LIGO VOYAGER:
risks and challenges

RXA, A. Brooks, C. Wipf, K. Arai, M. Laxen, B. Shapiro, R. Bhatt, F. Salces-Carcoba

G2300554

image: Eddie Sanchez

Voyager Update Summary:

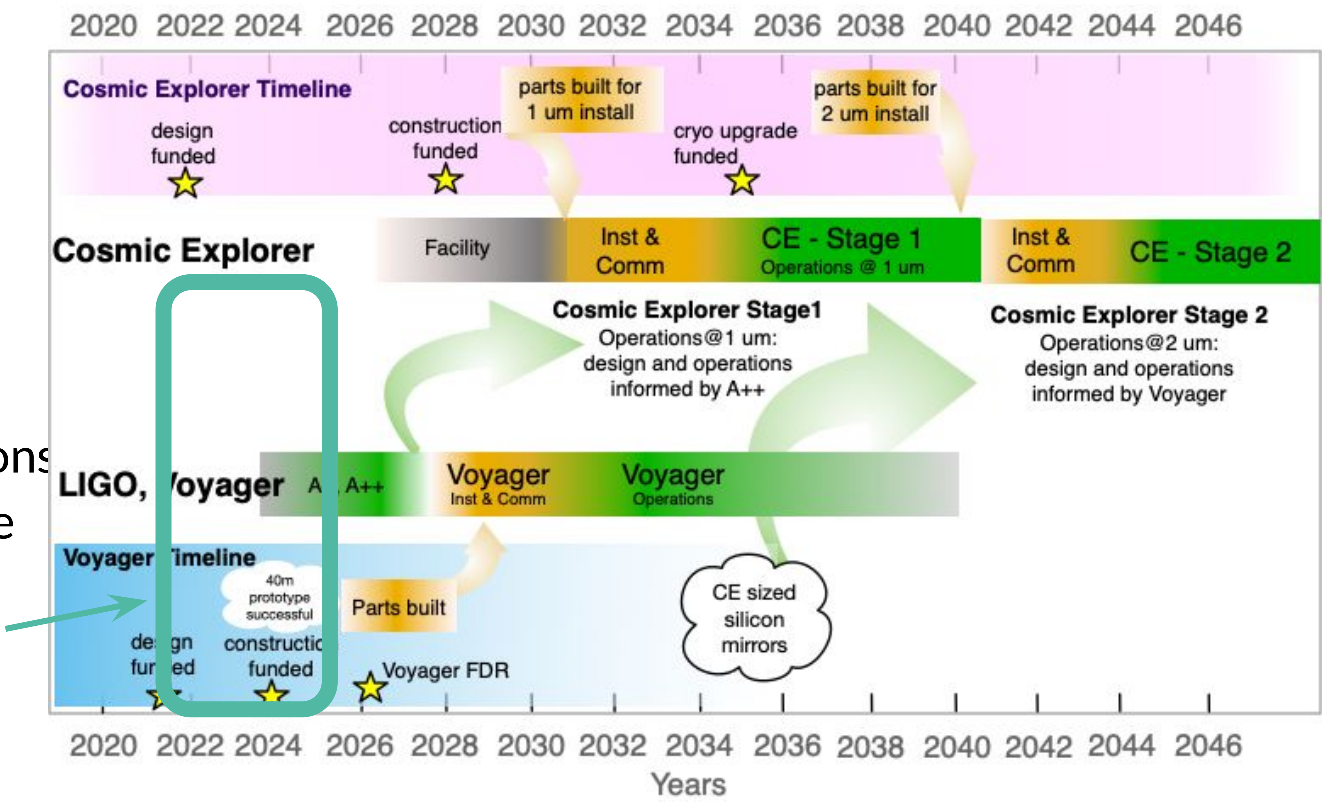
1) What is Voyager?
2) Why a Voyager?
3) initial/intermediate Voyager
4) Risks, etc.
5) Formation of Voyager Review Committee

Why Voyager?

1) We want a significant increase in Science Reach *soon*.
2) Likely that we cannot achieve this with glass / room temperature.
   a) high laser power degrades squeezing
   b) no low thermal-noise coating
3) Voyager:
   a) better high power handling
   b) ~4x lower coating noise

Outline:

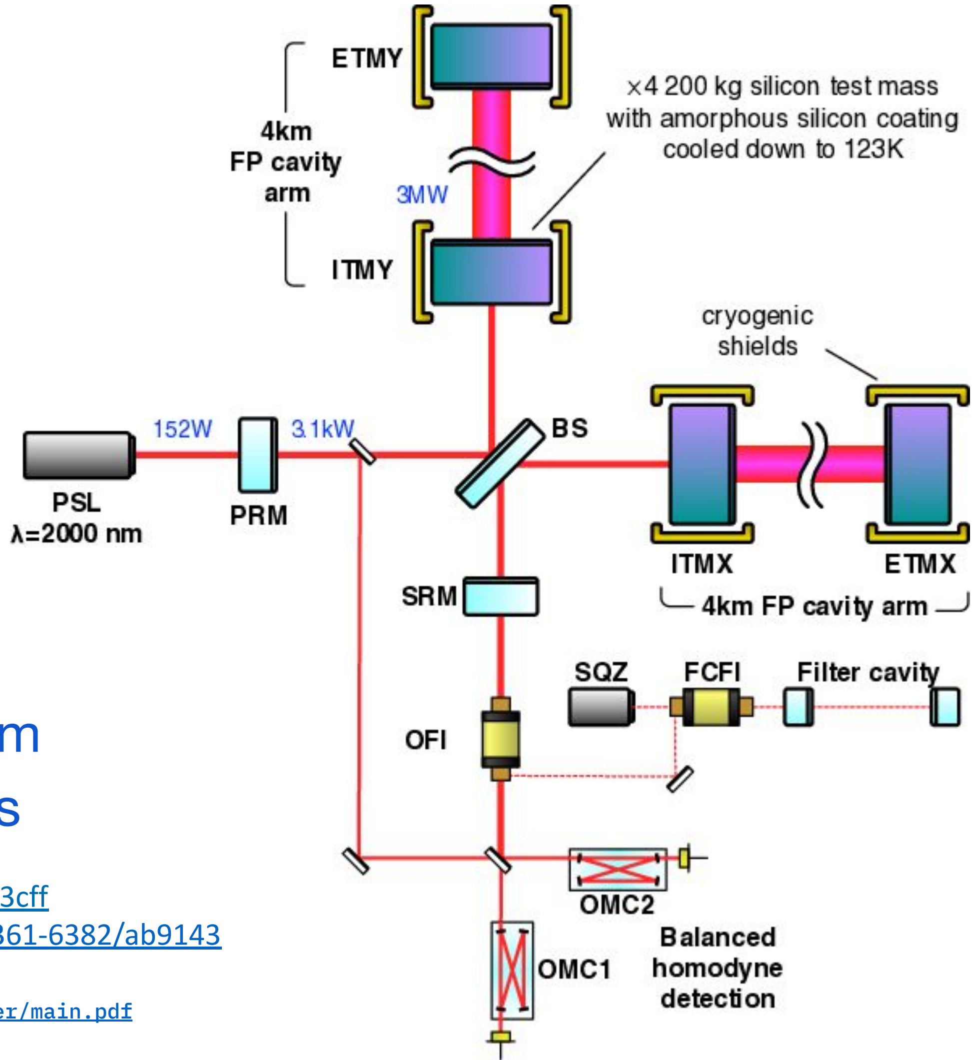
- Voyager Intro
- Open R&D questions
- Voyager Prototype
- Risks / Challenges



timeline has already slipped since 2020

Voyager

1) **~50x increase in rates**
2) Intermediate step on the way to future detectors
3) ~Less cost than Adv LIGO
4) Re-use most of LIGO parts (except optics & Quad SUS)
5) Mitigates some problems with room temperature / glass interferometers

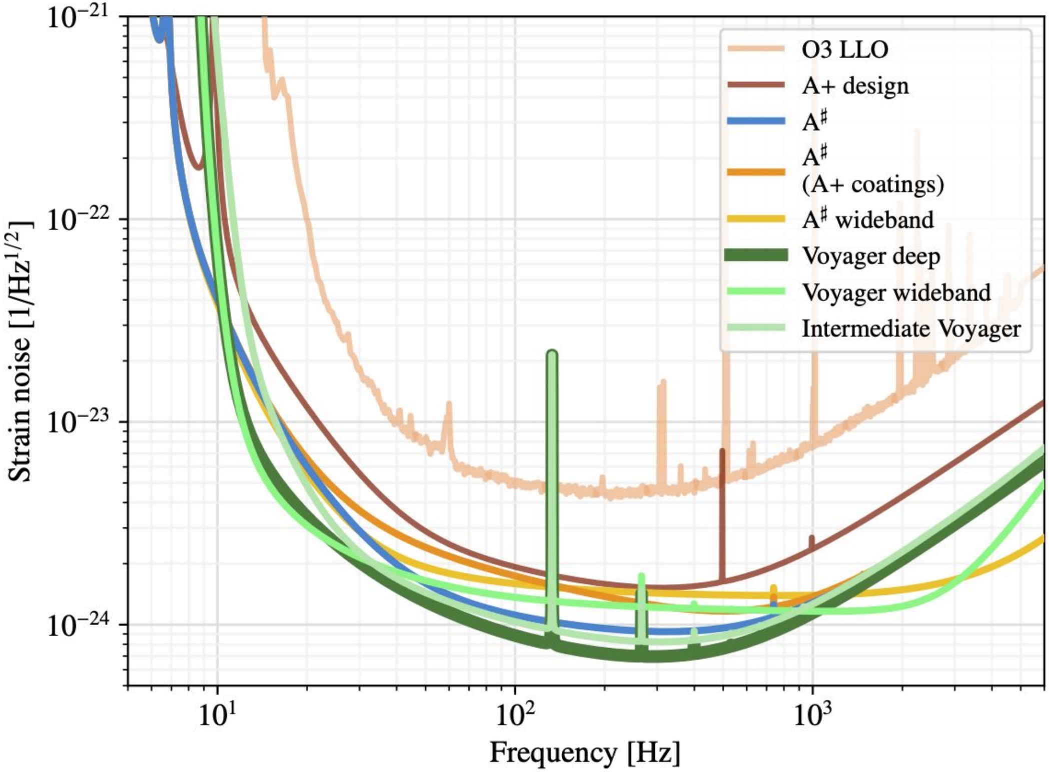


Science Metrics Paper: https://doi.org/10.1088/1361-6382/ab3cff
Instrument Paper: CQG (2020) https://doi.org/10.1088/1361-6382/ab9143

'Living' whitepaper: https://docs.ligo.org/voyager/voyagerwhitepaper/main.pdf

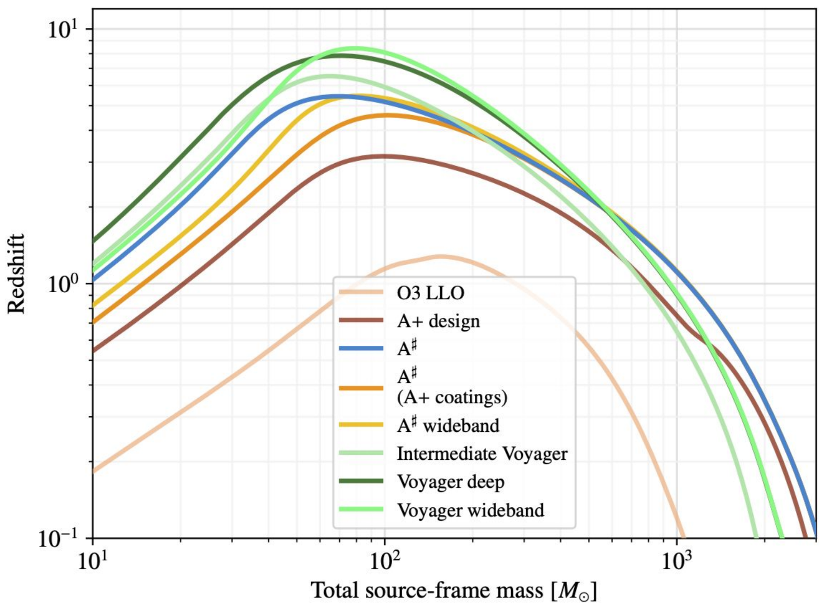
Voyager Noise & Range Estimates

```
CONFIGURATION   BNS/Mpc   BBH/z
Voyager deep    777       7.71
Voyager wide    594       7.48
```



Cosmological Reach:

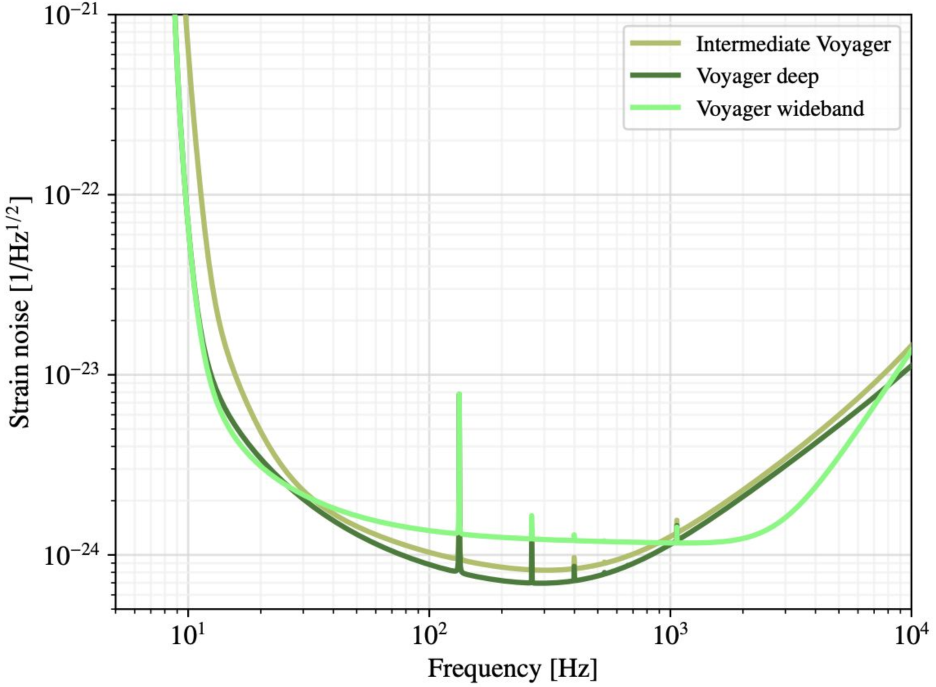
z > 6 for most the BBH range



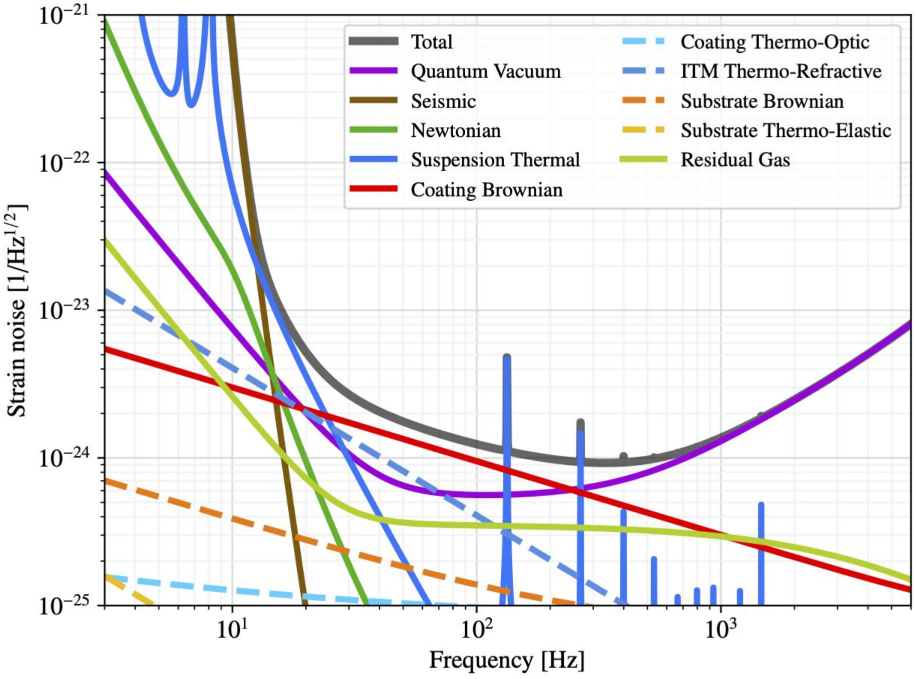
from post-O5 report (v1)

intermediate Voyager:
lowest risk version which gets 50% of sensitivity

Overview



Voyager Intermediate



Risks vs. Intermediate Voyager

Risks:

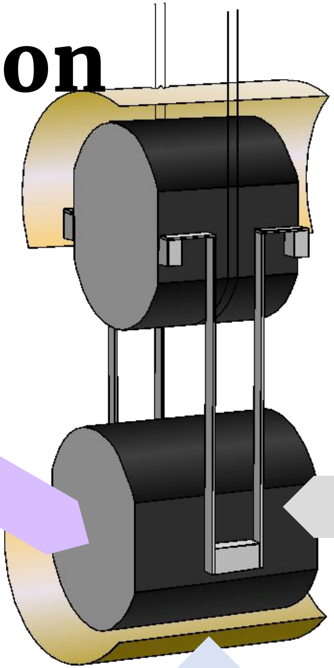
1. Sourcing* 45 cm Si w/ low absorption
2. Absorption in Si @ 2 um
3. Absorption in a-Si @ 2um
4. low QE in photodetectors
5. Birefringence in ITM
6. Birefringence in BS
7. Noisy Cryogenics

Risk Reducers:

1. Smaller (30 cm) ITM
2. Composite Mirror for efficient radiation
3. *Metal* Blade springs (PUM)
4. 95% QE PDs
5. lower (100 W) power lasers
6. silica BS

* large overlap Einstein Telescope on many aspects: sourcing 45 cm mCz Si, cryogenics, lasers, coatings, etc.

Cold Quad Suspension



① Amorphous silicon coating

- Reduces thermal noise. Prospect of ~5**x** reduction (ASD) from aLIGO level
- Favors **2 μm** wavelength

② Crystalline silicon substrate

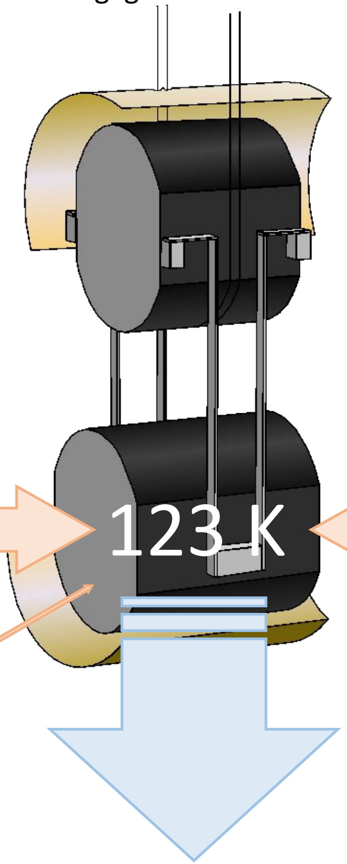
- Improves quantum noise. **200 kg** mass, **3 MW** power
- High thermal conductivity, ultra-low expansion at **123 K**

③ Radiative cooling (quiet)

- Efficient at **123 K**
- Suspension design not constrained by cryogenics

HEAT BUDGET

limits the tolerable absorption in the optical coating and substrate…



Coating: **3 W**

1 ppm absorption
x 3 MW circulating power

Substrate: **3 W**

10 ppm/cm absorption
x2 x 55 cm ITM x 3 kW

Beam tube: **15 mW**

10 W
net emission to cold shield

…are these limits achievable?

Having a Cold Quad Suspension is OK for ISI

Questions

1. What about the mass and moment of inertia budget?

2. Will the sensors/actuators change with temperature?

Responses

1. Quad moved to center to permit removal of ballast mass. Reaction chain less massive than main chain. Many cryo parts mounted to chamber or stage 0.

2. Modeling can set bounds. May already be sufficiently isolated given mounting geometry, but experimentation will confirm. Worst case, add heaters.

Having a Cold Quad Suspension is OK for ISI

3. Will the blade springs drift too much?

4. Will the cryo parts add low frequency eigenfrequencies or seismically short the ISI?

5. Will the ISI eigenfrequencies change too much?

3. Experimentation needed, modeling fidelity likely not good enough. Worst case, add heaters.

4. Most parts will be mounted to the chamber or stage 0. Inner shields, which may connect to stage 2, may be suspended.

5. See item 3 response. Heaters likely not helpful, may need a warm & cold control design.

more details in backup slides

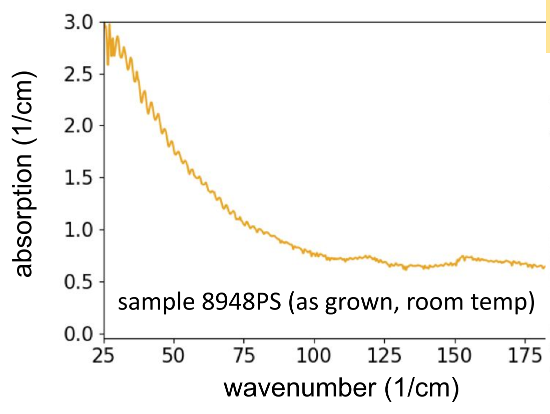
Magnetic Czochralski SILICON ABSORPTION

A Markosyan, D Tanner

Stanford

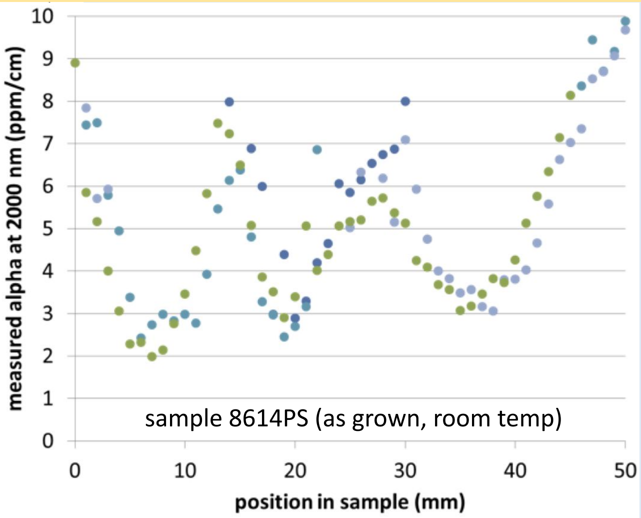
UNIVERSITY of FLORIDA

…dominated by **free carriers**



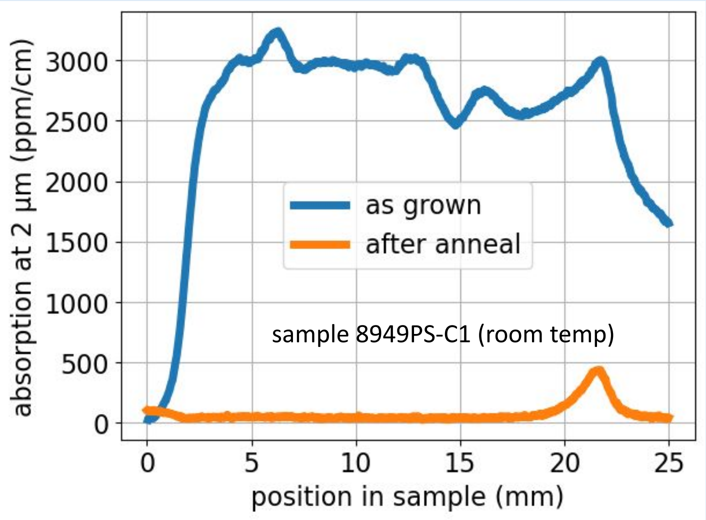
V. Martinez, G2101509

…reaches ~**2 ppm/cm** in best samples



A Markosyan, G1700480

…suppressed ~100× by **rapid anneal**

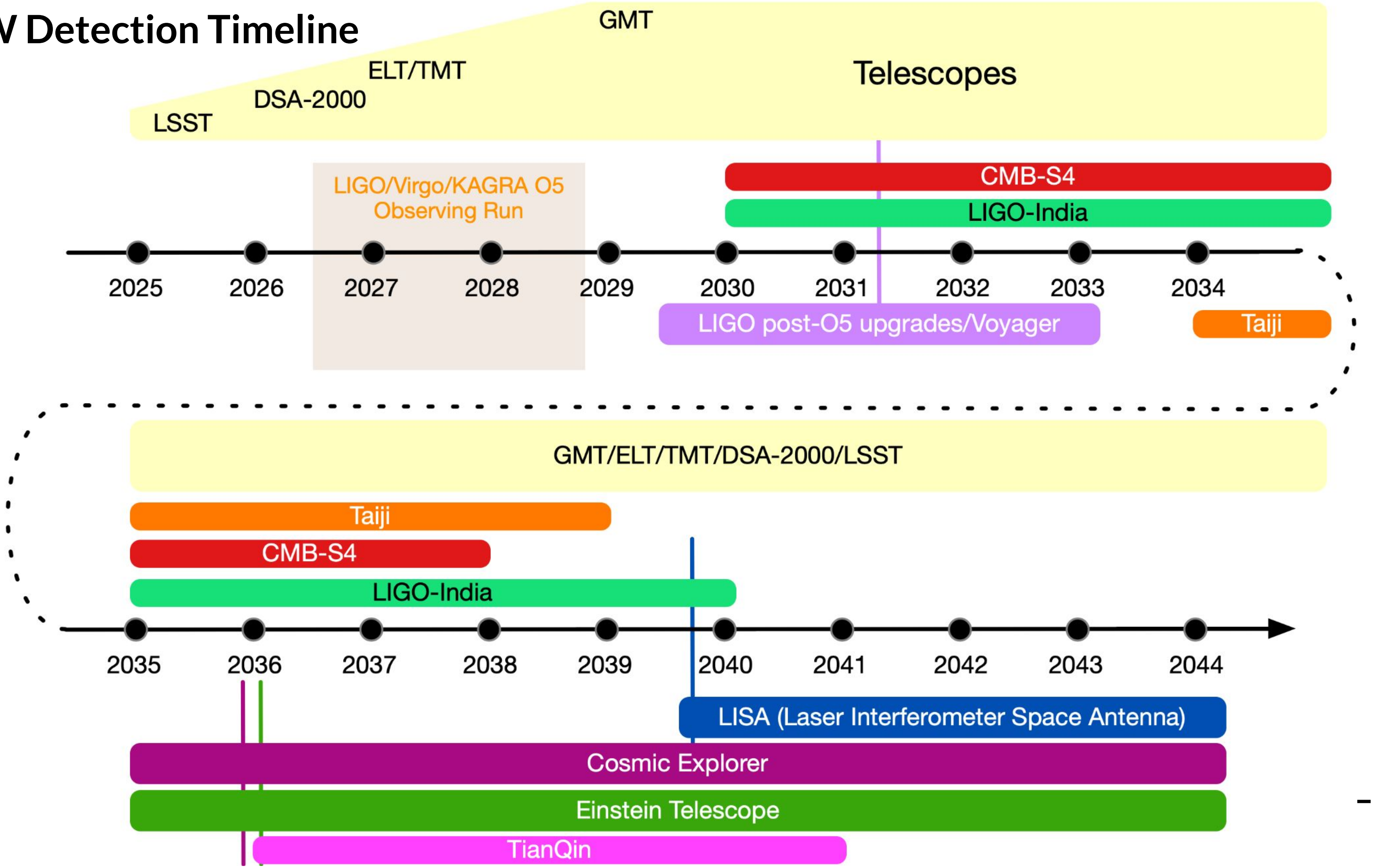


A Markosyan, G2200909

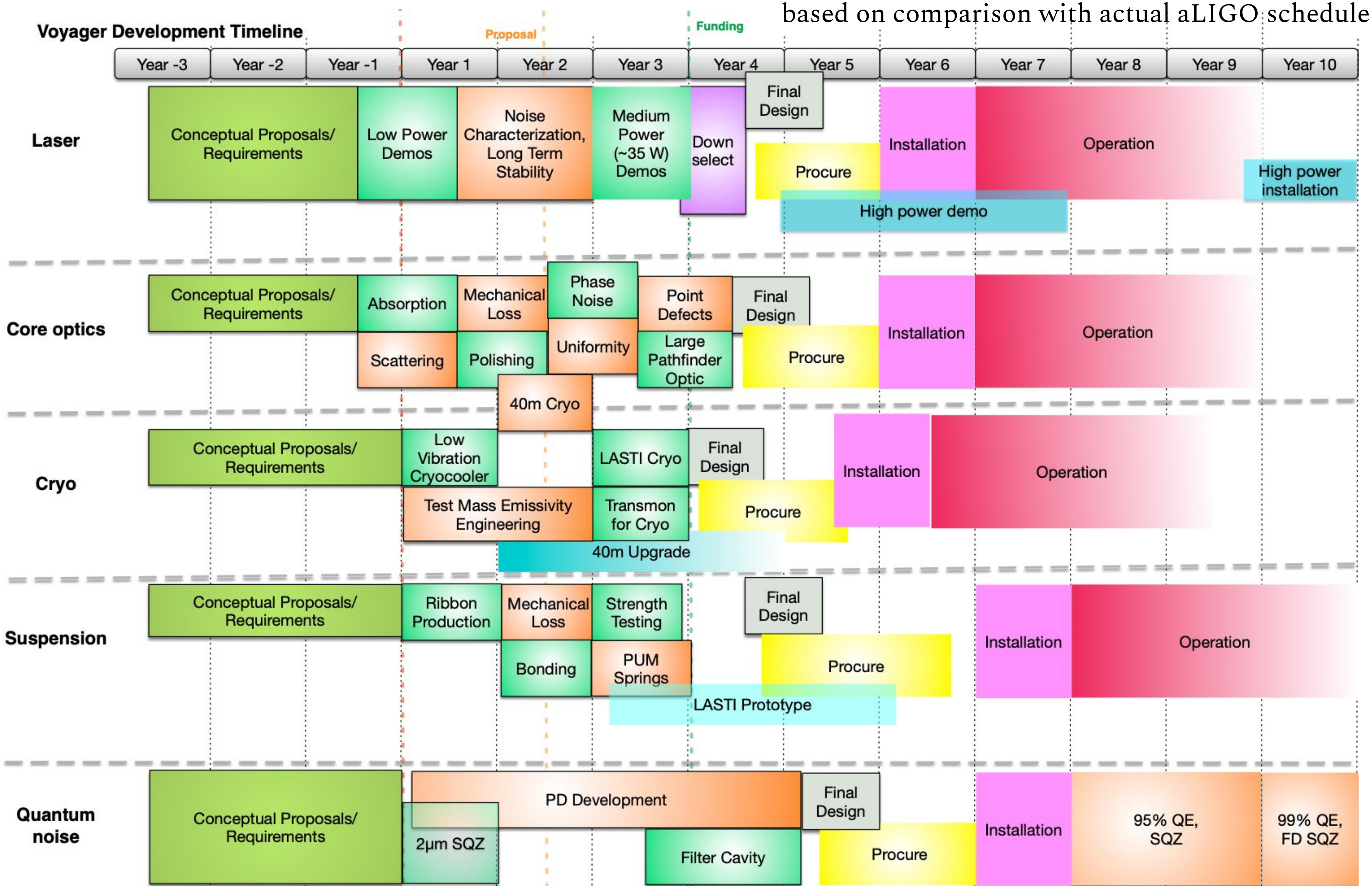
Future work

- Optimize anneal for absorption ≲ 20 ppm/cm (goal ≲ 5 ppm/cm)
- Scale up to 45 cm test mass, assess homogeneity
- Check compatibility with coating anneal

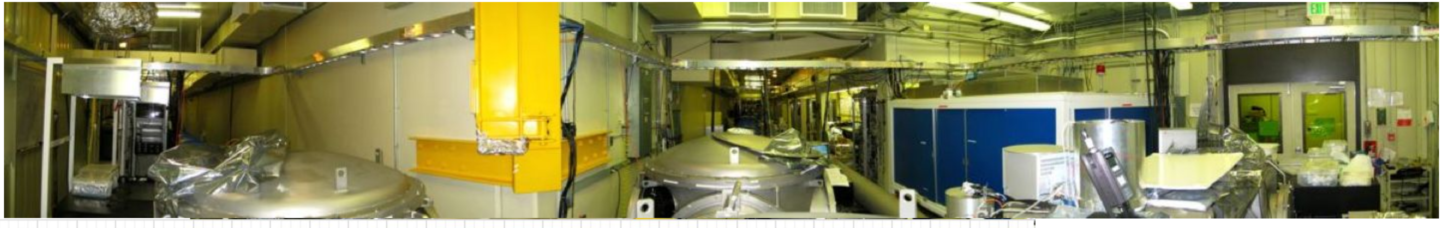
GW Detection Timeline



based on comparison with actual aLIGO schedule

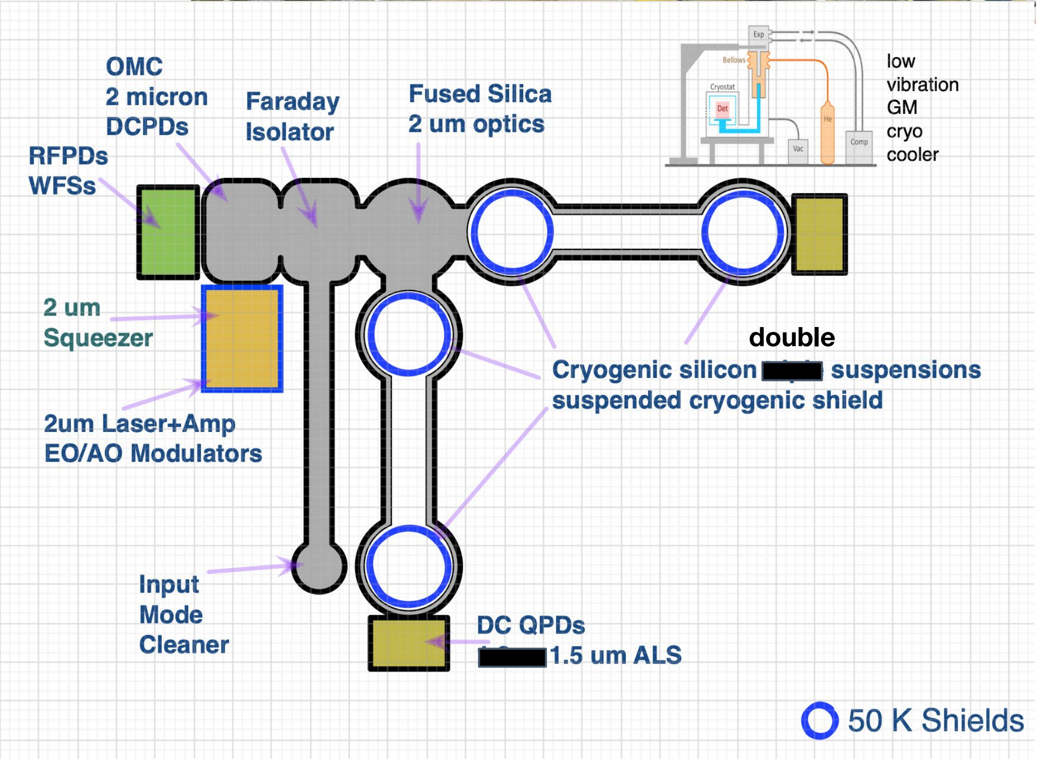


Mariner: the 40m Voyager prototype



Designing / Building: Now

Install: 2023



- ❏ Caltech 40m testbed
- ❏ Silicon Test Masses
- ❏ Double Suspensions
- ❏ Radiative cooling
- ❏ 123 K operation
- ❏ 2050 nm laser
- ❏ 1550 nm ALS laser

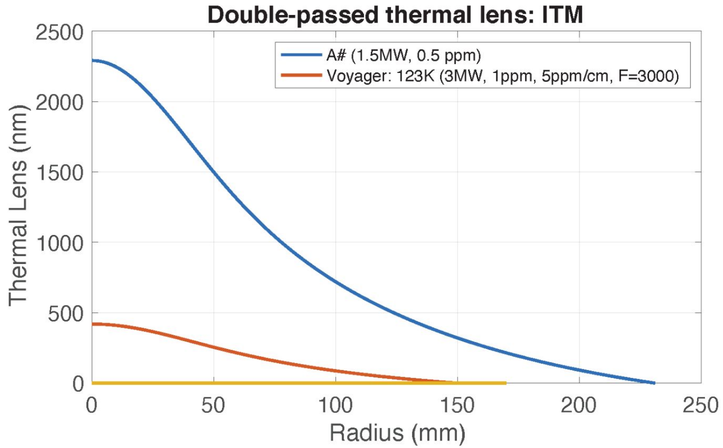
Risks / Challenges /Research Opportunities

1. 35 W laser amplifier for 2 microns
2. 2050 nm seed laser w/ high BW modulation
3. EOM for 2 microns with resonant modulation capability and a 35 W power handling capacity
4. birefringence in crystalline silicon (ITM & BS)
5. process to anneal large pieces of silicon to trap the Oxygen and lower the 2 micron absorption coefficient to 5 ppm/cm.
6. low noise, low absorption HR mirror coating for 2 microns (e.g. a-Si : (SiO2 or SiN))
7. ALS (1.5 microns, phase locked with carrier)
8. High QE Photodiode for 2 microns / nonlinear SFG
9. How to handle the ice formation on the HR surfaces of the mirrors?
10. Damping of Parametric Instabilities: beyond the "Mushrooms" approach
11. 2-micron squeezer (13 dB measured in a homodyne detector)
12. aLIGO Quad SUS: heavier load, 123 K TM/PUM
13. Seismic Isolation Platform: issues with cold payload?
14. Optical Rigid Body: lock all platforms with lasers
15. RoC actuator for test masses
16. UHV compatible 2um Faraday isolator

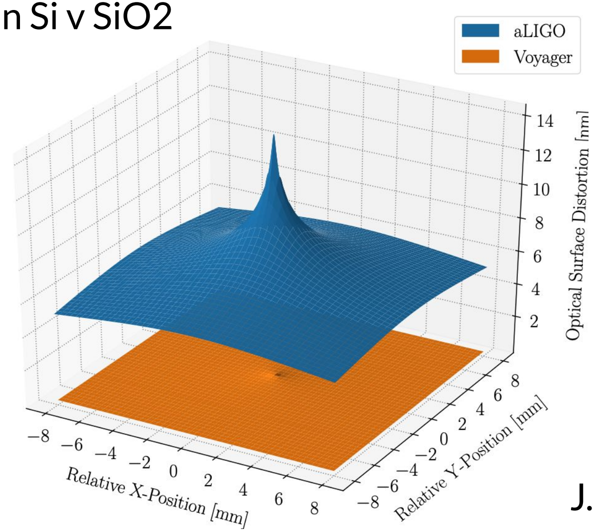
https://git.ligo.org/voyager/voyagerwhitepaper/-/wikis/Research-Projects

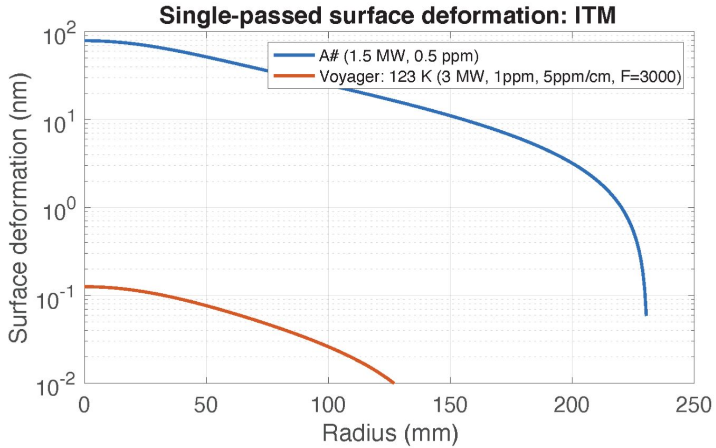
Risks - High Power Handling I: A# & Voyager

- Thermal Conductivity:
  - k_Si_123 ~ 700 W/(m K)
    k_SiO2_295 ~ 1.5 W/(m K)
- Thermal Expansion:
  - a_Si_123 ~ 0
  - a_SiO2_295 ~ 5e-7
- dn/dT: ~20x higher in Si v SiO2



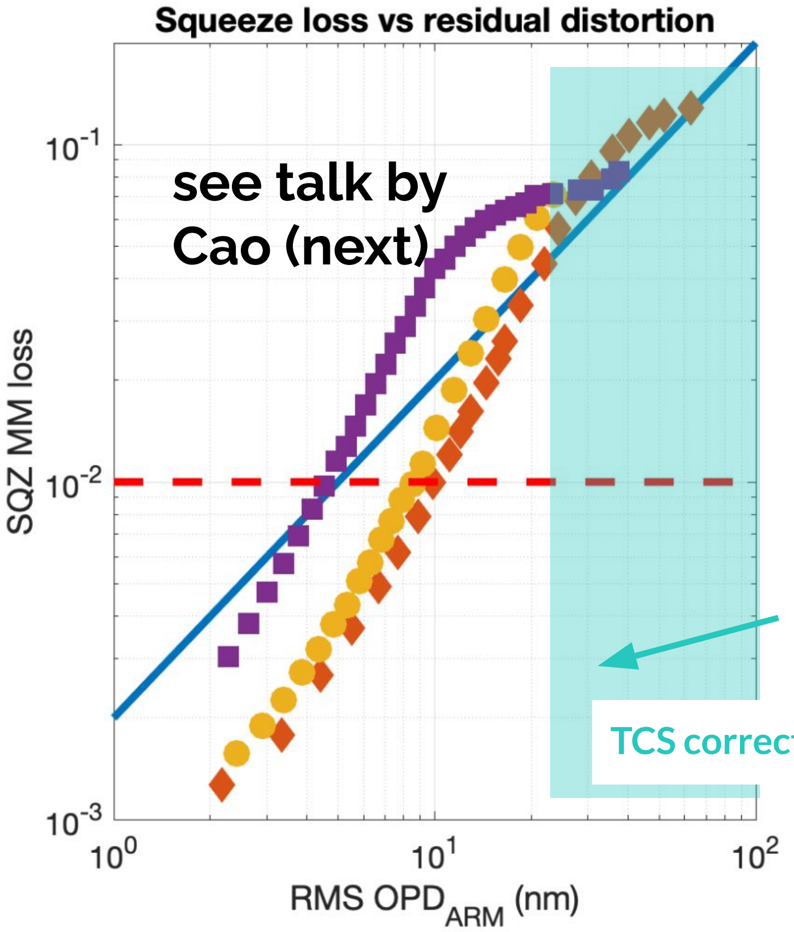
point absorbers:

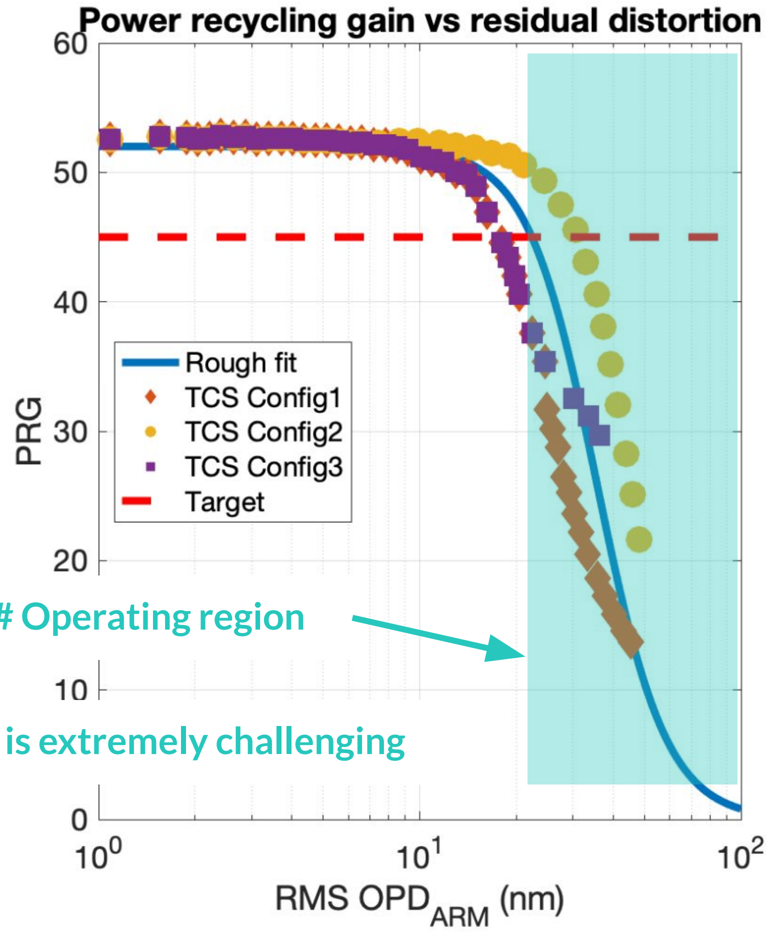




J. Richardson (UCR), A. Brooks (CIT)

High Power Handling II: A#





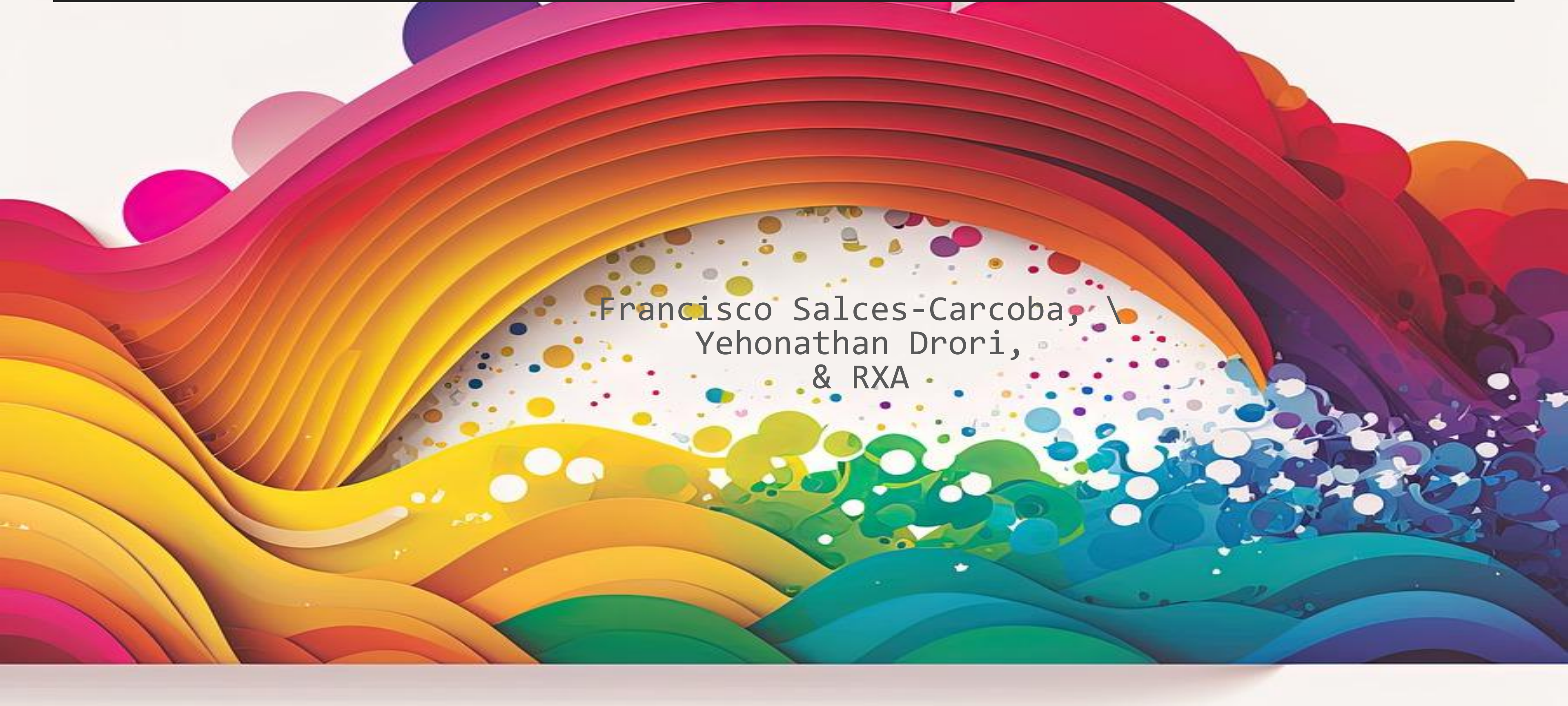
A# Operating region

TCS correction is extremely challenging

D. Brown (Adelaide), H-T, Cao, J. Richardson, L. McCuller, C. Wipf, H. Yamamoto, A. Brooks (CIT): T2200310 (soon)

LUCID (Light Upconversion for Improved Detection)

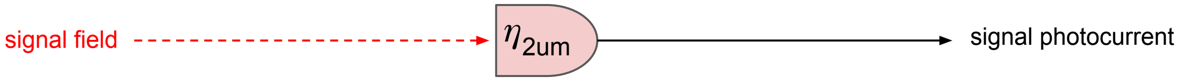
Beating the 2um PD quantum efficiency using upconversion



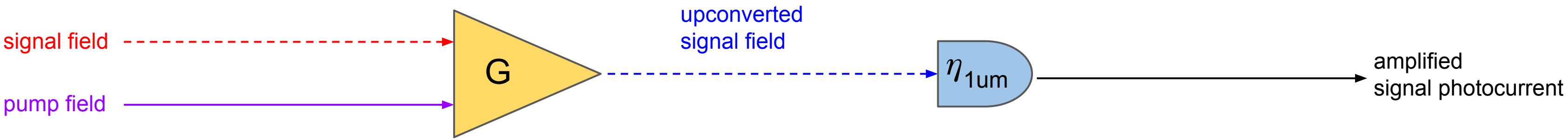
Francisco Salces-Carcoba, \
Yehonathan Drori,
& RXA

Upconverted QE

- Direct photodetection of 2.05 um signal using extended InGaAs maxes out at QE ~ 80%*
    - High dark noise levels may require cooldown, which in turn drops QE to < 70%.



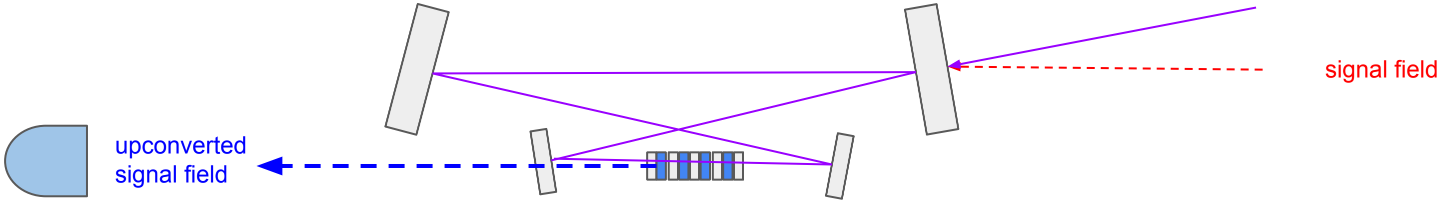
- Upconverted (2.05 um → ~ 1 um) photodetection enables conventional InGaAs QE > 99%



The upconversion efficiency “G” has to be greater than η_{2um} / η_{1um} to beat the 2um PD QE

* https://www.lasercomponents.com/fileadmin/user_upload/home/Datasheets/lc-ingaas/ig22-series.pdf

LUCID concept



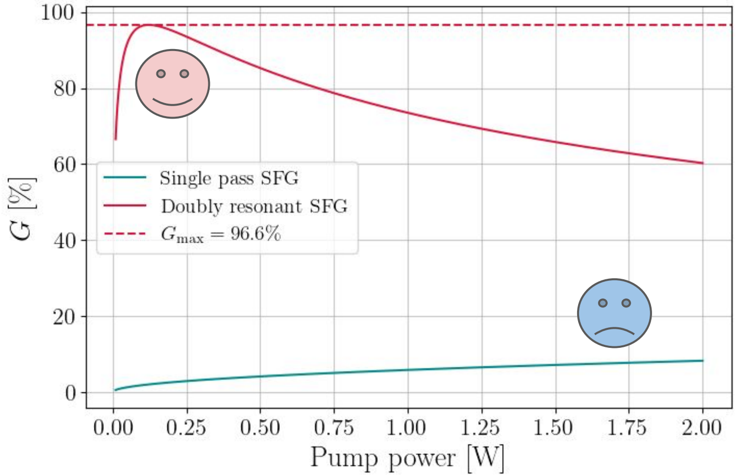
- Doubly resonant sum-frequency-generation (SFG)
  - Requires much lower pumping power compared to single pass →
  (used 99% mode-matching efficiency, 500 ppm rt loss, finesse ~ 300)

- Design may be optimized to reach G > 95% with low roundtrip loss, even when pumped with 150 mW

- What is the requirement on pump RIN?

IFO optical gain ~ 10^{14} W ⇒ RIN < 10^{-9} results in 10^{-23} detection noise ?

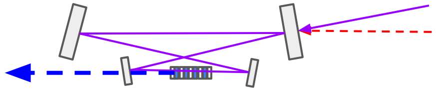
Upconversion efficiency



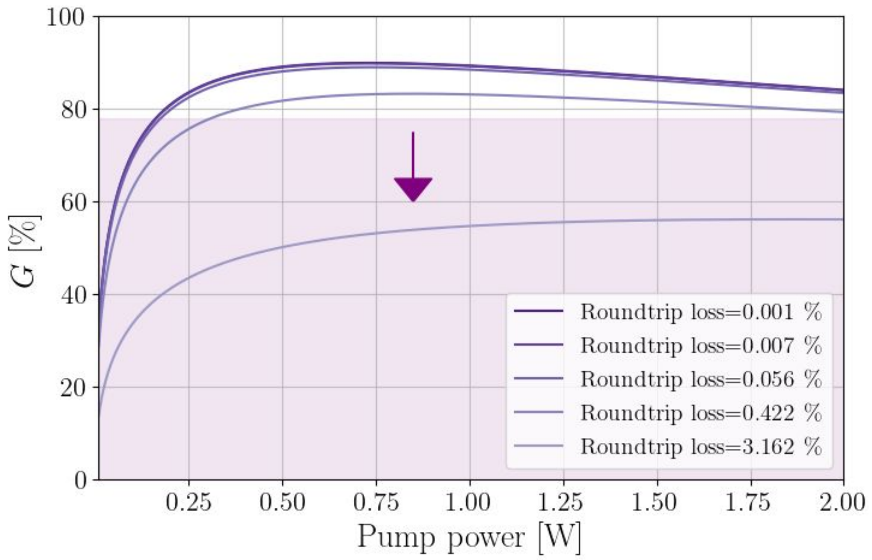
LUCID estimates

Calculated assuming 20mm long PPKTP pumped with 2050 um towards ~ 1 um.

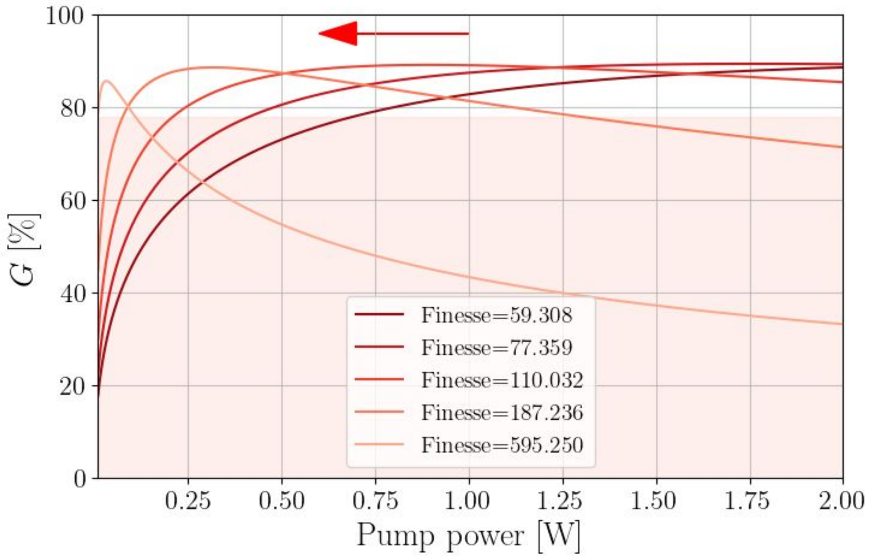
- Shaded regions represents G < 78% (QE limit to overcome)



Resonant efficiency vs loss



Resonant efficiency vs finesse



Lower roundtrip loss / higher finesse desirable to relax input pump power

References

0. Nonlinear Sum Frequency Generation, M. M. Fejer (Physics Today, 1994)

1. [Cavity-enhanced sum-frequency generation of blue light with near-unity conversion efficiency](https://arxiv.org/pdf/2002.05491.pdf)

2. [High-efficiency frequency upconversion of 1.5 μm laser based on a doubly resonant external ring cavity with a low finesse for signal field](https://link.springer.com/article/10.1007/s00340-016-6626-2)

3. [Efficient single-photon counting at 1.55 μm by means of frequency upconversion](https://doi.org/10.1364/OL.29.001449)

4. [Parametric Interaction of Focused Gaussian Light Beams](https://doi.org/10.1063/1.1656831)

Most Serious Worries:

1) Processing of Silicon mass: different annealing req for substrate and coating
2) a-Si absorption: already good enough to start; *might* need ~5x reduction in several years
3) Birefringence of Si: ITM/BS
4) **Budget**: LSC / need to increase 2-3x the existing workforce
5) **Schedule**: time to 'projectize' the Voyager upgrade study
6) too much absorption in silica at 2.05 microns (PRM, IMC)

Conclusions: What's the way forward?

Risks

1) A# has the advantage of incremental upgrades: easier to add/subtract new ideas
2) Voyager will require some years of commissioning to reach > 200 Mpc
3) Probably not enough funding to do multiple different upgrades.
4) Risk of stalled discoveries, slow decay of instrumental expertise in the field.

Rewards

1) Usual increased sensitivity / discoveries
2) Interesting new R&D: Voyager is more **R**, A# is more **D**
3) **Challenging Experiments** attract **Talented Experimentalists**
4) **Strong synergy with E.T.**

the LSC's Voyager Review Committee

Purpose

- Review the Voyager risks, readiness (TRL), plans
- **Gates**: conditions for doing Voyager instead of A#
- Give detailed technical recommendations
- Provide a summary recommendation to LSC

People

- optics
- SUS
- someone from ET Pathfinder
- 2 um lasers
- cryogenics
- someone from KAGRA

BACKUP SLIDES
(more details
re: main slides)

Mariner: A Voyager Prototype

- A Voyager-like prototype in the 40m lab at Caltech.
- 2-phase approach:
  - Phase I: cryo FPMI
  - Phase II: ~Voyager
- Silicon optics
- 123 K operation
- 2050 nm laser + amplifier
- DRFPMI + ALS + BHD
- Double cryo suspensions
- Radiative Cooling

- No Quad Suspensions
- Passive stack: no ISI
- ~100x lower power
- Smaller beams
- No TCS
- No filter cavities
- Maybe some squeezing

Mariner Details

More details

Main Laser :2050 nm
Linewidth <1 MHz
Power (seed/amplifier): 100 mW/ 10 W

Photodiodes QE > 95%
Diameter (min/goal): 1 mm / 3 mm
Bandwidth >10 kHz
Dark current (min/goal): <1 uA / <100 nA
Power handling: 5 mW

Silicon Optics Single Crystal Si
Absorption < 10 ppm/cm

Auxiliary Laser: Aux. Wavelength: 1550 nm
Linewidth <1 MHz
Power: 50-100 mW

Suspensions
Ribbon dimensions: 1 m x 1 cm x 200 um
Leaf Spring material: Si, Strength >500 MPa

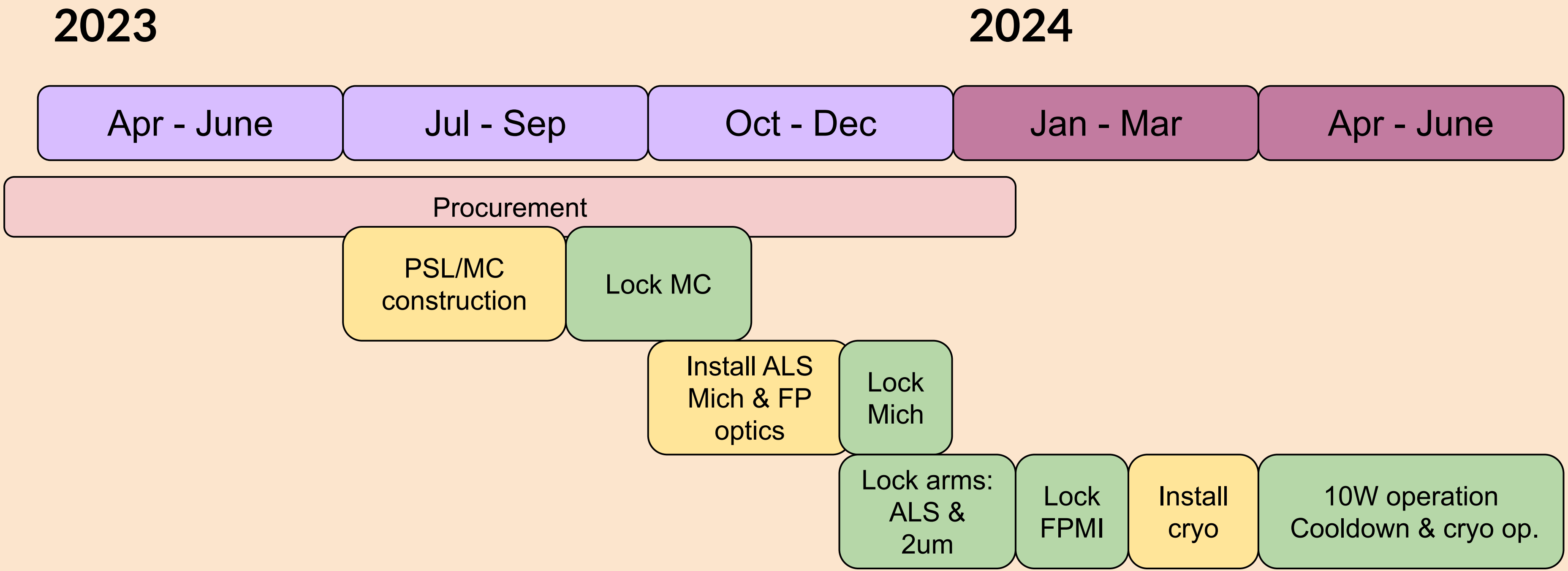
Cryogenics
Cooling scheme: LN2+cryocooler
Cryocooler: Stirling cryocooler

Mariner Parameters

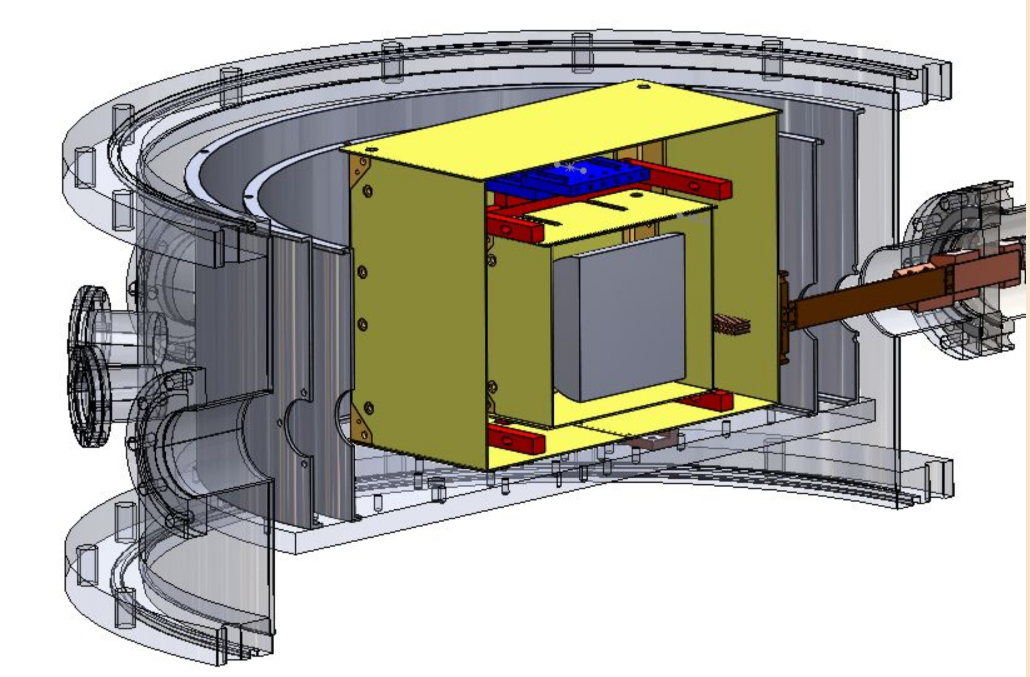
Parameter	Value
Laser wavelength	2050 nm
Polarization	s-pol
Mode cleaner length	13.545 m
MC2 ROC	19.01 m
Arm length	37.79 m
ITM ROC	83.1 km
ETM ROC	56.2 m
MC cavity finesse	XX
MC1/MC3 transmission	2000 ppm
MC2 transmission	10 ppm
Arm cavity finesse	$\simeq 3000$
ITM transmission	2.0×10^{-3}
ETM transmission	20×10^{-6}
Arm round-trip loss	xx ppm

Parameter	Value
ITM/ETM radius	75 mm
ITM/ETM thickness	150 mm
BS diameter	75 mm
BS thickness	25 mm
PR3/SR3 diameter	10 cm
PR3/SR3 thickness	10 cm
MC1/MC2/MC3 diameter	75 mm
MC1/MC2/MC3 thickness	25 mm

Mariner Timeline

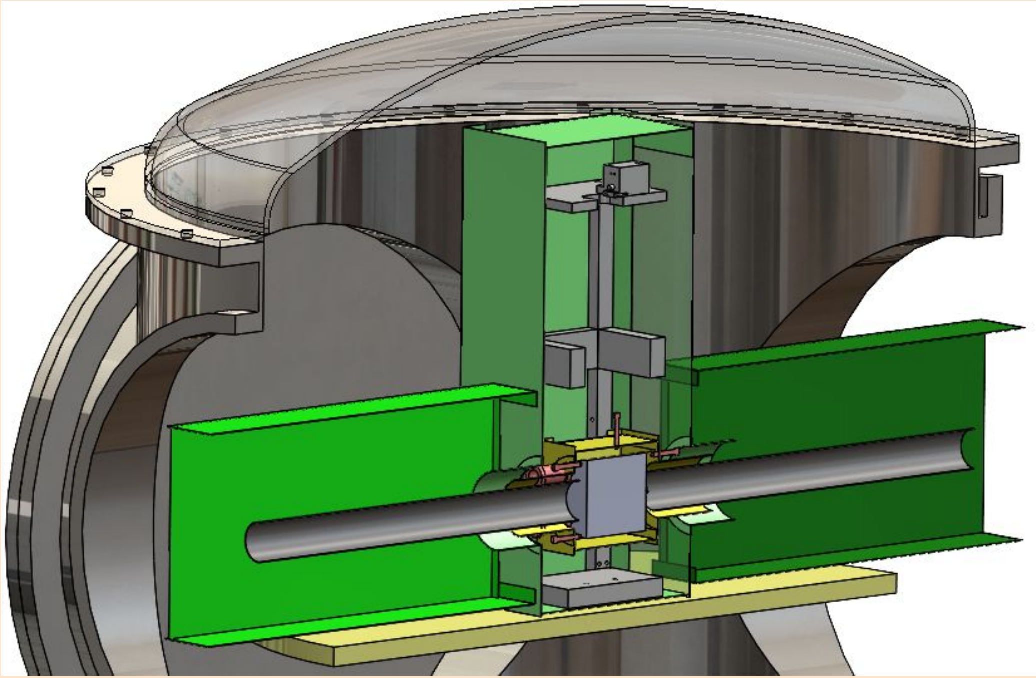


Cryogenic Engineering



- Development - cryostat setup
  - Demonstrate 123 K silicon temperature
  - Assess system time constant
  - Characterize parameter effects (shield coating, thermal isolation)
  - Validate best practices (bolted joints, material selection, sourcing)

Cryogenic Engineering



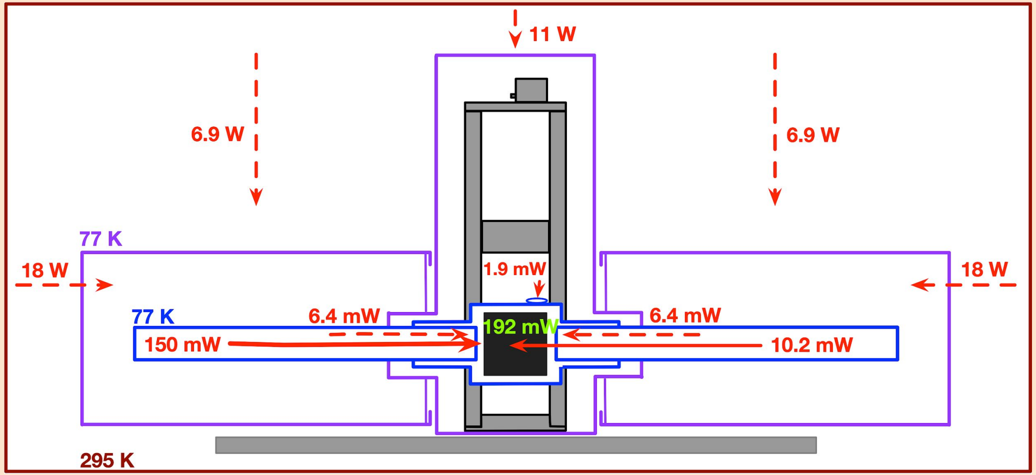
40m ETM chamber

- Development - cryostat setup

⇩

- Implementation - Mariner upgrade
  - Deliver adequate shield for steady state temperature control
  - Assess impact on instrument performance

Cryogenic Engineering



- Ongoing design effort
  - Modeling of thermal performance
    - First order analytical
    - FEA, including radiation and joint conduction parameters
  - Modeling of noise contributions
    - Stray light from suspended snout
  - (CAD) Modeling of cryo subsystem components
    - Interfaces and interferences
    - Suspension
    - Thermal linkages and breaks

SOME OPEN QUESTIONS

- How to tune mirror radius of curvature?
  - Ring heater avails us nothing; ring ESD?
- How to make the cold snout?
  - Need low backscatter, high emissivity
- How to avoid icing the mirrors?

Silicon Test Masses: risks

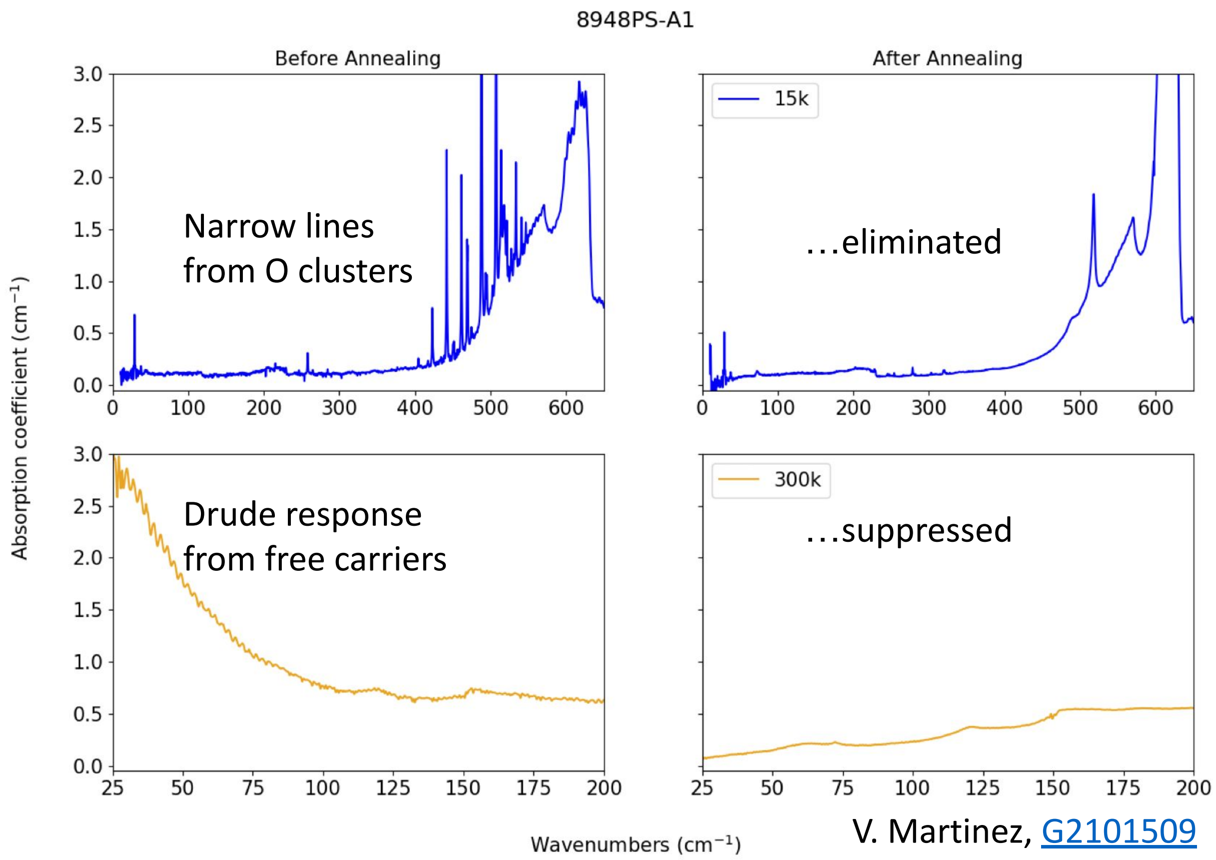
1. Source
2. Annealing
3. Birefringence
4. Unforseen thermodynamic noise sources
5. excess absorption
6. index homogeneity

Table 1. Birefringence of crystalline silicon depending on crystal orientation and wavelength as measured in previous experiments by other authors. (*) value reported 'not observed' in the original publication

Direction of light propagation	Wavelength in (nm)	Birefringence in (Δn)	Year	Source
$\langle 111 \rangle$	1100–1200	$7\text{–}9 \times 10^{-4}$	1959	Lederhandler *et al* [22]
$\langle 100 \rangle$	1150	$<10^{-6}$ (*)	1971	Pastrnak *et al* [23]
$\langle 110 \rangle$	1150	5×10^{-6}	1971	Pastrnak *et al* [23]
$\langle 111 \rangle$	1150	$<10^{-6}$ (*)	1971	Pastrnak *et al* [23]
$\langle 100 \rangle$	1300	$\approx 10^{-5}$	2001	Fukuzawa *et al* [24]
$\langle 110 \rangle$	1520	3.2×10^{-6}	2002	Chu *et al* [25]
$\langle 001 \rangle$	1520	$\approx 10^{-8}$	2002	Chu *et al* [25]

Christoph Krüger *et al* 2016 *Class. Quantum Grav.* 33 015012
– Einstein Telescope silicon birefringence study

Far-infrared spectra reveal annealing's effect on oxygen in silicon

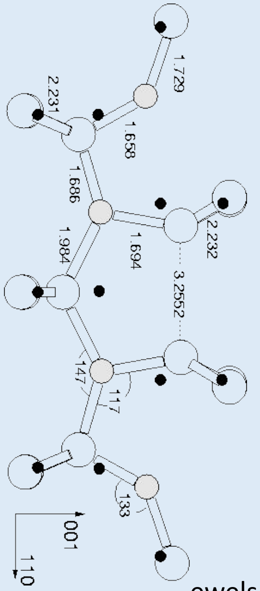


V. Martinez, G2101509

OXYGEN IN SILICON

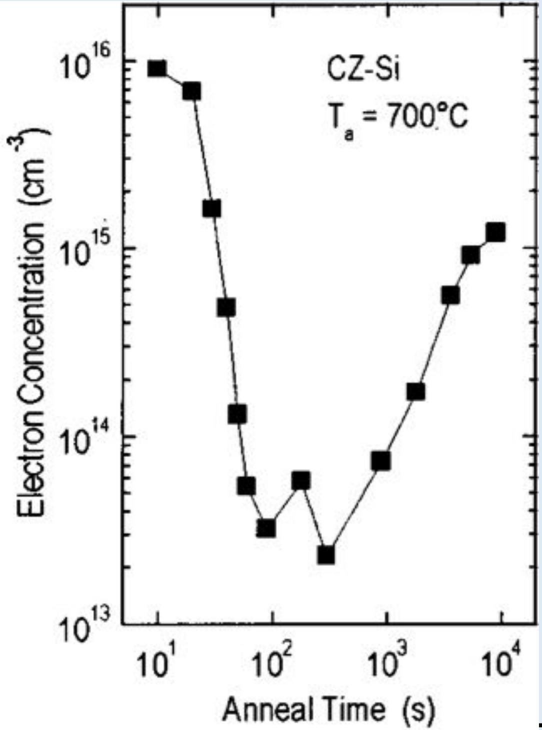
euroquarz.de

- Large silicon crystals contain interstitial oxygen
  - It comes from the SiO_2 crucible used for crystal growth
  - In low-O samples we received, the O concentration is ~4e17/cm^3
- Interstitial oxygen is a mostly harmless impurity
  - It mostly does not affect the concentration of free charge carriers
  - Free carriers lead to absorption and phase noise
- But oxygen can form clusters that contribute free electrons
  - Heating promotes migration of the interstitial oxygen
  - Clusters can be either created or destroyed, depending on the temperature and duration of the anneal
- Thus silicon absorption can be modified by **annealing**



ewels.info

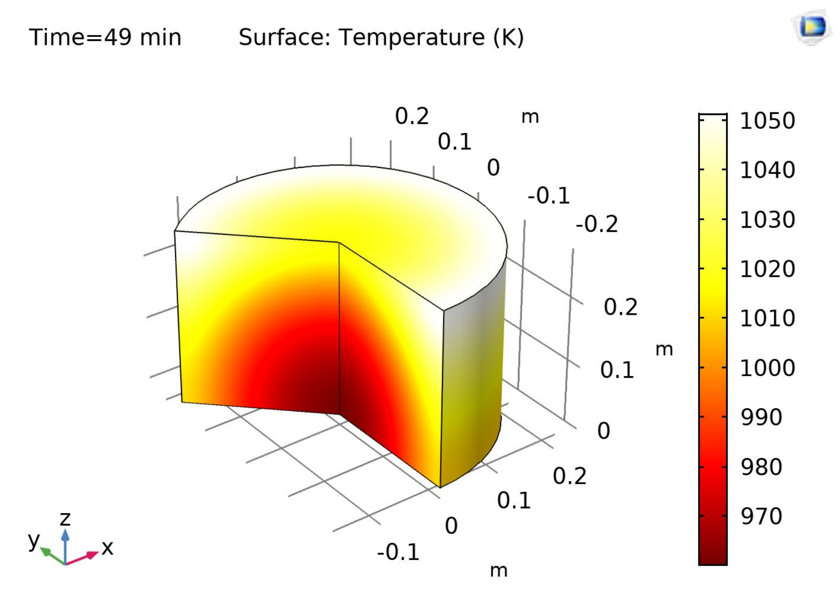
Substrate anneal dogma



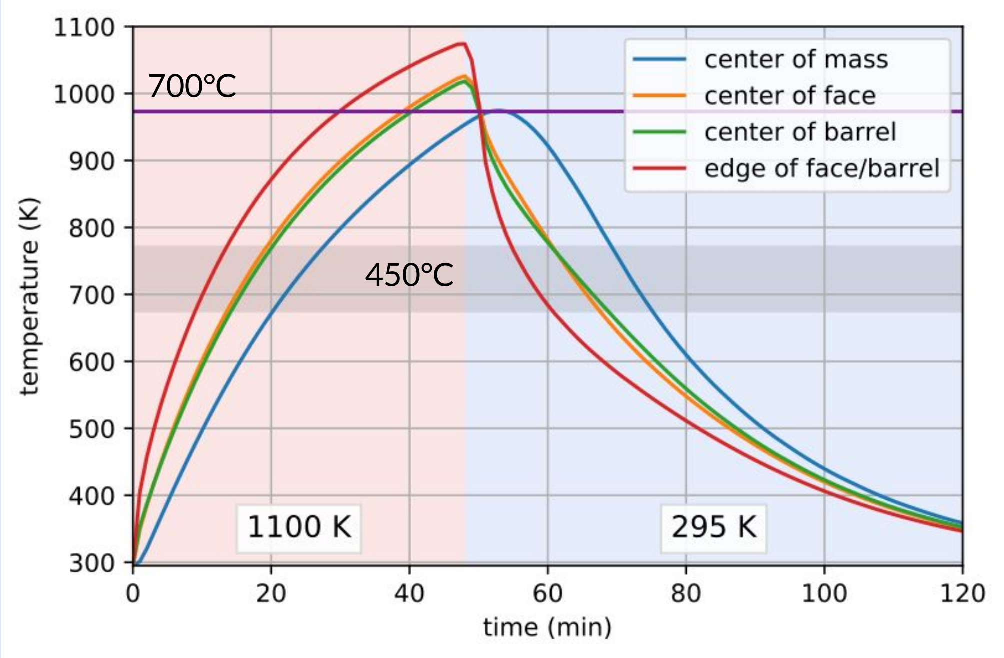
- Free charge carriers are culprits for 2 µm absorption
- Carriers come from clusters of oxygen atoms (impurities)
- Annealing changes free carrier density (and absorption)
  - T ~ 450°C forms one type of oxygen cluster, “thermal donors”
  - T ~ 700°C disrupts thermal donors… but slowly forms other clusters
- Silicon grown in a large ingot has clusters baked in
  - Lingers too long near 450°C while cooling after crystallization
- *Rapid* anneal at 700°C recovers low carrier density
  - This is routinely done on silicon wafers
  - It should also reduce the 2 µm absorption

doi:10.1063/1.368586

Rapid anneal of 200 kg substrate

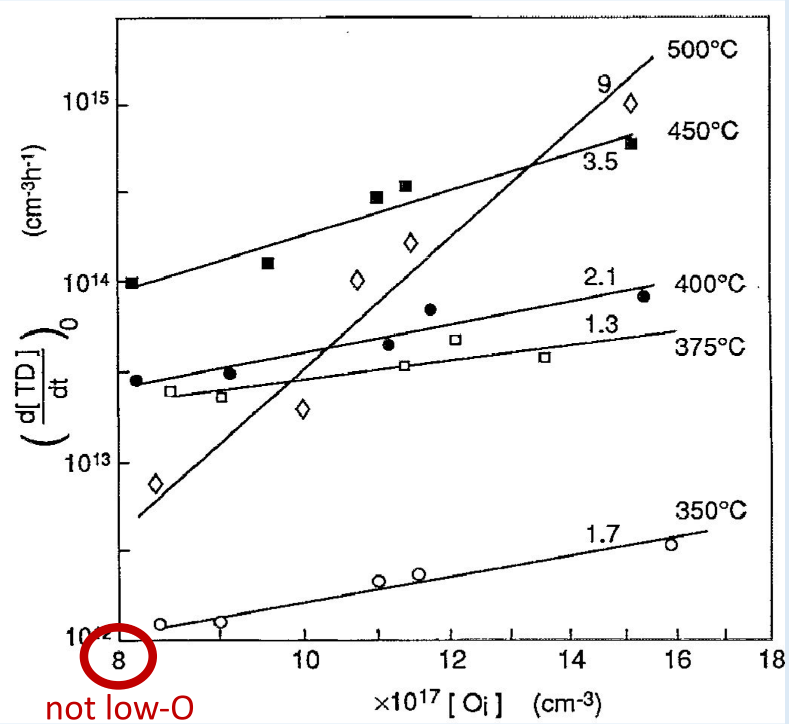


Assumes 100 $W/m^2/K$ convection
Radiative effects not considered



LORE OF ANNEALING

- The cluster formation rate depends on O concentration and temperature
- Use silicon with low oxygen content
- Don't let silicon sit at 450 °C
- Or if you must, then destroy clusters with a **rapid anneal** at 700+ °C
  https://doi.org/10.1063/1.368586
- A second population of clusters can slowly form at 700+ °C
- Cluster formation in the substrate may constrain the coating anneal
- Also need to consider what cooling rate a 200 kg test mass can support



Effect of oxygen concentration on the kinetics of thermal donor formation in silicon at temperatures between 350 and 500 °C

C. A. Londos,[a] M. J. Binns,[b] A. R. Brown, S. A. McQuaid, and R. C. Newman
Interdisciplinary Research Centre for Semiconductor Materials, The Blackett Laboratory, Imperial College of Science, Technology and Medicine, Prince Consort Road, London SW7 2BZ, United Kingdom

(Received 7 October 1992; accepted for publication 3 January 1993)

https://doi.org/10.1063/1.108628

Mid-IR absorption in fused silica
(Photon to multi-phonon interaction is fundamental)

Nominal TCS can handle around 10ppm/cm

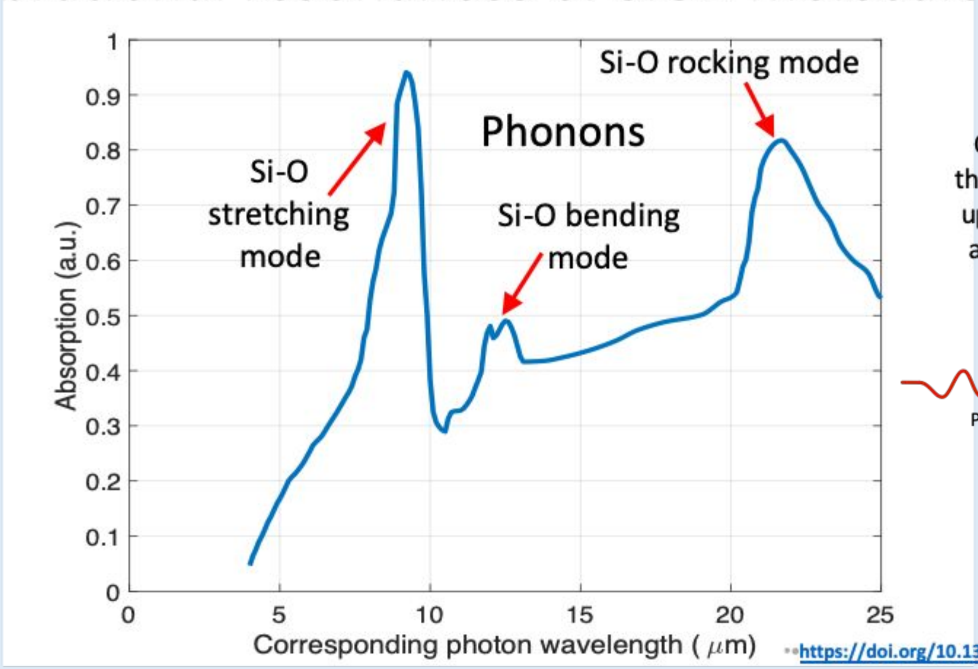
Wavelength	Absorption
1900 nm	7 ppm/cm
2000 nm	26 ppm/cm
2100 nm	82 ppm/cm
2128 nm	119 ppm/cm

Possible solutions

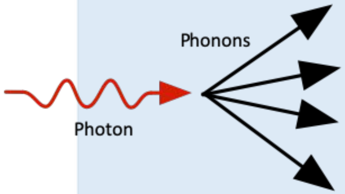
- Make absorption smaller
    - Increase molecular mass of glass by doping
- Make dn/dT smaller
    - Dope with P_2O_5 = -13.3E-6 K^{-1}

Optical Materials Express
Vol. 7, Issue 10, pp. 3654-3661 (2017)

Vibrational resonances of SiO2 molecules



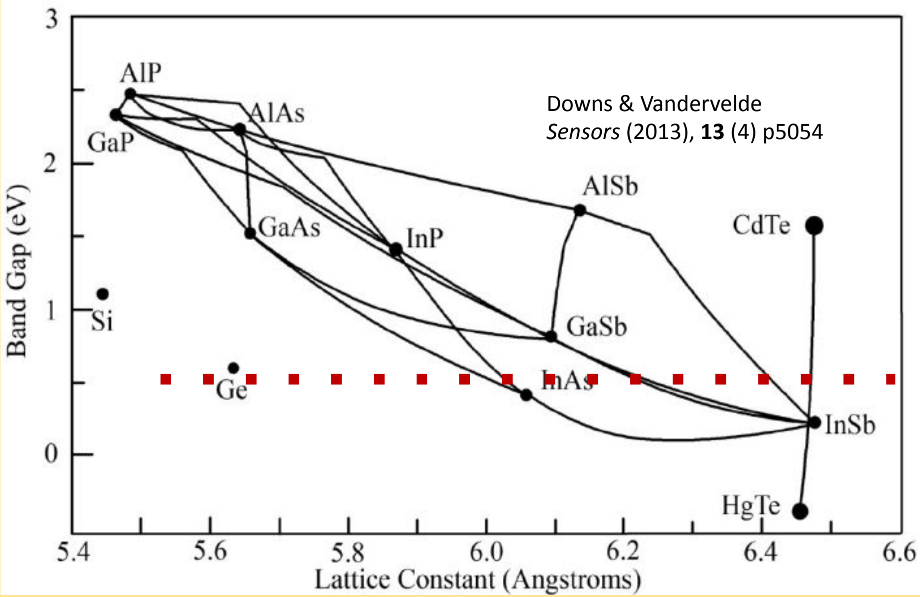
Combinations of these phonons sum up to same energy as mid-IR photon



https://doi.org/10.1364/AO.46.008118

High QE PD for 2 microns: needed for DARM/GW readout (only)

- Needs low bandgap energy, to work at 2 μm
- Needs good lattice matching with the substrate material, to avoid defects
  - "Extended InGaAs" lacks this
- InAsSb, HgCdTe appear to be the most promising systems
  - HgCdTe is relatively more difficult and costly to work with
- JPL's IR Photonics group is fabricating InAsSb devices, which we will test
- What are the ultimate limits to quantum efficiency?



PHOTODIODE REQUIREMENTS: https://dcc.ligo.org/T2100291

2um PD Q.E. Exploration

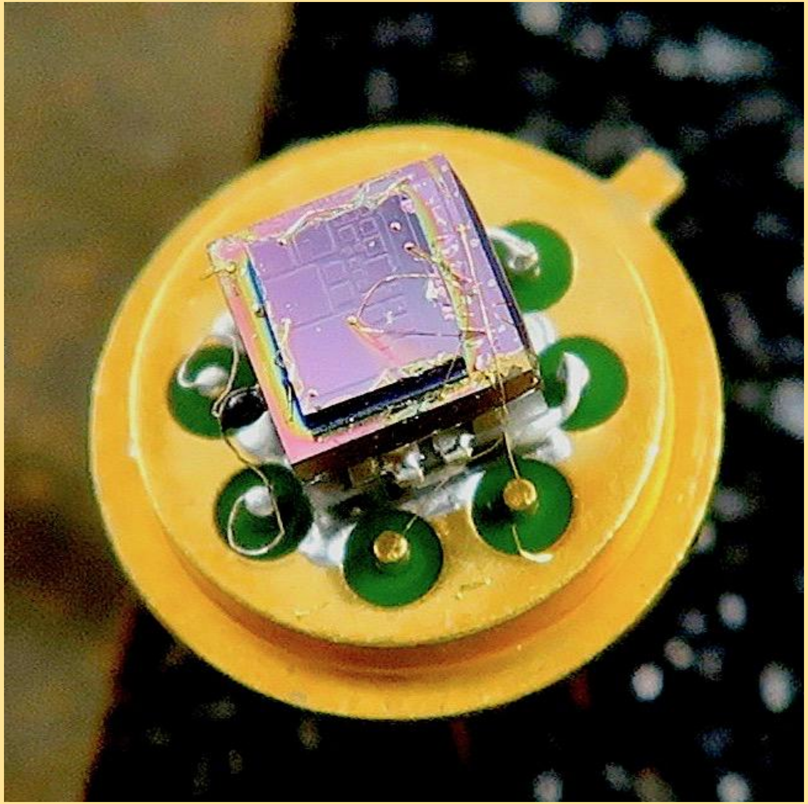
- **Tested two types of PDs so far:** InAsSb / ex-InGaAs

- **Both showed QE of ~80% at room temp**
high dark noise / current 👎

- **Cryogenic test of InAsSb:**
Significant reduction of dark noise/current by cooling
Did not indicate supposed improvement of the QE

=> New coating batch with improved QE is coming

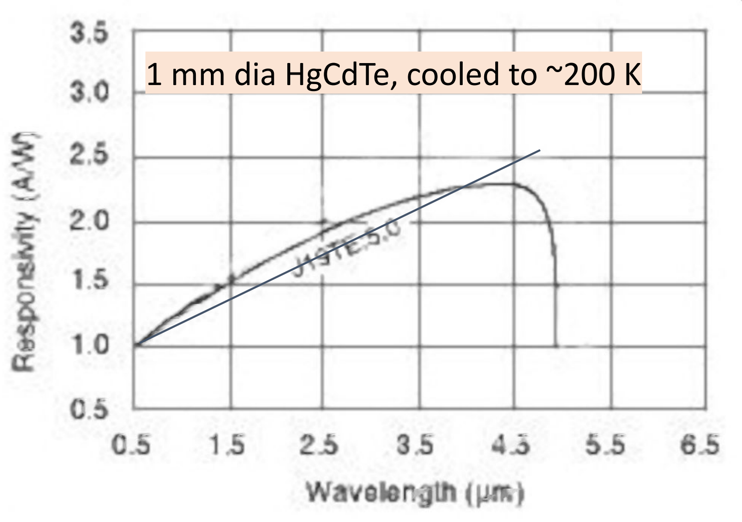
NASA JPL InAsSb



LaserComponents extended InGaAs

$Hg_{0.6}Cd_{0.4}Te$

- Widely used in astronomy
- Focus of Faraone group at UWA
- Teledyne, Raytheon, etc.



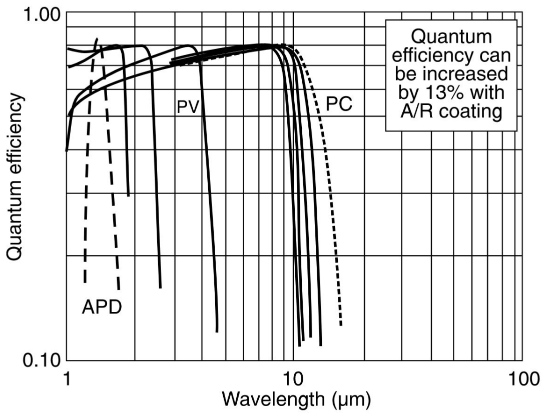
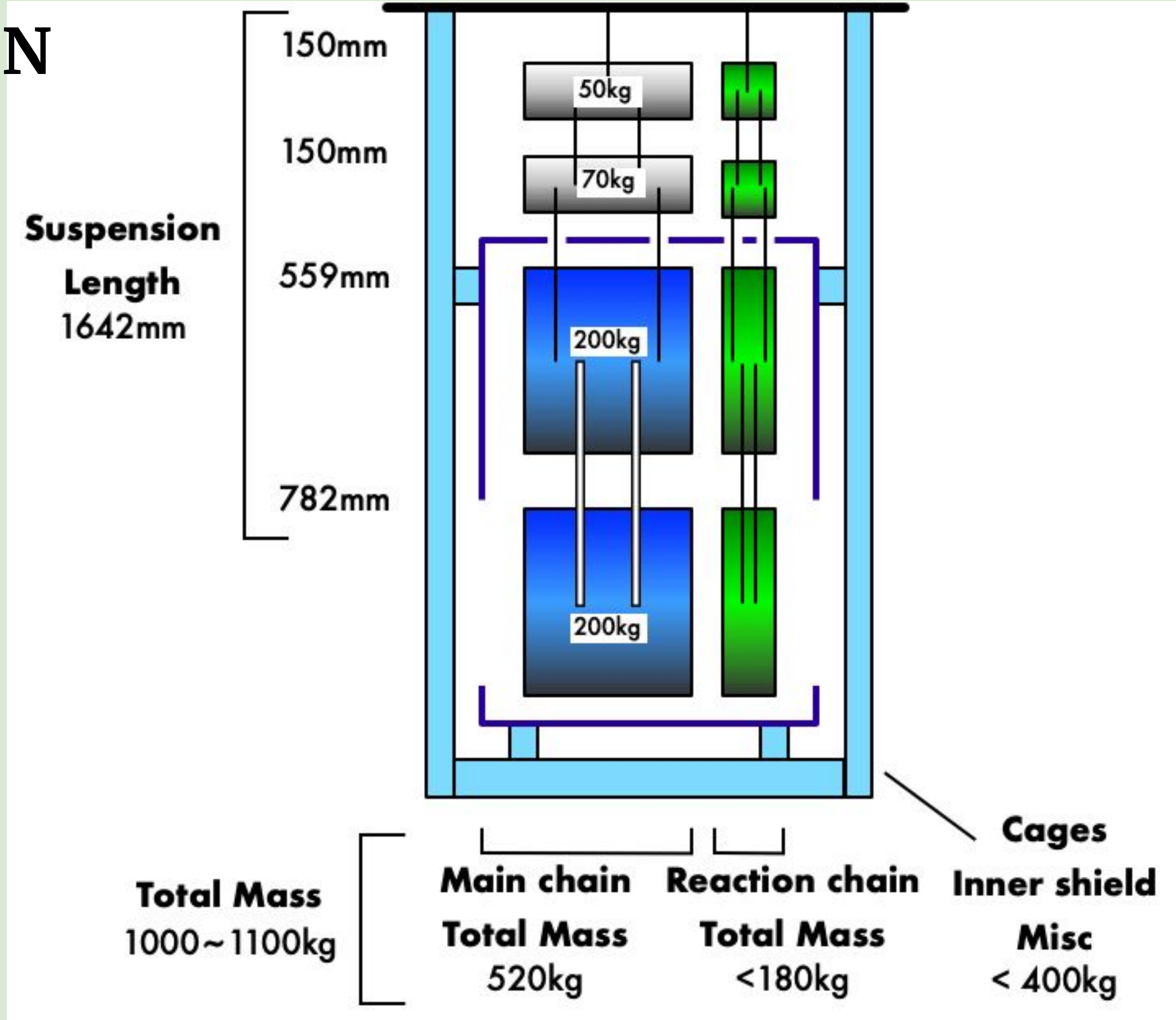


Fig. 10. Spectral quantum efficiency for HgCdTe devices without antireflection coating. Photodiodes span all but the longest wavelengths where photoconductors are still commonly used. At short wavelengths, avalanche photodiodes are in development. Antireflection coating raises the quantum efficiency to > 90%.

Raytheon: OPTO-ELECTRONICS REVIEW 10(3), 159–174 (2002)

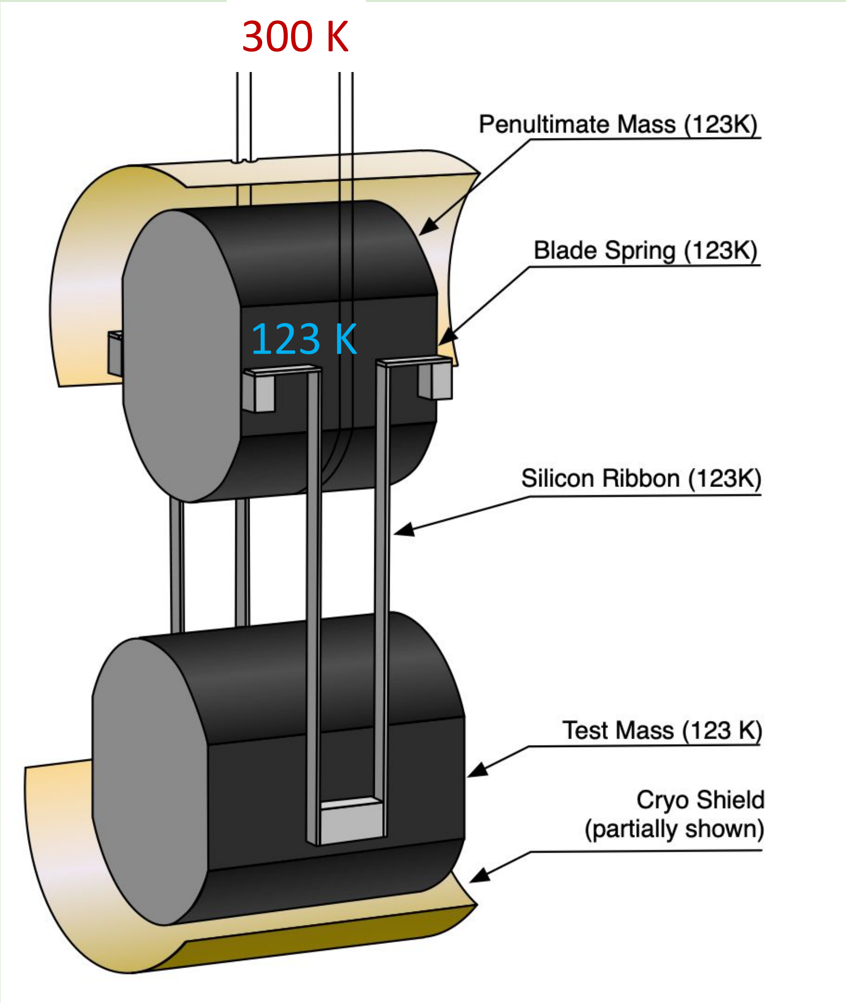
UWA: Journal of Electronic Materials (2022) 51:4742–4751 https://doi.org/10.1007/s11664-022-09809-y

SUSPENSION DESIGN



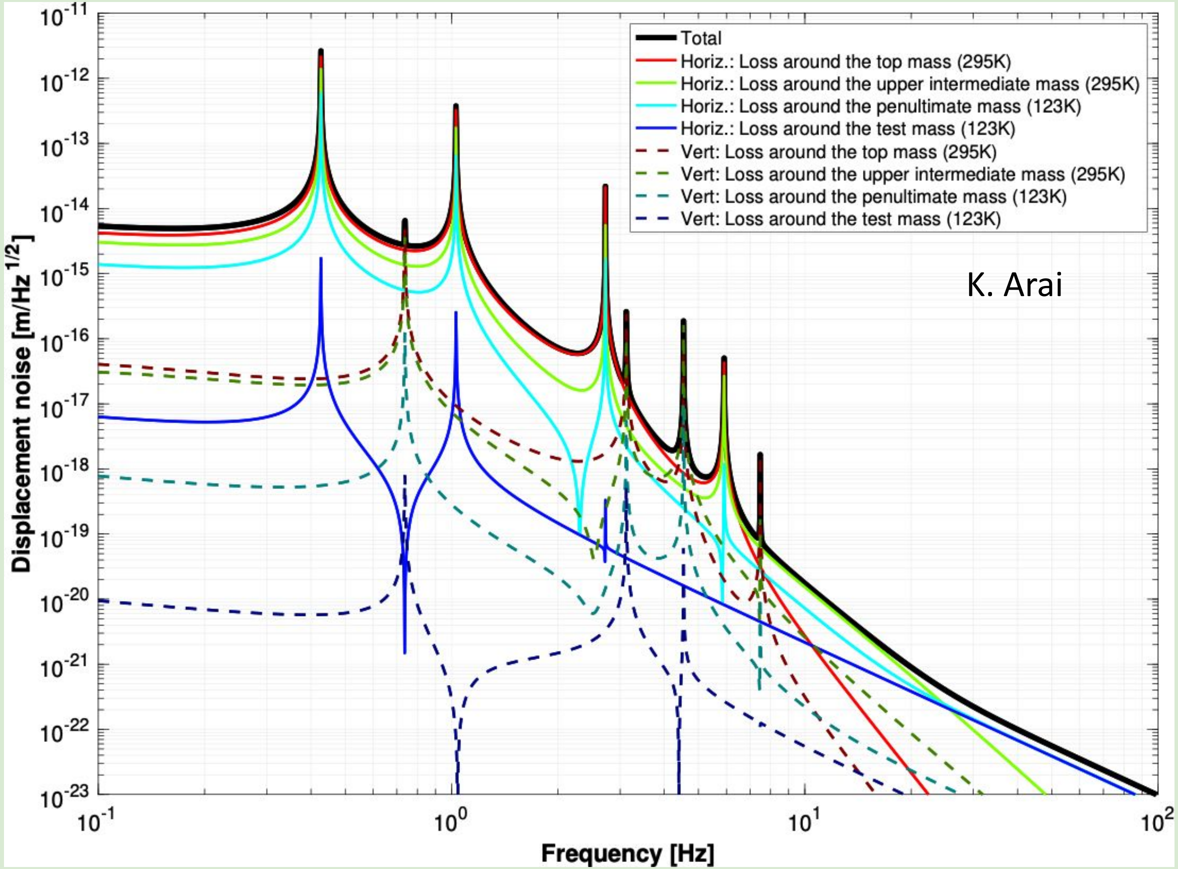
SUSPENSION THERMAL NOISE

- Quad suspension with cold penultimate mass and silicon ribbons/blade springs
- Temperature gradient across the penultimate mass suspension wires
- Noise model must treat separately the top and bottom of the wire
- Voyager’s alt-gwinc now supports this, and the design was re-optimized for improved thermal noise by Koji Arai



K

SUSPENSION THERMAL NOISE BUDGET



K. Arai

- Mass and length redistributed downward
- The tradeoff: degrades seismic attenuation
- Room-temperature upper stages now dominate
- Barely limits classical noise budget @ 12 Hz

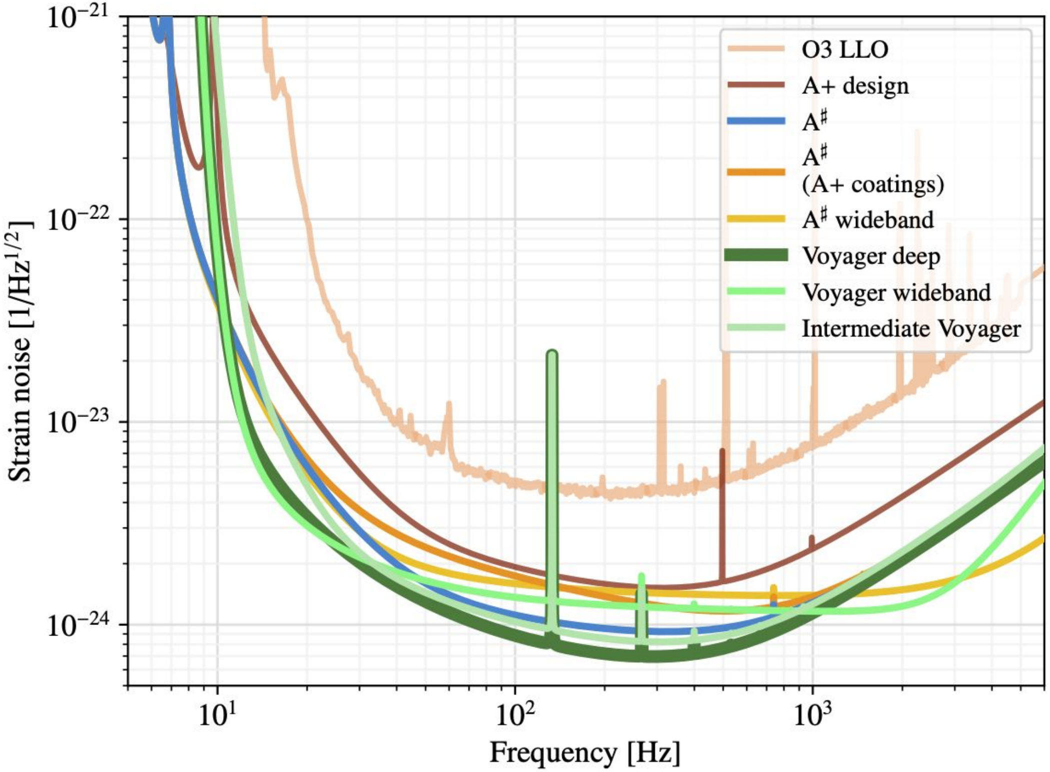
Configurations & Sensitivity Curves

– “minor” changes / parameter tuning

1) ITM Transmission
2) SRM Transmission
3) SRC detuning
4) Arm Cavity power

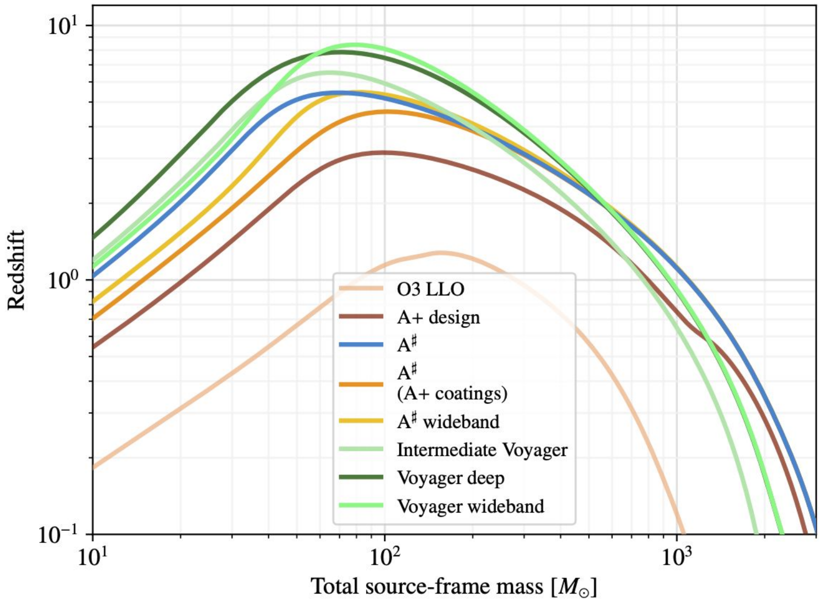
Voyager Noise & Range Estimates

CONFIGURATION	BNS/Mpc	BBH/z
Voyager deep	777	7.71
Voyager wide	594	7.48



Cosmological Reach:

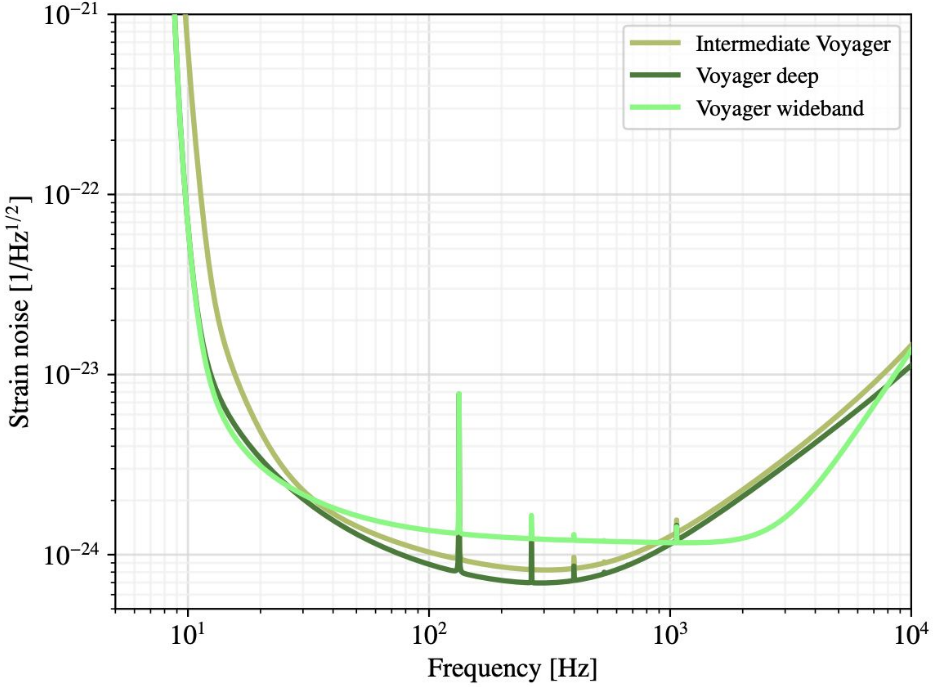
z > 6 for most the BBH range



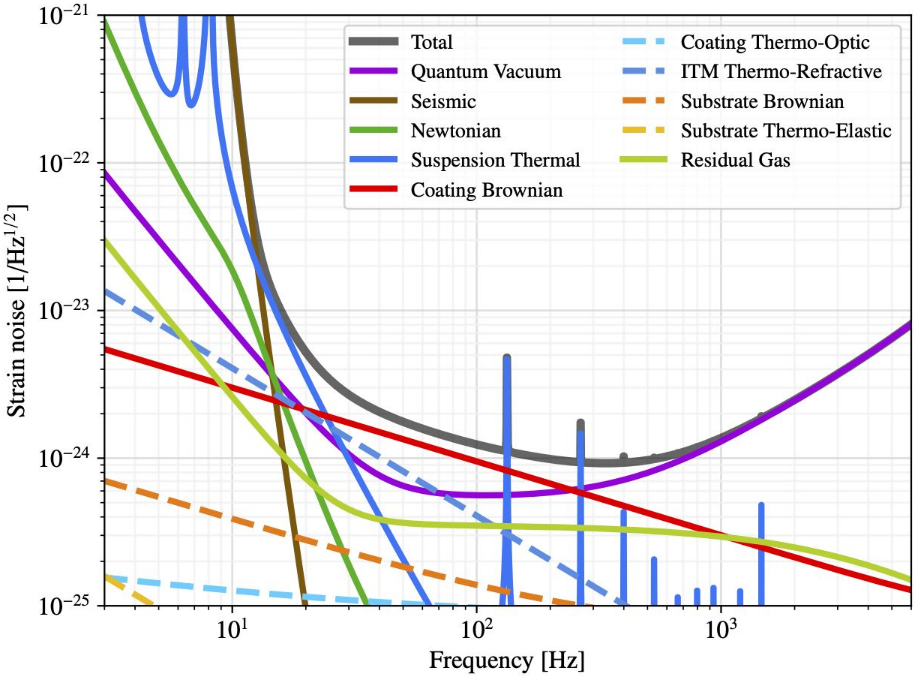
from post-O5 report (v1)

intermediate Voyager

Overview

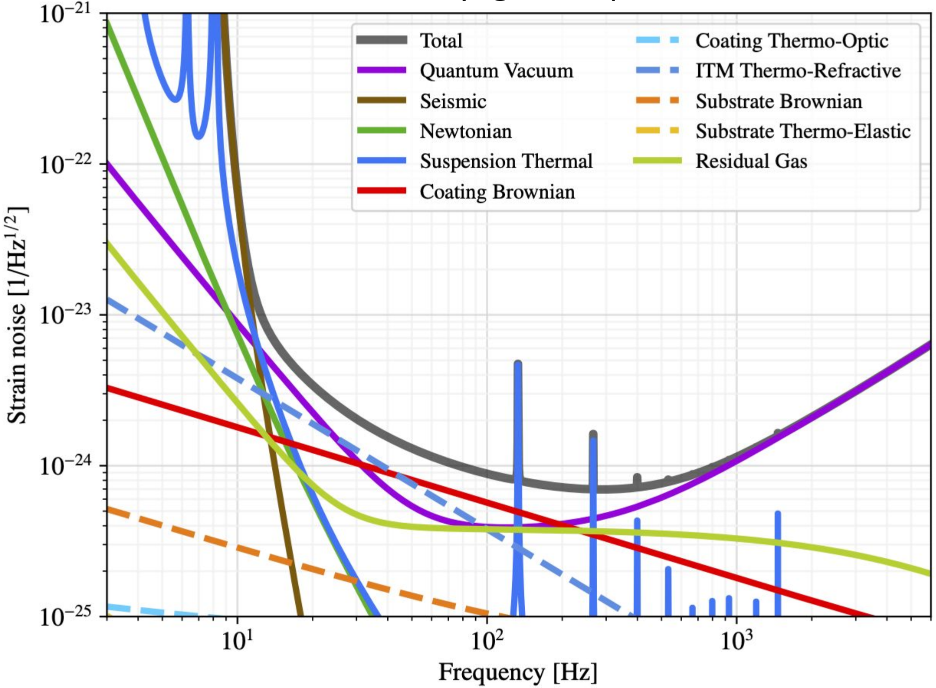


Voyager Intermediate

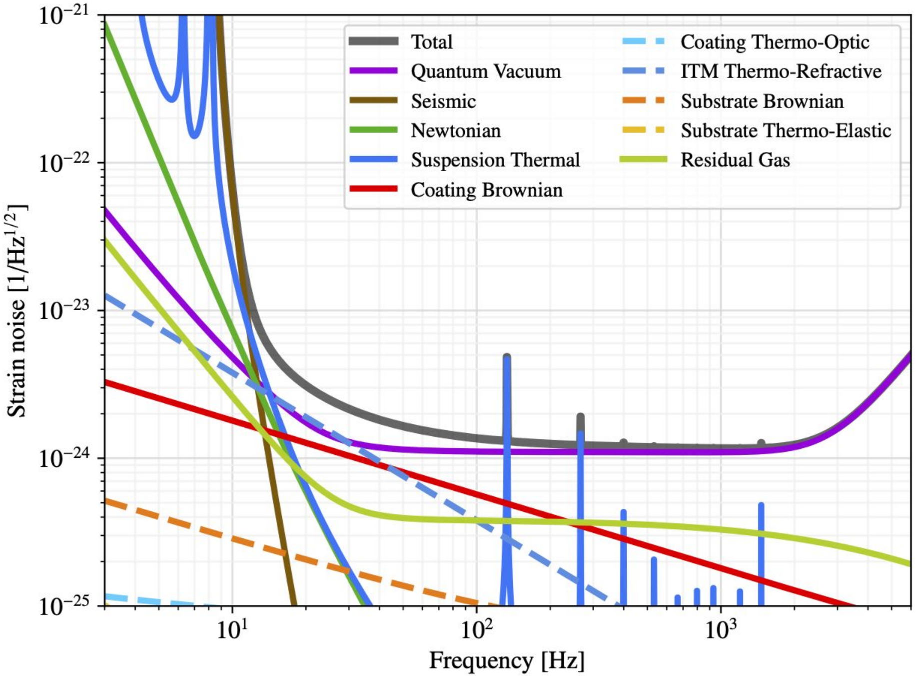


Noise budgets 2

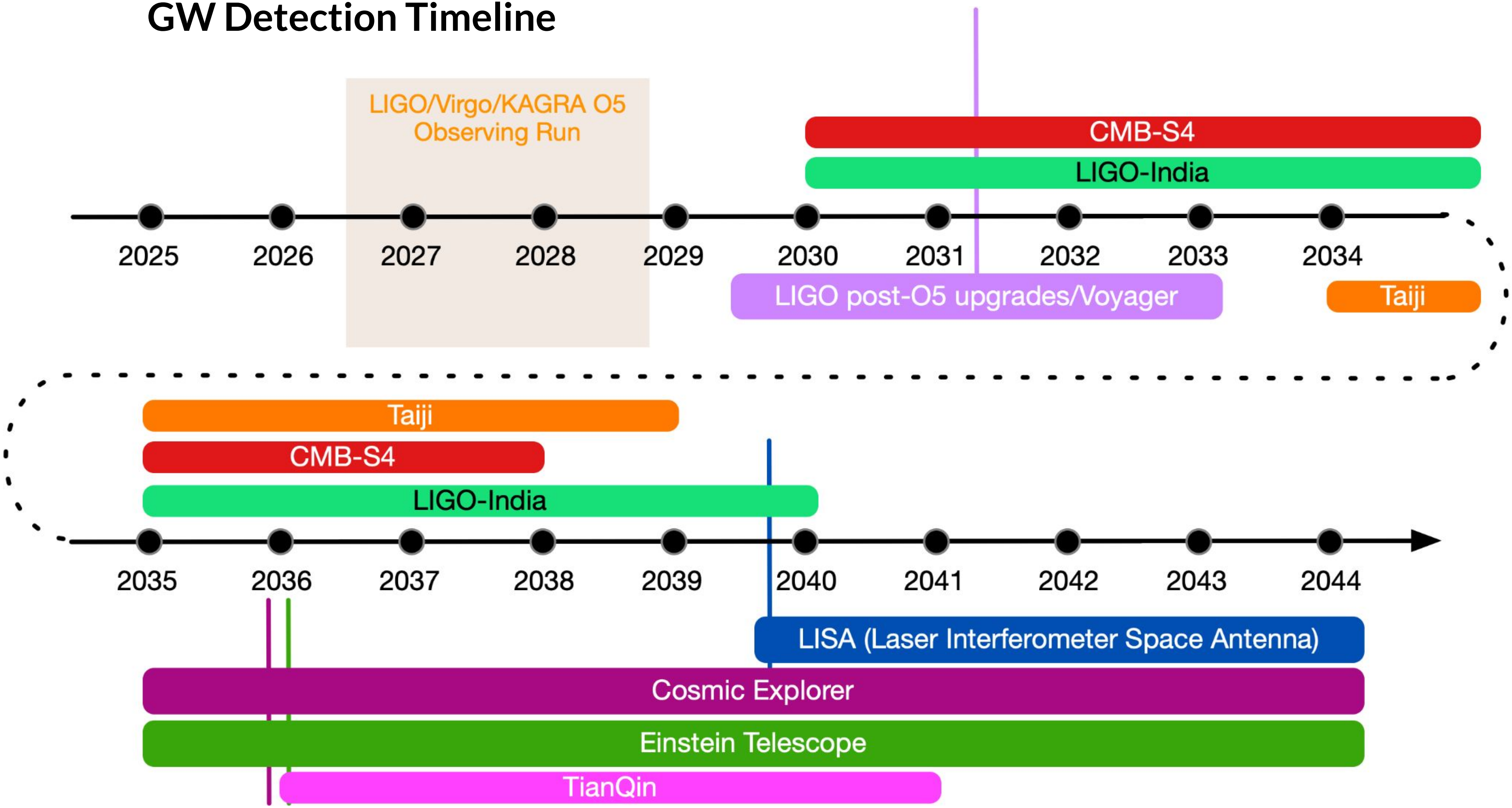
Voyager Deep



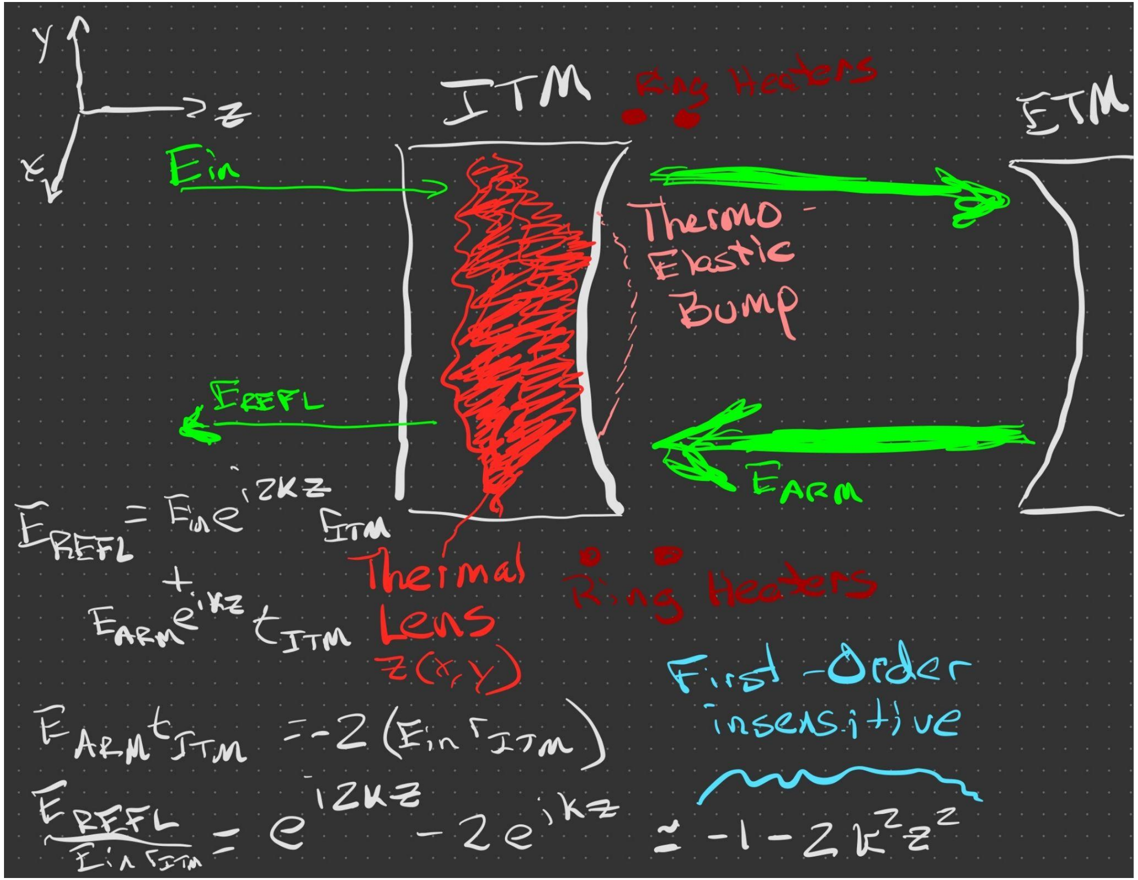
Voyager Wideband



GW Detection Timeline



Risks -
High Power Handling II: A# & Voyager



see talk by Cao (next)

D. Brown (Adelaide), H-T, Cao, J. Richardson, L. McCuller, C. Wipf, H. Yamamoto, A. Brooks (CIT): T2200310 (soon)