The Cockcroft Institute
of Accelerator Science and Technology

Lancaster University

Results of the CASCADE Microwave Hidden Sector Photon Search

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Hidden Sector Photons

- Many extensions to the SM manifest extra U(1) symmetries at low energies.
- The associated gauge bosons can have mass and are known generically as dark photons or hidden sector photons (HSP).
- HSPs can couple to SM $U(1)_Y$ photons through 'kinetic mixing'.
- HSPs have no direct couplings to electric charge.
- At low masses they are WISP dark matter candidates.

Electromagnetic Field

Kinetic Mixing Term

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{4}B^{\mu\nu}B_{\mu\nu} - \frac{1}{2}\chi F^{\mu\nu}B_{\mu\nu} + \frac{1}{2}m_{\gamma'}^{2}B_{\mu}B^{\mu}$$

HSP Field

HSP Mass Term

Modified Maxwell Equations

Considering linear admixtures of the fields gives the free-space equation:

$$\partial_\nu F^{\mu\nu} = m_{\gamma'}^2 \chi(\chi A^\mu - B'^\mu)$$

which leads to the associated wave equations:

$$(\partial^\mu \partial_\mu + m_{\gamma'}^2) B' = \chi m_{\gamma'}^2 A,$$

$$(\partial^\mu \partial_\mu + \chi^2 m_{\gamma'}^2) A = \chi m_{\gamma'}^2 B'$$

The source terms on the right allow the HSP field to generate an electromagnetic field and vice-versa.

Shining Light Through a Wall

- HSPs allow electromagnetic fields to penetrate regions of electric charge:
  - E.g. a metal wall, plasma, etc…
- We can search for the HSP by using a **'light shining through a wall'** experiment.

- At optical frequencies ALPs (DESY) is the current leading experiment.
- At microwave frequencies UWA , Yale and CERN have experiments of this kind.
- CASCADE is a UK-based microwave LSW experiment.

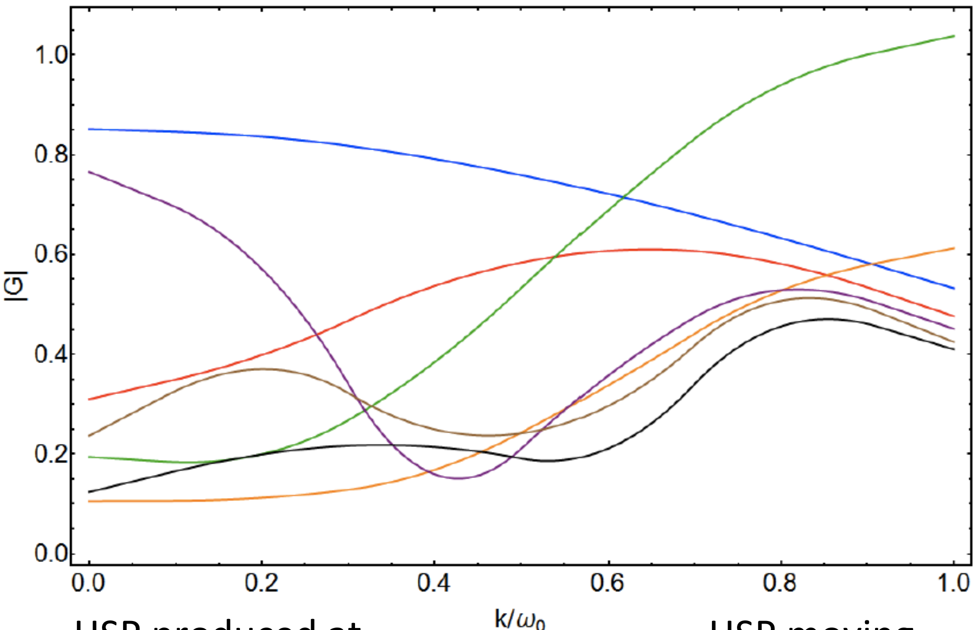
Probability of detection

Consider two 'cavities' with quality factors Q and Q' and resonant frequency ω_0 .

The probability of transmitting a photon via the hidden sector field associated with an HSP of mass $m_{\gamma'}$ is given by

$$P_{trans} = \chi^4 Q Q' \frac{m_{\gamma'}^8}{\omega_0^8} |G|^2$$

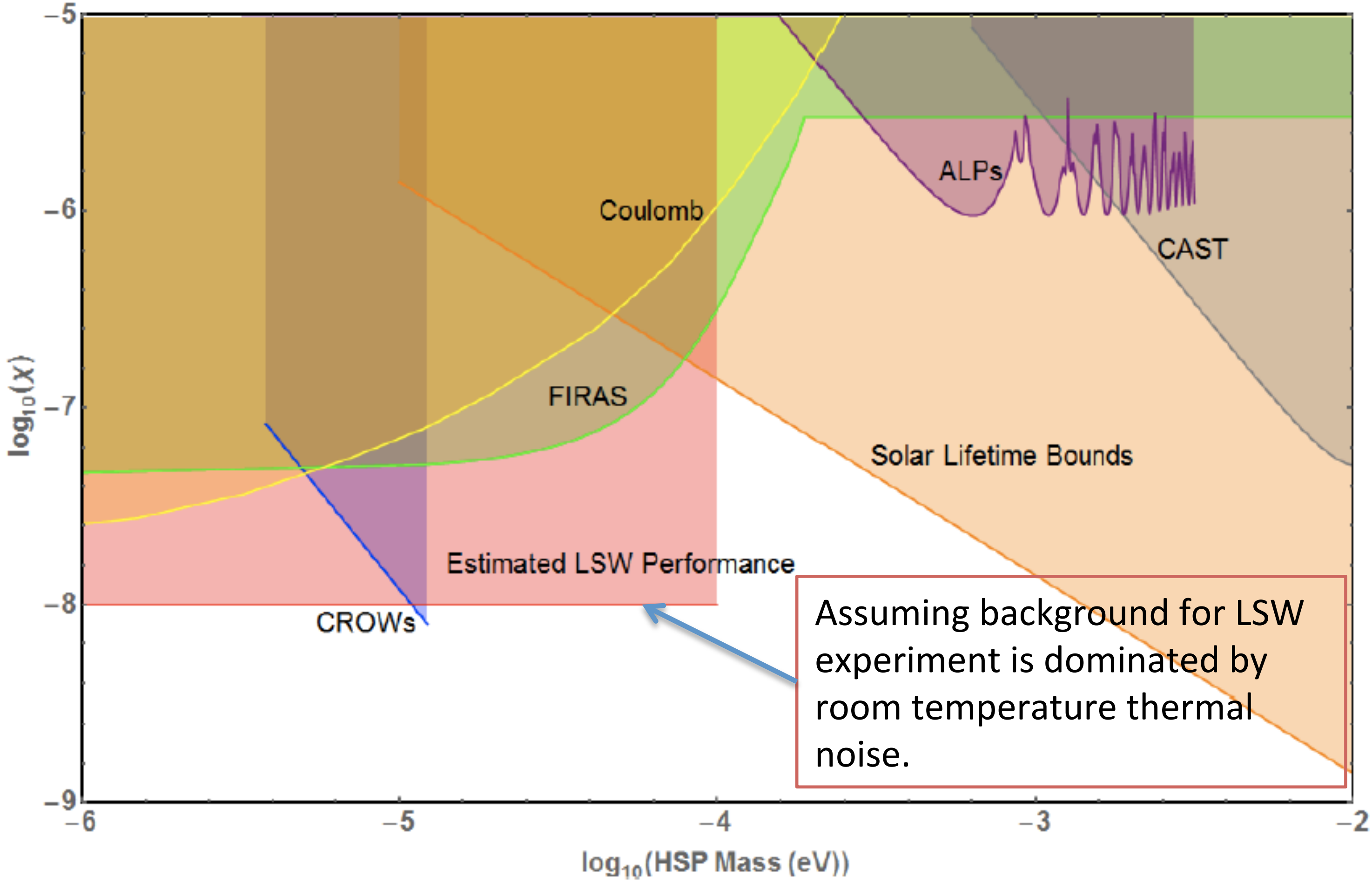
G factors for **low** and **higher** order electromagnetic modes in a cylindrical cavity.



HSP produced at rest

HSP moving relativistically

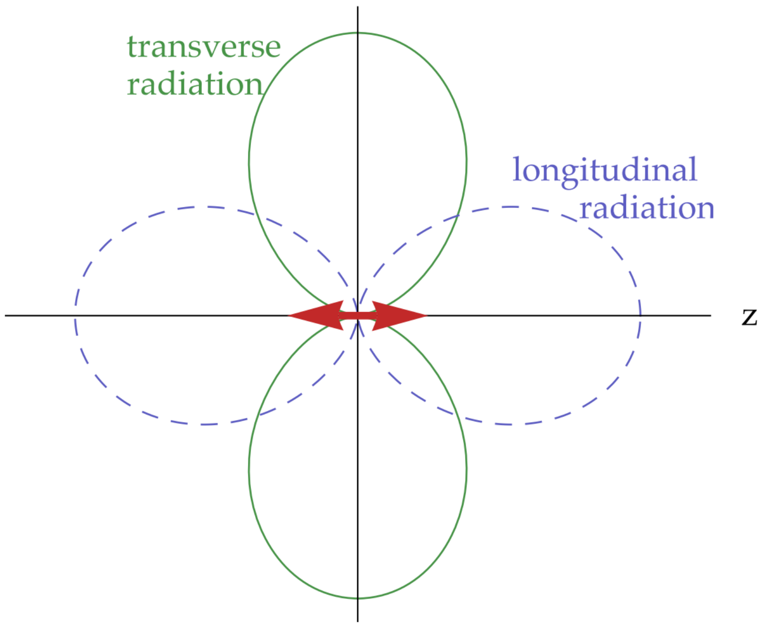
HSP low-mass Parameter Space



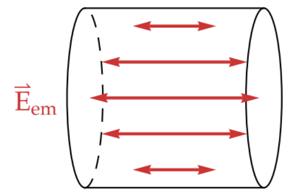
Assuming background for LSW experiment is dominated by room temperature thermal noise.

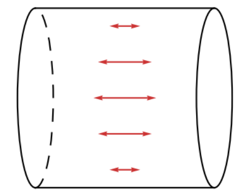
Longitudinal Coupling

P.W. Graham, J. Mardon, S. Rajendran, Y. Zhao, PRD90, 075017 (2014)

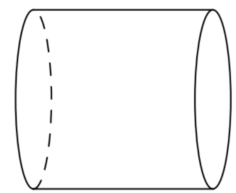


As the HSP has mass, it has a longitudinal polarisation mode which can be more effective at mediating photon transmission.





Well-positioned receiver cavity



Badly-positioned receiver cavity

$$P_{trans} = \chi^4 Q Q' \frac{m_{\gamma'}^4}{\omega_0^4} |G|^2$$

CASCADE is the first microwave LSW experiment to exploit this effect.

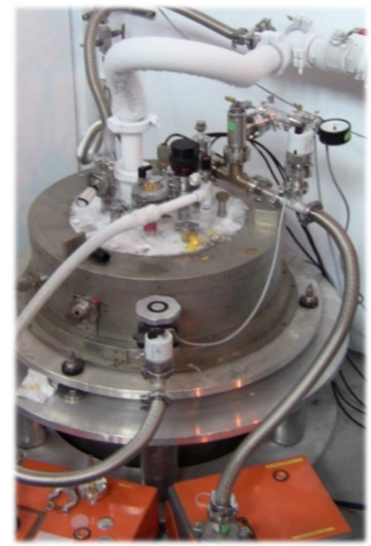
CASCADE motivation

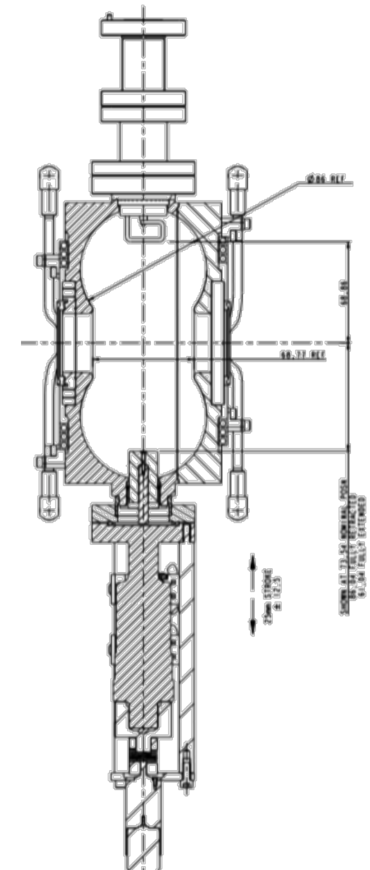
Daresbury Laboratory and Cockcroft Institute of Accelerator Science and Technology routinely tests superconducting RF structures.
CASCADE is designed to take advantage of these tests, acting as a resonant detector.

Proposed Tests*,

- 1.3 GHz Superconducting 2015/16
- 704 MHz Superconducting 2017/18
- 8 GHz Superconducting 2015
- 3 GHz Normal conducting 2015
- 12 GHz Normal conducting TBC

*Dates are provisional

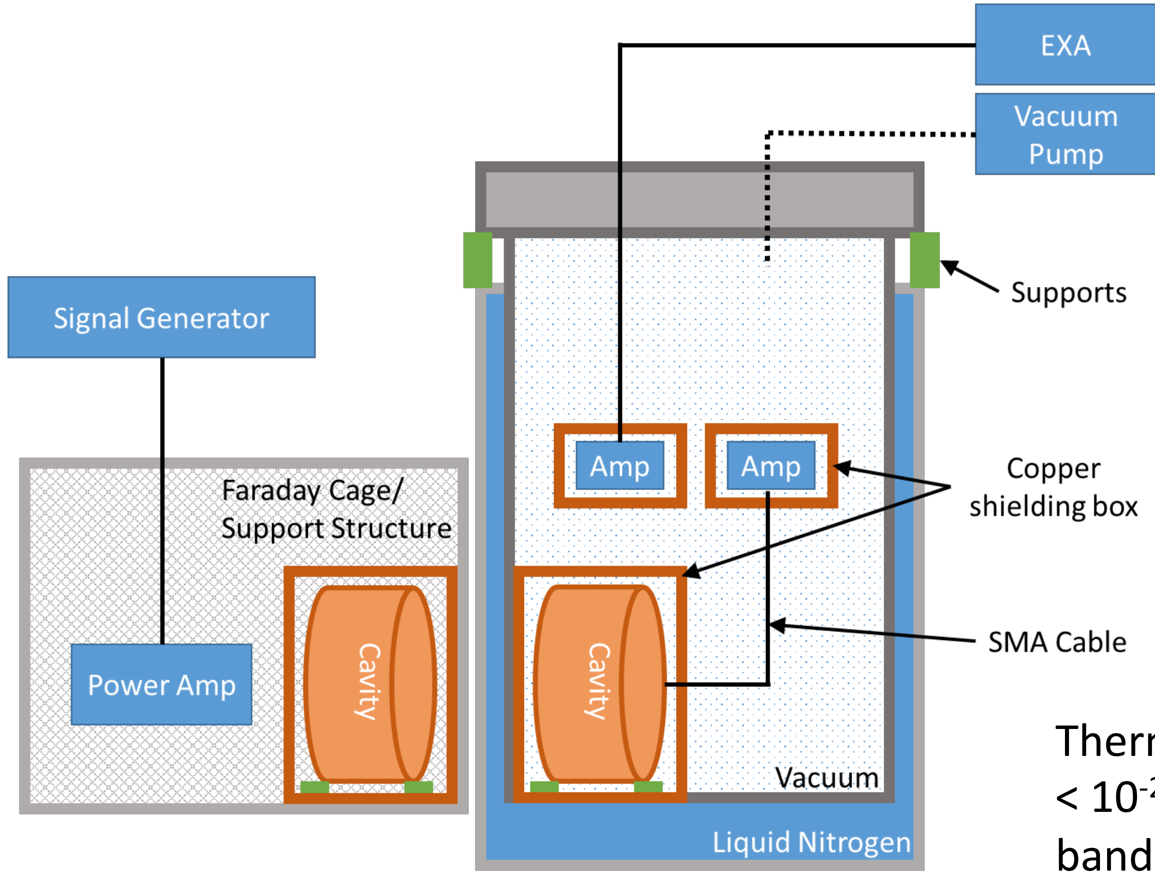




Vertical Test Facility (VTF)

CASCADE Phase 1 Schematic

(Longitudinal Coupling Orientation)



Power = 0.4W

Thermal noise power < 10^{-24}W in 1mHz bandwidth

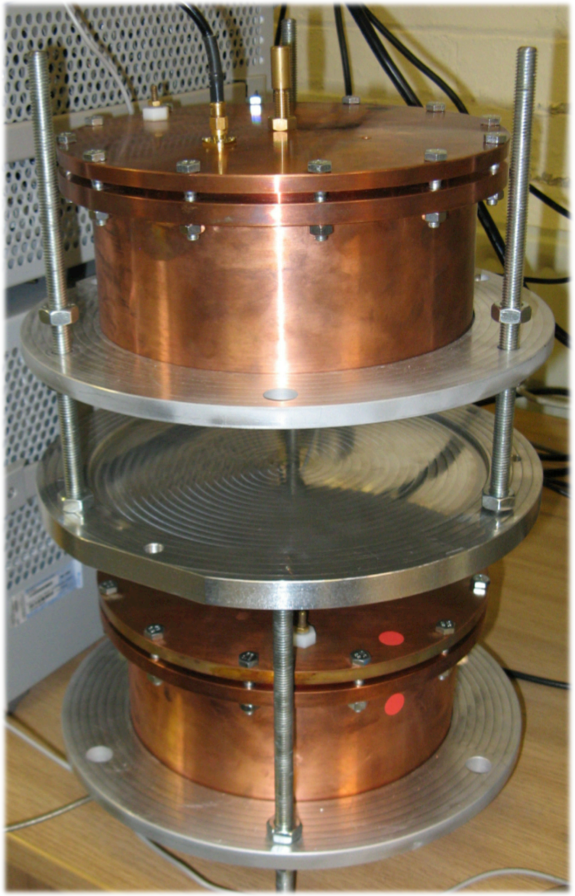
*Not to scale

CASCADE cavities

Simple copper pill-box RF cavities

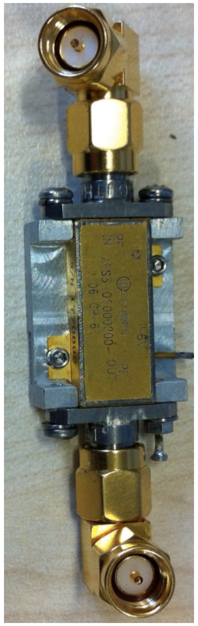
- Operating in the TM010 mode.
- Resonant at approx. 1.3GHz.
- Frequency adjustable via tuning screw
- Coupled to coaxial cables through simple stud coupler.
- Q ≈ 10^4 at room temperature (limited by the copper quality).


Stud coupler in cavity lid.

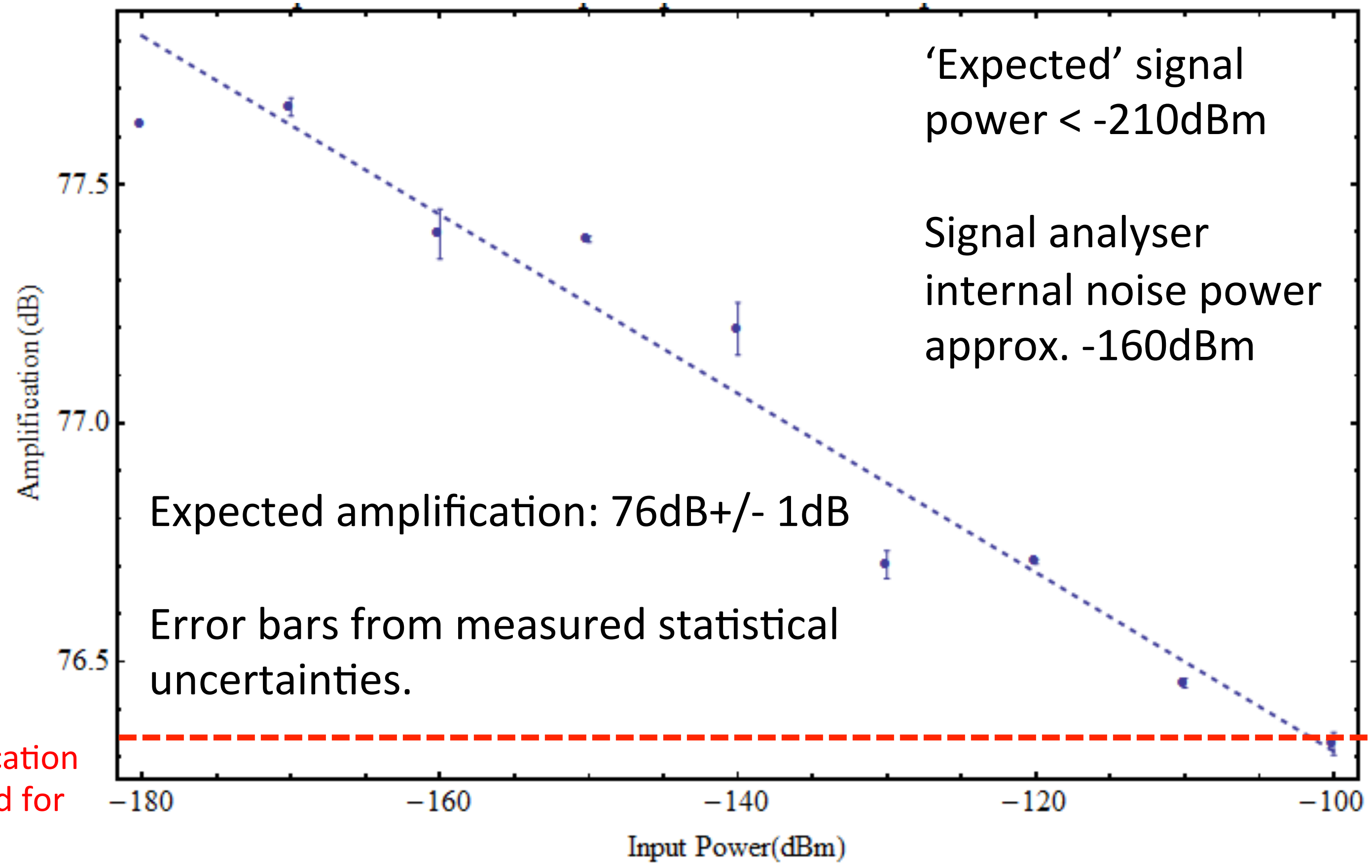

Cavities in original transverse coupling orientation.

CASCADE Amplifiers

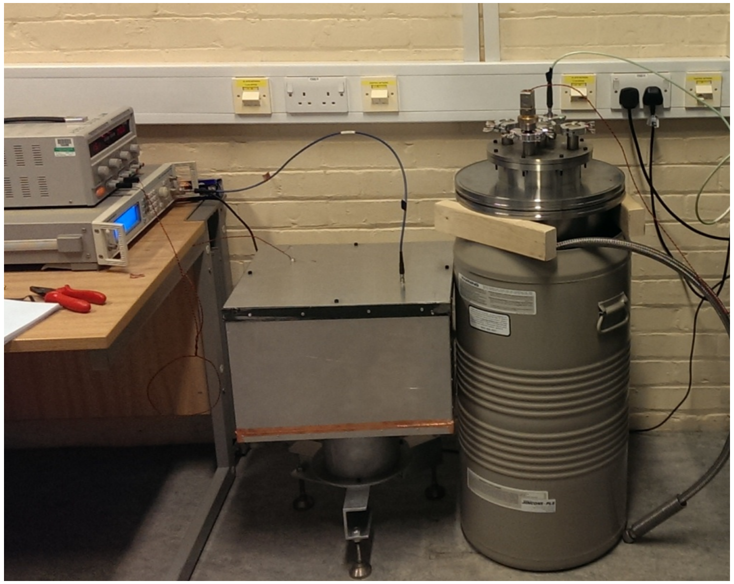
2 Miteq ASF3 CR amplifiers in series.



Amplification assumed for results.

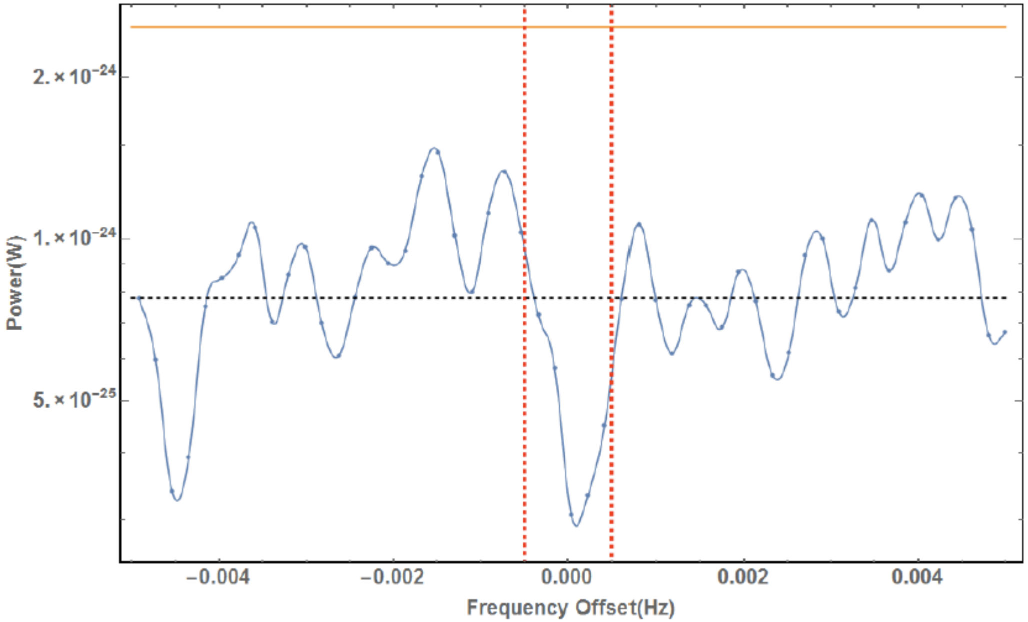


CASCADE Phase 1



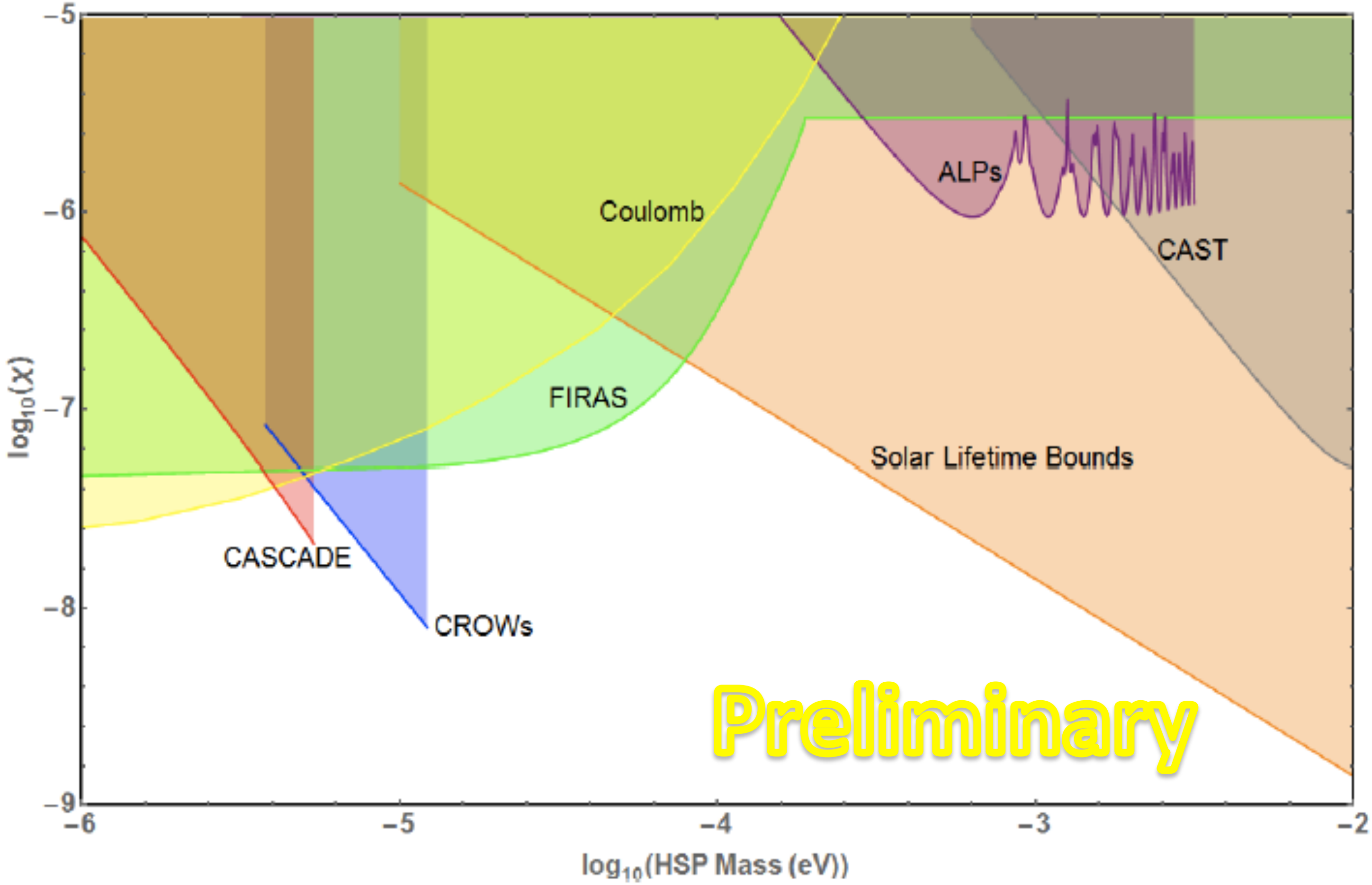
Data averaged over 10 hours. Temperature stable within 1 degree C.

Power observed in 1mHz signal window

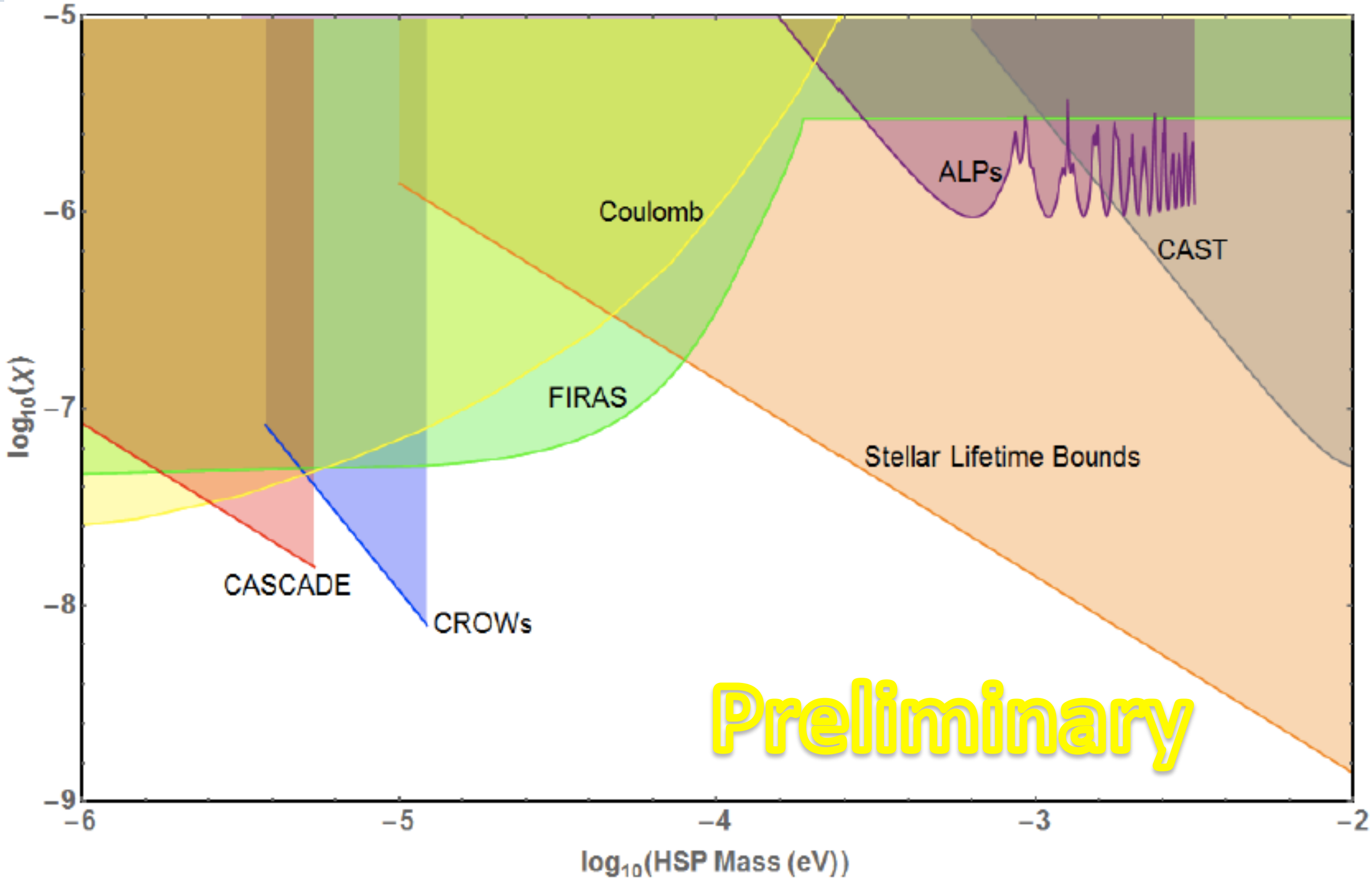


Black dashed line = noise power extrapolated from outside signal window.

Exclusion (transverse only)



Exclusion (longitudinal only)



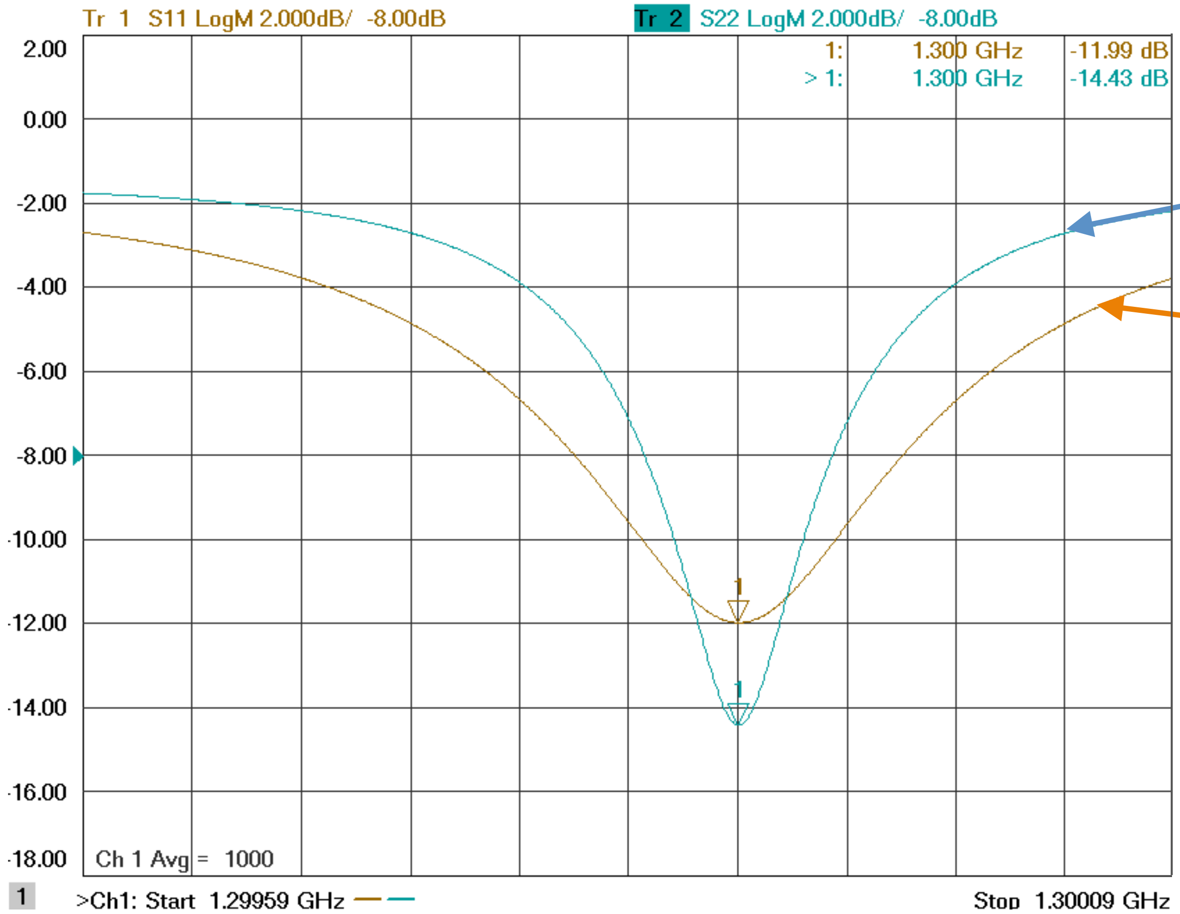
Summary

- CASCADE is the first microwave LSW HSP search to make use of the longitudinal polarisation mode of the HSP
- Room-temperature CASCADE results exclude new region of HSP parameter space in the mass range $10^{-5.42}$ to $10^{-5.27}$ eV/c^2 with a peak exclusion in the coupling constant of $10^{-7.75}$

- Future steps for UK contributions to sub-MeV HSP / WISP searches
  - CASCADE phase 2 and cryogenic operation.
  - Photonic lattice cavities (J. Phys. G: Nucl. Part. Phys. 41 (2014) 035005)
  - Accelerator-based light sources (c.f. ESRF and SPRING-8)
  - Involvement in international experiments: ADMX, IAXO, …
- Upcoming workshop at IPPP April 13th – 15th to discuss future direction.

Backup Slides

-CASCADE Cavity Optimisation



Trace 2, First optimisation Q=7652

Trace 1, Post cleaning Q=3569

Further optimisation resulted in emitter Q of 10690 and detector Q of 10680

-PHARAOH

- Our 2014 paper introduced the concept of a photonic structure based LSW.
- The experimental plan being known as PHARAOH.

Hidden-sector photon and axion searches using photonic band gap structures

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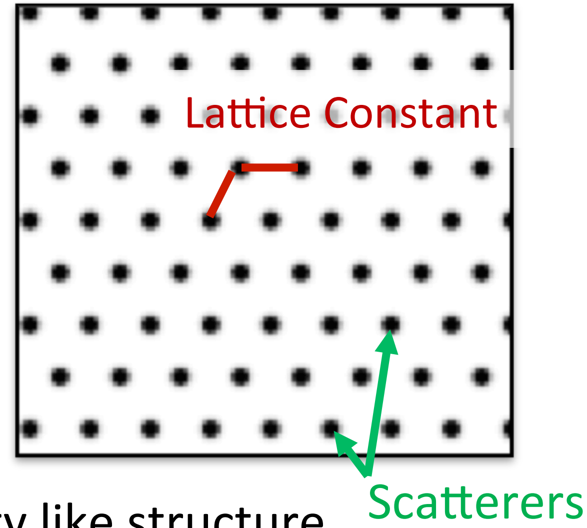
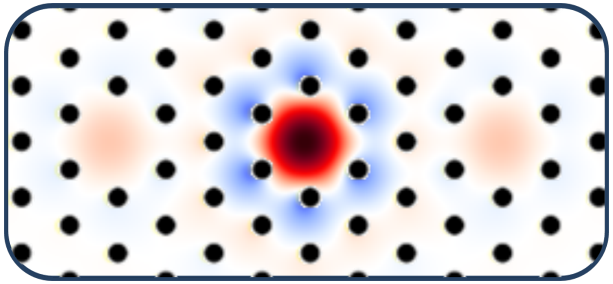
J. Phys. G: Nucl. Part. Phys. 41 (2014) 035005(10pp)
doi:10.1088/0954-3899/41/3/035005

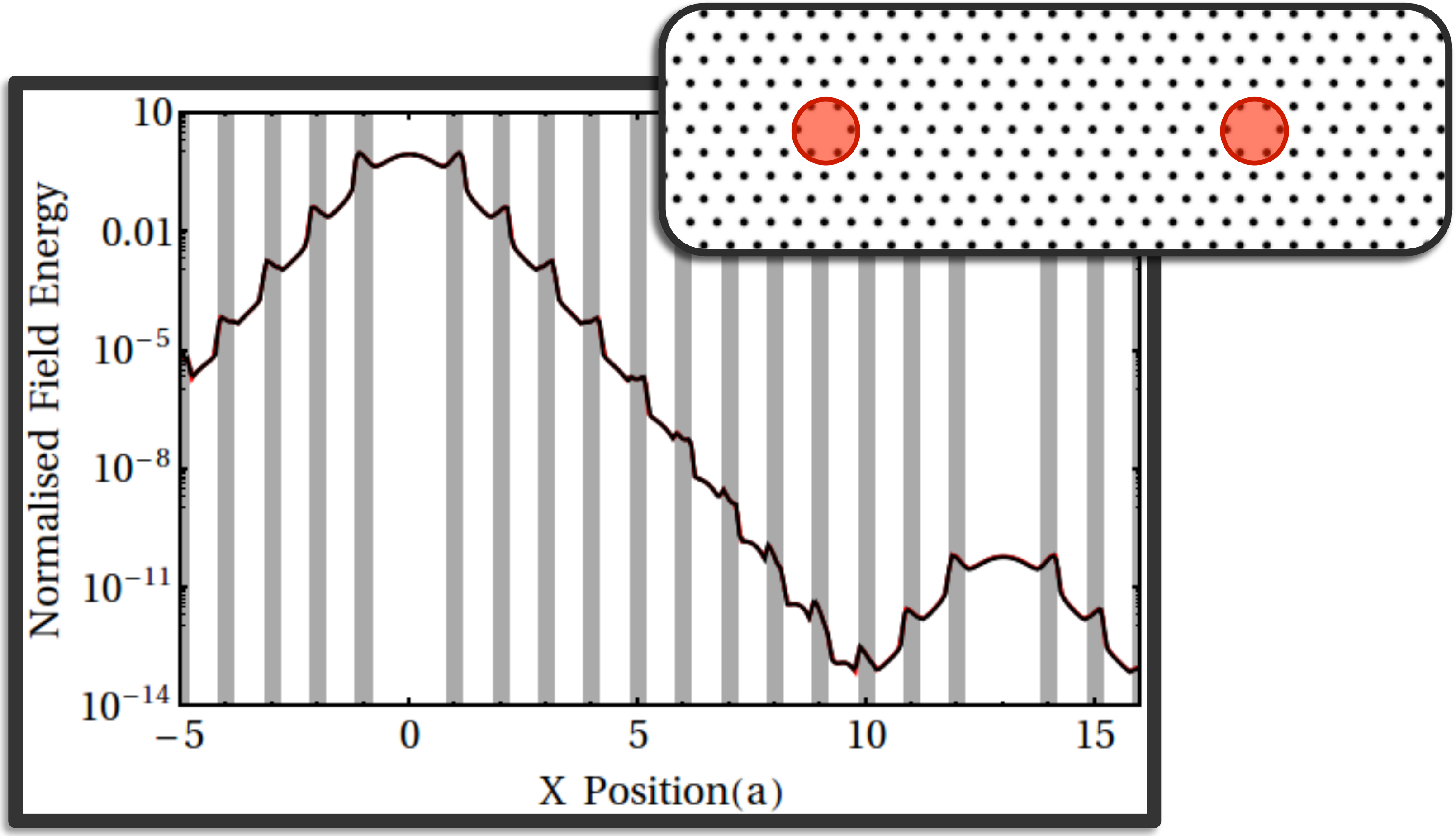
-PHARAOH

- Photonic structures are a formed from a periodic lattice of varying permittivity material.
- The lattice structure controls the flow of light through the material.
- Varying the lattice constant and scatterer size selects the operational frequency of the lattice.
- The removal of a scatterer creates a cavity like structure.

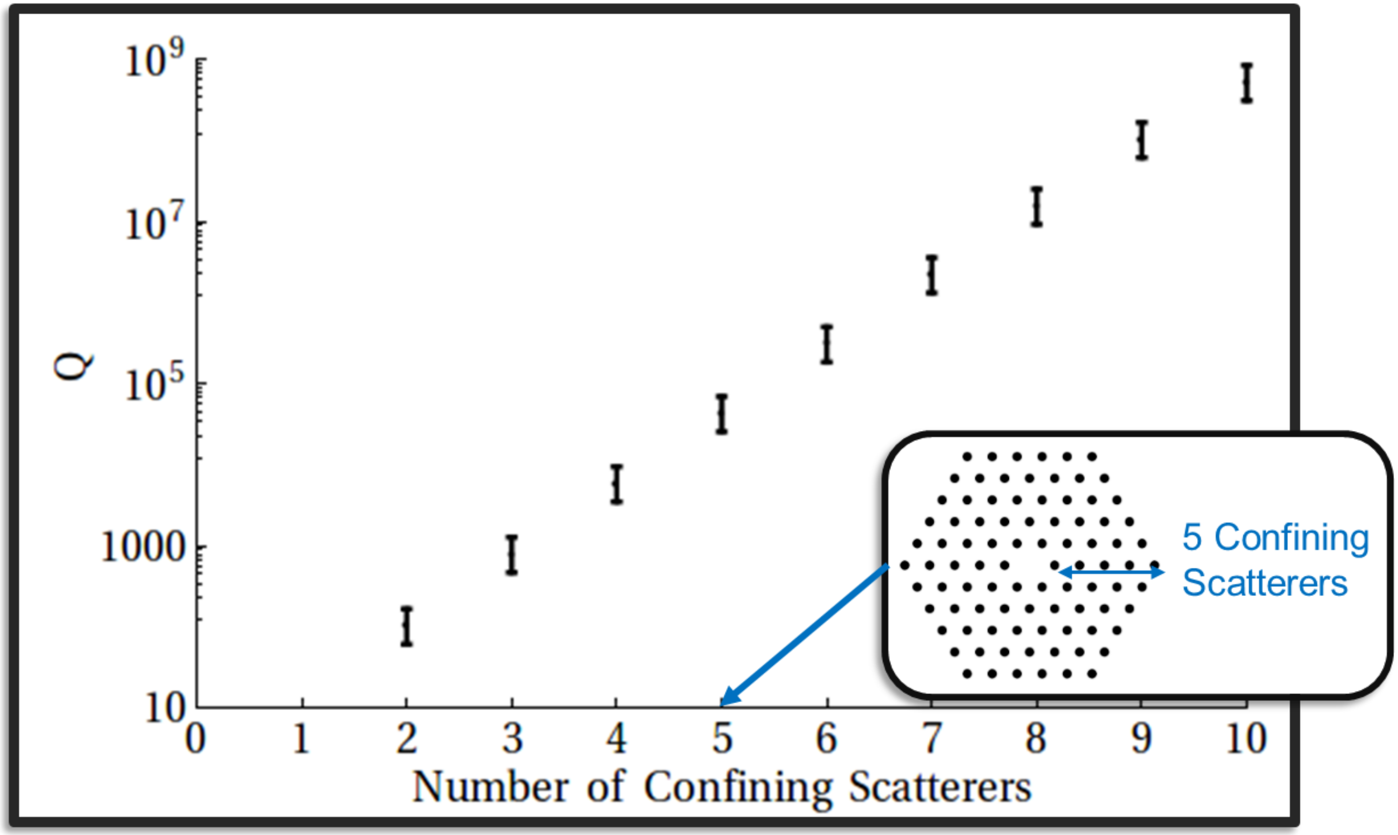




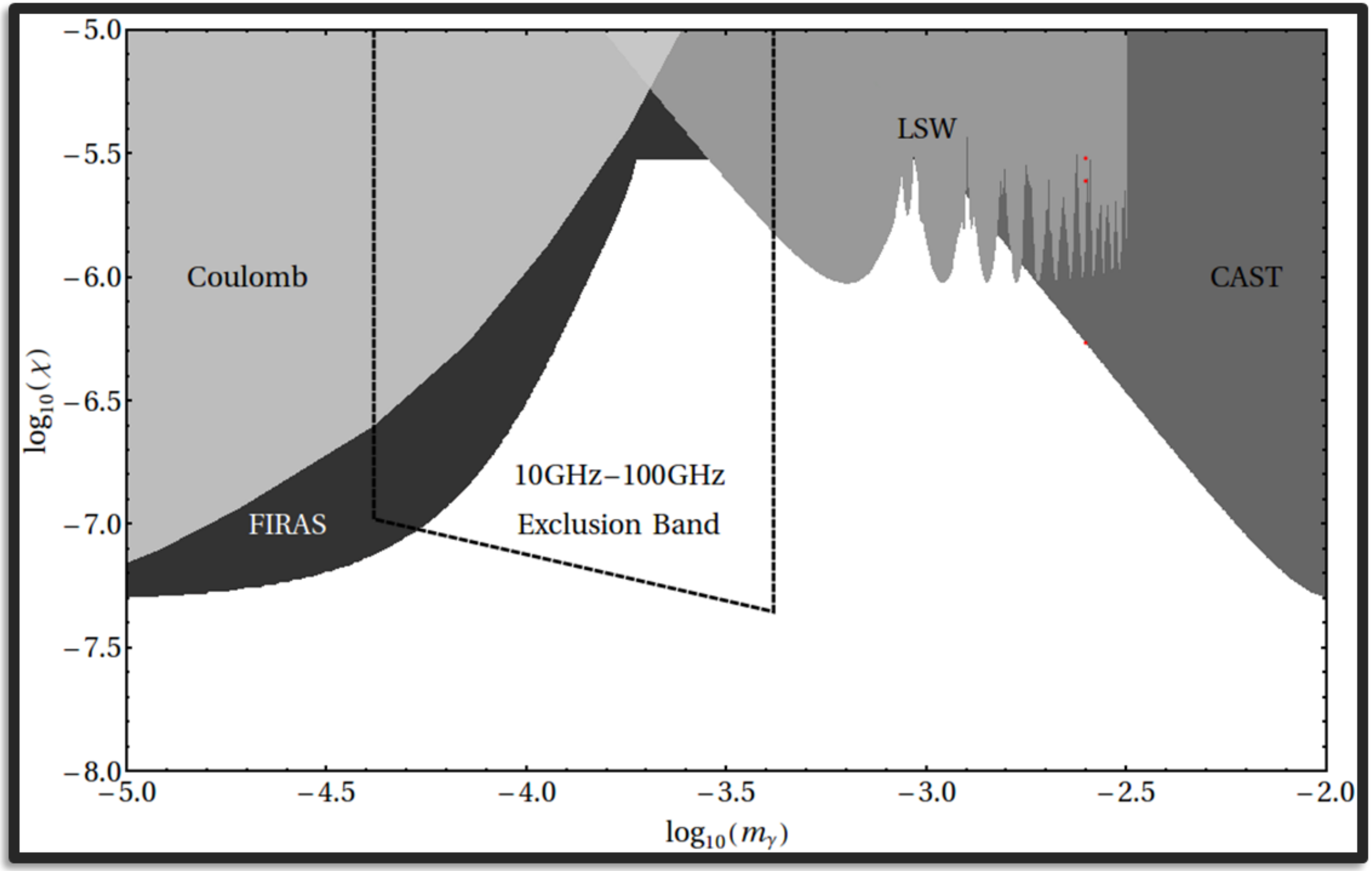
PHARAOH Isolation Simulations



PHARAOH Quality Factor Simulations



PHARAOH Expected Exclusion



G Factor

- By using cavities with high quality factors, Q, we can enhance the probability of transmission between the cavities.
- The probability of transmission is given by:

$$P_{trans} = \chi^4 QQ' \frac{M_{\gamma'}^8}{\omega_0^8} |G|^2$$

- G is the geometric factor which encodes the physical set up of the experiment. This is typically of order unity and is given by

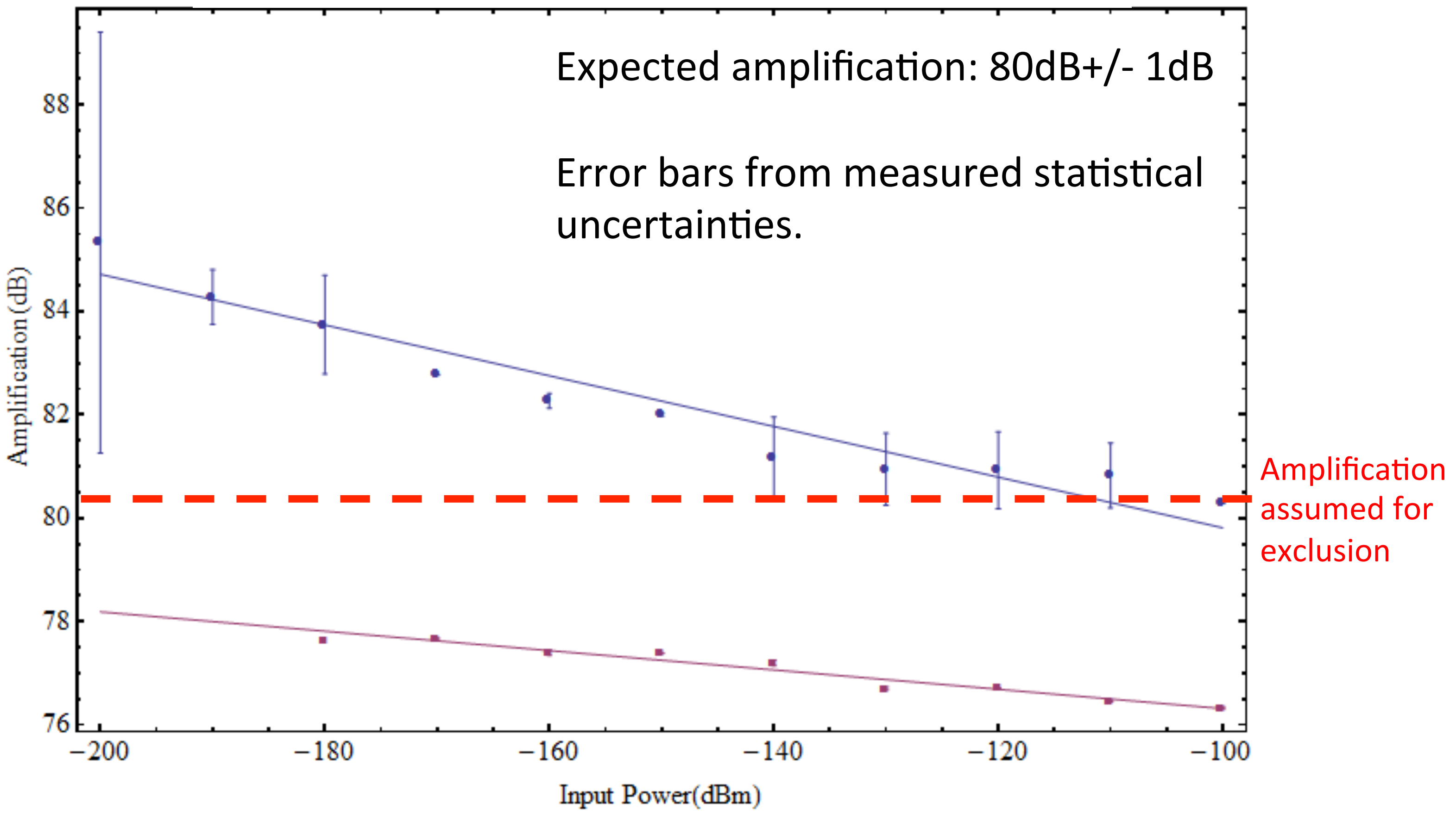
$$G\left(\frac{k_{\gamma'}}{k_\gamma}\right) = \iint \frac{e^{-ik|x-y|}}{4\pi|x-y|} A(x)A'(y)\, dx^3 dy^3$$

CASCADE lq N_2 Run

Cooling the experiment is expected to improve performance through:

- Increased Q factor of the cavities from 10500 to 13500.
- Increased amplification: +2dB.
- Reduced Noise Figure: -0.4dB .
- Reduced thermal noise.

Cryo Amp Amplification (Lq N_2)



CASCADE Expected lq N_2 Exclusion