Resonance HOM excitation in LCLS-II

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Motivation

- SRF cavities are very good resonance systems with multiple eigenmodes (HOMs) with very low losses (high Q-factors)
- Beam of charged particles interacts with HOMs in SRF cavities
  - Single bunch interaction
    - incoherent losses and wake fields
  - CW beam may have beam harmonics close to HOM frequencies
    - resonance excitation of HOMs
    - at exact resonance beam power loss may be high
      - for monopole modes:

$$P_{loss} = I_n^2 (R/Q)_m Q_L$$

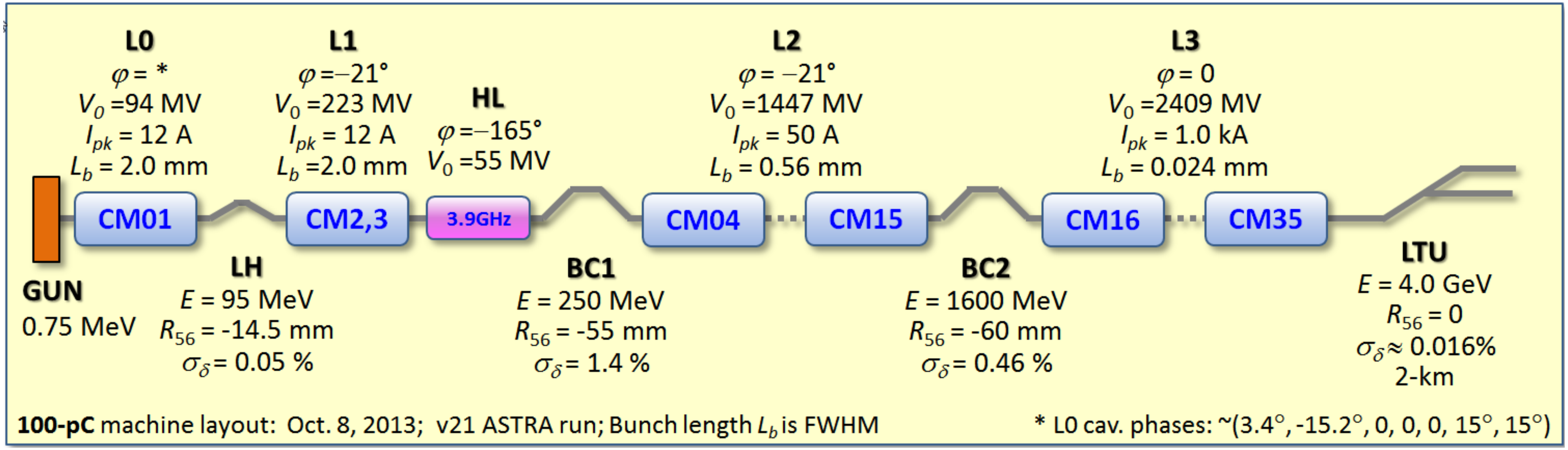
  - For a single cavity analysis of non-propagating modes is sufficient
  - For SRF CW linac of multiple cavities conditions may be realized when propagating modes become trapped

Analysis of resonance excitation of HOMs is important for design of CW SRF linacs

Introduction and outline

- Developed method for analysis of resonance HOM excitation in CW SRF proton (H^-) linac of PIP-II (Project X)
  - presented by V. Yakovlev at HOMSC12 in Daresbury
- Applied for HOM analysis in LCLS-II
  - monopole HOM excitation (this presentation)
    - heat load to cryomodule systems
  - dipole HOM excitation (A. Vostrikov poster presentation)
    - effects on beam dynamics, BBU, transition effects
- Outline:
  - Model
  - Properties of monopole modes in 1.3 GHz and 3.9 GHz 9-cell cavities
  - Results
  - Conclusion

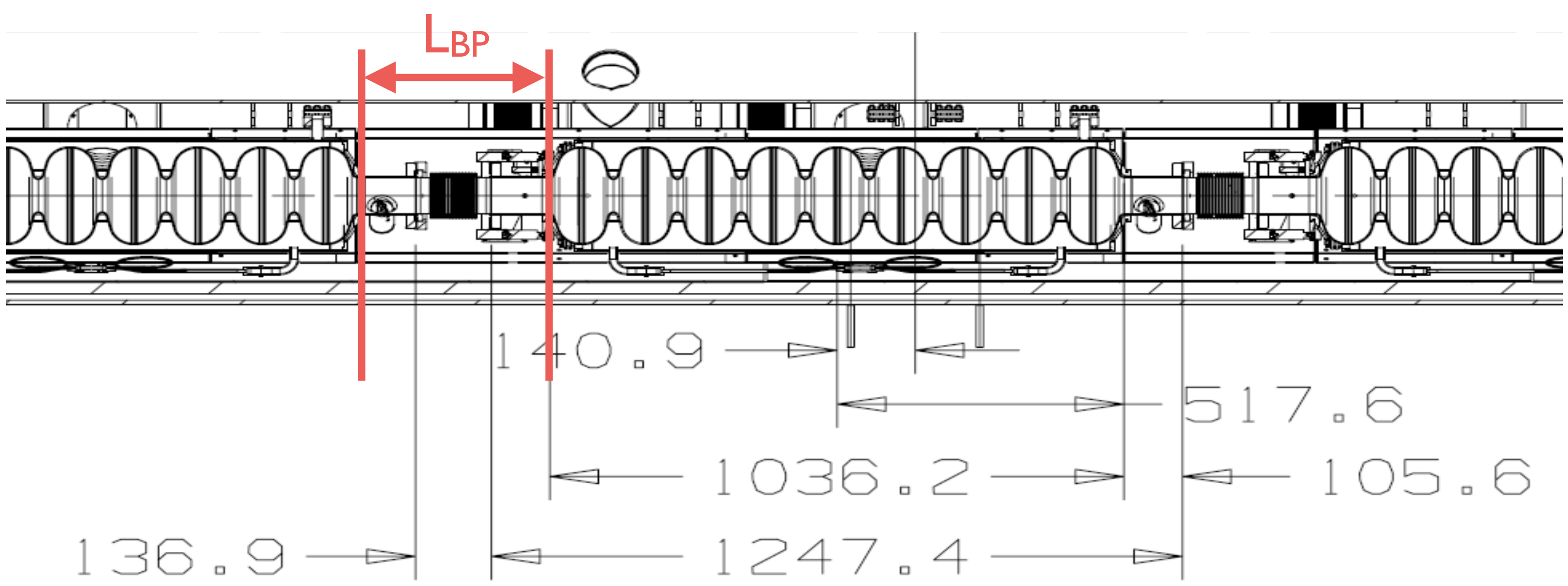
Introduction



- CW SRF electron linac
  - 35 TESLA-style cryomodules (each CM contain 8 1.3 GHz 9-cell TESLA-type cavities, 280 cavities in linac)
  - 1-2 CM of 3.9 GHz 9-cell cavities
  - bunch size from 2 mm to 25 um along the linac
    - THz range in beam spectrum, flat beam spectrum up to few hundred GHz
  - bunch charge 0.1-0.3 nC, bunch rep. rate up to 1 MHz, average beam current up to 0.3 mA

Model of resonance HOM excitation in LCLS-II

- TESLA 9-cell structure 1.3 GHz cavity and 9-cell 3.9 GHz cavity
- Use RF simulation code (SuperLANS) to calculate cavity spectrum, (R/Q), EM fields etc
  - 400 monopole modes (up to 11 GHz) in 1.3 GHz cavity
    - cut-off frequency of propagating modes: 2.94 GHz
  - 120 monopole modes (up to 16 GHz) in 3.9 GHz cavity
    - cut-off frequency of propagating modes: 5.74 GHz
  - Find worst trapping conditions (highest (R/Q)) for propagating monopole HOMs by varying distance between cavities L_{BP}, then use maximum value of (R/Q)
    - In real linac only very few (if any) of propagating modes may become trapped



Model of resonance HOM excitation in LCLS-II

- For each mode calculate losses in cavity walls (Q_0) and bellows (Q_b):
- Surface resistance of SC Nb (H. Padamsee, J. Knobloch, and T. Hays, RF Superconductivity for Accelerators):

$$R_s = R_{\text{res}} + R_{\text{BCS}}, \text{ where } R_{\text{res}} = 1\text{n}\Omega,$$

$$R_{\text{BCS}}[\Omega] = 2 \cdot 10^{-4} \frac{1}{T[\text{K}]} \left(\frac{f_n[\text{GHz}]}{1.5} \right)^2 \exp \left(-\frac{17.67}{T[\text{K}]} \right)$$

- Use simplified bellow geometry:
  - Cylinder with the radius of beam pipe and the length of the bellow
  - Small surface field variation at the length of single bellow convolution
  - Take into account increased surface of bellow by multiplying results by a factor 2-3 (depends on specifics of bellow geometry)
  - Normal skin effect in SS bellow, σ = 2 MSi, $R_s \sim \omega^{1/2}$
  - Anomalous skin effect in Cu bellow at 4.5 K in GHz range, $R_s=A\omega^{2/3}$, $A=3.3\text{x}10^{-10}$ Ohm $s^{2/3}$ (Reuter and Sondheimer, Proc. R. Soc. A195, 336 (1948), Podobedov, Phys. Rev. STAB, 12, 044401 (2009))

Model of resonance HOM excitation in LCLS-II

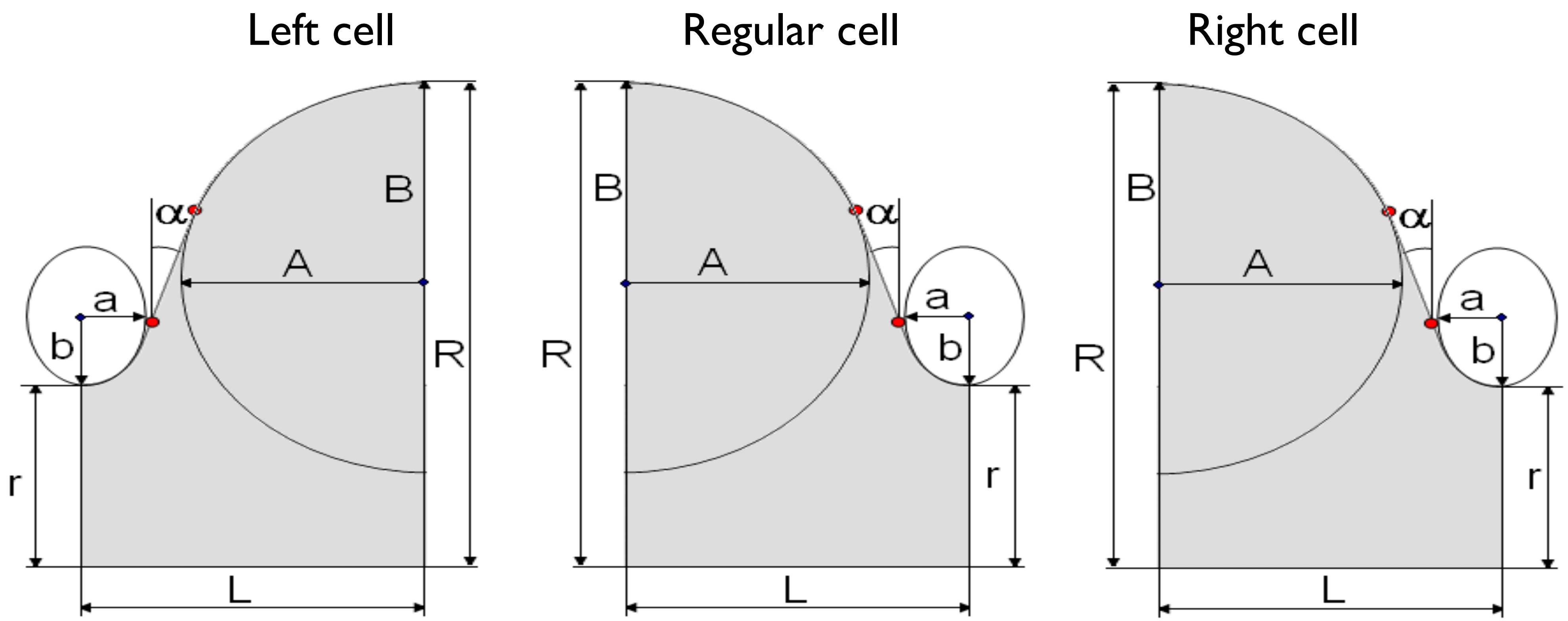
- Power removal through HOM couplers and power coupler (Q_h)
  - Measurements of Q_h for non-propagating modes at DESY (J. Sekutowicz) and Fermilab (T. Khabiboulline): $Q_h < 2\text{x}10^5$. May vary due to small variations in cavity geometry because of manufacturing tolerances. Trapped modes may have higher value of Q_h
  - Use the following values in our analysis: $Q_h = 2\text{x}10^5, 10^6, 10^7$.
- Total mode losses (loaded Q):

$$1/Q_L = 1/Q_0 + 1/Q_h + 1/Q_b$$

- Assume random variations of HOM frequencies from cavity to cavity along linac
  - $\sigma_f \approx 1$ MHz
    - Cornell model: $\sigma_f \approx 10.9 \times 10^{-4} \, (f_{HOM} - f_0)$
    - SNS model: $\sigma_f \approx (9.6 \times 10^{-4} - 13.4 \times 10^{-4}) \, (f_{HOM} - f_0)$
    - Data on HOM frequency spread in TESLA cavities at Fermilab (T. Khabiboulline)
- Idealized beam current spectrum
  - No time/charge jitter

Cavity geometry

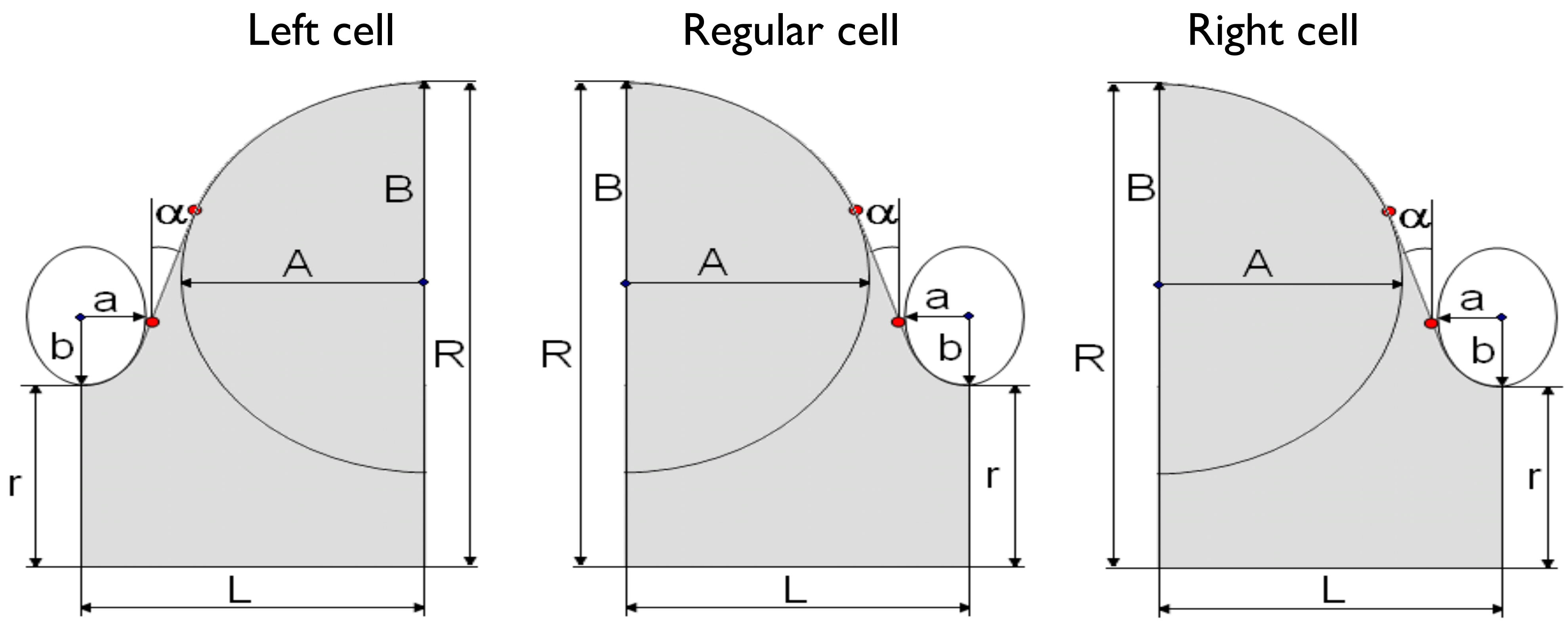
- TESLA 9-cell 1.3 GHz elliptical cavity



Dimension	Left cell	Regular cell	Right cell
r, mm	39	35	39
R, mm	103.3	103.3	103.3
L, mm	55.7	57.692	56.84
A, mm	40.34	42	42
B, mm	40.34	42	42
a, mm	10	12	9
b, mm	13.5	19	12.8
α	16.0	13.3	17.4

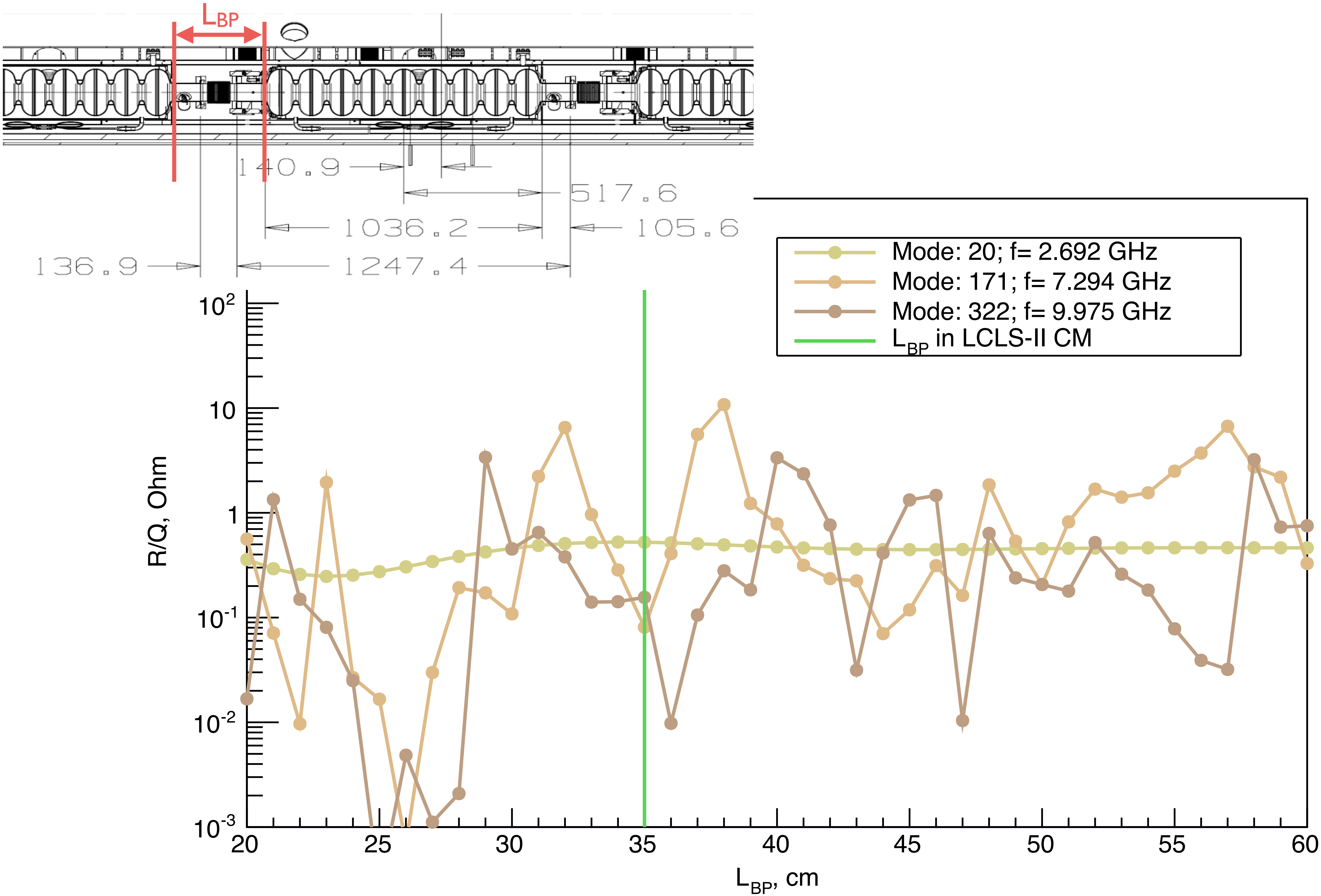
Cavity geometry

- 9-cell 3.9 GHz elliptical cavity

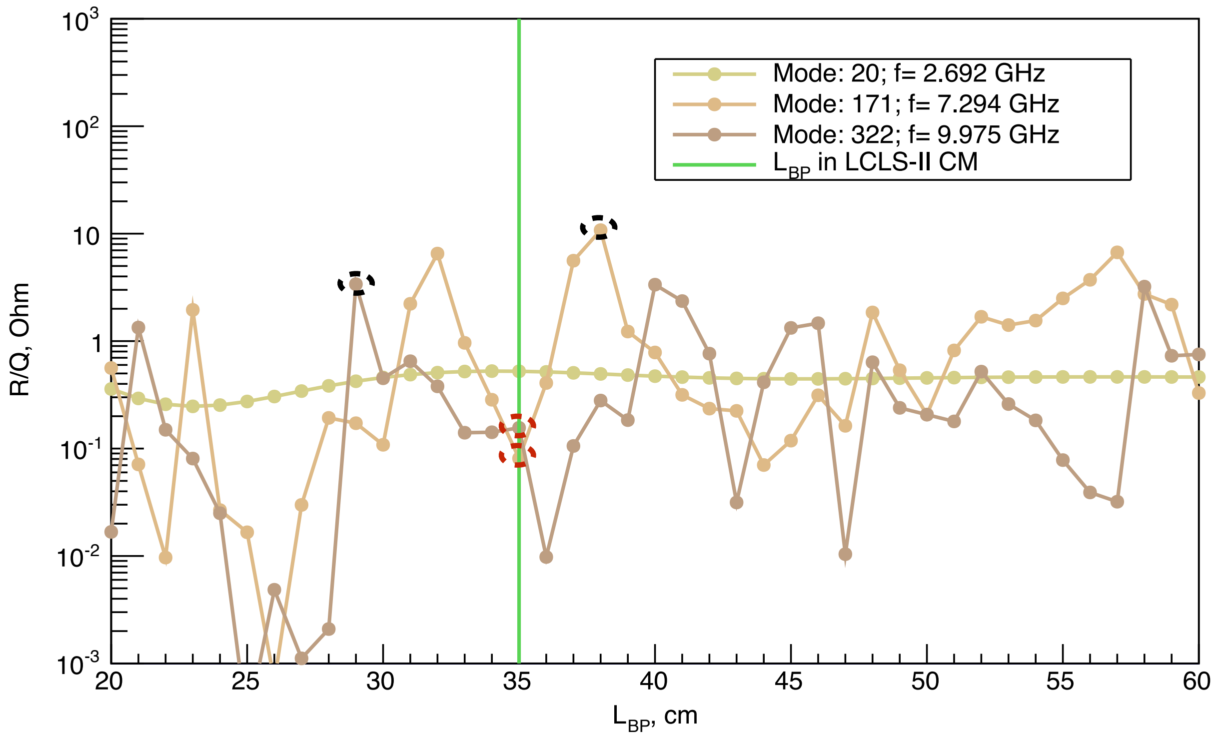


Dimension	Left cell	Regular cell	Right cell
r, mm	20	15	20
R, mm	35.79	35.79	35.79
L, mm	19.22	19.22	19.22
A, mm	14.4	13.6	14.4
B, mm	15.0	15.0	15.0
a, mm	4.5	4.5	4.5
b, mm	6.0	6.0	6
α	28.1	17.5	28.1

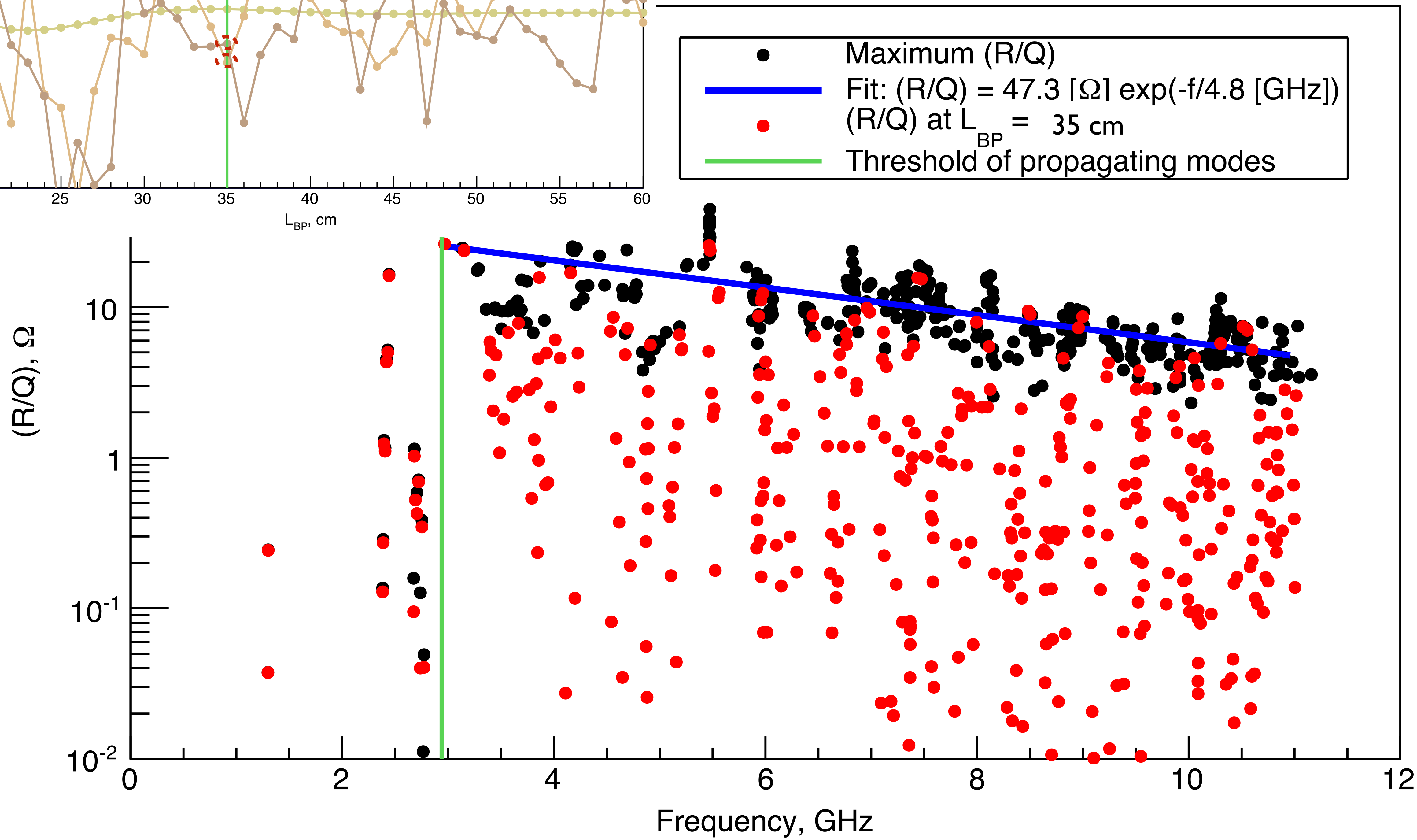
(R/Q) vs distance between cavities



Spectrum of monopole HOMs

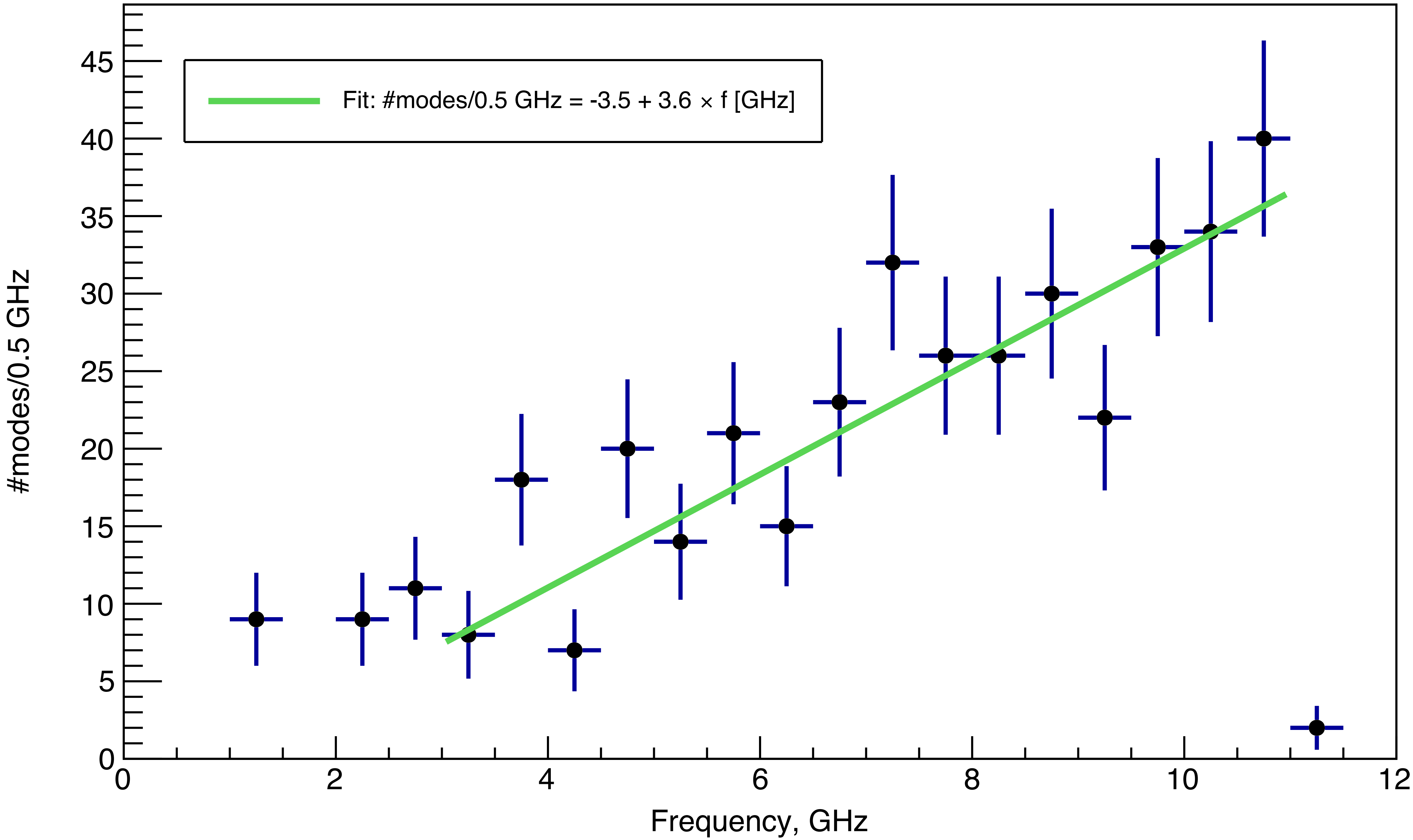


- (R/Q) approximated by exponential function (can be used to extrapolate to higher HOM frequencies)



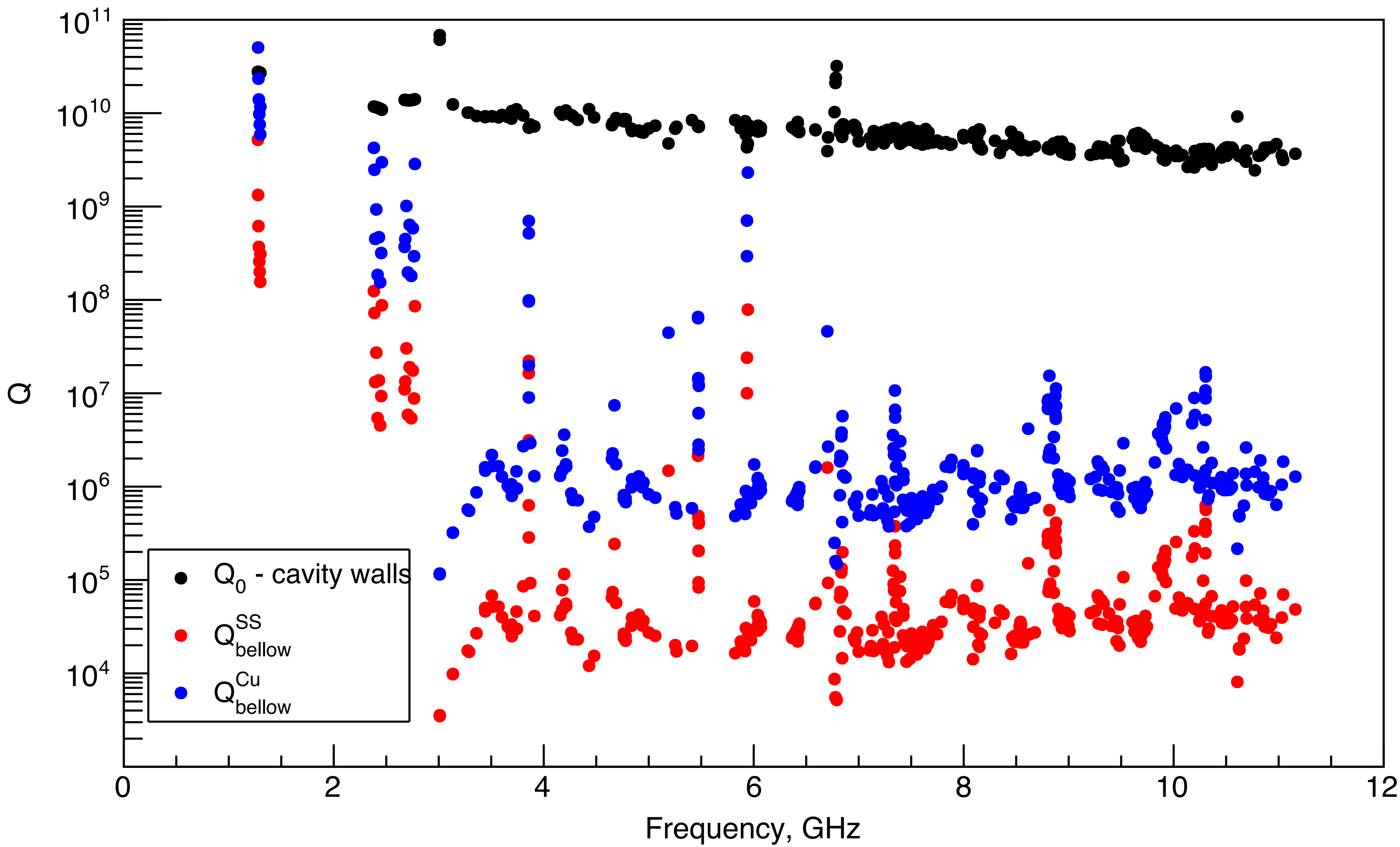
Density of monopole HOMs

- Approximated by linear function
  - Can be used to extrapolate to higher HOM frequencies



Losses in cavity walls and bellows

- $Q_0 \sim (5\text{-}10)\times10^9$, $Q_b \sim 10^6$ (Cu), $Q_b \sim 5\times10^4$ (SS).



Power loss calculation

- Magnetic field on the surface of cavity induced by the n^{th} component of the beam spectrum is equal to the sum of all exited modes:

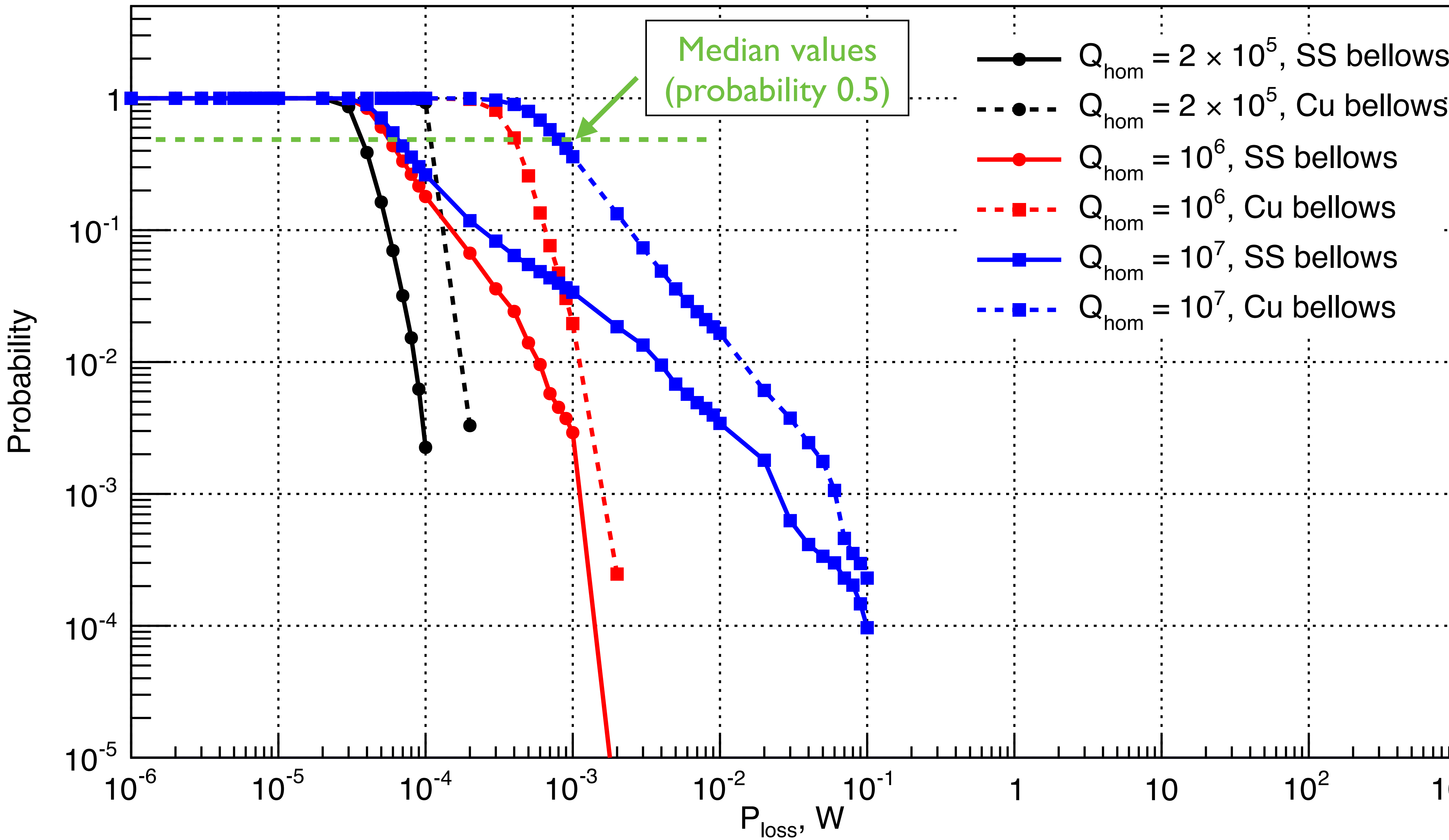
$$H_n = \sum_p H_{pn}(z), \text{ where } H_{pn} = \frac{-i\omega_p^2}{\omega_n^2 - \omega_p^2 - i\frac{\omega_n\omega_p}{Q_p}} \frac{I_n}{2} \sqrt{\frac{(R/Q)_p}{\omega_p W_p}} H_p^{sim}(z)$$

  - Here:
    - $H_p^{sim}(z)$ is the field calculated by RF simulation code for mode p
    - ω_p is the mode frequency
    - W_p is the mode stored energy normalized by LANS to 1 mJ
    - Q_p and $(R/Q)_p$ are the mode (loaded) quality factor and impedance
    - I_n and ω_n are the amplitude and frequency of beam harmonic
- Total power loss in the cavity walls is calculated as sum of losses by individual beam harmonics
  - in expression for $|H_n|^2$ cross-terms $H_{pn}H^*_{qn}$ have extremely small contribution and can be neglected
- Total power loss:

$$P_{(0,h,b)} = \sum_p \sum_n \frac{\omega_p^4}{(\omega_n^2 - \omega_p^2)^2 + \left(\frac{\omega_n\omega_p}{Q_p}\right)^2} \frac{I_n^2}{4} \left(\frac{R}{Q}\right) \frac{1}{Q_{(0,h,b)}}$$

Power loss in cavity walls

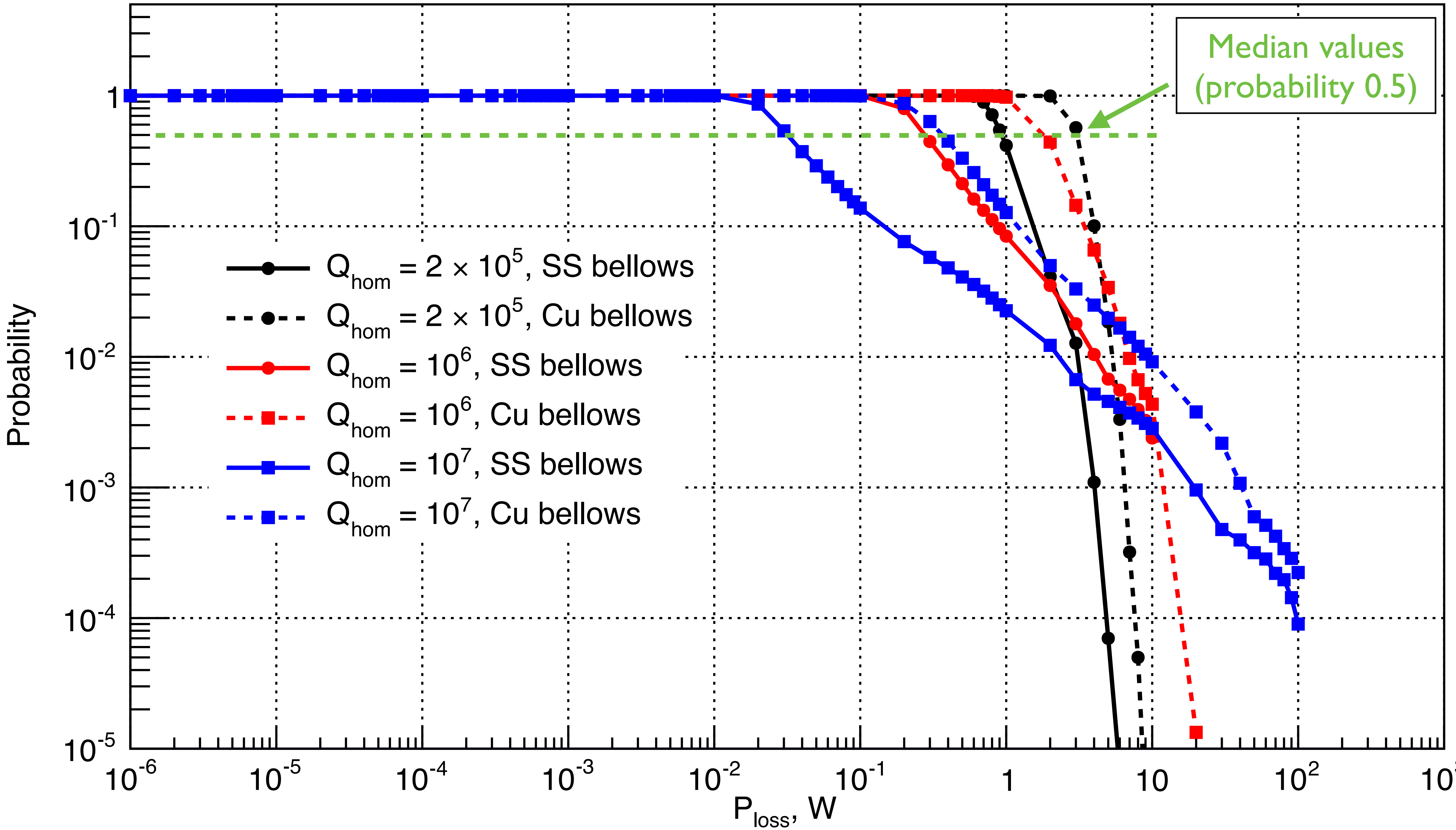
- Median (0.5 probability) values < 1 mW. Probability < $5x10^{-4}$ for losses > 100 mW



Heat load at 2K due to resonance HOM excitation is not a problem

Power removed by HOM couplers

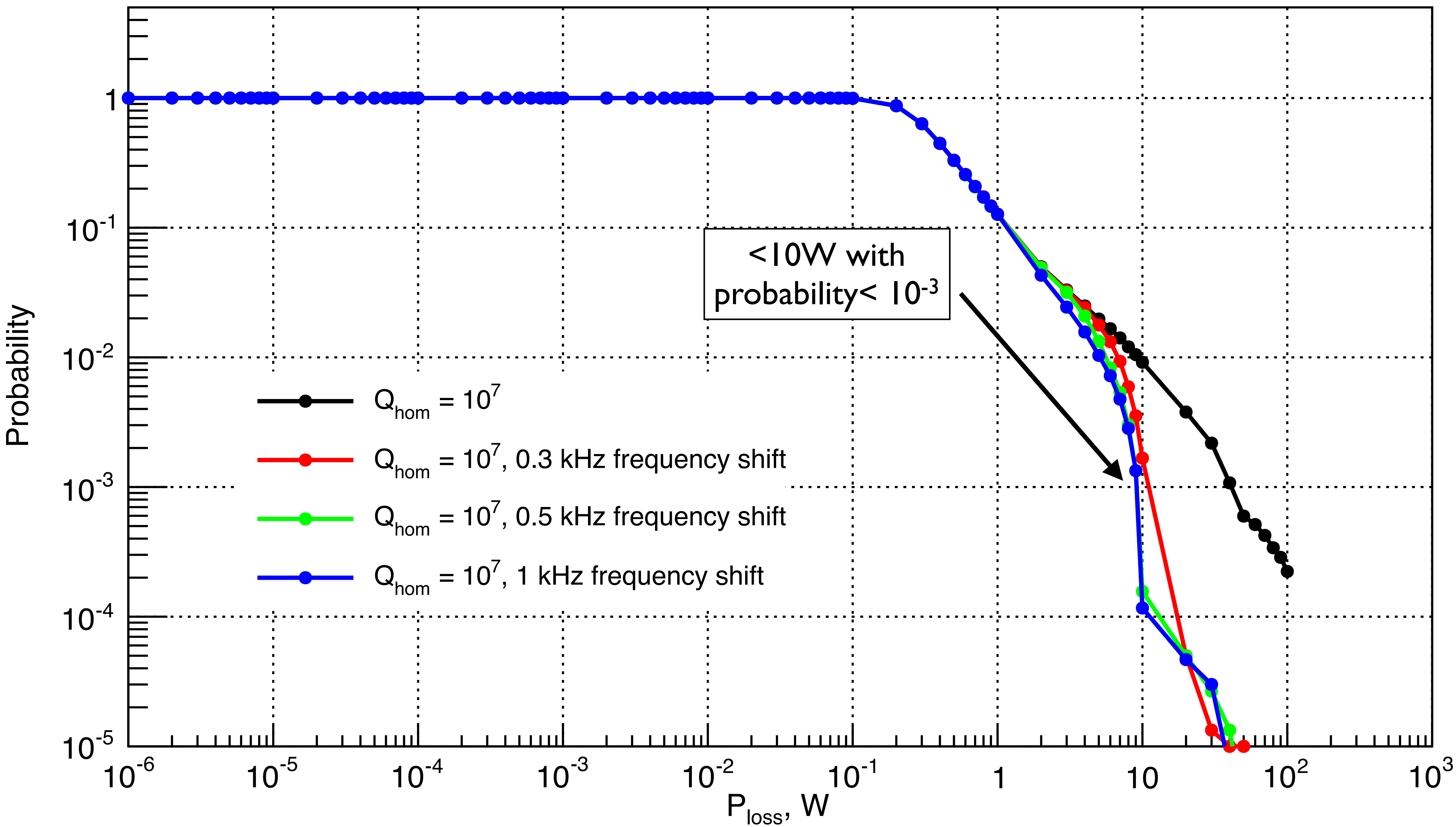
- Median P < 5 W; Prob. 10^{-3} (in 1/1000 cavities) to have P > 50 W



- Use HOM spectra manipulation (T. Khabiboulline): detune cavity and tune back

Power removed by HOM couplers: HOM spectra manipulation

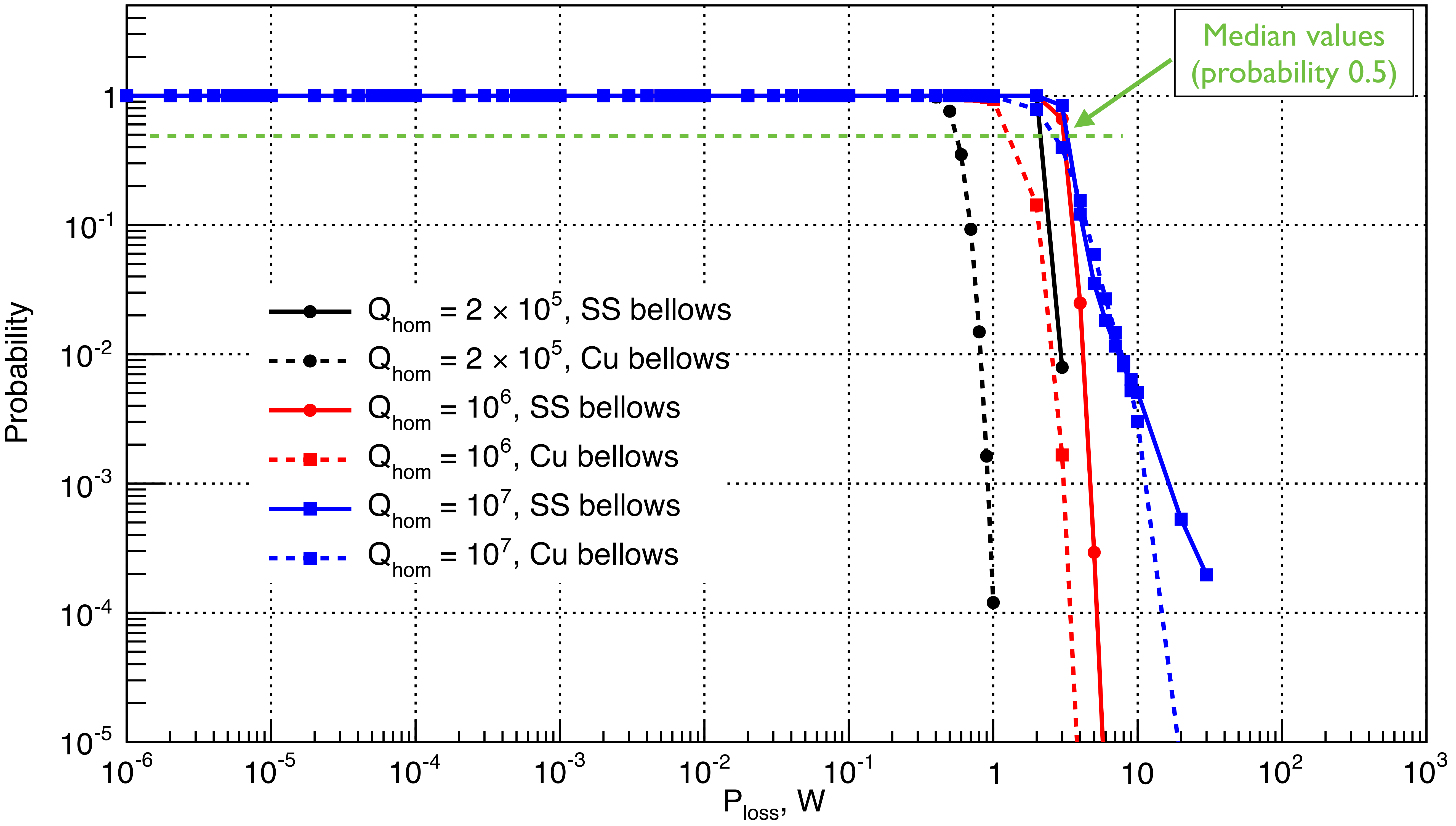
- Detune cavity and tune back: HOM frequencies shift by few 100 Hz



Median power < 5 W. HOM spectra manipulation: P < 10 W with prob. <10^{-3}

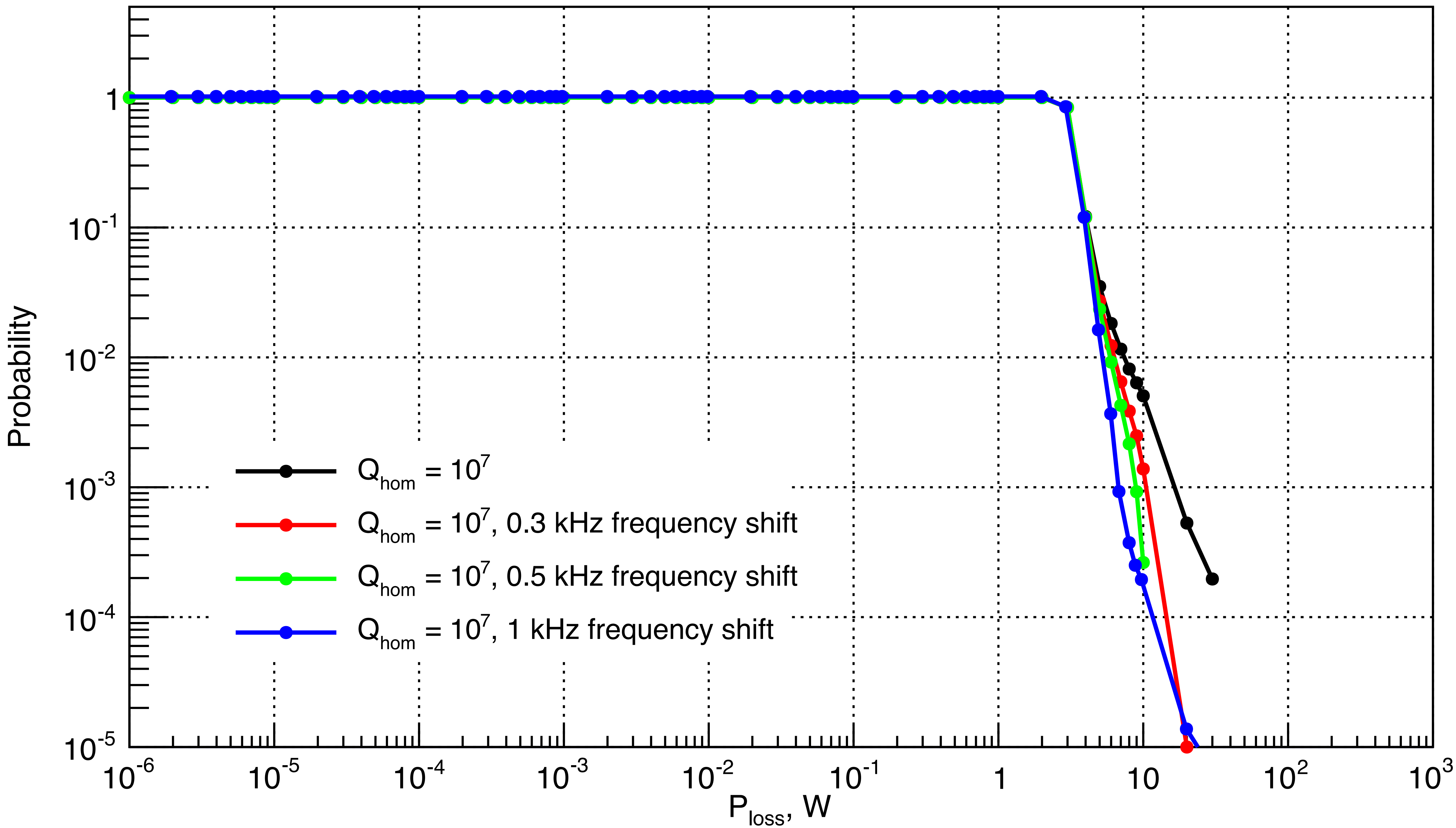
Power loss in bellows

- Median losses < 5 W ($Q_h=10^7$). Probability of higher losses can be reduced by HOM spectra manipulation



Power loss in bellows: HOM spectra manipulation

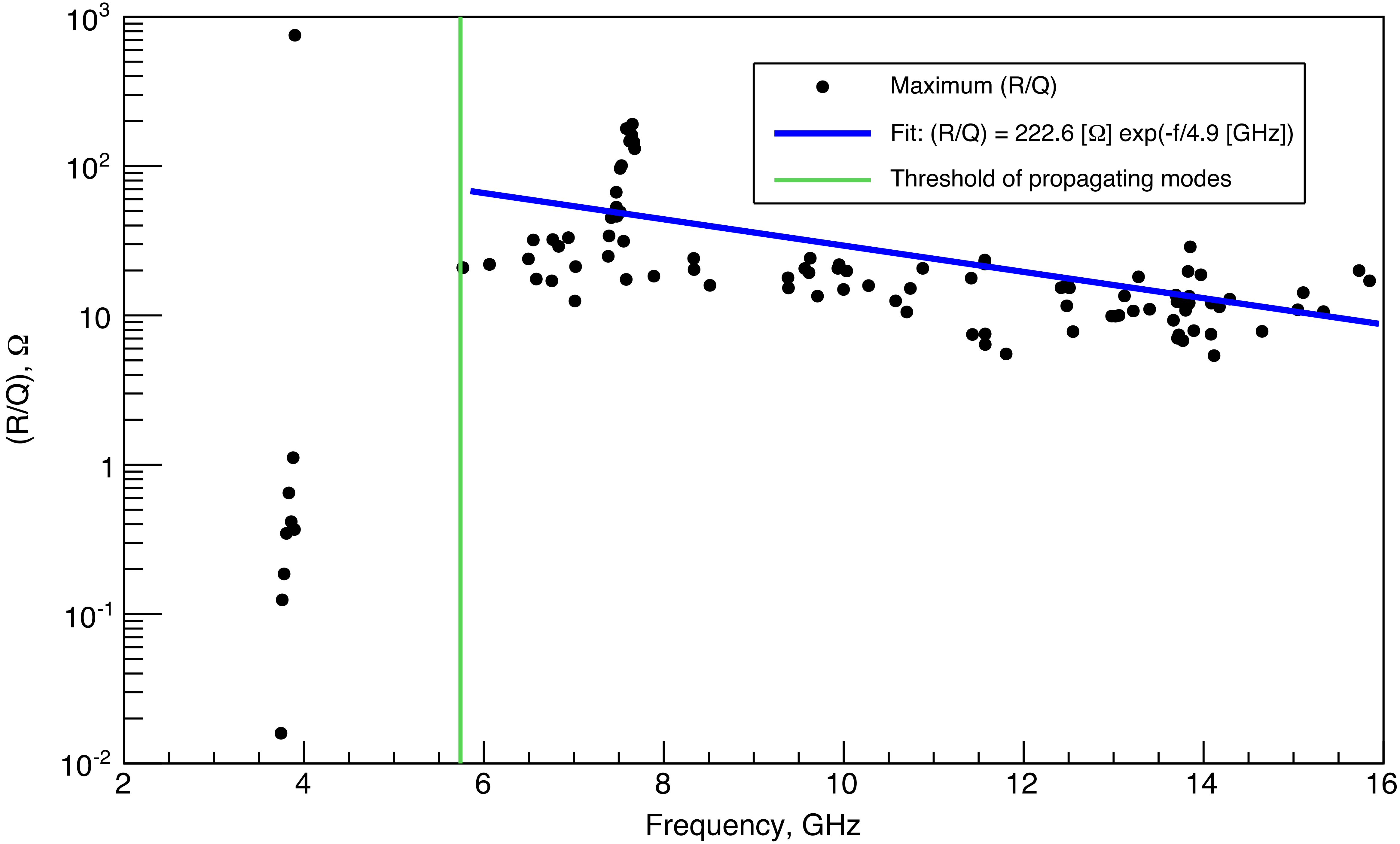
- Worst case ($Q_h=10^7$, SS bellows), losses reduced < 6 W with prob. 10^{-3}



Median power < 5 W. HOM spectra manipulation: P < 6 W with prob. <10^{-3}

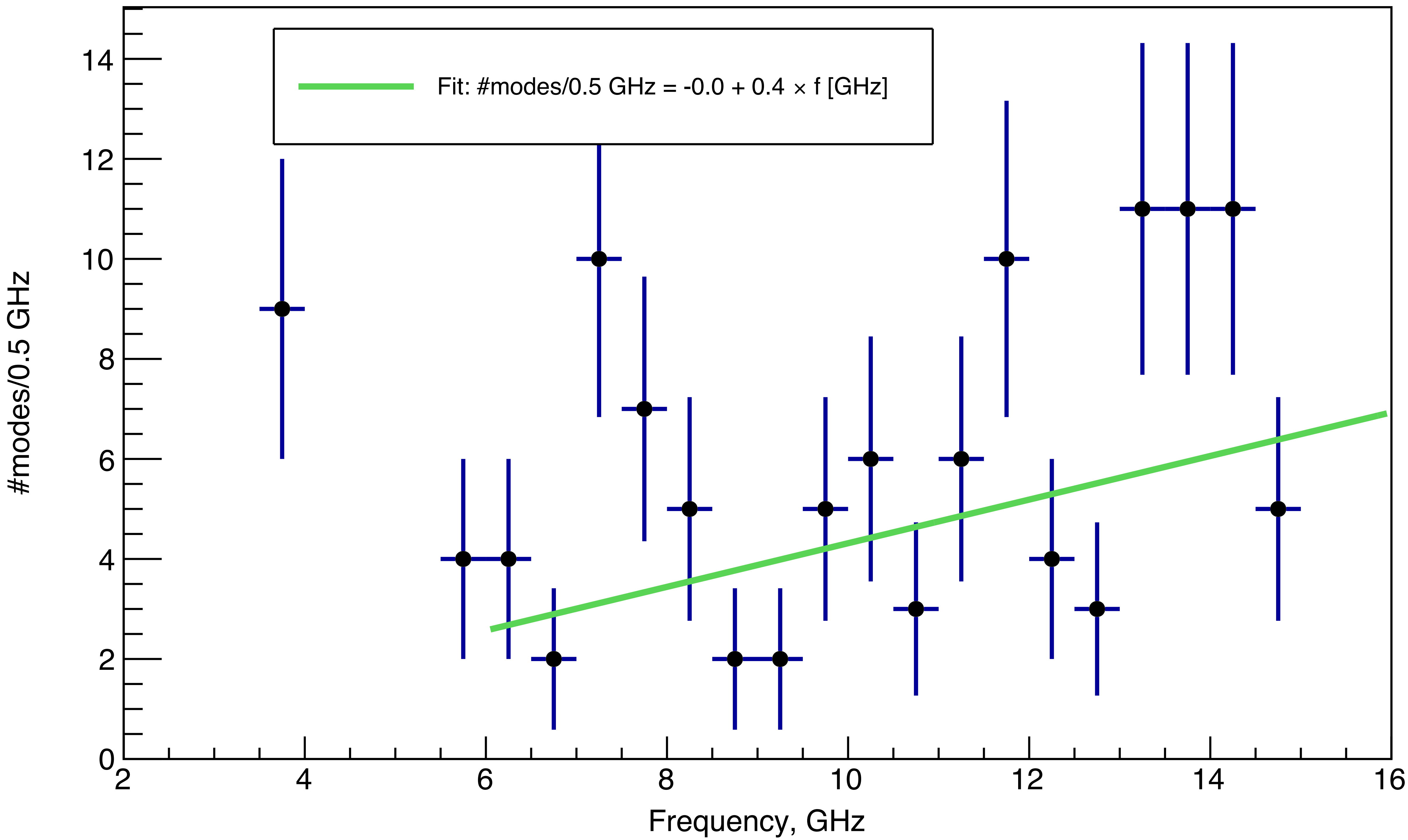
3.9 GHz: spectrum of monopole HOMs

- (R/Q) approximated by exponential function (can be used to extrapolate to higher HOM frequencies)



3.9 GHz: density of monopole HOMs

- Approximated by linear function
  - Can be used to extrapolate to higher HOM frequencies



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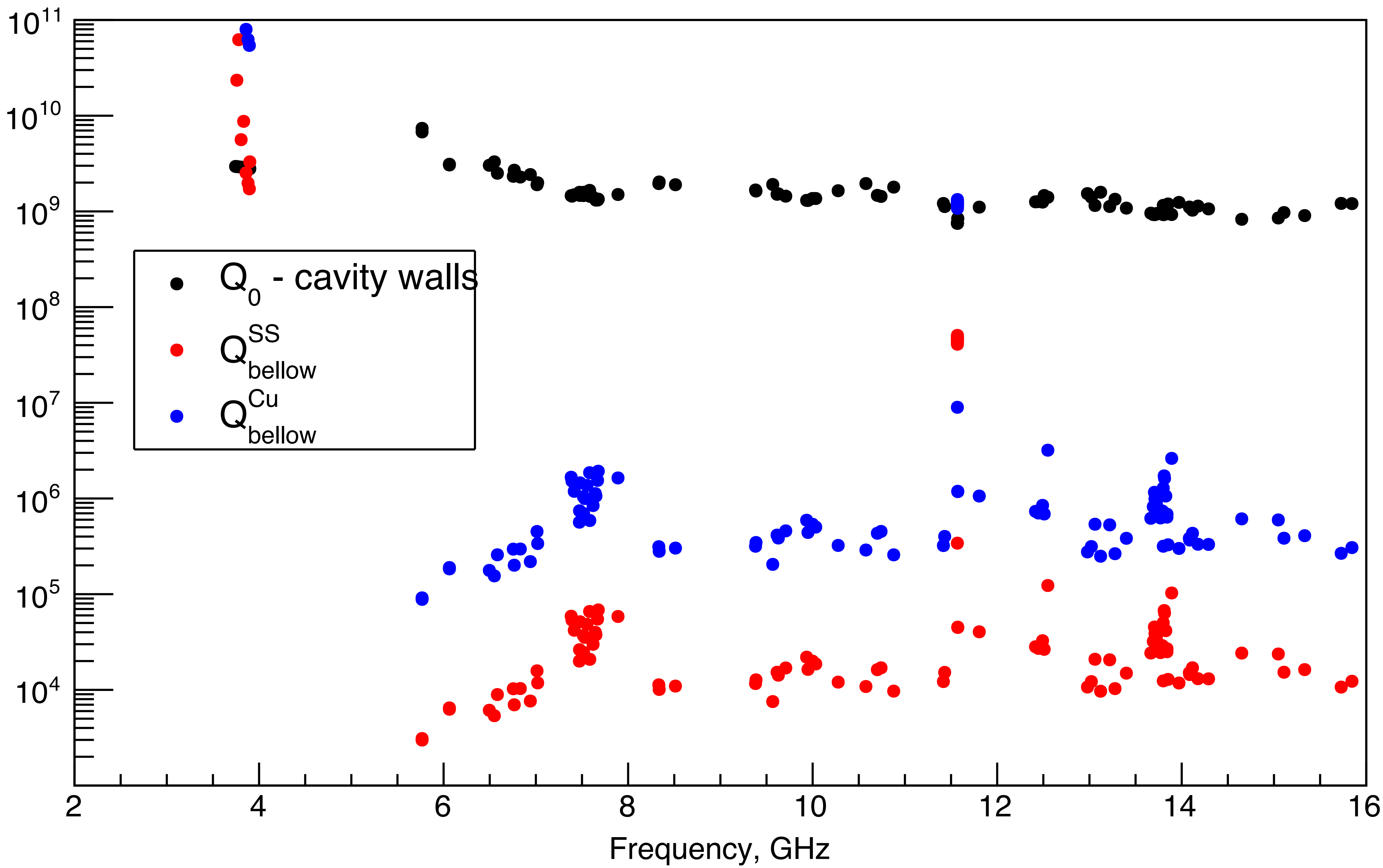
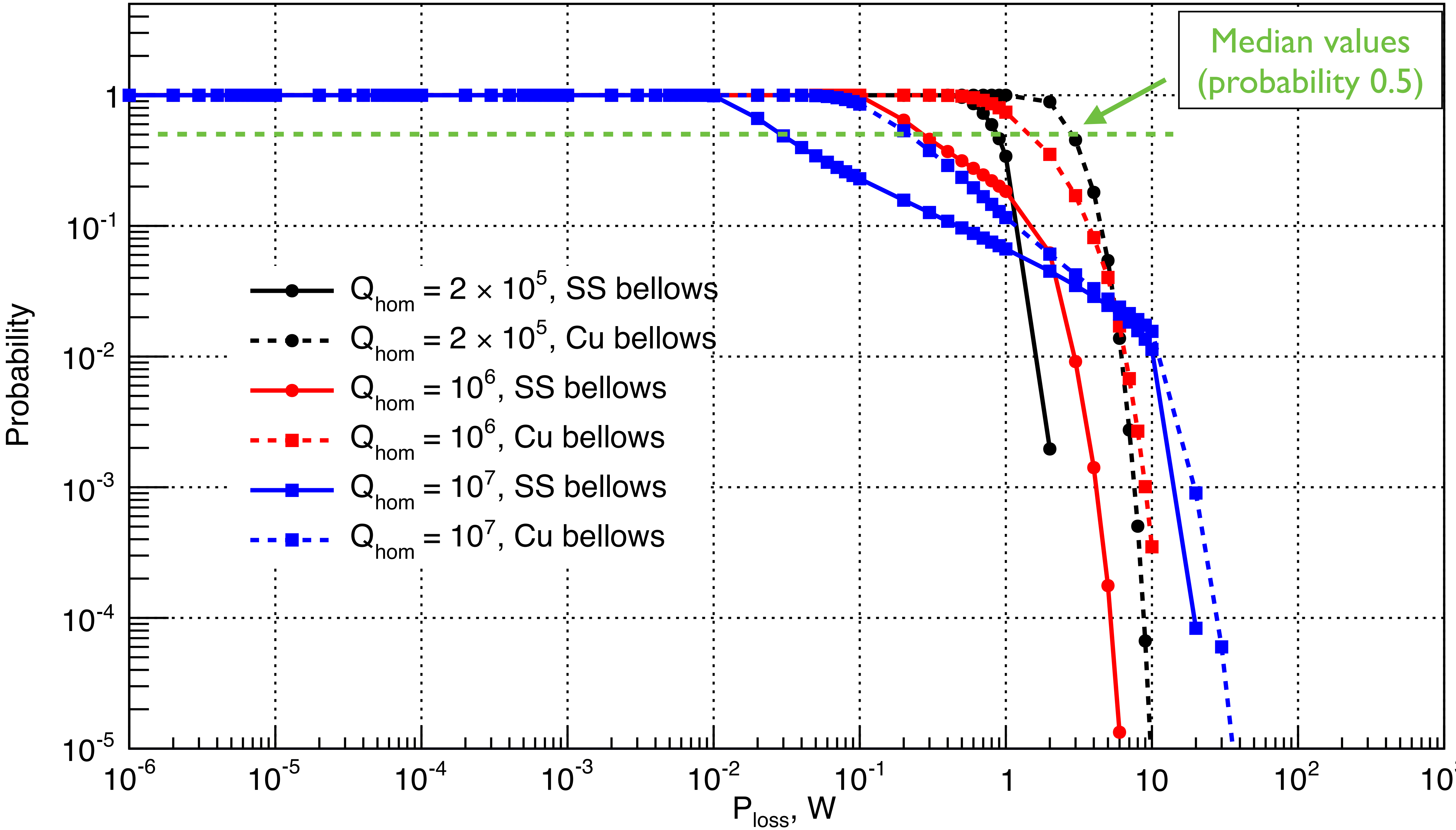


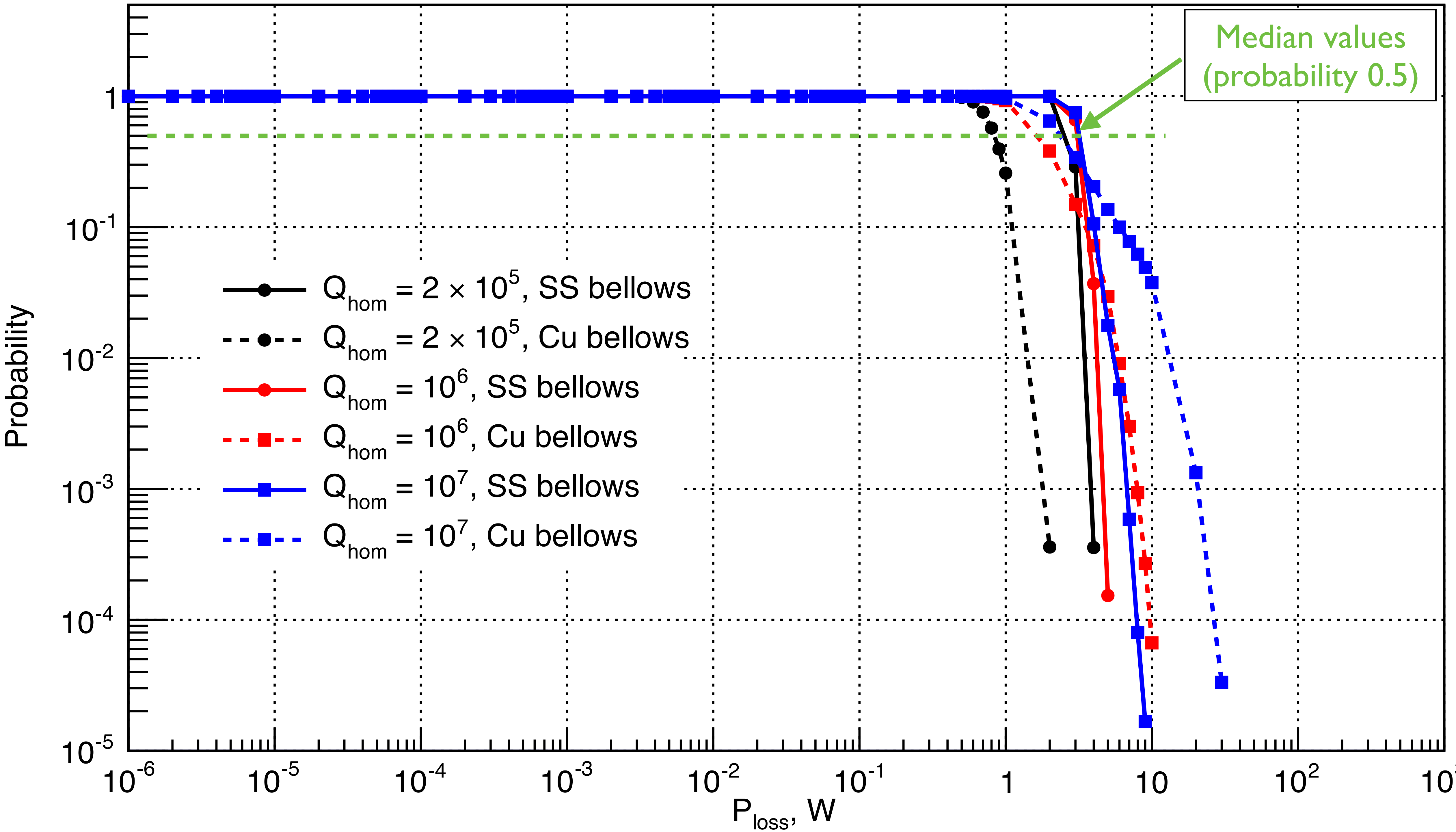
3.9 GHz: Power removed by HOM couplers

- Median P < 5 W
- Prob.10^{-3} (in 1/1000 cavities) to have P > 20 W
  - Can be controlled by HOM spectrum manipulation



3.9 GHz: power loss in bellows

- Median losses < 3 W ($Q_h=10^7$). Probability of higher losses can be reduced by HOM spectra manipulation



Summary

- Analyzed resonance excitation of monopole HOMs in LCLS-II linac
- Median heat load at 2 K < 1 mW
  - heat load > 100 mW has prob. < 5×10^{-4}
- Median power removed by HOM couplers (2 HOM couplers + 1 power coupler per cavity) < 5 W
- Median power dissipated in bellows < 5 W
  - higher power levels can be remedied by HOM spectrum manipulation (detuning cavity and tuning it back, which shifts HOM frequencies by 100s Hz)