Heterodyne Readout for Advanced LIGO

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and valuable discussions with Kip Thorne, Ken Strain, Peter Fritschel …

Background of the problem

- "Conventional" power-recycled interferometer
  - GW-induced audio-freq SB beat with a pair of RF SB at anti-symmetric port
  - RF SB resonant in power-recycling cavity for maximum transmission to AS port
  - Balanced heterodyne detection (immunity to technical noise sources due to cancellations)
- Signal-tuned interferometer with detuned RSE
  - RF sidebands moved off resonance in signal extraction cavity
  - Can compensate detuning with RF freq change, e.g., BUT can only make one of the two RF SB resonant
  - Unbalanced heterodyne detection (technical noise sources couple differently, fewer cancellations)

Homodyne readout

- Revisit homodyne (DC) readout
  (Strain, Fritschel, Mueller, others)
  - Offset arm cavity lengths to make DC component of carrier the LO
  - Find optimum homodyne phase by looking at ifo response to an inspiraling binary source (Fritschel)
  - Calculate optical noise with full quantum mechanical formulation of the EM field in ifo (Buonanno and Chen, 2000)
  - Find coupling of shot noise and radiation pressure noise due to SEC detuning (the two quadratures are mixed by the detuning)
  - This coupling gives rise to an optical-mechanical resonance
- Limitation of homodyne readout
  - Can't demodulate with both quadratures to find frequency-dependent optimum
- Heterodyne readout circumvents this, since we can phase shift LO arbitrarily

Heterodyne readout

- Do full QM calculation of RF modulated-demodulated EM field (Buonanno and Chen, 2002)
- Find additional noise term due to quantum noise at 2 f_m
- Similar to work of Niebauer et al (1991) and Meers and Strain (1991) BUT includes
  - Imbalanced modulation necessary for detuned RSE
  - Includes radiation pressure noise
- Use realistic (baseline) ifo parameters to calculate transmission of RF SB to detection port

$$t_{\pm} = \frac{\pm t_{prm} A_{bs} t_{srm} \mathrm{e}^{-i(\phi_{dt} \pm (2\pi f_m / c) 2\delta l_{\sec})/2}}{1 - r_{prm} r_{srm} A_{bs}^{2} \mathrm{e}^{-i(\phi_{dt} \pm (2\pi f_m / c) 2\delta l_{\sec})}}$$

Homodyne (DC) readout

$$S_h^{DC}(\Omega) = \frac{h_{SQL}^2}{2\kappa} \frac{1}{\tau^2 \left| D_1 \sin \varsigma_0 + D_2 \cos \varsigma_0 \right|^2} [(C_{11} \sin \varsigma_0 + C_{21} \cos \varsigma_0)^2 + (C_{12} \sin \varsigma_0 + C_{22} \cos \varsigma_0)^2]$$

ζ_0 = homodyne phase

κ = coupling constant (I_{SQL}, I_0, Ω, γ)

Φ, ϕ = GW sideband, carrier phase gain in SR cavity

β = GW sideband phase gain in arm cavity

ρ, τ = SRM reflection, transmission coefficient

C_{ij}, M, $D_{1,2}$ = $f(\rho, \phi, \Phi, \kappa, \beta)$

Heterodyne (RF) readout

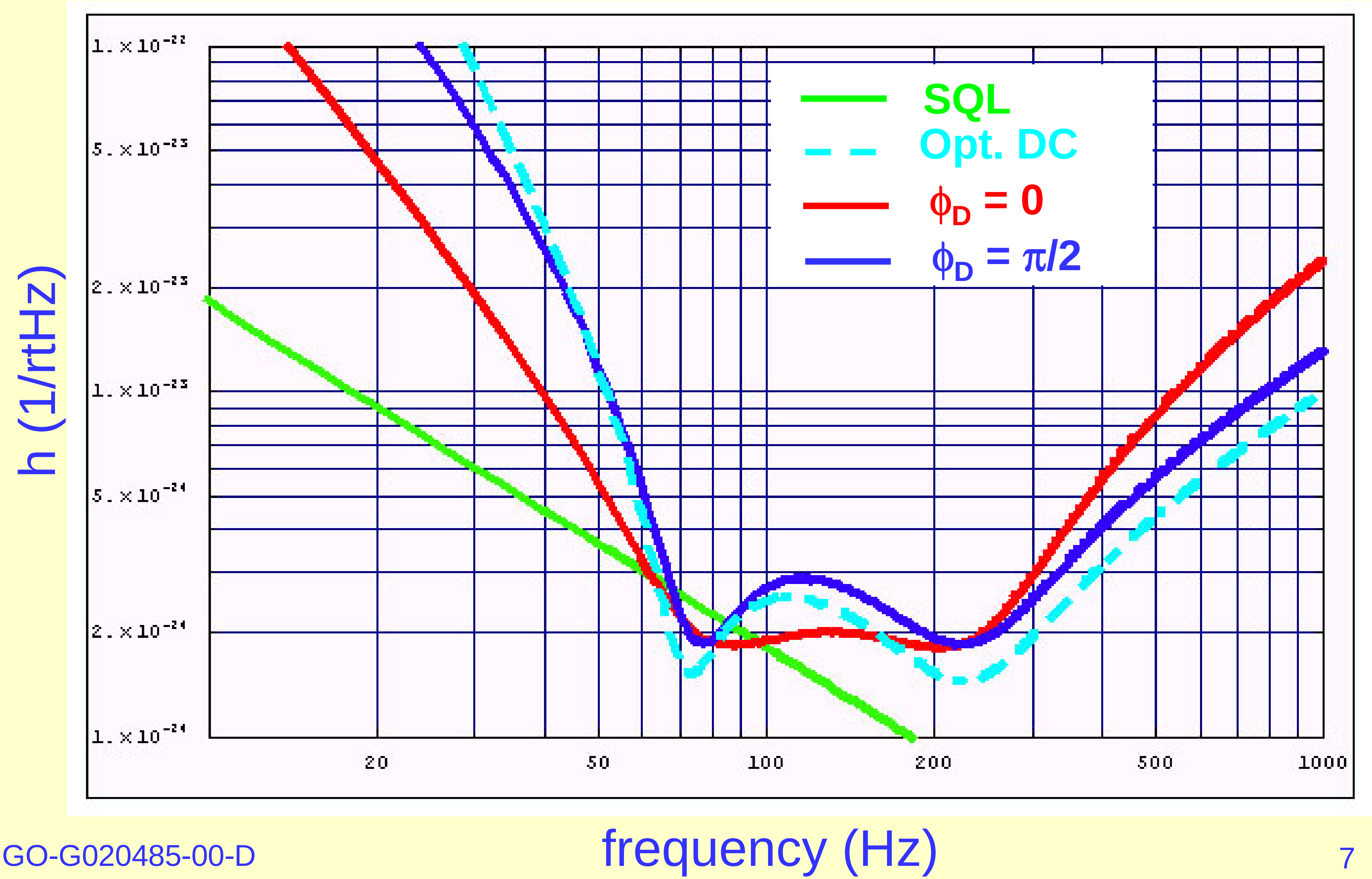
$$S_h^{RF}(\Omega) = \frac{h_{SQL}^2}{2\kappa} \frac{1}{\tau^2 \left| D_1 \sin\varsigma_0 + D_2 \cos\varsigma_0 \right|^2} [(C_{11} \sin\varsigma_0 + C_{21} \cos\varsigma_0)^2 + (C_{12} \sin\varsigma_0 + C_{22} \cos\varsigma_0)^2]$$

$$+ \underbrace{\frac{h_{SQL}^2}{2\kappa} \frac{1}{\tau^2 \left| D_1 \sin\varsigma_0 + D_2 \cos\varsigma_0 \right|^2} [\frac{\left|D_+\right|^2 + \left|D_-\right|^2}{\left| D_+ e^{-i\phi_D} + D_- e^{i\phi_D} \right|^2} \left|M\right|^2]}$$

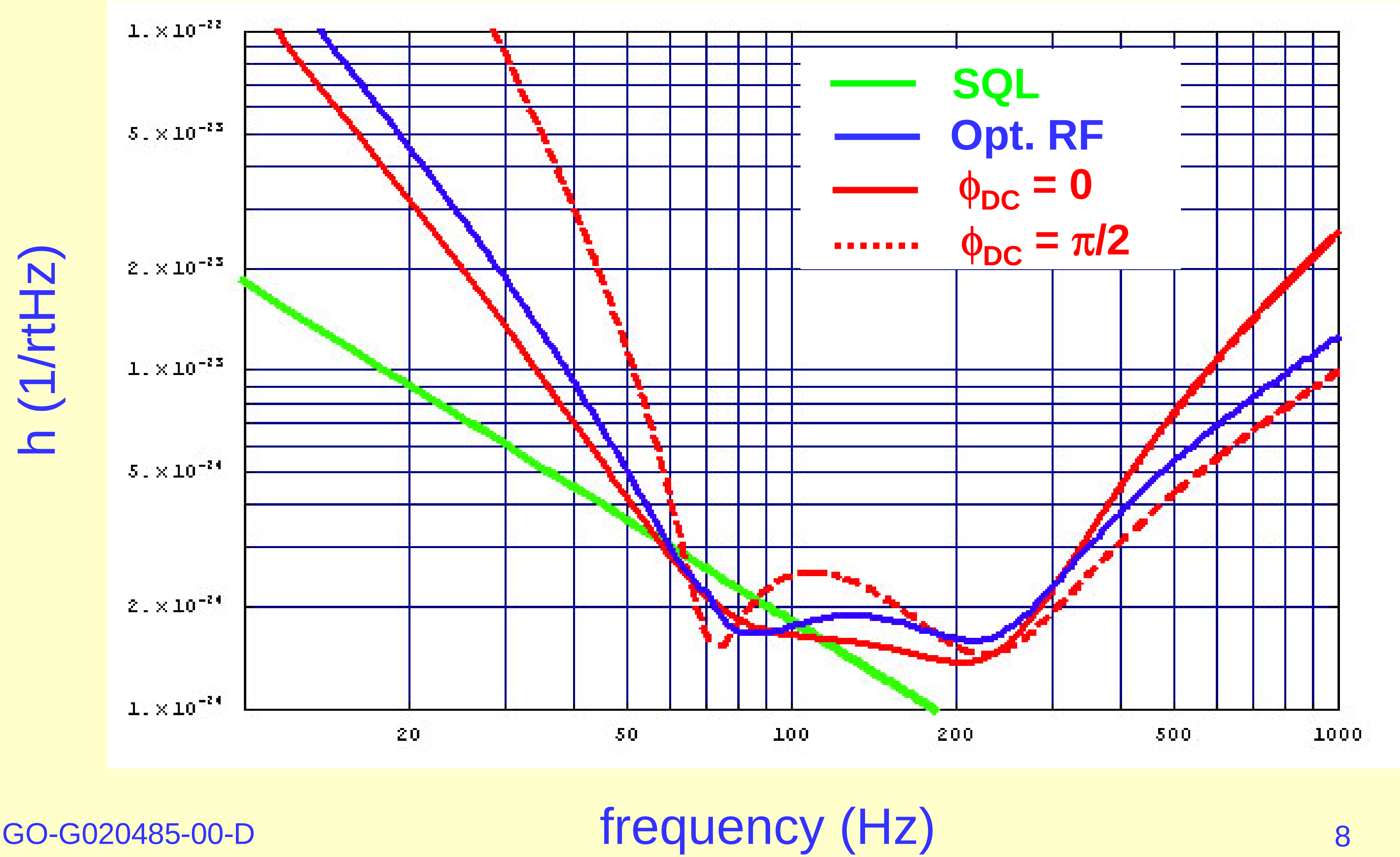
Extra term due to noise at 2 f_m

ζ_0 = "Homodyne" phase
ϕ_D = RF demodulation phase
$D_{+,-}$ = (complex) amplitude of upper, lower RF sideband

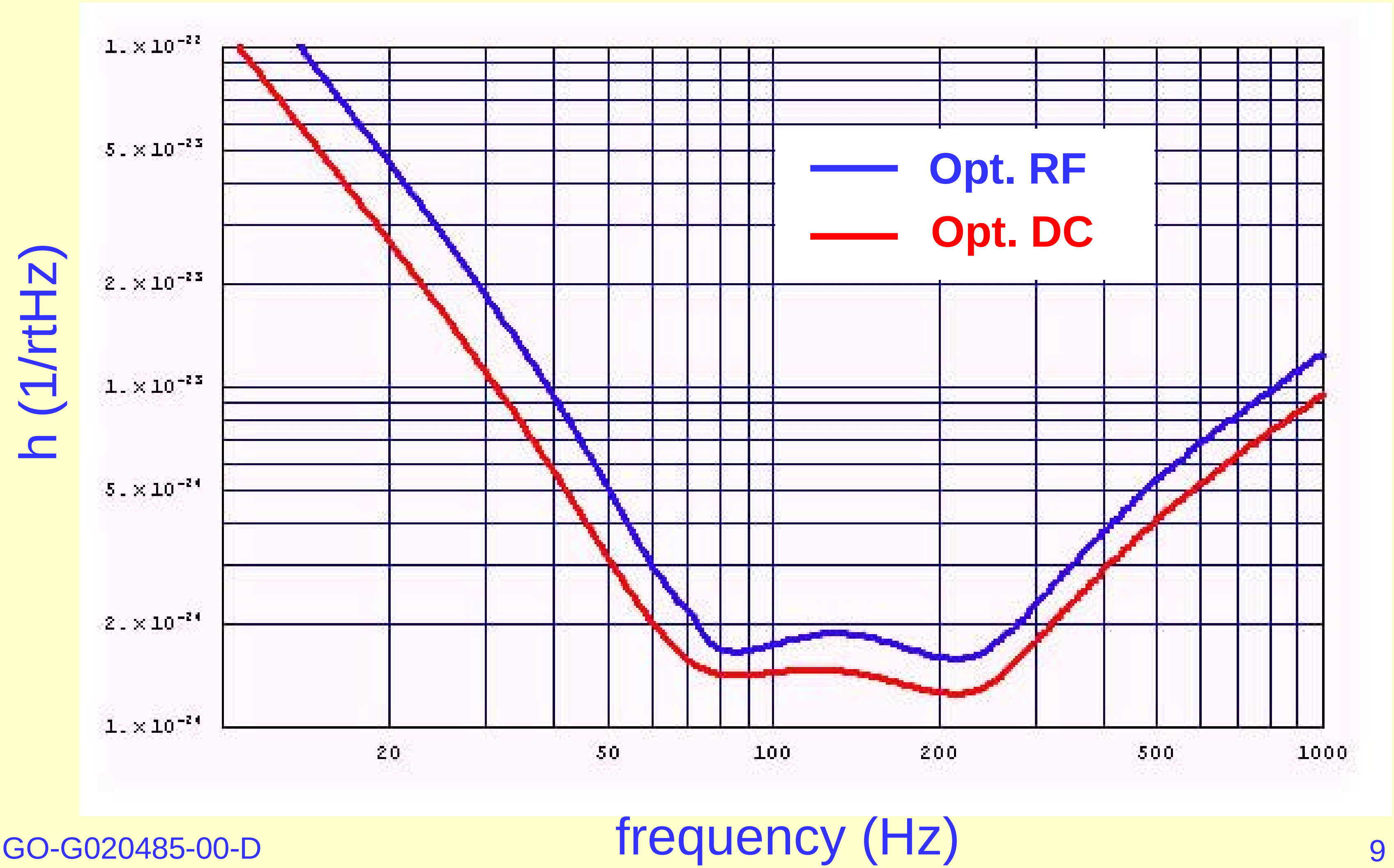
Frequency-dependent ϕ_D



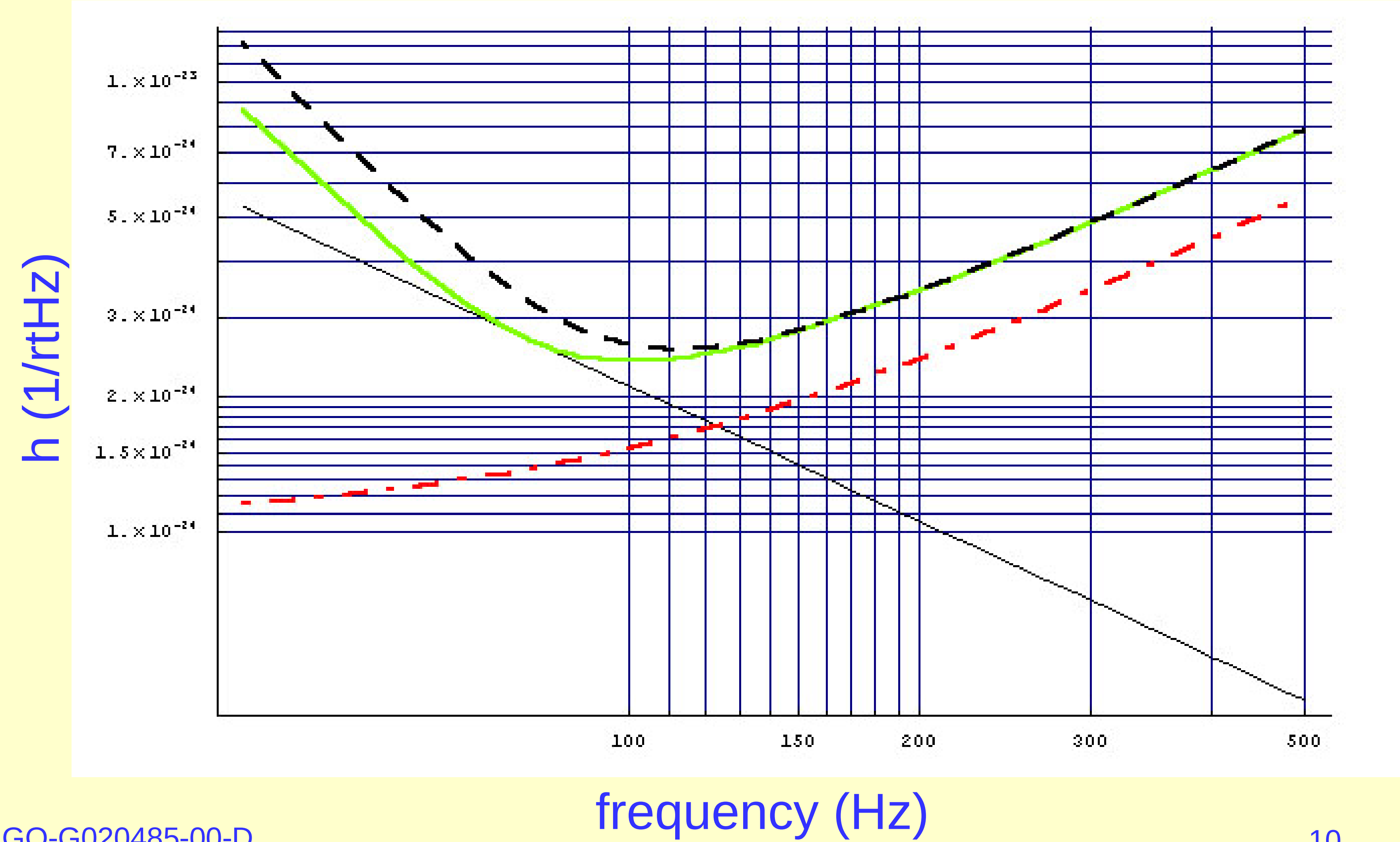
Frequency-dependent to ϕ_D minimize noise spectral density



If frequency-dependent homodyne angle were possible…



Effect of the additional noise term: conventional interferometer



Work still in progress

- Preliminary results, need to iron out details of contrast defect, modulation index,…
- Optimization of the readout scheme for different GW sources
- So far, we have considered only fundamental quantum noise on the light
- So need to consider technical noise as well (already begun by Mueller, Fritschel, others)