Global optimization of multilayer dielectric coatings for precision measurements

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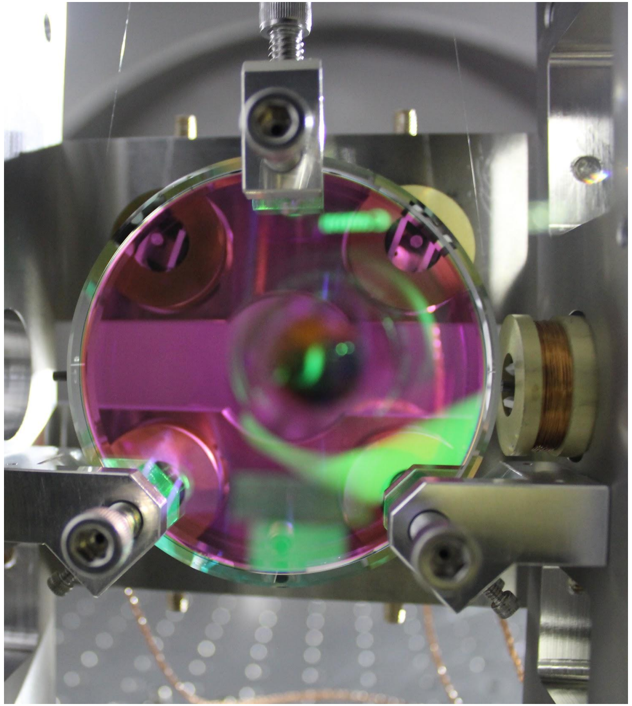
Overview

- Need custom coating designs
- Examples of performance requirements on dielectric coatings in GW interferometers
- Methodology - global minimization of a scalar cost function
- Case studies

Dielectric coatings

- At the heart of high finesse optical cavities in GW interferometers (and in other precision measurement experiments)
- Typical requirements (in LIGO):
  - Low power transmissivity
  - Custom transmissivities at carrier and at the second harmonic wavelengths
  - Low value of the surface electric field
  - Low integrated absorption
  - Low thermo-optic and Brownian noise
  - Minimal distortion of surface geometry on deposition
  - ….
- We'd like to work with manufacturers to design these coatings that have high likelihood of meeting the design requirements

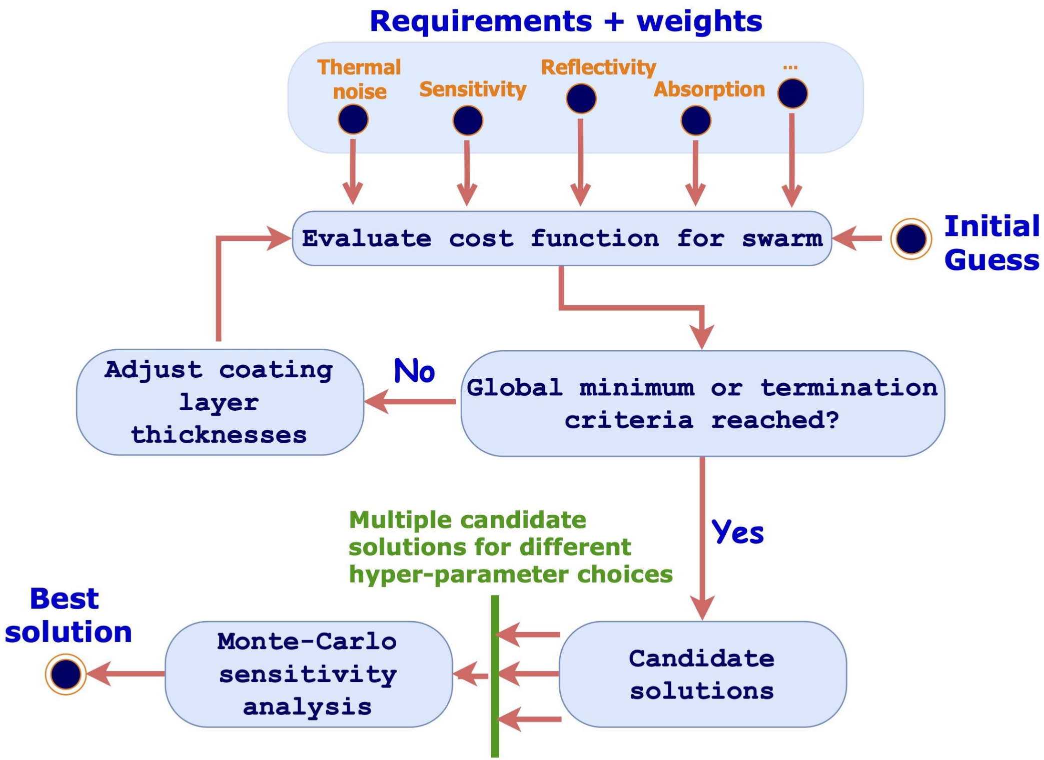


Optimal coating design

Design problem: What is the thickness of individual dielectric layers which will result in a coating that *satisfies all the design goals, with minimal sensitivity to perturbations in the model?*

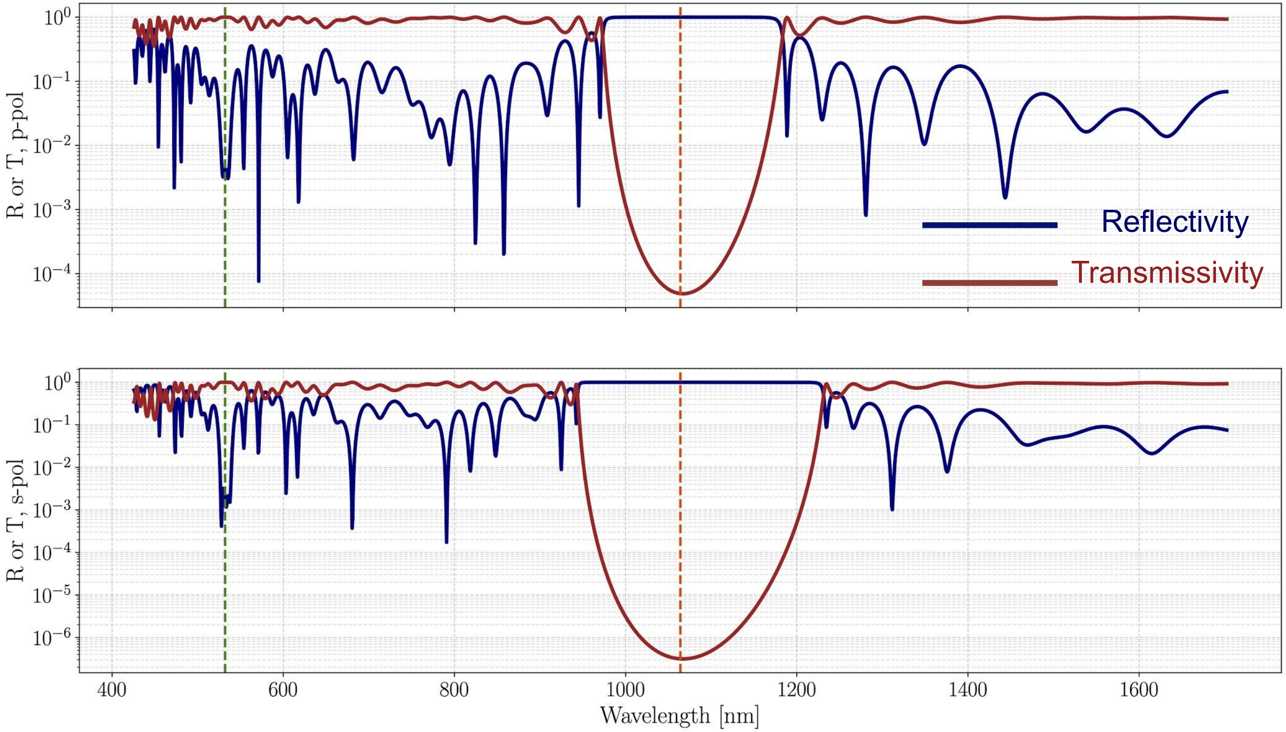
- In the case of LIGO, the coatings are bi-layer pairs
- Not all requirements are equally important (“best-effort requirements”)
- Scalar cost function minimization is easier to do than multi-objective optimization
- Reasonable computation time (but we have clusters)

Algorithm



- Cost function defined in a modular way, custom terms can be easily added in
- Weights to decide relative importance of different costs
- Global cost function algorithms are well developed, and there are several options
- Initially we used MATLAB's particle swarm. Now we are using algorithms like Differential Evolution (SciPy) so that the entire code suite is open source
- emcee sampler used to evaluate sensitivity to model parameters, optimize in the "hyper-parameter" space

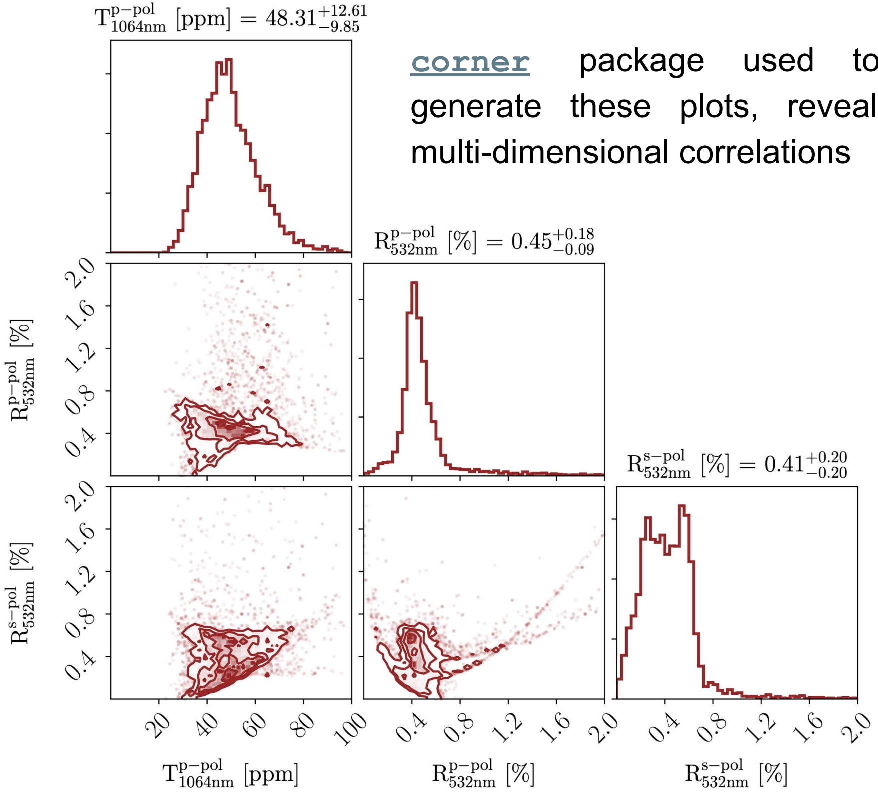
Case study #1 - Harmonic separator



Requirements

- T < 50 ppm @ 1064 nm for ~45 degree angle of incidence
- R < 1 % for s-pol *and* p-pol at 532 nm
- Low sensitivity to perturbations in dispersion model, thickness of layers

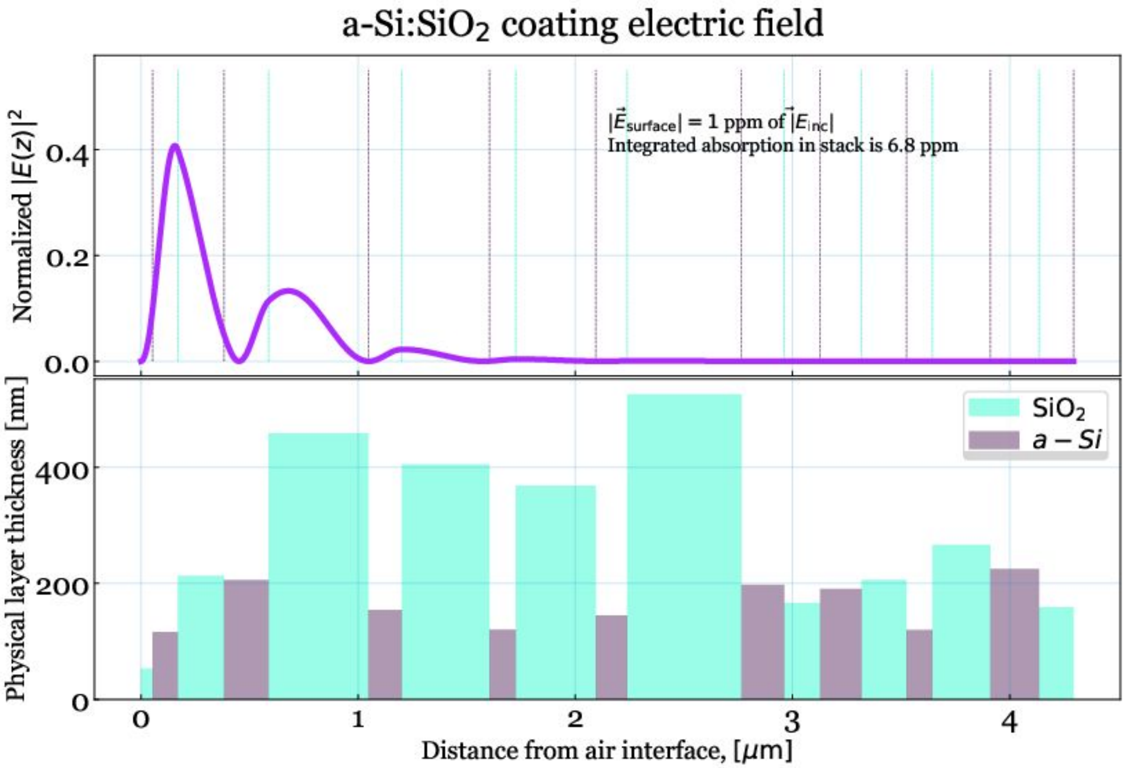
Case study #1 - Sensitivity analysis



corner package used to generate these plots, reveals multi-dimensional correlations

- There are some assumptions that go into the modeling, such as
  - Refractive indices of the dielectric layers
  - Dispersion model
  - Mechanical loss / absorption coefficients
  - Thermal noise model
- Furthermore, the manufacturer may not be able to deposit layers of the exact thickness required by the simulation
  - After discussion with the manufacturers, it seems that a *systematic* error is more likely than random perturbations
- We can predict the sensitivity of a design to such perturbations
- Goal is to have a design such that there is less than 1% probability of getting a mirror that is out of spec

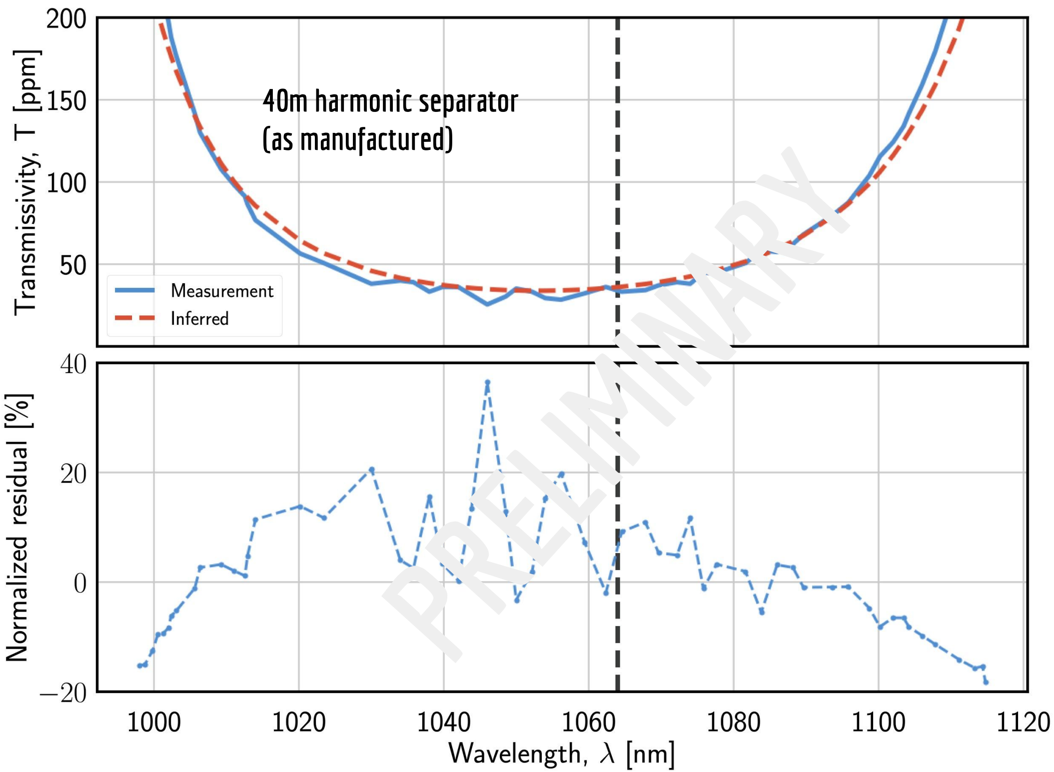
Case study #2 - Cryogenic ETM



Requirements

- T = 5 ppm @ 2128 nm for normal incidence
- Minimize absorption in coating and surface E-field
- Minimize thermal noise (Brownian, Thermo-Optic)
- Low sensitivity to perturbations in dispersion model, thickness of layers

Case study #3 - Application to Inverse Problem



Problem statement: Given a spectral reflectivity measurement, can we *infer* the dielectric coating properties, such that the residuals between the model and measurement is consistent with noise? These include:

- Coating layer thicknesses (initially, the minimal set of paramters)
- Refractive indices and dispersion of the constituent dielectrics

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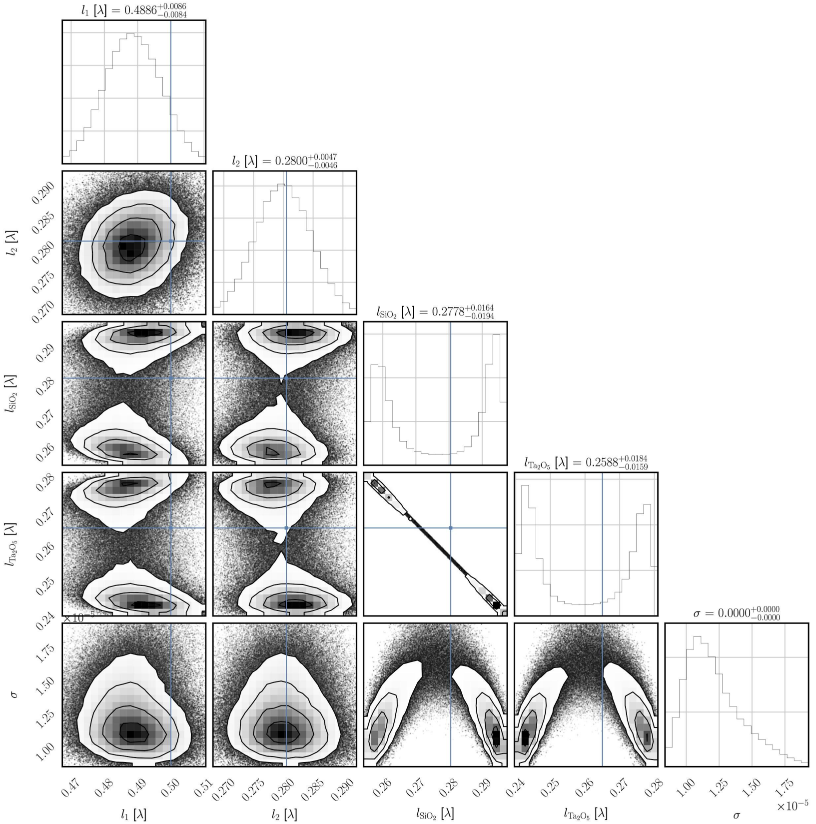

Algorithm

1. Set up a model of the coating
   - Some minimal set of assumptions is required, e.g. # of layers
2. Fit the model to measured data
   - Use your favorite algorithm, e.g. “Nelder-Mead”
3. With the “best-fit” parameters as a starting point, use `emcee` (or your favorite sampler) to investigate covariances

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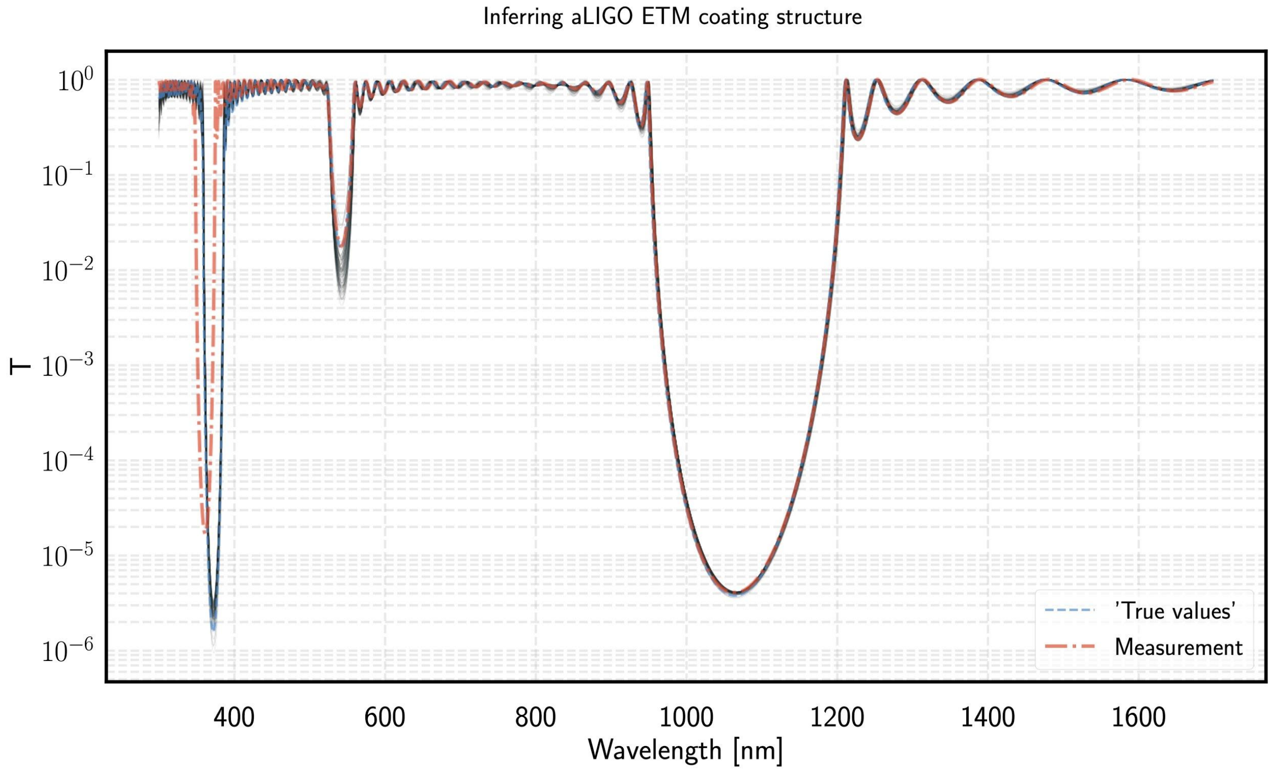
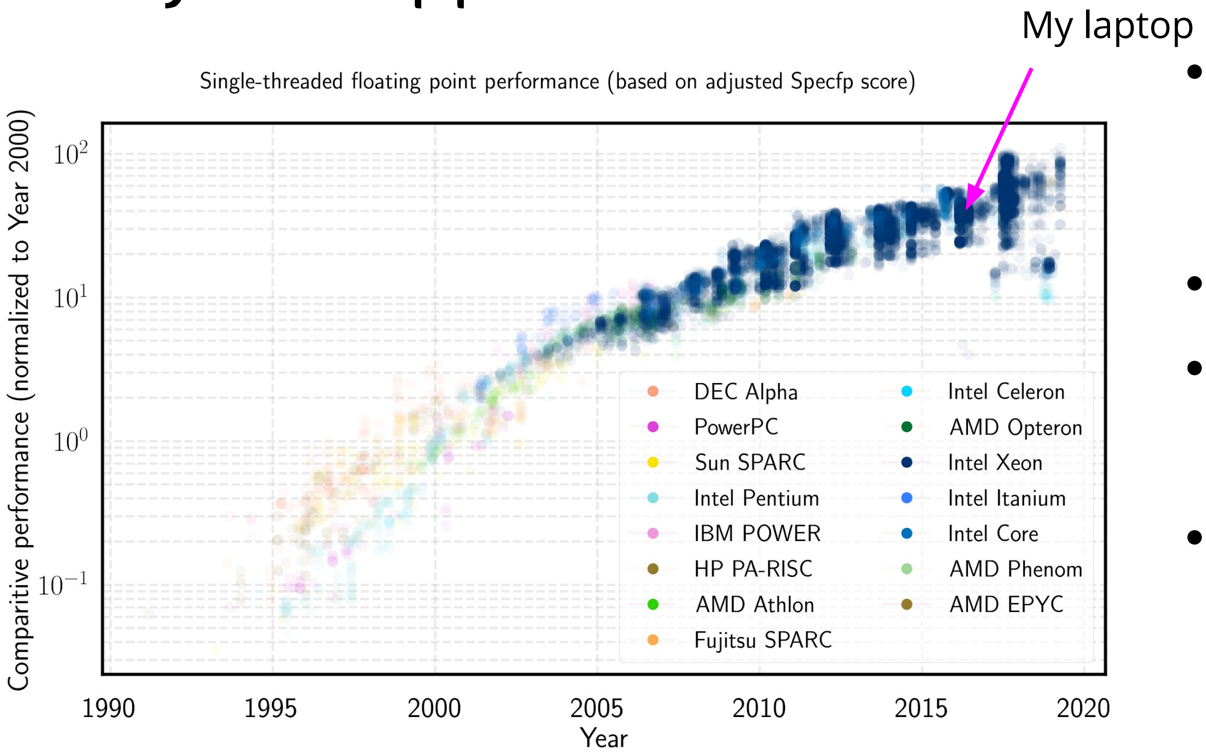


*Convergence of the MCMC chains requires a good dispersion model and good initial guesses

Why this approach?



- Main driver is that computational power has improved to the point where non-trivial coating design problems can now be solved on your laptop in ~10 mins
- For pathological cases, use clusters!
- The ecosystem of powerful yet free-and-open-source optimization tools is healthy and being actively developed
- Modular nature of the cost function means other communities (e.g. AMO, microscopic optomechanics etc.) can leverage this technique

Data scraped from SPEC's website

Summary

- The beginnings of a powerful and versatile coating design optimization toolbox has been developed
- Built using Python, so no licenses required
- We successfully fabricated an optic designed using this toolbox that met all specifications
- A paper based on this work is being prepared, we will circulate to the OWG shortly