次世代型重力波検出器の開発

宇宙線研セミナー

2008/12/12

宇宙線研重力波グループ　宮川　治

Einstein and relativity

Special Relativity (1906):

- 4-dim space-time geometry
- rest mass is a form of energy

$$E = mc^2$$

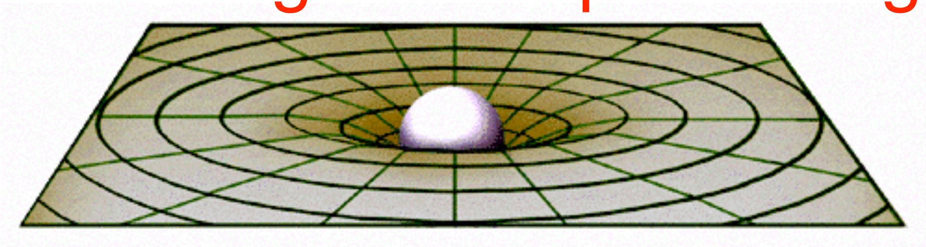
General relativity (1916):

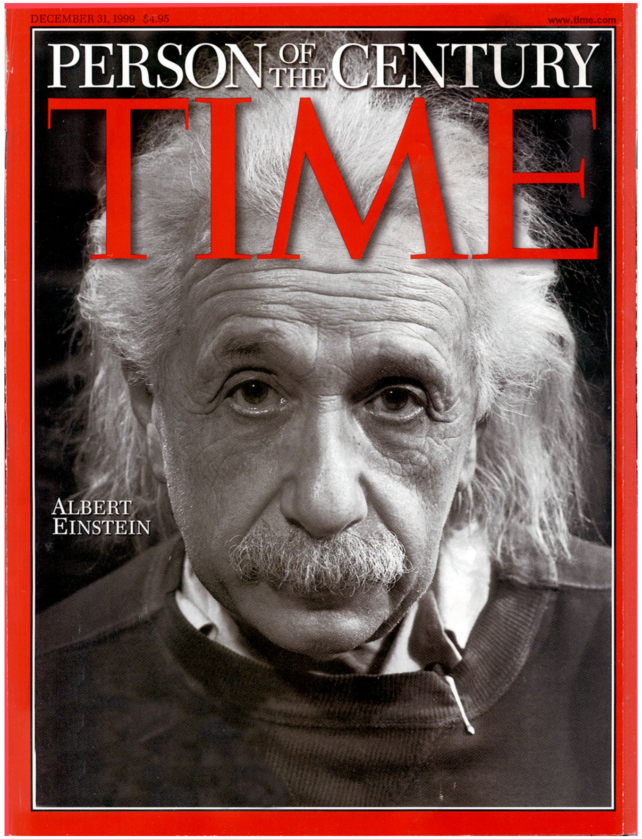
- Einstein's field equation :

$$G = 8pT$$

spacetime curvature ⇔ matter and energy

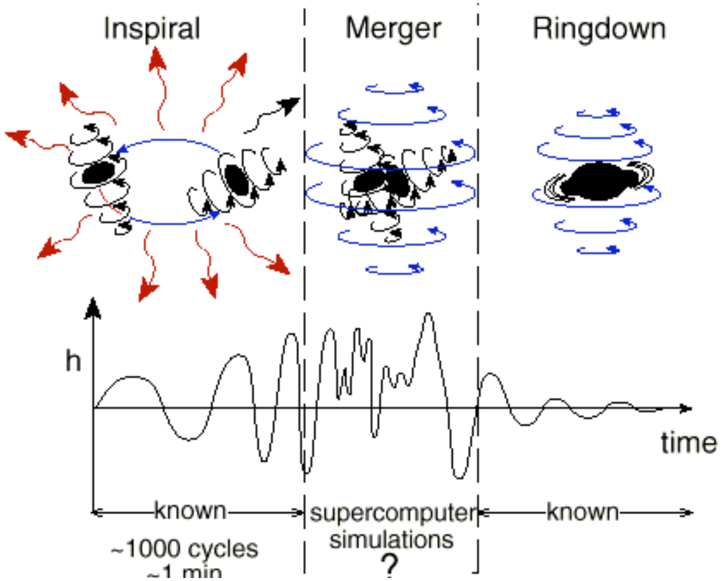
gravitational fields, travelling at the speed of light

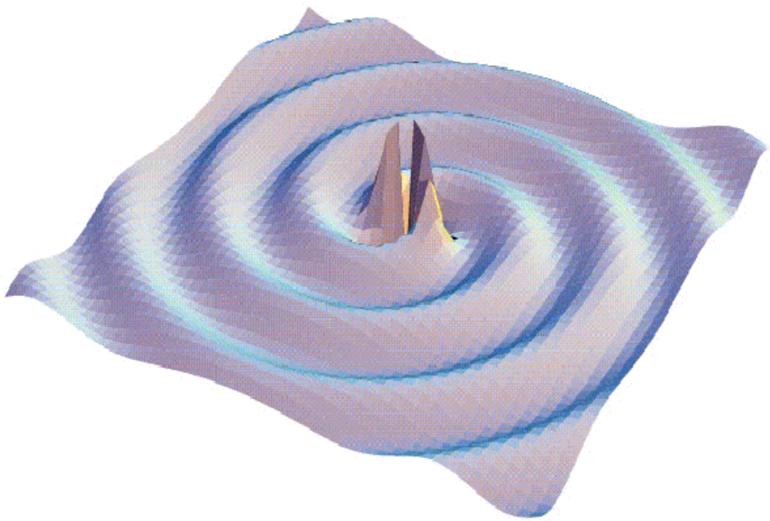




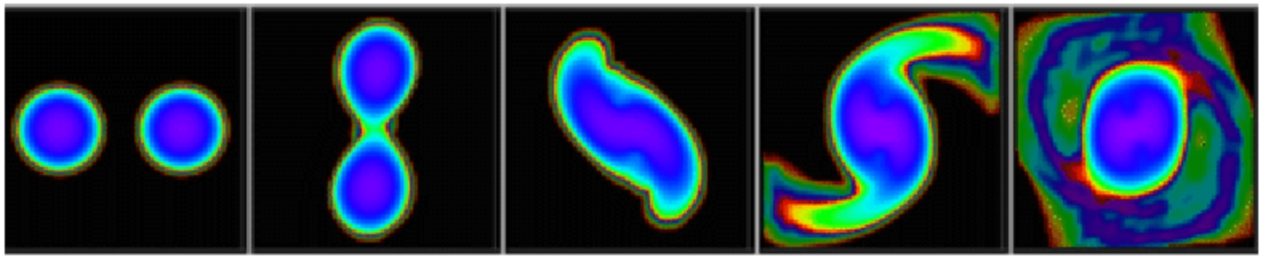
GWs from coalescing binaries

Compact binary mergers

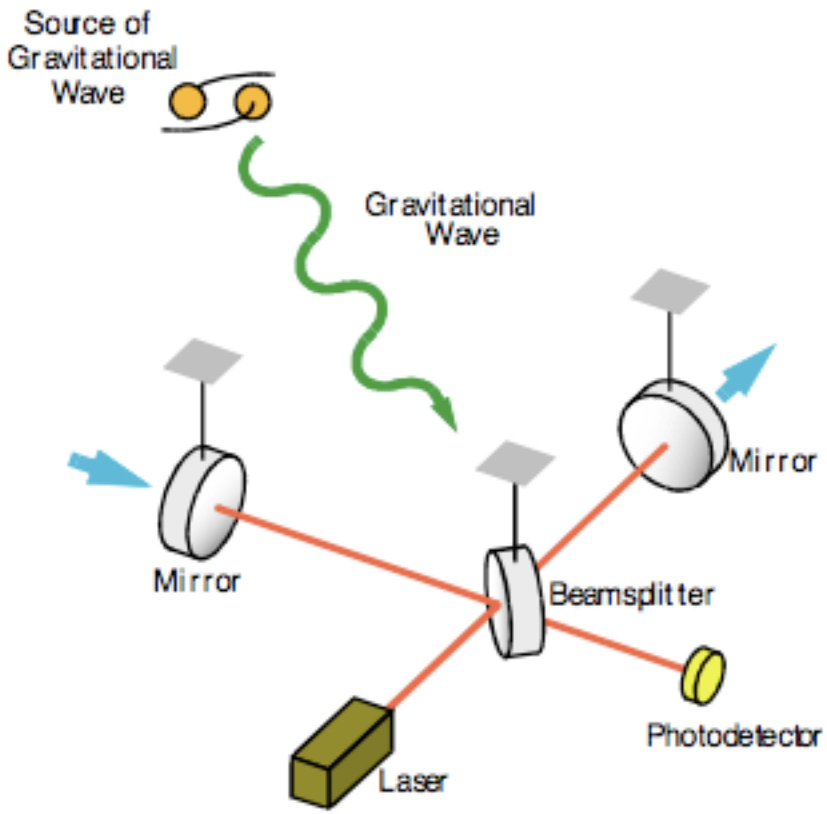


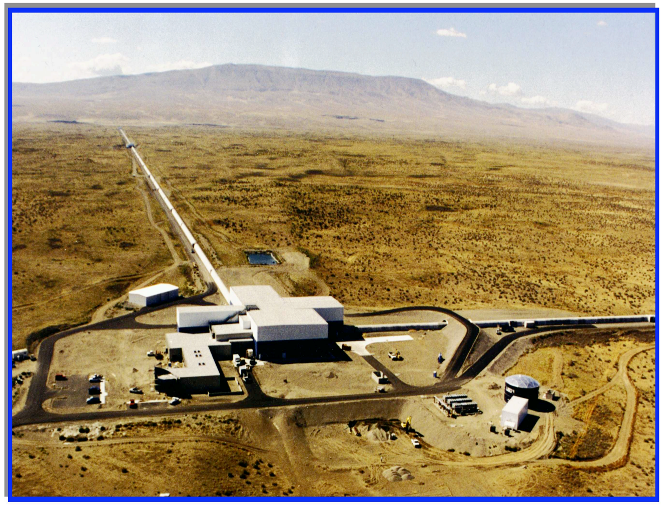


- Neutron star – neutron star (Centrella et al.)

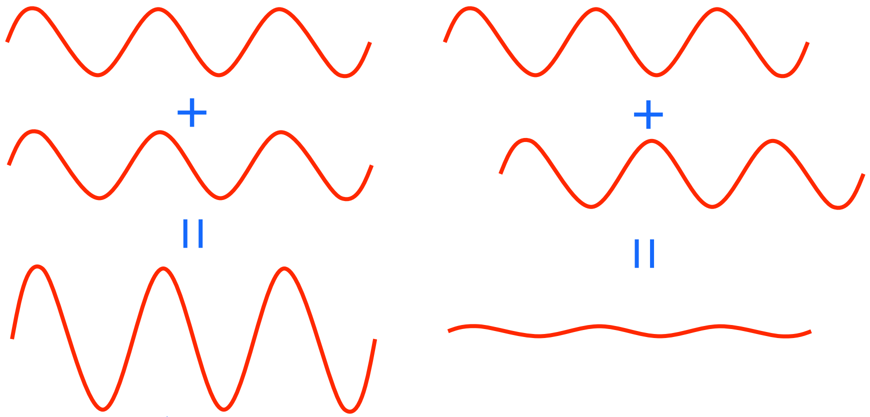


Michelson干渉計を使った重力波検出





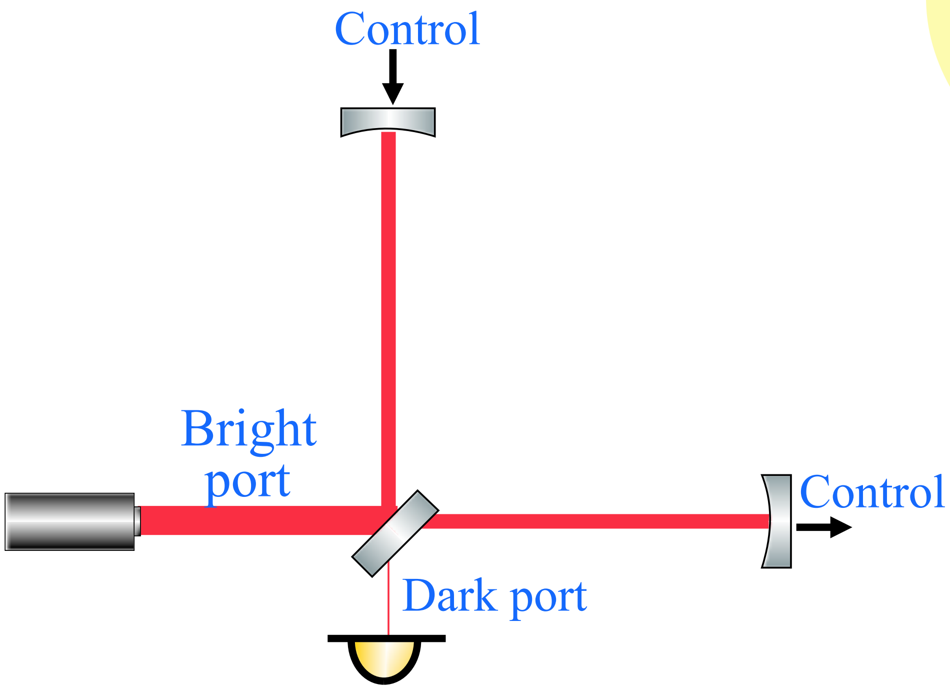
光の重ね合わせ

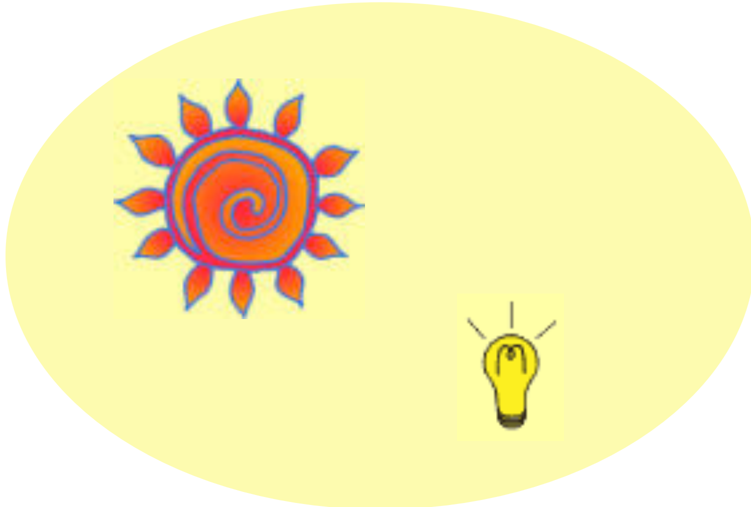


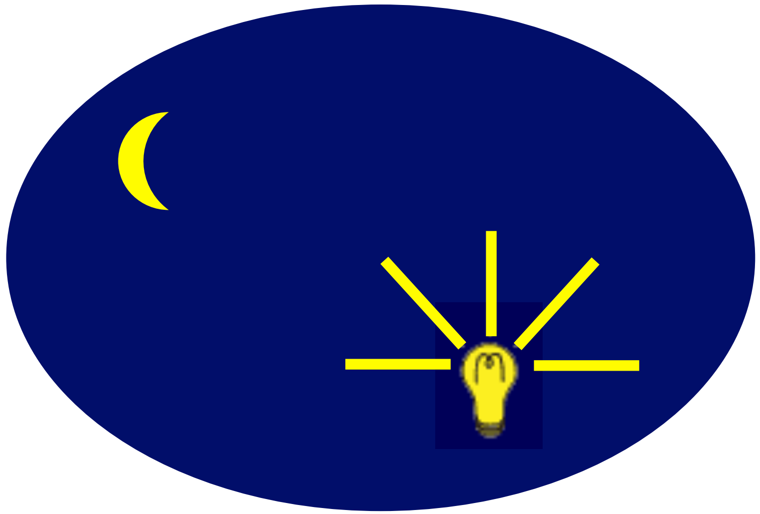
- 重力波が到達すると自由質点である鏡を差動に揺らす
- 微小距離の変化を光の明暗で測定

How to get More sensitivity with control?

Control to keep dart at detection port (Dark fringe locking)

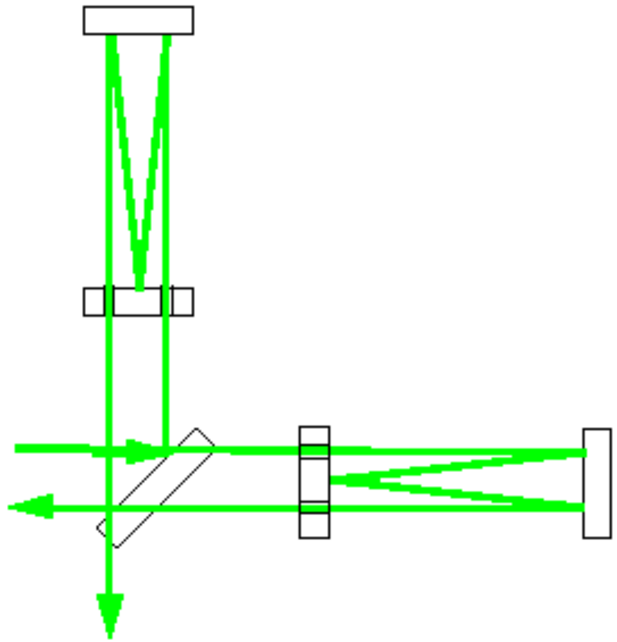


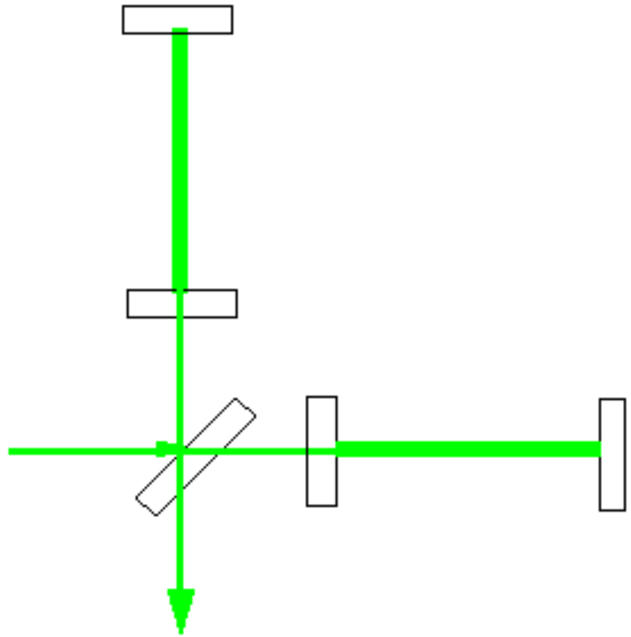




How to make arms longer?

Folding light!





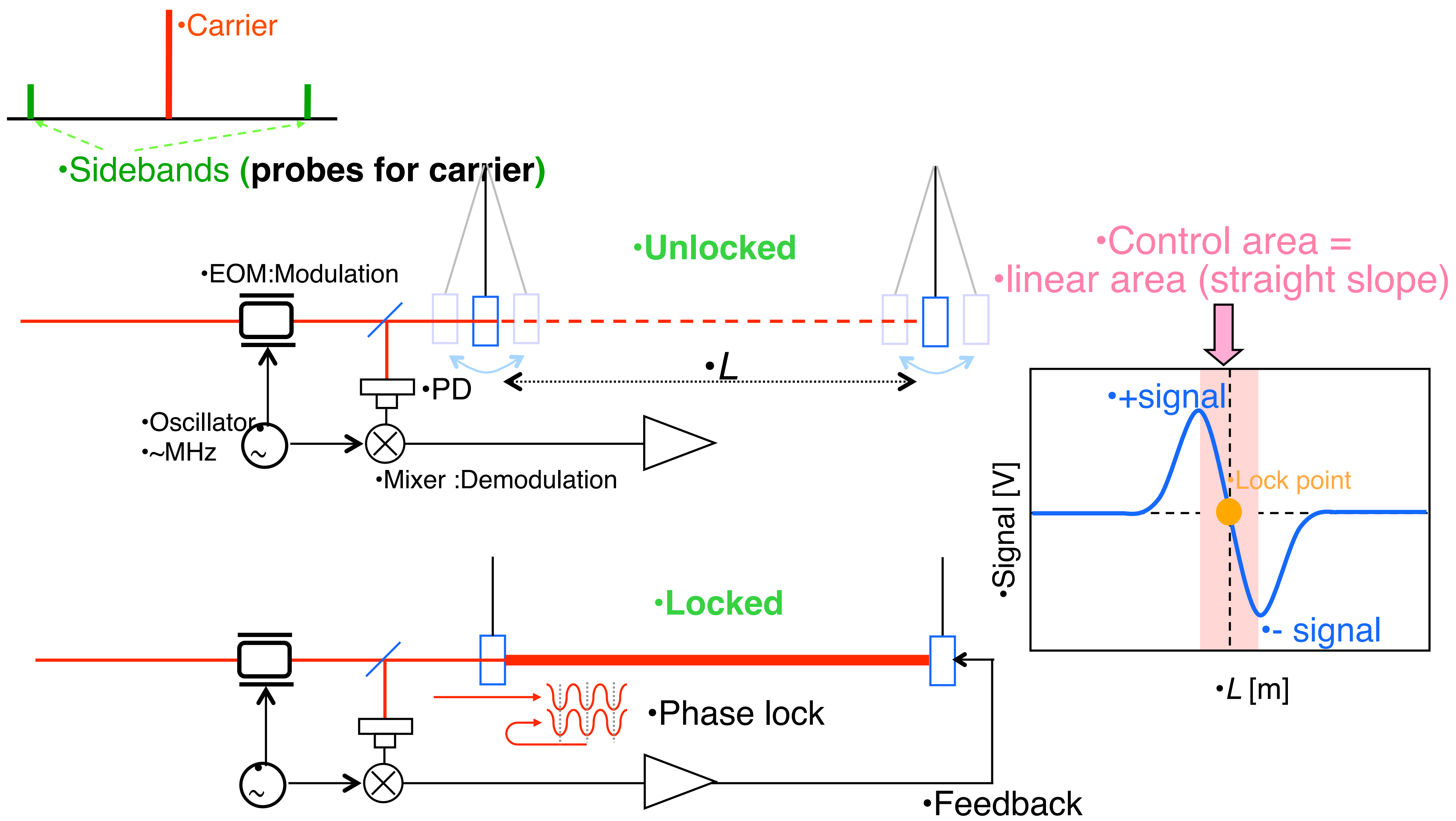
Delay line interferometer

Simple, large mirrors required

Fabry Perot interferometer

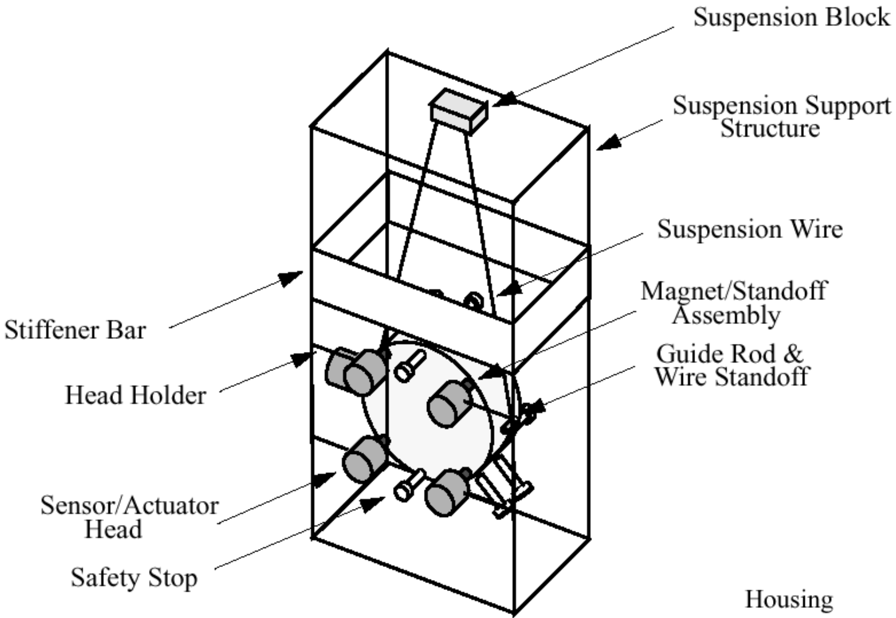
Small mirror, but difficult to control

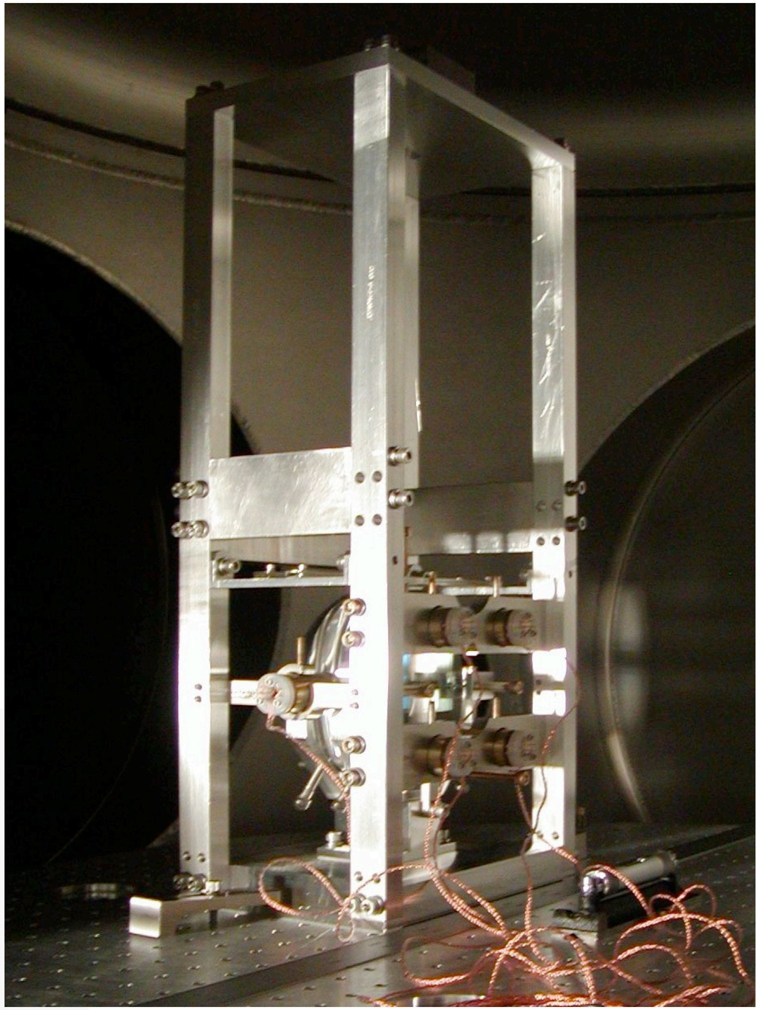
Importance of lock acquisition for the interferometer



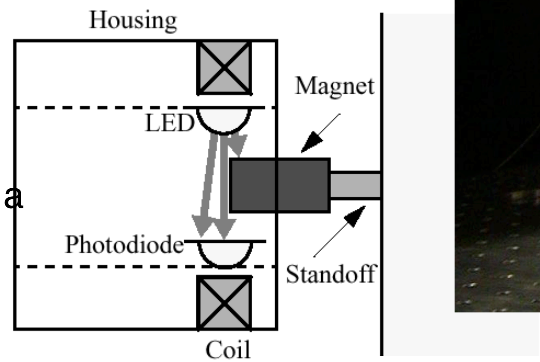
LIGO-I type single suspension

- Each optic has five OSEMs (magnet and coil assemblies), four on the back, one on the side



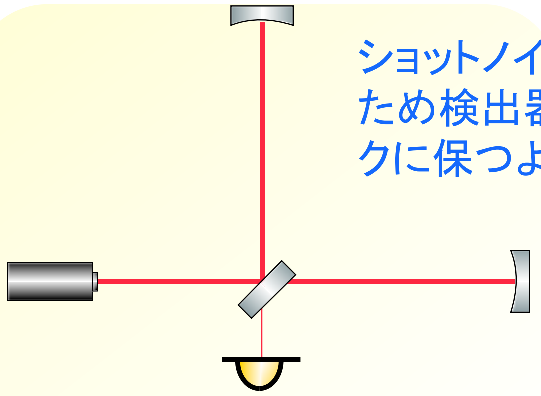


- The magnet occludes light from the LED, giving position
- Current through the coil creates a magnetic field, allowing mirror control



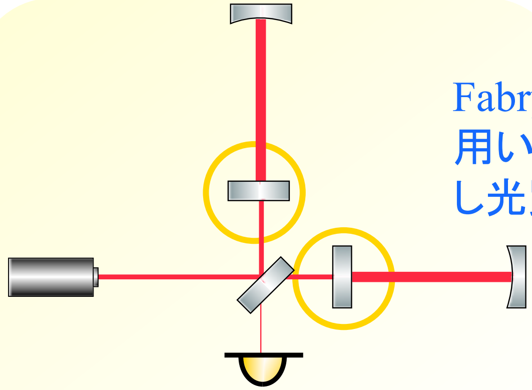
干渉計光学設定の発展

Michelson interferometer (MI)



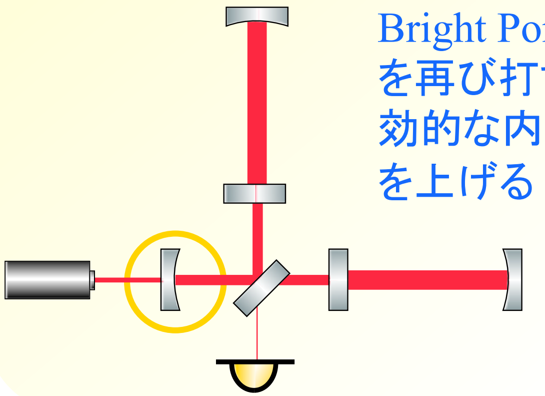
ショットノイズを下げるため検出器側をダークに保つよう制御

Fabry-Perot MI (FPMI)



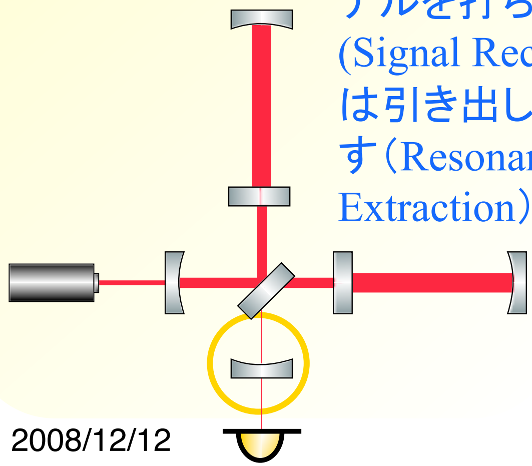
Fabry-Perot caivtyを用い、腕で光を折り返し光路長をかせぐ

Power recycling (PRFPMI)



Bright Port側の光を再び打ち返し、実効的な内部パワーを上げる

Dual recycling (DR)



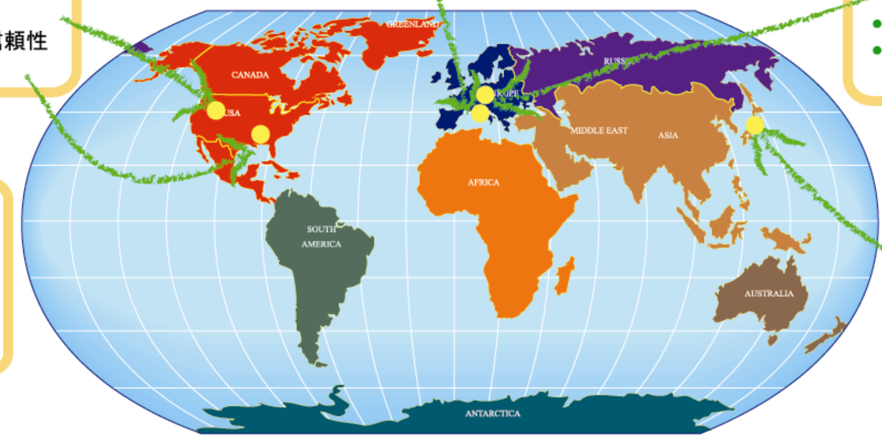
Dark Port側の重力波シグナルを打ち返し増幅する(Signal Recycling)、もしくは引き出しバンド幅を増やす（Resonant Sideband Extraction）

International GW detector network

VIRGO（伊・仏）
- イタリアのピサに基線長3kmの干渉計を開発中
- 2003年から観測開始
- 低周波防振により低い周波数での重力波検出を目指す

LIGO（米）
- ワシントン州と、ルイジアナ州にそれぞれ基線長4kmの干渉計を開発中
- 2002年から観測開始
- 2基の干渉計を作ることでデータの信頼性を向上させる

GEO（独・英）
- ドイツのハノーヴァに基線長600mの干渉計を開発中
- 2001年から観測開始
- 大型干渉計計画の中で、唯一デュアルリサイクリング方式を採用

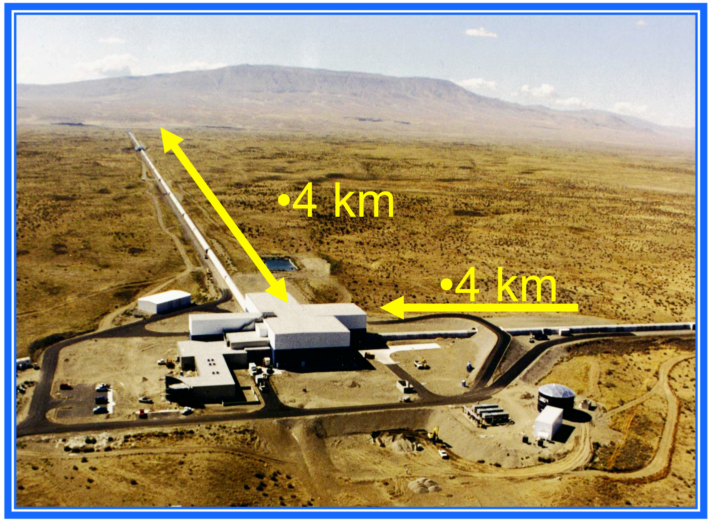


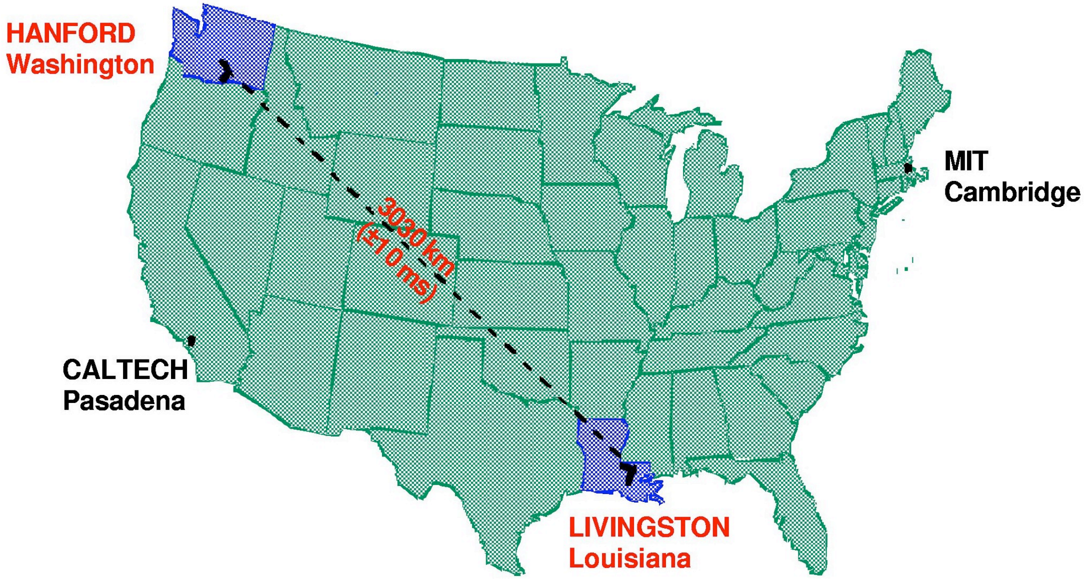
LISA
- 地球の公転軌道上に衛星を打ち上げ基線長500万kmの干渉計を実現する計画
- ESAとNASAとの共同計画

TAMA300（日）
- 国立天文台三鷹キャンパスに建設された基線長300mの干渉計
- 世界で最も早い1999年から観測を開始
- 総予算15億円

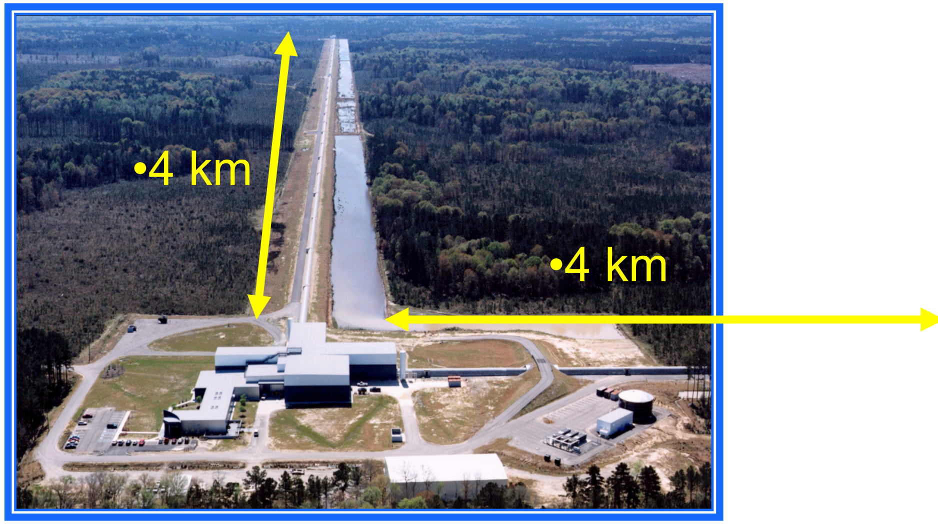
- 同時検出による検出の信頼性向上
- 最低3台あれば重力波源の方向がわかる

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



Other Gravitational Wave Projects: Virgo

- Virgo
  - » Italian, French, Dutch collaboration, located near Pisa
  - » Single 3 km interferometer, similar to LIGO in design and specification
  - » Advanced seismic isolation system ("Super-attenuator")
  - » Operation in coincidence with LIGO since May 2007
- Future Improvements
  - » Virgo+, Advanced Virgo (similar in scope and time to Enhanced LIGO and Advanced LIGO)

Other Gravitational Wave Projects: GEO

- GEO Collaboration
  - » Univ of Glasgow, Cardiff Univ, Albert Einstein Institute, Univ of Birmingham, Rutherford Appleton Lab, Univ of Hannover
  - » GEO as a whole is a member of the LIGO Scientific Collaboration
  - » GEO making a capital contribution to Advanced LIGO
- GEO600
  - » Near Hannover
  - » 600 m arms
  - » No arm cavities
  - » Signal recycling
  - » Fused silica suspensions
- GEO-HF
  - » Proposed up-grade
  - » Pioneer advanced optical techniques

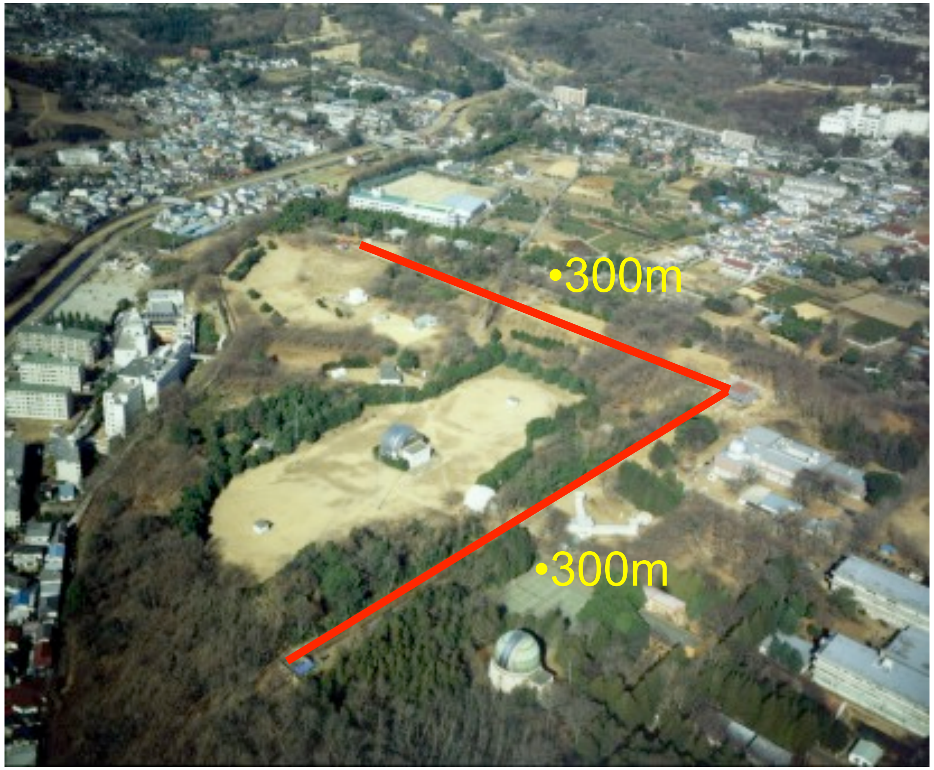
日本の主力重力波検出器

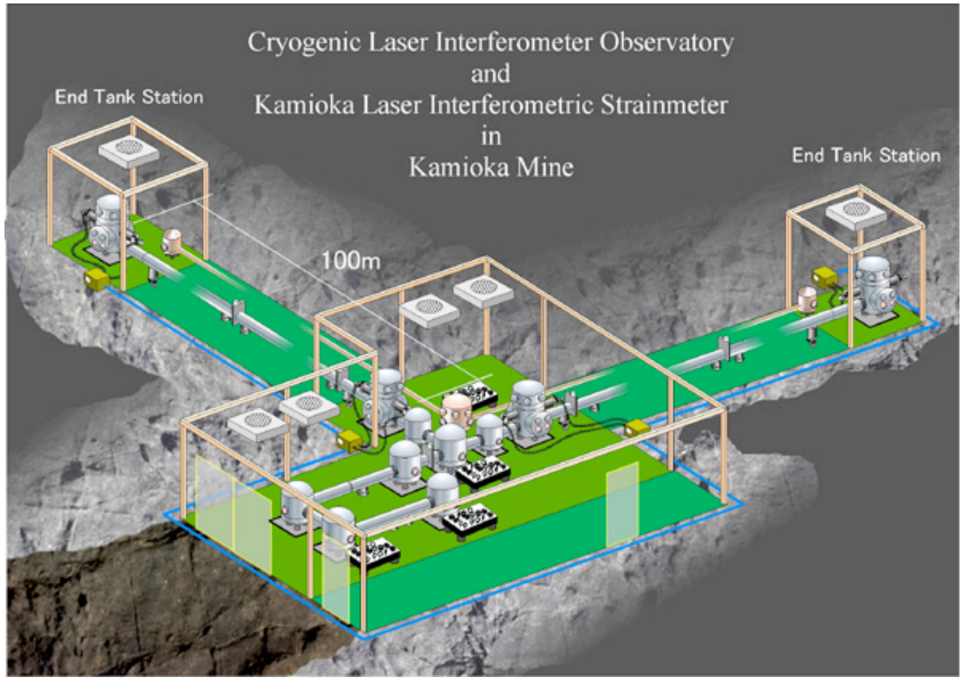
TAMA300

- 基線長 300m、国立天文台三鷹キャンパスに建設
- 銀河近傍で発生する重力波イベントを検出可能な**実証型検出器**の建設
- 将来の km 級干渉計のための**技術開発**

CLIO

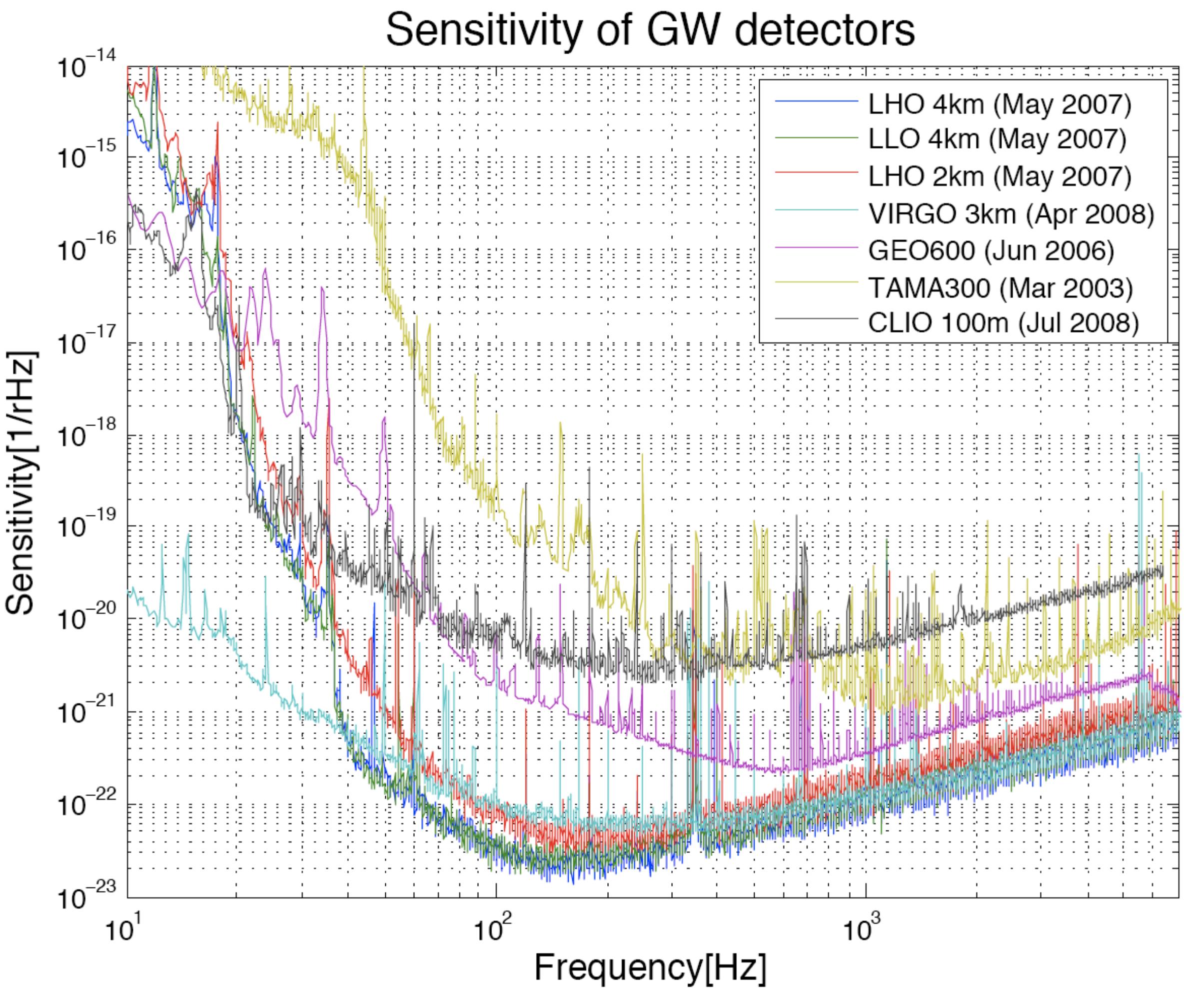
- 基線長100m、神岡鉱山内に設置
- LCGTの要素技術のひとつ**低温動作**の検証





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



LIGO is big science

- LIGO = LIGO Laboratory and the LIGO Scientific Collaboration
- LIGO Laboratory
  - » ~180 people, headquartered at Caltech with observatories in Livingston Louisiana and Hanford Washington and a very significant group at MIT
  - » Managed by Caltech under a cooperative agreement with NSF
  - » Annual operating budget is ~33M$
- The LIGO Scientific Collaboration (LSC)
  - » LSC has ~ 500 members (including LIGO Lab), 411 names on author list from 44 institutions
  - » LSC does R&D, analyses data and publishes science
  - » LSC has been integrated into the LIGO Lab management structure
    - – LSC maintains independent governance

LIGO *Beam Tube*

チューブの中は真空に保たれていて、光の位相揺らぎを小さくする

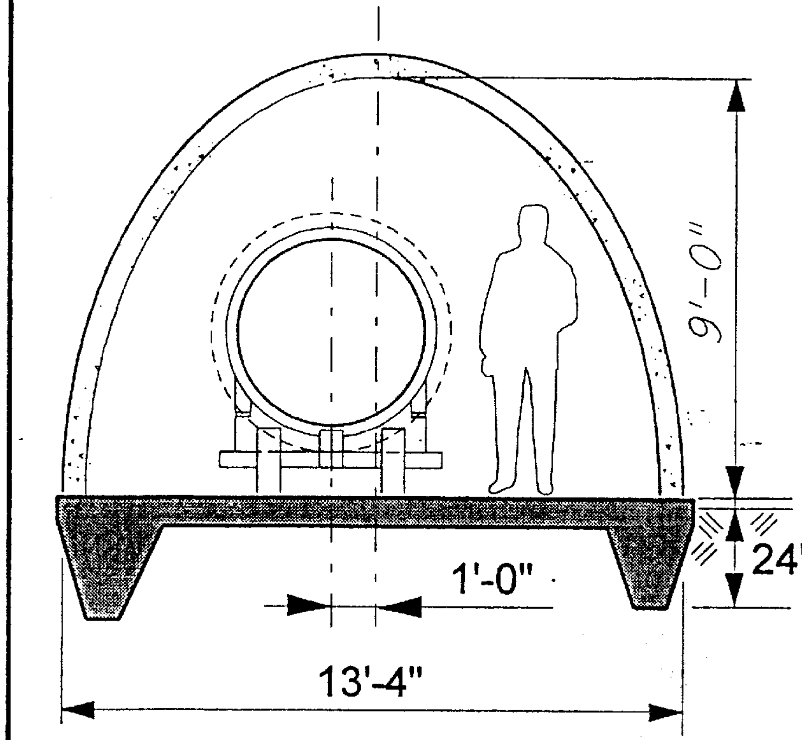
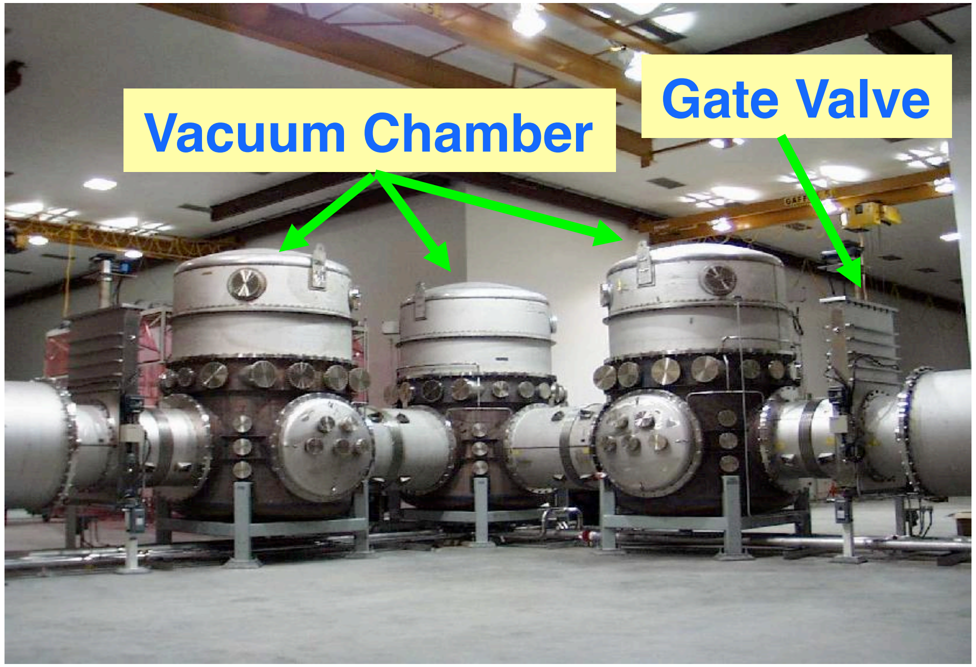


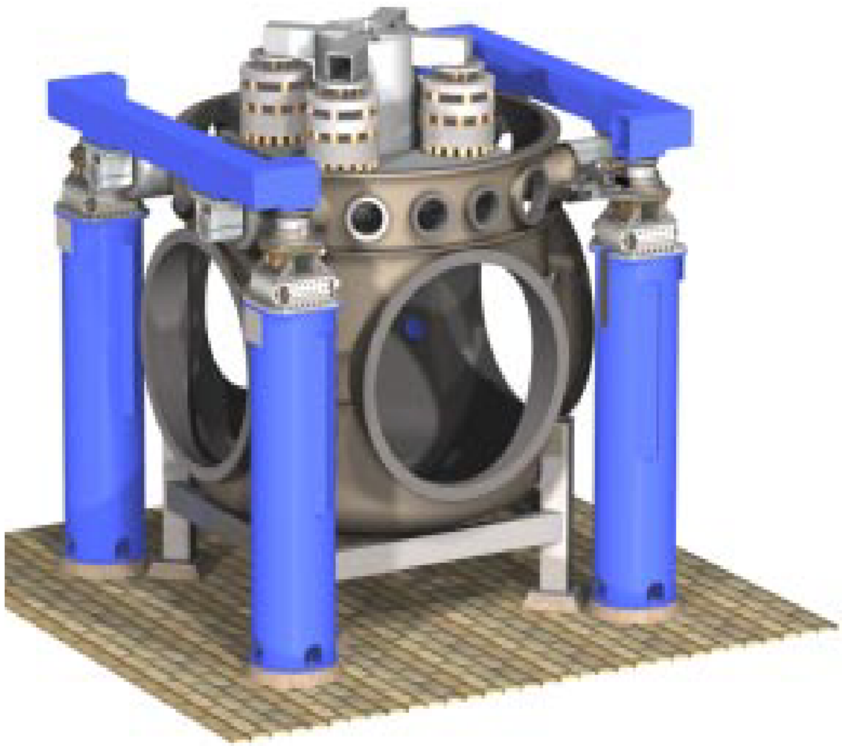
Figure 2.1-1 -- Cross Section of Design Baseline at Hanford

LIGO vacuum equipment

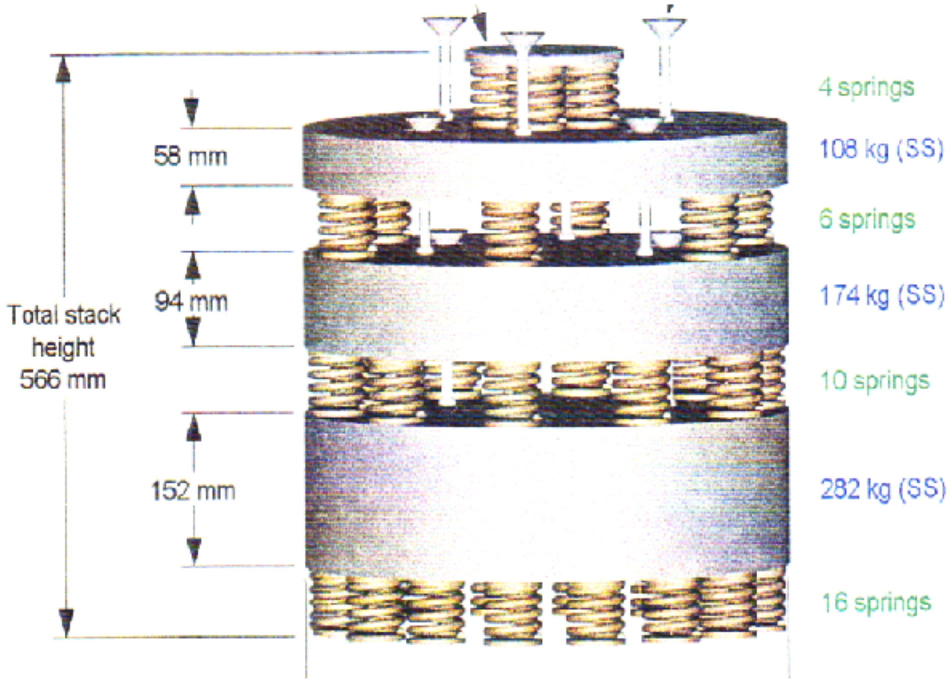
すべての光学部品は真空
中にあるため、気体の圧力
で鏡が揺らされない

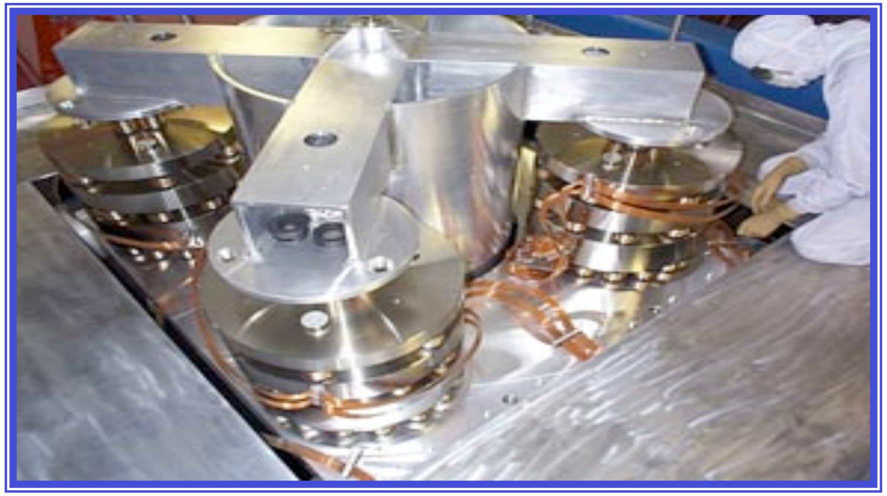


Active Isolation



Seismic isolation stacks



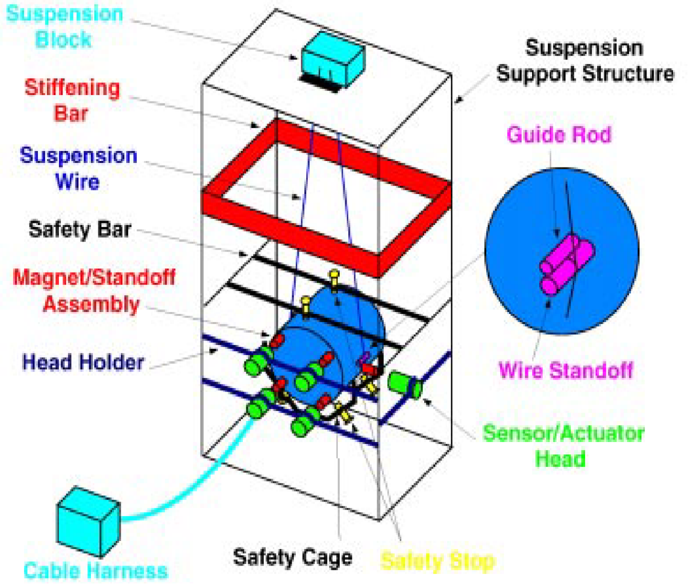


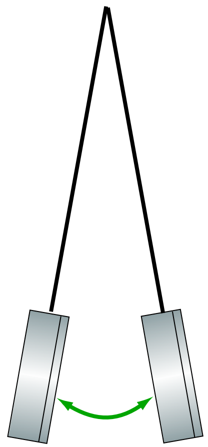
LIGO Optics

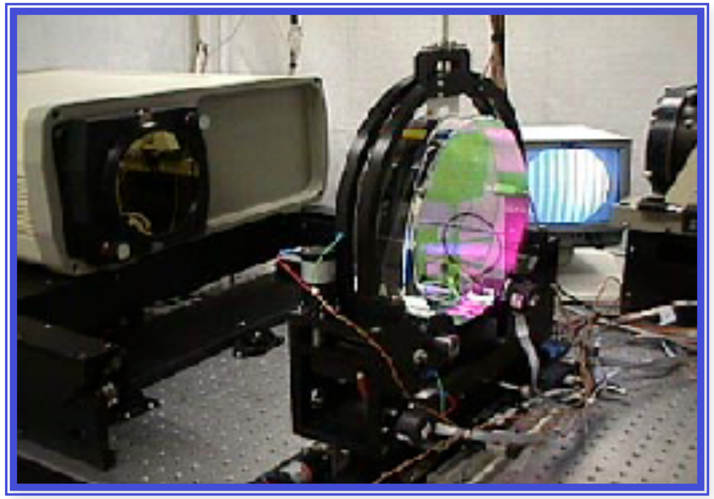
suspension mirrors, coating and polishing

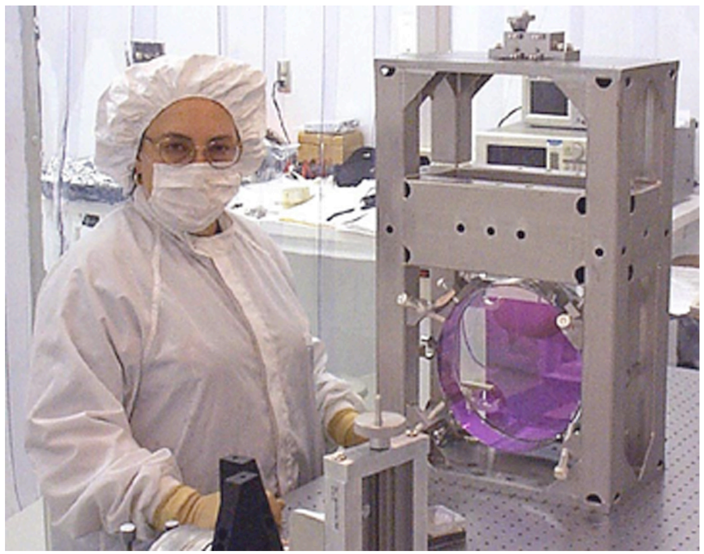
- 合成石英鏡: 重さ10kg
- 防振と自由質点実現のため振り子につられている

Single suspension 0.31mm music wire

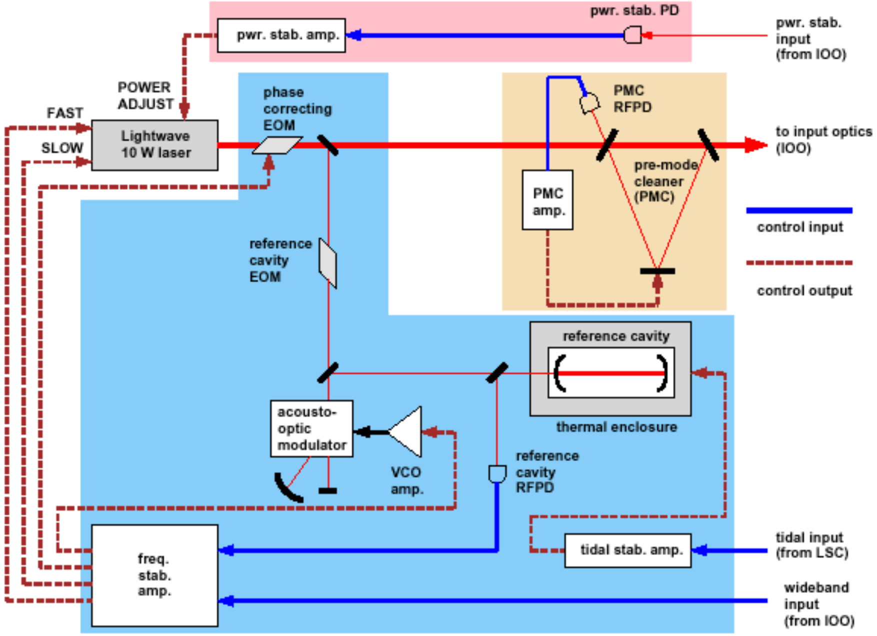




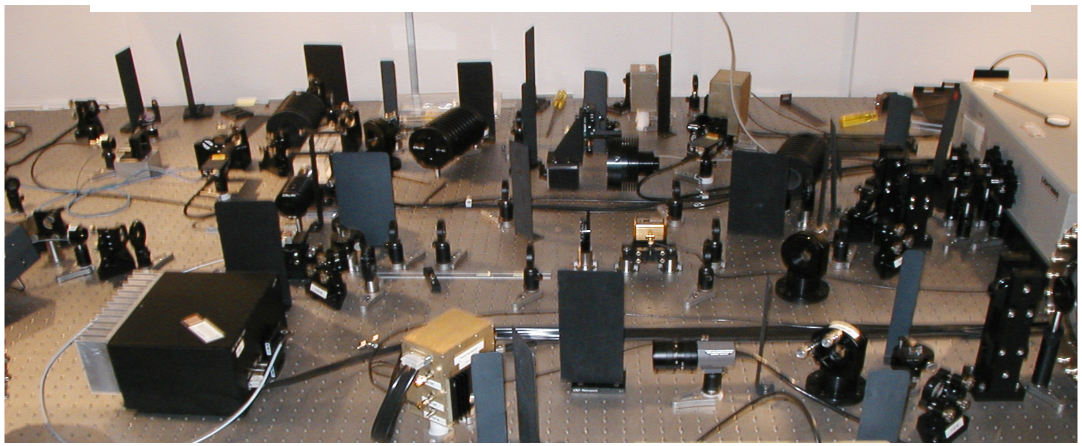


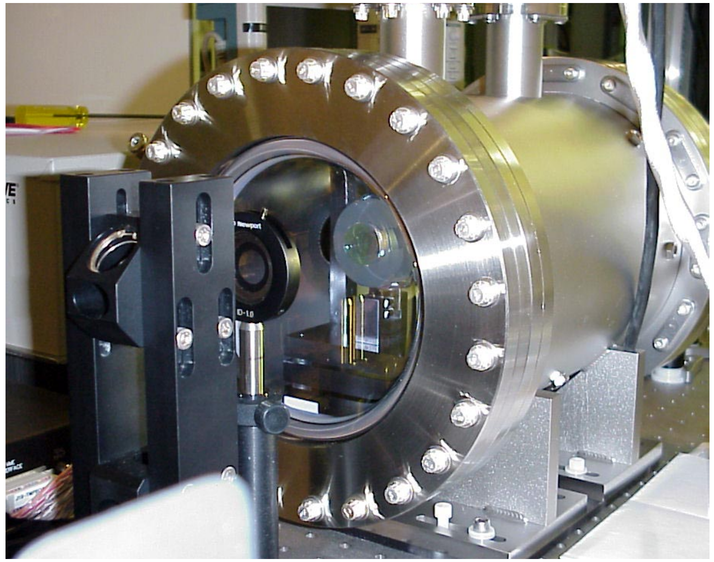


Pre-stabilized laser (PSL)

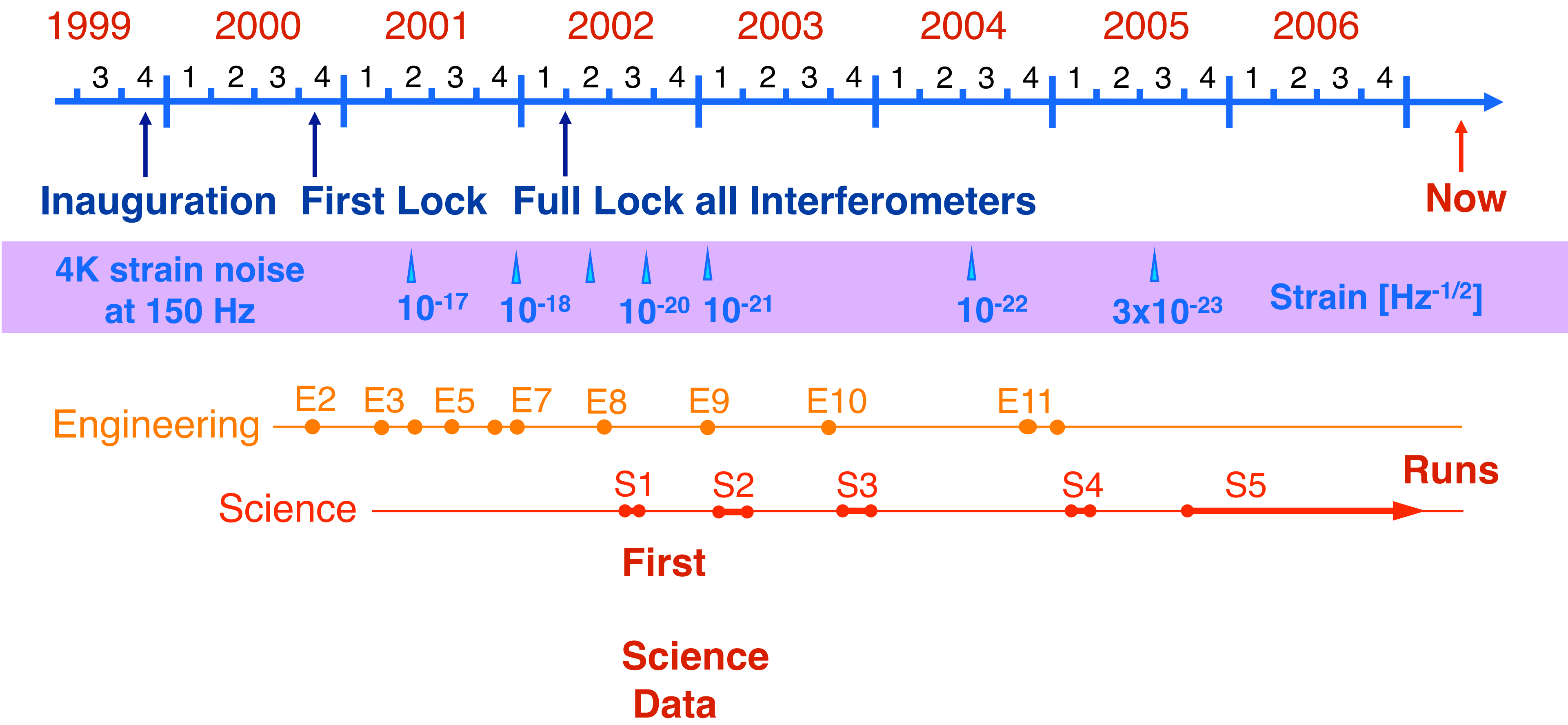


- 旧LIghtwave社製10W MOPA(LIGOとの共同開発)
- Reference cavityによる周波数安定化
- Pre-Mode Cleanerによる
- 強度安定化
- Mode Cleaner, 干渉計の腕キャビティーの同相成分による周波数安定化

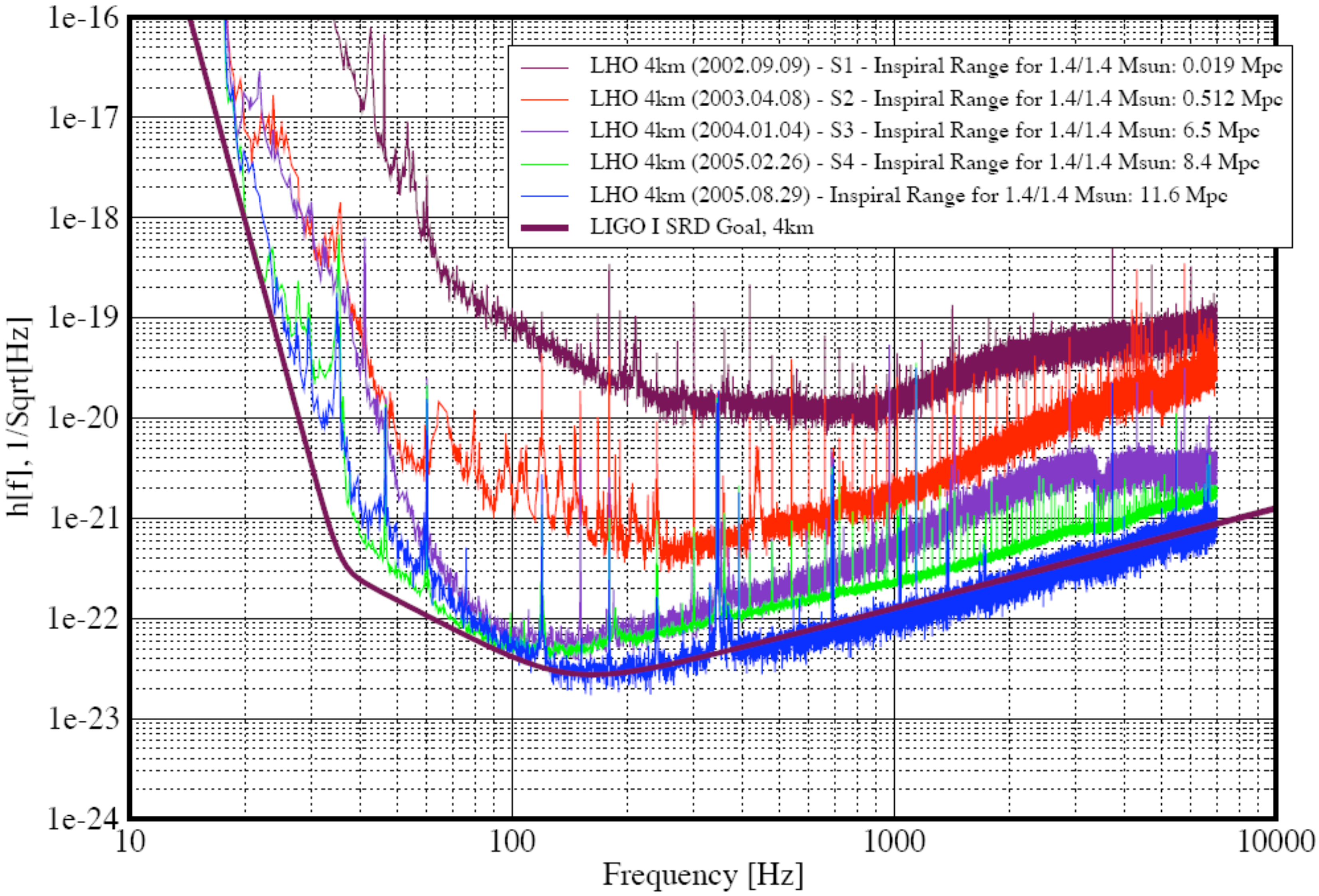


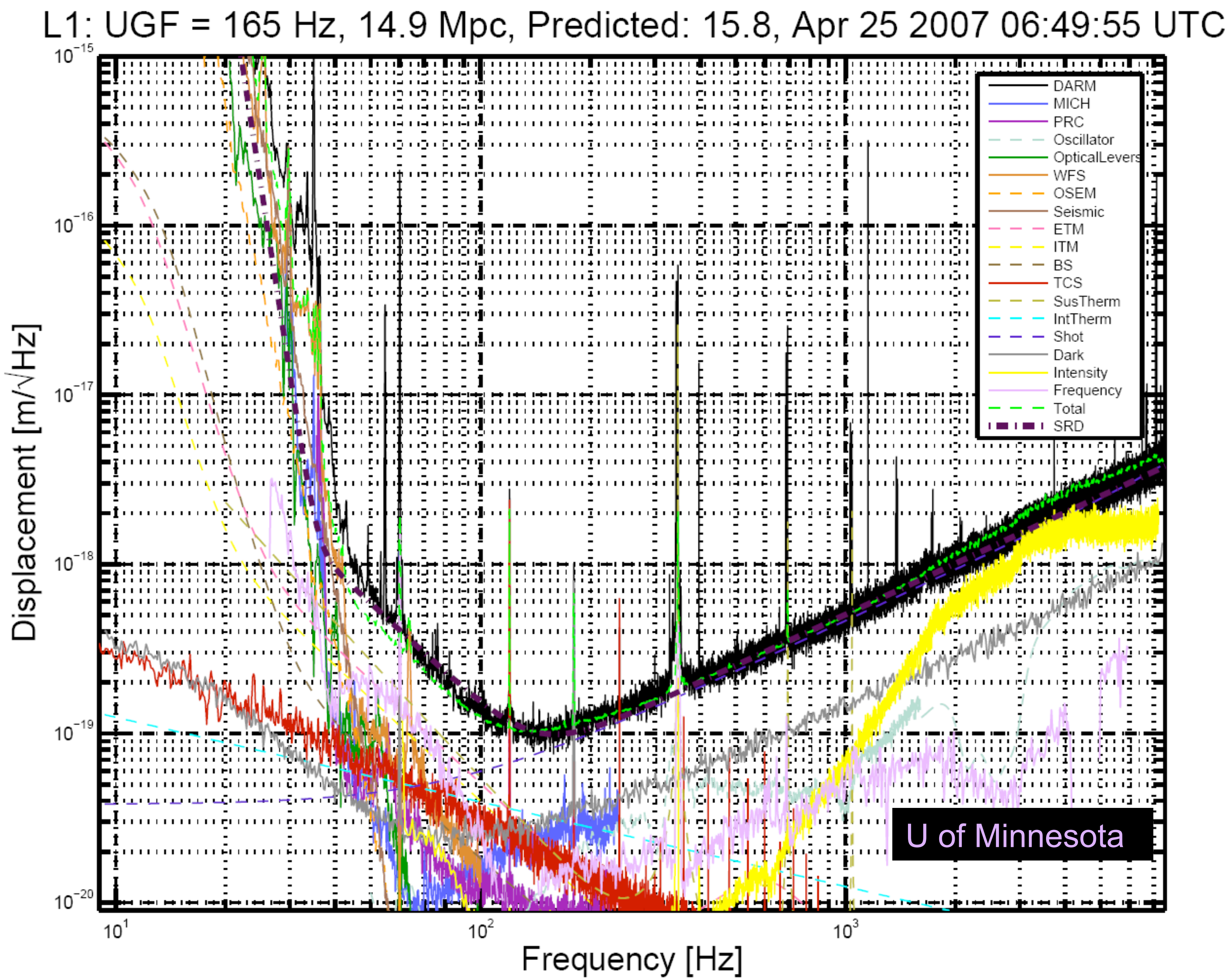


LIGO History

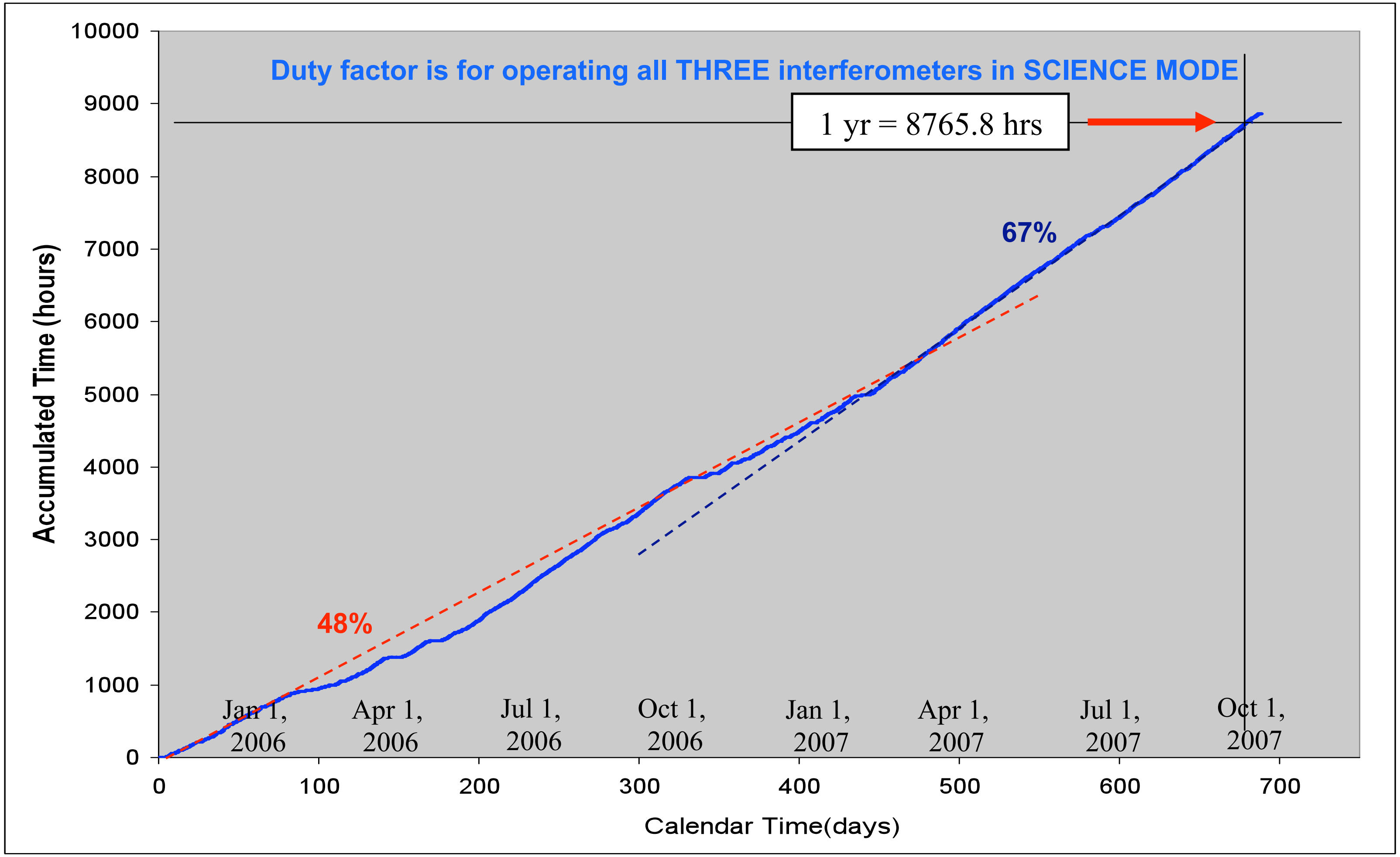


Progress of LIGO Sensitivity

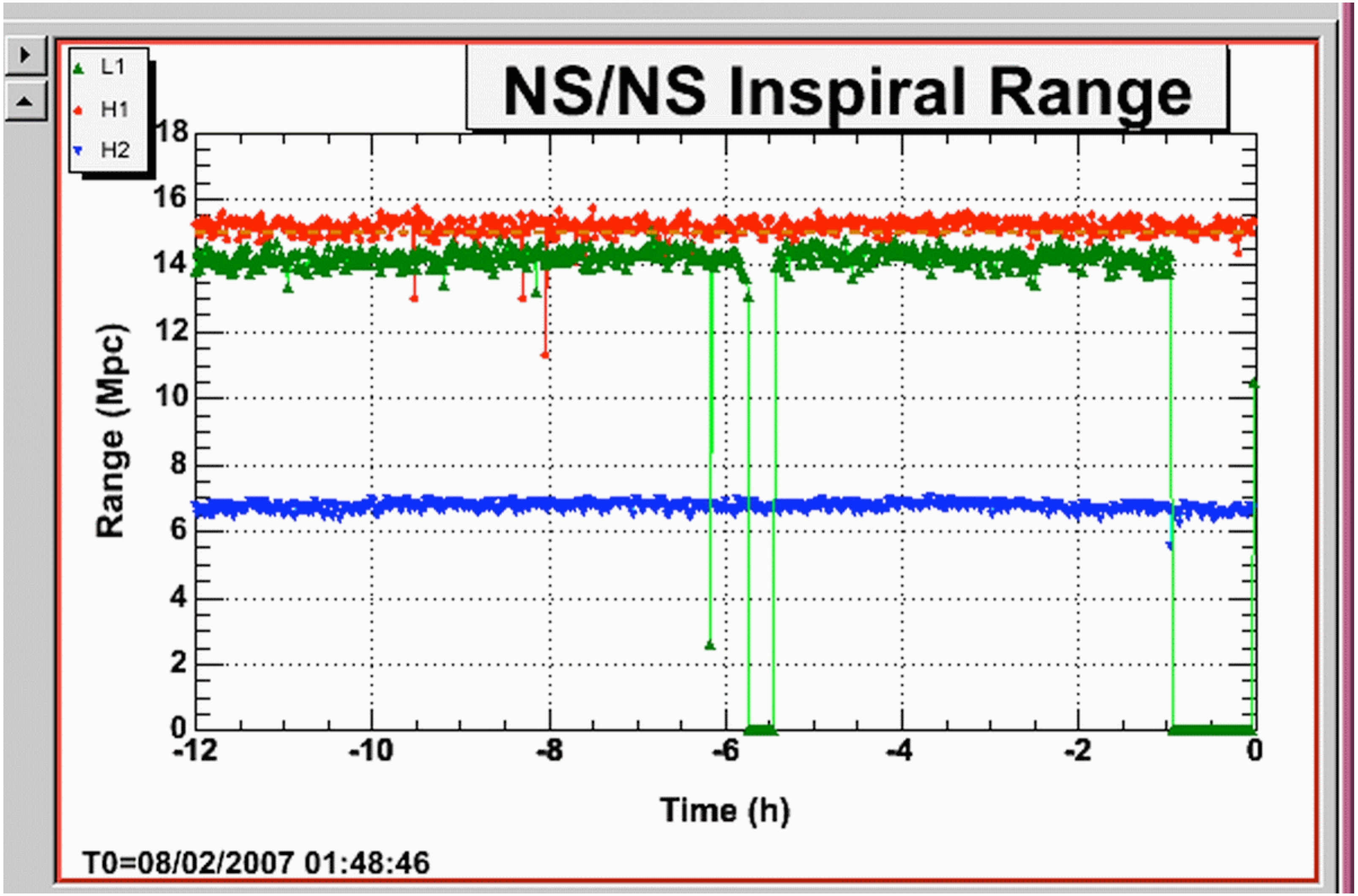



L1: UGF = 165 Hz, 14.9 Mpc, Predicted: 15.8, Apr 25 2007 06:49:55 UTC
Displacement [m/√Hz]
Frequency [Hz]
DARM
MICH
PRC
Oscillator
OpticalLevers
WFS
OSEM
Seismic
ETM
ITM
BS
TCS
SusTherm
IntTherm
Shot
Dark
Intensity
Frequency
Total
SRD
U of Minnesota

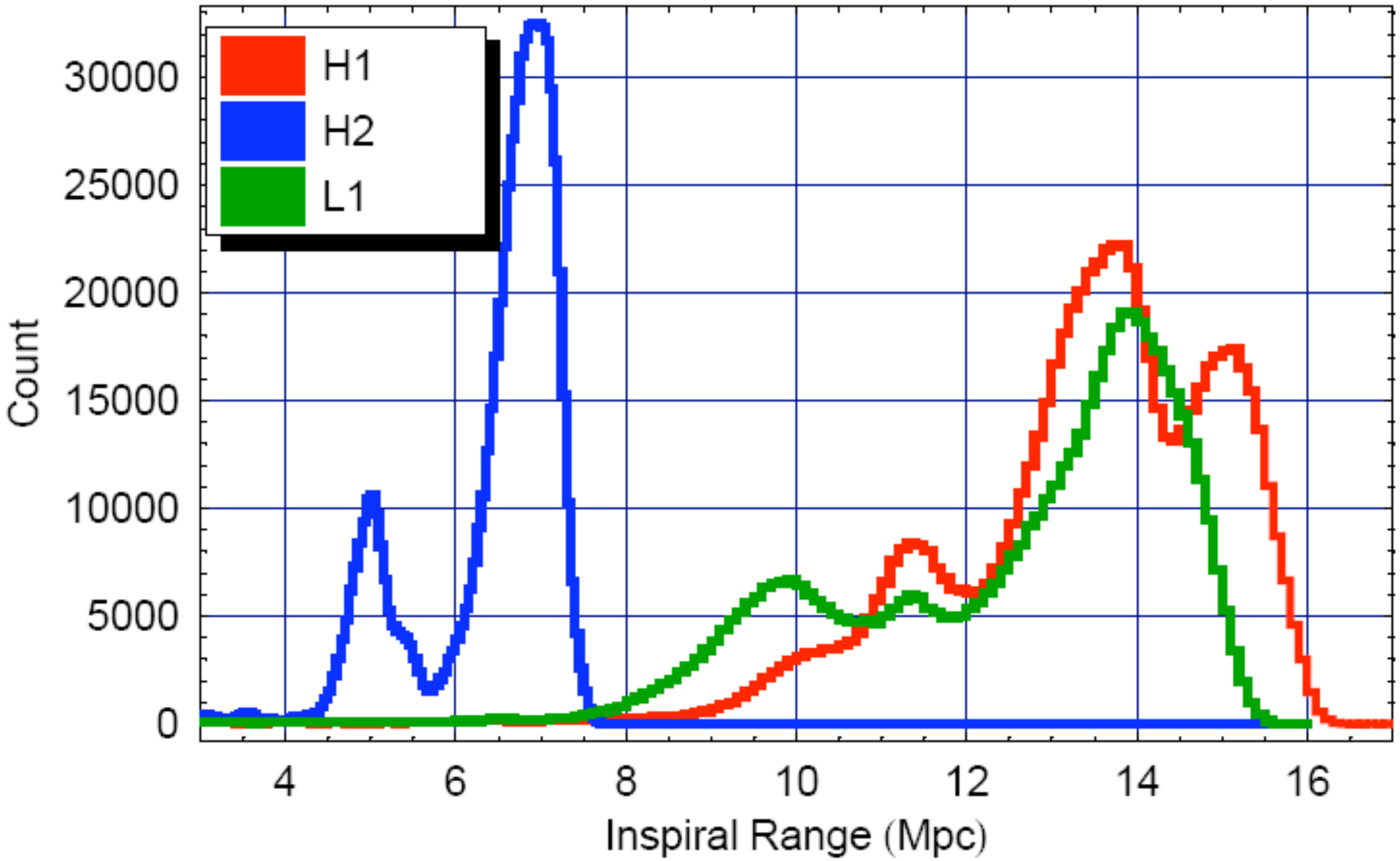
Triple-coincidence Science Mode Observation Time Accumulation vs. Calendar Time



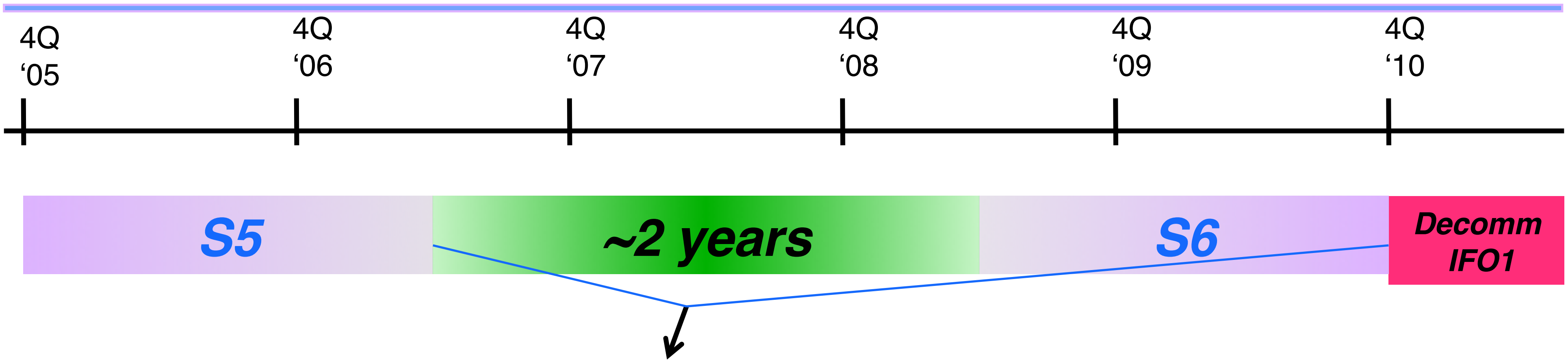
LIGO Duty Factor



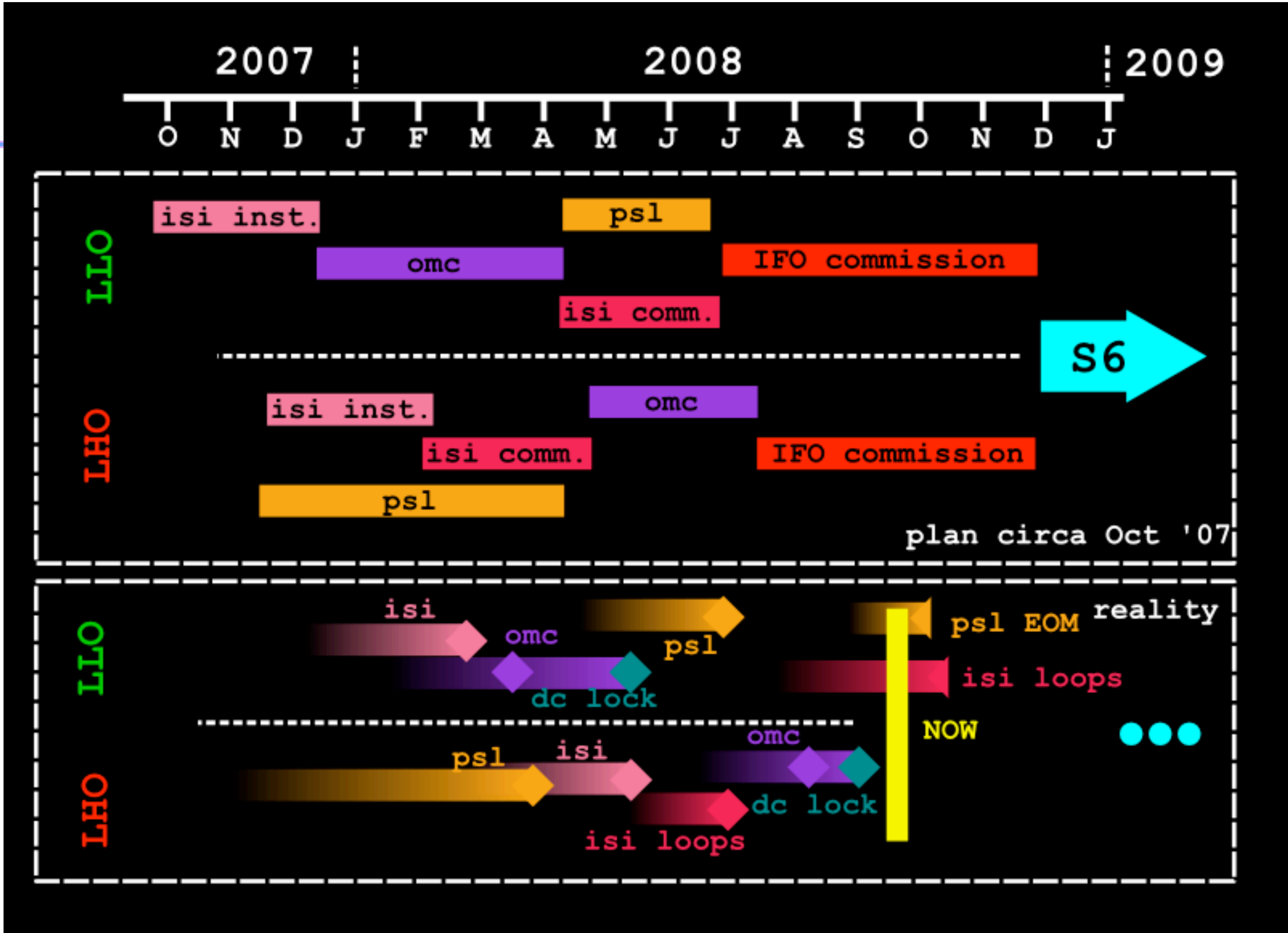
Duty Factor for S5



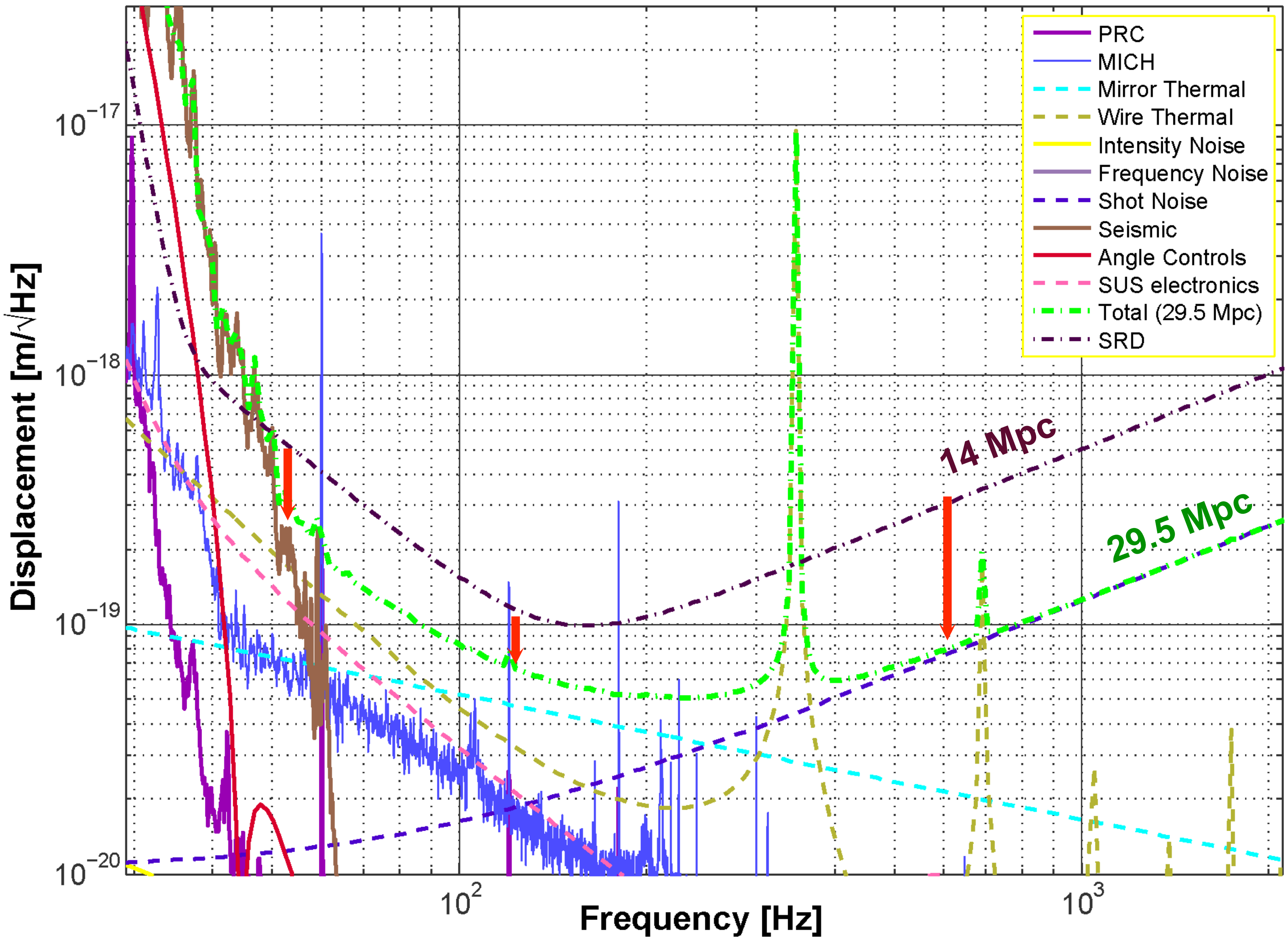
Enhanced LIGO

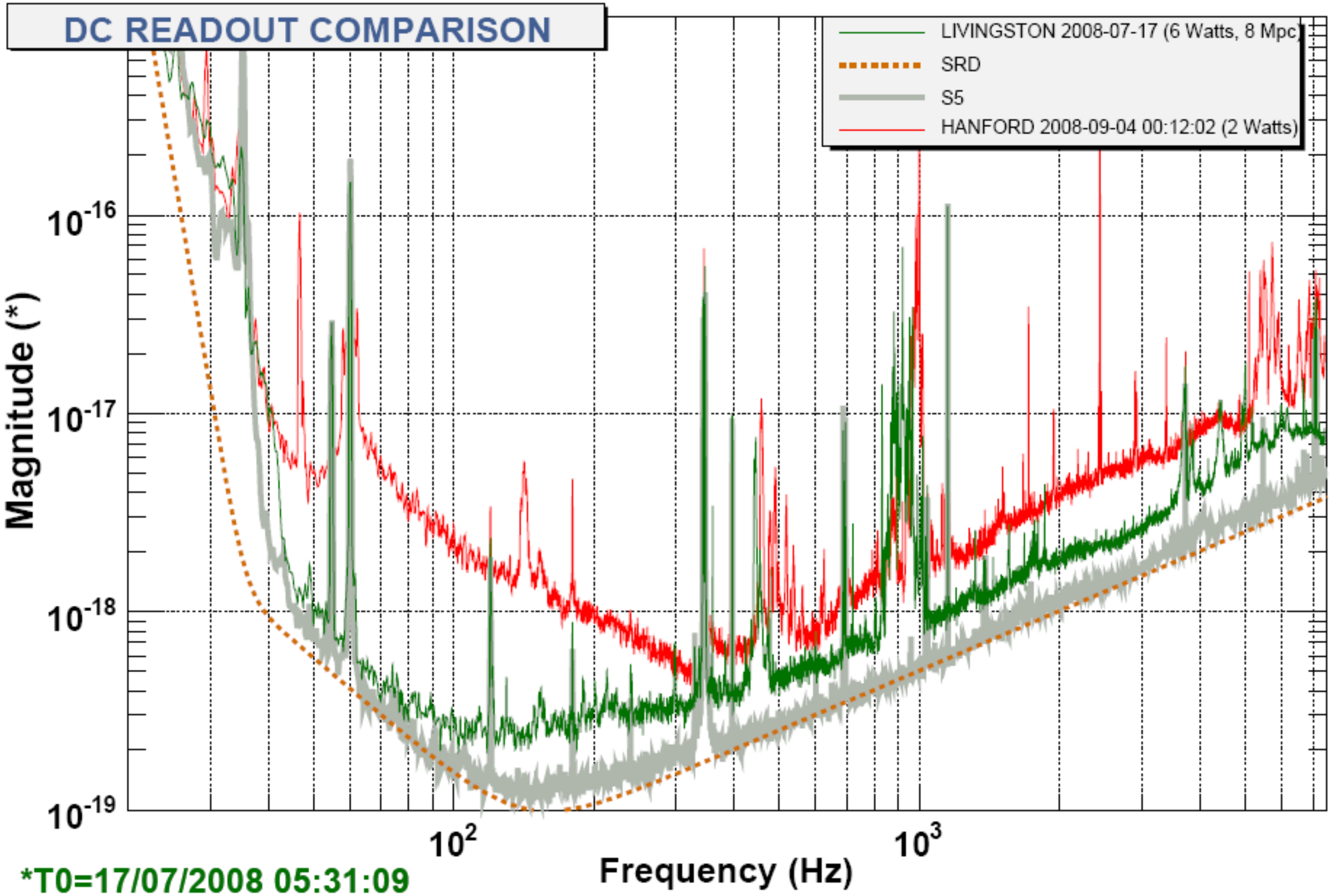


- Enough time for one significant set of enhancements
  - » Higher laser power
  - » DC readout
  - » Output modecleaner
- Aim for a factor of 2 improvement in sensitivity (factor of 8 in event rate)
- Early tests of Advanced LIGO hardware and techniques


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
omc
psl
isi
dc lock
isi loops

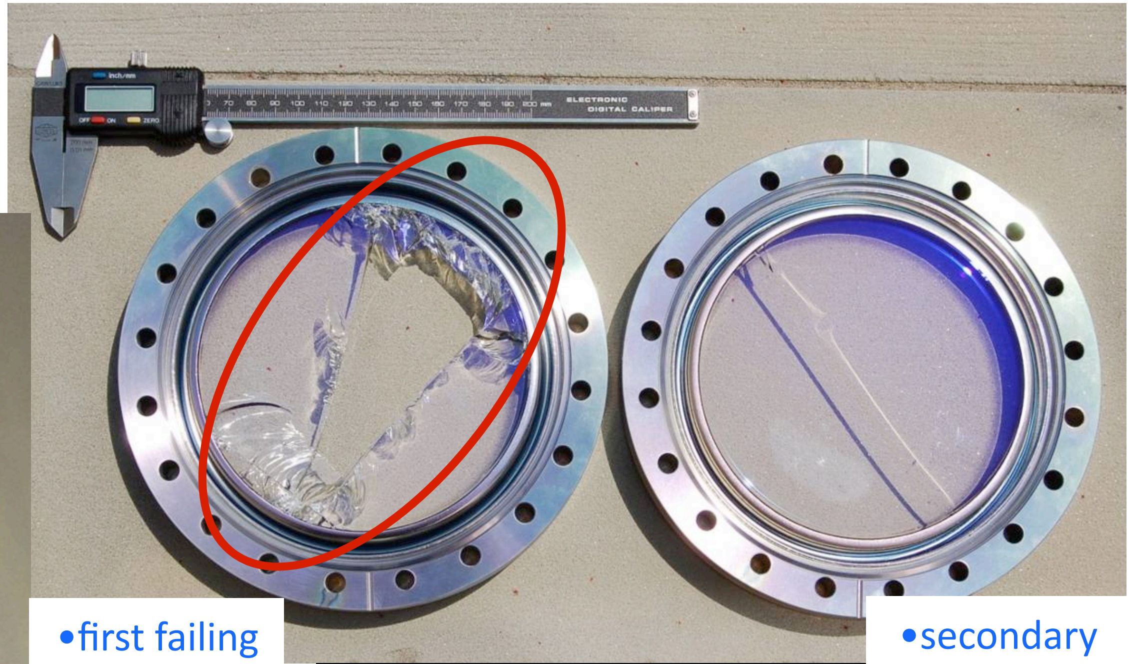
Limiting noise sources for an enhanced detector are understood




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

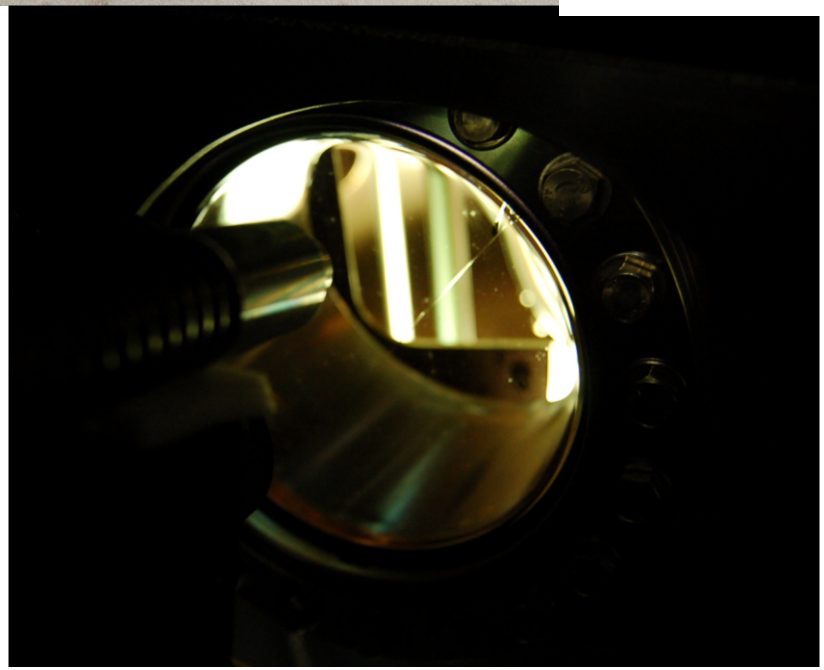
VIRGO Broken Viewports

•From inside



•first failing

•secondary



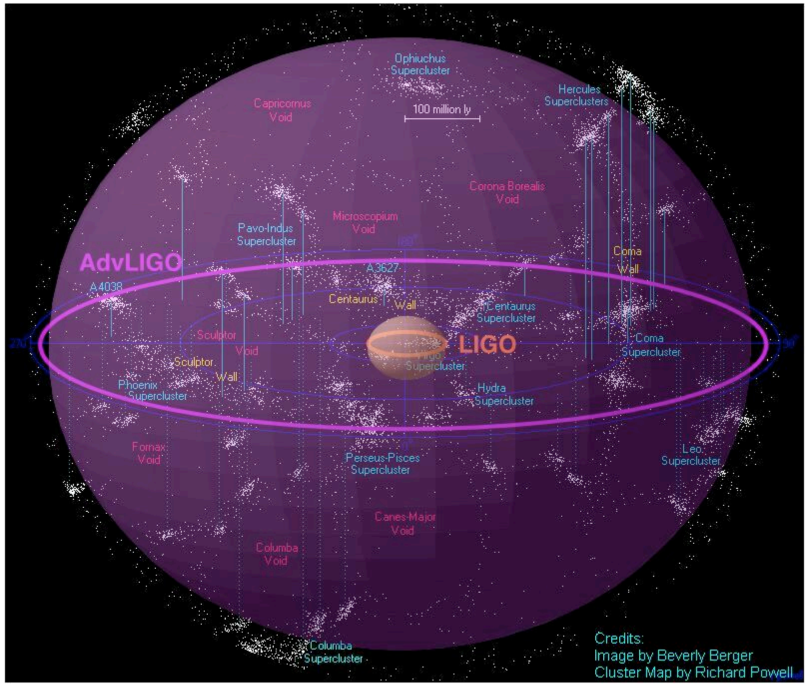
•From outside

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.

Advanced LIGO!

- Take advantage of new technologies and on-going R&D
  - » Active anti-seismic system operating to lower frequencies
  - » Lower thermal noise suspensions and optics
  - » Higher laser power
  - » More sensitive and more flexible optical configuration



x10 better amplitude sensitivity

⇒ x1000 rate=(reach)^3

⇒ 1 day of Advanced LIGO

» 1 year of Initial LIGO !

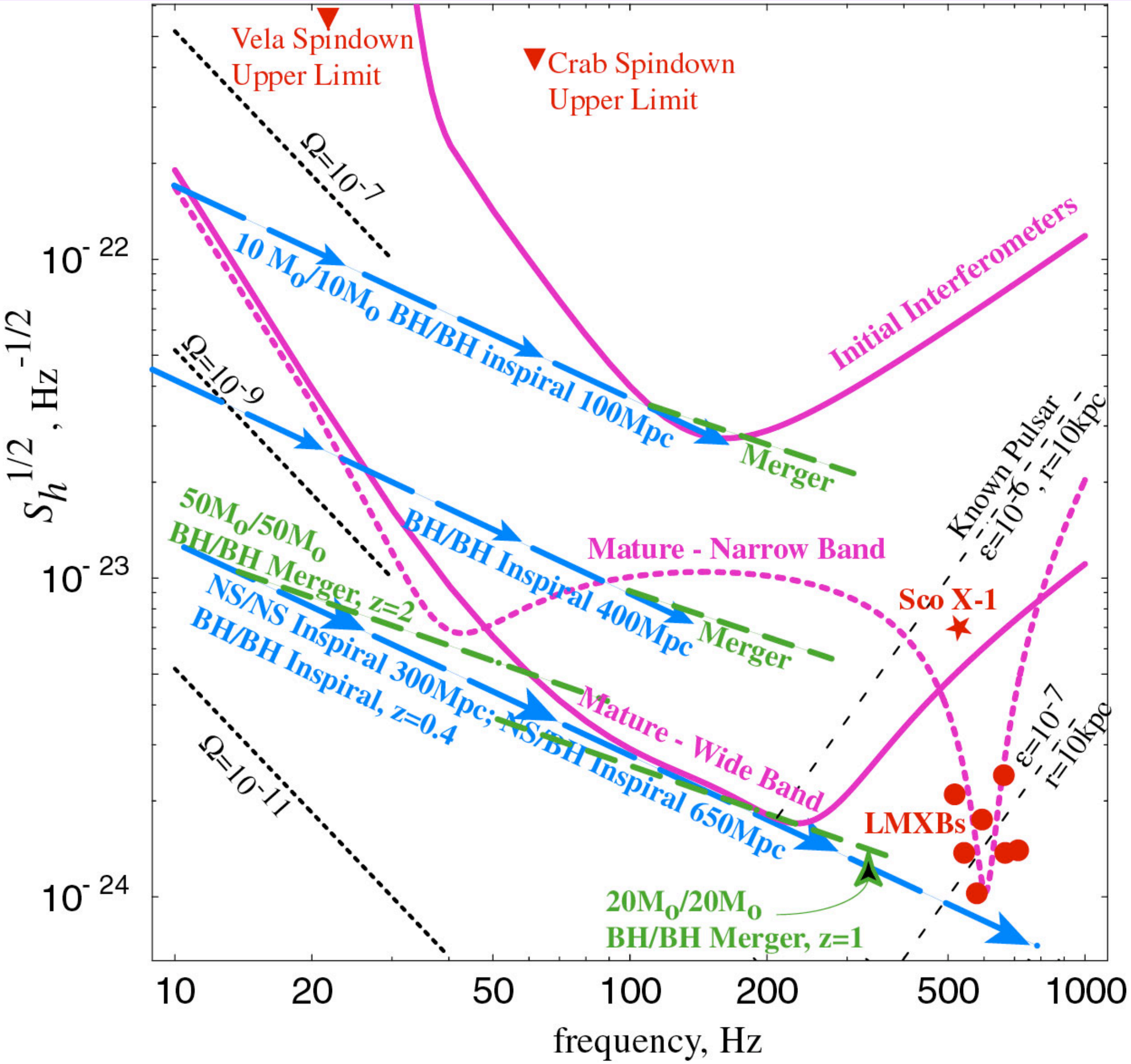
Planned for FY2008 start, installation beginning 2011

What is so Advanced about Advanced LIGO?

Parameter	*LIGO*	*Advanced LIGO*
Input Laser Power	10 W	180 W
Mirror Mass	10 kg	40 kg
Interferometer Topology	Power-recycled Fabry-Perot arm cavity Michelson	Dual-recycled Fabry-Perot arm cavity Michelson
GW Readout Method	RF heterodyne	DC homodyne
Optimal Strain Sensitivity	3×10^{-23} / rHz	Tunable, better than 5×10^{-24} / rHz in broadband
Seismic Isolation Performance	$f_{low} \sim 50$ Hz	$f_{low} \sim 10$ Hz
Mirror Suspensions	Single Pendulum	Quadruple pendulum

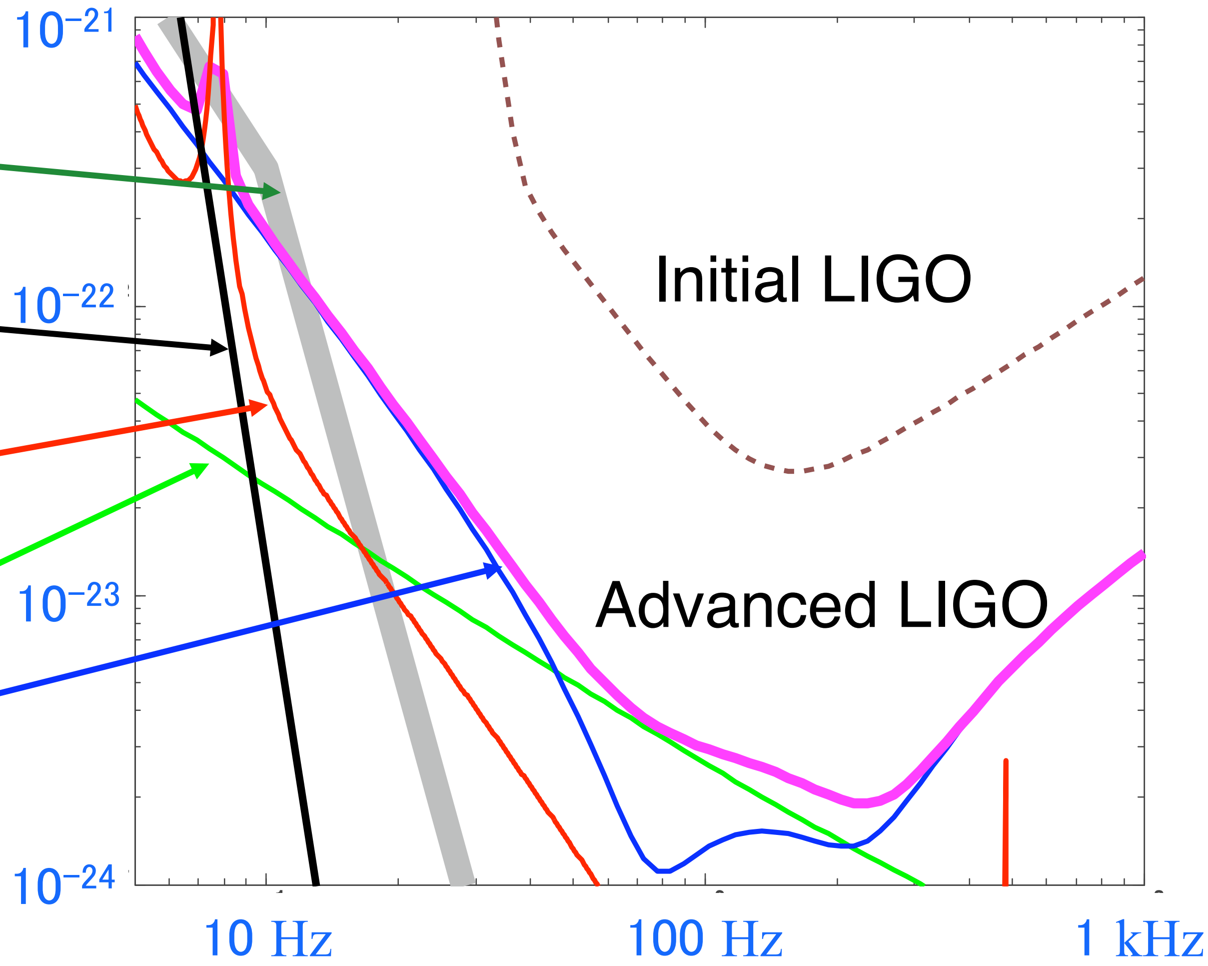
Astrophysical Targets for Advanced LIGO

- Neutron star & black hole binaries
  - » inspiral
  - » merger
- Spinning neutron stars
  - » LMXBs
  - » known pulsars
  - » previously unknown
- Supernovae
- Stochastic background
  - » Cosmological
  - » Early universe

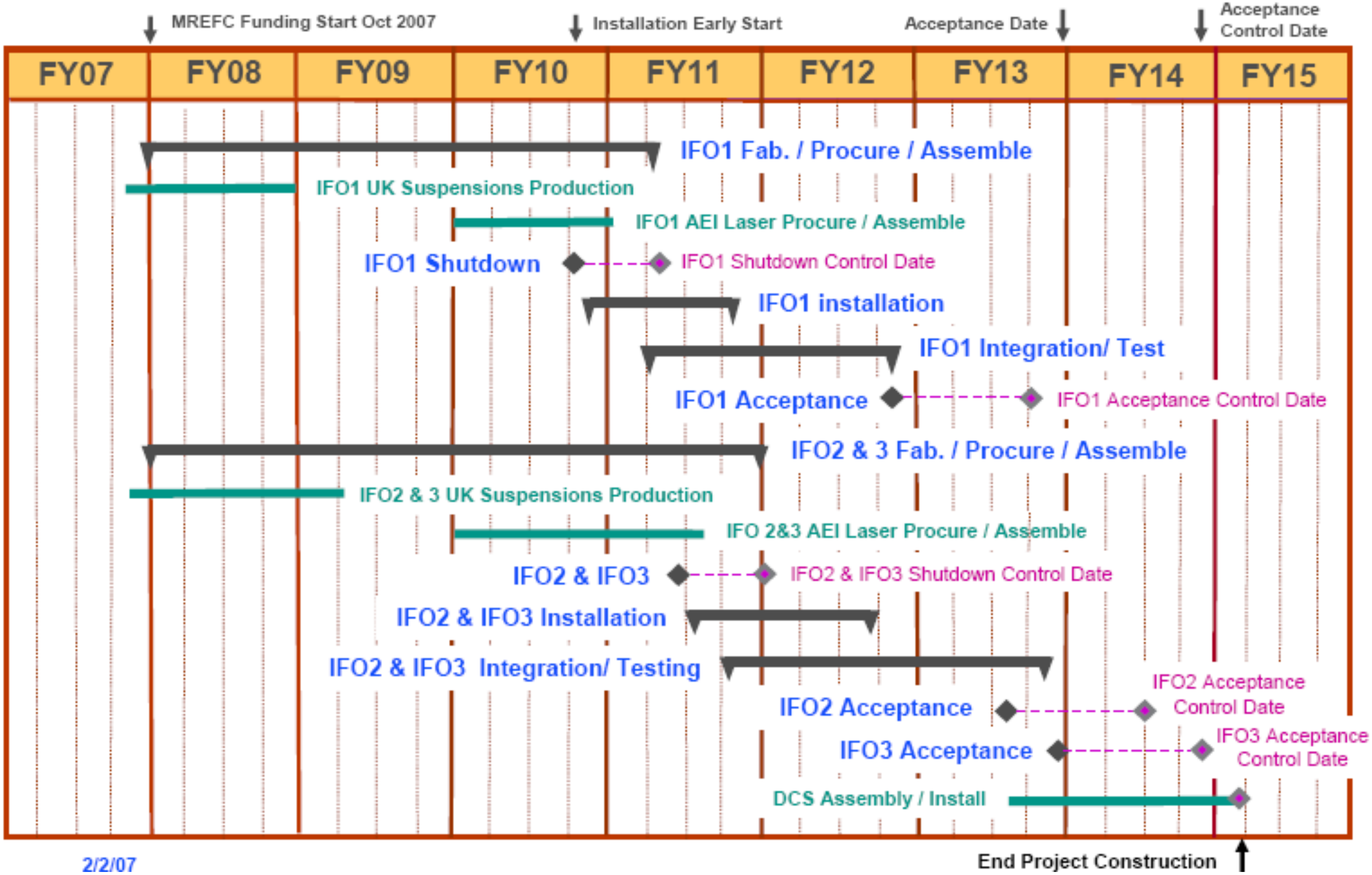


Anatomy of the projected Adv LIGO detector performance

- Newtonian background, estimate for LIGO sites
- Seismic 'cutoff' at 10 Hz
- Suspension thermal noise
- Test mass thermal noise
- Unified quantum noise dominates at most frequencies for full power, broadband tuning



Schedule


MREFC Funding Start Oct 2007
Installation Early Start
Acceptance Date
Acceptance Control Date
FY07
FY08
FY09
FY10
FY11
FY12
FY13
FY14
FY15
IFO1 Fab. / Procure / Assemble
IFO1 UK Suspensions Production
IFO1 AEI Laser Procure / Assemble
IFO1 Shutdown
IFO1 Shutdown Control Date
IFO1 installation
IFO1 Integration/ Test
IFO1 Acceptance
IFO1 Acceptance Control Date
IFO2 & 3 Fab. / Procure / Assemble
IFO2 & 3 UK Suspensions Production
IFO 2&3 AEI Laser Procure / Assemble
IFO2 & IFO3
IFO2 & IFO3 Shutdown Control Date
IFO2 & IFO3 Installation
IFO2 & IFO3 Integration/ Testing
IFO2 Acceptance Control Date
IFO2 Acceptance
IFO3 Acceptance Control Date
IFO3 Acceptance
DCS Assembly / Install
2/2/07
End Project Construction

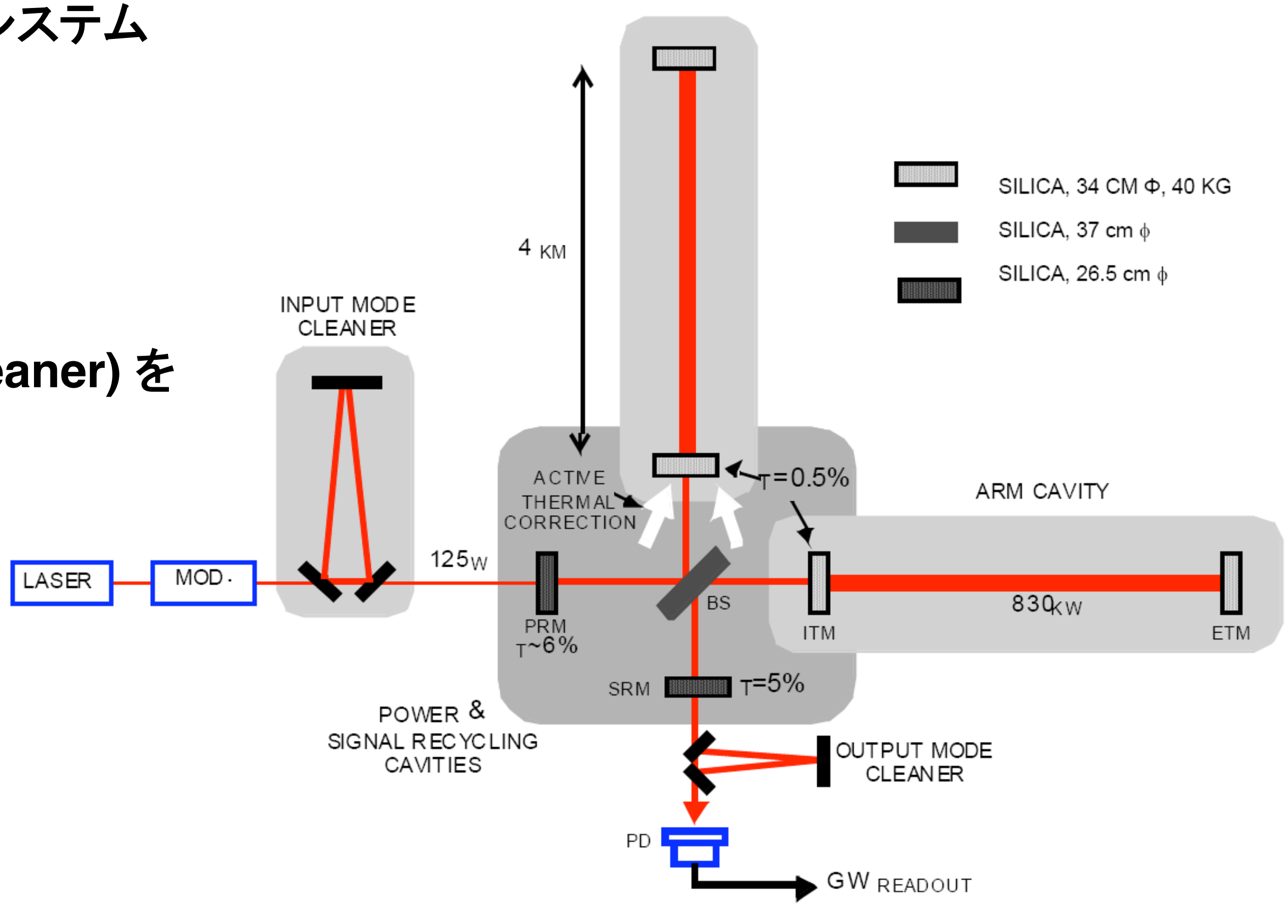
When is Advanced LIGO?

- 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

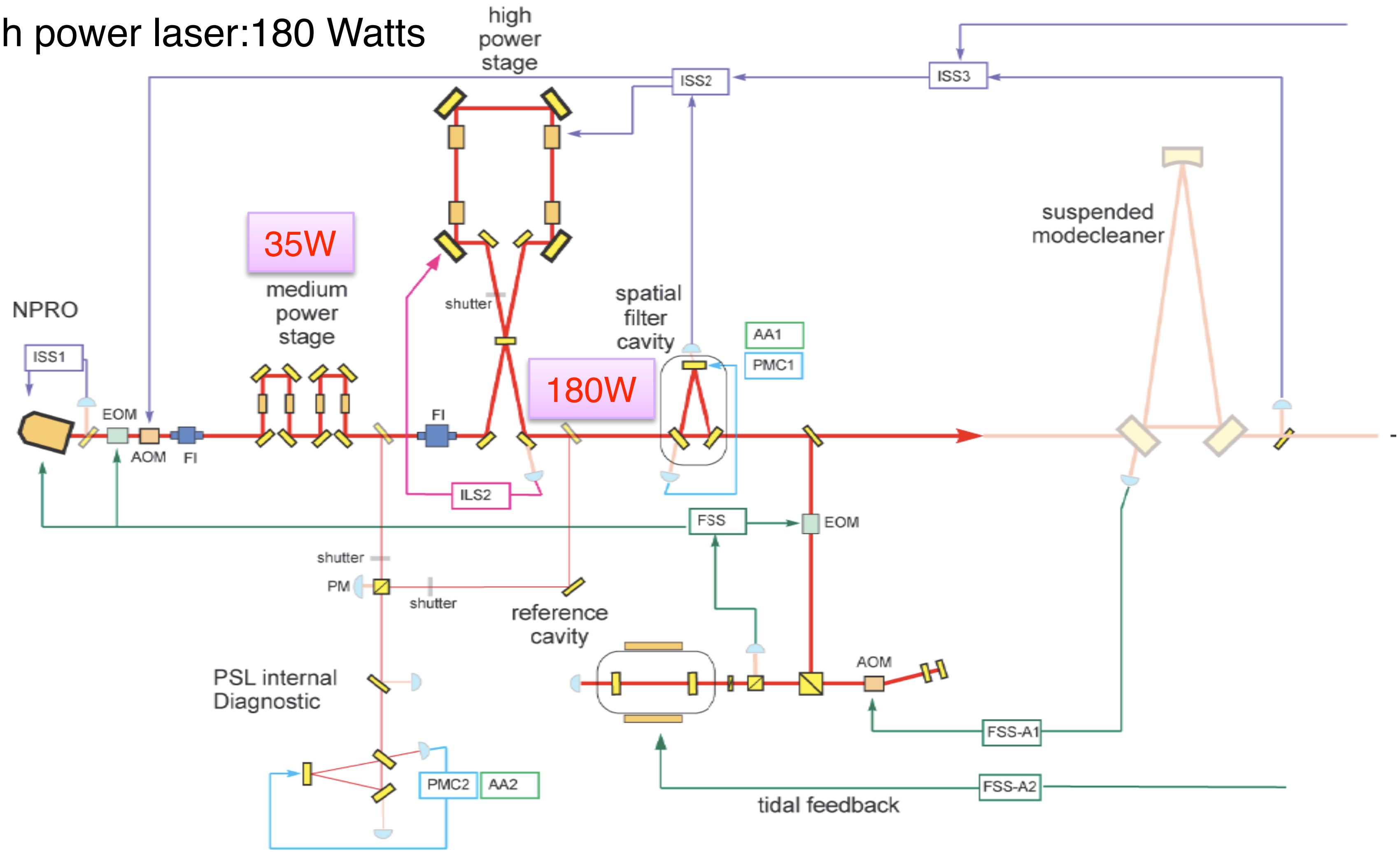
- 200Wクラスの高出力レーザー(~20x)
- アクティブな低周波防振システム
- 3 - 4段の多段振り子
- Digital control system
- 帯域可変のRSE
- OMC (output mode cleaner) を使ったDC readout

•ADVANCED LIGO LAYOUT



Advanced LIGO pre-stabilized laser system

High power laser:180 Watts



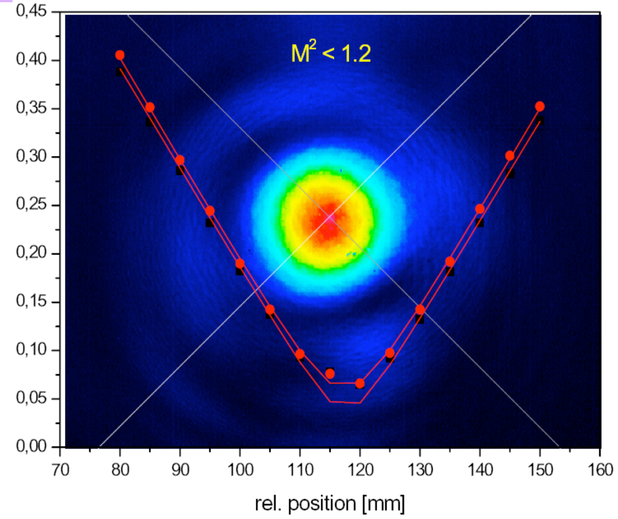
•Work lead by AEI (Hanover) in collaboration with LZH (Laser Zentrum Hanover)

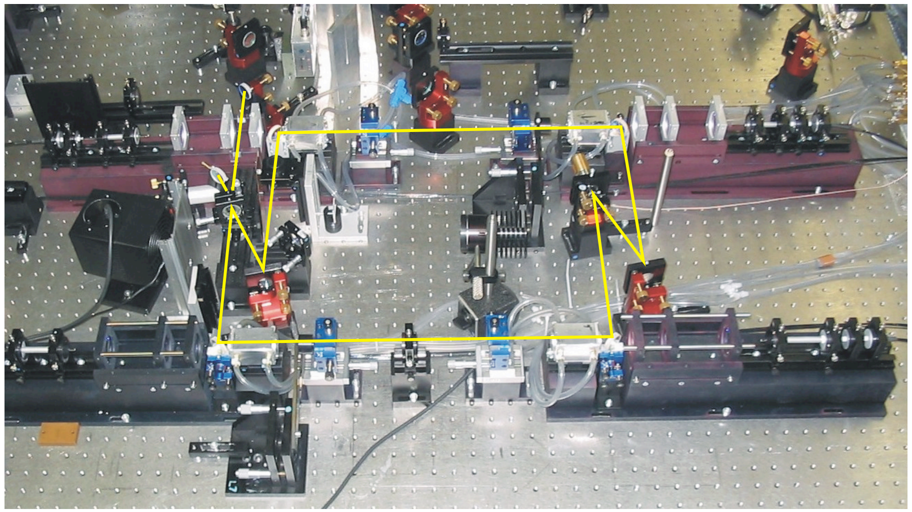
Pre-Stabilized Laser

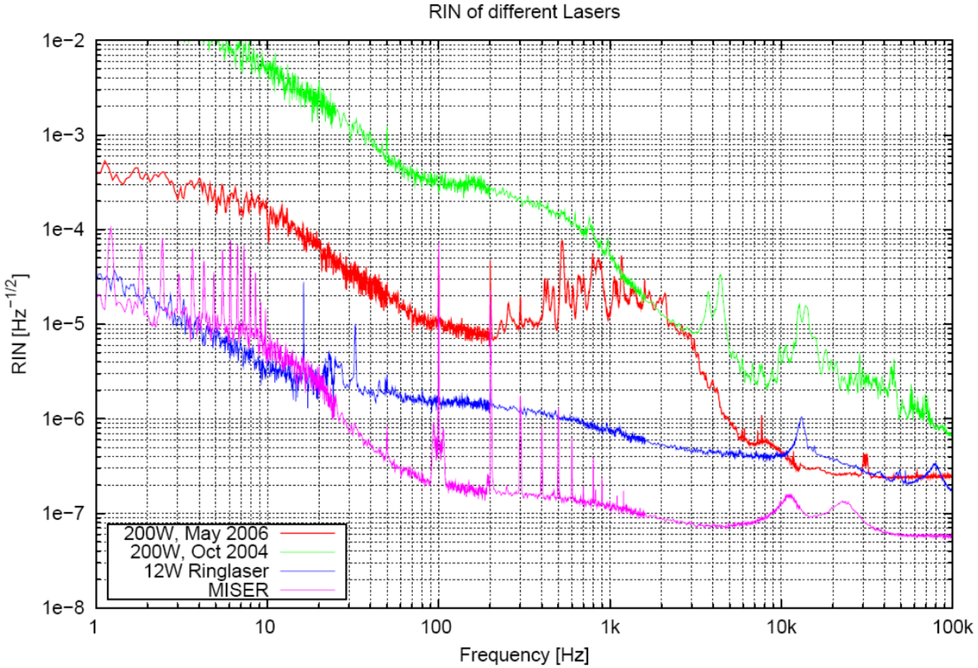
•

Max-Planck Institute Hannover, Laser Zentrum Hannover and CIT

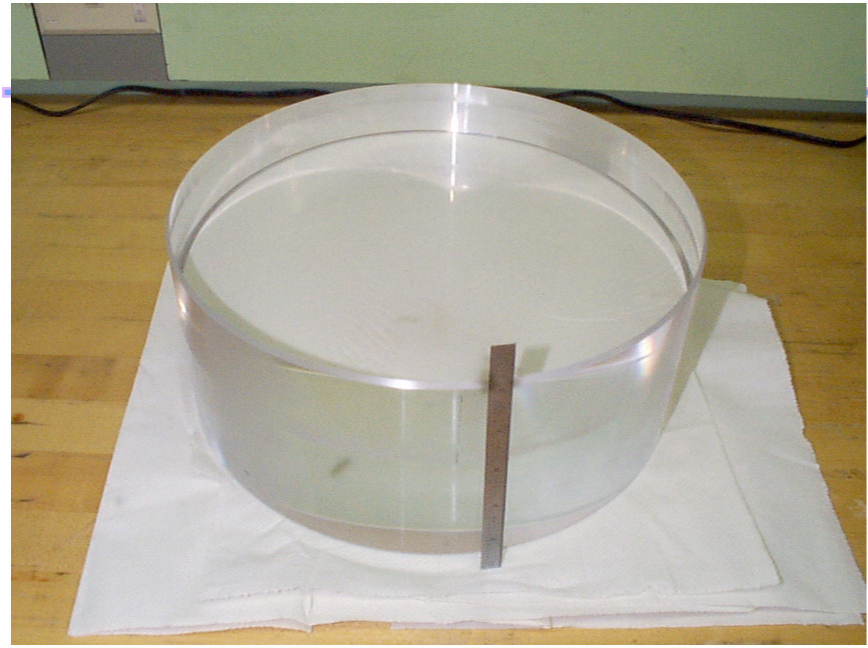
- **180W output power**
- **Transfer engineering model to MIT test interferometer (LASTI)**
- **Plans forming to supply this 30W source in an AdL 'early delivery' for initial LIGO update**
- **Frequency noise requirement achieved (LIGO)**
- **RIN = 3*10-9 / sqrt(Hz) above 20Hz (in table top experiment)**

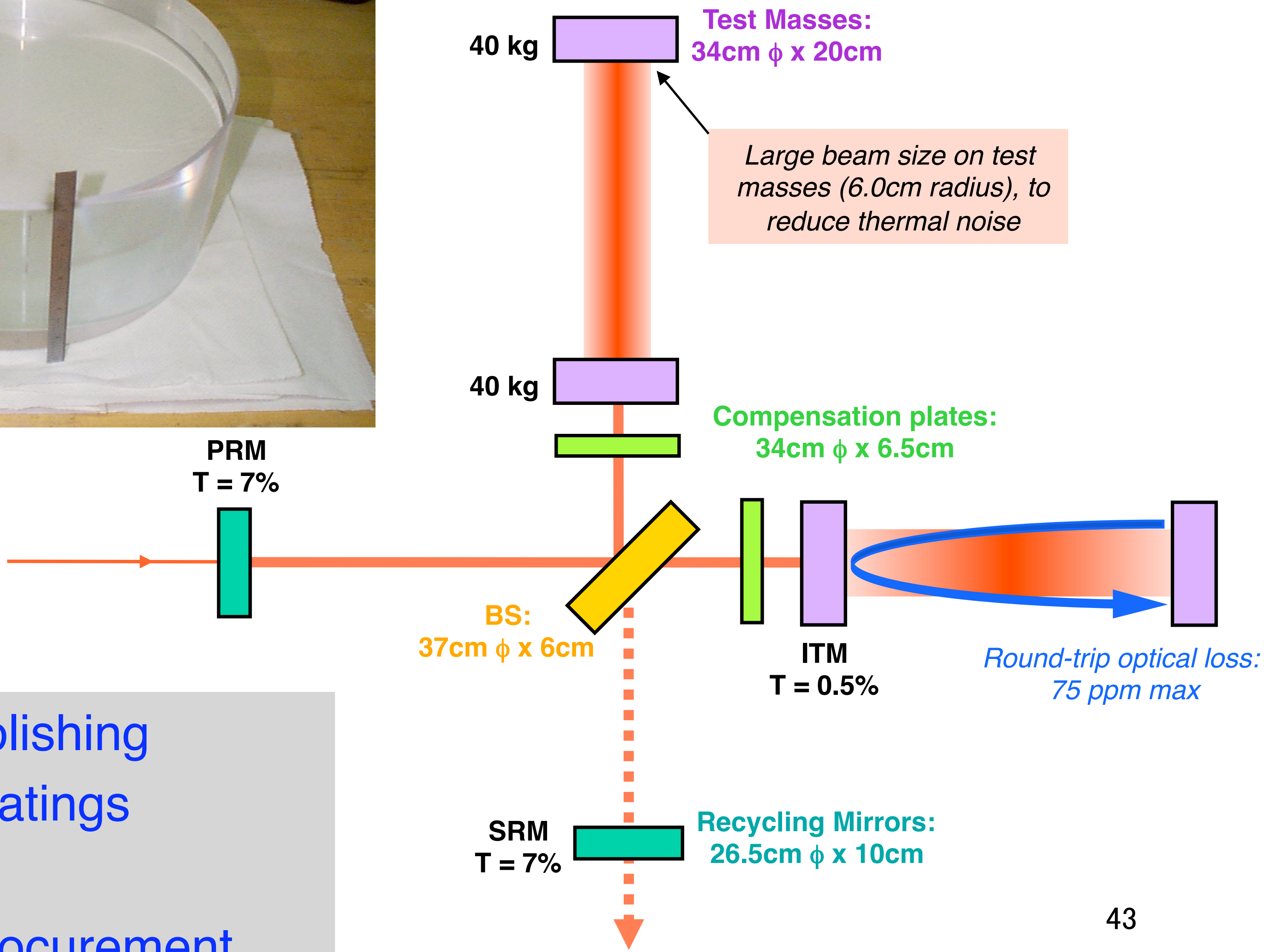






Core Interferometer Optics



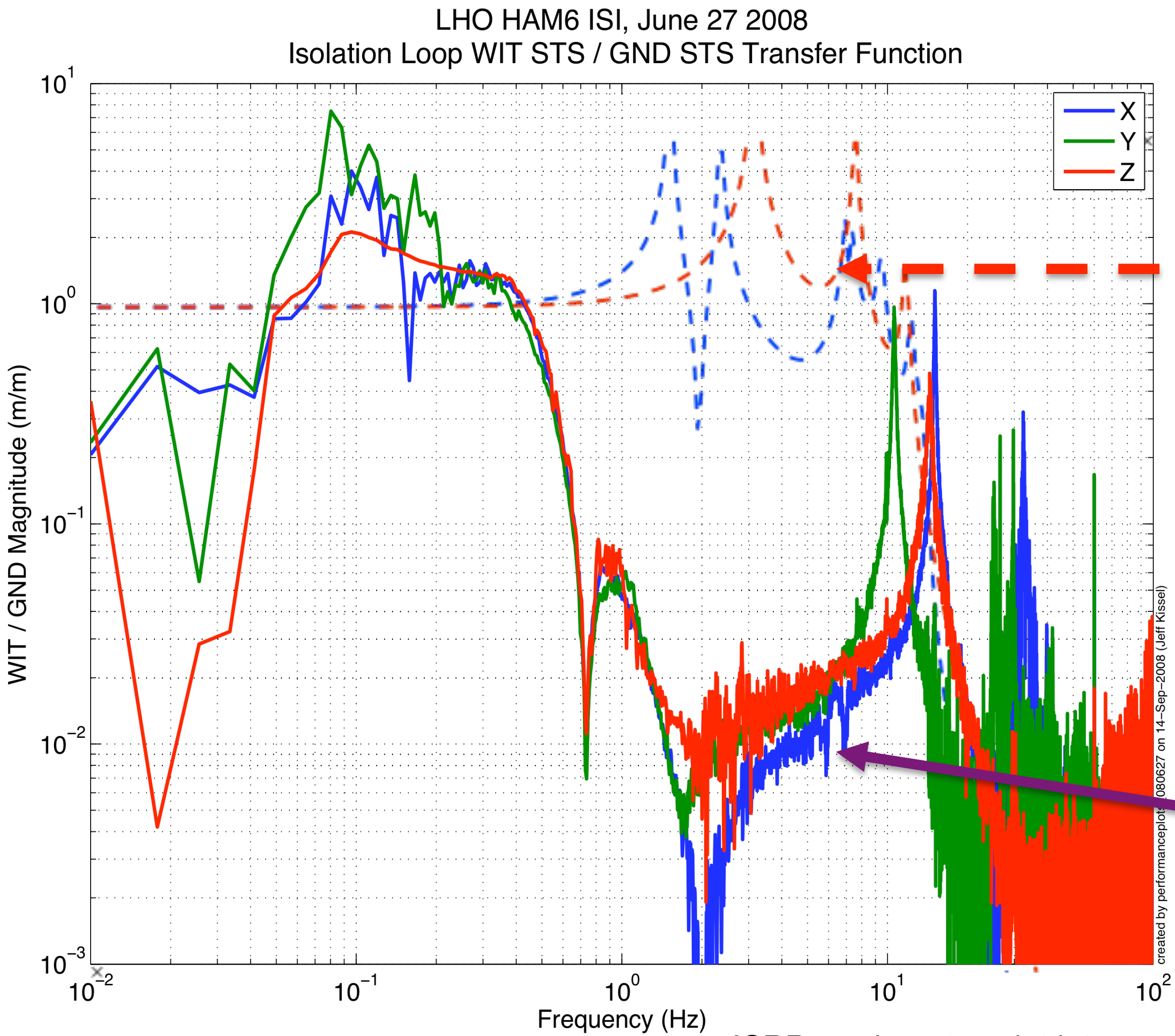


Challenges:

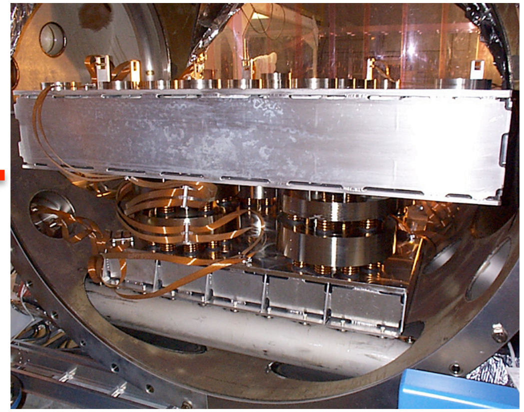
- Substrate polishing
- Dielectric coatings
- Metrology
- Substrate procurement

The HAM ISI

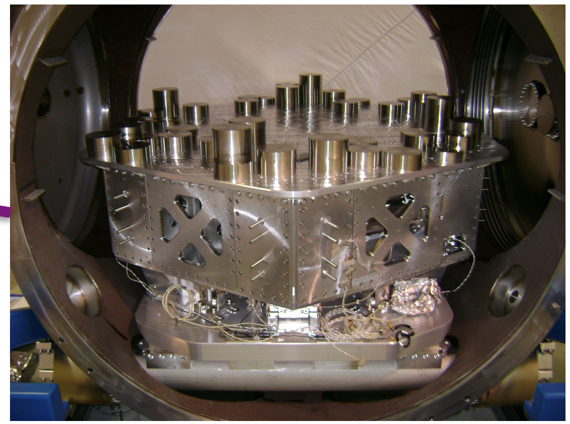
Old vs. New Isolation Comparison



•iLIGO Passive Isolation

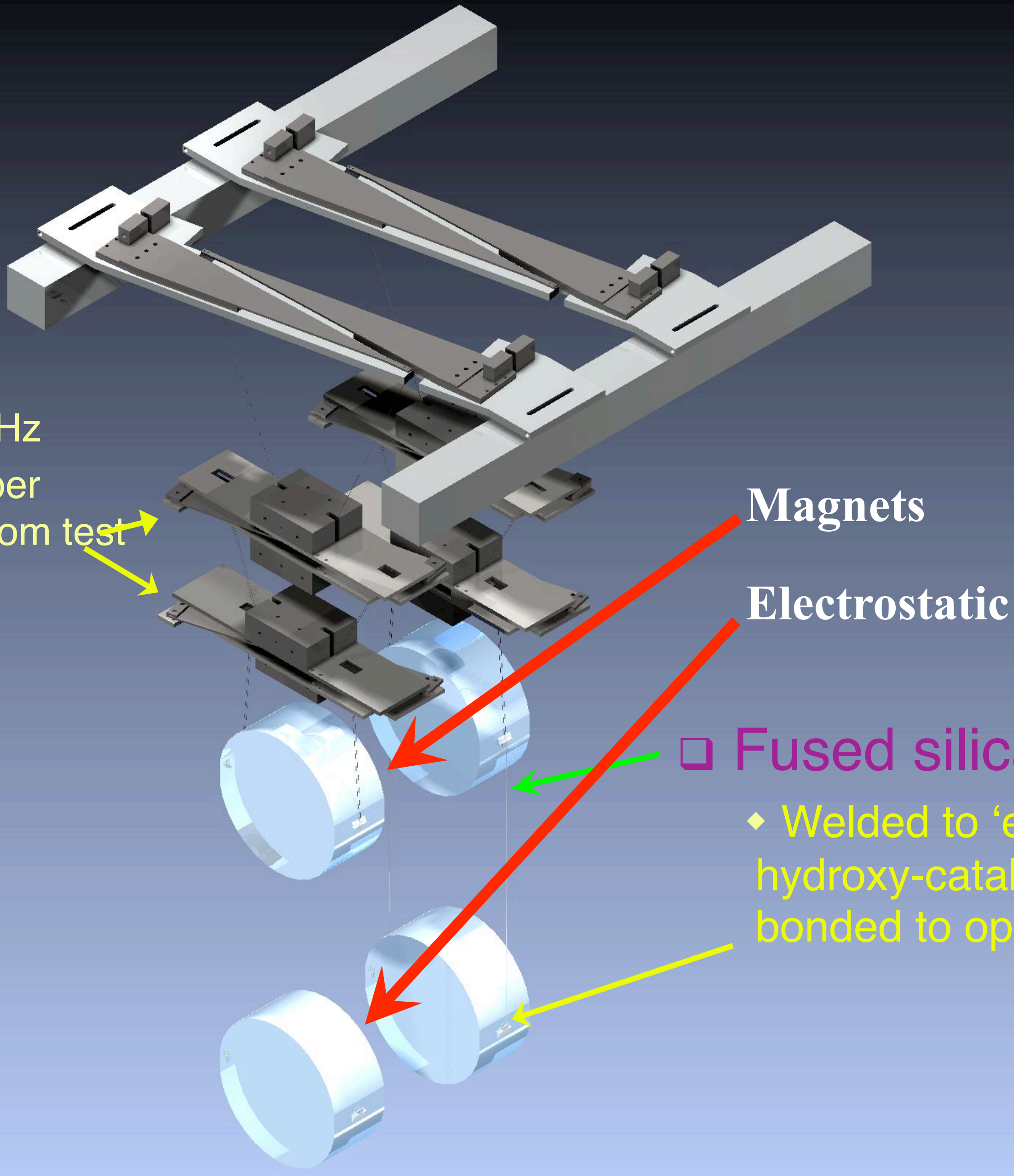


•eLIGO Passive & Active Isolation



Quad Suspensions

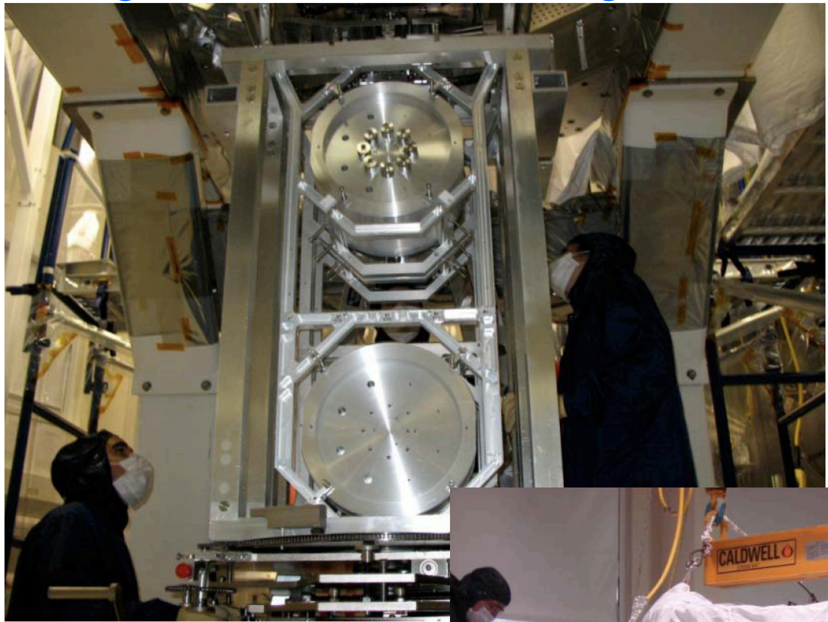
- Quadruple pendulum:
  - » ~10^7 attenuation @10 Hz
  - » Controls applied to upper layers; noise filtered from test masses
- Seismic isolation and suspension together:
  - » 10^{-19} m/rtHz at 10 Hz



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

Quad Pendulum Noise Prototype

August 2007 – mounting to ISI



October 2007 – Suspending

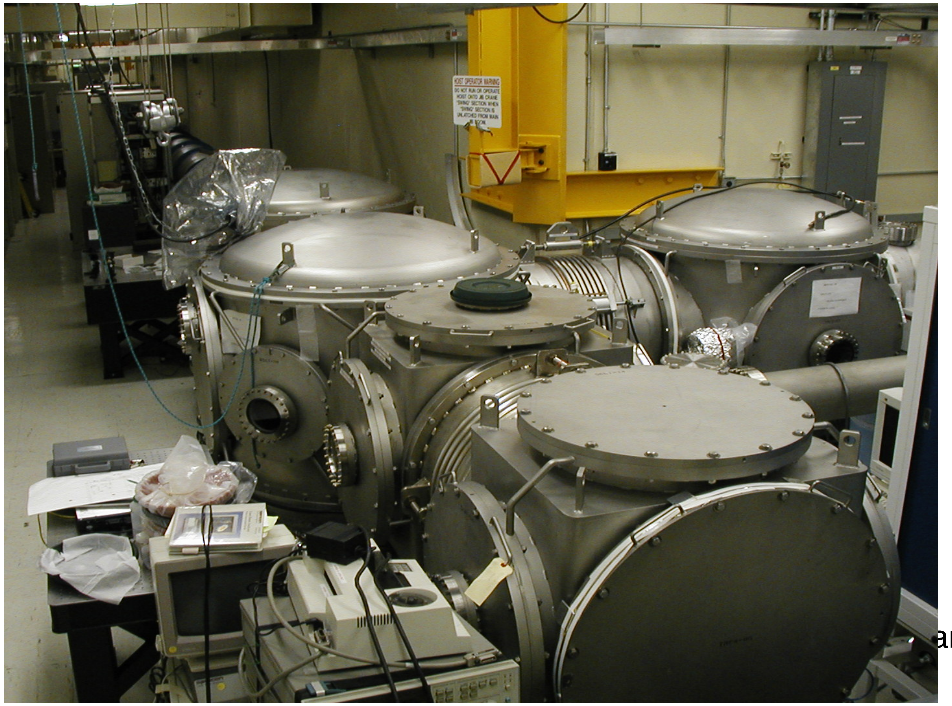
April 2008 – Quad-ISI BSC installation

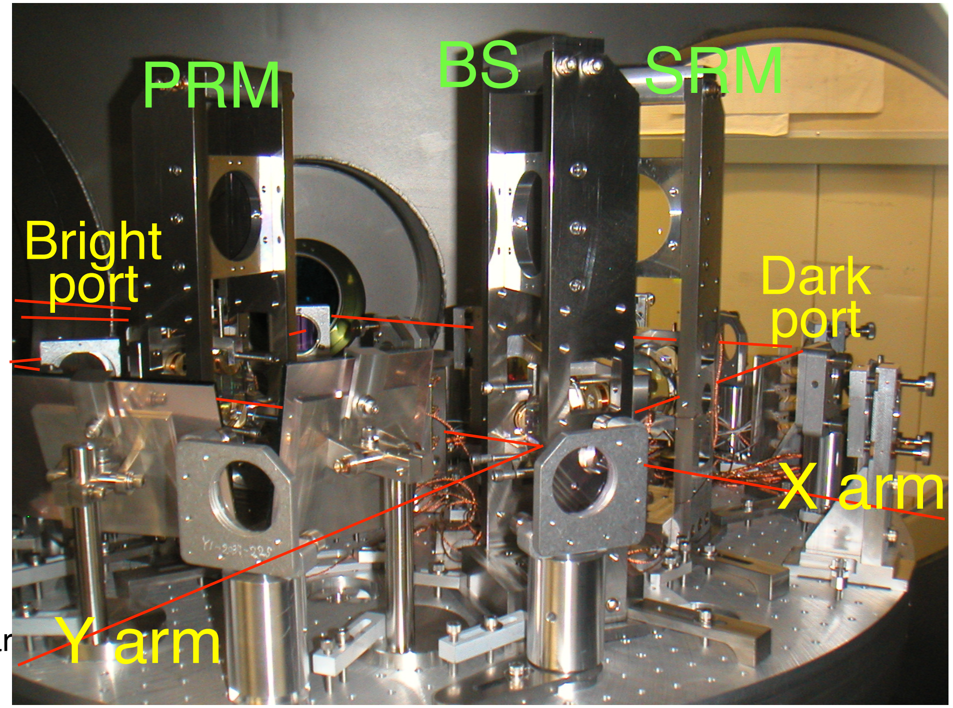
Caltech 40 meter prototype interferometer

Objectives

Develop lock acquisition procedure of detuned Resonant Sideband Extraction (RSE) interferometer, as close as possible to Advanced LIGO optical design

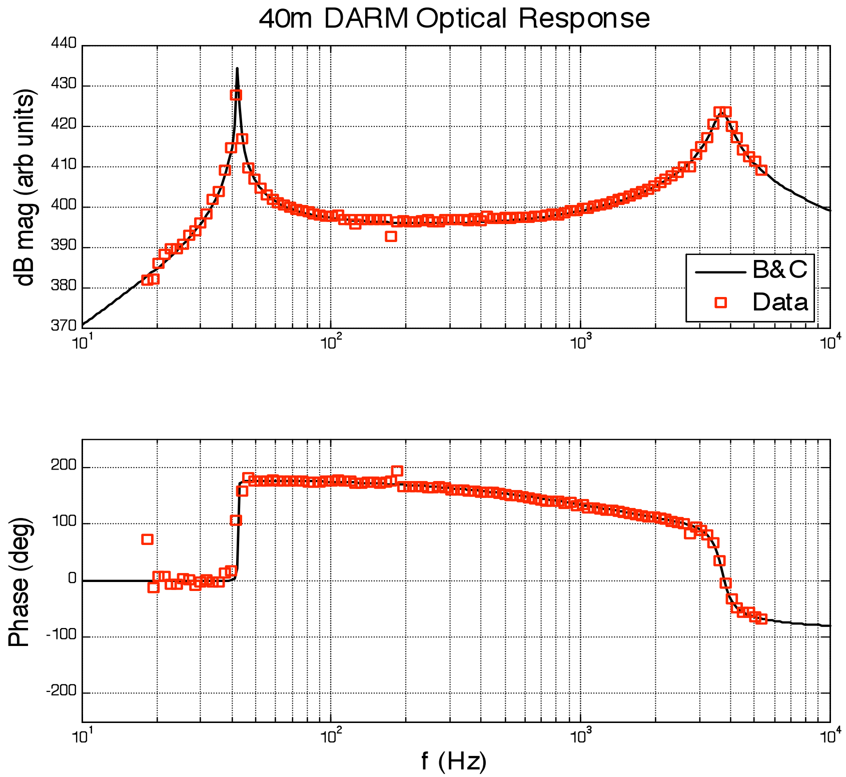
- **Verify optical spring and optical resonance effects**
- **Develop DC readout scheme**

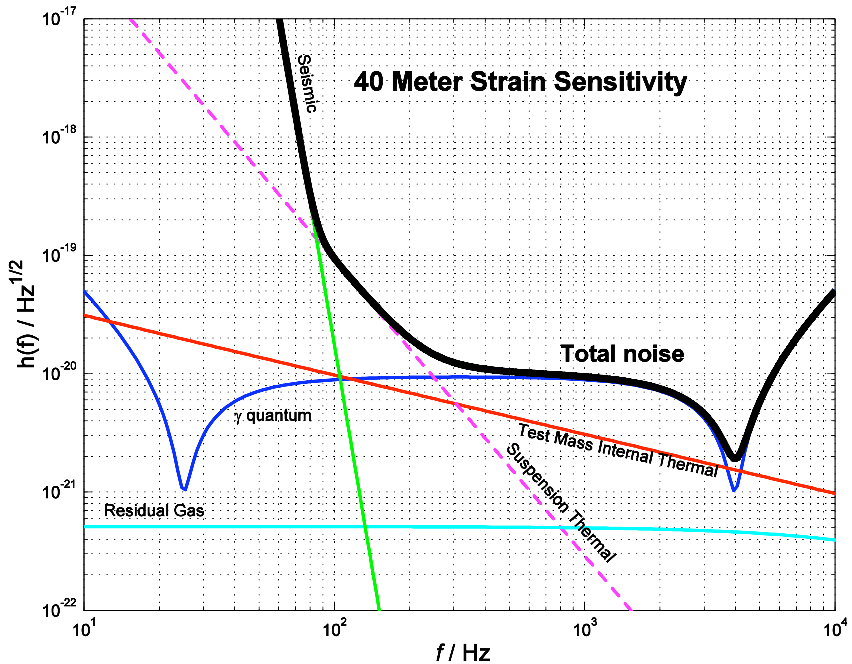




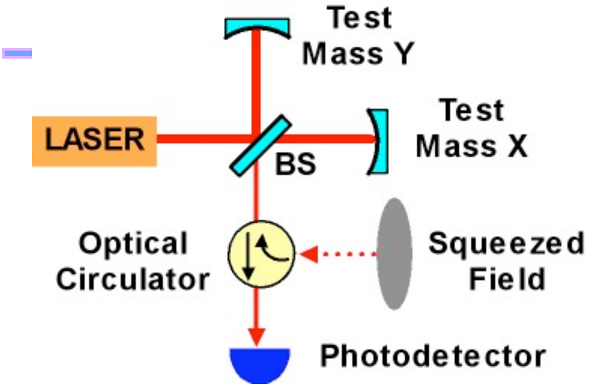
Caltech 40 meter プロトタイプ干渉計

- Caltech40m: 歴史的には現LIGOのプロトタイプであり、TAMAに抜かれるまでは世界最高感度を誇っていた、今はAdLIGOのプロトタイプ
- AdLIGOのための光学設計の基礎実験
- 検出ポート側に加えた新たな鏡(RSE: resonant sideband extraction)を含めた複雑な光学設計の動作確認と、光バネ、光共振による干渉計感度の増幅

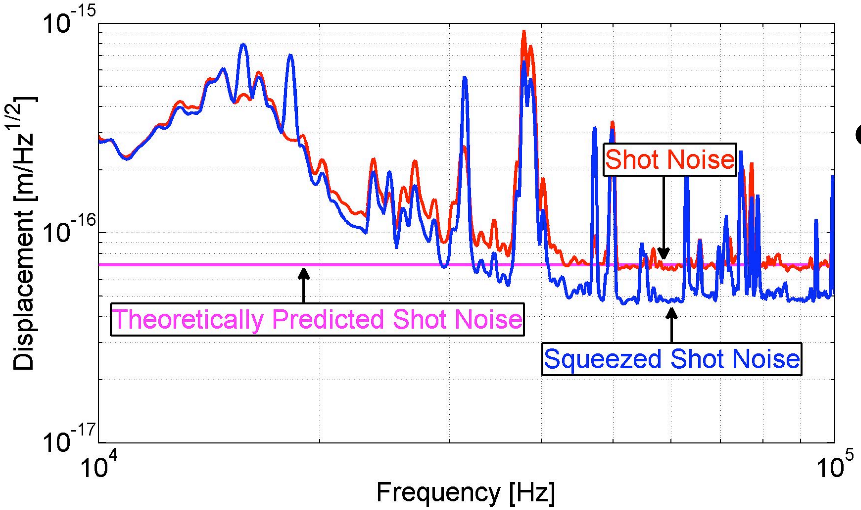




Squeezed vacuumのプロトタイプ干渉計への注入実験

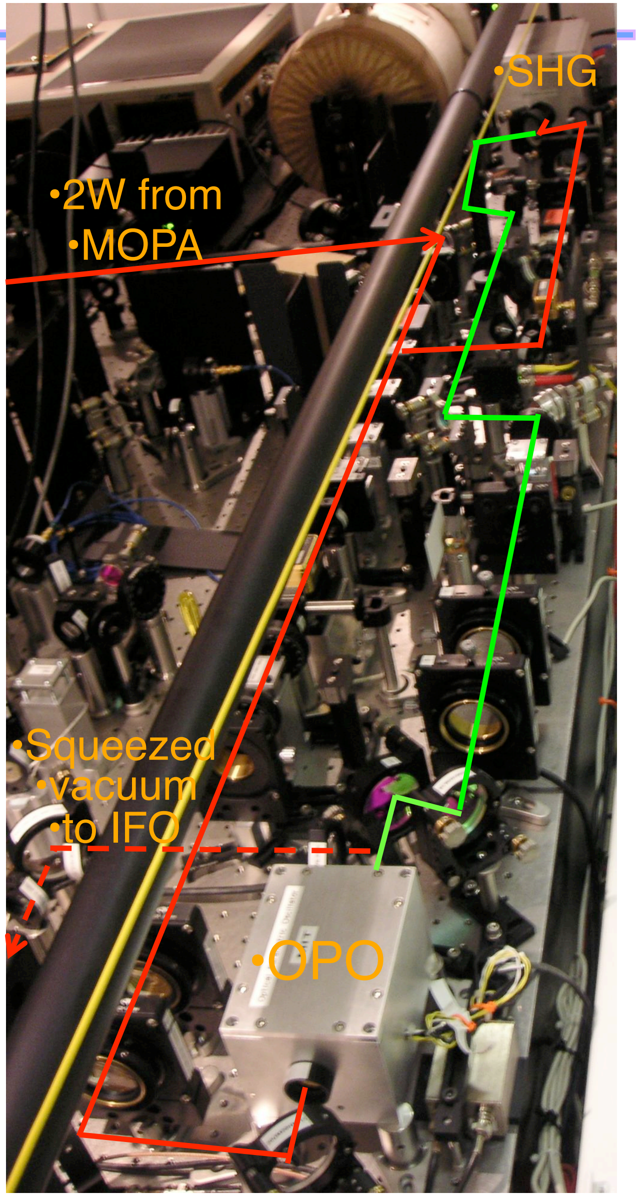


Squeezed された真空場を干渉計検出ポートから注入することにより、干渉計の量子ノイズを軽減することができる



•K. Goda et. al., Nature Phys. doi:10.1038/nphys920 (2008)

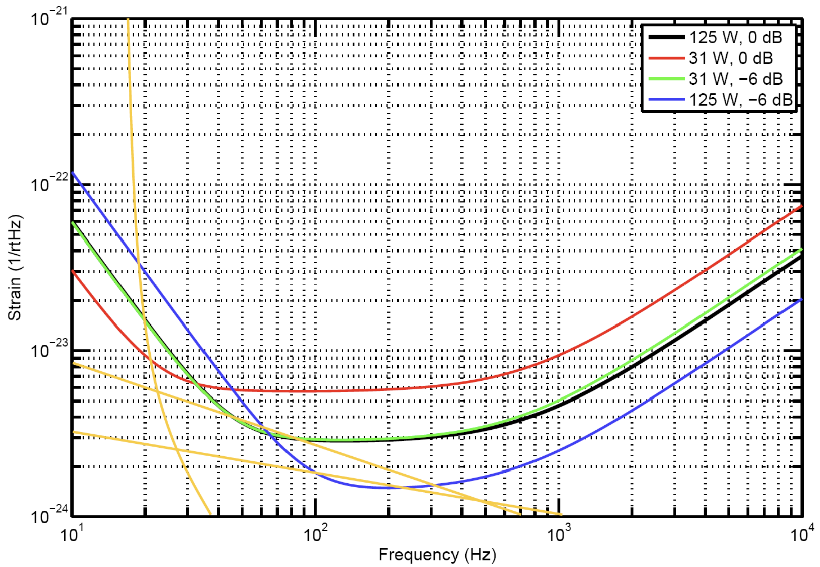
●プロトタイプ検出器(Caltech 40m)への入射は世界初、3dBのショットノイズ軽減に成功

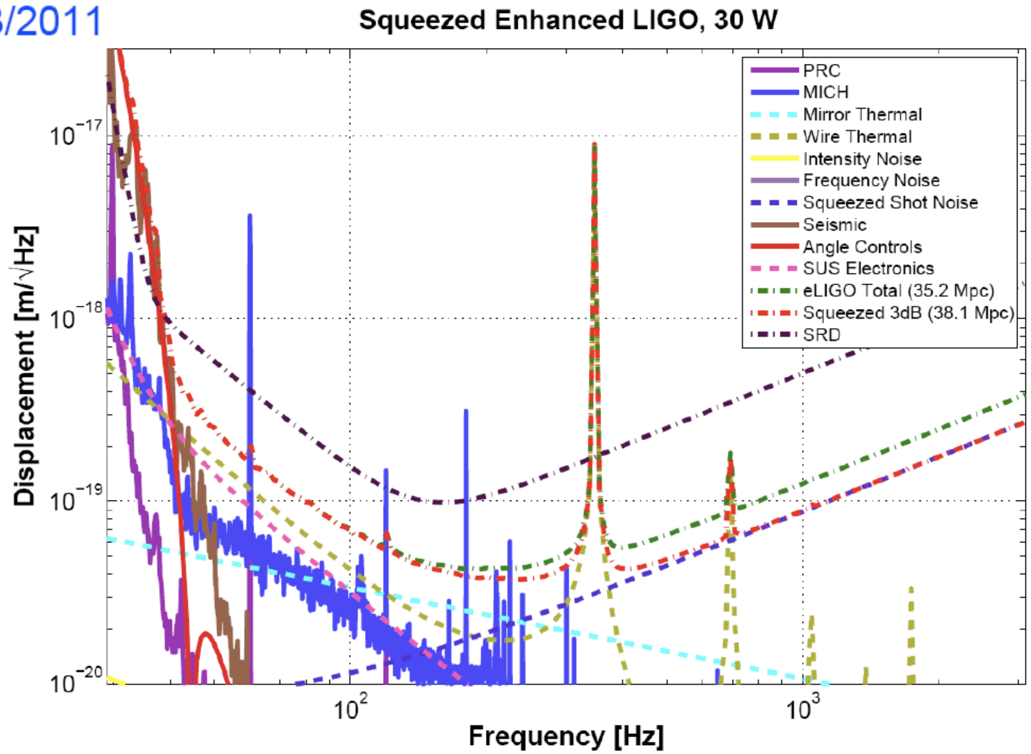


- 重力波検出器はSqueeze技術の数少ない応用例の一つ
- 将来6dBの感度向上が実現できれば、4倍のパワーのレーザーを使えることに相当する
- この結果がeLIGO/AdLIGOにsqueezerを導入する提案を生んだ
- 量子ノイズに制限されているLCGTにこの技術を使えば、感度が改善し熱雑音レベルに到達することが可能となる

Squeezing in H1

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

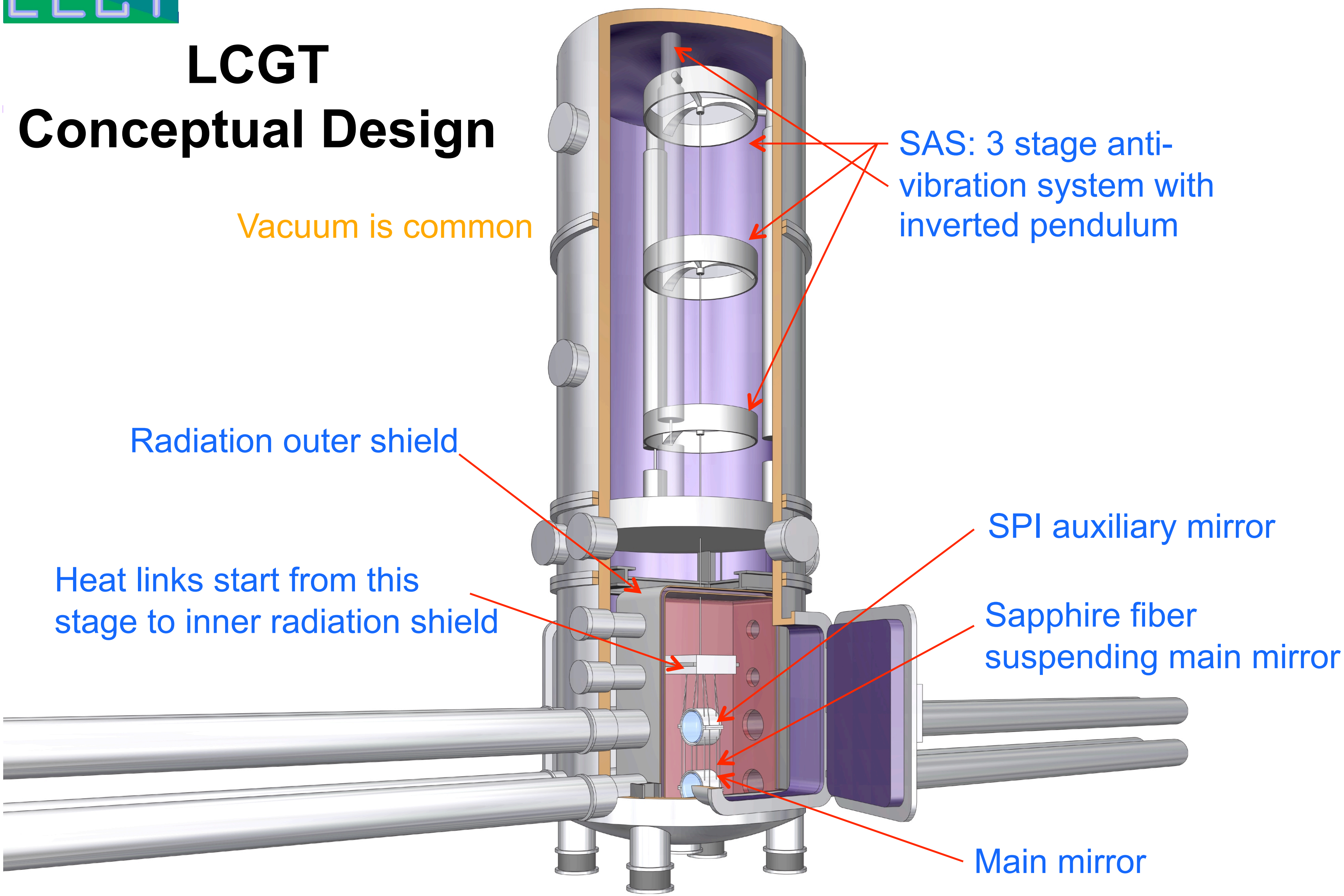




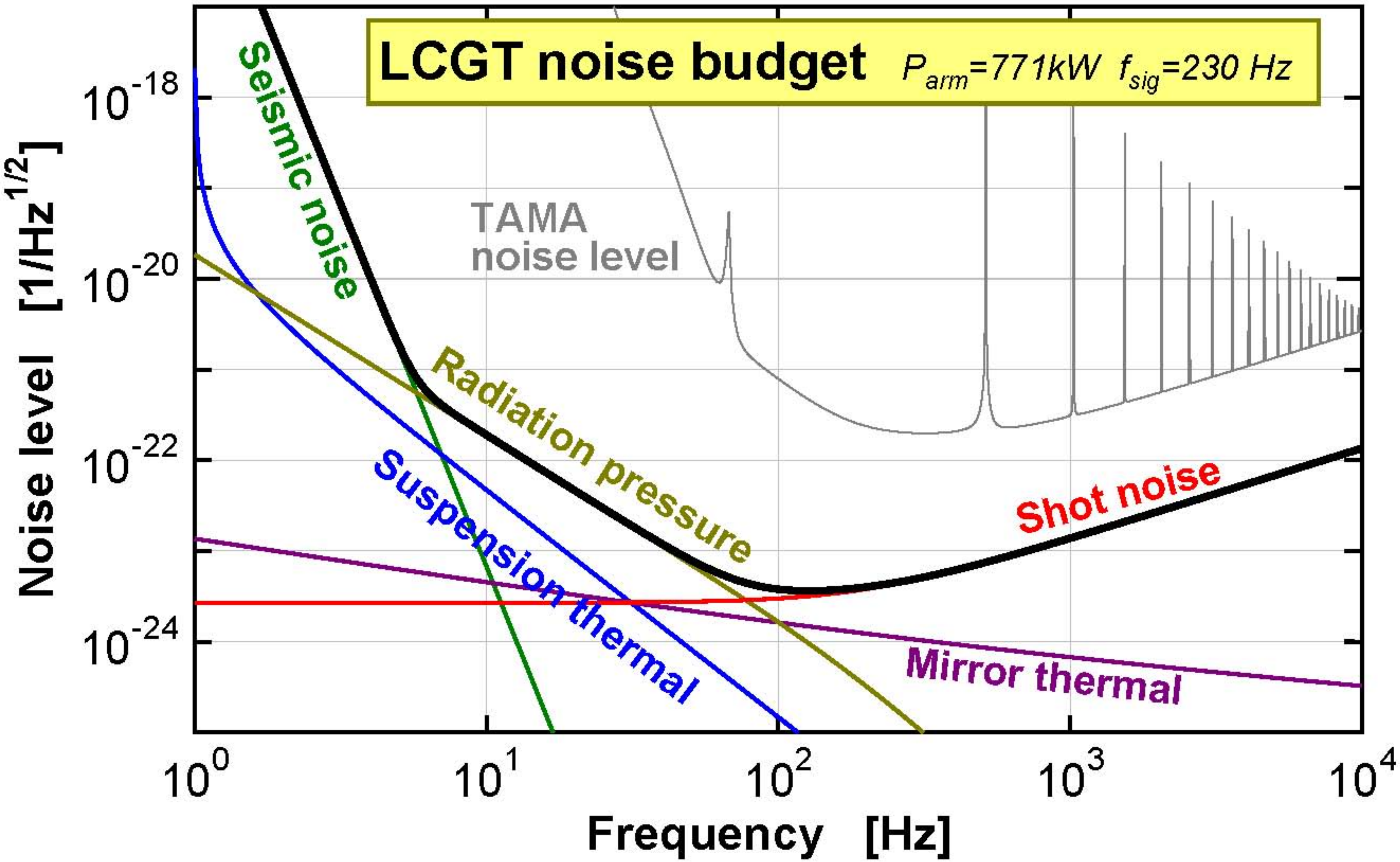
Large-scale Cryogenic Gravitational wave Telescope (LCGT)

- 3 km baseline
- Utilizes cryogenic mirrors (sapphire)
- Construction at an underground site (Kamioka mine)
- Two parallel interferometers installed in a common vacuum envelope
- Suspension point interferometer
- Proposal currently under consideration for 2008 funding

LCGT
Conceptual Design



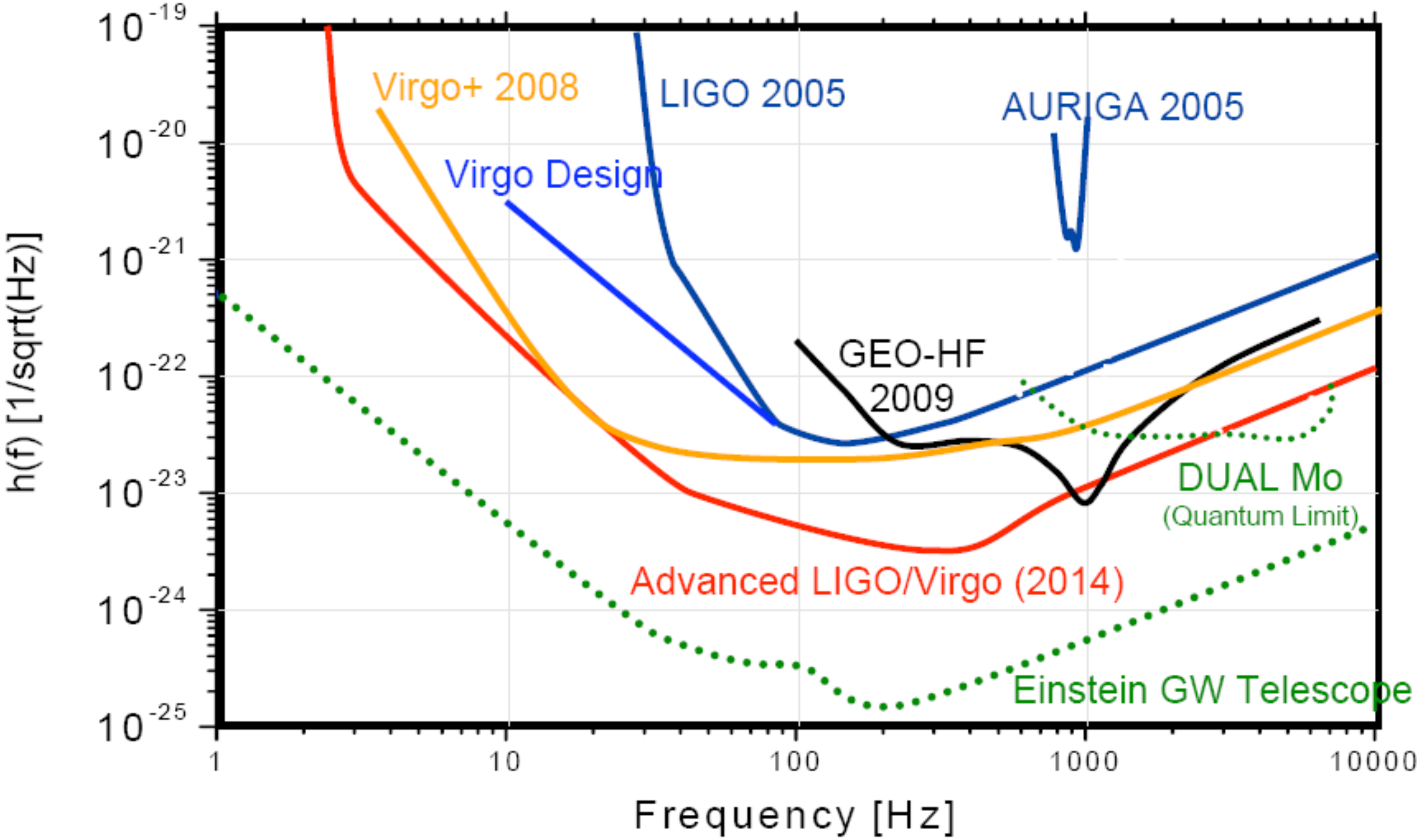
LCGT Design Sensitivity



ET Baseline Concept

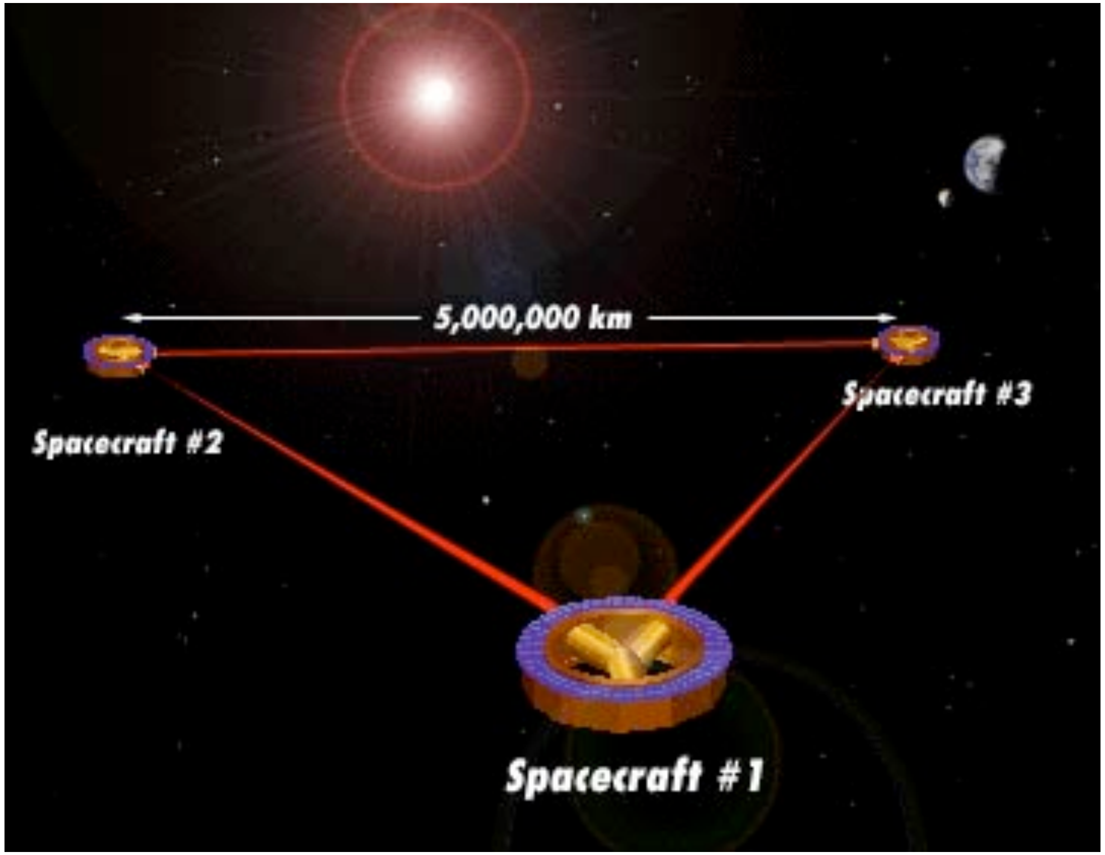
- Underground location
  - Reduce seismic noise
  - Reduce gravity gradient noise
  - Low frequency suspensions
- Cryogenic
- Overall beam tube length ~ 30km
- Possibly different geometry

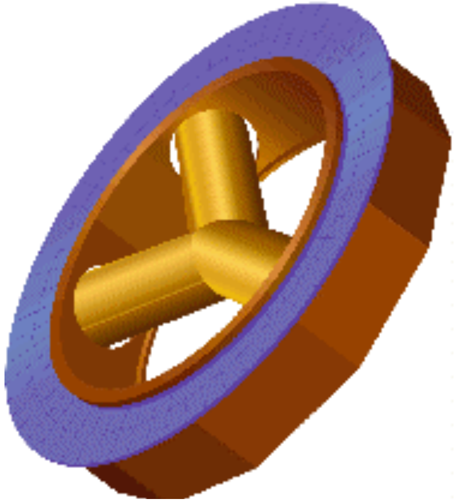
Einstein Gravitational-Wave Telescope (ET)

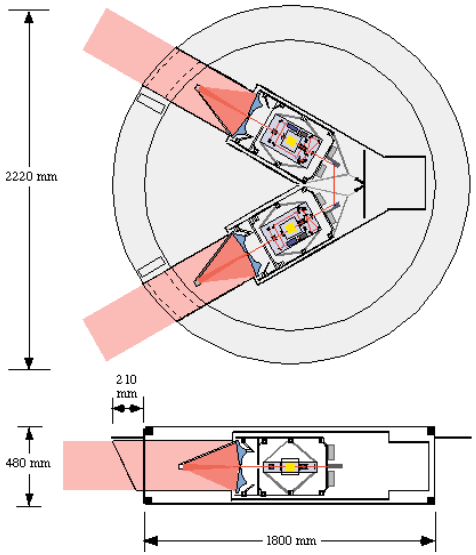


The Laser Interferometer Space Antenna
LISA

• 一辺500万km
• LISA (NASA/JPL, ESAの共同プロジェクト)
•10年後の打ち上げを目指す

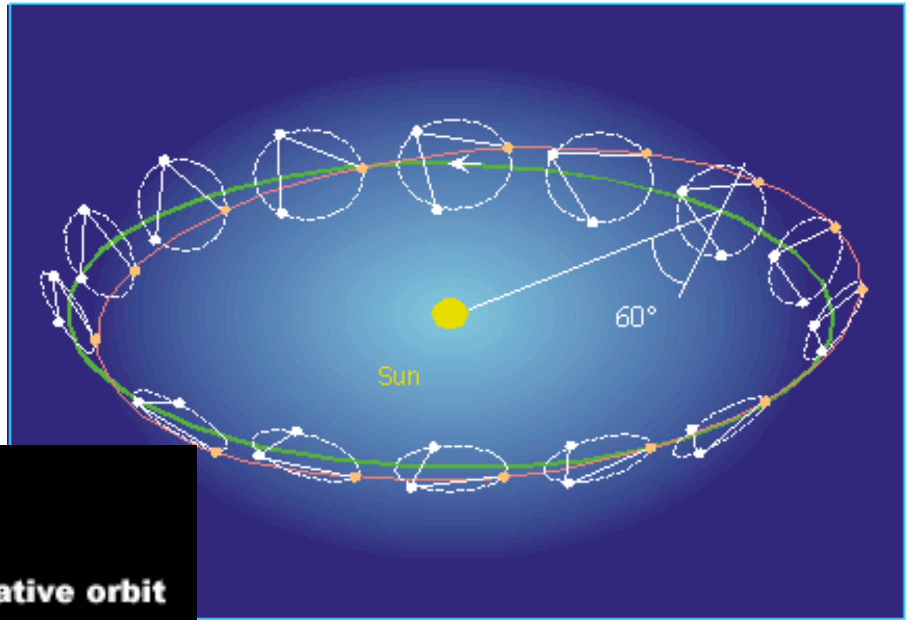


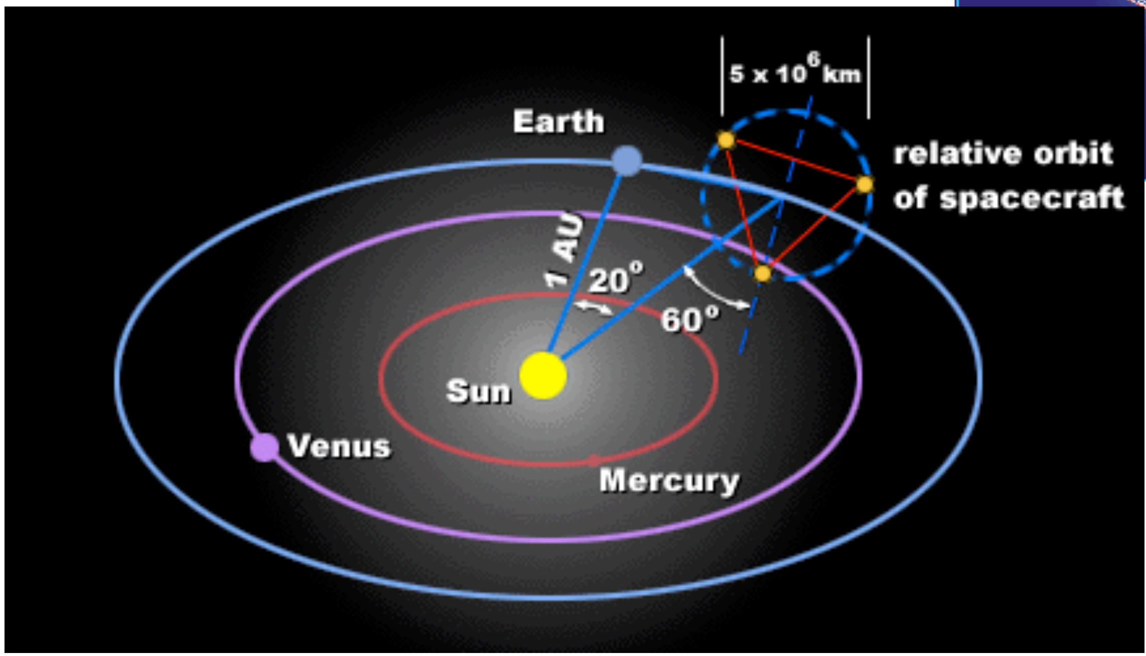




The Laser Interferometer Space Antenna
LISA

- 公転周期を回る



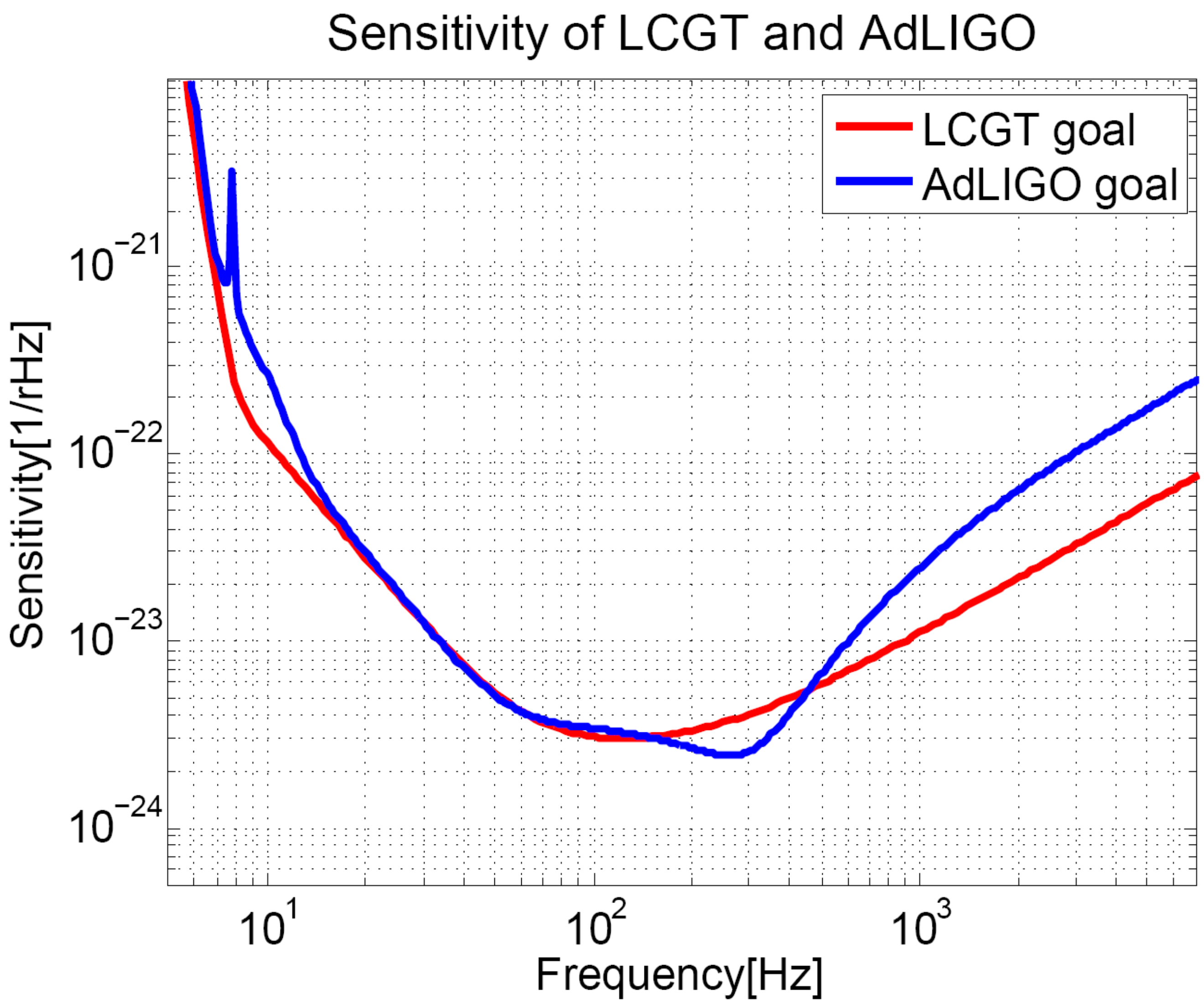


重力波検出に向けて

日本のグループは本当に重力波を検出できるのか?

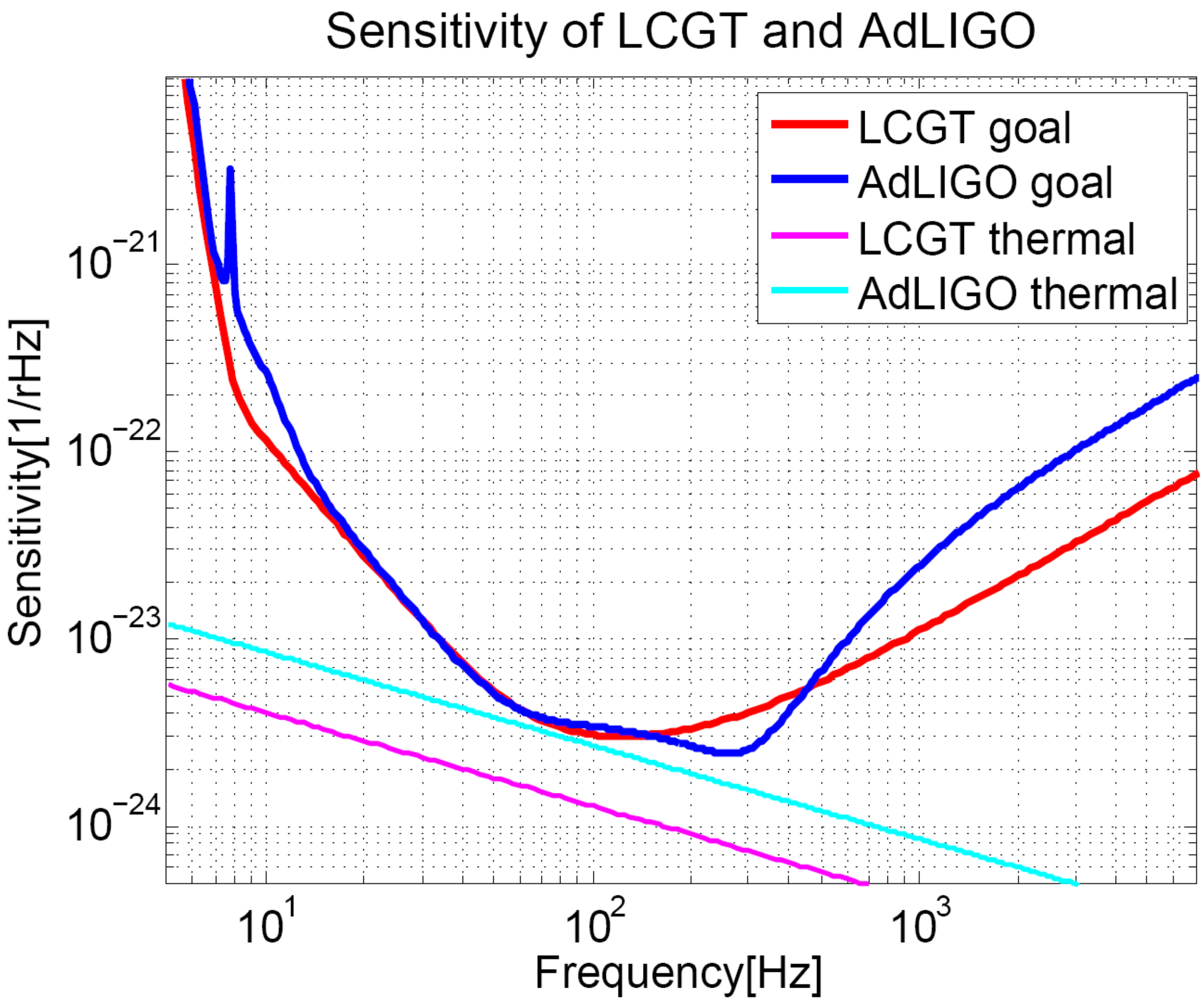
- 宇宙線研が進めている低温干渉計LCGTは(いつか)LIGO及び、Advanced LIGOを凌駕する
- LIGO計画を見ることでLCGTに必要なことが見えてくる

日米の将来計画 ~LCGTとAdvanced LIGO~



- 目標感度は大差ない

日米の将来計画 ~LCGTとAdvanced LIGO~



- 目標感度は大差ない
- しかしながらLCGTのほうが熱雑音に達するまでの余裕がある
- 現在LCGTの感度を制限すると考えられているのが輻射圧雑音、散射雑音を含んだ量子雑音
- これは光学設定により改善することが可能

米国LIGO計画とTAMA計画との差

- 人にやさしいインターフェース(Digital System)の有り無し
  - » 感度向上に貢献できる人数を増やすという意味で大きな違いがある
  - » 優れたソフトウェアの開発が、感度向上など全体の進展に大きく関わる時代になっている
- AdLIGOの要素技術開発と、それらのLIGO/eLIGOでの実装
  - » Caltech40m干渉計におけるAdLIGO光学設計のプロトタイプ実験
  - » 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
  - » 4段振り子の開発とテスト
- 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

デジタルシステムを使った干渉計制御

•LIGOの制御系

•(参考)TAMA300の制御系

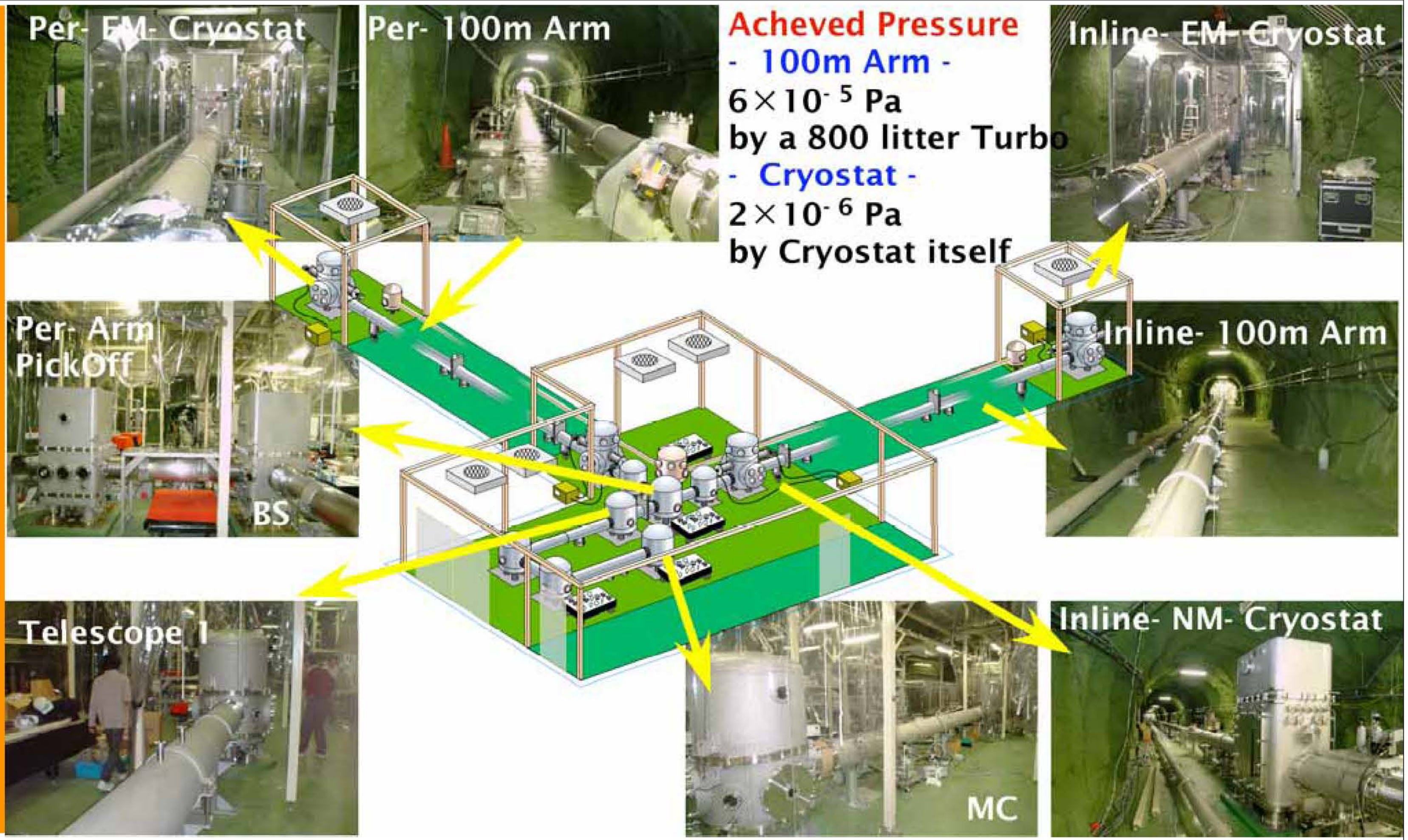
- LIGOでは、制御、測定、チューニングなど、ほとんどのことがコントロールルームの計算機上でできる
  - » これはヒューマンノイズを避ける面からも重要である
- 優れたソフトウェアの開発が、感度向上など全体の進展に大きく関わる時代になっている

なぜLIGOは計画通りの感度が出せるのか?

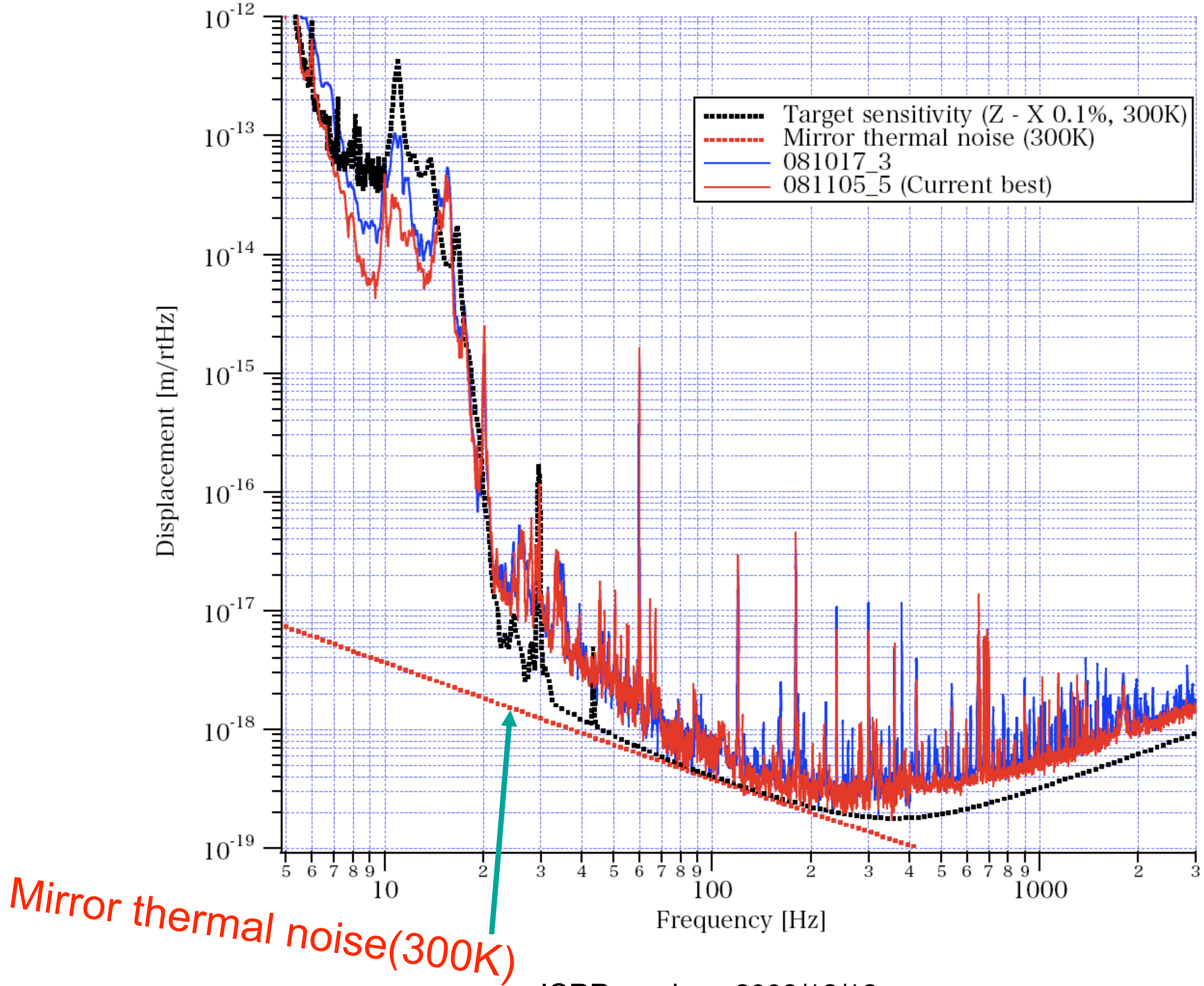
- 数十人規模の専門の技術者 (回路、計算機、真空など)
- 各サイト常駐の干渉計オペレーターと、24時間体制のシフト
- デジタル制御システムを利用した、一台目で開発された技術の二台目、三台目への簡単なコピー
- AdLIGOのためのあくなきR&Dと、そこからのフィードバック

» 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

Construction of CLIO



Current sensitivity of CLIO

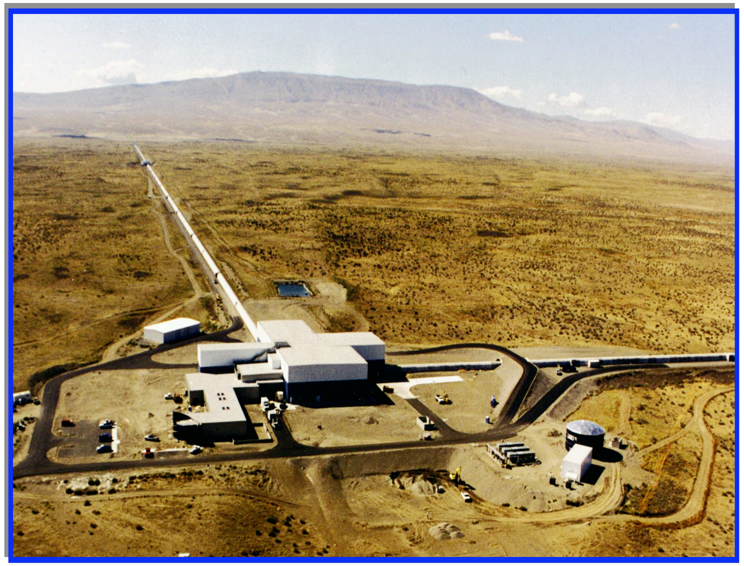


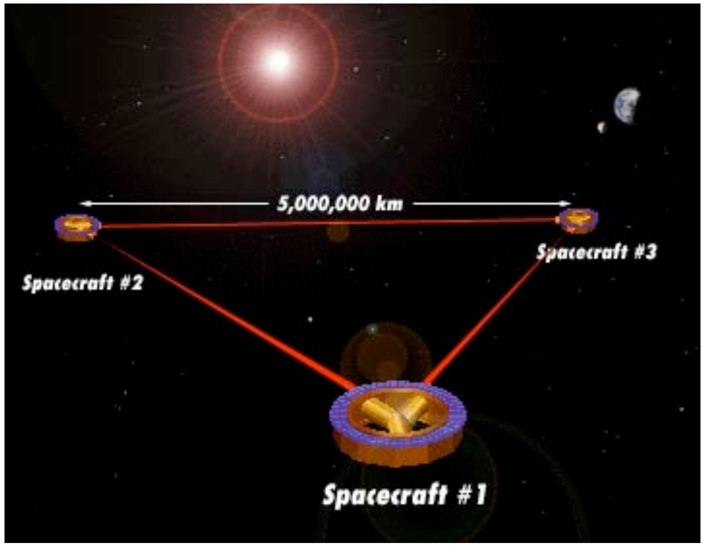
LCGT実現に向けて

- 大型計画であるという認識
  - » 組織作り(リーダー、現場責任者、各要素技術の責任者)
  - » 技術者(電気回路、計算機、オペレーター等)の整備
  - » ドキュメント(回路図、技術資料等)の整備
  - » 外部評価の導入
- 国際協力の必要性
  - » 各要素技術(レーザー、制御システム等)

CLIOの感度向上

Einstein's Symphony





- Einsteinは宇宙は時空のひずみで満たされていると予言した
- 人類はそのひずみを重力波として捉えることができるのだろうか?

END