Narrow-band regimes in future gravitational-wave detectors

F.Ya.Khalili

September 30, 2008

LIGO-G080531-00-Z

Scenario considered here

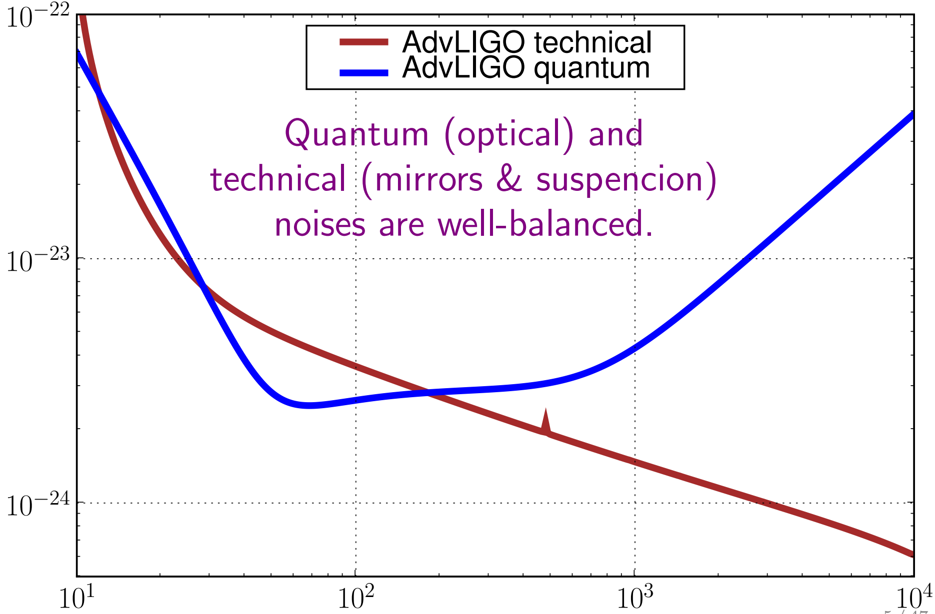
Suppose that:

- The year is 201?.
- Advanced LIGO starts to operate.
- The technical noises are reduced significantly in comparison with the initial plans.
- Advanced QND techniques (filter cavities etc) are still not available.
- But squeezed vacuum is available.

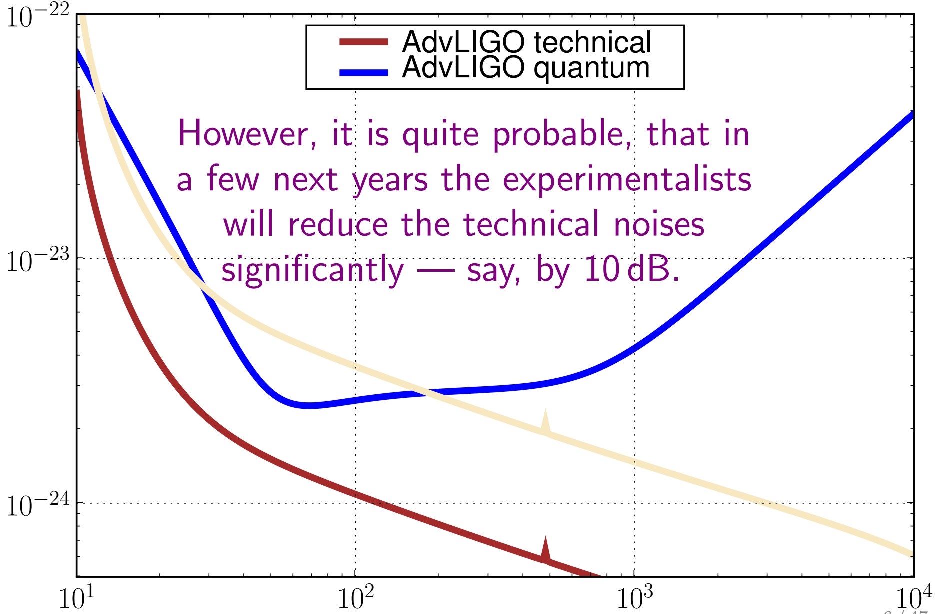
1. Introduction
2. Vacuum input, numerical optimization
3. Analysis
4. Squeezed input
5. Conclision

Work in progress; in particular, optical losses have not been taken into account rigorously.

AdvLIGO as it planned now

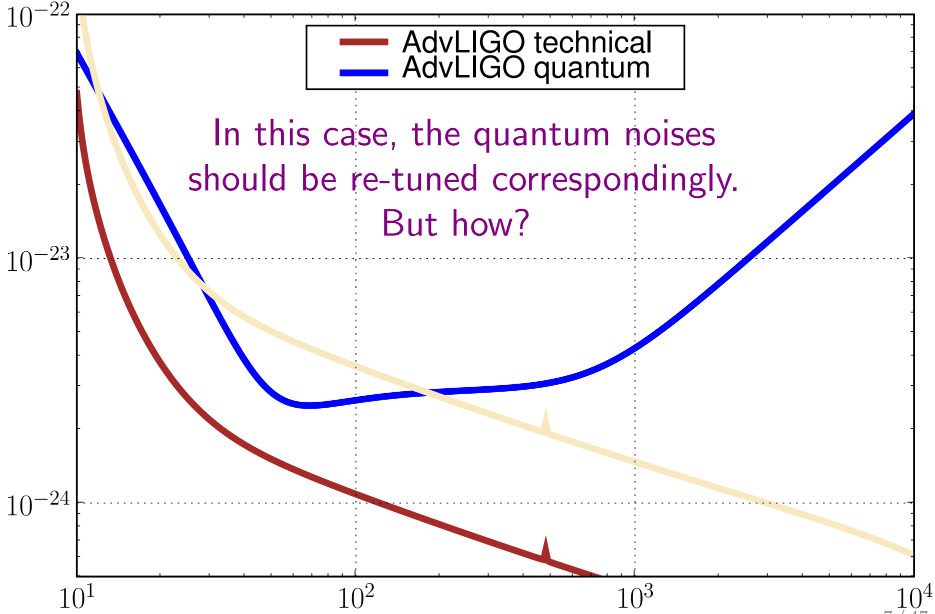


Reduced technical noises



However, it is quite probable, that in a few next years the experimentalists will reduce the technical noises significantly — say, by 10 dB.

Reduced technical noises



Parameters

World constants:

$$J = \frac{4\omega_p(I_c = 2 \times 840\,\mathrm{kW})}{McL} = (2\pi \times 100\,\mathrm{s}^{-1})^3$$

$$\Omega_0 = 2^{1/6} J^{1/3} \approx 2\pi \times 112\,\mathrm{s}^{-1}$$

$$e^{2r} = 10$$

Parameters to optimize:

$$\gamma = \frac{(1-\rho^2)\gamma_{\mathrm{ARM}}}{1 + 2\rho\cos 2\phi_{\mathrm{SRC}} + \rho^2}$$

$$\delta = \frac{2\rho\gamma_{\mathrm{ARM}}\sin 2\phi_{\mathrm{SRC}}}{1 + 2\rho\cos 2\phi_{\mathrm{SRC}} + \rho^2}$$

Homodyne angle ϕ

Squeeze angle θ

Parameters

Technical noises:

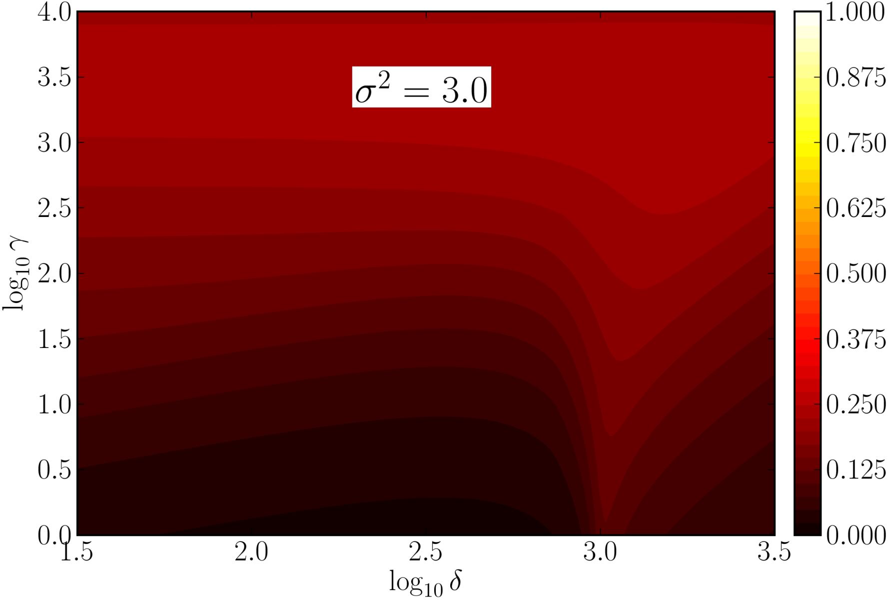
$$\sigma^2 = \left.\frac{S_{\rm tech}}{S_{\rm SQL}}\right|_{\Omega=\Omega_0} = 0.01 \ldots 3.0$$

The figure of merit:

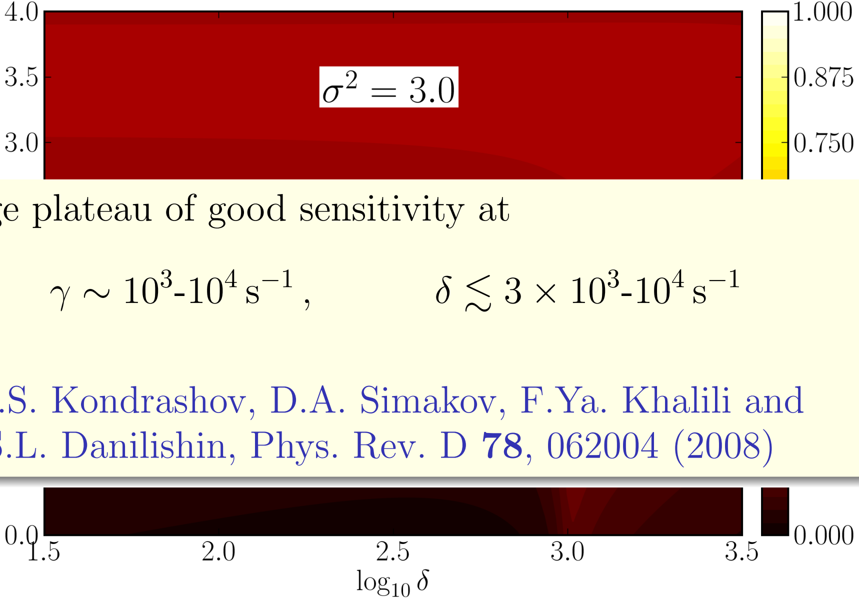
$$\mathsf{SNR} = \frac{1}{\pi}\int_0^\infty \frac{|h(\Omega)|^2 d\Omega}{S^h_{\rm quant}(\Omega) + S^h_{\rm tech}(\Omega)}$$

$$\approx \frac{|h(\Omega_0)|^2}{\pi}\int_0^\infty \frac{d\Omega}{S^h_{\rm quant}(\Omega) + S^h_{\rm tech}(\Omega_0)}$$

$\gamma - \delta$ plane



$\gamma - \delta$ plane

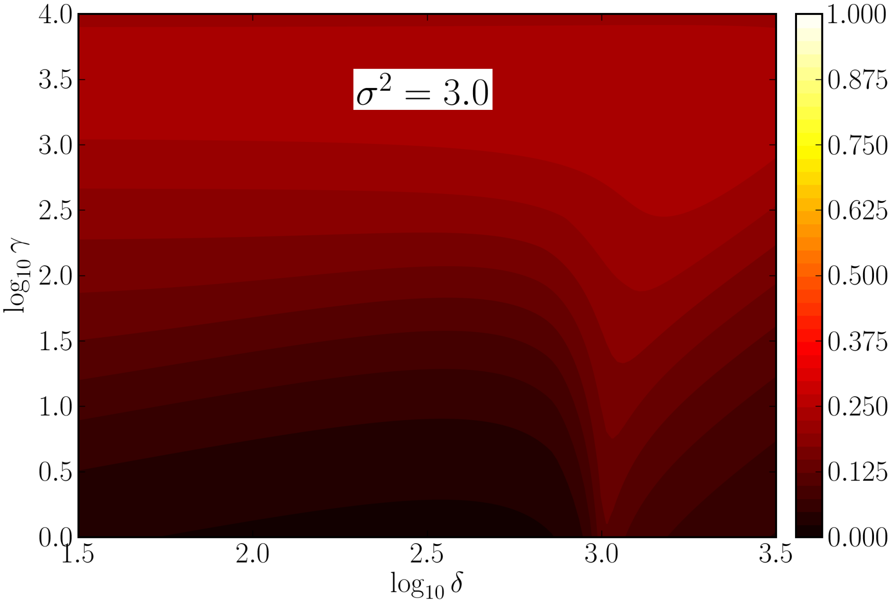


Large plateau of good sensitivity at

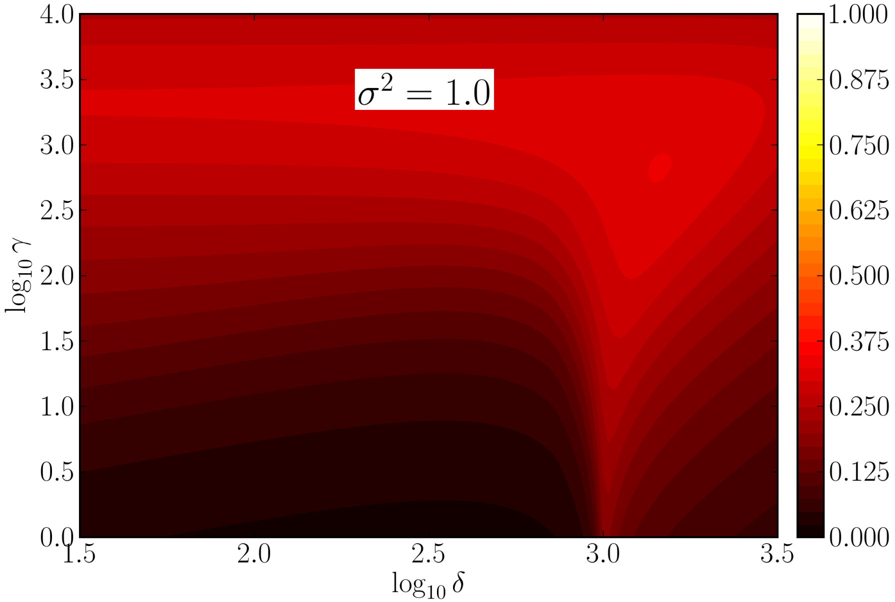
$$\gamma \sim 10^3\text{-}10^4\,\mathrm{s}^{-1}\,, \qquad \delta \lesssim 3 \times 10^3\text{-}10^4\,\mathrm{s}^{-1}$$

I.S. Kondrashov, D.A. Simakov, F.Ya. Khalili and S.L. Danilishin, Phys. Rev. D **78**, 062004 (2008)

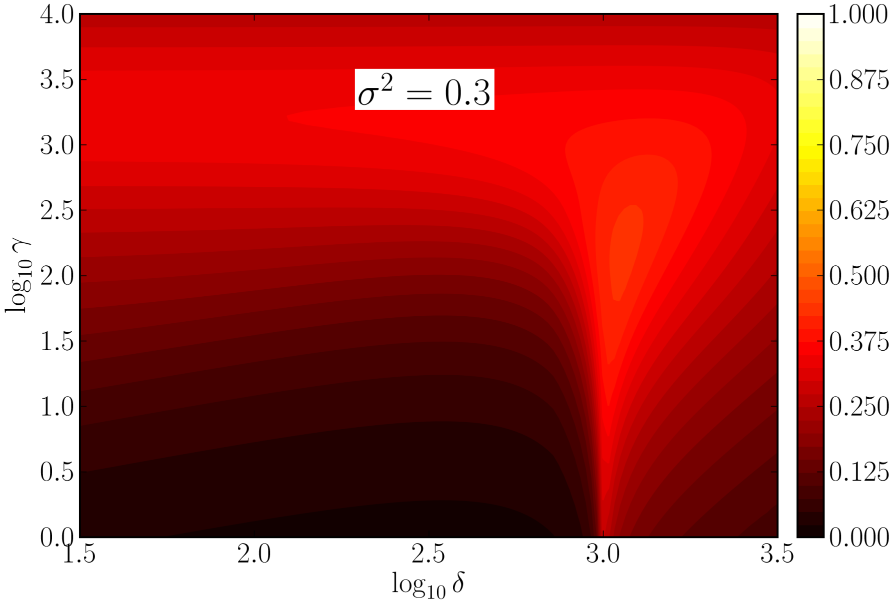
$\gamma - \delta$ plane



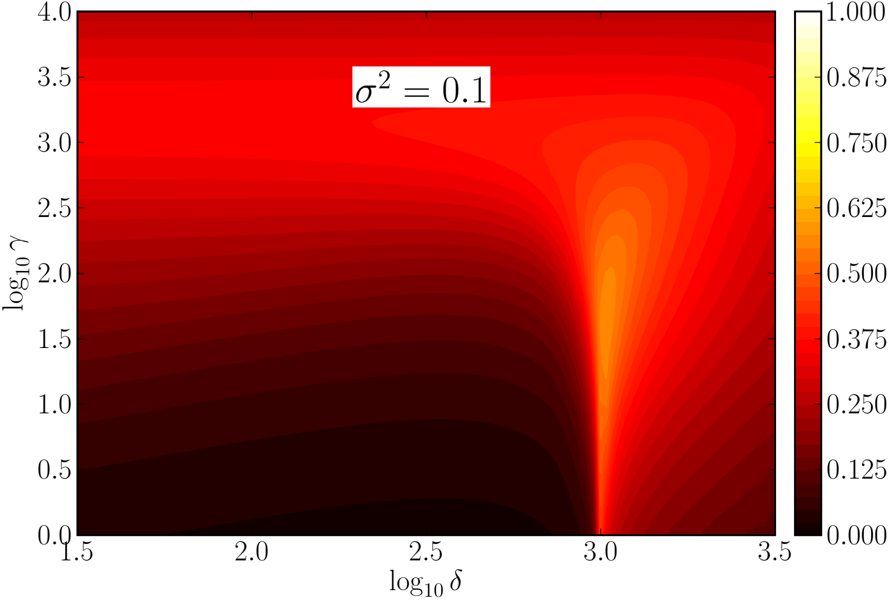
$\gamma - \delta$ plane



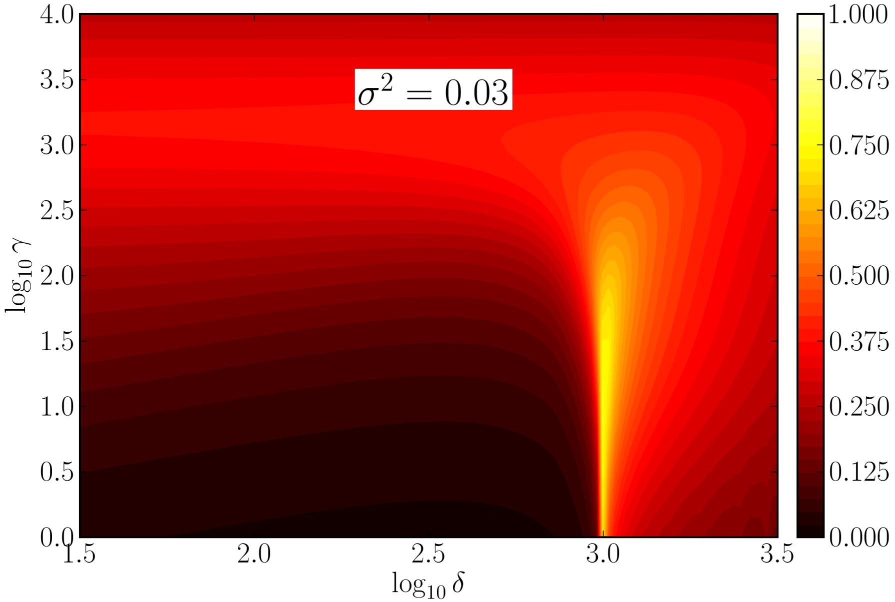
$\gamma - \delta$ plane



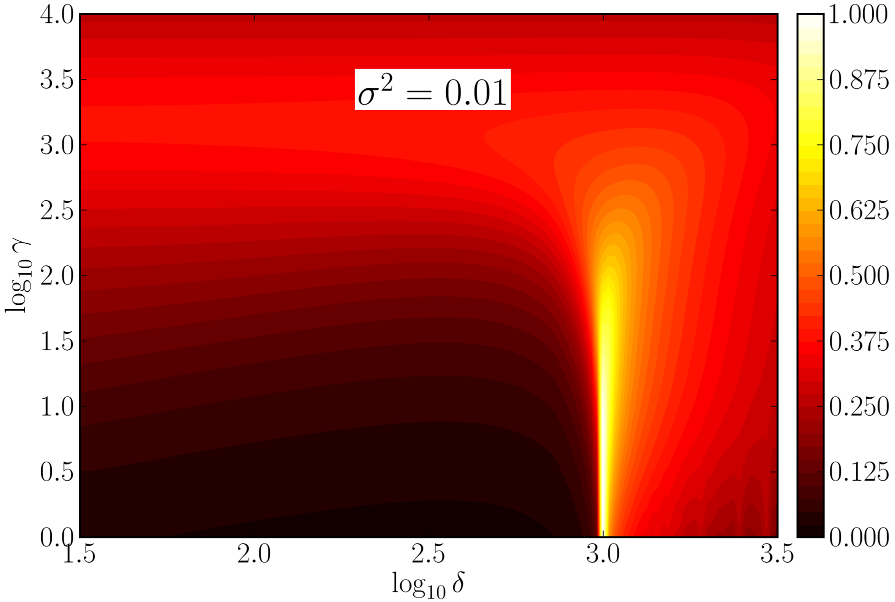
$\gamma - \delta$ plane



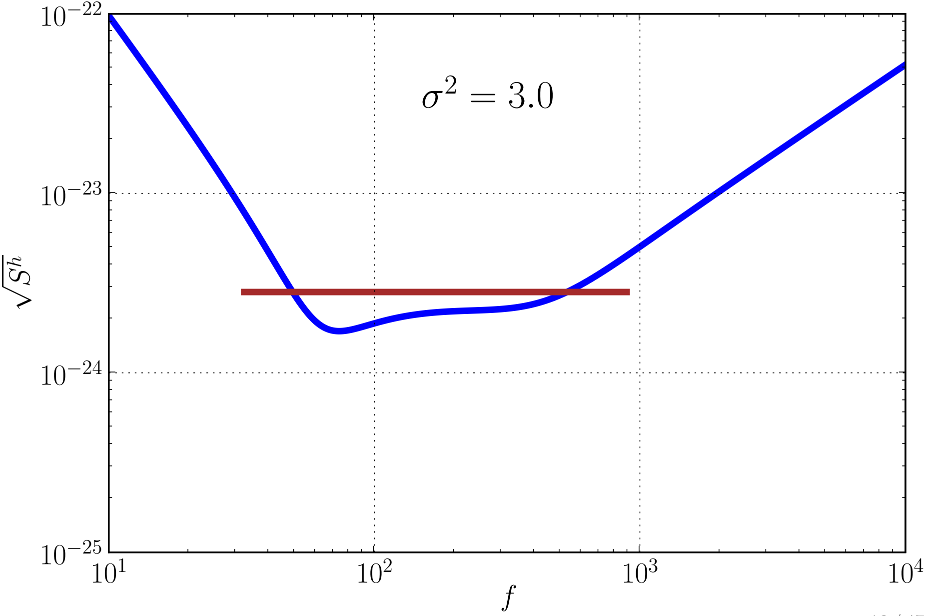
$\gamma - \delta$ plane



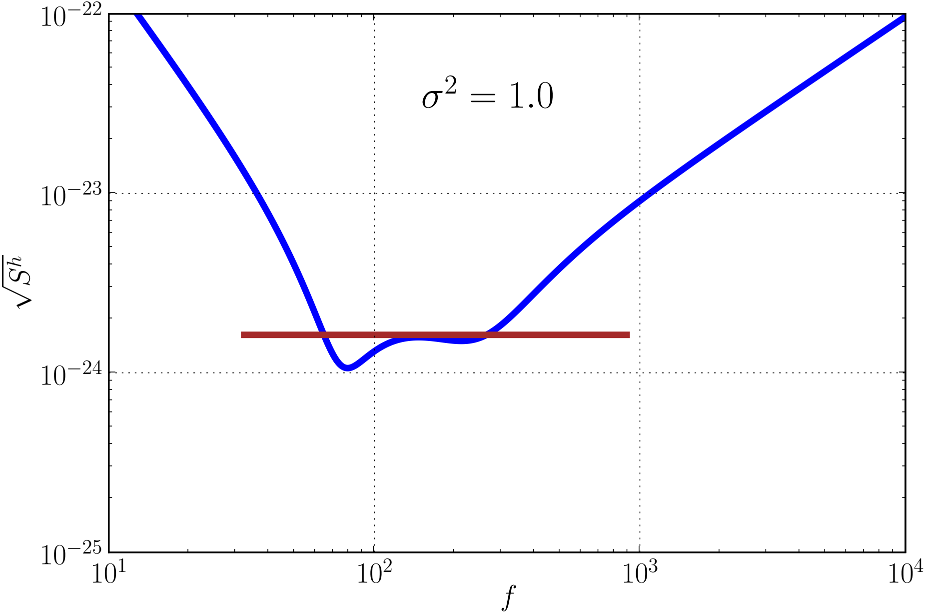
$\gamma - \delta$ plane



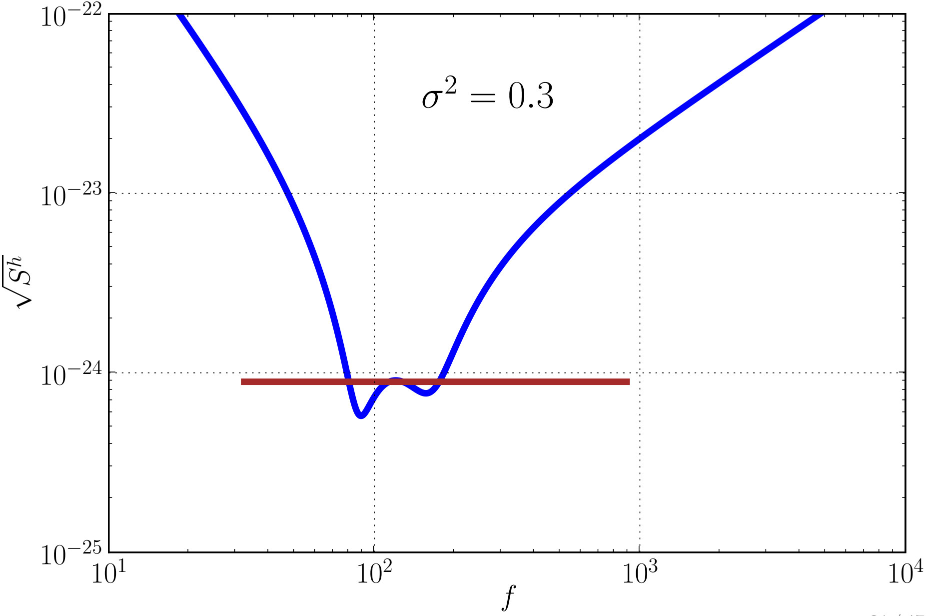
Optimal quantum noise



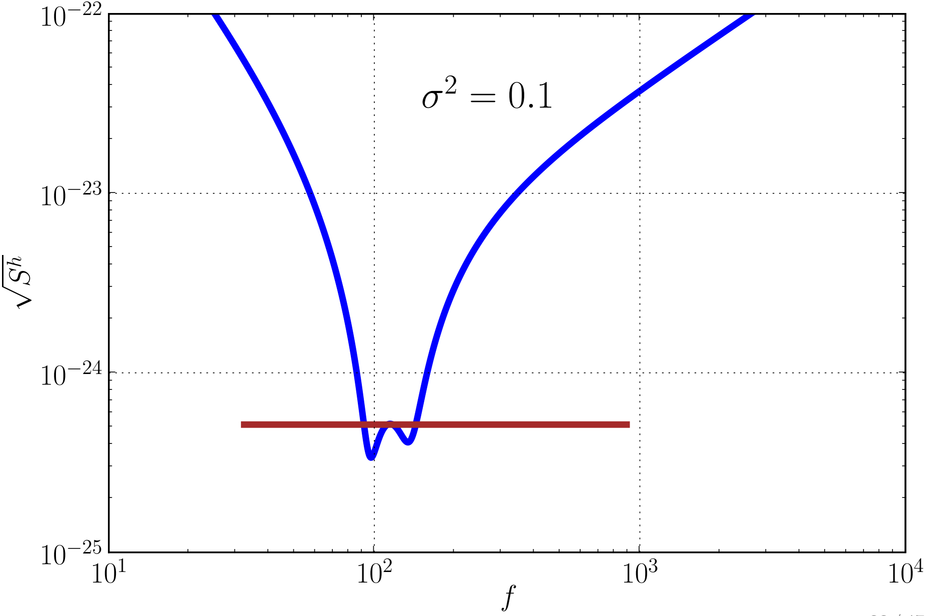
Optimal quantum noise



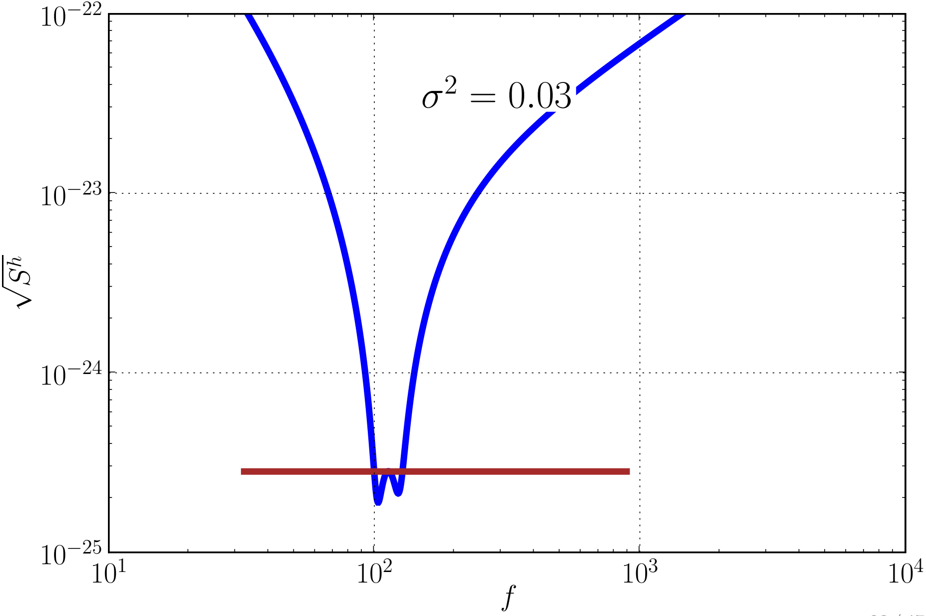
Optimal quantum noise



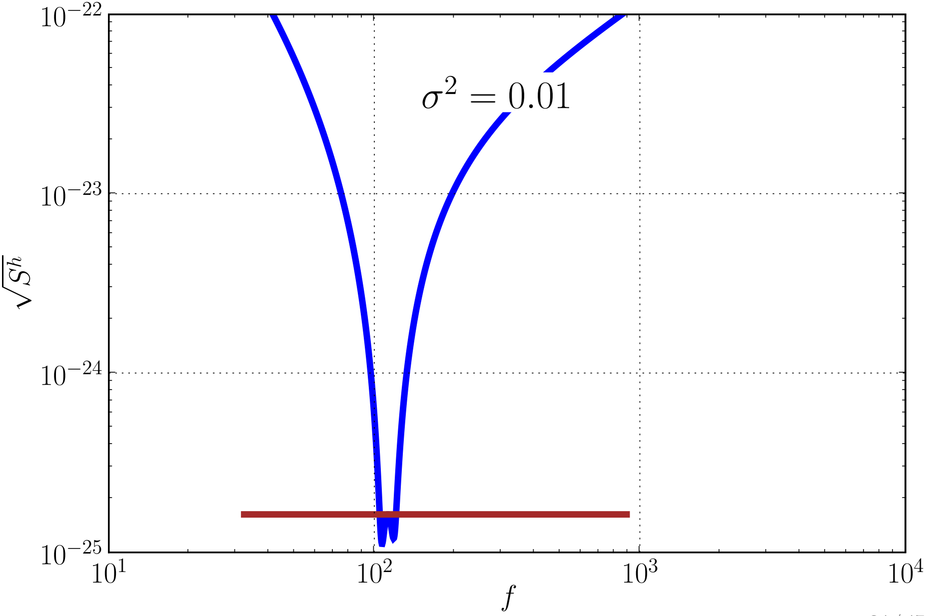
Optimal quantum noise



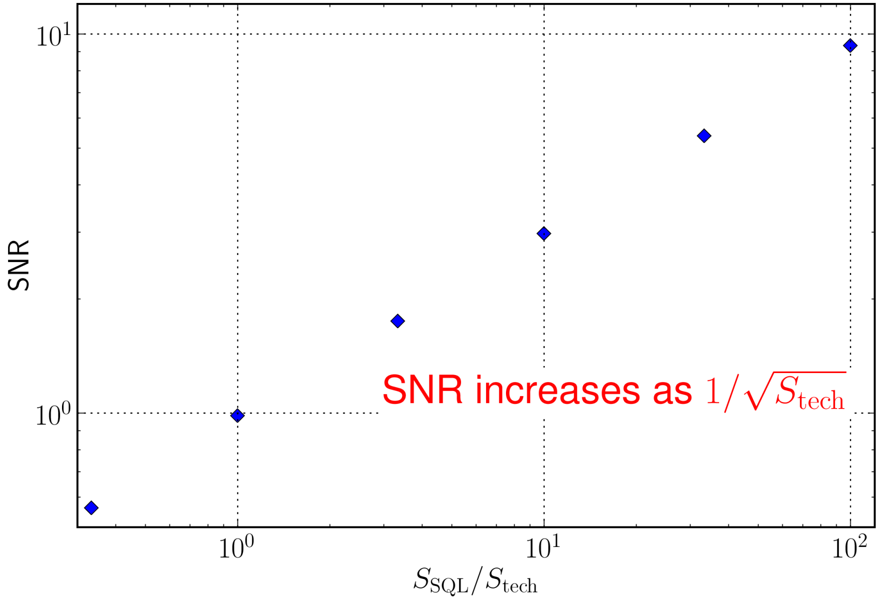
Optimal quantum noise



Optimal quantum noise



Gain in SNR

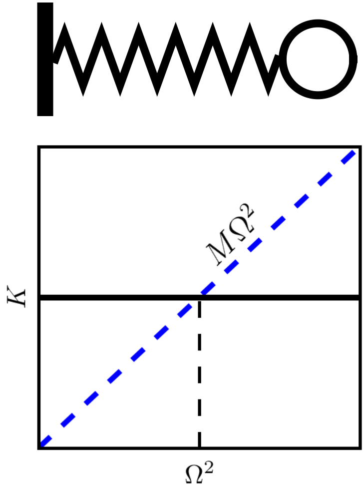


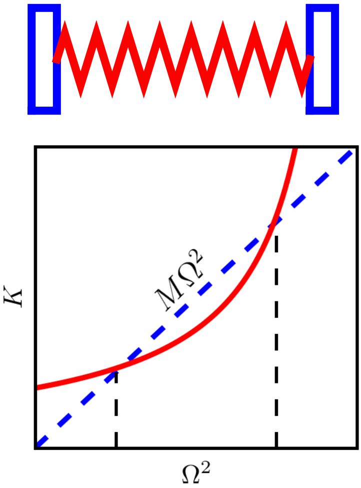
10^1
10^0
SNR
10^0
10^1
10^2
$S_{\mathrm{SQL}}/S_{\mathrm{tech}}$
SNR increases as $1/\sqrt{S_{\mathrm{tech}}}$

History

- F.Ya.Khalili, Physics Letters A **288**, 251 (2001)
- F.Ya.Khalili, V.I.Lazebny, and S.P.Vyatchanin, Physical Review D **73**, 062002 (2006).

Ordinary vs. optical rigidities

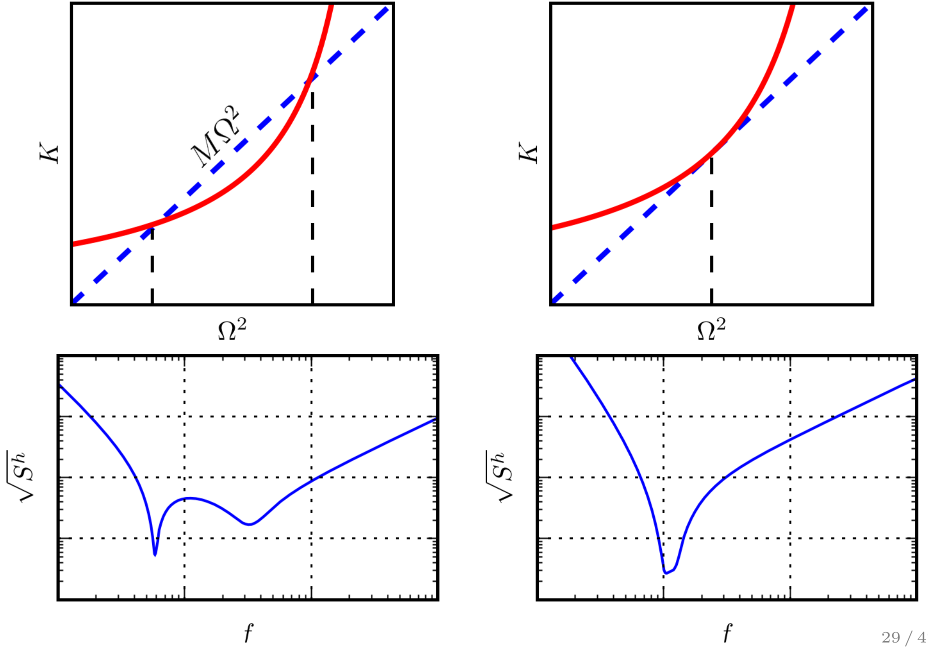




$$K = M\Omega_0^2$$

$$K(\Omega) \approx \frac{MJ\delta}{\delta^2 - \Omega^2}$$

Two regimes of the optical rigidity



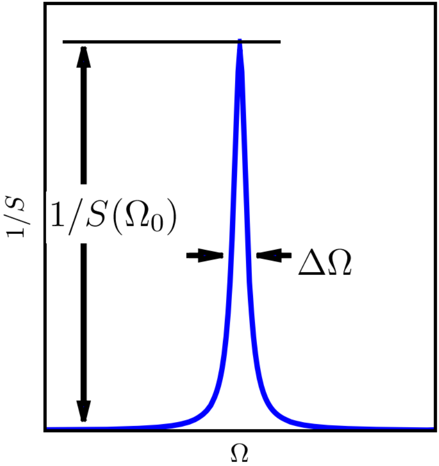
Conditions of the second-order pole regime

$$\delta = \sqrt[3]{4J} = 2\pi \times 2^{2/3} \times 100\,\mathrm{s}^{-1} \approx 997\,\mathrm{s}^{-1}$$

$$\Omega_0 = \frac{\delta}{\sqrt{2}} = 2\pi \times 2^{1/6} \times 100\,\mathrm{s}^{-1} \approx 2\pi \times 112\,\mathrm{s}^{-1}$$

SNR

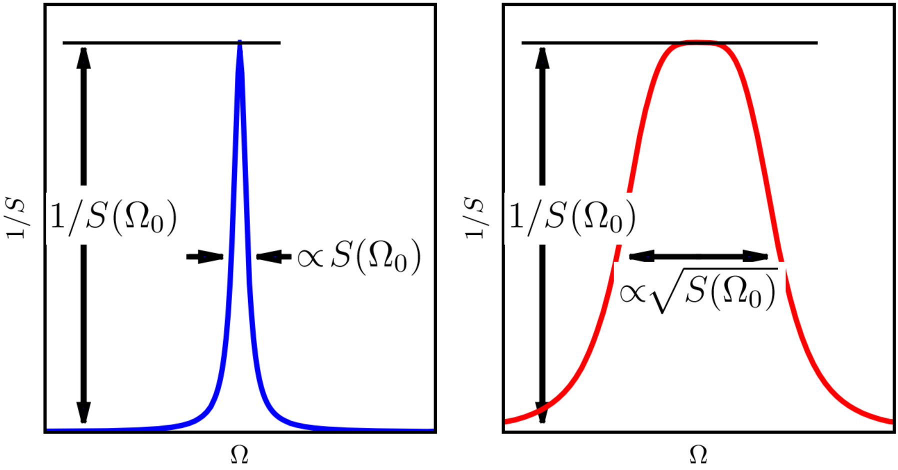
$$\text{SNR} \propto \int_0^\infty \frac{d\Omega}{S(\Omega)} \approx \frac{\Delta\Omega}{S(\Omega_0)}$$



SNR

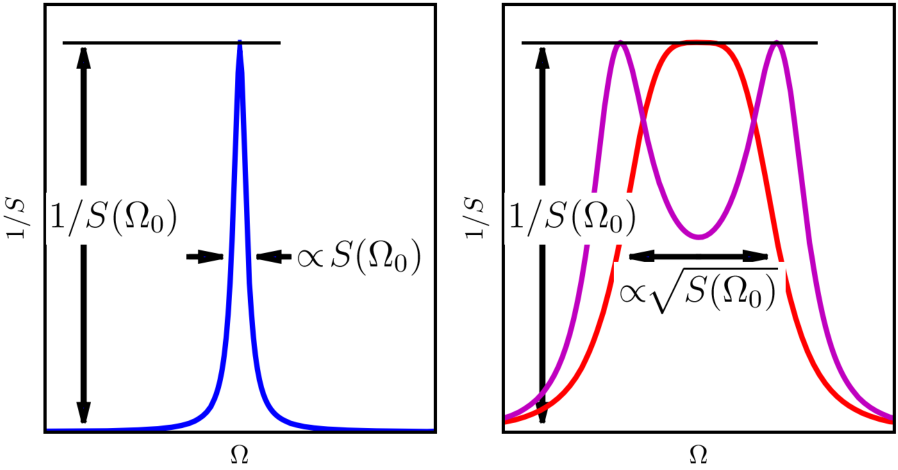
$\mathsf{SNR} \propto 1$

$$\mathsf{SNR} \propto \frac{1}{\sqrt{S(\Omega_0)}}$$

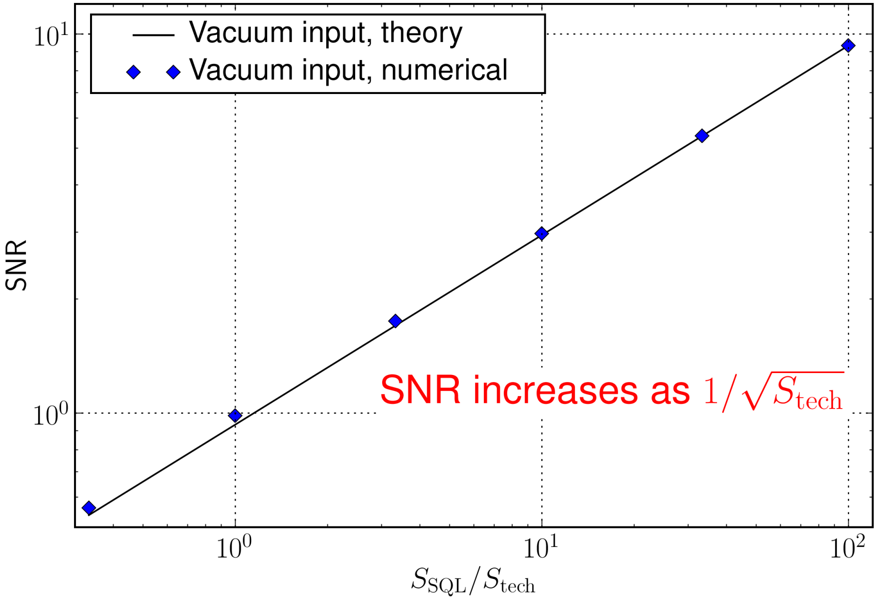


SNR

SNR $\propto 1$ SNR $\propto \dfrac{1}{\sqrt{S(\Omega_0)}}$



Gain in SNR

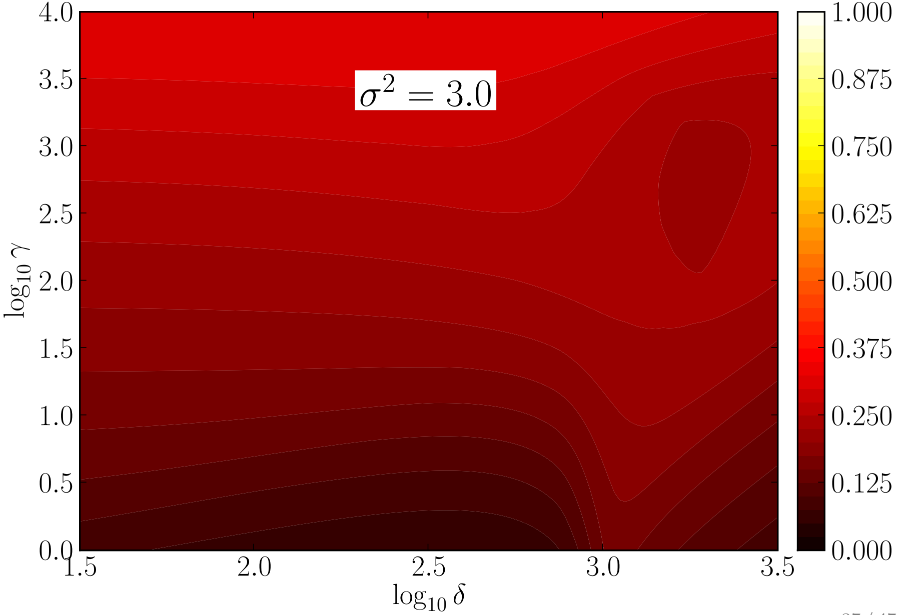


Vacuum input, theory
Vacuum input, numerical
SNR increases as $1/\sqrt{S_{\text{tech}}}$
SNR
10^1
10^0
10^0
10^1
10^2
$S_{\text{SQL}}/S_{\text{tech}}$

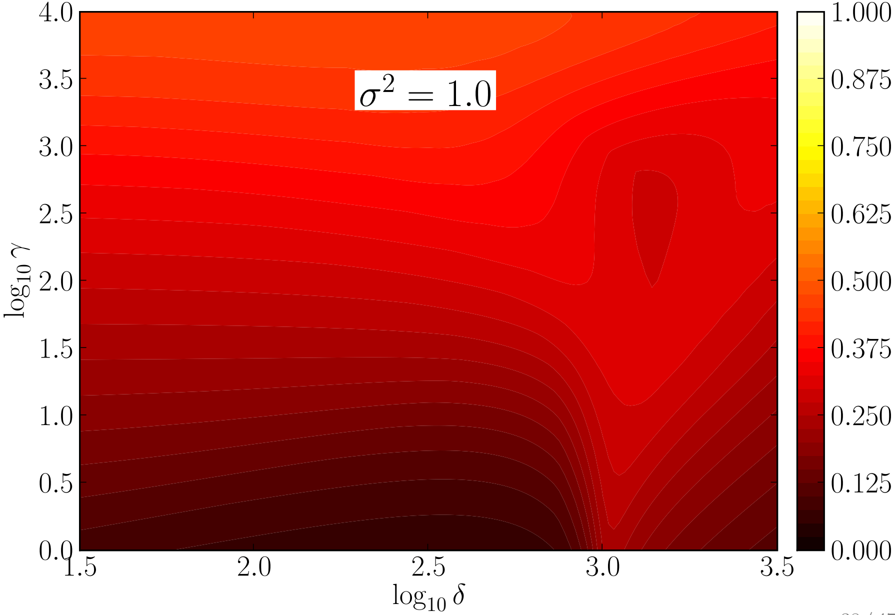
The price

Only spectral components with $\Omega \approx \Omega_0$ are detected.
Therefore,
information about signals shape is lost.

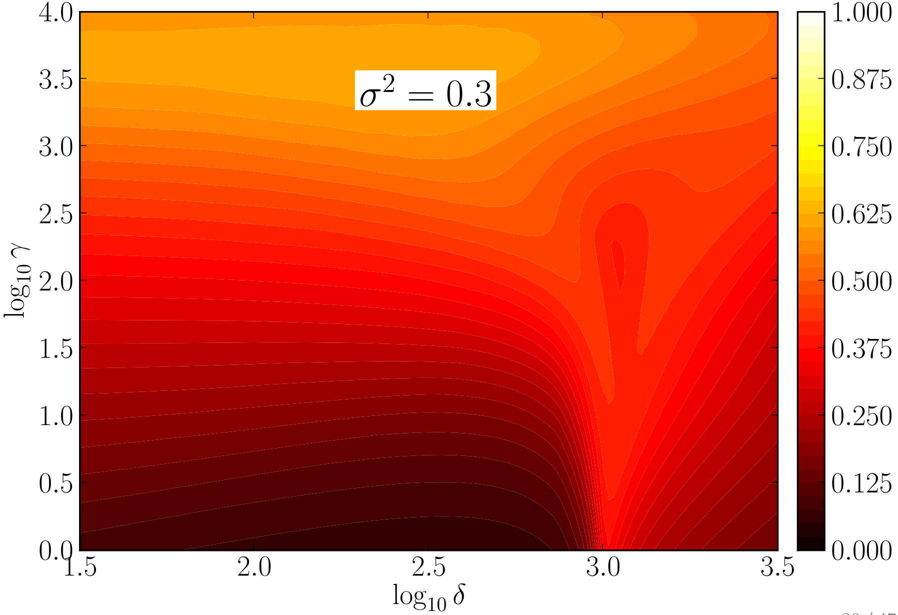
$\gamma - \delta$ plane



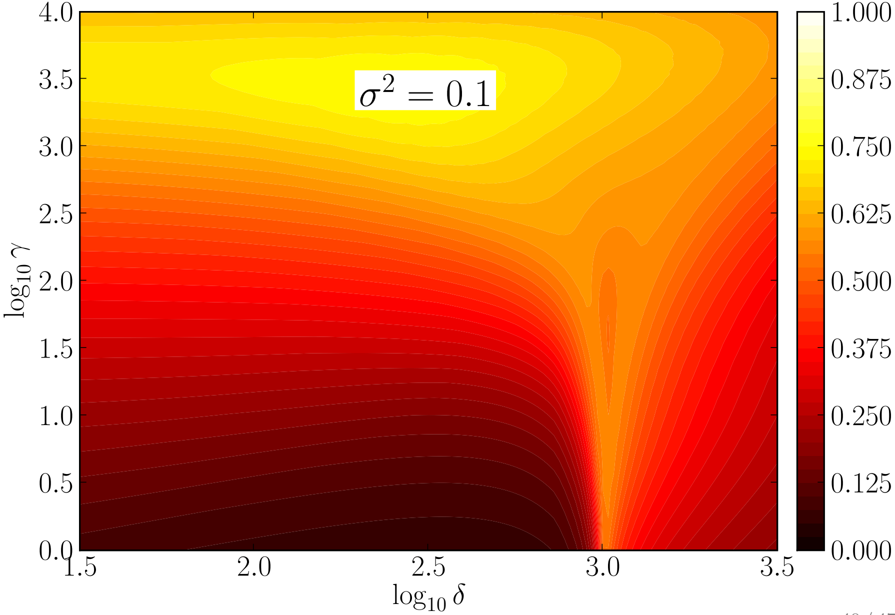
$\gamma - \delta$ plane



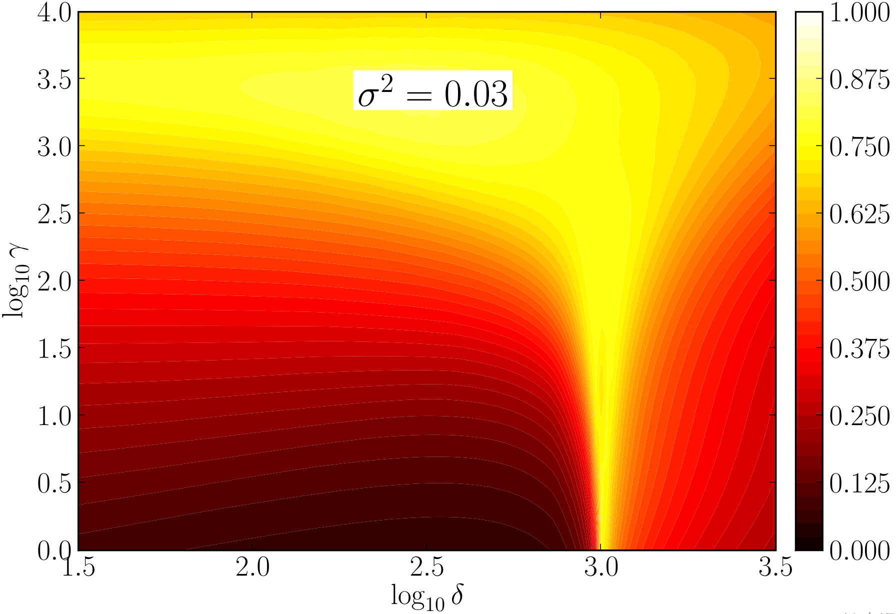
$\gamma - \delta$ plane



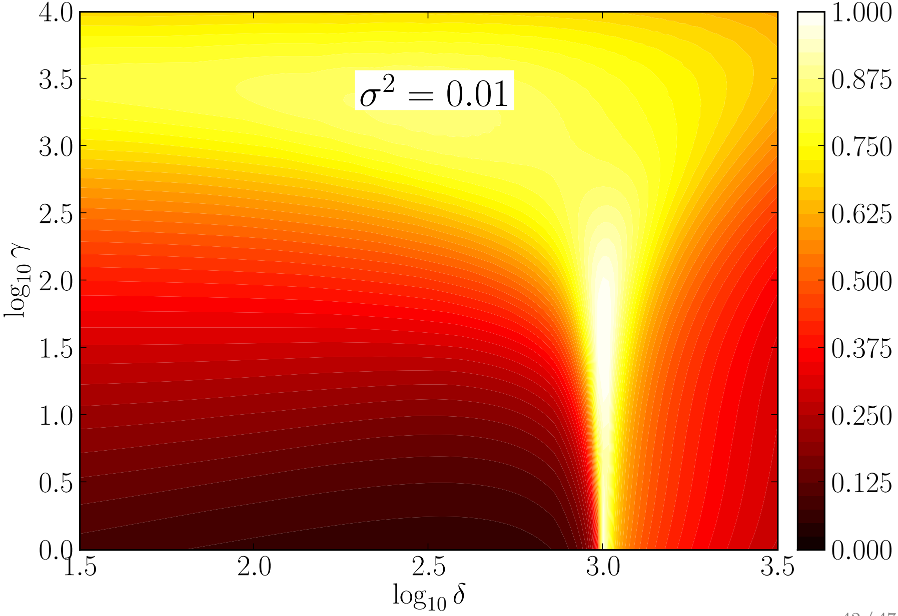
$\gamma - \delta$ plane



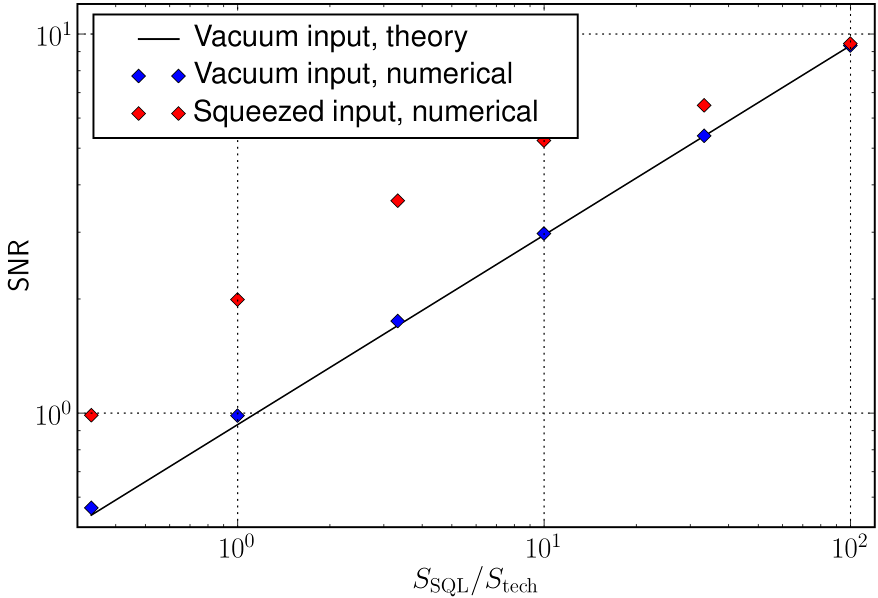
$\gamma - \delta$ plane



$\gamma - \delta$ plane



Gain in SNR


Vacuum input, theory
Vacuum input, numerical
Squeezed input, numerical
10^1
10^0
SNR
10^0
10^1
10^2
$S_{\mathrm{SQL}}/S_{\mathrm{tech}}$

Squeezed vs. vacuum

No significant gain in the sensitivity, but...

Squeezed vs. vacuum

No significant gain in the sensitivity, but...

Parameters for vacuum input:

$$\gamma = \frac{\Omega_0 \sigma^2}{\sqrt{2}(1+\sin^2\phi)} \approx 400\,\mathrm{s}^{-1} \times \sigma^2$$

$$T_{\mathrm{SRM}}^2 \approx \frac{4\gamma\gamma_{\mathrm{ARM}}}{\delta^2} \approx 10^{-3}\frac{\gamma}{1\,\mathrm{s}^{-1}} \approx 0.4\sigma^2$$

Therefore, for $\sigma^2 \ll 1$,

- γ appoaches γ_{loss} (not good!)
- special high-reflective SR mirror is required.

Squeezed vs. vacuum

Squeezed input "scales" γ:

$$\gamma_{\text{eff}} = \gamma e^{-2r} \, .$$

Therefore, moderate values of

$$\gamma \approx 10^2 - 10^3 \, \text{s}^{-1}$$

and "standard" SR mirror with

$$T^2_{\text{SRM}} \sim 0.1$$

can be used.

Conclusion

- The narrow-band double pole regime is (probably) the only way to increase the Advanced LIGO sensitivity without any hardware enhancements.
- The price is the loss of information about the signal shape.
- Squeezed vacuum injection do not increase the sensitivity significanty, but allows to use the standard "broadband" signal recycling mirror.