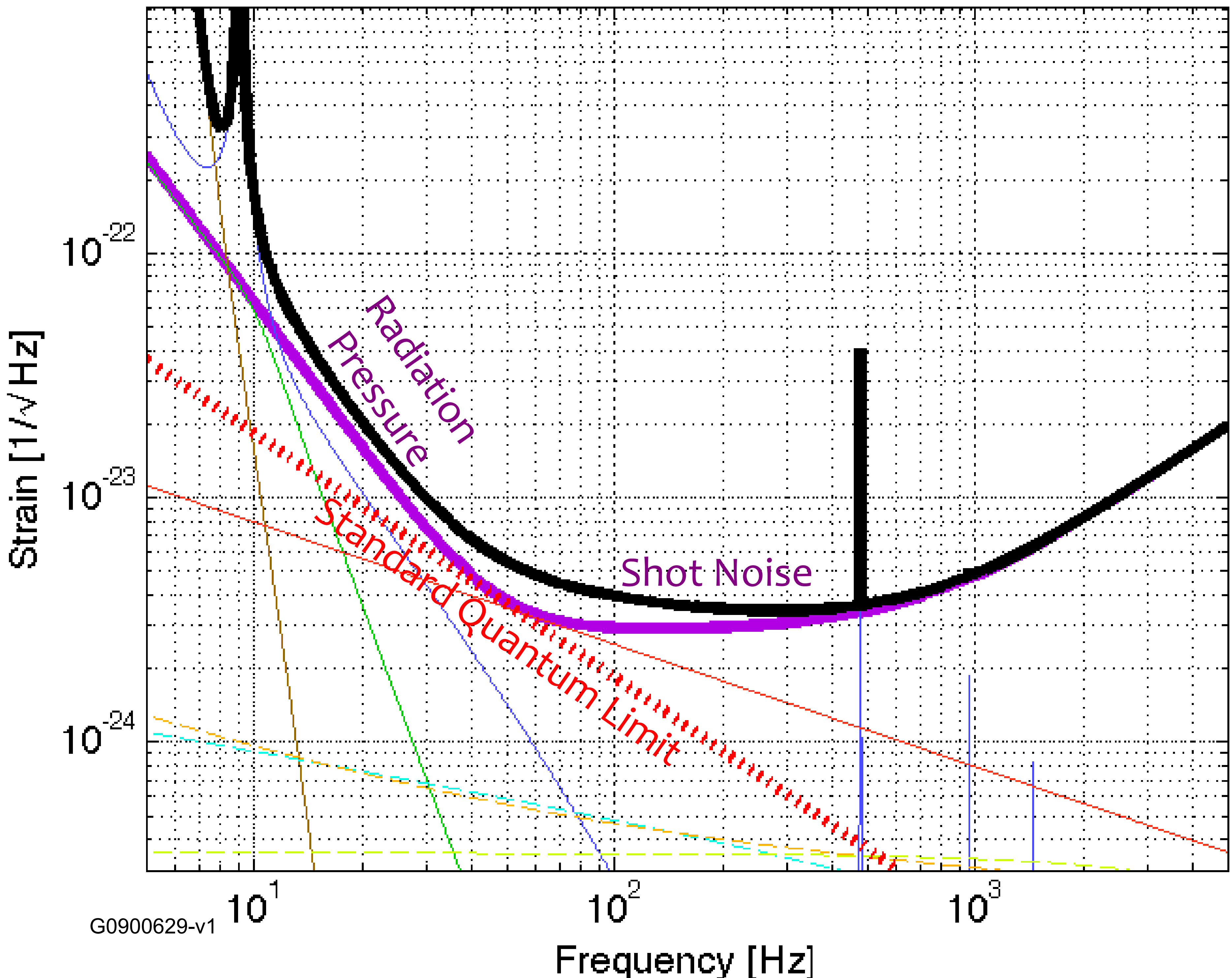
Experimental progress with the quantum noise limit

Christopher Wipf

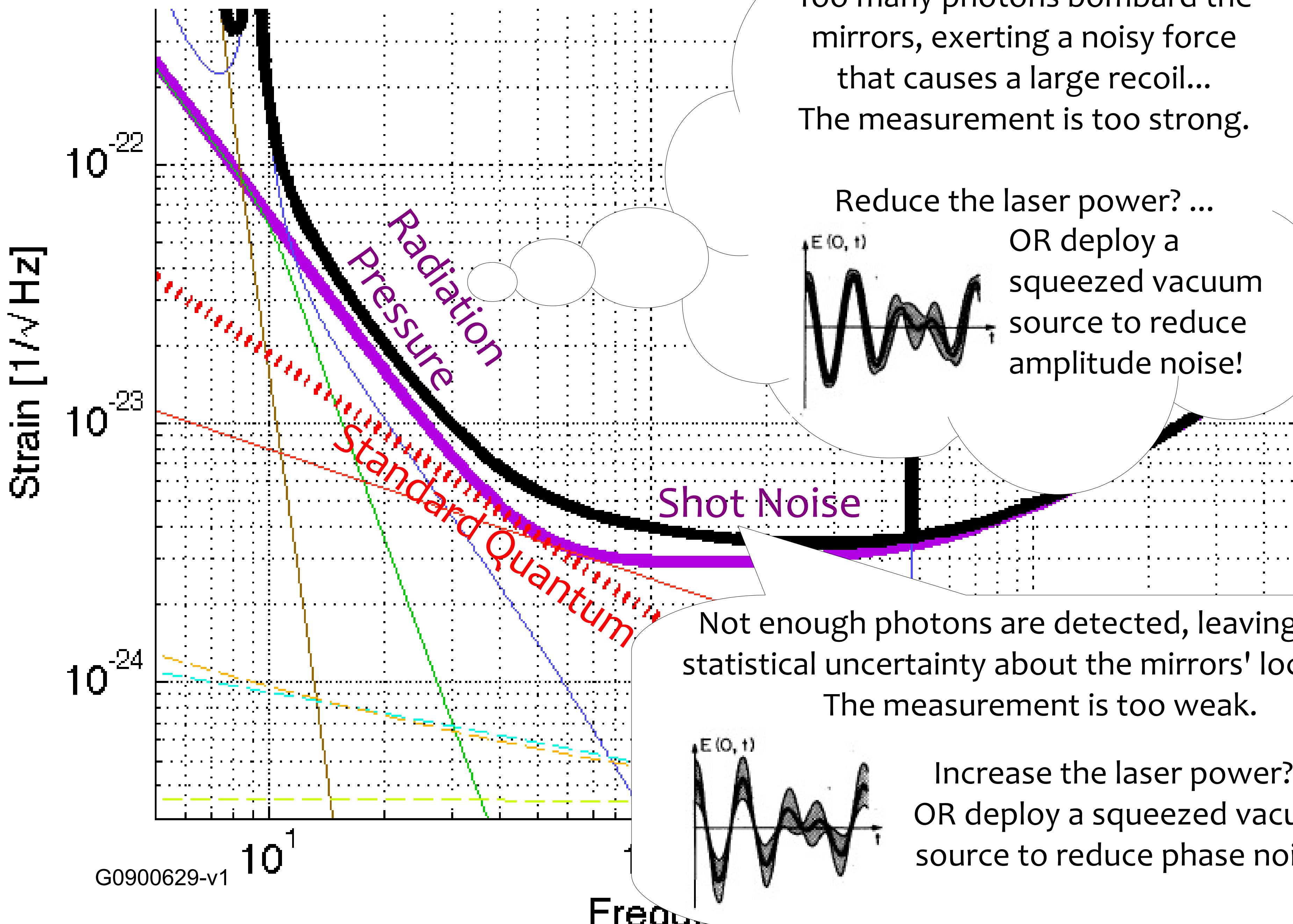
GWADW 2009

G0900629-v1

In Advanced Detectors, Quantum Noise Is Everywhere!



Mechanism



Too many photons bombard the mirrors, exerting a noisy force that causes a large recoil...
The measurement is too strong.

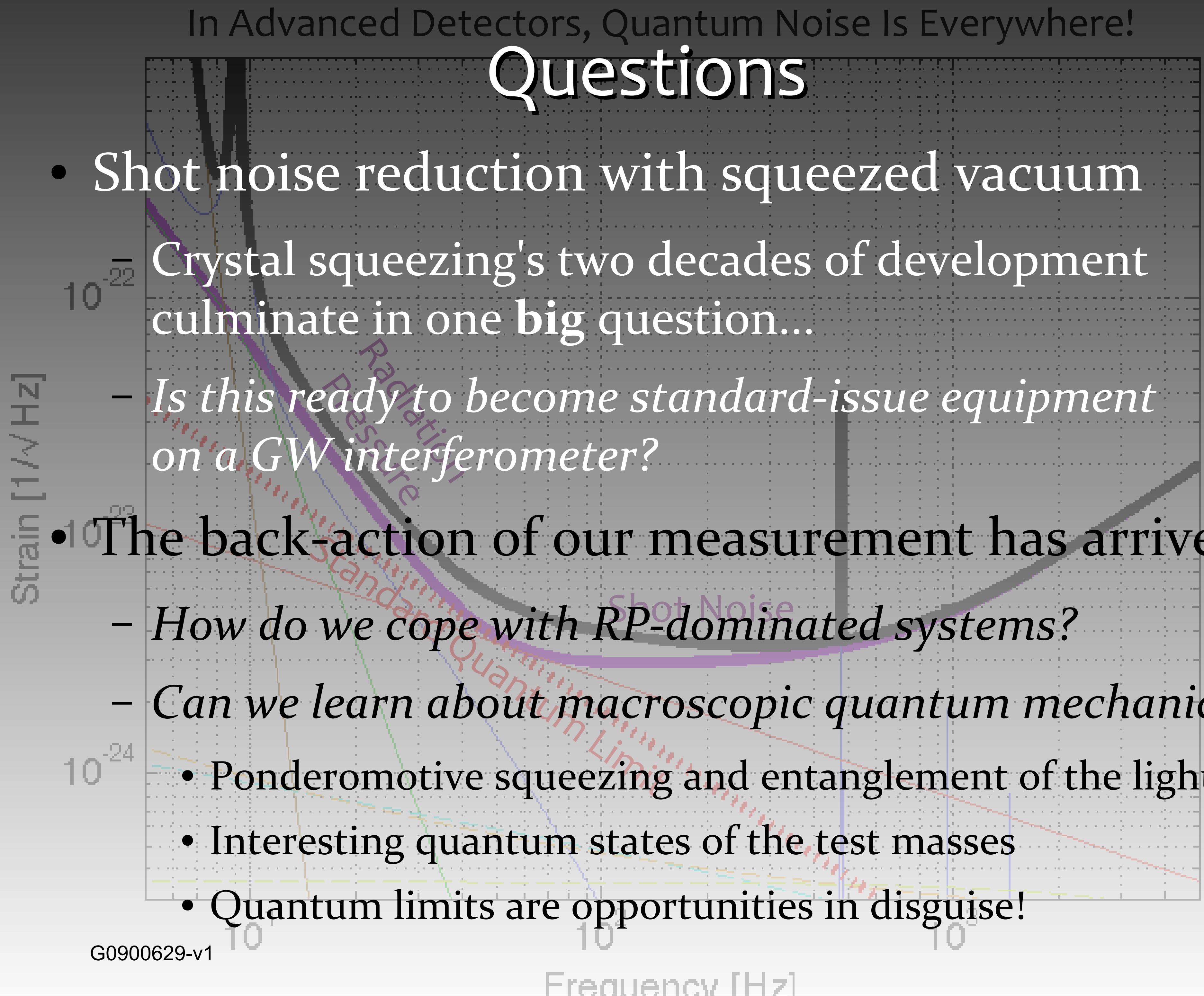
Reduce the laser power? ...
OR deploy a squeezed vacuum source to reduce amplitude noise!

Not enough photons are detected, leaving some statistical uncertainty about the mirrors' location...
The measurement is too weak.

Increase the laser power? ...
OR deploy a squeezed vacuum source to reduce phase noise!

Questions

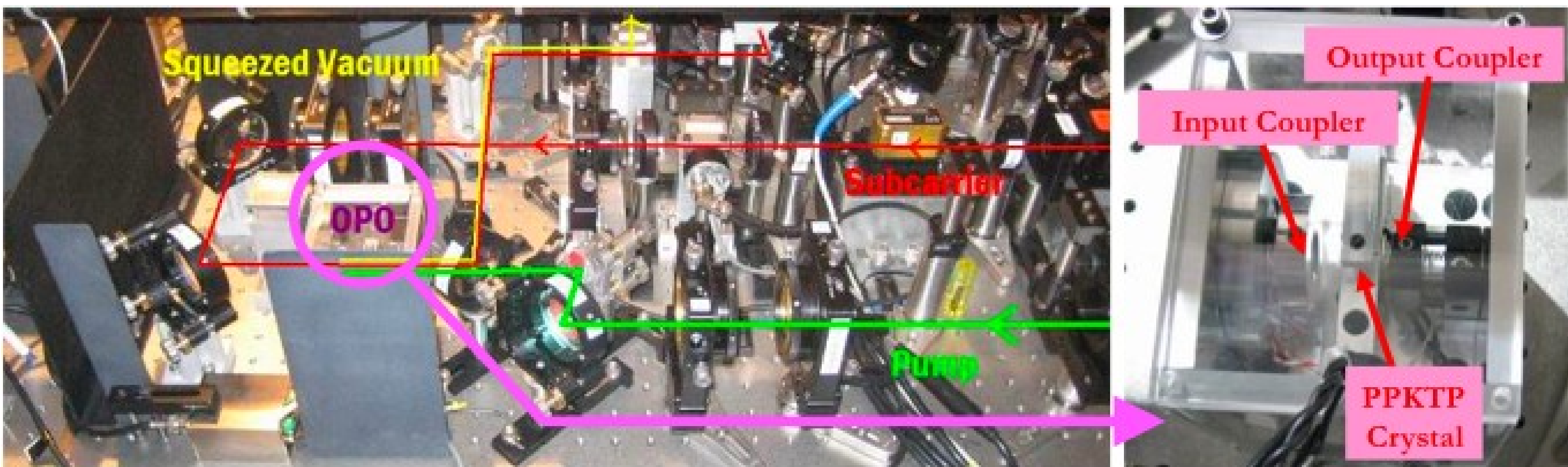
- Shot noise reduction with squeezed vacuum
  - Crystal squeezing's two decades of development culminate in one **big** question…
  - *Is this ready to become standard-issue equipment on a GW interferometer?*
- The back-action of our measurement has arrived
  - *How do we cope with RP-dominated systems?*
  - *Can we learn about macroscopic quantum mechanics?*
    - Ponderomotive squeezing and entanglement of the light
    - Interesting quantum states of the test masses
    - Quantum limits are opportunities in disguise!



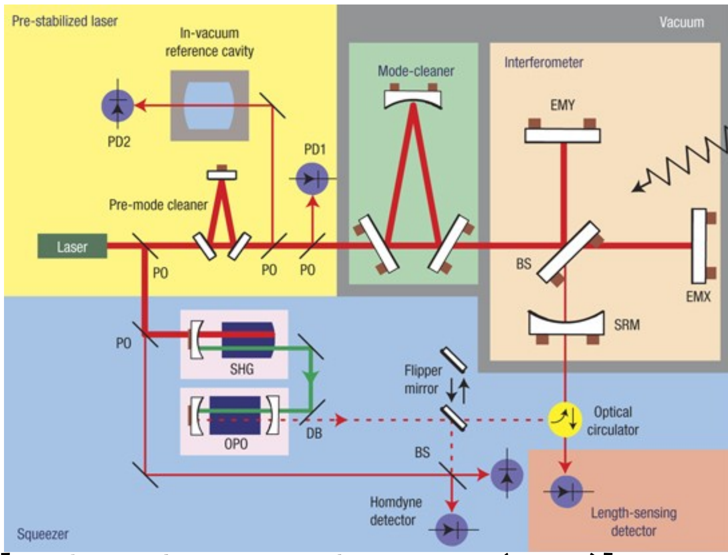
G0900629-v1

Squeezing with nonlinear crystals

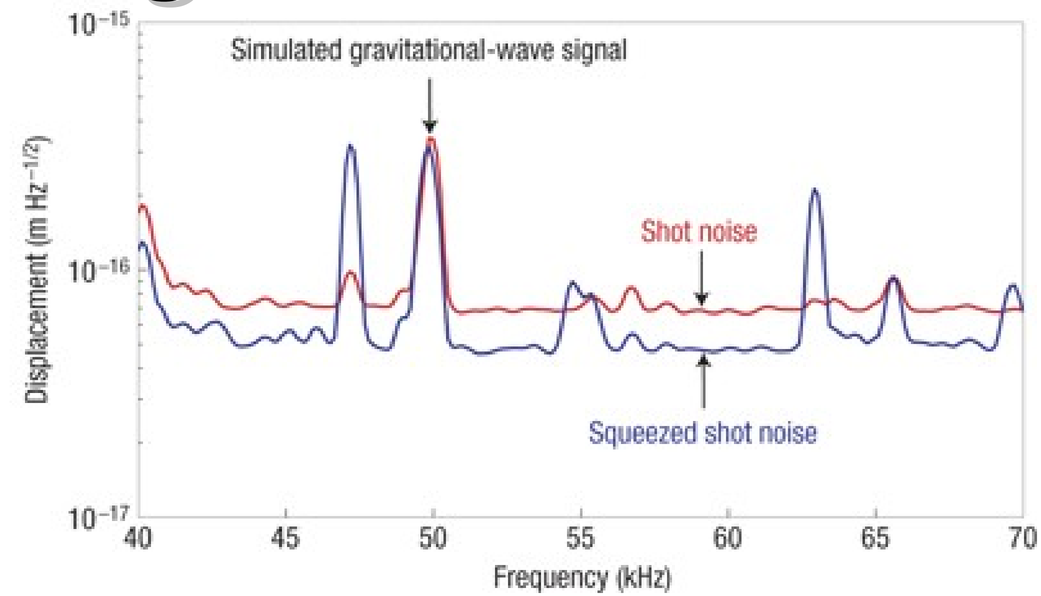
- Amplitude and phase correlated via Kerr effect (Refractive index $\Delta n \sim$ intensity I)
- Needs a bright frequency-doubled "pump" beam
- Use a cavity to amplify the effect



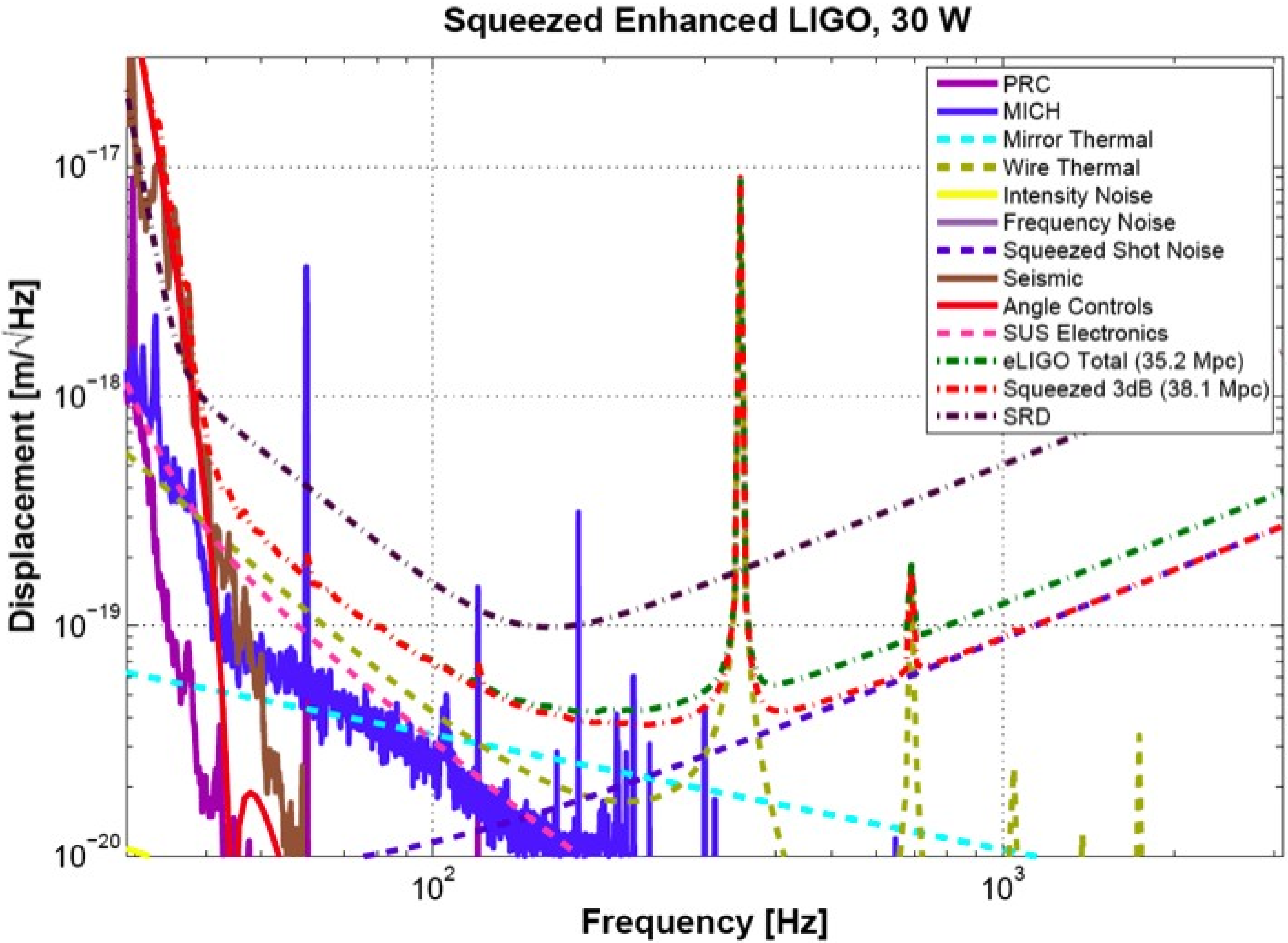
Time for a squeezing-enhanced LIGO ?



[Goda et al., Nature Phys. 4 472 (2008)]



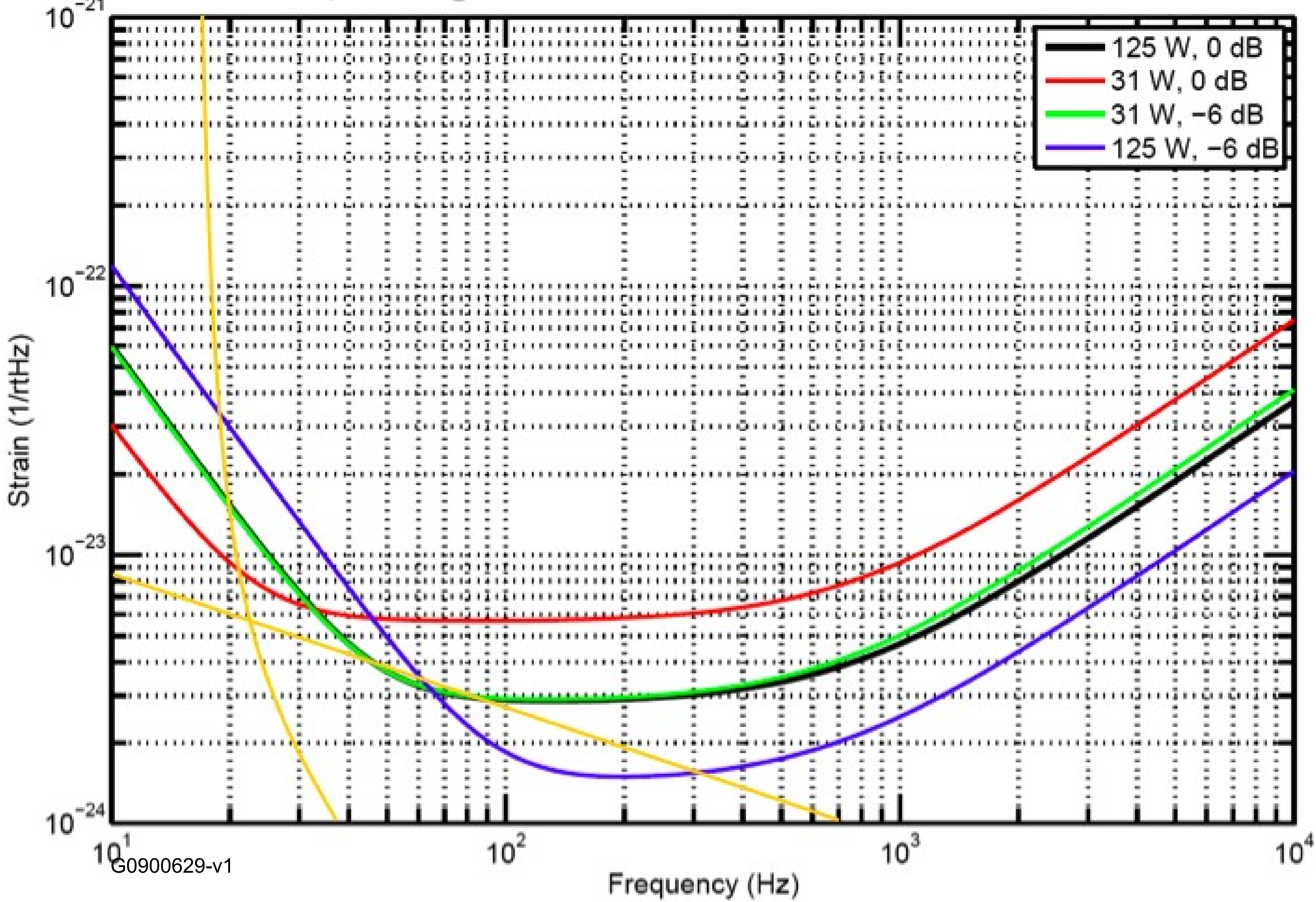
- Successful proof of principle at Caltech 40m IFO
- VLF squeezing (sub-10 Hz!) achieved at AEI
- Possible opportunity to test on H1 after S6
- Meet our sensitivity goals using less laser power
  - Fewer headaches from RP instability, thermal lensing



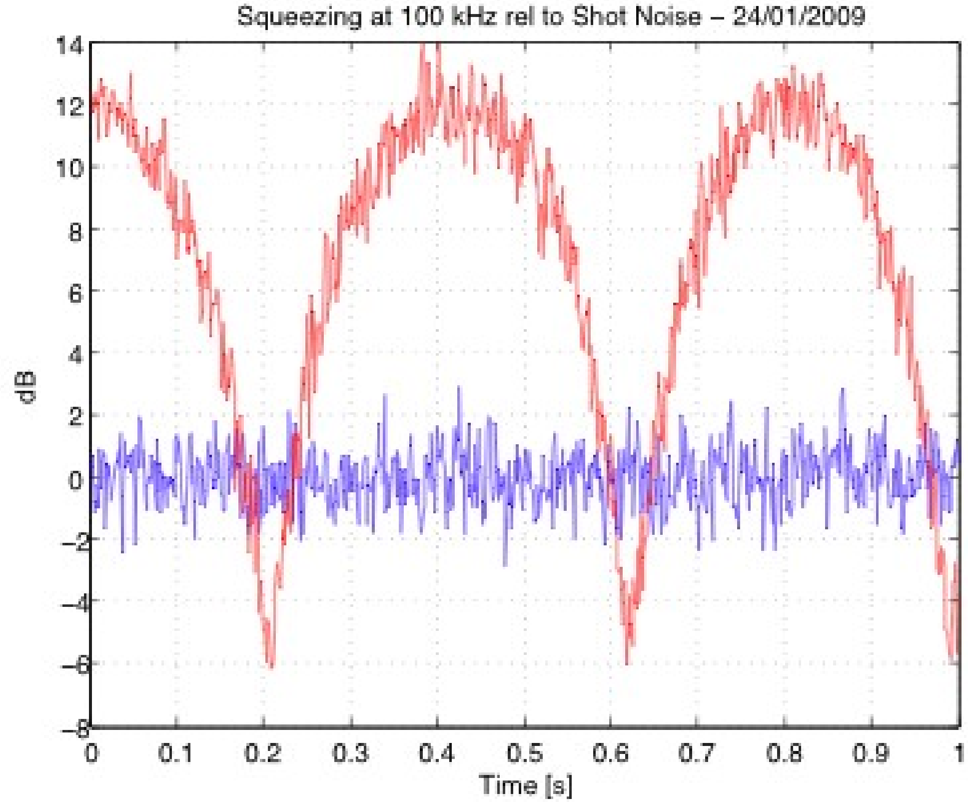
Squeezed Enhanced LIGO, 30 W
PRC
MICH
Mirror Thermal
Wire Thermal
Intensity Noise
Frequency Noise
Squeezed Shot Noise
Seismic
Angle Controls
SUS Electronics
eLIGO Total (35.2 Mpc)
Squeezed 3dB (38.1 Mpc)
SRD
Displacement [m/√Hz]
Frequency [Hz]
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{2}
10^{3}

G0900629-v1

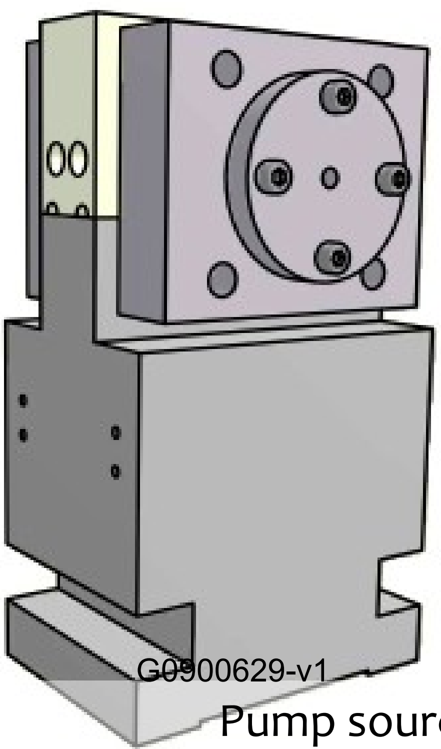
Squeezing enhancement of Advanced LIGO

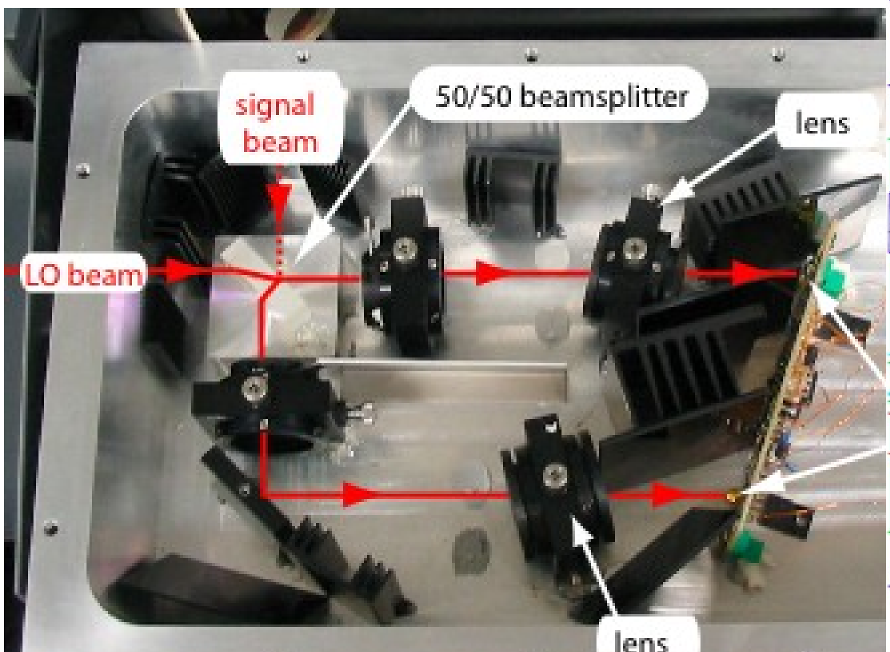


G0900629-v1



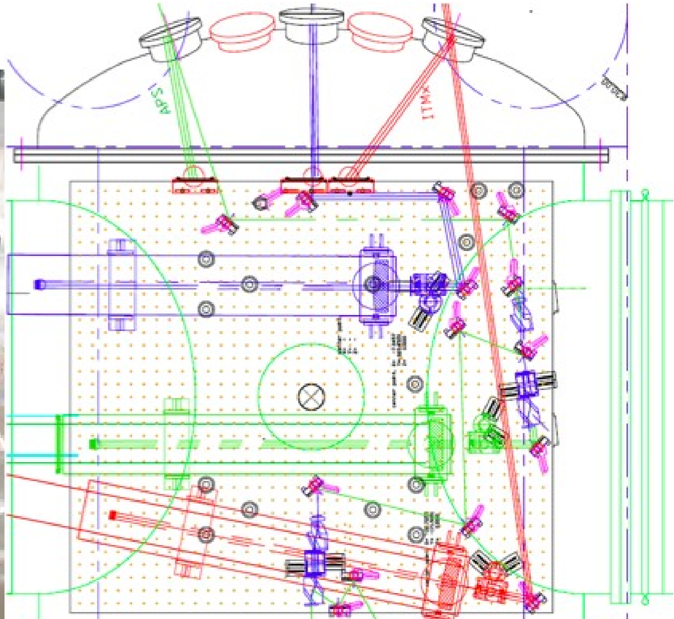
Squeeze source (ANU)





G0900629-v1

Pump source & homodyne detector (AEI)



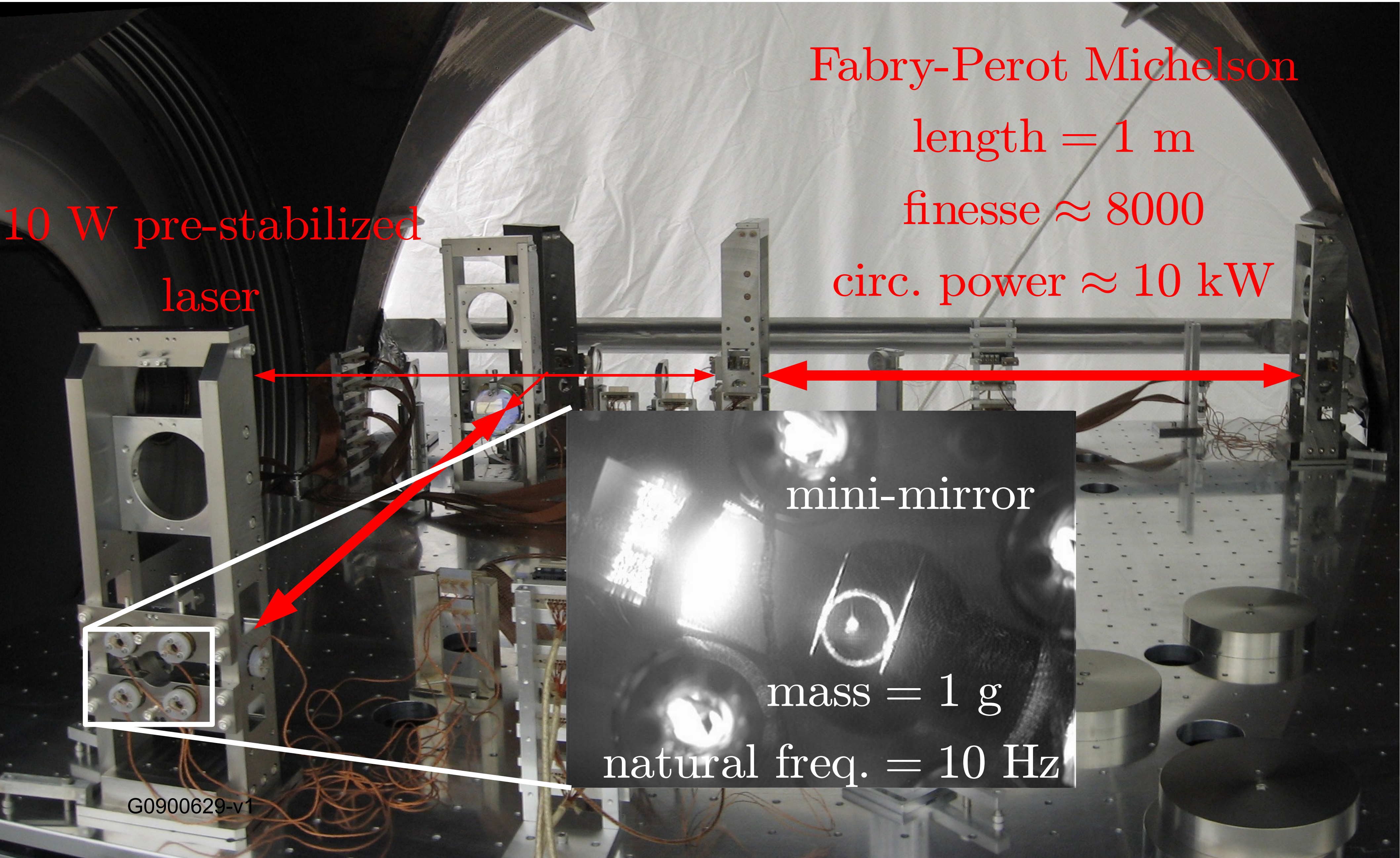
lasers and controls integration and test on H1 (MIT, LHO)

Coming soon to a detector near you…

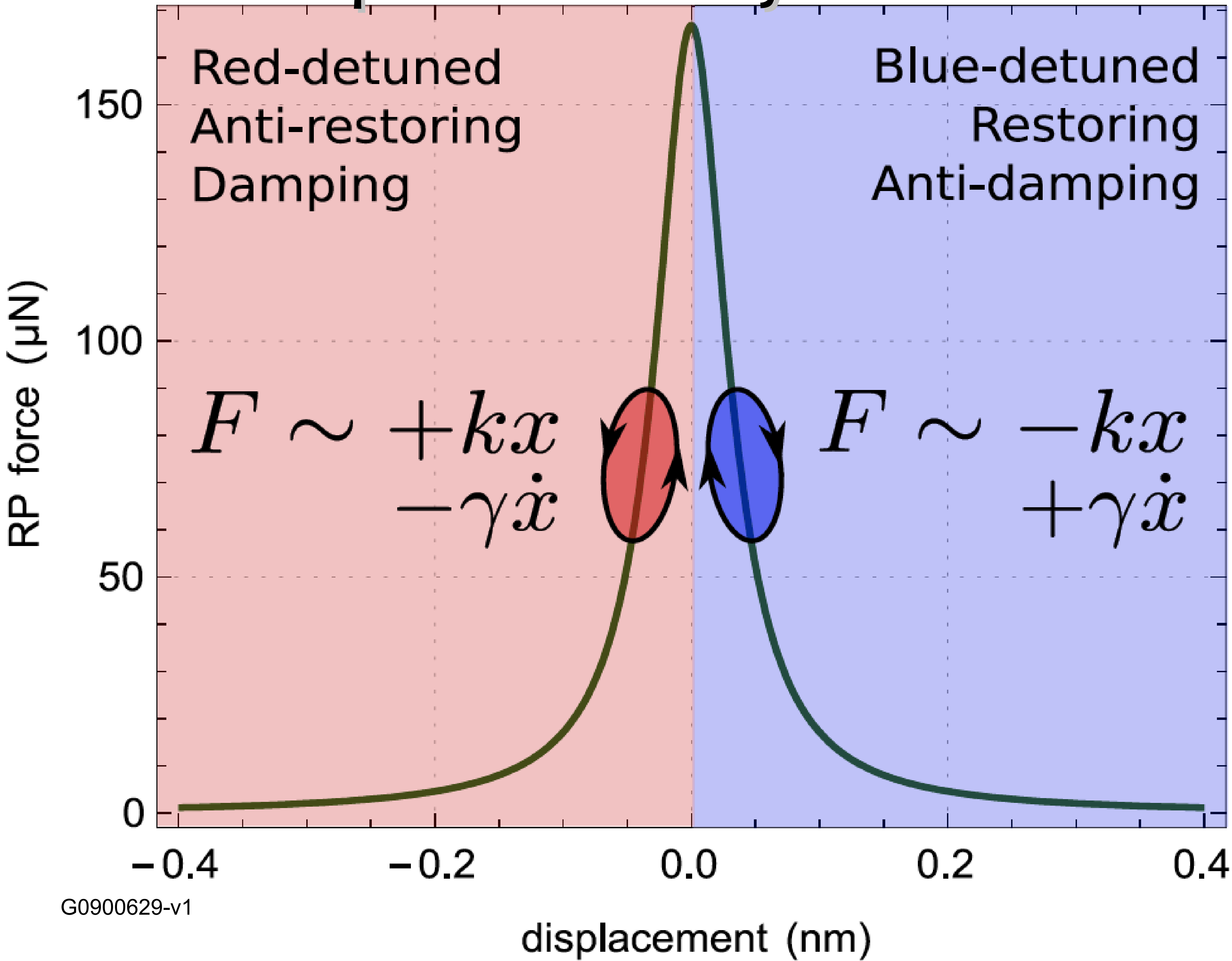
- First funds approved
- Laser, AEI SHG now being integrated at MIT
- OPO development ongoing at ANU
- Servo electronics (advLIGO prototypes) in progress at LHO
- No time to lose – we must be ready to go by 15 Feb 2011

G0900629-v1

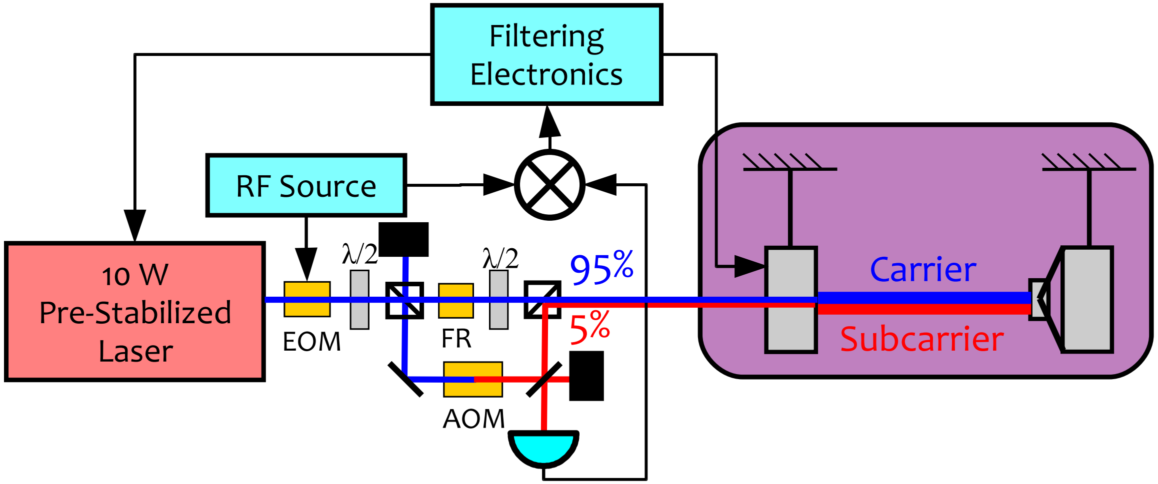
Back-action machine

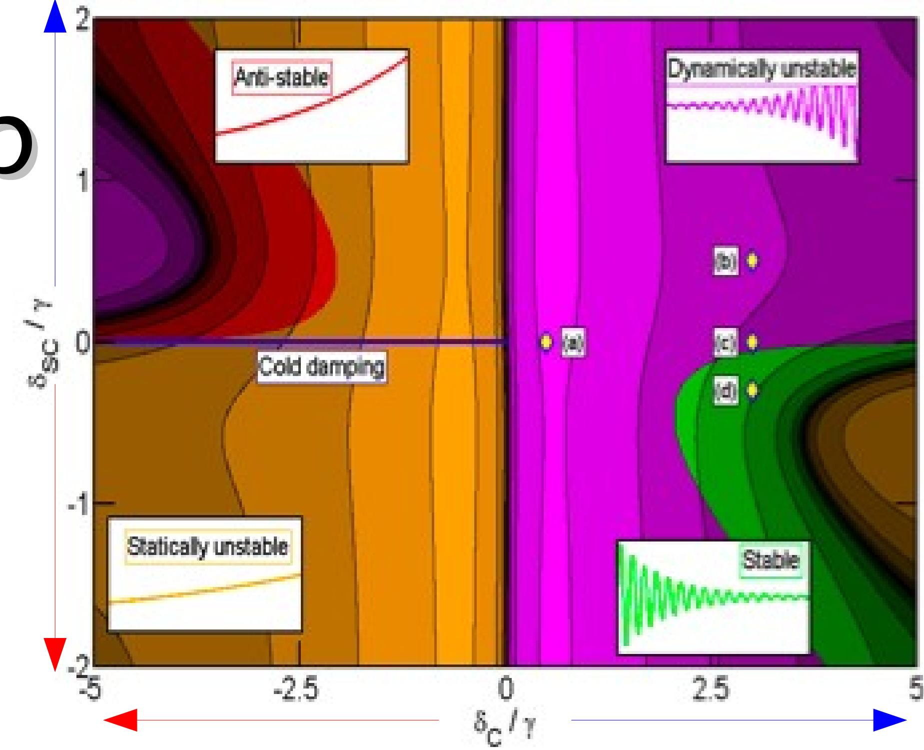


Radiation pressure's dynamical effects



Springing an optical trap



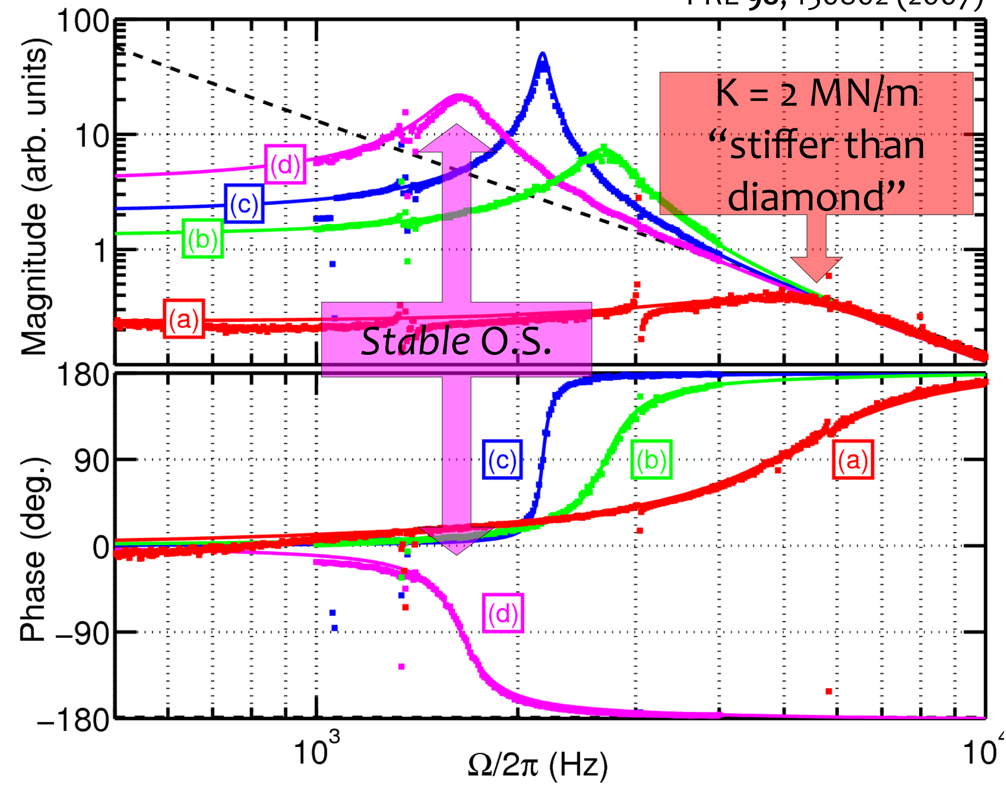


- Extreme optical rigidity
- Stable, self-locked system
- "Cold" optical forces dominate dynamics

$$S_F = 4k_B T \frac{\Gamma_{\rm mech}}{M} \approx 4k_B T_{\rm eff} \frac{\Gamma_{\rm opt}}{M}$$

thermal occupation number $N \sim \frac{k_B T_{\rm eff}}{\hbar \Omega_{\rm eff}}$

PRL **98**, 150802 (2007)



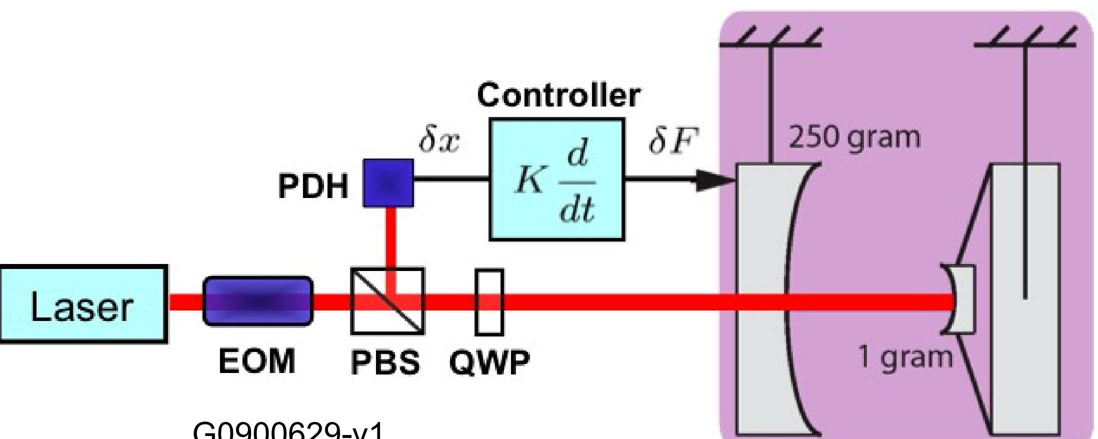
Feedback cooling

We are here!

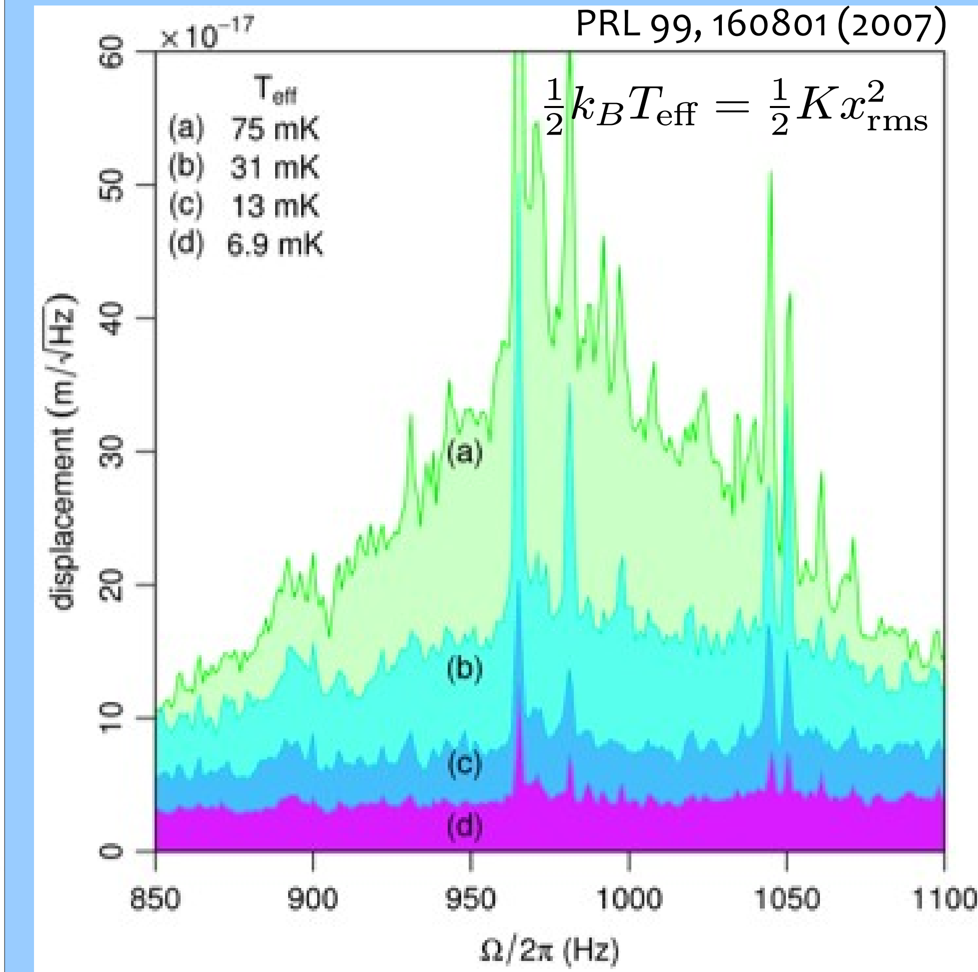
cavity "leakiness"

$\frac{\gamma_c}{\Omega_{\text{eff}}} \ll 1$	$\frac{\gamma_c}{\Omega_{\text{eff}}} \gg 1$
state remains pure	weak self-cooling
strong self-cooling	strong measurement
$N \rightarrow 0$	$N \rightarrow 0$
via self-cooling	via feedback control

Feedback forces can be "cold" when sensing noise is low!



G0900629-v1



1 kHz OS stabilized, damped by feedback

$N = 10^5$ constrained by laser frequency noise!

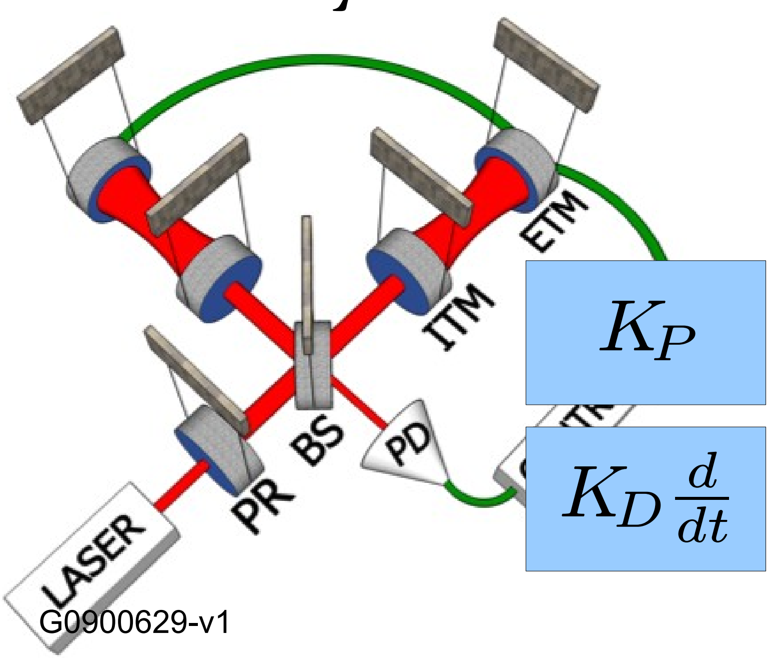
(ambient T)/(effective T) = 43 000

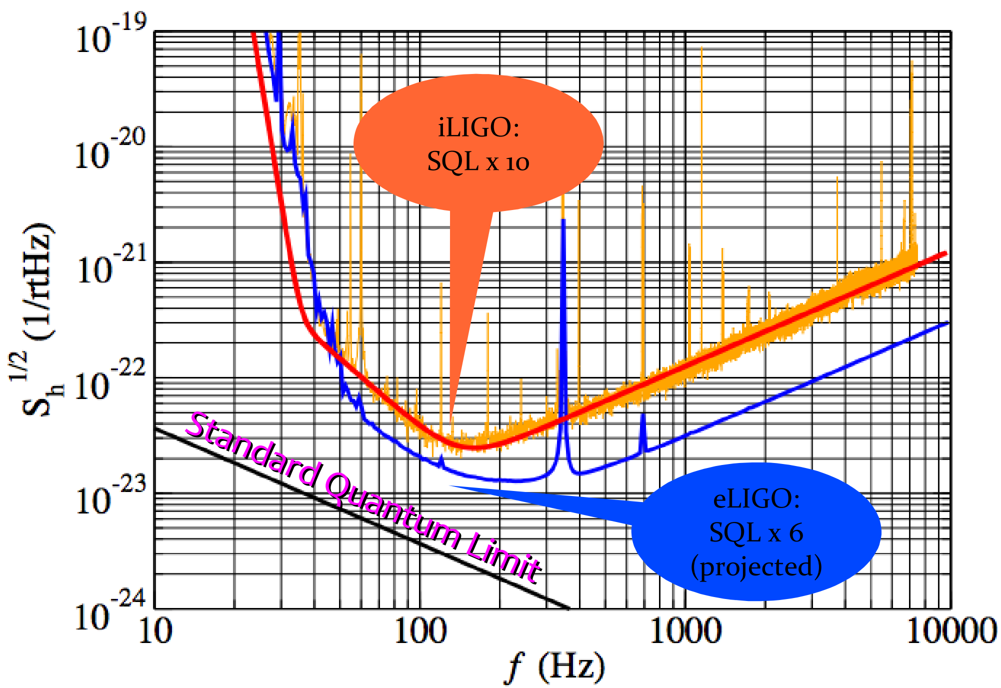
Suspension Q = 20 000

1st instance where "cooling factor" > natural Q

Servo spring

- Initial LIGO post-S5
  - kg-scale masses (10^{26} atoms)
  - factor 10 above SQL
  - BUT strong radiation pressure forces are not available yet



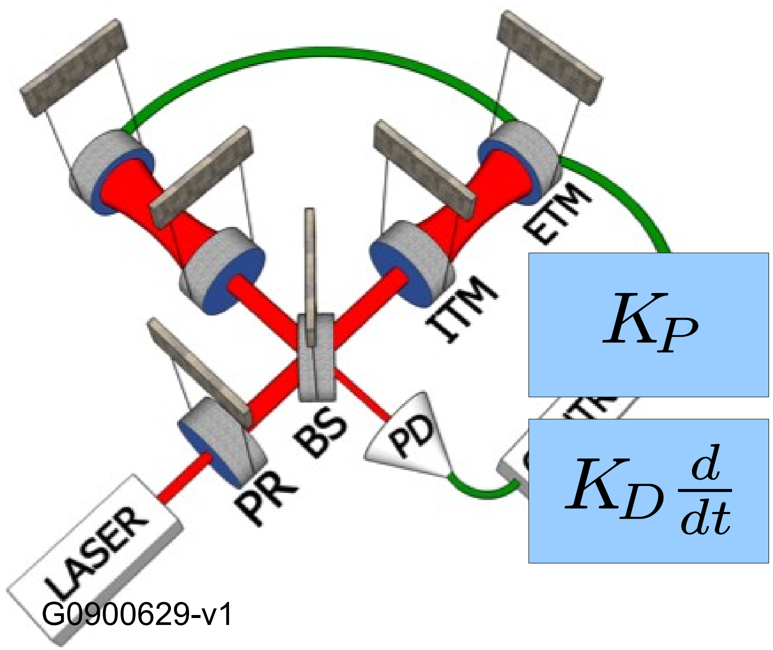


Feedback cooling and the SQL

The optimal control strategy shifts the mechanical mode to the nearest approach to the SQL, and damps it.

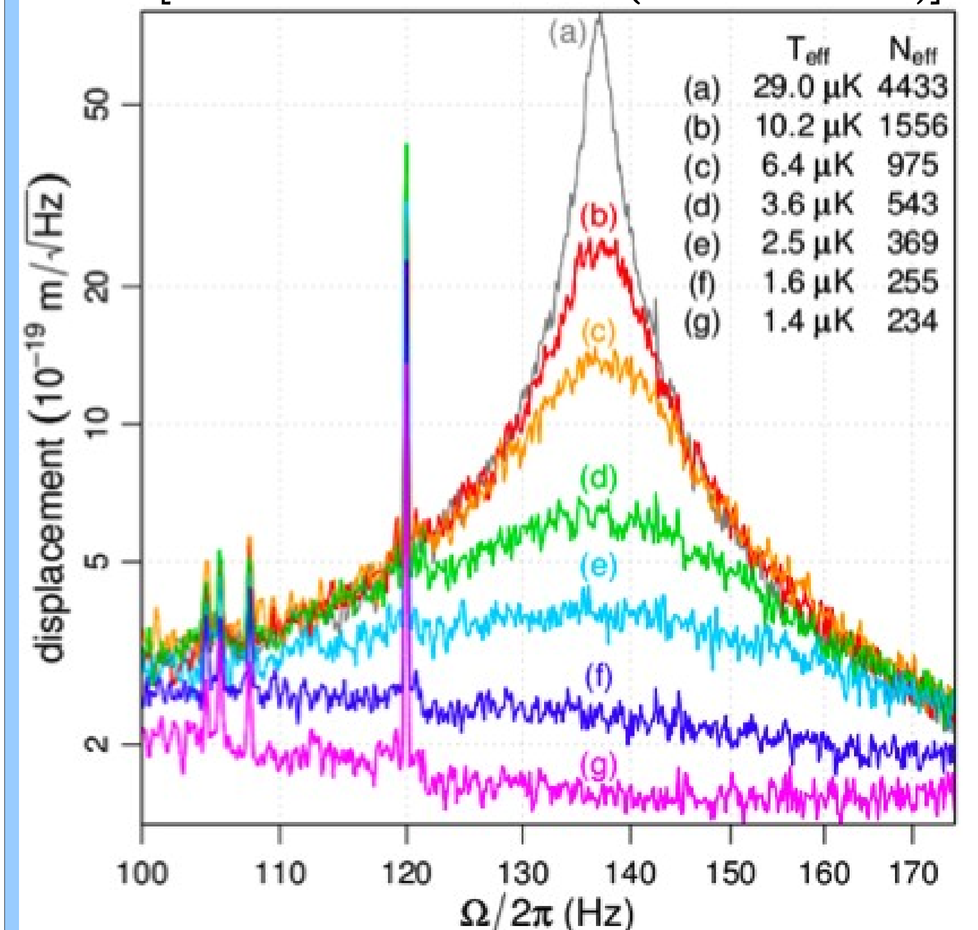
$$N_{\rm opt} = \frac{k_B T_{\rm eff}}{\hbar \Omega_{\rm eff}} \approx \frac{S_x(\Omega_{\rm eff})}{S_{\rm SQL}(\Omega_{\rm eff})} \frac{Q_{\rm eff}}{2}$$

[Danilishin et al., submitted to PRL]



G0900629-v1

[LIGO Scientific Collaboration (submitted to NJP)]



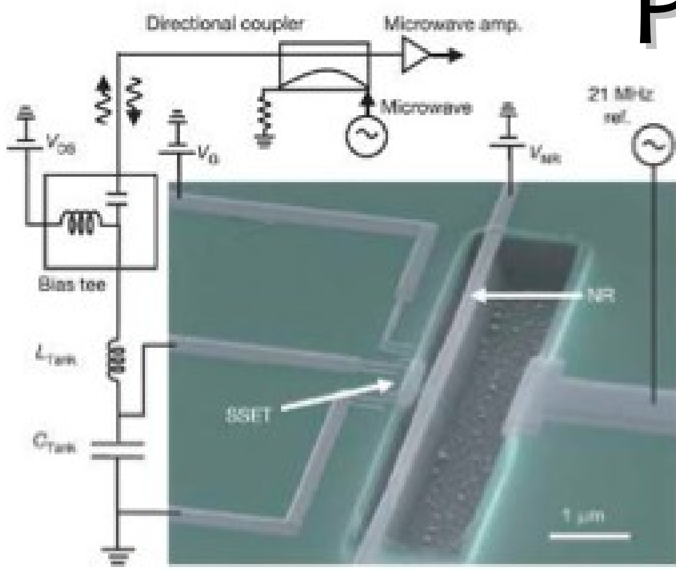
140 Hz EOS formed, damped by feedback

$N = 234$ - limited mainly by shot noise

(ambient T)/(effective T) = 2 x 10^8

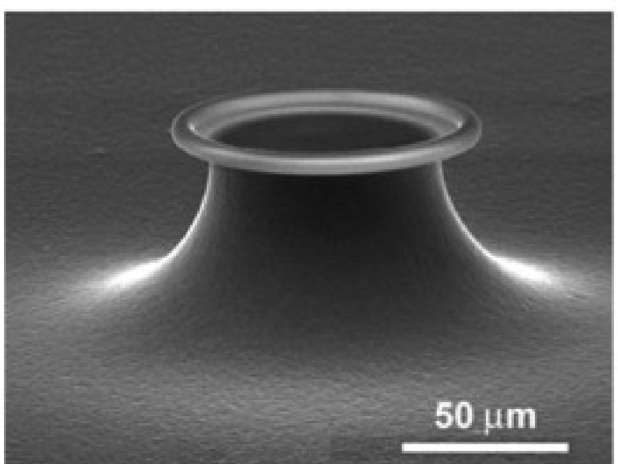
Displacement is estimated pessimistically since some noise sources are unknown

Photo finish

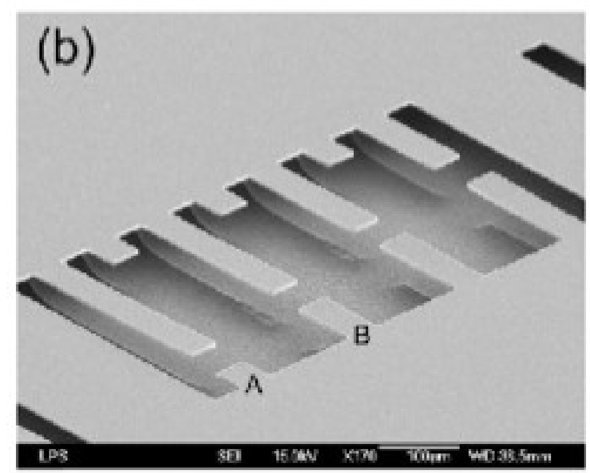


NEMS
M ~ picogram, $\Omega/2\pi$ ~ MHz
Naik et al., Nature (2006)

SiN micro-membrane
M ~ 10 picogram, $\Omega/2\pi$ ~ 100 kHz
Thompson et al., Nature (2008)



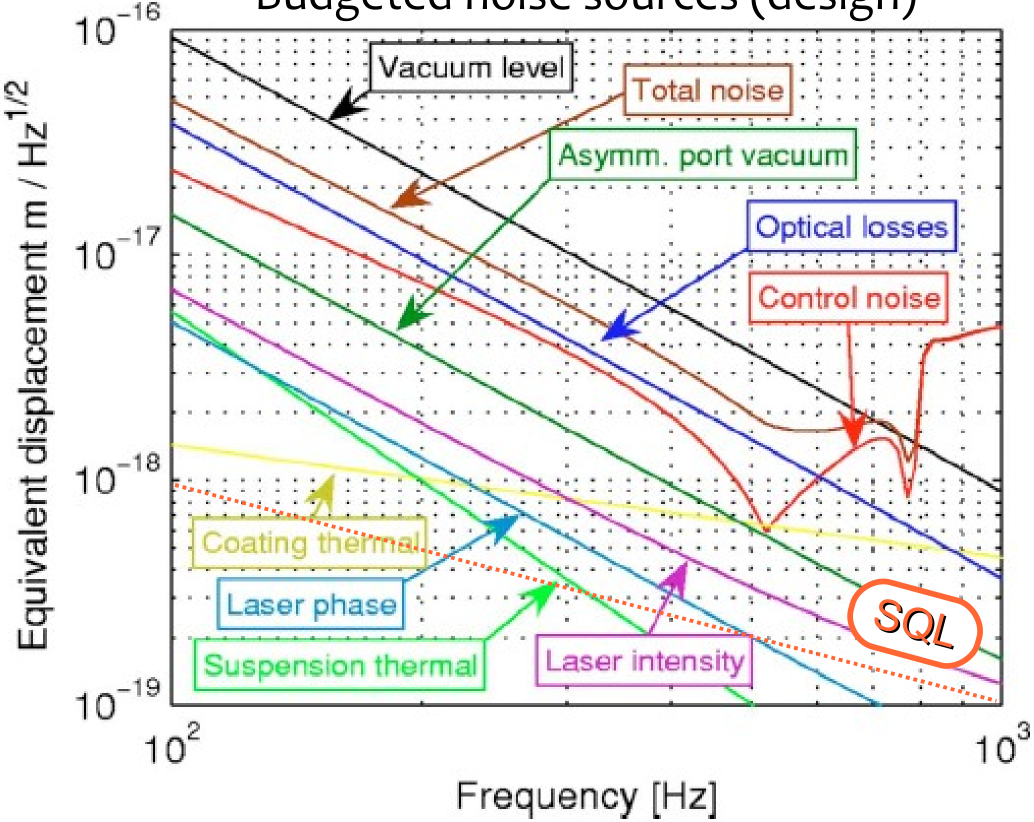
Micro-toroid cavity
M ~ 10 nanogram, $\Omega/2\pi$ ~ 50 MHz
Schliesser et al., PRL (2006)



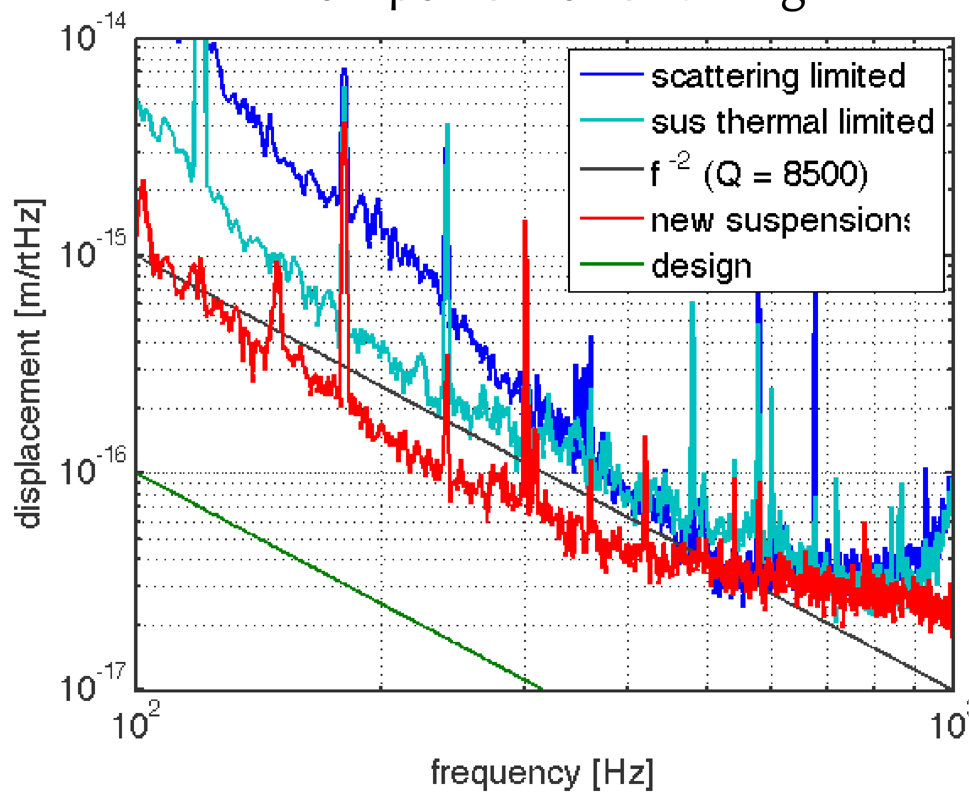
Micro-mirror
M ~ 100 nanogram, $\Omega/2\pi$ ~ MHz
Gröblacher et al., arXiv (2007)

Progress toward back-action

Budgeted noise sources (design)



Low power noise hunting

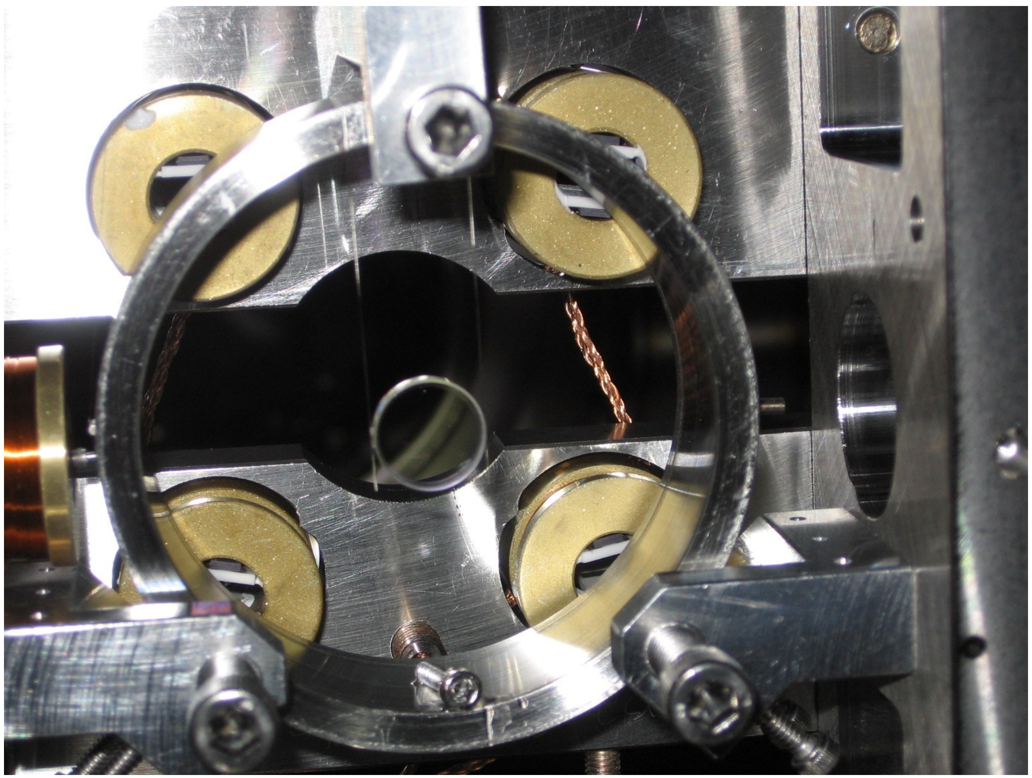


We presently operate about a factor of 5 above the back-action goal.
Scattering noise looms large in the detuned configuration
(where the displacement signal is suppressed by the optical spring).

The mini-mirror suspension thermal noise has been remediated.

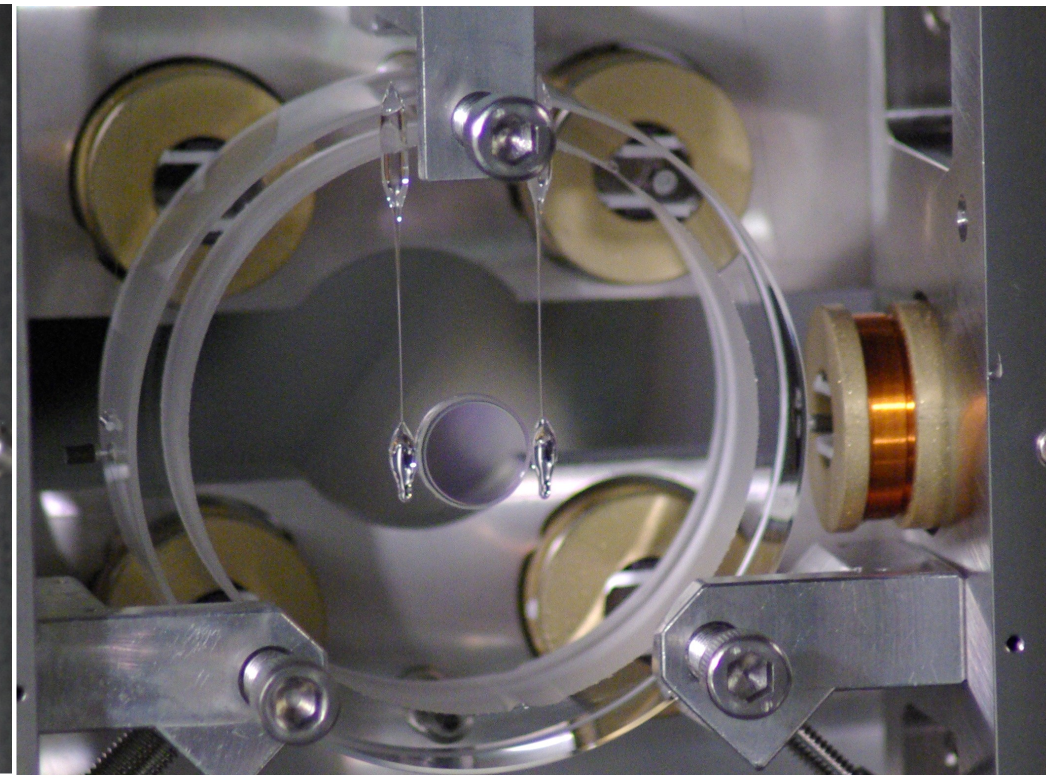
Suspension upgrades

Then



6 Hz natural frequency, quality factor ~ 10000 ?
Stainless steel, glass, and Vacseal adhesive
Commercial optical fiber (cladding scraped off)

Now

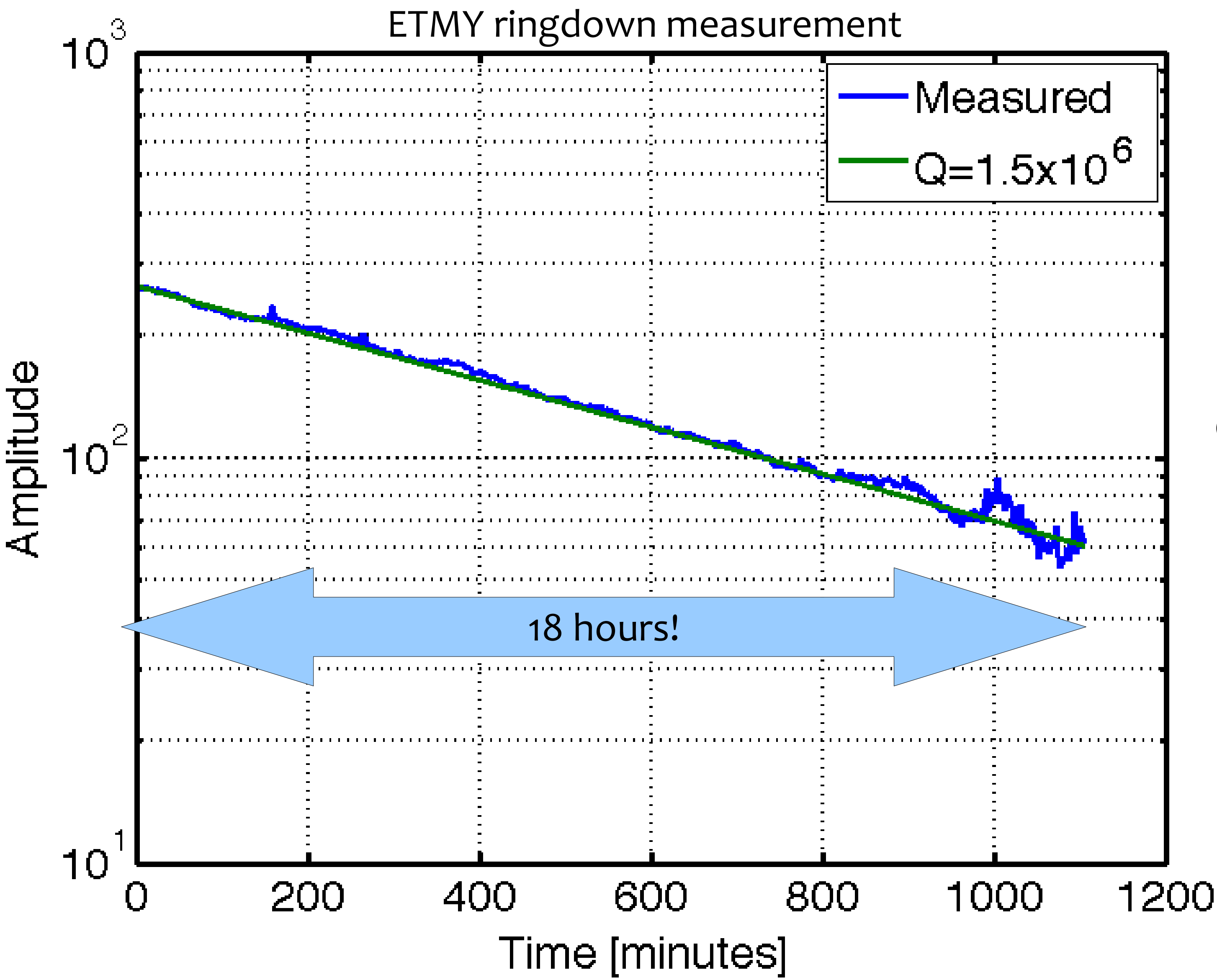


All glass -- still bonded with Vacseal
Custom-tapered fibers (courtesy of advLIGO)
Much refinement in fabrication and handling

Point scatterers on ETMs needed cleanup → ongoing vent to drag-wipe mini-mirrors in situ

G0900629-v1

Ring, Ring, Ring, Ring…



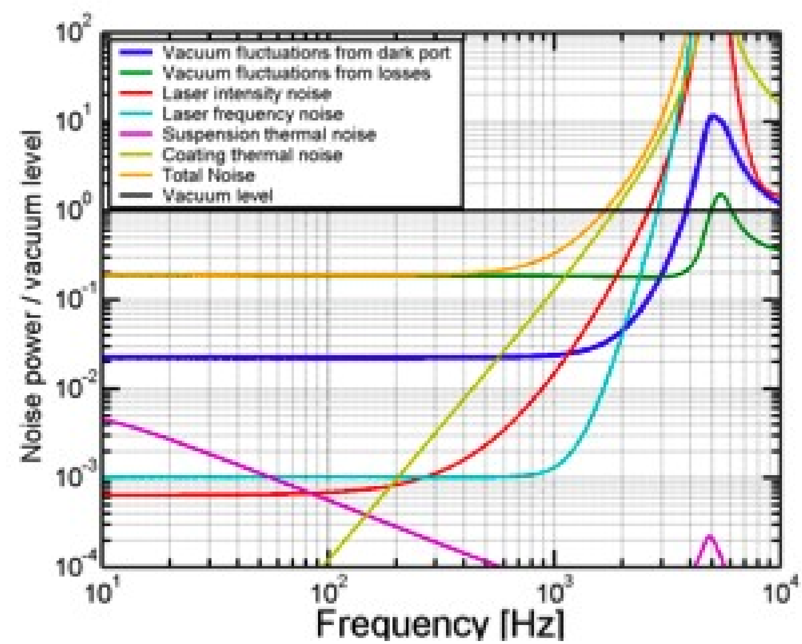
10 Hz natural frequency

Q surpasses requirement to observe quantum noise

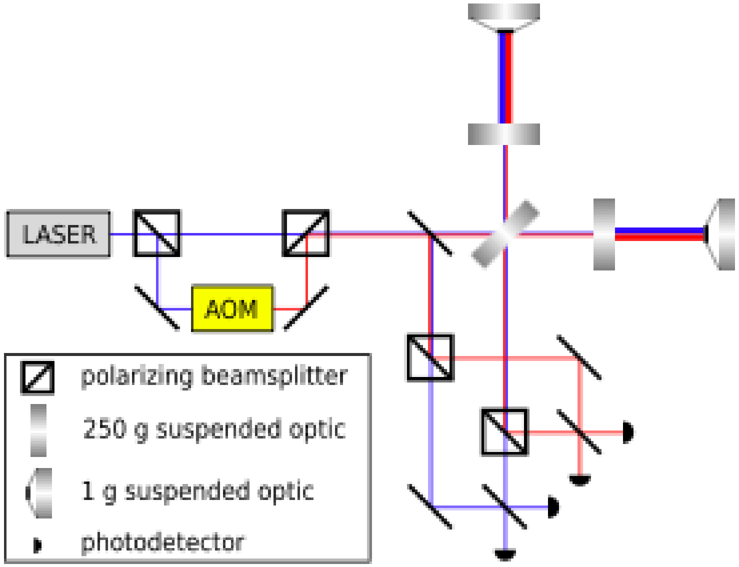
Pitch, Yaw Qs all >10^5

Entering the quantum RP regime

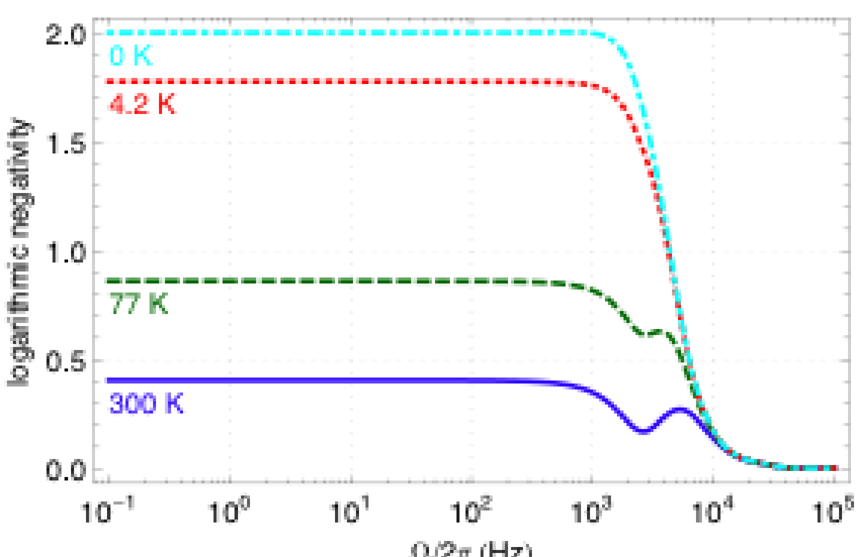
- First goal: verification of back-action noise
  - Power dependence (a weak signature)
  - Inject a squeezed state to manipulate it
  - 40m squeezer is being reconstituted for this purpose
- Ponderomotively squeezed light
  - amplitude fluctuations drive mirror motion, which then imprints on the phase
  - detuned operation makes broadband squeezing below the OS frequency



Quadrature entanglement



[Wipf et al., New J. Phys 10 095017 (2008)]



G0900629-v1

- Can form robust entanglement between carrier and subcarrier
  - joint squeezing of the two fields
- Exploits advantages of the optical trap configuration
  - high-power stability permits strong coupling via the mirror
  - optical entanglement is not overly sensitive to the mirror state
  - possibility to entangle optical fields of disparate wavelengths

Summary

- Squeezers prepare for a test in LIGO, GEO
  - demonstrate readiness to manipulate quantum noise in advanced detectors
- Back-action regime is nearly upon us
  - rich dynamics – stiff optical springs and trapping
  - should yield observations of quantum radiation pressure, squeezing, and entanglement
- Quantum opportunity knocks
  - the SQL opens the door to ground state cooling and *very* macroscopic quantum objects

Closing credits

- Tim Bodiya, Thomas Corbitt, Sheila Dwyer, Daniel Sigg, Nic Smith, Stan Whitcomb, Nergis Mavalvala (LIGO-MIT Quantum Measurement group)
- Rolf Bork, Alex Ivanov, Jay Heefner, Caltech 40m, many other LIGO Lab members
- Yanbei Chen and the MQM discussion group
- Fellow Squeezers at AEI and ANU