LIGO

Progress on Cryogenics for aLIGO upgrades

Brett Shapiro
Stanford University

LIGO

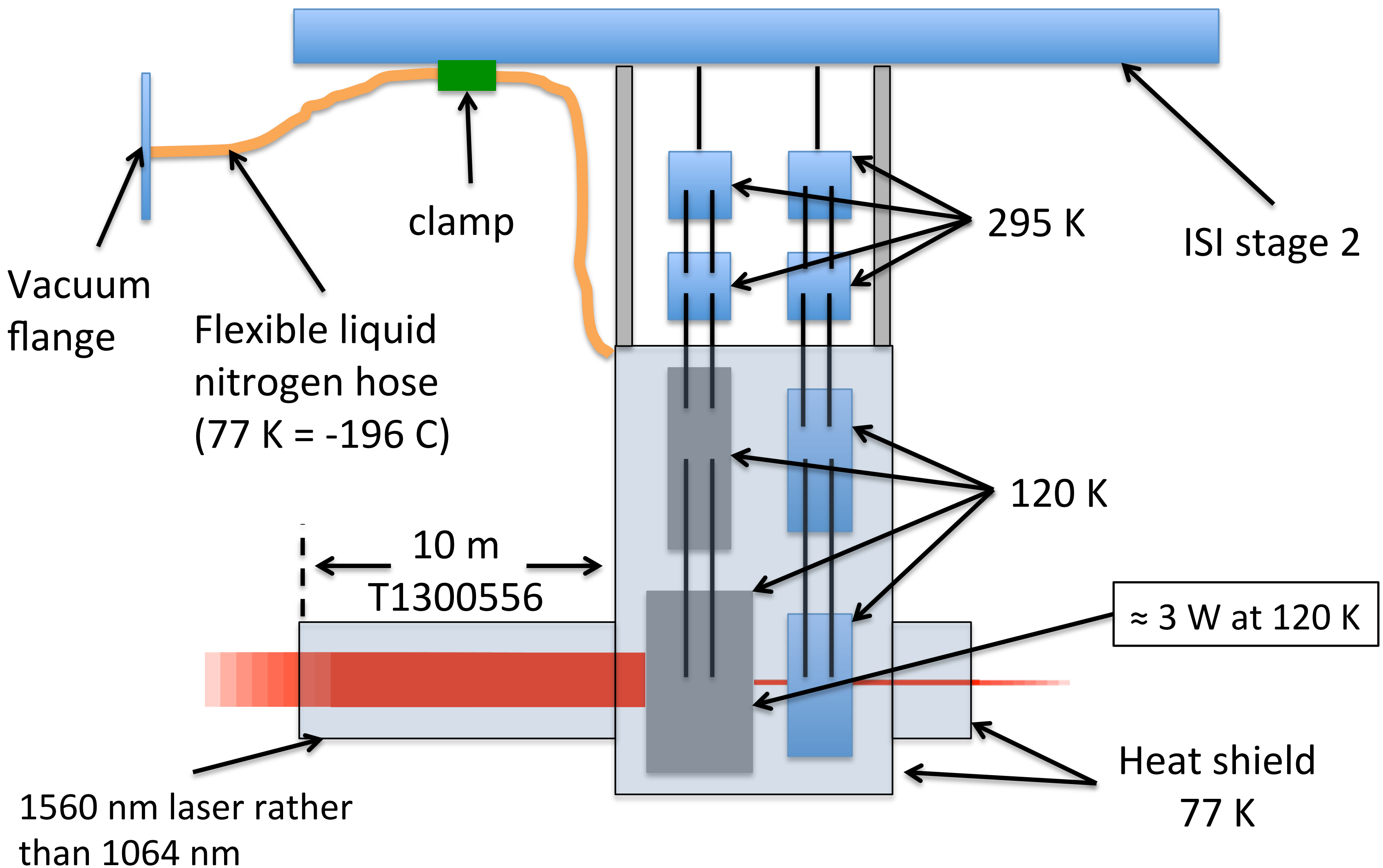
Summary

- Cryo test mass problem statement
- LIGO III quad pendulum modeling – summer student work
  - SUS conceptual design modeling
  - Heat shield beam tube length
- Stanford experiments
- Future Work

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 T1200031)
  - Get to 124 K in a timely manner
  - 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, 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 the ISI
  - Leave the rest of the BSC warm

Possible LIGO III Cryogenic Upgrade



See also G1200246-v1

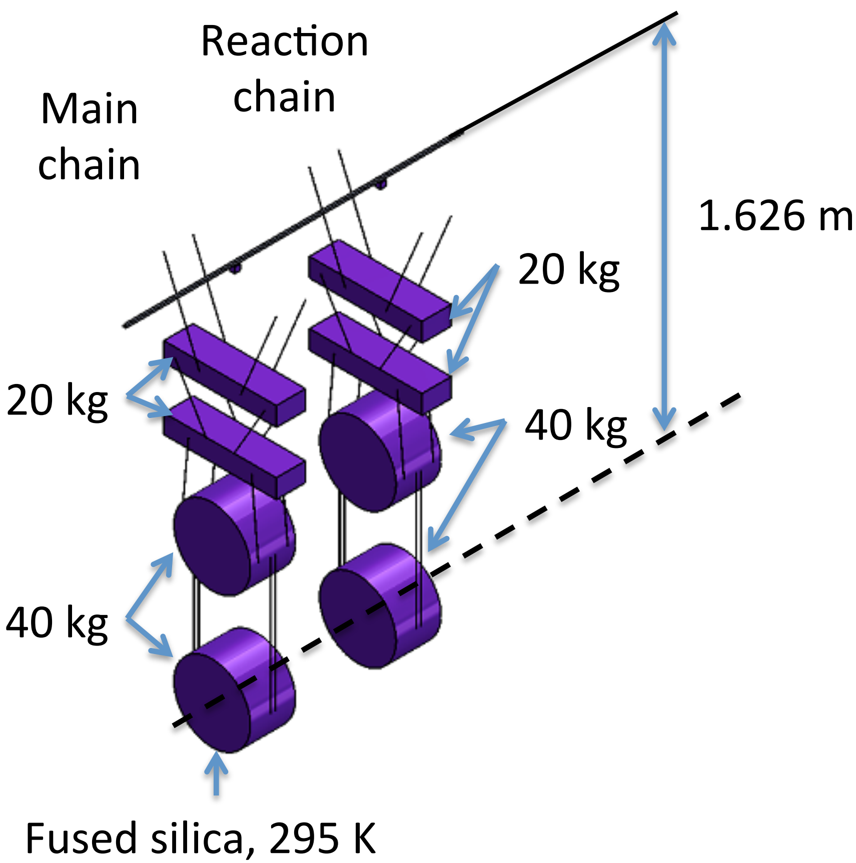
LIGO

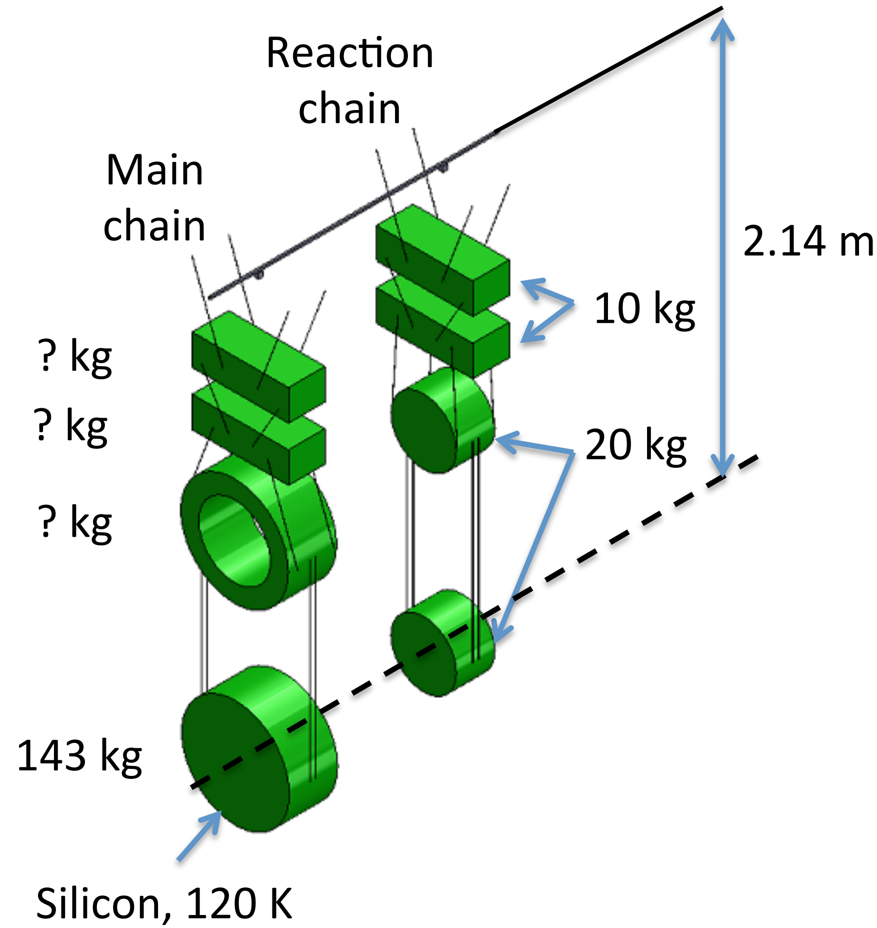
Quad pendulum modeling

LIGO III Conceptual Design
of blue team approach
in T1200031

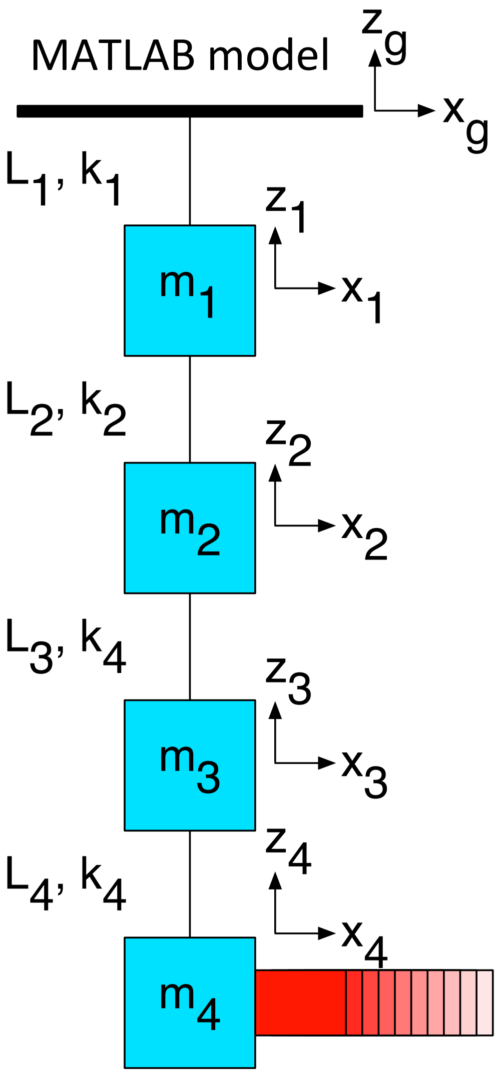
Possible LIGO III Mechanical Upgrades

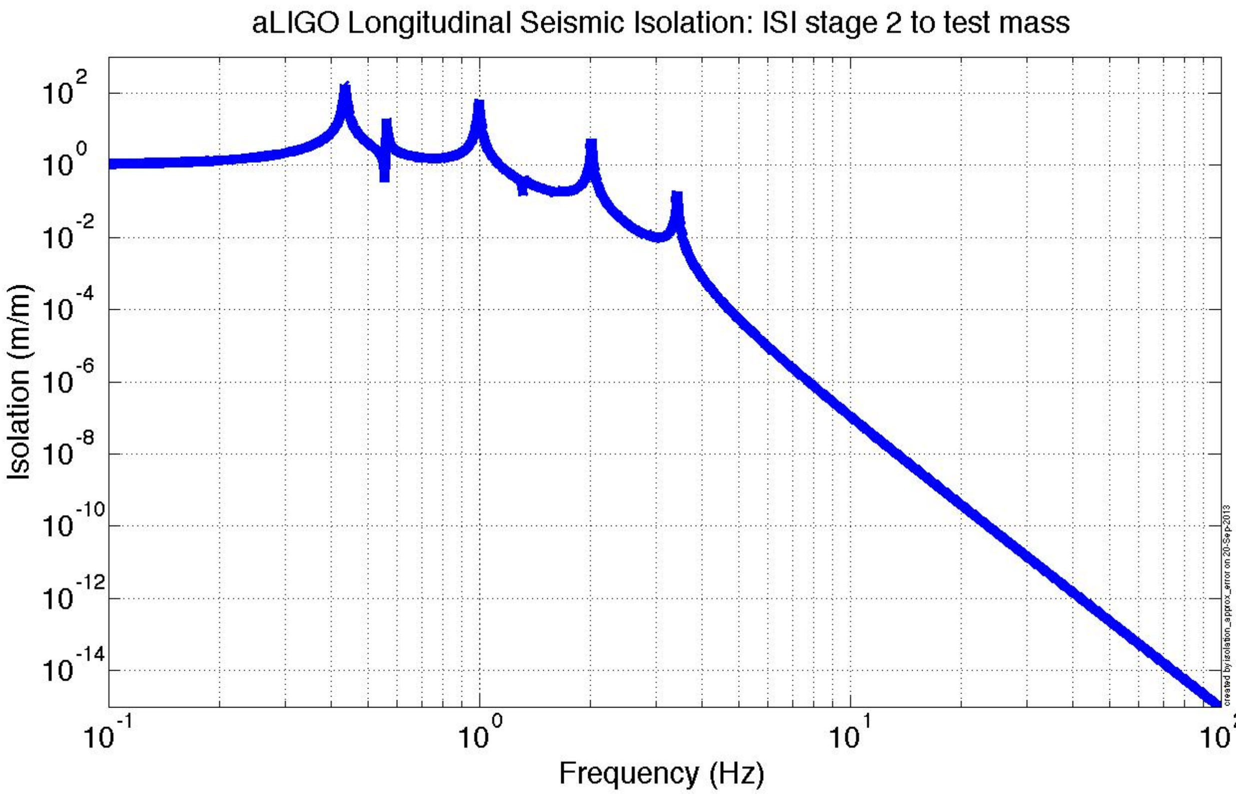
Advanced LIGO quad pendulum	Preliminary LIGO III quad pendulum





Optimizing the mass distribution

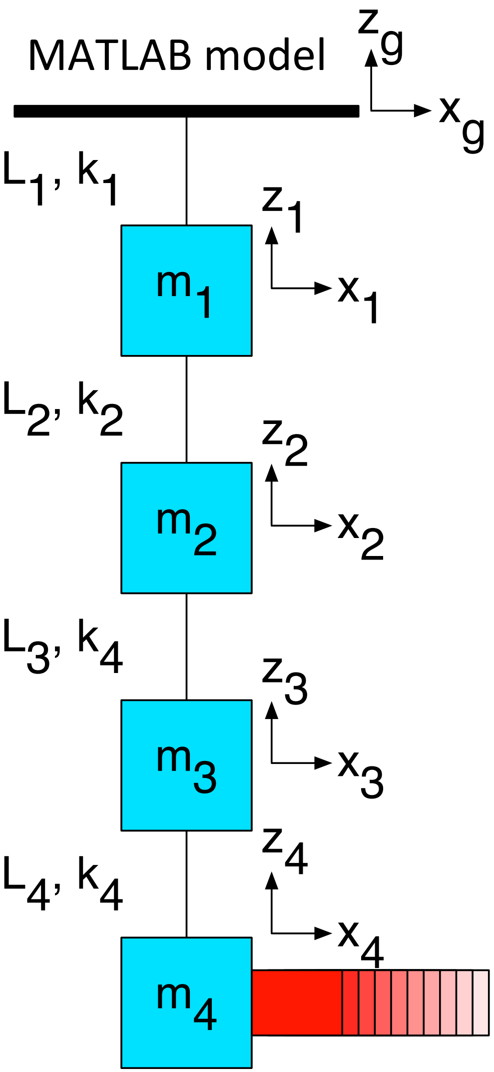


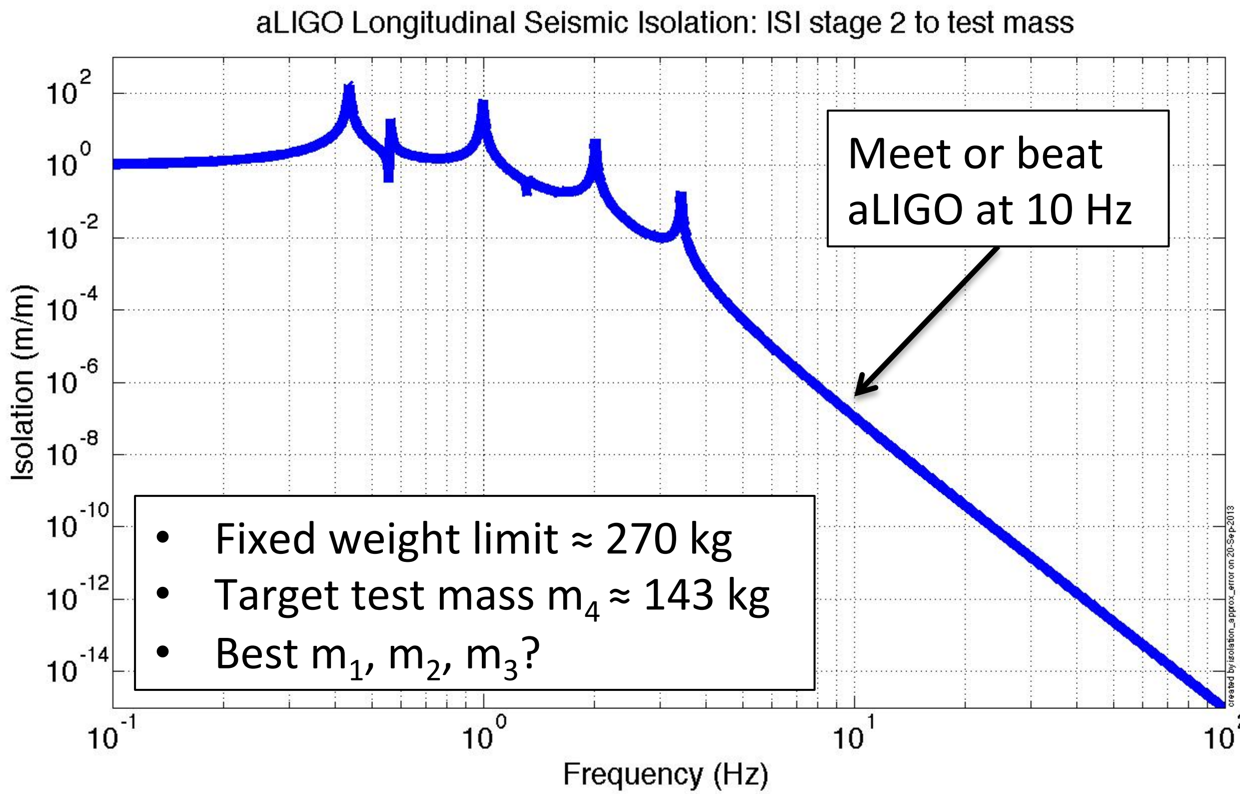


m: mass of stage
L: wire length
k: vertical stiffness

x: longitudinal displacement
v: vertical displacement

Optimizing the mass distribution





m: mass of stage
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k: vertical stiffness

x: longitudinal displacement
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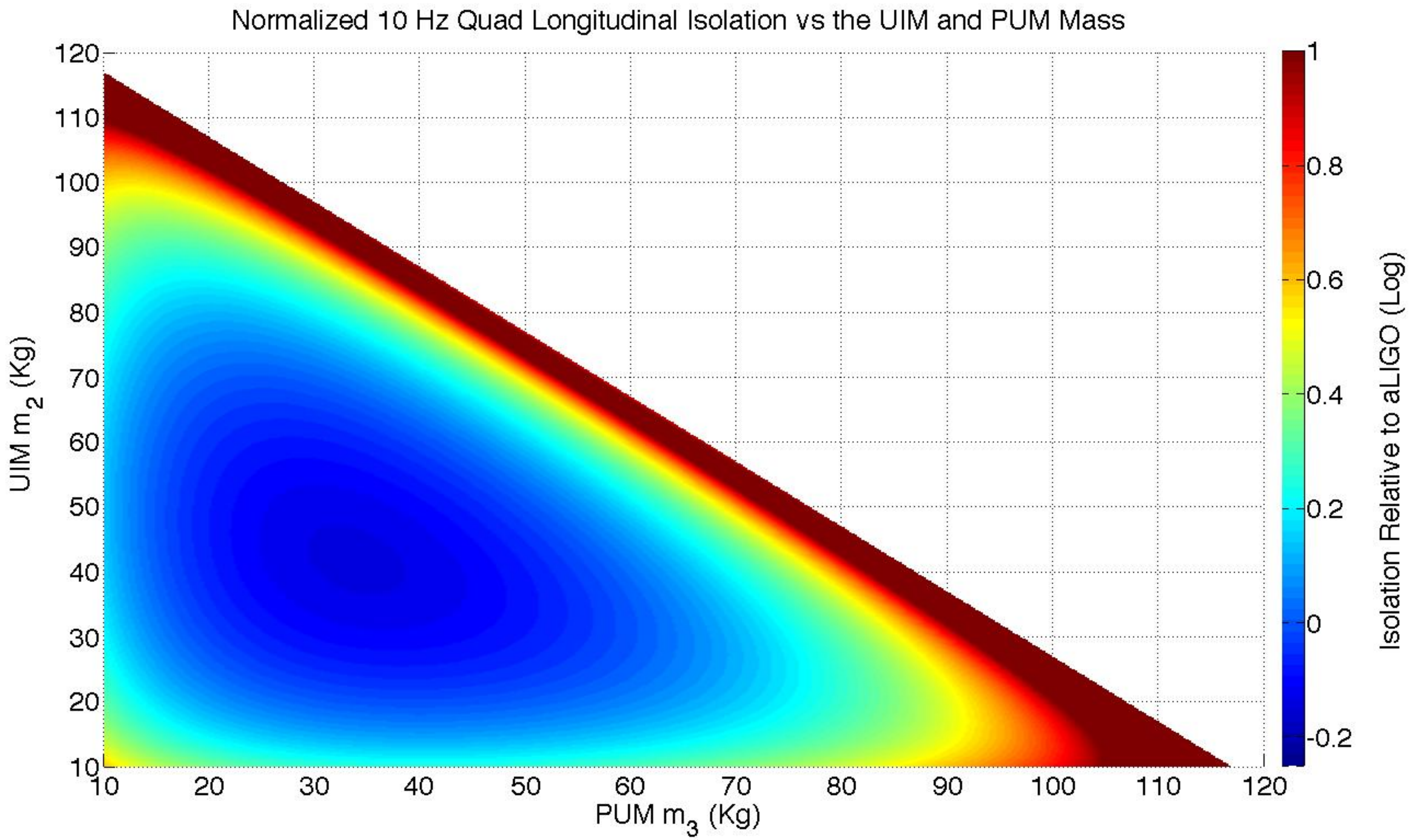
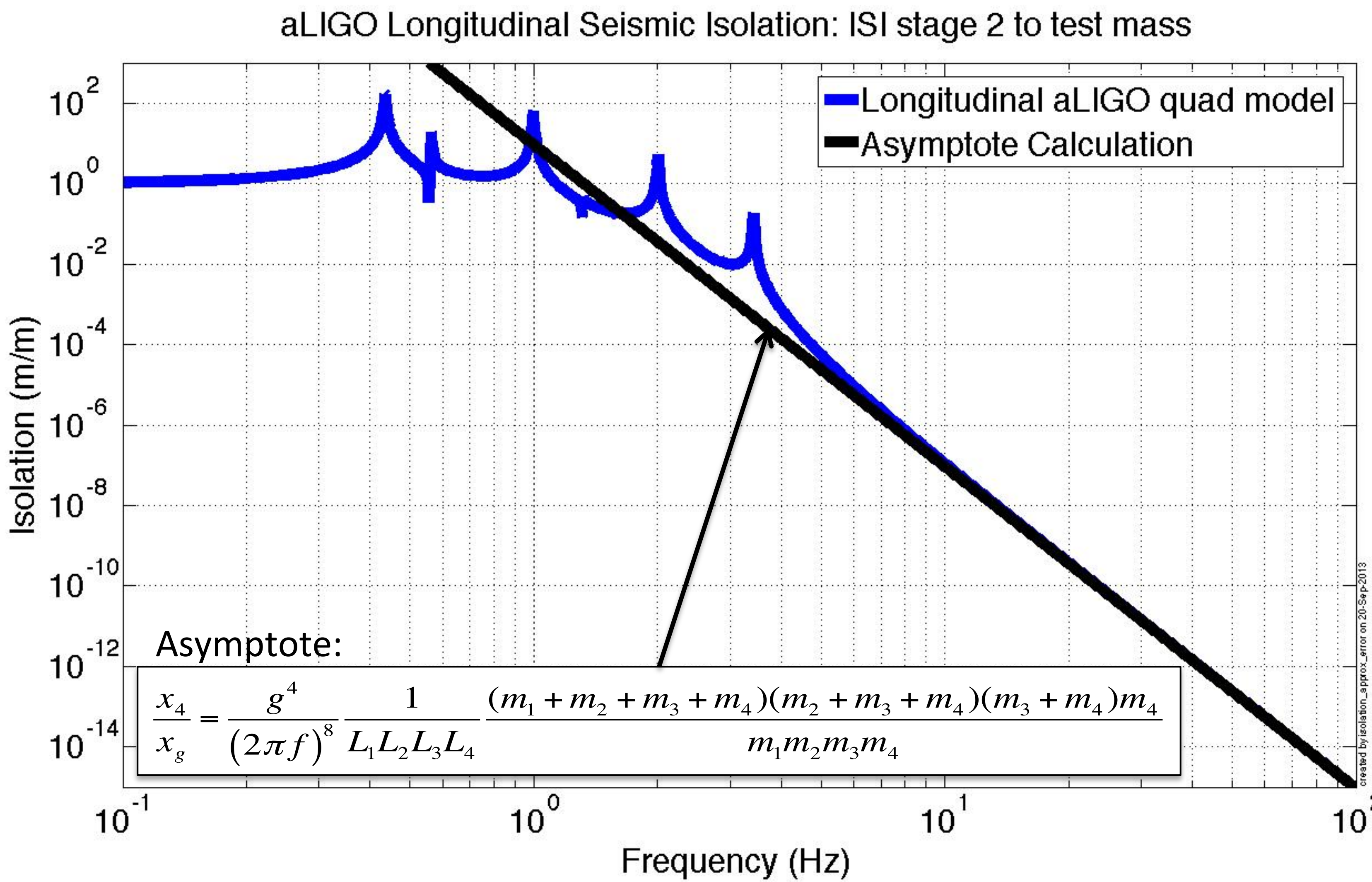
Model search for best mass values



Best values: $\mathbf{m_3}$**=33.68 kg,** $\mathbf{m_2}$**=42.65 kg** -> $\mathbf{m_1}$ **= 51.67 kg**
For 143 kg test mass, 270 kg payload, and 0.535 m wire lengths

See T1300786

Longitudinal Isolation Asymptote



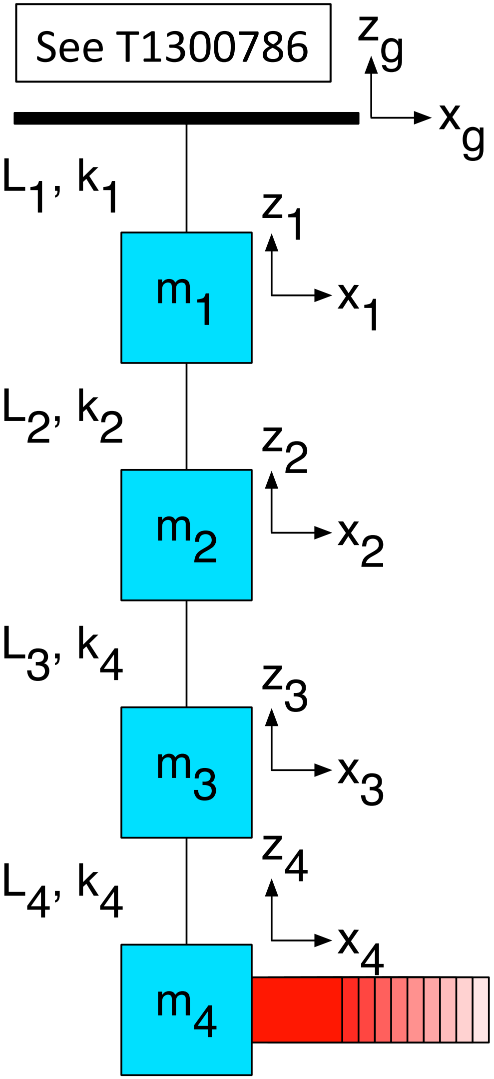
Asymptote:

$$\frac{x_4}{x_g} = \frac{g^4}{(2\pi f)^8}\frac{1}{L_1 L_2 L_3 L_4}\frac{(m_1+m_2+m_3+m_4)(m_2+m_3+m_4)(m_3+m_4)m_4}{m_1 m_2 m_3 m_4}$$

See T1300786

Optimal Longitudinal Isolation

See T1300786



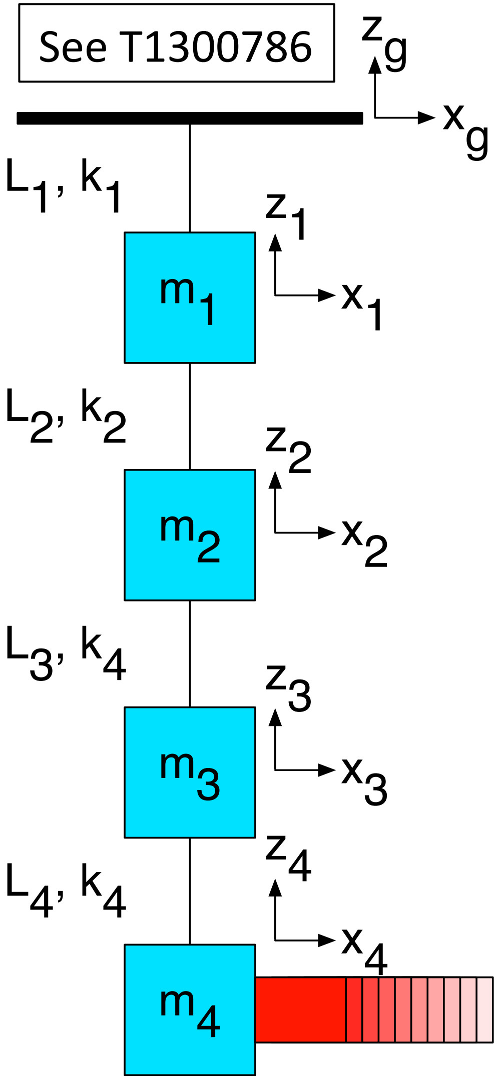
***Unique* optimal** solution of isolation asymptote:

$$\frac{x_4}{x_g} = \frac{g^4}{(2\pi f)^8} \frac{1}{L_1 L_2 L_3 L_4} \frac{(m_1 + m_2 + m_3 + m_4)(m_2 + m_3 + m_4)(m_3 + m_4)m_4}{m_4 m_4 m_4 m_4}$$

Given constrained test mass and payload:

- $m_4 = 143 \text{ kg}$
- $\text{P=m}_1 + m_2 + m_3 + m_4 = 270 \text{ kg}$

Optimal Longitudinal Isolation



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- $\frac{\partial}{\partial m_2} \frac{x_4}{x_g} = 0 \rightarrow$

Given constrained test mass and payload:

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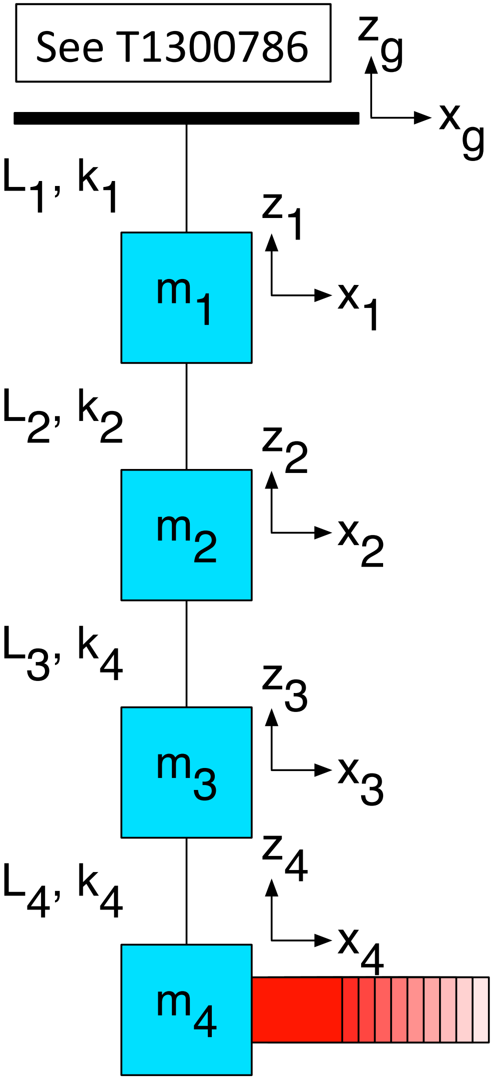
Optimal Longitudinal Isolation



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- $\frac{\partial}{\partial m_2}\frac{x_4}{x_g} = 0 \rightarrow$ $\boxed{m_2 = -(m_3+m_4) + \sqrt{P(m_3+m_4)}}$

Given constrained test mass and payload:

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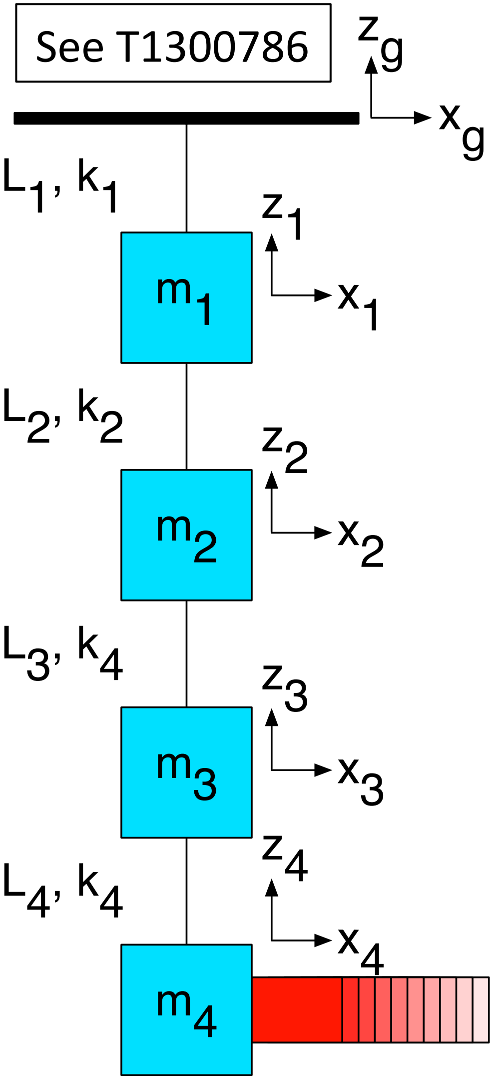
Optimal Longitudinal Isolation



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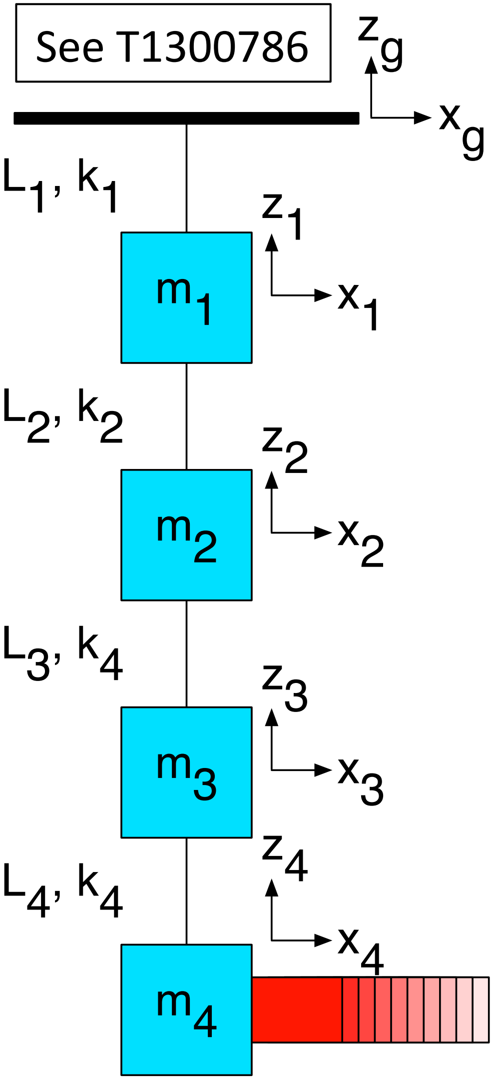
- $\frac{\partial}{\partial m_2} \frac{x_4}{x_g} = 0 \rightarrow$ $\boxed{m_2 = -(m_3 + m_4) + \sqrt{P(m_3 + m_4)}}$
- $\frac{\partial}{\partial m_3} \frac{x_4}{x_g} = 0 \rightarrow$

Given constrained test mass and payload:

- $m_4 = 143 \text{ kg}$
- $\text{P=m}_1 + m_2 + m_3 + m_4 = 270 \text{ kg}$

Optimal Longitudinal Isolation



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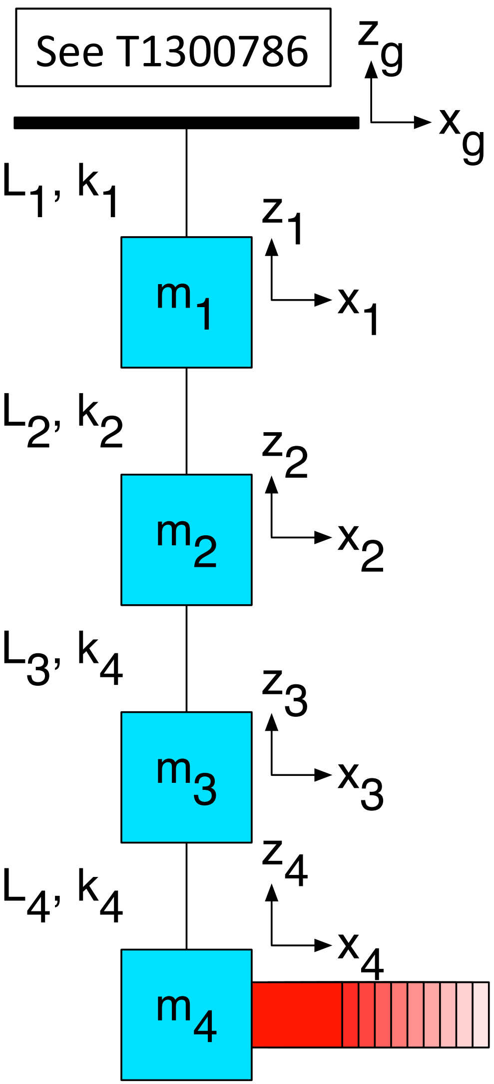
- $\frac{\partial}{\partial m_2} \frac{x_4}{x_g} = 0 \rightarrow$ $$m_2 = -(m_3 + m_4) + \sqrt{P(m_3 + m_4)}$$
- $\frac{\partial}{\partial m_3} \frac{x_4}{x_g} = 0 \rightarrow$ $$m_3 = -A + A\sqrt{A + P - (m_2 + m_4)}$$ $$\mathrm{A} = \frac{m_4(m_2 + m_4)}{P + m_4}$$

Given constrained test mass and payload:

- $m_4 = 143 \text{ kg}$
- $\mathrm{P} = \mathrm{m}_1 + m_2 + m_3 + m_4 = 270 \text{ kg}$

Optimal Longitudinal Isolation



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- $\frac{\partial}{\partial m_2}\frac{x_4}{x_g} = 0 \rightarrow$ $m_2 = -(m_3+m_4) + \sqrt{P(m_3+m_4)} = 41.71 \text{ kg}$
- $\frac{\partial}{\partial m_3}\frac{x_4}{x_g} = 0 \rightarrow$ $m_3 = -A + A\sqrt{A + P - (m_2+m_4)} = 33.74 \text{ kg}$, $\text{A} = \frac{m_4(m_2+m_4)}{P+m_4}$

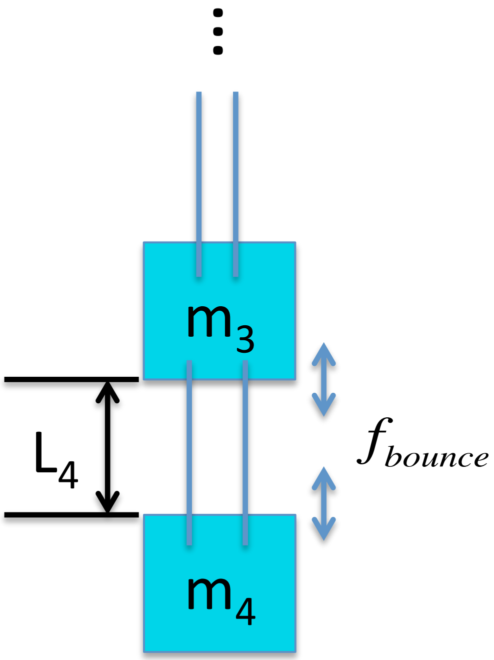
Iterate a few times to solve both simultaneously

- $m_1 = P - m_2 - m_3 - m_4 = 51.55 \text{ kg}$

Given constrained test mass and payload:

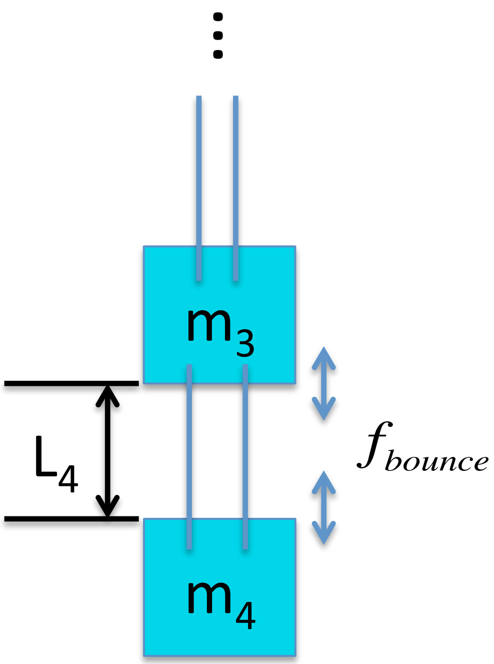
- $m_4 = 143 \text{ kg}$
- $\text{P}=\text{m}_1 + m_2 + m_3 + m_4 = 270 \text{ kg}$

PUM and Test Mass Bounce Mode



See T1300786

PUM and Test Mass Bounce Mode



- Vertical bounce frequency (Hz):

$$f_{bounce} \approx \frac{1}{2\pi}\sqrt{\frac{E_4 g}{L_4 \sigma_4}\left(1+\frac{m_4}{m_3}\right)}$$

$E_4 = 167.4$ GPa, silicon modulus of elasticity at 120 K *

$\sigma_4 = 1.4$ GPa, stress in fibers (estimated)

$L_4 = 1.025$ m, optimal fiber length for σ_4 (T1300786)

$g = 9.81\ \text{m/s}^2$, gravitational acceleration

* U. Gysin, S. Rast, P. Ruff, E. Meyer, D. W. Lee, P. Vettiger, C. Gerber. "Temperature dependence of the force sensitivity of silicon cantilevers", 2004, Physical Review B, Volume 69, Number 4, http://prb.aps.org/abstract/PRB/v69/i4/e045403

See T1300786

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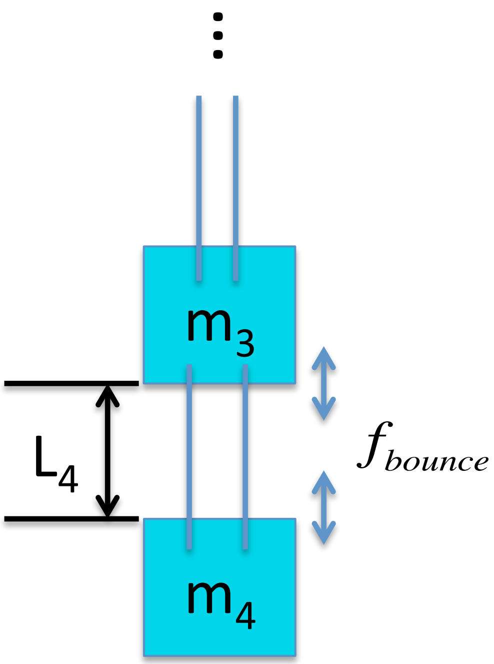

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- For longitudinal optimal solution with m_3 = 33.74 kg, m_4 =143 kg

$$f_{bounce} \approx 17.0\ \mathrm{Hz}$$

For aLIGO, f_{bounce} = 9.27 Hz

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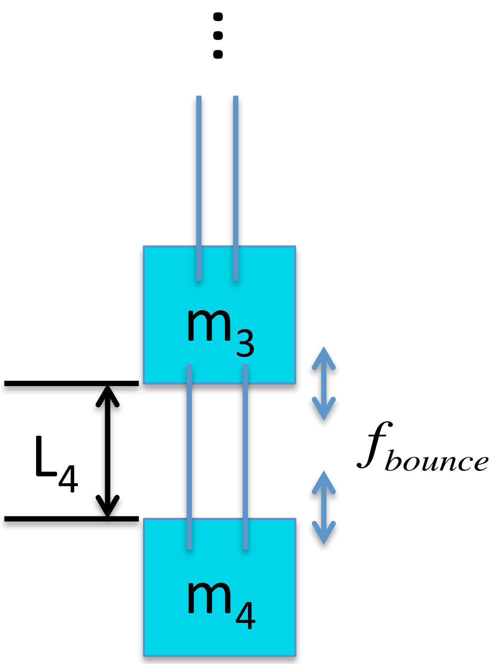
PUM and Test Mass Bounce Mode



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- For longitudinal optimal solution with m_3 = 33.74 kg, m_4 =143 kg

$$f_{bounce} \approx 17.0 \text{ Hz}$$

For aLIGO, f_{bounce} = 9.27 Hz

- No solution that meets both aLIGO performance and our goals for payload and test mass weight.

* U. Gysin, S. Rast, P. Ruff, E. Meyer, D. W. Lee, P. Vettiger, C. Gerber. "Temperature dependence of the force sensitivity of silicon cantilevers", 2004, Physical Review B, Volume 69, Number 4, http://prb.aps.org/abstract/PRB/v69/i4/e045403

See T1300786

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.

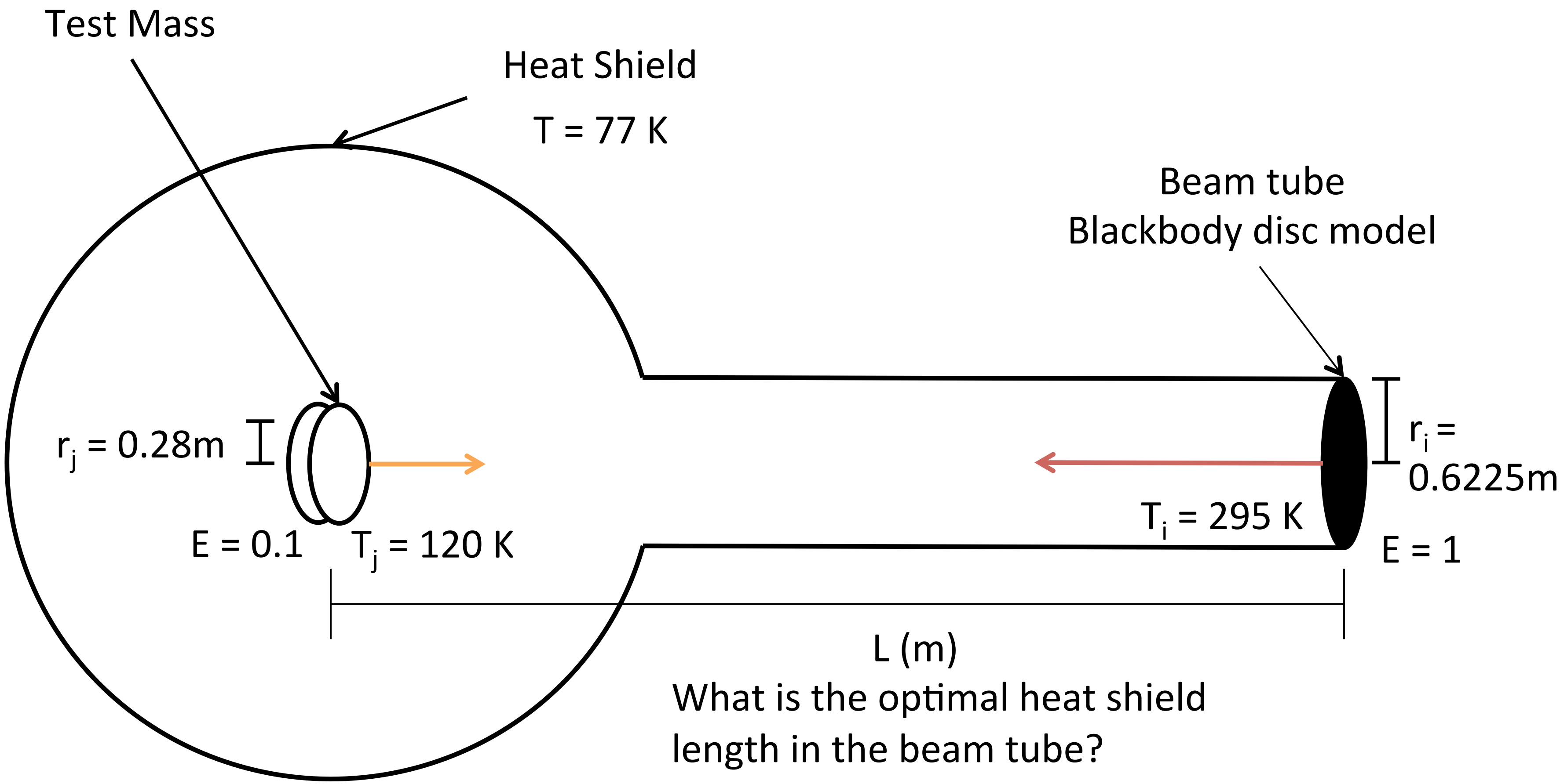
Parameters	Increased P	Decreased m_4	Penultimate Springs
P, Payload (kg)	301.9	270.0	270.0
m_1 (kg)	46.79	41.93	51.55
m_2 (kg)	39.54	35.42	41.71
m_3 (kg)	72.57	64.86	33.74
m_4 (kg)	143.0	127.8	143.0
L_1 (m)	0.372	0.372	0.535
L_2 (m)	0.372	0.372	0.535
L_3 (m)	0.372	0.372	0.535
L_4 (m)	1.025	1.025	0.535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

LIGO

Quad pendulum modeling

Heat shield beam tube length

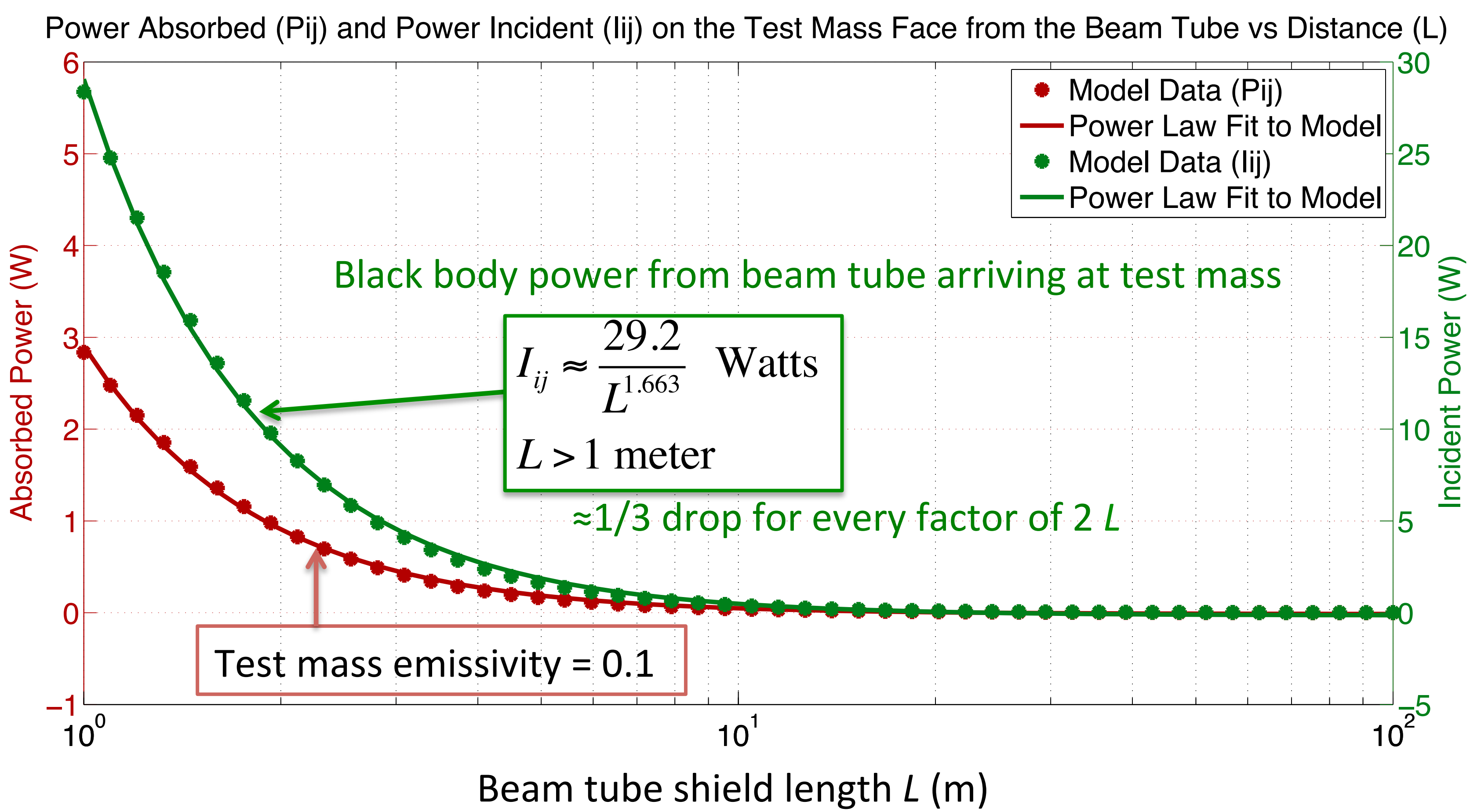
Beam Tube Heat Shield Length



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

See T1300556

Heat shield length in beam tube



See T1300556

LIGO

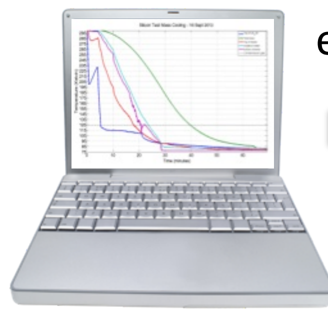
Stanford Cryo Test Mass Experiments

Goal of Stanford Cryo Experiments

Fastest method of cooling a LIGO III test mass to 124 K, -150 C

modify

understand



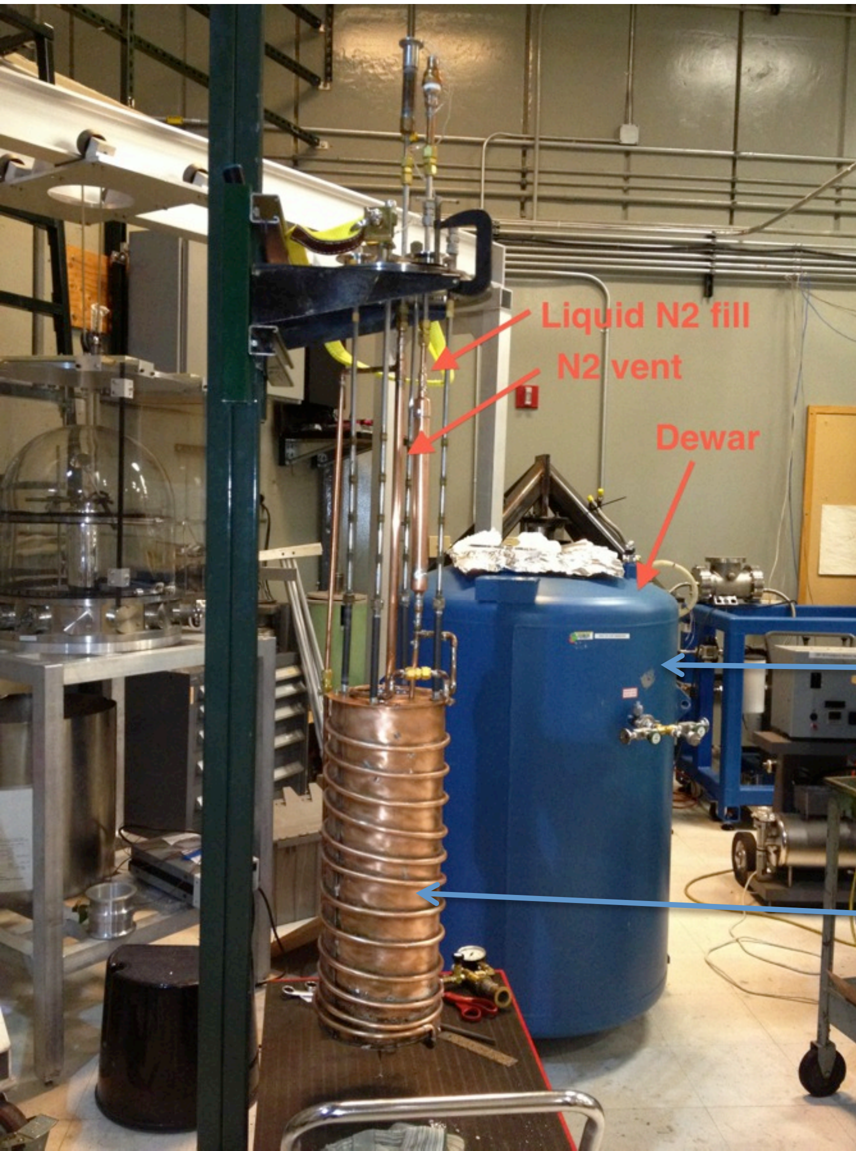
extrapolate

Stanford prototypes

Model

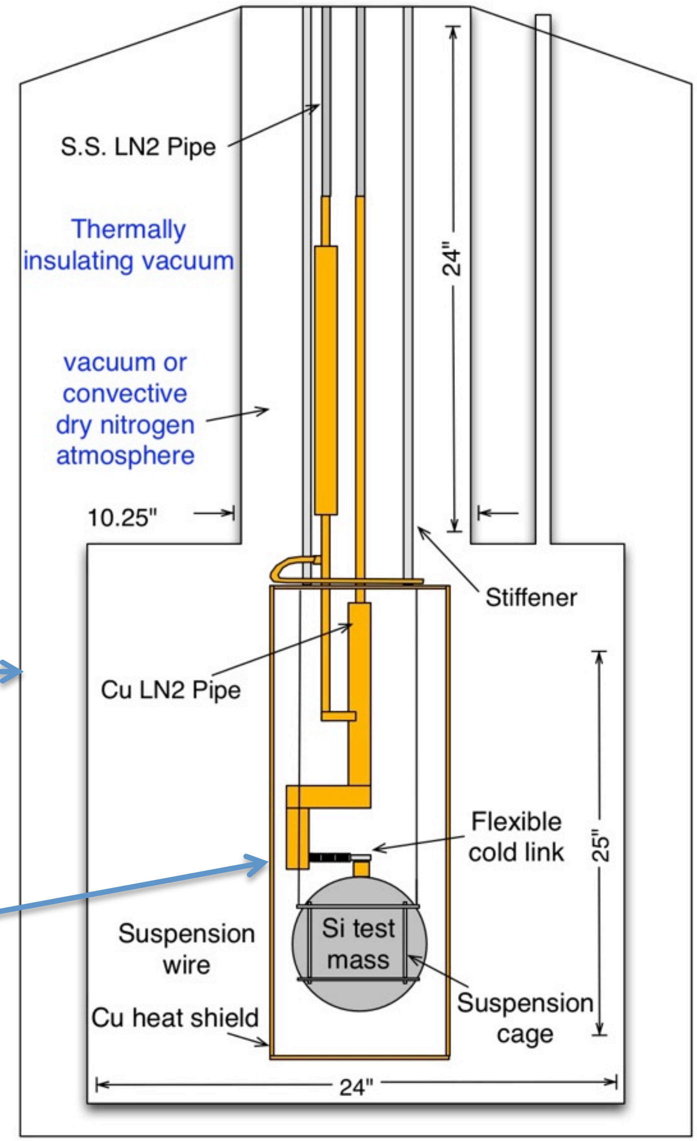
LIGO III design

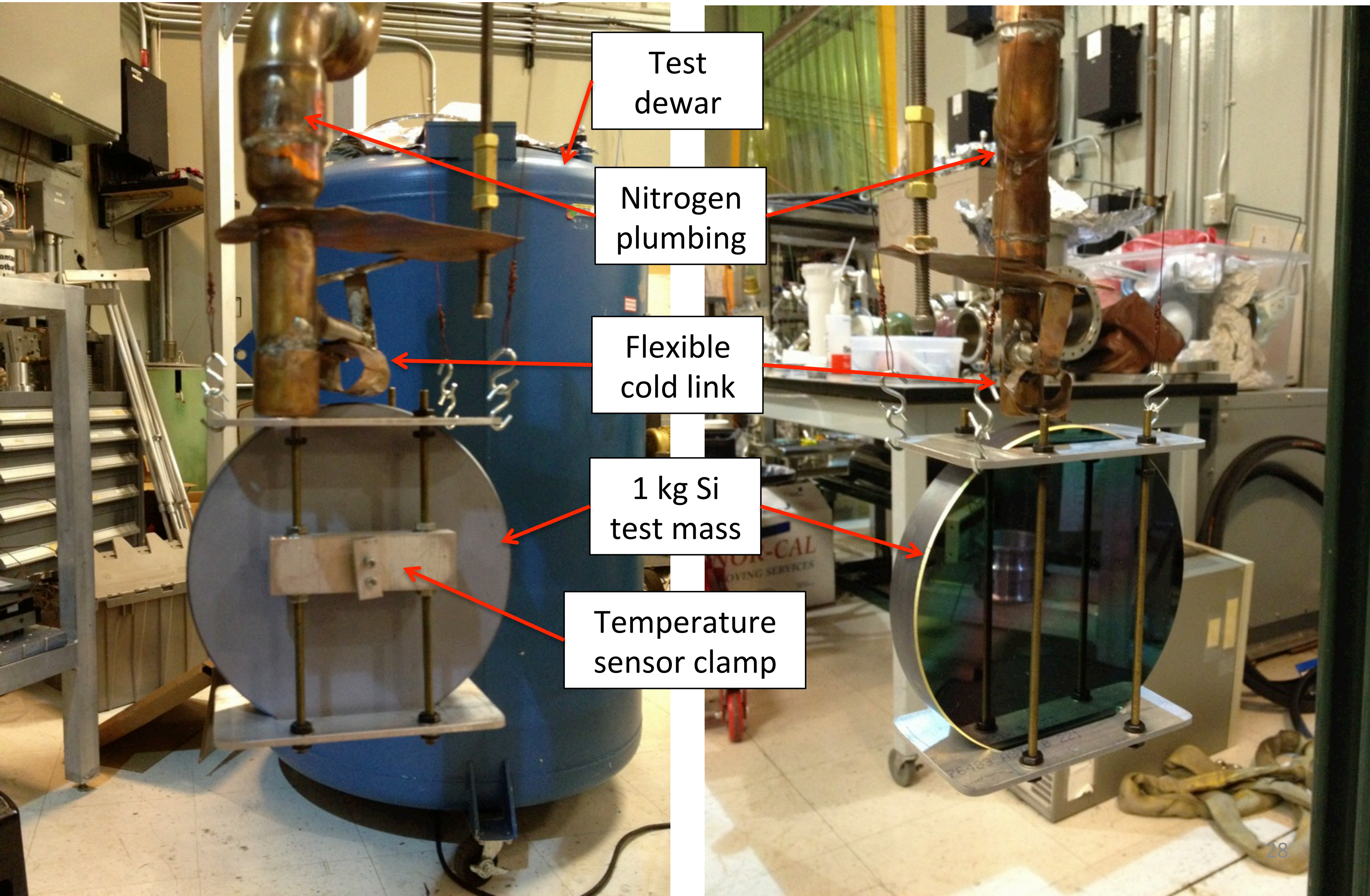
Experimental Setup



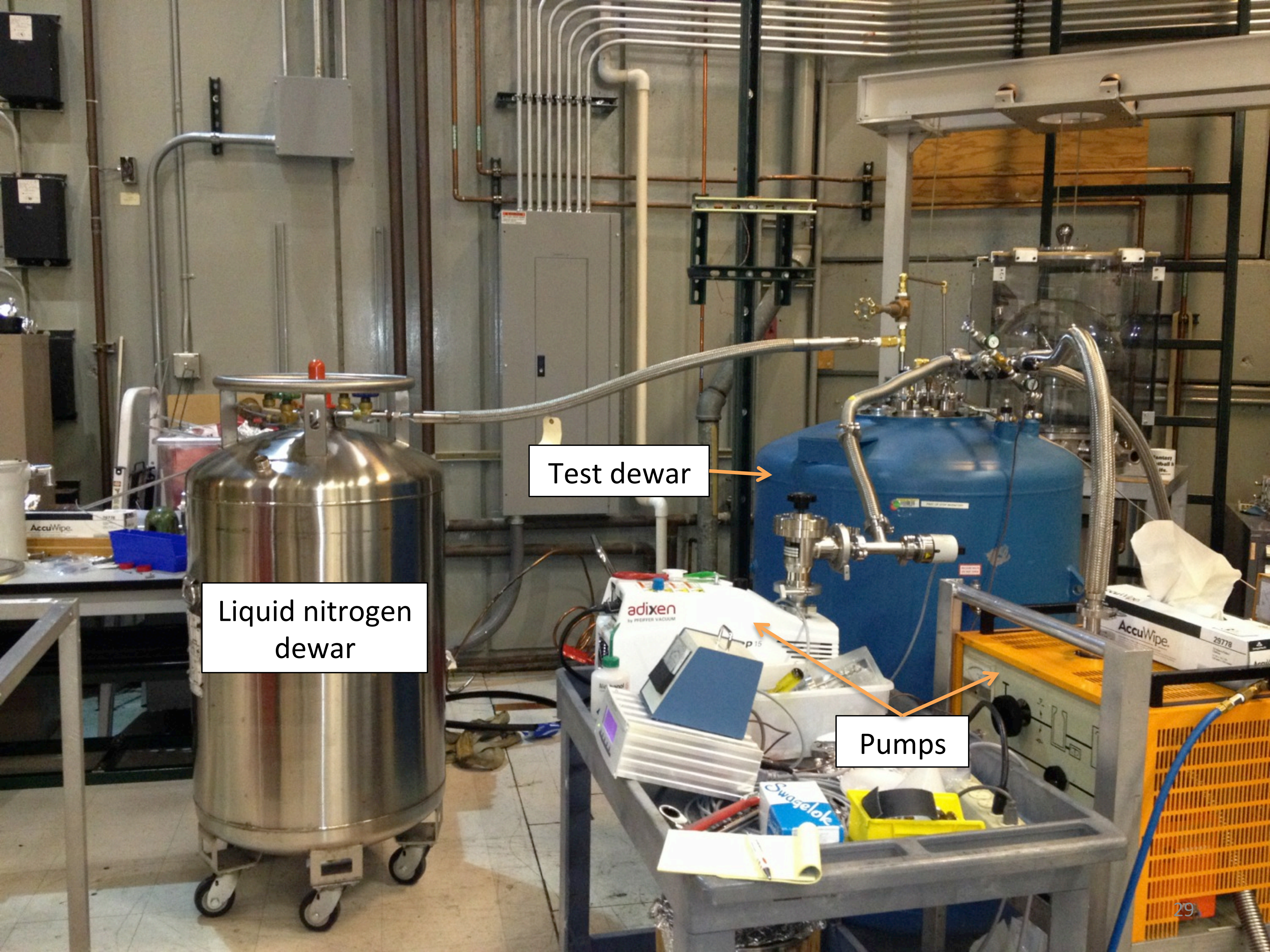
Test dewar

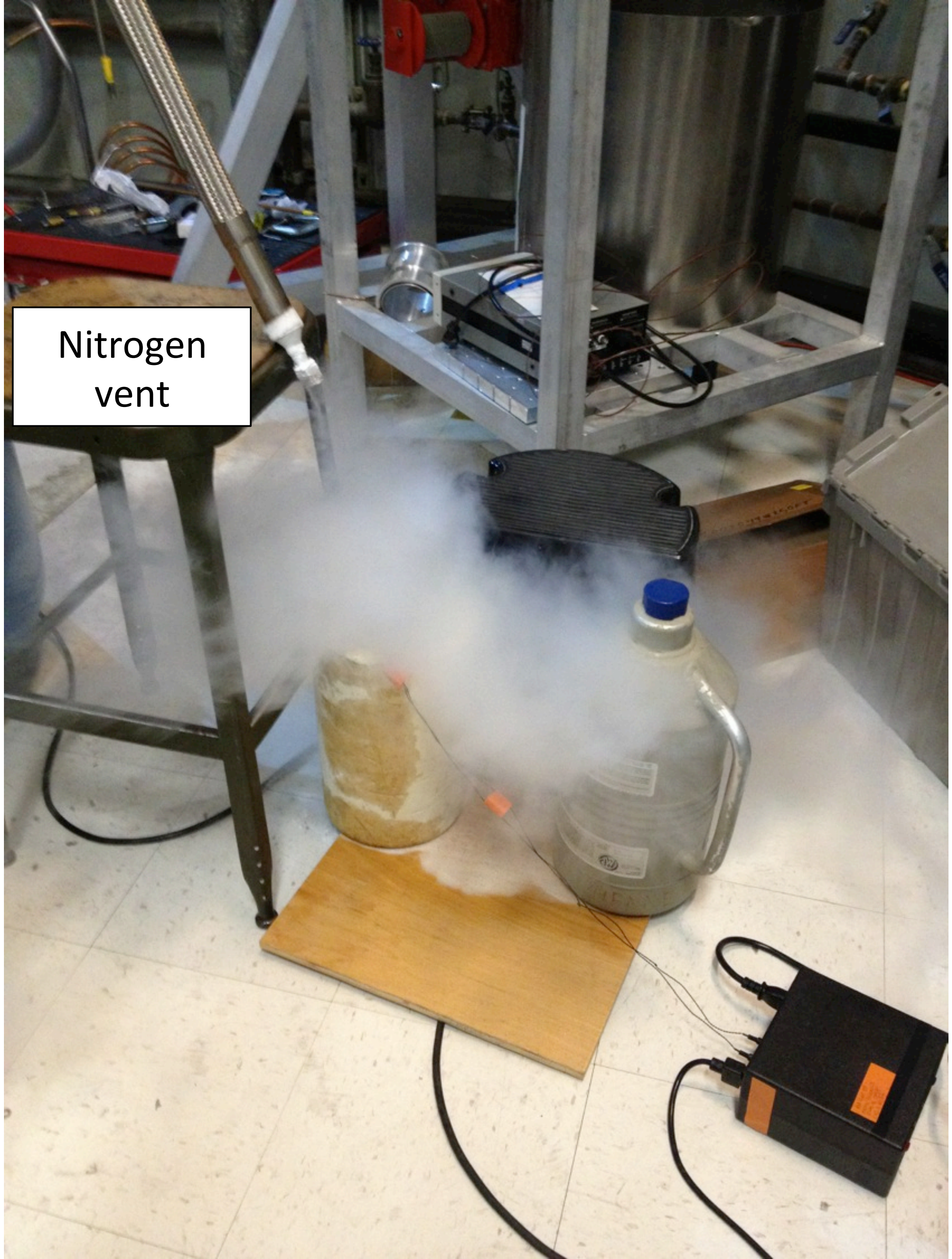
Heat shield

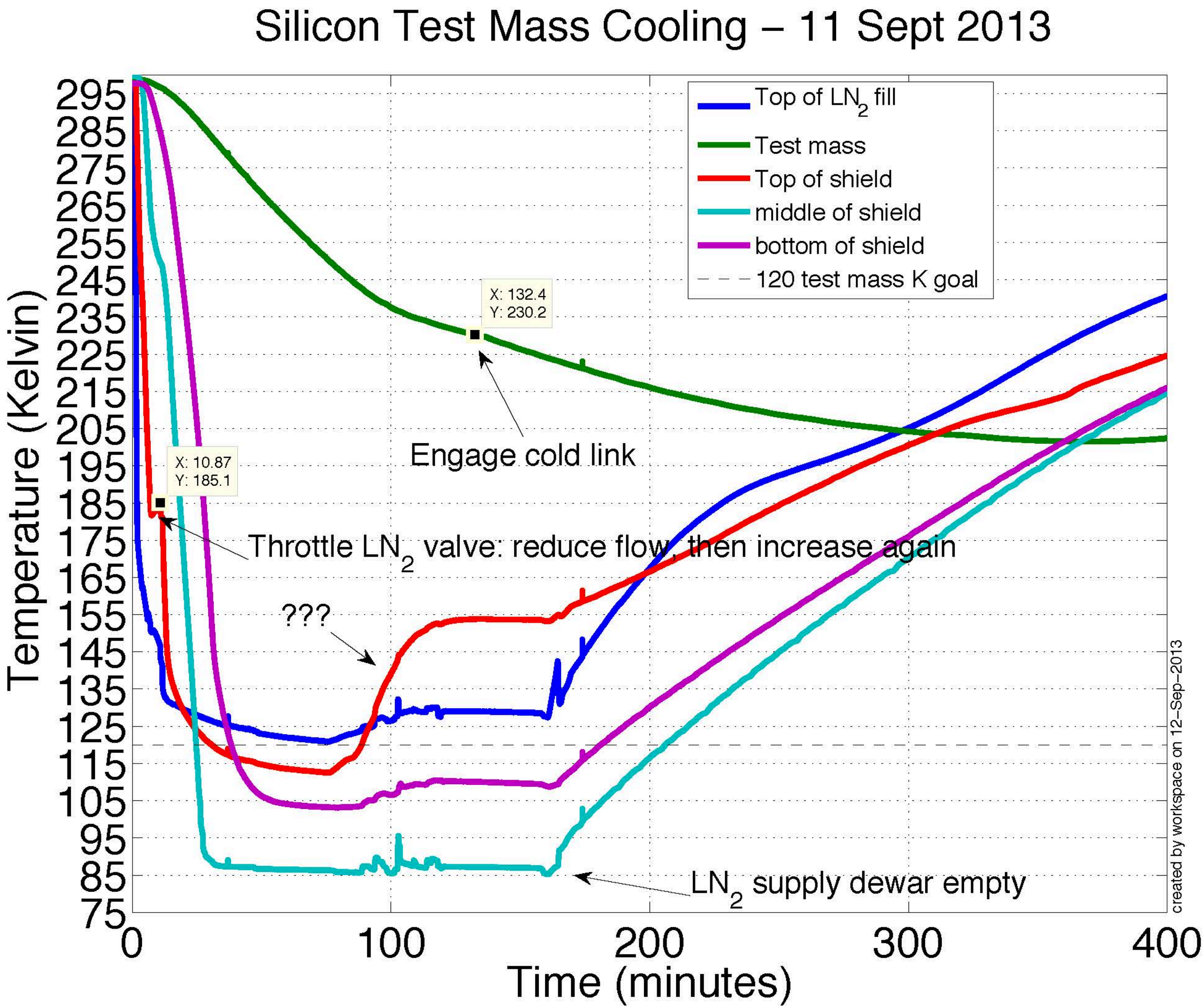




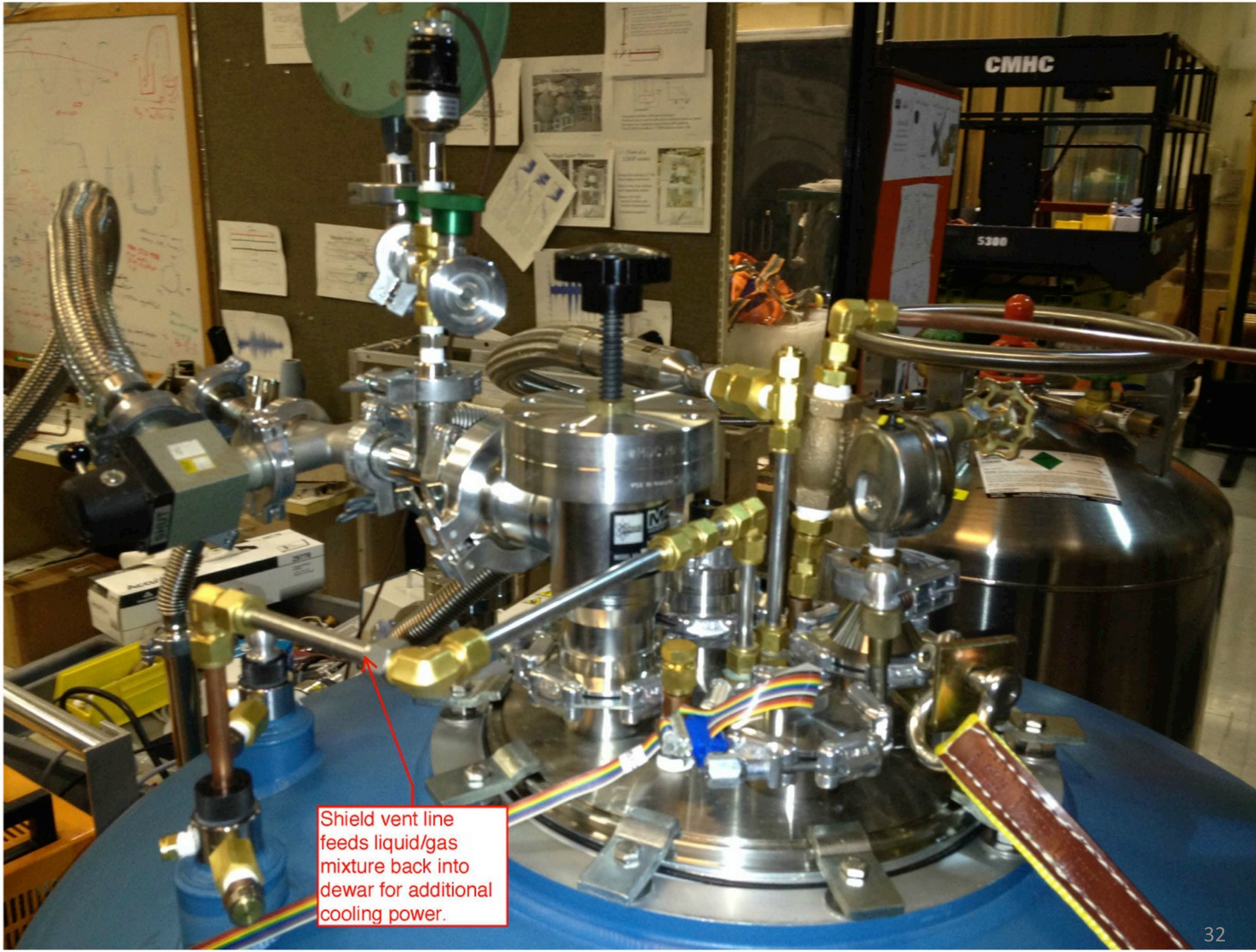
Test dewar
Nitrogen plumbing
Flexible cold link
1 kg Si test mass
Temperature sensor clamp


Test dewar
Liquid nitrogen dewar
Pumps

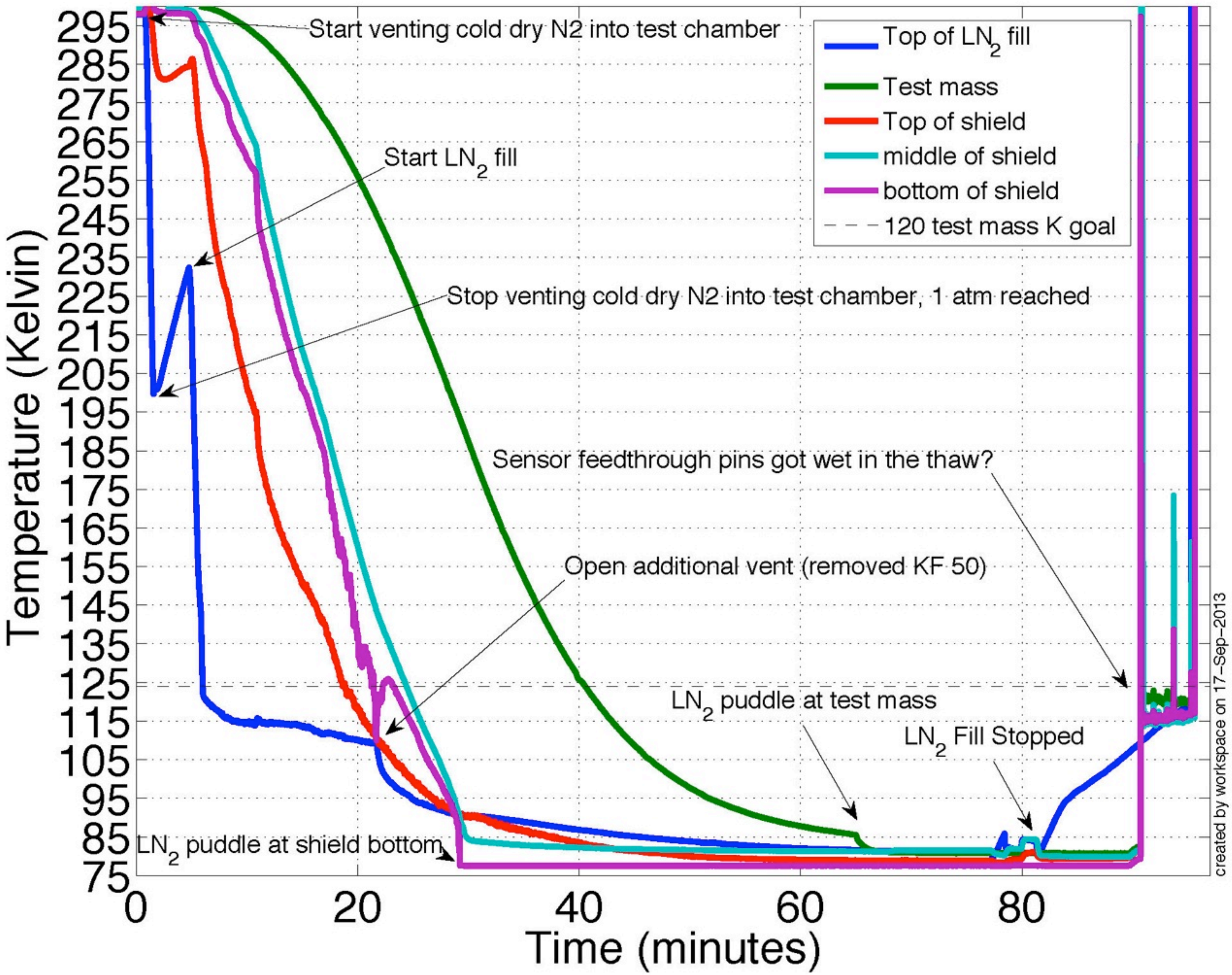

Nitrogen
vent



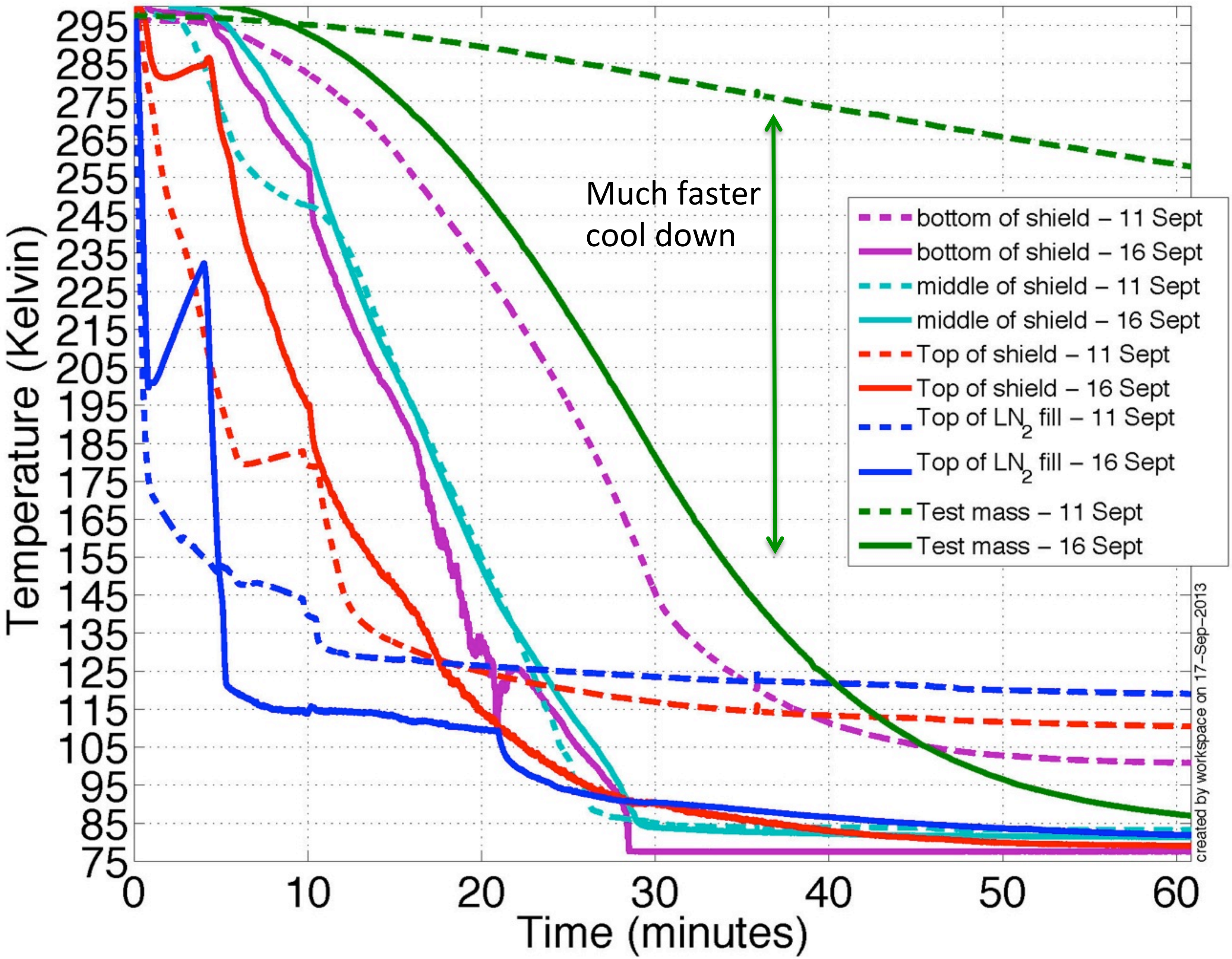
Silicon Test Mass Cooling – 11 Sept 2013
Temperature (Kelvin)
Time (minutes)
Top of LN2 fill
Test mass
Top of shield
middle of shield
bottom of shield
120 test mass K goal
X: 132.4
Y: 230.2
X: 10.87
Y: 185.1
Engage cold link
Throttle LN2 valve: reduce flow, then increase again
???
LN2 supply dewar empty
created by workspace on 12-Sep-2013


CMHC
5300
Shield vent line feeds liquid/gas mixture back into dewar for additional cooling power.

Silicon Test Mass Cooling – 16 Sept 2013



Silicon Test Mass Cooling – 11 and 16 Sept 2013



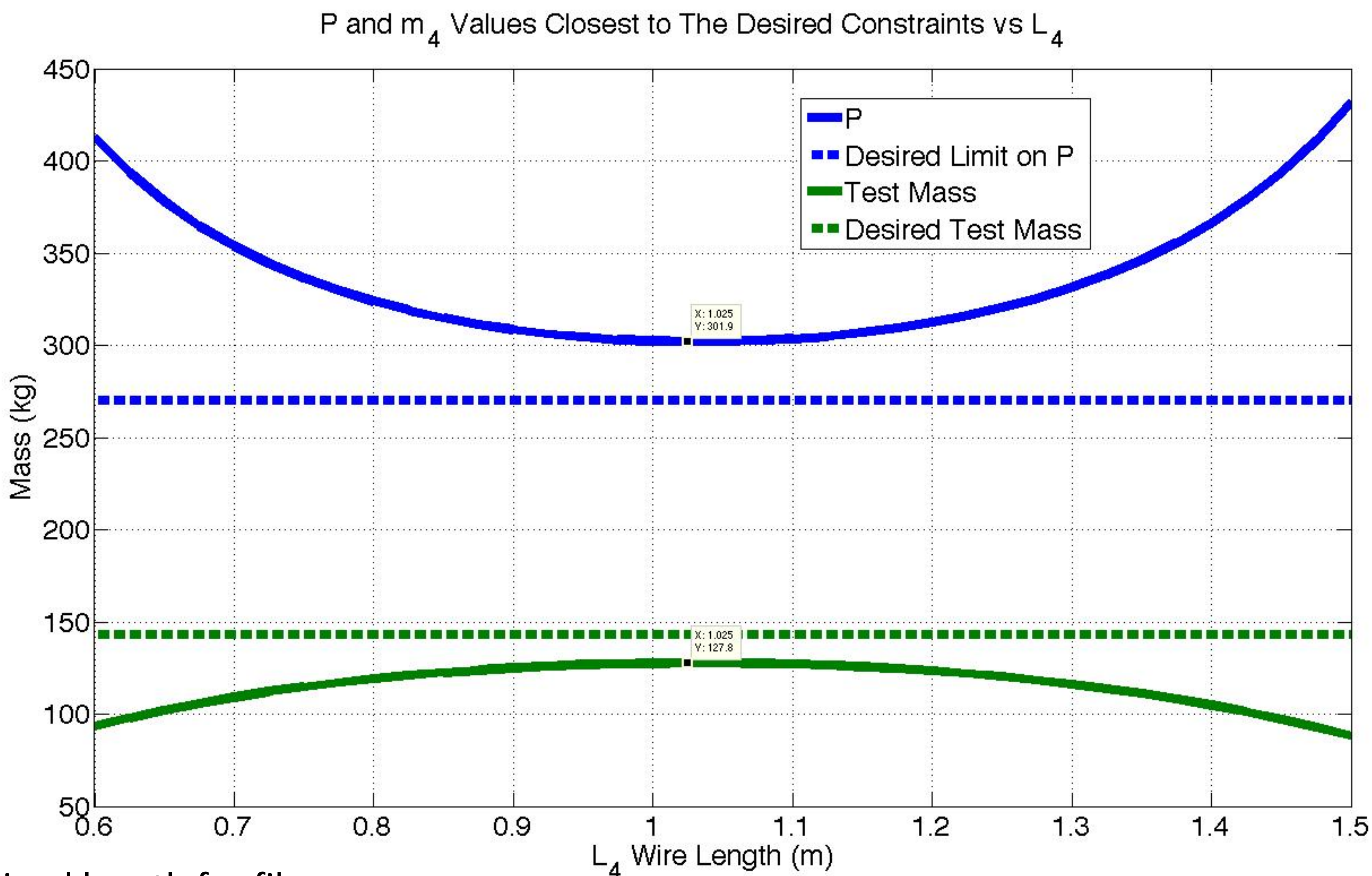
LIGO

Future work

- More cooling experiments
  - Iterate liquid nitrogen cooling design
  - Apply emissive coatings
- Modeling to understand cooling results
- Modeling to extrapolate results to LIGO III
- More complicated experiments
  - Hang test mass on blade spring
  - Move LN2 system onto vacuum seismic table with minimal seismic impact

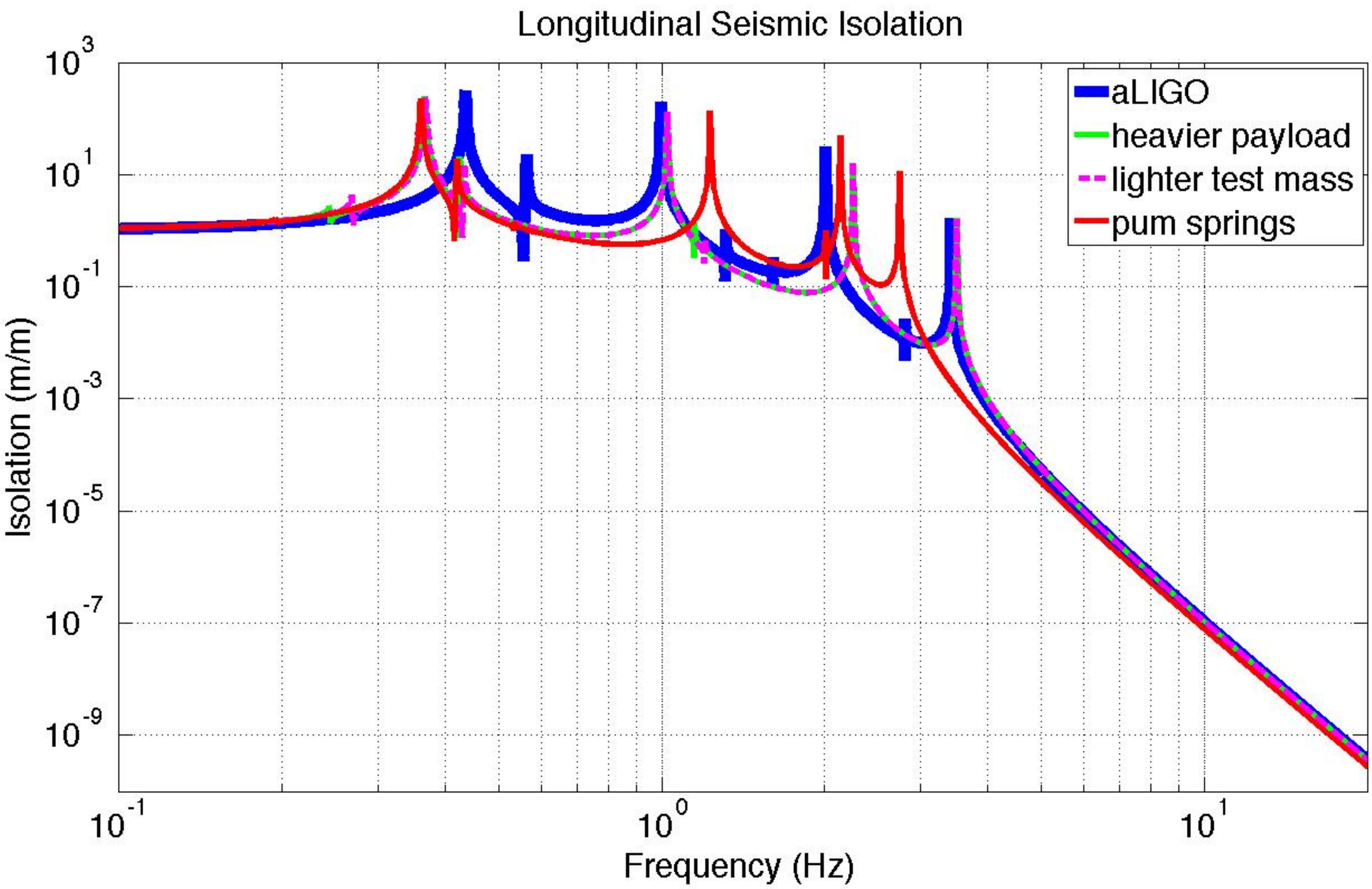
Backups

Optimal Fiber Length

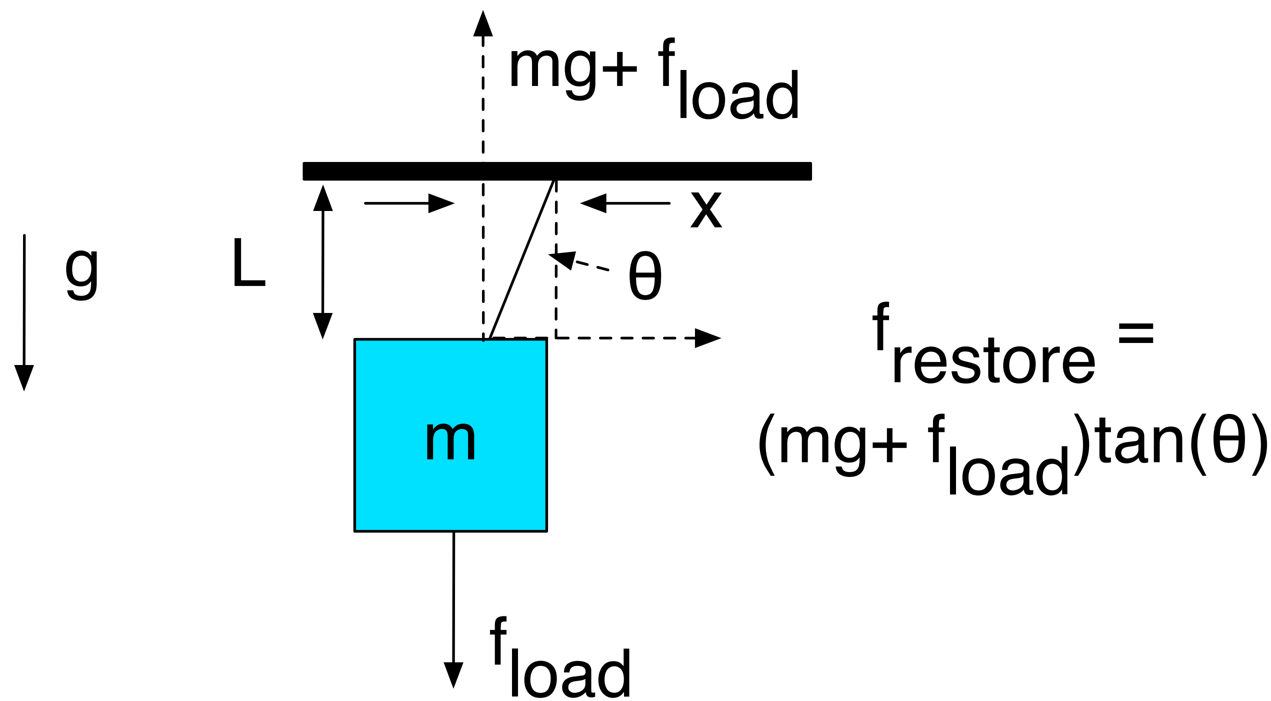


Optimal length for fiber stress of 1.4 Gpa.

Comparing Quad Models



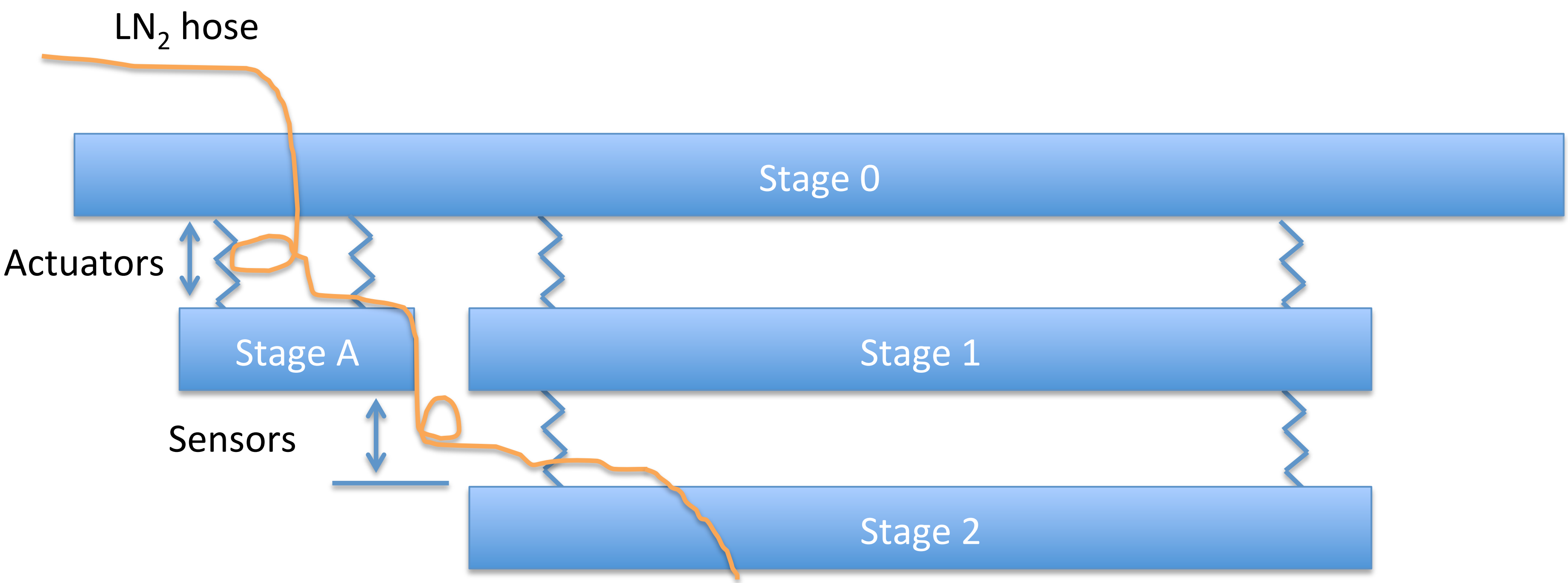
Longitudinal Stiffness



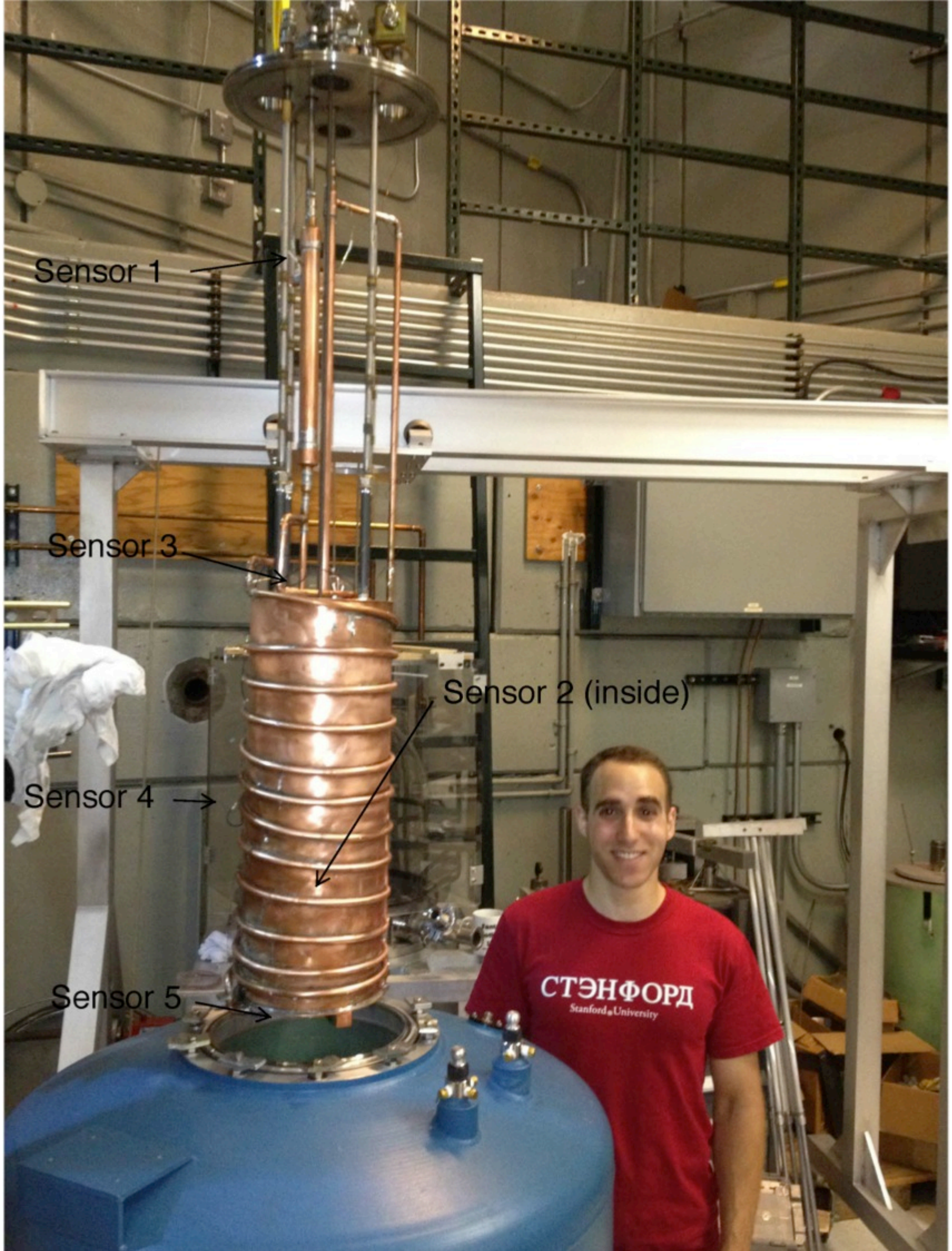
$$k_i = \frac{g}{L_i}\left(m_1 + m_2 + \ldots + m_i\right)$$

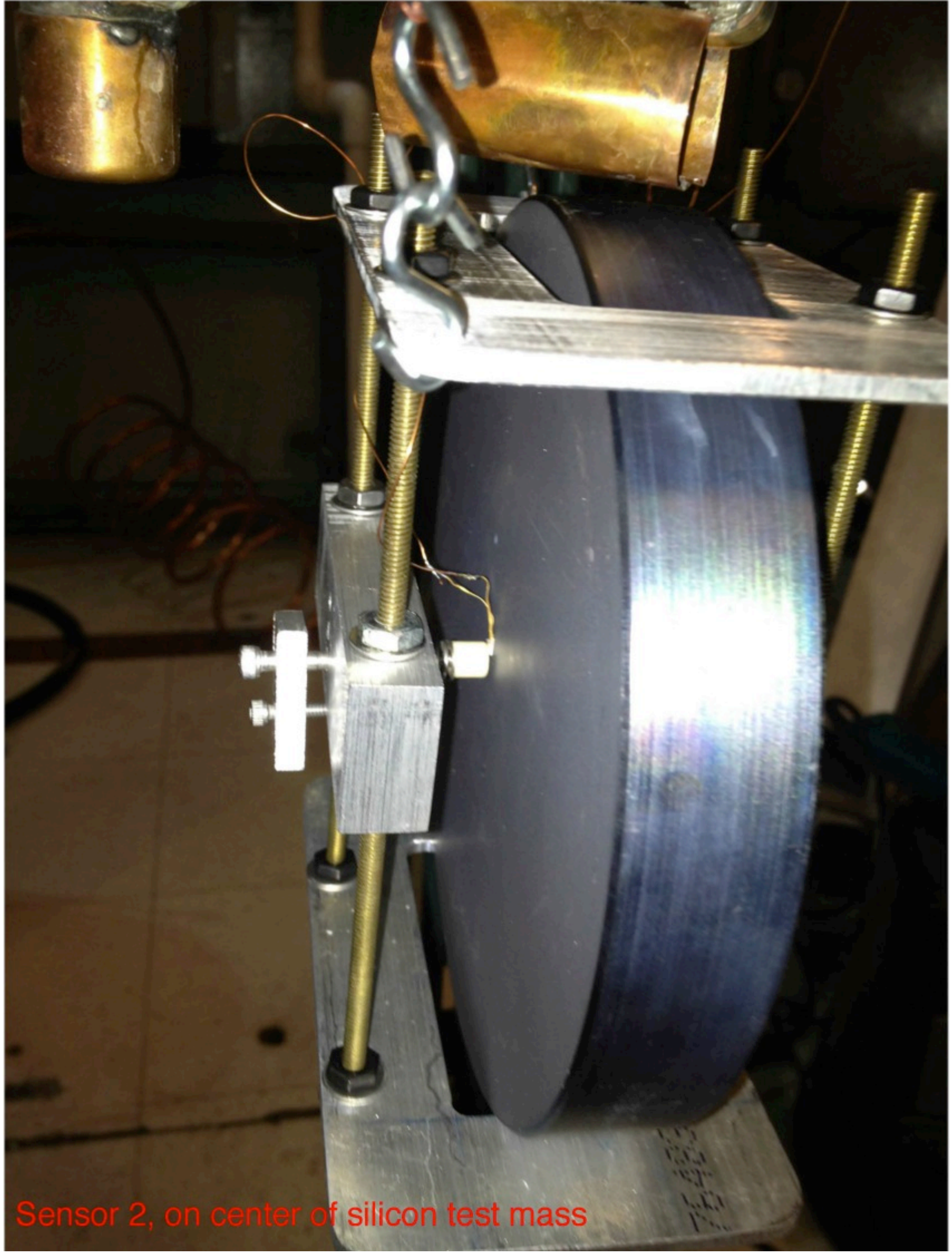
* Stiffness is the tension in the wire divided by the wire length

How to get a LN2 Hose to ST2

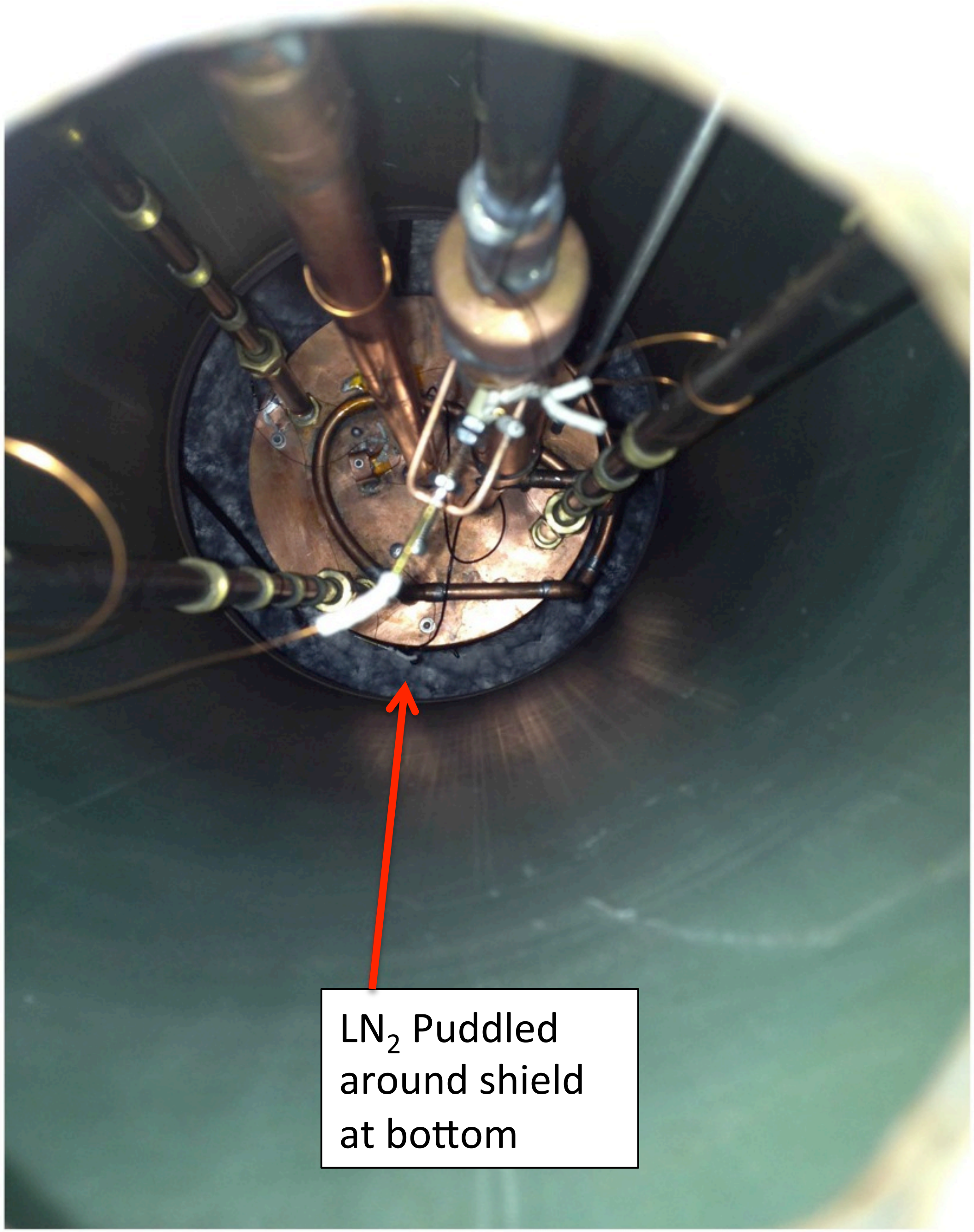


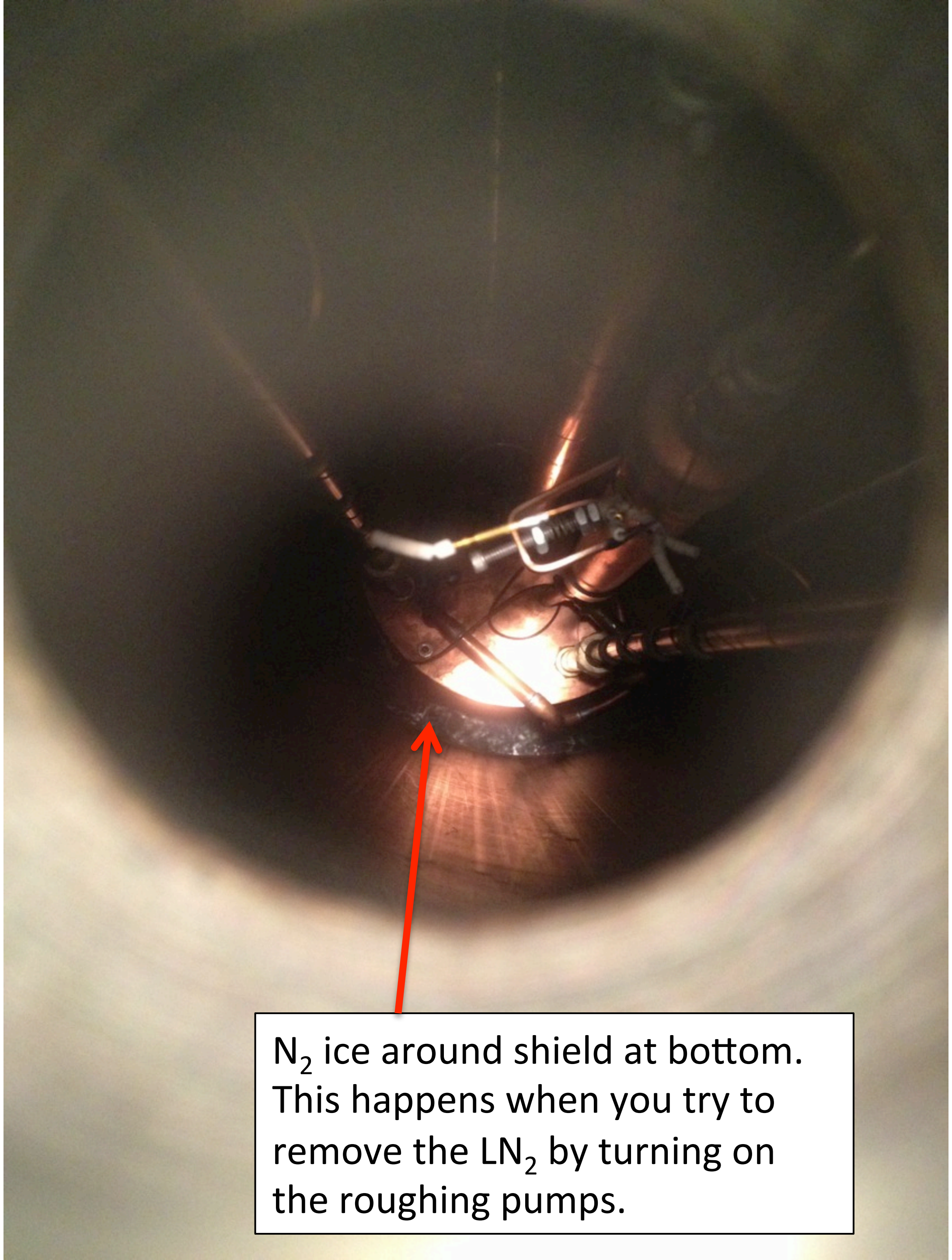
Extra stage, A, in parallel with stage 1 carries hose. Stage A is actuated to follow stage 2 so the hose has does not short seismic isolation.


Sensor 1
Sensor 3
Sensor 2 (inside)
Sensor 4
Sensor 5
СТЭНФОРД
Stanford University



Sensor 2, on center of silicon test mass


LN_2 Puddled around shield at bottom



N_2 ice around shield at bottom. This happens when you try to remove the LN_2 by turning on the roughing pumps.