# Lenses and Wedges for long arm cavities? Or: Terrain Following Interferometery

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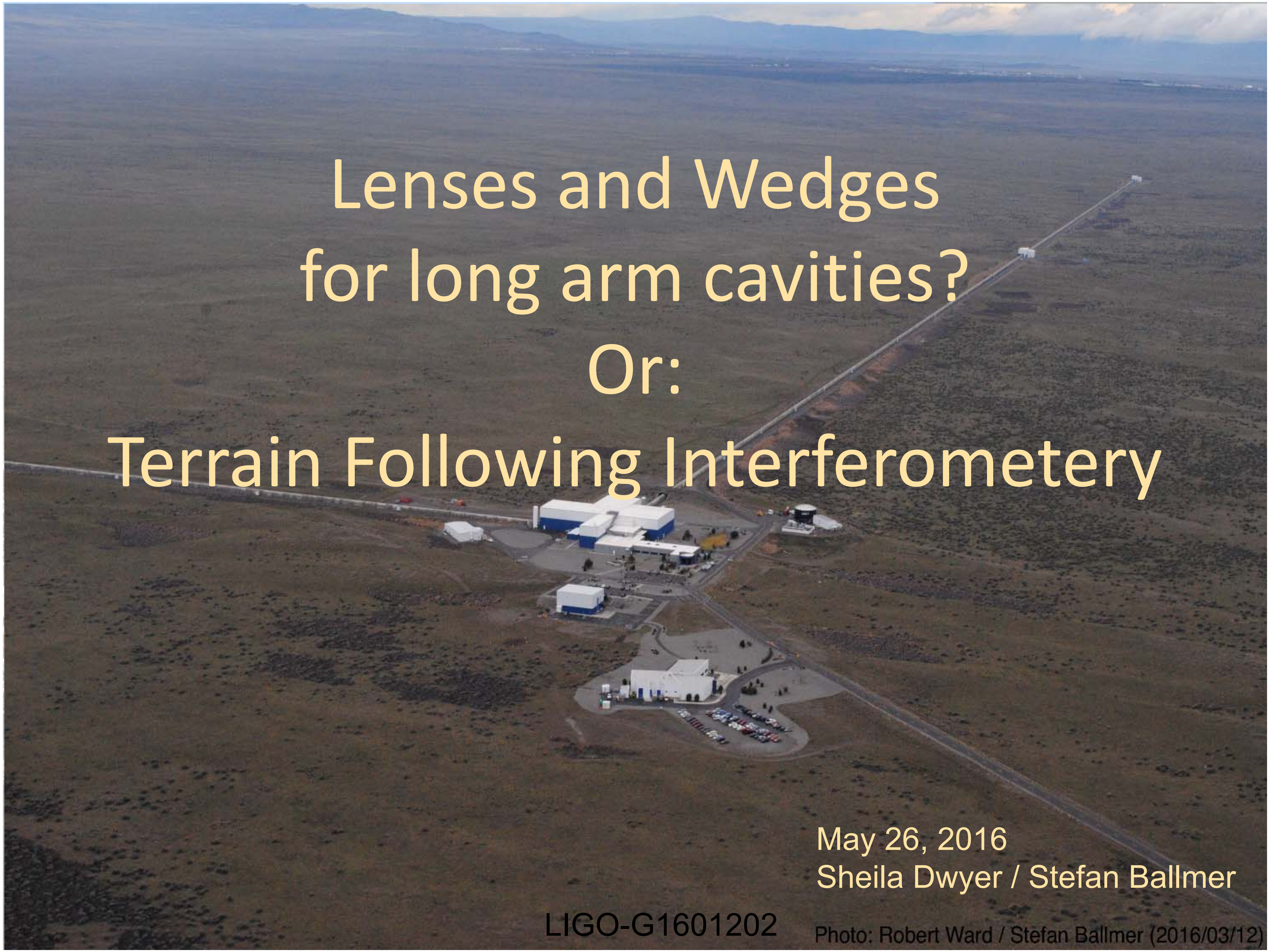
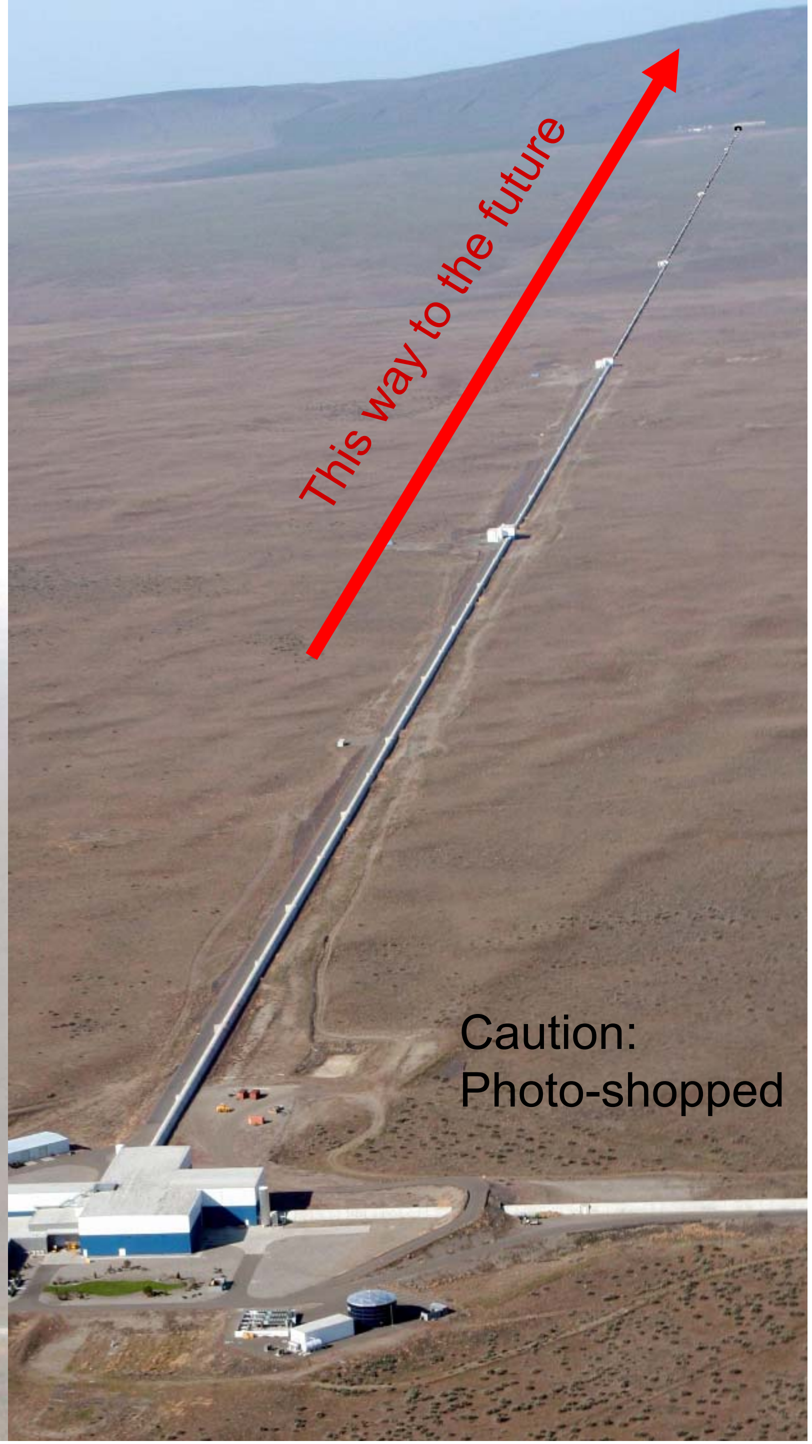


Photo: Robert Ward / Stefan Ballmer (2016/03/12)

LIGO

# The Idea

- Really long interferometers have two problems:
  - The required optics size becomes challengingly large
  - Straight beam tubes imply a lot of earth moving ($~L^3) (h=30m at 40km)



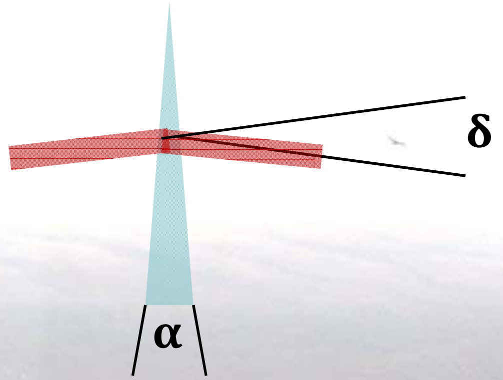
# LIGO The Idea

- Lenses / Wedges can
  - Keep the beam size reasonable
  - Steer the beam
- Can we get away with them in arm cavities? (esp. long ones?)

# Beam deflection and vertical coupling

- Beam deflection:

  $\boldsymbol{\delta}=(n-1)\,\boldsymbol{\alpha}$




- Vertical motion coupling:

  $dx=\boldsymbol{\delta}*dz$

  – Same as test mass!

  – Vertical motion can be distributed over N lenses + 2 mirrors (√(N+2) improvement)

# Noise Zoo

- Not much literature for thermal noise of "transmissive" optics:
  - GEO BS noise (Phys. Rev. D **80**, 062004, T0900209)
  - Radiative TO noise (Phys. Rev. D **90**, 0430130 (2014))
  - … ?

- A (incomplete?) list of relevant noises:

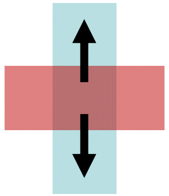
# Transmissive Brownian Noise

- Dominant noise source for thin lens
- Down by ~(n-1) in amplitude compared to mirror (includes double-pass)
- For thin disks:
  - Substrate scaling changes from 1/w to $a/w^2$ (Same scaling as coating loss)
  - Reduced coupling to floppy mech. modes

$$S_x(f) = \frac{2k_B T(1-\eta^2)(n-1)^2}{\sqrt{\pi^3} f \mathrm{w} Y}\left(\phi_{\mathrm{s}} + \frac{2}{\sqrt{\pi}}\frac{1-2\eta}{1-\eta}\frac{d_{\mathrm{c}}}{\mathrm{w}}\phi_{\mathrm{c}}\right)$$

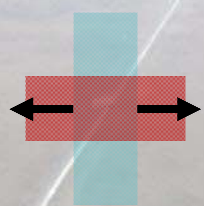
# LIGO Thermo-Optic Noise

- Dissipative (radial & standing wave)



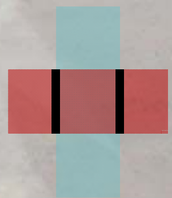
$$S_x(f) = \frac{16 k_B \kappa T^2 \beta_{eff}^2 a}{\pi C^2 \rho^2 \mathrm{w}^4 \omega^2}\left(1 + \frac{k^2 \mathrm{w}^2}{1 + \frac{16 k^4 \kappa^2}{C^2 \rho^2 \omega^2}}\right)$$

- Radiative (surface)



$$S_x(f) = \frac{16 k_B \epsilon \sigma T^5 \beta_{eff}^2}{\pi C^2 \rho^2 \mathrm{w}^2 \omega^2} N$$

- Coating (surface structure)



$$S_x(f) = \frac{2\sqrt{2} k_B T^2 (\beta_{eff}^c d)^2}{\pi \mathrm{w}^2 \sqrt{\kappa C \rho \omega}} N$$

# Another message

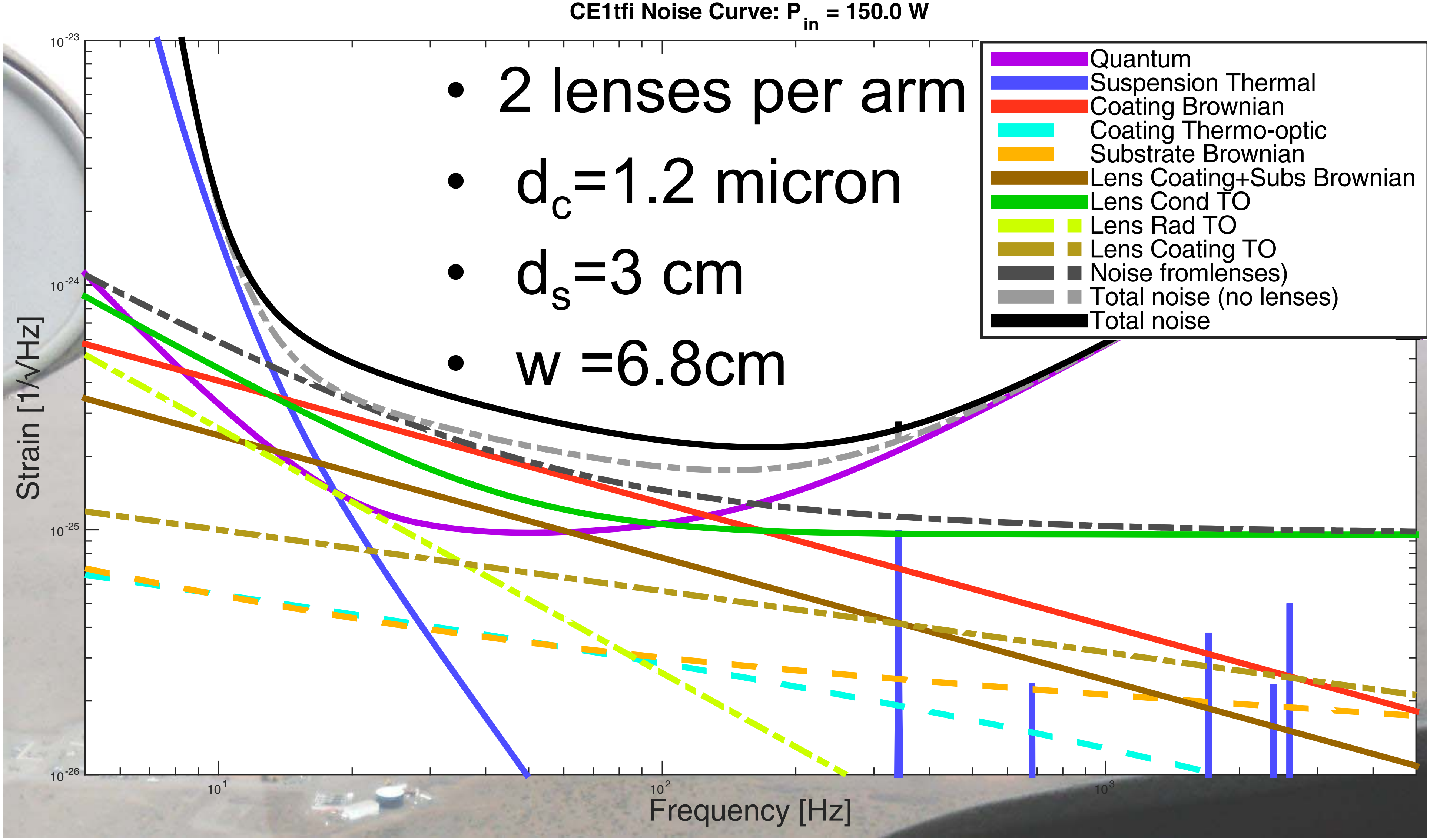
- For very large beam spots:
  - Substrate Brownian comparable to Coating Brownian

$$Sx \propto d_c\phi_c + (1.1w)\phi_s \quad d_s > w$$

$$Sx \propto d_c\phi_c + d_s\phi_s \quad d_s < w$$

$$\frac{\phi_c}{\phi_s} \approx 10^5 \;\;,\;\; d_c\frac{\phi_c}{\phi_s} \approx O(10\ cm)$$

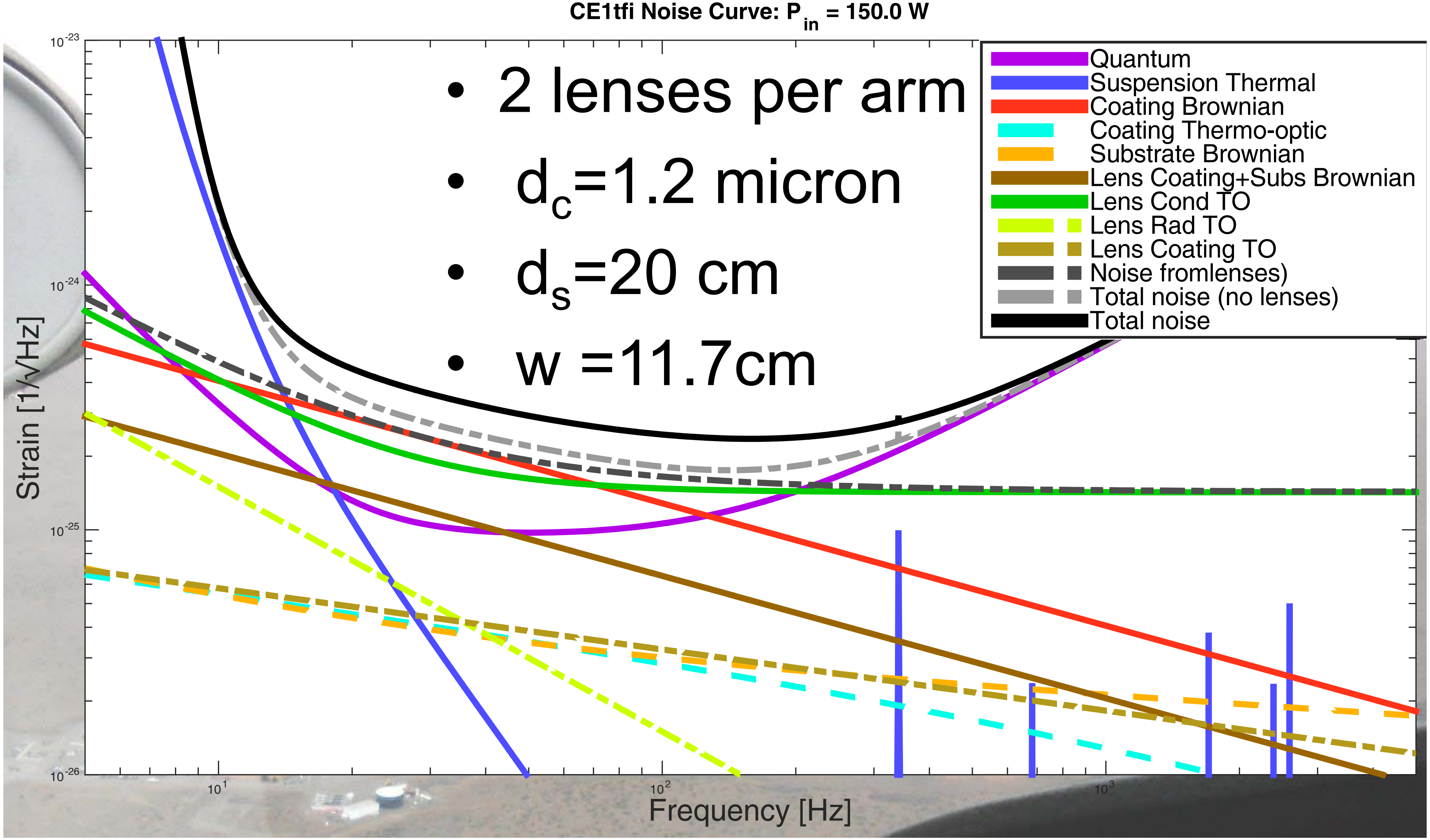
# “CE1” (T=300K) with lenses, an example



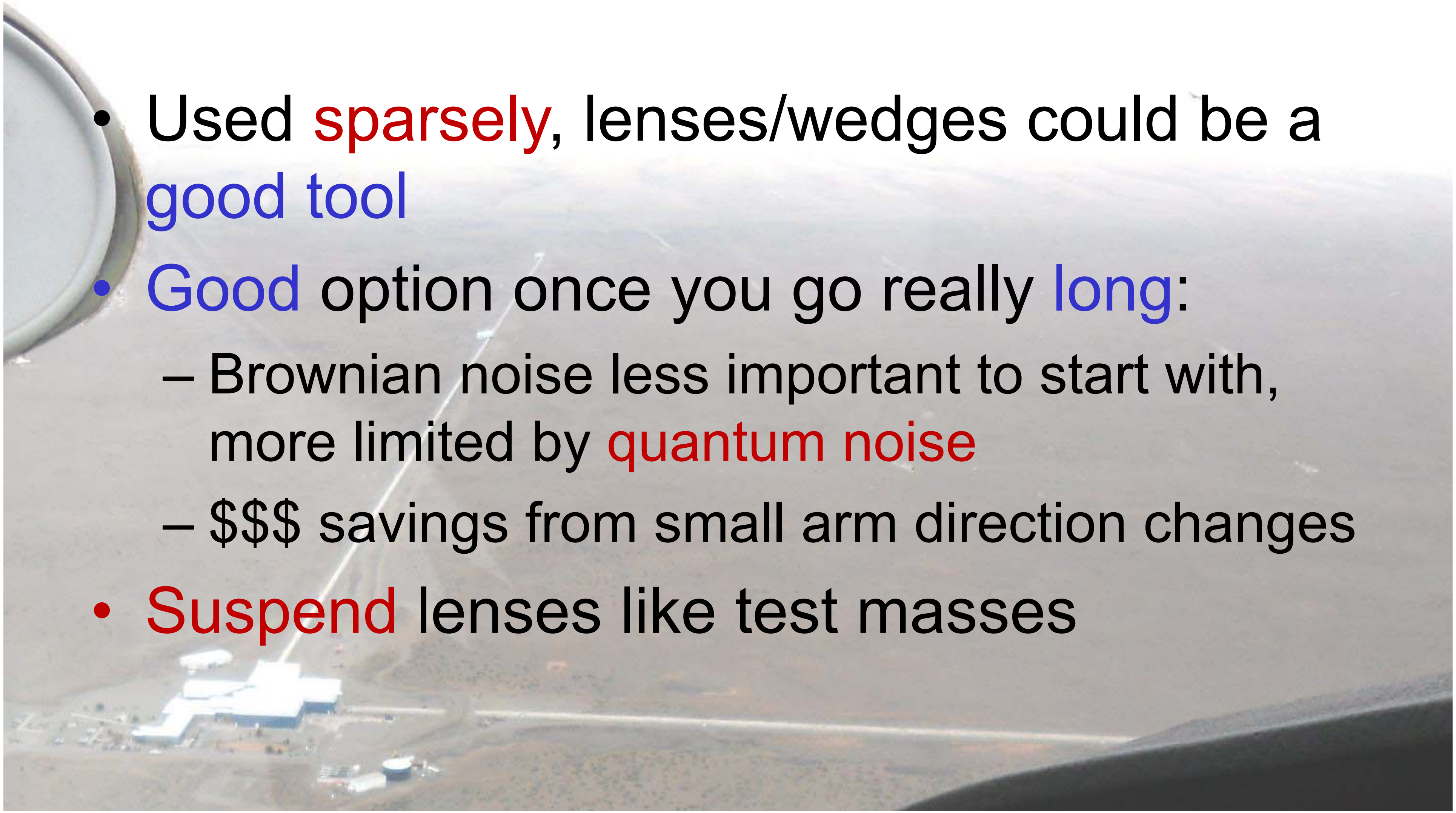

- 2 lenses per arm
- $d_c$=1.2 micron
- $d_s$=3 cm
- w =6.8cm

# “CE1” (T=300K) with lenses, an example

- 2 lenses per arm
- $d_c$=1.2 micron
- $d_s$=20 cm
- w =11.7cm



# Assessment



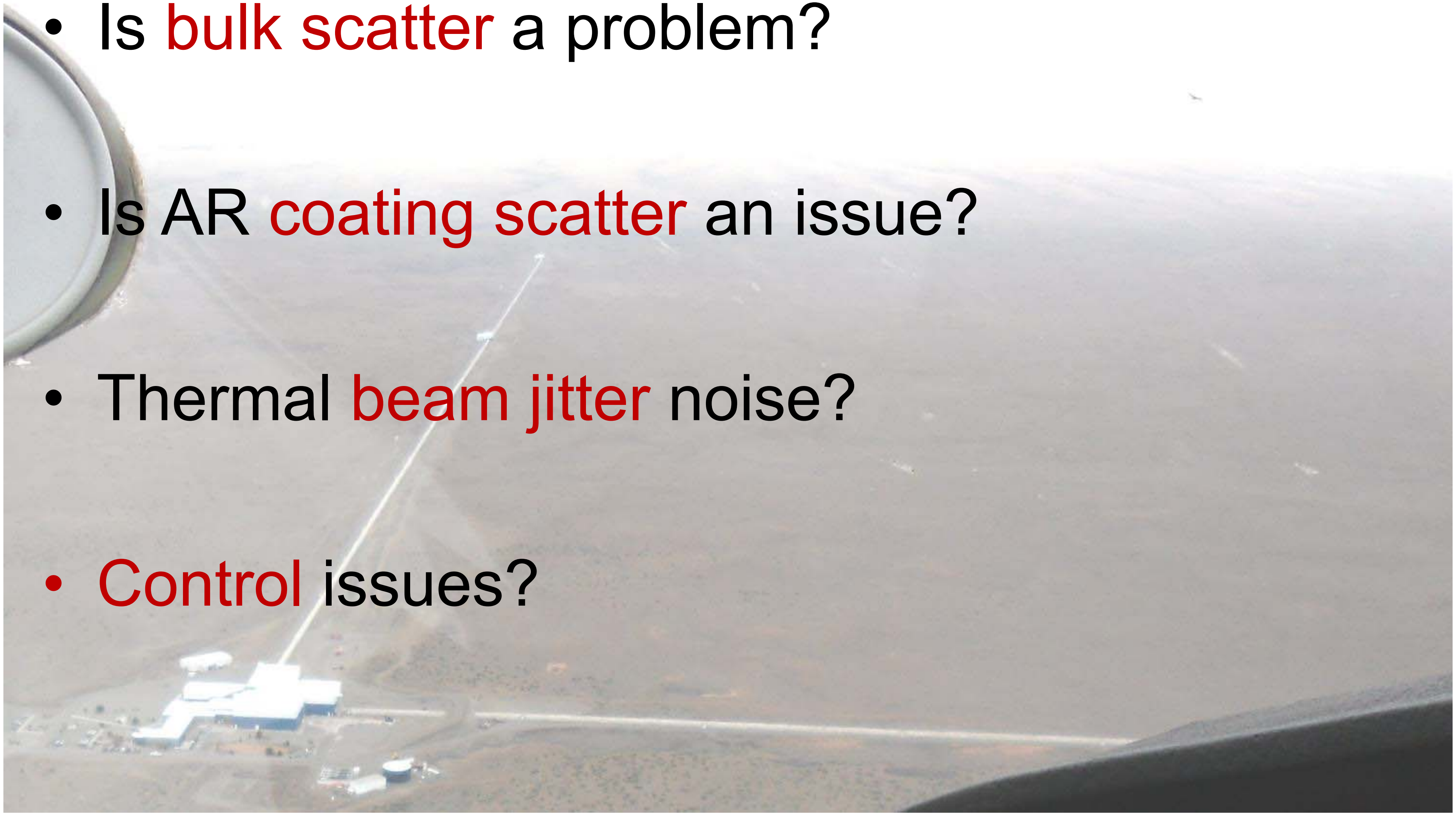
- Used sparsely, lenses/wedges could be a good tool
- Good option once you go really long:
  - Brownian noise less important to start with, more limited by quantum noise
  - $$$ savings from small arm direction changes
- Suspend lenses like test masses

# Possible Issues

- How good can AR coatings be?
  - Optical losses in arms acceptable for squeezing?
  - Low reflection requires thicker coatings
- What is the residual coupling to floppy mechanical modes to GW strain?
- Is thermal lensing an issue?

# Possible Issues

- Is bulk scatter a problem?
- Is AR coating scatter an issue?
- Thermal beam jitter noise?
- Control issues?



# Conclusion:
# Is this a good idea?

- Significant cost benefits once you go long
- Noise sources exist, but seem manageable
- A number of things still to be checked
  - What am I missing?