HAYSTAC

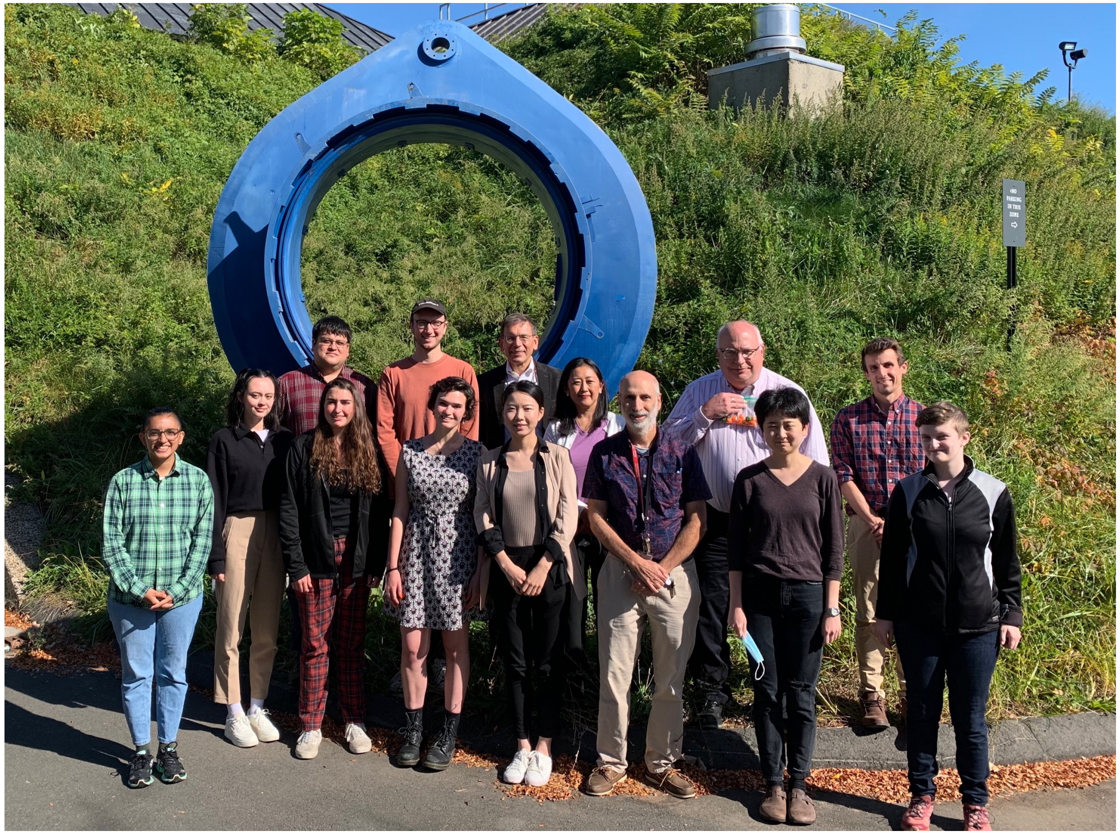
Current and future results from HAYSTAC experiments utilizing squeezed state receivers

SNOWMASS Restart CF2 – Dark Matter Wave
October 22nd, 2021

HEISING-SIMONS FOUNDATION

Alexander Leder on behalf of the HAYSTAC Collaboration
University of California Berkeley

HAYSTAC Collaboration



The HAYSTAC Collaboration has members from four institutions

UC Berkeley Yale University CU Boulder John Hopkins

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With support from:
NSF
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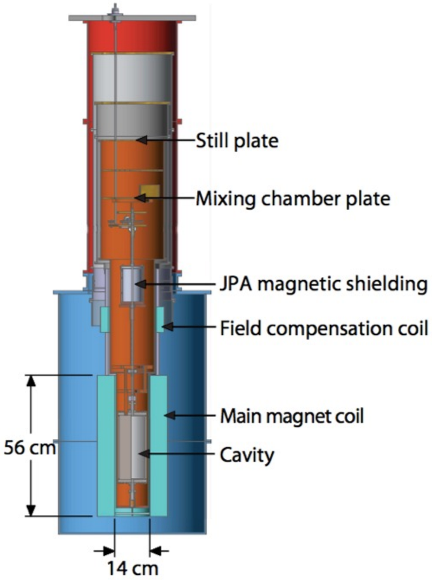
HAYSTAC

HAYSTAC Experimental Setup

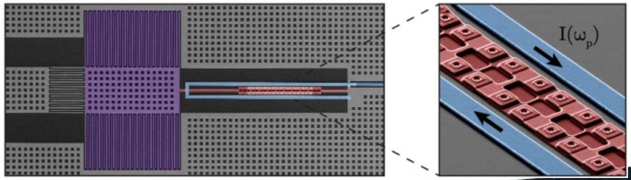
$$P_s \propto B_0^2 V Q_L C_{nml} g_{\gamma\gamma a}^2$$

$$SNR = \frac{P_S}{kT_S}\sqrt{\frac{t}{\Delta\nu_A}}$$



In order to probe the most DM parameter space in the shortest time we need:

- Large magnetic field (9 Tesla)
- Low temperature (60 mK)
- Low noise environment (2.3 quanta – phase I)
- Good Form Factor (C_{010} ~ 0.5)
- High Q (1e4)
- Large Volume (1.5 L)



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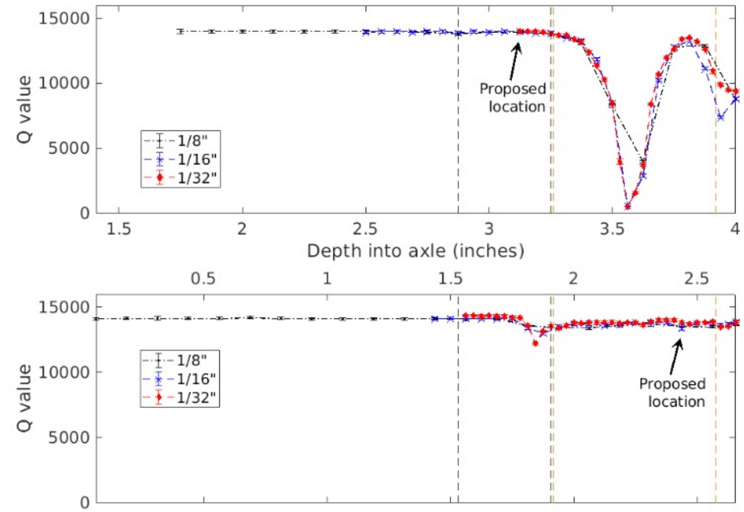
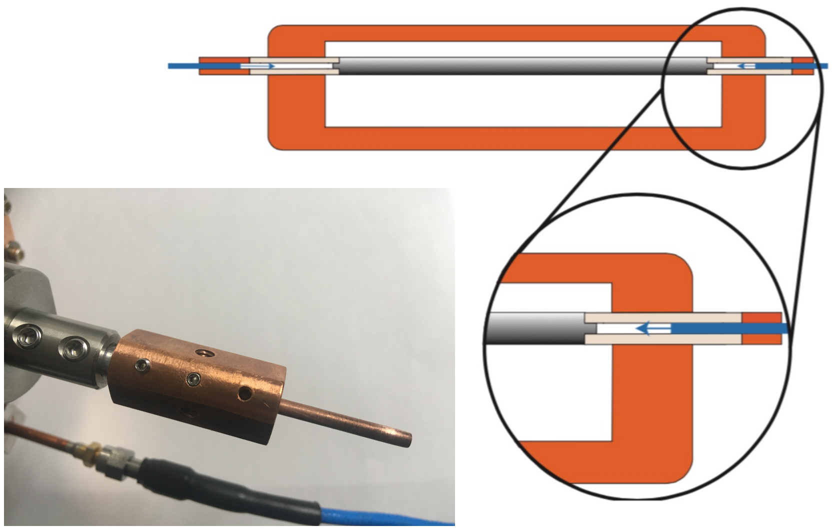
HAYSTAC Phase I – Hot Rod

- HAYSTAC designed to provide a platform for new cavity and amplifier technologies in the 3-12 GHz range
- Phase I implemented first solution to the hot rod problem
- Solution tested to ensure minimum effect on Q of cavity





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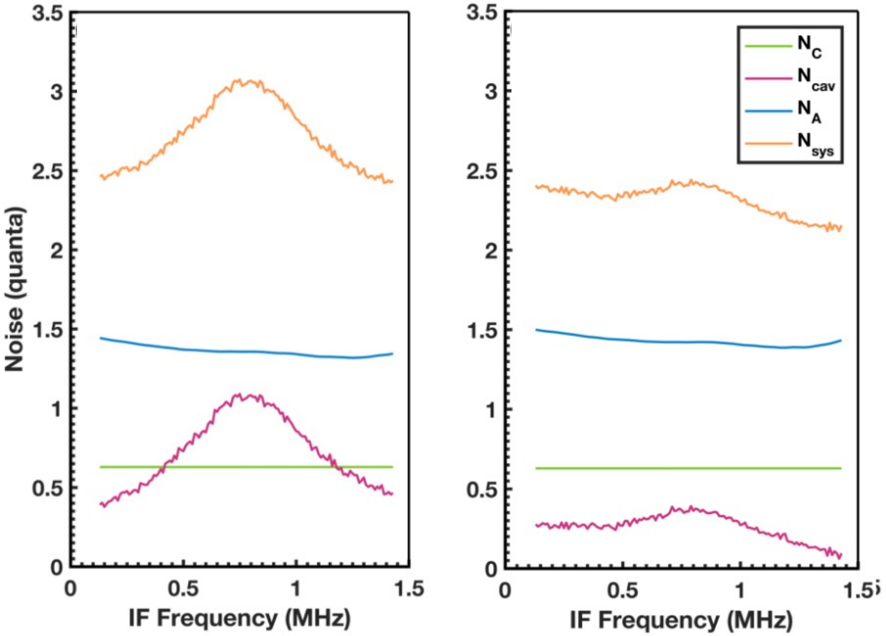
HAYSTAC Phase I – Noise Level

- Run 2 of Phase I achieved noise level 2 times the standard quantum limit
- This was possible thanks in part to solving the hot rod rod problem



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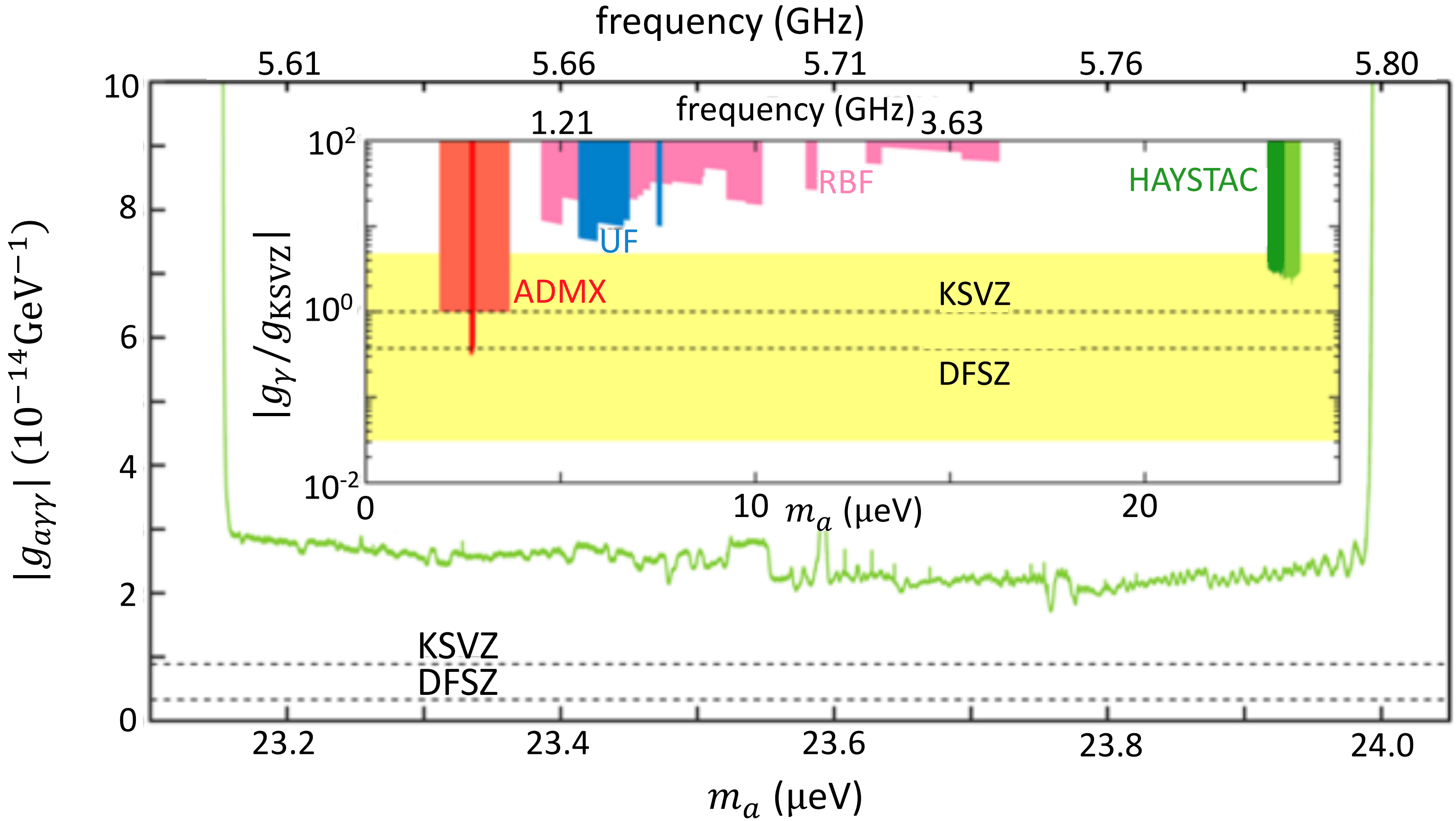
HAYSTAC Phase I – Results

Put it all together….



Highest frequencies/masses probed by a cavity experiment so far!

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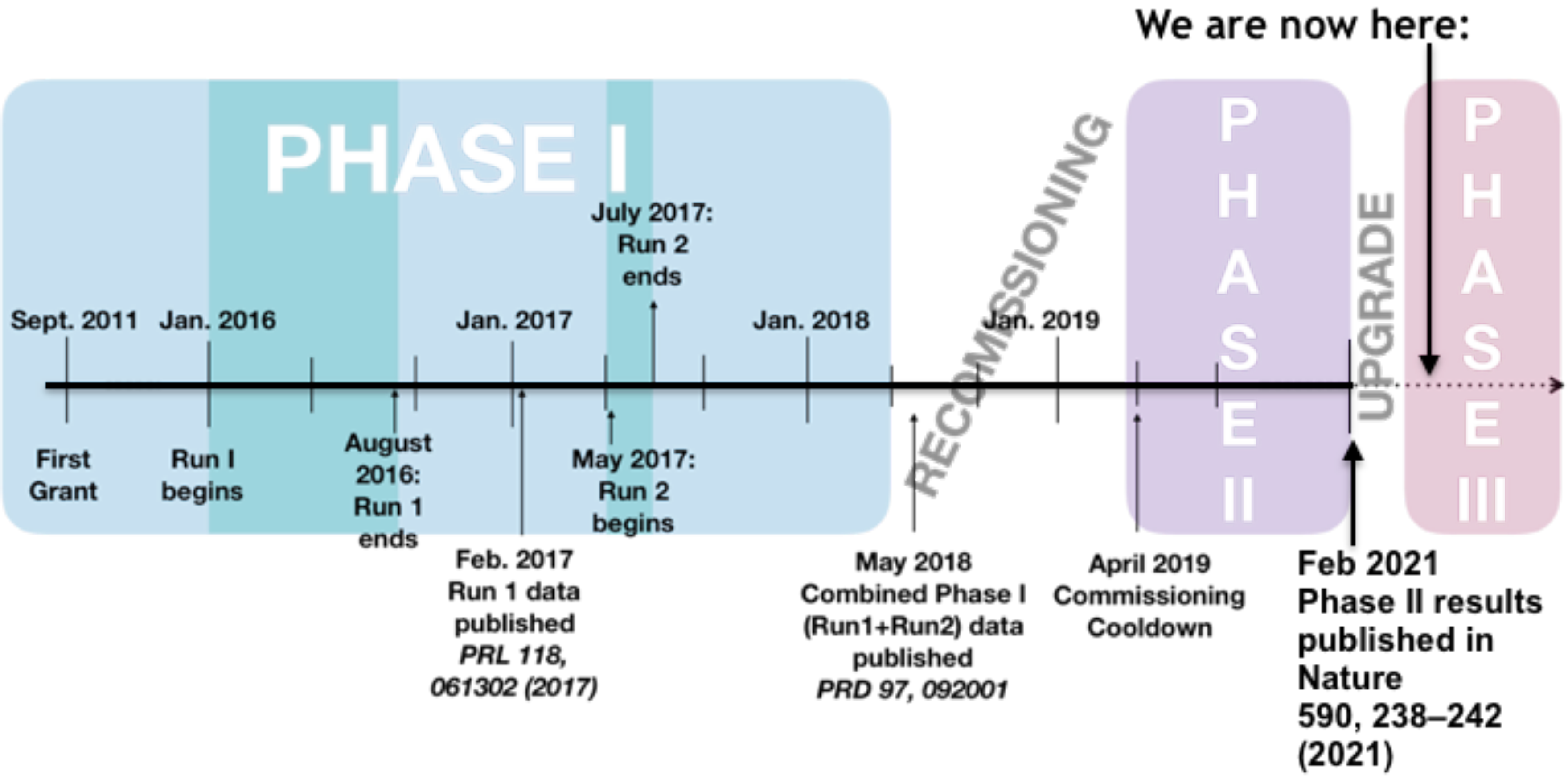
HAYSTAC Current Timeline



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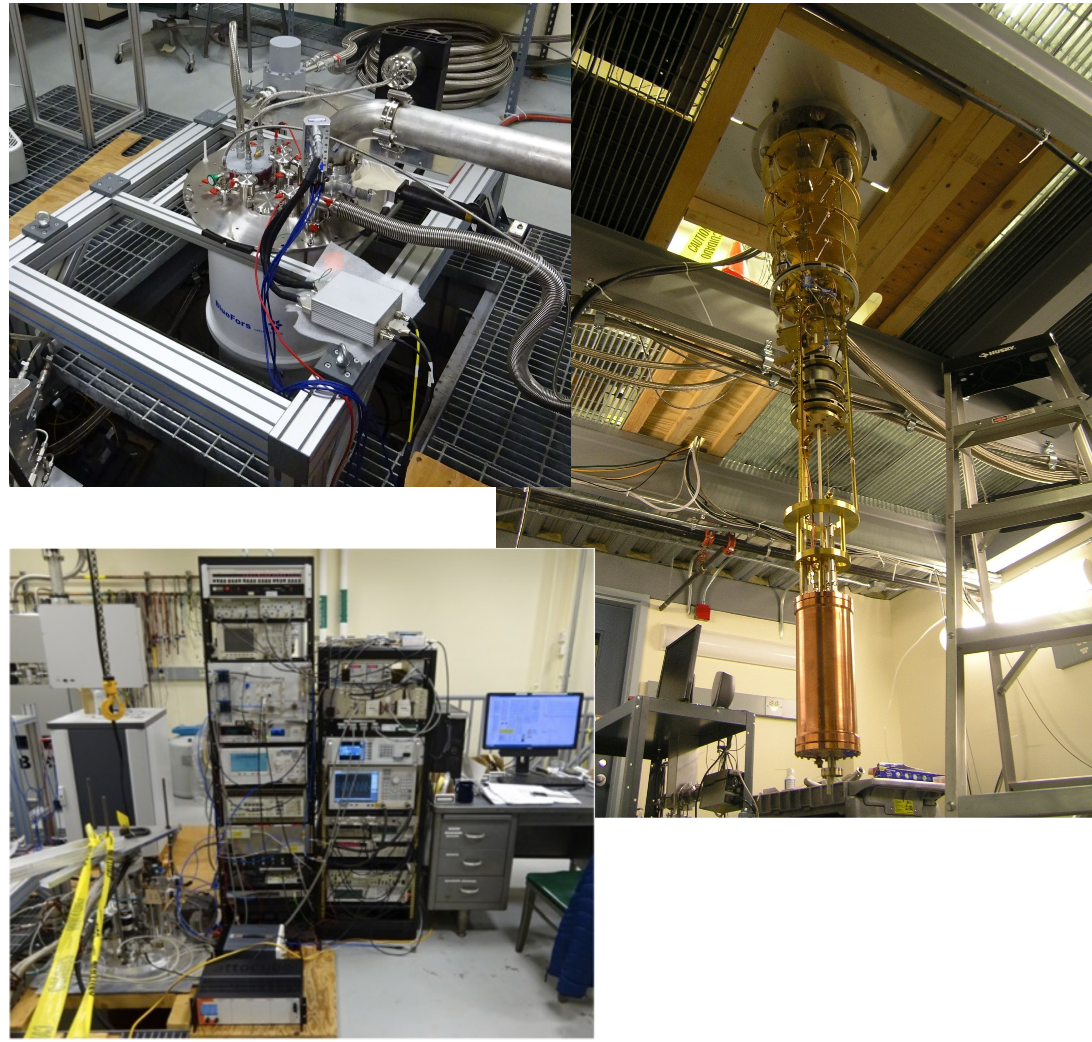
HAYSTAC Phase II – New Infrastructure

- New BlueFors dilution refrigerator installed at Yale
- New variable temperature stage
- Improved cavity support structure
- Software upgrades
- Improved analysis techniques



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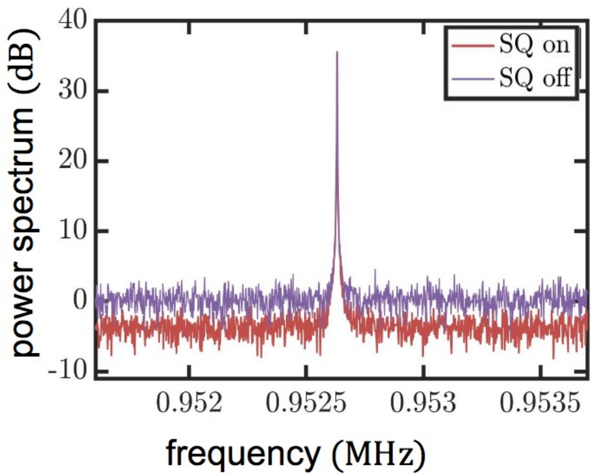
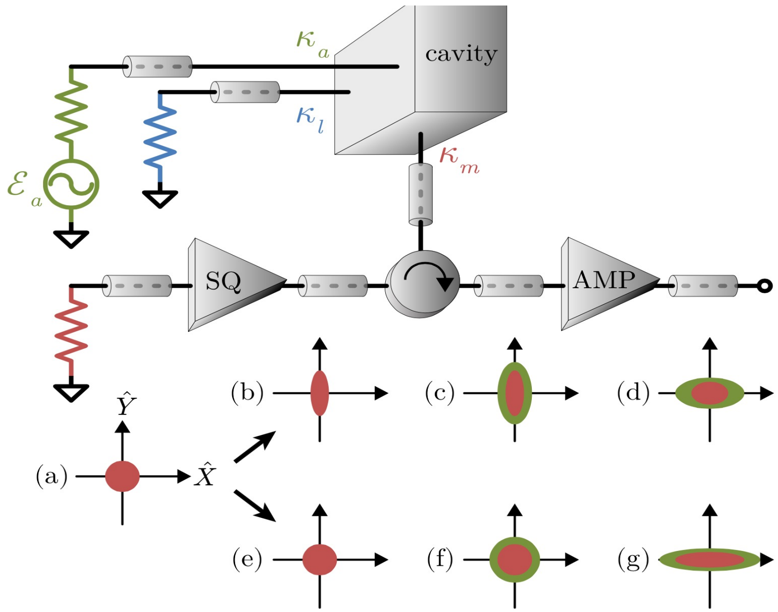
HAYSTAC Phase II – Squeezed State

- We have been able to demonstrate the first squeezed state receiver in a microwave cavity
- Improvement in SNR has been shown uniformly across a larger bandwidth





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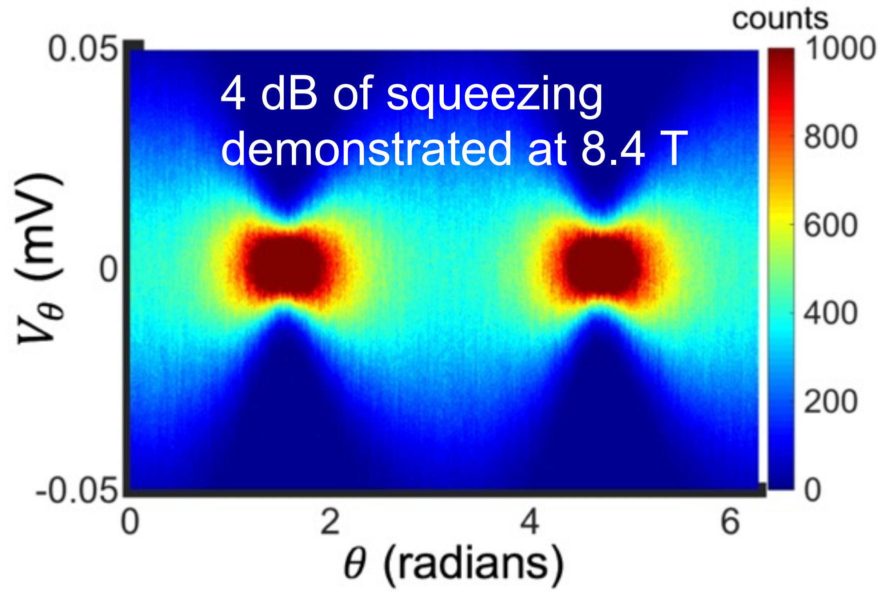
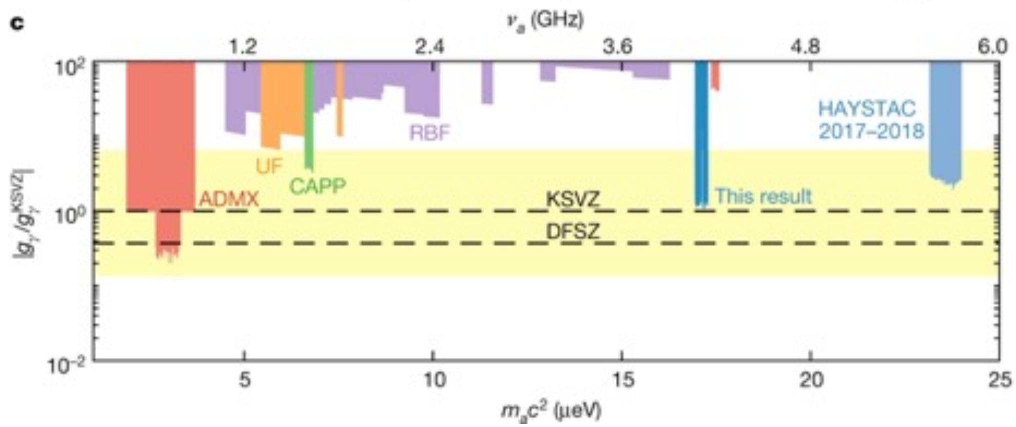
HAYSTAC Phase II – Results

- Phase II has implemented new squeezed state receivers to further improve performance – see a performance increase by ~ 2
- More information on Squeezed State Receivers coming up in Konrad's talk
- We are now entering the "data production" phase of the experiment seeking to fill in the scanning region





Full results can be found in: Nature. 2021 Feb;590(7845):238-242

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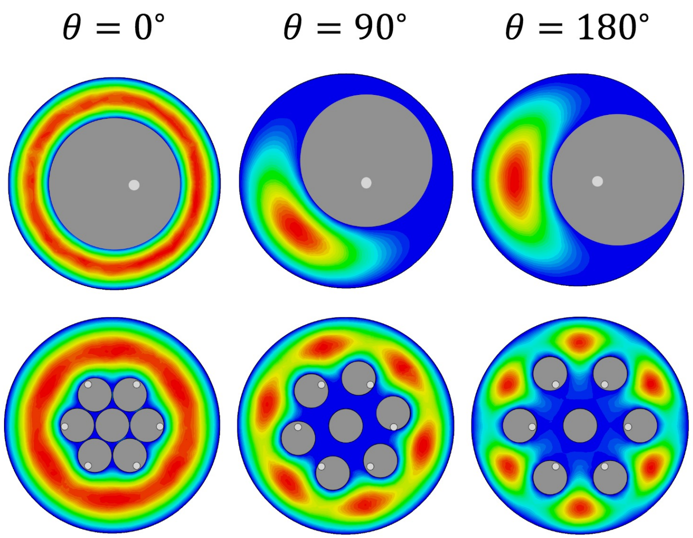
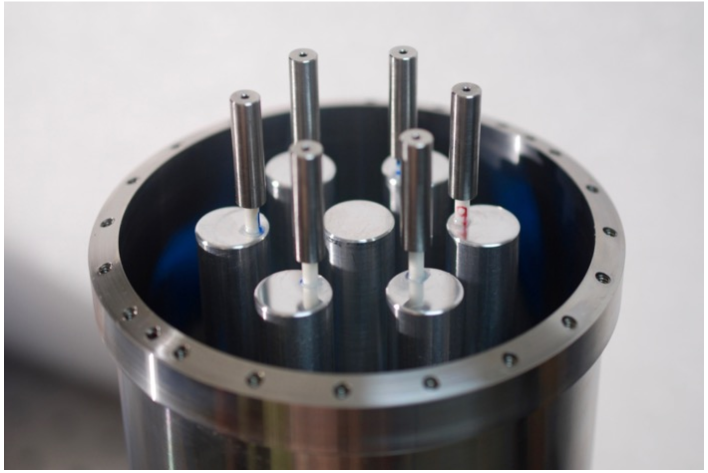
Current R&D Efforts

Current R&D Efforts– Multi-rod Cavity

- HAYSTAC is a testbed for new techniques to probe higher frequency axion
- Symmetric tuner has a superior form factor compared to asymmetric tuning mechanisms
- 7-rod cavity has been constructed and is undergoing testing at Berkeley





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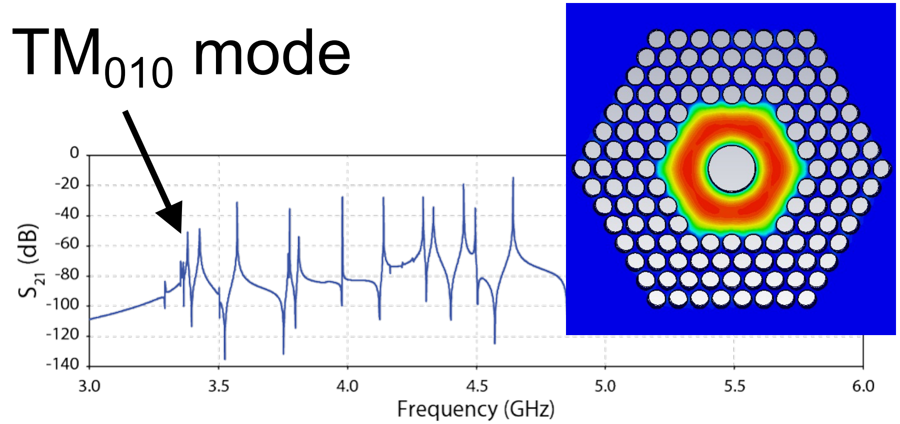
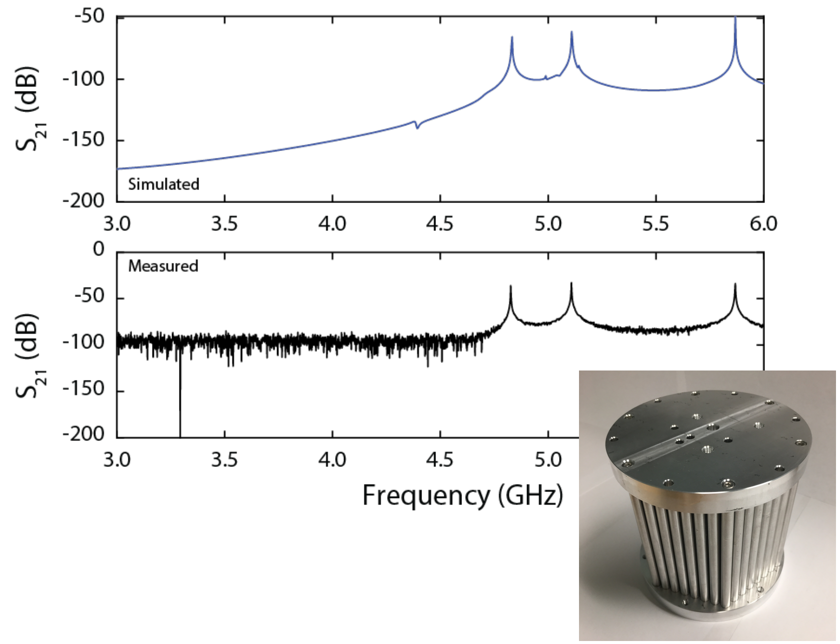
Current R&D Efforts– Photonic Band Gap (PBG)

- Other frequency modes create a forest of mode that can hybridize, reducing the overall form factor
- PBGs are a regular lattice of rods that contain a specific mode in their center region
- Other modes freely propagate out – clear out intruder modes





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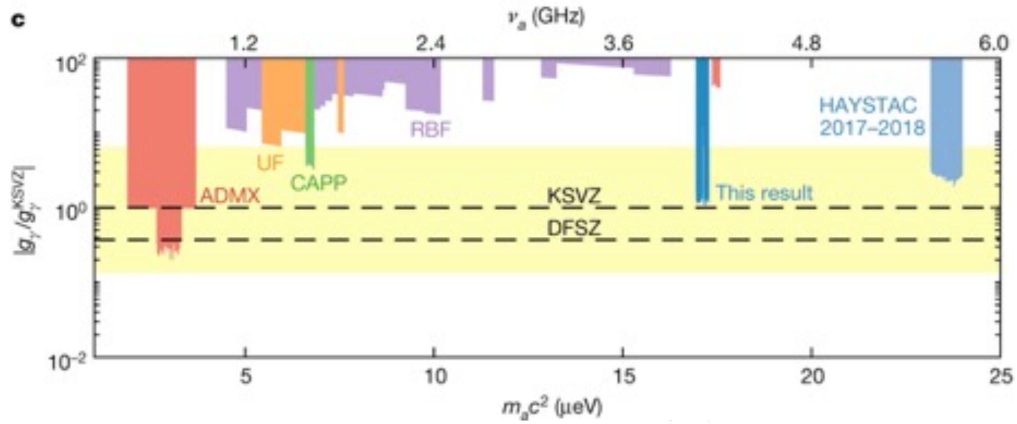
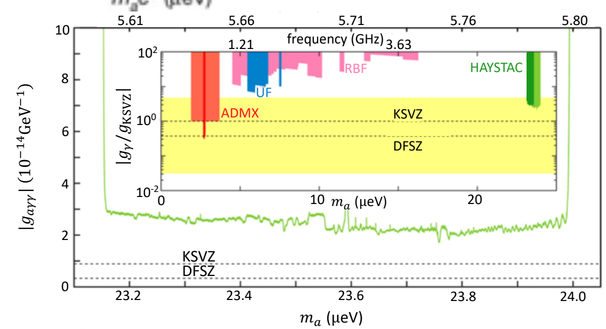
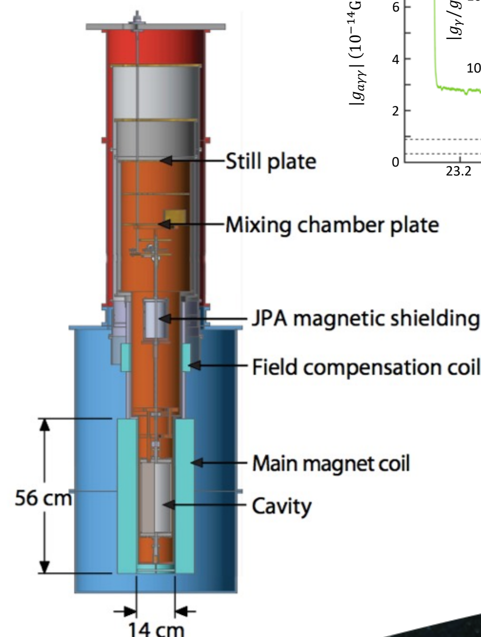
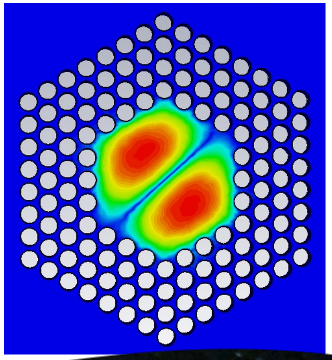
Summary/Conclusion

- Phase I/II have excluded axions at near KSVZ
- Highest frequency/mass limit probed by a cavity search
- Phase II has demonstrated **running with a squeezed state receiver**
- We are entering a phase of data production
- We have several new upgrades ready for testing in the near future









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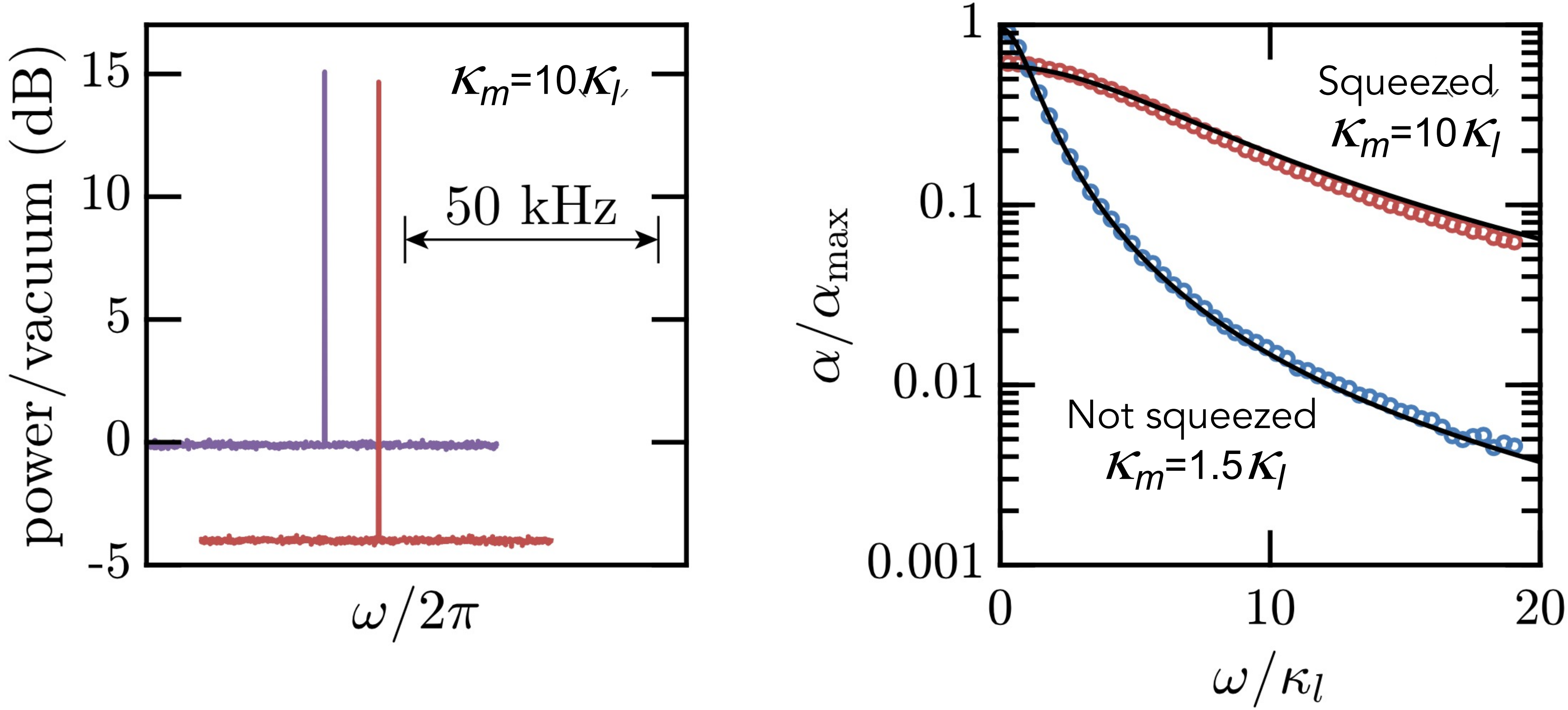
Questions/Comments?

Feel free to email me at aleder@berkeley.edu

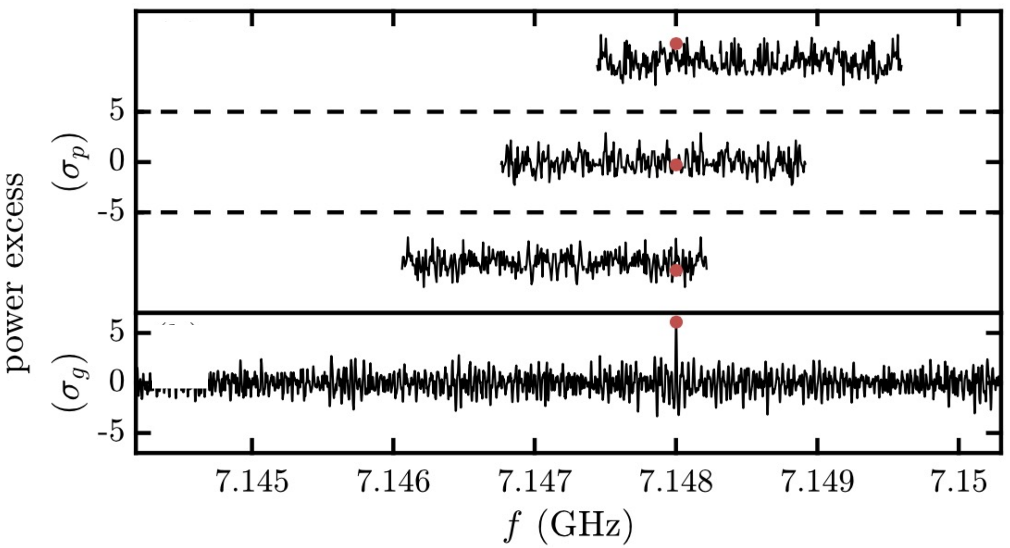
Extra Slides

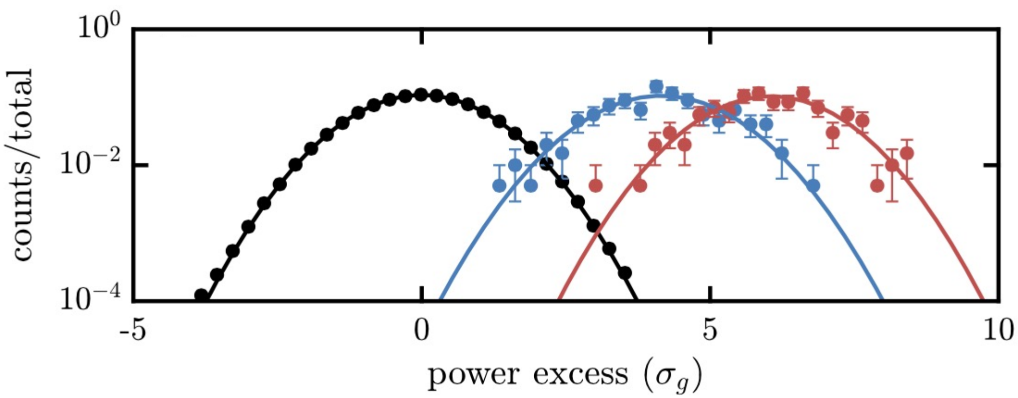
Squeezing implies uniformly higher S/N over a wider bandwidth



The scan rate with squeezing optimizes at large overcoupling of the cavity, thus higher BW

Corresponding factor of 2.12 speedup in scan rate demonstrated





- ❑ Mock axion search conducted on the JILA testbed
- ❑ Synthetic signal injected into the system of unknown frequency
- ❑ Search protocol repeated 200 times for each configuration, data plotted in terms of their standard deviation
- ❑ Results are $\mu_s = 6.05 \pm 0.07$ (with squeezing), $\mu_s = 4.15 \pm 0.07$ (w/o), leading to 2.12 ± 0.08 speedup
- ❑ HAYSTAC commissioning has now demonstrated squeezing
- ❑ JILA working on x10 speedup

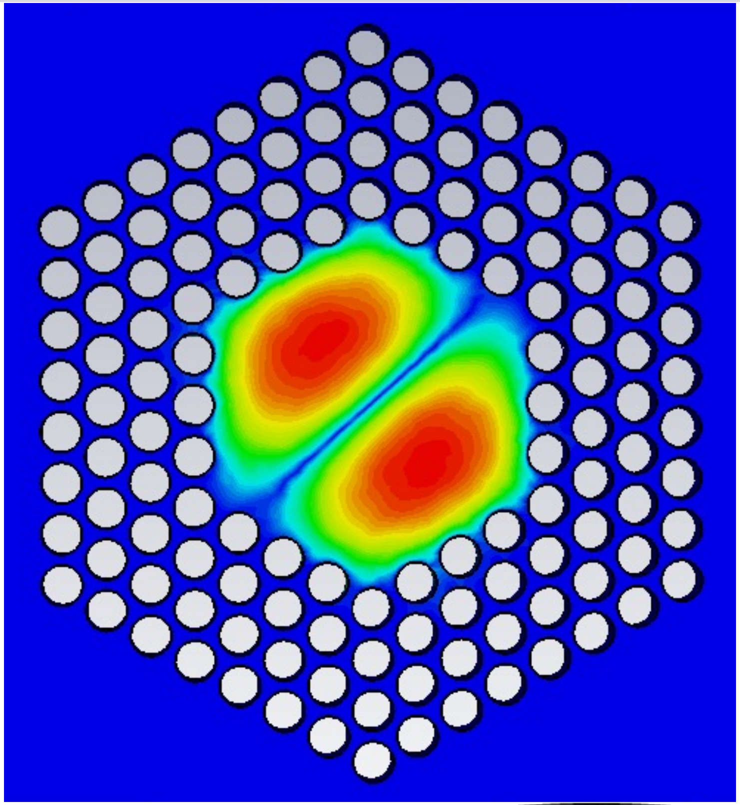
Photonic Band Gap (PBG) background

Basic definition

- Periodic lattice of metal and/or dielectric rods with an open boundary
- Band gap behavior: certain frequencies cannot propagate through lattice (“disallowed”)

Creation of a PBG resonator

- Defect in lattice confines “disallowed” modes
- All other modes propagate out
- Our case: confine TM modes, not TE modes



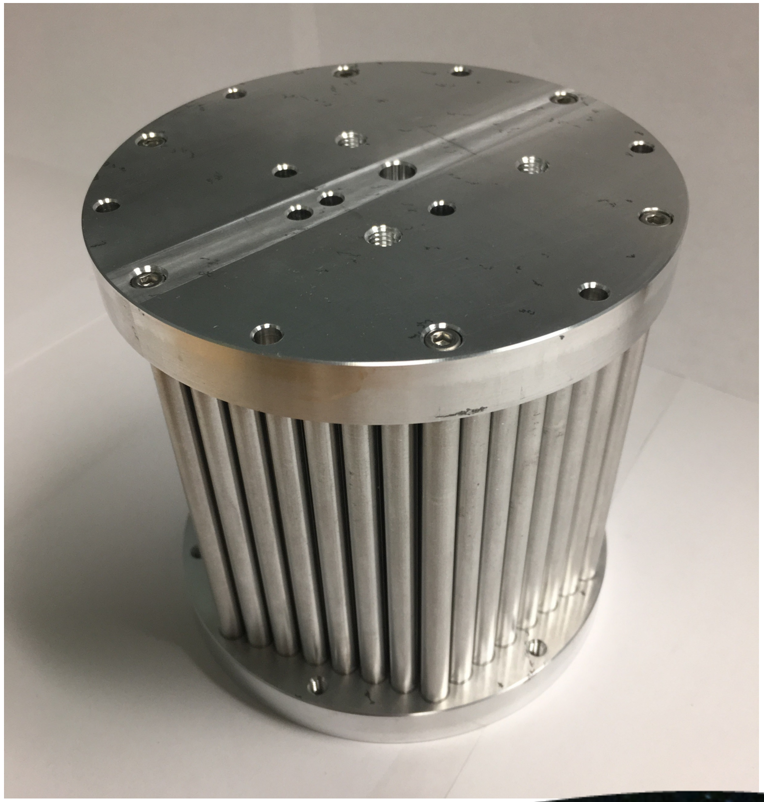
HAYSTAC

Aluminum prototype “stock” lattice

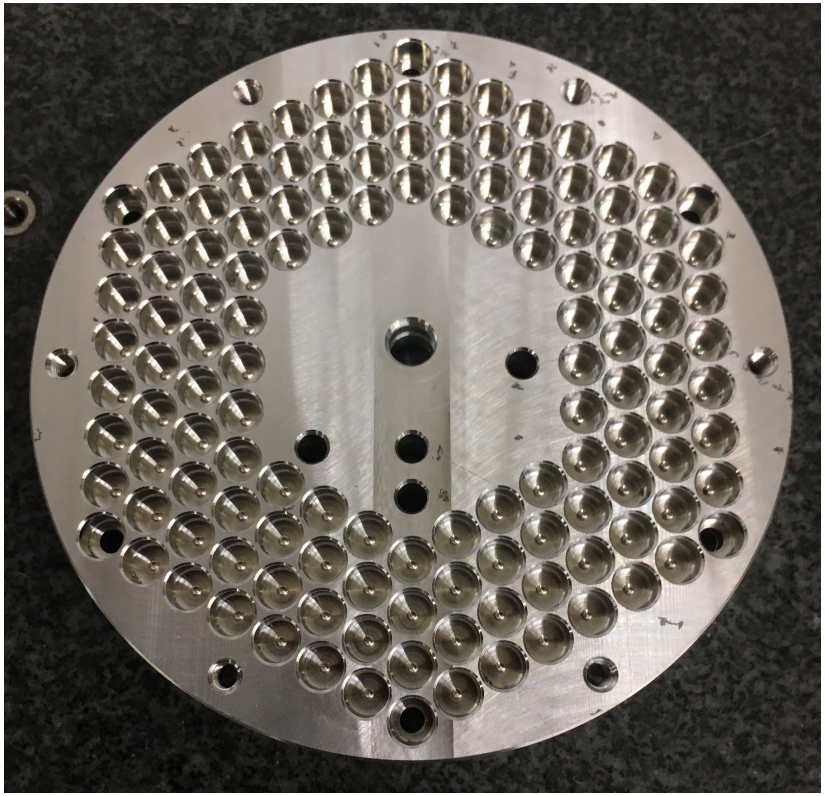
Prototype goals

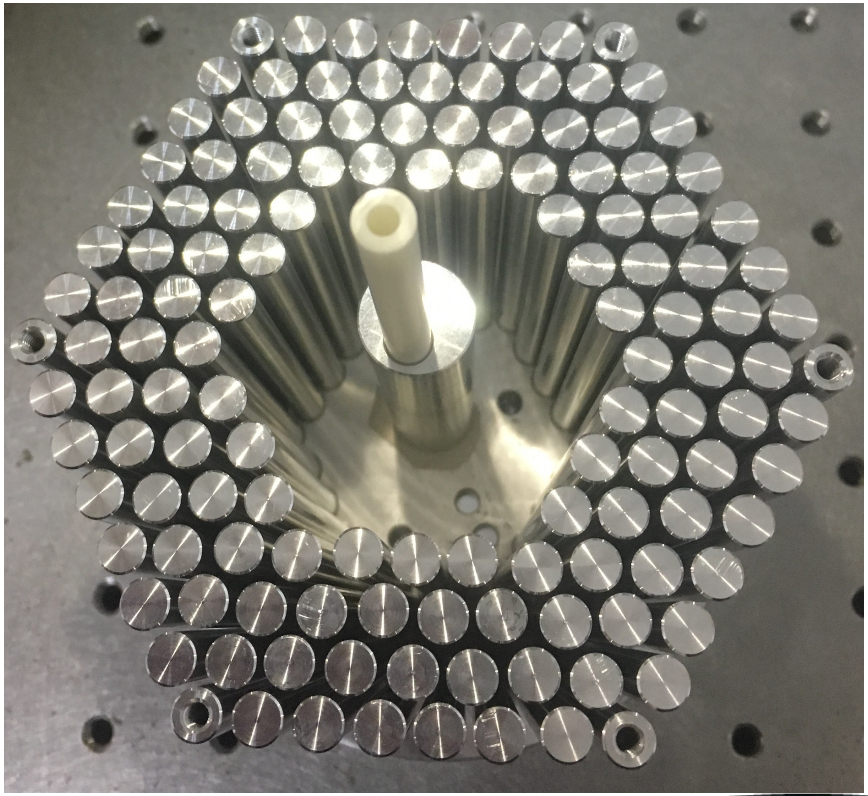
- Investigate tuning:
  - Single tuning rod in defect (same as HAYSTAC cavity)
  - Tuning range: 7.4 to 9.4 GHz

- Study fabrication possibilities:
  - Alignment/tolerances
  - Assembly options
  - Try plating



Aluminum prototype “stock” lattice





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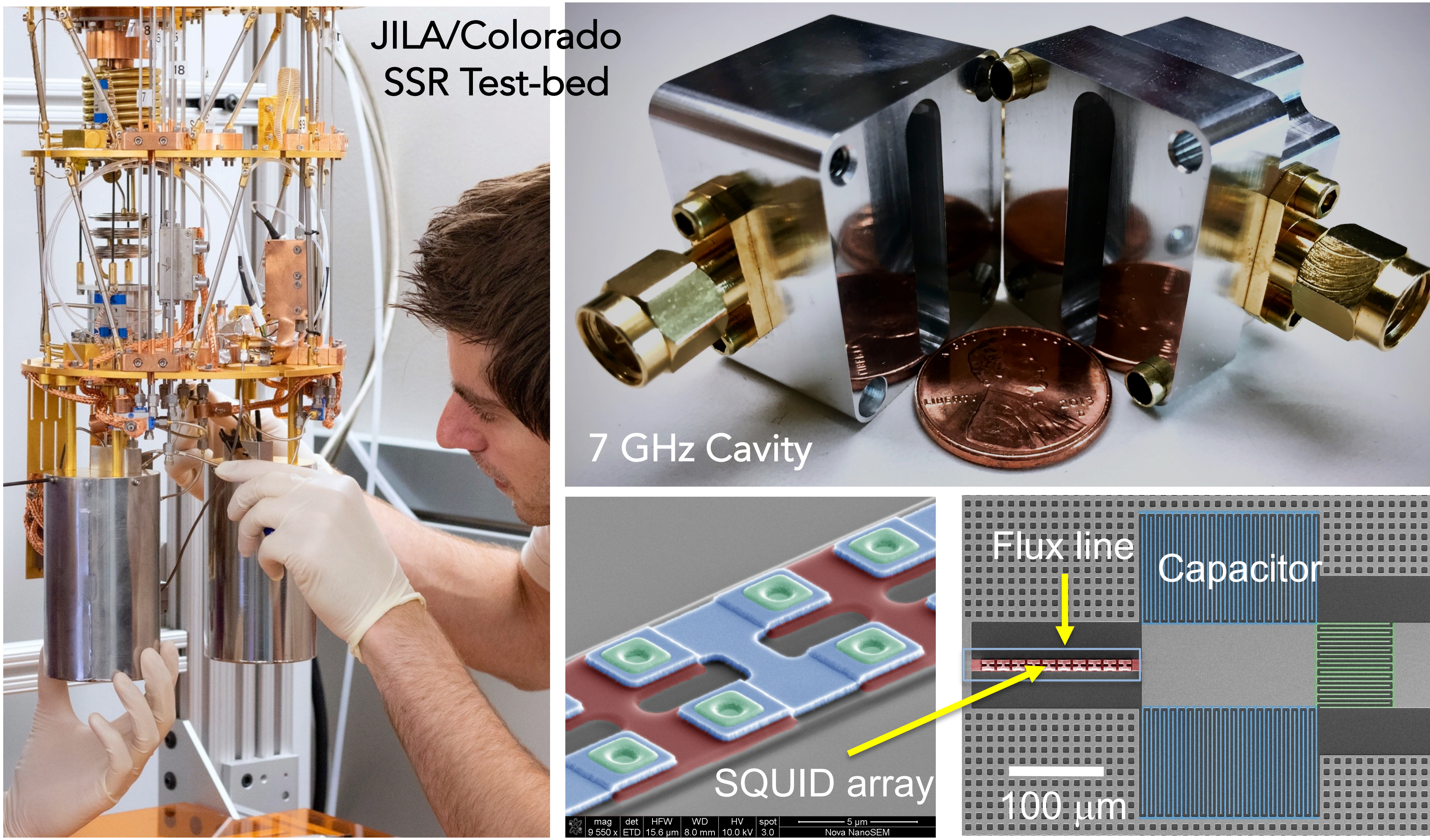
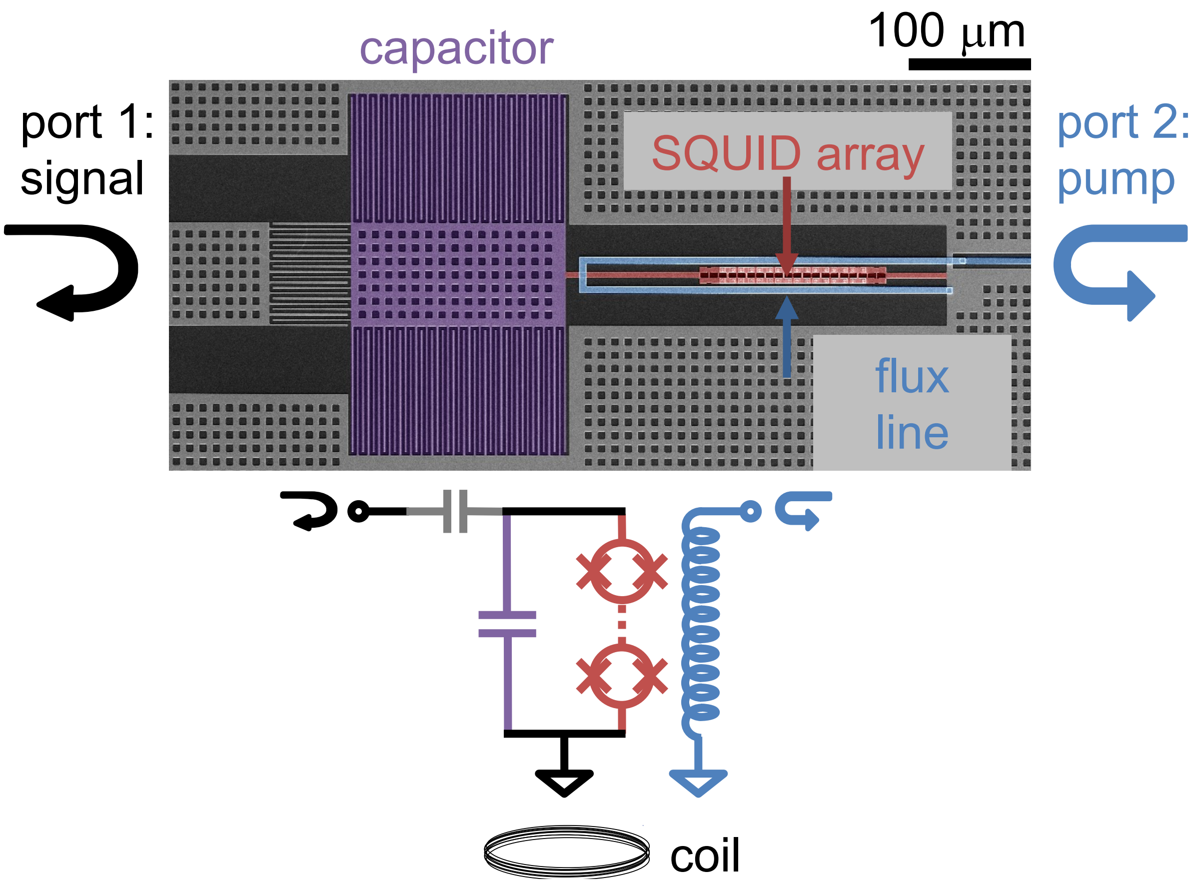
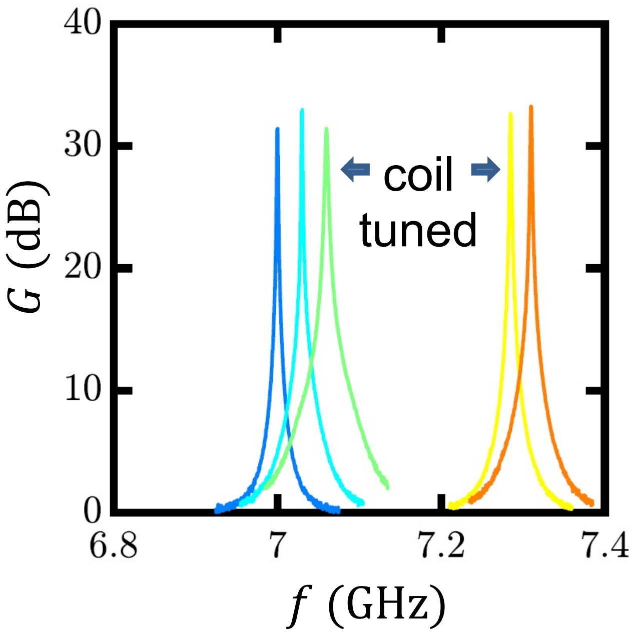

JILA/Colorado
SSR Test-bed
7 GHz Cavity
Flux line
Capacitor
SQUID array
100 µm
mag 9 550 x det ETD HFW 15.6 µm WD 8.0 mm HV 10.0 kV spot 3.0 5 µm Nova NanoSEM

Low noise amplification with Josephson parametric amplifiers





tunable over 1.5 GHz
gain > 30 dB

JILA
CU Boulder and NIST

Phase I Results