Superconducting RF Cavity Search for Hidden Sector Photons at Daresbury

6th July 2010

Peter Williams, STFC Daresbury Lab. & Cockcroft Institute

The Cockcroft Institute
of Accelerator Science and Technology

Science & Technology Facilities Council
Daresbury Laboratory

Hidden Sector Photons

- **SM extensions *generically* contain extra U(1) degrees of freedom**

- If there is no Yukawa coupling to SM, we say they belong to the "hidden sector"

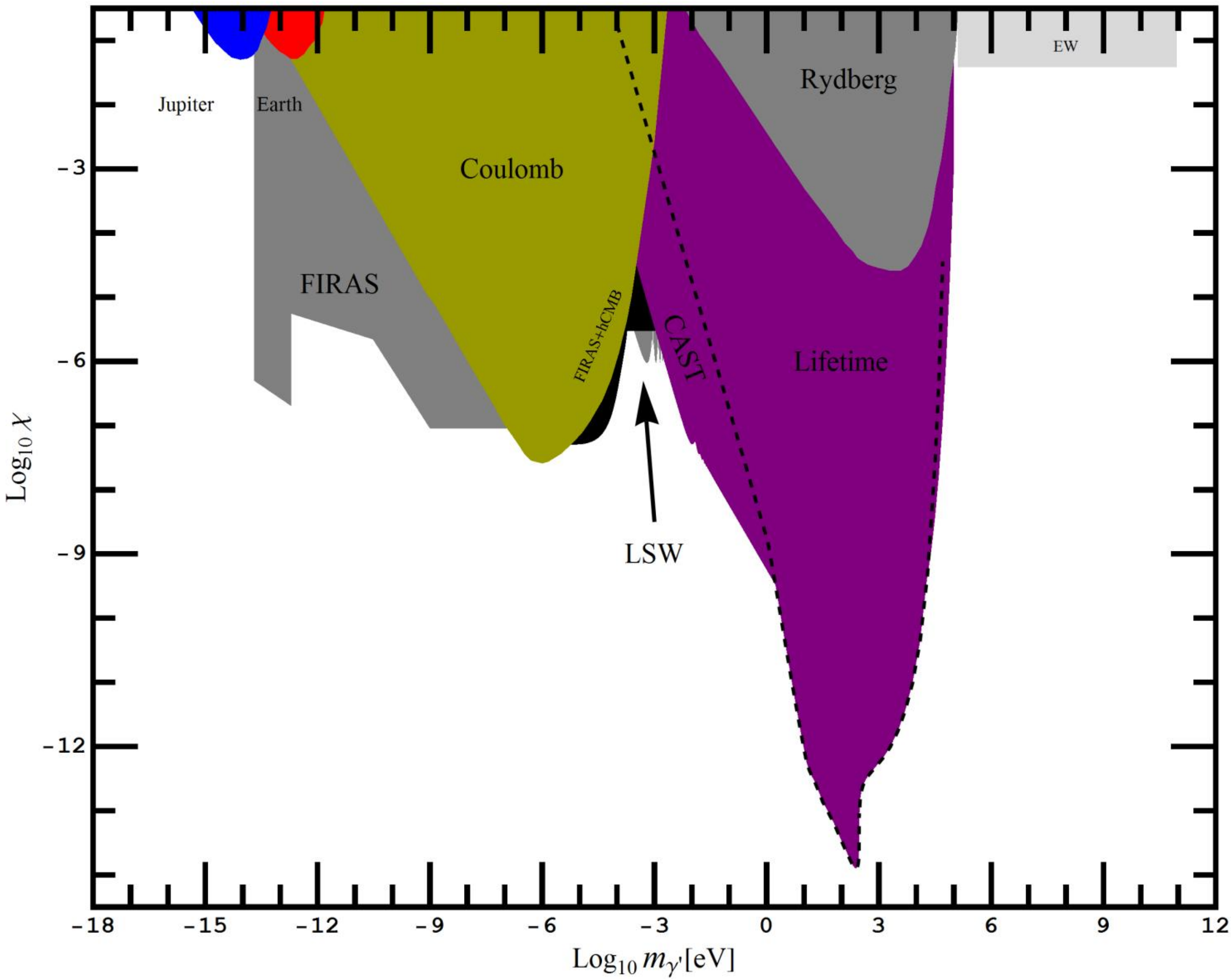
- If the hidden sector photon field exists, the only interaction term in the Lagrangian allowed is a "kinetic mixing" term, when diagonalised we see an explicit mass term that mixes photons and hidden photons

Photon kinetic term — Hidden photon kinetic term — mixing term

$$L = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{4}\tilde{B}^{\mu\nu}\tilde{B}_{\mu\nu} + \frac{1}{2}m_{\gamma'}^{2}\left(\tilde{B}^{\mu}\tilde{B}_{\mu} - 2\chi\tilde{B}^{\mu}A_{\mu} + \chi^{2}A^{\mu}A_{\mu}\right).$$

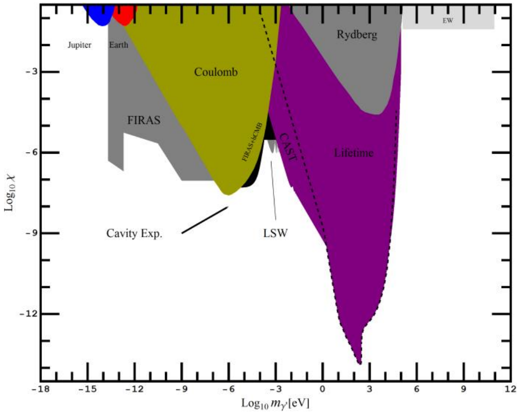
- So for a particular HSP mass, we want to measure kinetic mixing fraction, χ

Hidden Sector Photon Exclusion Plot: Current Limits



Hidden Sector Photon Exclusion Plot: Current Limits

1. **Coulomb**: Tests of $1/r^2$ dependence of Coulomb's law
2. **Lifetime**: Limit on lifetime of the Sun due to resonant photon-hidden photon oscillation and subsequent escape without further scattering thus accelerating nuclear fuel consumption
3. **Rydberg**: Comparisons of the Rydberg constant for different atomic transitions
4. **FIRAS**: COBE Far Infrared Absolute Spectrophotometer. - limit on distortions of blackbody nature due to resonant photon-hidden photon oscillations before decoupling
5. **CAST**: CERN Axion Solar Telescope
6. **LSW**: "Light Shining through the Wall" experiments (ALPS, BMV, GammeV, LIPSS, OSQAR, PVLAS)
7. **Jupiter**: Derived from bound on photon mass made by measuring magnetic field of Jupiter
8. **Earth**: Derived from bound on photon mass made by measuring magnetic field of Earth
9. **EW**: Precision electroweak measurements at colliders
10. **FIRAS + hCMB**: Concordance between cosmic radiation density measured at decoupling and at big bang nucleosynthesis epoch



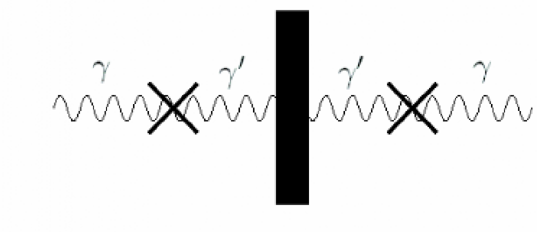
Hidden Sector Photons Will Couple Resonant Cavities

• An RF photon "mixes" into a HSP, propagates to the second cavity, and "mixes" back into identical frequency RF photon. Our cavities become coupled.

• The probability for this process is then:

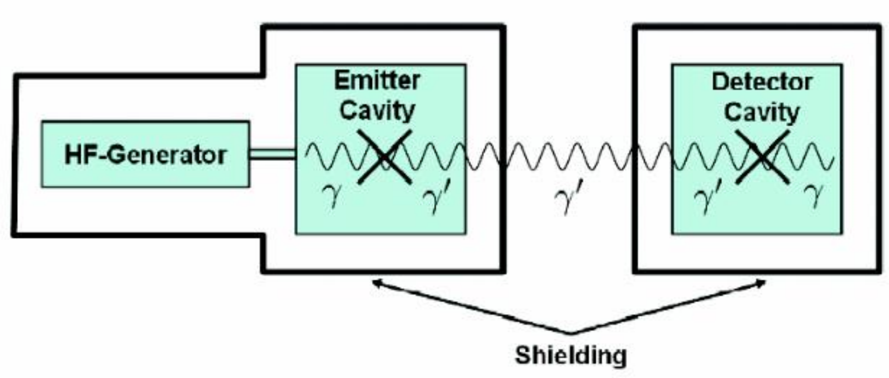
$$P = \chi^4 Q_1 Q_2 \frac{m_{\gamma'}^8}{\omega_0^8} \left|G\right|^2$$

where χ is the coupling, *Q* are the cavity quality factors, m is the hidden photon mass and ω is the cavity resonant frequency.



• *G* is a dimensionless parameter encoding the geometry of the experimental setup.

• Therefore we must maximise cavity Q's!



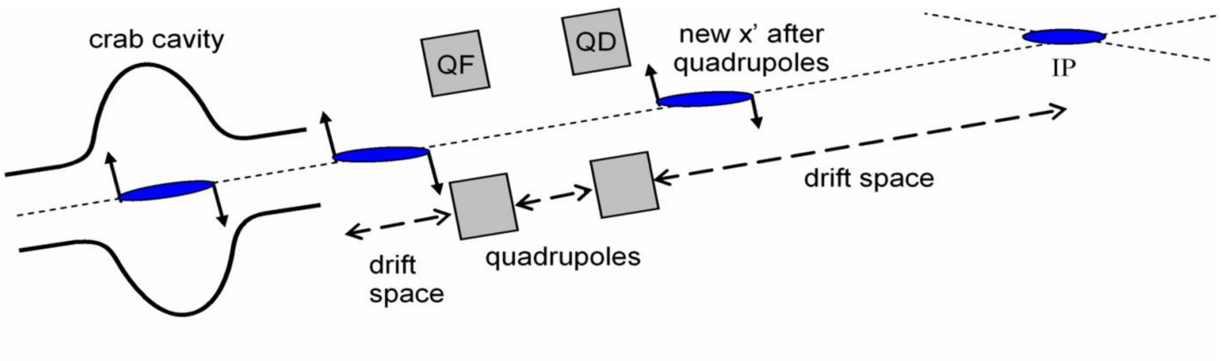
J. Jaeckel & A. Ringwald Phys. Lett. B 659 (2008) 509 - 514

Existing Equipment: International Linear Collider Crab Cavities

- Conduct HSP search using already existing infrastructure developed for ILC

- ILC reference design is TeV-scale e+e- collider based on 1.3 GHz SCRF accelerating structures

- Third harmonic (3.9 GHz) crab cavities located near interaction point to twist bunches – maximise overlap (and therefore luminosity).



- Technically demanding specifications - phase locked wrt each other to 0.125 degrees rms (= 90 fs @ 3.9 GHz)

- Daresbury in collaboration with Lancaster, Fermilab, SLAC has built and validated such a system

Shielding and Leakage Monitoring

- How do we distinguish between a signal and a leak when we want to measure signal levels of 10^{-24} W?

- For intended sensitivity we required shielding between emitter and receiver of ~ -300dB (factor of 10^{-30})

- Method proposed by F. Caspers, J. Jaeckel & A. Ringwald (**JINST 4:P11013,2009**., http://dx.doi.org/10.1088/1748-0221/4/11/P11013)

- Signal generator produces $f_0 = \omega_0 / 2\pi$

- Modulated by frequency locked synthesisers which return $f_0,\ f_0 + \Delta f_i,\ i = 1,2,3$

- f_0 fed to emitter, amplified and run through bandpass filter (BP), resonance checked by monitoring reflected wave

- Signal taken from receiver, amplified and run through BP, then to minimise number of cables use electro-optical converter (EOC), transmit to outside with fibre, then reconvert with OEC

- Receiver amp powered by similar EOC-OEC set

Shielding and Leakage Monitoring

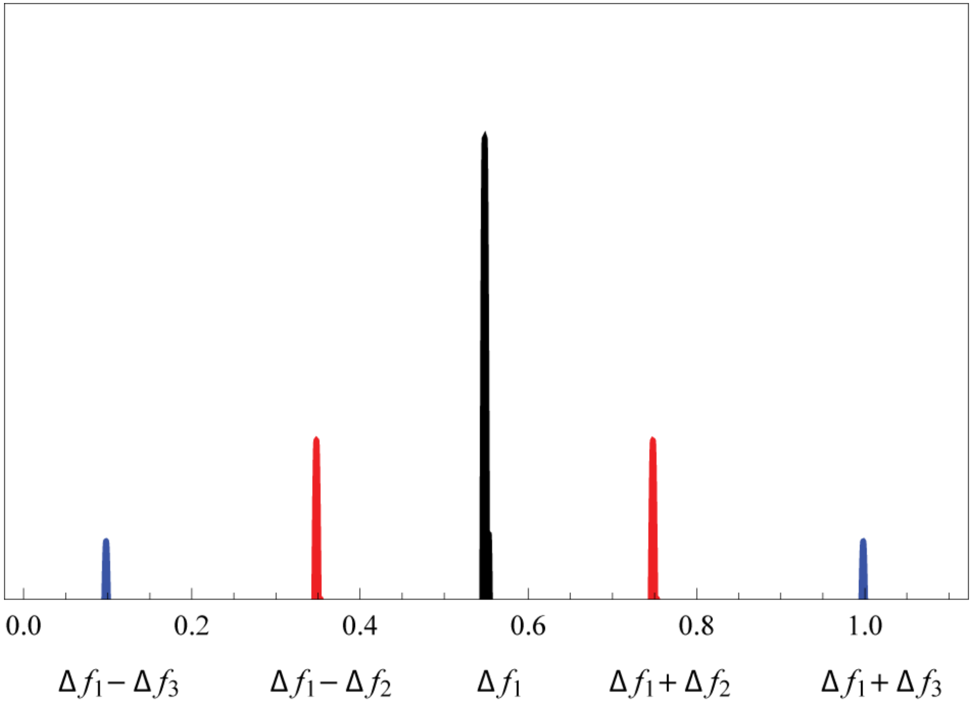
- Take $f_0 + \Delta f_1$ and combine with signal, then run through LP and record from ADC, FFT analyse this – a signal will appear at Δf_1

- Choose $f_0 + \Delta f_{2,3}$ to lie within bandwidth of the resonant cavities

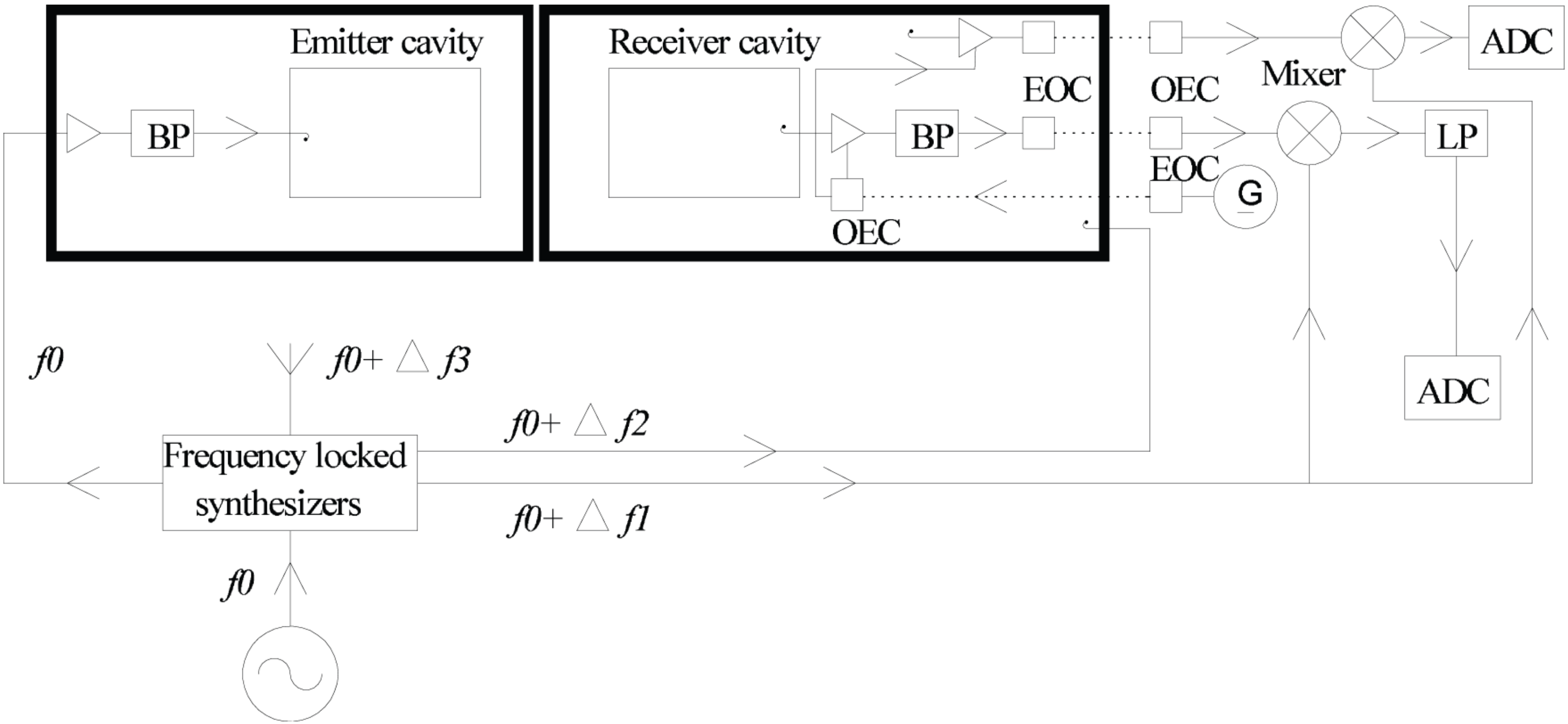
- Broadcast $f_0 + \Delta f_3$ from an antenna, look for $f_1 \pm \Delta f_3$ in signal spectrum, compare this “leaked” signal to antenna power to determine amount of shielding

- Optionally, put $f_0 + \Delta f_2$ into outer box to monitor shielding due to inner box, look for $f_1 \pm \Delta f_2$ in signal

- Optionally, put an antenna in outer box to monitor shielding due to outer box, look for Δf_1 and $f_1 \pm \Delta f_3$



Shielding and Leakage Monitoring



by F. Caspers, J. Jaeckel & A. Ringwald (**JINST 4:P11013,2009**., http://dx.doi.org/10.1088/1748-0221/4/11/P11013)

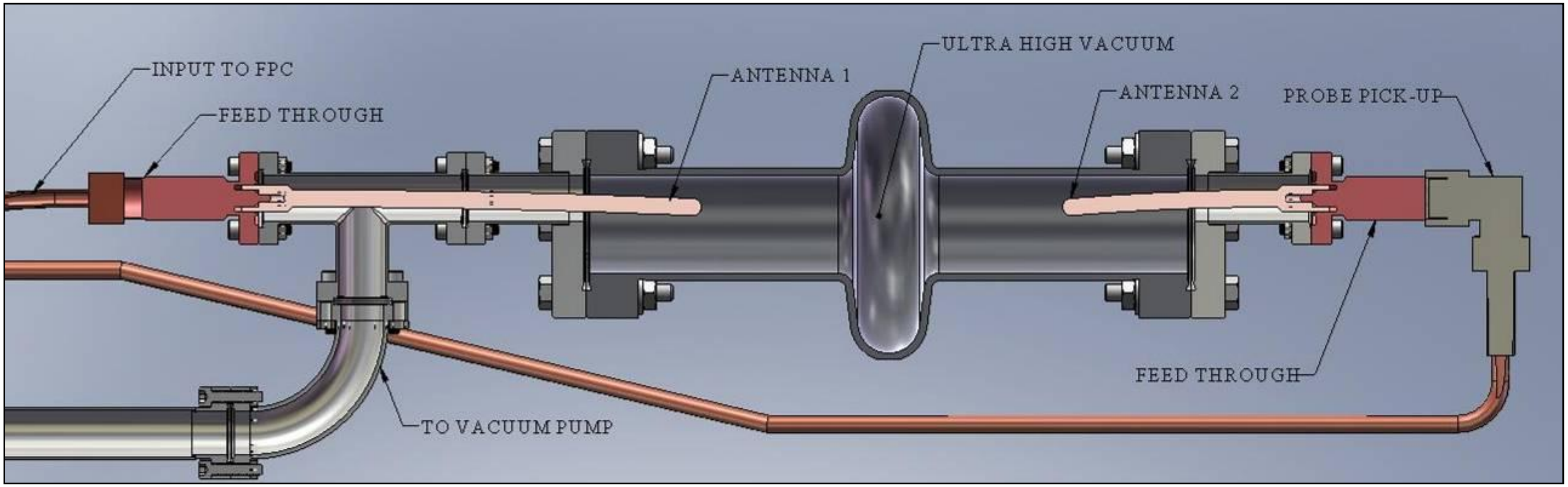
Crab Cavities 1 and 3 Measured Performance at 4K

Cavity S/N 001

Q_L = 0.97e7
Q_e (input) = 1.44e7
Q_e (output) = 3.0e9
Q_o = 3.0e7
Peak Voltage = 98 kV (limited by shielding)
Bandwidth = 400 Hz
Drift ~ 300 Hz over 10's minutes

Cavity S/N 003

Q_L = 1.52e7
Q_e (input) = 2.57e7
Q_e (output) = 9.6e9
Q_o = 3.7e7
Peak Voltage = 114 kV (limited by shielding
Bandwidth = 256 Hz
Drift = 5 kHz to 20 kHz (redesign of tuner required)



Vertical Test Facility

• Previously existing system at Daresbury

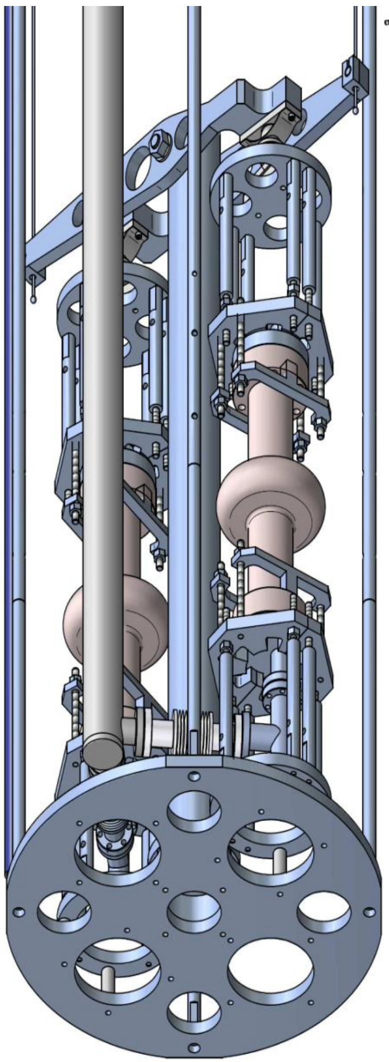
• Initial aim was to verify 3.9 GHz ILC crab cavity RF control and synchronisation

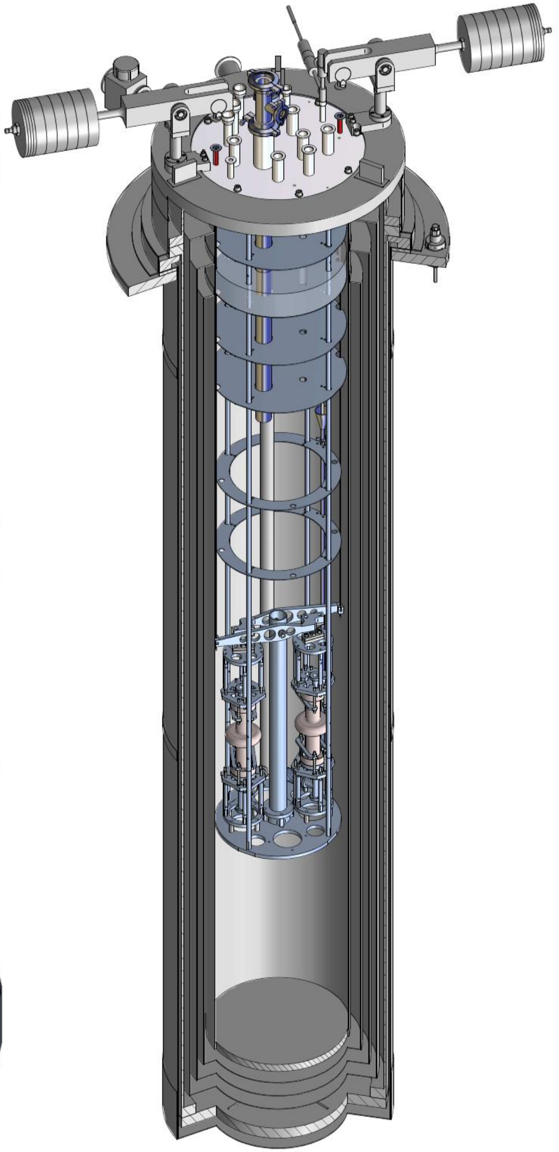
• Designed to match phases of 2 cavities at 2K

• In-situ ultra-high vacuum pumping to cavities ($<10^{-8}$ mbar)

• Double wall insulating dewer vacuum & radiation baffle. Mumetal outer shielding

• With modification to tuner mechanism, suitable for emitter cavity





Vertical Test Facility – Expansion of Infrastructure

• LHe recirculation for emitter cryostat: extended running at 2K now possible

• Fully shielded environment – buried in pit. Tunnel access in basement to space for second cryostat. Cavity may be powered to electrical breakdown – field strength limit to be determined by conditioning

• In phase control experiment, at 4K with both cavities powered the power dissipated to LHe was ~ 5W, equal to static losses for cryostat without cavities

• If care is taken with the cables, the helium is stable enough and some active but quiet tuners are operating on both cavities, then it should be possible to lock the cavity frequency over many minutes, then switch in a reference signal, correct, then measure again. (c.f. Dicke switching in radio astronomy)

Vertical Test Facility – Expansion of Infrastructure

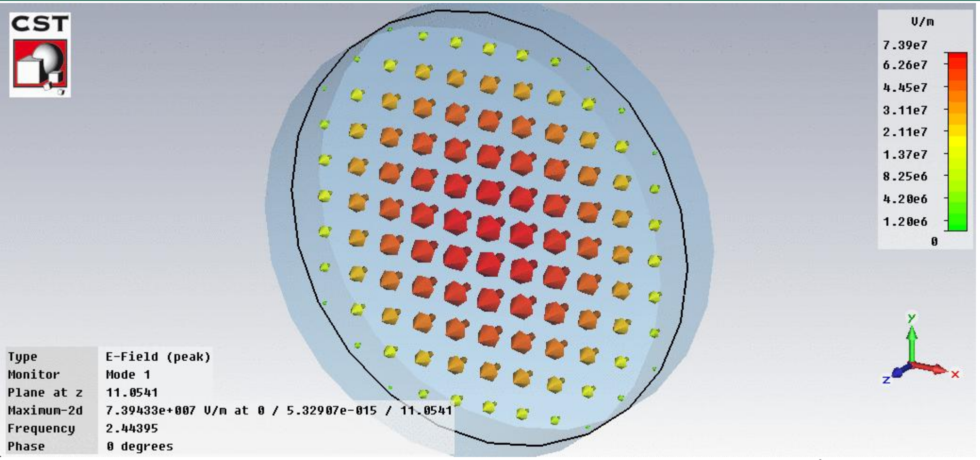
• LHe recirculation for emitter cryostat: extended running at 2K now possible

• Fully shielded environment – buried in pit. Tunnel access in basement to space for second cryostat. Cavity may be powered to electrical breakdown – field strength limit to be determined by conditioning

• In phase control experiment, at 4K with both cavities powered the power dissipated to LHe was ~ 5W, equal to static losses for cryostat without cavities

• If care is taken with the cables, the helium is stable enough and some active but quiet tuners are operating on both cavities, then it should be possible to lock the cavity frequency over many minutes, then switch in a reference signal, correct, then measure again. (c.f. Dicke switching in radio astronomy)

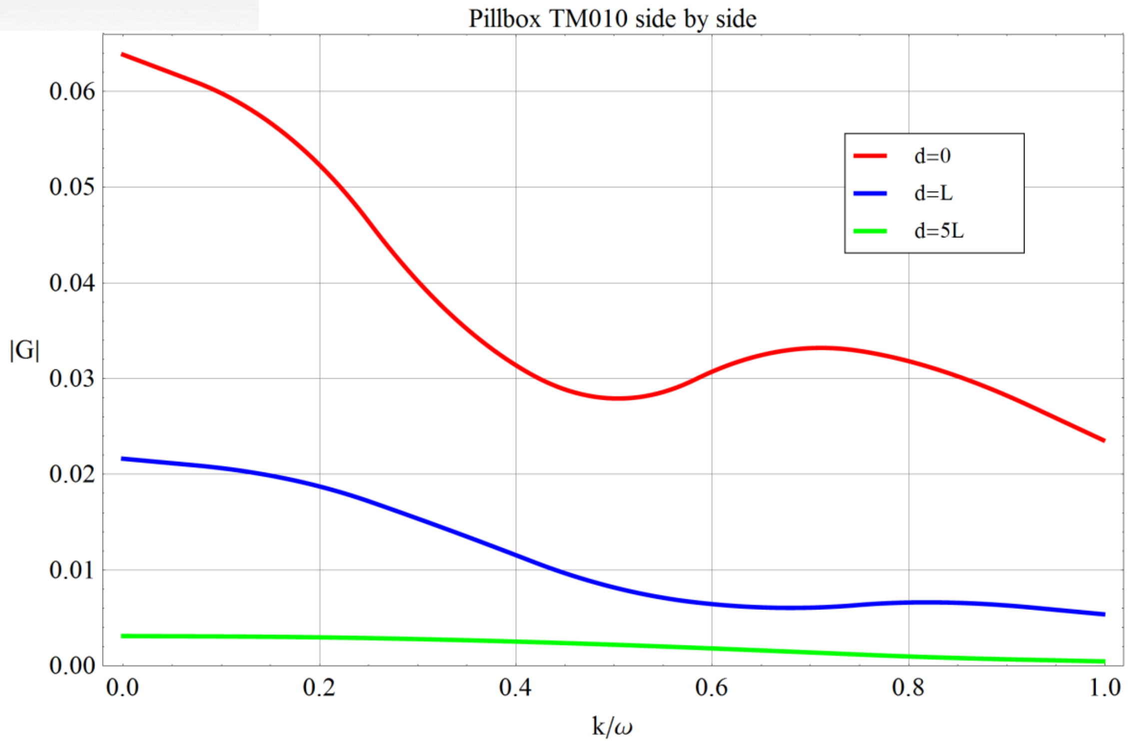
Geometric Form Factor – Pillbox in Fundamental Mode



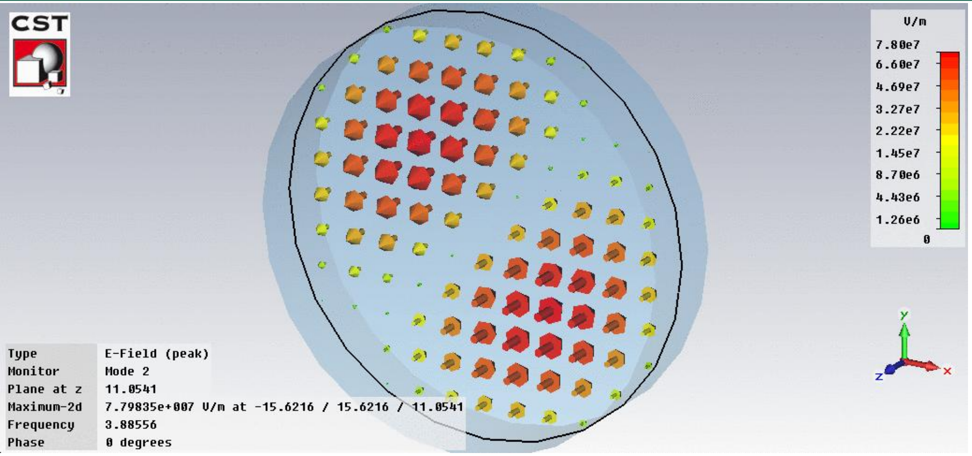
$$G(k/\omega_0) \equiv \omega_0^2 \int_{V'} \int_{V} d^3\mathbf{x}\, d^3\mathbf{y} \frac{\exp(ik|\mathbf{x}-\mathbf{y}|)}{4\pi|\mathbf{x}-\mathbf{y}|} A_{\omega_0}(\mathbf{y}) A'_{\omega_0}(\mathbf{x}).$$

- 2.4 GHz
- CST Q = 1.2 x 10^8 (scaled from measured)

- Plotted is |G| for two **pillbox** cavities, side L, side-by-side in fundamental mode (TM010)
- k/ω = 0 corresponds to paraphoton mass ~ cavity frequency
- d is cavity separation



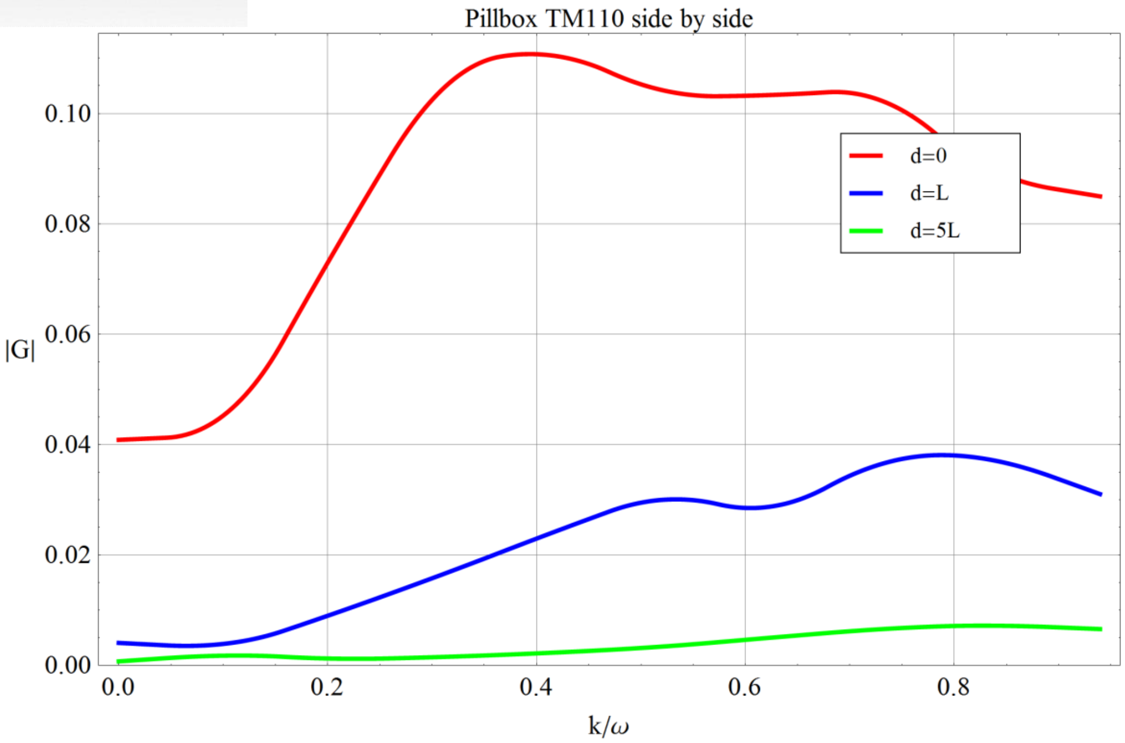
Geometric Form Factor – Pillbox in First Dipole Mode



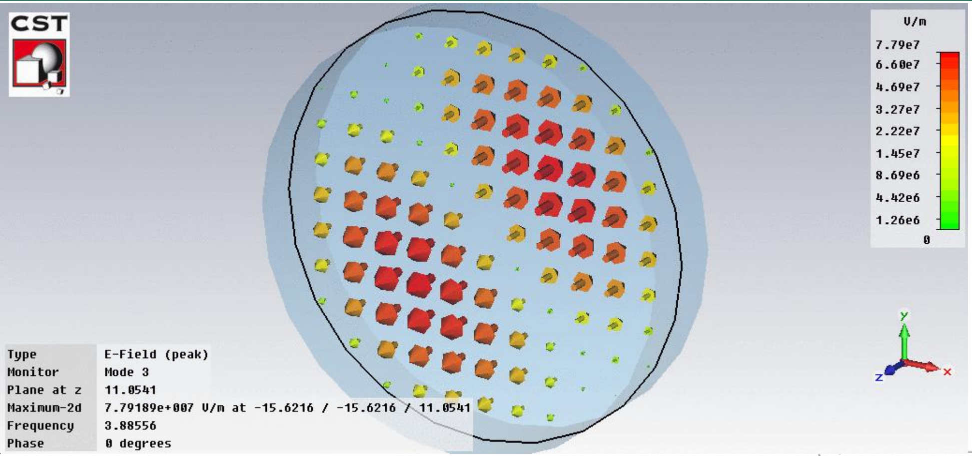
$$G(k/\omega_0) \equiv \omega_0^2 \int_{V'} \int_{V} d^3\mathbf{x}\, d^3\mathbf{y} \frac{\exp(ik|\mathbf{x}-\mathbf{y}|)}{4\pi|\mathbf{x}-\mathbf{y}|} A_{\omega_0}(\mathbf{y}) A'_{\omega_0}(\mathbf{x}).$$

- This is what we have now with the ILC crabs
- 3.9 GHz
- Measured Q = 1.6×10^8
  (4K measure – scaled to 2K)

- Plotted is |G| for two **pillbox** cavities, side L, side-by-side (not on top!) in **first dipole** mode (TM110)



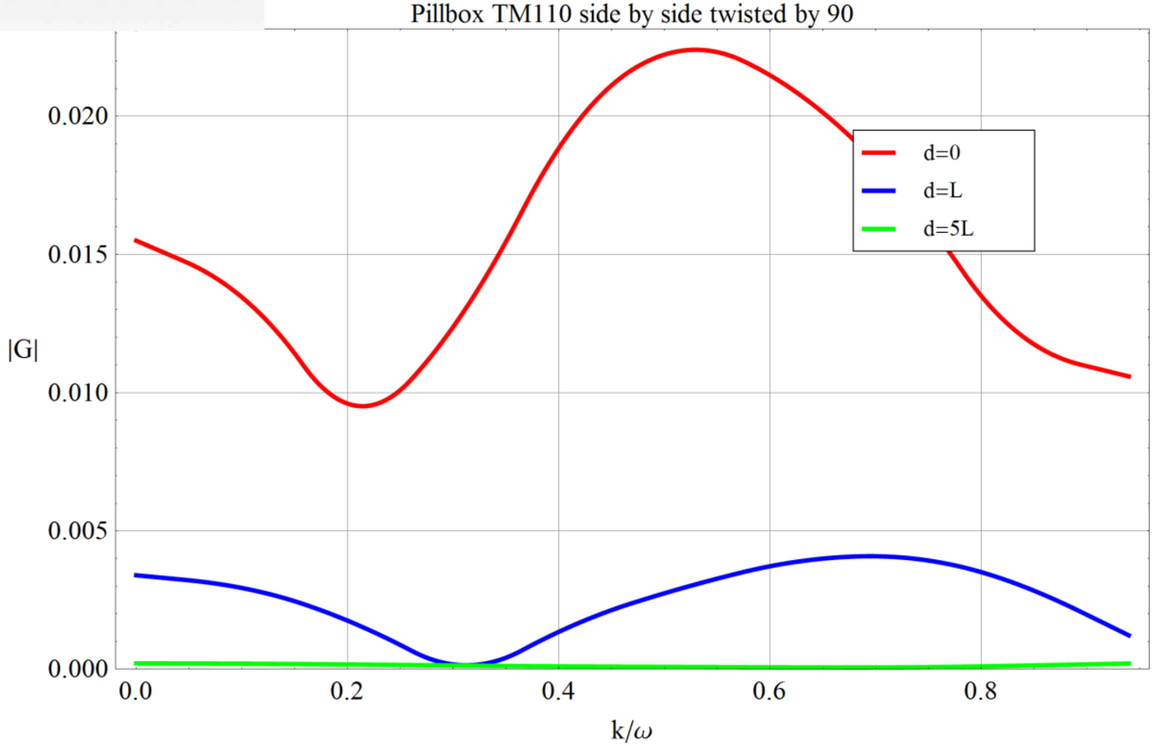
Geometric Form Factor – Pillbox in First Dipole Mode (Twisted)



$$G(k/\omega_0) \equiv \omega_0^2 \int_{V'} \int_{V} d^3\mathbf{x}\, d^3\mathbf{y} \frac{\exp(ik|\mathbf{x}-\mathbf{y}|)}{4\pi|\mathbf{x}-\mathbf{y}|} A_{\omega_0}(\mathbf{y}) A'_{\omega_0}(\mathbf{x}).$$

- BEWARE !!! – We lose an order of magnitude from the geometry

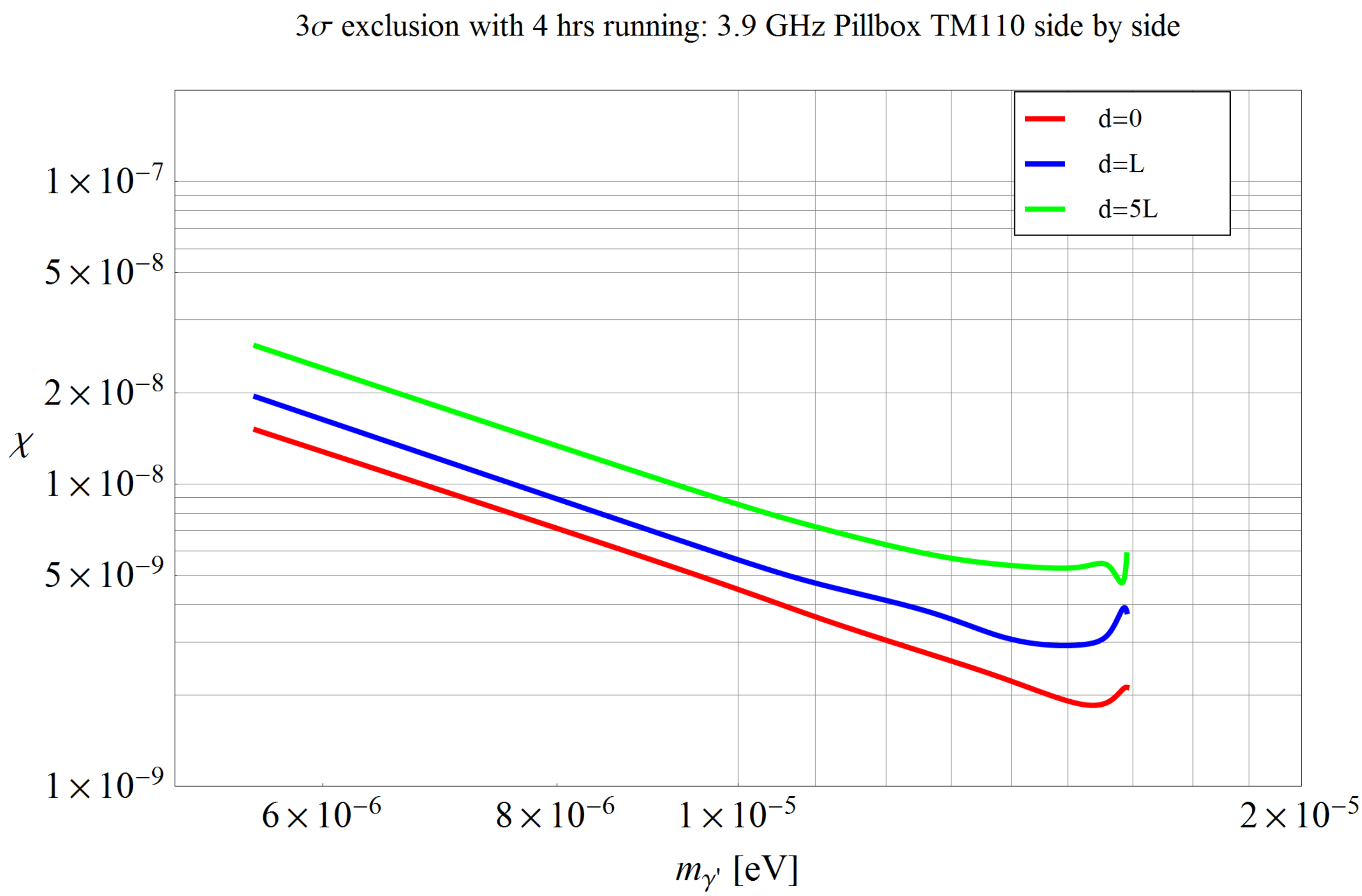
- Plotted is |G| for two **pillbox** cavities, side L, side-by-side (not on top!) in first dipole mode **twisted by 90 degrees azimuthally**



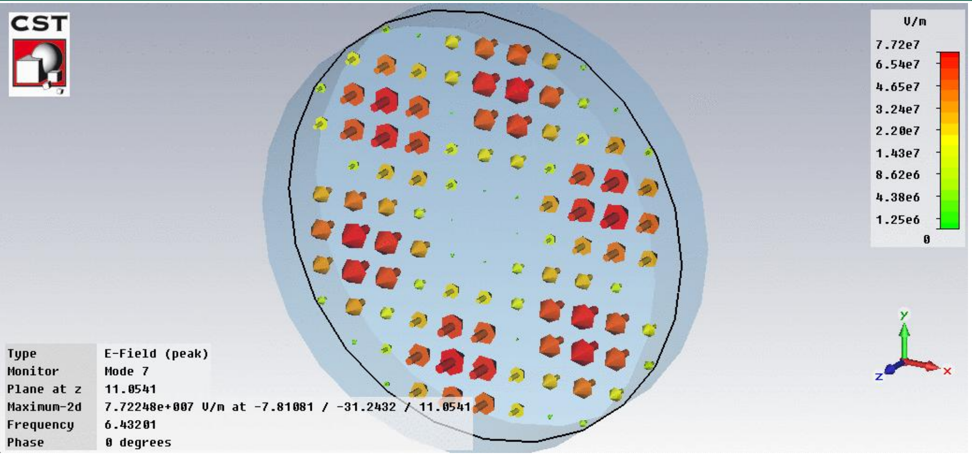
Proposed operating parameters - conservative

1. Operate in TM110 mode
2. Need to dent driven cavity to orientate azimuthally
3. Driven cavity Q = 1.6 x 10^8 - 2K scaled from Q measured at 4K
4. Receiver cavity Q' = 1.0 x 10^6
5. Thermal noise with T_{LNA} = 2K
6. Power gain of amplifier = 17 dB
7. Noise bandwidth = 1kHz
8. Power stored in driven cavity = 0.1 W – existing SSA, possible to go higher (klystron, even possibility of IOT)
9. 4 hours data taking at 2K

Hidden Sector Photon Search with 3.9 GHz TM110



Geometric Form Factor – Pillbox in TM310 Mode

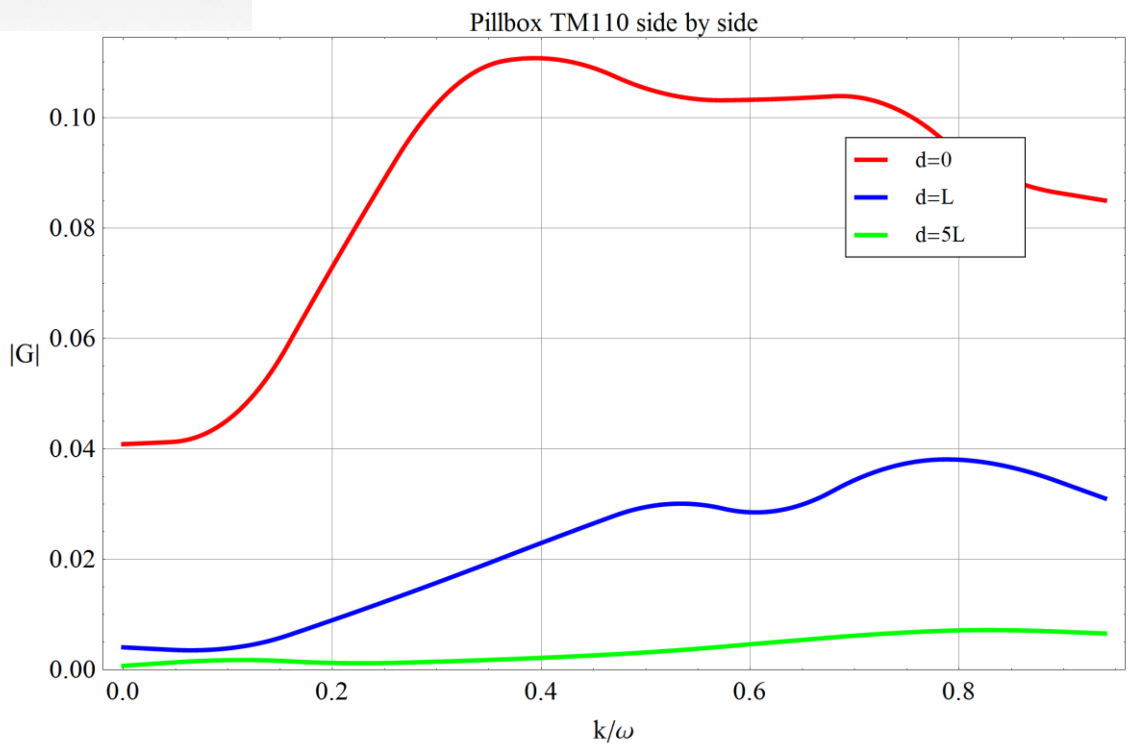


$$G(k/\omega_0) \equiv \omega_0^2 \int_{V'} \int_{V} d^3\mathbf{x}\, d^3\mathbf{y} \frac{\exp(ik|\mathbf{x}-\mathbf{y}|)}{4\pi|\mathbf{x}-\mathbf{y}|} A_{\omega_0}(\mathbf{y}) A'_{\omega_0}(\mathbf{x}).$$

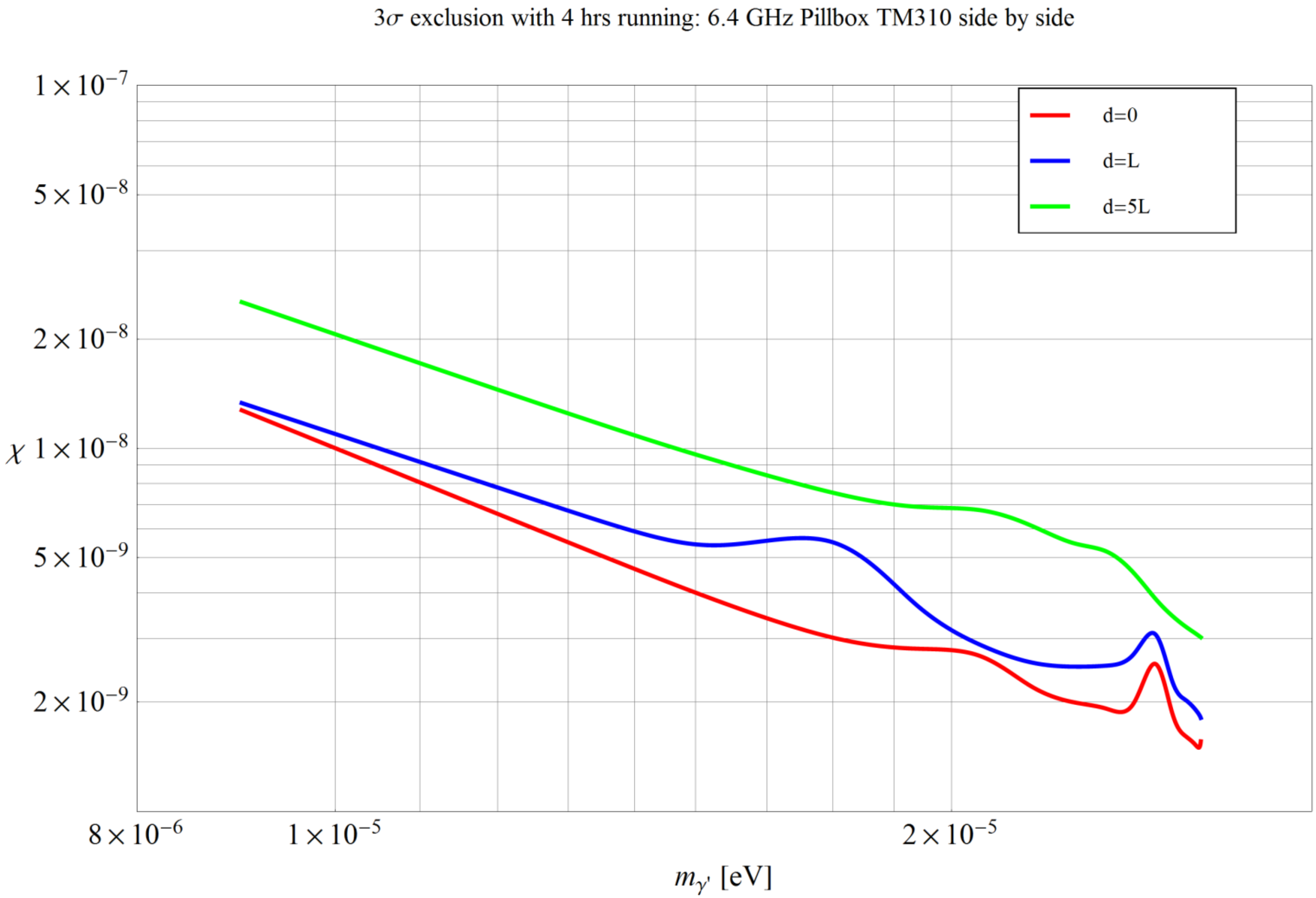
- 6.4 GHz
- CST Q = 2.1 x 10^8
  (scaled from measured)

- Possibility to extend the search – use higher order modes

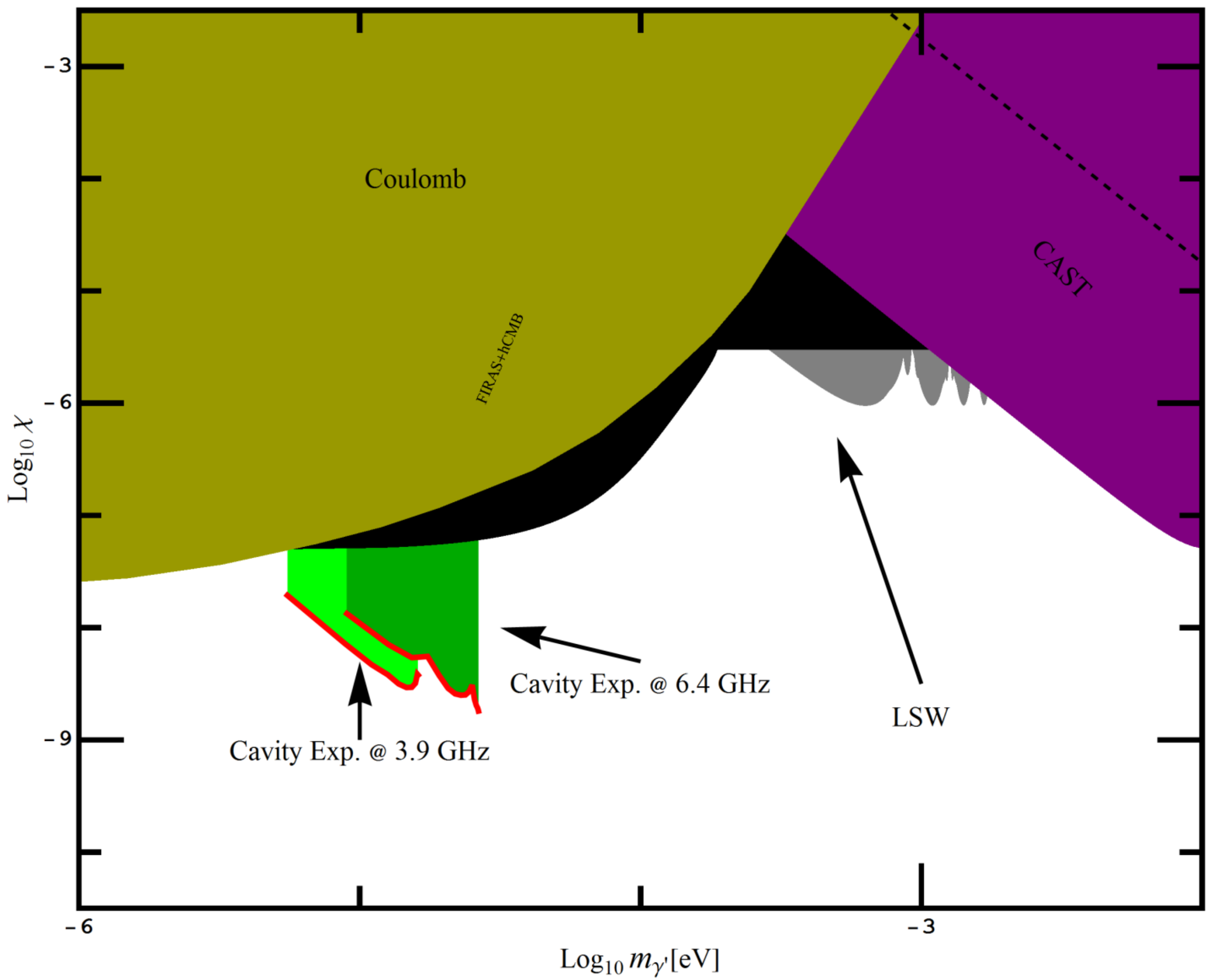
- Plotted is |G| for two **pillbox** cavities, side L, side-by-side (not on top!) in **third dipole** mode (TM310)



Hidden Sector Photon Search with 6.4 GHz TM310



Expected Daresbury HSP Search Limits



Next Steps

- Equipment existing: Emitter cryostat in shielded environment with LHe recirculation, network analysers, frequency synthesiser, low noise amplifier, 3.9 GHz SSA, high-Q SC cavities
- Equipment required: Detector cryostat, tuner mechanism with switching for detector cavity, EO set
- Further developments we may wish to explore: Manufacture of higher Q cavities, cooling detector cryostat down to millikelvins to improve S/N, SQUID

Thanks to…

Graeme Burt, Amos Dexter – U. Lancaster RF Engineering & Cockcroft Inst.
Phillipe Goudket, Steve Jamison, Andy Moss – ASTeC, STFC Daresbury Lab. & Cockcroft Inst.

And to John Dainton (Liverpool) & Joerg Jaeckel (IPPP, Durham) for encouragement

The Cockcroft Institute of Accelerator Science and Technology

Science & Technology Facilities Council Daresbury Laboratory

LANCASTER UNIVERSITY