A Preview of Future Cryogenic Suspensions for aLIGO Upgrades

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Stanford cryo people:
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G1400475 – 29 April 2014 – Caltech

Summary

- Moving from Advanced LIGO to LIGO III
- LIGO III quad suspension design
- Steady state cooling (science mode)
  - System layout
  - Length of heat shield extending into beam tube
- Initial Cool down
  - Stanford initial cool down experiments
- Future work

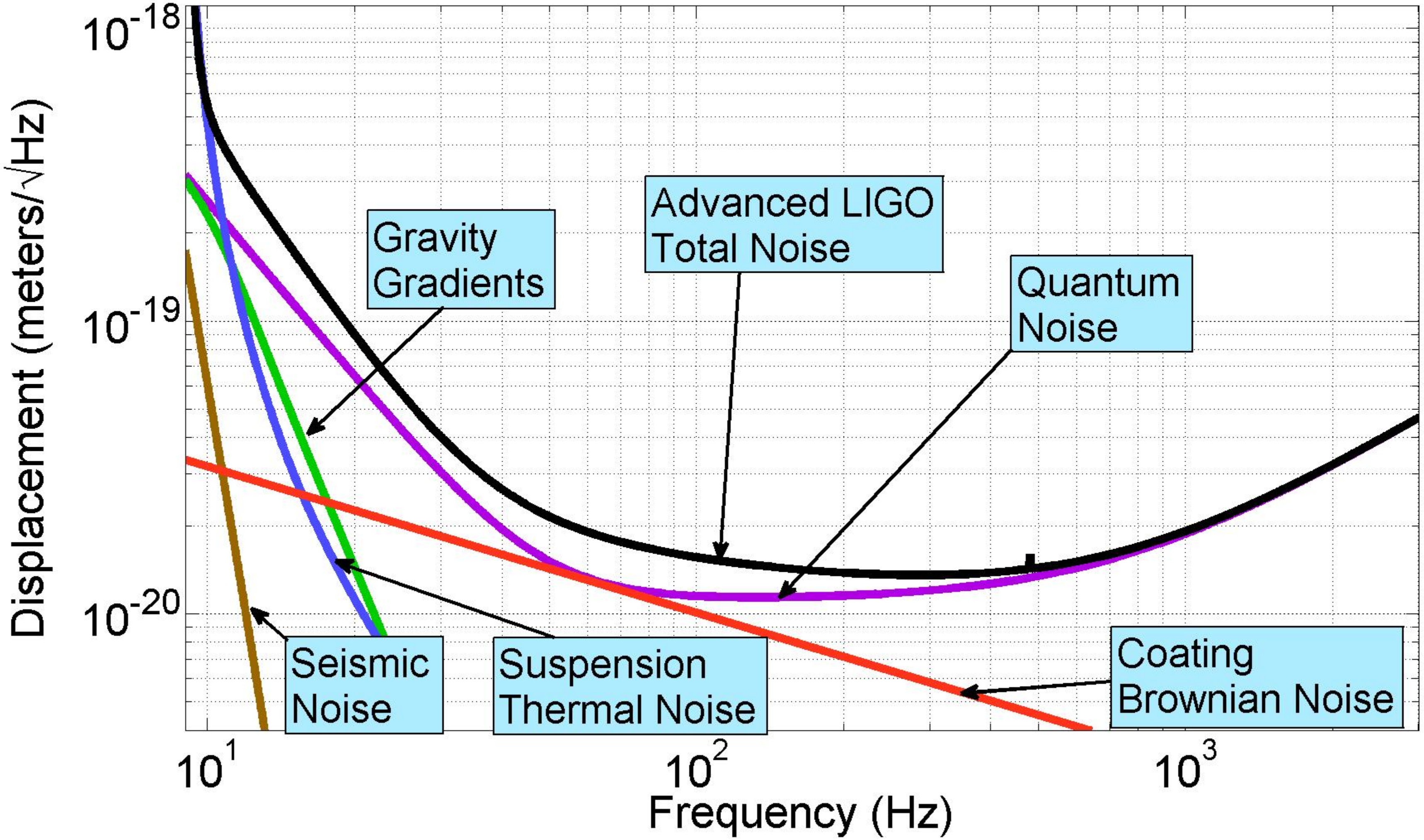
Advanced LIGO Timeline

Livingston, LA

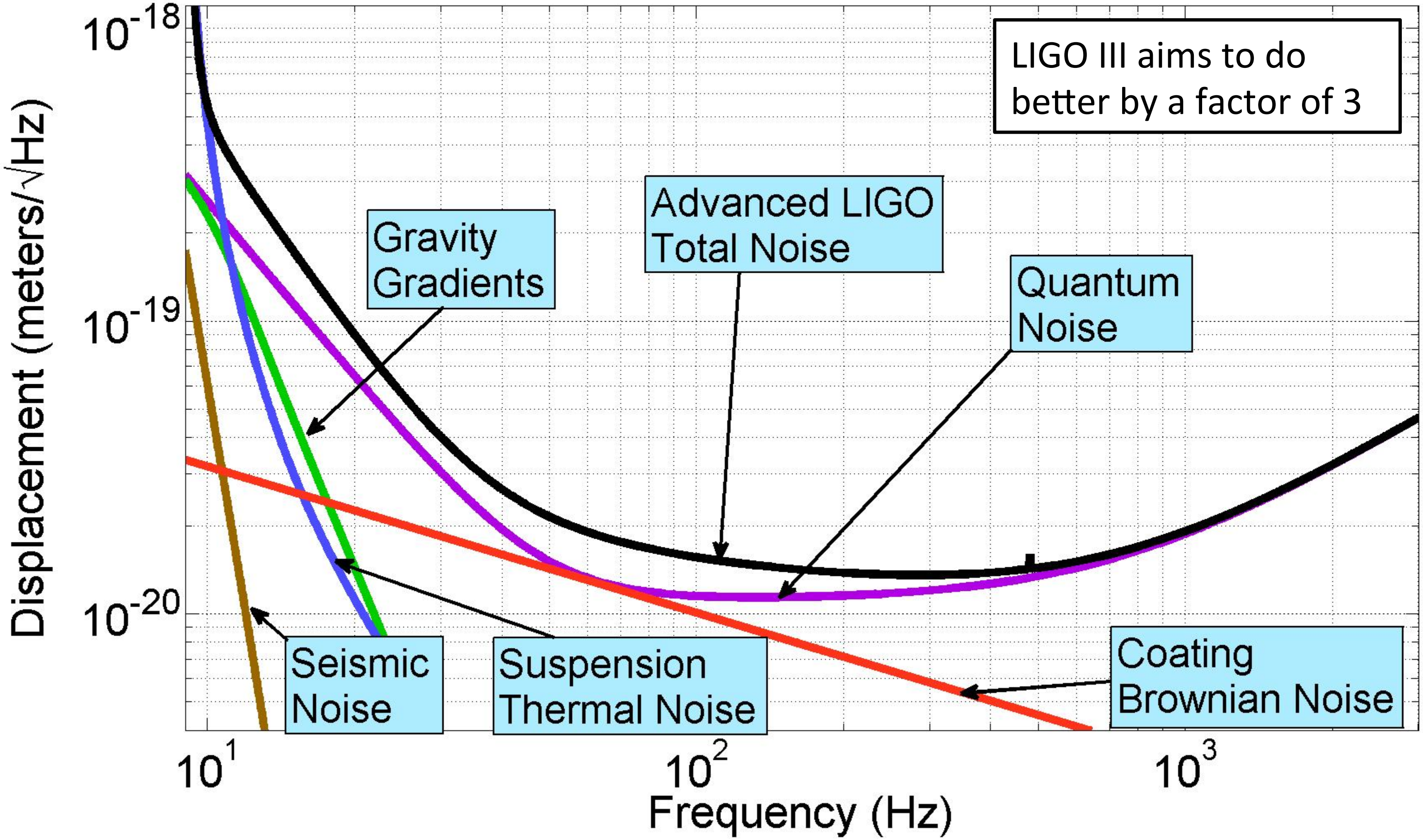
Hanford, WA

- Last core optics March 2014
- Full lock testing: Aug-Sept 2014
- 1st science run: Sept-Dec 2015
- GW astronomy: Soon after
- Build LIGO III: Far after

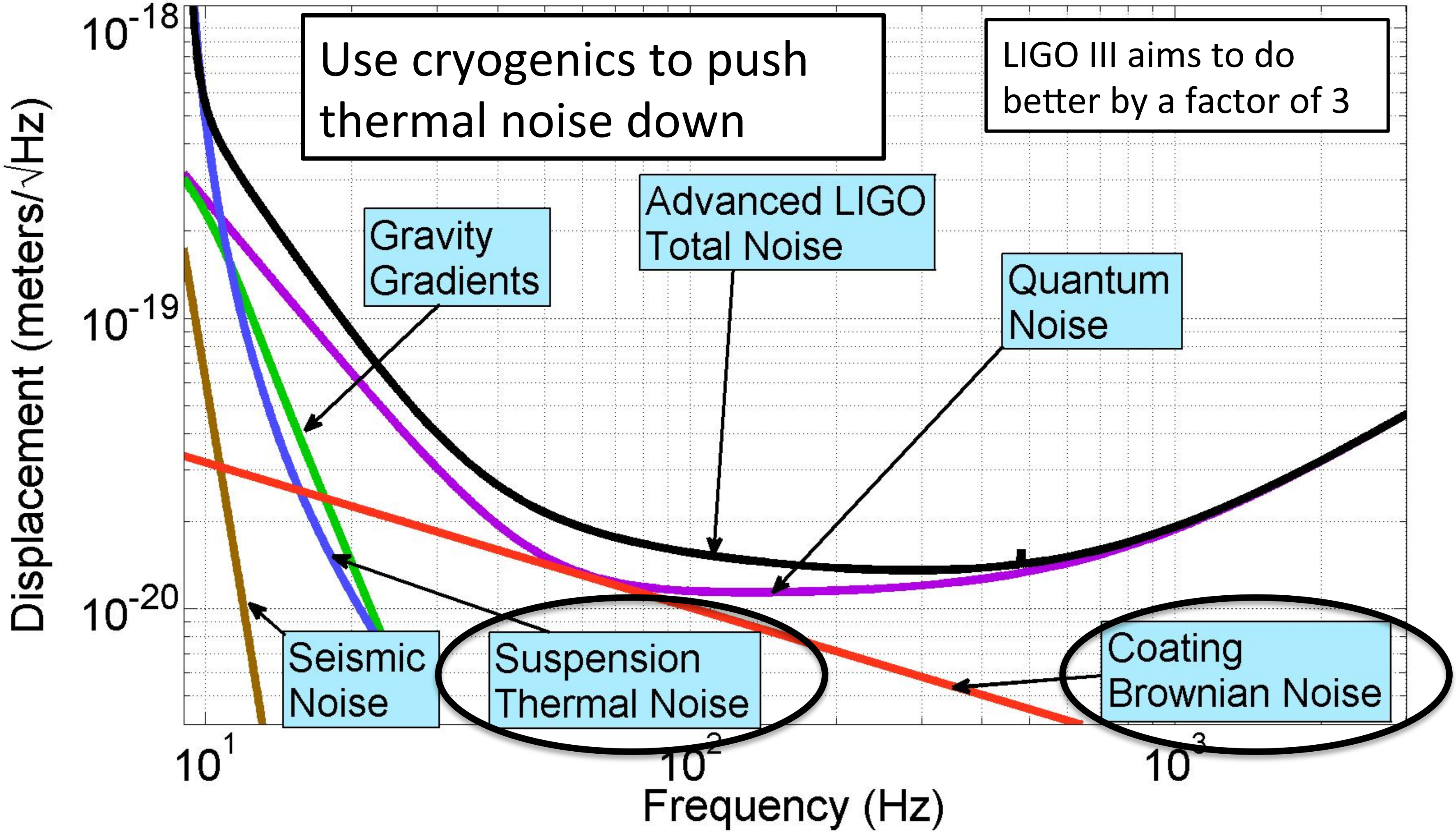
Predicted Advanced LIGO Sensitivity



Predicted Advanced LIGO Sensitivity



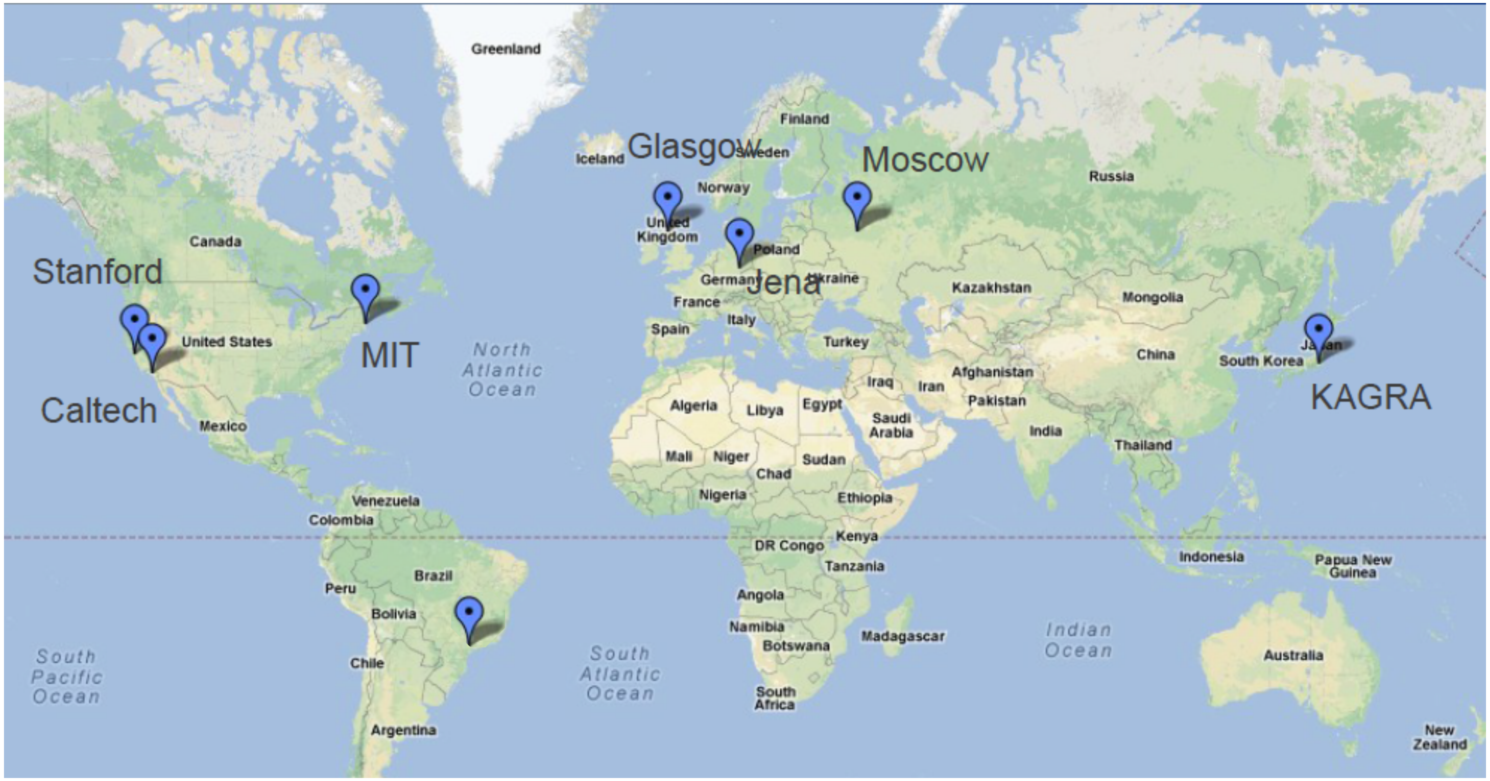
Predicted Advanced LIGO Sensitivity



Use cryogenics to push thermal noise down

LIGO III aims to do better by a factor of 3

LIGO III cryo work distribution



- Caltech - cryogenic reference cavities; direct thermal noise measurements
- Jena/Glasgow/Moscow - mechanical loss
- MIT – high emissivity coatings
- KAGRA – 20 K sapphire suspensions
- INPE Brazil – Cryogenic multi-nested pendulum
- Stanford – optical coatings; cryogenic technology

Courtesy of Nicolas Smith

Cyro Test Mass Problem Statement

* For LIGO III, reduce suspension and coating thermal noise by cooling the lower quad to 124 K (-149.15 C)

  - Si test masses (blue team in LIGO-T1200031)

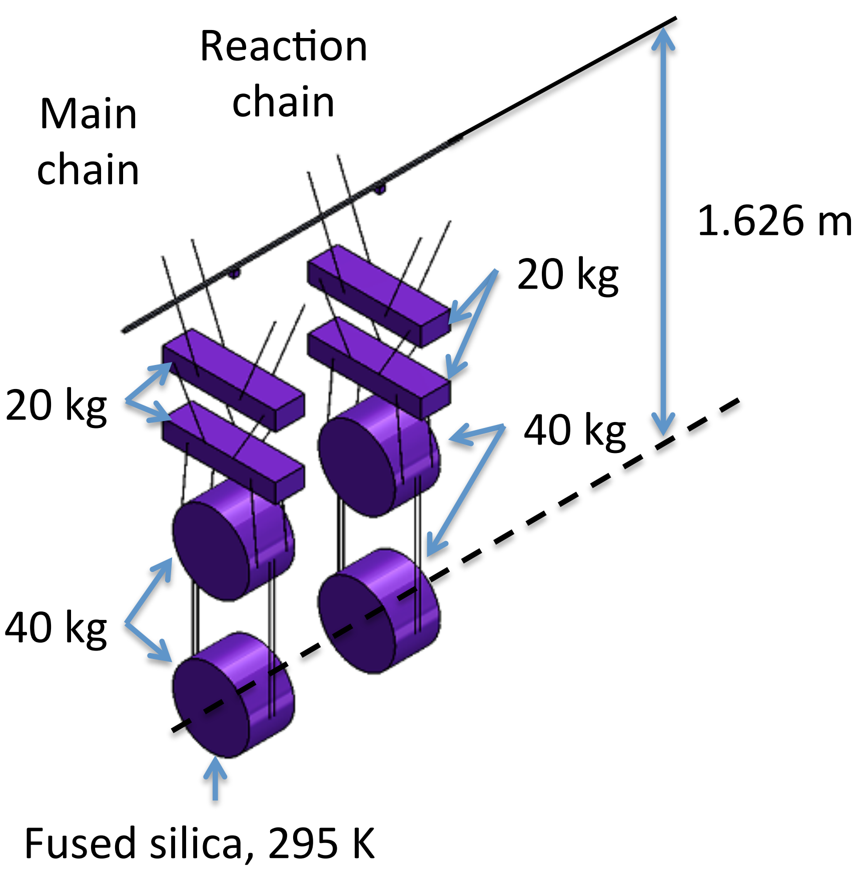
- **2 cooling regimes:**
  - **Initial cool down - get to 124 K quickly** <- Stanford experiment
  - **Steady state - maintain 124 K once you get there**
- Include a warm-up scheme (don't forget!)
- Use the same seismic isolation platforms (ISIs, HEPIs)
  - Limit the amount of extra weight on these plaforms
  - Leave the rest of the vacuum chamber warm
- Do not increase the test mass lossiness
  - Emissive coatings, heat links, thick sus fibers, optical coatings, substrate, suspension fiber bonding, etc
- Do not compromise passive seismic isolation
  - Cables, hoses, links, etc

Quad Suspension Design

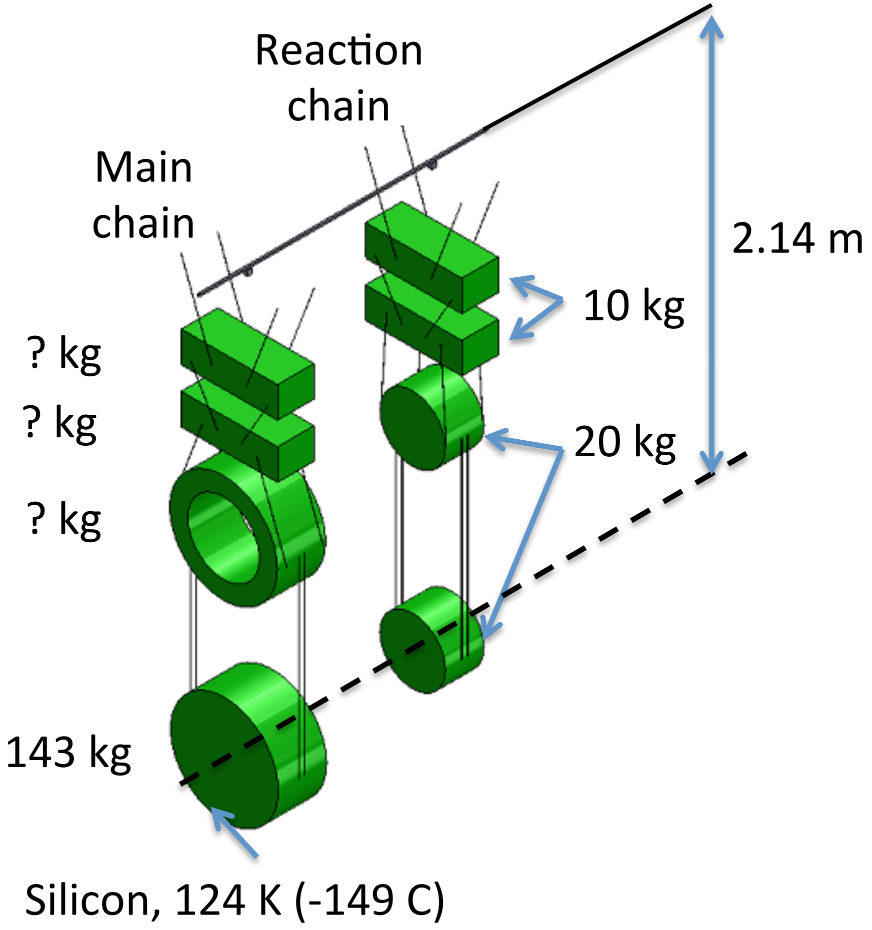
Must incorporate much larger test mass

LIGO III Quad Suspension Design

Advanced LIGO quad pendulum

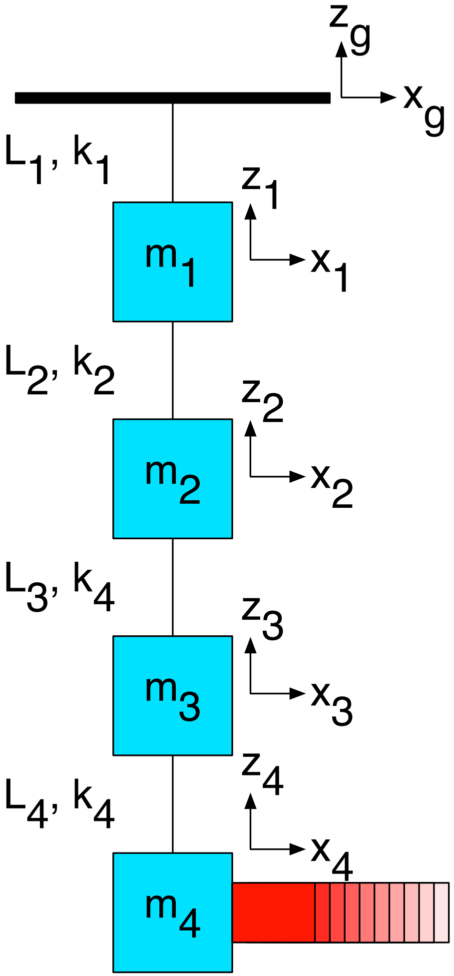


Preliminary LIGO III quad pendulum



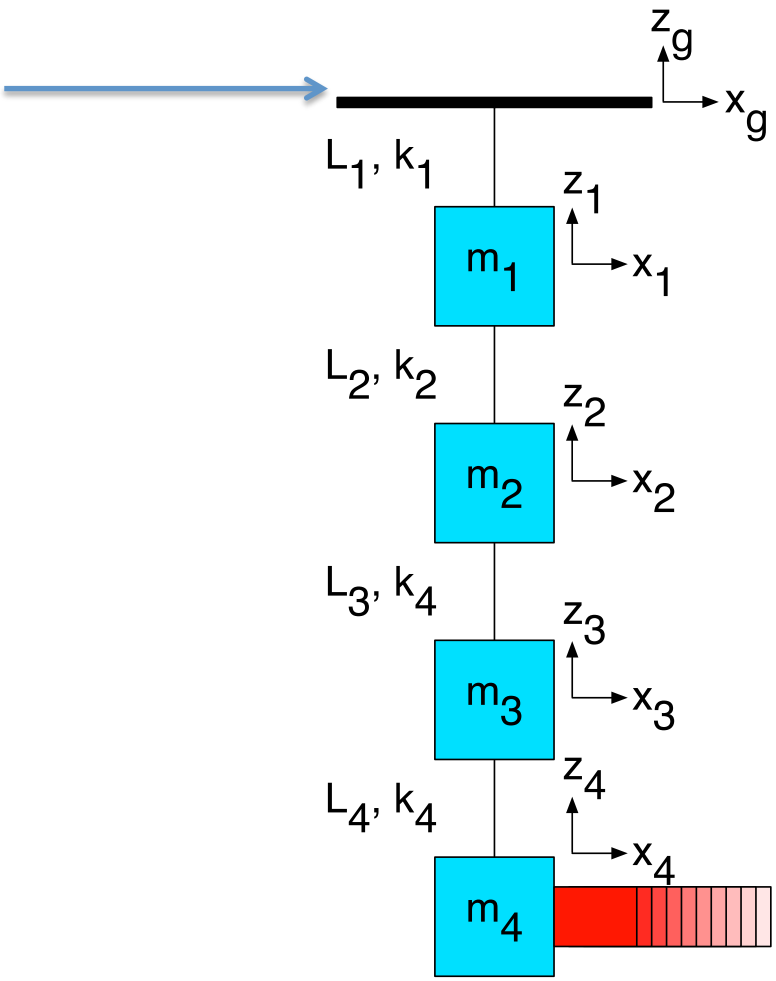
Adapted from G1200828, courtesy of Madeleine Waller, Norna Robertson, Calum Torrie

Quad Design Requirements



Quad Design Requirements

Payload **P ≤ 270** kg for the main chain for aLIGO BSC-ISI



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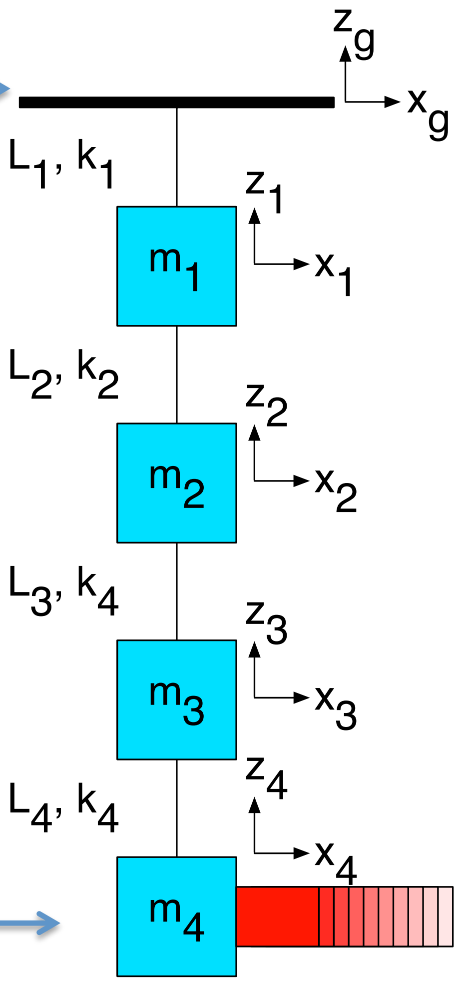


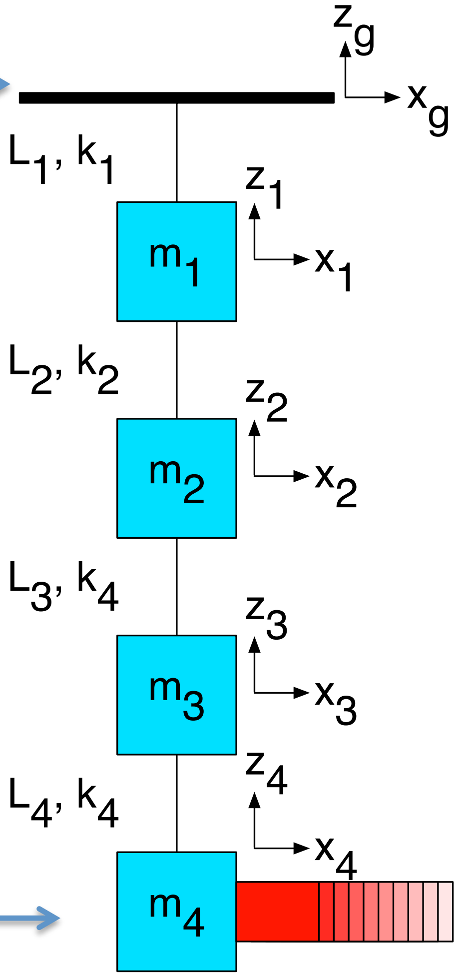
Test mass **$m_4 \approx 143$ kg** to minimize radiation pressure and thermal noise

Quad Design Requirements

Payload **P ≤ 270** kg for the main chain for aLIGO BSC-ISI

Total length **L ≤ 2.14 m** to fit in vacuum system

Test mass **m_4 ≈ 143 kg** to minimize radiation pressure and thermal noise



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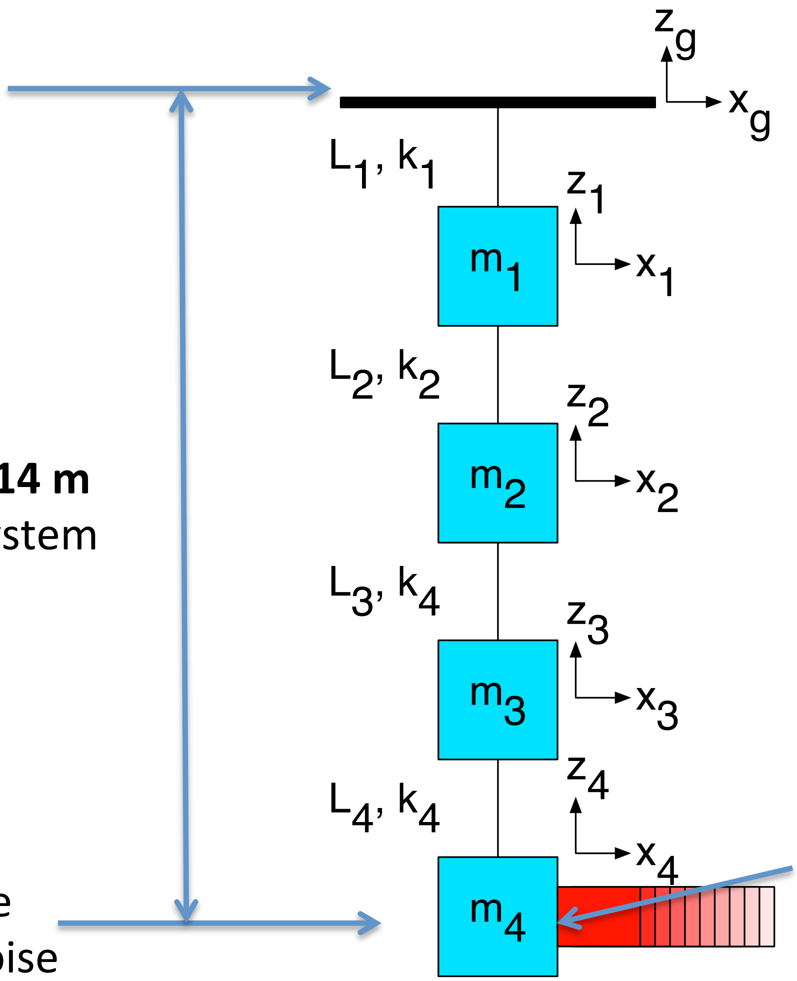

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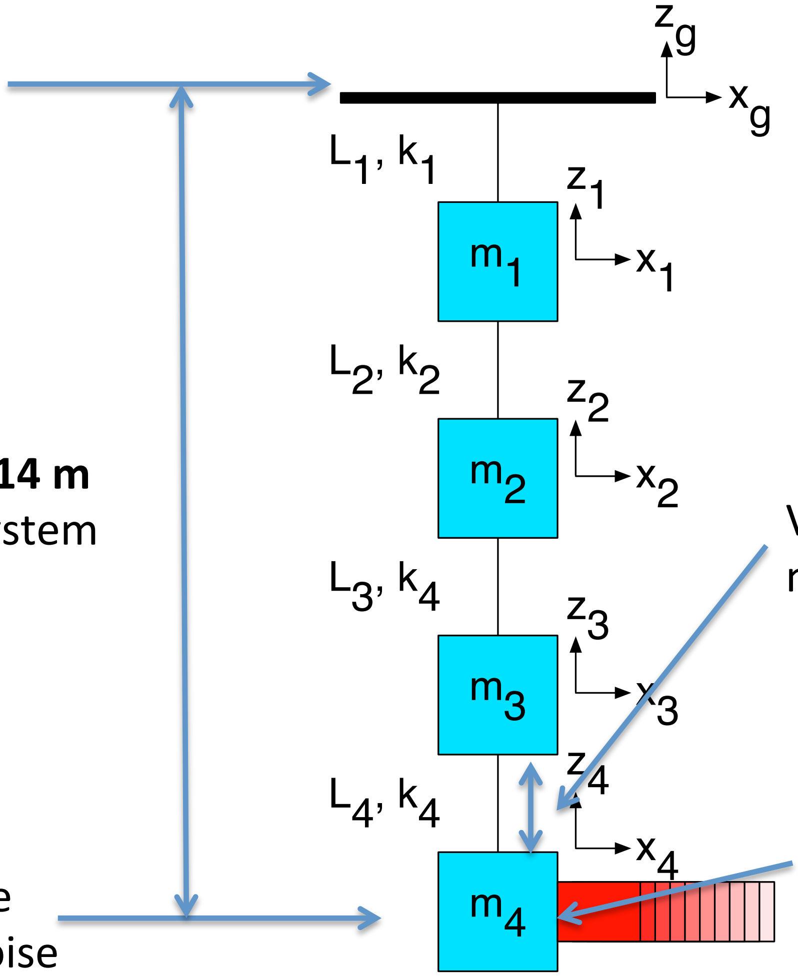
Seismic isolation as good as aLIGO

Quad Design Requirements



Payload **$P \leq 270$ kg** for the main chain for aLIGO BSC-ISI

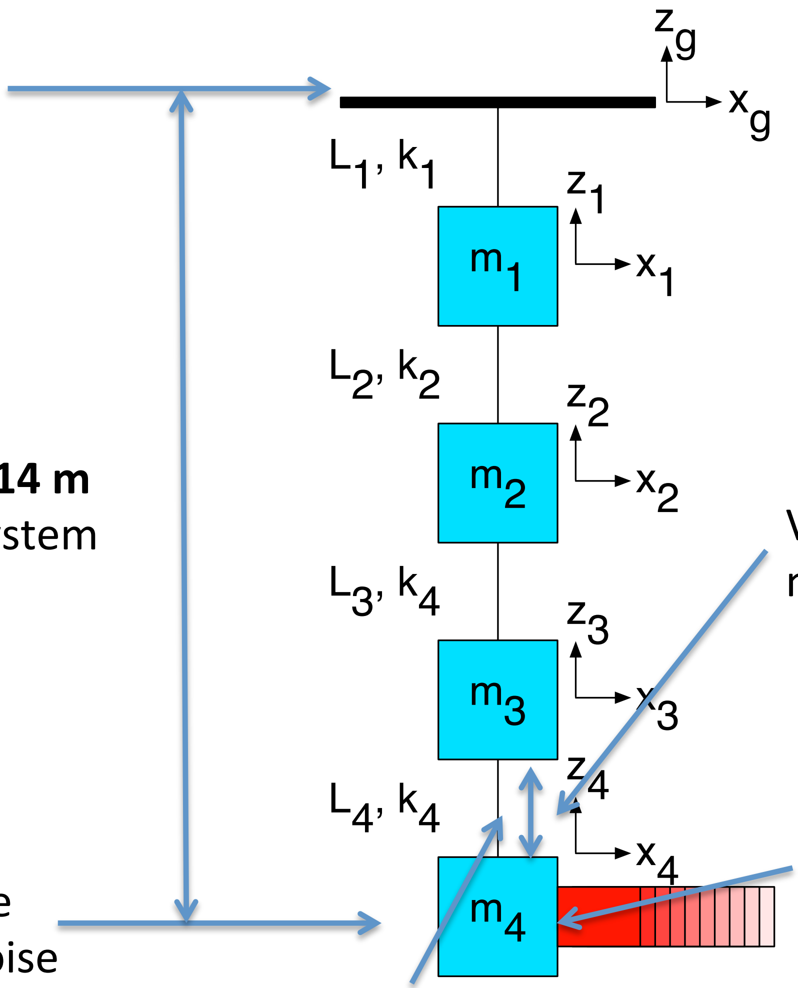
Total length **$L \leq 2.14$ m** to fit in vacuum system

Vertical bounce mode **$f_{bounce} \leq$ aLIGO**

Seismic isolation as good as aLIGO

Test mass **$m_4 \approx 143$ kg** to minimize radiation pressure and thermal noise

Quad Design Requirements



Payload **P ≤ 270** kg for the main chain for aLIGO BSC-ISI

Total length **L ≤ 2.14 m** to fit in vacuum system

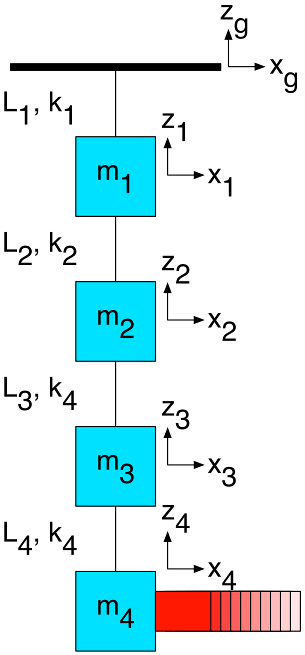
Vertical bounce mode **f_{bounce} ≤ aLIGO**

Seismic isolation no worse than aLIGO

Test mass **m_4 ≈ 143 kg** to minimize radiation pressure and thermal noise

Si fiber stress **σ_4 ≤ 1400 Mpa**
Very rough guess

3 Optimal Quad Designs



Higher payload

Lighter Test mass

PUM Si springs

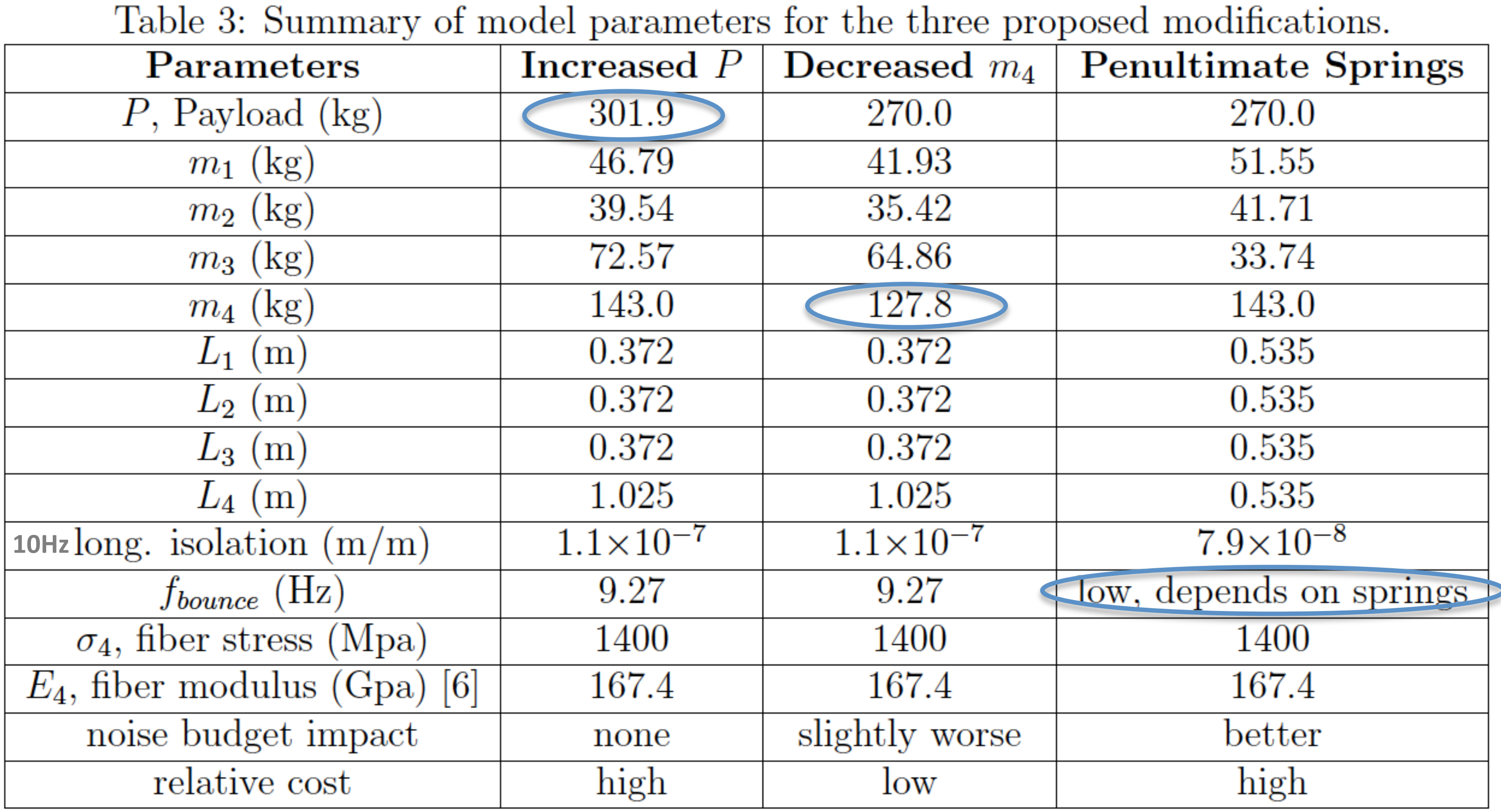


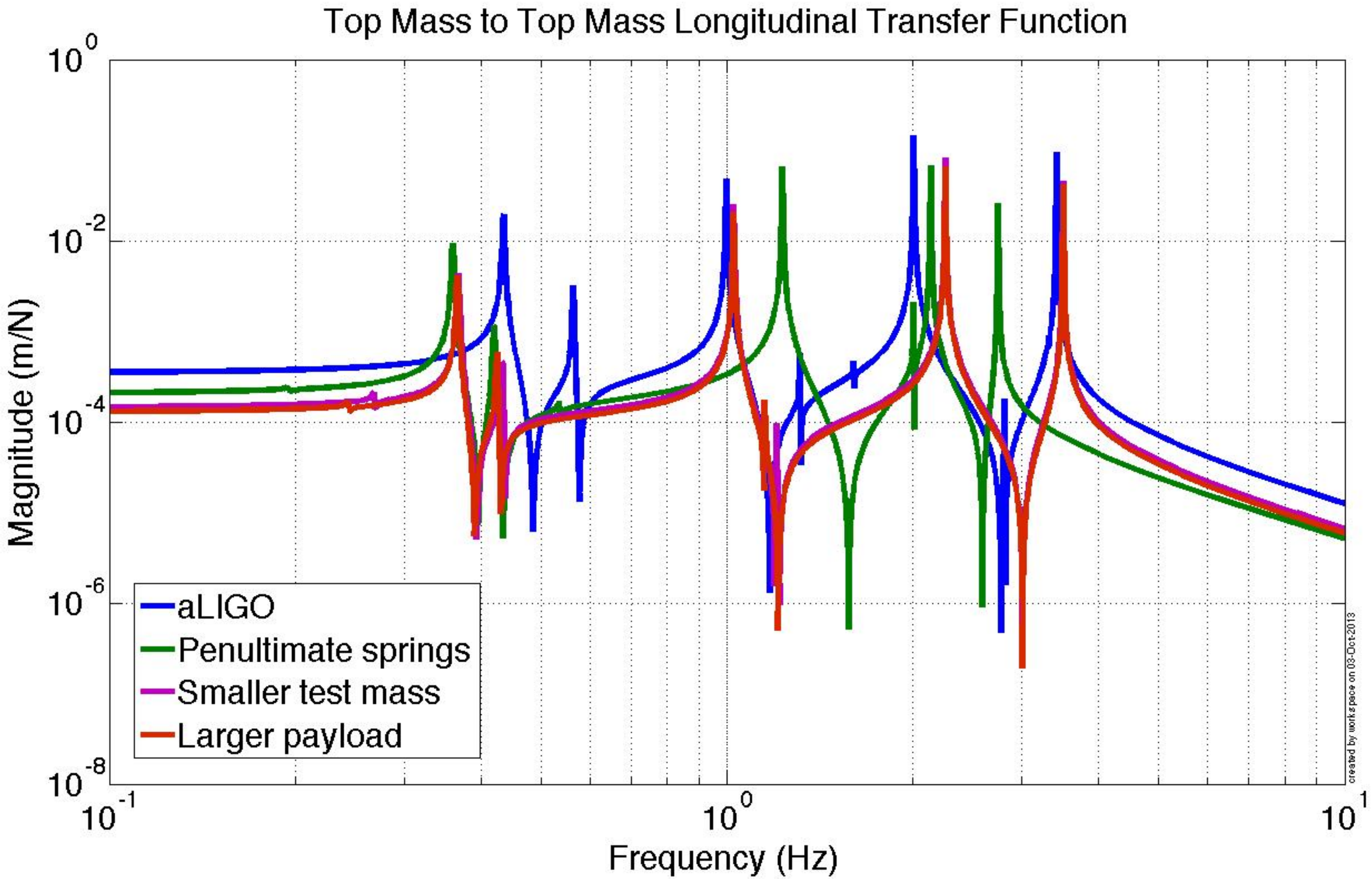
Table 3: Summary of model parameters for the three proposed modifications.

Parameters	Increased P	Decreased m_4	Penultimate Springs
P, Payload (kg)	301.9	270.0	270.0
m_1 (kg)	46.79	41.93	51.55
m_2 (kg)	39.54	35.42	41.71
m_3 (kg)	72.57	64.86	33.74
m_4 (kg)	143.0	127.8	143.0
L_1 (m)	0.372	0.372	0.535
L_2 (m)	0.372	0.372	0.535
L_3 (m)	0.372	0.372	0.535
L_4 (m)	1.025	1.025	0.535
10Hz long. isolation (m/m)	1.1×10^{-7}	1.1×10^{-7}	7.9×10^{-8}
f_{bounce} (Hz)	9.27	9.27	low, depends on springs
σ_4, fiber stress (Mpa)	1400	1400	1400
E_4, fiber modulus (Gpa) [6]	167.4	167.4	167.4
noise budget impact	none	slightly worse	better
relative cost	high	low	high

Note: these results are highly dependent on the allowed Si fiber stress, σ_4. There is still much uncertainty in this value.

See T1300786

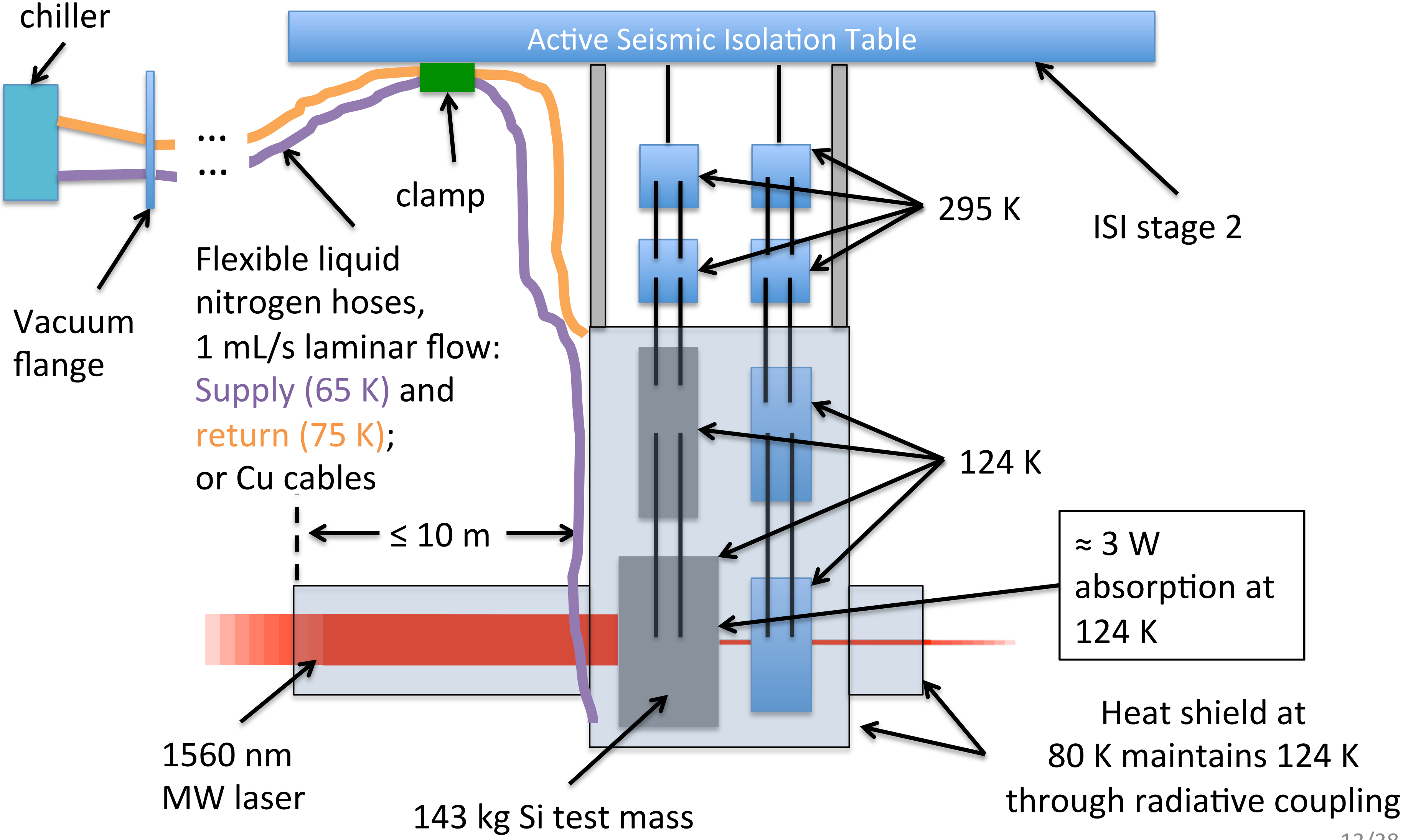
All designs permit top mass damping



Steady State Cooling

Keeping the test mass temperature at the operating point

LIGO III Steady State Cooling



See also G1200246-v1

Pros and Cons of LN_2 pipe vs. Cu cable

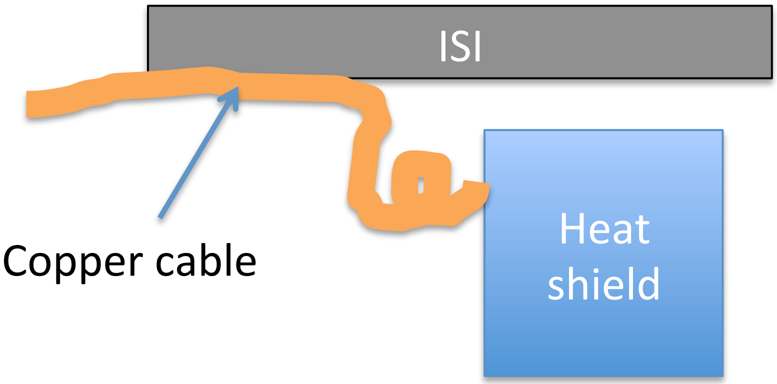
Cu cable

Pros:

- No fluid to make noise
- No LN_2 pumping mechanism
- No risk of N_2 leaks

Cons:

- Low heat transfer
- …



Copper cable

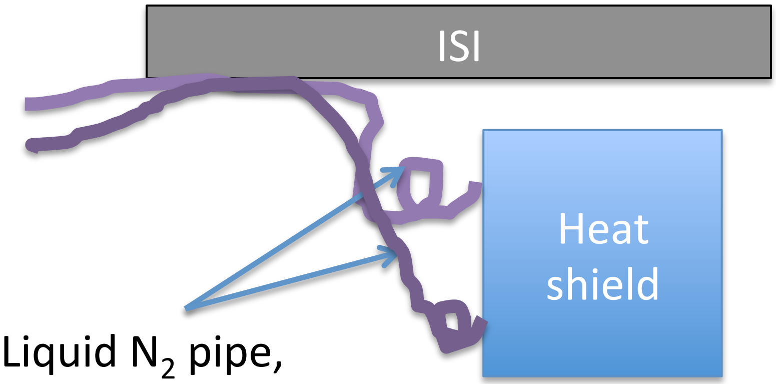
LN_2 pipe

Pros:

- High heat transfer
- No length / heat transfer trade-off
- Low weight
- …

Cons:

- Risk of leaking
- Fluid flow could contribute noise
- …



Liquid N_2 pipe, supply and return

Pros and Cons of LN_2 pipe vs. Cu cable

Cu cable

Pros:

- No fluid to make noise
- No LN_2 pumping mechanism
- No risk of N_2 leaks

Cons:

- Low heat transfer
- Cryo refrigerator must be placed near feedthrough
- High bulk: stiffness, weight, etc
  - $Q = K(A/L)\Delta T$
    1. Big L means big A
    2. Can reduce A by making cold end less than LN_2 (77 K). E.g. Cryomech's PT407 can pull 25W at 55 K.

  - Minimize stiffness by using lots of this wires, but wire dia must be > electron m.f.p.
- Thermal conductivity decreases when wire dia becomes smaller than electron m.f.p.
- Hysteresis
  - Lots of small wires sliding past each other
- High difficulty in minimizing seismic shorting
  - Minimize using:
    1. Lots of thin wires
    2. Intermediate masses along length

LN_2 pipe

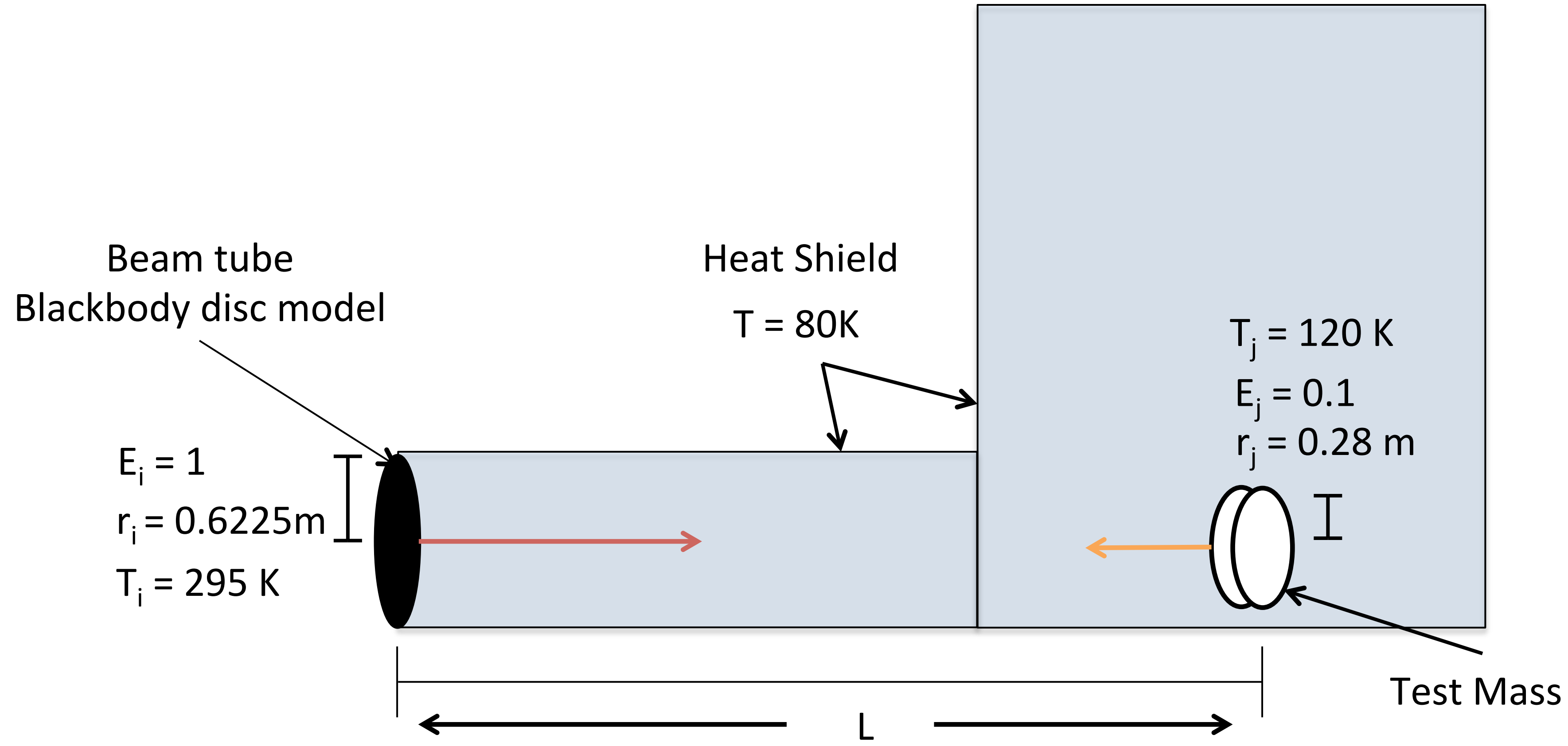
Pros:

- High heat transfer
- Low bulk
- Moderate difficulty in minimizing seismic shorting
- Length of pipe in vacuum not an issue for net heat transfer (longer pipes do require more pressure to push fluid)
- Vibrating cryorefrigerator can be placed further from vacuum feedthrough.

Cons:

- Complex LN_2 pumping mechanism
- Risk of leaking
- Fluid flow could contribute noise
  - Minimize by:
    1. Cooling the LN_2 so it doesn't boil
    2. Ensuring laminar flow
- Pressure of flow and thermal contraction can influence table displacement
  - Minimize by locating pipes in strategic locations

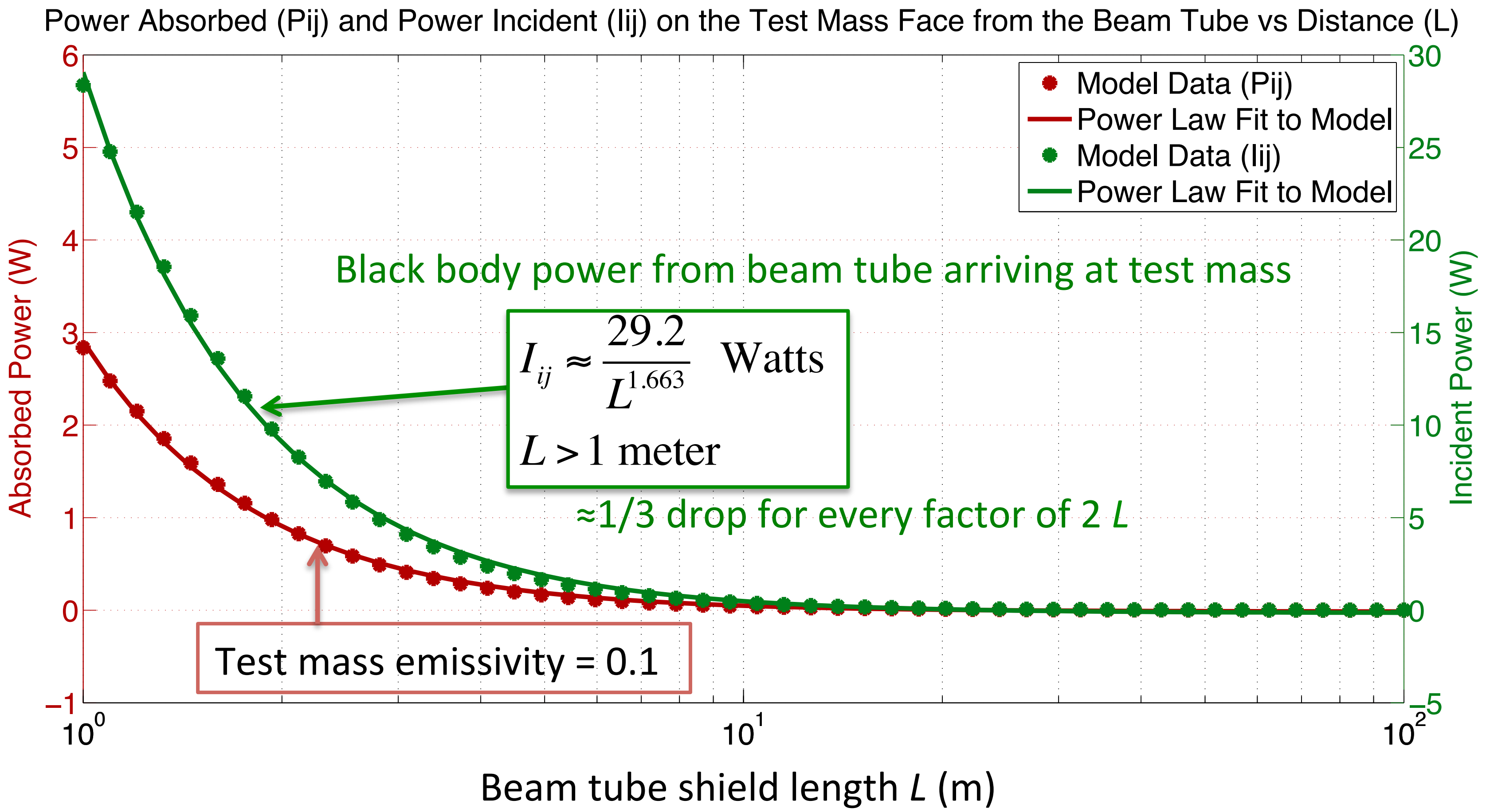
Beam Tube Heat Shield Length



What is the optimal heat shield length in the beam tube?

See T1300556

Beam Tube Heat Shield Length



Black body power from beam tube arriving at test mass

$$I_{ij} \approx \frac{29.2}{L^{1.663}} \text{ Watts}$$

$$L > 1 \text{ meter}$$

≈1/3 drop for every factor of 2 *L*

Test mass emissivity = 0.1

See T1300556

End Station Vacuum System

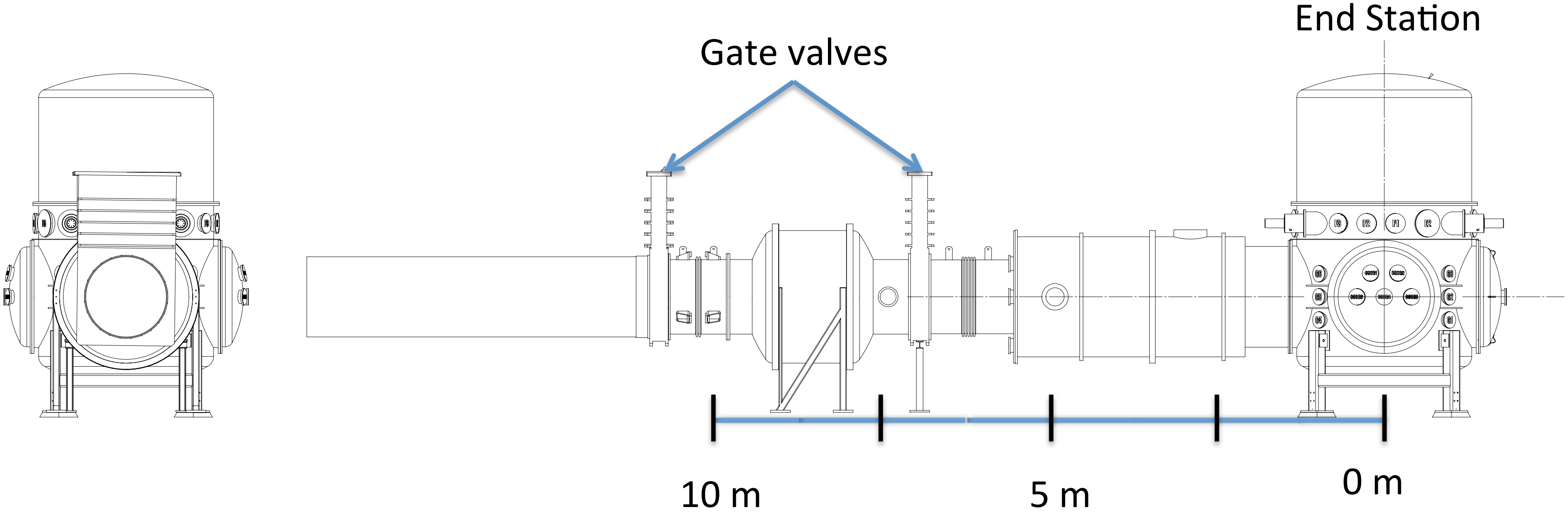


Image Courtesy of Nicolas Smith

Initial Cooldown

Acquiring the operating temperature

A Lot of Heat to Remove

143 kg Test Mass:
14 MJ to get cold (warm)

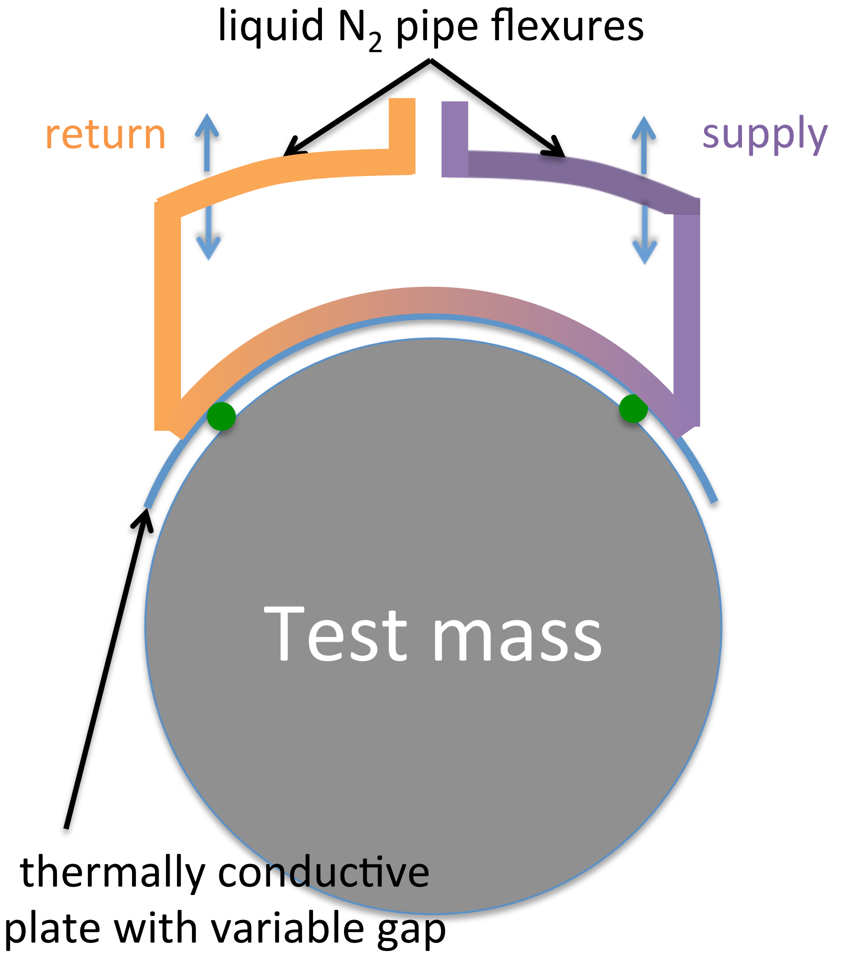
2.7 days to 124 K (295 K) at a constant 60 W

Maybe there is another way to cool the test mass quickly

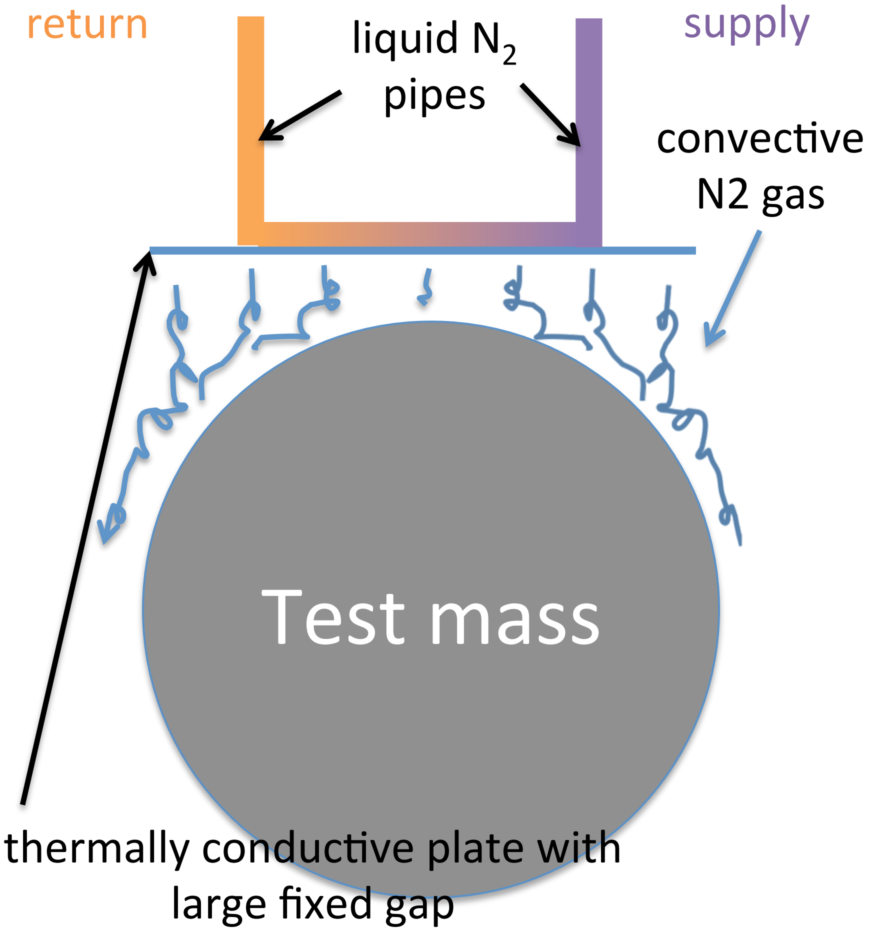
* Radiation to the heat shield alone would take ≈ 2 weeks.

Initial Cool Down Cold Link – 2 Designs

Conductive cooling, low pressure N_2 gas	Pros and Cons


liquid N_2 pipe flexures
return
supply
Test mass
thermally conductive plate with variable gap
	Pros
	• Operates in partial vacuum.
	• Low heat transfer between cold and warm parts of vacuum system.
	• Fine temperature control – just back away when at desired temperature
	• Versatility, design permits both conductive and convective cooling.
	Cons
	• Requires moving parts:
	  - flexible pipes
	  - actuators
	• Physically contacts barrel of test mass

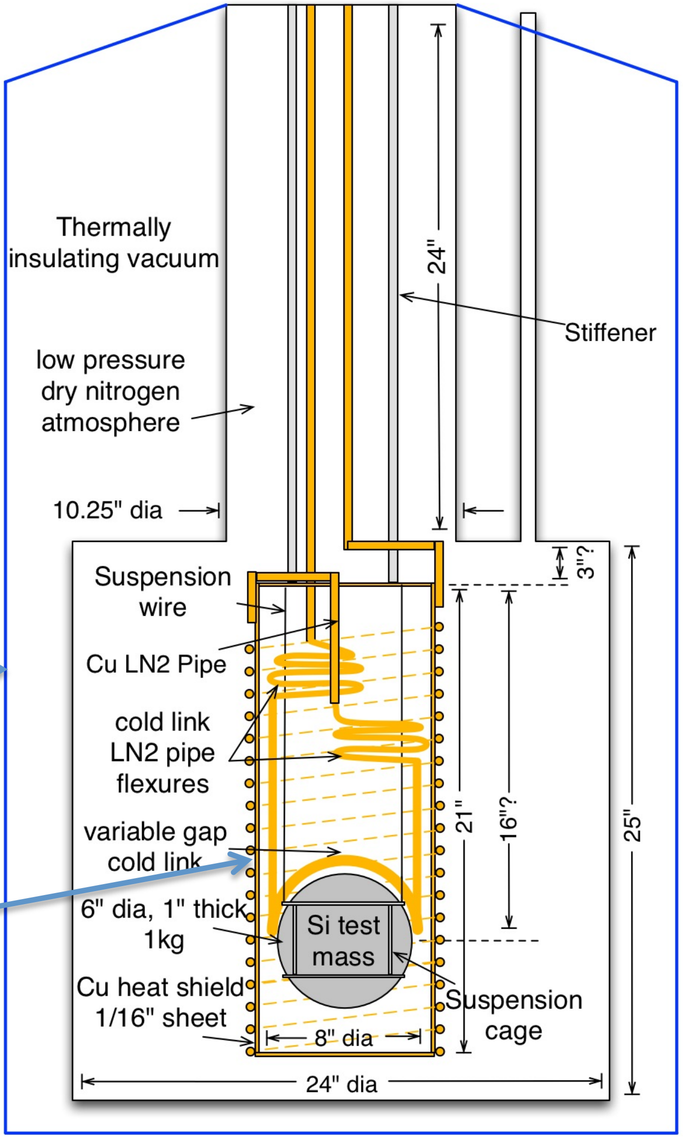
Initial Cool Down Cold Link – 2 Designs

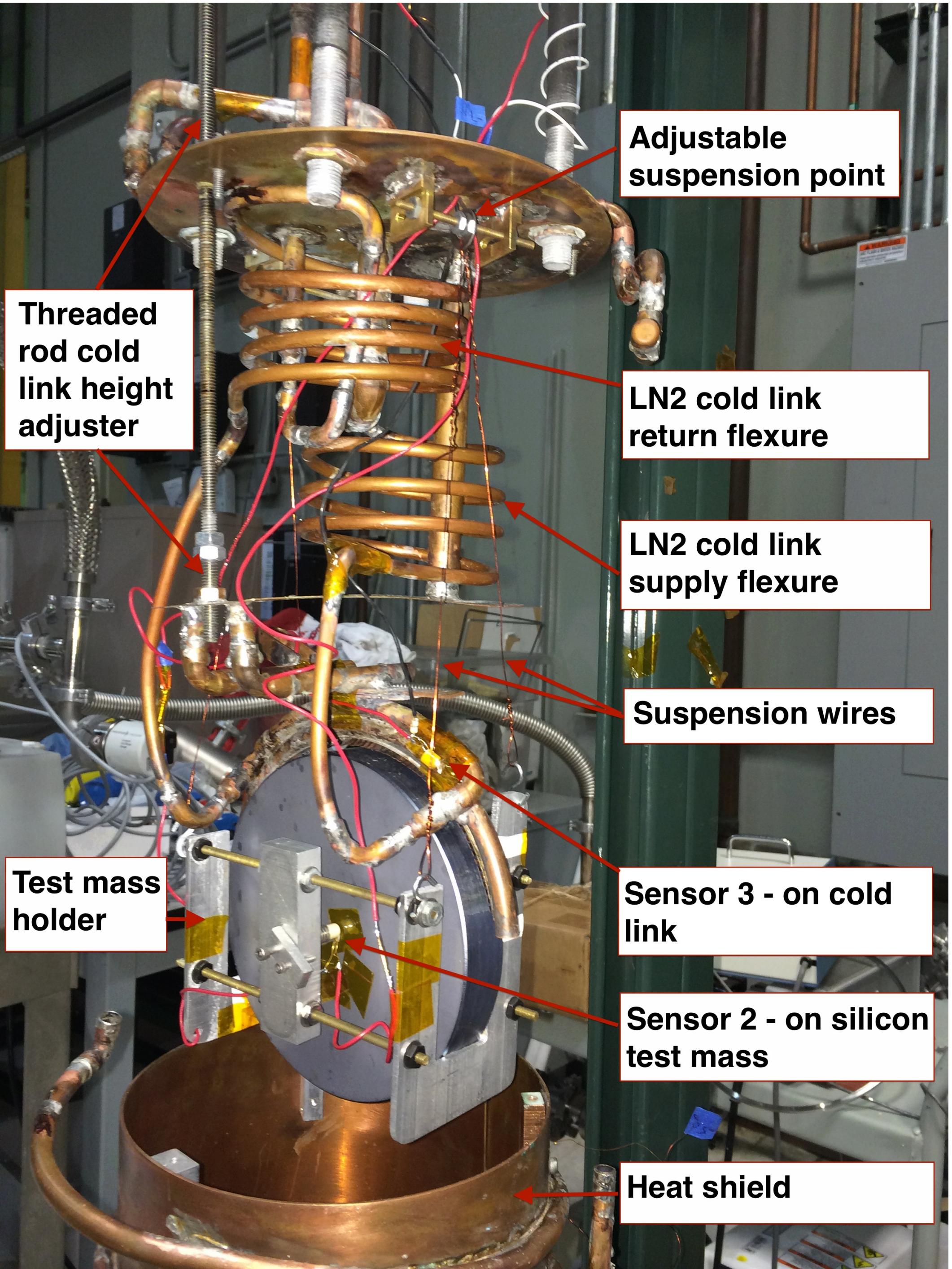
Pros and Cons	Convective cooling, up to 1 atm N_2 gas
Pros • No moving parts or actuators • No contact with test mass • Faster cooling than conduction **Cons** • Convection between cold and warm parts of vacuum system • No fine temperature control – must return to vacuum to ‘turn off’ cold link. • Does not operate under vacuum	 return liquid N_2 pipes supply convective N2 gas Test mass thermally conductive plate with large fixed gap

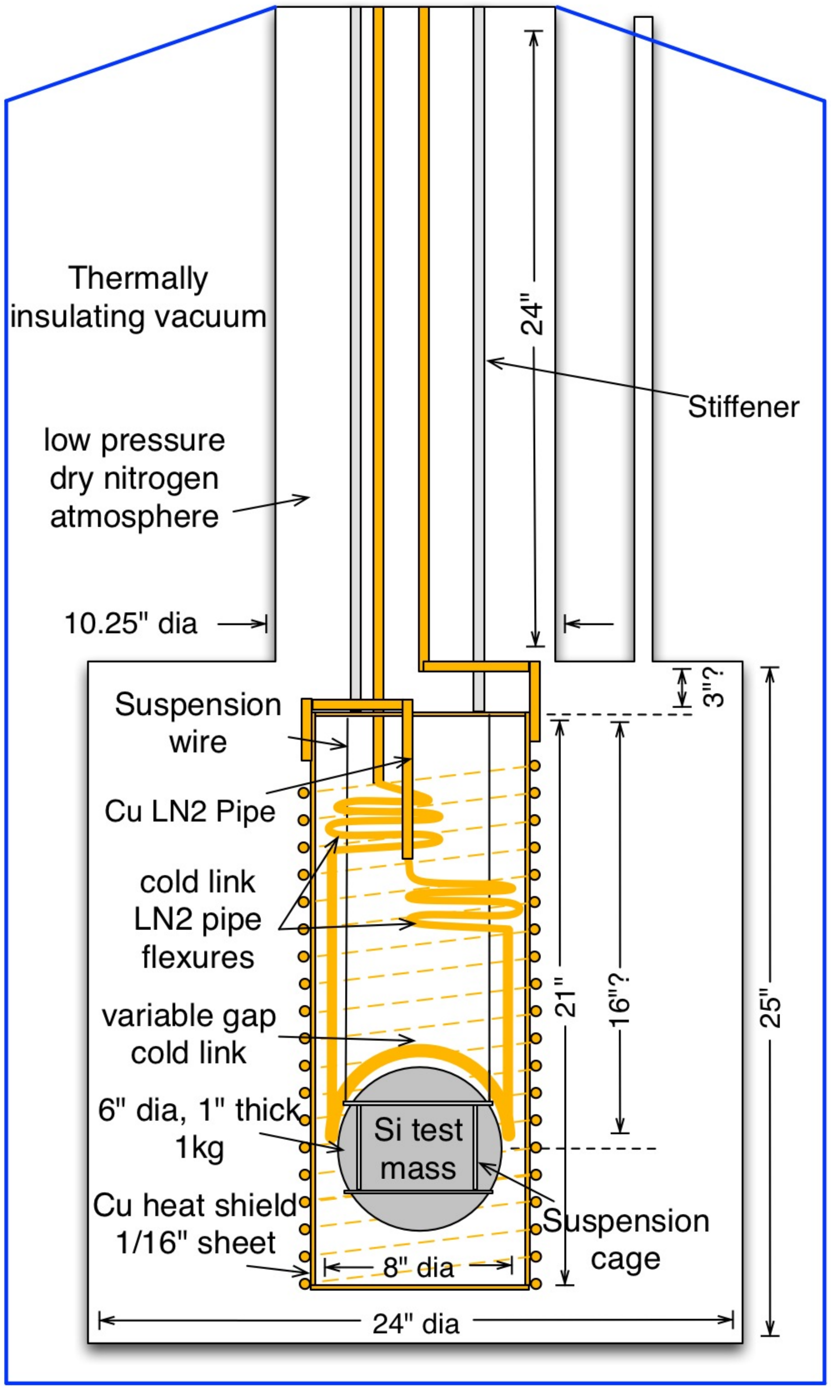
Experimental Setup

Test dewar

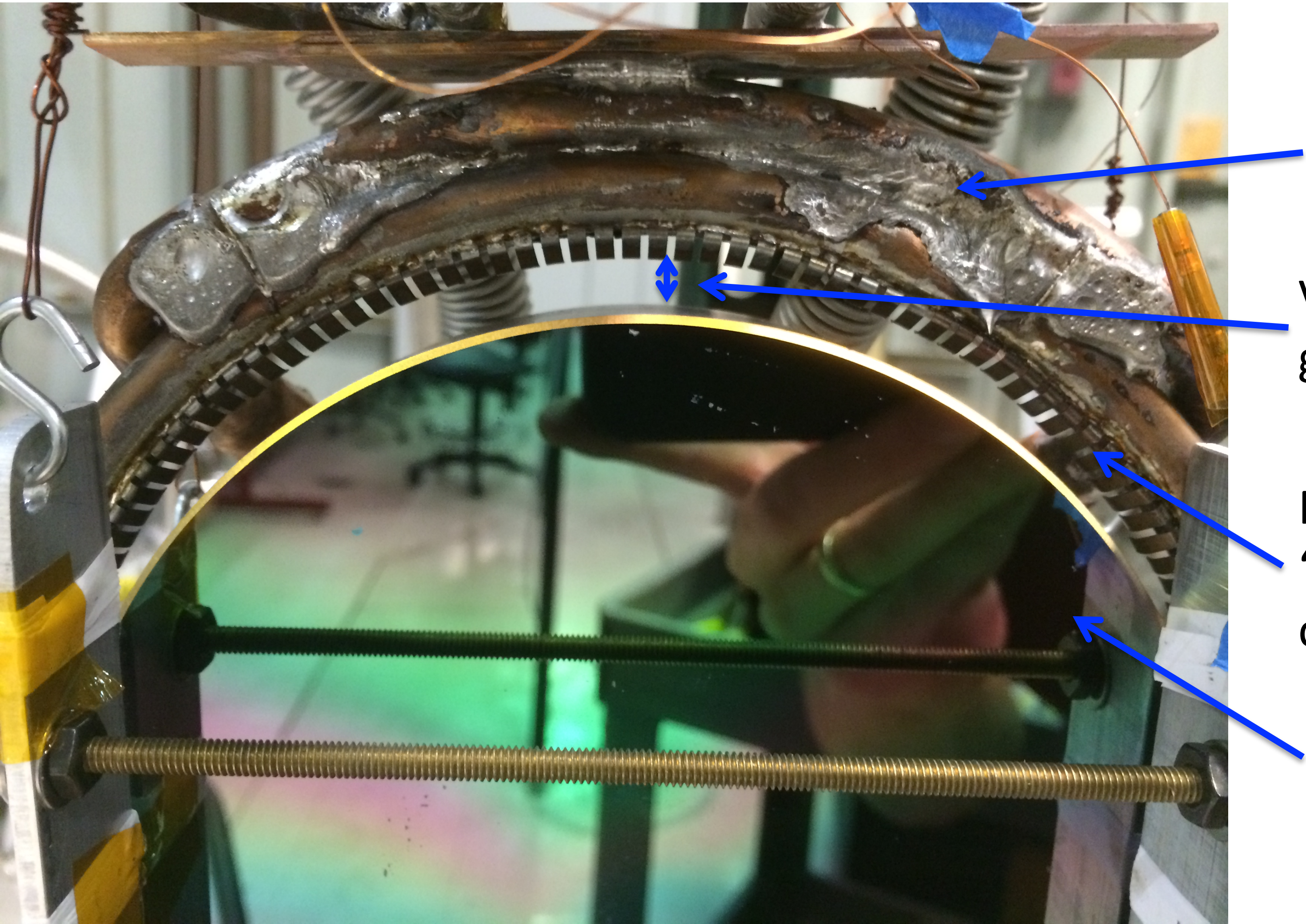
Heat shield




Adjustable suspension point
Threaded rod cold link height adjuster
LN2 cold link return flexure
LN2 cold link supply flexure
Suspension wires
Test mass holder
Sensor 3 - on cold link
Sensor 2 - on silicon test mass
Heat shield


Thermally insulating vacuum
low pressure dry nitrogen atmosphere
10.25" dia
24"
Stiffener
3"?
Suspension wire
Cu LN2 Pipe
cold link LN2 pipe flexures
variable gap cold link
6" dia, 1" thick, 1kg
Si test mass
Cu heat shield 1/16" sheet
8" dia
Suspension cage
21"
16"?
25"
24" dia

Close up of cold link



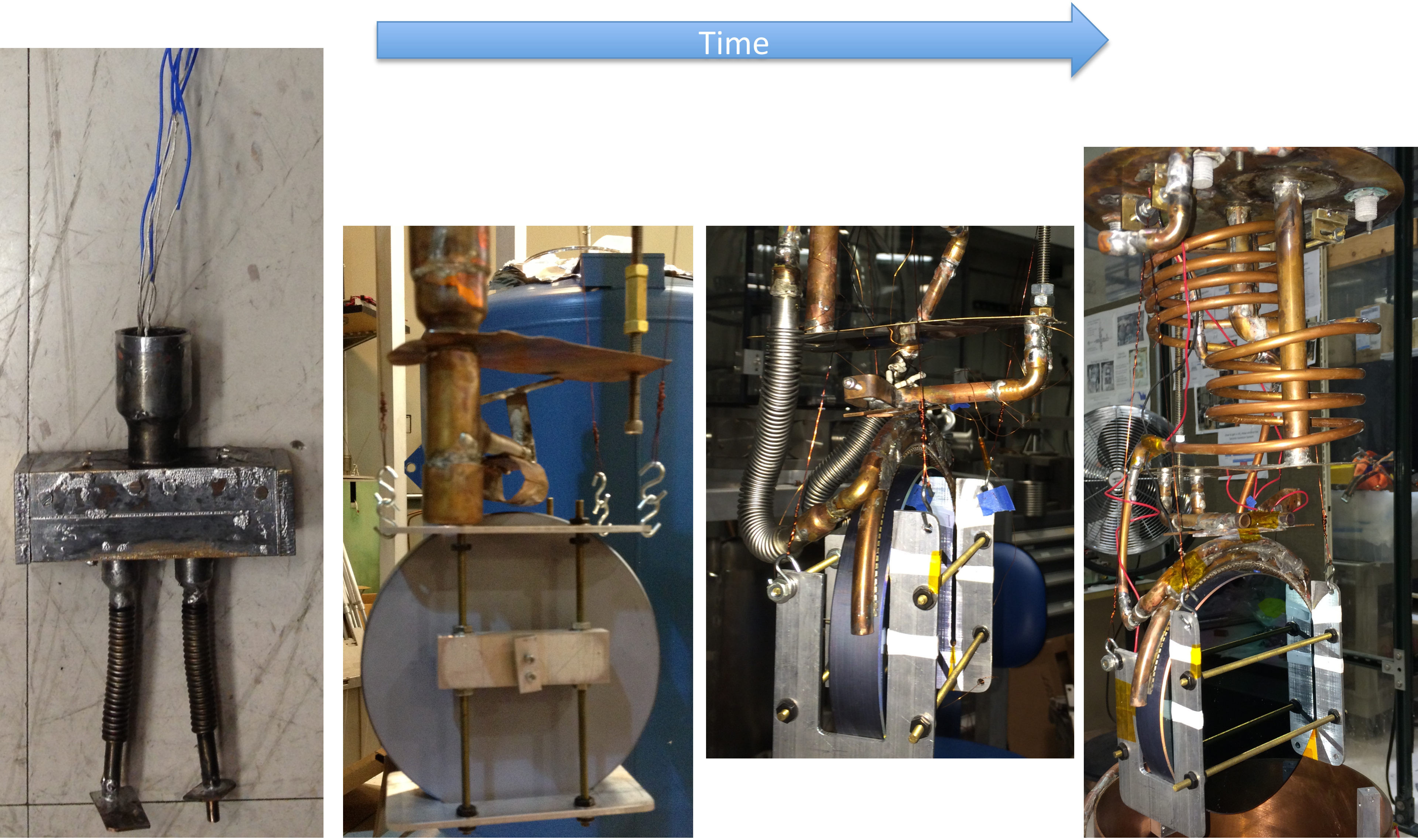
Cold link

Variable gap

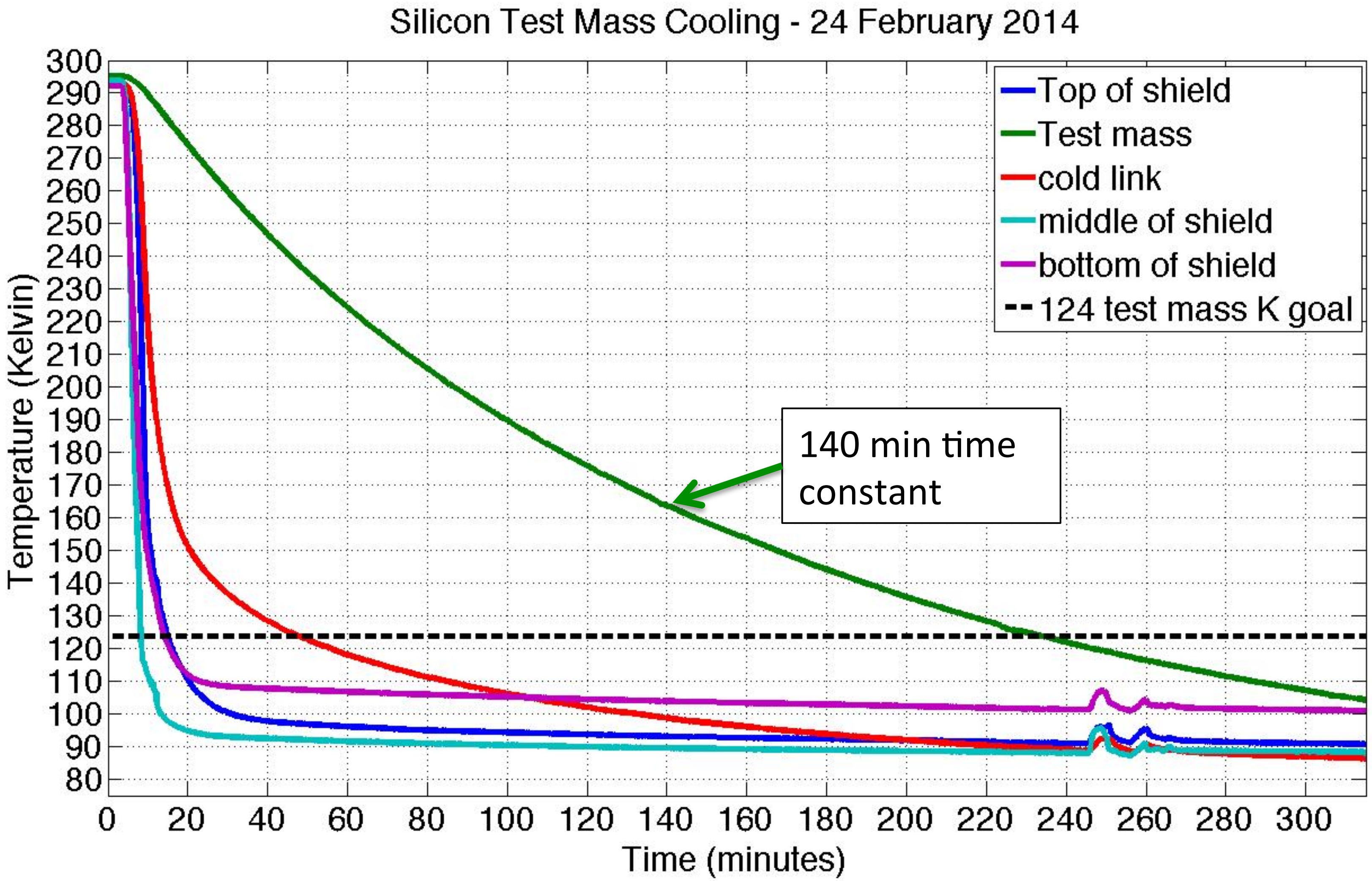
Flexure 'point' contacts

Test mass

Flexible cold link evolution

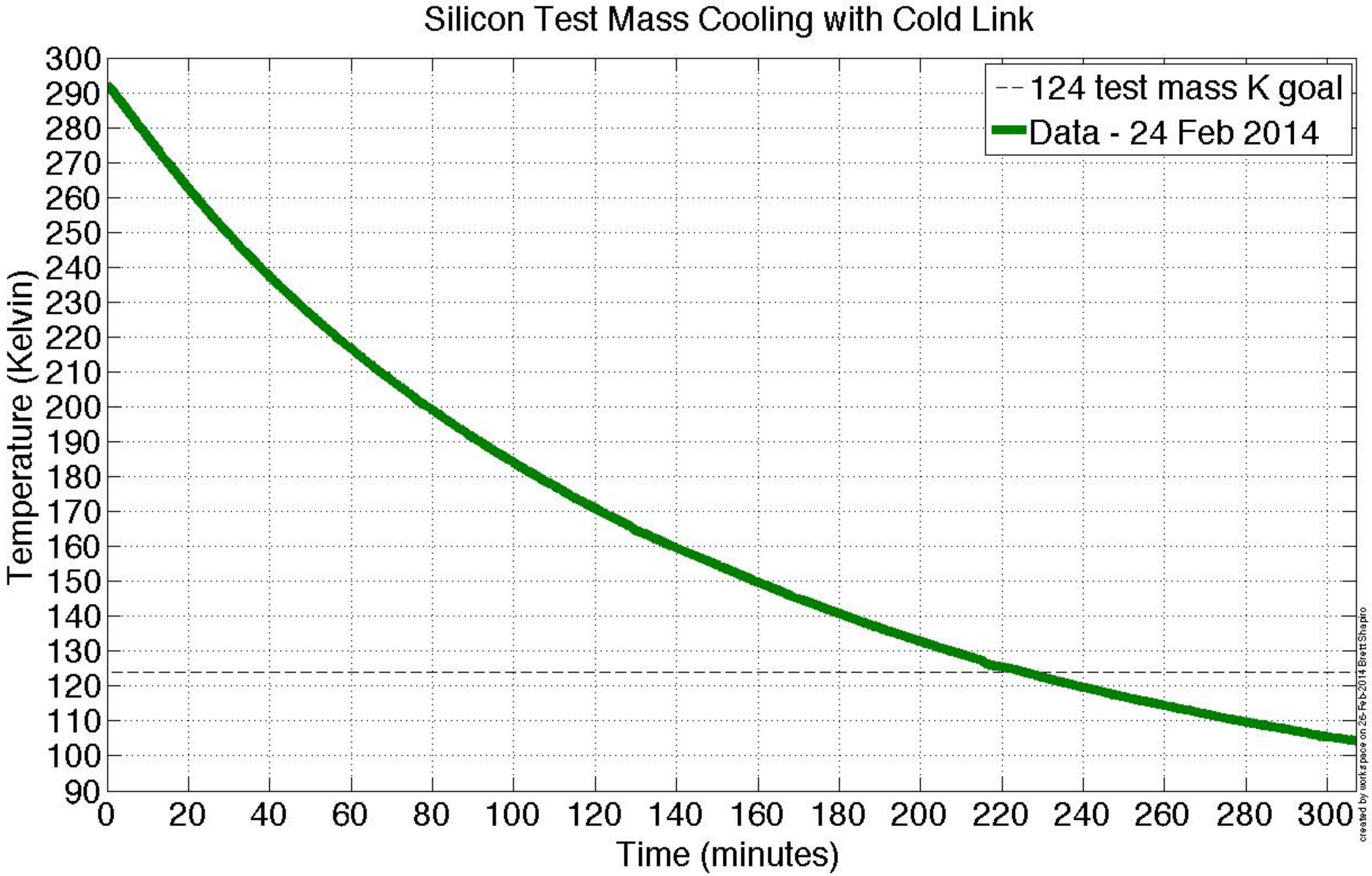


Measurement – cold link engaged

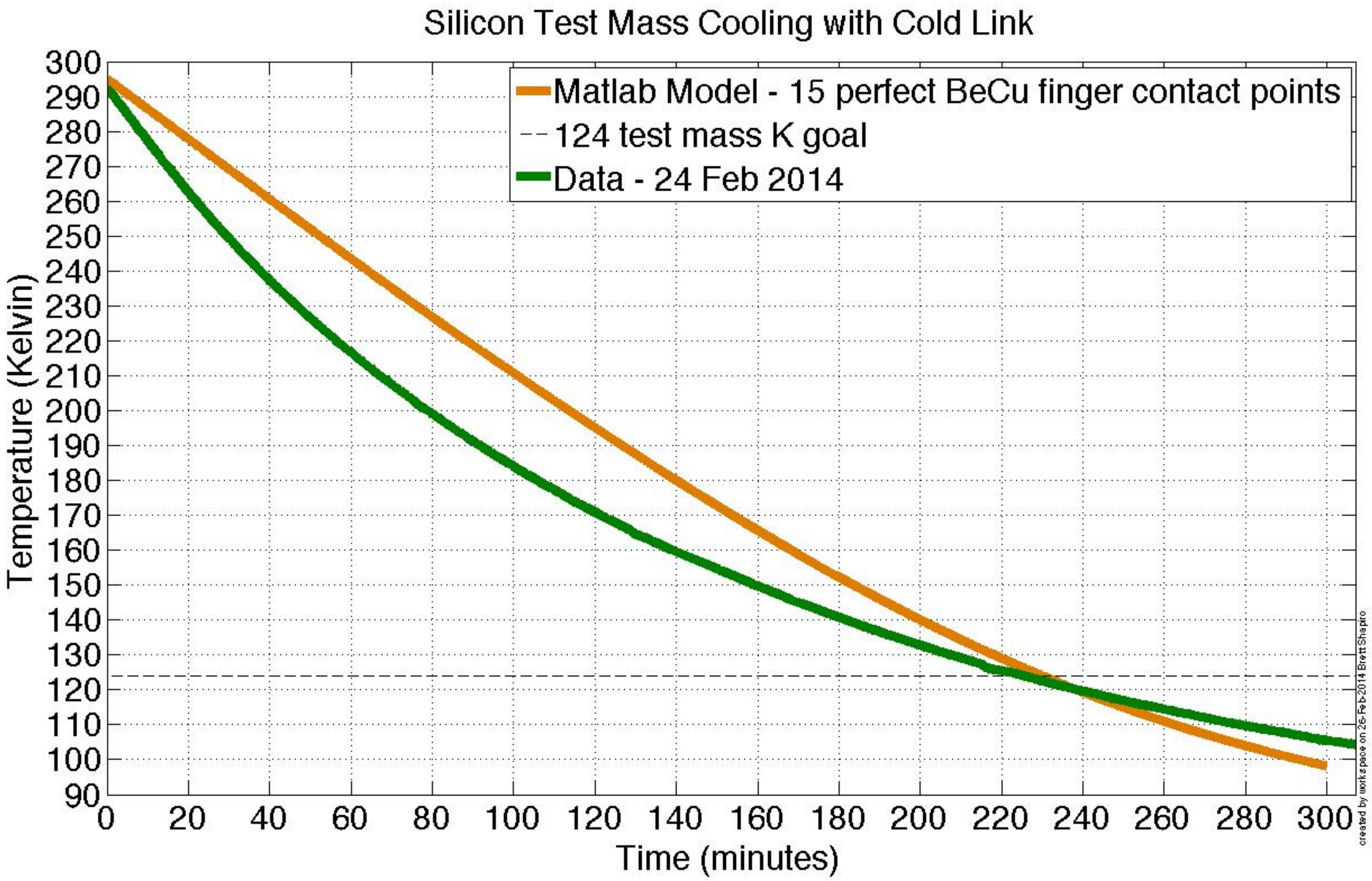


140 min time constant

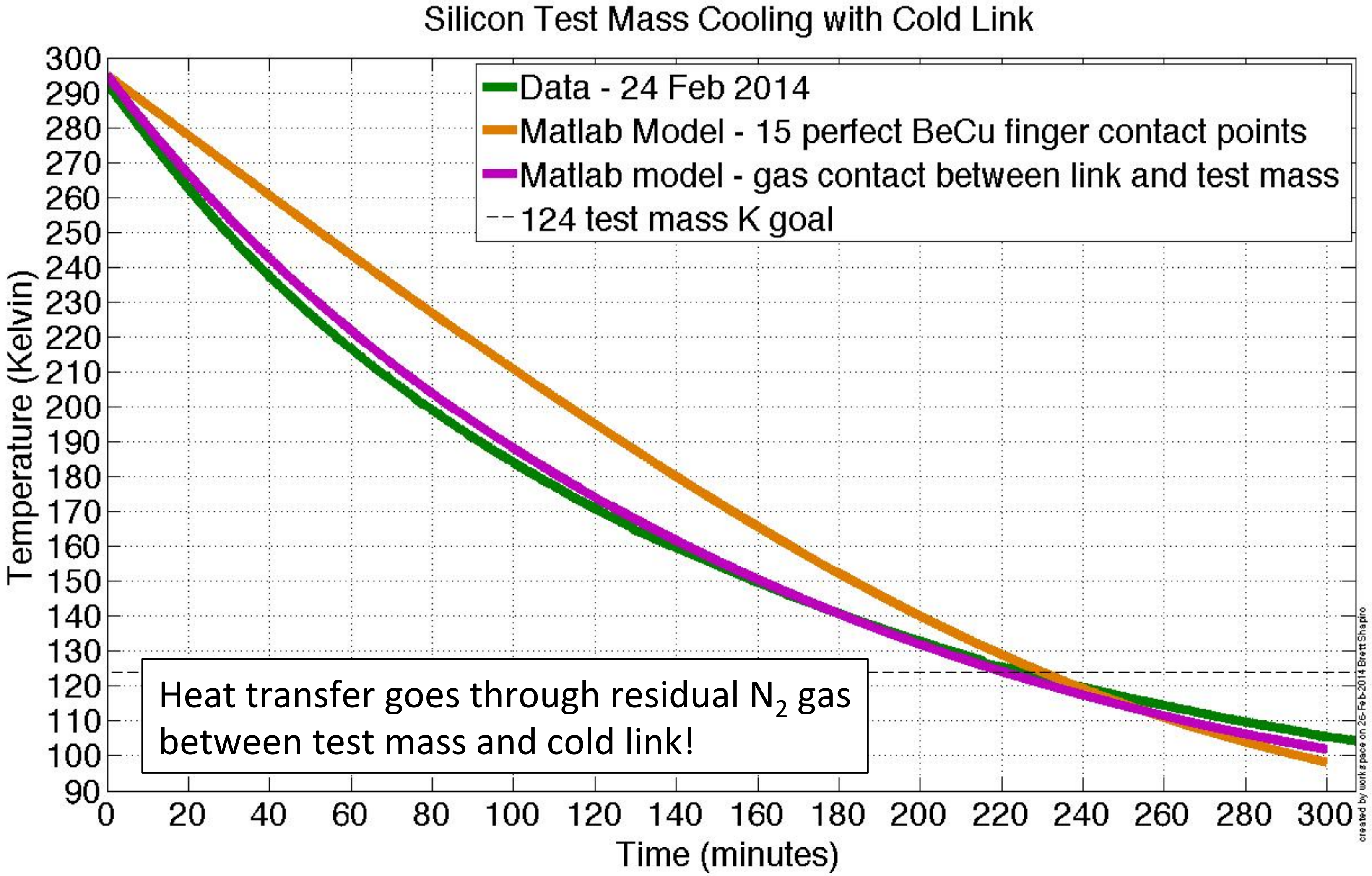
Test mass temperature modeling



Test mass temperature modeling

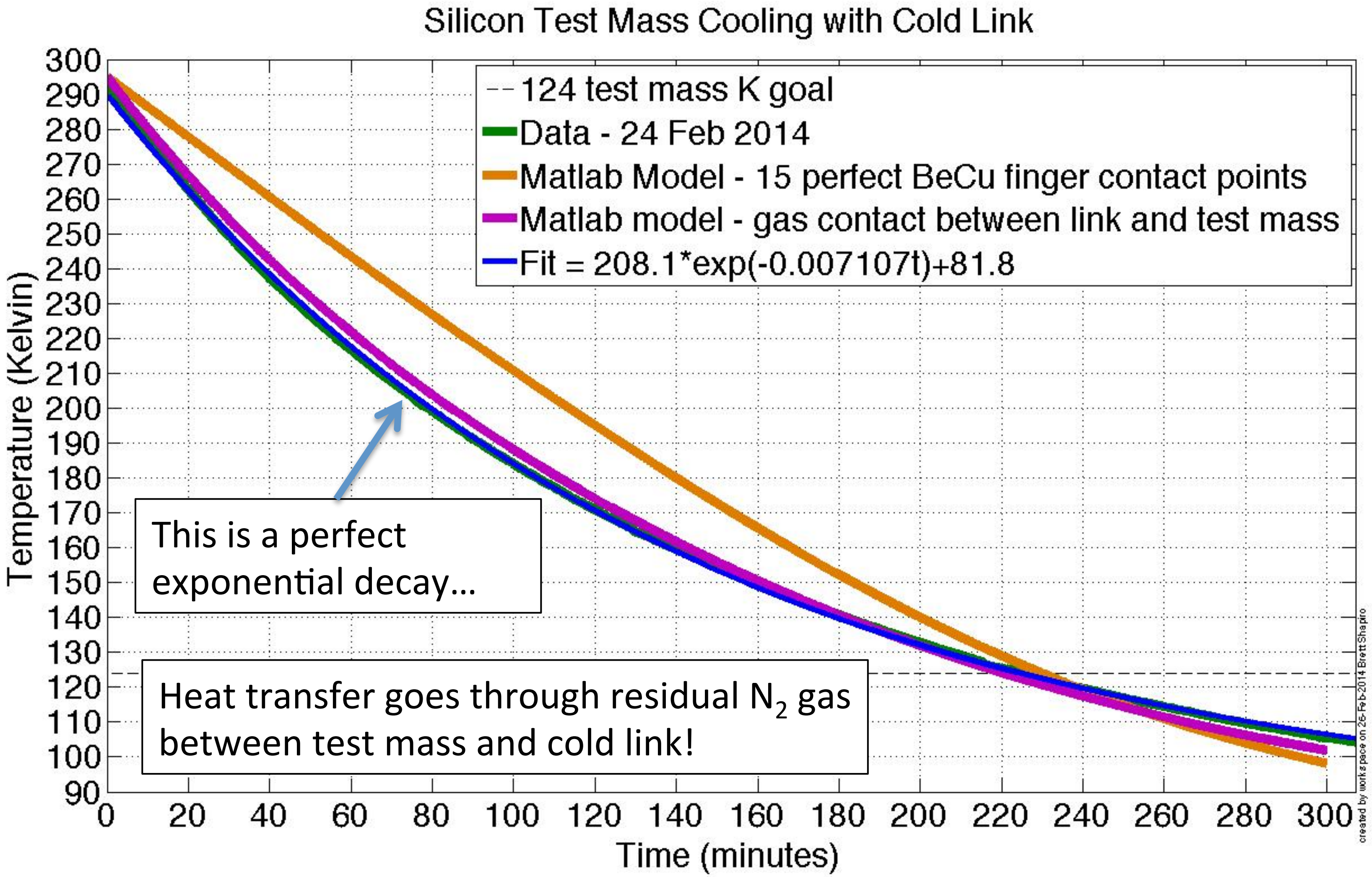


Test mass temperature modeling



Heat transfer goes through residual N_2 gas between test mass and cold link!

Test mass temperature modeling



This is a perfect exponential decay…

Heat transfer goes through residual N_2 gas between test mass and cold link!

Exponential Temperature Decay

$$\dot{T}_{Si} + \frac{K_{CL}}{C_{Si}} T_{Si} = \frac{K_{CL}}{C_{Si}} T_{cold} \quad \longrightarrow \quad T_{Si} = T_{hot} e^{-\frac{K_{CL}}{C_{Si}} t} + T_{cold}$$

K_{CL} = thermal conductance of cold link

C_{Si} = heat capacity of silicon

- These are both functions of temperature.
- In general, the solution is not truly exponential since the time ‘constant’ changes.

Exponential Temperature Decay

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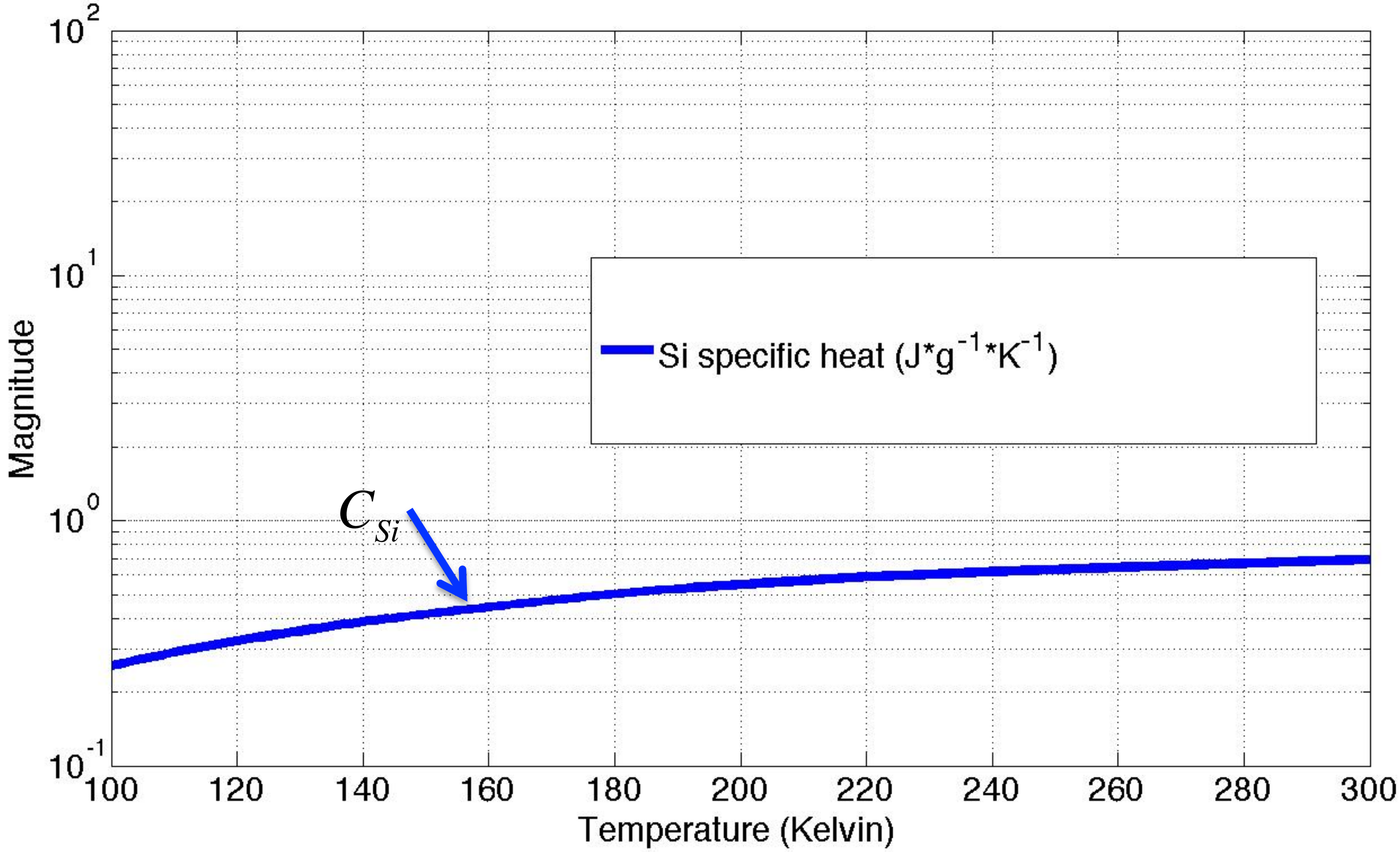

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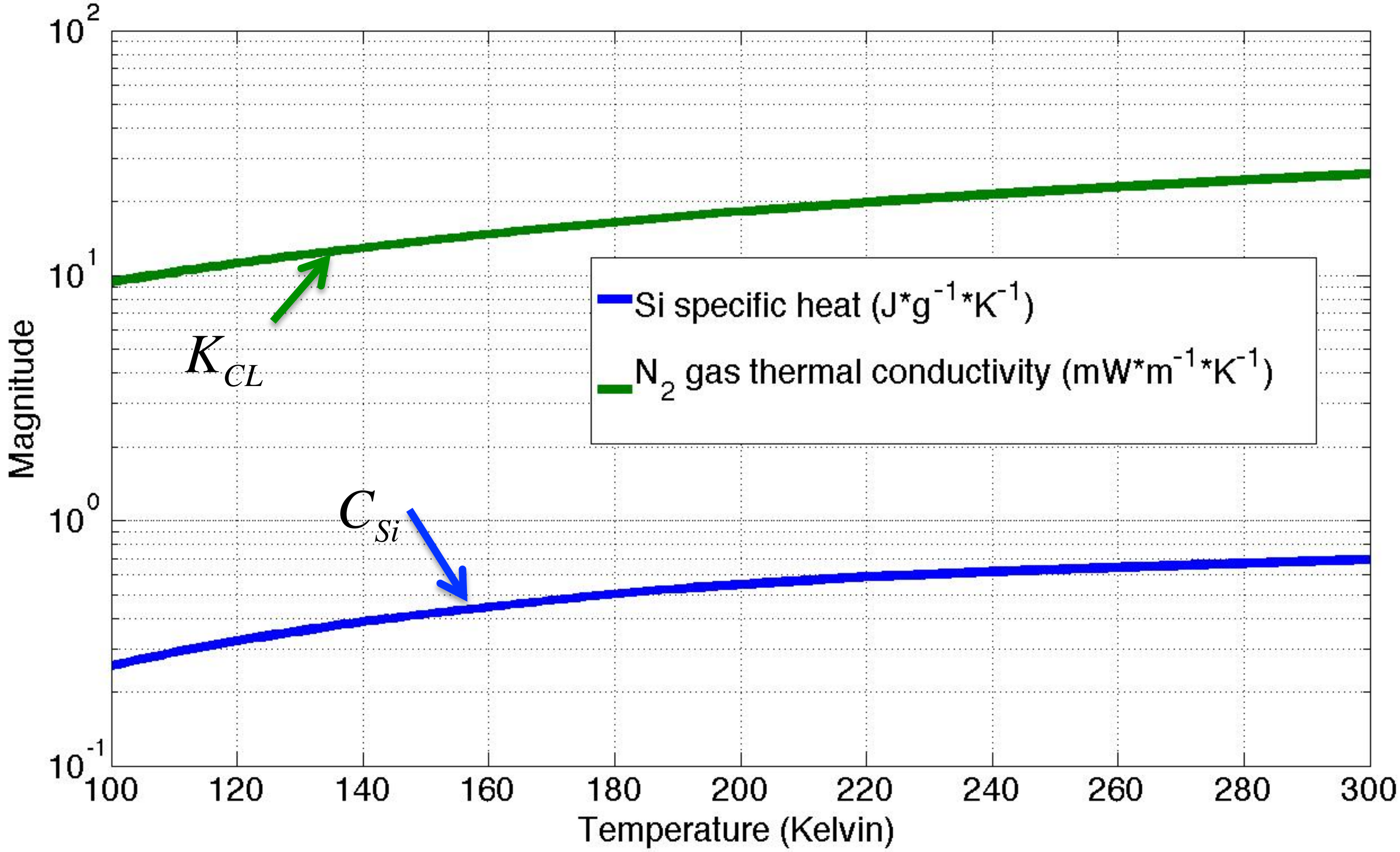

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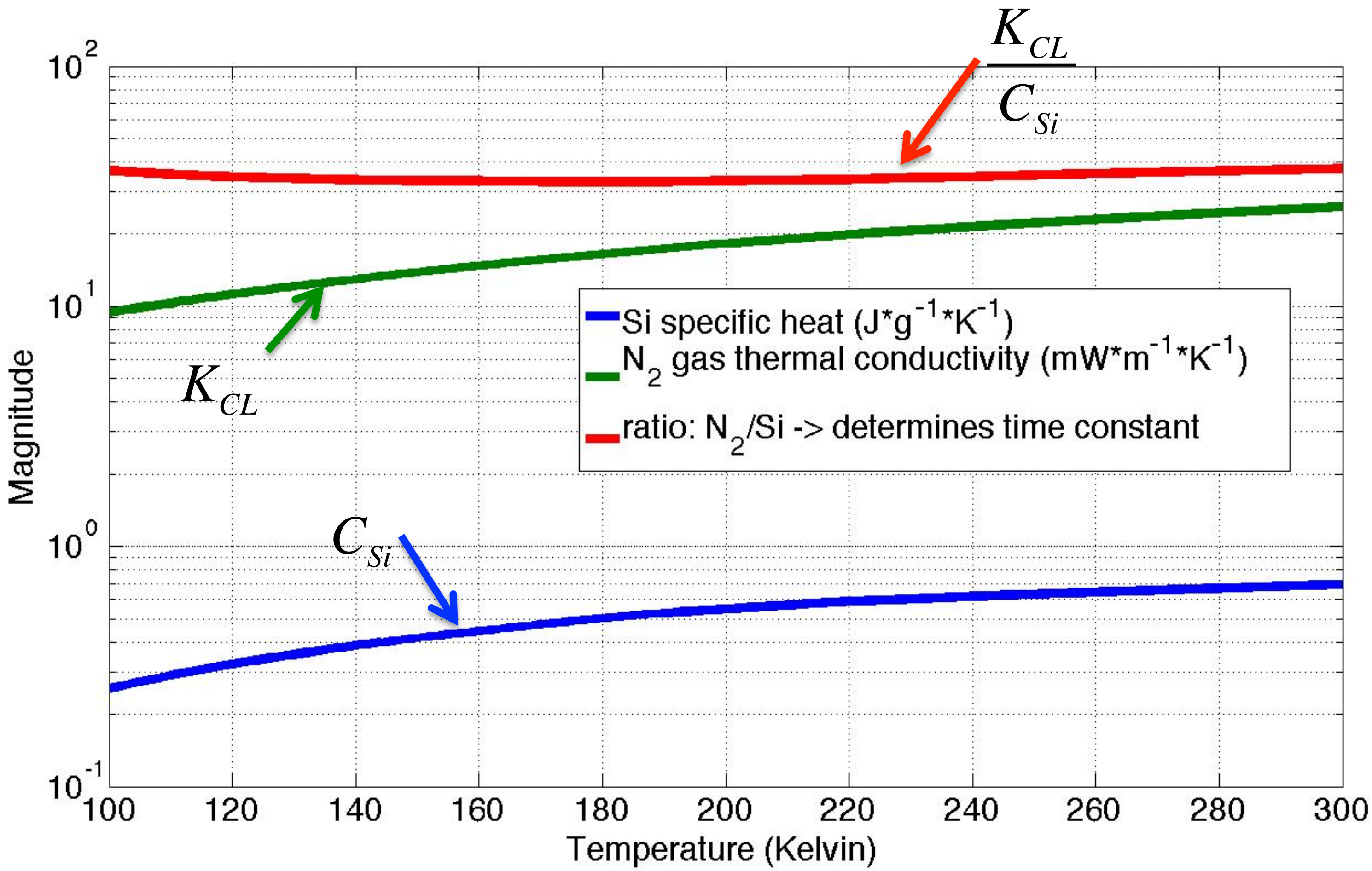
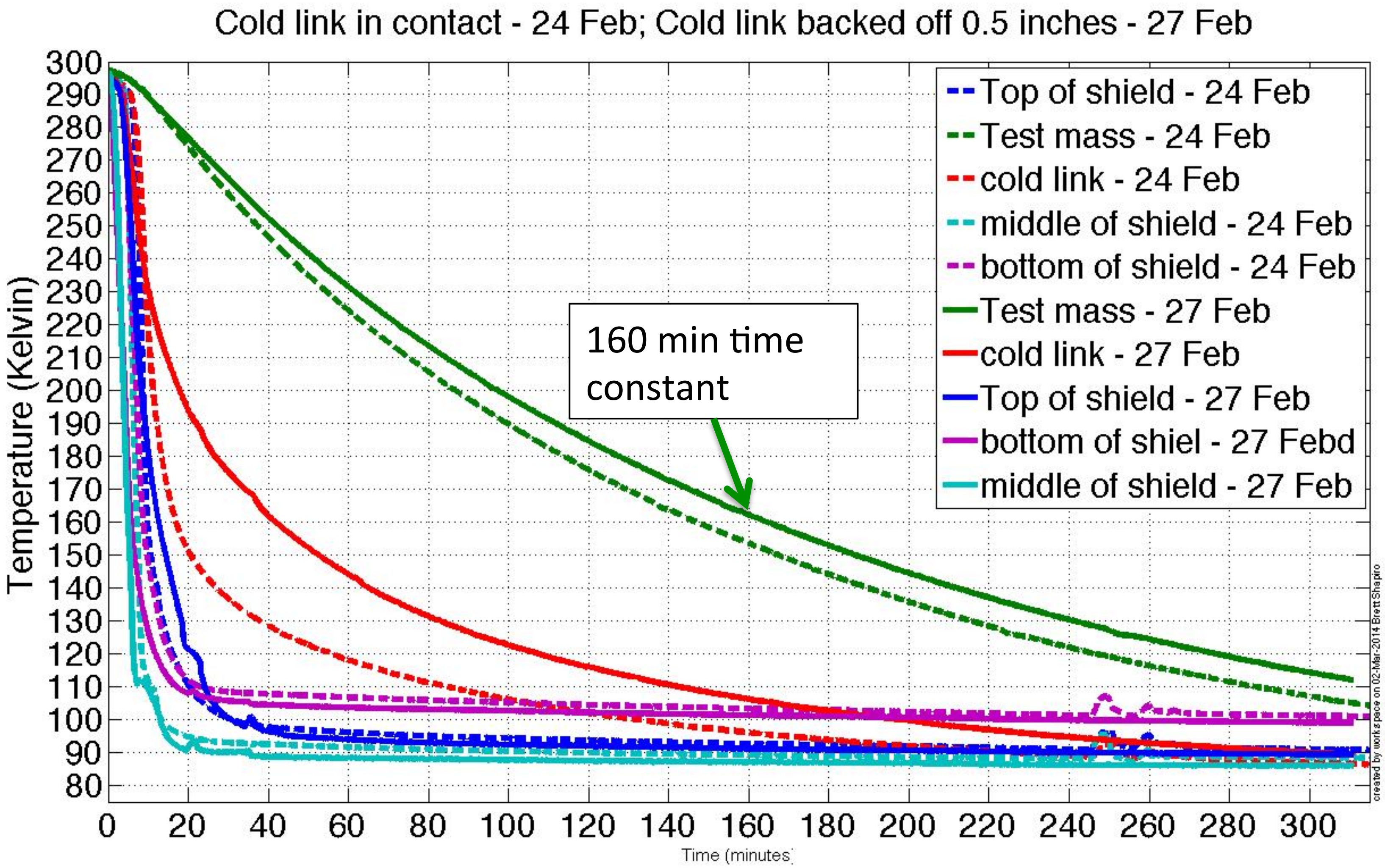
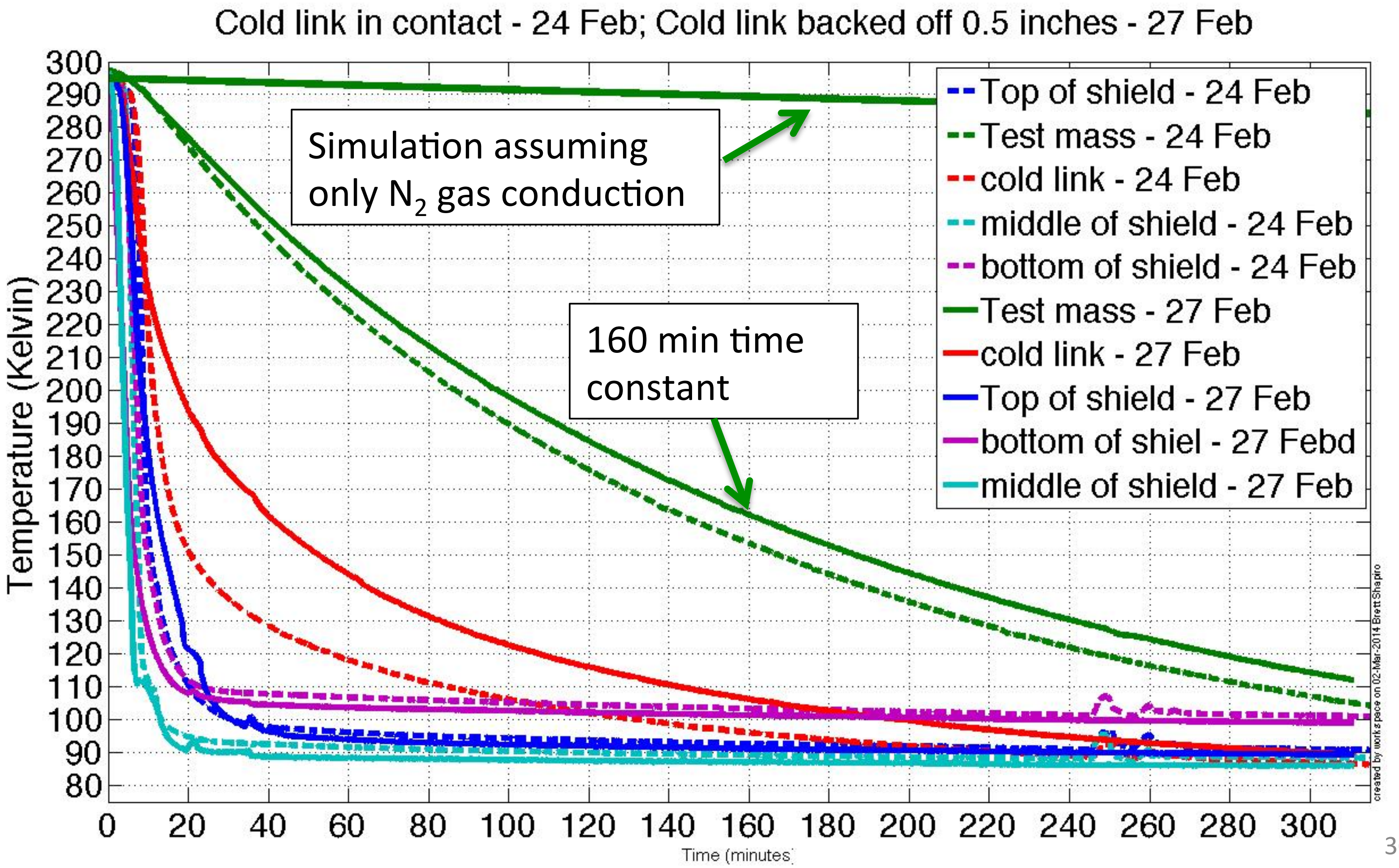


Measurement – cold link disengaged


Cold link in contact - 24 Feb; Cold link backed off 0.5 inches - 27 Feb

160 min time constant

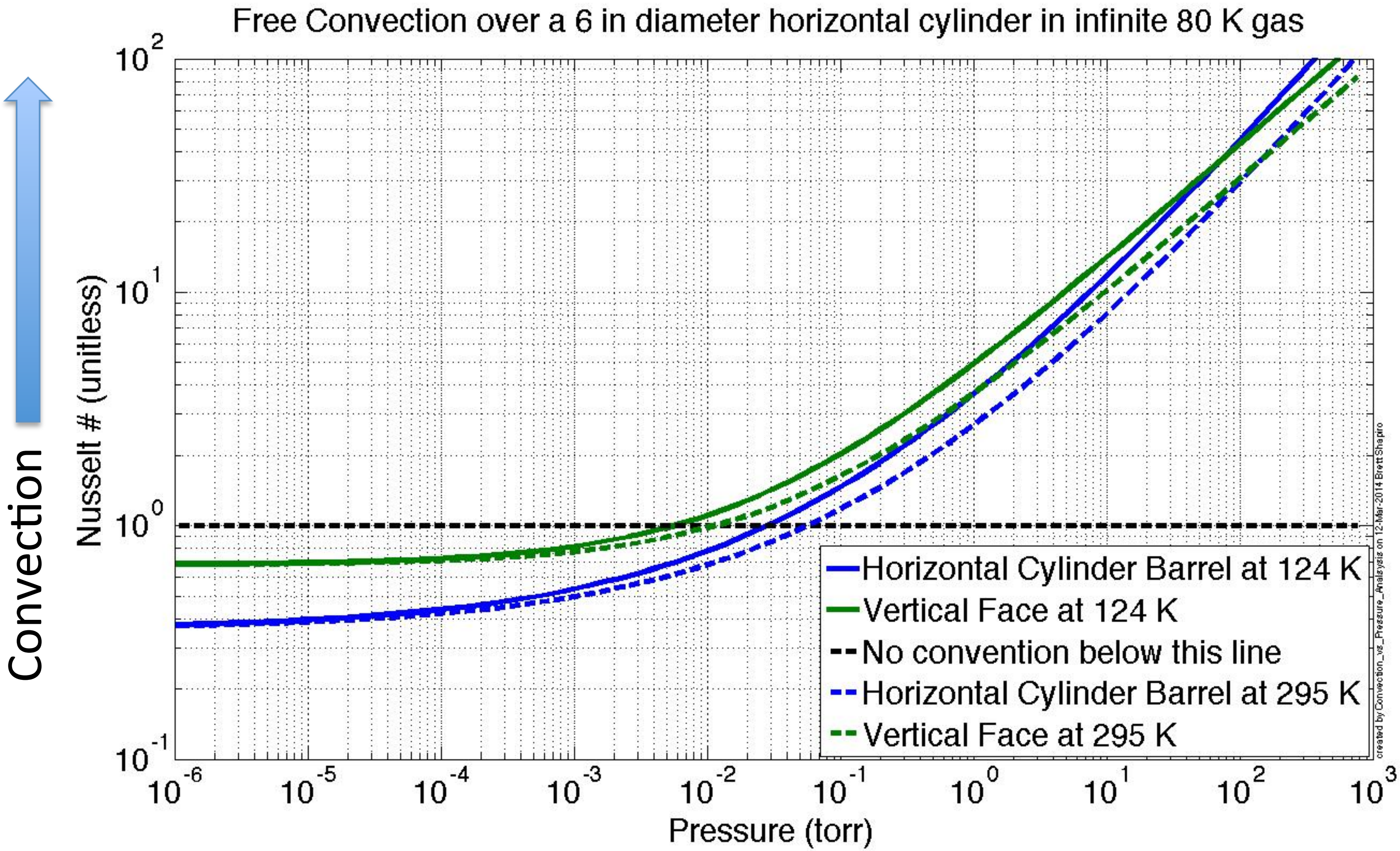
Measurement – cold link disengaged



Simulation assuming only N_2 gas conduction

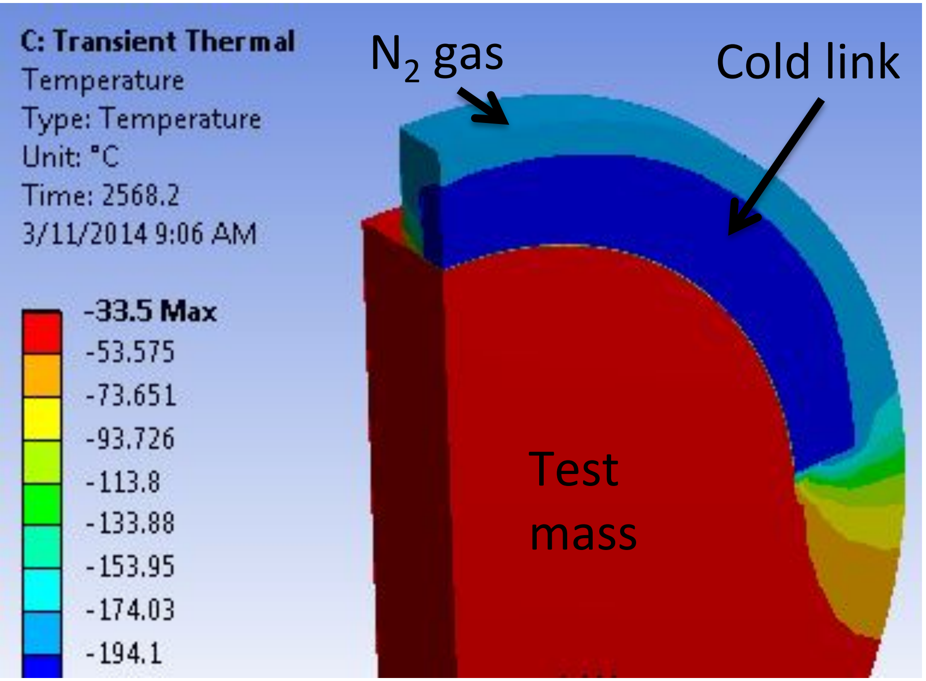
160 min time constant

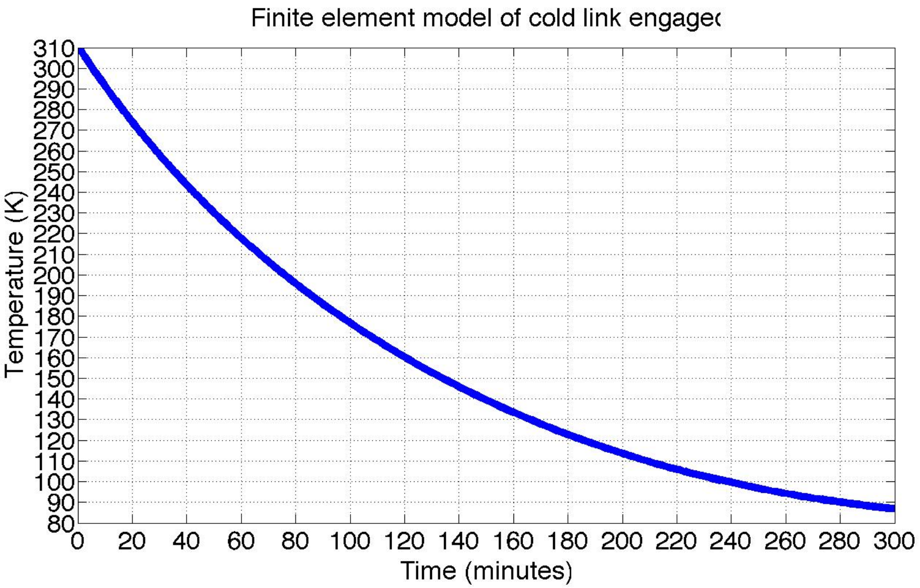
Conductive vs Convective Regimes



Finite Element Modeling

- Due to complexity, LIGO III designs must be verified with modeling or FEM
- Below: FEM of conduction through N_2 gas to cold link for Stanford experiment



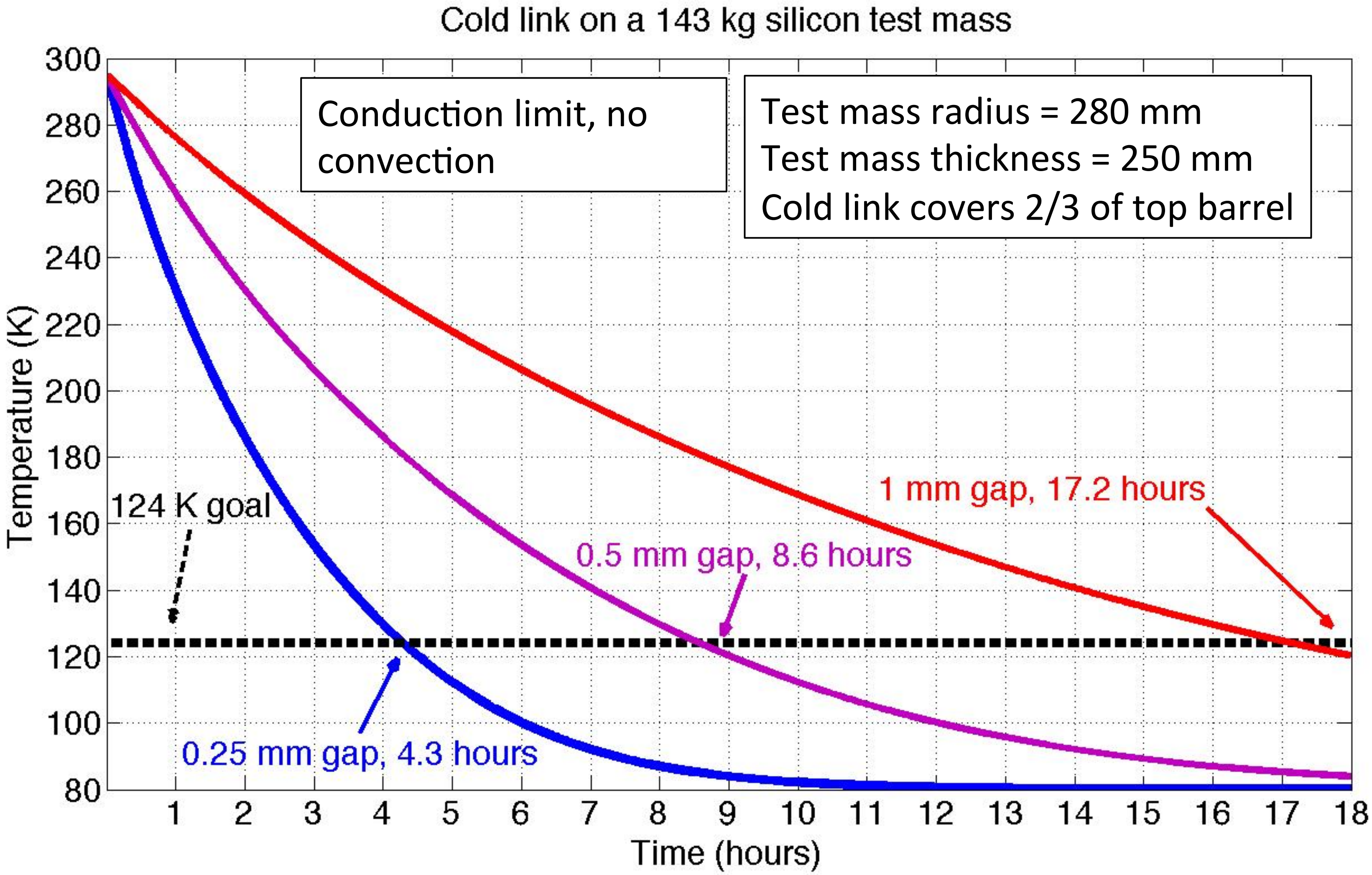


≈ 43 min into cool down

- Convective FEM is proving to require large amounts of computing power

Images courtesy of Tim MacDonald

Cold link on a LIGO III test mass

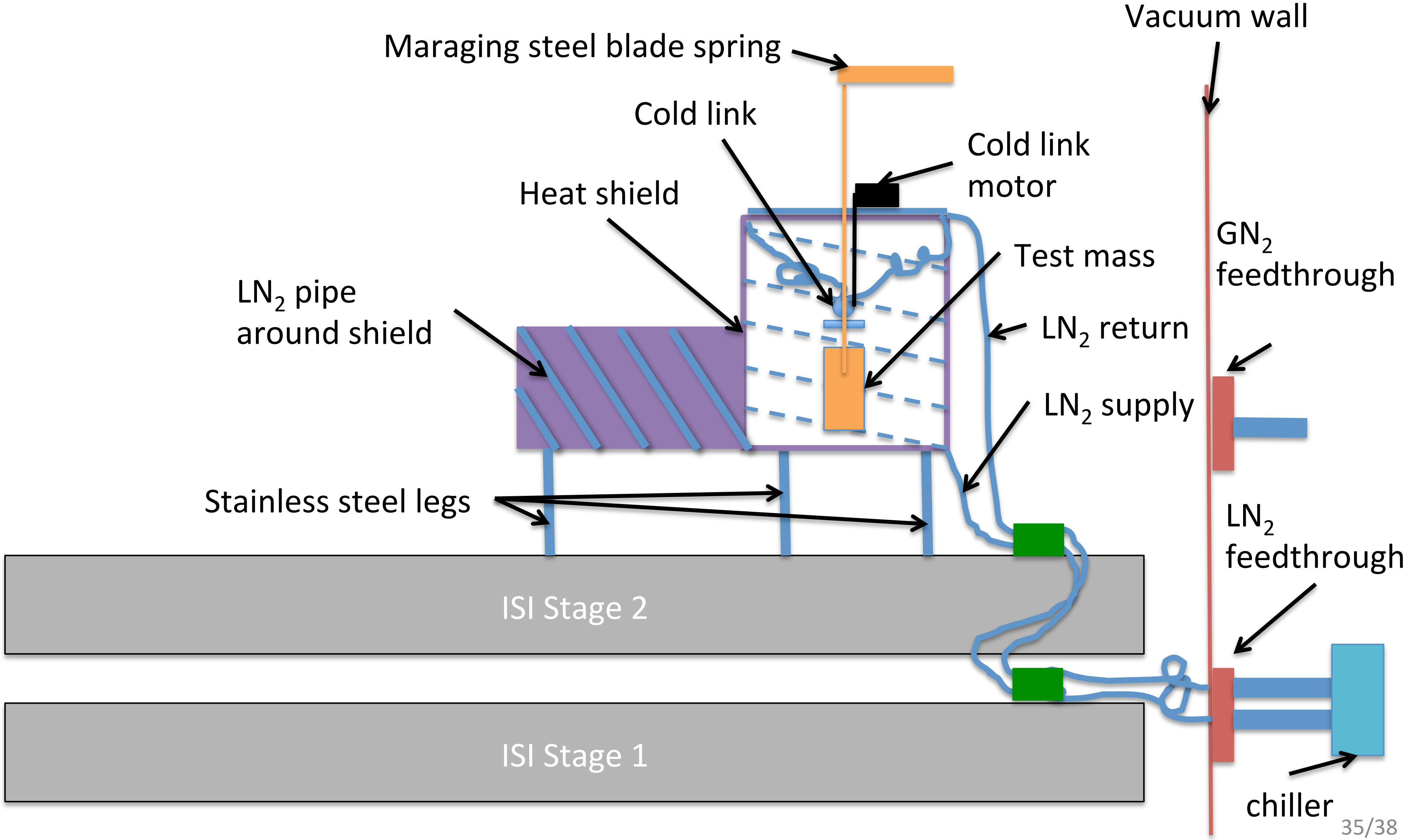


Conduction limit, no convection

Test mass radius = 280 mm
Test mass thickness = 250 mm
Cold link covers 2/3 of top barrel

Stanford Next Gen Experiment

Stanford Next Gen Experiment Layout



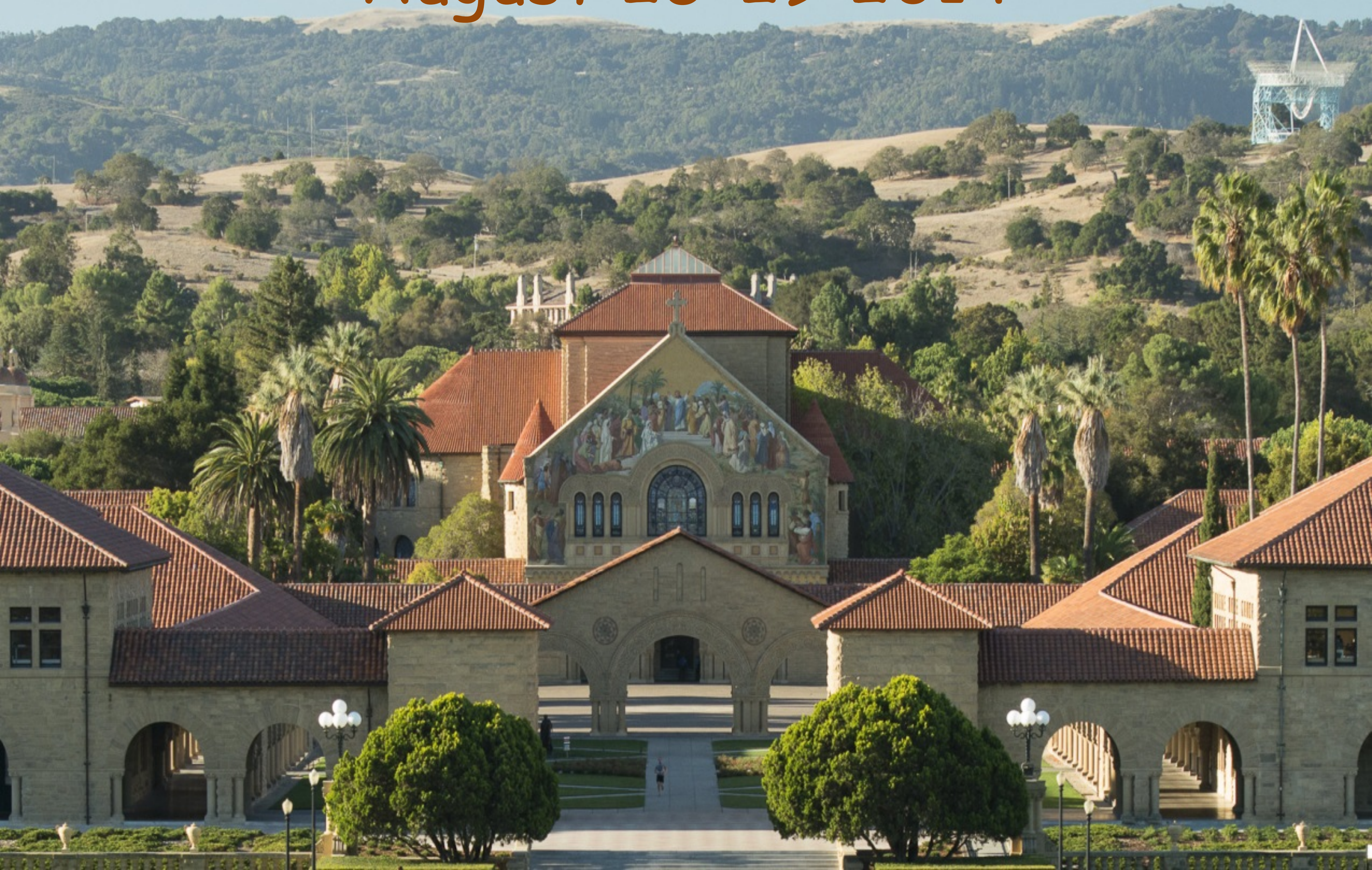
LIGO

Future work

Next generation experiment using the Stanford ETF (experimental test facility)

- More realistic LIGO setup
- Measure temperature drifts on LIGO hardware, e.g. blade springs
- Measure seismic noise of nitrogen delivery and/or copper cables
- Test heat shield design
  - Black coatings
  - baffles
- Test a variety of cooling techniques
- System integration: how to make all this stuff work together
- Implement in stages
  - Cables/hoses first – test seismic noise
  - Heat shield and suspended optic
  - Install cryogenic refrigerator
  - Cavity?
  - Anything we haven’t thought of yet

LVC STANFORD
August 25-29 2014



LVC STANFORD
August 25-29 2014

Accommodations

Carothers Hall

(30) Single Rooms: $77.20 per person/night
(85) Double Rooms: $56.70 per person/night

Benefits:
- 5 minute walk to conference.
- Outdoor facilities available:
- Telephone in each
- Comfortable and clean facility.
- Onsite management.
- Free laundry facilities.
- Linens provided
- Quiet areas including business center/lounge.
- Crothers Hall is exclusive to LVC.
- Free shuttle service to shopping/restaurants

Alternate accommodations (hotel)
$180-350/night

Registration – webpage coming soon

$250	Student rate
$500	Non-student rate

Includes:
- Breakfast and lunch
- Banquet dinner
- Conference rooms
- AV and AV Technicians
- Poster session

Does not include:
- Parking passes ($10/day)
- Transportation to/from airport
- Poster printing

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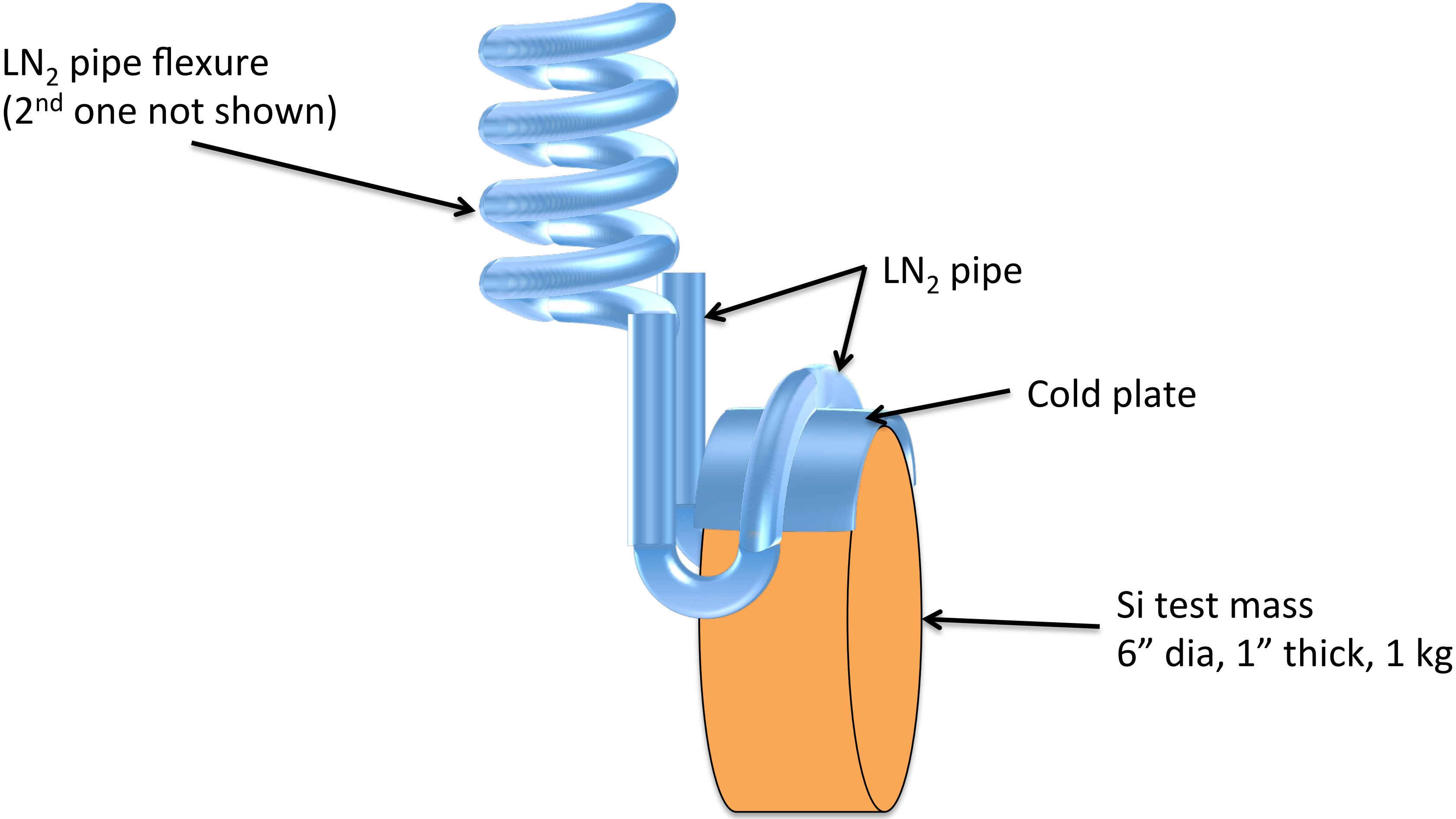
Backups

Test Mass in Next Gen Prototype


LN$_2$ pipe flexure
(2nd one not shown)

LN$_2$ pipe

Cold plate

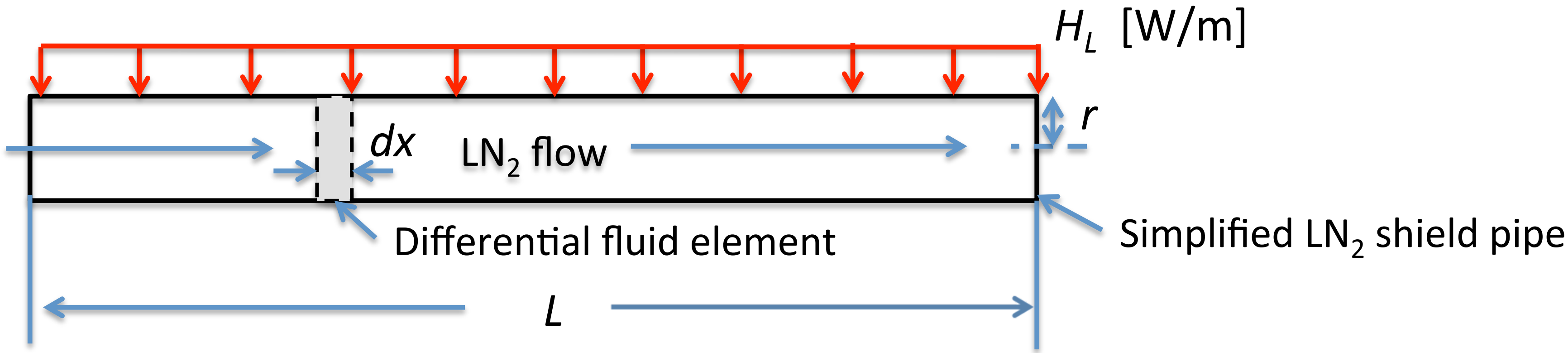
Si test mass
6” dia, 1” thick, 1 kg

Experimentation lessons learned

- Air dominates most heat flow across contacts
- Cold links should have distributed contacts
- Solder is not leak tight against high pressure cryogenic fluids – welding is probably best
- Cryogenic fluid should have 1 flow path
- Send fluid from bottom up
- Use fatter pipes to minimize fluid pressure
- Minimize the number of materials in the plumbing – joining and contraction issues
- Leave room for differential contraction
- Silicon diode temperature sensors are great

Steady State LN_2 flow rate

What flow rate do we need to maintain the shield at about ≈ 80 K?



Liquid nitrogen parameters

$C_p = 2041$ J/kg·K at boiling

$\rho = 806.1 \text{ kg/m}^3$

Q_m = mass flow rate in kg/s

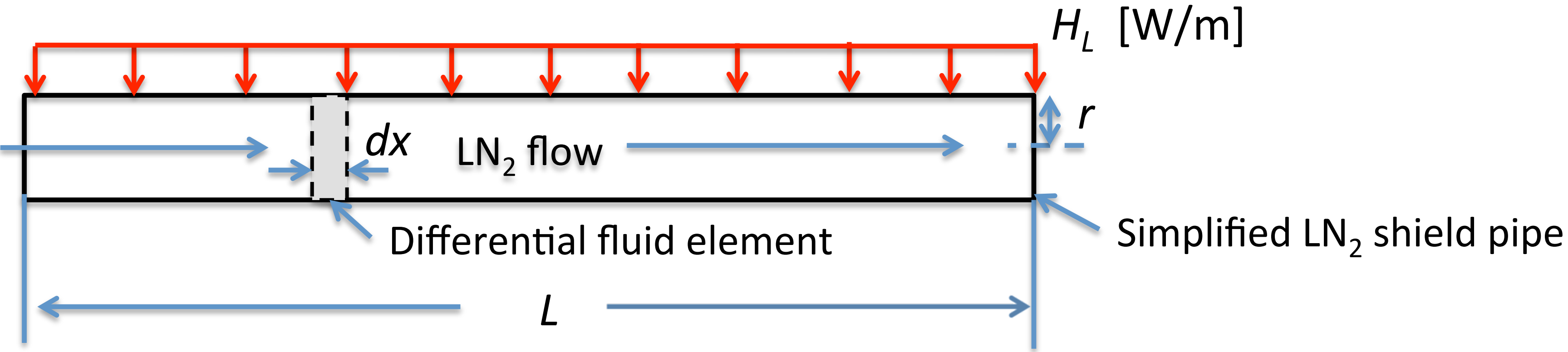
$Q_v = Q_m / \rho$ = volumetric flow rate in m^3/s

1 m^3 = 1000 liter

Heat load in shield

$P = 10$ W

$H_L = P / L$ [W/m]



Velocity of fluid element for a given flow rate

$$v = \frac{Q_v}{\pi r^2} = \frac{Q_m}{\rho \pi r^2} \ [\text{m/s}]$$

Time it takes fluid element to travel pipe

$$t = L / v = \frac{L \rho \pi r^2}{Q_m} \ [\text{s}]$$

Mass of fluid disk-element

$$dm = \rho \pi r^2 dx \ [\text{kg}]$$

Heat capacity of fluid element

$$C_p dm = C_p \rho \pi r^2 dx \ [\text{J/K}]$$

Power into fluid element

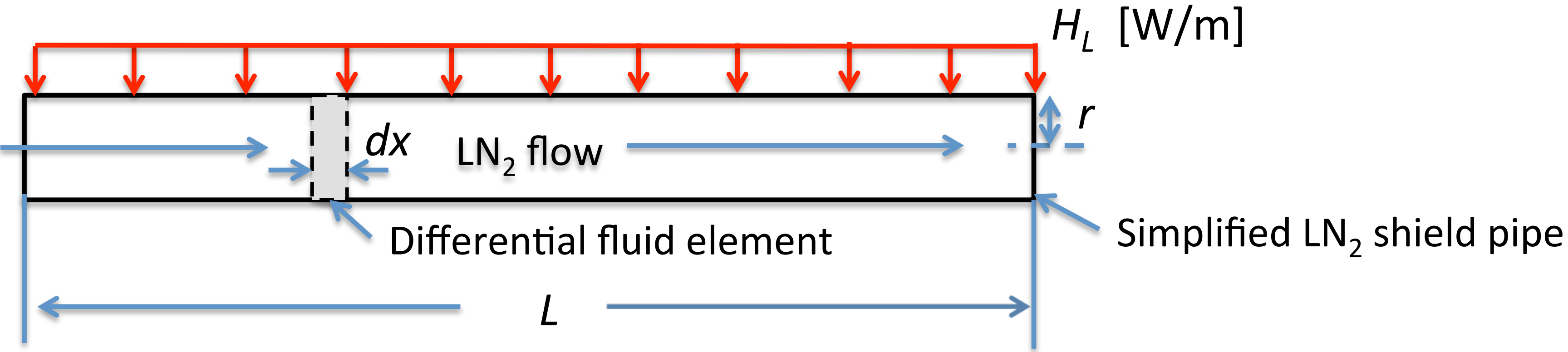
$$H_L dx = \frac{P}{L} dx \ [\text{W}]$$

Total heat energy into fluid element for time in pipe

$$H_L t dx = \frac{P \rho \pi r^2}{Q_m} dx \ [\text{J}]$$

Temperature rise in fluid

$$\Delta T = \frac{H_L t dx}{C_p dm} = \frac{P}{\rho C_P Q_v} \ [\text{K}]$$



Volumetric flow rate

$$\boxed{Q_v = \frac{H_L t dx}{C_p dm} = \frac{10^6 P}{\rho C_P \Delta T} \text{ [ml/s]}}$$

if we allow for

$\Delta T = 10$ K, P = 10 W

then,

$$Q_v = \frac{10^6(10)}{806.1(2041)10} = 0.61 \text{ ml/s}$$

Scaling laws of LN_2 pipes vs. Cu cables

Cu cable

$$H = K_{th} \frac{N\pi r^2}{L} \Delta T$$

$$K_L = \frac{NEr^4}{nD^3(1+\nu)}$$

In general,

$$K_{\text{any axis}} \alpha \frac{r^4}{L^3}$$

LN_2 pipe

$$H = \rho C_{P,LN2} Q_v \Delta T$$

$$\mathrm{Re} = \frac{2\rho Q_v}{\mu N \pi r_i} < 2000$$

$$K_L = \frac{NE(r_o^4 - r_i^4)}{nD^3(1+\nu)}$$

$$\Delta P = \frac{8\mu L Q_v}{N\pi r^4} < 1 \text{ atm}$$

$H =$ heat flow [W]

$\mathrm{Re} =$ Reynolds #

$K_L =$ Longitudinal coil spring stiffness [N/m]

$P =$ pipe pressure [Pa]

$r =$ conductor radius

$\rho = LN_2$ density [kg/m^3]

$C_{P,LN2} =$ specific heat of LN_2 [J/kg$\cdot$K]

$Q_v =$ LN_2 flow rate [m^3/s]

$K_{th} =$ thermal conductivity

$L =$ pipe or conductor length [m]

$T =$ temperature [K]

$E =$ Young's modulus [Pa]

$\nu =$ Poisson ratio

$\mu = LN_2$ viscosity [Pa$\cdot$s]

$D =$ coil spring diameter [m]

$n =$ number of spring turns

$N =$ number of conductors

Scaling laws cont.

Cu cable

$$r = \sqrt{\frac{H}{\Delta T}\frac{L}{N\pi K_{th}}}$$

$$\boxed{K_L = \frac{E}{nD^3(1+\nu)N}\left(\frac{H}{\Delta T}\frac{L}{\pi K_{th}}\right)^2}$$

In general,

$$K_{\text{any axis}}\alpha\frac{r^4}{L^3}$$

LN$_2$ pipe

$$Q_v = \frac{H}{\Delta T\rho C_{P,LN2}}$$

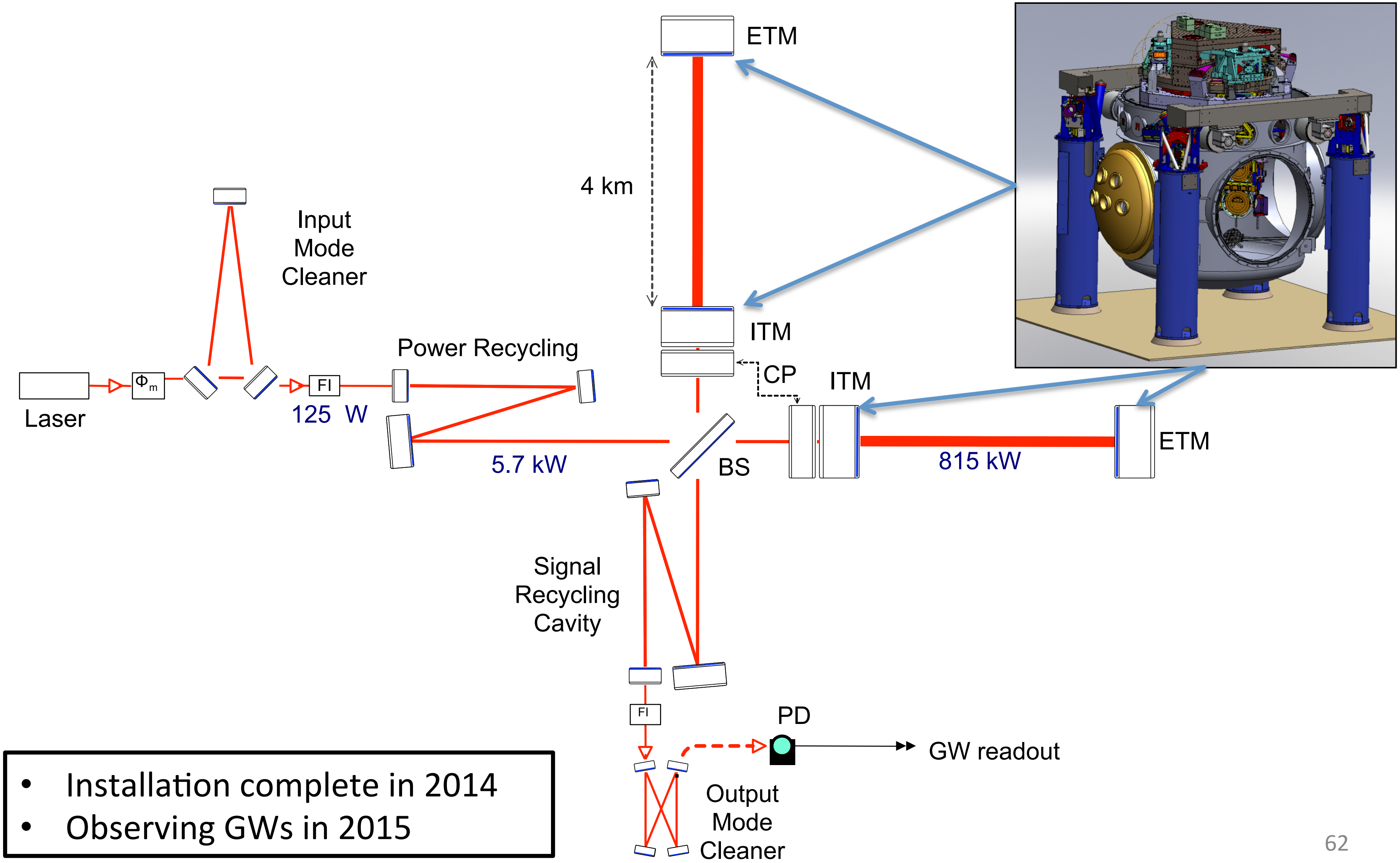
$$\mathrm{Re}_{\max} = \frac{2}{\mu N\pi r_i C_{P,LN2}}\frac{H}{\Delta T} = 1200$$

$$r_i[N] = \frac{2}{\mathrm{Re}_{\max}\,\mu N\pi C_{P,LN2}}\frac{H}{\Delta T}$$

$$K_L = \frac{NEr_i^4\left[\left(1+{}^{t}\!/\!_{r_i[N]}\right)^4 - 1\right]}{nD^3(1+\nu)}$$

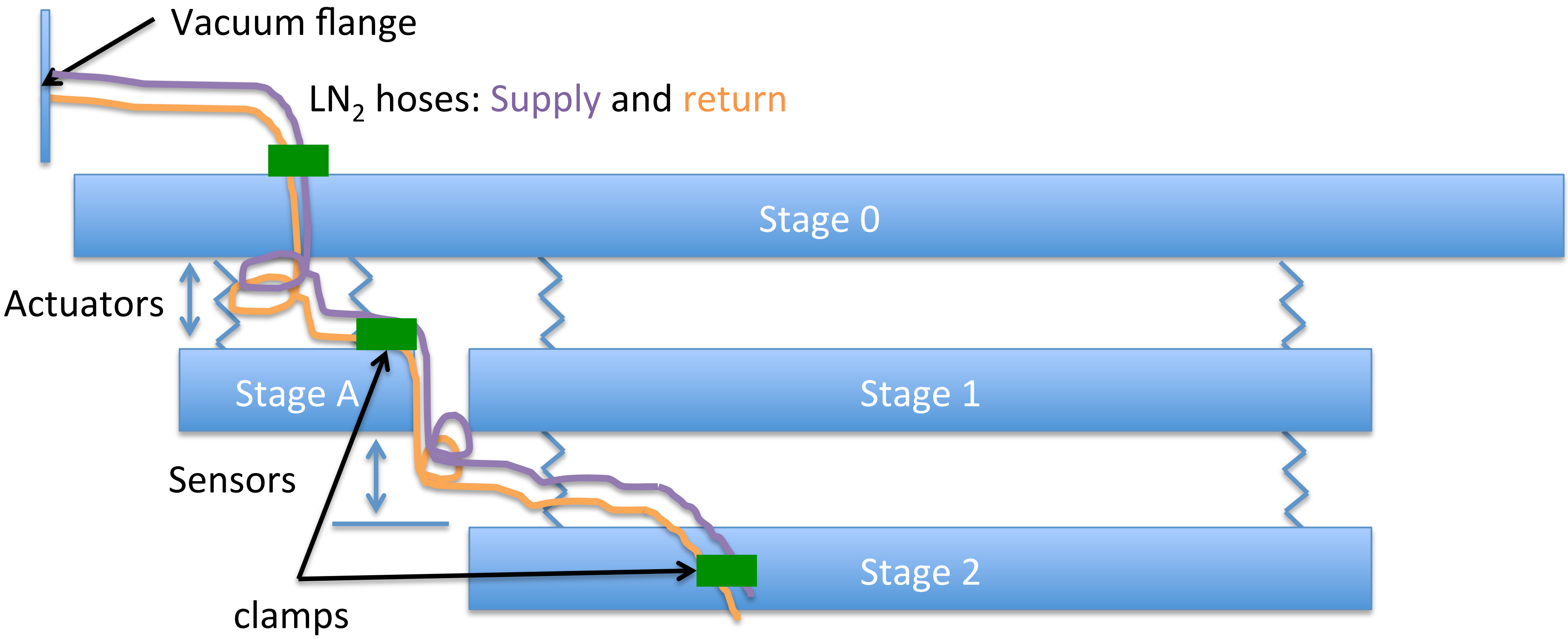
$$\boxed{K_L = \frac{E\left[\left(1+{}^{t}\!/\!_{r_i[N]}\right)^4 - 1\right]}{nN^3D^3(1+\nu)}\left(\frac{2}{\mathrm{Re}_{\max}\,\mu\pi C_{P,LN2}}\frac{H}{\Delta T}\right)^4}$$

Advanced LIGO Layout



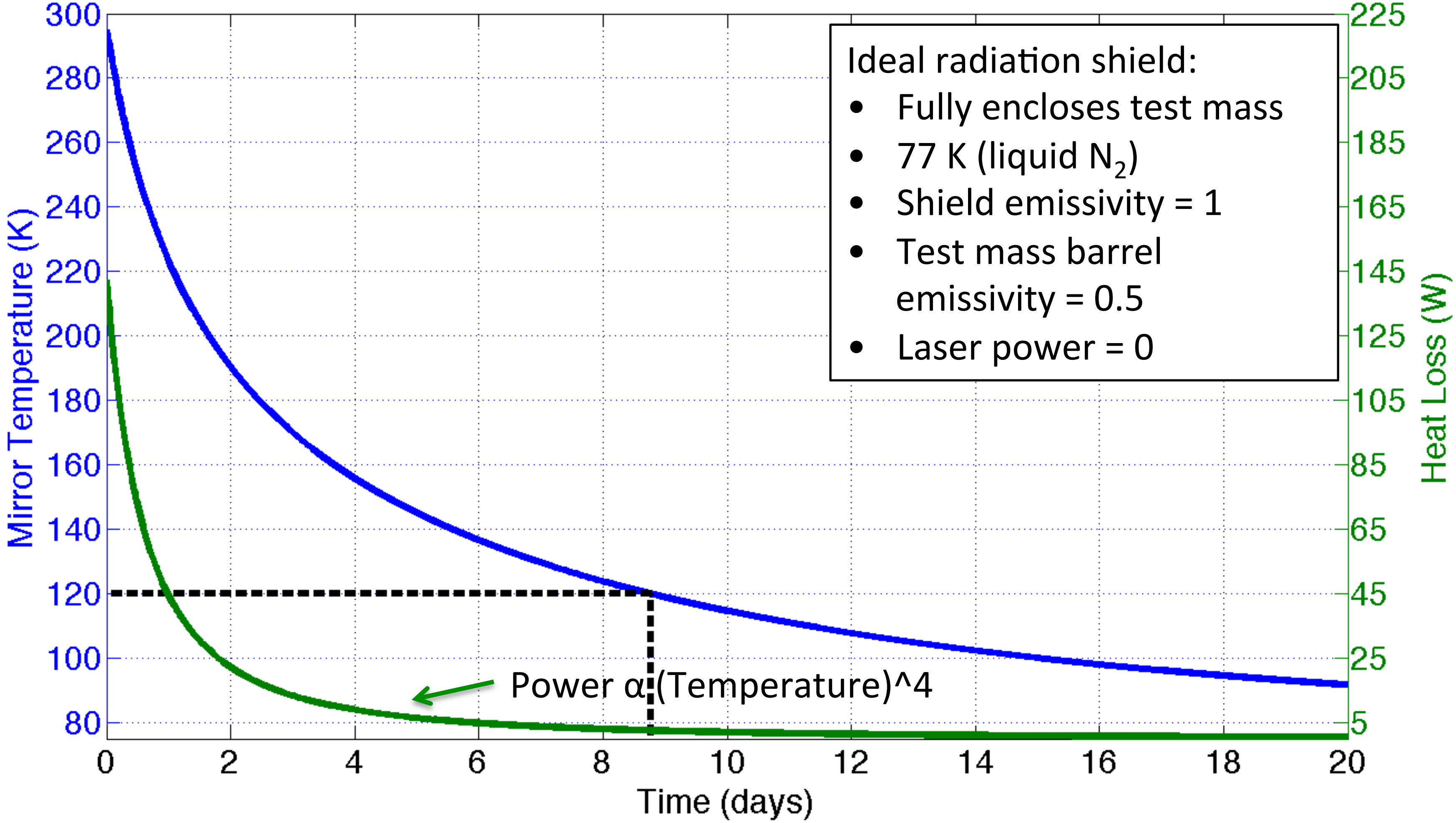
- Installation complete in 2014
- Observing GWs in 2015

How to get a LN2 Hose to ST2



Extra stage, A, in parallel with stage 1 carries hose. Stage A is actuated to follow stage 2 so the hose has does not short seismic isolation. Stage A sensor noise is set by the stage 2 isolation requirement (so it follows stage 2 and not the sensor noise).

Test Mass Radiation Simulation



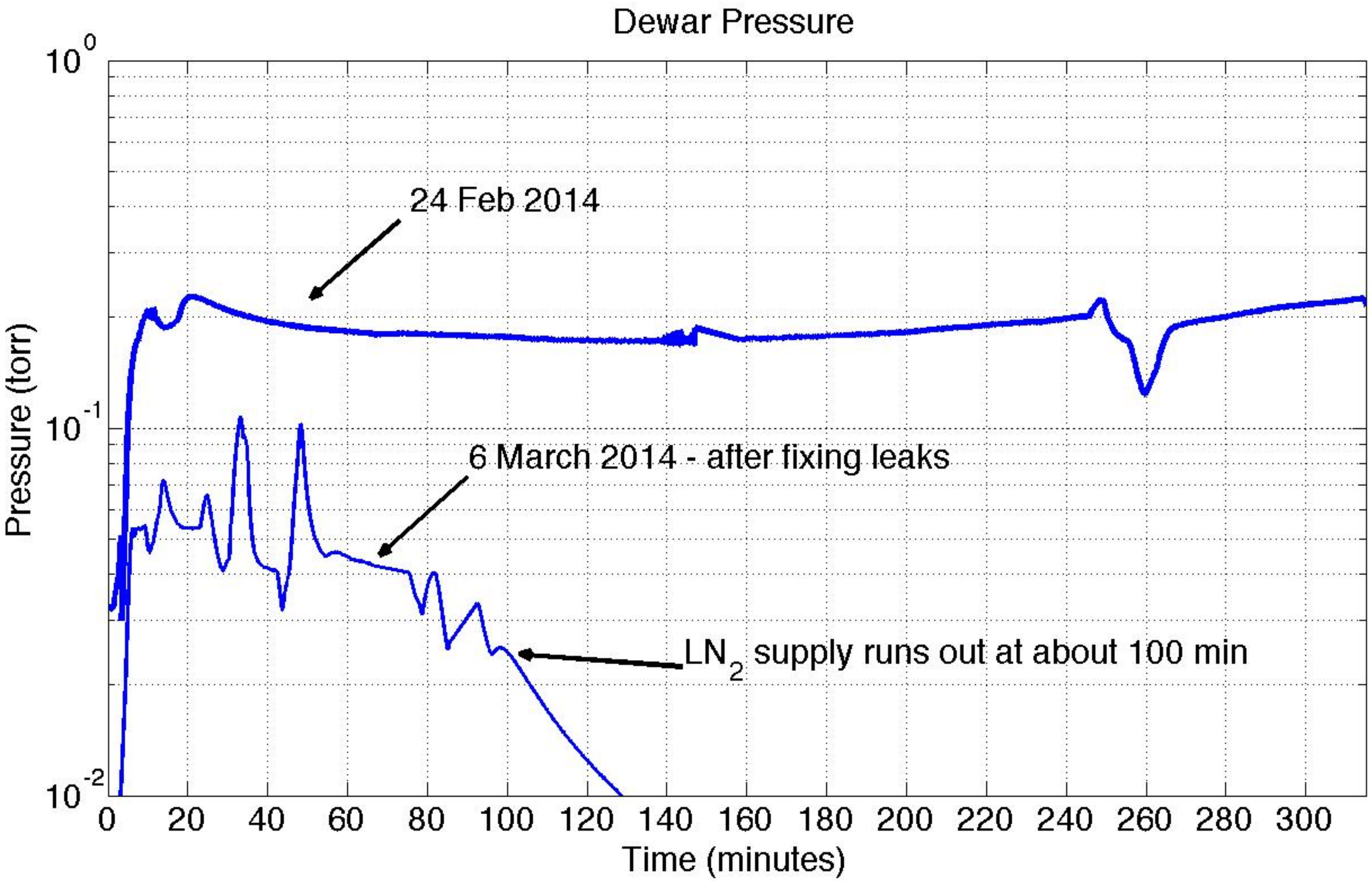
Temperature evolution of a 143 kg silicon test mass. Time to 120 K = 8.7653 days.

Ideal radiation shield:

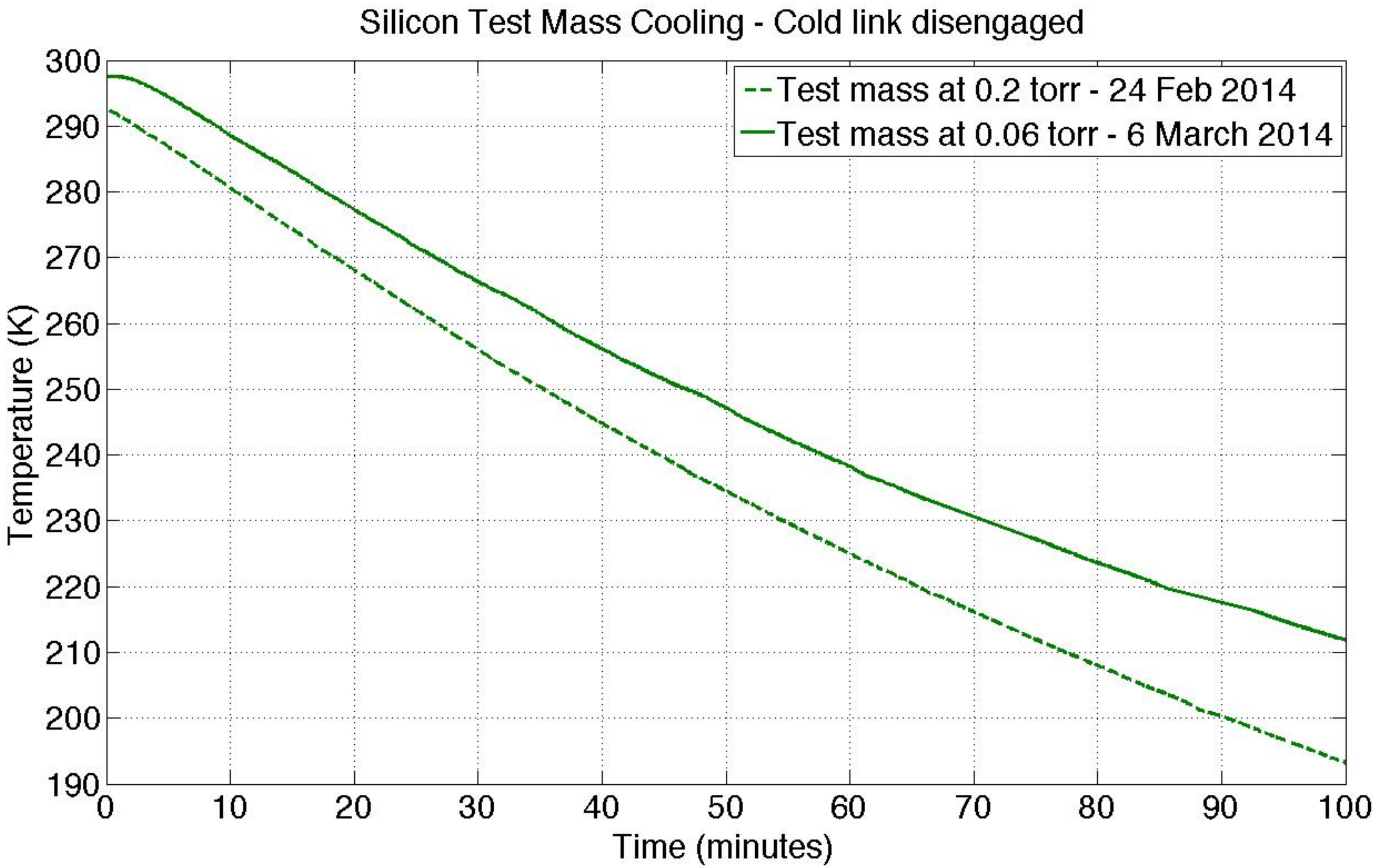
- Fully encloses test mass
- 77 K (liquid N_2)
- Shield emissivity = 1
- Test mass barrel emissivity = 0.5
- Laser power = 0

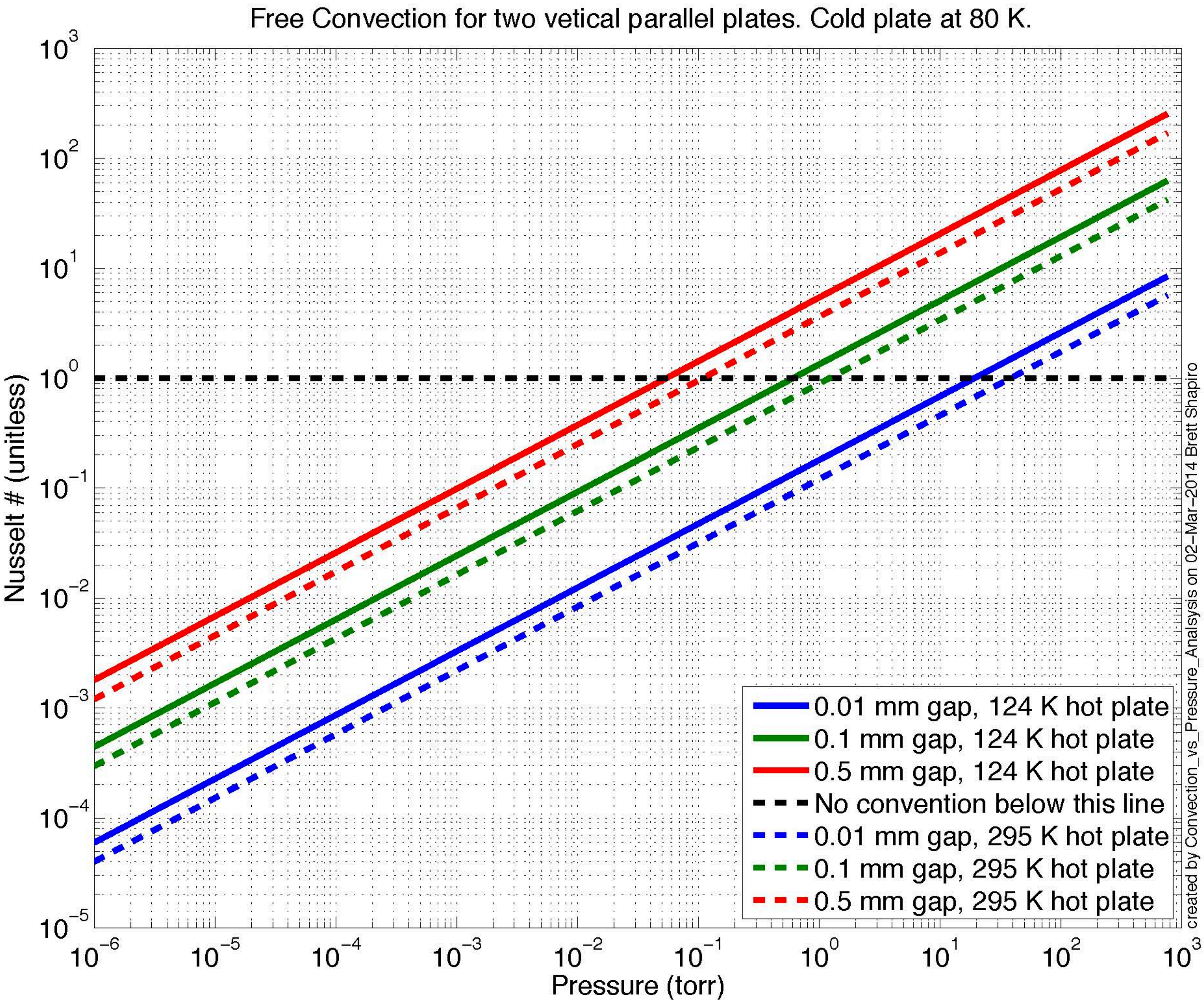
Power α (Temperature)^4

Dewar pressure during measurements



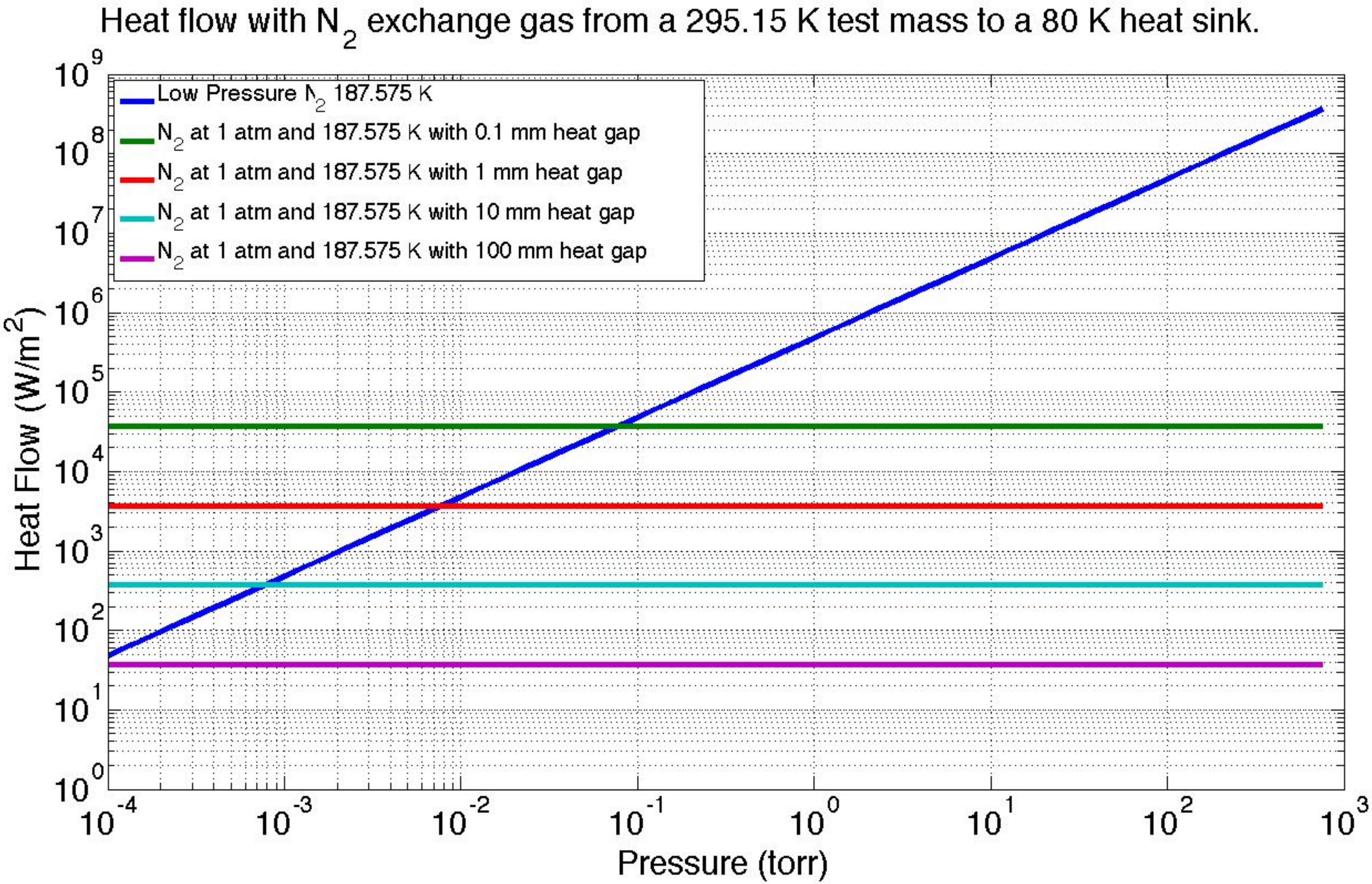
Effect of pressure on test mass temp



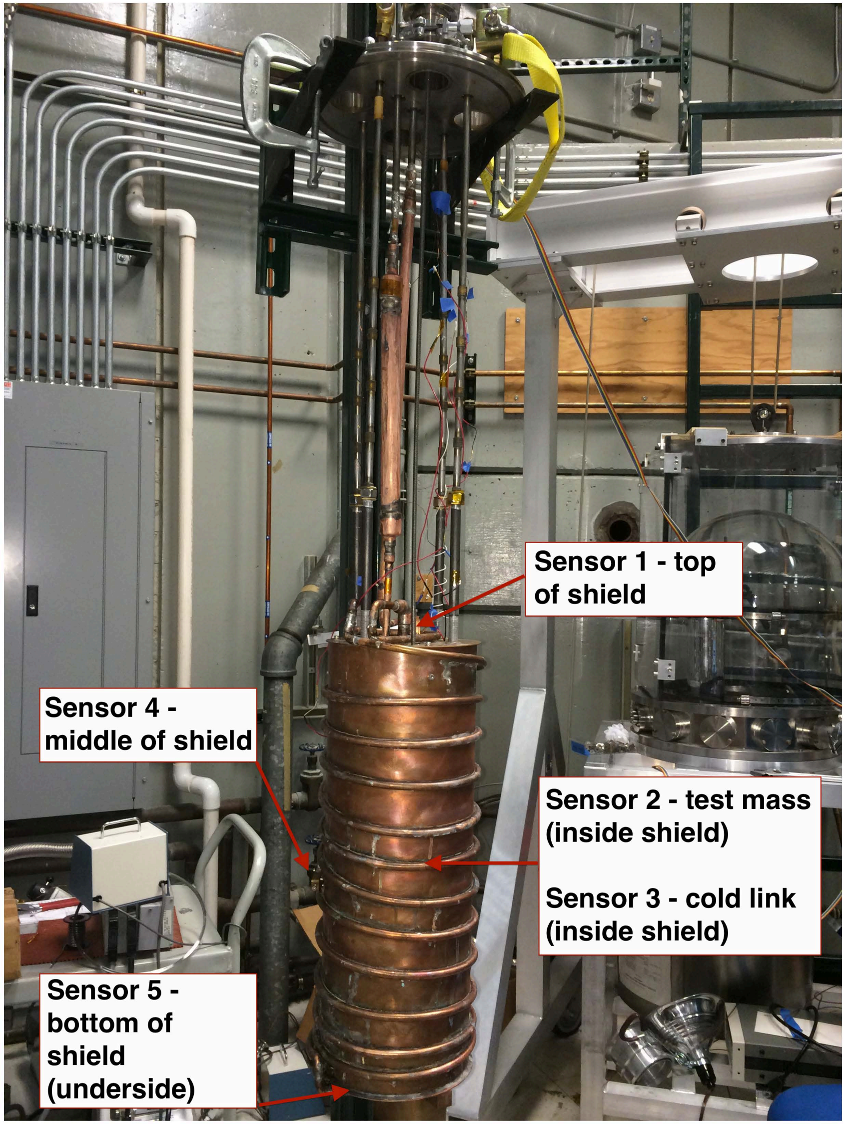


Free Convection for two vetical parallel plates. Cold plate at 80 K.

N_2 gas therm. cond. vs pressure



Temperature Sensor Locations



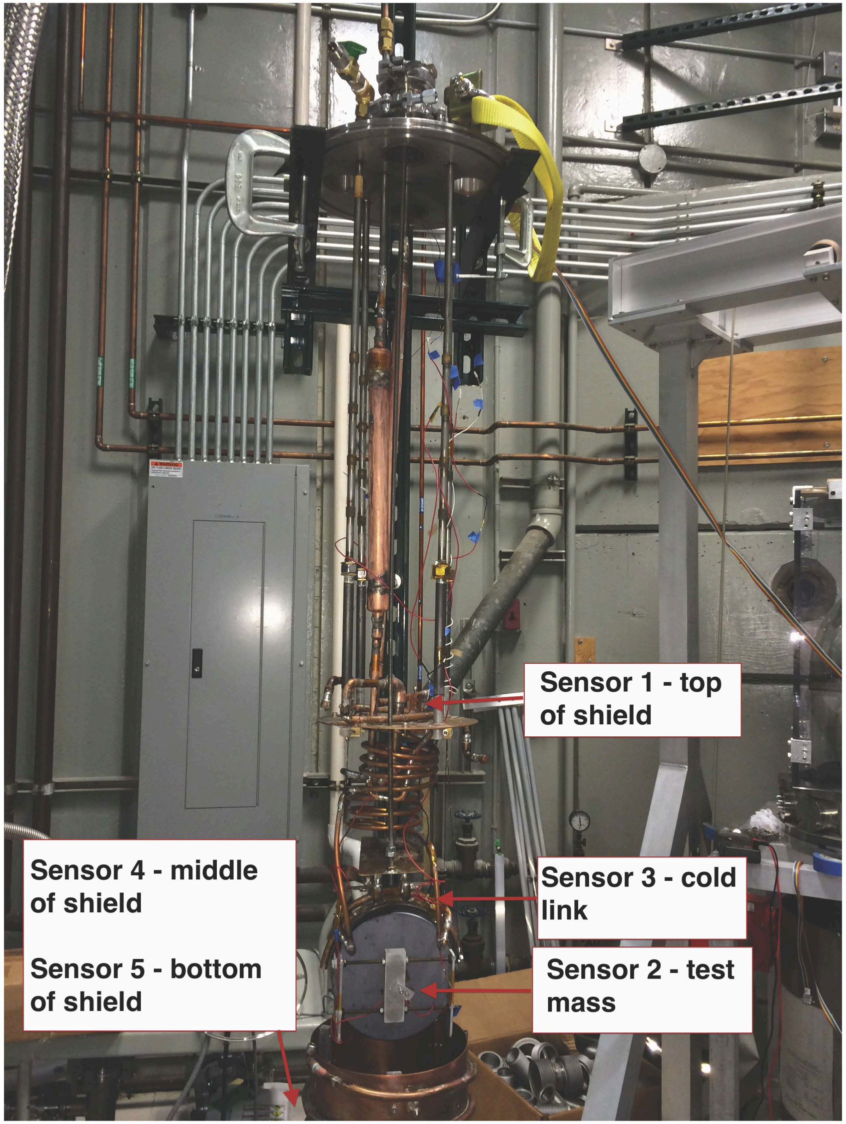
Sensor 1 - top of shield

Sensor 4 - middle of shield

Sensor 2 - test mass (inside shield)

Sensor 3 - cold link (inside shield)

Sensor 5 - bottom of shield (underside)



Sensor 1 - top of shield

Sensor 4 - middle of shield

Sensor 5 - bottom of shield

Sensor 3 - cold link

Sensor 2 - test mass

Test Mass Temperature Equations

$$\dot{Q}_{Si} = K_{CL}\Delta T$$

$$\dot{T}_{Si} = \frac{\dot{Q}_{Si}}{C_{Si}}$$

$$\dot{T}_{Si} = \frac{K_{CL}}{C_{Si}}(T_{cold} - T_{Si})$$

$$\dot{T}_{Si} + \frac{K_{CL}}{C_{Si}}T_{Si} = \frac{K_{CL}}{C_{Si}}T_{cold}$$

$$T_{Si} = T_{hot}e^{-\frac{K_{CL}}{C_{Si}}t} + T_{cold}$$

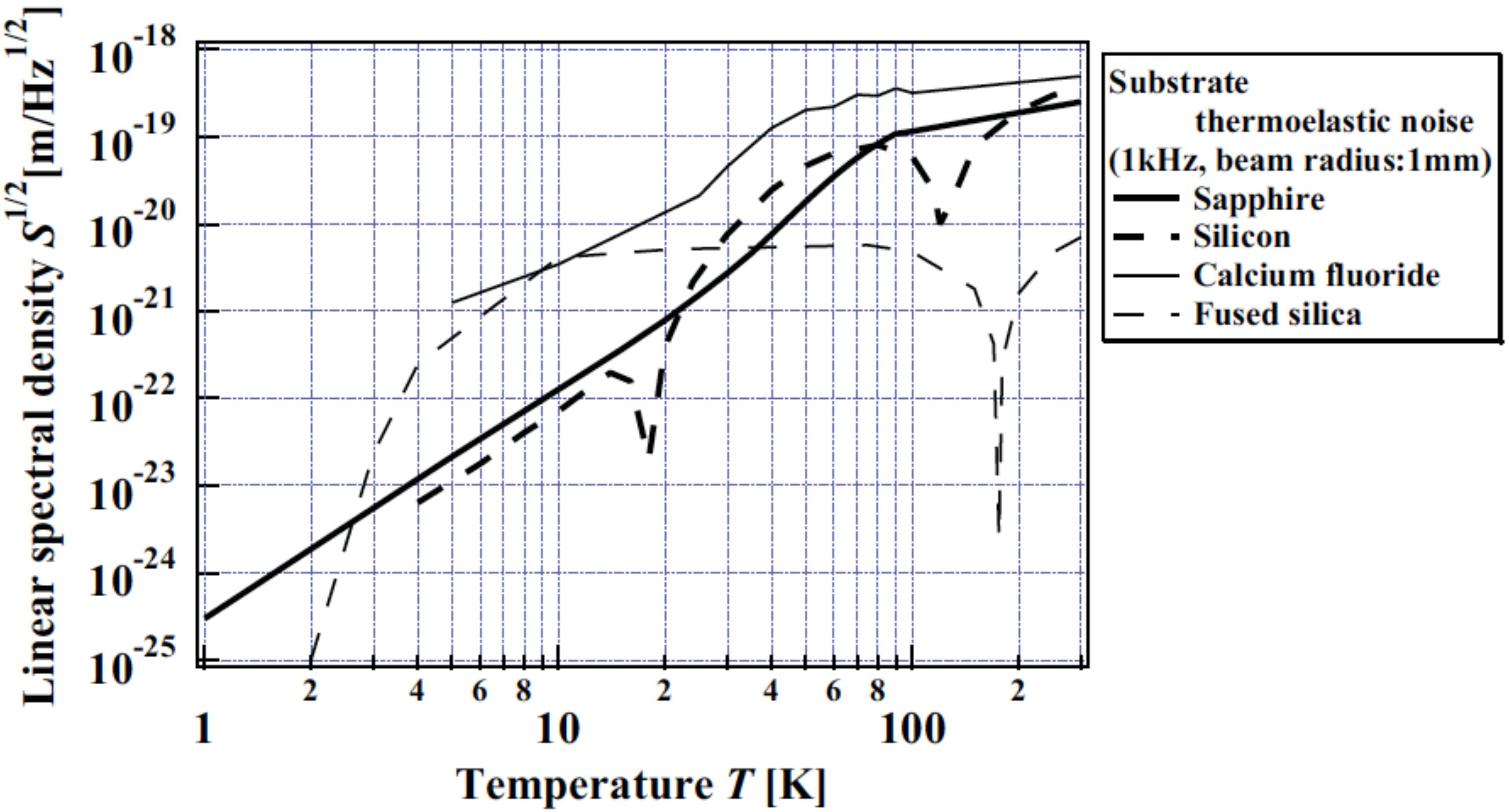
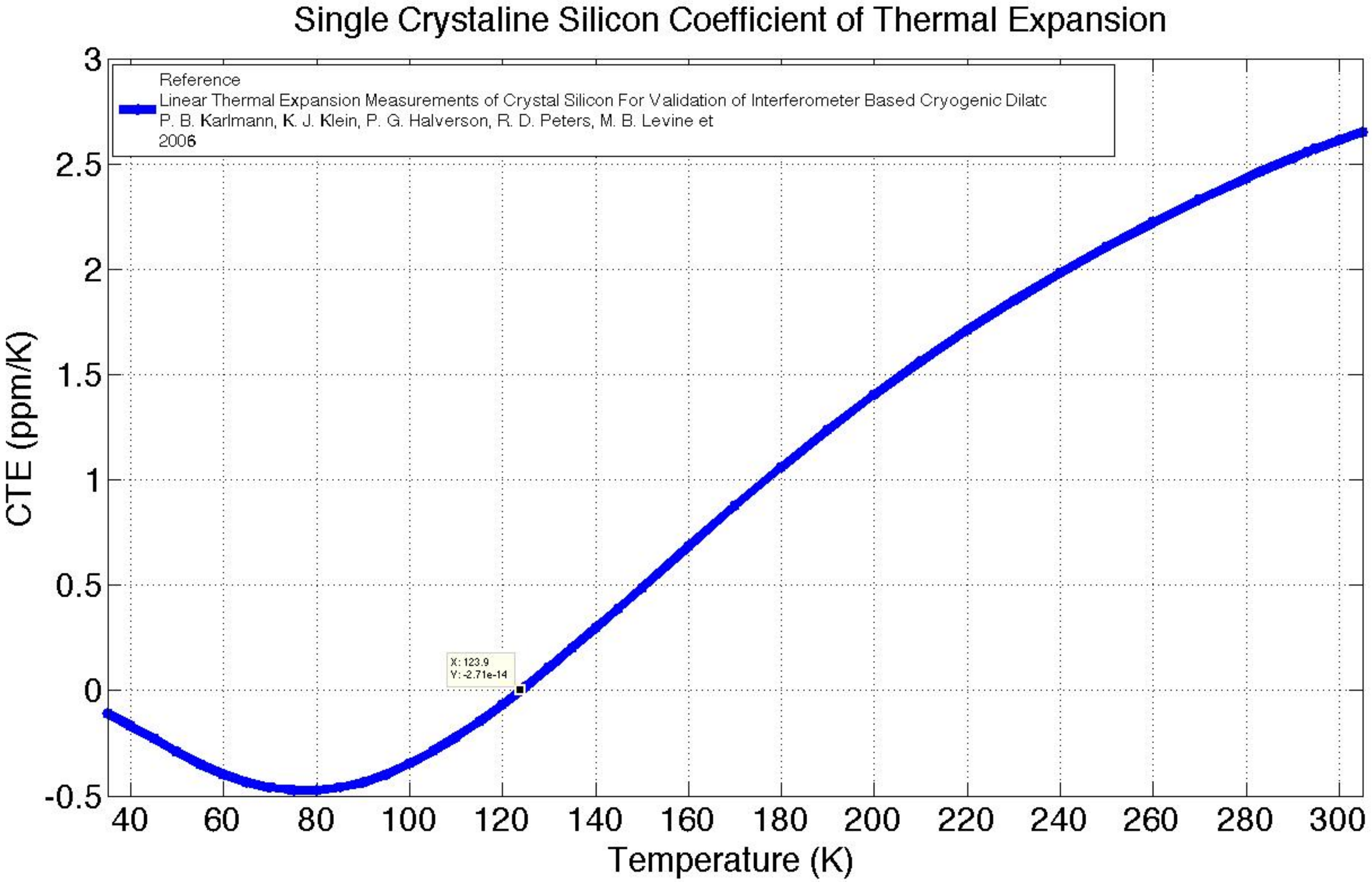


Figure 7.4 Temperature dependence of substrate thermoelastic noise. Frequency f is 1 kHz and beam radius w_0 is 1 mm.

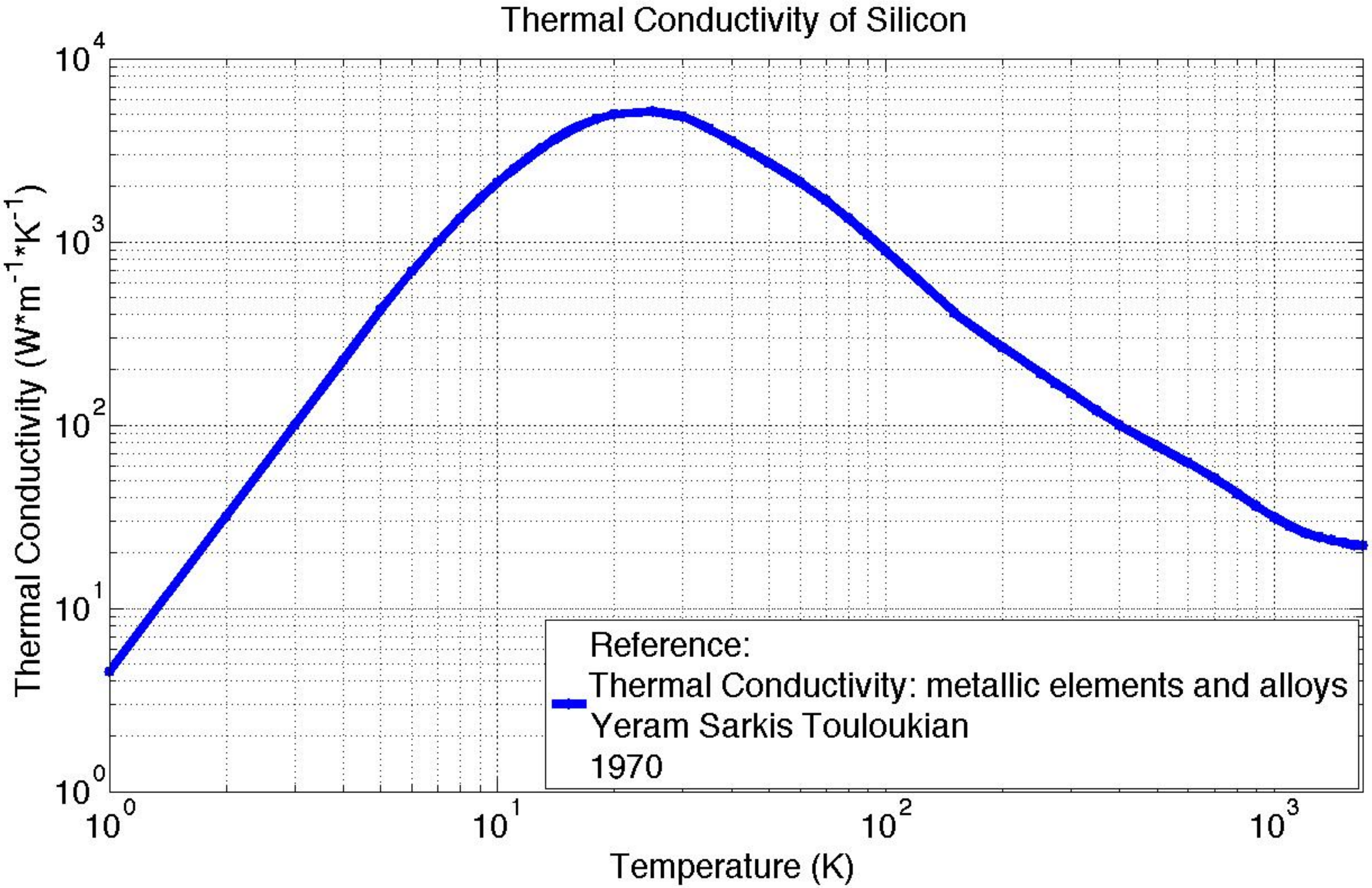
ref: Harry, Bodiya, Desalvo. Optical Coatings and Thermal Noise in Precision Measurement. 2012. pg 113.

Si CTE vs Temperature

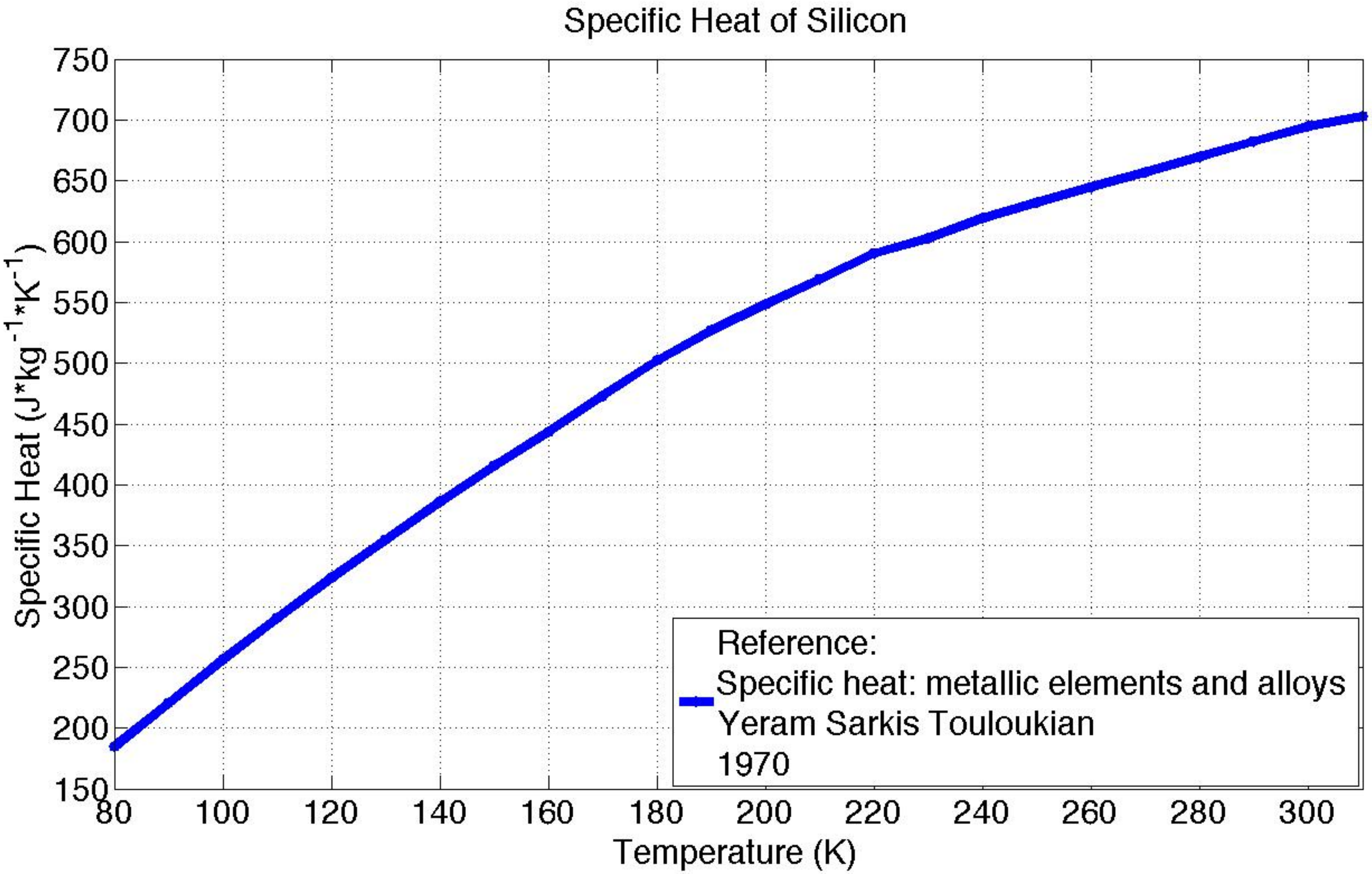


Thermoelastic component of thermal noise goes to zero with CTE.

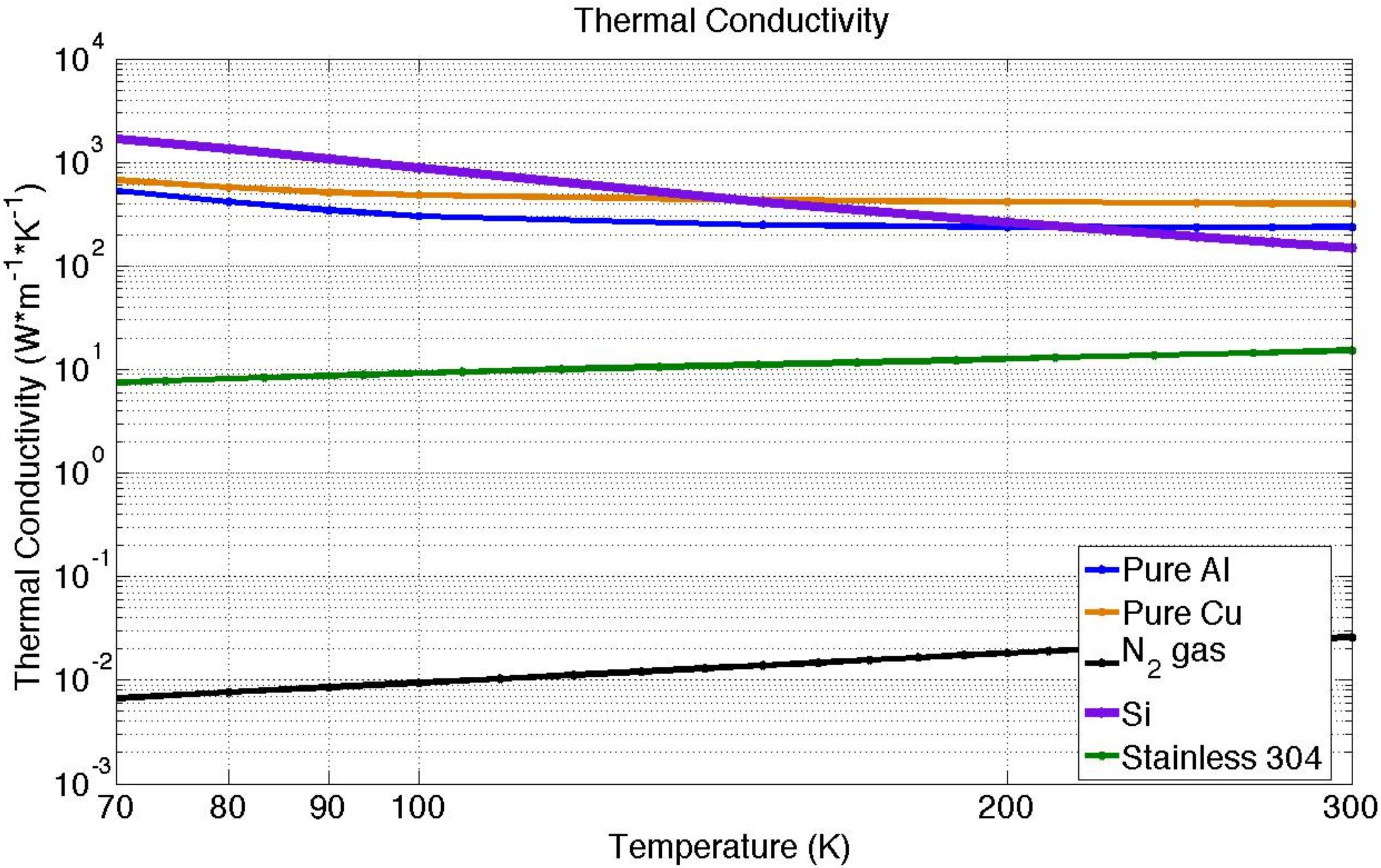
Si Thermal Conductivity vs Temp.



Si Specific Heat vs Temperature



Thermal Conductivity of Materials



References: Stainless: NIST, CRYOGENICS TECHNOLOGIES GROUP, http://cryogenics.nist.gov/
Al, Cu, Si: Thermal Conductivity: metallic elements and alloys, Touloukian 1970
N_2 gas: Thermal conductivity: nonmetallic liquids and gases, Touloukian 1970

Other Problems To Solve

- Flexibility if liquid N_2 hoses or Cu cables
- Temperature/height control of blade springs
- Test mass temperature control
- Test mass temperature tolerance
- How to measure temperature?
  - Measure acoustic modes – Young's modulus is temp. dependent
  - Measure test mass diameter – combined with CTE data gives temperature
  - Infrared camera
- Emissivity of optical coatings
- Lossiness of emissive coatings
- Good emissivity estimates/measurements of Si?
- Power absorption in Si and Si coatings (ppm, W, etc)?
- How noisy is flowing laminar liquid nitrogen: seismic, Newtonian?
- Optical coating thermal noise at 124 K
- How to actuate the test mass – is the ESD out?
- Can we put viewports in the heat shield?