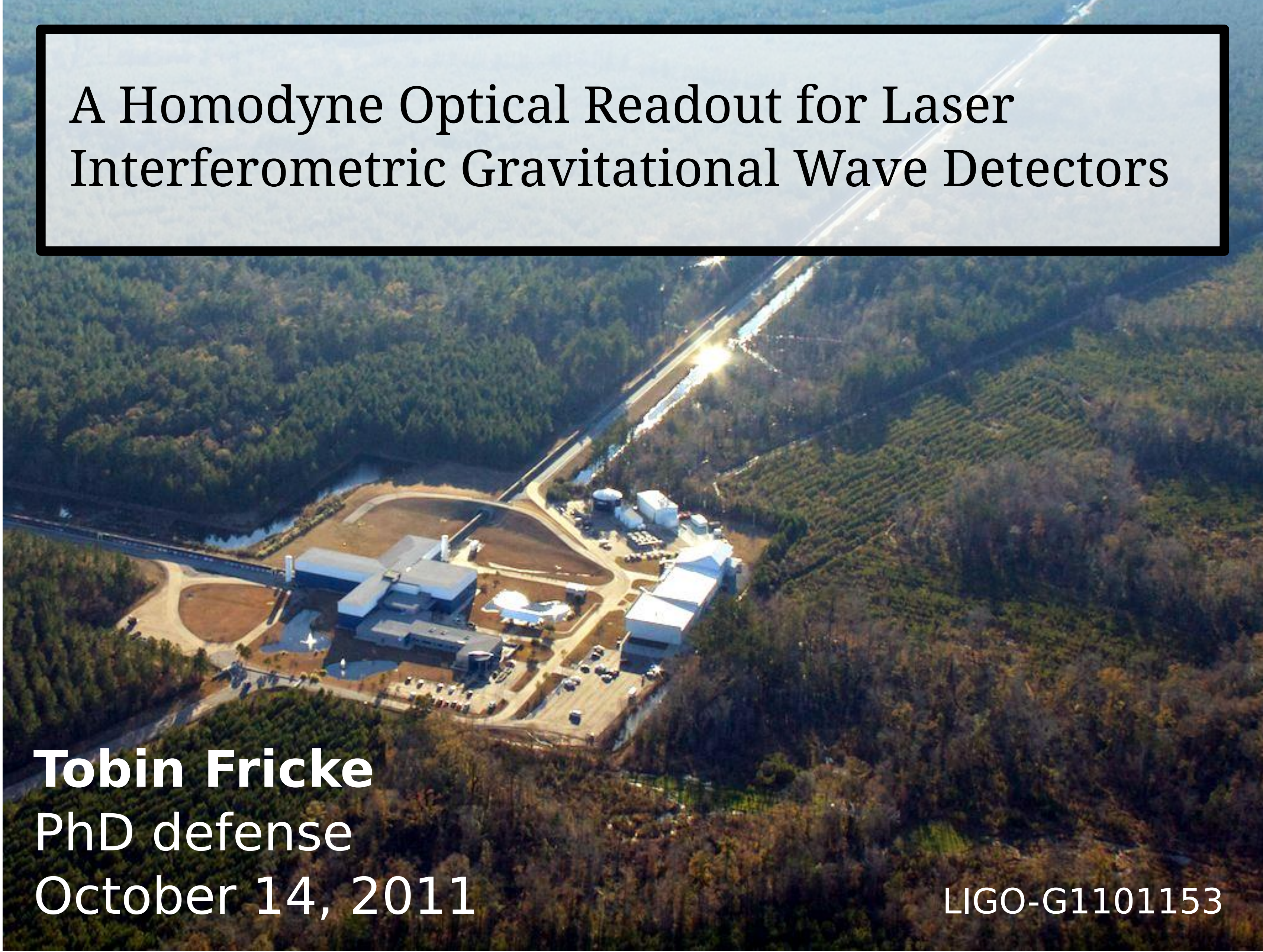
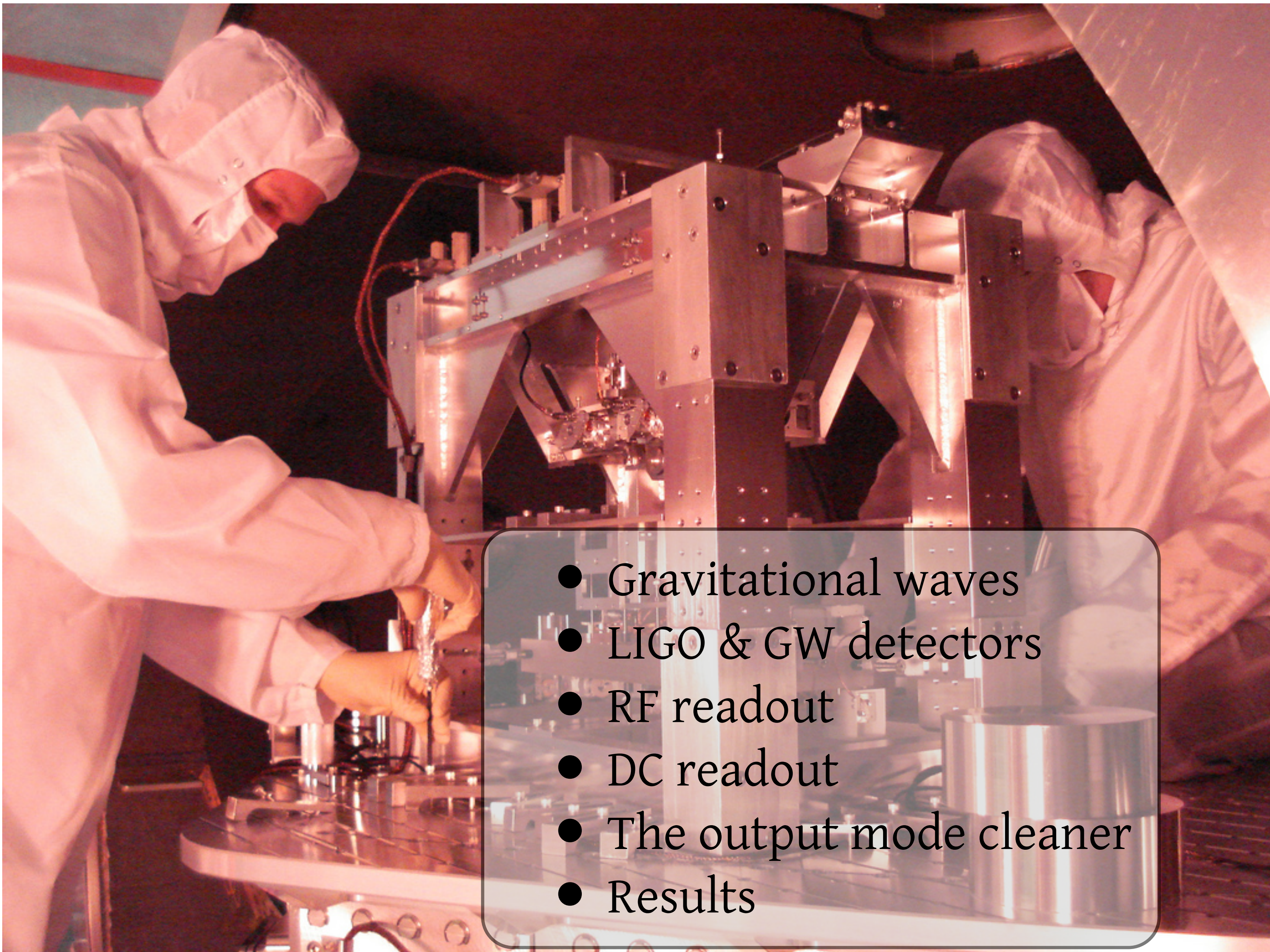


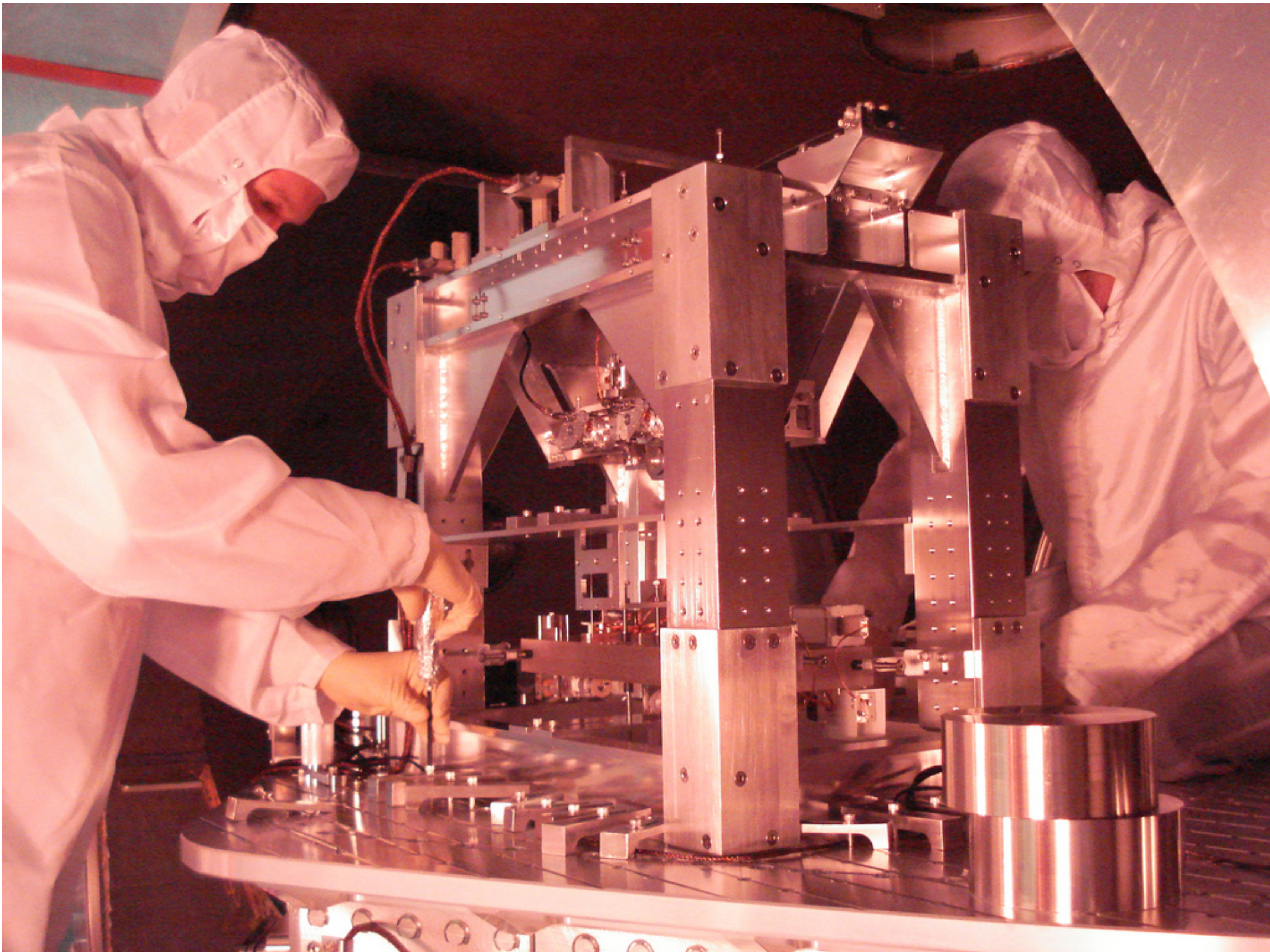
A Homodyne Optical Readout for Laser Interferometric Gravitational Wave Detectors

Tobin Fricke
PhD defense
October 14, 2011

LIGO-G1101153

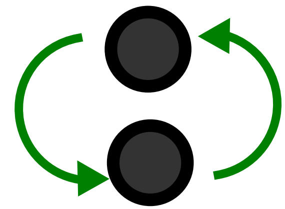


- Gravitational waves
- LIGO & GW detectors
- RF readout
- DC readout
- The output mode cleaner
- Results



Gravitational waves

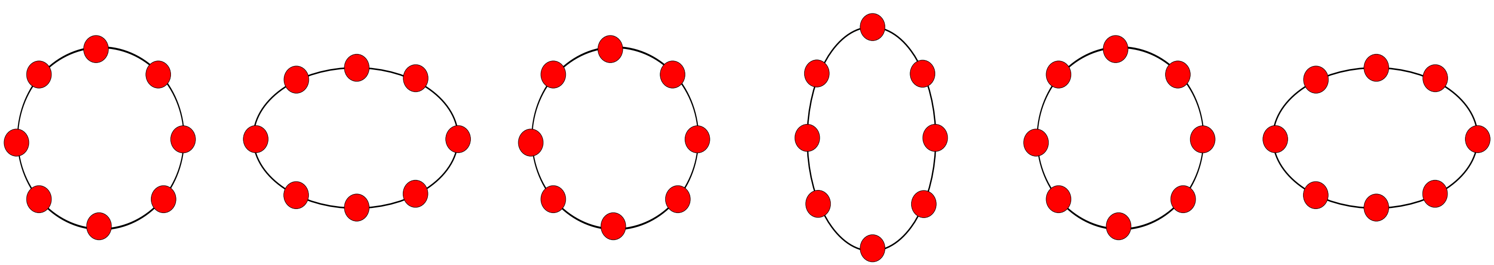
$$F = G\frac{m_1 m_2}{r^2}$$



- predicted by general relativity
- generated by accelerating mass
- propagate at the speed of light
- not yet detected directly
- appear as a strain of spacetime

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

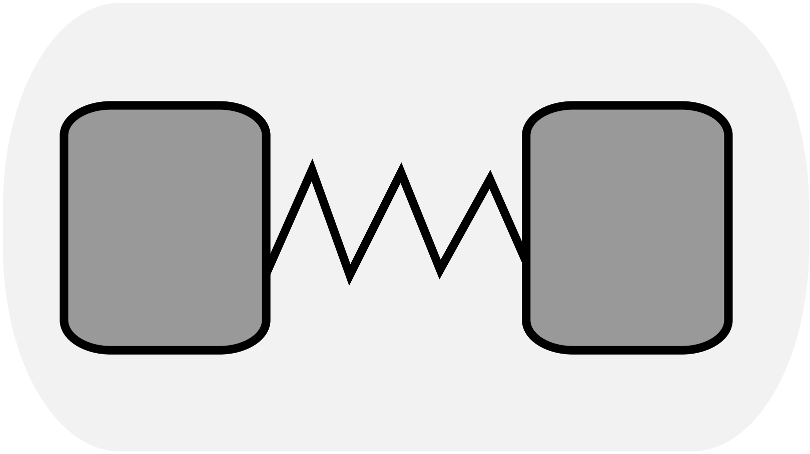
$$h_{\mu\nu}(x^\lambda) = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \cos(k_\lambda x^\lambda)$$

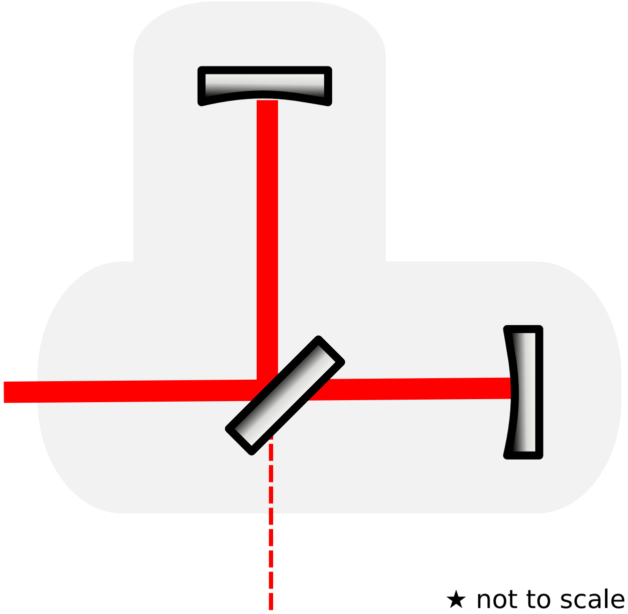


Gravitational wave sources

	modeled	unmodeled
long-term	"pulsars"	stochastic background
transient	binary inspirals	supernova & other bursts

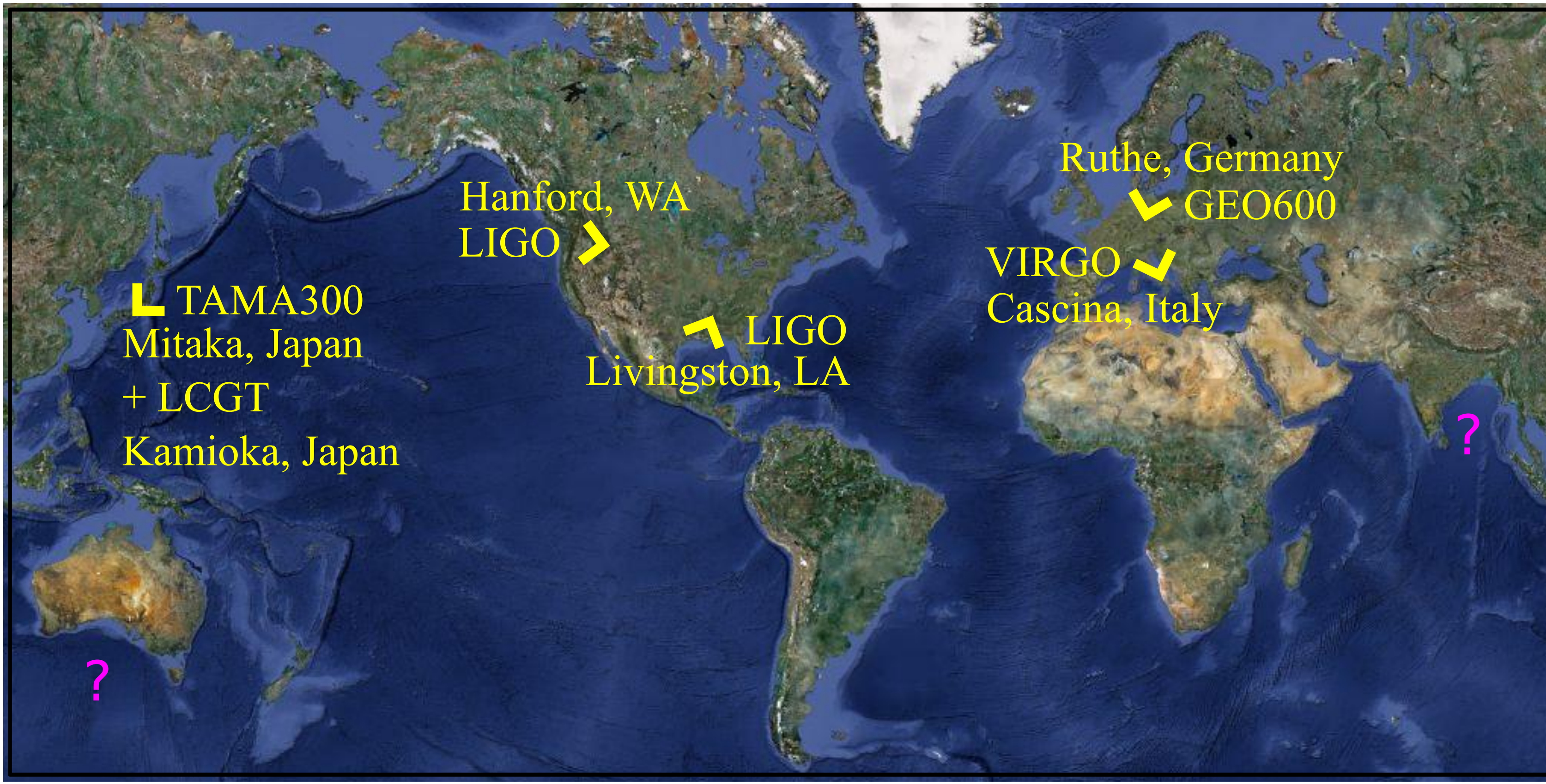
Gravitational wave detectors



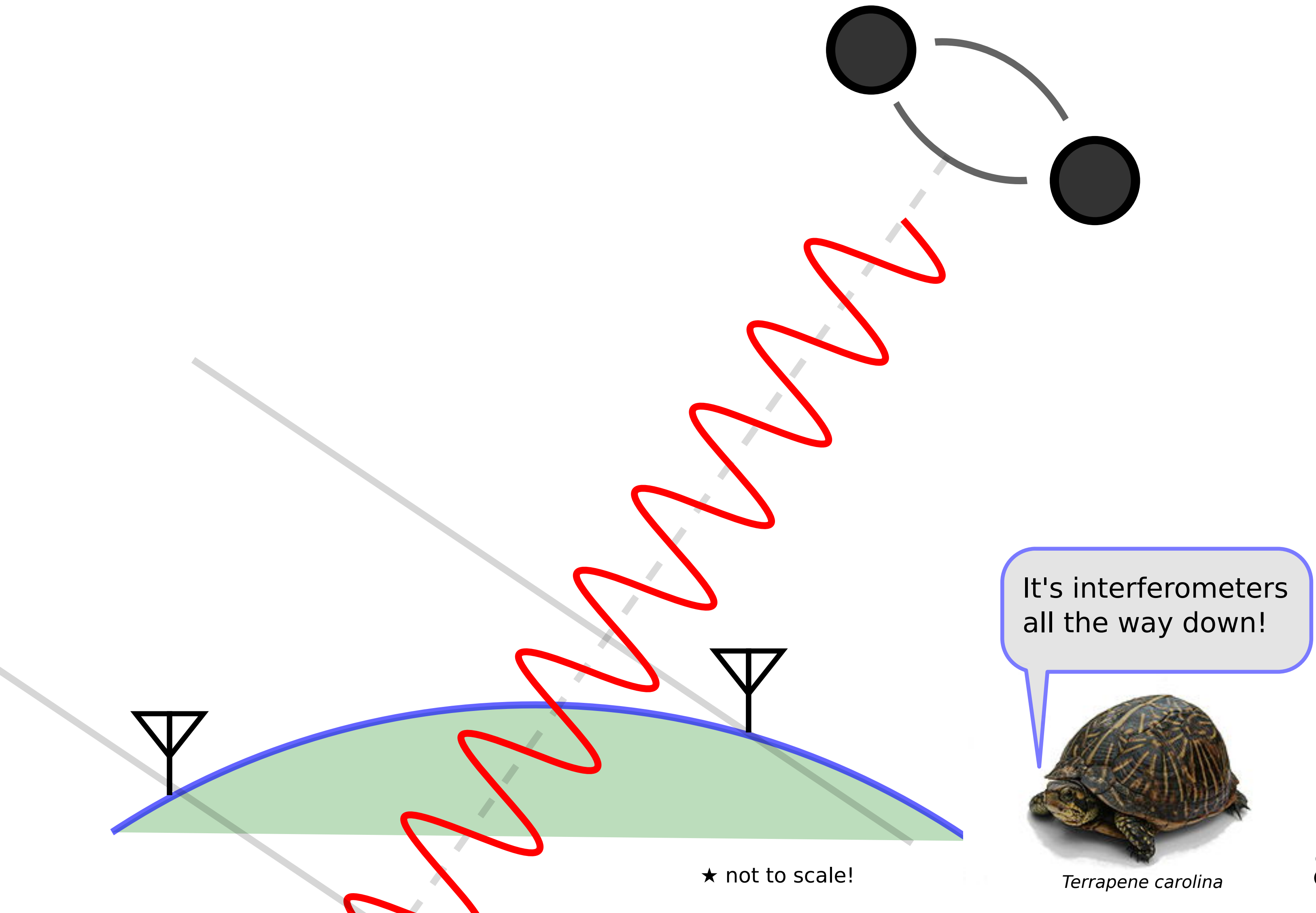


★ not to scale!

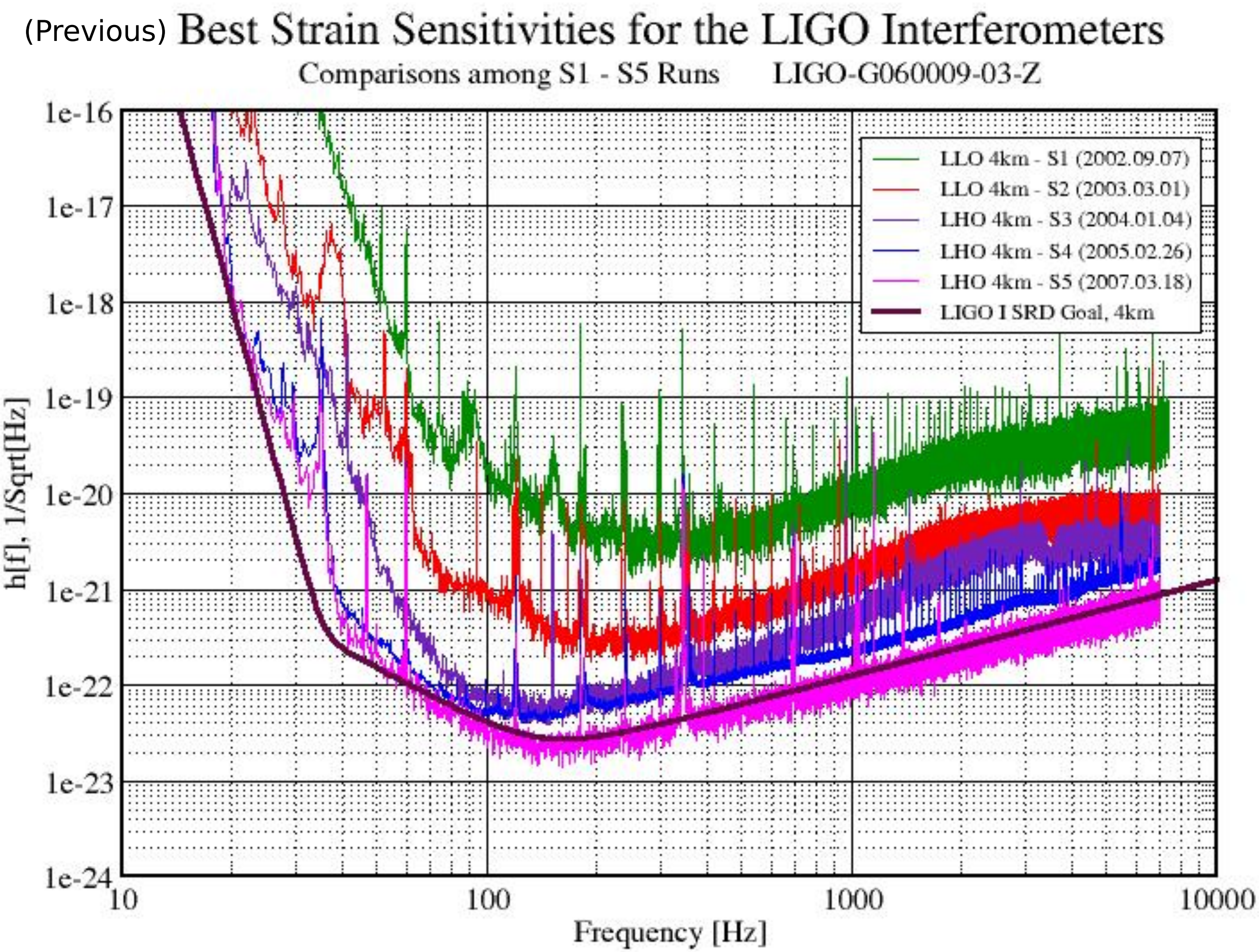
Network of detectors



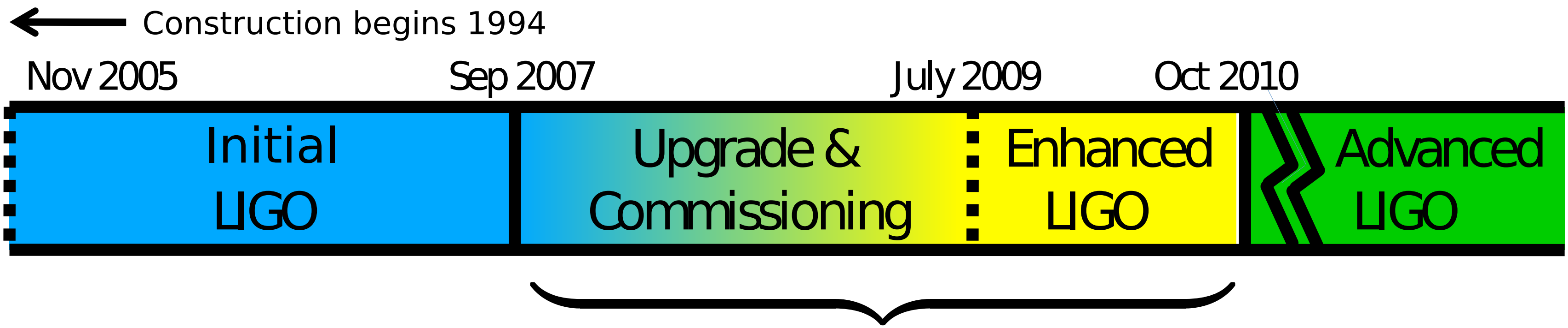
An interferometer of interferometers



Sensitivity (noise floor)



Enhanced LIGO



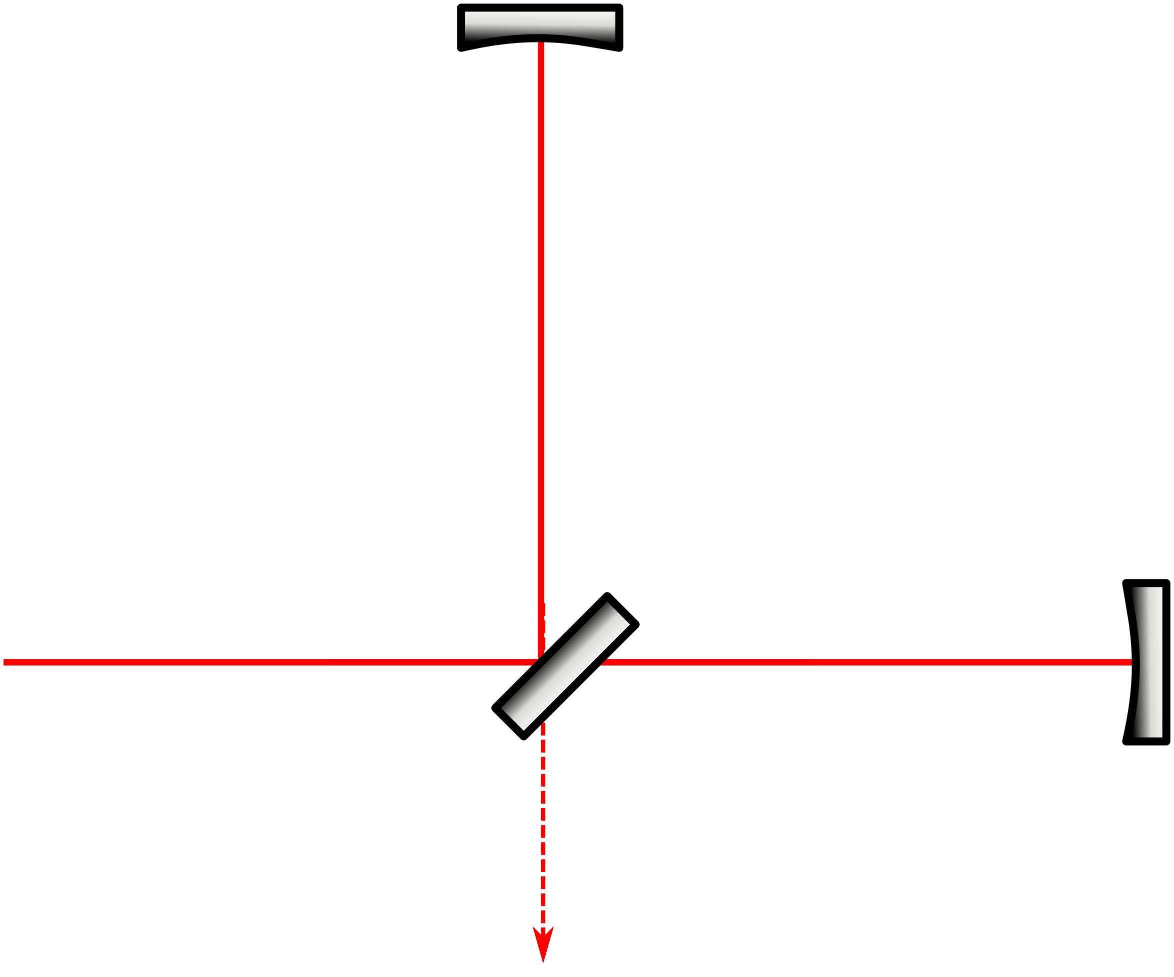
- Try out Advanced LIGO technologies
- Bet that increased sensitivity outweighs the downtime

exposure = time * (range)^3

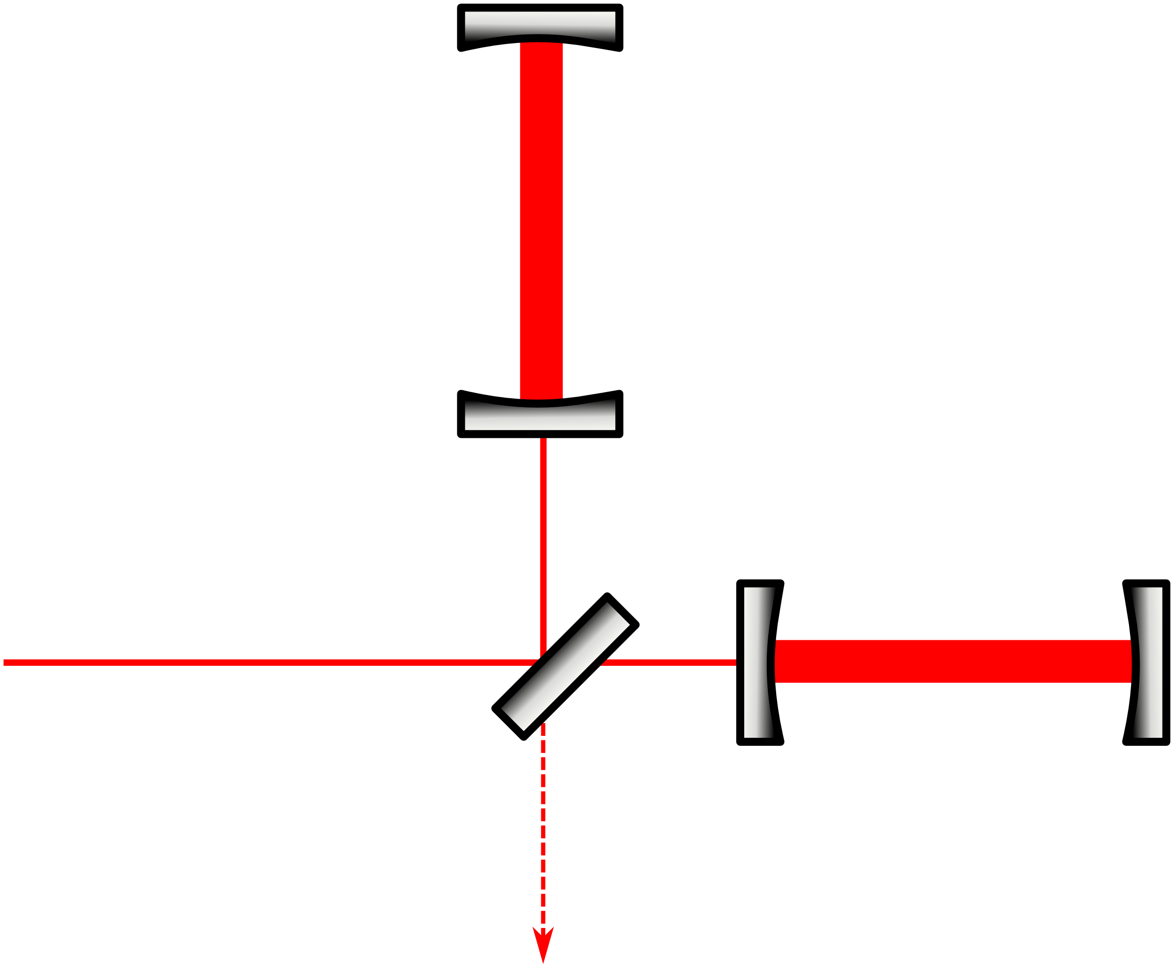
Increase the laser power
Output mode cleaner
DC readout

New Laser
New input optics
New Thermal Compensation
New Alignment Control

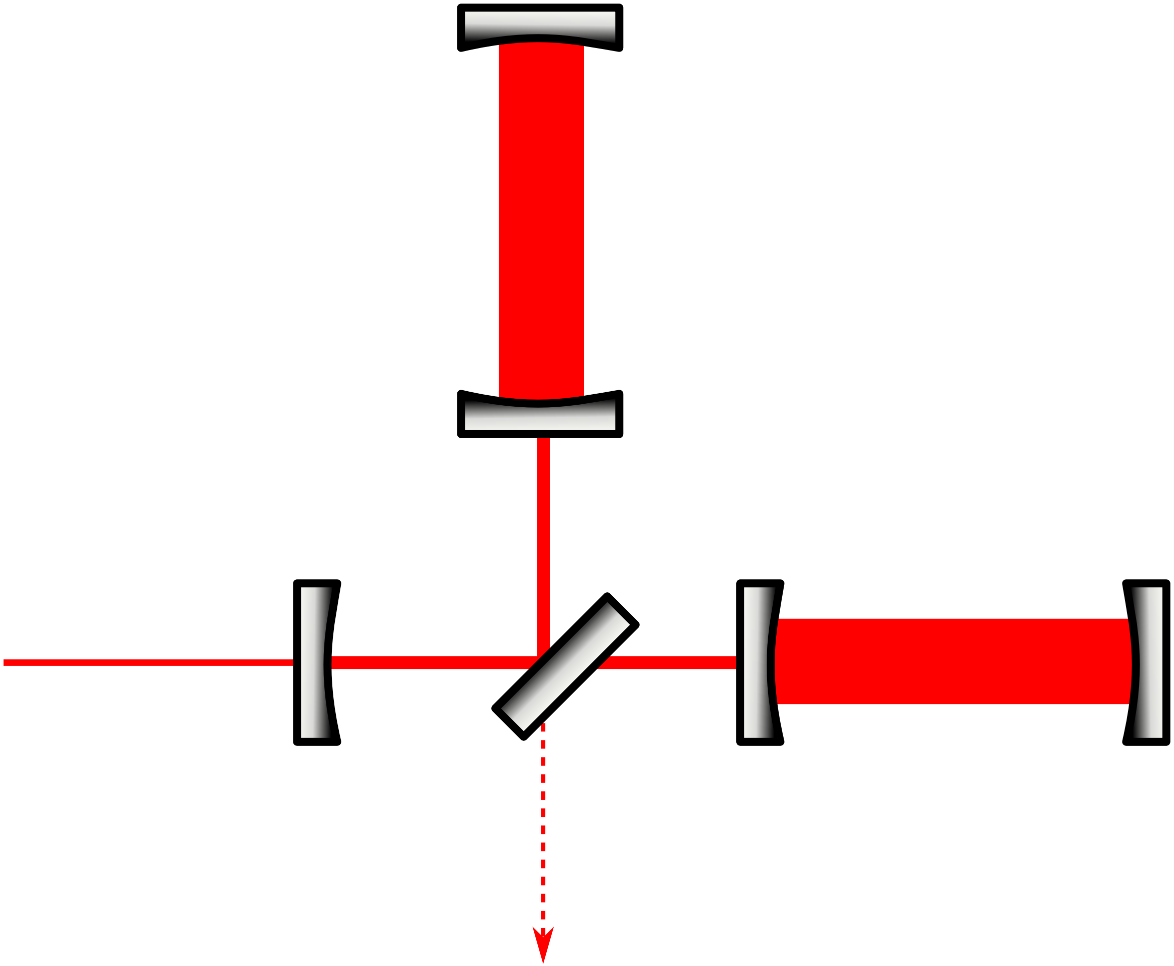
Michelson



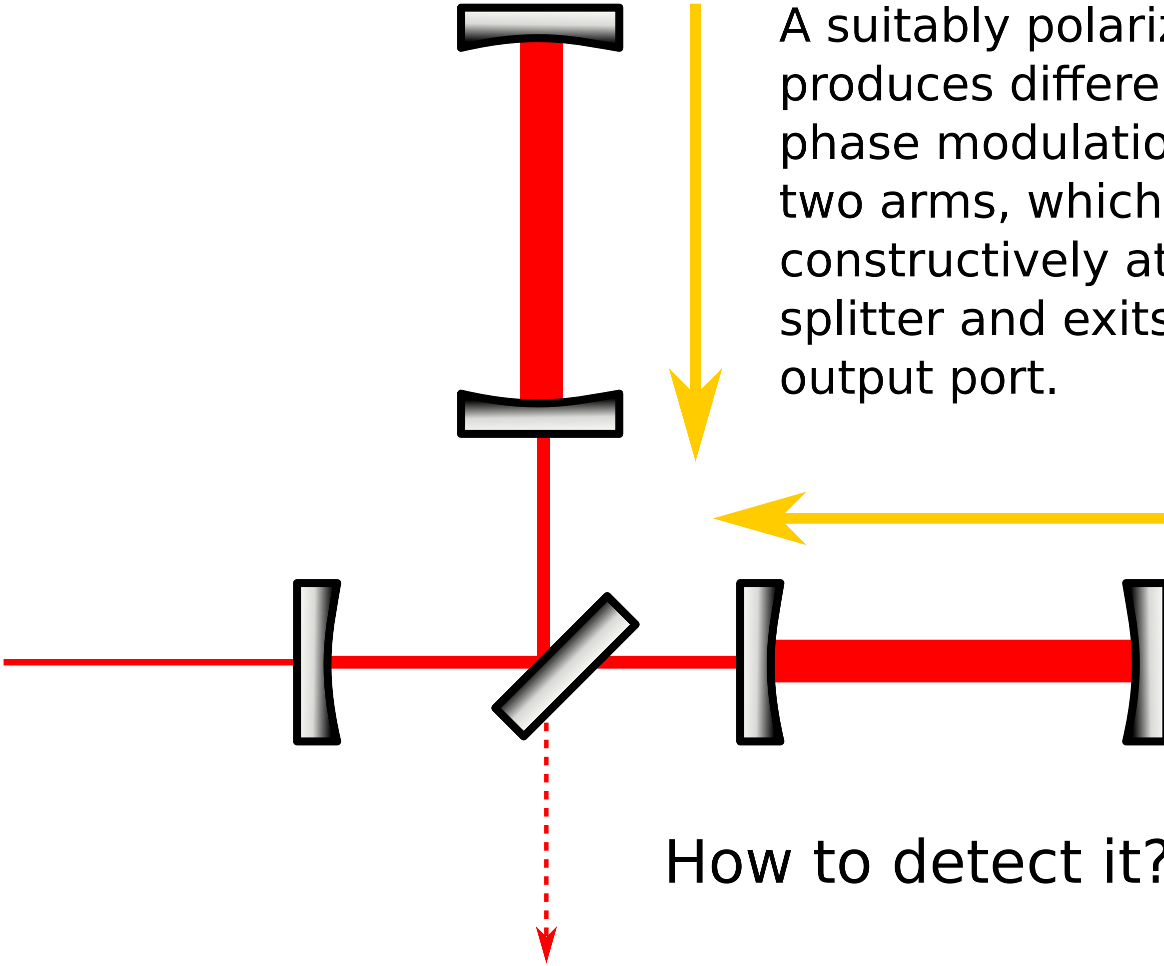
Fabry-Perot Michelson



Power-Recycled Fabry-Perot Michelson



Interferometer

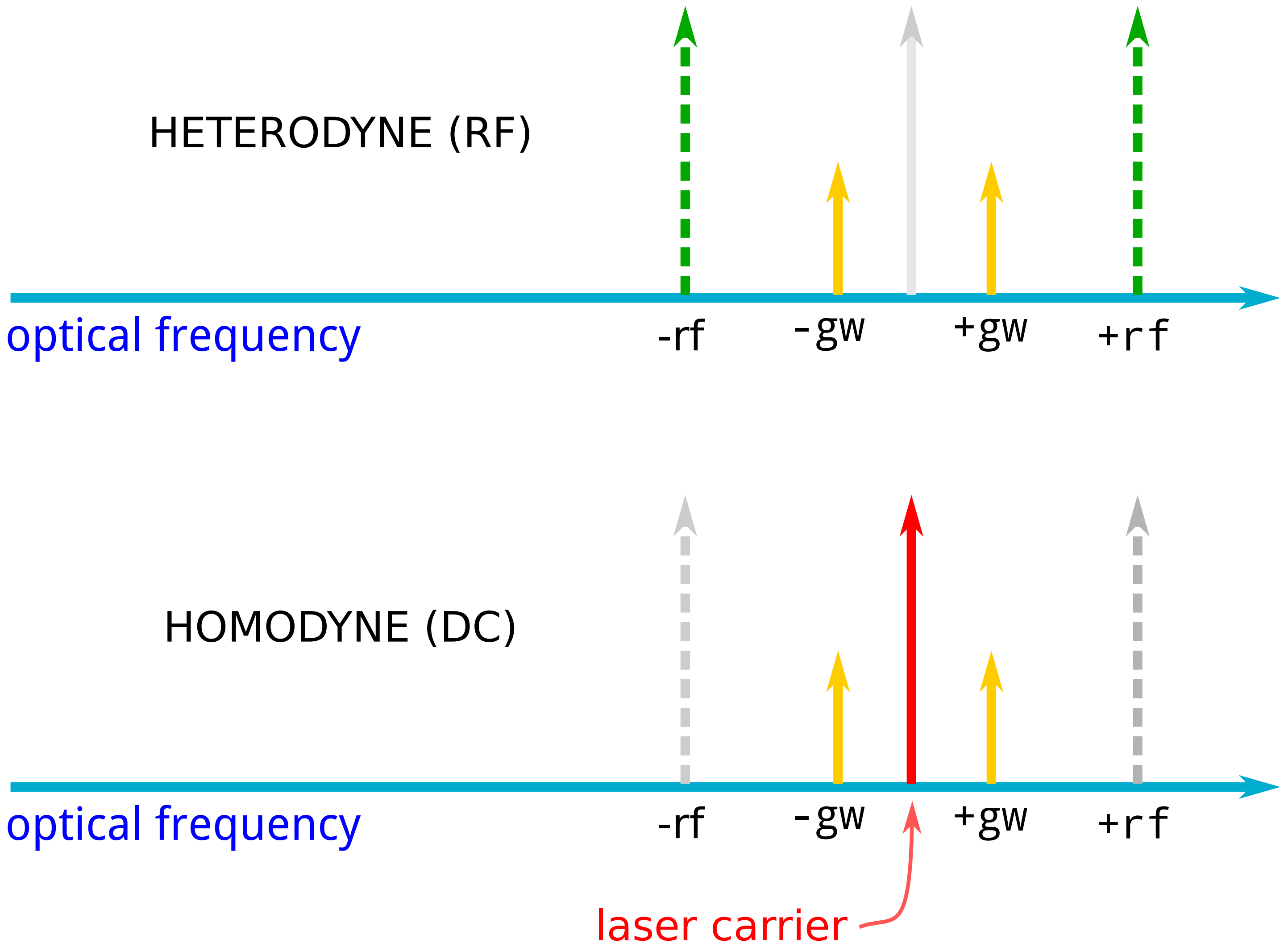


A suitably polarized GW produces differential phase modulation in the two arms, which interferes constructively at the beam splitter and exits at the output port.

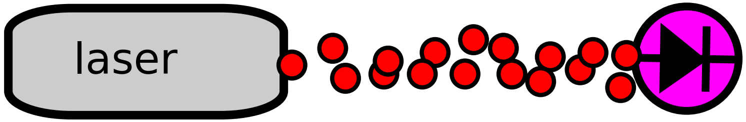
How to detect it?

?

Detection: frequency domain picture

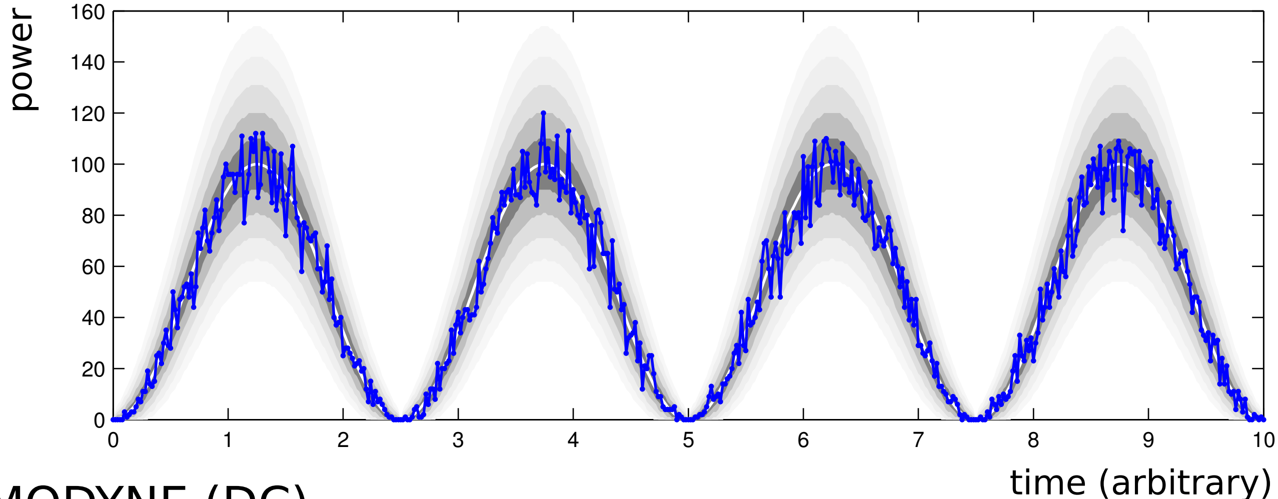


Shot noise

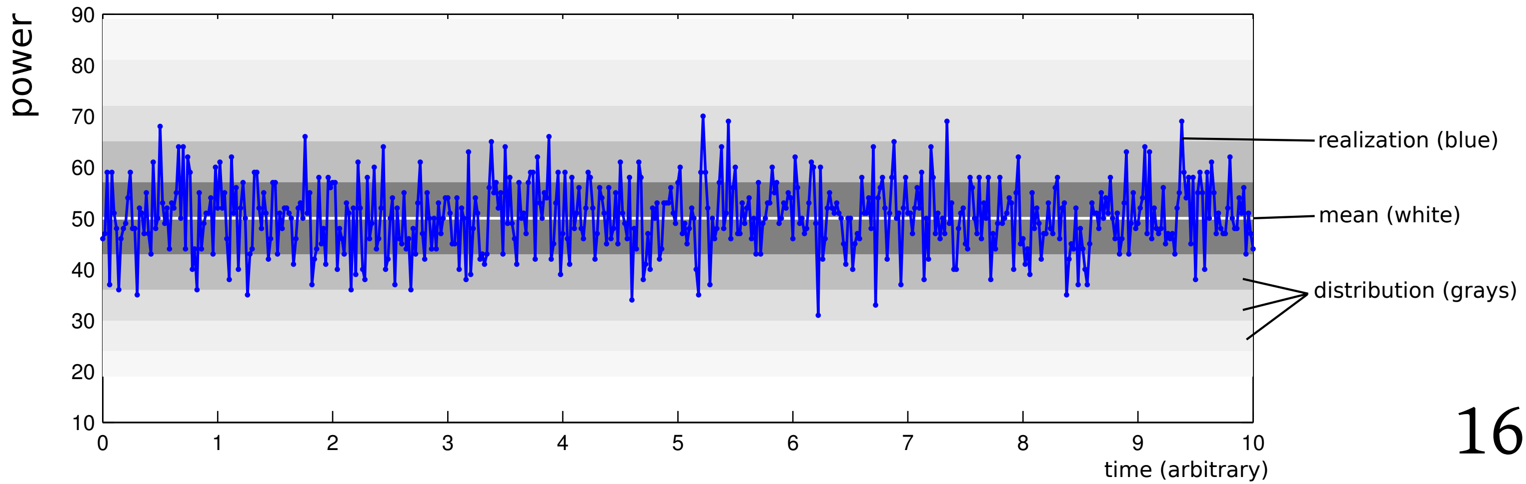


★ semiclassical picture

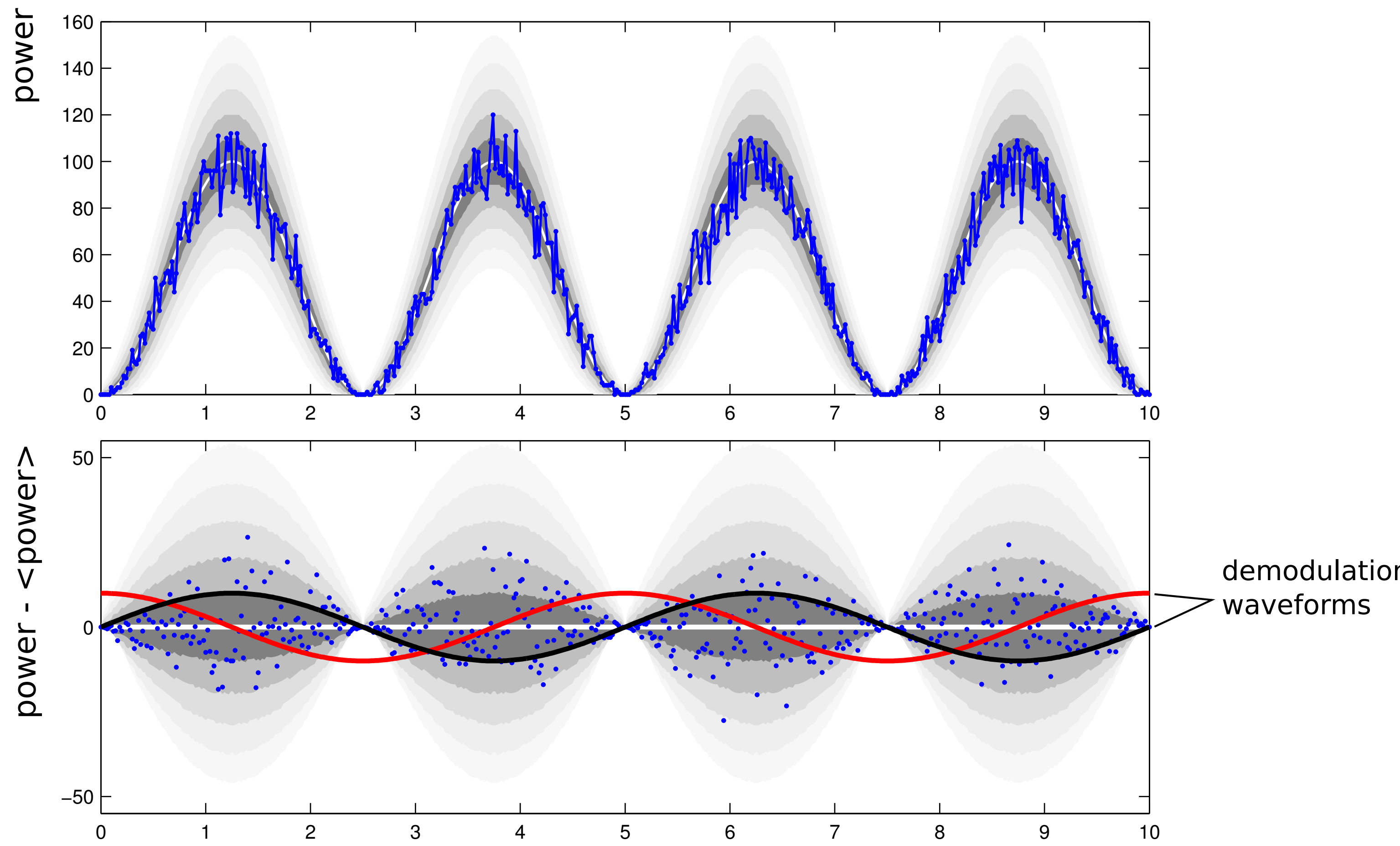
HETERODYNE (RF)



HOMODYNE (DC)



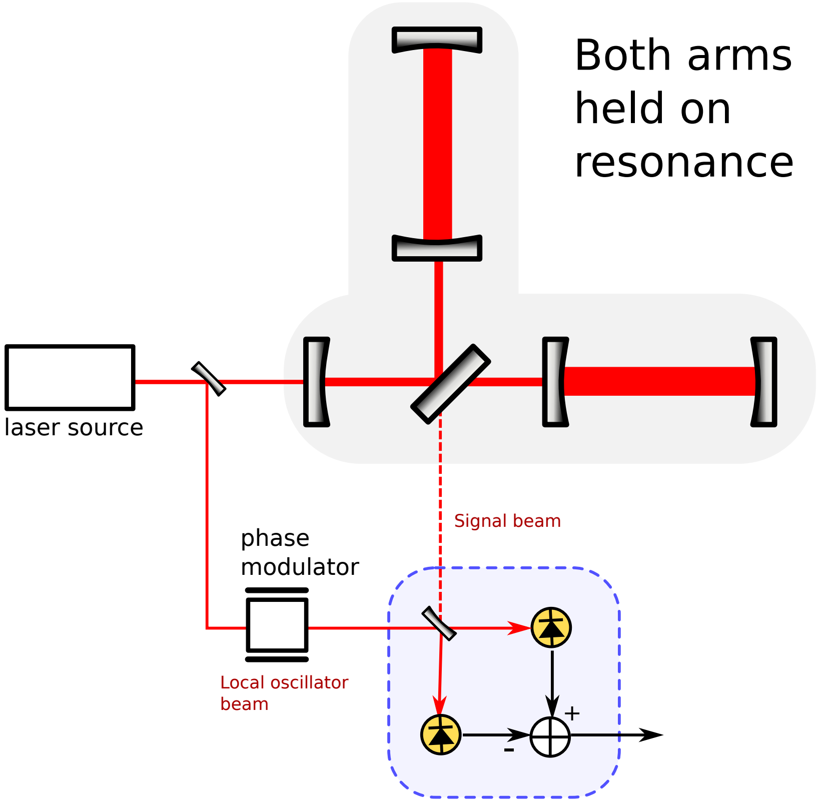
Heterodyne shot noise



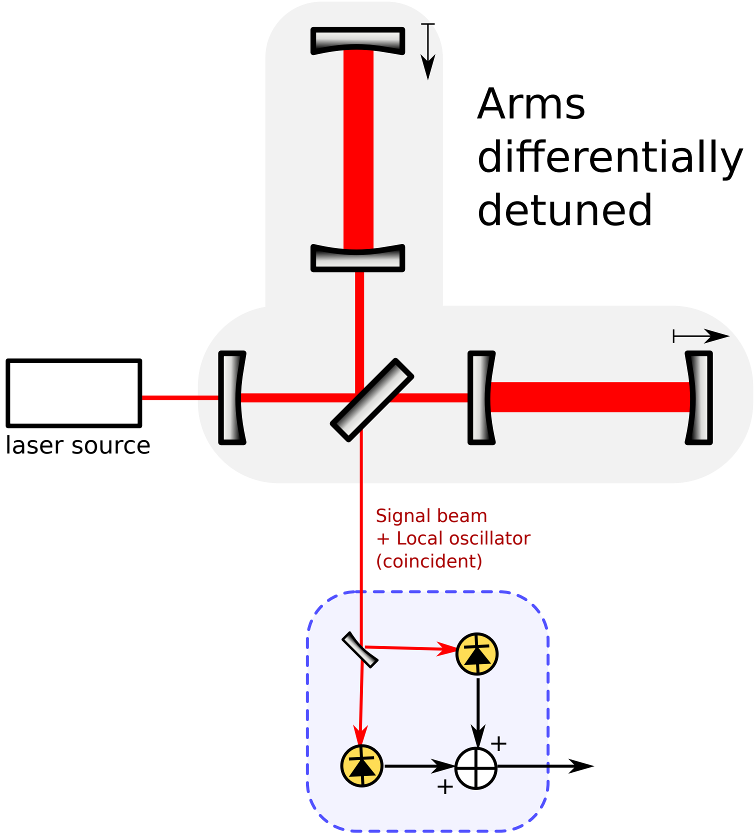
The in-phase demoulation selectively samples the noisiest parts of the time series!

DC Readout vs balanced homodyne

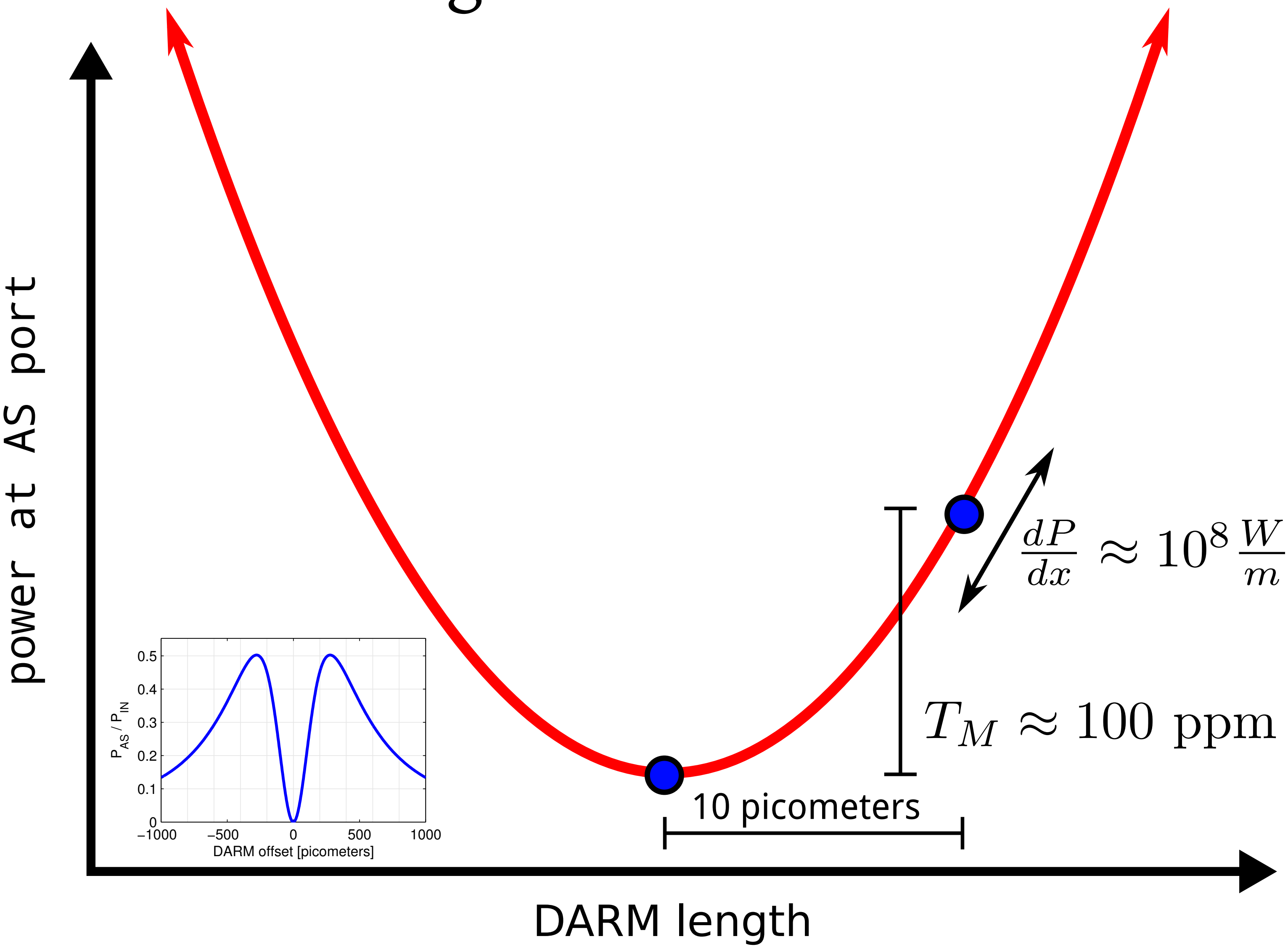
Balanced homodyne



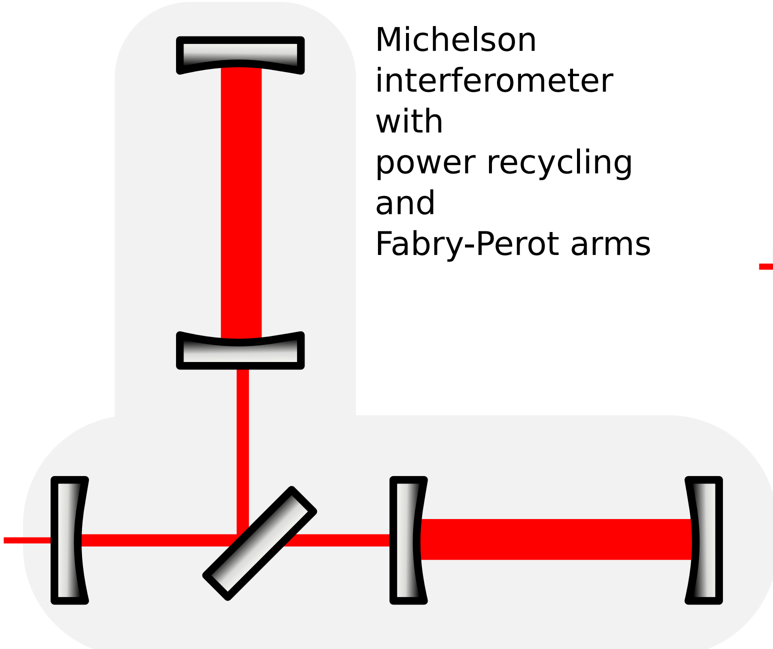
DC Readout



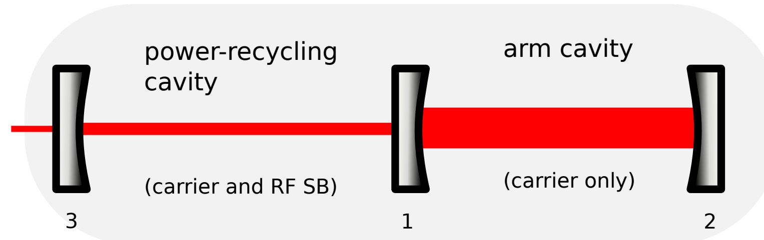
DC Readout: fringe view



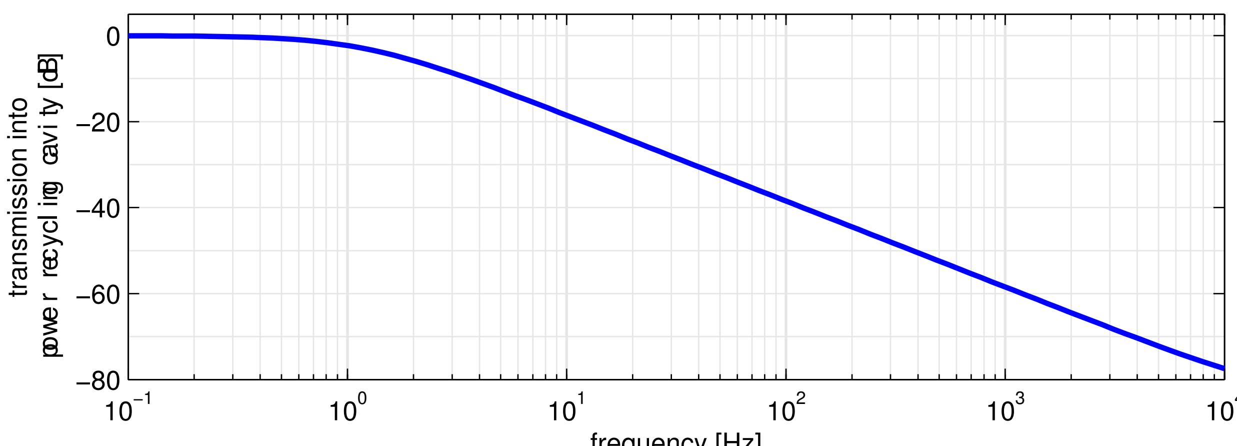
The Coupled Cavity



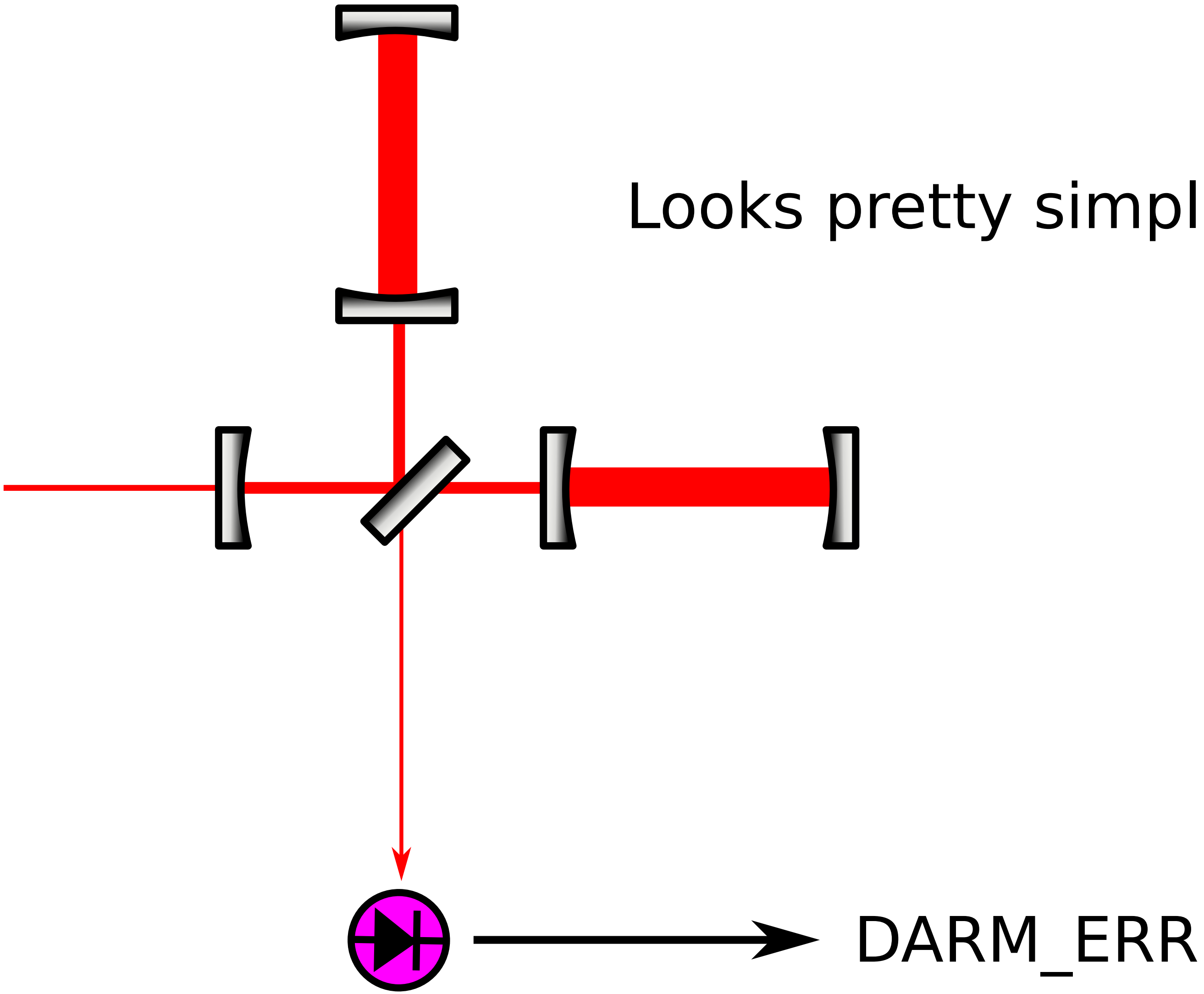
Michelson interferometer with power recycling and Fabry-Perot arms



three mirror cavity



DC Readout



Looks pretty simple...

DC Readout promises

- fundamental improvement in SNR

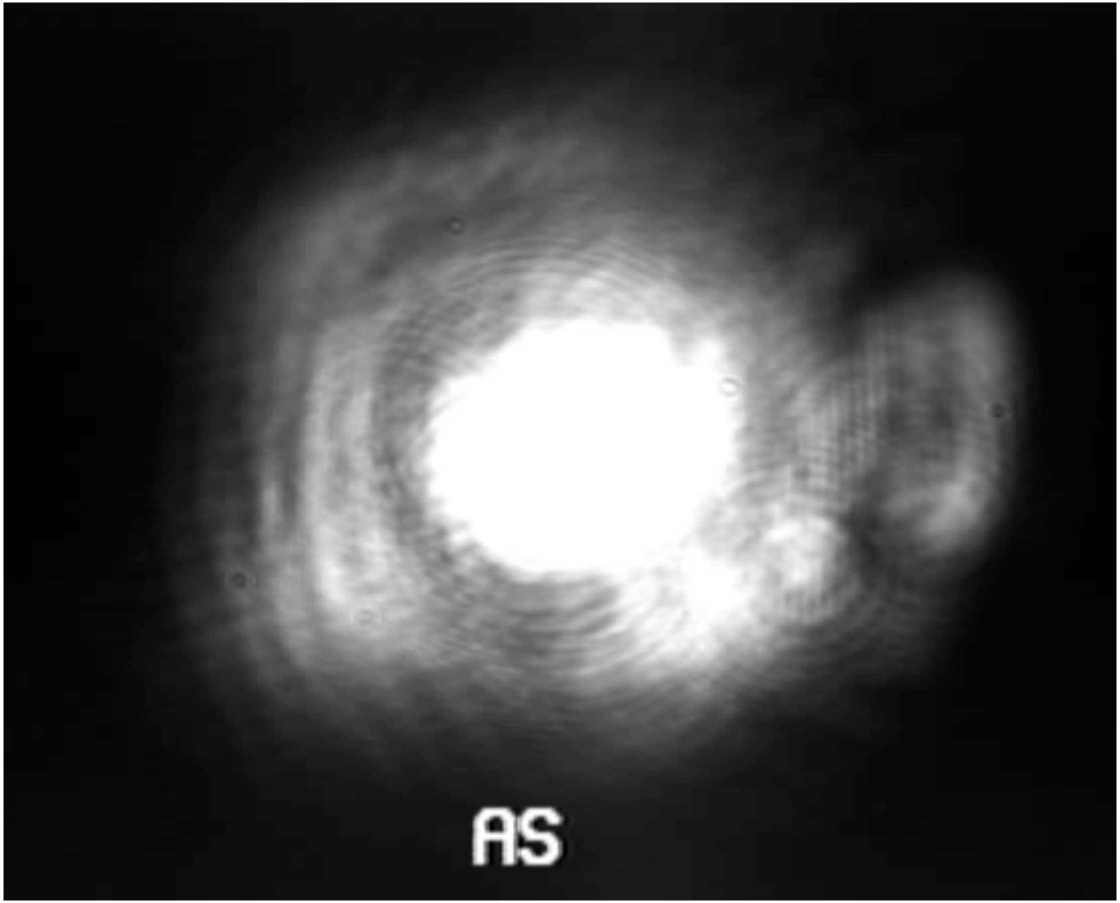
- technical improvement in SNR
  - perfect overlap of local oscillator and signal beams
  - junk light removal by OMC

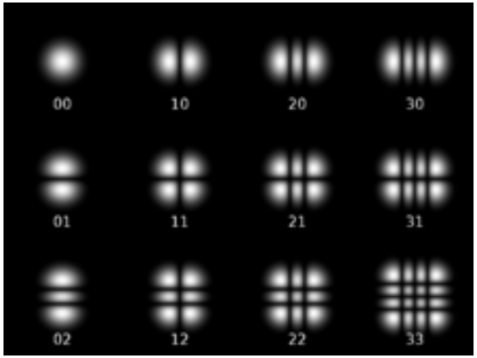
- improved laser and oscillator noise couplings
  - exploit the amazing filtering ability of the interferometer

- Easier platform for squeezed light injection

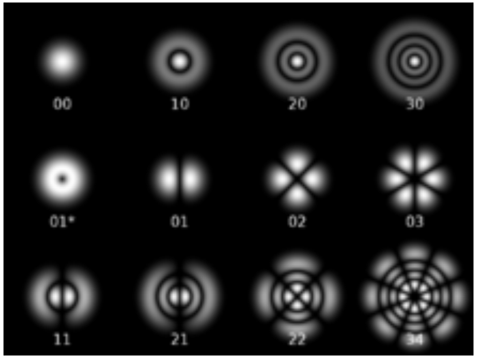
- Easier to handle higher power

Junk Light





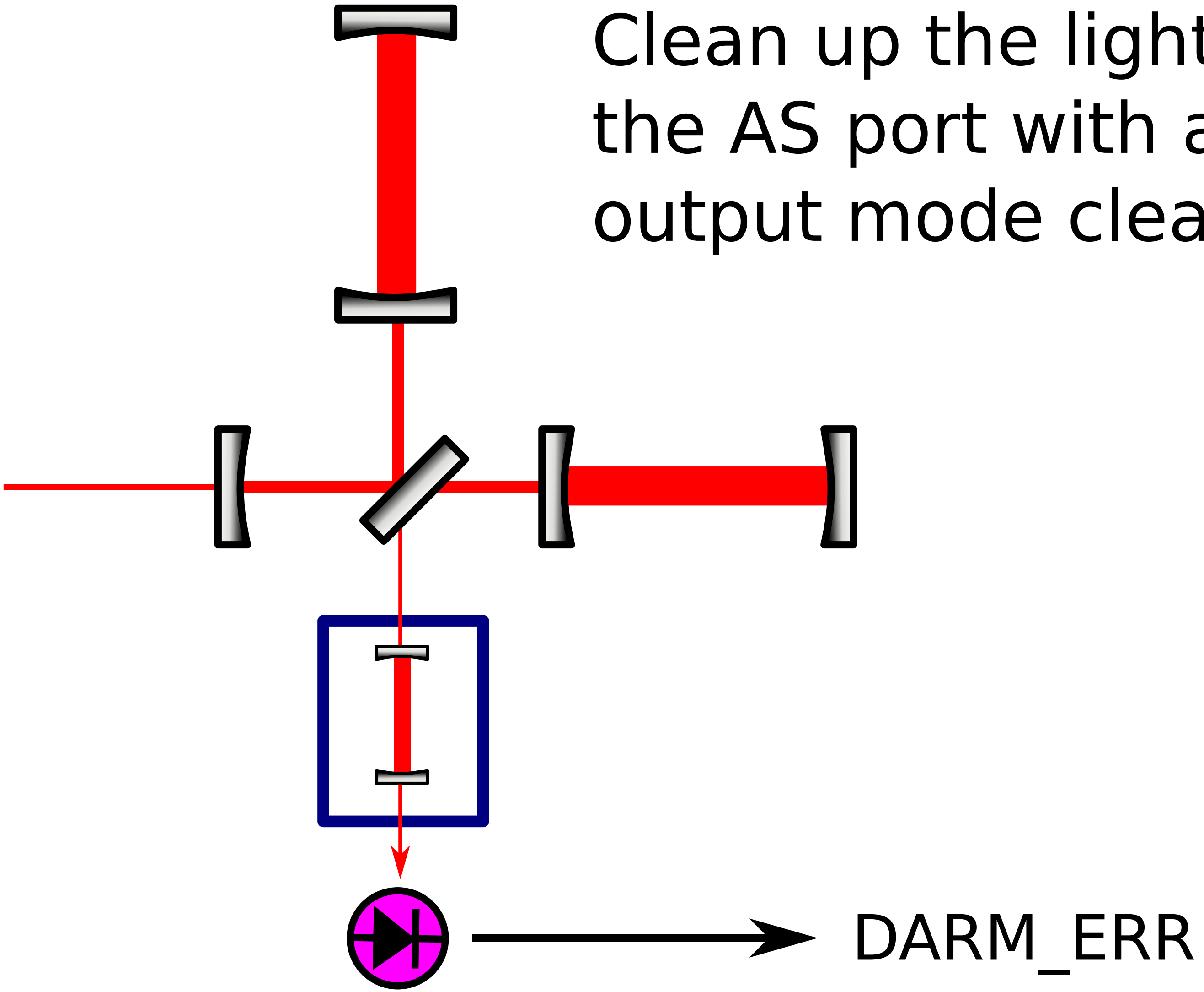
Hermite-Gauss modes ★ wikipedia



Laguerre-Gauss modes ★ wikipedia

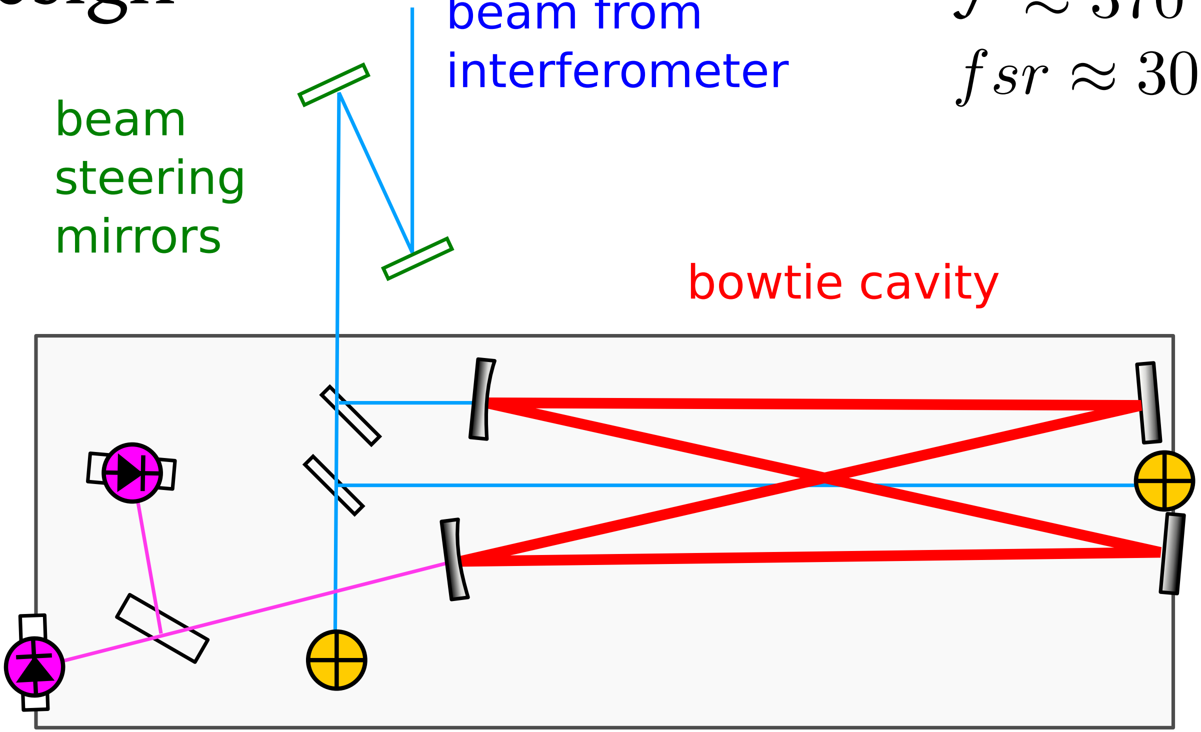
DC Readout with OMC

Clean up the light at the AS port with an output mode cleaner.



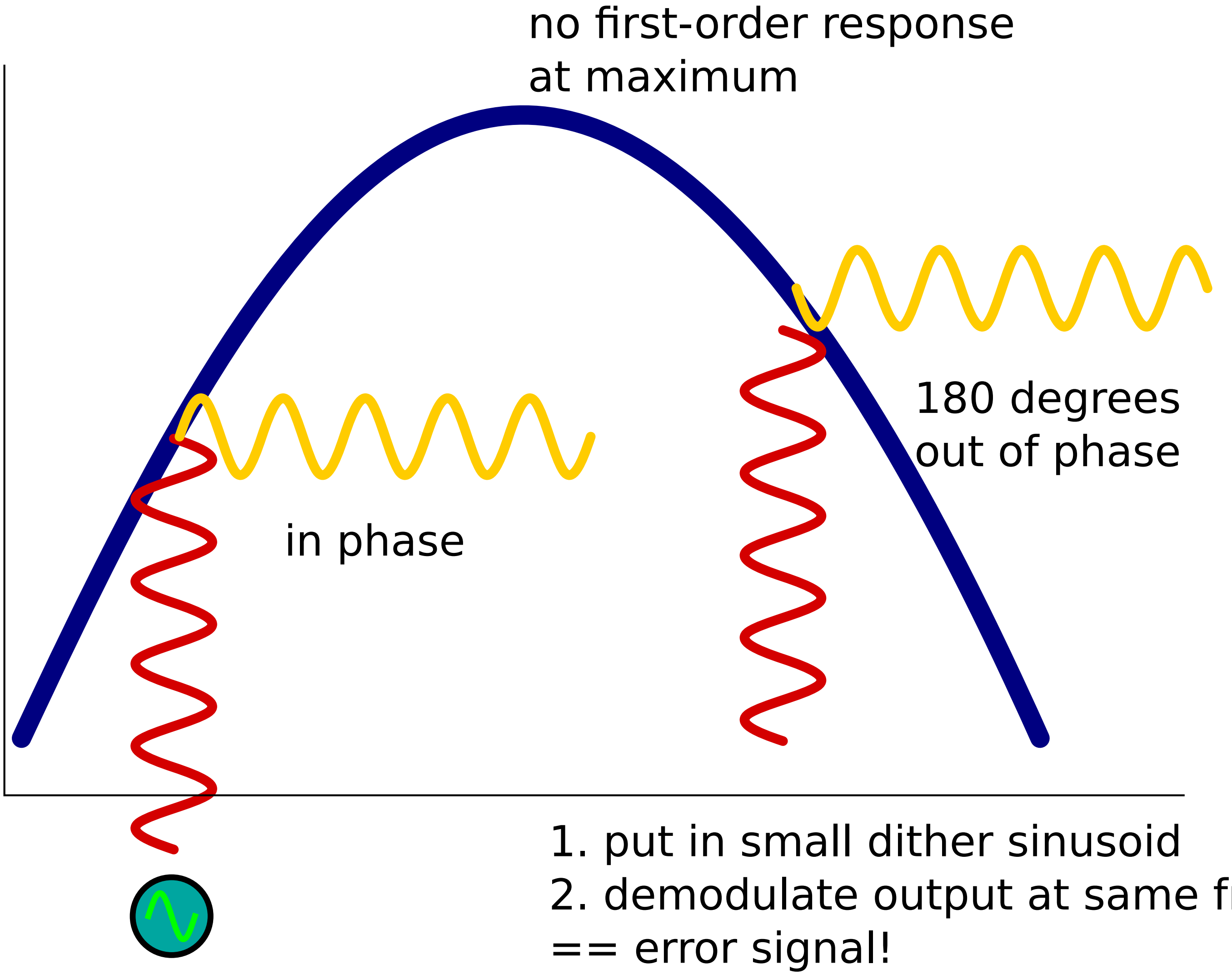
OMC design

$$\mathcal{F} \approx 370$$
$$fsr \approx 300\ \mathrm{MHz}$$



monolithic, suspended, in-vacuum

Dither Locking

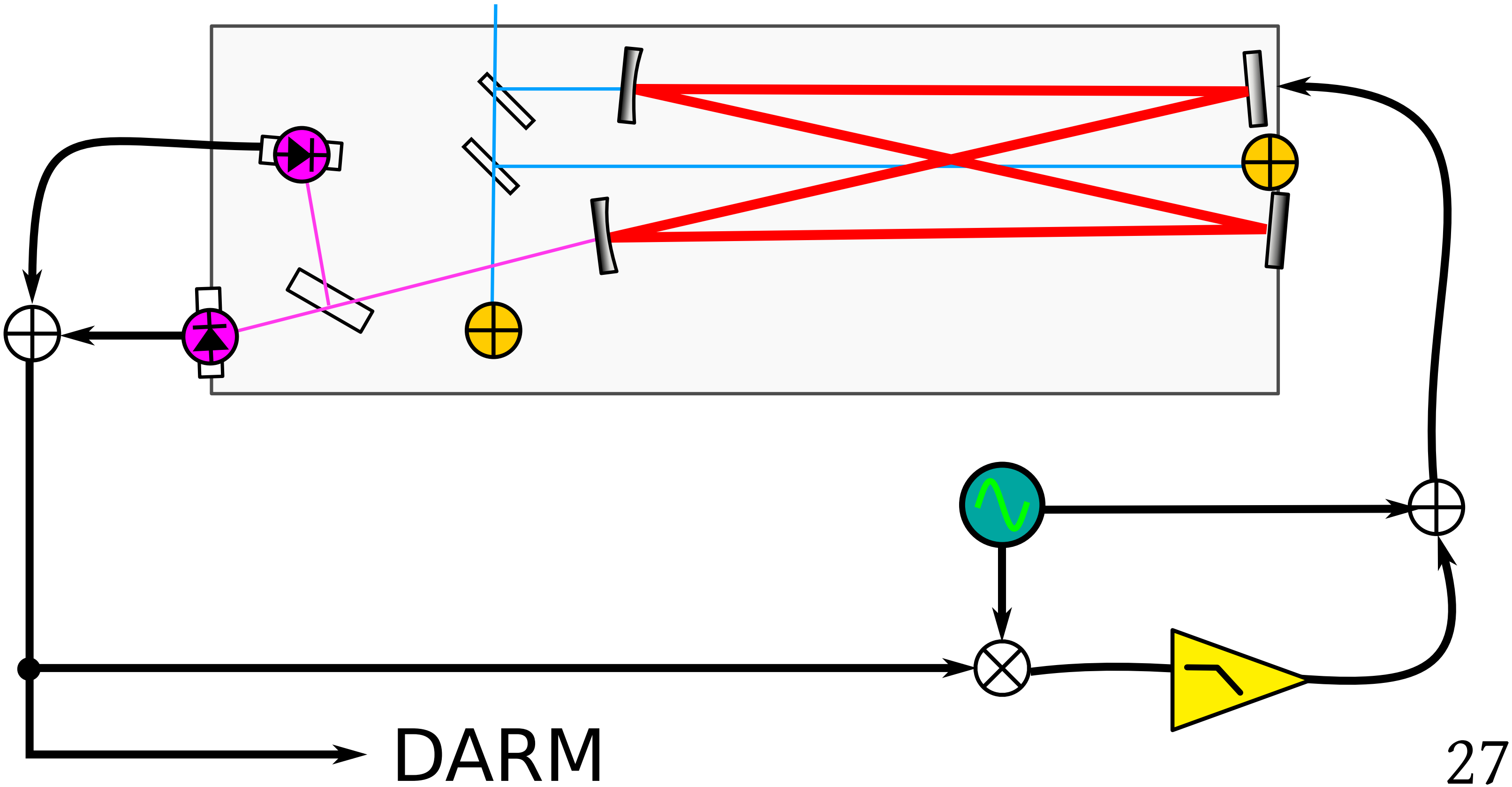


1. put in small dither sinusoid
2. demodulate output at same freq
== error signal!

OMC Length Control

Cavity length dithered at ~10 kHz via PZT actuator

PZT offloaded onto slow, long-range thermal actuator

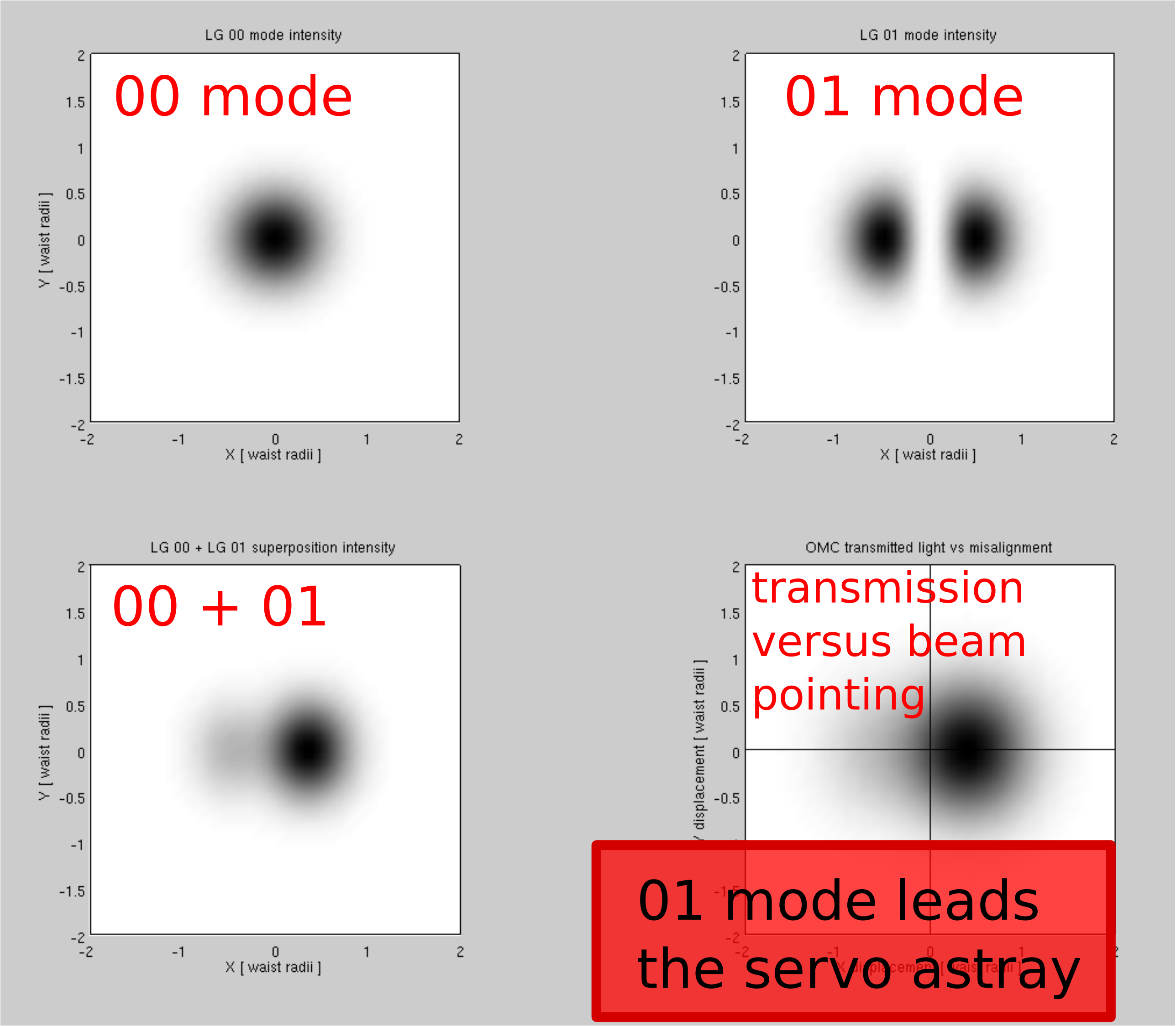


OMC Alignment Control

```
The mode cleaner will clean the modes if you can
identify what mode you want to keep.
```

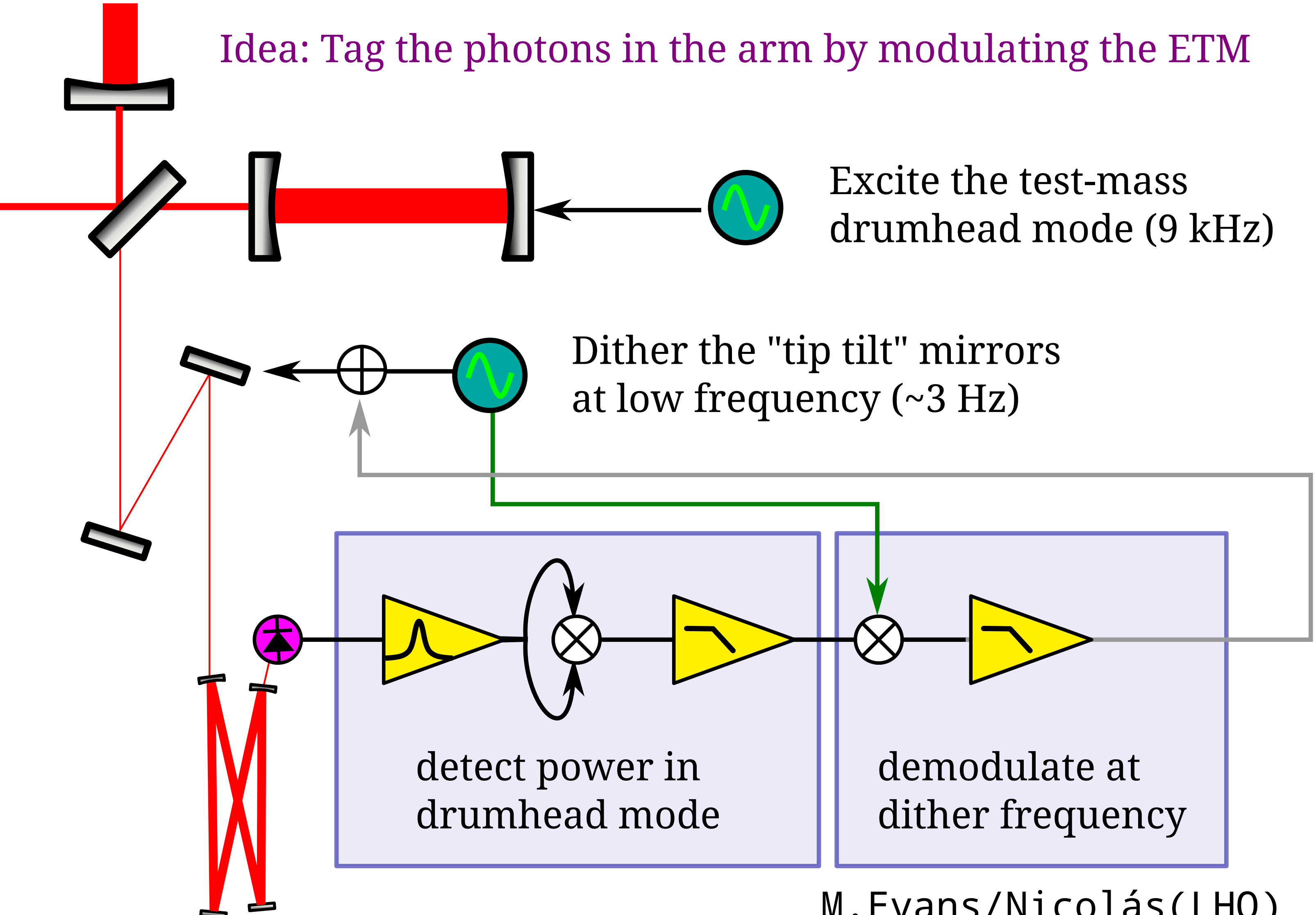
Initial idea: maximize transmission through the OMC

Junk light confuses simple servo



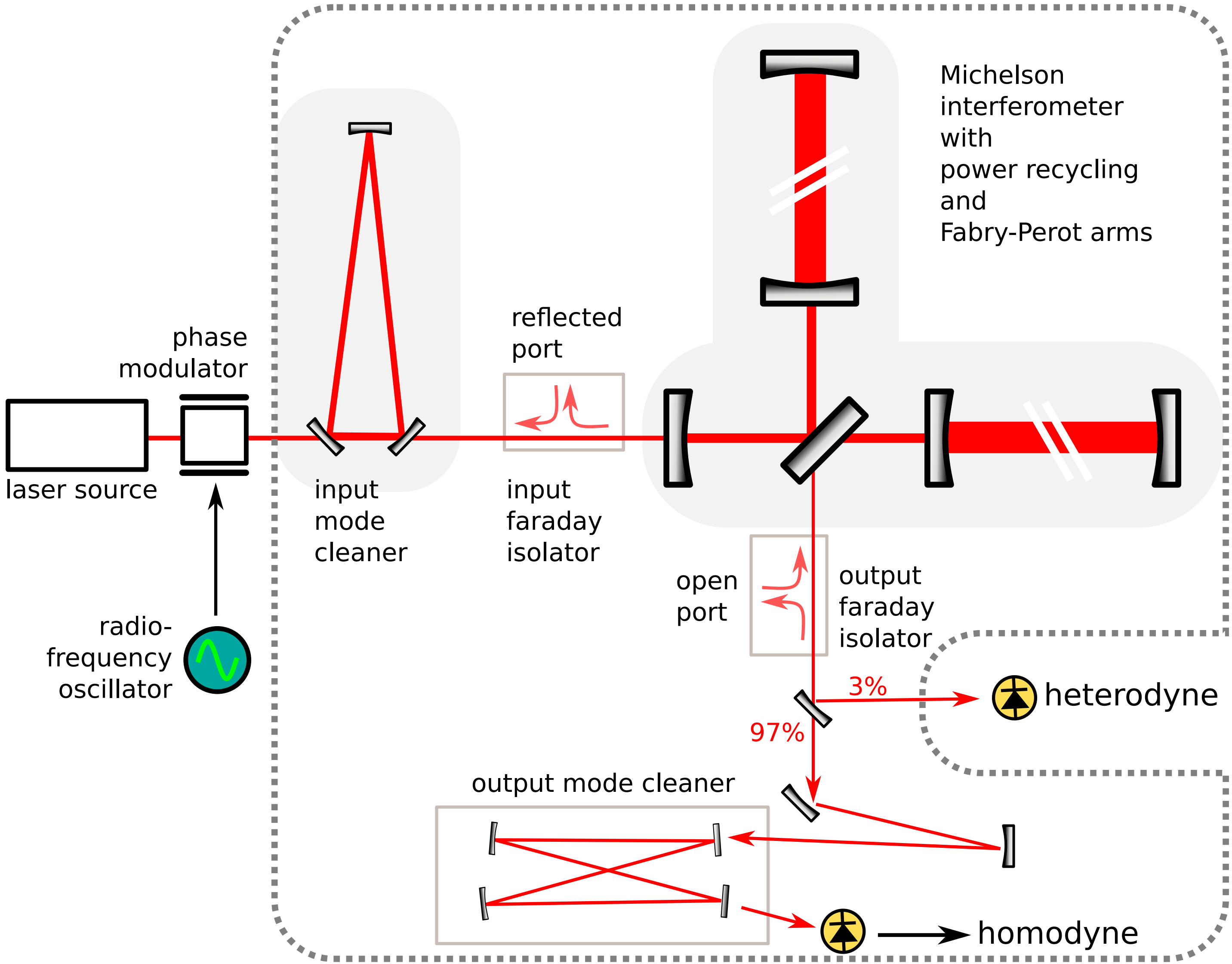
Drumhead Beacon Dither

Idea: Tag the photons in the arm by modulating the ETM

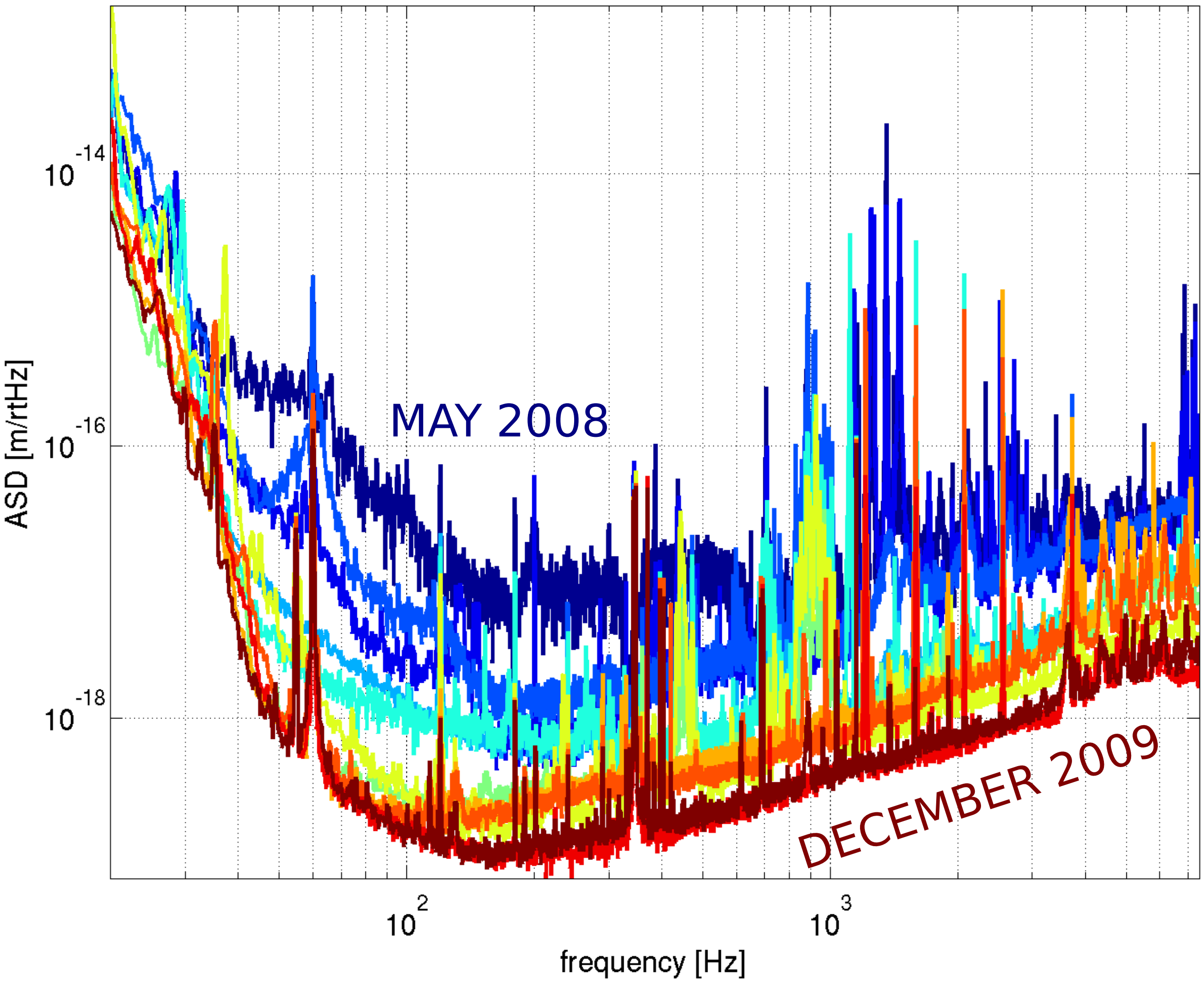


M.Evans/Nicolás(LHO)

The eLIGO interferometer

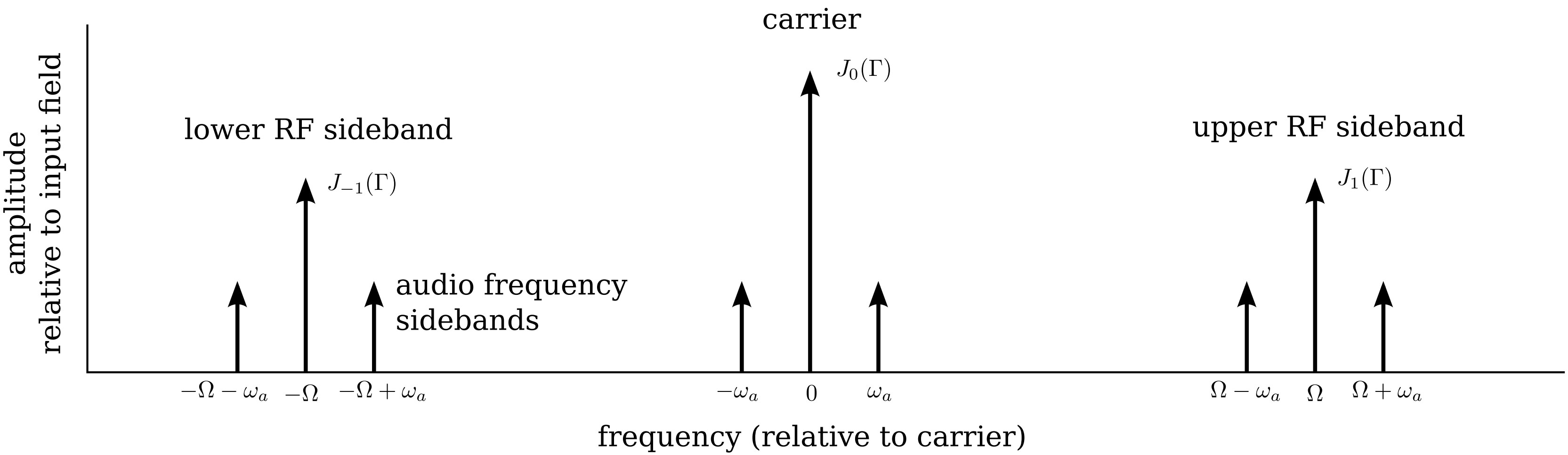


Commissioning



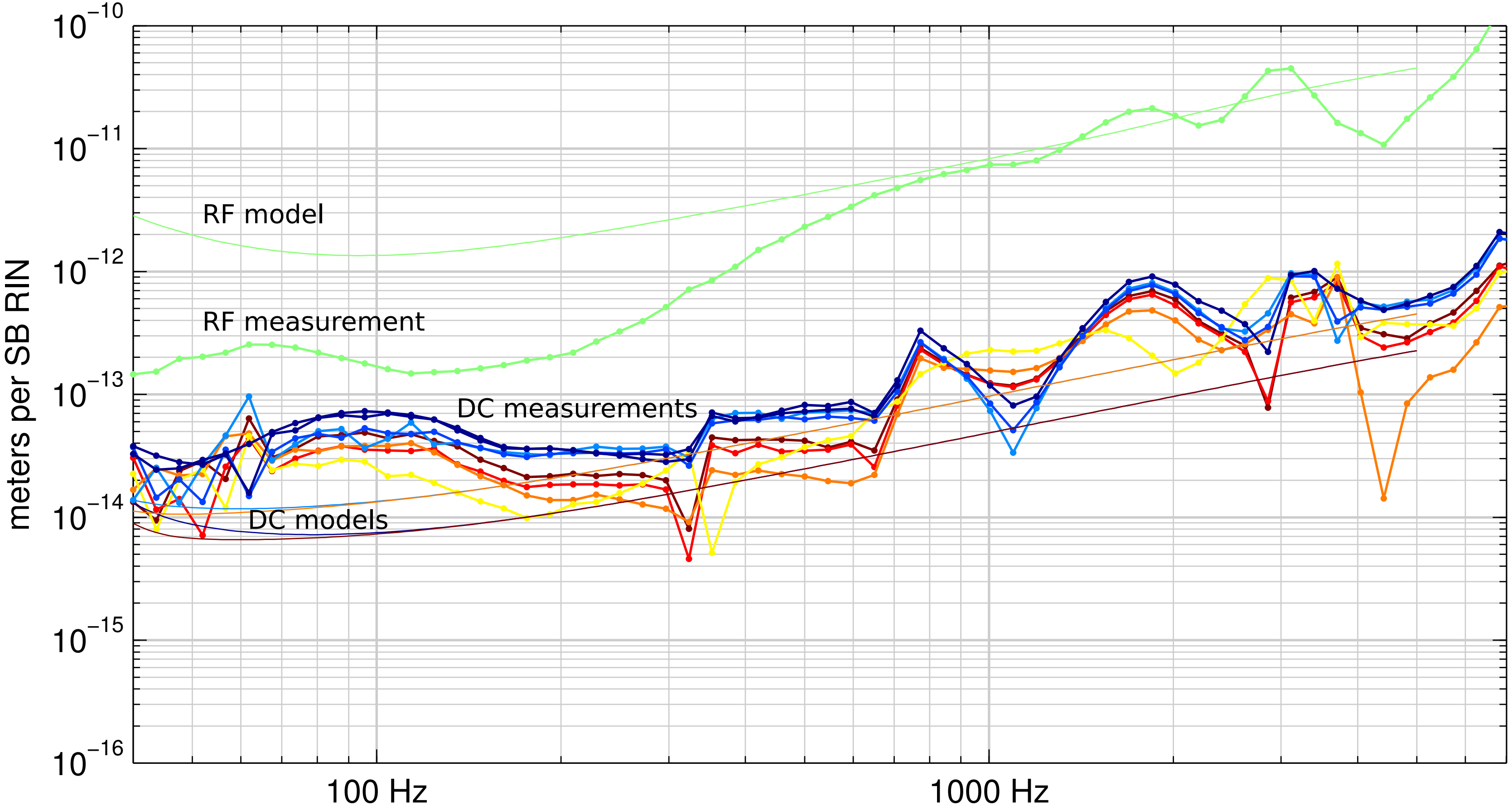
Noise Couplings

- Oscillator amplitude
- Oscillator phase
- Laser intensity
- Laser frequency

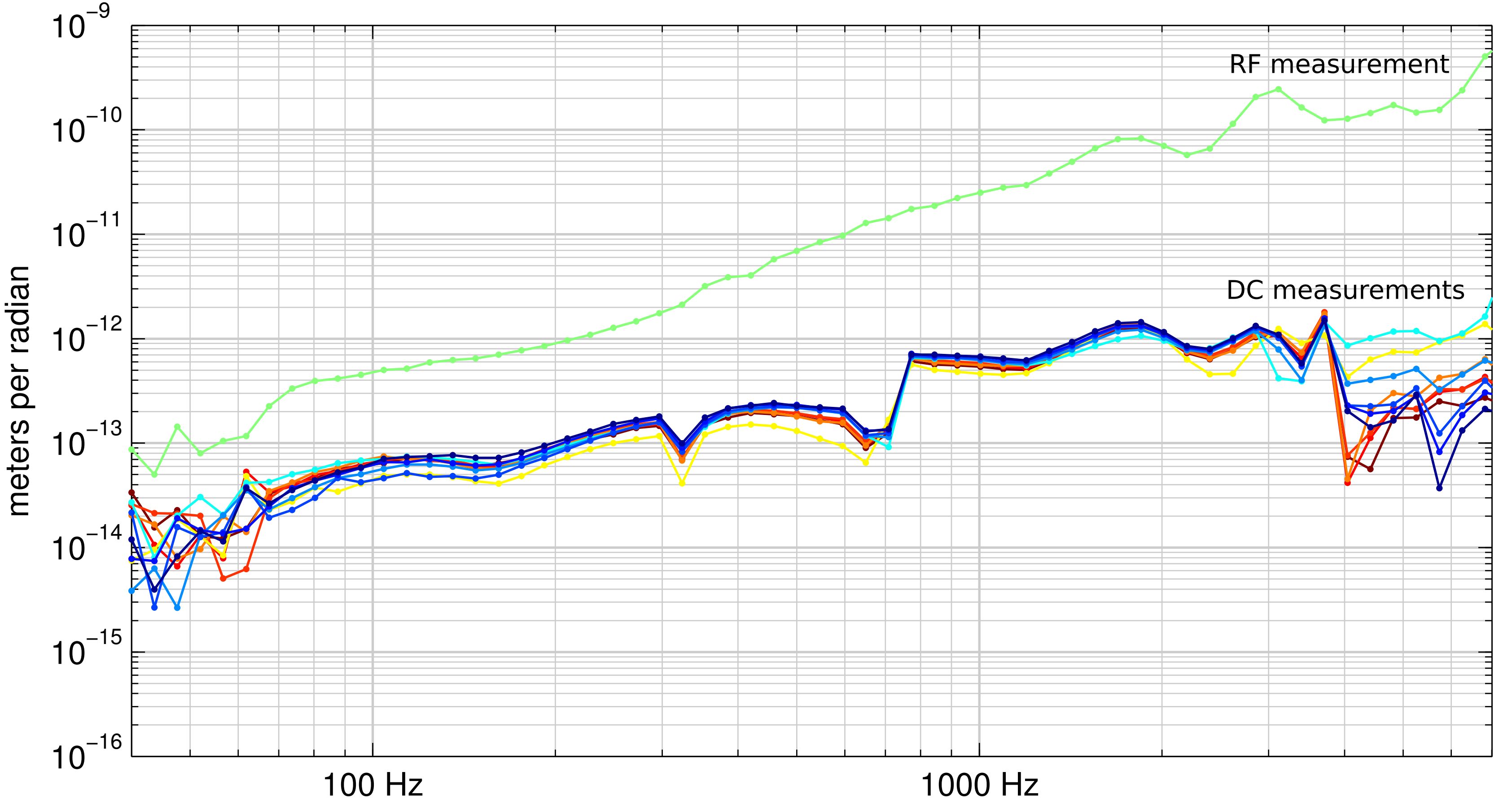


Ref: J. Camp, et al., J. Opt. Soc. Am. A/ Vol. 17, No. 1/January 2000

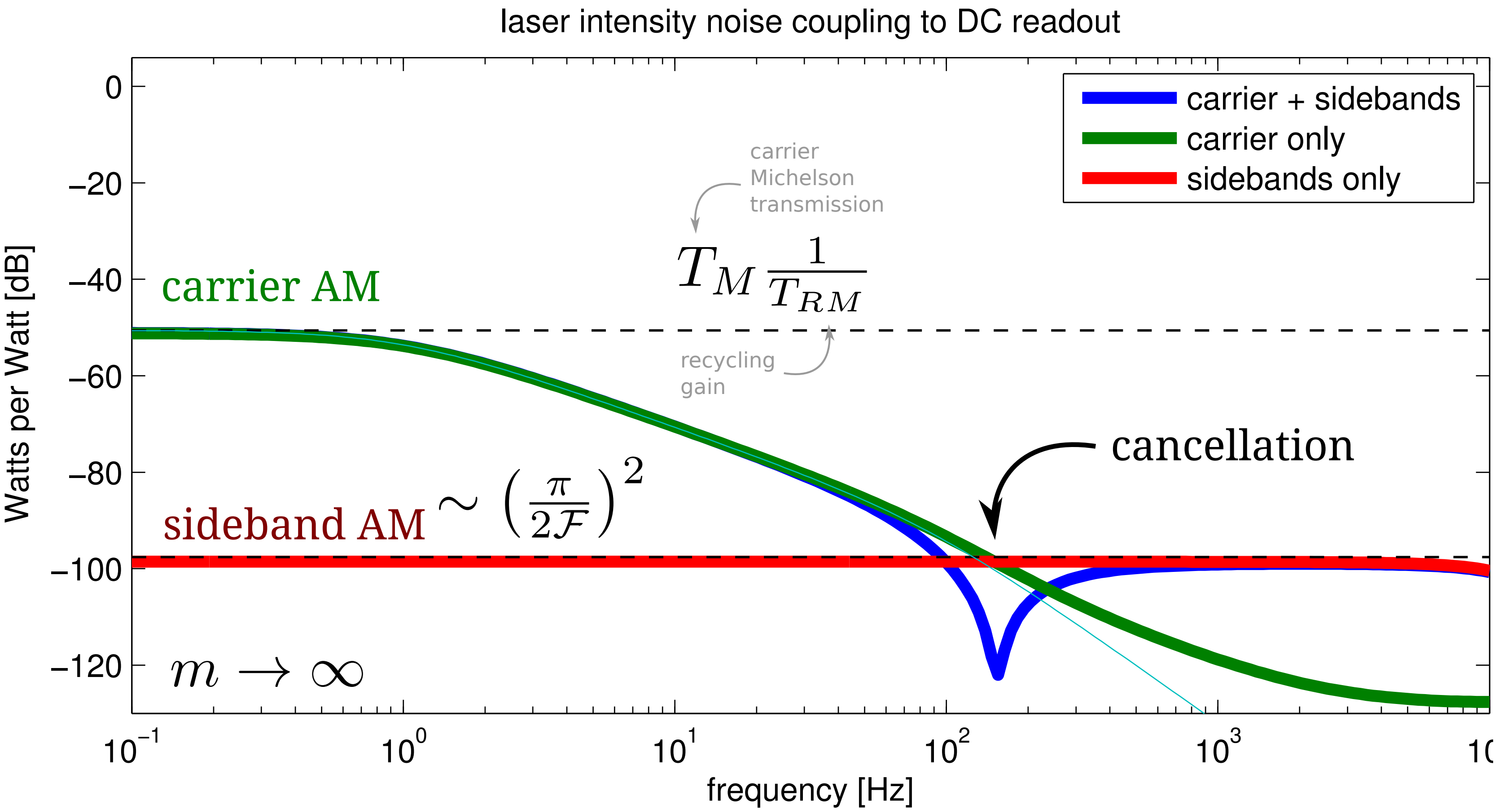
Oscillator Amplitude noise



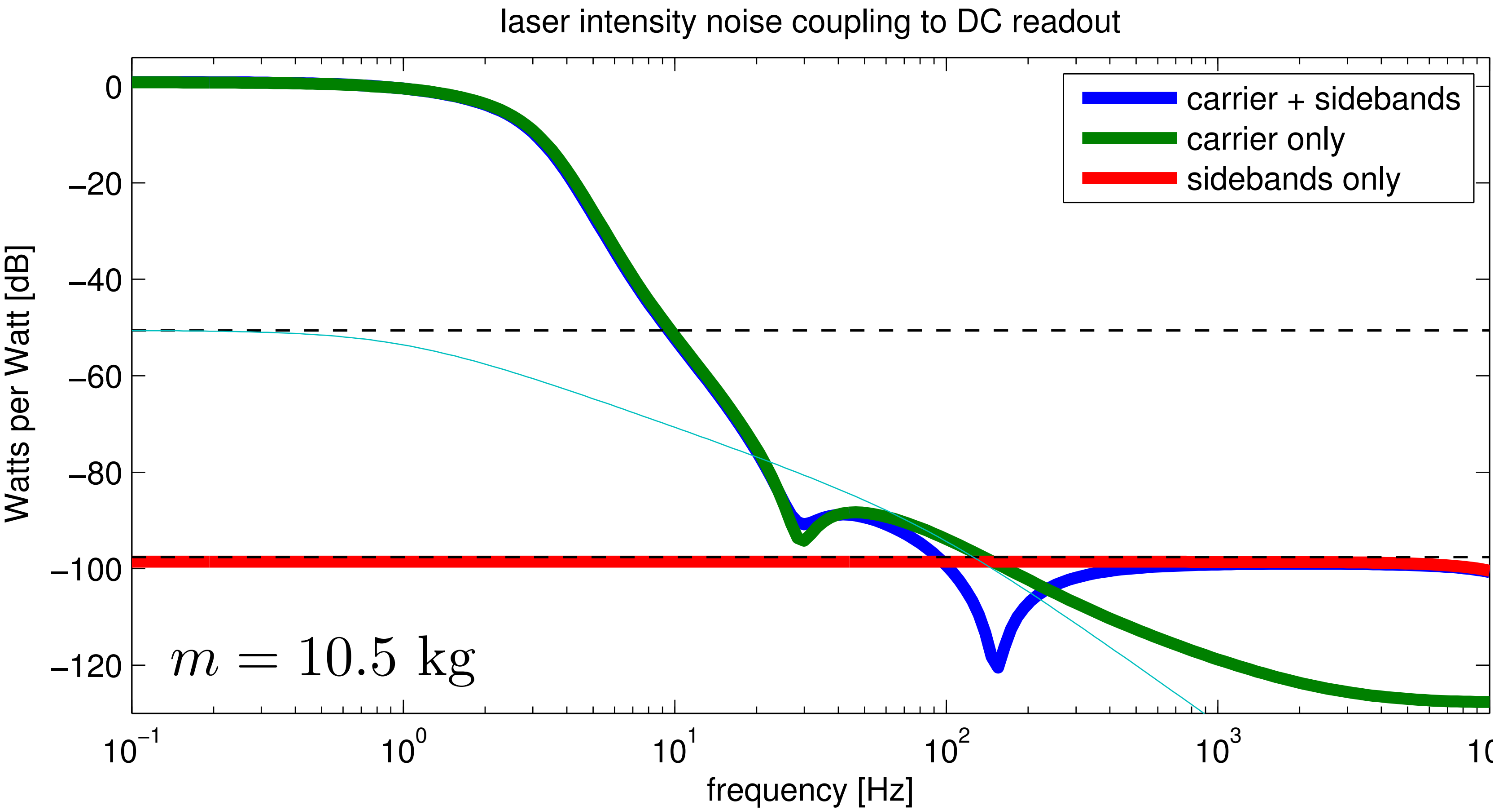
Oscillator Phase noise



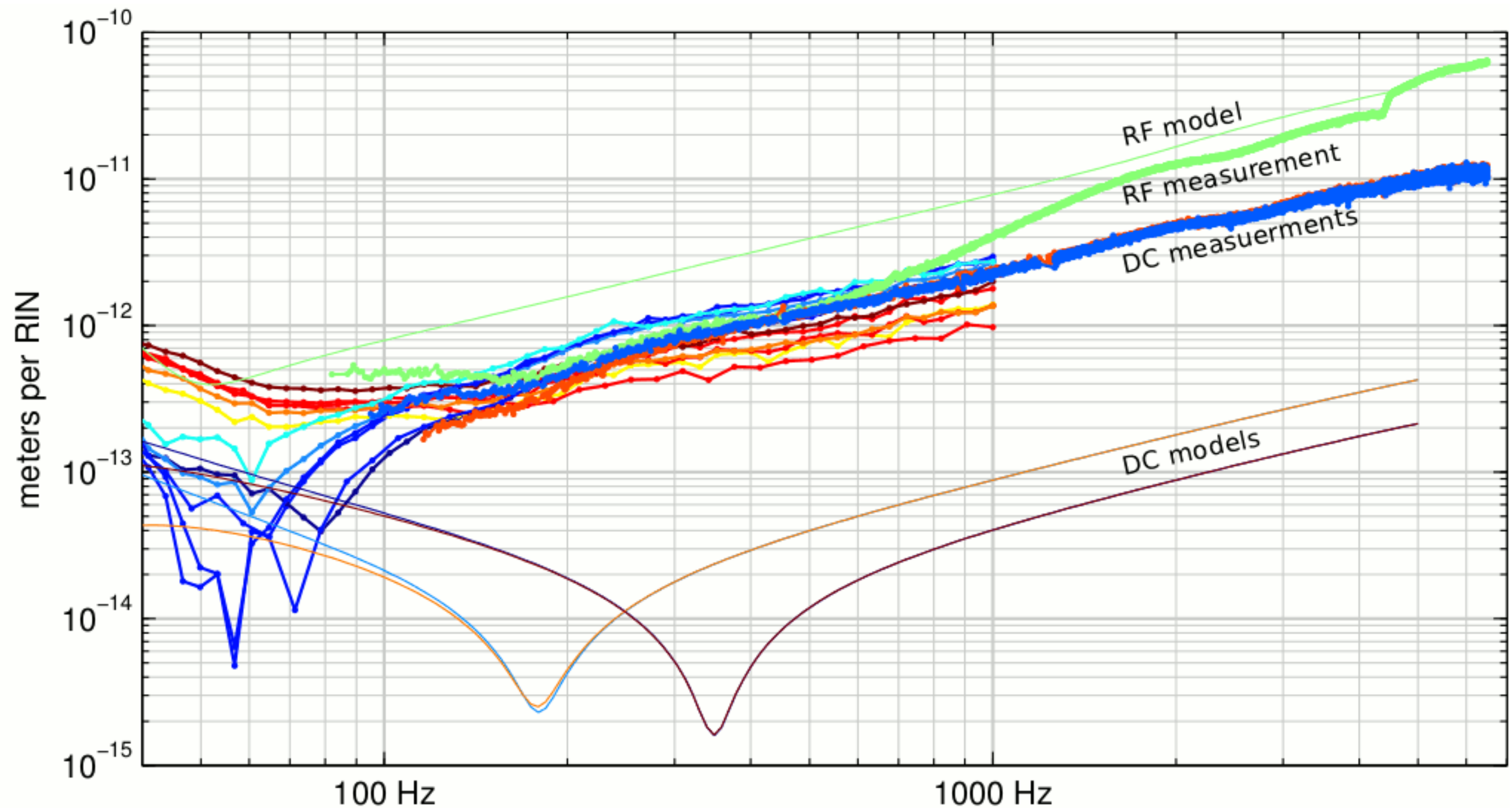
Anatomy of intensity noise coupling



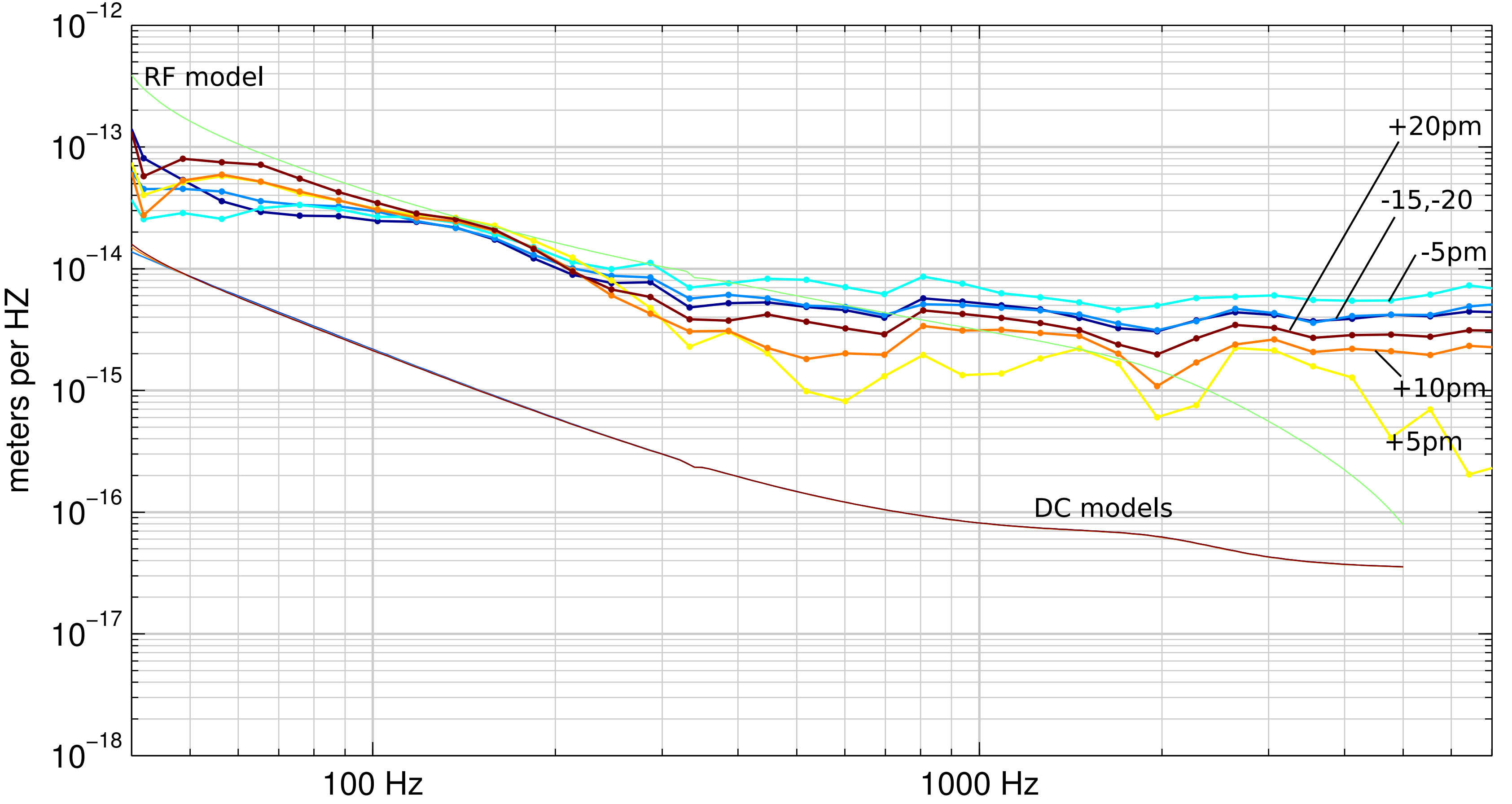
Anatomy of intensity noise coupling II



Laser intensity noise



Laser frequency noise

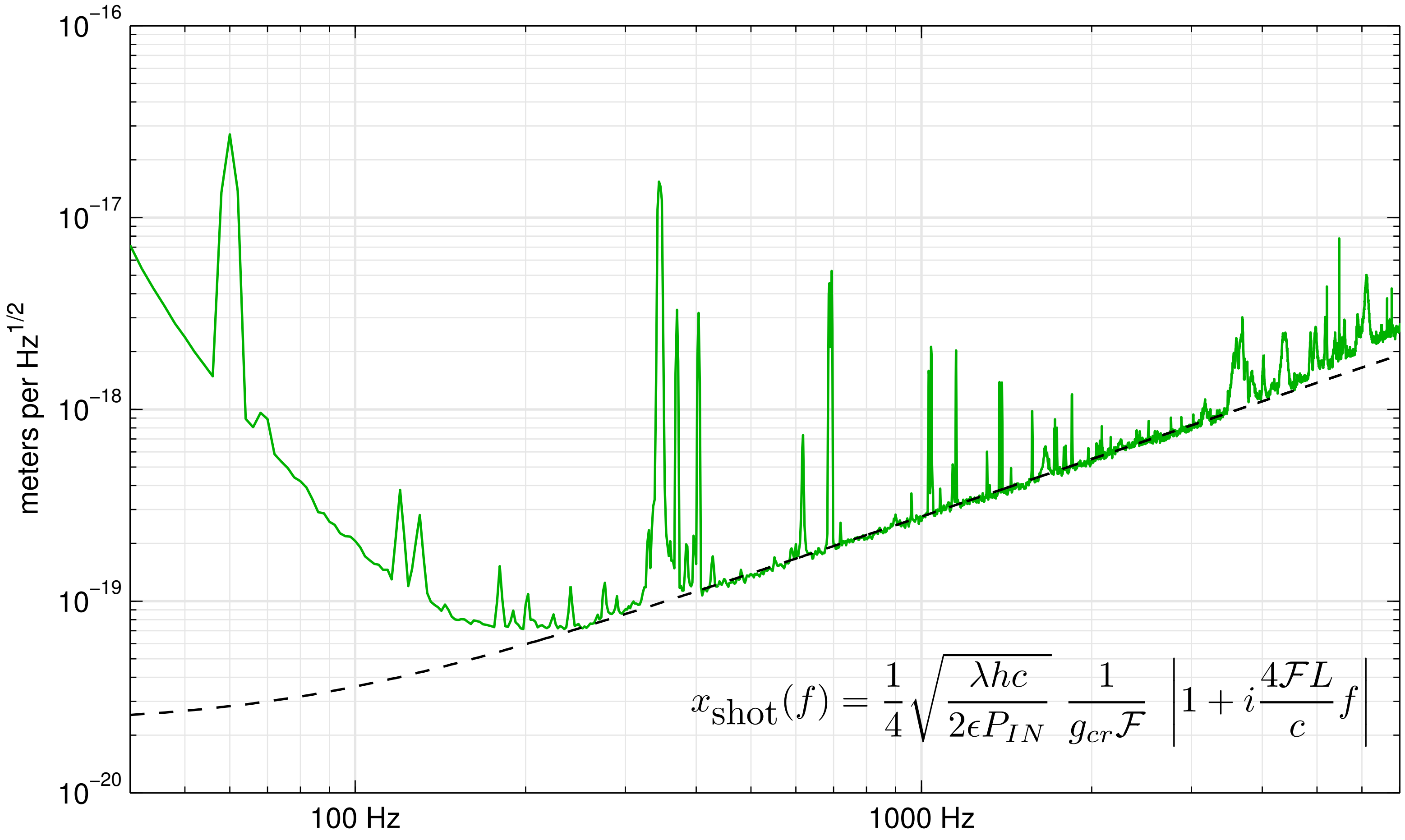


Shot noise

$$x_{\rm shot}(f) = \frac{1}{4}\sqrt{\frac{\lambda hc}{2\epsilon P_{IN}}}\ \frac{1}{g_{cr}\mathcal{F}}\ \left|1 + i\frac{4\mathcal{F}L}{c}f\right|$$

parameter	symbol	H1	L1
input power	P_{IN}	20.27 W	11.65 W
arm cavity pole	f_c	83.7 Hz	85.6 Hz
finesse	$\mathcal{F}_{\rm arm}$	224	219
power recycling gain	${g_{cr}}^2$	59	41
carrier fraction after phase modulation	$J_0(\Gamma)^2$	0.94	0.95
input optics		0.82	0.75
interferometer mode-matching		0.92	0.92
output faraday isolator transmission		0.94	0.98
DC readout pickoff fraction		0.953	0.972
OMC mode-matching		0.70	0.95
OMC transmission and PD quantum efficiency		0.95	0.95
net power efficiency	ϵ	0.42	0.56

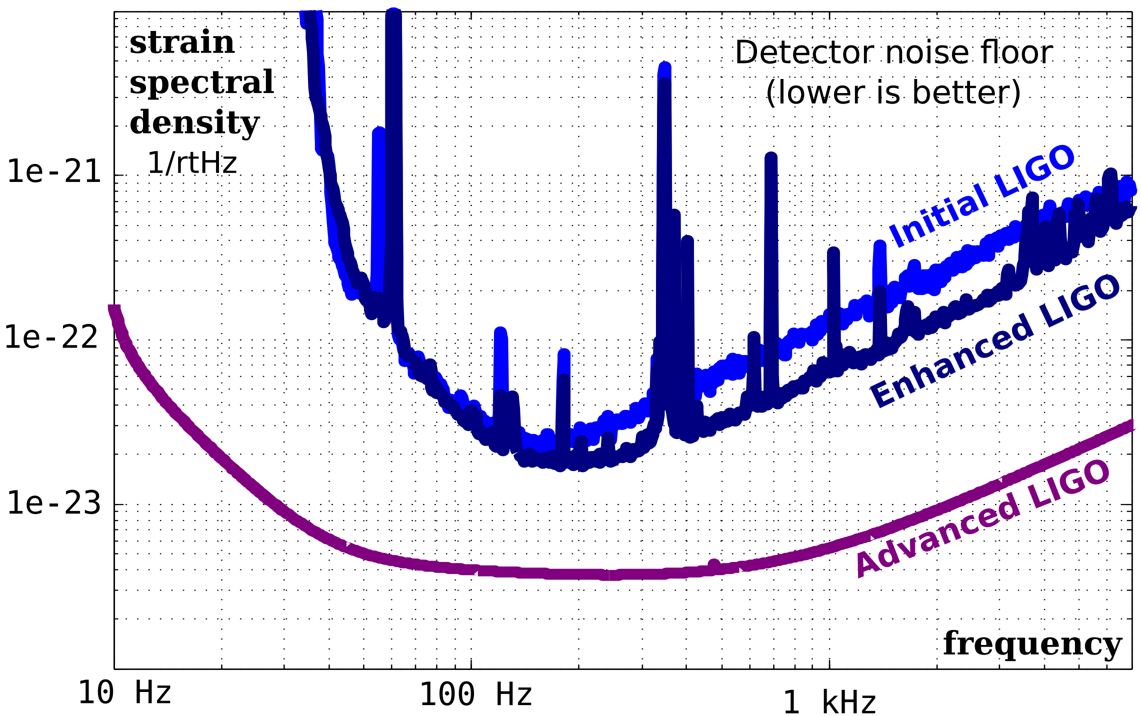
Shot noise II



$$x_{\text{shot}}(f) = \frac{1}{4}\sqrt{\frac{\lambda hc}{2\epsilon P_{IN}}}\ \frac{1}{g_{cr}\mathcal{F}}\ \left|1 + i\frac{4\mathcal{F}L}{c}f\right|$$

Summary

- Installed OMC and set up DC readout
- Commissioned control systems for OMC and DC readout
- Measured and modeled noise couplings
- Modeled and verified shot-noise performance
- paper: `http://arxiv.org/abs/1110.2815`

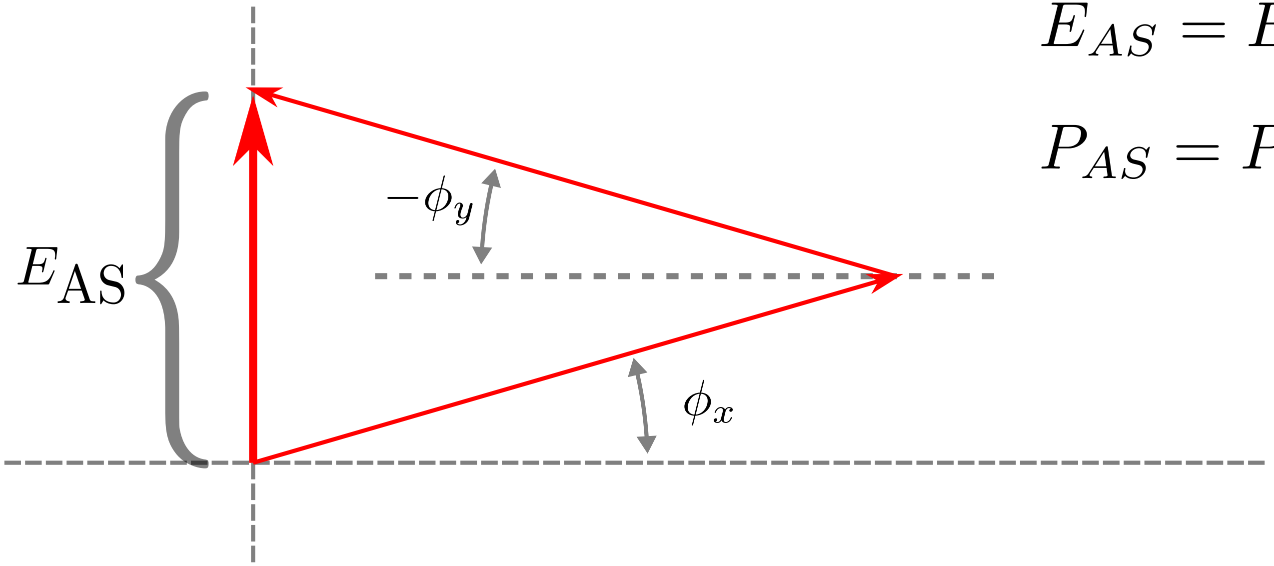


walrus without tusks

Thanks for listening!

Special thanks to
Gaby González, Valera Frolov,
Rana Adhikari, Adrian Melissinos, and
everyone who worked on Enhanced LIGO.

DC Readout: phasor view



$$E_{AS} = E_{BS} \sin(\delta\phi)$$

$$P_{AS} = P_{BS} \sin^2(\delta\phi)$$

optical gain: $S_{DC} = \frac{\partial P}{\partial x} \approx 2\sqrt{P_{BS} P_{AS}}\,(137)\left(\frac{f_c}{f}\right)\left(\frac{2\pi}{\lambda}\right)$

How do we choose the DARM offset?

- Must be much greater than residual DARM displacement
- Must overcome contrast defect and electronics noise
- But not excessively detrimental to power recycling

In practice: turn the knob to get the best sensitivity