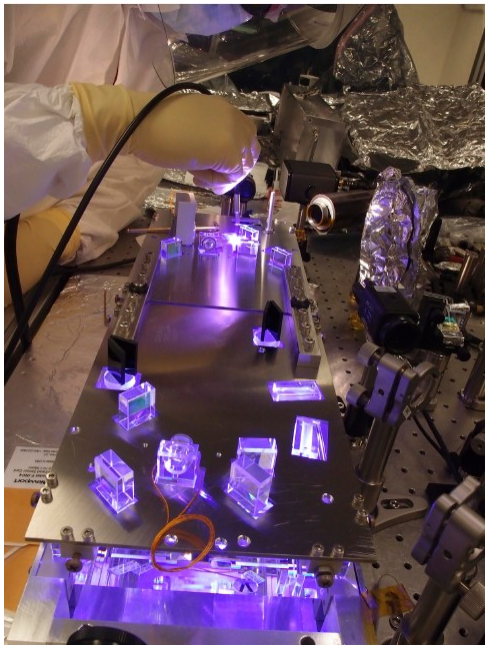
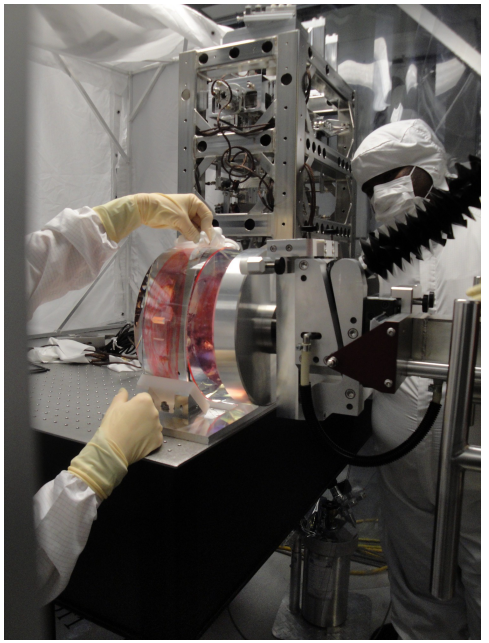
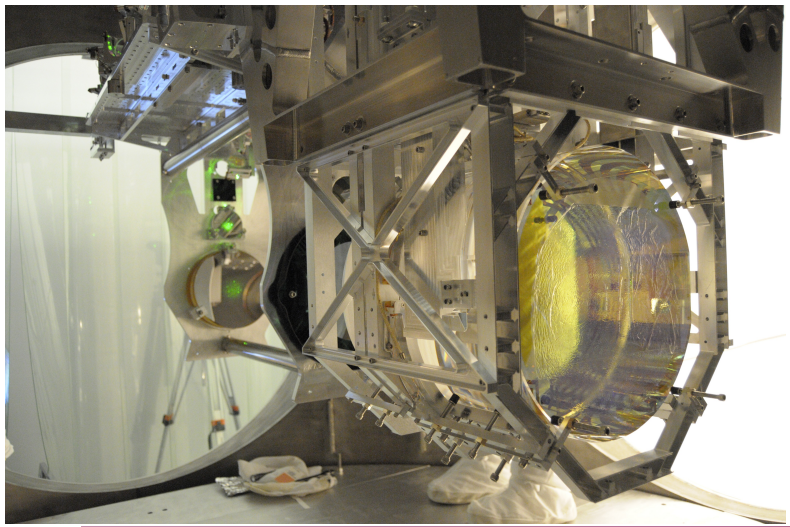
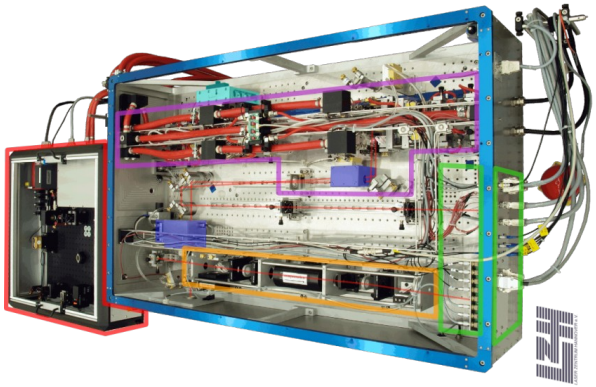
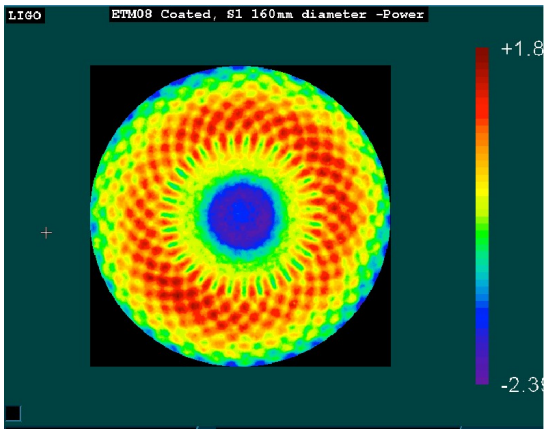
Advanced LIGO











Keita KAWABE, LIGO Hanford, Caltech

LIGO

TOC

- Introduction
- Current status
- Future

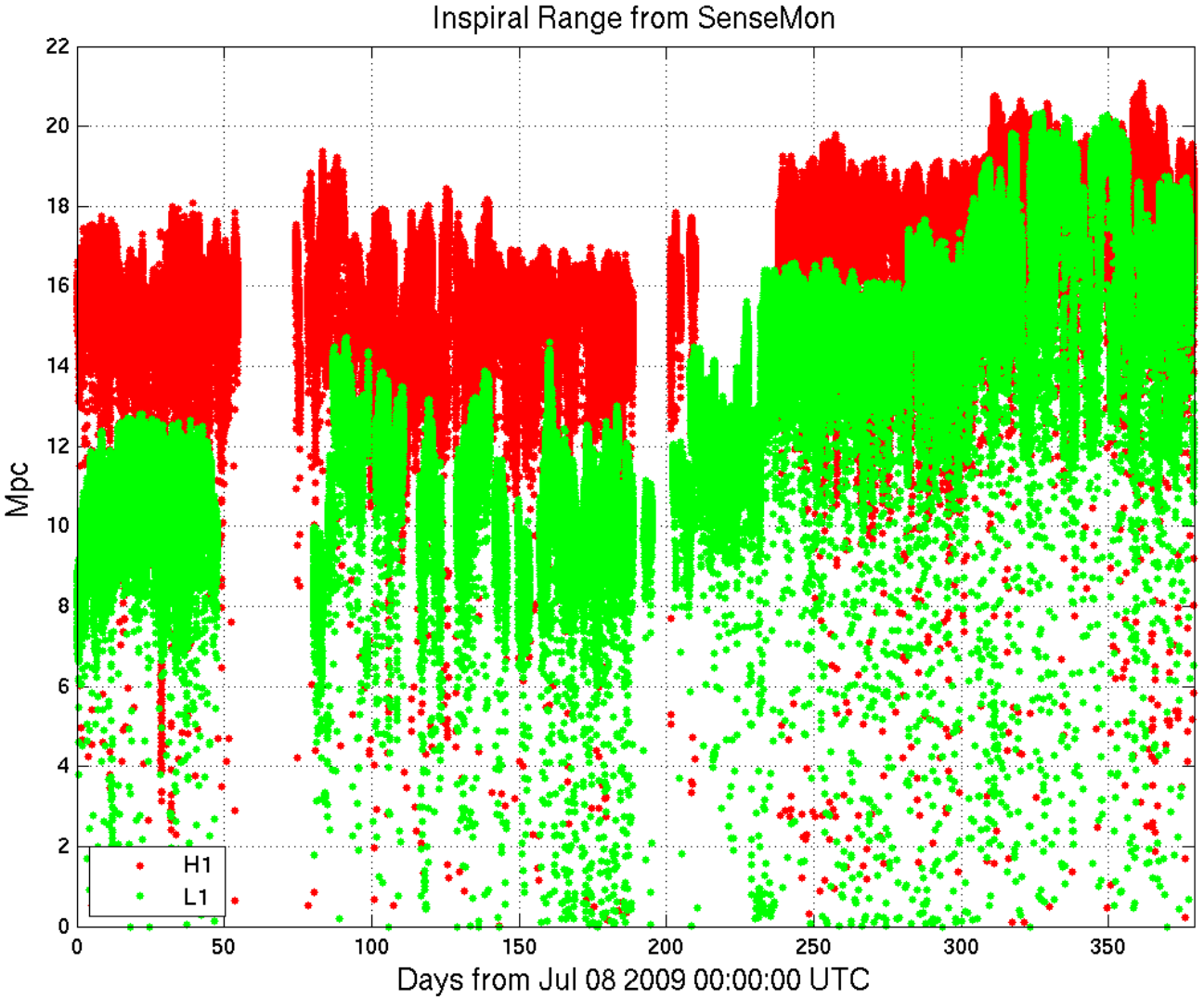
LIGO

Introduction

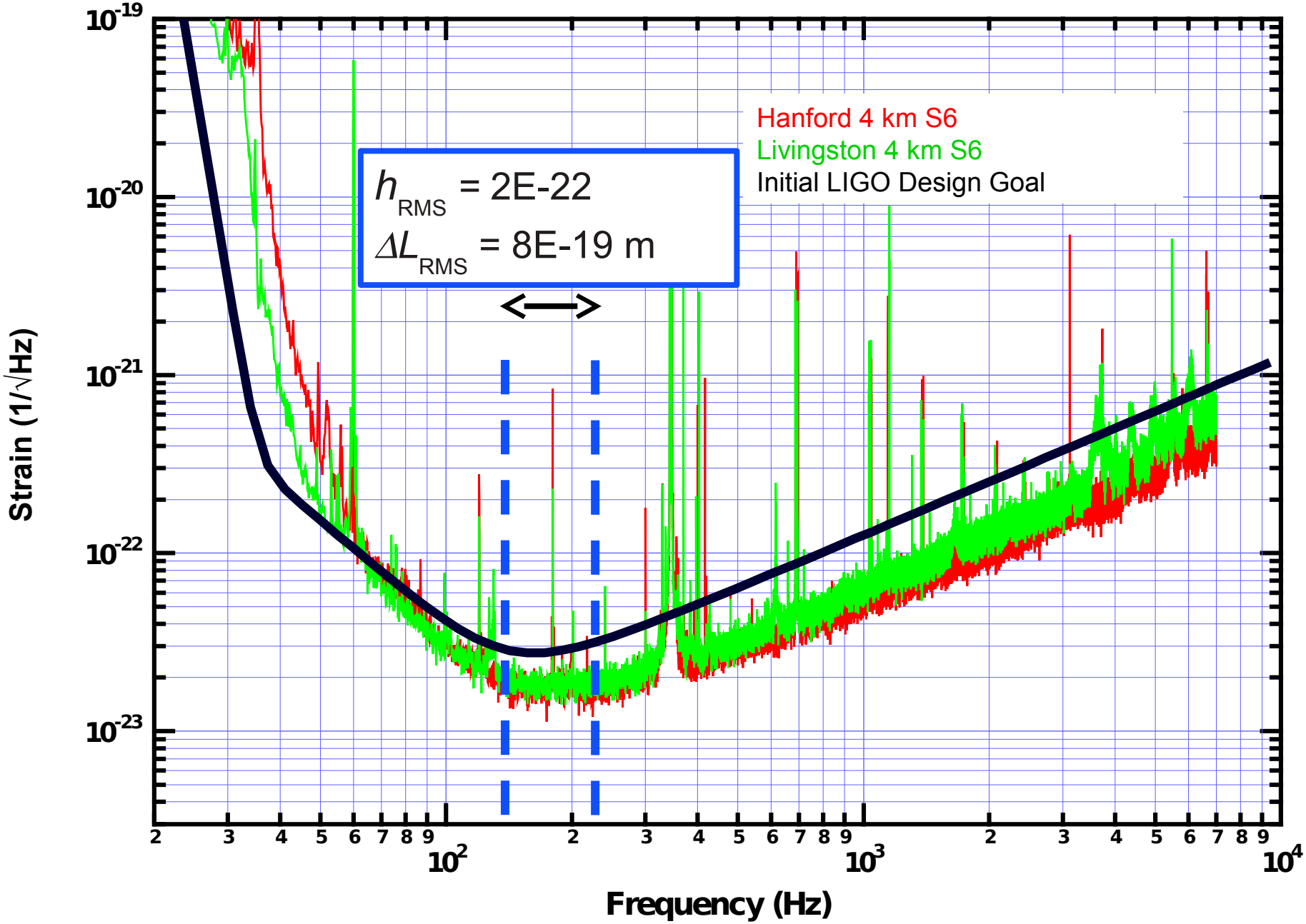
- Why aLIGO
- What is aLIGO

Why aLIGO: iLIGO was not that bad

- S6 (peak, average) NSNS ~(21, 16) Mpc (H1) and ~(20, 14) Mpc (L1), took 1yr's worth of data



Strain Sensitivities from Initial LIGO

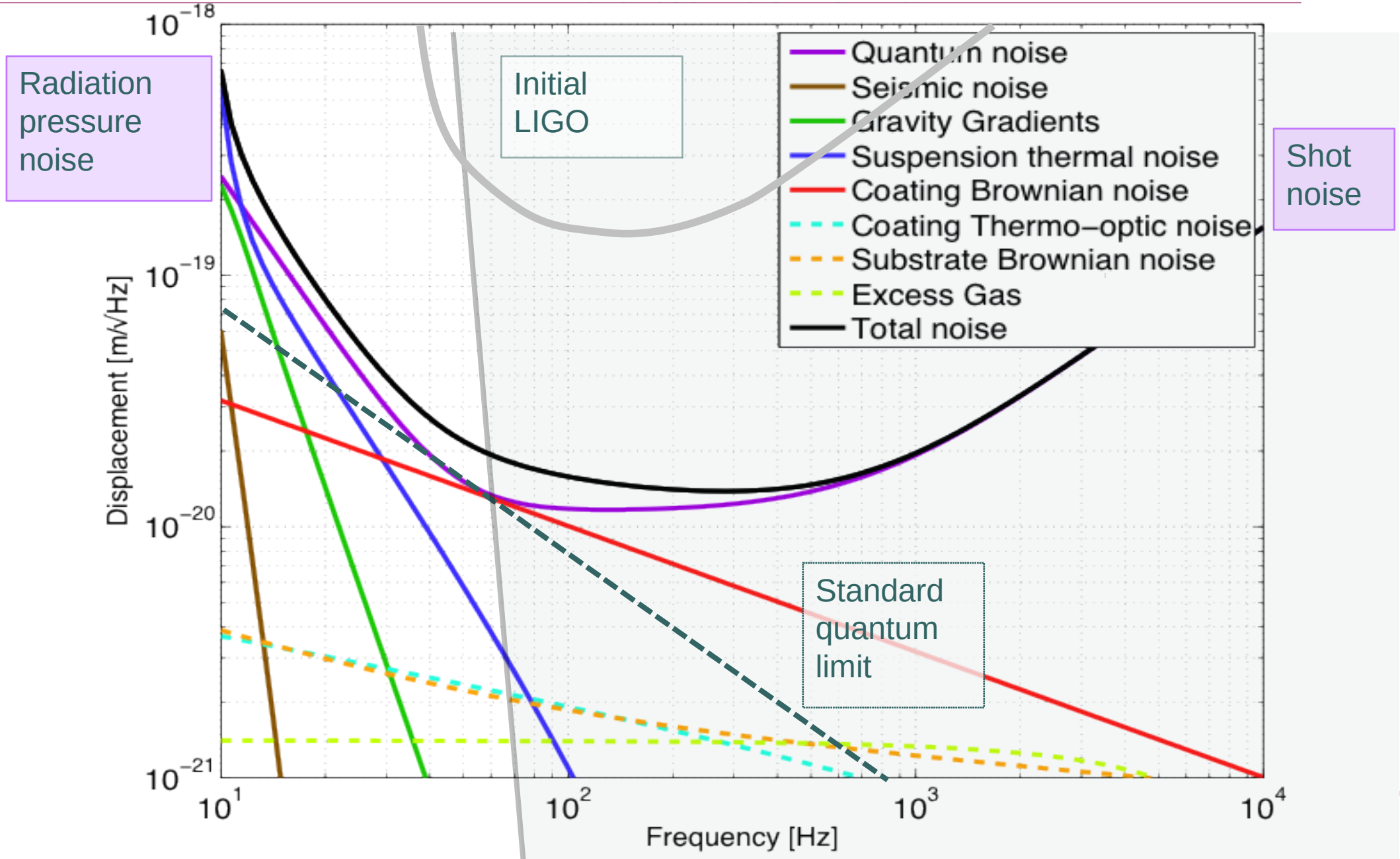


LIGO

Not bad, yes.
But...

- iLIGO needed to depend on luck to detect.
- We need something much better!

Thus advanced LIGO (aLIGO)

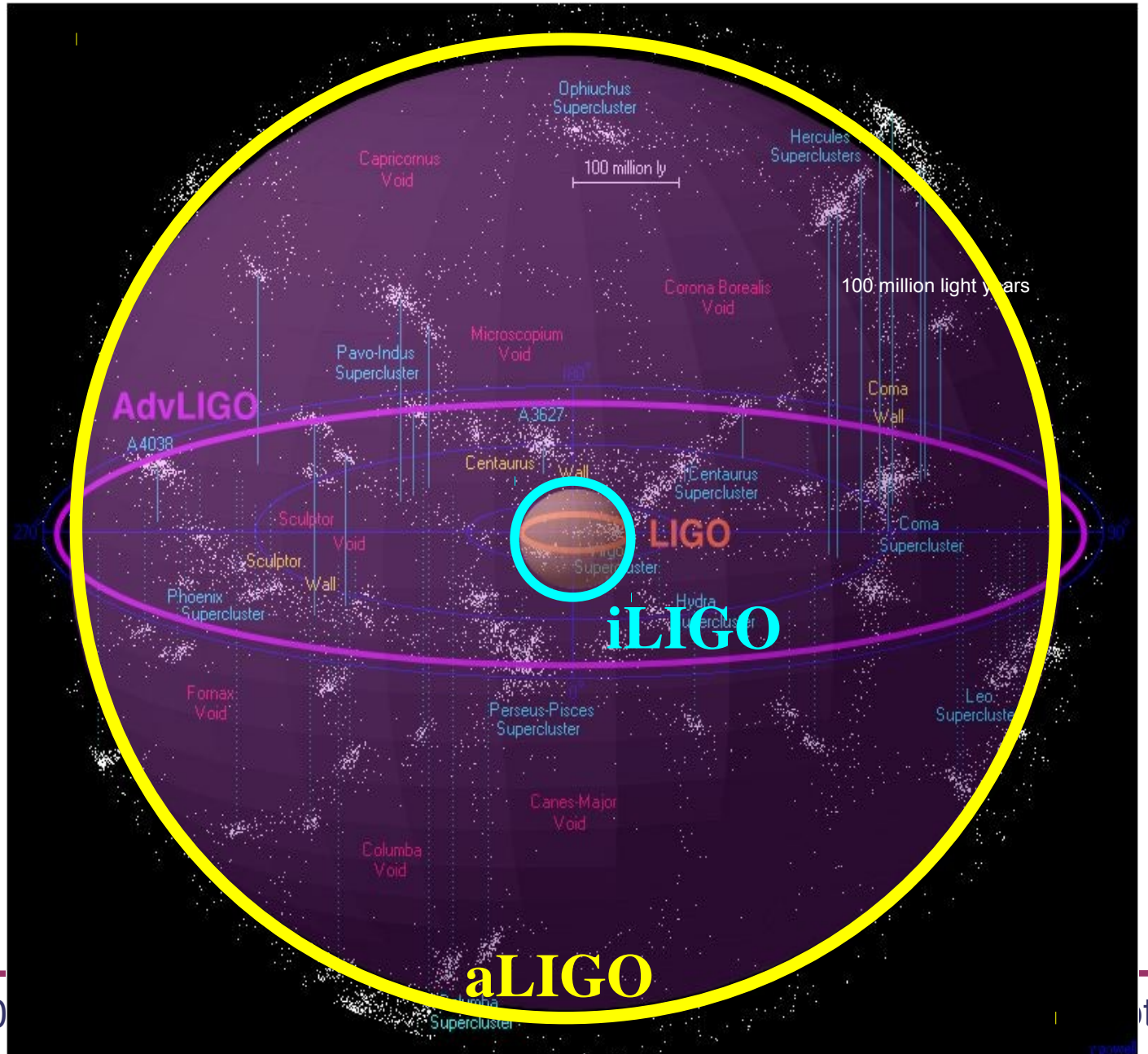


LIGO

What is aLIGO

- 10 times lower noise floor
  - x1000 larger astrophysical volume

10x distance, 1000x volume



LIGO

What is aLIGO

- 10 times lower noise floor
  - x1000 larger astrophysical volume.
- Will detect events routinely.
  - Tens of detections per year expected.
- Highest priority of the LIGO Laboratory.

We want to open a new window to the universe

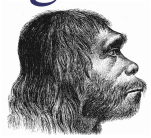
Visible light

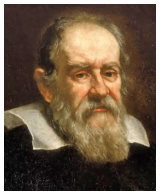
X-ray

Gamma

Gravitational Wave!

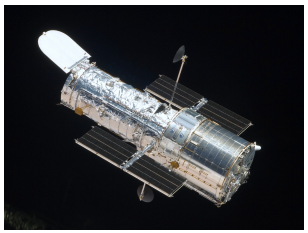
Visible light



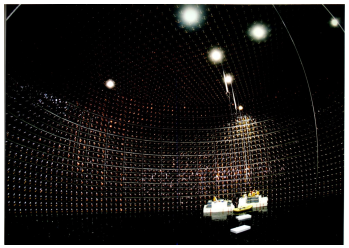


radio

IR, UV etc.



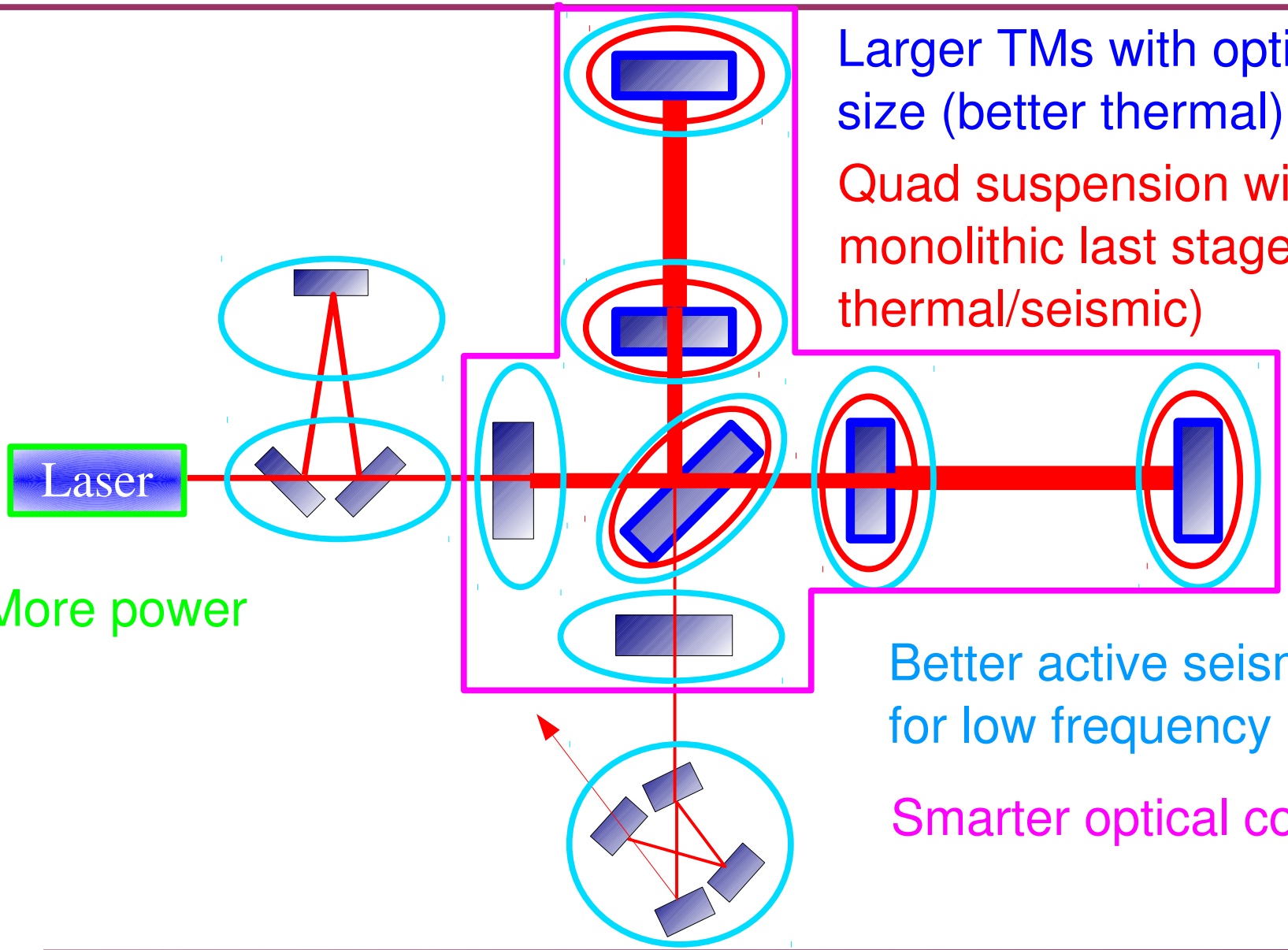
Neutrino



LLTA 1600's Starting 1930' – 60's Starting 1980's Starting 2010's

All images wikimedia commons except Gallilei's telescope which is from IMSS Firenze

But how? It's a multi-front attack (simplified view)



Larger TMs with optimized beam size (better thermal)

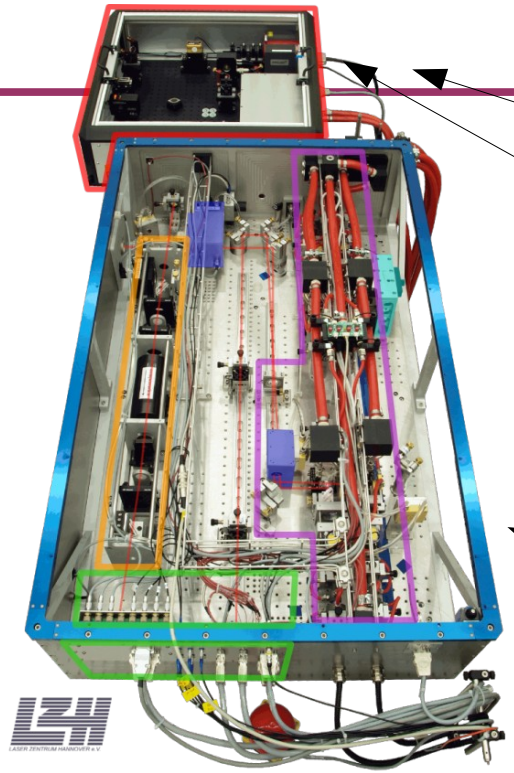
Quad suspension with monolithic last stage (better thermal/seismic)

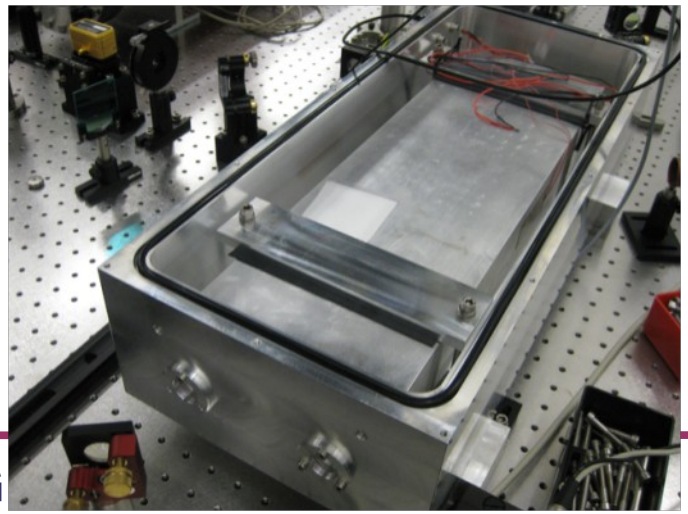
More power

Better active seismic isolation for low frequency performance

Smarter optical configuration

Pre-Stabilized Laser

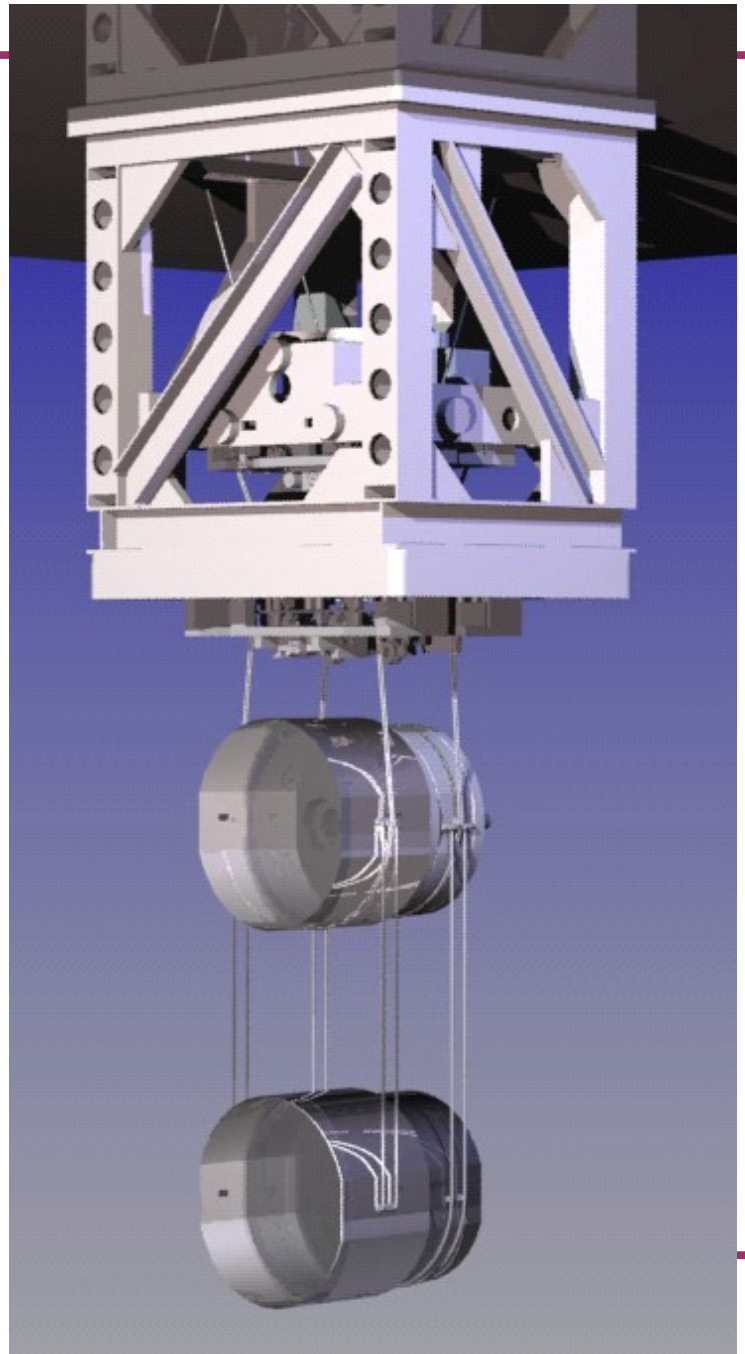




- 2W NPRO master
- 35W medium-power amplifier (used in eLIGO system)
- 180W high power stage
- Pre-modecleaner (PMC)

LIGO

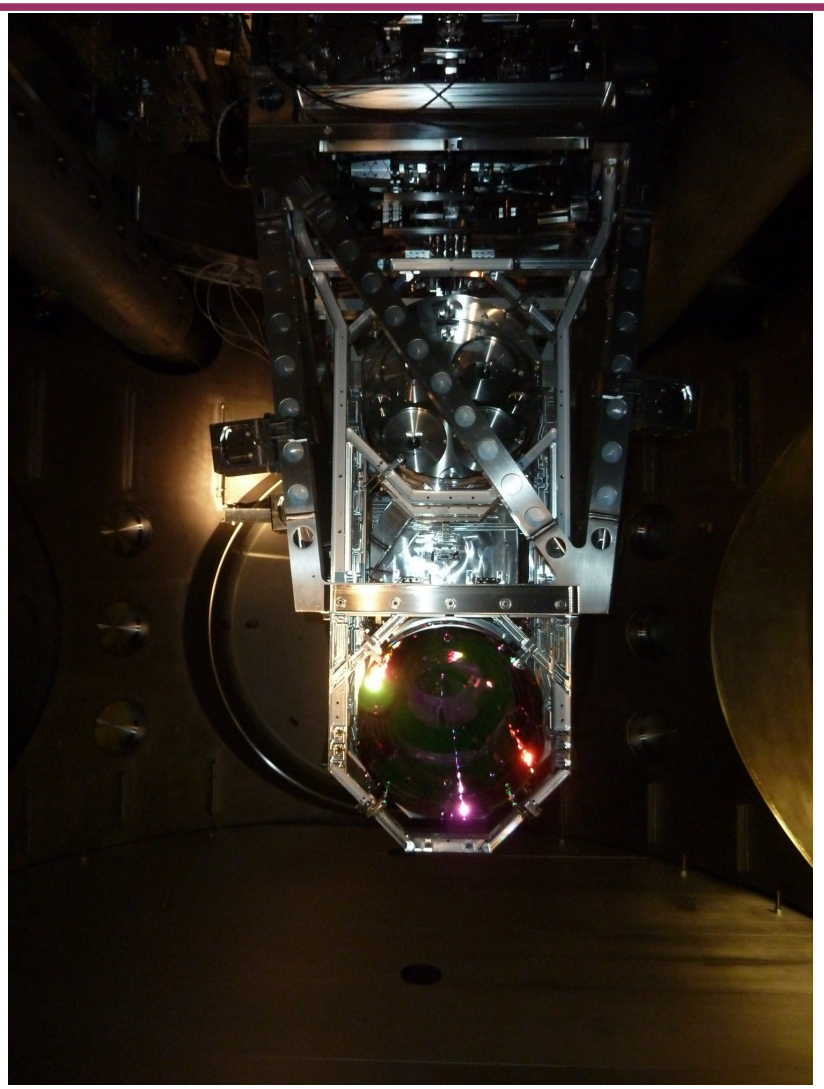
Quad suspension



- Four-stage pendulum
- Monolithic last stage
- Actuation chain also suspended by the same structure (“reaction masses”)

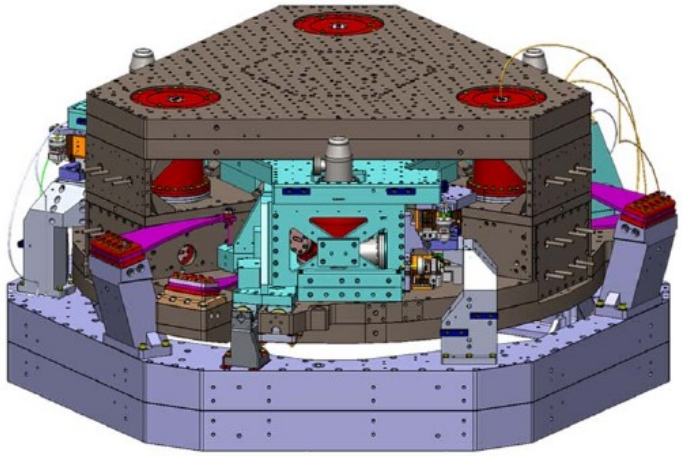
LIGO

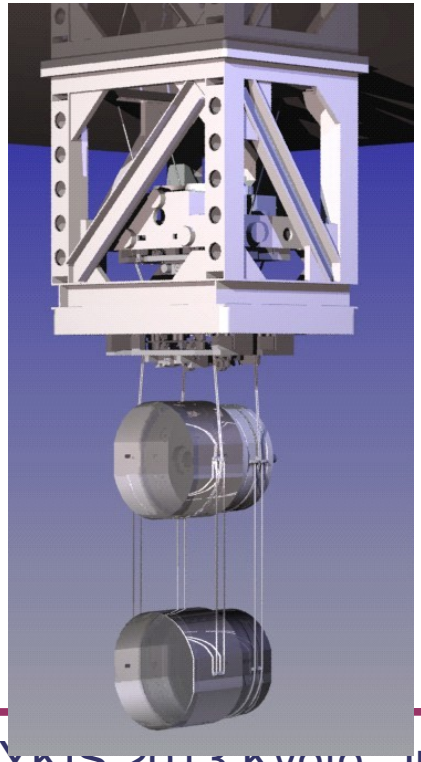
Quad suspension



Internal Seismic Isolation (ISI) isolates SUS

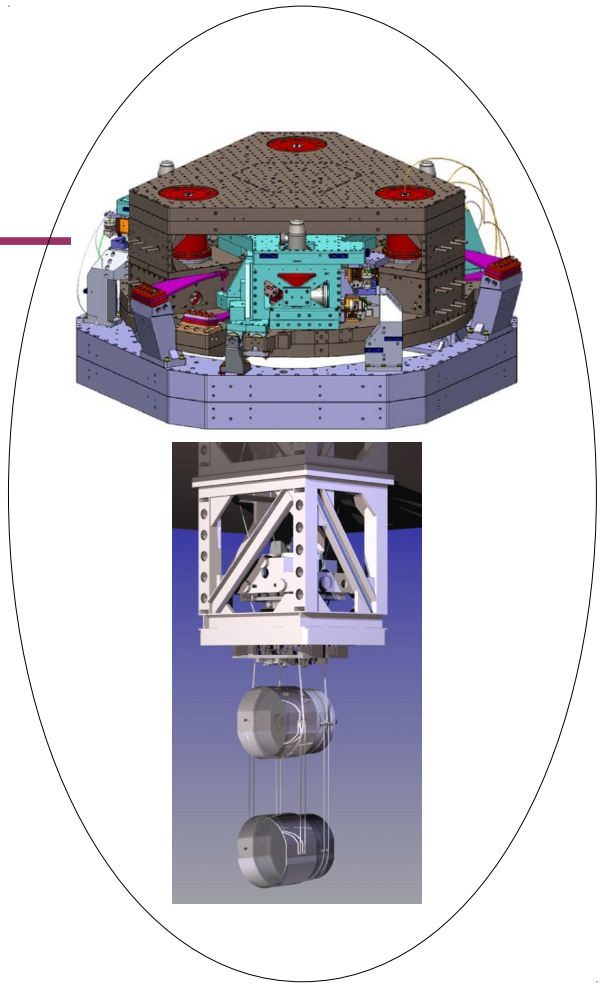
- TM SUS is attached under ISI
- ISI for TM is two-stage active isolator
- Provides isolation ~0.2Hz and higher.

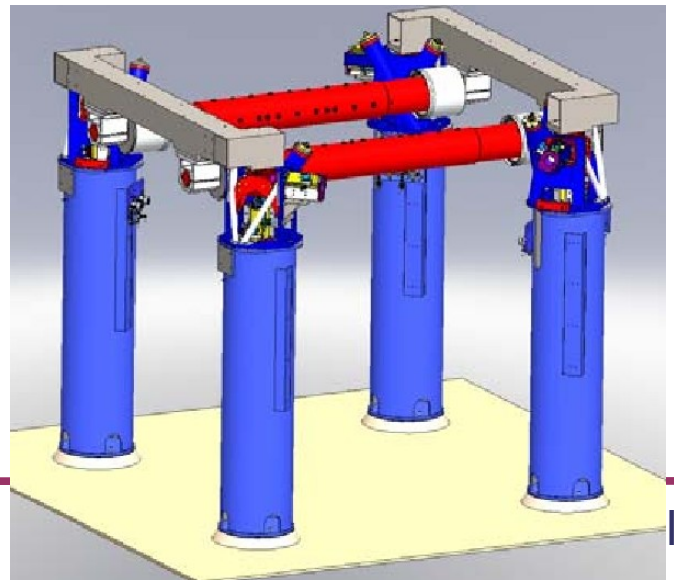




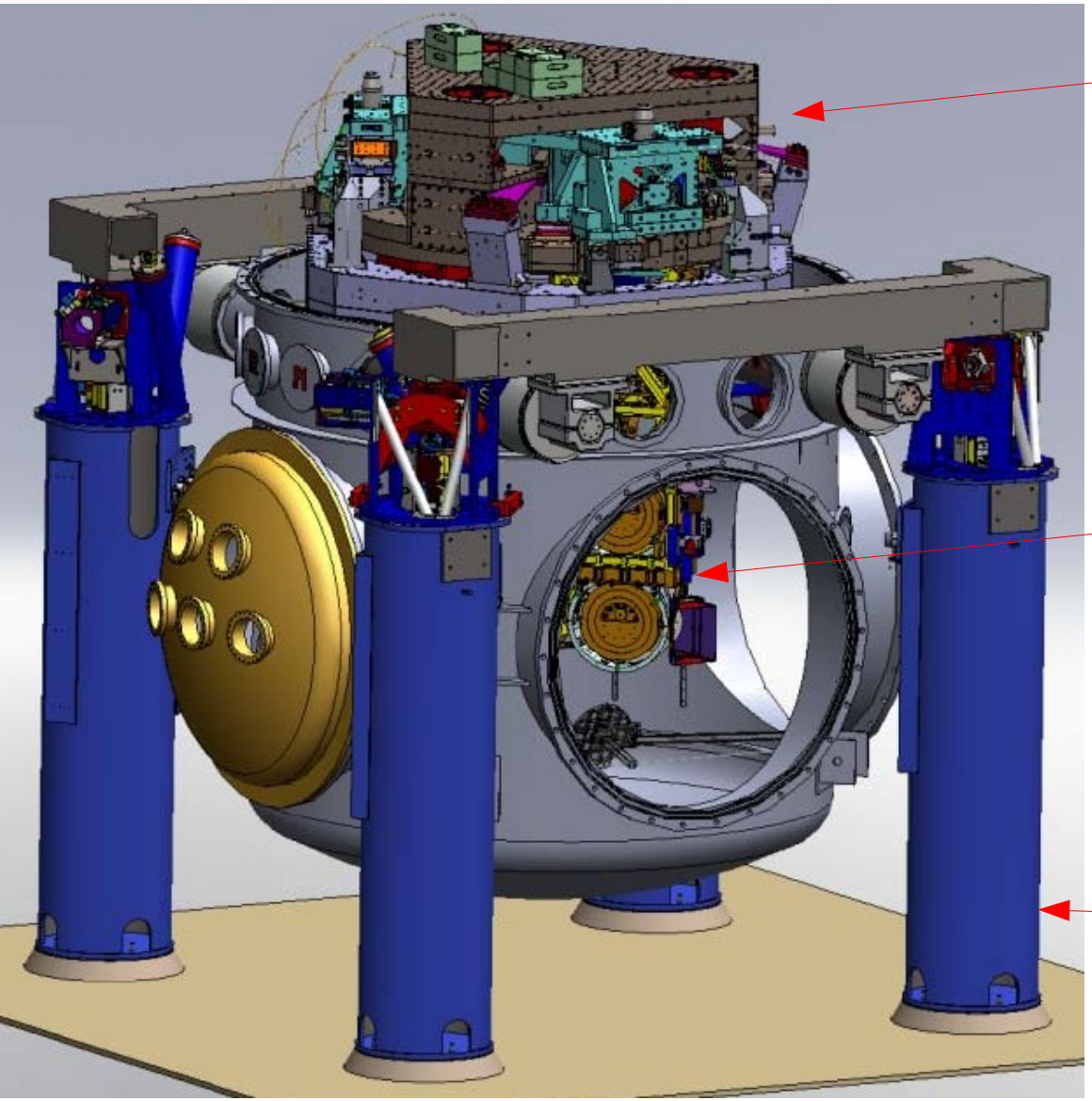
ISI+SUS is isolated by HEPI

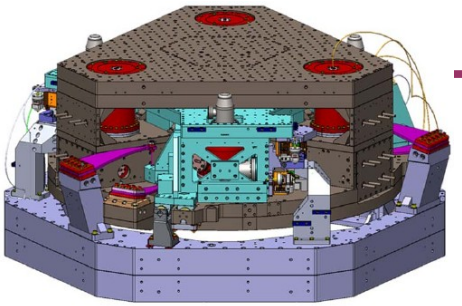
- SUS+ISI mounted on top of Hydraulic External Pre Isolator
- HEPI is connected to ISI via crossbeams and support tubes
- 0.1Hz to 5Hz isolation

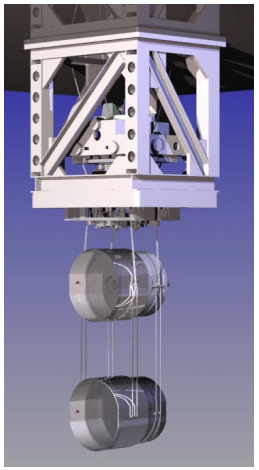


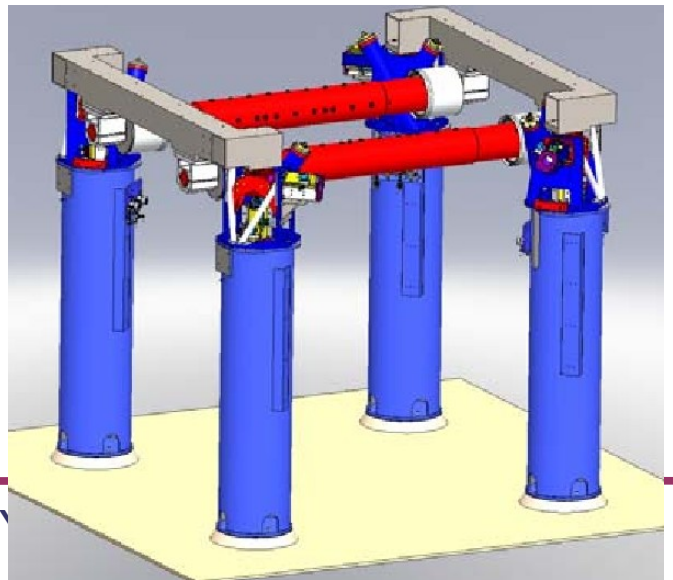


7 stages of isolation in series

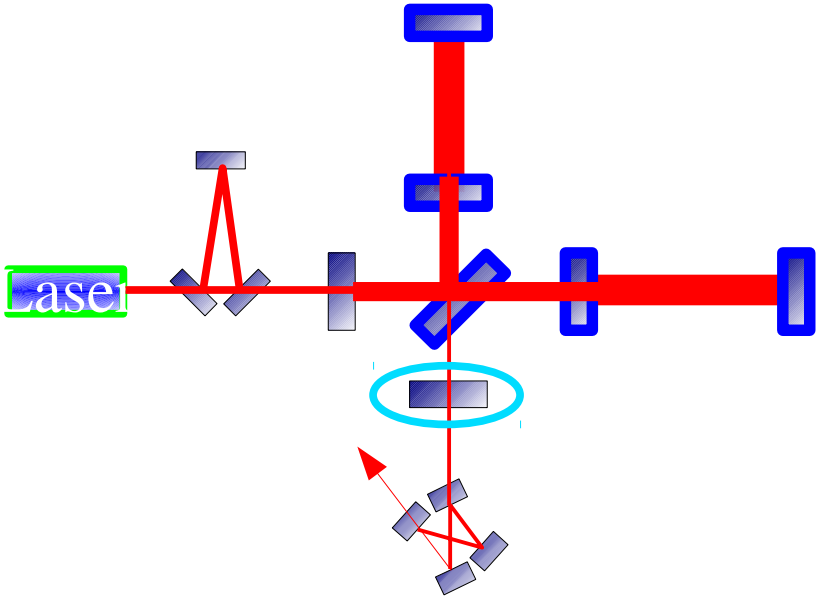








Interferometer Sensing and Control (ISC) upgrade



- Signal recycling
- ALL important beams are detected in-vac on isolated platforms
- Improved lock acquisition

  (Arm Length Stabilization, or ALS)
- Improved output mode cleaner, electronics, and everything (really)

LIGO

Current Status

- aLIGO project overview
- Recent developments

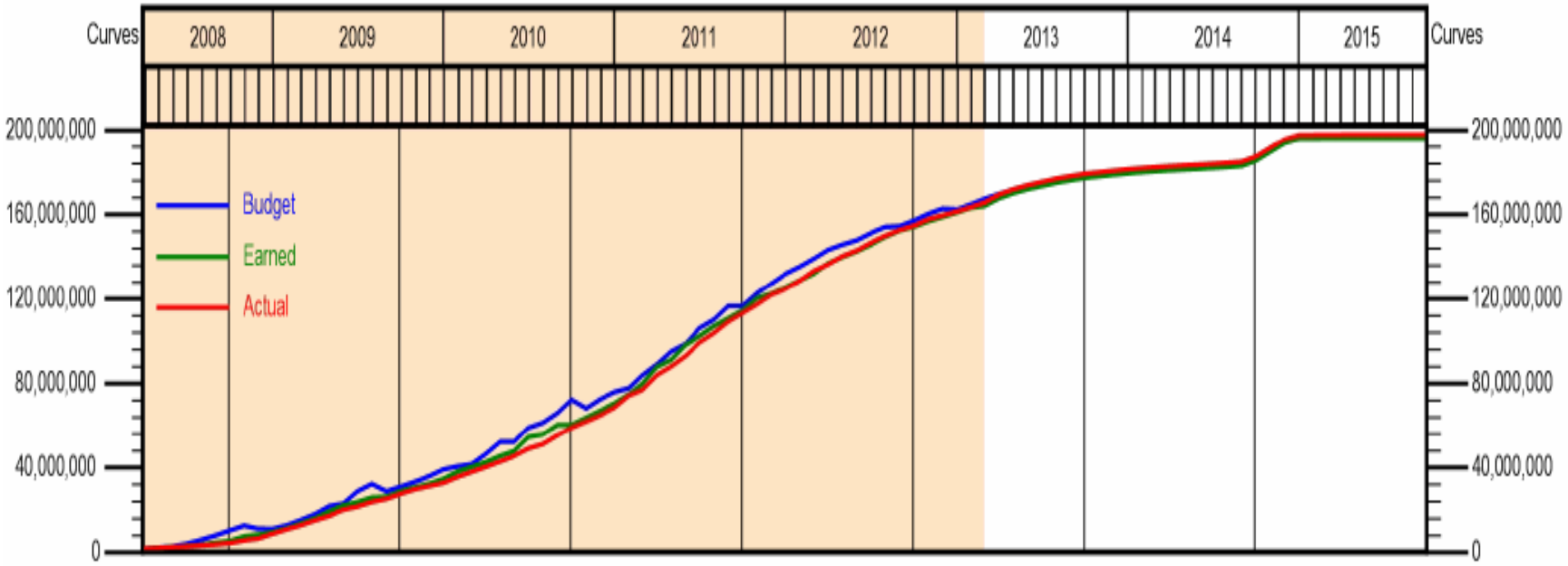
LIGO

aLIGO project

- This is a project to build aLIGO
- 100% completion means that 2 IFOs are fully locked for two hours, and the 3rd IFO parts are cleaned, assembled and/or stored.
- It doesn't necessarily mean that IFOs are running with good sensitivity (though they could, in principle).
- 205M USD over 2008-2015
- After completion, sensitivity improvement will be covered by LIGO operations, which is out of the scope of aLIGO project

aLIGO project, continued

- 183M received out of 205M total.
- 83% completed in terms of actual commitment as of March, 2013.
- 61 months into 80 months total as of now (~73%)



LIGO

aLIGO project, continued

- We're still on track for:
  - Feb 2014, 3rd IFO storage
  - July 2014 L1 acceptance
  - Sept. 2014 for H1 acceptance

LIGO

Not aLIGO project, but...

- USA sequestration = 13% cut for FY2014-FY2018 operations budget. 233.1M requested VS 202.5M.
  - This is the money used, among others, for bringing the sensitivity up to the design goal.
- Serious blow to the initial plan, still committed to maximize the scientific outcome within this boundary.

LIGO

3rd IFO

- We're still calling it “the 3rd IFO”.
- Strong commitment from India as well as LIGO.
- Increased LIGO $\leftrightarrow$ India visits.
- Assembly/storage activities ongoing.
- If you're a LVC or KAGRA member, see http://dcc.ligo.org/LIGO-G1300221

LIGO

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LIGO

Recent Developments

- Vacuum leak at LLO
- Mirror coating
- Integration tests
  - High power + IMC test at LLO
  - One arm test at LHO
  - DRMI test at LLO
  - HIFO-Y test at LHO

LIGO

Vacuum leak at LLO

- Leak opened ca. 2008, ~2.5E-4 torr-litter/sec
- True nature was found only recently
- 4 major leaks found (as of mid Apr.) but a leak check effort is ongoing.
- Weld+water+animal residue (mice and/or wasp) seems like a formula for leak development.

LIGO

TM coating

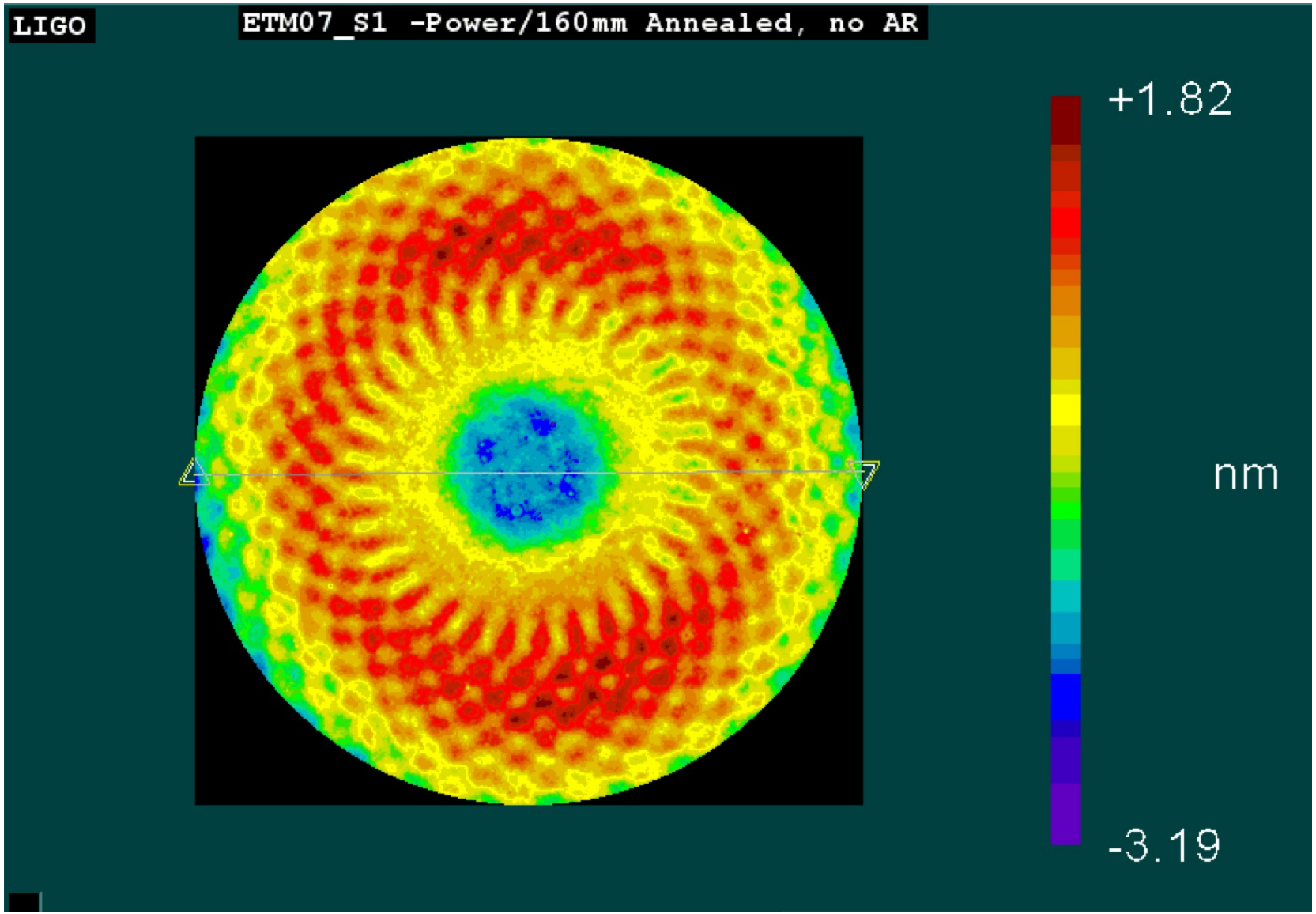
- Mirror substrate is polished in two steps
  - Superpolish: 1 Angstrom micro-roughness, within 100nm of the ideal figure
  - Ion beam figuring: Corrects figure while maintaining the micro-roughness.
- This was excellent (0.12nm rms figure error over 160mm diameter)
- But the coating has been problematic (it “distorts” the mirror)

LIGO

TM coating, continued

- Finally a good usable pair of ETMs was produced by LMA Lyon in collaboration with aLIGO.
- Each is out of spec, but used as a pair at EX and EY, the loss would be in spec (75ppm per surface)
- Periodic pattern coming from planetary action.
  - Scattering effect (mostly into baffle) is being studied.
  - Vigorous modeling effort is ongoing.
- Right now we're using totally-out-of-spec mirrors at LHO, will install good ones for HIFO-X test.

Periodic structure



LIGO

Integration testing

- Build each subsystem, install, and that's it, isn't it?

LIGO

Integration testing

- Build each subsystem, install, and that's it, isn't it?
  - No! It's unlike most industrial projects.
- Proof is in the pudding. What if your window frame only accepts 1m X 1.2m +- 1e-9 m glass panel?
- For some of the subsystems, a stand-alone test is not possible/practical at the level that is ultimately necessary.
  - Accuracy and/or overall noise level: Can you measure TM vibration at 10e-20m/sqrtHz level?
  - Complexity: If your system comprises 100s of sub components, each comprising 100s of sub-sub components, is the testing of each sub-sub component good enough?

LIGO

Integration testing, continued

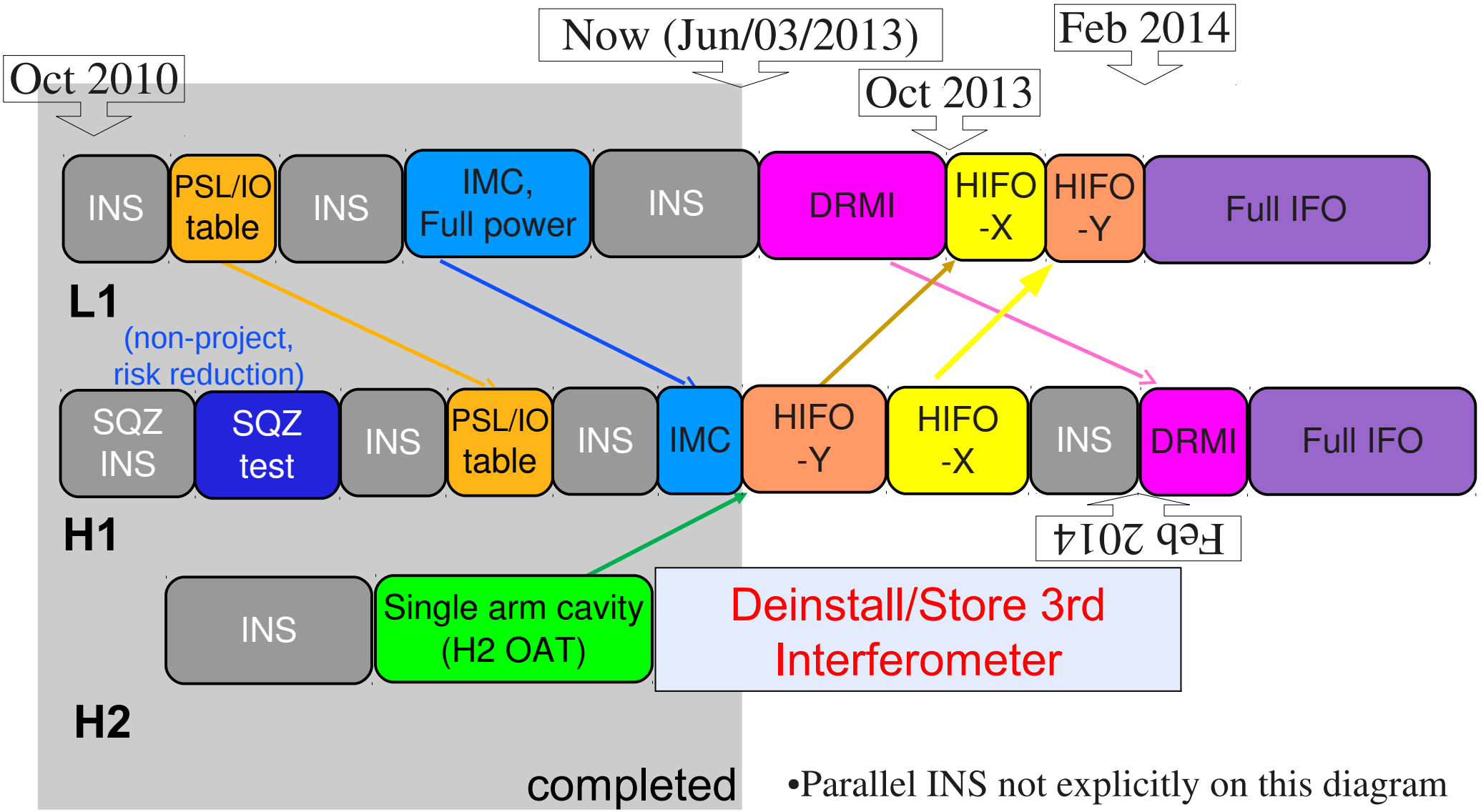
- We define some milestones.
- At each milestone, we perform “integration tests” to evaluate if all subsystems involved in the test satisfy the standard that can be tested at that time.
- Installation – Integration – Integration cycles
- Staggered schedule so the sites don't have to repeat the same effort again and again

LIGO

Integration testing milestones

- High power test of PSL+IMC (done @LLO)
- One arm test (done @LHO)
- DRMI test (being done @LLO)
- HIFO-Y (being done @LHO first)
- HIFO-X (to be done @ LHO)
- Full IFO (to be done @ both sites, LLO first)

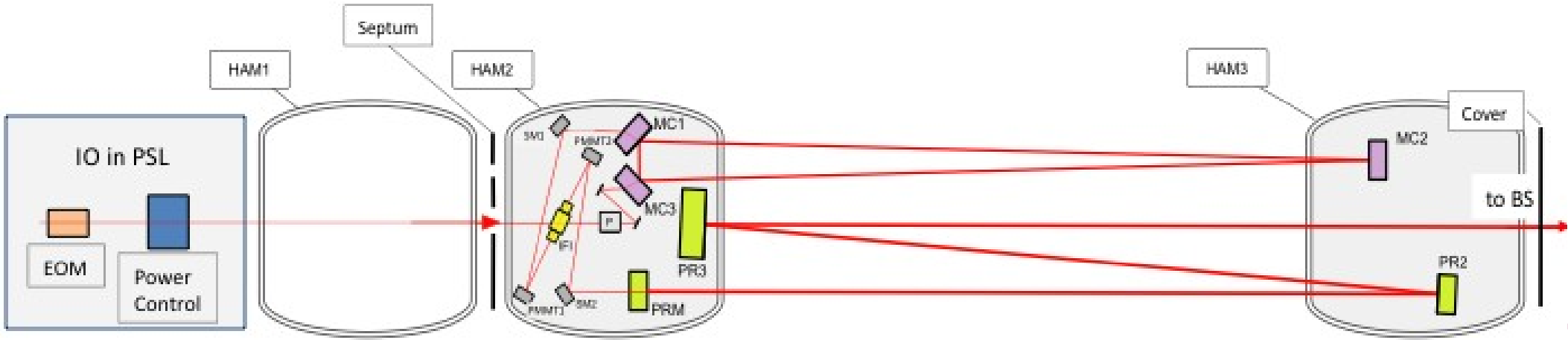
Integration Testing Progress So Far, and Future Schedule



- Parallel INS not explicitly on this diagram
- Arrows represent copying
- X axis is not necessarily proportional to time.

IMC + high power test

- Full power PSL
- Remain locked as long as we'd like (req. 90% duty cycle)
- 86% throughput from PSL to IFO (req. 75%)
- Visibility 97-98% (req. 95%)
- Control BW 60kHz (req. 40k or higher)
- IMC transmission 0.5% RIN (req. 1% or less)



LIGO

IMC, some action items

- PSL noise (freq, amp, pointing) larger than expected, some room for improvement
  - Being worked on
- Second ISS with in-vac detector needs re-engineering
  - Updated electronics to be installed
- MC optics absorption (2 of 3) larger than expected (2ppm vs 0.6-0.7)
  - An item for contamination control

LIGO

One Arm Test (OAT)

- This is the first step for the new lock acquisition scheme called Arm Length Stabilization (ALS)
- We inject doubled 1064nm (i.e. 532nm) light offset-locked to PSL from the end, and lock this green light to the arm.

LIGO

ALS: What's that?

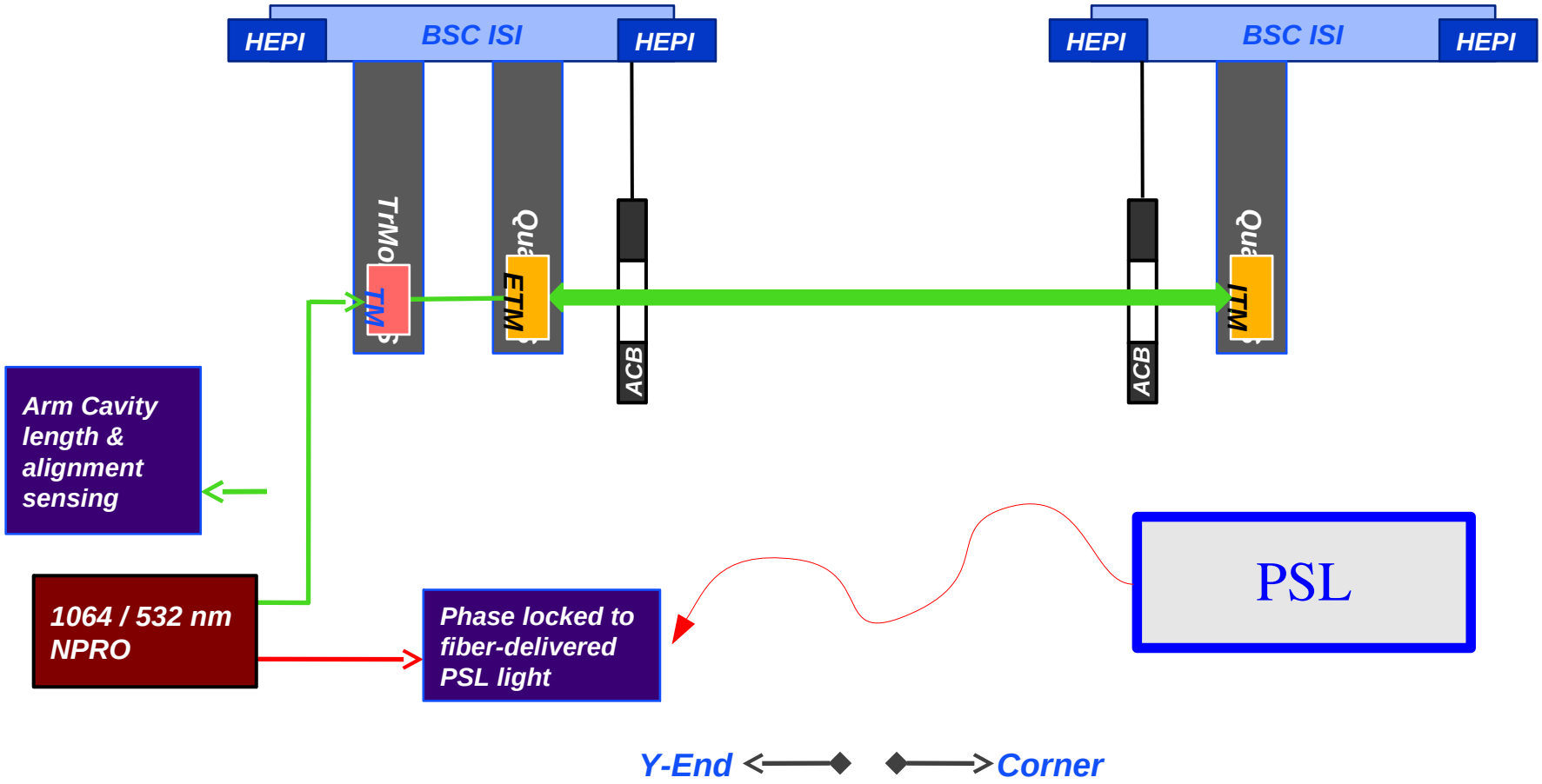
- In iLIGO lock scheme, sensing matrix was changed dynamically every time one or both of the arms crossed resonance.
- There was roughly 50% chance of success (depending on the carrier or the SB crossing the cavity resonance first) per each crossing, thus ¼ chance of successful full lock.
- In real world, this empirically meant 5min down time when lock is lost IF EVERYTHING ELSE IS PERFECT.
- And this is without signal recycling.

LIGO

ALS: Continued

- In aLIGO, arms are locked first using green light from end stations that are offset-locked to PSL.
- The arms are “slowed down” using the beat signal of green light from the end and frequency-doubled PSL light
- PSL IR light is slowly brought into the arm resonance in a controlled manner

One Arm Test: The first test of ALS and an arm cavity of aLIGO



LIGO

OAT

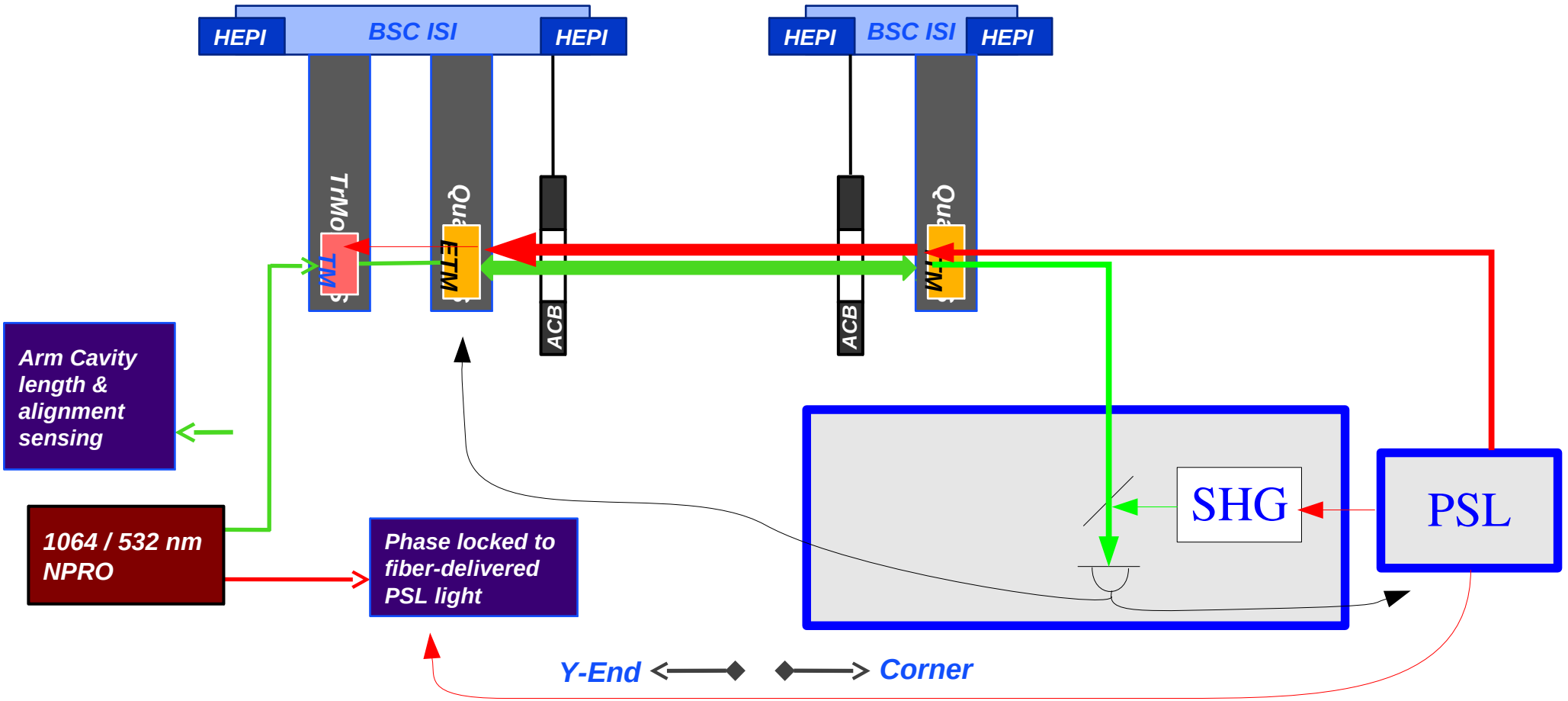
- Green beam cavity locking: Works
- Basic test of Quad SUS + ISI + HEPI: Works
- Intial alignment procedure: Works
  - Locked 7 days after the arm was opened (very good, benefit of extensive component-level testing)
- Ring heater for thermal compensation: Works
- Some action items and design changes
  - WFS determined unnecessary
  - Additional photo diodes for automation
  - PZT steering determined indispensable

LIGO

Integration testing so far

- Both IMC/PSL test and OAT went very well
- Identified things that worked, and things that need further attention
- Helped to finalize the design of some of subsystems
- Very succesful.

HIFO-Y (or HIFO-one arm): Next stage of ALS test



LIGO

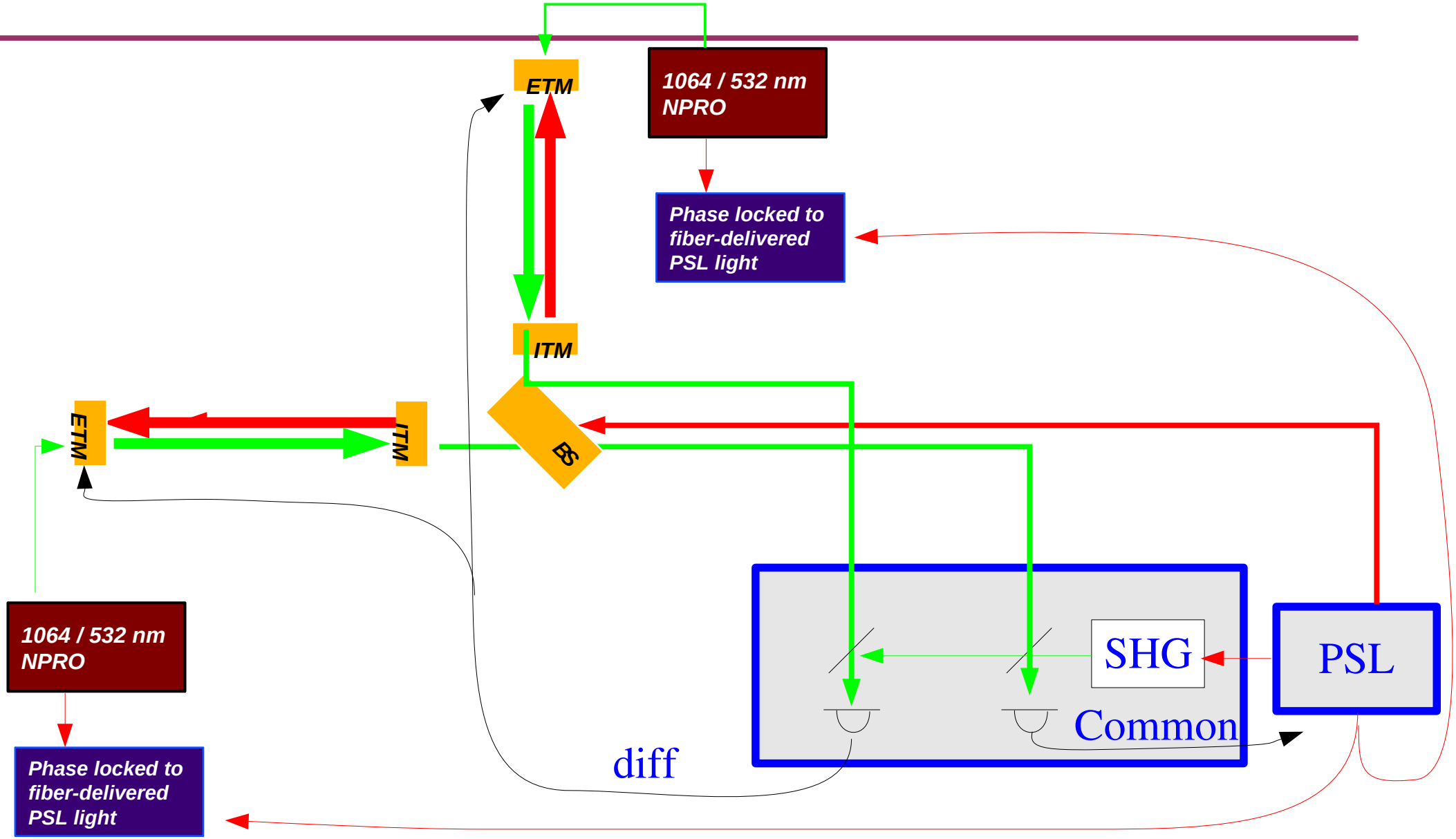
HIFO-Y

- Being tested at LHO right now.
  - Green beam went into Y arm again last week.
- First test of corner station ALS system
  - Green beam from EY detected at the corner
  - Beat note of EY green and doubled PSL fed back to the laser and TM
  - Red light is slowly brought into resonance.

HIFO-X (or full ALS test): Next-next stage of ALS test

- Next-next stage of LHO testing (late 2013?).
- Two arms are installed.
- PSL-X beat for “common mode” that is used for controlling PSL
- X-Y beat for “differential mode” used for differential length of X and Y.
- Both arms are brought into IR resonance
- First test of TM vibration that is not limited by frequency noise of the PSL/IMC.

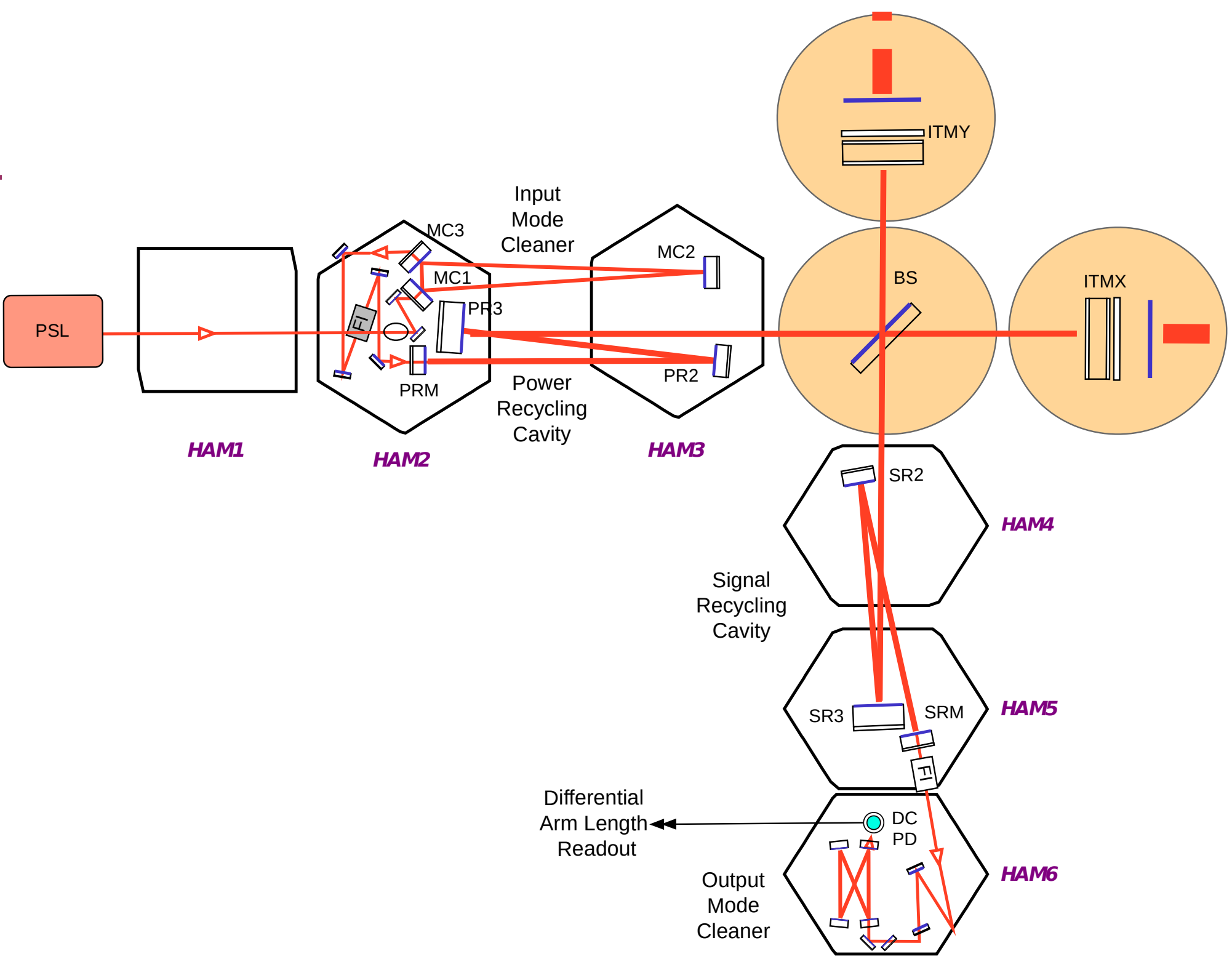
HIFO-X (or full ALS test)



LIGO

Dual Recycled Corner Michelson

- Not a full IFO, but a near-final stage of all critical sensing chains necessary for a full IFO.
- Everything except ETMs (and thus ALS)
  - Michelson
  - DC differential phase read out using output mode cleaner
  - Power and signal recycling
- Installation in progress at LLO, test to start in June.


PSL
HAM1
MC3
MC1
PR3
FI
PRM
HAM2
Input
Mode
Cleaner
MC2
PR2
Power
Recycling
Cavity
HAM3
ITMY
BS
ITMX
SR2
HAM4
Signal
Recycling
Cavity
SR3
SRM
HAM5
FI
Differential
Arm Length
Readout
DC
PD
Output
Mode
Cleaner
HAM6

LIGO

Current status summary

- We're still on track for Jul/2014 (L1) and Sep/2014 (H1) acceptance (i.e. 2hr lock), and 3rd IFO storage.
- Integration tests very successful for far:
  - Providing good FOM for what works and producing action items.
- There are still some risks (not everything was covered in this talk, e.g. contamination, software etc.)
- Each major risk is being investigated by a team of specialists

LIGO

Future

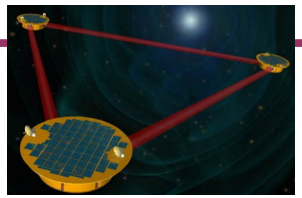
- At the very least IFOs will have been accepted by the end of aLIGO project (2015).
- Will take some time to bring IFOs to full sensitivity.
- Somewhere along the way, the first GW WILL be detected, possibly together with other projects.
  - Drama, politics, committees, usual mundane things.
- And then what?

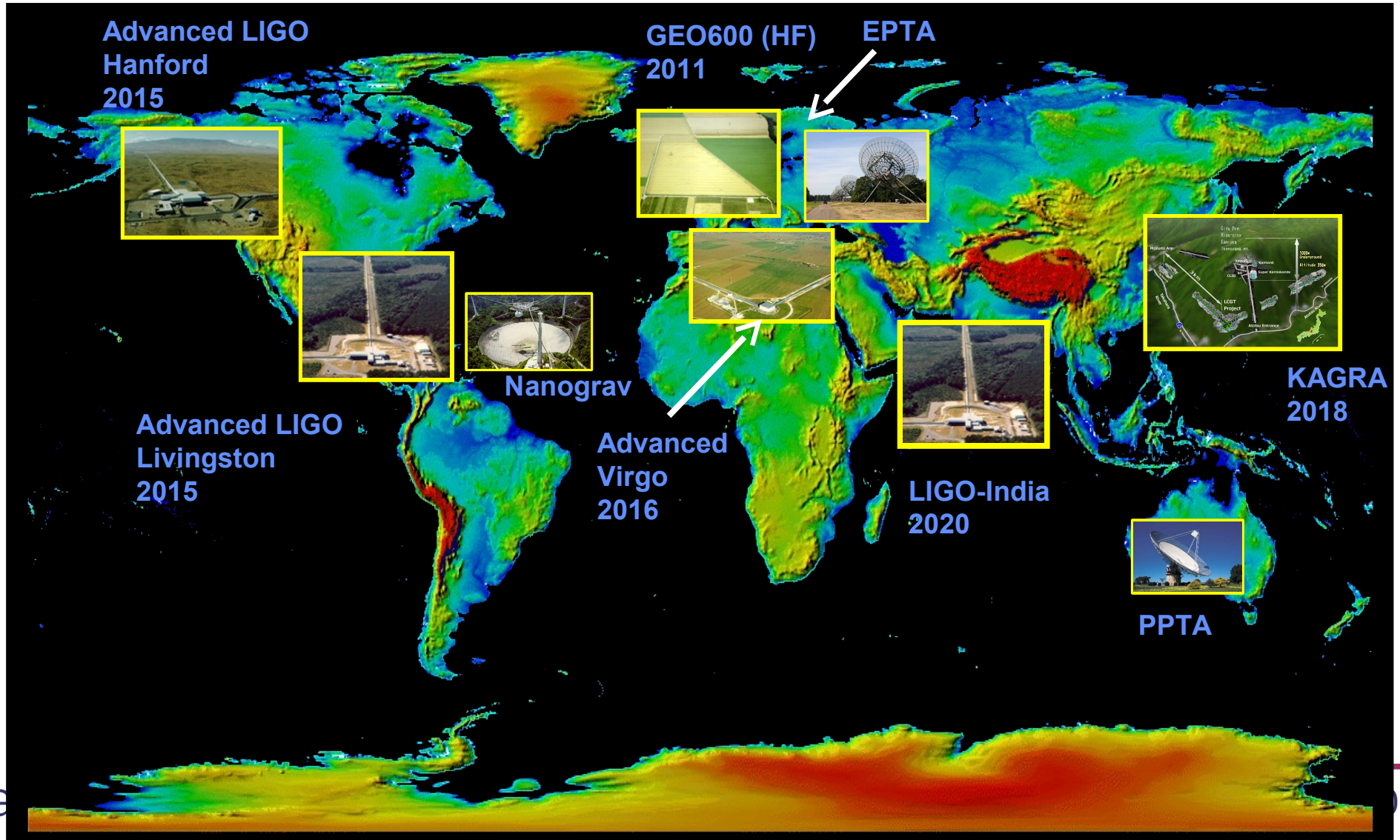
LIGO

Future

- Global network: LIGO USA, Indigo?, VIRGO (talk by Ricci), KAGRA (Kajita), GEO-HF, 3rd generation detector(s) like EGO (Somiya), pulsar timing arrays (Manchester), space based detectors.

Global network

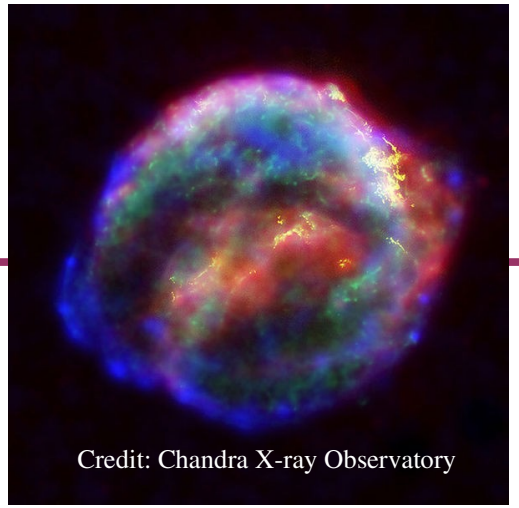




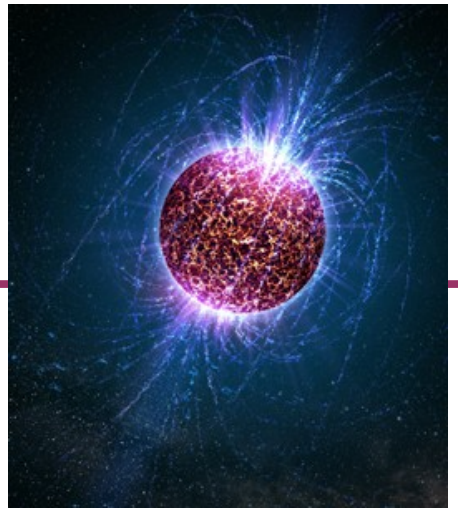
This is already after the aLIGO project is done, but...

- Upgrade?
  - If so, SQZ (demonstrated at H1 and GEO) is a necessity.
  - Other possibilities (again Kentaro's talk).
- And we'll be doing real astronomy together while we keep beating our own sensitivity!

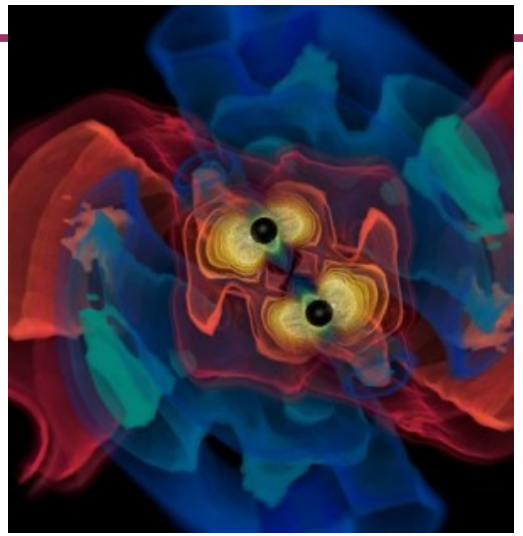
LIGO



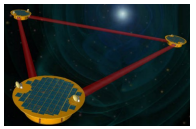
Credit: Chandra X-ray Observatory

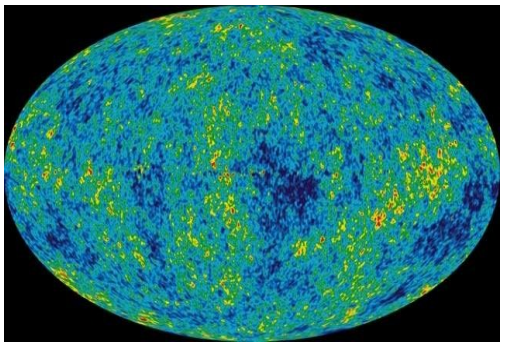


Casey Reed, Penn State



Credit: AEI, CCT, LSU





NASA/WMAP Science Team