WIDEBAND, NEXT GEN, GRAVITATIONAL-WAVE ANTENNAE

APS - Atlanta - April - 2012

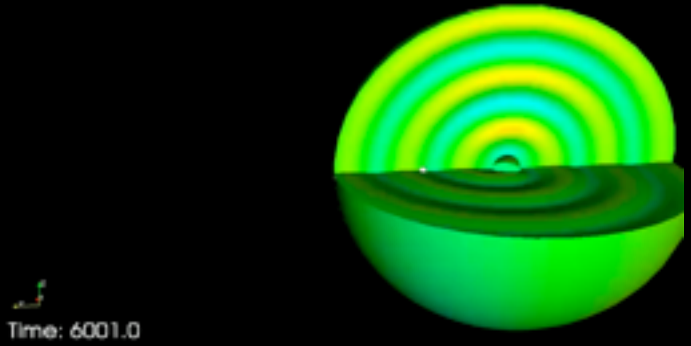
Rana Adhikari

Caltech

OUTLINE

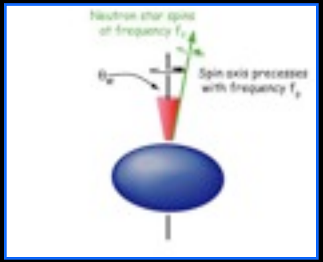
- Gravitational Waves and the Past
- The LIGO Detectors
- The Global Network and the Indian Possibility
- The Future of GW Detectors & Observations

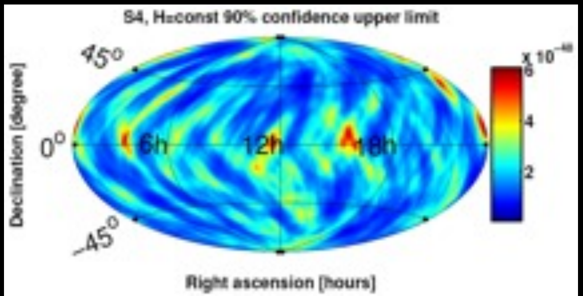
GW Sources in LIGO Band 50-1000 Hz

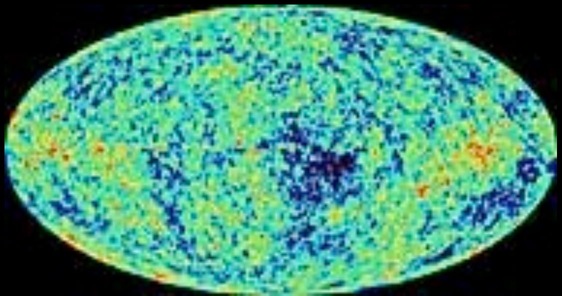


Caltech/Cornell - SXS

- ☐ **Compact binary inspirals:** ***“chirp”***
  - NS-NS waveforms are well described.
  - **inspiral is a standard candle.**
  - BH-BH merger simulations exist!
- ☐ **Supernovae / Mergers:** ***“burst”***
  - Short signals. Waveforms not well known.
  - Search in coincidence between two or more interferometers and possibly with electromagnetic and/or neutrinos signals
- ☐ **Spinning NS:** ***“continuous”***
  - search for signals from observed pulsars
  - all-sky search computing challenging
- ☐ **Cosmic Background:** ***“stochastic”***
  - Metric fluctuations amplified by inflation, phase transitions in early universe, topological defects
  - Unresolved foreground sources







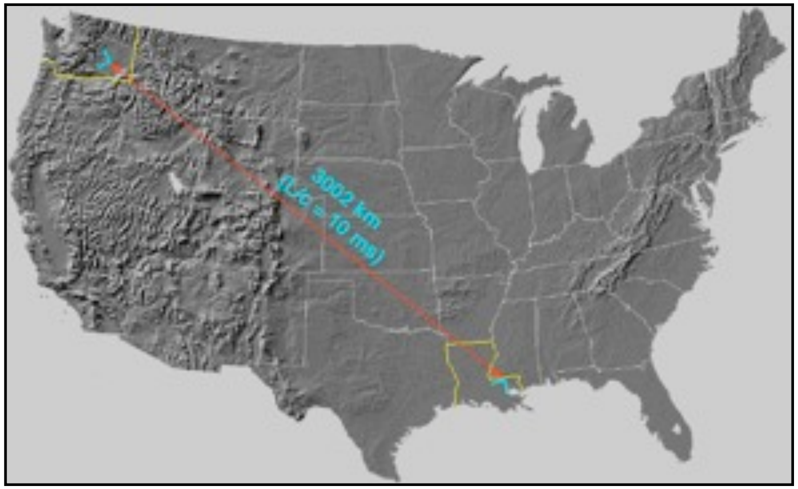
LIGO: **L**aser **I**nterferometer **G**ravitational-wave **O**bservatory

Hanford Nuclear Reservation, Eastern Washington

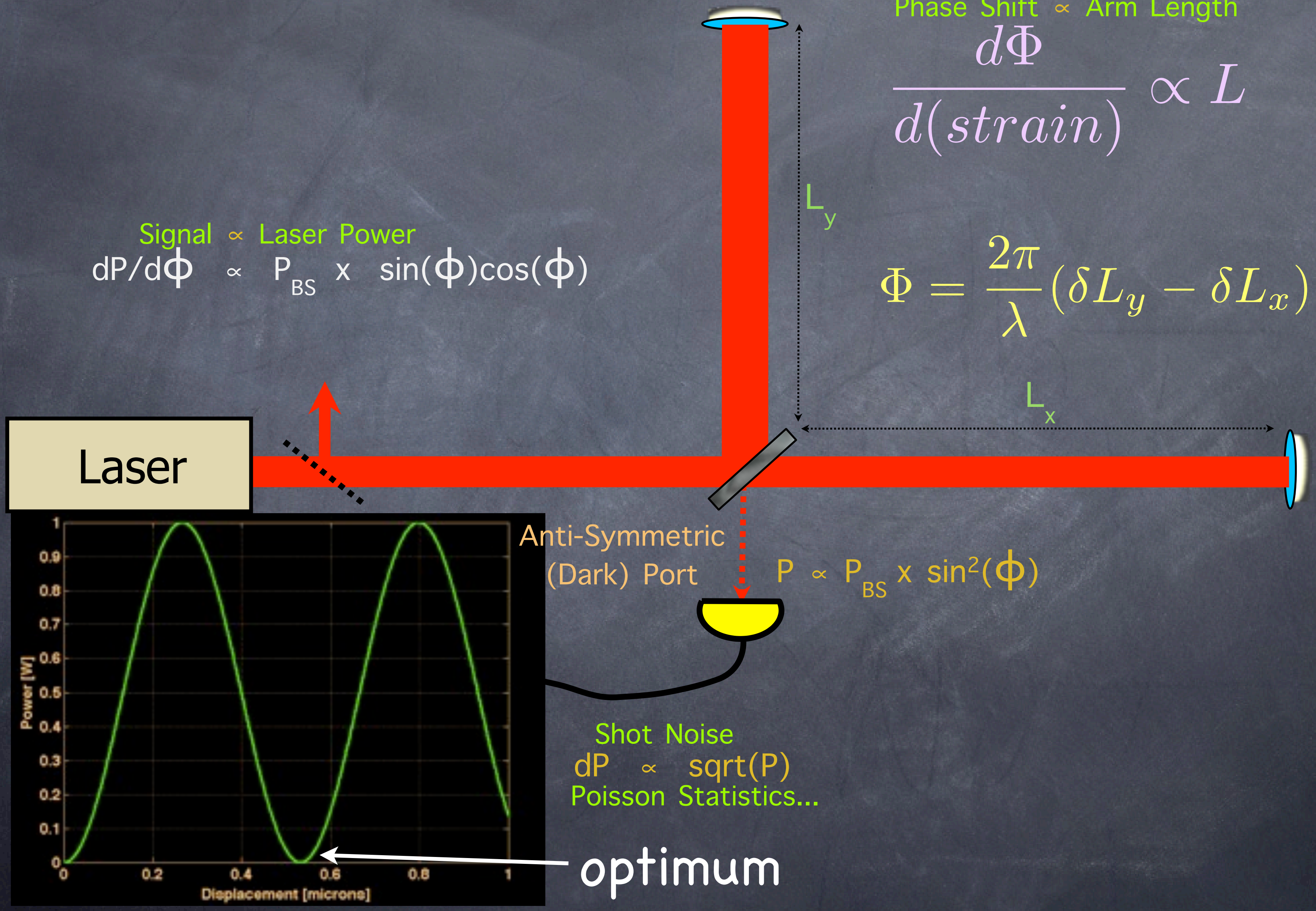
- *Interferometers are aligned to be as close to parallel to each other as possible*
- *Observing signals in coincidence increases the detection confidence*
- *Determine source location on the sky, propagation speed and polarization of the gravity wave*

Livingston, LA (L1 4km)

~1 hour from New Orleans



A Michelson Interferometer



Phase Shift ∝ Arm Length

$$\frac{d\Phi}{d(strain)} \propto L$$

Signal ∝ Laser Power

dP/dϕ ∝ P_{BS} x sin(ϕ)cos(ϕ)

$$\Phi = \frac{2\pi}{\lambda}(\delta L_y - \delta L_x)$$

Anti-Symmetric (Dark) Port

P ∝ P_{BS} x $\sin^2$(ϕ)

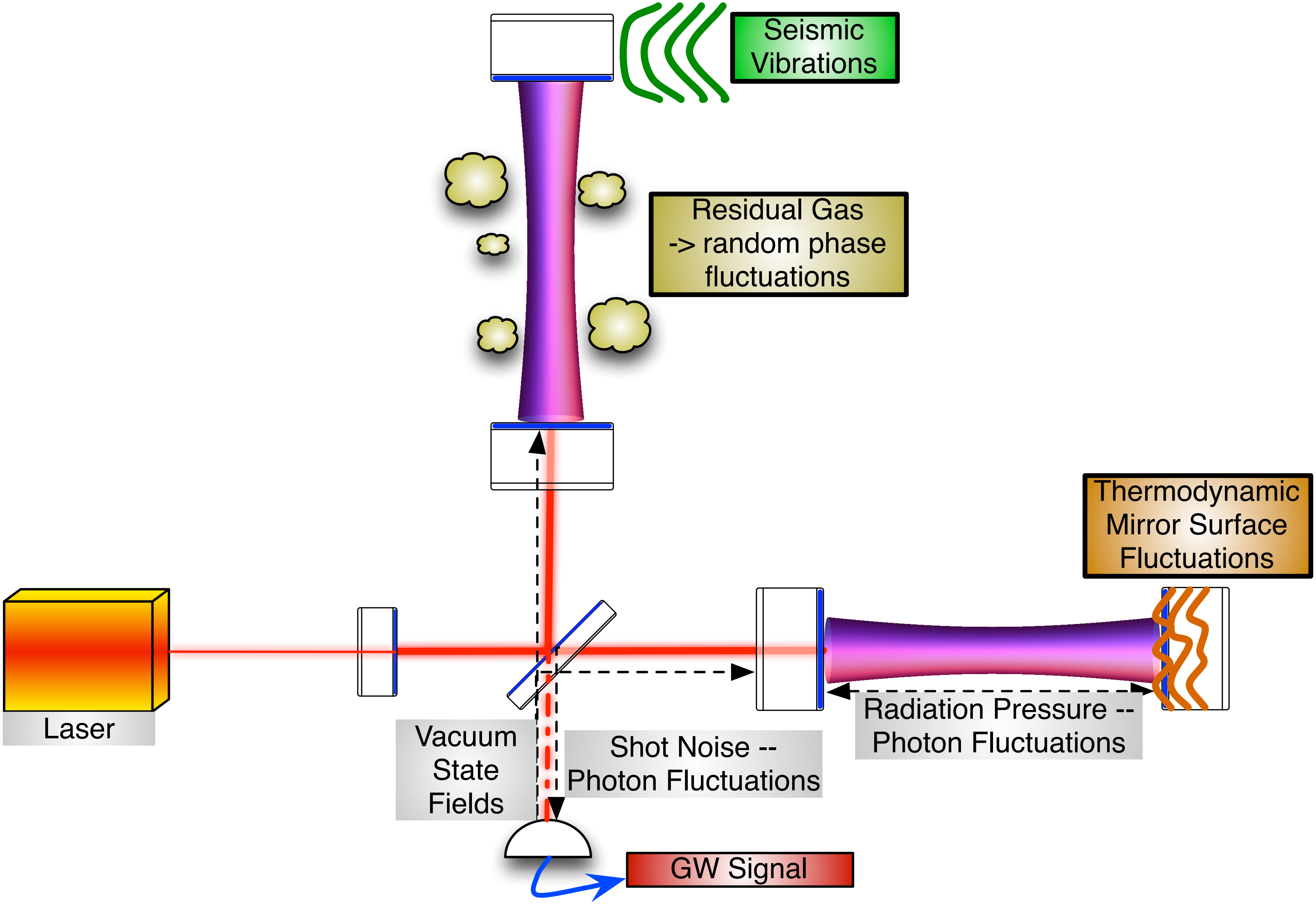
Shot Noise

dP ∝ sqrt(P)

Poisson Statistics...

optimum

LIGO: Major Sources of Noise



Seismic Vibrations

Residual Gas -> random phase fluctuations

Thermodynamic Mirror Surface Fluctuations

Laser

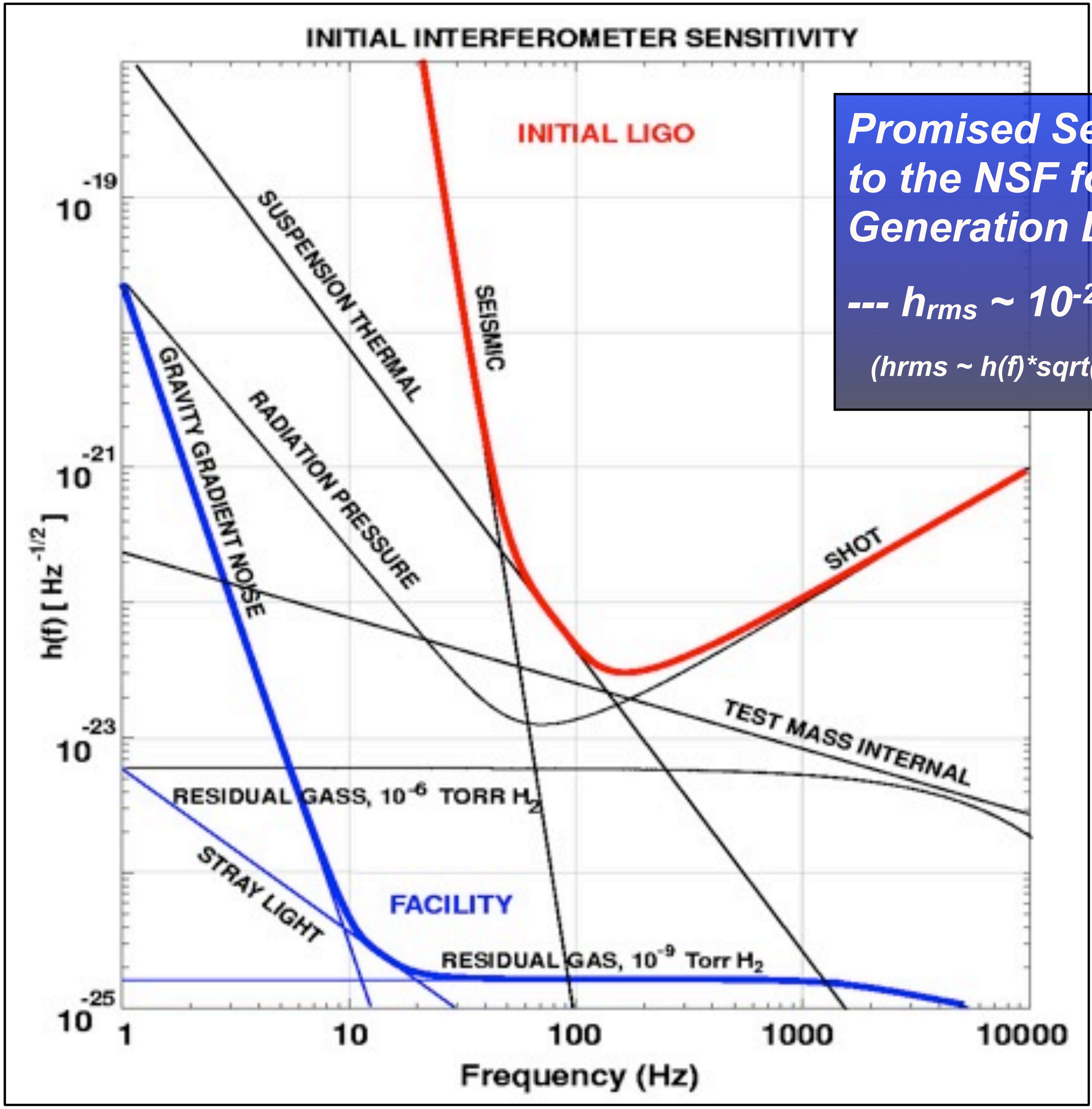
Vacuum State Fields

Shot Noise -- Photon Fluctuations

Radiation Pressure -- Photon Fluctuations

GW Signal

initial LIGO Science Requirement

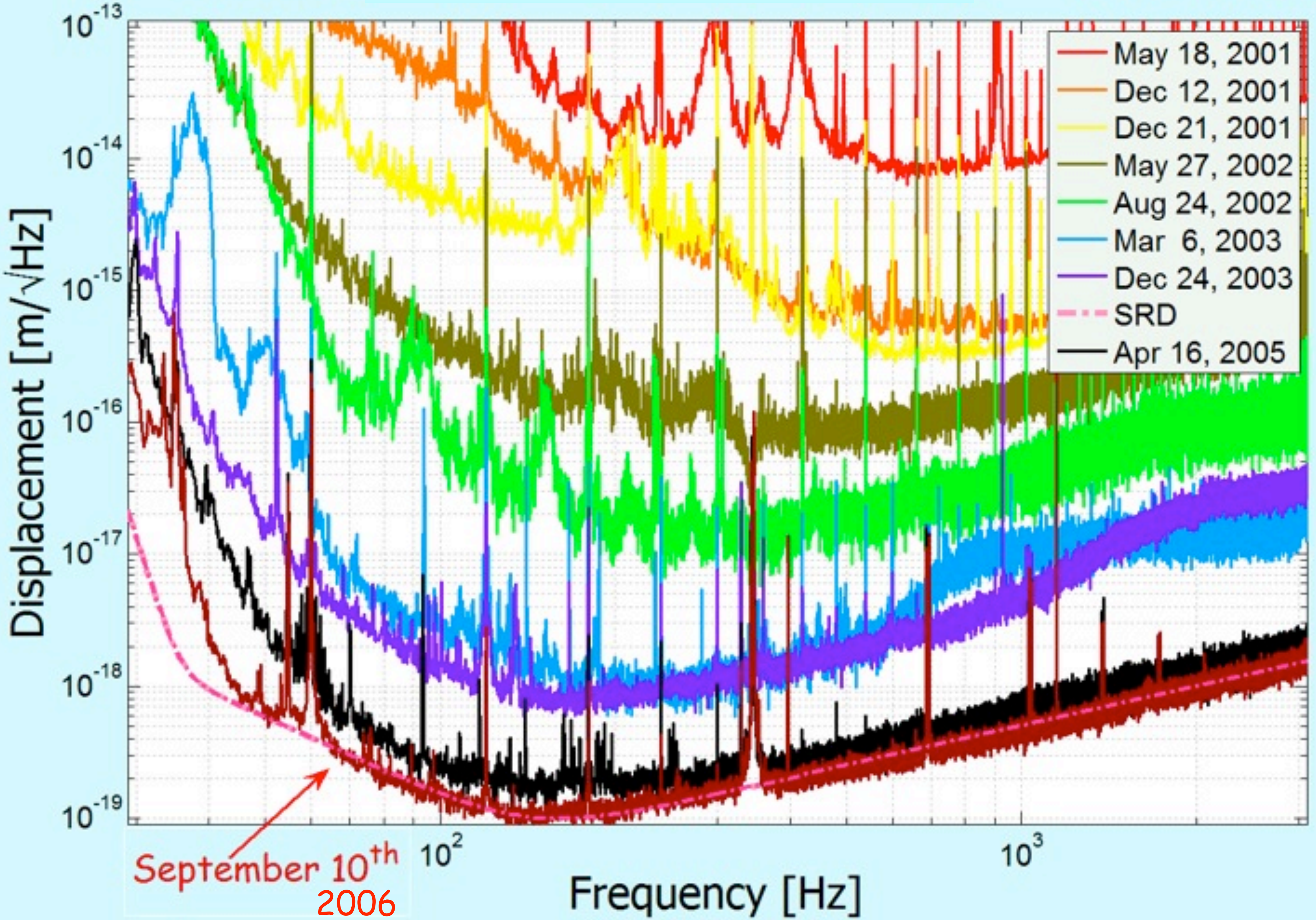


Promised Sensitivity to the NSF for the 1st Generation Detectors.

--- $h_{rms} \sim 10^{-21}$

*(hrms ~ h(f)*sqrt(f))*

initial LIGO Noise Progression



2006

A Michelson Interferometer

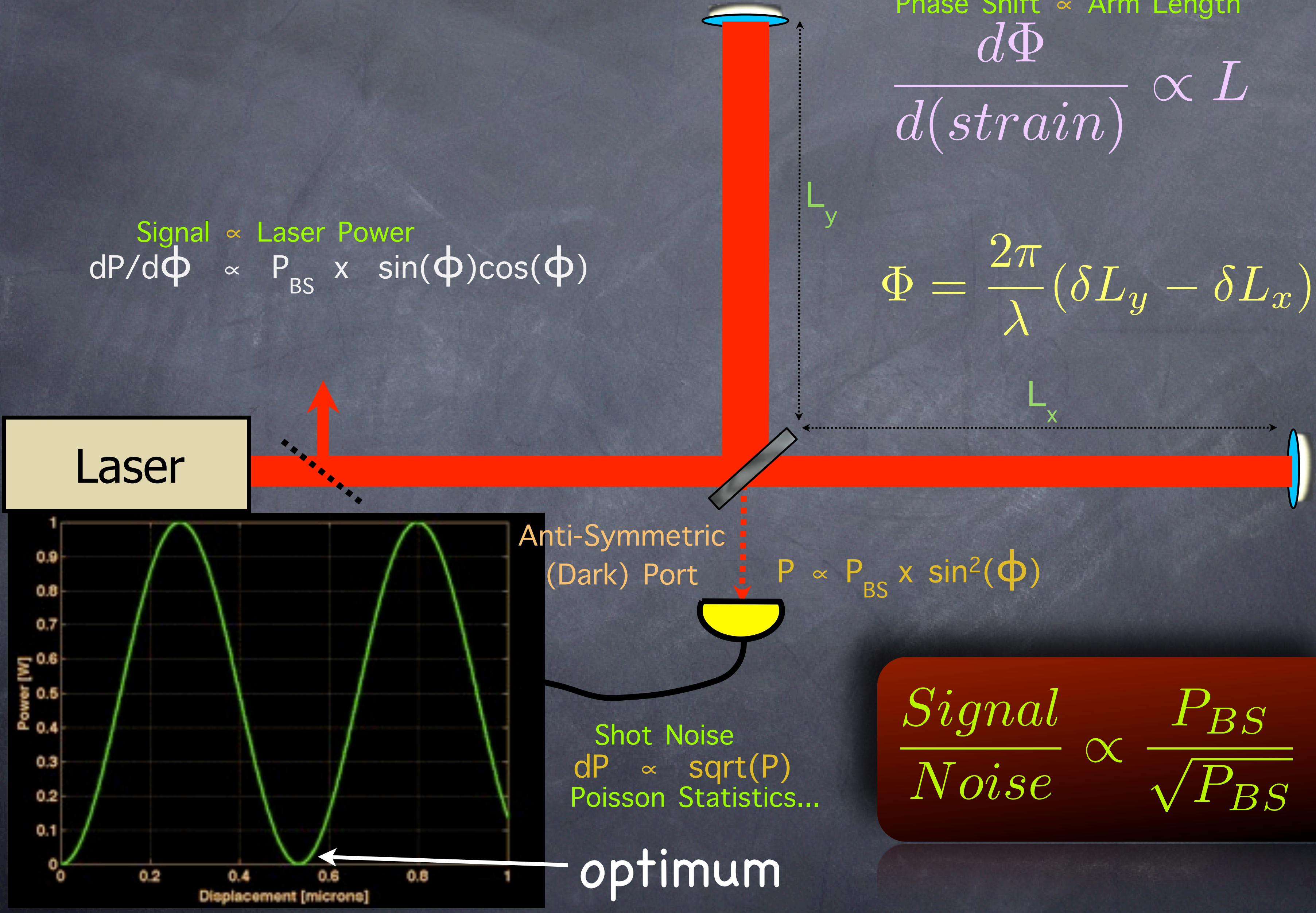
Phase Shift ∝ Arm Length

$$\frac{d\Phi}{d(strain)} \propto L$$

Signal ∝ Laser Power

$dP/d\phi \propto P_{BS} \times \sin(\phi)\cos(\phi)$

$$\Phi = \frac{2\pi}{\lambda}(\delta L_y - \delta L_x)$$



optimum

Anti-Symmetric (Dark) Port

$P \propto P_{BS} \times \sin^2(\phi)$

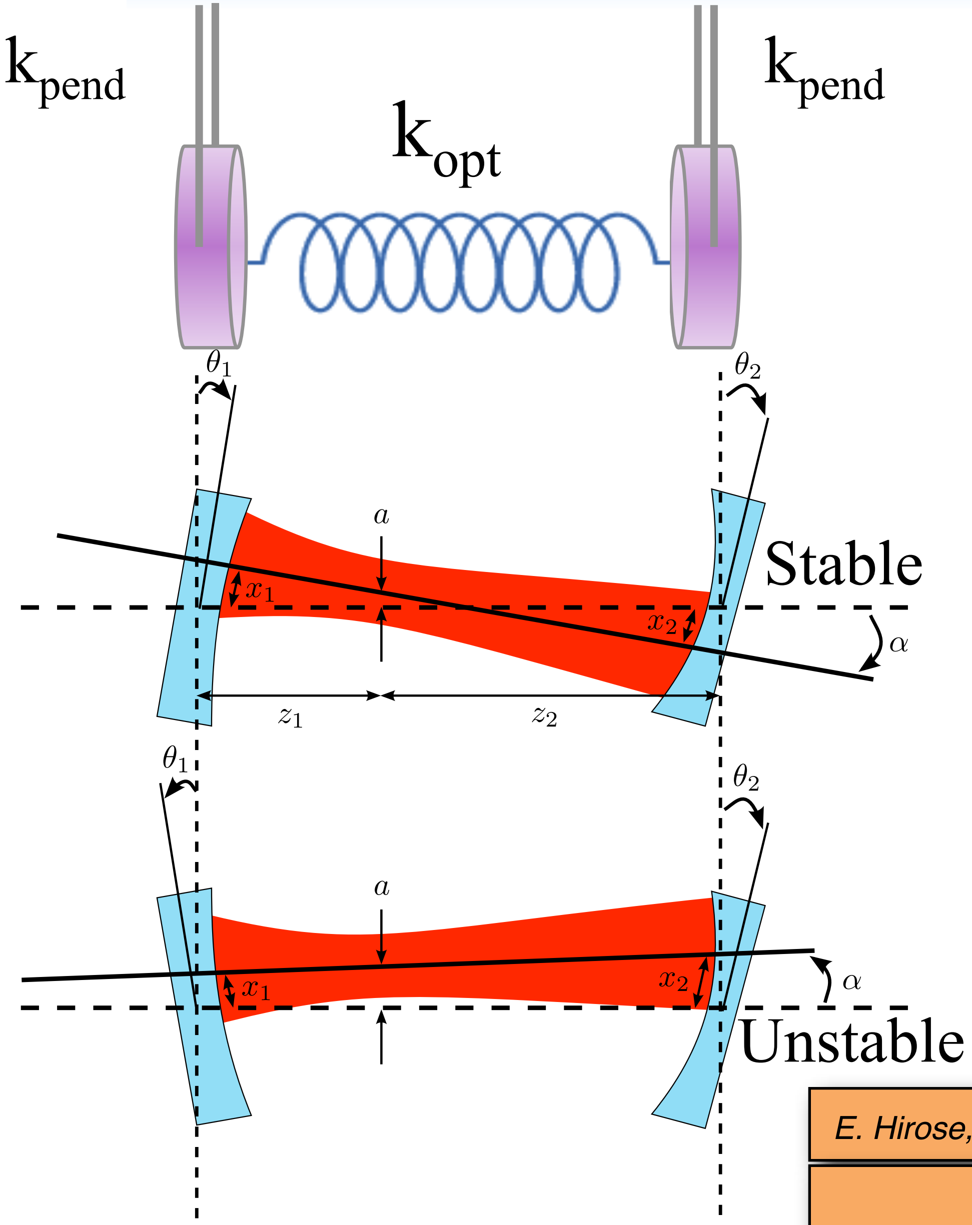
Shot Noise

$dP \propto \mathrm{sqrt}(P)$

Poisson Statistics...

$$\frac{Signal}{Noise} \propto \frac{P_{BS}}{\sqrt{P_{BS}}}$$

High Power Limit #1: Opto-Mechanical Angular Instability



Torque for single mirror

$$\tau_{RP} = \frac{2Px}{c} = F_{RP} \times x$$

Torque in a Fabry-Perot Cavity

$$\boldsymbol{\tau} = \hat{k}_{opt}(g_1, g_2, L, P)\begin{pmatrix}\theta_1 \\ \theta_2\end{pmatrix}$$

$$\omega^2_{stable} = \frac{k_{stable} + k_{pend}}{I}$$

$$\omega^2_{unstable} = \frac{k_{unstable} + k_{pend}}{I}$$

J.A. Sidles and D. Sigg, PLA (2006)

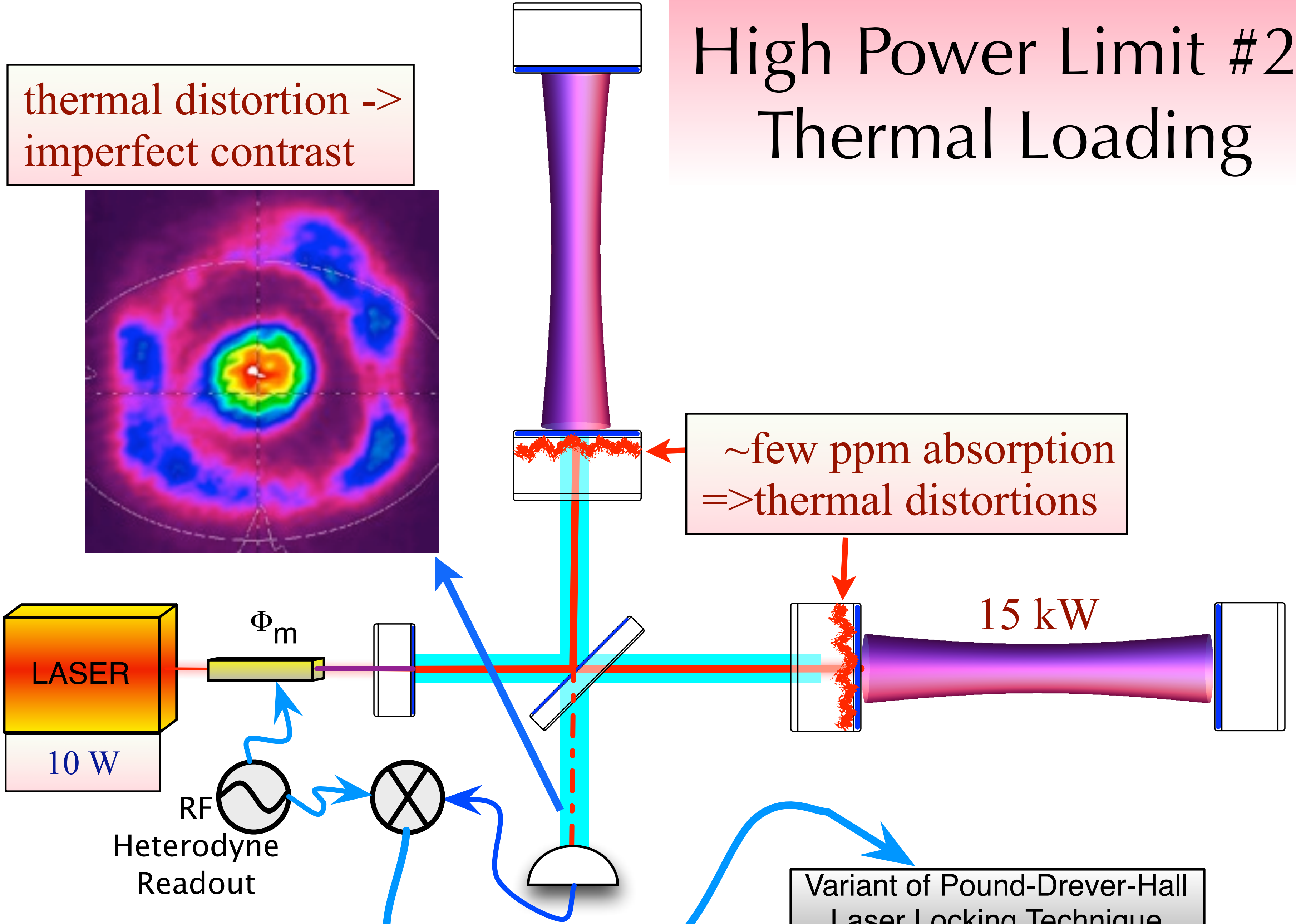
- *Unstable in (5) Mirror Basis: increasing feedback gain fails*

- *Change to Opto-Mechanical basis to provide conditional stability*

*E. Hirose, K. Kawabe, D. Sigg, **RA**, and P.R. Saulson, App. Optics (2010)*

*K.A. Dooley, L. Barsotti, M.Evans, **RA**, in prep (2012)*

High Power Limit #2: Thermal Loading



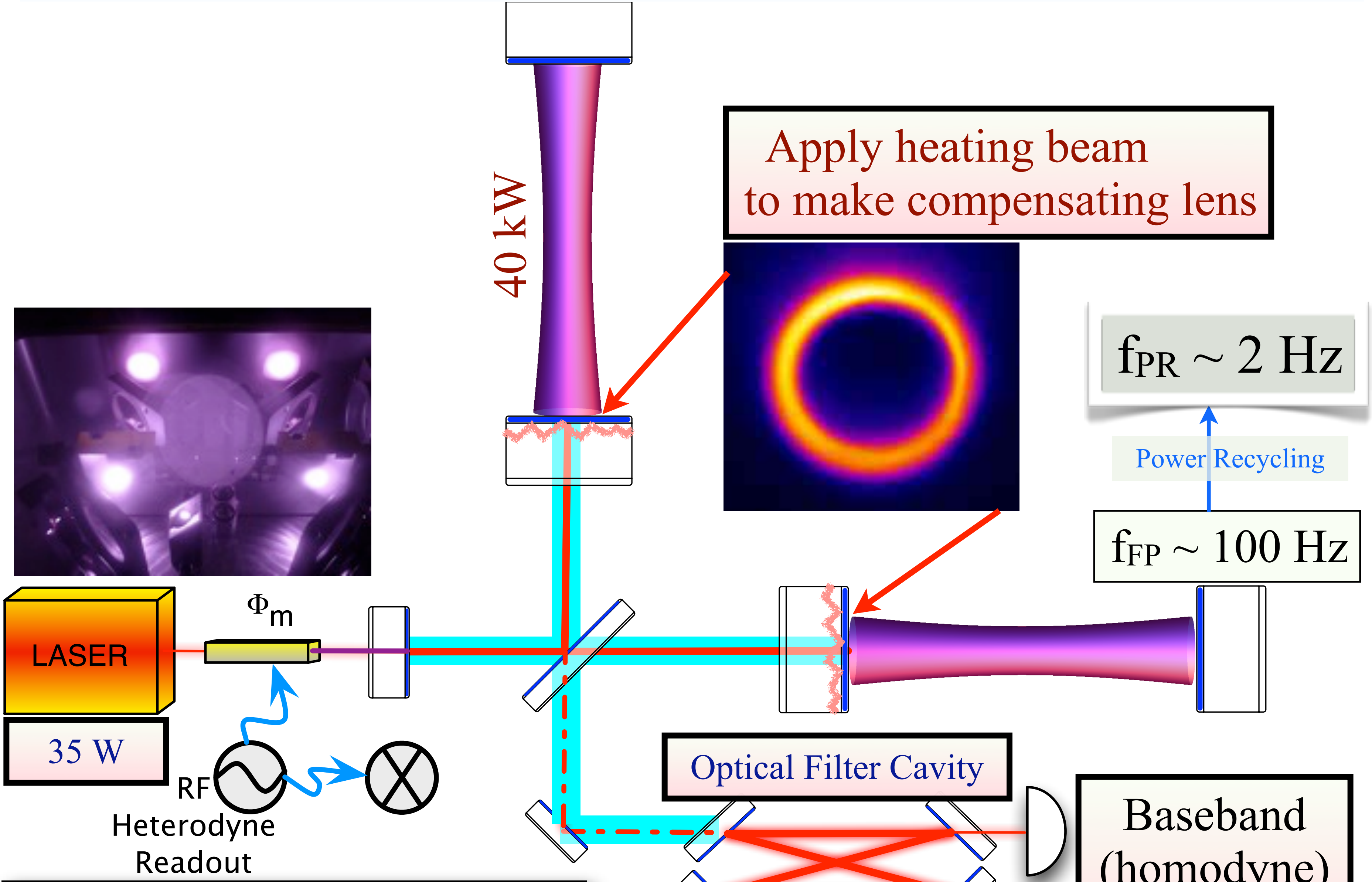
thermal distortion -> imperfect contrast

~few ppm absorption =>thermal distortions

Variant of Pound-Drever-Hall Laser Locking Technique

*W. Z. Korth, K. Izumi, K. Arai, **RA**, in prep (2012)*

Enhanced LIGO



Apply heating beam to make compensating lens

Optical Filter Cavity

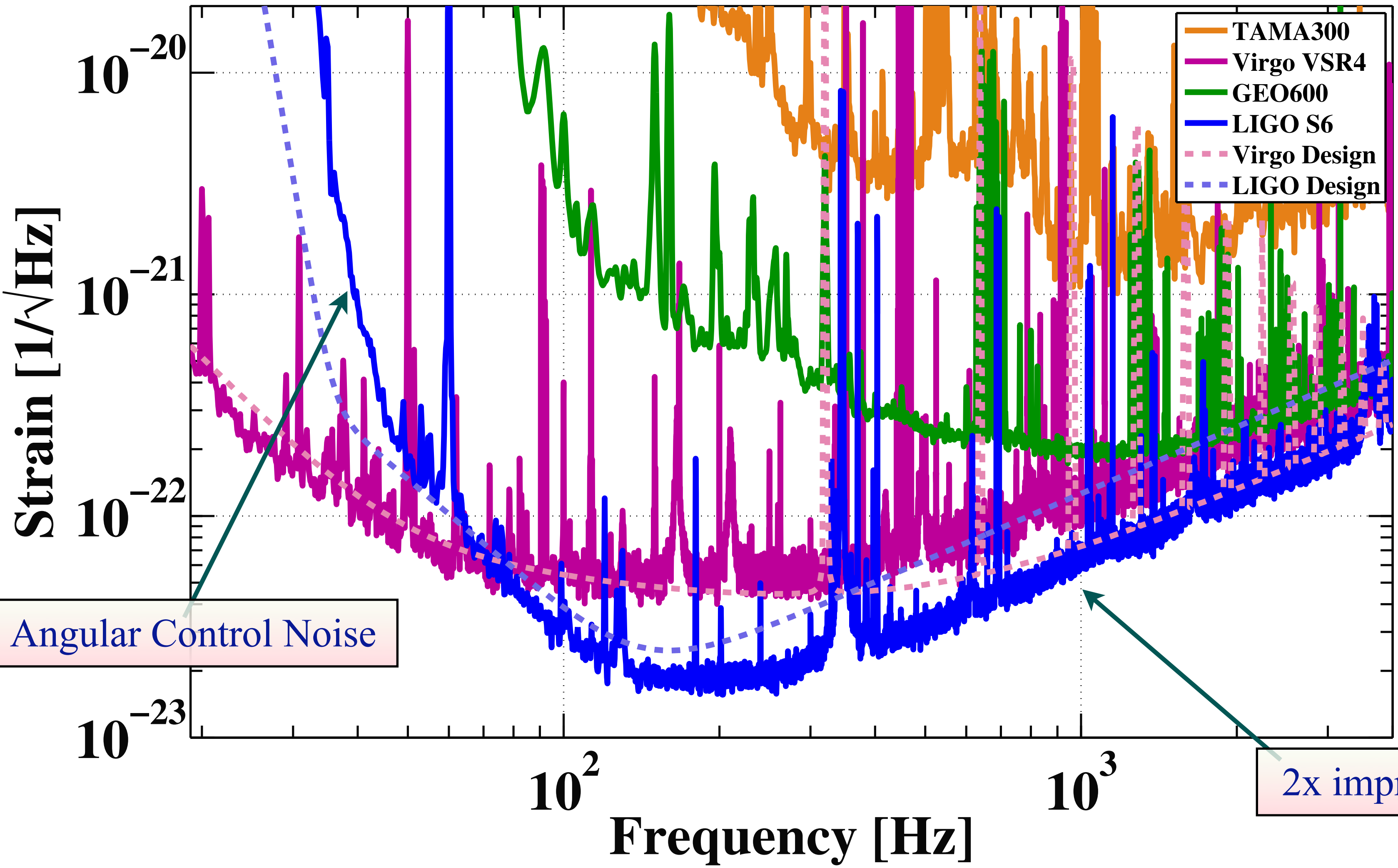
Baseband (homodyne) readout

RF Heterodyne Readout

N. Smith, et al., Opt. Lett. (2012)

*T. Fricke, N. Smith, R. Abbott, **RA**, et al.,CQG (2012)*

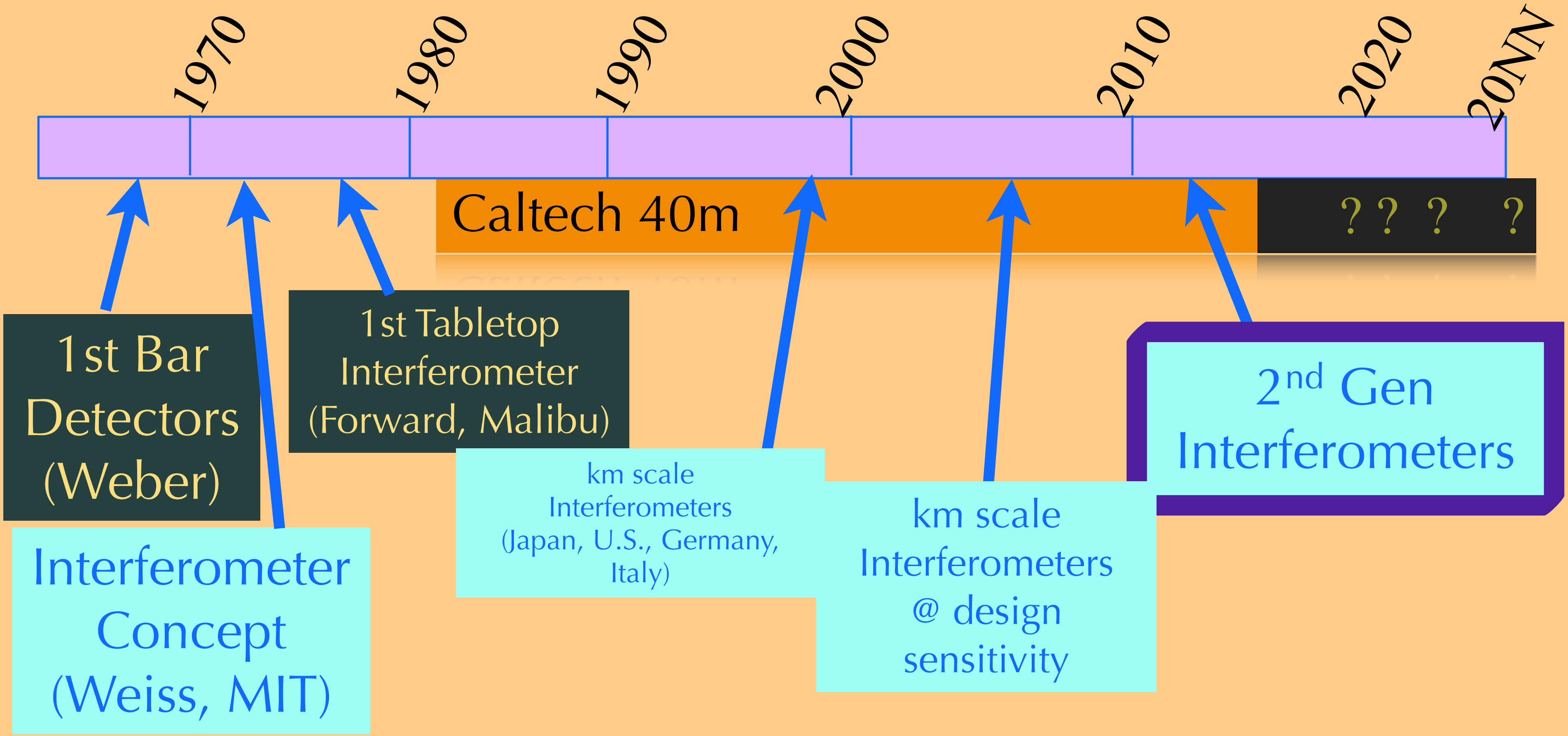
Enhanced LIGO Performance



Angular Control Noise

2x improvement

Timeline of GW Detectors



1st Bar Detectors (Weber)

Interferometer Concept (Weiss, MIT)

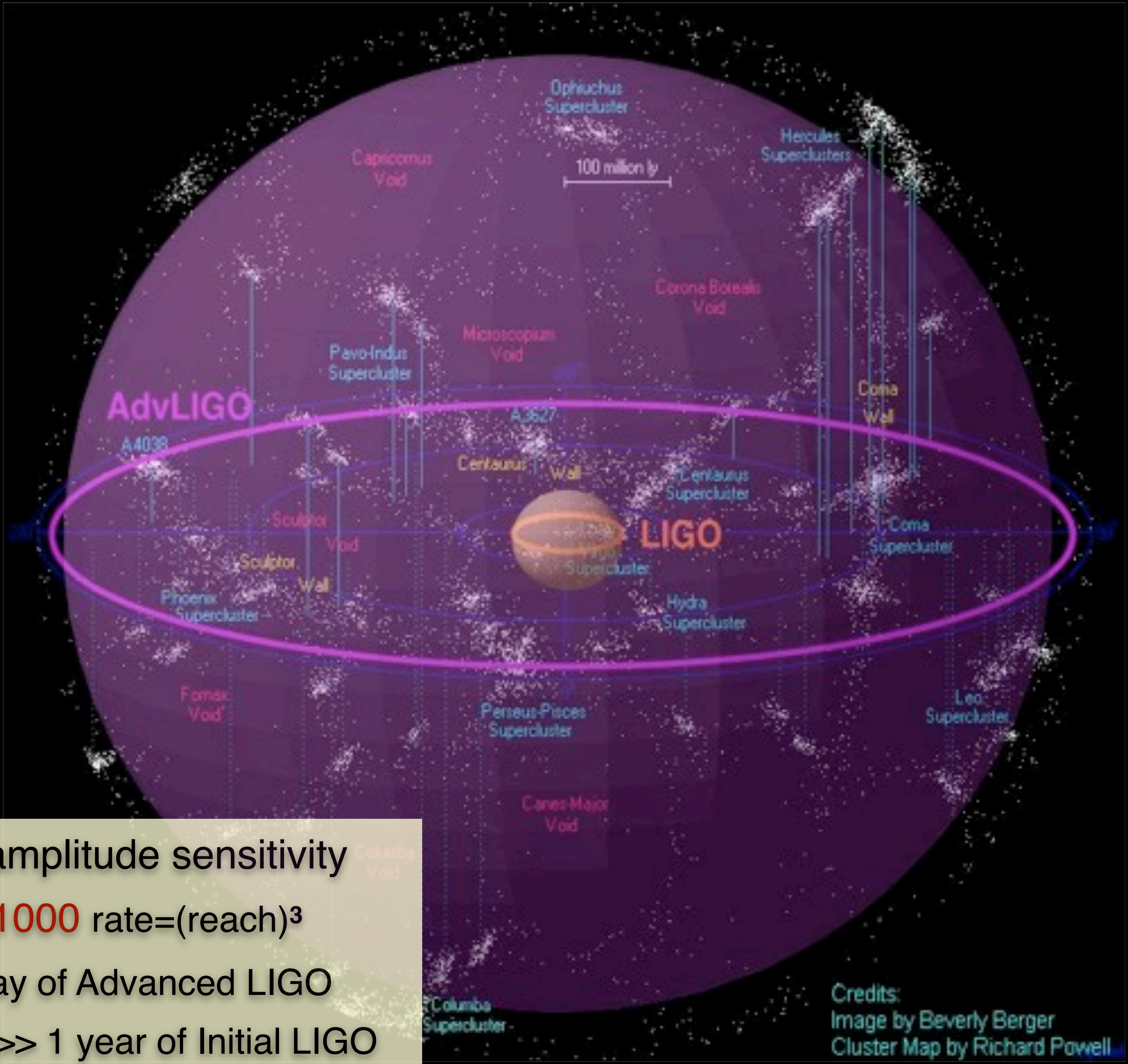
1st Tabletop Interferometer (Forward, Malibu)

km scale Interferometers (Japan, U.S., Germany, Italy)

km scale Interferometers @ design sensitivity

2nd Gen Interferometers

Advanced LIGO



Credits:
Image by Beverly Berger
Cluster Map by Richard Powell

x10 better amplitude sensitivity

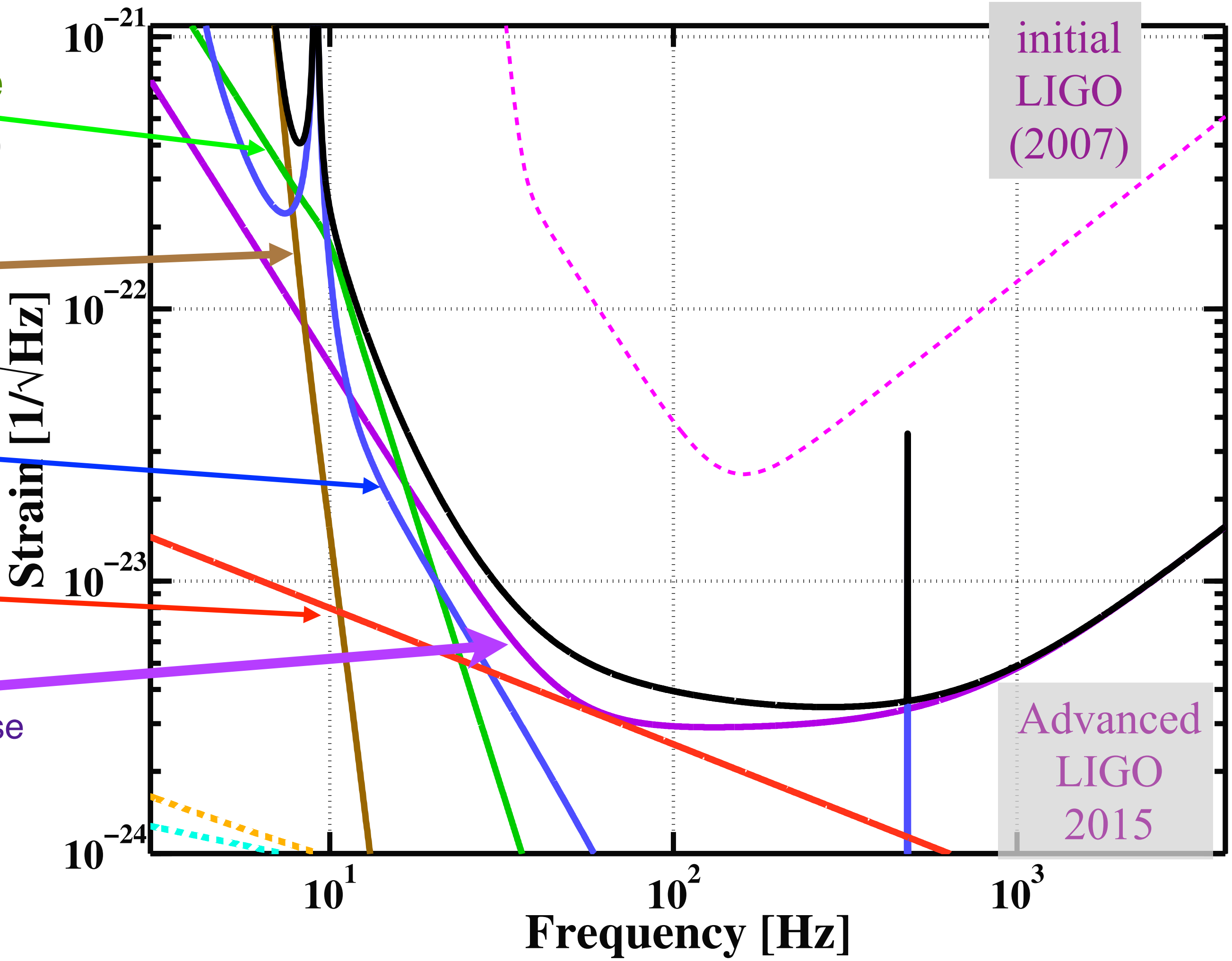
⇒ x1000 rate=(reach)^3

⇒ 1 day of Advanced LIGO

>> 1 year of Initial LIGO

Anatomy of the Interferometer Performance

- ☑ Newtonian gravity noise
  (a.k.a. Gravity Gradients)
- ☑ Filtered Seismic
- ☑ Silica Suspension Thermal Noise
- ☑ Mirror Coating Thermal
- ☑ Quantum Noise:
  Radiation Pressure / Shot Noise



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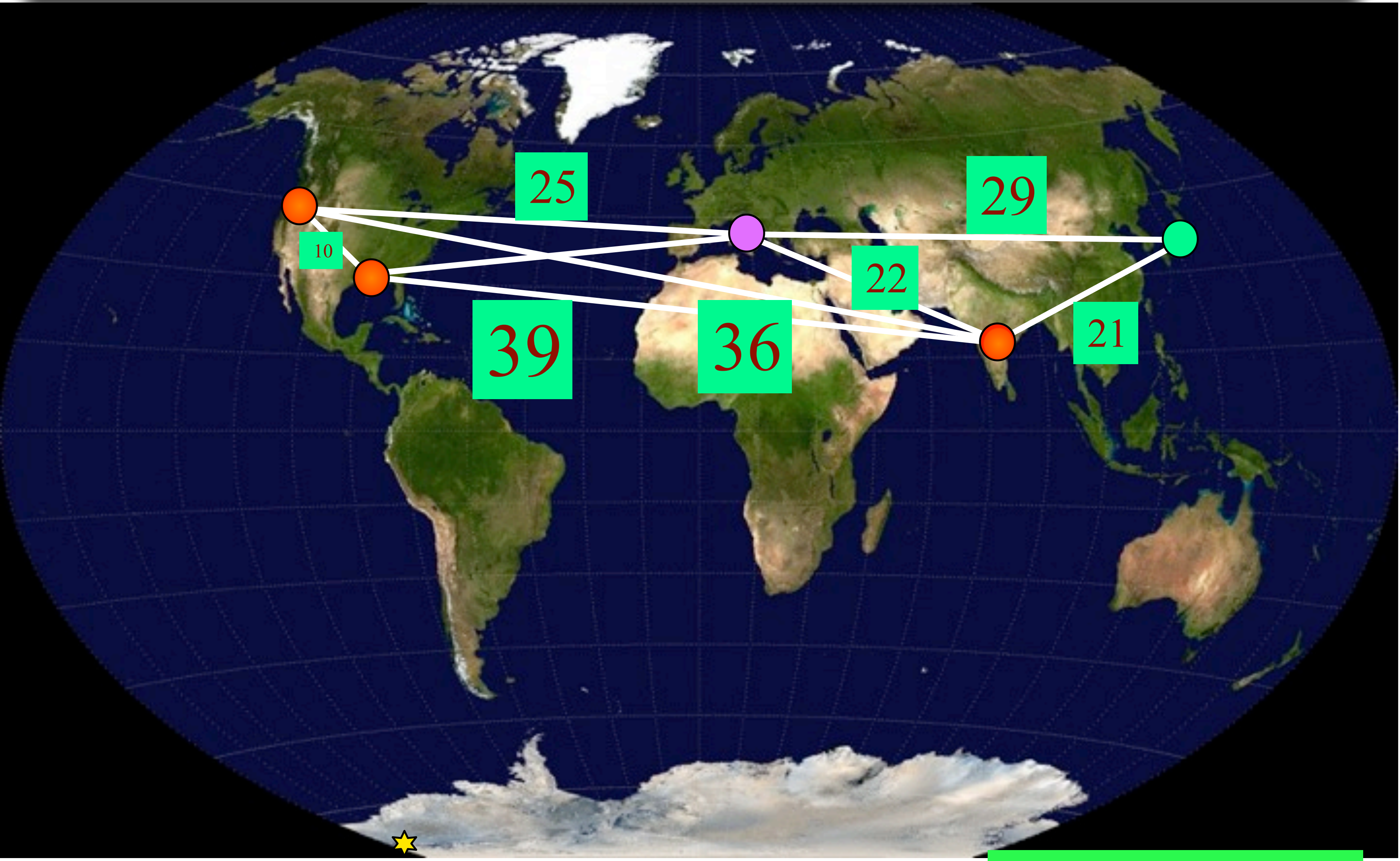
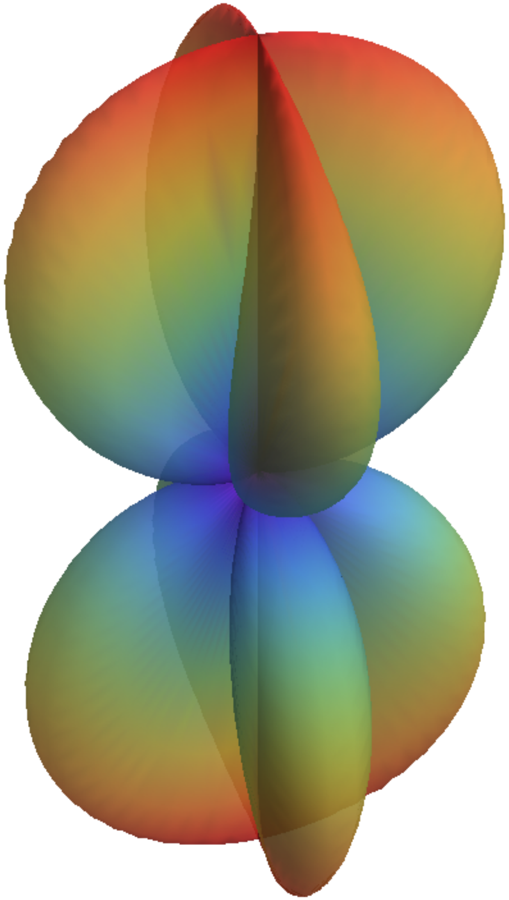
A Future GW Detector Network



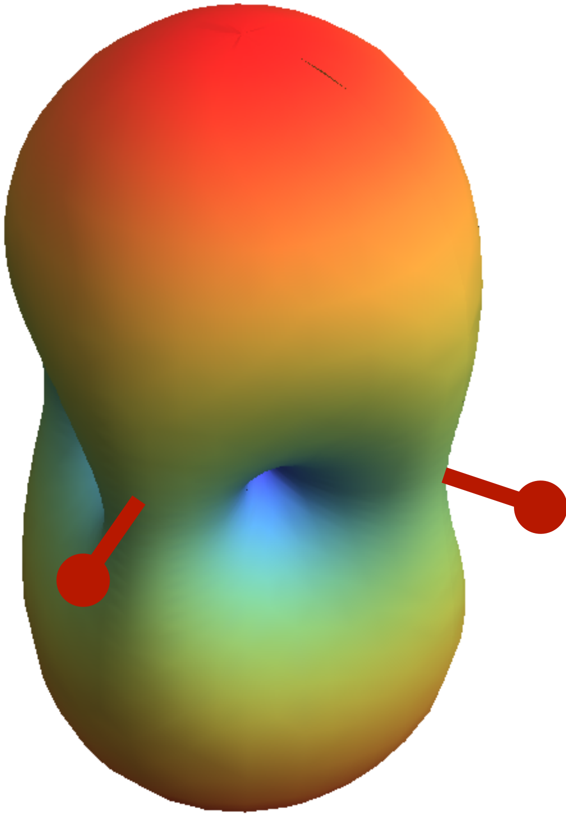
light-speed travel time [ms]

Single Detector Response

+ polarized



x polarized

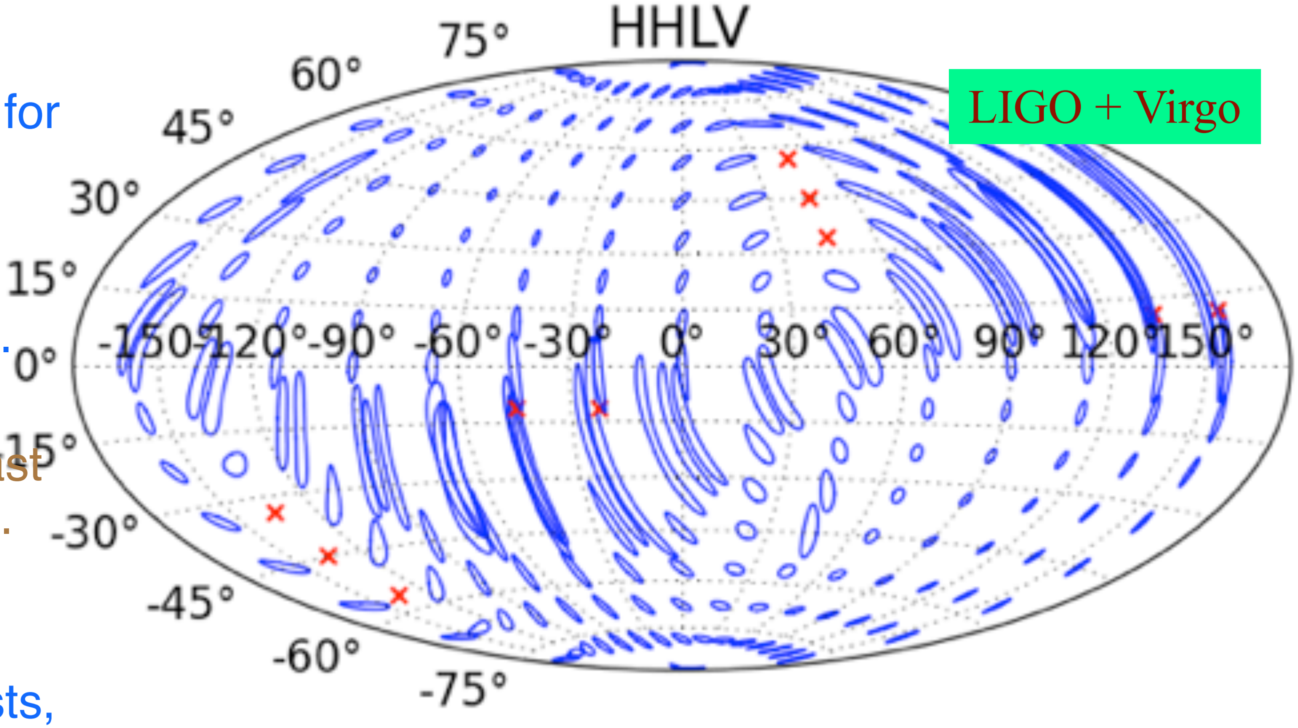


quadrature sum

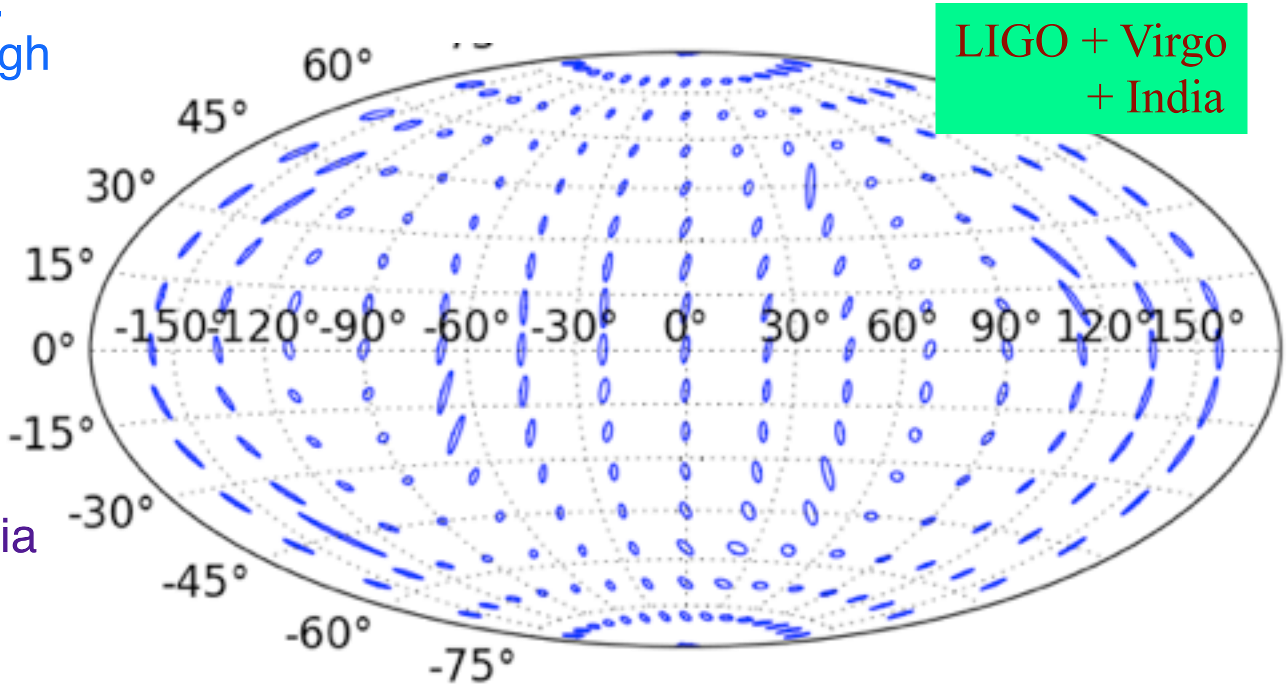
Worldwide network needed for sky localization as well as polarization extraction:

Move 1 of 2 Hanford interferometers to the south.

- ☑ Australian bid expired last year for budget reasons.
- ☑ Indian team coming together: experimentalists, large project experience. Good indications from high level funding officials.
- ☑ ***RA*** *lab tours in August*
- ☑ Multiple visits by senior LIGO scientists to India
- ☑ Preliminary go-ahead by NSF to pursue LIGO-India
- ☑ LIGO Lab: go ahead.



LIGO + Virgo



LIGO + Virgo + India

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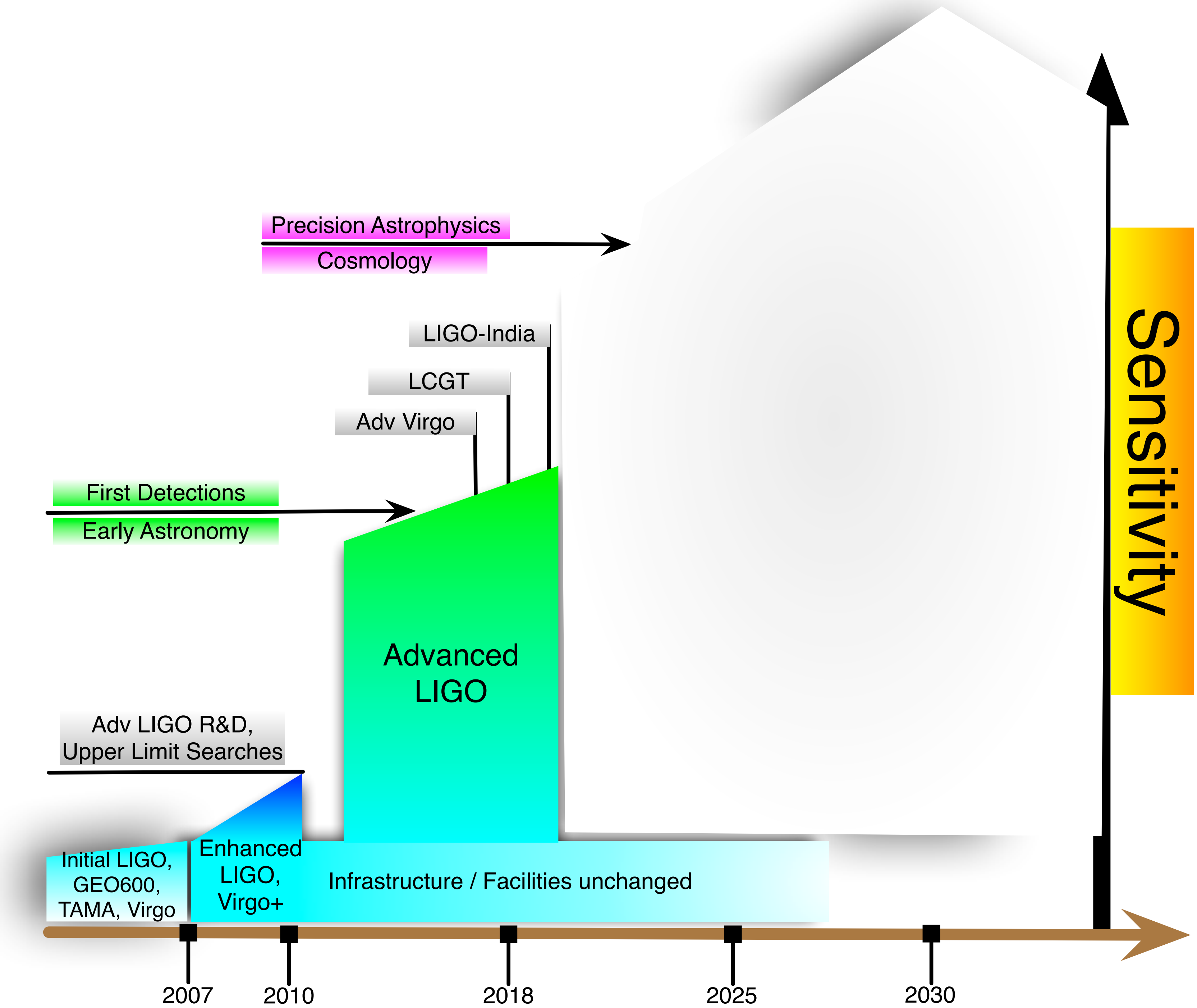


Precision Astrophysics

Cosmology

LIGO-India

LCGT

Adv Virgo

First Detections

Early Astronomy

Advanced LIGO

Sensitivity

Adv LIGO R&D,
Upper Limit Searches

Initial LIGO,
GEO600,
TAMA, Virgo

Enhanced
LIGO,
Virgo+

Infrastructure / Facilities unchanged

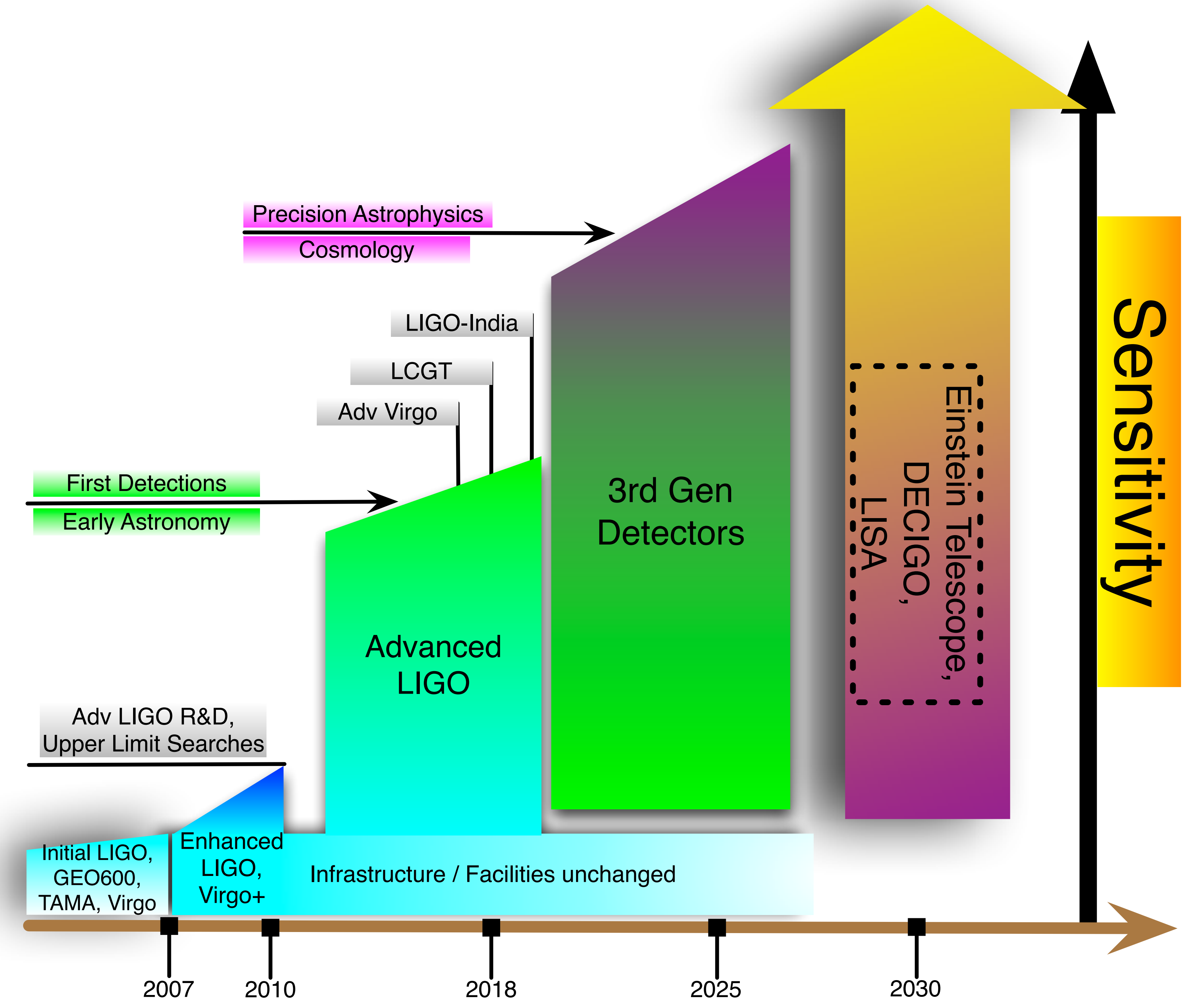
2007

2010

2018

2025

2030


Precision Astrophysics
Cosmology
LIGO-India
LCGT
Adv Virgo
First Detections
Early Astronomy
3rd Gen Detectors
Einstein Telescope, DECIGO, LISA
Sensitivity
Advanced LIGO
Adv LIGO R&D, Upper Limit Searches
Initial LIGO, GEO600, TAMA, Virgo
Enhanced LIGO, Virgo+
Infrastructure / Facilities unchanged
2007
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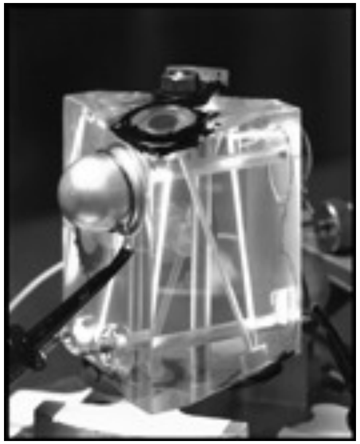
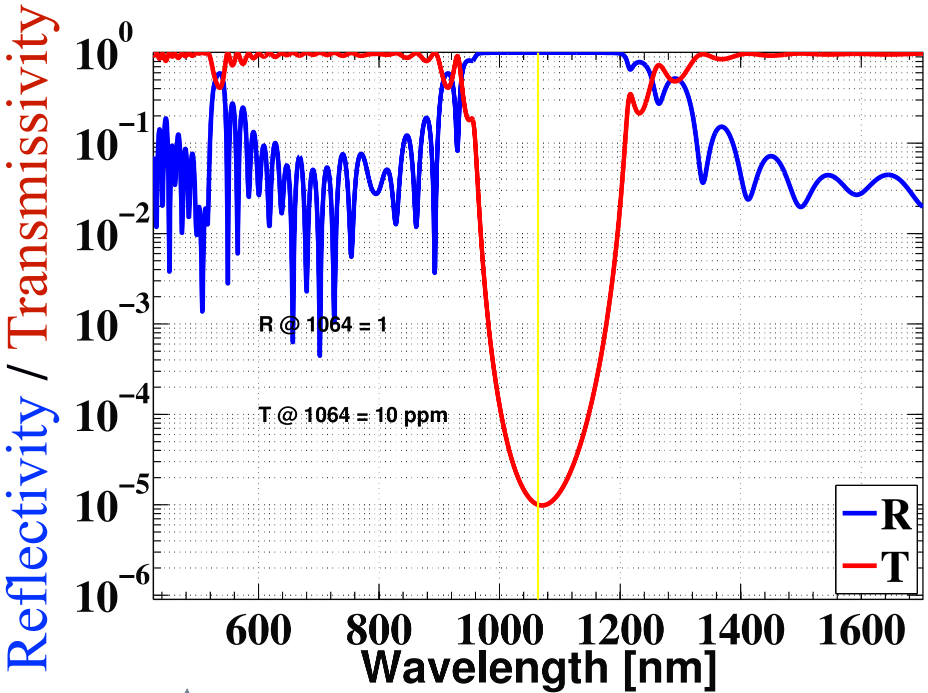
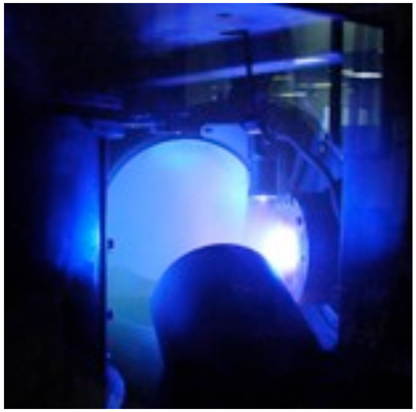
Thermal Noise of a Mirror

Inertial Guidance

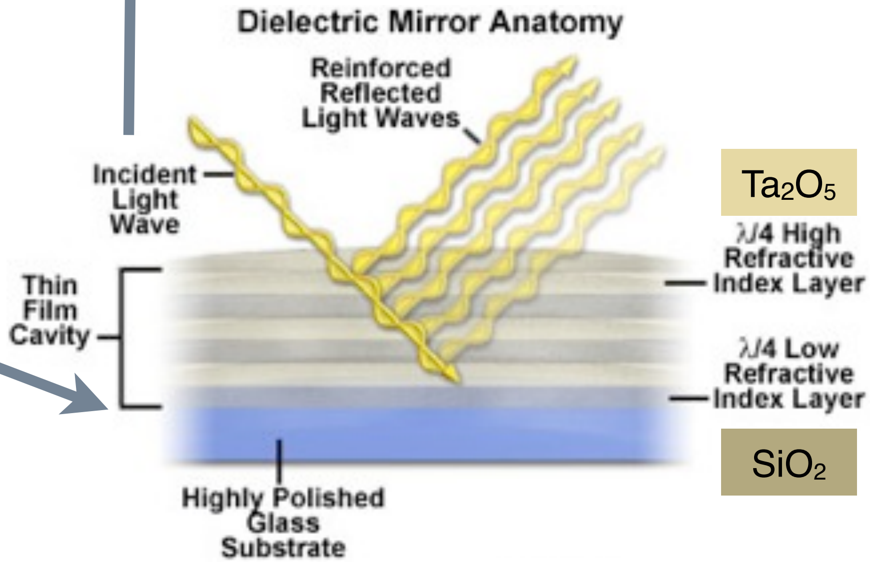


Litton (1979)
Ring Laser Gyro





Ion Beam Sputtered
Mirror Coatings



Thermal Noise of a Mirror

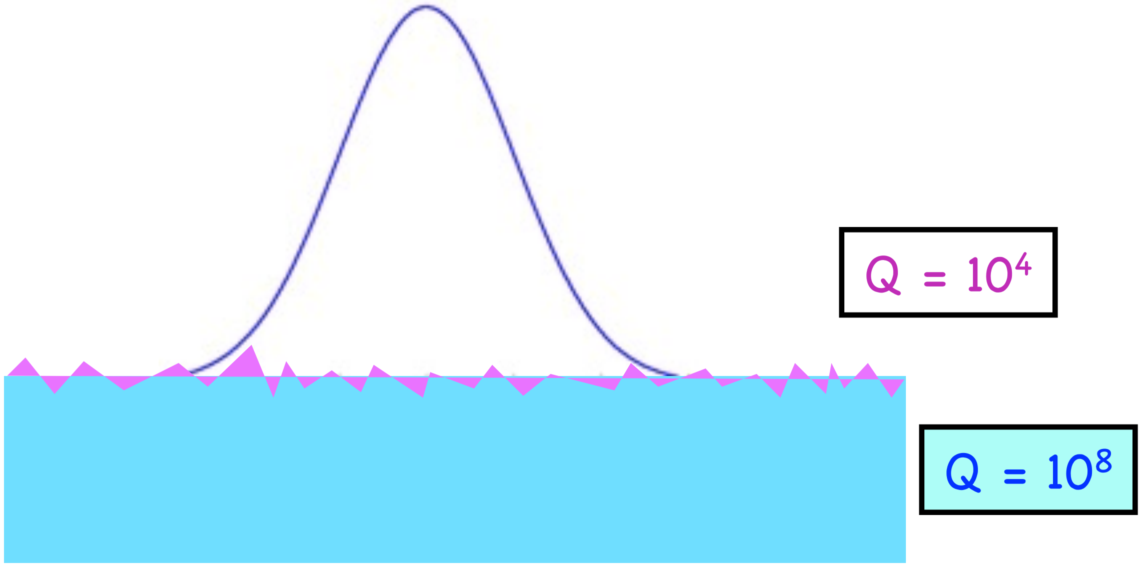
$$S_x(\omega) = \frac{4k_B T}{\omega^2 Re[Z(\omega)]}$$

Fluctuation-Dissipation Theorem

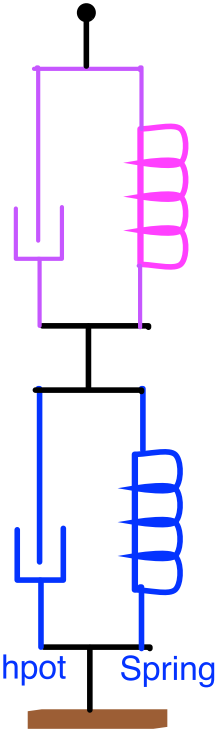
Callen and Welton, Phys. Rev. (1951)

$$Z(\omega) = m\frac{\omega_0^2 - i\omega_0\omega/Q - \omega^2}{i\omega}$$

Single Damped Harmonic Oscillator



Mirror Surface
Thermal Fluctuations

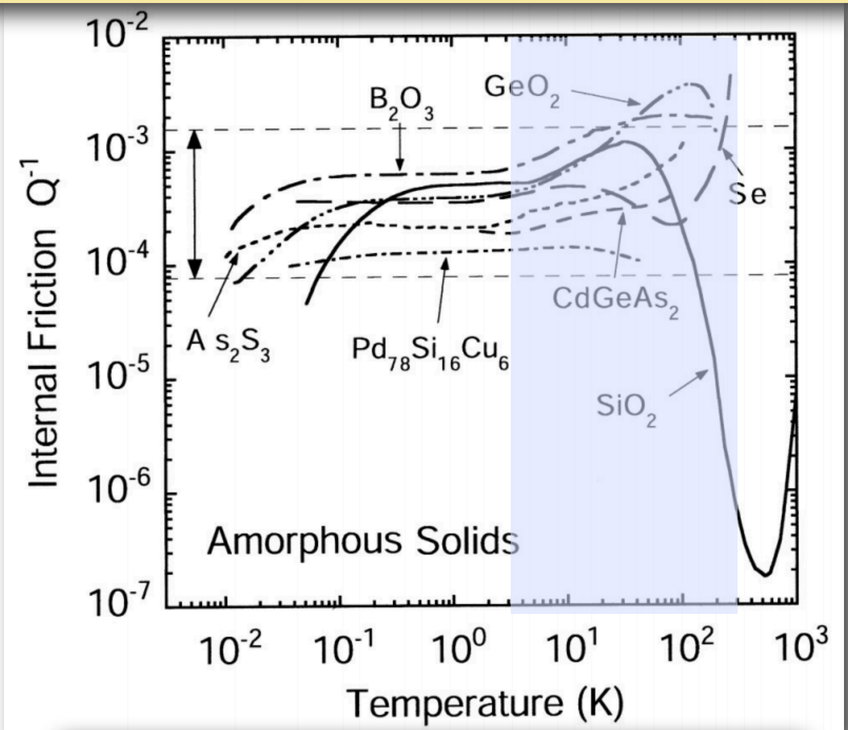


Yuri Levin, PRD (1998)

Hong, Yang, Gustafson, **RA**, and Chen, PRD (2012)

Thermal Noise of a Mirror

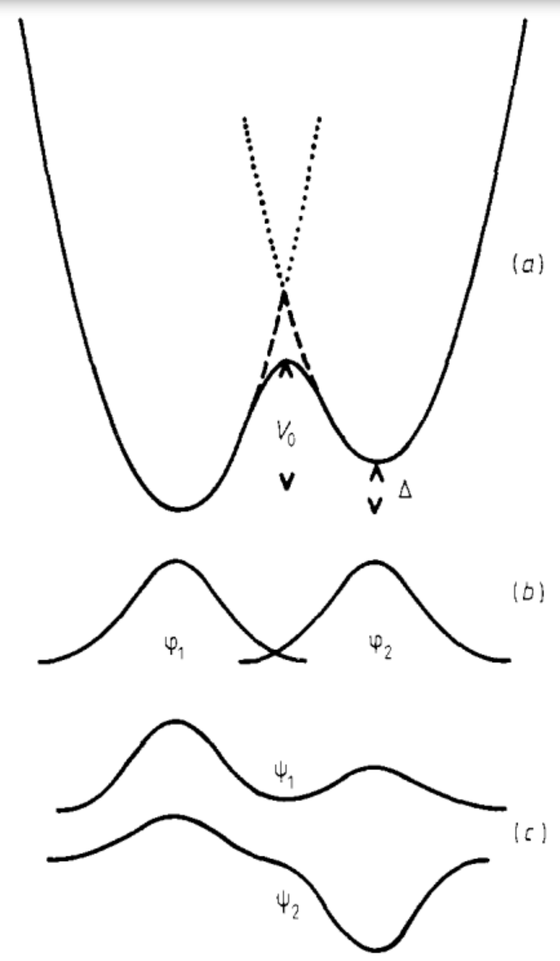
Why a ratio of 10^4 in dissipation?



R.O. Pohl, et al., Rev. Mod. Phys. (2002)

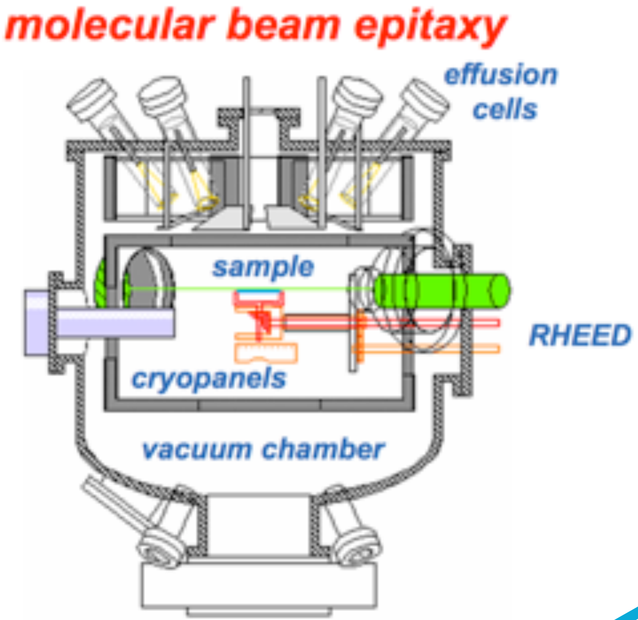
- ***Nearly all high quality optical coatings use amorphous oxides.***
- ***Nearly all amorphous materials have a (low Q) large internal friction.***

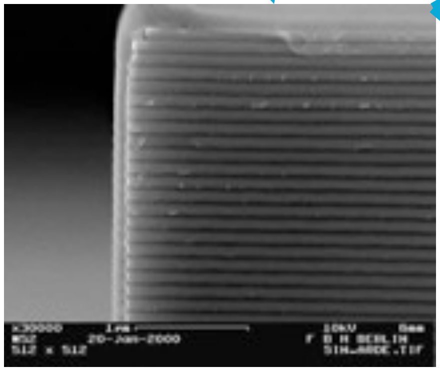
2-level tunneling model

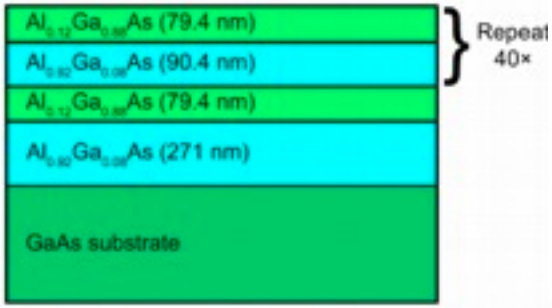


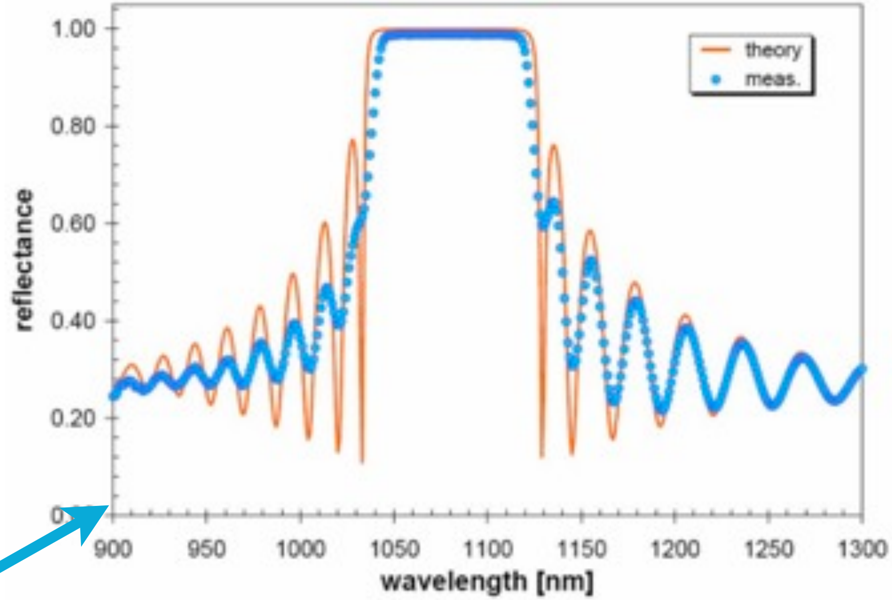
W.A. Phillips, Rep. Prog. Phys. (1987)

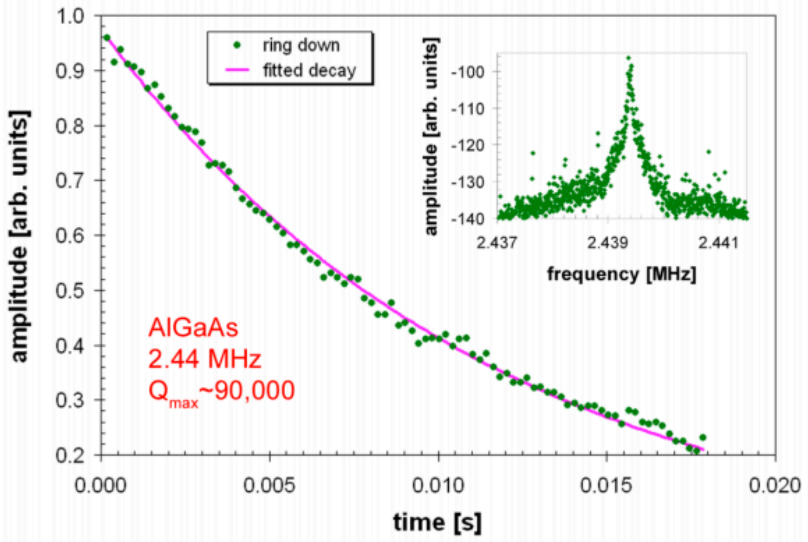
Crystalline Mirror Coatings







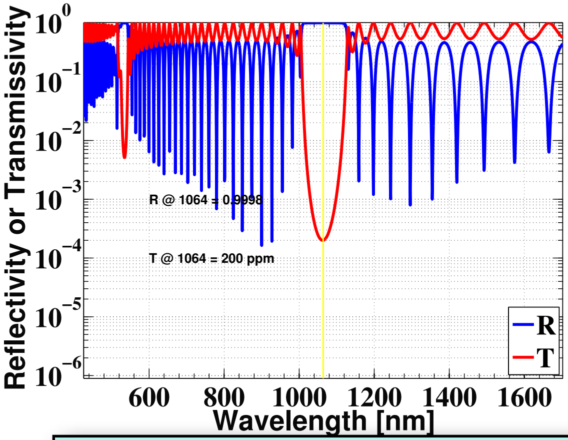




G. D. Cole, et al., Appl. Phys. Lett. (2010)

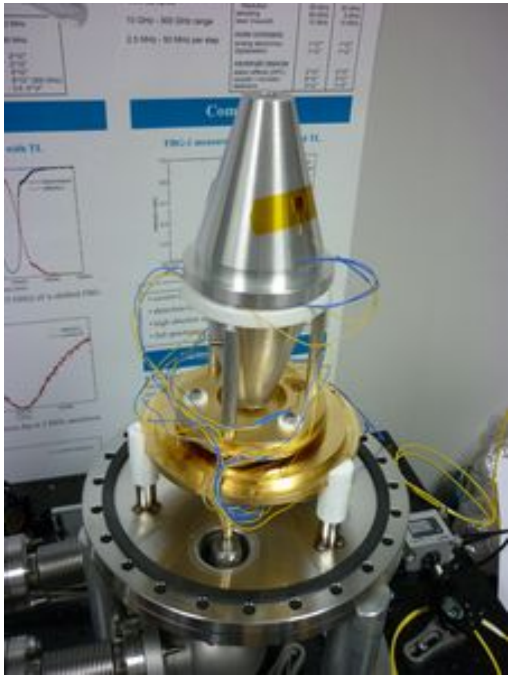
$$Q_{coating} \sim 10^5 - 10^6$$

The Road to Noiseless Mirrors



300K design

*G. D. Cole, **RA**, F. Seifert, in prep. (2012)*

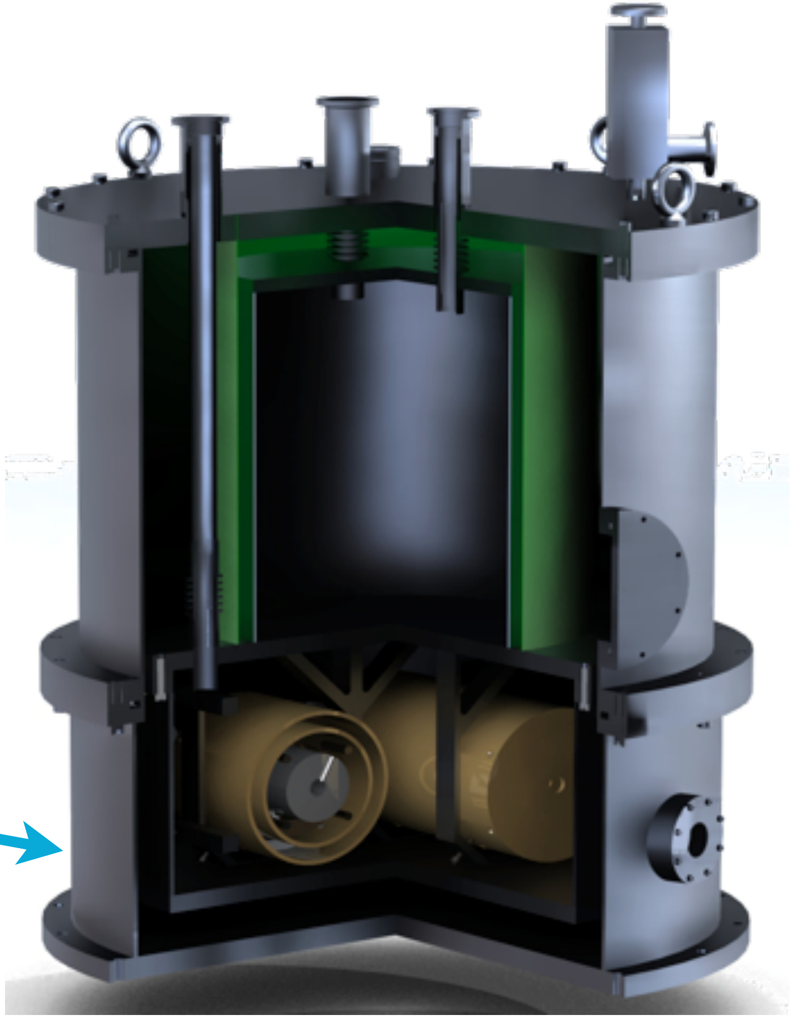


JILA / PTB

<u>120K Silicon:</u>

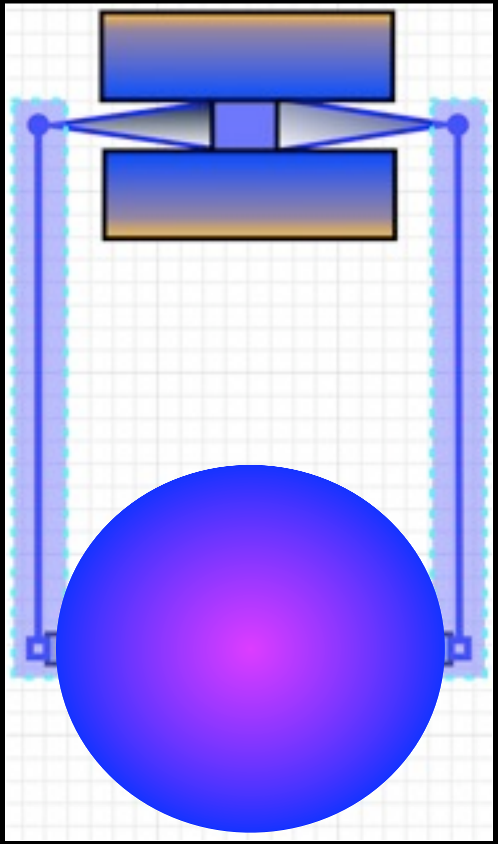
CTE = zero,

High Thermal Conductivity

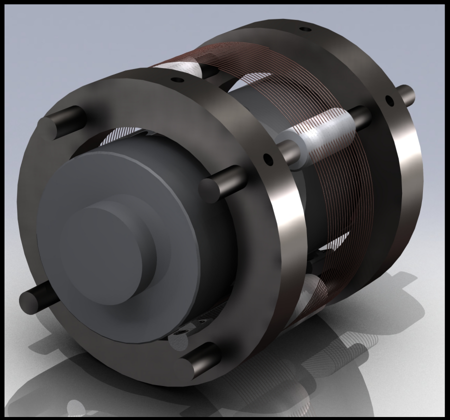


Caltech IQIM

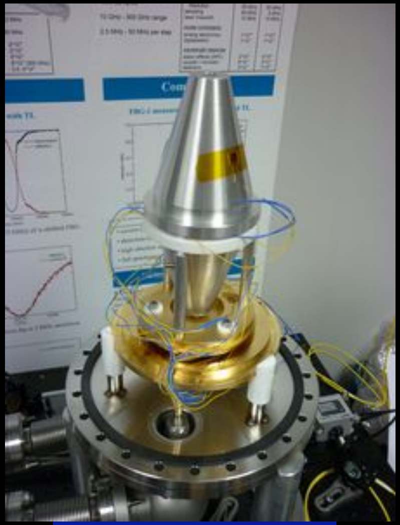
Cryogenic LIGO



Monolithic Silicon Suspension

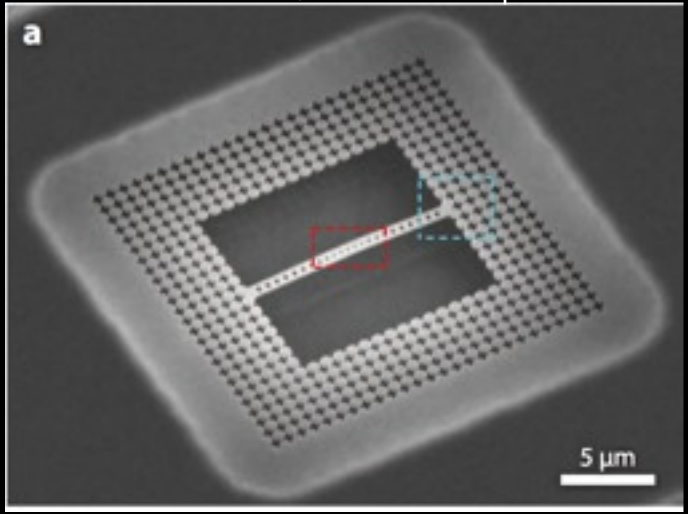


Caltech
Institute for Quantum
Information and Mechanics



JILA / PTB

Silicon etch process from O. Painter @ Caltech for ground state cooling

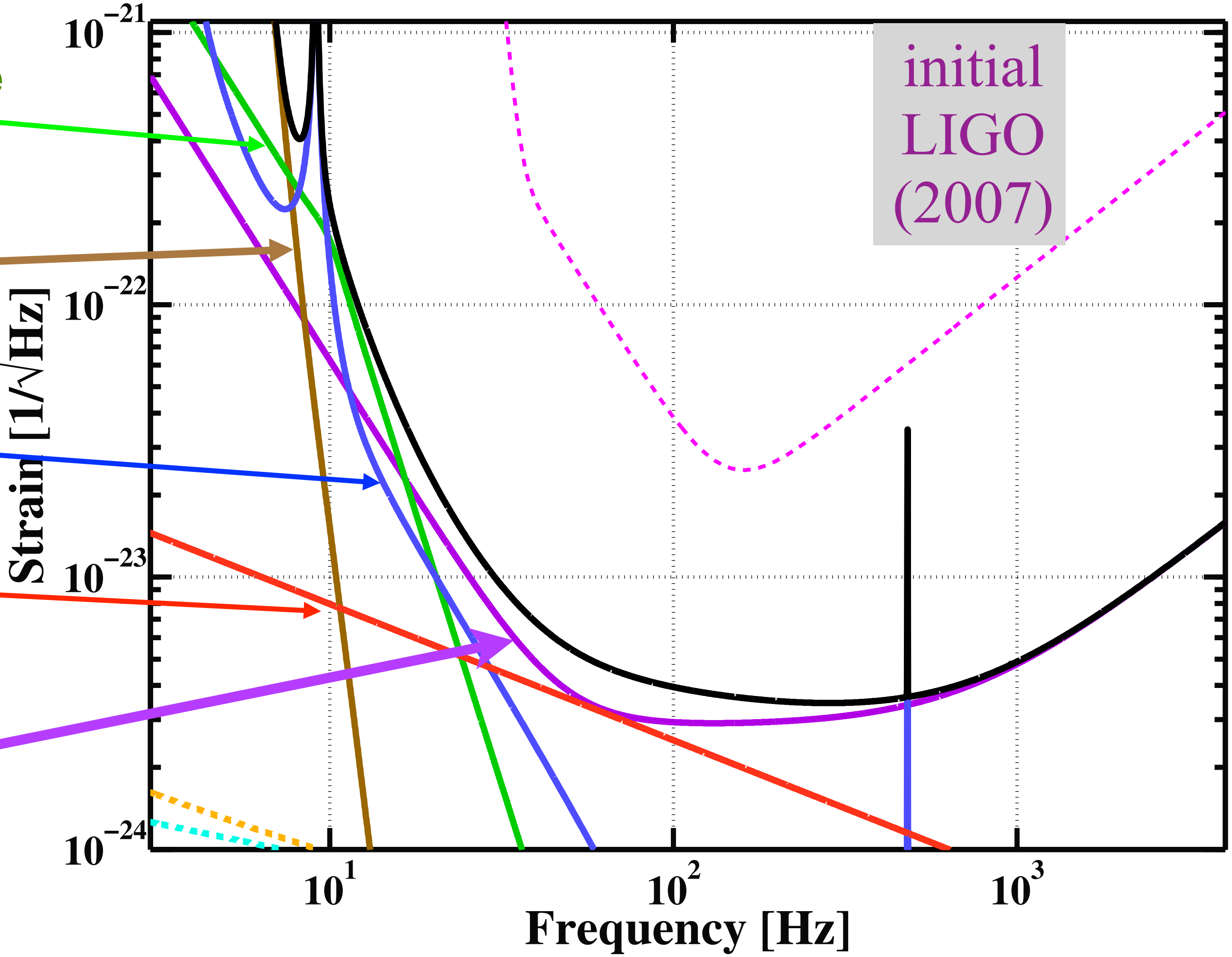


f ~4 GHz, Q $\sim 10^5$, $N_{quanta} < 1$

Requires switching the laser technology:
1064 nm => 1550 nm

Anatomy of the interferometer performance

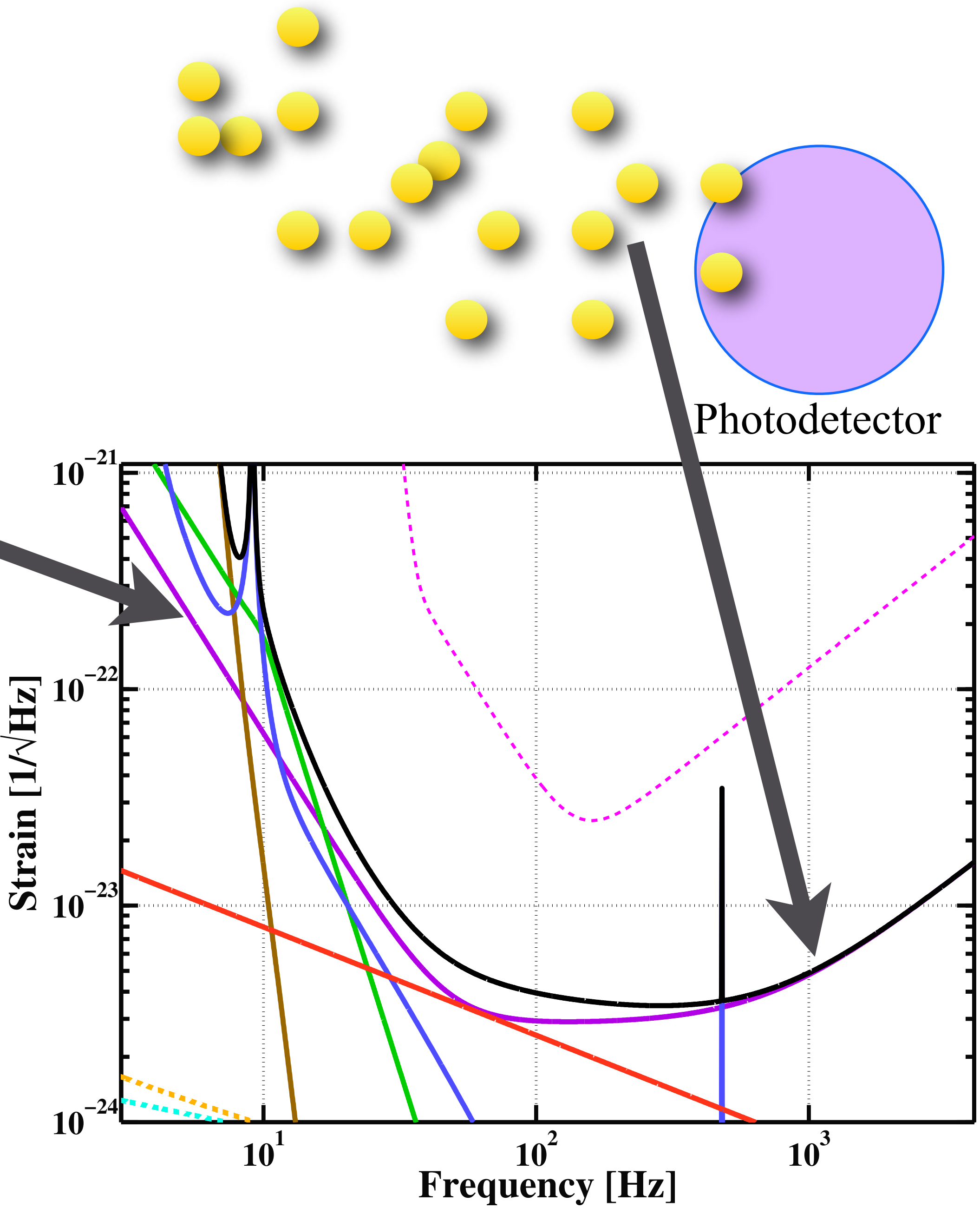
- Newtonian gravity noise (aka Gravity Gradients)
- Filtered Seismic
- Silica Suspension Thermal Noise
- Mirror Coating Thermal
- Quantum Noise
  - Radiation Pressure
  - Shot Noise



What about this Quantum noise?

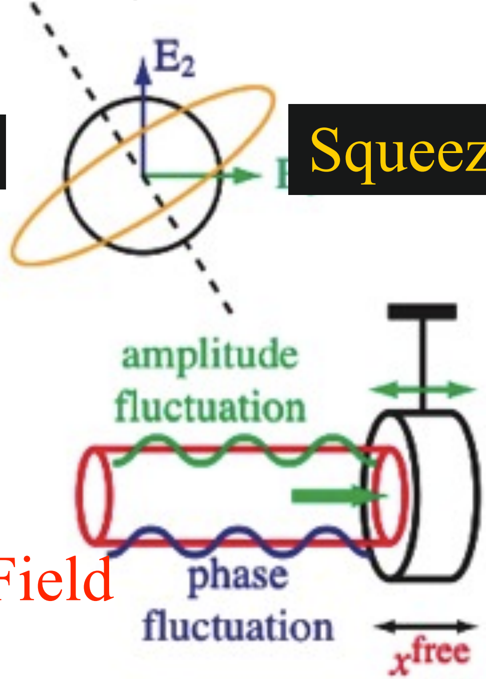
Shot Noise Picture:
Poisson statistics govern arrival time of photons at the photodetector. Also arrival times at the test mass (radiation pressure).

Vacuum Photon Picture:
Losses couple the fluctuating vacuum field to the interferometer. Noise is a beat between the amplitude of the vacuum field and the local field (field at the dark port or field at the test mass).



Circumventing Usual Quantum Noise

Vacuum



Squeezed Vacuum

Carrier Field

Atomic Polarization of a Dielectric Medium

$$P = \varepsilon_0(\chi^{(1)}E + \chi^{(2)}E^2 + \chi^{(3)}E^3 + \ldots)$$

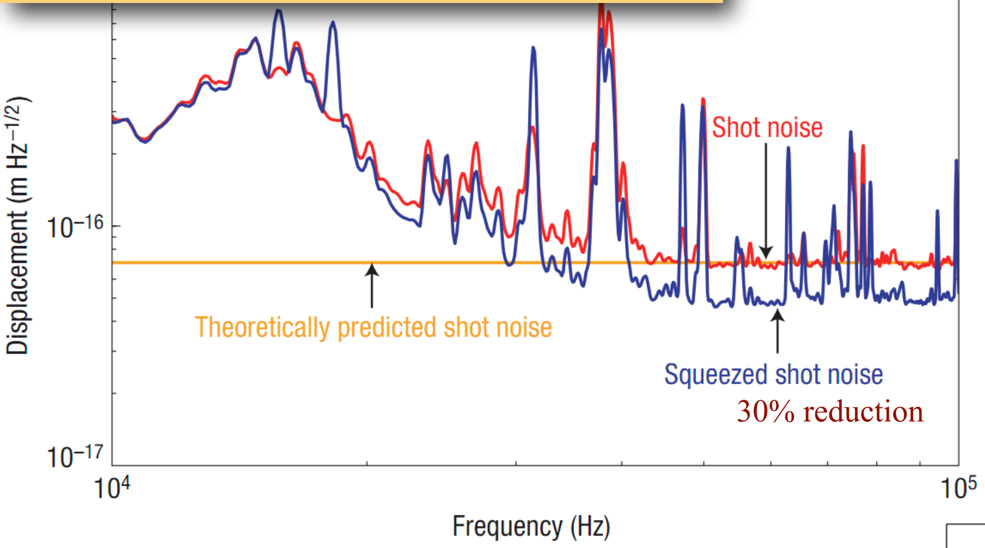
Braginsky, Vorontsov and Thorne, Science **(1980)**

C. M. Caves, PRD (1981)

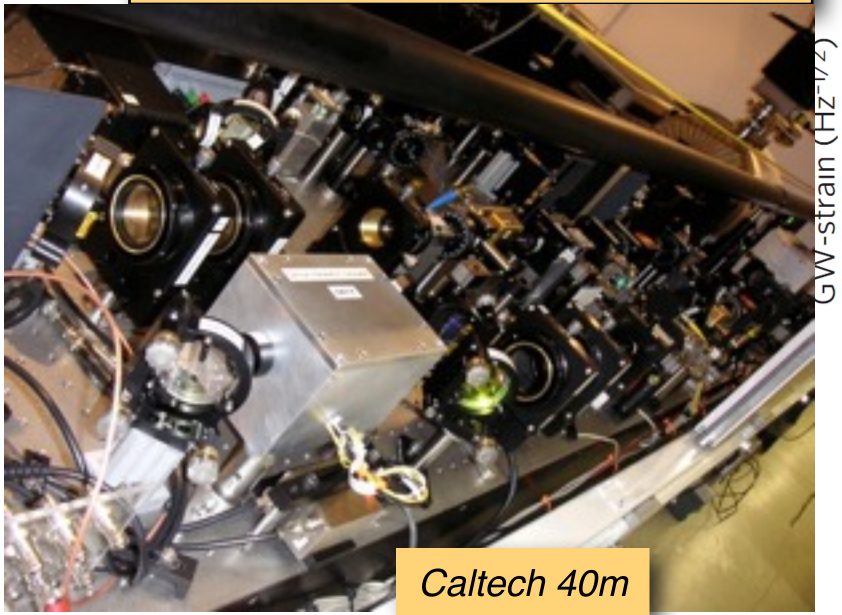
Wu, Kimble, Hall, Wu, PRL (1986)

Squeezed Interferometers

Caltech 40m prototype

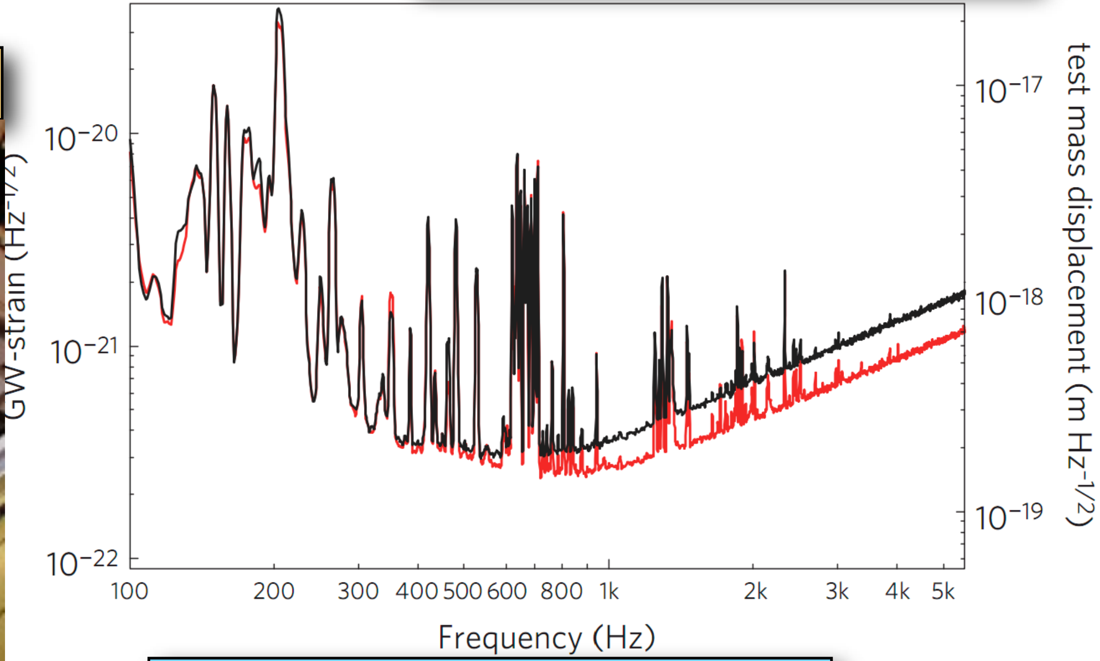


K. Goda, et al., Nature Physics (2008)



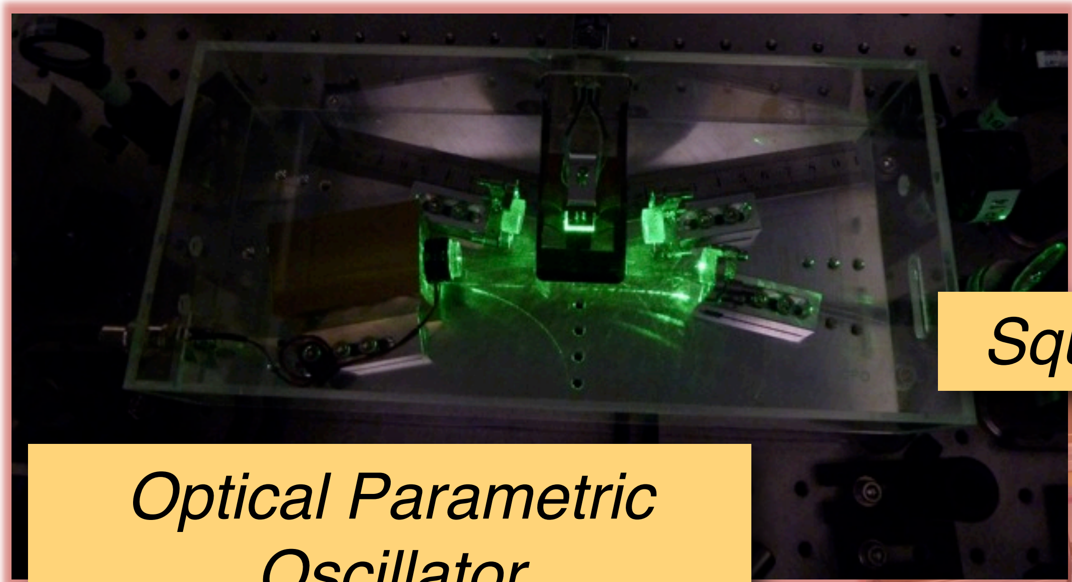
Caltech 40m

GEO Squeezer (Hannover)



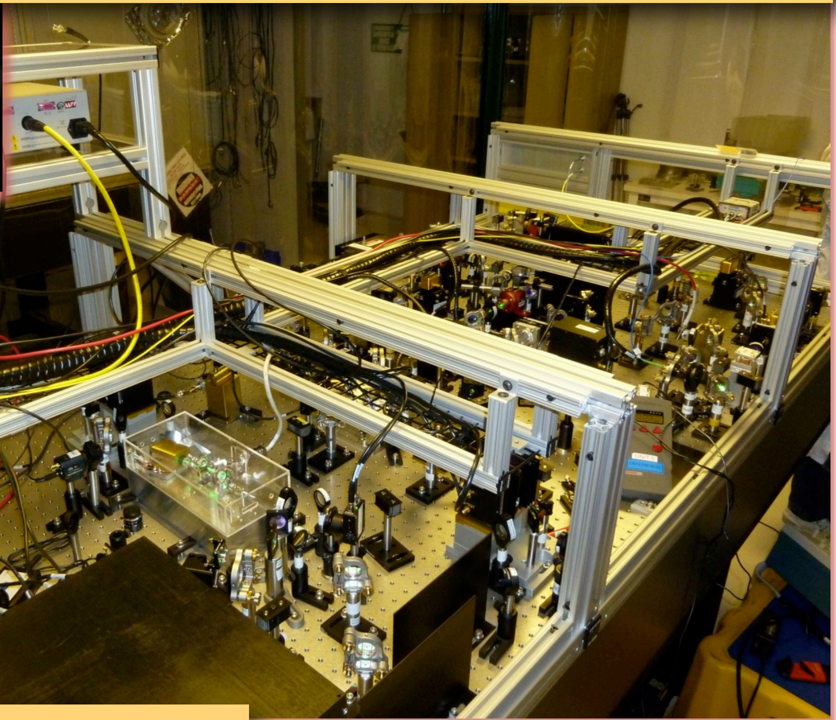
LIGO, Nature Physics (2011)

Squeezed Light in Action: LIGO 4km



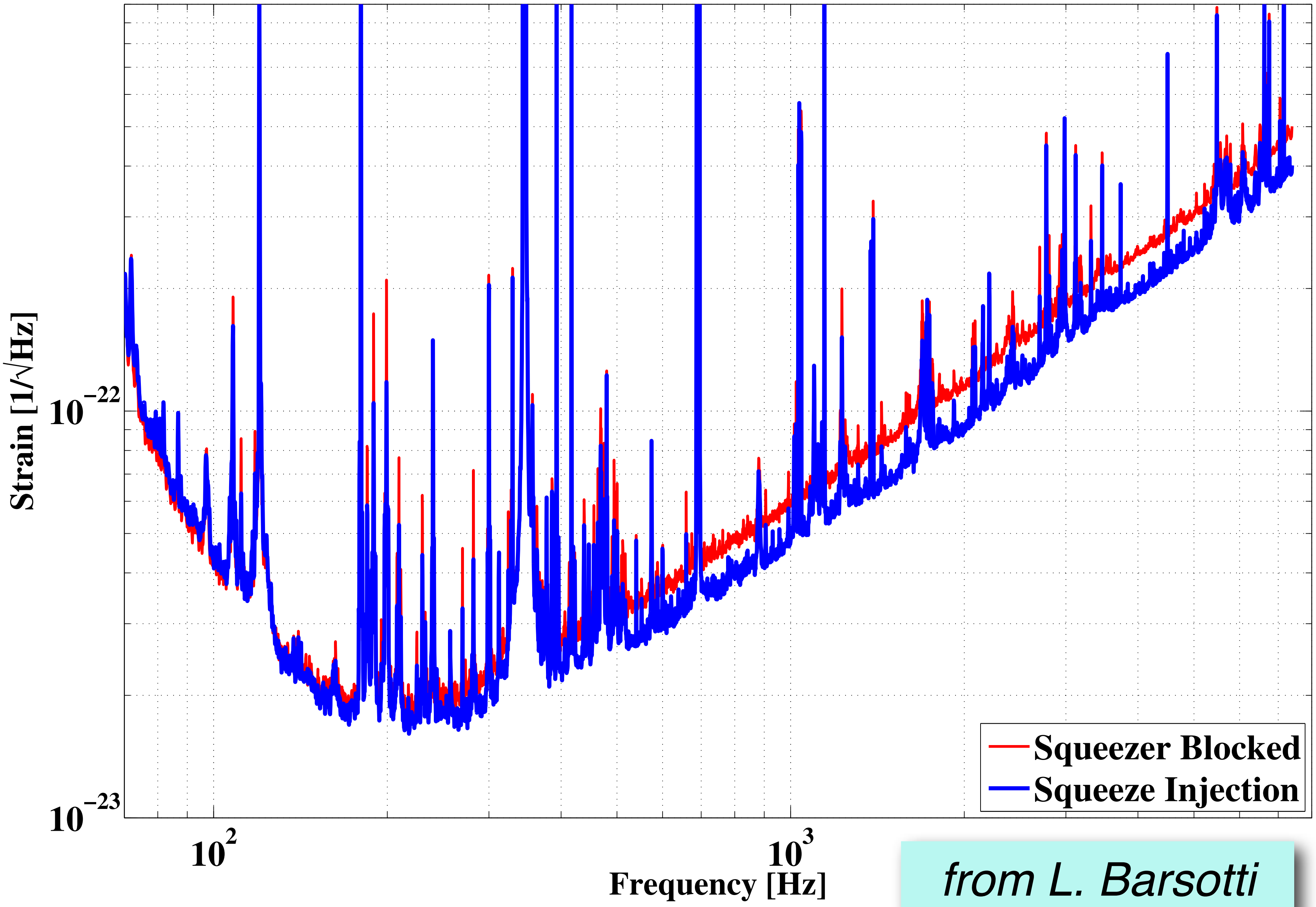
Optical Parametric Oscillator (from ANU)

Squeezed Light Injection Table



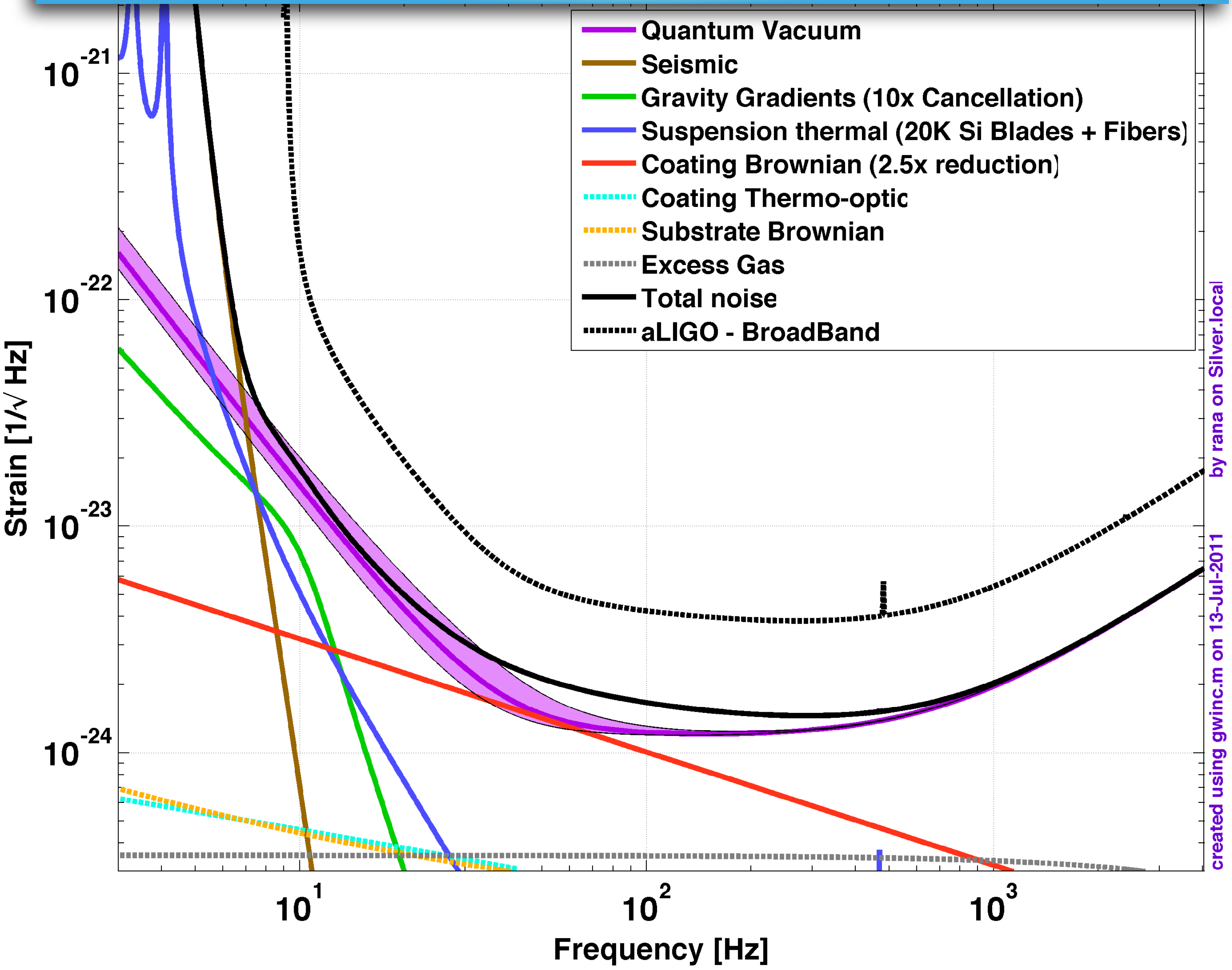
Installed at LIGO Hanford throughout 2011

Squeezed Light in Action: LIGO 4km

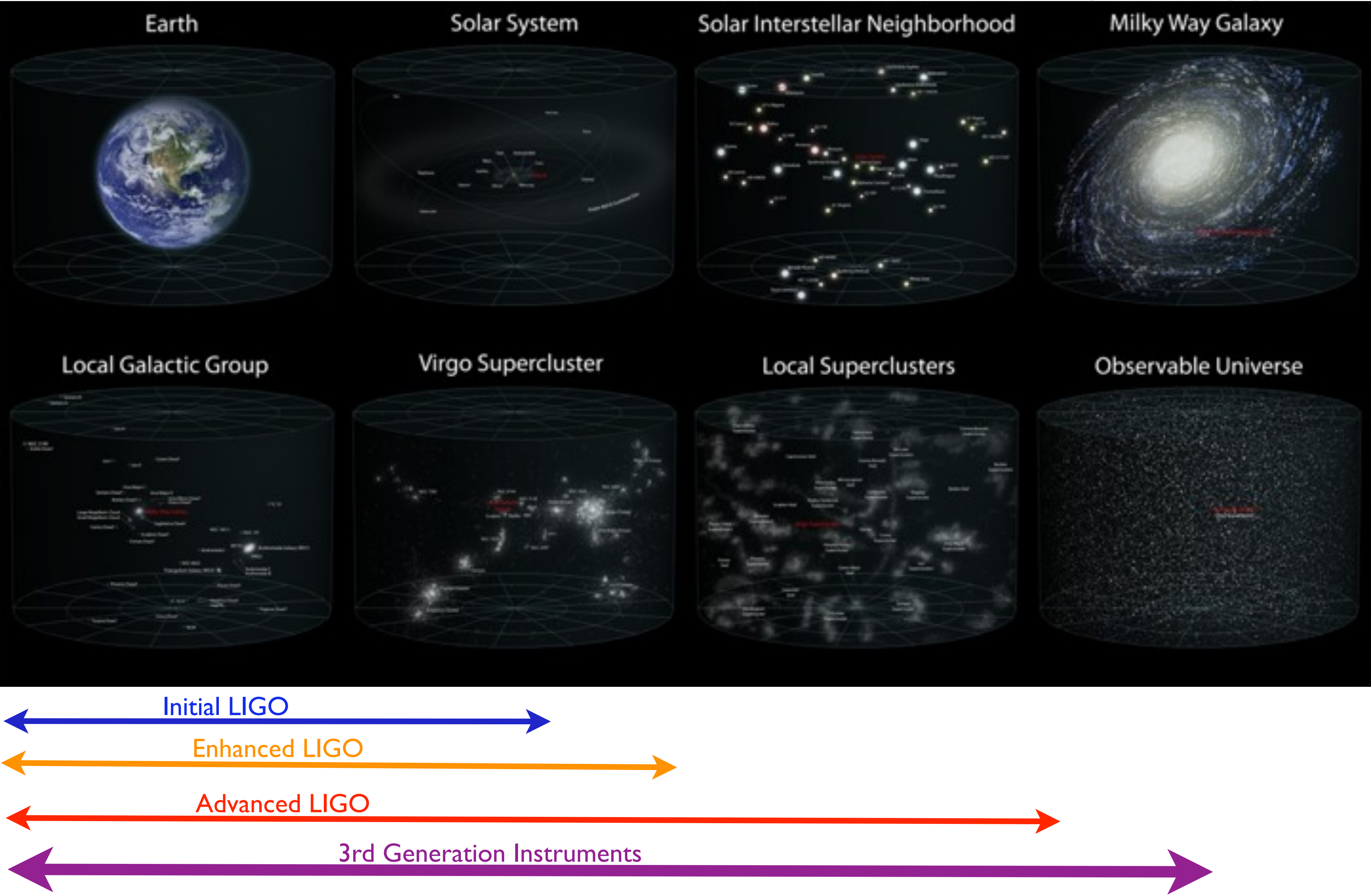


from L. Barsotti

3rd Generation LIGO



Caltech 40m prototype



Initial LIGO

Enhanced LIGO

Advanced LIGO

3rd Generation Instruments

Summary

- The Advanced LIGO Detectors are on track for a 2014-2015 Science Run.
- The Global Network of 2nd Generation detectors is coming together in the next 5-10 years.
- Recent developments make the future potential bright.
- We have never before been closer to GW Astrophysics.