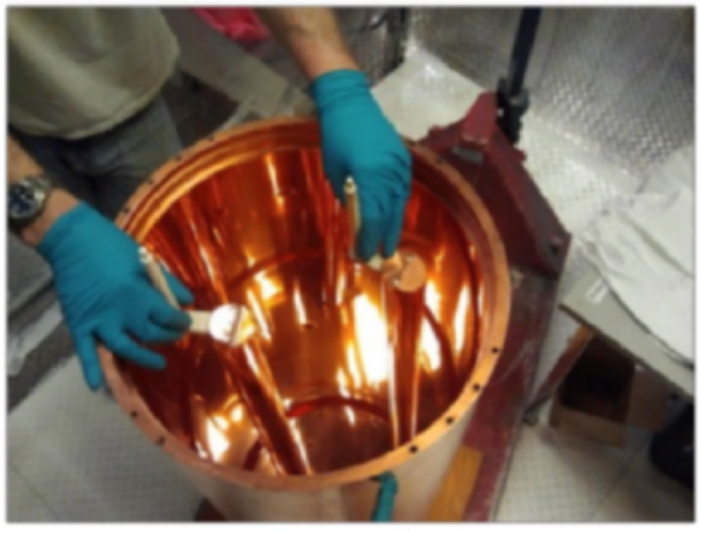


对未来宽带轴子实验提出设计要求

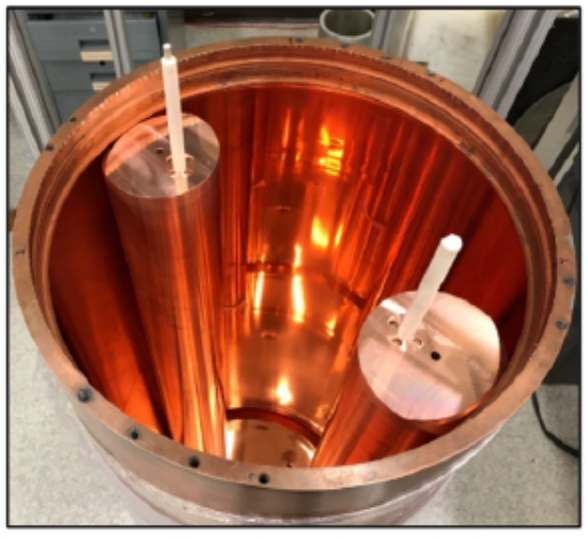


D. Zhang et.al., 2026 New J. Phys. 28 083601

ADMX 2024 —Run1D-Part1



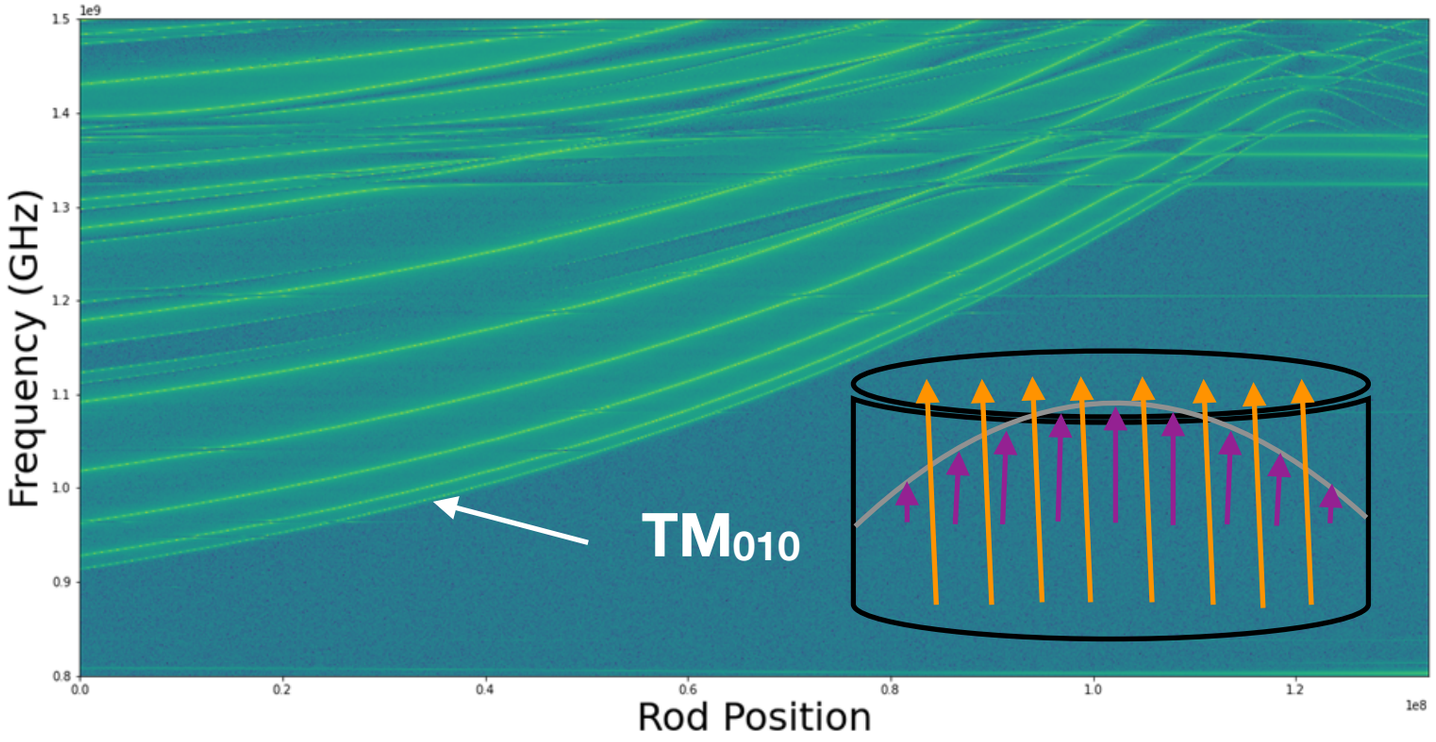
Run 1A+1B



Run 1C

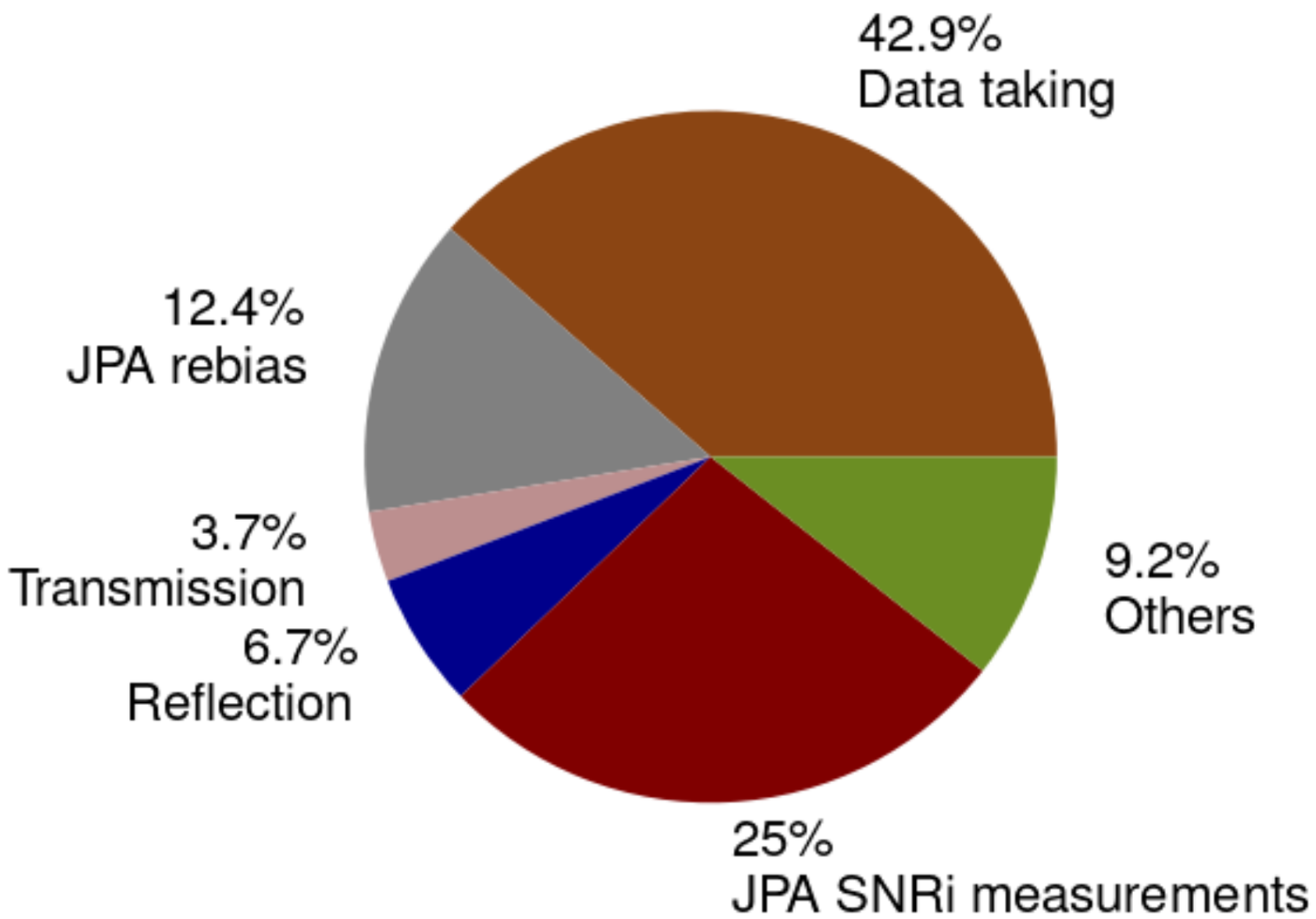


Run 1D

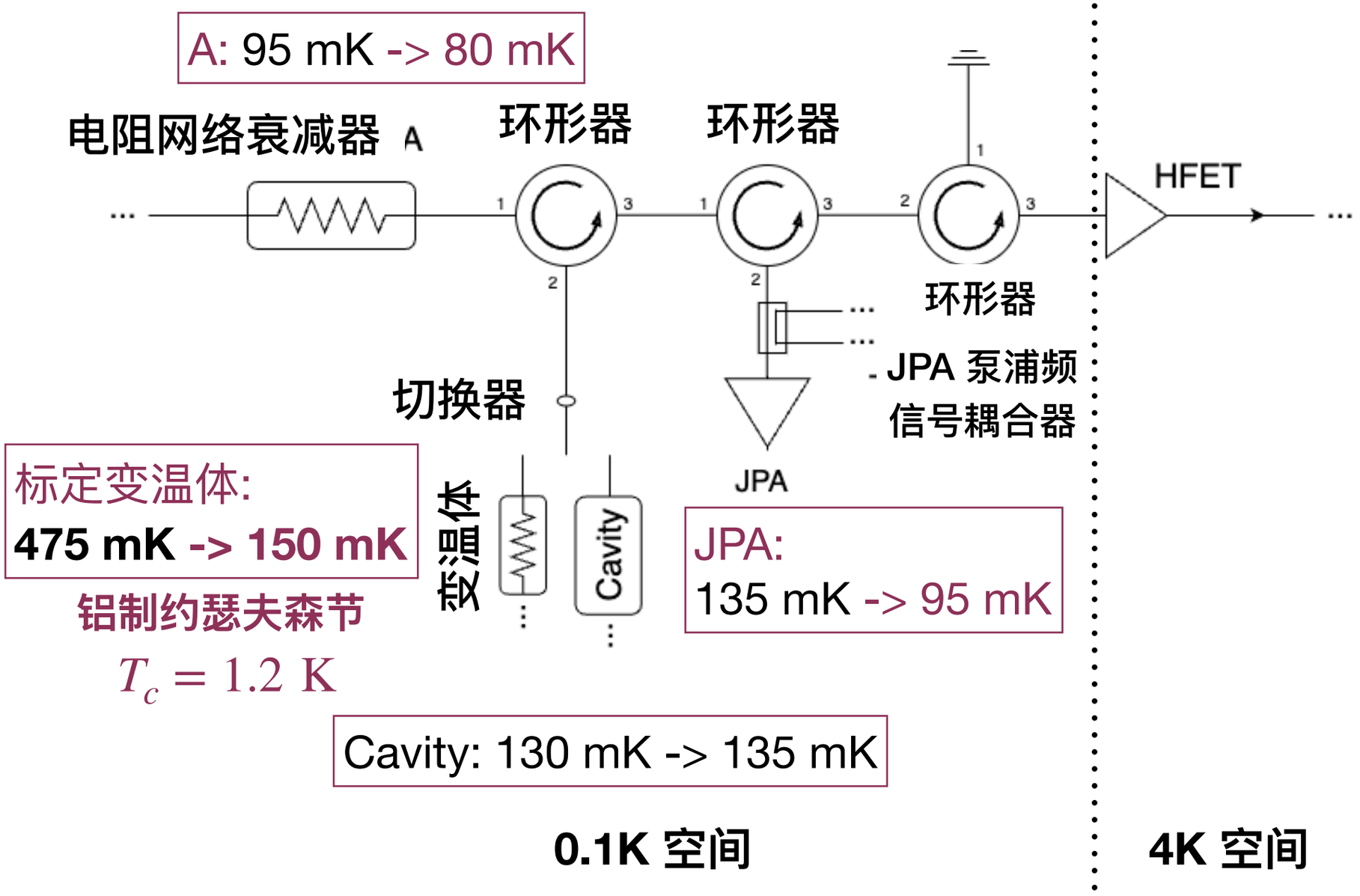


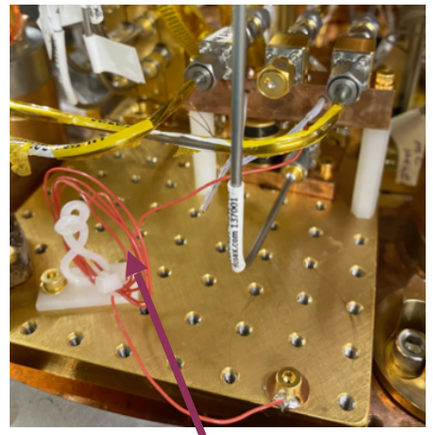
- 1-1.4GHz, 4-6μeV
- 腔内灵敏区域: 136L - 29L
- KSVZ 90%发现能力
- 自ADMX安装稀释制冷机后**最长的无间断运行**

实验运行采数

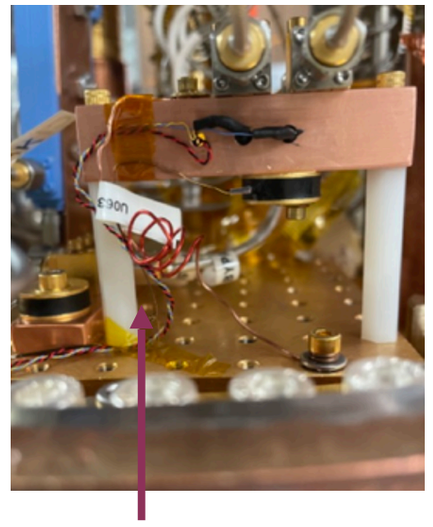

42.9%
Data taking
12.4%
JPA rebias
3.7%
Transmission
6.7%
Reflection
9.2%
Others
25%
JPA SNRi measurements

低温表现



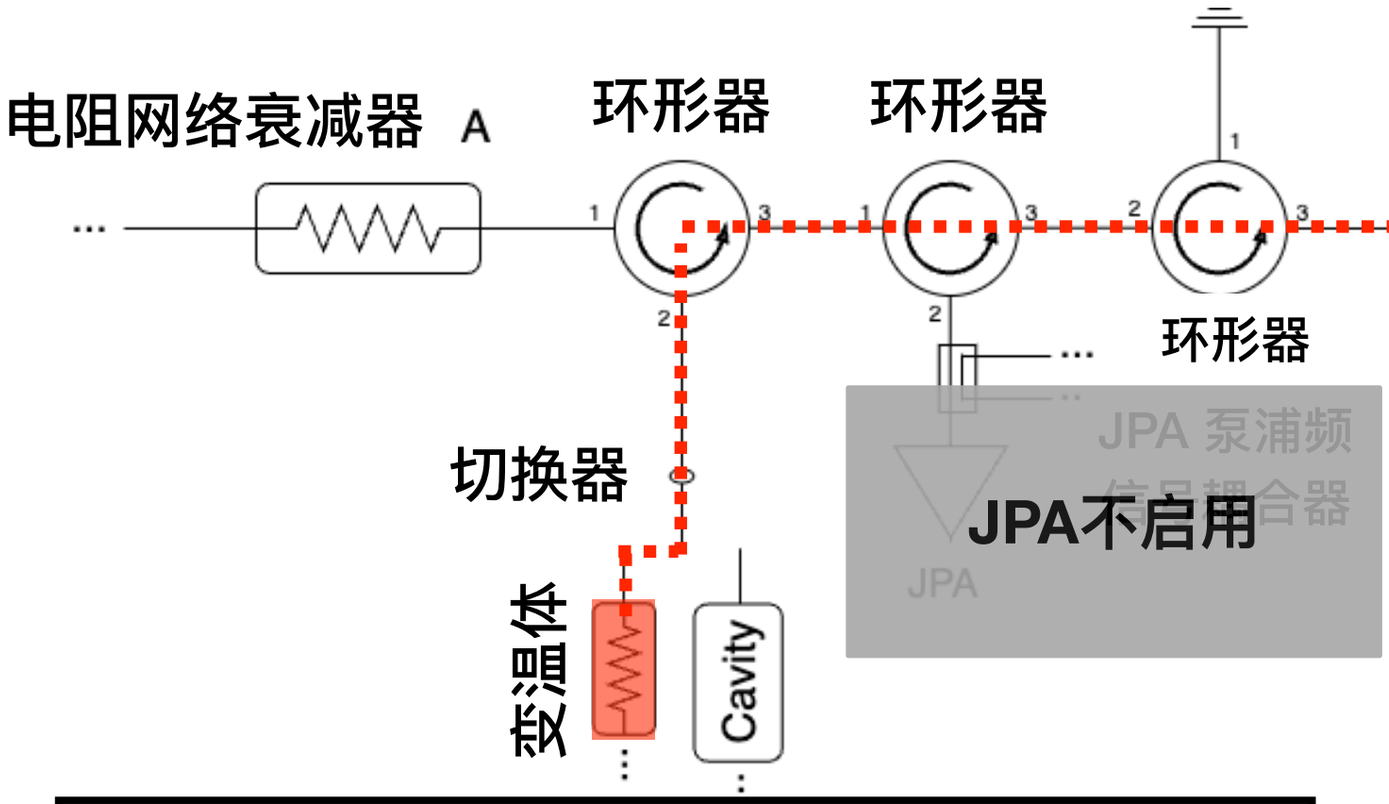


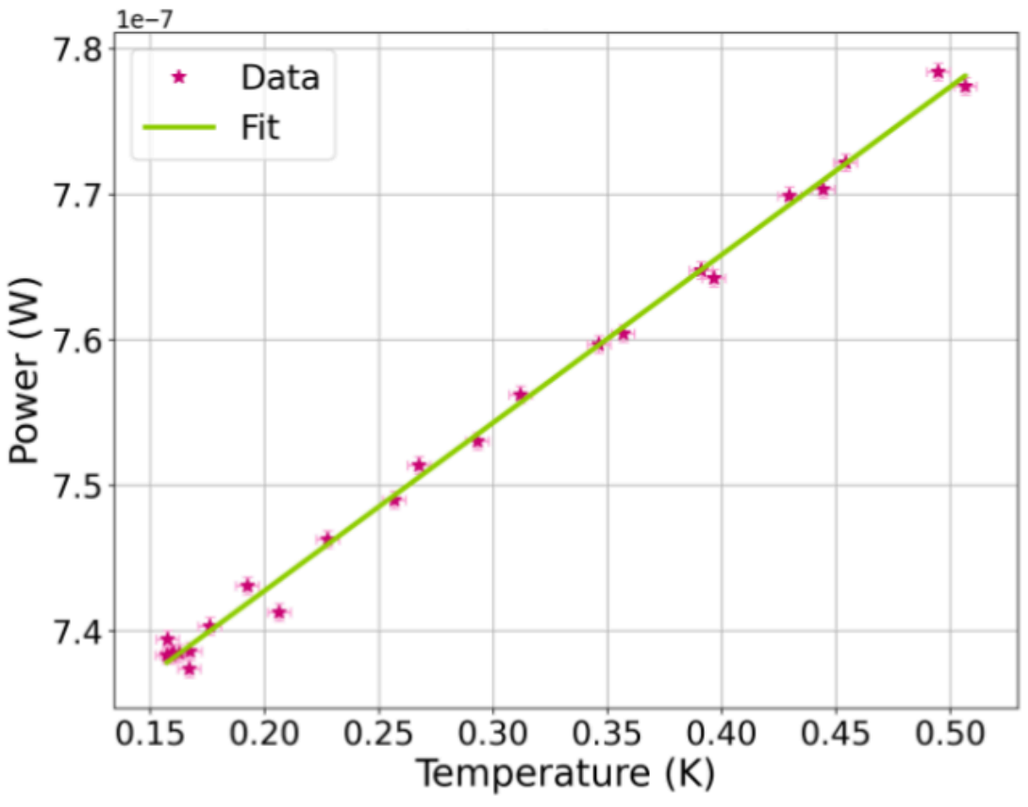
旧变温体的热链接



新变温体的热链接

传统y-factor噪声标定





Y-factor 测量

$$P_{\text{off}} = C(T + T_{\text{fit}})$$

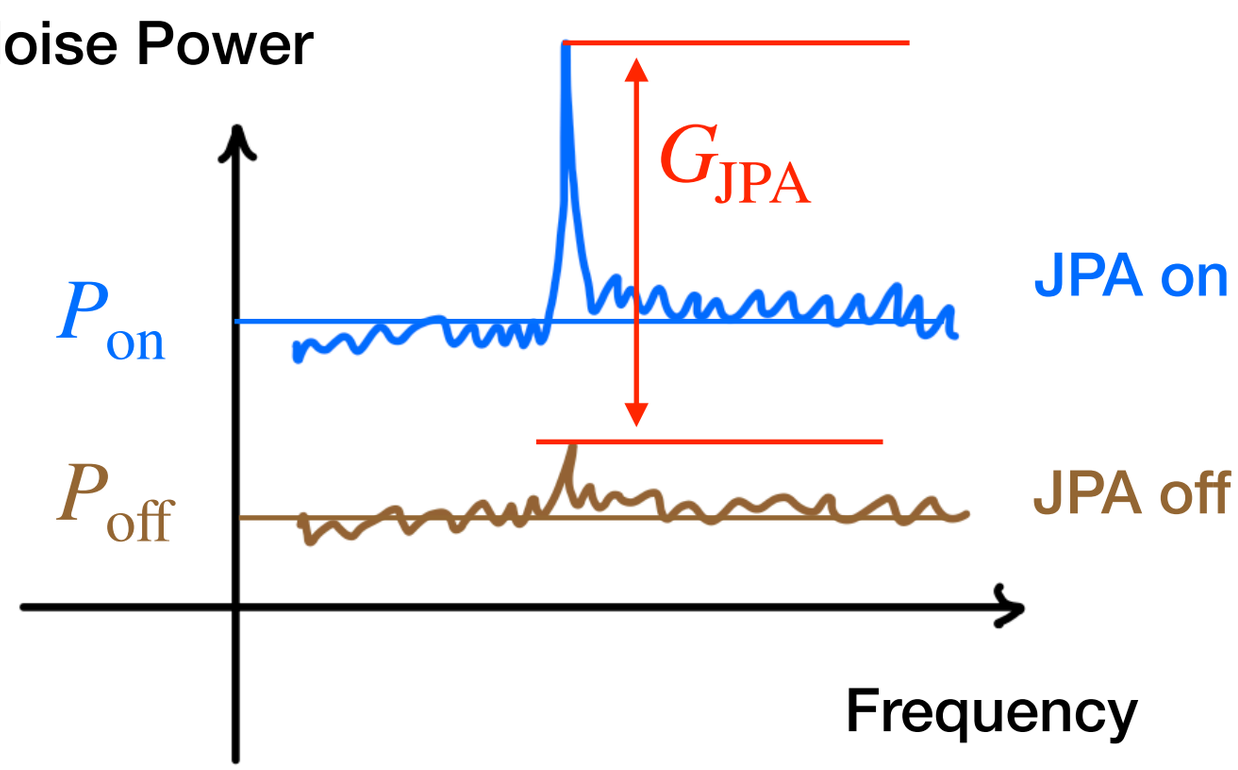
$$T = T_{\text{HL}}$$

$$T_{\text{fit}} = T_{\text{HFET}}/\alpha_{\text{eff}}$$

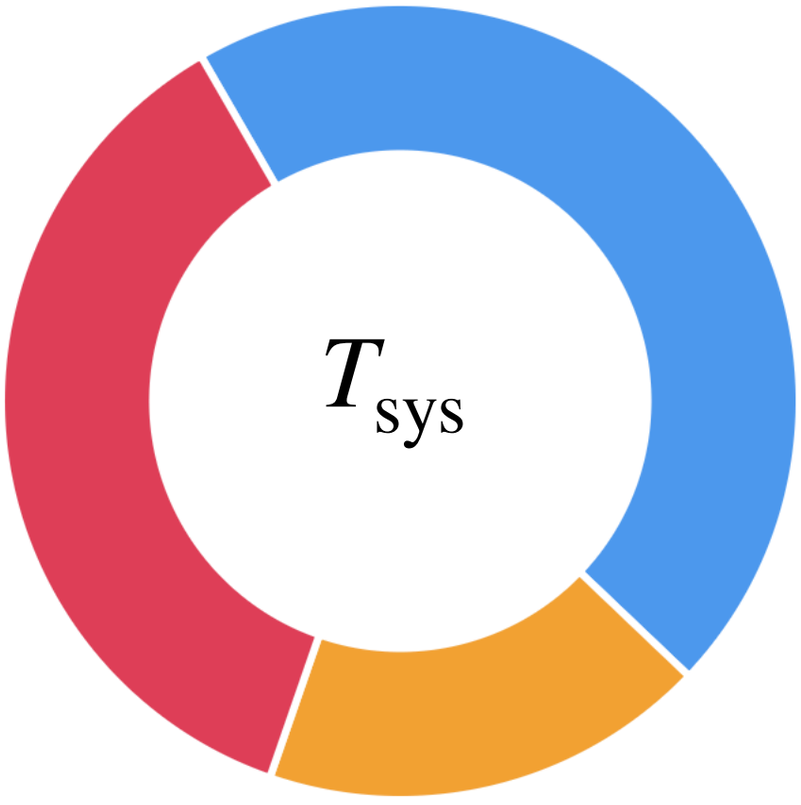
From $T_{\mathrm{HFET}}/\alpha_{\mathrm{eff}}$ to T_{sys}

- Signal-to-noise ratio improvement (SNRI)

$$T_{\mathrm{sys}} = \frac{T_{\mathrm{HFET}}/\alpha_{\mathrm{eff}}}{\mathrm{SNRI}} \qquad \mathrm{SNRI} = G_{JPA} \cdot \frac{P_{\mathrm{off}}}{P_{\mathrm{on}}}$$



对噪声组成成分的理解提升

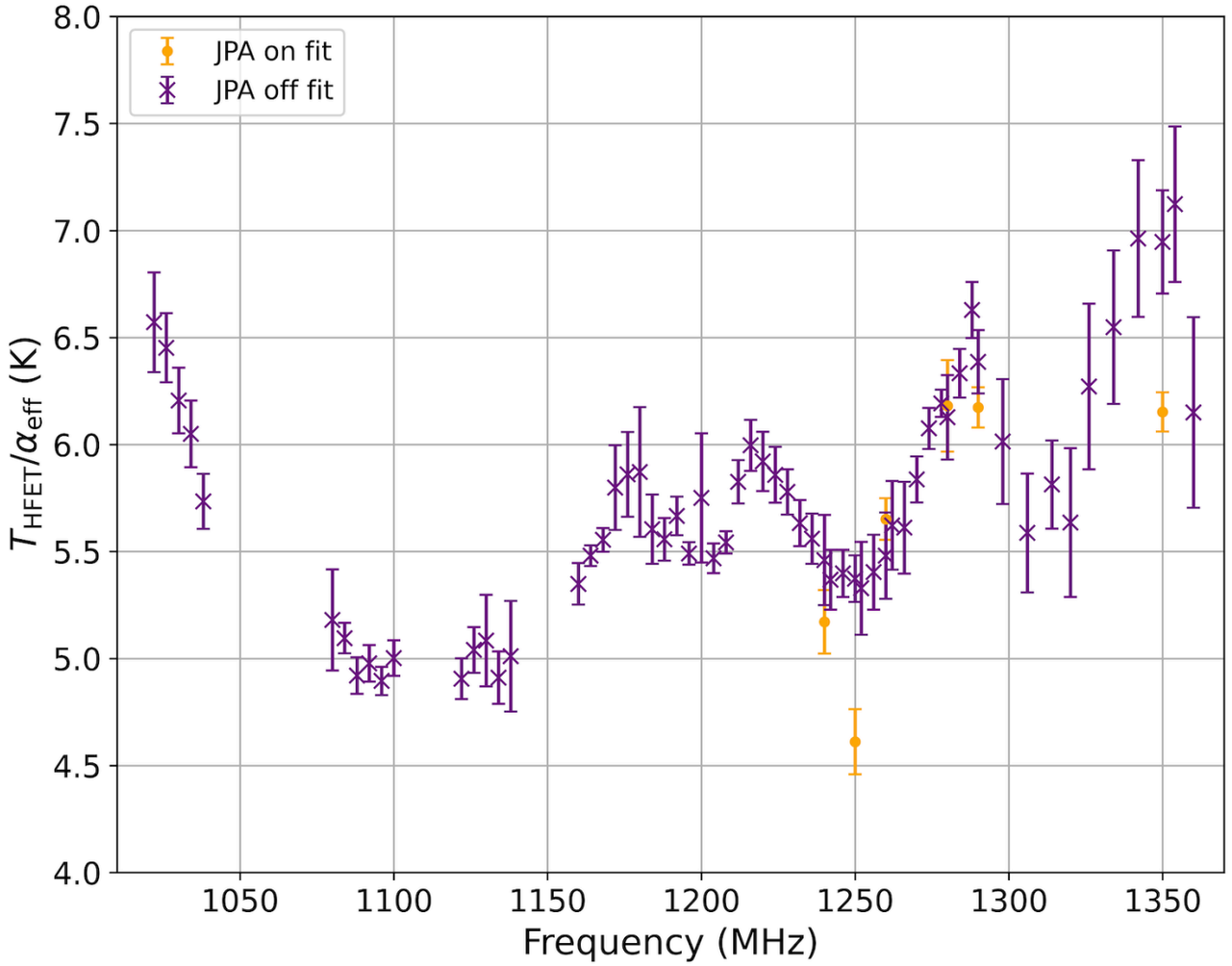


- 热噪声: 250 mK
- 来自JPA的噪声: 100 mK
- “JPA-Cavity interaction” 或“hot rod”: 200 mK

$$T_{\mathrm{sys}} : 500 - 600 \ \mathrm{mK}$$

M. Guzzetti, D. Zhang et.al, PhysRevD.111.092012

2024运行完整的噪声标定



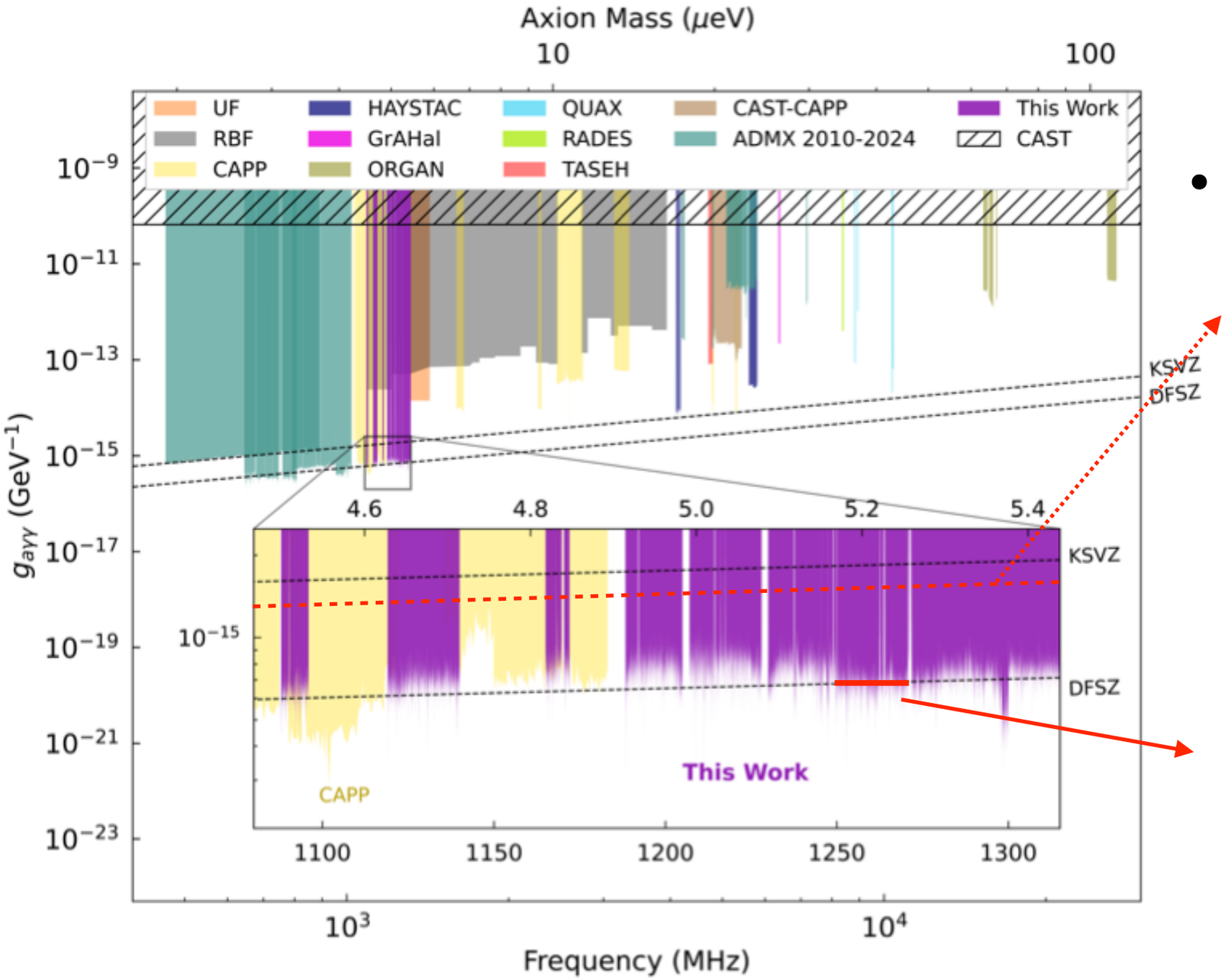
- 连接变温体的两种方法给出噪声估计的系统误差在5%
- 在取数中
  - 主要采用“HFET 噪声 + SNRI”方法来及时监控噪声变化

当下2026年采数的噪声情况

Run1D noise [mK]	Part1	Part2
JPA added noise	100	50
“JPA-Cavity Interaction” or “hot rod”	450	450
Total Tsys	550	500

Typical numbers used, T_{sys} varies every couple of minutes

2024年结果和现阶段进展

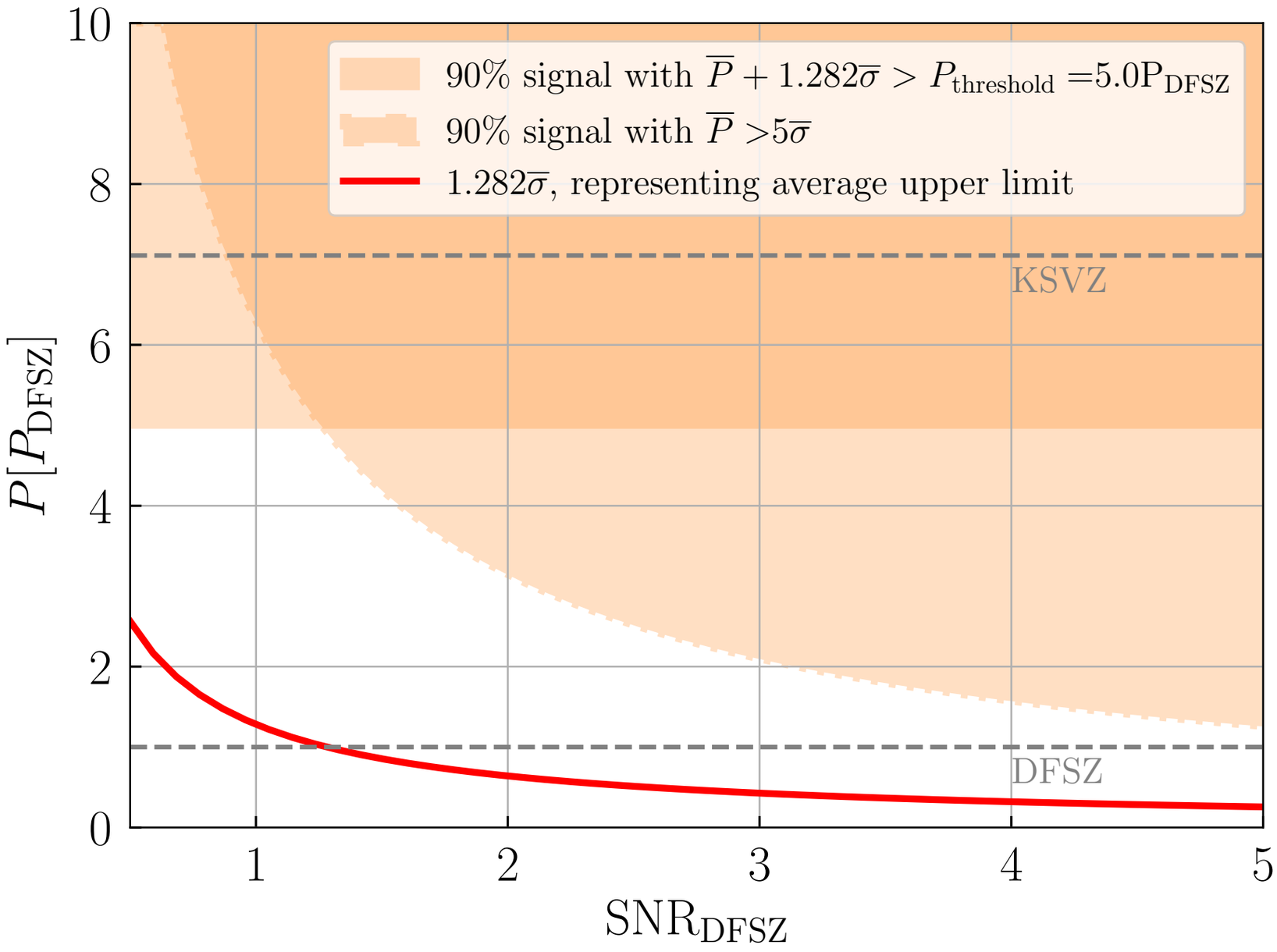


- 考虑重筛标准的 “发现能力”
  - 每~1kHz 是一个独立实验
  - 2024年数据覆盖160MHz

(Preliminary) Part2达到 DFSZ 轴子探测要求的区间

G. Carosi et.al., Phys. Rev. Lett. 135, 191001 (2025)

置信度区间与发现能力的比较



未来如何提升ADMX及同类实验

$$\frac{df_a}{dt} = 3\ \text{MHz/day} \times \left(\frac{3.5}{\text{SNR}}\right)^2 \left(\frac{g_\gamma}{0.36}\right)^4 \left(\frac{\rho}{0.45\ \text{GeV/cm}^3}\right)^2 \left(\frac{f_a}{1.3\ \text{GHz}}\right)^2$$

$$\times \left(\frac{B_0}{7.68\ \text{T}}\right)^4 \left(\frac{V}{107\ l}\right)^2 \left(\frac{C_{010}}{0.34}\right)^2 \left(\frac{Q_0}{75{,}000}\right) \left(\frac{0.35\ K}{T_{\text{sys}}}\right)^2 \left(\frac{\beta^2/(1+\beta)^3}{4/27}\right)$$

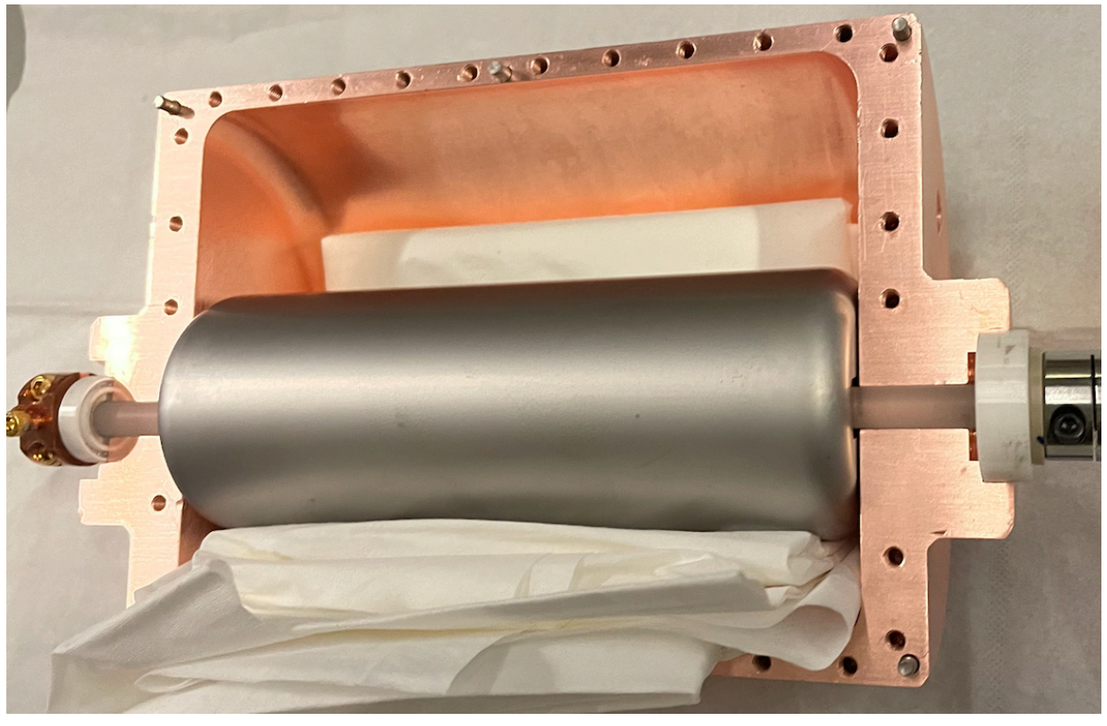
$10 - 100\ \mu\text{eV}$ 参数区间: 需要至少10倍提升

- Q_L: 超导腔
- $V \cdot C_{nlm}$: 多腔体, 非基高频膜, 更复杂的腔体结构设计
- T_{sys}: 光子计数器

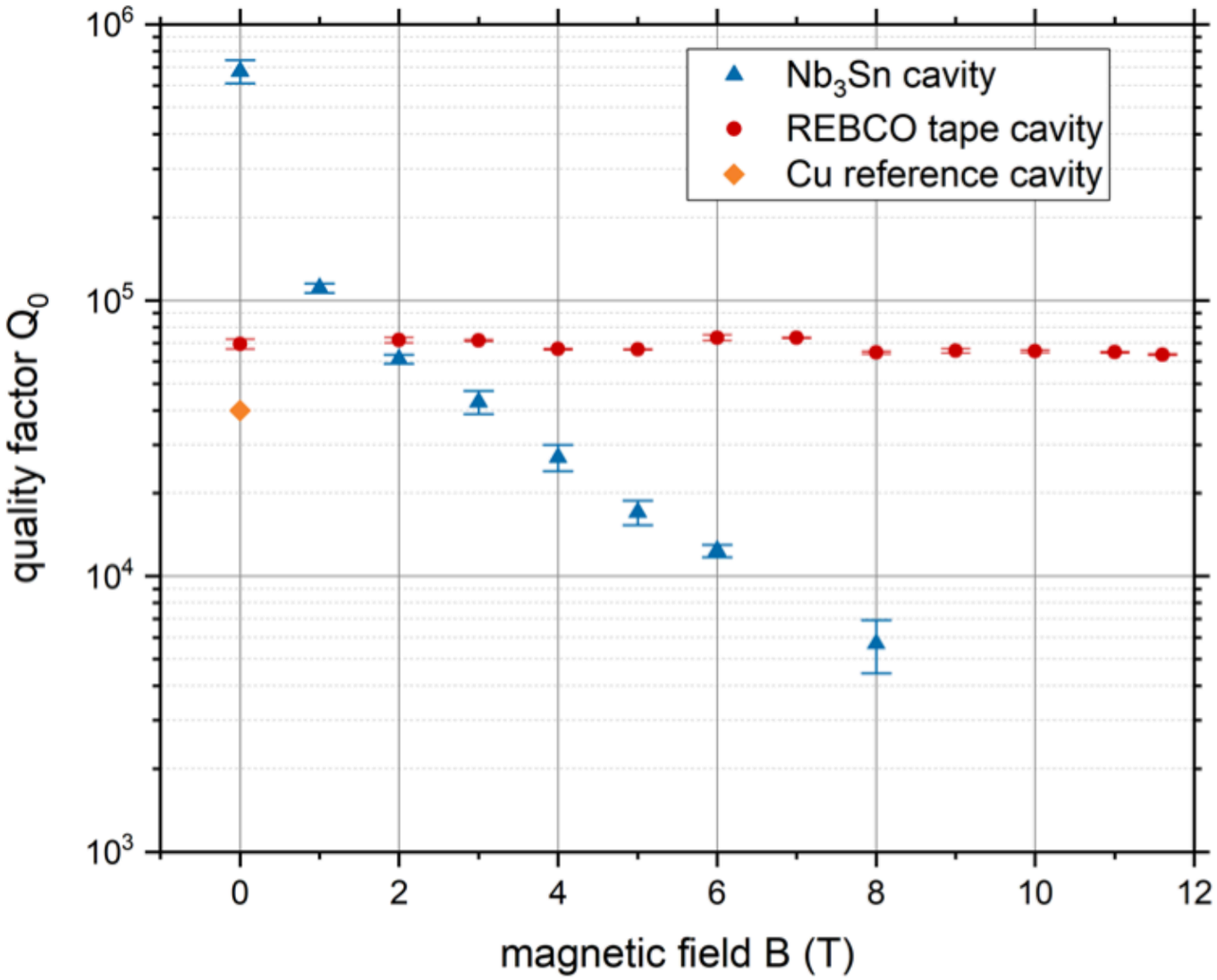
ADMX SideCar

- 2024年运行测试超导杆，未来可提升Q
  - 3 μm镀膜 Nb_3Sn （铌三锡），纯 Nb（铌）基底 (SQMS at Fermilab)
- 无磁场时: Q值未达到预期，但验证了铌三锡在强磁场下维持超导体的能力
- 超导杆可调 20MHz（5.2GHz）





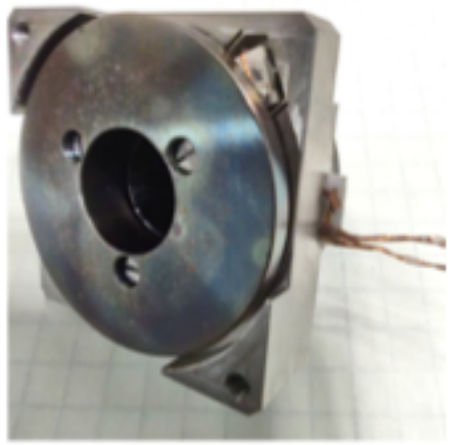
高温超导在强磁场下更有潜力

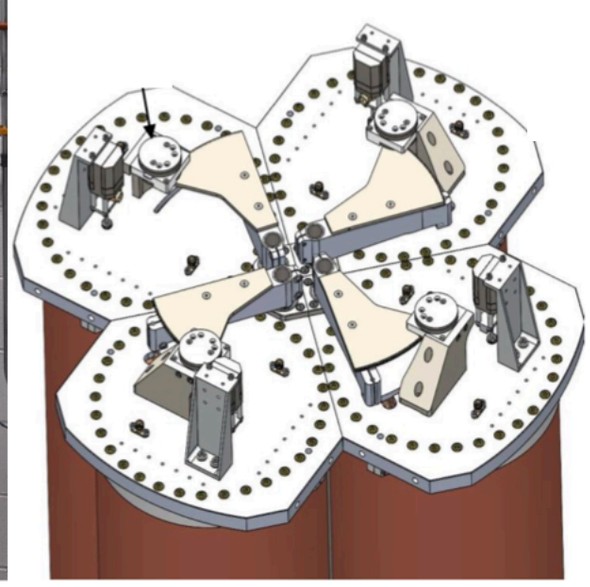


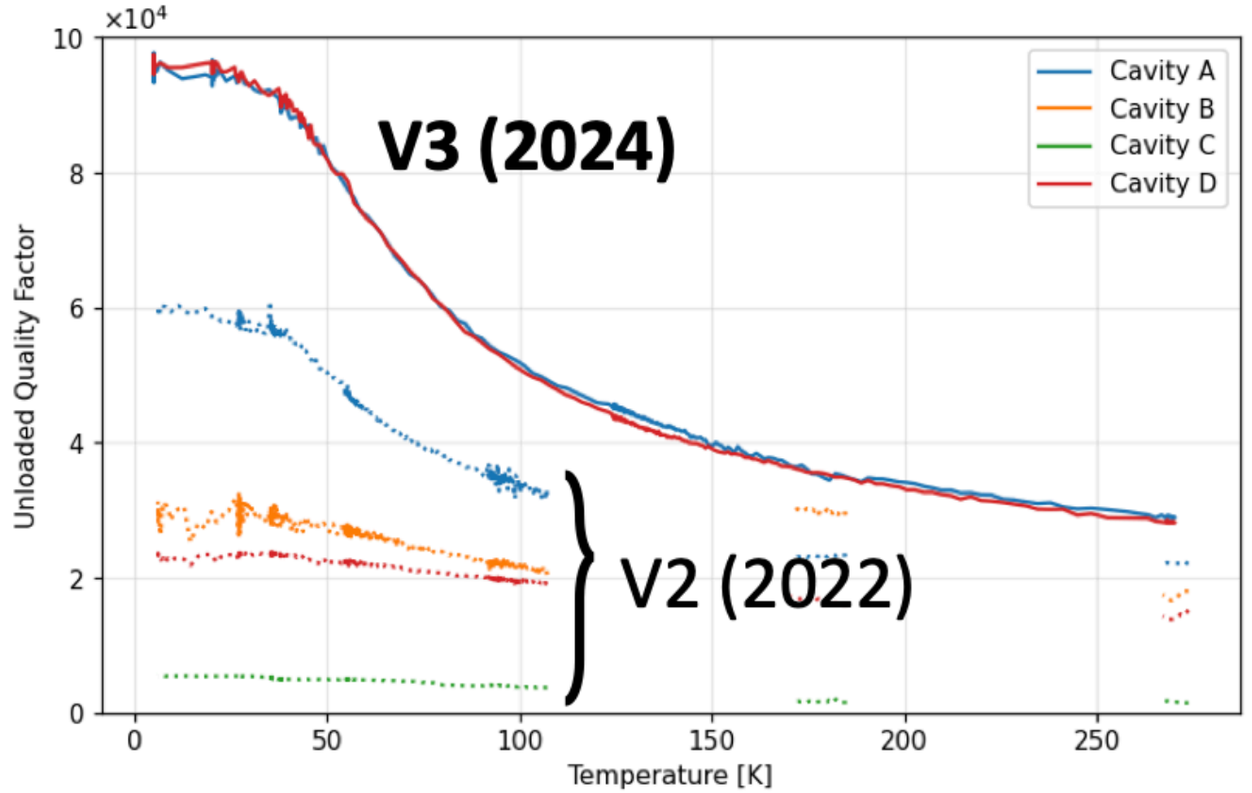
’ *J. Golm (RADES collaboration) et al., IEEE Trans. Appl. Supercond. 32 (2022), no. 4 1500605,*

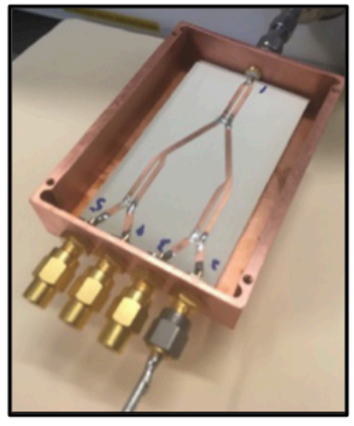
ADMX四腔系统









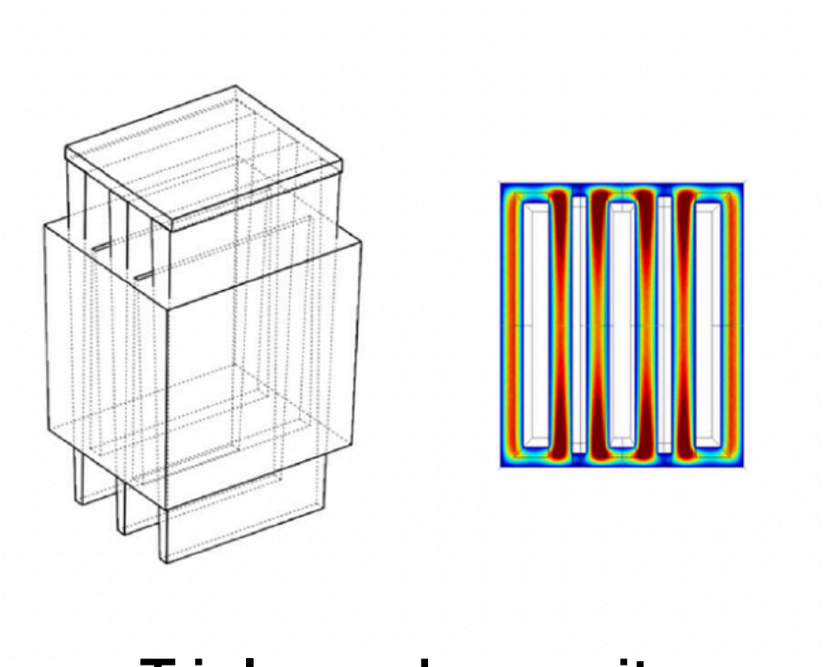


- 1.7 to 2.2 GHz
- 4 共振腔, V = 85 L
- 相干功率叠加
- JPA 读出

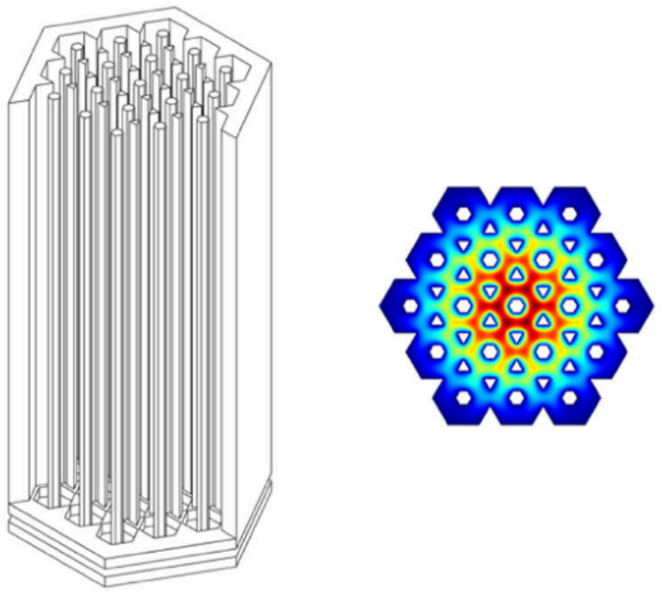
Plot credit: Stefan Knirck, PI at Harvard

针对更高频轴子探测器的创新设计

Chao-Lin Kuo et. al.,Phys. Rev. D 111, 123018 (2025)



Triple-wedge cavity

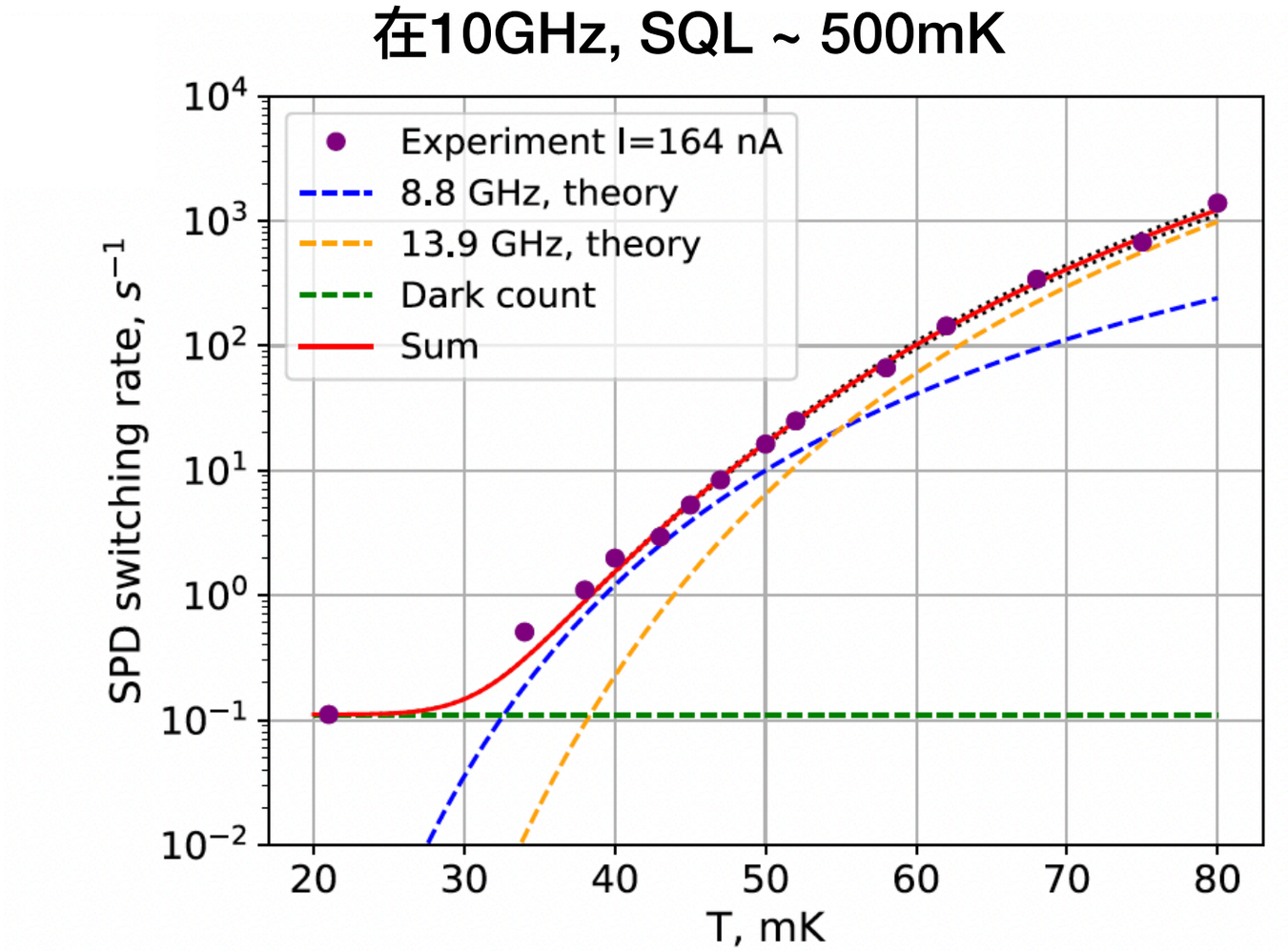


Beehive cavity

Use the volume more effectively at higher frequencies

为什么要光子计数器?

- 标准量子极限来源于 $\Delta E \cdot \Delta t \geq \hbar/2$
- 光子计数器不保留能量 E 信息, 时间测量可以很准确Δt （事例数的测量）

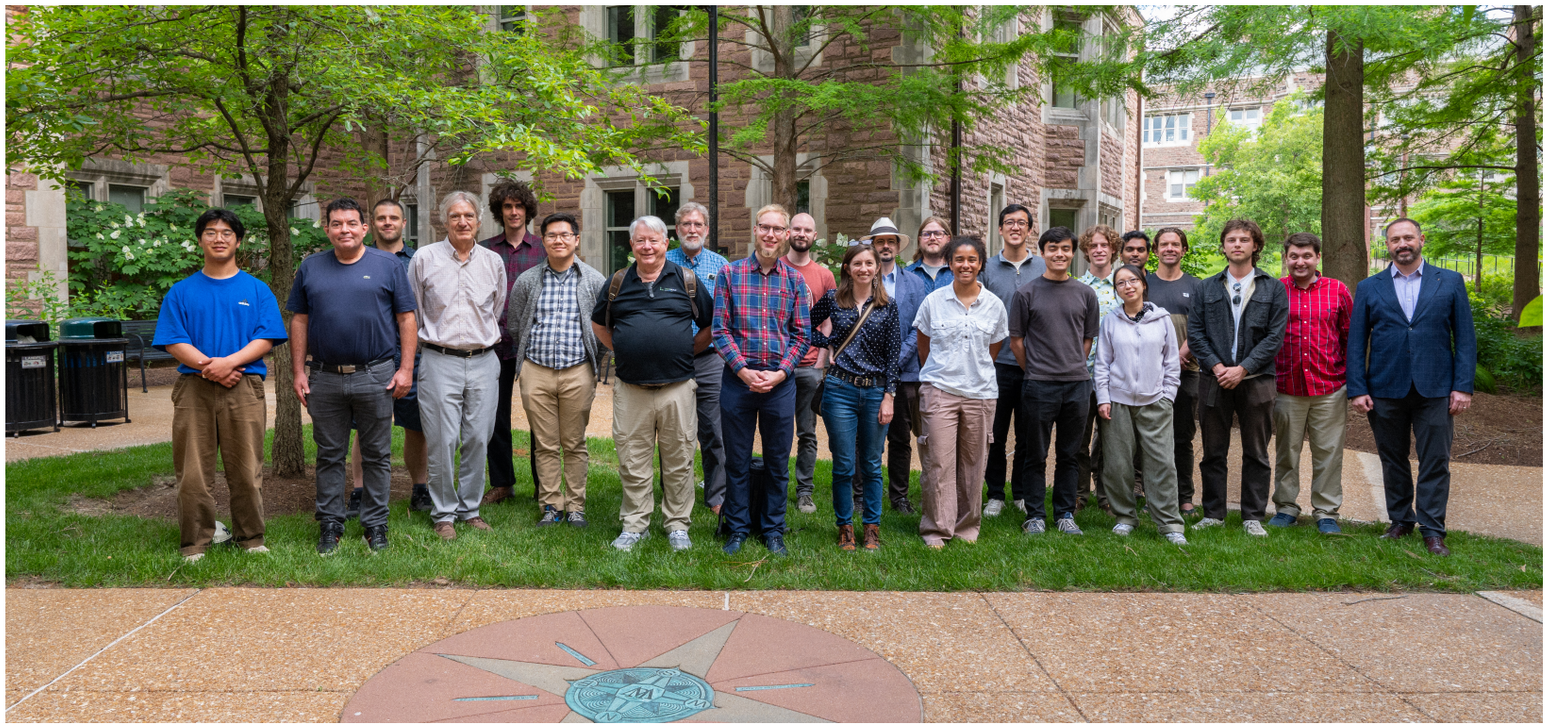


About 5 times lower than SQL

Pankratov, A.L. et. al., Nat Commun 16, 3457 (2025)

致谢

May 2025 ADMX Collaboration Meeting



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结论

- ADMX 是一个具有QCD轴子暗物质**发现能力**的先锋实验

- 研究重点：第二类**超导体共振腔**，新型低噪声微波**量子读出技术**

- 实验重点：在1-1.4GHz 达到DFSZ轴子探测要求，同时准备1.7-2.2GHz的四腔实验