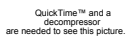
# LIGO *Enhanced LIGO: So how's that turning out?*




*Structure A-4 "El Castillo", Xunantunich, Belize*

LIGO

# Outline

- ***Reference frame***
- ***The Pitch***
- ***The Swing***
- ***Where we are now***
- ***Technical Hits & Misses***
- ***Strategic Hits & Misses***
- ***Closing thoughts***

# eLIGO Creation Myth

- Initial LIGO achieved design sensitivity ('SRD')
- S5: 1 year double coincidence commitment
- Extensive lore of known problems (e.g., doomed RF readout) and planned solutions (DC readout with output mode cleaner)
- Adhikari 2004: "SRD is a scam! We can do better!"
- AdL MRE funding start delayed
- How to strategically apportion "extra" pre-AdL time?
  - Extended S5 running?
  - Attempt pre-AdL noise improvement?
- Proposal ***T060156*** floated by Adhikari, Waldman, Fritschel:
  - Redirect AdL prototypes (mainly associated with DC readout) to sites
  - Collect and focus commissioning funds to build duplicates, where needed
  - Graft AdL DC readout onto IL, taking ~ half the time (?); run the other half

LIGO

# *The real superheroes*

Kate Dooley

Tobin Fricke

Jeff Kissel

Nic Smith

Ryan, Vorvick, Worden, Schofield, McCarthy, Radkins, Gray, Cook, Bland, Landry, Atkinson, Barker, Douglas, Lubinski, Reed, Sandberg, Santini, Schwinberg, Thomas, Kawabe, Savage, Effler, Moreno, Amin, Traylor, Overmier, Fyffe, Hanson, O'Reilly, Frolov, Feldbaum, Lucianetti, Myers, Bridges, Romie, Smith, Sellers, Adams, Birch, Forsi, Gonzalez, Kinzel, Grote, Sibley, Thorne, Wooley, Weiss, Abbott, Abbott, Billingsley, Brooks, Bork, Quitsche, Reitze, Tanner, Williams, Mueller, Martin, Coyne, Etzel, Gustafson, Wagner, Schulz, Wachter, Veltkamp, Janssen, Vessels, Frede, Kracht, Heefner, Ivanov, King, Mageswaran, Robertson, Mailand, Sannibale, Smith, Taylor, Torrie, Vass, Ward, Willems, Weiss, Mittleman,Matichard, Foley, Mason, Stein, MacInnis, Evans, Barsotti, Rollins, Thrane, Slagmolin, Willke, Clark, Lantz,…

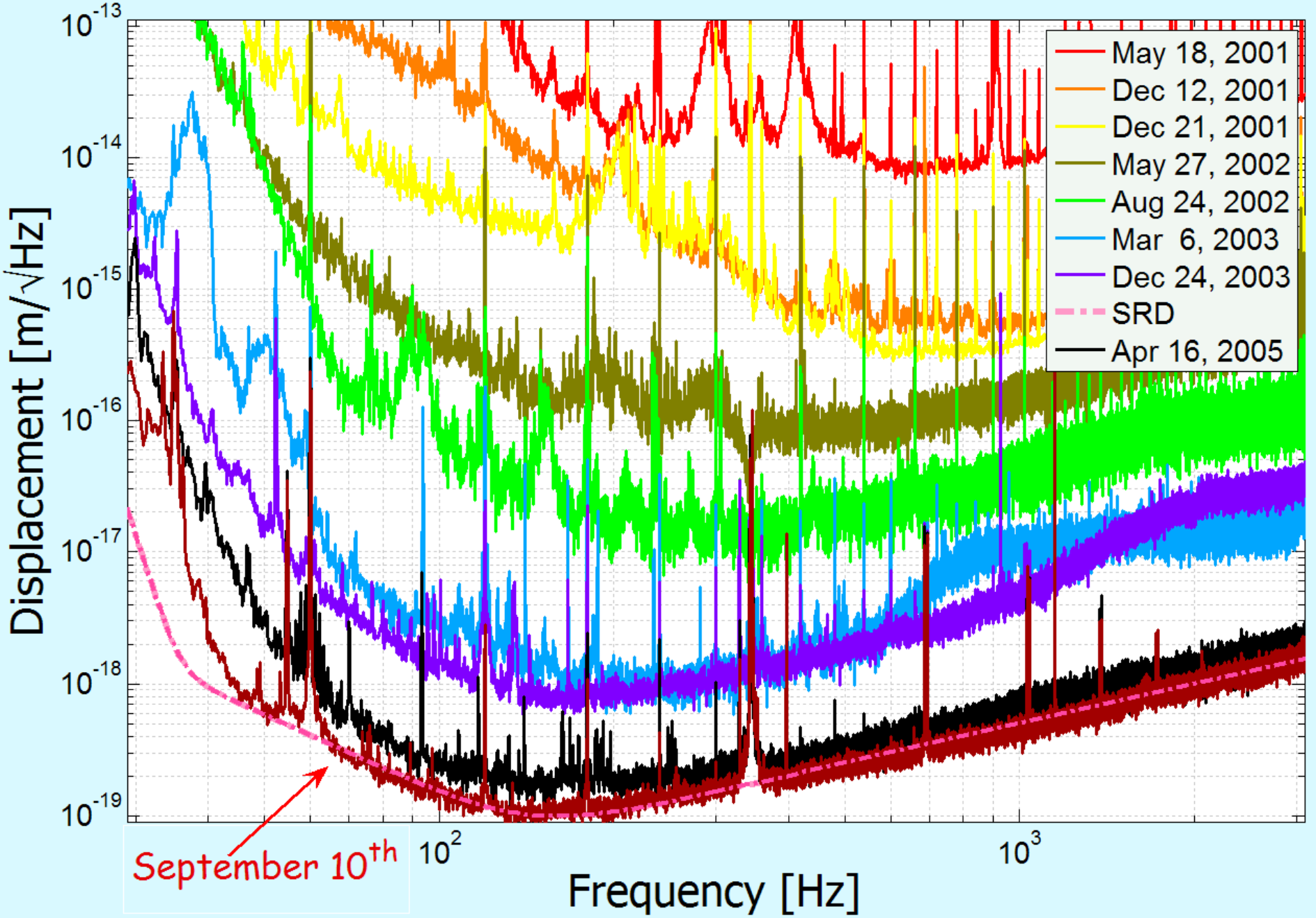
LIGO

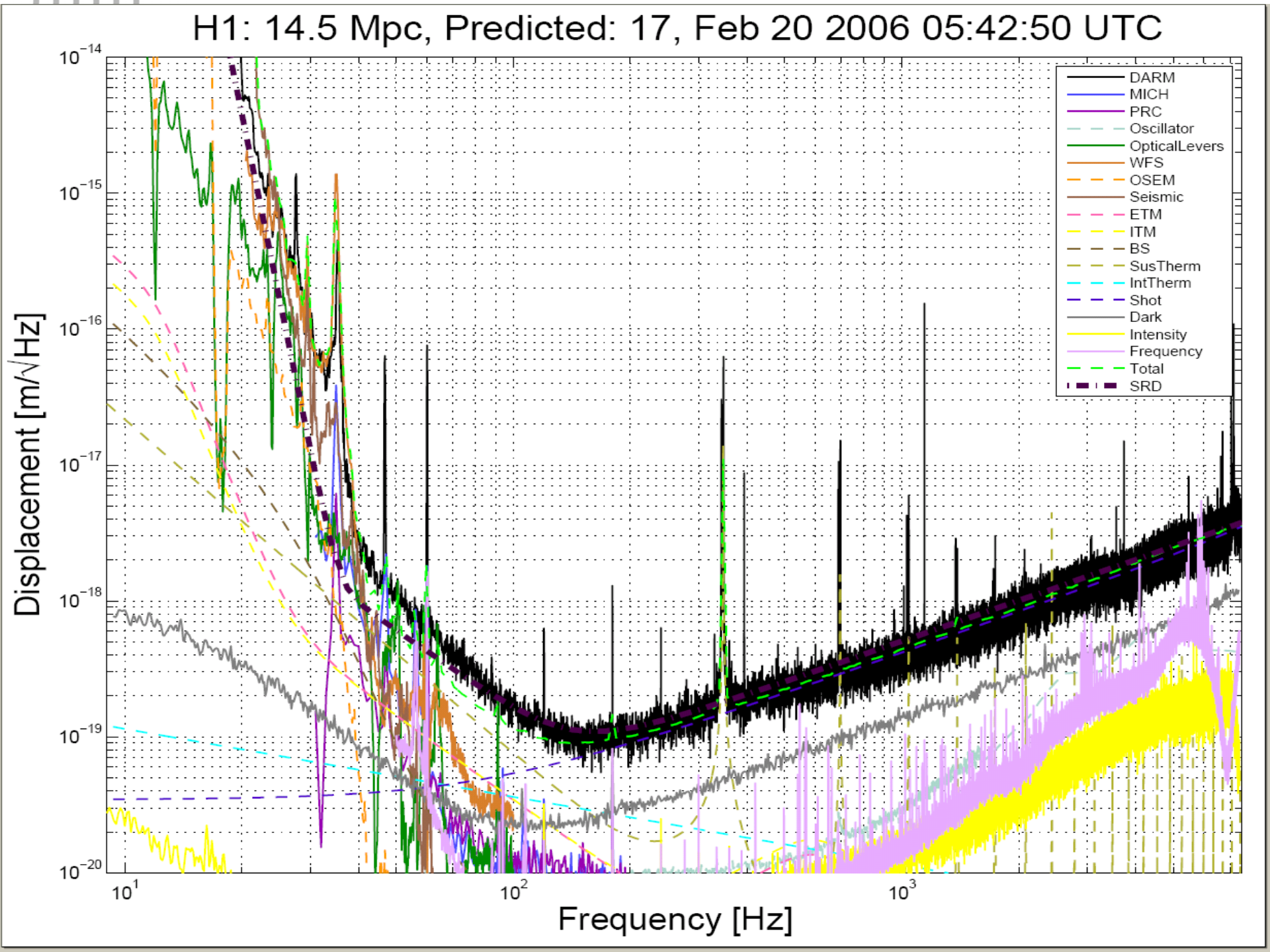
# Enhancements to Initial LIGO

R. Adhikari

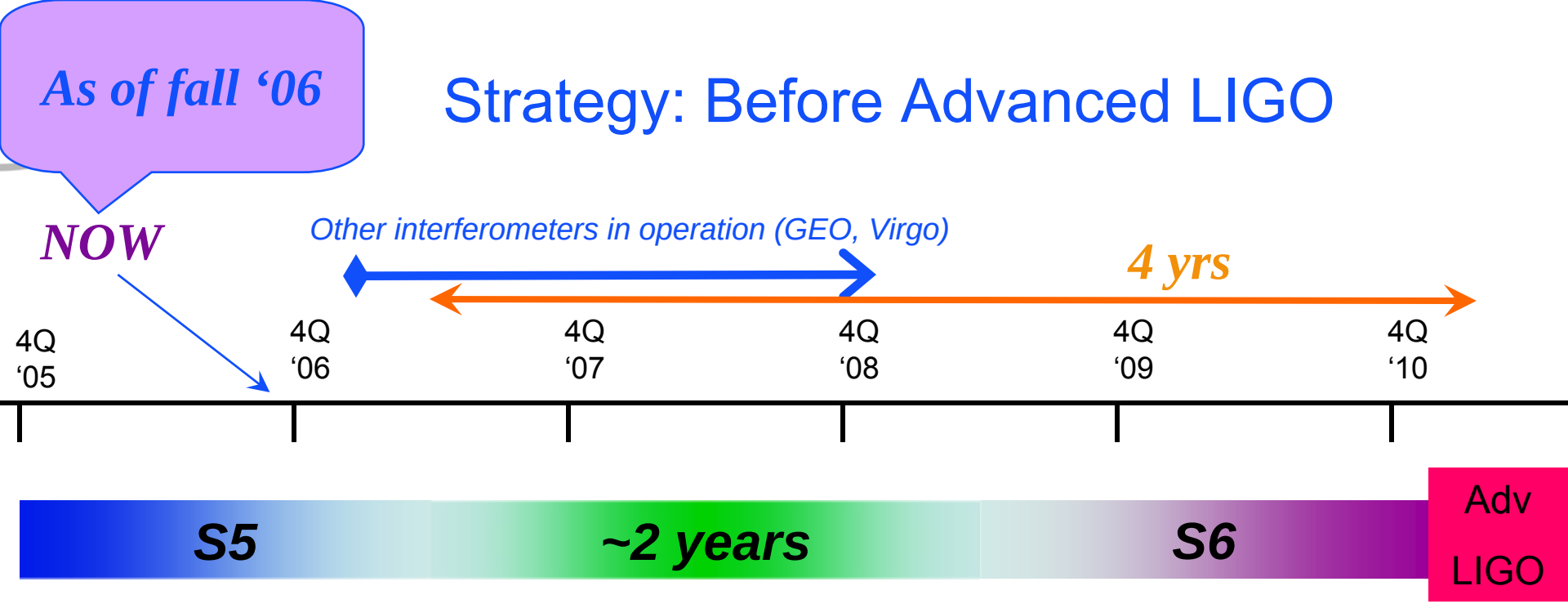
NSF Review, Hanford 2006

# 5 years of debugging in Louisiana…




H1: 14.5 Mpc, Predicted: 17, Feb 20 2006 05:42:50 UTC
Displacement [m/√Hz]
Frequency [Hz]
DARM
MICH
PRC
Oscillator
OpticalLevers
WFS
OSEM
Seismic
ETM
ITM
BS
SusTherm
IntTherm
Shot
Dark
Intensity
Frequency
Total
SRD

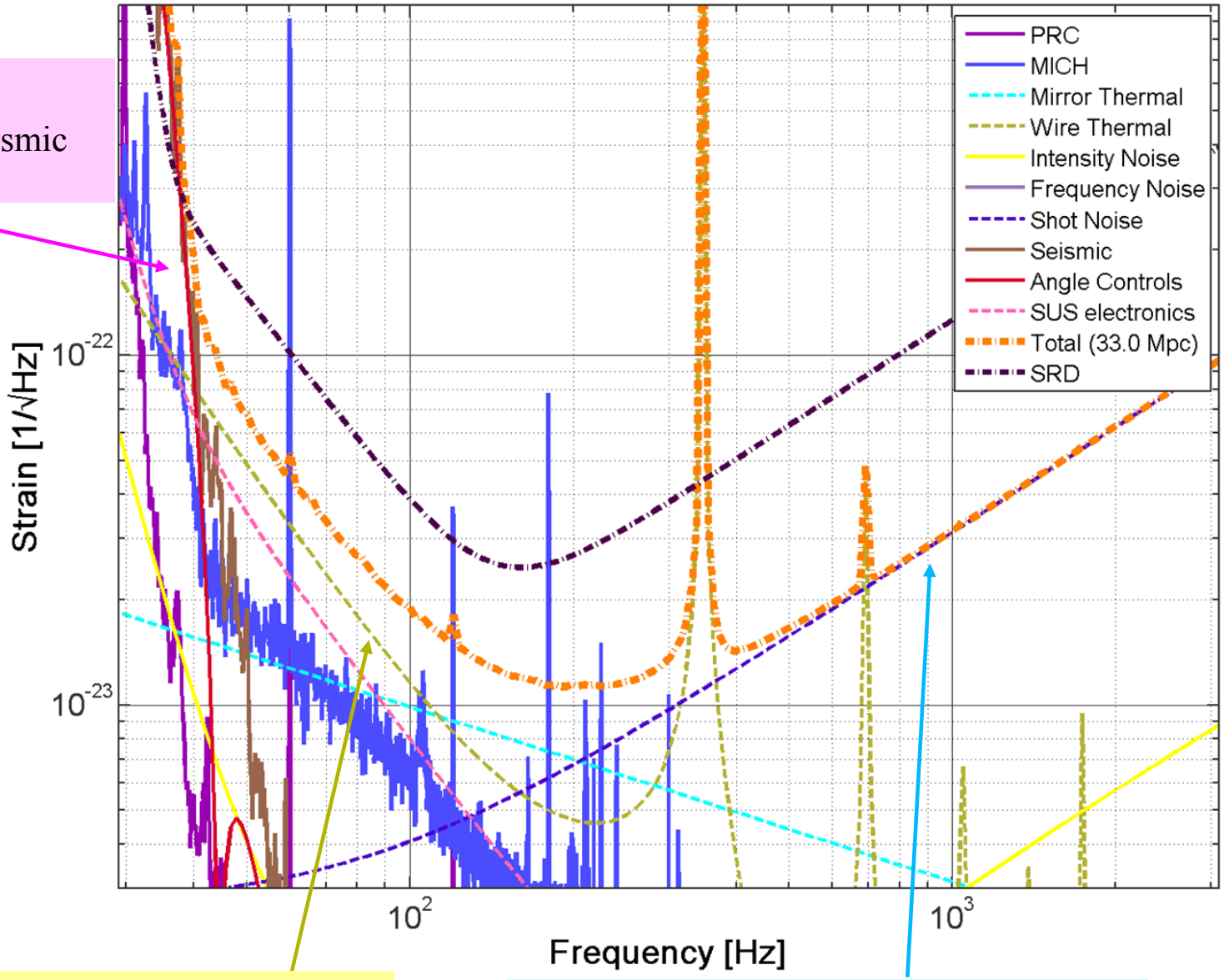
# Strategy: Before Advanced LIGO




About 4 years between now and AdL installation
S5 scheduled to continue for ~ one more year
Worth investing some of that time *if improvement is reasonably predicted*
e.g., a factor of ~2 in noise will yield ~8 in event rate
**This will increase likelihood of detection before Advanced LIGO**
But…
Routine GW observations with AdL remain our primary mission objective
**Enhancements must also be planned as stepping stones**

## Seismic:

No modification in seismic isolation systems



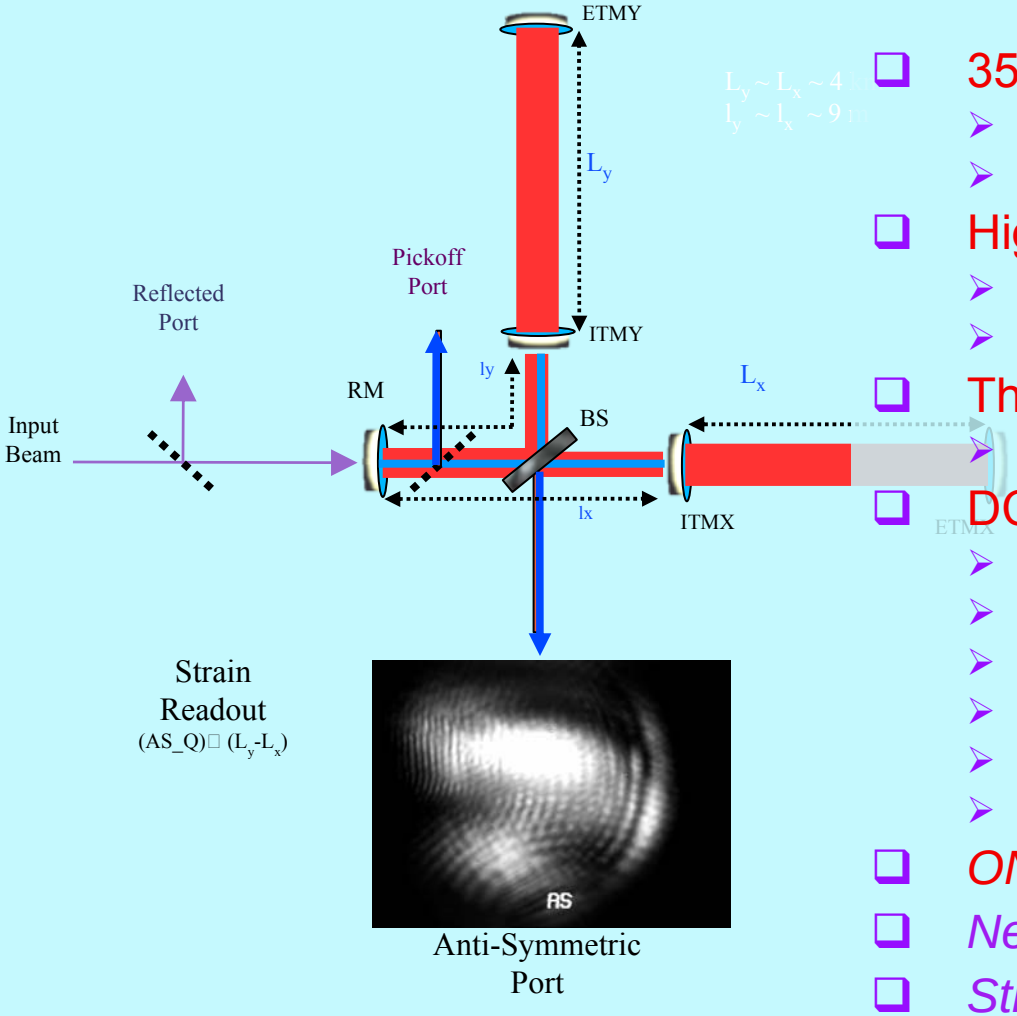

## Thermal:

Good wires, good mirrors, and control of "technical" noises

## Shot Noise:

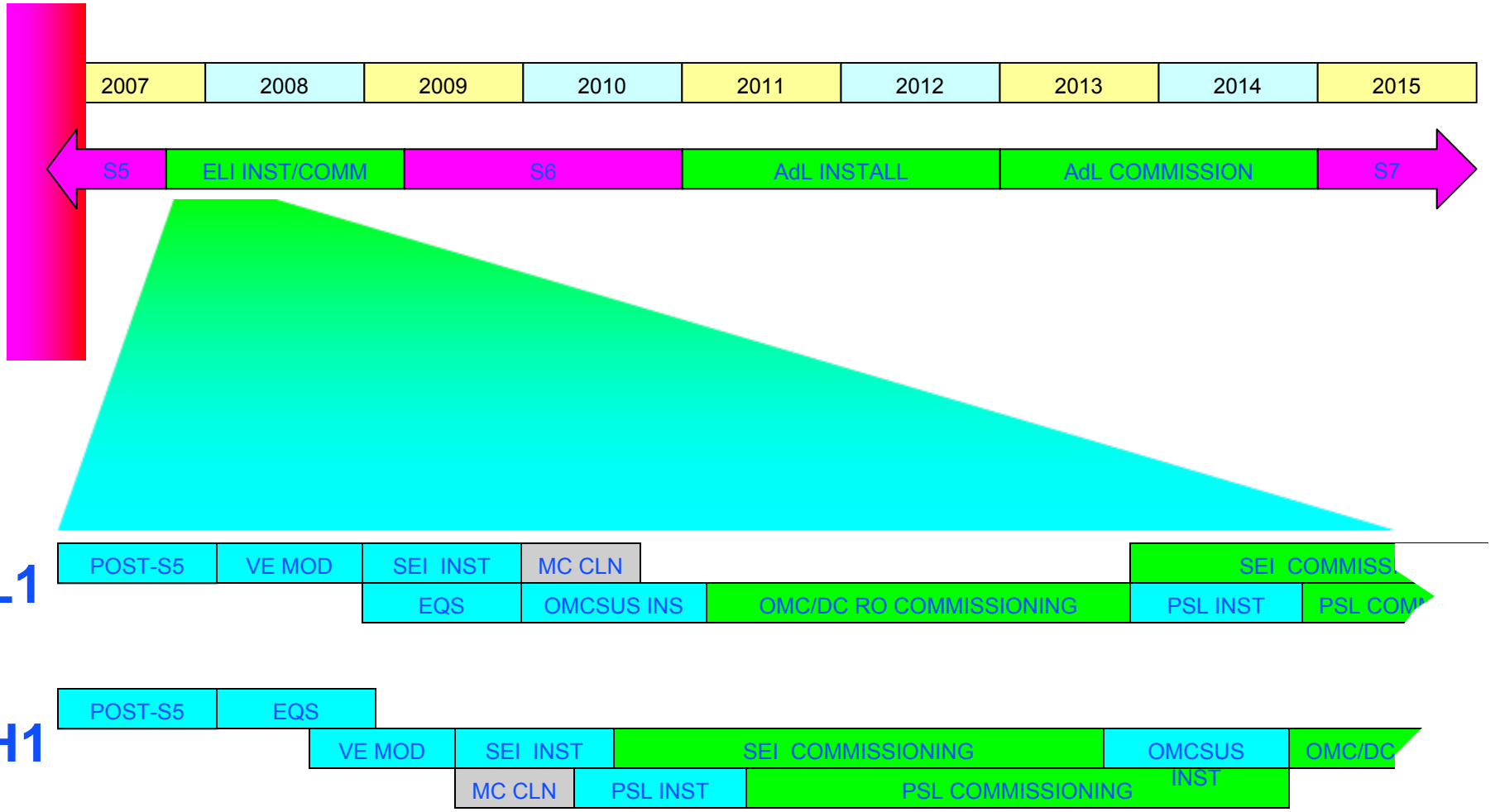
- New in-vac filter cavity
- **4-5x more laser power**
- **Advanced readout technique**

# Baseline ELI Scope

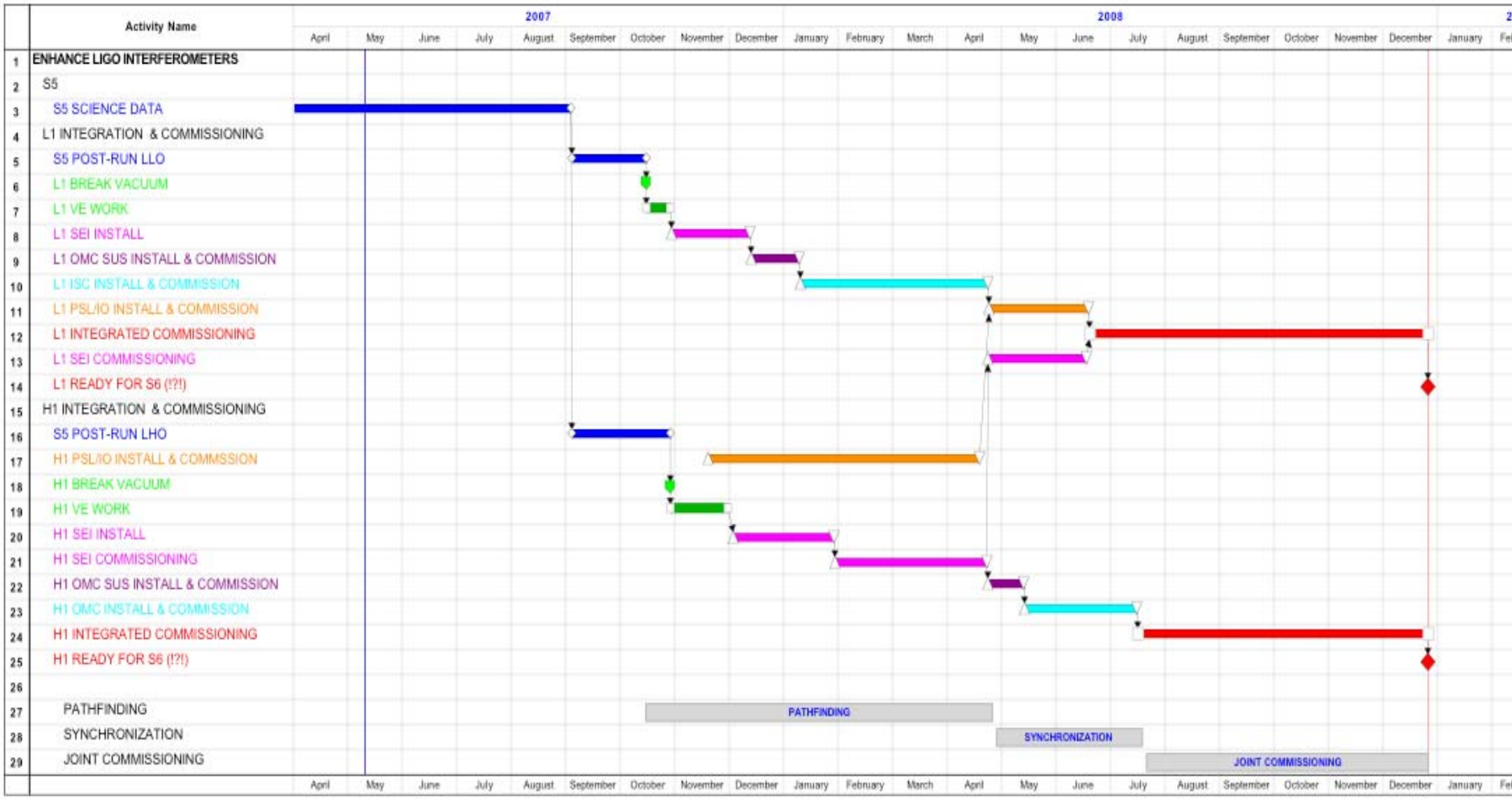



- 35 W Laser
  - 3.5x increase in power
  - Front-end of the AdL laser (supplied by AEI)
- High Power Input Optics
  - AdL EO Modulators
  - AdL Faraday Isolators
- Thermal Compensation
  - Upgraded power & beam shaping
- DC Readout of GW Strain
  - AdL readout (DC instead of RF)
  - In-vac photodetectors, behind
  - …AdL Output Mode Cleaner cavity
  - …on AdL Double Suspension
  - …on AdL HAM SEI system in HAM6
  - …behind Isolation septum with window
- *ONLY RETROFIT H1 AND L1*
- *New Silica EQ Stops*
- *Stray Light Baffles*
- *Changed ETM Drive Magnets*

# Installation Timeline in Context



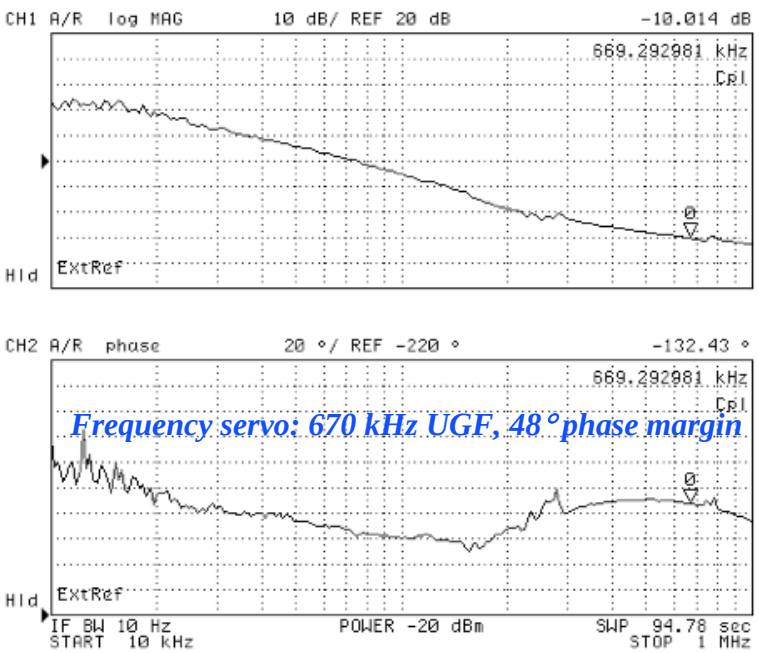
# TAG-TEAM INTEGRATION SCHEME (mez 5/07)



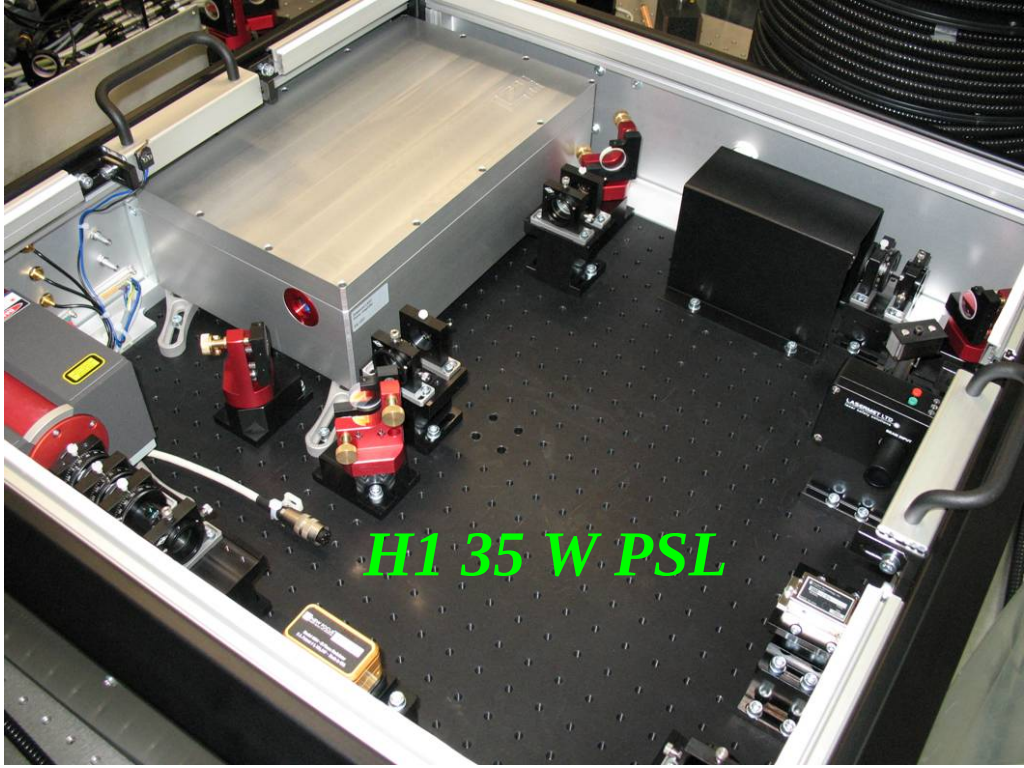
LIGO

# Main milestones

- Early ‘06: *T060156* (Adhikari, Fritschel, Waldman)
- July ‘06 LIGO Lab internal review
  - Endorses technical goals but…
  - Requests more ‘project-ized’ organization, option pruning
  - Requests ‘strategic integration’ with Lab priorities (AdL)
- Nov. ‘06 Baseline Review: scope/cost/schedule approved
  - (Jan. ‘07: bookkeeping *merged with AdL* )
- Nov. ‘07 Break vacuum both sites
- Sep. ‘08 Phase A (pathfinder) installation complete
- Dec. ‘08 Phase B (hardware sync) complete
- July ‘09 (expected) Ready for S6 Science Run




QuickTime™ and a
decompressor
are needed to see this picture.





***Pump diodes housed in new remote lab***

***39 W, > 95% $TEM_{00}$***

LIGO

UF UNIVERSITY of FLORIDA

# High Power Input Optics:
# Phase Modulators

- RTP modulators develope
- Thermal lensing is 30-50x
- Multifrequency/multielectr
- Custom RF matching & H

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

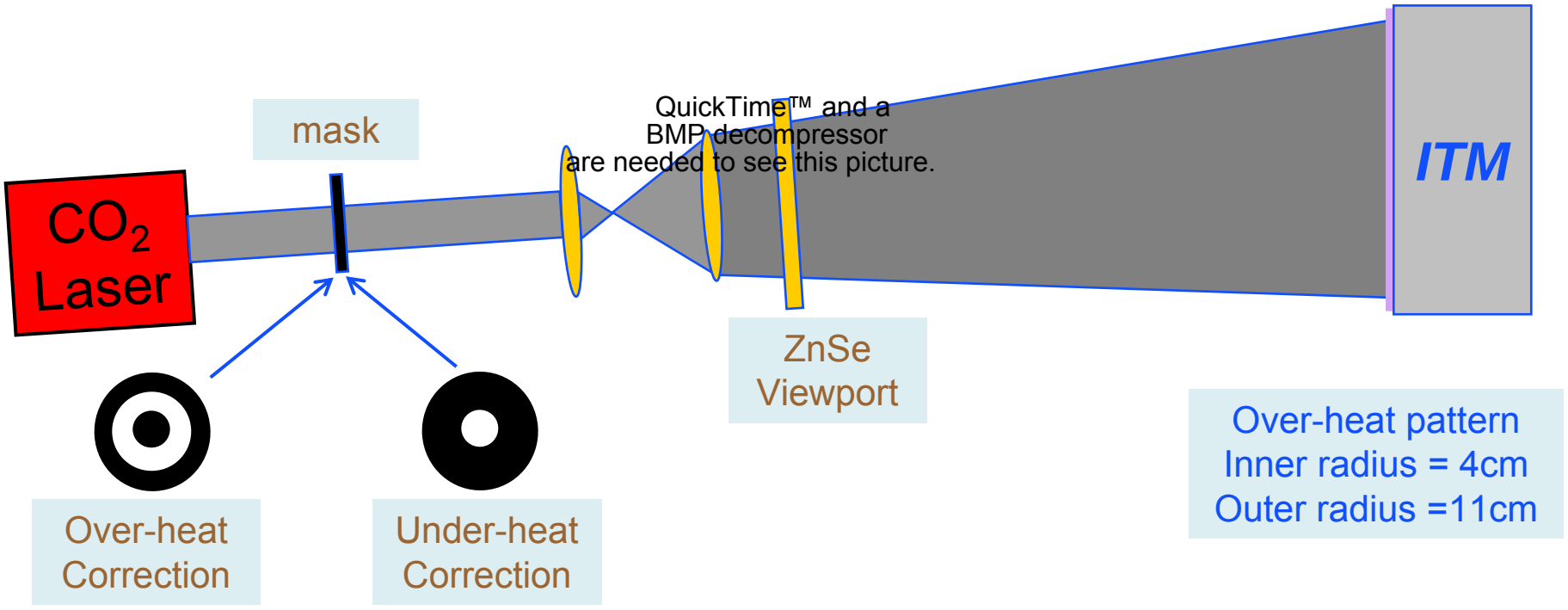
QuickTime™
TIFF (Uncompressed)
are needed to see th

LIGO

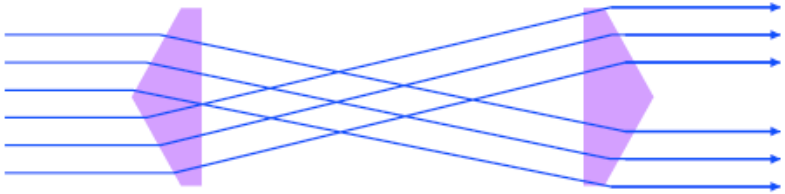
QuickTime™ and a
decompressor
are needed to see this picture.

# Thermal Compensation System

- Cold power recycling cavity is unstable: poor buildup and mode shape for the RF sidebands
- Require 10's of mW absorbed by 1μm beam for optimal thermal lensing
- Can't count on a specific level of 1μm beam absorption, so we provide our own:

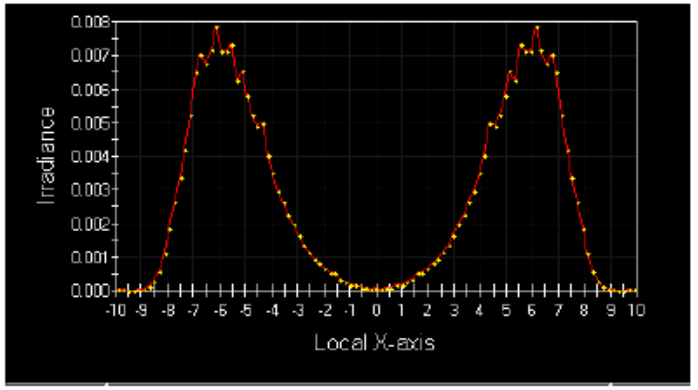


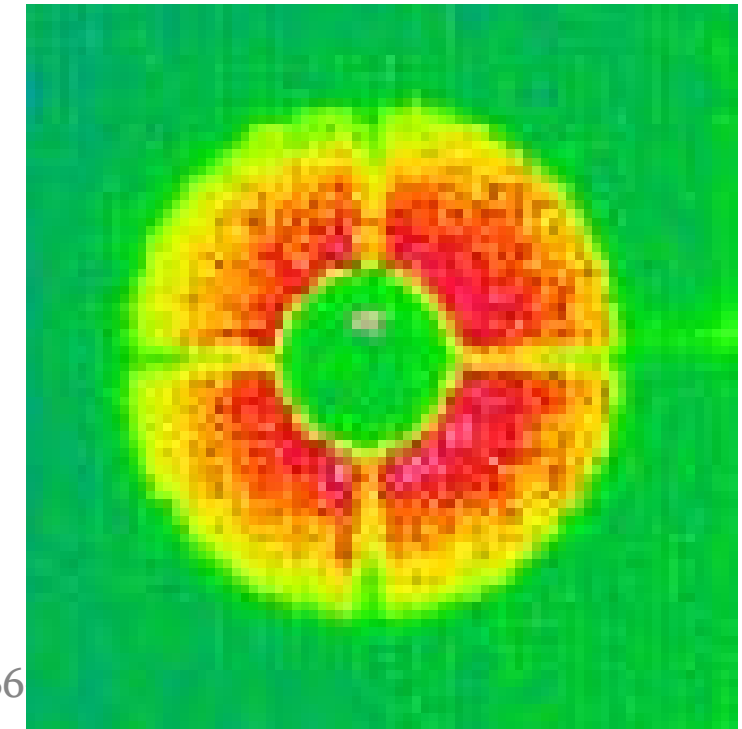
# Axicon – a better way to create an annulus



ray trace of axicon pair

typical expected output intensity



onical rather than
onvert incident
ar patterns.

QuickTime™ and a
BMP decompressor
are needed to see this picture.

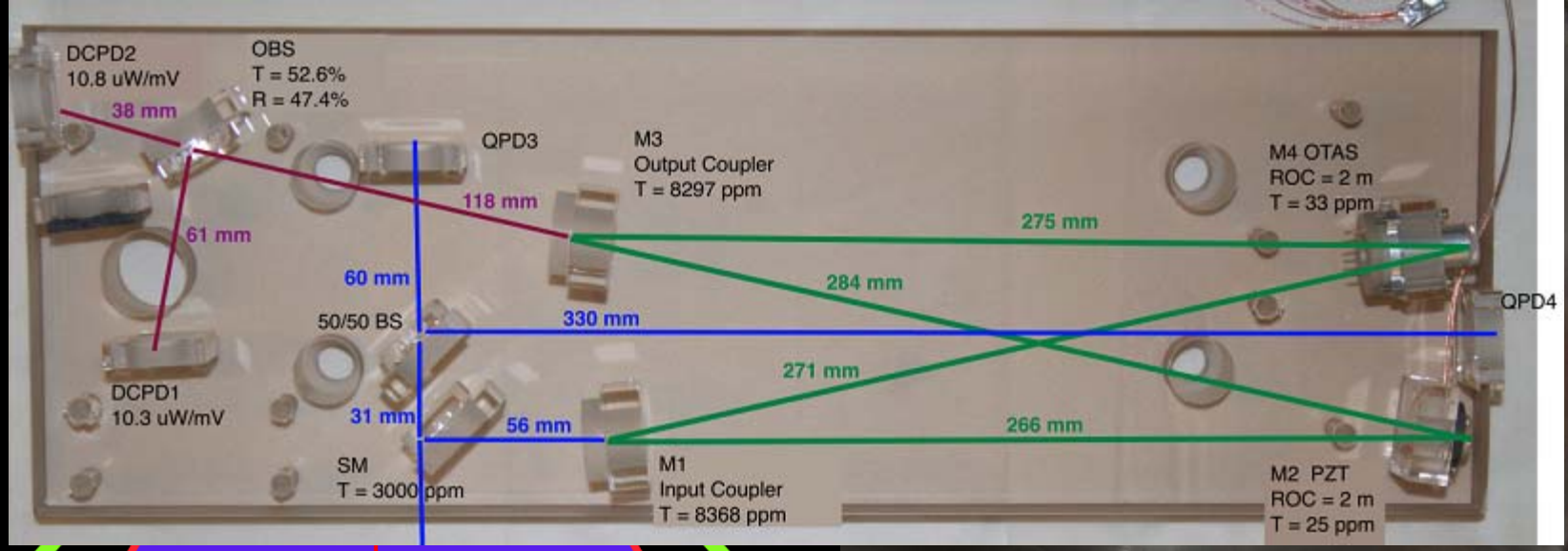
# New ASC Scheme for High Power

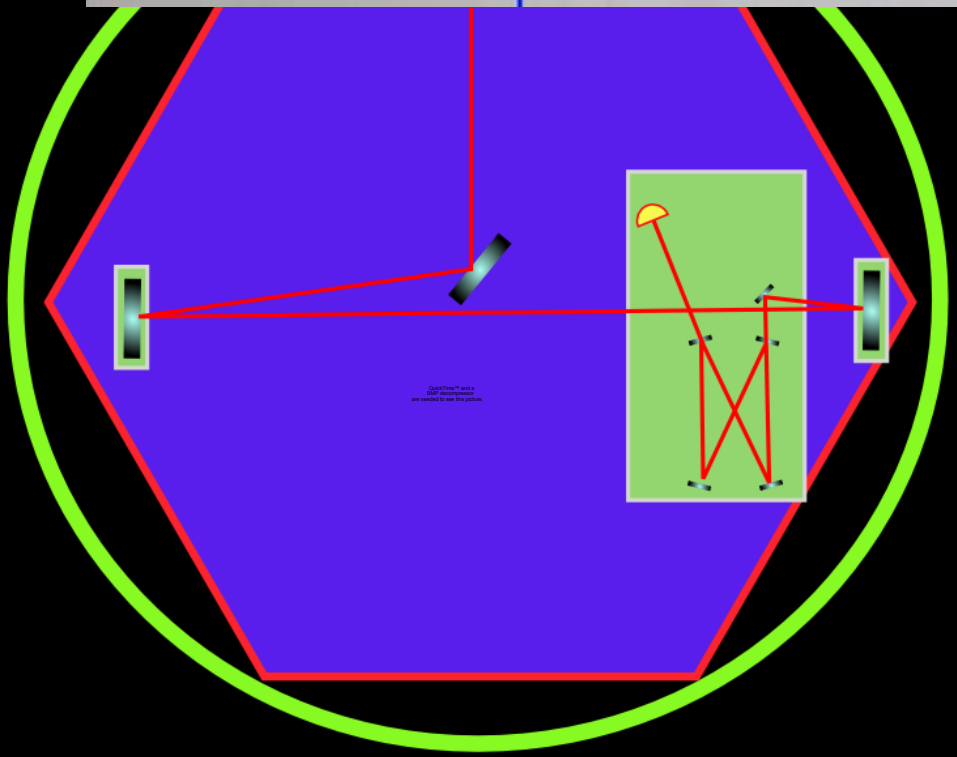
- Sigg-Sidles instability requires new alignment strategy at high power
- WFS alignment basis recast into (diff, comm) X ('stable', 'unstable') + global angle (assigned to PRM)

QuickTime™ and a
BMP decompressor
are needed to see this picture.

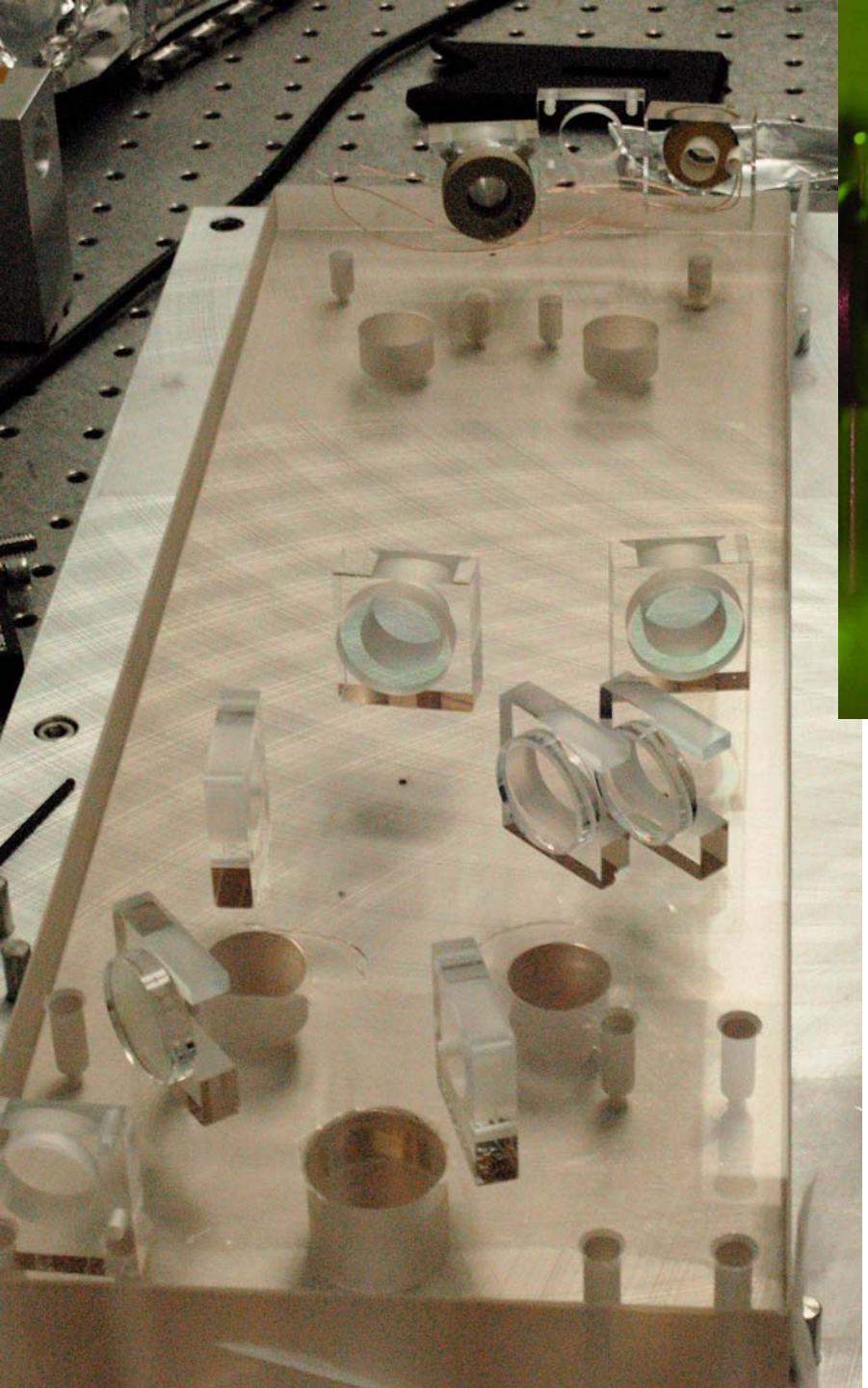
QuickTime™ and a
BMP decompressor
are needed to see this picture.

QuickTime™ and a
BMP decompressor
are needed to see this picture.

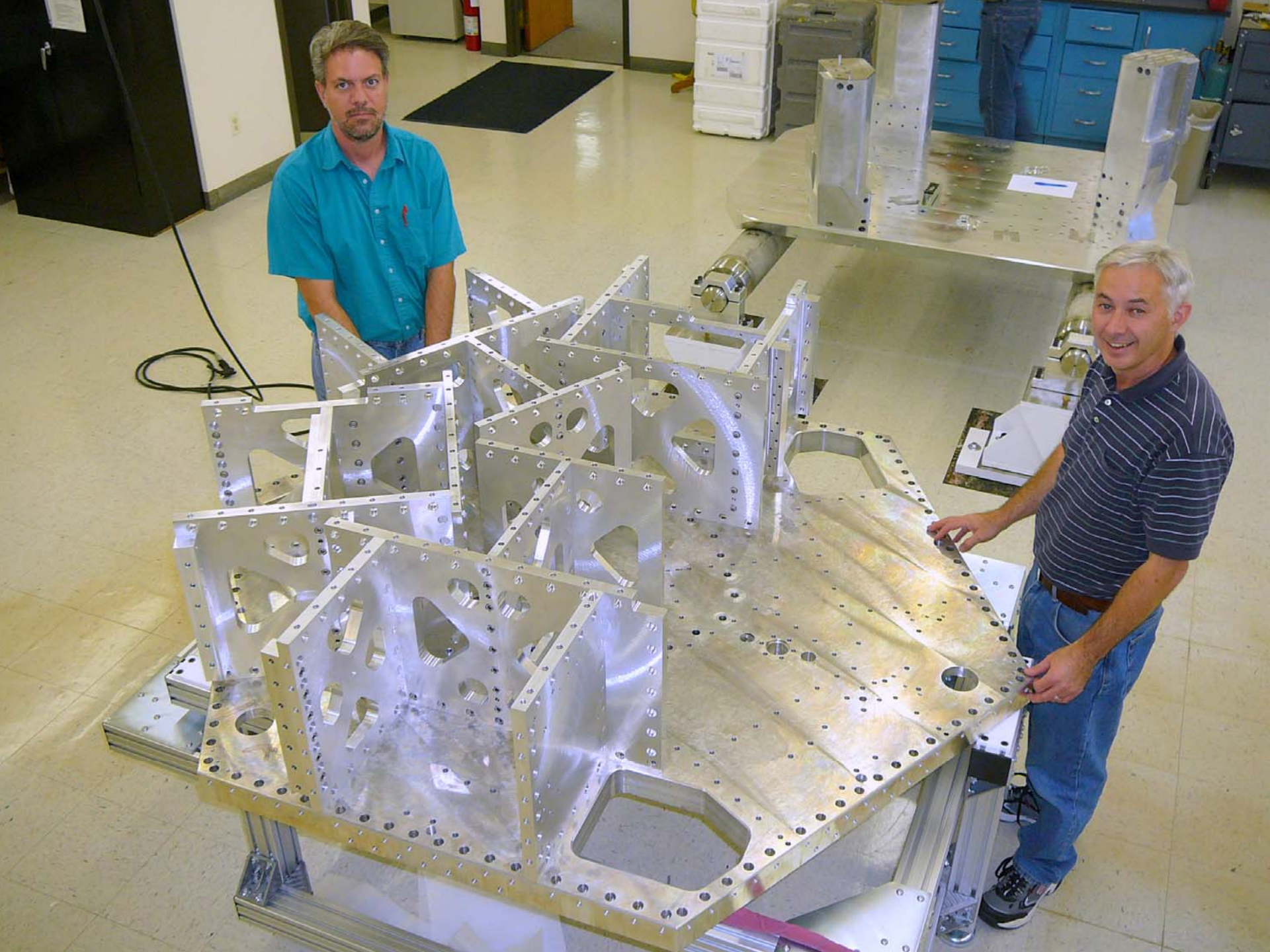


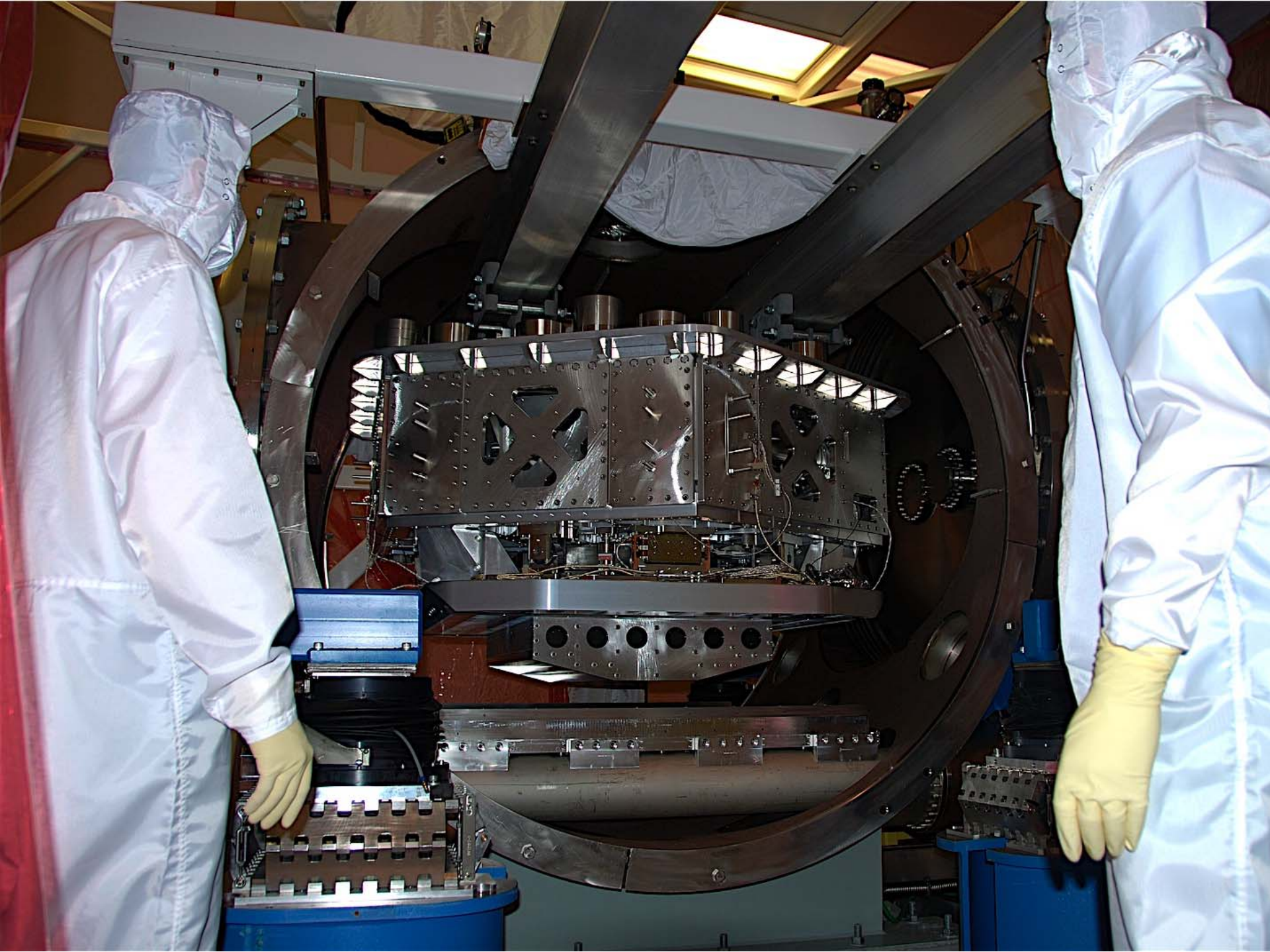



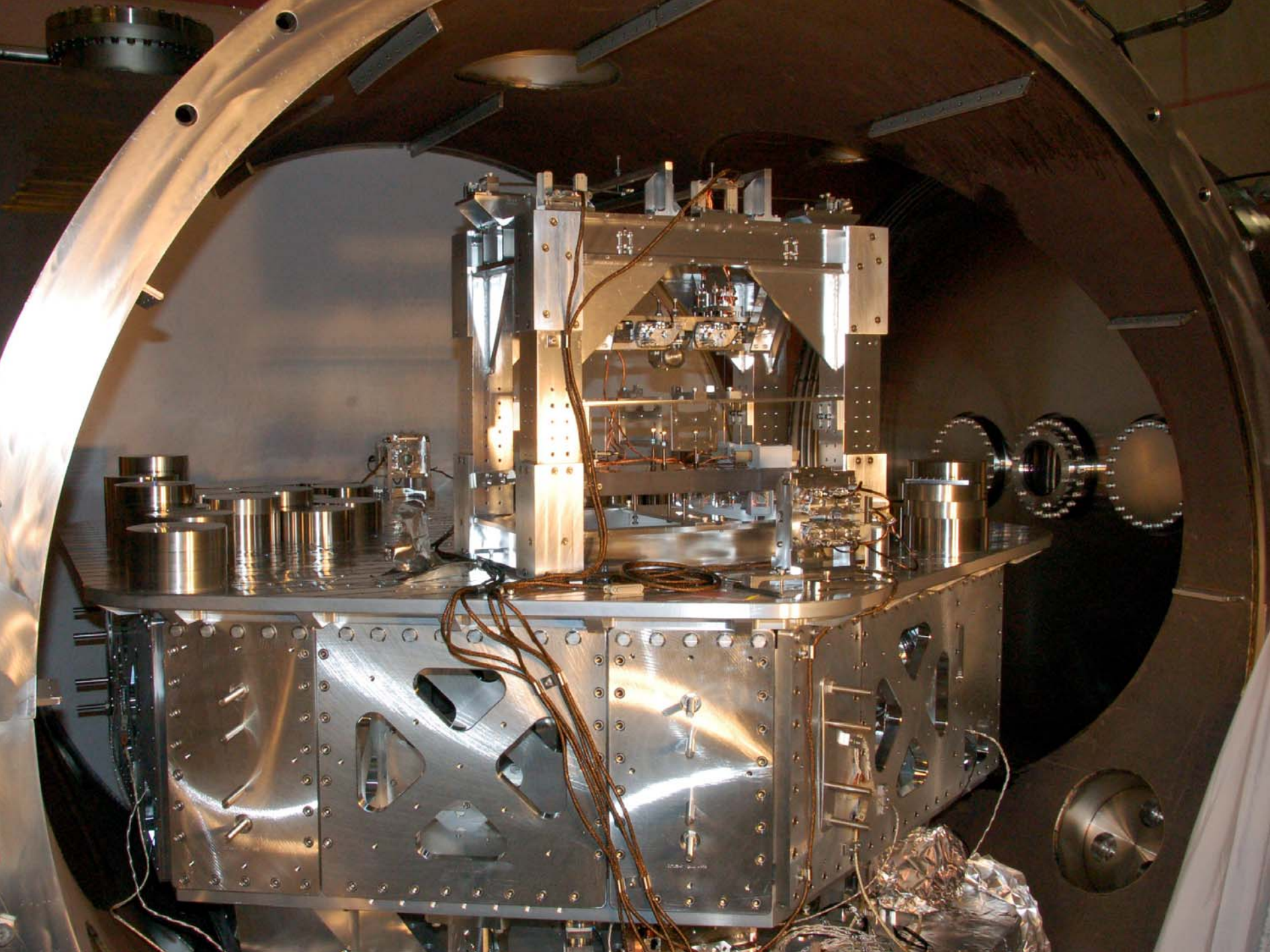
HAM 6 Chamber



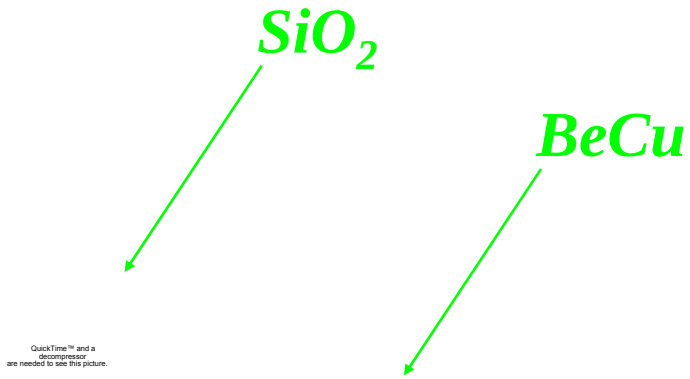
QuickTime™ and a
BMP decompressor
are needed to see this picture.







# Silica-tipped, non-galling EQ stops



LIGO

# Stray Light Baffles

***ITM/CP Baffle***

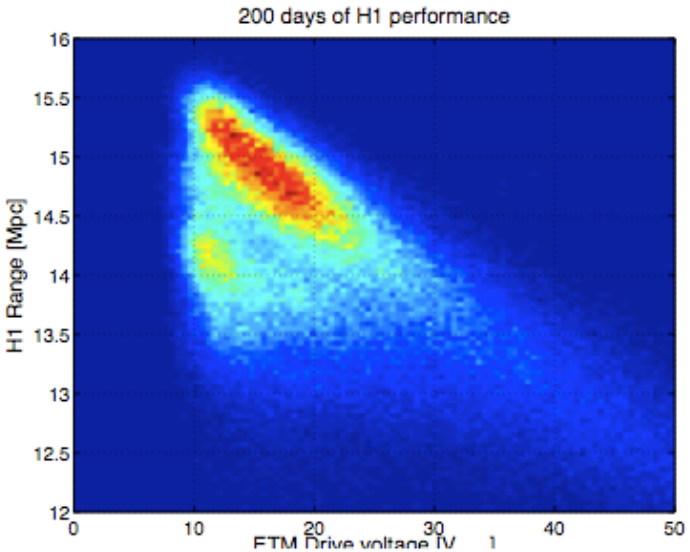
***ETM Before***

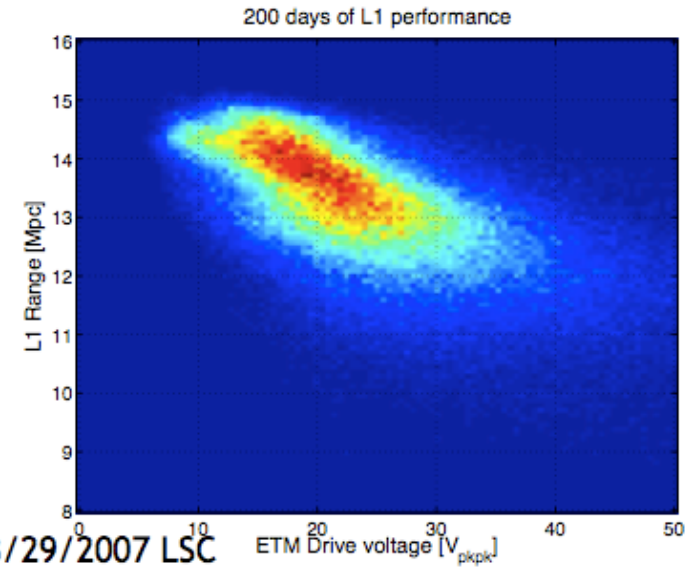
QuickTime™ and a
decompressor
are needed to see this picture.

QuickTime™ and a
decompressor
are needed to see this picture.

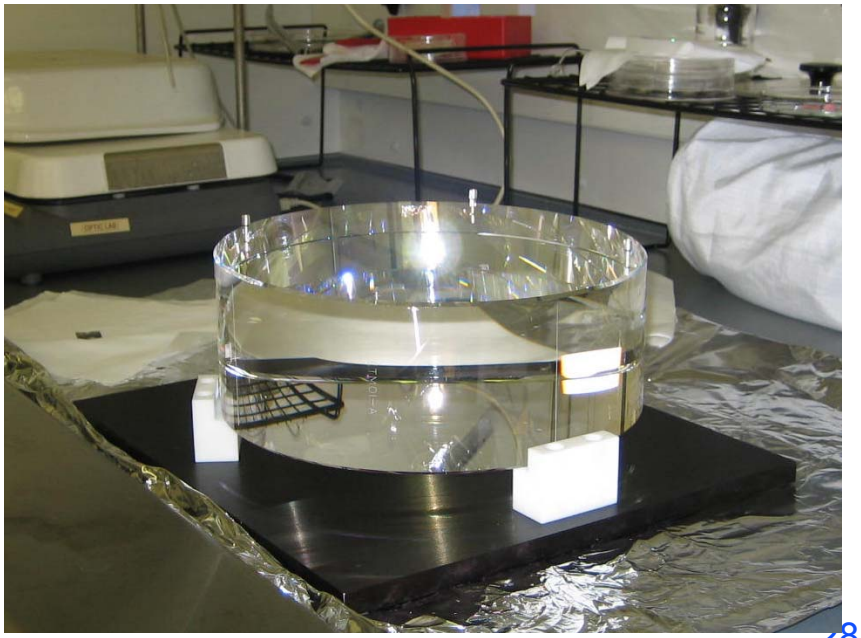
***ETM After***

# Other: Upconversion --> magnet swap




- Low-frequency upconversion observed in both sites throughout S5
- Found to be Barkhausen noise from domain-flipping in NdFeB drive magnets
- Swapped NdFeB for SmCo on ETM's



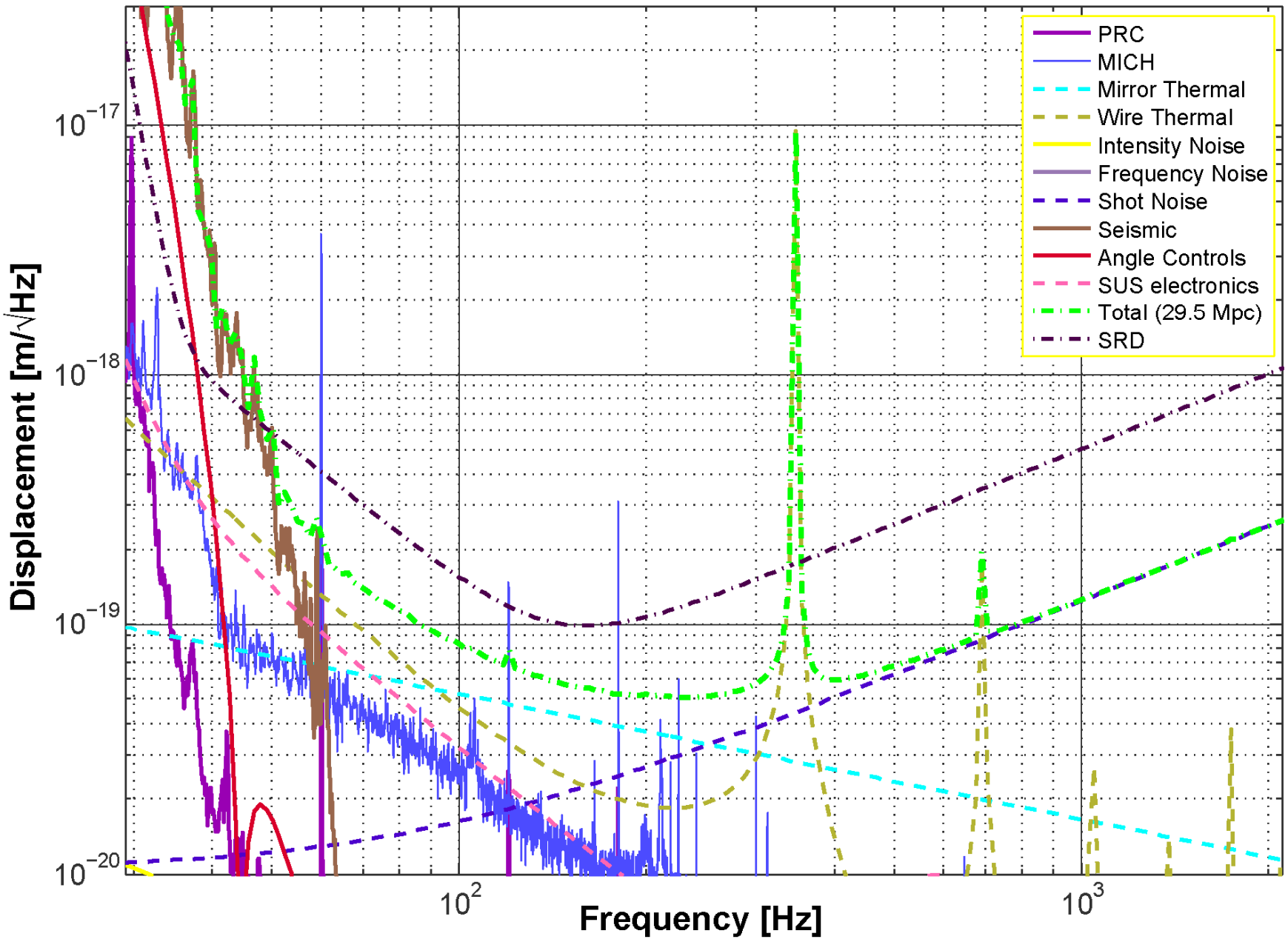
LIGO

# SO… WHAT WORKED?

QuickTime™ and a
decompressor
are needed to see this picture.

LIGO

# Noise sources for an enhanced detector



LIGO

QuickTime™ and a
BMP decompressor
are needed to see this picture.

# Persistent Technical Issues

- Aligning the OMC to the differential arm cavity field
  - At least four different methods tried
  - Even after strong measures to exclude RF sidebands, something's very weird about the carrier field in the PRC
- Shot noise doesn't seem to scale properly
- Beam jitter coupling to DC readout
  - Seems related to resonant spikes in the bucket
- Other anomalous (badly measured?) noise couplings
  - e.g., frequency noise (should be tiny for DCR)
- The low-frequency noise (Suspension wire rubbing?)

# But Many REAL Technical Successes…

- Laser & reworked PSL (FSS, ISS, PMC, etc.) √
- High-power IO (EO, Faraday, etc.) √
- HAM ISI √
- OMC suspensions √
- OMC, DC Readout , & AdL ISC concept in general √
- High-power ASC WFS alignment √
- Stray light baffles √
- $SiO_2$ earthquake stops √
- SmCo magnets √
- TCS with Axicons (eventually) √

# ELI PSL Frequency Noise

QuickTime™ and a
decompressor
are needed to see this picture.

# New High-power Faraday Isolator

- AdL design developed by UF w/ IAP Nizhny-Novgorod

eciprocal 67.5

nsated in the second.

terial: deuterated
DP').

nent

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

nal Lens
sation

Polarizer

# H1 IO & Mode Cleaner high-power run

***AEI/LZH LASER for ELI (AdL front end)***

QuickTime™ and a
decompressor
are needed to see this picture.

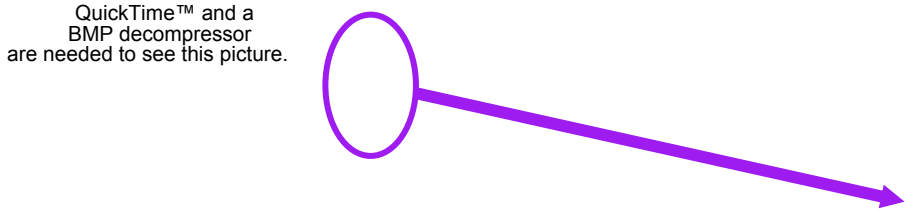
QuickTime™ and a
decompressor
are needed to see this picture.

***No mode cleaner throughput degradation seen up to 28 W input***

# ELI/AdL HAM ISI Performance

SEI commissioning complete for H1 and L1

Meets or Beats AdLIGO requirements, all 6 dofs, most frequencies*



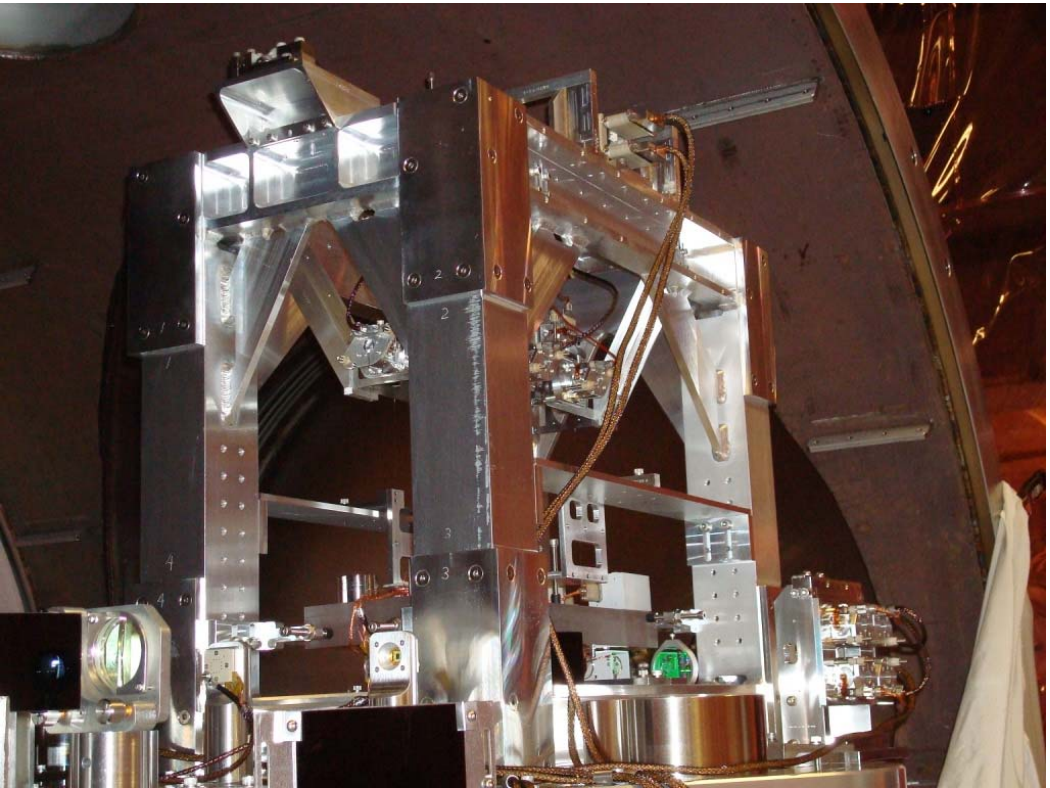

QuickTime™ and a
BMP decompressor
are needed to see this picture.

**** artifact from legacy "gullwings," slated for AdL replacement***

LIGO

# *ELI/AdL OMC Double Suspensions*

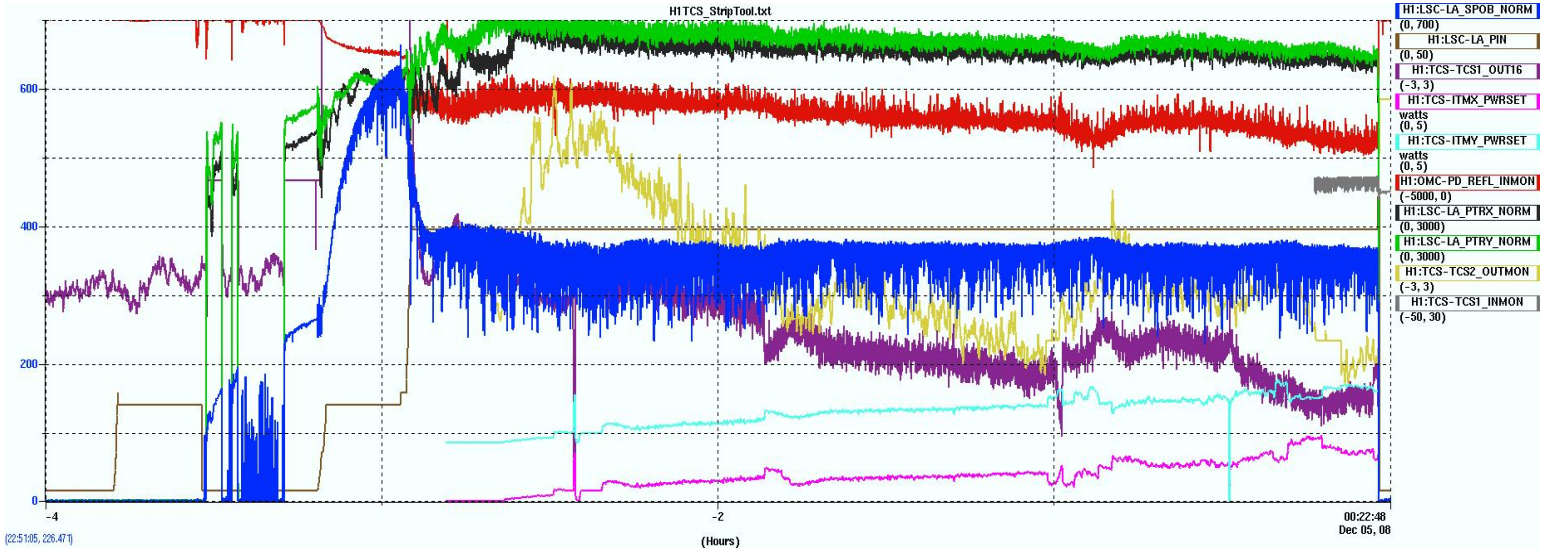
QuickTime™ and a
decompressor
are needed to see this picture.



- First AdL compound suspensions in service
- Modes match design model
- Controls/damping work as designed

# High-Power ASC System Test

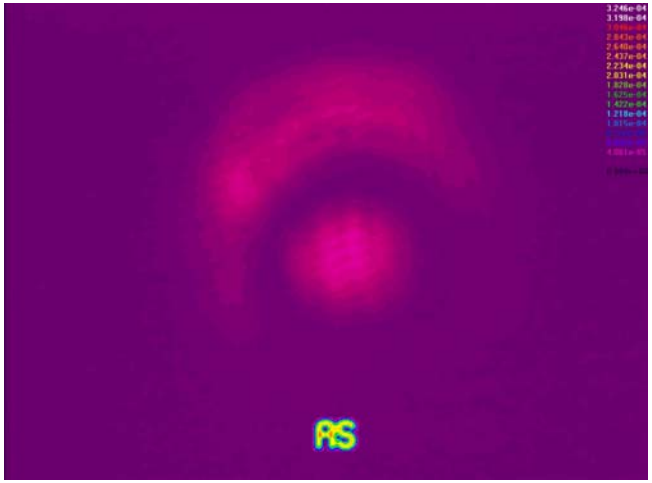
- Stable IFO and good sensitivity @ 11.7 W on DC
- IFO locked @ 21 Watts on RF (AS5) for 3 hours with TCS on

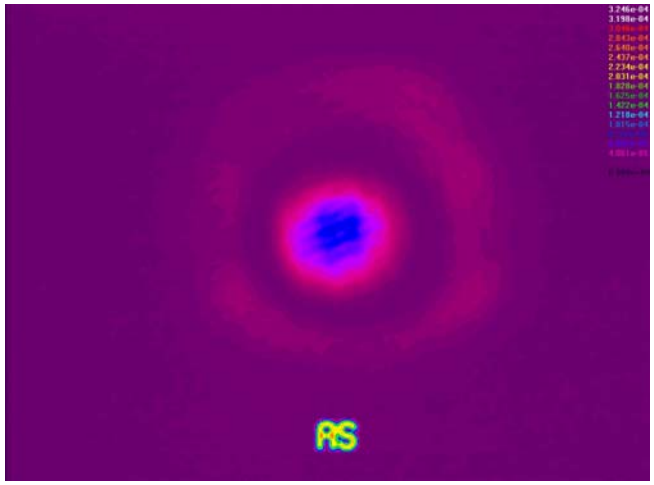



*Lisa Barsotti, Dec. '08*

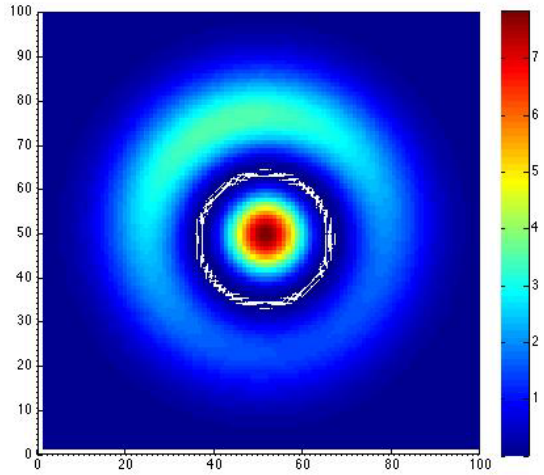
# TCS Alignment to IFO

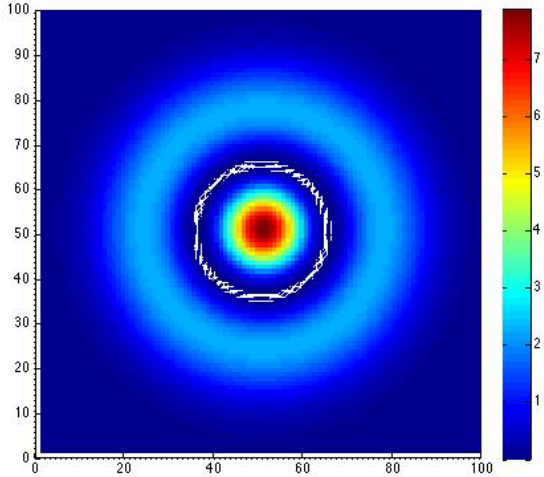
Image at AS port




MATLAB model




Misaligned ~3.5 mm

***Interferometry is needed to get adequate coincidence between heating and interferometer beams***

Optimized alignment

LIGO

# My take: Some Strategic (PM ?) Misses

- Didn't take excess SUS noise seriously enough, early enough (maybe)
  - Weak evidence, limited team resources *not a good enough excuse*
- Pushed high power too seriously, too early (maybe)
  - TCS difficulties caught us by surprise
  - Waiving off a while might have fostered better TCS re-engineering
- Slow to get noise budget, model comparisons organized
  - Succumbed to "let's try this" too long
  - Still not where I'd like us to be (w.r.t. model confidence *OR* noise level)
- No explicit effort on non-gaussian impulses
  - Not clear how we could have attacked this, but anyway, we didn't
  - Plausible magnet swap helped, but at this point we are crossing our fingers as we approach S6.

# My take: Some Strategic (PM ?) Successes

- Organizing (and selling) "project within a project"*
  - Strict priority for common goals over internal competition
  - Communication: everyone knows where "point B" is
  - Good communication --> self-organizing, "ground up"
- Tag-team "pathfinding" commissioning strategy
  - Fastest route to problems & solutions on each new system
  - Load-levels dribbling supply chains
  - Best for team, site dynamics (busts "NIH")
- Student mentoring
  - OK it's true, this particular group is unbelievably talented!!
  - Still, I think we mostly gave them good backup (and enough rope)
- Going "BIG" on HAM ISI
  - Painful, but cheap options would have us in trouble now
  - AdL: "Stick a fork in it, it's done!"

* (Actually a project within *TWO* projects)

# *Deep Prophetic Conclusion Slide*

**"The first principle is that you must not fool yourself; and you are the easiest person to fool."**

**- Feynman**

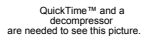
**"GW interferometry is a dynamic research effort: [designs should] be made flexible, because no one is smart enough."**

**- Adhikari**

**"Always buy the students dinner. Some day you may need a job."**

**- Zucker**

# Home Office


QuickTime™ and a
decompressor
are needed to see this picture.