$A^{\#}$ Thermal Modeling

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Massachusetts Institute of Technology

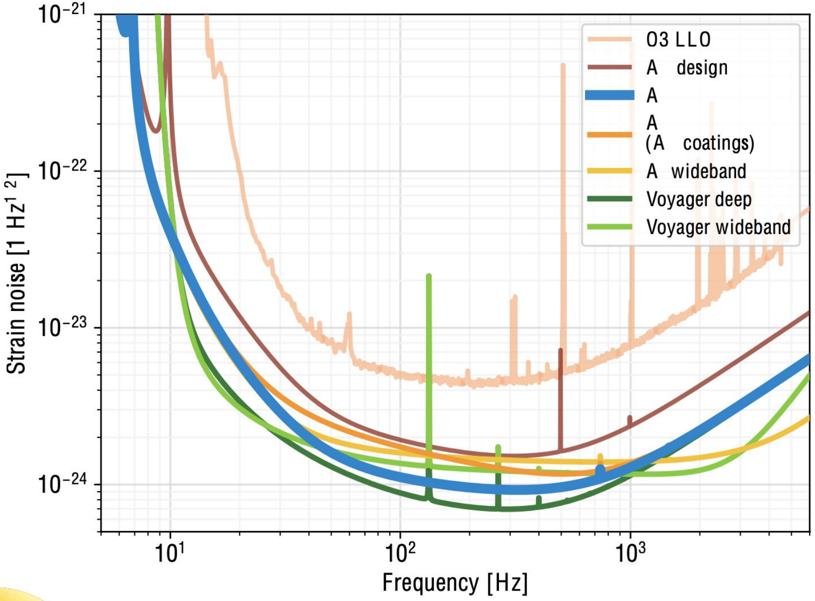
$A^{\#}$ Concept & Implications for Compensation

A# Design Changes (post-O5)

- 100kg test masses
- 10dB SQZ
- 1.5M in the arms

Requirements

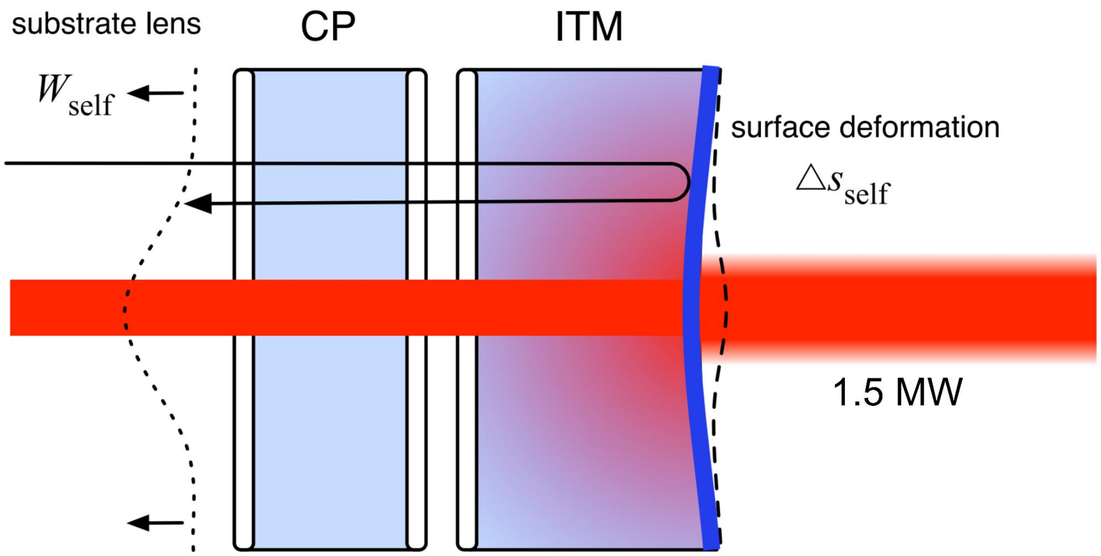
- Maintain PRG with 750mW absorbed power (0.5ppm)
- 1% mode-matching SQZ loss
    - OPD O(5nm RMS)



T2200287-v2

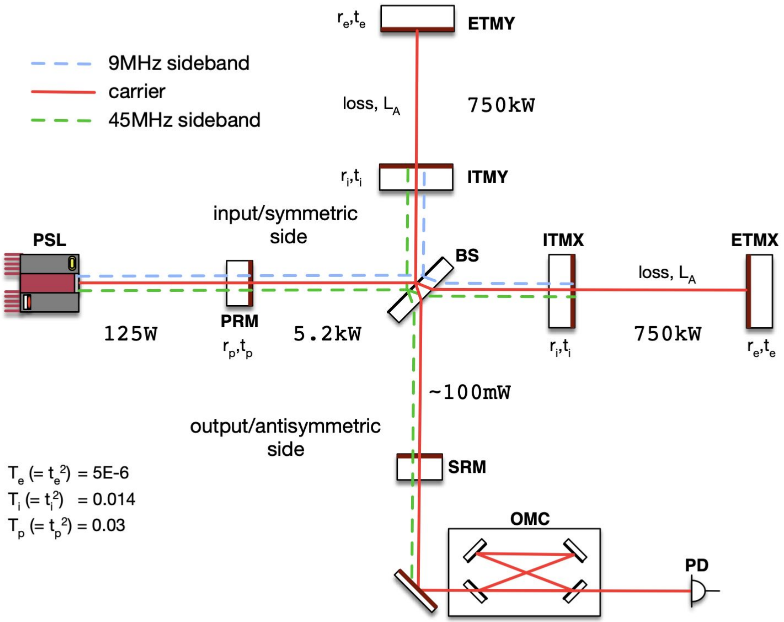
Thermal effects overview: LOCAL

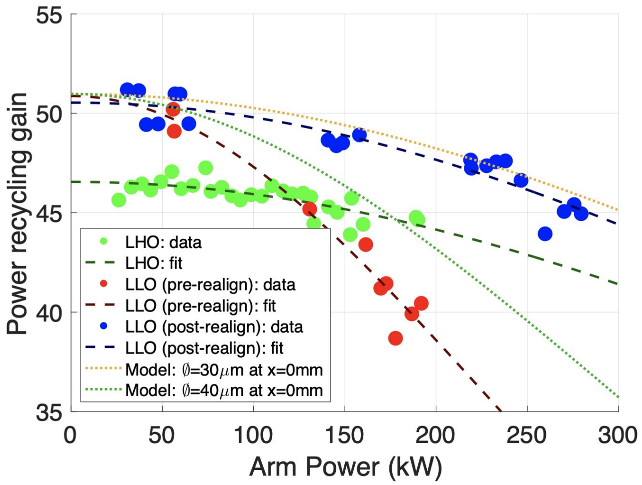
- Finite amount of absorption
- Temperature gradient
- Thermo-elastic (surface)
- Thermo-refractive (substrate)
- Distortions **not quadratic** (more like bumps)

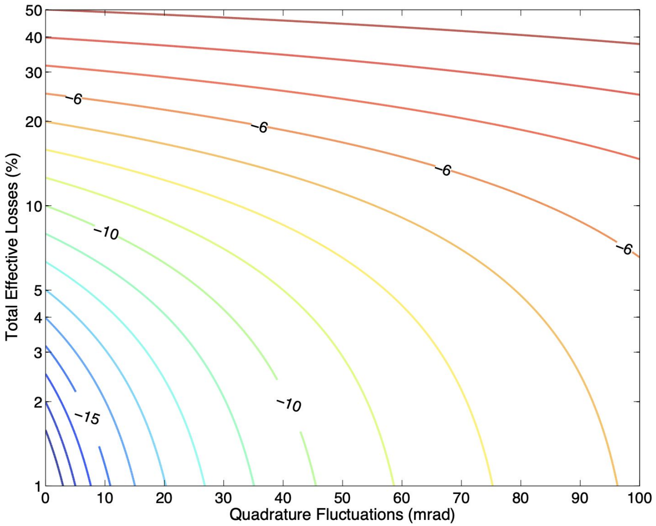


Global effects of thermal distortions: PRG, SQZ, controls

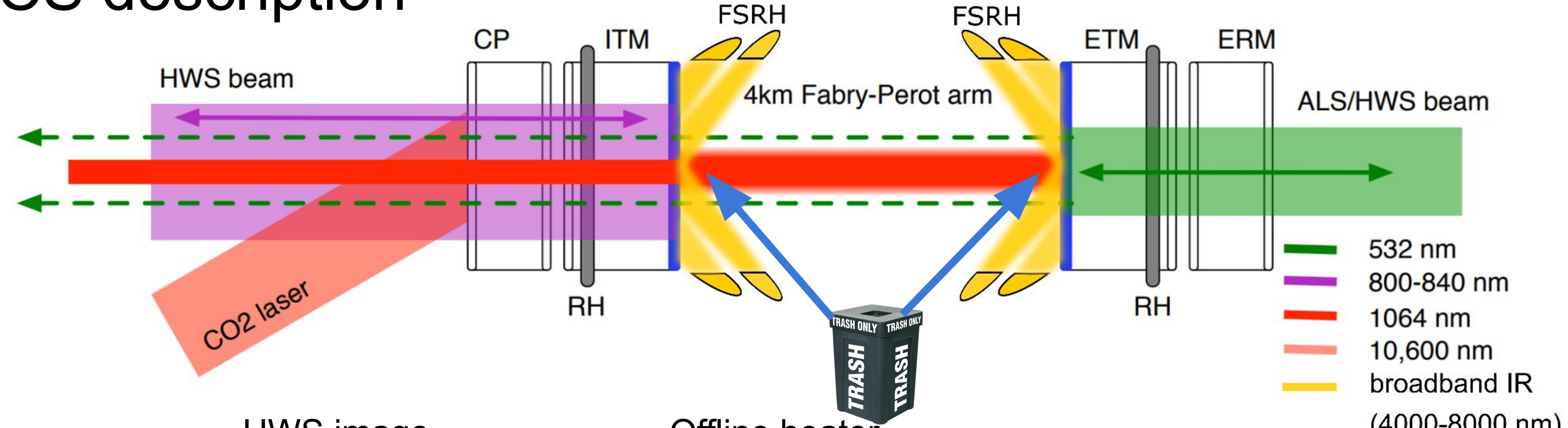
HOM are not negligible contributions here







TCS description



Offline heater

HWS image

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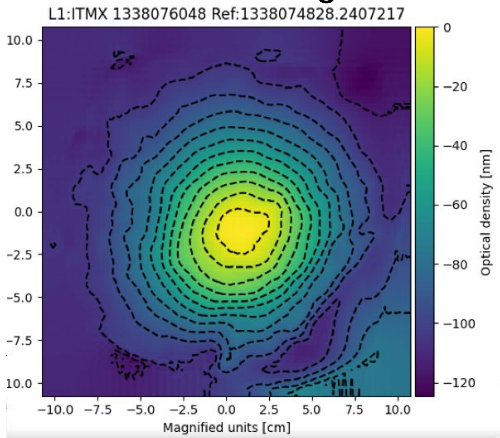
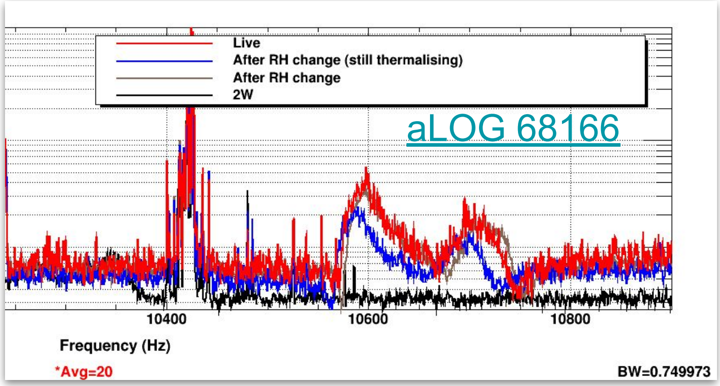


DARM



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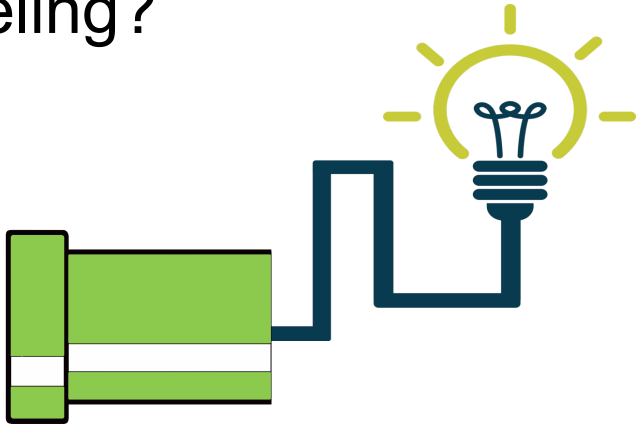
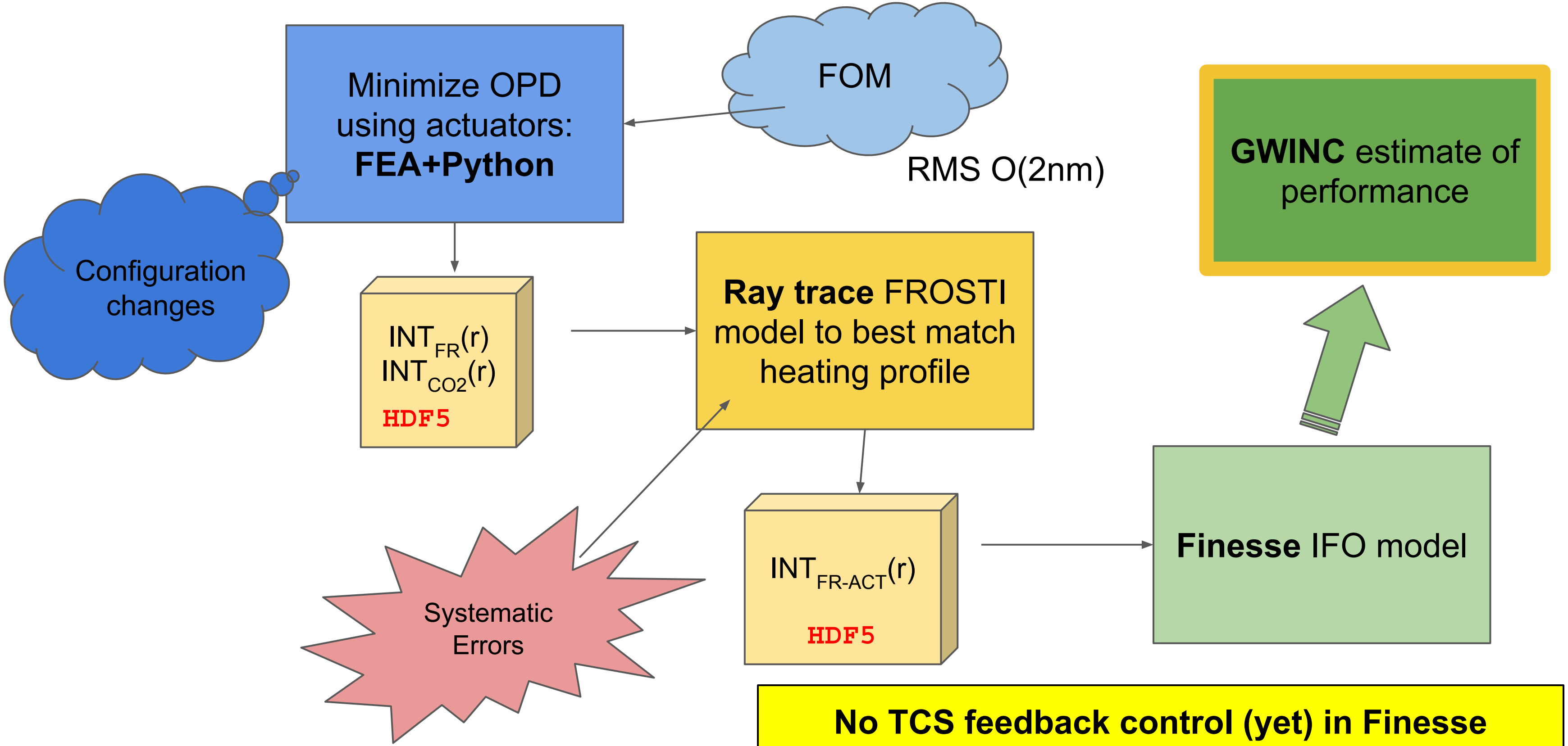
What is the Summary of ASharp Modeling?

1. Have a method/pipeline
    a. Is local correction (not global)
    b. Quick and streamlined.
    c. Can be remodeled quickly
2. Two reasonable ASharp solutions
    a. Some work on tolerancing, not complete.
        i. 5nm RMS looks like target
    b. With and without CO_2 laser
3. Some limitations in modeling



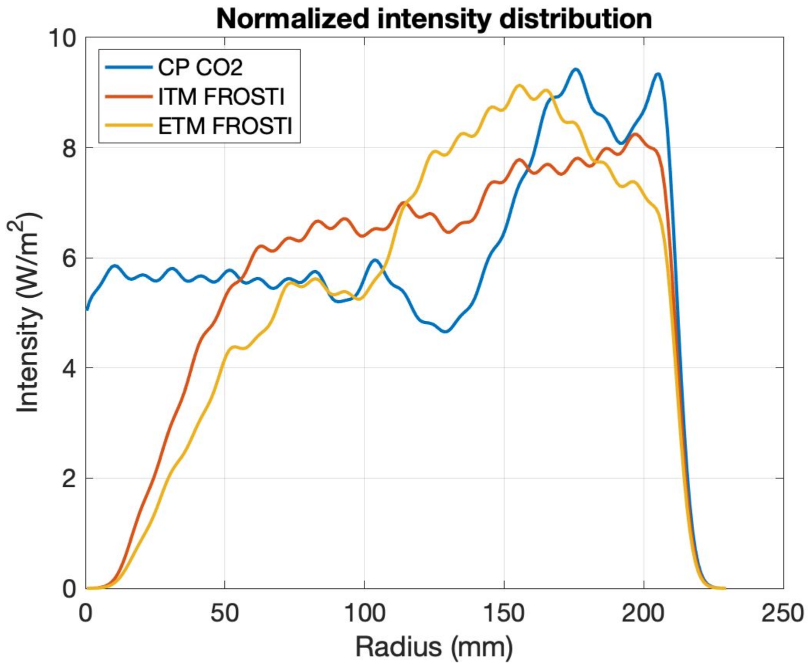
Decoupling optimization parts: not one giant model

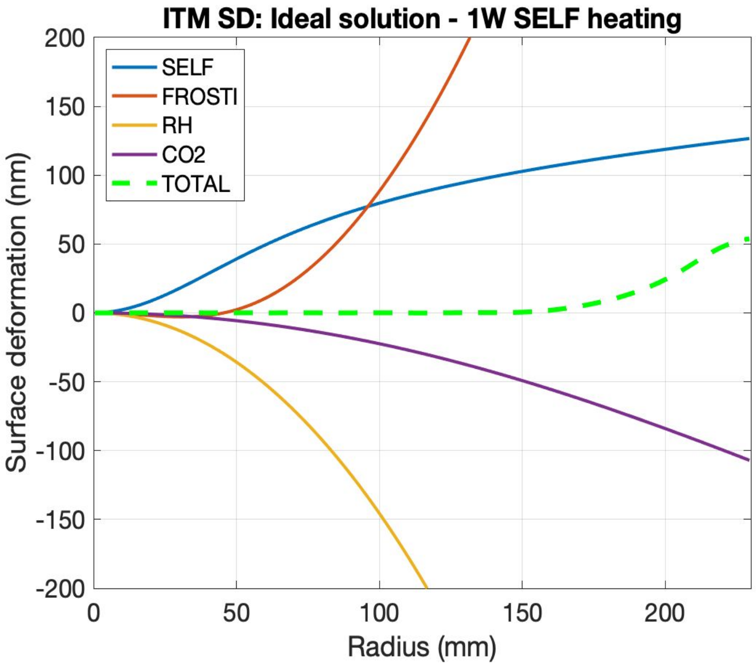


No TCS feedback control (yet) in Finesse

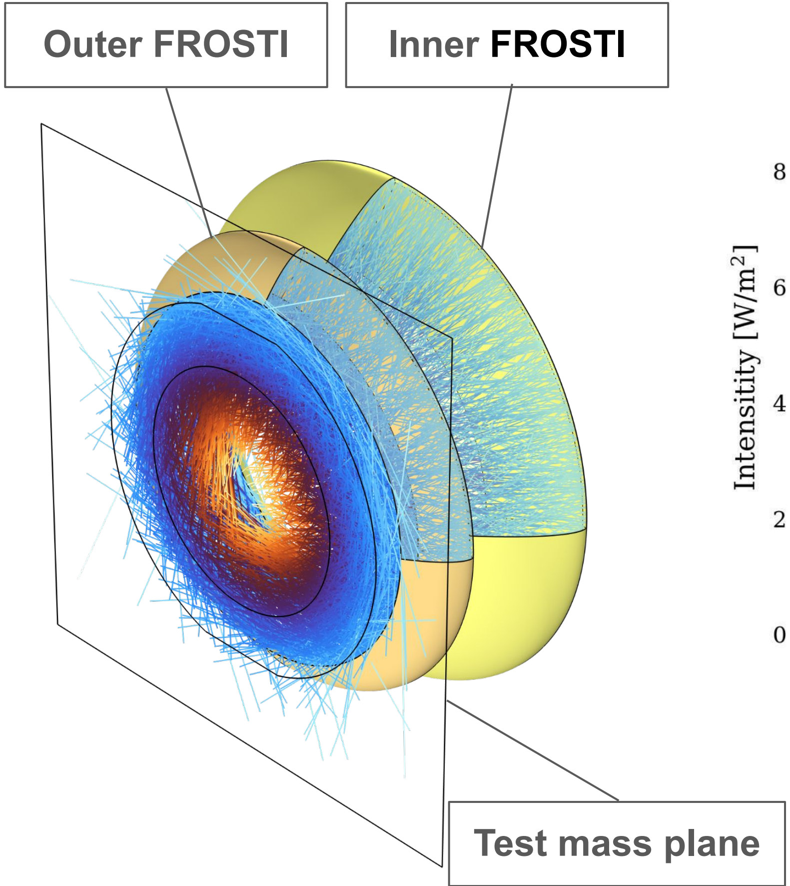
Presentation of **one** result (OPD/Intensity Profiles/Finesse)

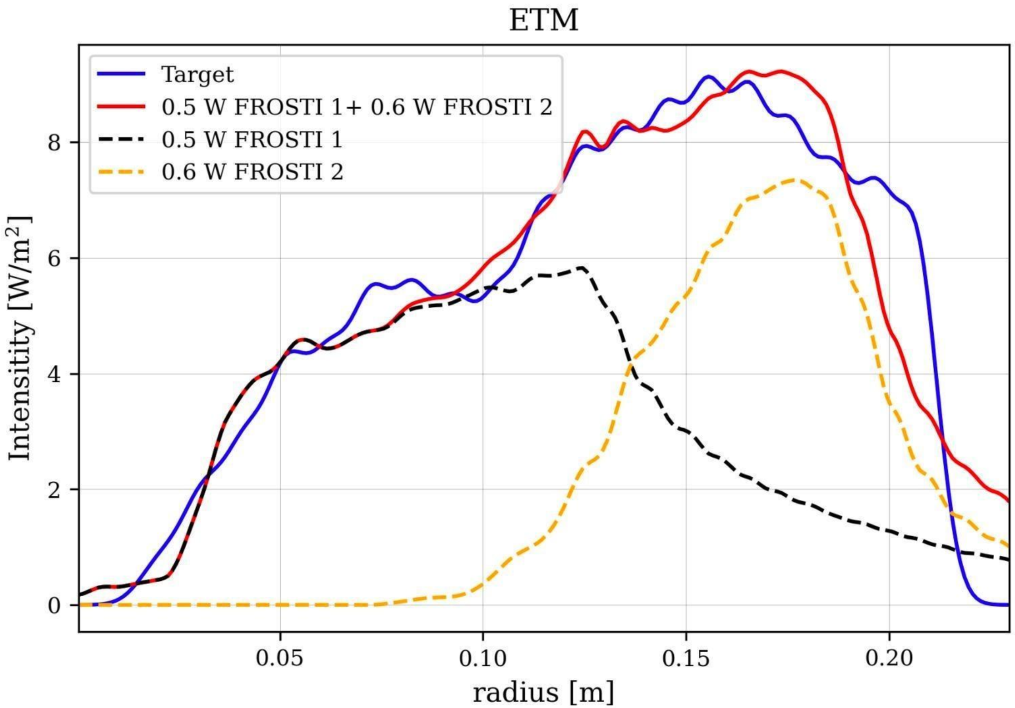
	ITM	ETM
SELF	1W	1W
CO2	21.8W	NA
RH	73.8W	69.3W
FROSTI	33.7W	30.8W





FROSTI fitting





Two output of results from Finesse

```
****  FROSTI + RH

Input power needed       = 238.5 [W]
Arm power                = 1500.0 [kW]
ITM - HR absorbed        = 0.750 [W]
    - FROSTI power       = 27.0 [W]
    - RH power           = 54.0 [W]

ETM - FROSTI power       = 20.4 [W]
    - RH power           = 45.4 [W]
PRG - Carrier            = 44.8
    - 9MHz               = 114.3
    - 45MHz              = 13.7
RMS - ITM (w=53mm)       = 0.29 [nm RMS]
    - ETM (w=62mm)       = 0.06 [nm RMS]
    - ITM SUB (w=53mm)   = 3.19 [nm RMS]
Squeeze loss - 100Hz     = 0.62 [%]
             - 450Hz     = 0.82 [%]
             - 5kHz      = 1.04 [%]
```

```
****  FROSTI + CO2 + RH

Input power needed       = 267.4 [W]
Arm power                = 1500.0 [kW]
ITM - HR absorbed        = 0.750 [W]
    - FROSTI power       = 24.3 [W]
    - RH power           = 55.5 [W]
    - CO2 power          = 4.4 [W]
ETM - FROSTI power       = 22.1 [W]
    - RH power           = 54.4 [W]
PRG - Carrier            = 40.0
    - 9MHz               = 125.7
    - 45MHz              = 14.1
RMS - ITM (w=53mm)       = 0.27 [nm RMS]
    - ETM (w=62mm)       = 0.59 [nm RMS]
    - ITM SUB (w=53mm)   = 1.63 [nm RMS]
Squeeze loss - 100Hz     = 0.51 [%]
             - 450Hz     = 0.51 [%]
             - 5kHz      = 0.54 [%]
```

Tolerancing/MCMC

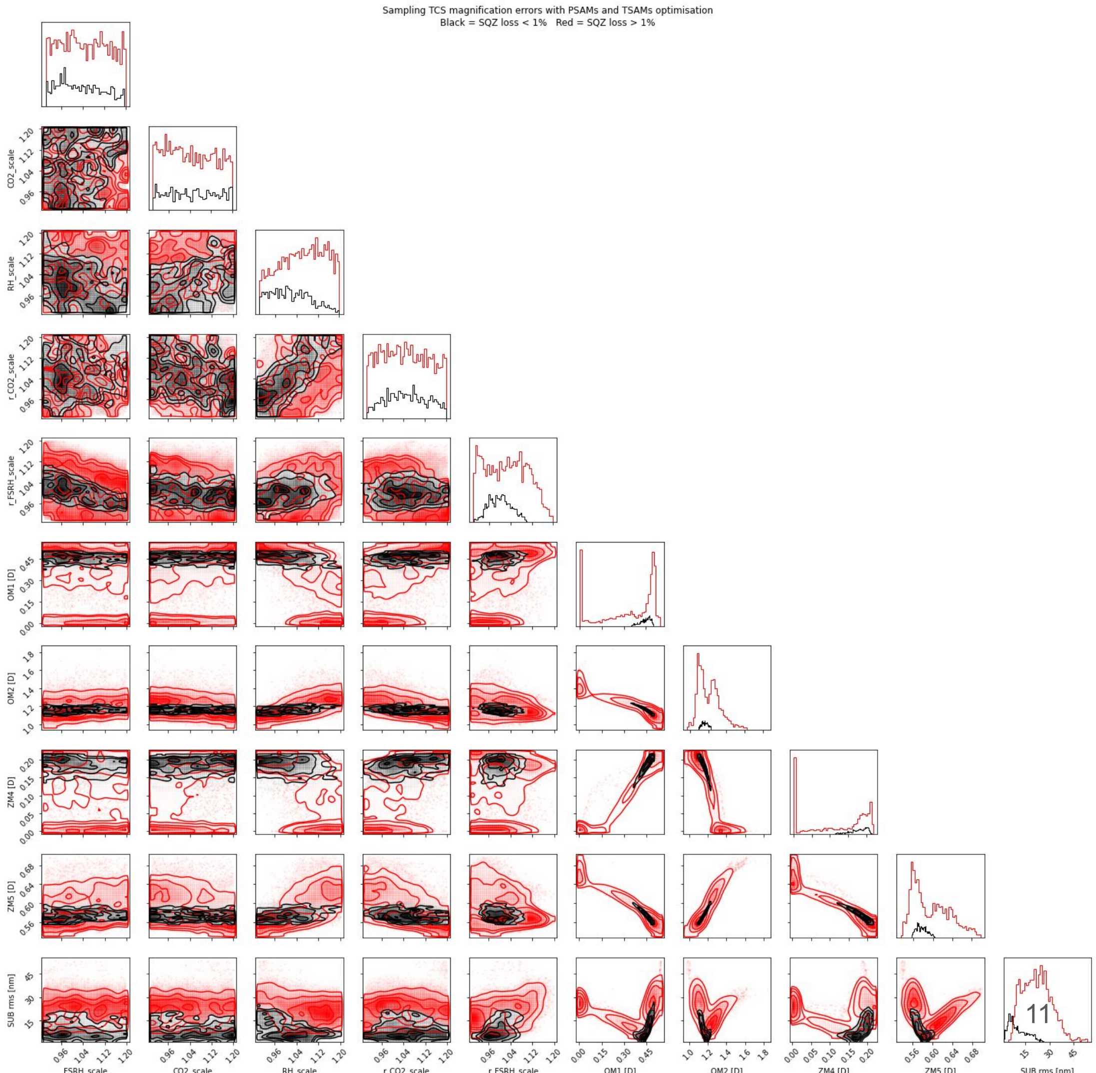
Full A# optical model, sampling different IFO thermal actuator states and optimising each:

- DC operating point using RF error signals
- SQZ->IFO actuators
    - Minimise squeezing losses
- IFO->OMC actuators
    - Maximise optical gain

Reject samples that:

- Too low PRG for carrier, 9 and 45MHz sidebands
- Too high squeezing losses broadband (>1%)

Ask: How well do we need to control our adaptive optics?

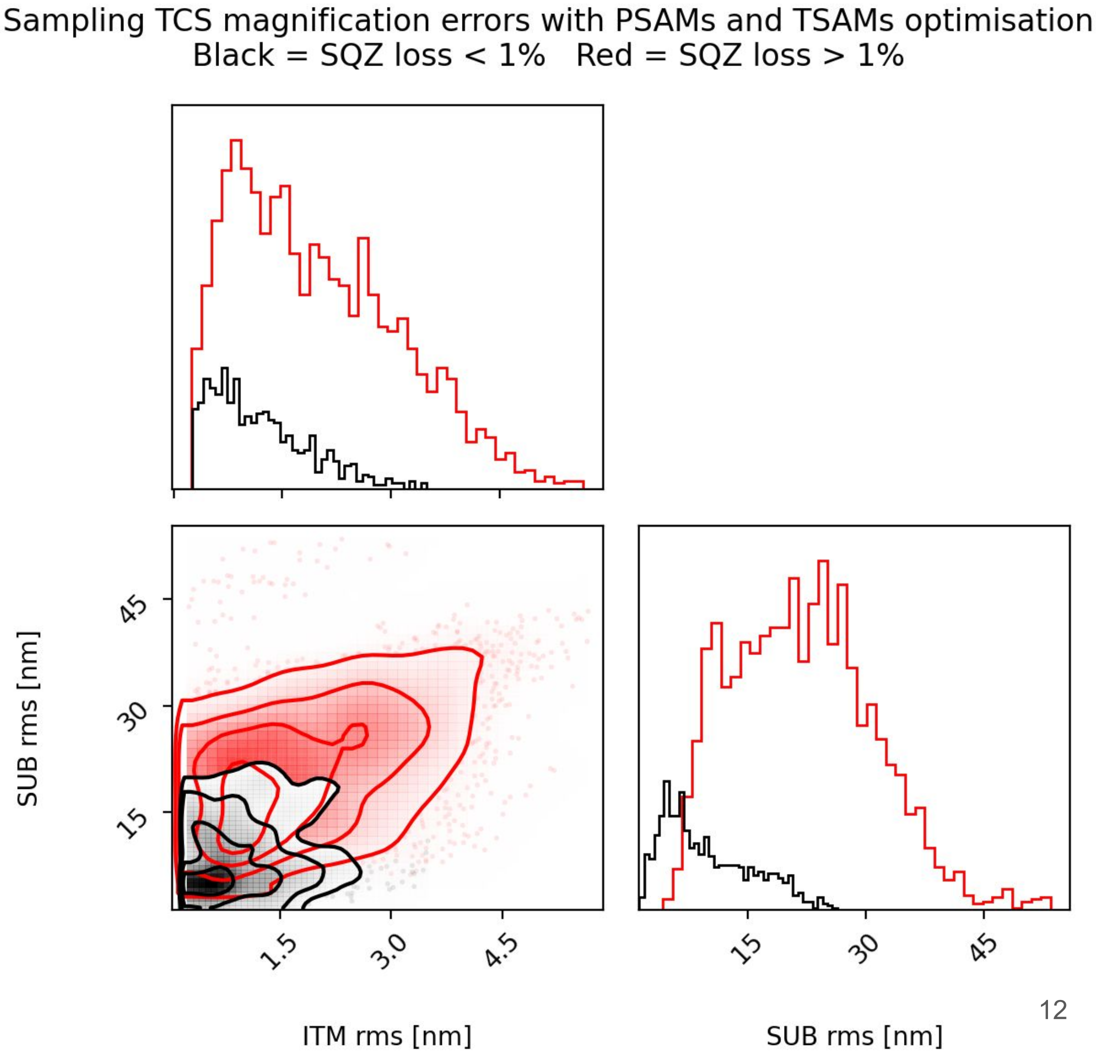


Surface and substrate

Most critical parameter is substrate RMS error.

RMS is a simplistic figure of merit, the actual shape of the the RMS can cause unfortunate HOM scatter **and/or** HOM gouy phase shifts.

HWS itself can measure this, but how much better does the injection optics need to be?



Recycling gains

Typically seen are that sideband recycling gains are a better predictor of performance for squeezing losses.

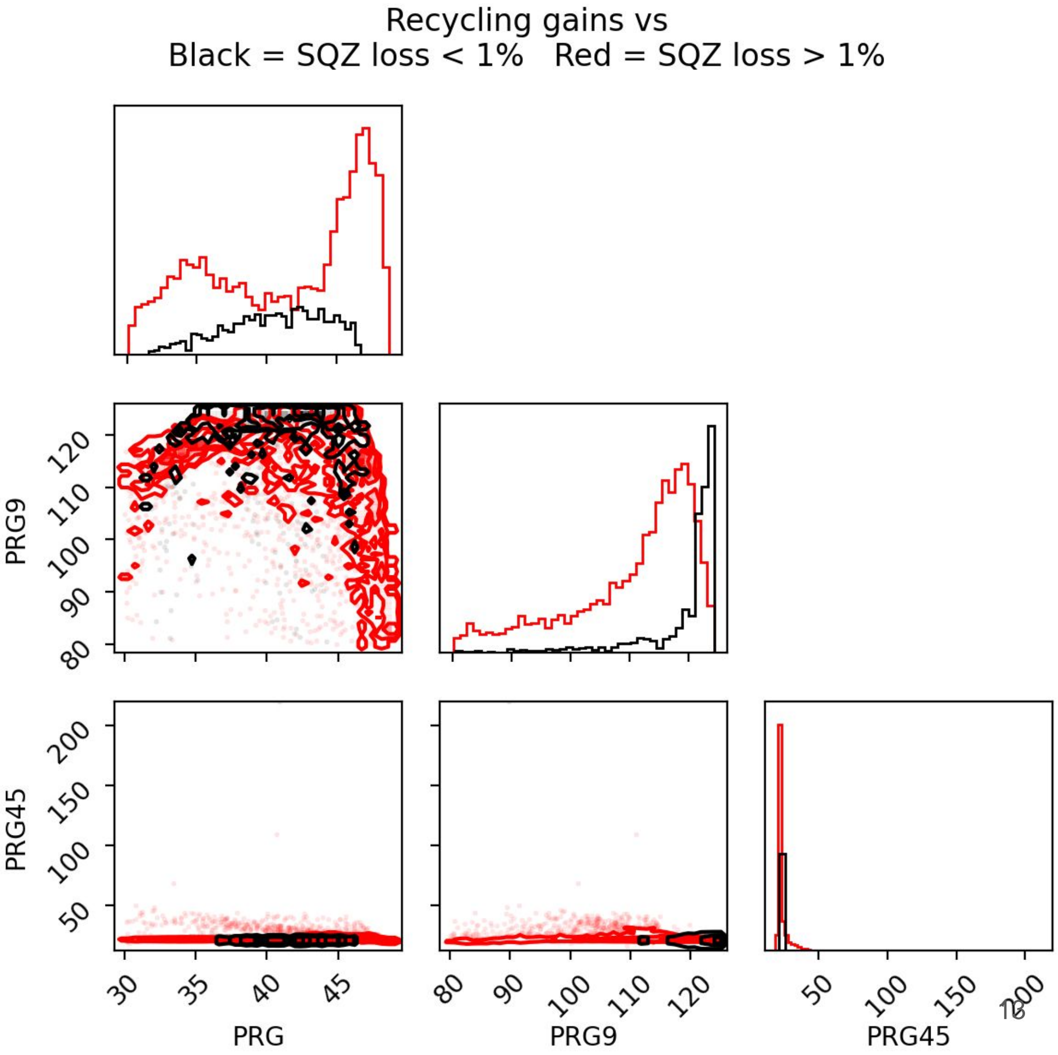
aLIGO design they should be:

- Carrier ~ 45
- 9 ~ 120
- 45 ~ 15

9 MHz is much more sensitive to substrate errors.

This suggests, if the 9MHz performance is bad the chance of getting low squeezing losses is slim…

LHO O4 cold (input 2W) already only sees a PRG9 of 90 and gets worse with more power (down to 50)



Actuator control

So far we considered

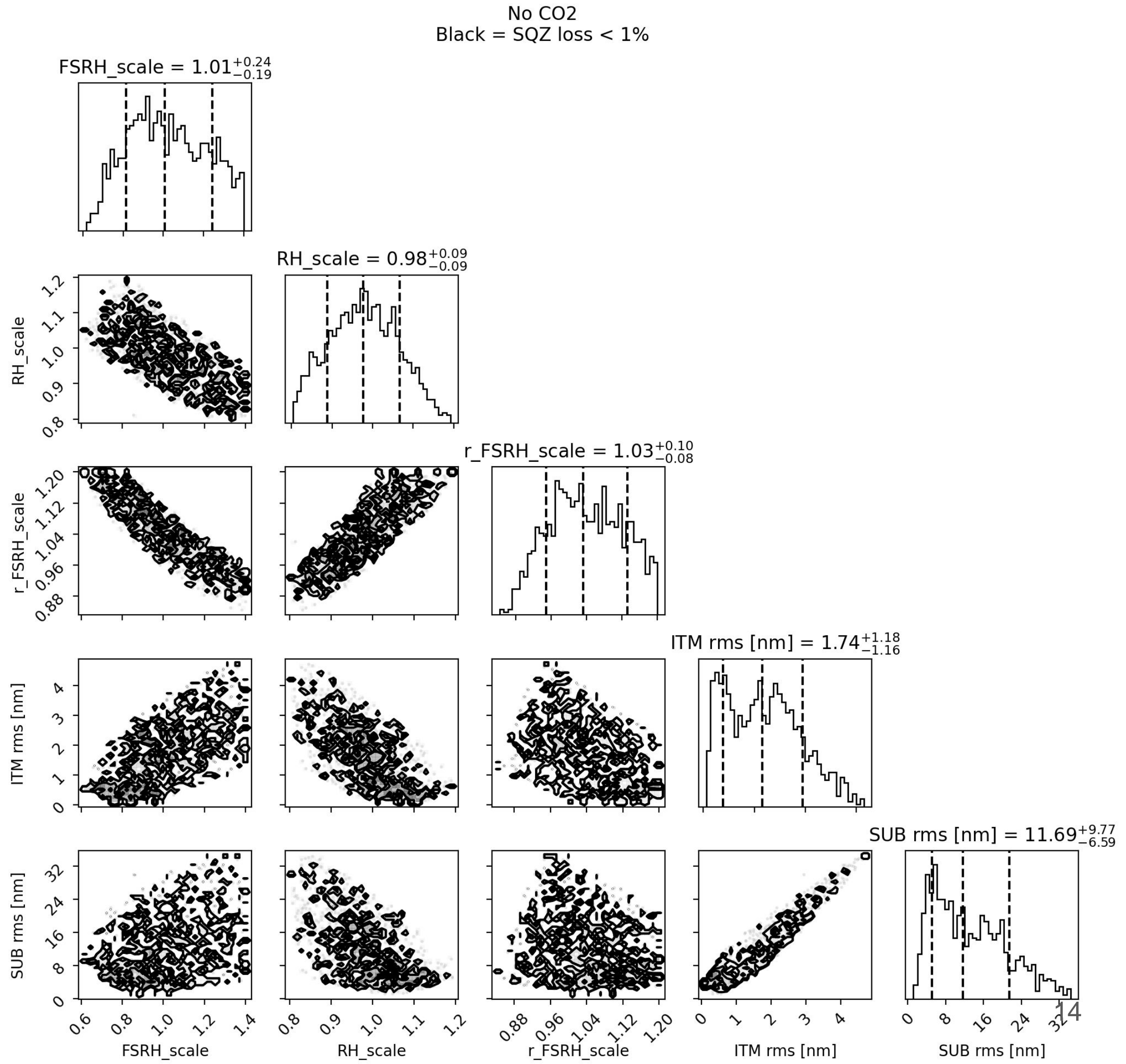
- TCS actuator power
- Magnification of CO2 and FROSTI

There is still more effects to add to this process!

Overall requirements are we need to be within ~10% of the optimal case

Using CO2+RH+FROSTI and RH+FROSTI we are able to find cases that work

Covariance between parameters we can control and those we cannot, means we can fix these issues whilst commissioning.



What can't we do/haven't done: where to go from here

- Parameterizing all errors
  - Beam sizes/positions
  - FROSTI profiles, etc
- Closed wavefront control systems
  - We've done T-SAMS, P-SAMS.
- Different IFO configurations?
  - Bigger apertures
  - Different SRC Gouy phases
- Limit power of actuators?
- Noises?

How do we automate this?

- Massive modeling effort only useful if we have a realistic control system.
- Almost all the parameters space is empty of locked solutions.

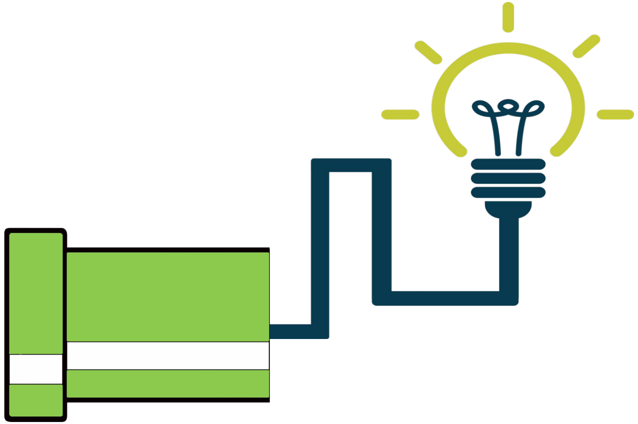
Refine the requirements for $A^{\#}$ actuators

What do we need for sensing to get to operating point?

- HWS only gets us part of the way there.
- In practice, is this enough?
- We need IFO derived error signals (FAST ones)

Conclusion

1. Have a method/pipeline
    a. Is local correction (not global)
    b. Quick and streamlined.
    c. Can be remodeled quickly
2. Two reasonable ASharp solutions
    a. Some work on tolerancing, not complete.
        i. 5nm RMS looks like target
    b. With and without CO_2 laser
3. Some limitations in modeling
4. Many things to discuss/consider/model



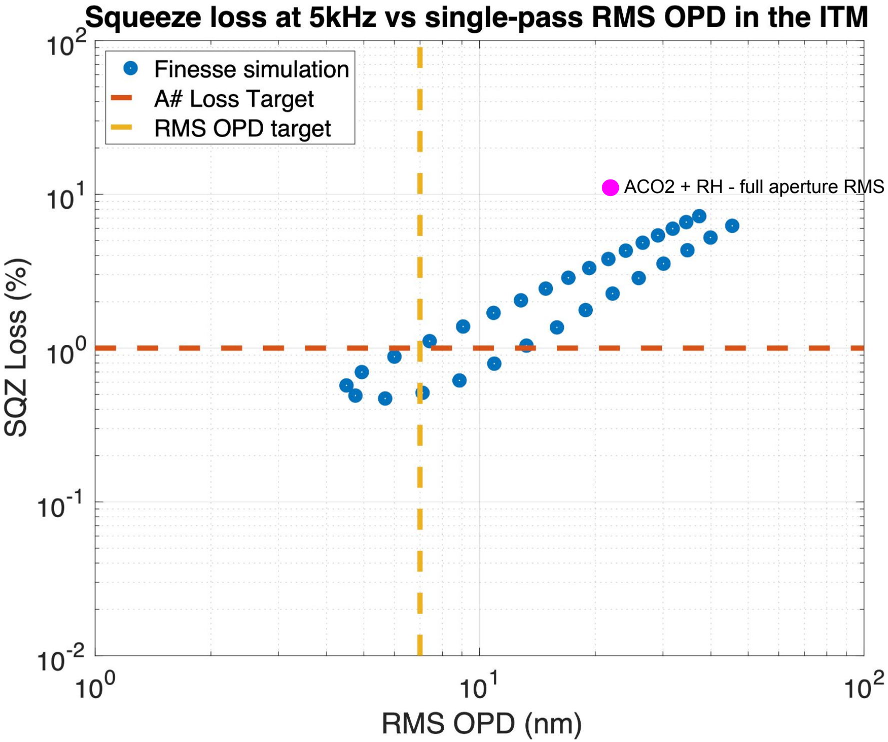
Discussion points (Many specific things to simulate)

- Get rid of CO2?
  - Pros: reduce complexity
  - Cons: Moving towards a point-design
  - What happens if the IFO isn't aligned to the center
  - What is the actual absorption profile?
- Multi-DOF FROSTI
  - What is the most efficient breakdown of actuator DOF?
- Should we change SRC Gouy-phase?
- Auxiliary stuff
  - FROSTI on SRM?
  - TRASH laser (optimize everything offline?) [G2300456]
  - Need heavy duty RH: 70W - 100W
- Mirror polish: implications for FROSTI?
  - Do we model for a larger coating aperture?
- What is the junk light situation with lower PRG?
- Sensing & control
  - Mode tracking HOM? Inject frequency noise?
  - How do we sense?
    - Local/interferometer signals?
  - Local/Global minimum in phase space?
- Commissioning: How do we use FROSTI? (vary power and then what?)
  - Time constants? How long does it take to Commission? Like, genuinely, how are we going to commission this?
- Why are we not seeing high power gains
  - Is there increased noise at low frequency
  - Is the excess noise from control loops?
- Modeling & Design
  - Redo optimization with more end-to-end model?
  - What about 3D model? Flats on the side?
  - Do we limit the amount of correction power?
    - CO2 < 20W, for example

Discussion points/backup slides

SQZ losses vs RMS error

- Worked out squeezing loss for different errors in Complement Gaussian heating beam size
- Characterized residual OPD by Gaussian weighted RMS
- Plot SQZ loss vs RMS OPD
- Not sure if we optimize RMS across full aperture or partial?



Philosophical Question: Why Model Stuff?

Design (In Principle)

- Solve for actuator design that is maximally insensitive to systematic errors
    - Consider CLOSED LOOP performance

Operation (In Practice)

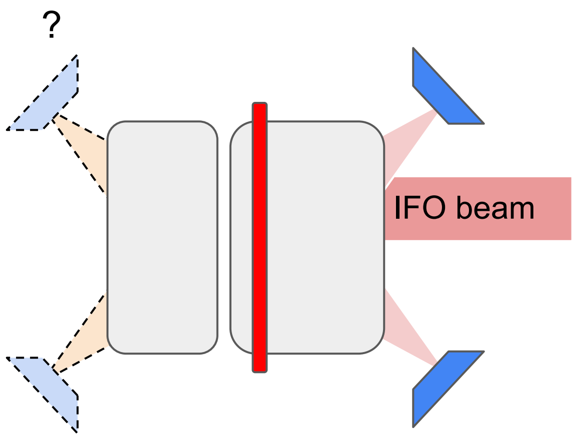
- Solve for specific actuator settings in a particular interferometer
    - Why is the Optical Gain in LLO in O4 the amplitude that it is?
    - Include TRASH laser
- TCS is conceptually simple to other control systems, BUT: UGF << 1uHz
    - Modulate actuators and get error signal?
    - Is it implicit in this statement that we can't find the optimum operating point in a reasonable time? Or, what do we need for error signals get to the optimum point?

Modeling implications

Notes

- Optical fields: We know we need many HOM coverage in models
    - That’s where the action is!
- FEM: Larger test masses (new thermal environment)
- Optical ray tracing: FROSTI actuators

Discussion: Getting Rid of CO2?



- Rely entirely on HR FROSTI
- Maybe add a recycling cavity FROSTI?

Pros:

- Cosmic Explorer is looking to eliminate CP
- Reduces complexity (CO2 tables have a LOT of overhead)
  - Less maintenance (like recharging CO2 lasers)

Cons:

- Removes flexibility of “dynamic” changes in thermal lens in recycling cavity
- Moving toward a point design.
  - What if the absorption is not uniform?
  - What if the interferometer isn’t aligned to center?
- What is the actual absorption profile on the test masses?

Discussion: Multi-DOF FROSTI

- Multiple actuators just heating individual regions?
- Actuators that overlap but provide different heating patterns
- Is axial distribution of actuators efficient, or does it have a lot of redundancy and only actuate on tilt/pitch, astigmatism

Discussion: Sensing and Control

Control:

- Local - measuring thermal lenses with Hartmann sensors
- Interferometric - using interferometer signals (which are what?)
- Are we at a Global or Local minimum in phase space?
  - Do we need to push through current operating points to better global ones?

Sensing

- How do we sense well enough to get to 2% residual OPD?
- Hartmann sensors realistically will get us about 10% residual OPD (guesstimate). How can we do better?

Discussion: Commissioning FROSTI

- What channels are we monitoring to determine FROSTI levels?
- What, quantitatively, are the targets that determine optimum FROSTI performance?
- How do we avoid the “Install Actuator and Make Things Better” trap?
    - We won’t avoid this without a well-defined control loop
- How do we deal with the time constants?
    - Commission offline with the Hartmann sensor and TRASH laser
        - While ETM work is on-going, work on optimizing the ITM FROSTI and TRASH laser using the HWS. And vice versa.

Discussion: Change Signal Recycling Cavity Gouy Phase

- Pros and cons?
- Do we even know it accurately?

Pros:

- Better control architecture
- Less sensitivity to thermal effects?

Cons:

- Redesign of a lot more optics and associated positions on ISIs
-

Discussion: Auxiliary stuff

TRASH laser/heater (TRansient Attenuation Surface Heater): G2300456

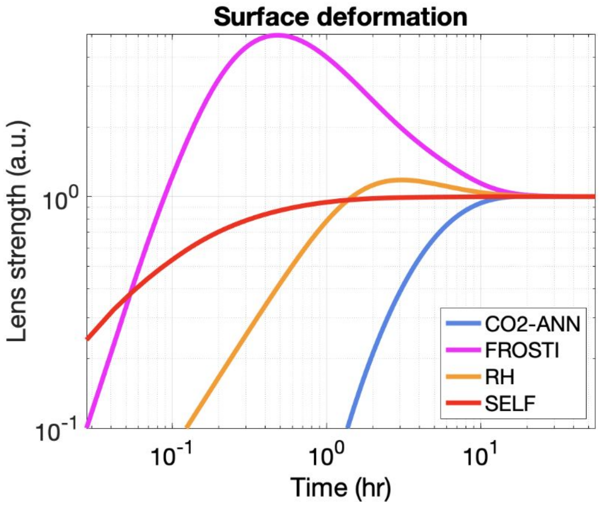
- Stability of IFO will be improved
- Doesn’t have to be a laser - but check what best option is
    - E.g. is 60% matching with a front surface thermal projector sufficient and easier than 90% matching with a CO2 laser? Is 90% matching with a thermal projector easy or difficult?

FROSTI on SRM

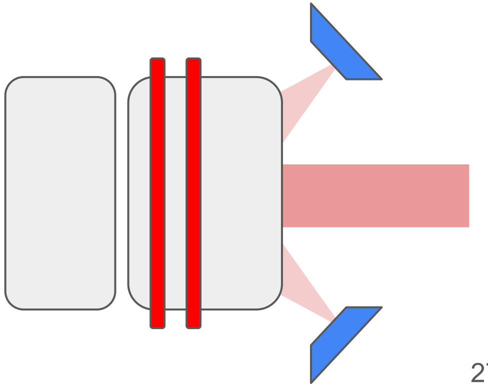
- Central heating on SRM to give more actuation in the SRC?
- Easier than CO2 heaters previously used in O3

Heavy-lifting RH

- We’ll need better part of 70W to get correction in ASharp
- What will the design be?
- Have several elements?



IFO beam



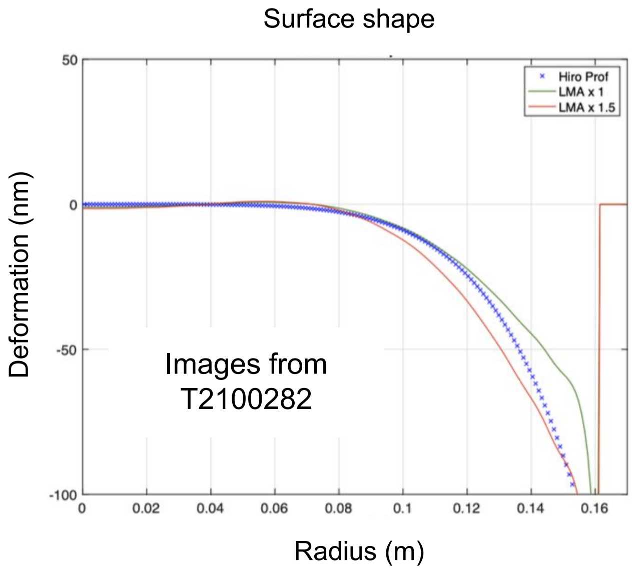
Discussion: Power recycling gain and junk light

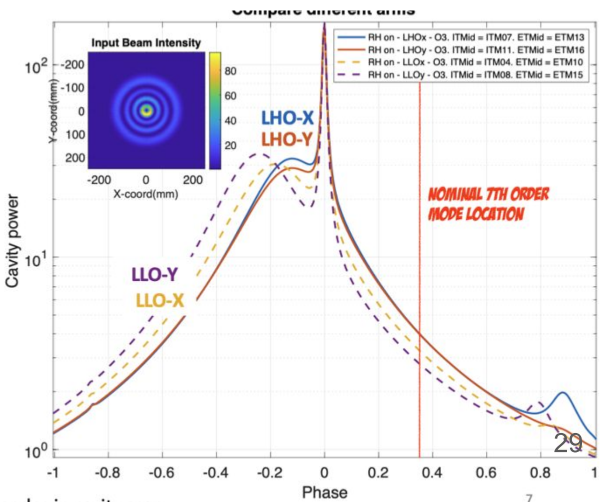
- Suppose we’ve reduced the losses and maximized performance
- Have a PRG of 44 vs 50 but compensate with more laser power
- End up with desired arm power
- What is the residual junk light at the beam splitter?
- Is it causing problems with the optical gain?

Discussion: Mirror surface polish?

How does the mirror surface influence the FROSTI design? T2100282

What tolerance is required for both FROSTI and surface polish?

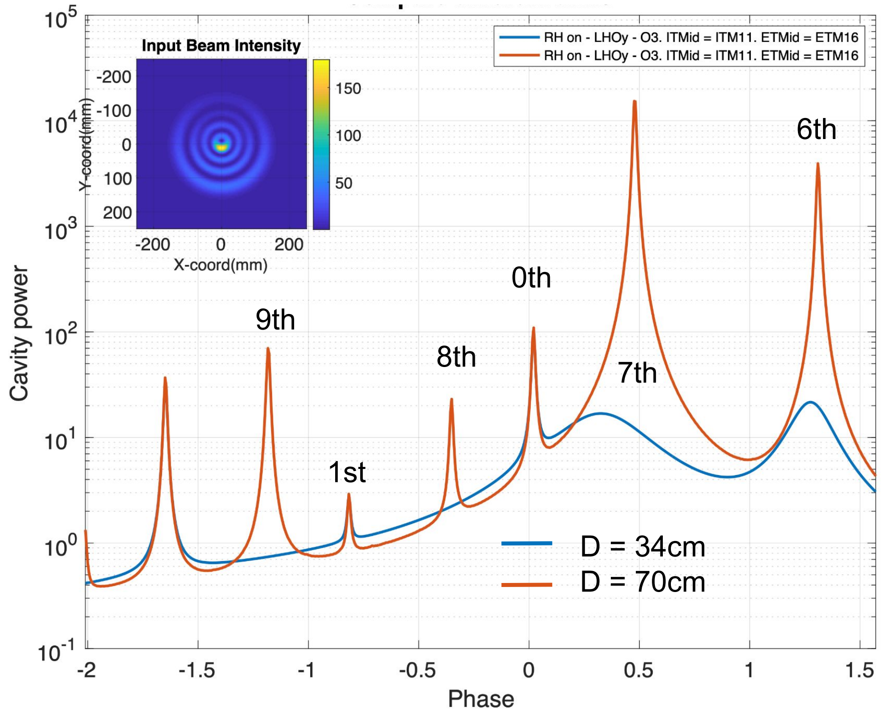




Discussion: Larger coating diameter

What about a larger mirror coating?

- Lower losses to HOM?
- Parametric instability risk?
    - More gain for HOM
    - But narrower peaks - easier or harder to avoid?



Discussion: not seeing high power gains?

- LLO: operation vs target
- LHO: operation vs target

Discussion: further modeling

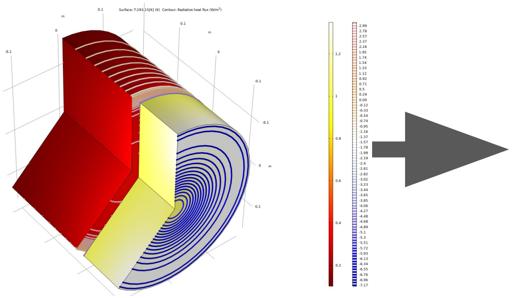
- Redo optimization with more end-to-end model?
- What about 3D model? Flats on the side?
- Do we limit the amount of correction power?
  - CO_2 < 20W, for example

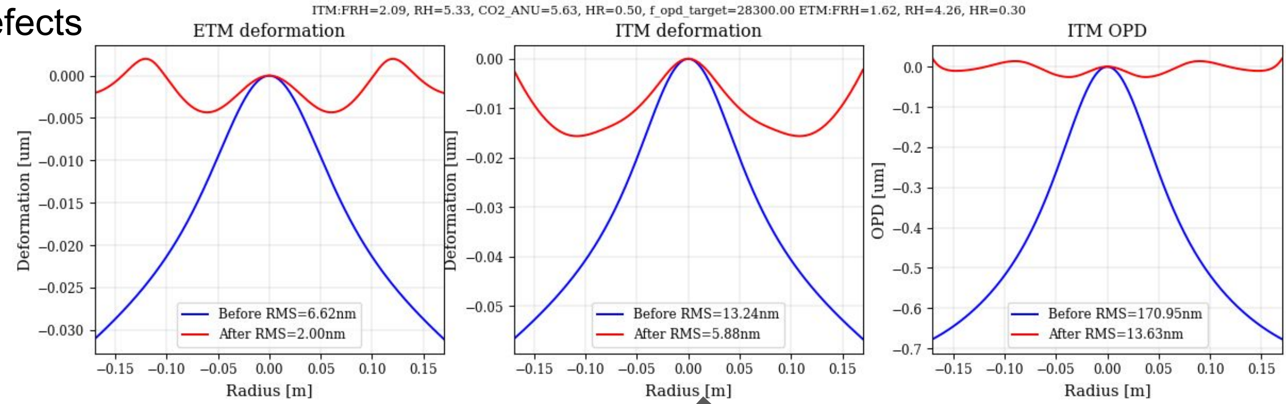
Extra slides

Optical Model

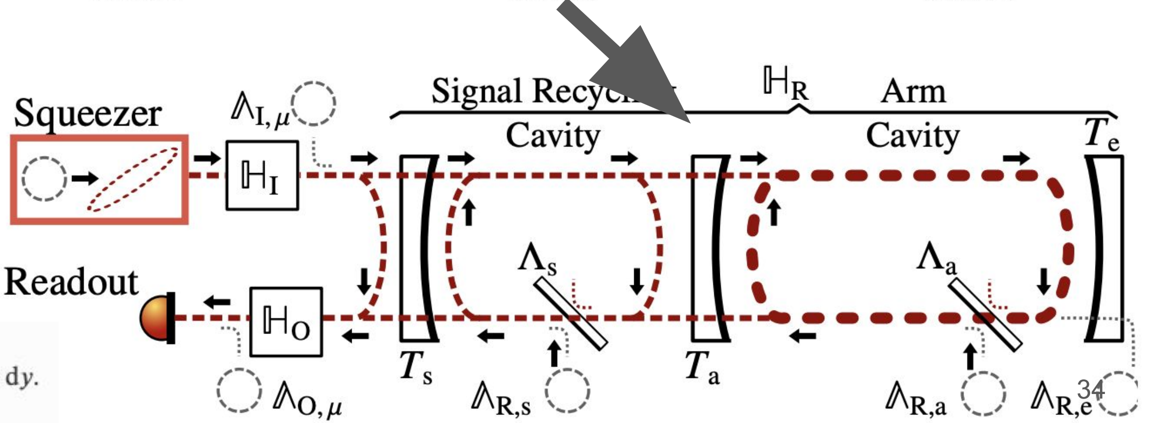
FEA data for each actuator then optimised to minimise RMS optical path distortions and ***maps*** generated.
These are loaded into FINESSE and applied to each mirror

FEA to generate model thermal defects





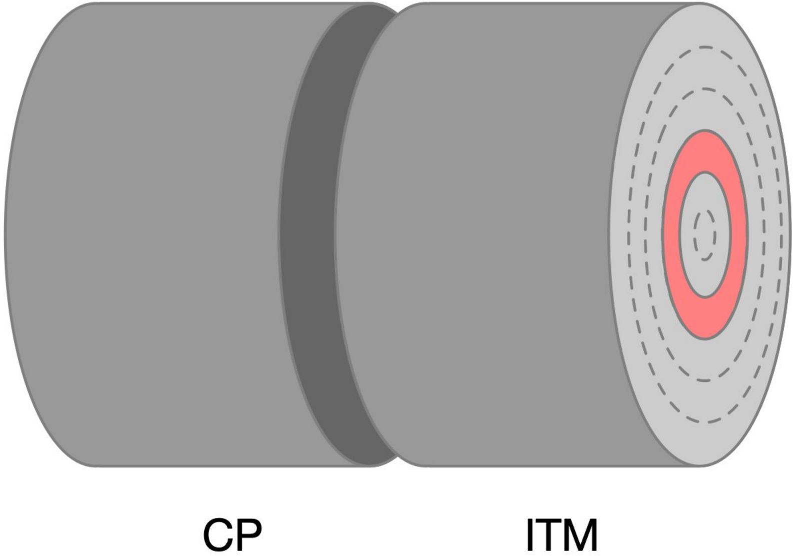
FINESSE then computes mode scattering matrices and all the various resonant behaviours in the model



$$k_{n,m,n',m'}(q, q', A) = \iint_{-\infty}^{\infty} u_{nm}(x, y;\ q)\, A(x, y)\, u^{*}_{n'm'}(x, y;\ q')\, \mathrm{d}x\, \mathrm{d}y.$$

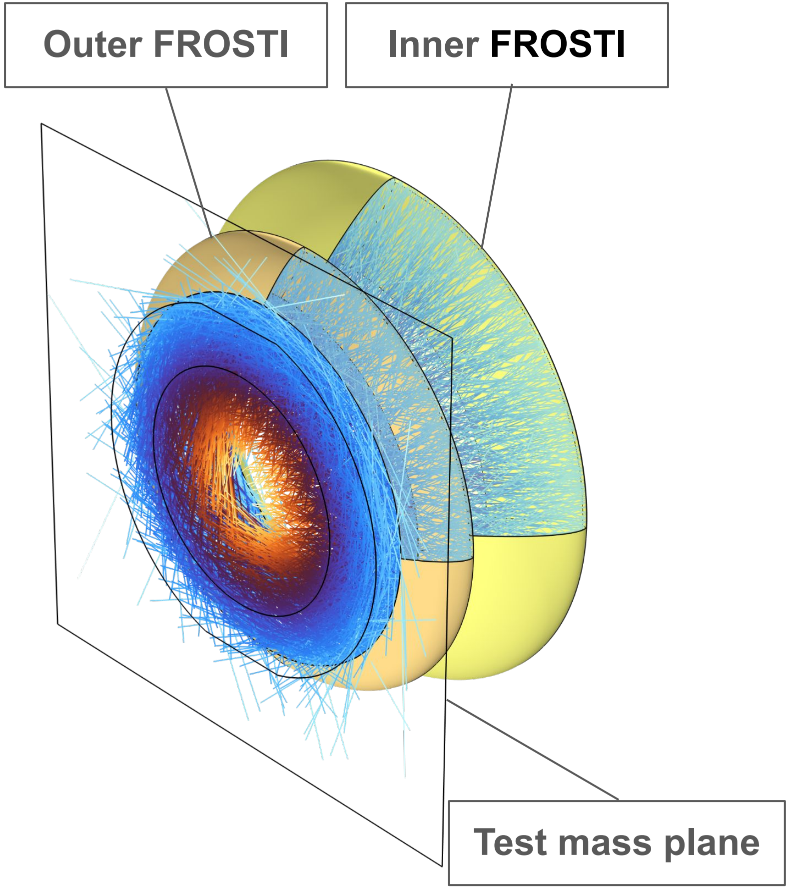
Linearize Finite Element Model > intensity distributions

- Evaluate thermo-elastic and thermo-refractive response for set of concentric heating annuli
    - Heating “elements”
- Work out ring heater and self-heating
- Response is TE+TR:
    - SELF heating +
    - RH +
    - Weighted sum of CO_2 annuli
    - Weighted sum of FROSTI annuli
- Minimize FOM of this sum



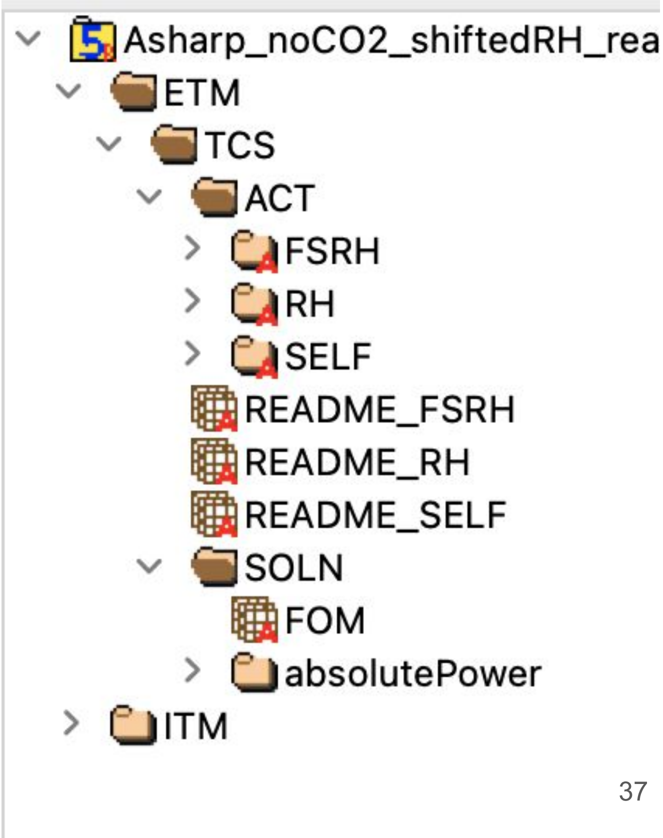
FROSTI

- **FROSTI** : **FRO**nt **S**urface **T**ype **I**rradiator
- Non-imaging elliptical reflectors to deliver broadband IR radiation to test mass HR surface
- Ellipsoid surface parameters are tuned to shape delivered intensity profile
- Minimum 2 FROSTIs required to generate target ideal FROSTI intensity solution:
    - **Inner FROSTI**: Correction from 0-150 mm
    - **Outer FROSTI**: Correction from 90-230 mm
    - **(Optional) Edge FROSTI:** Control edge roll off at 210-230 mm

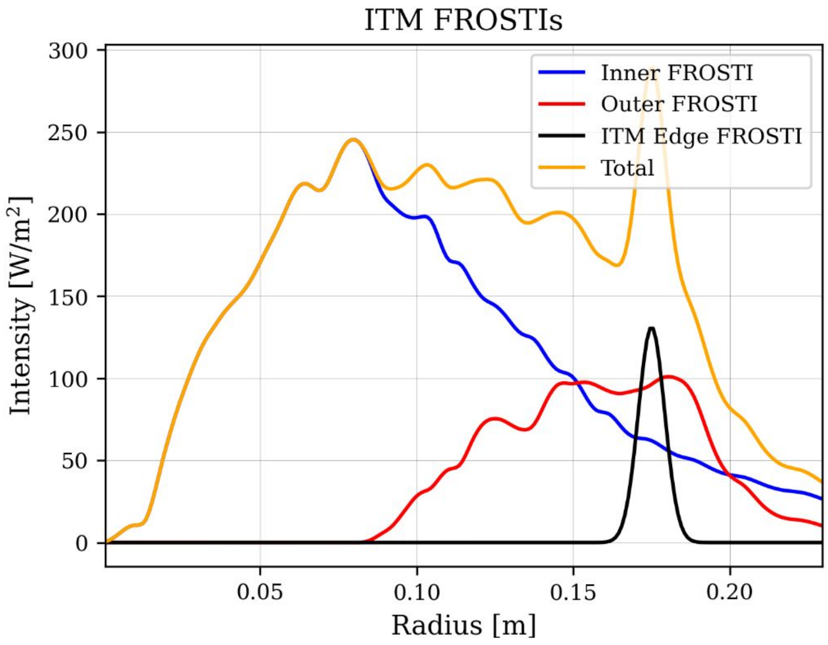


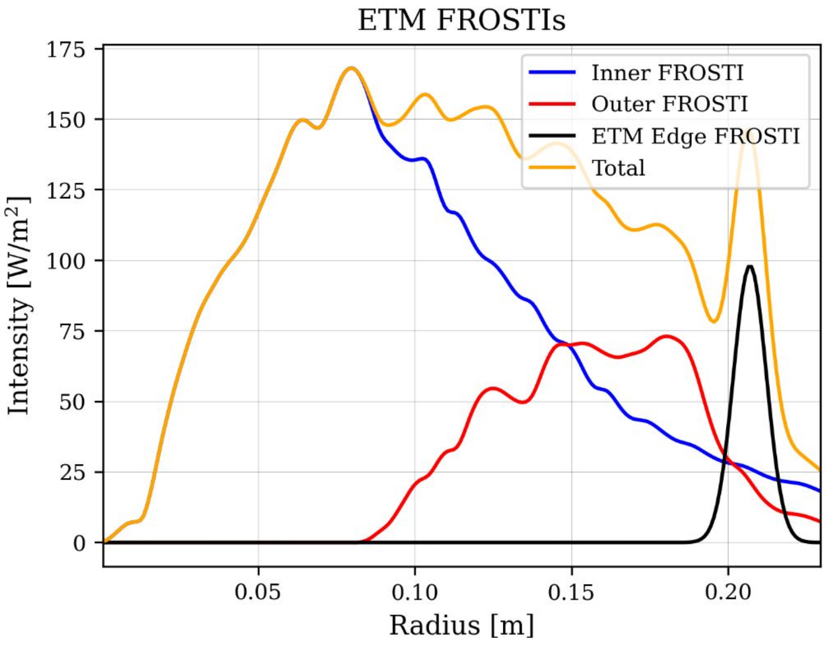
Results from COMSOL modeling/optimization

- Determine optimum heating profile using linear sum of annuli in COMSOL
- $\mathrm{OPD}[\ \mathrm{SUM}\ a_i\ \mathrm{ANN}_i\ ] = \mathrm{SUM}\ a_i\ \mathrm{OPD}[\mathrm{ANN}_i]$
- Works because radiation and conduction are linear in dT
- Determine a figure of merit for the thermo-refractive and thermo-elastic deformations
- Questions over what is the ideal FOM
- Solve for CO2 and FROSTI intensity profiles simultaneously



FROSTI intensity distribution (no CO2)





- Inner and Outer FROSTIs are identical for both ITM and ETM
- Edge FROSTIs control edge profile

Similar to 7th order effects in aLIGO for point absorbers

https://doi.org/10.1364/AO.419689

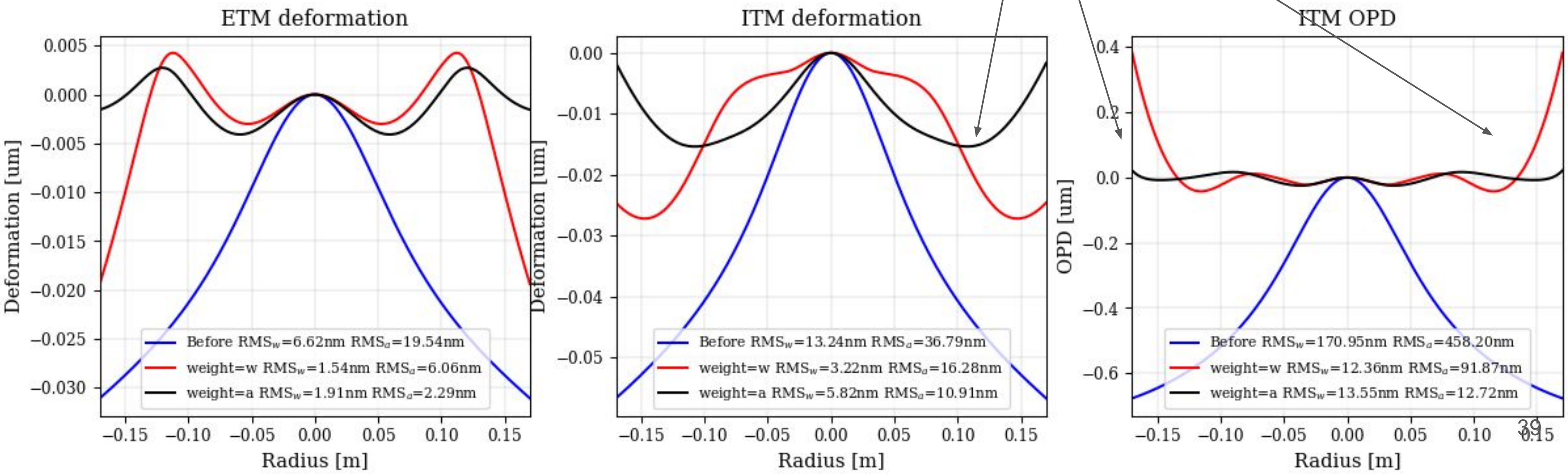
https://doi.org/10.1364/JOSAA.433575

Optimising thermal actuators

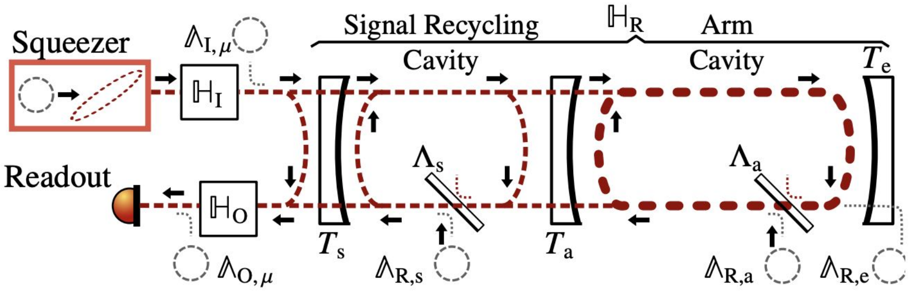
The FRH data used here is just some initial model that showed this problem, you can do much better by optimising the design!

These edge effects are pushing HOM resonances around, which matter a lot for higher orders!

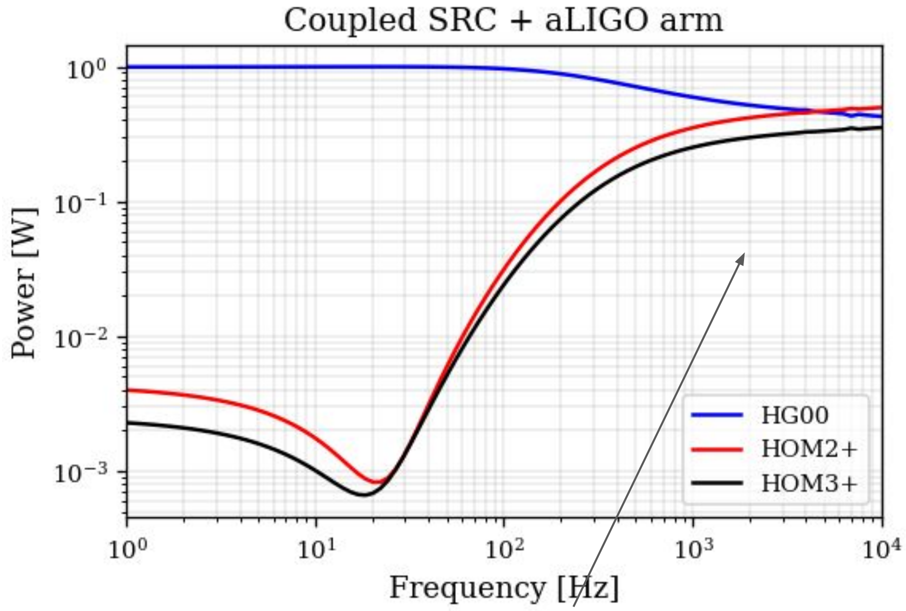
Different OPD optimisation strategies can generate very different system responses

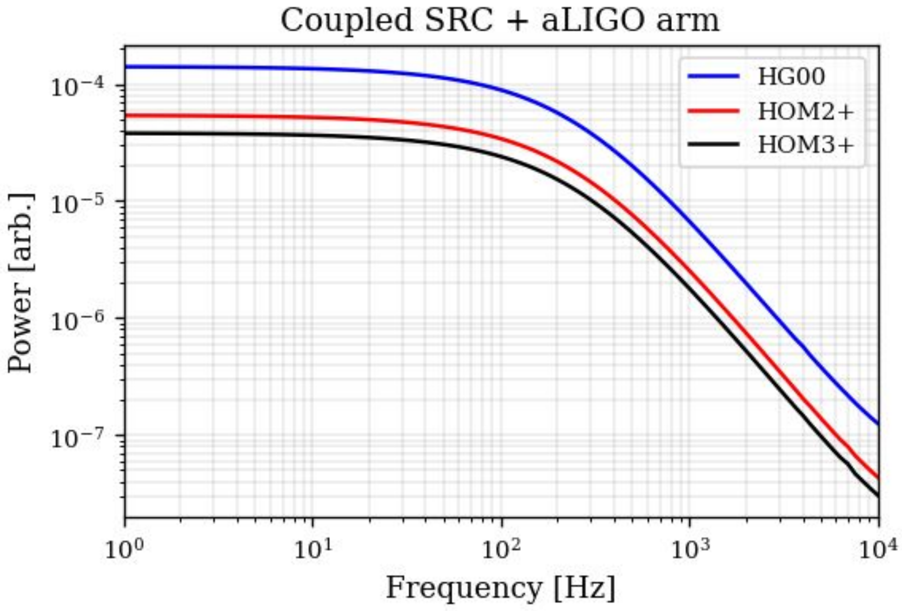


DARM Reflection



total refl. mode content $P_{abs} = 0.5$W
$T_{SRM} = 0.32$ single pass SRC Gouy=20.0





Reflected squeezed field has frequency dependent mode shape?? **HOMs are worse at higher frequencies**

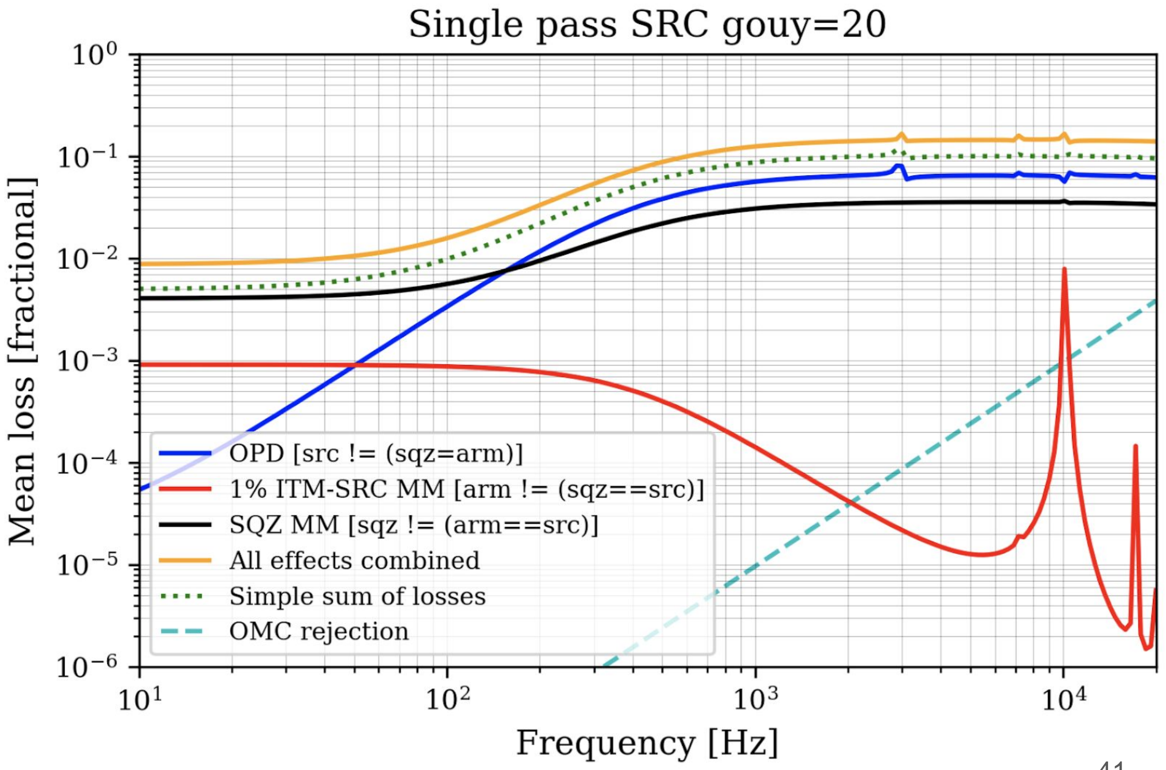
The GW signal sideband shape does not…

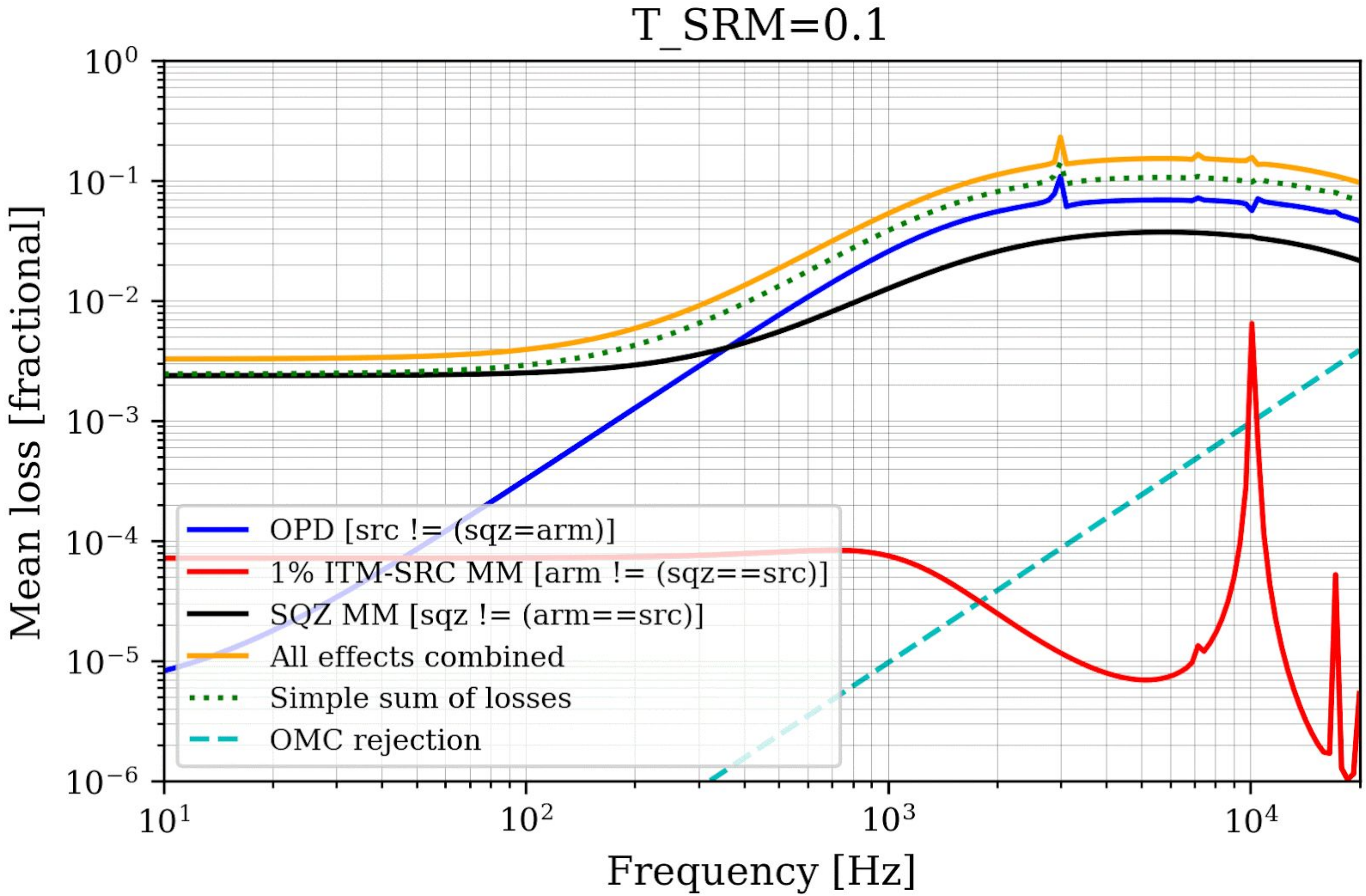
Mode mismatch loss breakdown

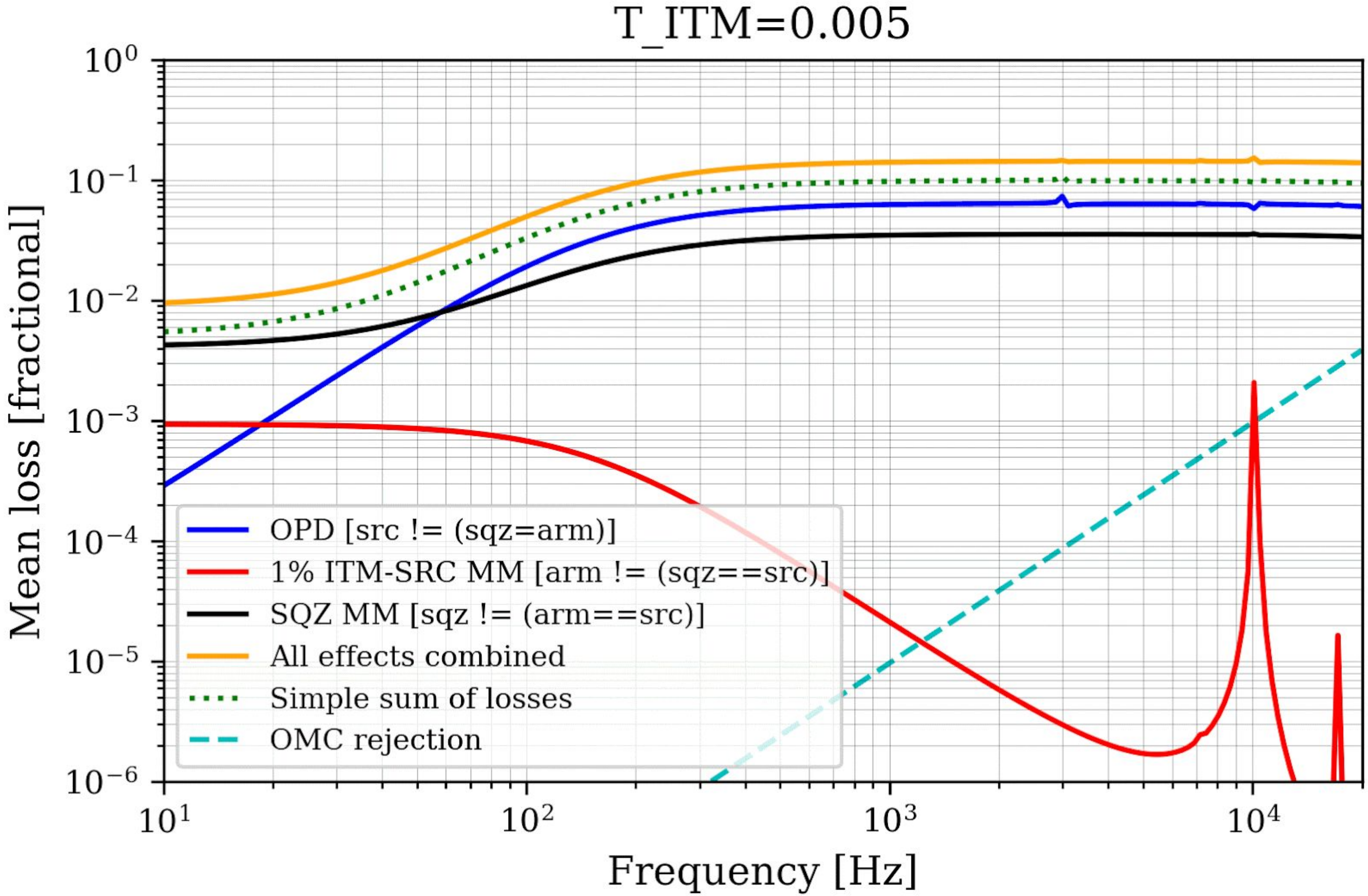
Three primary mode mismatches. All behave differently and can add coherently

All three pivot around the DARM coupled cavity pole

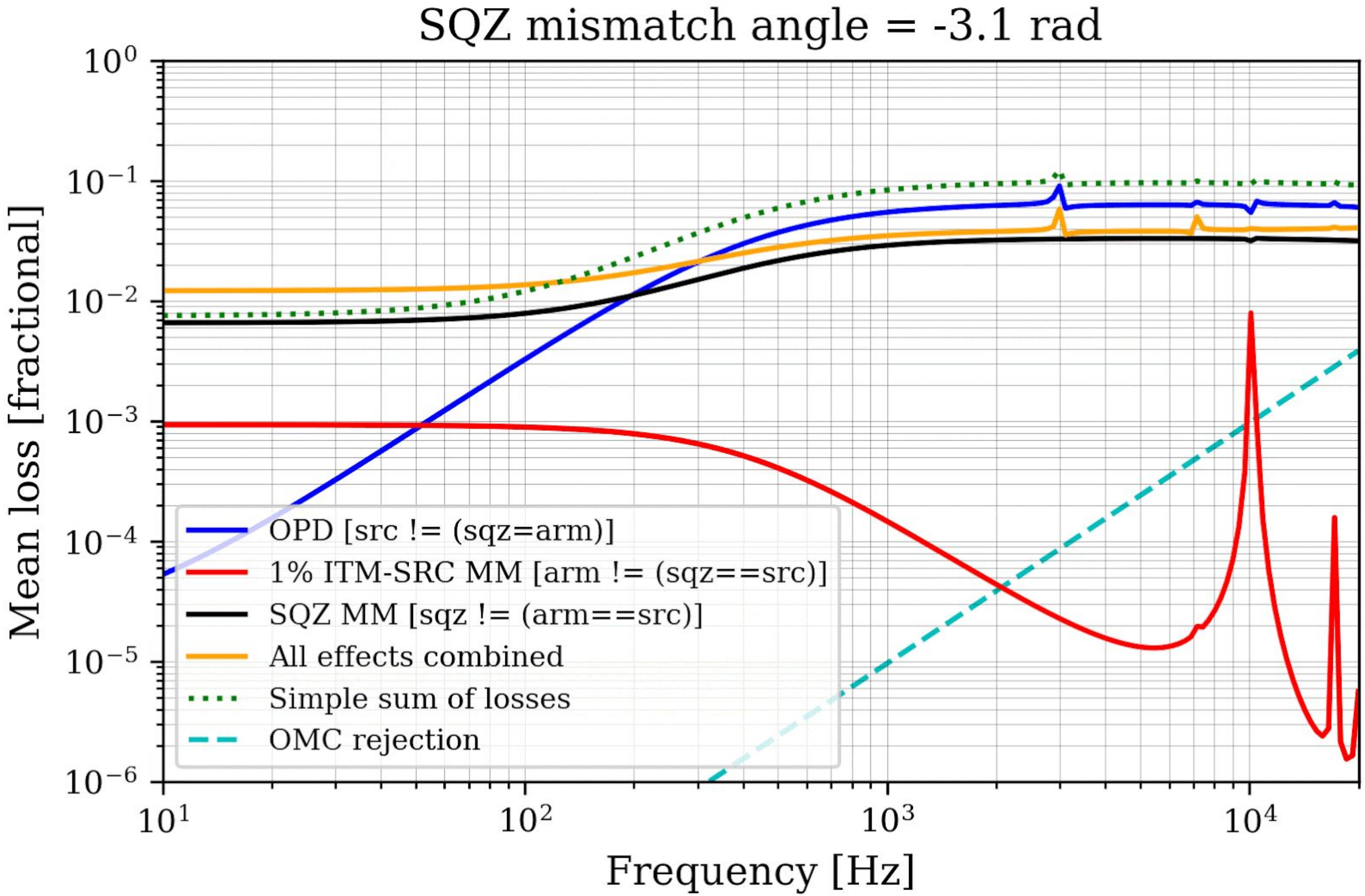
OPD is loss when using the FEA thermal actuator model outputs

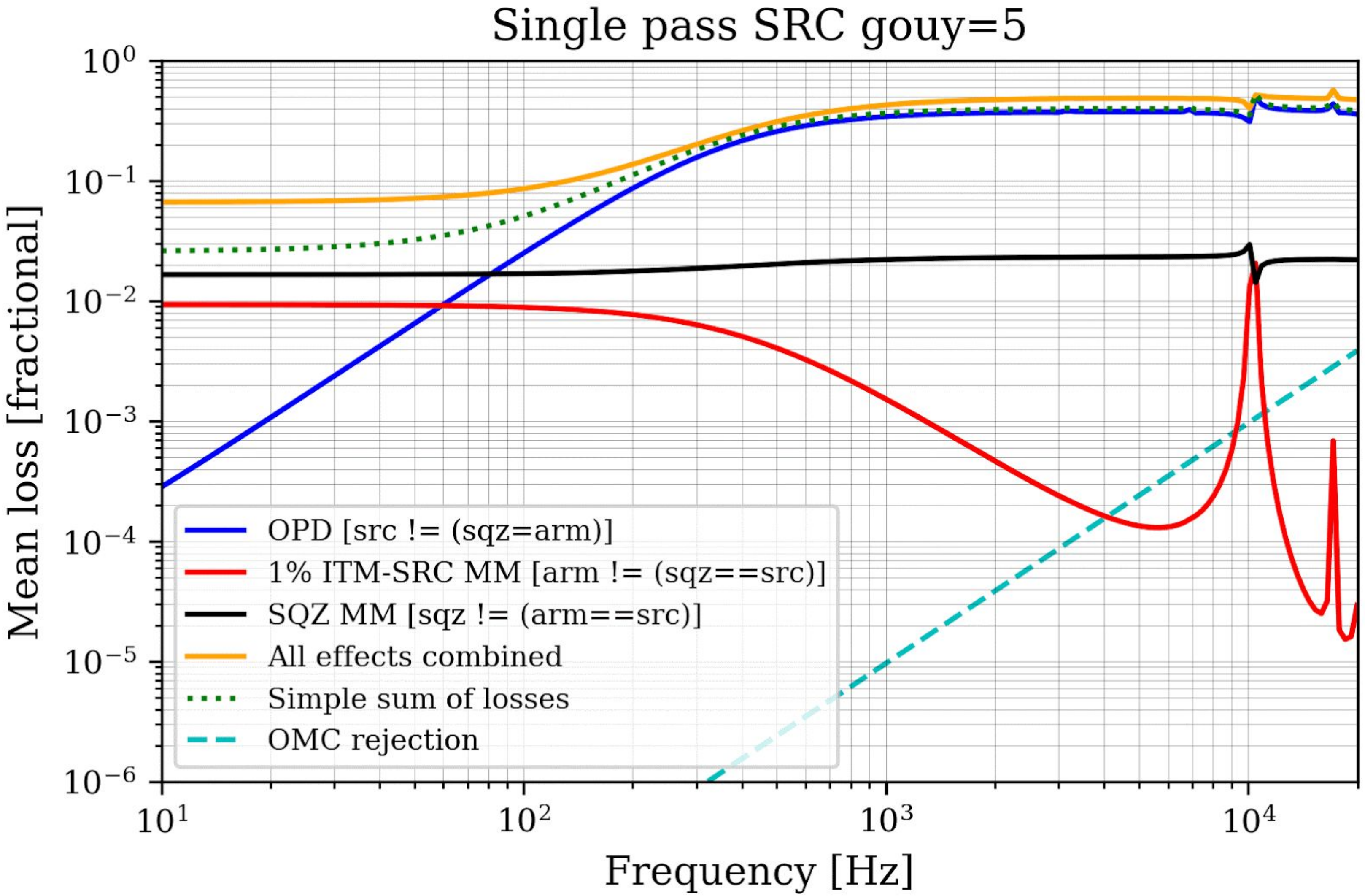



T_SRM=0.1
Mean loss [fractional]
Frequency [Hz]
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^1
10^2
10^3
10^4
OPD [src != (sqz=arm)]
1% ITM-SRC MM [arm != (sqz==src)]
SQZ MM [sqz != (arm==src)]
All effects combined
Simple sum of losses
OMC rejection



T_ITM=0.005
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
Mean loss [fractional]
OPD [src != (sqz=arm)]
1% ITM-SRC MM [arm != (sqz==src)]
SQZ MM [sqz != (arm==src)]
All effects combined
Simple sum of losses
OMC rejection
10^1
10^2
10^3
10^4
Frequency [Hz]


SQZ mismatch angle = -3.1 rad
Mean loss [fractional]
Frequency [Hz]
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{1}
10^{2}
10^{3}
10^{4}
OPD [src != (sqz=arm)]
1% ITM-SRC MM [arm != (sqz==src)]
SQZ MM [sqz != (arm==src)]
All effects combined
Simple sum of losses
OMC rejection



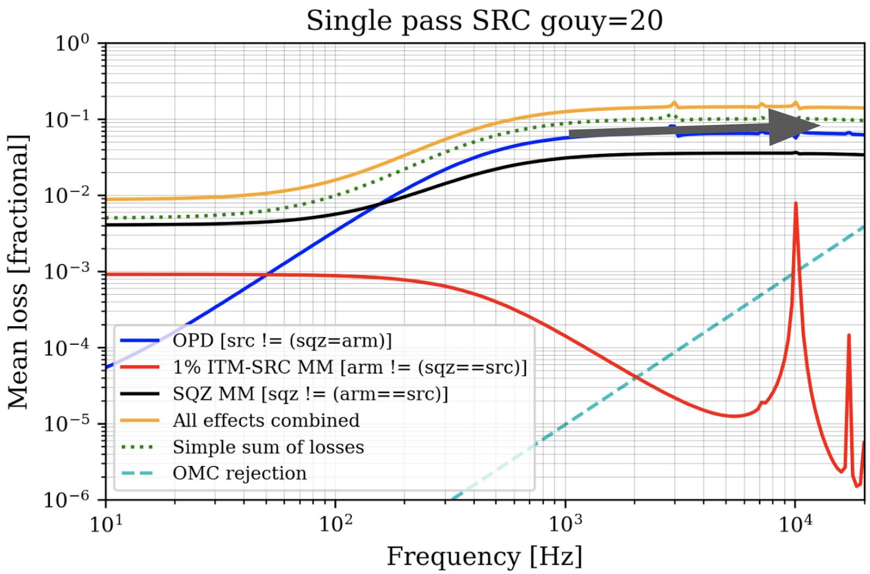
Single pass SRC gouy=5
Mean loss [fractional]
Frequency [Hz]
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^1
10^2
10^3
10^4
OPD [src != (sqz=arm)]
1% ITM-SRC MM [arm != (sqz==src)]
SQZ MM [sqz != (arm==src)]
All effects combined
Simple sum of losses
OMC rejection

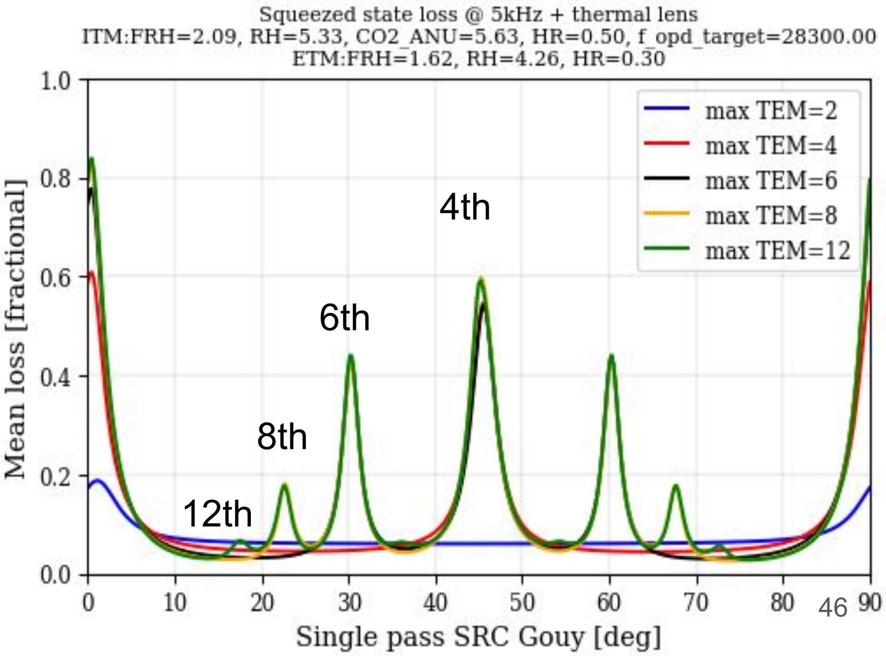
What is going when changing the SRC gouy phase?

We are hitting HOM resonances in the SRC…

How does this high frequency OPD loss depend on gouy phase?

Overall loss level set by this high-f limit



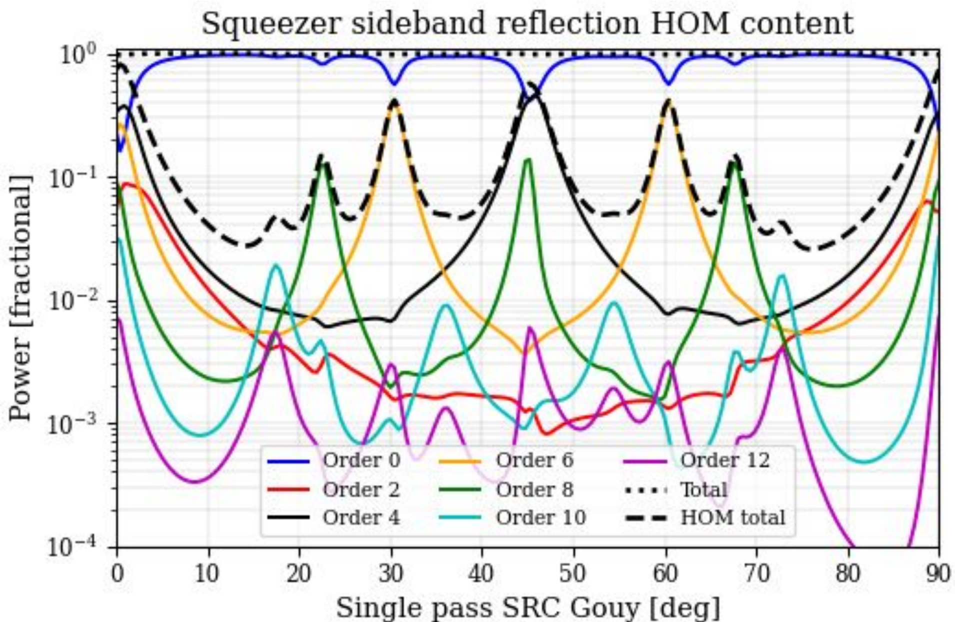


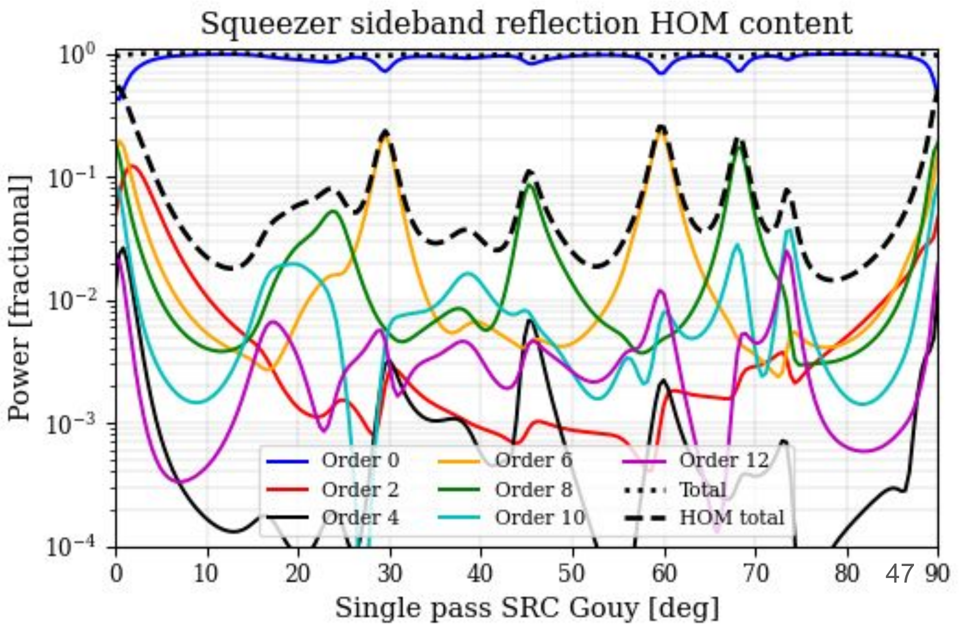
What is going when changing the SRC gouy phase?

SRC thermal deformations can easily change the mode content and distribution

left optimised for full aperture RMS reduction

right for central part of the mirror





SRC no aperture

SRC with A+ apertures