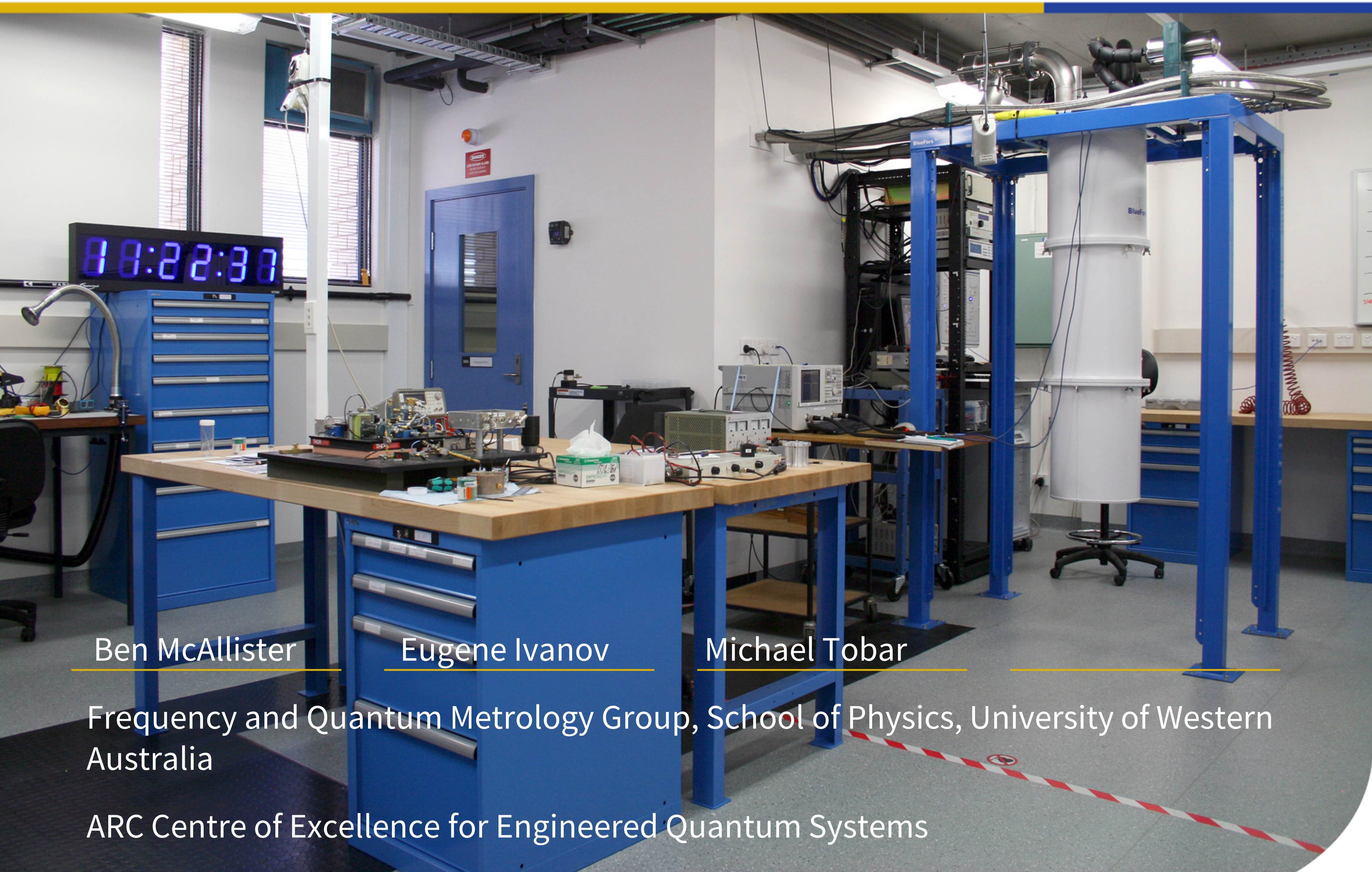
The ORGAN Experiment



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Motivation for high frequency haloscope

- Beck result: potential signal of axions at **~26.6 GHz (~10^-4 eV)**
- Higher frequency than typical haloscopes…or easily accessible
- Considered a spurious result by many
- Beck's hypothesis:
Shapiro step-like features in Josephson Junctions could be as a result of axions

Possible resonance effect of axionic dark matter in Josephson junctions

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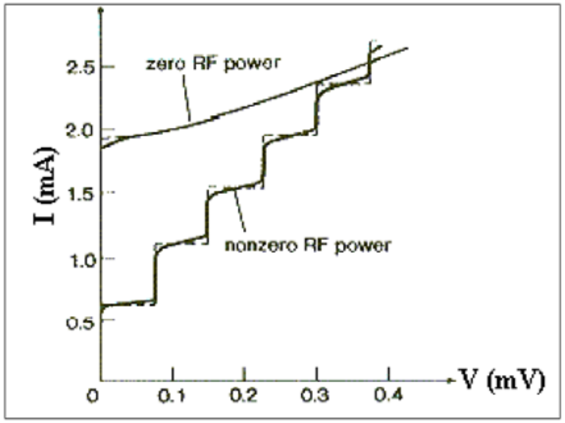
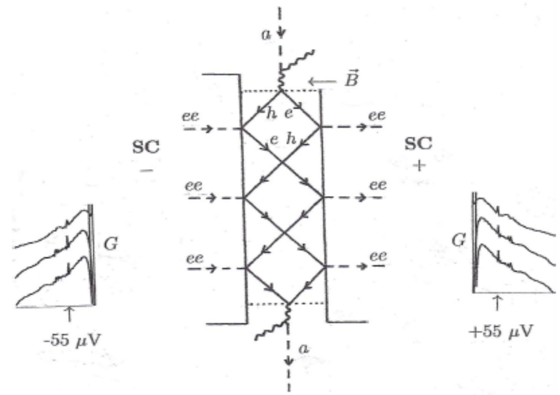
We provide theoretical arguments that dark matter axions from the galactic halo that pass through the earth may generate a small observable signal in resonant S/N/S Josephson junctions. The corresponding interaction process is based on uniqueness of the gauge-invariant axion Josephson phase angle modulo 2π and is predicted to produce a small Shapiro step-like feature without externally applied microwave radiation when the Josephson frequency resonates with the axion mass. A resonance signal of so far unknown origin observed in [C. Hoffmann et al. PRB 70, 180503(R) (2004)] is consistent with our theory and can be interpreted in terms of an axion mass $m_a c^2 = 0.11$meV and a local galactic axionic dark matter density of 0.05 GeV$/cm^3$. We discuss future experimental checks to confirm the dark-matter nature of the observed signal.

- DOI:http://dx.doi.org/10.1103/PhysRevLett.111.231801
- **No direct test of this candidate signal has been performed – seems like as good a place as any to start looking**

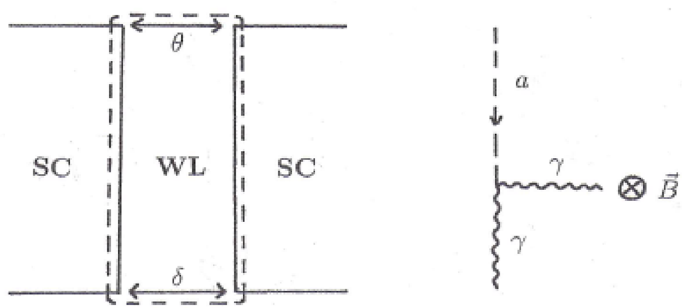
Motivation for high frequency haloscope

- Shapiro step-like features observed in experiments [C. Homann et al. PRB 70, 180503(R) (2004)]





Beck's Proposal: Axion entering WL region, transport of excess Cooper pairs



C. Hoffmann, F. Lefloch, M. Sanquer, B. Pannetier, Phys. Rev. B 70, 180503(R) (2004) [arXiv:cond-mat/0409723]
T.E. Golikova et al., Phys. Rev. B 86, 064416 (2012) [arXiv:1202.5460]
L. He, J. Wang, M.H.W. Chan, arXiv:1107.0061
M-H. Bae, R.C. Dinsmore, M. Sahu, H-J. Lee, A. Bezryadin, Phys. Rev. B 77, 144501 (2008)

Motivation for high frequency haloscope

- Curiosly: g cancels

$$B = \frac{8\pi^2 \Gamma f_a^2 d}{g_\gamma \hbar c^3 e}.$$

$$P_{a\to\gamma} = \frac{1}{4\beta_a}(g\ Bec\ L)^2 \frac{1}{4\pi\alpha}\left(\frac{sin\frac{qL}{2\hbar}}{\frac{qL}{2\hbar}}\right)^2$$

$$P_{a\to\gamma} = \frac{1}{\beta_a \hbar^2 c^4}(f_a \Gamma d L)^2 4\pi\alpha$$

$$L = \frac{\hbar c^2}{\sqrt{4\pi\alpha}}\sqrt{\beta_a}\frac{1}{f_a \Gamma d}$$

- L ~ 10^-22 m
- We are left with a mass/frequency range: 110+/- 2 micro-eV, or 26.6 +/- 0.5 GHz

High Frequency Haloscope Design

- High frequency haloscope at UWA (~26 GHz), known as **ORGAN**
- Multi-stage project:
  - Direct test of Beck result
  - Wider scan at high frequency
  - Novel resonators
- Designing a haloscope at high frequency is difficult
- TM Mode frequency inversely proportional to cavity size

→ **Lower volume**
→ **Lower sensitivity**
→ **Lossier material**

- **Quantum noise limit increases**
- Harder to tune, and couple to modes

High Frequency Haloscope Design

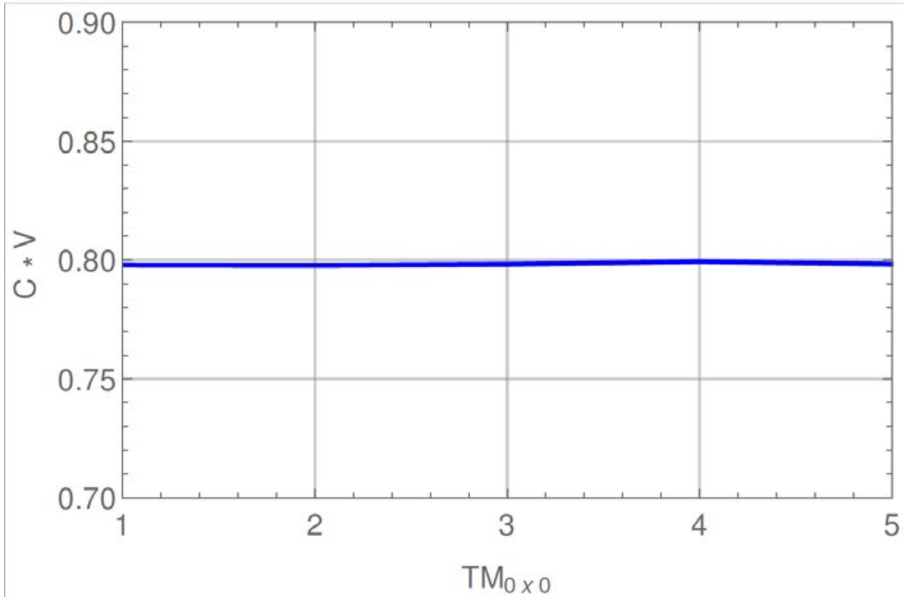
- TM010 mode almost always employed in haloscopes due to highest **form factor**

$$\mathrm{C_E} = \frac{\left| \int dV \vec{E}_c \cdot \vec{\hat{z}} \right|^2}{V \int dV \mid E_c \mid^2}$$

- Measure of mode overlap with axion induced EM field
- TM010 ~0.69
- High frequency → very low volume
- **We explored the possibility of higher order modes**

High Frequency Haloscope Design

- TM_{010} mode offers the greatest form factor, but the lowest volume for given cavity length and frequency



- Essentially no change **for given cavity length**
- Other considerations:
  - Higher order modes have higher G factors at a given frequency
  - Aspect ratio problem → Likely to be more spurious modes
  - **We chose TM_{020} as the detecting mode**

High Frequency Haloscope Design

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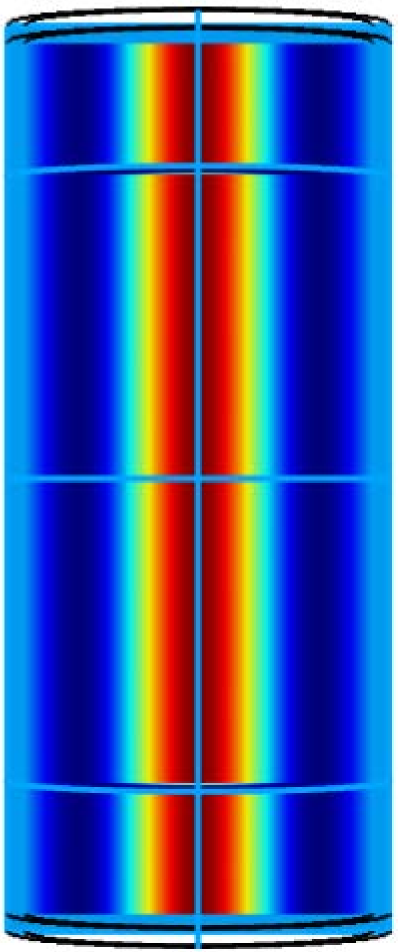
Mode	C	V (cm^3)	G
TM010	0.69	1.45	386.5
TM020	0.13	7.783	744.6
TM030	0.053	18.87	1244.3

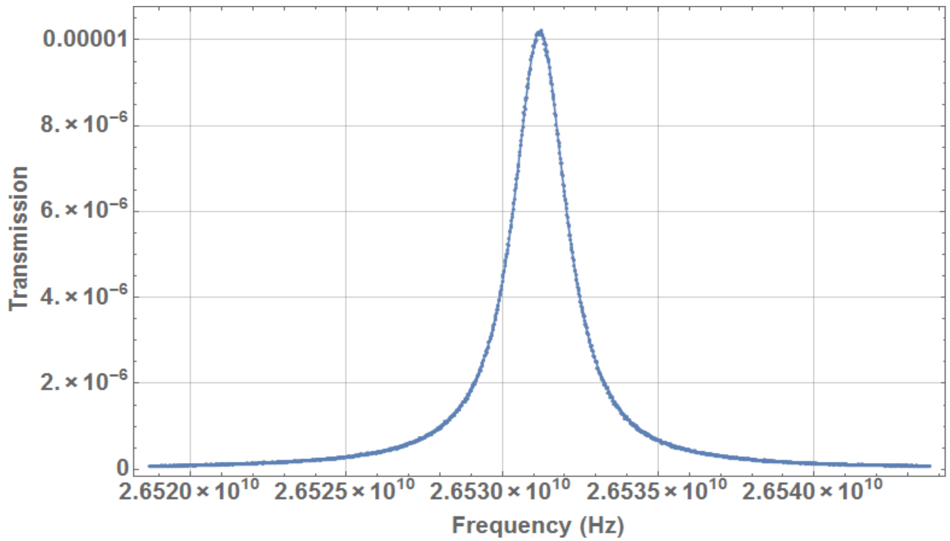
- Mode crowding gets worse at higher frequency
- But, worth considering in a given length, depending on required tuning range

ORGAN

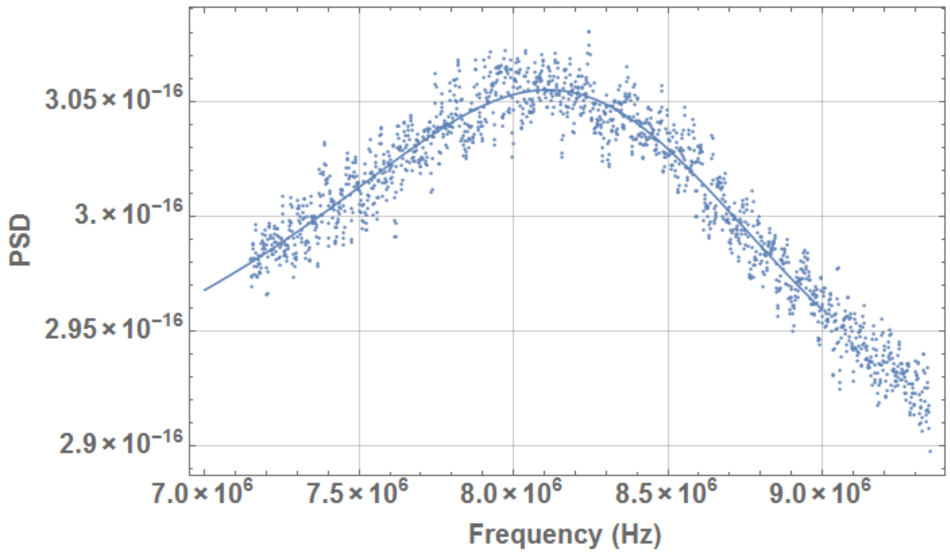
- Cavity dimensions:
  - ~1 cm radius
  - ~5 cm length
- TM_{020} Mode frequency ~26.5 GHz
- First "path-finding run" complete
  - Stationary frequency, single cavity
  - Traditional HEMT amplification
  - 4 K
  - 7 T
  - Commercial FFT
- Successful test of entire system, ready for tunable run
- Scale up sensitivity



ORGAN



0.00001
$8.\times10^{-6}$
$6.\times10^{-6}$
$4.\times10^{-6}$
$2.\times10^{-6}$
0
Transmission
2.6520×10^{10}
2.6525×10^{10}
2.6530×10^{10}
2.6535×10^{10}
2.6540×10^{10}
Frequency (Hz)



3.05×10^{-16}
$3.\times10^{-16}$
2.95×10^{-16}
2.9×10^{-16}
PSD
7.0×10^{6}
7.5×10^{6}
8.0×10^{6}
8.5×10^{6}
9.0×10^{6}
Frequency (Hz)

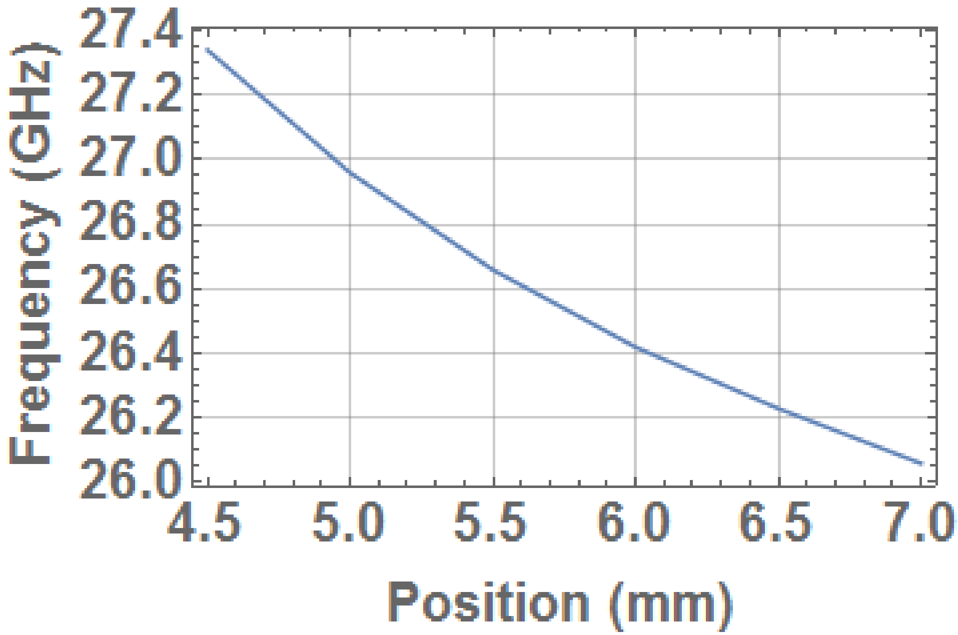
Future of search

- Federal funding for 7 years, can scale up experiment
- ARC Centre of Excellence for Engineered Quantum Systems (EQuS) – expertise and assistance
- 14 T magnet
- Multiple cavity search
- Quantum or near-quantum limited amplification (JPAs, NQL HEMTs)
- Other areas we are exploring:
  - Signal processing techniques
  - Methods to increase Q factor (superconductivity, 3D printing, Bragg resonators)
  - Novel resonators (as per Mike's talk)

Tuning

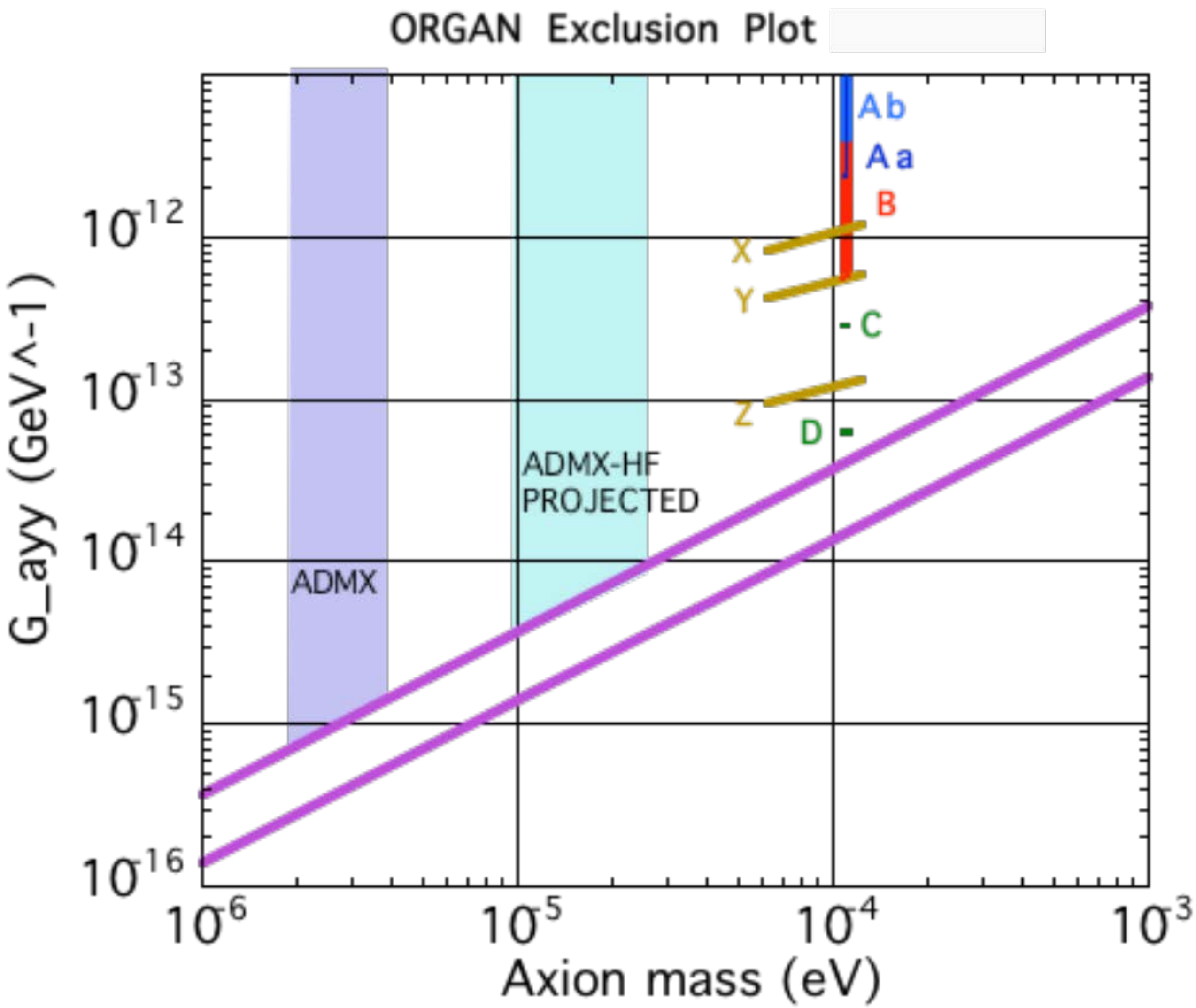
- Exploring tuning options
  - Next stage will utilize regular copper post tuning (~ 1 GHz)
  - Later stages may utilize dielectrics (ie sapphire disk)
  - Coupling of mode to other, highly tunable resonances (ie magnon modes in YIG)

Tuning



- Reduction in C and G makes about a factor of 2
- Slightly more sensitive near the centre
- Possibility of re-design moving to larger cavity numbers

Sensitivity Projection

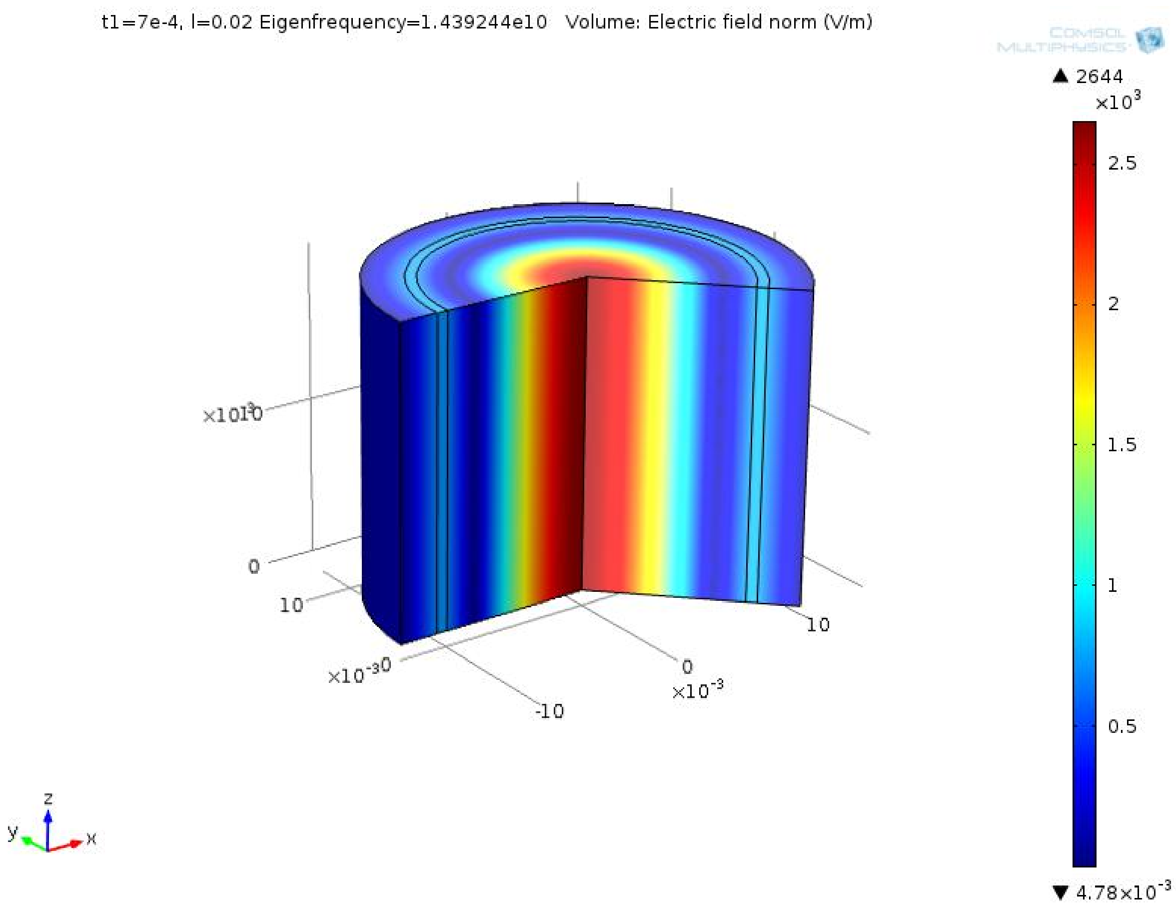


Sensitivity Projection

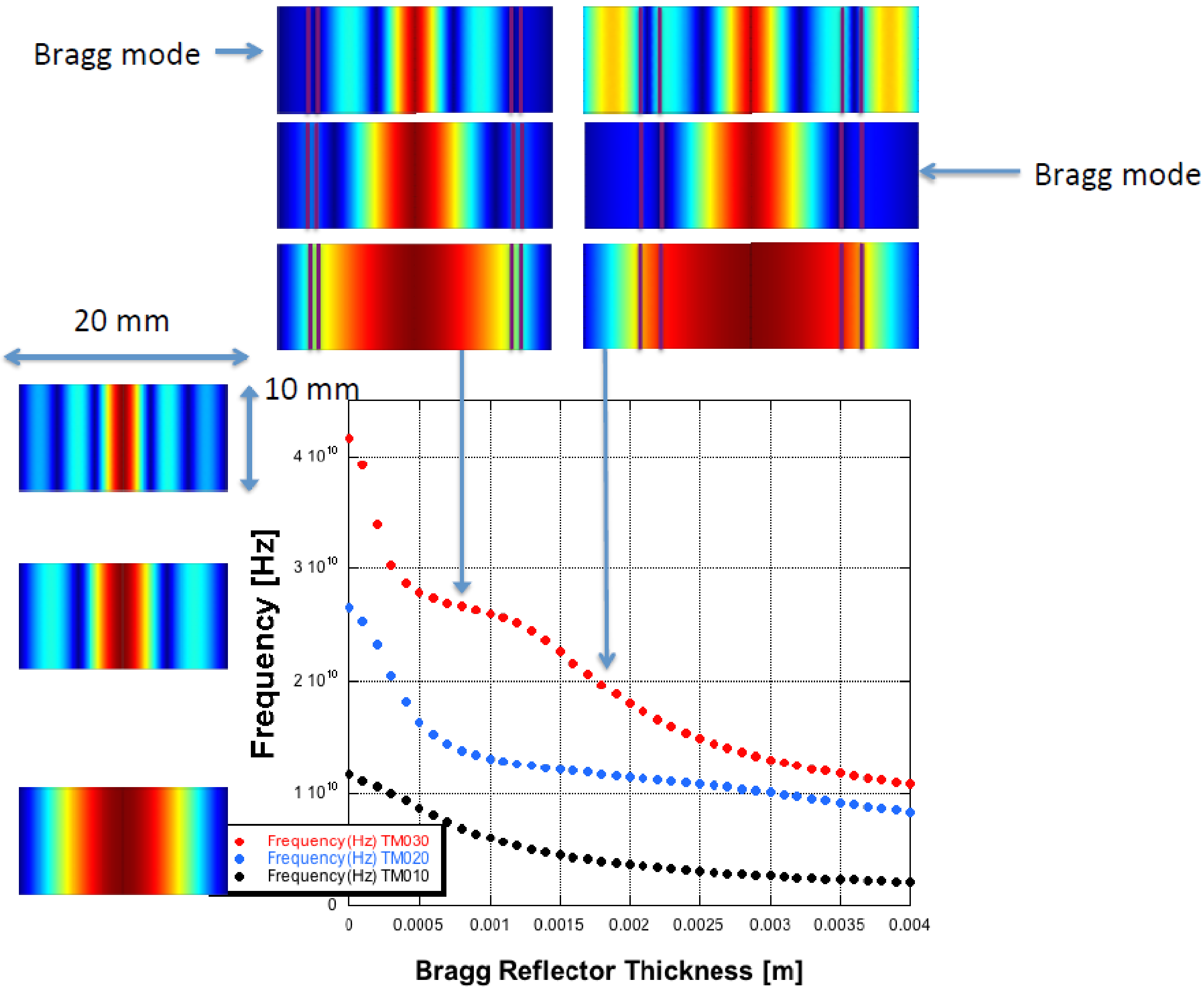
- Aa is the search we have just run
- Ab is a planned search for the Beck range with current technology and equipment
- B, C, D, X ,Y Z represent various stages of scale-up to the experiment
- Generous scale-up projection:
  - 14 T magnet
  - 8 cavities
  - Quantum noise limited amplifier
  - Q to 1 million (axion linewidth)

Bragg Resonators

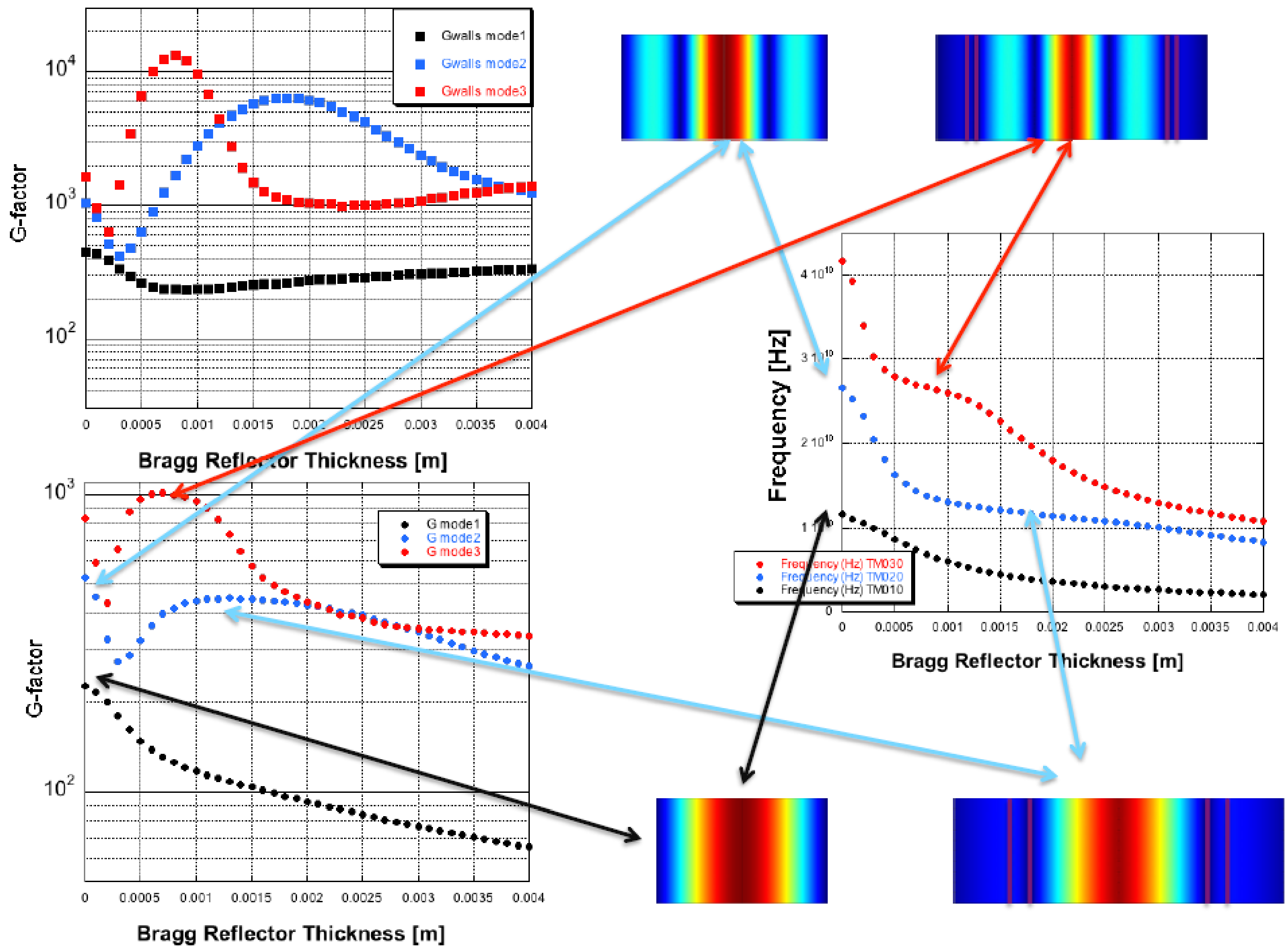
- Dielectric walls in cavity
- Air gap
- Confine modes, virtual boundary conditions
- Improve Q factor



Bragg Resonators



Bragg Resonators

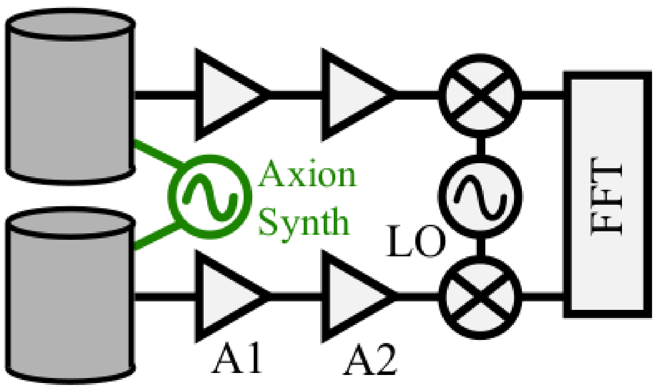


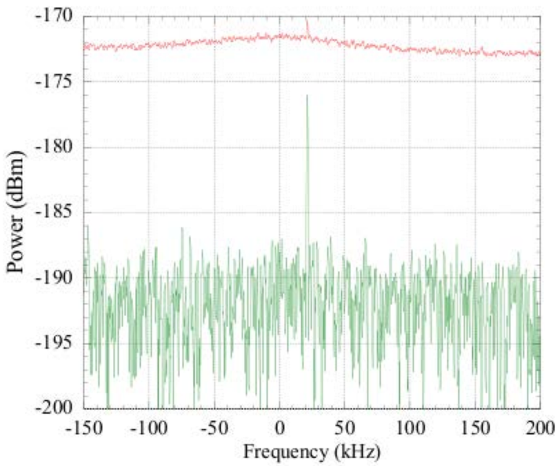
Cross-correlation techniques

- High frequency cavities very small

→ Would like to combine multiple cavities

- Cross-correlation measurements are two-channel measurements which reject uncorrelated noise sources





- Cross-correlate signals from two cavities

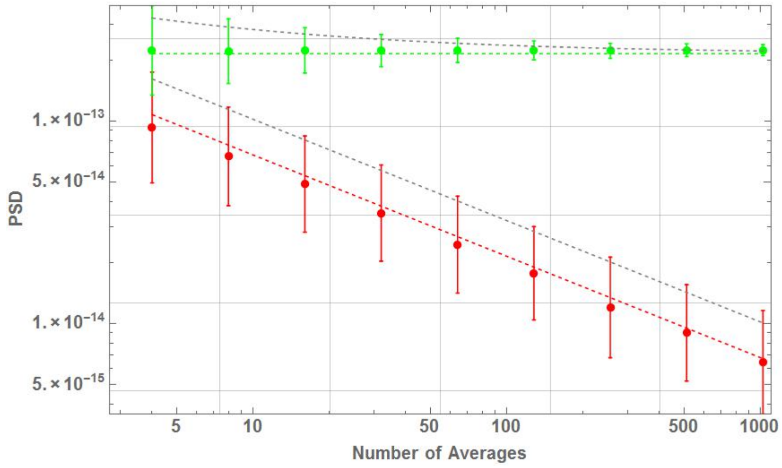
→ Reject the uncorrelated thermal cavity noise and amplifier noise
→ Retain correlated axion signal

Cross-correlation techniques

- Define SNR as signal divided by spread of background noise, for purpose of scheme comparison

- With cross-correlation spread (standard deviation) of background noise goes down proportional to $\frac{1}{2\sqrt{n}}$

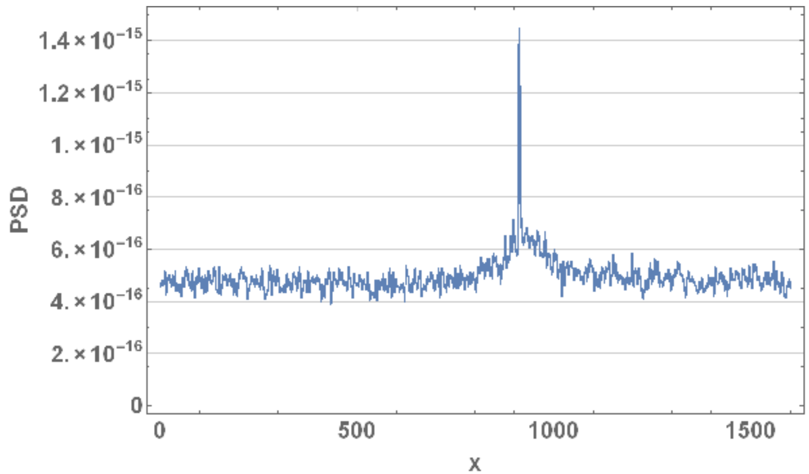
- Compared with $\frac{1}{\sqrt{n}}$ for single channel

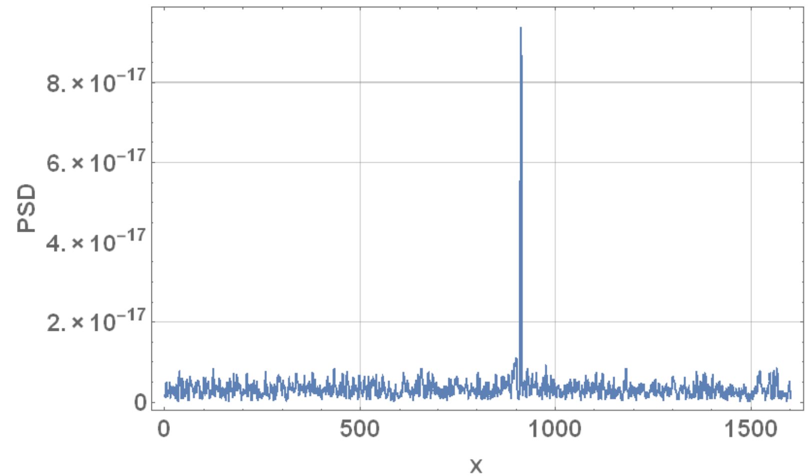


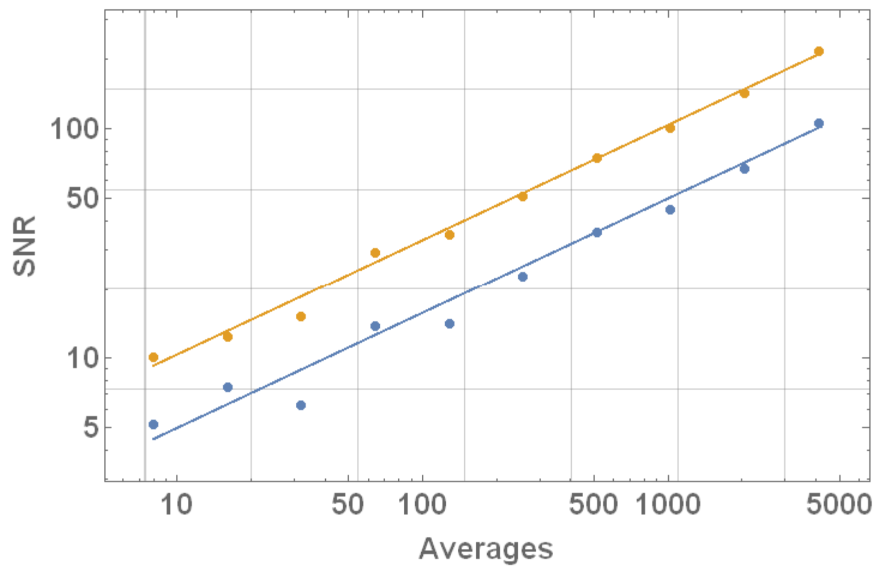
- Factor of 2 reduction in background spread, same improvement as doubling signal power by combining two cavities

- Downside: need two readouts, amps etc

Cross-correlation techniques







Cross-correlation techniques

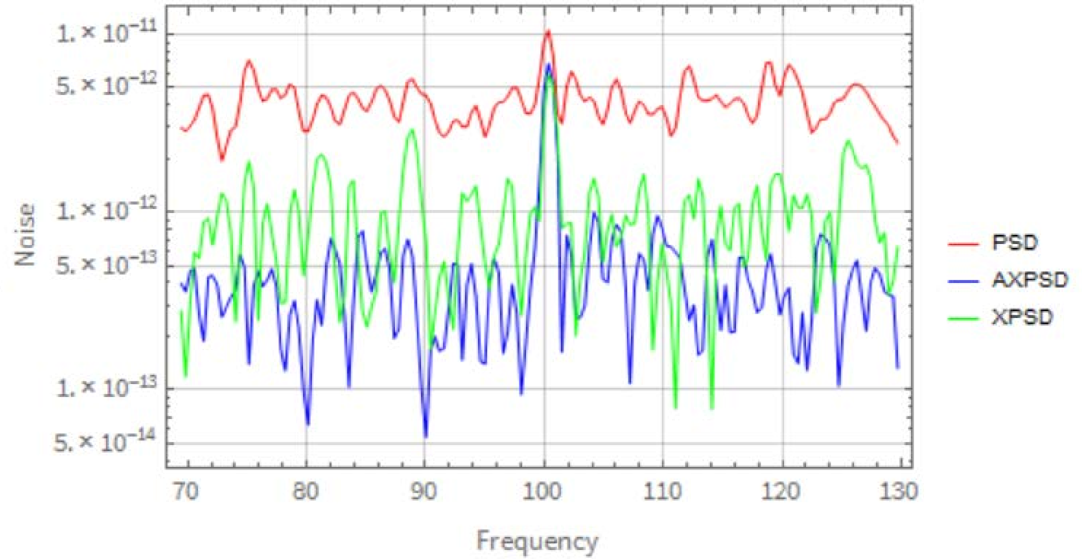
- Real benefit achieved when synchronizing larger numbers of cavities

- Can compute "averaged cross spectrum"

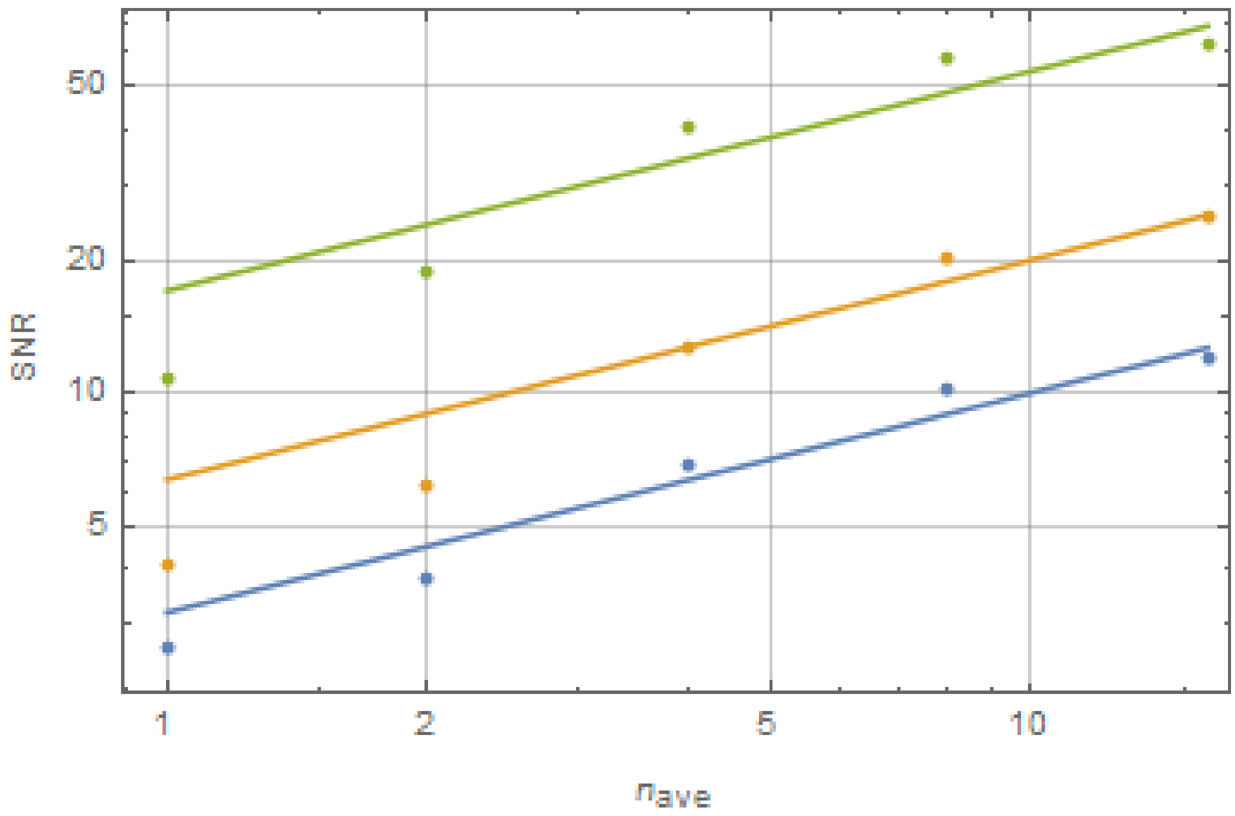
- For n cavities we can compute n(n-1)/2 independent cross spectra

- Averaging these cross-spectra produces a new spectrum
→ WISP signal of interest retained
→ Mean of thermal noise reduced
→ Standard deviation of thermal noise reduced

- Achieve $2 \cdot \sqrt{n\,(n-1)/2}$ reduction in spread of background noise, compared with n from power combining

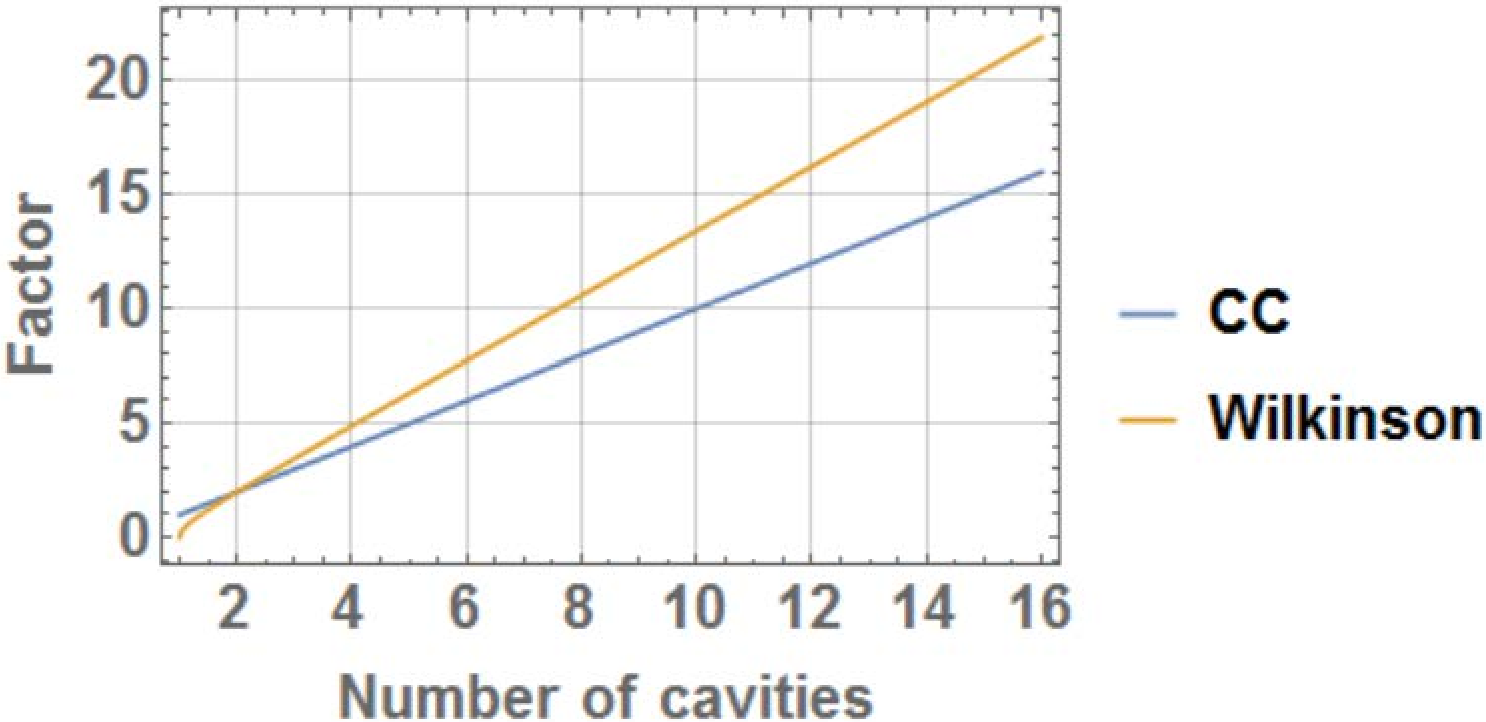


Cross-correlation techniques



Cross-correlation techniques

- **This is not magic or free → We have a tonne more data/readouts, this is all post-processing**
- We need n readouts, rather than one
- n digitization channels
- n times as much data
- Equivalent to averaging a Wilkinson system for longer in terms of data, but we do it simultaneously



Cross-correlation techniques

- Synchronizing 4+ cavities is a long term goal of ORGAN
- **Cross-correlation has other uses than increasing SNR:**
  - Power summation of multiple cavities is difficult
  - Cavities need to be inside same system, in phase
  - CC measurements can be performed with cavities spatially well separated
  - Characterize WISP signals e.g. coherence length
- **See arXiv:1510.05775v2** for more information on these techniques, update forthcoming

Conclusion

- UWA EQuS node developing multi-stage haloscope (ORGAN)
  - Direct test of Beck result at 26.6 GHz
  - Wide scanning at high frequency
  - TM_{020} mode employed
  - Search now underway
  - Planned future phases rely on experimental scale-up, new technologies and ideas
- Novel experimental techniques will improve sensitivity
  - Synchronize multiple cavities and employ cross-correlation techniques
- References:
  - ORGAN Experiment: **arXiv:1611.08082**
  - Cross-correlation schemes: **arXiv:1510.05775v2 (update forthcoming)**