Getting an A+ :
Enhancing Advanced LIGO

LIGO-DAWN Workshop II
Georgia Tech
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LIGO Laboratory

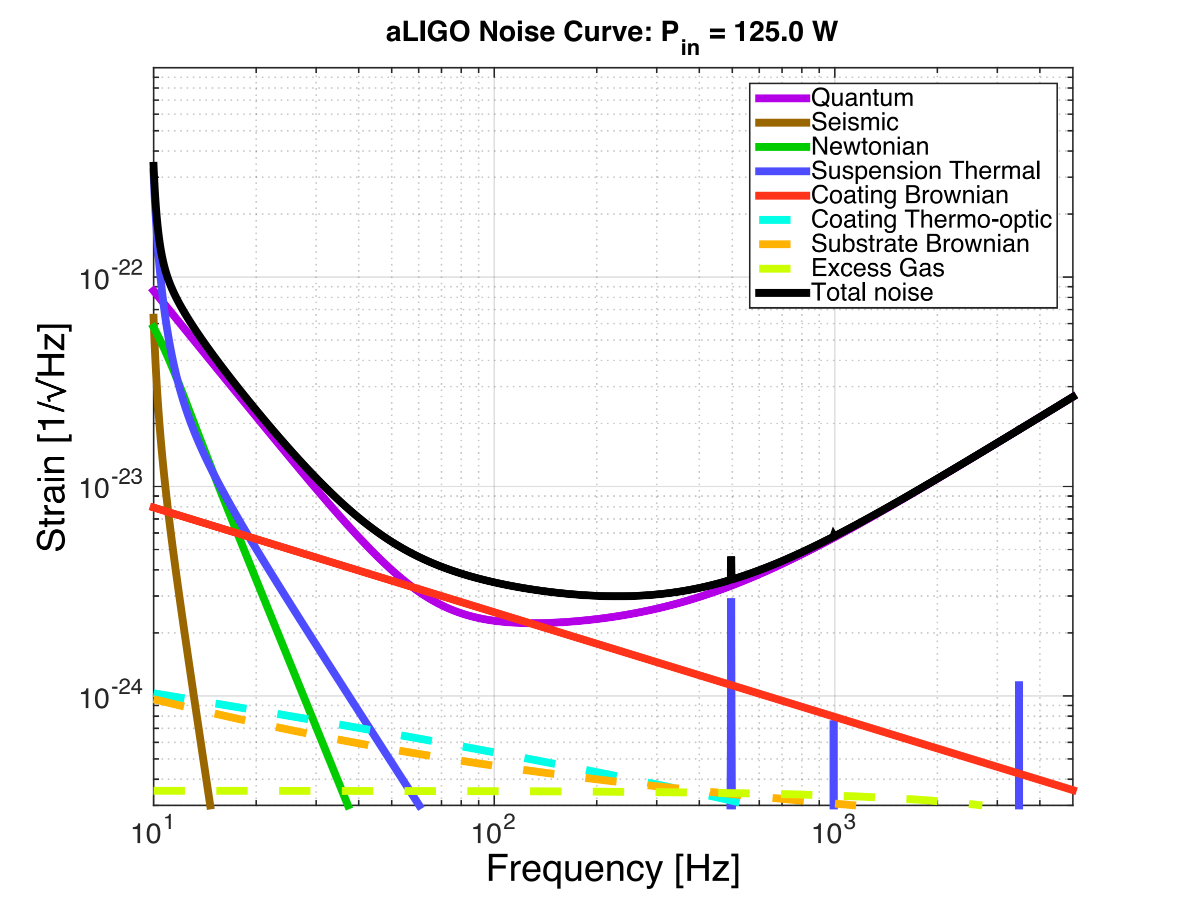
Topics for today

- Context and motivation
- Our target
- What will it look like ?
- How long will it take ?
- How much it will cost ?
- Summary

Set the stage: Where we expect to be

- O2 and O3 *will* yield many BBH detections by late 2018
  - BNS and other important astrophysical targets may remain elusive, or too rare for full exploitation
- L1 and H1 should reach design sensitivity by mid-2019
  - At this point, observational horizons freeze at limits set by aLIGO technology
- "Next-generation" detectors optimistically ready no earlier than end of next decade
  - And only with immediate funding commitments

aLIGO operating at full power



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Stochastic Omega: 2.42e-09

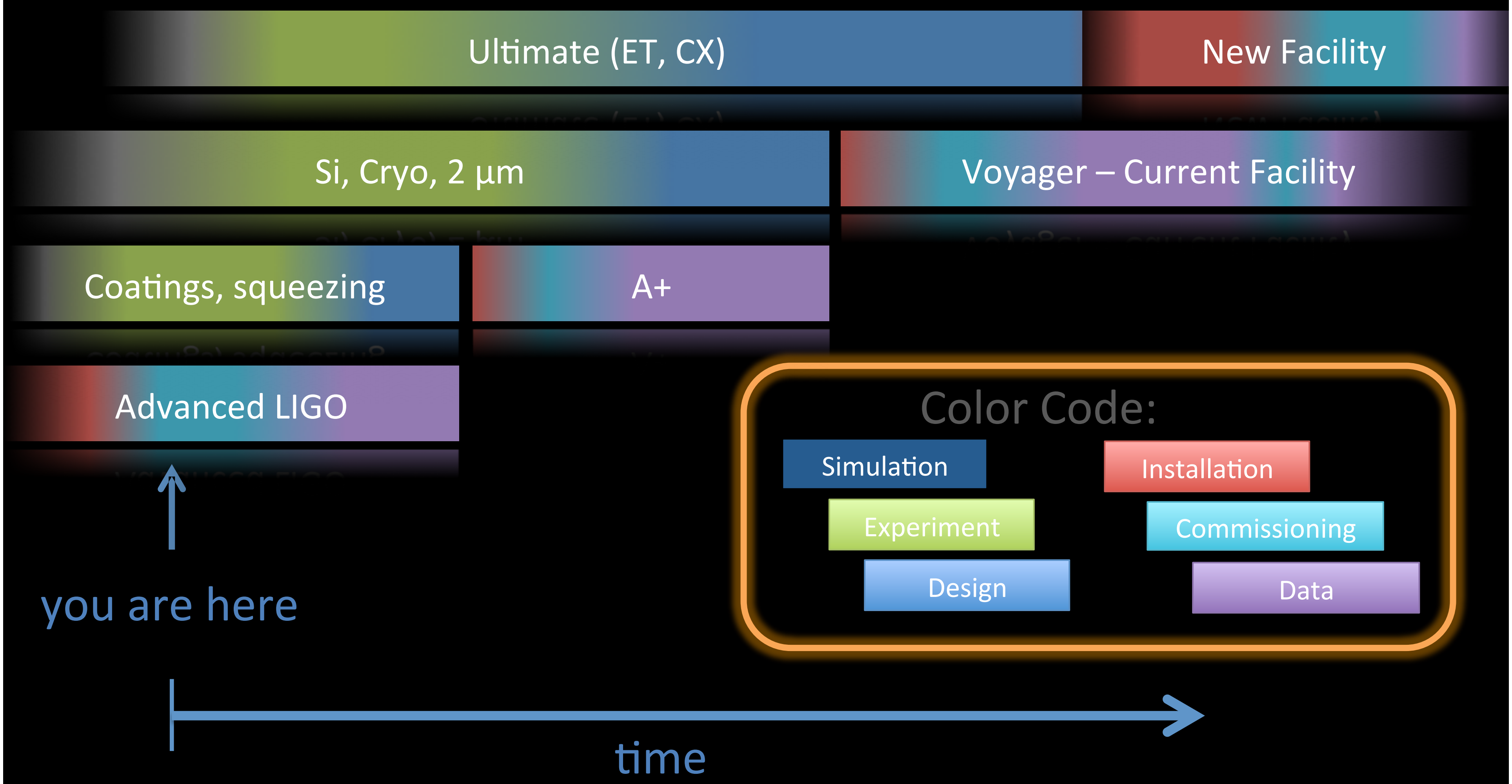
What can we do?

- aLIGO design is limited by quantum noise at high and at low frequencies
- Mid-band (the "bucket") limited by Brownian thermal noise in mirror coatings
- We've learned a lot on both fronts since aLIGO designs were frozen
- We've also learned much about the detectors by commissioning and operating them
- We now have a lot of capable, well-proven technology in our toolkit
- These afford a realistic prospect to improve aLIGO sensitivity at all frequencies*

*LIGO-P1400164

Concept Roadmap

(adapted from G1401081)

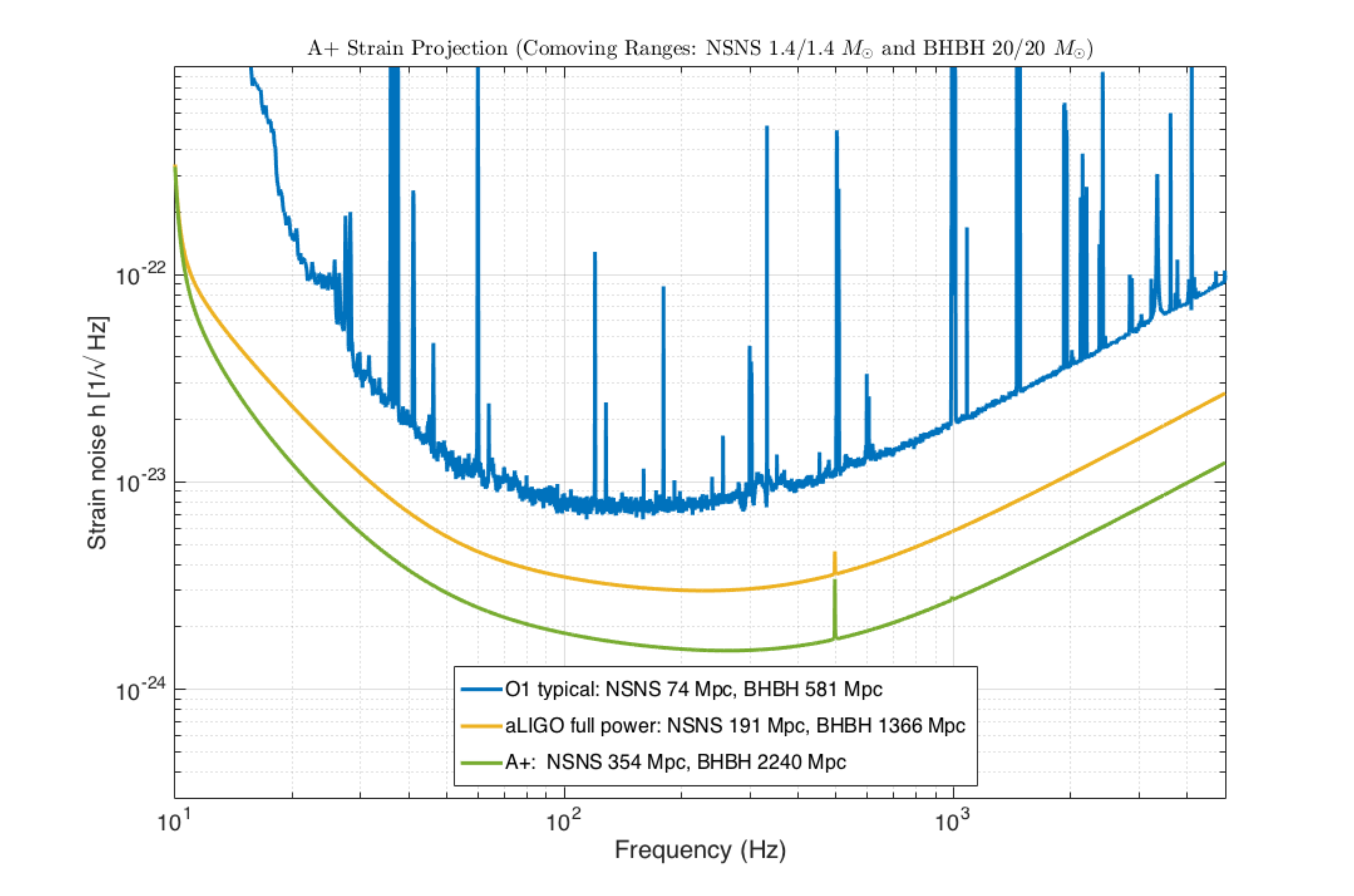


A+

- An incremental upgrade to aLIGO that leverages existing technology and infrastructure, with minimal new investment and moderate risk
- Target: factor of 1.7* increase in range over aLIGO
  - ➔About a factor of 5 greater event rate
- Stepping stone to future 3G detector technologies
- Link to future GW astrophysics and cosmology
- Could be observing within < 6.5 years (mid-2022)
  - – with prompt funding (FY'19 or earlier)
- "Scientific breakeven" within 1/2 year of operation
- Incremental cost: *a small fraction of aLIGO*

*BBH 20/20 $M_{\odot}$: 1.64x
*BNS 1.4/1.4 $M_{\odot}$: 1.85x

A+ Strain Sensitivity Projection



A+ key parameters:

12dB injected squeezing
15% readout loss
100 m filter cavity
20 ppm RT FC loss
CTN half of aLIGO

LIGO-G1600769-v5

Coating Thermal Noise (CTN) Reduction

- Existing dielectric coatings have excess mechanical dissipation, leading to Brownian thermal noise
- Recent LSC Coatings working group results point to reduced loss through modified deposition and/or composition
  - Elevated-temperature, ion assisted or low-rate deposition
  - Trinary (hybrid layer) designs
- Each requires investment (NRE) in 'nonstandard' industrial capacity (LIGO requirements are special)
- We anticipate a factor of 4 lower dissipation, for a factor of 2 reduction in strain noise

A+ Coatings Plan

- Current R&D on small samples will inform a new A+ Coating Pathfinder development program, which we propose to launch in 1.5 years (FY2018)
- Will spin up industrial vendor(s) to demonstrate full-aperture coatings with new low-dissipation process
  - Requires tooling, chamber and process investments
- In parallel,we'll repolish spare aLIGO ITM and ETM optics
  - (+ buy a few additional spares)
  - Metrology, QA, lab infrastructure, suspensions, tooling, procedures, etc. all identical to aLIGO installation
- Begin production coating with new process early 2020
  - Expect production rate similar to aLIGO
- Low-CTN test masses ready for installation early 2021

Quantum Noise Reduction: Frequency-Dependent Squeezing

- Expect *squeezed light injection*, now in preparation, to be operating by 2019
- Effective substitute or assist for high-power operation
  - Phase squeezing at HF causes amplitude anti-squeezing (radiation pressure) at LF
  - Added radiation pressure increasingly bothersome as other LF noise is improved; forces trade
- Solution: Frequency-dependent squeezing (FDS)
- NOTE: FDS is key to planned future detectors (Voyager, ET, CX, etc.)

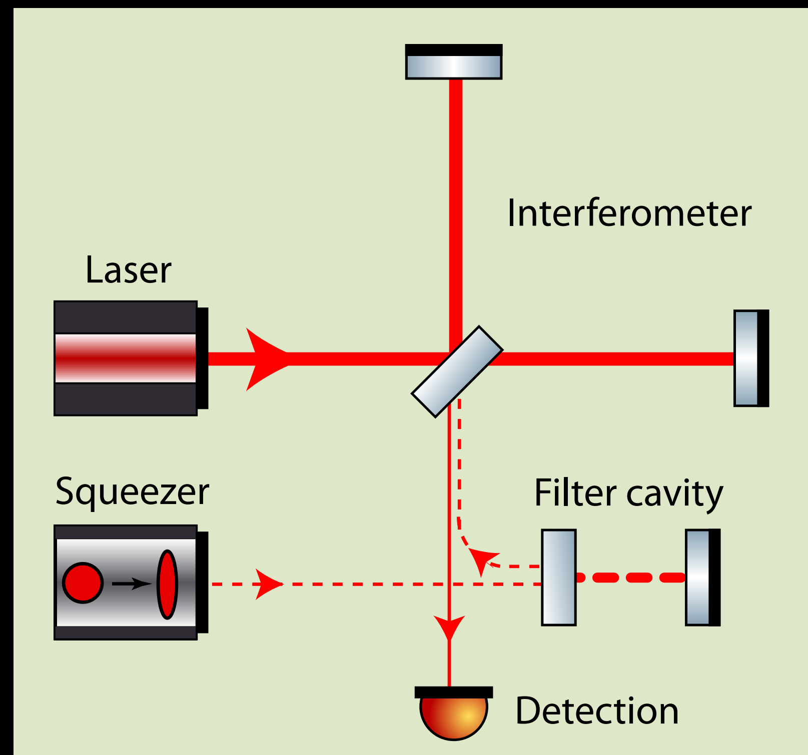
Frequency-Dependent Squeezing

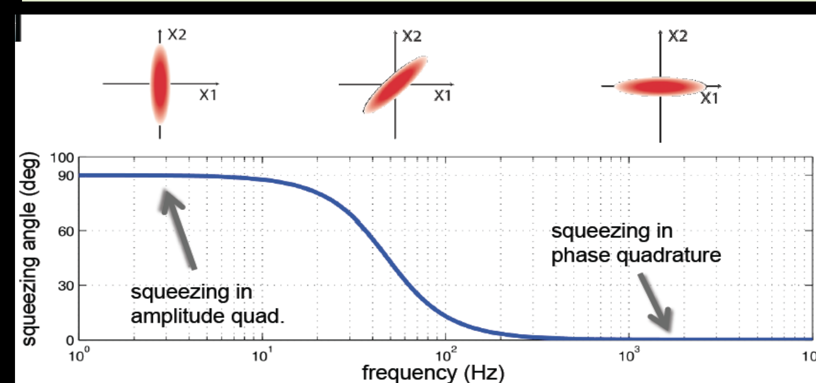
- Optical “filter cavity” (FC)
- Rotates squeezing phase to both improve radiation pressure at LF *and* phase noise at HF
- Low-loss, high finesse cavity with bandwidth ~100 Hz
- Sensitive to optical losses, scattering and mirror motion

➔ Requires L_{FC} ~ 100 m

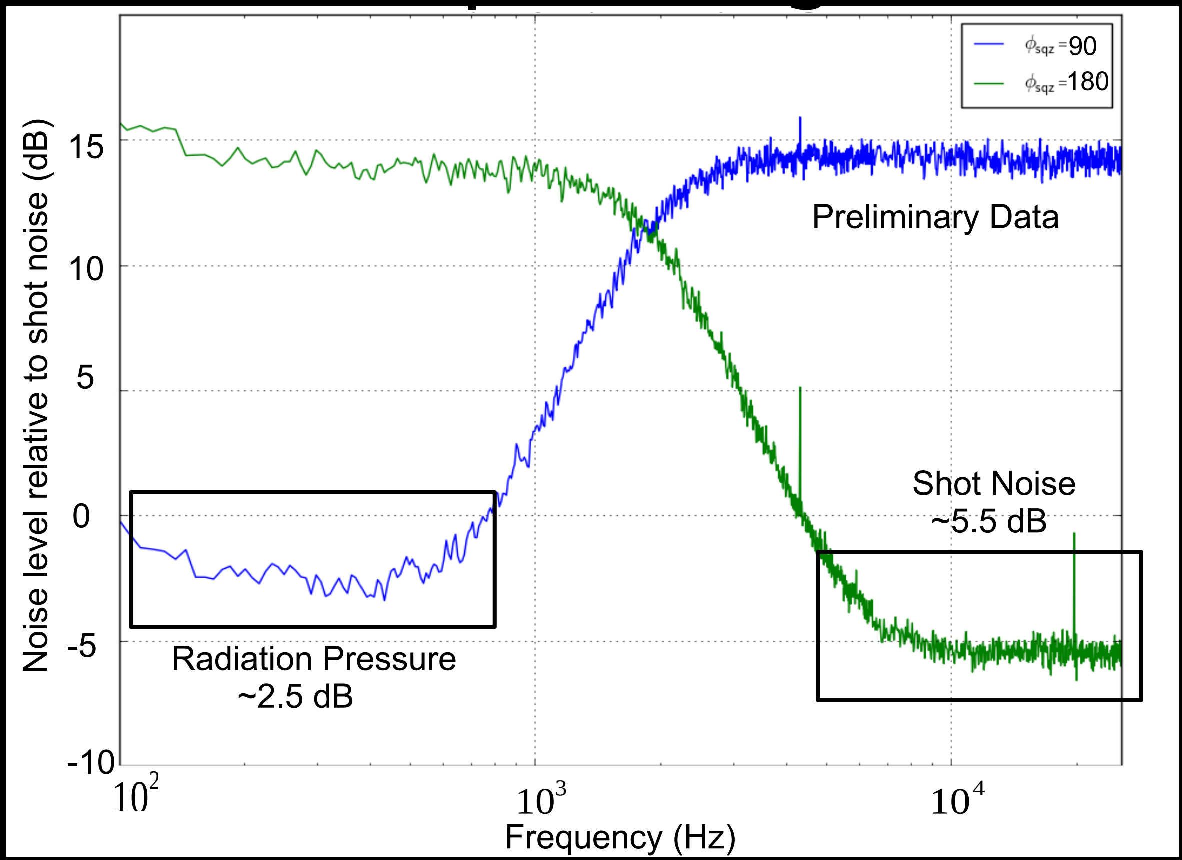
➔ Requires *high-quality FC mirrors*

➔ Requires *seismic isolation and quiet mirror suspension*





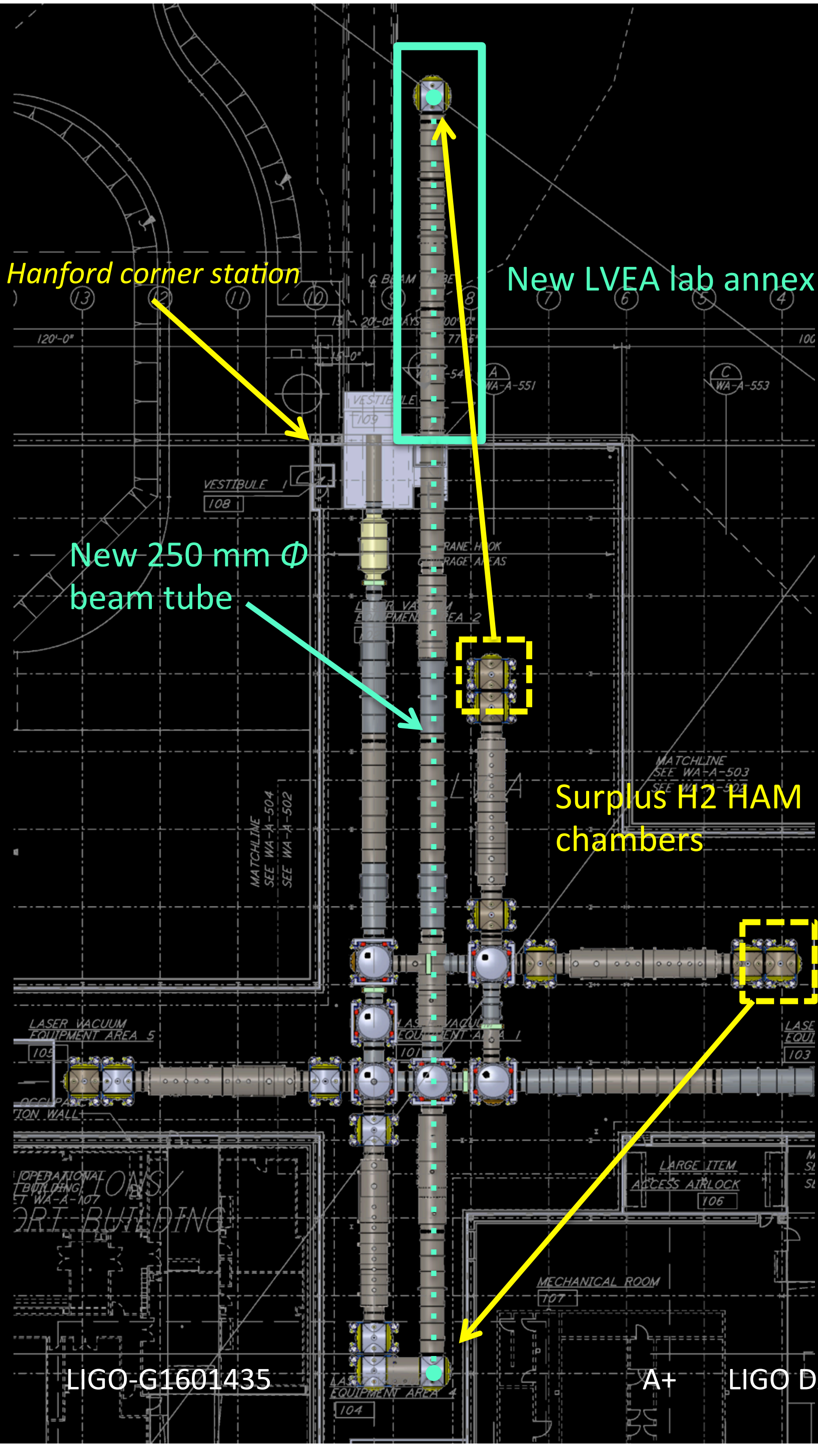
FDS demonstration with 2m filter cavity



Oelker et al, LIGO-P1500062

16m FC FDS test is now in progress at MIT LASTI (LIGO-E1600058)

Potential option to install 16m FC on H1 and L1 after O3 as an interim stopgap, if required

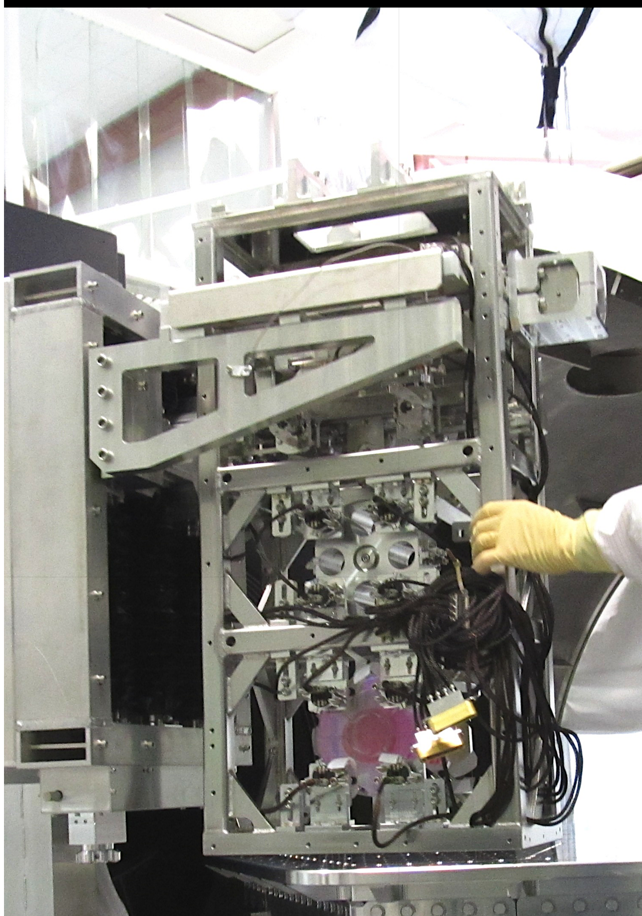


100m Filter Cavity Facility Layout Concept

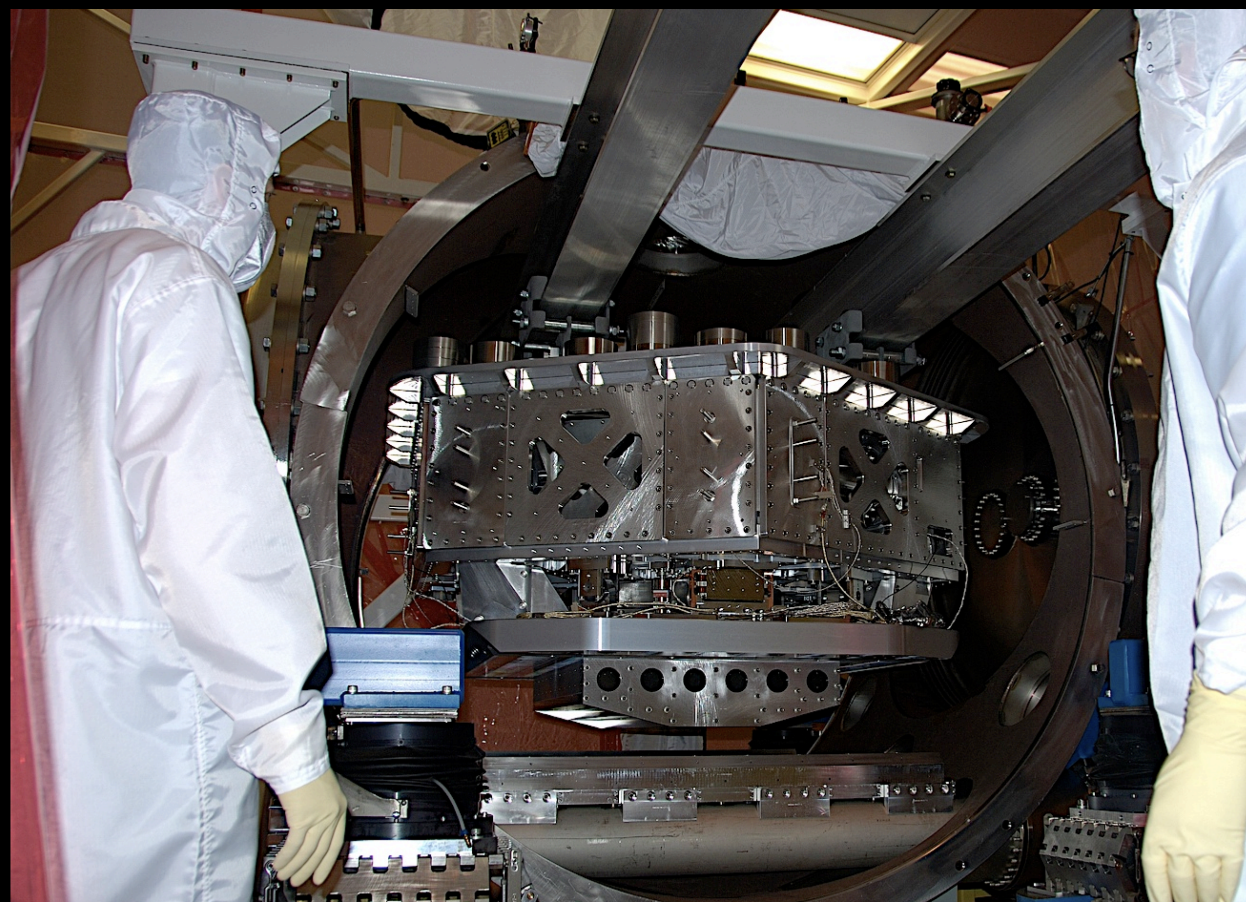
- Recycle four H2 HAM vacuum chambers
  (ship 2 ➔ LLO)
- Small (250 mm) FC beamtube
- FC beam penetrates ITMx chamber
- 25m x 6m lab extension/ annex alongside existing Y tube enclosure

A+ filter cavity mirror suspension & seismic isolation

aLIGO HAM Small Triple Suspension (HSTS)

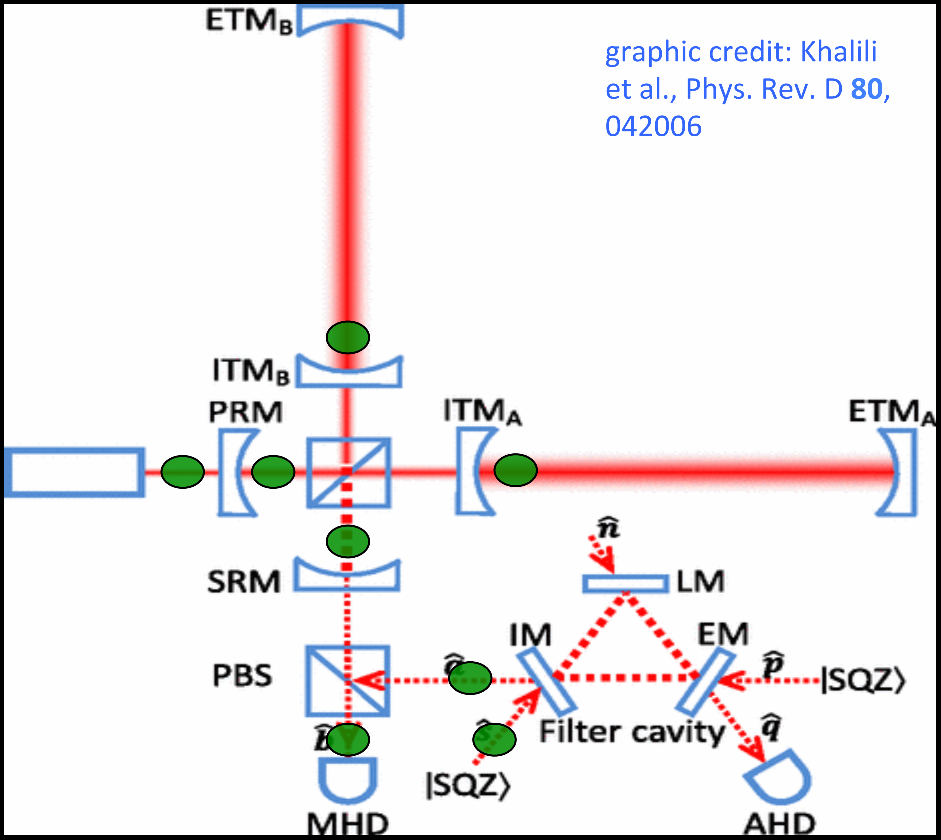


aLIGO HAM Internal Seismic Isolator (HAM-ISI)



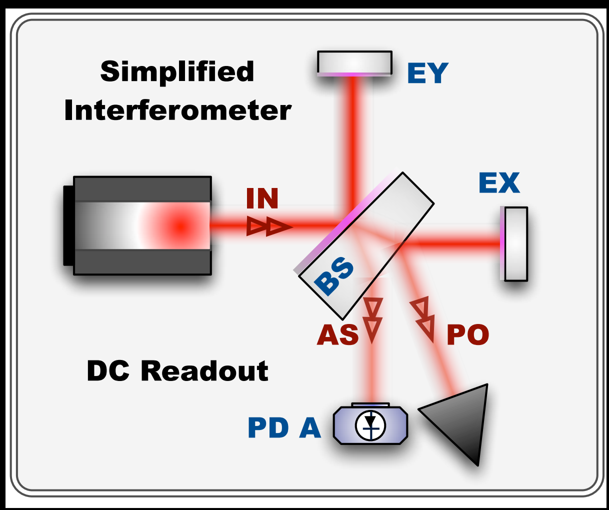
A+ Quantum Noise Optimization: Optical Loss Reduction

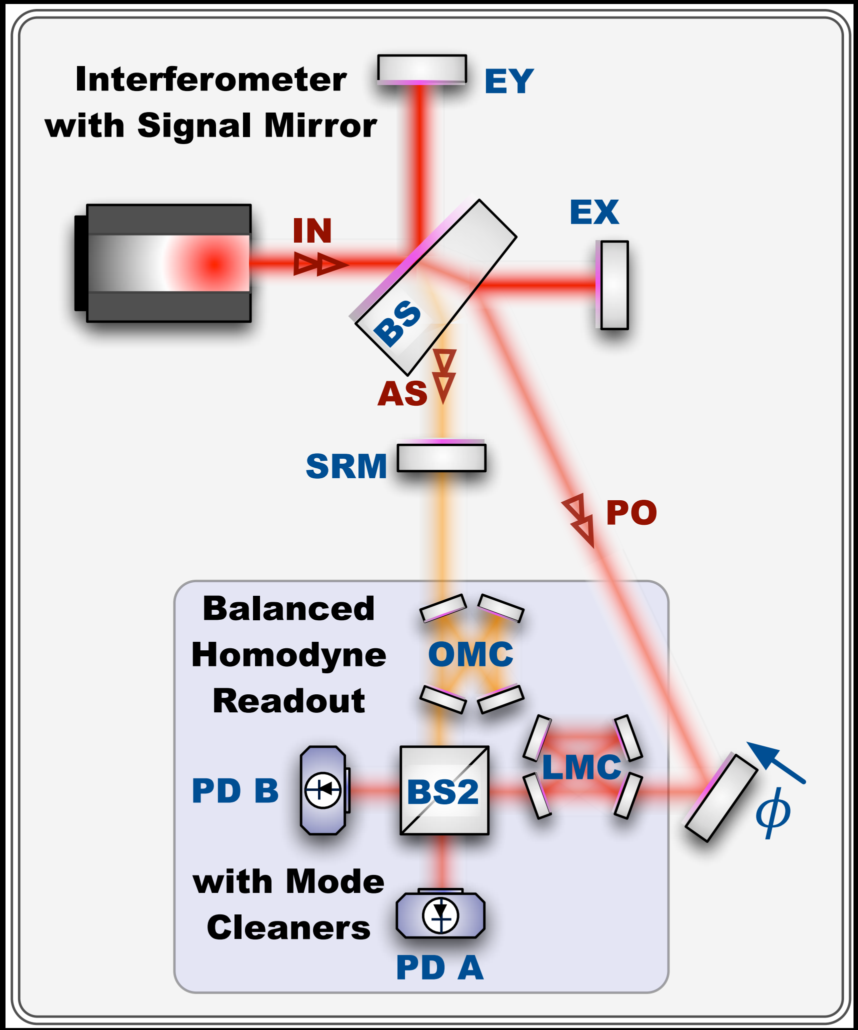
- Output losses degrade squeezing benefit
- Aim to reduce output losses from ~ 25% to <10%
- Lossy aLIGO components will be replaced
- An enlarged main beam splitter will reduce aperture losses (LIGO-T1400296)
- Active mode matching will improve coupling losses (LIGO-T1500188)



Balanced homodyne readout

- Reduced dark-port loss
- Improved backscatter immunity
- Reduced LO noise sensitivity
- Improved phase tuning flexibility
- Enhanced readout dynamic range

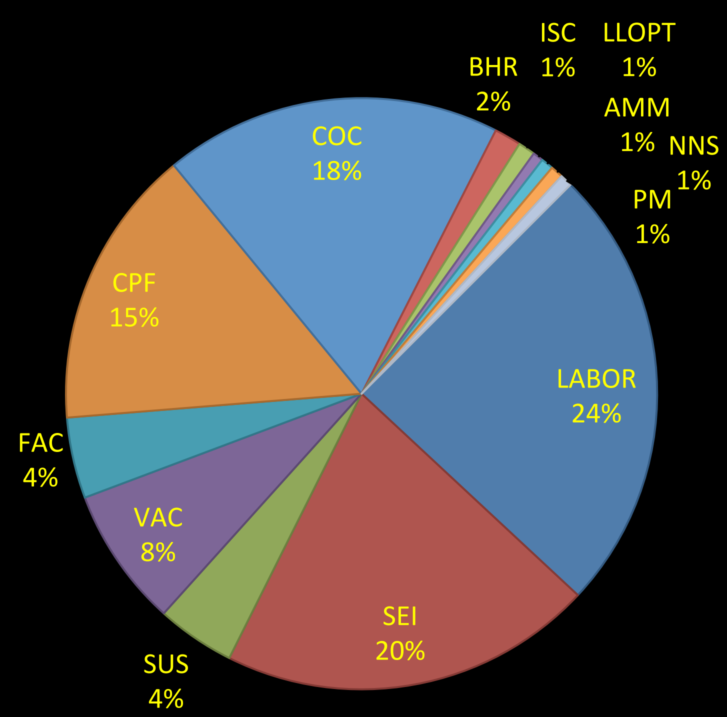




LIGO-P1300184

Projected A+ Upgrade Cost (H1 and L1)

A+ projected cost breakdown (w/o contingency)



Category+	ROM Estimate (FY'17k$)*
Core optic coating pathfinder	3,546
Core optic production	4,266
FC facility mods	1,023
FC vacuum	1,761
FC seismic isolation	4,728
FC suspensions	990
Balanced homodyne readout	339
Sensing & control	214
Other equipment	601
Labor	5,648
Contingency (25%)	5,779
Total	**28,896**

+Color code: scaled from aLIGO; new engineering

PRELIMINARY

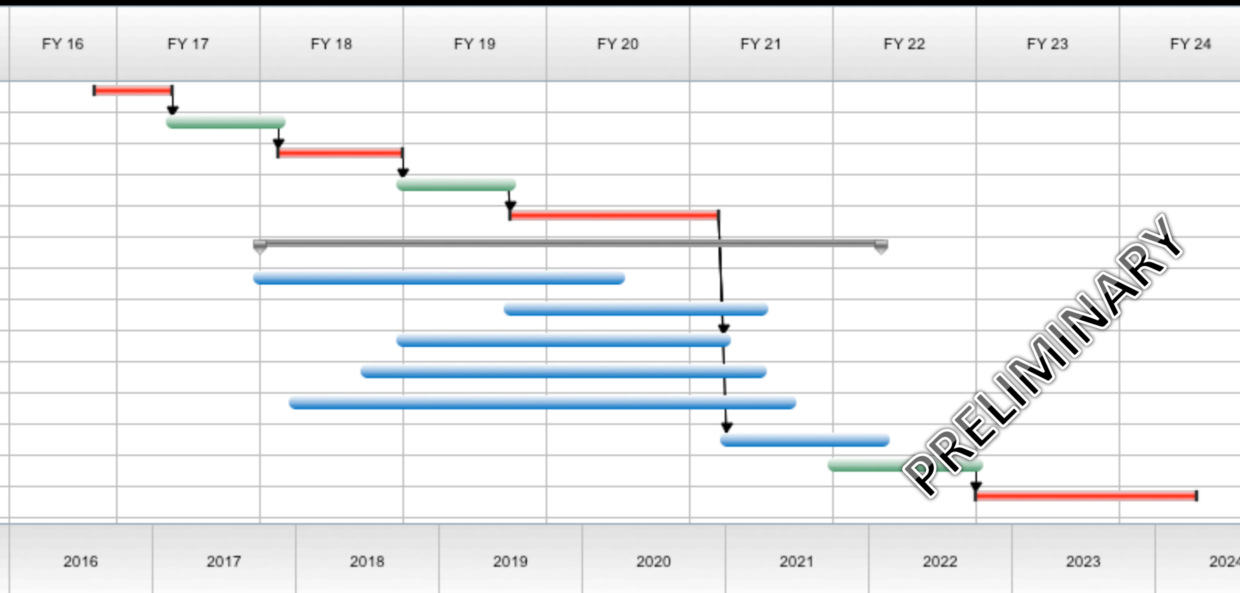
*6/30/2016 rollup; aL labor scaling, no indirect

Challenge: Exceeds nominal NSF Physics Division "Mid-Scale Project" guideline, but well below MREFC threshold

Simplified Schedule*

*FY18 funding start; 5y POP; LIGO-P1200087-v32 observing scenario

Work Package	Duration (Days)	Start Date	Finish Date
O2 OBSERVING RUN	140.00	8/8/16	2/17/17
COMMISSIONING INTERVAL 3	195.00	2/20/17	11/17/17
O3 OBSERVING RUN	225.00	11/20/17	9/28/18
COMMISSIONING INTERVAL 4	195.00	10/1/18	6/28/19
O4 OBSERVING RUN (TBR)	380.00	7/1/19	12/11/20
A+ UPGRADE	1,135.00	10/2/17	2/4/22
Coating Pathfinder	652.00	10/2/17	3/31/20
Core Optic Production	458.00	7/1/19	3/31/21
FC FAC, VAC Systems	586.00	10/1/18	12/28/20
FC SEI, SUS Systems	716.00	7/2/18	3/29/21
FC ISC, BHR Systems	900.00	1/1/18	6/11/21
Installation	285.00	1/4/21	2/4/22
A+ COMMISSIONING	260.00	10/4/21	9/30/22
O5 OBSERVING RUN	400.00	10/3/22	4/12/24



- Under (mostly) conservative assumptions, supports installation start @ 2QFY21
- Installation, commissioning times scaled from 'comparable' aLIGO experience
- Goal: coincidence operation (@improved sensitivity) by end of calendar 2022

Risks and decision points

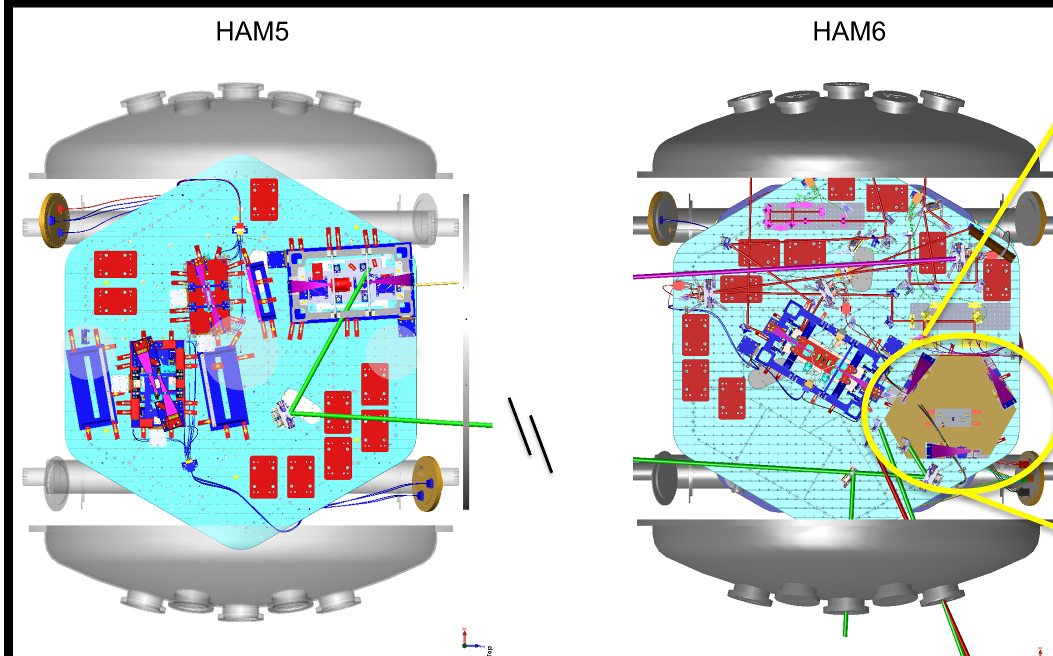
- Low-CTN coating process not ready in time?
  - Can decouple & delay TM replacement
  - Requires 2 installation phases; but intermediate enhanced performance is available for observing, in between
- Problems commissioning new FC and readout?
  - Can quickly and seamlessly revert to baseline aLIGO configuration while problems are diagnosed and resolved
- Unforeseen obstacle to aL design sensitivity?
  - Impact and reaction depends on nature of the problem
  - Precedent shows many such obstacles are mitigated by upgrades, or by opportunities they present (e.g., HEPI, TCS, eLIGO, etc.)
  - Improvements at the cutting edge take time and preparation. We have always needed to anticipate success, or find ourselves unprepared for it.

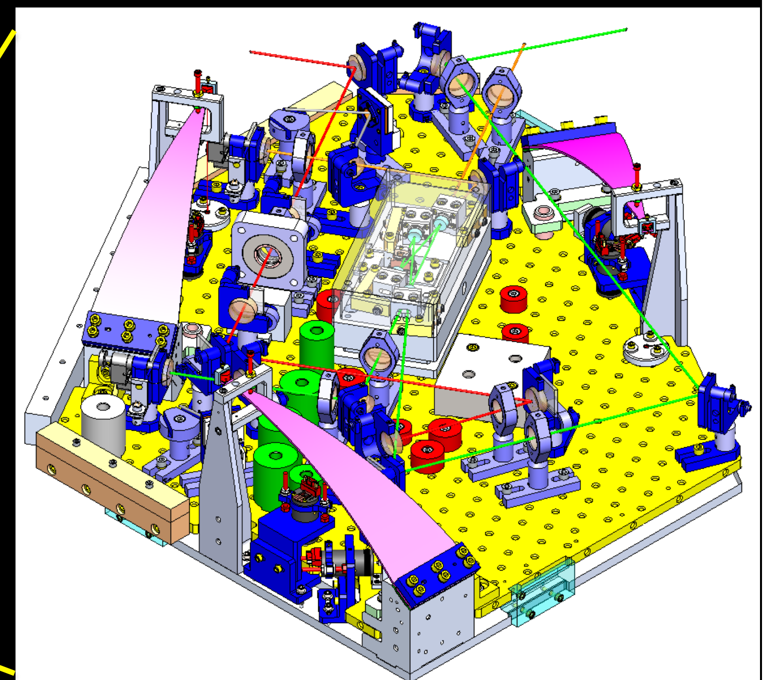
Summary

- Our newborn science will continue to be *sensitivity driven* for the foreseeable future
- Whenever we can devise a clear plan to better sensitivity, it is our duty to look beyond the current horizon
- A+ is such a plan, and now is the time

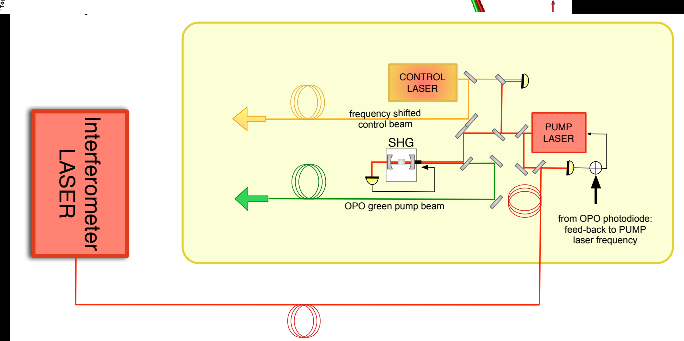
Extra slides

Squeezed light injection*





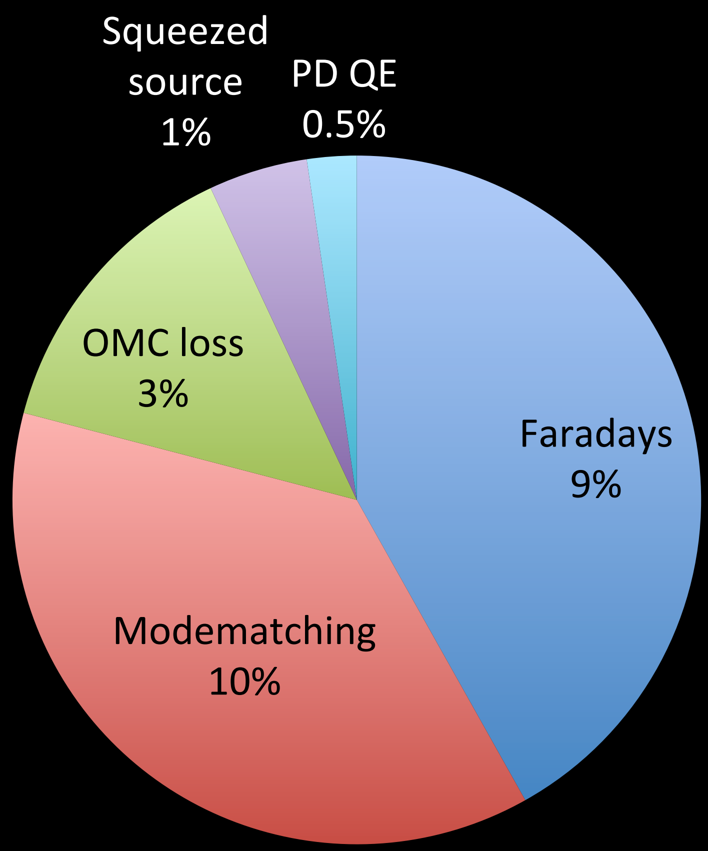
Vacuum Optical Parametric Oscillator (VOPO)



* Not part of A+; this should already be in operation by mid-2019

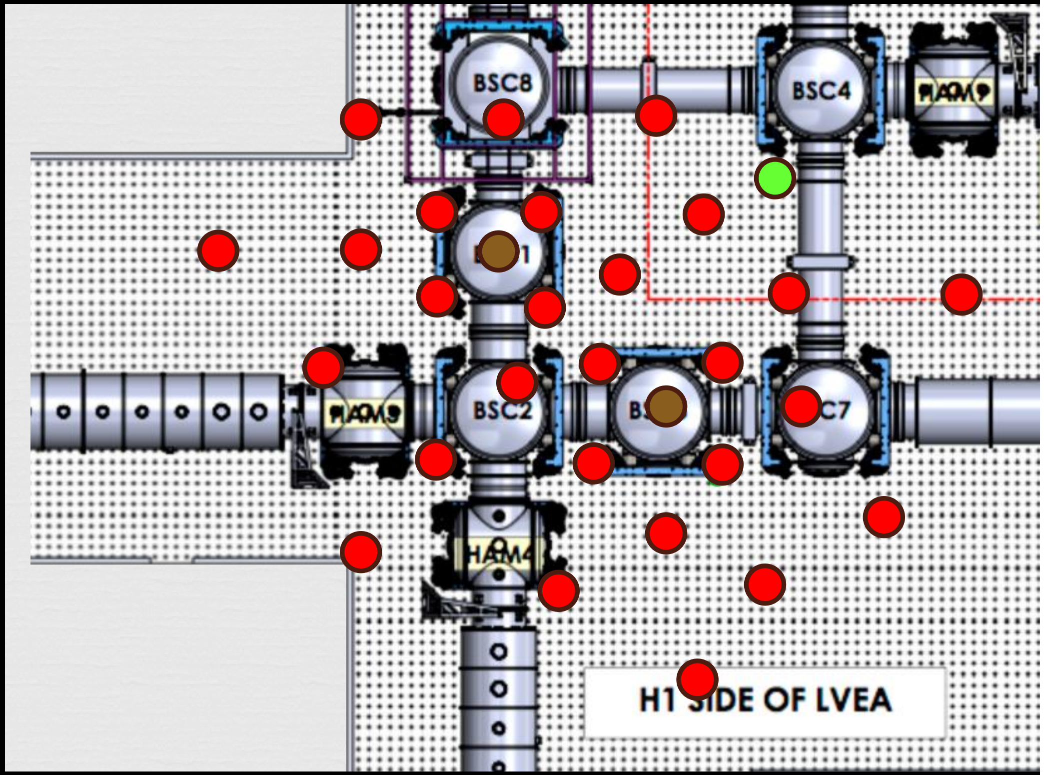
Dark Port Loss Budget

- If we injected squeezing in aLIGO today, we would endure 25% loss from known sources.
- Most can be eliminated by installing better optical components that are now available, plus adaptive mode matching techniques we're developing in the lab.



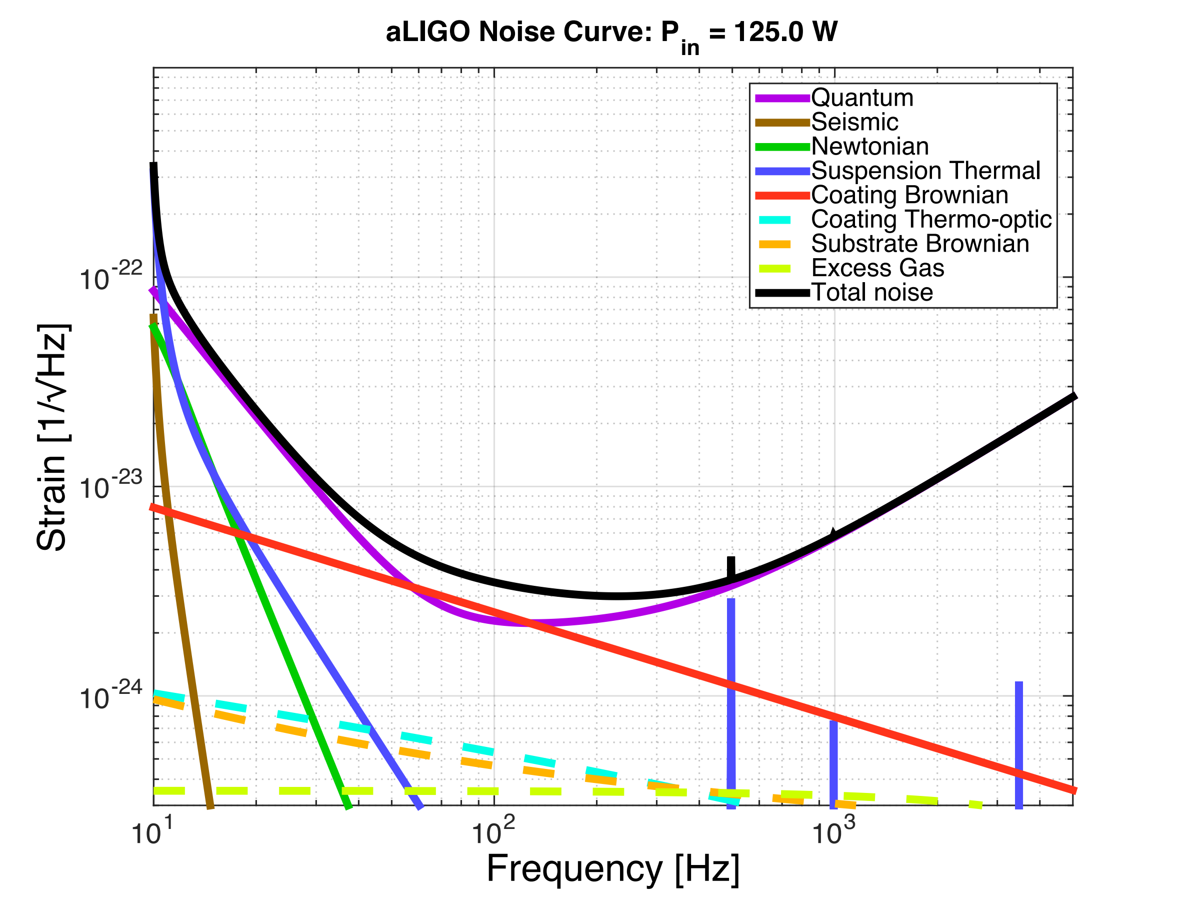
Added Opportunity: Newtonian Gravity Gradient Noise Cancellation

- Local density gradients may limit A+ during high seismicity, and will routinely affect 3rd generation successors
- Can be mitigated by modeling & subtracting local gravity fluctuations
- Prototype array now in preparation at LHO



(LIGO-P1600146)

aLIGO operating at full power



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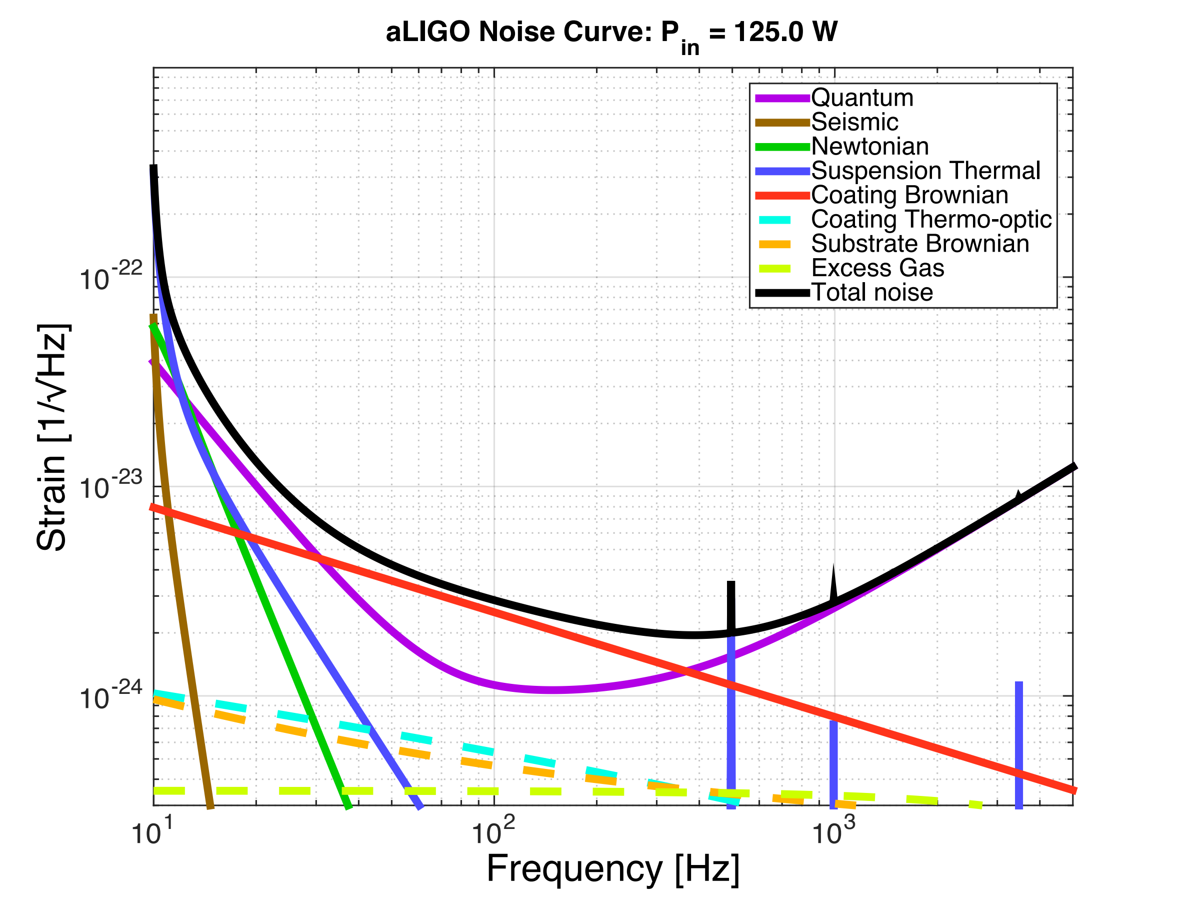
..plus squeezing with ~100m scale filter cavity



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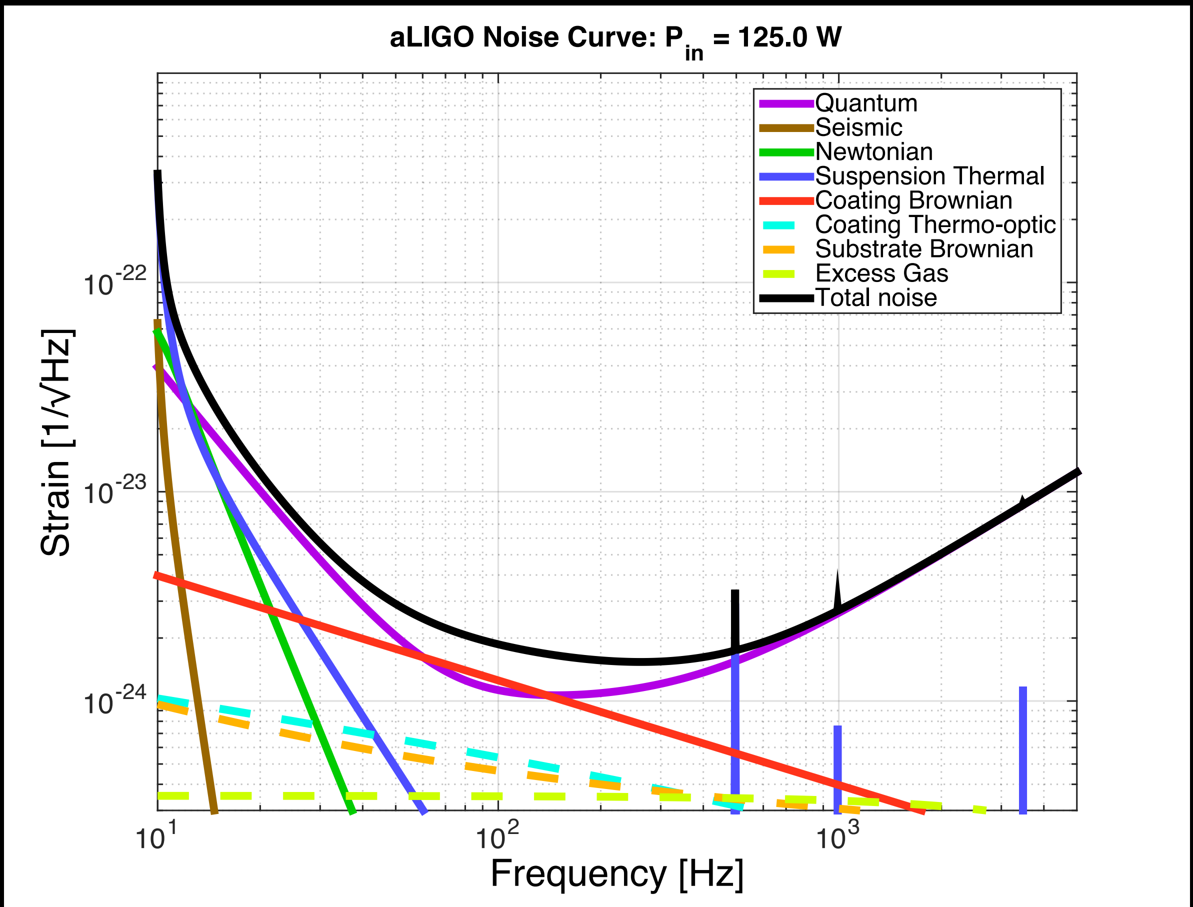
BNS range: 258.72 Mpc (comoving)
BNS horizon: 592.49 Mpc (comoving)
BNS reach: 370.29 Mpc (comoving)
BBH range: 1.74 Gpc (comoving, z = 0.4)
BBH horizon: 4.14 Gpc (comoving, z = 1.3)
BBH reach: 2.77 Gpc (comoving, z = 0.8)
Stochastic Omega: 9.32e-10

..plus coating thermal noise reduction



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BNS horizon:	814.04 Mpc (comoving)
BNS reach:	510.28 Mpc (comoving)
BBH range:	2.24 Gpc (comoving, z = 0.6)
BBH horizon:	5395.58 Mpc (comoving, z = 2.1)
BBH reach:	3700.64 Mpc (comoving, z = 1.1)
Stochastic Omega:	6.78e-10