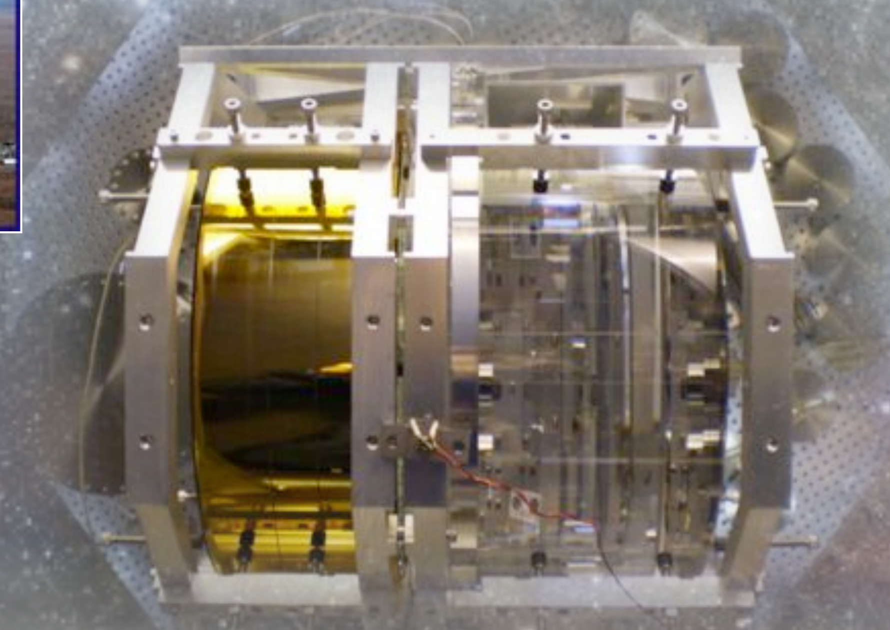
# Ground Based Gravitational-Wave Antennae

## Long baseline interferometers and what makes them “interesting”

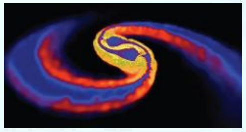
Matthew Evans, MIT

Apr 2012, Fermilab

# An Exciting Time



# Outline

- Gravitational-Wave Essentials 
- GW Observations To-Date 
- Current Activity and the Near Future 
- Future Directions (current R&D) 

# Context and Plea

I' ve been working on LIGO for 15 years…

So, if I use some incomprehensible jargon, please stop me!


Laser Interferometer

Gravitational-wave Observatory

# Gravitational-Wave Essentials

- What are gravitational-waves?
- Why try to detect them?
- How can they be detected?

# Gravitational Waves

- Caused by moving masses
  (mass distributions with changing quadrupole)
- Distortions of space-time
  - linearization of GR gives wave equation
  - propagate at speed of light
  - 2 polarizations

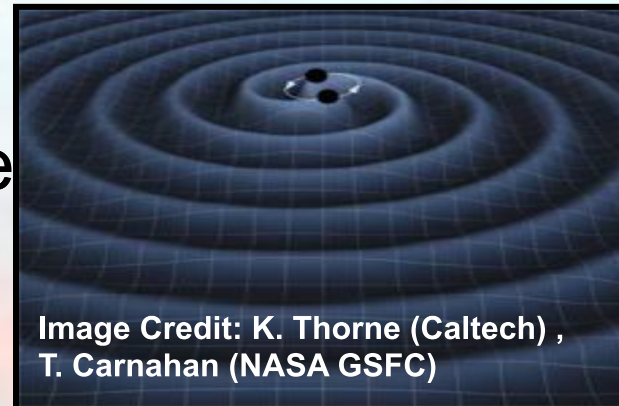
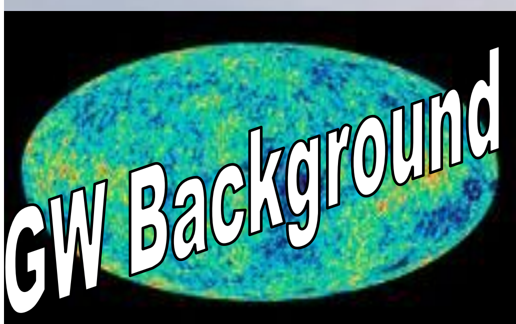
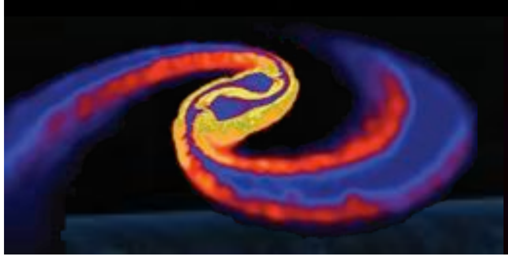


Image Credit: K. Thorne (Caltech) , T. Carnahan (NASA GSFC)

# More Sources

- There are many potential GW sources
- Today, just compact binaries
  - NS-NS, NS-BH, BH-BH
  - “inspiral, merger, coalescence”


# Direct Detection Payoffs

- Direct observation of strong-field GR
- Constrain evolution of stellar populations that produce compact objects
- Constrain neutron-star equation of state (and thus theories of nuclear matter)
- A “standard siren” …

# Standard Siren

- Waveform and amplitude determined by source mass
- Weak interaction with matter
  - Astrophysical sources unscreened by intervening matter
  - Disturbed only by gravitational lenses

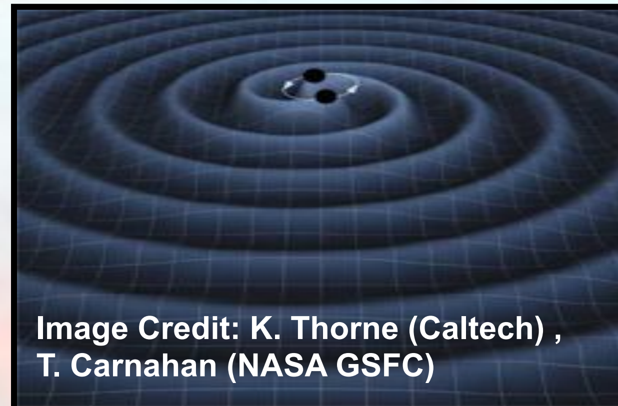
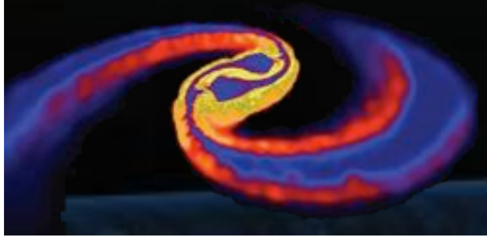
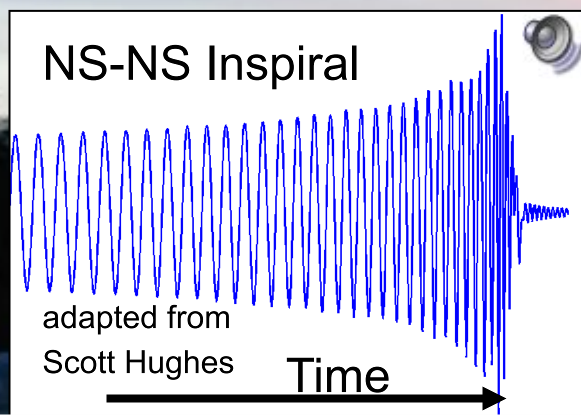
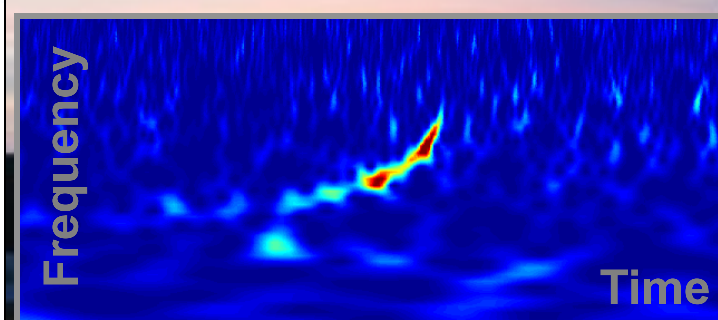


Image Credit: K. Thorne (Caltech) , T. Carnahan (NASA GSFC)

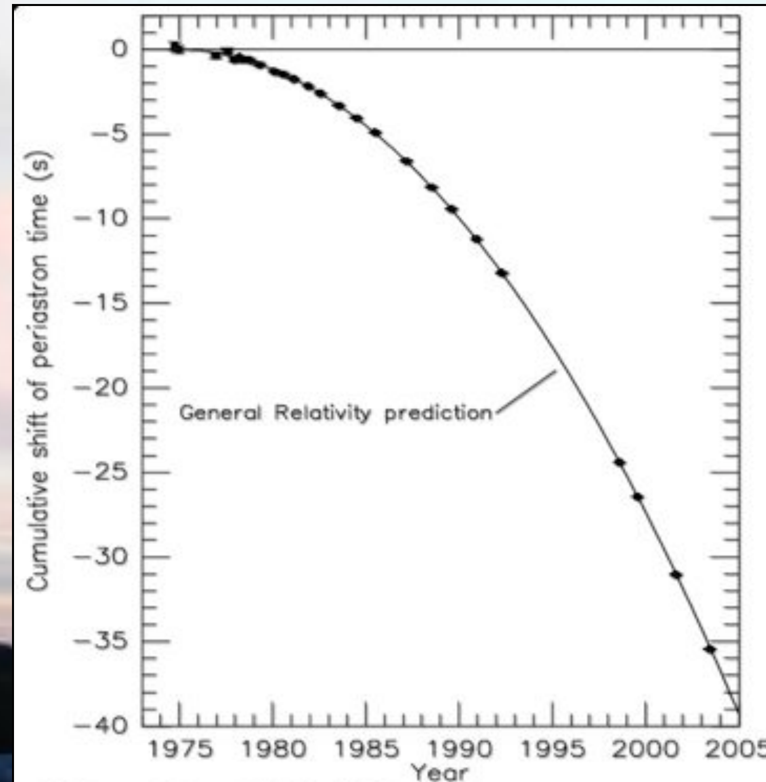




# Already Detected! Indirectly…

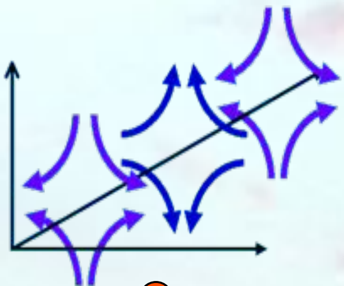
- PSR 1913+16, the Hulse-Taylor binary
  - First clear demonstration of GW radiation
  - Binary neutron star
  - 8 hour orbital period
  - Will merge in 300Myr



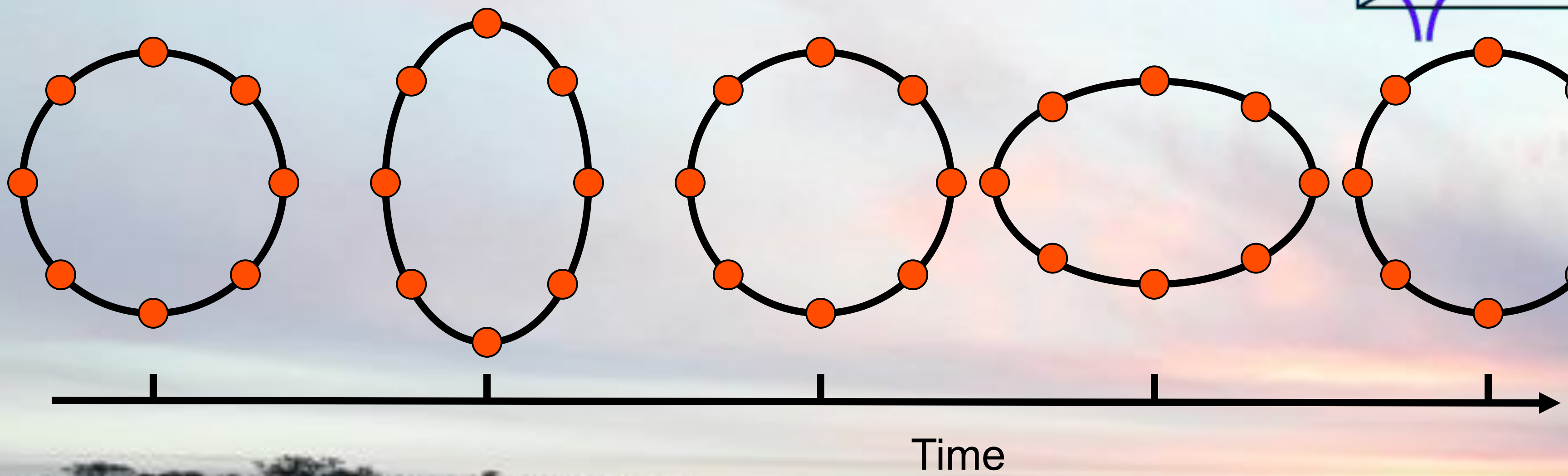

Weisberg, Taylor - ASP Conf. Series 2004

# Direct Detection: How

- Gravitational Waves Distort Space



$$h = \Delta L / L \sim 1/5$$

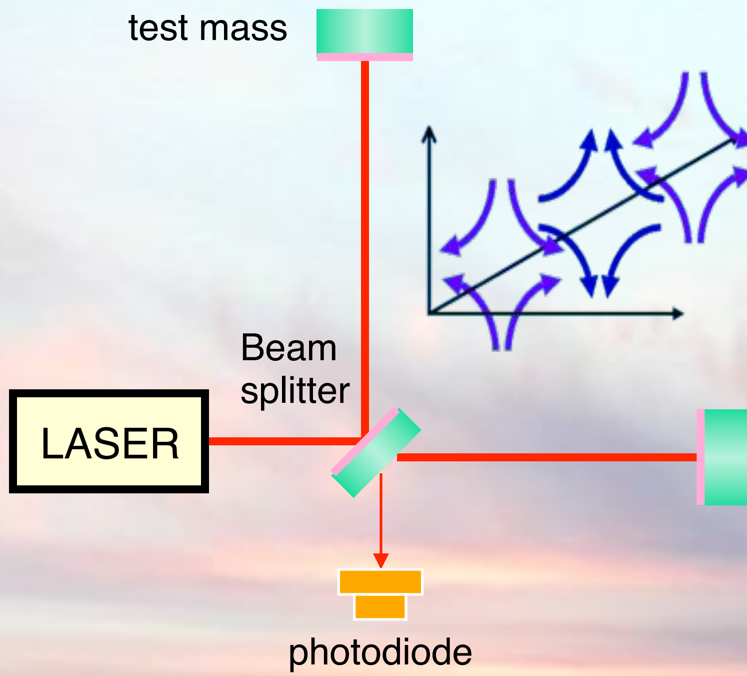


# Direct Detection: Not Easy

- Interferometers
- How sensitive?
  – For a binary neutron star coalescence…

$$h_{\mu\nu} = \frac{2G}{c^4 r}\ddot{I}_{\mu\nu} \Rightarrow h \approx \frac{4\pi^2 G M R^2 f_{orb}^2}{c^4 r}$$

I =quadrupole mass distribution of source



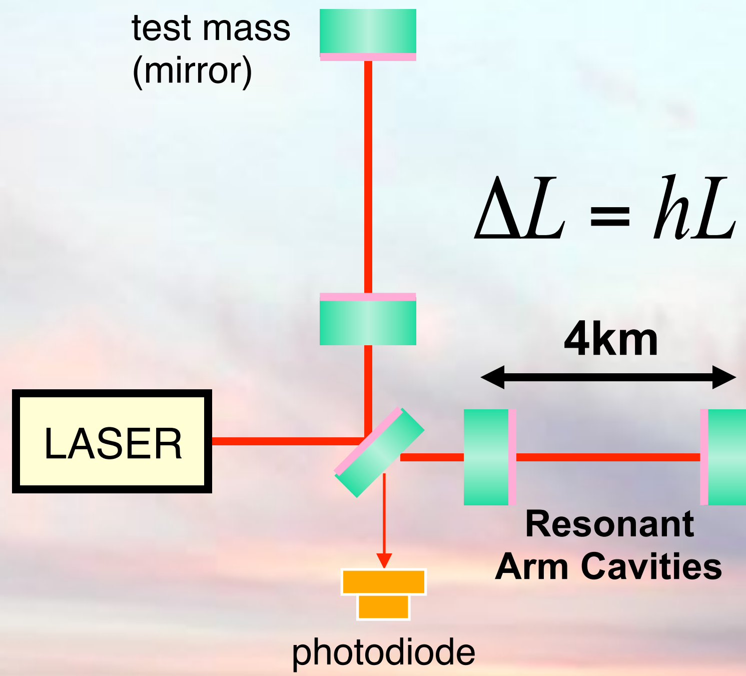

M ≈ 6x10$^{30}$ kg ≈ 3 M solar
R ≈ 20 km
F ≈ 100 Hz
r ≈ 5x10$^{23}$ m ≈ 15 Mpc

→ $h \sim 10^{-23}$

# Detector Noises: Setting

- Example: first generation LIGO

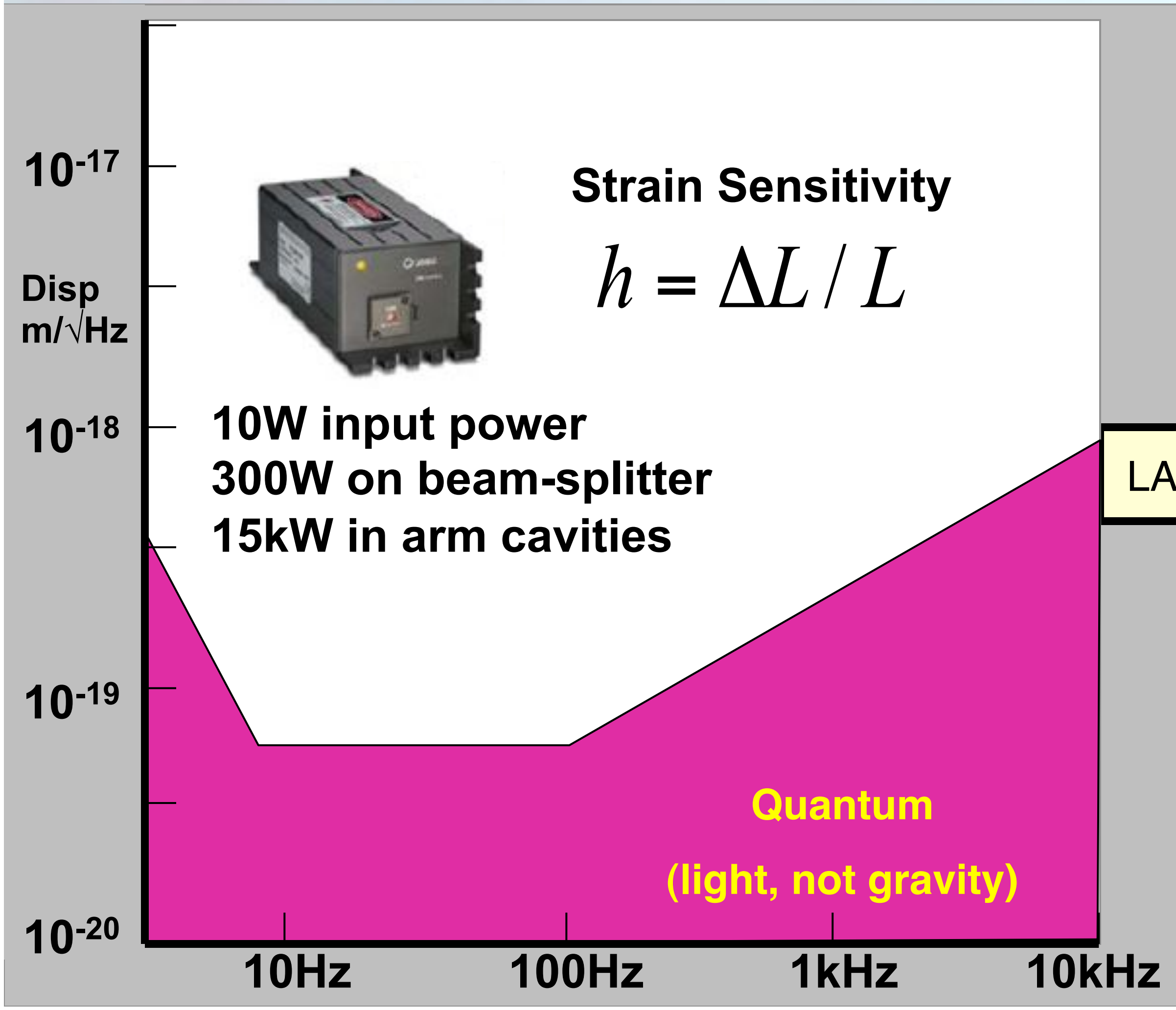
  1997-2010

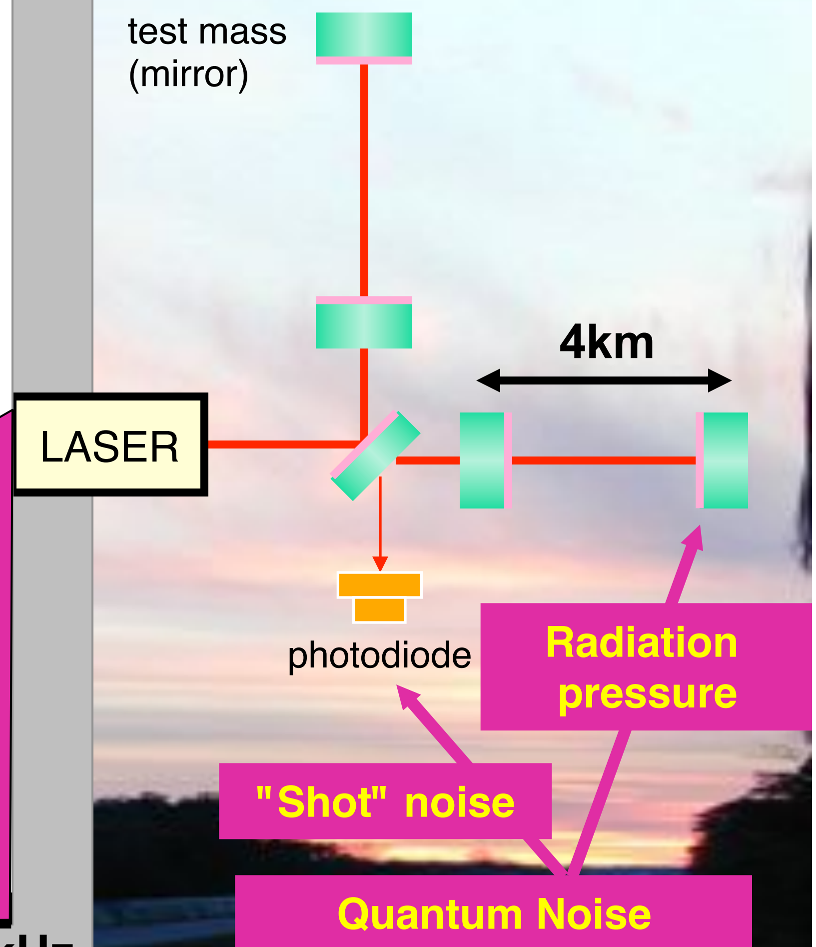




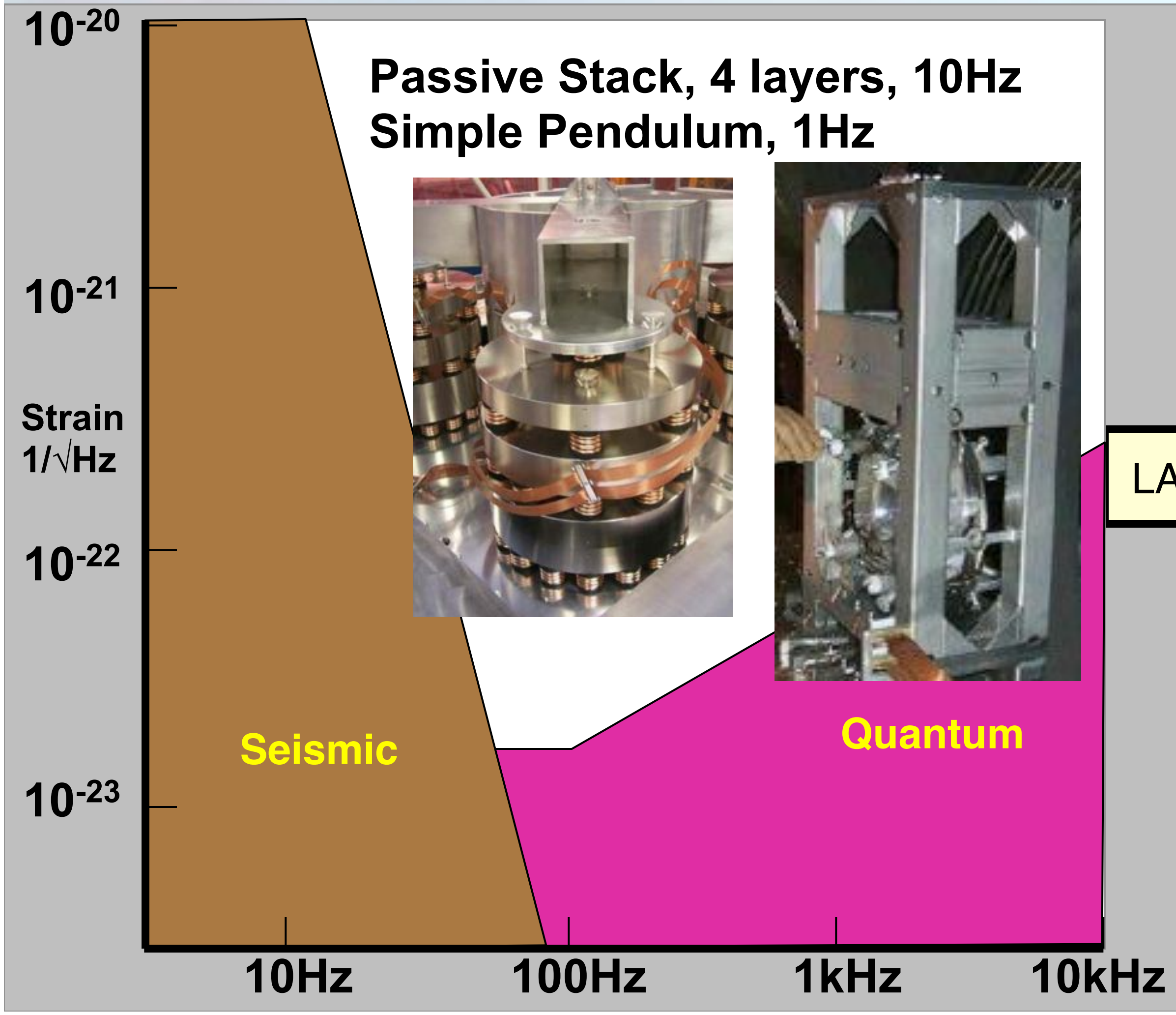
LIGO Hanford Observatory

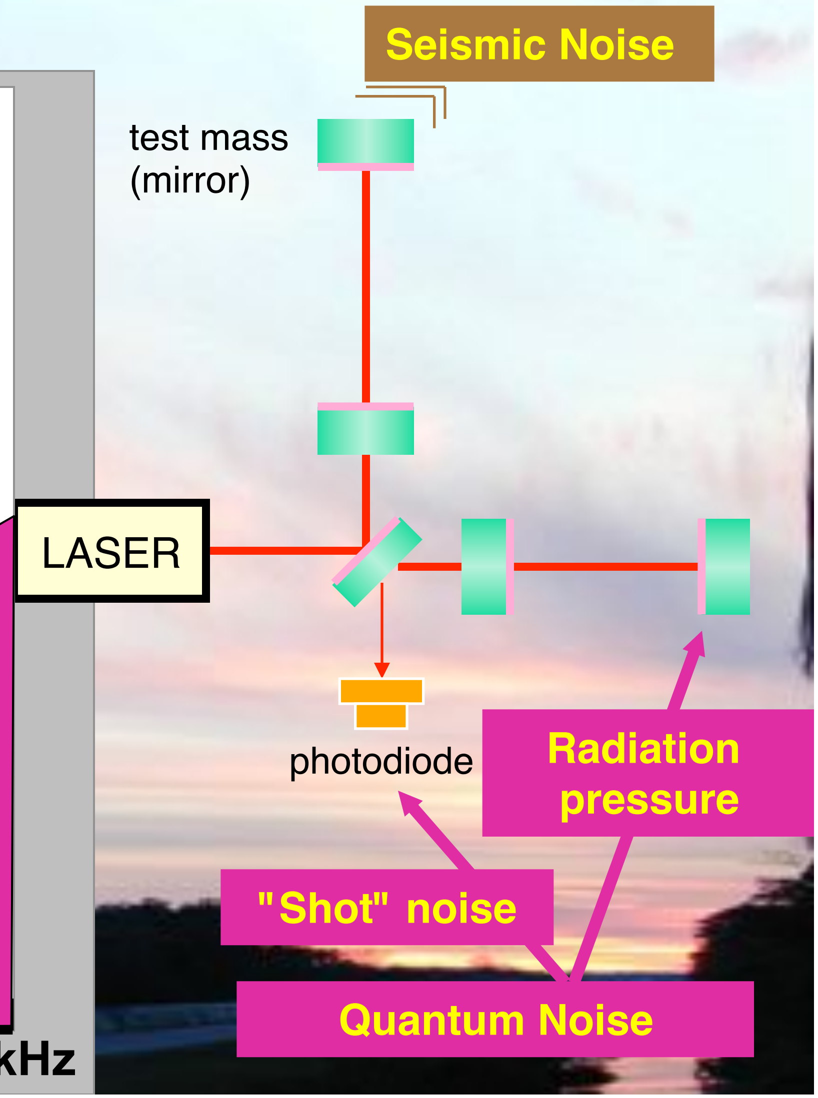
# Detector Noises: Quantum



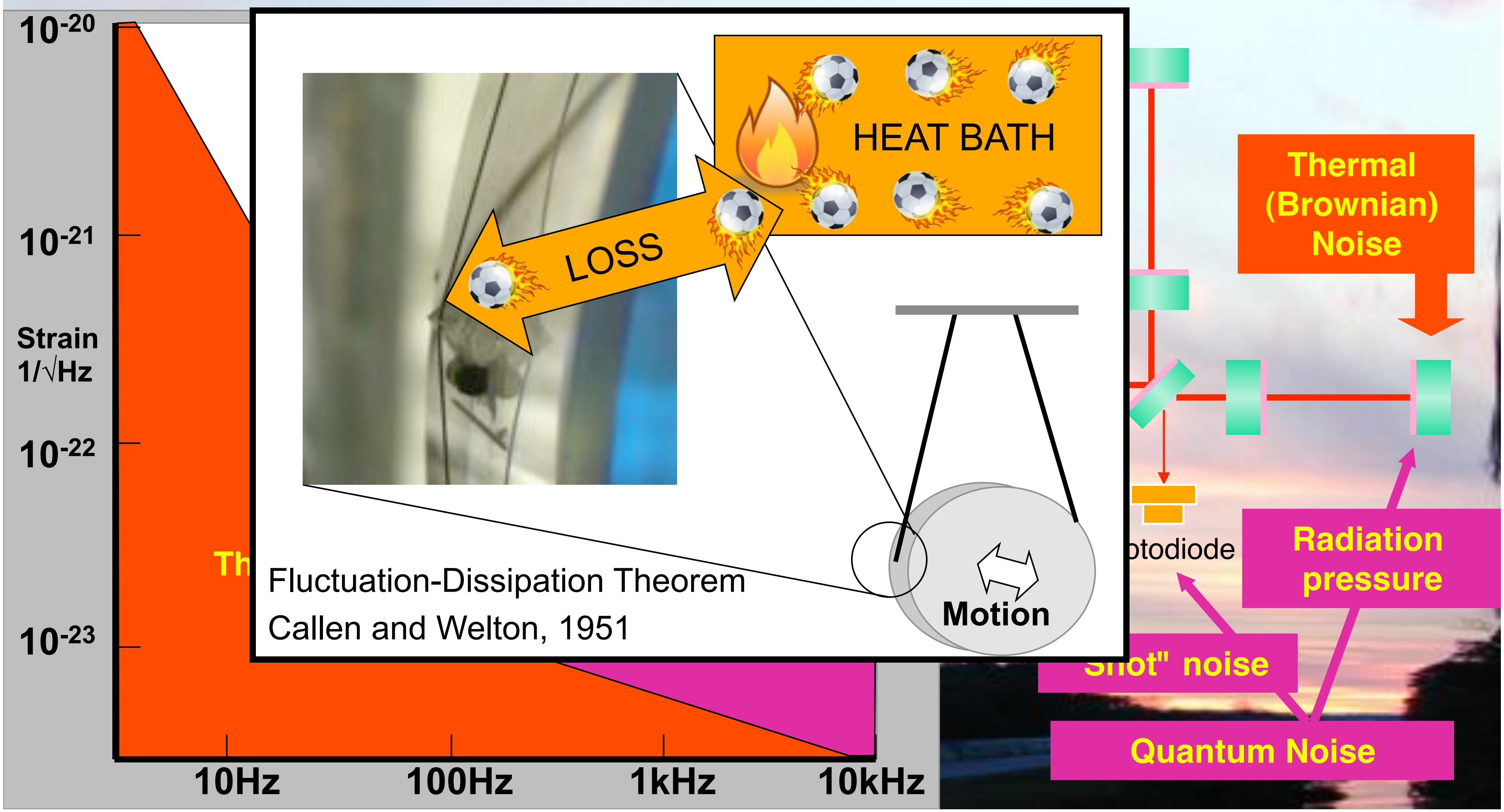



# Detector Noises: Seismic

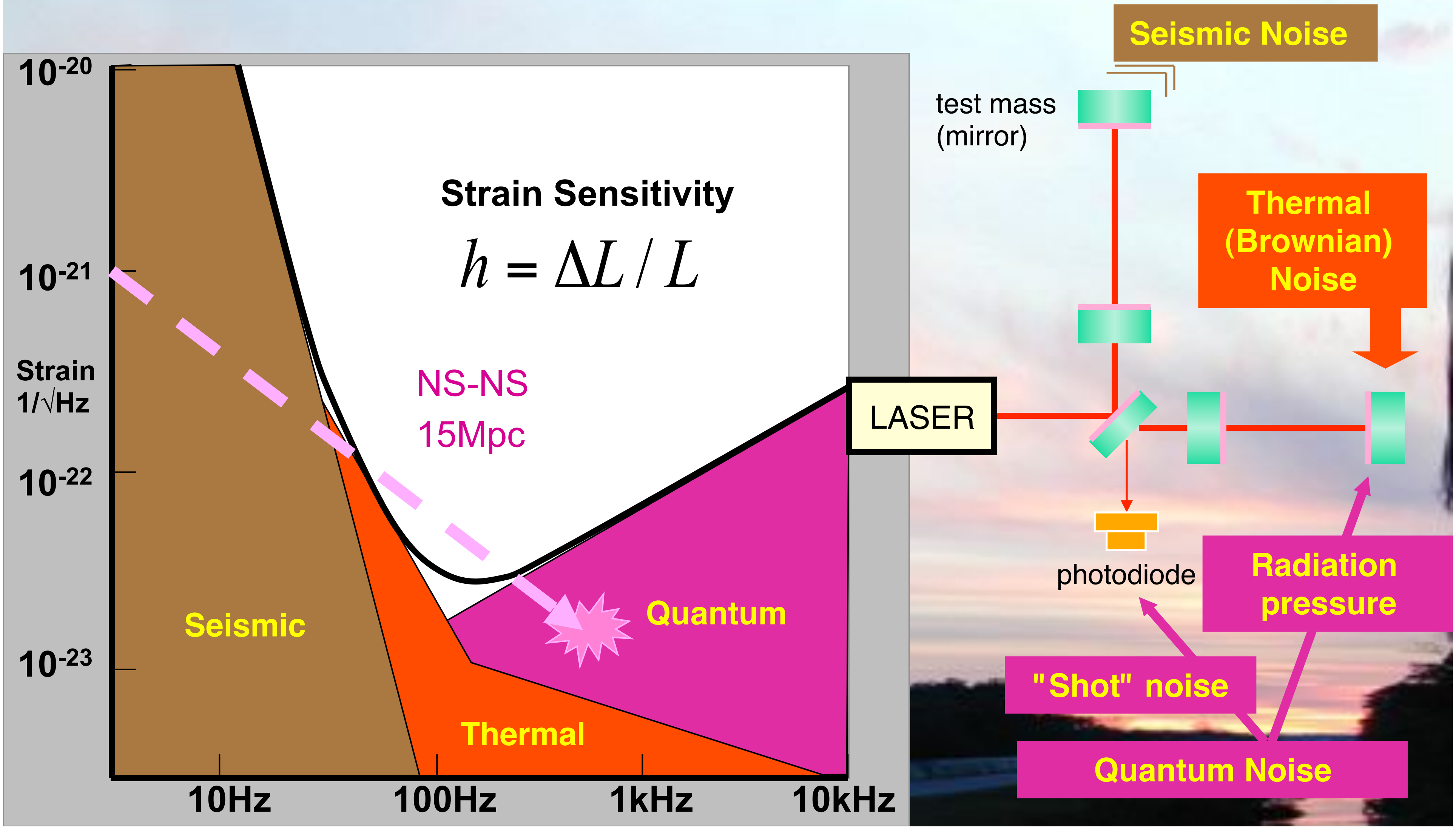


# Detector Noises: Thermal



# Detector Noises: Summary



# Fundamentals: The Message

- Direct detection of gravitational waves has a lot to offer
- The physics of gravitational wave detection is straight forward
- The numbers work out… we can do it

# GW Observations To-Date

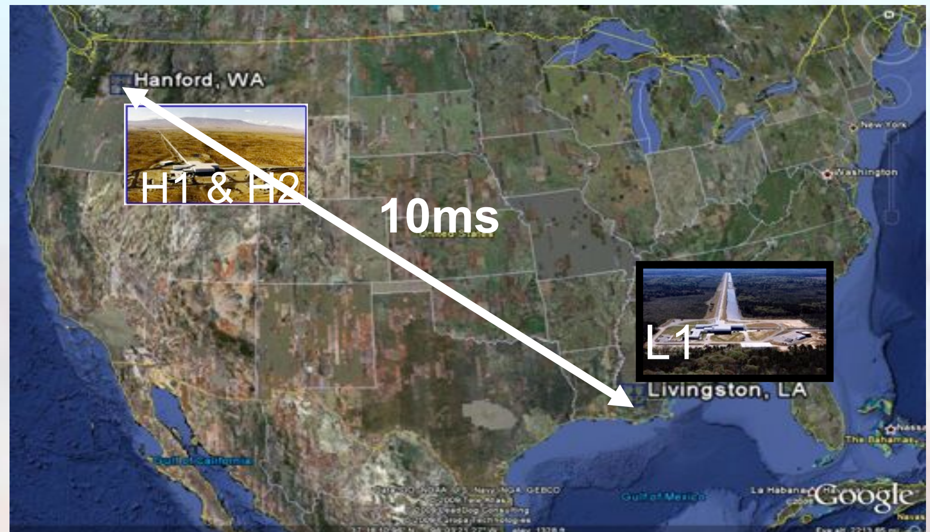
- A brief history of the detectors
- How much data has been taken?
- What have we found?

# First Generation Detectors


Credit: C. Mayhew & R. Simmon (NASA/GSFC), NOAA/ NGDC, DMSP Digital Archive

# Why so many detectors? Detection confidence…

- Coincidence
  - Multiple detectors
  - Same signal
  - Same time
  - EM counterpart?

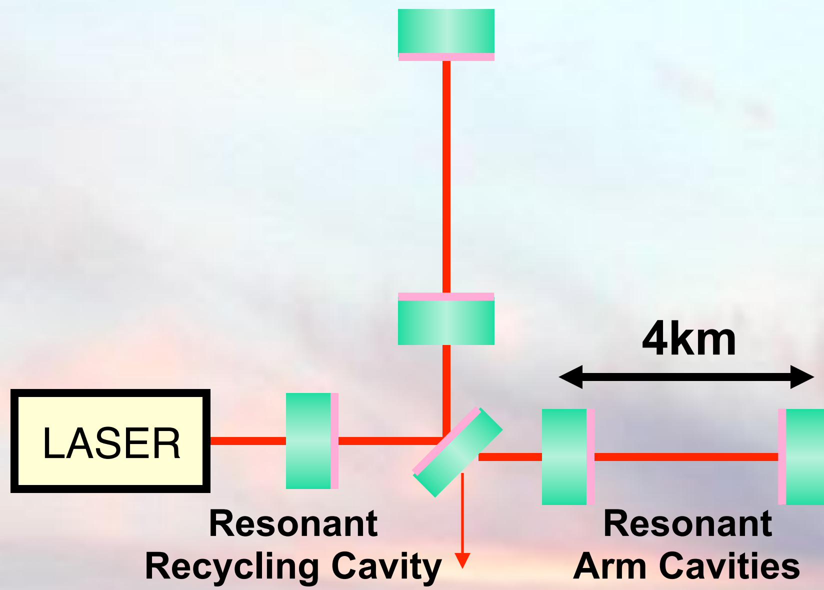


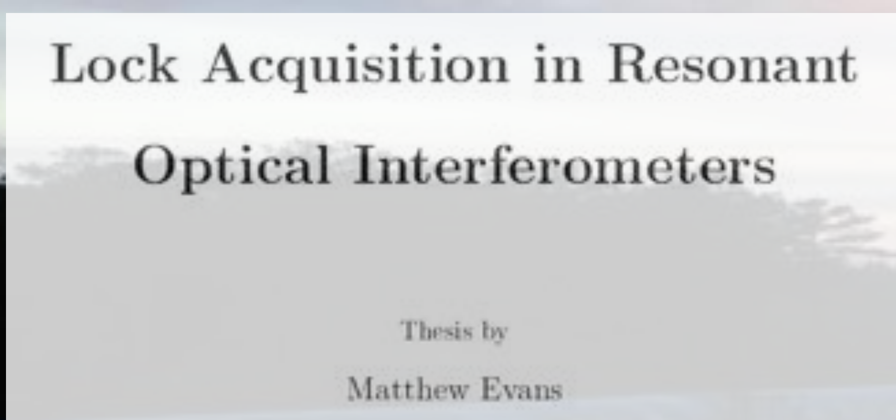

- Triangulation on the sky
  - Need at least 3 detectors

# How I became famous!

(and the curse of being a physicist who can code)

- In 1999, I was working on simulating the LIGO interferometer
- My thesis happened where simulation and instrument met

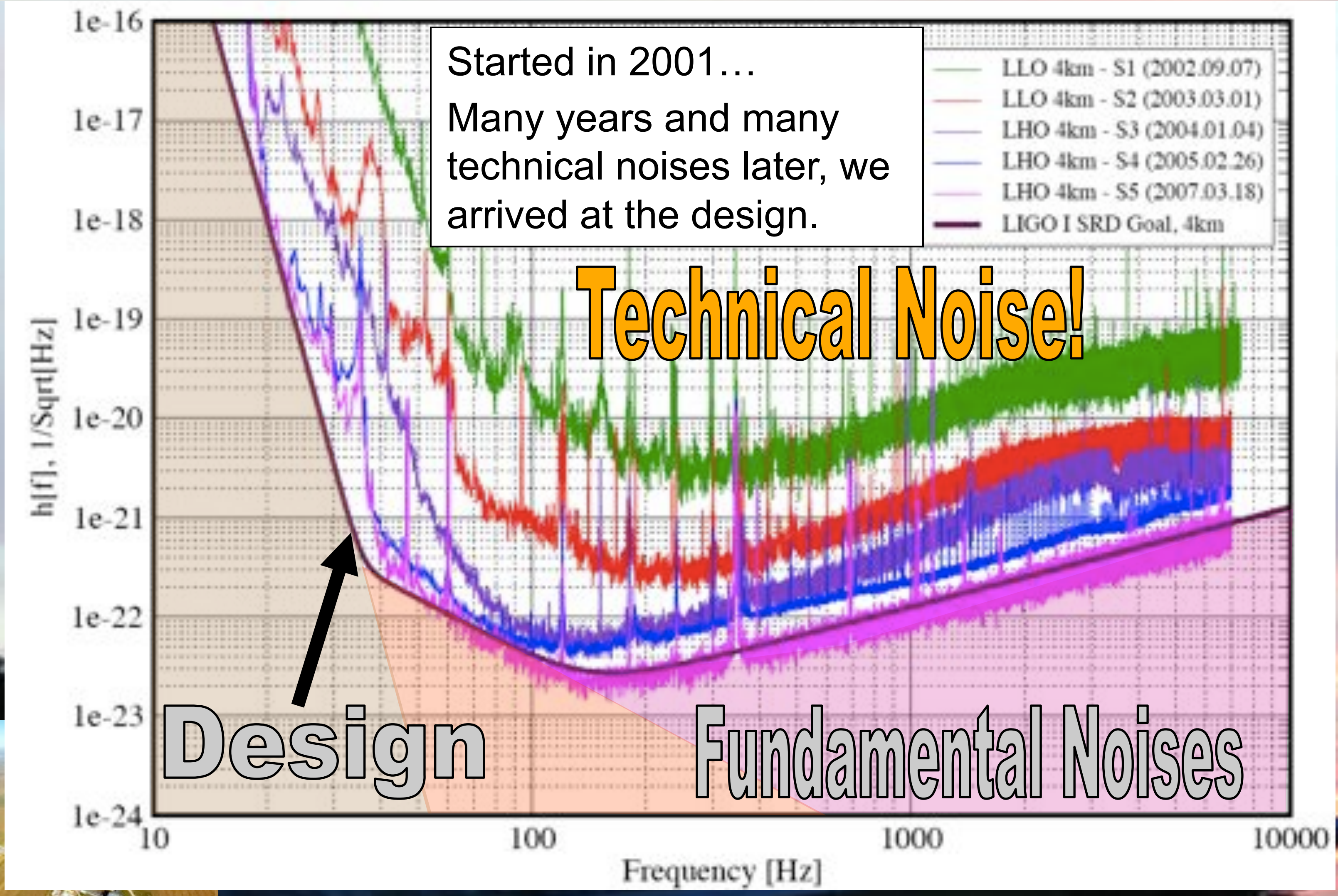




Lock Acquisition in Resonant Optical Interferometers

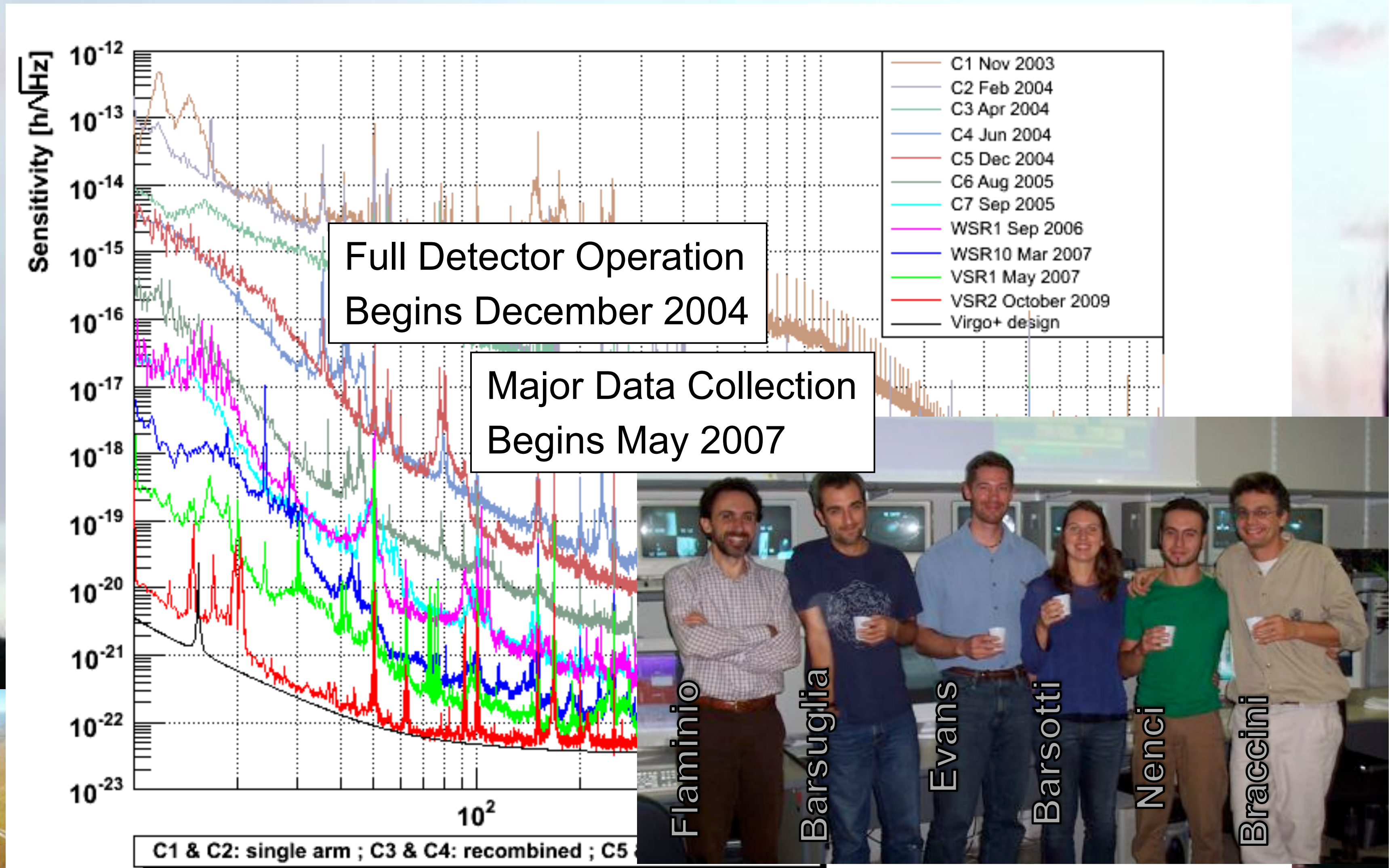
Thesis by

Matthew Evans

# Not Fast or Easy… LIGO



# Not even the second time… Virgo

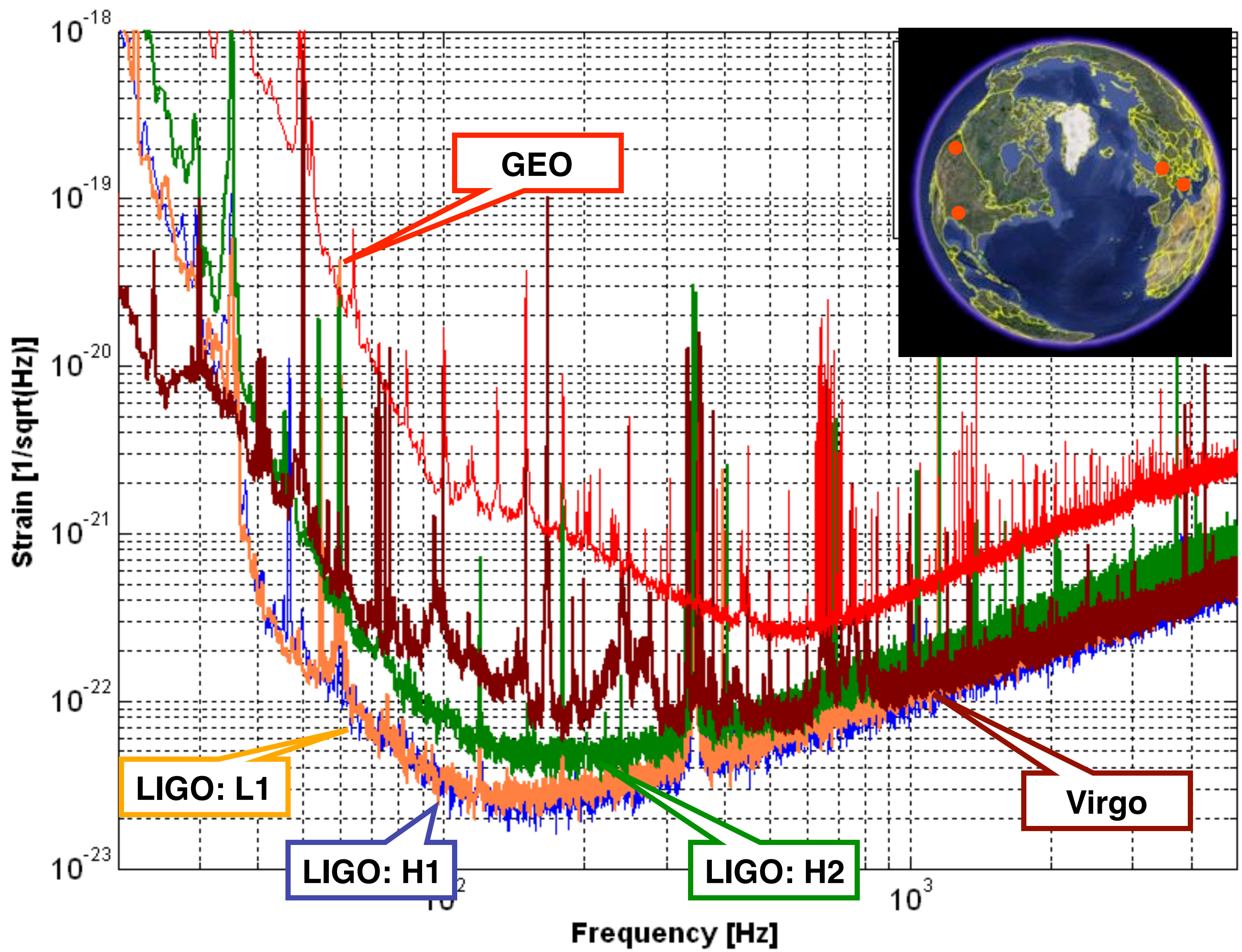


# Achieved Sensitivity

LIGO, GEO and Virgo share all data to form a global detector network.

Since 2006, roughly 2 years of network data have been collected.

The LIGO Scientific Collaboration includes over 50 Universities and about 1000 researchers.



# Publications

- Over 70 publications
  - Analysis still underway
- GRB070201
  - Short GRB… merger?
    - Andromeda in the error box!
  - not NS-NS in Andromeda
  - Astrophys. J 681

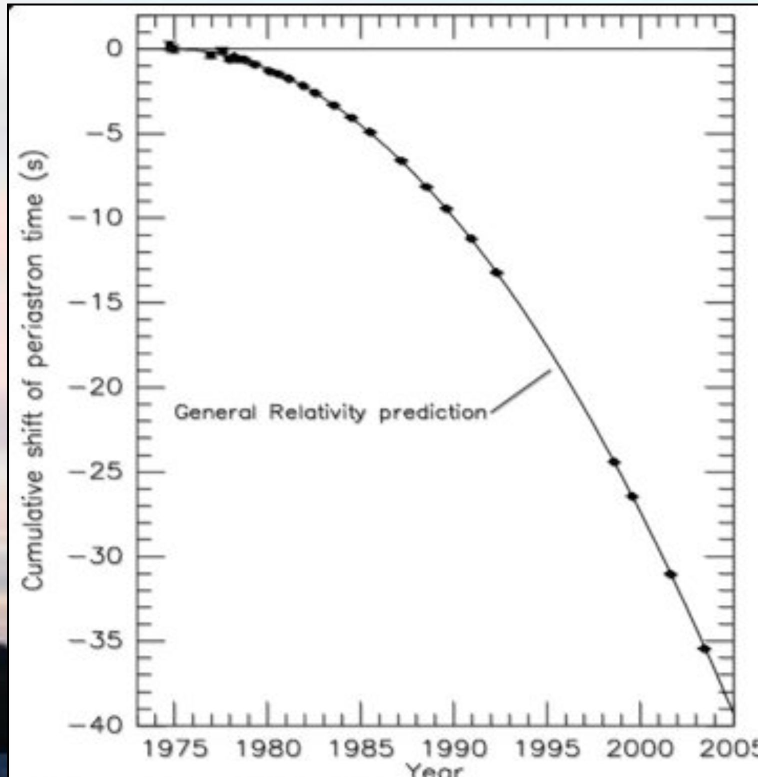
FIG. 1.— The IPN3 (IPN3 2007) (γ-ray) error box overlaps with the spiral arms of the Andromeda galaxy (M31). The inset image shows the full error box superimposed on an SDSS (SDSS 2007) image of M31. The main figure shows the overlap of the error box and the spiral arms of M31 in UV light (Thilker et al. 2005).

# Why we didn't hear anything yet

- Consider our favorite source... binary neutron stars, like PSR 1913+16
  - 5 known tight NS binaries

$$R \sim \sum_{n=1}^{5} \left\langle \frac{\text{detection probability}}{\text{lifetime}} \right\rangle_n$$

  - Gives R ~ 100 / Myear



Weisberg, Taylor - ASP Conf. Series 2004

# Why we didn’t hear anything yet

- Extrapolate to other galaxies weighted by blue-light luminosity
  - Roughly 1 MW of blue-light every 100 $Mpc^3$
  - Detection Rate ~ Rate x Detection Volume

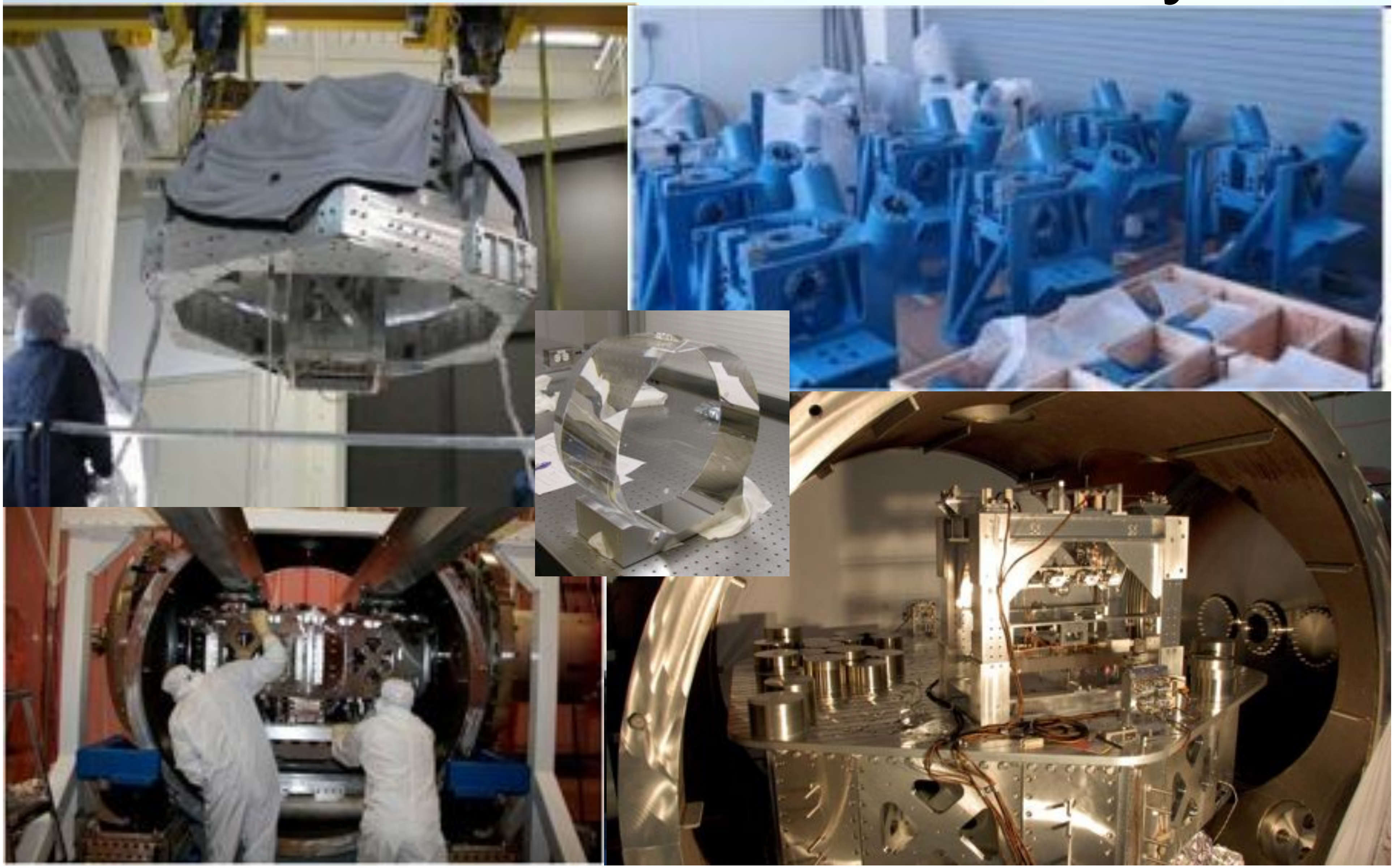
$$\frac{1}{100\,Mpc^3}\,\frac{100}{Myr}\times\frac{4\pi}{3}(15\,Mpc)^3\sim\frac{1}{70\,yr}$$

# Current Activity and the Near Future

- 2nd generation detectors around the world
- Advanced LIGO

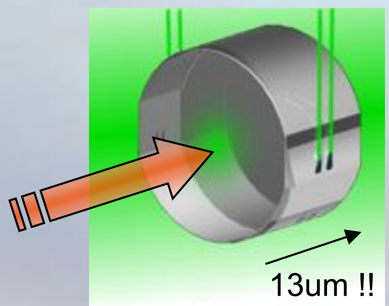
# Advanced GW Network

# Advanced LIGO: Underway!

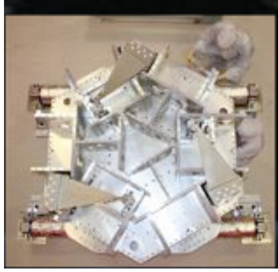


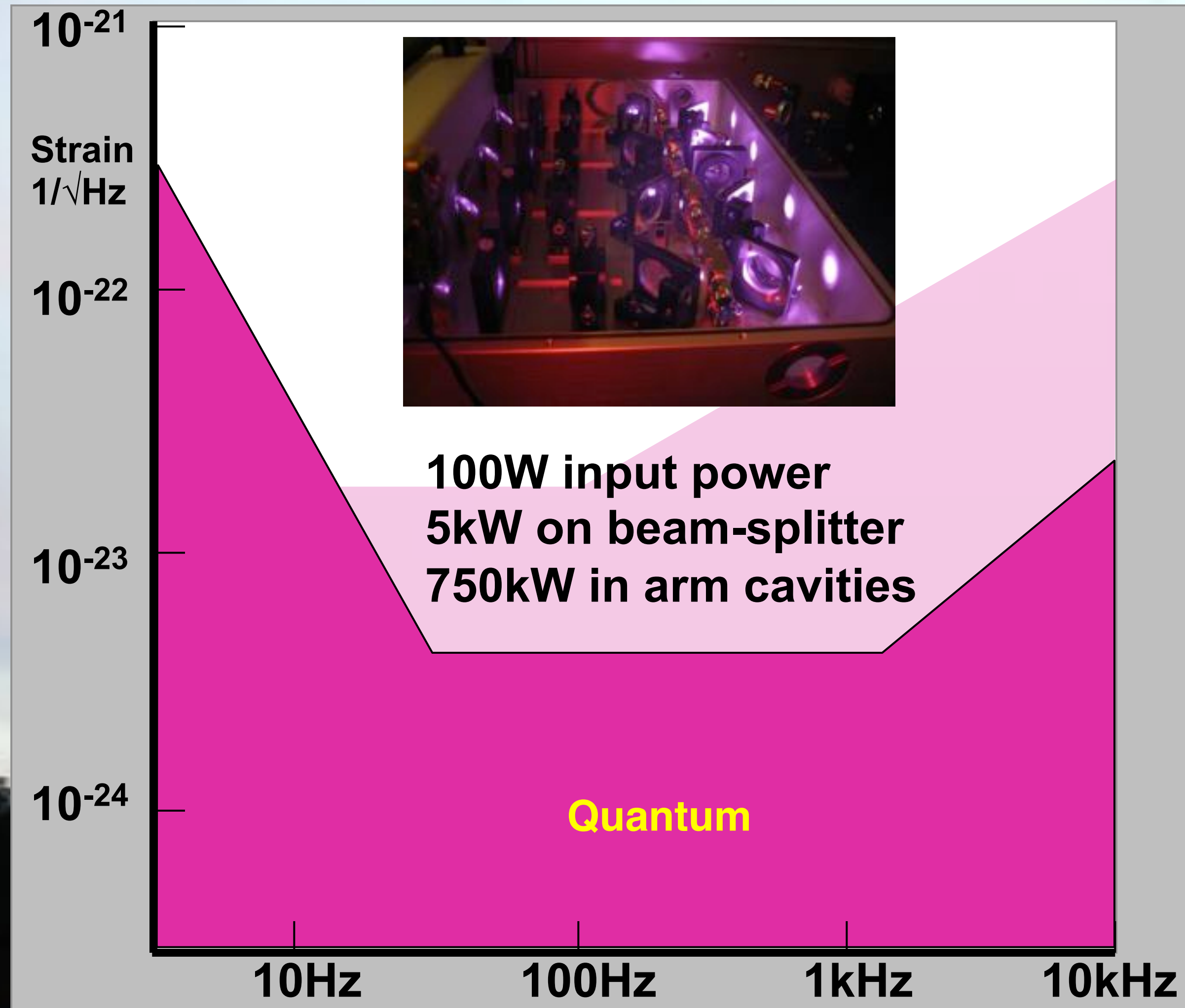
# Advanced LIGO: More Power

With nearly 1MW of circulating power, radiation pressure becomes a serious problem…




Interferometer simulations developed for LIGO are now used world-wide

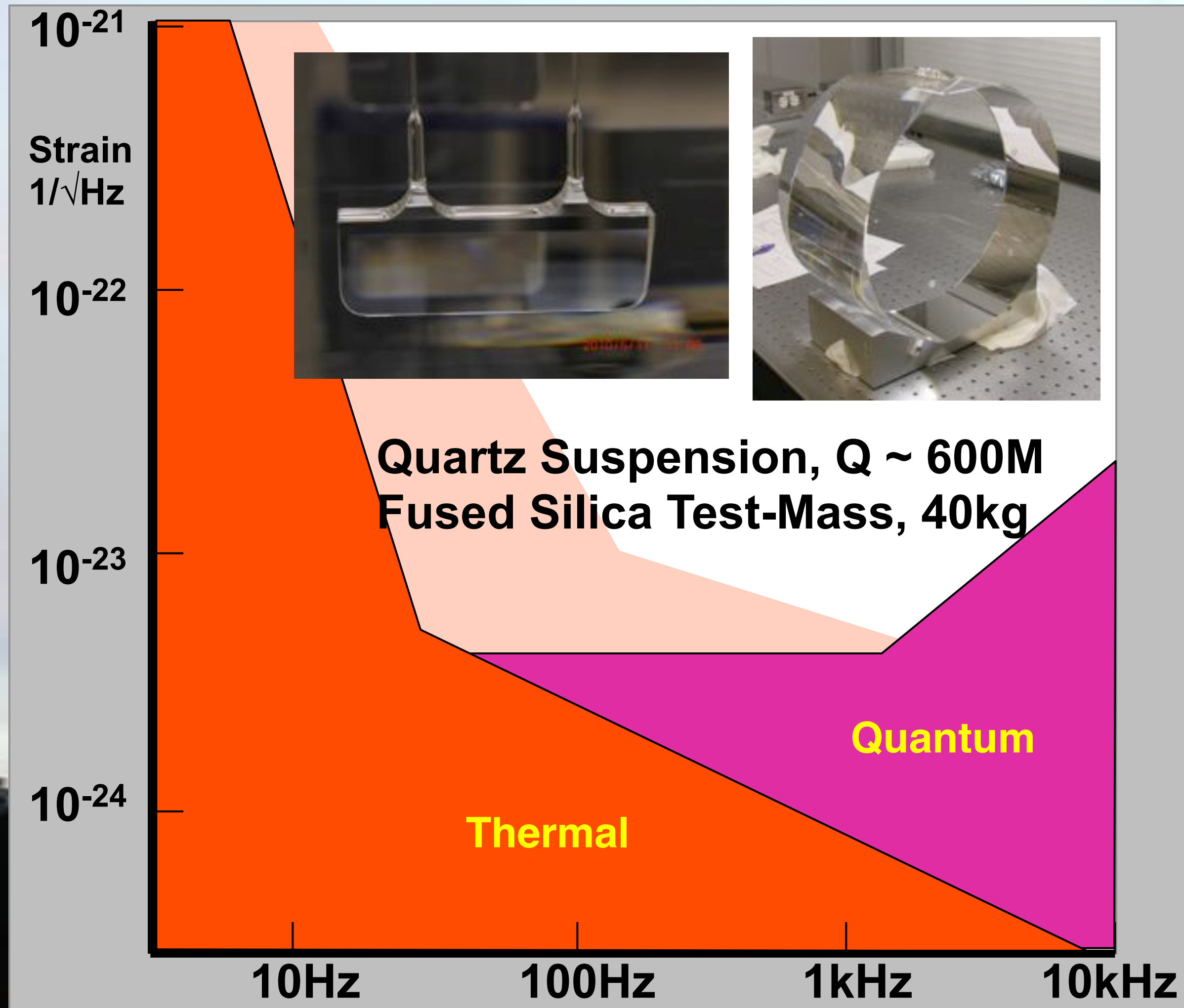


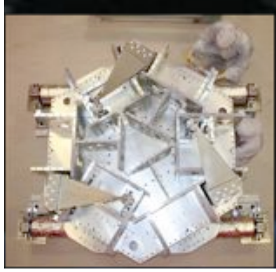


# Advanced LIGO: Less Loss

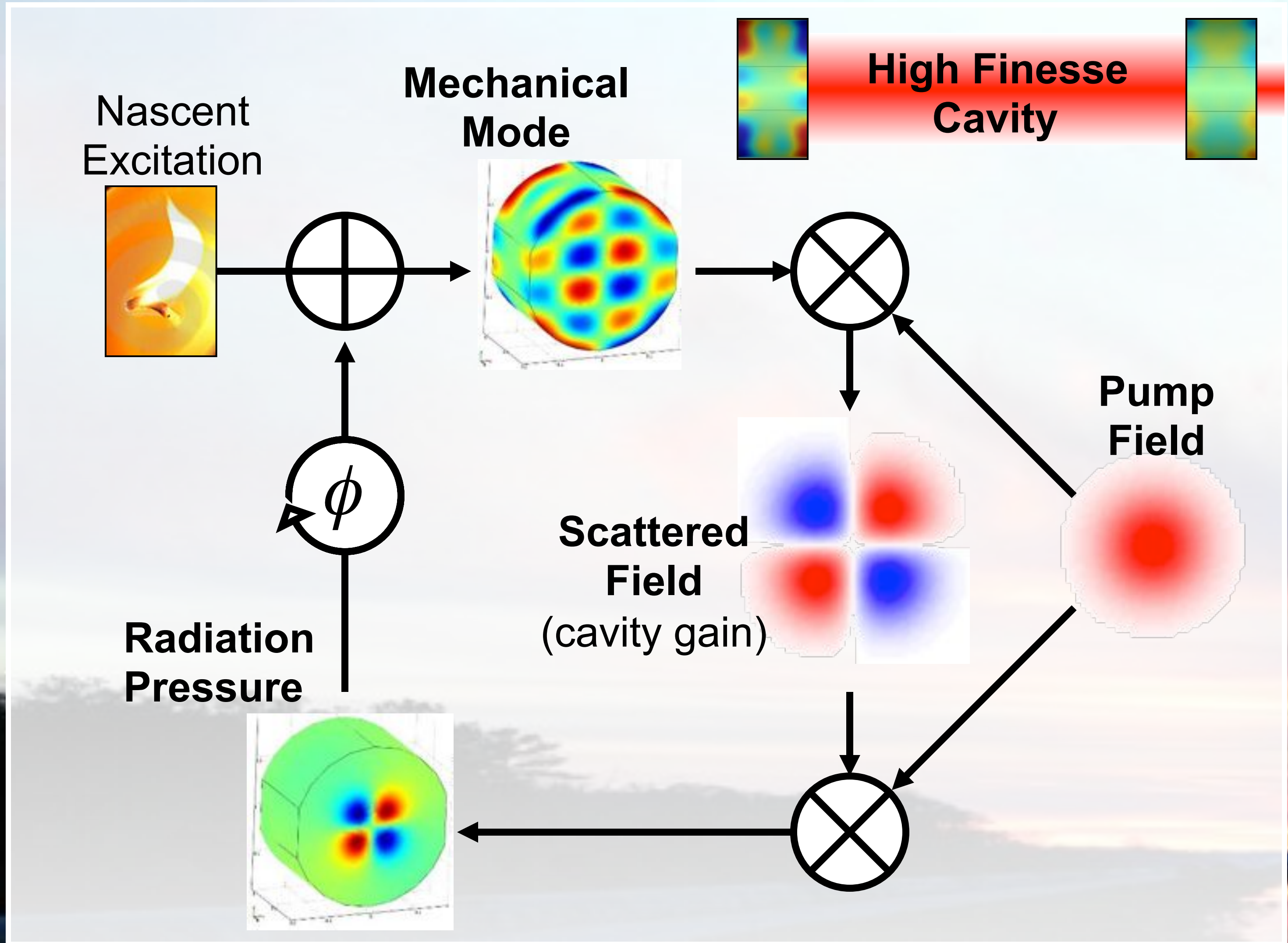
It all ends in a 40kg glass suspended by 400 micron glass fibers…

Prototype Suspension at MIT



# More Power, Less Loss… Unstable?



# Students damp instabilities to save Advanced LIGO

**Thanks to…**

**Post-doc: Slawek Gras**

**Grad: John Miller, Brett Shapiro**

**Undergrad: Natania Antler, Jonathan Soto**

A general approach to optomechanical parametric instabilities

M. Evans*, L. Barsotti, P. Fritschel

Massachusetts Institute of Technology, Cambridge, MA 02139, USA

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ABSTRACT

We present a simple feedback description of parametric instabilities of optical systems. Parametric instabilities are of particular interest

Passive Damping of a LIGO Mirror

by

Natania Antler

Submitted to the Department of Physics in partial fulfillment of the requirements for the degree of

Bachelor of Science in Physics

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 2009



Damping parametric instabilities in future gravitational wave detectors by means of electrostatic actuators

John Miller[a,*,1], Matthew Evans[a], Lisa Barsotti[a], Peter Fritschel[a], Myron MacInnis[a], Richard Mittleman[a], Brett Shapiro[a], Jonathan Soto[a], Calum Torrie[b]

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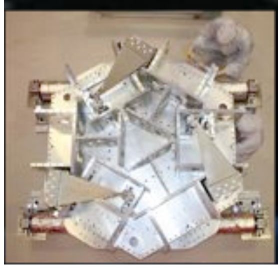
ABSTRACT

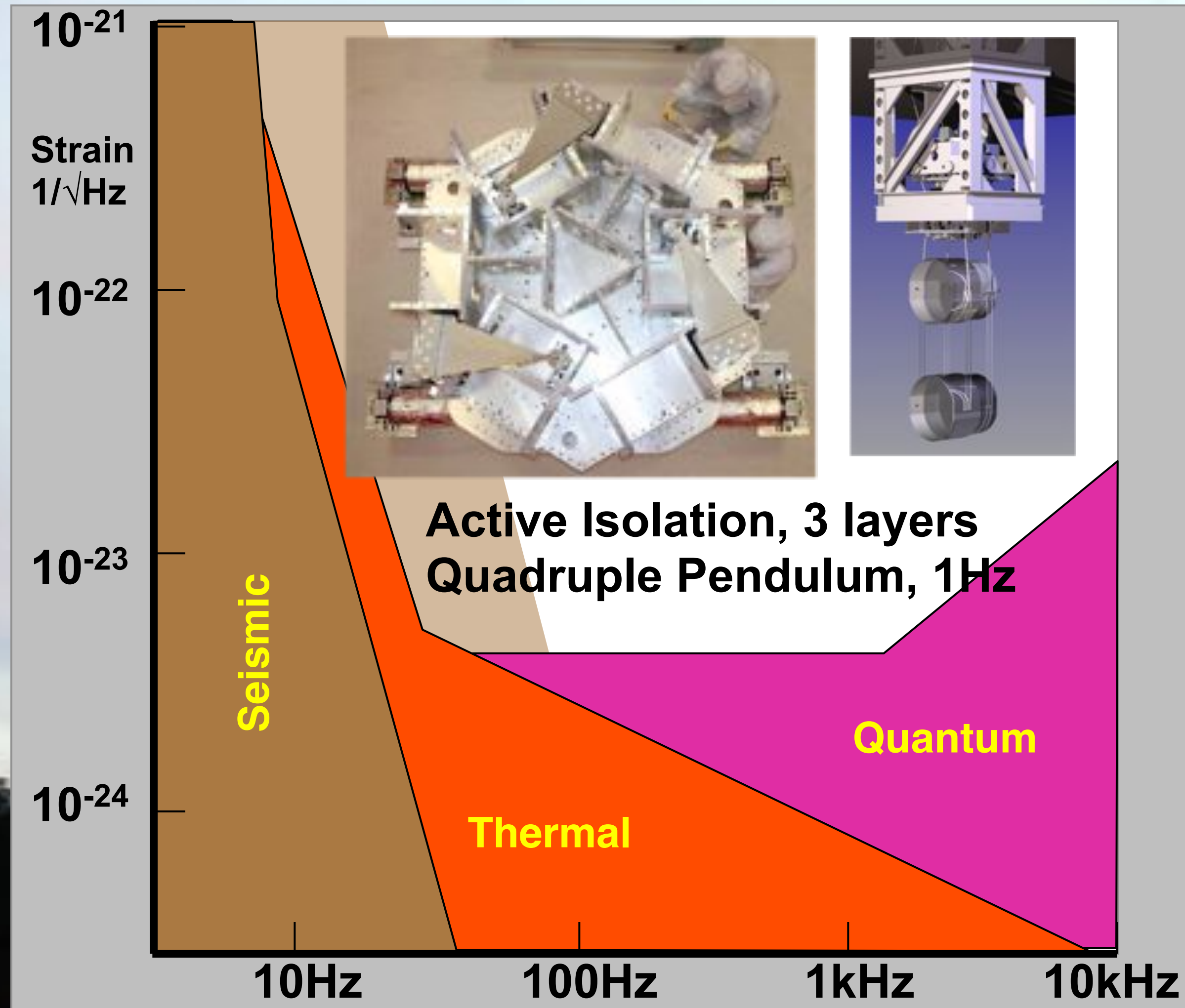
It has been suggested that the next generation of interferometric gravitational wave detectors may observe spontaneously excited parametric oscillatory instabilities. We present a method of actively suppressing any such instability through application of electrostatic forces to the interferometers

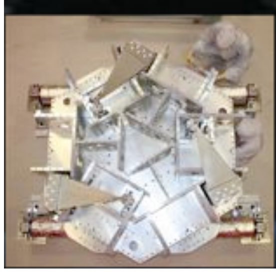


# Advanced LIGO: Better Isolation

Each interferometer floats on tons of metal with hundreds of active control loops…

Active Seismic Isolator

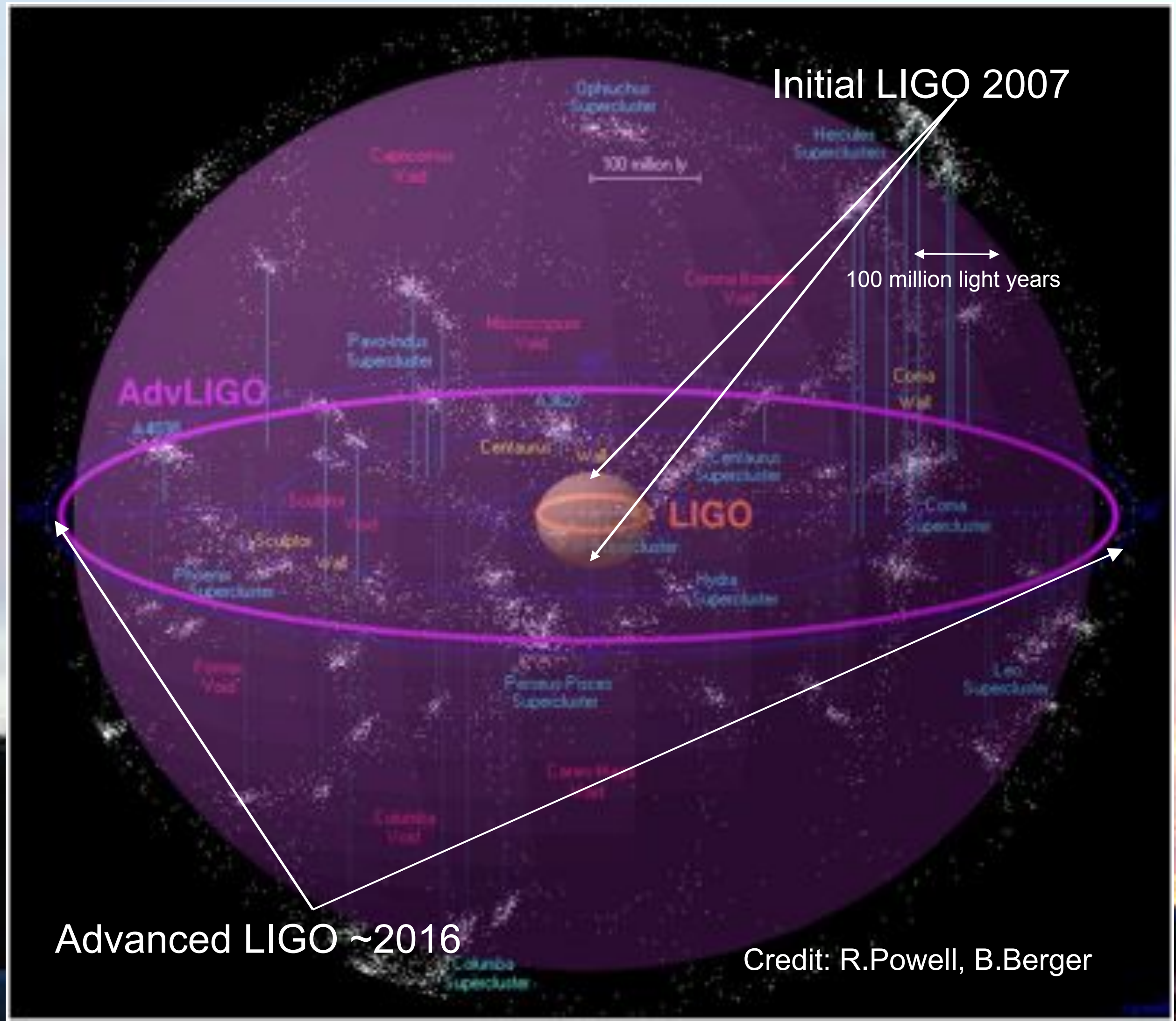


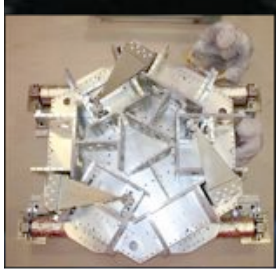
# Advanced LIGO

1000/70 yr ~ 14/yr

That's about 1 NS-NS detected each month.




Credit: R.Powell, B.Berger



# Payoffs: Advanced LIGO

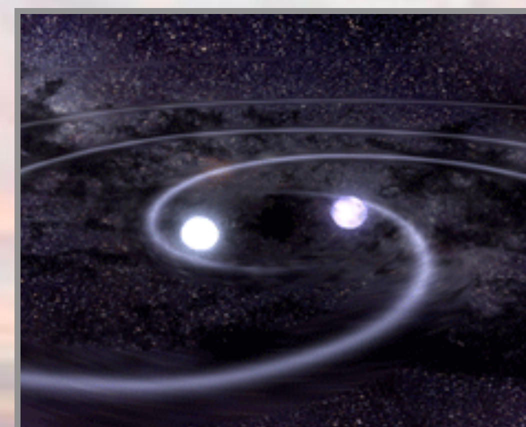
- ✓ Direct observation of strong-field GR
- ✓ Constrain evolution of stellar populations that produce compact objects
- ? Constrain neutron-star equation of state (and thus theories of nuclear matter)
- ? Standard siren

# Future Directions (current R&D)

- We heard something… now what?
- Where to go next
- Detector Upgrades
- Lab Scale R&D

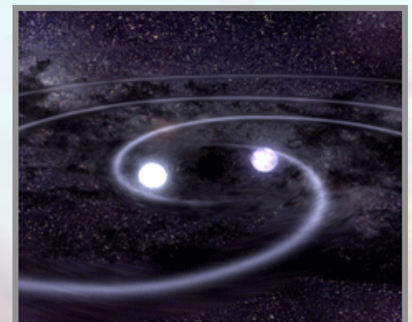
# We heard something… now what?

- Detecting gravitational-waves is not the end of our journey, it is the beginning
- "First detection" is an exciting landmark
- But, most of the payoff comes from
  - – observing a variety of sources
  - – preferably for many cycles each



# How we make an observatory

- Regular detections – more sensitive
- Long time in-band for inspirals
  - Good parameter estimation
  - Good distance estimate

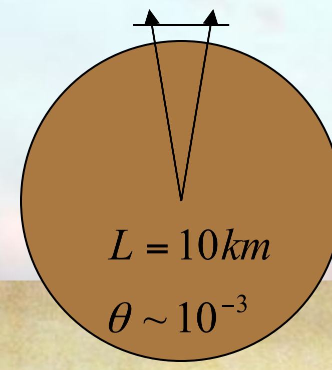


- Low-frequency performance
  - Time in-band scales like $f_{min}^{-8/3}$
  - Example… NS-NS with $f_{min}$ = 3, 10, 30 Hz, time is 7 hours, 17 minutes, 1 minute

# "Obvious Improvements"

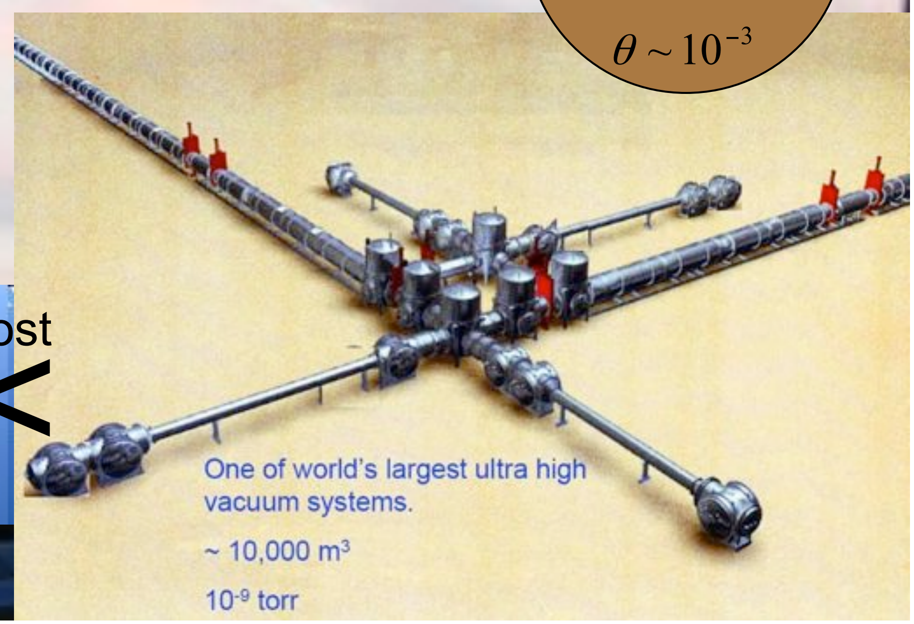
$$h = \Delta L / L$$

- Longer
  - Pro: gain at all frequencies
  - Con: increased vertical coupling
  - Con: new facility = time and money



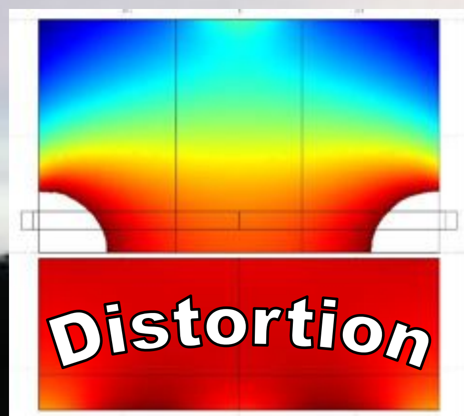

- 3rd generation, 2030?
  - not soon


Cost <



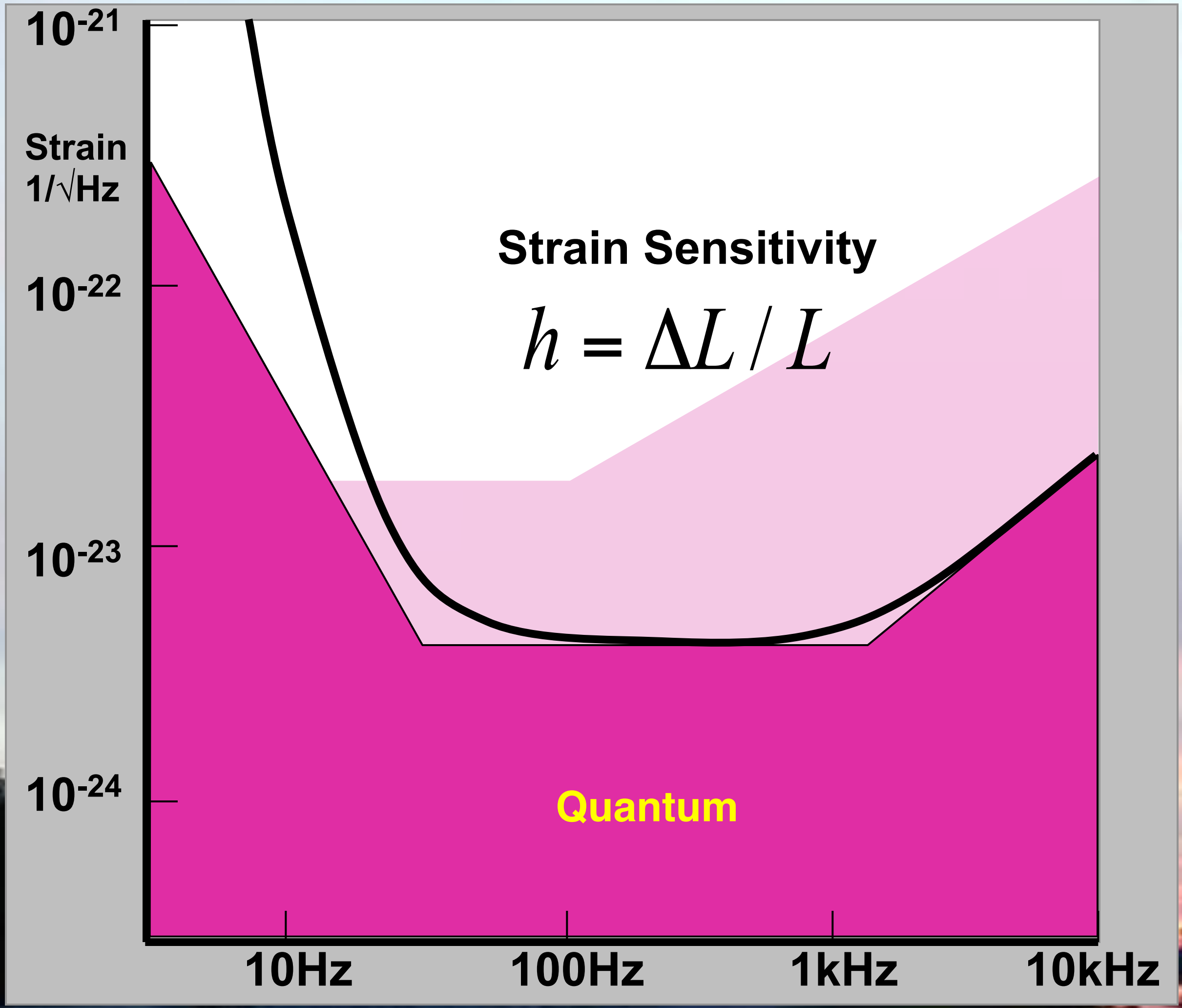
# "Obvious Improvements"

- More Power
  - Pro: lower shot noise
  - Con: higher radiation pressure noise
  - Con: mirror thermal distortion




# "Obvious Improvements"

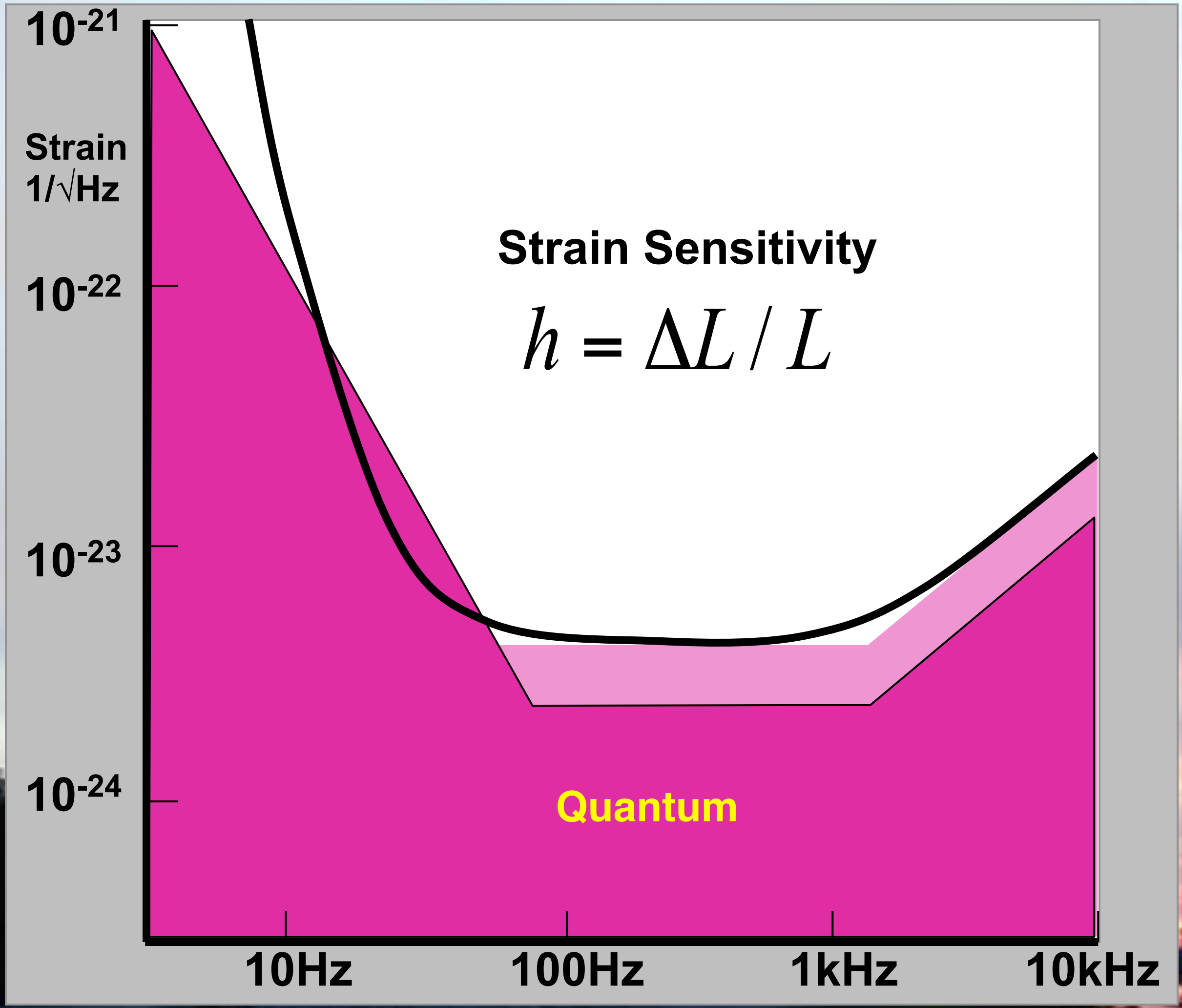
Increasing the power helped last time…




# "Obvious Improvements"

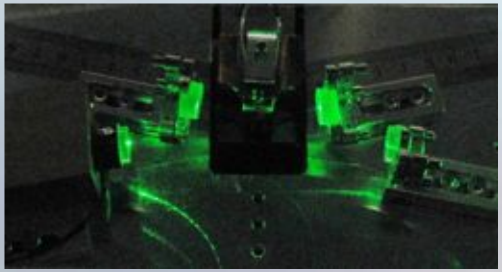
… but now radiation pressure noise makes things worse at low-frequency!

This has already been optimized.

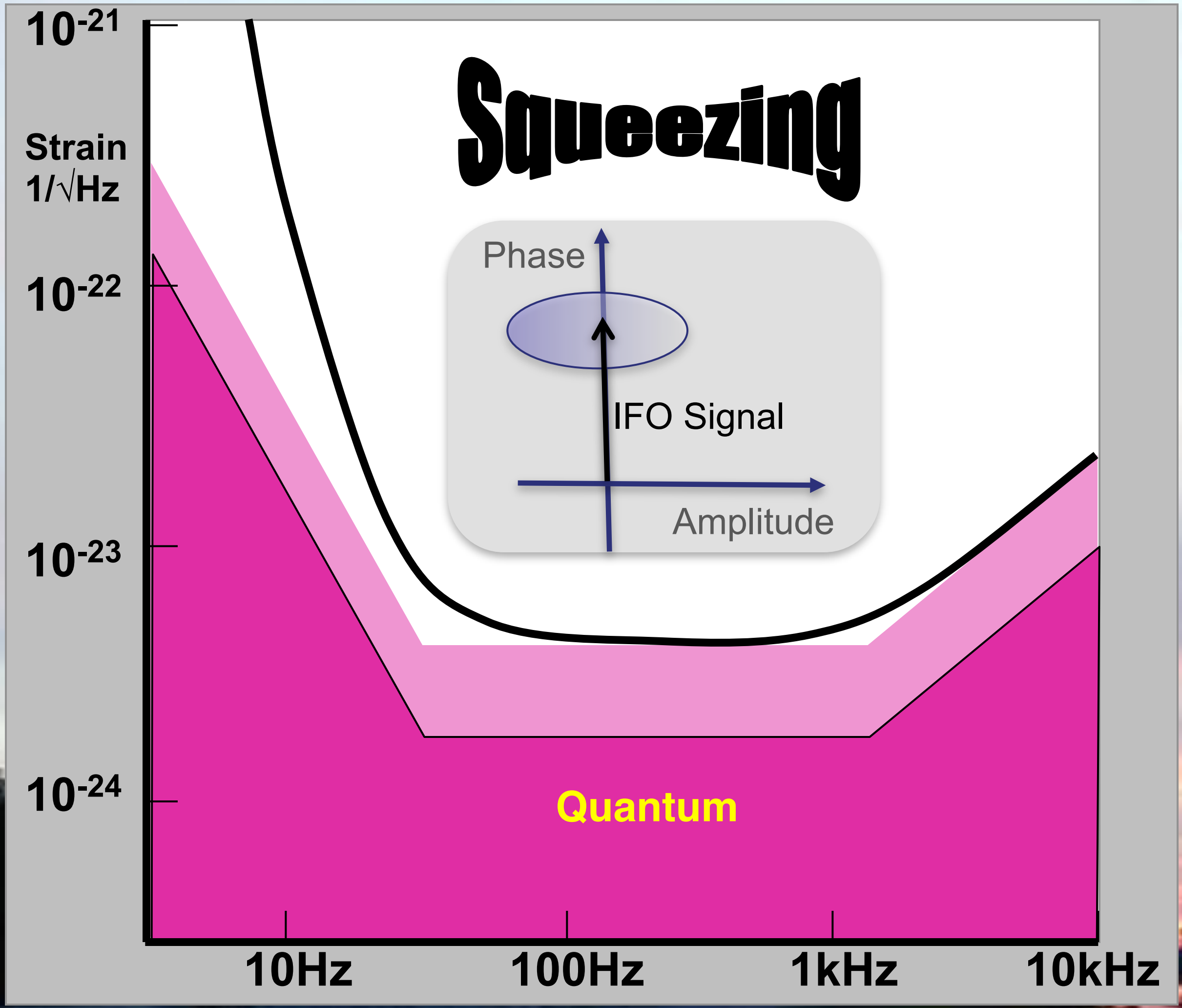


# Squeezing: The Next Step

Quantum noise can be reduced by squeezing…

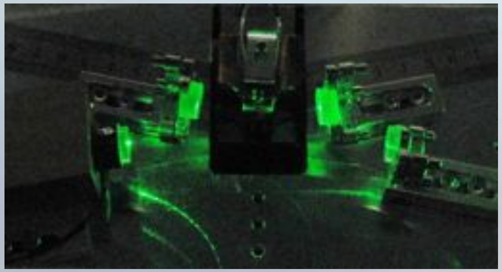


Recently demonstrated by Barsotti/Mavalvala at the Hanford Observatory



# Squeezing: It works!

Quantum noise can be reduced by squeezing…



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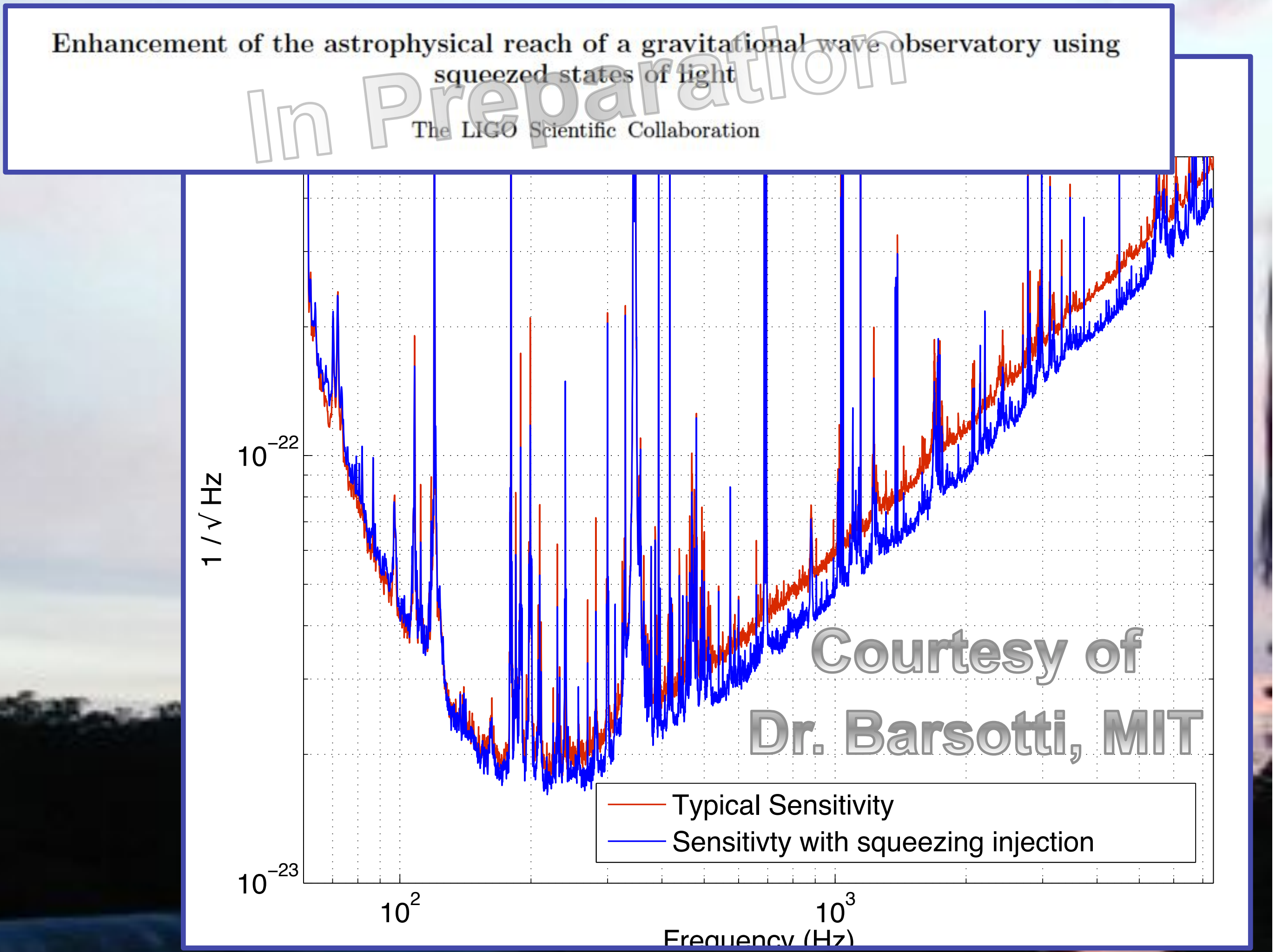
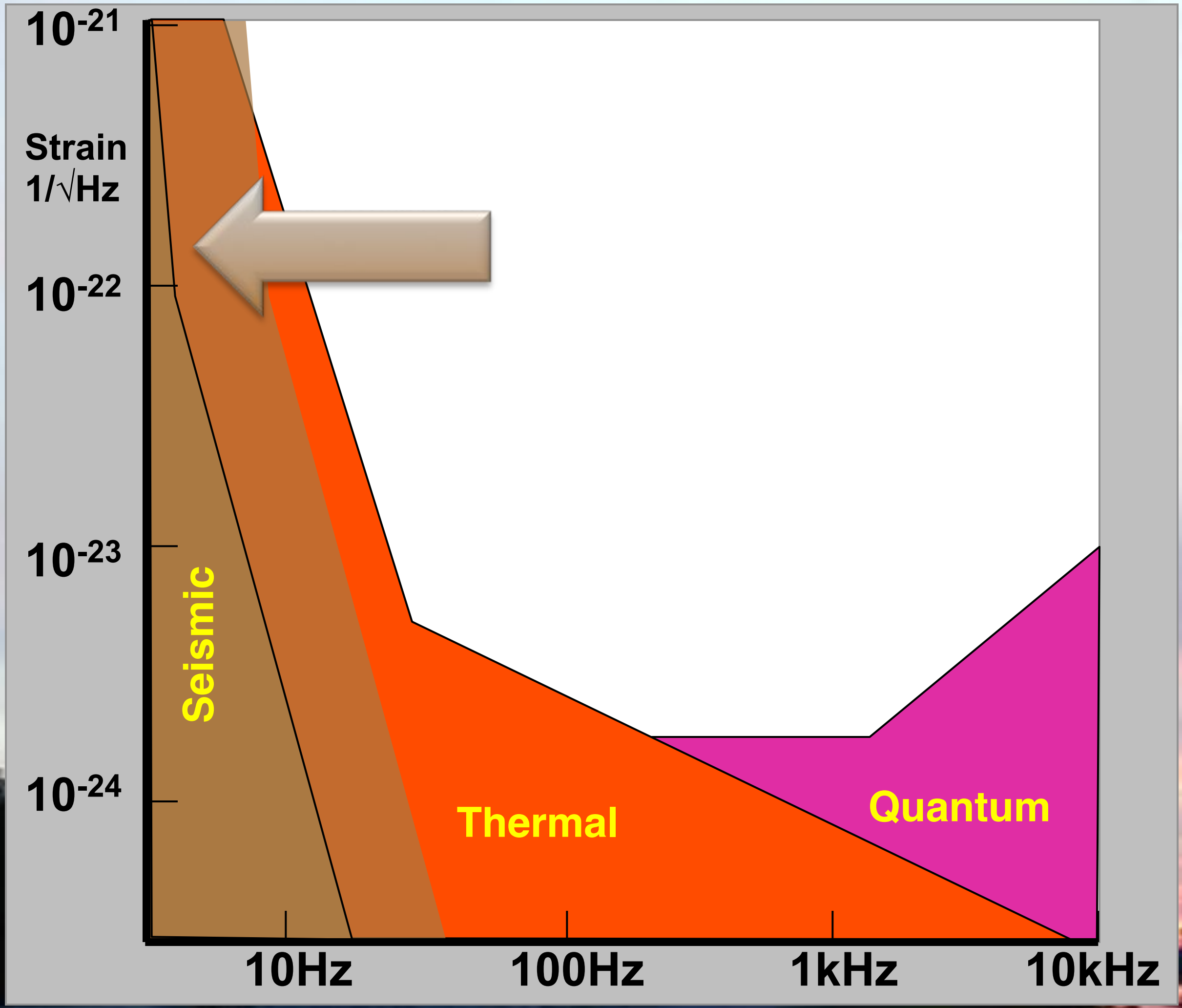


# Low Frequency: Moving the Wall

We moved seismic down, but it doesn’t help much…

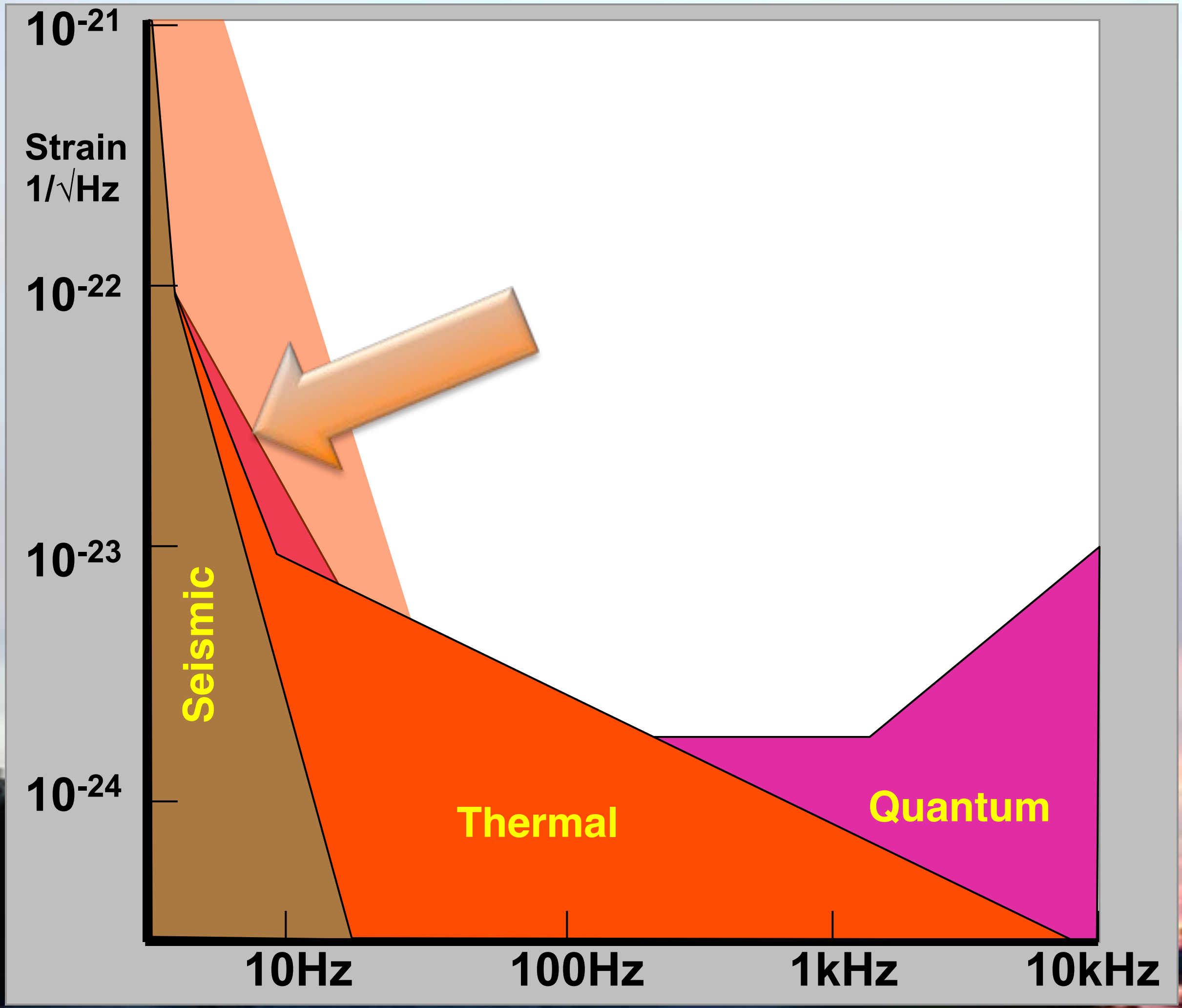
Let’s work on suspension thermal noise.



# Where is the big payoff?

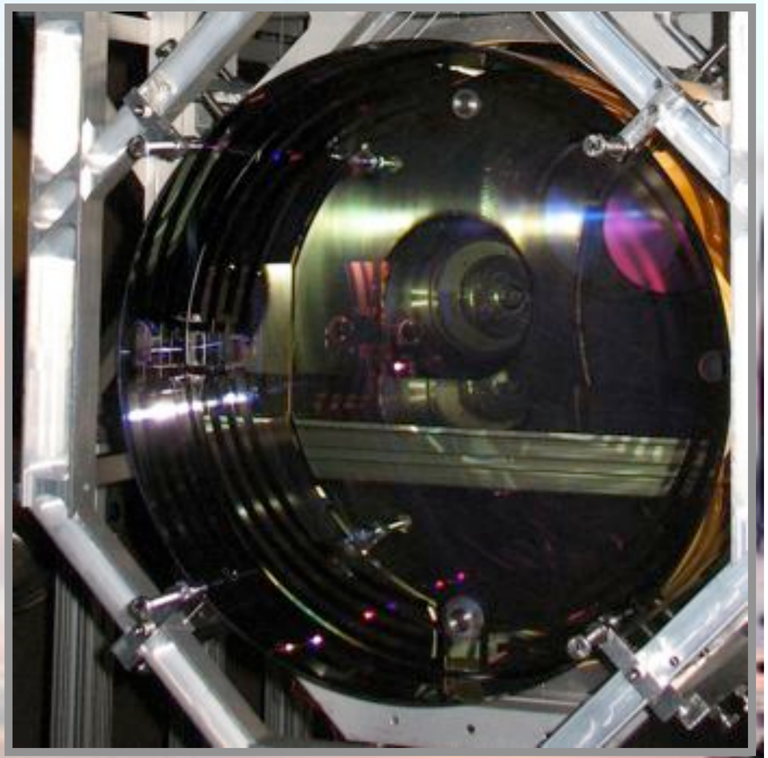
We know how to reduce seismic noise and suspension thermal noise, but coating thermal noise is still a problem.

The next generation will be all about coatings and quantum noise…




# Coating R&D

- Example: coating thermal noise
- Scales with beam radius
  - GW detector: r ~ 6cm
  - Lab scale: r ~ 60um
- Need measurements in GW band ~100Hz



# Thermal Noise

Optical Coatings and Thermal Noise in Precision Measurements

*Edited by*

Gregory M Harry and Timothy Bodiya

Massachusetts Institute of Technology

PHYSICAL REVIEW D **78**, 102003 (2008)

**Thermo-optic noise in coated mirrors for high-precision optical measurements**

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(Received 25 July 2008; published 10 November 2008)

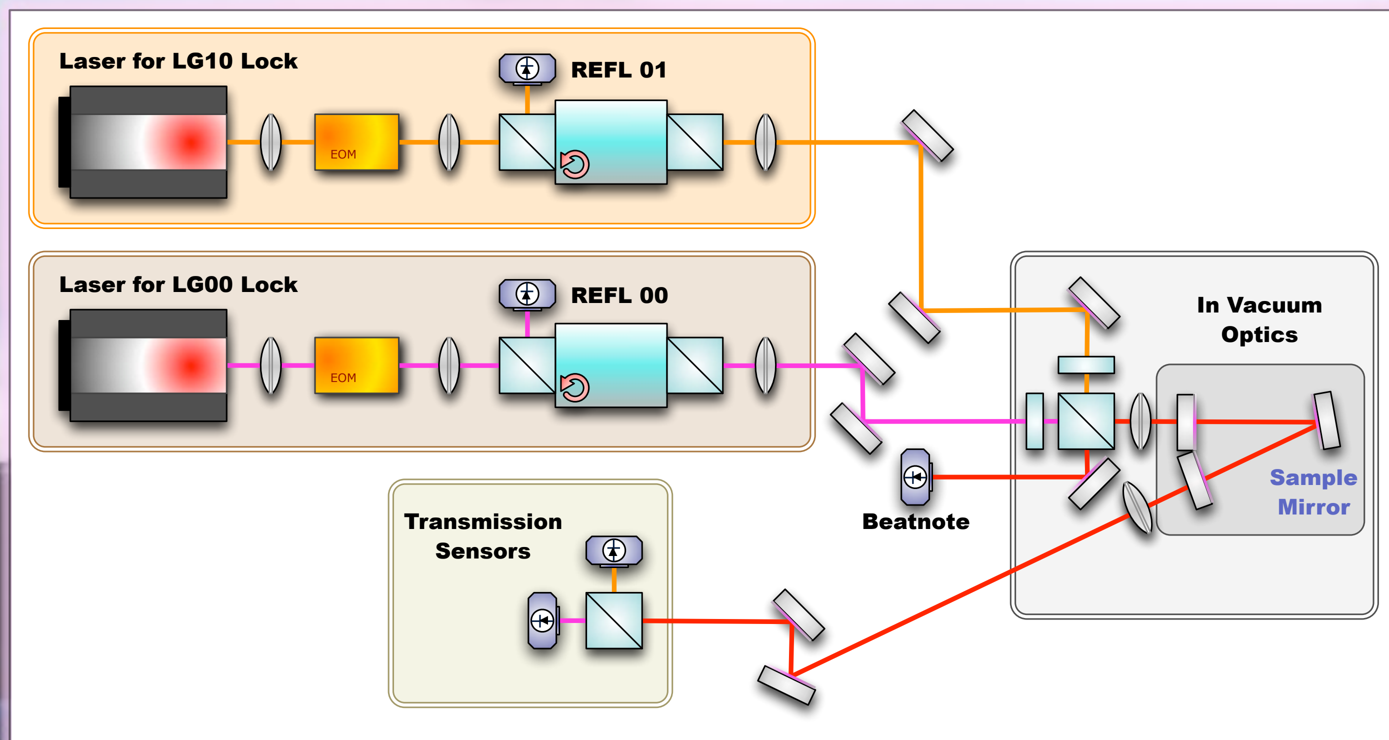
– Also important also for frequency references,

spectroscopy, atomic clocks, quantum information,

macro-quantum measurement…

# Starting now at MIT

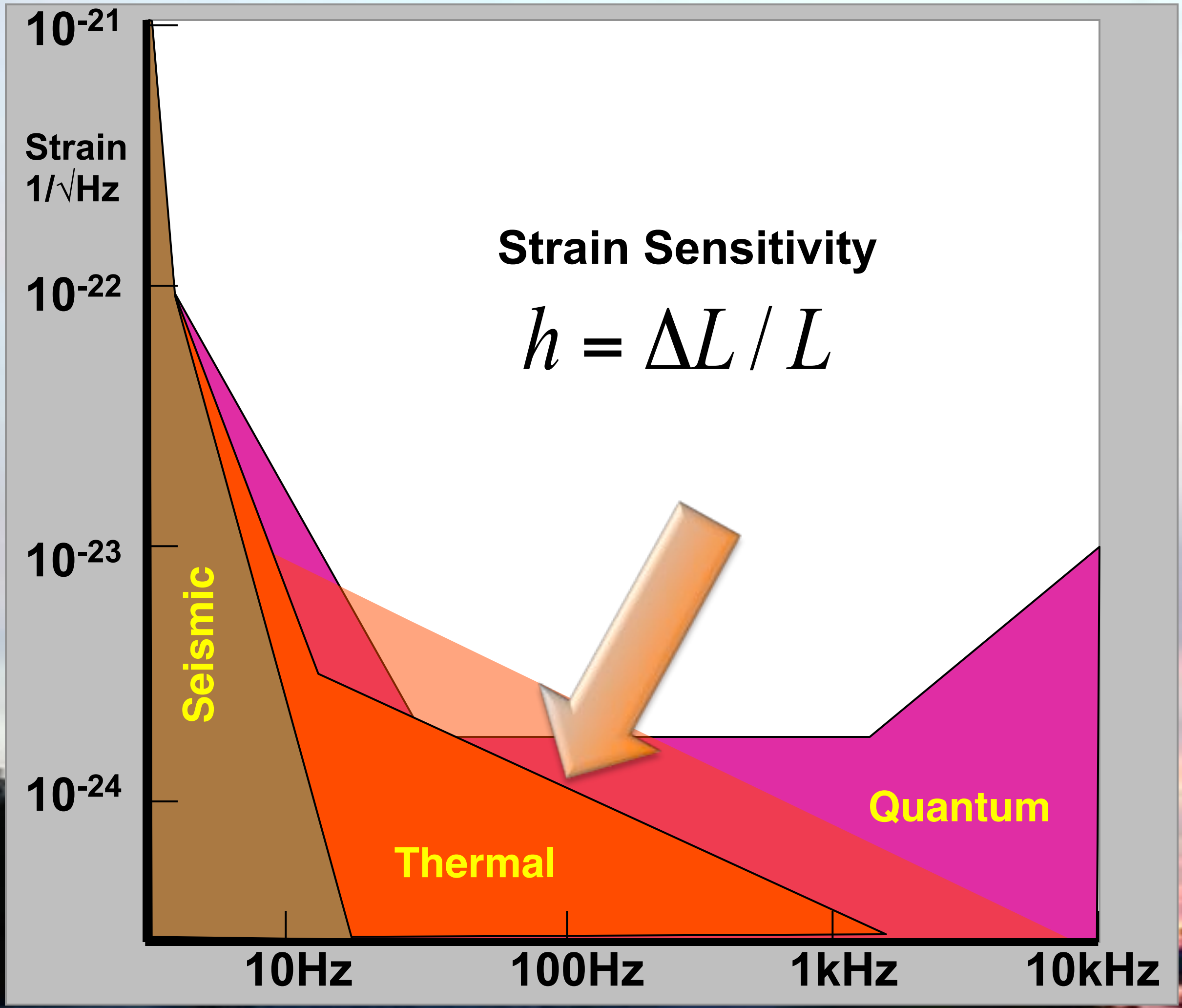
- Coating noise measurement for Advanced LIGO and coatings
- Facility for coating characterization



# Back to Quantum Noise

Now we're back to quantum noise.

The radiation pressure part can be addressed by making the mirrors more massive…



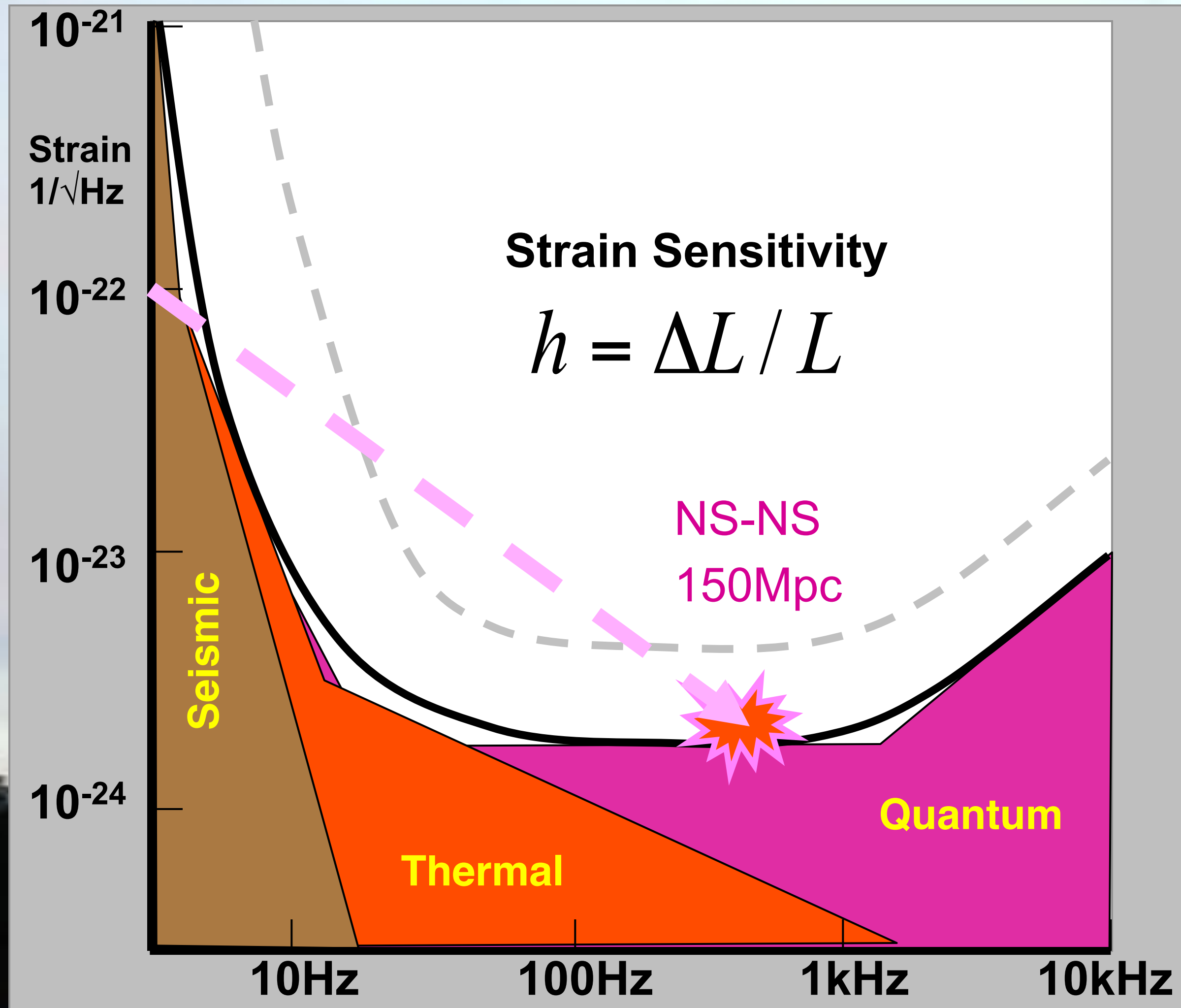

# Upgraded Advanced Detector

Let's say we get this far… what have we gained?

NS-NS mergers at 150Mpc

BH-BH inspirals at z of 1

Back to our list of payoffs!



# Payoffs: Upgraded Detectors

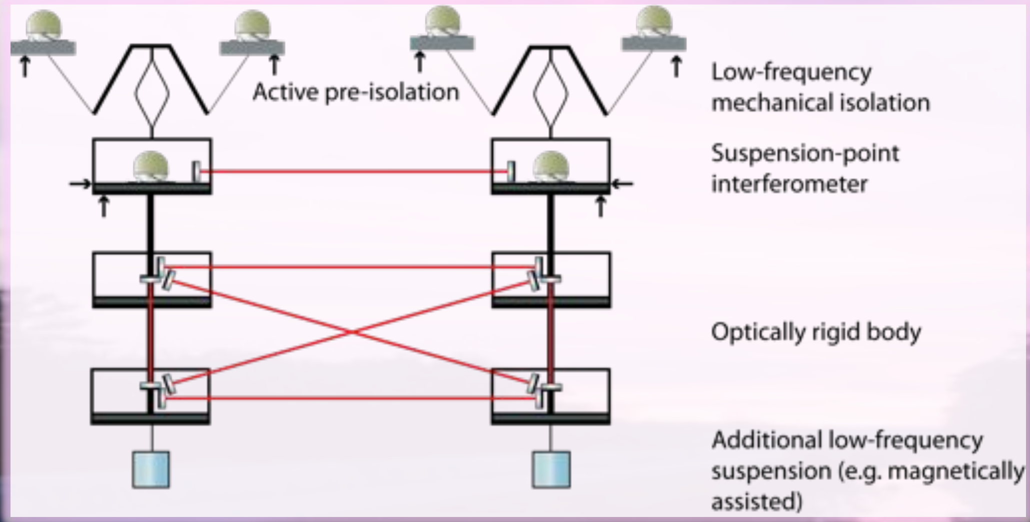
- Direct observation of strong-field GR
- Constrain evolution of stellar populations that produce compact objects
- Constrain neutron-star equation of state (and thus theories of nuclear matter)
- A “standard siren” for cosmology

# Other Directions

- Bigger, better LIGO is not the only way…
  - Depending on what we find, we may need to change direction
    - narrow-band detectors for CW sources
    - low-frequency detectors for IMBH, …

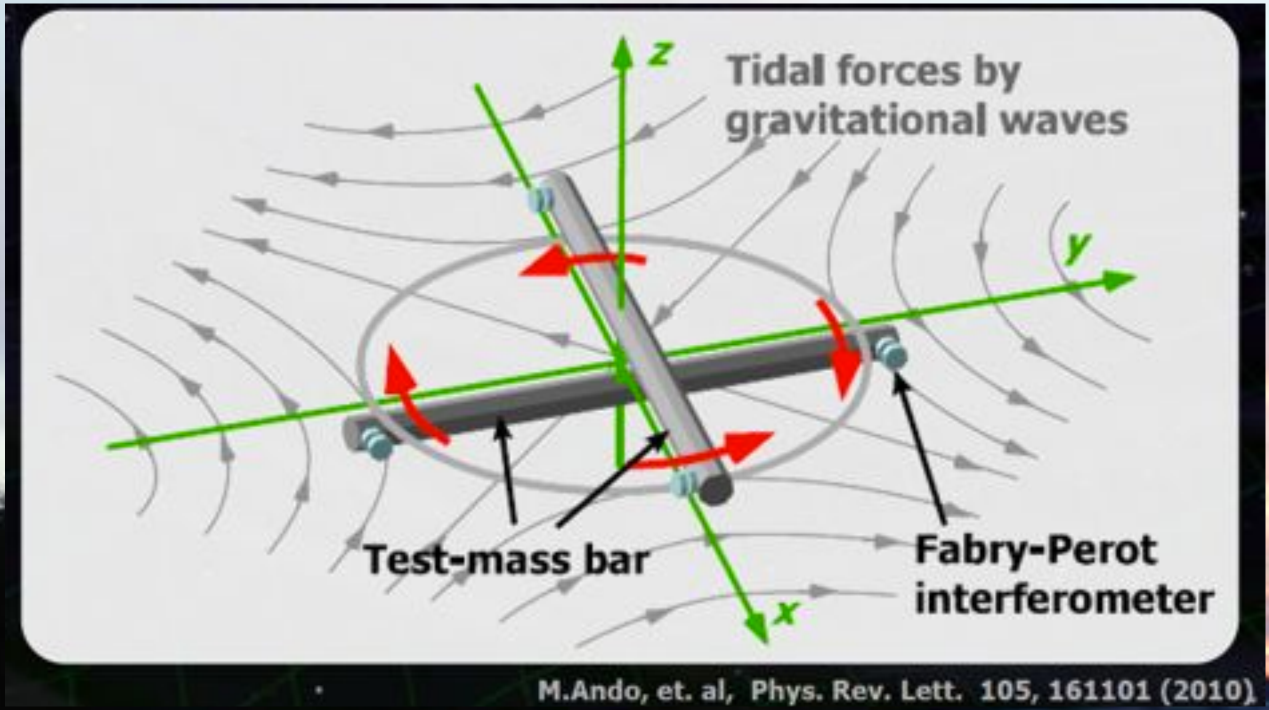
**Optical Space Frame**

**A long, vibration isolated, rigid platform for high precision experiments**



# TOBA – torsion bar antenna

- 10 mHz to 10 Hz
- First prototype built in Japan (Ando et. al)



# The Message

- First generation detectors
  - operated as designed
- Advanced detectors, coming soon
  - First detection 2017?
- Upgrades will take us from
  - Detector: “Wow! We heard something!” to
  - Observatory: “How many sources are in band now?”


Thanks!