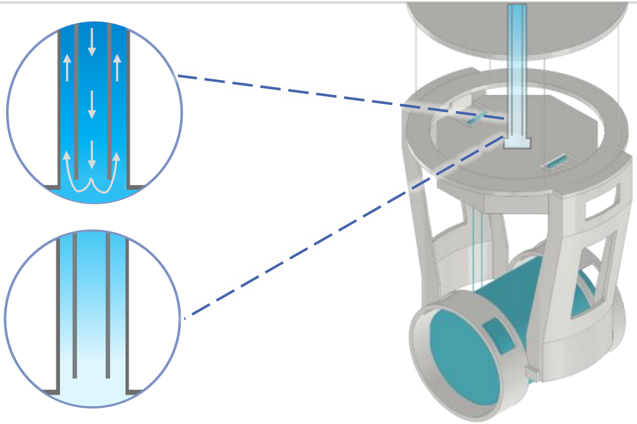
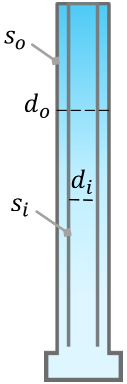
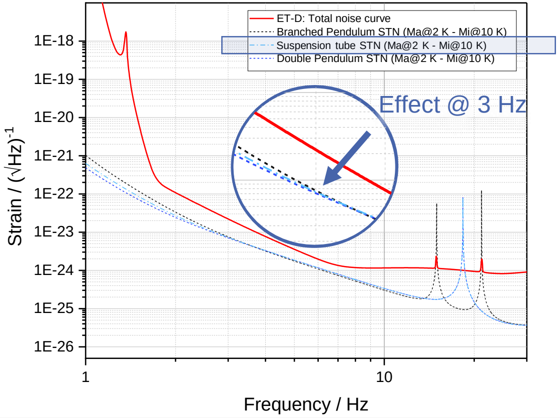
He-II filled marionette suspension for the cryogenic payload of the ET-LF interferometer

Xhesika Koroveshi
Steffen Grohmann

Gravitational Wave
Advanced Detector Workshop
23-27 May 2022







Sensitivity goal of ET-LF

- ET-LF's goal for sensitivity at the detection frequency band **(3 Hz ... 30 Hz)**

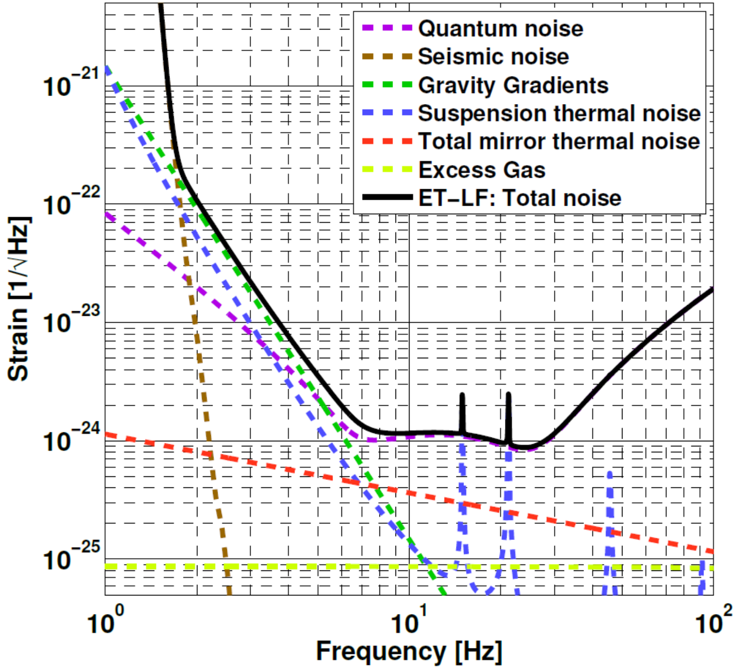


Figure: ET Conceptual Design Study (2011)

ET Low-frequency Interferometer

- Cryogenic optics at T~ 10..20 K
- Suspension thermal noise (STN) dominant at this frequency range
- Low-noise cooling methods required

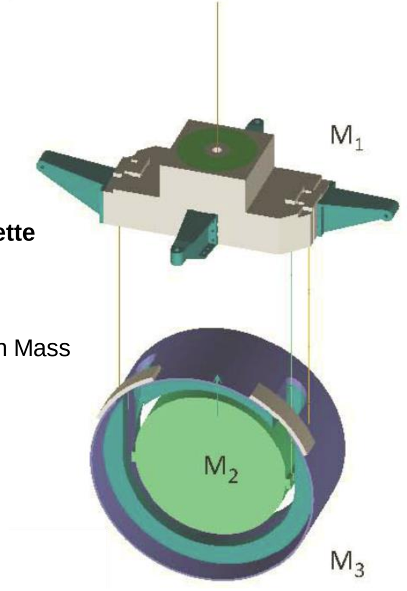
ET-LF Payload basic design parameters

Branched pendulum suspension

M_1: Marionette

M_2: Mirror

M_3: Reaction Mass



VIRGO-like payload - ET Design Report Update (2020)

ET-LF suspension design parameters (2011)

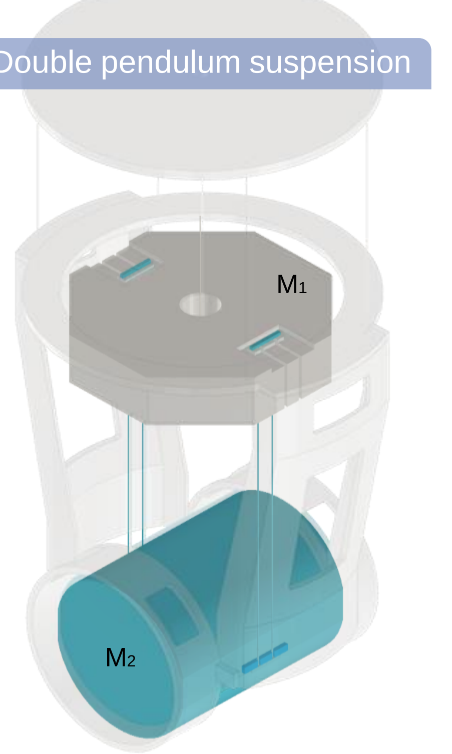
	Marionetta	Recoil Mass	Mirror
Masses for ETDLF (kg)	422	211	211
Wire Diameter (mm) **(updated)**	3 **5**	3	3
Wire length (m)	2	2	2
Wire Material	Ti6Al4V	Silicon	Silicon
Loss Angle	10^{-5}	10^{-8}	10^{-8}
Temperature (K)	2	10	10

ET Conceptual Design Study (2011)

Crutial parameters for:

- Suspension thermal noise (STN)
- Cryostat tower dimensions
- Mechanical and thermal dimensioning
- …

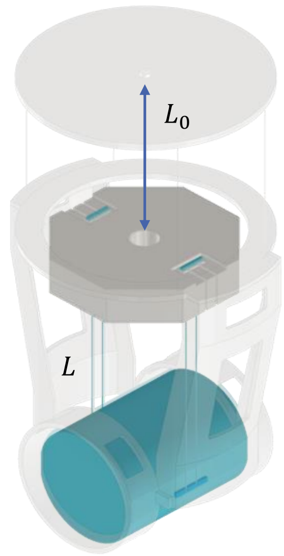
Double pendulum suspension



AdVirgo-like payload - M. Stamm (2021)

Conclusions based on STN sensitivity analysis [1]

- A general STN sensitivity analysis shows that in order to achieve the **ET-D sensitivity goal** [2] :
  - $T_{\text{marionette}}$ has a crutial role in the relation: STN ↔ payload design
    - $T_{\text{marionette}}@2\ \text{K}$ → Marionette suspension length of $L_0 < 2.0\ \text{m}$ possible
    - $T_{\text{marionette}}@10\ \text{K}$ → Marionette suspension length of $L_0 = 2.0\ \text{m}$
    - ➡ **Crucial for ET-LF cryostat tower dimensions!**
  - Mirror suspension length no less than $L = 2.0\ \text{m}$



Feasible solution to achieve a marionette temperature $T_{\text{marionette}} = 2\ \text{K}$?

Source: [1] Koroveshi X and Grohmann S. Feasibility of He-II suspensions based on thermal noise modelling (2021) – TDS Link.
[2] ET Science Team. ET Conceptual Design Study (2011) – TDS Link

Helium-based cooling concept using He-II suspension tube

Payload heat extraction via He-II

Two liquid phases of ^{4}**He**:

- **He-I** (classical liquid helium)
  - Behaviour: ~ideal gas

$T > T_\lambda$

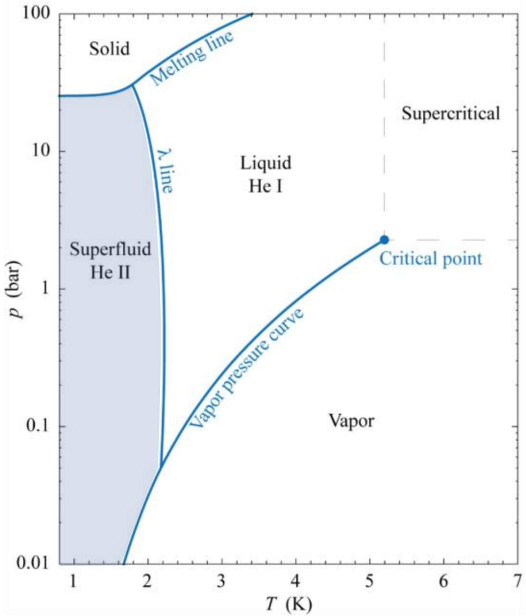
$T_\lambda(1\ \mathrm{atm}) \approx 2.17\ \mathrm{K}$

$T < T_\lambda$

- **He-II** (*"two fluid model"* [1][2])
  - Normal component
  - Superfluid component
    - **Bose-Einstein condensate**

He-II = Ultra-quiet,
thermally efficient liquid phase!

^{4}He phase diagram:



Sources: [1] Tisza, L. Transport Phenomena in Helium II. Nature 141, 913 (1938).
[2] Landau, L. Theory of the Superfluidity of Helium II. Phys. Rev. 60, 356-358 (1941).

Payload heat extraction via He-II

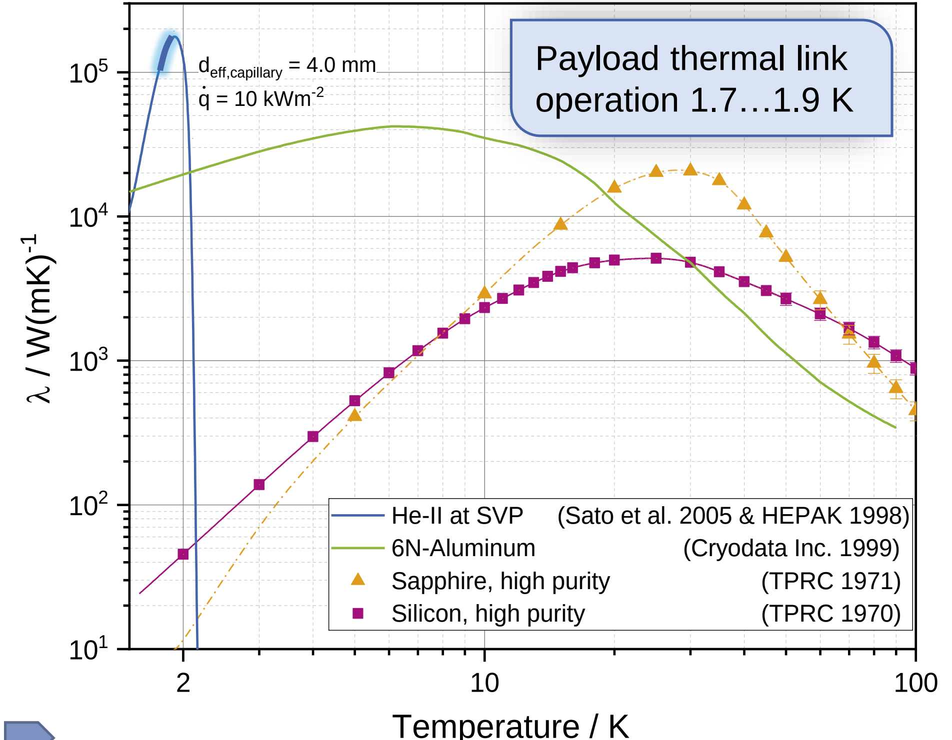
Two liquid phases of ^{4}**He**:

- **He-I** (classical liquid helium)
  - ➢ Behaviour: ~ideal gas

$T_\lambda(1\ \text{atm}) \approx 2.17\ \text{K}$ $T > T_\lambda$ / $T < T_\lambda$

- **He-II** (*"two fluid model"* [1][2])
  - Normal component
  - Superfluid component
    - ➢ **Bose-Einstein condensate**

He-II = Ultra-quiet,
thermally efficient liquid phase!



Courtesy of L.Busch (2021)

Sources: [1] Tisza, L. Transport Phenomena in Helium II. Nature 141, 913 (1938).
[2] Landau, L. Theory of the Superfluidity of Helium II. Phys. Rev. 60, 356-358 (1941).
[3] Liquid Helium II the superfluid (part 2 The transition to the superfluid state) - YouTube

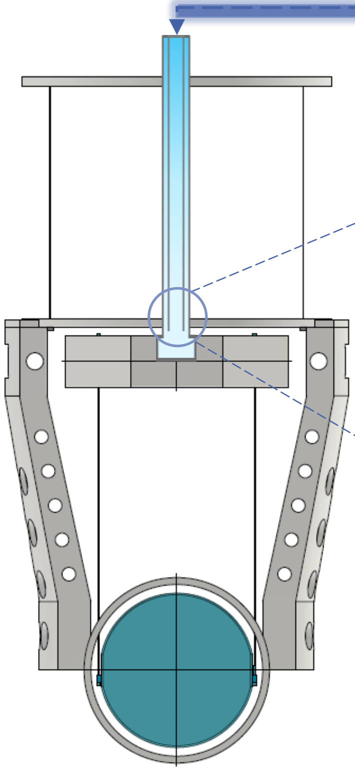
[3]

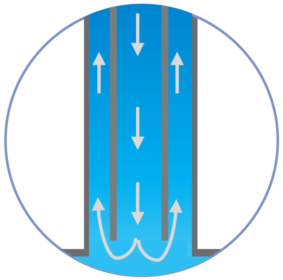
ET-LF payload: Cooling via He-II suspension tube

Platform (PF)

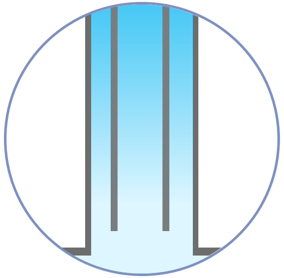
Marionette (MAR)

Mirror (MI)

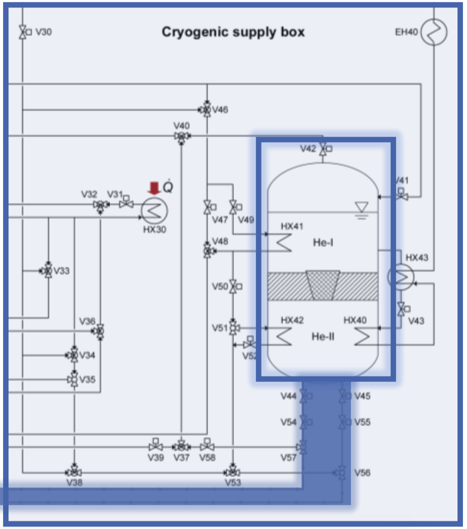




- He-I flow for cool-down



- He-II (no macroscopic flow) for steady-state operation



L. Busch (KIT, 2021) – TDS Link

He supply capillaries:

- Cryogenic supply box ↔ Payload (i.e. suspension tube) interface
- Length ~ x·10 m → cryogenic supply box remotely placed from optics to minimize vibration input

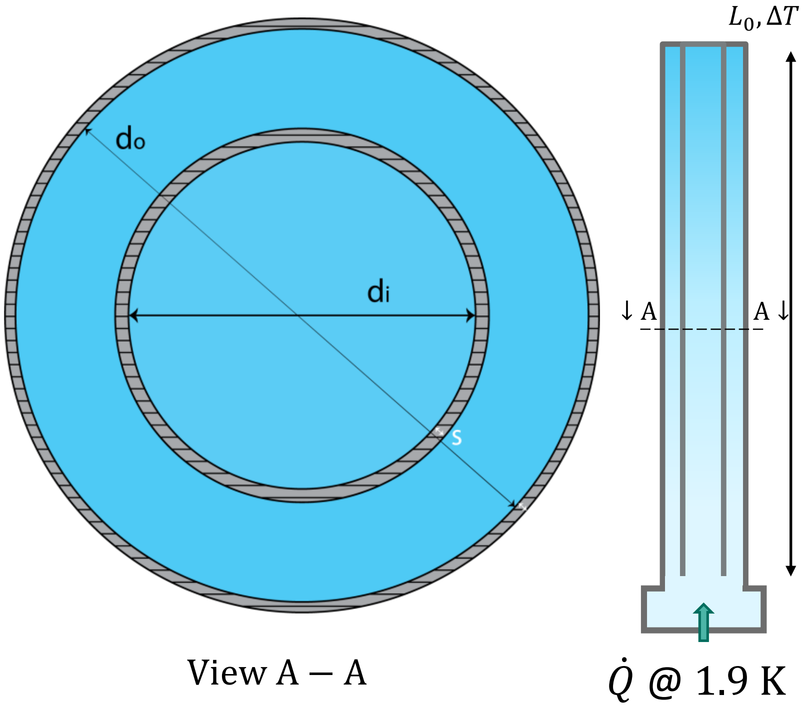
Courtesy of M. Stamm (2021)

He-II suspension tube:
Thermal & mechanical dimensioning

Design of He-II suspension tube

Design parameters:

- T – operational temperature @ 1.9 K,
- ΔT – gradient along suspension capillary,
- d_i, d_o – inner and outer diameter,
- s_i, s_o – inner and outer wall thicknesses,
- L_0 – suspension capillary length,
- $\dot{Q}$ – cooling capacity



Thermal and mechanical dimensioning

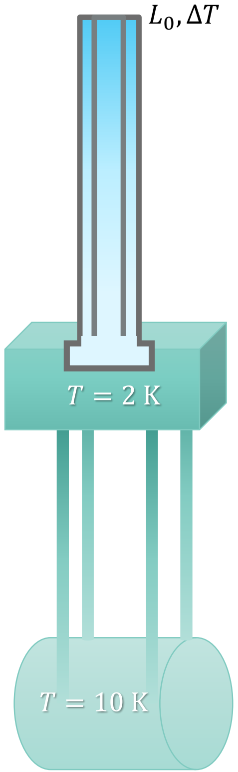
$\dot{Q} \rightarrow d_o \rightarrow s_o$

with: $d_i, \lambda_{He-II}(\dot{q}, d_h)$
@ $\Delta T = 50$ mK or 100 mK
@ $L_0 = 0.8 - 2.0$ m

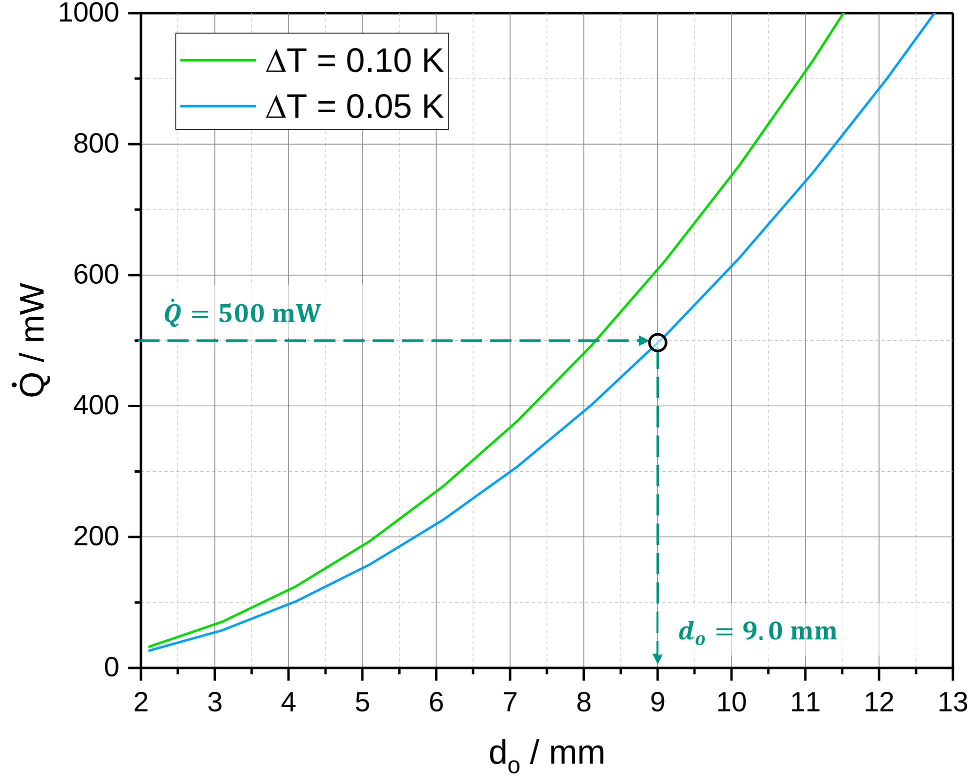
with: mechanical safety factor
(SF = 2 or 3), $\sigma_{Ti-Alloy}$, F_{ma}

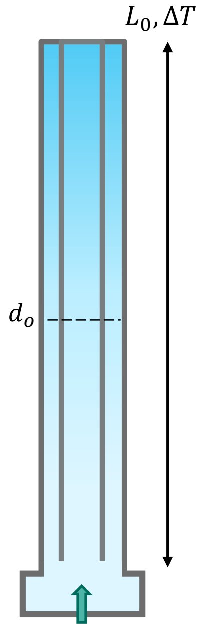
+ **Payload design parameters**

Suspension thermal noise



Cooling capacity via suspension tube



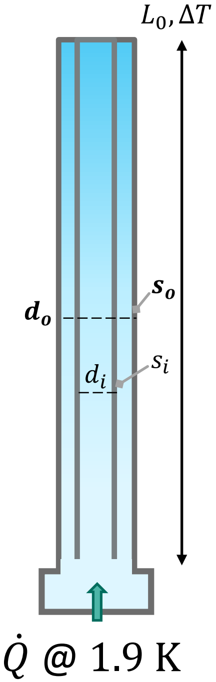


$\dot{Q}$ @ 1.9 K

$(L_0 = 2.0\ \mathrm{m})$

Conclusions I

- Cooling the marionette @ 2 K using a double-walled, suspension tube filled with He-II is thermally & mechanically feasible:
  - Cooling capacities up to $0.5\ \mathrm{W}$, or even up to $1.0\ \mathrm{W}$, are possible.
  - $T_{\mathrm{marionette}}$@ $2\ \mathrm{K}$ and T_{mirror}@ $14 - 20\ \mathrm{K}$, with $\Delta T \approx 50\ \mathrm{mK}$ along suspension.
  - Consistency with the STN analysis is shown in the next slides!



Suspension thermal noise (STN) modelling

Suspension thermal noise model

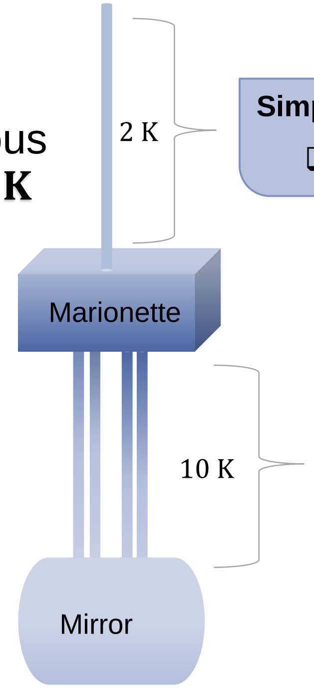
Karlsruhe Institute of Technology

Suspension thermal noise modelling:

- **Discrete FDT model [1]** for inhomogeneous stage temperatures $\boldsymbol{T}$ @ $\mathbf{Ma: 2\ K\ - Mi: 10\ K}$

- Payload system as double pendulum
  - Marionette suspension → rigid spring
  - Mirror suspensions → elastic beams

- Energy dissipation via loss angle Φ
  - included in complex $\boldsymbol{k}$ or $\boldsymbol{E}$



Simple pendulum model

- $k = k_g \cdot (1 + D + i \cdot \boldsymbol{\Phi}_{\mathbf{fiber}}(\boldsymbol{\omega}) \cdot D)$

Pendulum model with elastic beam fiber

- $E = E_0 \cdot (1 + i \cdot \boldsymbol{\Phi}_{\mathbf{fiber}}(\boldsymbol{\omega}))$

[1] Concept based on Komori et al. Direct approach for the fluctuation-dissipation theorem under nonequilibrium steady-state conditions Phys. Rev. D 97, 102001 (2018).

Suspension thermal noise model

Suspension thermal noise modelling:

- **Discrete FDT model [1]** for inhomogeneous stage temperatures $\boldsymbol{T}$ **@ Ma: 2 K – Mi: 10 K**

Loss angle Φ

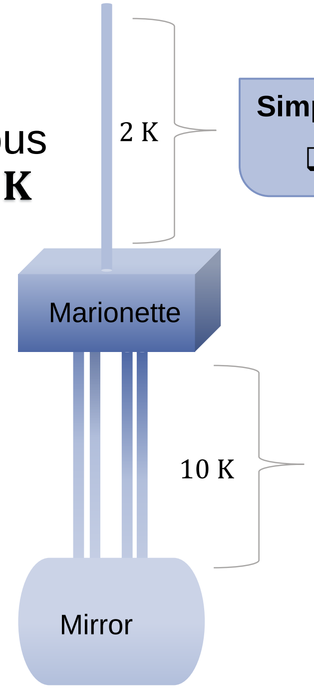
→ Energy dissipation: included in complex $\boldsymbol{k}$ or $\boldsymbol{E}$

$$\Phi_{\text{fiber}}(\omega) = \Phi_{\text{bulk}} + \Phi_{\text{thermoelastic}}(\omega) + \Phi_{\text{surface}}$$

For marionette stage

$$\Phi_{\text{fiber}}(\omega) \cdot D$$

Dilution factor: $\mathrm{D} = \frac{\sqrt{M \cdot g \cdot E \cdot J}}{2 \cdot M \cdot g \cdot L}$



Simple pendulum model

- $k = k_{\mathrm{g}} \cdot (1 + D + i \cdot \boldsymbol{\Phi}_{\text{fiber}}(\boldsymbol{\omega}) \cdot D)$

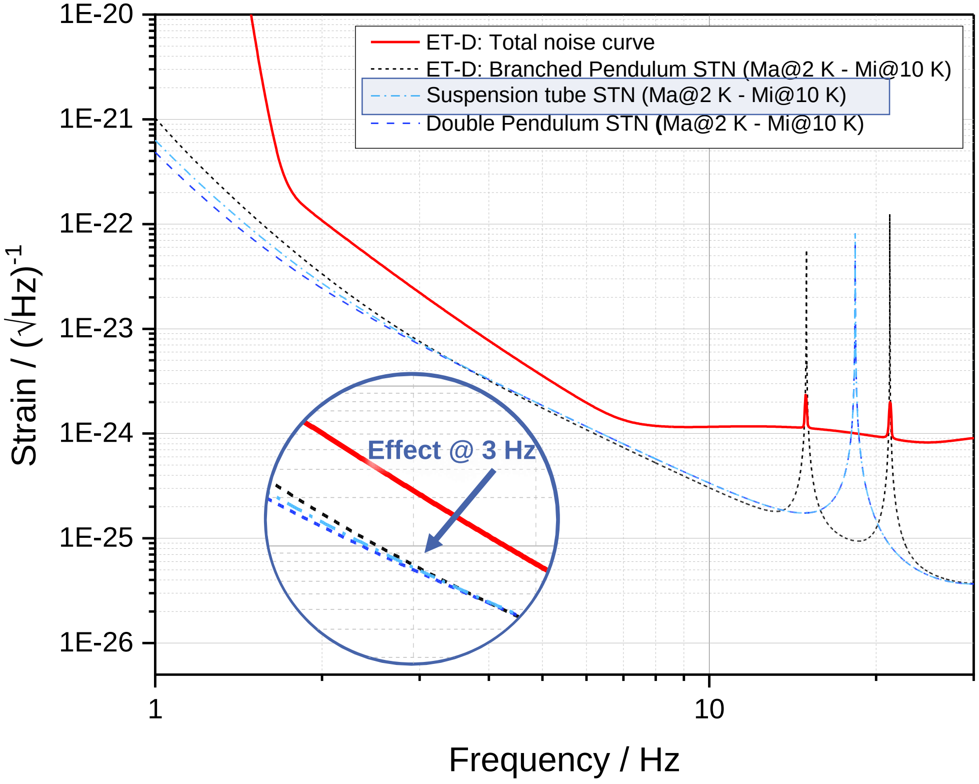
Pendulum model with elastic beam fiber

- $E = E_0 \cdot (1 + i \cdot \boldsymbol{\Phi}_{\text{fiber}}(\boldsymbol{\omega}))$

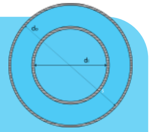
[1] Concept based on Komori et al. Direct approach for the fluctuation-dissipation theorem under nonequilibrium steady-state conditions Phys. Rev. D 97, 102001 (2018).

He-II suspension tube: Suspension thermal noise analysis

Suspension thermal noise (Suspension tube)



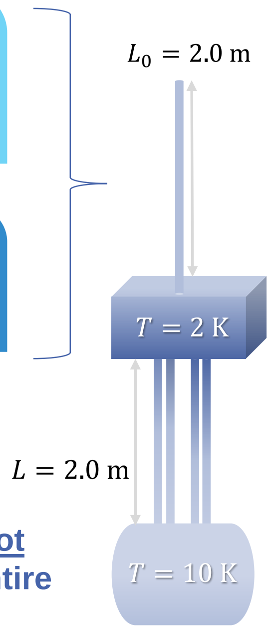
Suspension tube scenario:



- ✓ $\dot{Q} = 0.5$ W, $\Delta T = 0.05$ K
- ✓ $d_o = 9.0$ mm, $d_i = 4.5$ mm, $s_o = 0.39$ mm

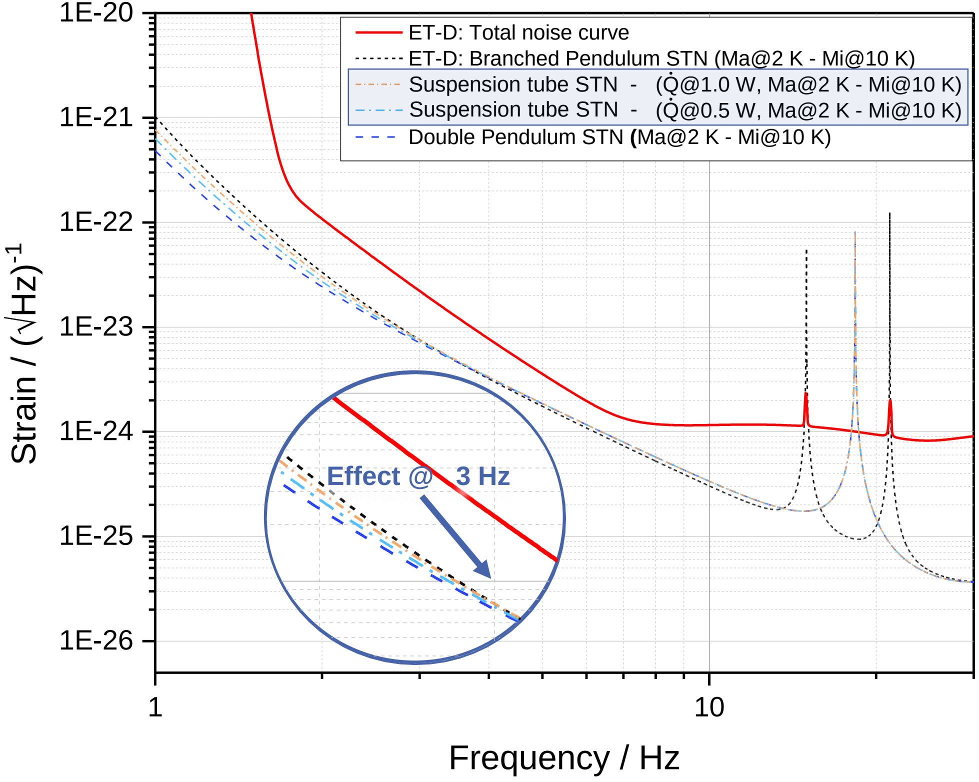
Double pendulum scenario:

- ✓ $d_o = 5$ mm



➡ **He-II suspension tube <u>does not</u> affect ET-LF sensitivity over entire frequency band**

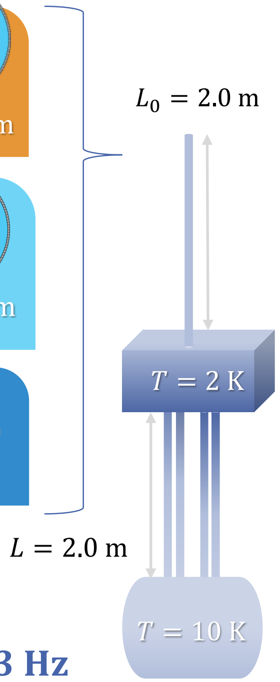
Suspension thermal noise (Suspension tube, $\neq \dot{Q}$)



Suspension tube scenario:
- ✓ $\dot{Q} = 1.0$ W, $\Delta T = 0.05$ K
- ✓ $d_o = 12.75$ mm, $d_i = 6.3$ mm, $s_o = 0.28$ mm

Suspension tube scenario:
- ✓ $\dot{Q} = 0.5$ W, $\Delta T = 0.05$ K
- ✓ $d_o = 9.0$ mm, $d_i = 4.5$ mm, $s_o = 0.39$ mm

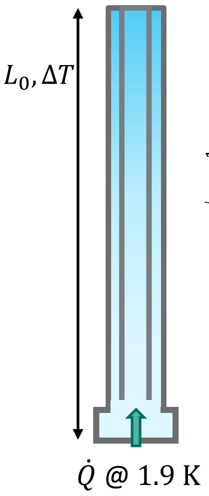
Double pendulum scenario:
- ✓ $d_o = 5$ mm

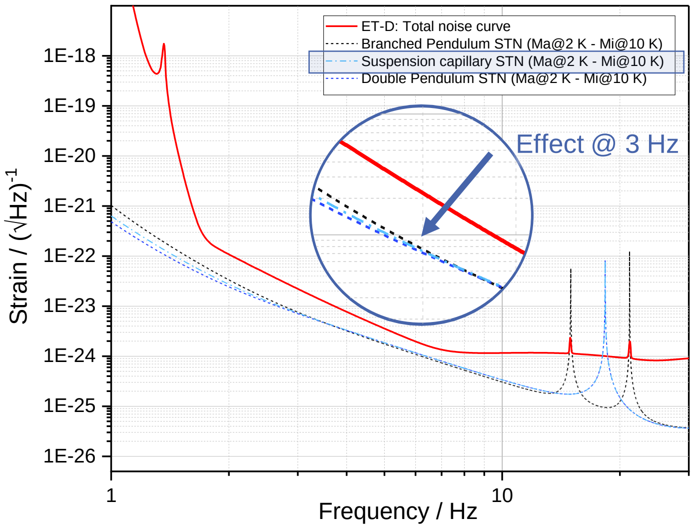


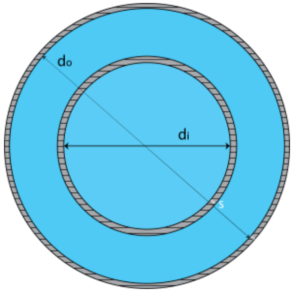
➡ **Suspension tube has a marginal effect on STN @ $f \geq 3$ Hz**

Conclusions II

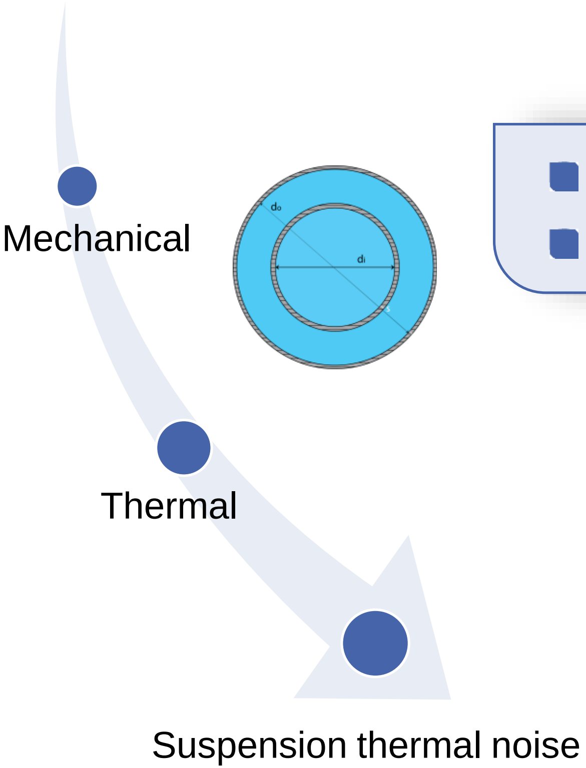
- Double-walled suspension tube filled with He-II for cooling marionette @ 2 K is feasible regarding thermal suspension noise:
  - The increase of STN is negligable @ $f > 3\ \mathrm{Hz}$, for both scenarios of cooling capacity @0.5 W and @1.0 W.



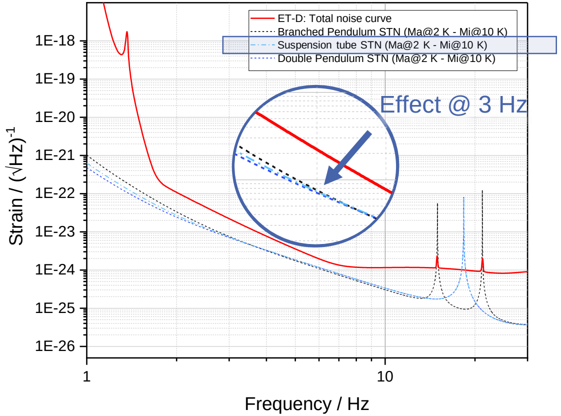


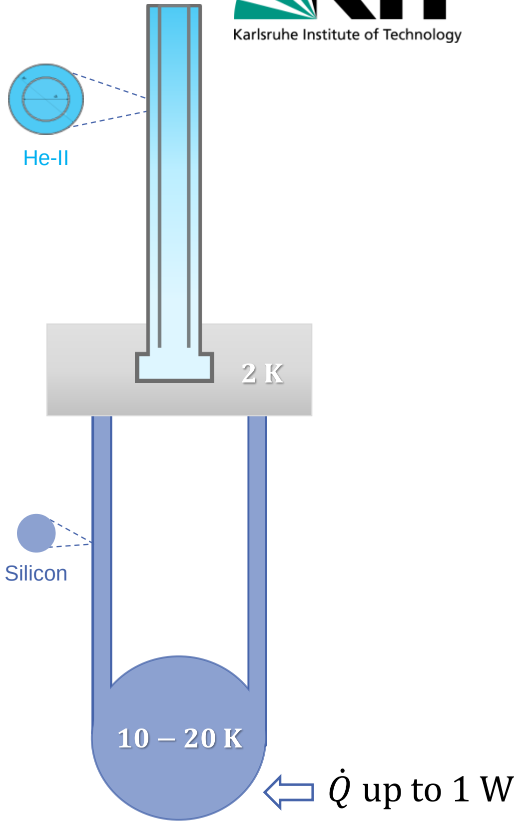


Status of He-II suspension concept



- Feasibility shown theoretically
- Experimental proof of concept!





Thank you for your attention!

xhesika.koroveshi@kit.edu
steffen.grohmann@kit.edu


Institute of Technical Thermodynamics and Refrigeration in Karlsruhe, Germany