Noise from stray light in interferometric gravitational waves detectors

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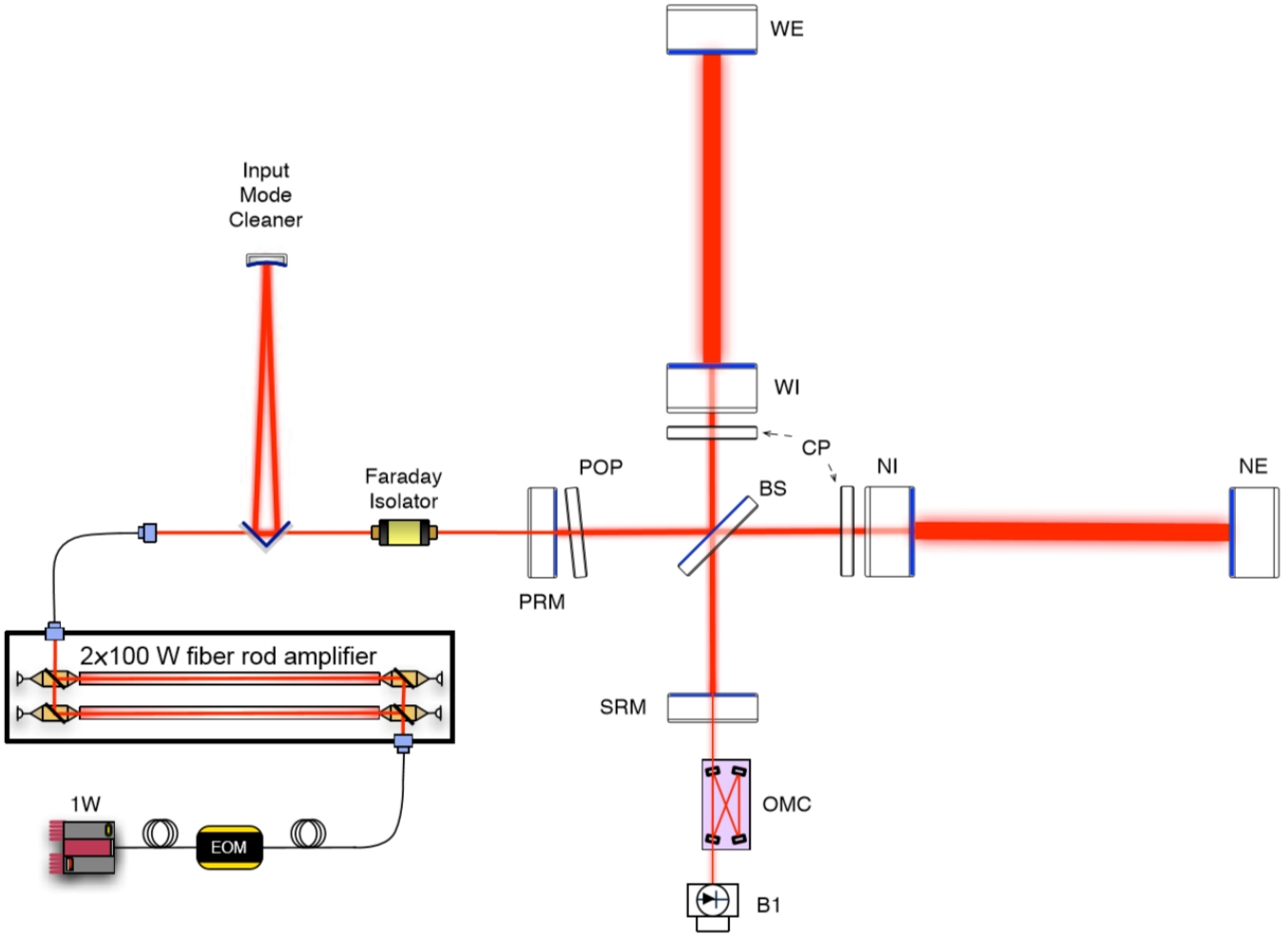
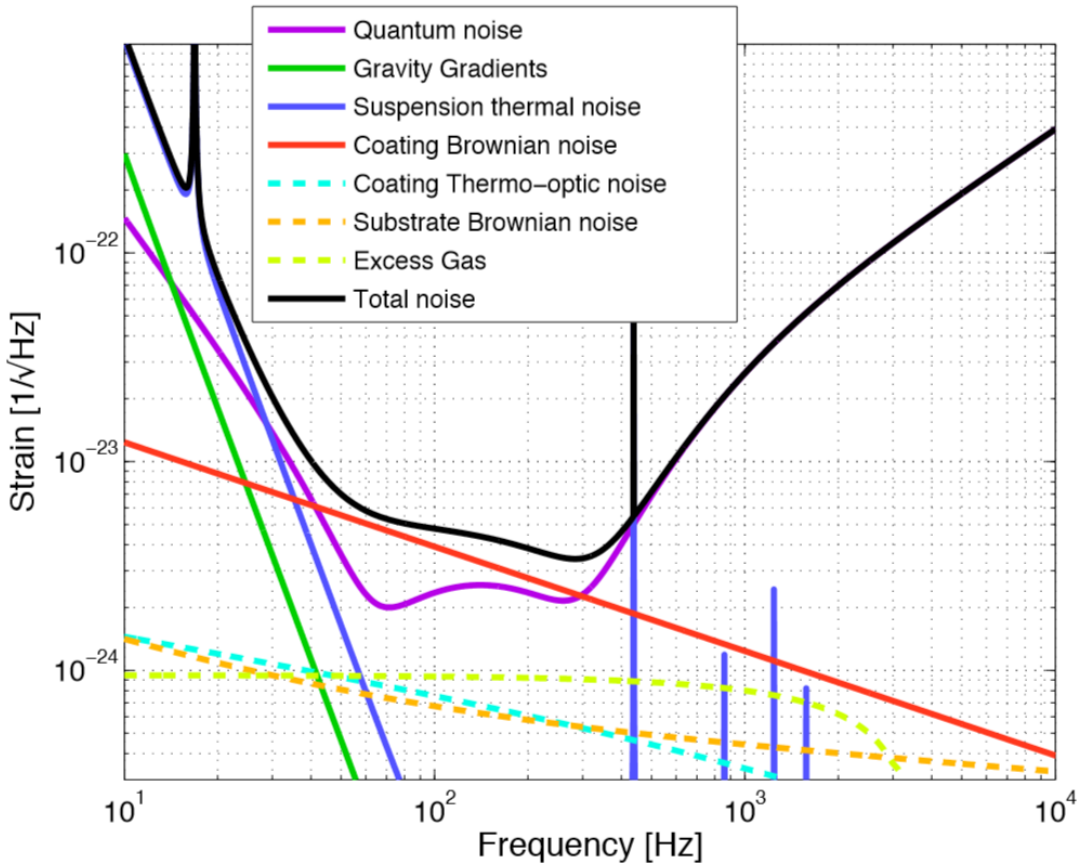
Outline

- Interferometric gravitational waves detectors
  - Advanced Virgo
  - Stray light issues
- Ray tracing
  - Ray tracing fundamentals
  - Shading
  - Interference with particle model of light
- Coupling between light and mechanics
  - Phase noise
  - Fabry-Perot cavities

Advanced Virgo configuration



Advanced Virgo design Sensitivity



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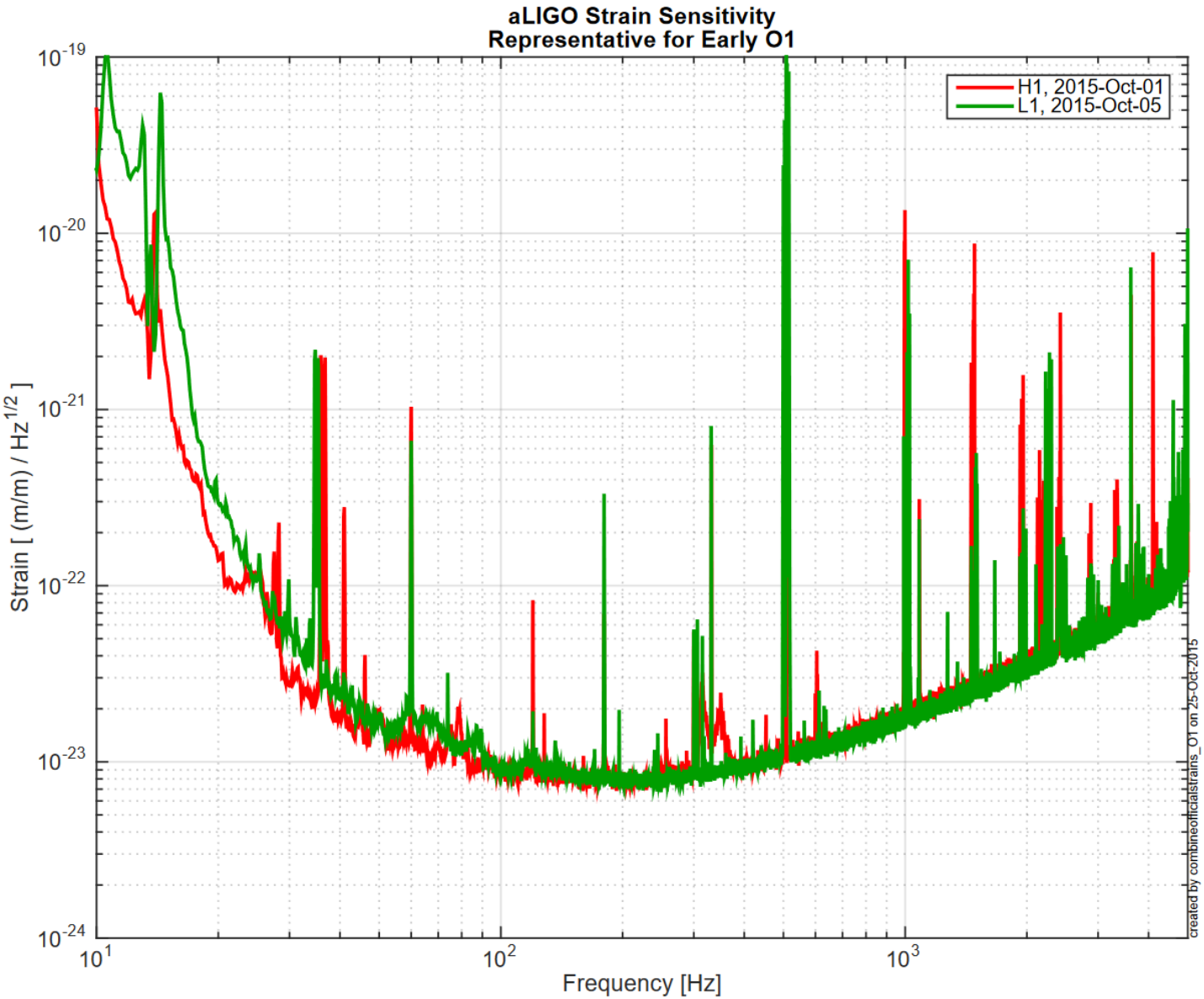
Ligo Sensitivity: SR1



Stray light

Stray light is all the light that follows a non expected path.
Mainly there are 4 sources:

- Secondary beams
- Rough surface scattering
- Point defect scattering
- Diffraction

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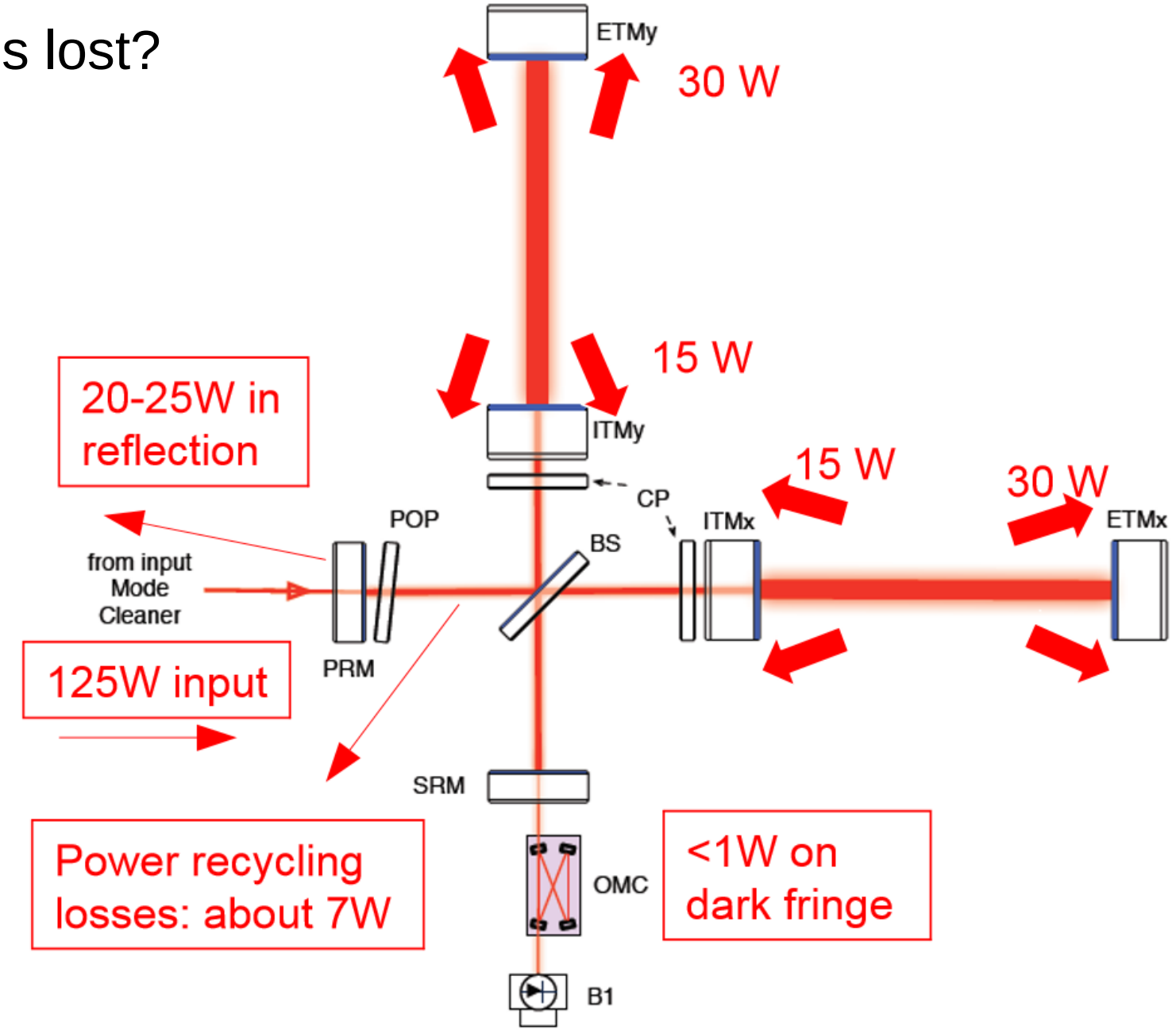
Stray light

Where the light is lost?



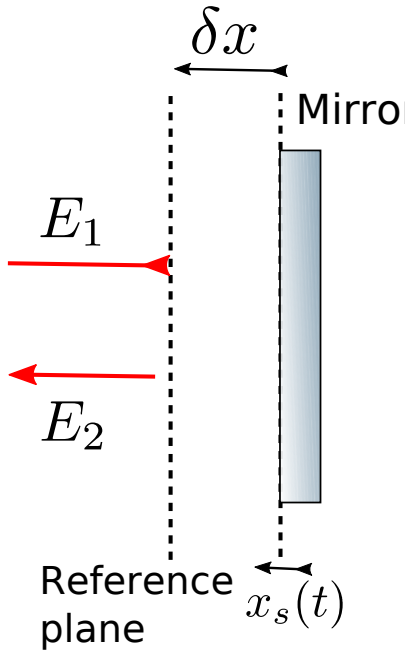
Stray light noise

- Phase change due to a moving element:

$$\phi(t) = \frac{4\pi}{\lambda}(x_0 + \delta x_{sc}(t)) = \phi_0 + \delta\phi_{sc}(t)$$

- Which can recouple as:

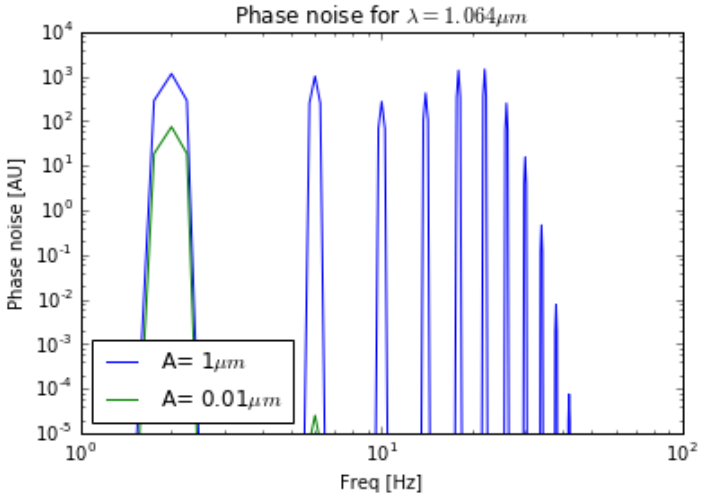
$$h = G \cdot \sin\phi_{sc}$$



Stray light noise II

- Two regimes:
  - Linear regime: small amplitude

$$h(f) = G\phi_{sc}$$

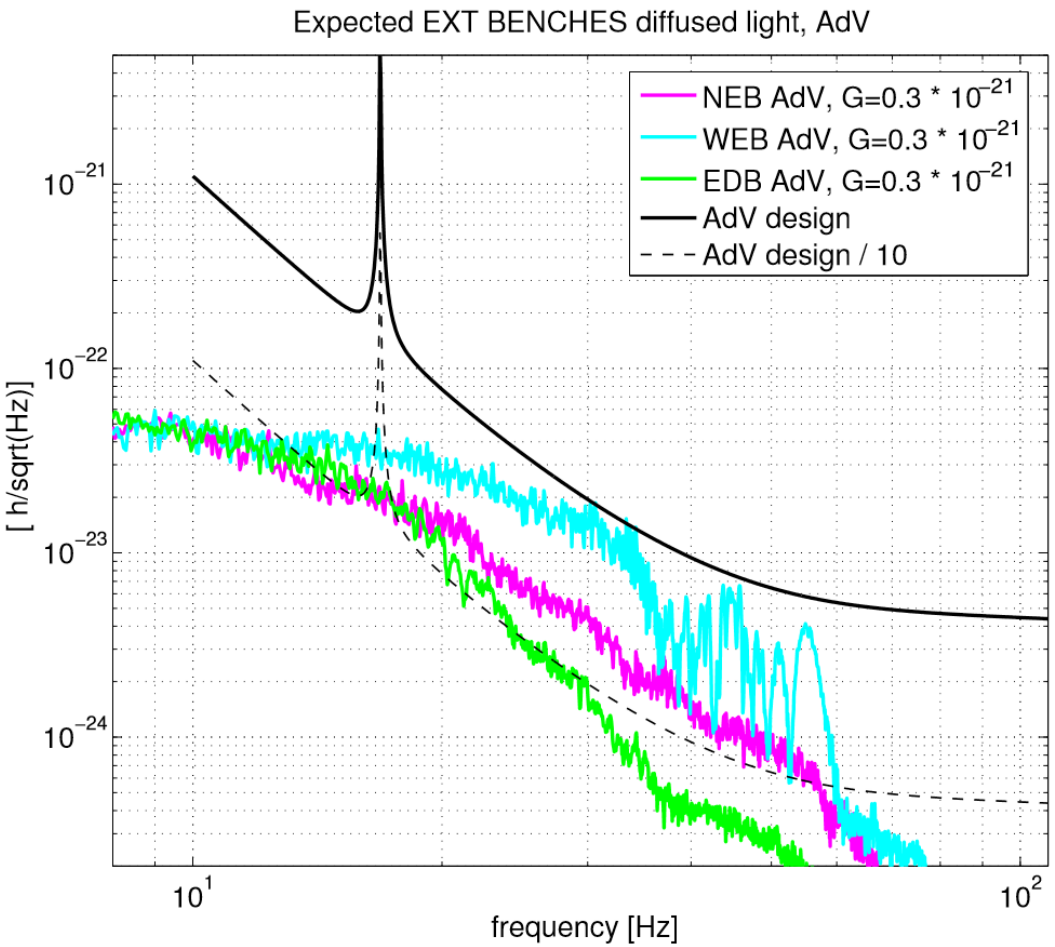


  - Non-linear regime
    - Upconversion phenomena:

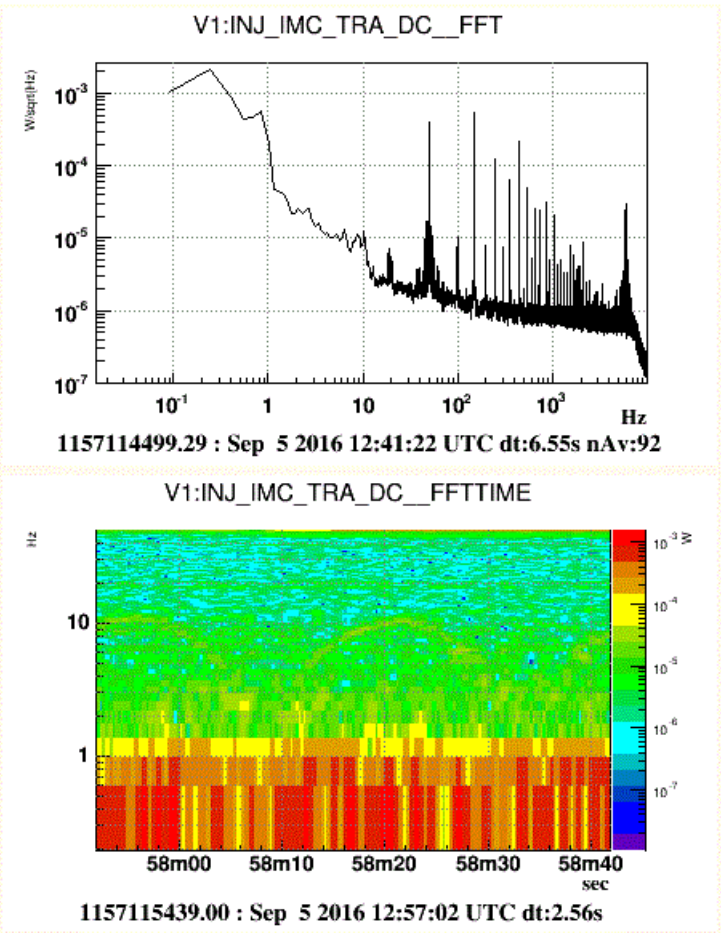
$$\sin(a\sin\psi) = 2\sum_{n=1}^{\infty} J_{2n-1}(a)\sin[(2n-1)\psi]$$

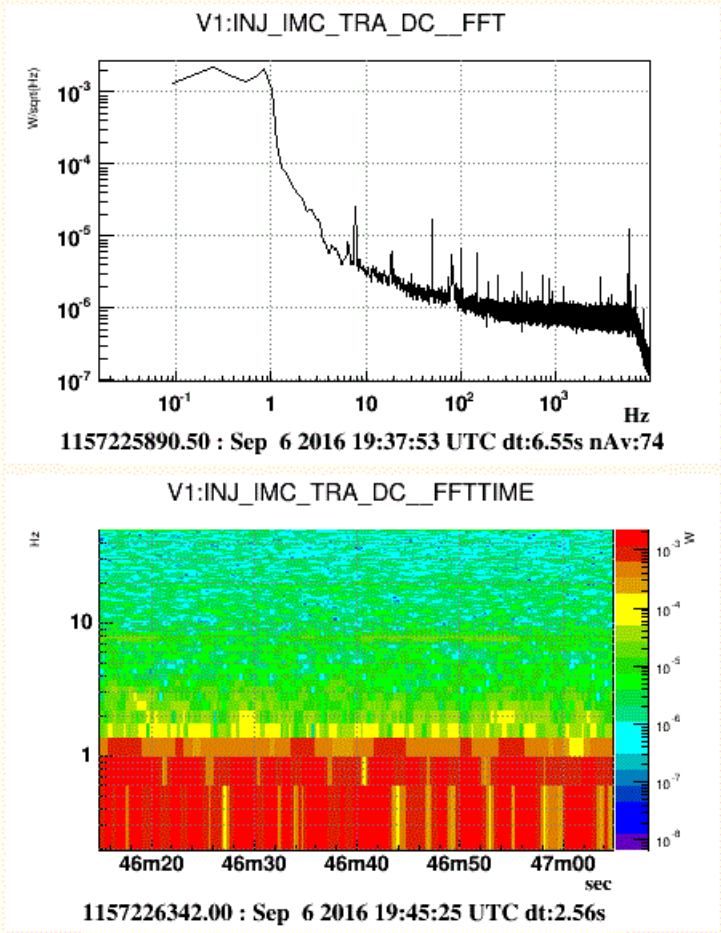
$$f_{max} = \frac{2A_x}{\lambda}2\pi f_{sc}$$

Expected noise during sea activity



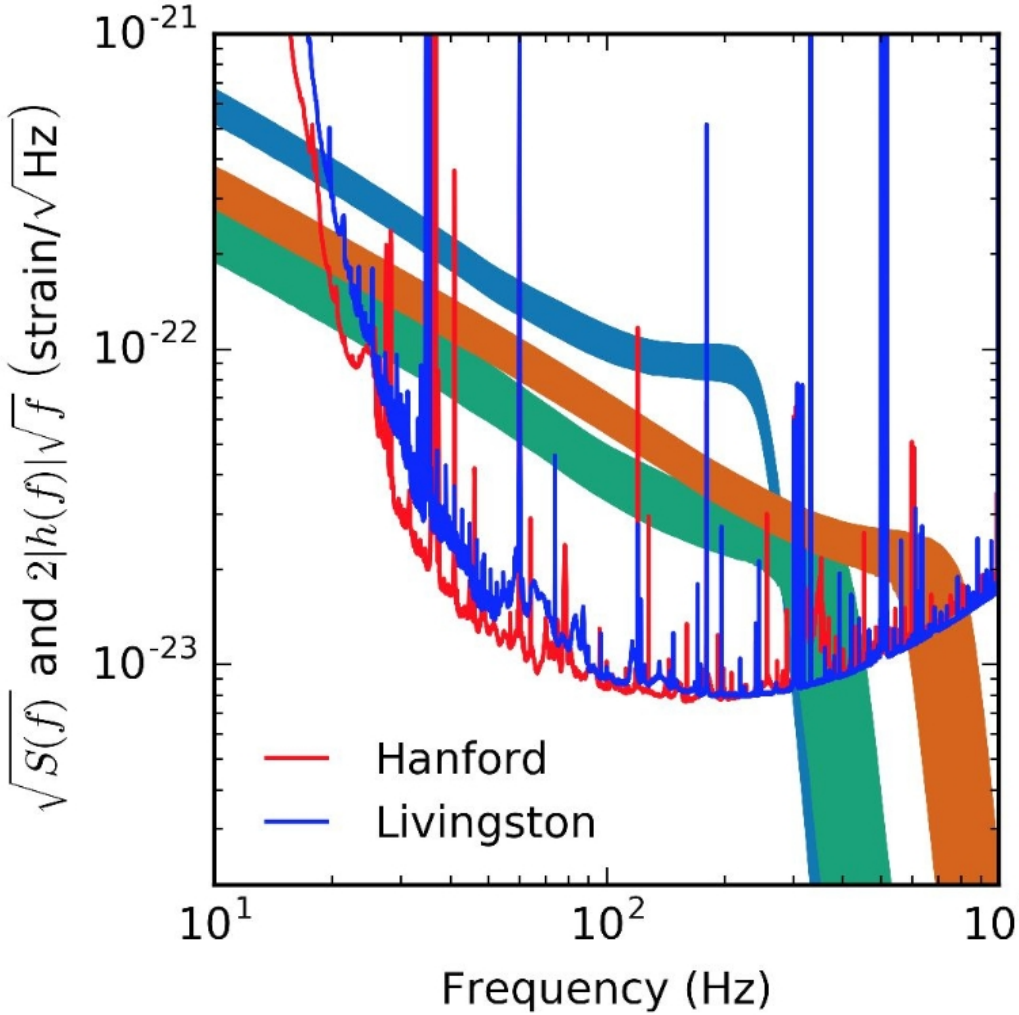
Recent case during AdV commisioning

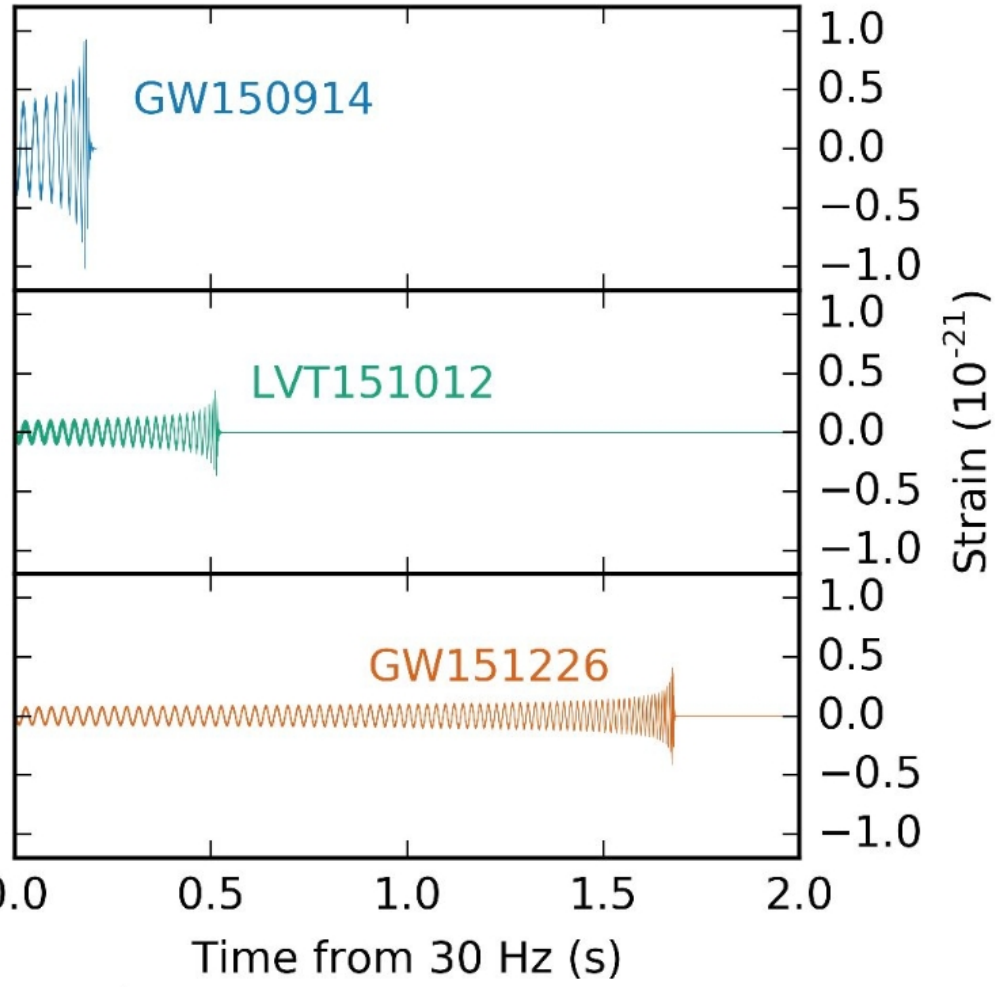




Spurious light inside IMC at 50Hz before and after intervention

Importance of Low frequency sensitivity

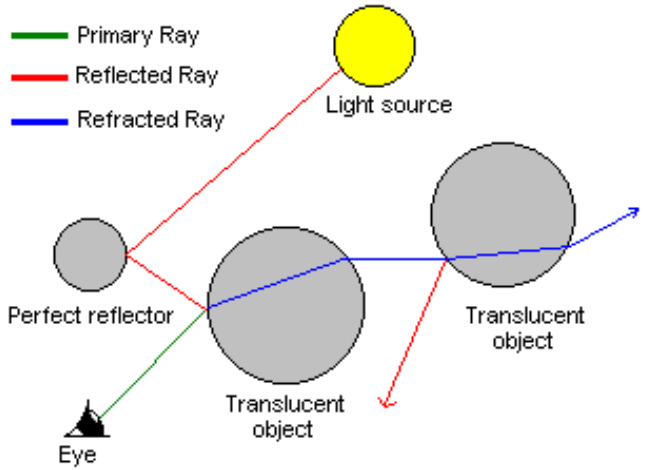




Ray tracing

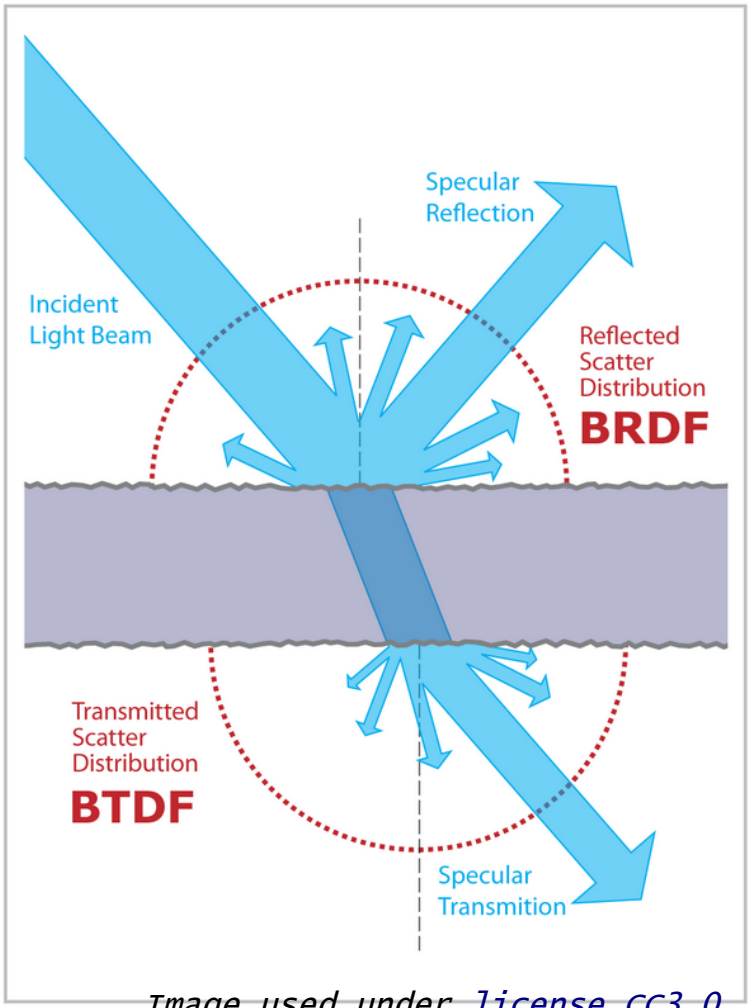
- Basic technique to simulate ray as a particle

```
1  initialization;
2  Set up Objects;
3  for i ∈ Range(1, MaxRays) do
4  |  Generate new Ray;
5  |  while exists Ray do
6  |  |  Find Interesection of Ray with Objects;
7  |  |  Select MinInteresection;
8  |  |  if MinInteresection = Null then
9  |  |  |  return 0
10 |  |  else if MinInteresection = Sensor then
11 |  |  |  Save the Ray on the Sensor;
12 |  |  |  return 0
13 |  |  else
14 |  |  |  Do Shading → Generate new Ray
15 |  |  end
16 |  end
17 end
```



Shading

Shading: Model of the interaction between light and matter, usually BRDF divided in:

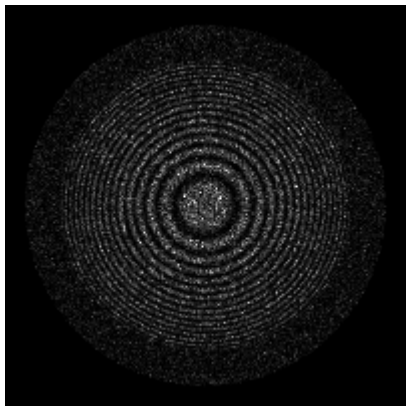


- Reflection
- Transmission
- Scattering
- Absorption

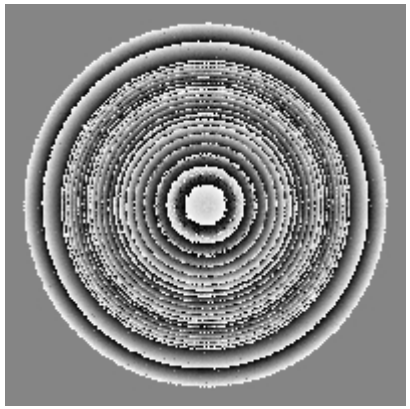
Interference

Wave property that can be simulated with ray tracing

- Transform Optical Path Length into Phase



Amplitude: $|E|^2$ [au]



$-\pi \leq \text{Phase} \leq \pi$

Interference pattern simulated with a Michelson configuration of a collimated beam with spherical mirrors of 2.2m and 9.2m

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Coupling between light and mechanics

As has been previously explained, the movement of a mechanical component may induce noise on a specific frequency

Phase noise

- Modulation of a photon hitting a moving surface:

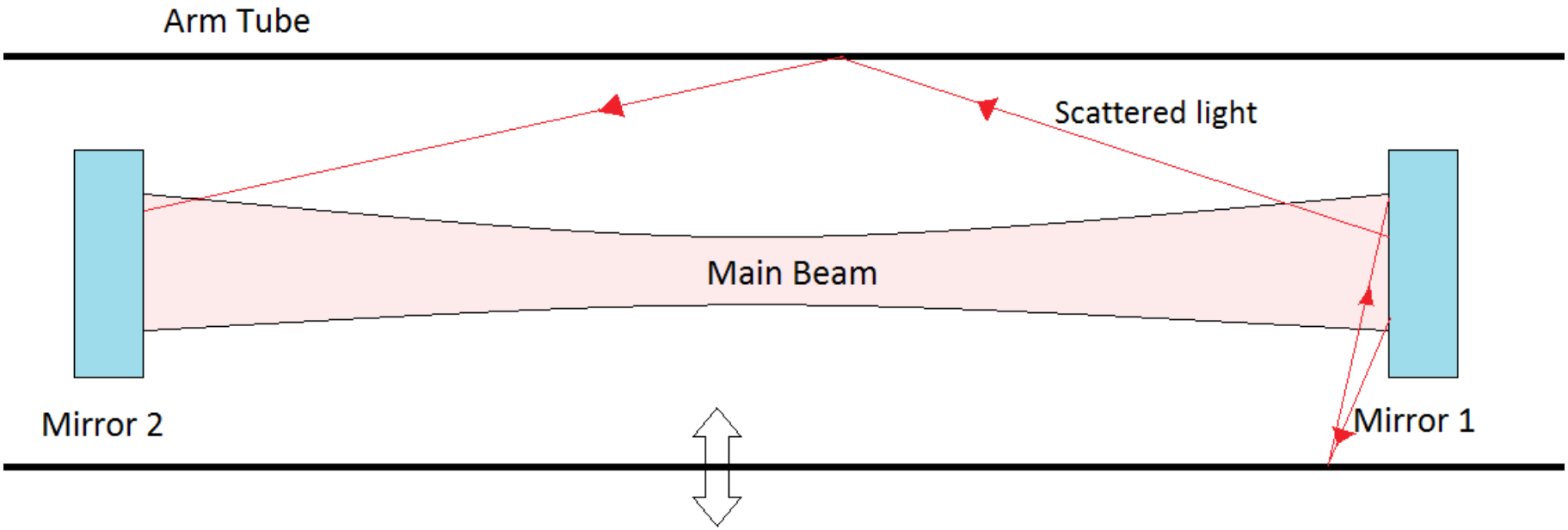
$$\Delta\phi(t) = \frac{2\pi}{\lambda}(\vec{s} - \vec{\omega}) \cdot \vec{X}(t)$$

- Phase change on main beam and GW strain:

$$\Delta\phi_{rec}(t) = Im[\gamma(t)]/\sqrt{P}$$

$$\Delta\phi_{rec}(t) = \frac{4\pi L}{\lambda}h(t)$$

Noise on Fabry-Perot cavities

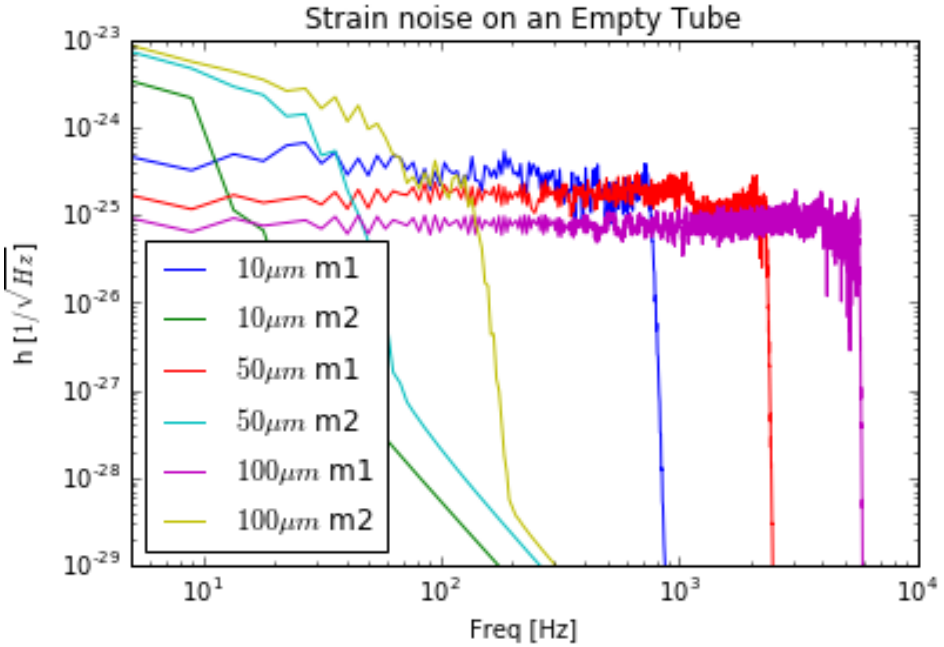


Total noise inside the Fabry-Perot Cavity

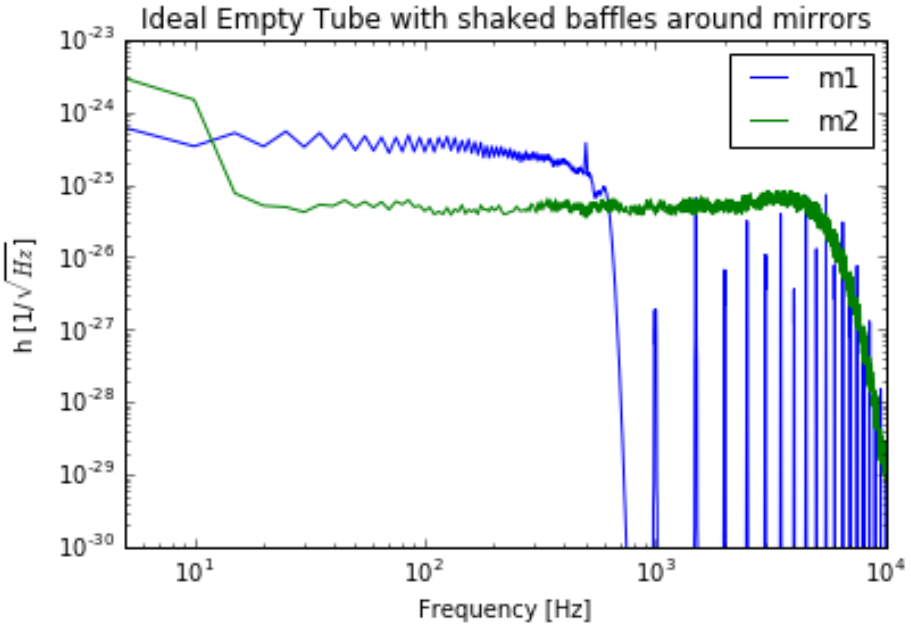
$$h_{tot}(f) = \frac{\lambda^2 \epsilon}{2^{2.5}\pi^2 L R_m} \sqrt{\frac{1}{n_s} \sum_{j=1}^{n} b(\theta_j) n_j(f)^2}$$

Noise on Fabry-Perot cavities

2 different cases:



Tube shaking at *10Hz*



Tube at *5Hz* with *A=8μm* → f_{max} =0.5Khz

Baffle at *500Hz* with *A=1μm* → f_{max} =6Khz

Previous results obtained by Vinet et.al.

	Noise $[1/Hz]$
Analytical method	$1.23X10^{-23}$
Statistical	10^{-23}

Note: the statistical method was using seismic noise already in frequency domain

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Conclusions and future work

- Conclusions
  - Ray tracing can be used to simulate some wave optics phenomena.
  - It is possible to estimate strain noise produced by stray light.
- Future work
  - Physics side:
    - Find new important cases to find out the contribution to the total noise.
    - Perform experiments to validate the results of the code.
  - SW side:
    - Optimize the code and include GPU computing.
    - Obtain input for realistic optomechanical components, probably from CAD files.

Thank you for your attention