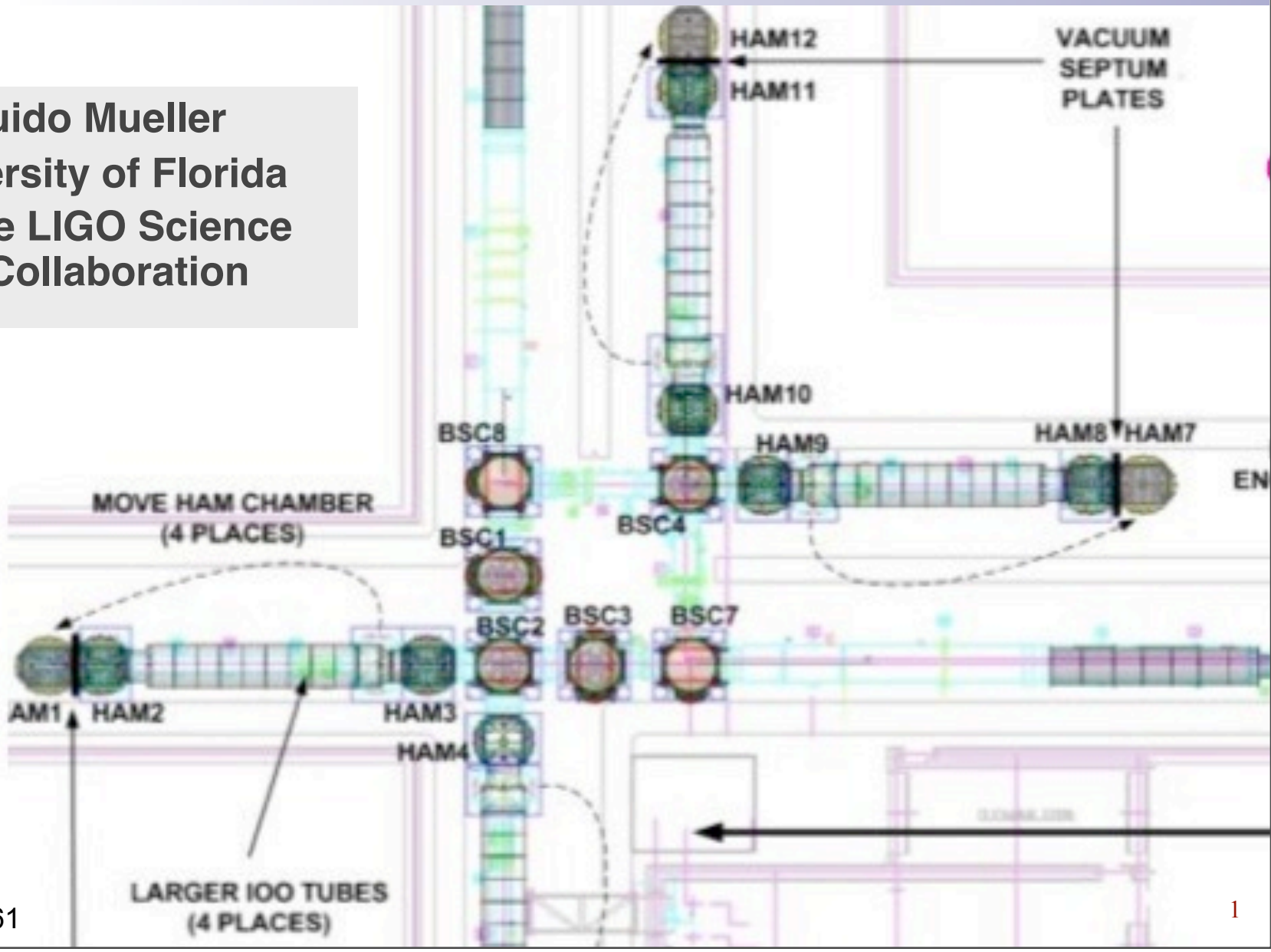
Advanced LIGO Status and Prospects

Guido Mueller
University of Florida
for the LIGO Science Collaboration



25 years ago ...

CALTECH/MIT PROJECT

FOR A

LASER INTERFEROMETER

GRAVITATIONAL WAVE OBSERVATORY

December 1987

LIGO-M870001-00-M

1987

Signing of the Intermediate Range Nuclear Forces Treaty

1st Visit of East Germany's head of state in West German capitol

1987

Signing of the Intermediate Range Nuclear Forces Treaty

Top Movie of the year

Fatal Attraction

1st Visit of East Germany's head of state in West German capitol

LIGO

CALTECH/MIT PROJECT

FOR A

LASER INTERFEROMETER

GRAVITATIONAL WAVE OBSERVATORY

December 1987

LIGO-M870001-00-M

By comparing the source strengths and benchmark sensitivities in Figure II-2 and in the periodic and stochastic figures A-4b,c (Appendix A), one sees that *(i) There are nonnegligible possibilities for wave detection with the first detector in the LIGO. (ii) Detection is probable at the sensitivity level of the advanced detector. (iii) The first detection is most likely to occur, not in the initial detector in the LIGO but rather in a subsequent one, as the sensitivity and frequency are being pushed downward from the middle curve toward the bottom curve of Figure II-2.*

LIGO

25 Years Later:

They were correct!

By comparing the source strengths and benchmark sensitivities in Figure II-2 and in the periodic and stochastic figures A-4b,c (Appendix A), one sees that *(i) There are nonnegligible possibilities for wave detection with the first detector in the LIGO. (ii) Detection is probable at the sensitivity level of the advanced detector. (iii) The first detection is most likely to occur, not in the initial detector in the LIGO but rather in a subsequent one, as the sensitivity and frequency are being pushed downward from the middle curve toward the bottom curve of Figure II-2.*

LIGO

which leads us to the 'subsequent one':

Advanced LIGO

By comparing the source strengths and benchmark sensitivities in Figure II-2 and in the periodic and stochastic figures A-4b,c (Appendix A), one sees that *(i) There are nonnegligible possibilities for wave detection with the first detector in the LIGO. (ii) Detection is probable at the sensitivity level of the advanced detector. (iii) The first detection is most likely to occur, not in the initial detector in the LIGO but rather in a subsequent one, as the sensitivity and frequency are being pushed downward from the middle curve toward the bottom curve of Figure II-2.*

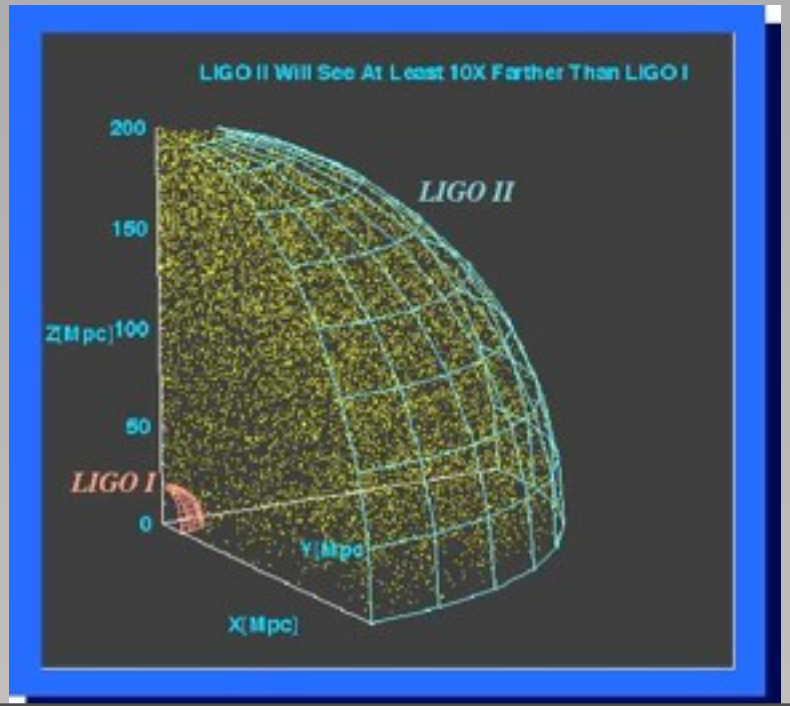
Advanced LIGO

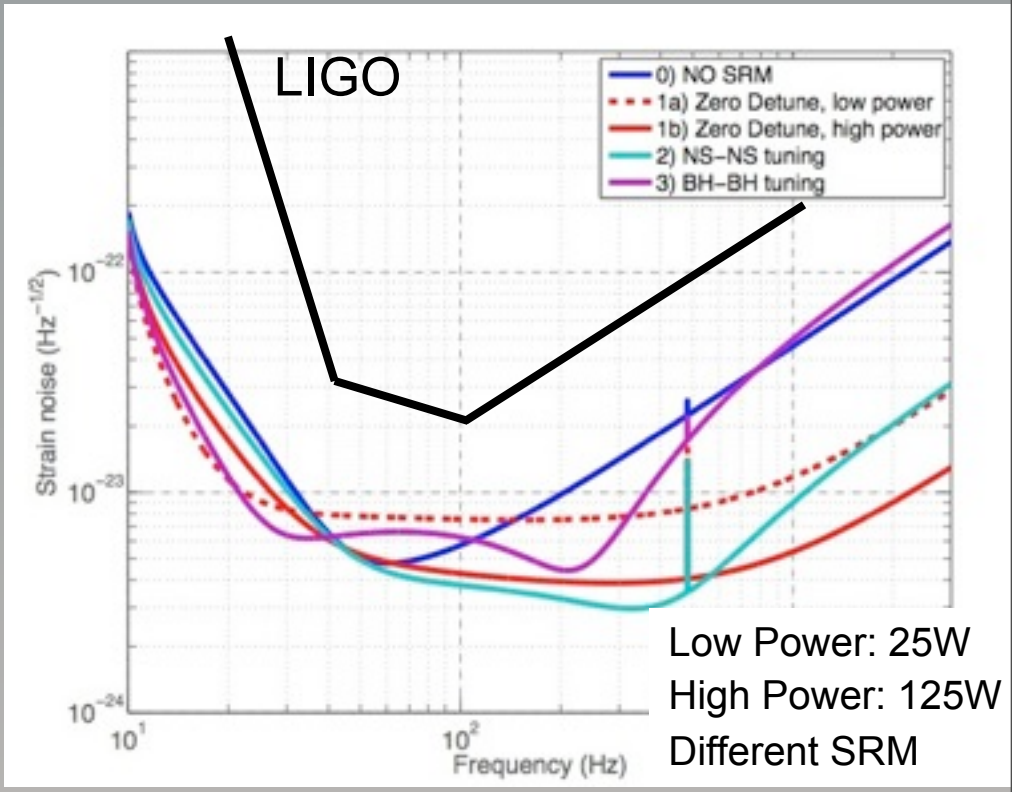
- Design began in earnest in 1999 as a LIGO Scientific Collaboration concept paper
- Major Advanced LIGO R&D and design work during 1999-2006
- Final baseline review by NSF in November 2007
  - At this point, many aLIGO subsystem designs were far along
- Advanced LIGO Project officially began on April 1, 2008

Advanced LIGO

Different Operational Modes

- Capital Partners: UK/DE/AU
- Installation started 2010
- First Science Run 2014
- Parallel VIRGO upgrade
- KAGR under development





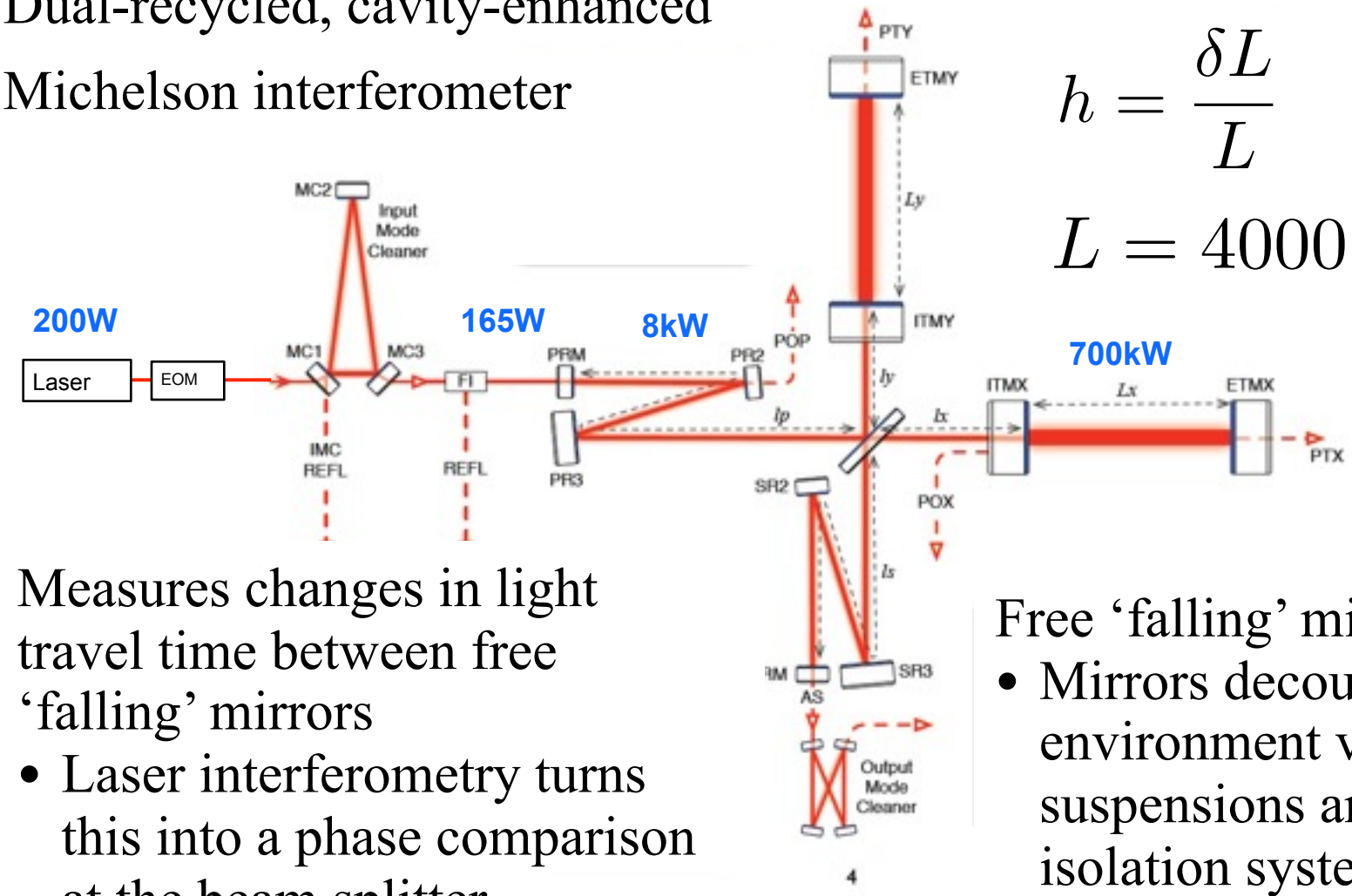
- 10 times more sensitive > 60Hz
- Push low frequency limit to 10Hz
- Tunable detector
- **First Detection 2015/6**

Advanced LIGO

Dual-recycled, cavity-enhanced Michelson interferometer

$$h = \frac{\delta L}{L}$$

$$L = 4000 \text{ m}$$



Measures changes in light travel time between free 'falling' mirrors

- Laser interferometry turns this into a phase comparison at the beam splitter

Free 'falling' mirrors

- Mirrors decoupled from environment via suspensions and seismic isolation systems

Advanced LIGO vs. LIGO

Key Improvements:	Helps mainly at
• Better Seismic Isolation • Better Suspension • Larger Mirrors	Low Frequencies
• Better Stray Light Control • Better Mirrors/Coatings	Mid Frequencies
• Higher Laser Power • Signal Recycling (RSE)	High Frequencies
• Better Sensing and Control • Better Modeling Capabilities • Stable Recycling Cavities • *Cleaner* Vacuum ...	All Frequencies

Vacuum System

Remove oxide layer from interior heat-treated surfaces

- Pneumatic tools used, all lubricants removed (contamination risk; tool failure rates thus high)

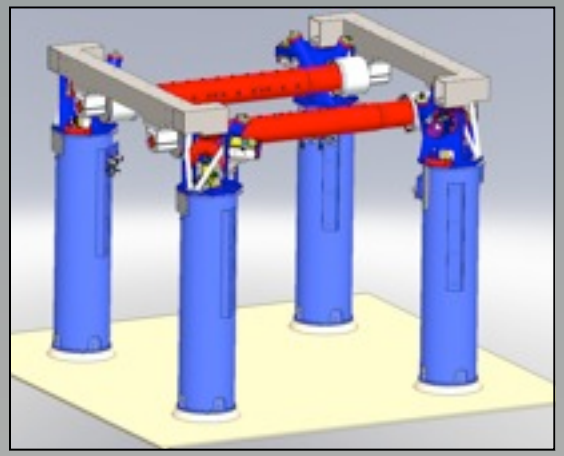
- LLO: All Chambers cleaned
- LHO: Last BSC chambers will be cleaned early summer

Installed larger mode cleaner beam tubes for larger beam diameter inside PR cavity

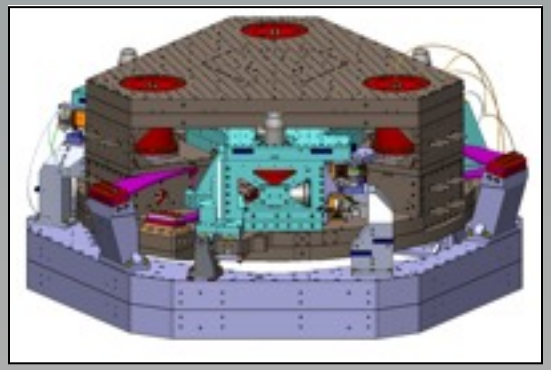
Vacuum System

Seismic Isolation

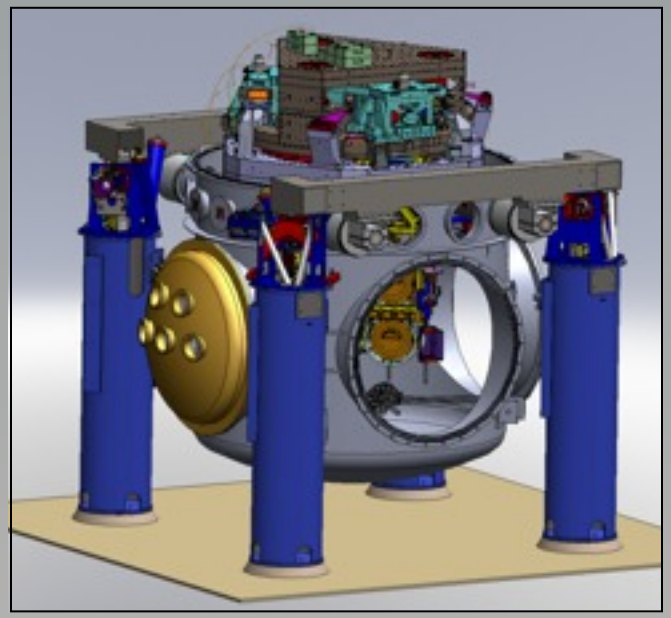
For Main Optics



HEPI:
Hydraulic External
Pre Isolator



ISI:
Two-Stage
Internal Seismic Isolator

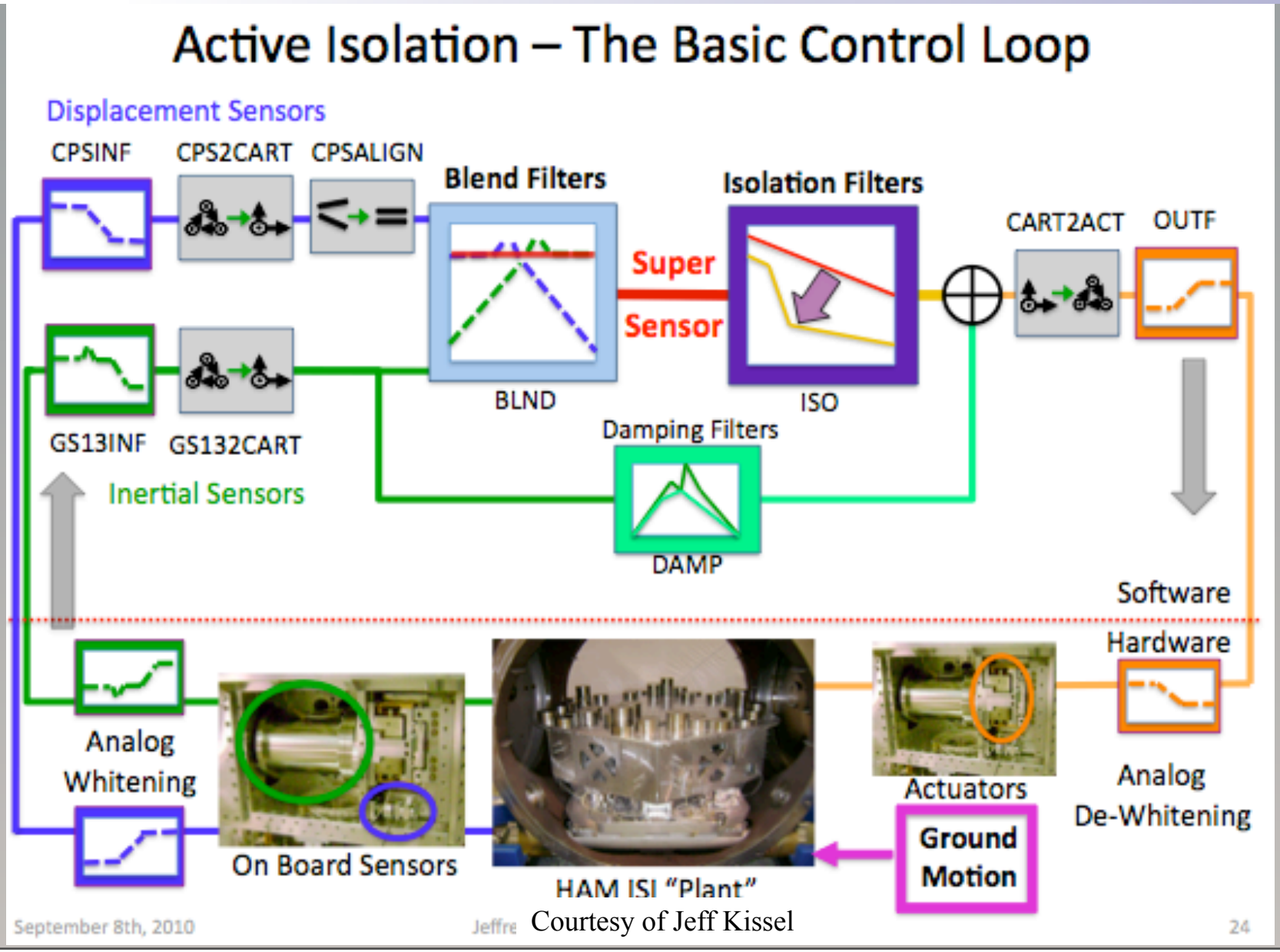


BSC Chambers Equipment

BSC:

- Suspensions hanging off the Internal Seismic Isolator (ISI)
- ISI placed on top of Hydraulic External Pre-Isolators (HEPI)
  - Both use a combination of active and passive damping mechanism to reduce seismic noise

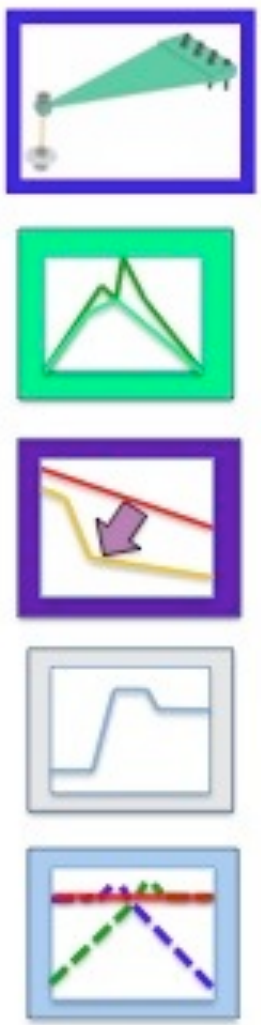
Seismic Isolation

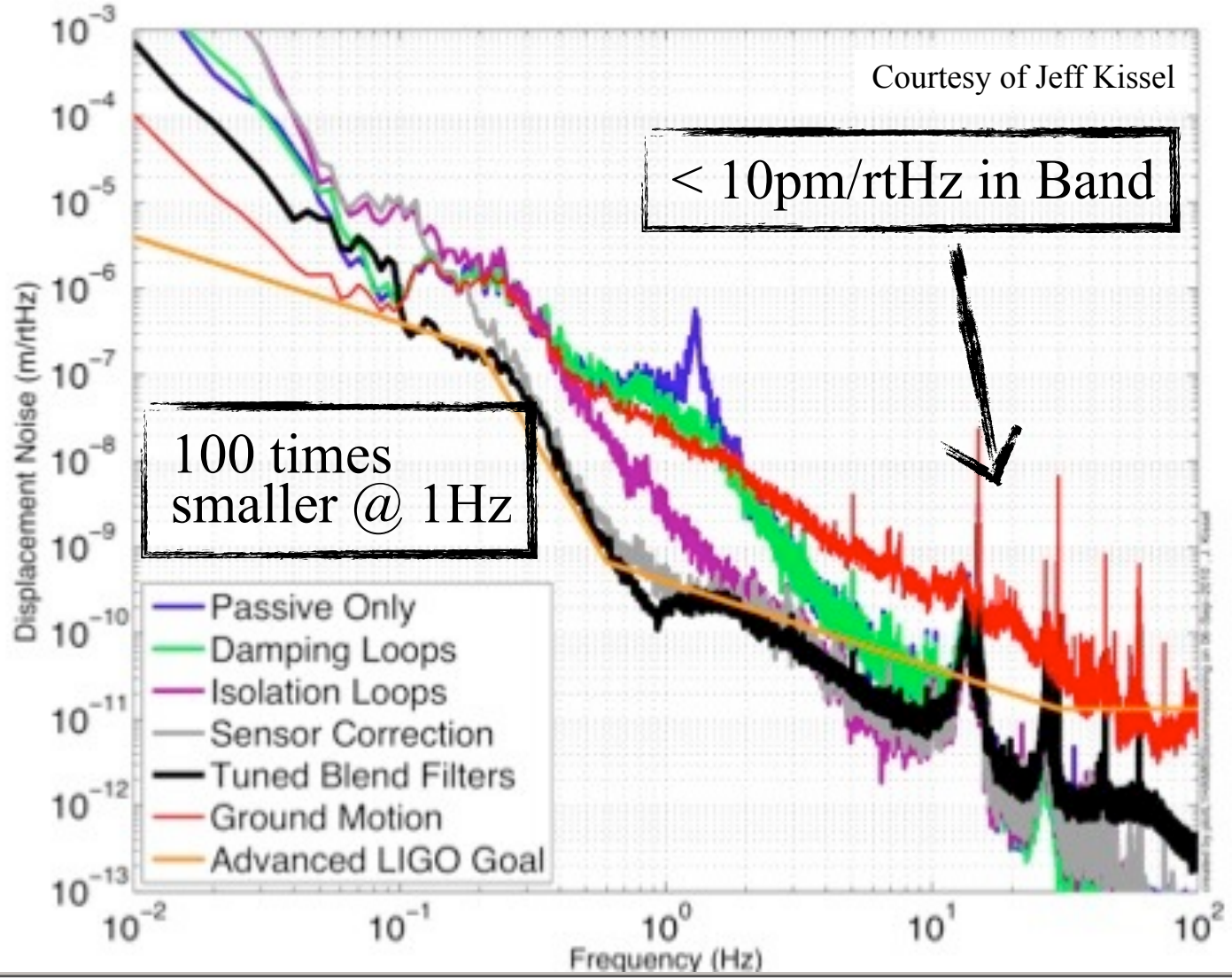


Courtesy of Jeff Kissel

Seismic Isolation

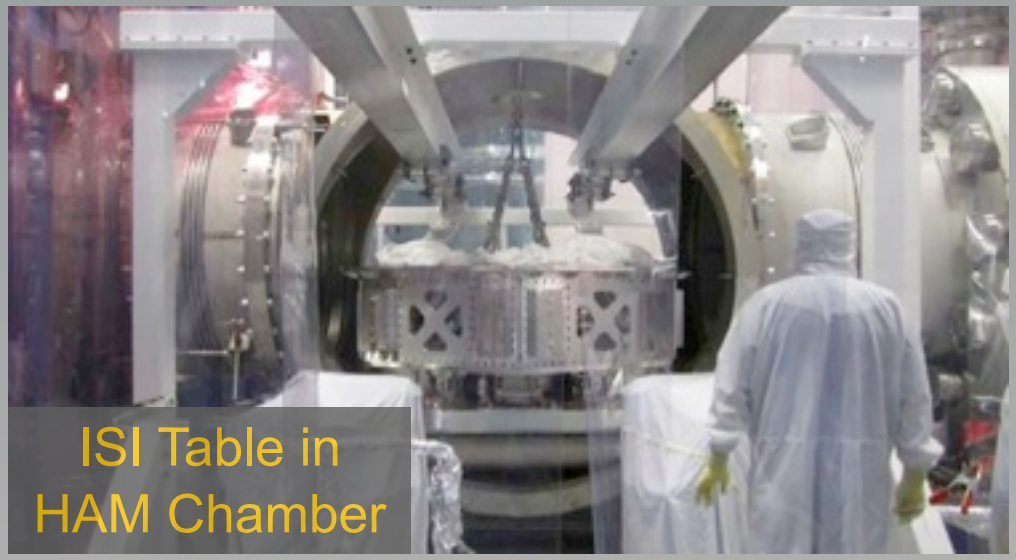
Active Isolation – Successive Loop Closure





Seismic Isolation

HEPI for HAM Chambers



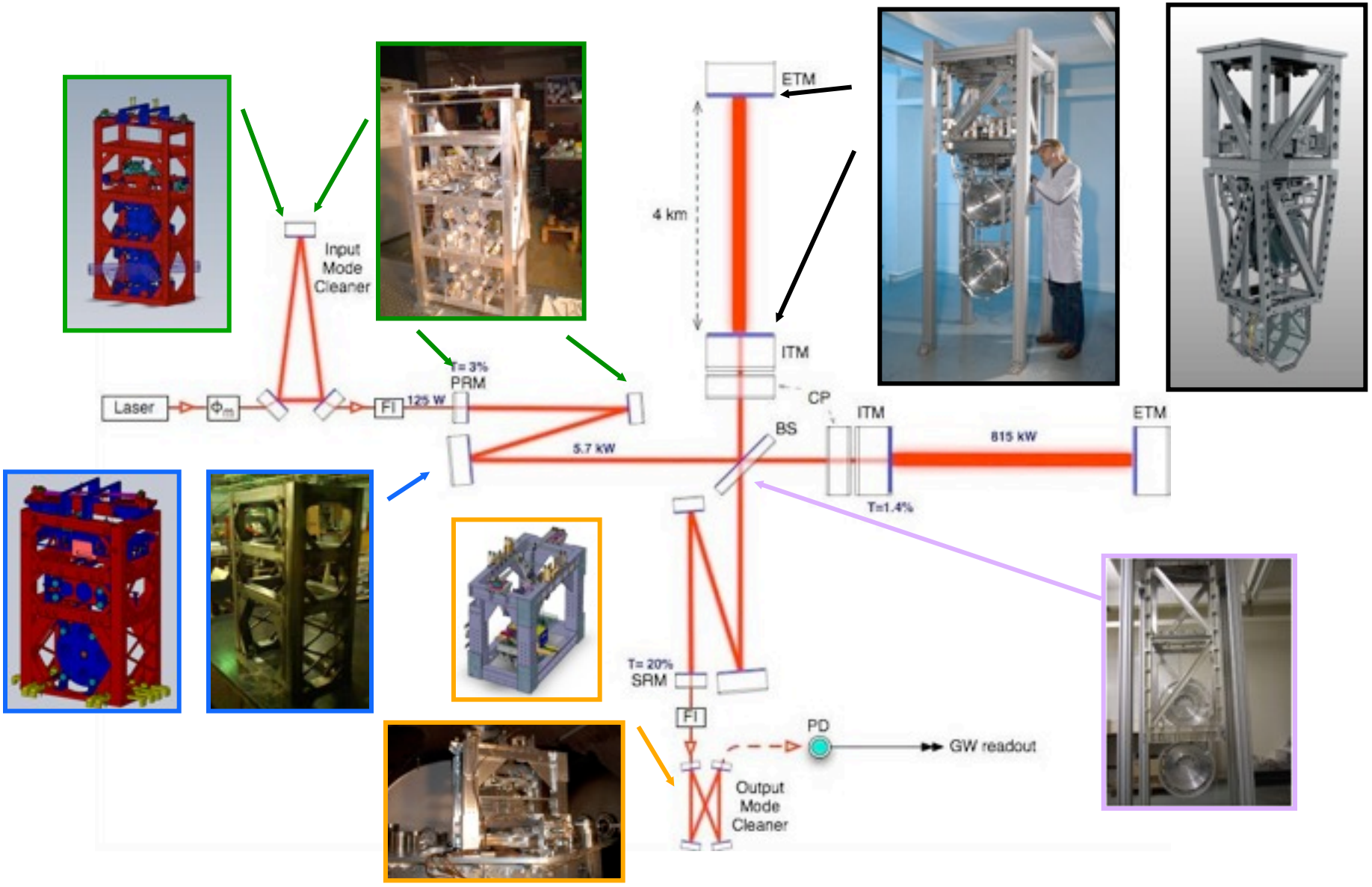
ISI Table in HAM Chamber

HAM Chambers for

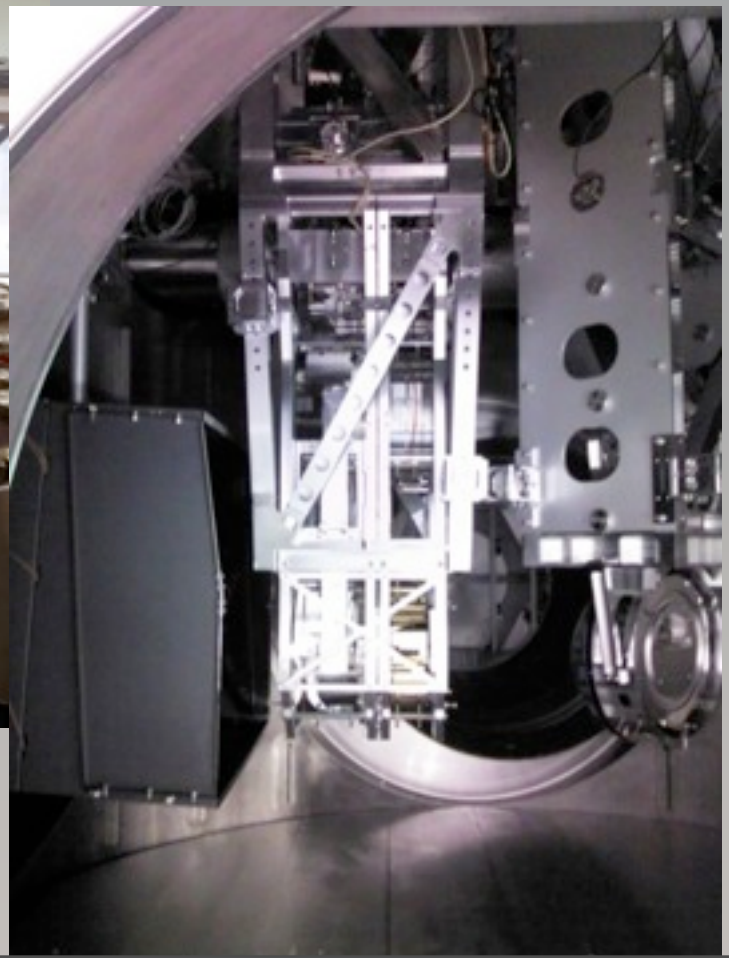
- secondary optics (Recycling Cavities, Mode Cleaner, ...)

PR2 & IMC2 on ISI Table

Suspensions



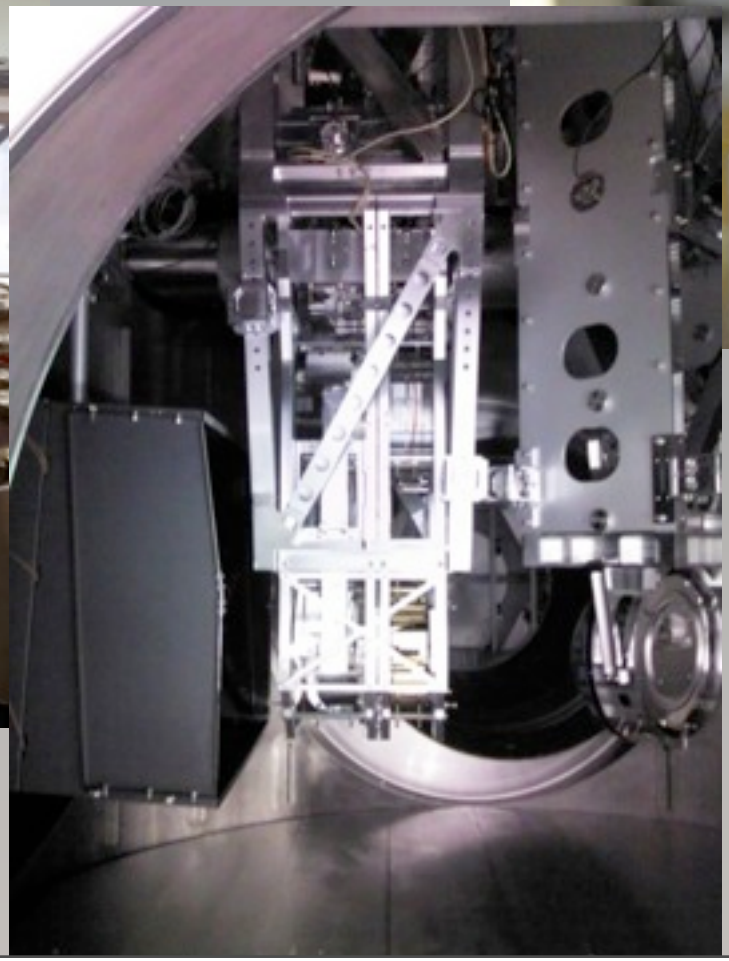
Suspensions



Installation of Quad Suspension in Hanford

Suspensions

Installation of Quad UK-Suspensions in Hanford



Broken Fiber

Can all be fixed ...

More important: See now continuous progress with installation

Advanced LIGO

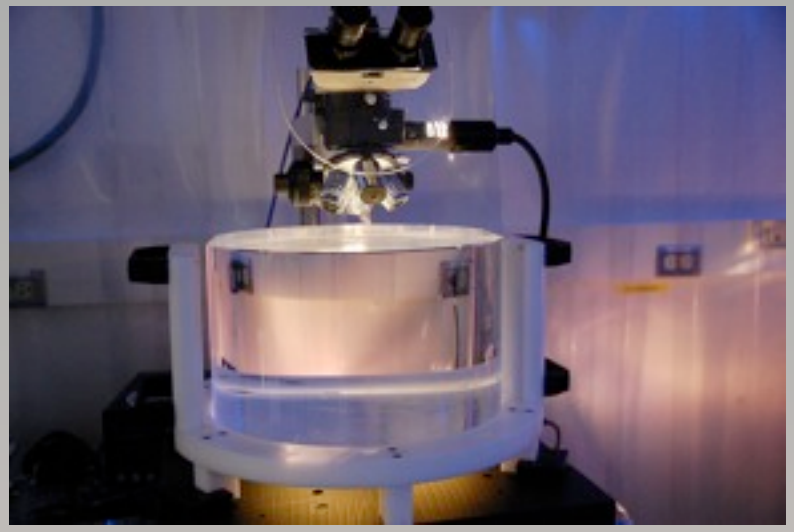
Better test masses:

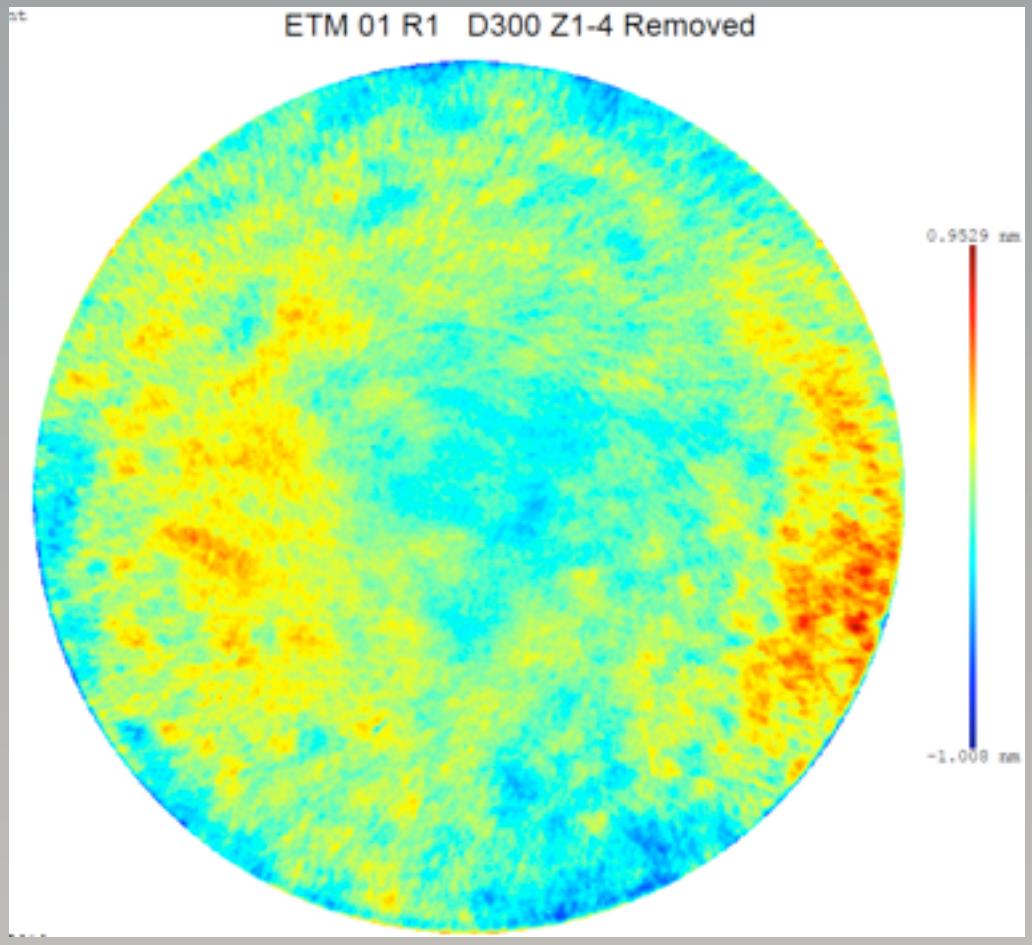
10 kg → 40 kg

Higher Q

Lower Absorption (< ppm/cm)

Better Surface profiles (< nm)





Still issues with coating uniformity over large area

Advanced LIGO

Pre-stabilized Laser (PSL)

30 W → 200 W

Built and delivered by AEI-Hannover

- **Operating at LLO since Summer 2011**
- **Operated in H2 since December 2012**
  - **Just moved to H1**

Input Optics I:

Modulators

- **Wedged to also act as polarizers**
- **High Power qualified**

Power Control

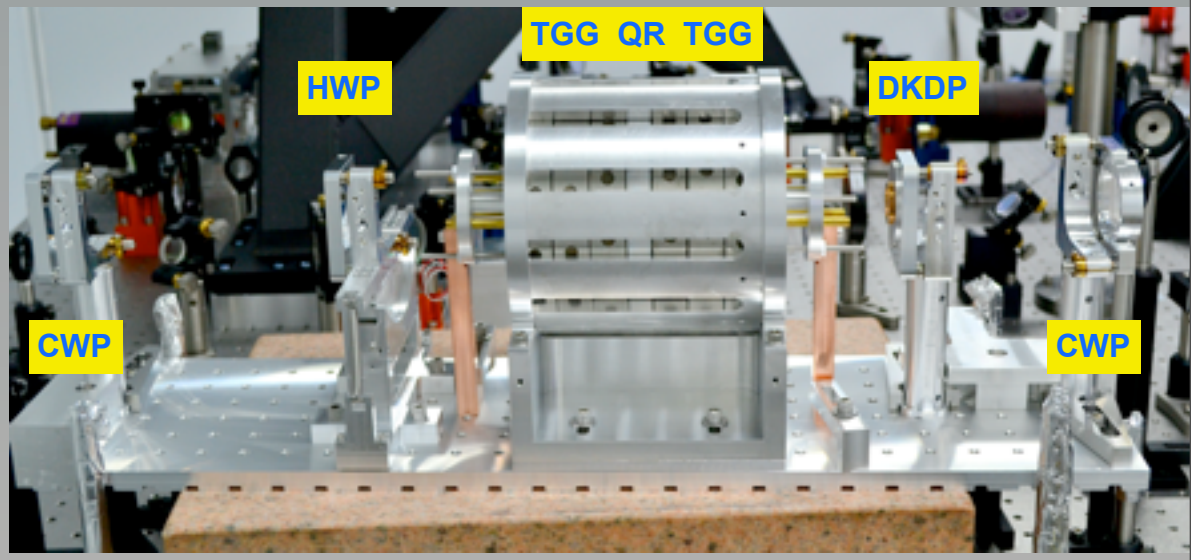
Mode matching

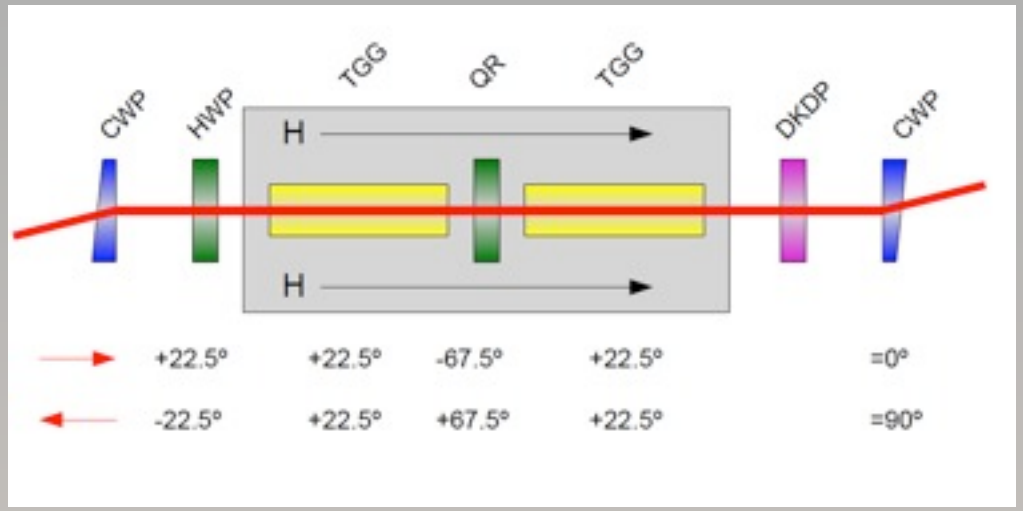
Diagnostic

Advanced LIGO

Input Optics II (In Vacuum):

- **Input Mode Cleaner**
- **Faraday Isolator**
- **Mode matching**
- **Diagnostic**





Faraday Isolator:
(tested with PSL in air)

- Losses 3.3%
  - eLIGO 7%
  - iLIGO 14%

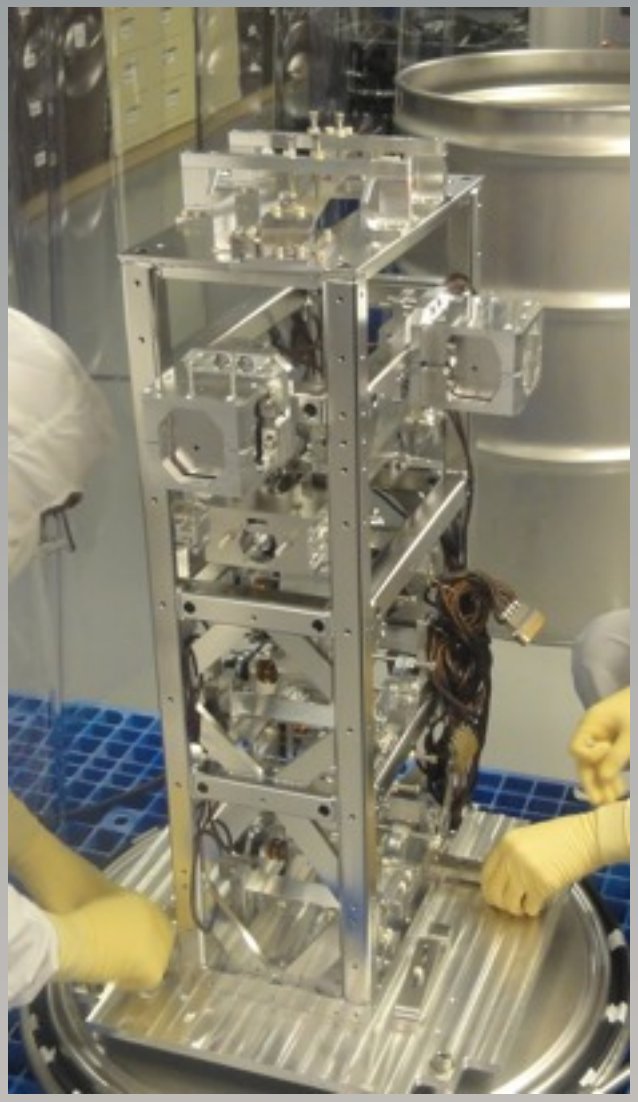
Isolation Ratio:

- > 34 dB up to 70W

Advanced LIGO

Suspended Optics in IO

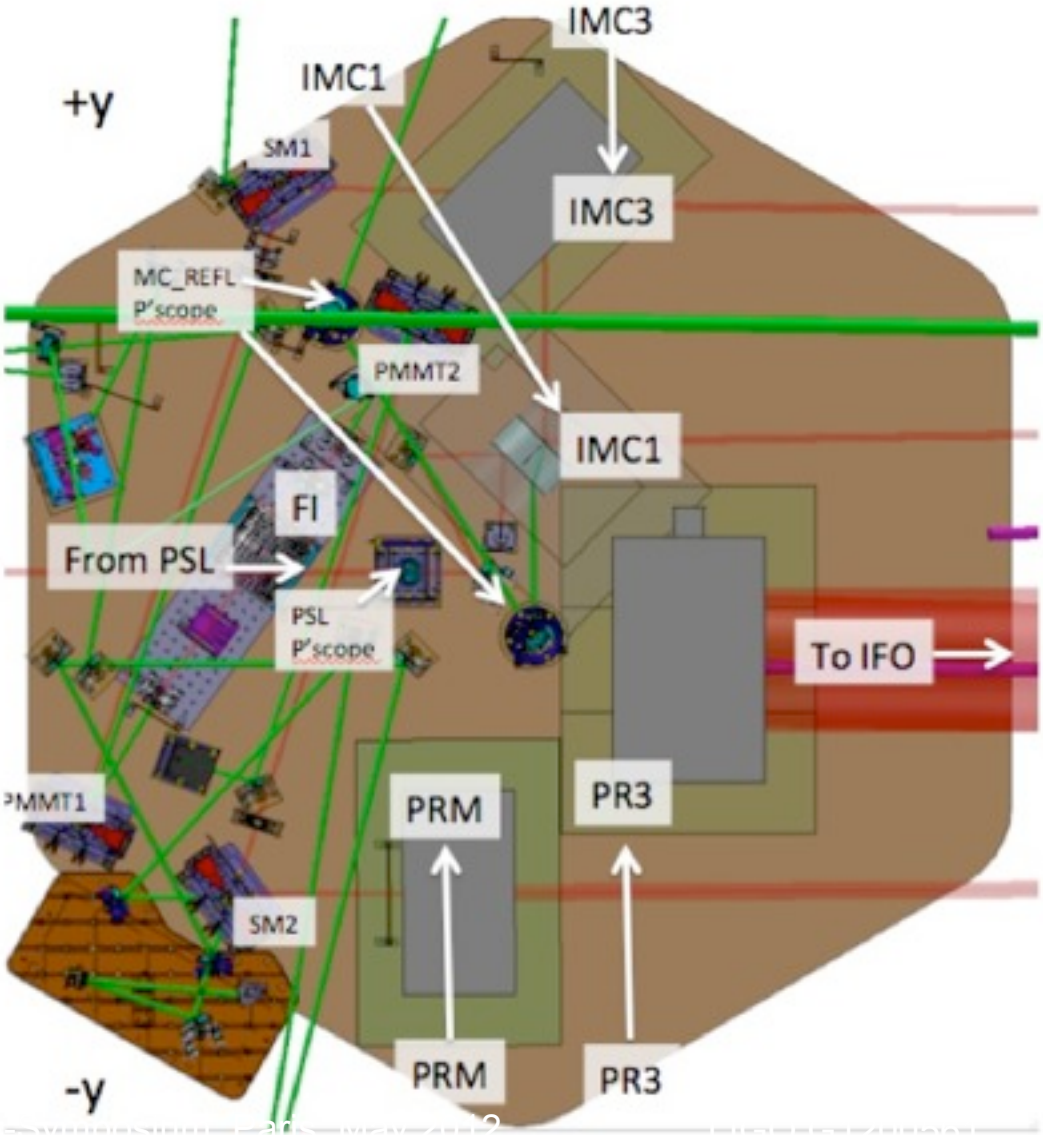
- **Input Mode Cleaner**
- **Mode Matching Optics**
- **Beam Steering Optics**



HAM 3 @ LLO


Input
Mode
Cleaner 2
Power Rec.
Mirror 2
Steering
Mirrors +
Black Glass
Baffles to control
stray light missing

Next
HAM 2 @ LLO



Little crowded ...

- **PR3, IMC 1 & 3 are chamber-side**
- **Final testing followed by installation early next week**

Advanced LIGO

Advanced LIGO

Current Schedule:

- L1 (Livingston)
  - Short Michelson test Feb 2013
    - incl. Power Recycling
  - Full Interferometer Testing June 2013
  - Acceptance Tests May 2014

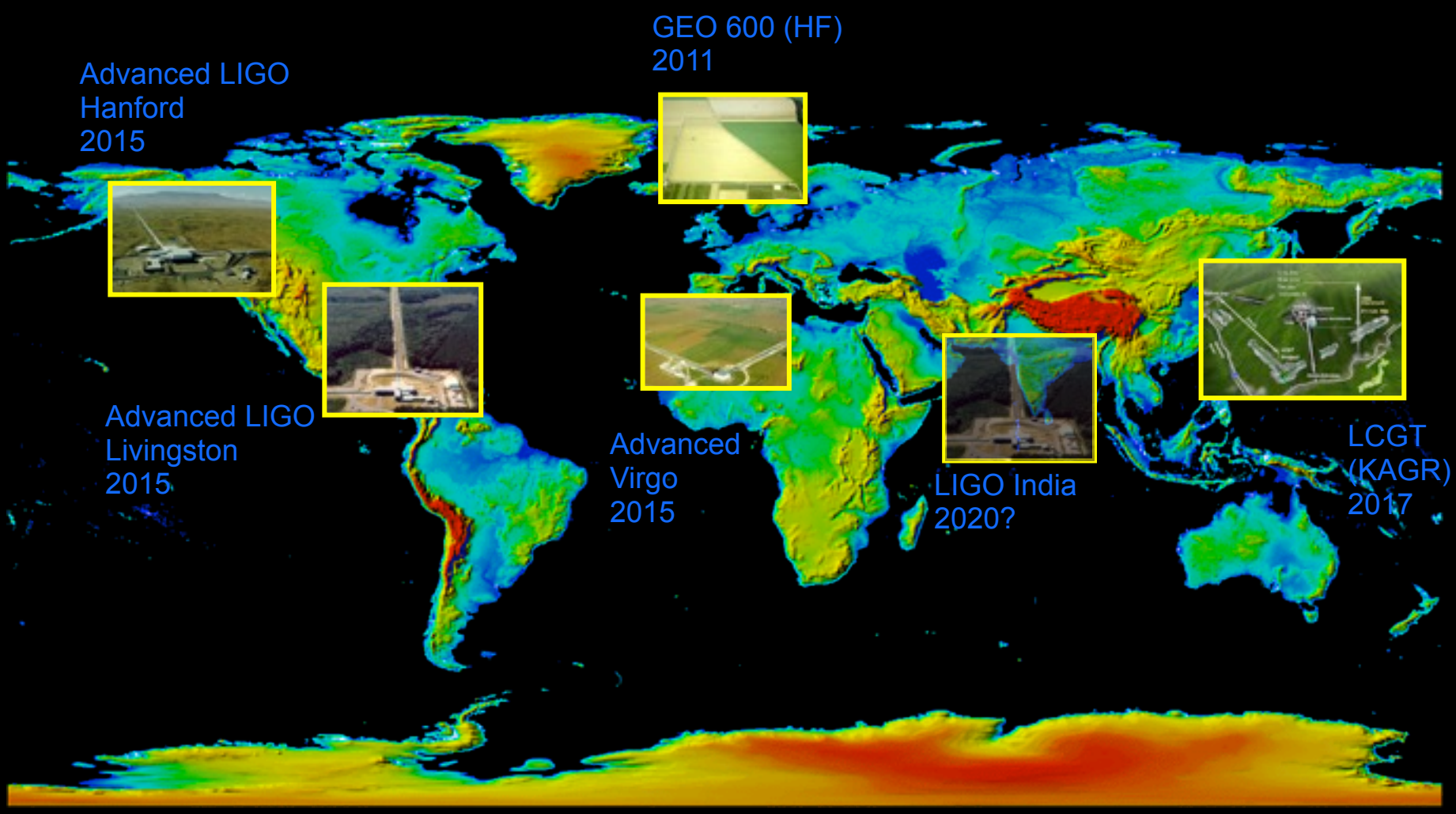
- H1 (Hanford)
  - Single Arm Test July 2012
  - Full IFO locked Dec 2013
  - Acceptance Tests July 2014

Advanced LIGO

- Acceptance Tests:
  - Need ~2h of full interferometer lock
  - No requirement on Sensitivity
- Finishes Project Phase

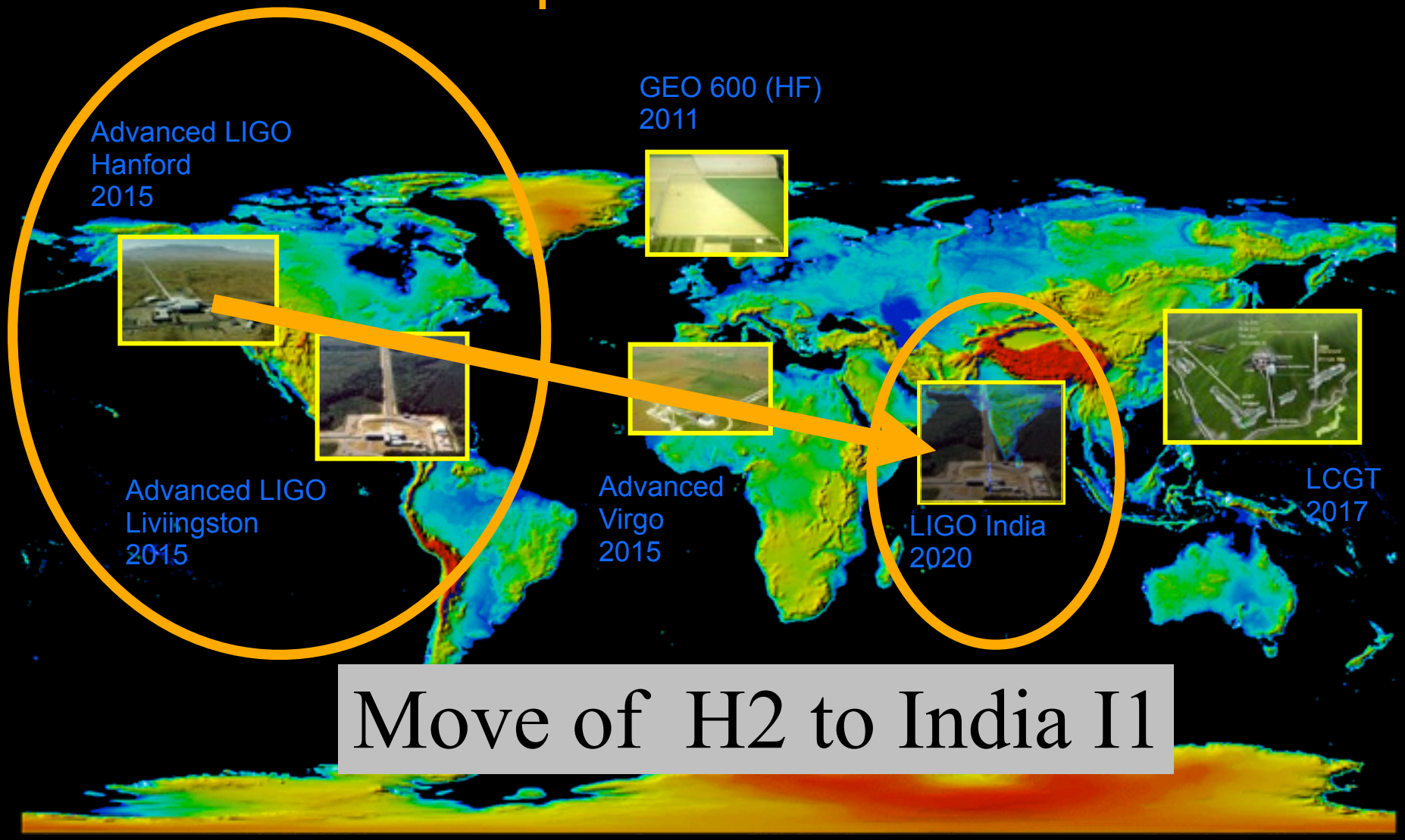
- Followed by Operations Phase
  - Commissioning work to improve
    - sensitivity
    - duty cycle
    - understanding of the instrument
  - interspersed by science runs at (~50MPc, ~100MPc, >150MPc)

The Advanced GW Detector Network



Advanced LIGO

Prospects and Status



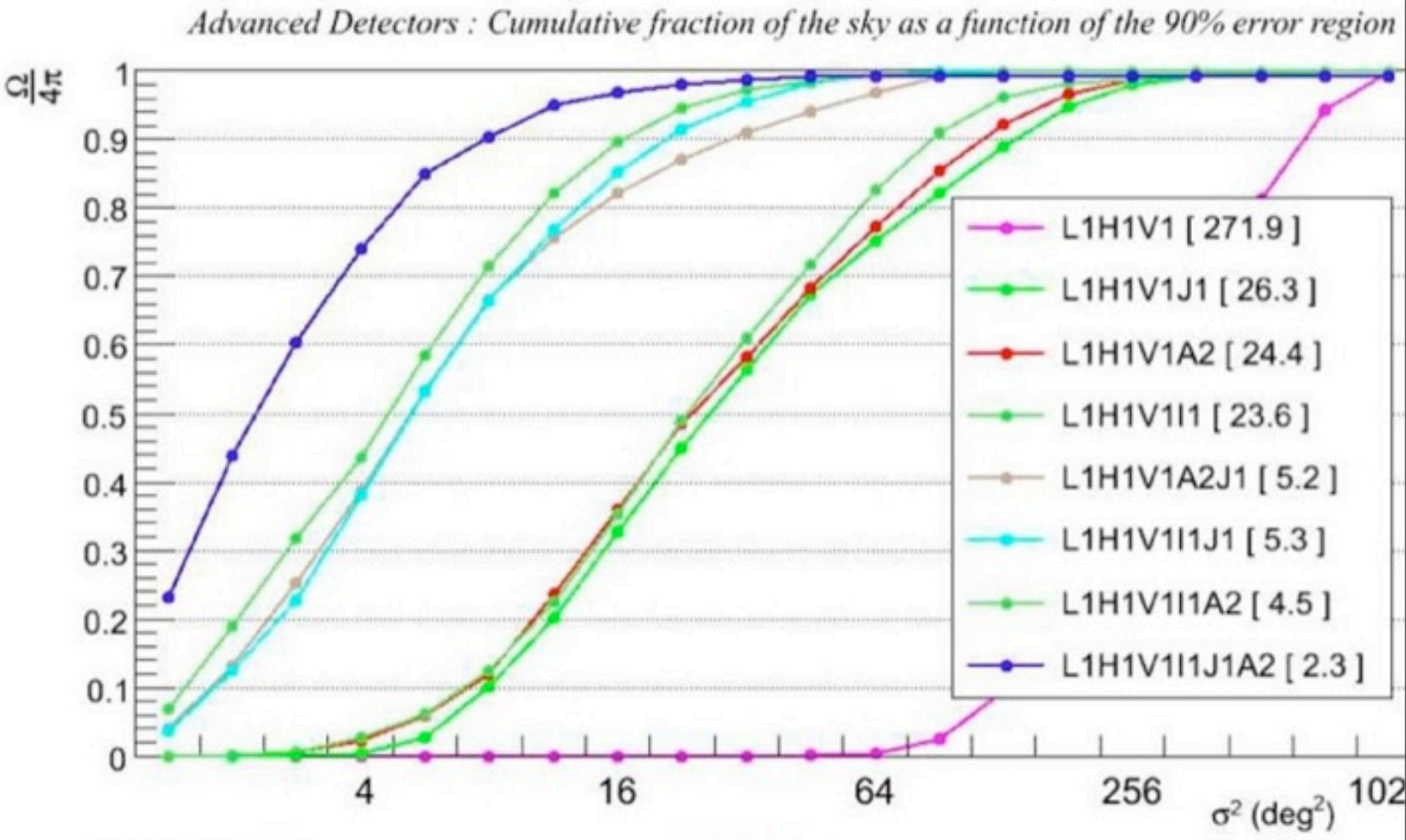
Move of H2 to India I1

Advanced LIGO in India

LIGO India Master Plan:

- India provides vacuum system, infrastructure, S&H, Operations Costs and local staff
- LIGO sends 2nd Hanford interferometer to India
    - Design will change to an unfolded L1 interferometer
    - Requires some re-polishing of Input Optics mirrors
- LIGO-India would be operated as part of the LIGO Network

Advanced LIGO in India



Advanced LIGO in India

Three phases to LIGO-India:

» Phase 1 (2012-2013)
  – Establish project office, site selection, facility design, vacuum system design update

» Phase 2 (2014-2016)
  – Site preparation, facility and vacuum construction

» Phase 3 (2017-2019)
  – Detector installation and commissioning

Advanced LIGO in India

Directors of three institutions have agreed to serve as nodal institutions

» Institute for Plasma Research (IPR, Department of Atomic Energy autonomous institute), vacuum system and facility

» Raja Ramanna Centre for Advanced Technology (RRCAT, DAE laboratory), detector responsibilities

» Inter-University Centre for Astronomy and Astrophysics (IUCAA, University Grants Commission-funded centre), data analysis and astrophysics

Advanced LIGO in India

Approval Status in India:

- IPR Governing Board has approved role in project
- Project presented to Atomic Energy Commission
  - » All comments positive, prepared recommendation for Cabinet consideration
- Cabinet approval needed because project spans multiple 5-year plans
  - » Cabinet approval can trigger seed funding by DAE
  - » Scheduling uncertain, but should be possible within 2 months
- Continuing site visits and evaluations
- Beginning process of getting Visas for entry to US
  - » Typically 2 month process » Will enable first visits from India by summer or fall

Advanced LIGO in India

Approval Status in US:

Following successful review of recommendation to proceed, LIGO asked NSF for permission to cease H2 installation

» Granted immediately by Physics Division,

- NSF asked for “mini-Project Execution Plan”
- Replanning aLIGO installation and testing for two interferometer US configuration underway
- Submit both to NSF by June 1 for review June 12/13
- NSB information item May 2, action item July 17-18
- Beginning export license application

Advanced LIGO in India

Approval Status in Europe/Australia:

UK, Germany and Australia are capital partners in LIGO who make significant financial contributions

- Suspensions from UK
- Laser from Germany
- Wavefront Sensing from Australia

Official requests for approval will be made following probably the NSB decision in the US

Advanced LIGO in India

Approval Status in Europe/Australia:

UK, Germany and Australia are capital partners in LIG

LIGO India is (very likely) coming ...

- S
- Laser from Germany
- Wavefront Sensing from Australia

Official requests for approval will be made following probably the NSB decision in the US

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- Binary coalescences rates
  - » neutron star (NS) = 1.4 $M_\odot$, Black Hole (BH) = 10 $M_\odot$

TABLE V: Detection rates for compact binary coalescence sources.

IFO	Source	$\dot{N}_{\rm low}$ yr^{-1}	$\dot{N}_{\rm re}$ yr^{-1}	$\dot{N}_{\rm pl}$ yr^{-1}	$\dot{N}_{\rm up}$ yr^{-1}
Initial LIGO	NS-NS	2×10^{-4}	0.02	0.2	0.6
	NS-BH	7×10^{-5}	0.004	0.1	
	BH-BH	2×10^{-4}	0.007	0.5	
	IMRI into IMBH			$< 0.001^b$	0.01^c
	IMBH-IMBH			$10^{-4\,d}$	$10^{-3\,e}$
Advanced LIGO	NS-NS	0.4	40	400	1000
	NS-BH	0.2	10	300	
	BH-BH	0.4	20	1000	
	IMRI into IMBH			10^b	300^c
	IMBH-IMBH			0.1^d	1^e

Abadie, et al. "Predictions for the Rates of Compact Binary Coalescences Observable by Ground-based Gravitational-wave Detectors" CQG 27 173001 (2010), arXiv:1003.2480

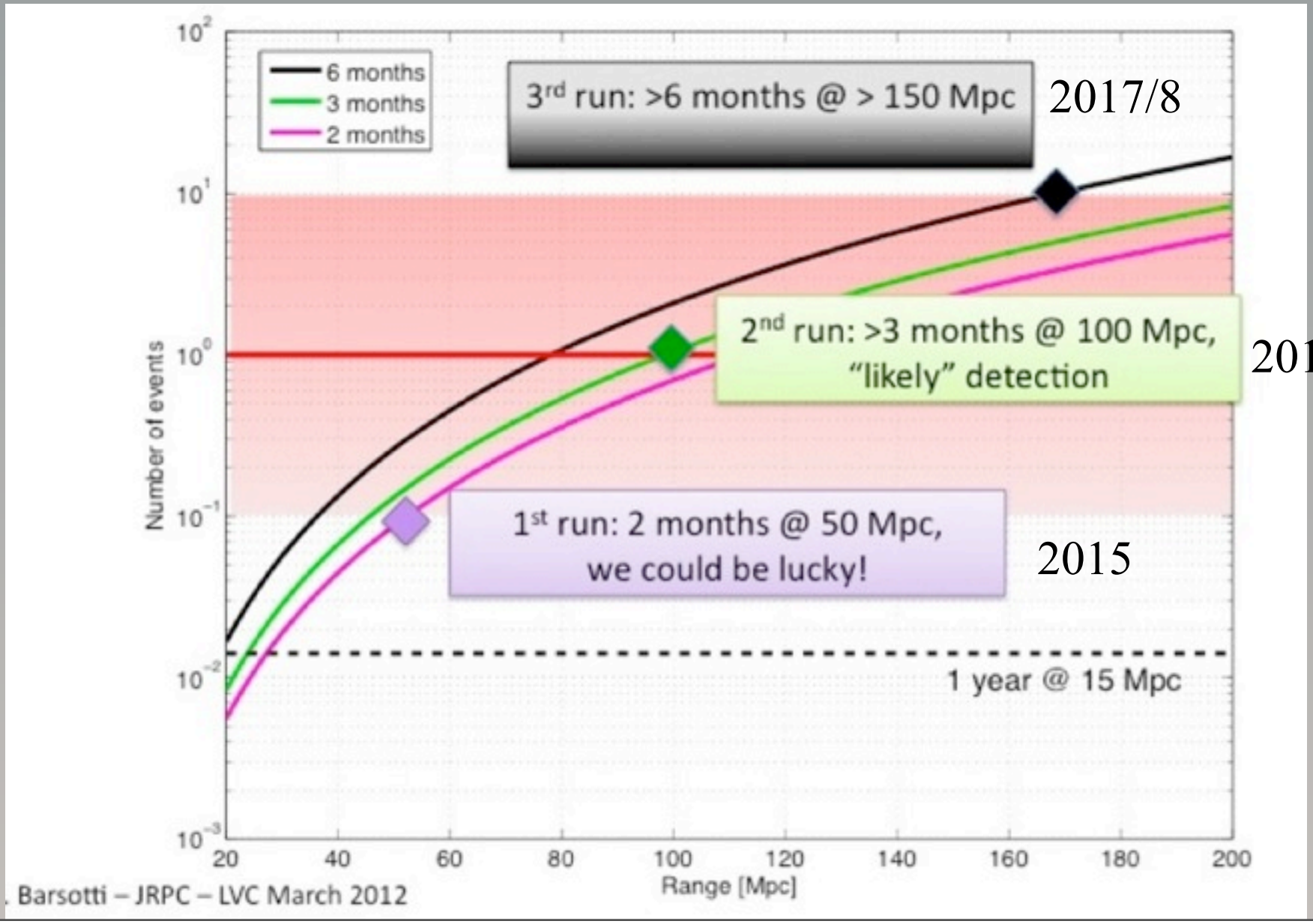
Summary

The Message:

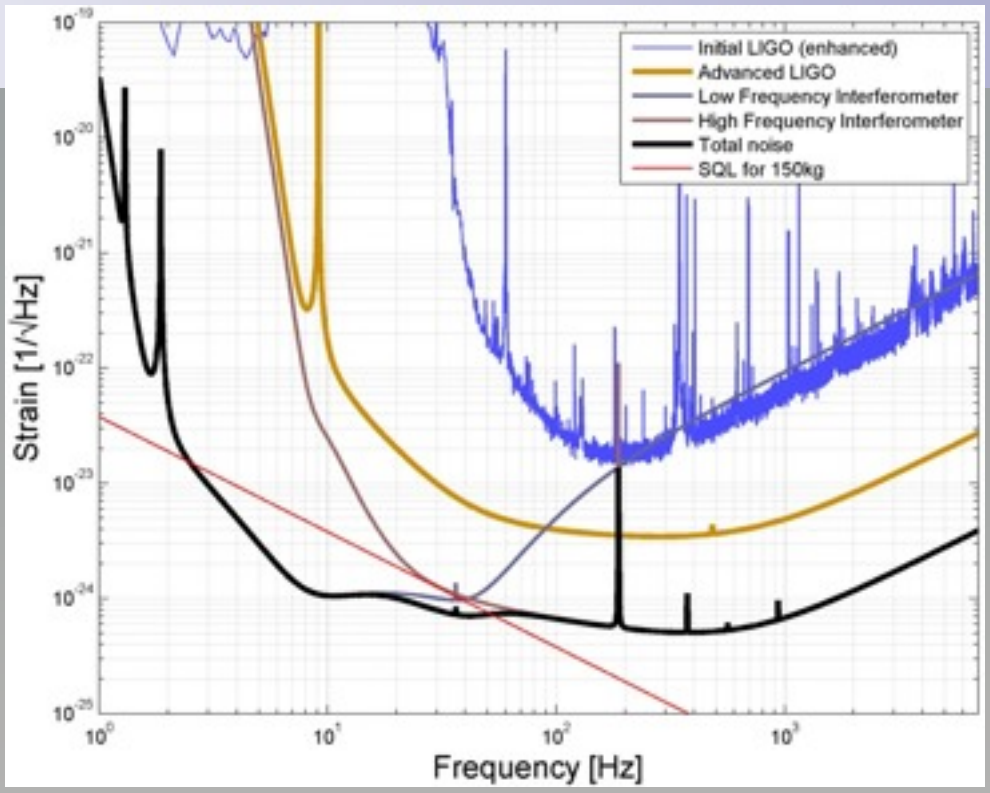
- Advanced LIGO is progressing fairly well
  - No major problems in sight right now
  - Have certainly seen our share of delays
    - Still within schedule and budget contingency

- Deliverable for Advanced LIGO Project:
  - 2h continuous lock of each interferometer in full configuration (that could mean: No SR)
    - No sensitivity requirement
  - LIGO Operations will do the follow-up optimization and noise hunting

Current Plan



Beyond Advanced LIGO



Beyond Advanced LIGO:

- Improve sensitivity by another factor 10
- Reduce low frequency to around 1 Hz

R&D for 3G:

- Better suspensions
  - lower resonance freq.
  - less thermal noise
- Gravity gradient noise
  - Underground
  - Measure and subtract
- Lower thermal noise
  - Material research
- Squeezing
  - Modify the Vacuum
- ...

Beyond Advanced LIGO

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- Improve s
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R&D for 3G

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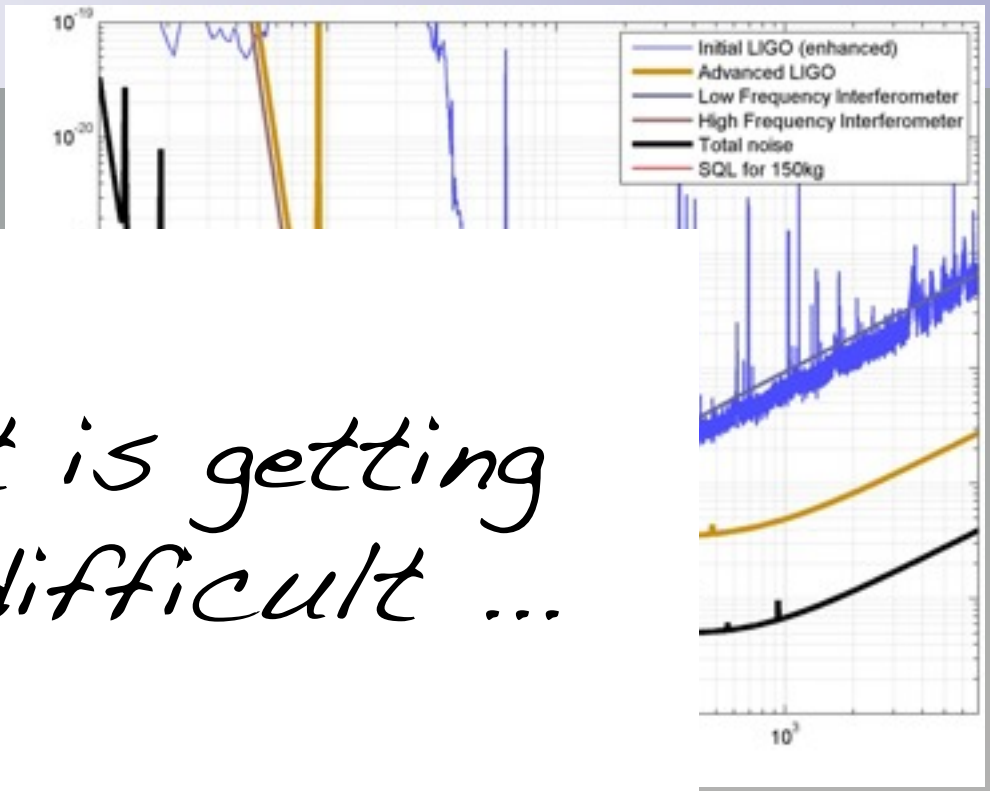

Now it is getting really difficult ...

and we leave that for 'next week' ...

- ...

Beyond Advanced LIGO

Questions?

Comments?

or Coffee?

Seismic Isolation

SEI Sensors and Their Noise

"Low" Frequency

DC

IPS

Kaman's Inductive Position Sensors

Used On: HEPIs

Used For: ≤ 0.5 Hz Control, Static Alignment

Used 'cause: Reasonable Noise, Long Range

CPS

MicroSense's Capacitive Displacement Sensors

Used On: HAM-ISIs and BSC-ISIs

Used For: ≤ 0.5 Hz Control, Static Alignment

Used 'cause: Good Noise, UHV compatible

10 mHz

STS2

Strekheisen's STS-2

Used On: HEPIs

Used For: 0.01 ≤ f ≤ 1Hz Control

Used 'cause: Best in the 'Biz below 1 Hz, Triaxial

T240

Nanometric's Trillium 240

Used On: BSC-ISIs

Used For: 0.01 ≤ f ≤ 1Hz Control

Used 'cause: Like STS-2s, Triaxial, no locking mechasim -> podded

1 Hz

GS13

GeoTech's GS-13

Used On: HAM-ISIs and BSC-ISIs

Used For: ≥ 0.5 Hz Control

Used 'cause: awesome noise above 1Hz, no locking mechanism -> podded

L4C

Sercel's L4-C

Used On: All Systems

Used For: ≥ 0.5 Hz Control

Used 'cause: Good Noise, Cheap, no locking mechanism -> podded

800 Hz

"High" Frequency

G1100431 J. Kissel, Apr 7 2011 10