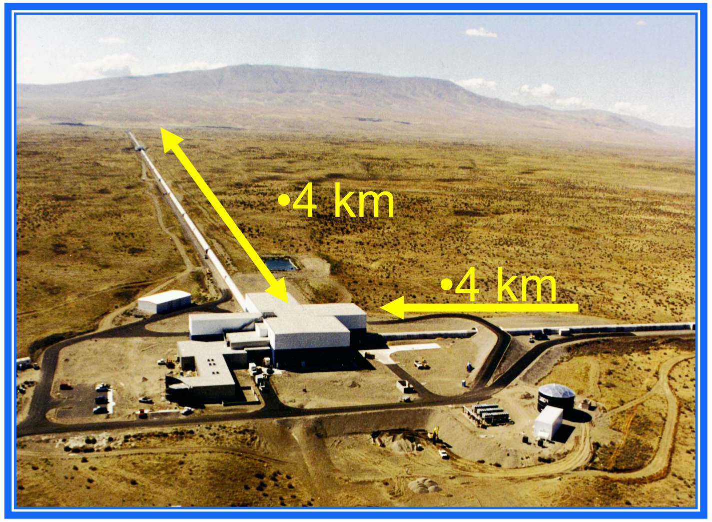
iLIGOからeLIGO、
そしてAdLIGOへ

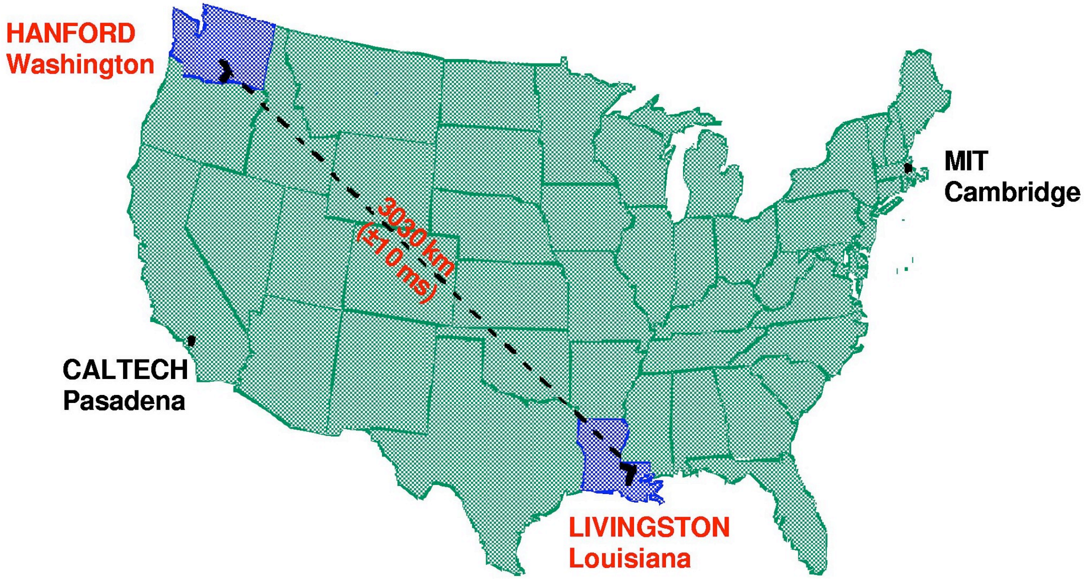
重力波研究交流会

2008/12/12(金)

東京大学宇宙線研究所: 宮川　治

二ヶ所、計三台のLIGO

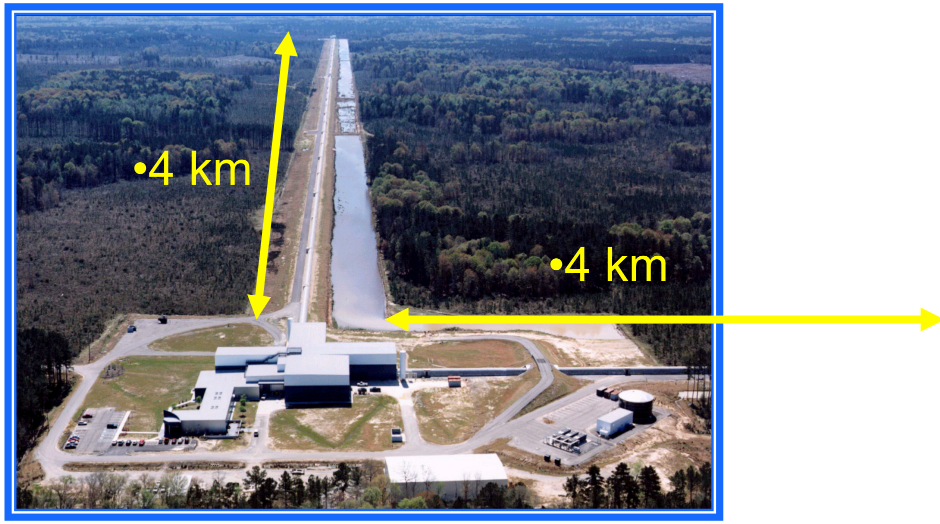




•ワシントン州、Hanford (LHO)
• 砂漠の中
• 一番近い町から約25 km
• 2km and 4kmの二台の干渉計

•ルイジアナ州、Livingston (LLO)
• 森の中
• 多くの湿地帯
• Baton Rougeから約50km
• 4km一台の干渉計

•複数台の同時観測による信頼度の向上



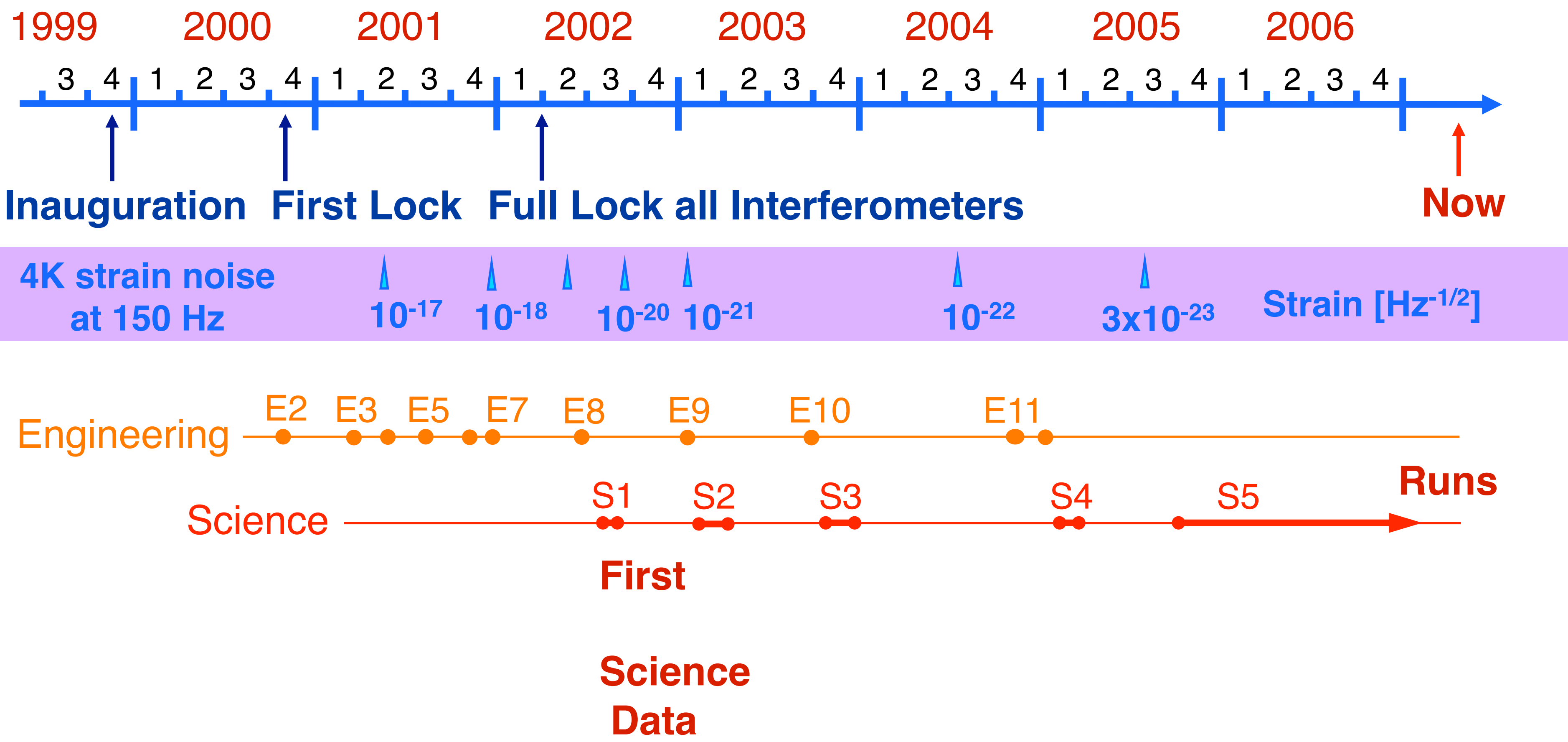
iLIGOからAdLIGO

- **iLIGO (initial LIGO):ほぼ目標感度を実現、S5で、1年分のデータ蓄積**

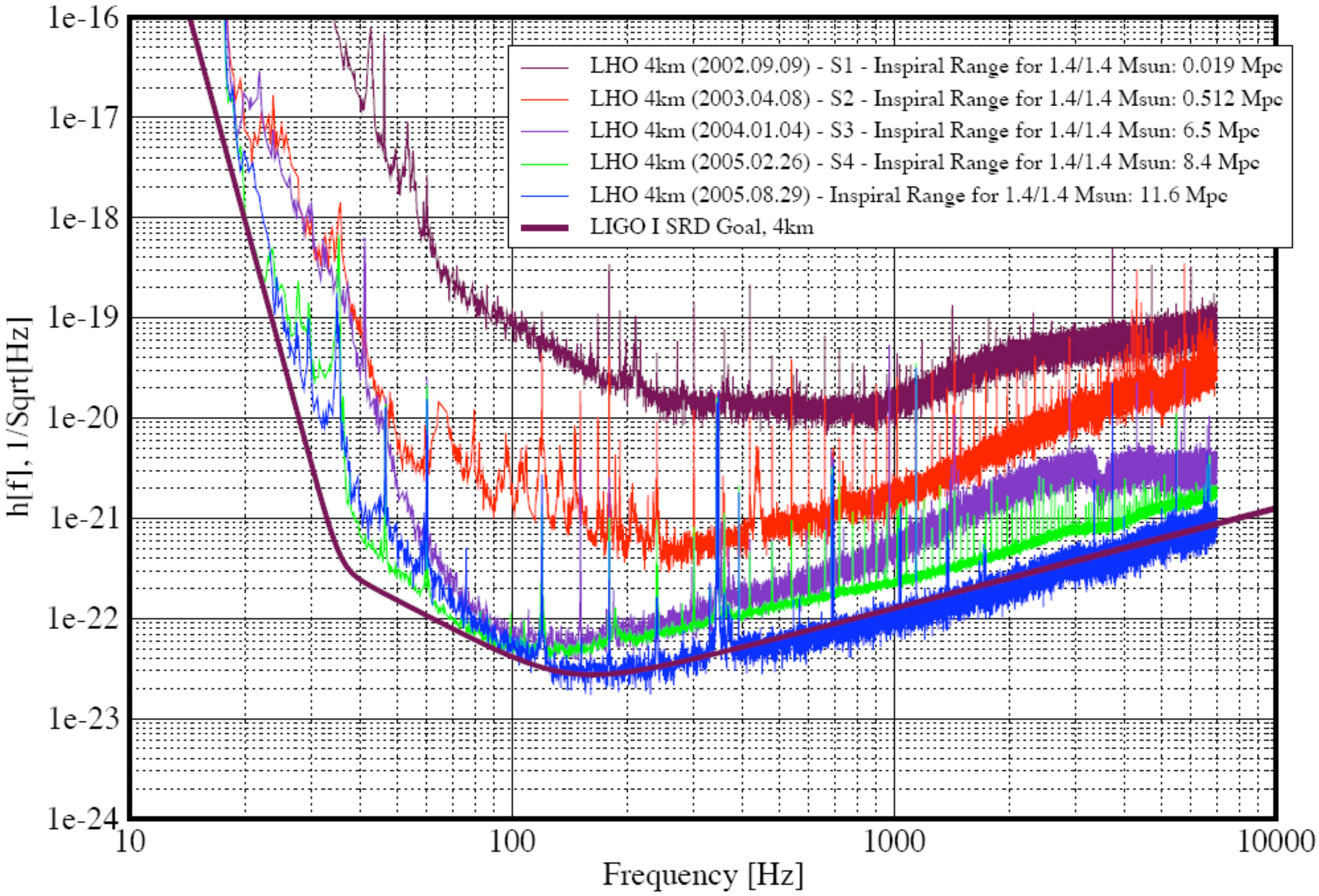
- **eLIGO (enhanced LIGO):35W laser、DC readoutの採用で、感度をiLIGOの約2倍(30Mpc)に更新**
  - AdLIGO用のいくつかの技術はiLIGO及び、eLIGOで実現済み
    - 35W laser
    - Multiple input EOM
    - HEPI(Hydraulic External Pre-Isolation)、PEPI(Piezo Electric Pre-Isolation)
    - ISI(active防振)
    - OutputMC
    - DC readout
    - new Digital system
  - 1年間の観測
  - 観測後最終段系ではSqueezingのインストール

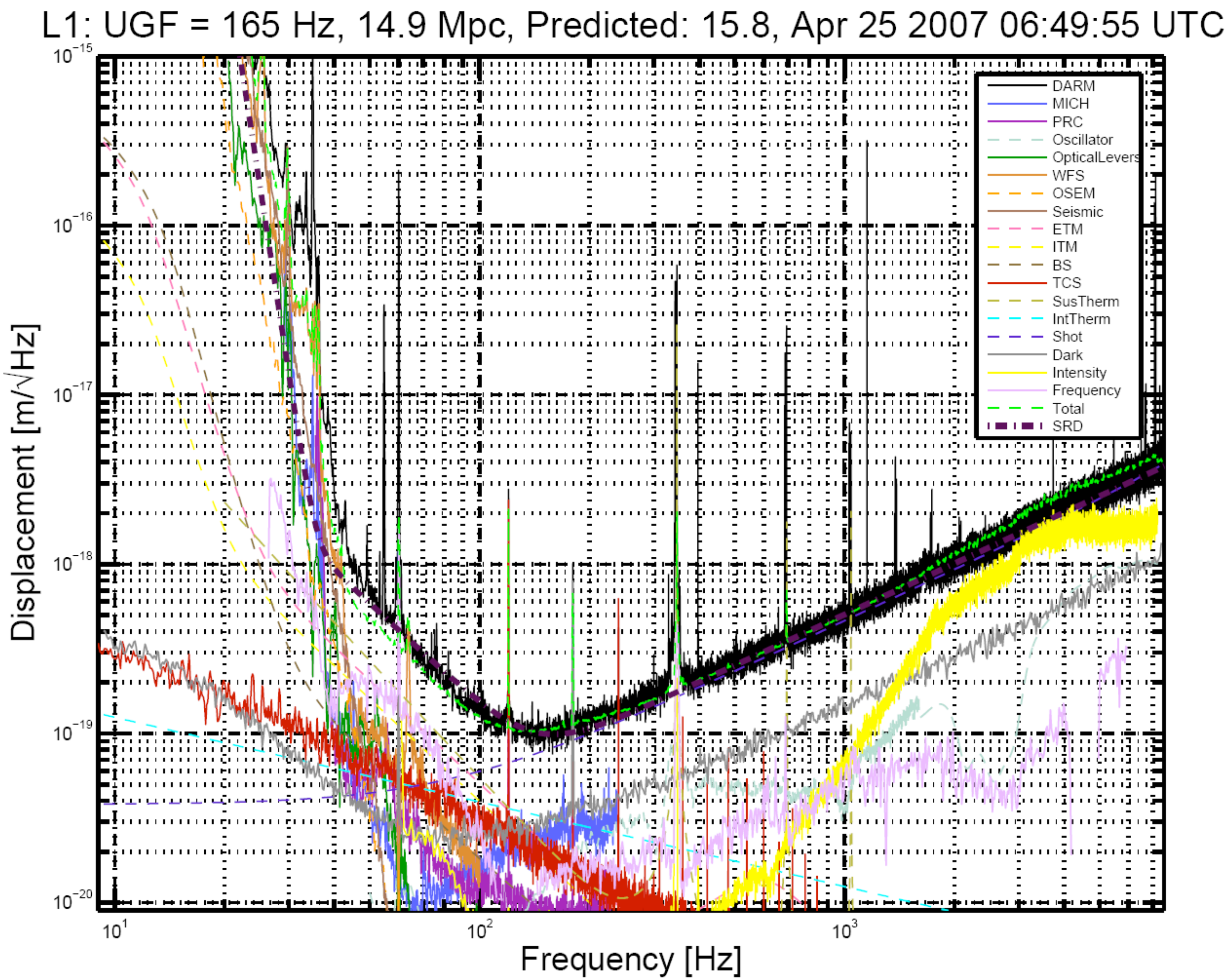
- **AdLIGO:iLIGOの10倍の感度**
  - 200Wレーザー
  - RSE
  - 4段振り子

LIGO History



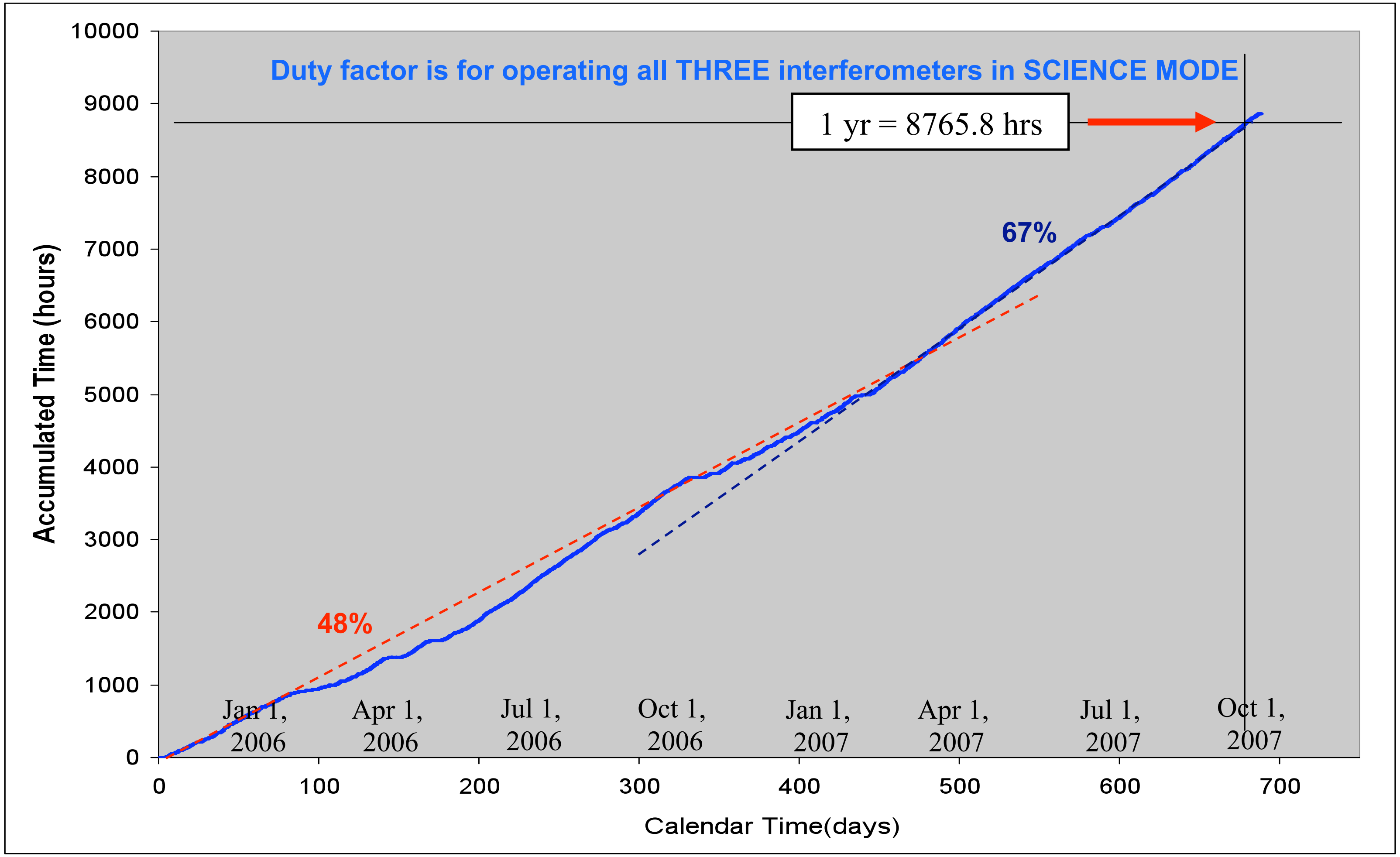
Progress of LIGO Sensitivity



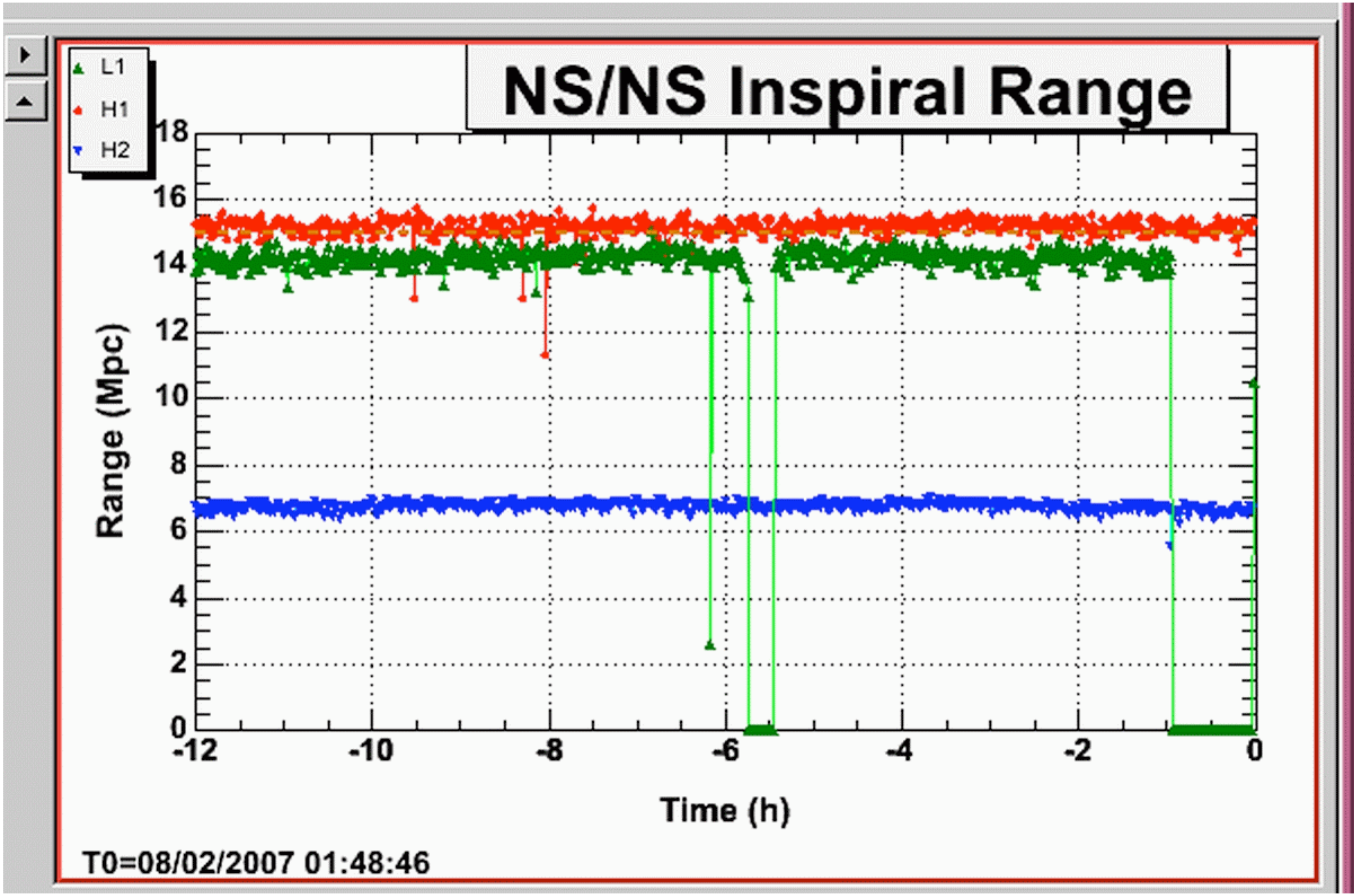


L1: UGF = 165 Hz, 14.9 Mpc, Predicted: 15.8, Apr 25 2007 06:49:55 UTC
Displacement [m/√Hz]
Frequency [Hz]
DARM
MICH
PRC
Oscillator
OpticalLevers
WFS
OSEM
Seismic
ETM
ITM
BS
TCS
SusTherm
IntTherm
Shot
Dark
Intensity
Frequency
Total
SRD

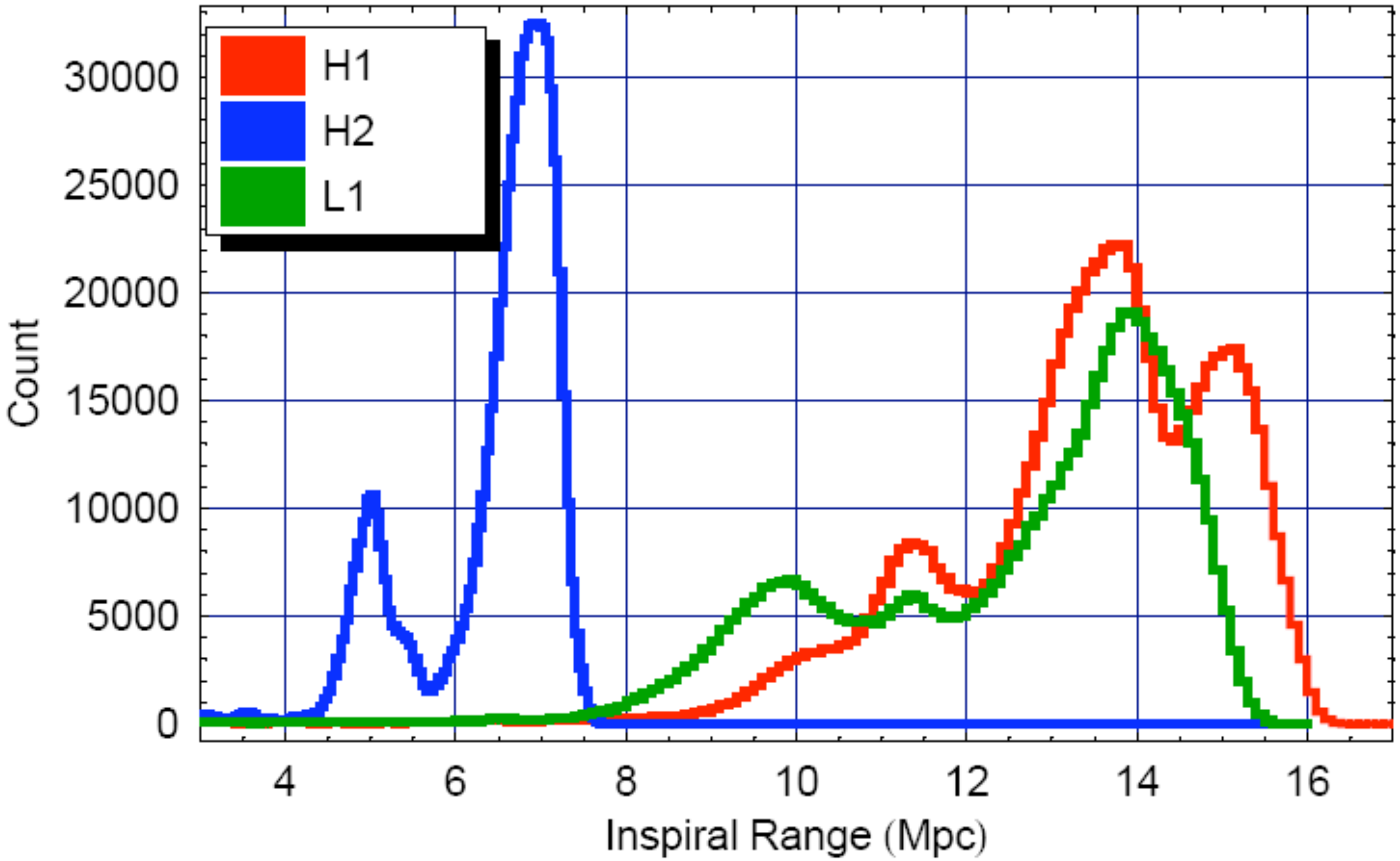
Triple-coincidence Science Mode Observation Time Accumulation vs. Calendar Time



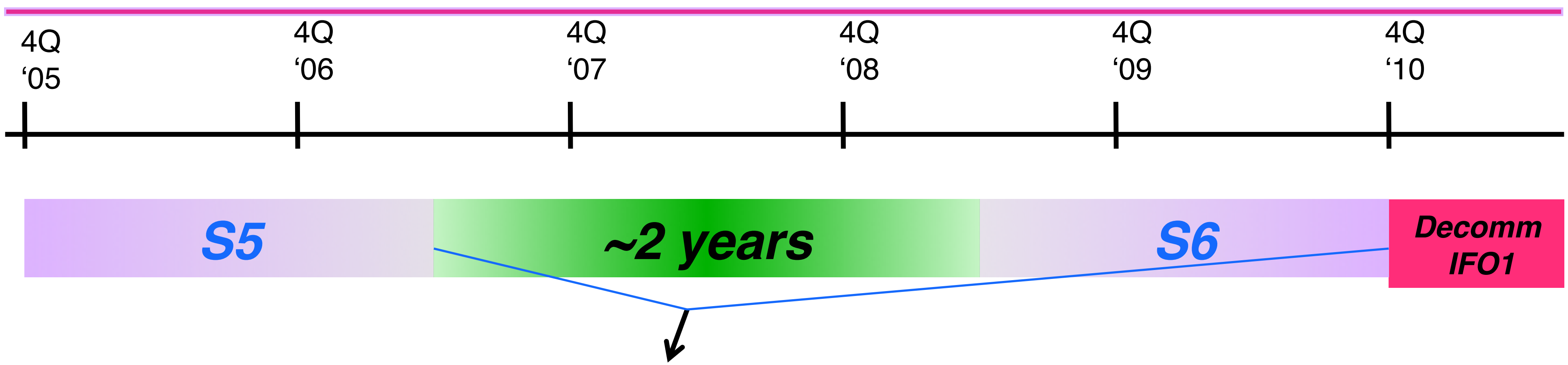
LIGO Duty Factor



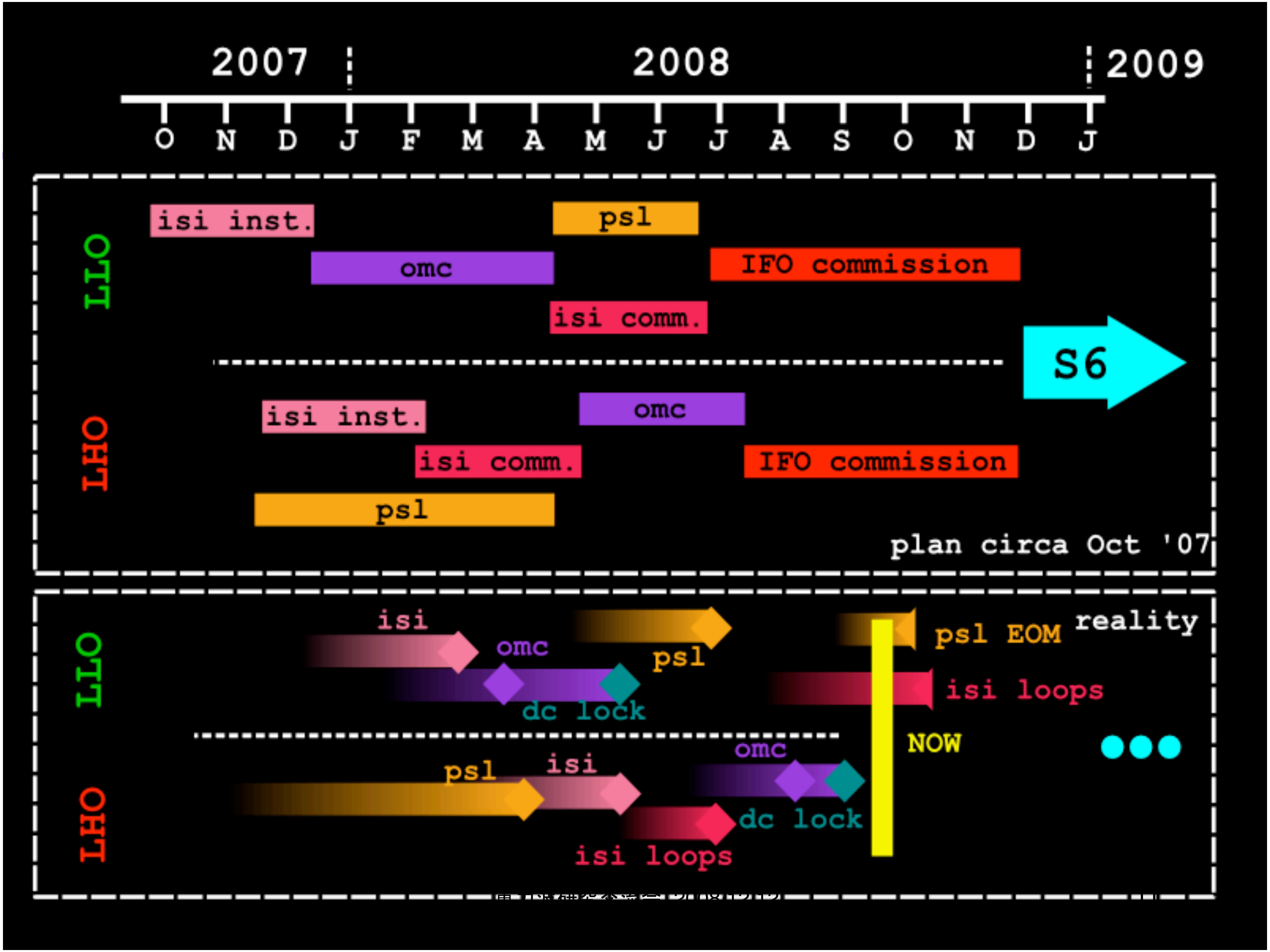
Duty Factor for S5



Enhanced LIGO

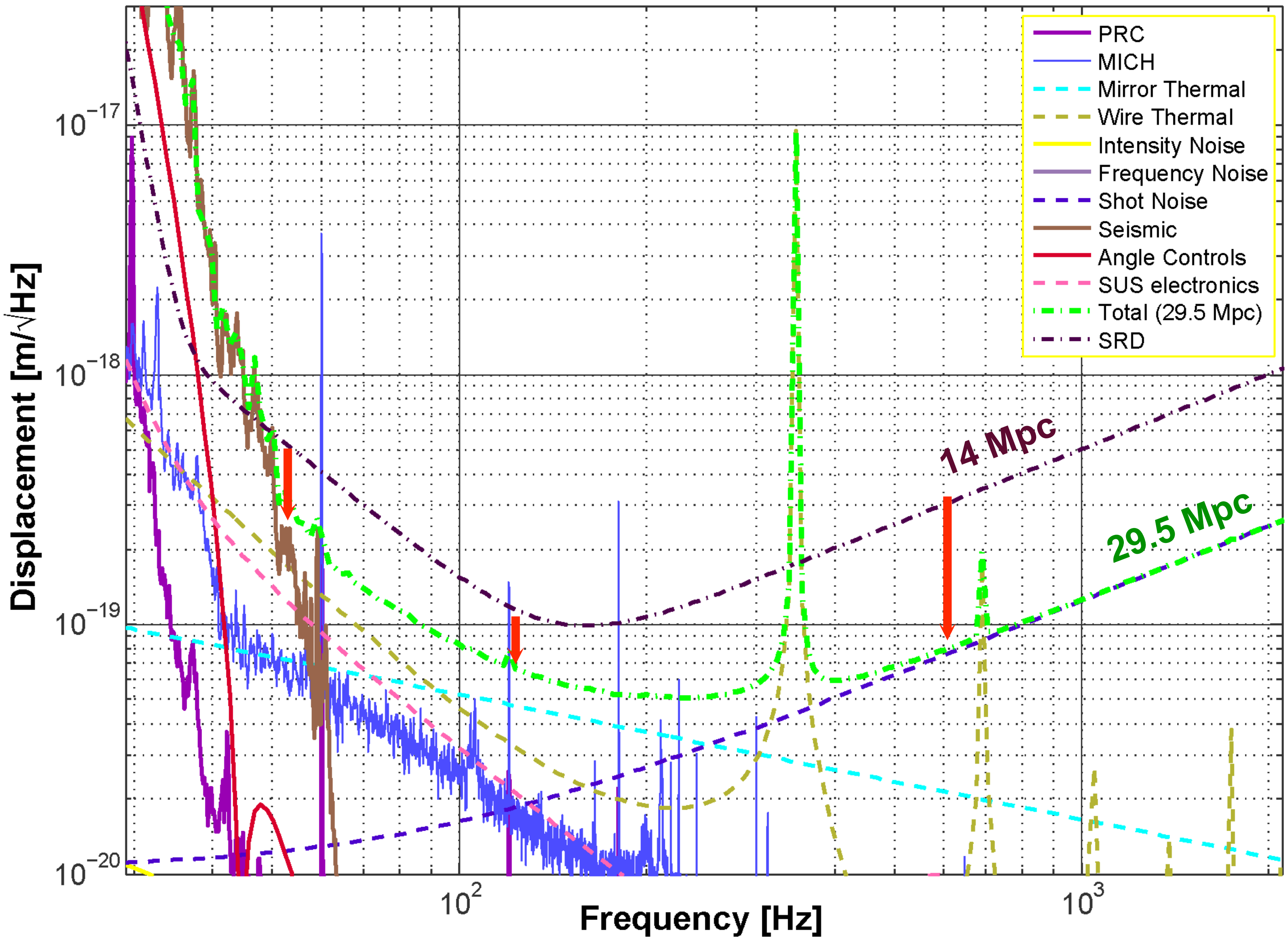


- Enough time for one significant set of enhancements
  - » Higher laser power
  - » DC readout
  - » Output modecleaner
- Aim for a factor of 2 improvement in sensitivity (factor of 8 in event rate)
- Early tests of Advanced LIGO hardware and techniques



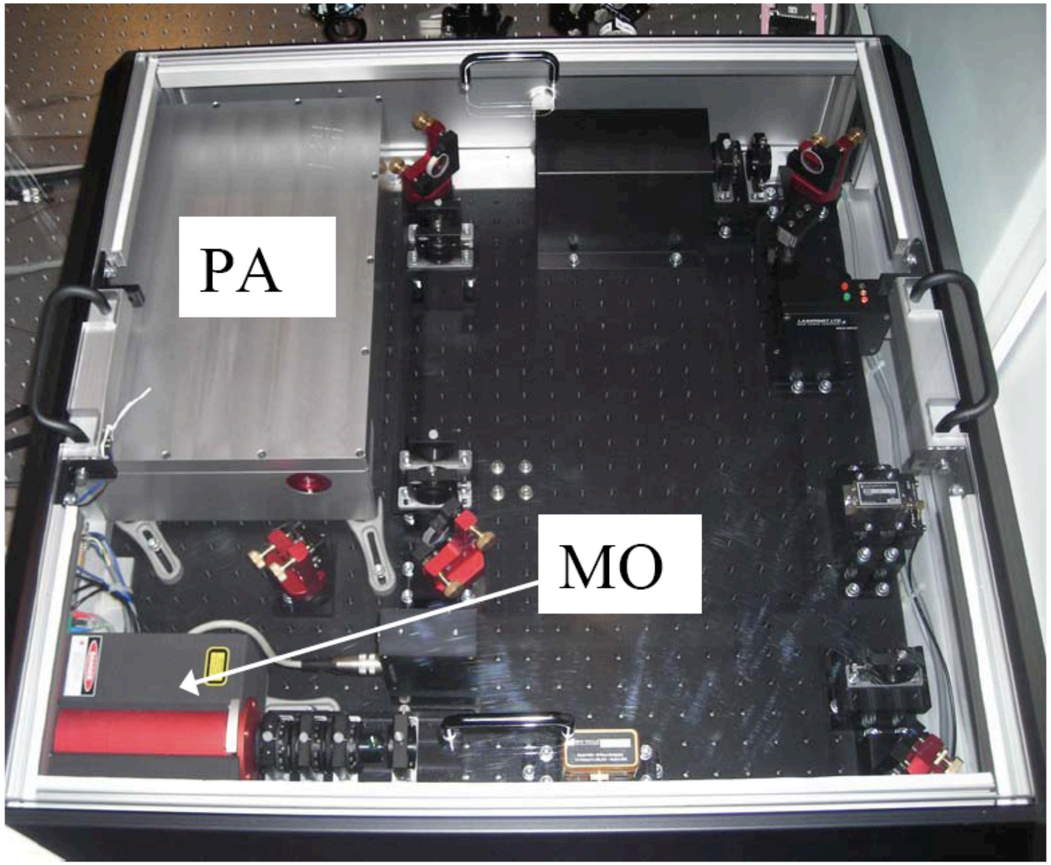
2007
2008
2009
O N D J F M A M J J A S O N D J
LLO
isi inst.
psl
omc
IFO commission
isi comm.
S6
LHO
isi inst.
omc
isi comm.
IFO commission
psl
plan circa Oct '07
LLO
isi
omc
psl
dc lock
psl EOM
reality
isi loops
NOW
LHO
psl
isi
omc
dc lock
isi loops

Limiting noise sources for an enhanced detector are understood



eLIGO 35W laser from LZH

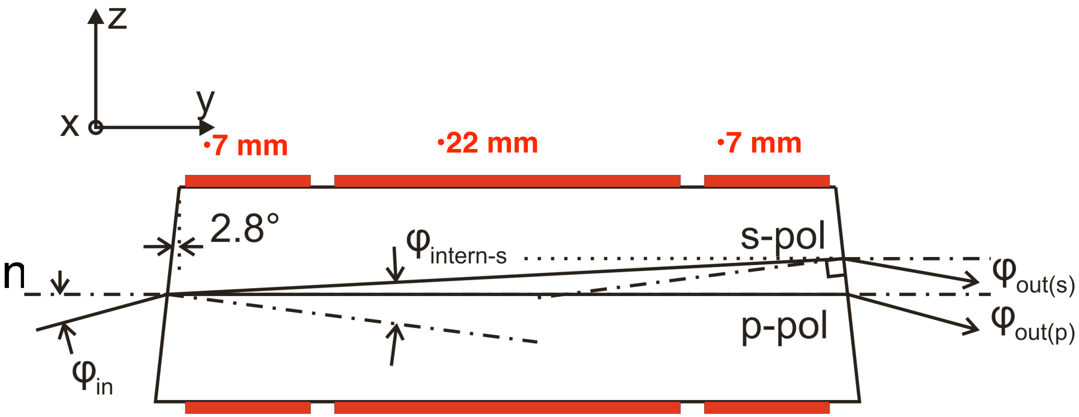
- Built in a master-oscillator-power-amplifier (MOPA) configuration – similar to iLigo laser
- Uses 2-W Innolight non-planar ring oscillator (NPRO)
- Designed for integration into PSL
  - » Phase-correcting EOM between MO and PA
  - » AOM for power stabilization between MO and PA
- Four longitudinally-pumped, water-cooled amplifier heads
- Pump diodes (4 x 45 W) located remotely with fiber optic delivery to laser heads.



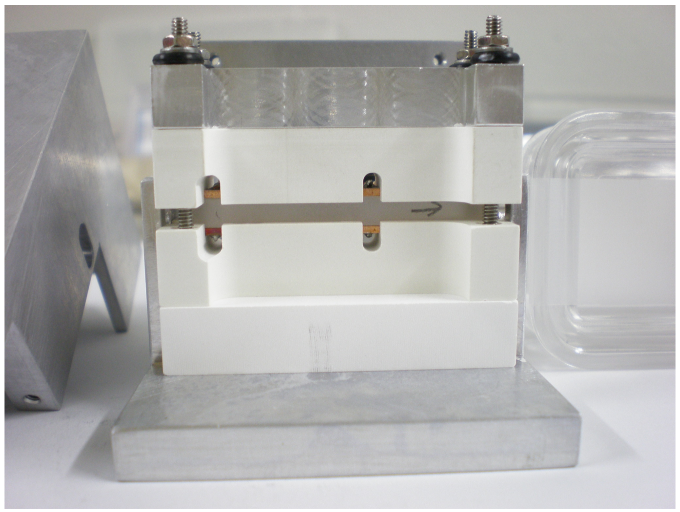
Wedged RTP crystal

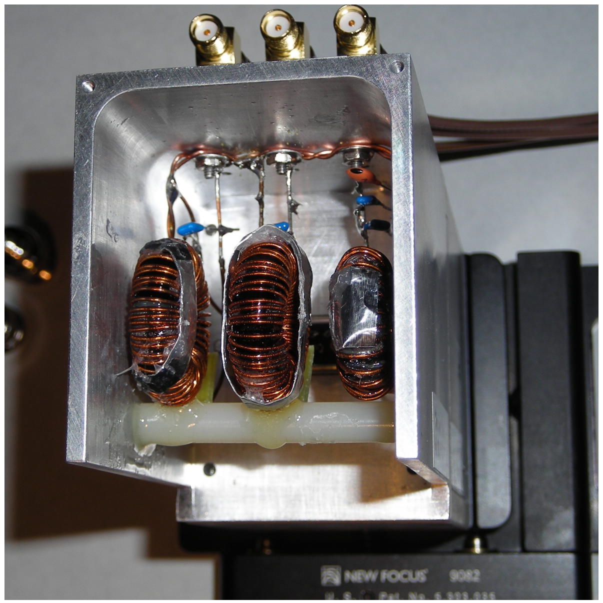
(rubidium titanyl phosphate - RbTiOPO4)

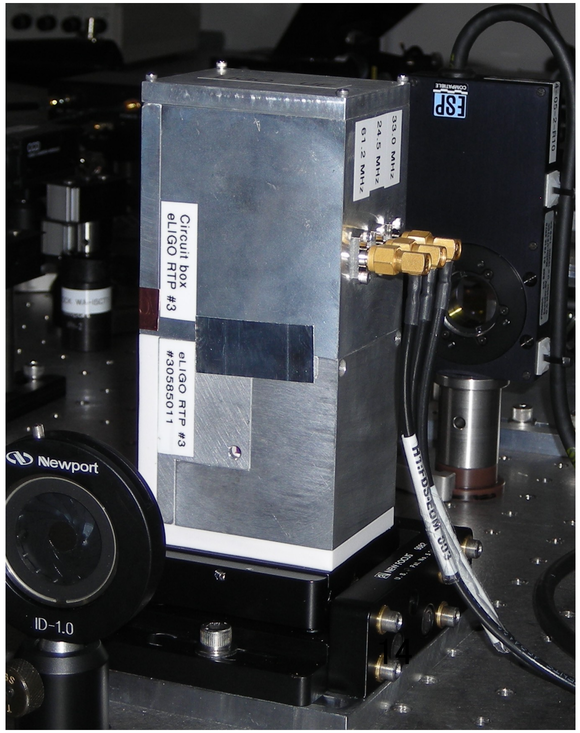
- Wedged crystal separates the polarizations and acts as a polarizer
  - » This avoids cavity effects and reduces amplitude modulation



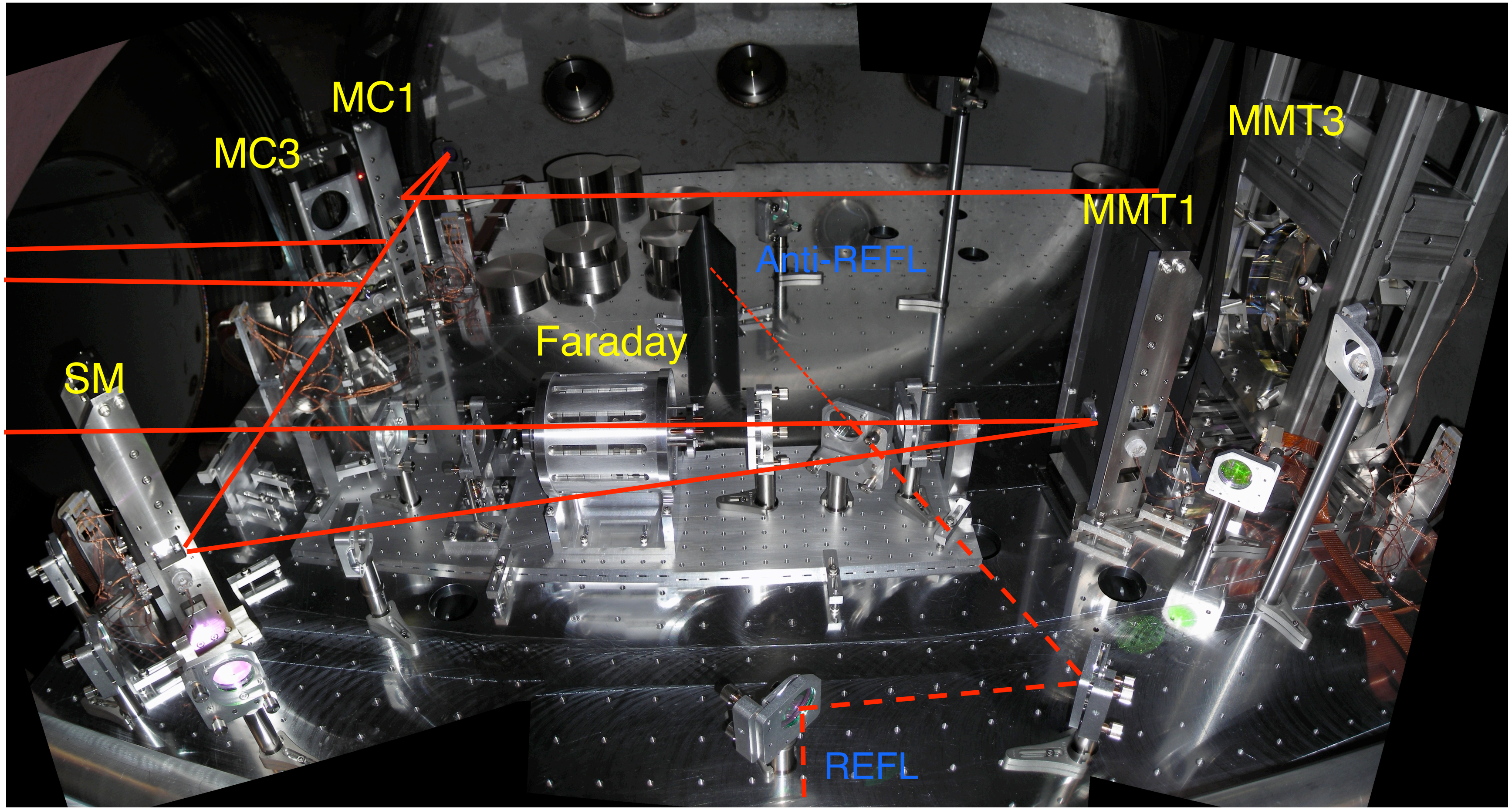
•Impedance matching circuit in separate housing.







HAM 1 – MC1&3, MMT1&3, Faraday



- IO efficiency (PSL to RM):
  - LLO: 70% (MC visibility of 93%)
  - LHO: 77% (MC visibility of 92% +/- 2%)

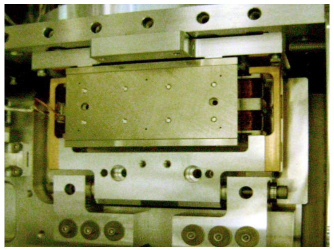
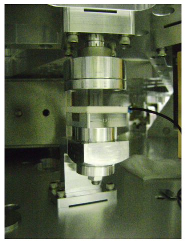
(compare with 55%-65% for iLIGO, LHO elog Dec 31, 2002)

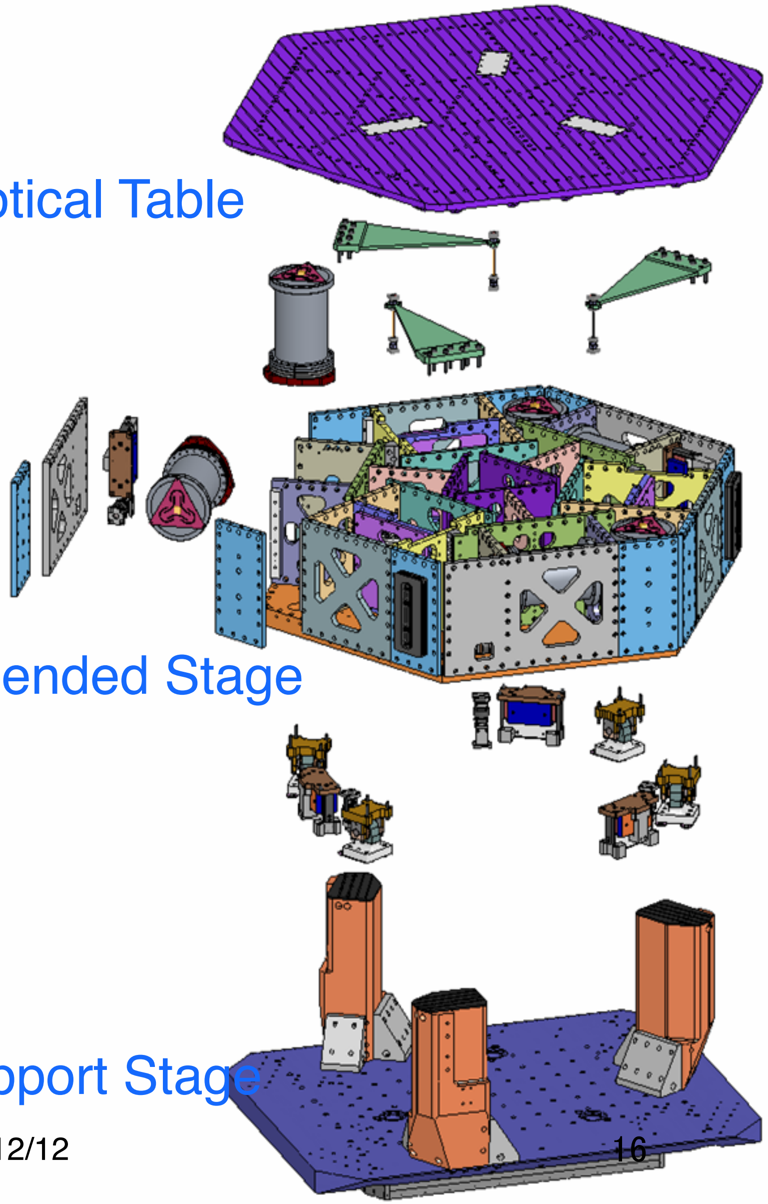
•Enhanced LIGO Seismic Isolation Prototype
•Horizontal Access Module In-vacuum Seismic Isolation
•(The **HAM ISI**)

- "Single Stage" Passive and Active seismic isolation and alignment platform
-
- Composed of 2 main components:
  - Support Stage ("Stage Zero")
  - Suspended Stage ("Stage One")

- Passive isolation

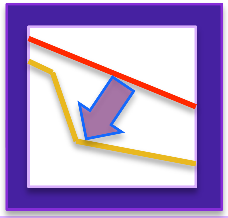

- Active isolation

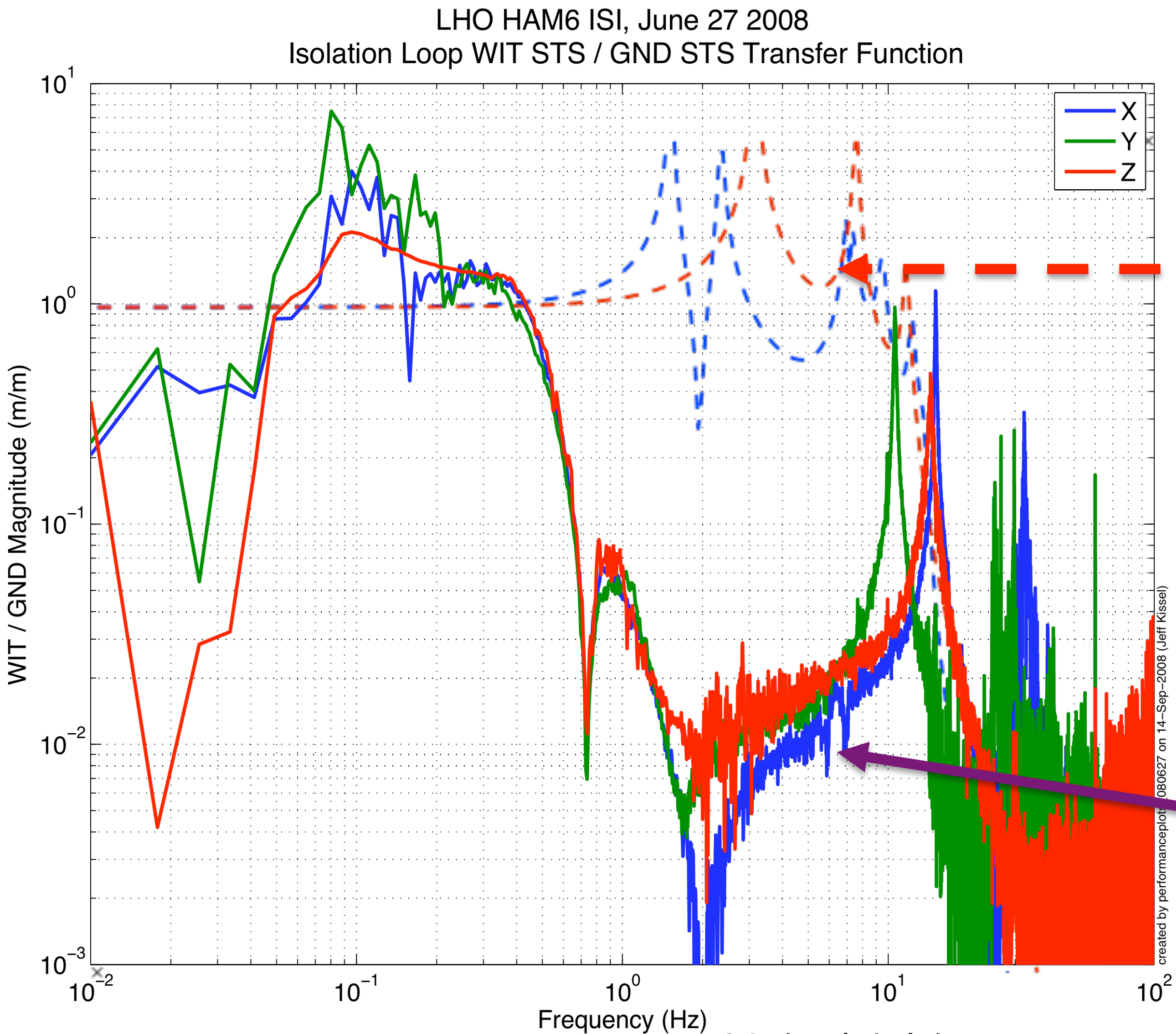



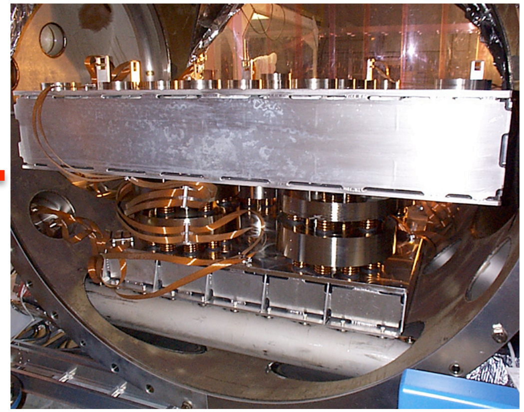
•The HAM ISI

Old vs. New Isolation Compariso

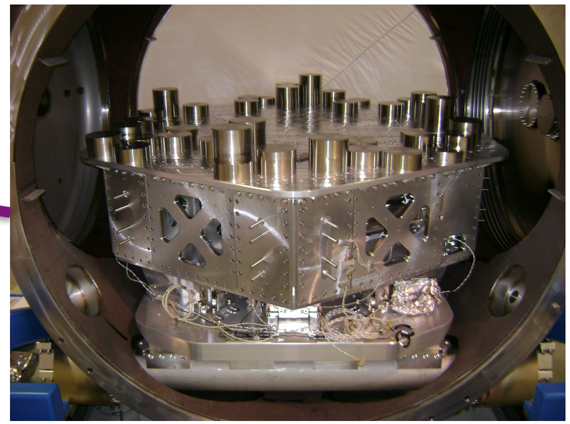




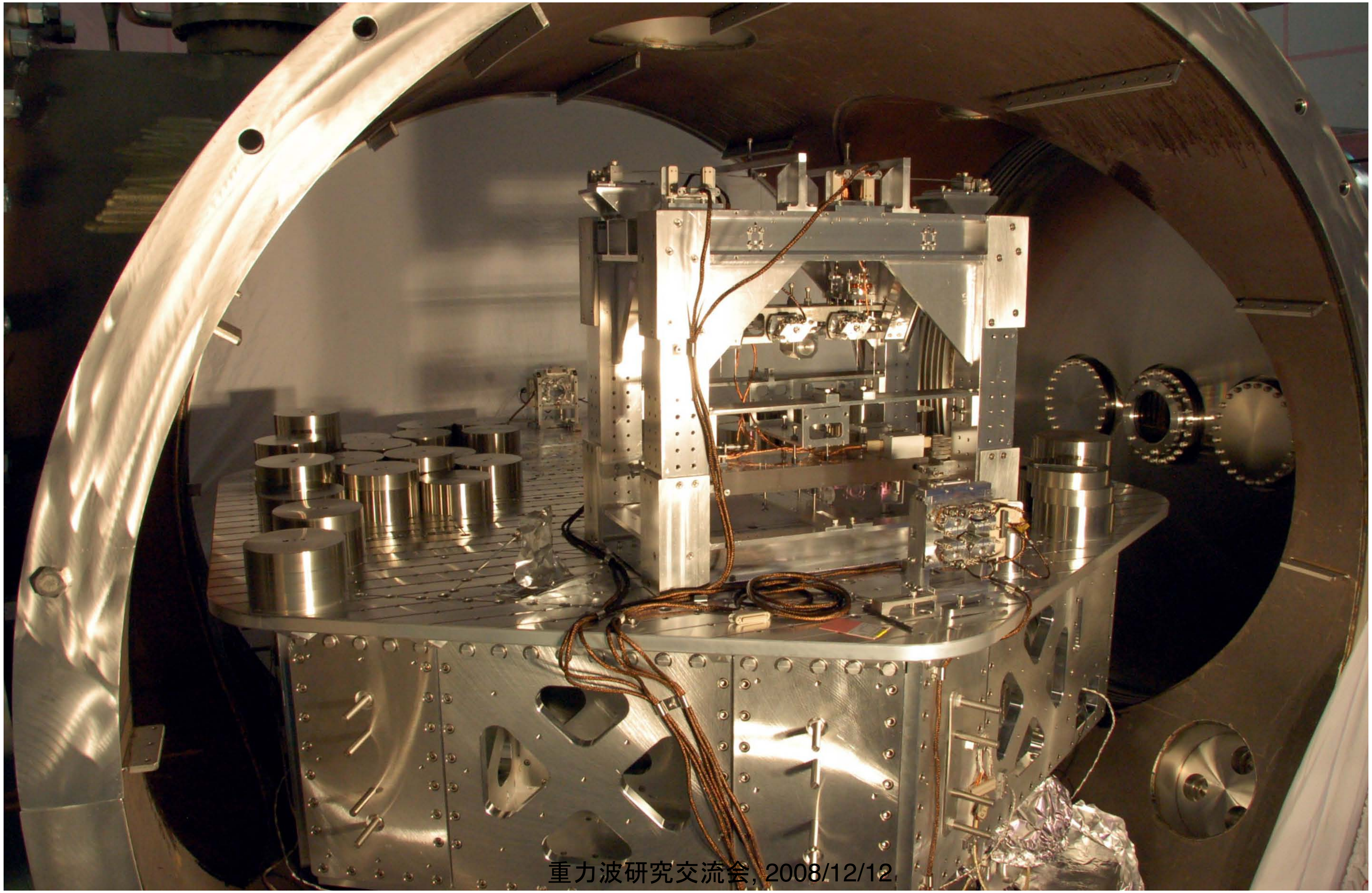
•iLIGO Passive Isolation



•eLIGO Passive & Active Isolation

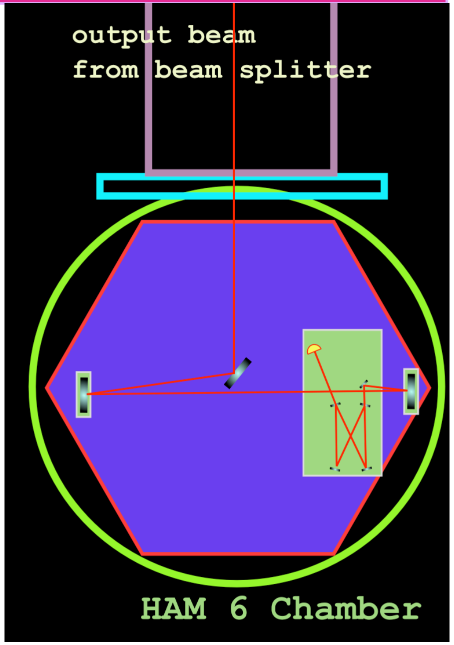


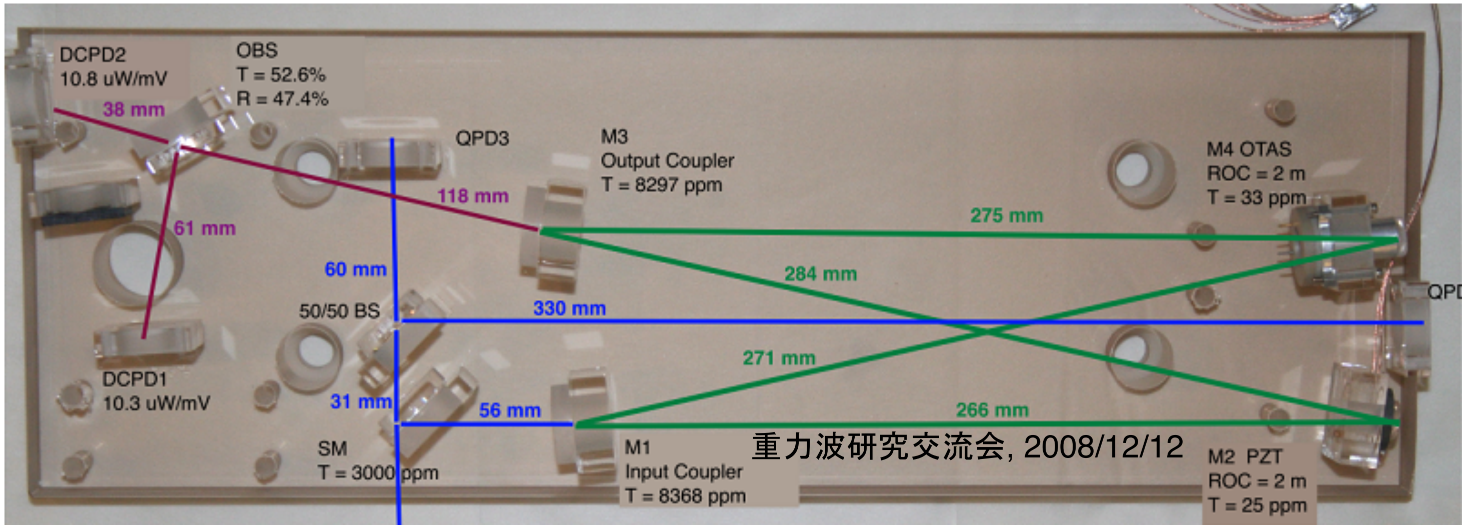
LLO OMC SUS

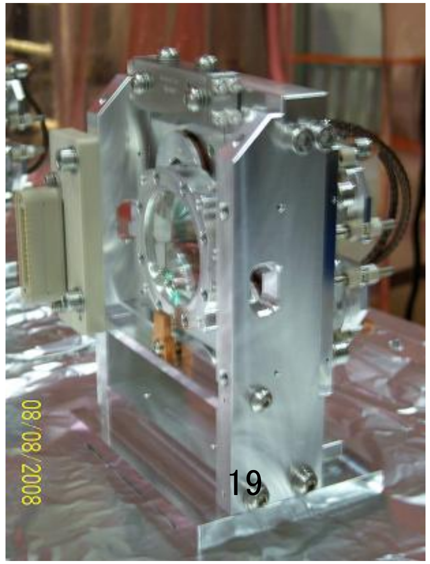


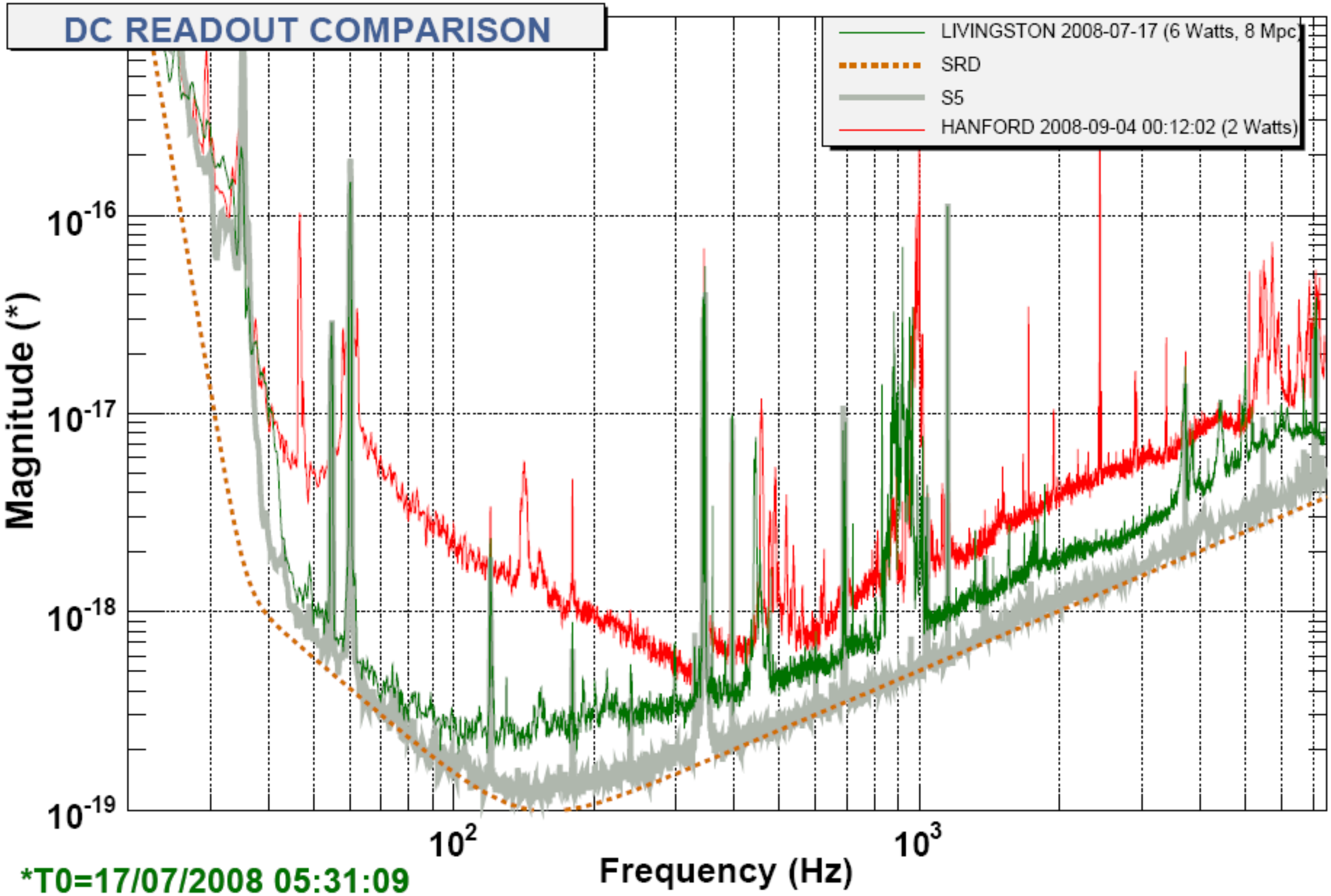
DC readout hardware

- Tip Tilts
- OMC-SUS
  - double pendulum
  - low <10Hz eigenfrequencies
- OMC
  - monolithic cavity, ULE breadboard
  - in-vac, high QE, 3mm DC-PDs
  - finesse ~350, 380MHz FSR, g ~0.75
- aLIGO style control system hardware/software

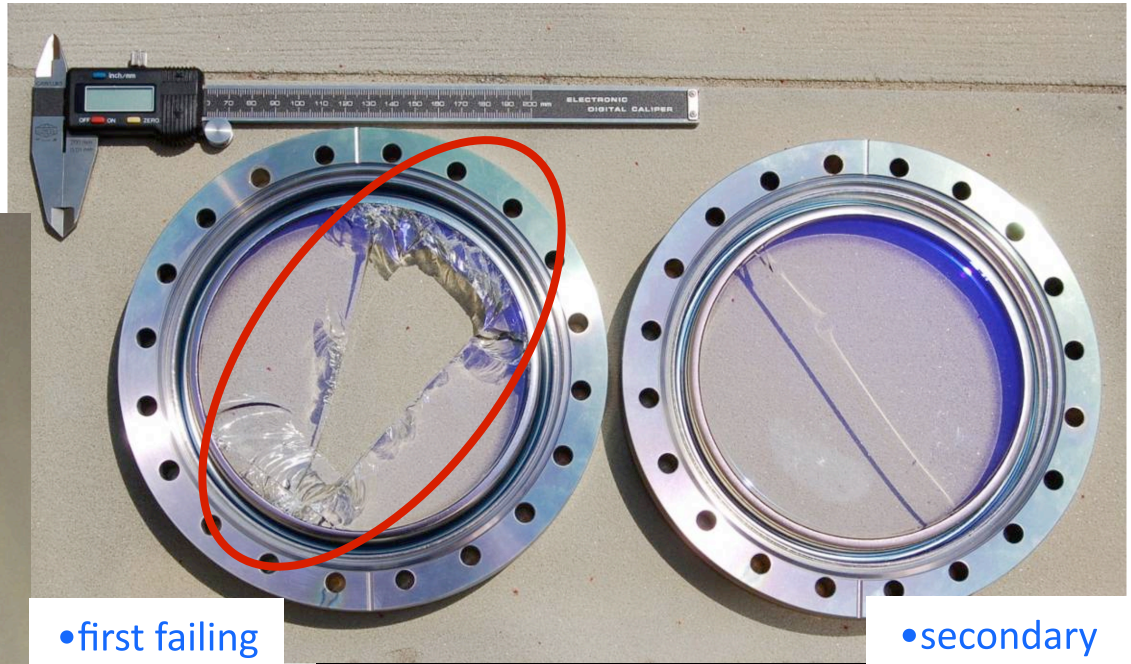







DC READOUT COMPARISON
LIVINGSTON 2008-07-17 (6 Watts, 8 Mpc)
SRD
S5
HANFORD 2008-09-04 00:12:02 (2 Watts)
Magnitude (*)
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{2}
10^{3}
Frequency (Hz)
*T0=17/07/2008 05:31:09

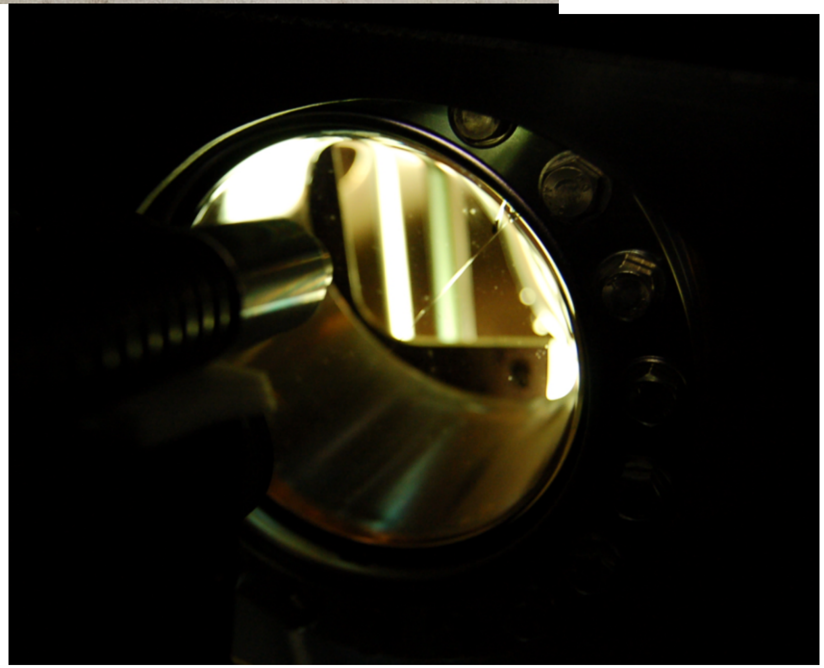
VIRGO Broken Viewports



•first failing

•secondary

•From inside



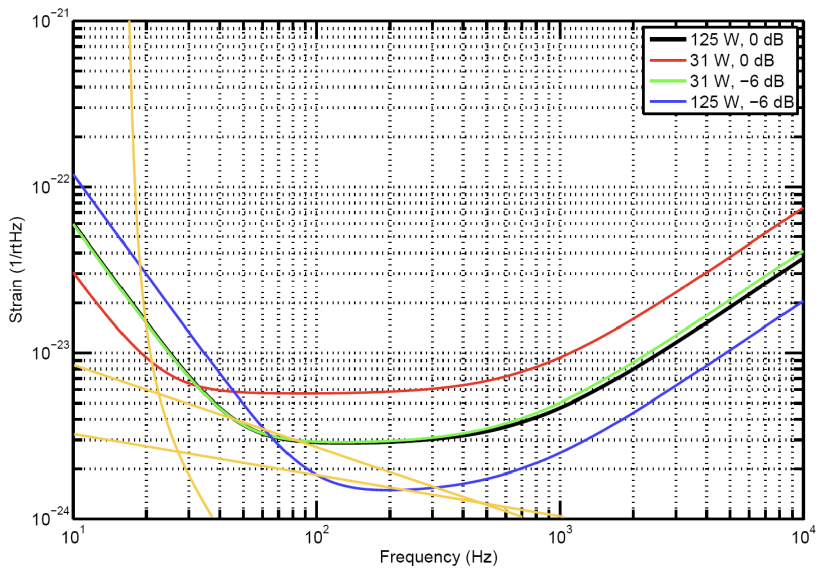
•From outside

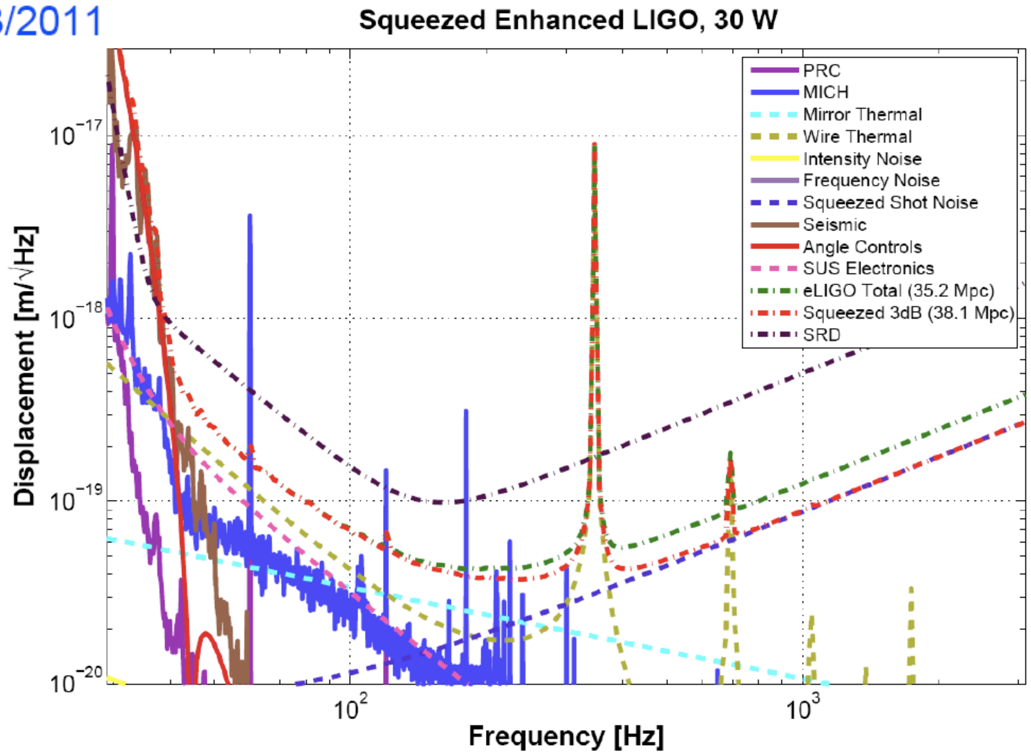
AstroWatch with H2 at Hanford Observatory

- A5 began 18Feb2008
- Run by LSC grad students
  - Good training for students
  - Frees up most experienced labor for eLIGO work on H1
- Successfully running (stats for 18Feb-2Sep08)
  - Science mode up time ~28%
  - Total up time ~52%
  - H2 range varies 6-7.5 Mpc, depending on eLIGO activity/hardware.
- Astrowatch will continue until beginning of S6 in spring 2009
  - Need more student volunteers for January 2009 and beyond.

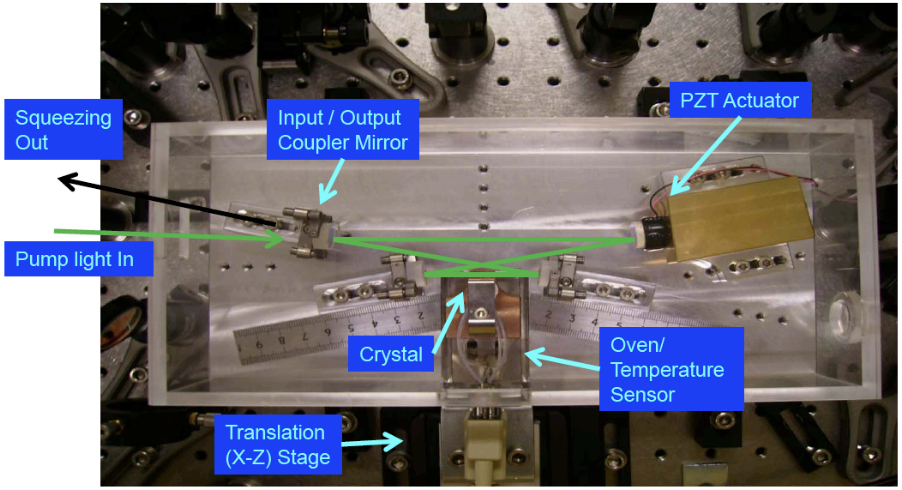
Squeezing in H1

- Fixed start date for H1 experiment: 2/15/2011
- Fixed end date for H1 experiment: 10/3/2011

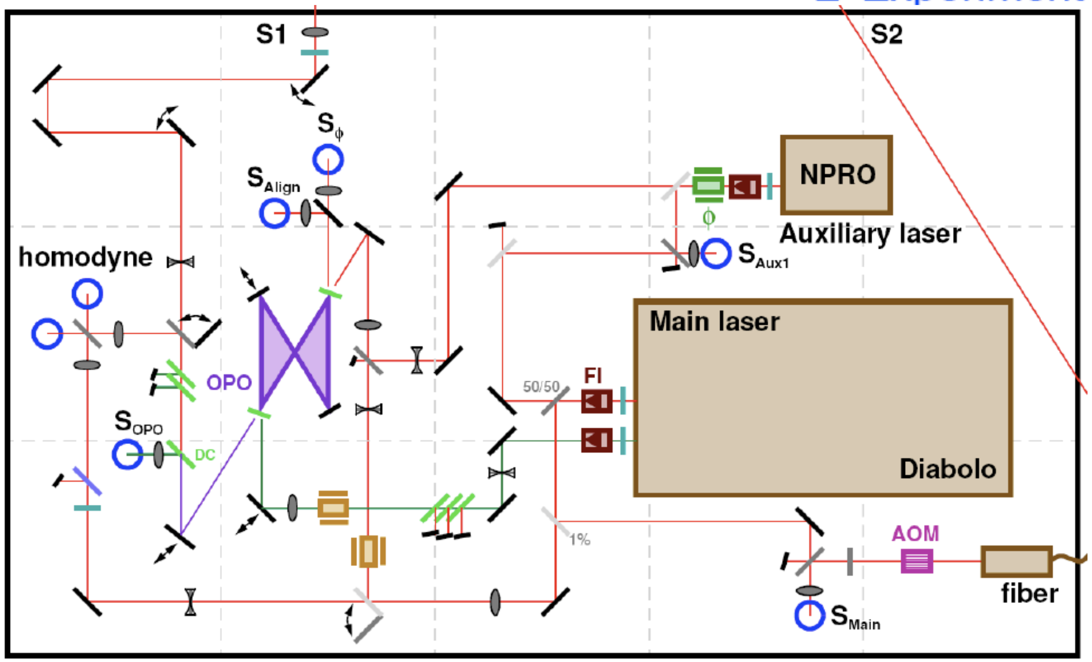




Squeezing in H1



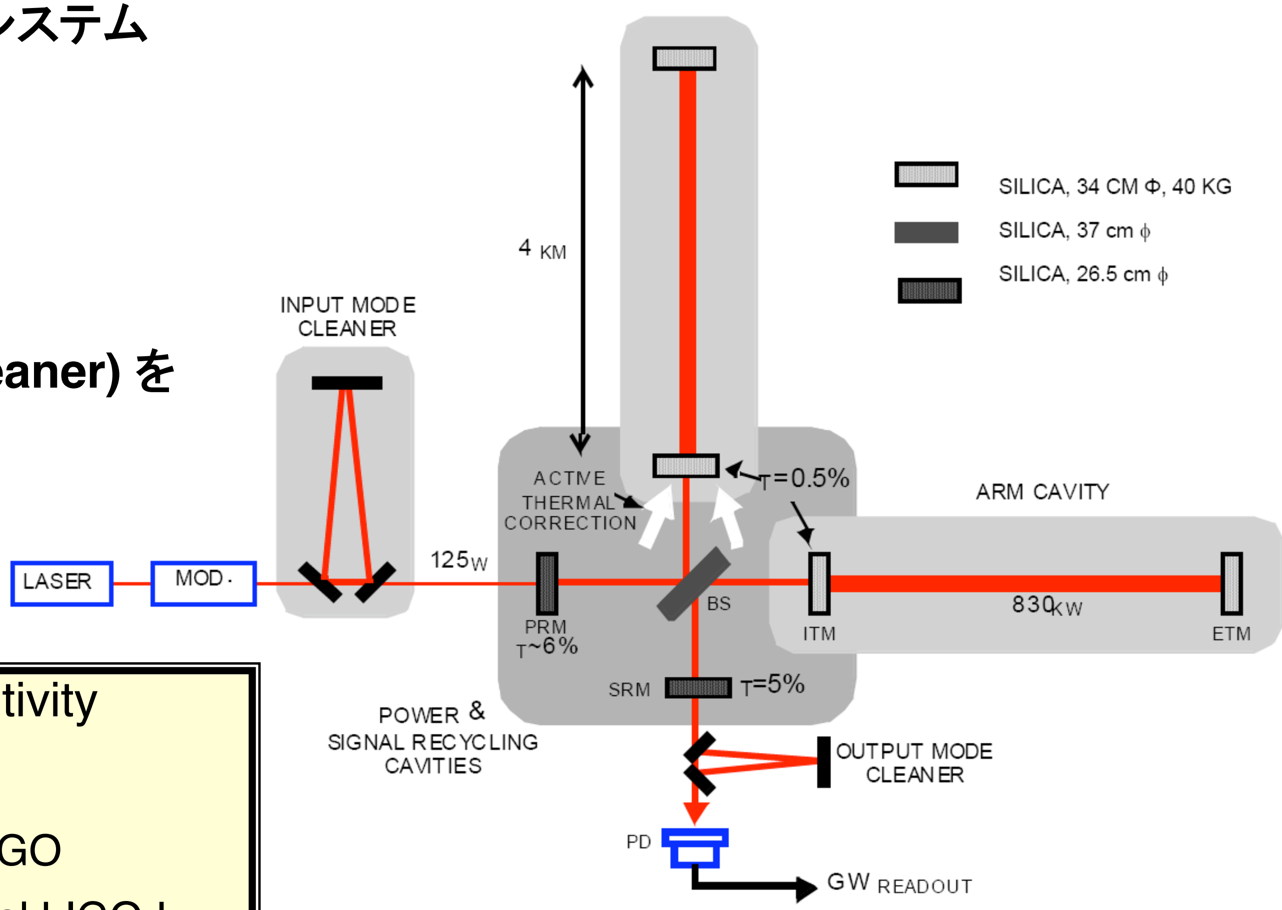
- Setting up the lasers (MIT/LHO)
  - Critical path: building the electronics
  - Grad student from MIT
  - Electronics support from LHO
- Building and commissioning the OPO (ANU)
  - Grad student from ANU
  - Electronics support from LHO
- Characterization of the squeezer (ANU/LHO)
- Homodyne detector (AEI)
- Experiment at H1



Advanced LIGOの特徴

- 200Wクラスの高出力レーザー(~20x)
- アクティブな低周波防振システム
- 3 - 4段の多段振り子
- Digital control system
- 帯域可変のRSE
- OMC (output mode cleaner) を使ったDC readout

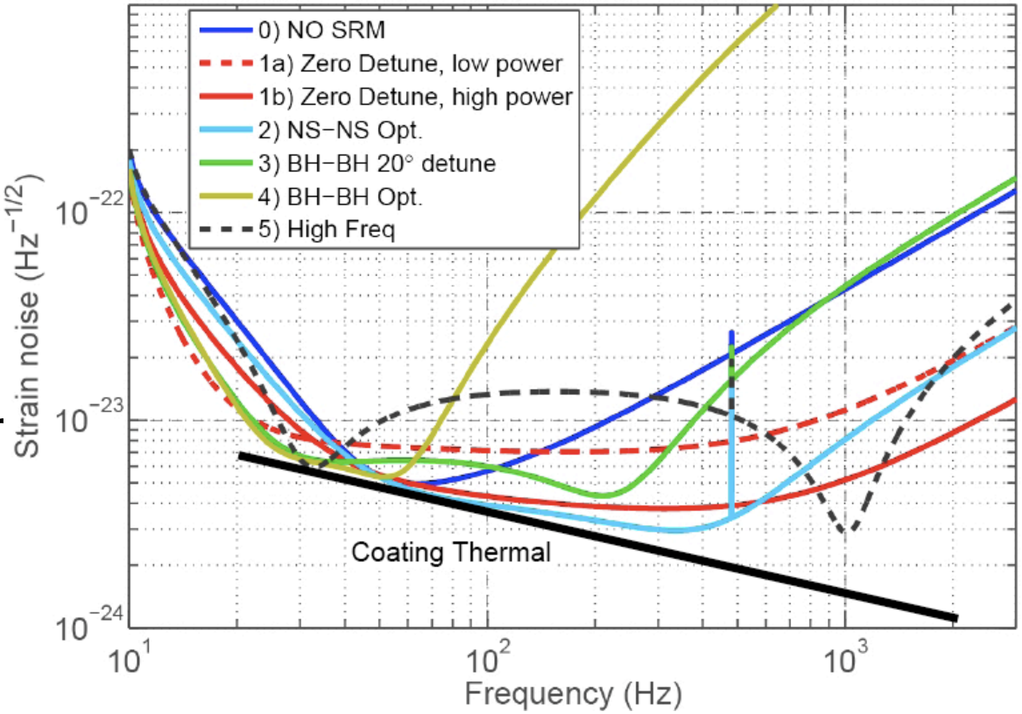
•ADVANCED LIGO LAYOUT



> x10 better amplitude sensitivity
>
> ⇒ x1000 rate=(reach)^3
>
> ⇒ 1 day of Advanced LIGO
>
> » 1 year of Initial LIGO !

What is Advanced LIGO?

- Replacement of all of the LIGO detector components, reuse of the facilities – vacuum, buildings
- Three 4km instruments – two at Hanford, one at Livingston
- Signal–recycled power–recycled Fabry–Perot Michelson
- Some tunability, can be used over a range of input laser power
- Limited by quantum noise at most frequencies at high input power, thermal noise otherwise

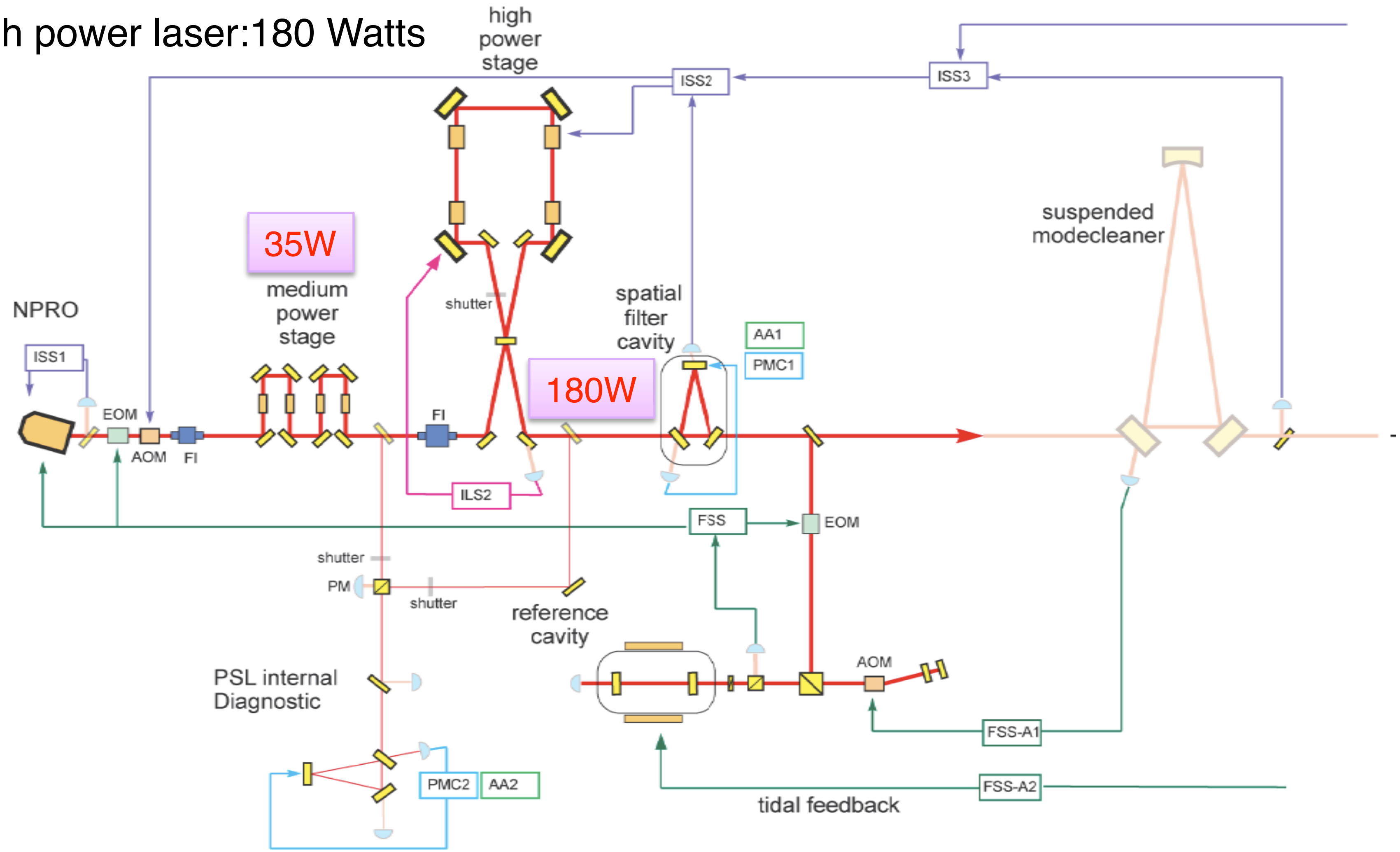


When is Advanced LIGO?

- 2009
  - » eLIGO installation now complete, in commissioning
  - » In parallel, AdL completes development, fabricates parts
- 2010
  - » eLIGO observes
  - » AdL manufactures, assembles, aligns, tests subsystem parts
- 2011
  - » eLIGO wraps up
  - » Maybe squeezing experiment follows at LHO
  - » Observatory shutdown as early as Feb '11, second Oct '11
- 2012 – INSTALL, integrate, test, tune
- 2013 – First Interferometer Acceptance as early as June'13
- 2014 – Second, third IFO acceptance earliest Jan'14, April'14
- 2015 on – Observe with AdL, interleaving with further tuning

Advanced LIGO pre-stabilized laser system

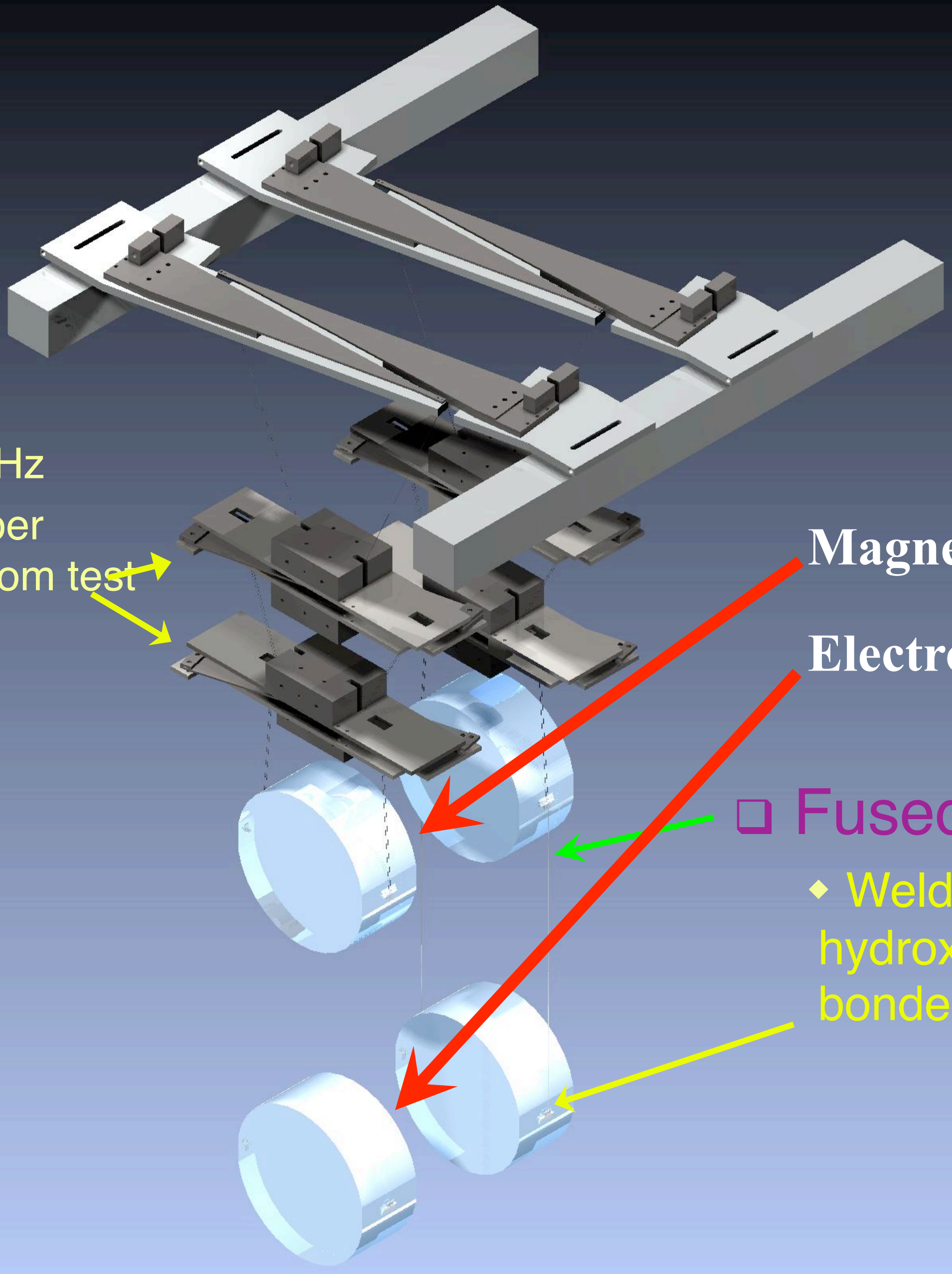
High power laser:180 Watts



•Work lead by AEI (Hanover) in collaboration with LZH (Laser Zentrum Hanover)

Quad Suspensions

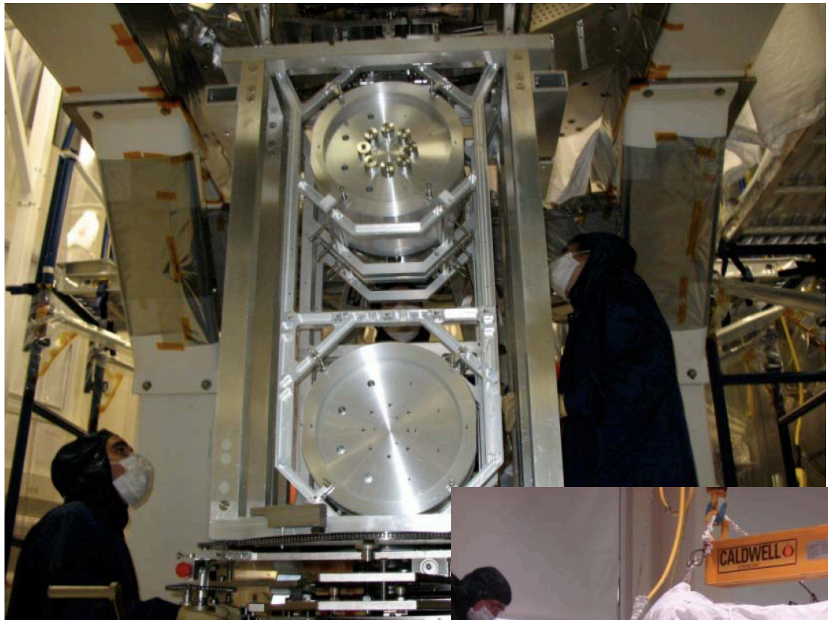
- Quadruple pendulum:
  - » $\sim 10^7$ attenuation @10 Hz
  - » Controls applied to upper layers; noise filtered from test masses
- Seismic isolation and suspension together:
  - » 10^{-19} m/rtHz at 10 Hz



- ❑ Fused silica fiber
  - ◆ Welded to 'ears', hydroxy-catalysis bonded to optic

Quad Pendulum Noise Prototype

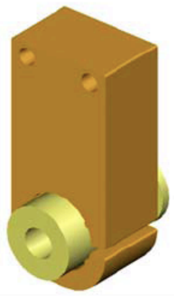
August 2007 – mounting to ISI



October 2007 – Suspending

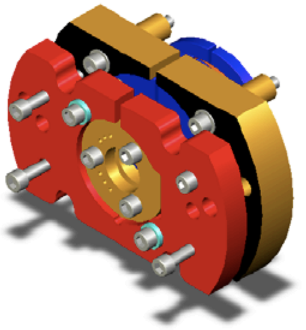
April 2008 – Quad-ISI BSC installation

OSEM to BOSEM:- Evolution



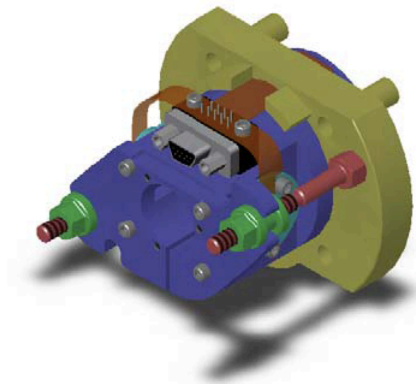
Initial LIGO

(OSEM)



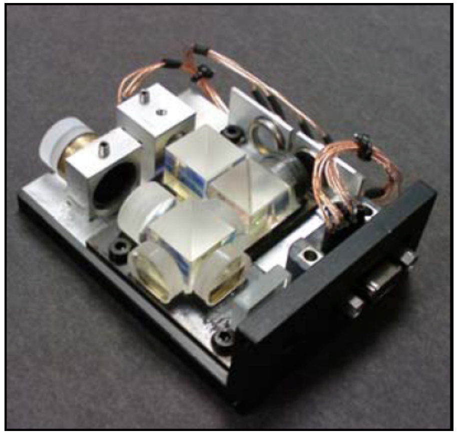
Advanced LIGO

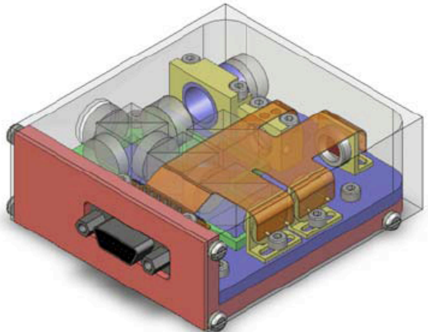
Controls Prototype (Hybrid OSEM)



Advanced LIGO

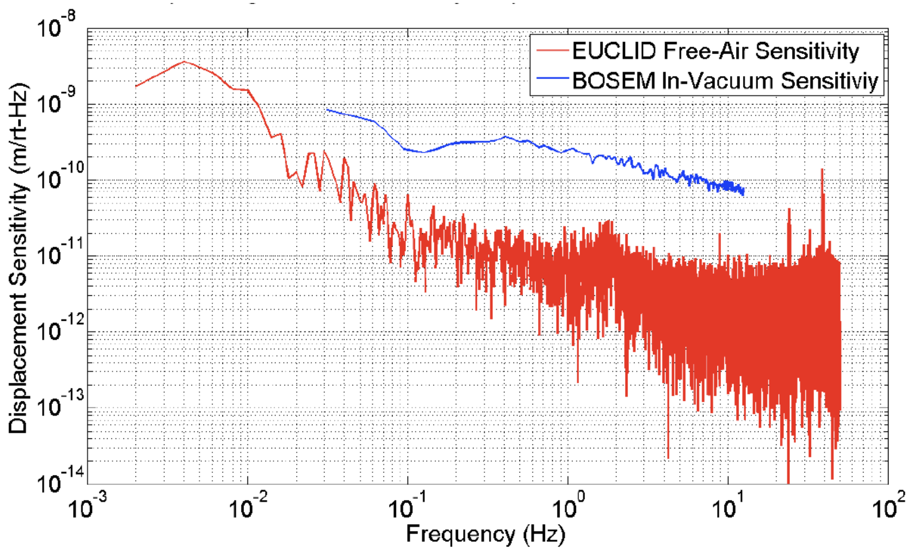
Noise Prototype & Final Production (BOSEM)



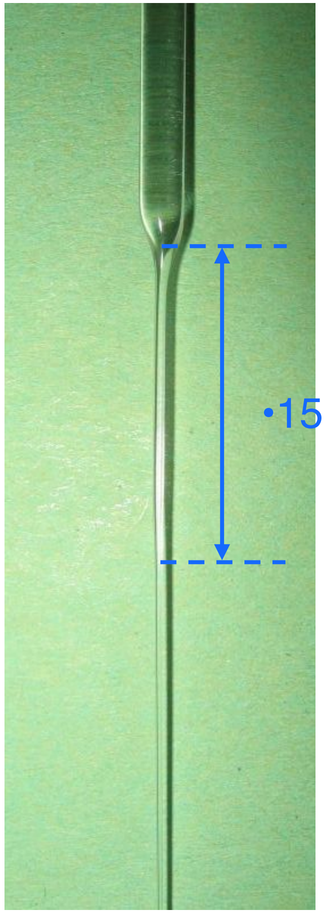


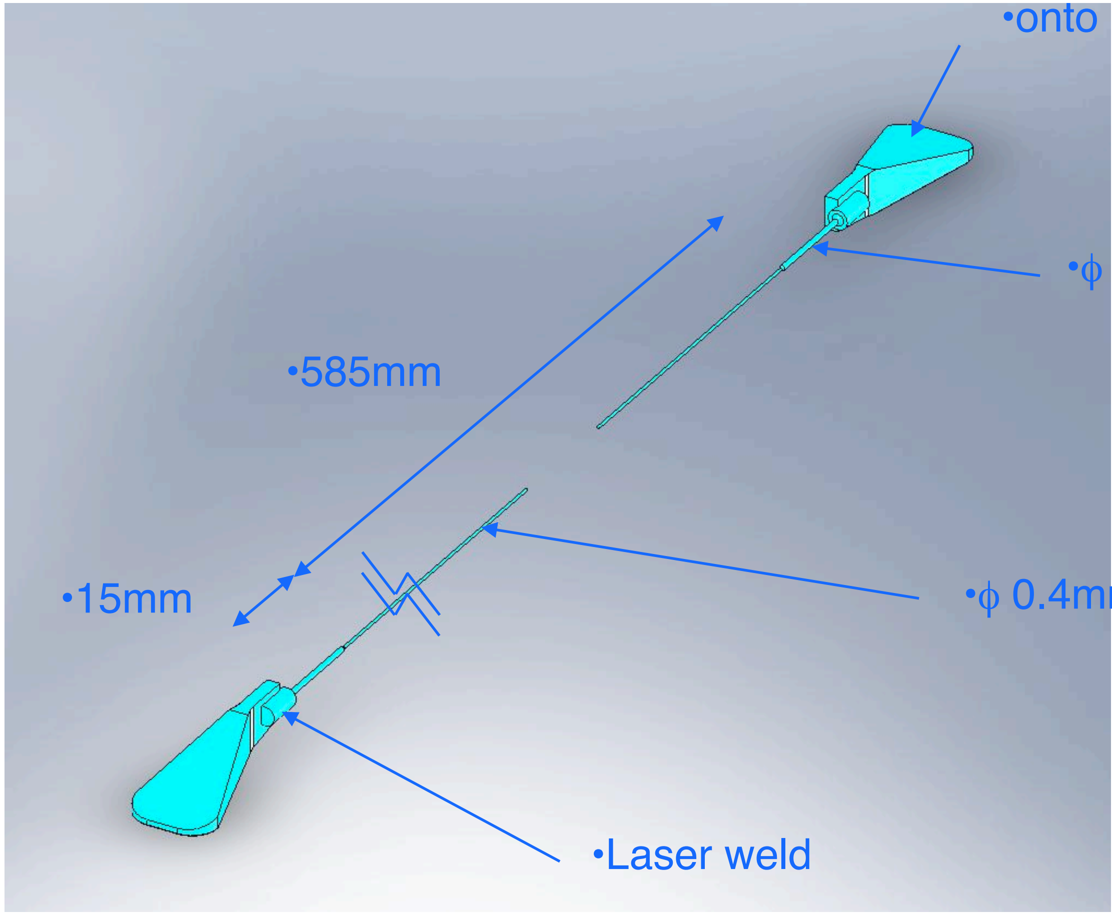
Advanced / Ultra LIGO

(Interferometric Sensor (EUCLID))

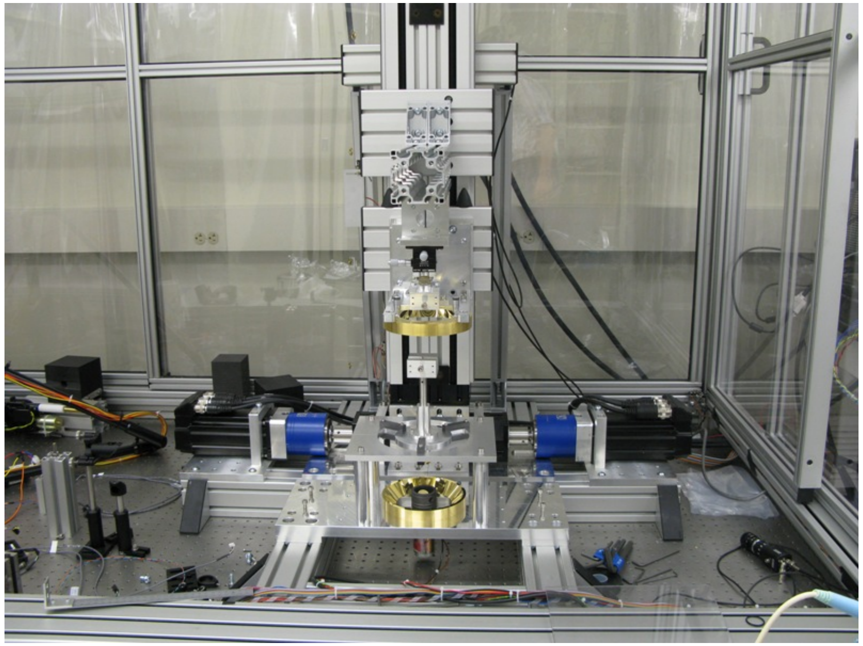


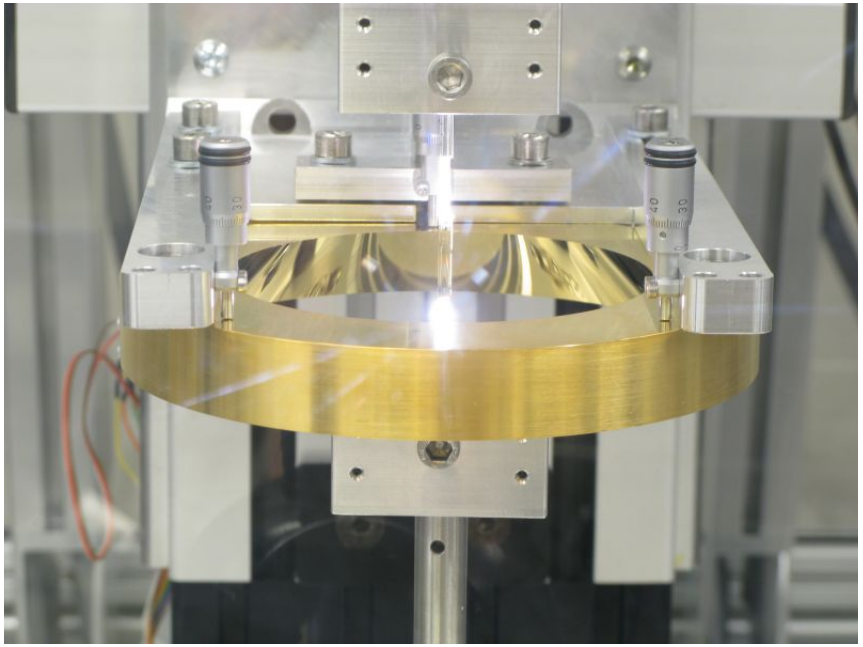
Baseline Fibre for Advanced LIGO





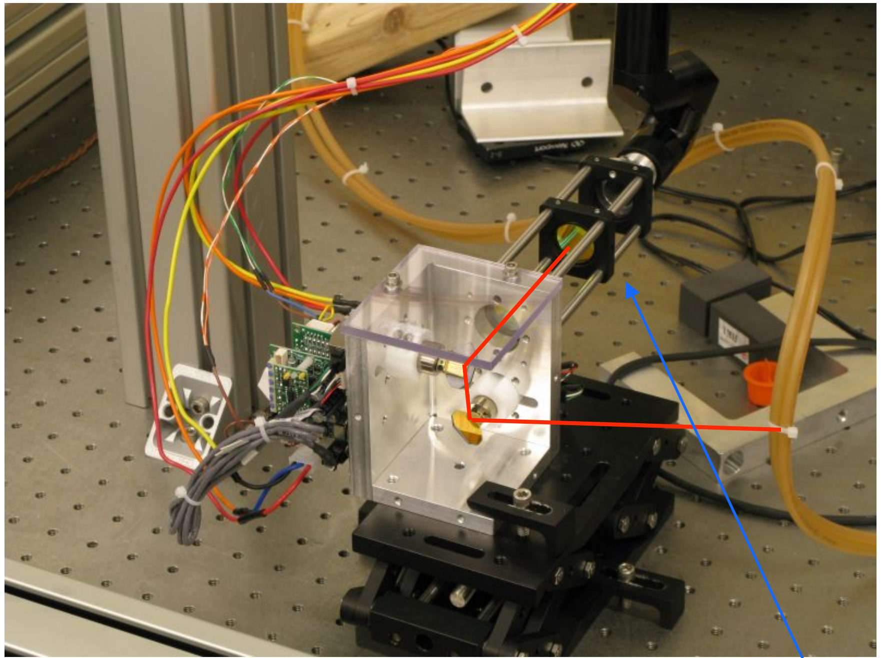
Pulling Machine at LASTI





- Pulling machine is well aligned and capable of good reproducibility
- Length tolerance ≈0.1mm
- Recipe for fibres developed in collaboration with Glasgow/LASTI
- Fibres are stored in racks within a low humidity enclosure
- Strong fibres (>5GPa) are possible with high power + laser polishing

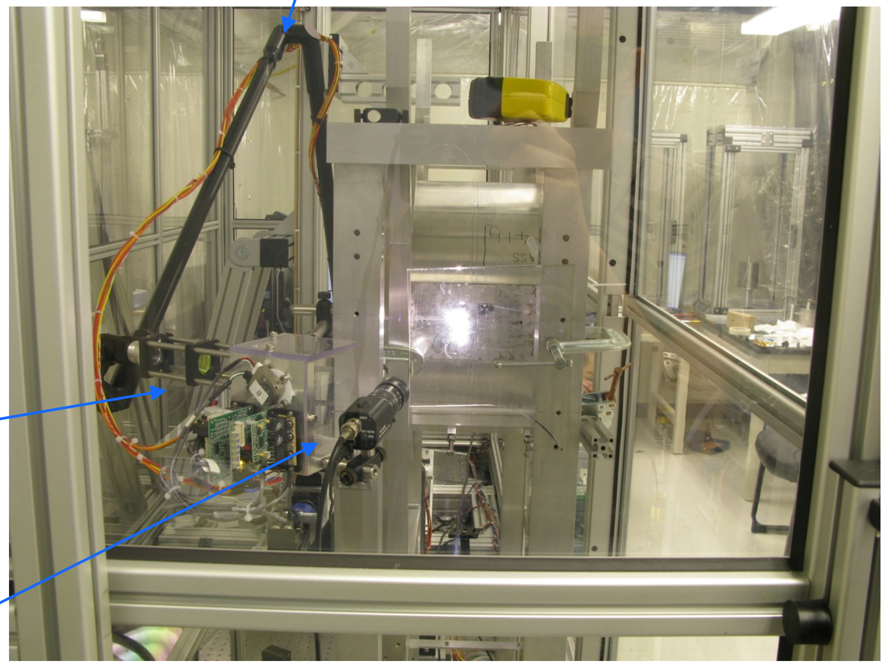
Welding at LASTI and Glasgow



•articulated arm

•optics

•camera



Tooling at LASTI

• Fibre
•storage

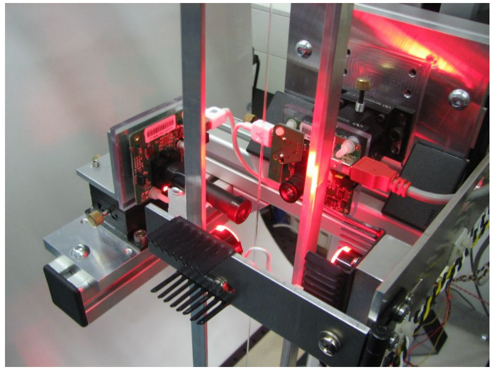
• Fibre
•handling

•Cut fibre
•on “bow”

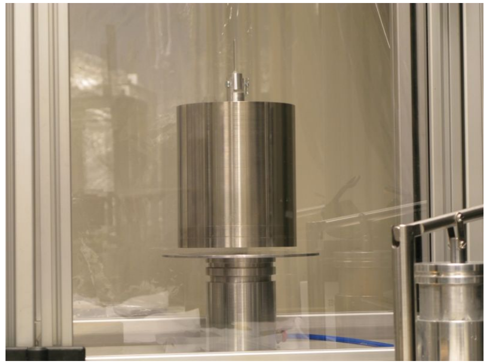
•Profiler
•

Cutter

Bounce
tester

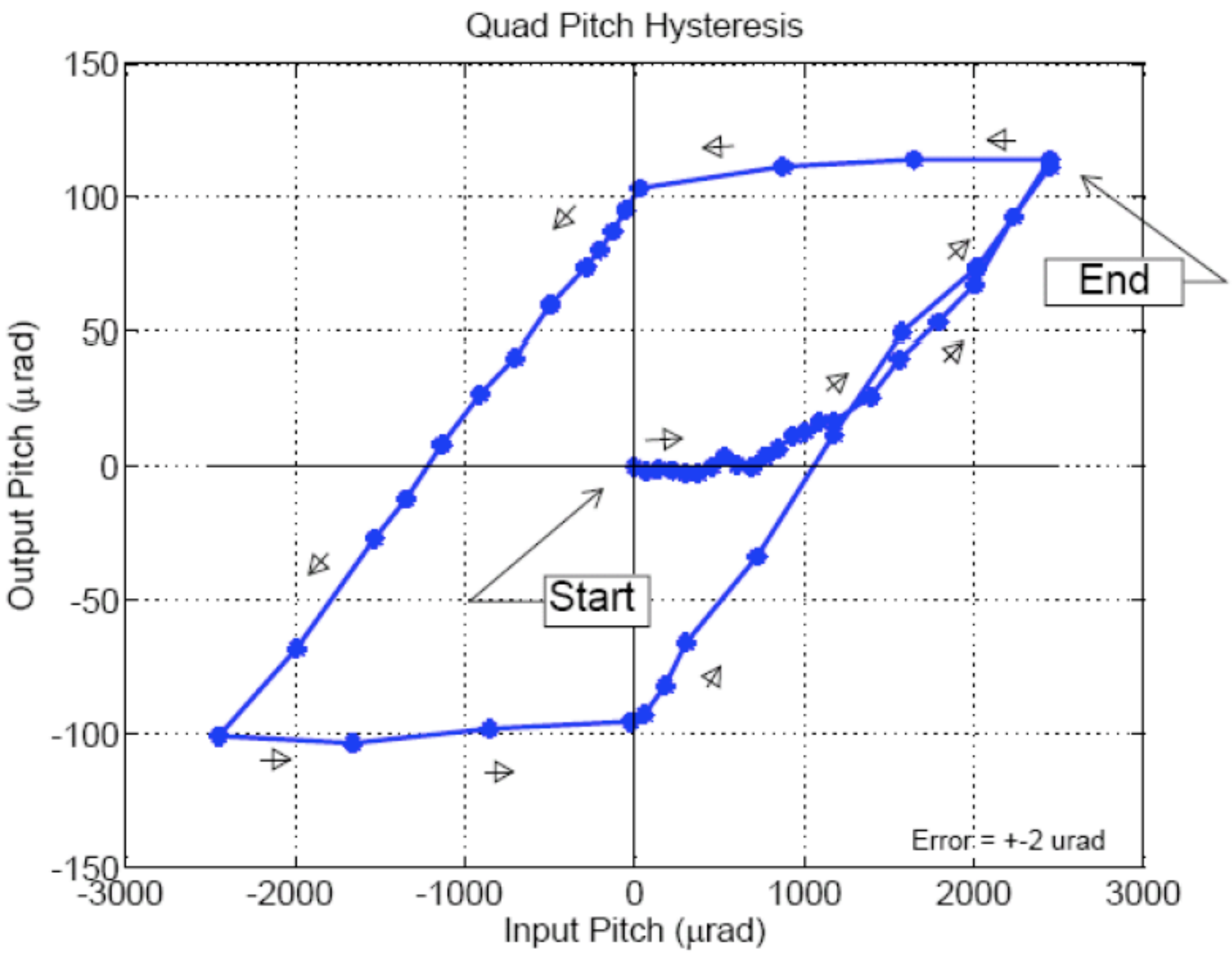


•Profiler



•Proof test
• (12.5kg)

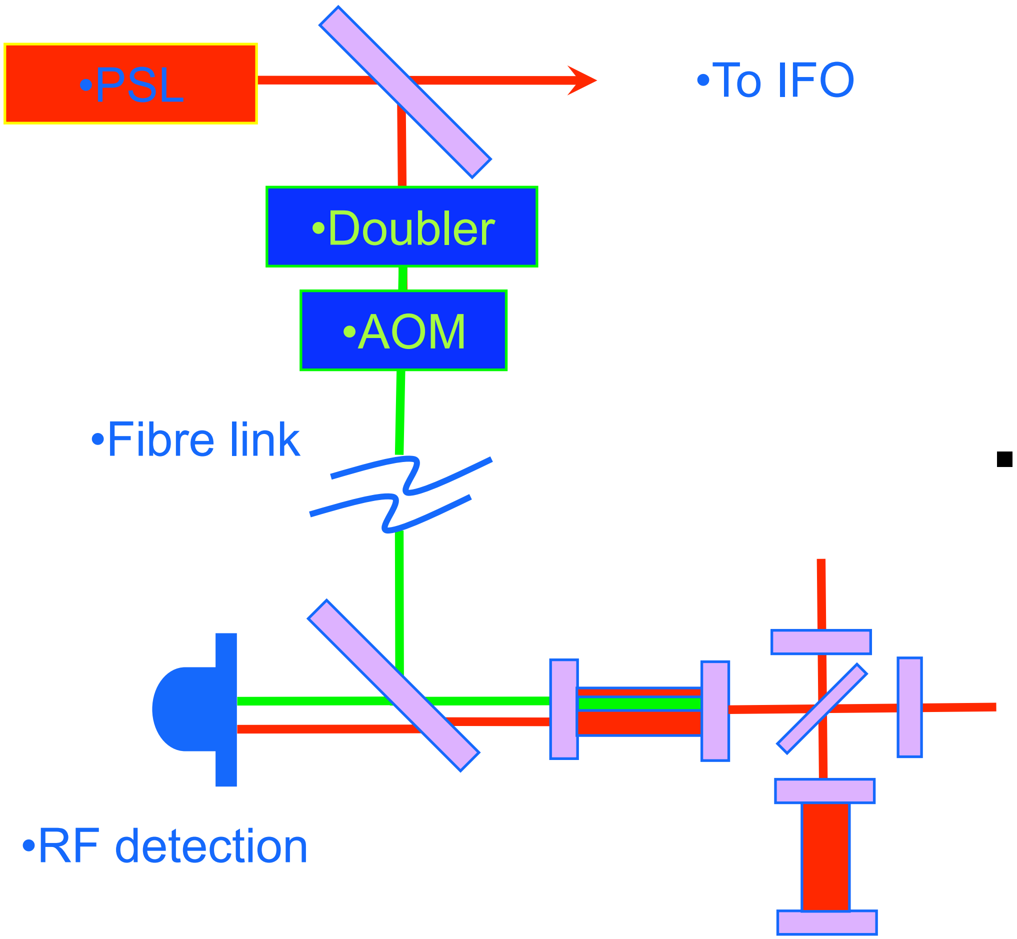
Pitch hysterisis



Caltech 40 meter prototype

- Arm Finesse : 1200 -> 450
- Mod. Freqs: 33->9 MHz, 166->45 MHz
- Recycling: Longer cavities (requires folding)
- Mach Zehnder: Gone
- Control System: Many VME->One Fast MultiCPU box
- Adaptive NC: Adaptive FIR, Inputs from PEM
- Alt Locking: Green light, fiber delivery, AOM shifting
- Misc:
  - GigE Cameras: Fast Image Processing – Fast Network
  - PEM Sensors: For FF cancellation
  - Longer Oplevs: More stable – instead of full ASC
  - Dither alignment: DC BW, Audio " WFS"

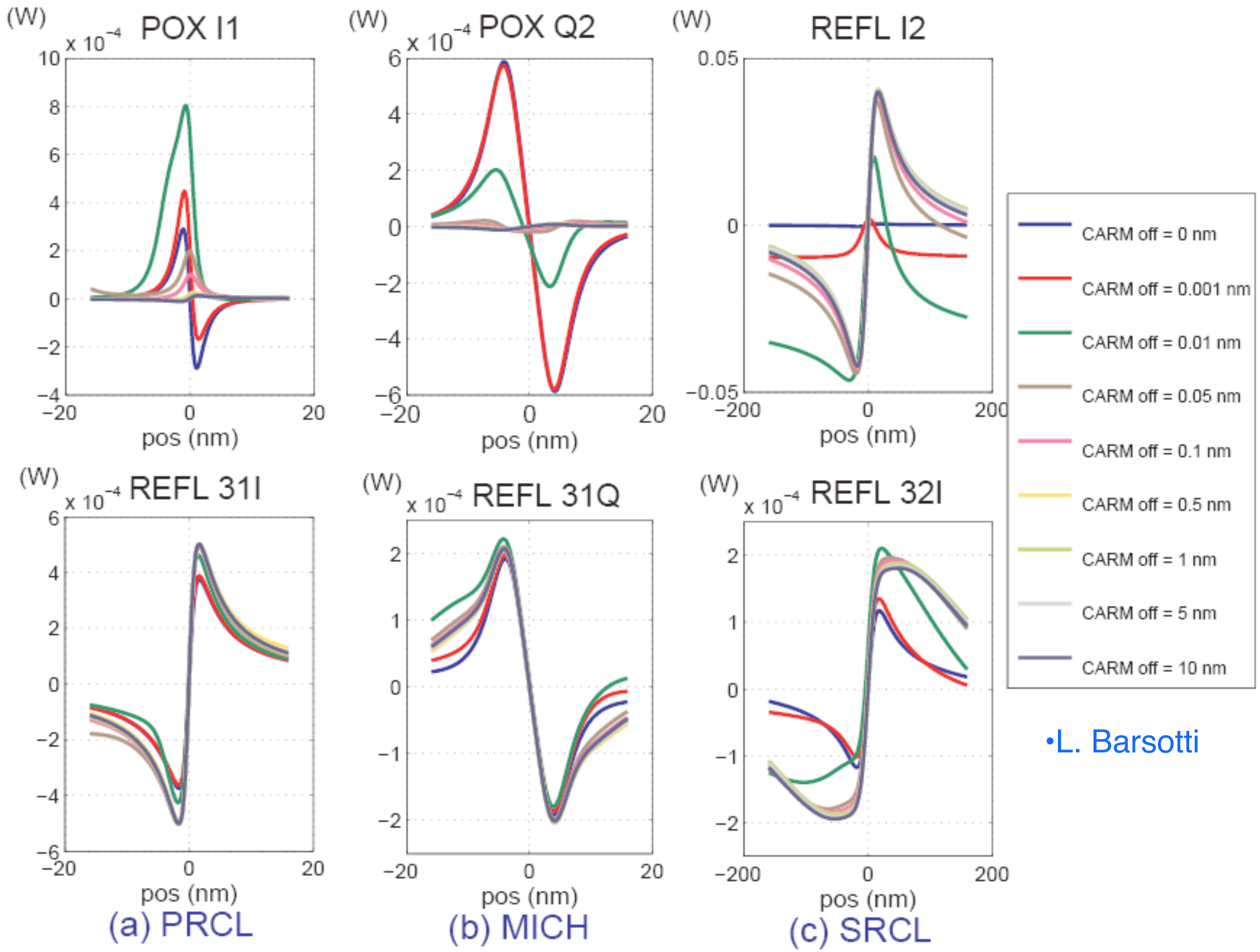
Auxiliary locking



- Example scheme
  - » doubled PSL
  - » single pass AOM, sweep frequency to resonance of PSL
  - » dichroic coatings for ETM/ITM
  - » fibre distribution
  - » light injected through ETM
  - » Normal PDH locking
- Just one idea other routes available - pick path of least resistance

•Independent sensing and control of arm cavity advancedligo

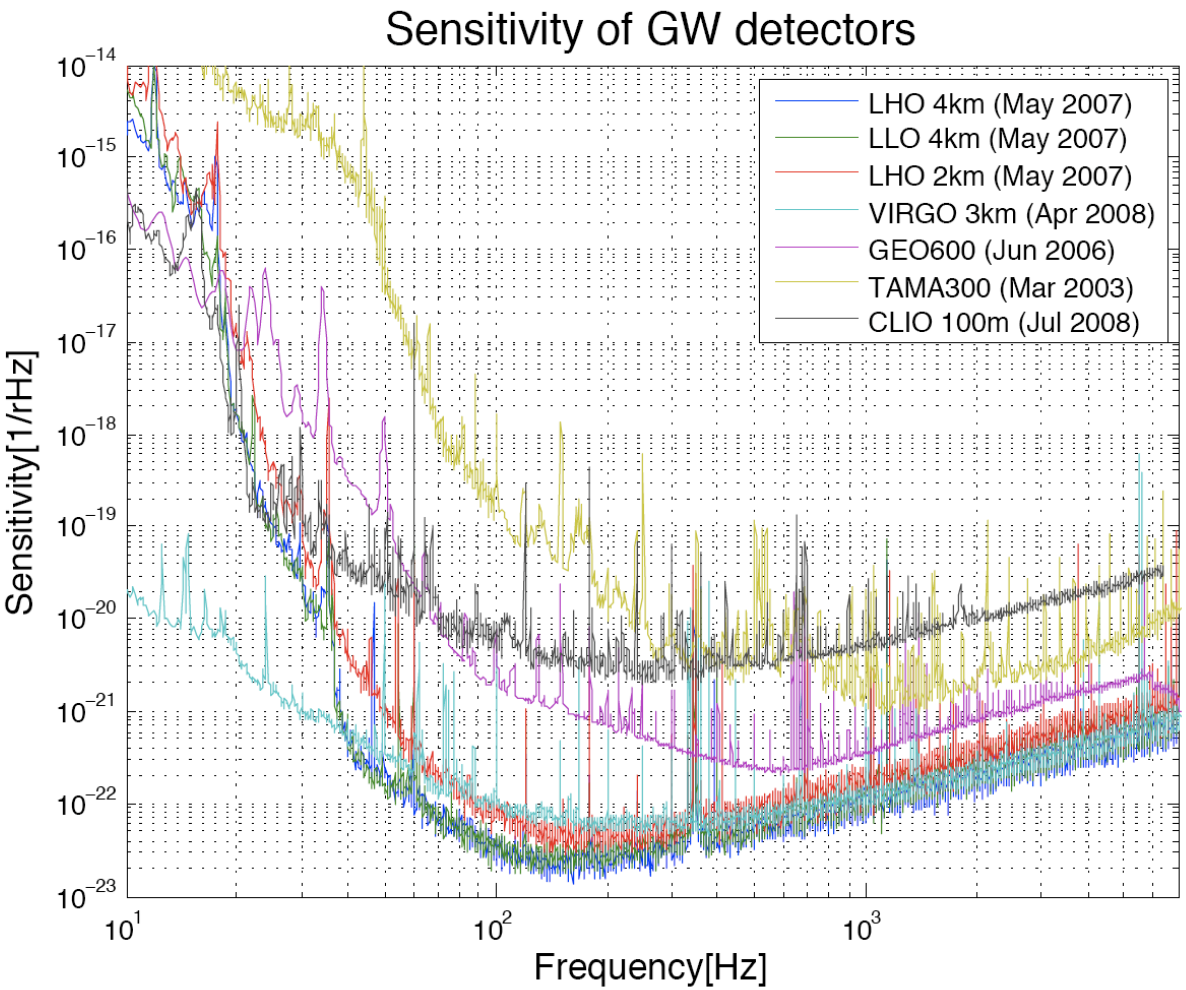
- Comparison of 1f and 3f signals for various CARM offsets 0 ->10 nm



•L. Barsotti

世界の主力検出器の感度

- 2000年当時TAMAは世界最高感度を誇っていた
- CLIOを入れると低周波は比較的検討しているといえる
- Kmクラスでなければとても太刀打ちできない
- LIGOは複数台の感度を同じにできる技術がある



なぜLIGOは計画通りの感度が出せるのか?

- 数十人規模の専門の技術者 (回路、計算機、真空など)
- 各サイト常駐の干渉計オペレーターと、24時間体制のシフト
- デジタル制御システムを利用した、一台目で開発された技術の二台目、三台目への簡単なコピー
- 豊富なドキュメント群の蓄積
- AdLIGOの要素技術開発と、それらのLIGO/eLIGOでの実装
  - » 30Wレーザーの開発と実装、180Wレーザの開発
  - » 低周波防振の開発と実装
- シミュレーションおよびツール類の強力な開発体制
  - » 量子効果を含んだ周波数領域 (Optickle)
  - » 時間領域 (E2E)
- 量子効果を取り入れるなどの理論グループとの強い協力体制
- Squeezing効果の導入などのアドバンストなR&D実験

日本一ヶ国では無理

– 国際協力、特にLIGOとの協力体制を確立する事が大切

LCGTに不足しているもの

- 低周波防振
  - SASのきちんとした性能評価、Active防振の可能性
- suspensionのプロトタイプの制作と性能評価
  - ESD(electro static drive)
- 150Wレーザーの開発
  - ハイパワー用EOM、FIの開発
- Digital control
- RSEのロックアクイジションテスト
  - 2変調をどのようにかけるかと、そのノイズ評価
  - Single demodulationの再評価
  - loop noiseの評価
- RSEでのWFS
  - WFS noiseの評価(radiation pressureを含む、できればloop noiseも)
  - optical springによる角度不安定性の回避策
- 時間領域でのロックアクイジションシミュレーション
- 低温下でのダンピングテスト
  - タンデム干渉計:複雑すぎないか?
  - OSEM:低温でLEDとPDが動くか?
  - Optical lever:lengthはうまく切り分けられるか
- 鉱山内のクリーン環境の確保

END

CLIO wiki

http://gw.icrr.u-tokyo.ac.jp:8888/JGWwiki/CLIO