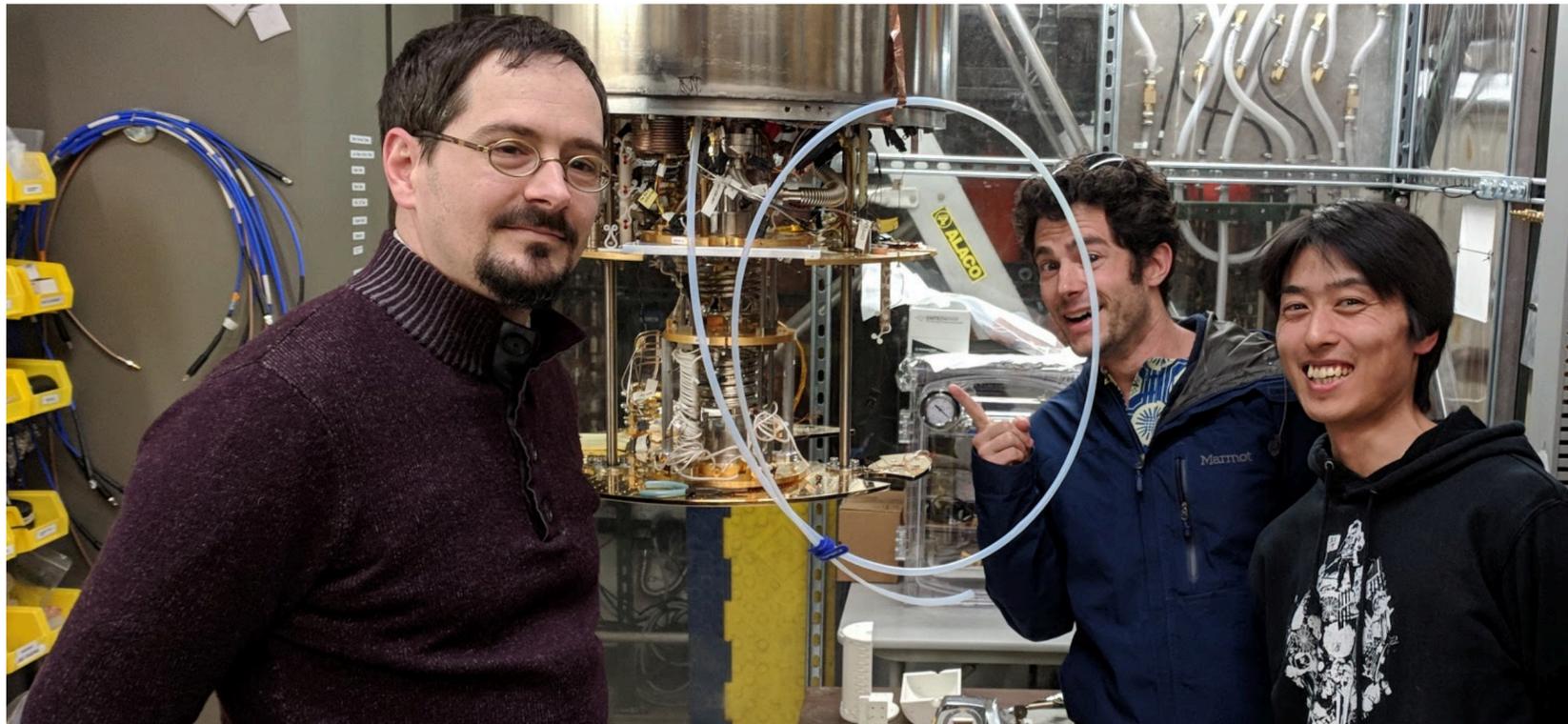


ADMIX

(+ ABRACADABRA + CAST/IAXO)



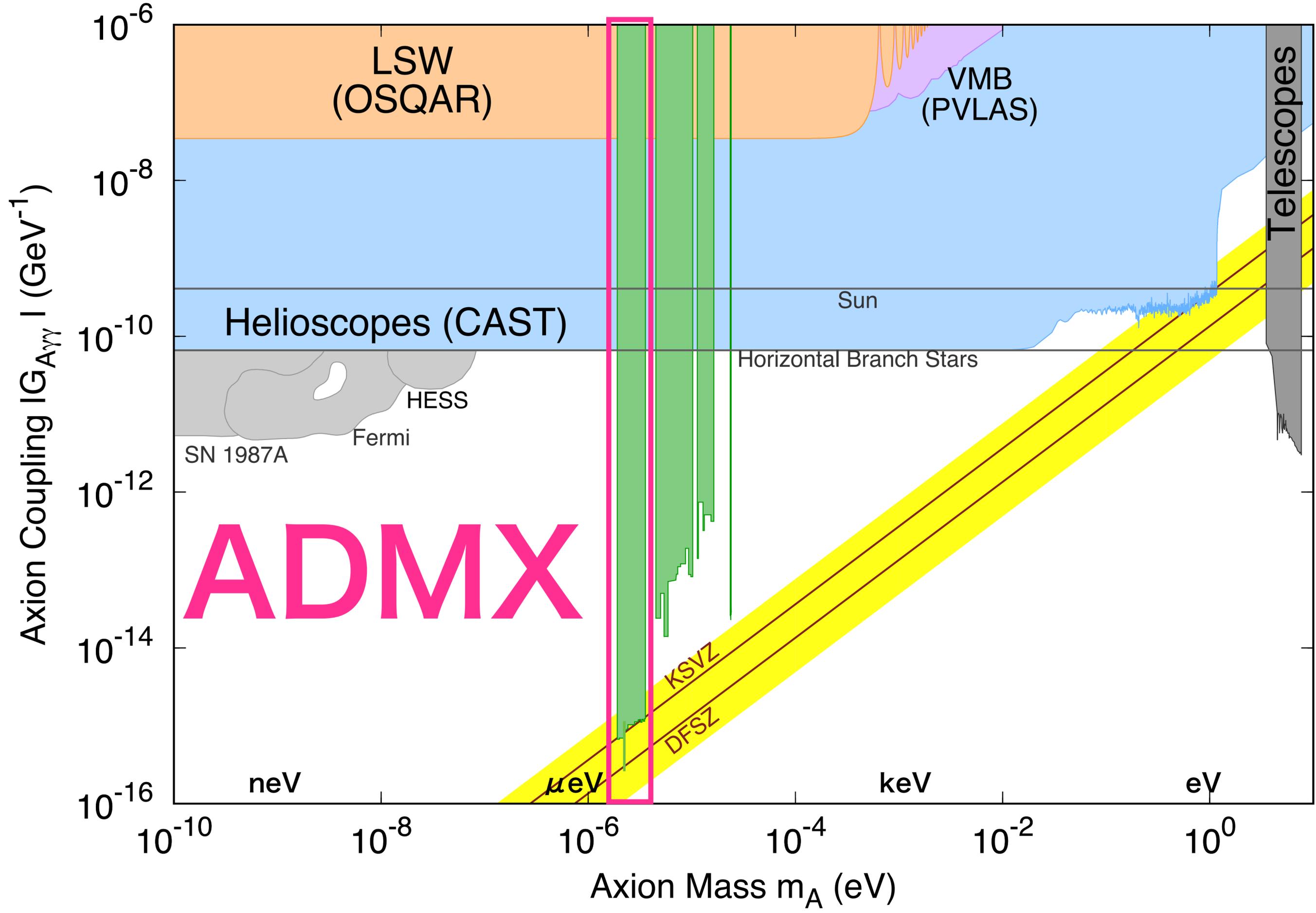
ダークマターの懇談会2019
2019年 7月 6日
新田 龍海 (早稲田)

導入

トーク目的：海外のaxion探索現状と戦略のレビュー

取り上げる実験

- ADMX
- ABRACADABRA
- CAST/IAXO

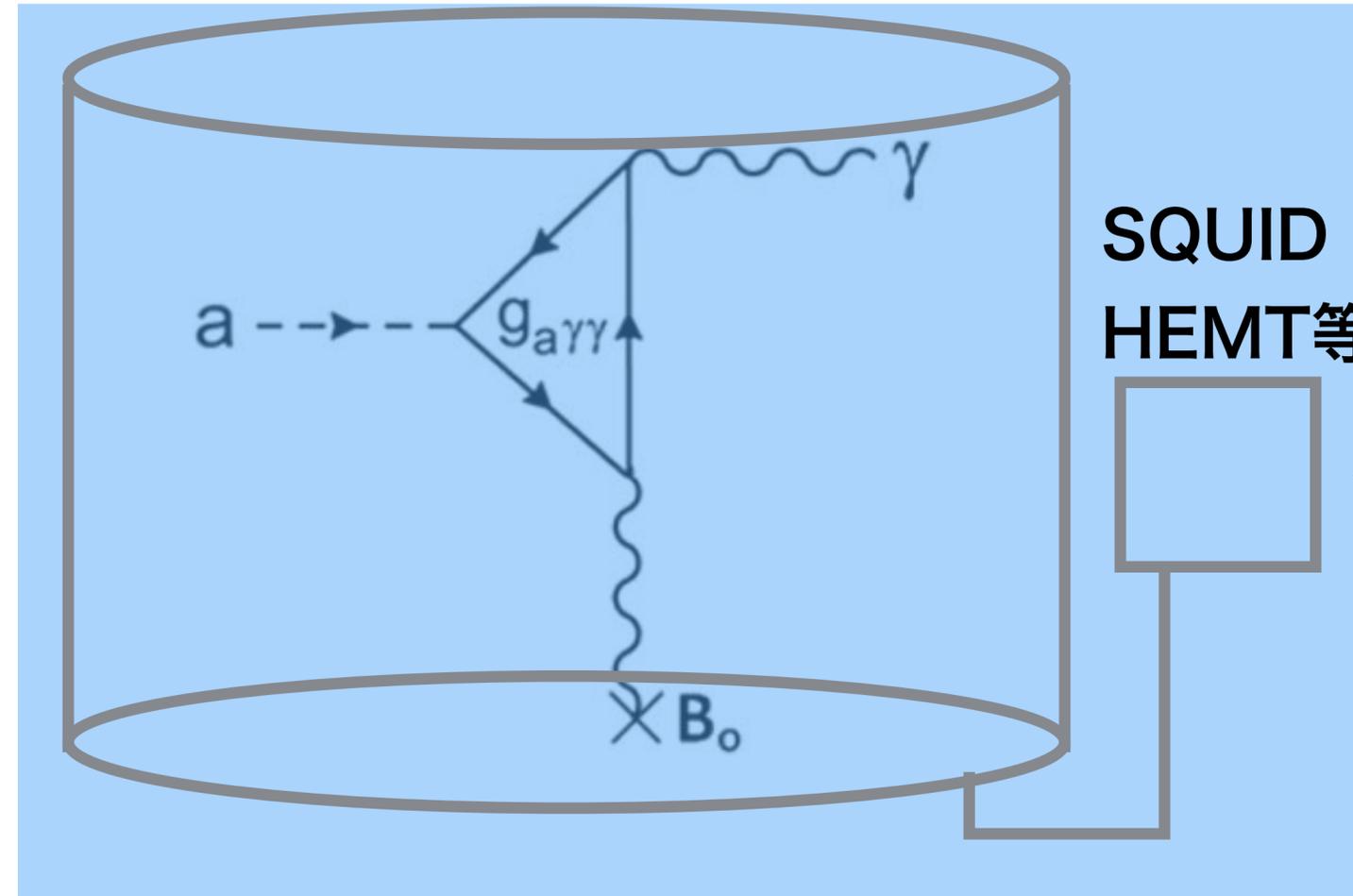


探索原理と感度

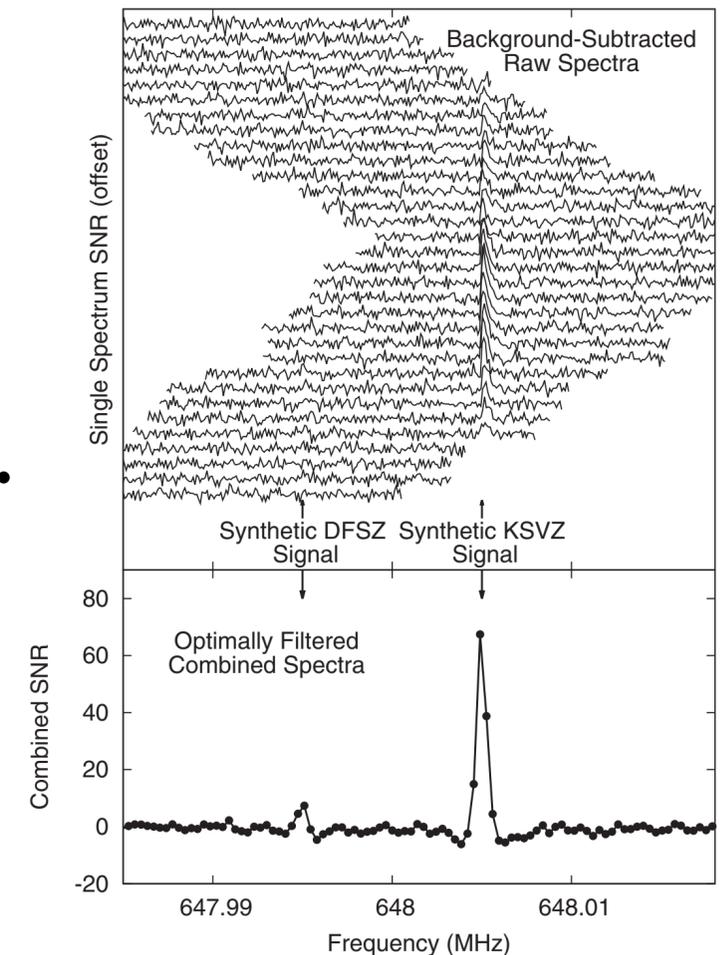
DM Axion



高磁場 & 共振空洞 & 低温



ピークサーチ



$$P_{\text{axion}} = 1.9 \times 10^{-22} \text{ W} \left(\frac{V}{1361} \right) \left(\frac{B}{6.8 \text{ T}} \right)^2 \left(\frac{C}{0.4} \right) \left(\frac{g_\gamma}{0.97} \right)^2 \\ \times \left(\frac{\rho_a}{0.45 \text{ GeV cm}^{-3}} \right) \left(\frac{f}{650 \text{ MHz}} \right) \left(\frac{Q}{50000} \right). \quad (1)$$

$$\text{SNR} = (P_{\text{axion}} / kT_{\text{system}}) (t/b)^{1/2}$$

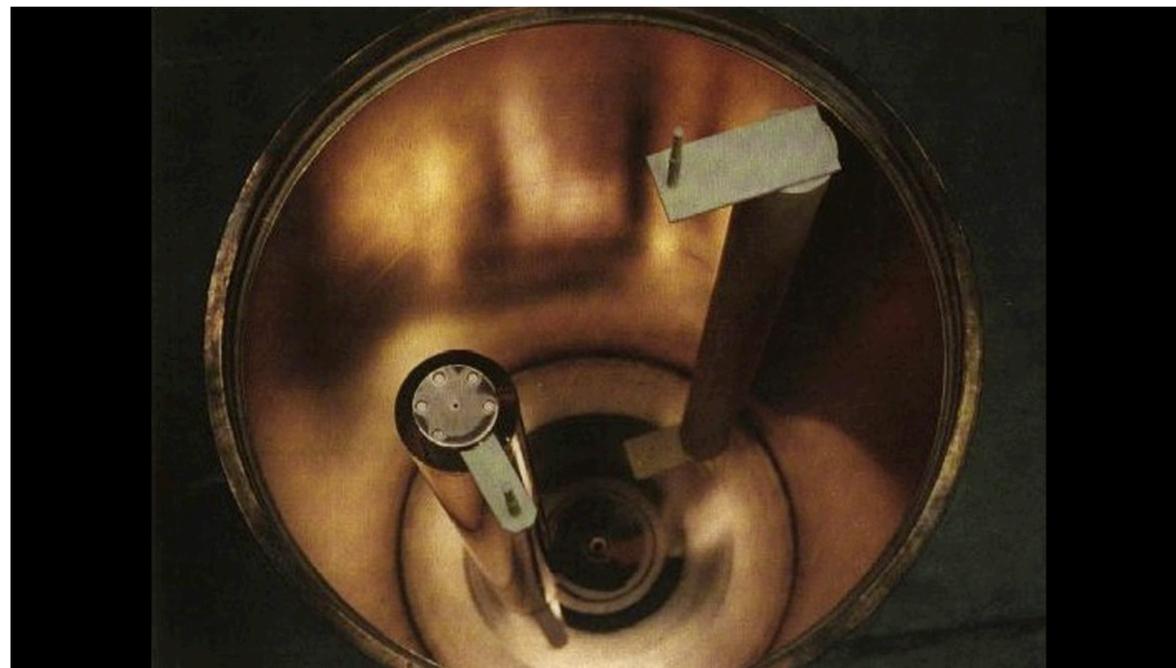
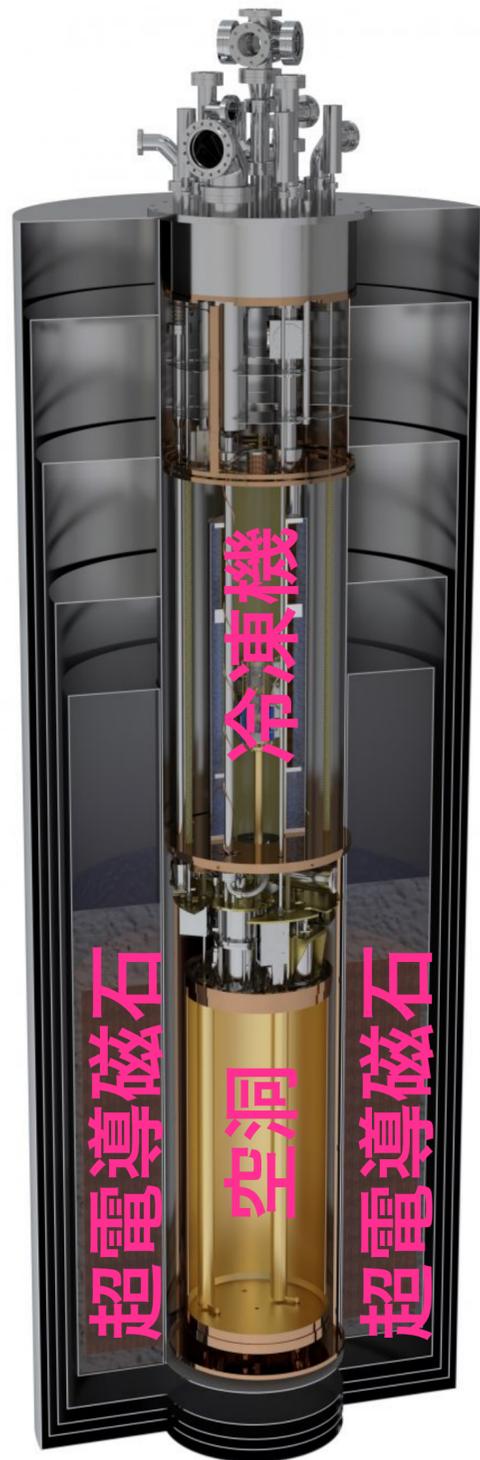
Axion Dark Matter eXperiment (ADMX)



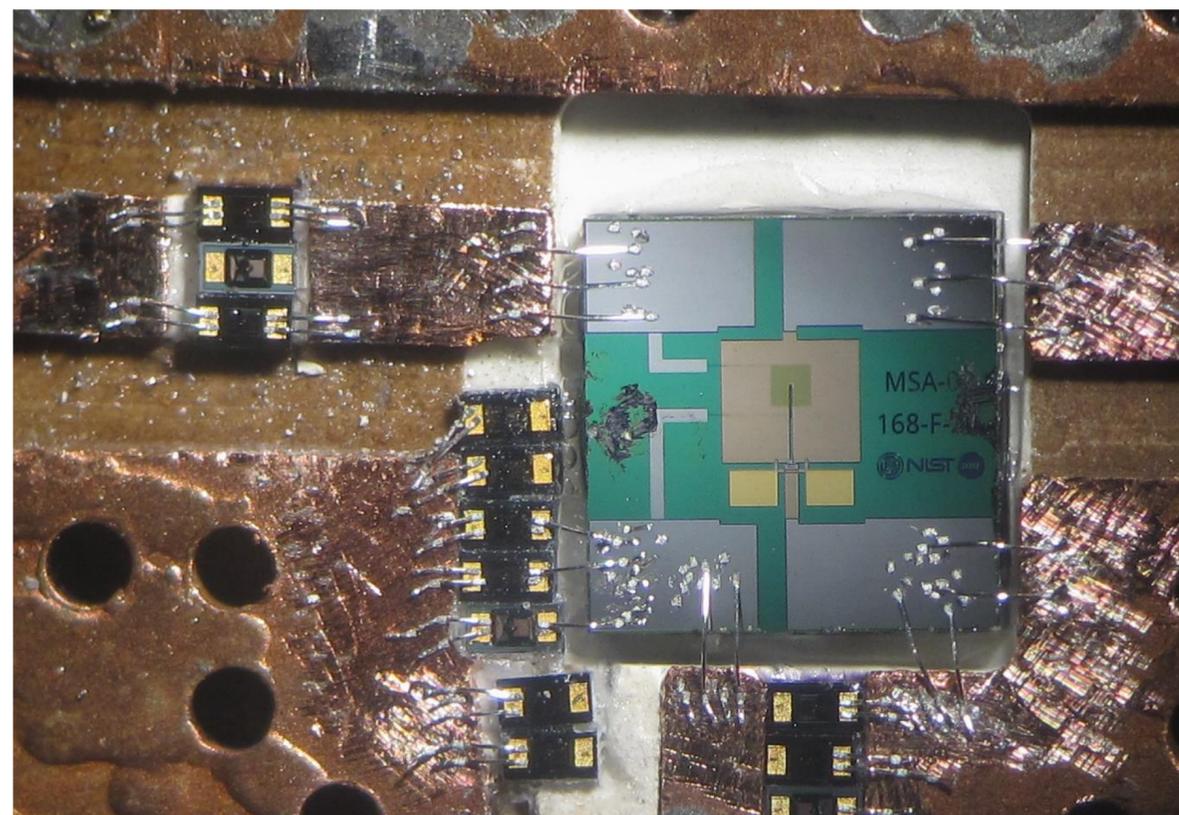
1996年にLLNLで開始。現在はワシントン大に移設。
2018年にDFSZモデルに到達。30人規模の実験。
(Washington, Florida, Berkeley, LLNL, LANL, PNNL, Fermilab, ...)



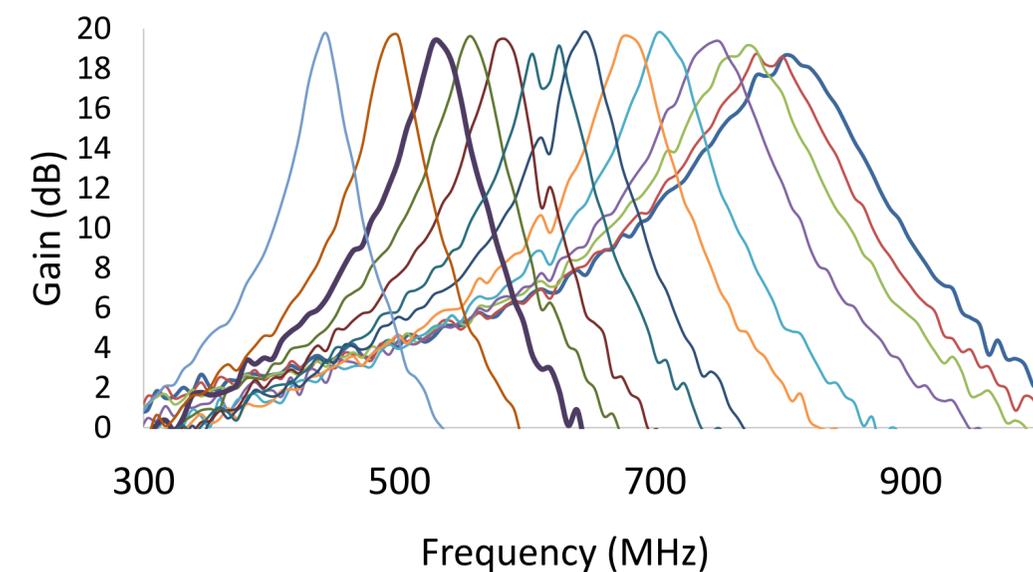
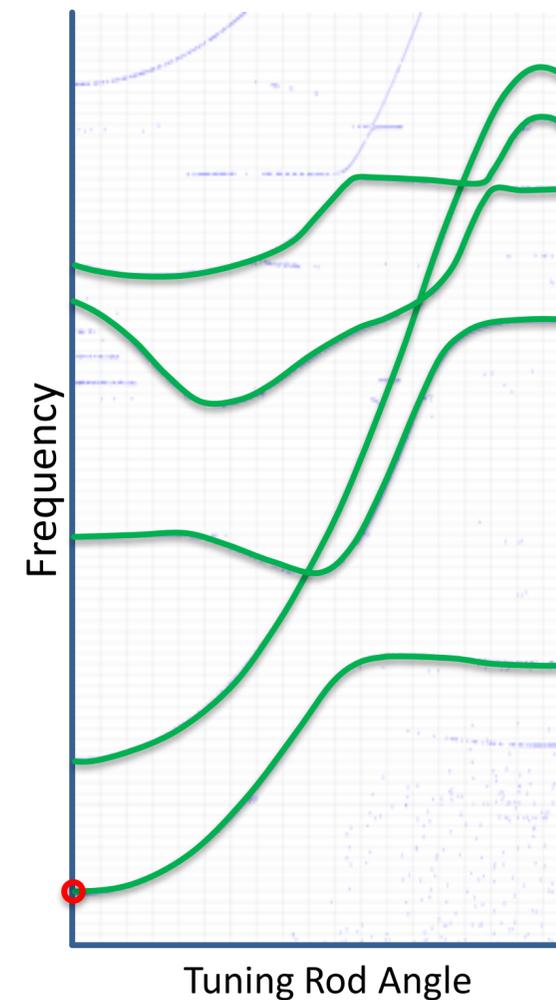
装置



2本の棒で共振周波数を調整



Microstrip SQUID Amplifier (MSA)



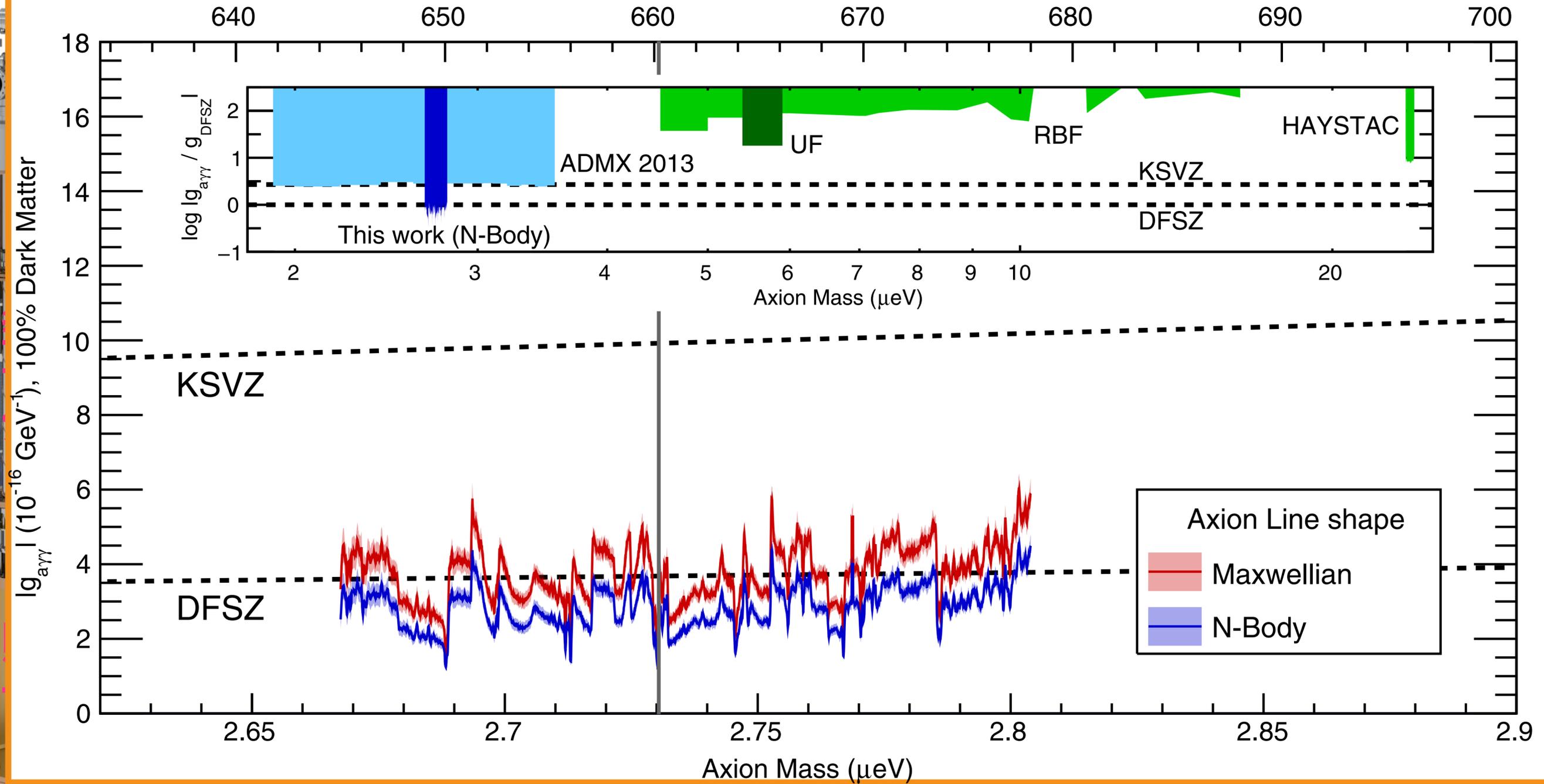
<1GHzまで対応

資料

資料

PRL 120, 151301

Frequency (MHz)

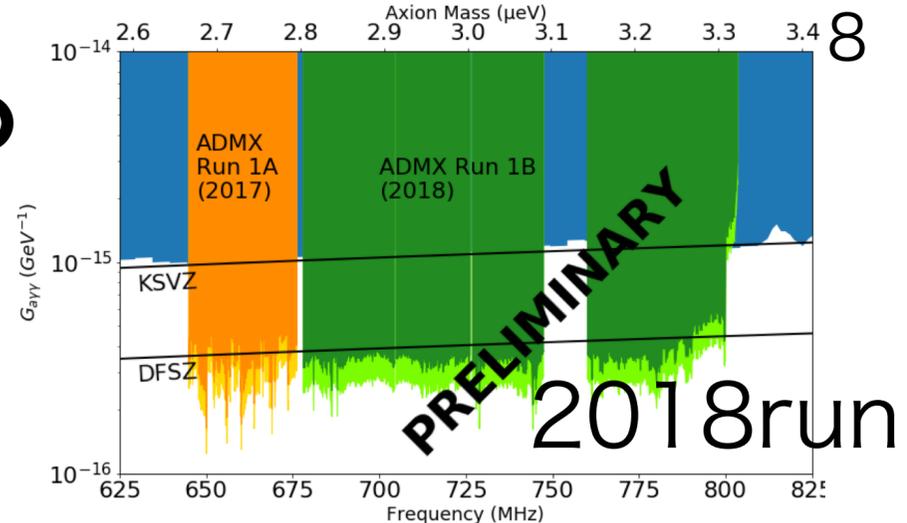


超電導磁石

Microstrip SQUID Amplifier (MSA)

Frequency (MHz)

ADMXロードマップ



Run year	探索領域 (DFSZ感度)		アンプ	キャビティ	現状
2017	2.7-2.8 μeV	0.65-0.68GHz	MSA(<~1GHz)	Single Cavity	Published PRL 120, 151301
2018	2.8-3.3 μeV	0.68-0.8GHz	JPA (>0.5GHz)	↓	解析中 Preliminary結果
2019	3.3-5 μeV	0.8-1.3GHz	↓	new tuning rod	データ 取得中
2020-	6-9 μeV	1.5-2.2GHz	↓	4-Cavity	小型prototype テスト中
202X-	10-40 μeV	2.5-10GHz	↓	14-Cavity Photonic Bandgap	R&D
	40- μeV	10GHz	単一光子検出	↓	R&D

ほぼ決定

進捗次第



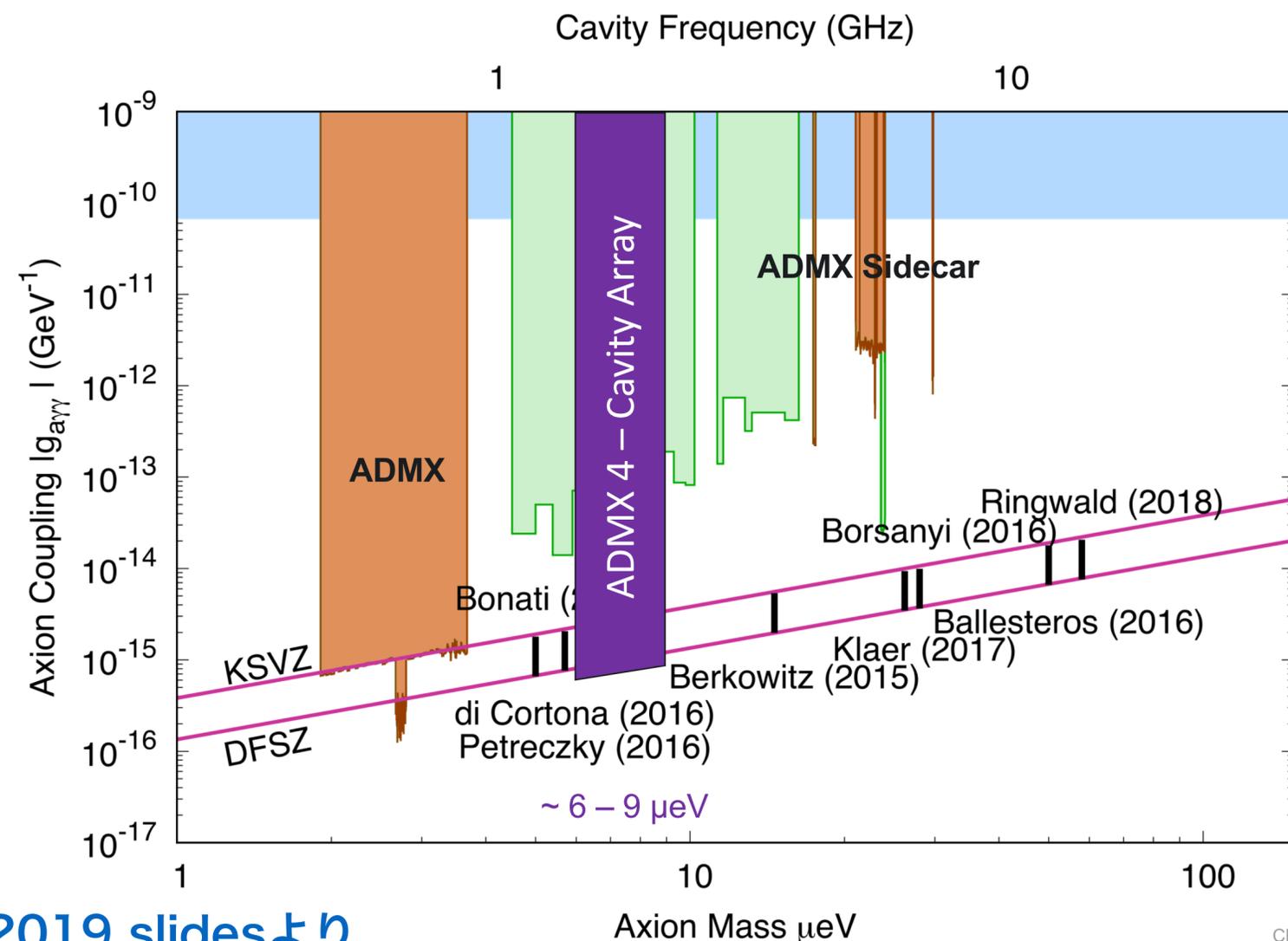
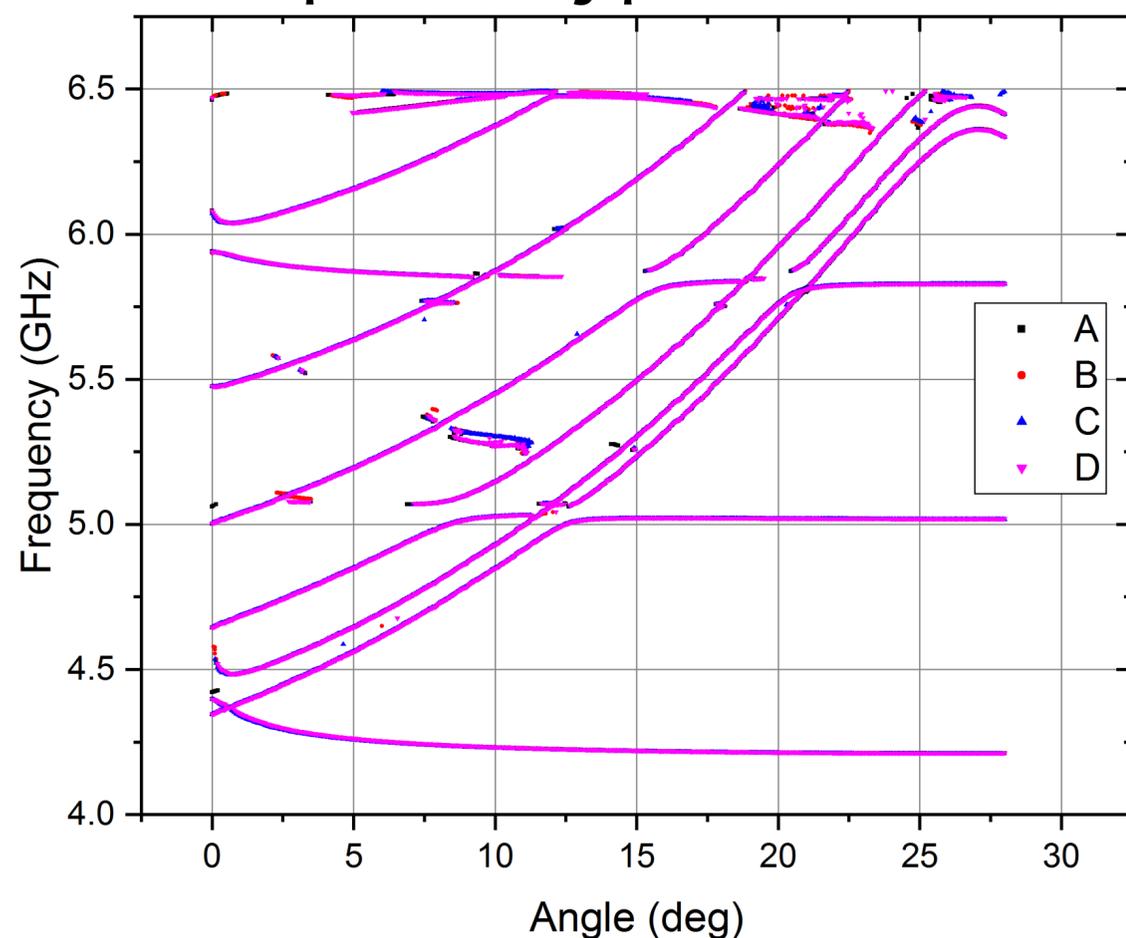
4-Cavity (5-10 μeV)

直径を細しつつ、有感領域を確保。

直径：42cm \rightarrow 16cm \times 4本

4つの出力をまとめて増幅するため、共振周波数の一致が重要

小型prototypeでのテスト



ADMXの40 μeV 以上の戦略

資料

課題1:

Standard Quantum Limit (SQL)

増幅は強度と位相の同時測定: $\Delta n \cdot \Delta \phi > 1/2$

SQL bkg. $\sim \hbar f / k_B \propto f$

信号量 $\propto V \sim f^{-3}$

→ SQLは高質量でより深刻に

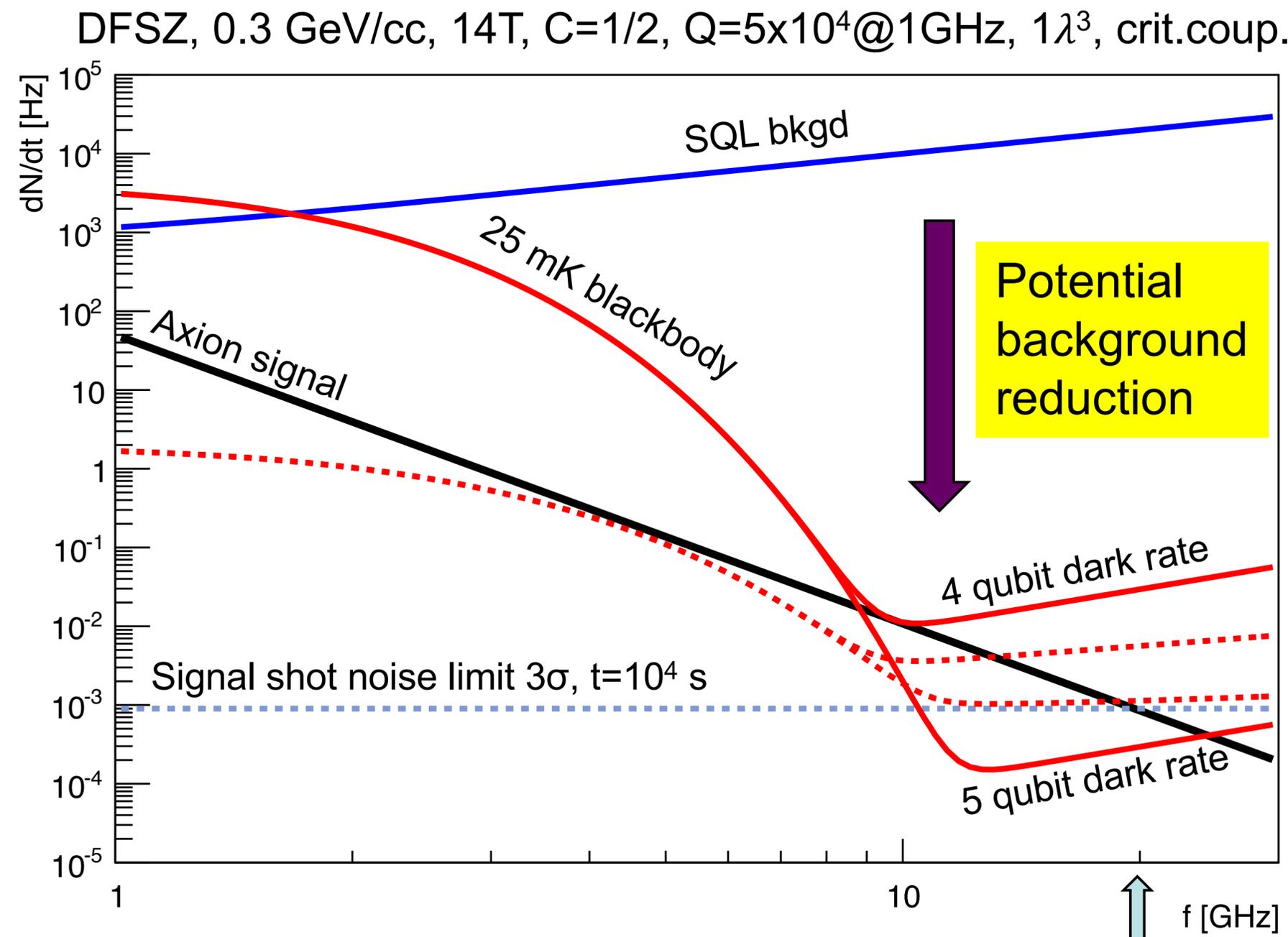
解) 単一光子検出: 特にQubit

→ 位相のランダム化と
引き換えにSQL回避

課題2: 信号の統計ゆらぎ

SQL回避後の唯一のbkg.

解) 信号パワーの増加: CavityのQ値改善 (or V,B)

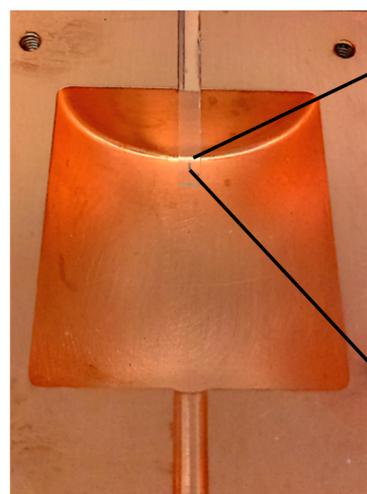


Qubitを用いたマイクロ波単光子検出

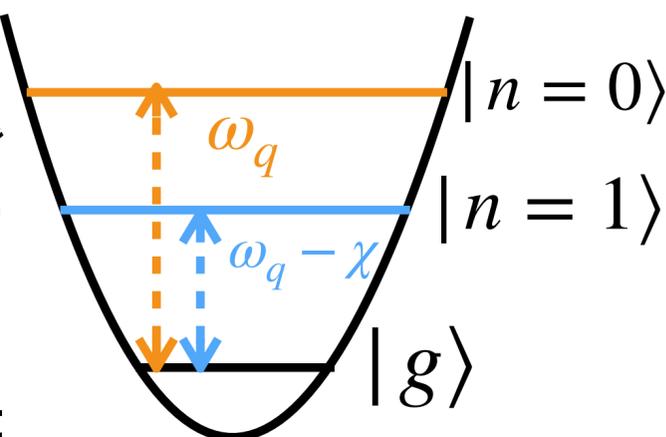
調和振動子+二準位の系 (cavity + qubitなど)

Jaynes-Cummings Hamiltonian

$$H/\hbar = \omega_c a^\dagger a + \omega_q \sigma_z - \chi a^\dagger a \sigma_z$$

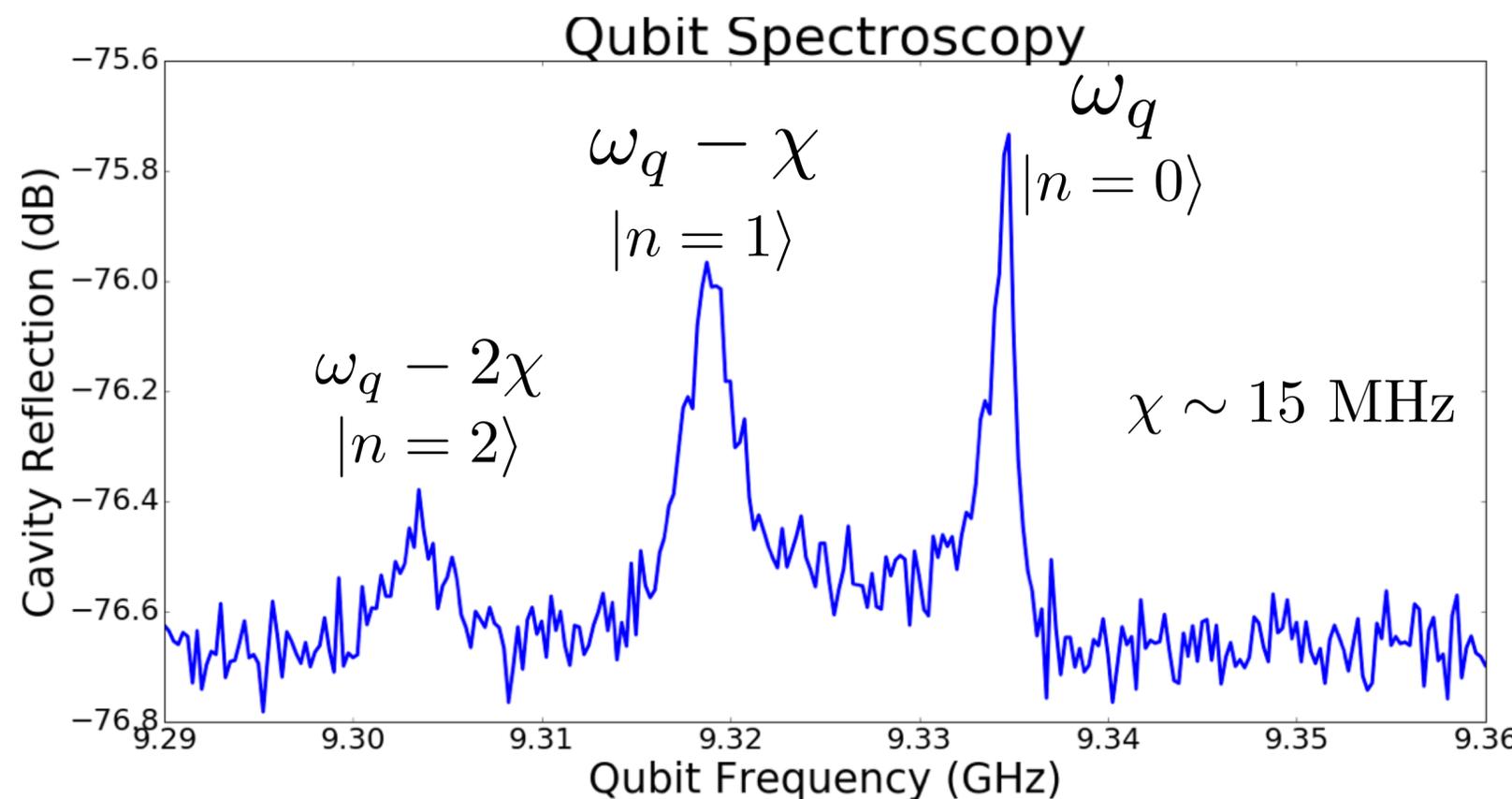


ジョセフソン接合



$$= \omega_c a^\dagger a + (\omega_q - \chi a^\dagger a) \sigma_z$$

- 光子の存在が、qubitの遷移周波数をずらす。
- 測定で光子が壊れない。(Quantum Non-Demolition)
→ 複数回の測定で測定効率を上げられる。



量子コンピュータの制御技術でもある。

Fermilab等がAxion探索への応用の基礎研究([talk](#))

日本も最先端の技術を持つ。

先端研, 中村氏他 : [2018, Nature physics letter](#)

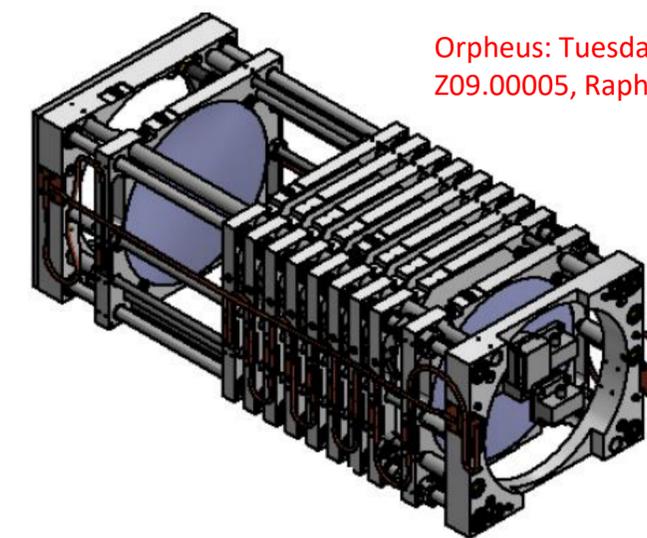
理研, 猪俣氏他 : [2016, Nature communication](#)

キャビティ種々技術 (10 μeV -)

Cavities #	Res freq. MHz	Tuning range MHz	Tuning range μeV
1	575	402-575	1.7-2.4
1	575	575-908	2.4-3.8
2	897	897-1417	3.7-5.9
4	1207	1207-1907	5-7.9
8	1899	1899-3001	7.8-12
16	2959	2959-4675	12-19
32	3983	3983-6293	16-26

Future-Higher Frequency Searches, >4 GHz

- R&D platforms for higher frequency searches
 - Difficult to design systems with a large volume and small tuning structures

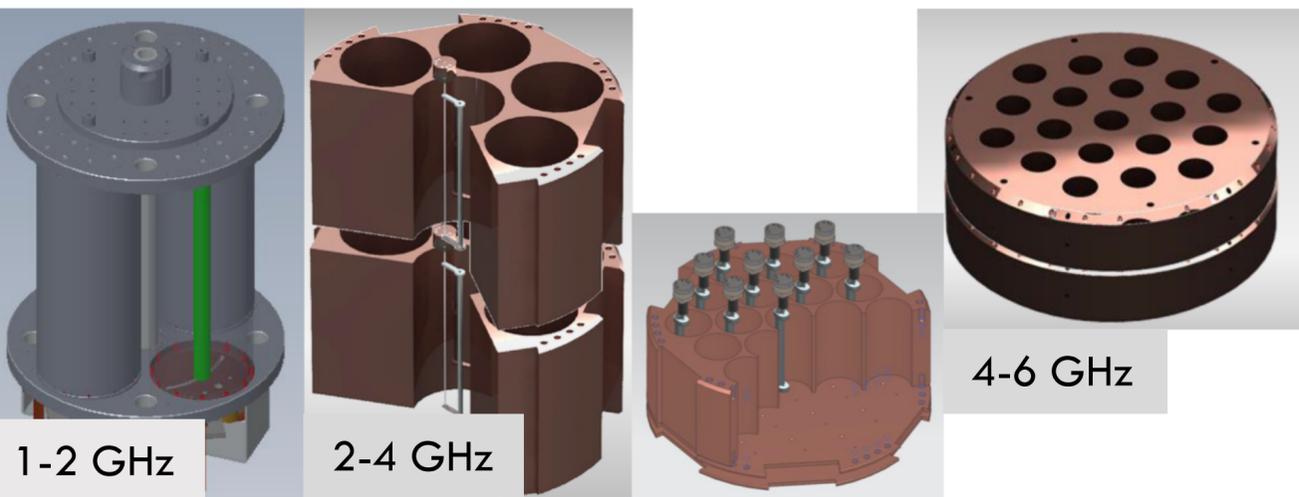


Orpheus: Tuesday, April 16, 4:18 Z09.00005, Raphael Cervantes

Orpheus (U. Washington)



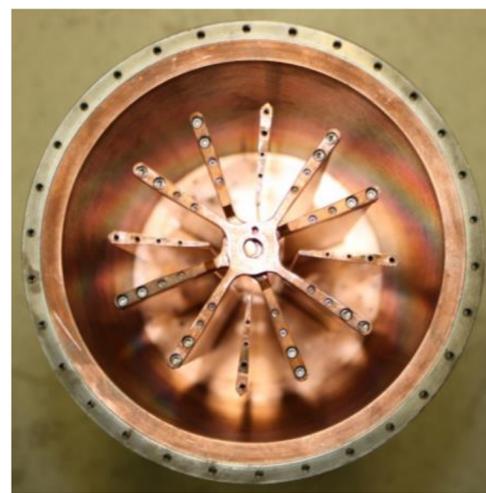
Comb cavity (FNAL)



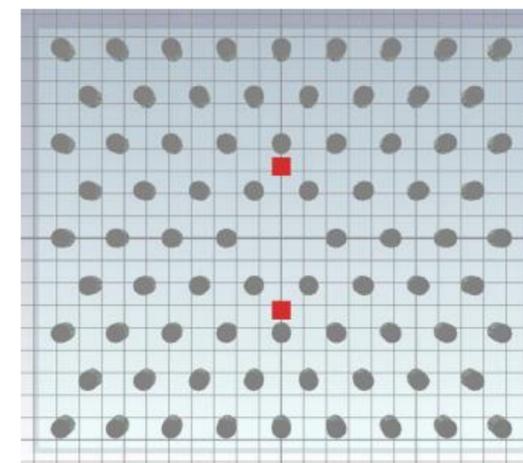
1-2 GHz

2-4 GHz

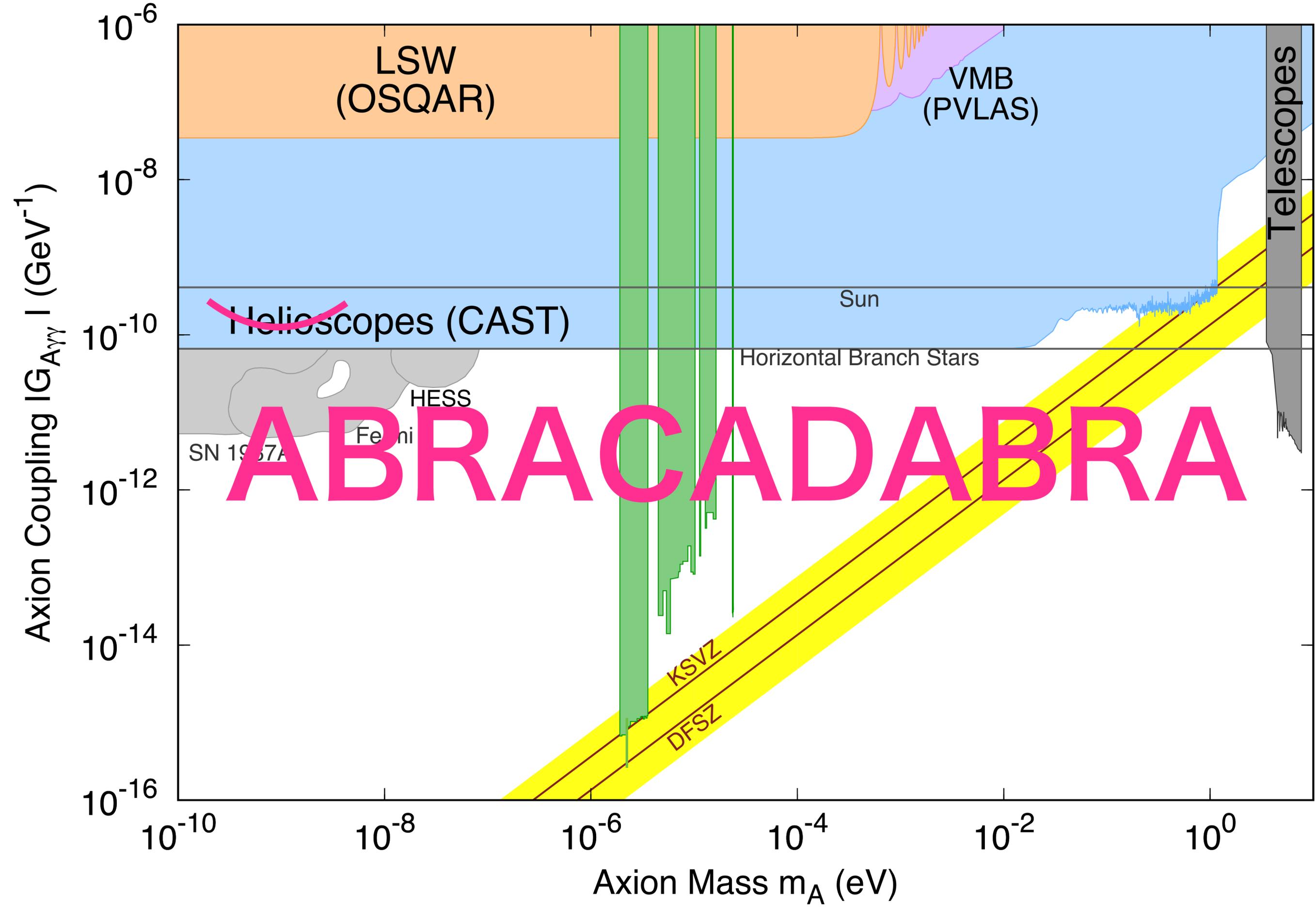
4-6 GHz



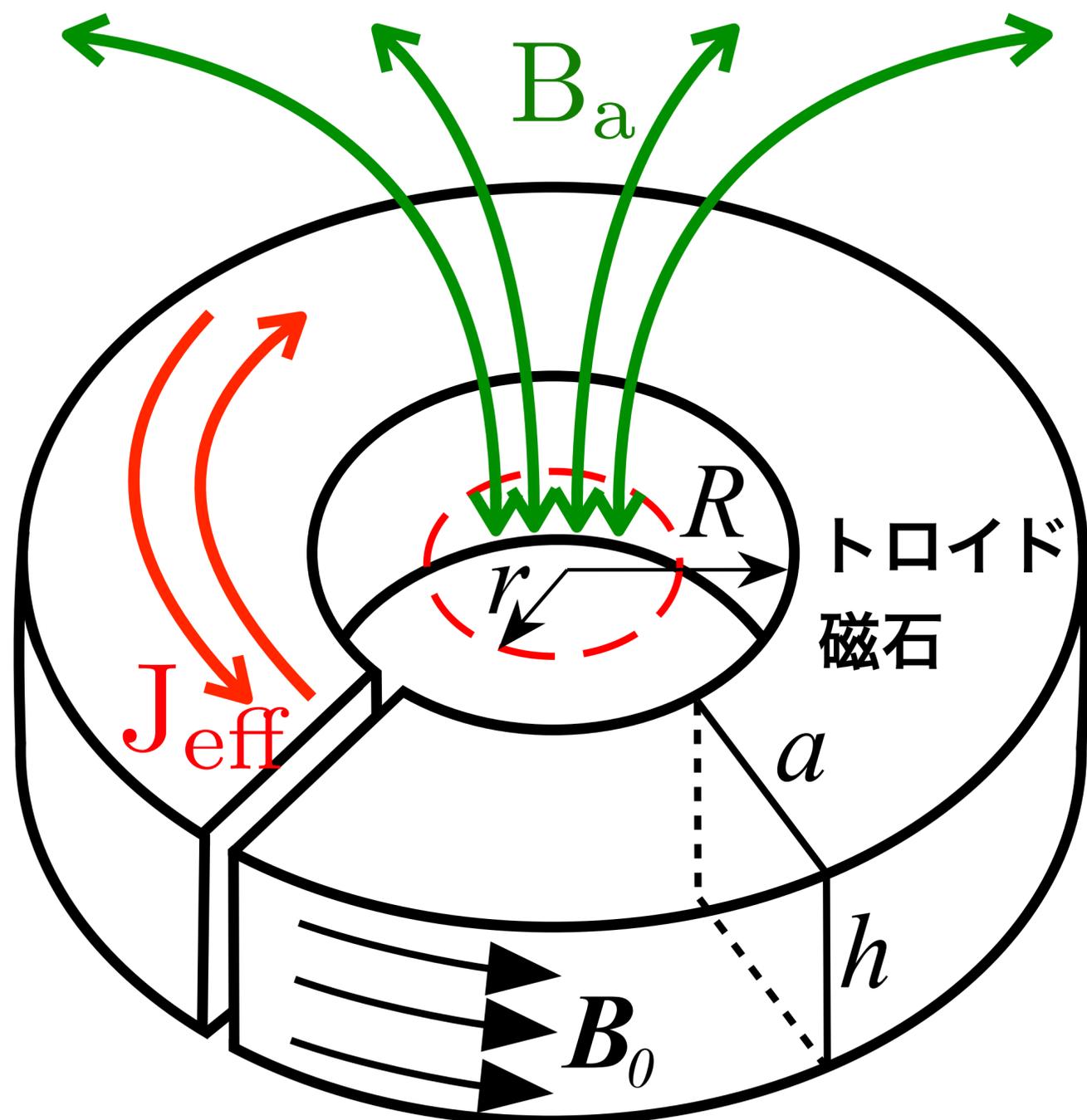
"Pizza" Cavity (U. Florida)



Photonic Bandgap(LLNL)



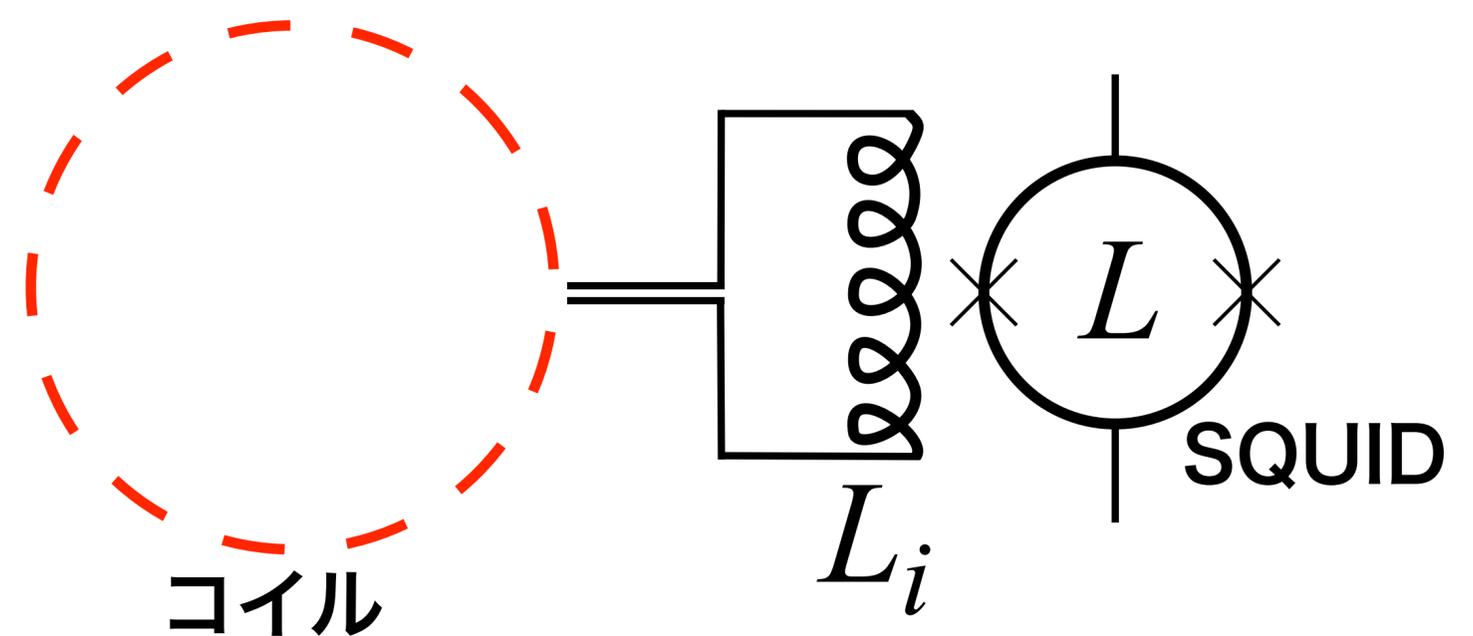
実験原理



$$\nabla \times \mathbf{B} = \frac{\partial \mathbf{E}}{\partial t} - g_{a\gamma\gamma} \left(\mathbf{E} \times \nabla a - \mathbf{B} \frac{\partial a}{\partial t} \right)$$

$$\mathbf{J}_{\text{eff}} = g_{a\gamma\gamma} \sqrt{2\rho_{\text{DM}}} \cos(m_a t) \mathbf{B}_0$$

$$|\Phi_a|^2 = g_{a\gamma\gamma}^2 \rho_{\text{DM}} V^2 \mathcal{G}^2 B_{\text{max}}^2 \equiv A$$



2016年提案、2018年に初結果

MIT主導, 総勢15人のコラボレーター

装置

冷凍機(運転時1K)



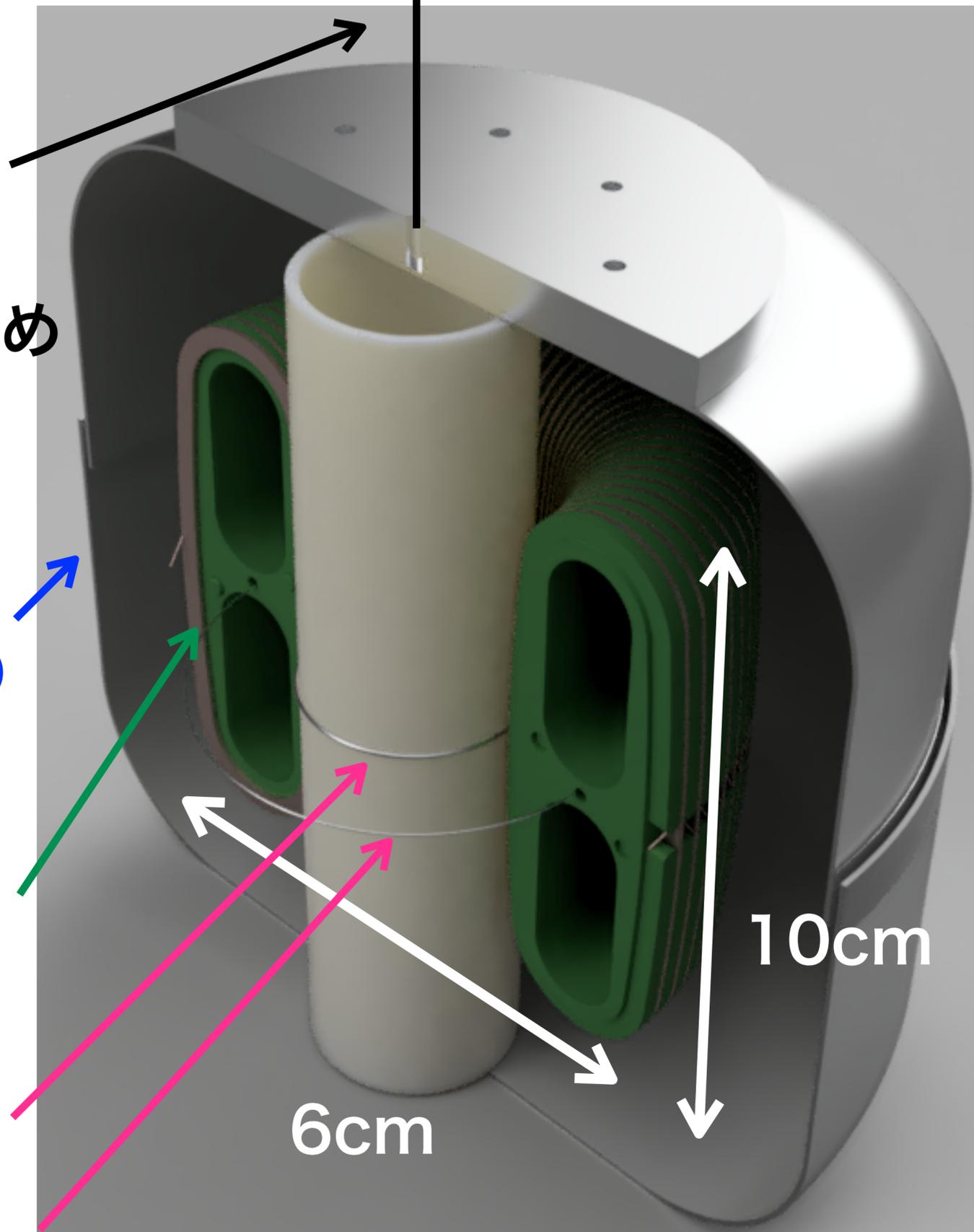
冷凍機上部
から紐で吊る
振動分離のため

磁場シールド
(すずコーティング)

トロイド磁石
NbTi, 1T

検出用ループ

校正用ループ



10cm

6cm

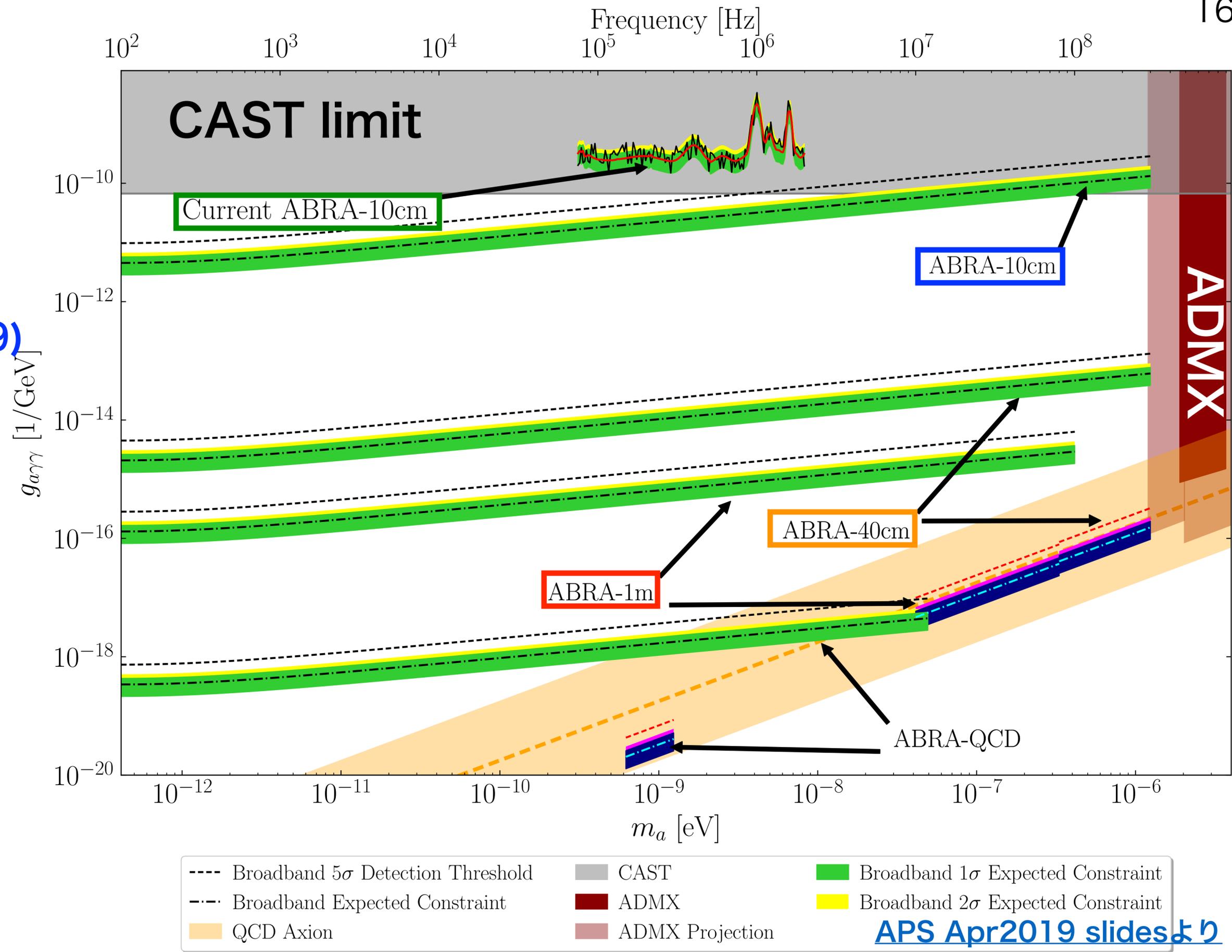
感度

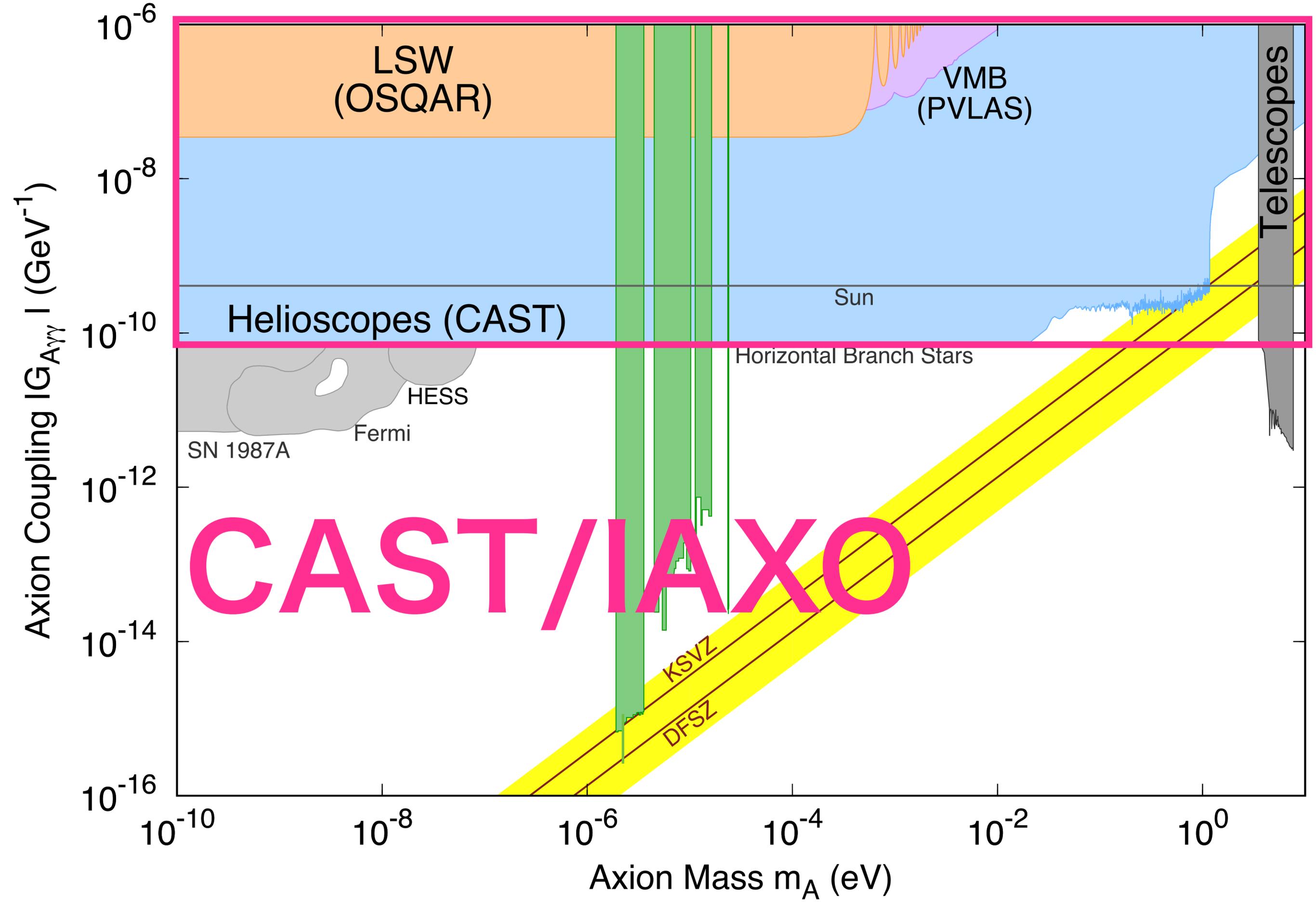
ABRA-10cm (2018)
 - 1T, $\phi \sim 10\text{cm}$

ABRA-10cm改良版 (2019)
 - 寄生インピーダンス除去
 - 振動抑制
 → CAST感度を更新予定

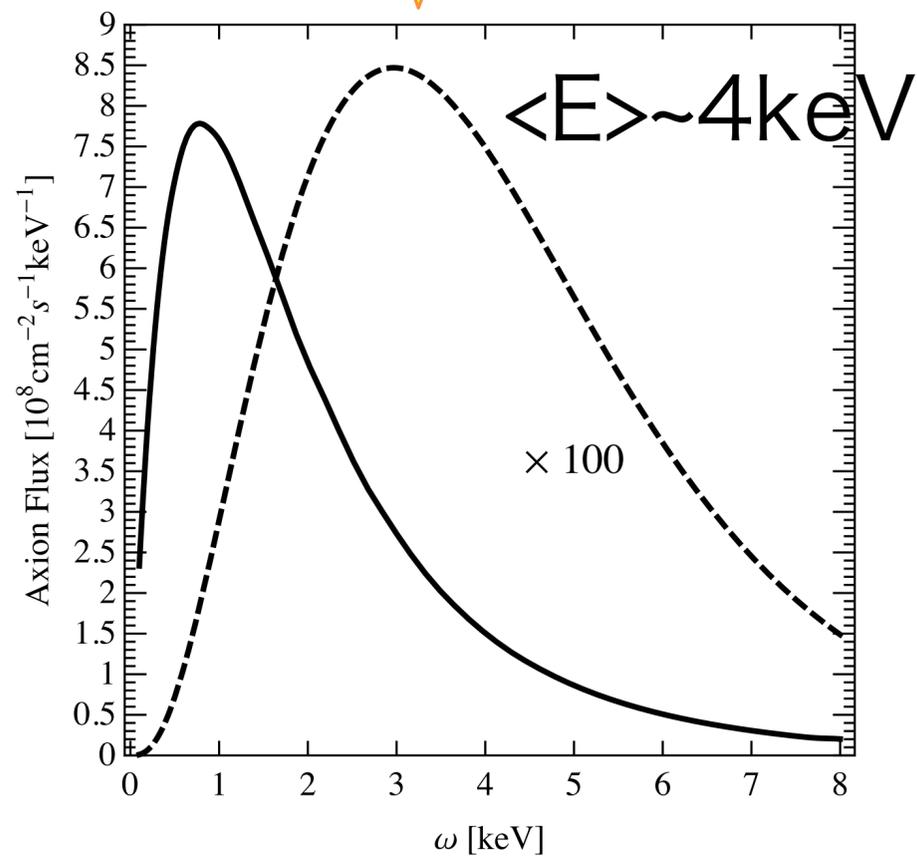
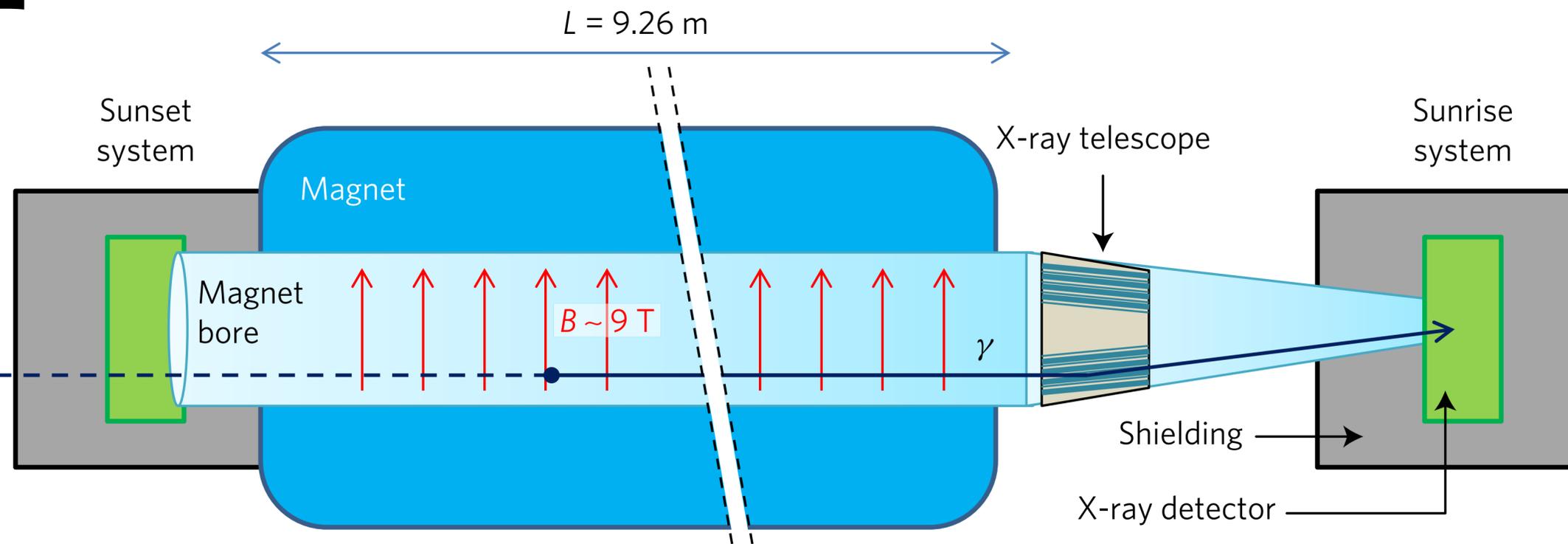
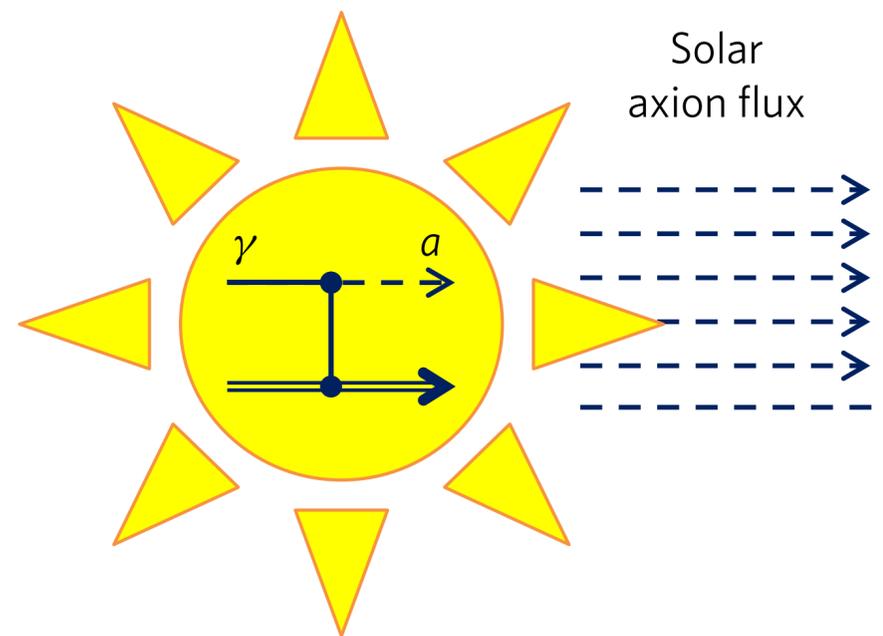
ABRA-40cm
 - 5T, $\phi \sim 40\text{cm}$
 - Readout改善: $m_a < 1\mu\text{eV}$
 - Resonant readoutも実装

ABRA-1m
 - $\phi \sim 1\text{m}$
 - **SQL突破が必須**





検出原理



$m_a < 0.02$ [eV] のとき

$$N_\gamma \propto B^2 L^2 A \epsilon t \times g^4$$

B : 磁場

L : 有感領域の長さ

A : 有感領域の断面積

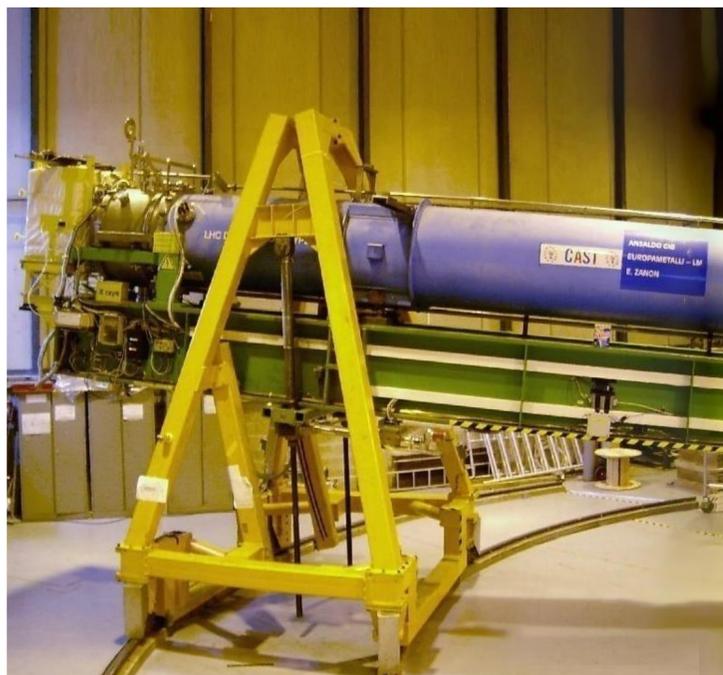
$\epsilon = \epsilon_d \epsilon_o \epsilon_t$: 量子効率, 集光効率, 運転効率

t : 運転時間

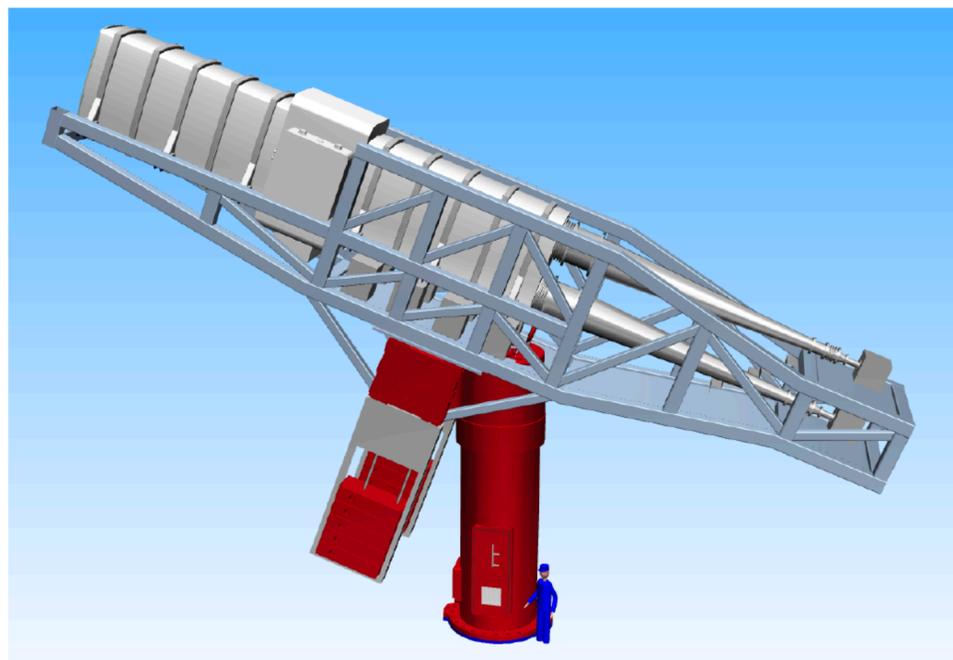
展望

Slides@ European Strategy Granada

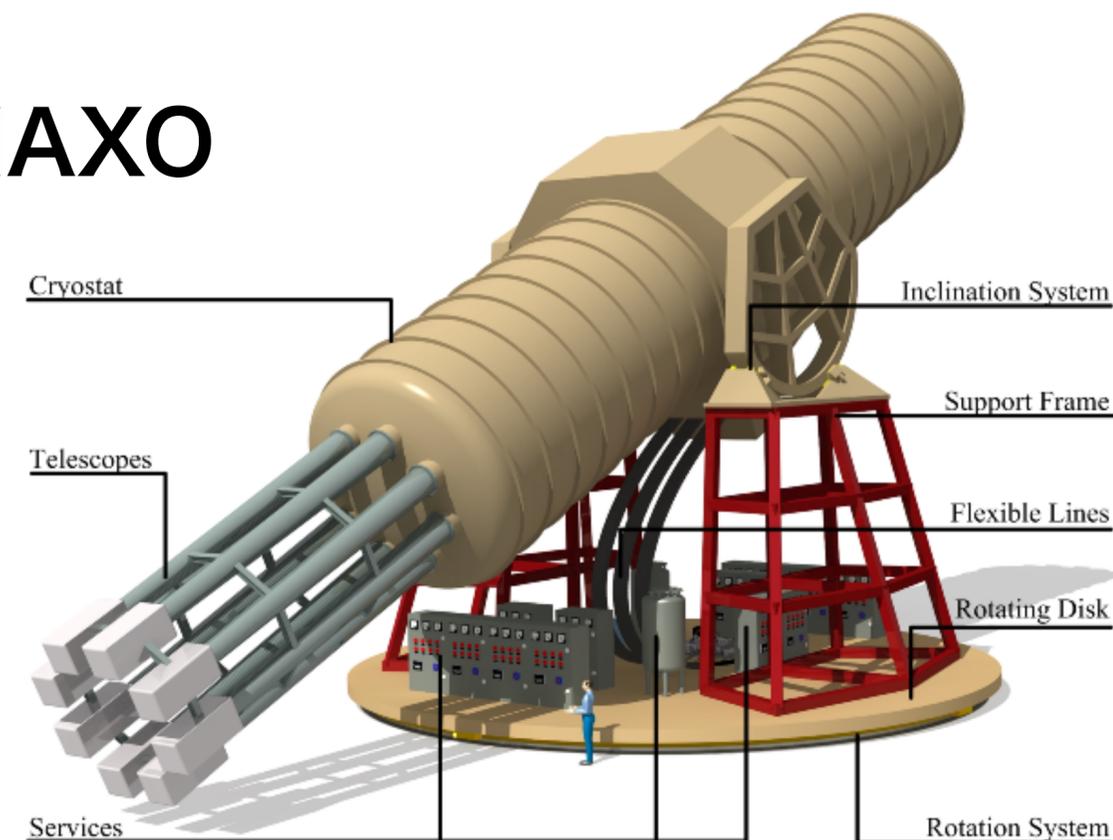
CAST@CERN



Baby-IAXO@DESY?



IAXO



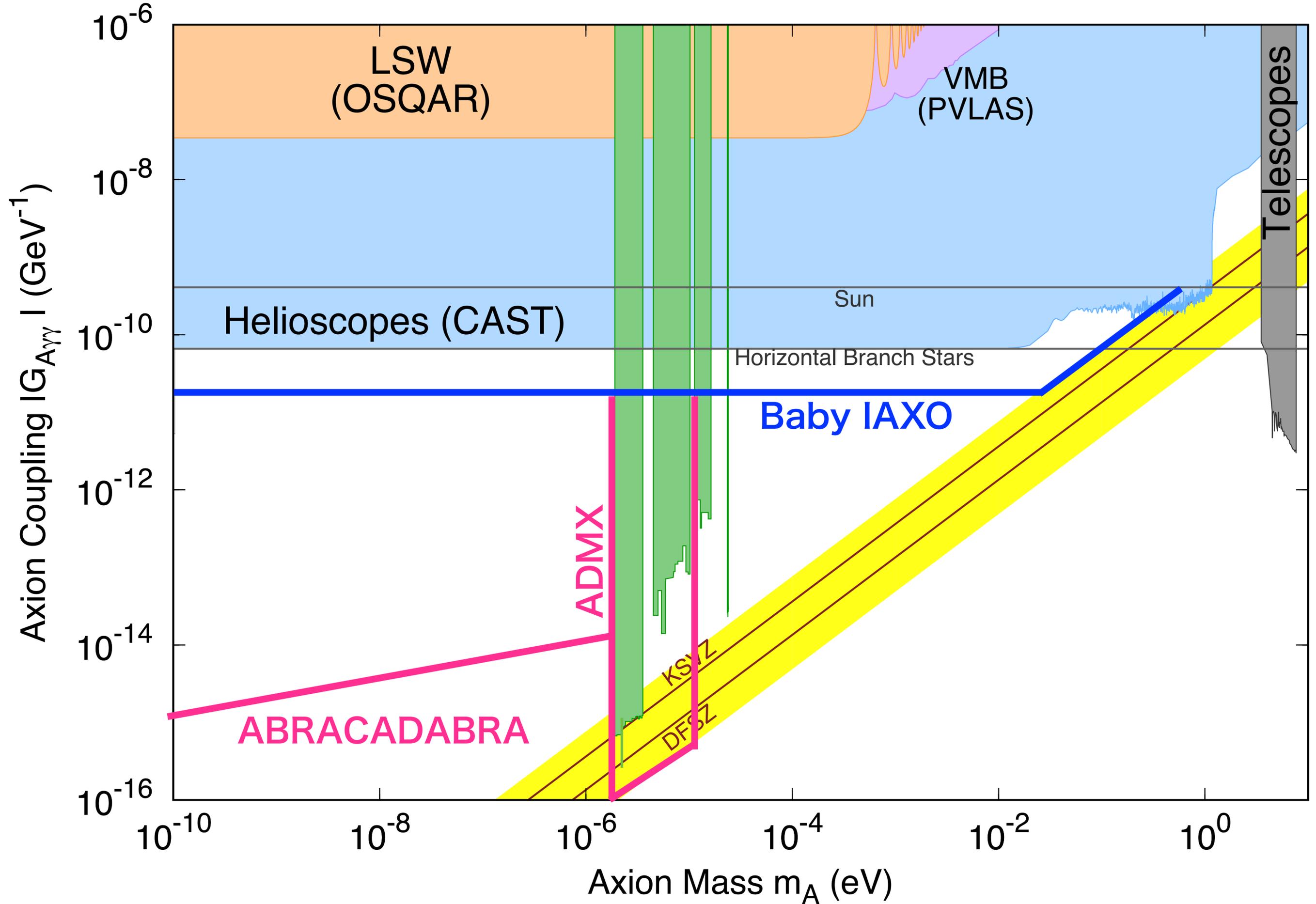
CAST

Baby-IAXO

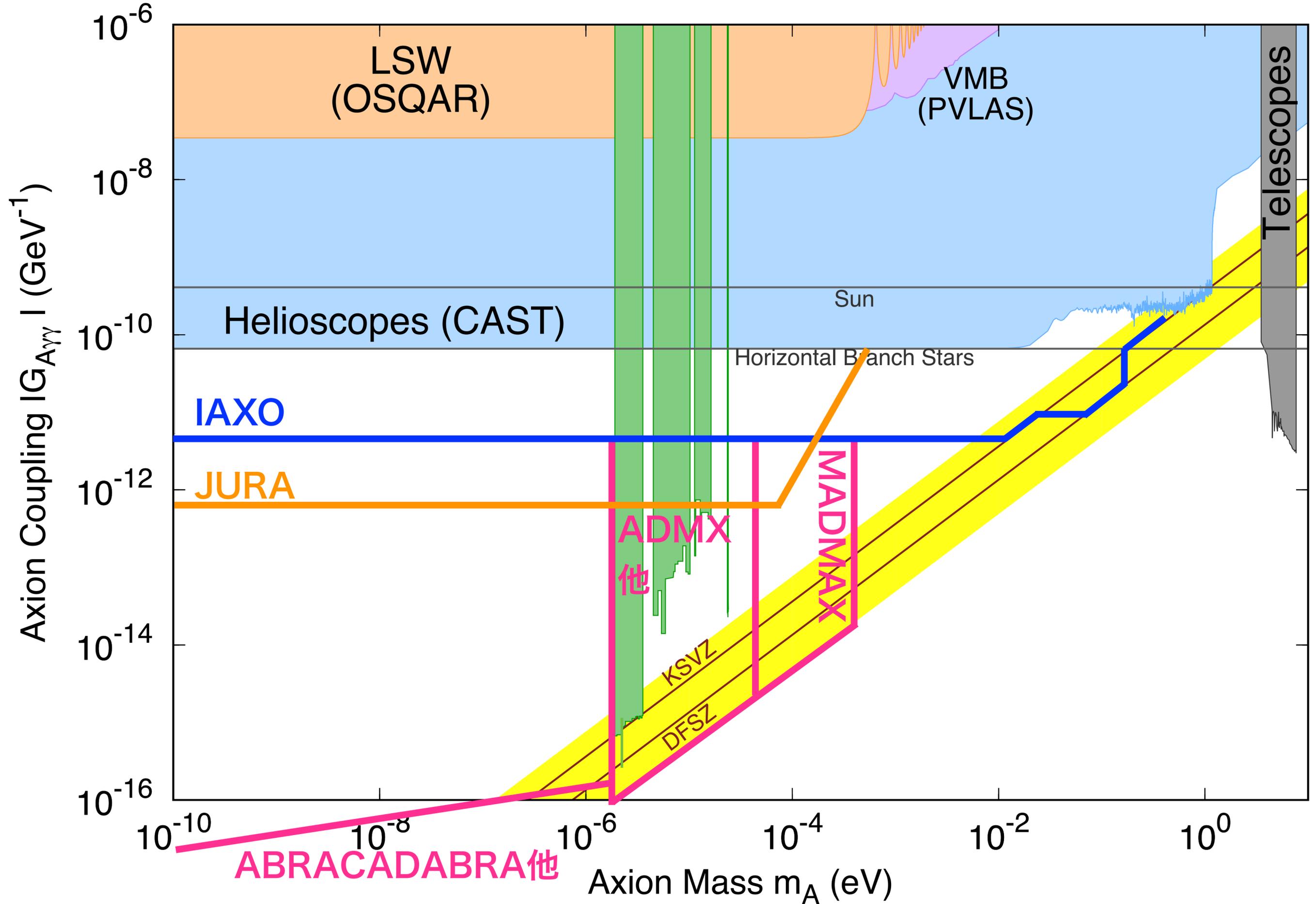
IAXO

期間	-2015	2023 - 202X (予定)	-2030 (予定)
長さ L	9m	20m	20m
断面積 A	15cm ²	2800cm²	2800cm ²
磁場 B	9T	5T	5T
テレスコープ	-	開発中	左に同じ
X線検出器	Micromegas	左に同じ (option有り)	左に同じ
感度	$ g_{a\gamma} < 7 \times 10^{-11} [\text{GeV}^{-1}]$	$ g_{a\gamma} < 2 \times 10^{-11} [\text{GeV}^{-1}]$	$ g_{a\gamma} < 4 \times 10^{-12} [\text{GeV}^{-1}]$

~2025



~2040



まとめ

ADMX@UW

- DM QCD axionの探索に唯一成功
- $<40 \mu\text{eV}$ 領域の独走を狙う
- $>40 \mu\text{eV}$ 領域の技術開発中

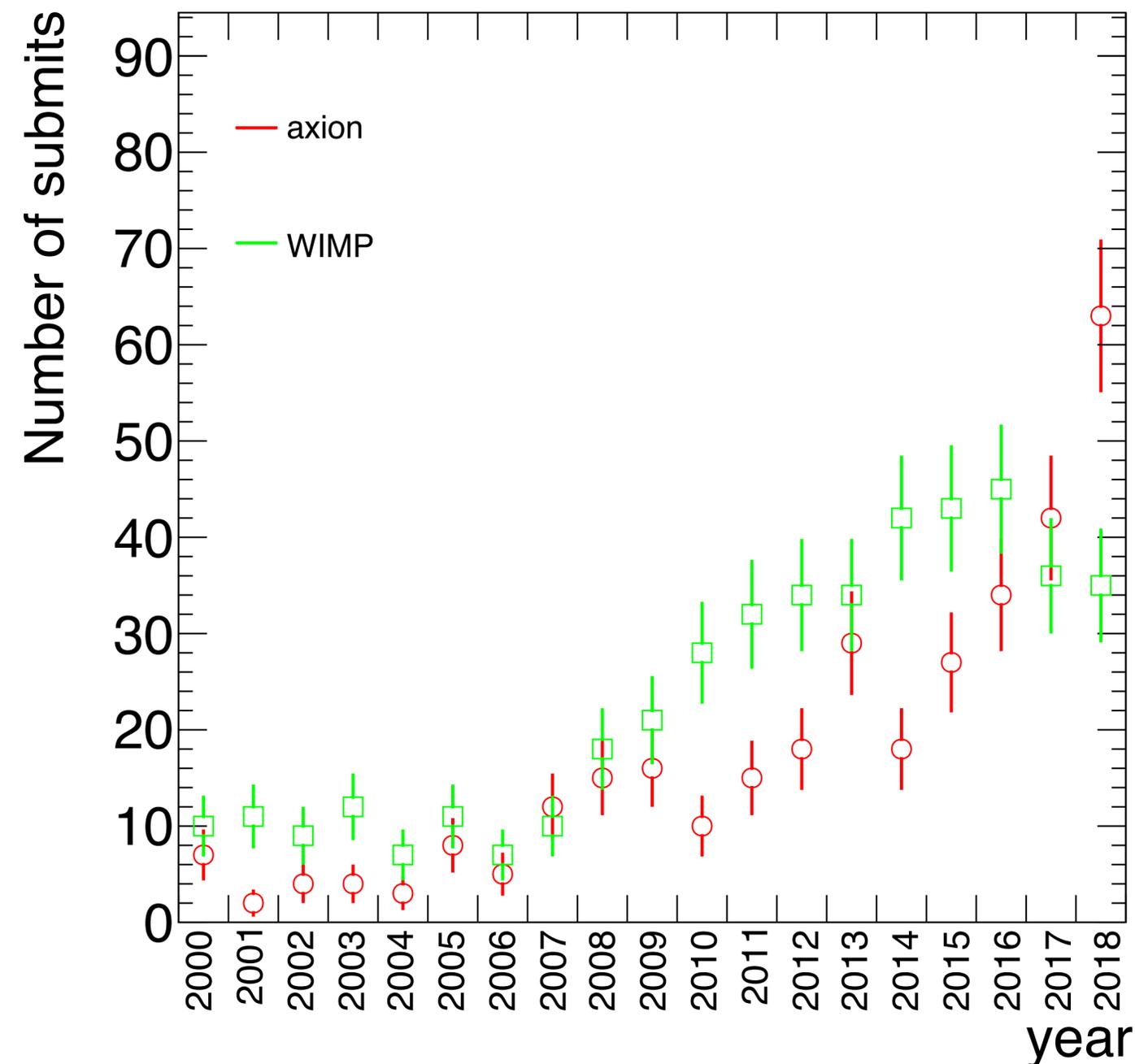
ABRACADABRA@MIT

- sub- μeV axion 急先鋒
- 今年にCAST Limit 超えを狙う

CAST/IAXO@CERN/DESY?

- solar axionの市場独占中
- baby-IAXO/IAXOで
堅実に探索範囲を拡大予定

hep-exのヒット件数/年

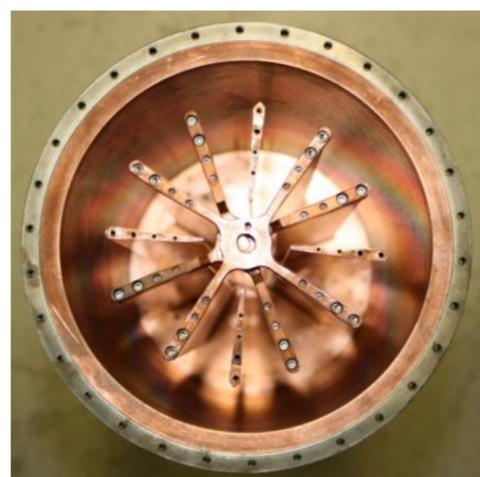


紹介した実験はほんの一部

Backup

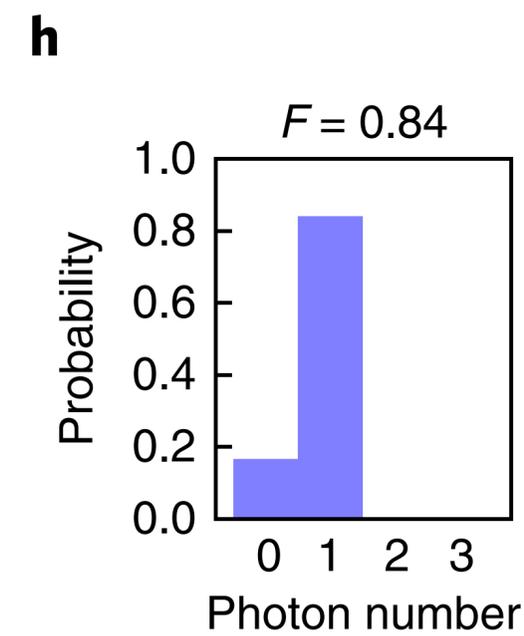
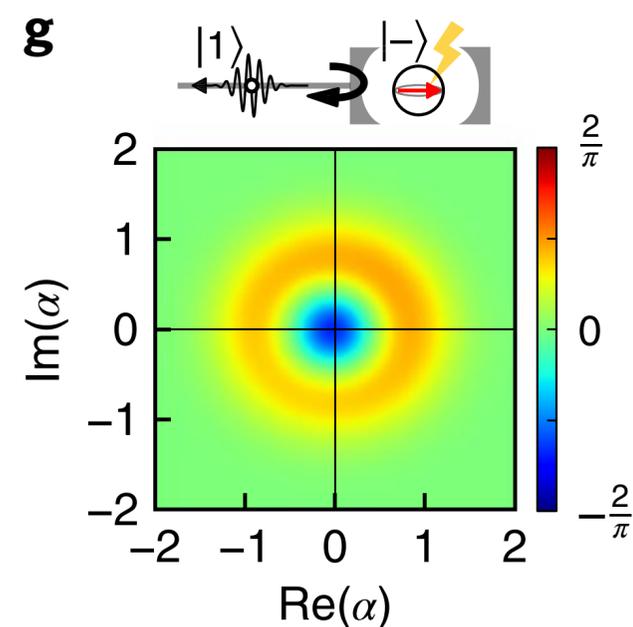
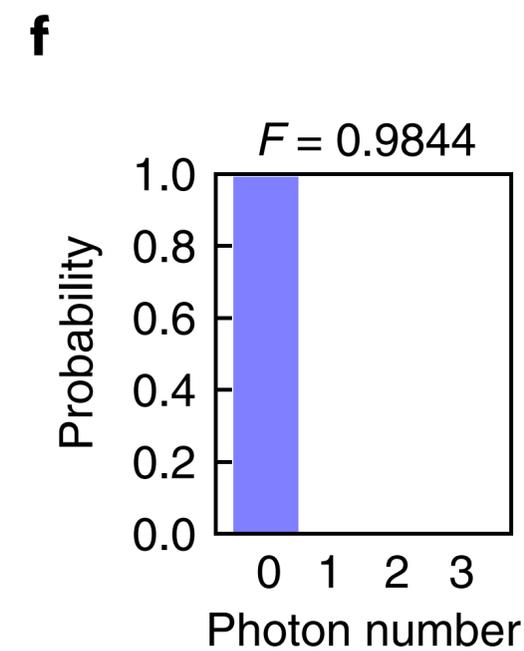
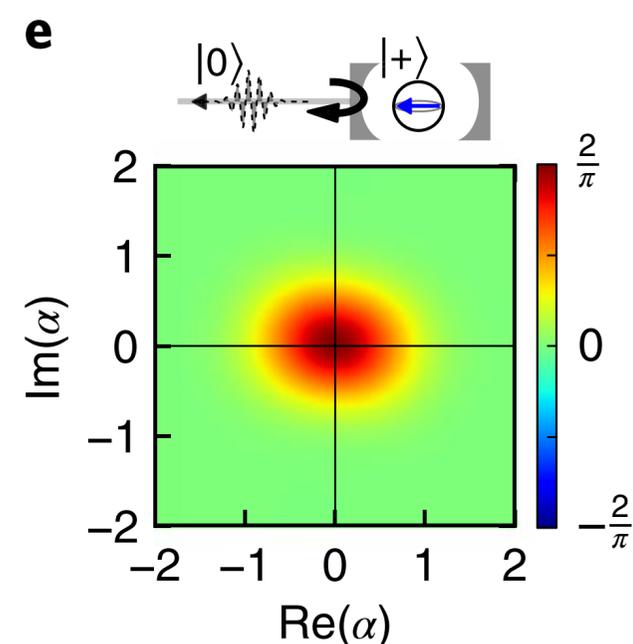
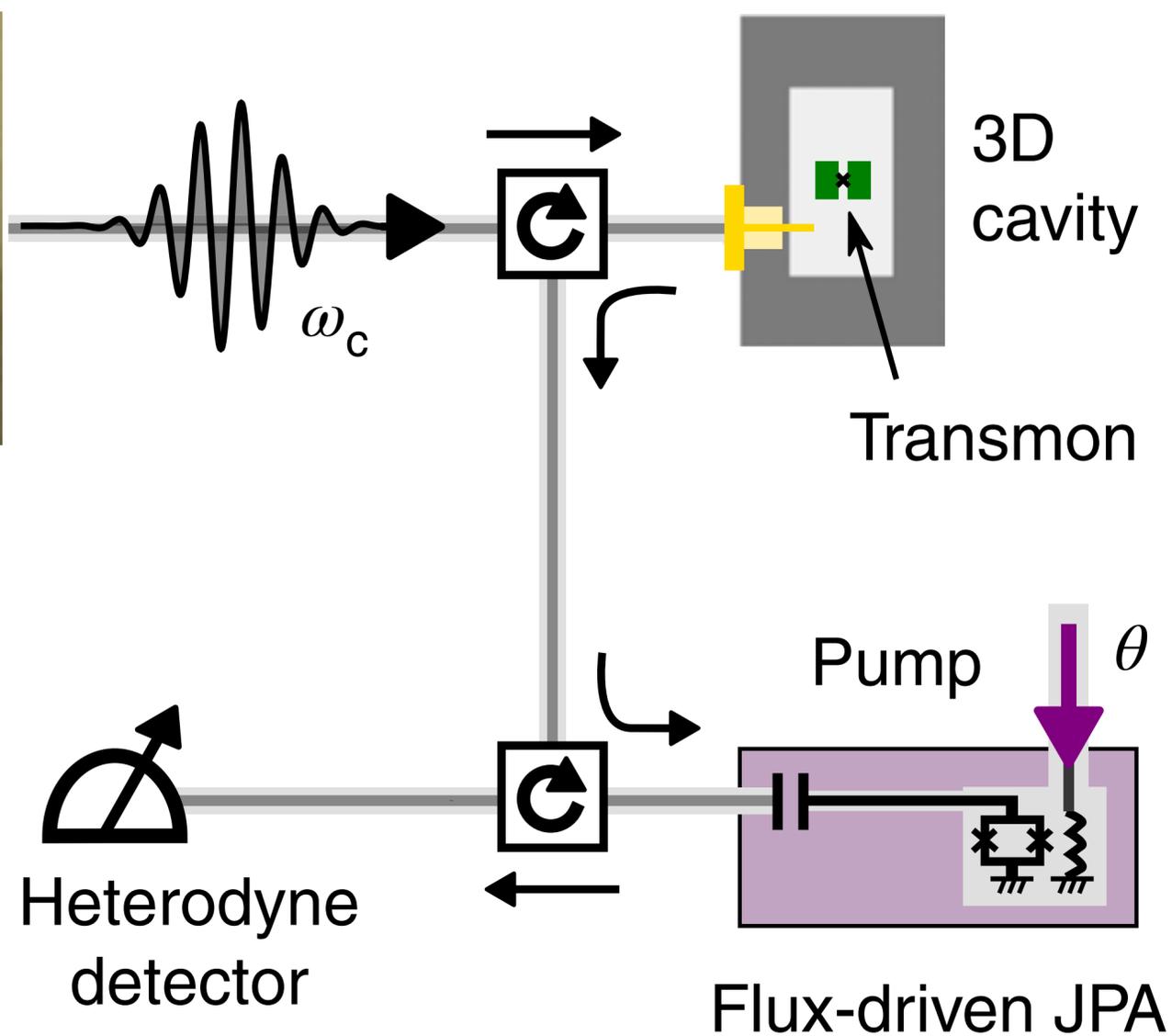
Axion + qubit detector

high-Q cavity



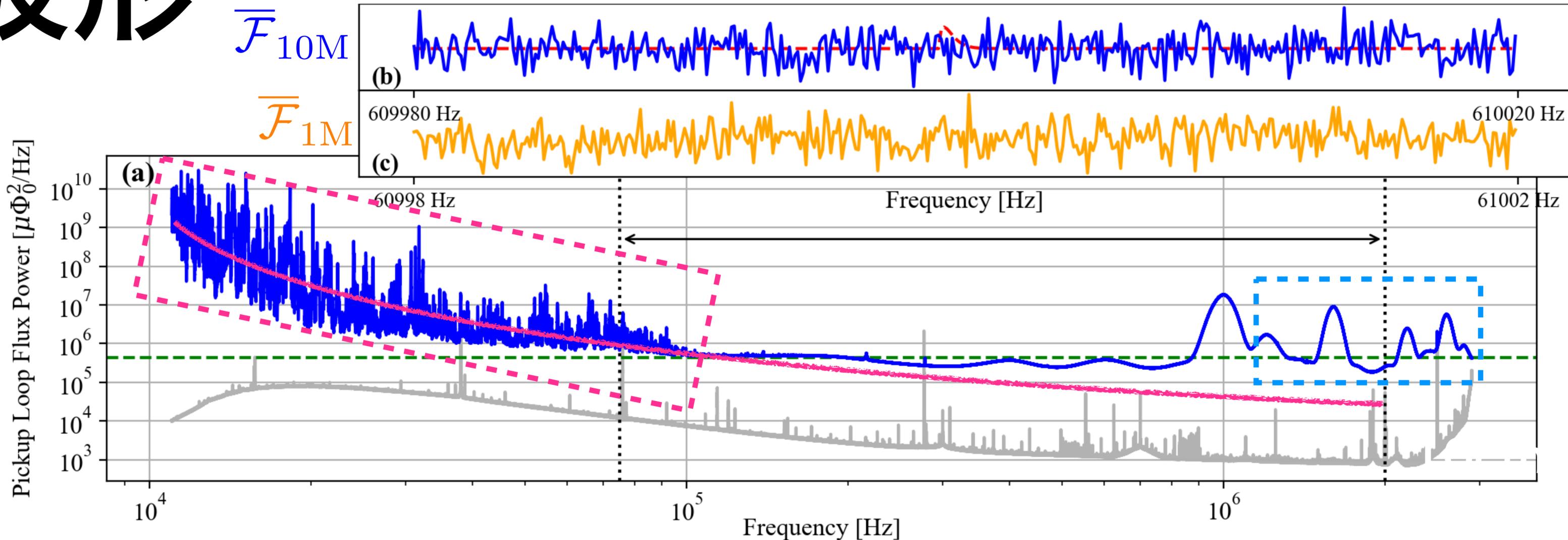
"Pizza" Cavity (U. Florida)

など

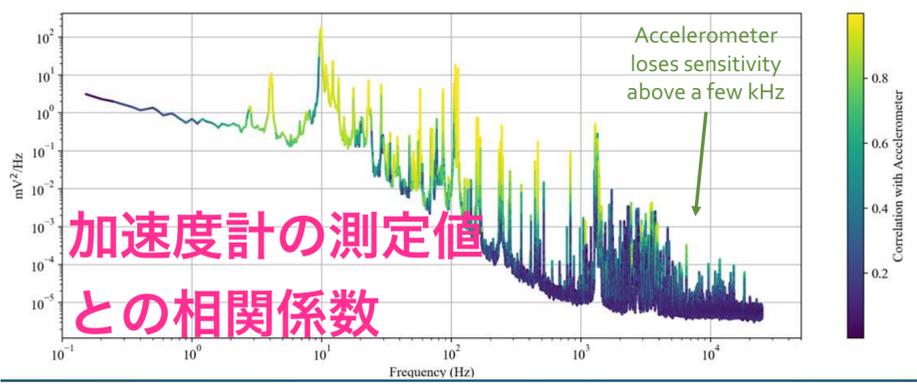


quantum efficiency 84%

波形

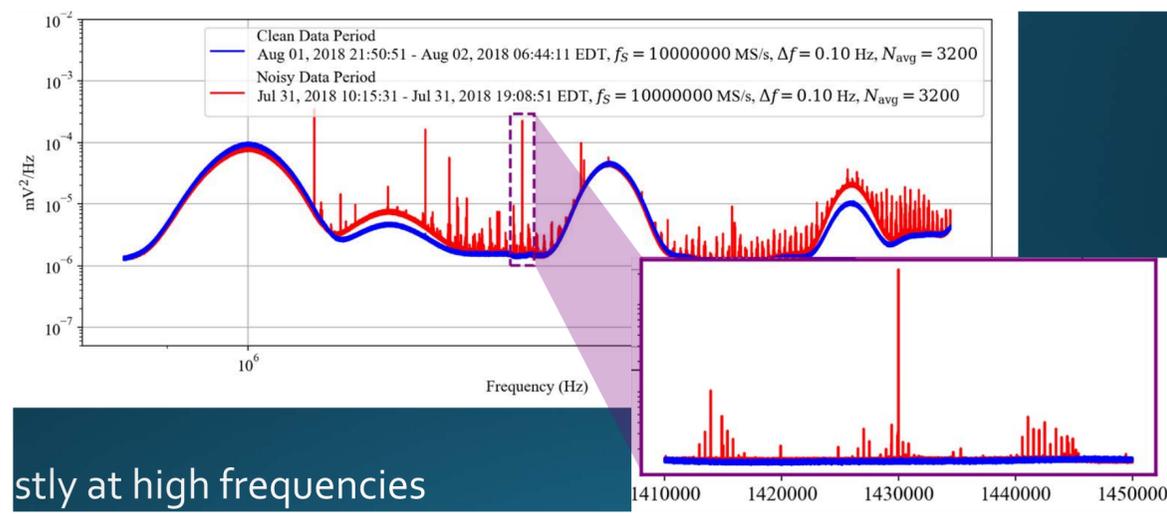


物理的振動と同期



加速度計の測定値
との相関係数

部屋に入ると発生,
2-3日で減少(原因不明)
→30%のデータロス



CAST high mass limit

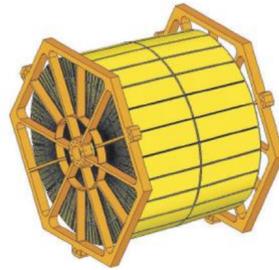
$$P_{a \rightarrow \gamma} = \left(\frac{g_{a\gamma} BL}{2} \right)^2 \left(\frac{\sin\left(\frac{qL}{2}\right)}{\frac{qL}{2}} \right)^2 \underset{\substack{qL \ll 1 \\ \sin x \sim x \ (x \sim 0)}}{\sim} \left(\frac{g_{a\gamma} BL}{2} \right)^2$$

$$q = \left| \frac{m_\gamma^2 - m_a^2}{2E_a} \right|$$

希ガス圧微調整でeffectiveに $m_\gamma > 0$

BabylAXO optics

- 2 detection lines in BabylAXO
- Optics:
 - IAXO Custom segmented-glass optics **and** flight spare XMM optics from ESA
 - **Prototyping + physics** considerations
 - **Risk reduction** for final IAXO segmented-glass optics
 - XMM optics specs very close to IAXO optics design
 - **ESA preliminary support** to the use of XMM optics in BabylAXO (2 XMM optics exist)



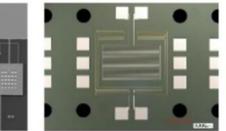
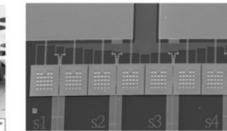
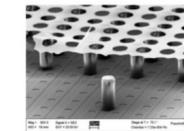
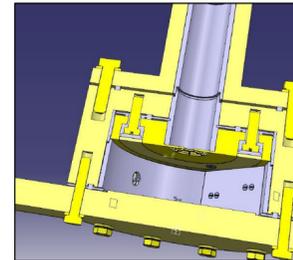
ESSP Granada, 14-May-2019

Igor G. Irastorza

44

BabylAXO detectors

- Detectors (**baseline option**):
 - 2 “microbulk” Micromegas detectors
 - “Discovery detectors” (priority to low background)
 - Experience in CAST
 - Low background capability, radiopurity, shielding.
- Beyond baseline:
 - “high precision” detectors (post-discovery?)
 - Better threshold & resolution
 - 2 low-background Micromegas setups
 - R&D in several technologies: GridPix, MMCs, TES, NTD, SSD.



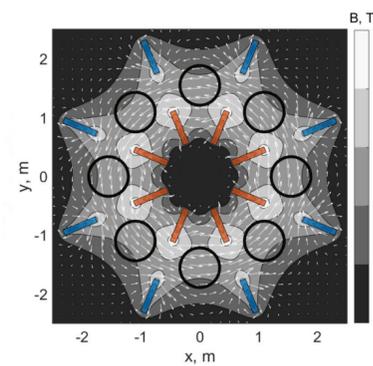
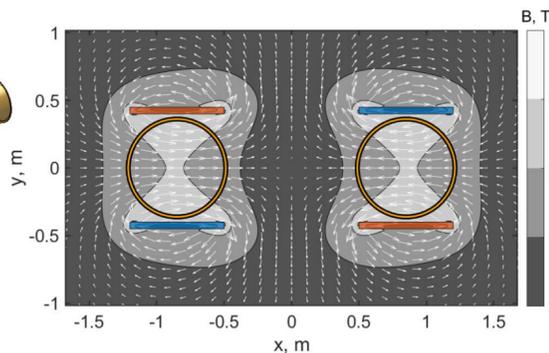
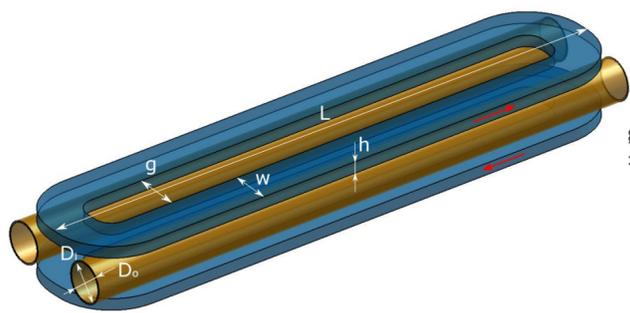
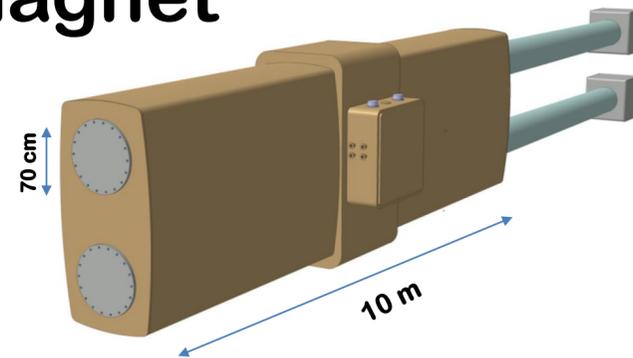
ESSP Granada, 14-May-2019

Igor G. Irastorza

45

BabylAXO magnet

- “Common coil” configuration chosen
 - **Minimal risk**: conservative design choices
 - **Cost-effective**: Best use of existing infrastructure (tooling) at CERN
 - **Prototyping** character: winding layout very close to that of IAXO toroidal design.



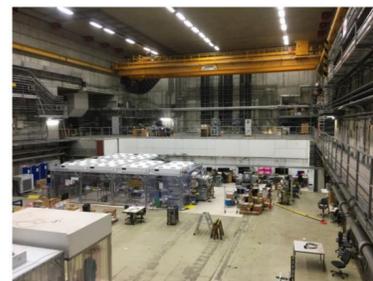
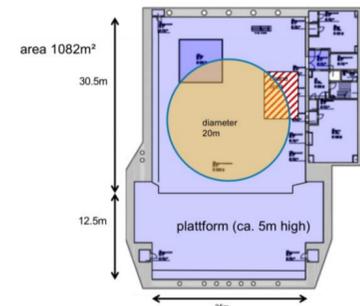
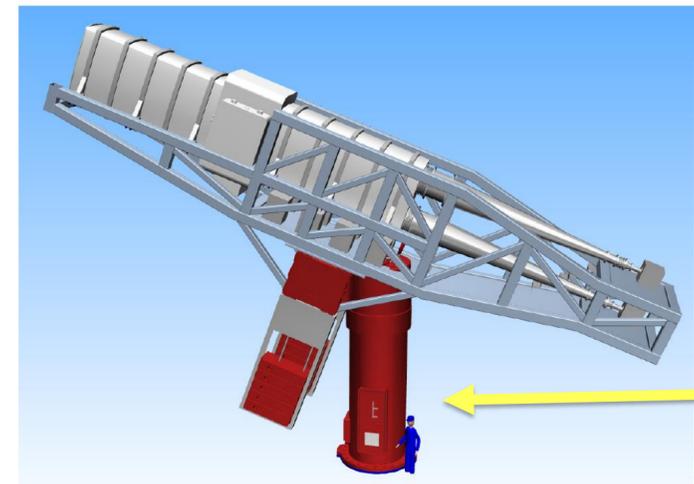
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43

BabylAXO platform & infrastructure

- Existing CTA MST mount matches BabylAXO specs remarkably well
- HERA South hall: perfect site for BabylAXO



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46

LSW

	OSQAR	ALPS- I	ALPS- II	JURA
磁場	9T		5.3T	13T
長さ	14.3m × 2		189m	960m
感度	$3 \times 10^{-8} [\text{GeV}^{-1}]$		$10^{-11} [\text{GeV}^{-1}]$	$10^{-12} [\text{GeV}^{-1}]$
reference	https://arxiv.org/abs/1410.2566	https://arxiv.org/abs/1302.5647	https://arxiv.org/abs/1302.5647	