
LIGO VOYAGER
UPDATE
C WIPF GWADW 2017
IMAGE CREDIT: SKYSAT-6 (N SMITH)

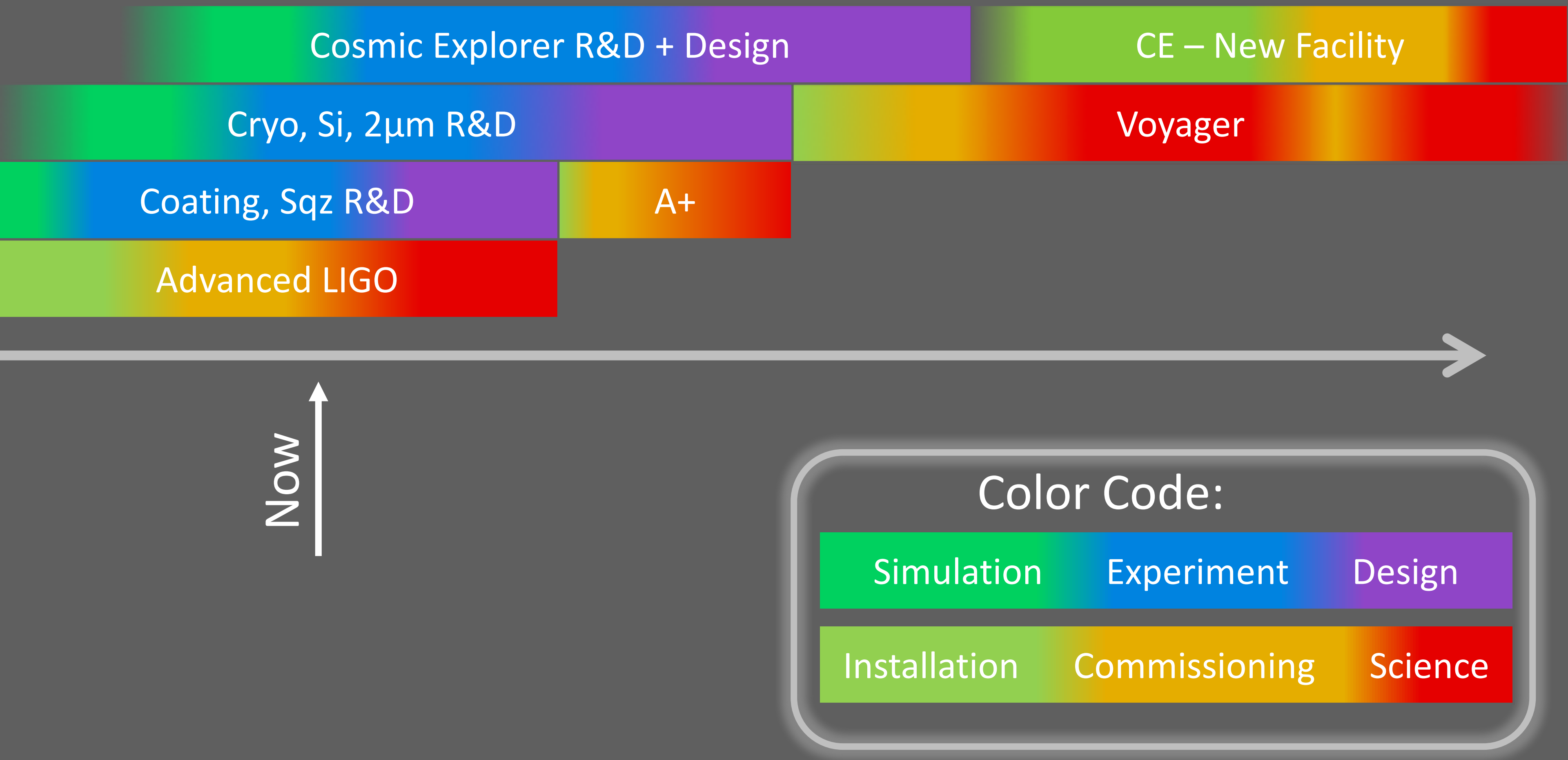
# TOPICS

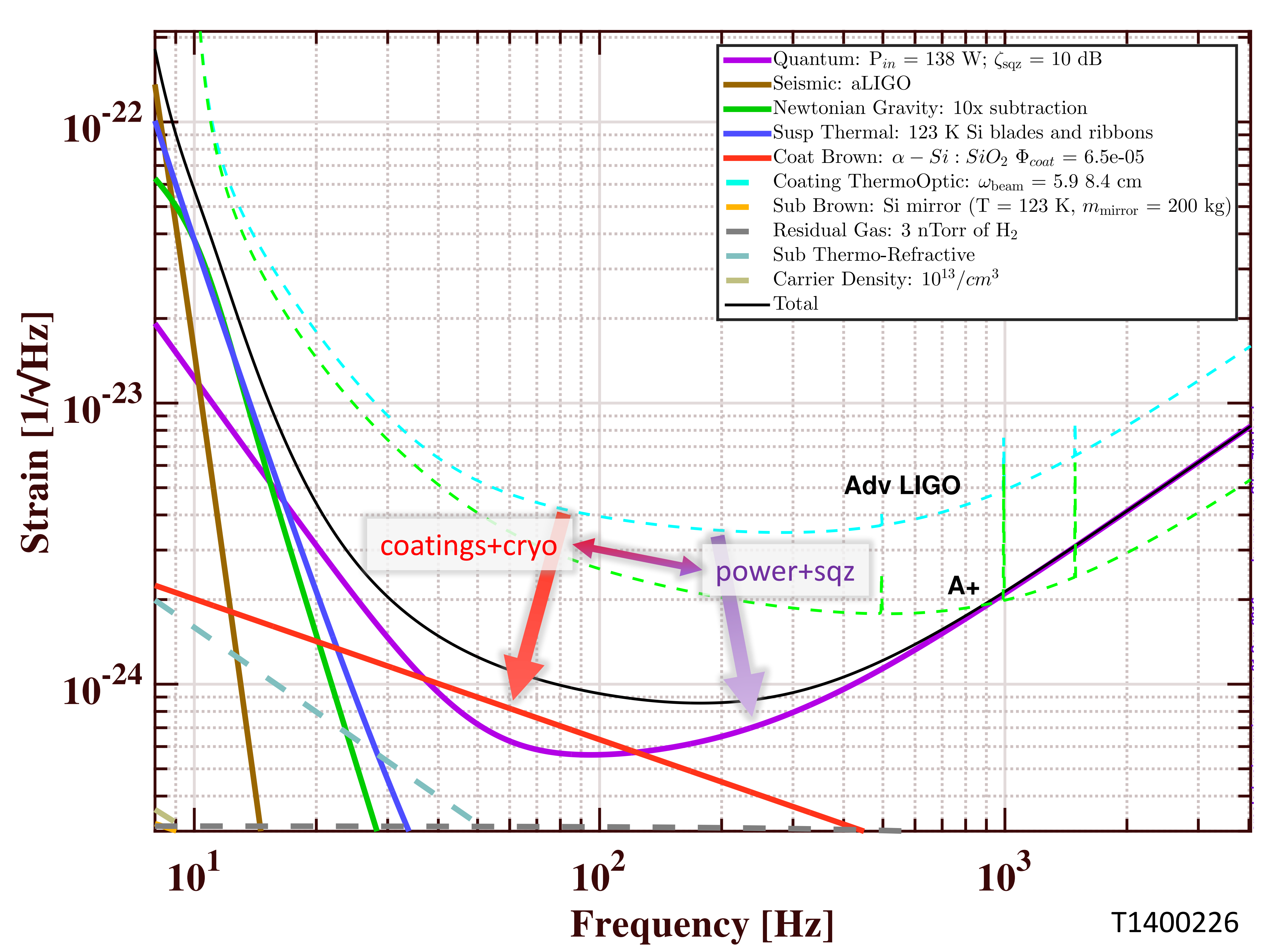
- Cryogenics
  - Low vibration heat shields
  - High emissivity coatings
- Silicon test mass
  - Fabrication
  - Absorption
  - Defects and scatter
- Next steps

Other design aspects: subsequent talks
Also Voyager draft white paper, T1400226

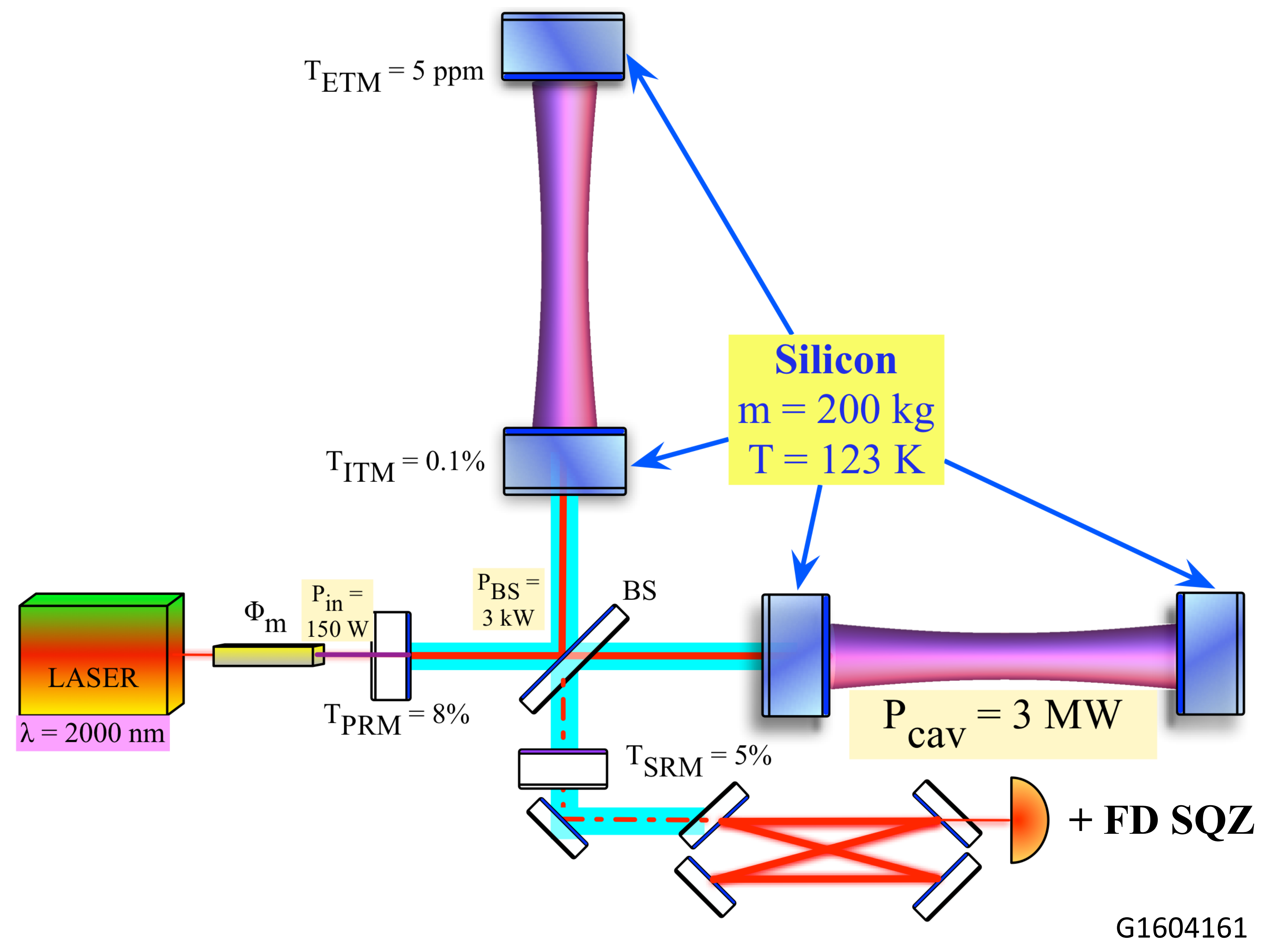
# DETECTOR UPGRADE SEQUENCE

from G1401081





Quantum: $P_{in}$ = 138 W; $\zeta_{sqz}$ = 10 dB
Seismic: aLIGO
Newtonian Gravity: 10x subtraction
Susp Thermal: 123 K Si blades and ribbons
Coat Brown: $\alpha - Si : SiO_2$ $\Phi_{coat}$ = 6.5e-05
Coating ThermoOptic: $\omega_{beam}$ = 5.9 8.4 cm
Sub Brown: Si mirror (T = 123 K, $m_{mirror}$ = 200 kg)
Residual Gas: 3 nTorr of $H_2$
Sub Thermo-Refractive
Carrier Density: $10^{13}/cm^3$
Total
Adv LIGO
A+
coatings+cryo
power+sqz
$10^{-22}$
$10^{-23}$
$10^{-24}$
$10^{1}$
$10^{2}$
$10^{3}$
Strain [1/√Hz]
Frequency [Hz]
T1400226

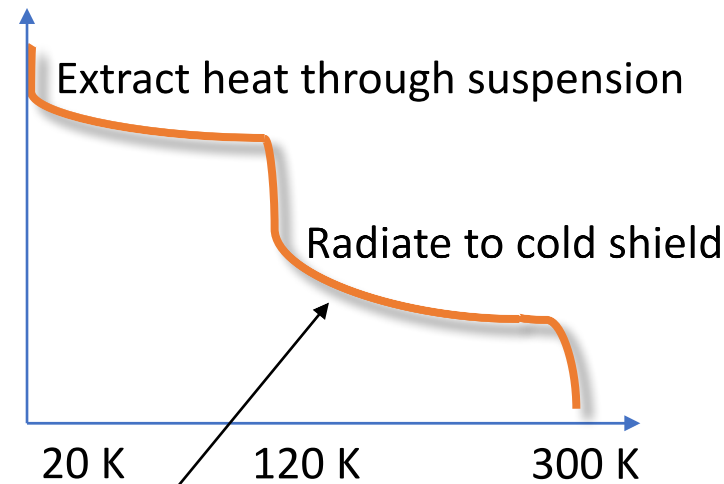


$T_{ETM}$ = 5 ppm
Silicon
m = 200 kg
T = 123 K
$T_{ITM}$ = 0.1%
$P_{BS}$ = 3 kW
BS
$\Phi_m$
$P_{in}$ = 150 W
LASER
λ = 2000 nm
$T_{PRM}$ = 8%
$P_{cav}$ = 3 MW
$T_{SRM}$ = 5%
+ FD SQZ
G1604161

# CRYO-OPTICS LANDSCAPE

| | Silica | Silicon | Sapphire |
|---|---|---|---|
| 300 K | LIGO, VIRGO, GEO600 | thermoelastic | thermoelastic |
| 120 K | cryo loss | Voyager | thermoelastic |
| 20 K | cryo loss | EINSTEIN TELESCOPE<br>ET-D-LF | KAGRA |

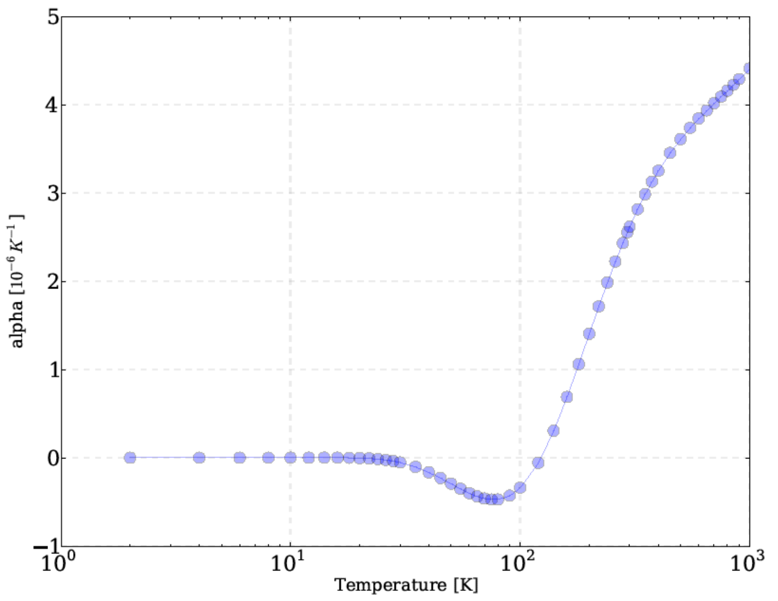
Cryo cost function: two regimes



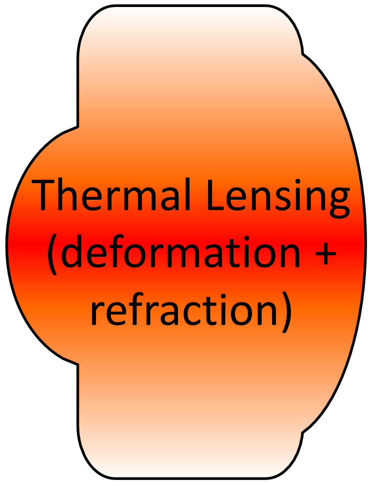

Voyager: minimal cryogenics

Leave some thermal noise on the table, pursue higher power to fully exploit the TN improvement

# WHY SILICON

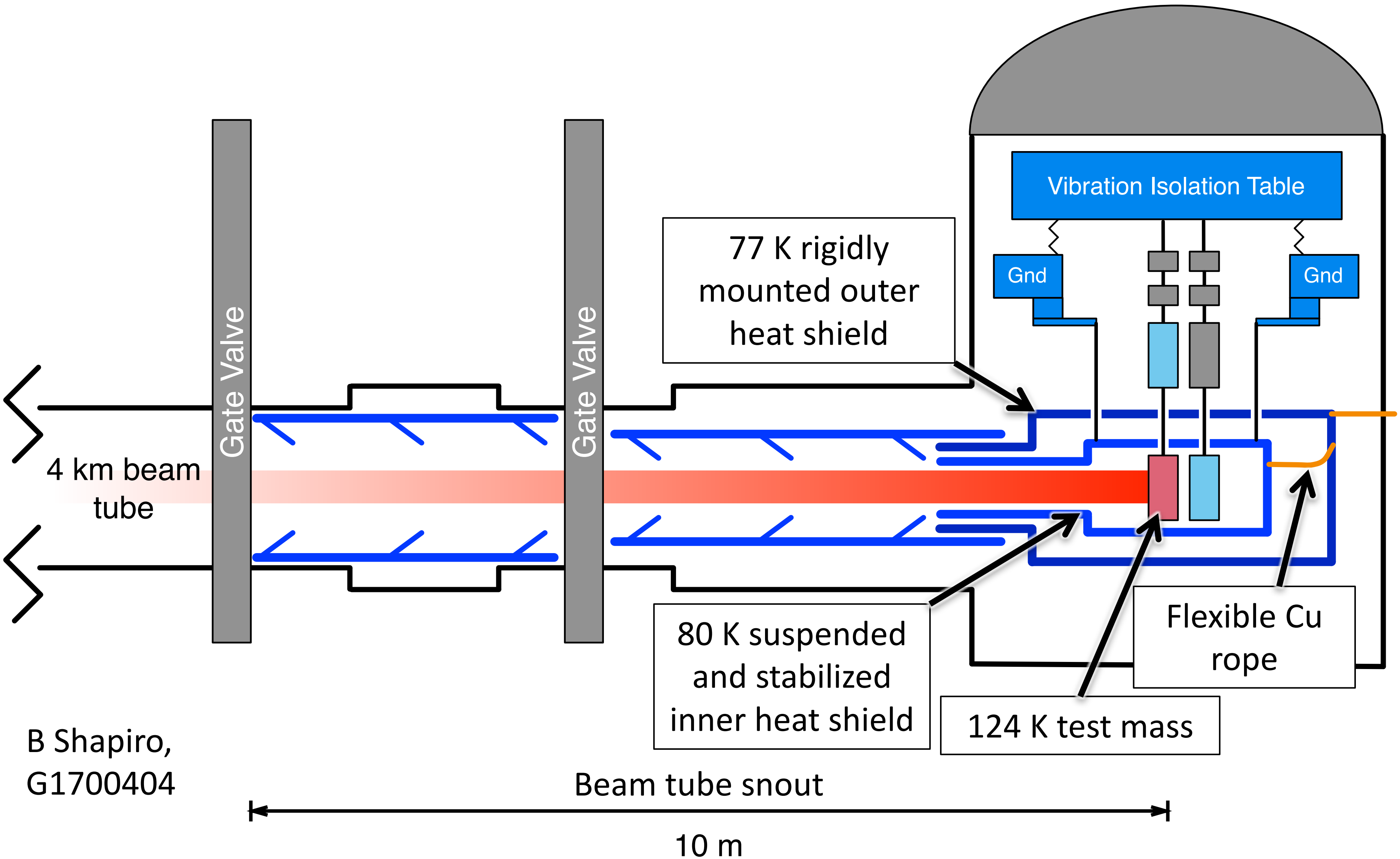



- As with sapphire:
  - No cryogenic loss peak
  - High thermal conductivity
- Thermal expansion coeff $\alpha \rightarrow 0$ for $T \sim 120$ K
- Thermal deformation and thermoelastic noise both vanish
- Minimal thermal lensing + Minimal cryo @ 120 K
  => Opportunity for high power



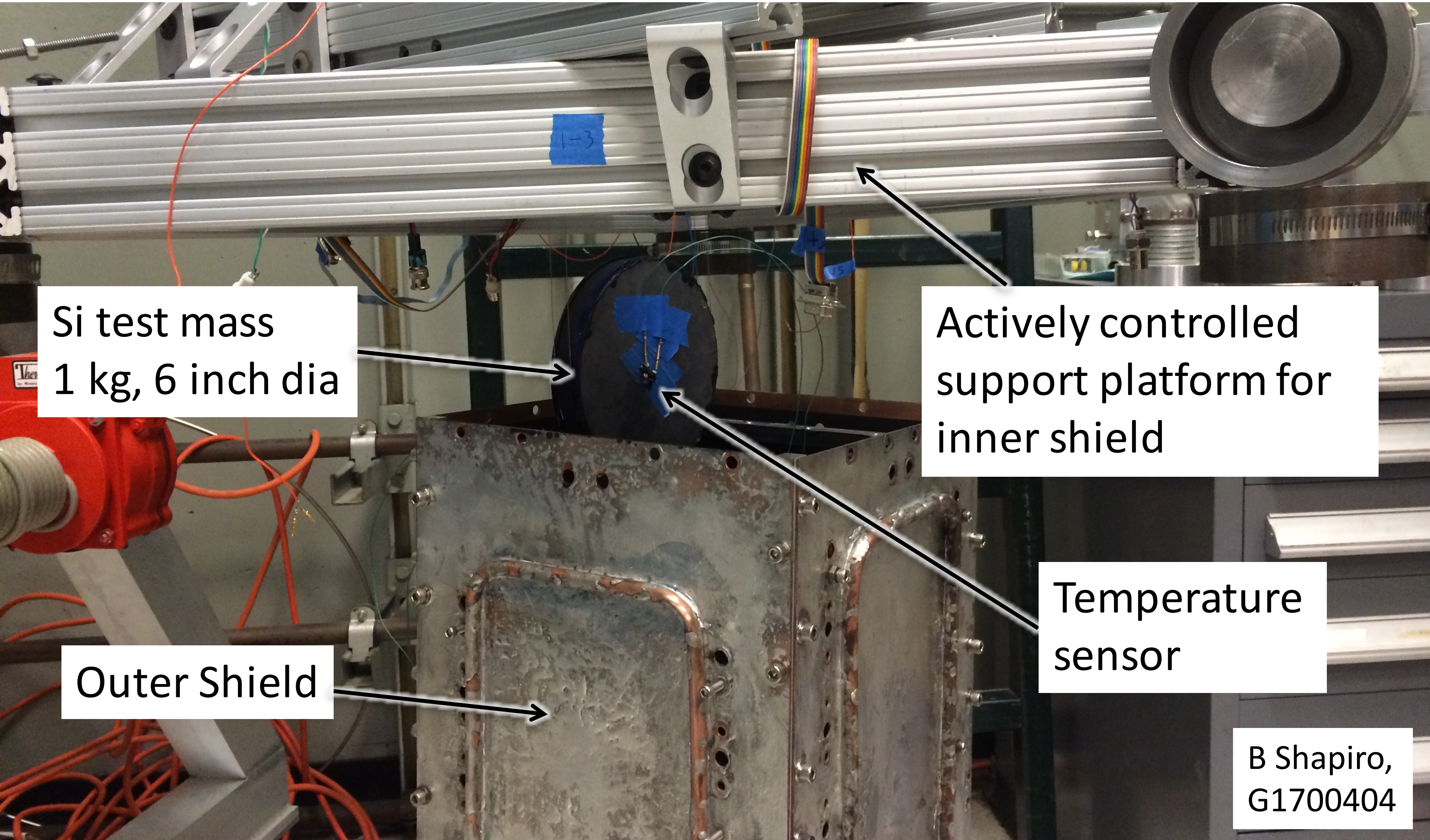

A. Brooks, G1501017

# CRYO DESIGN FOR VOYAGER



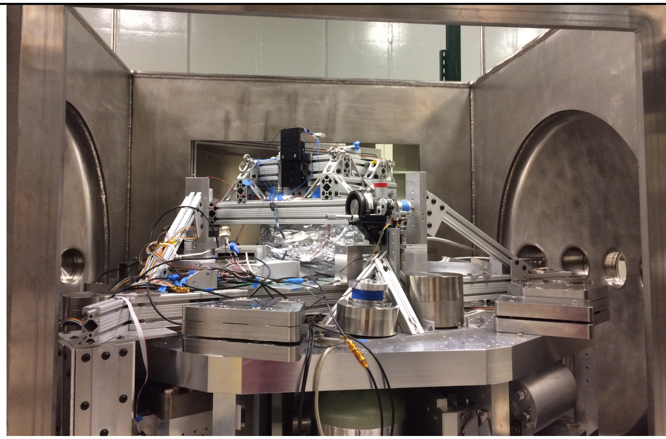

B Shapiro, G1700404

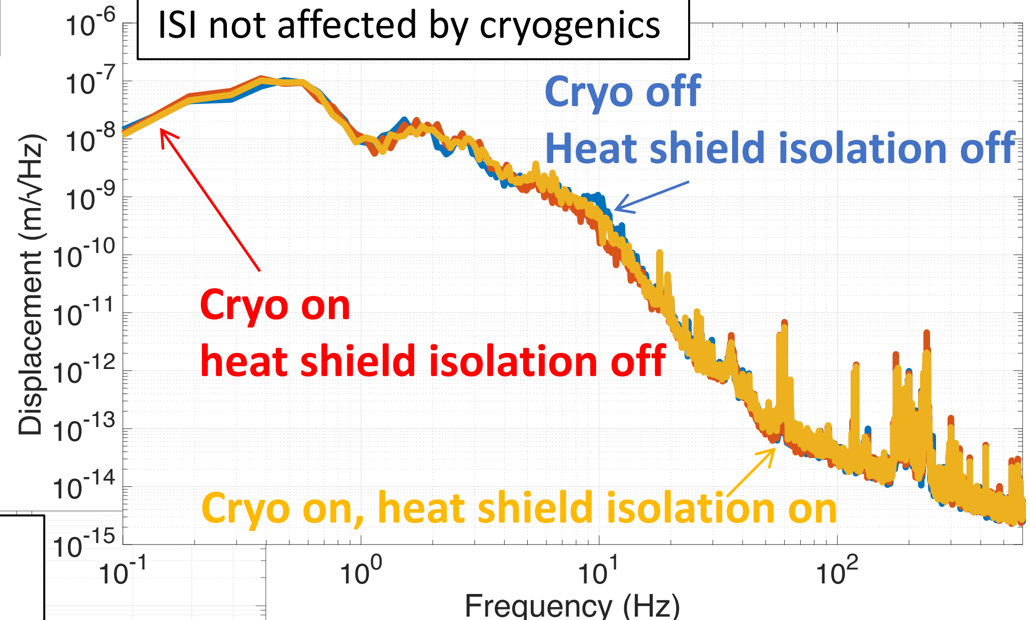
# CRYO PROTOTYPE @ STANFORD

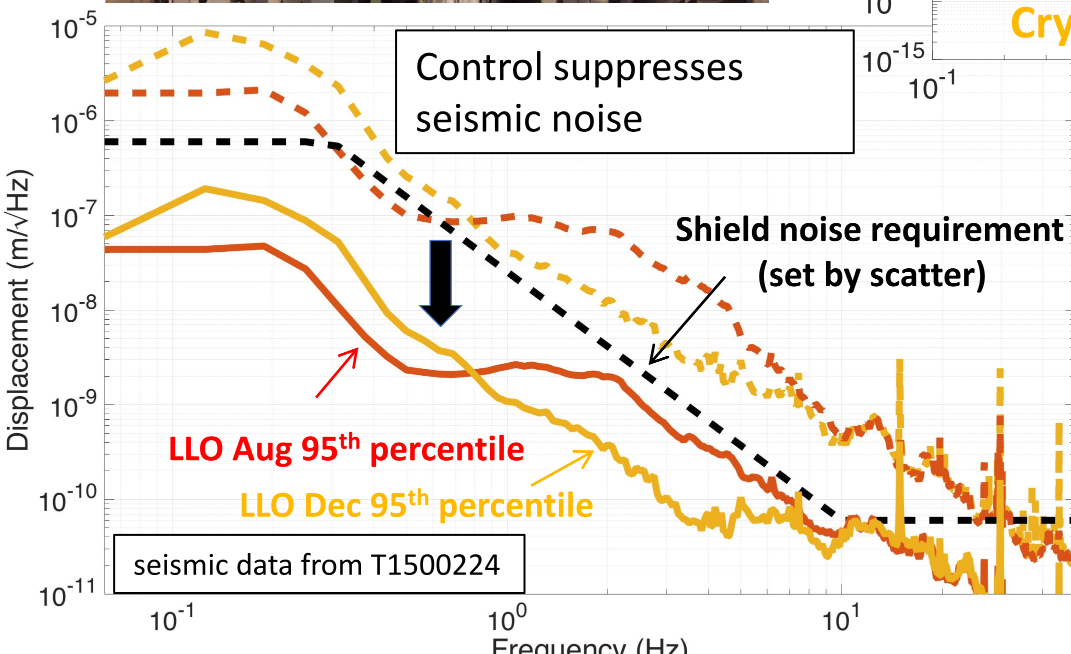


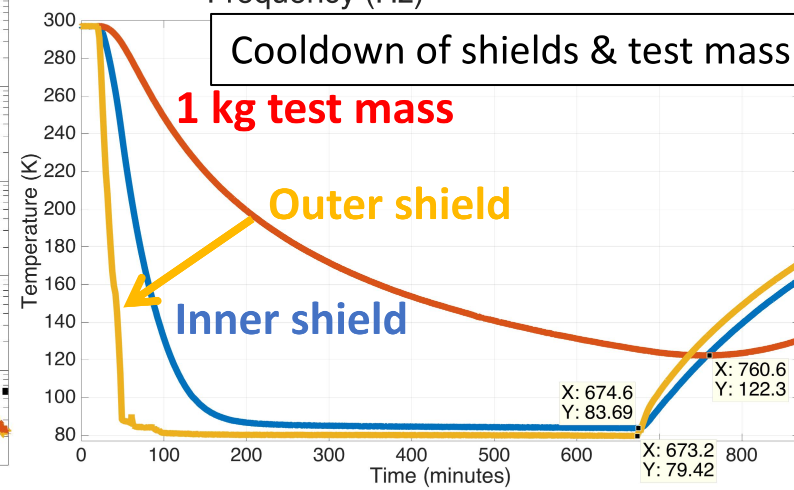
# CRYO PROTOTYPE @ STANFORD

B Shapiro et al, Cryogenics, 81:83-92, 2017

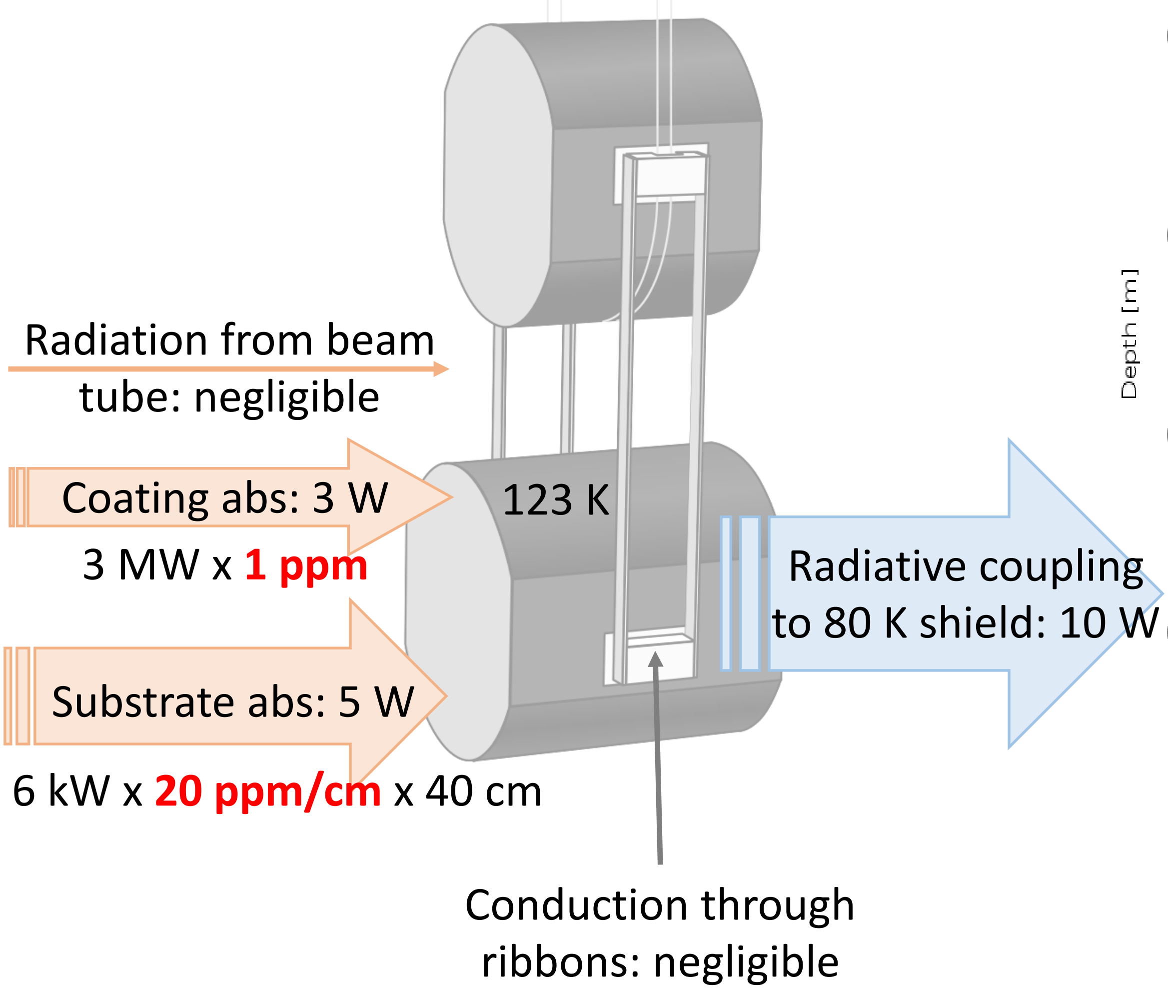




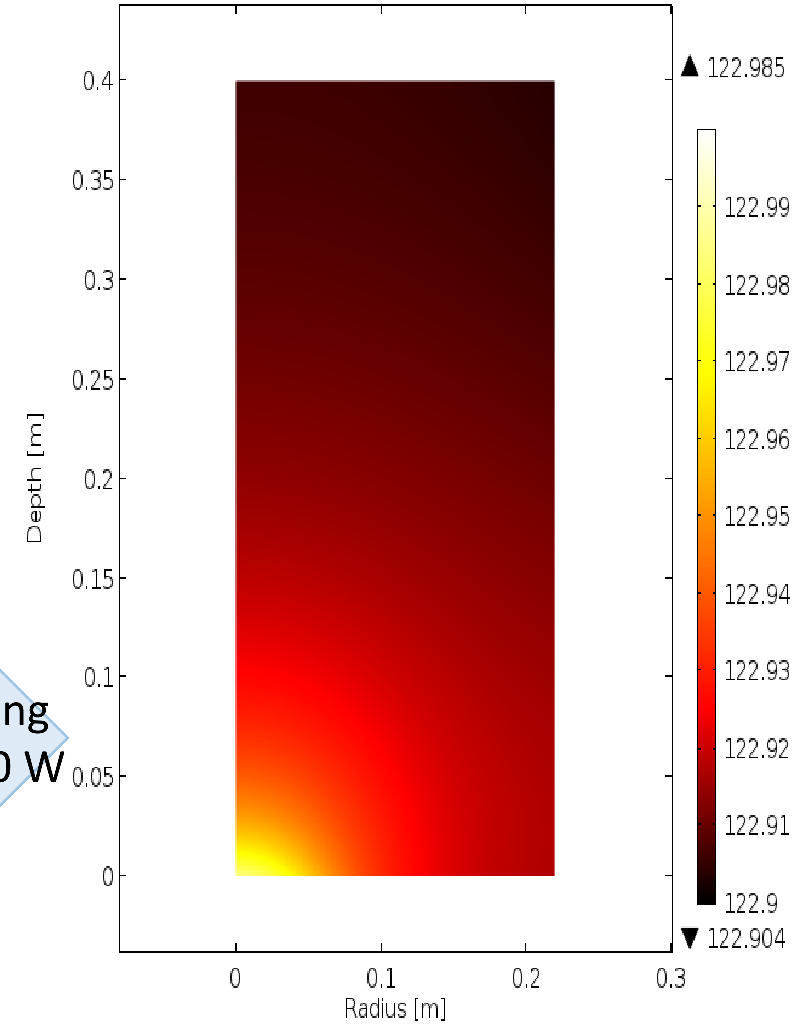



# HEAT BUDGET




Temperature in Si ETM
(10 W absorbed at surface)




$e_{barrel}$ = ~~0.1~~ **0.95** $e_{HR}$, $e_{AR}$ = 0.75

$T_{shield}$ = 80 K $P_{abs}$ = 10 W

$w_{beam}$ = 8 cm

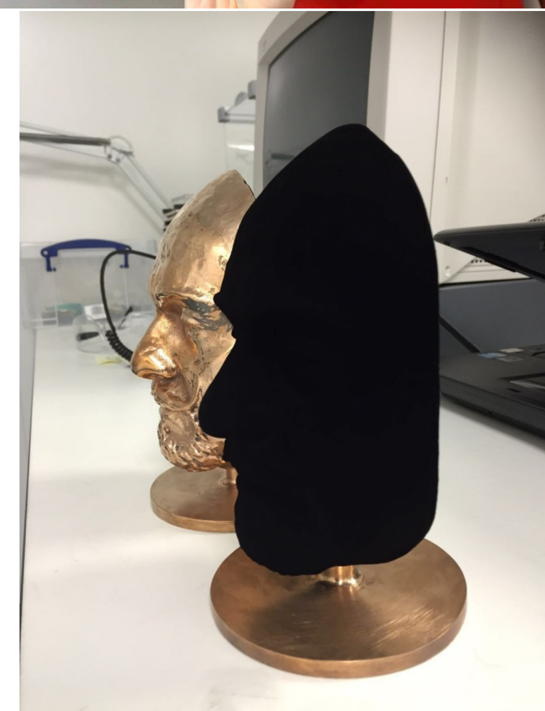
T1400226

# BARREL COATINGS

Vantablack artistic license:

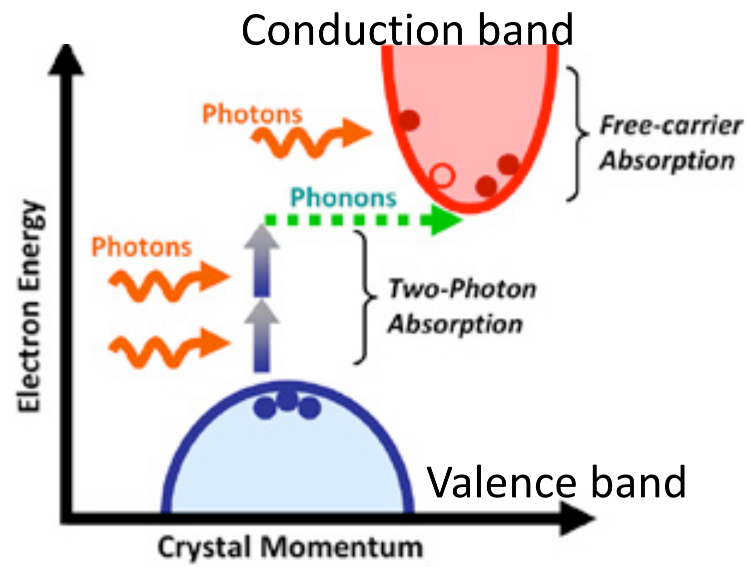
The Worlds "Blackest Black" and the Hilarious Artist Feud Behind It


- Several options on the market
  - Acktar Black, Surrey Vantablack, Goddard coating, DLC
  - Aimed at e.g. spacecraft thermal management
- Detailed look at the Acktar coating
  - $e \approx 0.85$, $\varphi \approx 3.1\text{x}10^{-3}$
  - Projects to ~1.5x below coating noise
  - Silver lining: reduced Q for acoustic modes?
  - Abernathy et al, CQG 33 185002 (2016)
- Alternatives are now being evaluated



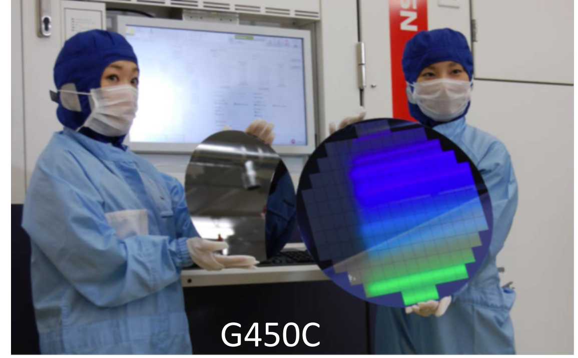
# ABSORPTION IN SILICON

- Requirement was 20 ppm/cm
  (so input mirror does not overheat)
- Inter-band, 1 photon
  - Photon with ~1 band gap of energy excites a carrier to the conduction band
  - Band gap is $\lambda \sim 1.1\ \mu m$
    => pick a new laser wavelength
  - Negligible effect for $\lambda \gtrsim 1.5\ \mu m$
- Inter-band, 2 photon
  - Two photons combine to excite a carrier
  - Non-linear, power dependent process
  - Seems OK for our power density levels
- Intra-band, free carrier
  - Photon kicks a free carrier
  - Need to minimize free carrier density
  - Impurities act as unintended dopants
- Several other processes are possible…



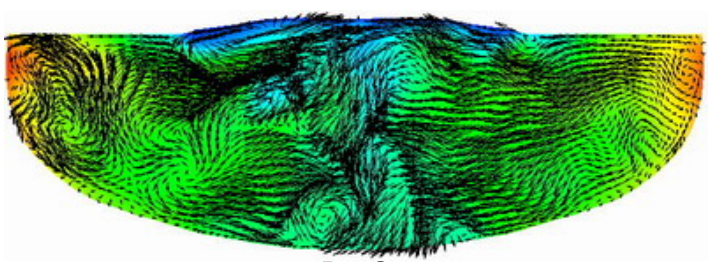

Jalali et al, OPN 6/2009

# FABRICATION

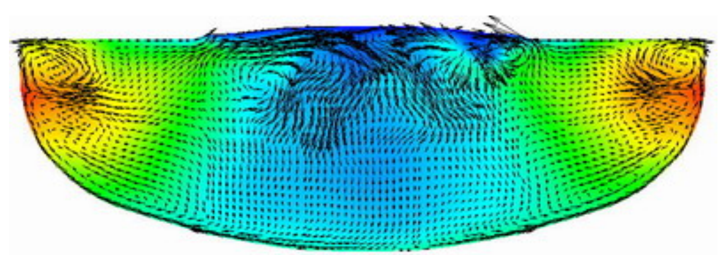




- Very pure mono-crystalline silicon is made commercially by the Czochralski (CZ) process
- Crystals typically grown at 20-30 cm diameter
  - 45 cm/200 kg has been demonstrated
- Main impurity is oxygen (from silica crucible)
  - Trace amounts of carbon, boron, phosphorus
- Magnetic CZ process adds B field to modify convection in the melt (limits oxygen transport)



B=0

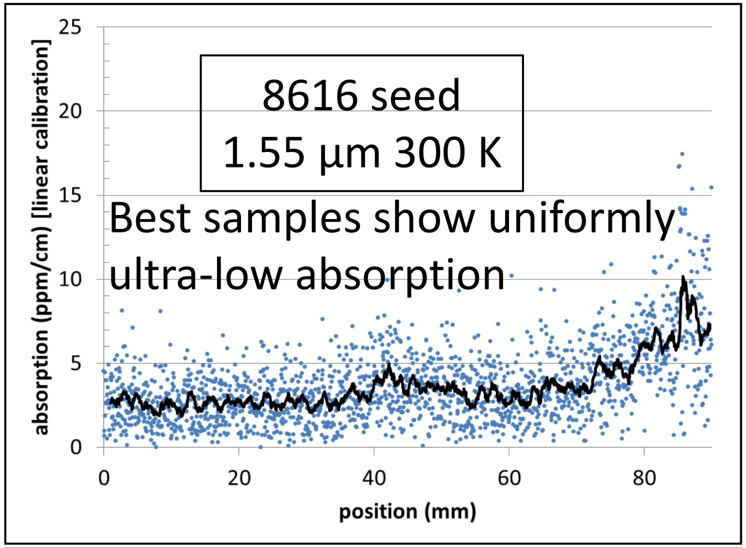


B=30 mT

str-soft.com

# ABSORPTION: 1D RADIAL PROFILE

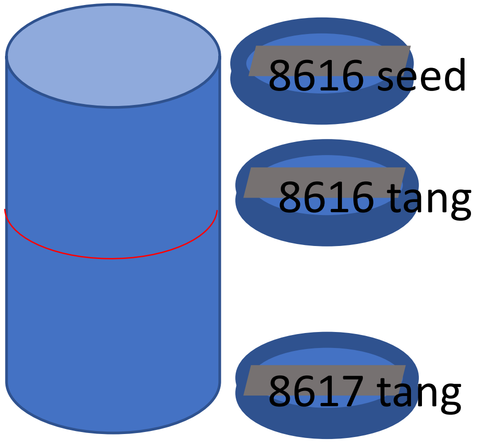

A Markosyan, A Bell

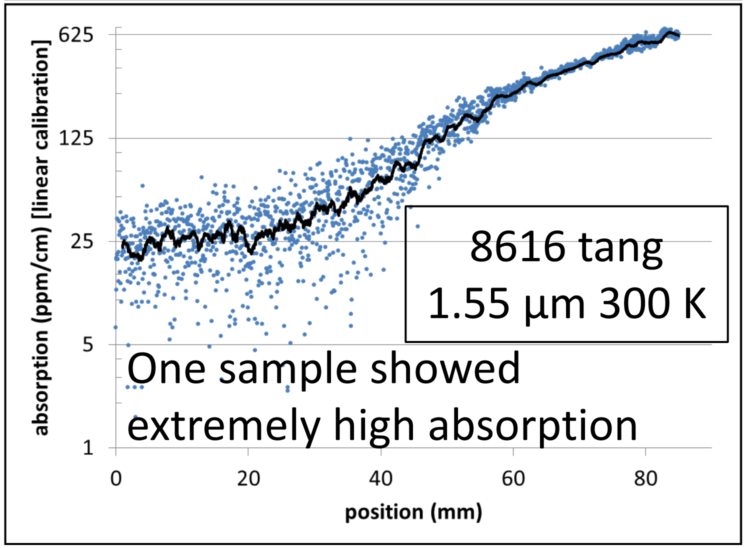


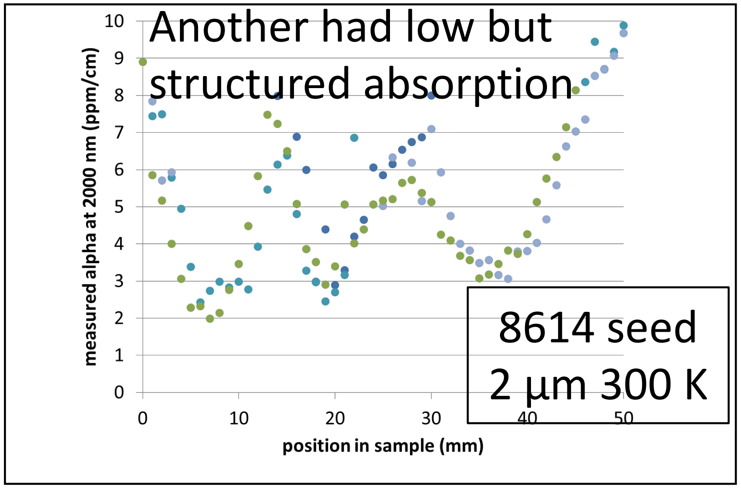

Few to ~10 ppm/cm

25 to ~625 ppm/cm

Few to ~15 ppm/cm

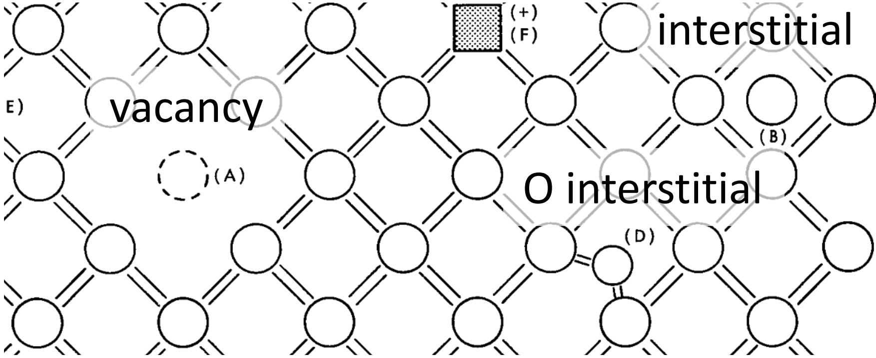


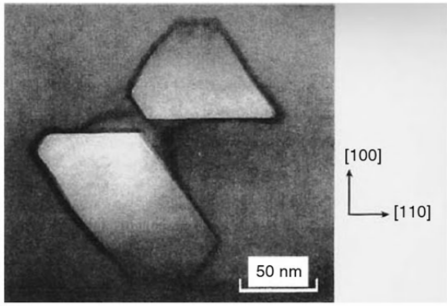




A Markosyan, G1700480

# DEFECTS AND SCATTER

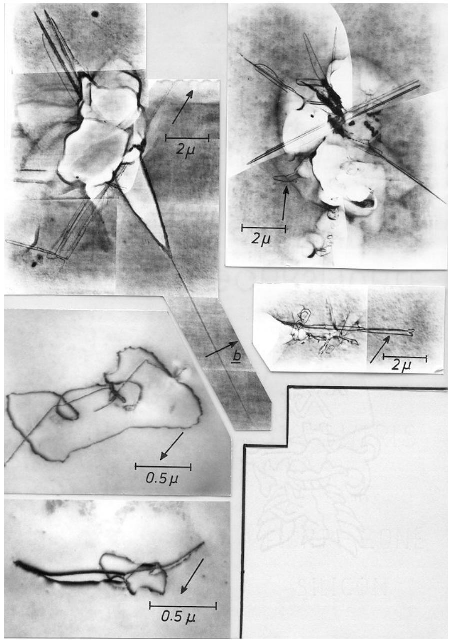


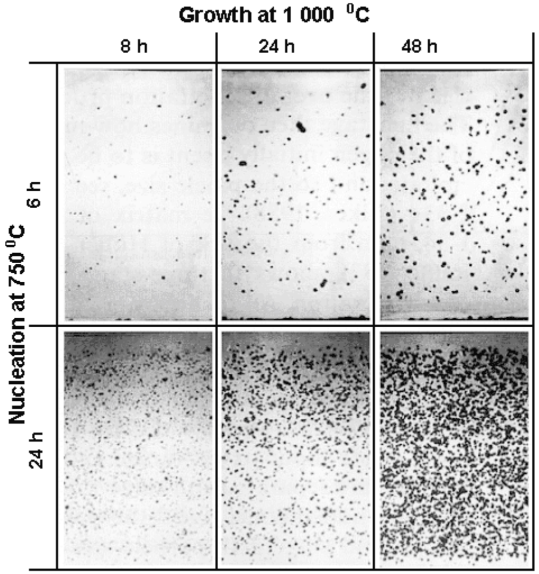

## Defect populations depend on crystal growth parameters:




Void defects typically <0.2 µm (vacancy rich)

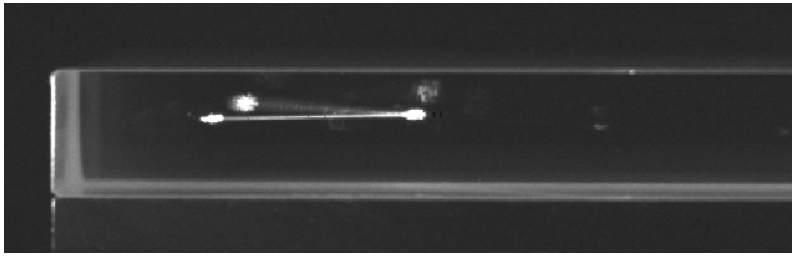
Dislocation structures (interstitial rich)




$SiO_2$ precipitate after anneal (O rich)

*Lower T anneals can create or eradicate free carriers (thermal donors)*



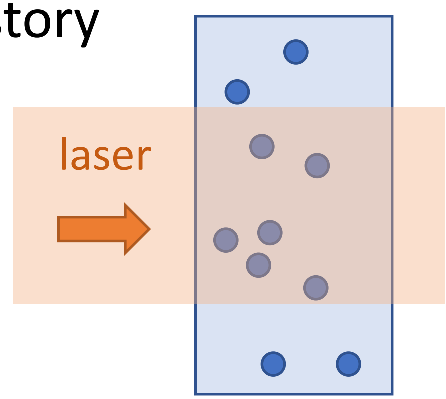
Scatterometry underway at Glasgow
InGaAs camera image of MCZ silicon sample
Z Tornasi et al, G1700444

# NEXT STEPS

- Cryo technologies
  - Optimization of black coatings and heat straps
  - Rapid cooling system (conductive heat switch)
  - Detailed thermal analysis and mechanical design
- Silicon optics
  - Annealing study
  - Polishing/surface absorption
  - Phase noise
- Integration
  - Caltech 40m lab as Voyager prototype

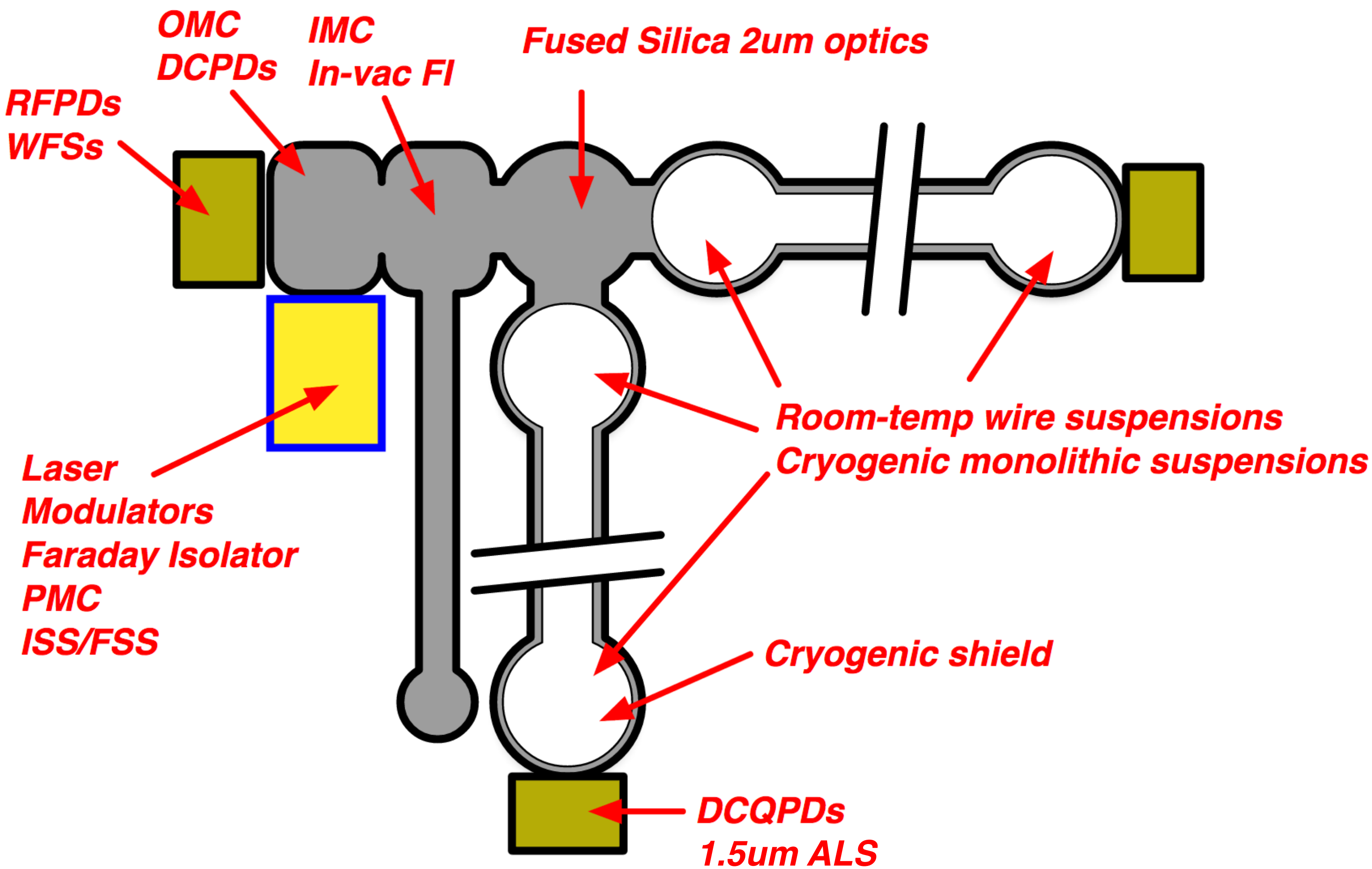
# PHASE NOISE IN SEMICONDUCTORS

- All optics impose thermo-refractive noise
  - $T$ dependent refractive index, $\beta = \mathrm{d}n/\mathrm{d}T$…
  - …combines with random localized fluctuations in $T$…
  - …to produce phase noise
- Additionally, **semiconducting optics** suffer from **carrier density noise** (predicted by Heinert et al)
  - Index depends on free carrier density, $\beta_{CD} = \mathrm{d}n/\mathrm{d}n_e$ (or $n_h$)…
  - …combines with random CD fluctuations… same story
  - Effect size grows with carrier density (another motivation to keep impurities low)
- CD noise presently predicted to be negligible
  - Need to check this theory with MCZ Si samples




D Heinert, G1401034

# 40M PROTOTYPE



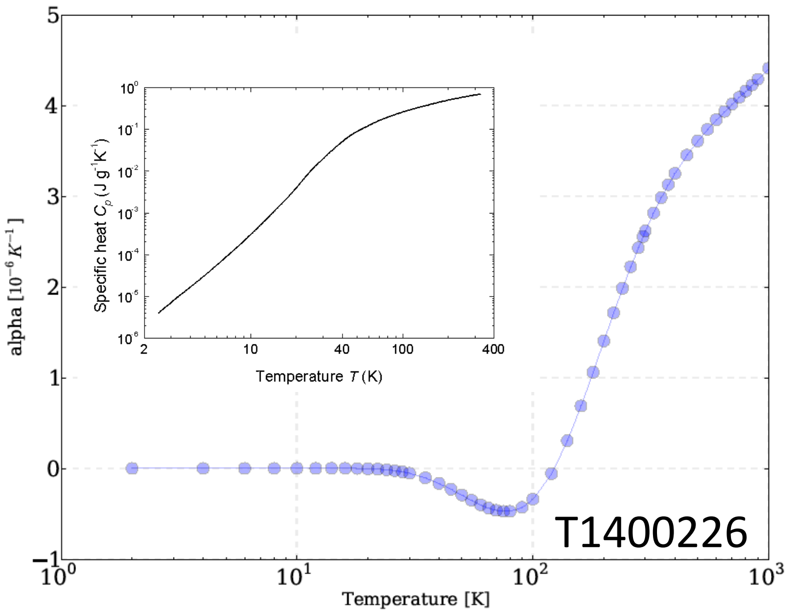
# CONCLUSIONS

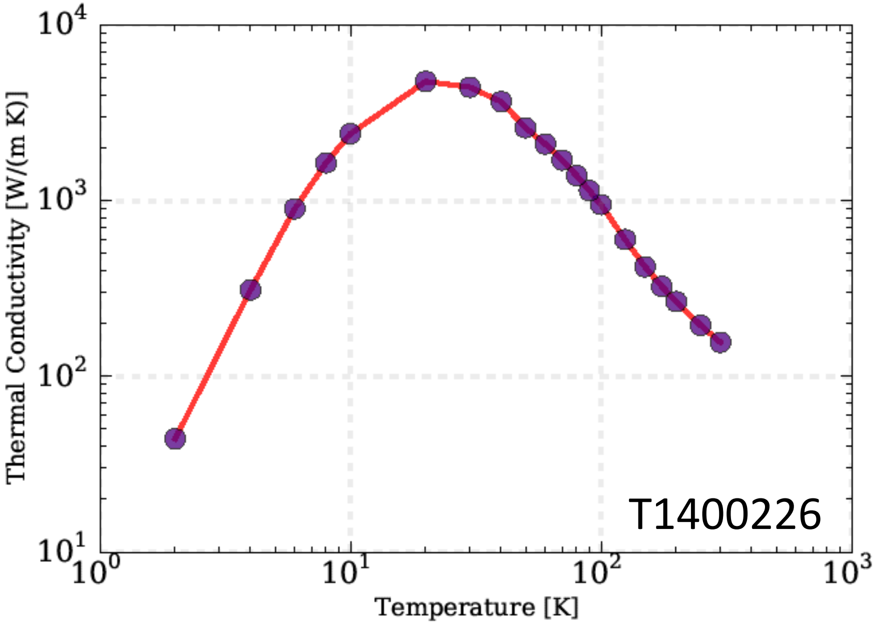
- Cryo system progressing toward design phase
  - Low vibration cryoshields demonstrated
  - Black coating options being explored
- Magnetic CZ silicon still looks promising
  - Test mass sized crystals are manufacturable
  - Evidence of uniform ultra low absorption
  - Much more to be learned on scatter, phase noise, etc
- Stay tuned
  - After the break: challenges with high power
  - Tomorrow: coatings development and testing
  - Thursday: 2 μm lasers and squeezers

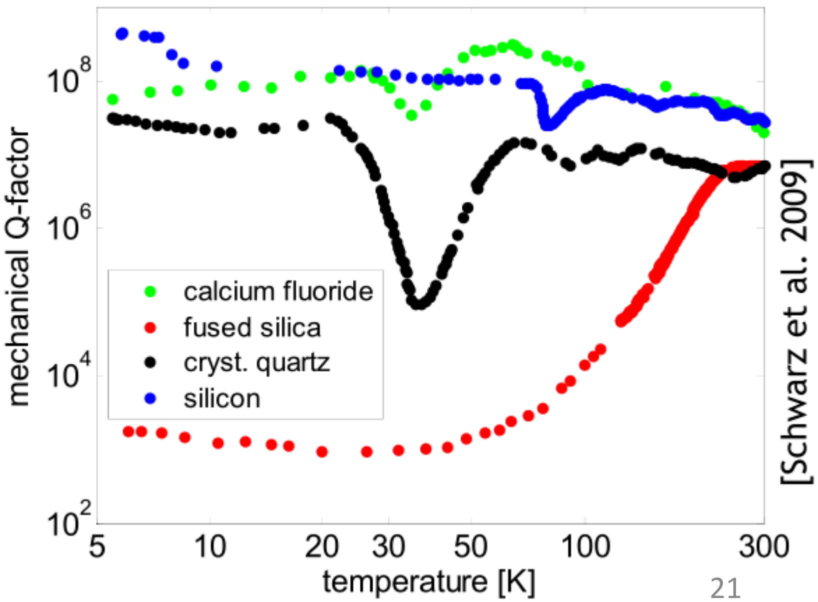
J. Eichholz, G1602184

# Crystalline Silicon

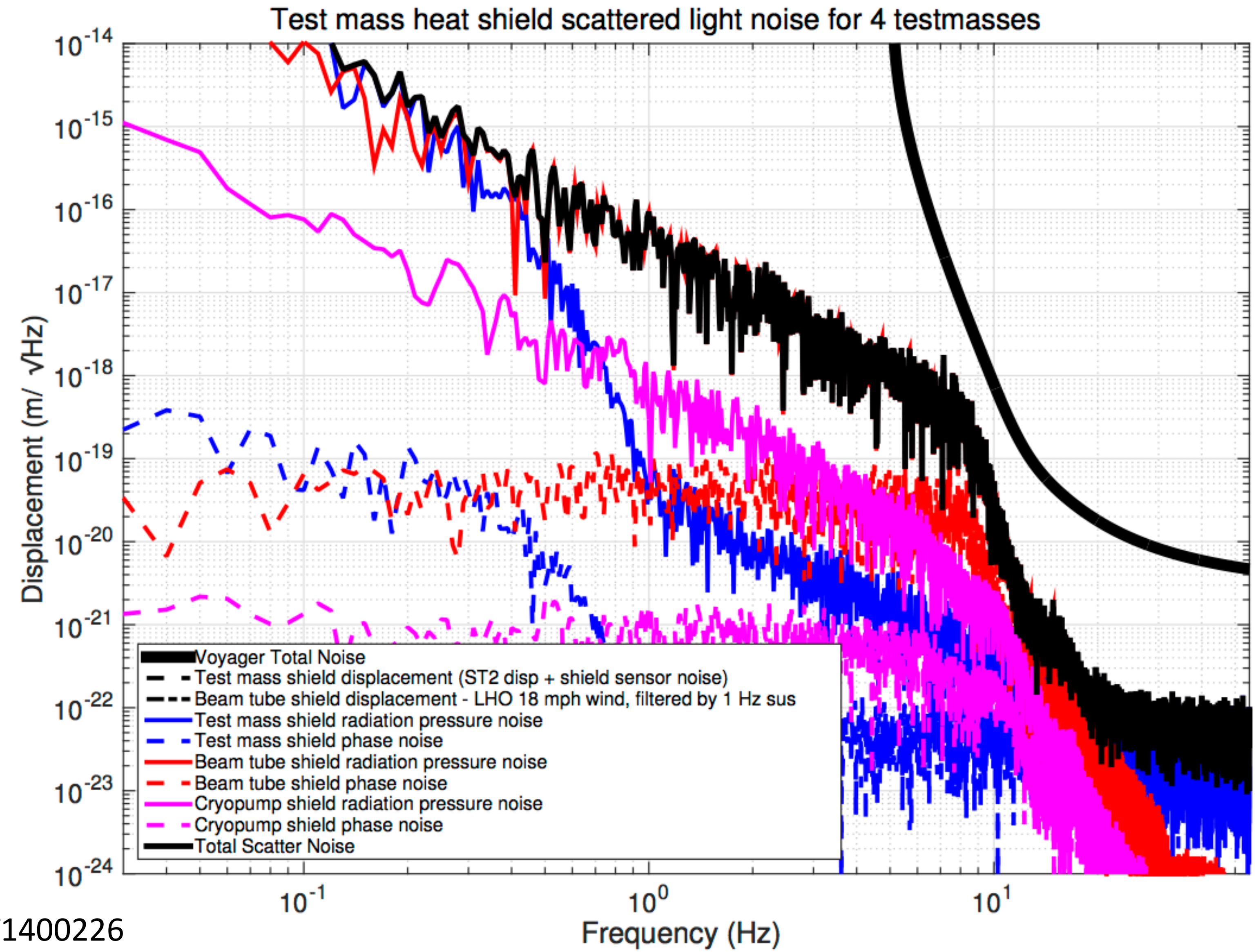
- Zero CTE at 123 K
- Good thermal conductivity
- Low mechanical loss
- Transparent above 1500 nm



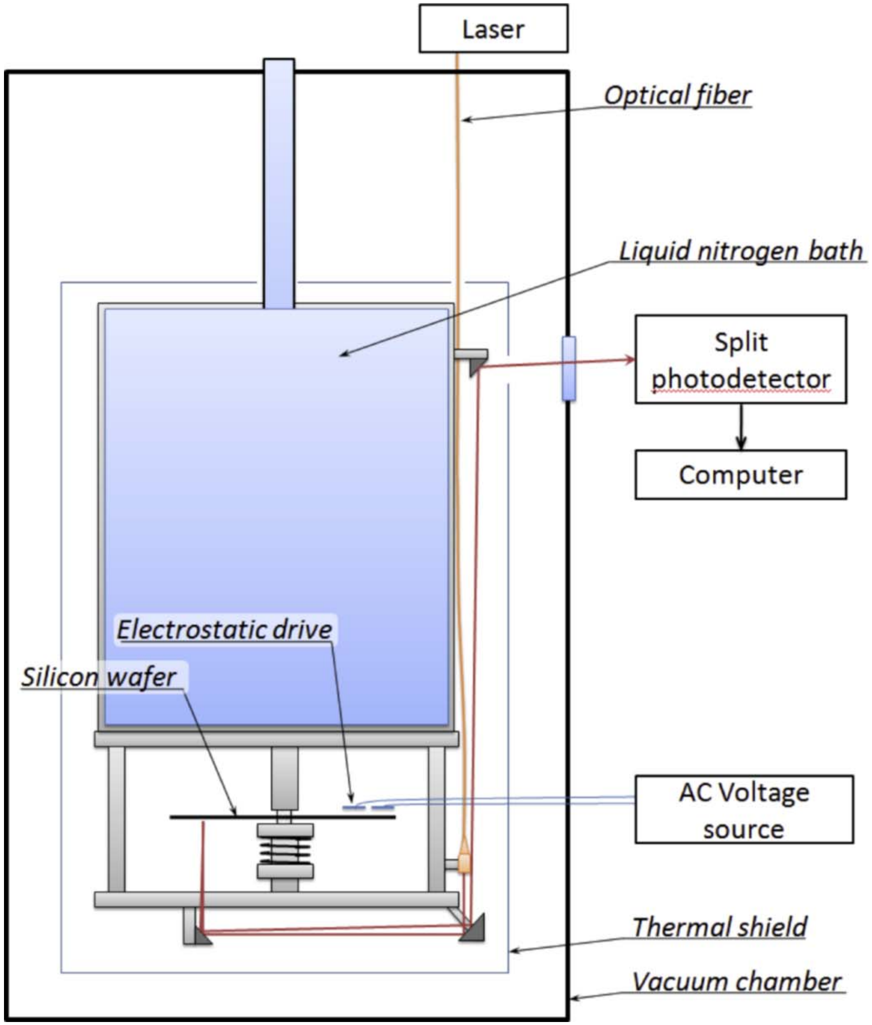



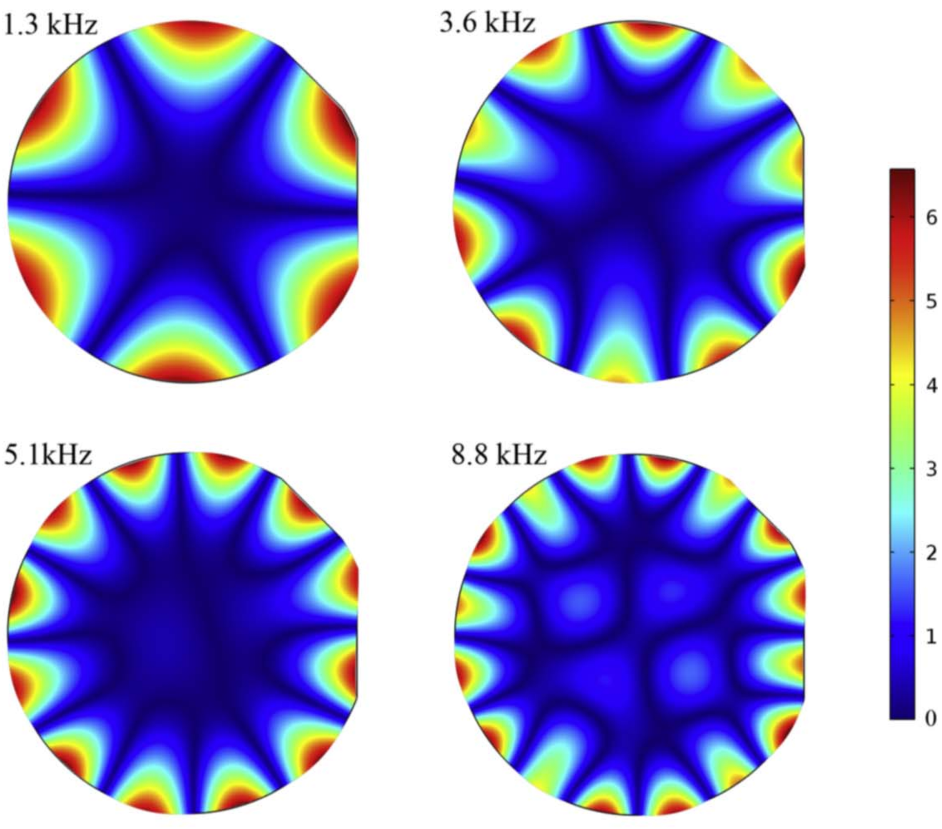
# Heat Shield Scatter Estimation




Source: T1400226

# ACKTAR EXPERIMENT

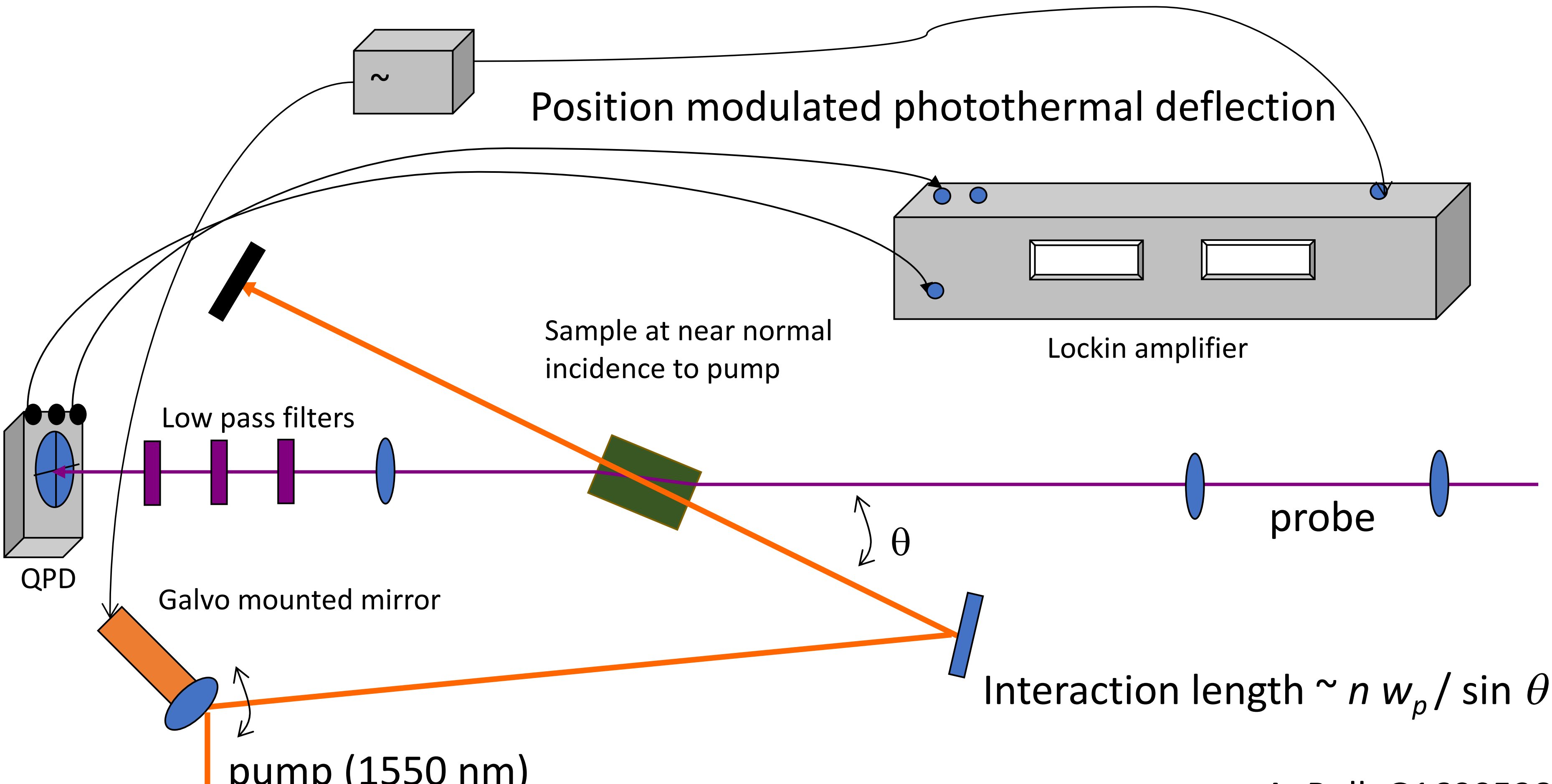



(b)

# IR ABSORPTION MEASUREMENTS


A. Markosyan, A. Bell



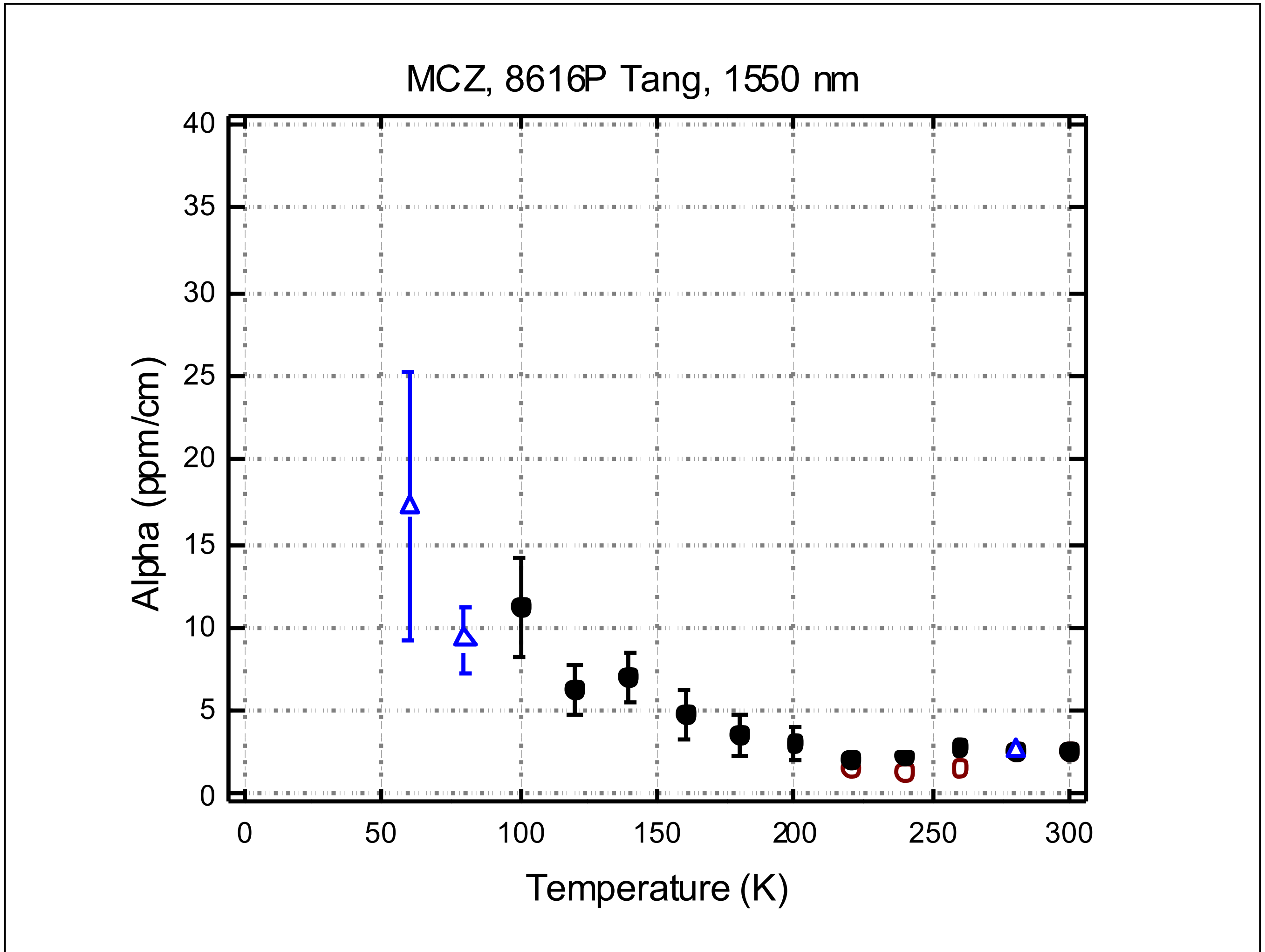

A. Bell, G1600538

# IR ABSORPTION RESULTS

A. Markosyan, A. Bell

Stanford

University of Glasgow



# WHY CRYOGENIC SILICON?

S. Rowan, G000069

Silicon : similar to sapphire **but**
coefficient of thermal expansion = 0
at ~ 120K , ~ 20K

→ Thermo-elastic noise → zero at these temperatures

→ silicon looks very interesting