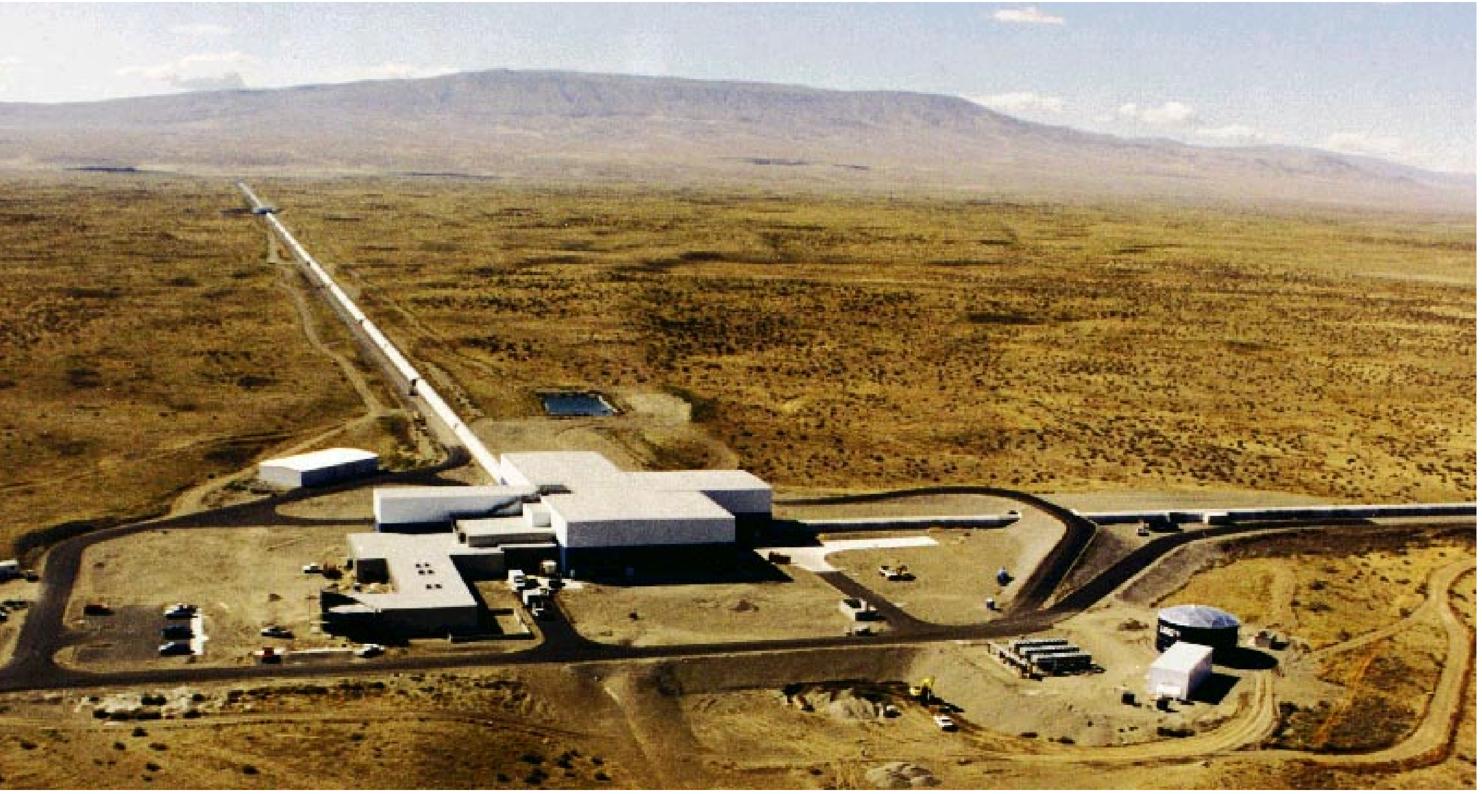
LIGO A$^{\#}$;
Post O5 upgrade and step toward Cosmic Explorer

G2301738-v2, Sept 14, 2023, Toyama

Brian Lantz, Peter Fritschel, Lisa Barsotti,
Post O5 committee and many others



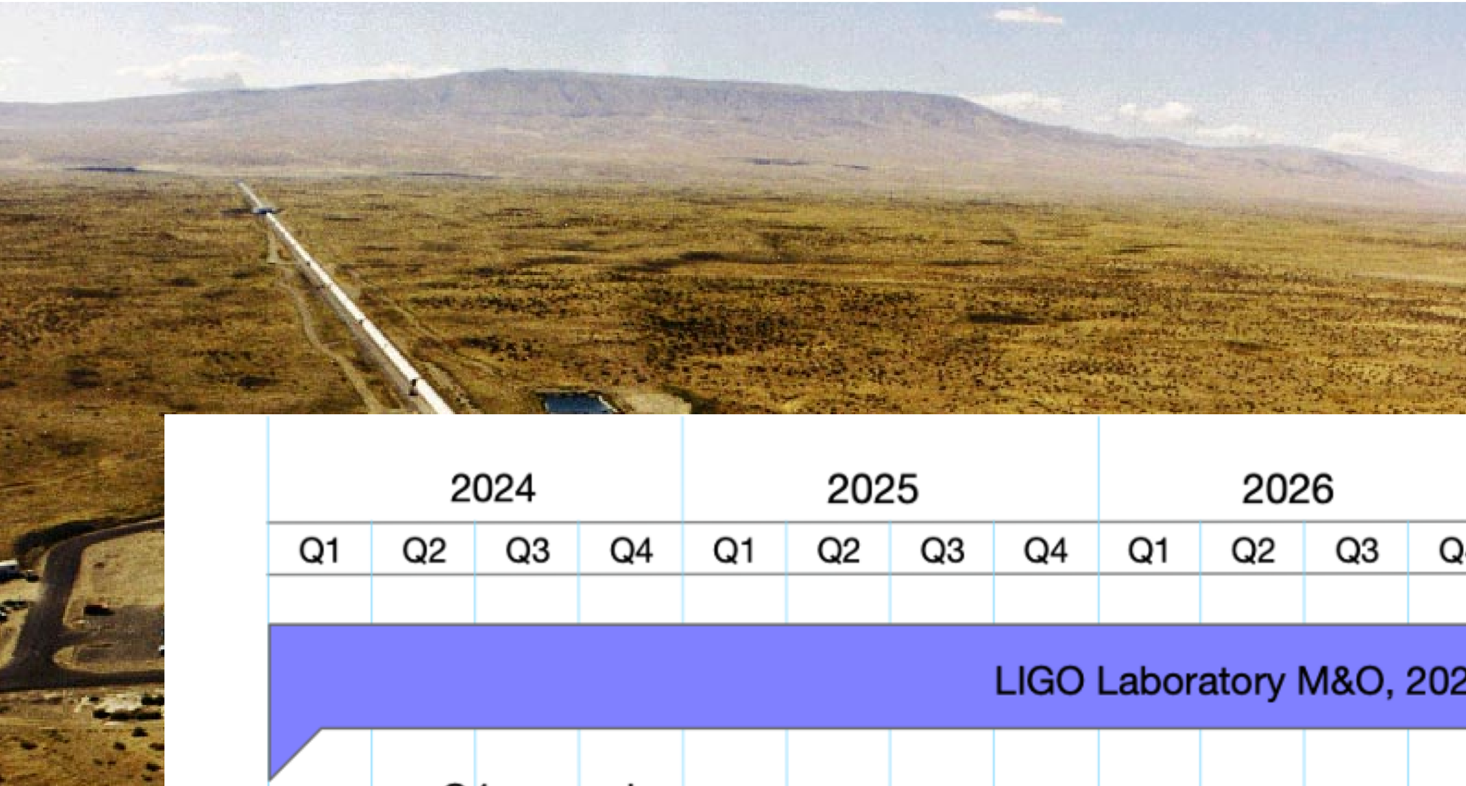
What is A$^{\#}$?

- Upgrade to the LIGO detectors after O5 (install ~ end of 2029)
- Recommendation of the Post-O5 committee (see T2200287)

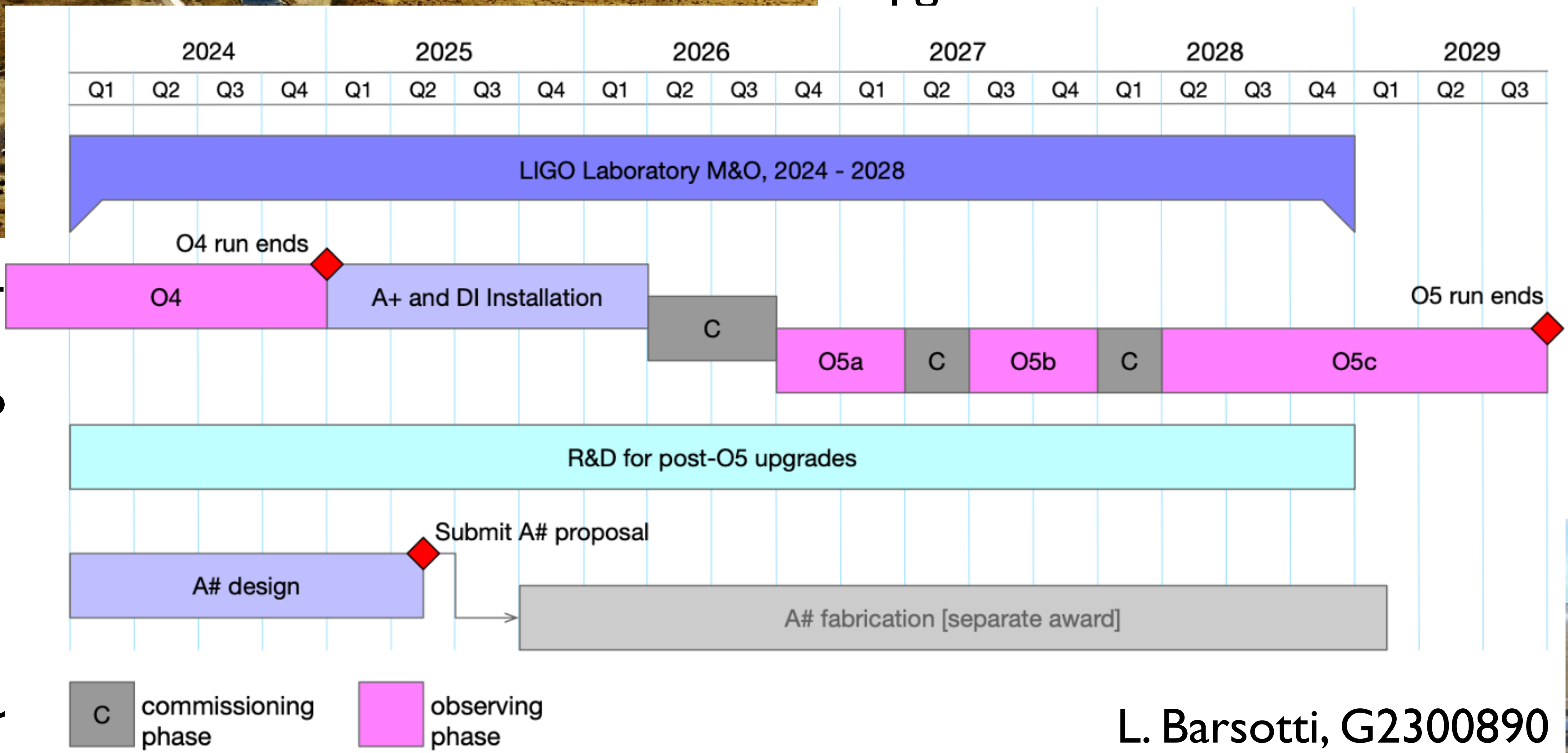
- Leverages what we are good at (1 micron laser, room temp. GEO-style suspensions), but
- Pushes hard on the technology
  - 100 kg optics on upgraded suspension with high-stress fibers
  - Coatings are even better than A+
  - 1.5 MW power,10 dB of squeezing
- Use good ideas now, practice for 3G detectors

Work led by Josh Smith (CSUF) and Kate Daniel (UA)

What is A#?



- Upgrade to the LIGO detectors



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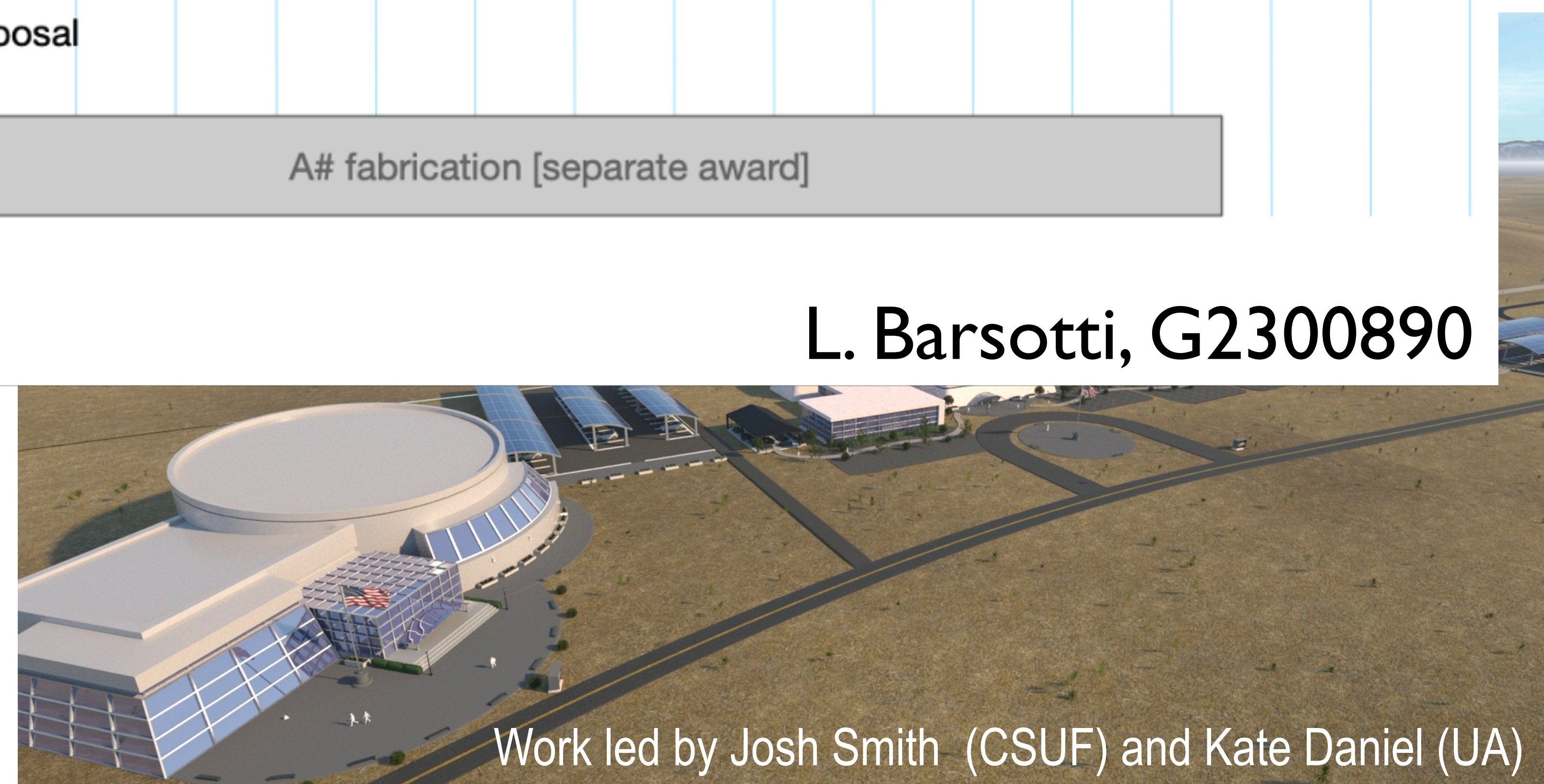
practice for 3G detectors

L. Barsotti, G2300890



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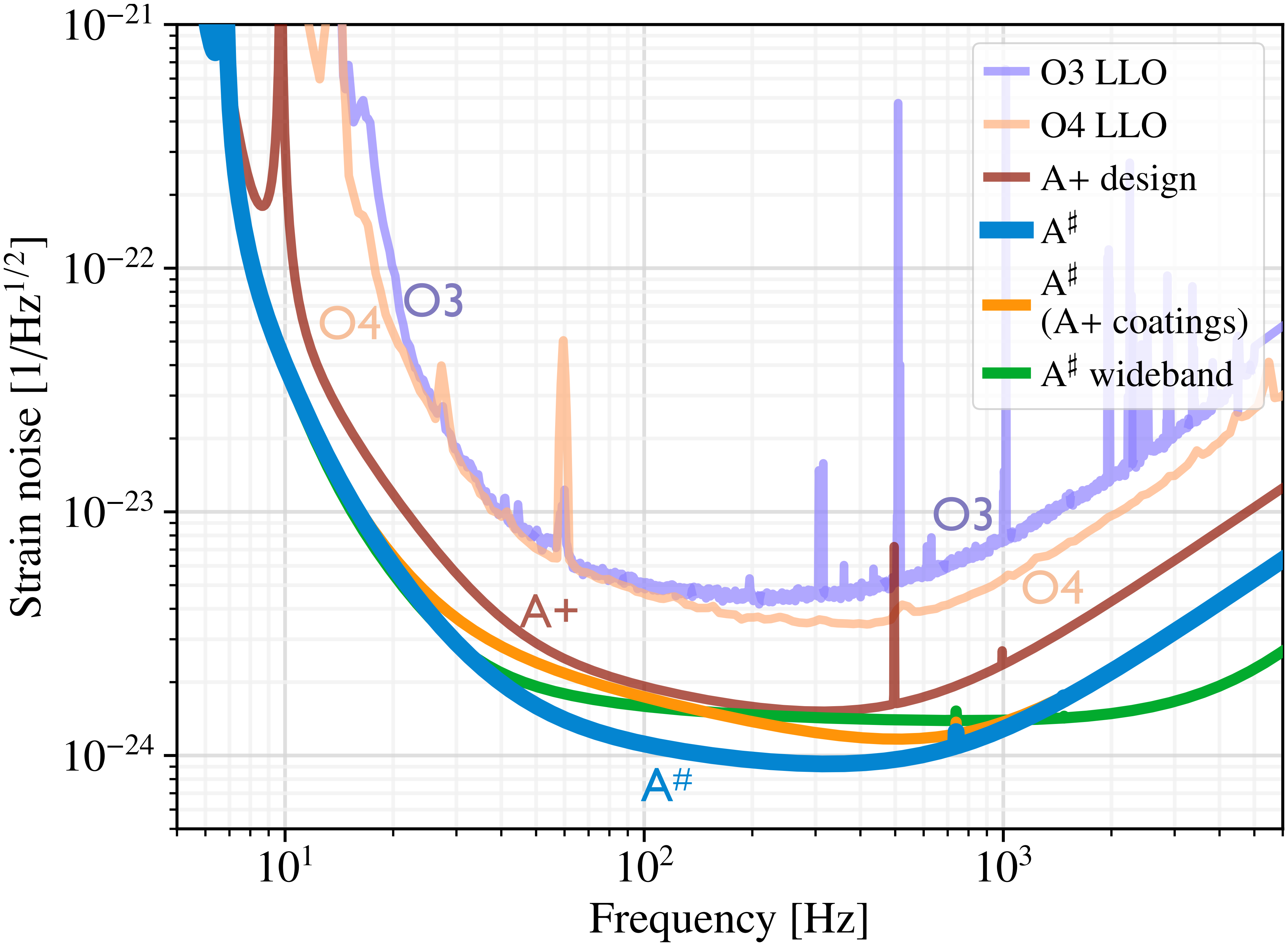
A# noise budget



K. Kuns, adapted from T2200287

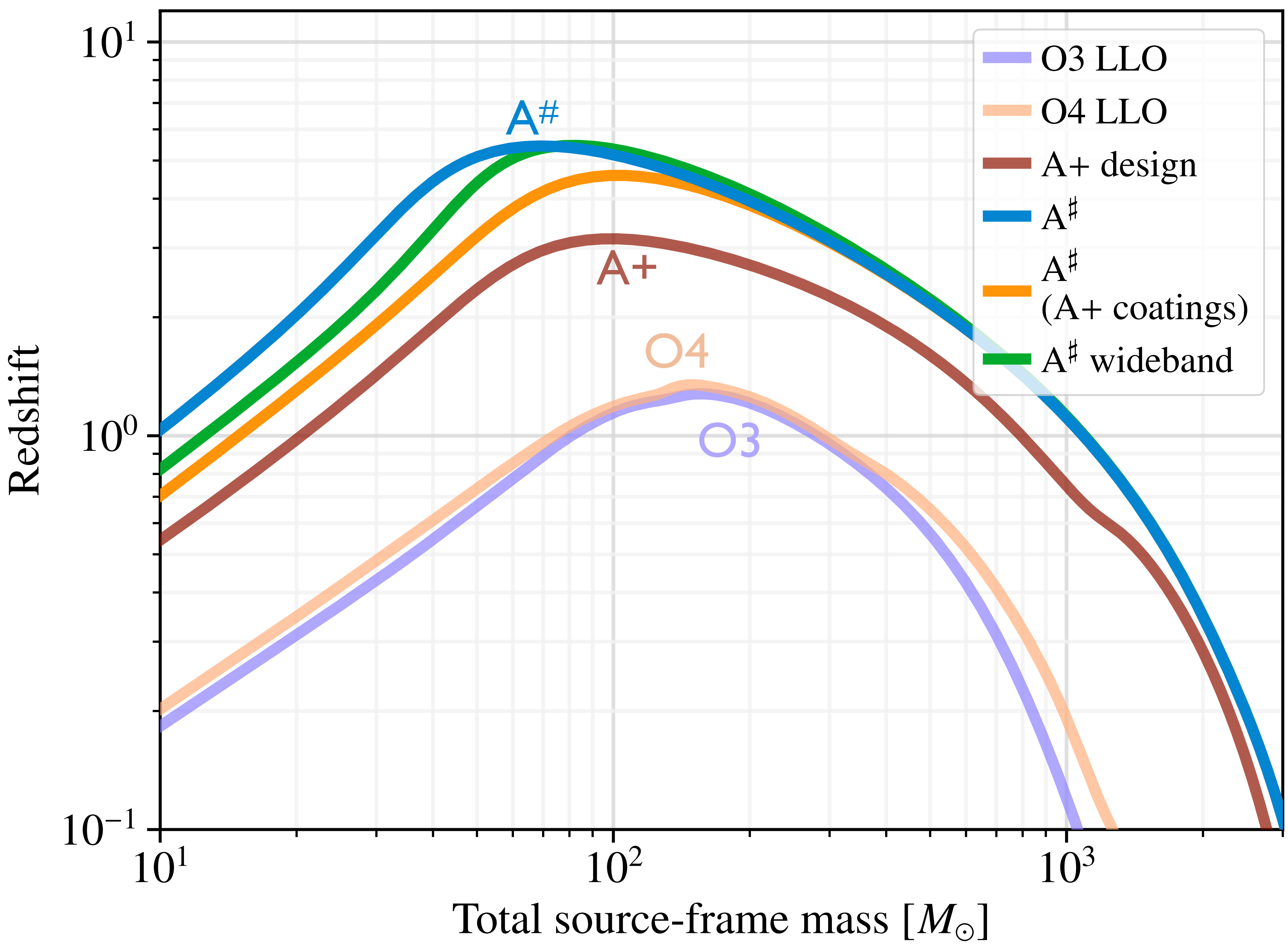
Event rates

- BNS and NSBH event rates are more than 4 time A+ rate (about 2x for A+ coatings)
- BBH is almost 3x the A+ rate

Configuration	Annual Detections		
	BNS	NSBH	BBH
A+	135^{+172}_{-78}	24^{+34}_{-16}	740^{+940}_{-420}
A$^\sharp$	630^{+790}_{-350}	100^{+128}_{-58}	2100^{+2600}_{-1100}
A$^\sharp$ (A+ coatings)	260^{+320}_{-140}	45^{+60}_{-27}	1150^{+1450}_{-640}
A$^\sharp$ Wideband (A+ coatings)	200^{+250}_{-110}	40^{+54}_{-25}	970^{+1220}_{-540}

Table 5: Plausible range of number of detections in a calendar year observing run for each class of binary. Ranges are based on the central 90 % credible intervals on astrophysical rates from O3 [28].

Astrophysical range for A#



Early warning

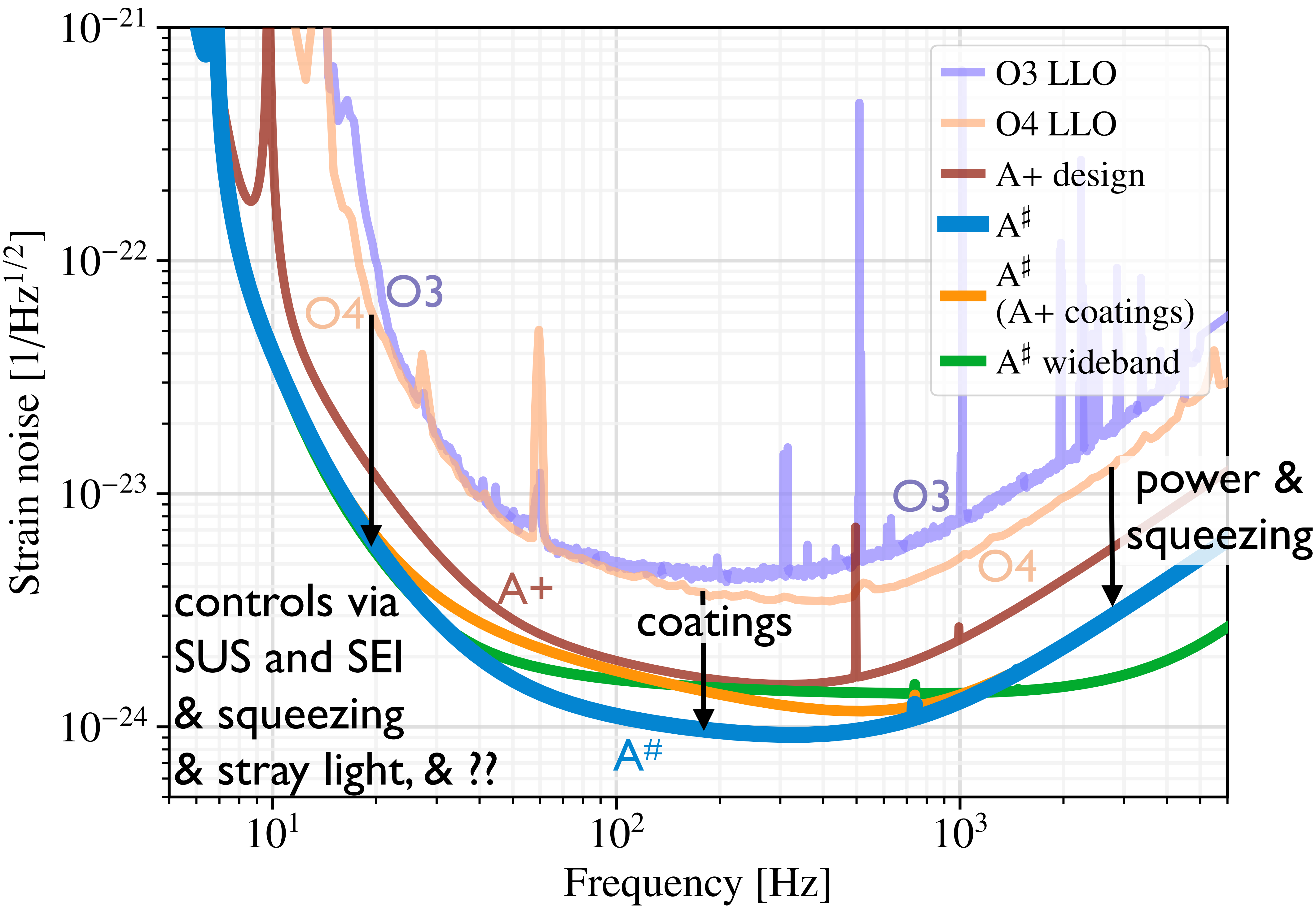
- Low frequency improvements allow 6 minutes of early warning for a BNS merger
  (SNR =8, z=0.03, ~3 times distance of GW170817)

Configuration	Range [Mpc] BNS	BBH	$t_{\rm early}$[min]	$z_{\rm max}$	Post-Merger $\rho_{\rm pm}^{(10)}$	$\rho_{\rm pm}^{(\rm max)}$
O3 LLO	130	1200	0.3	1.3	0.4	0.6
July 2022 LLO	120	1200	0.5	1.5	0.3	0.5
A+	350	2600	2.7	3.2	1.4	2.0
$A^\sharp$	600	3700	6.2	5.4	2.7	3.7
$A^\sharp$ (A+ coatings)	440	3000	6.1	4.6	2.7	3.4
$A^\sharp$ Wideband	490	3300	6.8	5.5	4.8	5.6

Table 4: Astrophysical performance of the scenarios shown in Fig. 1 for optimally oriented non-spinning binary systems. The BNS and BBH range estimates are for 1.4+1.4 $M_\odot$ and 30+30 $M_\odot$ systems, respectively. The early warning time $t_{\rm early}$ is the time before merger of a 1.4+1.4 $M_\odot$ system at $z = 0.03$ at which the cumulative SNR in a given detector reaches 8; $t_{\rm early}$ is heavily dependent on the low frequency noise (as illustrated by $t_{\rm early}$ for the July 2022 LLO case, at 28 s, compared to O3, at 16 s, even though the latter has a bit higher BNS range), and the GWINC design curves do not include excess technical noise which has historically been present. $z_{\rm max}$ is the maximum redshift at which an equal mass binary can

A# noise budget

What do we need to achieve the A$^{\#}$ target?

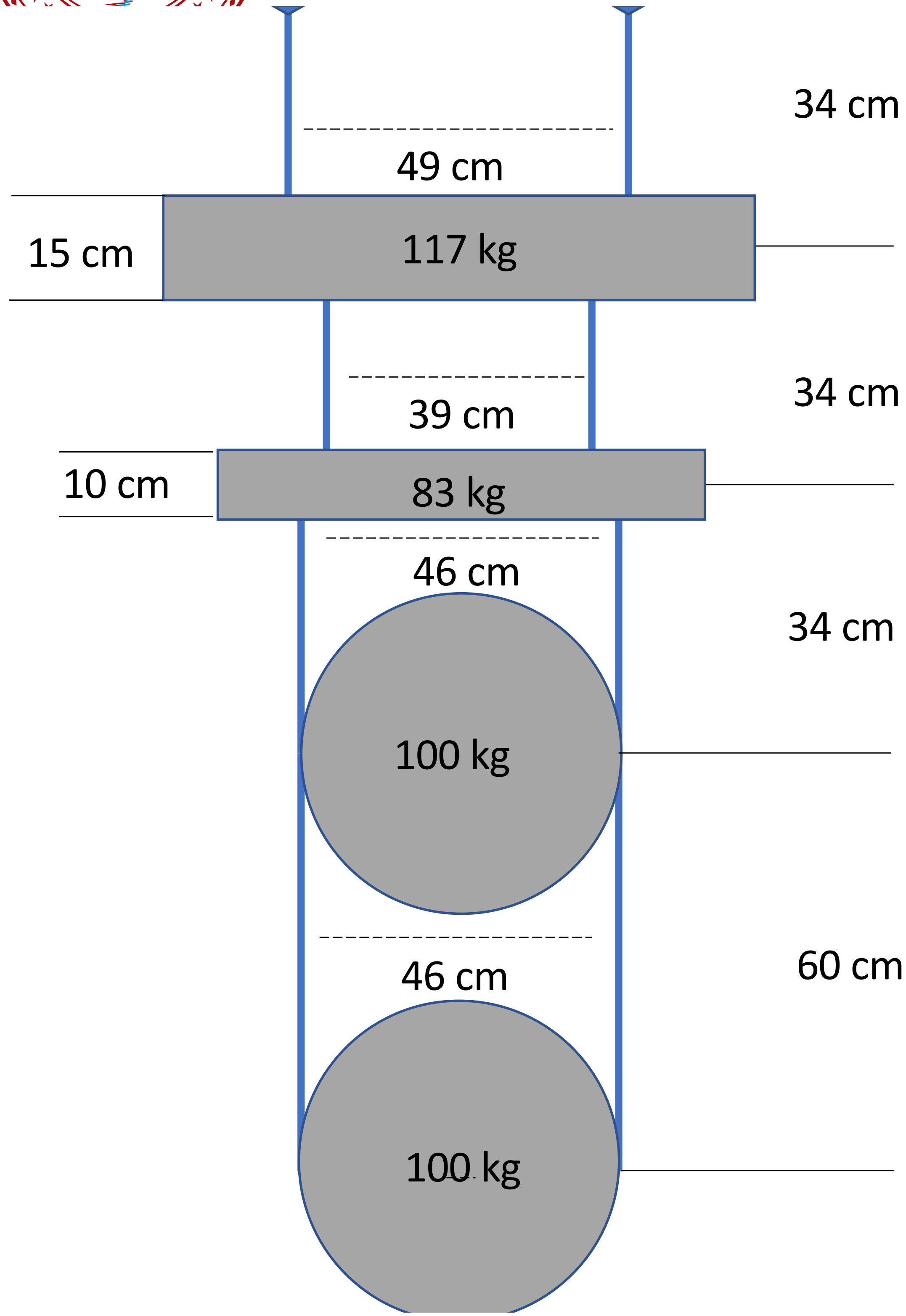


K. Kuns, adapted from T2200287

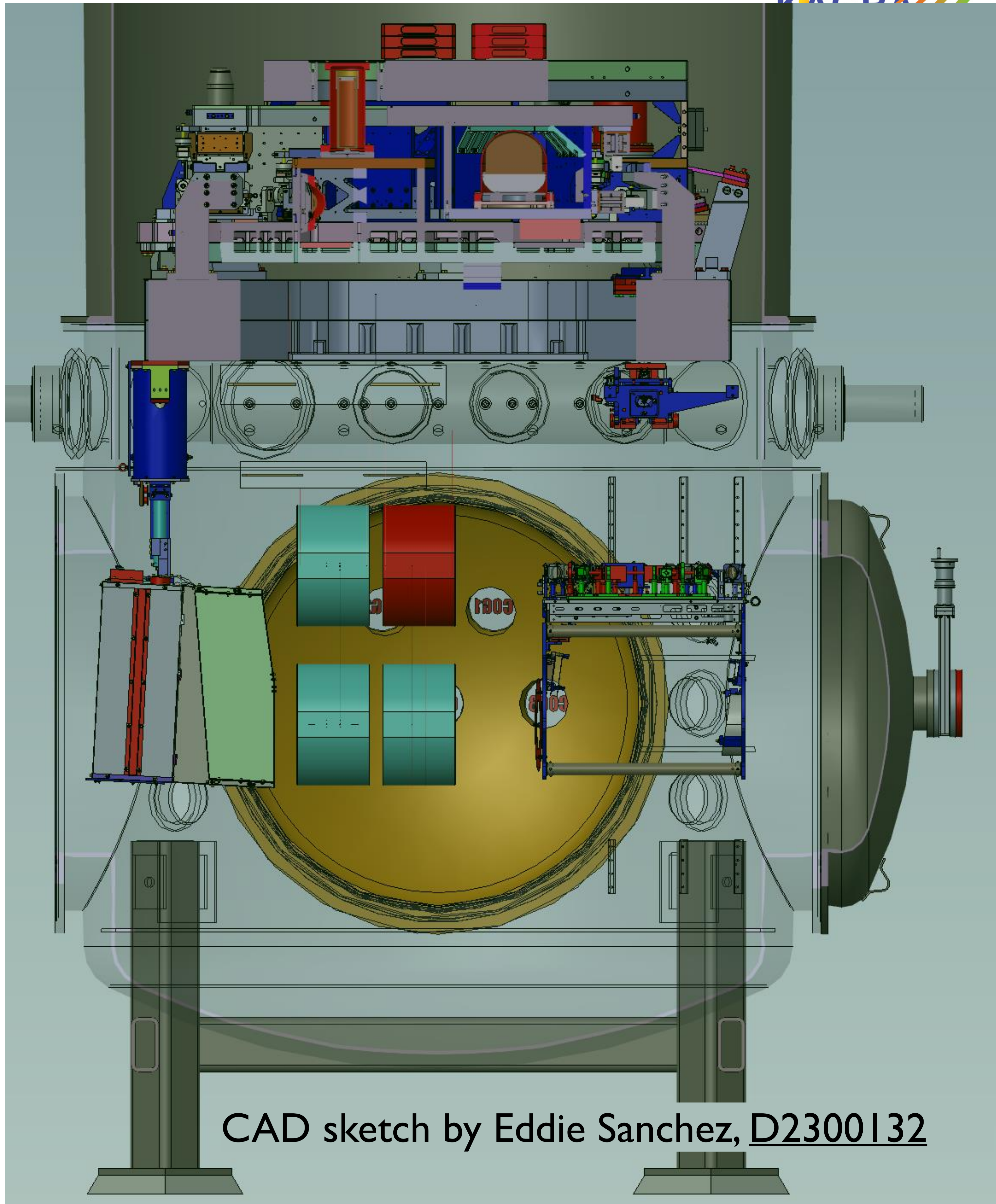
Low Frequency

- Design based on GEO-style aLIGO suspension,
  updated with LVK research & lessons from aLIGO
  design being done by the Heavy SUS group of the SWG
- 100 kg optics on upgraded suspensions
- Higher stress fibers (1.6 GPa)
  - Lower thermal noise
  - reduce bounce & roll modes below 10 Hz
  - raise violin mode frequencies
- Replace OSEMs with local IFO sensors (HoQI, SmarAct, COBRI)
- Suspend from 4 wires & adjust mass ratios
  improve the controllability, reduce the cross-couplings
- New sensing systems for seismic isolation (CRS, SPI, geophones)
- Faster installation, violin mode dampers

SUS pictures



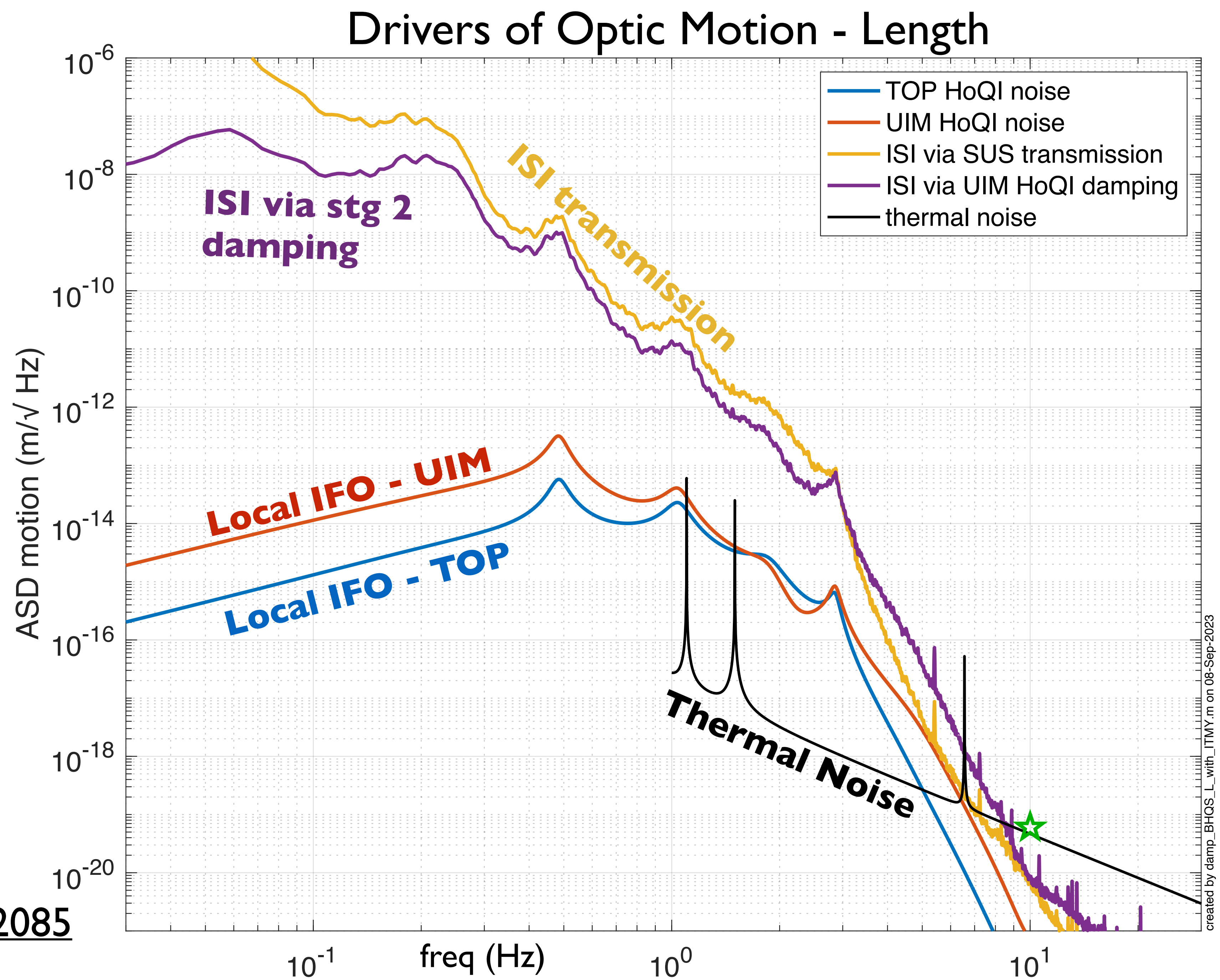
E. Bonilla, G2300711, T2300137



CAD sketch by Eddie Sanchez, D2300132

Optic Motion

- Total is below the 6e-20 target @10 Hz
- Assumes local IFO sensors on the TOP and UIM
  - the ISI motion dominates at all frequencies (best chamber, quite time)
  - opportunity for better ISI sensors

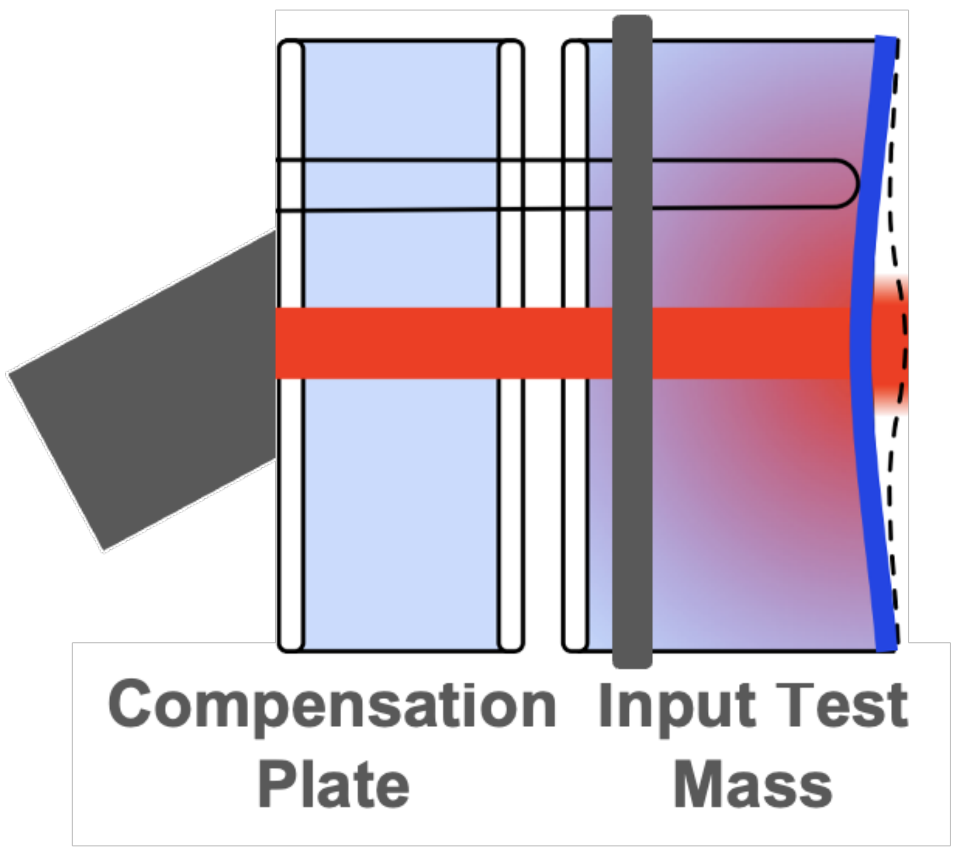


B. Lantz, SWG log 12085
LVK talk G2301746

High Power

- Increase the circulating power to 1.5 MW (4x the current arm power)

- Higher power laser (LZH, AEI), better thermal control
- 10 dB squeezing (best at LLO 6 dB) lower loss, better mode matching
- Challenge for point absorbers (coatings) and TCS



First Detection:	100 kW
O3:	239 kW
Now:	375 kW
A+ target:	750 kW
A#:	1500 kW

first det: P1500248
O3: P2000122
now: LHO alog 72441

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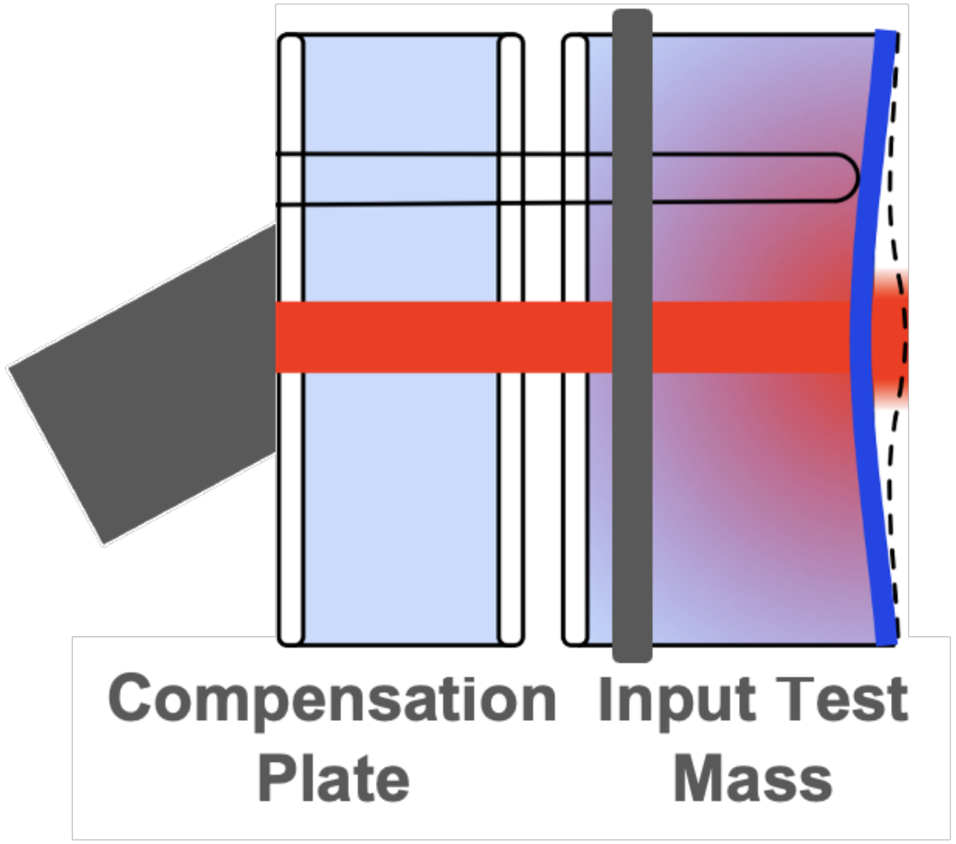

First Detection:	100 kW
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LHO was 420
LLO only 320

first det: P1500248
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Huy Tuong Cao, G2300624

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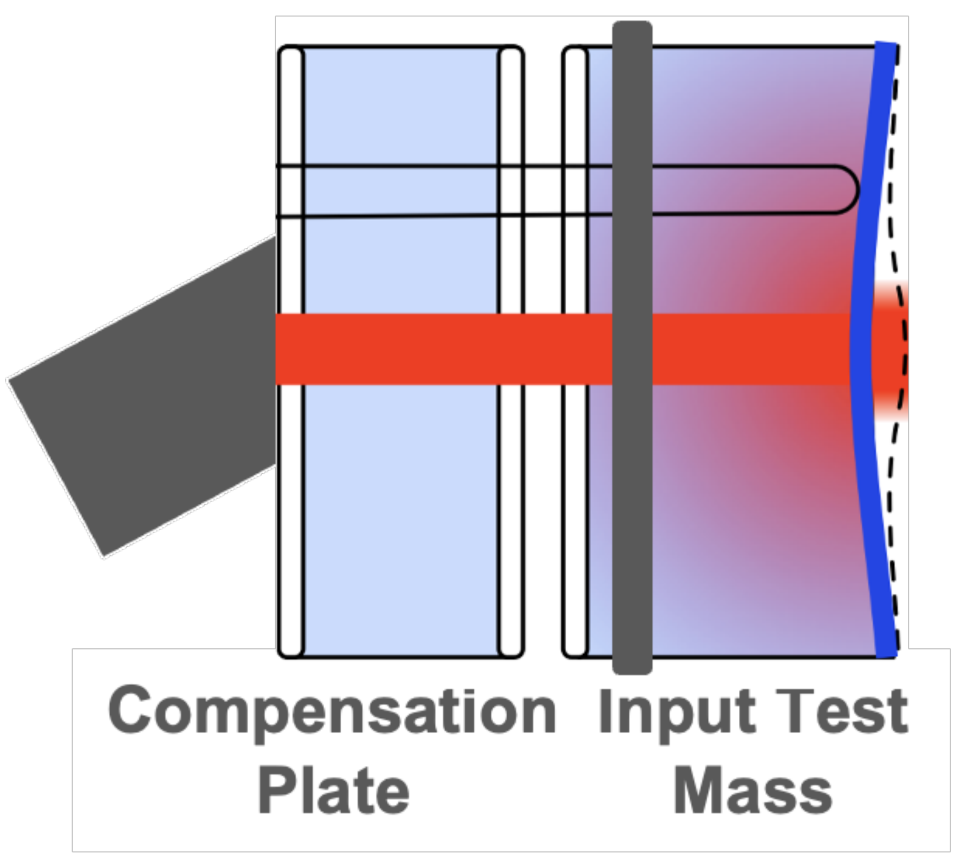

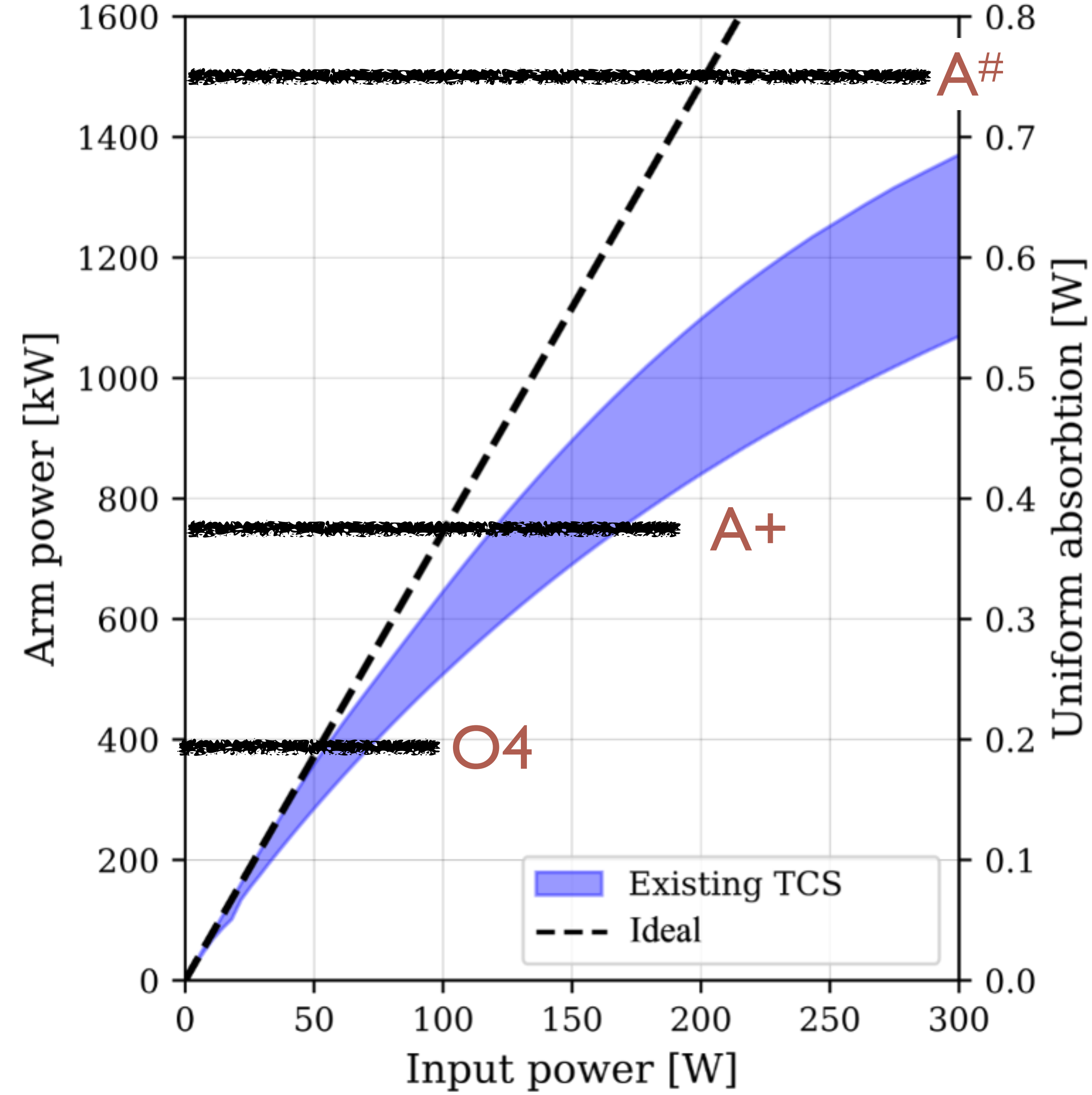

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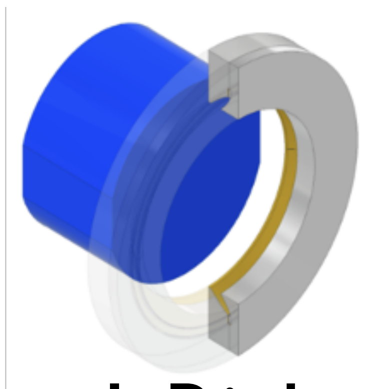
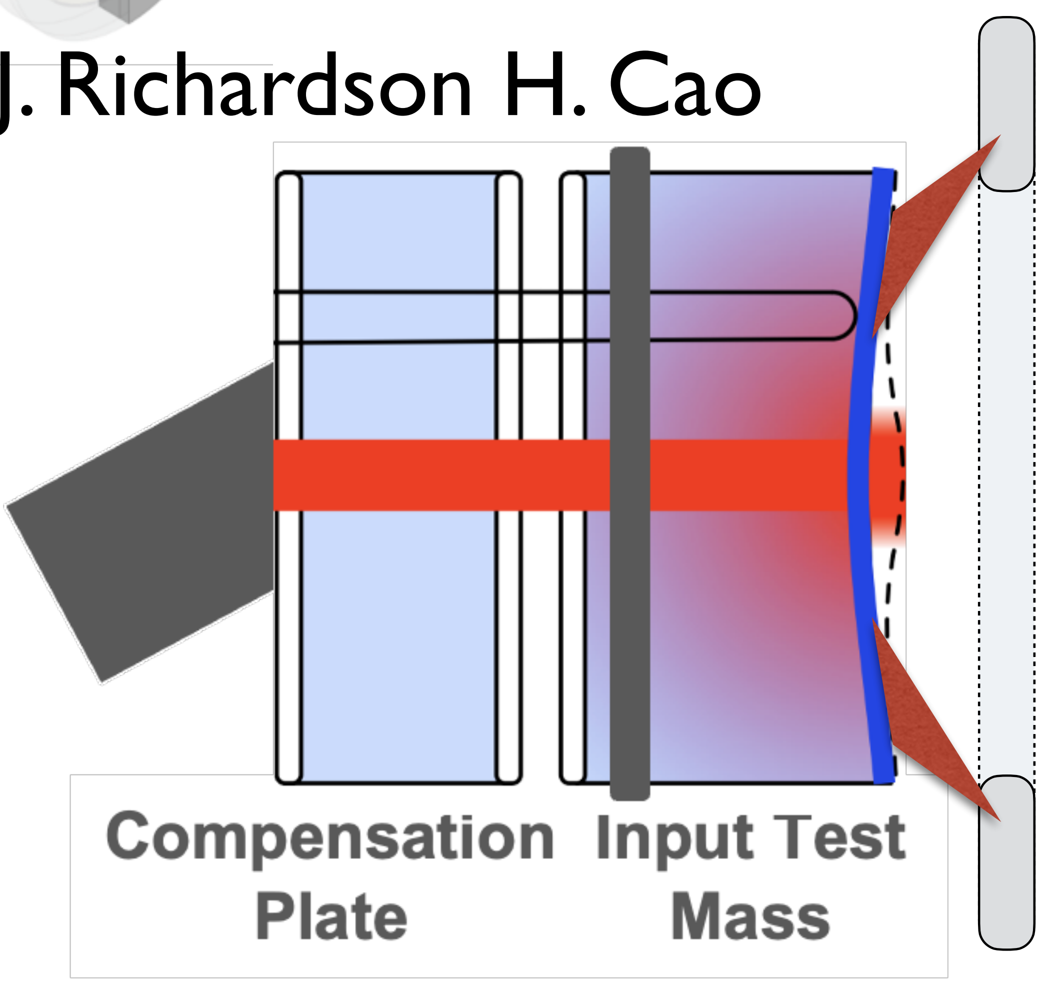
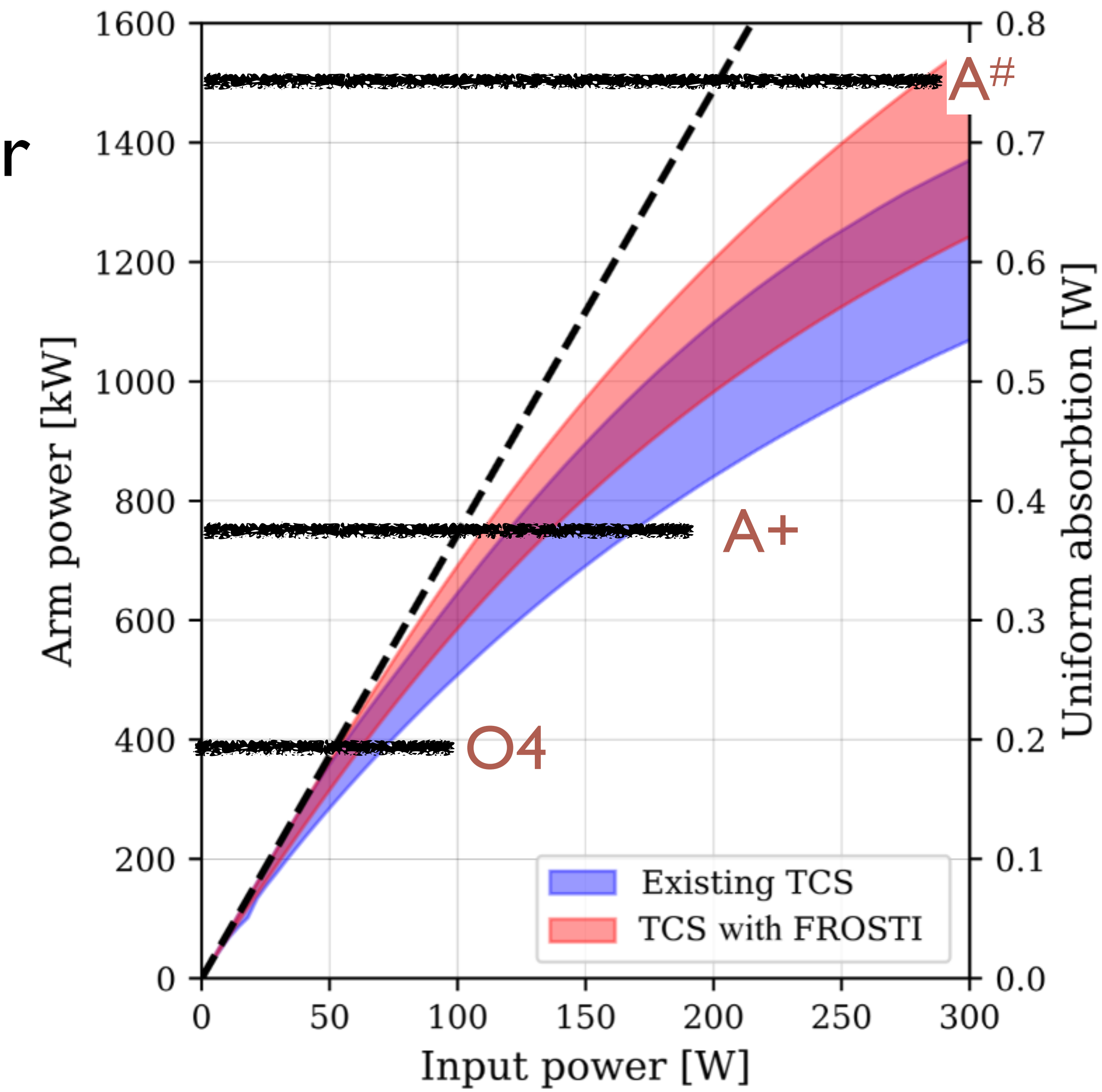


- New FROnt Surface Thermal compensator (FROSTI)

J. Richardson H. Cao

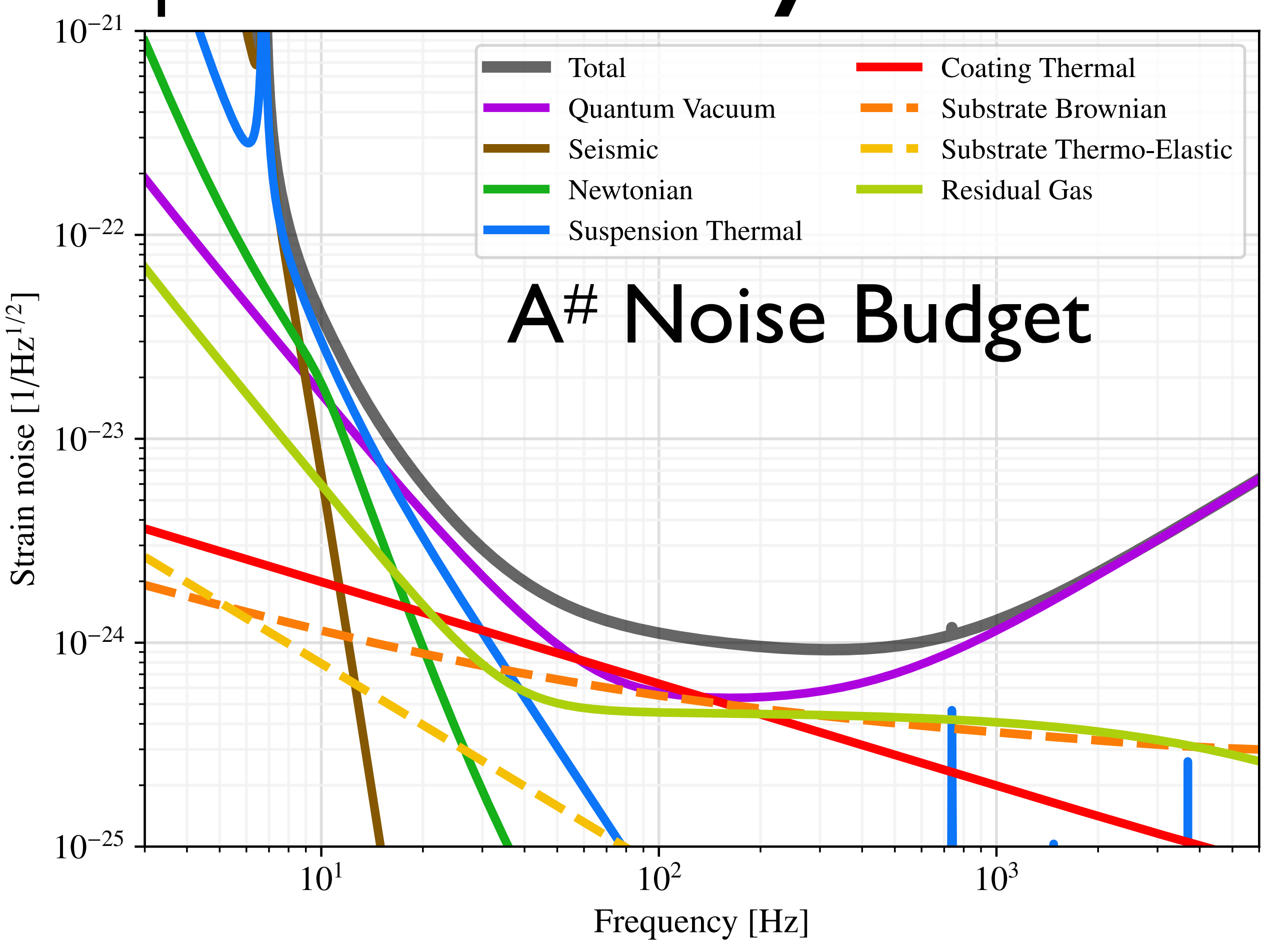


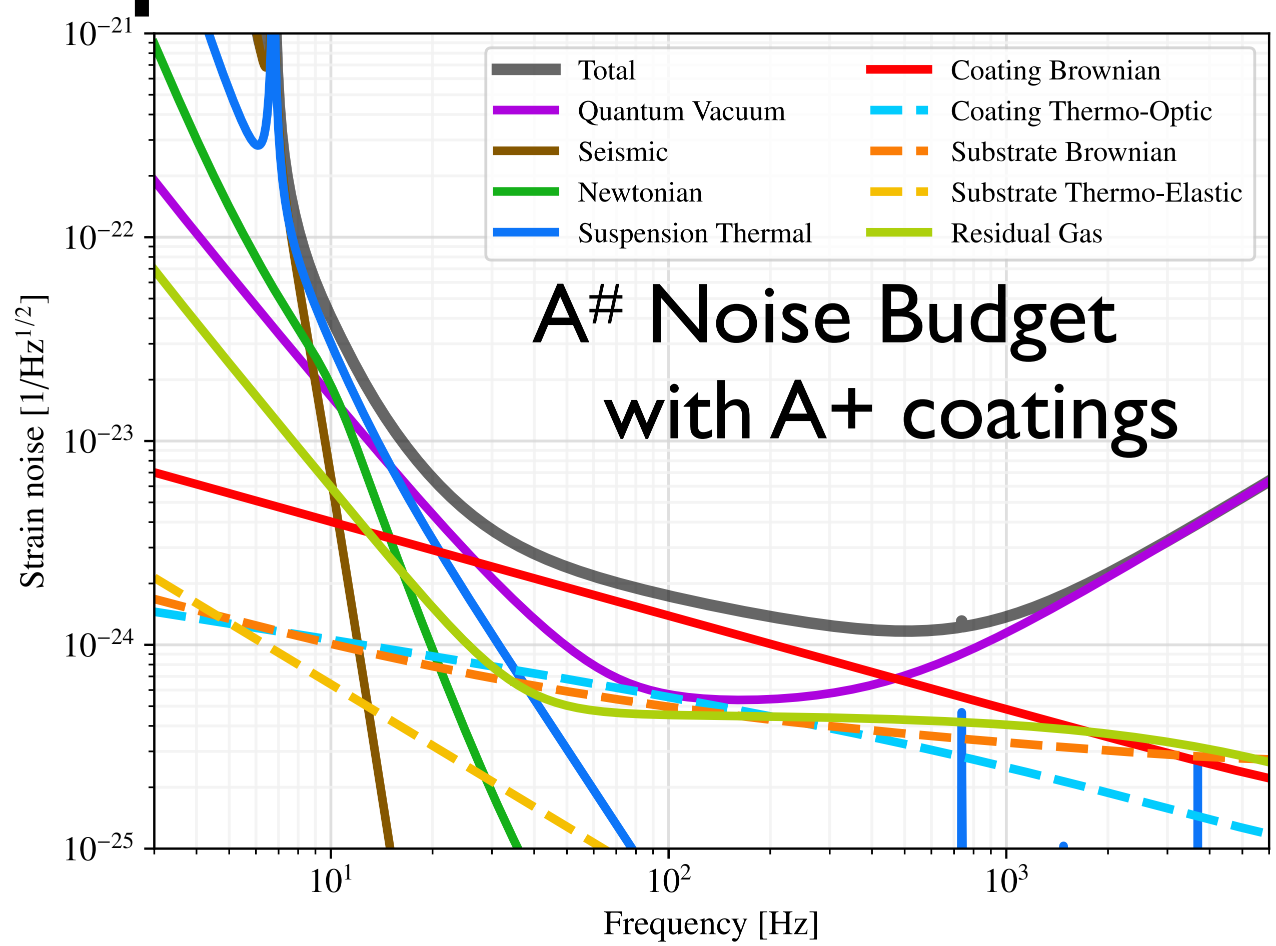


Coatings

Developing improved coatings for A# is critical.

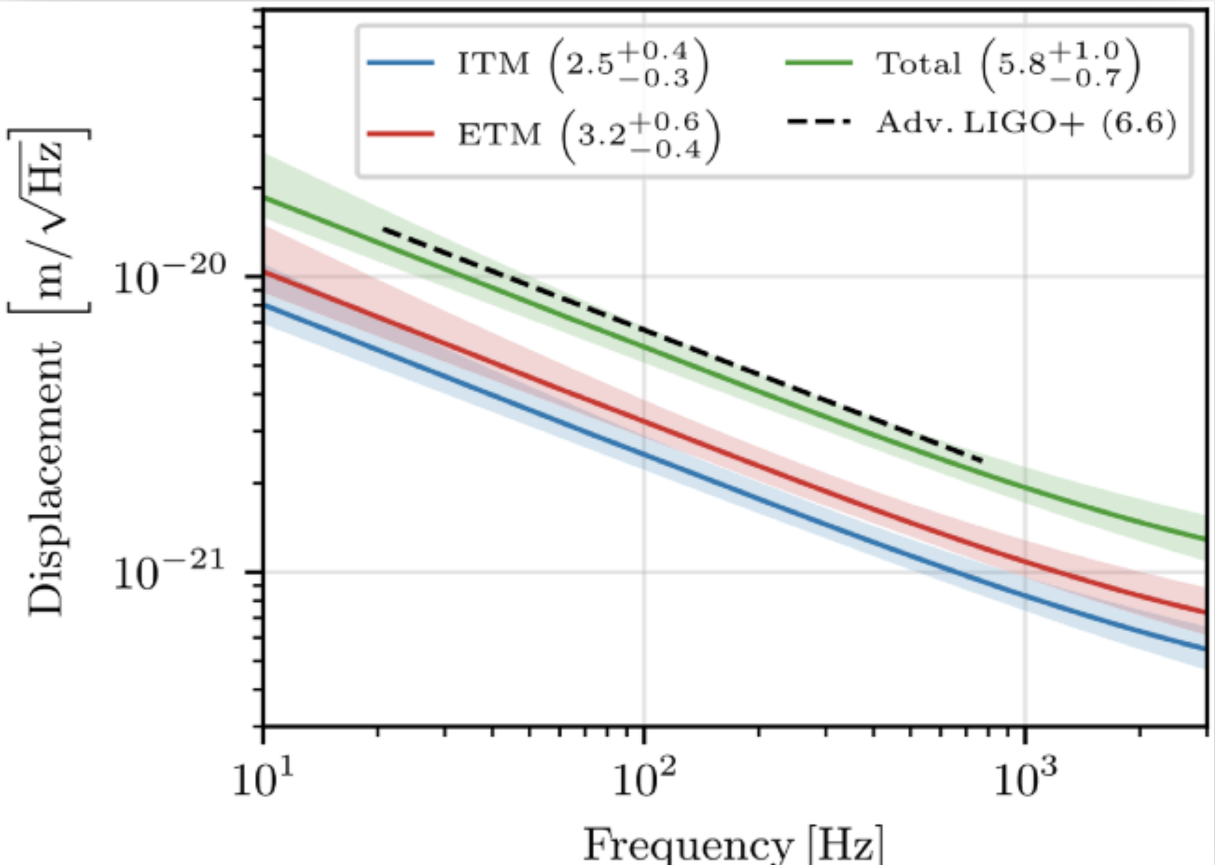
- A+ coatings could be used, but 2x lower noise in the design gives significantly improved science. **Crystalline** & **Amorphous** are both in R&D





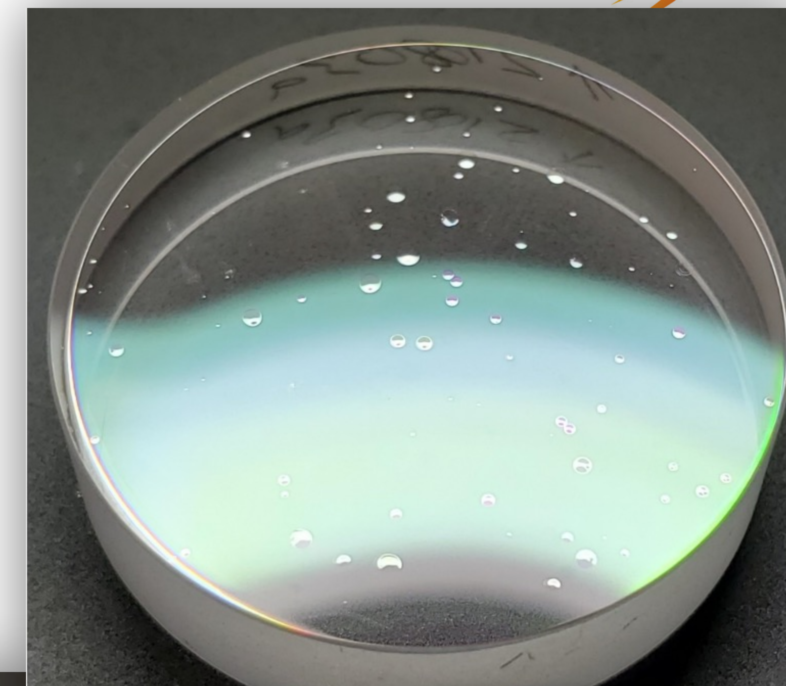
- Extensive work is underway to improve the **amorphous coatings**
  Focus is lower mechanical loss and fewer point absorbers.
  Silica is good enough, but we don't have a good-enough high index material
- Leading systems: Ti-doped Germania, Ti-doped silica, and Silicon Nitride

Not just a loss…



Vajente et al. Phys. Rev. Lett. 127, 071101 (2021)

multi-layers
optical absorption
point absorbers
deposition
annealing

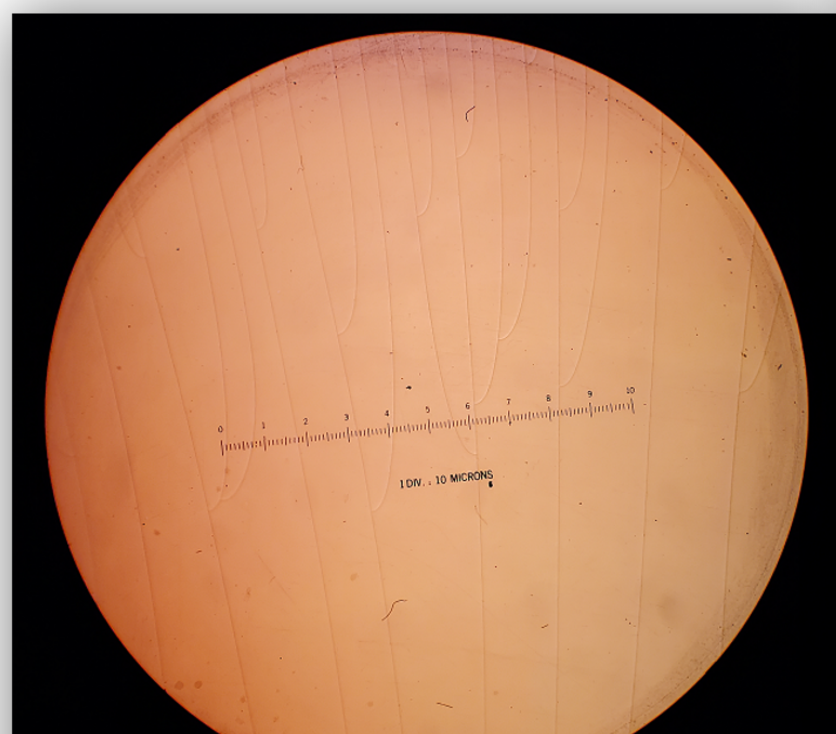

Credit: A. Davenport, G2200805

bubbles

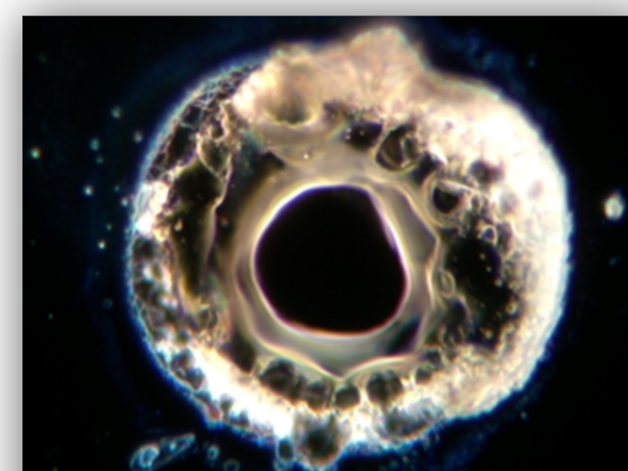
a good process is hard to find…


Credit: A. Davenport, G2200805

cracks



Credit: A. Davenport, G2200805


Credit: Billingsley *et. al*, G1800345

point absorbers

AlGaAs coatings

- Crystalline GaAs/AlGaAs coatings have very low thermal noise
- But - Experiments underway to explore the thermo-optic/elastic noise, intensity-dependent non-Brownian noise observed at JILA* and NIST (both isotropic and birefringent), effects of static and thermal-gradient-induced birefringence, phase errors over large areas, and point absorbers and optical damage effects at high average power.
- LIGO Lab has several 10 cm mirrors, but no one has made one big enough for LIGO
- For 30 cm coatings, estimate for
  - GaAs substate growth, MBE depositions, coating transfer
    $22 M & 3-5 years
  - $3 M to start the substrate process

MBE machine at IQE, North Carolina

* JILA systems at different temperature & freq

S. Penn, G2301065, G. Harry, G2301351

Conclusion

- A# is the plan for upgrades in the current facilities after O5.
- Its going to be expensive and hard.
- but it's worth it -
- The astrophysics is compelling - bigger masses, more events, possible early warnings
- and it flexes our CE muscles -
  low freq, big optics, high power, squeezing, ~coatings…
  the sooner we push these upgrades into operation, the sooner we can push the range out to the edge of the earliest star formation

Technical Risks

Inability to operate at the power level of 1.5 MW in the arms

- Thermal distortions in the test masses – can we really get rid of point absorbers?
- Parametric instabilities
- Control problems associated with radiation pressure should be mitigated by larger test masses

- Insufficient compensation of thermal distortions at 1.5 MW
  - Resulting optical loss would limit squeezing (particularly at high frequencies)

- No improvements in coating thermal noise
  - AlGaAs doesn't work out: has excess noise, or can't fund the large-scale development
  - No improvements in amorphous material mechanical loss

- Inability to identify & mitigate low-frequency technical/mystery noises

G2202126, P. Fritschel