Optical Techniques for Reducing Thermal Noise

GWADW
La Biodola,
Isola d'Elba, Italy

LIGO-Gxxxxxxx

May 2013
Stefan Ballmer

~~Coast~~- Out-line

Types of thermal noise

Correlation length

Strategies for mitigation

Examples

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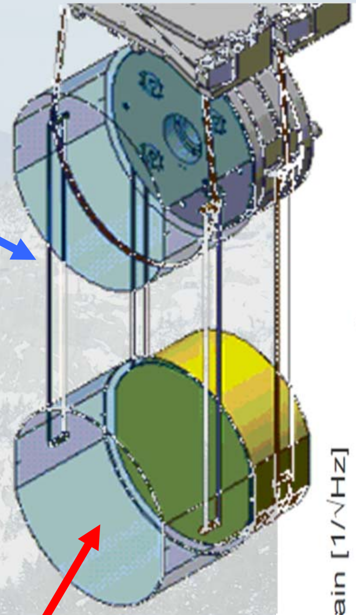
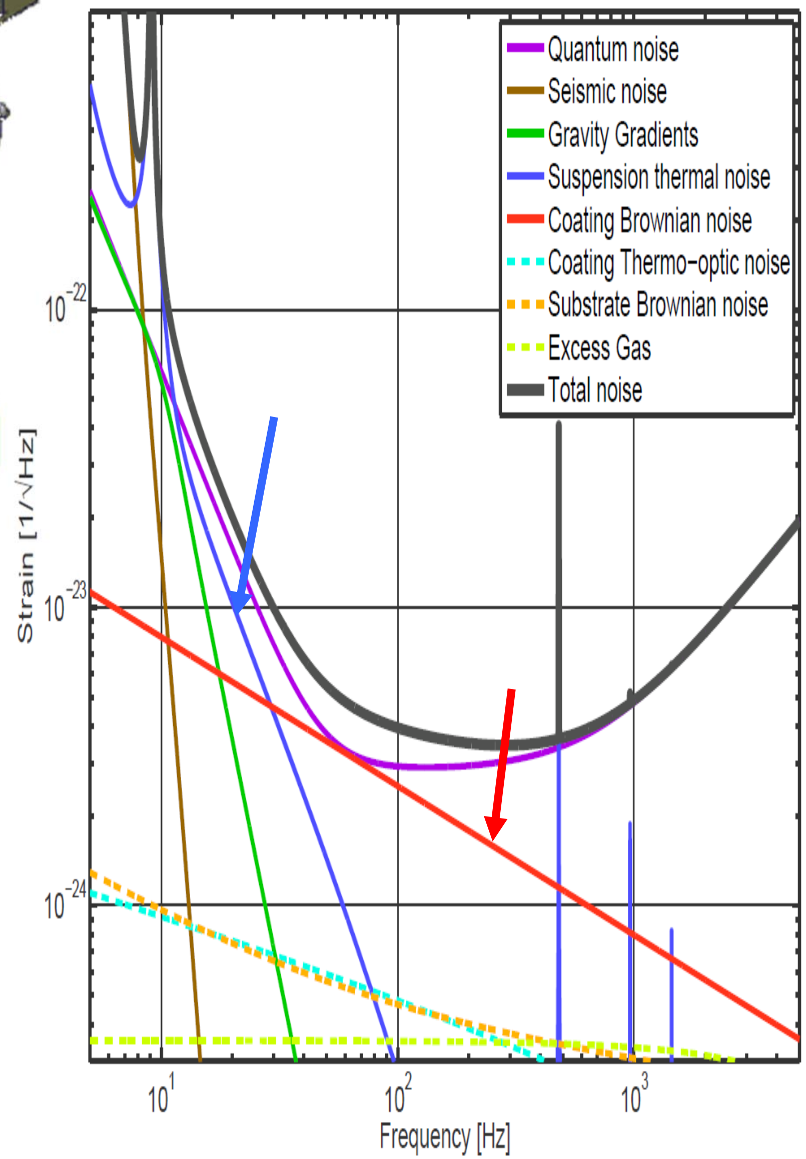
The types of Thermal Noise

- Suspension
- Optic
  - Coating (dominant)
  - Substrate





The types of Thermal Noise

$$dF(T,\vec{\varepsilon}) = -SdT + \vec{\sigma}d\vec{\varepsilon}$$

E.g. coatings

- Coating Brownian
  - Mechanical coating loss
  - Scales with beam area
  - Limiting 2nd gen. detectors
- Thermo-optic Noise
  - Scales w/ beam area
  - Key for crystalline coatings

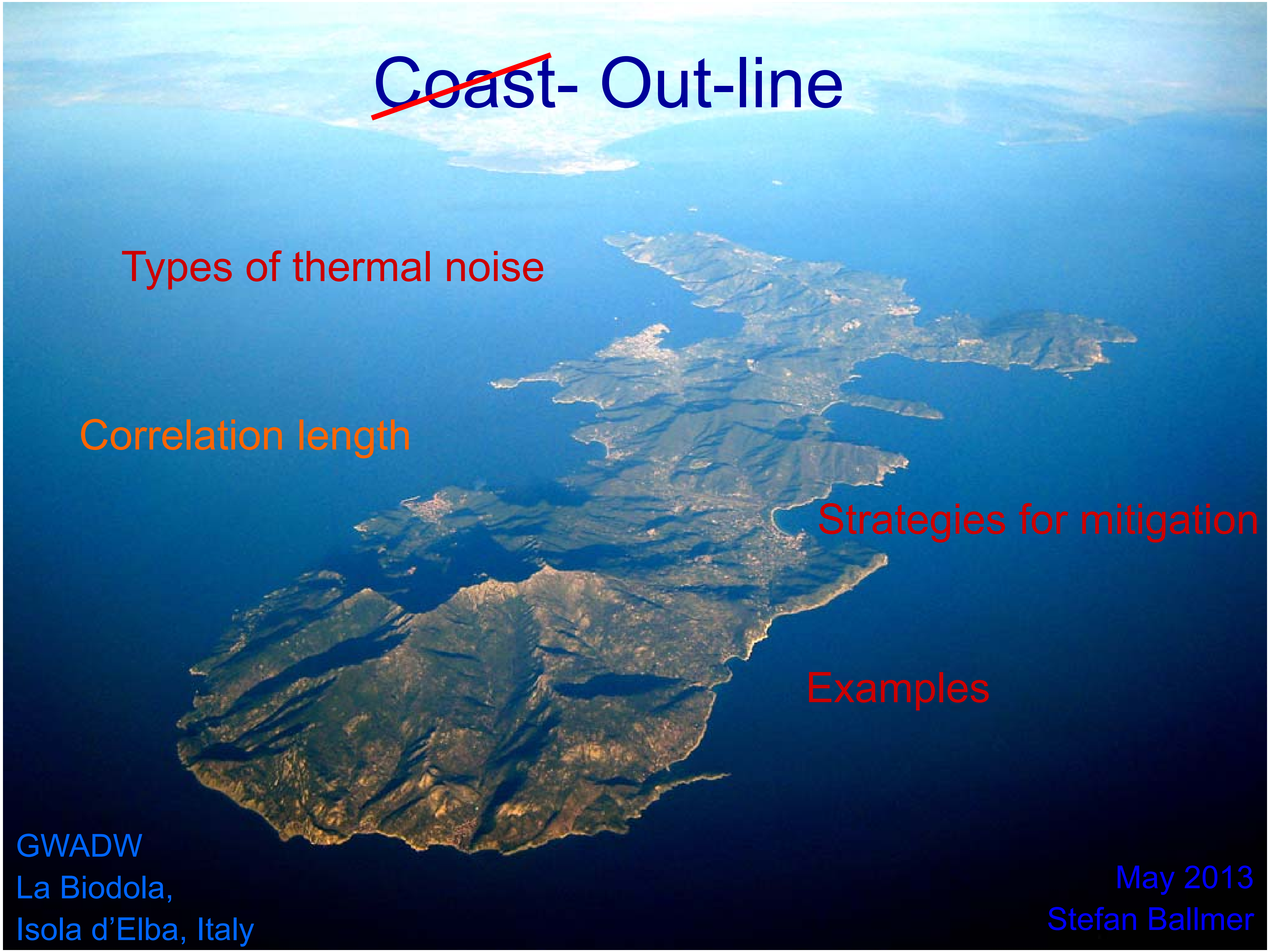
$$S_{xx} \approx \frac{4k_B T}{\pi f} \frac{\delta_c}{\pi w^2 Y} \phi$$

Coating Brownian

$$S_{xx} \approx \frac{(\alpha_{\text{eff}} d - \beta_{\text{eff}} \lambda)^2 k_B T^2}{\pi w^2 \sqrt{\kappa \rho C f}}$$

Thermo-optic

Note : $O(1)$ constants dropped (e.g. Poisson raito)



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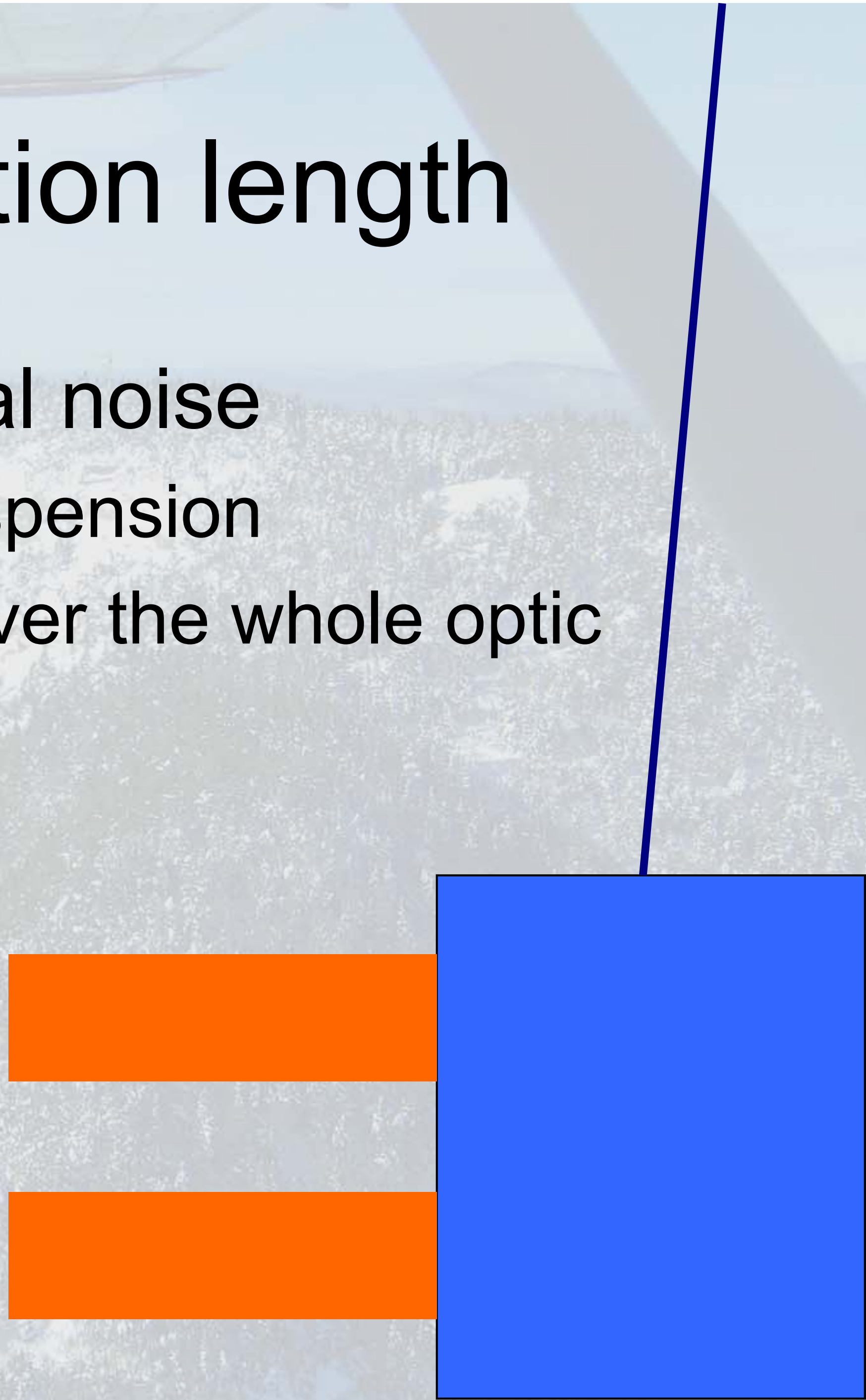
Correlation length

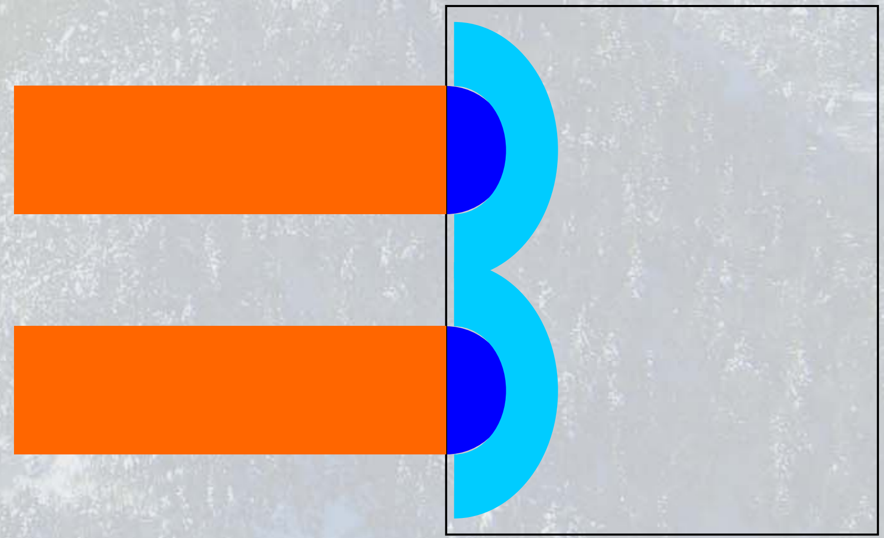
- Suspension thermal noise
  - Optic driven by suspension
  - Coherent motion over the whole optic



Correlation length

- Substrate Brownian noise
  - Set by elastic Greens function
    - '1/x' convolved with beam profile
  - Correlation length ~ beam radius w
    - Transverse correlation drop-off ~1/x

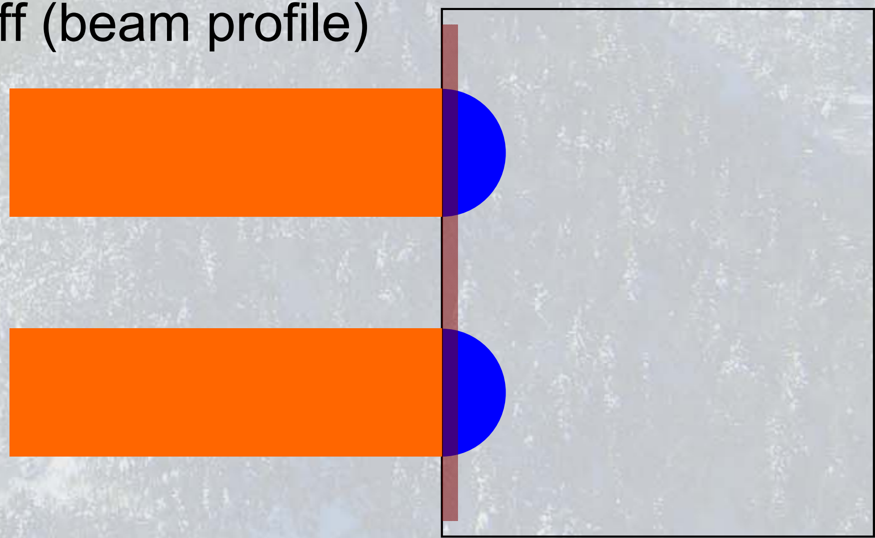
Nakagawa et. al.
PRD, vol 65, 082002



Correlation length

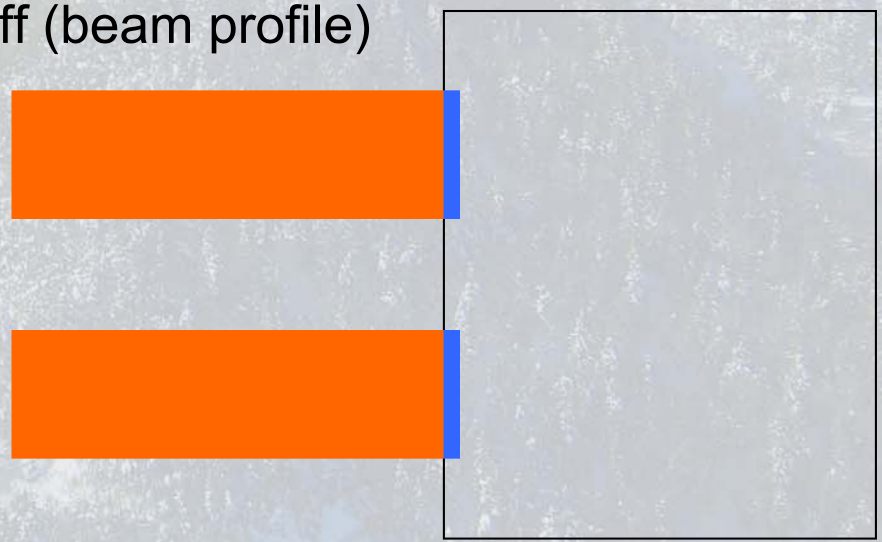
gr-qc/0610041v3 (2007)

- Coating Brownian noise
  - Set by elastic Greens function
    - But driven on surface only – short range!
  - Correlation length, on surface
    - Transverse correlation ~coating d (<<w)
      - Exponential drop-off (beam profile)



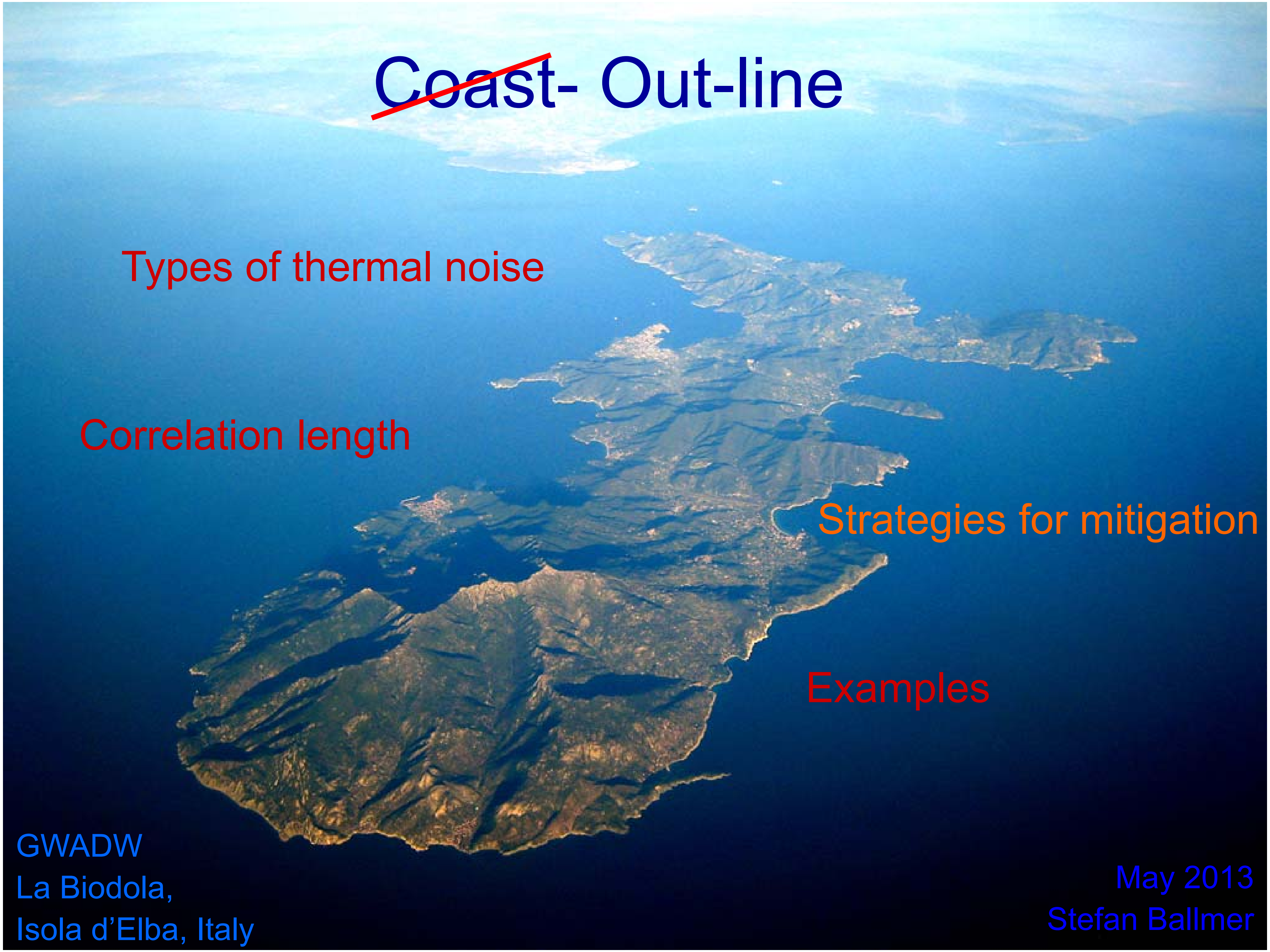
Correlation length

- Thermo-optic noise
  - Set by (freq. dependent) diffusion length
  - Correlation length ~ diffusion length
    - O(30u) around 100Hz
    - Transverse correlation ~diff. length (<<w)
      - Exponential drop-off (beam profile)



Caution: Not true for cryogenic
reference cavities

small spot &
large diffusion length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Strategies for Optical Thermal Noise Mitigation

- Divide et impera: avoid correlation
  - Add noise incoherently
- The enemy of your enemy is your friend
  Cancellation:
  - Coupling to fluctuations through 2 mechanisms with opposite sign

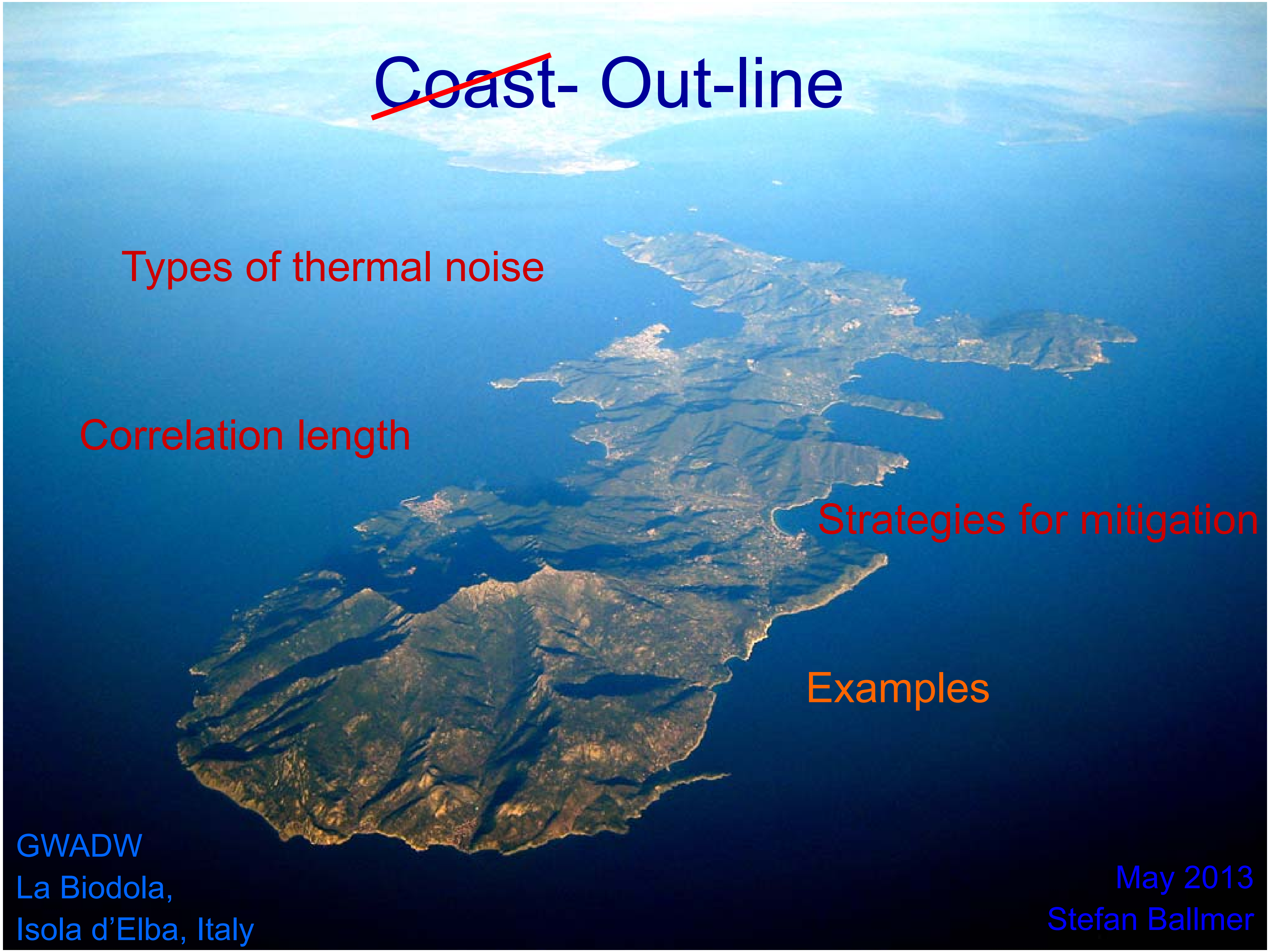
Strategies for Optical Thermal Noise Mitigation

- Divide et impera
  - Transverse:
    - Large spots
    - Special beams: LG, flat-top, etc.
    - Multiple beams
  - Longitudinal: de-correlate dielectric layers
    - Khalili cavities

Strategies for Optical Thermal Noise Mitigation

- Cancellation:
  - – Through different coupling mechanisms e.g. for thermo-optic noise: α and dn/dT
  - – Measuring and subtraction
    - Measure thermal noise independently (i.e. with no/different GW sensitivity)
    - Displacement-free interferometry

~~Coast~~- Out-line



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Divide
et
imperia!

Big Gaussian

- Long arms!
  - ALL (amplitude) displacement noises: ~ L^{-1}
  - Thermal noise: ~ $L^{-1.5}$ (beam spot grows with L)
- For fixed arms
  - Rapidly approaching degeneracy for significant beam size increases

Laguerre-Gaussian beams

- Effective beam area larger - Noise averages
  - For LG33: x1.61 (in power noise)

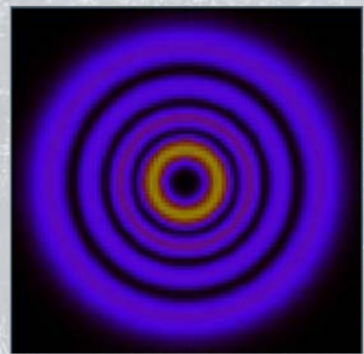
$$S_x \propto \frac{\int I^2(\vec{r})d^2\vec{r}}{[\int I(\vec{r})d^2\vec{r}]^2}$$

- But modes are degenerate
  - Contrast defect unacceptable

PRD 84, 102001 (2011)

  - Ideas for thermal correction

PRD 87, 082003 (2013)



LG33 beam

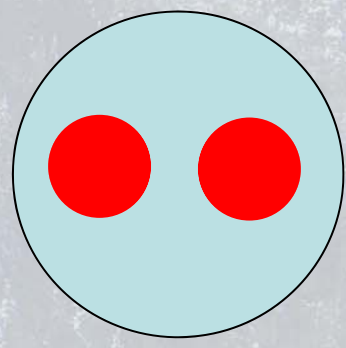
Other beam shapes

- Laguerre-Gauss: uses spherical mirrors
- Idea: Choose other mirror profiles
  - e.g. Flat-top beams, conical beams
  - Avoids degeneracy problem
  - Issues
    - Beam profile not conserved under propagation
    - Alignment (beam shape changes)

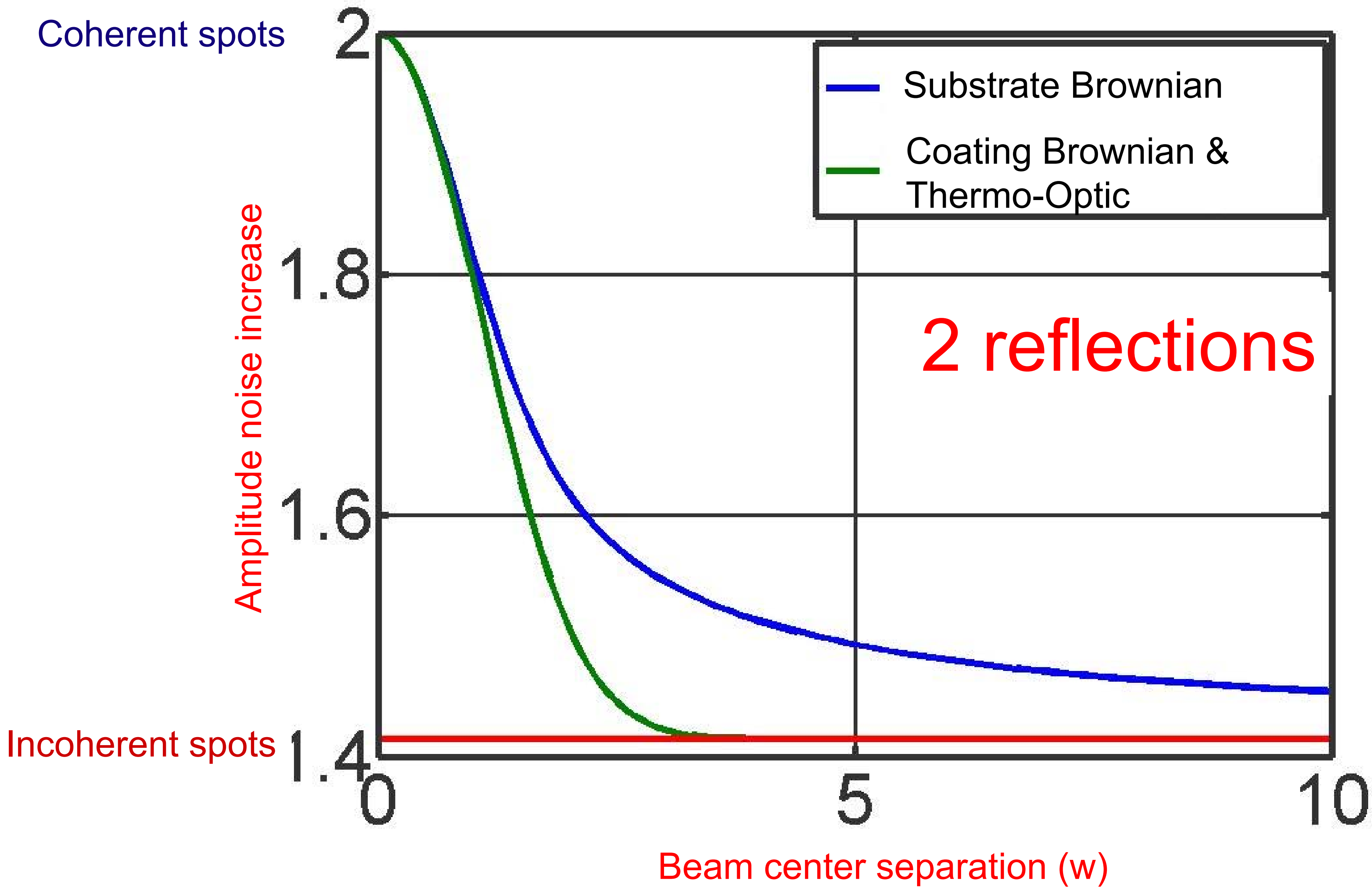
Multiple beams

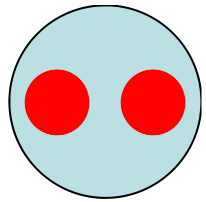
- TEM00 is good – use more of them!

- Multiple spots per mirror
  - exploit spatial de-correlation



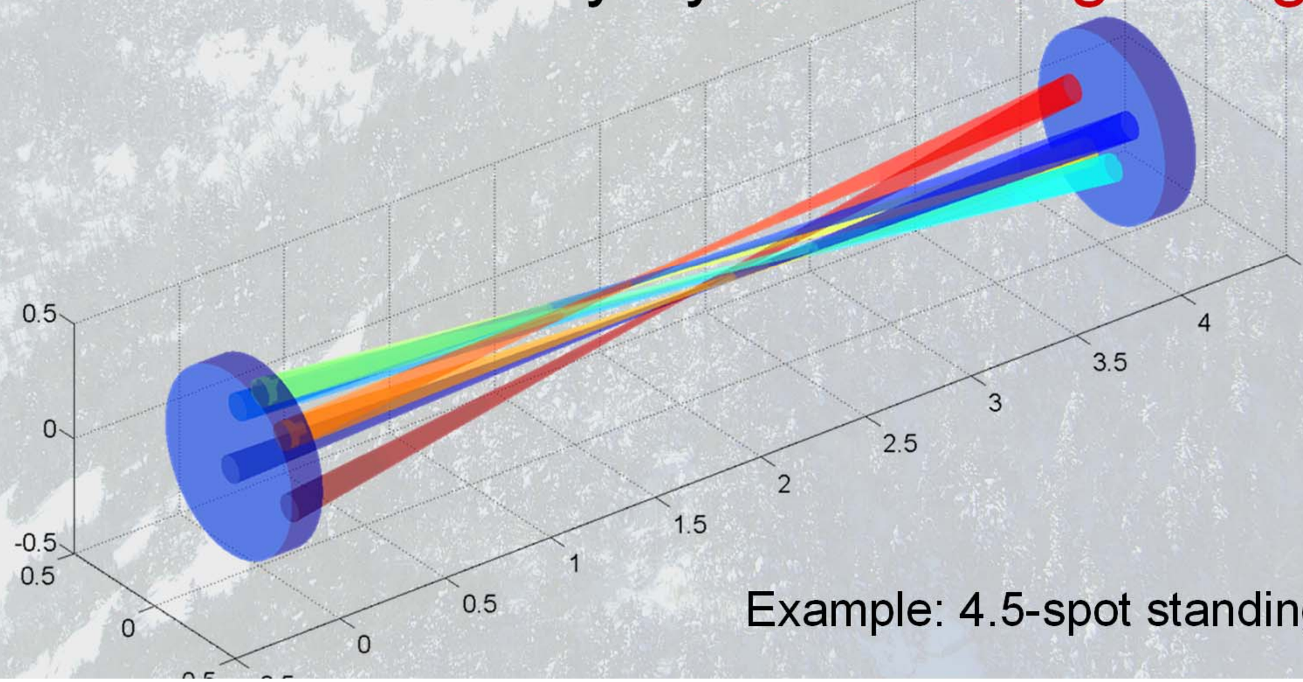
Spatial correlation (for TEM00)





Realizing multiple beams

- Delay line with spherical mirrors (Herriot, APPLIED OPTICS, **Vol.** 4, No. 8 (1965))
  - g-factor determines beam orbit
  - Size and ellipticity of orbit unrestricted
  - closed as FB cavity by terminating wedges

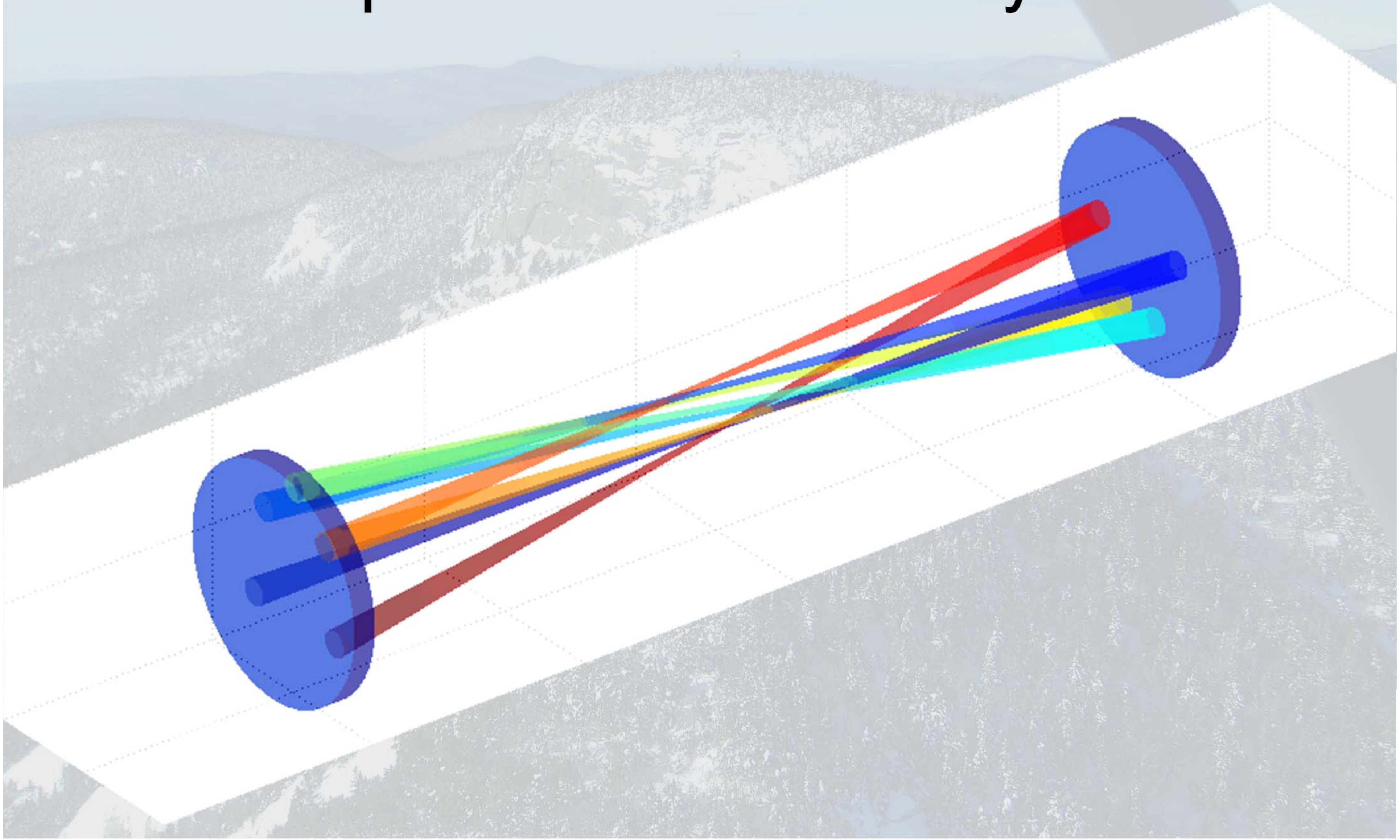


Example: 4.5-spot standing-wave cavity

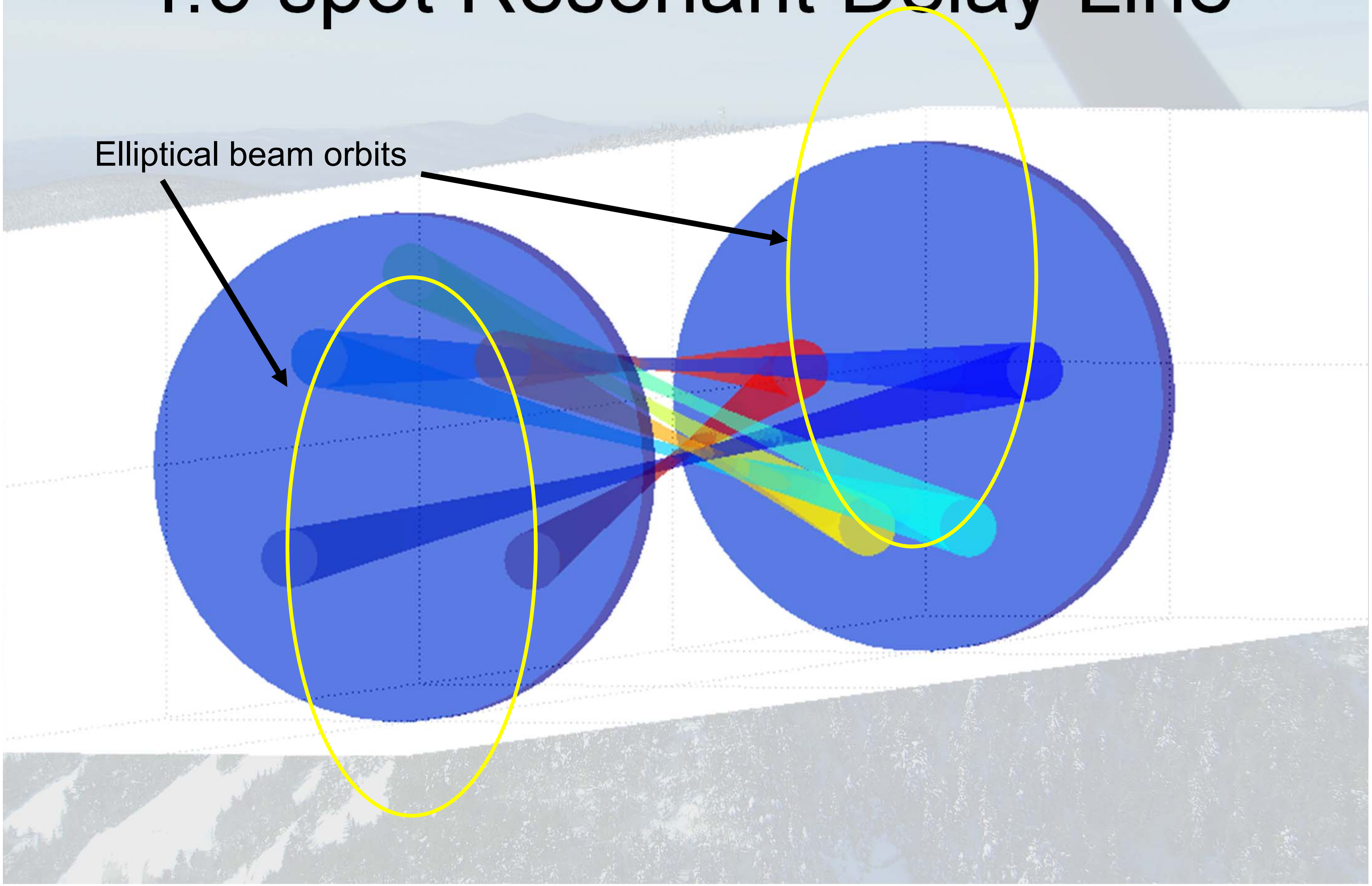
Optimizing spot locations and size

- Both individual spot size and # of spots per orbit directly dependent on g-factor
  - E.g. aLIGO g=0.83, #spots = 7.40
- # reflections limited to ~<10
  - (no sensitivity at FSR=c/(2*N*L))
- Possible solution:
  - Optimize g-factor for big beam sport
  - Inject beams in an elliptical orbit
  - Use less than one full orbit

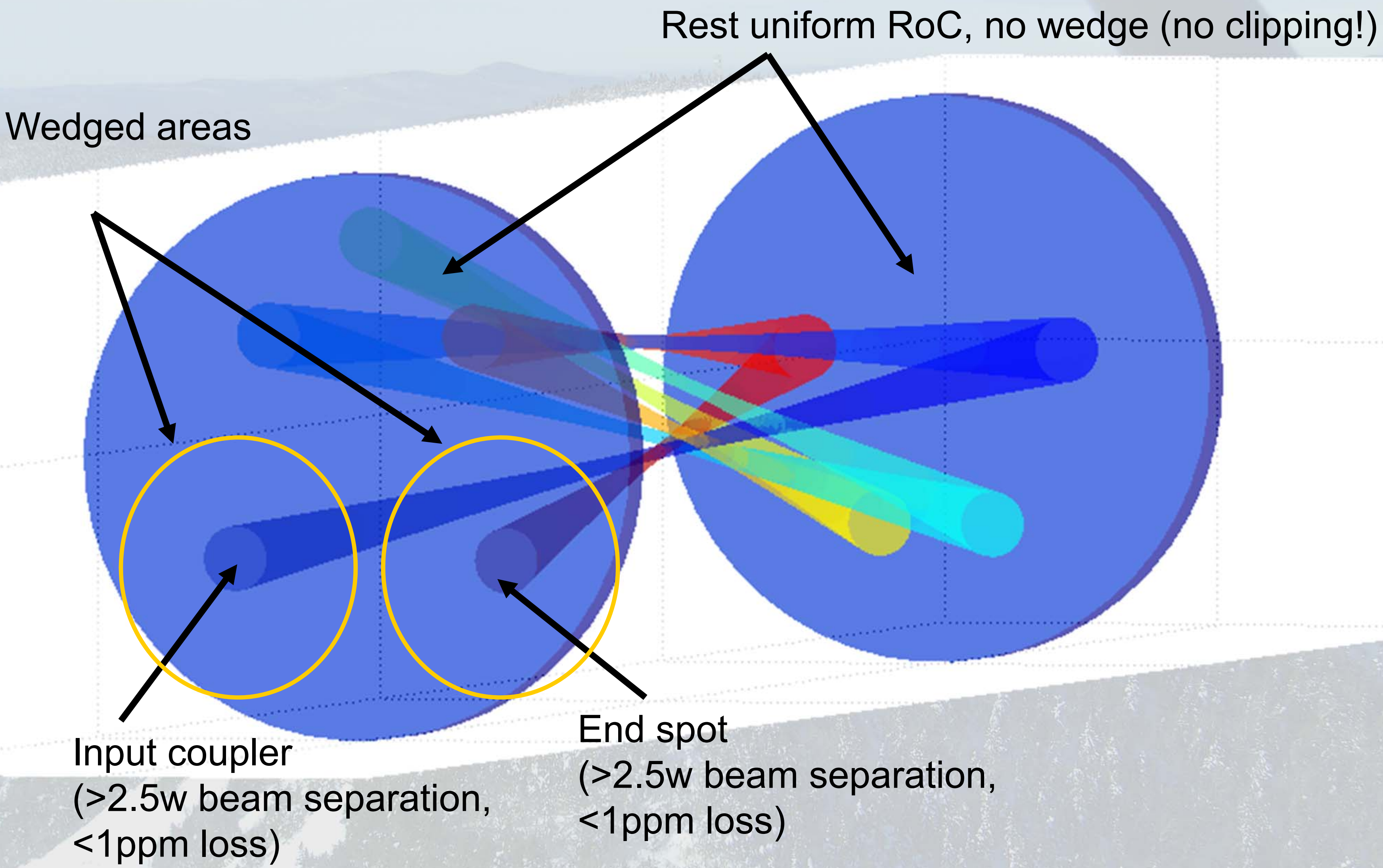
Example:
4.5 spot Resonant Delay Line



4.5 spot Resonant Delay Line



4.5 spot Resonant Delay Line

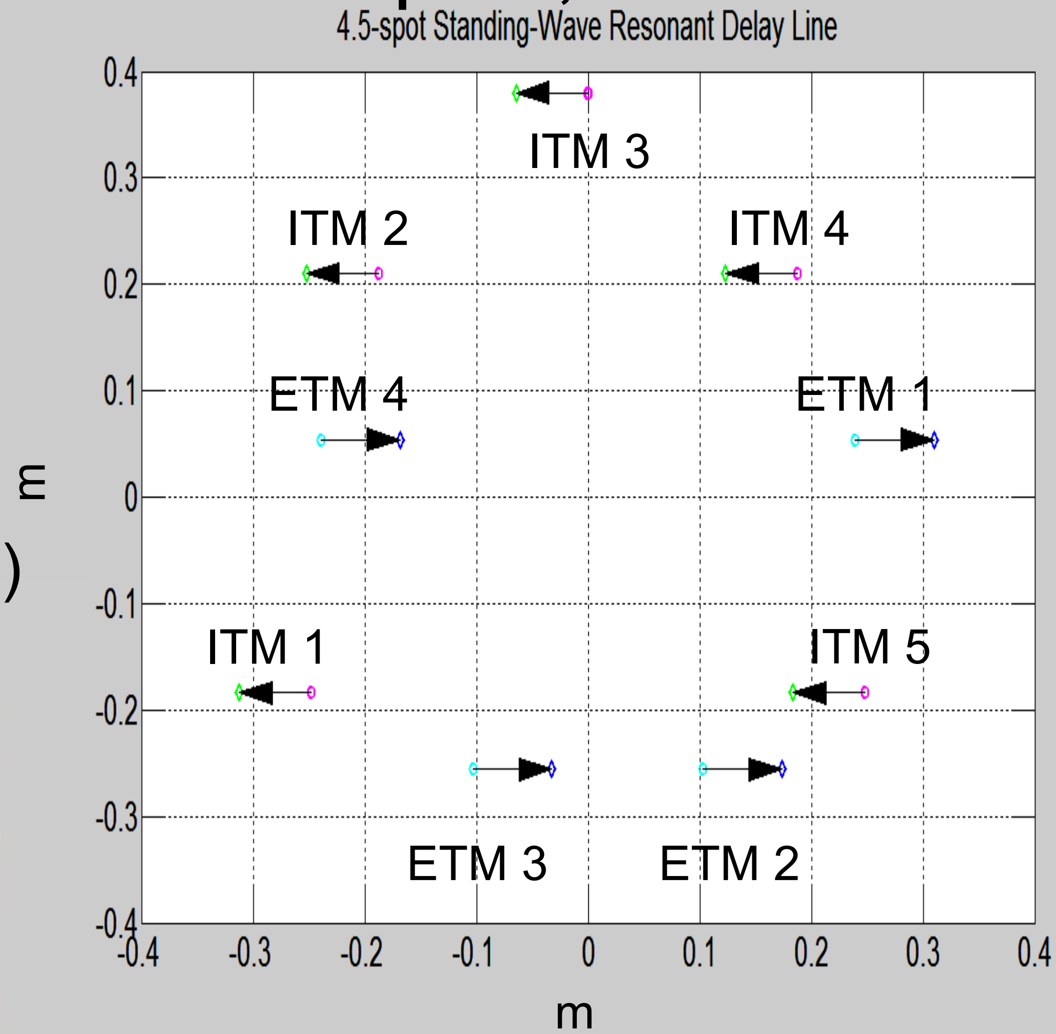


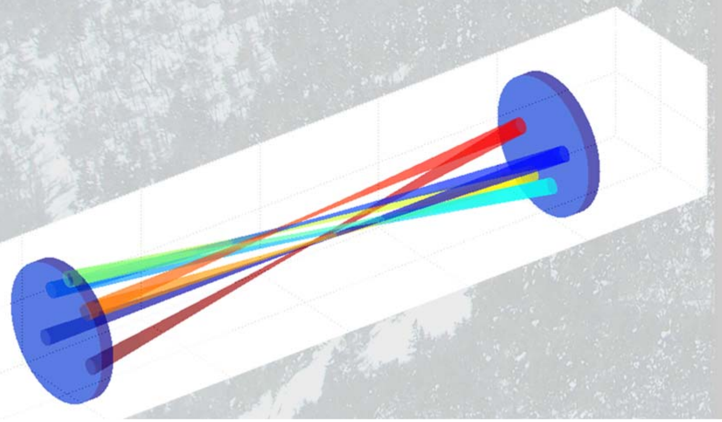
Easier than traditional delay lines!

- N much smaller than traditional delay lines
- Two mirrors define optical mode
  - No “threading of the beam”
  - Mode-matching identical to regular FB cavity
  - As easy to align as a regular FB cavity
- Scatter
  - Exists, but cavity is locked, no fringe wrapping
- Alignment sensitivity
  - identical to simple 2-mirror FB cavity

Alignment signals / Spot motion

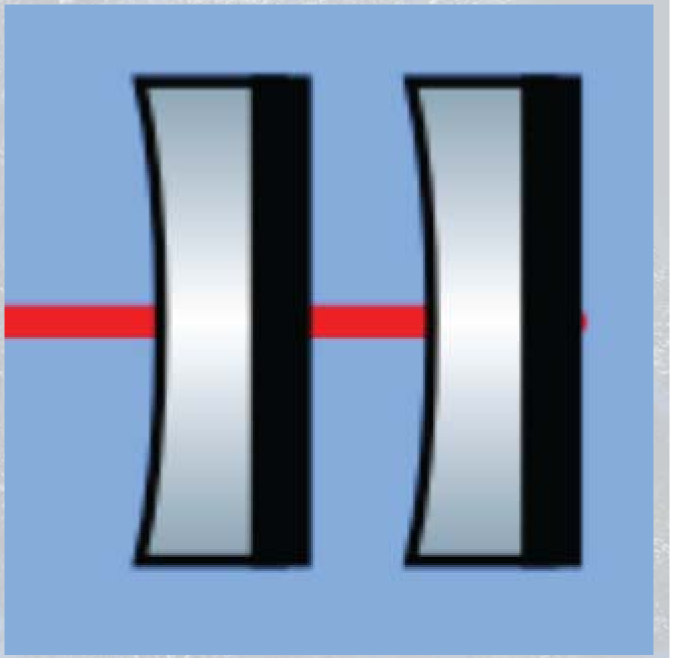
- RDL with 4 ETM and 5 ITM spots, all same size as aLIGO
  - w=57.3mm
  - For 3urad ITM misalignment
    - Spot move 6.4cm
    - (identical to aLIGO)

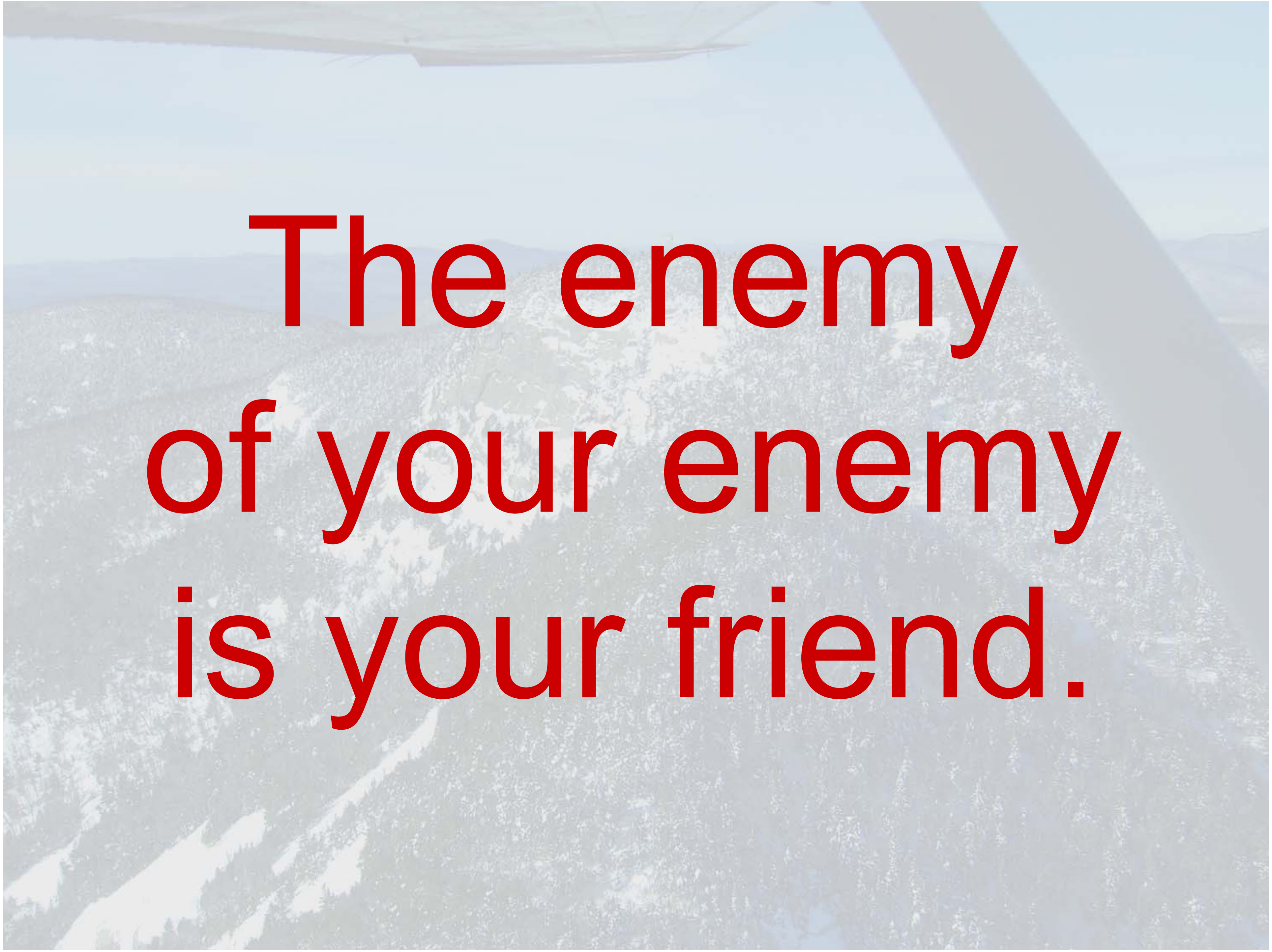




Khalili cavity

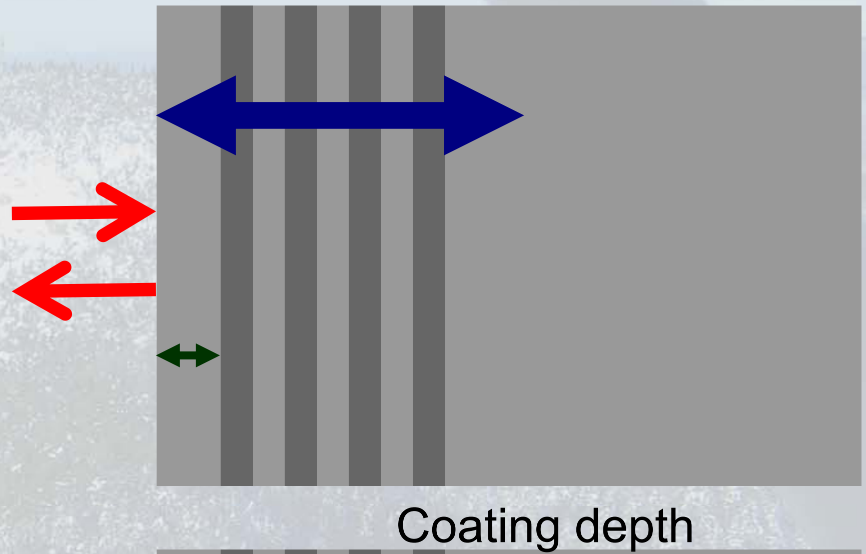
- Split single mirror (dielectric stack) into anti-resonant cavity (Phys Let A V334, 1, 2005, 67-72)
  - TN of the two mirrors uncorrelated
  - Only ~2-doublet stack on M1
  - M2 high reflector
- Requires 2x the mirrors, incl. control system…




The enemy
of your enemy
is your friend.

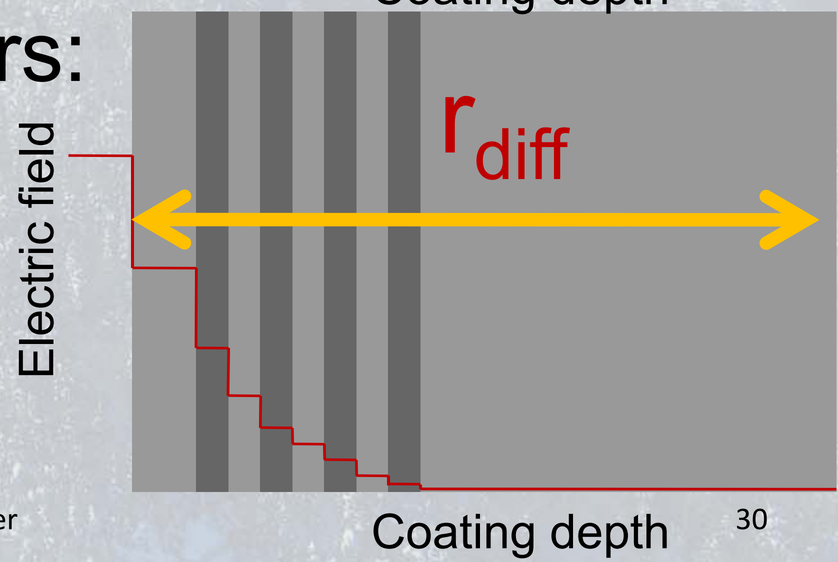
Thermo-optic cancellation

- 2 enemies
  - thermal expansion, α
  - dn/dT, tunable
  - opposite sign



- Thermal diffusion matters:
  - d << r_{diff} :
    - Noise is coherent

$$r_{diff} = \sqrt{\frac{\kappa}{2\pi f C}} \approx 40\mu \text{ @80Hz}$$



Brownian cancellation?

- Same idea for Brownian noise…
  - dn/dσ : photo-elastic coupling

PRD 87, 082001 (2013)`

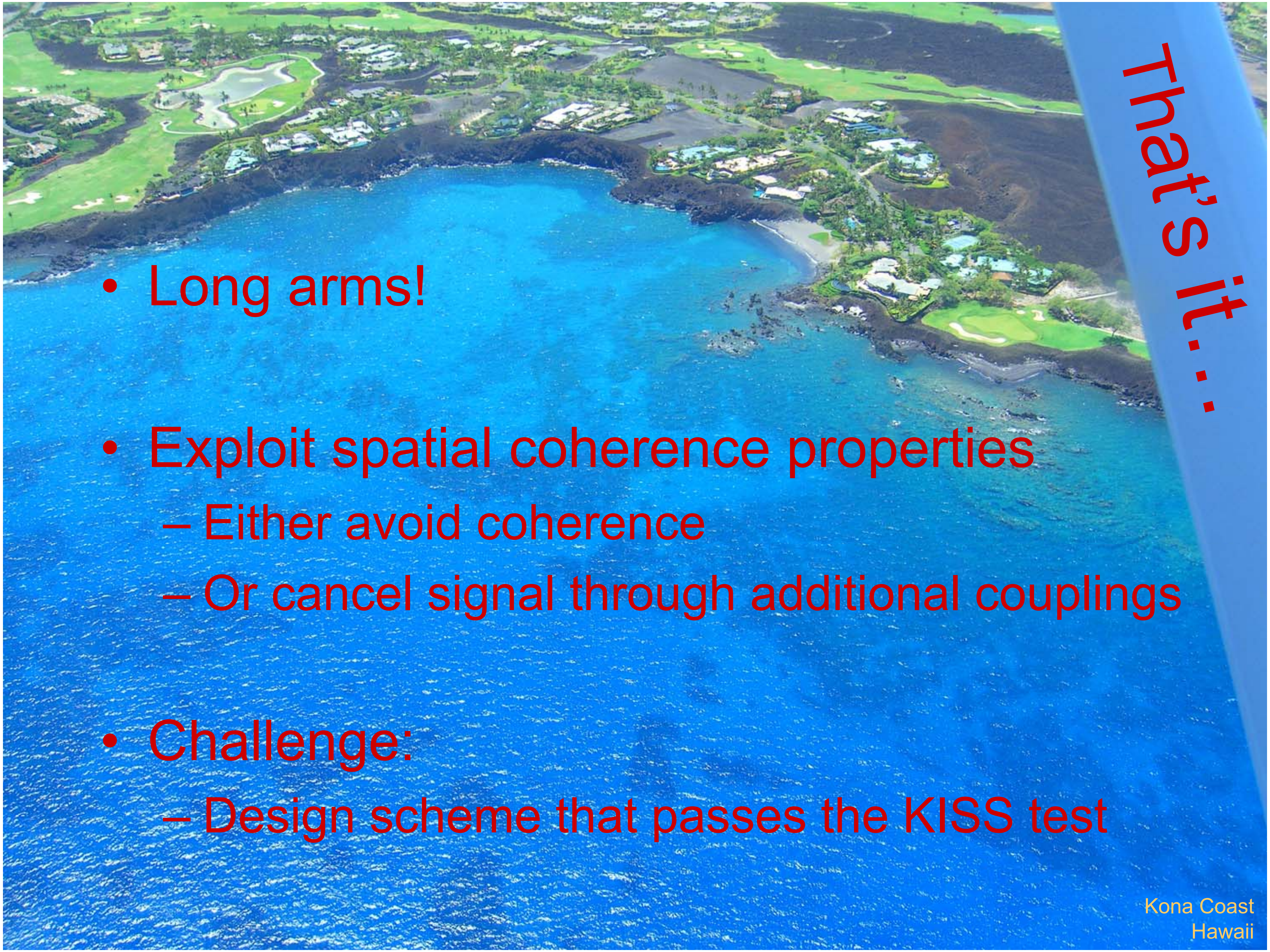
  - Small for SiO_2:Ta_2O_5
  - Check for crystalline coatings ?

Sensing thermal noise

- TN could be measured by 2nd interferometer
  - need comparable sensitivity…
- Displacement-free interferometry
  - Displacement couples at discrete times (t-nT)
  - GW strain couples continuously
  - Devise readout that cancels signals at (t-nT), but preserves (some) GW sensitivity
    - Effectively AC-couples the signal…

That's it…

- Long arms!
- Exploit spatial coherence properties
  - Either avoid coherence
  - Or cancel signal through additional couplings
- Challenge:
  - Design scheme that passes the KISS test



Kona Coast
Hawaii

Conclusion

- Long arms!
- Exploit spatial coherence properties
  - Either avoid coherence
  - Or cancel signal through additional couplings
- Challenge:
  - Design scheme that passes the KISS test