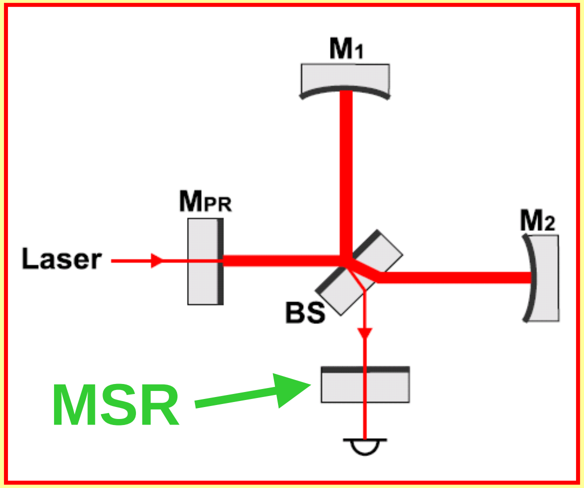
Comparison of tuned and detuned Signal-Recycling

Stefan Hild for the GEO-team

Signal-Recycling in short

An additional recycling mirror (MSR) at the dark port allows:

- **enhancing the GW signal**
- **shaping the detector response**



Two main parameters:

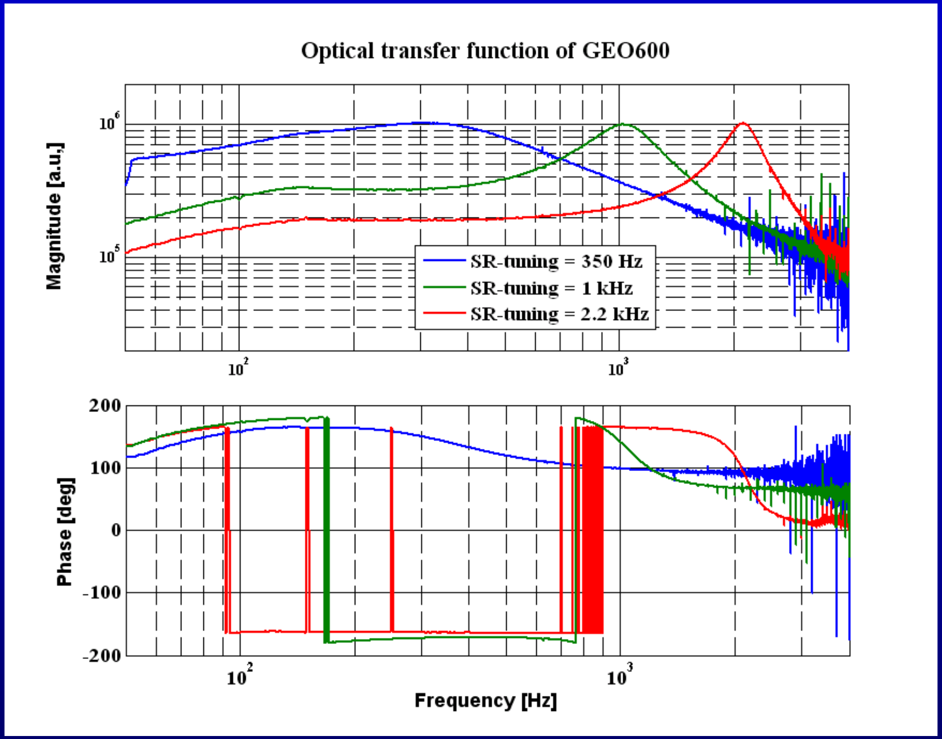
- **Bandwidth** (of the SR resonance) → broadband / narrowband
- **Tuning** (Fourier frequency of the SR resonance) → tuned / detuned

SR-Tuning in GEO so far

- For various reason we are not able aquire lock for tuned SR.
- Lock takes place at a detuning of a few kHz.
- Afterwards the aquisition detector is tuned to ist operation point.
- So far tunings between 5kHz and 250 Hz had been realized.

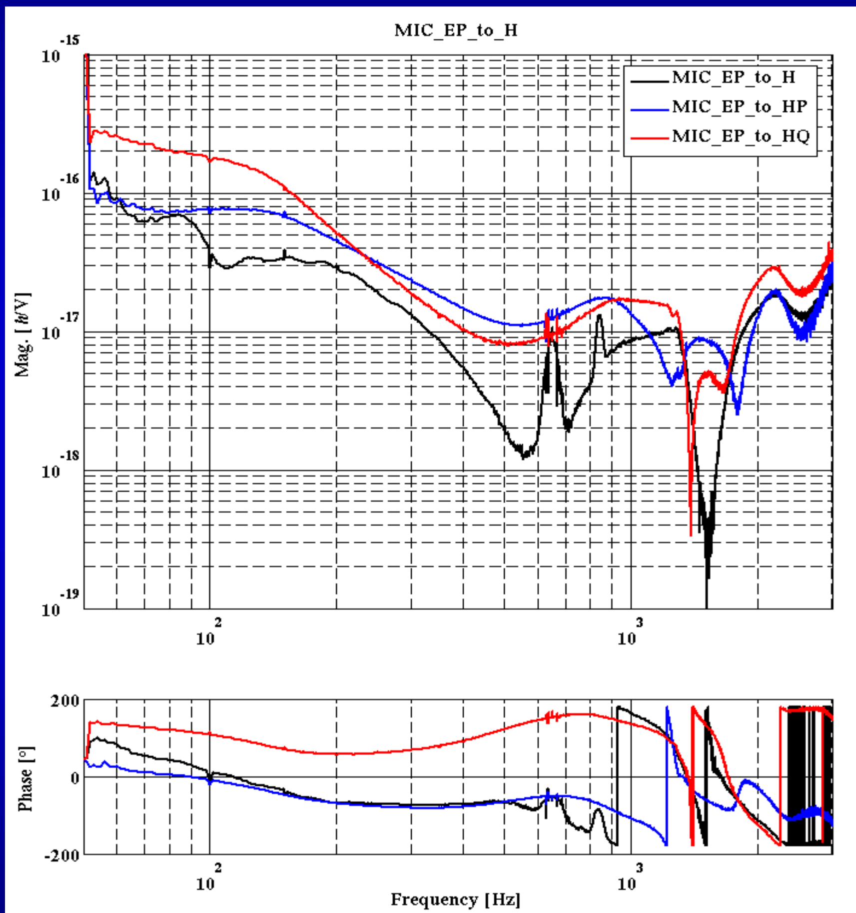
<u>Downtuning in steps of 25 Hz, 6 Parameters need to be adjusted:</u>

- SR frequency
- SR gain
- SR phase
- MI gain
- MI phase
- MI autoalignment gain

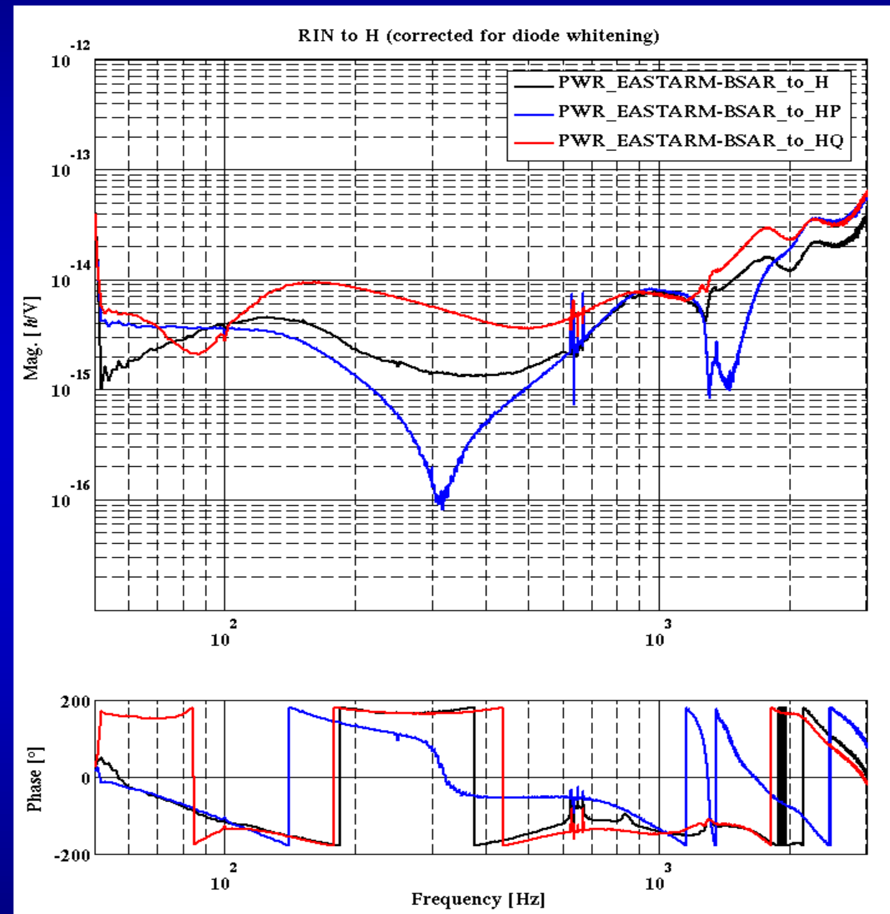


Motivation (1):
Detuned SR complicates noise couplings and TFs

Frequency noise coupling to h(t)

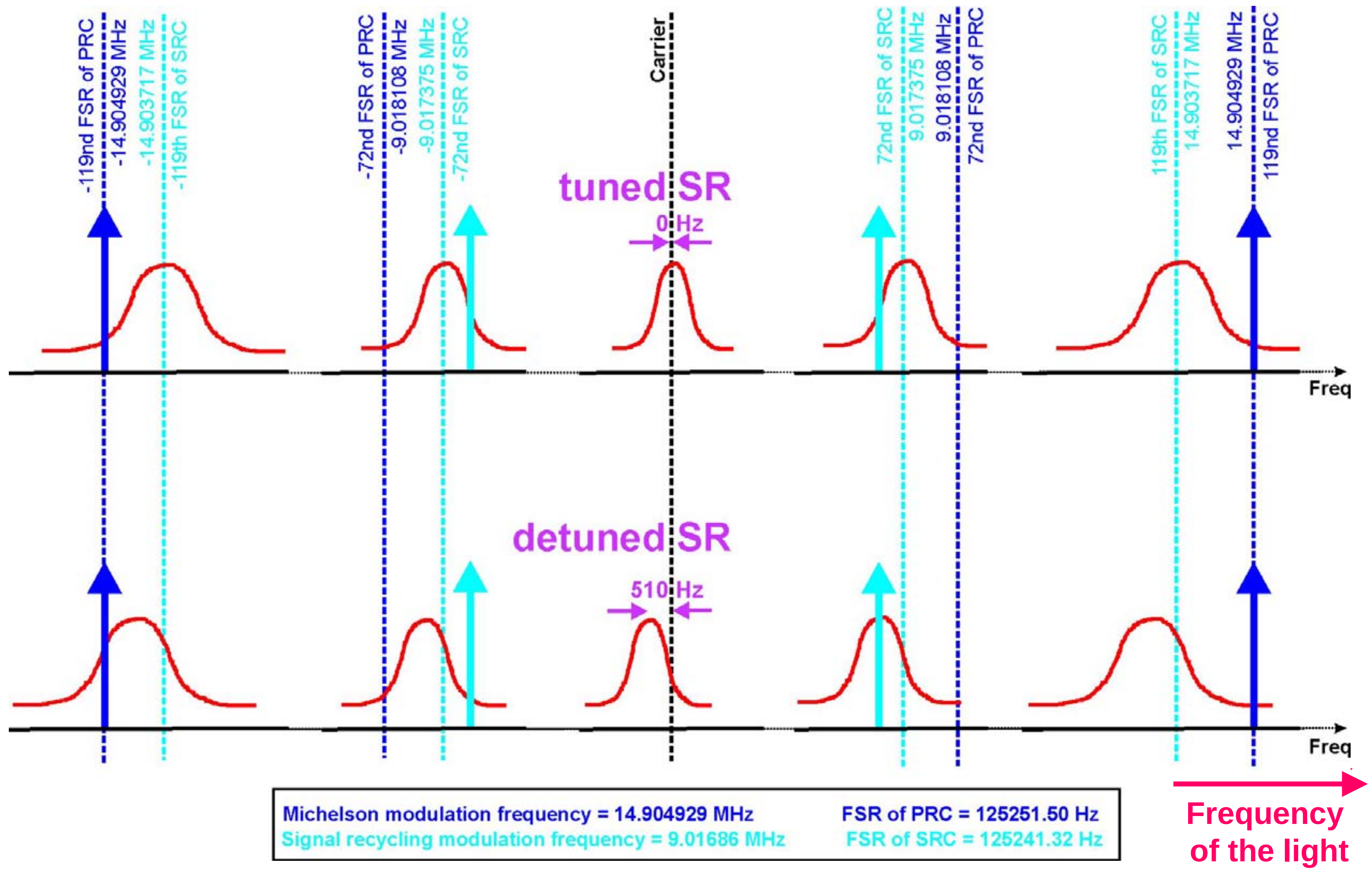


Laser intensity noise coupling to h(t)

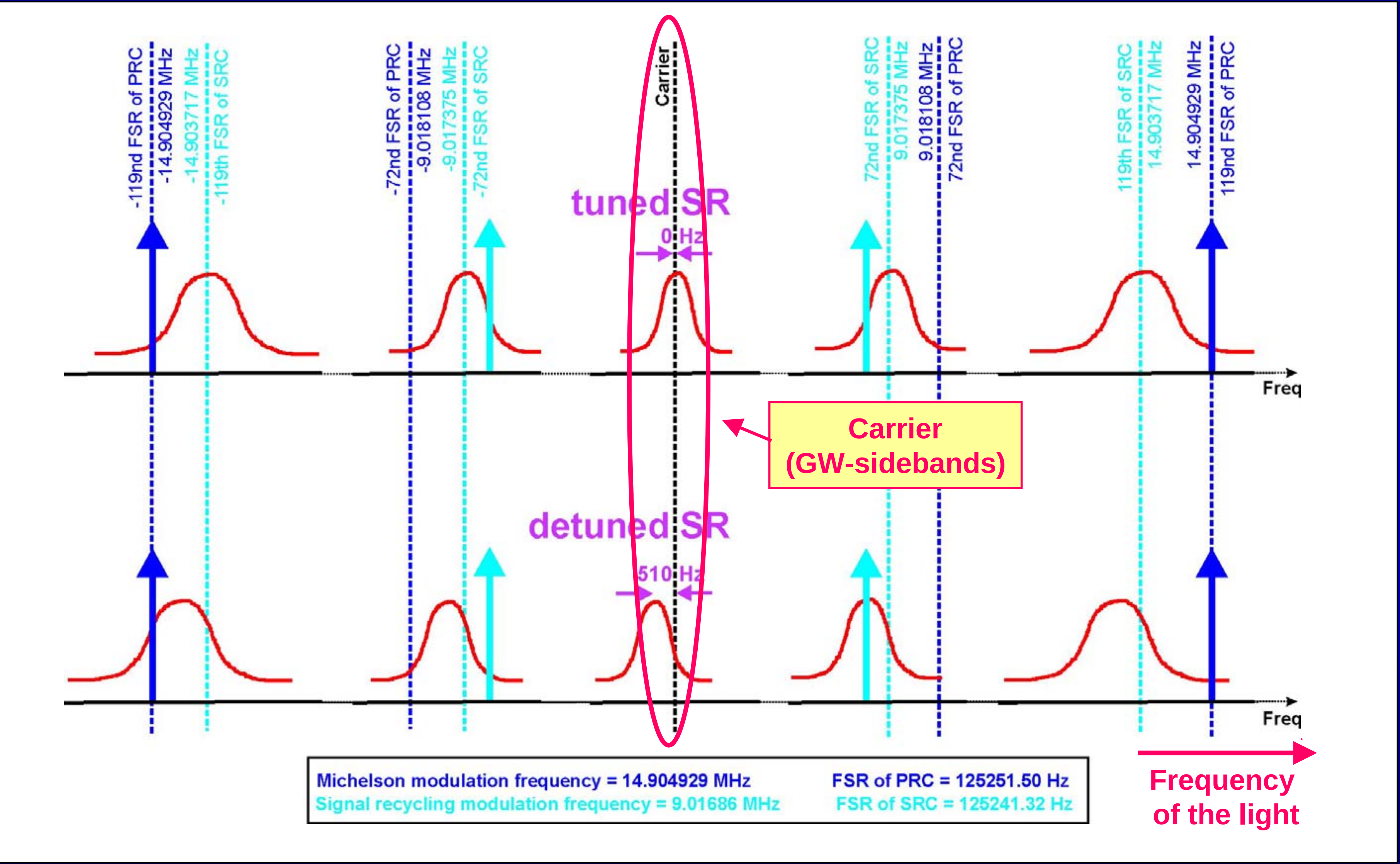


In a detuned detector TF may become complicated due to interaction and different resonance conditions of various sidebands.

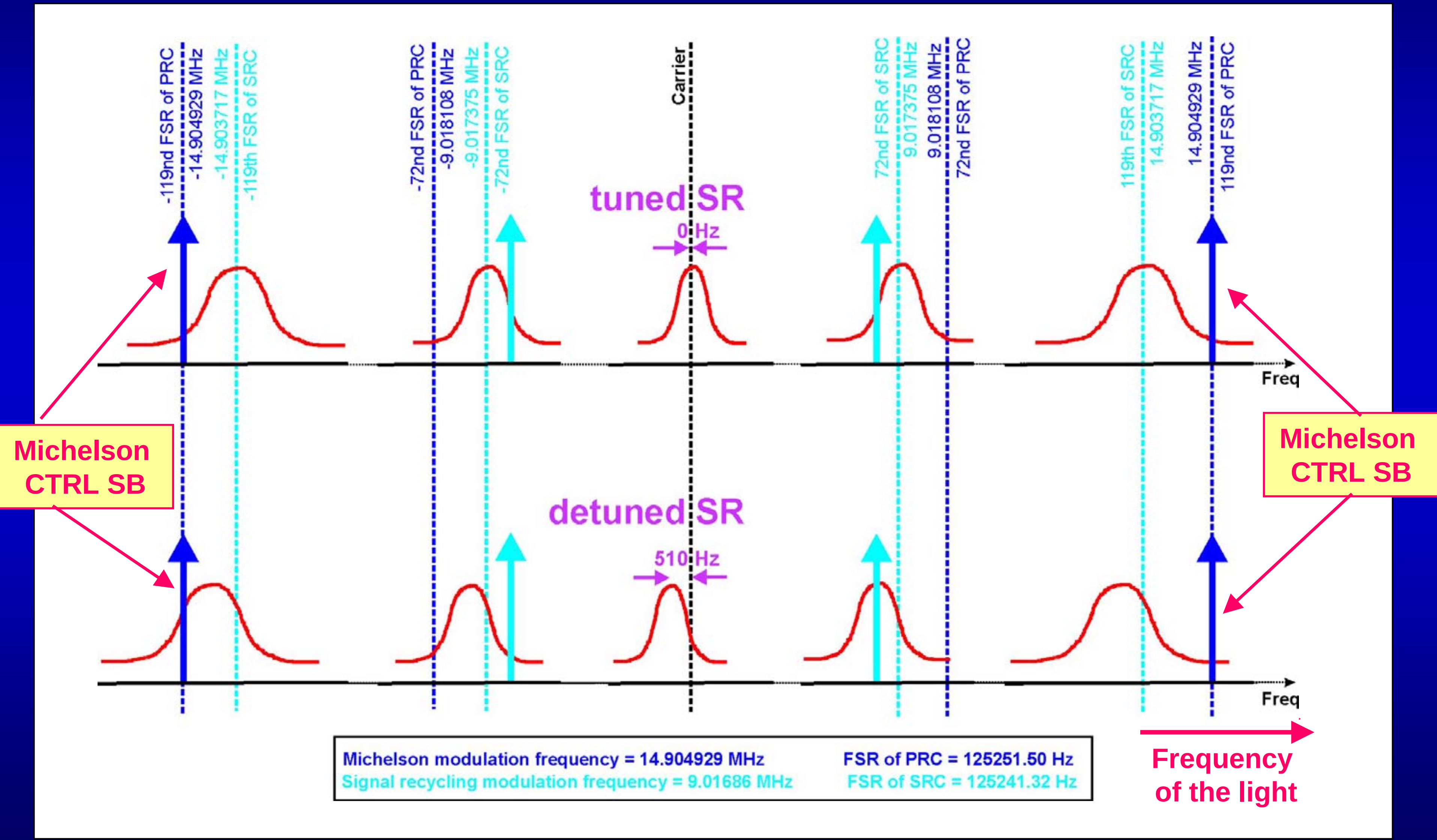
Motivation (2):
Sideband picture for tuned and detuned SR



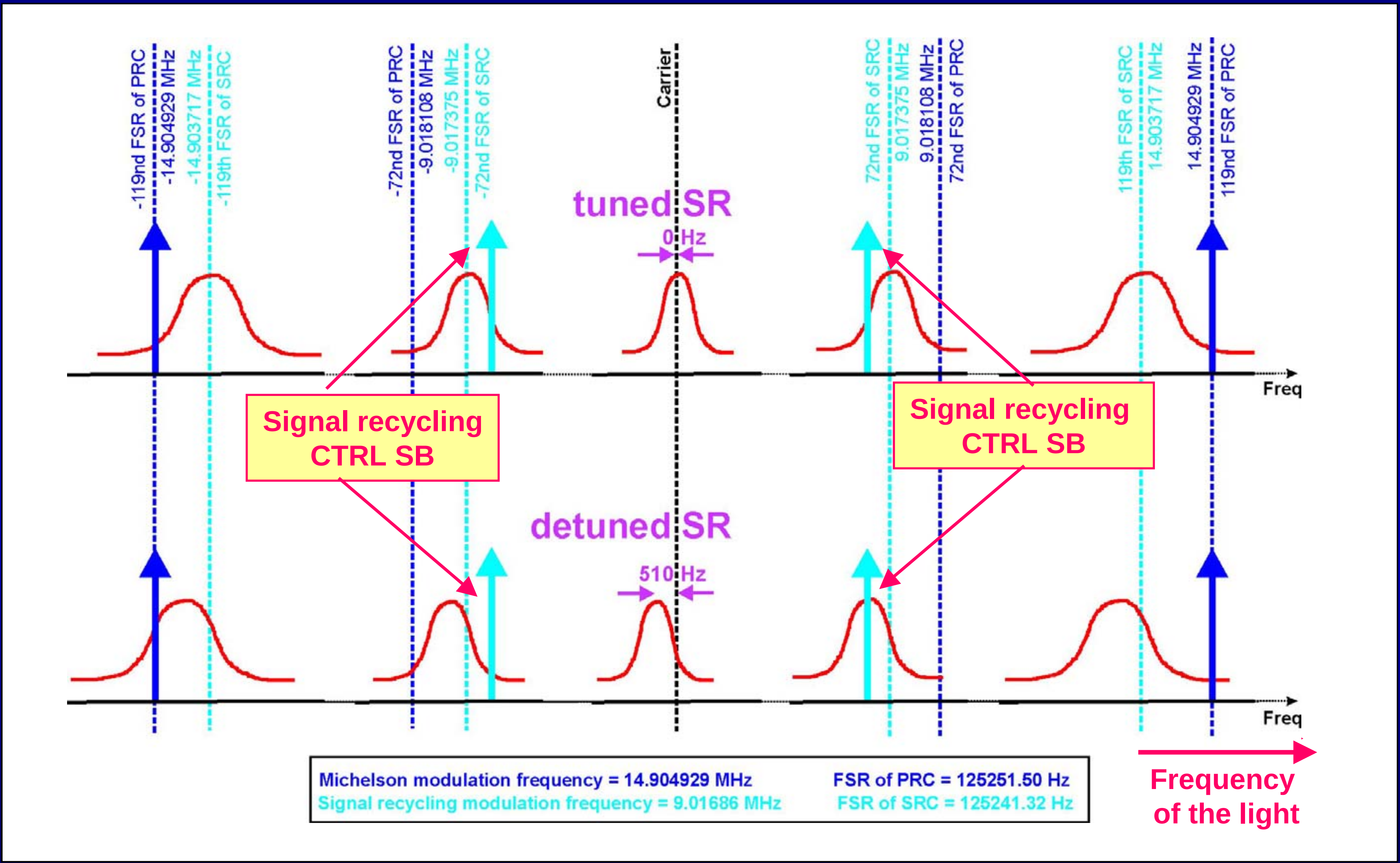
Motivation (2):
Sideband picture for tuned and detuned SR



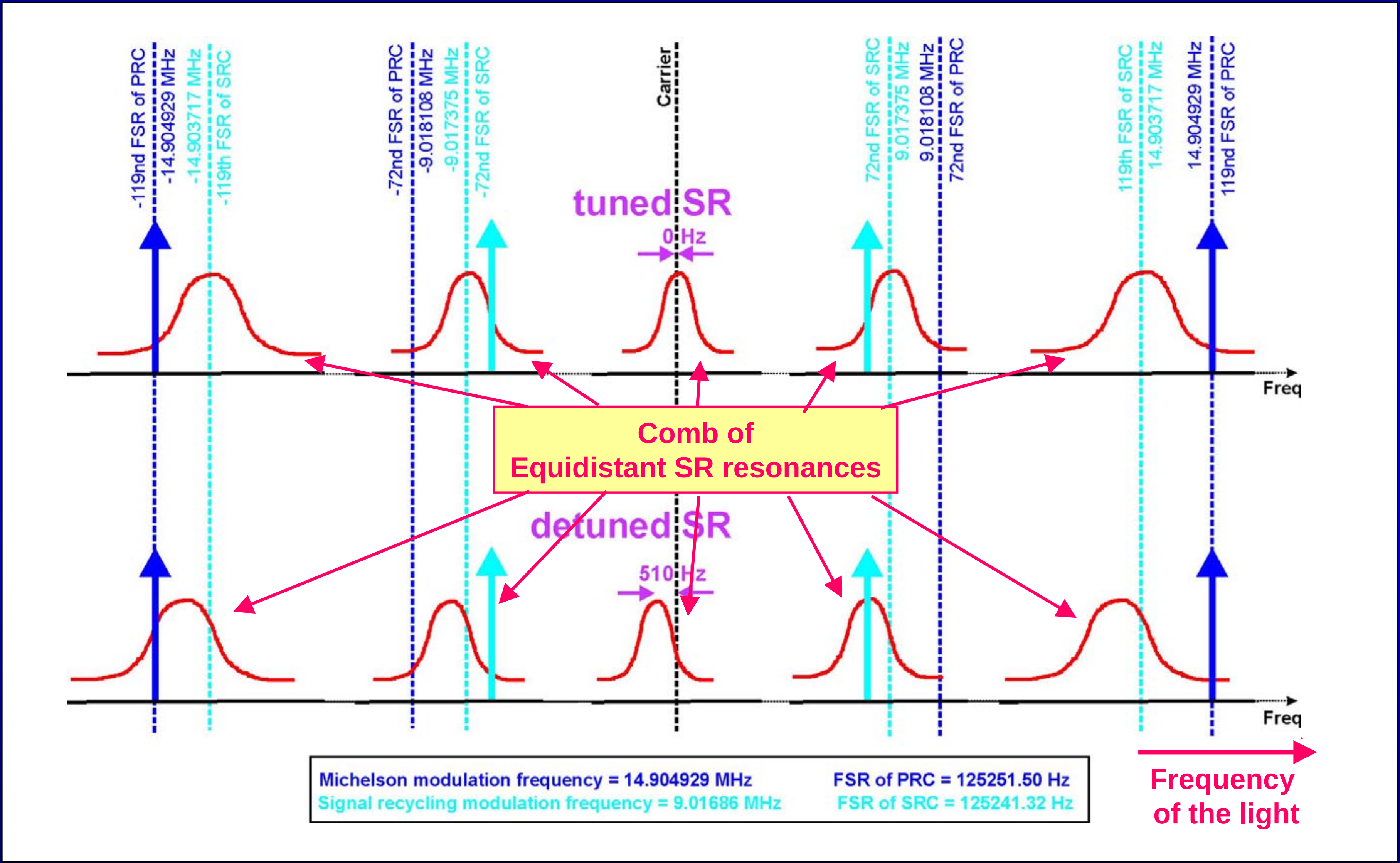
Motivation (2): Sideband picture for tuned and detuned SR



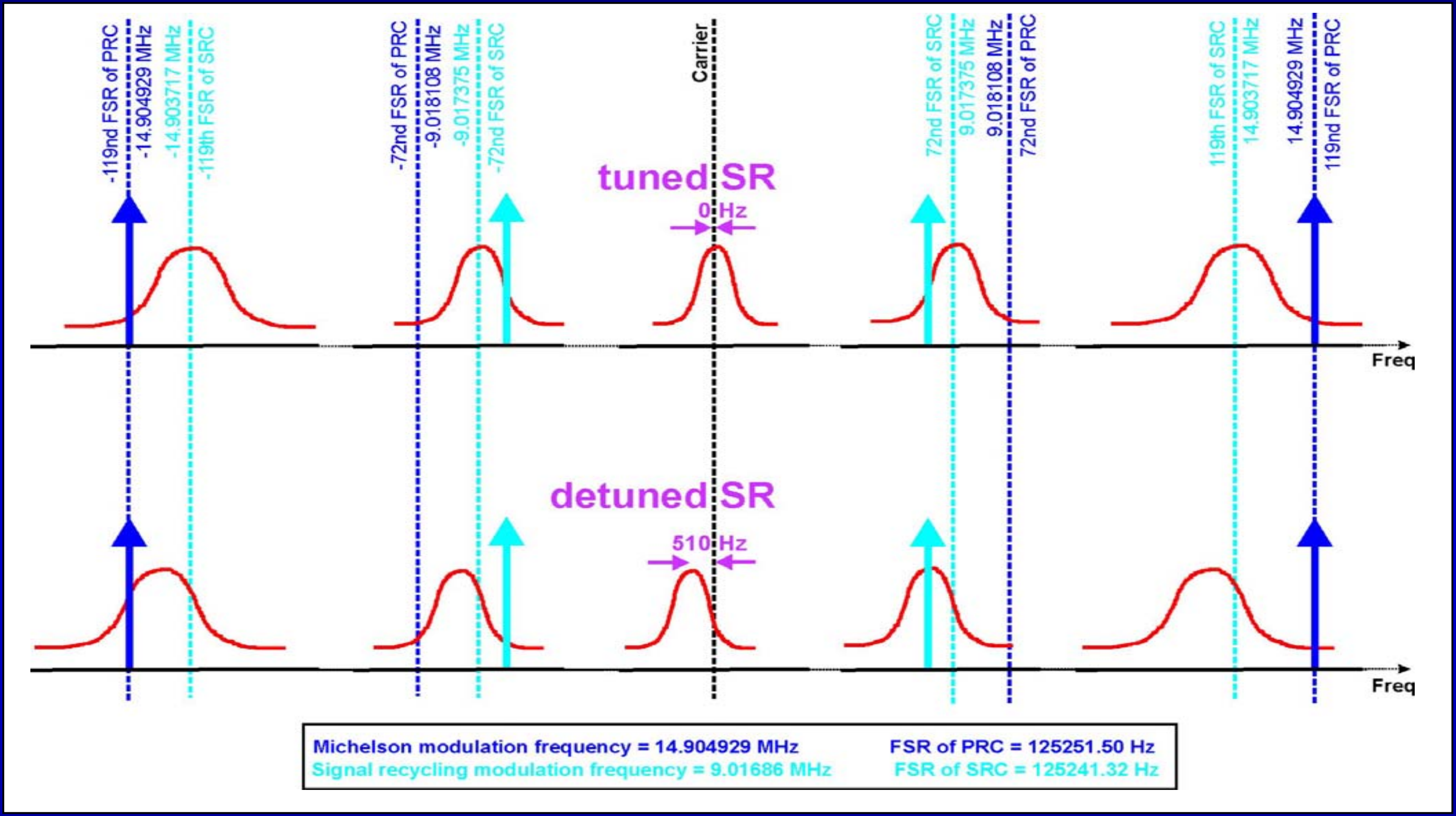
Motivation (2):
Sideband picture for tuned and detuned SR



Motivation (2): Sideband picture for tuned and detuned SR

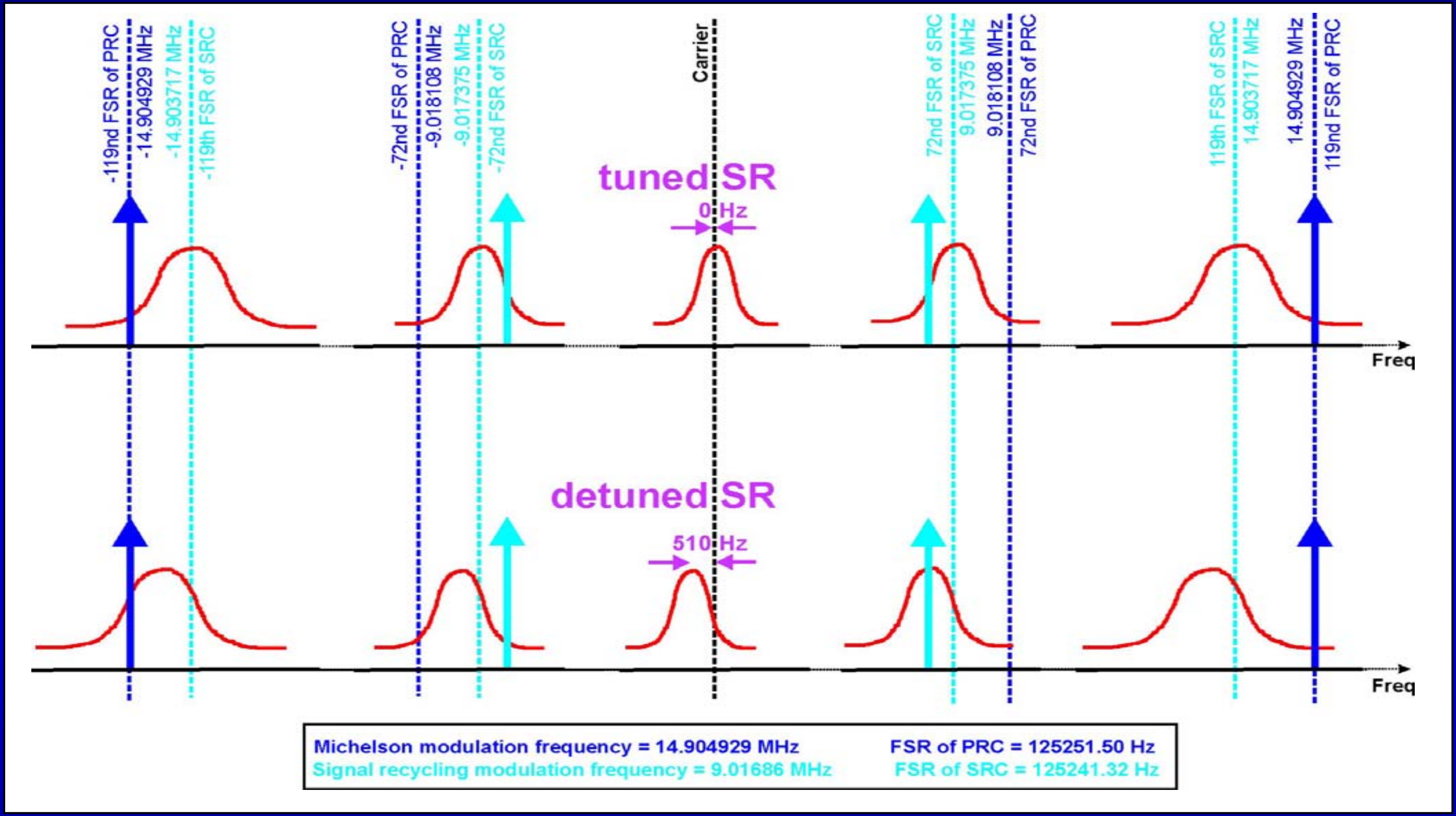


Motivation (3): Sideband picture for detuned SR (510 Hz)



- MSR is locked onto upper SB => each SR resonances is 510 Hz left of a FSR of SRC.
- Upper SR-SB resonant, lower SR-SB off resonance.
- Lower MI-SB nearly resonant, upper MI-SB far off resonance.
- Upper and lower GW signal see different completely different resonance condition.

Motivation (4): Sideband picture for tuned SR



- Going form detuned (510Hz) to tuned: comb of SR resonances is shifted 510 Hz to the right.
- Upper and lower SR-SB see the same resonance condition (nearly resonant).
- Upper and lower MI-SB see the same resonance condition.
- Upper and lower GW signal SB see the same resonance condition.

Motivation for tuned SR

There is the possibility:

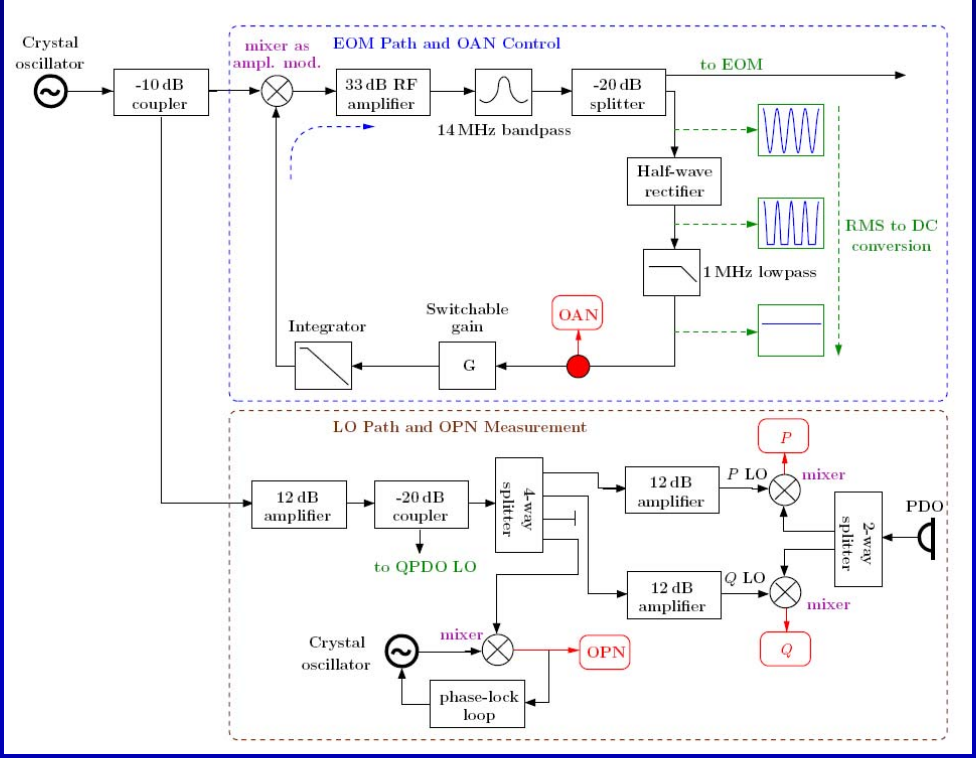
- Get better noise performance due to symmetric sidebands.

Phase noise in P originates from big DC in Q

We believe that a large contribution of the phase noise in P originates from a large DC signal in the Q quadrature.

Therefore it would be nice to reduce the DC signal in Q.

(see Josh's talk)



Here a large DC signal in the Q quadrature mixes OPN of the LO strongly into the P quadrature,

$$\phi_P = \langle Q \rangle \phi_{\mathrm{OPN}}, \tag{3.10}$$

where ϕ_P is the phase noise contribution to P, ϕ_{OPN} is the OPN of the LO signal, and $\langle Q \rangle$ is the time-averaged (DC) signal in Q

Motivation for tuned SR

There is the possibility:

- Get better noise performance due to symmetric sidebands.
- Less RF amplitude modulation on main photodiode (reduction of potential saturation / nonlinear effects)

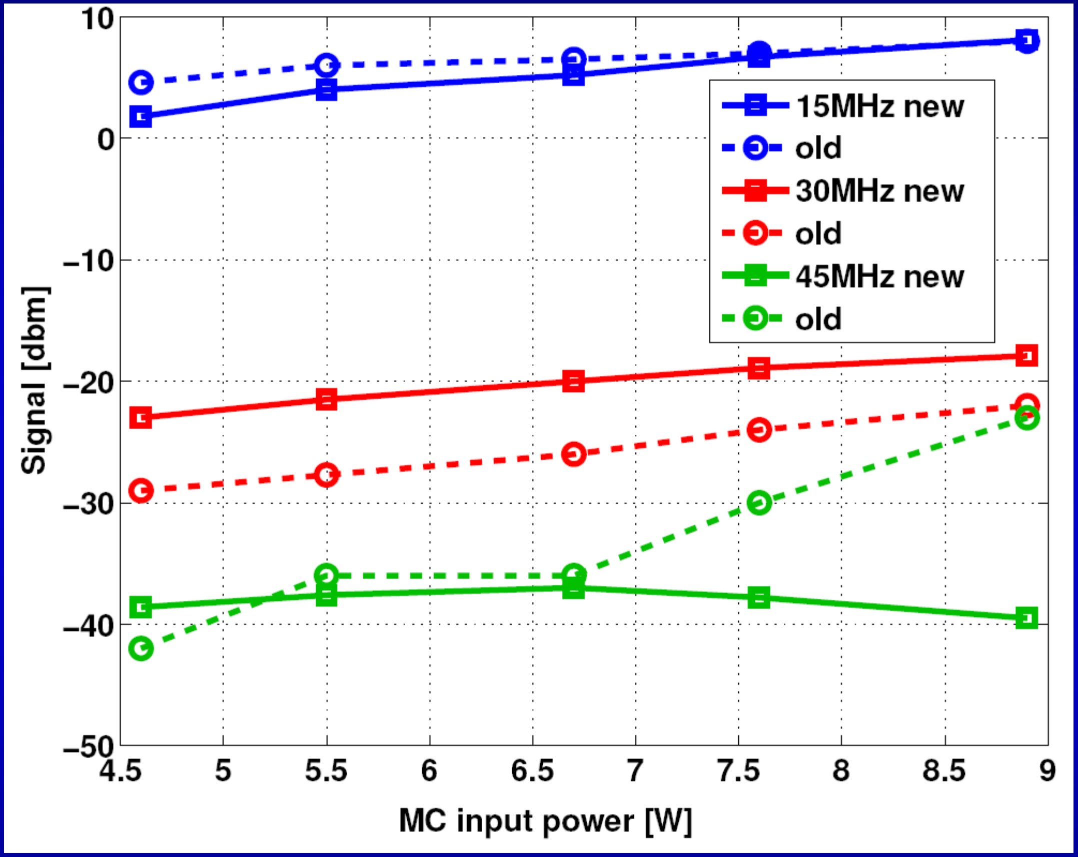
Saturation in our main photo diode

We believe we saw some saturation in the main photodiode due to the large RF amplitude modulation (Q-DC).

The signal voltage (1V @15MHz) modulated the bias voltage (5V) by about 20%.

Problem was for the moment (higher bias, different circuit).

For long term it would be desirable to reduce Q-DC !!



High-power, low-noise, and multiply resonant photodetector for interferometric gravitational wave detectors

Grote H [1§]

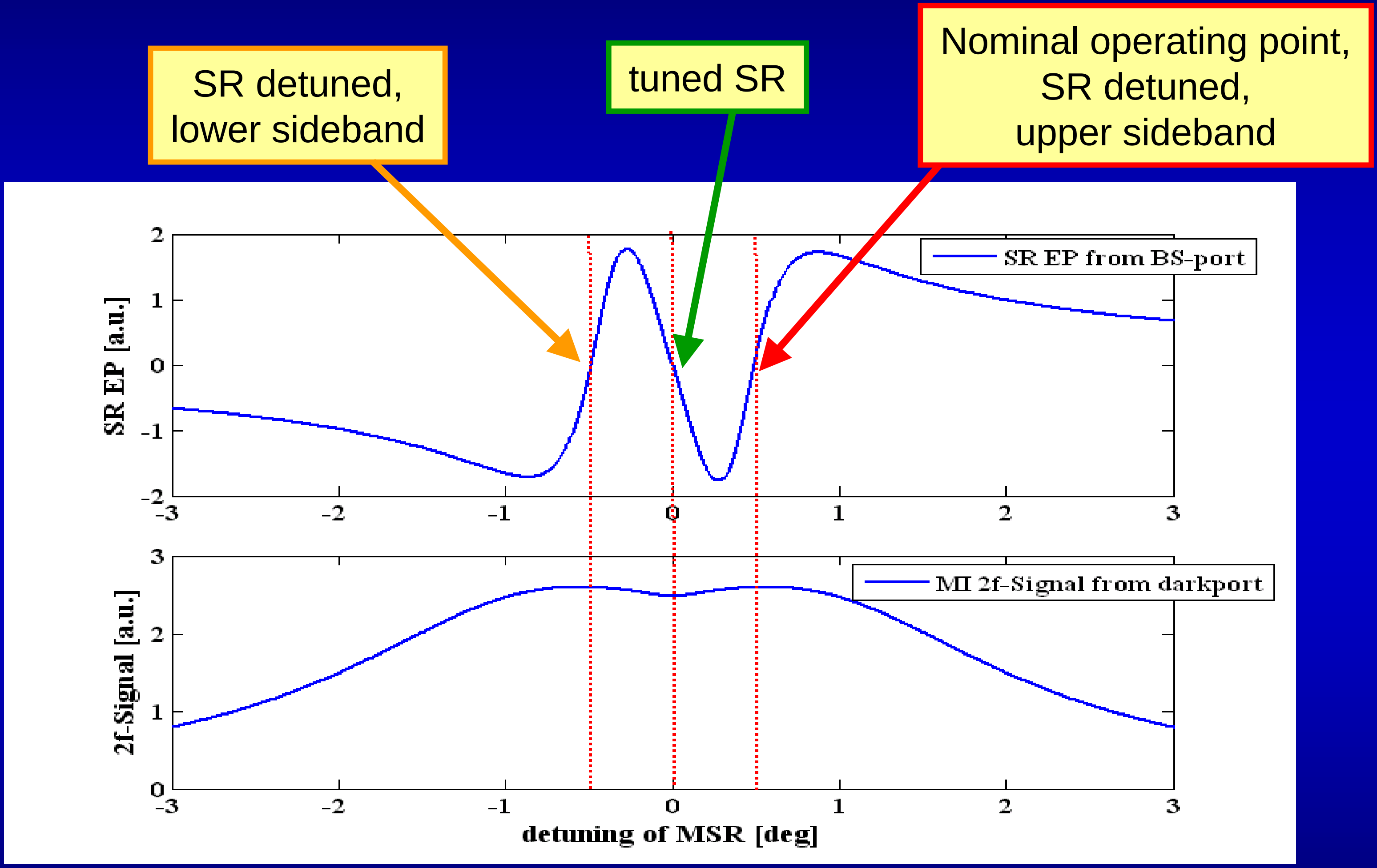
Motivation for tuned SR

There is the possibility:

- Get better noise performance due to symmetric sidebands.
- Less RF amplitude modulation on main photodiode (reduction of potential saturation / nonlinear effects)
- Get simpler noise couplings and transferfunctions.
- Get a better understanding of the detector.

- Nice research / demonstration project

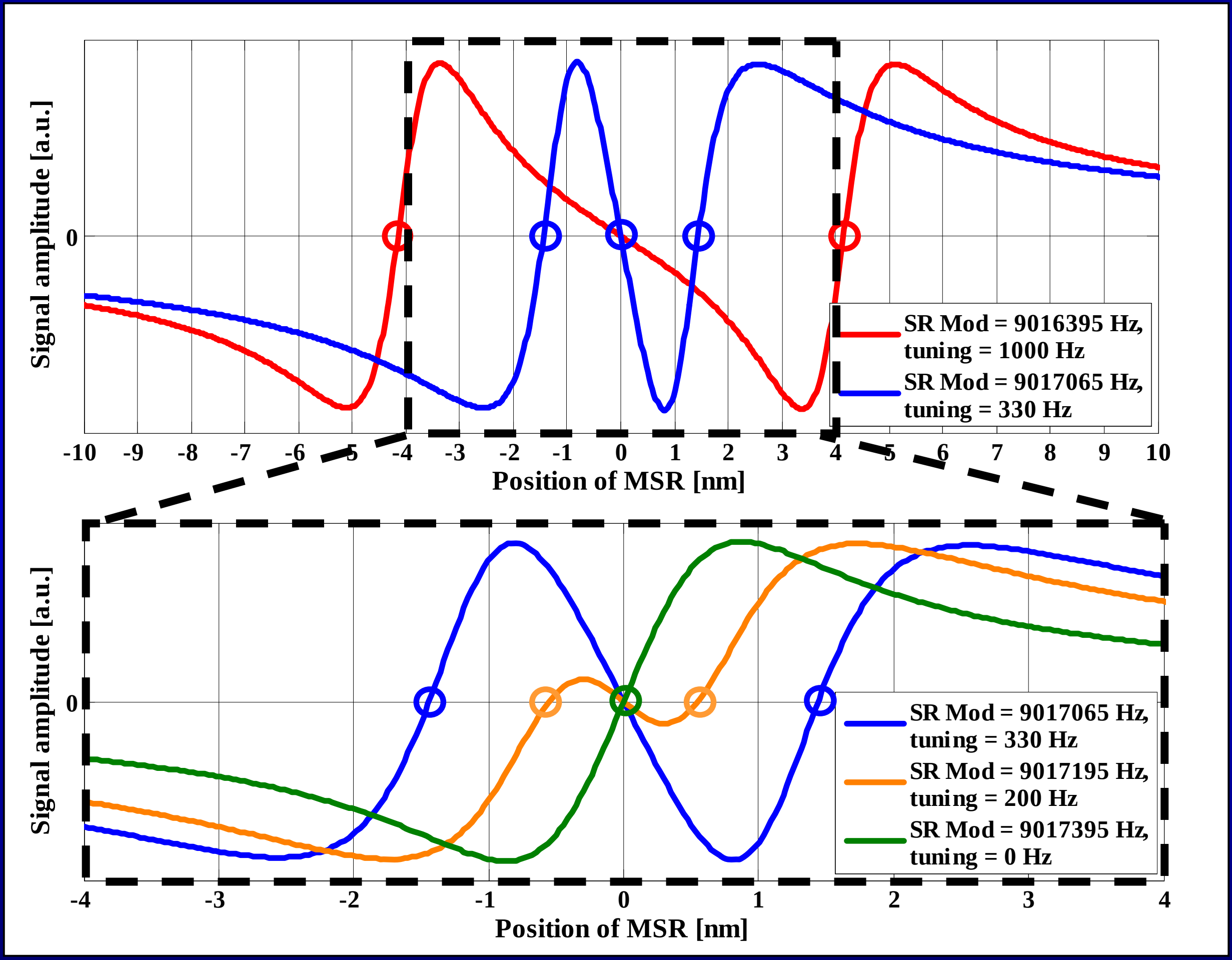
Signal-Recycling errorsignal



Derived from an RF modulation-demodulation technique.

Why can‘t we tune down to tuned SR ?

Tuning is done by changing the SR RF-modulation frequency.

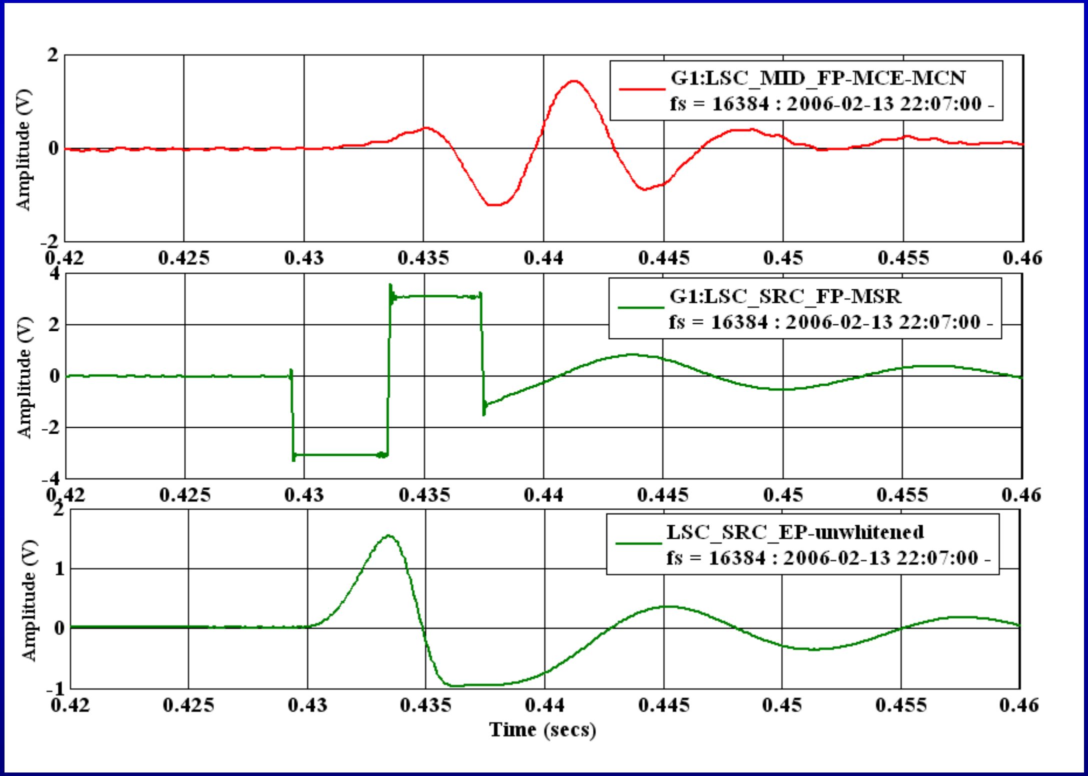


When we tune below 250 Hz the controlsignal vanishes / goes „cracy“.

Kicking MSR

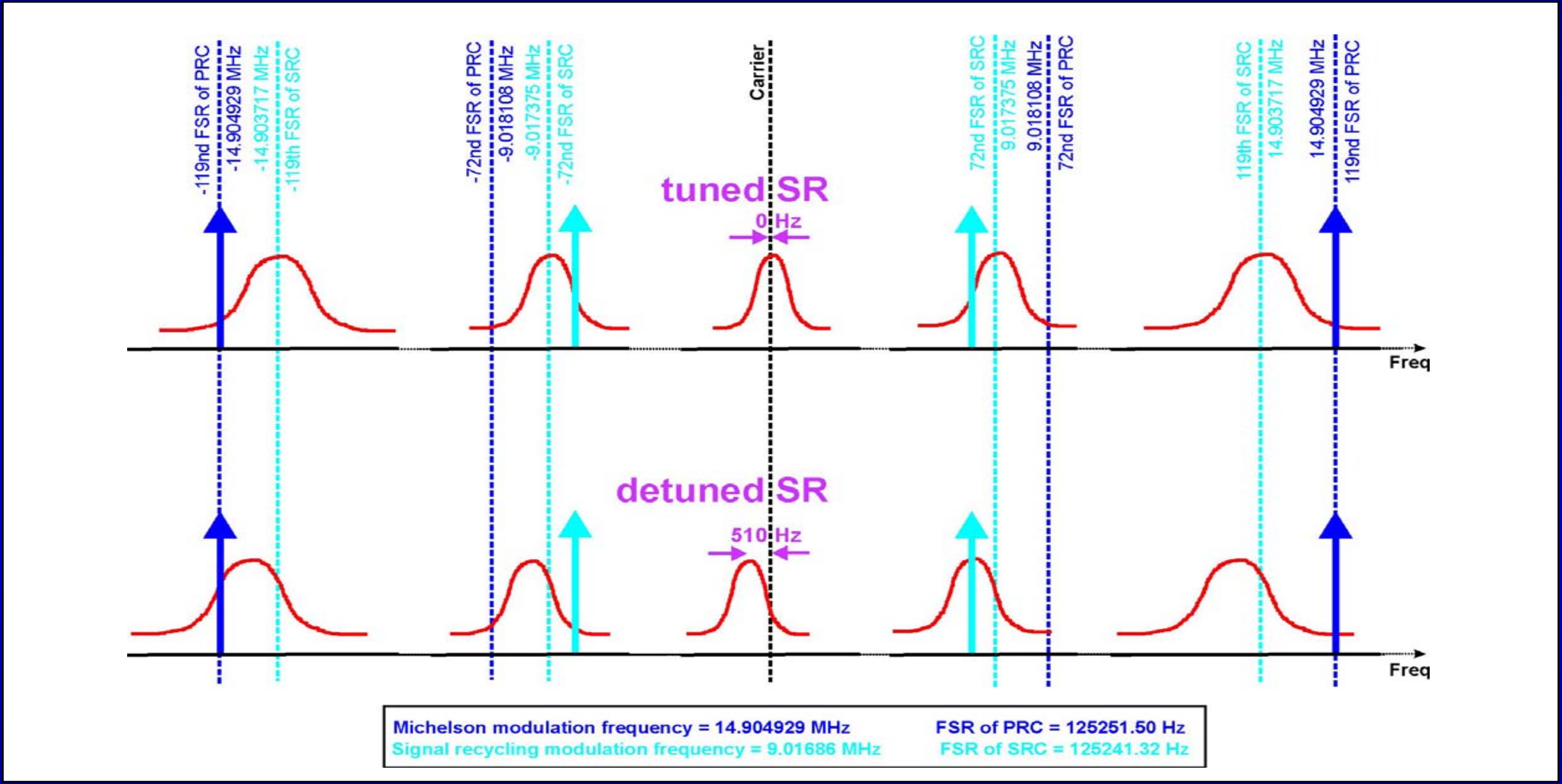
Kicking MSR in a controlled way:

- Fast enough that all other loops can‘t recognize.
- 4 ms of acceleration and 4 ms of deceleration.



Works fine: Jumping to tuned and to the lower SR sideband

Sideband picture for tuned and detuned SR



From detuned to tuned:

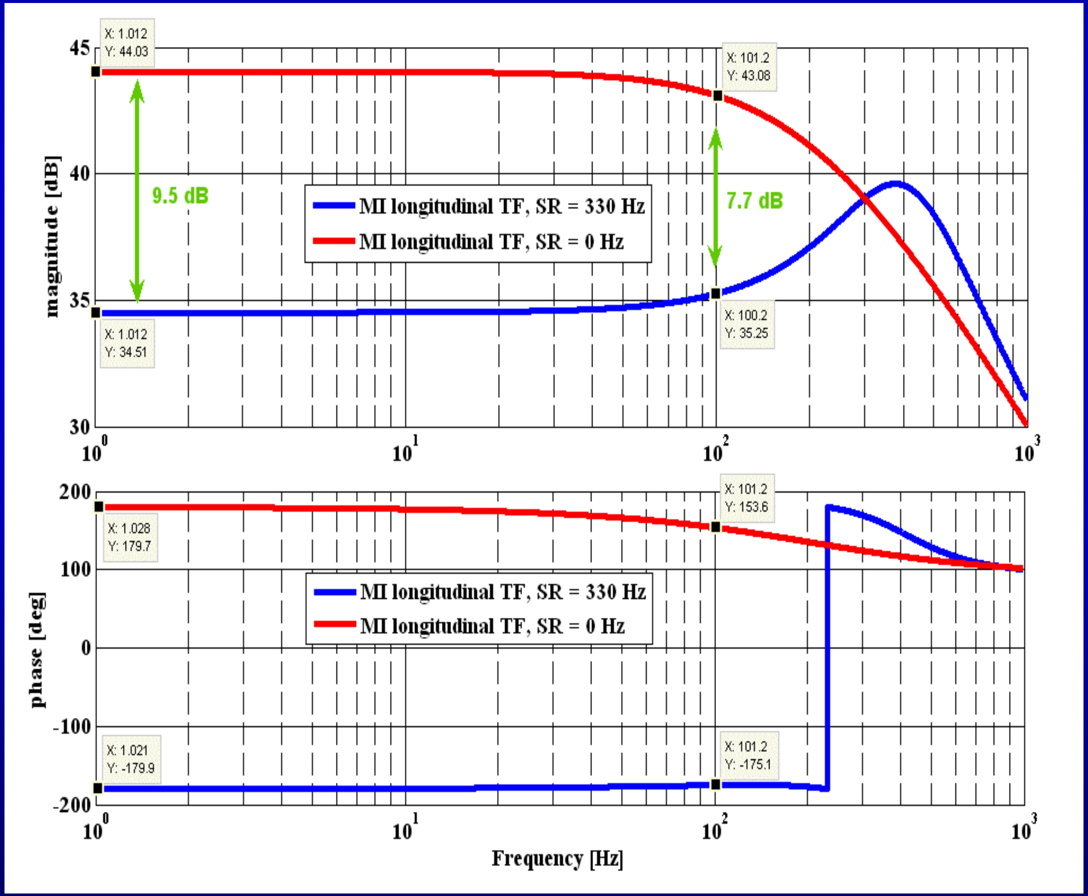
CTRL-signals that are generated from ‚carrier‘ need to be adjusted for the different resonance condition of the carrier.

Parameter adjustment

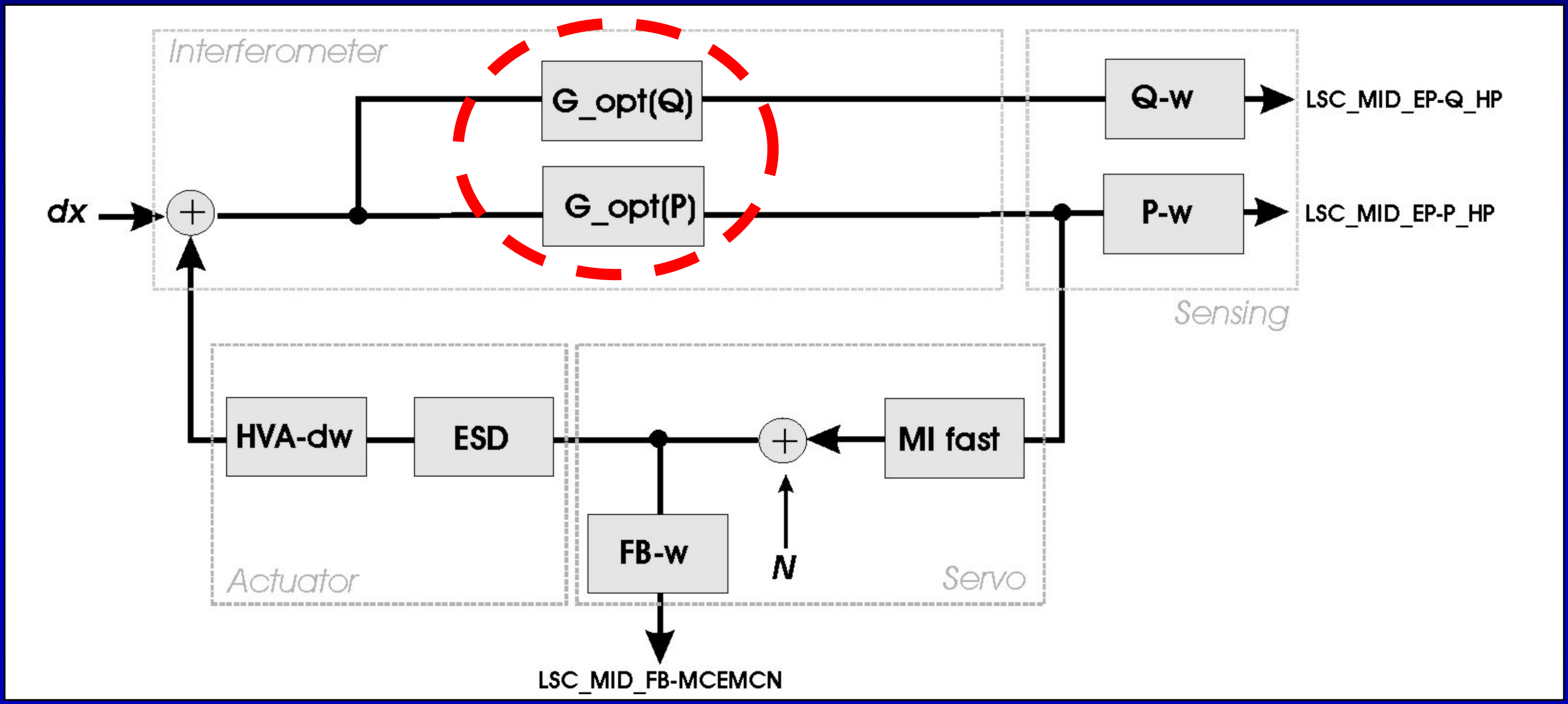
When jumping to tuned SR you need to change a few parameters / compensate for the pole of the SR cavity:

- MI long needs an additional differentiator switched in.
- MIAA gains need to be adjusted.
- Swap sign of SR_EP.
- Adjust SR long gain.

Simulations done with FINESSE



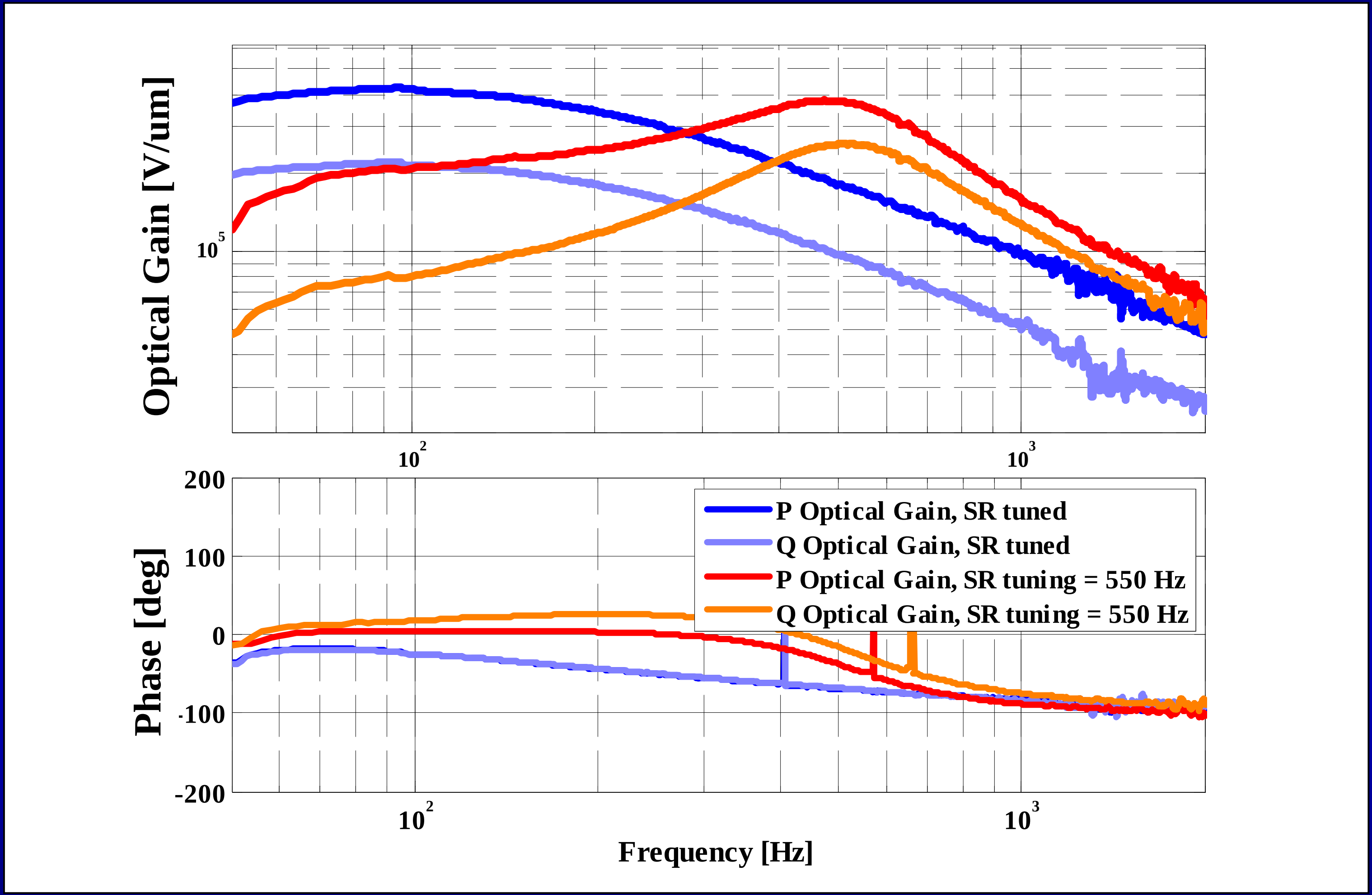
Determine the optical gain for P- and Q-quadrature (TF from diff armlength change to detector output)



$$\frac{\text{MID\_EP-P\_HP} \cdot \text{P-dw}}{\text{MID\_FB-MCEMCN} \cdot \text{FB-dw}} = \text{ESD} \cdot \text{HWA-dw} \cdot \text{G\_opt}$$

$$\text{G\_opt} = \frac{\text{MID\_EP-P\_HP} \cdot \text{P-dw}}{\text{MID\_FB-MCEMCN} \cdot \text{FB-dw}} \cdot \frac{1}{\text{ESD}} \cdot \frac{1}{\text{HWA-dw}}$$

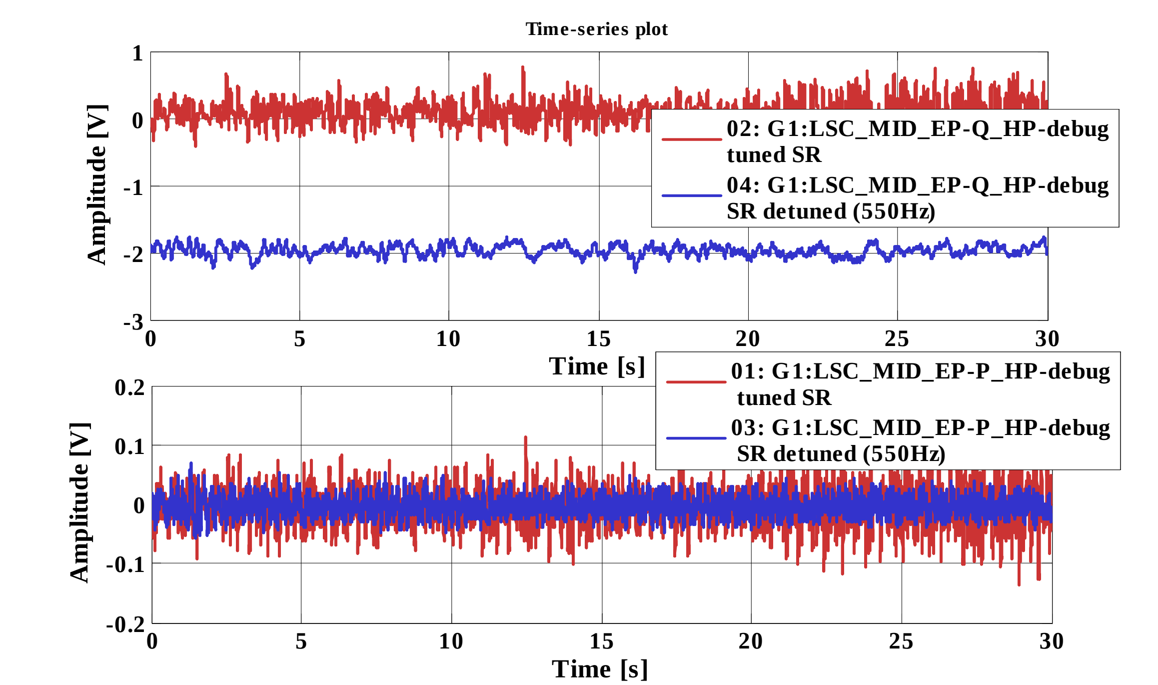
Optical gain for tuned and detuned SR



Matches our expectations:
Bandwidth of the TF goes down by a factor of 2.

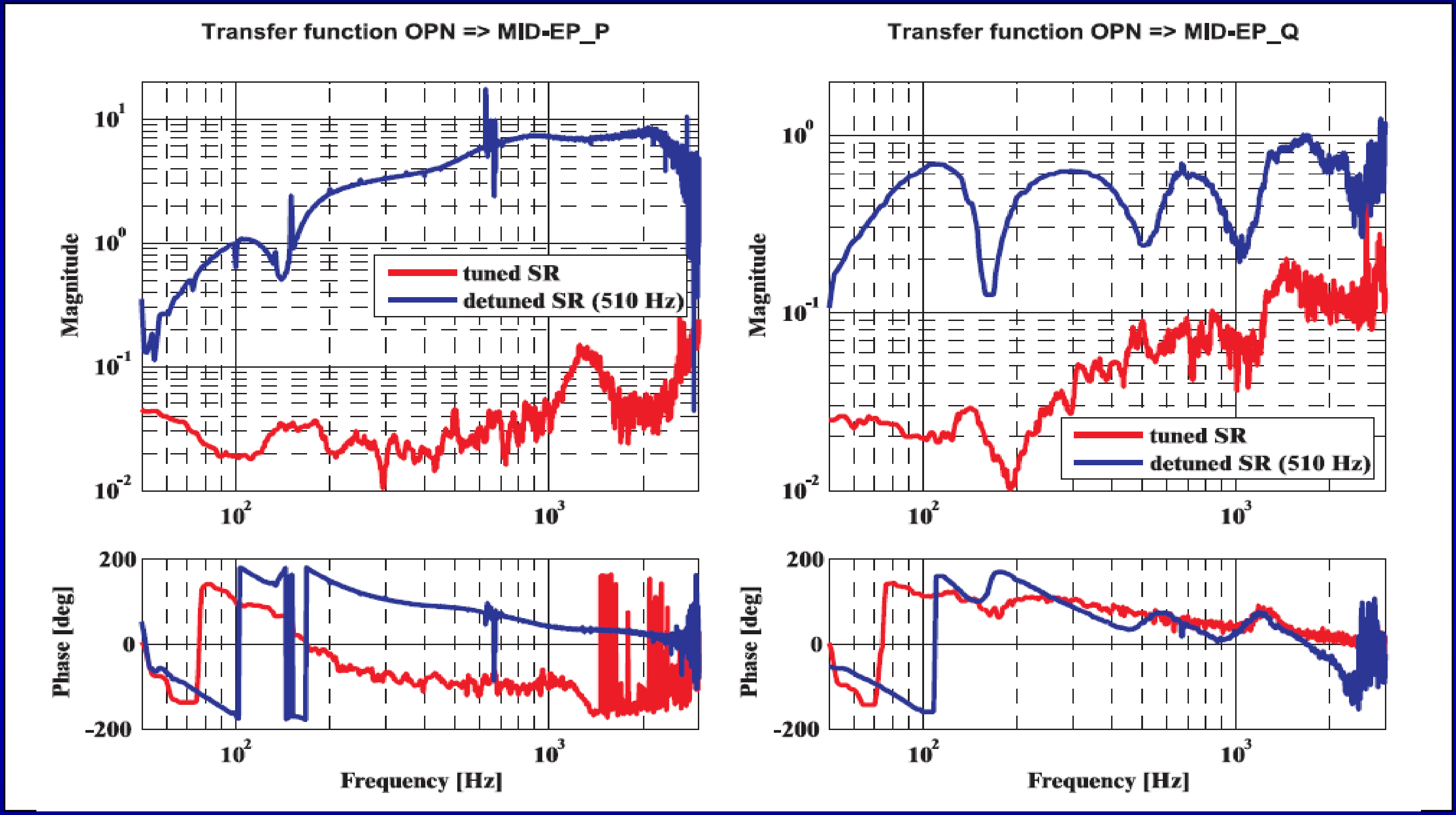
Significantly recuded RF AM.

The signal from the Q-quadrature is in the tuned case reduced to nearly zero (red). RMS of Q-signal is reduced by a factor of 12 !!



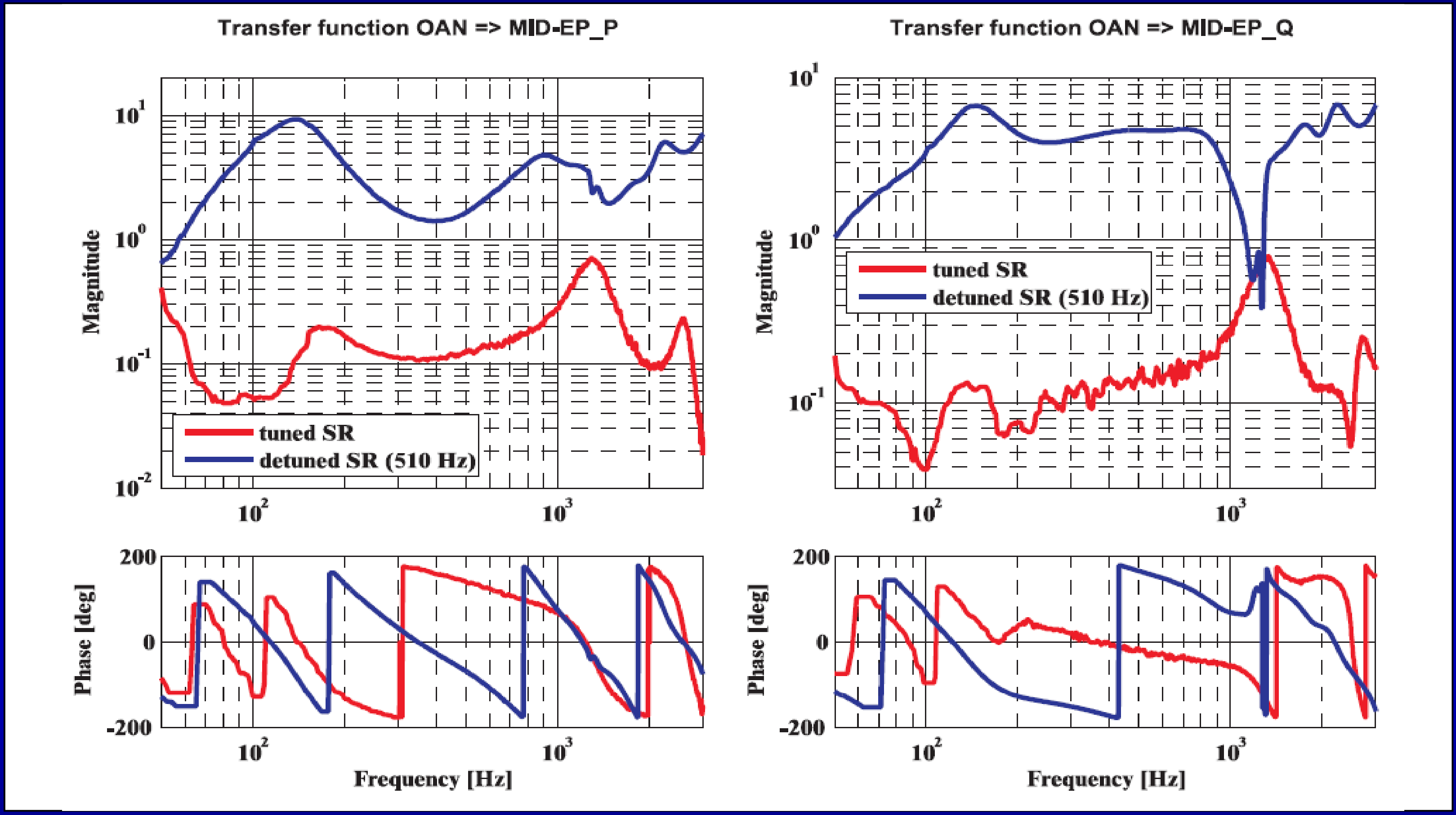
- Nice for the photodiode: Less potential saturation / nonlinearitis !!
- What is about phase noise in P-quadrature??

MI Oscillator phase noise (OPN)



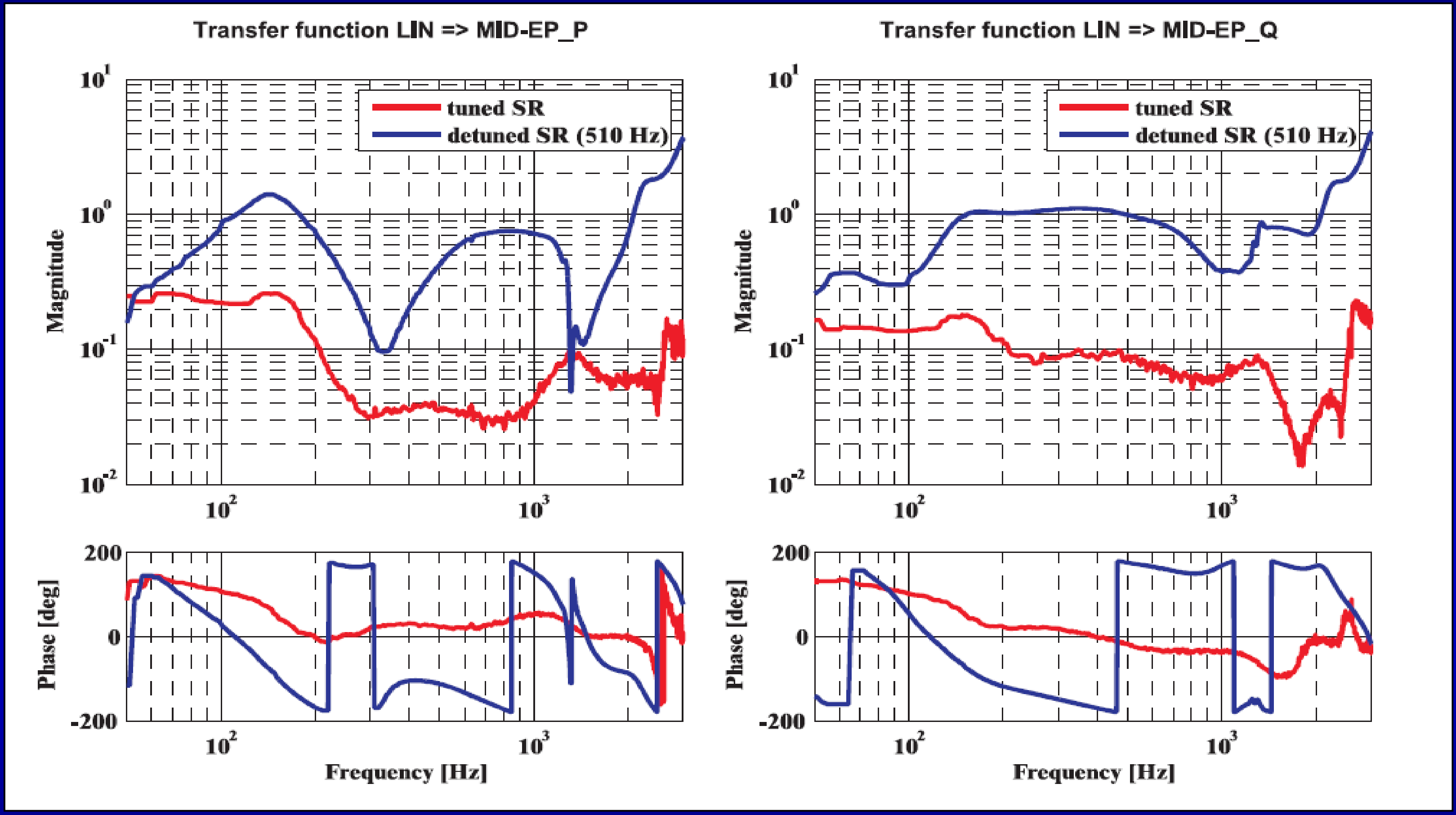
OPN coupling @ tuned SR:
P dramatically reduced, Q significantly reduced.

MI Oscillator amplitude noise (OAN)



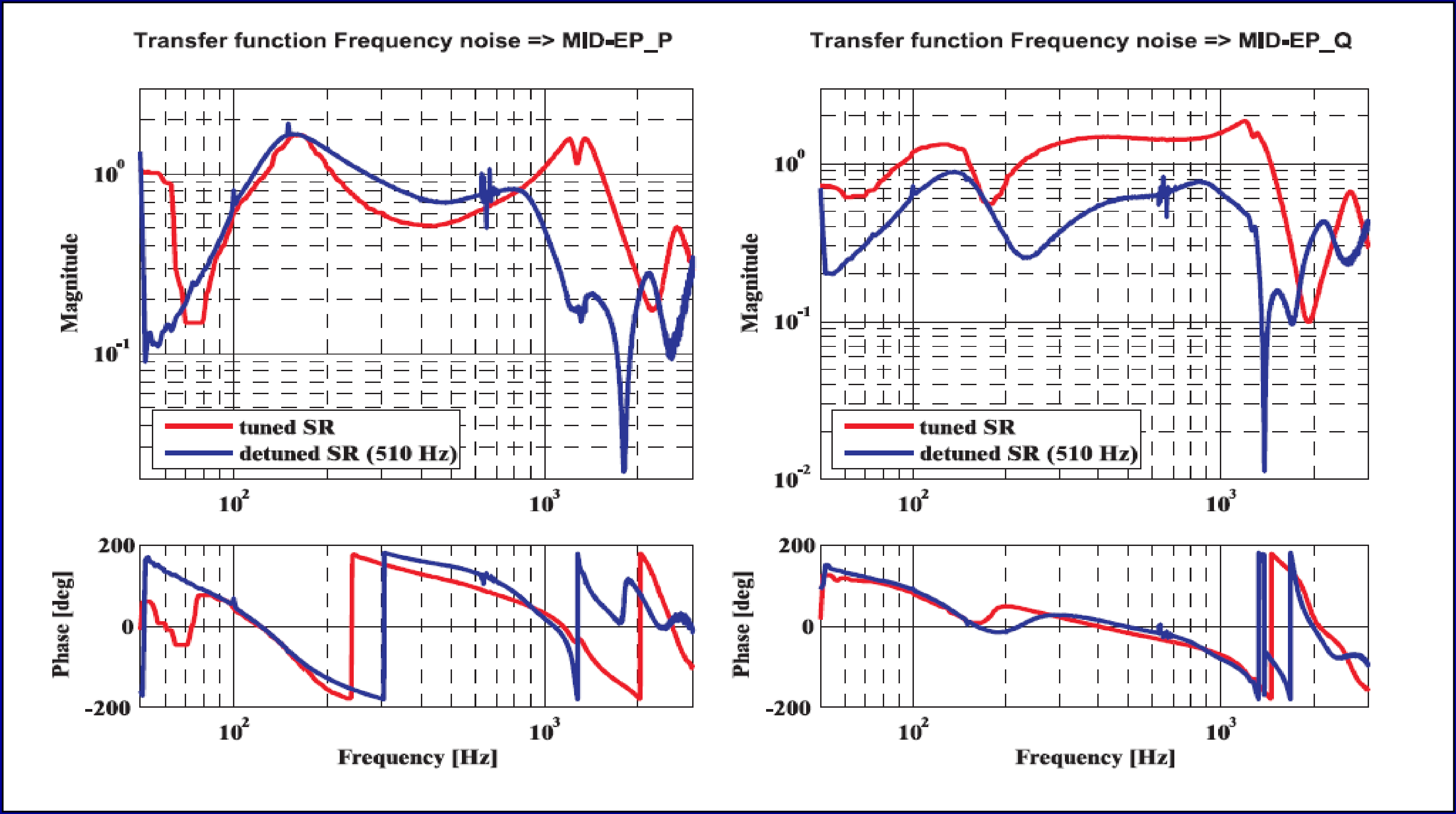
OAN coupling @ tuned SR:
P and Q significantly reduced.

Laser intensity noise (LIN)



LIN coupling @ tuned SR:
P and Q significantly reduced.

Laser frequency noise



Laser freq noise coupling @ tuned SR: P and Q worse (but structure slightly simpler).

Summary of noise couplings

- OPN coupling @ tuned SR:
P dramaticcaly reduced, Q significantly reduced.

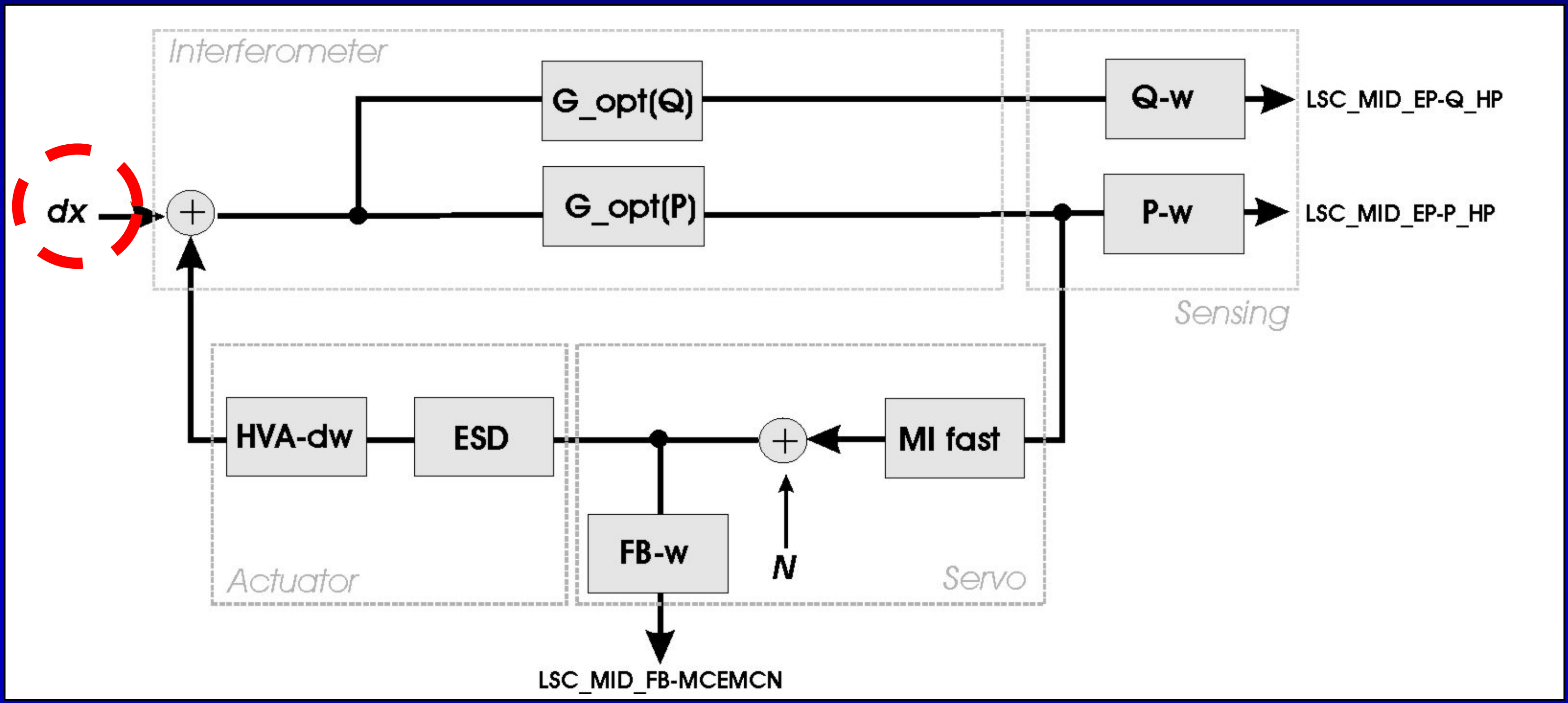
- OAN coupling @ tuned SR:
in both quadratures clearly reduced.

- Laser frequency noise coupling @ tuned SR:
worse in both quadratures.

- Laser intensity noise coupling @ tuned SR:
P and Q significantly reduced.

In general:
The size of TFs for the noise couplings are reduced on average and the structure of the TFs look a bit simpler.

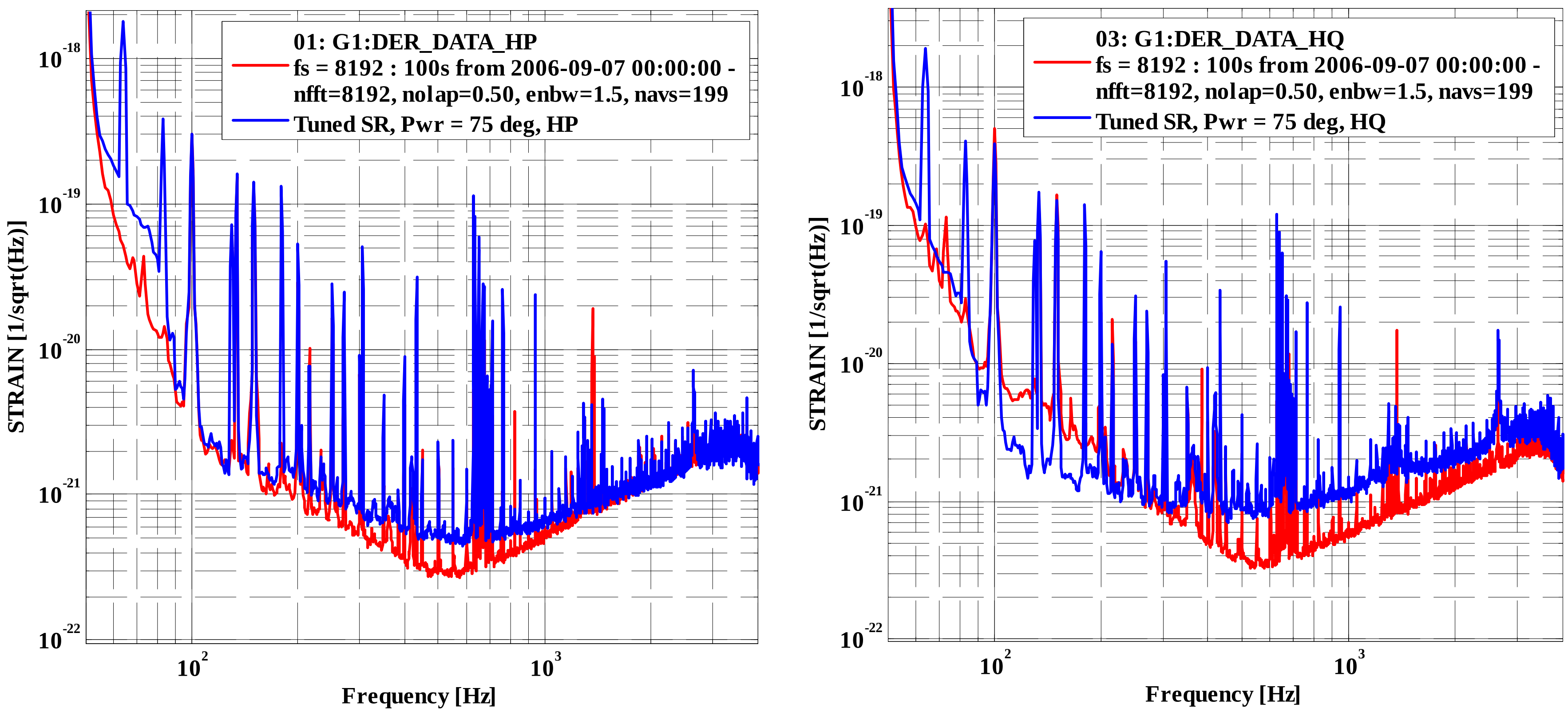
Calibration to starin sensitivity (frequency domain)



$$dx = \frac{\text{MID\_EP-P\_HP} \cdot \text{P-dw}}{\text{G\_opt(P)} \cdot \text{CLTF}}$$

$$HP = \frac{dx}{1200\,\mathrm{m}}.$$

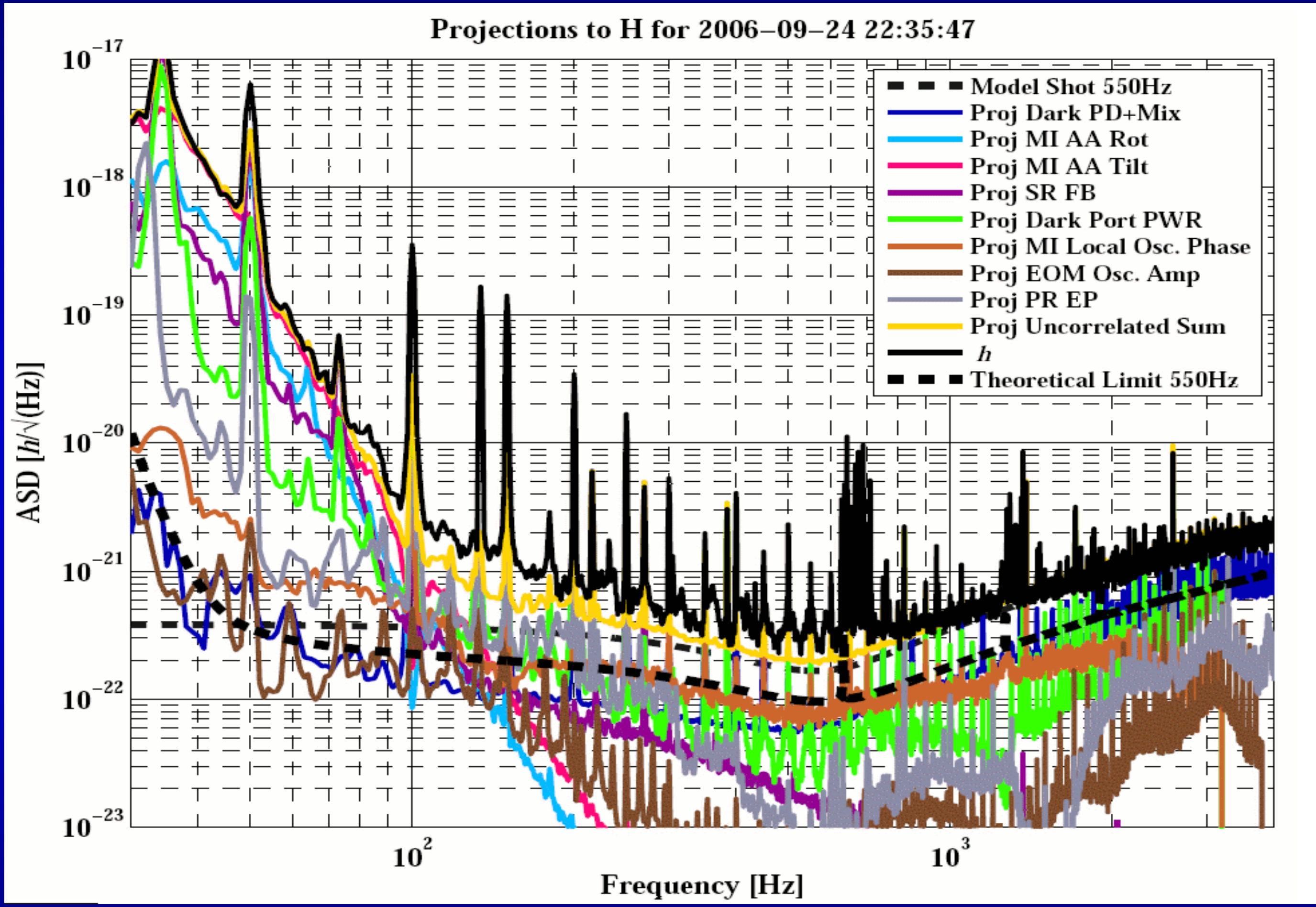
Sensitivity: tuned vs detuned (550Hz) SR



No improvement in sensitivity

(not surprising, as we are not limited by shotnoise at low frequencies and we did not optimize the detector / parameters for tuned SR)

Noise projections for a time of S5



So far we don‘t understand why Q got worse

at high frequencies for tuned SR. (?)

Summary

- **Demonstrated controlled jumping to tuned SR.**
- **No sensitivity improvement for tuned SR at the moment (spend no time for optimization).**
- **Some of the noise couplings are significantly reduced for tuned, but their structure is still complicated.**
- **In tuned case the RF AM is reduced by a factor of 12**

Outlook:
To gain understanding of the noise couplings:
- *seems important in order to speed up comissioning of GEO*
- *is essential for good design of next generation of instruments*

E n d

Acquisition of Dual Recycling