Can you get there from here?

Thinking about paths from AdV+/A+ to 3 G

D. McClelland, M. Zucker

Dawn IV

30-31 August 2018

LIGO-G1801680

Outline

- Perspective on A+
  - *Can someone offer symmetrical view for AdV+? Sorry, was planning to do more homework.*
- Constraints: real vs. imagined
- “Baby steps” vs. “Giant Leaps”
- Some ideas

A+ ‘elevator pitch’

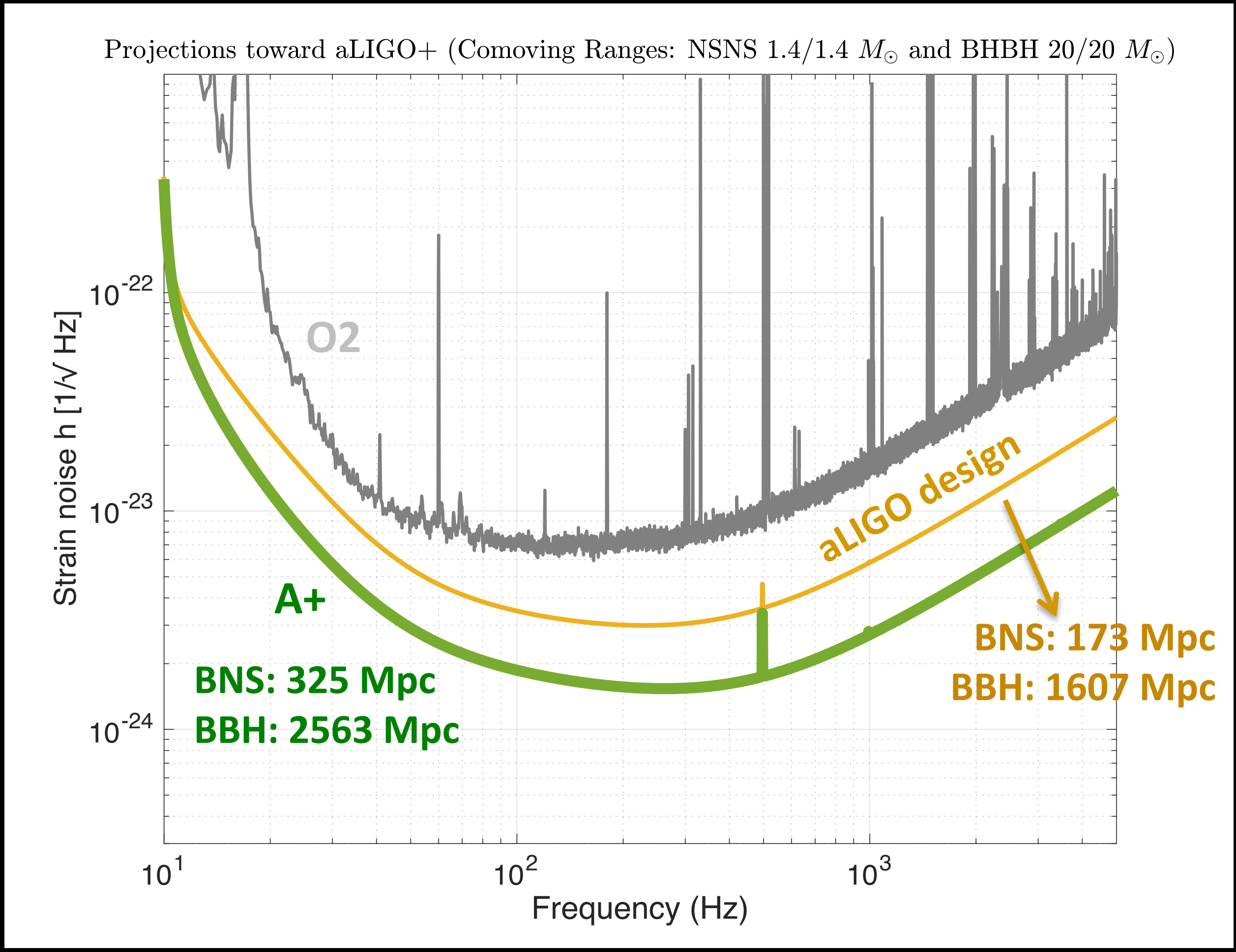
(we’ll come back to this later)

- 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 4-7 greater CBC event rate
- Bridge to future 3G GW astrophysics, cosmology, and nuclear physics
- Stepping stone to 3G detector technology
- Can be observing within 6 years (mid- 2024)
- “Scientific breakeven” within 1/2 year of operation
- Incremental cost: *a small increment on aLIGO*
- *Joint international effort: ~ 35% UK and Australia funding*

*BBH 30/30 $M_{\odot}$: 1.6x
*BNS 1.4/1.4 $M_{\odot}$: 1.9x

A+: a mid-scale upgrade to Advanced LIGO

- Reduced quantum noise
  - Improved optical losses
  - Improved readout
  - Frequency-Dependent Squeezing
- Reduced thermal noise
  - Improved mirror coatings
- Observing by mid-2024



Selected A+ Discovery Targets

Based on P170608 and P170817 rate density estimates:

BBH rate 4.1x aLIGO → ***17-300 BBH/month***

Off-axis observations → *BH component spins*

BH Spins → *Origins of stellar-mass BH*

Z_{max} ~ 1.5 → *BBH cosmological evolution*

SNR ~ 100 → *Ultra-precision tests of GR*

BNS rate 6.7x aLIGO → ***1-13 BNS/month***

*(2-11 BNS x SGRB coincidences/year)**

Multimessenger coincidences → *precision H_0 measurement, kilonovae, etc.*

High inspiral SNR → *BNS tidal deformation*

BNS remnant "ringdown" → *NS matter equation of state*

**(or more, if GW170817 represents hidden sub-threshold SGRB population)*

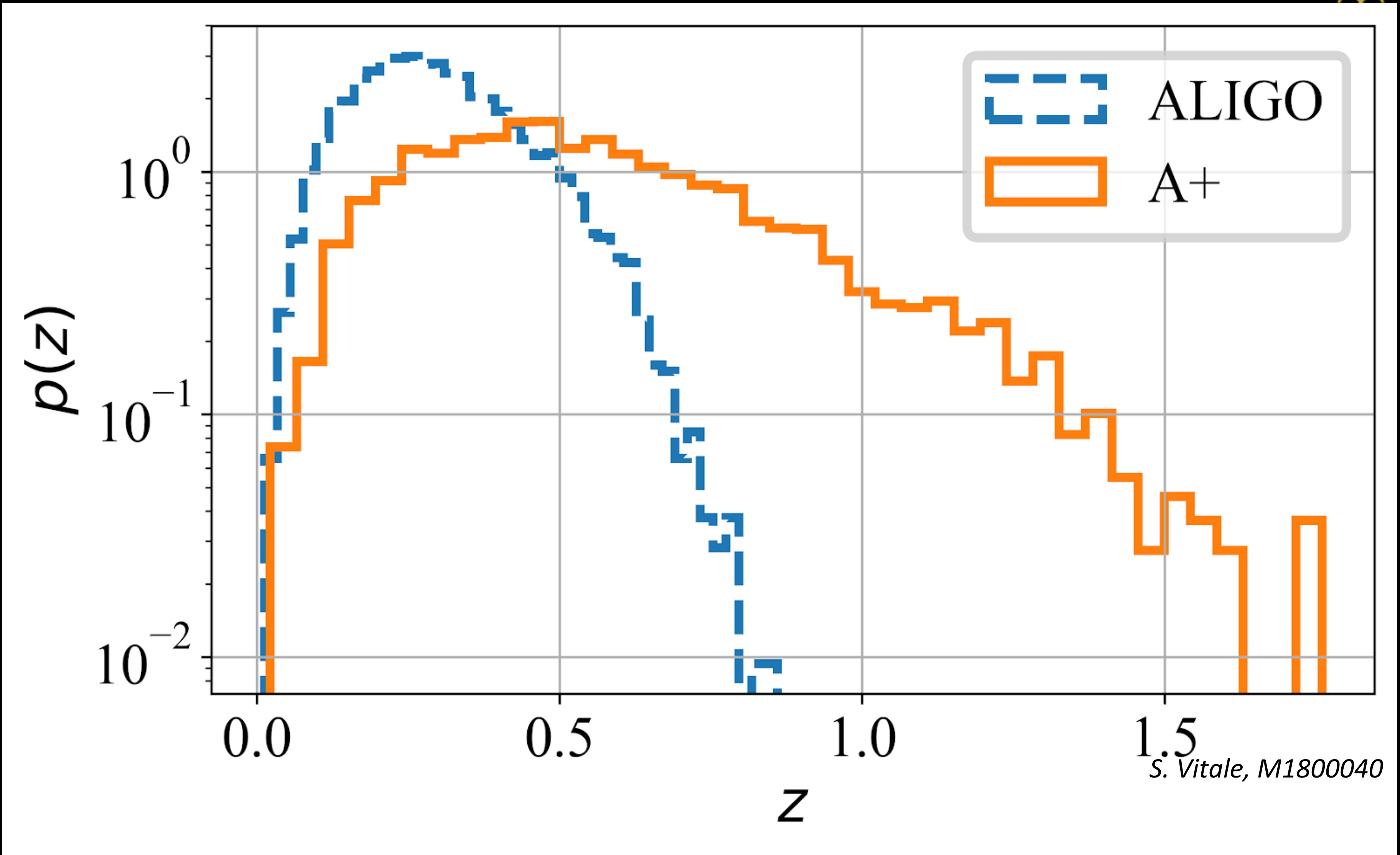


Figure 7: Redshift distribution of binary black hole sources detectable with SNR > 10 in a single A+ detector, as compared to baseline aLIGO at design sensitivity.

BNS post-merger "ringing" vs. NS EOS

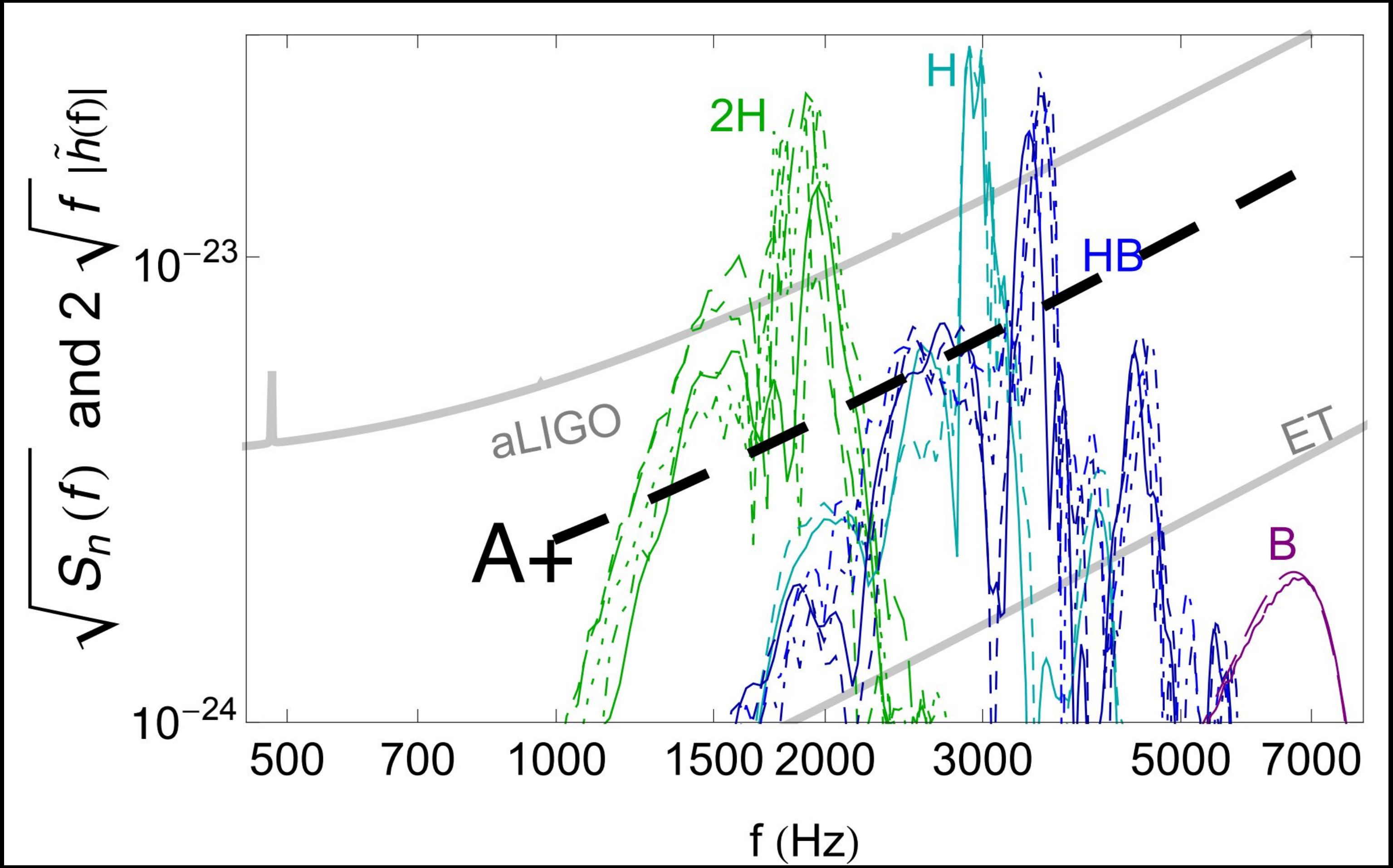


Figure 6: BNS post-merger signal models vs. aLIGO and A+ detector noise for a range of speculated neutron-star equations of state (labeled 2H - B). A+ will have significantly improved capacity to detect post-merger "ringing" modes, whose characteristic frequencies are determined by the equation of state of super-nuclear matter. The low-frequency inspiral waveform component, which can also bear signatures of tidal deformability in the progenitor stars, is not shown. Simulations presume a reference BNS coalescence at 100 Mpc. (courtesy J. Veitch and S. Vitale, adapted from Read et al. [31])

A+ Upgrade Status

- NSF awarded US funds, 18 months earlier than original request
  - Same end date (4QFY2023, limited by COC coatings) but *much faster start*
  - Acceleration may allow facility and vacuum upgrades between O3 and O4
  - Retires risk, may well accelerate commissioning and O5 (no promises!)
  - LIGO Lab team has formed and mobilized; formal start in 1 month, 10/1/2018
- Australian ARC funding has already been awarded
- Companion UK proposal is now under UKRI/STFC review
  - We are cautiously optimistic for a similar accelerated UK start
  - This would relieve schedule pressure on core optics polishing (sequential fabrication) and suspension design pipelines

Big picture: we expect LIGO will be observing with A+ sensitivity by late 2024

A+ ~~elevator pitch~~ *constraints*

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Look at all the constraints:

- "Your next investment should…
  - …be incremental in cost
  - …minimize loss of observing for existing instruments
  - …provide immediate scientific return
    - e.g., improved *rate**time* integral should 'quickly' wipe out observing hiatus due to upgrade
  - …build upon and fully exploit *prior* investment
    - "we already invested 10^9 $/€/£…"
  - …simultaneously support *following* investments, e.g.,
    - test technology for "(n+1)G"
    - probe future astro source landscape

…all the constraints (2):

- All good and wholesome, but taken together, recipe for a *holding pattern*
- Nothing big happens that way
  – (certainly not Initial or Advanced LIGO)
- Which constraints to challenge here?
  – (really asking, I don't know).

Are there other constraints we *should be* considering?

- For example:
  - We naturally fret about seismic, quantum and thermal noise
  - Our reviewers (perhaps the more influential ones?) may fret about 15% cost growth in steel, earthmoving, or concrete
    - Even "routine" roads and tunnels see 100% overruns
  - Are we investing responsibly to bound and manage large, "conventional" risks, or are we only looking after the novel "interesting" ones?

Suggestion: diversify

- Increments like A+, AdV+ and Voyager are necessary, but too overconstrained to put us in the strike zone
- Always the possibility of a visionary patron and a leap of faith; hope for this, but can't plan on it
- *3G technology demonstration* investments can retire investment risks
  - Without interfering with 2/2.1/2.5G observations
  - Without forcing 'profitable' integration on an existing (obsolete) instrument
- LIGO and Virgo invested millions and decades to pre-qualify
  - beamtube construction;
  - phase noise at the MIT 5m;
  - displacement noise at the CIT 40m;
  - optic polishing, metrology & coating pathfinders;
  - etc.
- What are the analogs for 3G?

Possible "Large-scale" 3G technology demonstration investments

- 3G Value-Engineered Beamtube Demo
  - LIGO is planning a water vapor desorption test on a spare 7m tube section at LLO
  - NSF just funded a LIGO workshop for early '19 on Very Large Scale Vacuum Systems
  - What about a 500m scale 3G beamtube fabrication and degassing test?
- 3G Tunnel/Earthwork Demonstration
- 3G Very Large Optic Polishing & Coating Pathfinder
- ...?...(ideas welcome)

Discussion points

- Nobody wants to wait
- Nobody wants to invest 10-100M $/€/£ in engineering demo projects that don't detect GW's

BUT

- Moving directly to full scale design without some proofs of concept may meet resistance
- We can't demonstrate all of what we need on H1/L1/V1/K1/I1
- We probably need to break *all* the risky problems (not just the interferometry) into pieces and show what we can do in each domain separately.
- We hope that increments like A+, AdV+, and Voyager will buy us time and let us hold our place at the forefront of modern astrophysics


LIGO
NSF
THANKS
(and sincere apologies from MZ)
Caltech
LSC

Spare Slides

A+ WBS & foreign effort

- UK ISC
  - BHD readout
- UK COC
  - Large beamsplitter
  - COC substrates, polish, coatings
- UK SUS
  - BOSEMs
  - BHD SUS
  - Large BS SUS
- UK CDS
  - Coil drivers (partial)
- AUS ISC
  - SQZ optics (partial)
  - Adaptive mode match (partial)

Code	Title	Description	US	UK	AUS
1. PM	Project Management	Resource management, safety, budget, scheduling, earned value reporting, contingency allocation, procurement, travel	✔	✔	✔
2. SYS	Systems Engineering	System integration, interface control, standards compliance, integrated layout and ray tracing, stray light control, installation tooling, installation and test coordination, quality assurance	✔	✔	✔
3. VAC	Vacuum System Modifications	Decommissioning, rearrangement and recycling of legacy H2 vacuum chambers; creation/adaptation of new 300m auxiliary beamtube, vessels and support systems to house FDS filter cavity at each site.	✔		
4. FAC	Facility Modifications	Alterations to corner stations and creation of new FC beamtube enclosures and end station laboratory structures at each site; support for interferometer subsystem installation	✔		
5. CDS	Control and Data Systems	Electronic modules, sensors, cabling, feedthroughs and software to support control and operation of ISC, SUS and SEI components	✔	✔	
6. COC	Core Optic Components	Filter cavity mirrors, enlarged main beamsplitters, and input and end test masses bearing reduced-dissipation reflective coatings.	✔	✔	
7. SUS	Suspensions	Isolated suspensions for beamsplitters, filter cavity mirrors, readout components, and beam relays; improved suspension fiber infrastructure and tooling for core optics installation	✔	✔	
8. SEI	Seismic Isolation	Active single-stage seismic isolation platforms for filter cavity end mirrors	✔		
9. ISC	Interferometric Sensing and Control	Balanced homodyne antisymmetric port readout, adaptive mode matching, high-efficiency optical isolators, squeezed light injection adaptation, and frequency-dependent squeezing filter cavity control.	✔	✔	✔

Table 1: Project work breakdown structure (WBS) and definitions, denoting areas of US, UK and Australian participation.

A+ Proposal Team

- LCCL- Zucker
  - Science targets- Vitale
- Lead Engineer- Billingsley
- Project Manager- Hansen
  - Schedule & resources- Toon
- Subsystem Leads:
  - Systems- Torrie
  - Core Optics- Billingsley
  - Seismic- Mason
  - Suspensions- Robertson
  - Facilities- Oram
  - Vacuum- Romel
  - CDS- Abbott
  - ISC- Barsotti
- UK
  - Lead- Strain
  - Science Case- J. Veitch
  - ISC (BHD)- Hild
  - SUS- O'Dell
  - COC- Hammond
- Australia
  - Lead- McClelland
  - ISC- McClelland, P. Veitch

(CIT and MIT departments covered US proposal prep costs ☺)

A+ NSF Proposal Review: Panel Summary

"Over the last several years LIGO has made tremendous discoveries which have inspired people around the world and demonstrated the value of gravitational-wave observation as a new tool for astronomy. The proposed effort promises to make a major advance in that effort for even better science. The proposed technical improvements take careful aim at the dominant noise sources remaining at the aLIGO design sensitivity, with a very carefully thought through approach, deploying cutting-edge technological innovations with careful thought to mitigating risks of delay and/or lost science opportunity. While some minor concerns are described in the section notes these are far outweighed by the overwhelming strengths of the proposal. The panel strongly recommends funding the proposed upgrade."

A+ parameters vs. aLIGO

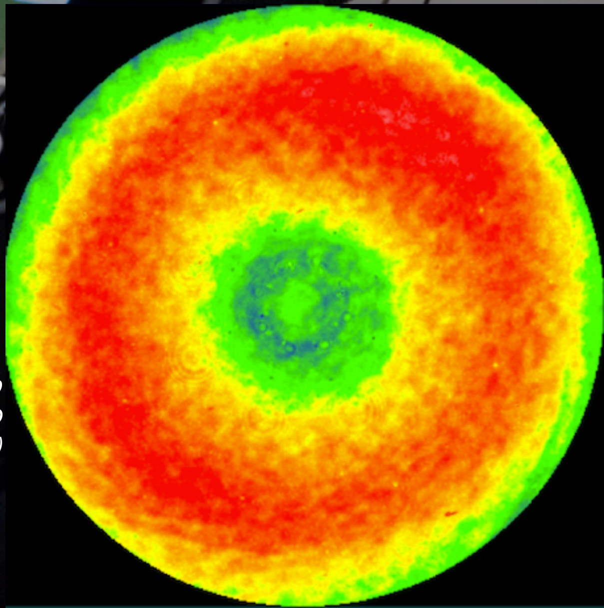
Parameter	aLIGO	A+	units	comment
input power	125	125	W	
arm power	750	750	kW	
coating loss angle	360	90	μrad	elastic loss
FC length	-	300	m	
FC finesse	-	446	-	
injected squeezing	0-3	12	dB	
BNS range	173	325	Mpc	1.4/1.4 $M_\odot$
BBH range	1610	2560	Mpc	30/30 $M_\odot$

Table 1: Key A+ design parameters and performance metrics, compared with the aLIGO baseline.

Improved Mirror Coatings for A+

400mm LIGO Fizeau interferometer at CIT

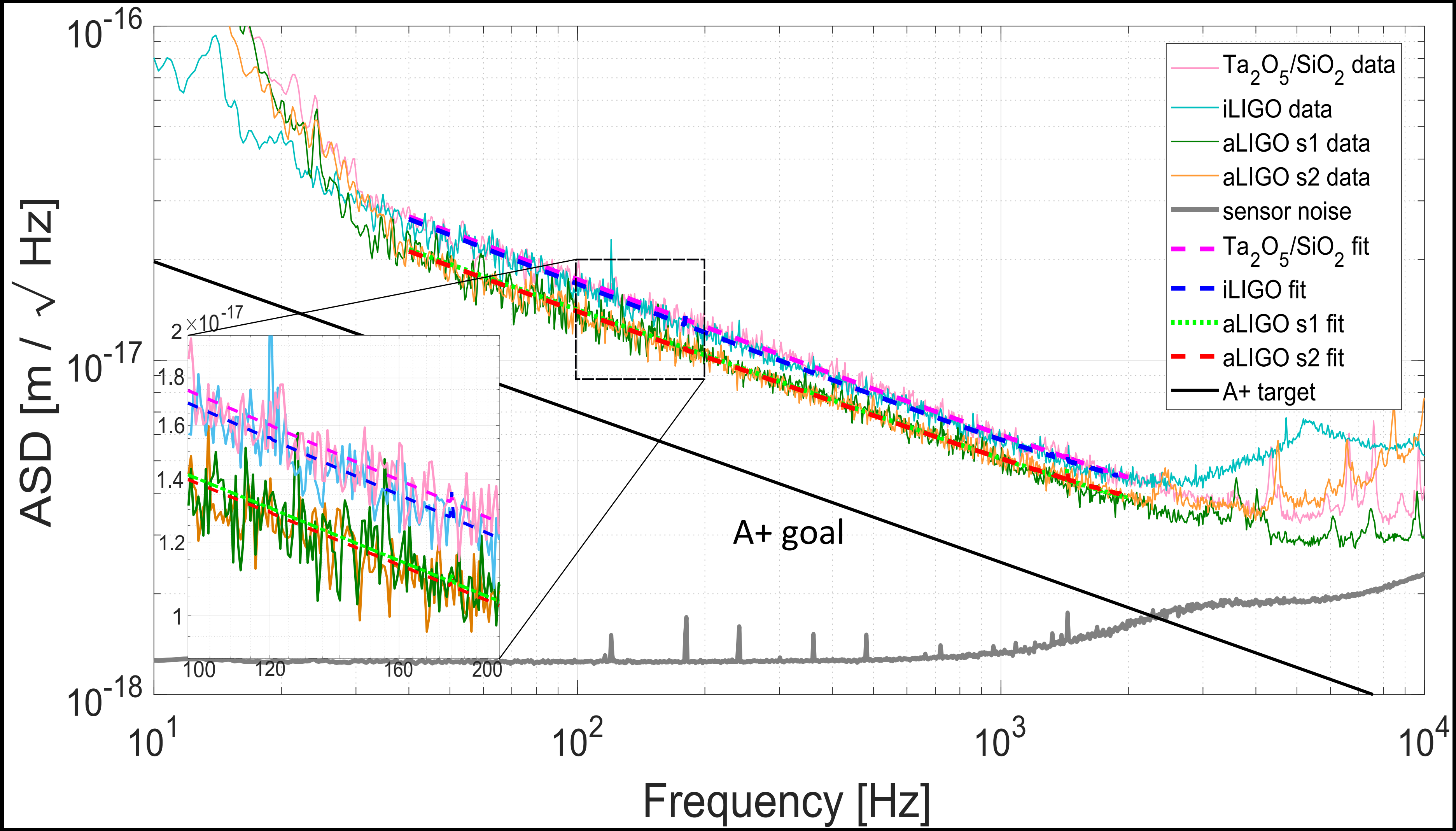
- TARGET: Elastic loss angle $\phi < 9 \times 10^{-5}$
  - (aLIGO $\phi = 3.6 \times 10^{-4}$)
- Current R&D on small samples
- UK, Europe and US Center for Coatings Research initiative to select best low-loss coating design in about 2 years
- A+ Coating Pathfinder program will spin up industrial vendor(s) and qualify full-aperture coatings for production
- In parallel, new and existing spare aLIGO optics will be polished
- Metrology, QA, lab infrastructure, tooling, procedures all same as aLIGO & reused
- Replacement core optics delivered for final phase of A+ installation (mid-FY23)



aLIGO ETM figure map
6.5 $Å_{RMS}$ over central 160 mm Φ
(LIGO Lab/G. Billingsley)

A+ Coatings

Gras & Evans, P1700448



Quantum Noise Reduction for A+: Frequency-Dependent Squeezing

- Expect *squeezed light injection* to be operating soon
- Effective substitute or assist for high laser power
  - Phase squeezing at HF causes amplitude anti-squeezing (radiation pressure) at LF
  - Added radiation pressure bothersome as other LF noise is improved
- Solution: Frequency-dependent squeezing (FDS)
  - NOTE: FDS is also key for planned future detectors (Voyager, ET, CE, etc.)

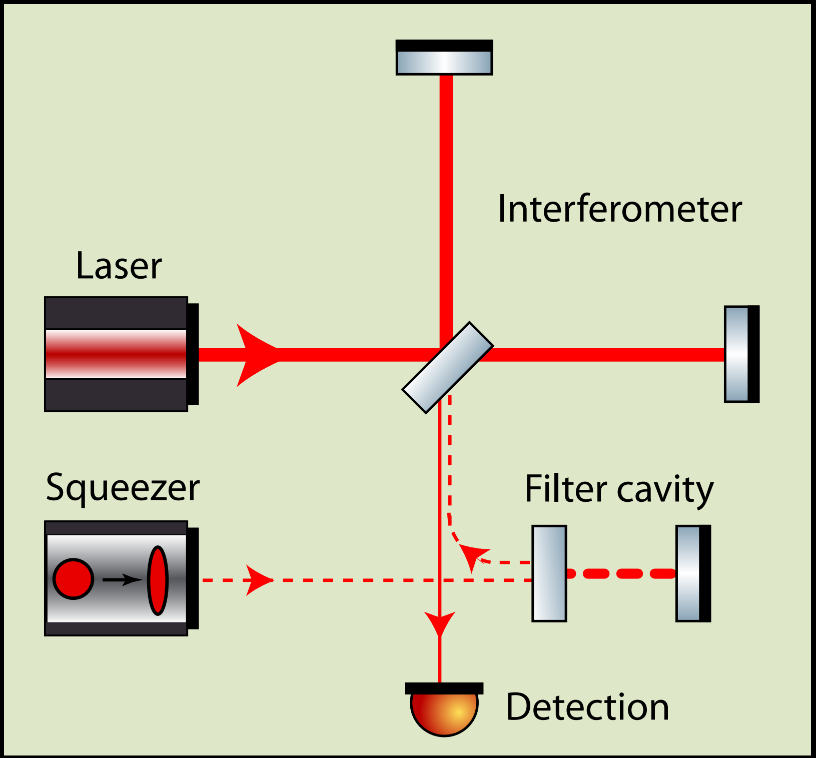
Frequency-Dependent Squeezing

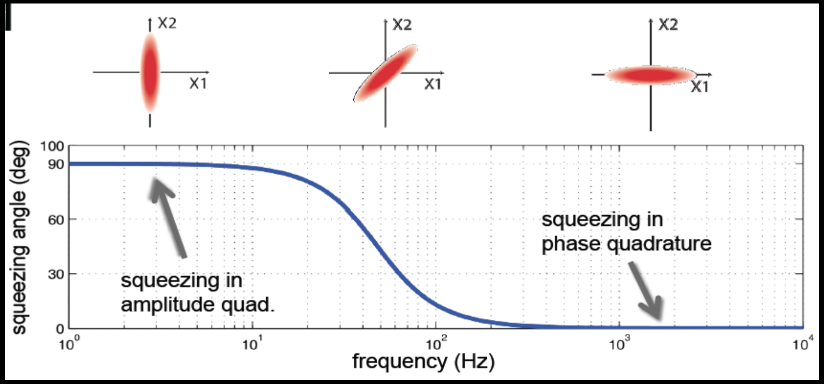
- Optical “filter cavity” (FC)
- Rotates squeezing phase to both improve radiation pressure at LF *and* phase noise at HF
- Low-loss, high finesse cavity with bandwidth ~100 Hz
- Sensitive to optical losses, scattering and mirror motion

➔ Requires *seismic isolation and quiet mirror suspension*

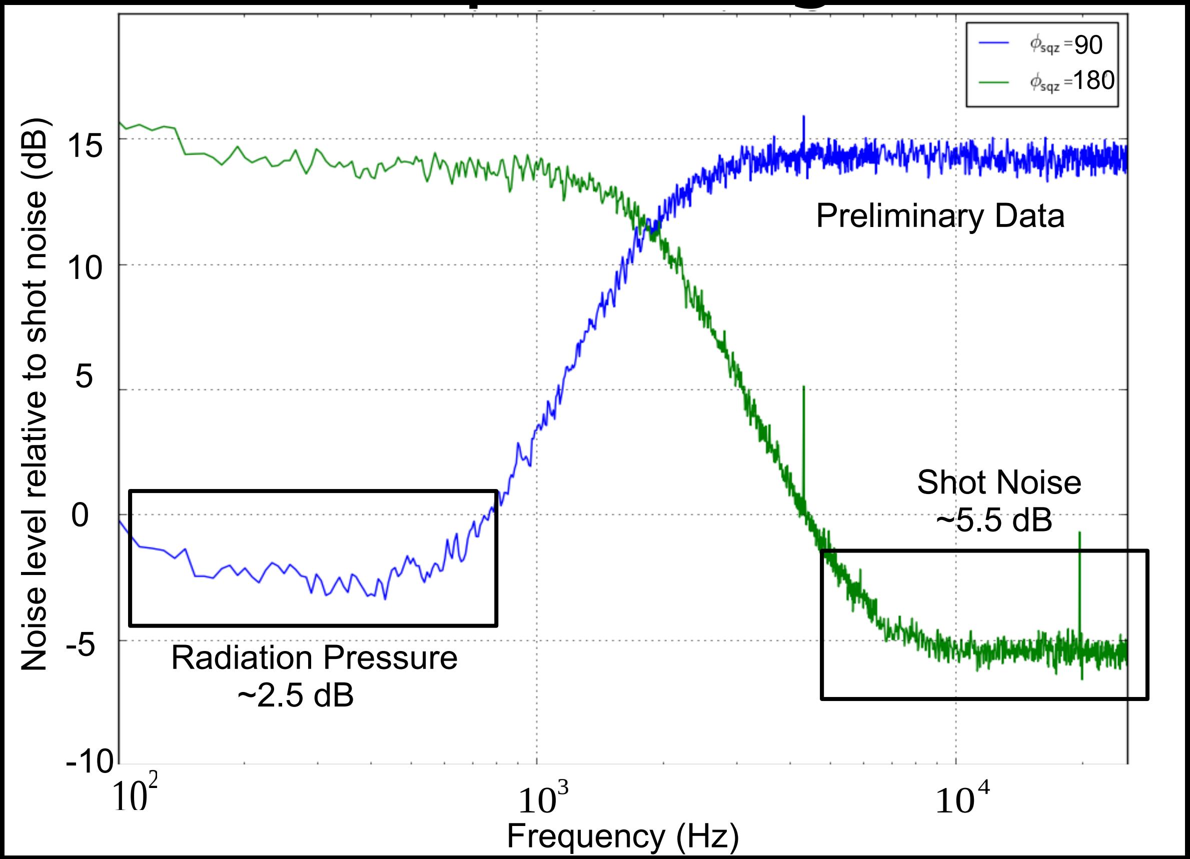
➔ Requires *high-quality FC mirrors*

➔ Requires L_{FC} ~ 300 m





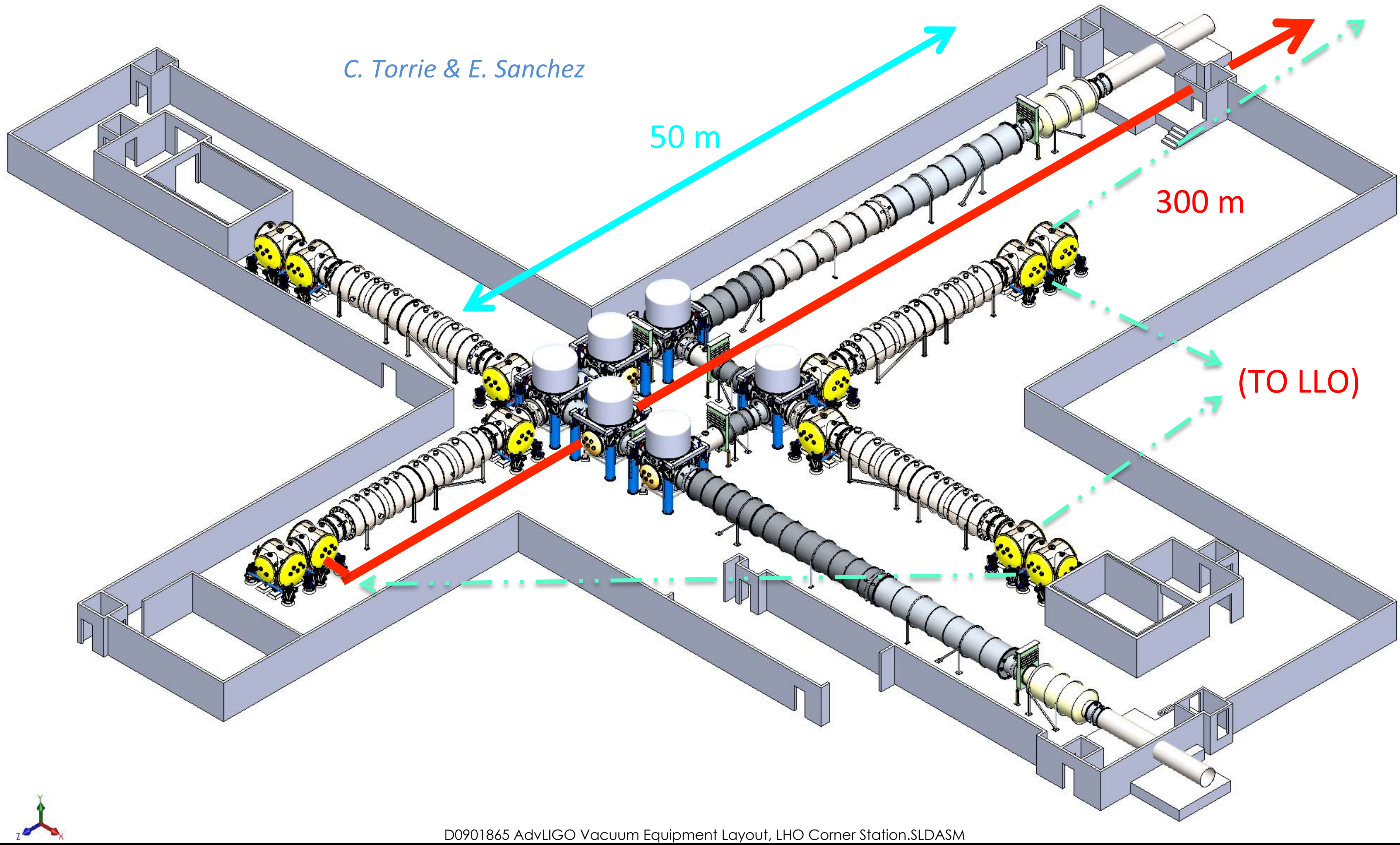
FDS demonstration w/ 2m filter cavity



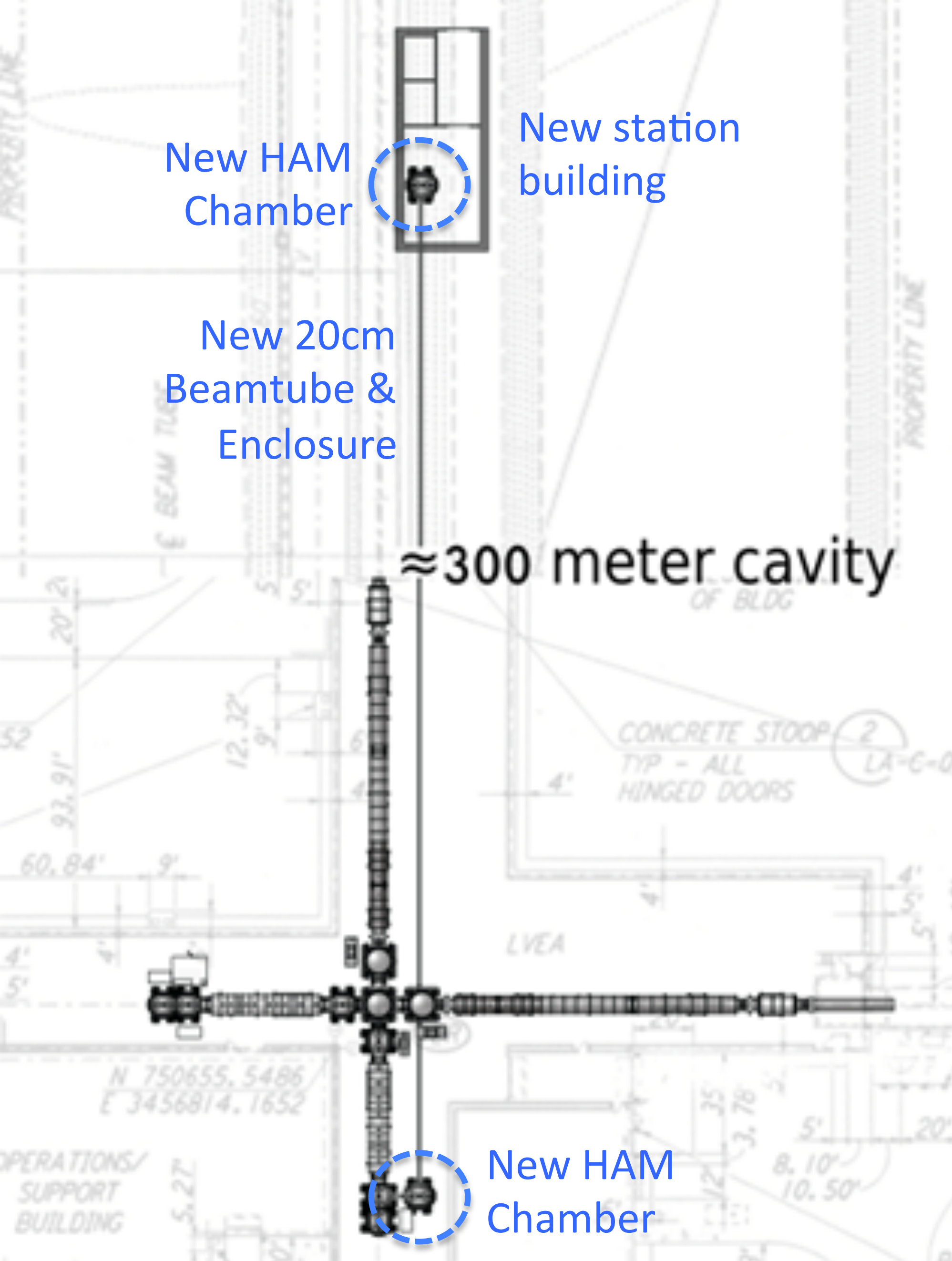
Oelker et al, LIGO-P1500062

LIGO demonstration of audio-band frequency dependent squeezing
(A+ Proposal figure 3)

Filter cavity vacuum system and facility modifications



A+ FILTER CAVITY BEAMLINE

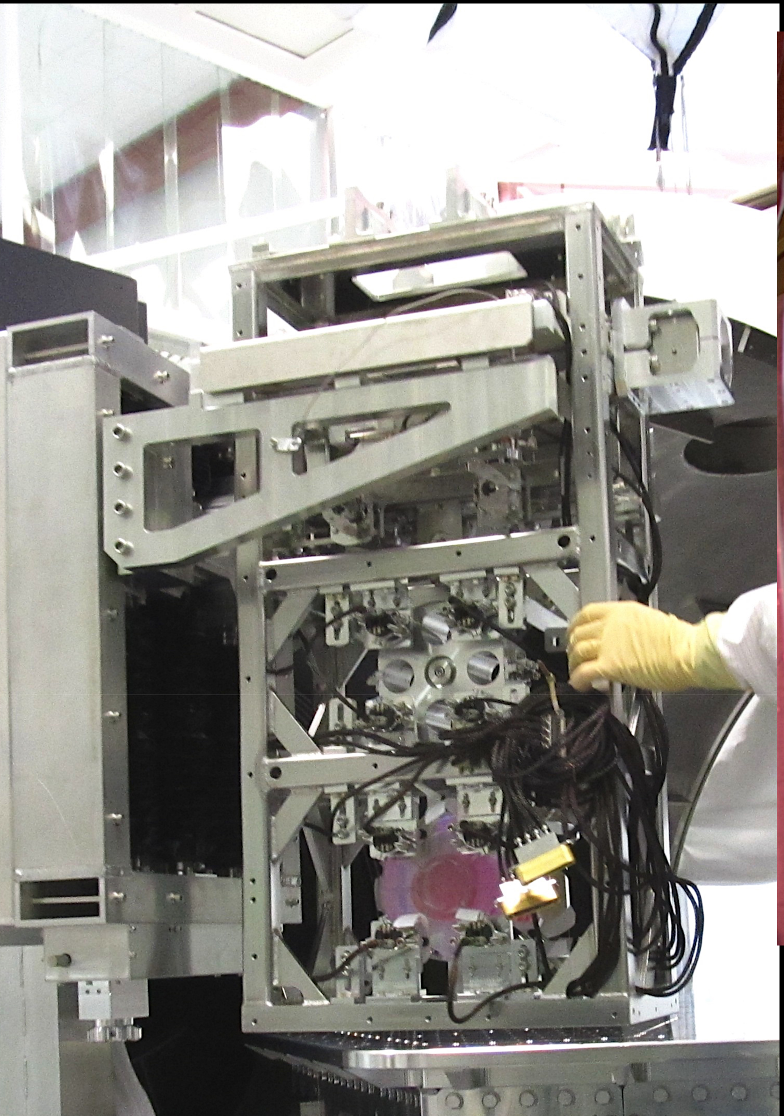


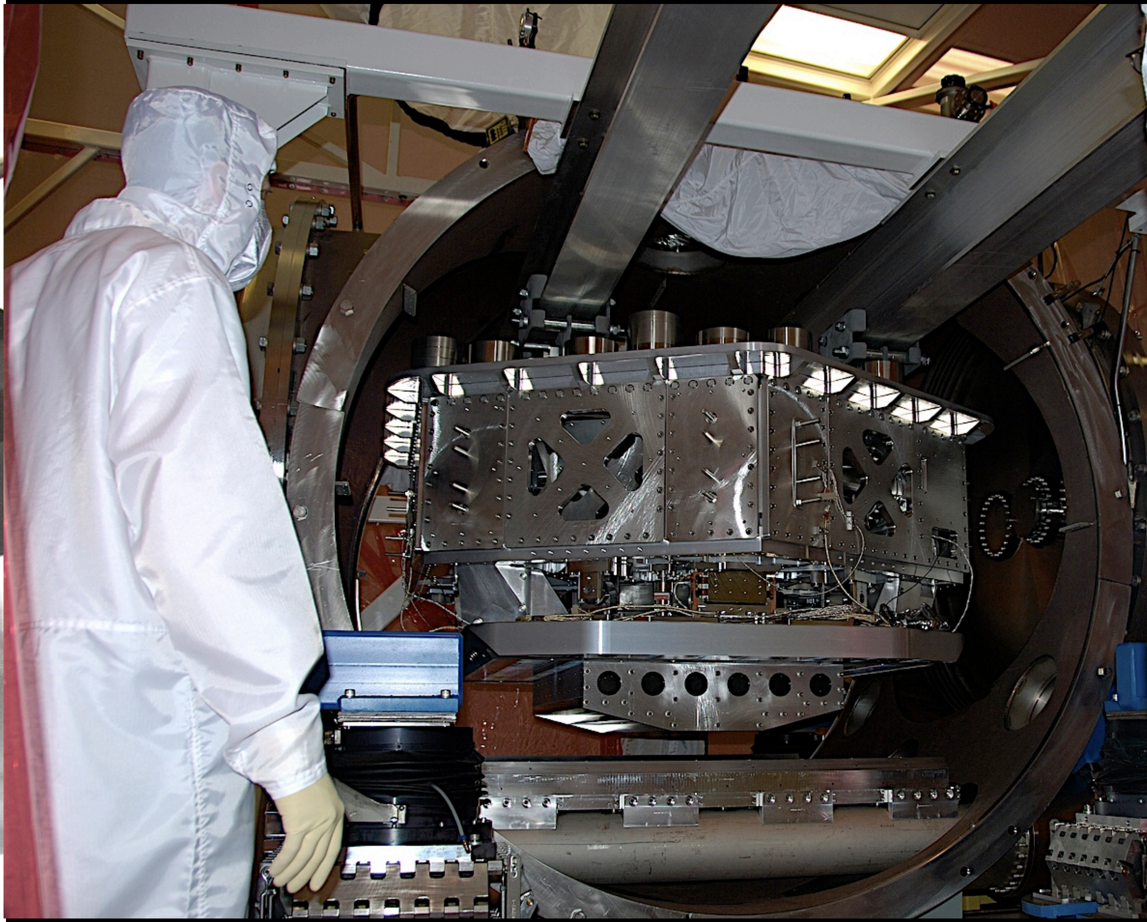
C. Torrie, E. Sanchez , G. Billingsley
M1800040

View from future LLO FC end station back to corner

A+ filter cavity: mirror suspension & seismic isolation

aLIGO HAM Small Triple Suspension (HSTS)

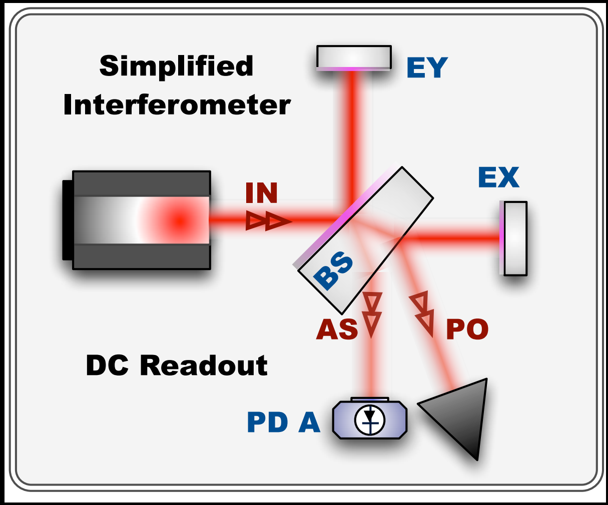


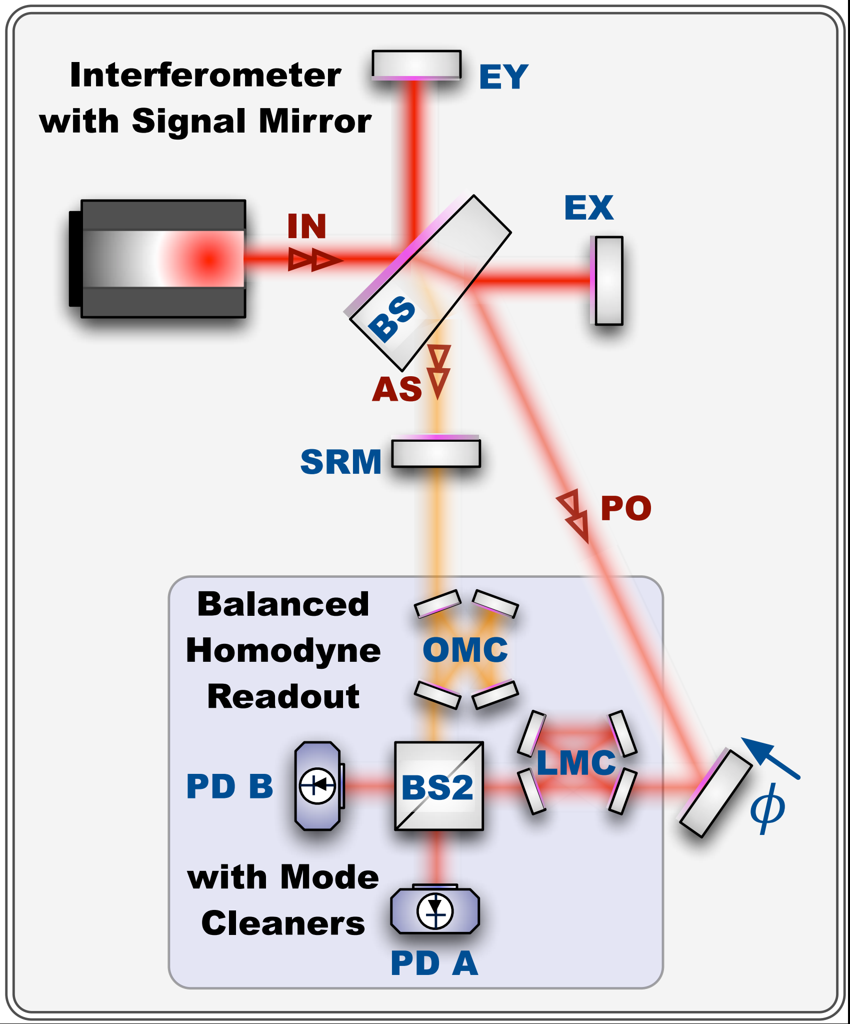


aLIGO HAM Internal Seismic Isolator (HAM-ISI)

Balanced Homodyne Readout (UK)

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

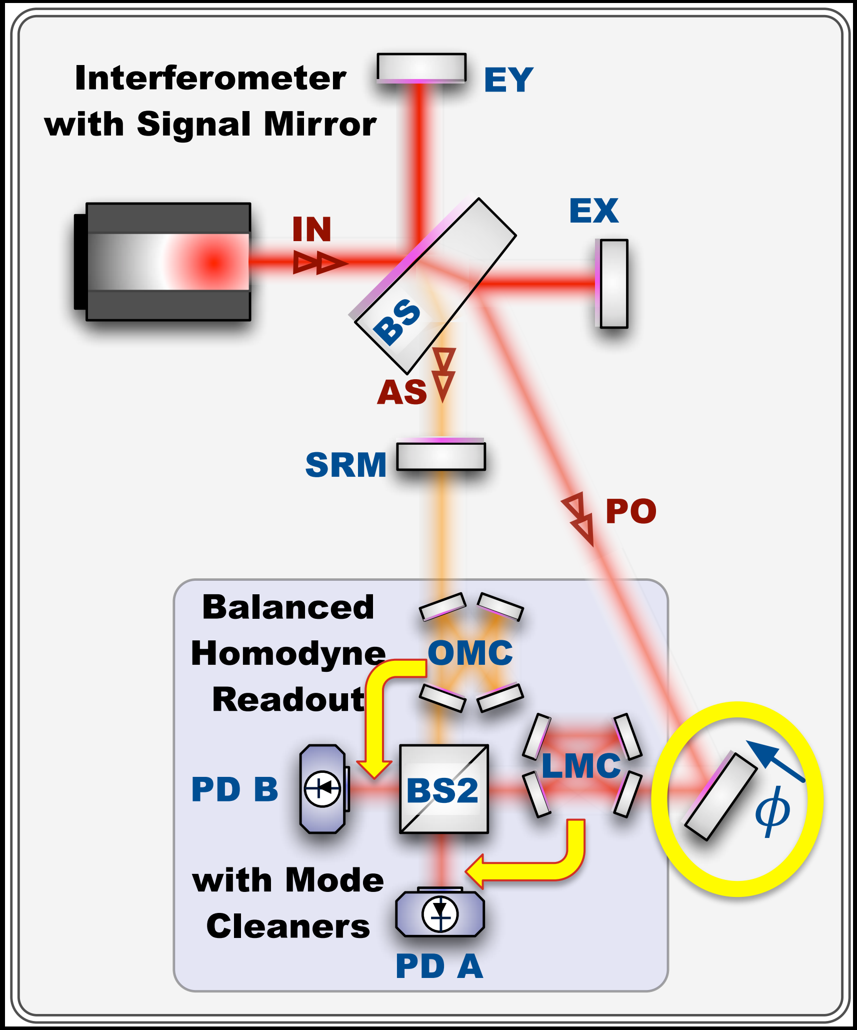




LIGO-P1300184

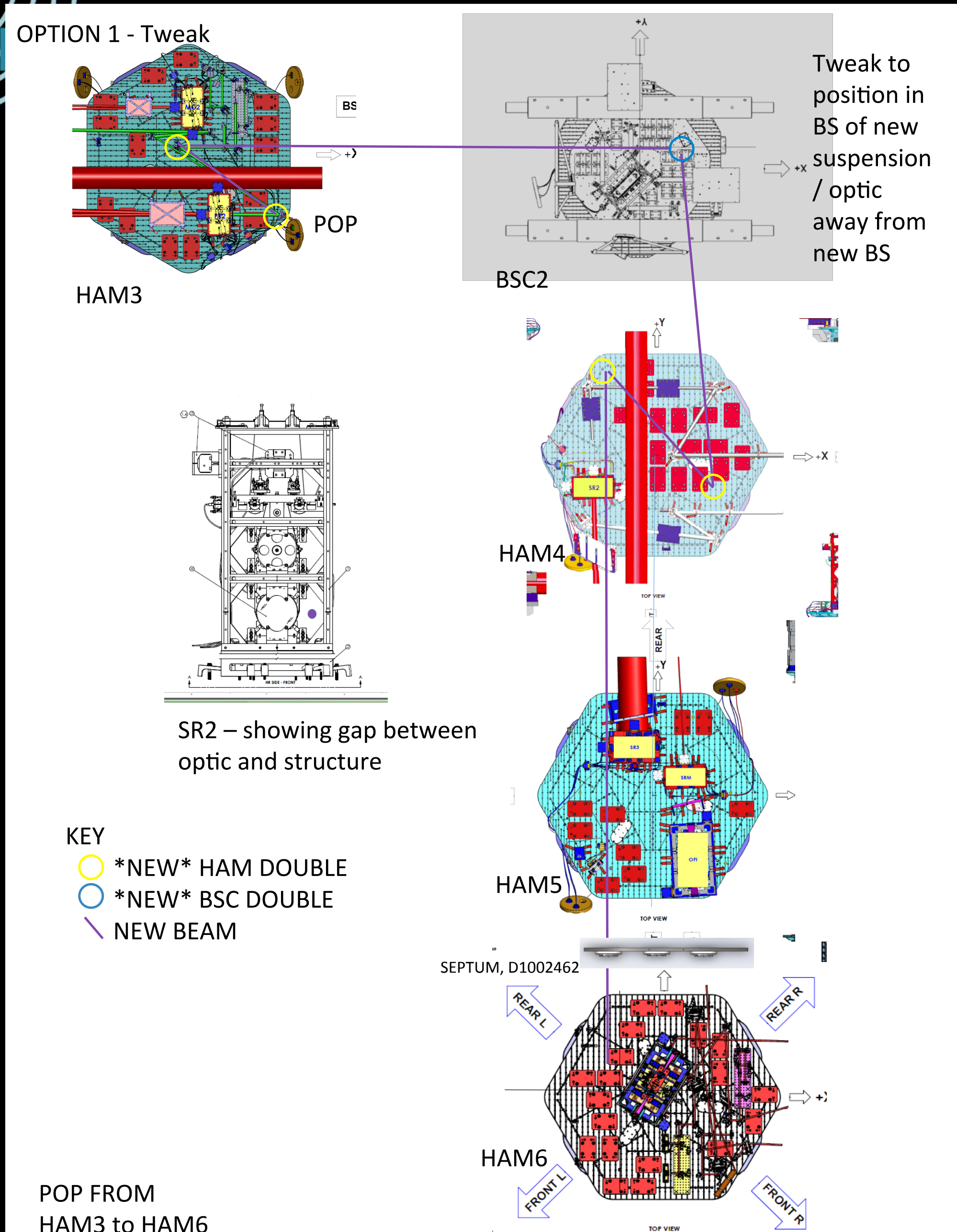
Balanced homodyne readout

- Revised: LO DIFFERENTIAL PHASE NOISE IS CRITICAL!
- Need low-noise beam relay mirrors
- OMC's now after LO/AS interference



LIGO-P1300184

A+ BHR
LO beam relay
(work in progress)

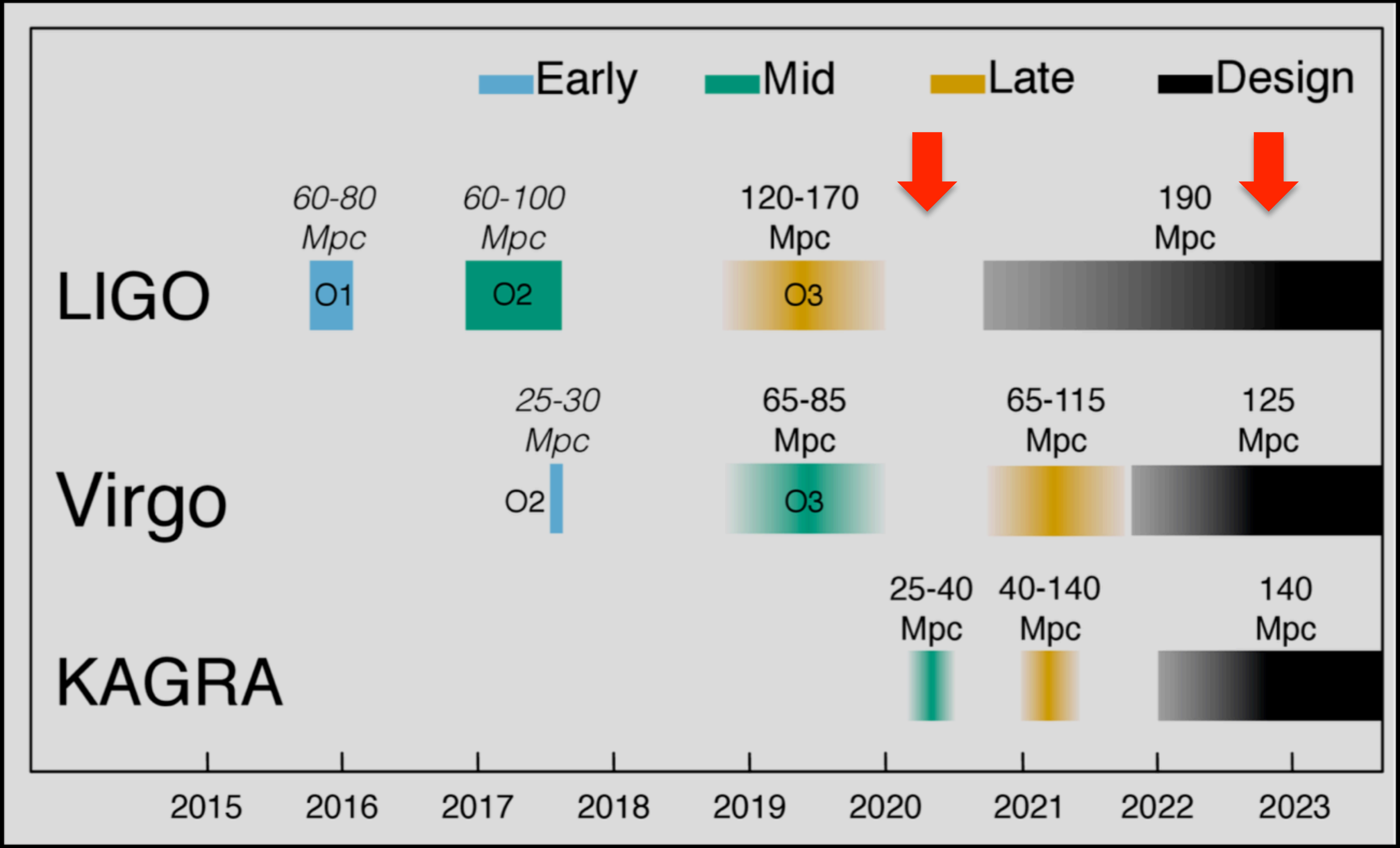


- POP pickoff beam used for homodyne local oscillator
- LO phase noise critical
- ➔ Requires *sub 10^{-18} m/Hz$^{1/2}$* mirror noise at 100 Hz
- ➔ Triple-stage suspension for relay optics
- Space constraints → *new compact triple suspension design is required*

A+ Technical Updates

- Filter cavity length → 300m
  - Model showed insufficient backscatter margin at 100m
  - Modest hit in civil & vacuum cost
- Low-noise relay optics for BHD local oscillator
  - Models revealed enhanced phase noise susceptibiity
  - Now baselining ~ 11 triple-pendulum suspended small optics to deliver low-noise LO beam (new design)
  - US to do design, UK to fund production
- BHD topology changed
  - AS and LO beams to be interfered *before* mode cleaners
  - Modified OMC suspensions needed
- Anticipating coating progress…
  - Looking closely at zirconia-doped tantala

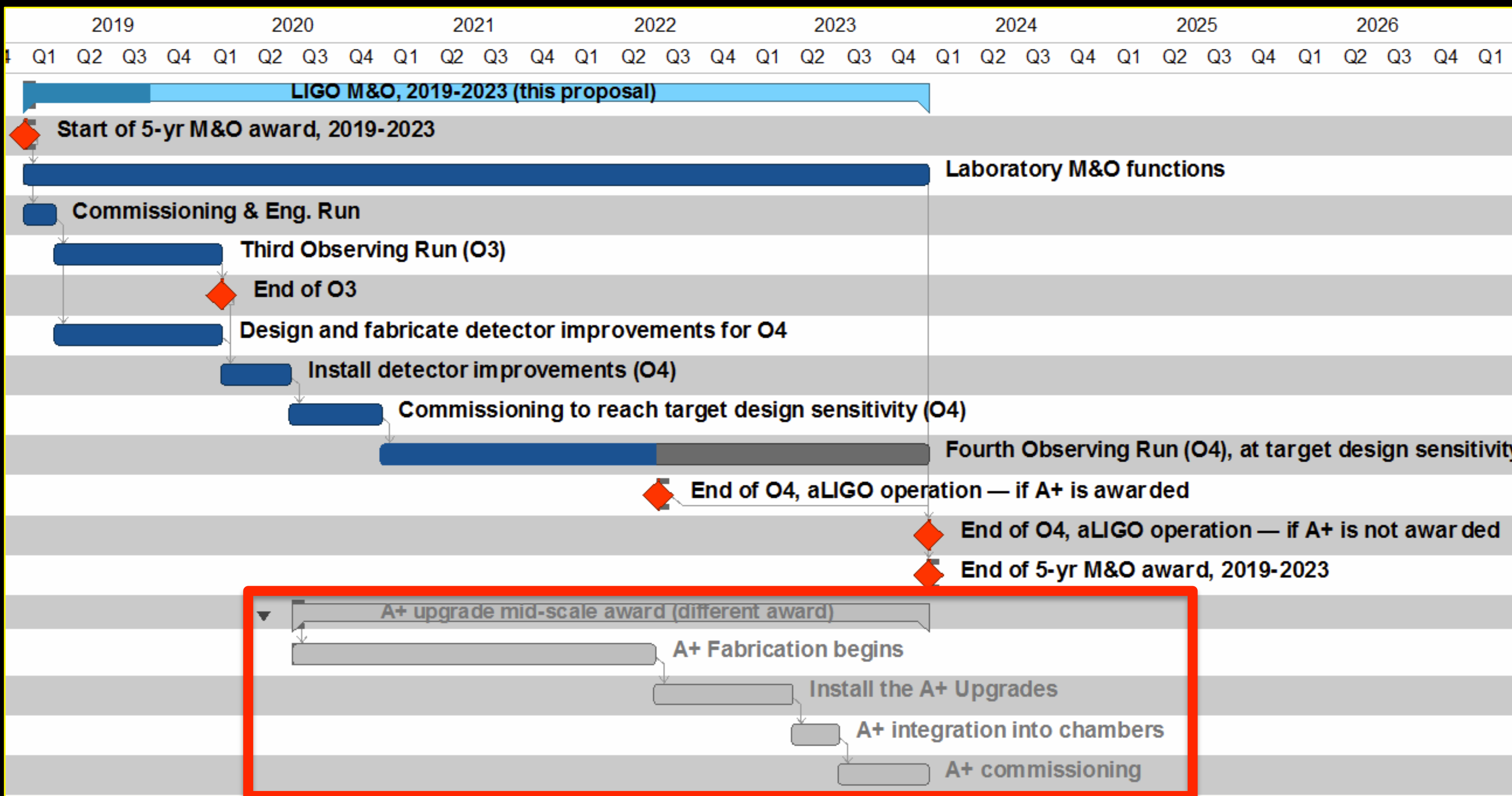
Observing scenario



From P1200087-v47

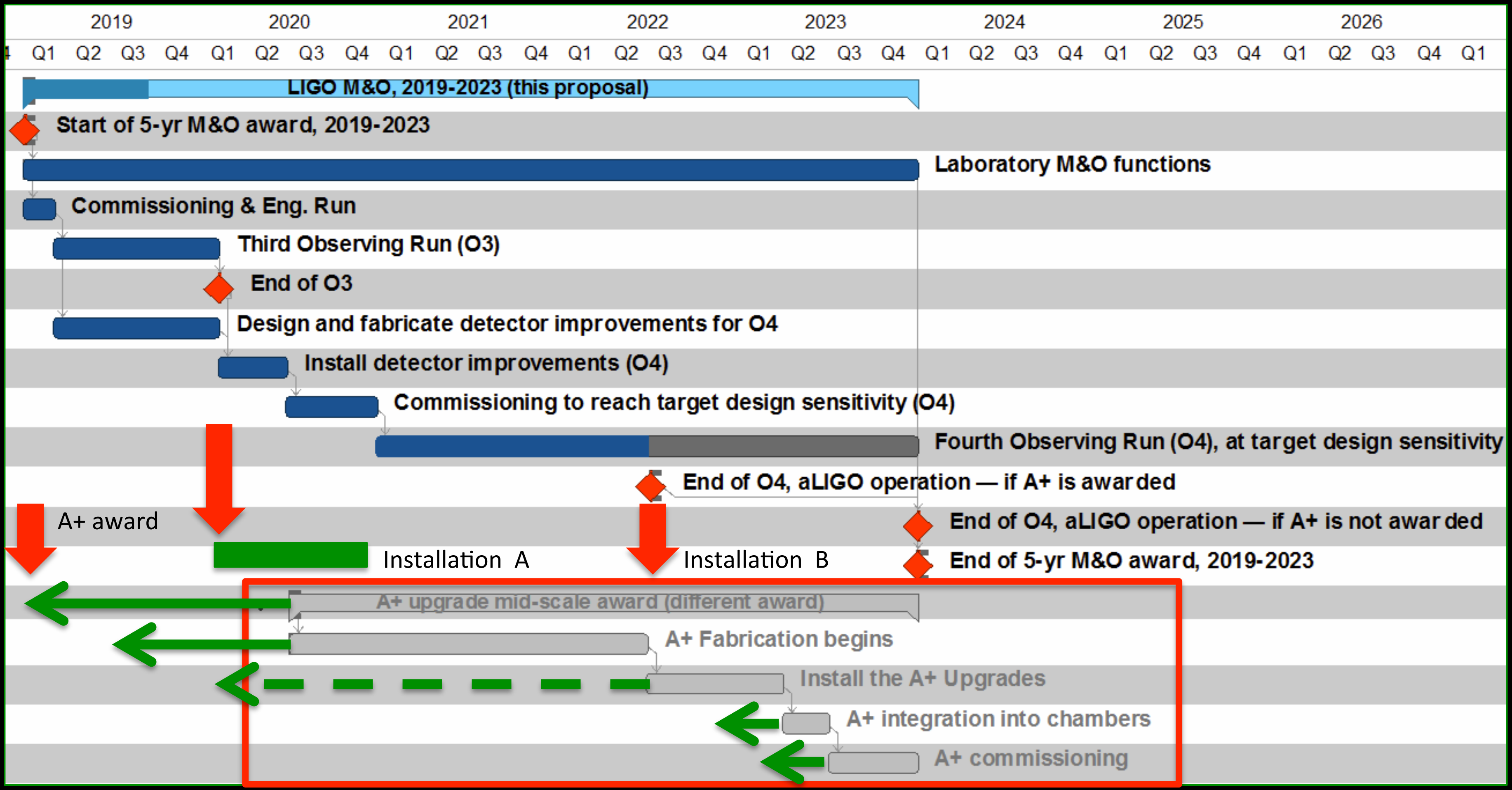
Original simplified schedule

From '19-23 LIGO ops renewal proposal



Sample revised schedule (schematic)

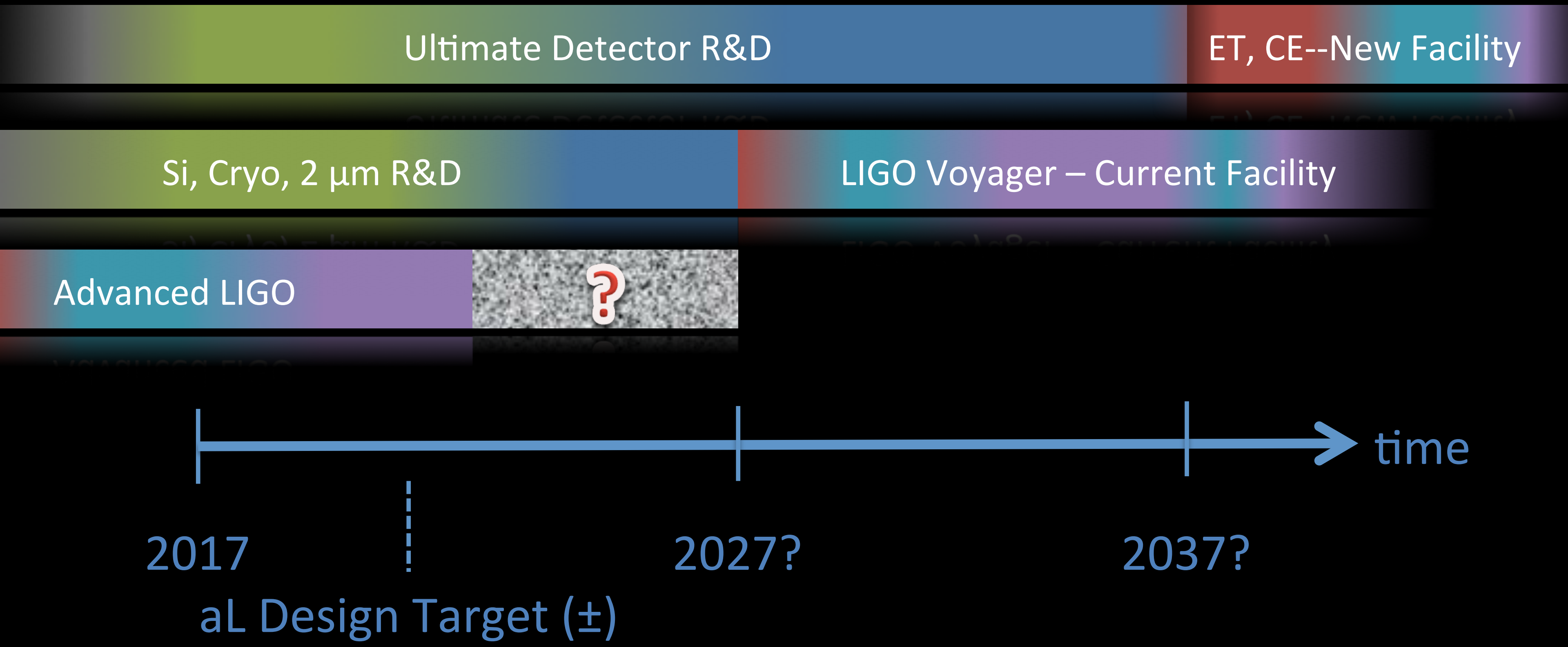
Advance civil & vacuum construction to O3-O4 break
Start optics integration immediately at end of O4

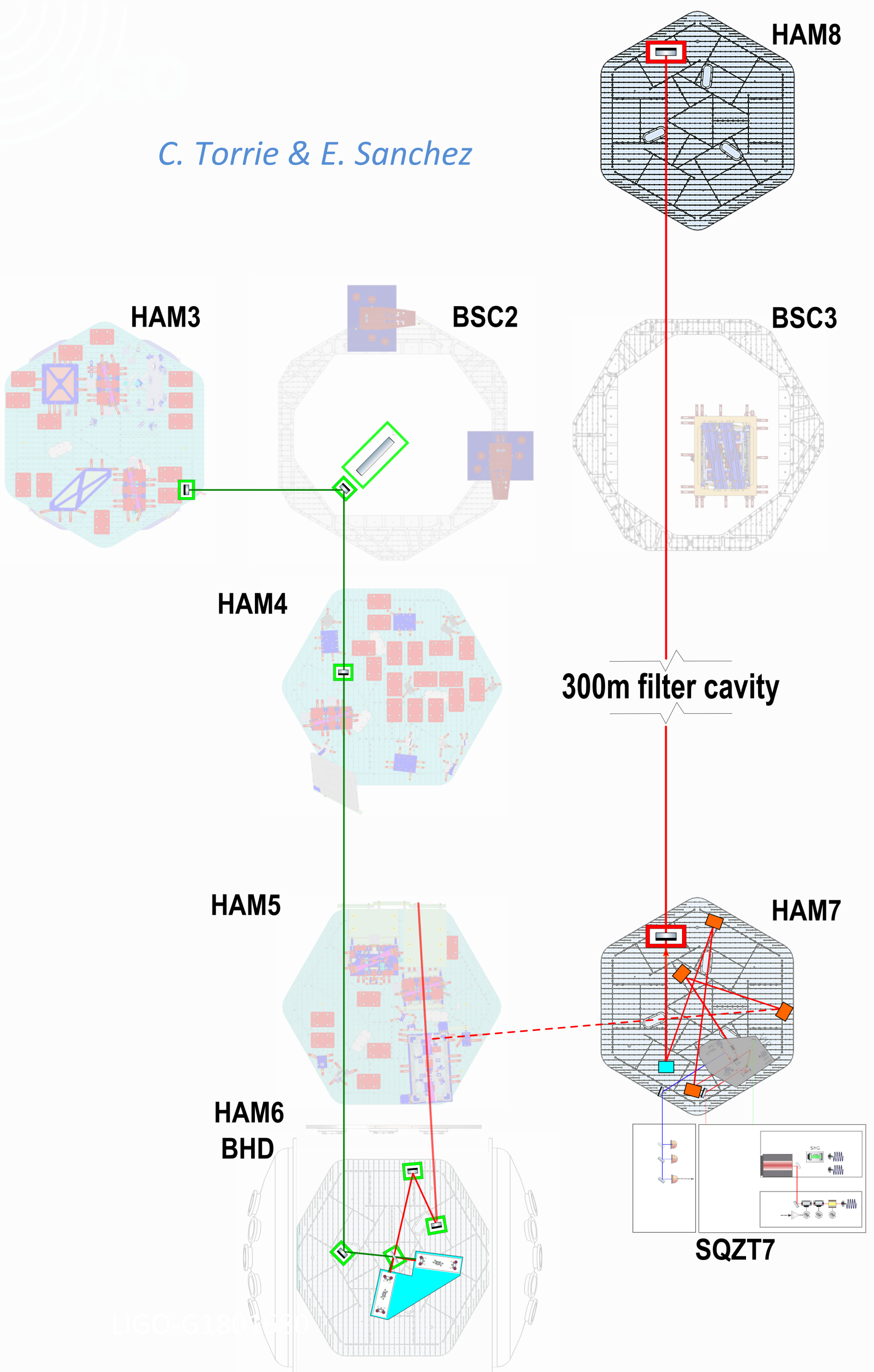


Context: Bridging the Gap

(adapted from G1401081)

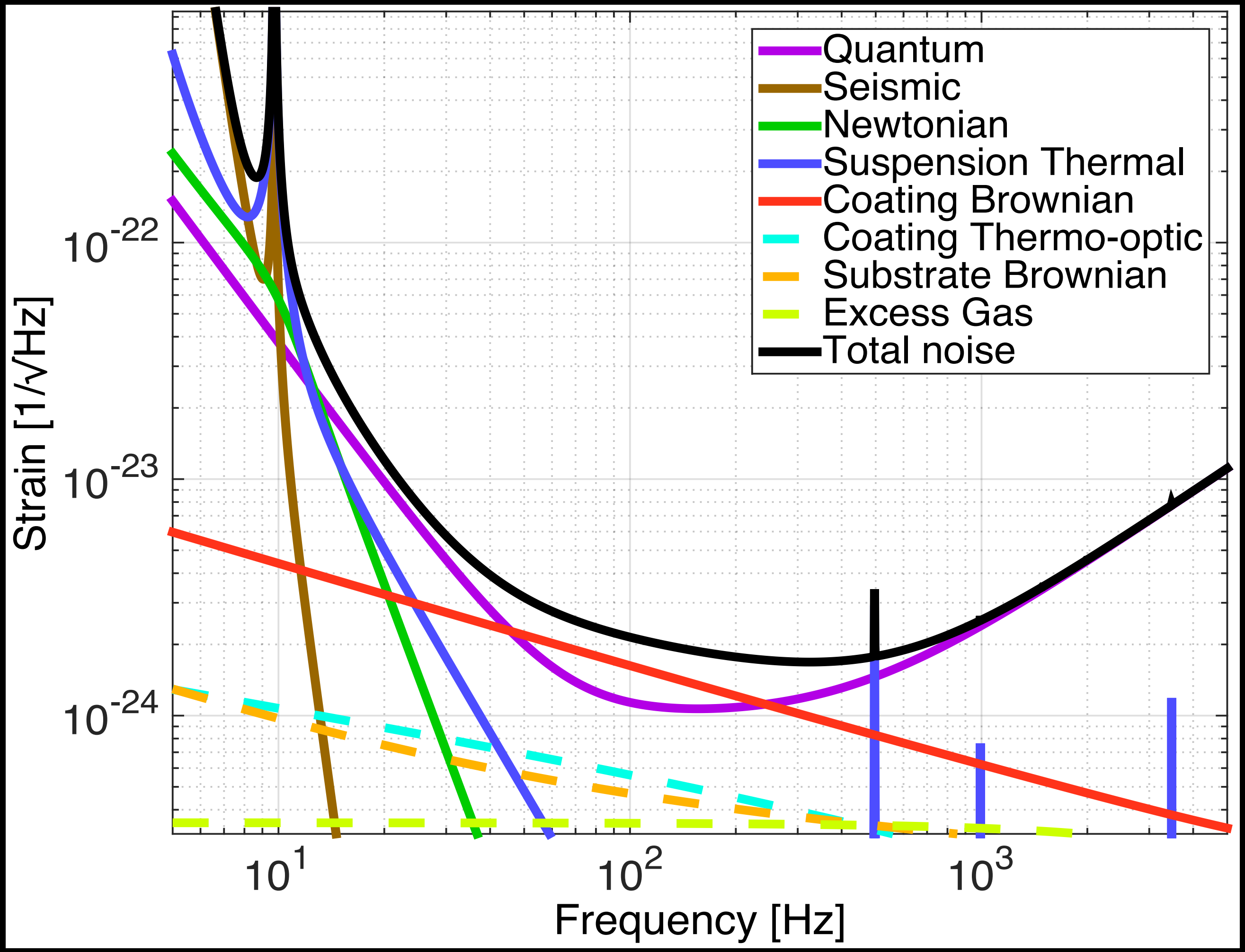
It may take a decade for "next-generation" GW instrument technology to come online. Is extended observation at aLIGO performance limits the best we can do?





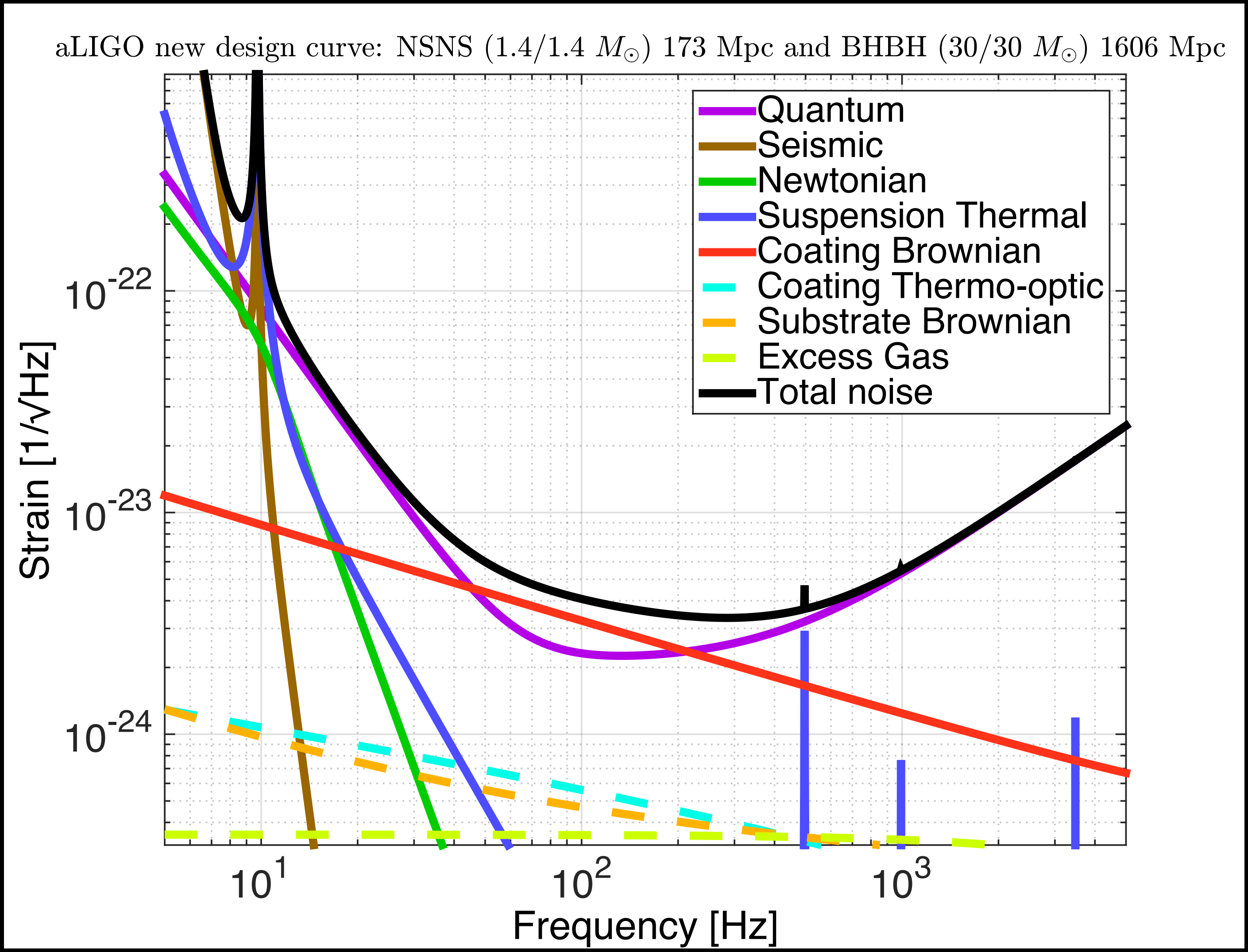
- “New” FC HAM chambers (HAM7,8) salvaged from H2
- New HAM ISI and HSTS for FC mirrors
- LO beam relay to use new “HRTS” triple suspension for low phase noise
- BHD OMC’s may use a common suspended platform (based on VPI)
- FC pipe penetrates BSC3 (beam passes behind ITMX)

A+ target noise budget

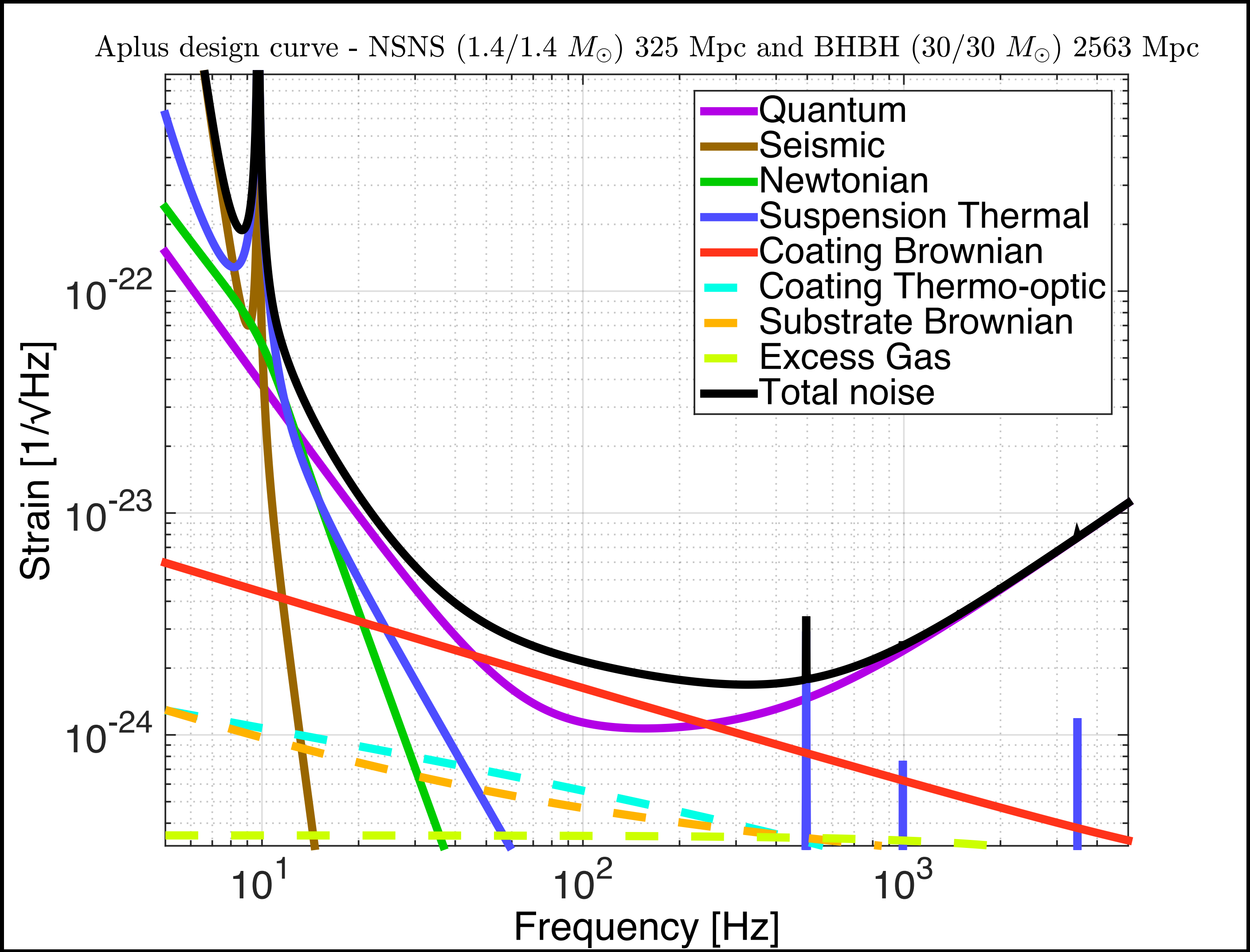


Barsotti et al, T1800043

aLIGO Design Target



A+ Design Target



A+ FDS with no CTN improvement