Reduction of coating thermal noise using coupled cavities

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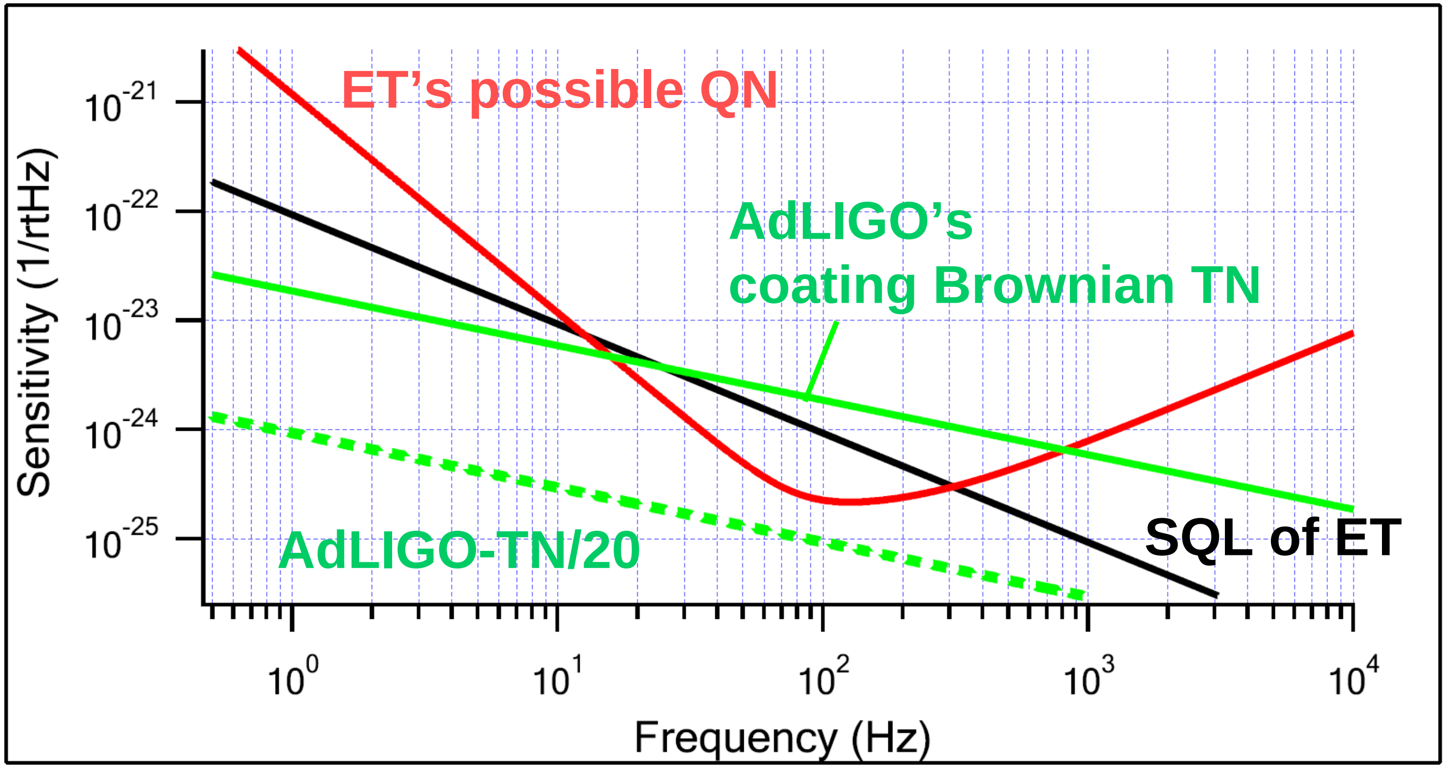
Coating thermal noise

(QN: 2MW FPMI or 500W RSE with RG 20 x SQ 20dB, 5% loss, w/filter cavity, L=5km, m=100kg, F=60 for FPMI)



We need a factor of 20 improvement from AdLIGO (16 if L=5km)

Coating thermal noise

How can we reduce TN by a factor of 16?

(256 in Sx)

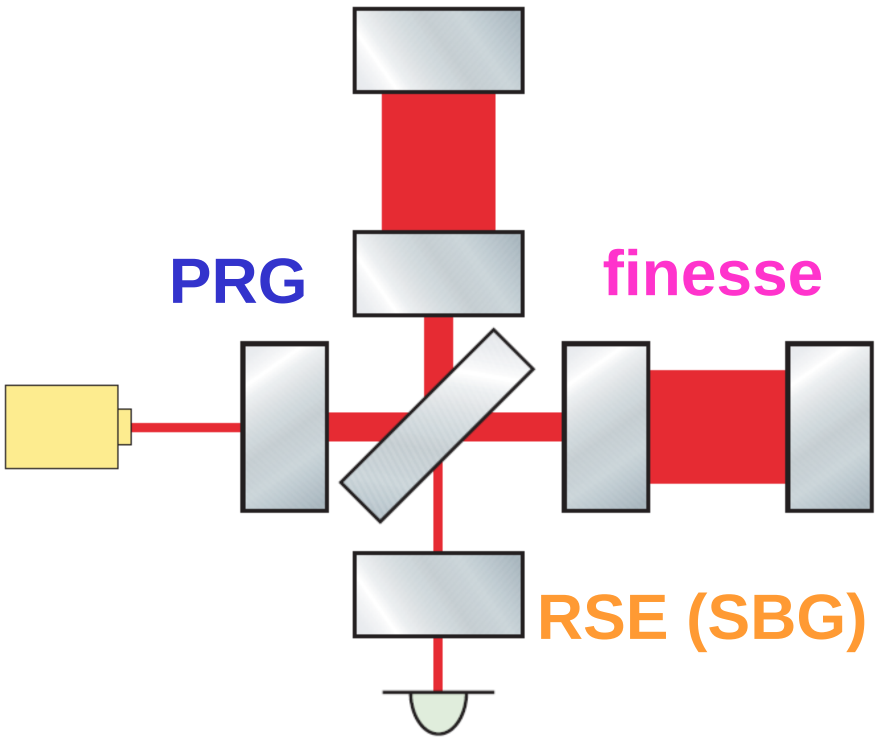
$$S_x(\Omega) = \frac{4k_{\rm B}T}{\Omega}\frac{(1+\sigma_c)(1-2\sigma_c)2d_{\rm coa}}{\pi E_c w_0^2}\phi_c$$

- T could be reduced by 20 (cryogenic)
- ϕ_c could be reduced by 2 (doped tantala)
- w_0 could be increased by 1.36 (larger mass)
- w_0 could be effectively increased by 1.4 (mesa beam)

We need another factor of 3~4 improvement

How? → Let us decrease d_{coa} (=λ/4xN/n)

Power balance



Ex.1

F=1250, PRG=15, SBG=20

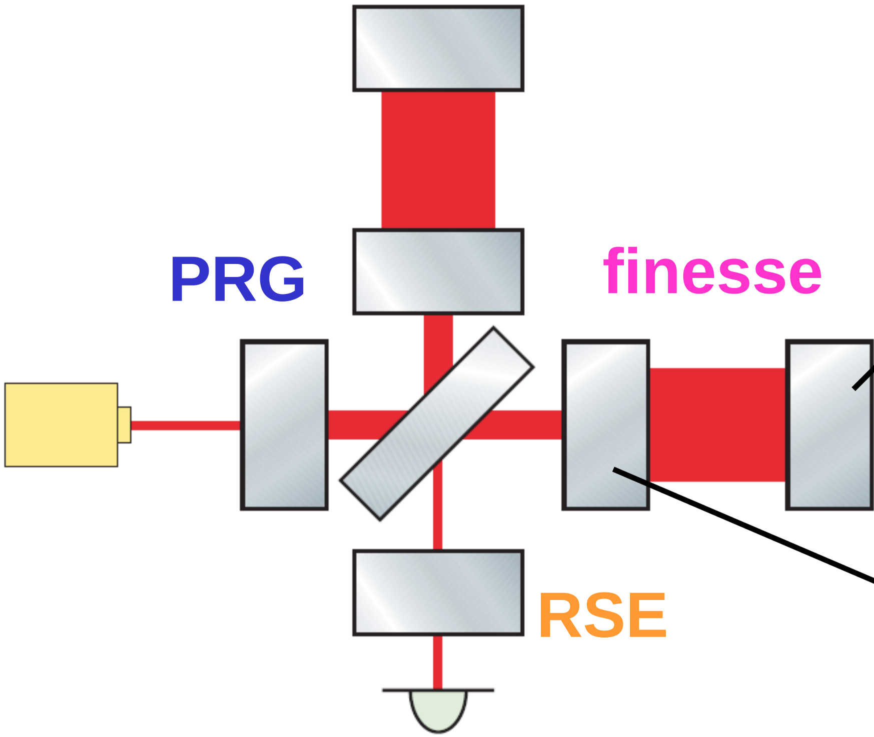
Ex.2

F=625, PRG=30, SBG=10

QN curves are same.
What's the difference?

- The lower the finesse, the higher laser noise and BS noise
- The lower the finesse, the less coating on ITM
- (Practical difference; imbalances, heat problem, etc.)

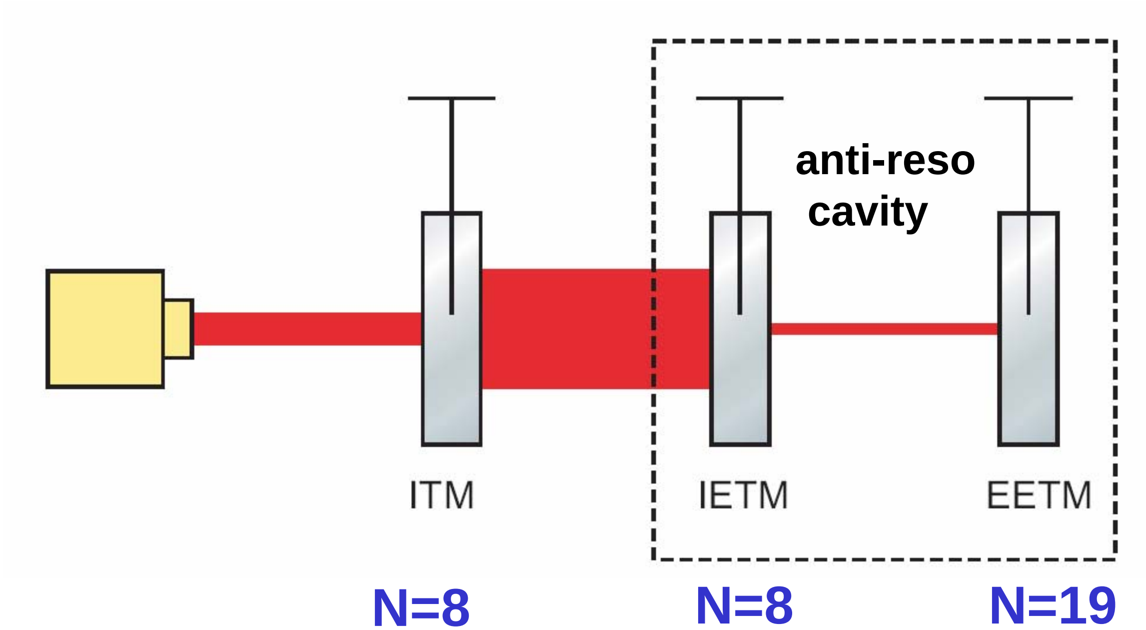
Lowering the ITM reflectivity



- However, the benefit is small (~only 4% improvement in Sx)
- Contribution of the ETM is much larger

End-mirror cavity

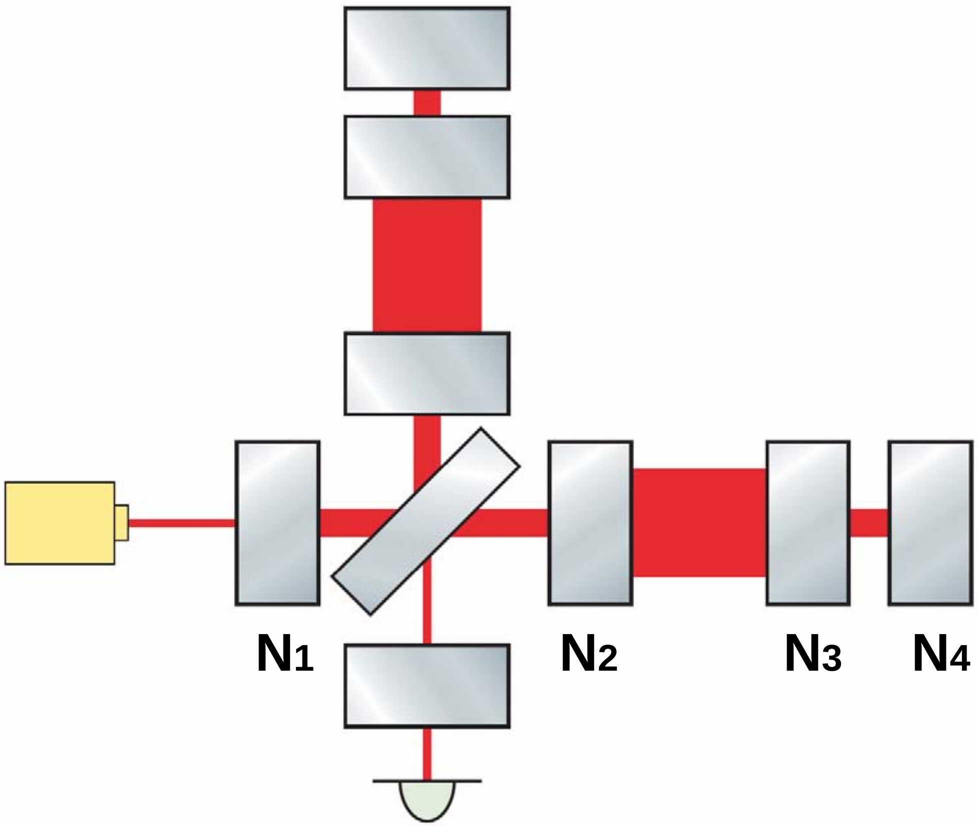
[F.Khalili 2005]



- **Almost same reflectivity with less coatings**
- **Heat problem is as small as the ITM**
- **EETM noise is negligible**

- **Coating noise is reduced by 16/27 in Sx**
- **Can we further decrease N?**

4-mirror cavity system



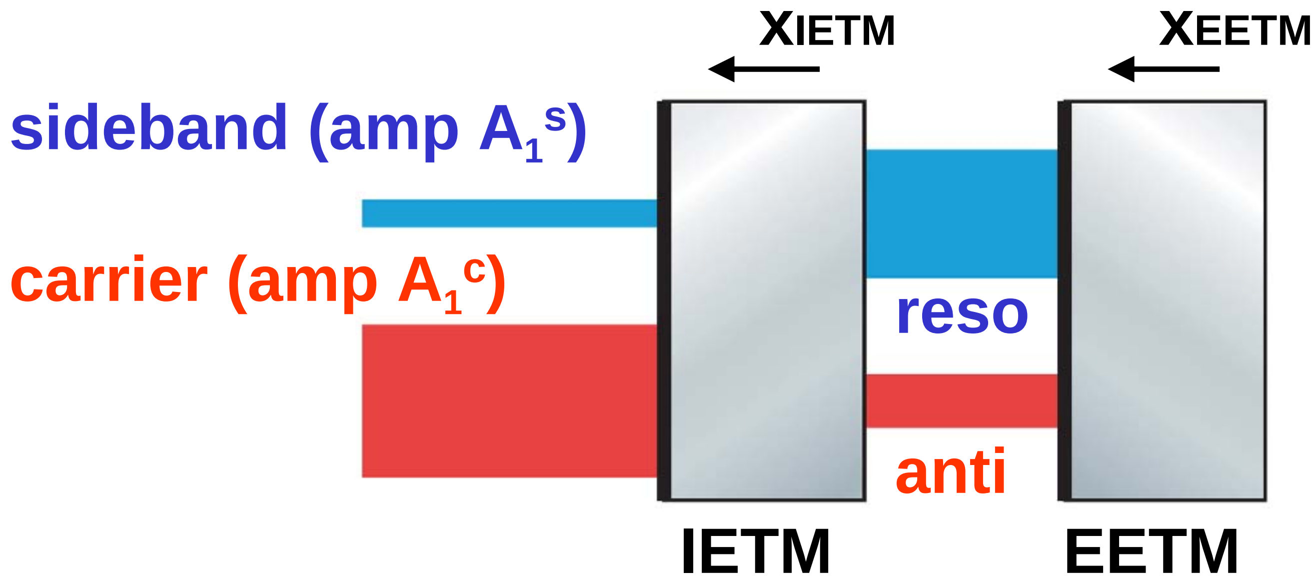
Reduction of N_2 is effective as we reduce N_3 at the same time.

On the other hand, reducing N_2 and N_3 results in…

- noise from EETM and BS
- TR noise from ITM, IETM sub.
- laser noise, heat problem, etc.

These can be suppressed by control!!

Rigid end-mirror cavity



output after the cancellation of x_{EETM}

RP noise of SB!

$$z_2 = a_2^c - \tilde{r}\mathcal{K}a_1^c + \frac{\sqrt{2\mathcal{K}}}{x_{SQL}}\tilde{r}x + \underbrace{\frac{A_1^c(1-r)^2}{A_1^s(1+r)^2}a_2^s - \tilde{r}\mathcal{K}\frac{A_1^s}{A_1^c}a_1^s}_{\text{excess ctrl noise}}$$

vacuum field

$$\mathcal{K} = \frac{8I_0\omega_0}{m\Omega^2 c^2}$$

excess ctrl noise

QL of excess ctrl noise

excess ctrl noise = $$\frac{A_1^{c}(1-r)^2}{A_1^{s}(1+r)^2} a_2^{s} - \tilde{r}\mathcal{K}\frac{A_1^{s}}{A_1^{c}} a_1^{s}$$

vacuum field

$$\mathcal{K} = \frac{8 I_0 \omega_0}{m \Omega^2 c^2}$$

There is a minimum with appropriate A_1^s/A_1^c at each freq.

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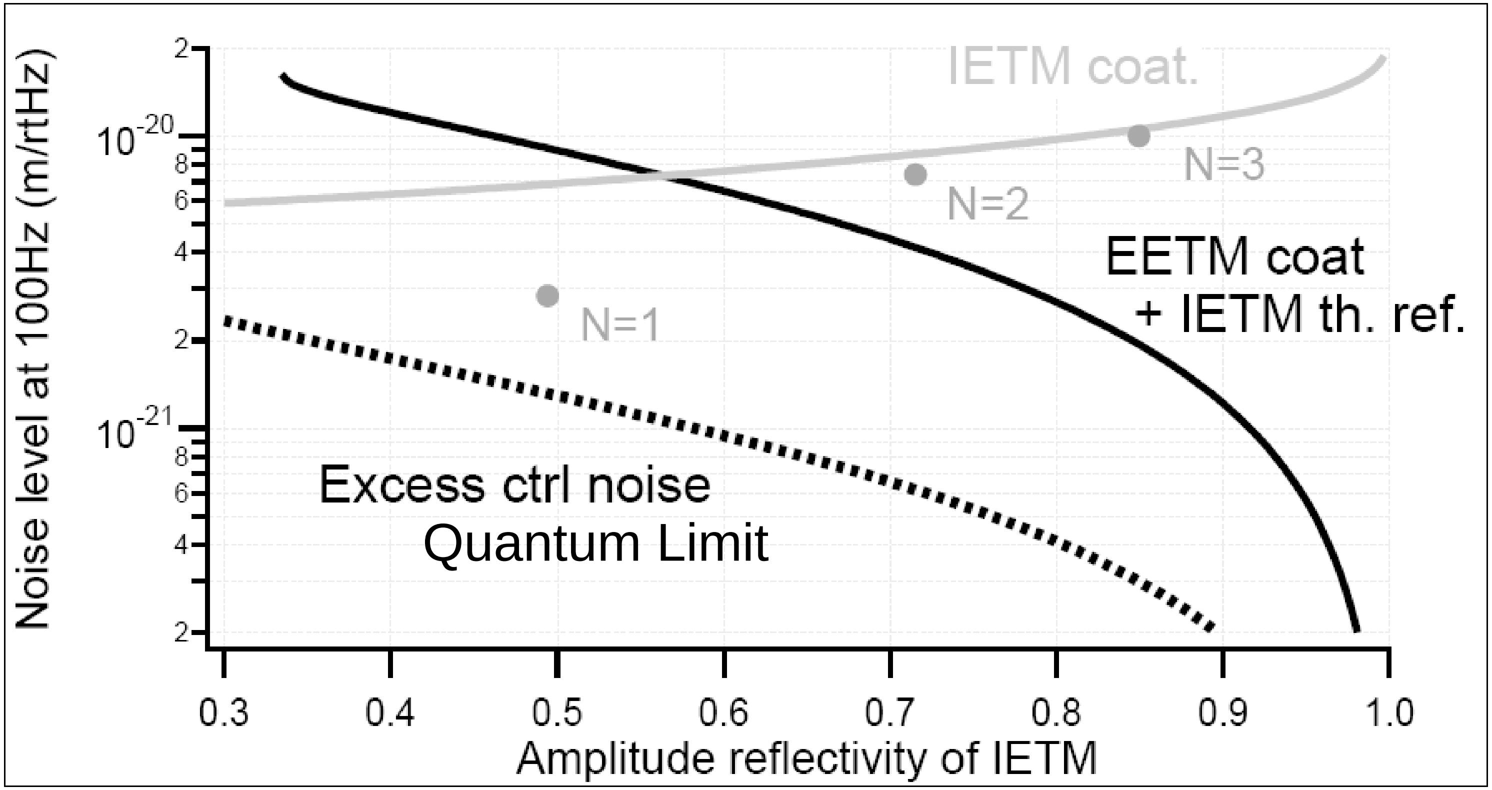
Quantum Limit of excess ctrl noise!!

QL of excess noise vs TN of ETMC

[quant-ph 0811.1780v]



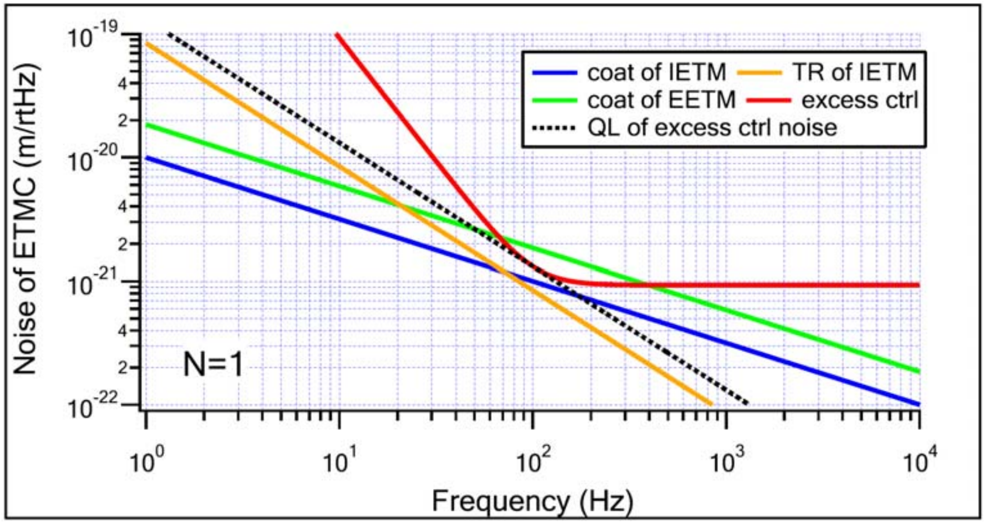
m=40kg
T=300K

- **without the rigid control, N=2 is the optimal number**
- **with the rigid control, N=1 is the optimal number**

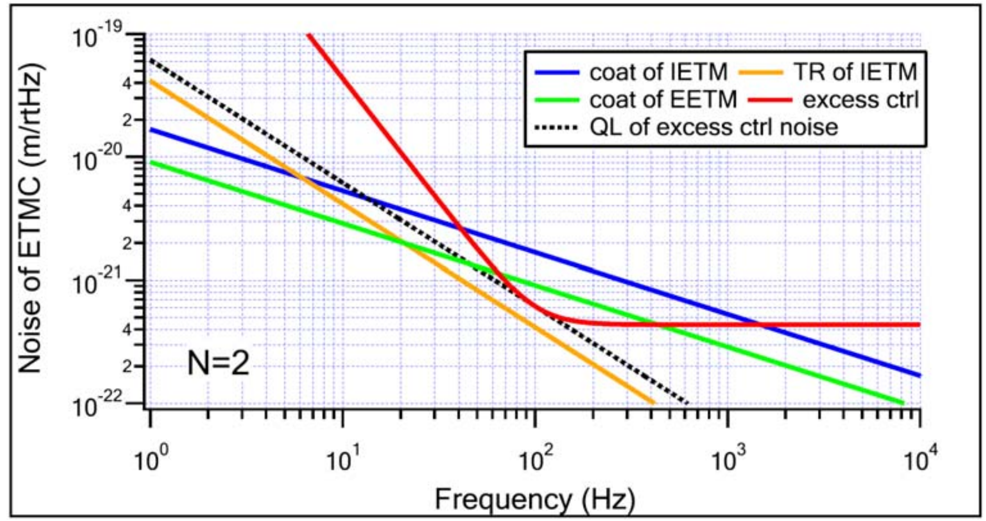
Note that QL can be reached only at one frequency

QL of excess noise vs TN of ETMC

m=40kg, T=300K



(SB/Ca=570%)



(SB/Ca=52%)

Total noise level of ETMC

N=1 w/o ctrl: 2.27e-21 m/rtHz at 100Hz

N=2 w/o ctrl: 1.95e-21 m/rtHz at 100Hz

N=1 with ctrl: 1.65e-21 m/rtHz at 100Hz

N=2 with ctrl: 1.79e-21 m/rtHz at 100Hz

QND control of ETMC

We can do a sort of *variational readout scheme*

~ Feeding back the RPN information to EETM so that RPN of IETM cancel.

$$z_2^{\mathrm{VR}} = a_2^{\mathrm{c}} - \tilde{r}\mathcal{K} a_1^{\mathrm{c}} + \frac{\sqrt{2\mathcal{K}}}{x_{\mathrm{SQL}}}\tilde{r}x + \frac{A_1^{\mathrm{c}}(1-r)^2}{A_1^{\mathrm{s}}(1+r)^2}\left(a_2^{\mathrm{s}} + \underbrace{a_1^{\mathrm{s}}\tan\zeta) - \tilde{r}\mathcal{K}\frac{A_1^{\mathrm{s}}}{A_1^{\mathrm{c}}}a_1^{\mathrm{s}}}_{\text{RPN can be cancelled}}\right.$$

readout phase (ζ)

RPN can be cancelled

- **VR + Filter + high-power SB ⟹ no excess noise!**
- **N=0 is in principle possible (no coating noise)!**

Summary

- We need a factor of 2~4 reduction of coat TN for ET
- Conventional end-mirror cavity helps a factor of 1.3
- The more decreasing N, the more EETM noise
- EETM noise can be suppressed by a control
- The control imposes excess shot noise
- Increasing the ctrl SB power results in RP noise
- Quantum limit of excess ctrl noise exists
- QND control can erase excess noise
- Coating-free is in principle possible
- Heat problem will be an issue