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 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:

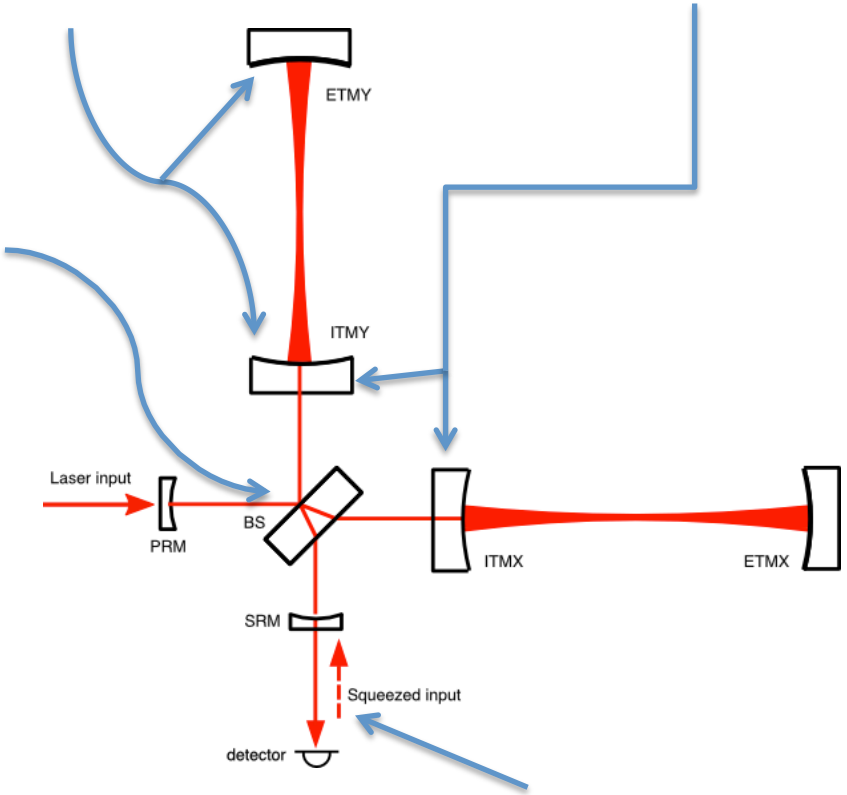
- Mitigating high power: thermal distortions, radiation pressure
- Reducing quantum noise: squeezed light, QND schemes

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

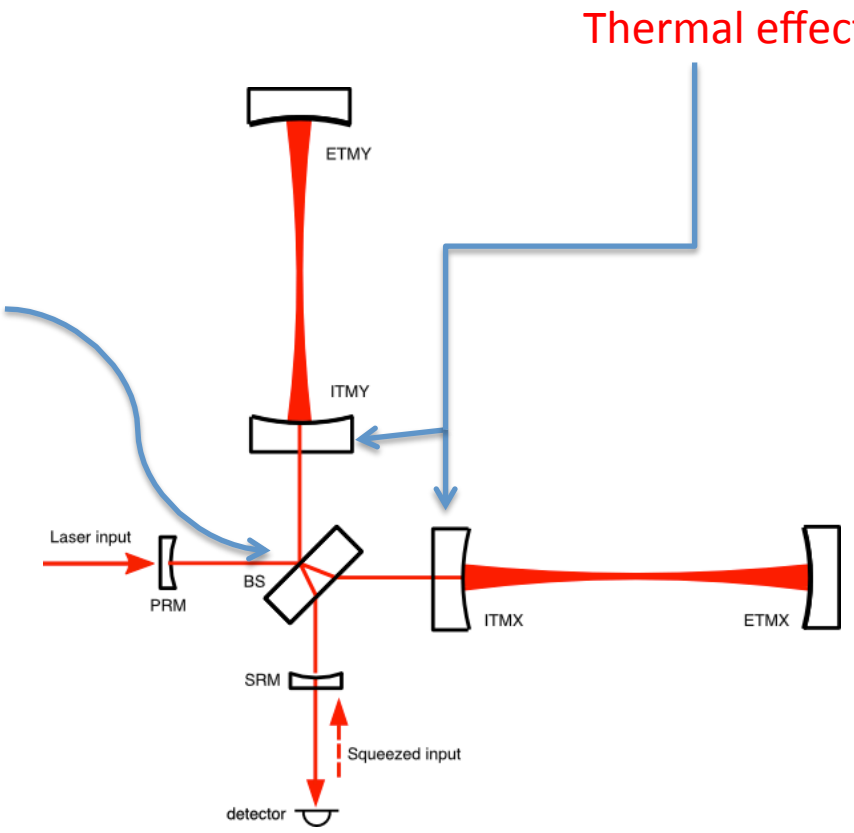
Complex optical setup means increased noise couplings = model noise couplings in non-idealised system



Beyond aLIGO = quantum noise modelling for squeezing and filter cavities

1. aLIGO commissioning: beam shape

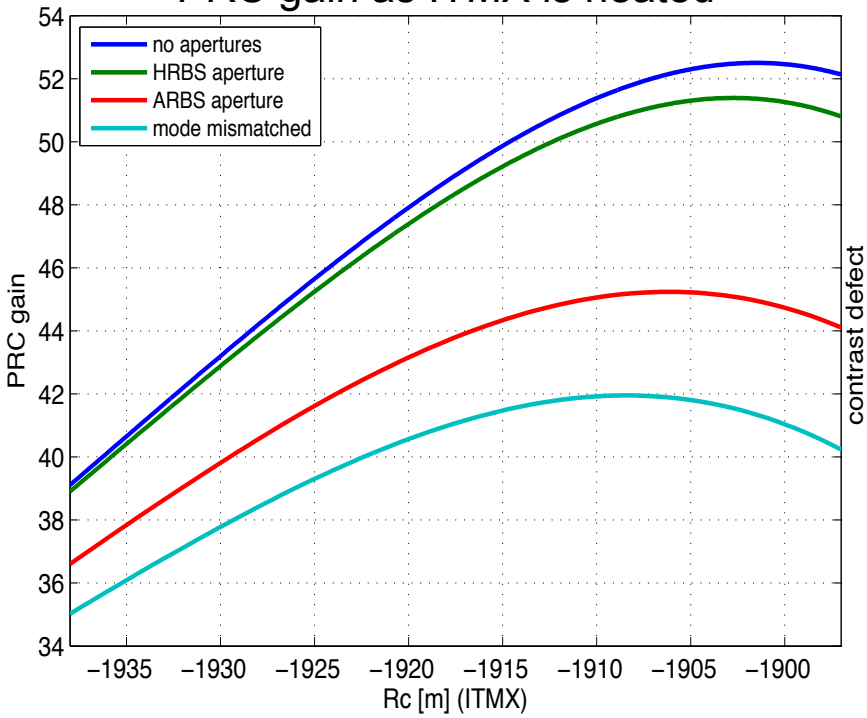
Higher sensitivity means need to look at more details, e.g. finite optical elements = maps, higher order modes



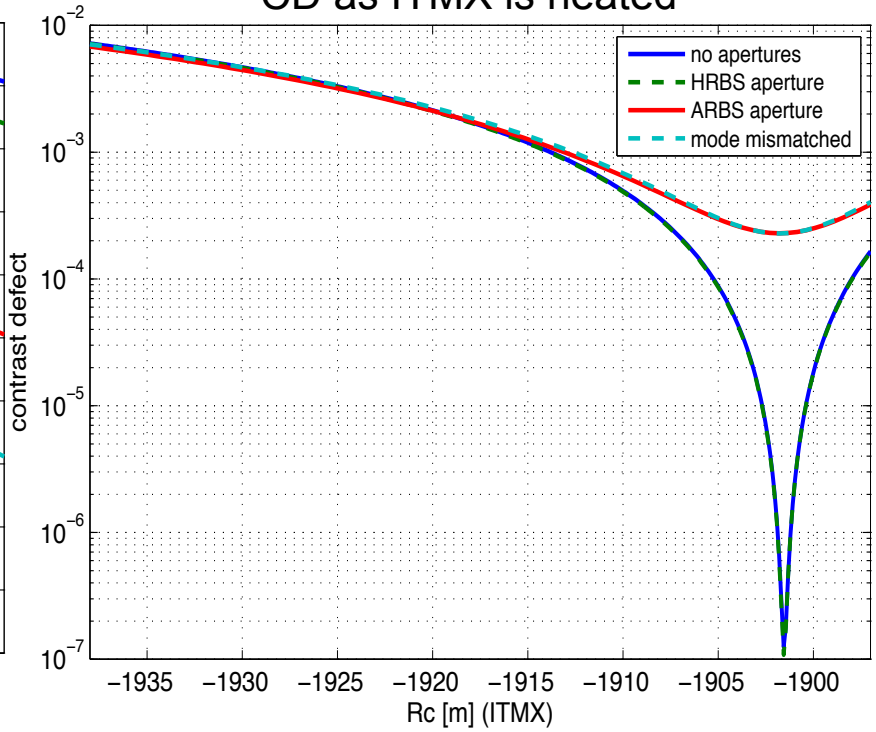
1. aLIGO commissioning: beam shape

DCC G1301276, T1300954, G1400222

PRC gain as ITMX is heated



CD as ITMX is heated

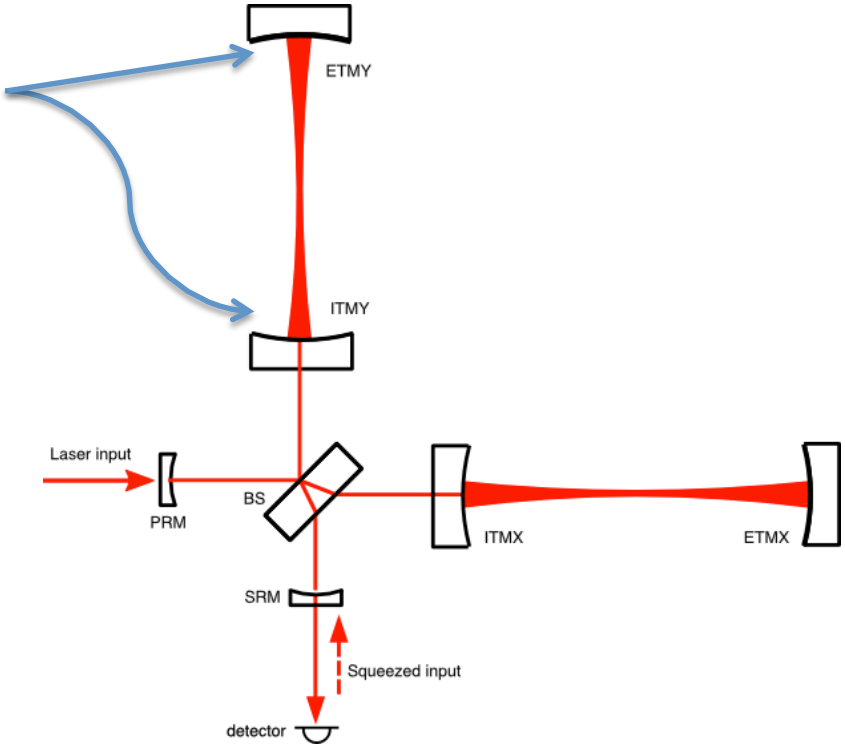


Using beamsplitter apertures and maps to determine how clipping affects the PRC gain difference in LLO (before arm cavities)

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

2. aLIGO commissioning: control

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

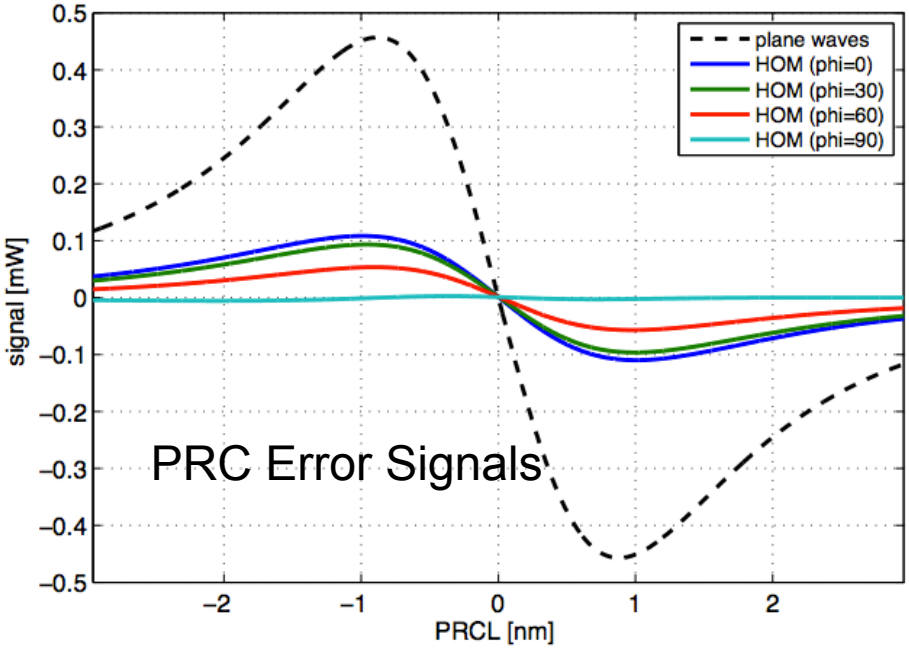


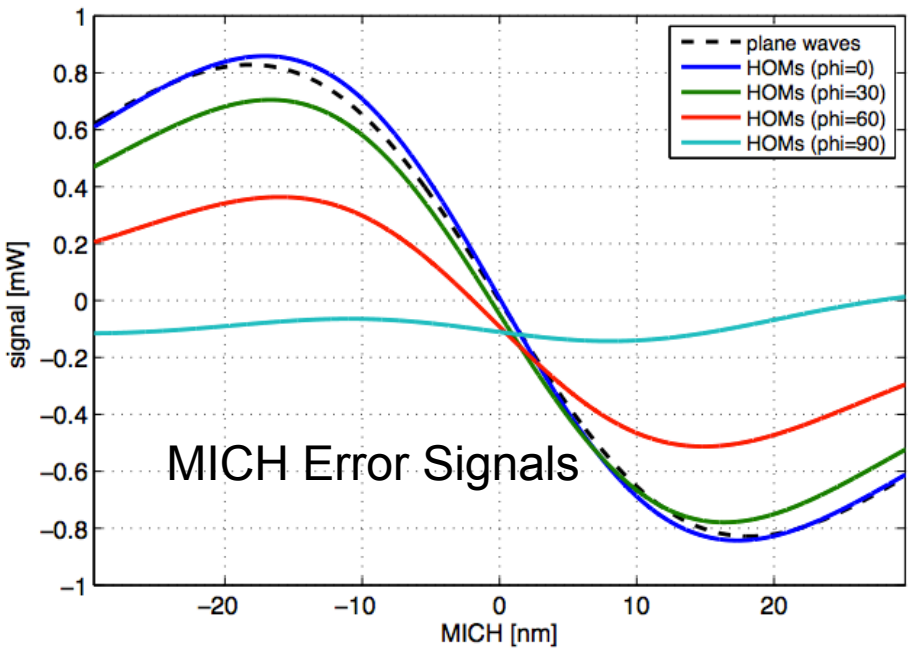
2. aLIGO commissioning: control

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.





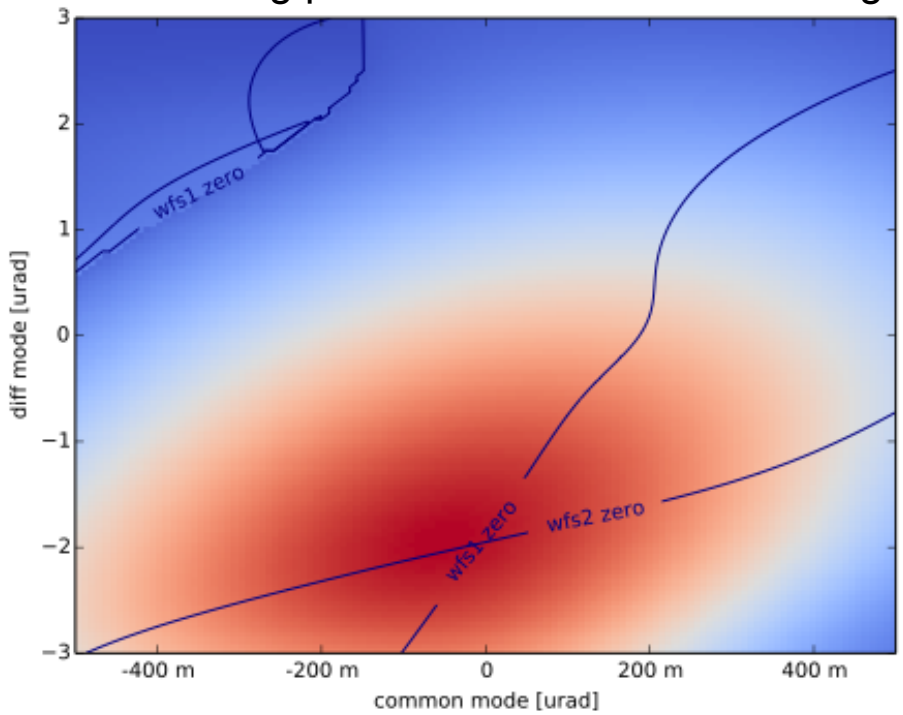
2. aLIGO commissioning: control

Preliminary results! ALS WFS control signals

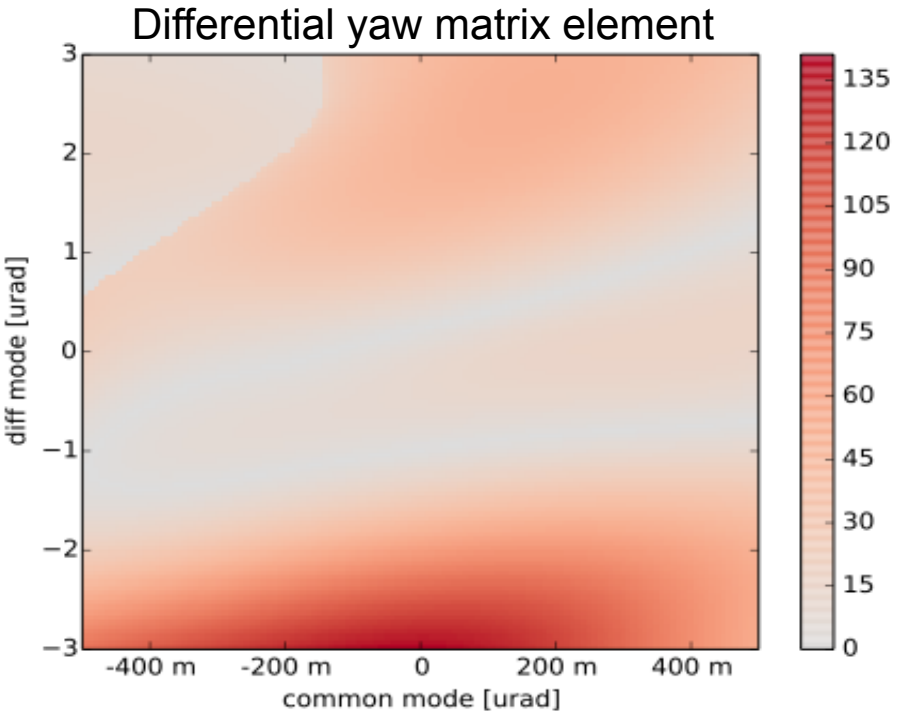
Investigating possible reasons for large variations in alignment matrix elements of the green arm lock (low finesse arm cavity).

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

Circulating power with WFS zero-crossing

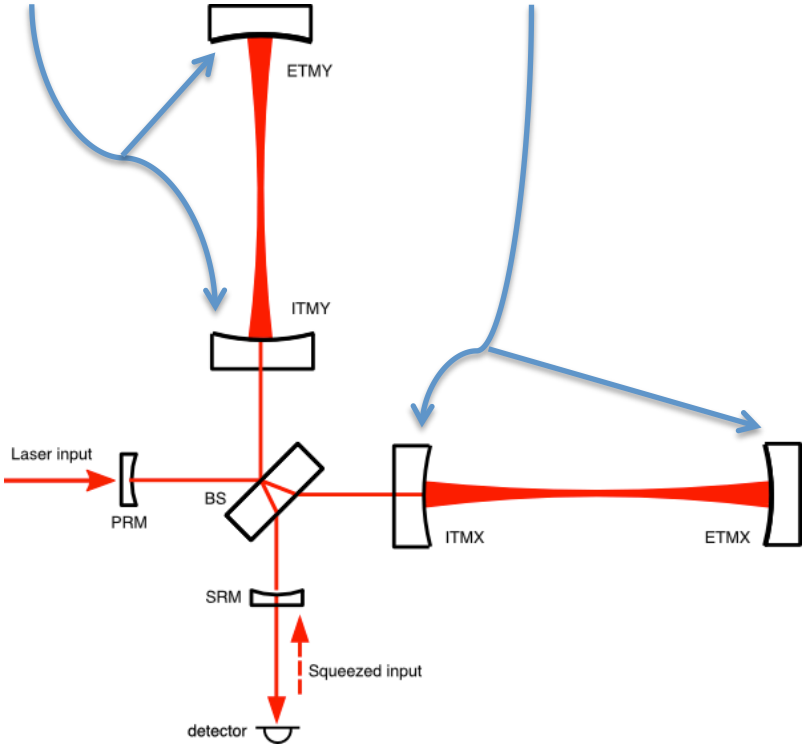


Differential yaw matrix element



3. aLIGO commissioning: next steps

Radiation pressure effects during high power operation, a control challenge

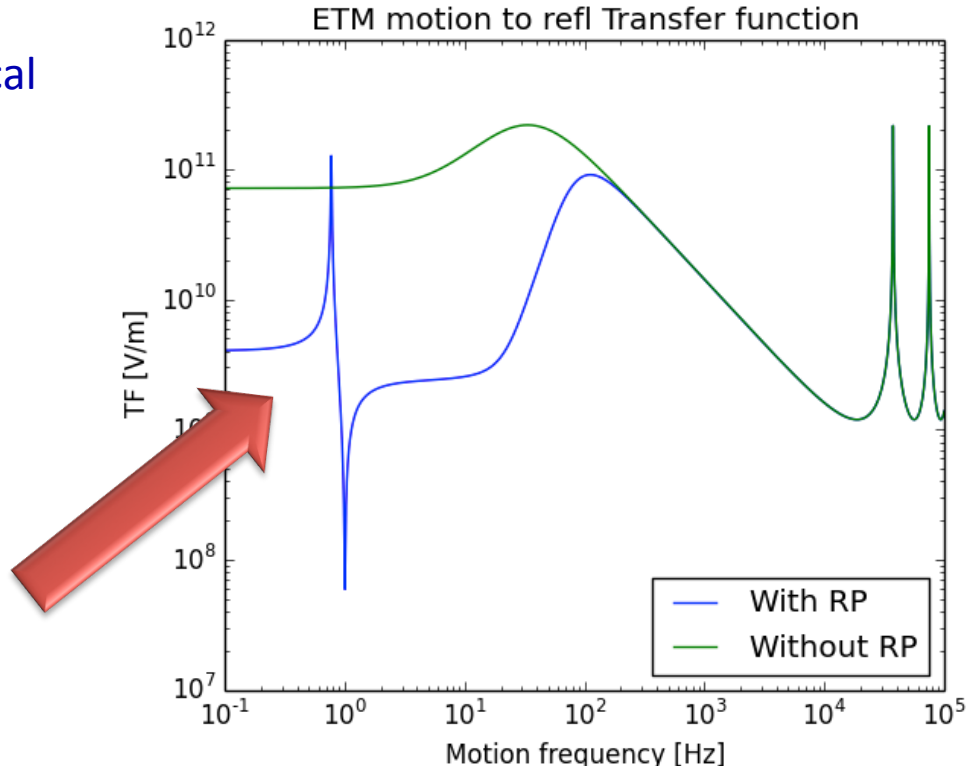


Radiation pressure effects

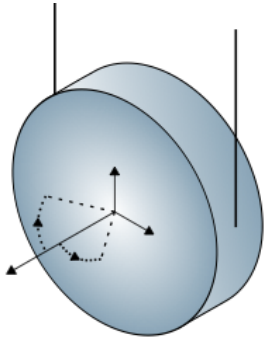
Radiation pressure creates opto-mechanical coupling

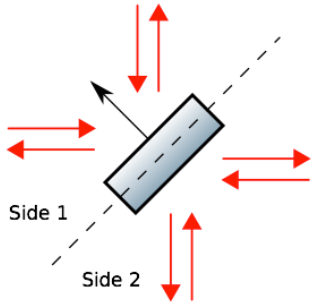
Yaw, pitch and longitudinal motions are coupled with optical fields, so this affects:

- 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 to model optical springs

- = new command in v2

optical_spring_mechTF.kat

```
1  tf sus 1 0 p 1 100000
2
3  l l1 3 0 n1
4  m ITM 0.9937 0.0063 0 n1 n2
5  s cav1 1 n2 n3
6  m ETM 1 0 -0.048 n3 n4
7
8  attr ITM M 0.25 zmech sus
9  attr ETM M 0.25 zmech sus
10
11 fsig aforce ETM Fz 1 0 1
12
13 xd zETM ETM z
14 xd zITM ITM z
15
16 xaxis aforce f log 0.1 1k 1000
17 yaxis log abs:deg
18
```

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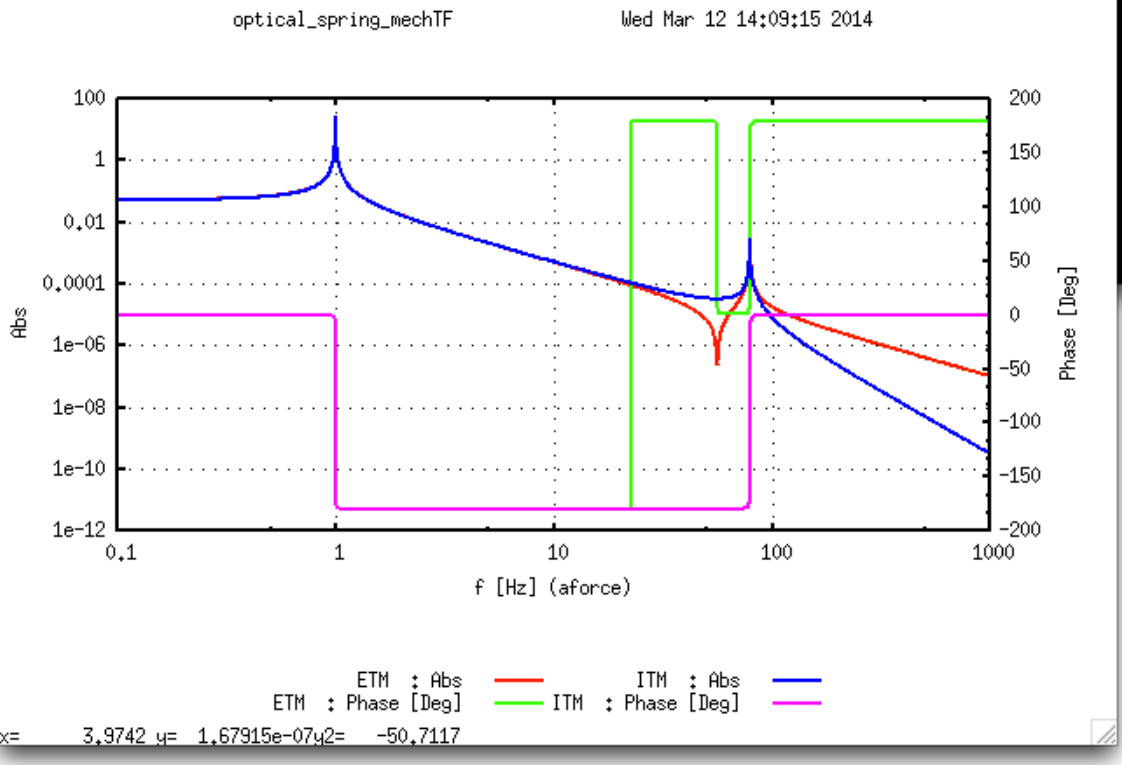
1. bash — Python | bash

```
ddb@godel kats$ kat optical_spring_mechTF.kat

----------------------------------------------------------------
                FINESSE 1.2.beta      (build 1.2.beta-53-g5d1deba)
     o_.-=.     Frequency domain INterferomEter Simulation SoftwarE
    (\'".\|     11.03.2014          http://www.gwoptics.org/finesse/
```

Gnuplot



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

...and angular RP effects

cav_torque_spring.kat

```
1  tf rxpend 1 0 p 0.6 1000
2
3  l l1 100 0 n1
4  m Min 0.99 0.01 0 n1 n2
5  s cav 4000 n2 n3
6  m Mend 1 0 0 n3 n4
7
8  attr Min Ix 1 rxmech rxpend
9  attr Mend Ix 1 rxmech rxpend
10
11 attr Min Rc -2076
12 attr Mend Rc 2076
13
14 cav c1 Min n2 Mend n3
15
16 fsig aforce Mend Frx 1 0 1
17
18 xd rx_in Min rx
19 xd rx_end Mend rx
20
21 xaxis aforce f log 2e-1 3 1000
22 yaxis log abs:deg
23 maxtem 1
```

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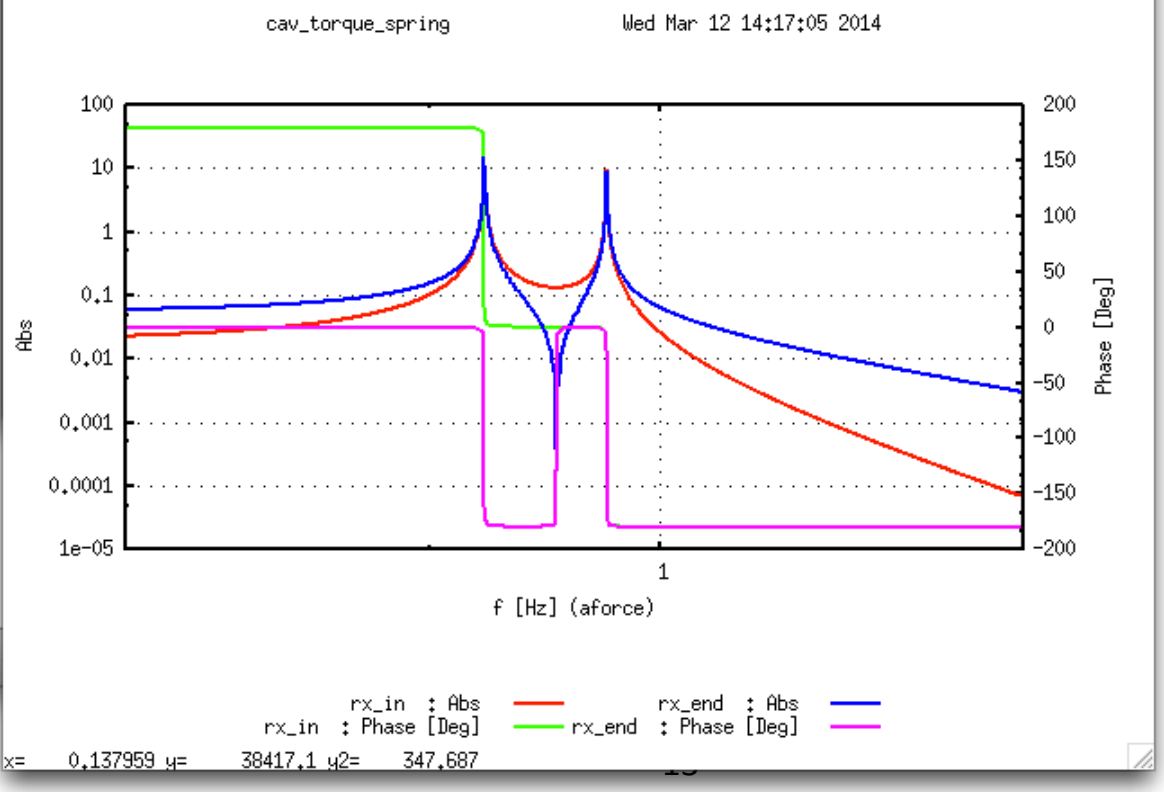
1. bash

Python | bash

```
ddb@godel kats$ kat cav_torque_spring.kat

----------------------------------------------------------------
```

Gnuplot



...and parametric instabilities

evans10_comparison.kat

```
1  l l1 3530 0 n1 # power
2  tem l1 0 0 0 0
3  tem l1 1 1 1 0
4
5  m m1 0.986 0.014 0 n1 n
6  s s1 3994.5 n2 n3
7  m m2 0.99999 1e-5 0 n3
8
9  cav c1 m1 n2 m2 n3
10
11 attr m1 Rc -1934
12 attr m2 Rc 2245
13
14 fsig l_sig l1 1 0 1
15 put tf1 fp1 $x1
16
17 tf tf1 1 0 p 30k 1E7
18 smotion m2 surf_mod.map
19
20 pgaind oltfd1 m2 s0
21
22 xaxis l_sig f lin 20e3
23 maxtem 2
```

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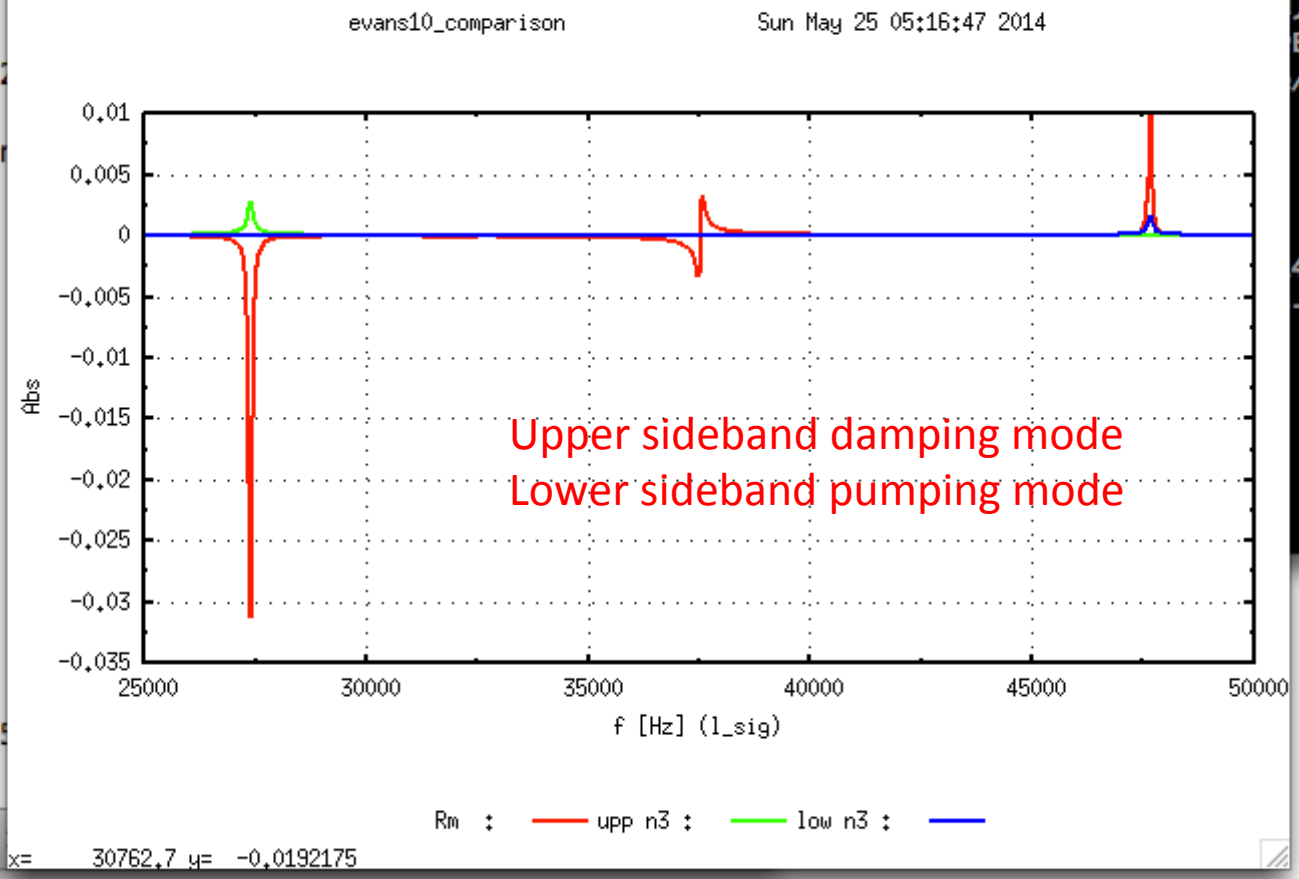
1. bash

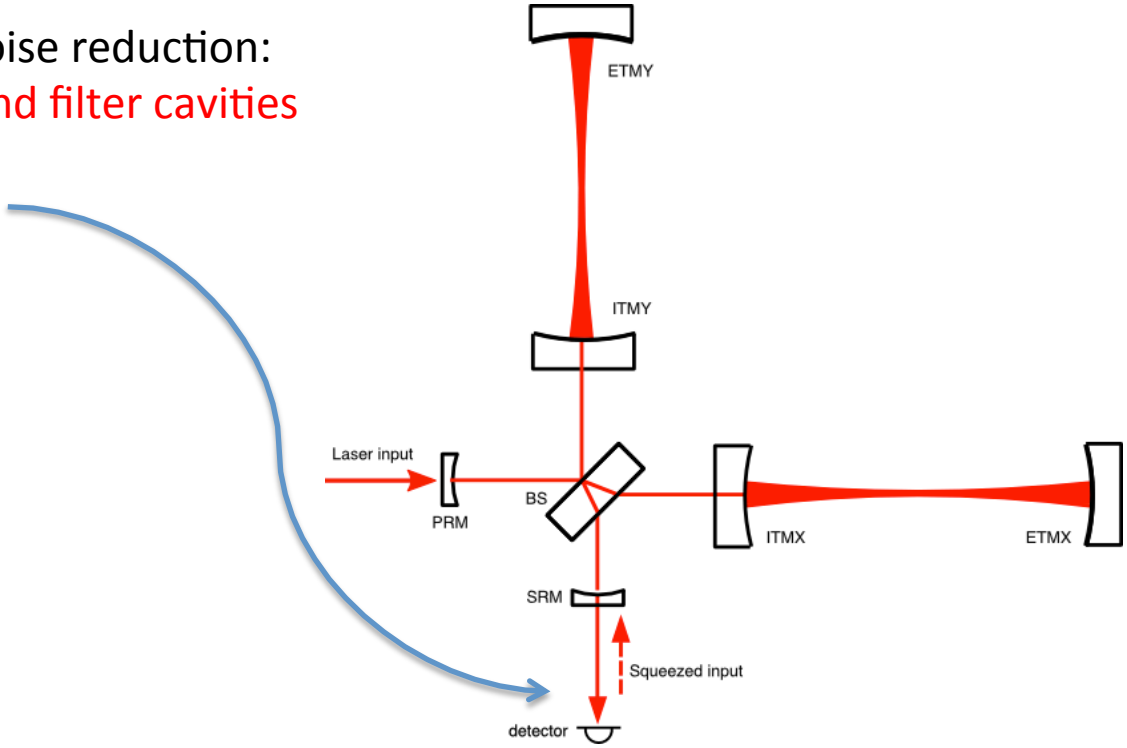
bash | Python | bash | bash | bash | bash | Python

Gnuplot



Beyond Advanced LIGO

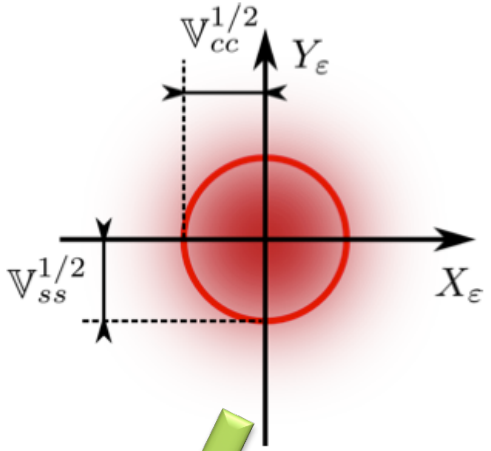
Quantum noise reduction:
squeezing and filter cavities



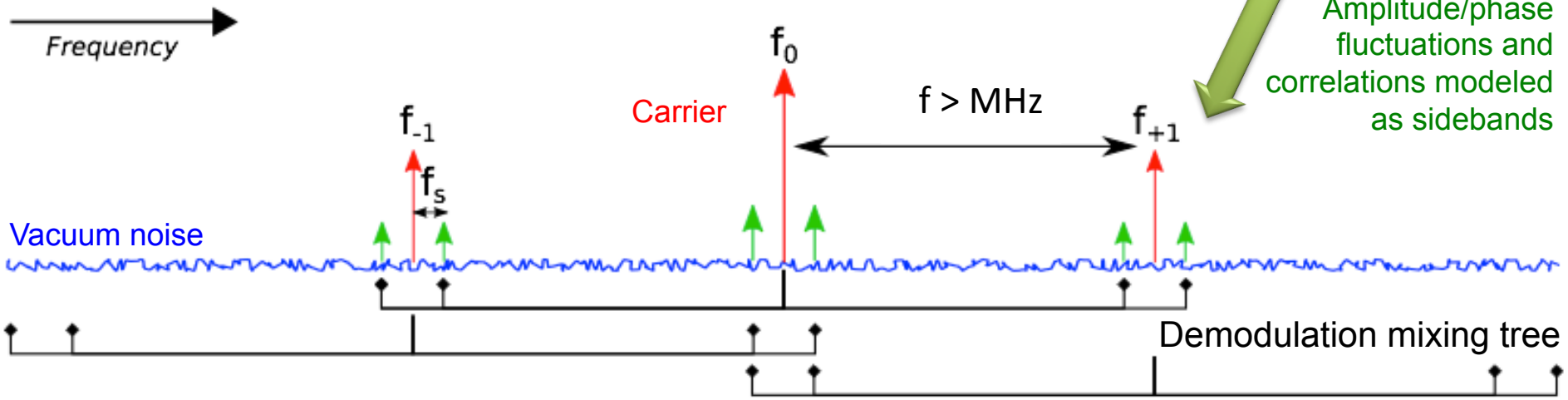
Modelling quantum noise

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

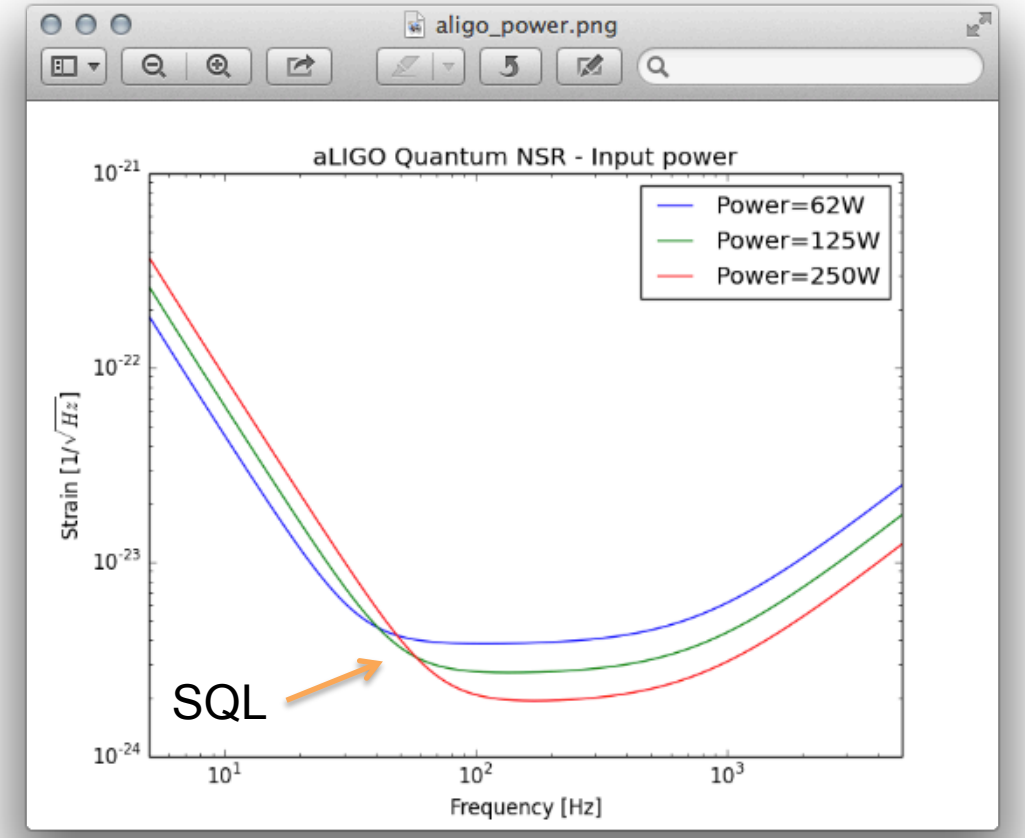


Amplitude/phase fluctuations and correlations modeled as sidebands



Some aLIGO examples…

Can we model aLIGO QN limited senstivity?



Easy enough, just use the new detector…

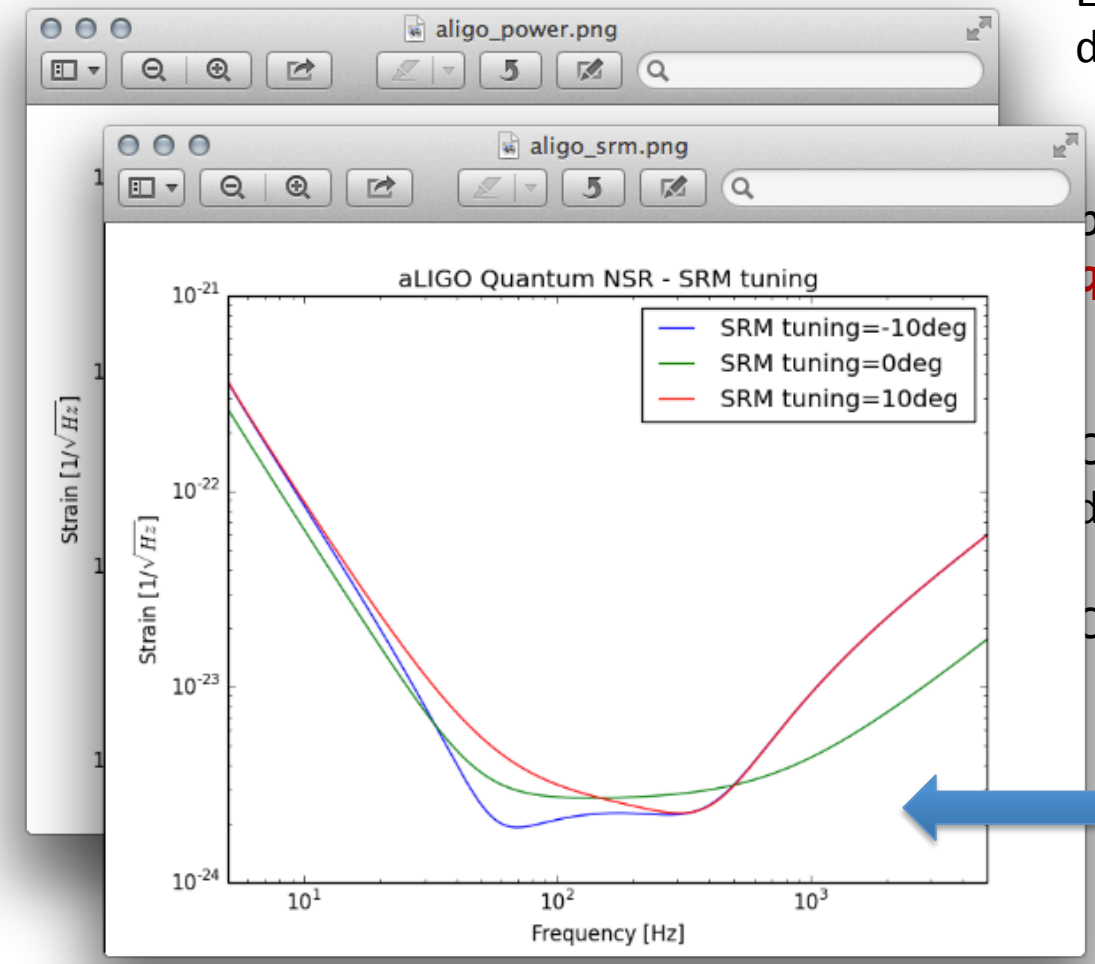
```
pd1 signal $fs node
qnoised noise 1 $fs 0 node
```

Outputs the quantum noise for a demodulated photodiode signal.

Compares well to GWINC

Some aLIGO examples…

Can we model aLIGO QN limited senstivity?



Easy enough, just use the new detector…

```
od1 signal $fs node
qnoised noise 1 $fs 0 node
```

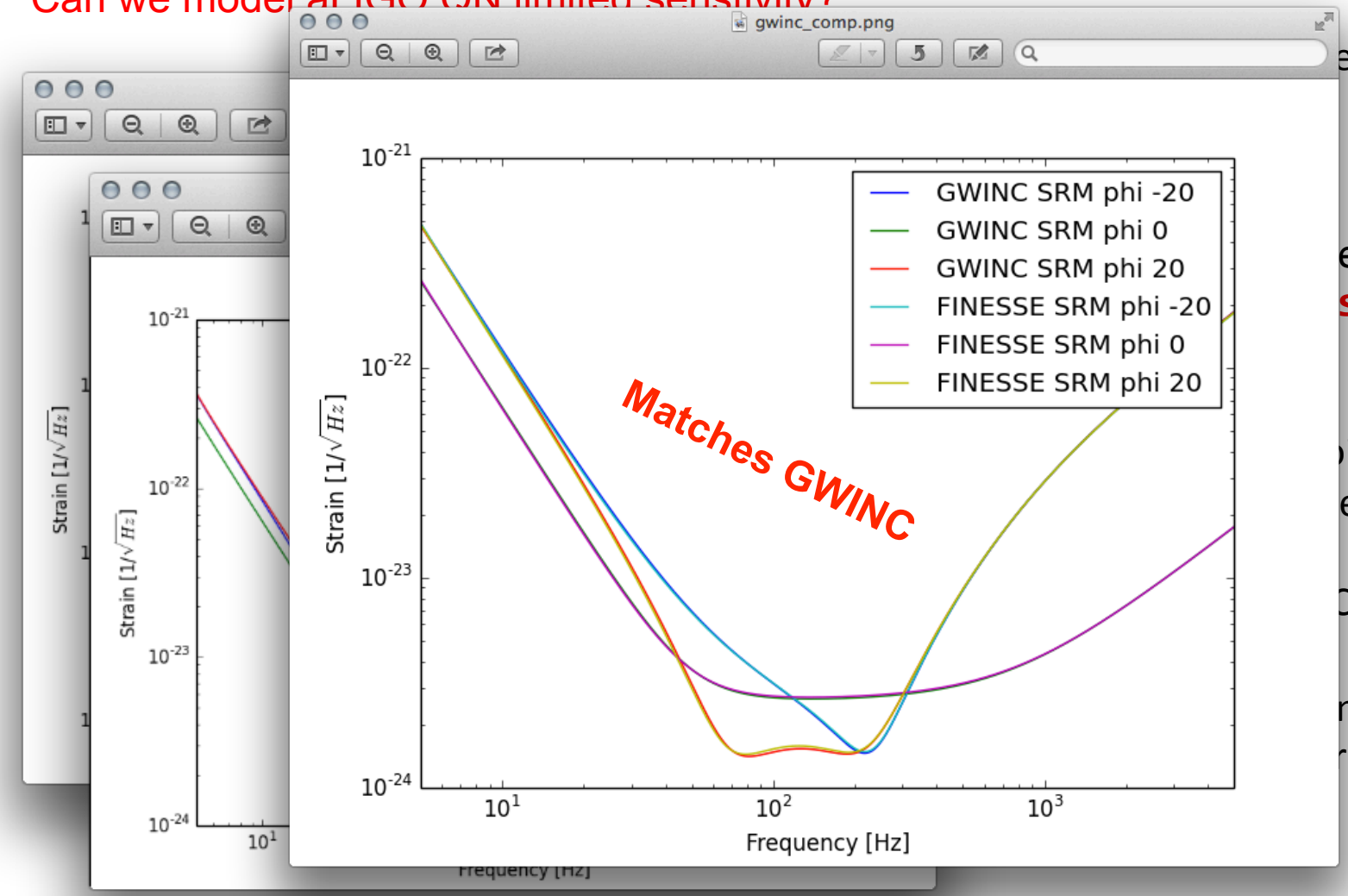
Outputs the quantum noise for a demodulated photodiode signal.

Compares well to GWINC

Then just experiment with different parameters, like SRM tuning

Some aLIGO examples…

Can we model aLIGO QN limited senstivity?



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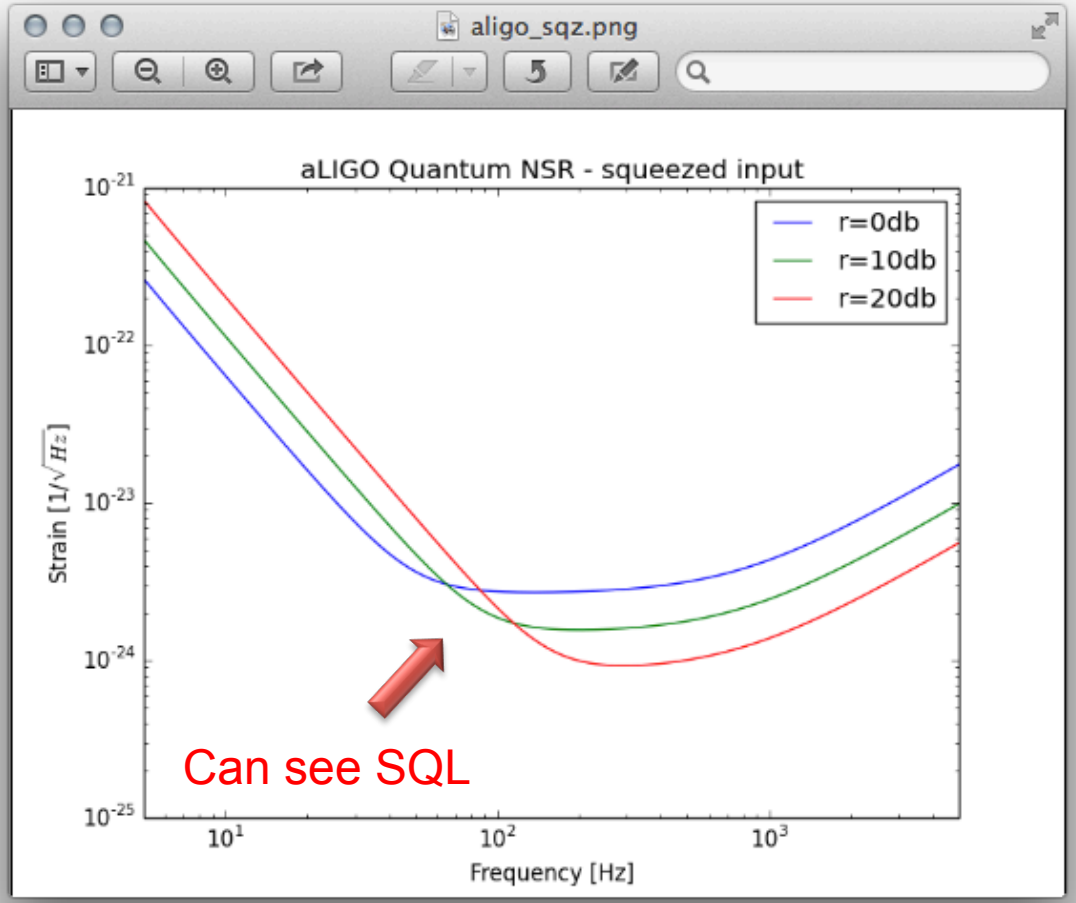
rs, like SRM

How about some squeezing?



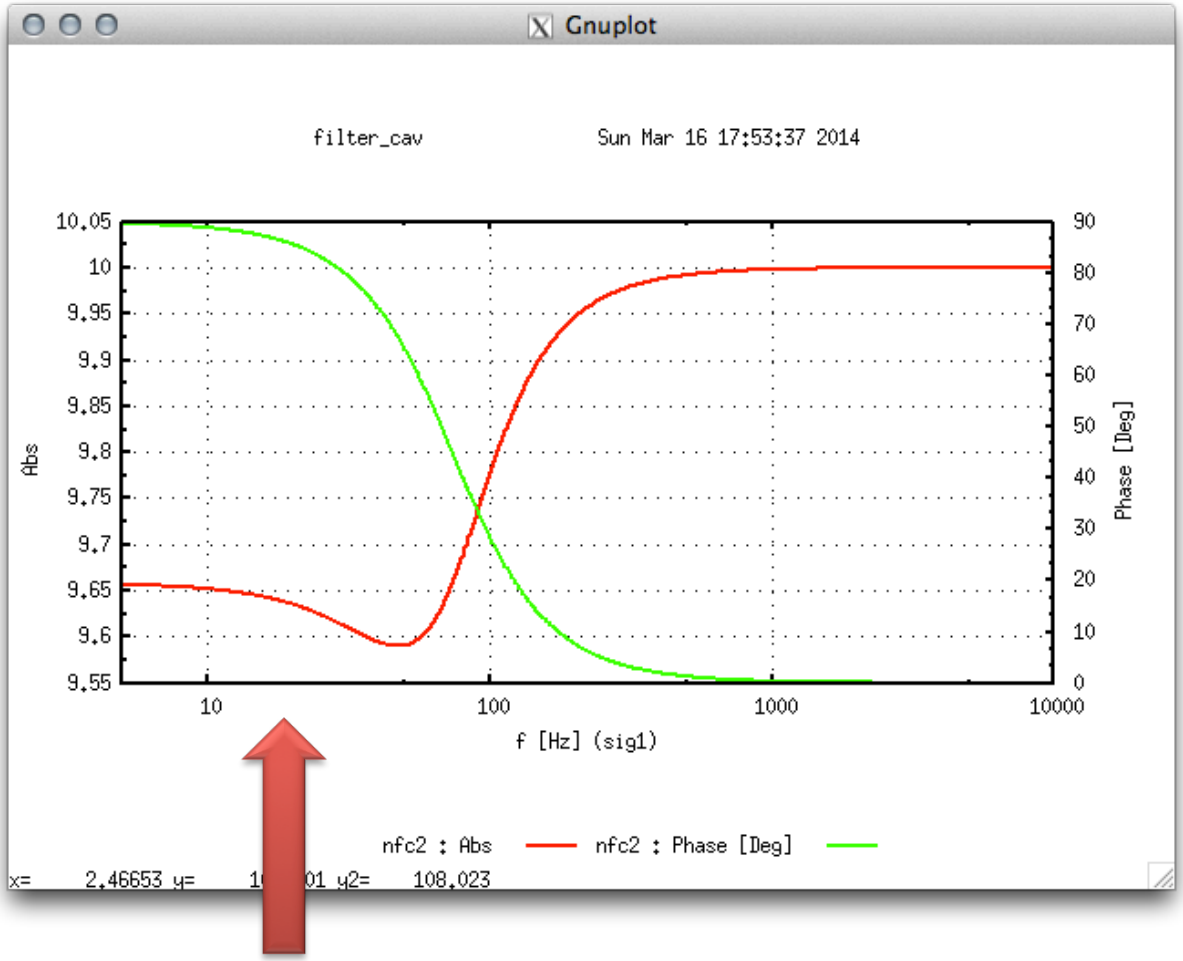
Easy enough, just add a squeezed source at the dark port…

Squeezing db and angle

```
sq sq1 0 10 90 nfc1
```

Carrier frequency to squeeze

...Filter cavities?

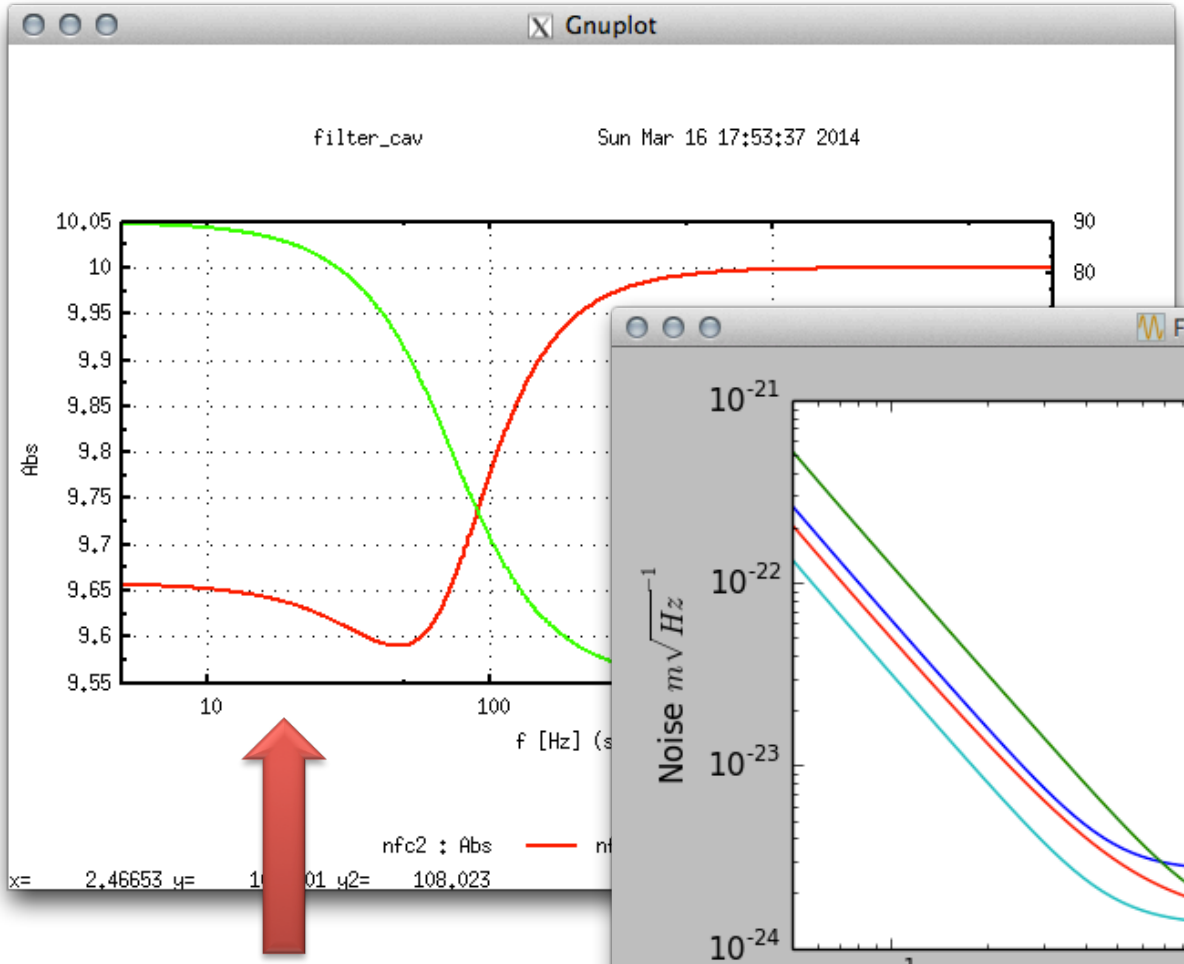


Idea is that cavity will rotate squeezing so we have amplitude squeezing at low frequencies and phase squeezing at high frequencies, e.g. phase rotation of 90 deg.

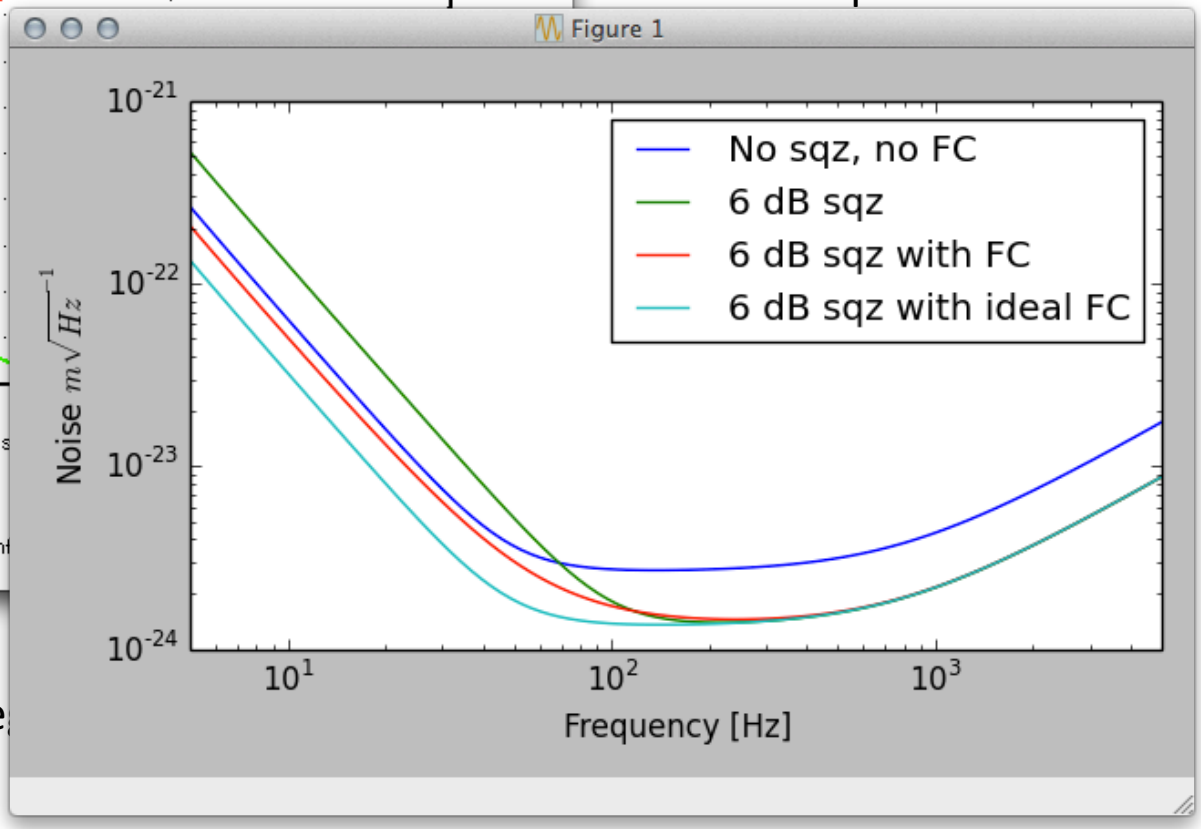
Model 10db squeezed field reflected from a cavity, then output squeezing factor r_{dB} and *squeezing angle*

Cavity is has lossy ETM so degrades squeezing at low frequencies

...Filter cavities?

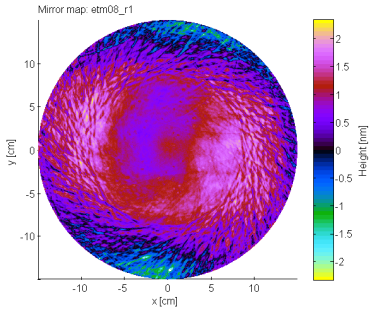


Idea is that cavity will rotate squeezing so we have amplitude squeezing at low frequencies and



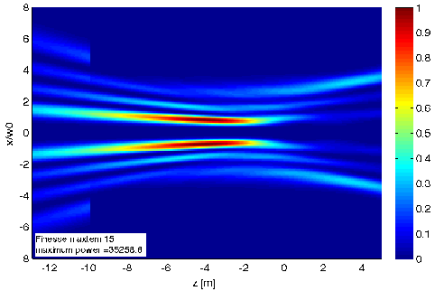
Cavity is has lossy ETM so de
at low frequencies

What Finesse can do for you



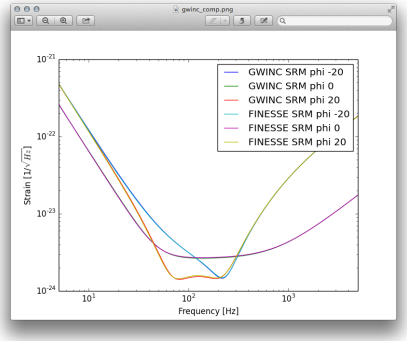
Surface and bulk distortions

- Thermal effects
- Manufacturing errors
- Surface maps



Finite optics

- Beam clipping
- Offsets



Quantum noise

- Squeezed light
- Filter cavities
- QND schemes

Frequency domain modelling of interferometers

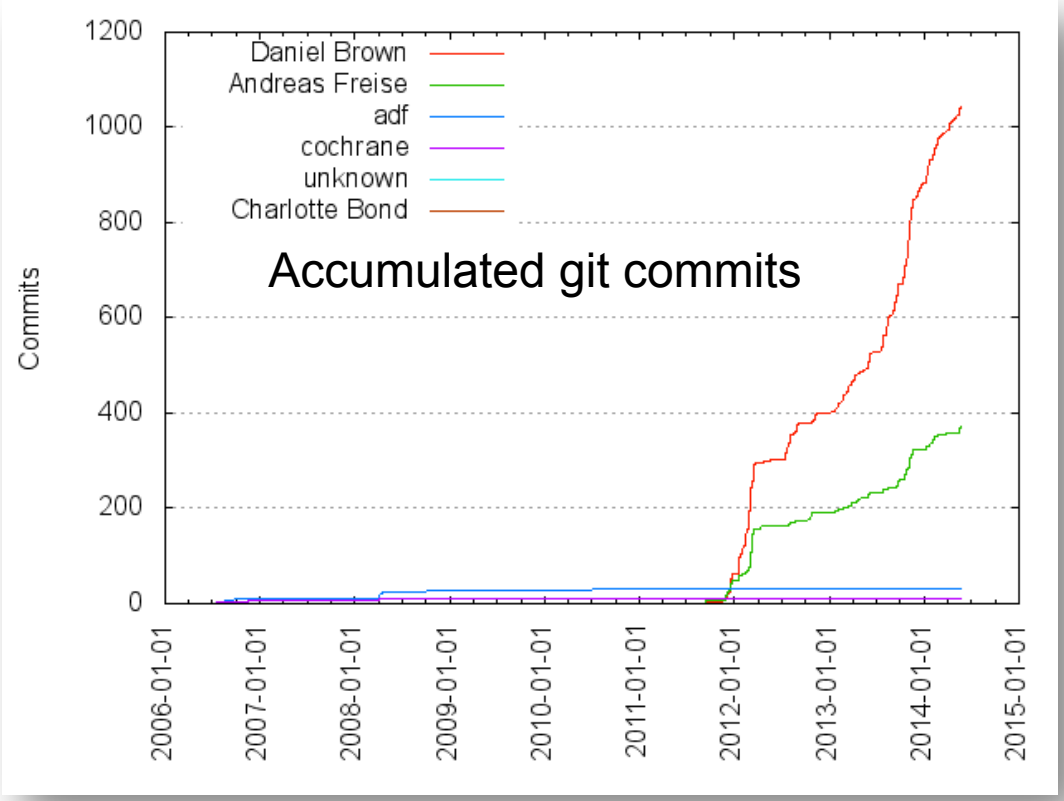
Want to model:

- 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.

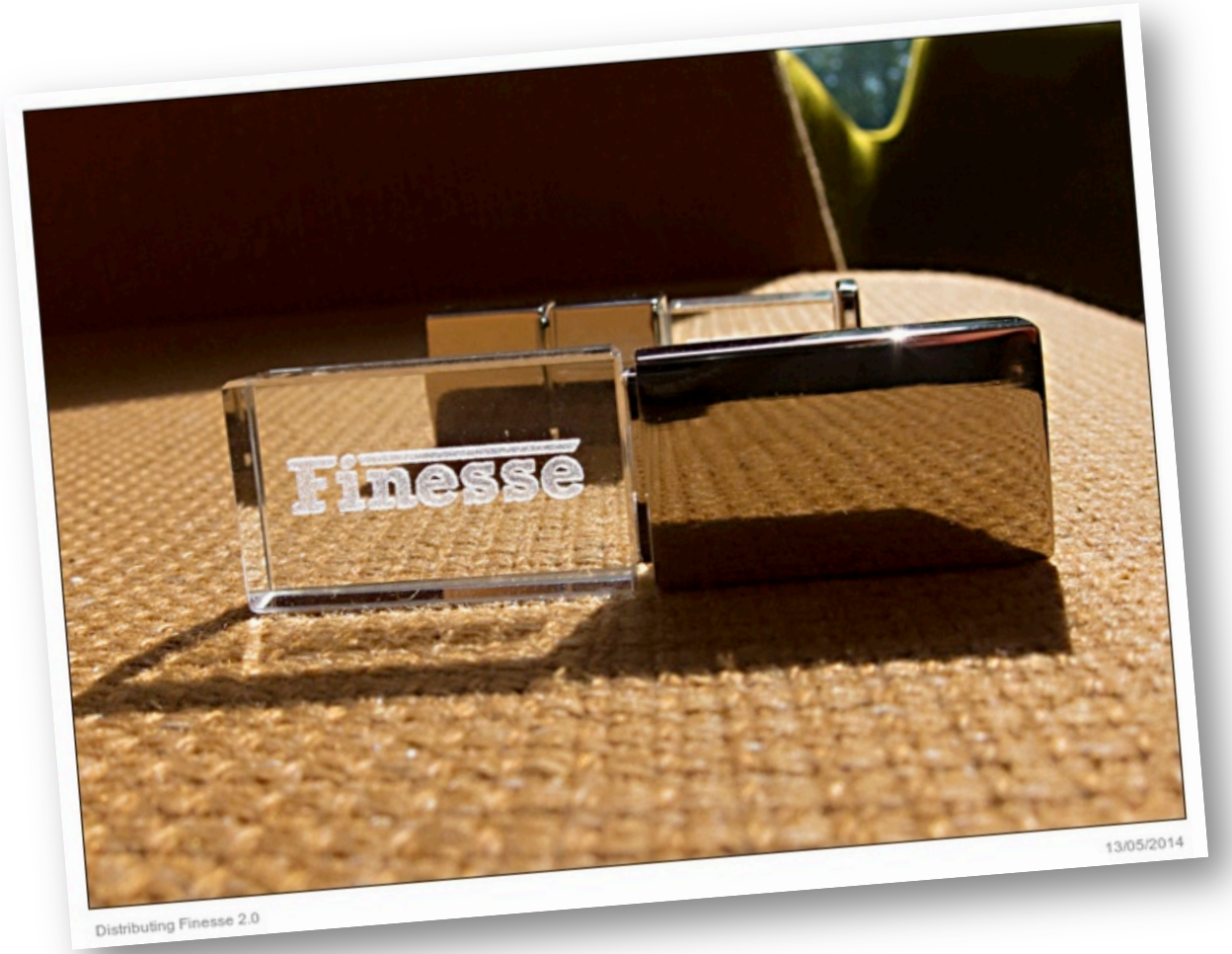
Join in, use it, and help improve it!

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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