LIGO A+ UPGRADE STATUS REPORT

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On Behalf of
LIGO Laboratory
Advanced LIGO UK Group
Oz-Grav ANU, Oz-Grav UA

20 May, 2019

LIGO-G1900980

A+ Orientation

- 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 binary inspiral detection range over aLIGO baseline design
  - ➔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 (late 2024)

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

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

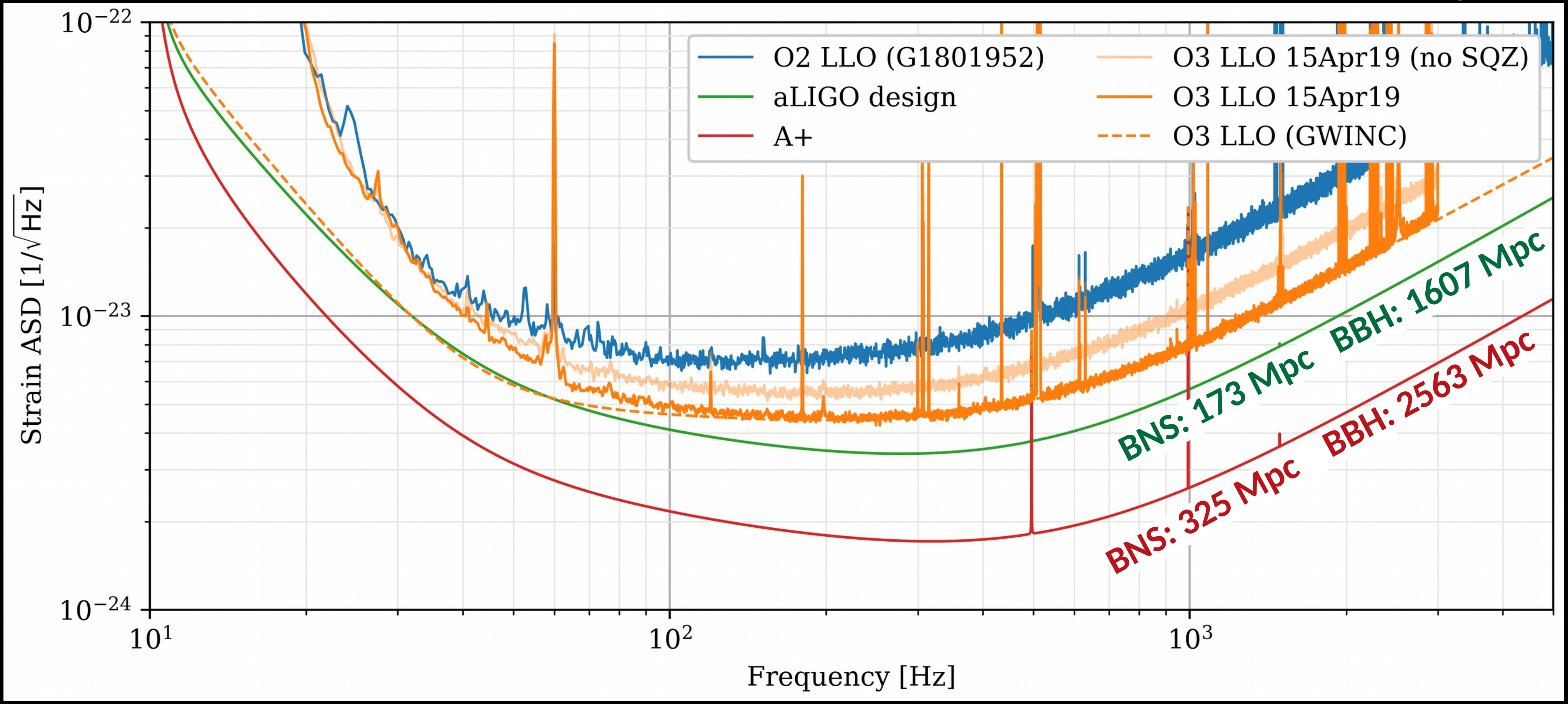
A+ Enhancements

- Improved Coatings
- Frequency Dependent Squeezing
- Boosted Optical Efficiency for Deeper Squeezing
  - High-efficiency Faraday isolators
  - Adaptive Wavefront Control (US/Australia)
- Balanced Homodyne Readout (UK)
  - Several improvements, SRC control, backscatter (see G1800459)
- Enlarged Beamsplitter and Suspension (UK)
- Improved Suspension Fibers (UK)
  - see G1900942

A+ Upgrade: Sensitivity Target

- Reduce quantum noise
  - Improved optical losses
  - Improved readout
  - Frequency-Dependent Squeezing
- Reduce thermal noise
  - Improved mirror coatings

Reference Curves LIGO Document T1800042-v5 (public)



A+ Technical Updates

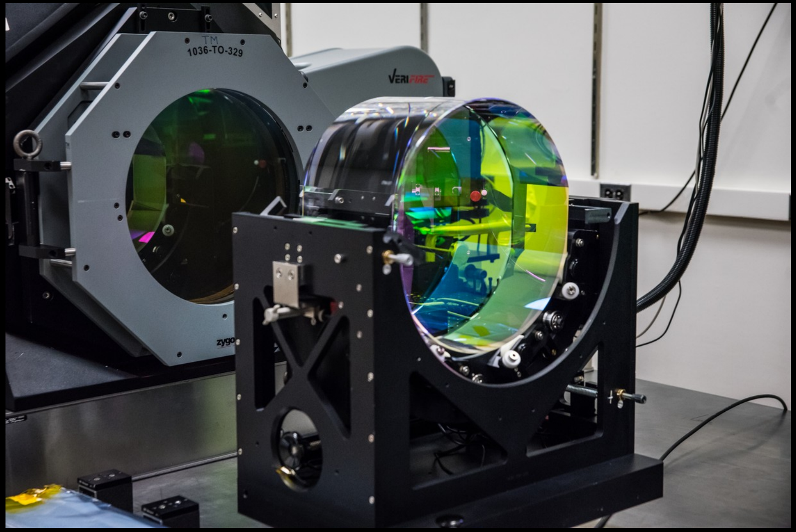
- Filter cavity length 300m
  - Nearly ideal overcoupled cavity (optical all-pass filter)
  - Backscatter also drives length requirements
- Balanced Homodyne Readout: topology
  - LO Differential phase noise is critical
  - AS and LO beams to be interfered *before* mode cleaners
  - Modified OMC suspensions needed
- 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)

Mirror Coatings Target for A+

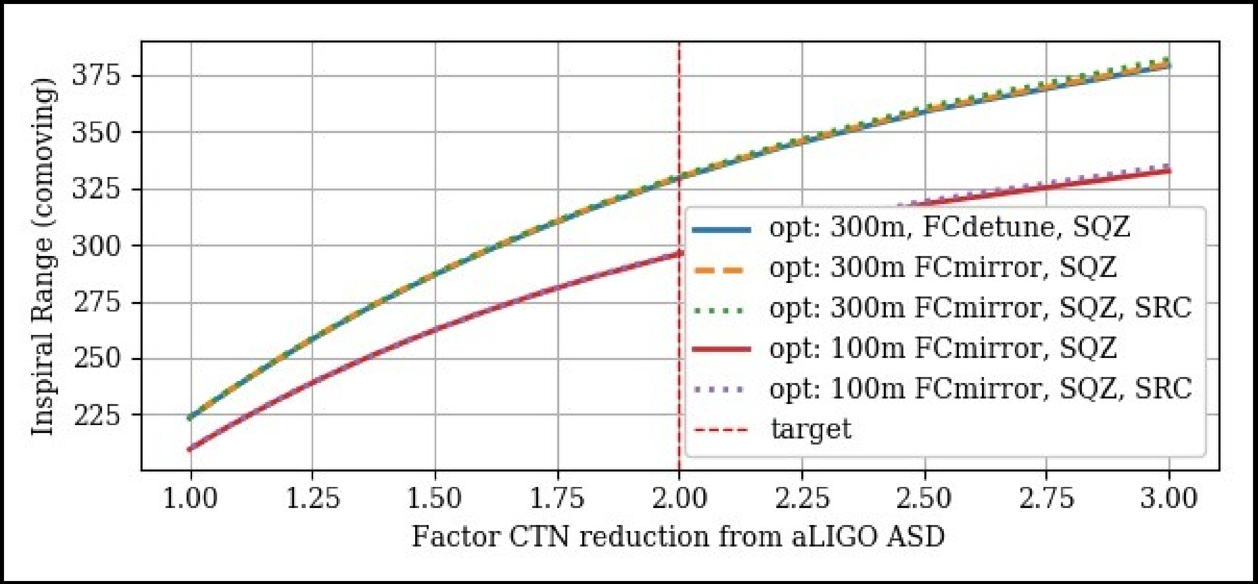
- TARGET: Elastic loss angle $\varphi < 9 \times 10^{-5}$
  - (aLIGO $\varphi = 3.6 \times 10^{-4}$)
  - 2x lower noise in amplitude spectral density from aLIGO coatings
- Current R&D on small samples
- General commissioning goal to reach design-power operation (coatings likely play a role)

- UK, Europe and US Center for Coatings Research initiative to select best low-loss coating design
- Replacement core optics delivered for final phase of A+ installation

400mm LIGO Fizeau interferometer at CIT

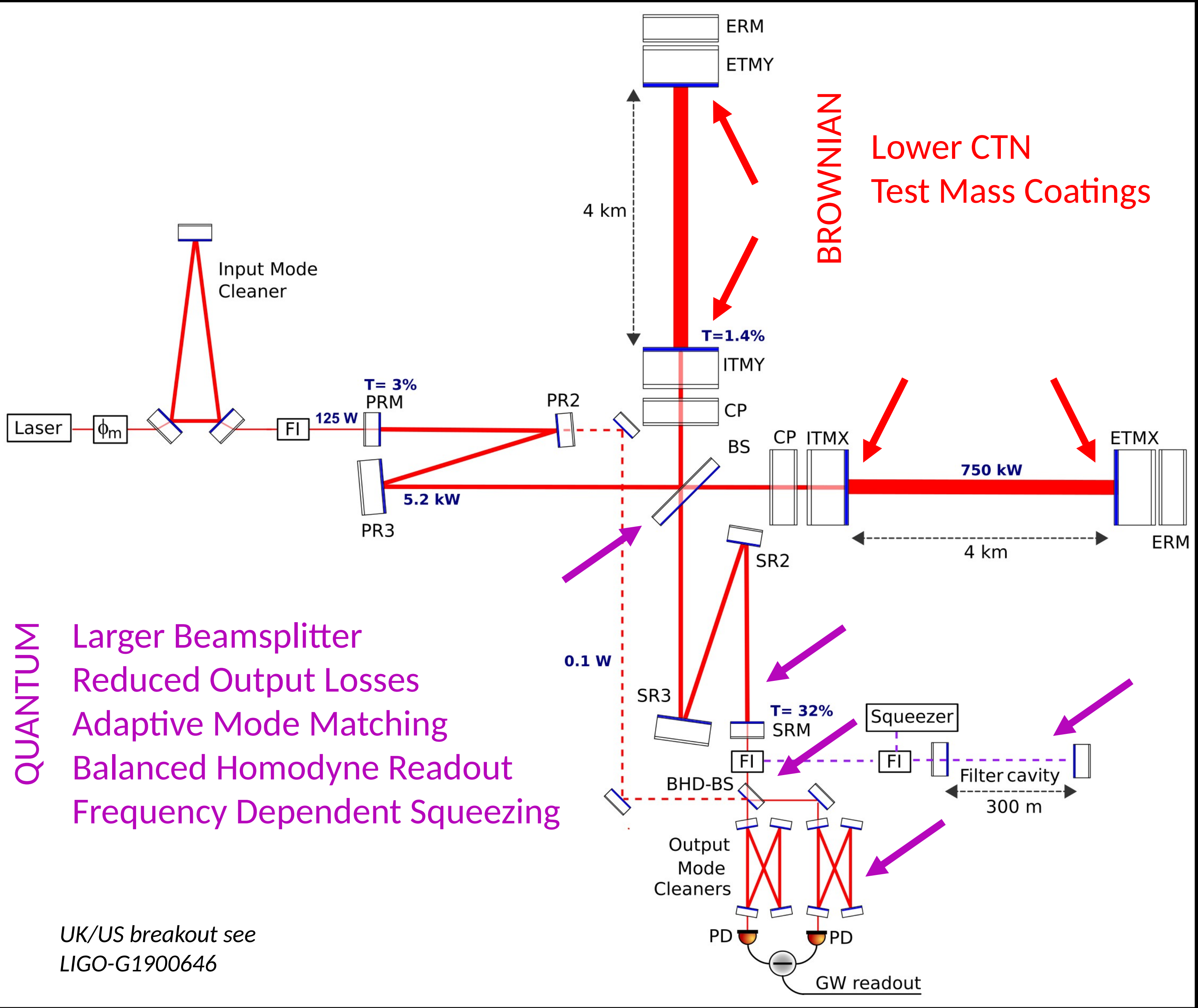


BNS Range as a continuous function of CTN reduction (T1800447)
Also shows that optimized filter cavity design is decoupled from final CTN



A+ Core Optics Layout

P. Fritschel, S. Hild



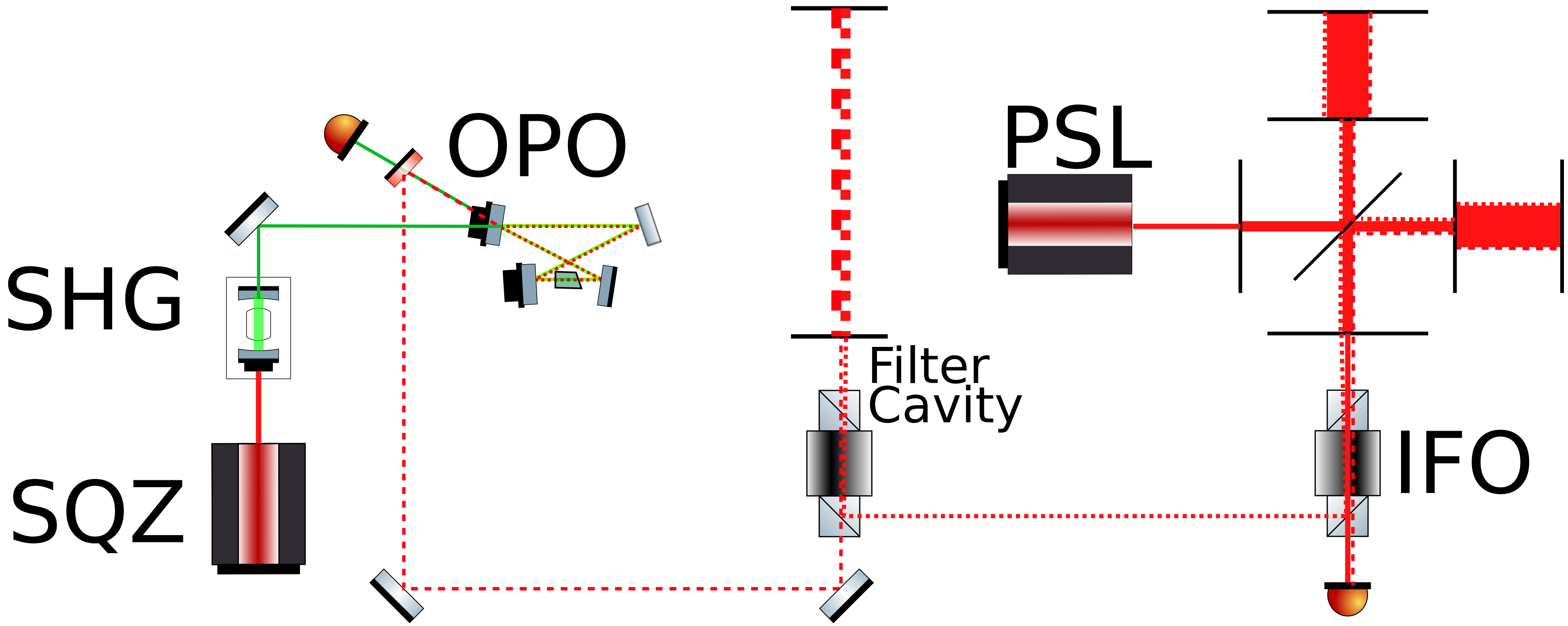
Larger Beamsplitter
Reduced Output Losses
Adaptive Mode Matching
Balanced Homodyne Readout
Frequency Dependent Squeezing

UK/US breakout see LIGO-G1900646

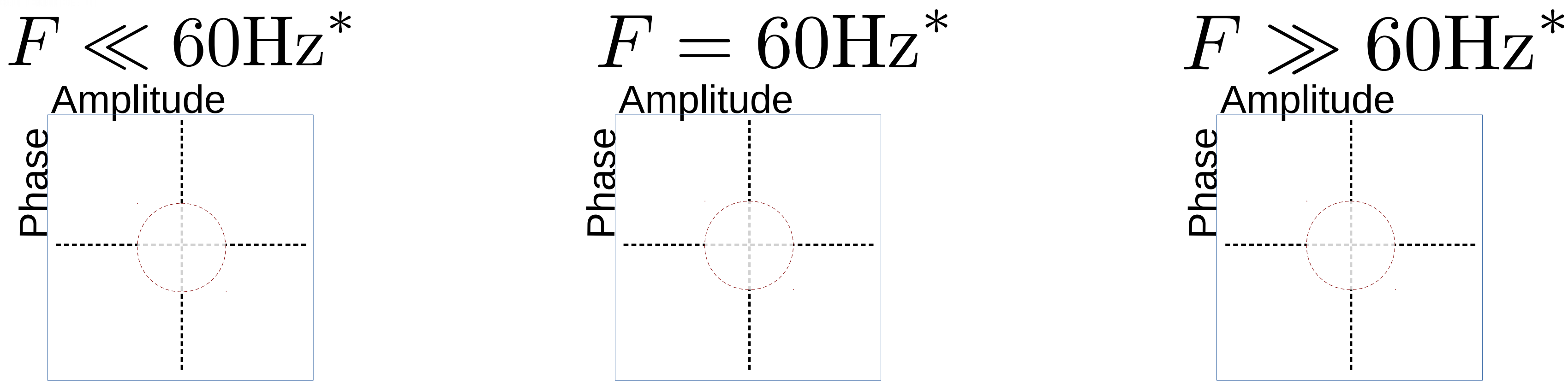
Frequency-Dependent Squeezing for A+

- Optical "filter cavity" (FC)
- Rotates squeezing phase to both improve radiation pressure at LF *and* phase noise at HF
- Sensitive to optical losses, scattering and mirror motion

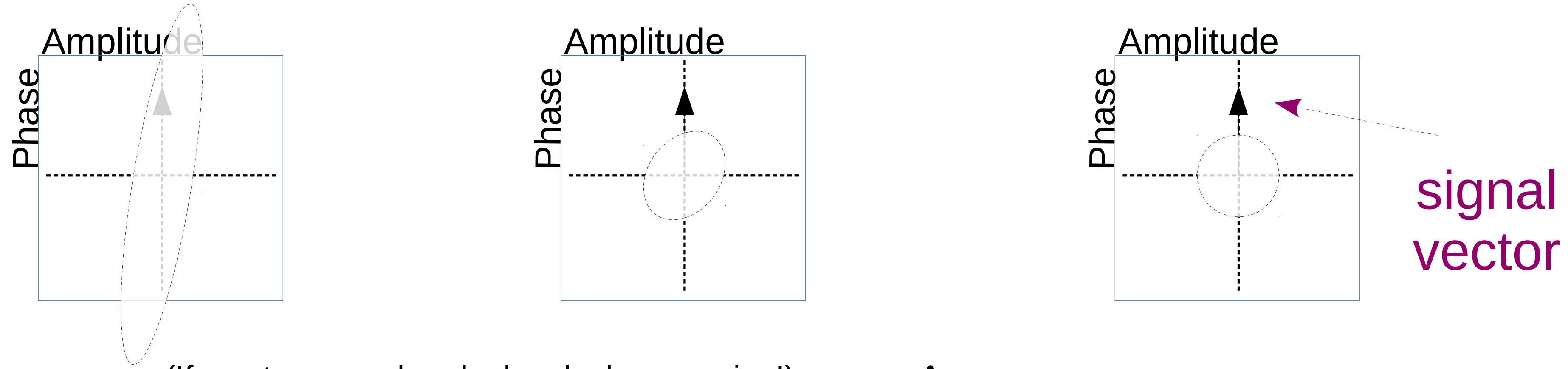
- Requires Low-loss, cavity with bandwidth ~100 Hz (finesse ~5000)
- Requires *seismic isolation and quiet mirror suspension*
- Requires *high-quality FC mirrors*
- Requires L_{FC} ~ 300 m



Standard Quantum Limit



Amplitude → Force → Displacement → Phase:
Phase-space Shear $\begin{bmatrix} 1 & 0 \\ -\kappa & 1 \end{bmatrix}$

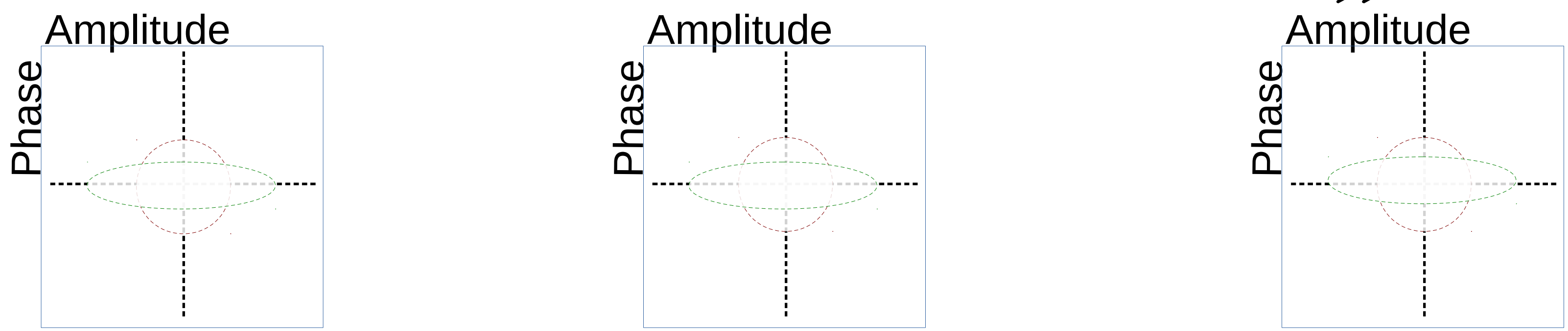


(If you turn your head – hey look squeezing!)

* ~60Hz is approximate crossover only in aLIGO full power design

Squeezing Side Effects

$F \ll 60\text{Hz}^*$ $F = 60\text{Hz}^*$ $F \gg 60\text{Hz}^*$



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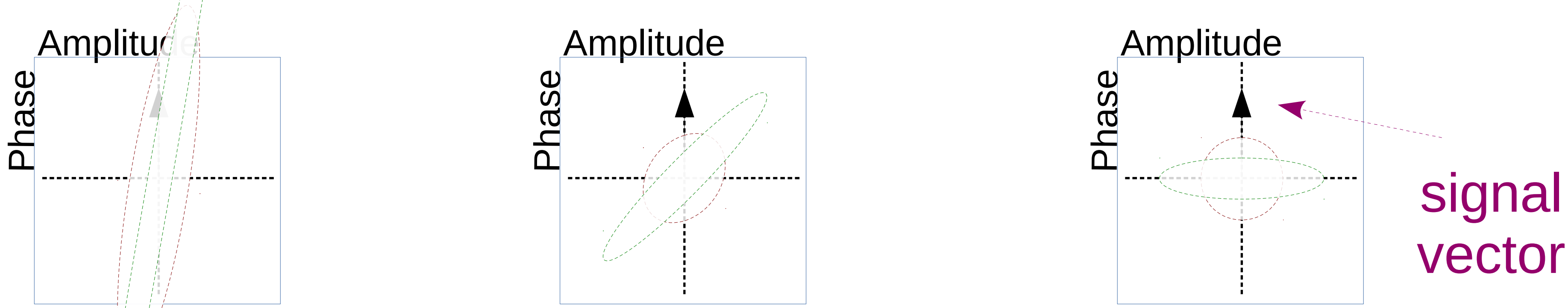

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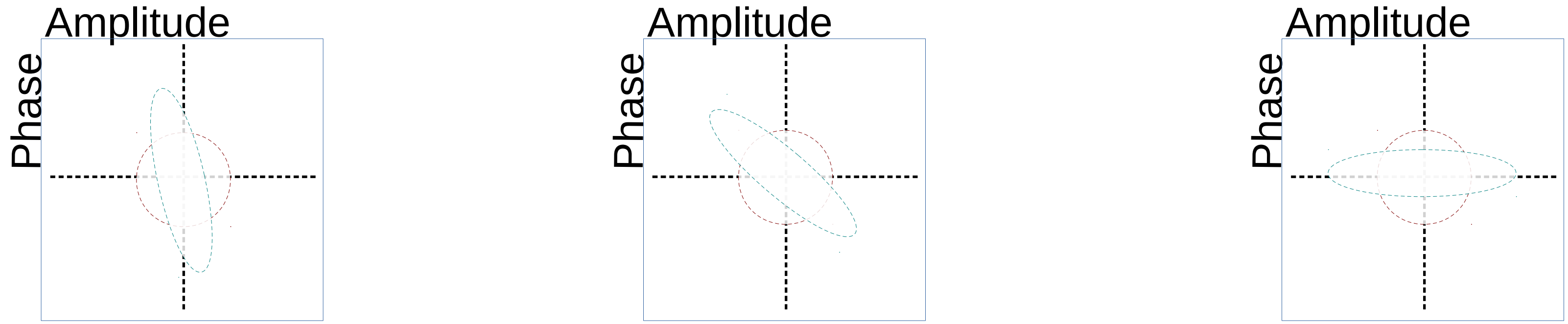
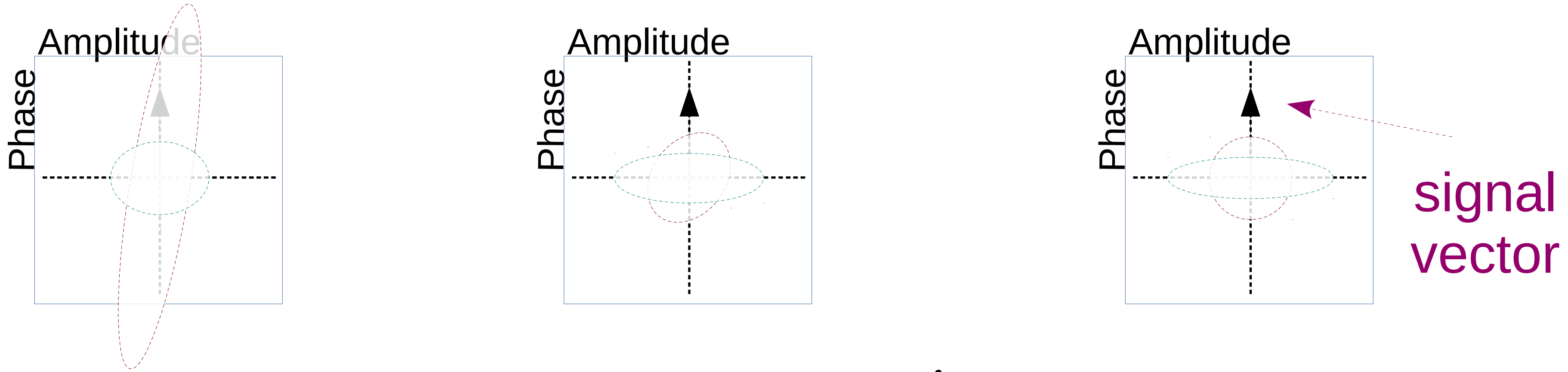
Remedy

$F \ll 60\mathrm{Hz}^*$ $F = 60\mathrm{Hz}^*$ $F \gg 60\mathrm{Hz}^*$



merely
unsqueezes

Frequency Dependent Squeezing



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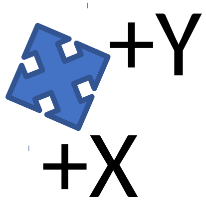
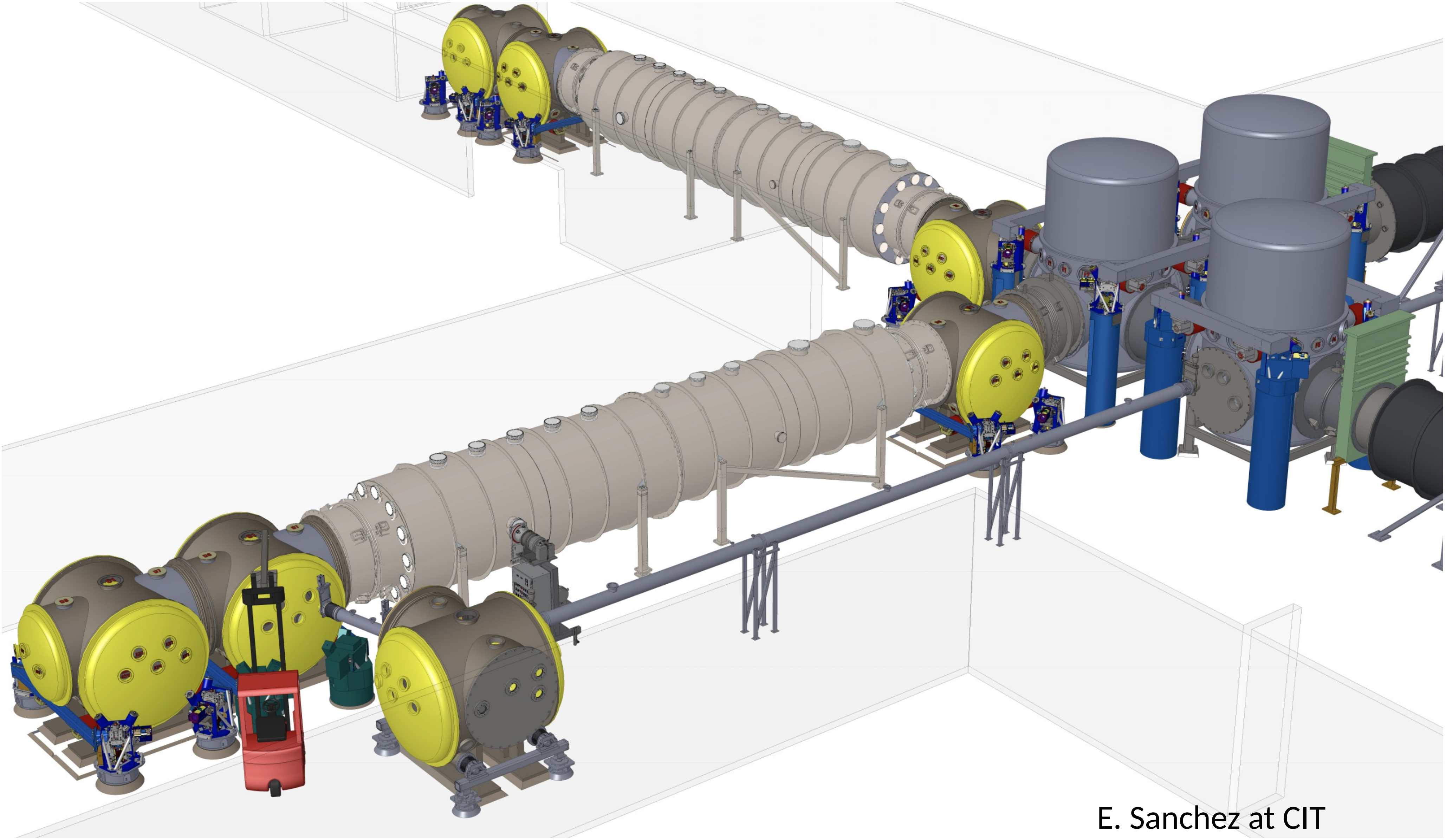




E. Sanchez at CIT
More at LIGO-G1900621

Very Non-Quantum Reqs.

- Length Noise requirement
  - (in cavity, 90db from 3 Faradays): $\approx 3 \cdot 10^{-16} \frac{\mathrm{m}}{\sqrt{\mathrm{Hz}}}$

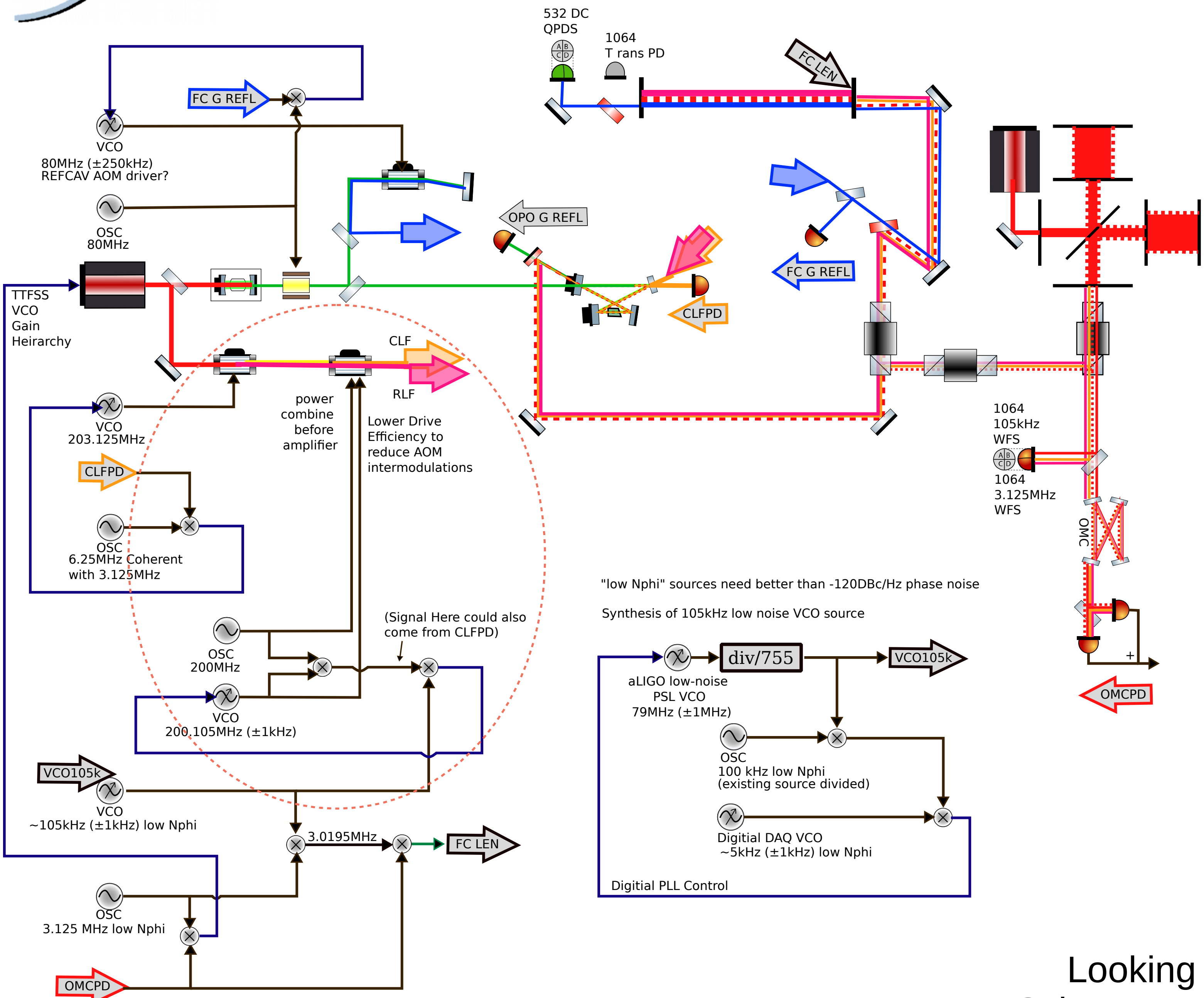
- Phase Noise requirement on resonant length-witness field
  - Must be closed-loop with stabilized IFO as ref: $\approx 10^{-6} \frac{1}{\sqrt{\mathrm{Hz}}}$

- Need sufficiently stable VCOs for Frequency Shifts
- Already studied multi-field AOM phase stability with audio-field ("secondary CLF") injections in LIGO

T1800475 (phase noise analysis)

LLO41737 LLO41643 LLO42297 LLO42297 LLO42233 LLO41796 LLO41737

Existing Tech. Scheme

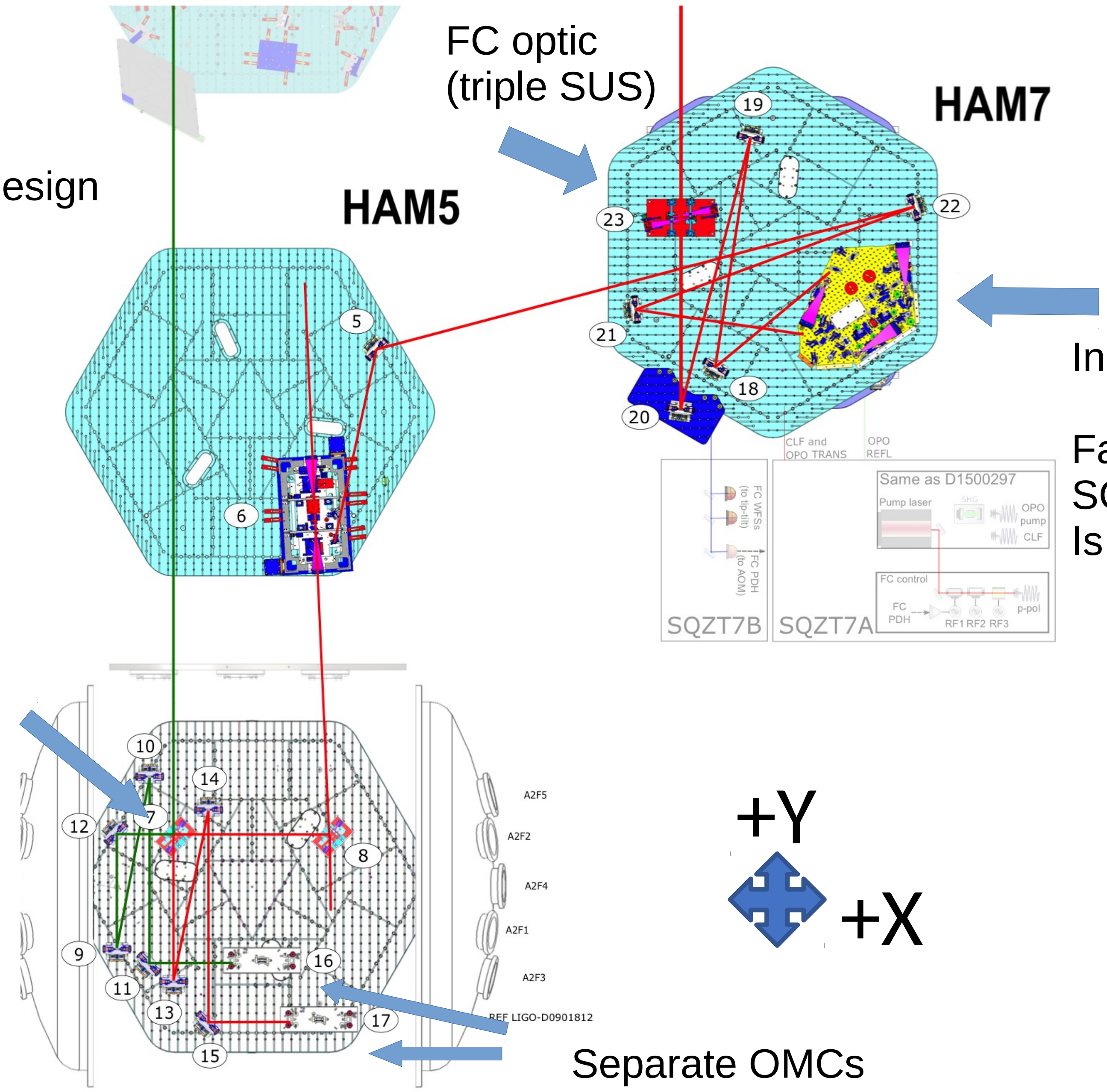


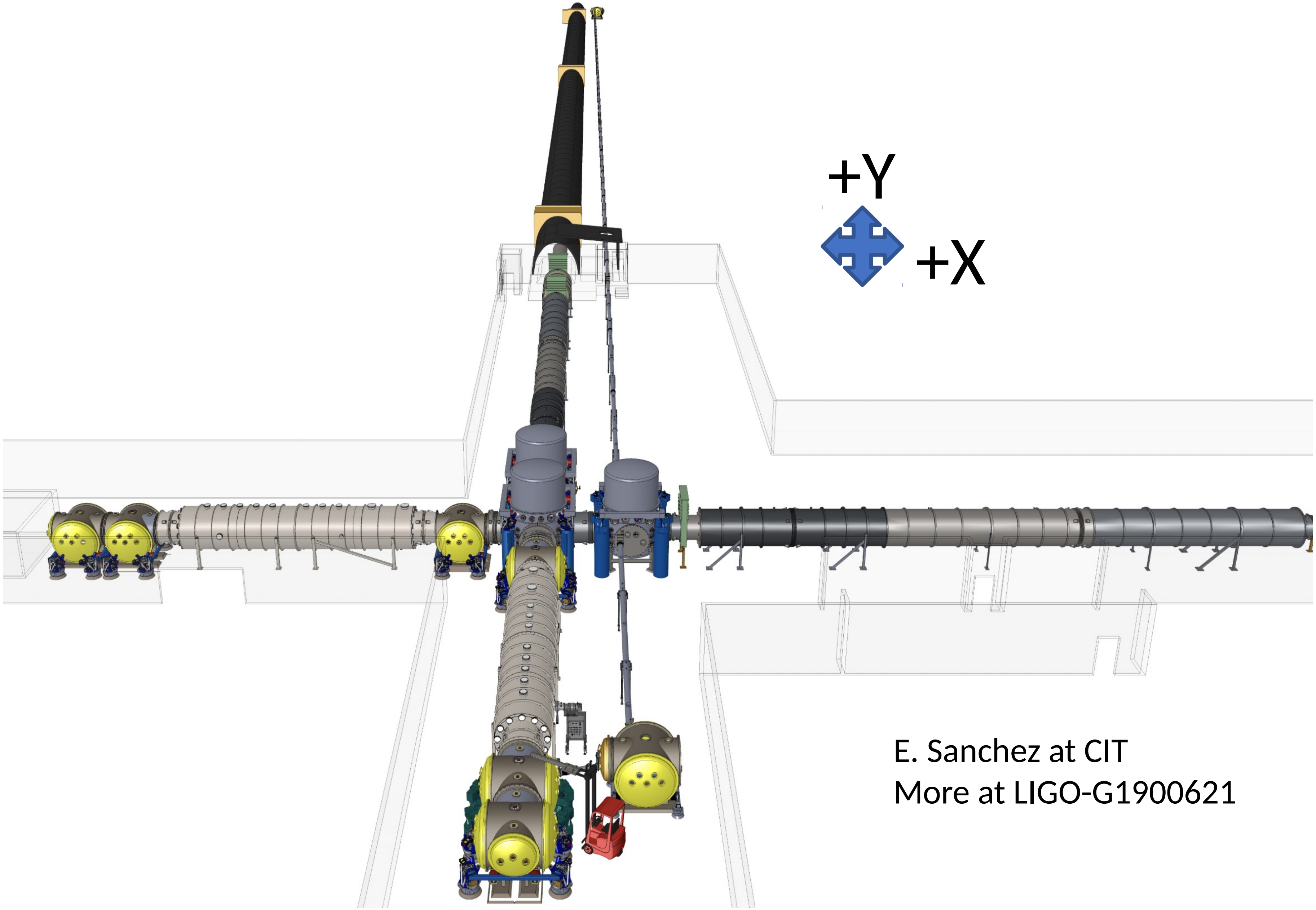
Soon tested in LASTI
Optically configured
with cavity + SQZ
Our audio-field
implementation → RLF

Looking forward to comparing
Schemes with N. Aritomi Poster #55

A+ Layout Cartoon

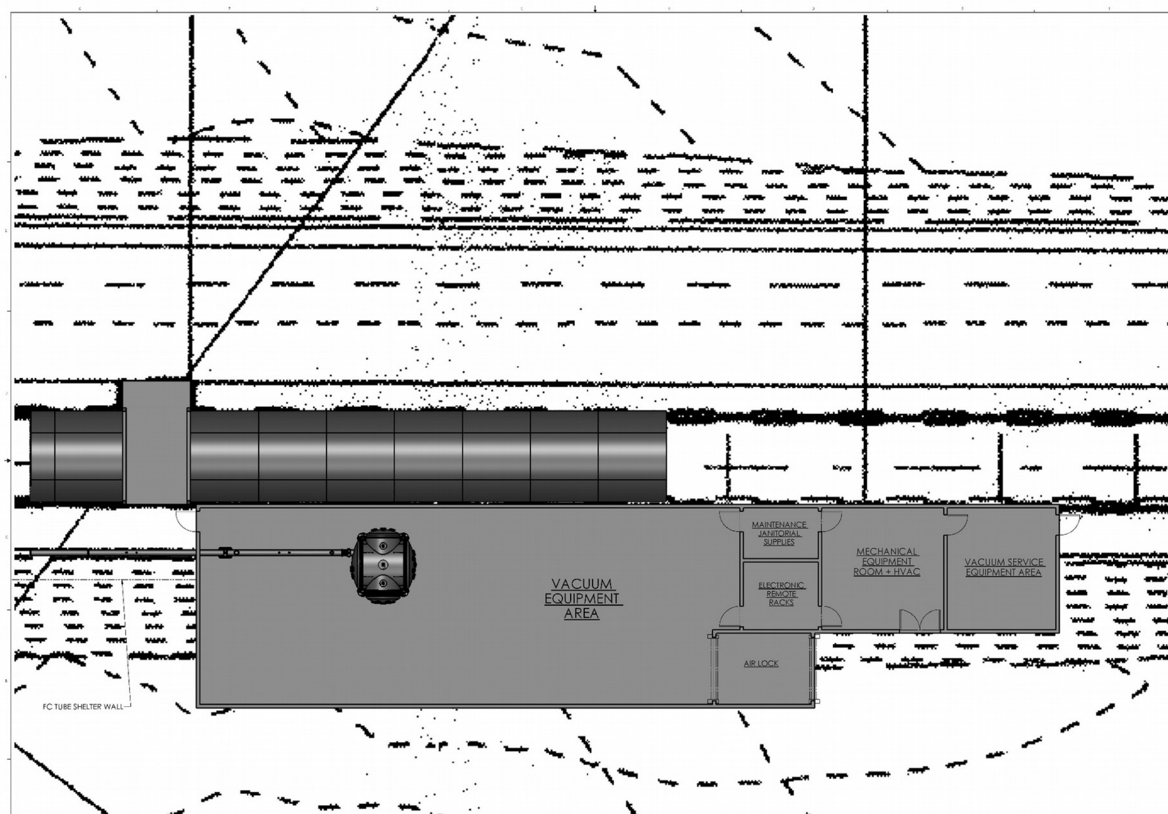
A+ Conceptual Design
D1800027

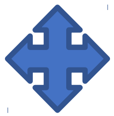




E. Sanchez at CIT
More at LIGO-G1900621

A+, SITE LAYOUT (H1): END STATION

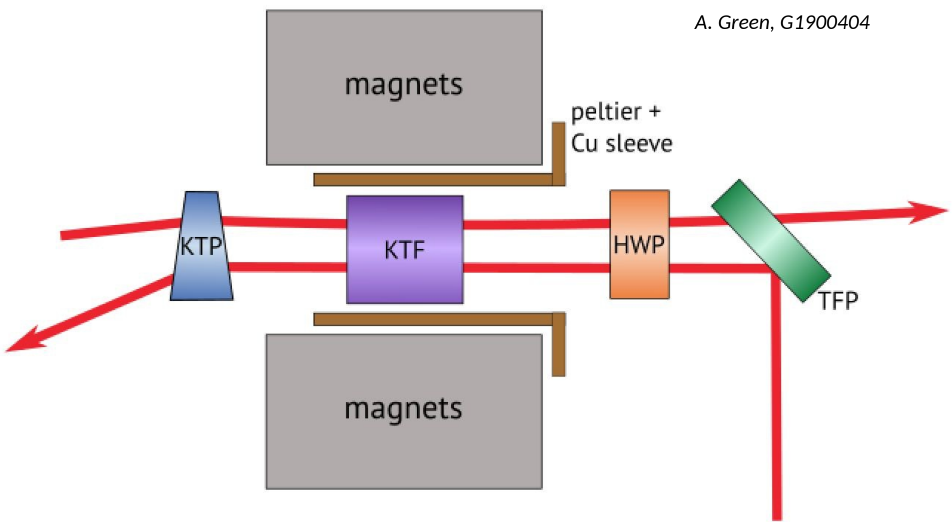


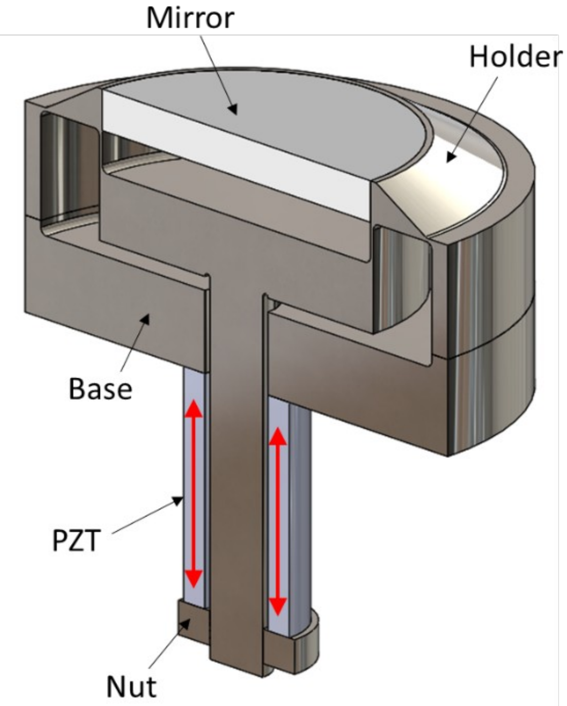


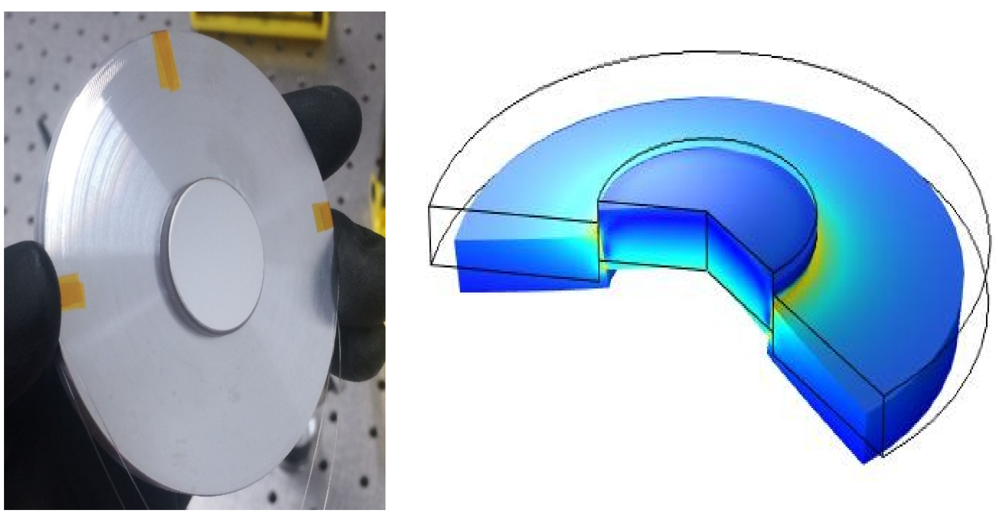
(EXTRACTED FROM LIGO D1900060)

New technology for reducing losses

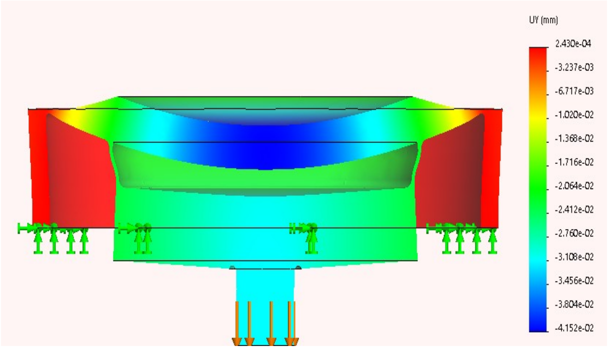
Ultralow-loss Faraday isolator (UF/Montclair)







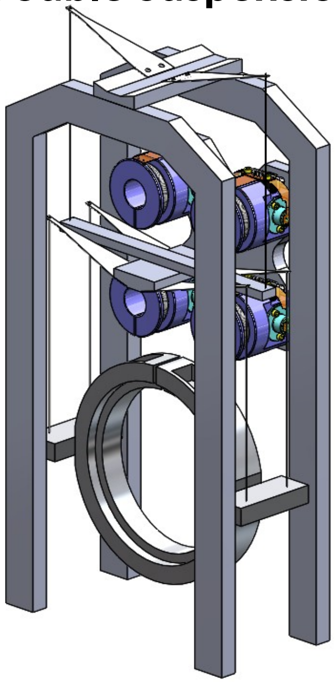
Thermal Deformable Mirror (CIT/Adelaide)



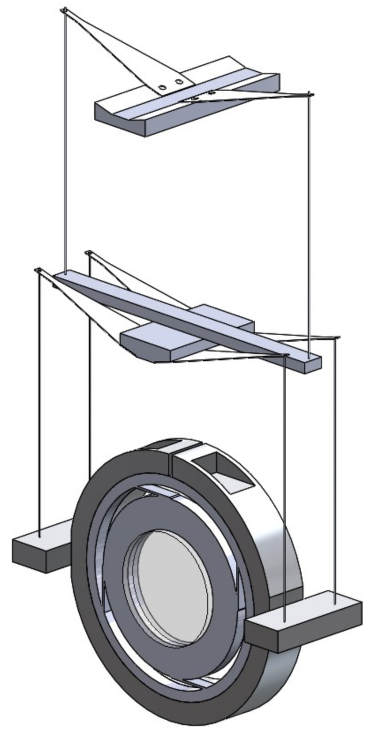
PZT Deformable Mirror (Syracuse/MIT)

New double suspensions for Lower noise beam relays and wavefront control

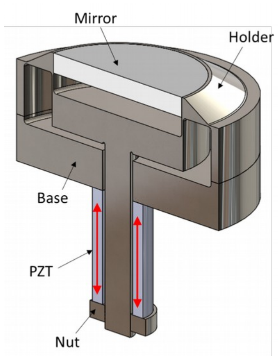
Double Suspension

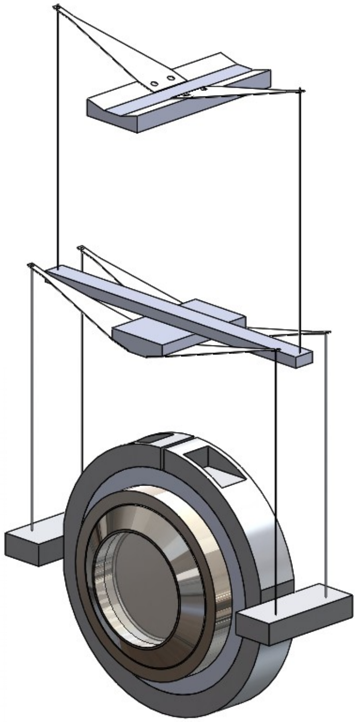


Thermal Deformable Mirror



Piezo Deformable Mirror

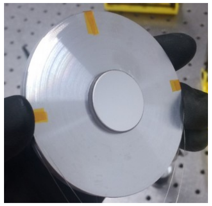


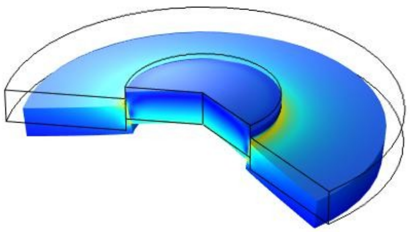


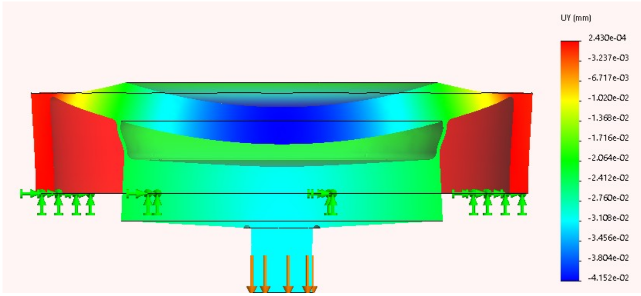
Up to 12 Double Suspensions for A+

First units possibly installed for O4

HDS Main functionalities:
- **Seismic isolation (2 stages)**
- **DC tip-tilt steering**
- **Dither for alignment signals (2kHz tip-tilt)**
- **Mode matching (Mirror curvature control**







LIGO-E1900056: [SAMS - Suspension Interface]

LIGO-E1900066: [SAMS - Suspension Interface: Bracket Option]

LIGO-E1900044: [SAMS-Compression fit mirror A+ Stress and deformation optimization]

LIGO-E1900073: [SAMS - Thermal adaptive optics geometry parameter optimization]

LIGO-E1900007: [SAMS Development - Summary 4 - Piezo flexure mechanism]

Thank You

Status

- PM infrastructure is in place
  - Resource-loaded schedule now under baseline review
- UK announcement in February 2019
  - now integrated into project schedule

- Early deliverables on track for pre-O4 integration
  - Facility Design Requirements complete and reviewed
  - Vacuum Design Requirements complete and reviewed, moving into procurement
  - Seismic isolation systems, fabrication underway
  - Low Loss Output Faraday Design Requirements complete, moving into procurement

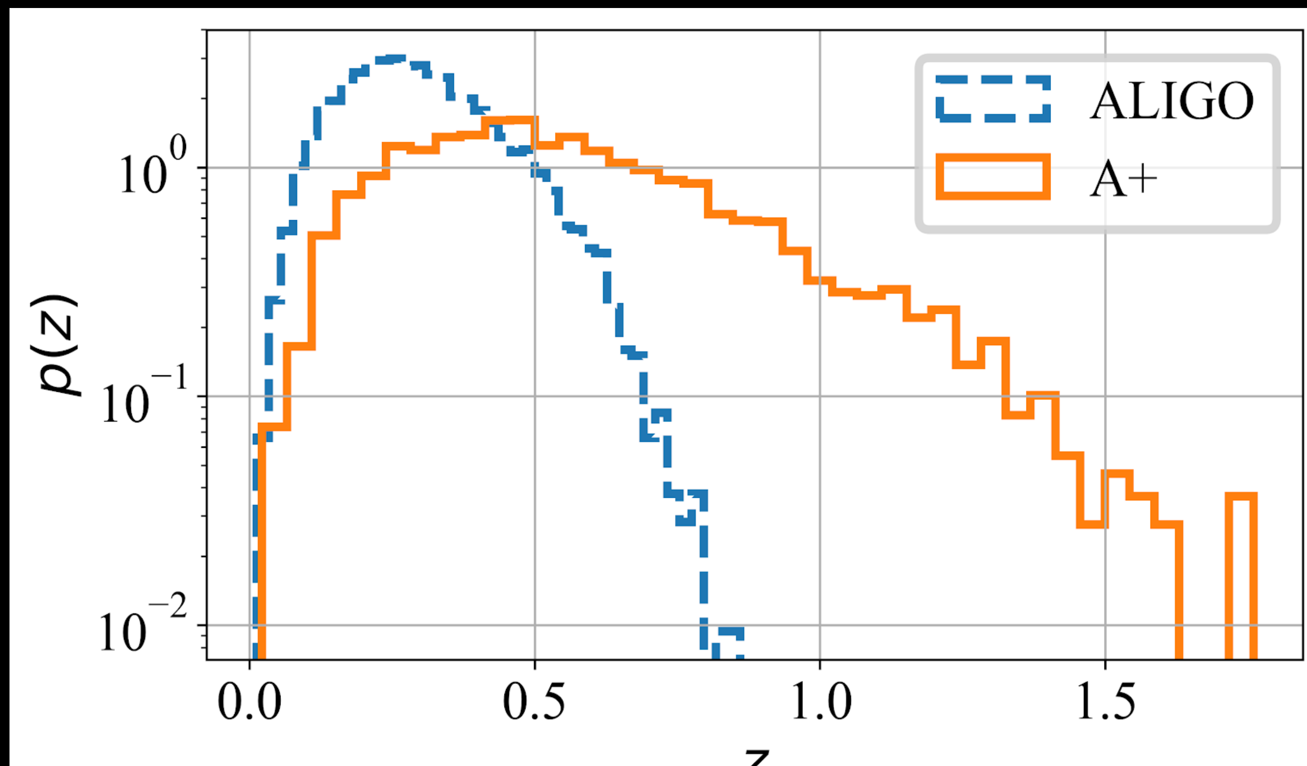
A+ Team

Name	Home	A+WBS/ WP	A+ Project Subsystem/WP Title
D. Reitze	CIT	PM	PI
A. Lazzarini	CIT	PM	Co-PI
M. Zucker	MIT	PM, FAC	Co-Pi, Facilities
G. Billingsley	CIT	PM, COC	Project Lead Engineer, Optical Test
H. Hansen	LHO	PM	Business
C. Torrie	CIT	SYS	Systems Engineering
N. Robertson	CIT	SUS	Suspensions
K. Mason	MIT	SEI	Seismic Isolation
R. Abbott	CIT	CDS	Controls & Data Systems
C. Romel	LHO	VAC	Vacuum Systems
L. Barsotti	MIT	ISC	Interferometric Sensing & Controls
S. Rowan	GU	WP1	Test Mass Production/Coatings
K. Strain	GU	WP2/ WP7	Beamsplitter Production and Project Management
J. O'Dell	RAL	WP3	Suspensions
C. Mow-Lowry	BU	WP4	Sensors and Actuators
S. Hild	GU+CU	WP5	Balanced Homodyne Readout
G. Hammond	GU	WP6	Suspension Upgrades

BBH Science Opportunities

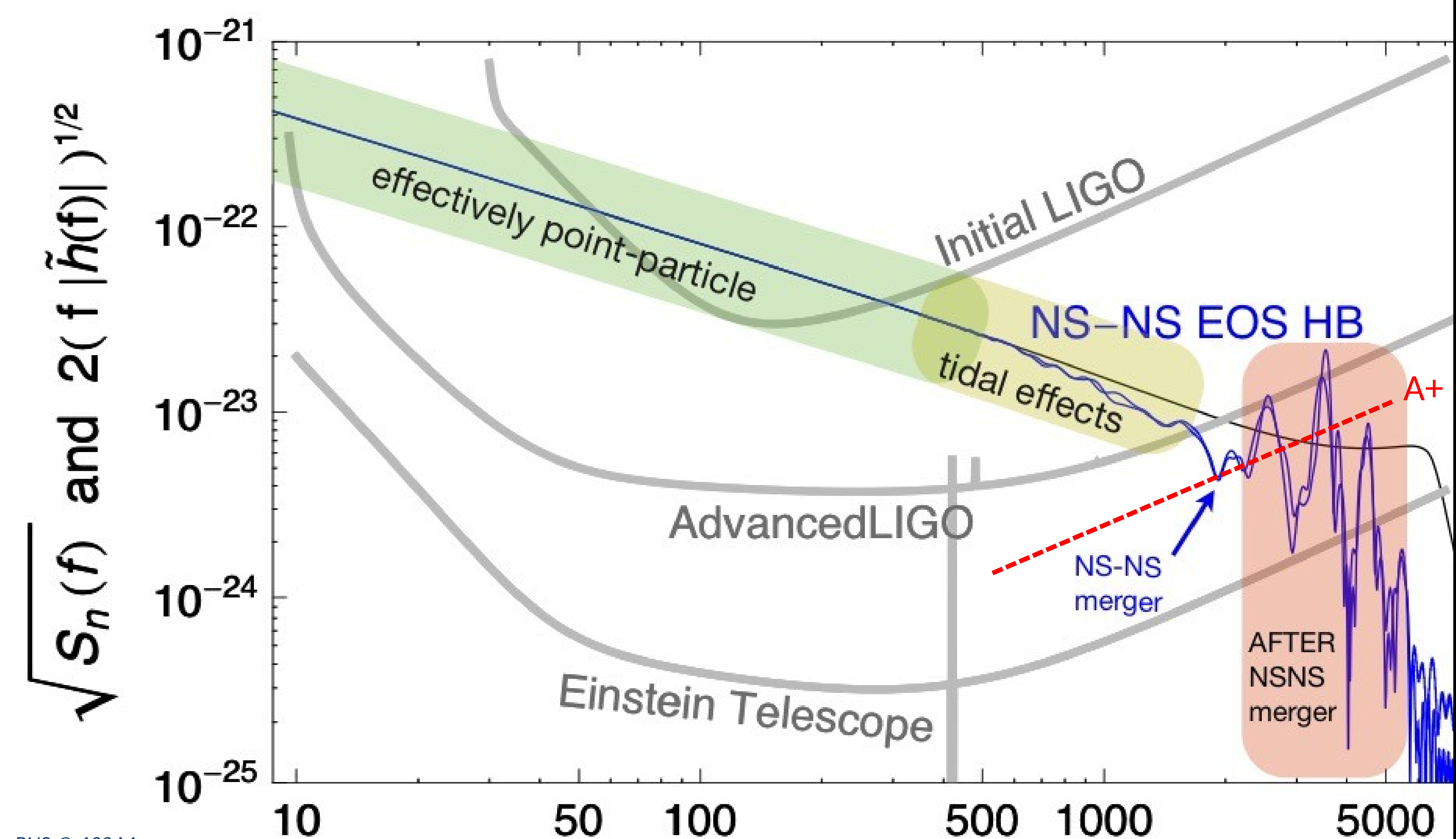
- Stringent Tests of GR
  - Very high SNR BBH signals enable very strong GR tests- e.g., GW150914 would have SNR > 100 in A+
- With A+, BBH detections will *not ONLY be numerous*-
  - The heavy stellar-mass BBH population LIGO discovered is selection-biased; face-on orbits favored by marginal SNR
  - A+ SNR reduces bias, admitting 'typical' inclined systems
  - Edge-on waveforms have less degeneracy, uniquely encoding component spins and putative "non-GR" anomalies
  - Spins are key to understanding progenitor population and origins (e.g., common envelope vs. dynamical capture)

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



S. Vitale, M1800040

BNS disruption & post-merger NS physics



BNS @ 100 Mpc
Read, Schmidt, Clark and Lackey, G1700453
Read et al, Phys. Rev. D 88, 044042 (2013)

BNS post-merger “ringing” vs. NS EOS

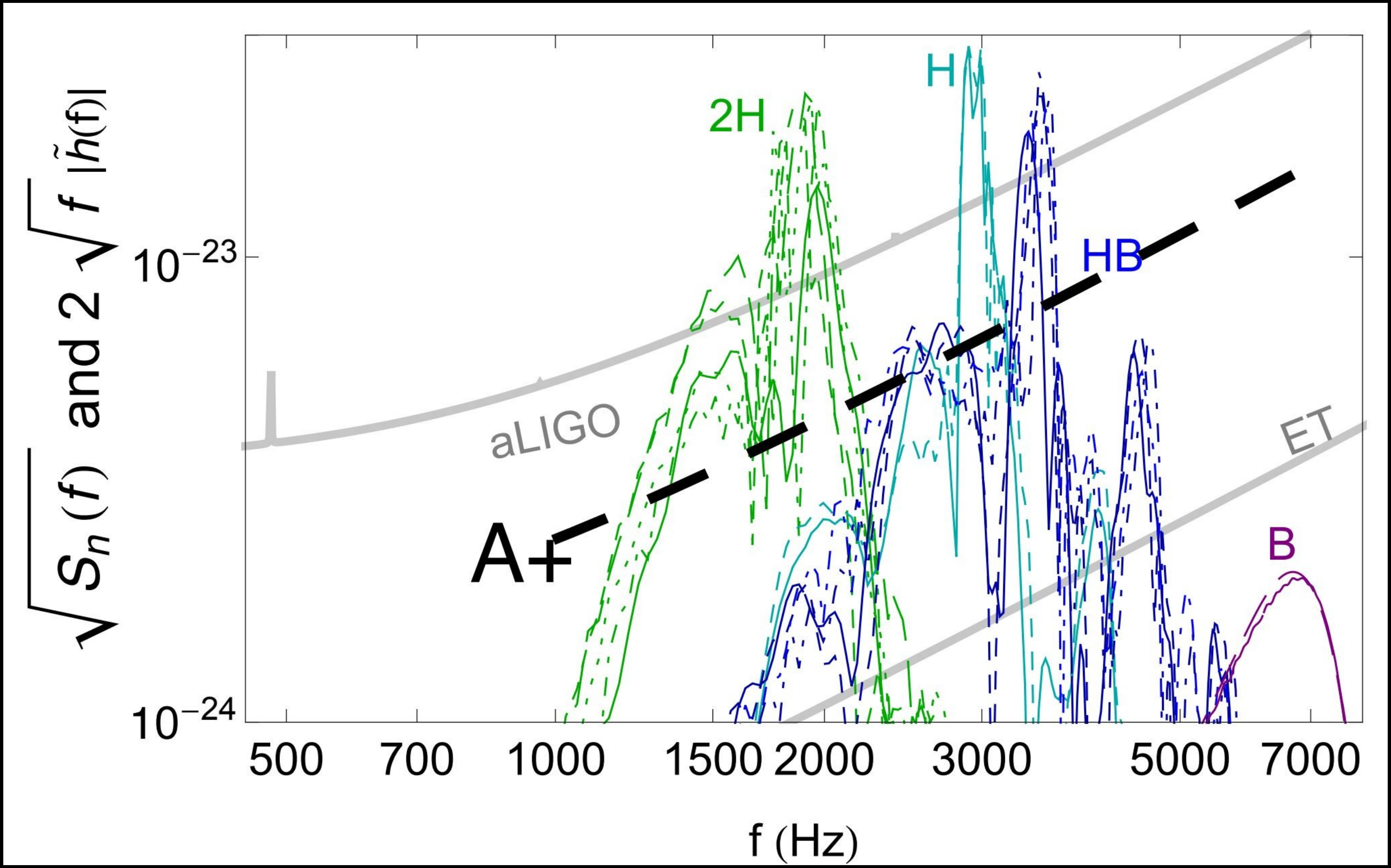


Figure 6: BNS post-merger signal models vs. aLIGO and A+ detector noise for a range of speculated neutron-star equations of state (labeled 2H - B). A+ will have significantly improved capacity to detect post-merger "ringing" modes, whose characteristic frequencies are determined by the equation of state 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. 2013)