LIGO

Progress on Cryogenic Test Masses for aLIGO Upgrades

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G1400250 - 18 March 2014 – Nice, France

Summary

- Moving from Advanced LIGO to LIGO III
- LIGO III cryogenic test mass suspensions
- Stanford experiment
- LIGO III simulation
- Lessons learned / changes made
- Future work

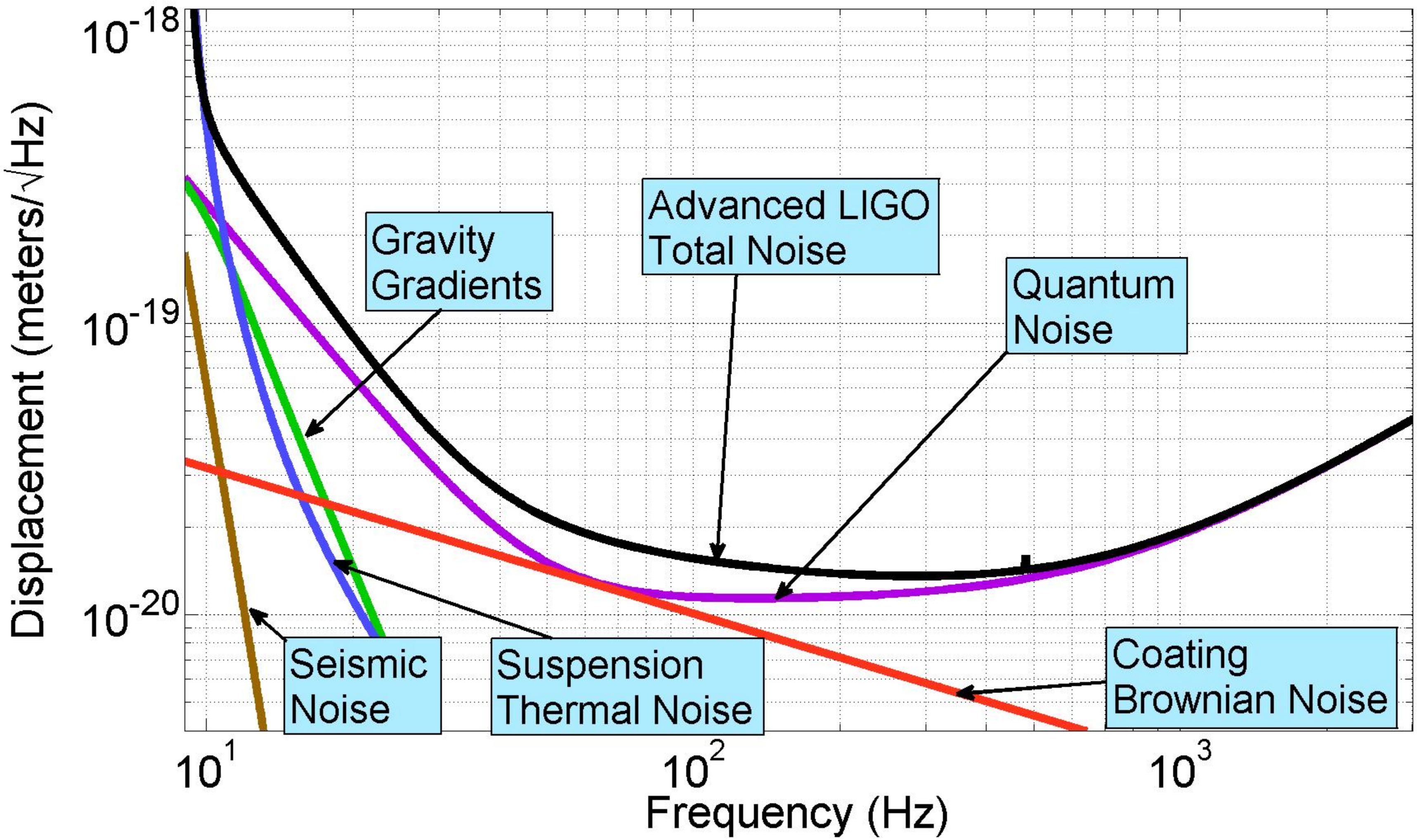
Advanced LIGO Timeline

Livingston, LA

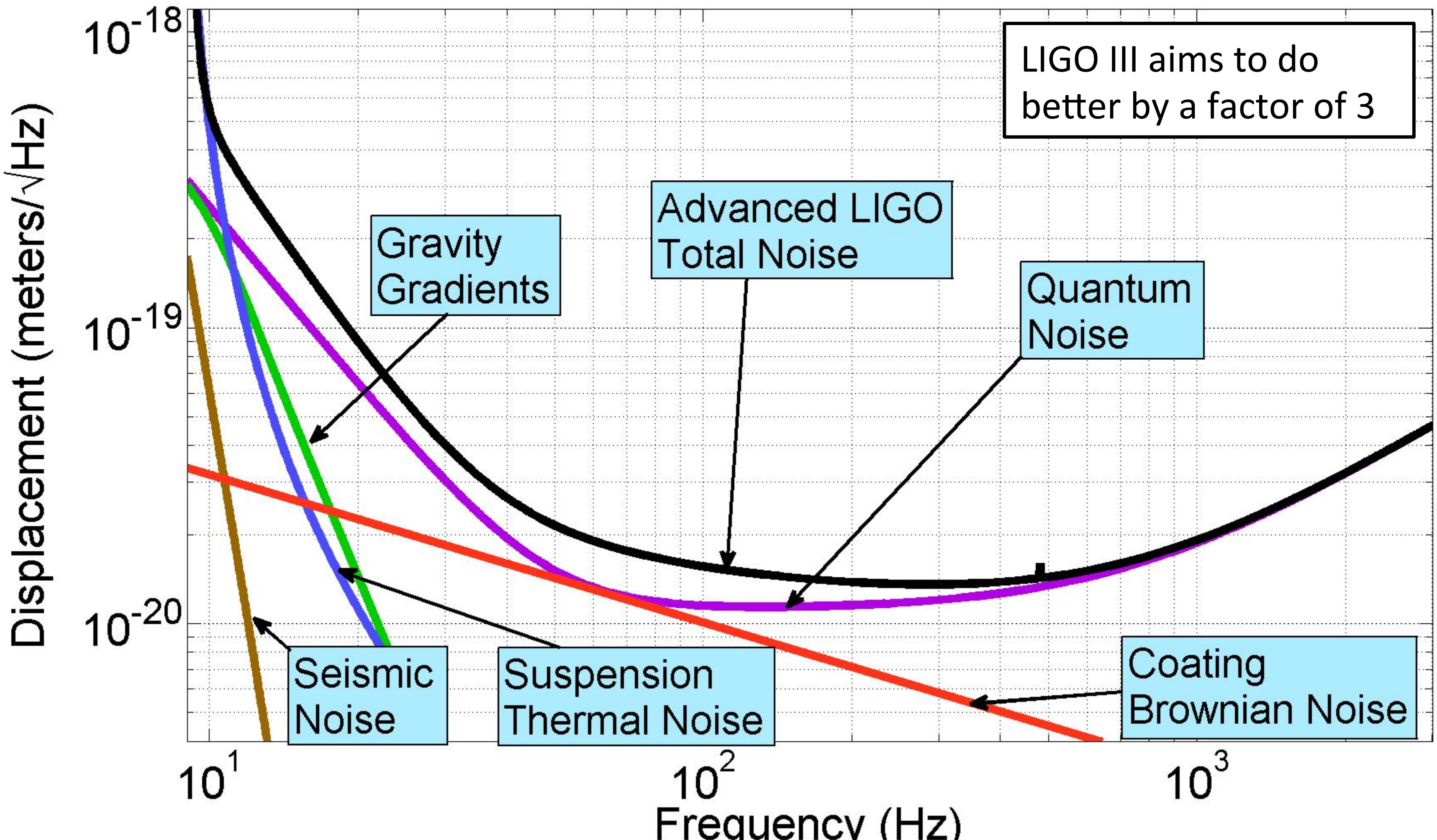
Hanford, WA

- 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

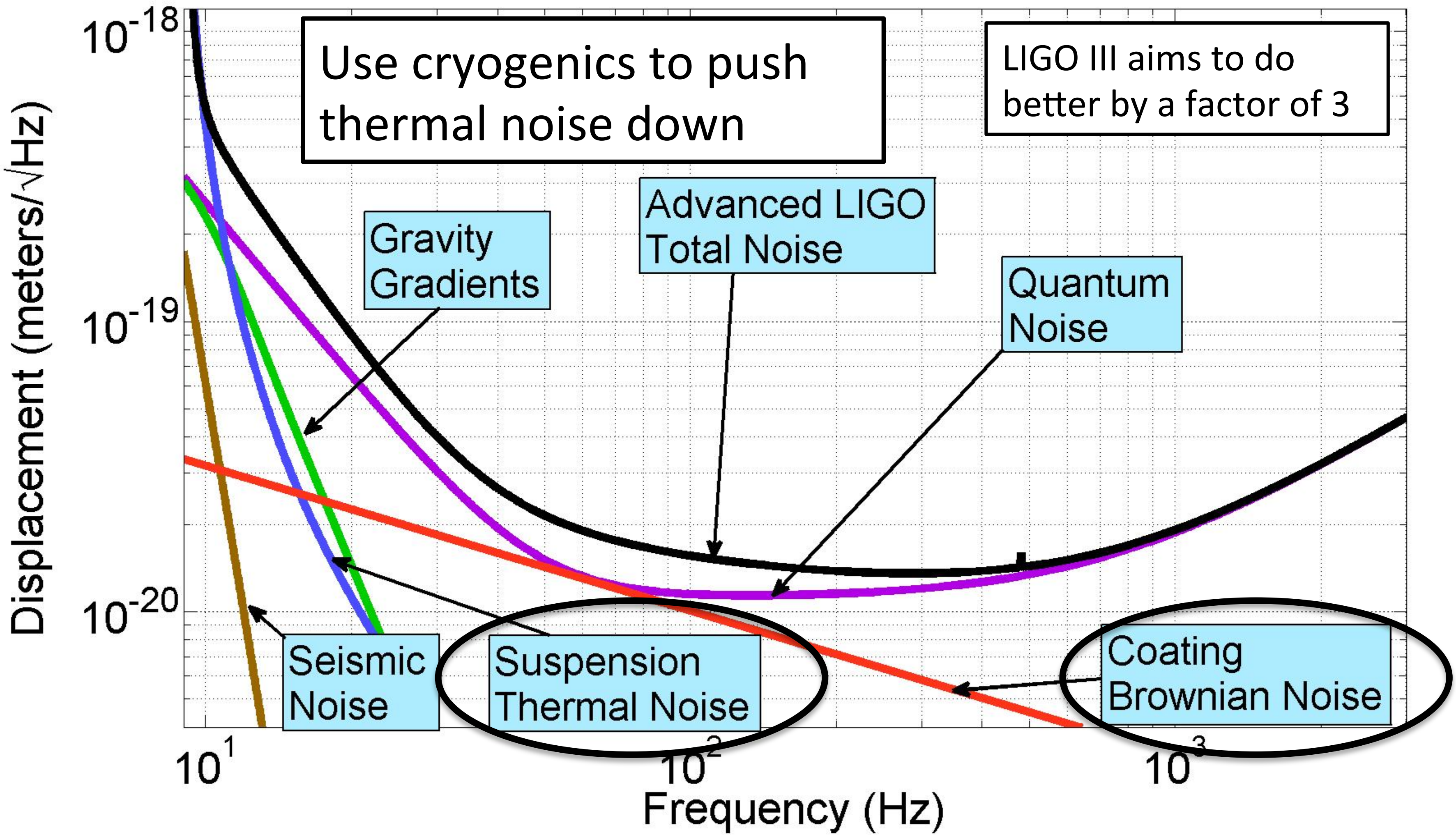
Predicted Advanced LIGO Sensitivity



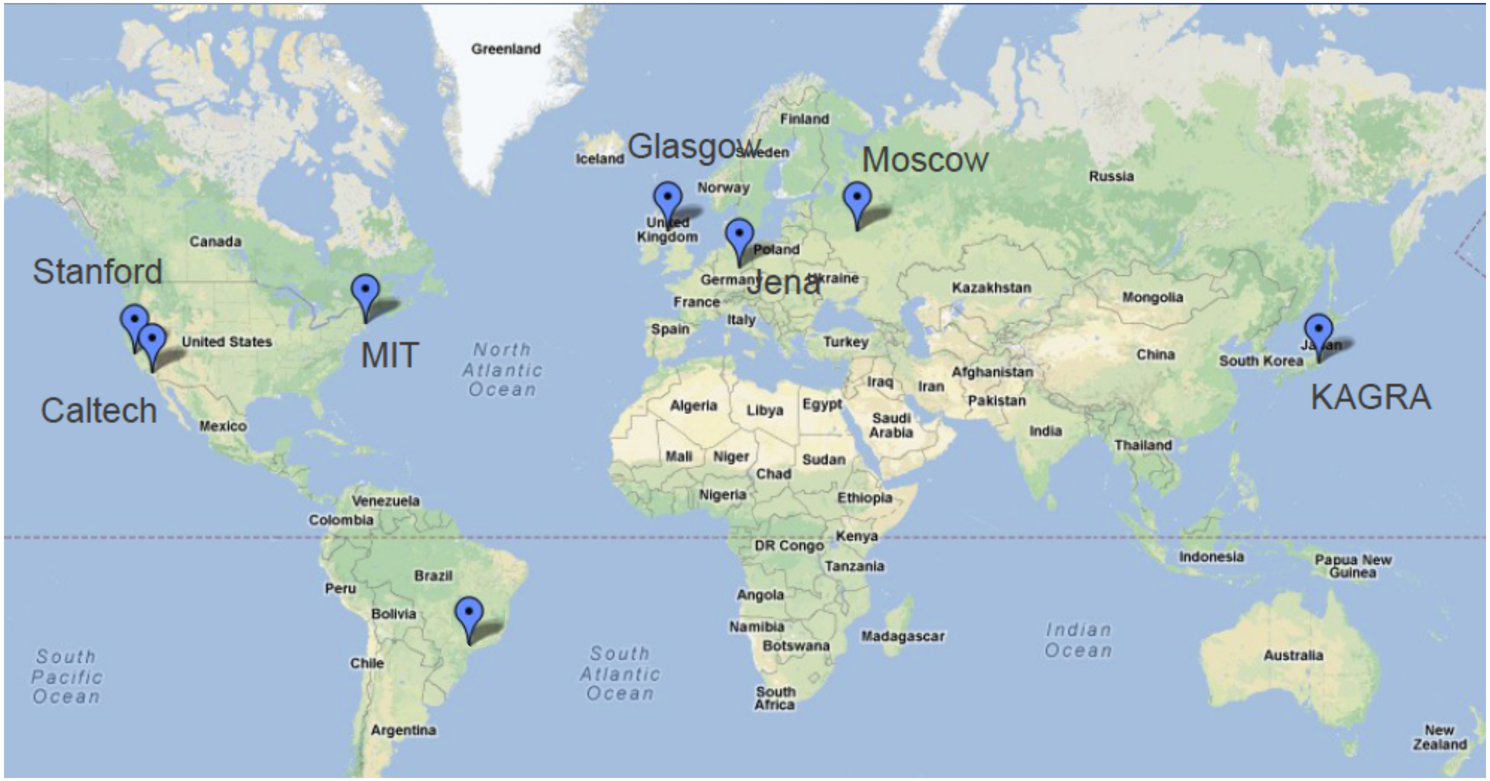
Predicted Advanced LIGO Sensitivity



Predicted Advanced LIGO Sensitivity



LIGO III cryo work distribution



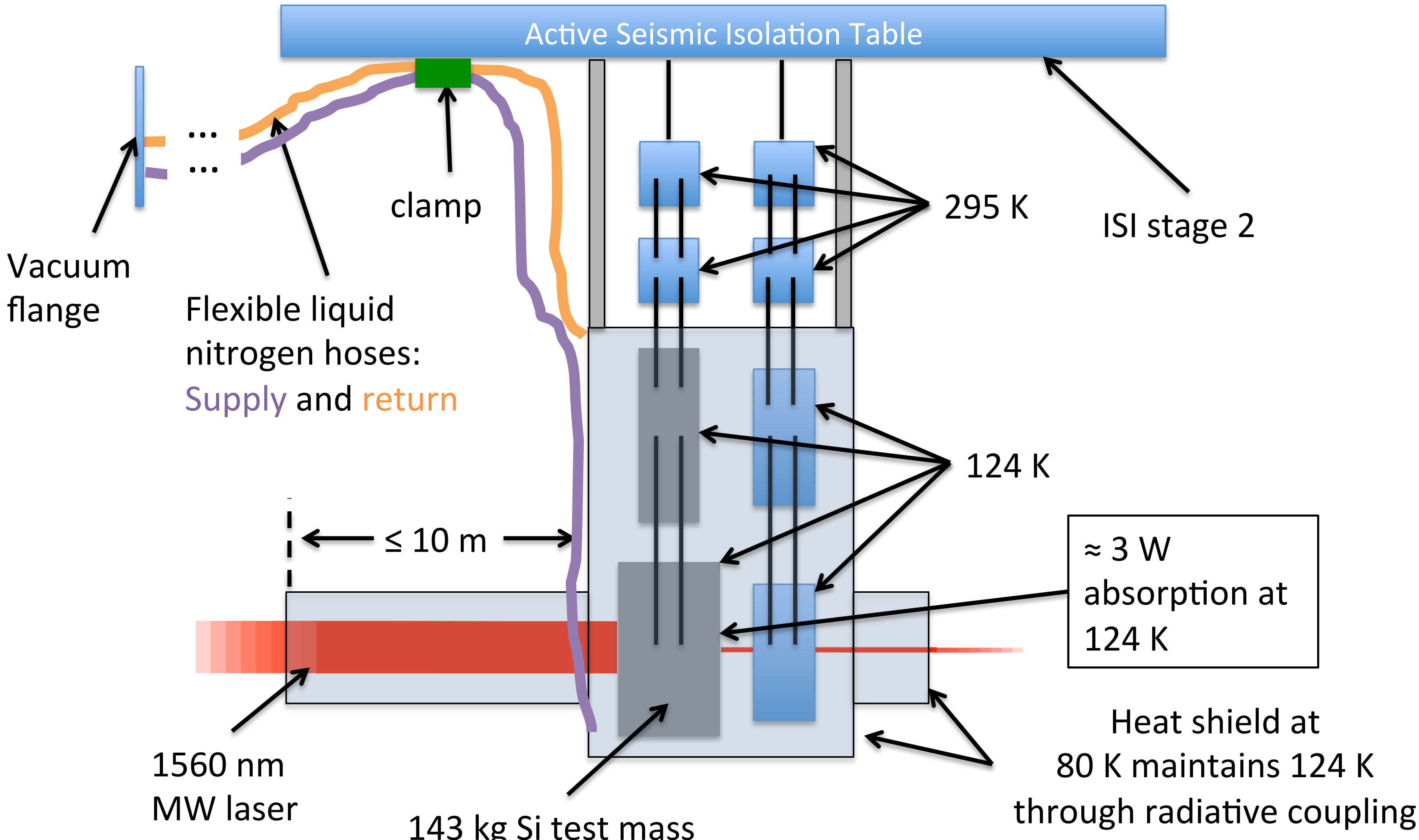
- Caltech - cryogenic reference cavities; direct thermal noise measurements
- Jena/Glasgow/Moscow - mechanical loss
- MIT – high emissivity coatings
- KAGRA – 20 K sapphire suspensions
- INPE Brazil – Cryogenic multi-nested pendulum
- Stanford – optical coatings (Riccardo Bassiri's talk); cryogenic technology

Courtesy of Nicolas Smith-Lefebvre

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)
  - **Get to 124 K in a timely manner** <- Stanford experiment
  - **Then maintain 124 K**
- Include a warm-up scheme (don't forget!)
- 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
- The same seismic isolation platforms (ISIs, HEPIs)
  - Limit the amount of extra weight on these plaforms
  - Leave the rest of the vacuum chamber warm

LIGO III Steady State Cooling



See also G1200246-v1

Initial Cool Down Cold Link – 2 Designs

<table>
<tr><th>Conductive cooling, low pressure N_2 gas</th><th>Pros and Cons</th></tr>
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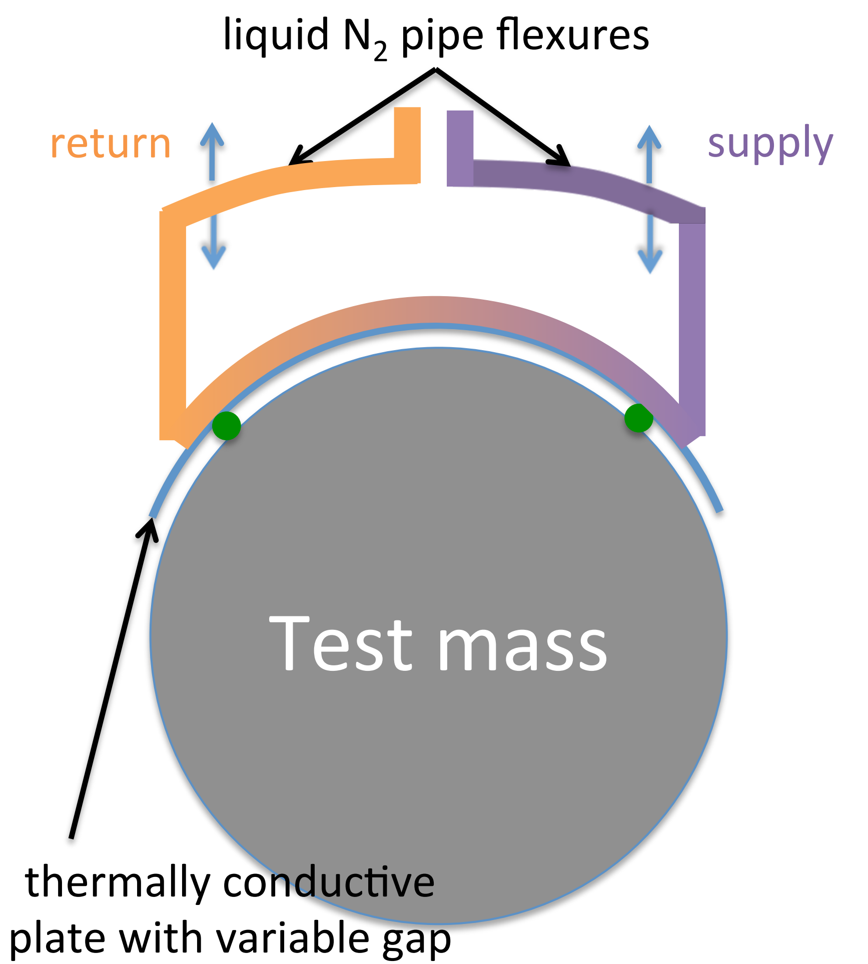

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Pros

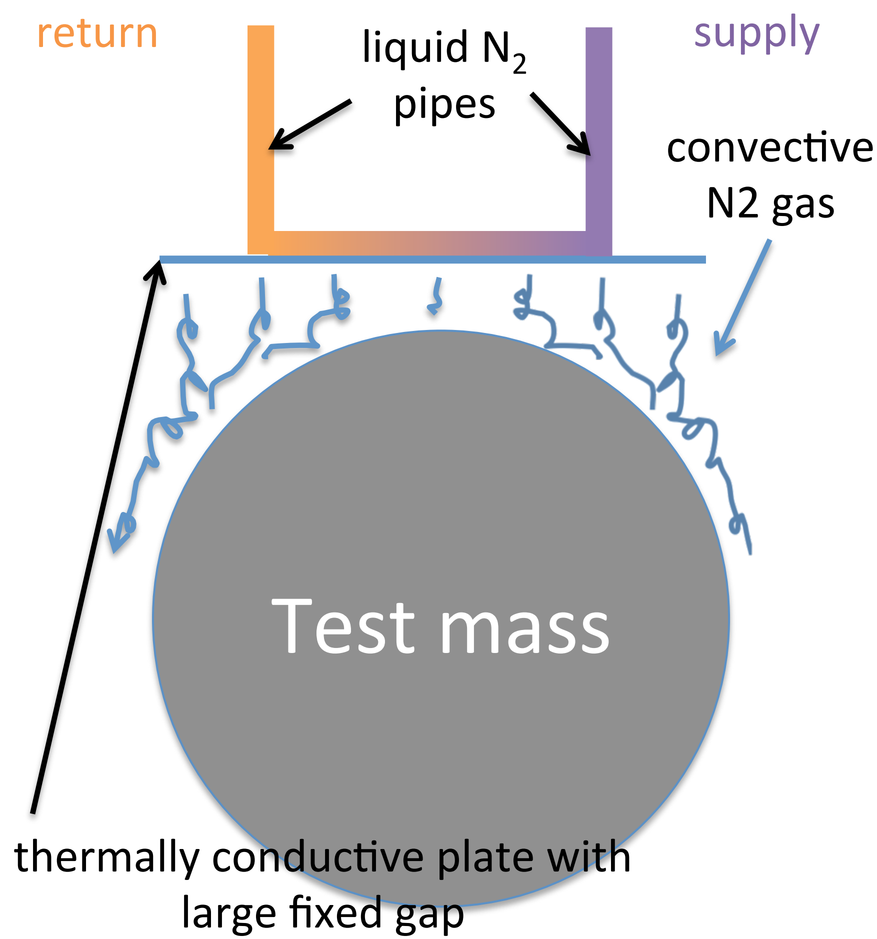
- Operates in partial vacuum.
- Low heat transfer between cold and warm parts of vacuum system.
- Fine temperature control – just back away when at desired temperature
- Versatility, design permits both conductive and convective cooling.

Cons

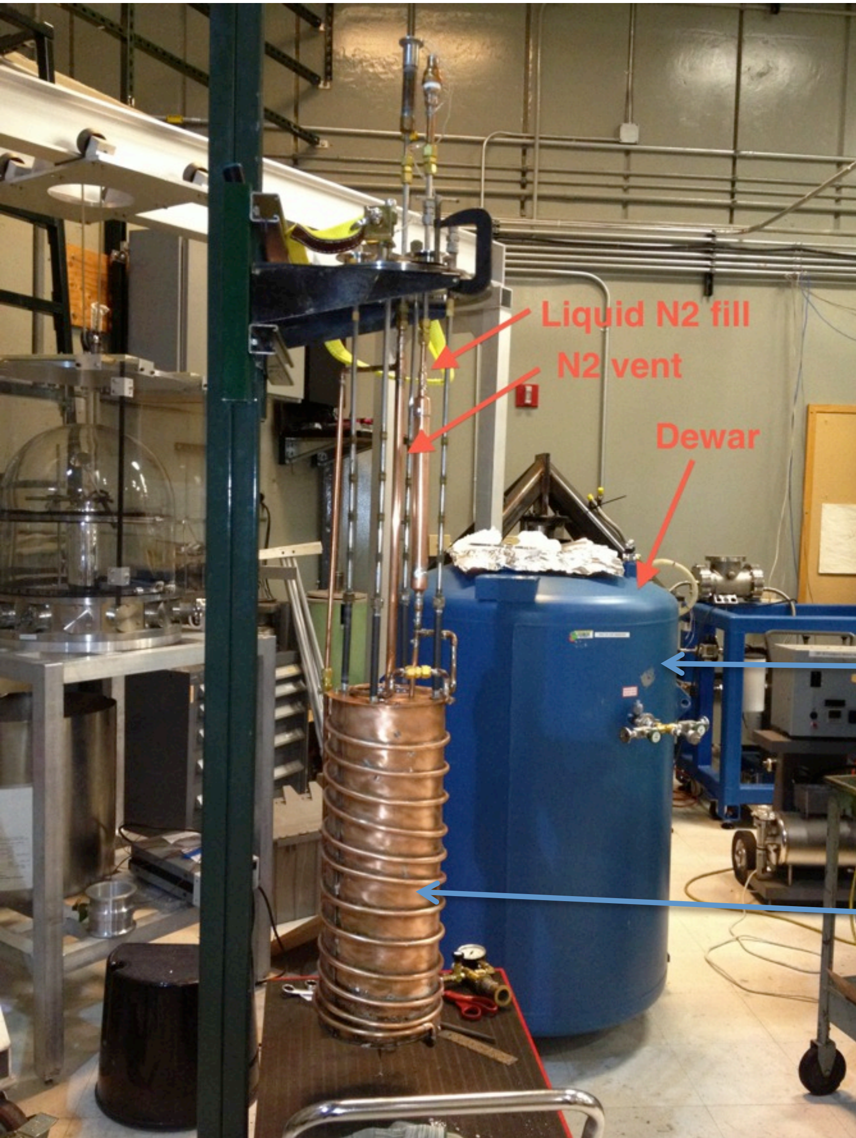
- Requires moving parts:
  - flexible pipes
  - actuators
- Physically contacts barrel of test mass

</td></tr>
</table>

Initial Cool Down Cold Link – 2 Designs

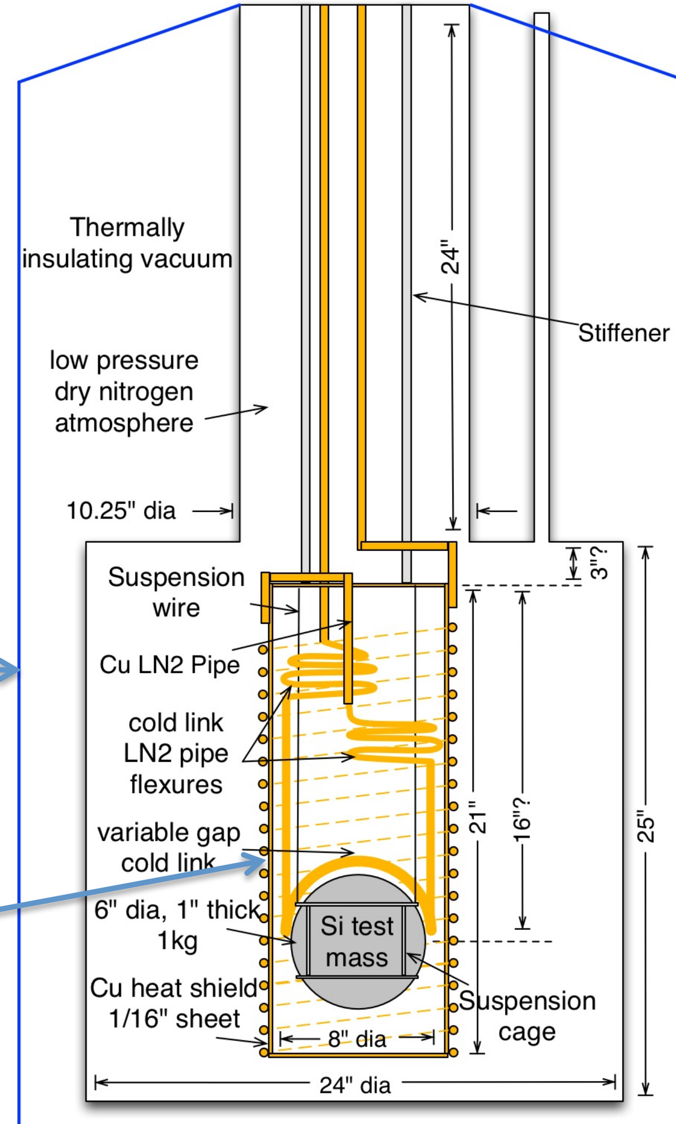
Pros and Cons	Convective cooling, up to 1 atm N_2 gas
Pros • No moving parts or actuators • No contact with test mass • Faster cooling than conduction **Cons** • Convection between cold and warm parts of vacuum system • No fine temperature control – must return to vacuum to 'turn off' cold link. • Does not operate under vacuum	

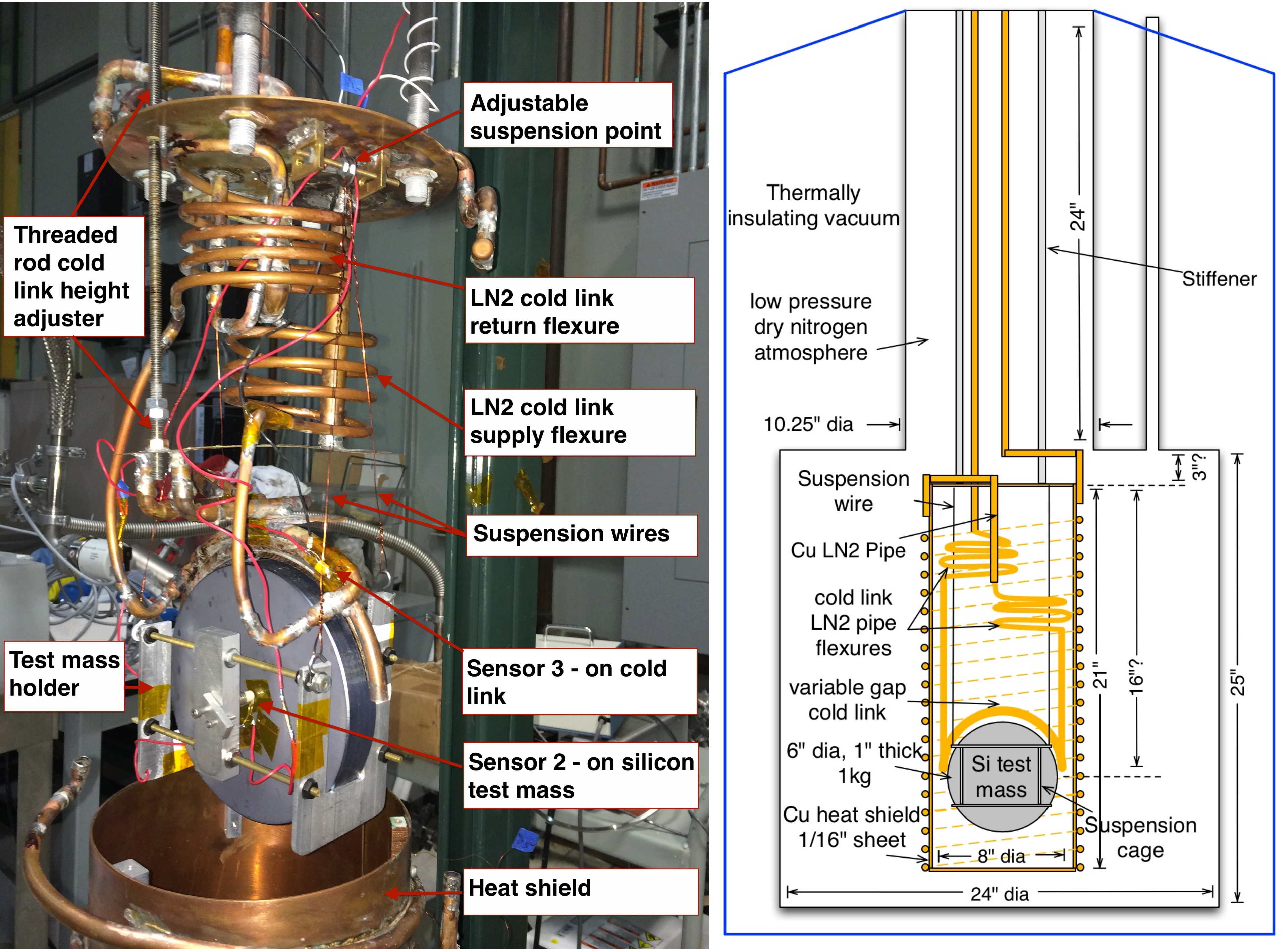
Experimental Setup



Test dewar

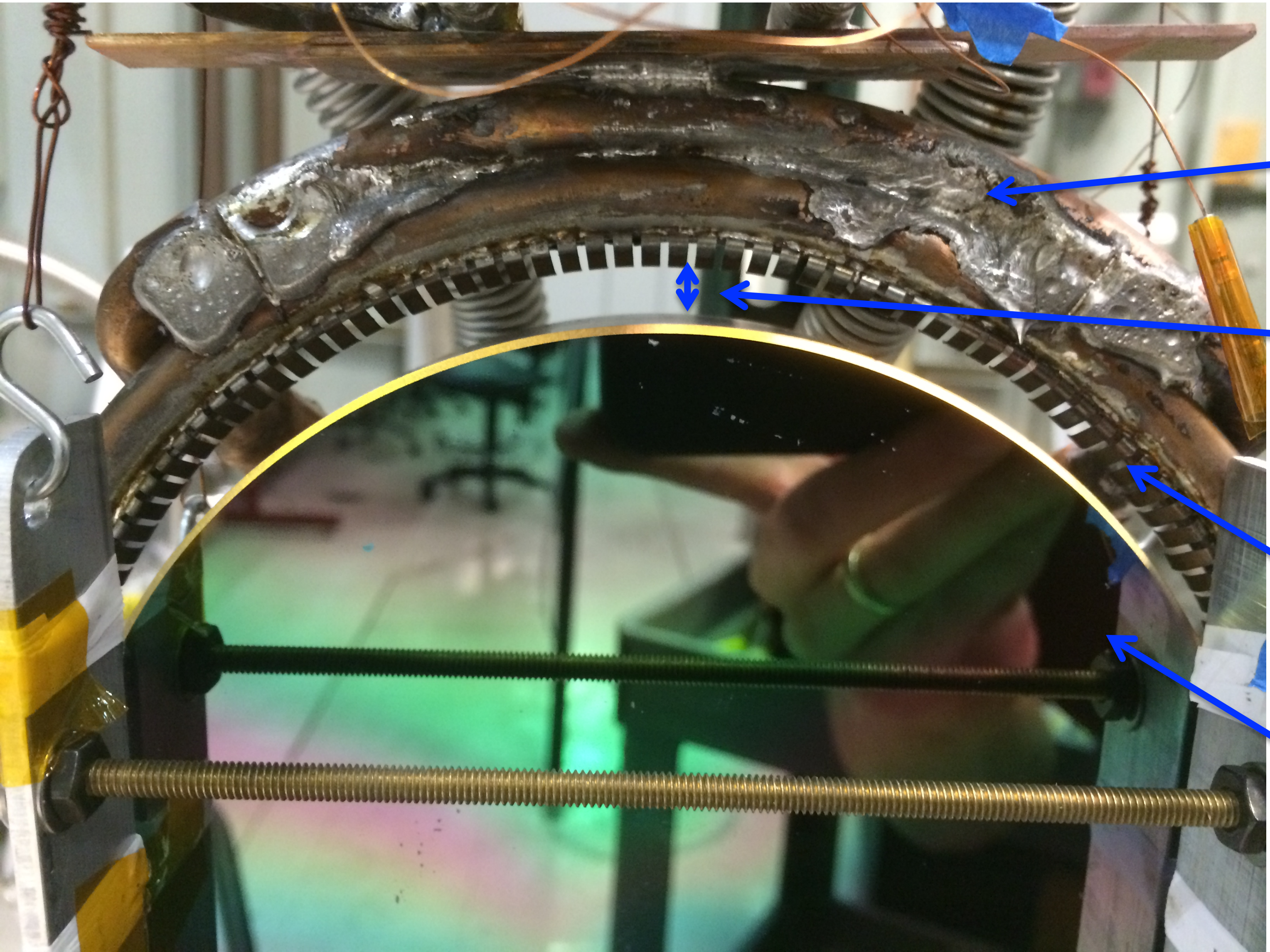
Heat shield



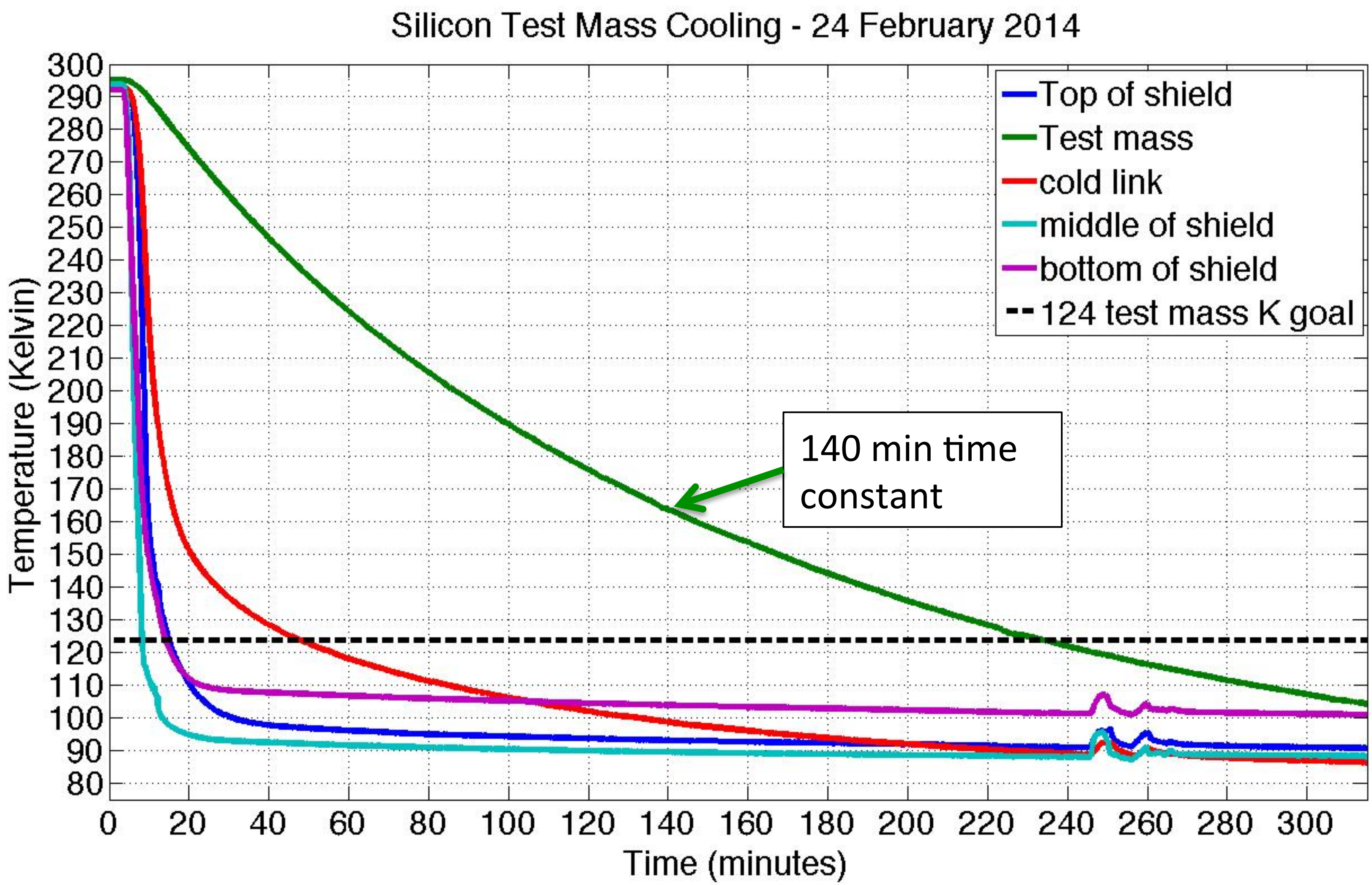


Adjustable suspension point
Threaded rod cold link height adjuster
LN2 cold link return flexure
LN2 cold link supply flexure
Suspension wires
Test mass holder
Sensor 3 - on cold link
Sensor 2 - on silicon test mass
Heat shield
Thermally insulating vacuum
24"
Stiffener
low pressure dry nitrogen atmosphere
10.25" dia
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
21"
16"?
25"
Suspension cage
8" dia
24" dia

Close up of cold link

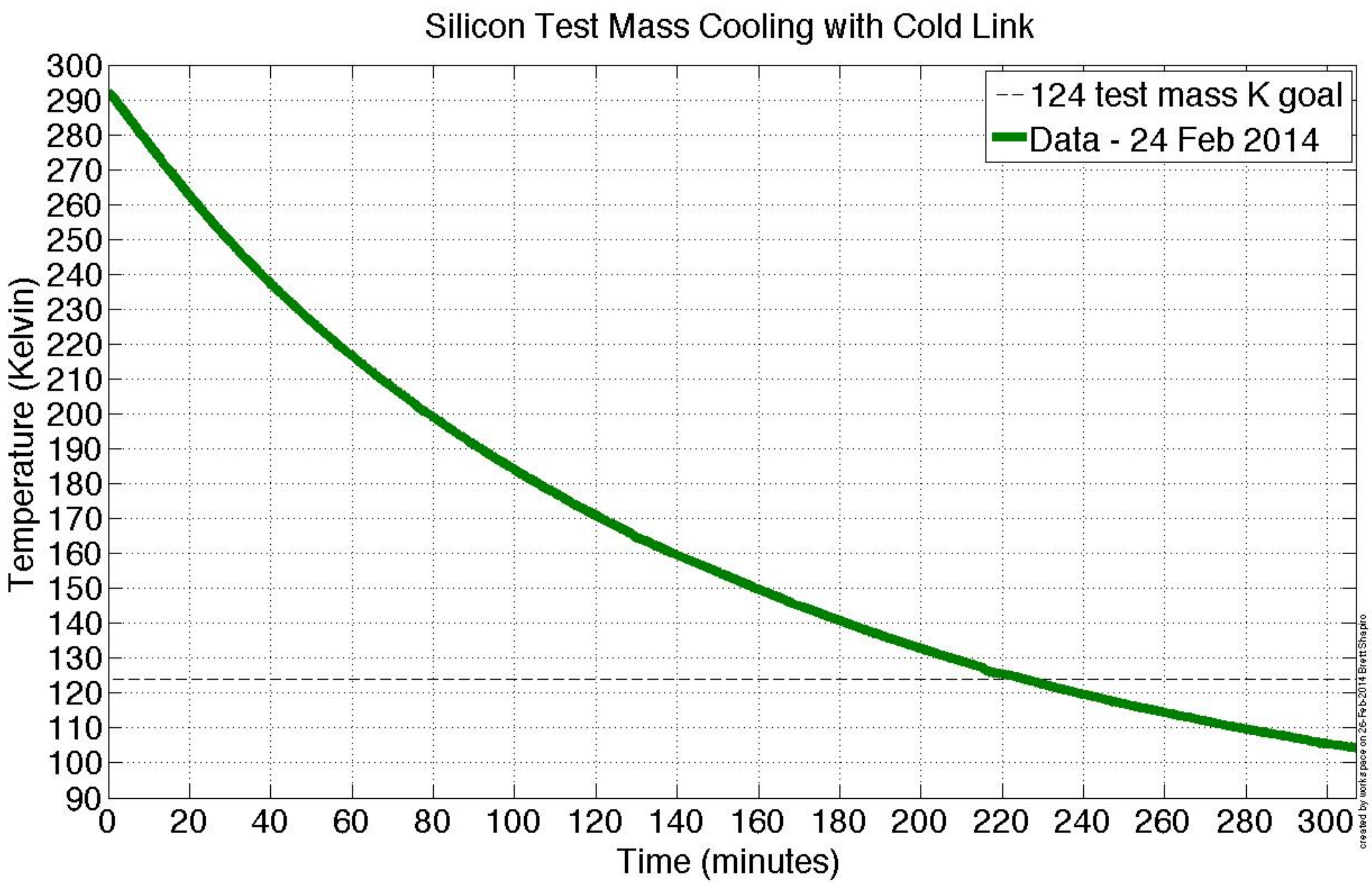


Measurement – cold link engaged

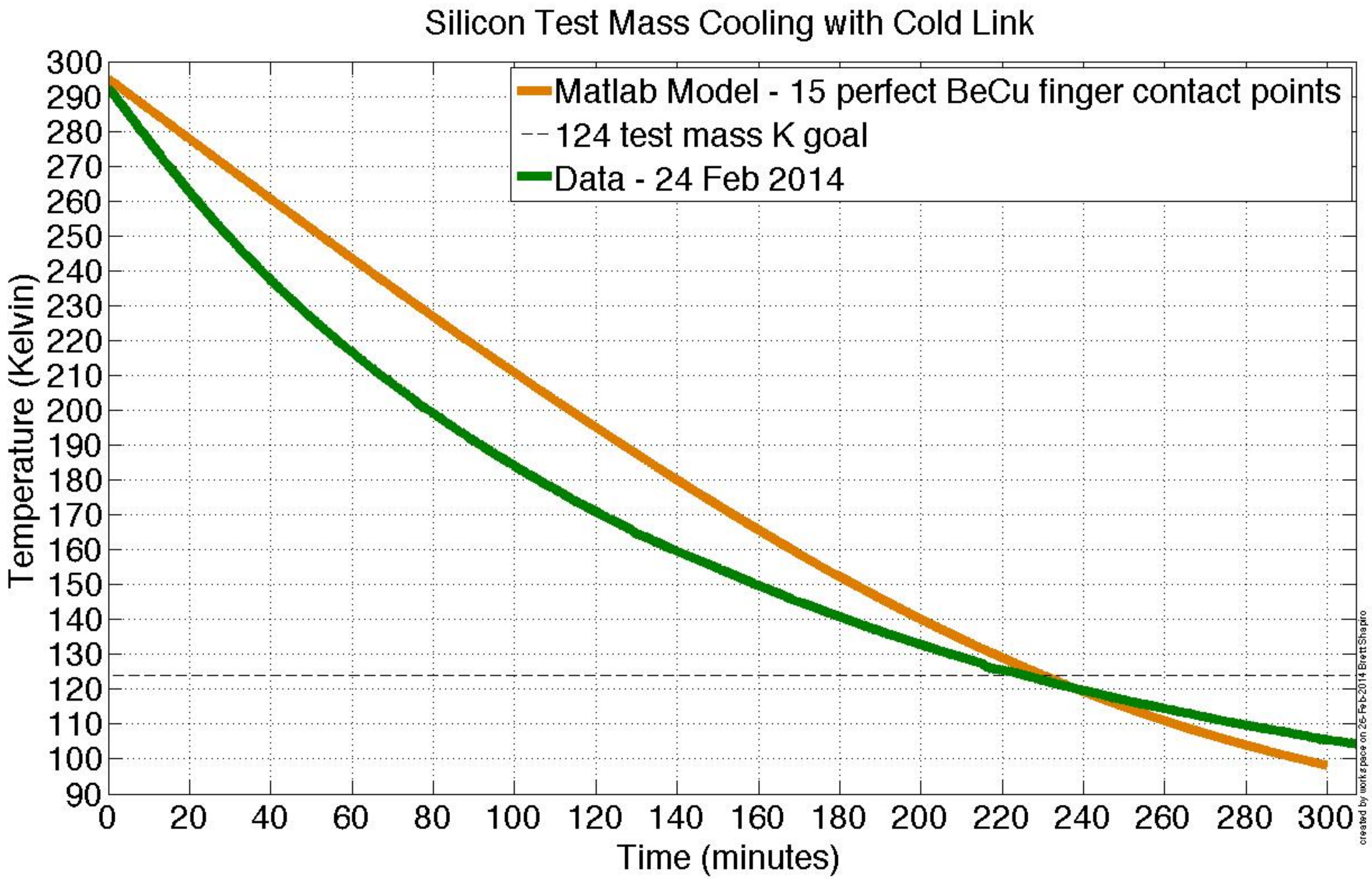


LIGO

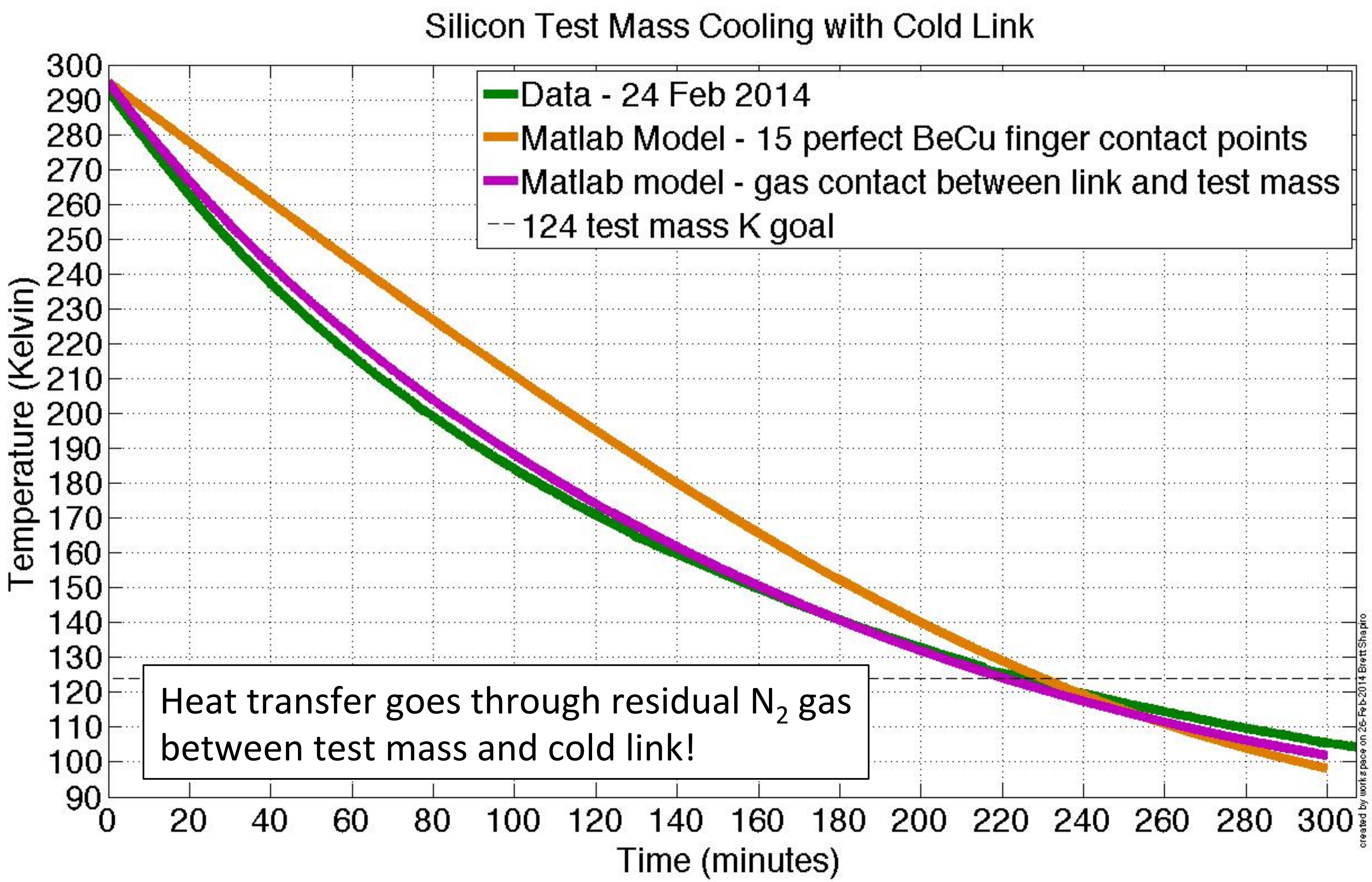
Test mass temperature modeling



Test mass temperature modeling

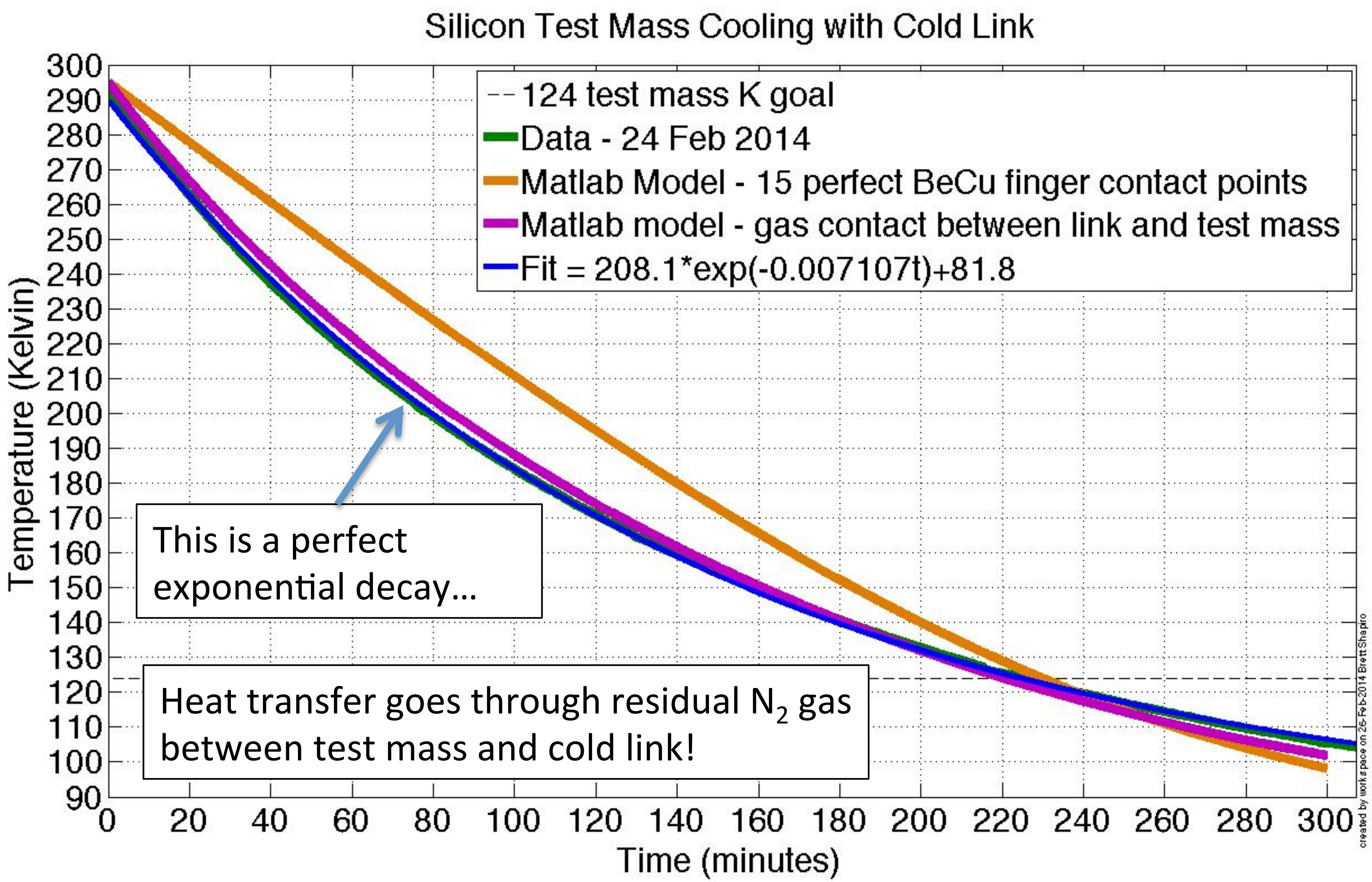


Test mass temperature modeling



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

Test mass temperature modeling



Exponential Temperature Decay

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

$$K_{CL} = \text{thermal conductance of cold link}$$
$$C_{Si} = \text{heat capacity of silicon}$$

- 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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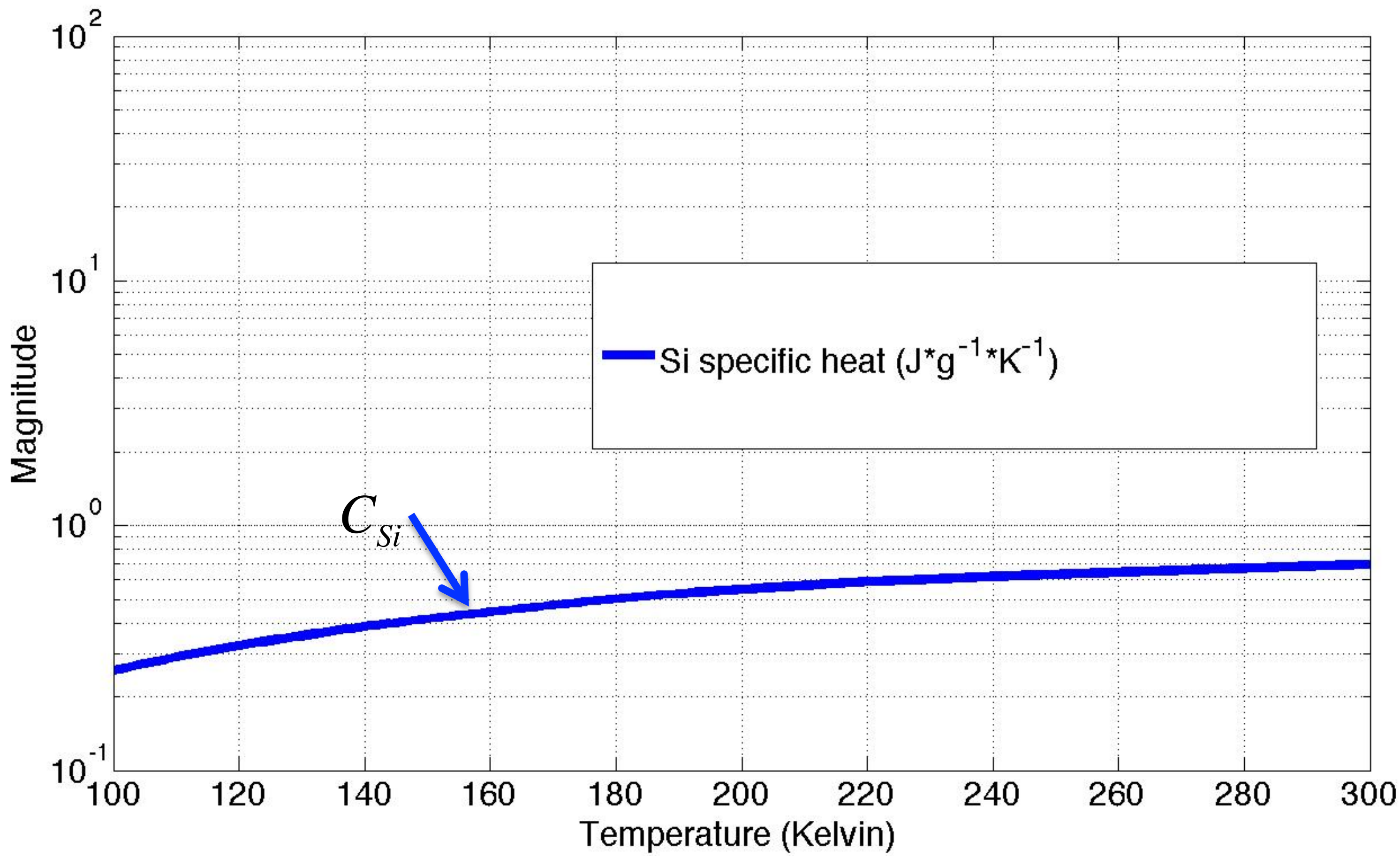

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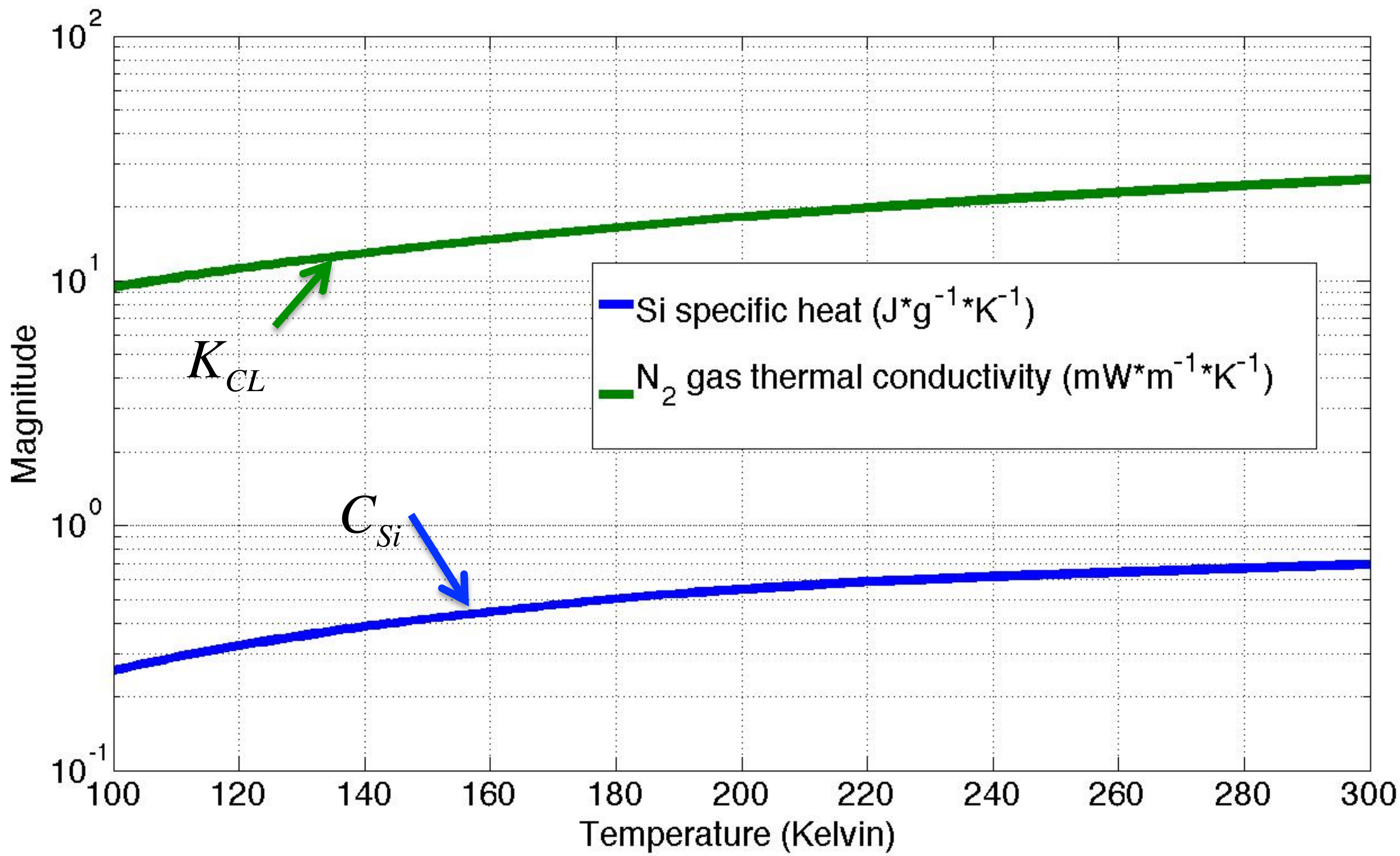

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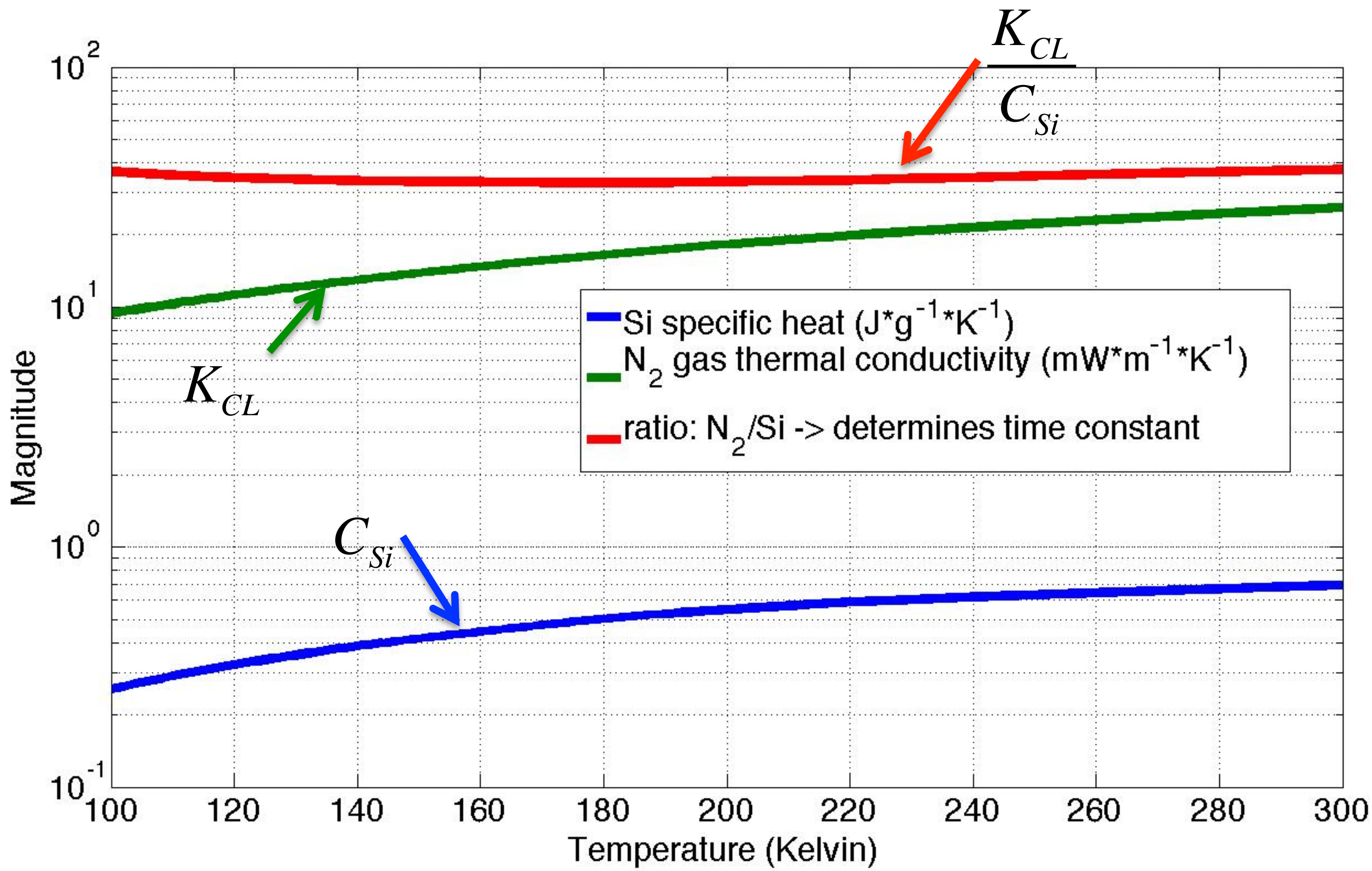
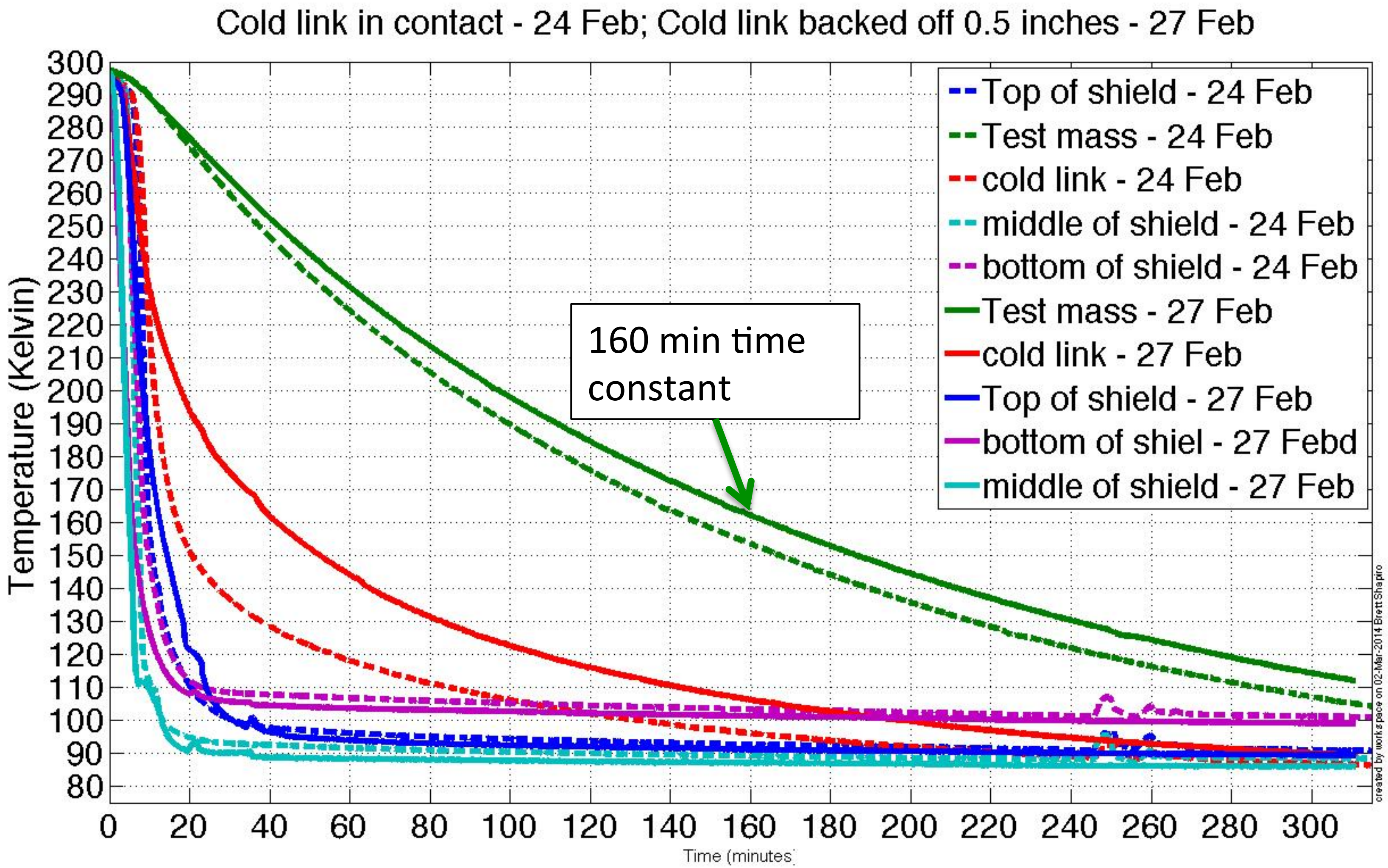
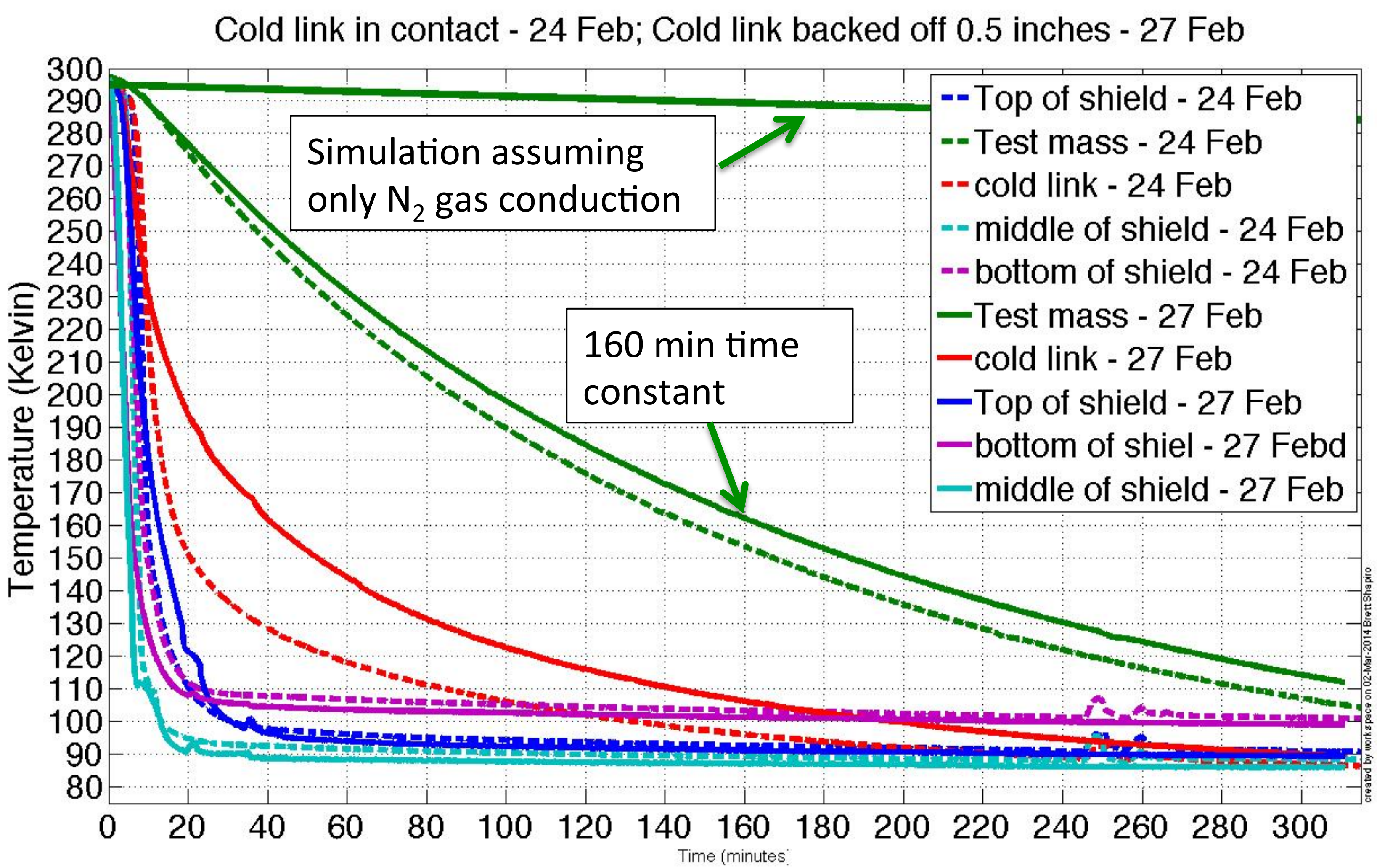


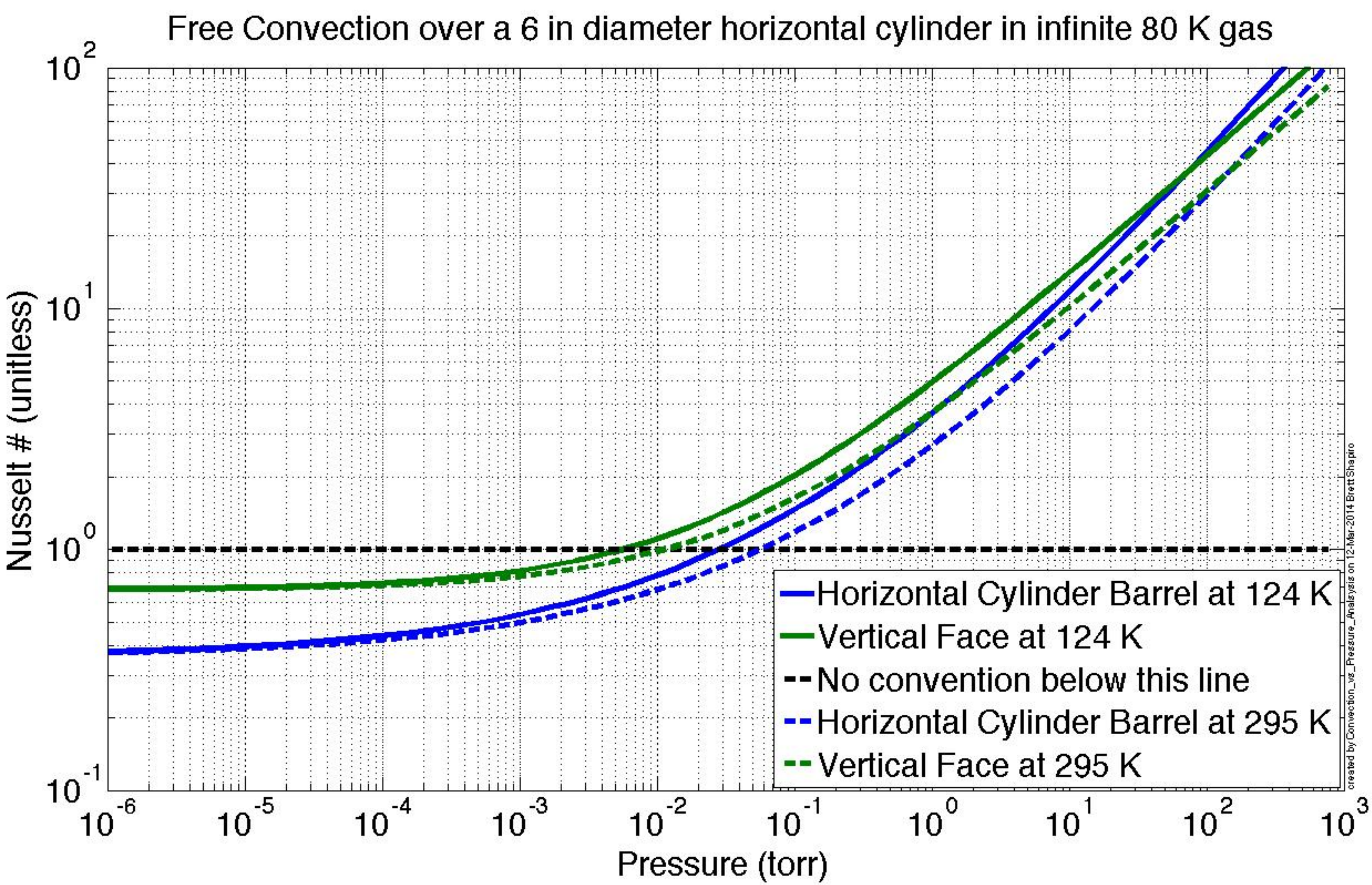
Measurement – cold link disengaged



Measurement – cold link disengaged

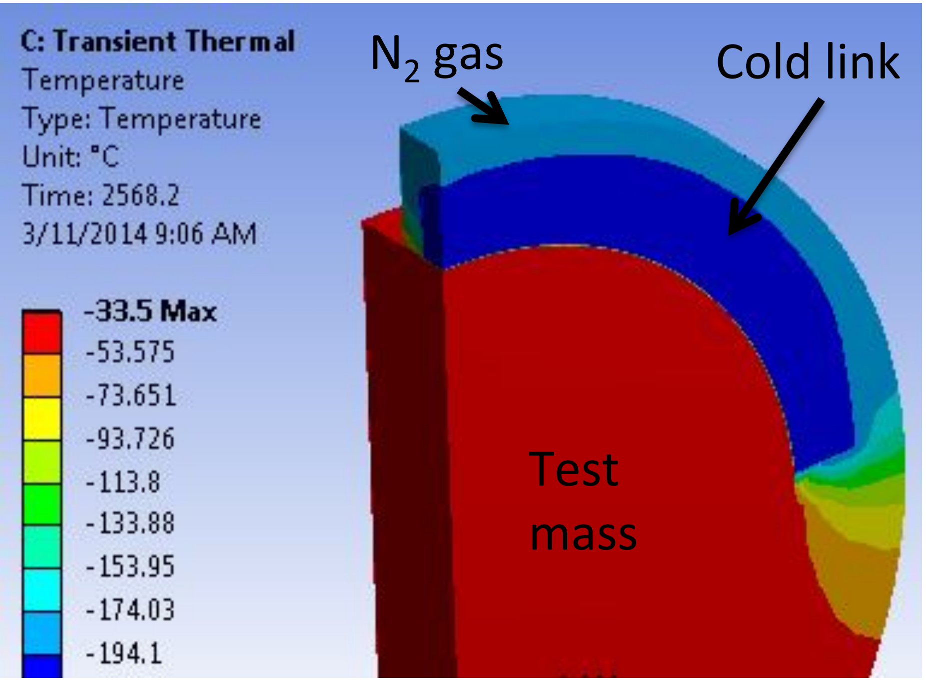


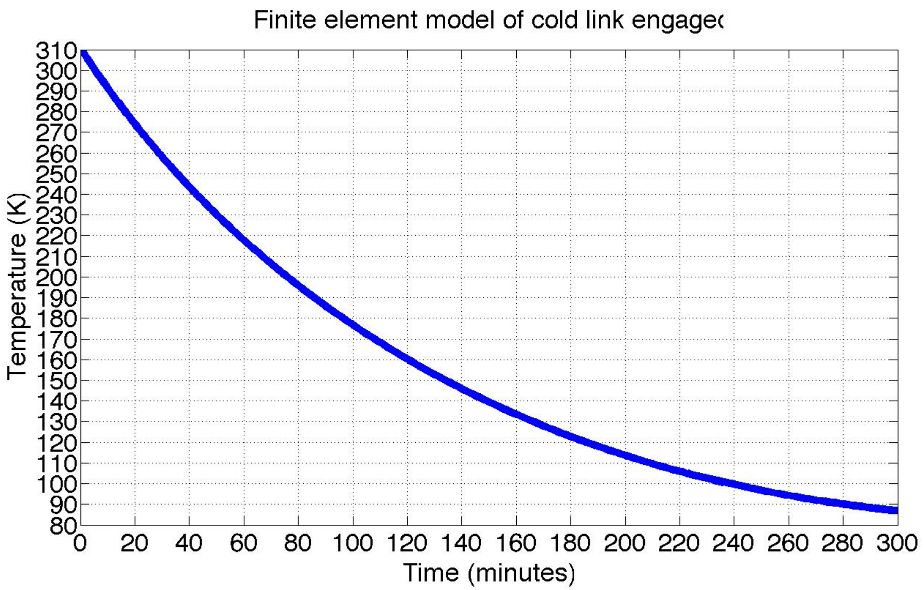
Conductive vs Convective Regimes



Finite Element Modeling

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



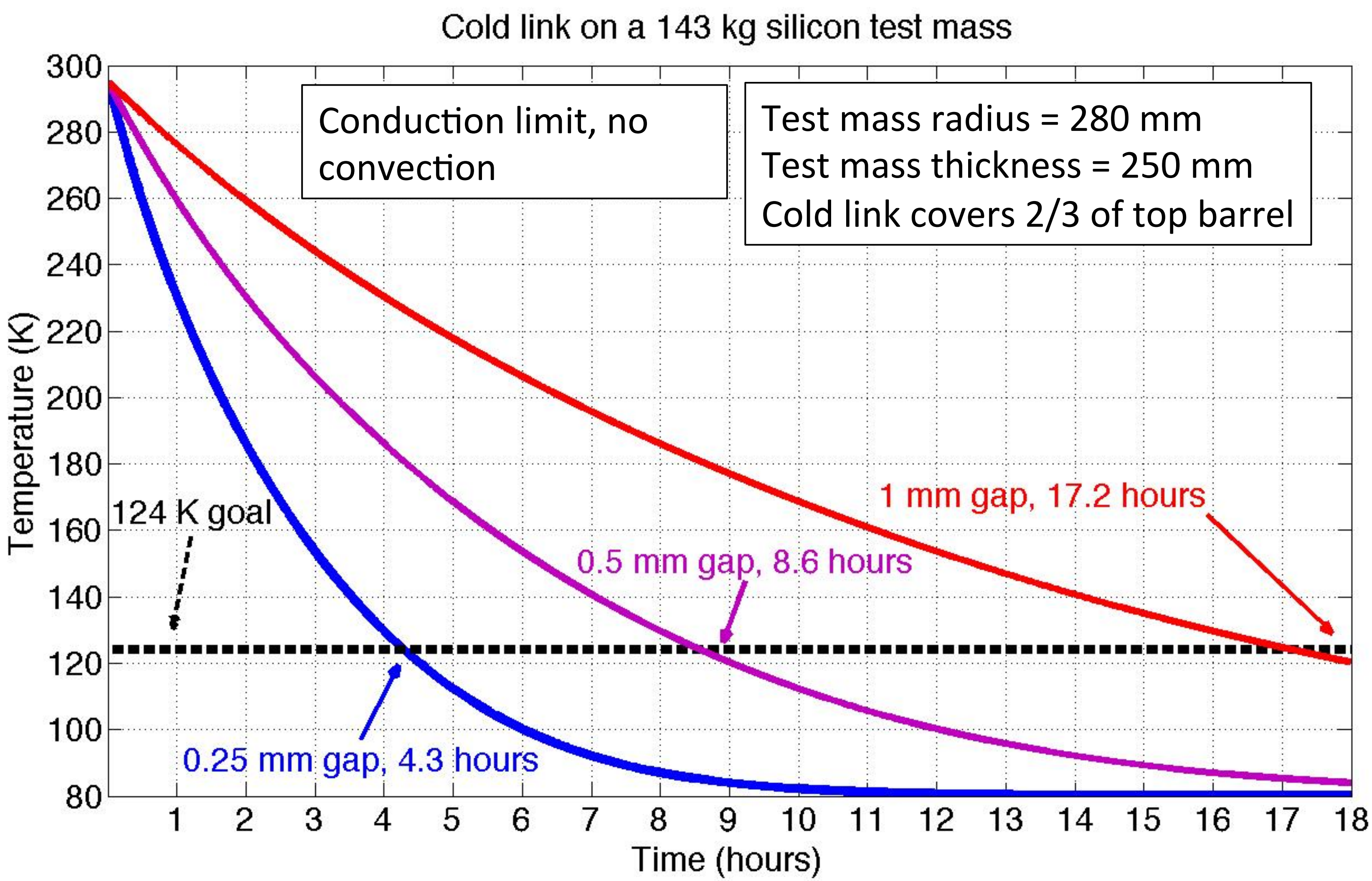


≈ 43 min into cool down

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

Images courtesy of Tim MacDonald

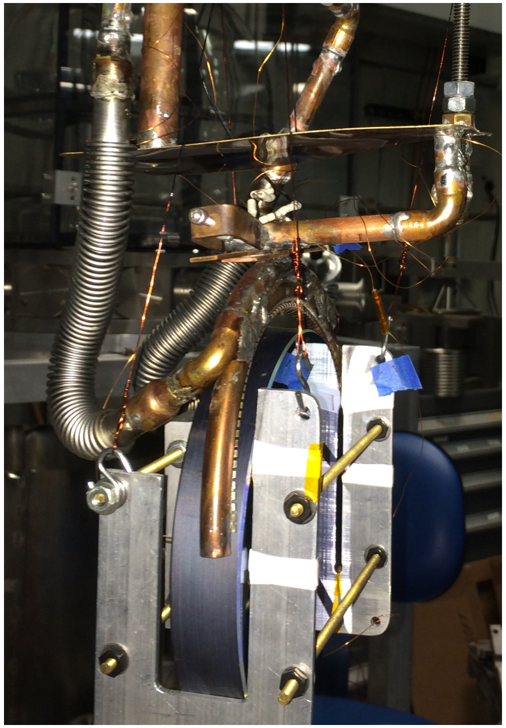
Cold link on a LIGO III test mass

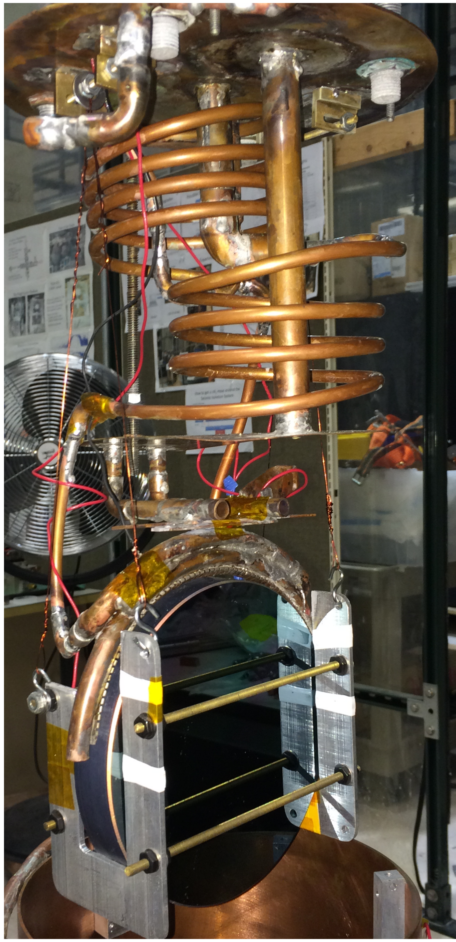


Experimentation lessons learned

- 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

Flexible cold link evolution





LIGO

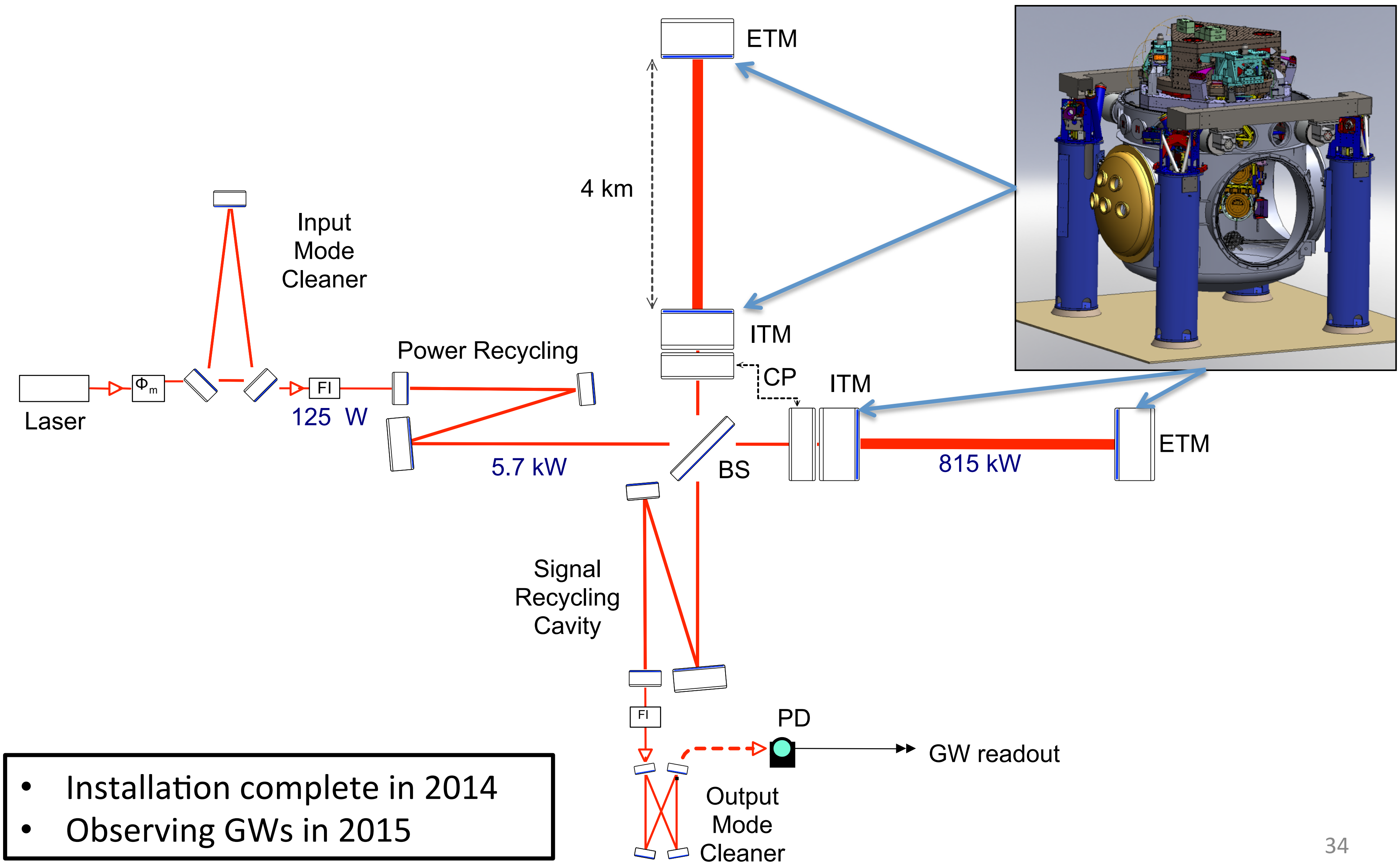
Future work

- Get bigger pump to reduce pressure
- Better computing for FEM of convection
- Next generation experiment on the prototype aLIGO in-vacuum seismic isolation table.
  - More realistic LIGO setup
  - Measure temperature drifts on LIGO hardware
  - Measure seismic noise of nitrogen delivery
  - Use welded joints to prevent leaks.

LVC STANFORD
August 25-29 2014

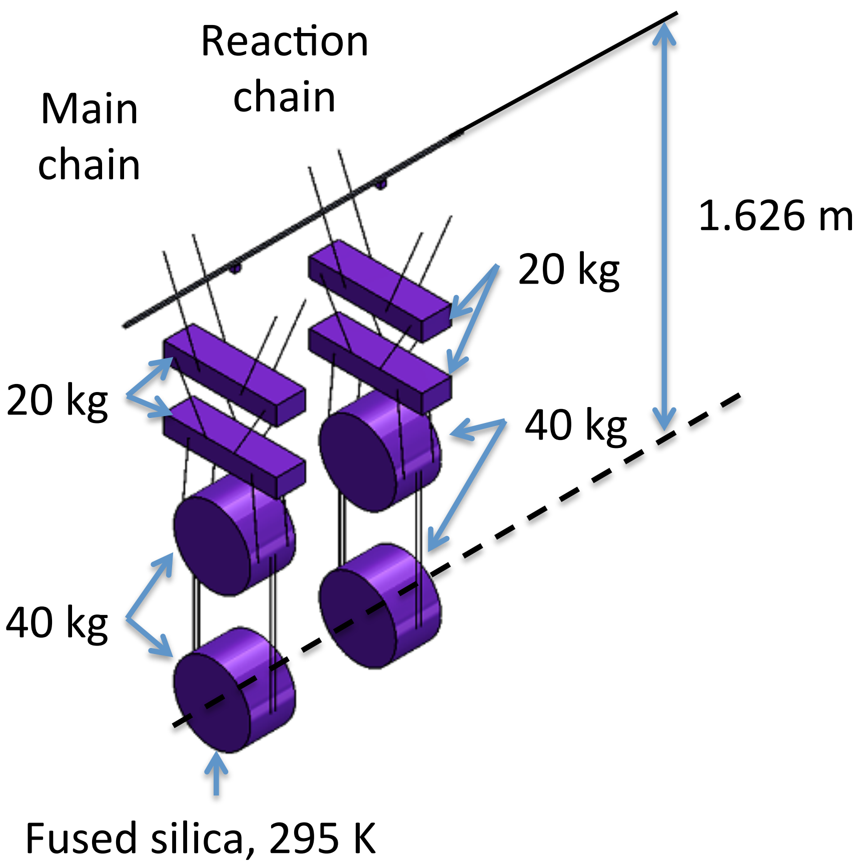
Backups

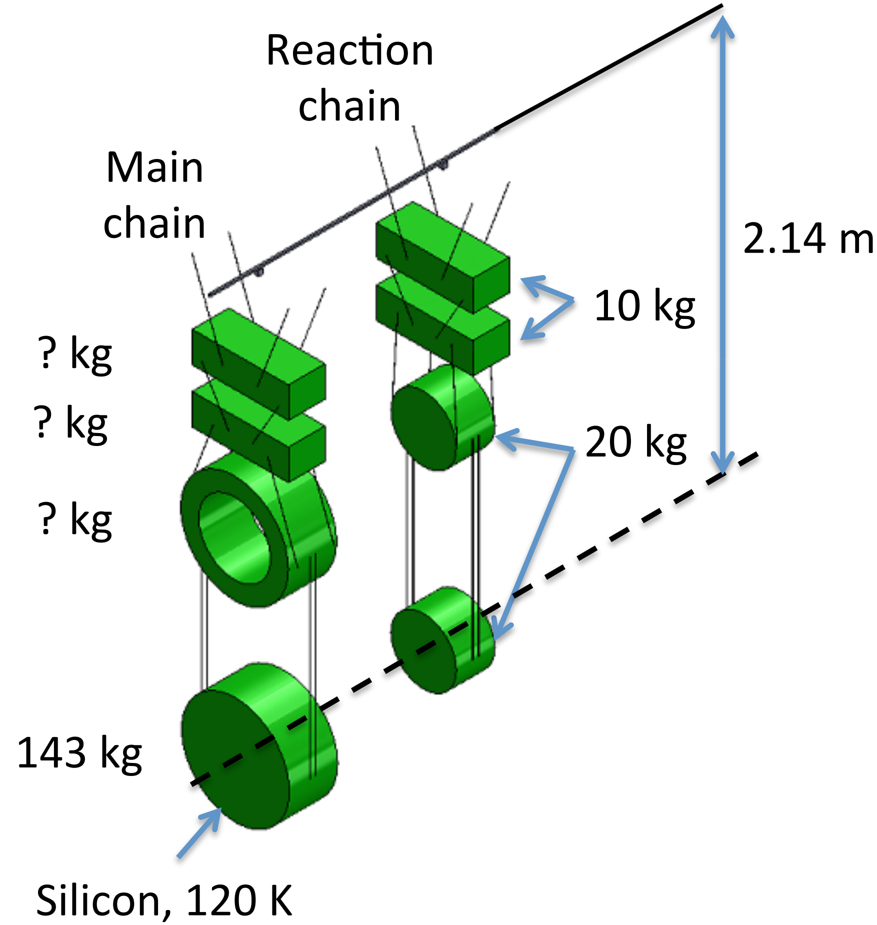
Advanced LIGO Layout



- Installation complete in 2014
- Observing GWs in 2015

Possible LIGO III Mechanical Upgrades

Advanced LIGO quad pendulum	Preliminary LIGO III quad pendulum




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

3 Quad Conceptual Designs

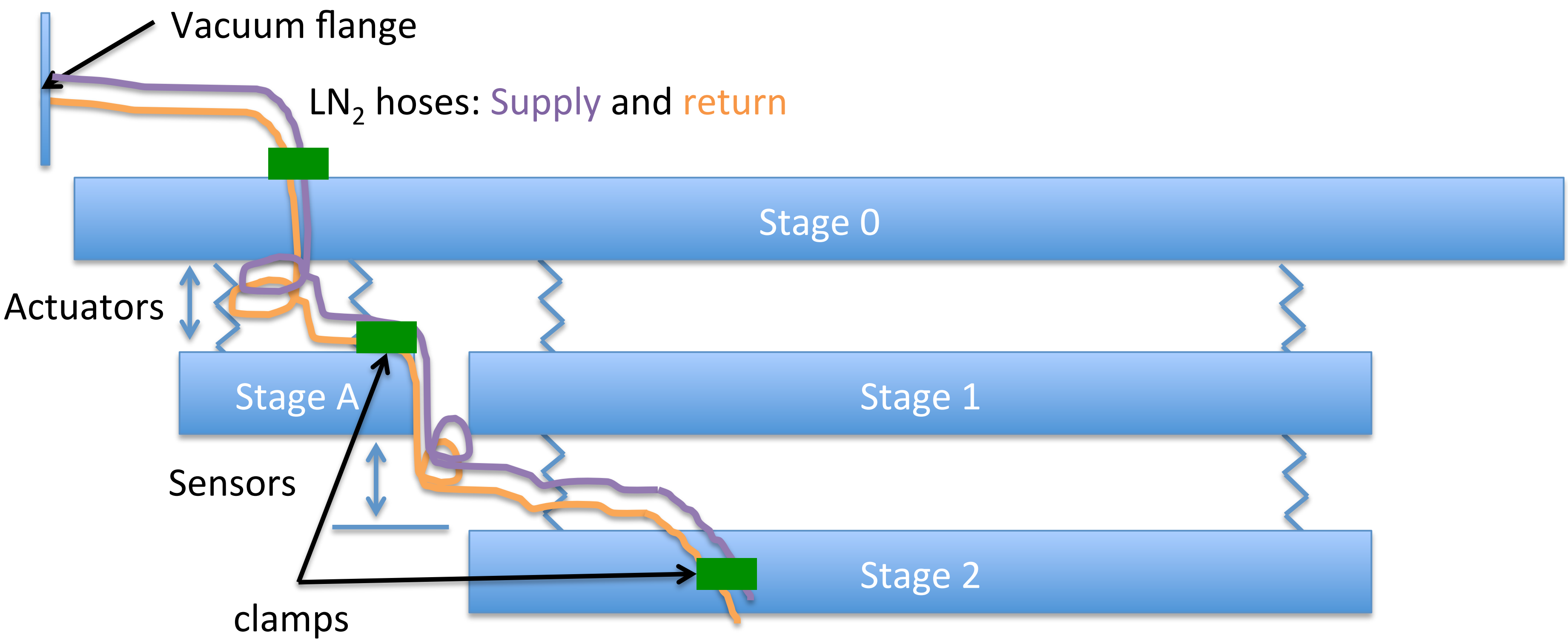
T1300786

Higher payload | **Lighter Test mass** | **Ideal masses with PUM springs**

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

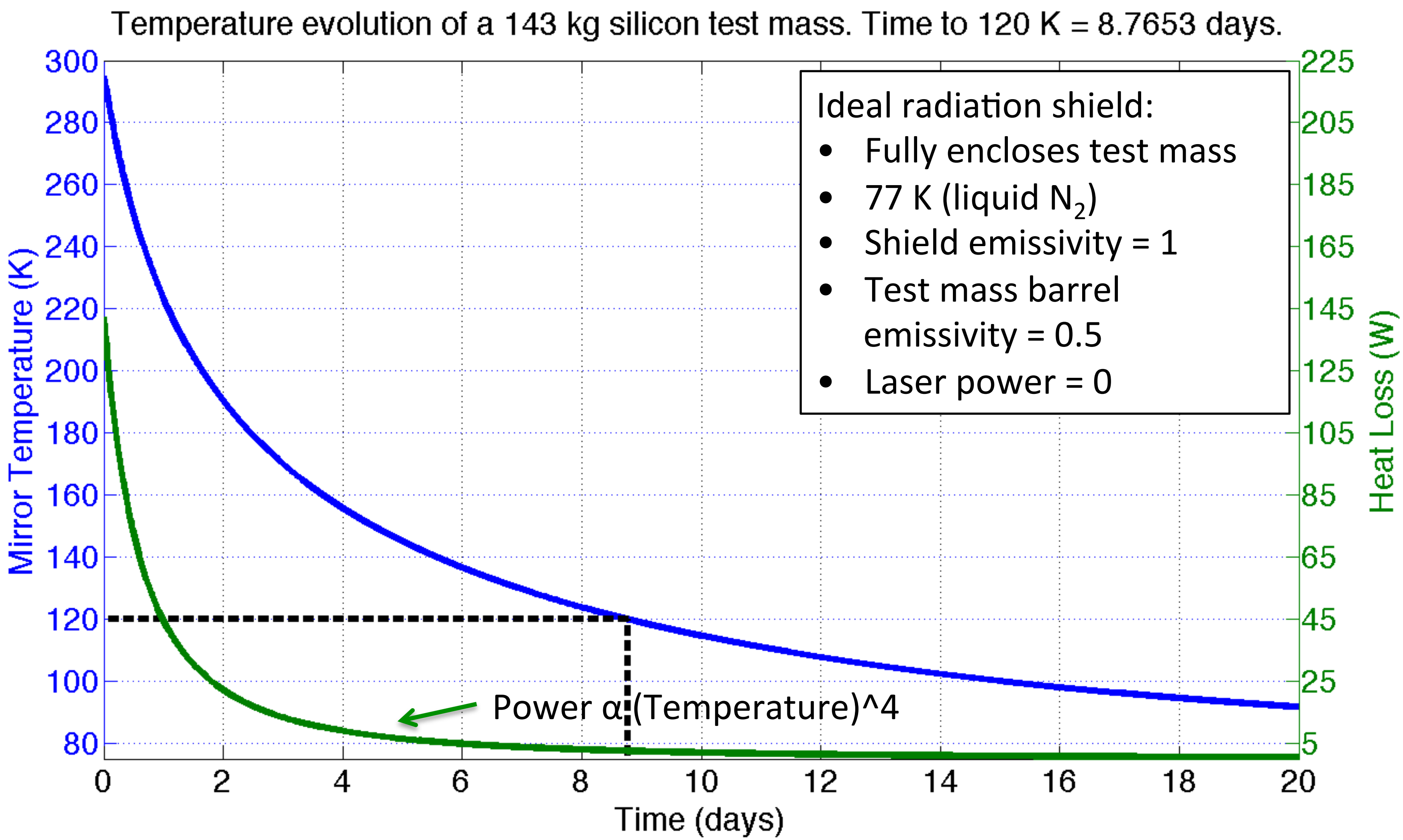
Parameters	Increased P	Decreased m_4	Penultimate Springs
P, Payload (kg)	301.9	270.0	270.0
m_1 (kg)	46.79	41.93	51.55
m_2 (kg)	39.54	35.42	41.71
m_3 (kg)	72.57	64.86	33.74
m_4 (kg)	143.0	127.8	143.0
L_1 (m)	0.372	0.372	0.535
L_2 (m)	0.372	0.372	0.535
L_3 (m)	0.372	0.372	0.535
L_4 (m)	1.025	1.025	0.535
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

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



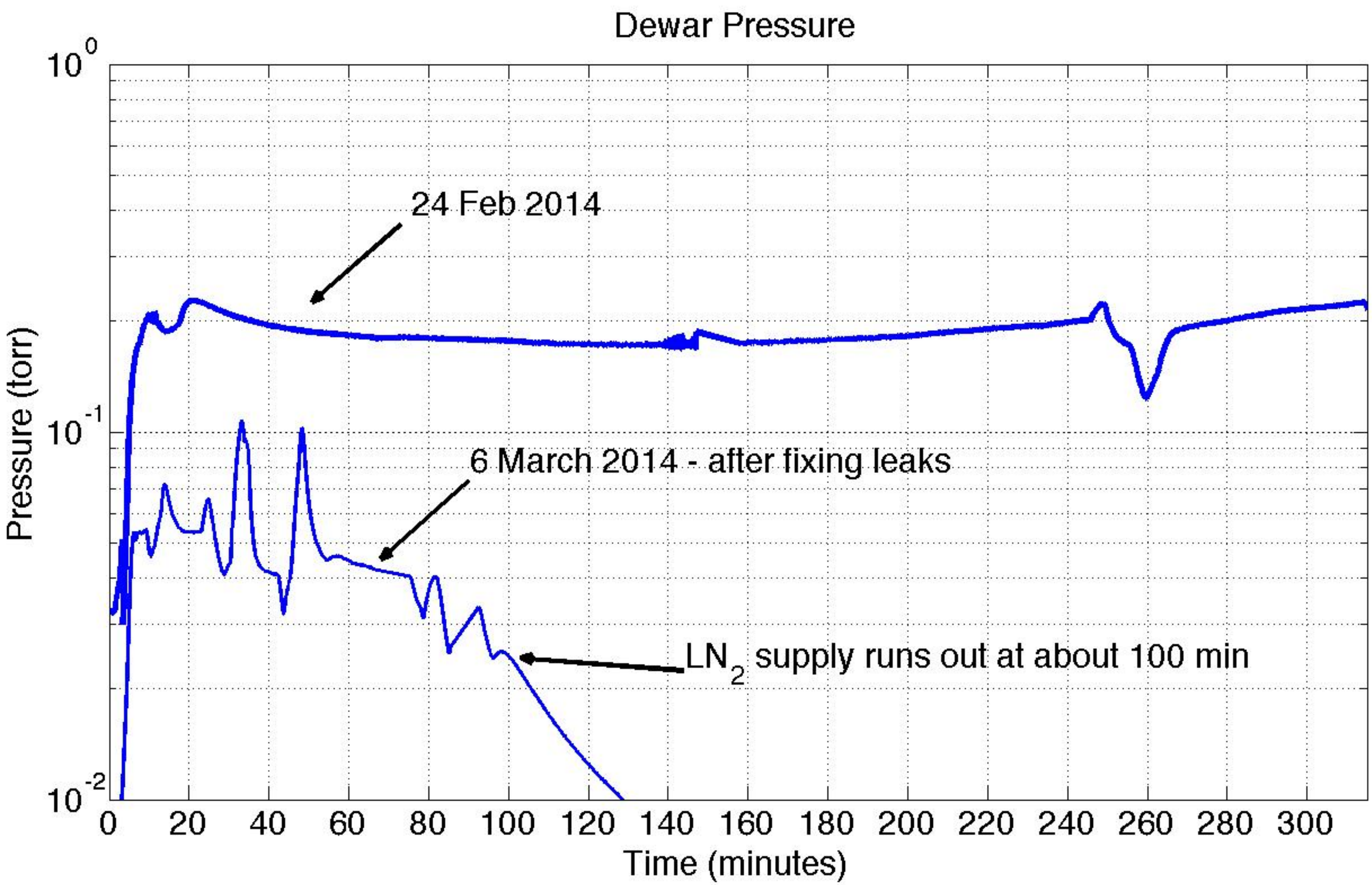
A Lot of Heat to Remove

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

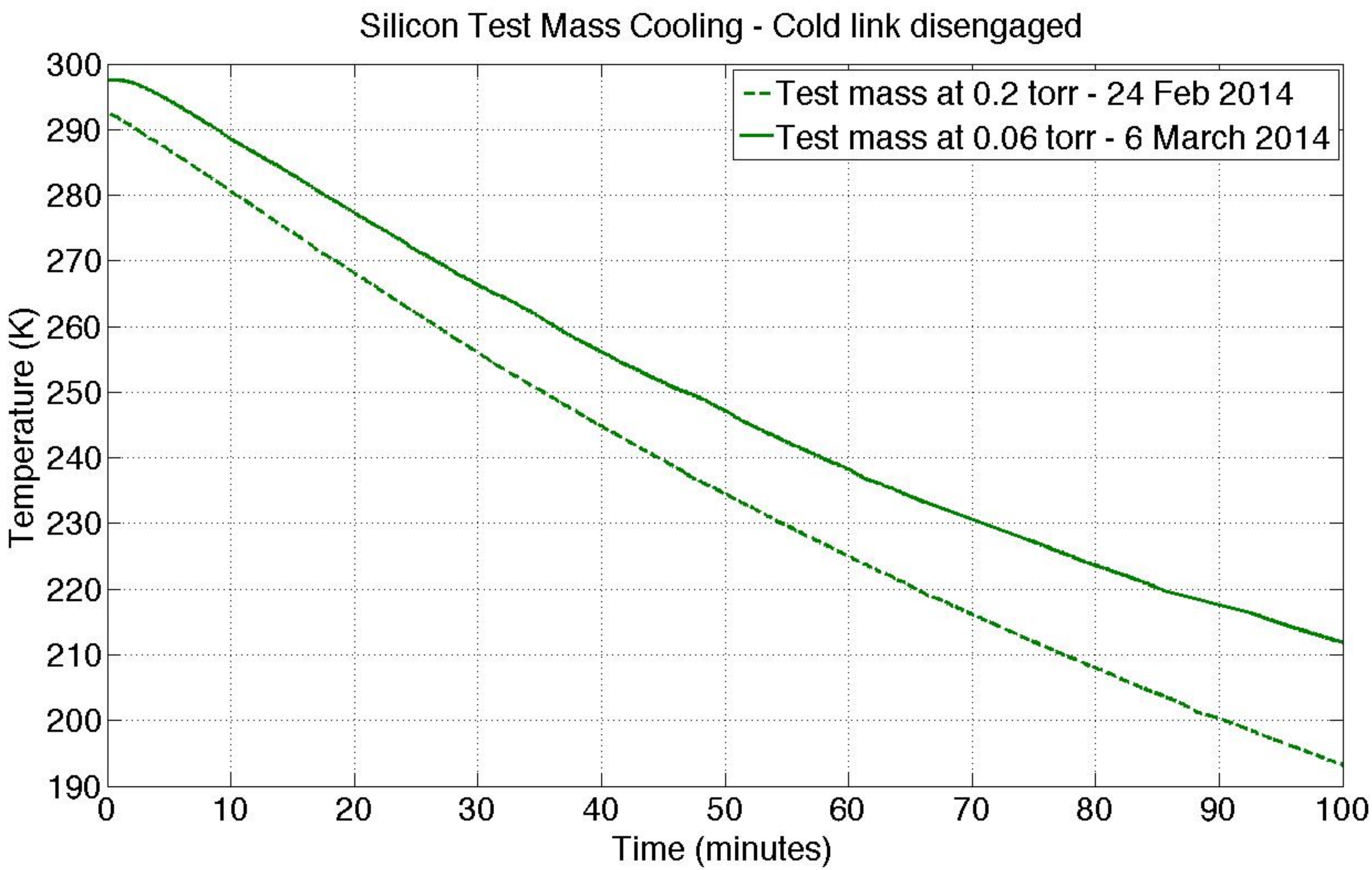
2.7 days to 120 K (295 K) at a constant 60 W

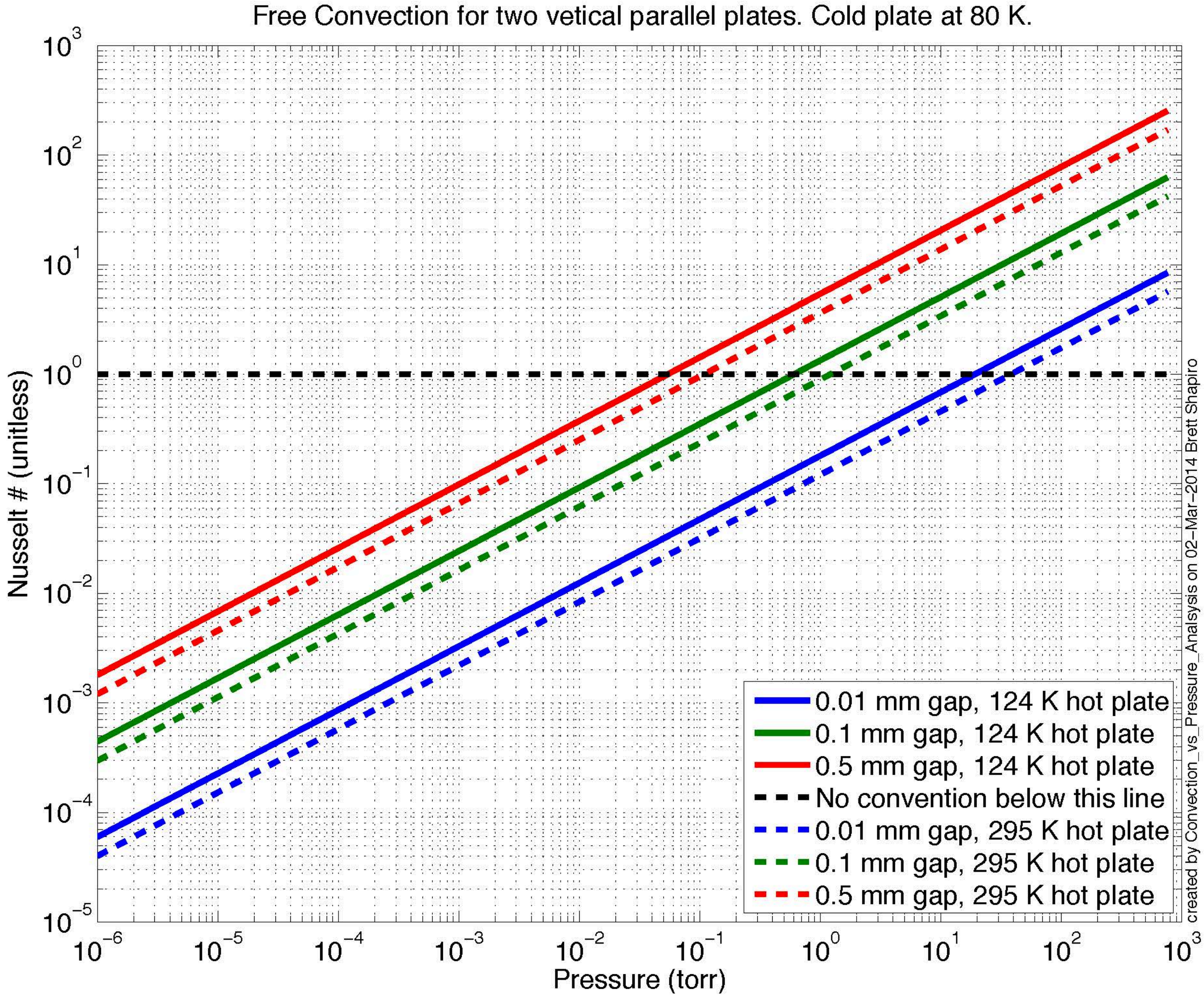
Maybe there is another way to cool the test mass quickly

Dewar pressure during measurements



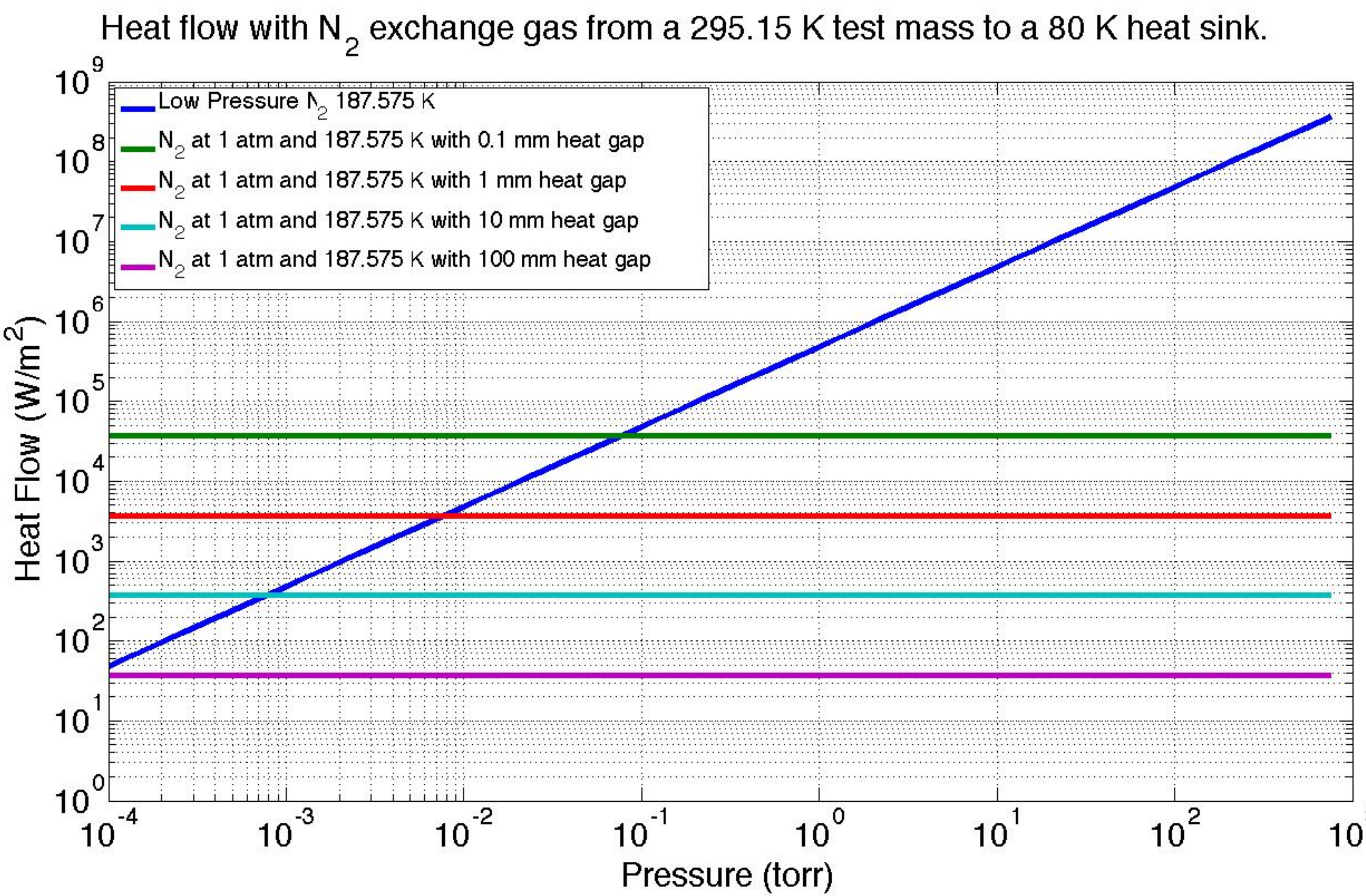
Effect of pressure on test mass temp



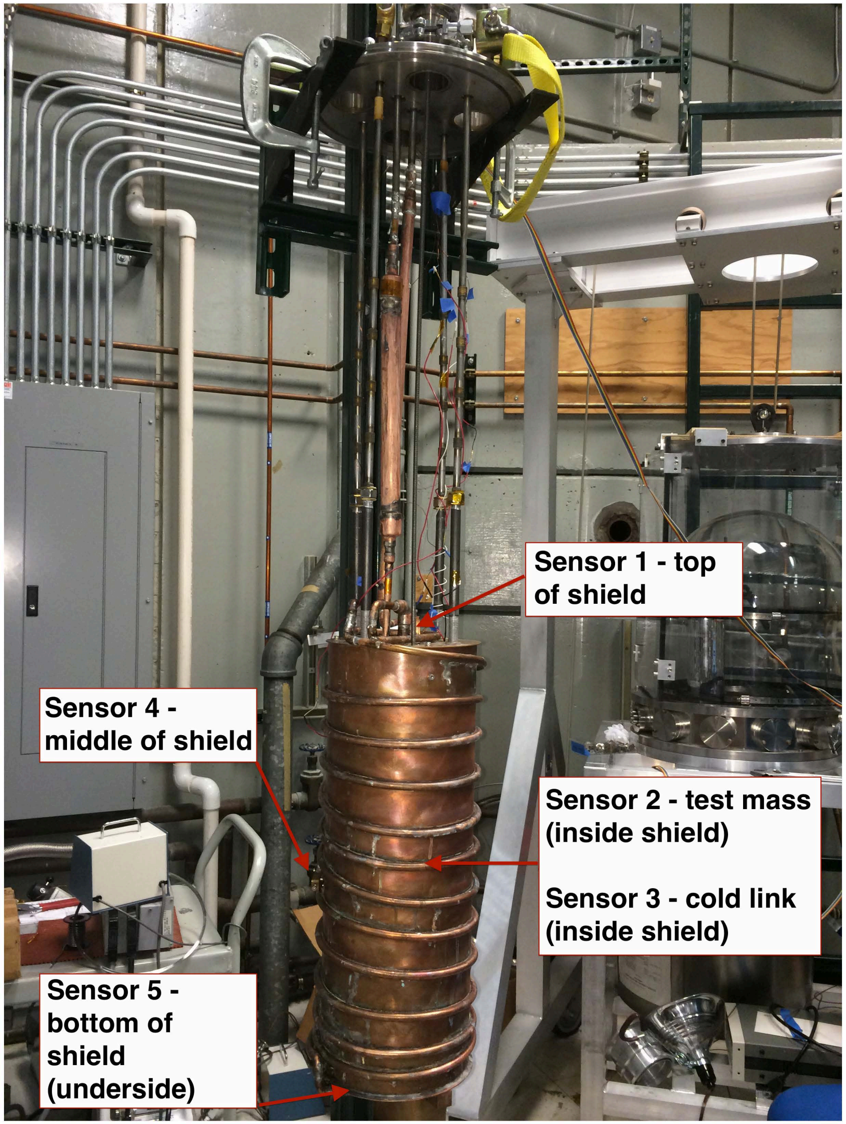


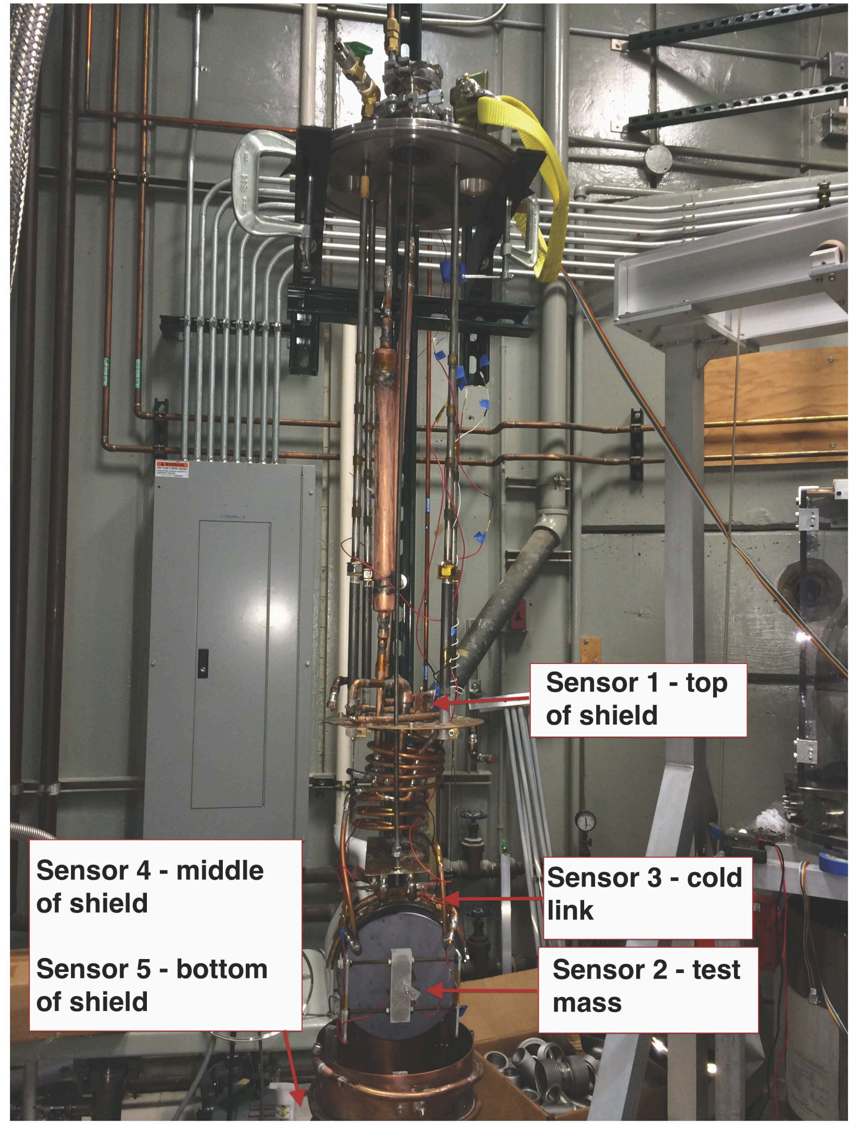
Free Convection for two vetical parallel plates. Cold plate at 80 K.
Nusselt # (unitless)
Pressure (torr)
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
0.01 mm gap, 124 K hot plate
0.1 mm gap, 124 K hot plate
0.5 mm gap, 124 K hot plate
No convention below this line
0.01 mm gap, 295 K hot plate
0.1 mm gap, 295 K hot plate
0.5 mm gap, 295 K hot plate
created by Convection_vs_Pressure_Analsysis on 02–Mar–2014 Brett Shapiro

N_2 gas therm. cond. vs pressure



Temperature Sensor Locations





Test Mass Temperature Equations

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

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

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

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

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

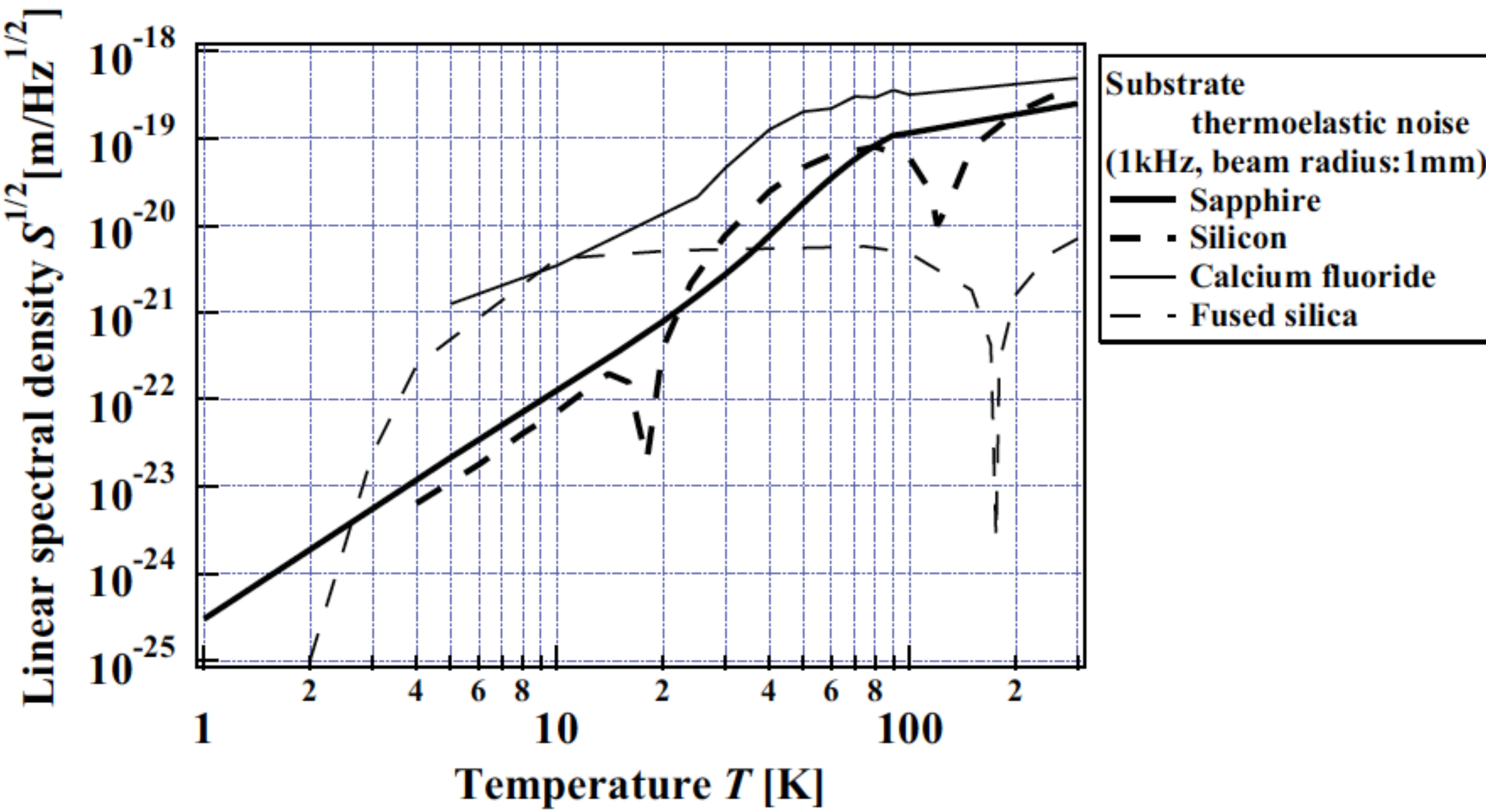
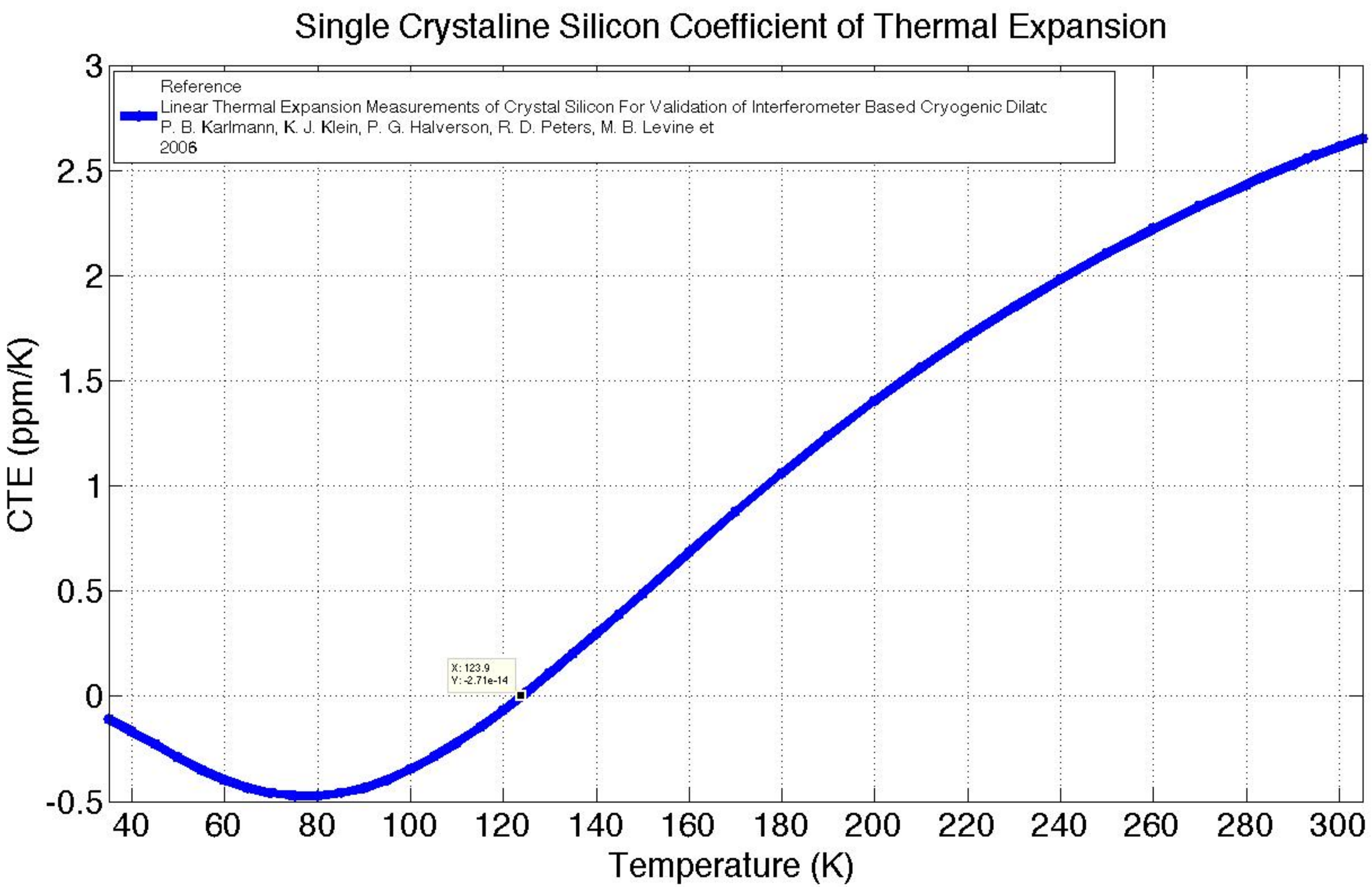


Figure 7.4 Temperature dependence of substrate thermoelastic noise. Frequency f is 1 kHz and beam radius w_0 is 1 mm.

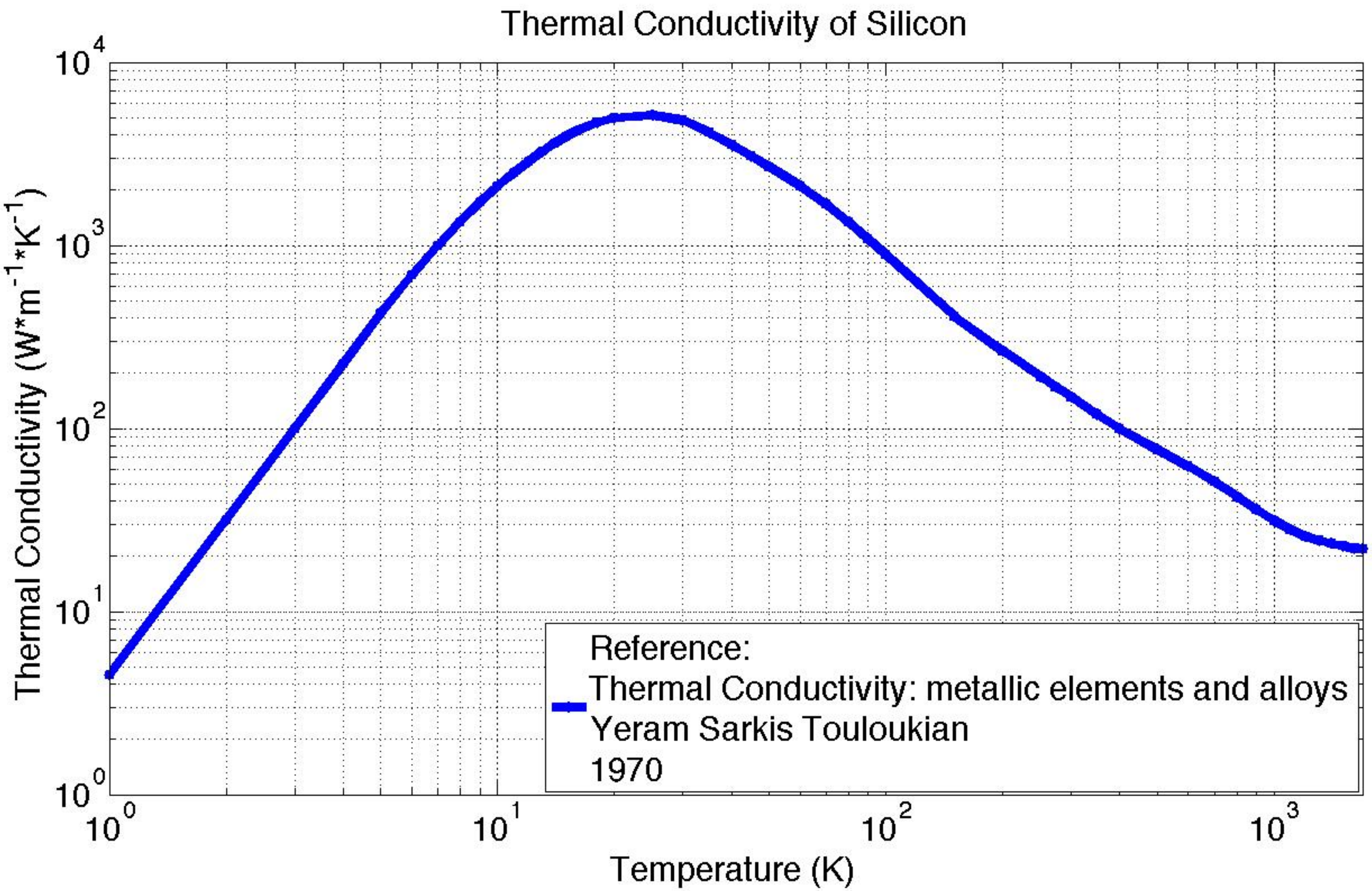
ref: Harry, Bodiya, Desalvo. Optical Coatings and Thermal Noise in Precision Measurement. 2012. pg 113.

Si CTE vs Temperature

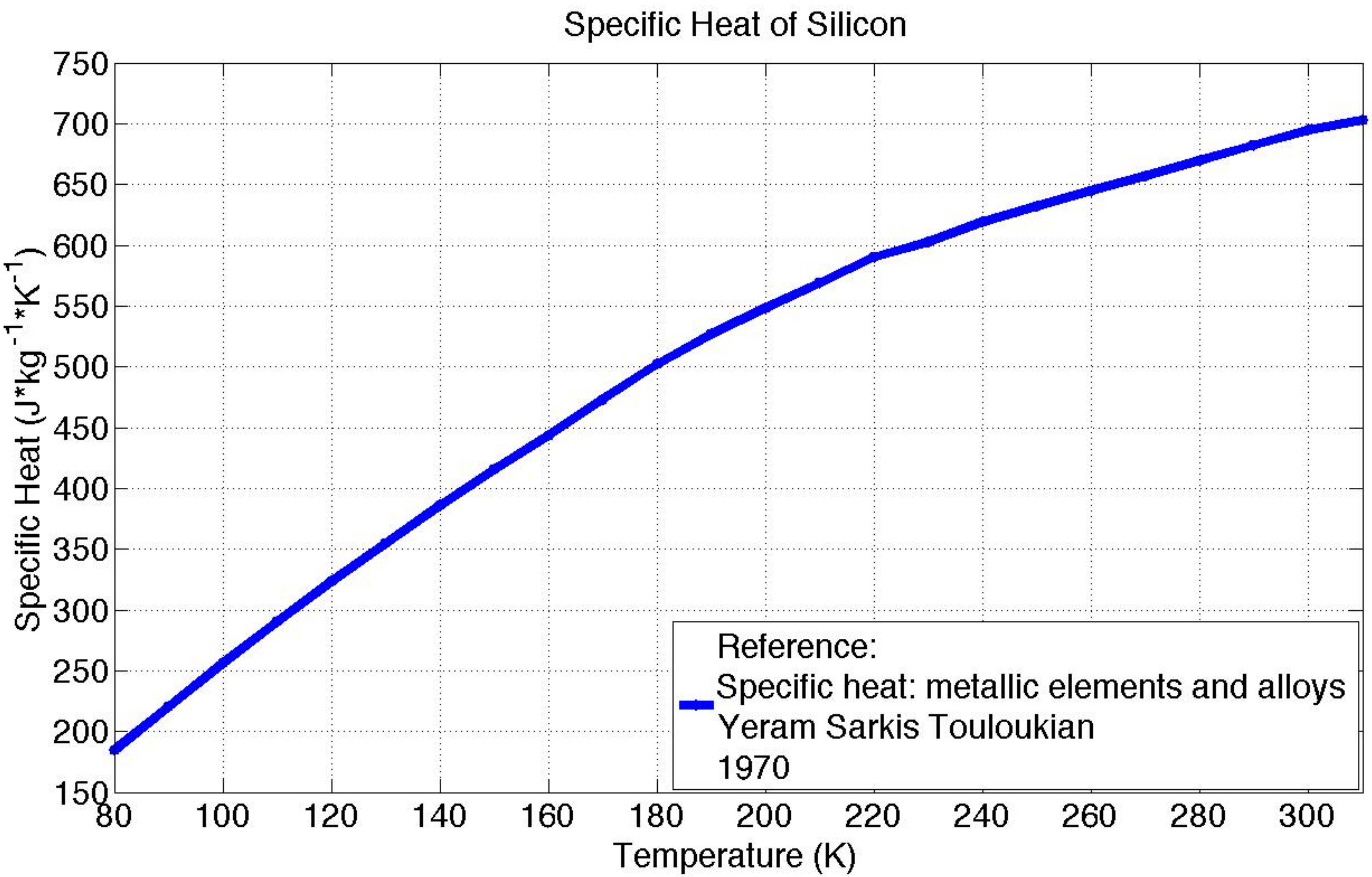


Thermoelastic component of thermal noise goes to zero with CTE.

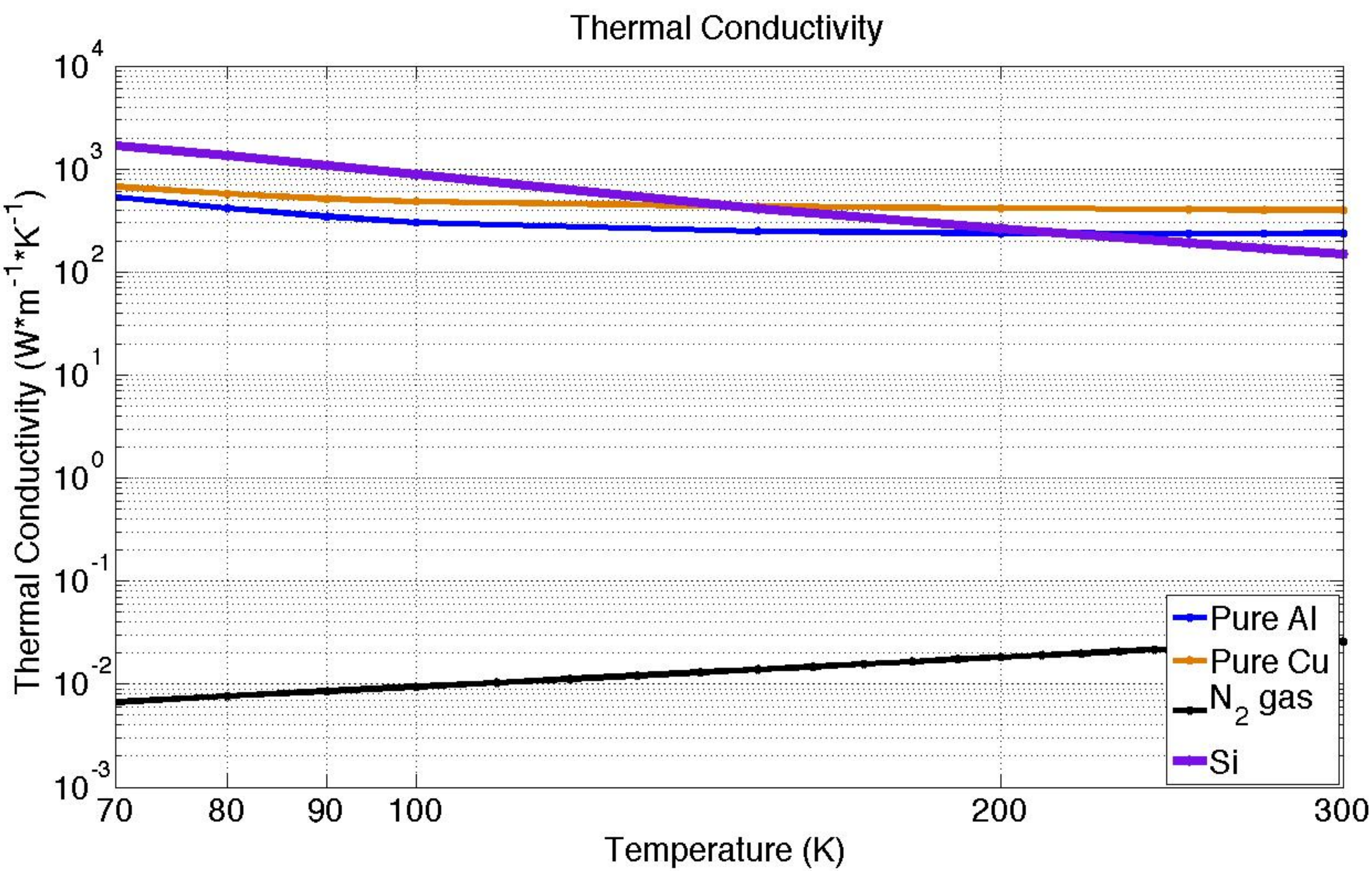
Si Thermal Conductivity vs Temp.



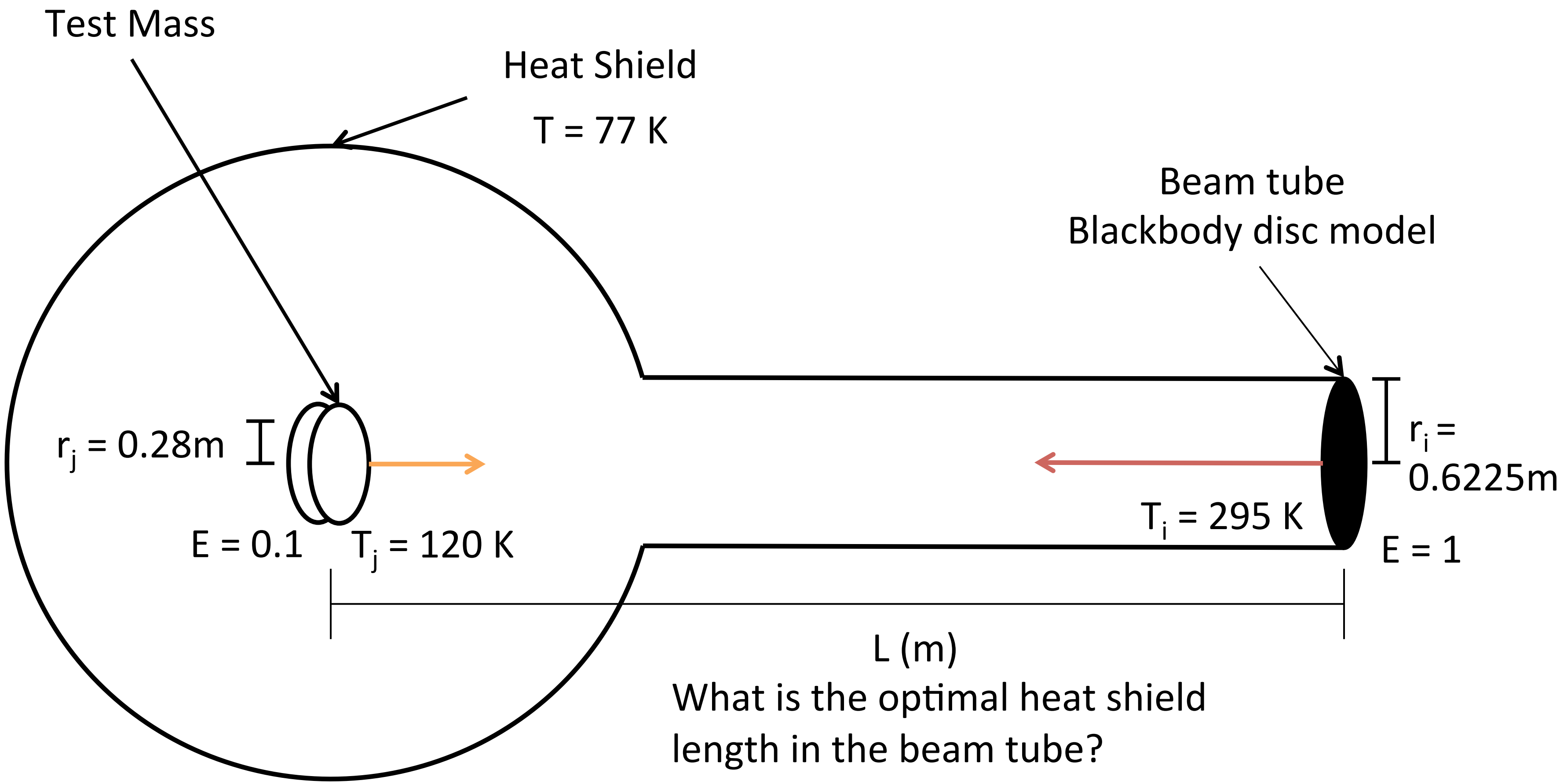
Si Specific Heat vs Temperature



Thermal Conductivity of Materials



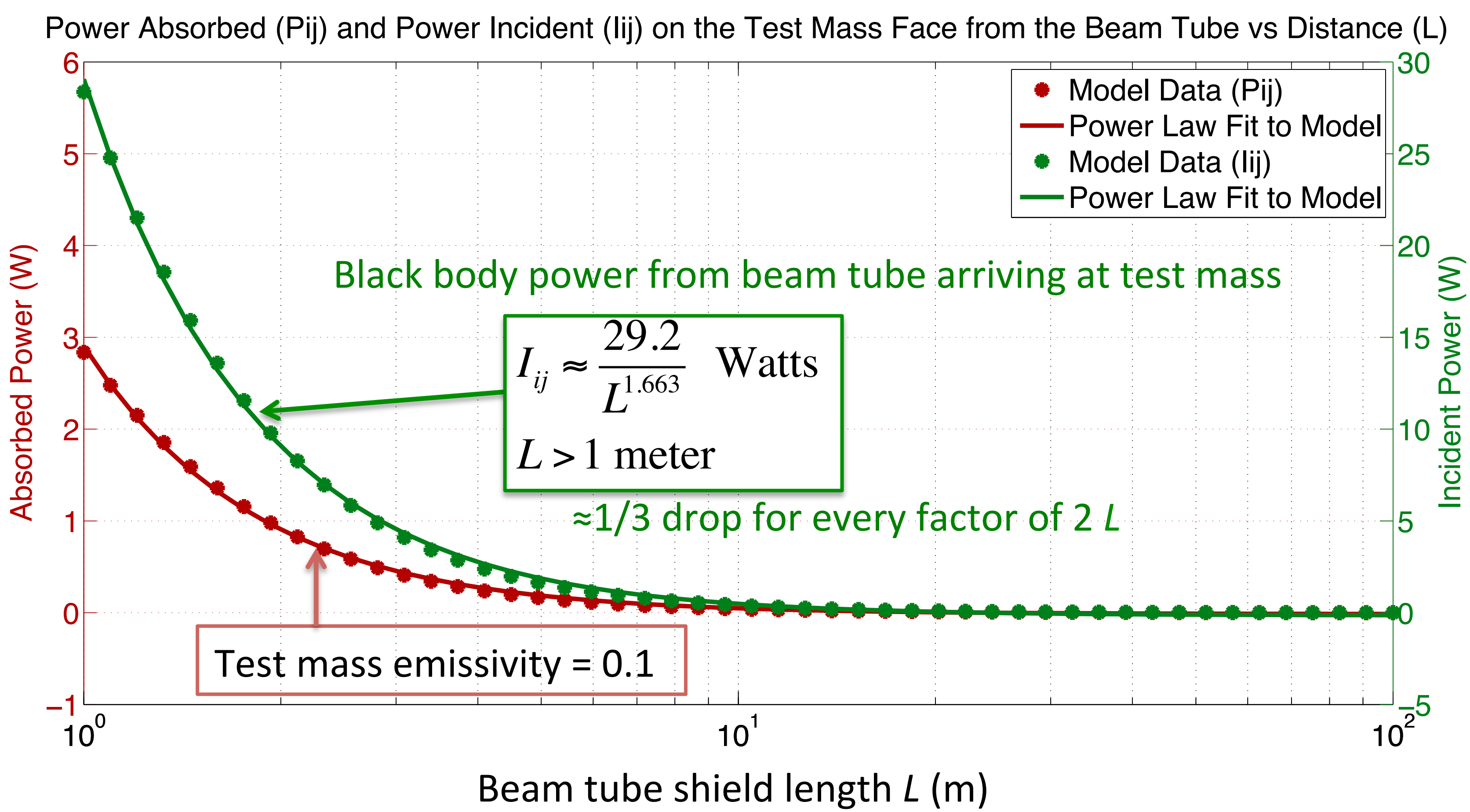
Beam Tube Heat Shield Length



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

See T1300556

Heat shield length in beam tube



See T1300556

Other Problems To Solve

- Liquid N_2 hoses flexible enough for ISI under vacuum
- Temperature/height control of blade springs
- Test mass temperature control
- How to measure temperature?
  - Measure acoustic modes – Young's modulus is temp. dependent
  - Infrared camera
- Emissivity of optical coatings
- Lossiness of emissive coatings
- Good emissivity estimates/measurements of Si?
- Power absorption in Si (ppm, W, etc)?
- How noisy is bubbling nitrogen: seismic, Newtonian? Do boiling chips help?
- Optical coating thermal noise at 120 K