Finesse 2: Radiation pressure and the quantum kat


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Daniel Brown and many others!

ddb@star.sr.bham.ac.uk

DCC: G1400580

GWADW, Takayama, Japan – 05/2014

Following up on last years promise…

Finesse 2 can now:

- model radiation pressure effects
- model quantum noise

Finesse 2.0 is not just code but a program with 14 years of heritage of user feedback, testing and documentation

Finesse 2.0 comes with a new manual, easy examples, GW detector files

The new Finesse

Started in 1997 by Andreas Freise as side project during his PhD, Finesse has been used extensively worldwide for since 2000:
http://www.gwoptics.org/finesse/impact.php

My first Finesse own journey started in 2012, I was responsible for making Finesse open source, released in 2012
http://kvasir.sr.bham.ac.uk/redmine/projects/finesse

My goal: use Finesse for Advanced LIGO commissioning and design of Advanced LIGO upgrades and ET:

- Mitigating high power: thermal distortions, radiation pressure
- Reducing quantum noise: squeezed light, QND schemes

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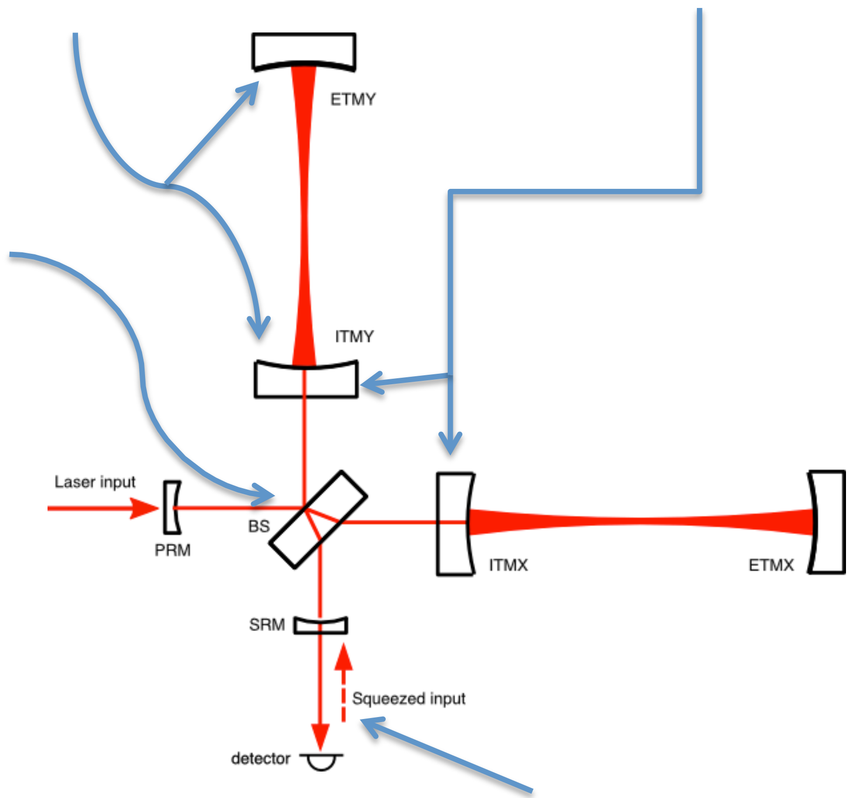
Finesse 2

Advanced LIGO and beyond

Higher laser power = Radiation pressure effects and thermal effects (maps)

Higher sensitivity means we need to look at more details, e.g. finite optical elements = maps, higher order modes

Complex optical setup means increased noise couplings = model noise couplings in non-idealised system



Beyond aLIGO = quantum noise modelling for squeezing and filter cavities

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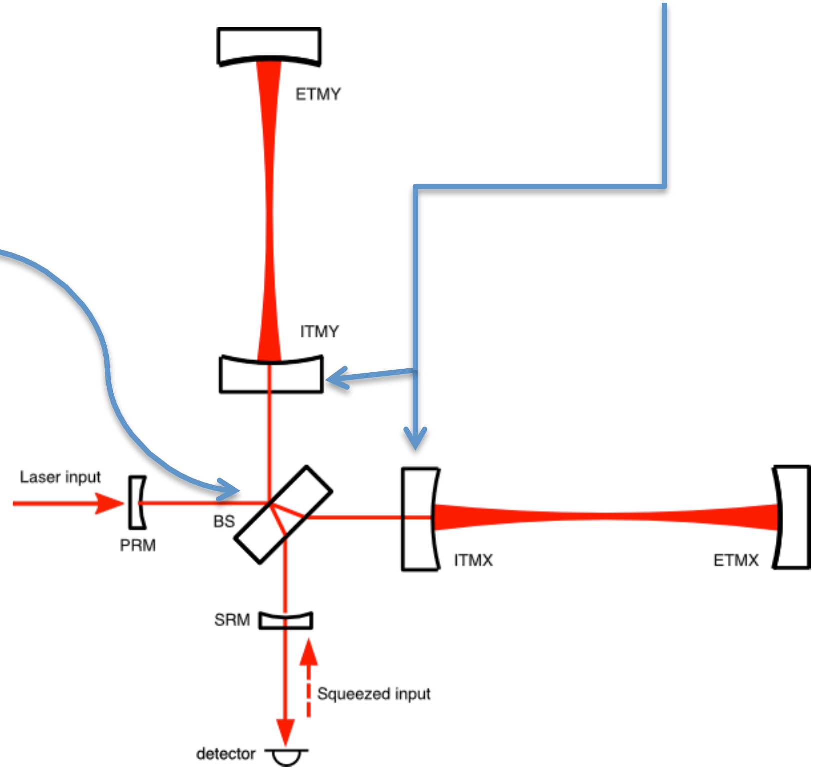
1. aLIGO commissioning: beam shape

Higher sensitivity means need to look at more details, e.g. finite optical elements = maps, higher order modes

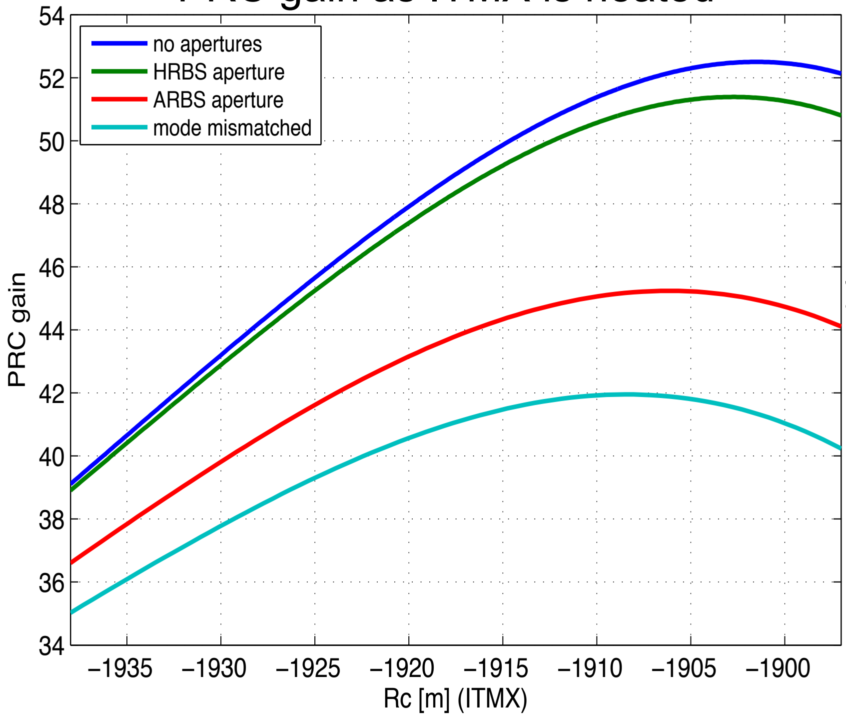
Thermal effects



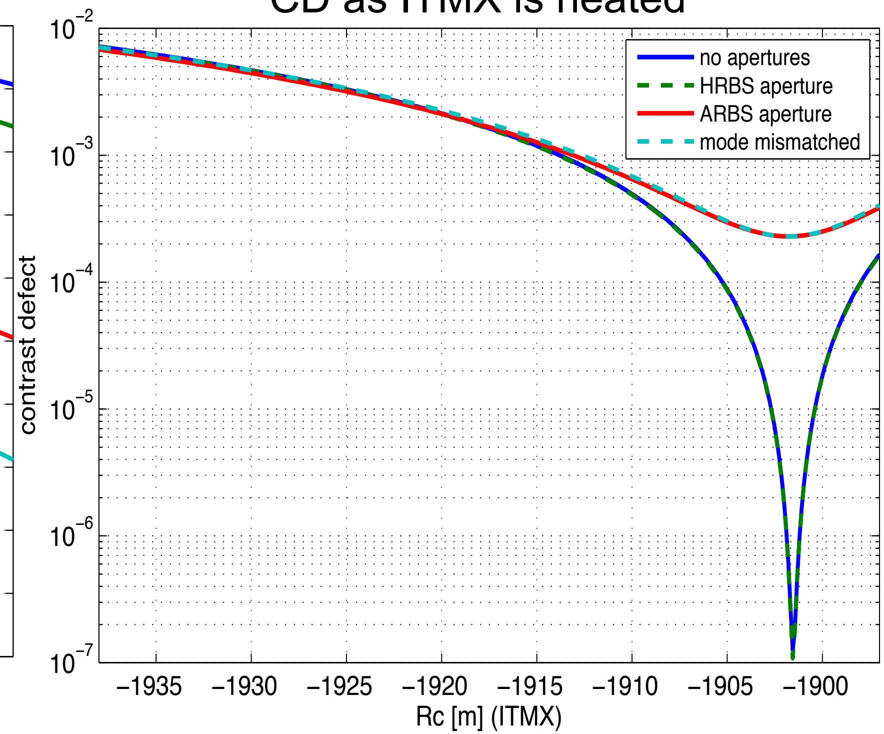
1. aLIGO commissioning: beam shape

DCC G1301276, T1300954, G1400222

PRC gain as ITMX is heated



CD as ITMX is heated



Using beamsplitter apertures and maps to determine how clipping affects the PRC gain difference in LLO (before arm cavities)

Clipping limiting PRC gain, the small BS is something that needs looking at in future simulations

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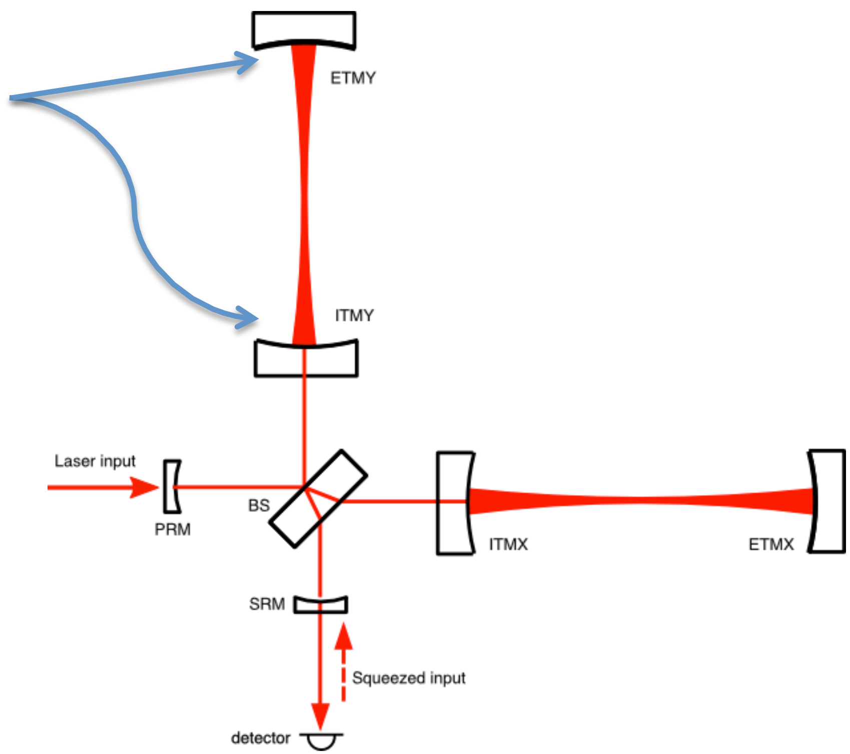
2. aLIGO commissioning: control

Complex optical setup means increased noise couplings = model noise couplings in non-idealised system

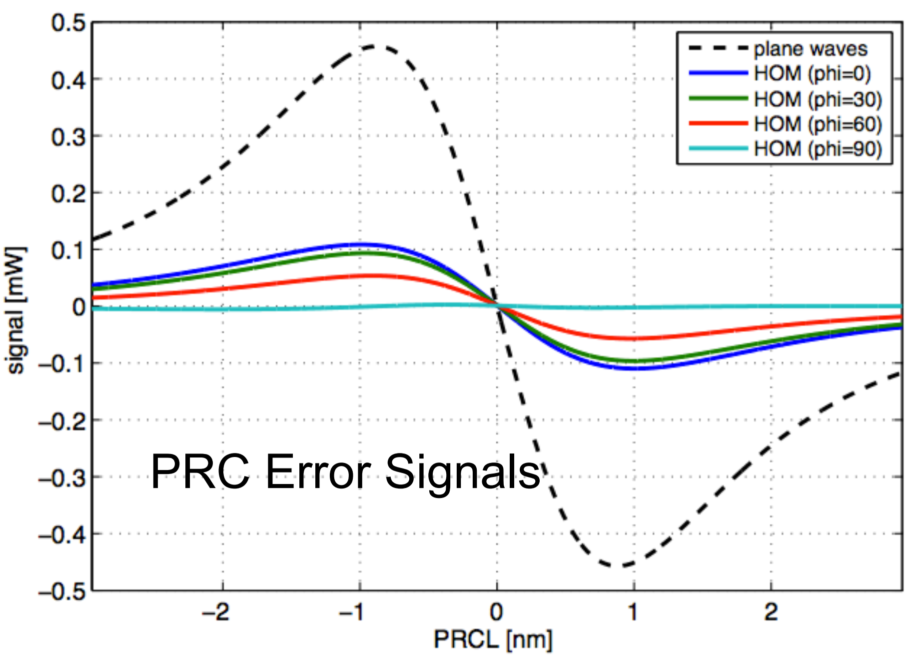


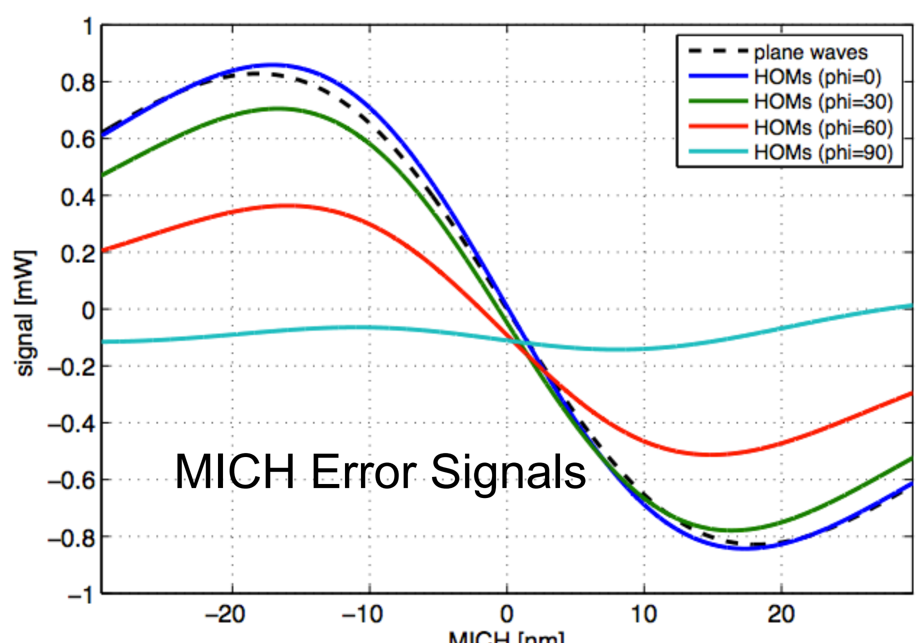
2. aLIGO commissioning: control

DCC T1400182

Mode-mismatch between x-arm and y-arm (cold case) due to different non-thermal lenses in ITM substrates (ITMX f = +300km, ITMY f = -80km). Beams in PRC are larger than expected (7cm/6cm compared to design of 5.3cm).

This mode-mismatch reduces the control signals compared to plane wave models and different offsets vs demod. phase.



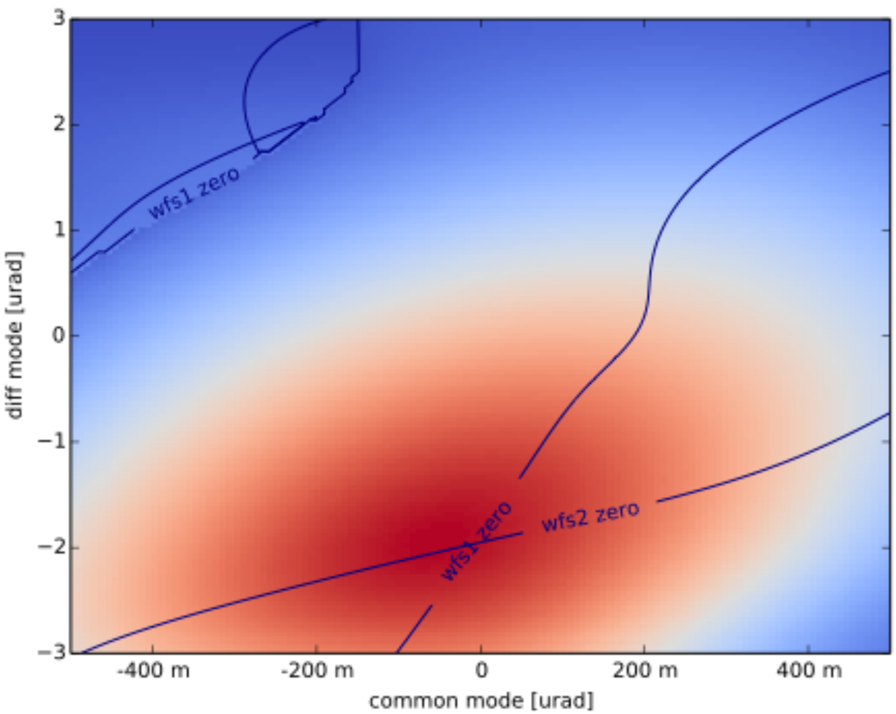


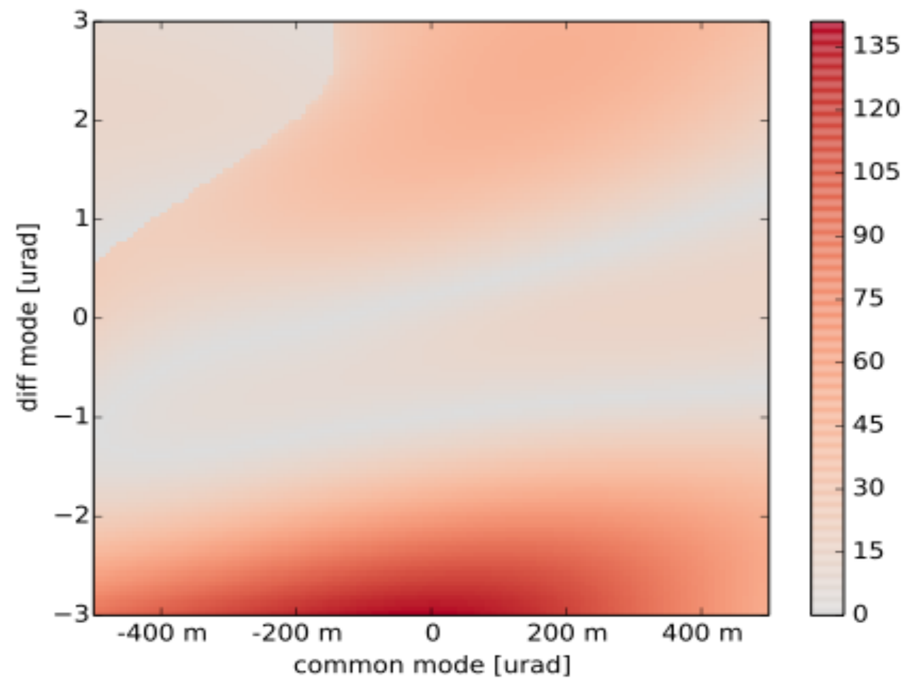
2. aLIGO commissioning: control

Preliminary results! ALS WFS control signals

Investigating possible reasons for large variations in alignment matrix elements of the green arm lock (low finesse arm cavity).

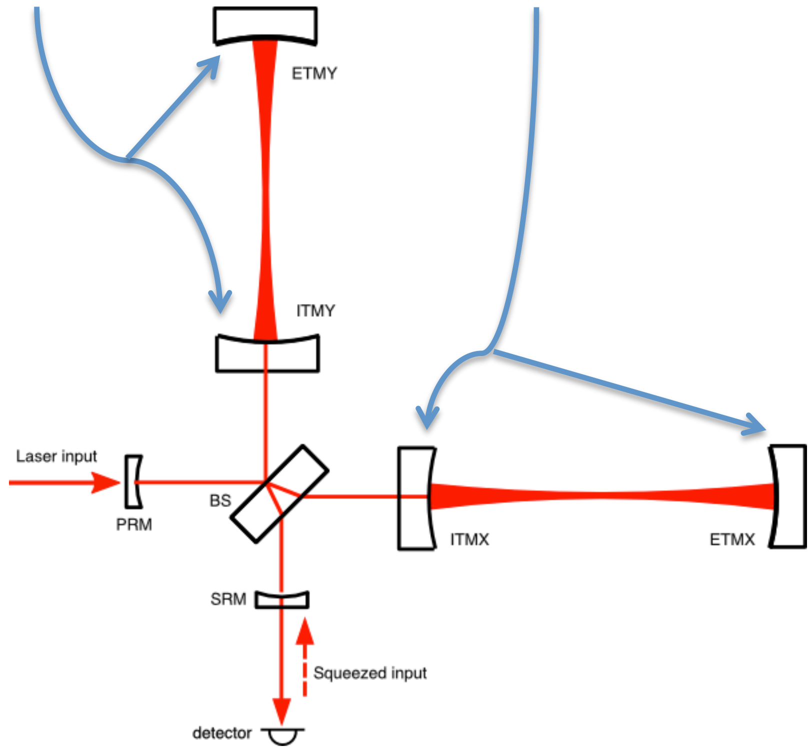
Mode-mismatched (10%) and misaligned still producing usable control signals. Order of magnitude variation in certain elements seen depending on alignment.





3. aLIGO commissioning: next steps

Radiation pressure effects during high power operation, a control challenge



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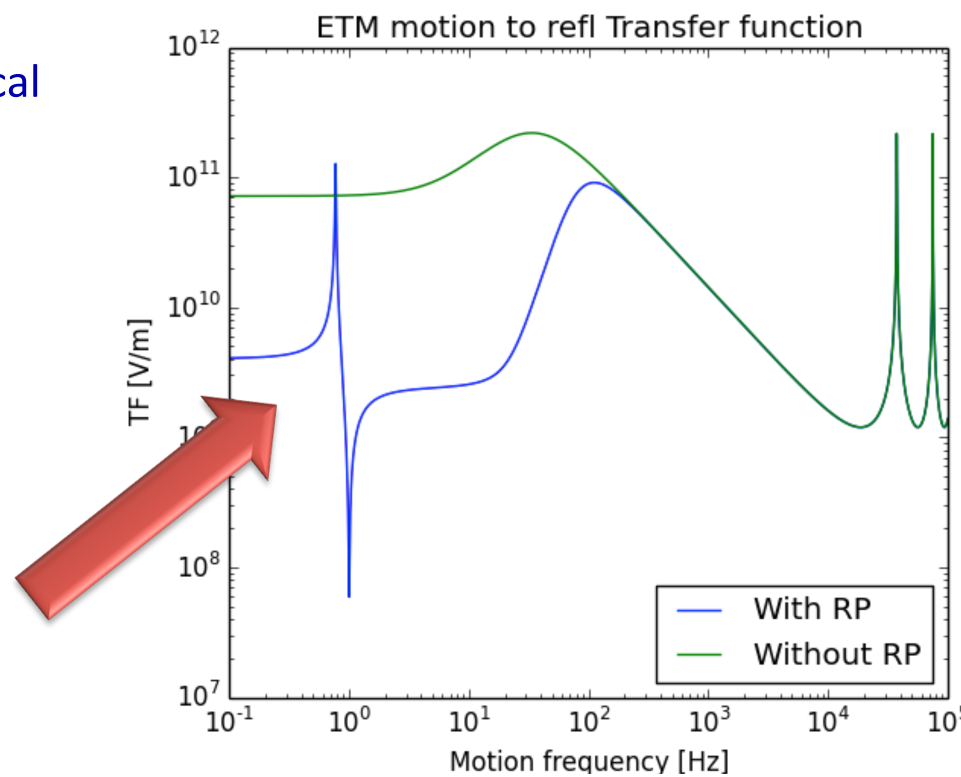
Radiation pressure effects

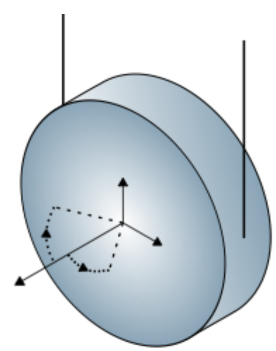
Radiation pressure creates opto-mechanical coupling

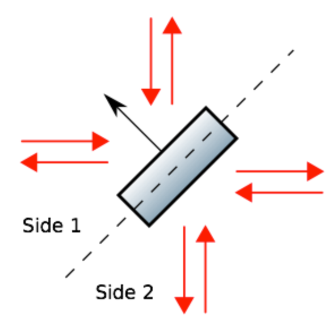
Yaw, pitch and longitudinal motions are coupled with optical fields, so this affects:

- Quantum noise transfer functions
- Displacement noise transfer functions
- Control signals
- Stability – Angular Sidles-Siggs instability for example

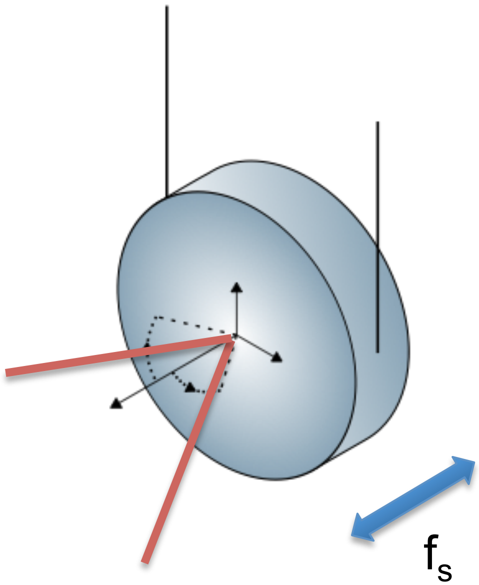


Need tool that can model both thermal distortions (HOM) along with radiation pressure effects for commissioning and design work

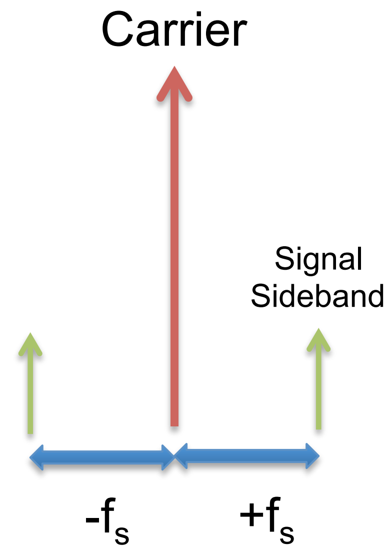




How do we model it?



General surface motion to optical field coupling



$$K^{o}_{nmn'm'} = \iint_{\infty}^{\infty} u_{n'm'}(x,y) e^{i2kz_o(x,y)} u^{*}_{nm}(x,y)\,dx\,dy,$$

$$K^{s}_{nmn'm'} = \iint_{\infty}^{\infty} u_{n'm'}(x,y) z_s(x,y) u^{*}_{nm}(x,y)\,dx\,dy,$$

$$a^{\pm}_{s,jnm} = \frac{irkA^{\pm}_{s}}{\cos(\alpha)} \sum_{n',m'} a_{c,jn'm'} (K^{s}K^{o})_{nmn'm'}$$

Incoming carrier

What do we need to solve?

Longitudinal motion to optical field coupling

Surface motion is just a constant, no x/y dependence

$z_s(x,y) = Z_s$

First compute surface motion distortion, just identity matrix in this case

$$K^s_{nmn'm'} = \delta_{nn'}\delta_{mm'},$$

$$a^{\pm}_{s,jnm} = \frac{irk}{\cos(\alpha)} Z^{\pm}_s \sum_{n',m'} a_{c,jn'm'} K^o_{nmn'm'}$$

Surface motion amplitude

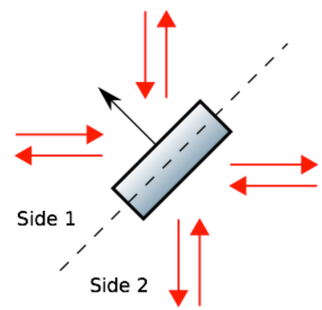
Static surface distortion

r = mirror reflectivity
k = wave number
α = angle of incidence

Optical field to longitudinal coupling

Power fluctuations at signal frequency f_s

$$P_s = \sum_j \sum_{n,m} \left(a^{+}_{s,jnm} a^{*}_{c,jnm} + a^{-*}_{s,jnm} a_{c,jnm}\right)$$



Compute power fluctuations in ALL incoming and outgoing beams

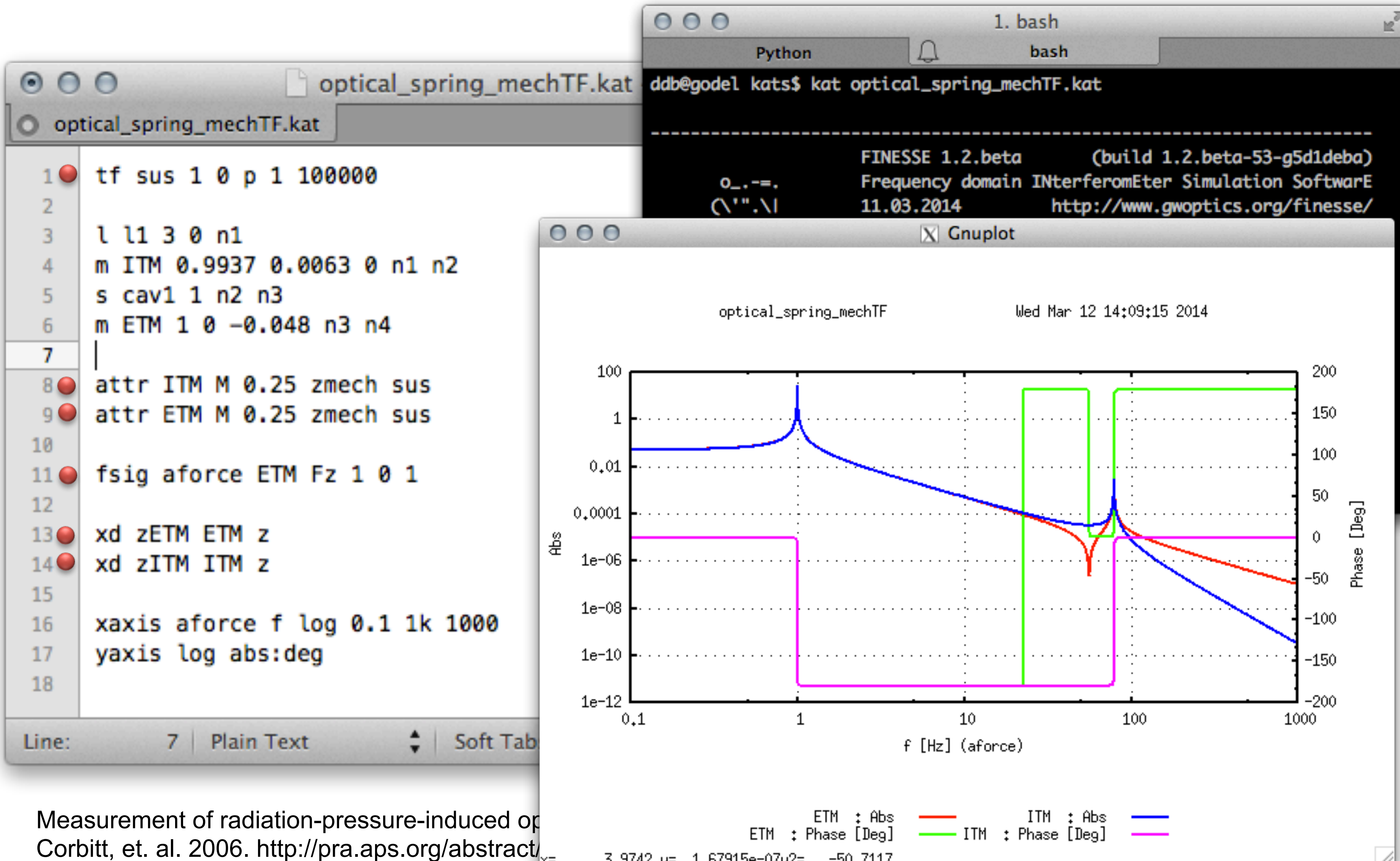
$$F_s = \frac{\cos(\alpha)}{c}\left(-P_{s,1i} - P_{s,1o} + P_{s,2i} + P_{s,2o}\right)$$

$$Z_s = H_s \sum_n^{N_F} F_{s,n}$$

Final motion at frequency f_s is then sum of all forces acting on it

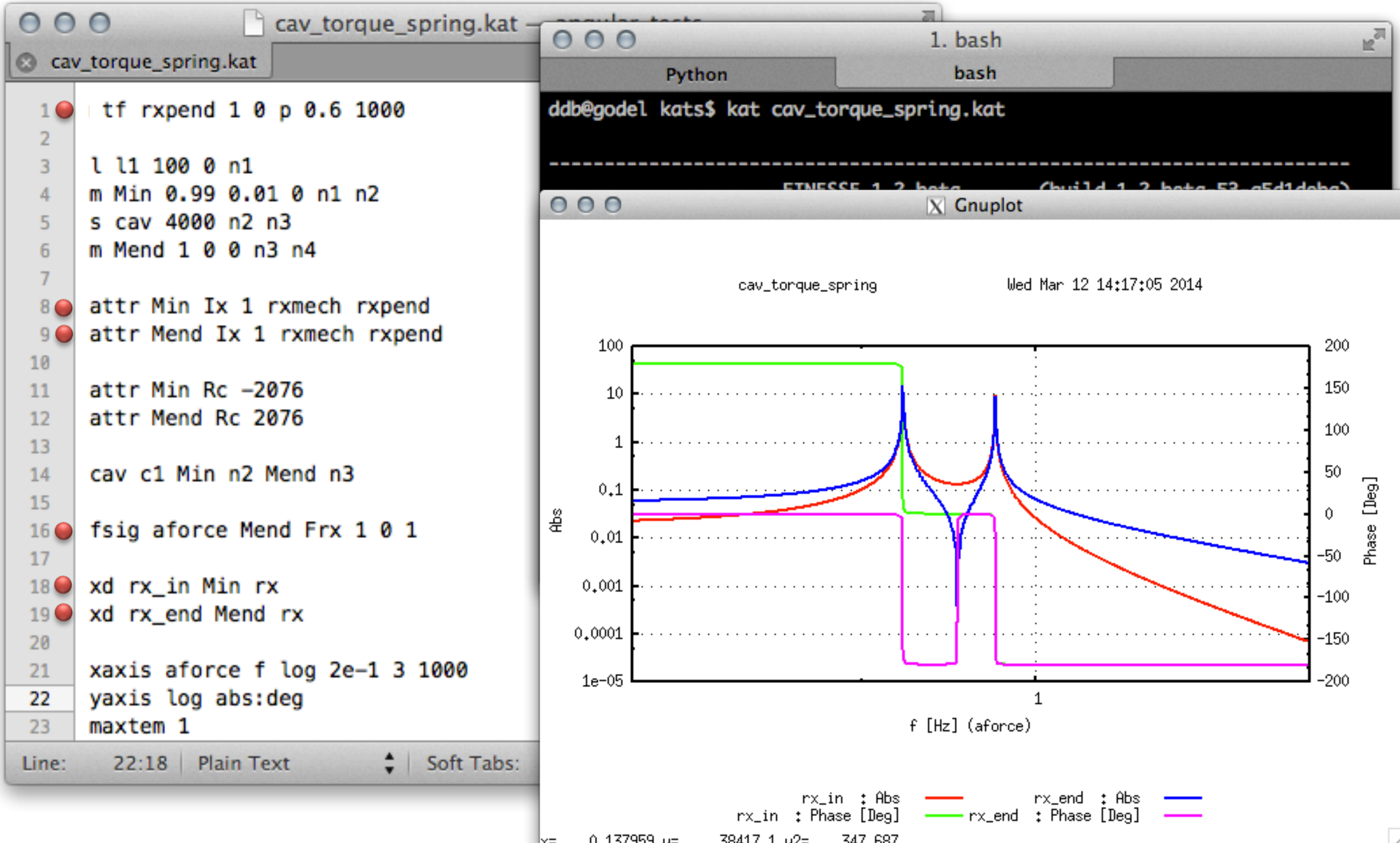
Mechanical transfer function

How to model optical springs

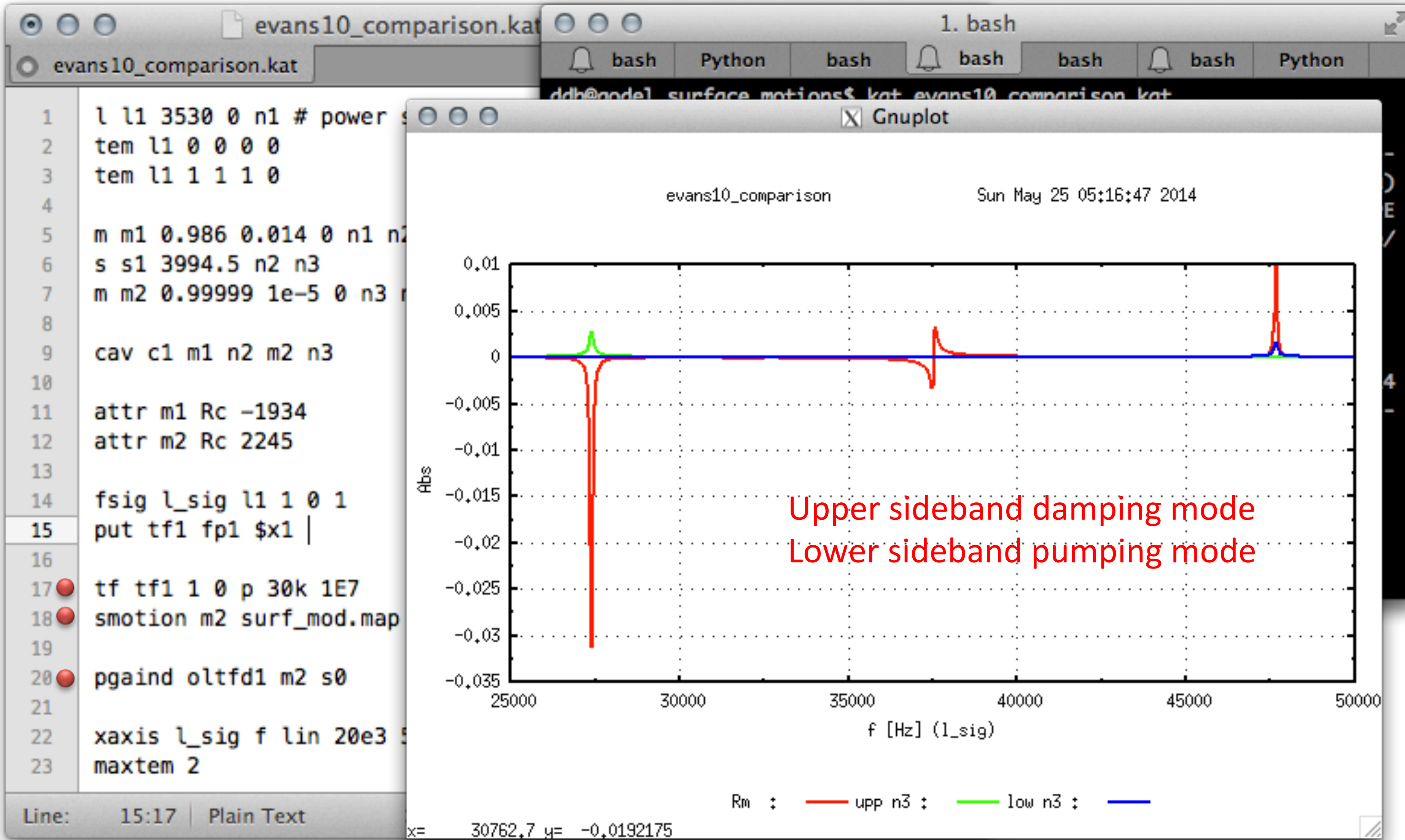


Measurement of radiation-pressure-induced op
Corbitt, et. al. 2006. http://pra.aps.org/abstract/

…and angular RP effects



…and parametric instabilities



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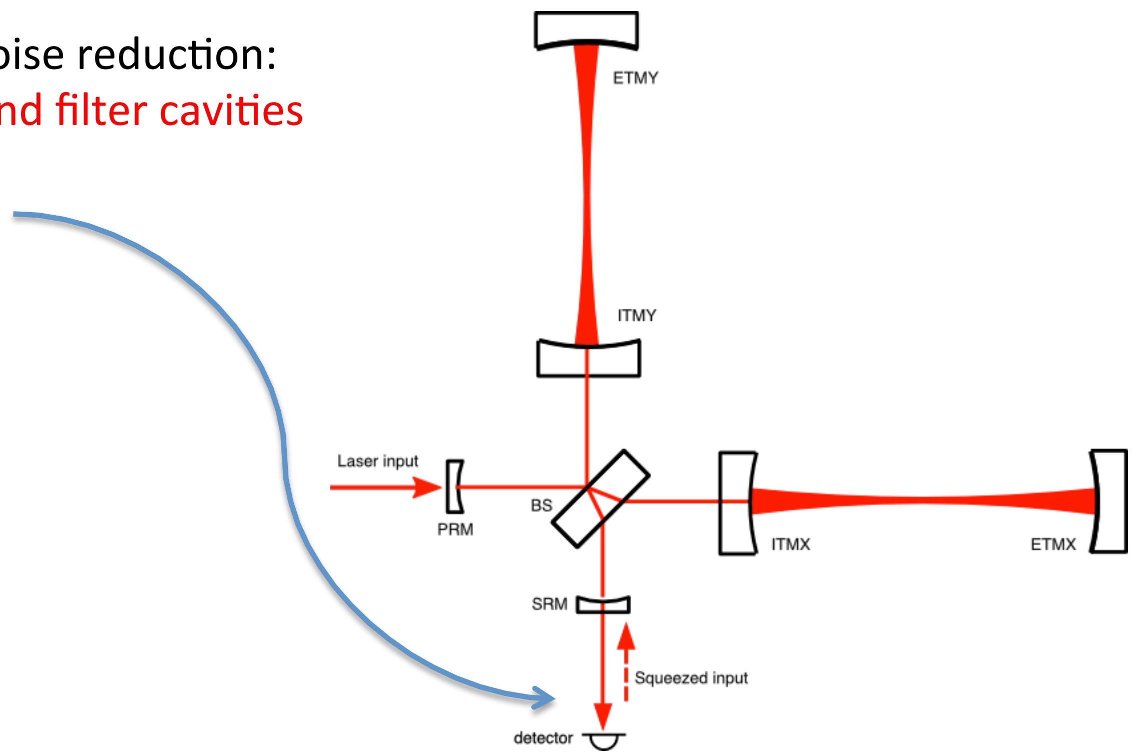
Beyond Advanced LIGO

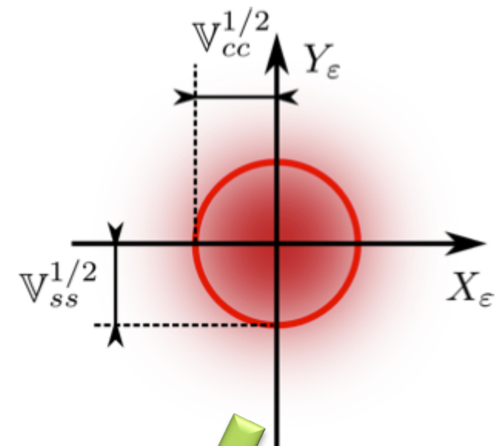
Quantum noise reduction:
squeezing and filter cavities

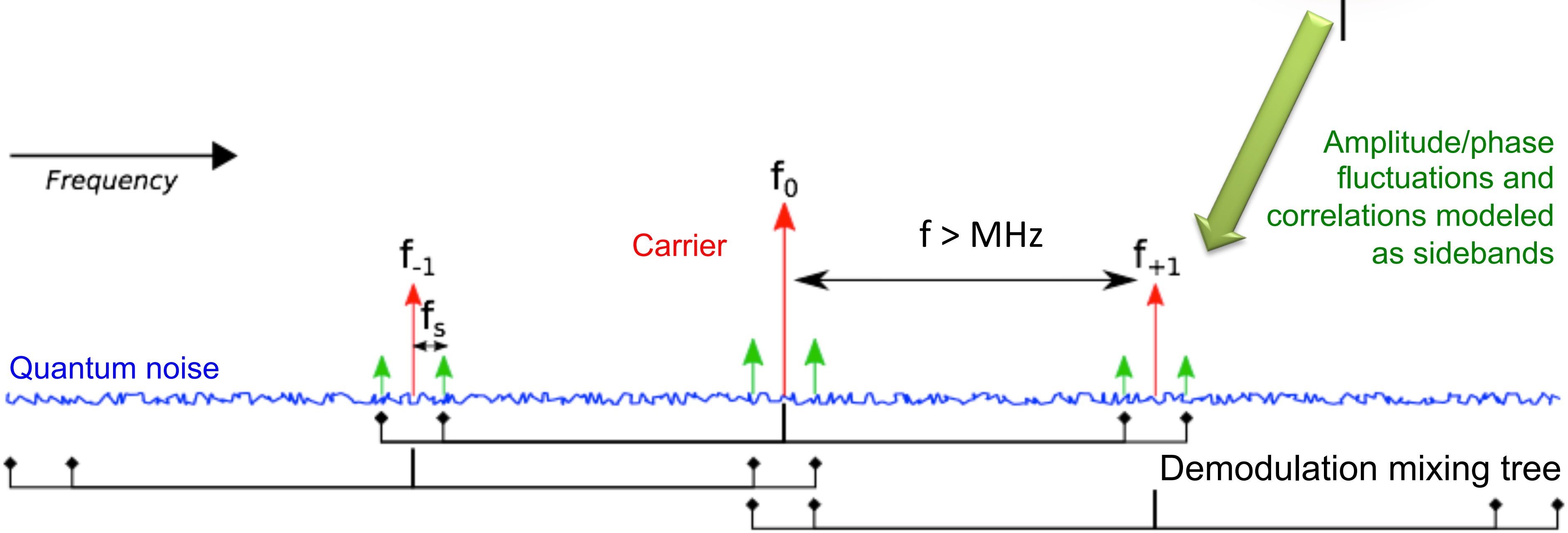


Modelling quantum noise

We implemented the two-photon formalism in FINESSE to compute noise at a photodiode detectors.

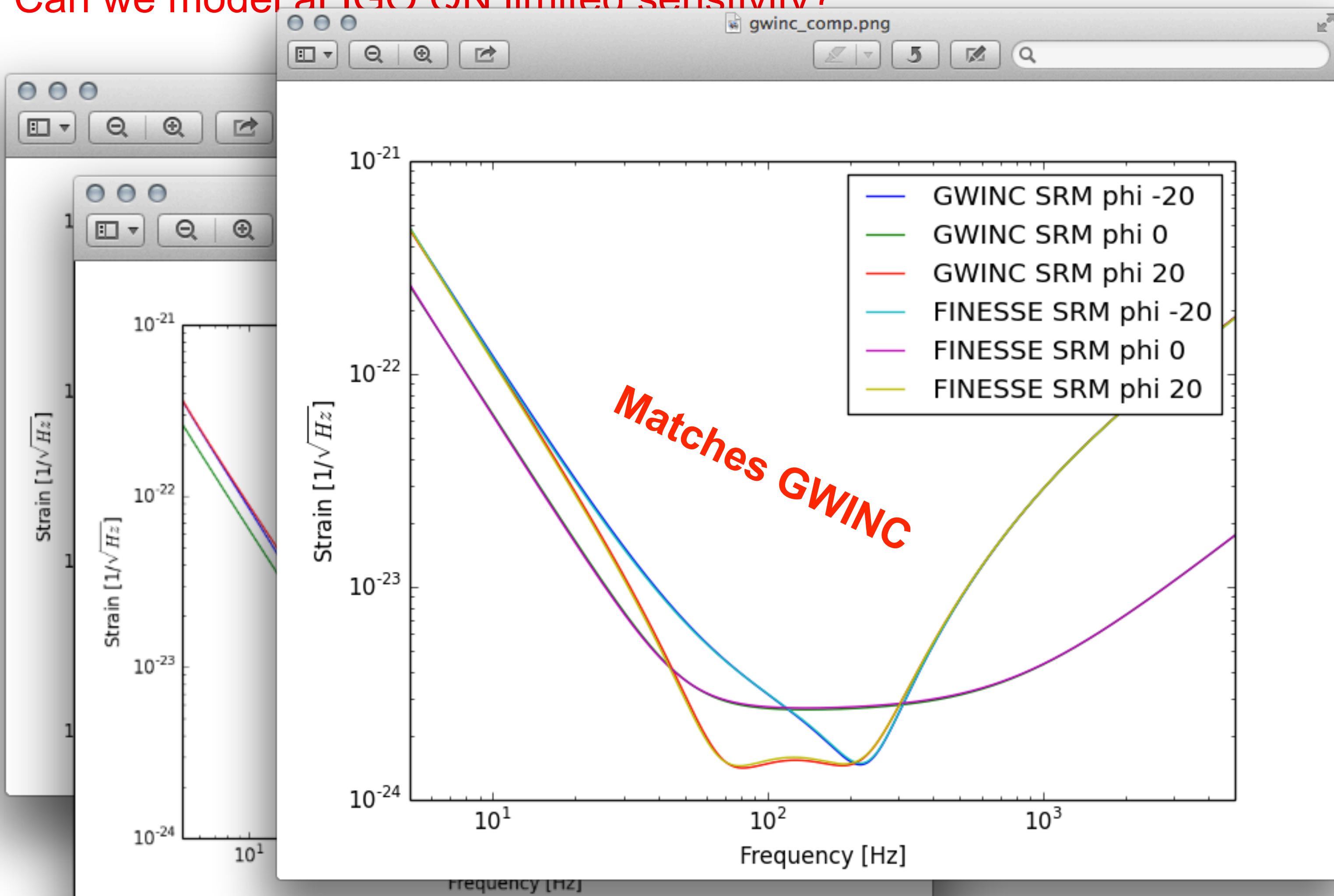
- Need to easily include many noise sources
- Handle higher-order modes correctly
- Noise PSD computation needs to take into account multiple carrier fields and their contribution to the noise when demodulated





Some aLIGO examples...

Can we model aLIGO QN limited senstivity?



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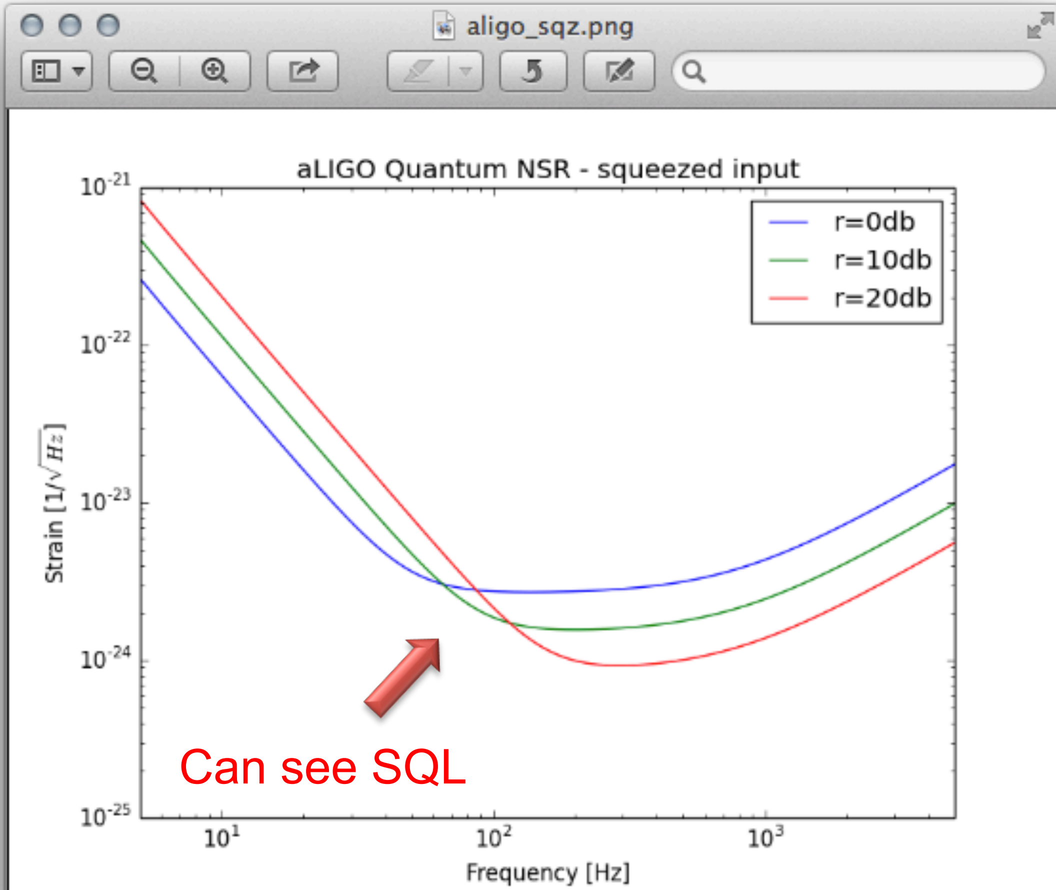
How about some squeezing?



Easy enough, just add a squeezed source at the dark port…

Squeezing db and angle

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sq sq1 0 10 90 nfc1
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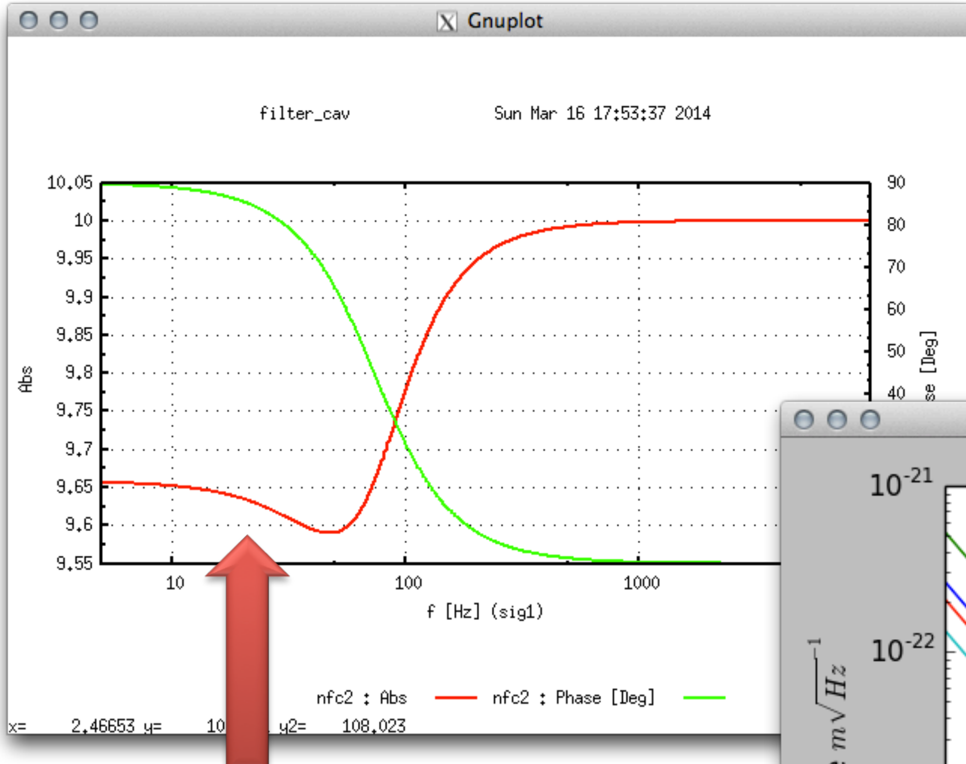
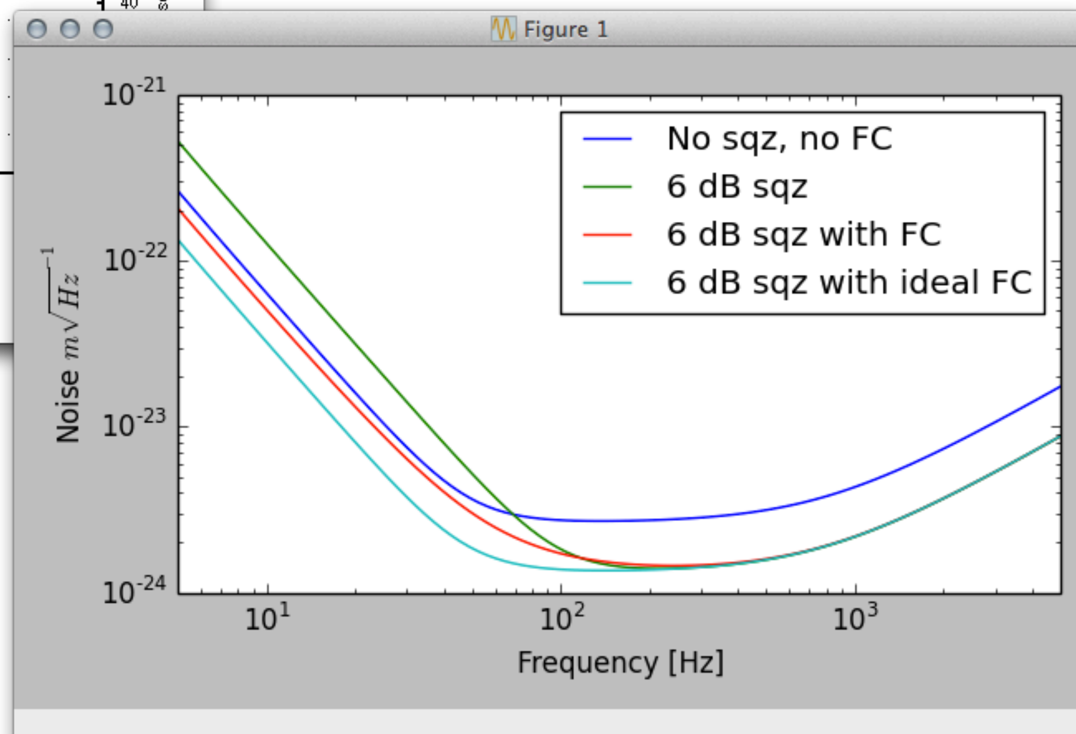
Carrier frequency to squeeze

...Filter cavities?



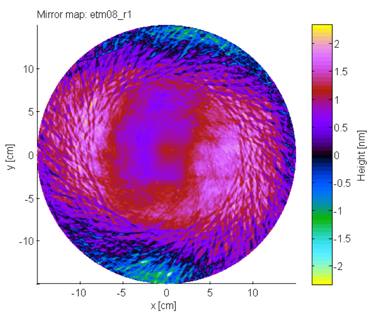
Model 10db squeezed field reflected from a cavity, then output squeezing factor *r* and *squeezing angle.*

Experiment with effects of a realistic filter cavities on generic interferometer setup.



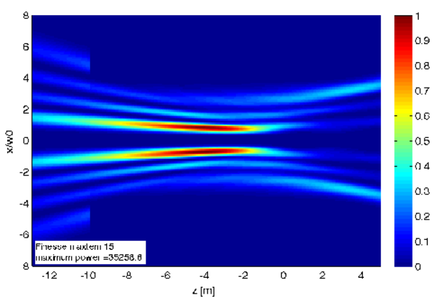
Cavity has lossy ETM so degrades squeezing at low frequencies

What Finesse can do for you



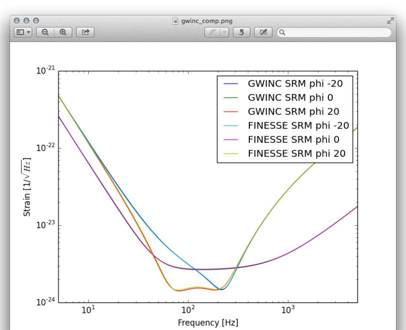
Surface and bulk distortions

- Thermal effects
- Manufacturing errors
- Surface maps



Finite optics

- Beam clipping
- Offsets



Quantum noise

- Squeezed light
- Filter cavities
- QND schemes

Frequency domain modelling of interferometers

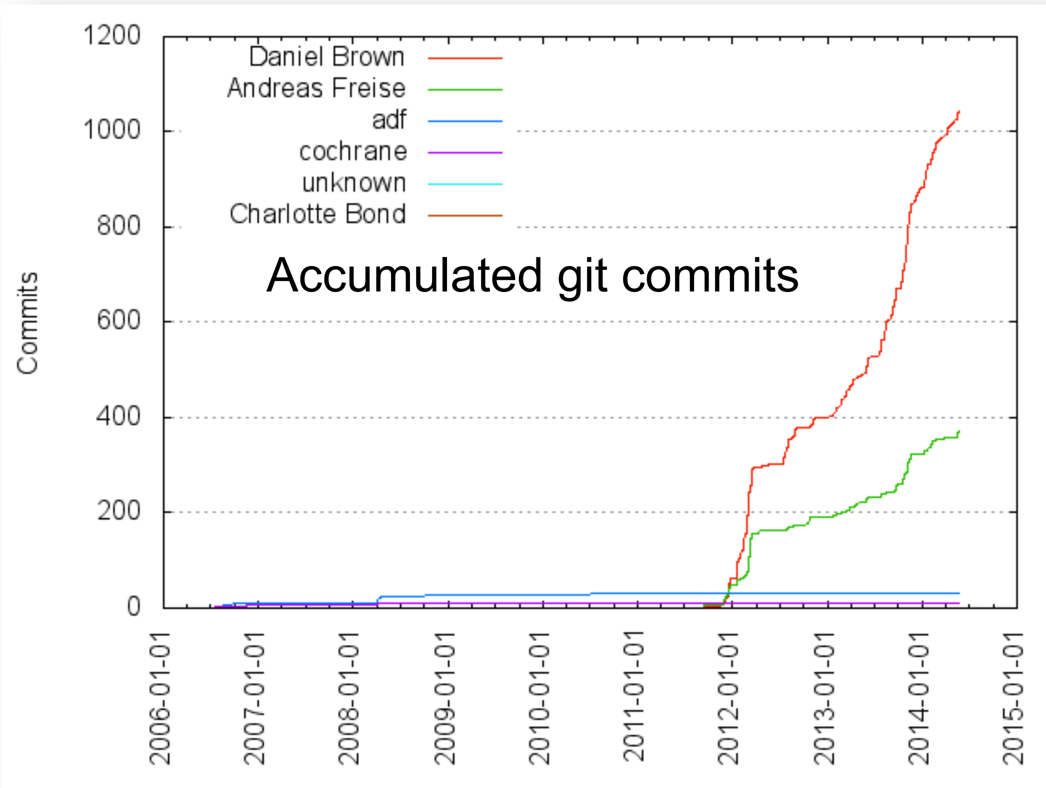
Want to model:

- Noise couplings
- Transfer functions
- Control schemes
- Optical losses
- Beam shapes

More features:

- Radiation pressure effects, parametric instabilities
- Quantum noise computations
- Sidebands-of-sidebands

FINESSE is under active development



Have plenty of new features now to keep us busy.

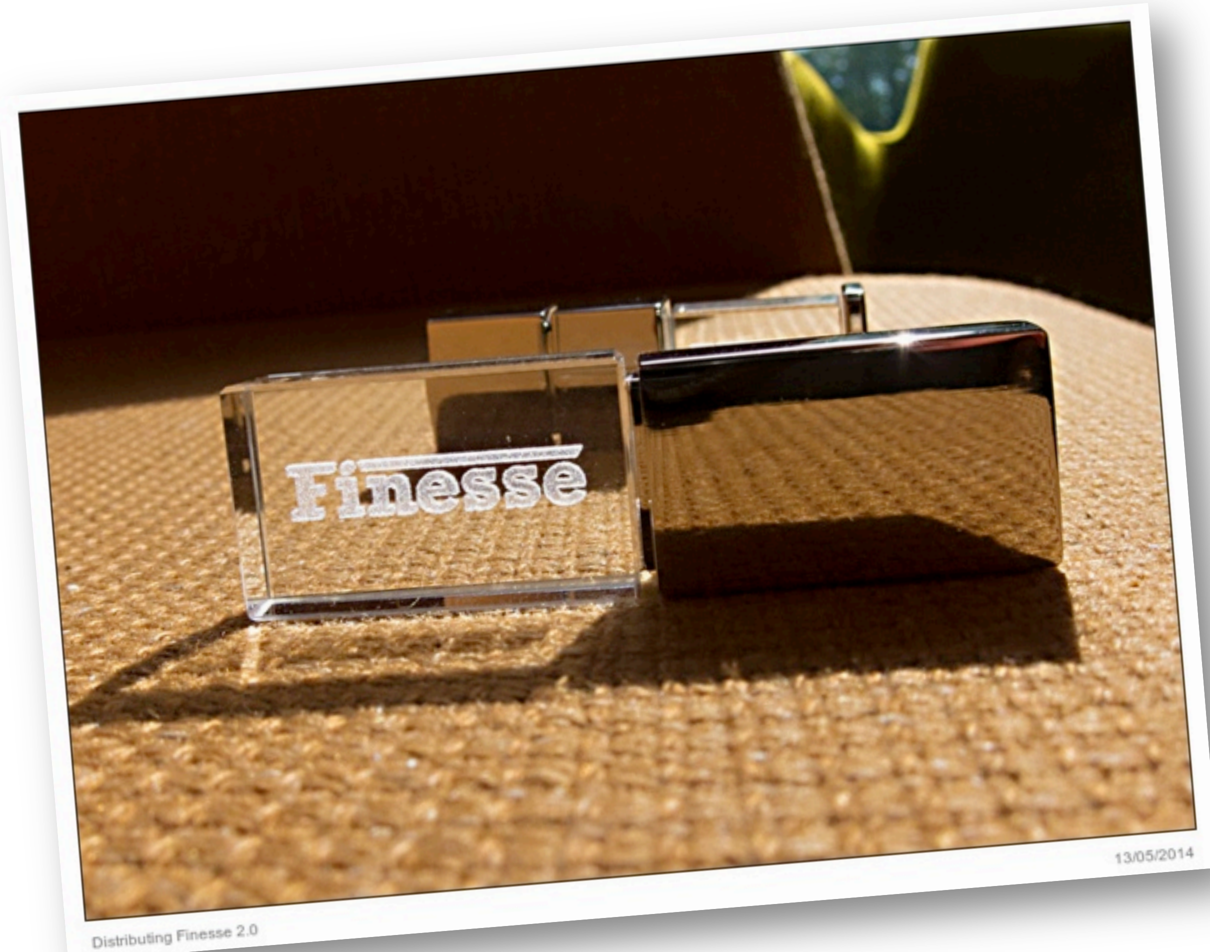
Join in, use it, and help improve it!

Finesse is a tool for the community so feedback, requests and questions all help improve it.

But where next now we have radiation pressure and quantum noise?

Although still quick, explore areas for making use of GPUs, other speed improvements and smarter algorithms

Free 4GB FINESSE USB sticks



FINESSE related material:

Detectors files: LIGO, KAGRA, GEO, ET, VIRGO,

Finesse 2.0 Binaries for Windows, Linux and OSX

Various pictures, documents, papers, etc. from over many years of FINESSE development

Conclusion

- FINESSE now includes radiation pressure:
  - Suspend mirrors and beamsplitter components
  - Longitudinal, yaw, pitch and higher order surface motions
  - Specify generic transfer functions for modelling suspensions
  - Compute new noise couplings, control signals and more
- Full quantum noise computations for generic setups
  - Two photon formalism implemented
  - Can model QN limited sensitivity
  - Can model squeezing, filter cavities and QND schemes
- Grab a free USB stick!

Thanks for listening!

…see our website http://www.gwoptics.org/finesse

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Finesse 2

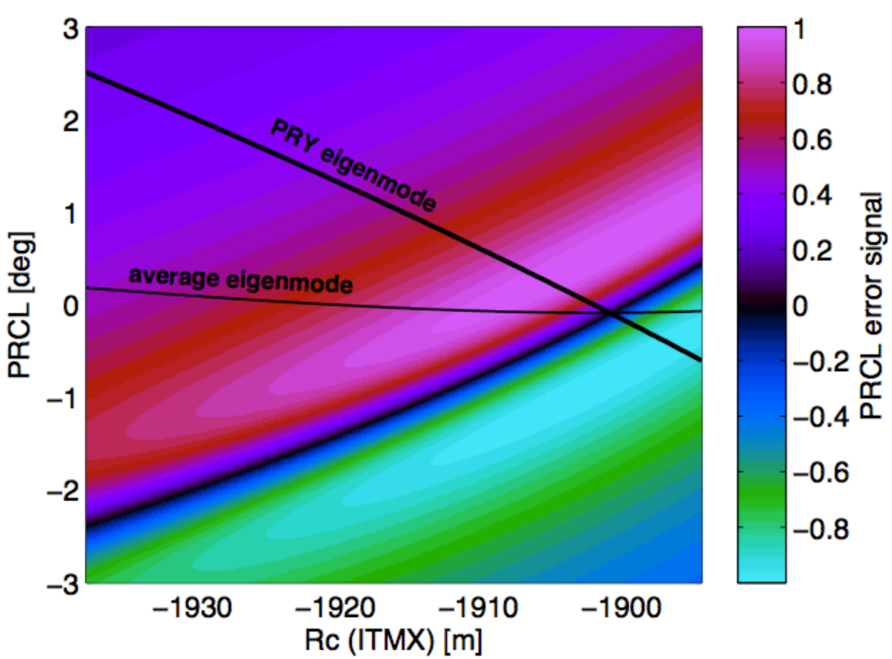
2. aLIGO commissioning: control

C. Bond Thesis

When modelling complex interferometers you must always ensure that your interferometer is on the correct operating point. With use of HOM for modelling distortions and mode-mismatches this becomes a tricky task.

LLO PRCL control signal vs different user definable eigenmodes. If done properly with enough HOMs, operating point should be identical despite different control signals

PRCL



PRC power