Modal simulation of dual recycled interferometers

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GWADW Elba 2013

Modal simulations

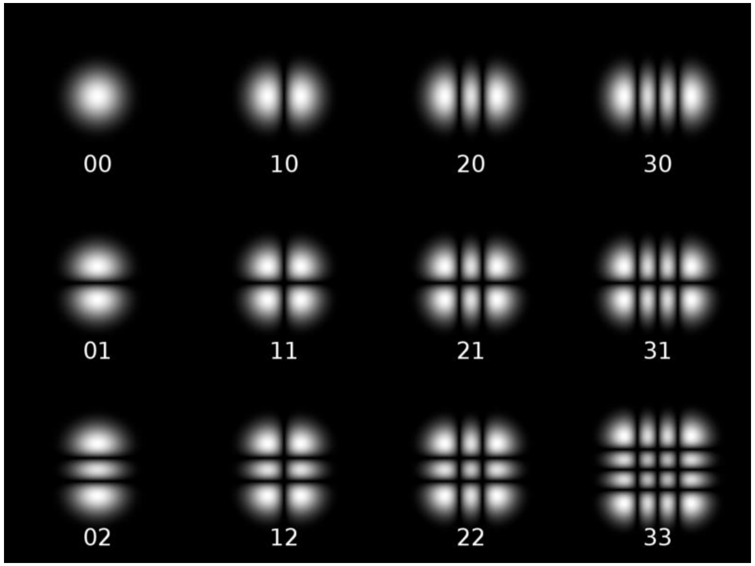
Field at each point inside the interferometer is expanded in a sum of free space propagation eigenmodes (Hermite- or Laguerre-Gauss modes)

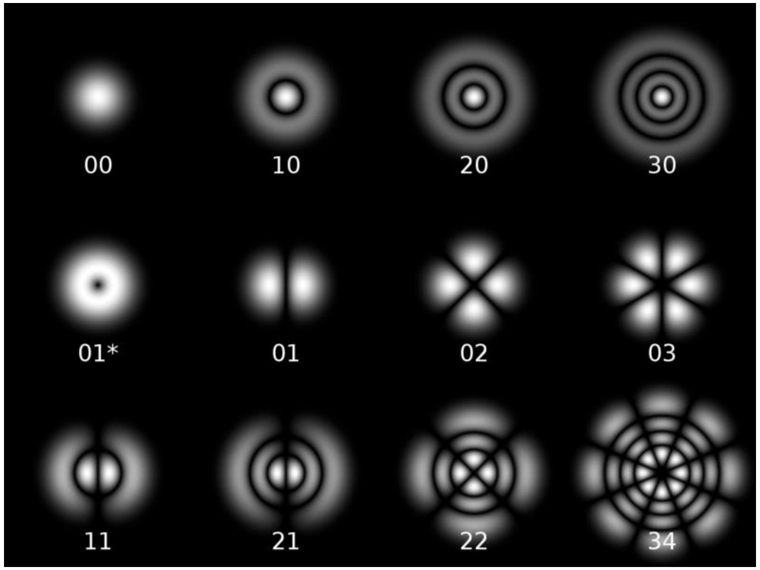
Propagation is simply described by multiplication with Gouy phase

Resonant cavities eigenmode is normally taken as the basis

The action of reflecting surface is described with scattering matrices between modes

The simulation code handles matrices: it is typically quite fast





Motivations and limitations

Motivations

Fast: modal simulations can be used to perform quick simulations, changing parameters: it is a good way to extract error signals

Intuitive: description of field in terms of modes is intuitive when stable resonant cavities are used: it can provide good physical insight

Limitations

Spatial frequency: to include the effect of medium-high spatial frequencies Λ^{-1} one must use a lot of modes: slow and ill-converging

$$M \geq \left(\frac{\pi w}{\Lambda}\right)^2$$

Cavity stability: convergence is particularly poor when marginally stable cavities are present

Winkler et al, Appl. Opt. 33, 7547 (1994)

Thermal effect simulation

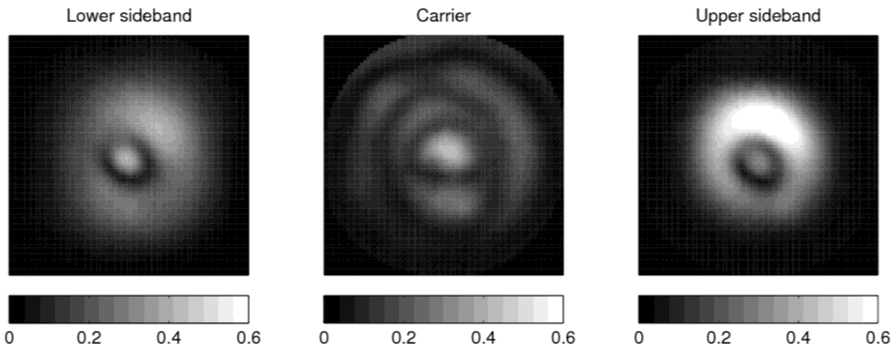
High power stored inside the Fabry-Perot arms is partly absorbed in the input mirror coating and substrate.

Temperature gradients create variation of refractive index and thermal lens (not only spherical…)

This was the main issue in first generation detectors

Advanced LIGO will use stable recycling cavities

Advanced Virgo will use marginally stable cavities



It is enough to introduce simple spherical lenses into the substrates to get interesting phenomena

Strain et al. Physics Letters A 194, 124-132 (1994)
Accadia et al. Astroparticle Physics 34 521–527 (2011)
Rocchi et al. J. Phys.: Conf. Ser. 363 012016 (2012)
Lawrence et al Class. Quantum Grav. 19 1803 (2002)

Common and differential lenses

Common: the same lens on both input substrates

it mainly affects the recycling gain of the sidebands

This is the main weakness of marginally stable cavities

Differential: it changes the amount of sideband power leaking to the antisymmetric port and introduce unexpected couplings in stable cavities

Effect of common lens in a marginally stable configuration (Virgo and Advanced Virgo)

Effect of differential lens in a stable configuration (old Advanced Virgo design and Advanced LIGO)

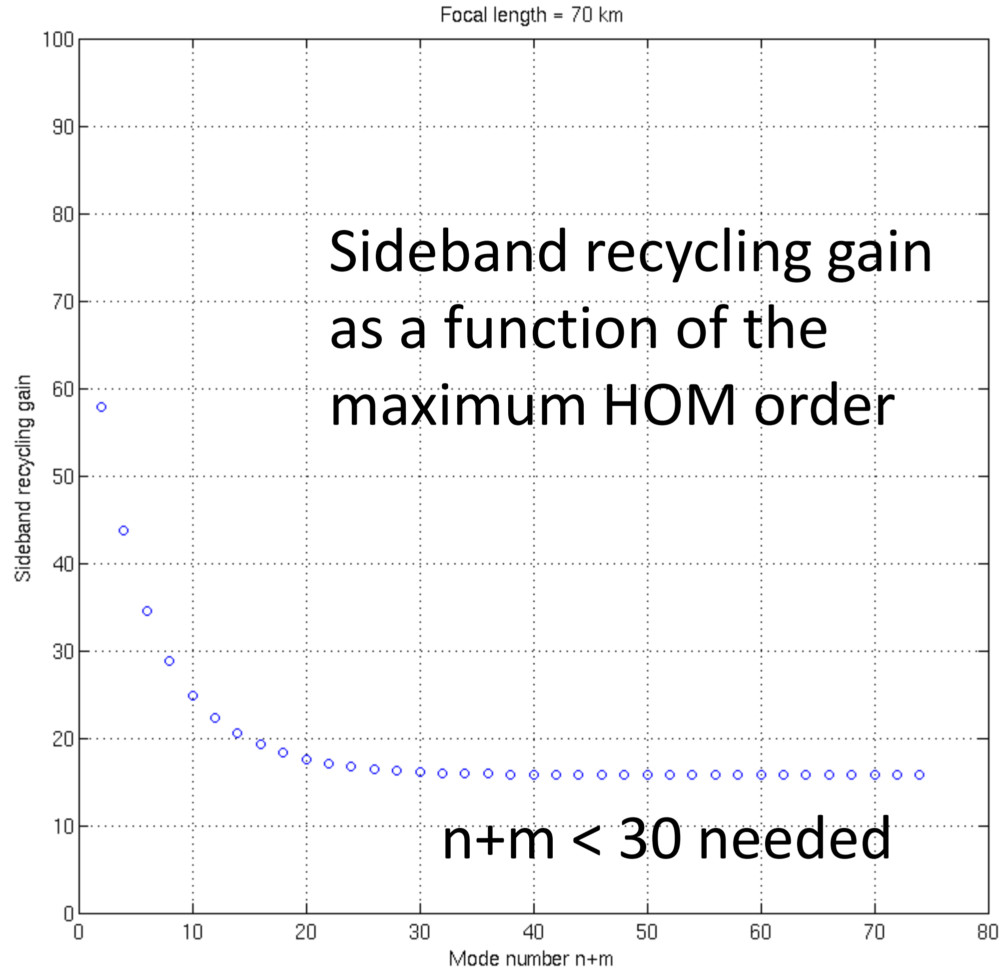
MARGINALLY STABLE RECYCLING CAVITIES

Convergence issues

Number of modes needed to converge to stable result can be large.

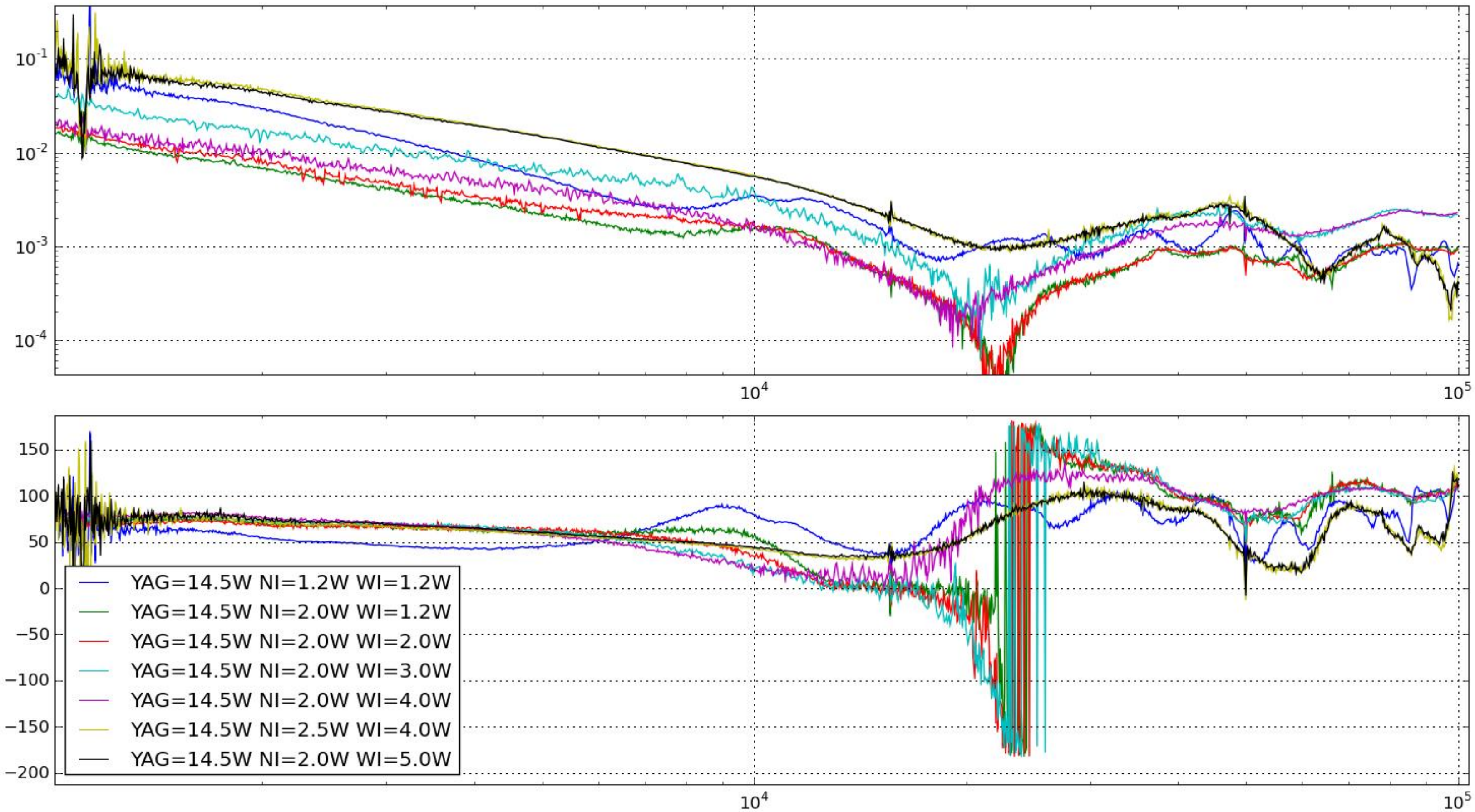
The number of modes needed depends on what we are simulating

Typically carrier-related quantities behave better than sideband related ones (PRC is stabilized by arm for the carrier



Response to frequency noise

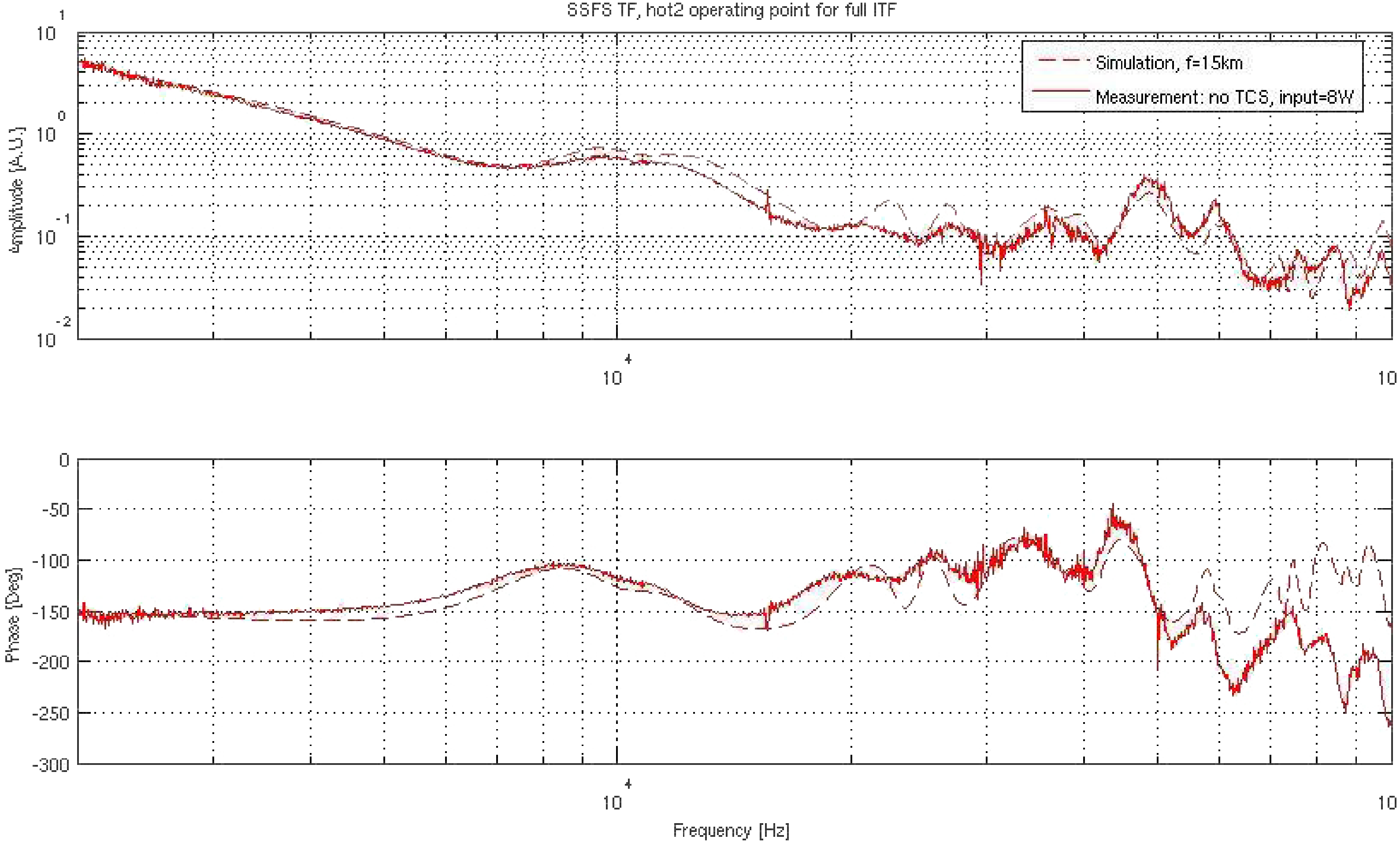
Experimentally: we discovered in Virgo and Virgo+ that the optical response of the interferometer to frequency noise is largely affected by thermal lens.



Campagna, Vajente elog #23028 (2009)

Simulation of Virgo/Virgo+

Using Finesse, simple spherical lenses and modes up to n+m<=8 we could reproduce well the measurement and estimate the common lens focal

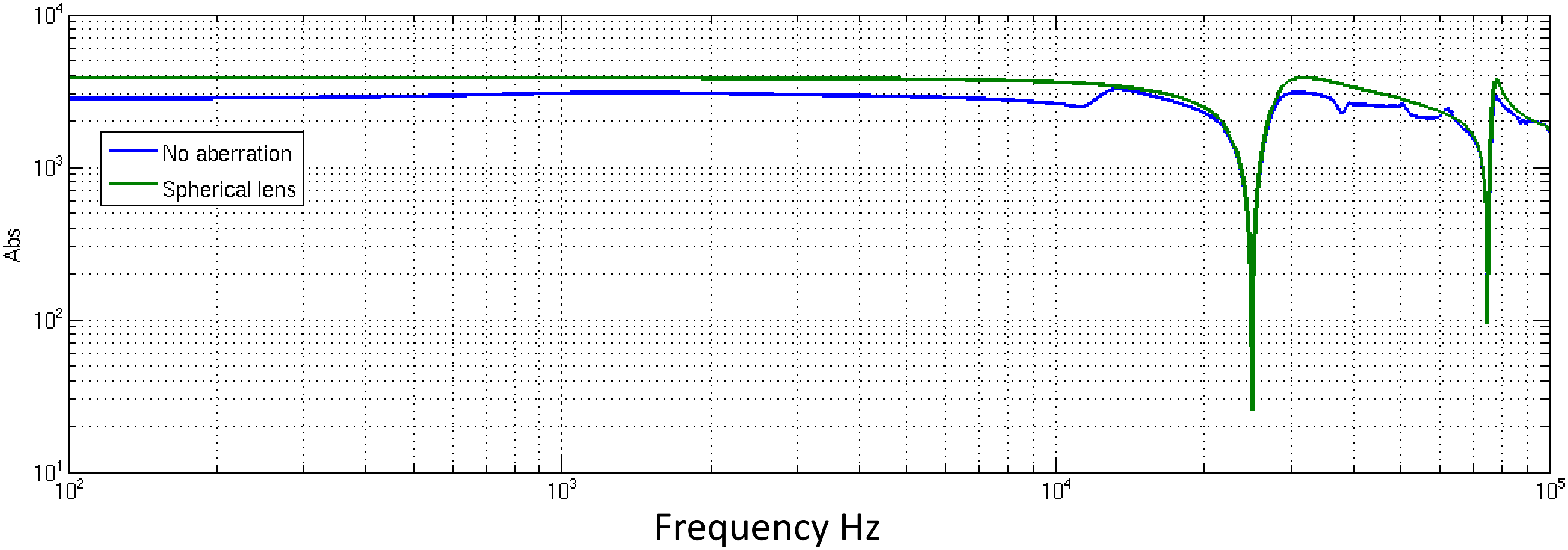


Day et al. VIR-0191A-10 (2010) https://tds.ego-gw.it/ql/?c=7325

Origin of wiggles - 1

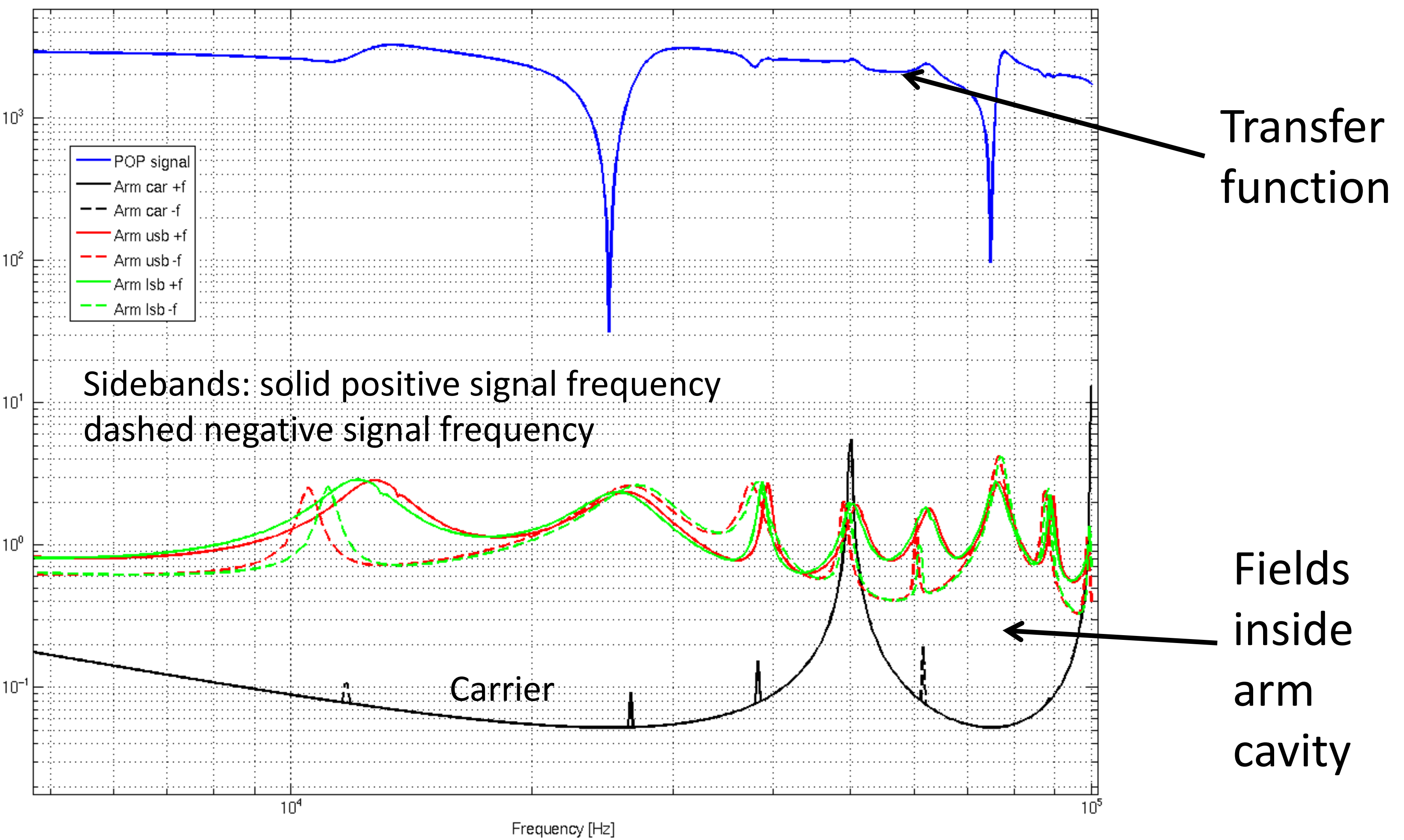
Advanced Virgo configuration, error signal extracted form PRC pick-off (POP beam)

Focal length of 90 km, some small effect on transfer function

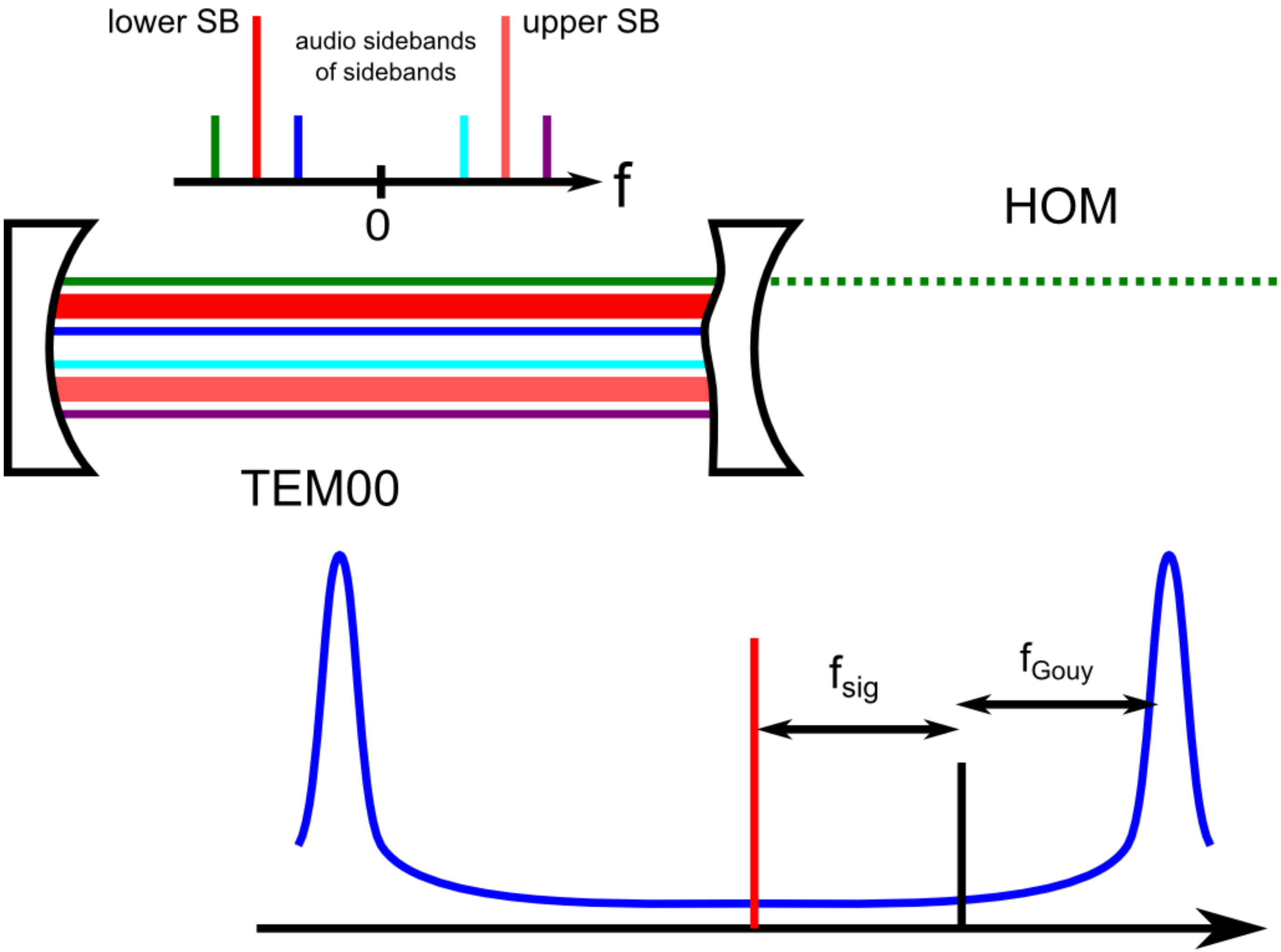


1/f dependency of transfer function removed for clarity of presentation

Origin of wiggles - 2

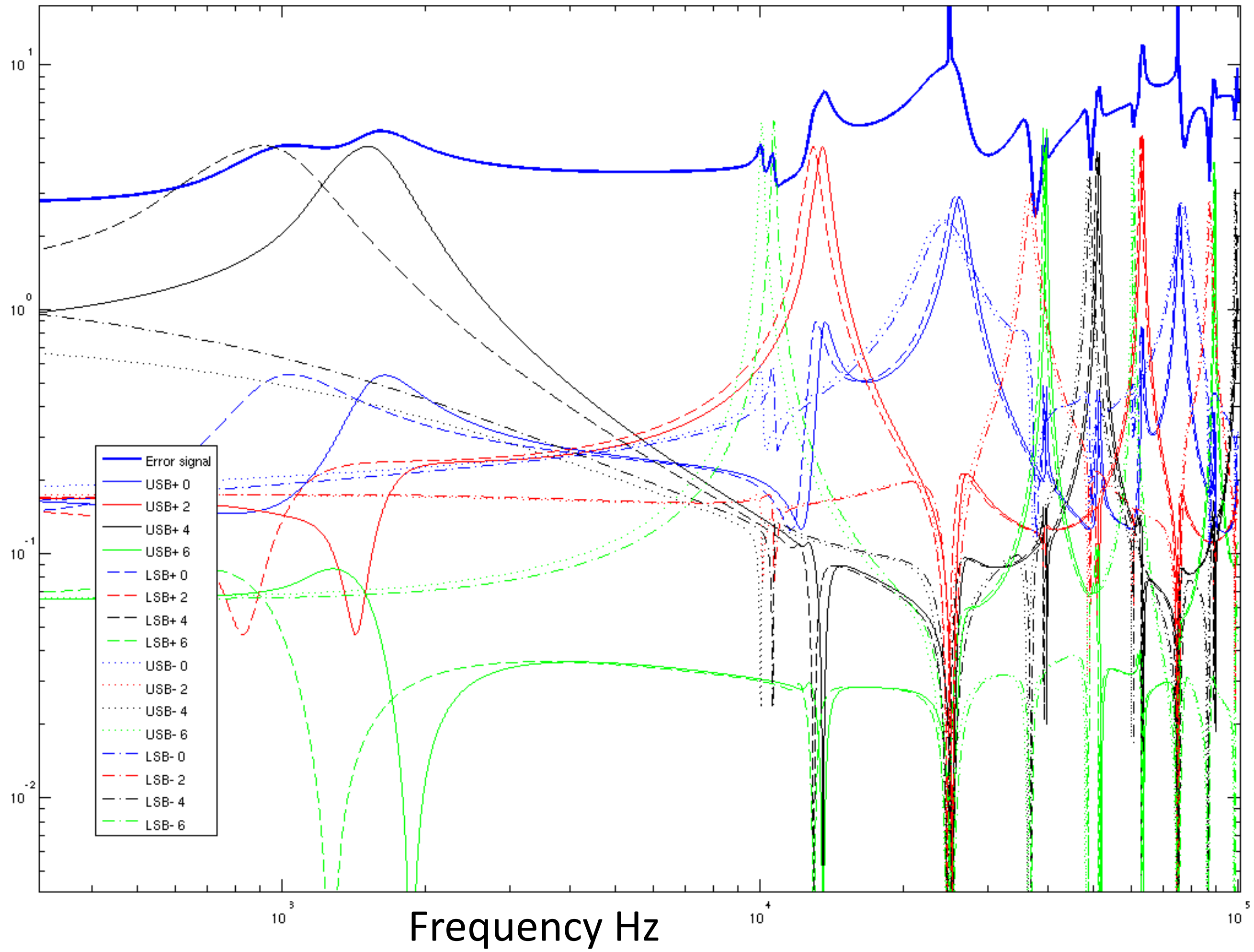


Mechanism



This is a second order effect in the coupling coefficient: you can't get it with first order analytical computations!

Origin of wiggles - 3



Blue: ratio of aberrated TF to unaberrated TF

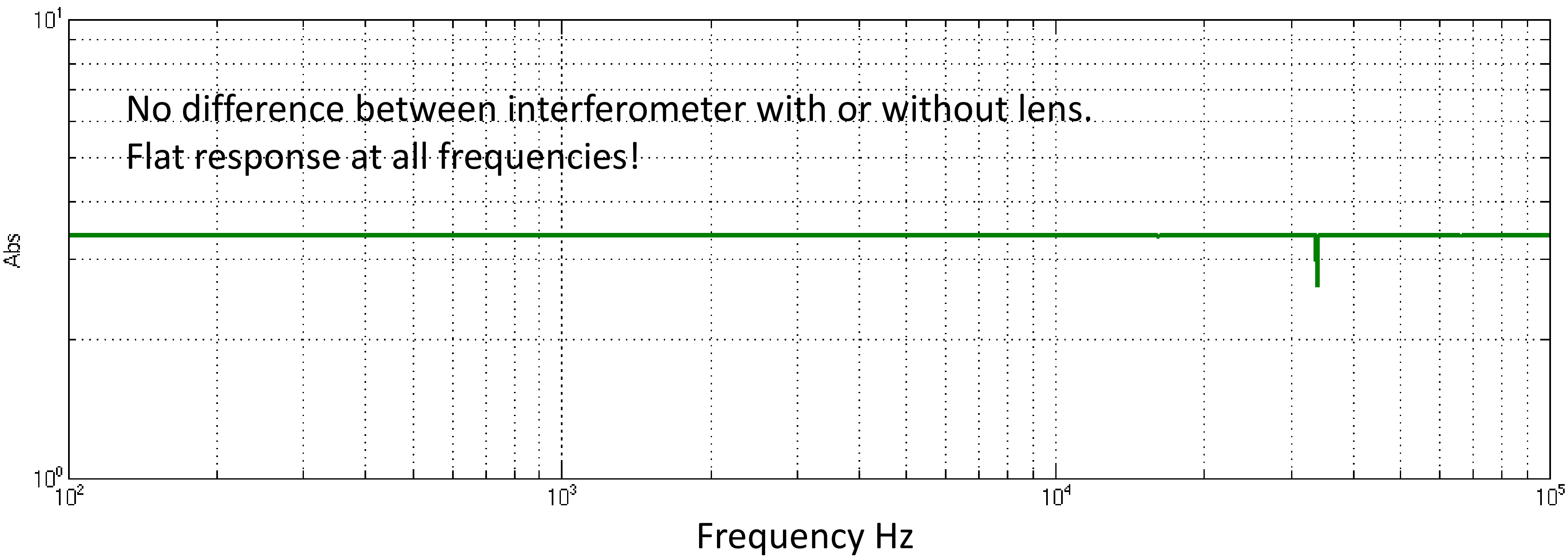
All other traces: resonance of sideband HOM's inside the arm cavity

Conclusion: we get a structure on the TF every time one HOM of one of the sideband is resonant inside the arm cavity. This extracts power from PRC with a "resonant absorption line"

Use of better signals

In Advanced Virgo we plan to use a 8 MHz modulation which is anti-resonant inside PRC

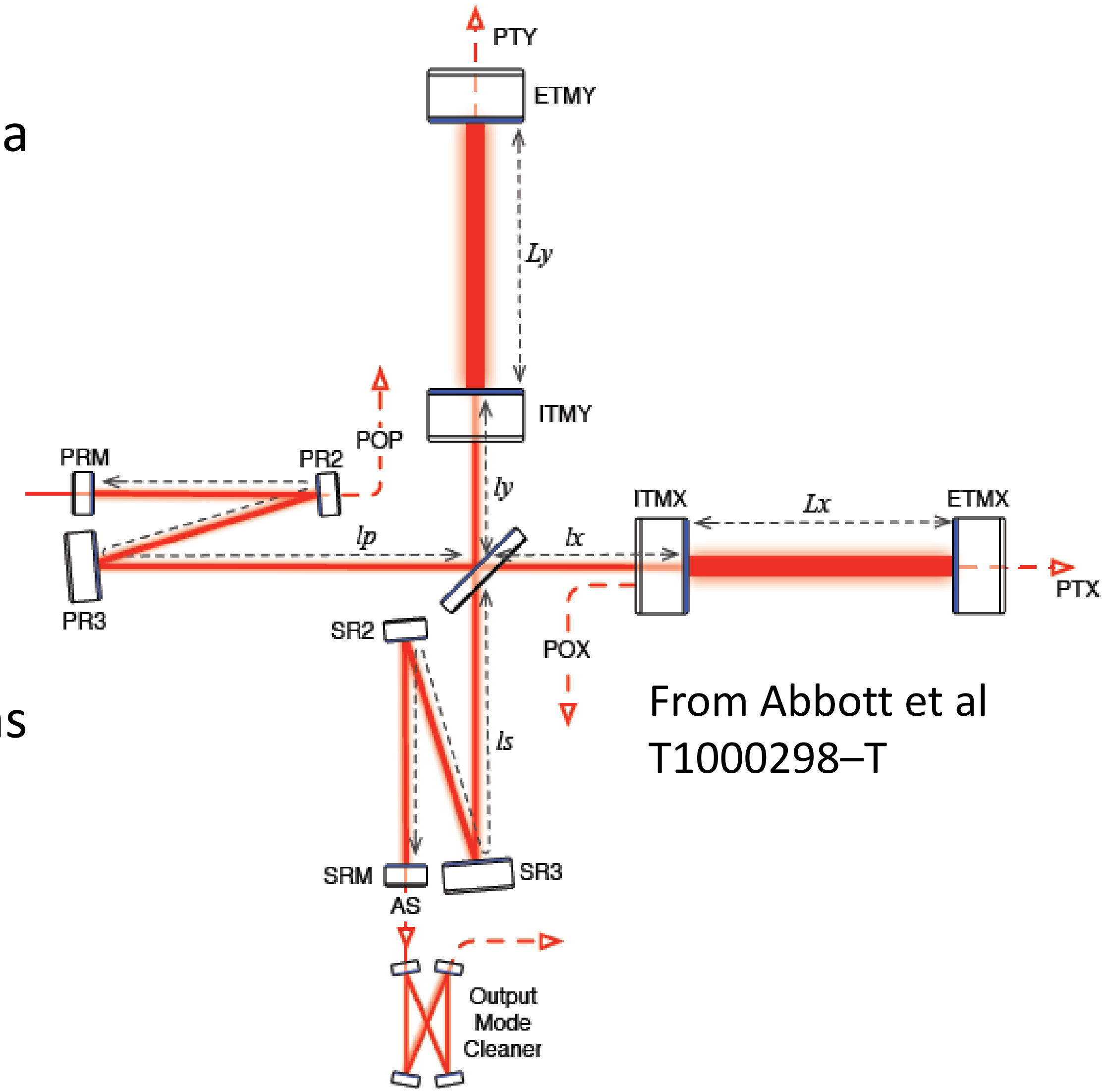
This is insensitive to thermal effects and could provide a very robust error signal



STABLE RECYCLING CAVITIES

Dual recycled interferometer

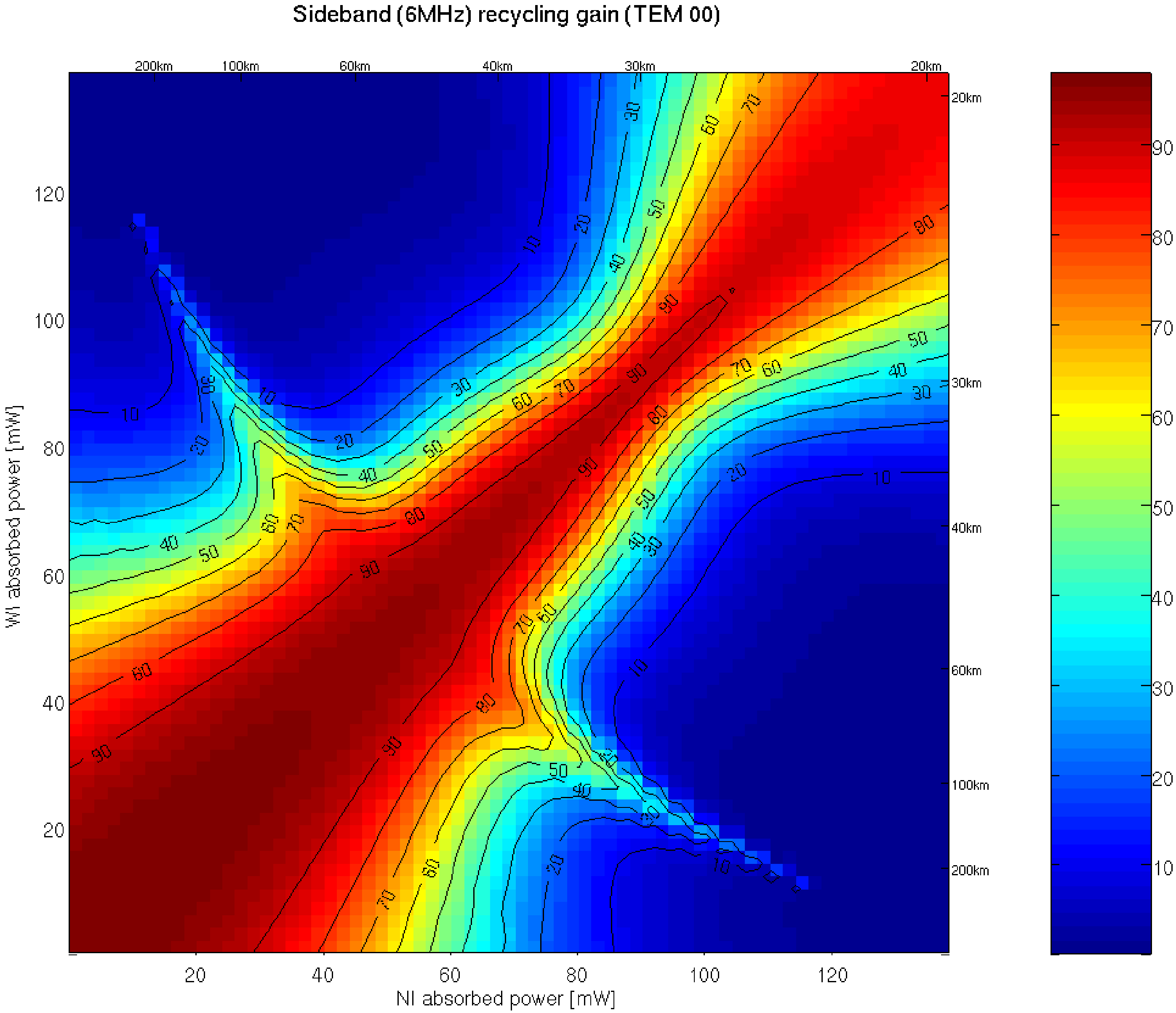
- Hermite-Gauss modal description of fields inside a Dual Recycled Fabry-Perot Michelson interferometer
- Analytical computations to solve field equations, then numerical computation of coupling matrices for aberrated elements
- Sidebands and carrier fields, as well as error signals can be computed
- Any kind of lens (or other defect) in input mirror can be added



From Abbott et al T1000298–T

Vajente VIR-0332A-10 (2010) https://tds.ego-gw.it/ql/?c=7474
Vajente, Class. Quantum Grav. 30 (2013) 075014

An AdVirgo stable cavity configuration

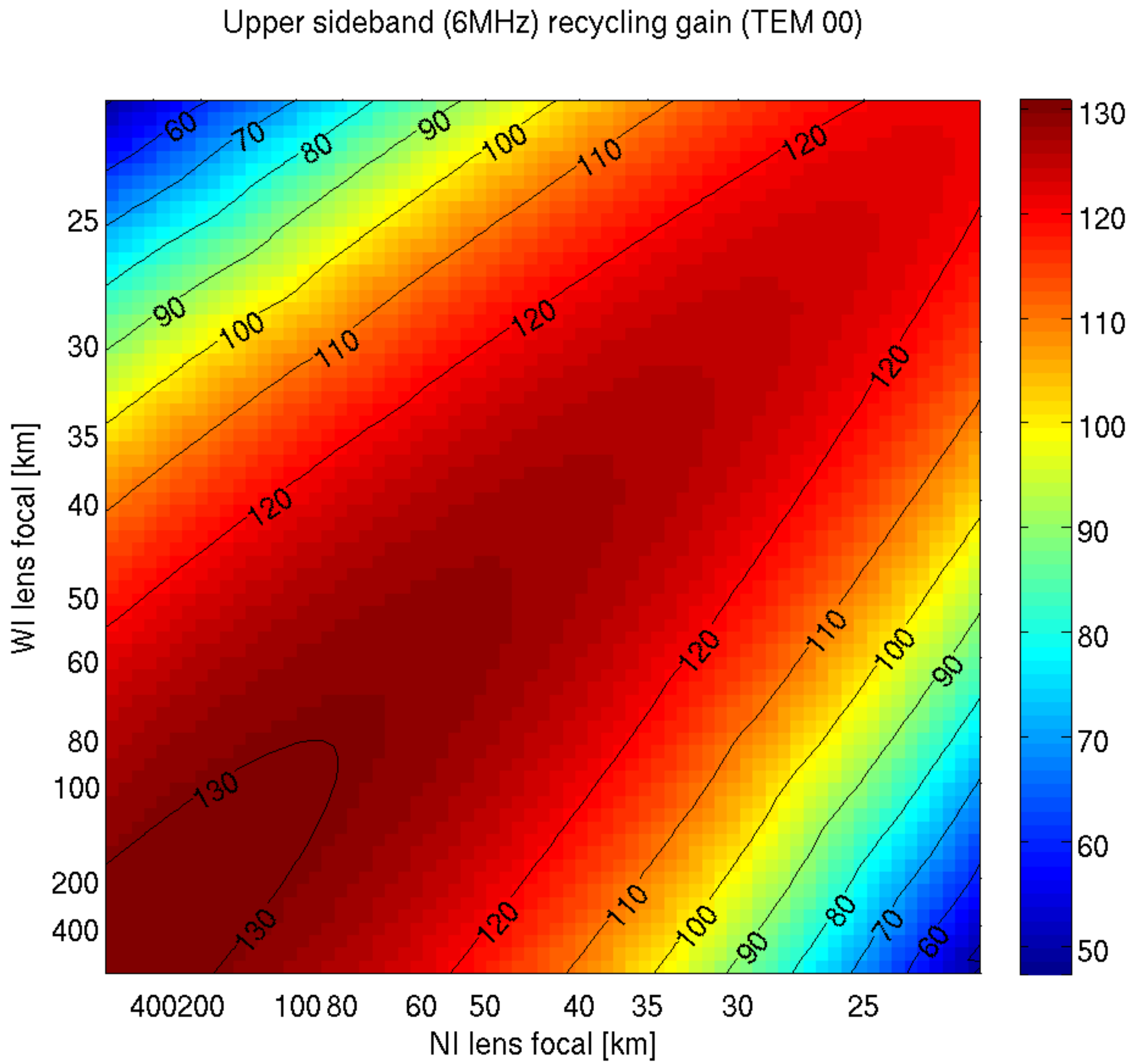


Pure spherical thermal lenses in the input mirror substrates
When the thermal lenses are different in the two mirrors (**differential lens**) there is a unexpected large effect

Differential lens creates differential HOM's inside the Michelson interferometer. Because of dark fringe, these are perfectly transmitted into SRC.
If they resonate inside SRC, power is extracted from the sidebands into PRC.
The amplitude of the effect depends on the Gouy phase, length and tuning of the SRC.

Vajente, Marque, VIR-0148A-10 (2010) https://tds.ego-gw.it/ql/?c=7281

Application to aLIGO



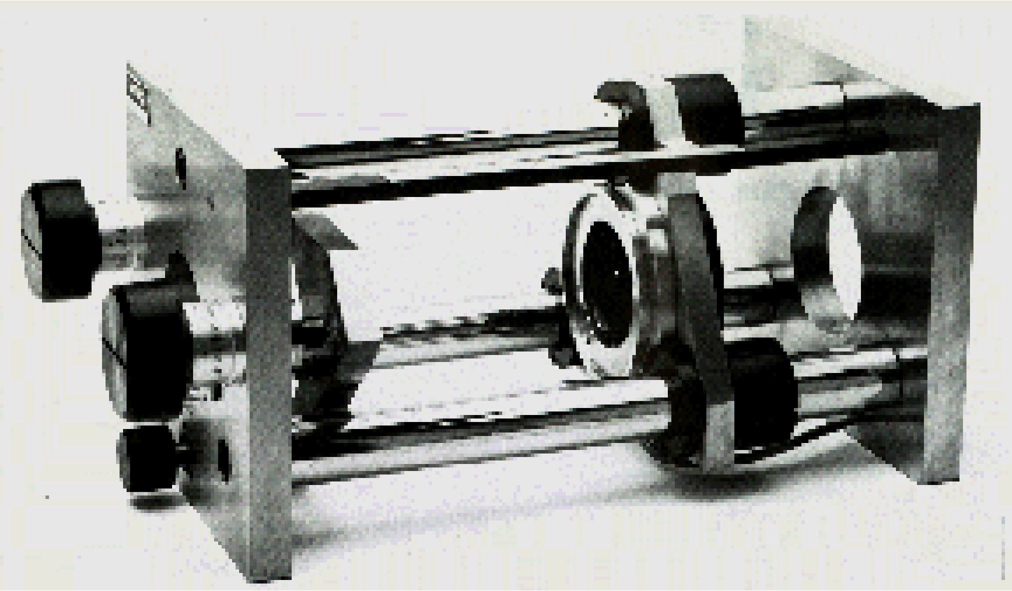
- Configuration from T0900043-11 T1000298–T
- In broad-band SRC configuration
- There is no large loss of sideband gain, you made a good choice of the combination of SRC length and sideband frequency
- The operating point of the IFO is tuned to maintain the good resonance conditions

Arain et al LIGO-T0900043-11 (2012)
Abbott et al LIGO-T1000298–T (2010)

Tuning procedure

- Move PRC length in order to maximize the 9MHz sidebands into PRC
- Then move CARM in order to maximize carrier power inside arms
- Then move DARM to maintain constant power at dark port
- Finally, tune SRC in order to optimize sensitivity at high frequency (for broad band)

Alternatively, simulate error signal and use them into simple iterative loops…



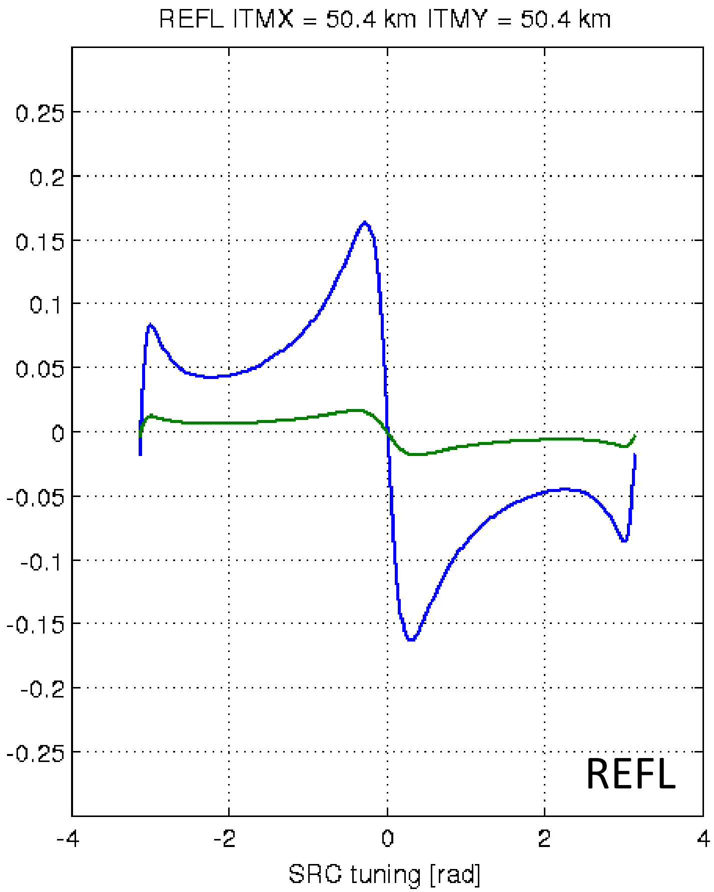
Error signal in broad band for aLIGO from T1000298–T

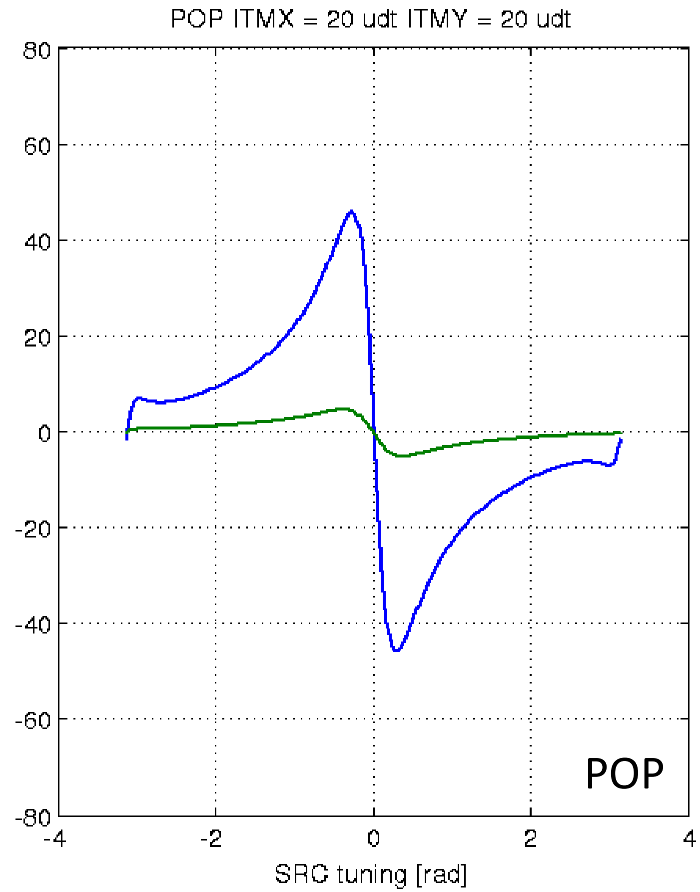
The result is interesting…

Signal Recycling Cavity lock

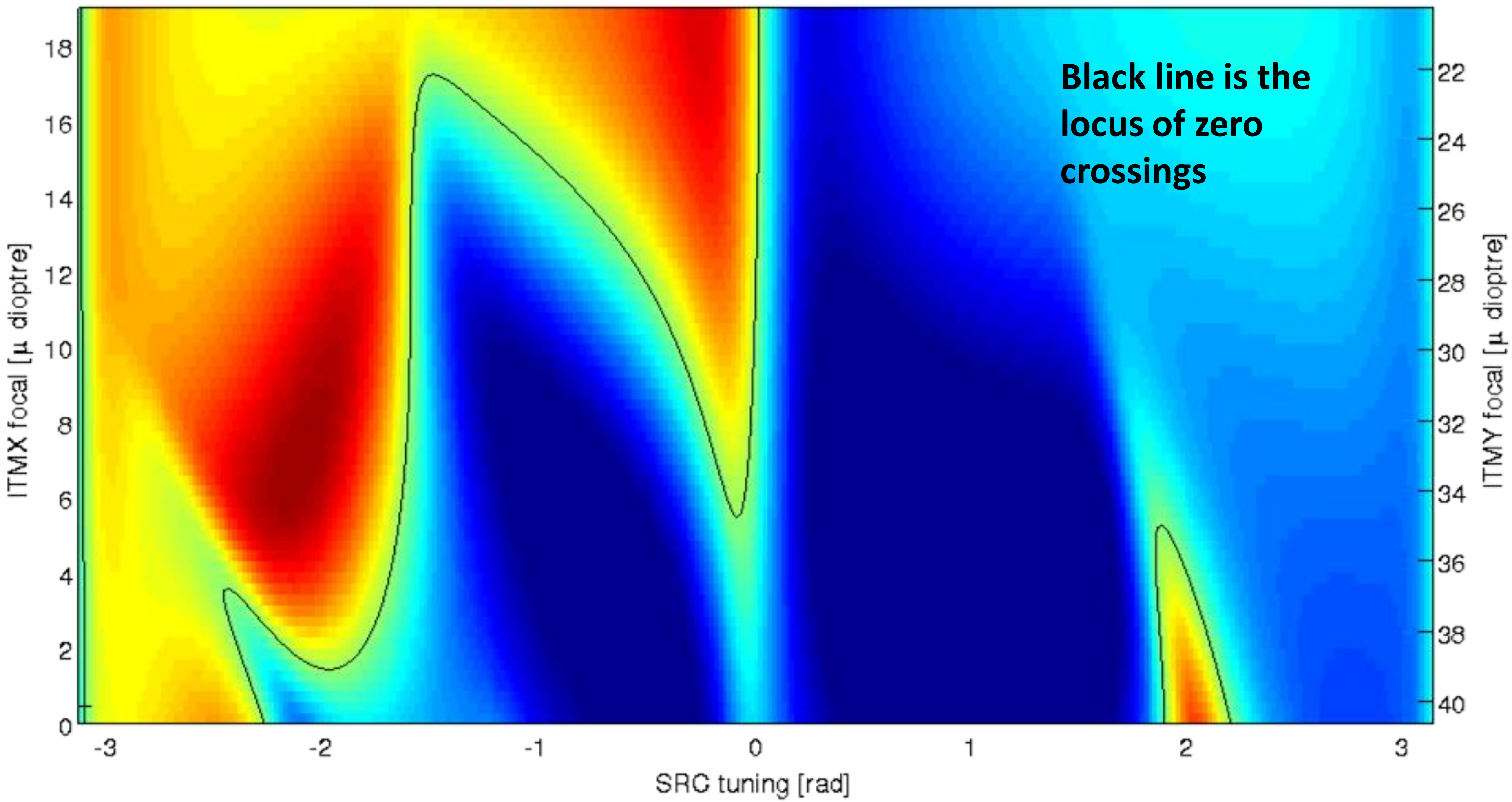
Error signals can be REFL_I2 or POP_I2

When there is some differential lens the simulation is not able to lock SRCL on these error signals





SRCL error signal



At the top of the plot the two input mirrors are equally aberrated.
At the bottom the ITMX is almost perfect, and the ITMY has a lens with focal of 40 km

What's happening?

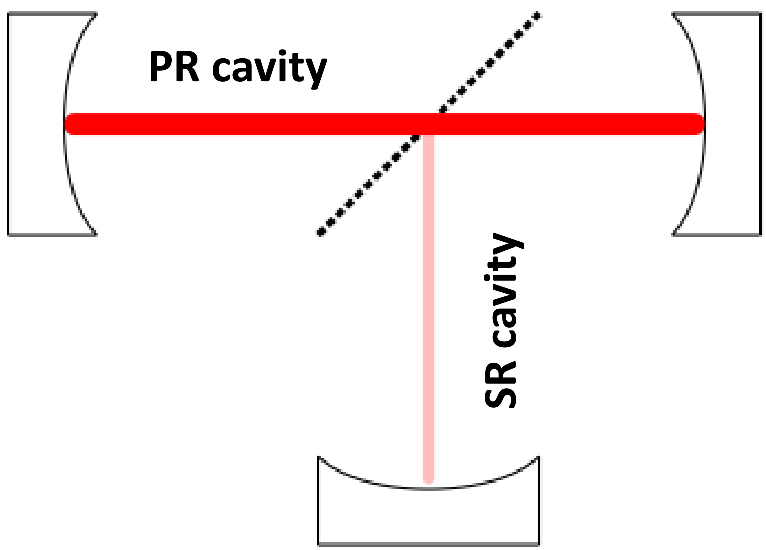
How is the SRCL error signal built?

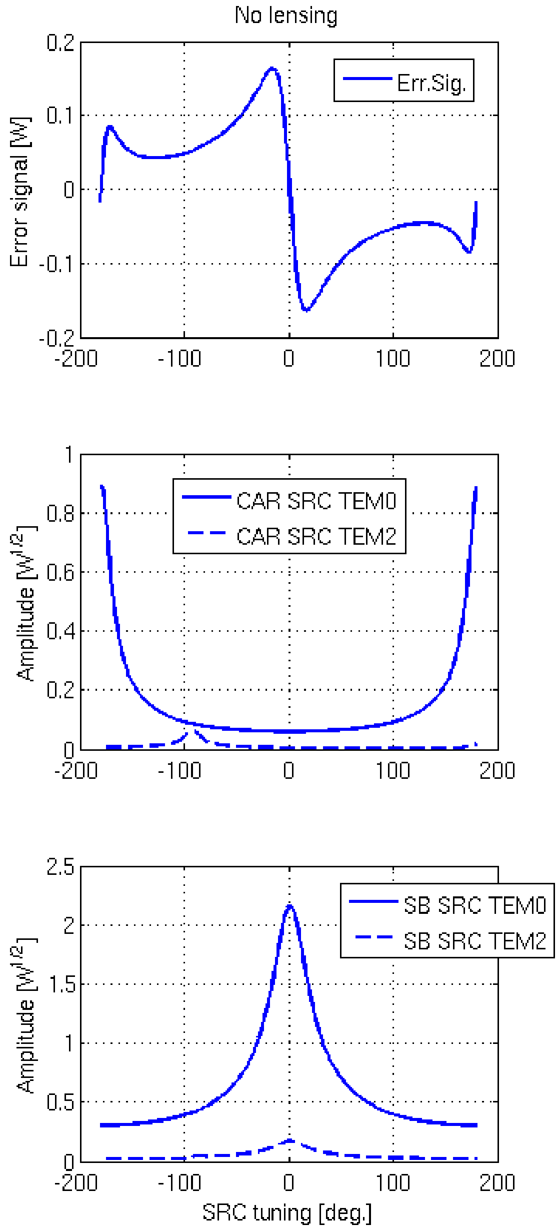
In both cases, we have a cavity (PRC) with an additional output port through AS and SRC cavity

The signal is the beating of sideband and carrier

The carrier is anti-resonant in SRC at zero point.

When the sidebands are resonant in SRC, their amplitude decreases in PRC, since power is extracted. As in all resonant absorption lines, there is also a phase shift that creates the error signal



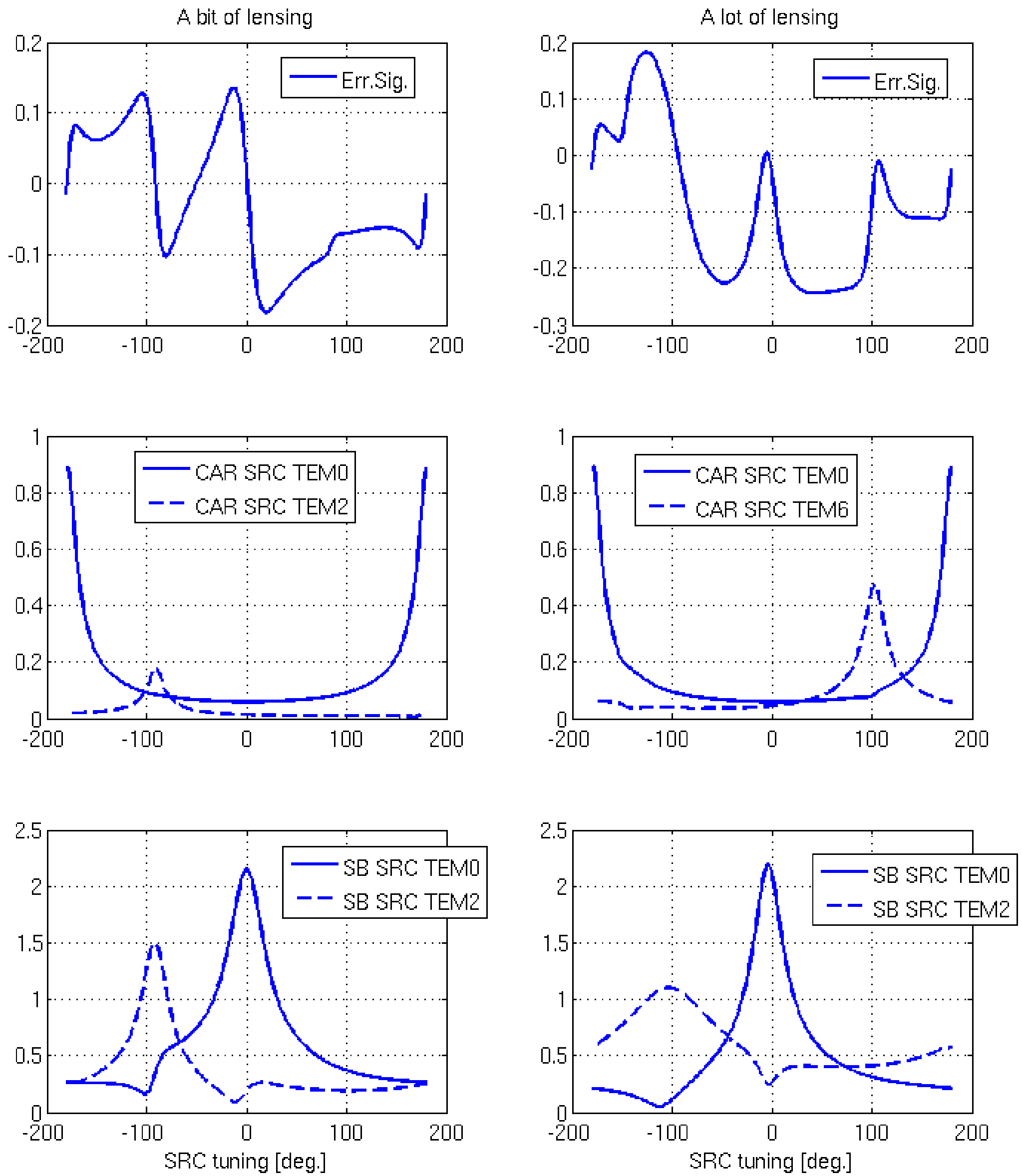


What's happening

When there is differential lens, we have an additional output port: **sidebands TEM00 converted to TEM02 by the lens and perfectly transmitted to SRC**

When SRC is resonant for TEM02, this again extract power from the sidebands TEM00: another resonant absorption line and another error signal summed to the first.

Unfortunately, error signals extends for a large fraction of the SRC tunings



70km / 40 km

170km / 30 km

CONCLUSIONS

Conclusions

Use of modal simulations

Modal simulations are well suited to obtain quick qualitative results

They can provide good qualitative results in the case of stable cavities, more tricky for marginally stable cavities

Simulation results

In Advanced Virgo we could use measurement of optical TF at high frequency to characterize common thermal lenses

In Advanced LIGO, stable signal recycling cavity might suffer from differential lenses, which can affect the SRCL error signal