Advanced LIGO

the Laser Interferometer Gravitational-wave Observatory

Brian Lantz
for the LIGO Scientific Collaboration

SPRC, Sept. 2014

black hole image courtesy of LISA,
http://lisa.jpl.nasa.gov

Environmental Sensor?!

But, we try to **not** be sensitive to:

- Earthquakes in Tonga
- Lightning strikes in Denver
- Waves in the Gulf of Mexico
- Wind in the Columbia river gorge
- Tidal deformations of the ground
- Power line fluctuations in amplitude and phase
- Acoustic signatures of Planes,
- Rickety bridges of the Lumber Trains,
- Rumbling on the cattle guards by Automobiles

We are trying to do astronomy!

Environmental Sensor?!

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We are trying to measure local perturbations in the space-time metric.

Environmental Sensor?!

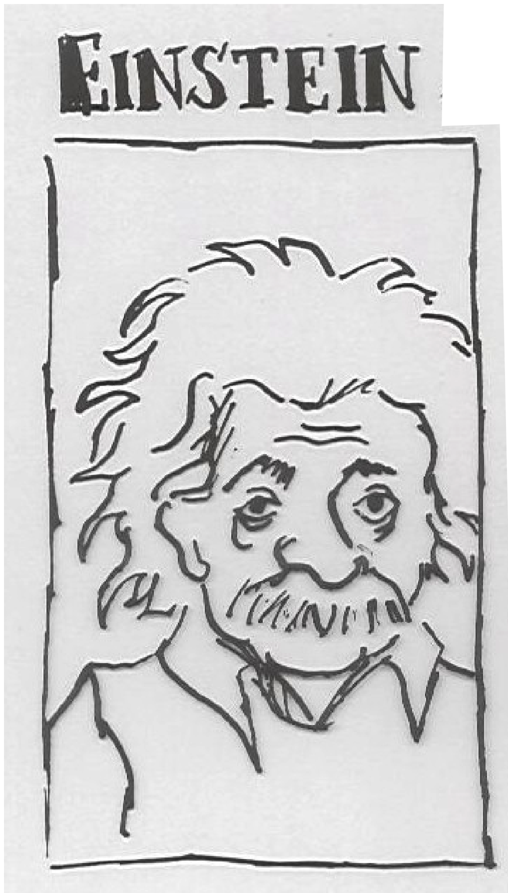
Why are we trying to measure space-time disturbances (in the form of Gravitational Waves)?

How do we do that?

How close are we to success?

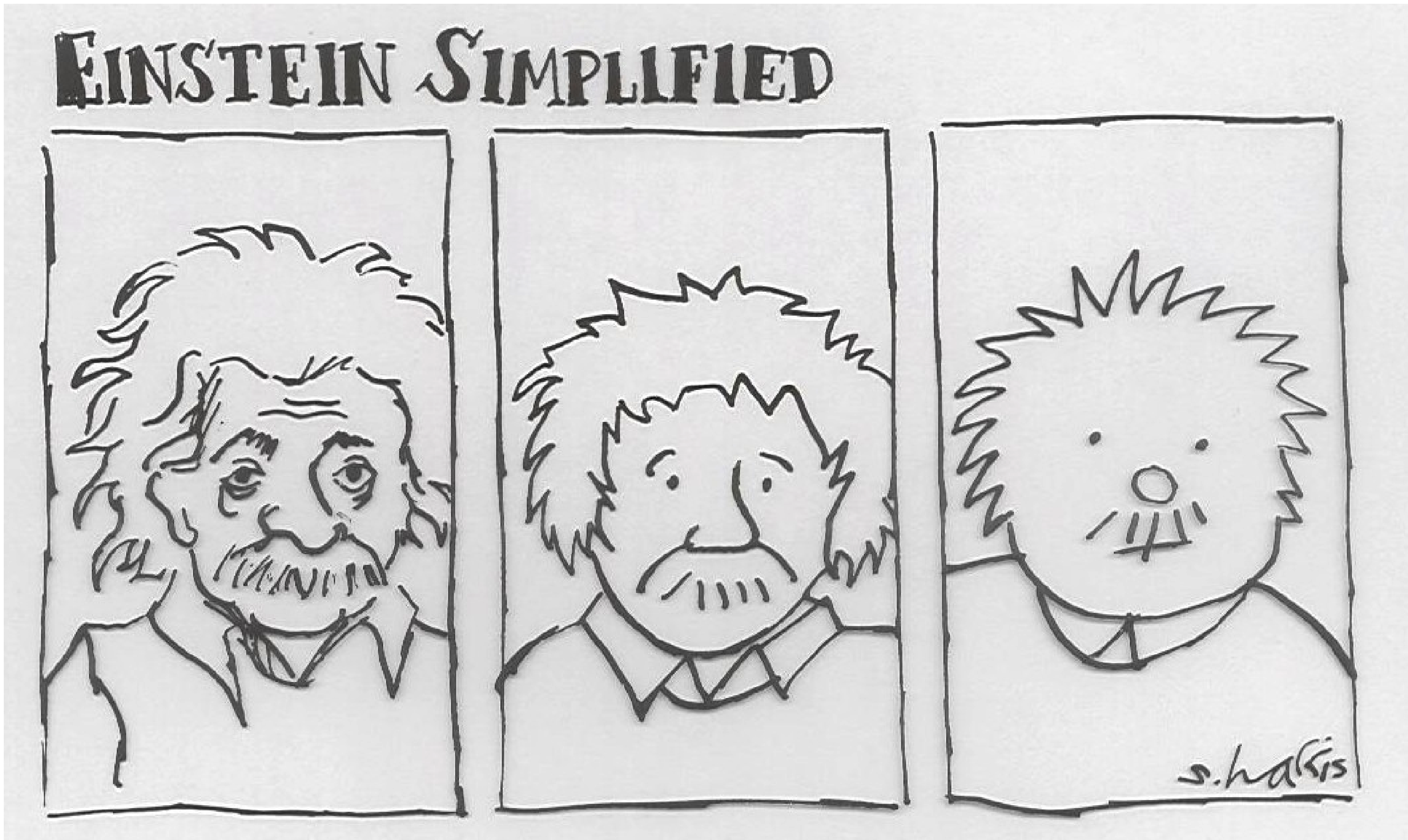
We are trying to measure local perturbations in the space-time metric.

What is a Gravitational Wave?

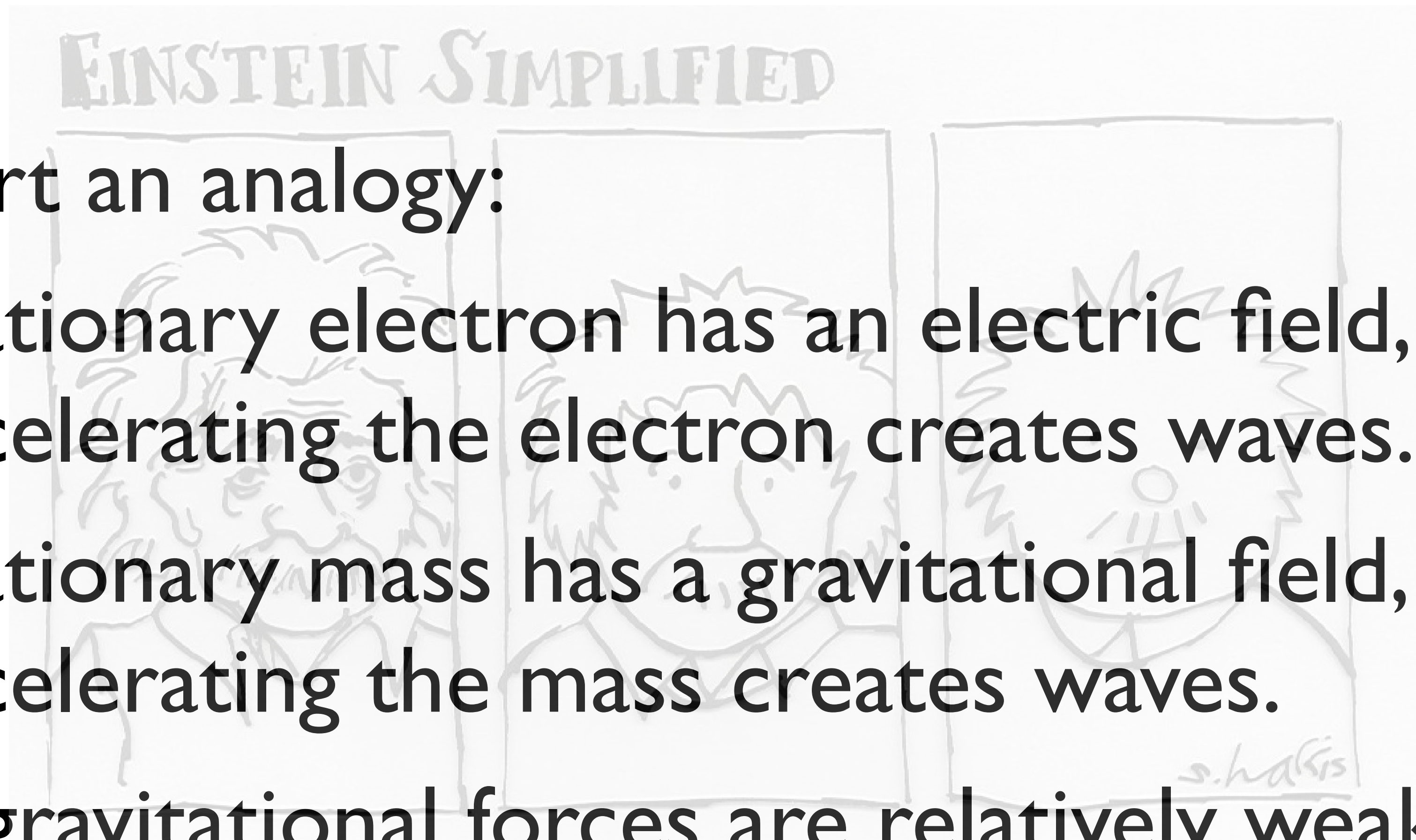


- Predicted by Einstein in 1916 as part of GR.
- Mass tells space how to curve, curved space tells mass how to move.
- There are traveling wave solutions, the waves propagate at the speed of light.

What is a Gravitational Wave?



What is a Gravitational Wave?



Assert an analogy:

A stationary electron has an electric field, and accelerating the electron creates waves.

A stationary mass has a gravitational field, and accelerating the mass creates waves.

But, gravitational forces are relatively weak, or space is very stiff.

$$(for\ electron\ and\ proton)\ \frac{electrical\,force}{gravitational\,force} \approx 2 \cdot 10^{39}$$

What is a Gravitational Wave?

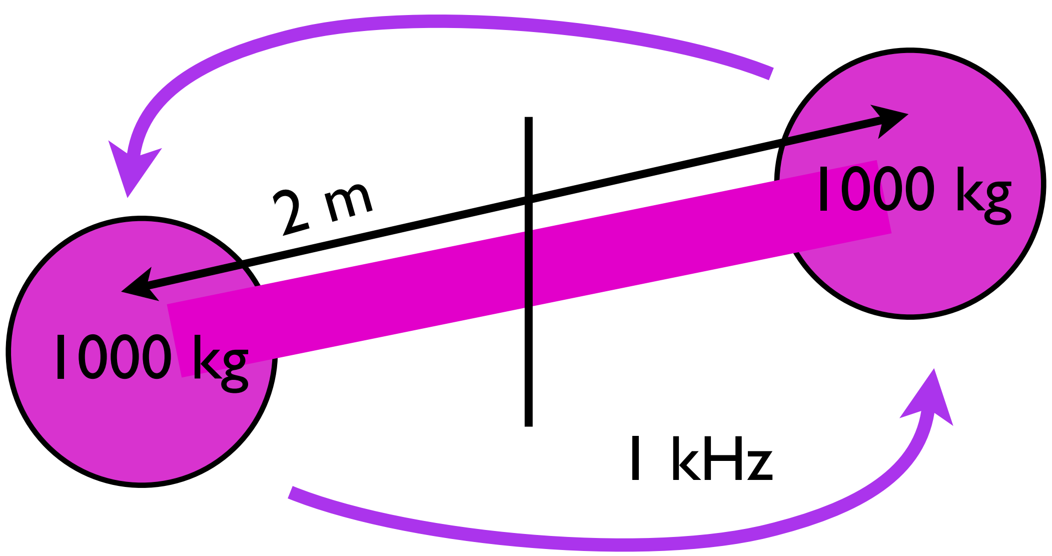
Assert an analogy:

A stationary electron has an electric field, and accelerating the electron creates waves.

A stationary mass has a gravitational field, and accelerating the mass creates waves.

But, gravitational forces are relatively weak, or space is very stiff.

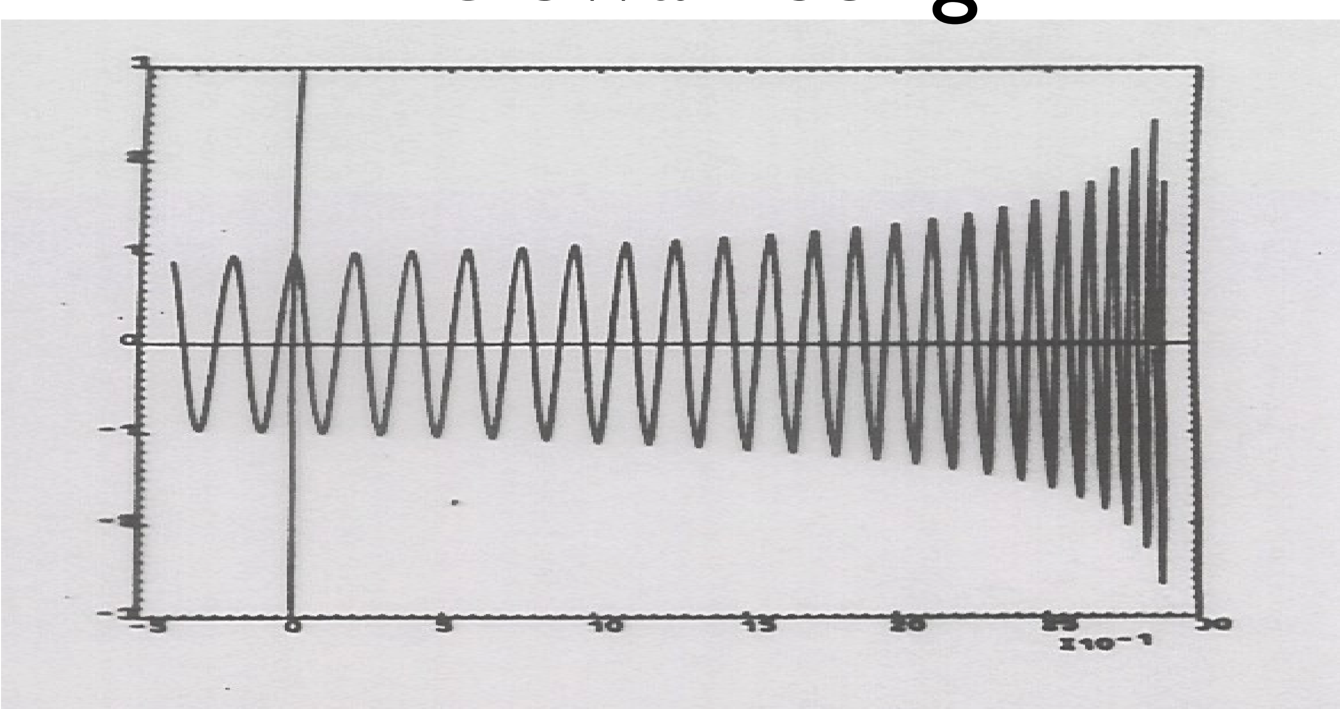
spinning a barbell in the lab is hopeless, $h \sim 10^{-38}$

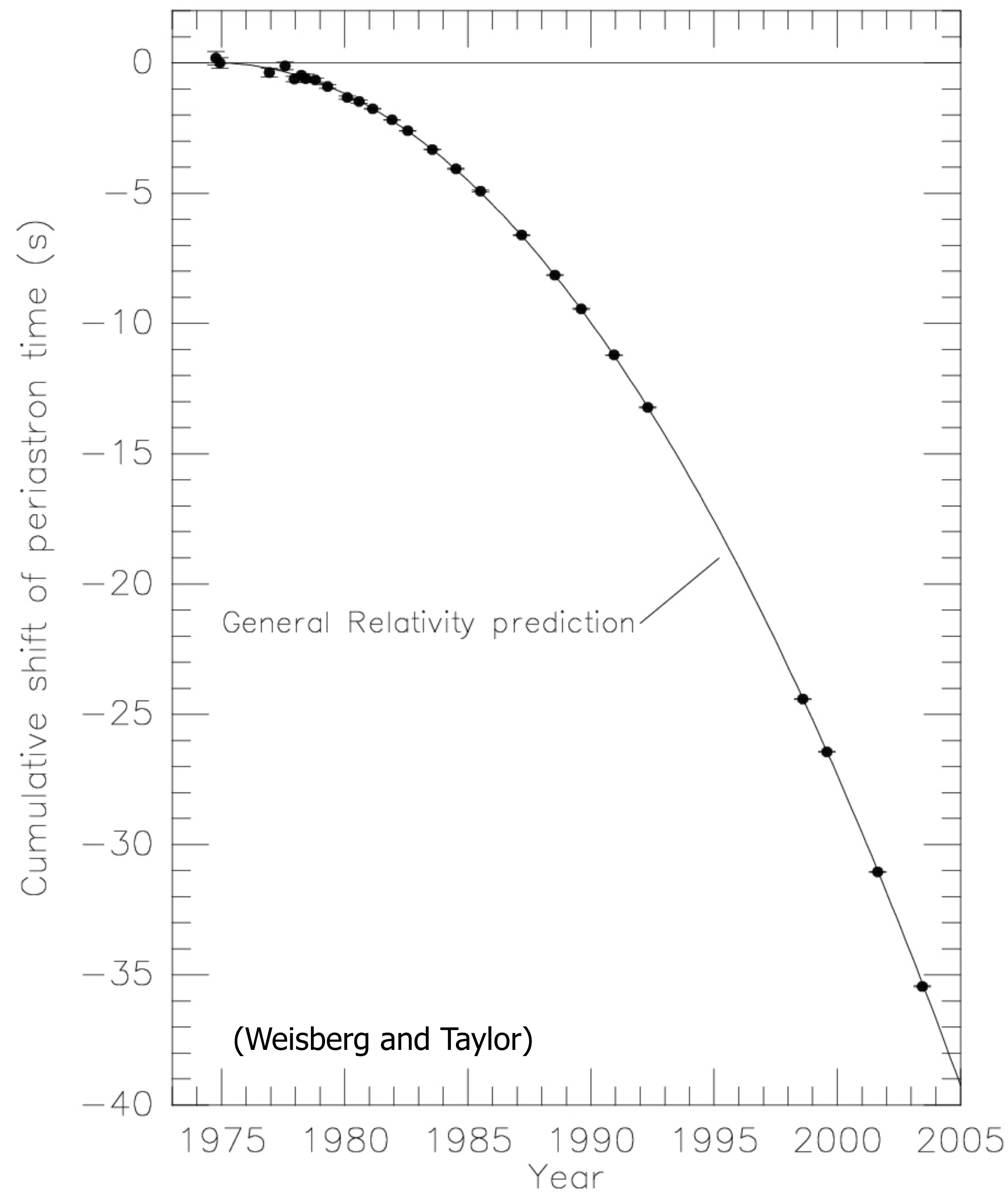


Astronomy!

- How about Neutron stars?
- Hulse and Taylor '93. (PSR 1913+16)
- and in 300 MYears…

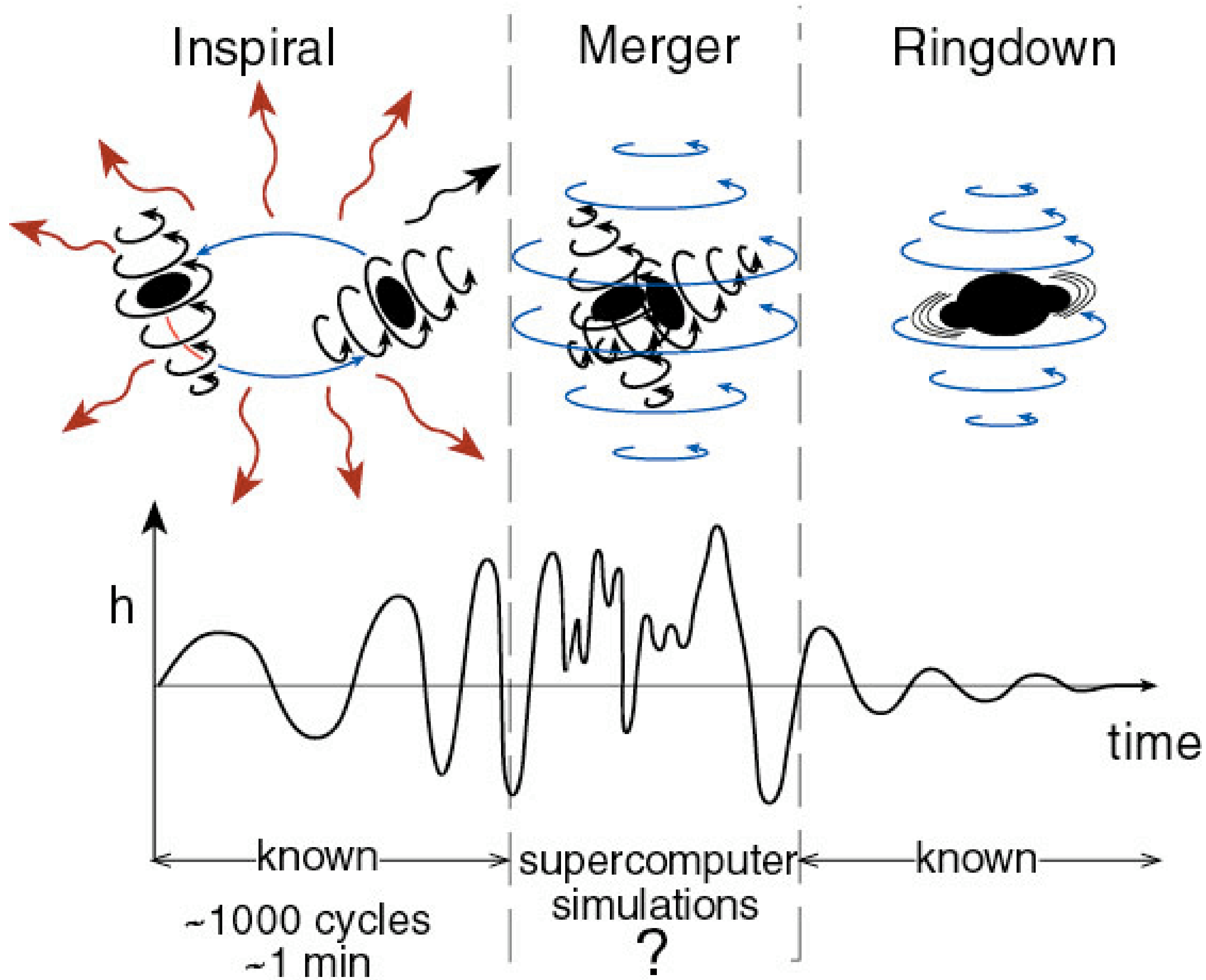
The Swan-song





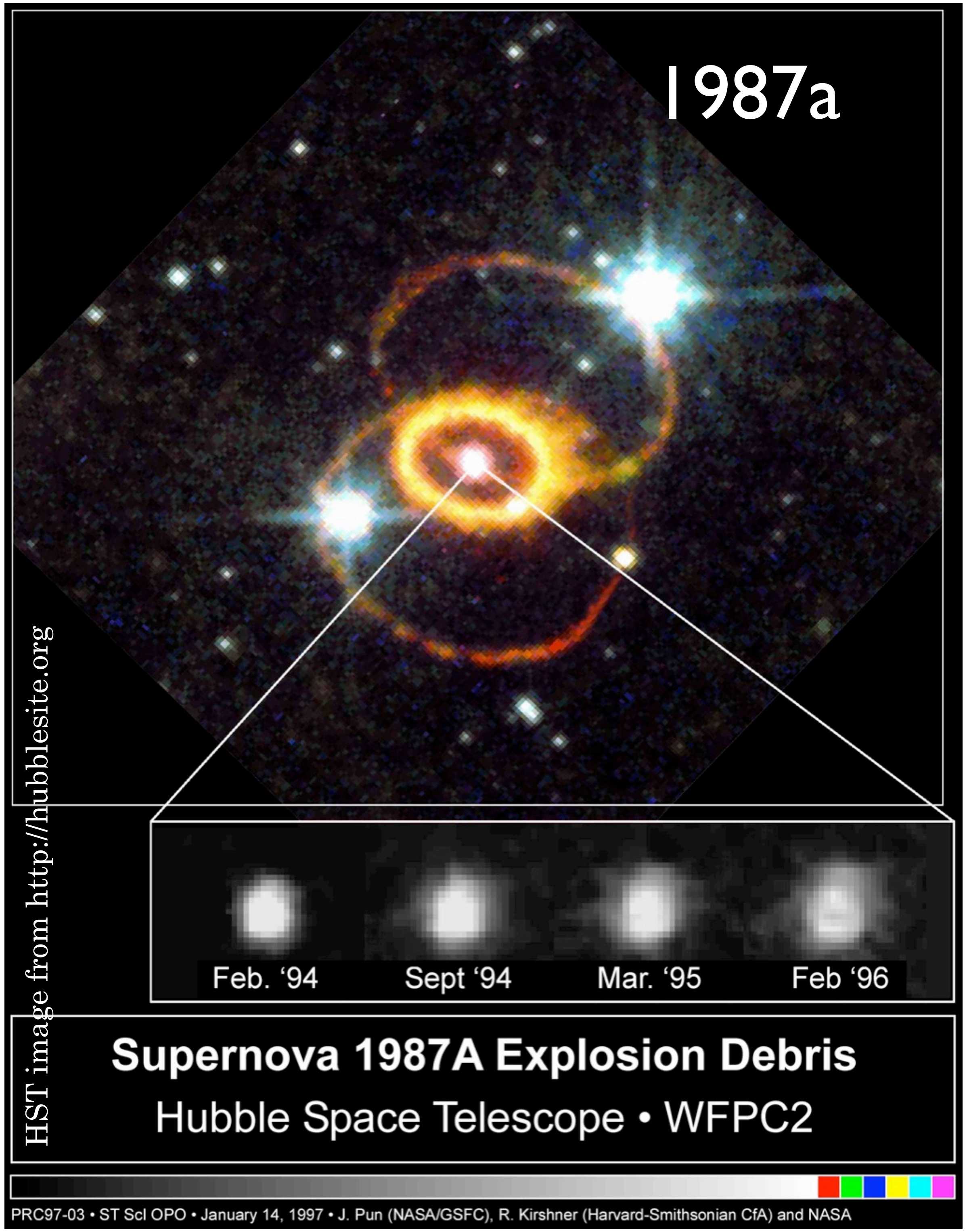
Black Hole Collisions

Black hole collisions

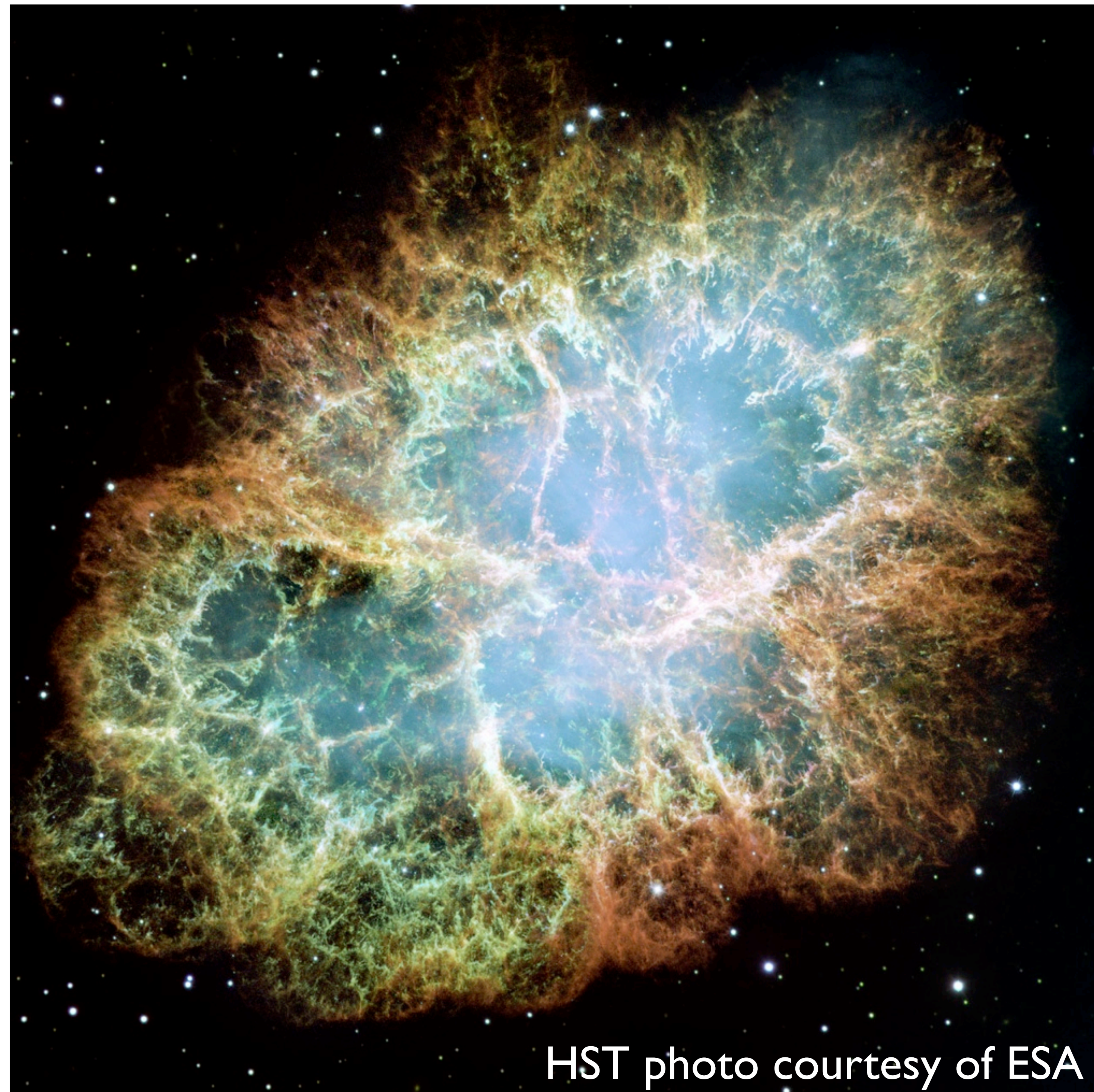


courtesy of Kip Thorne, G030311, June 2003

Supernovas and remnants



Crab Nebula, supernova in 1054, now a spinning neutron star



LIGO Scientific Collaboration

LIGO

LSC

University of Maryland 1856

Michigan

University of Strathclyde

Universitas Budapestinensis de Rolando Eötvös nominata

ACIGA

Loyola University New Orleans

Leland Stanford Junior University 1891

Montana State University

PAH

University of Washington

ANU
The Australian National University

Montclair State University

Syracuse University Founded AD 1870

Tsinghua University
清華大學

Trinity University

San José State University

University of Wisconsin UW Milwaukee

부산대학교
Pusan National University

The University of Western Australia

1754

University of Glasgow

NASA
Goddard Space Flight Center

Per Ardua Alta

Università degli Studi del Sannio

LSU

UTB TSC

R·I·T

The University of Melbourne

KiSTi

Andrews University

Massachusetts Institute of Technology 1861

Southeastern Louisiana University

The University of Texas at Austin

Moscow State University

California Institute of Technology 1891

Northwestern University

Hanyang University 한양 1939

University of Cambridge

The University of Adelaide Australia

PAN

GEO 600

Embry-Riddle Aeronautical University

University of Massachusetts Amherst 1863

Lund University

ISI

University of New Hampshire

PennState 1855

Carleton College Northfield, Minn. AD 1866

Cardiff University

California State University Fullerton

Washington State University

국가수리과학연구소
National Institute for Mathematical Sciences

Charles Sturt University

Universitat de les Illes Balears

UF University of Florida

PI Perimeter Institute

CITA-ICAT

Seoul National University

The University of Mississippi 1848

University of Rochester

NAOJ

University of Southampton

Hobart and William Smith Colleges

William Smith College 1908

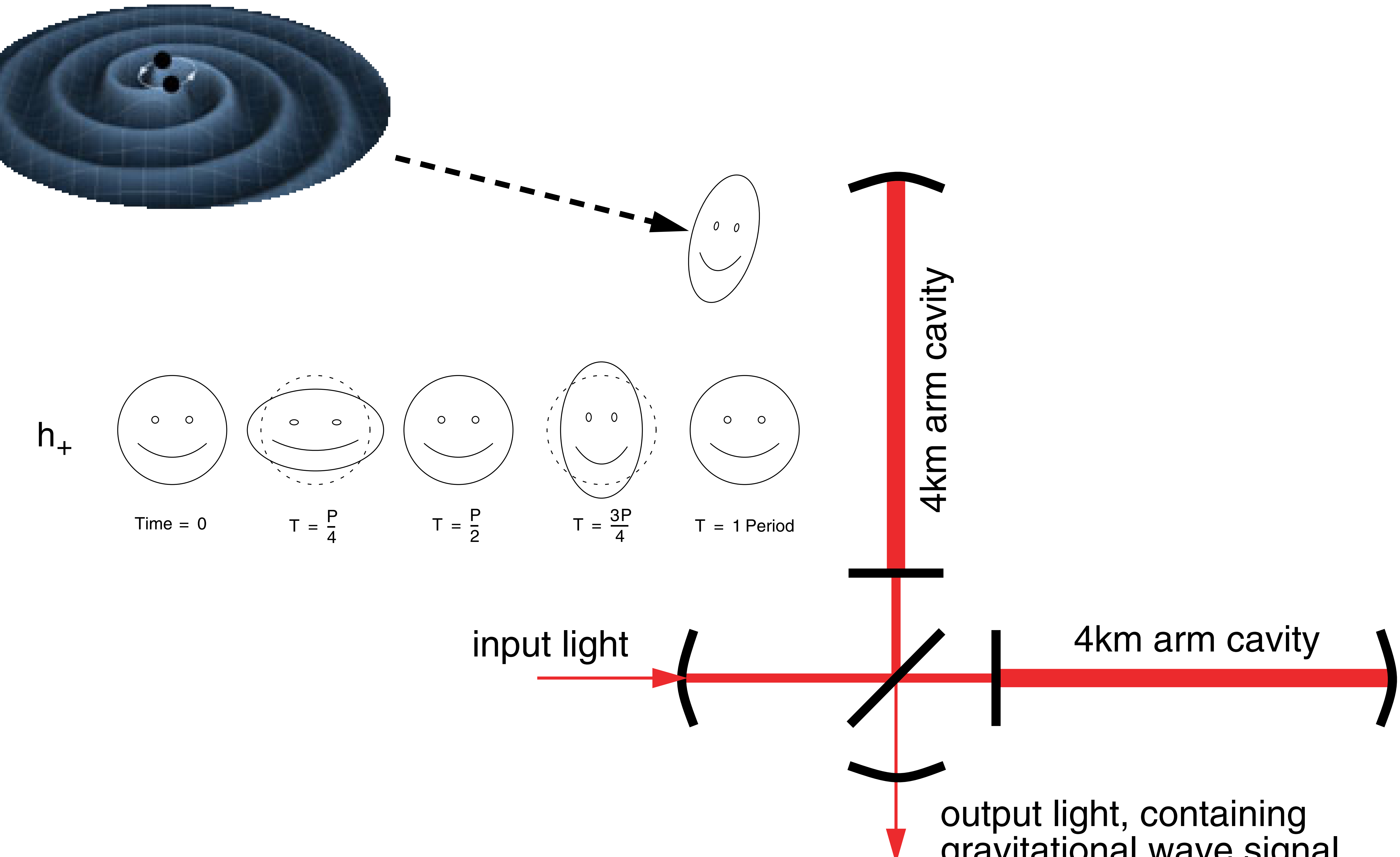
University of Minnesota

Universität Hannover

Southern University and Agricultural & Mechanical College

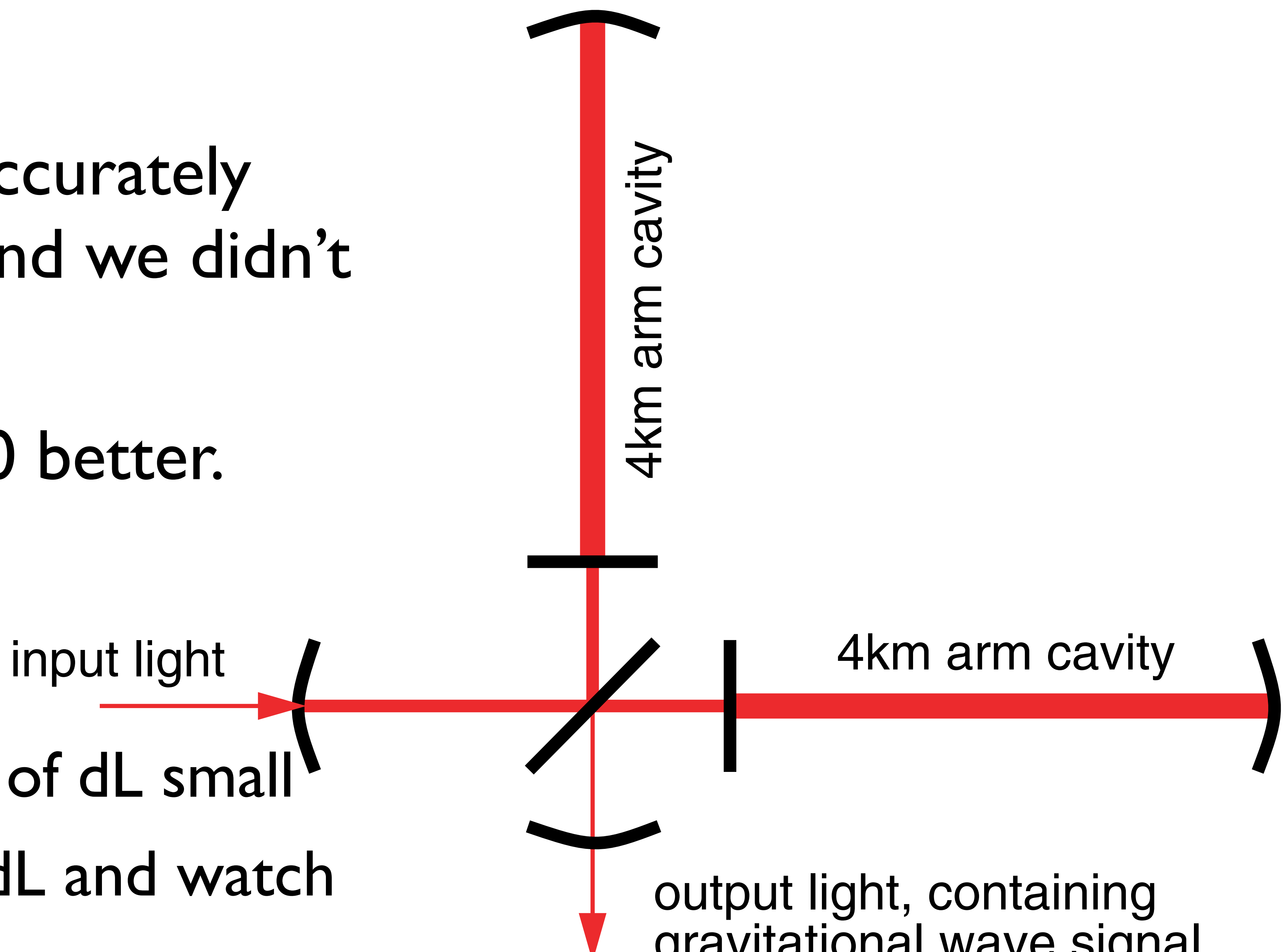
Science & Technology Facilities Council
Rutherford Appleton Laboratory

The LIGO concept



The LIGO concept
why it is nearly impossible

- Gravitational waves are hard to measure because space doesn't like to stretch.
- Initial LIGO could accurately measure $h = 10^{-21}$, and we didn't see anything.
- Advanced LIGO x10 better.
- $h = dL/L$, so
  - make L big,
  - make other sources of dL small
  - read out remaining dL and watch signals.



Advanced LIGO / Sources

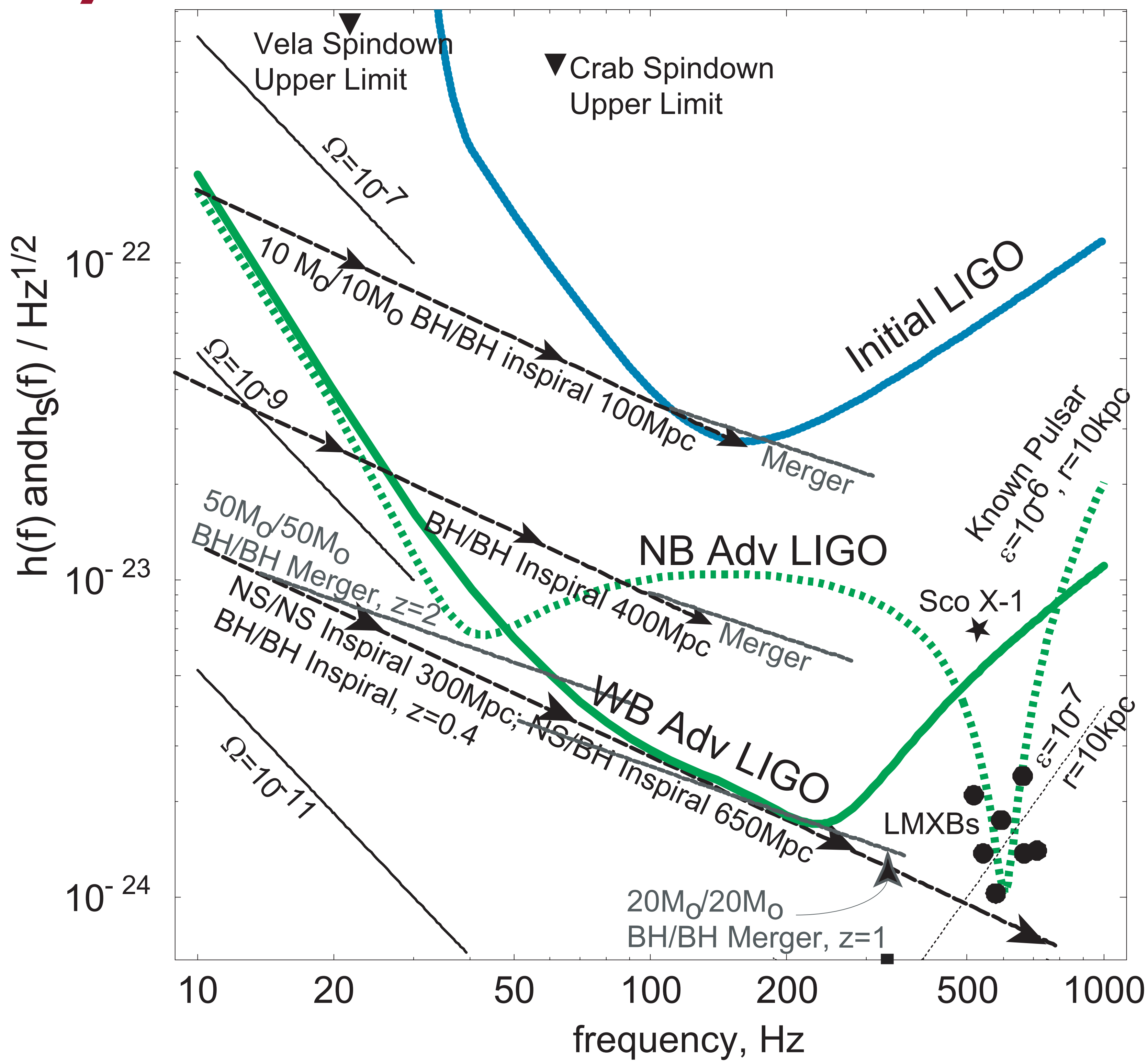
or, why is this so hard?

Neutron star and Black hole binaries
- inspiral
- merger
- GRBs?

Spinning NS's
- LMXB
- known pulsars
- unknown?

Birth of NS (supernovas)
- tumbling
- convection

Stochastic Background
- remnants of the big bang



With Advanced LIGO, expected event rate is 10-100 NS/NS events per year.

Advanced LIGO / Technology

or, what are you going to do about it?

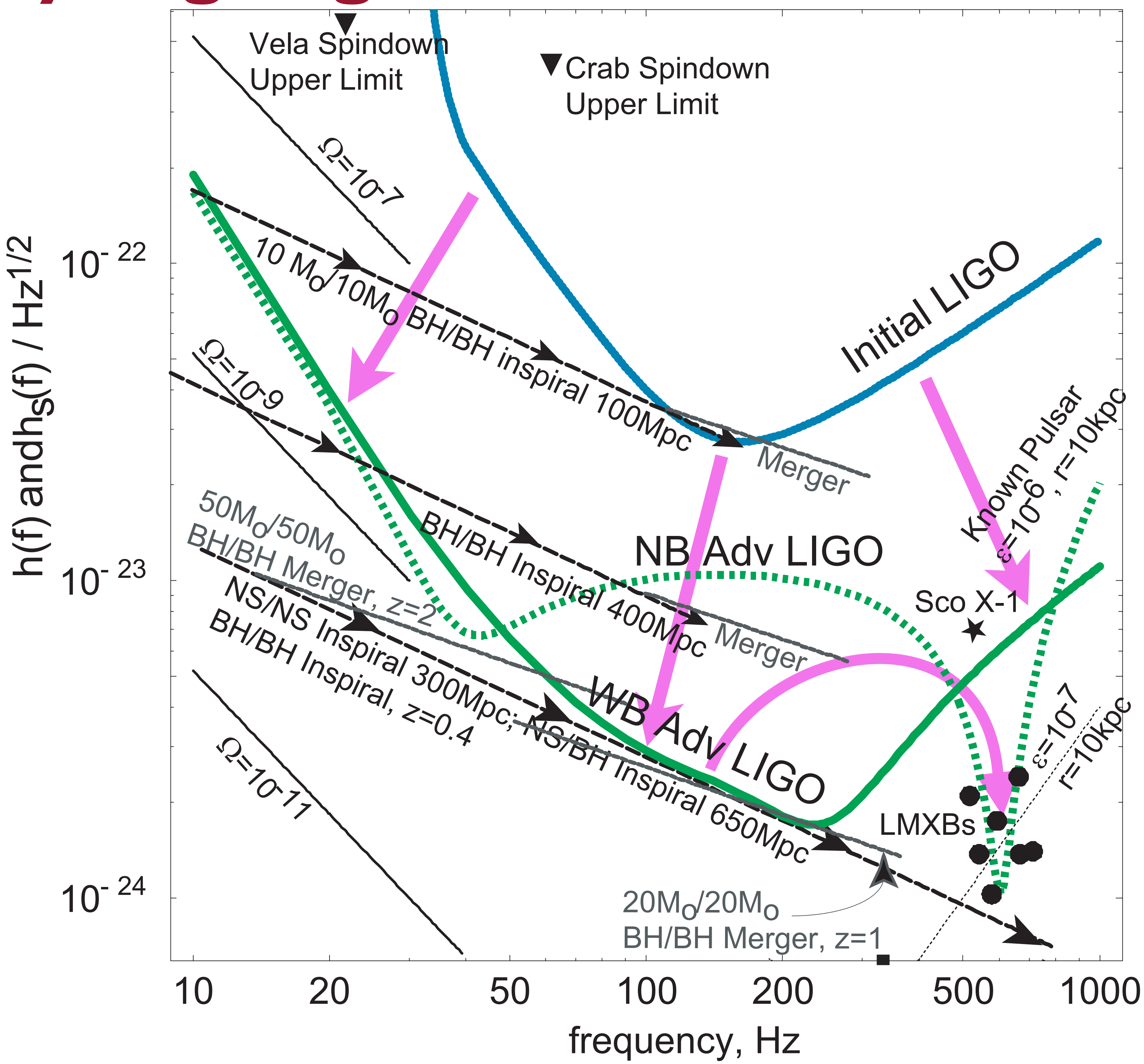
<u>Technical Improvements</u>

Specialized interferometer configuration

More Power
- 180 W laser
- 800 kW circulating in arms

Environmental Isolation:
- platforms & pendulums

Thermal Noise control:
- suspensions & coatings



International Network

map from http://www.nationsonline.org/maps/political_world_map3000.jpg

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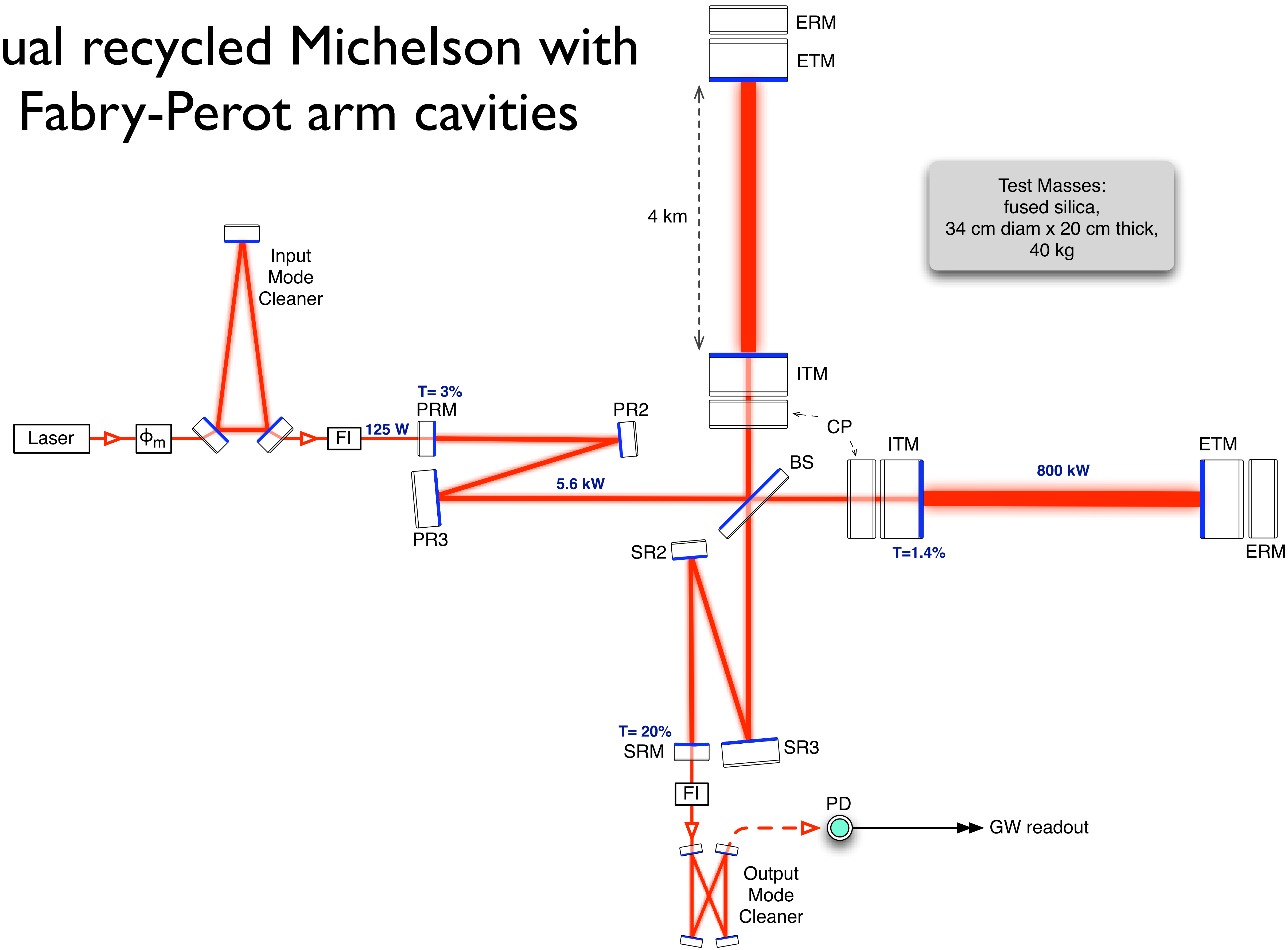
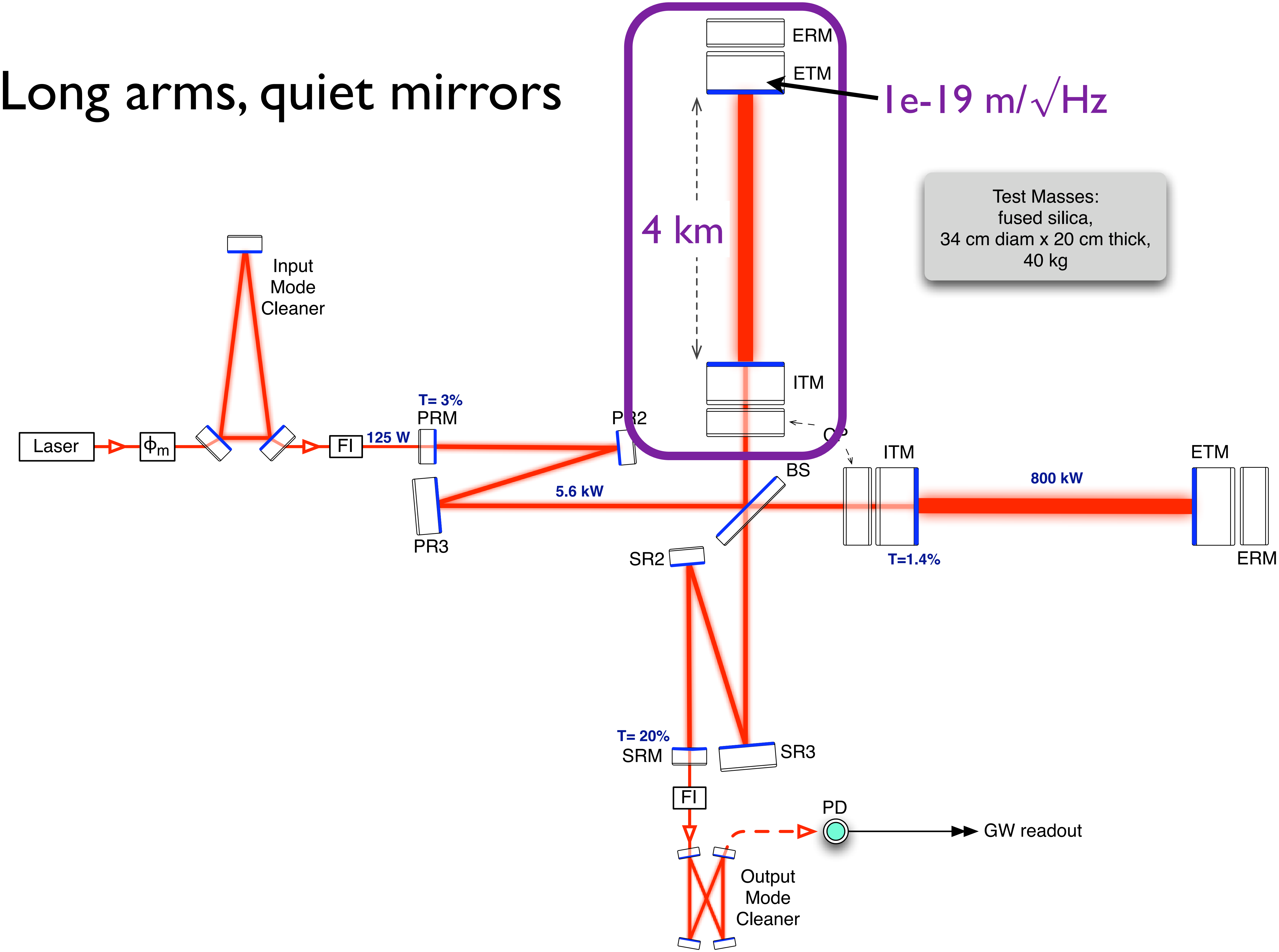
Technical Tricks

Dual recycled Michelson with Fabry-Perot arm cavities

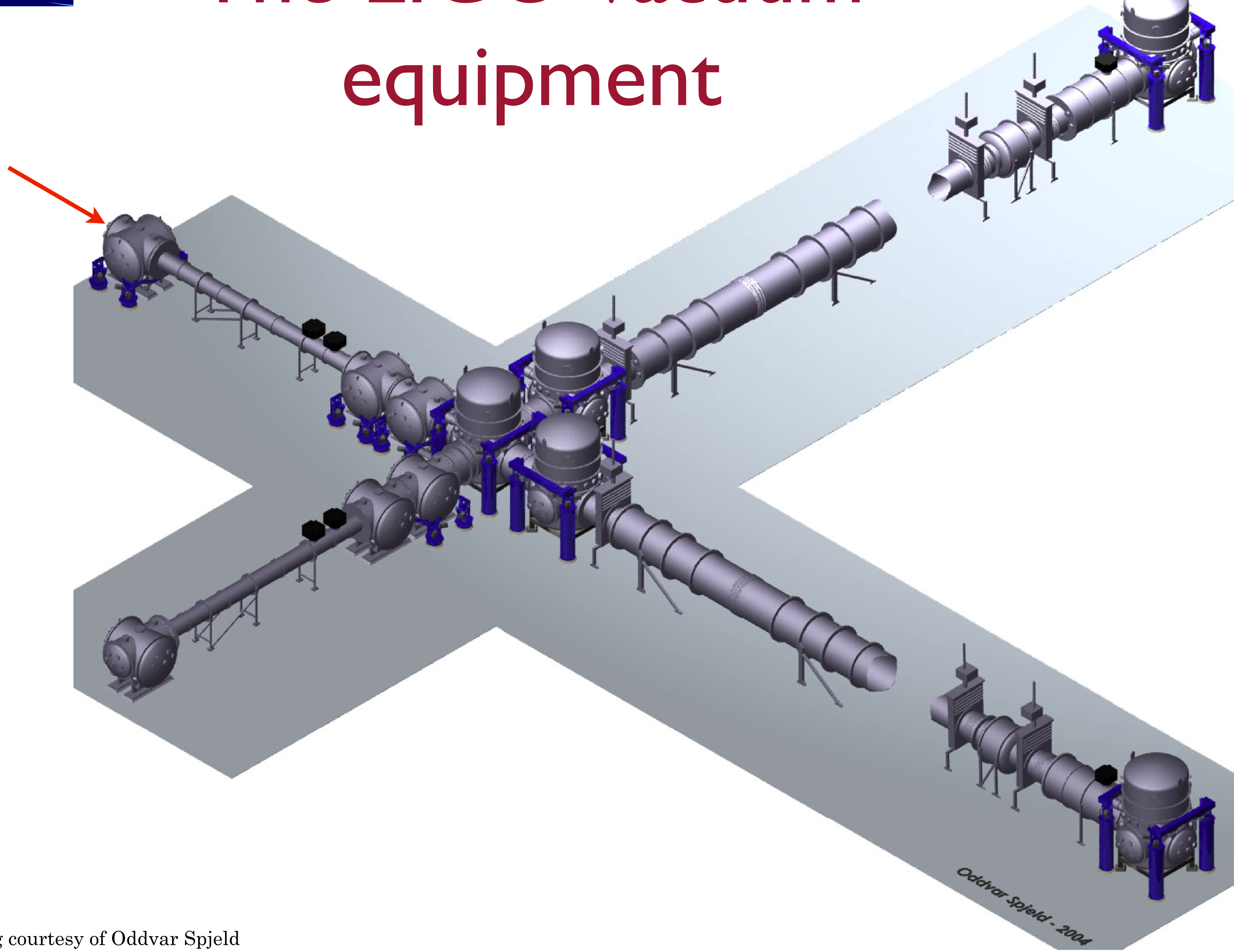


Technical Tricks

Long arms, quiet mirrors



The LIGO vacuum equipment



drawing courtesy of Oddvar Spjeld

Overall Isolation of Test Masses

- 7 total layers
  - HEPI (1)
  - BSC-ISI (2)
  - Quad SUS (4)
- HEPI: Hydraulic External Pre-Isolator
  large throw,
  isolation below ~5 Hz
- ISI
  Internal Seismic Isolation
  Isolates above ~0.2 Hz
  Quiet, well controlled table
- Quad pendulum
  superior performance
  at 10 Hz and above

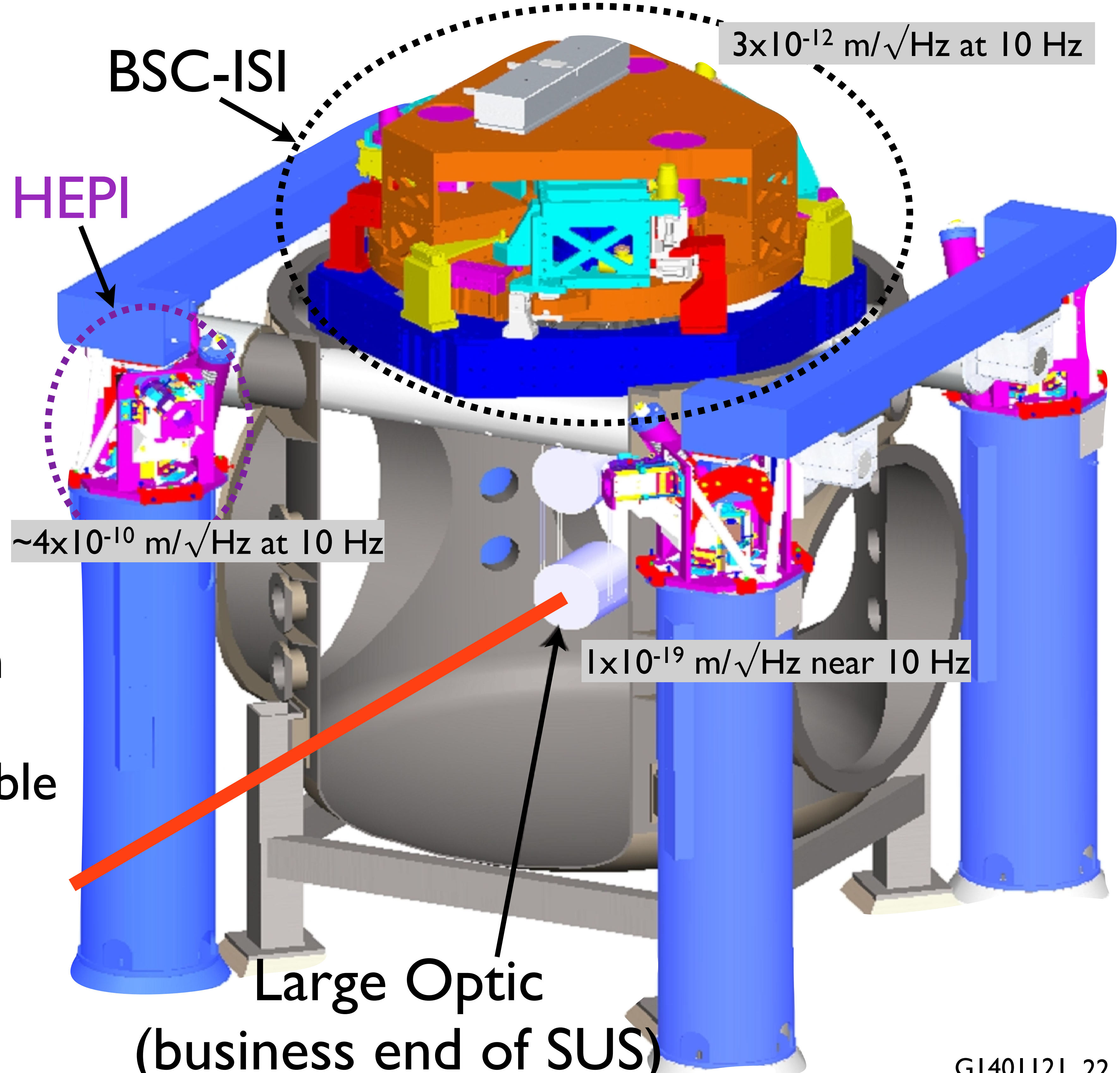
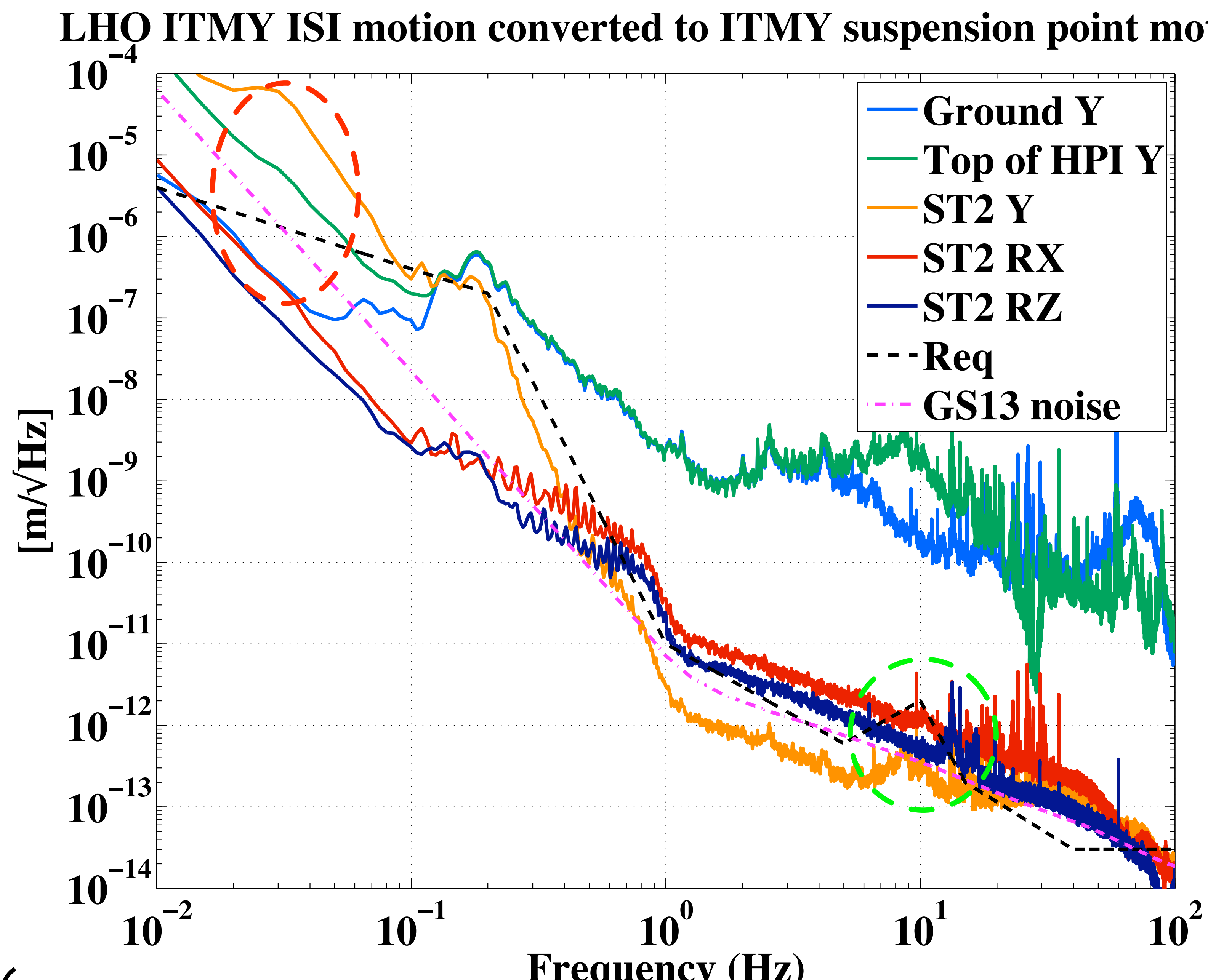


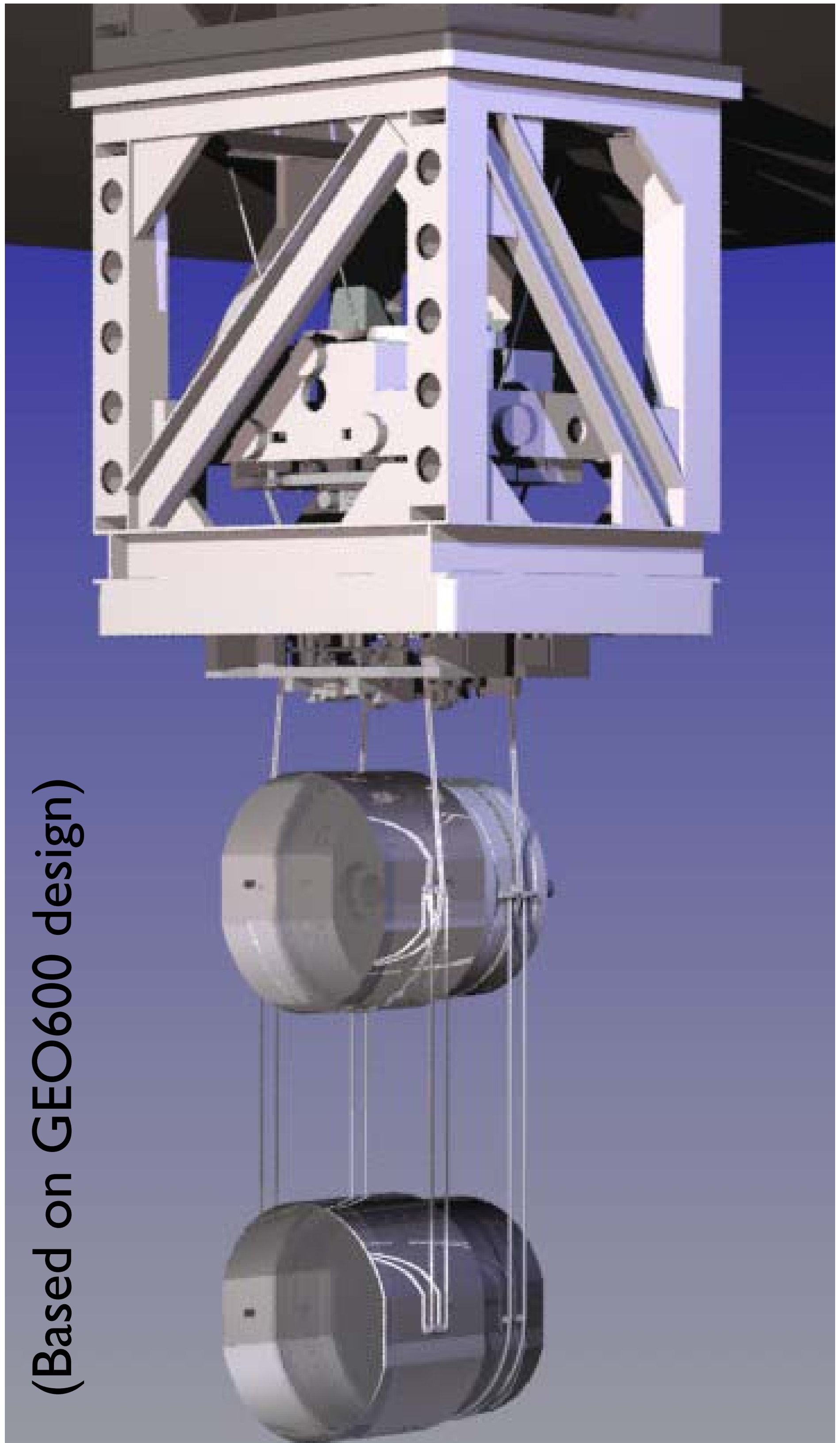
Table motion example

- At LHO the BSC ISI isolation is working at or better than the requirements from 0.1 Hz and up.
- Below 0.1 Hz there is some noise injection which may be removed with better tilt decoupling



Pendulum Suspension

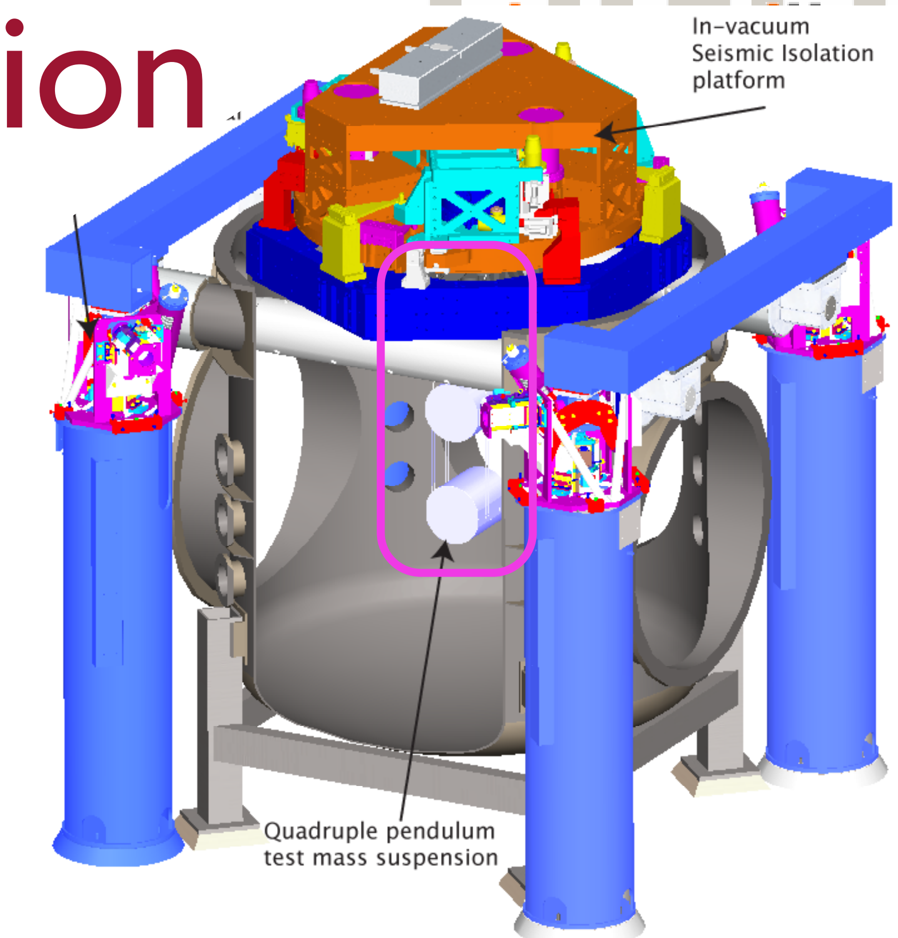
Suspensions material from N. Robertson, GEO600, and the SUS team



Drawings courtesy of Calum Torrie and GEO600

Multiple-pendulums
for control flexibility &
seismic attenuation

Each stage gives ~1/f2
isolation above the
natural frequency.
More that 1e6 at 10 Hz.



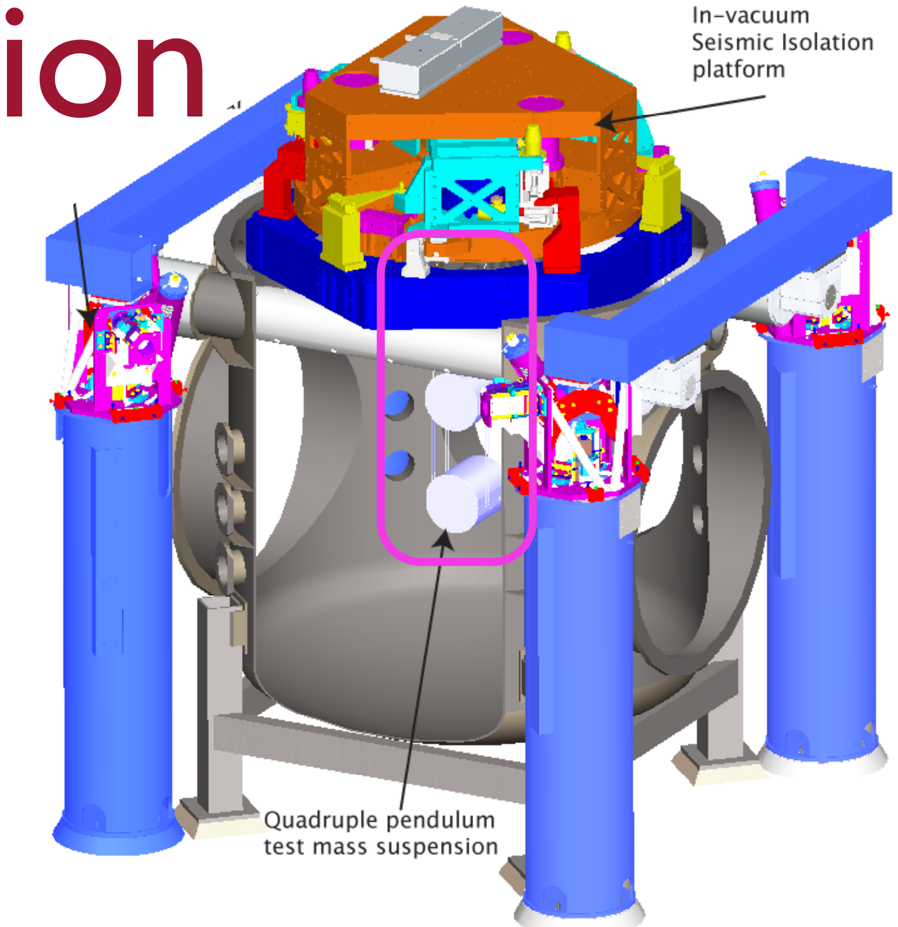
Test masses:
Synthetic fused silica,
40 kg, 34 cm dia.

» Q ≥ 1e7
» low optical absorption

Final suspensions are fused silica,
joined to form monolithic final stages.

Thermal vibrations at the optical surface set
the performance limit of the suspension.

Pendulum Suspension



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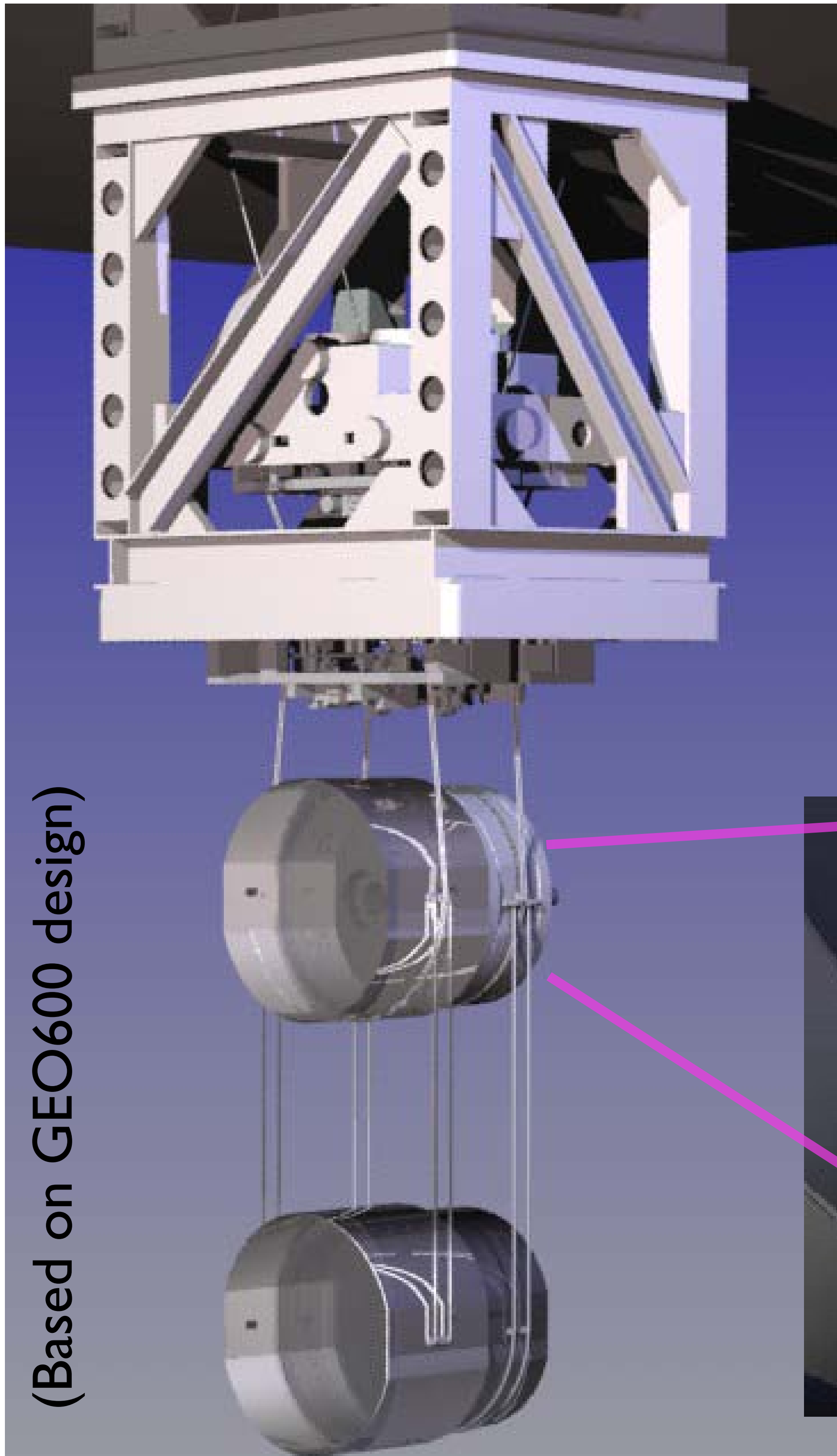
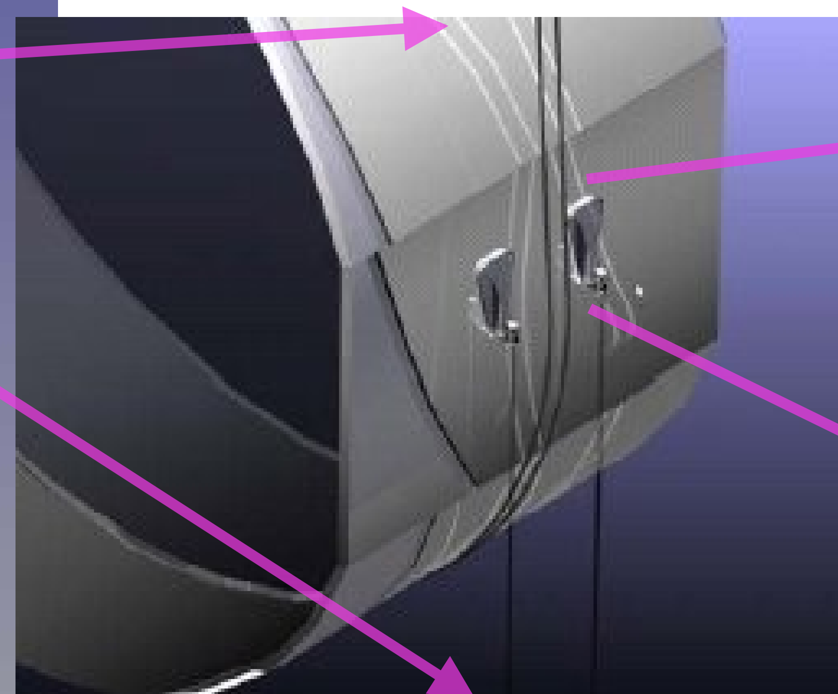


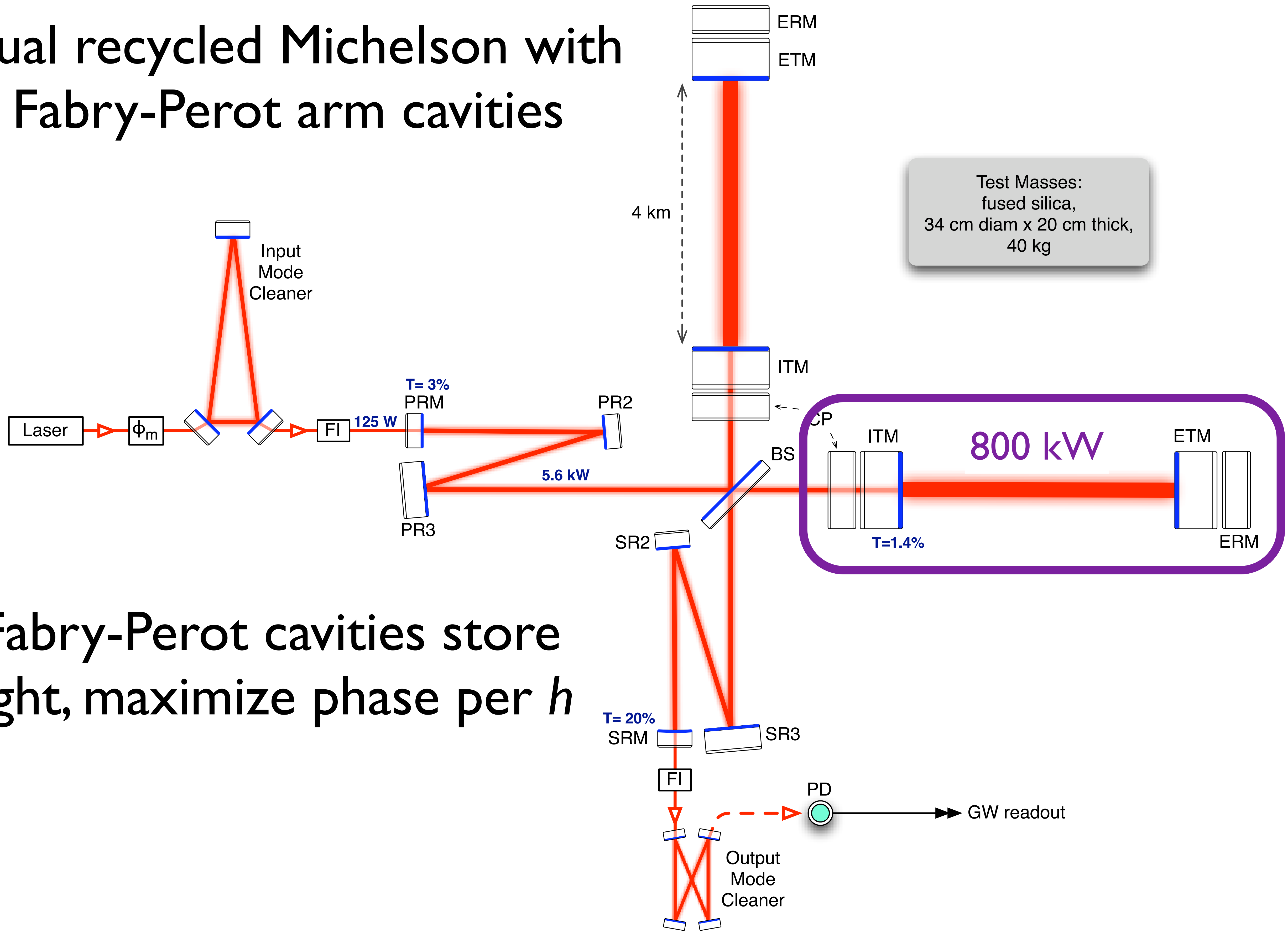
Drawings courtesy of Calum Torrie and GEO600



silicate bonding creates a monolithic final stage

Technical Tricks

Dual recycled Michelson with Fabry-Perot arm cavities



Fabry-Perot cavities store light, maximize phase per *h*

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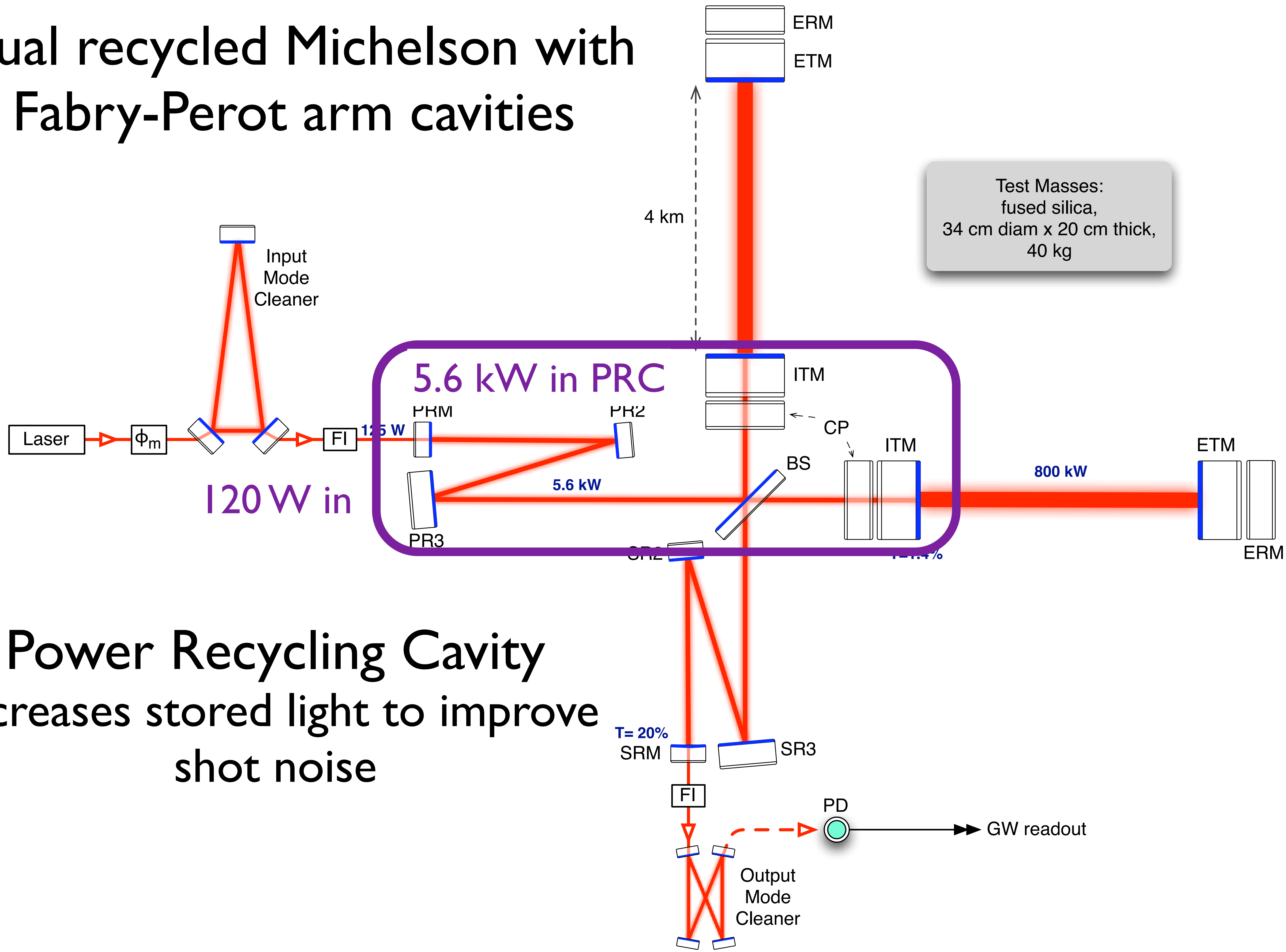
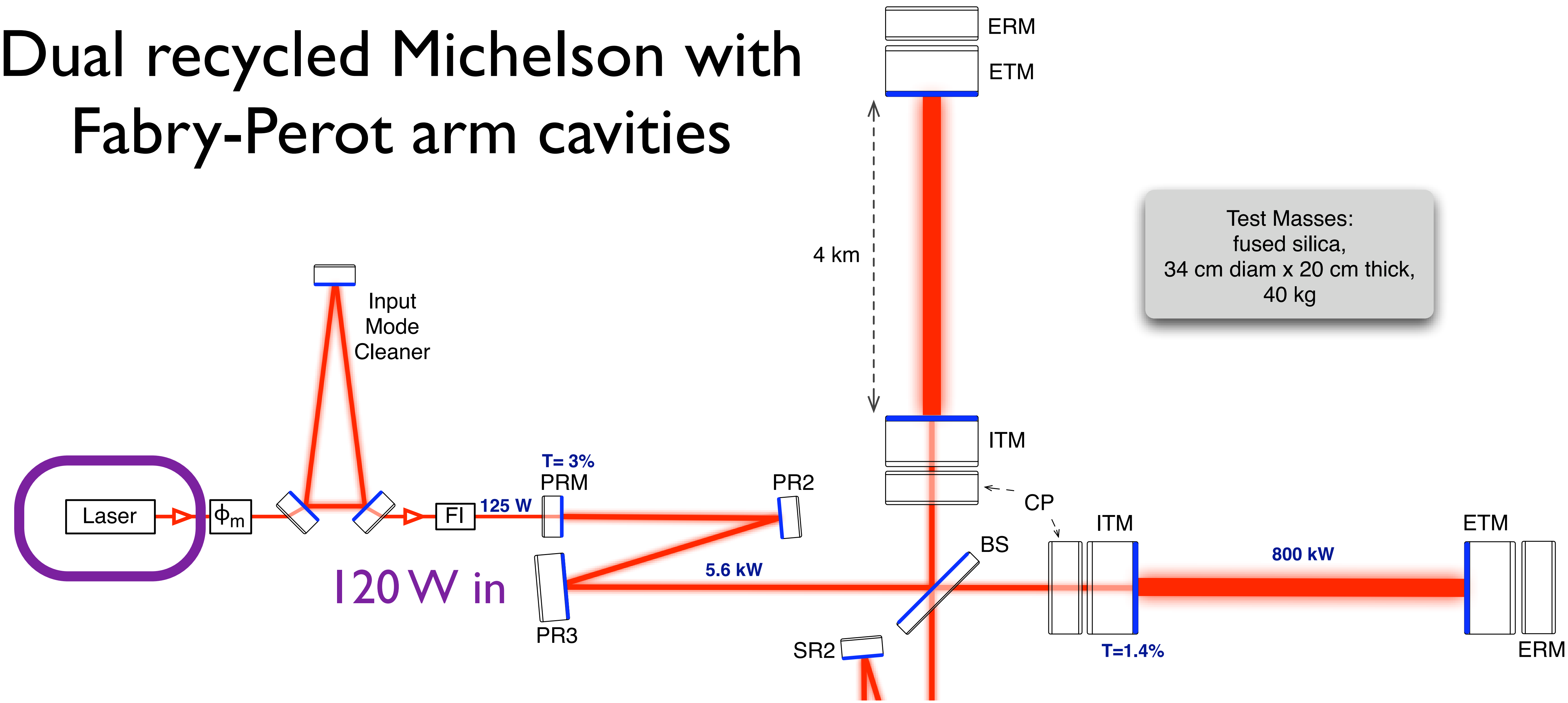


Power Recycling Cavity

increases stored light to improve shot noise

Technical Tricks

Dual recycled Michelson with Fabry-Perot arm cavities



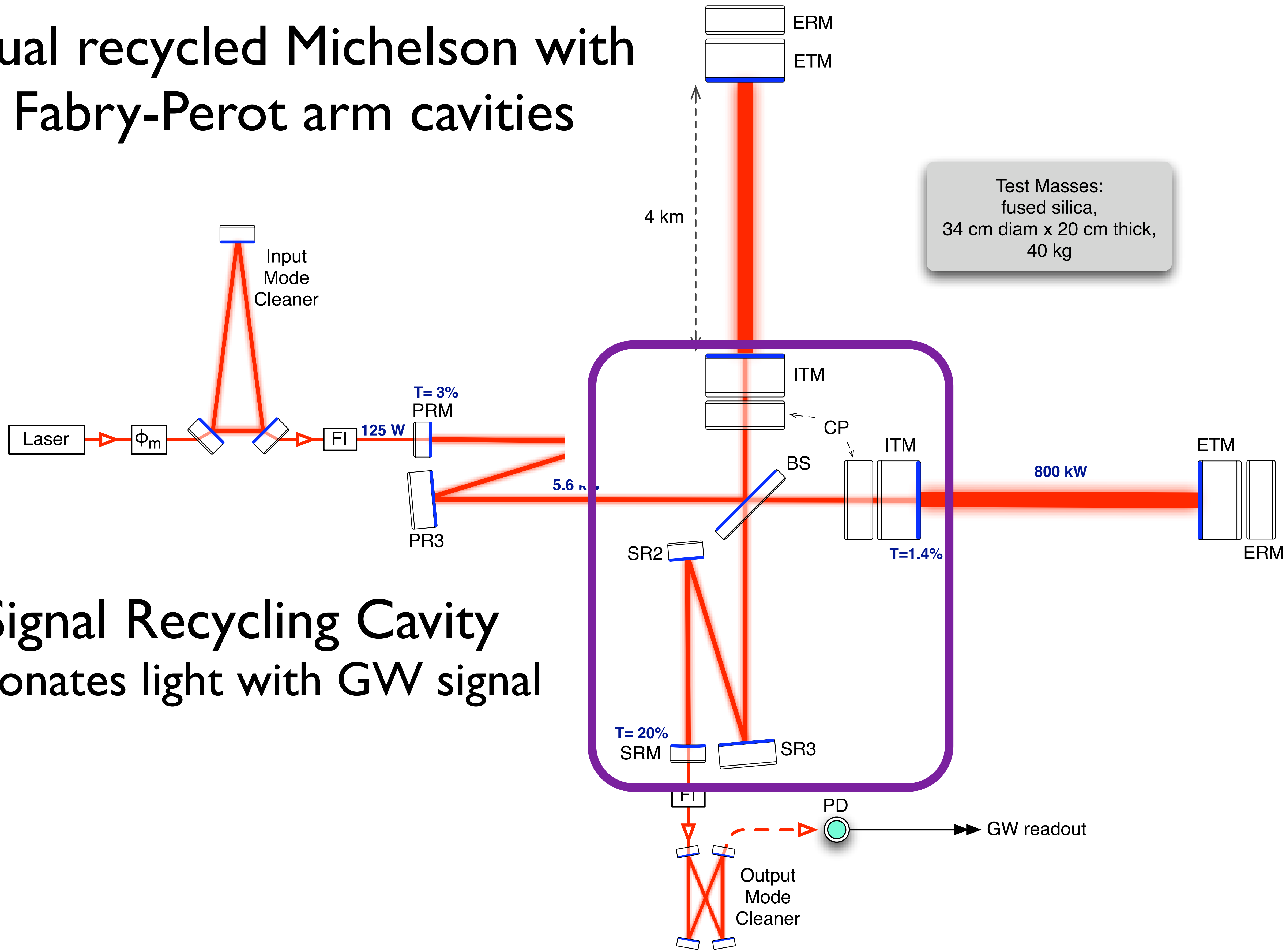
Laser

- delivers 120 W TEM_{00} to IFO
- use common mode arm length,

frequency noise < 1e-7 Hz/√Hz at 10 Hz.

Technical Tricks

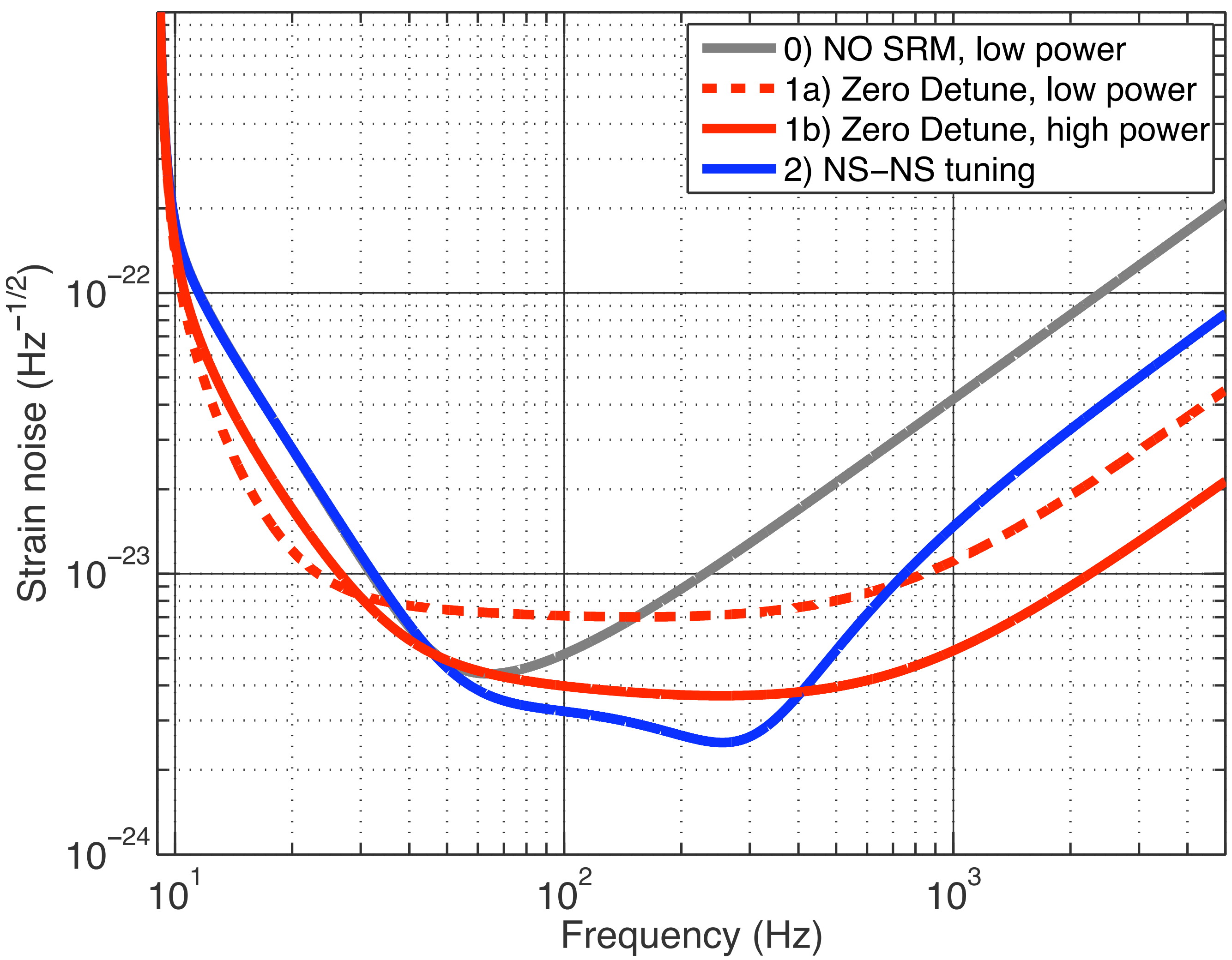
Dual recycled Michelson with Fabry-Perot arm cavities

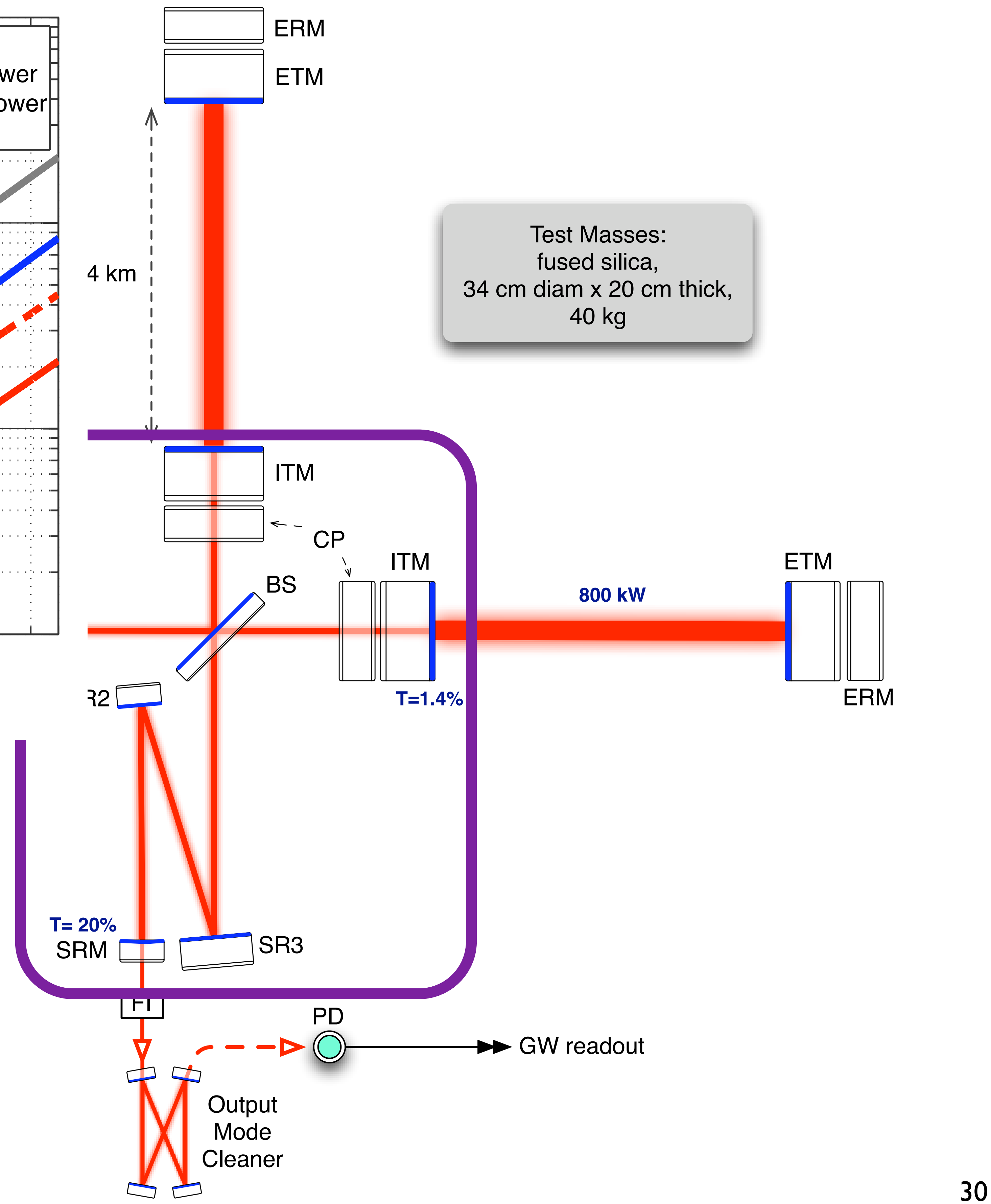


Signal Recycling Cavity

resonates light with GW signal

Technical Tricks





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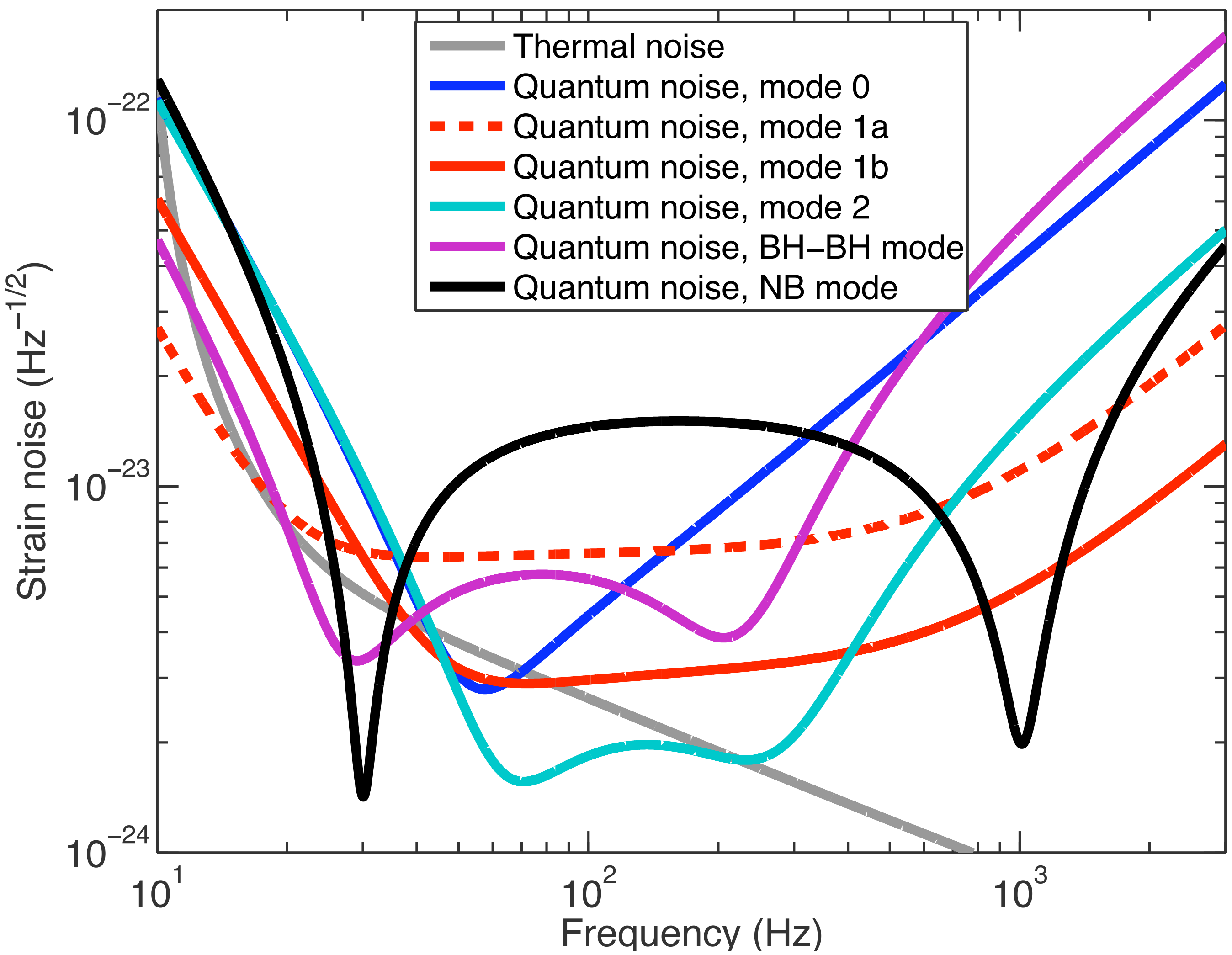
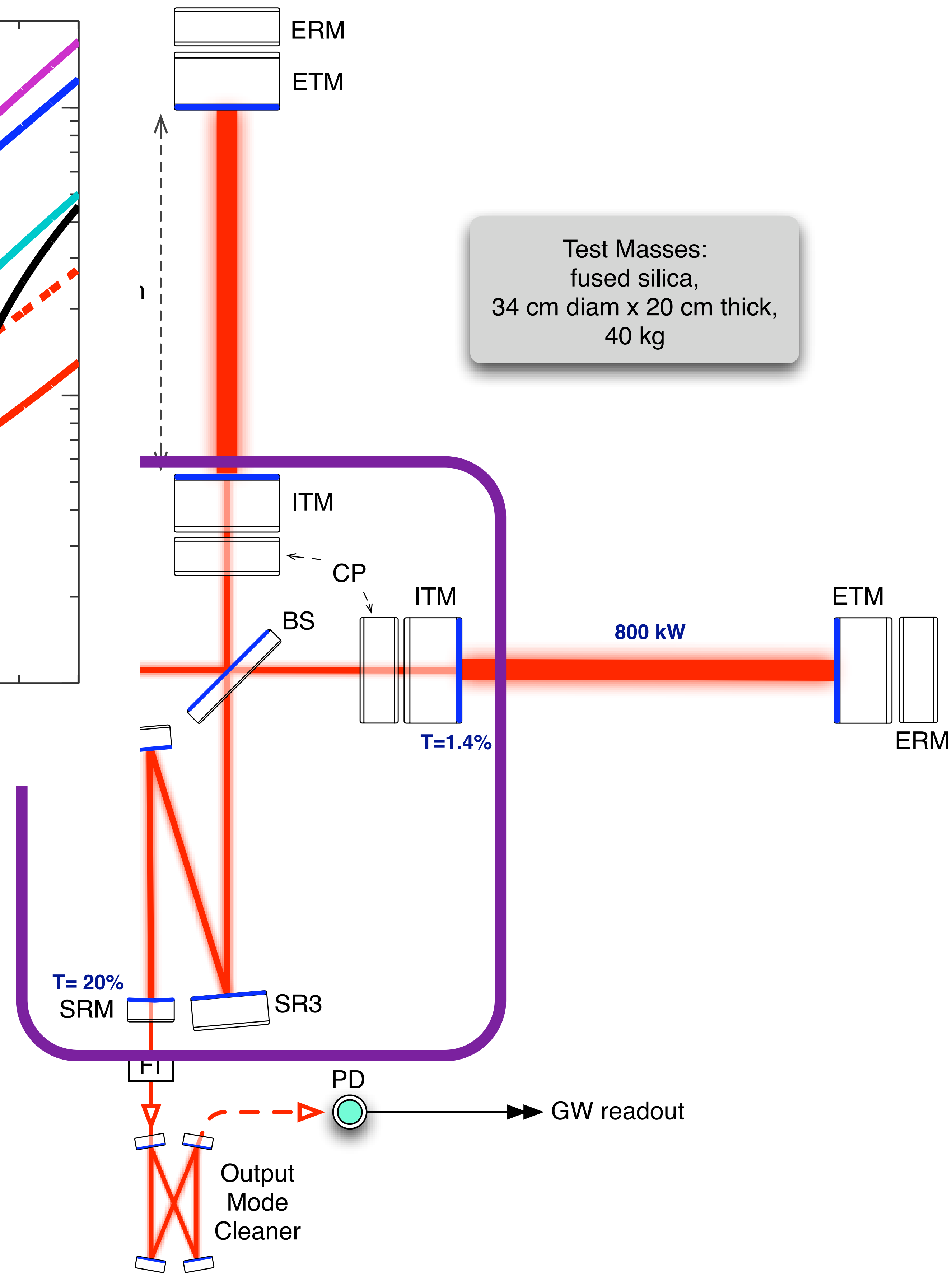




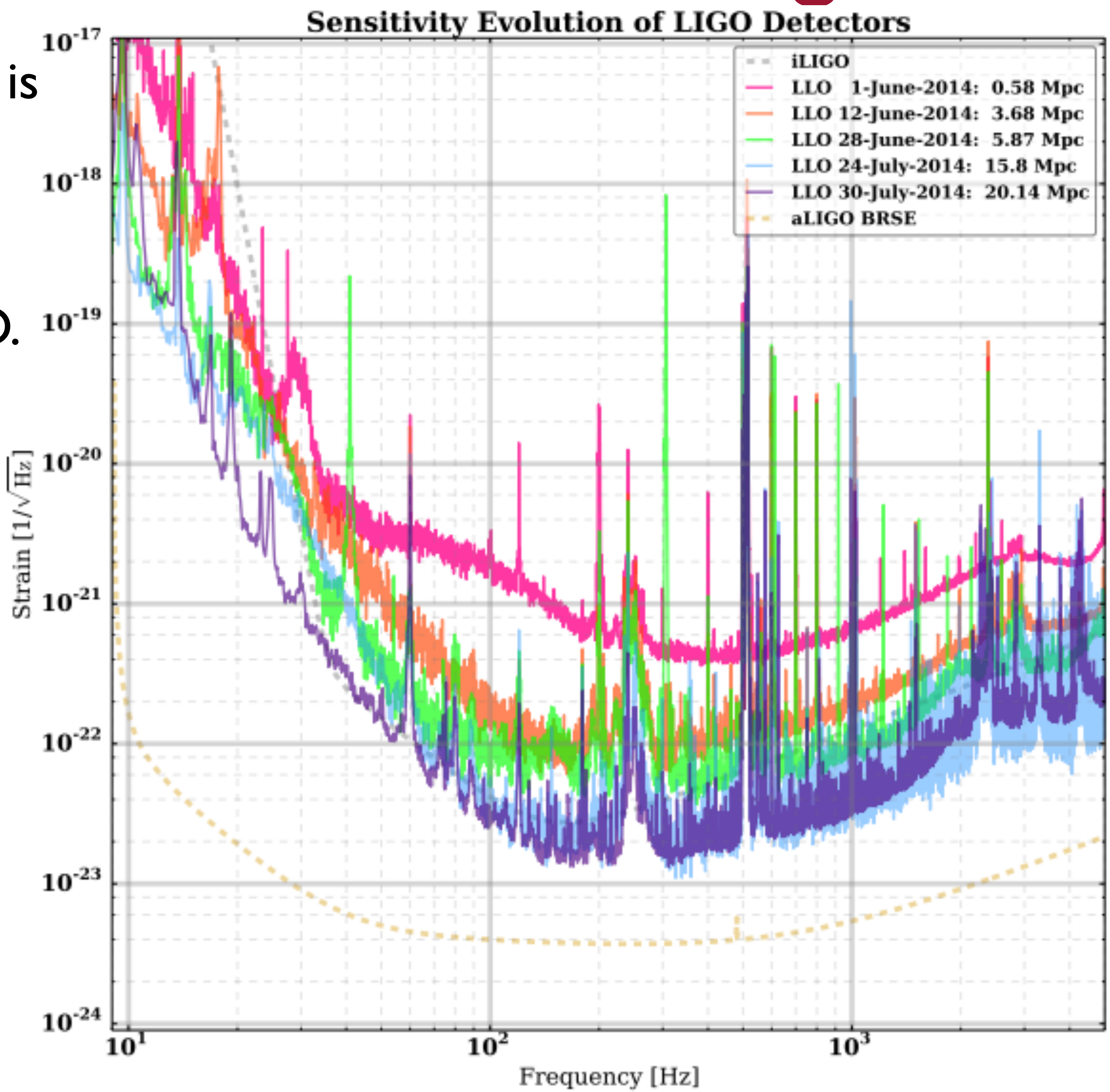
Signal Recycling Cavity
resonates light with GW signal

How are we doing?

Commissioning is moving quickly.

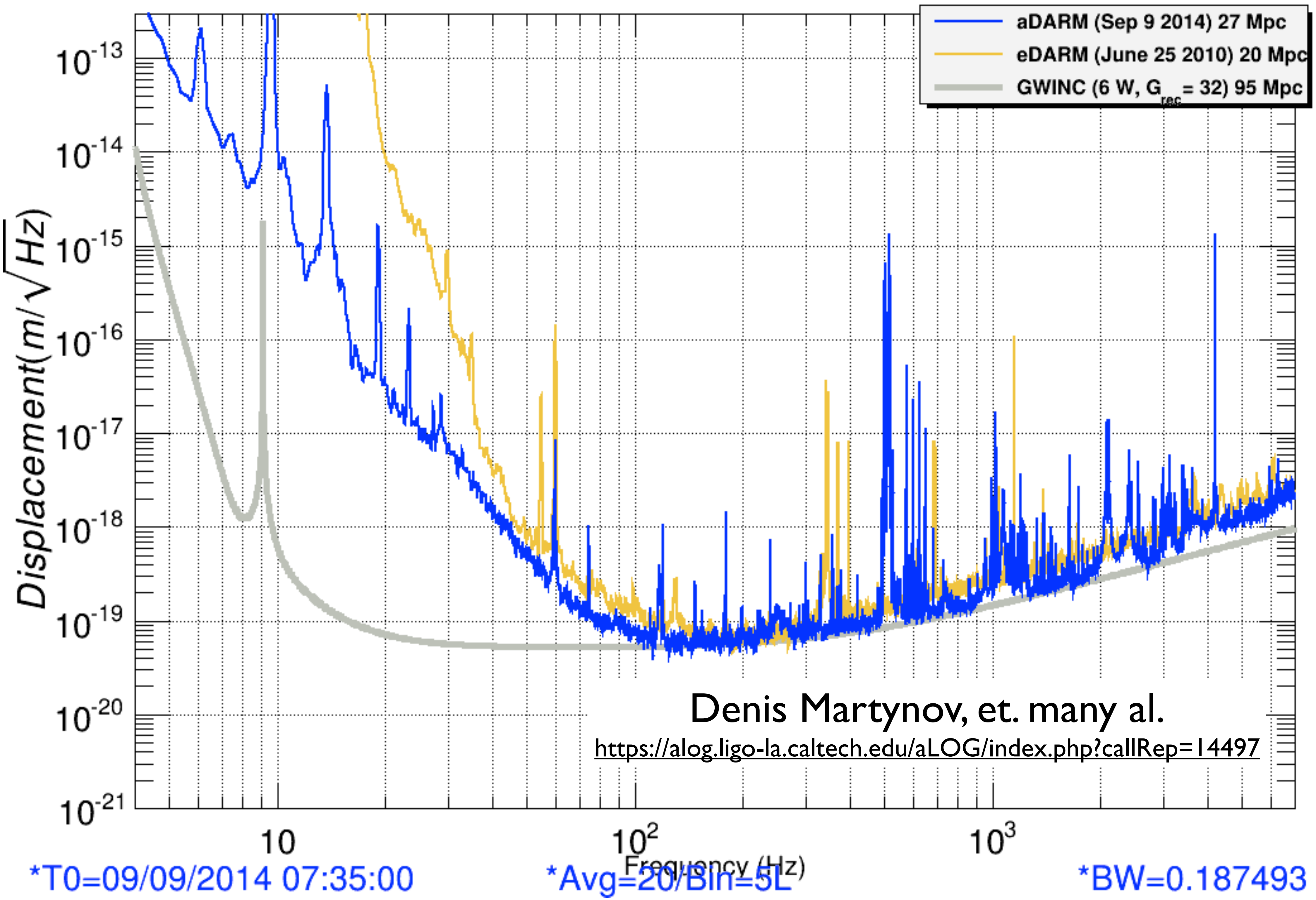
2 months of progress at LLO.

Longest lock stretch
 ~ 7.5 hours



27 MPc on Tuesday

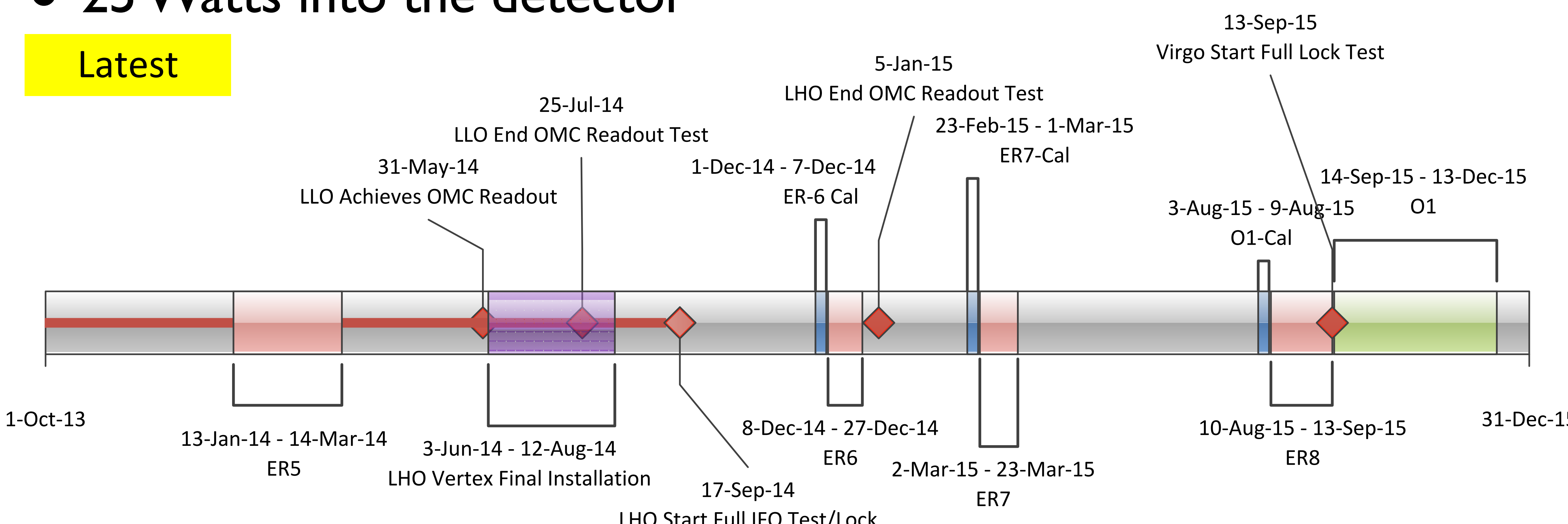
Warning: From the publicly viewable electronic log book, not a reviewed paper, so this plot 'illustrates progress'



Observation Run 1

- Commission/ Observe/ Commission/ Observe
- First Observational Run, O1, in 2015
- 3 months of Observation with 2 LIGO detectors (& Virgo)
- Target Sensitivity:
  - 40 - 80 MPc (120 - 240 million light years)
    (~ 2x - 4x better than ever before)
  - 25 Watts into the detector

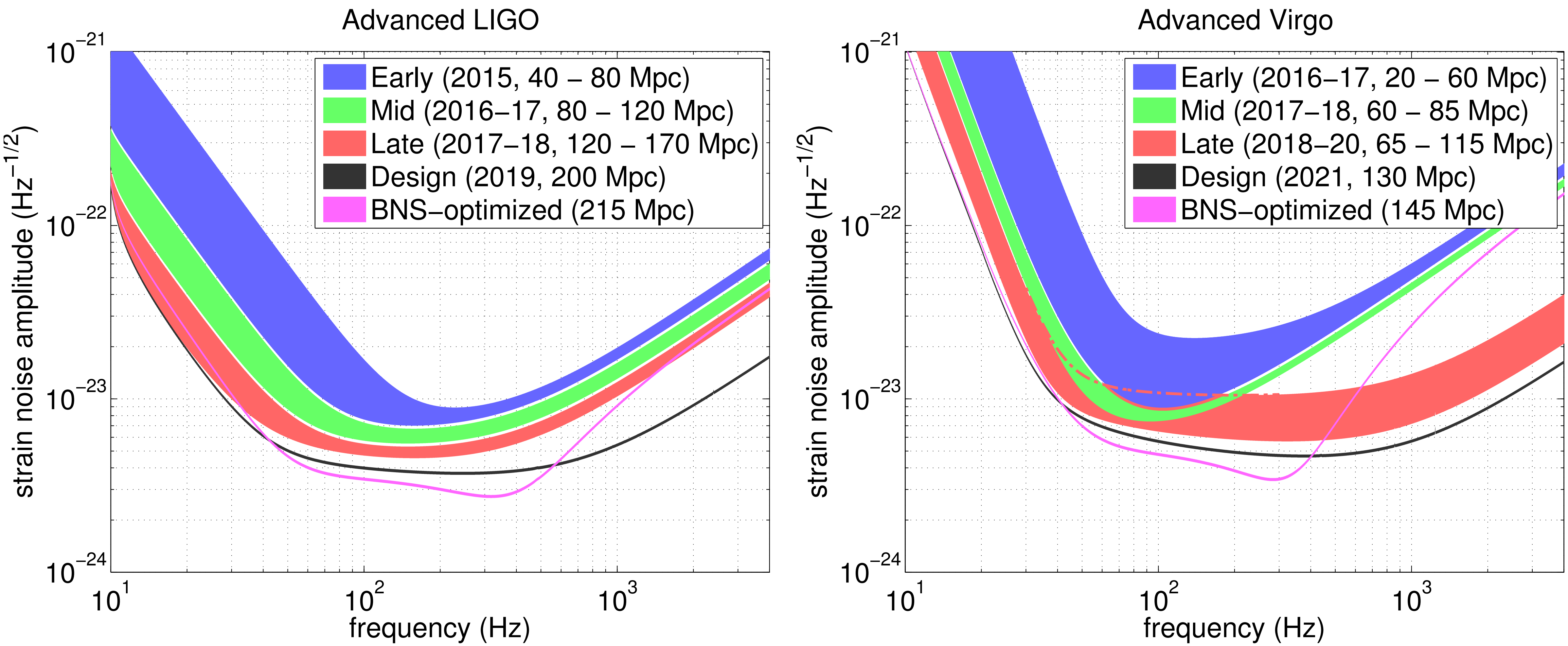
Latest



P. Fritshel, G1401078, JRPC G1301309

Working towards detection

- O1 in mid 2015, range of 40-80 MPc
  exp. detection of NS/ NS binary = 0.0004 - 3 events
- by 2019, predicted rate is 0.4 - 400 / year



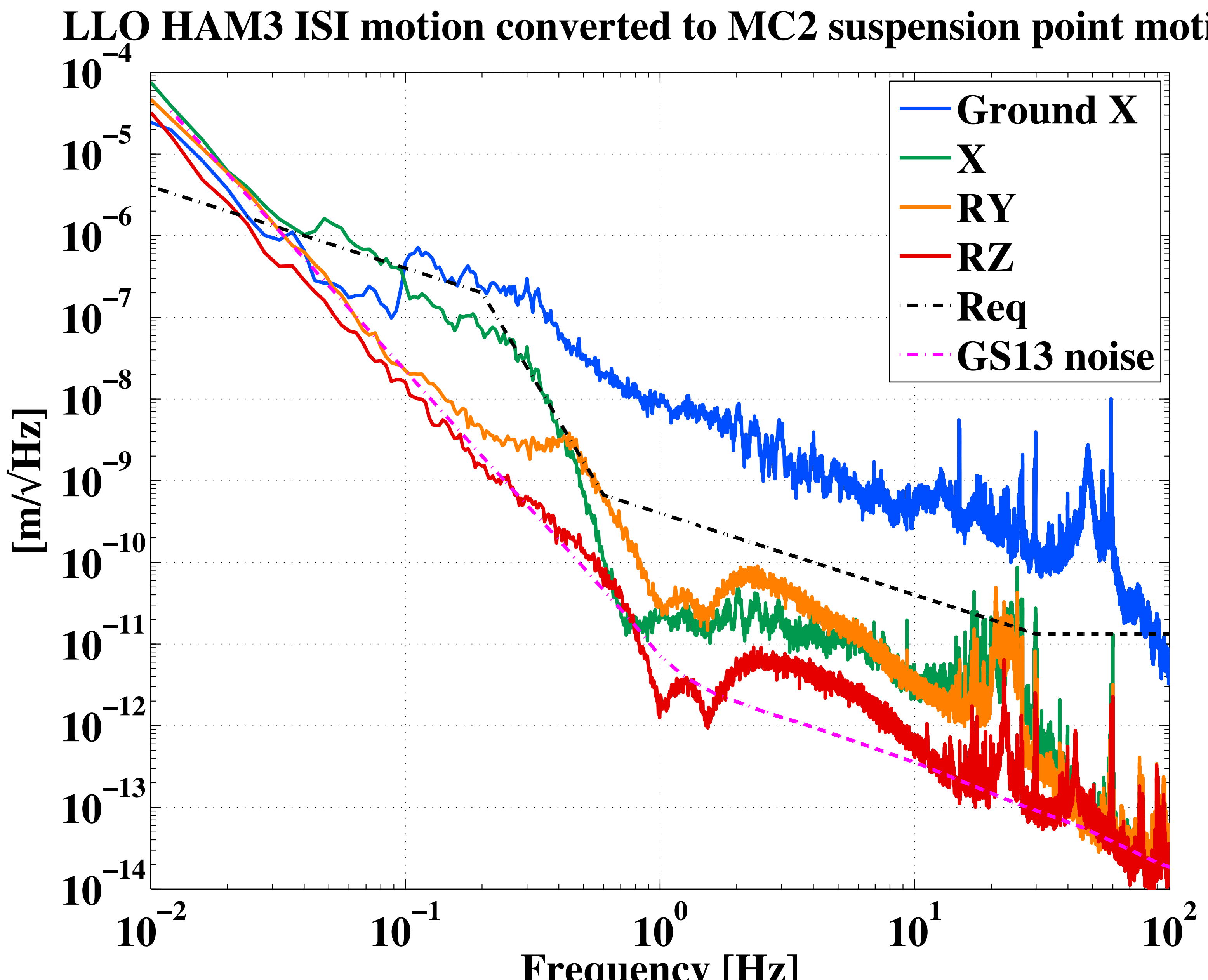
Aasi et. al., Accadia et. al. P1200087

It is an exciting time to be building interferometers, & soon we will be doing astronomy

Extra slides

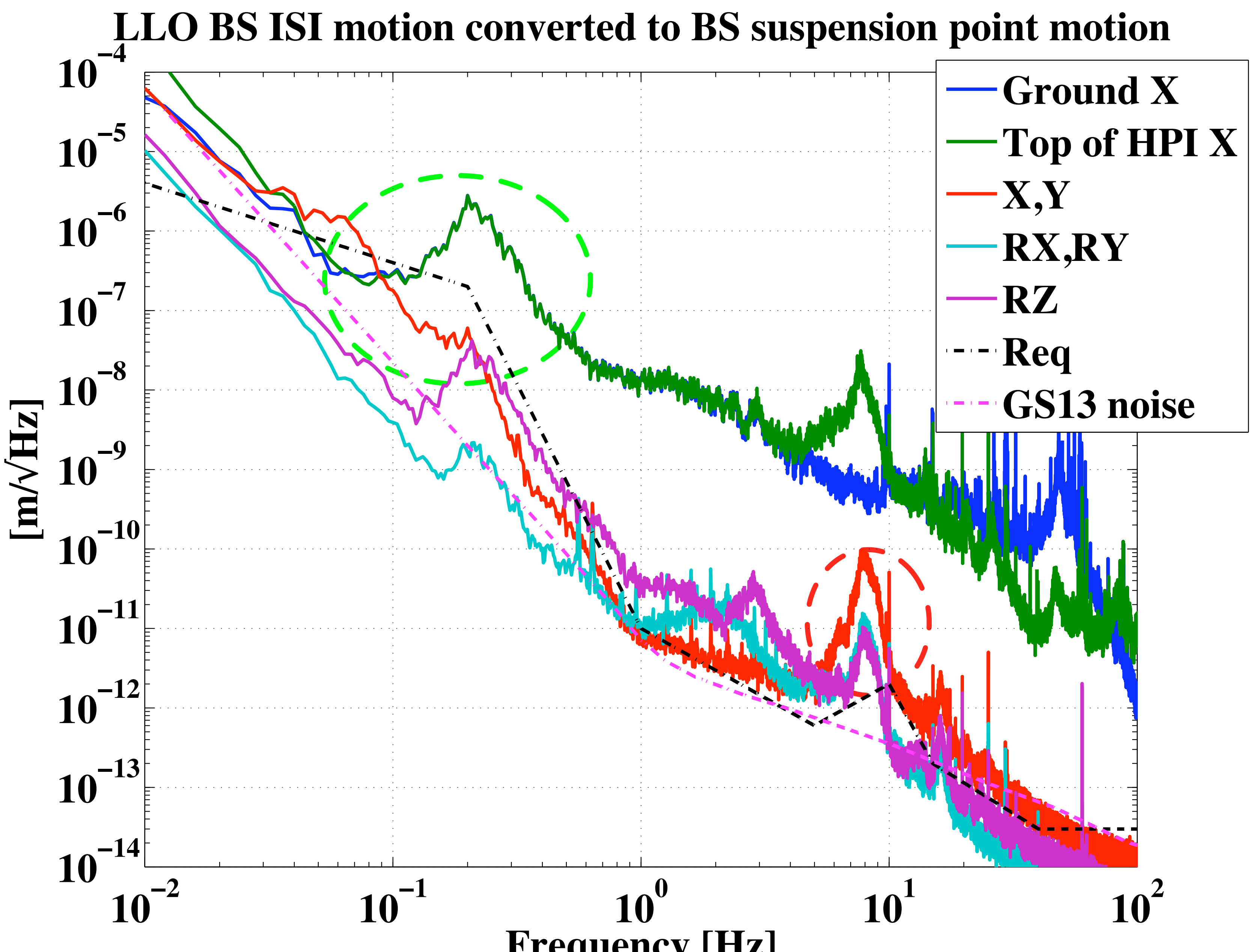
HAM-ISI motion

- At both sites HAM performance is at or better than the requirement
- All DOFs can be important, direct tilt coupling is limiting between 0.5 and 5 Hz



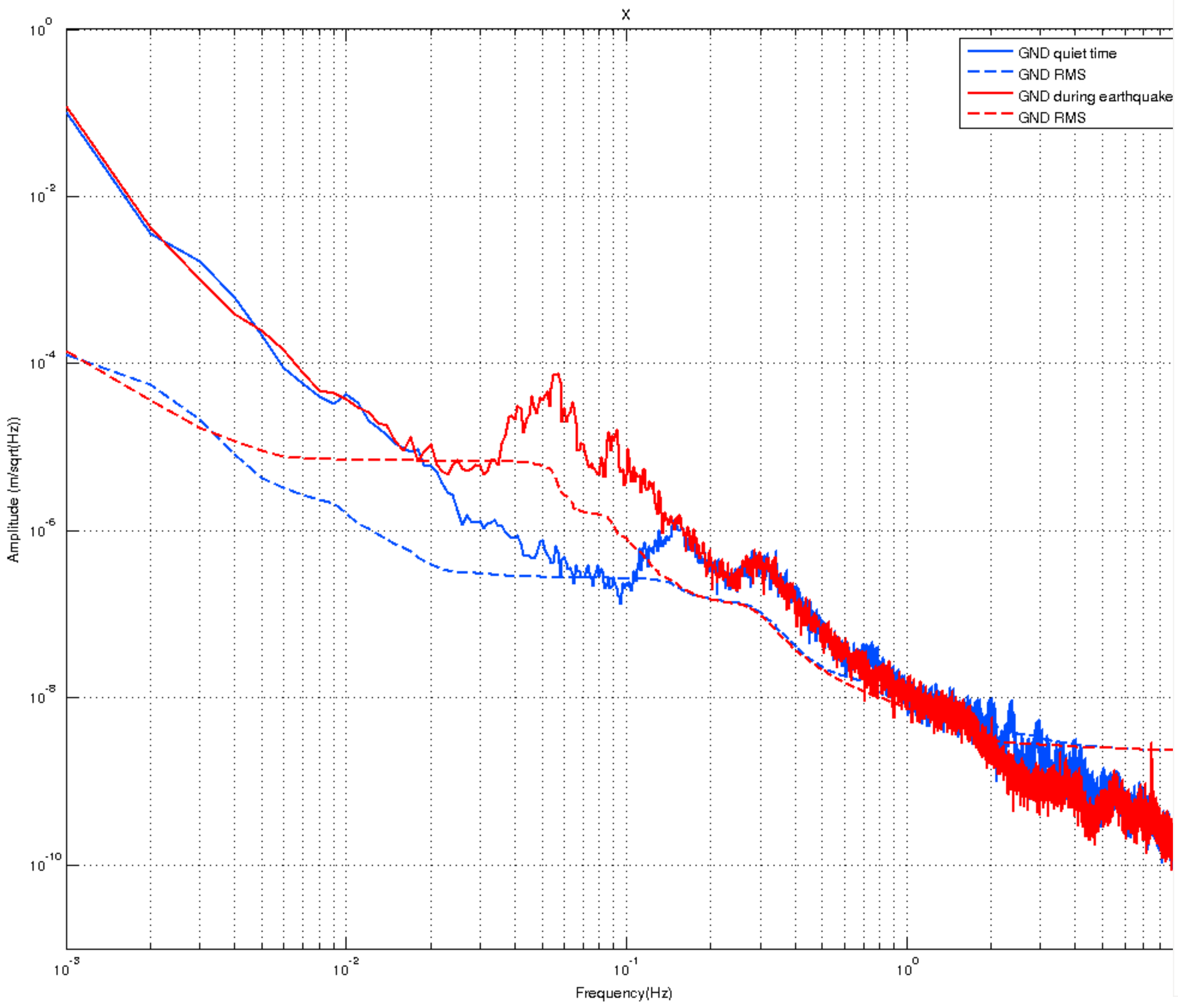
BSC-good low freq

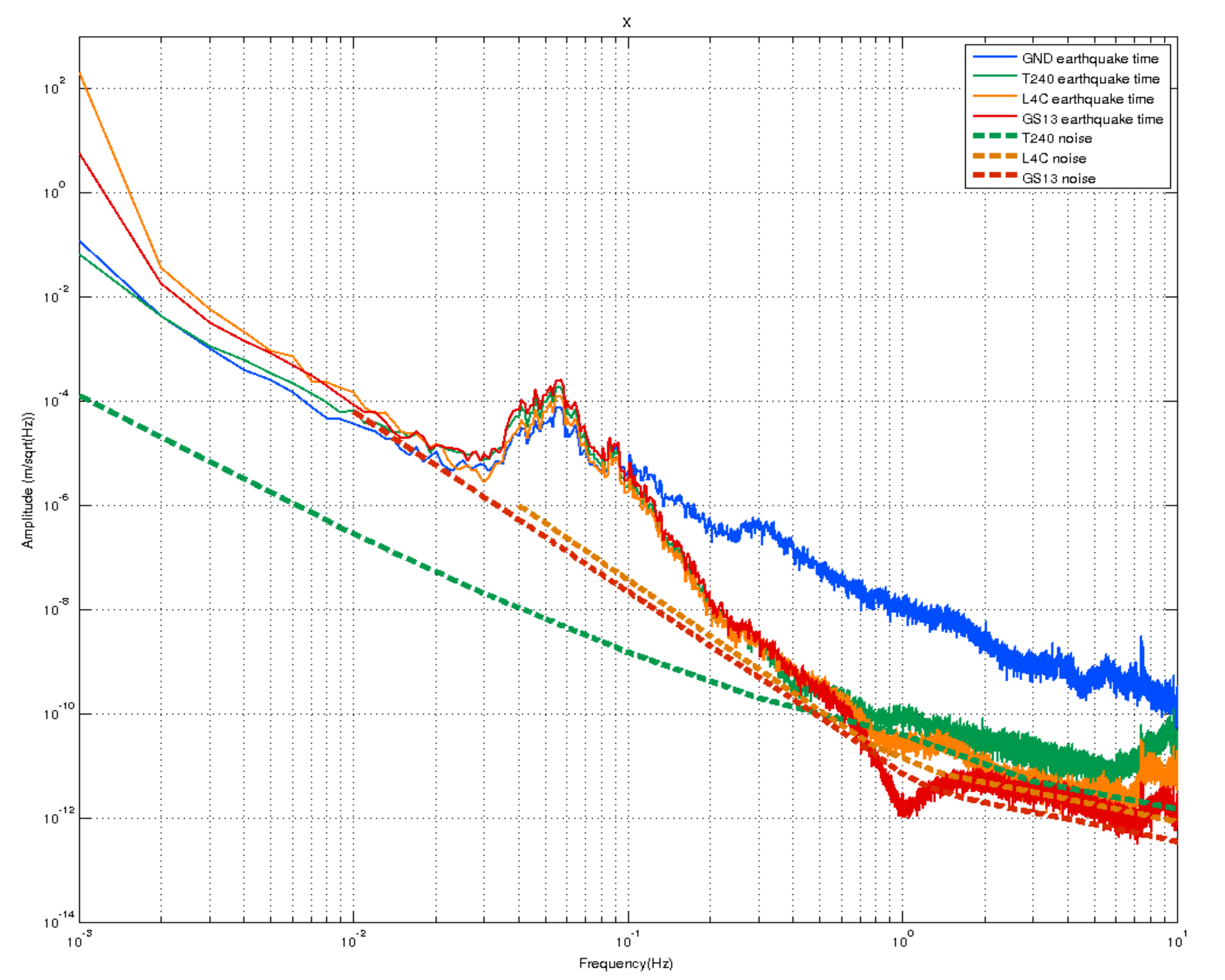
- At LLO we tried using feedback for the microseism isolation, instead of sensor correction
- Careful tilt decoupling helped significantly, as did high gain HEPI position control



Earthquake in Tonga

- 6.4 magnitude earthquake in Tonga felt at LLO
- Amplification of the ground motion by a factor of ~100 between 20mHz and 150mHz
- Amplification stays the same during the entire event (~4hours)
- The earthquake didn't trip the ISI nor HEPI
- Configuration: HEPI not controlled, ISI-Stage1 controlled, ISI-Stage2 damping only
- The earthquake didn't generate non-linearities (ISI is linear)

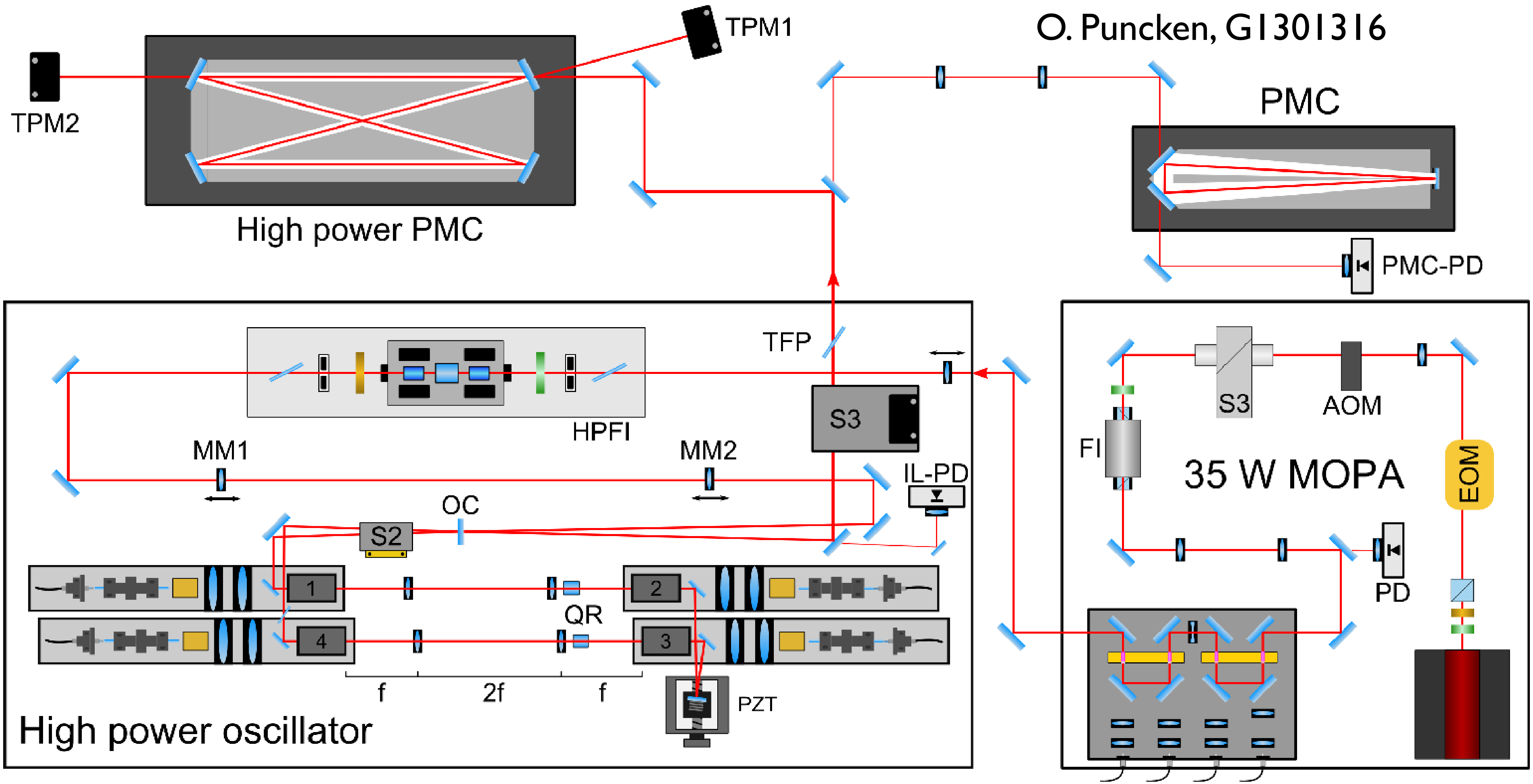




PSL design requirements (T050036)

- Fundamental Mode Power > 165 W
- Single TEM_{00} mode at IO interface
- Higher-order Mode Power < 5 W
- Horizontal polarization to within 1%
- Frequency Stability 10 Hz / $Hz^{1/2}$ at 10 Hz in the PSL
  10^{-7} Hz / $Hz^{1/2}$ at 10 Hz at the IFO
- Amplitude Stability $2x10^{-9}$ / $Hz^{1/2}$ at 10 Hz
- Low pointing noise

aLIGO Laser (by L.Z.H.)



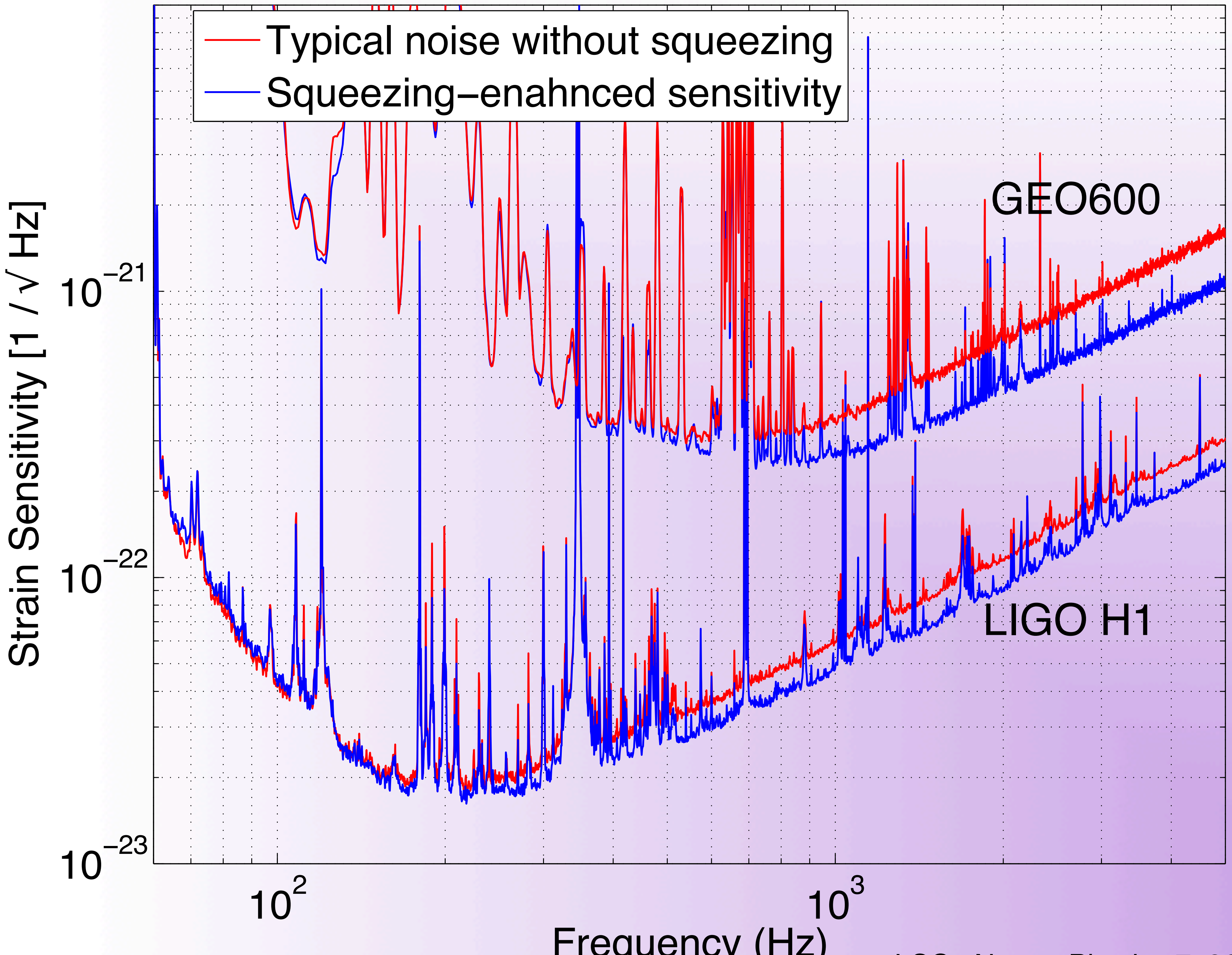
Commercial NPRO, 2 W, Nd:YAG crystal pumped by laser diodes at 808 nm

Medium power amp, 35 W, 4 Nd:YVO_4 crystals pumped fiber-coupled LD at 808 nm

Ring oscillator, 220 W, 4 Nd:YAG crystals each pumped by 7 LD at 808 nm

L. Barsotti, G1140192

Squeezing in GEO600 and LIGO H1 to reduce shot noise



3.5 dB (1/1.5)

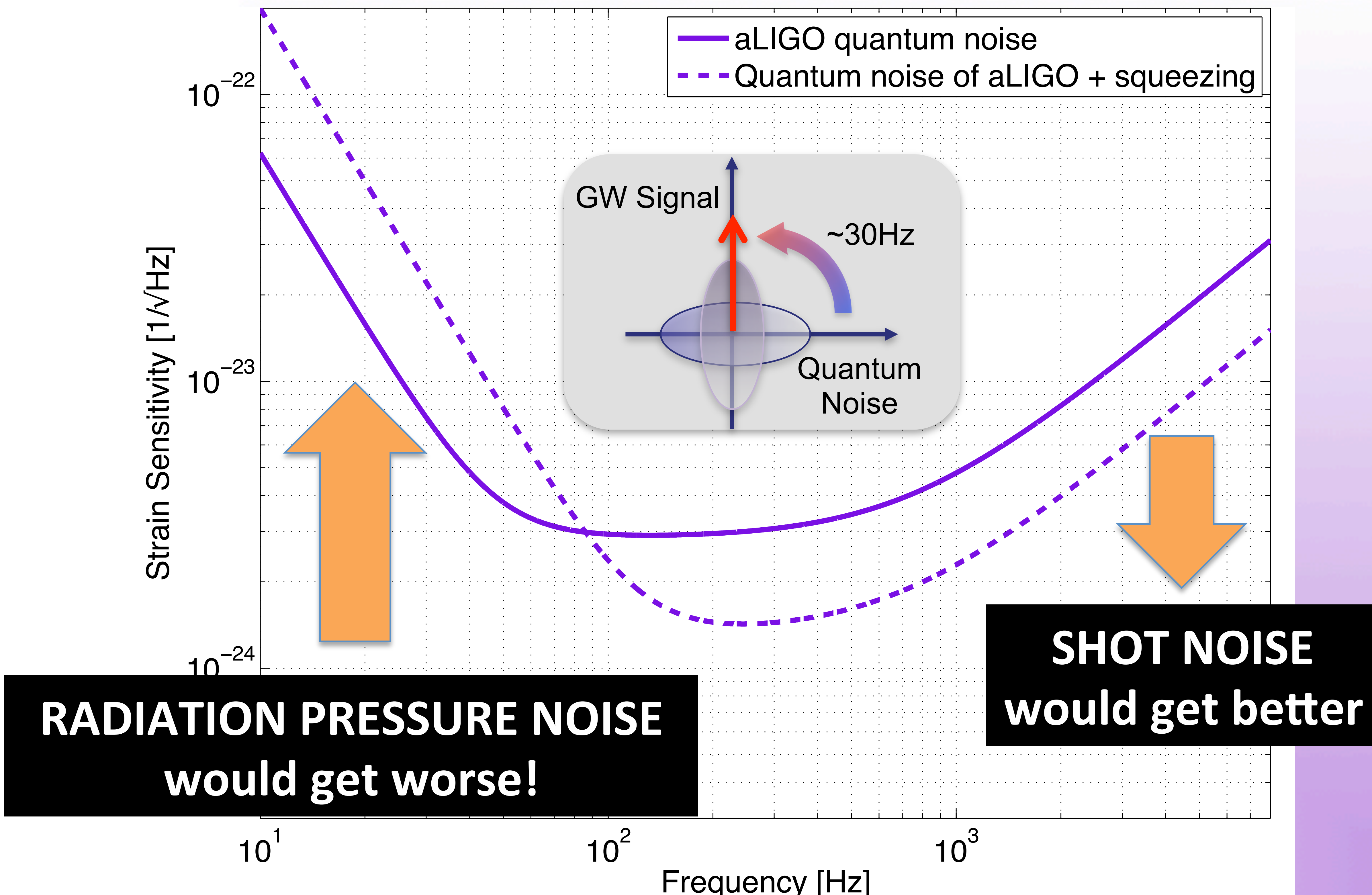
2.1 dB (1/1.27)

LSC, Nature Physics 7, 962 (2011)
LSC, Nature Photonics 7, 613–619 (2013)

GEO data are courtesy of H. Grote

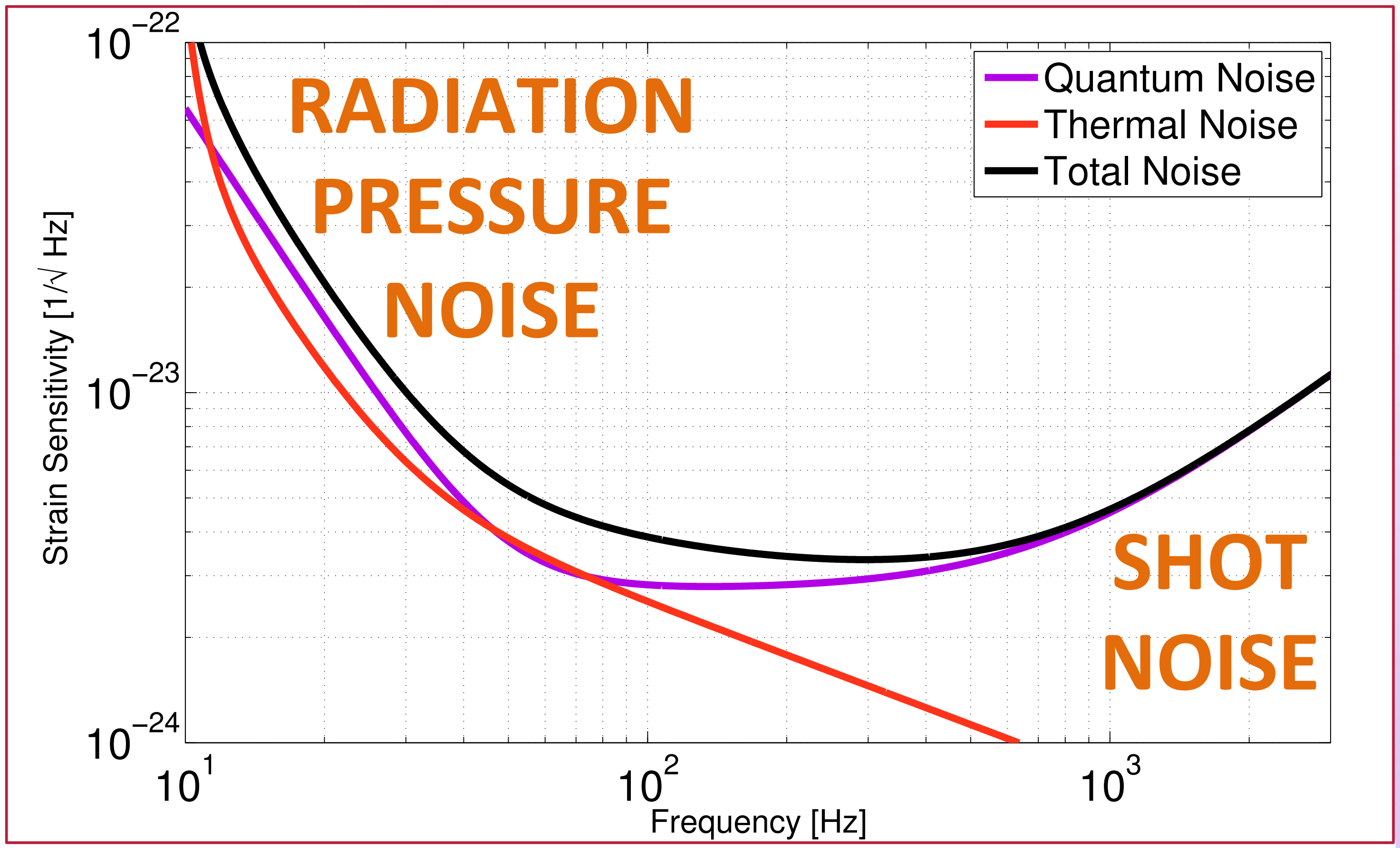
L. Barsotti, G140192

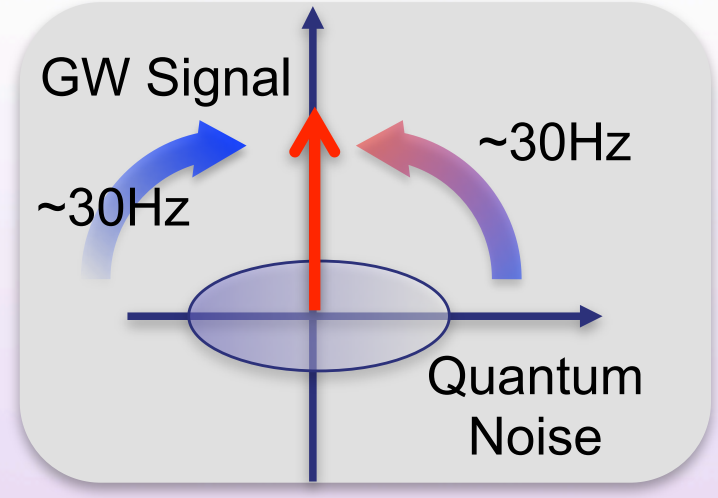
...not the end of the story: aLIGO will be limited by radiation pressure noise!

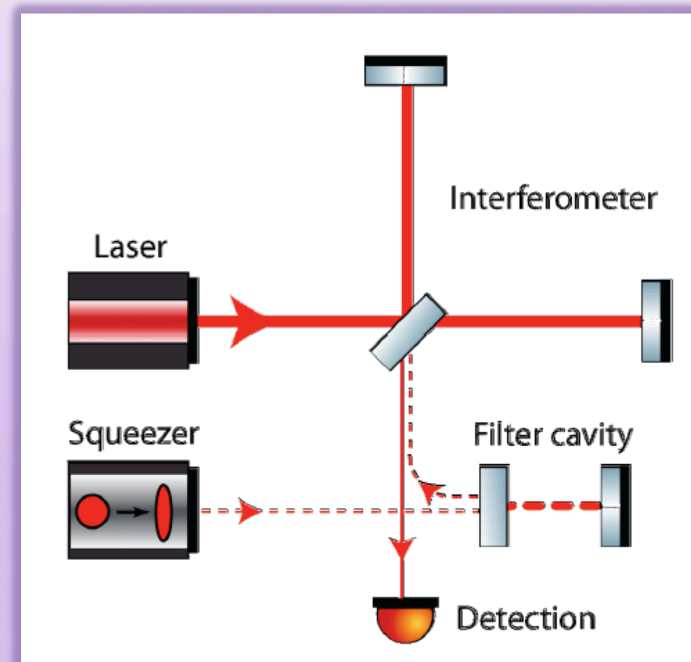


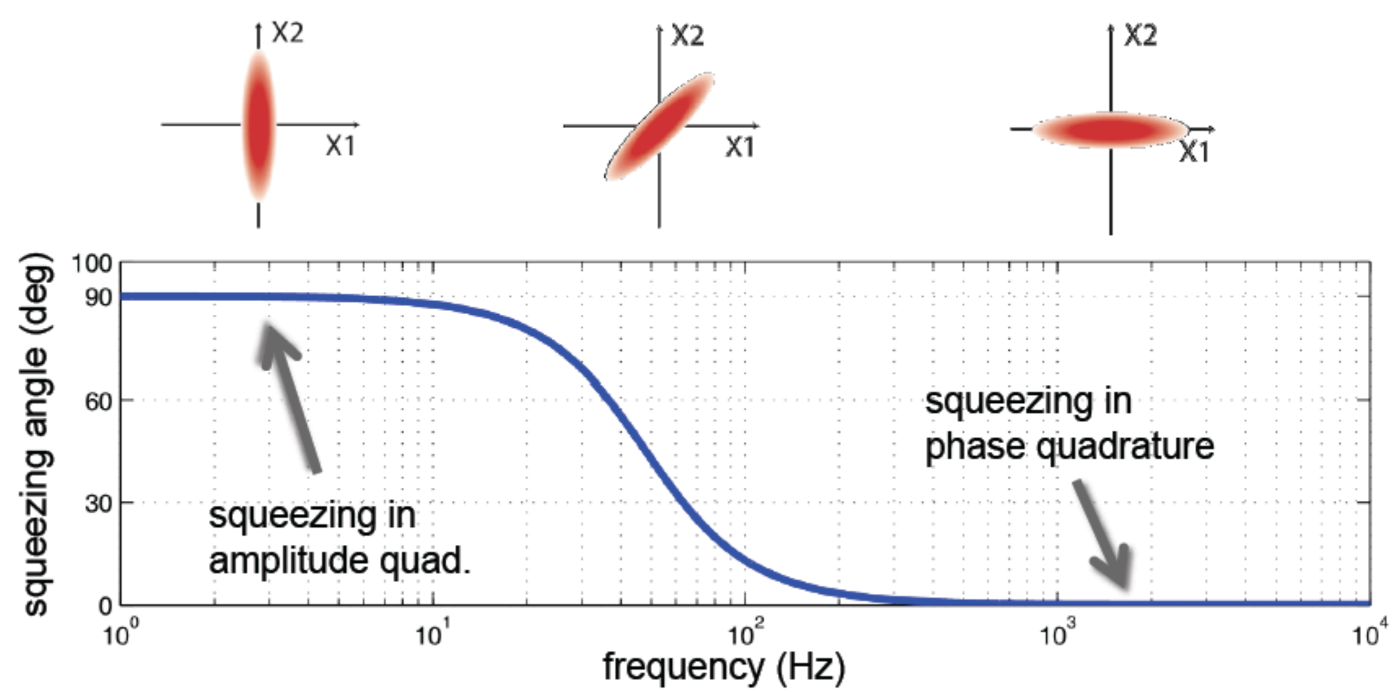
L. Barsotti, G140192

Frequency Dependent Squeezing (aka filter cavity)





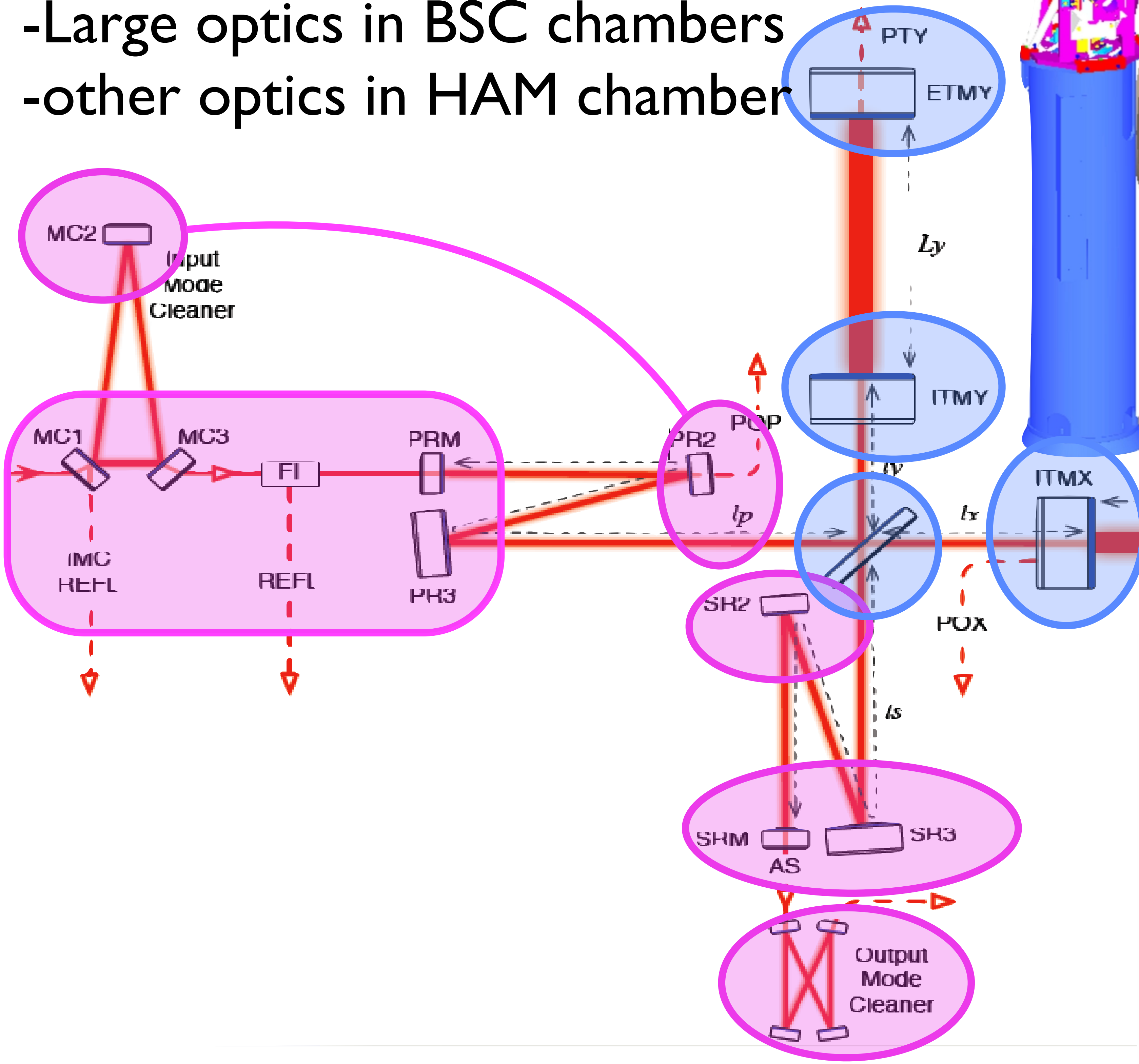


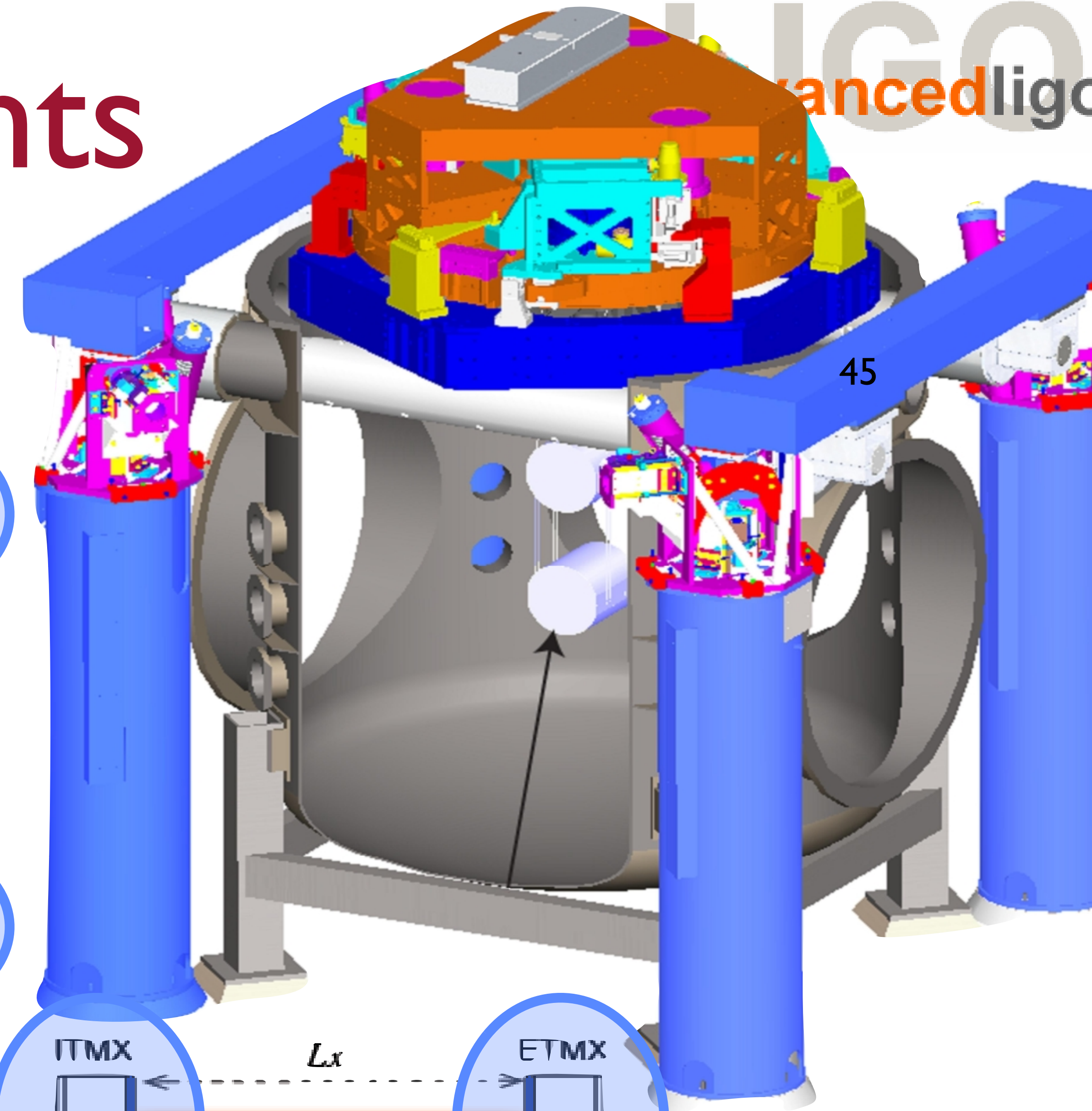


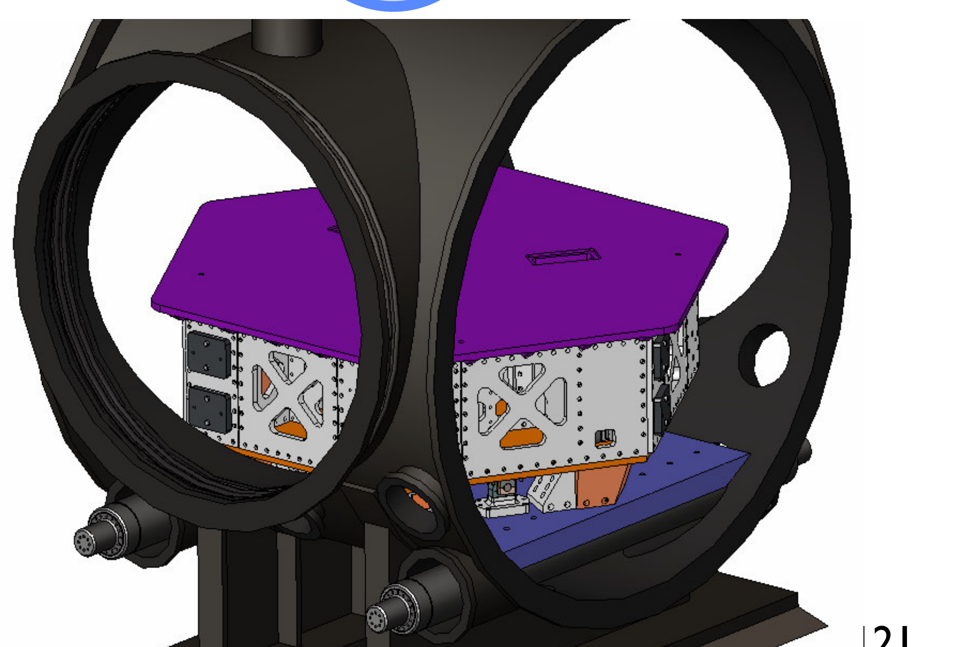
High finesse detuned **“filter cavity”** which rotates the squeezing angle as function of frequency

Requirements

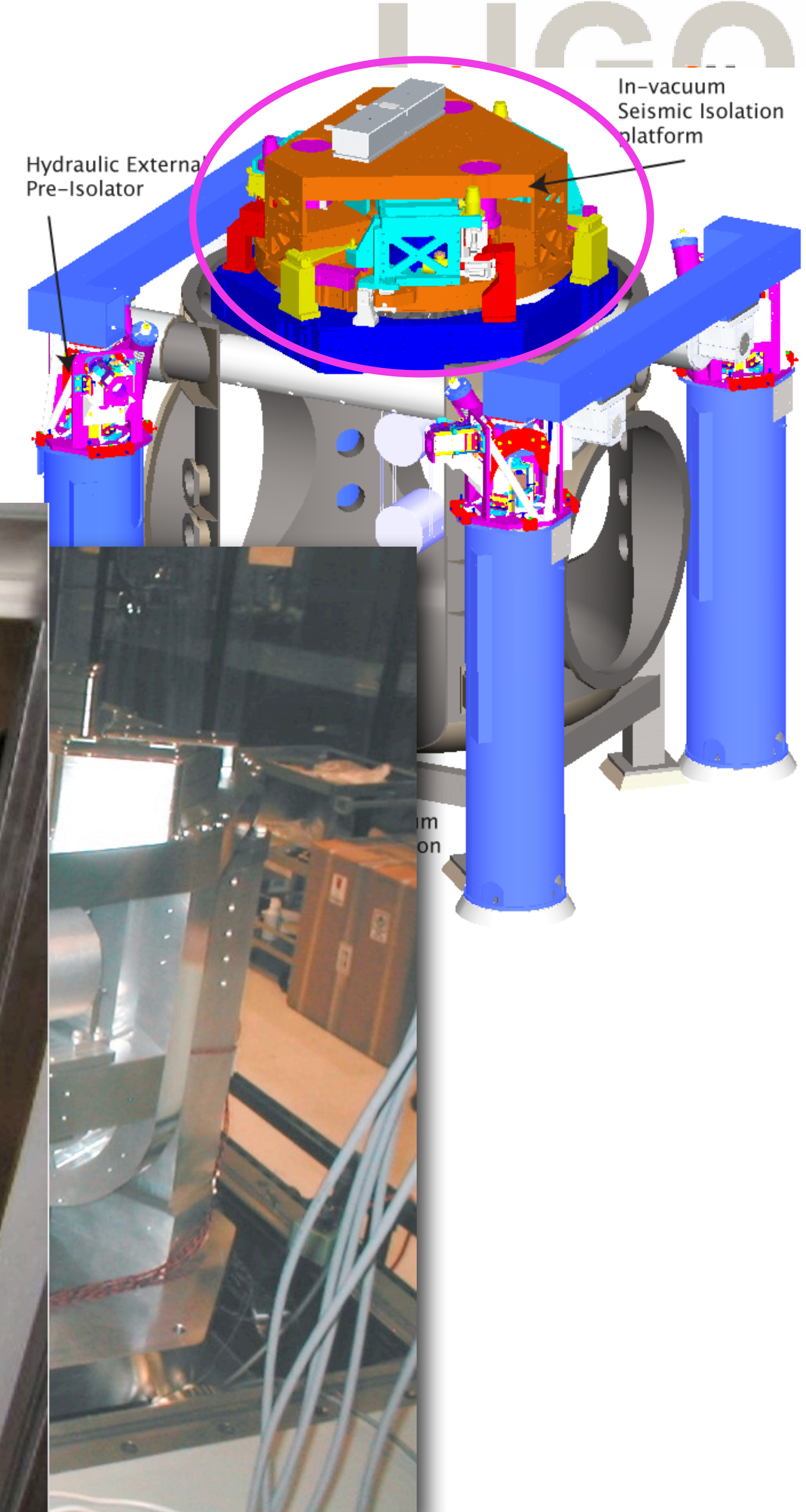
Support all the in-vacuum IFO optics
- -Large optics in BSC chambers
- -other optics in HAM chamber



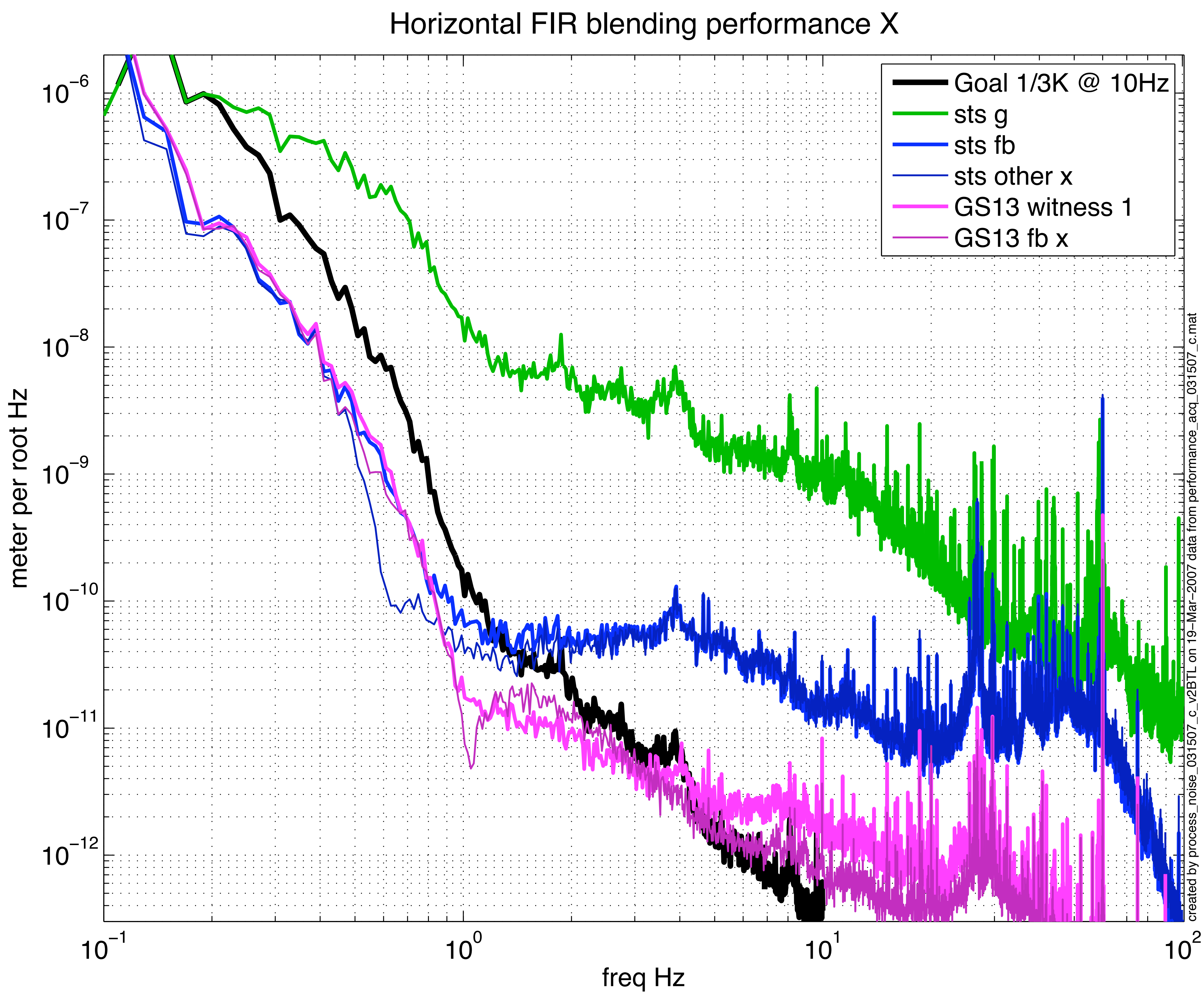




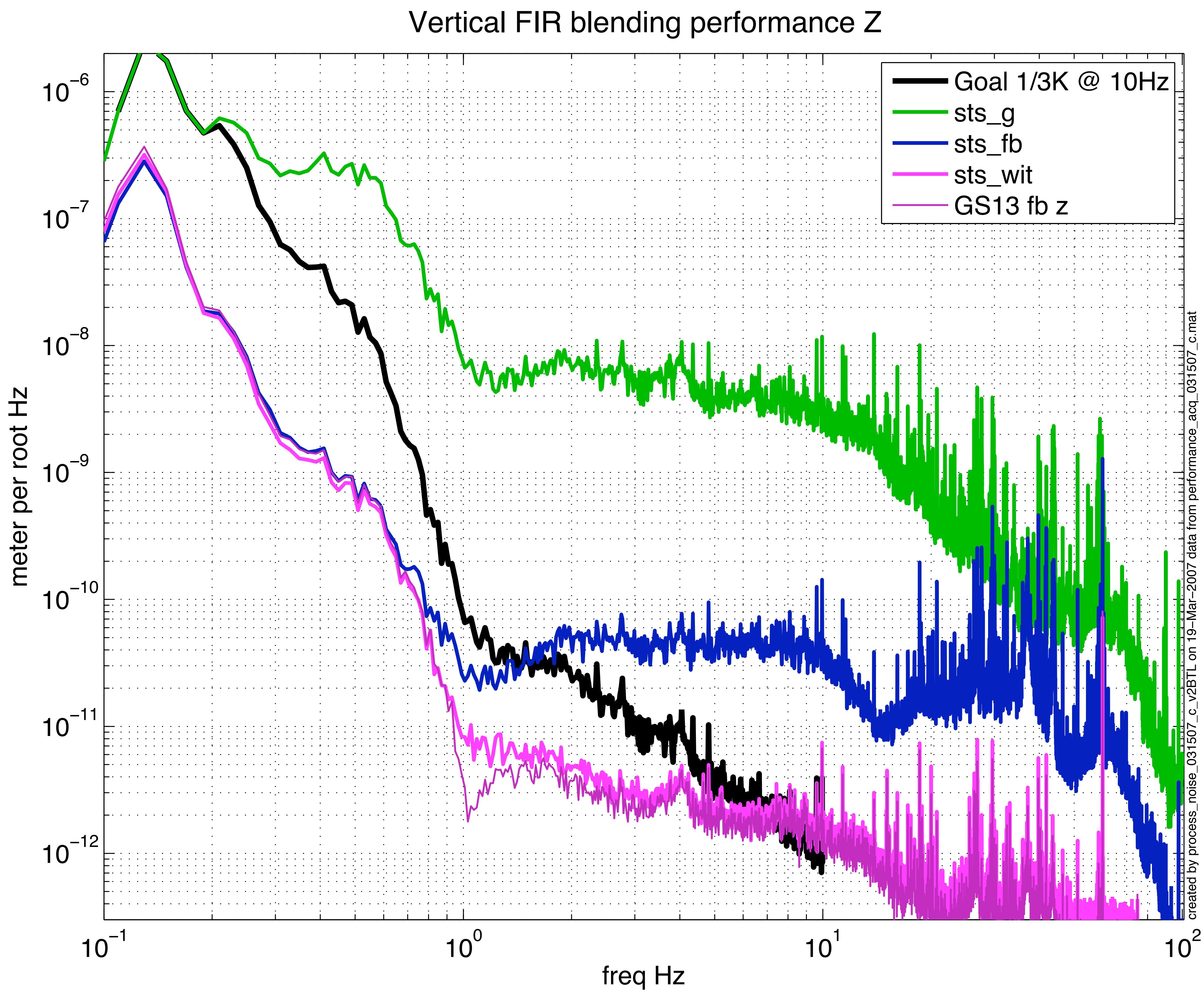
Prototype at Stanford



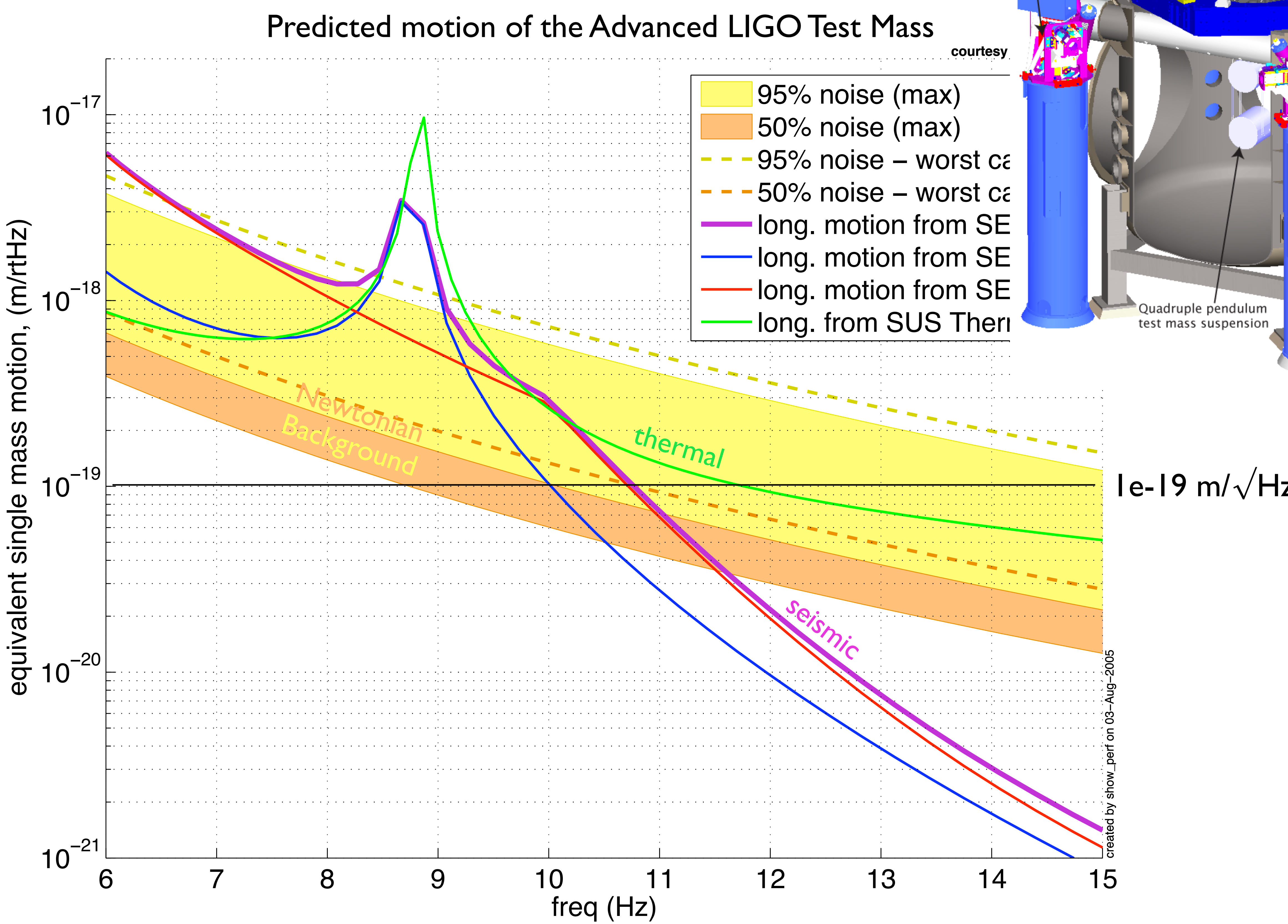
Performance X

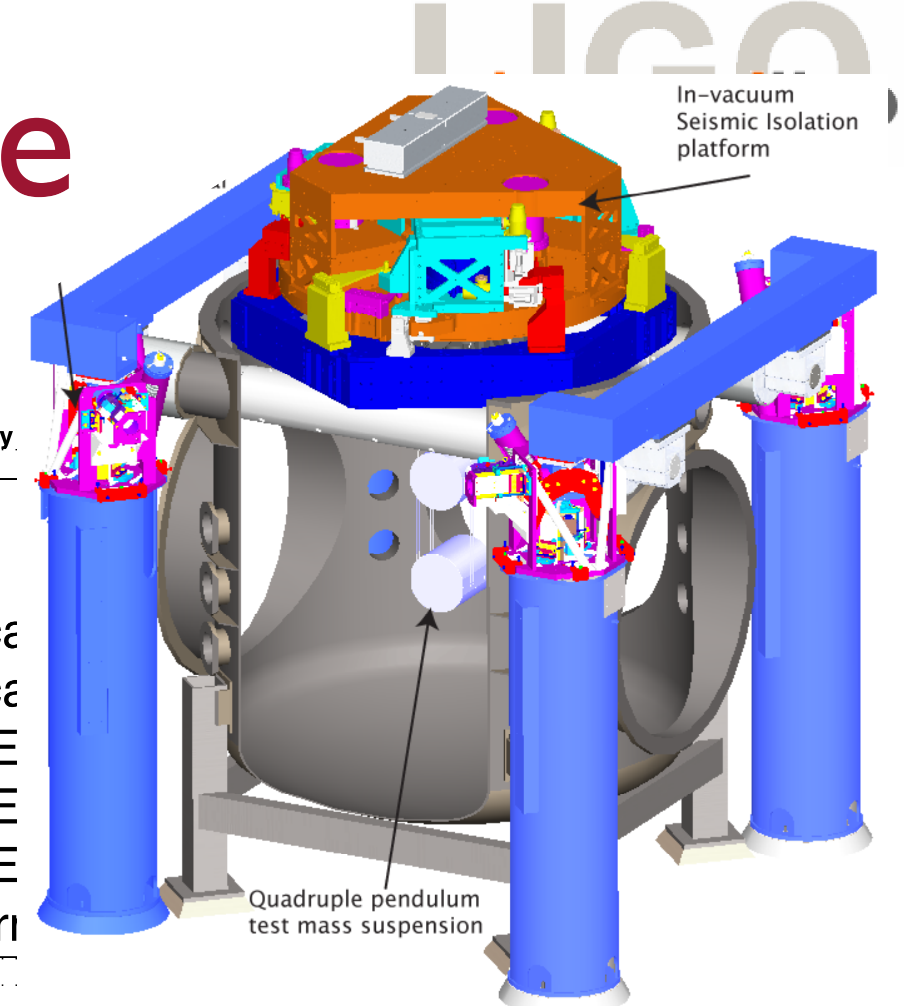


Performance Z



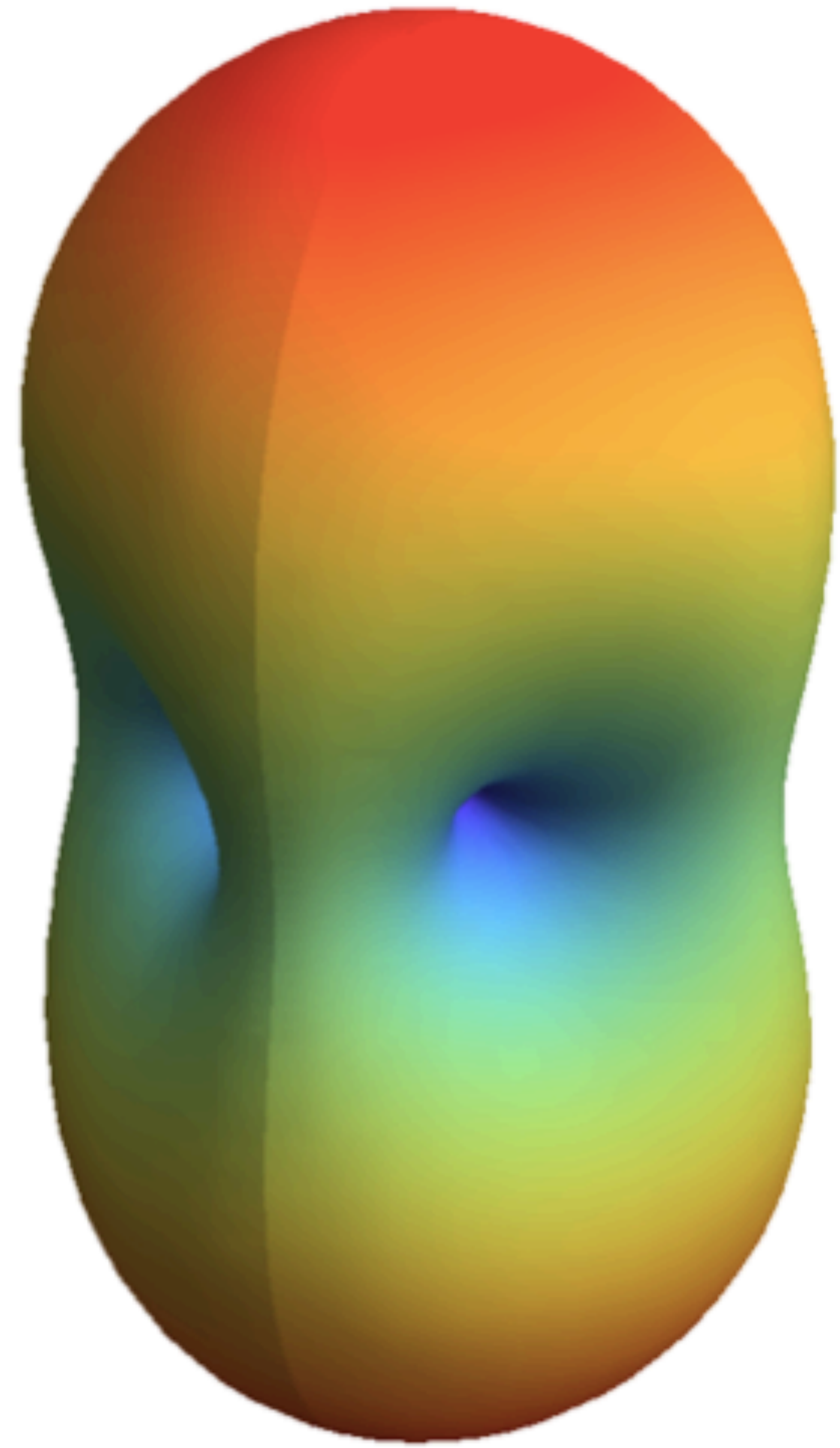
Final Performance





Interferometer's Antenna Pattern
LIGO is not an Imaging Detector

- Antenna pattern for aLIGO, for an optimally polarized wave.
- LIGO is more like a microphone than a telescope.
- i.e. We measure the amplitude of a wave coming from pretty much any direction.
- Good for first detections, but not so good for finding the source.



From R. Adhikari, P1200121.