Residual gas Brownian noise in LISA PAthfinder

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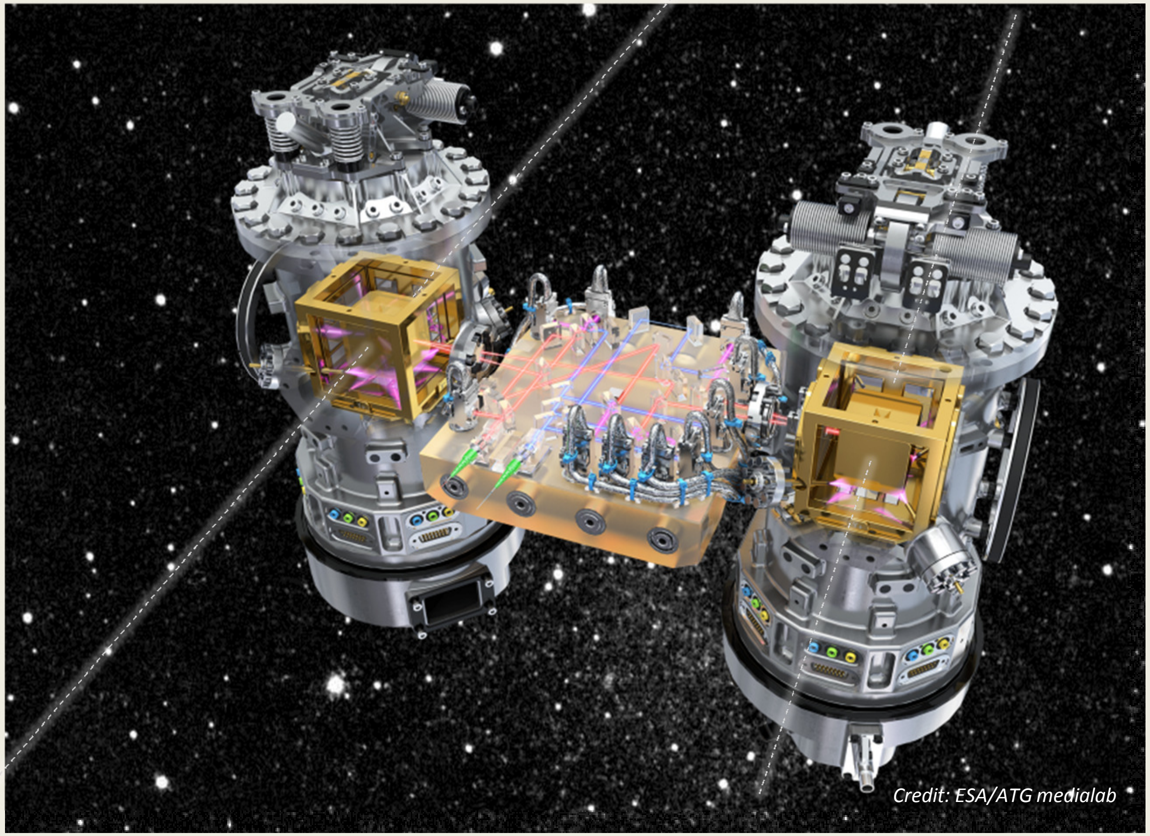
on behalf of LISA PF Team



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Residual gas Brownian noise

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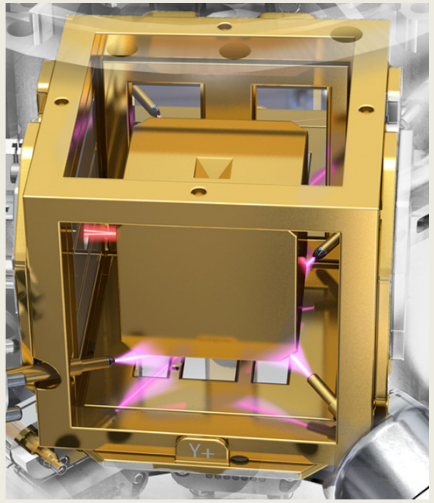
Gas damping of the motion of a macroscopic body is characterized by a viscous damping coefficient proportional to the pressure P

$$\beta = \left| \frac{\partial F}{\partial v} \right|$$



→Brownian force noise arises via the fluctuation -dissipation theorem

$$S_F(\omega) = 4kT\mathrm{Re}\left(\frac{\partial F}{\partial v}\right)$$

Increased over that obtained for a TM in an infinite gas volume by a geometric factor **ρ**
related to the constrained geometry TM inside a
housing with gaps of size «TM side length of s

As demonstrated by simulations and verified with torsion pendulum facility measurements

$$S_{gas_d}^{\frac{1}{2}} = \left(\frac{2\rho P s^2}{m^2} \sqrt{\frac{512\, m_0 k_B T}{\pi}} \left(1 + \frac{\pi}{8}\right) \right)^{\frac{1}{2}}$$

PRL **103,** 140601 (2009) PHYSICAL REVIEW LETTERS week ending 2 OCTOBER 2009

Increased Brownian Force Noise from Molecular Impacts in a Constrained Volume

where m_0 is the mass of the residual gas molecules.

Strategies for suppressing Brownian noise

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Design the Gravitational Reference Sensor with large gaps surrounding the TM.

PRL **103,** 140601 (2009) PHYSICAL REV

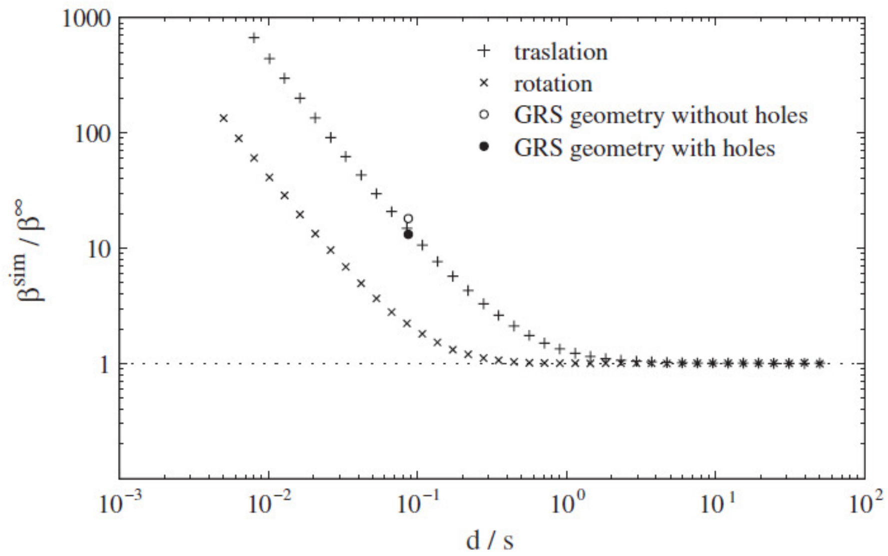
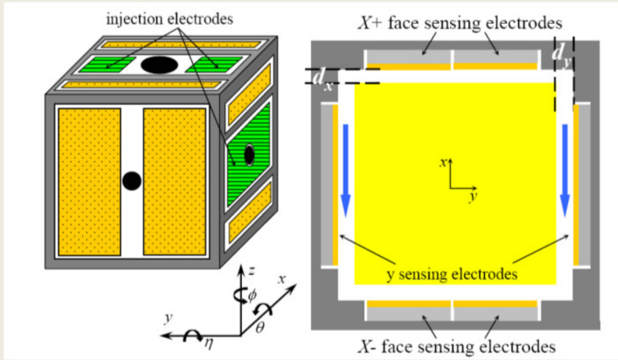
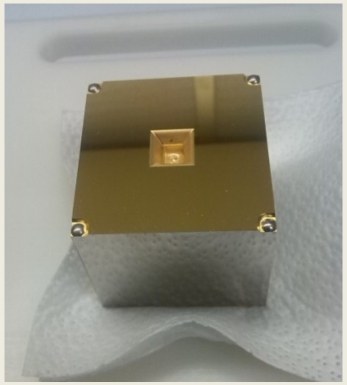


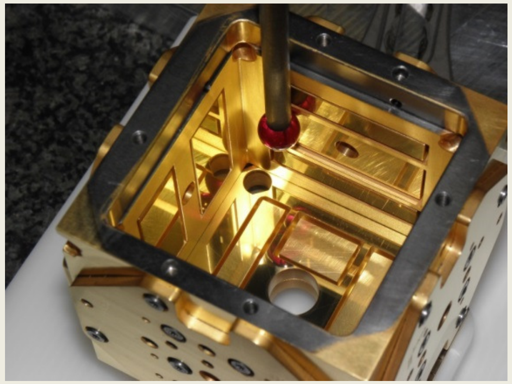
FIG. 5. Gas damping β^{sim} obtained from the numerical simulation for different test mass side lengths s and gap sizes d, normalized to the infinite-volume model prediction β^{∞}.

$$\beta_{tr} \approx \frac{\beta_{tr}^{\infty}}{\ln(s/d)(d/s)^2}. \qquad (7)$$

TM size 46 mm
Sensing electrodes at
d_x=4 mm
d_y=2.9 mm, d_z=3.5mm







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Strategies for suppressing Brownian noise

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Design the Gravitational Reference Sensor with large gaps surrounding the TM.

Brownian noise

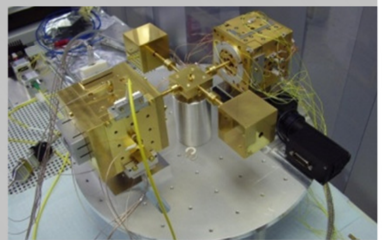
Residual gas (<10^{-5}Pa) damps motion, and causes Brownian noise.
In constrained geometries friction is higher than in infinite volume

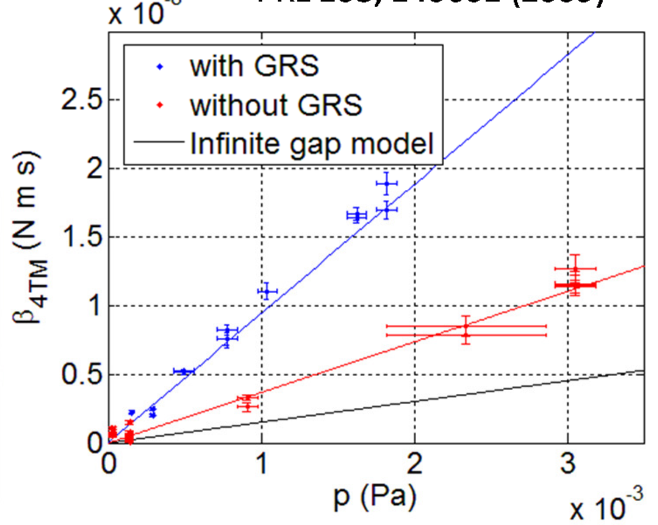
PRL 103, 140601 (2009)

Measurements of viscous gas damping coefficient

$$\beta = -\frac{\partial N}{\partial \dot{\varphi}} = \frac{2I}{\tau}$$

Agreement within 10% with numerical simulations

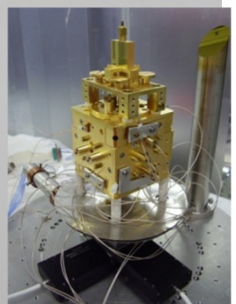


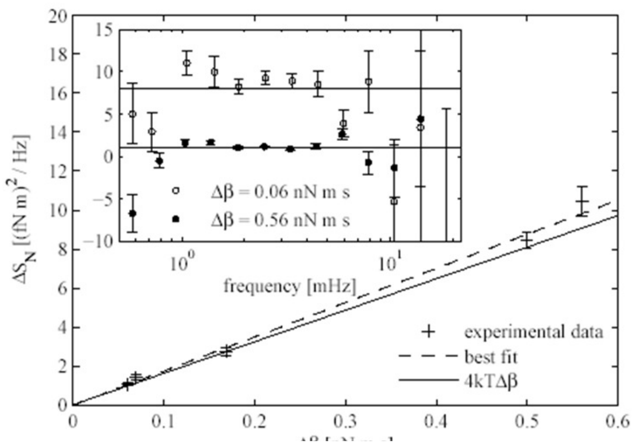


Measurements of torque noise

Difference in measured force noise power within 10% of Fluctuation-Dissipation Theorem prediction

$$S_F = 4k_B T\beta$$





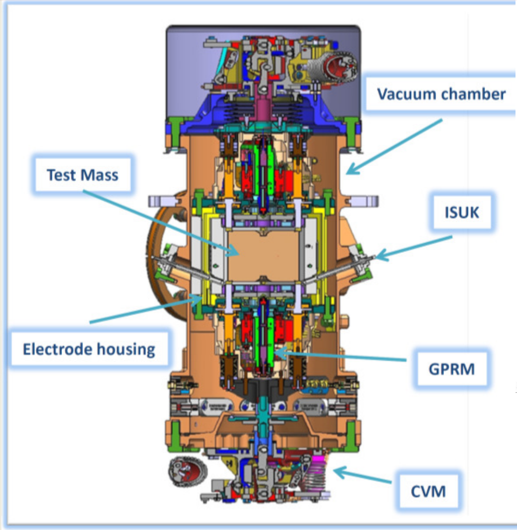
Strategies for suppressing Brownian noise

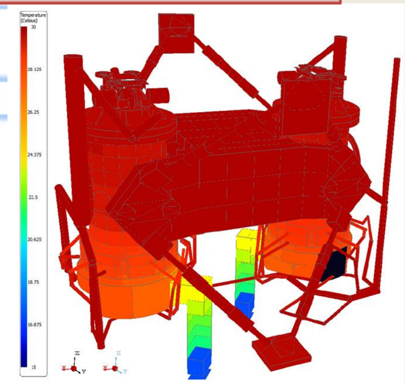
Low residual gas pressure P around the TM

-dedicated vacuum chamber
-pumping line: vent to space via venting duct
-stringent requirements on outgassing contribution of all items inside VC
- at least a mild bake-out to decrease outgassing: 1 day at 115C

$$P = \frac{1}{C_{vent\,duct}} \frac{Q_{eff}}{t - t_{vent}} e^{-\frac{\Theta}{T}}$$

Q_0 is a flow prefactor
θ is the activation energy of the outgassing process





LCA internal temperature maps with boundaries at +30°C.

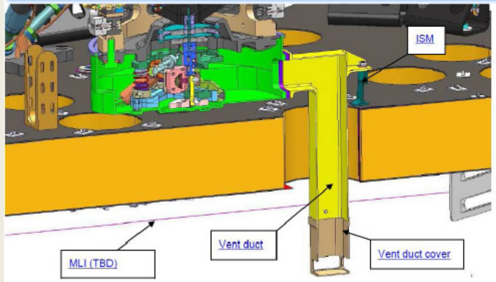
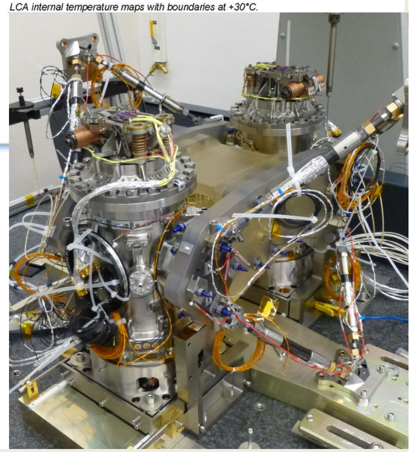


Figure 7 Venting duct cut-out



expected P < requirement of 10 microPa down to several μPa thanks to decay of the outgassing rate once the system is vented to space.

Residual gas composition?
Due to the short and low temperature bake-out likely to be dominated by H_2O (and H_2.)

Residual gas Brownian noise in LISA PF

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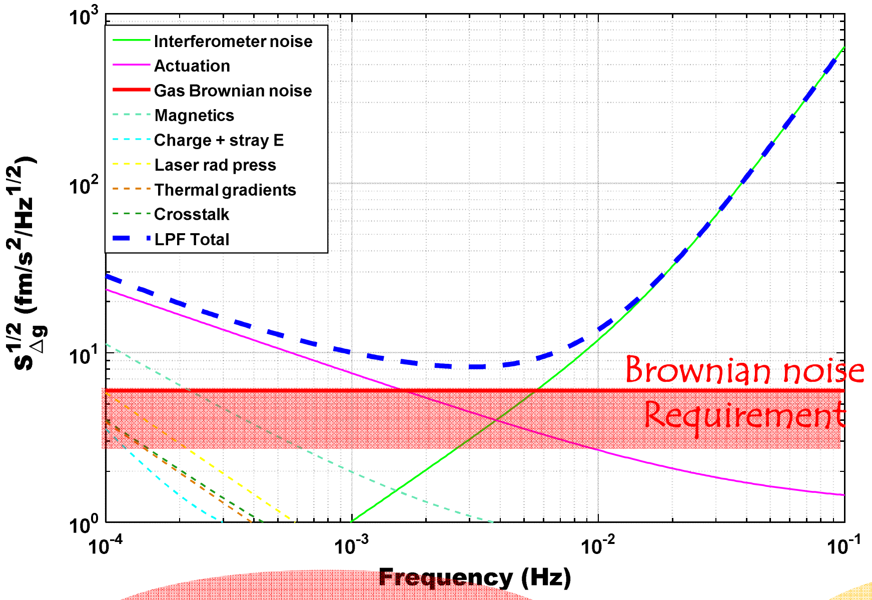
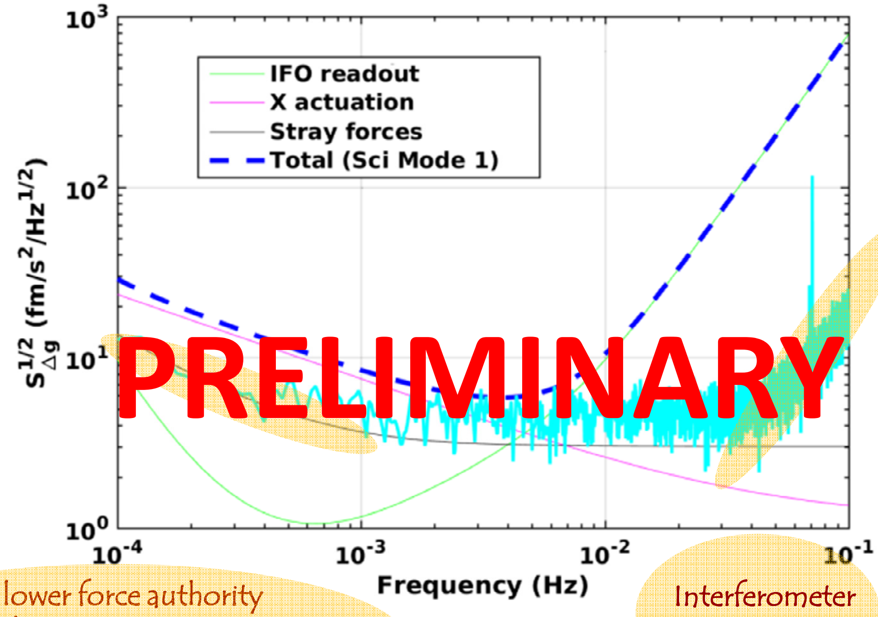
Prediction



Requirement 10 μPa
Expected down to several μPa

Measurement



lower force authority
→lower actuation noise
And at 1mHz is now neglibile

Interferometer sensing

White noise dominates most of the frequency band

Residual gas Brownian noise ?

How much is the pressure P of the residual gas surrounding the TMs ?

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Forces induced by temperature gradients

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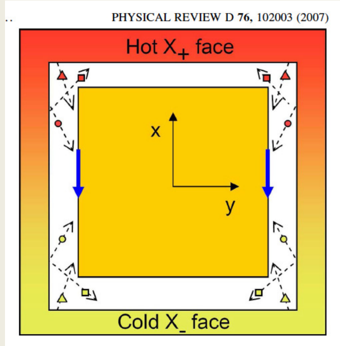
$$S_{F_{th}}^{\frac{1}{2}} = \frac{dF_{th}}{d(\Delta T_x)} S_{\Delta T_x}^{\frac{1}{2}}$$

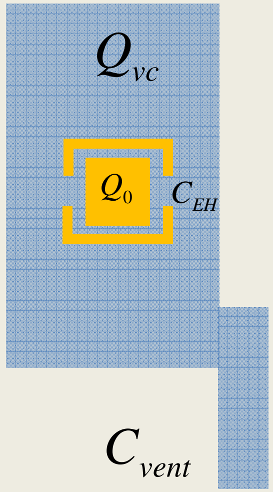
See Ferran Gibert Poster



$$\left.\frac{dF_x}{d(\Delta T_x)}\right|_{Tot} \cong k_R \frac{AP}{4T_0} + \frac{A}{C_{eff}} Q_0 e^{-\frac{\Theta}{T_0}} \frac{\Theta}{T_0^2} + k_{rp} \frac{8\sigma}{3c} T_0^3$$

Radiometer effect | Temp. dependent outgassing | Radiation pressure

$$P = P_{vc} + Q_0 e^{-\frac{\Theta}{T_0}} \frac{1}{C_{EH}} = \frac{Q_{vc}}{C_{vent}} e^{-\frac{\Theta}{T_0}} + \frac{Q_0}{C_{EH}} e^{-\frac{\Theta}{T_0}} = \frac{1}{C_{vent}} \frac{Q_{consvc}}{t - t_{vent}} e^{-\frac{\Theta}{T_0}} + \frac{Q_{const0}}{t - t_{vent}} e^{-\frac{\Theta}{T_0}} \frac{1}{C_{EH}}$$



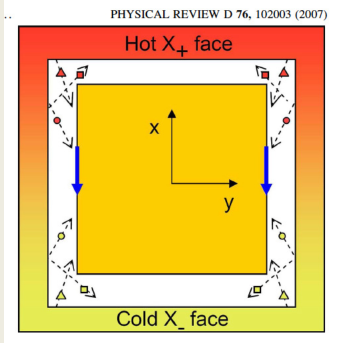
$$\left.\frac{dF_x}{d(\Delta T_x)}\right|_{Tot} \cong \frac{Ak_R}{4T_0} \left(\frac{Q_{constvc}}{t - t_{vent}} e^{-\frac{\Theta}{T_0}} \frac{1}{C_{vent}} + \frac{Q_{const0}}{t - t_{vent}} e^{-\frac{\Theta}{T_0}} \frac{1}{C_{EH}} \right) + \frac{A}{C_{eff}} \frac{Q_{const0}}{t - t_{vent}} e^{-\frac{\Theta}{T_0}} \frac{\Theta}{T_0^2} + k_{rp} \frac{8\sigma}{3c} T_0^3$$

$$\left.\frac{dF_x}{d(\Delta T_x)}\right|_{Tot} \approx \frac{Q_{consteff}}{t - t_{vent}} e^{-\frac{\Theta}{T_0}} + k_{rp} \frac{8\sigma}{3c} T_0^3$$

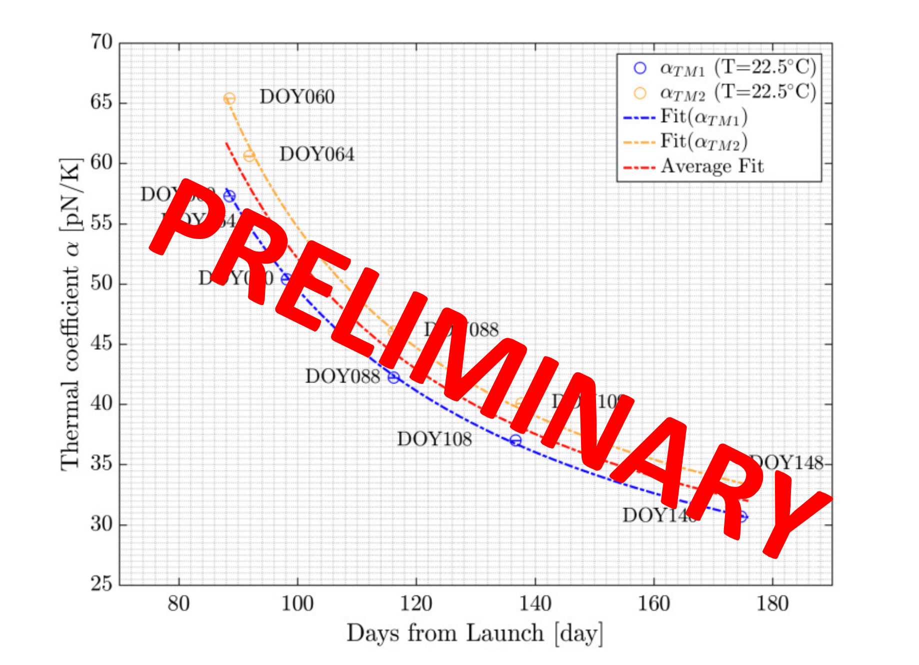
Forces induced by temperature gradients

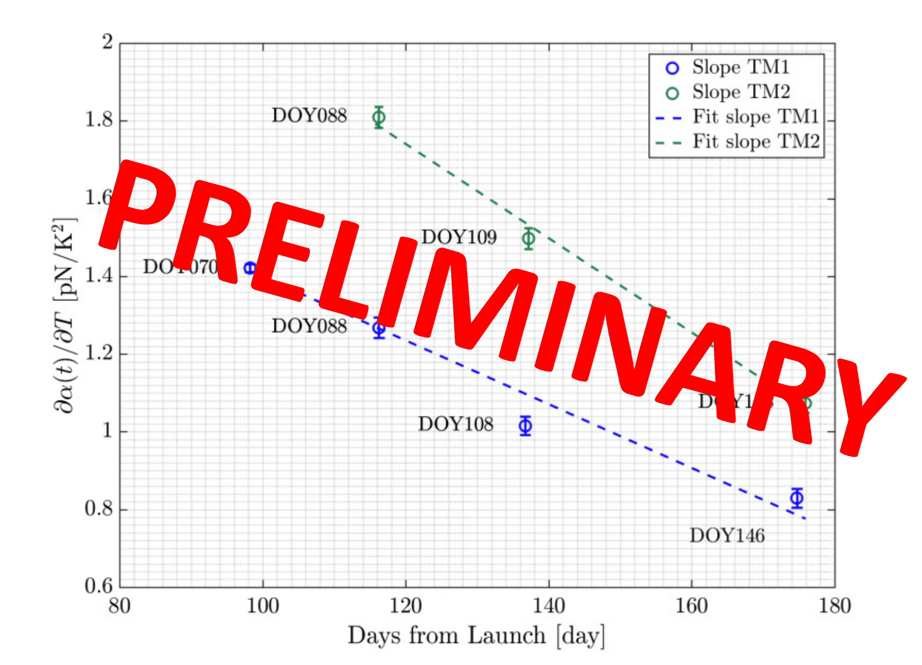
$$\left.\frac{dF_x}{d(\Delta T_x)}\right|_{Tot} \cong k_R \frac{AP}{4T_0} + \frac{A}{C_{eff}} Q_0 e^{-\frac{\Theta}{T_0}} \frac{\Theta}{T_0^2} + k_{rp} \frac{8\sigma}{3c} T_0^3$$

Radiometer effect — Temp. dependent outgassing — Radiation pressure



$$\left.\frac{dF_x}{d(\Delta T_x)}\right|_{Tot} \approx \frac{Q_{consteff}}{t - t_{vent}} e^{-\frac{\Theta}{T_0}} + k_{rp} \frac{8\sigma}{3c} T_0^3$$

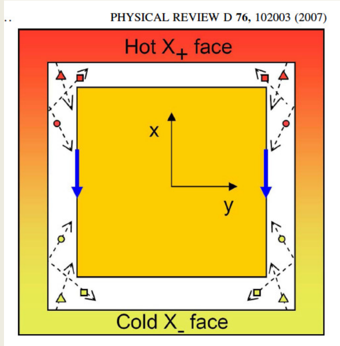




Forces induced by temperature gradients

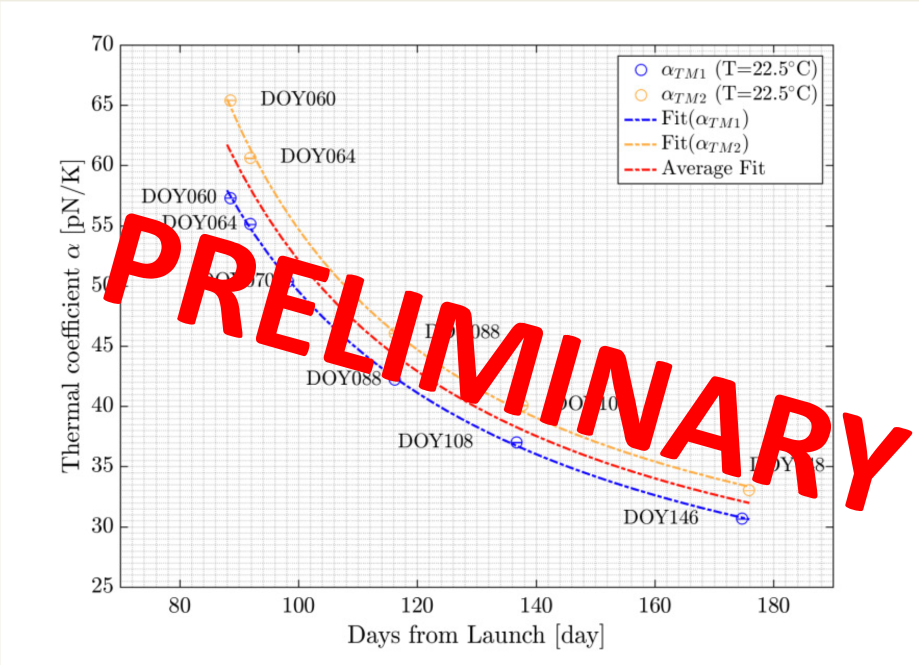
$$\left.\frac{dF_x}{d(\Delta T_x)}\right|_{Tot} \cong k_R \frac{AP}{4T_0} + \frac{A}{C_{eff}} Q_0 e^{-\frac{\Theta}{T_0}} \frac{\Theta}{T_0^2} + k_{rp} \frac{8\sigma}{3c} T_0^3$$

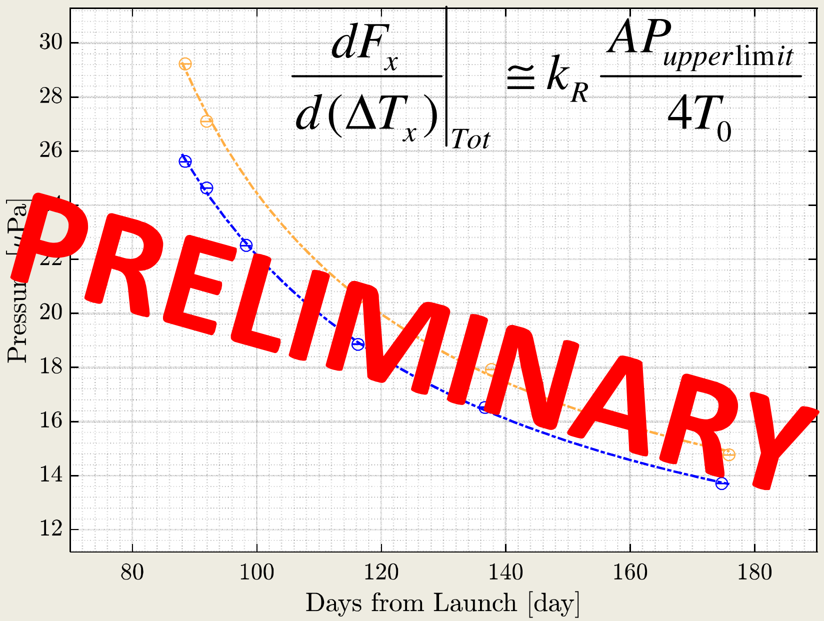
Radiometer effect — Temp. dependent outgassing — Radiation pressure



$$\left.\frac{dF_x}{d(\Delta T_x)}\right|_{Tot} \approx \frac{Q_{consteff}}{t - t_{vent}} e^{-\frac{\Theta}{T_0}} + k_{rp} \frac{8\sigma}{3c} T_0^3$$

Ascribe the entire effect to radiometer Effect → pressure upper limit





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Residual gas pressure estimation

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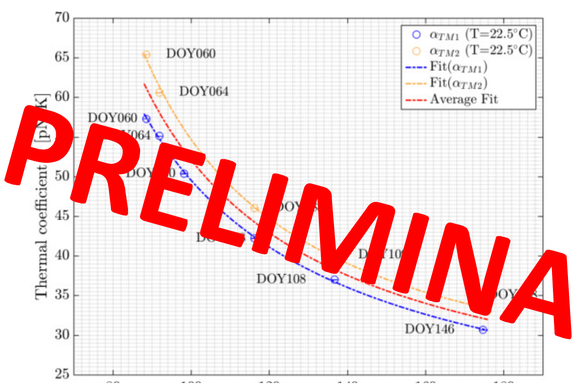
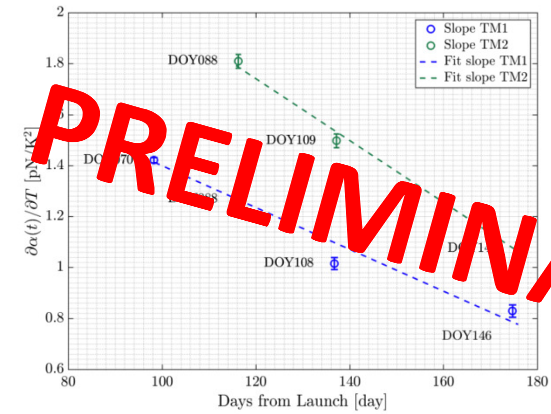




$$\left.\frac{dF_x}{d(\Delta T_x)}\right|_{Tot} \cong k_R \frac{A\left(P_{vc}+Q_0 e^{-\frac{\Theta}{T_0}}\frac{1}{C_{EH}}\right)}{4T_0} + k_{rp}\frac{8\sigma}{3c}T_0^3 + \frac{A}{C_{eff}} Q_0 e^{-\frac{\Theta}{T_0}} \frac{\Theta}{T_0^2}$$

$$\frac{d}{dT}\left(\left.\frac{dF_x}{d(\Delta T_x)}\right|_{Tot}\right) \cong -k_R\frac{A}{4T_0^2}\left(P_{vc}+Q_0 e^{-\frac{\Theta}{T_0}}\frac{1}{C_{EH}}\left(1-\frac{\Theta}{T_0}\right)\right) + 3k_{rp}\frac{8\sigma}{3c}T_0^2 + \frac{A}{C_{eff}}\frac{\Theta}{T_0^3}Q_0 e^{-\frac{\Theta}{T_0}}\left(\frac{\Theta}{T_0}-2\right)$$

→ Q_0 and P_{vc} as function of time

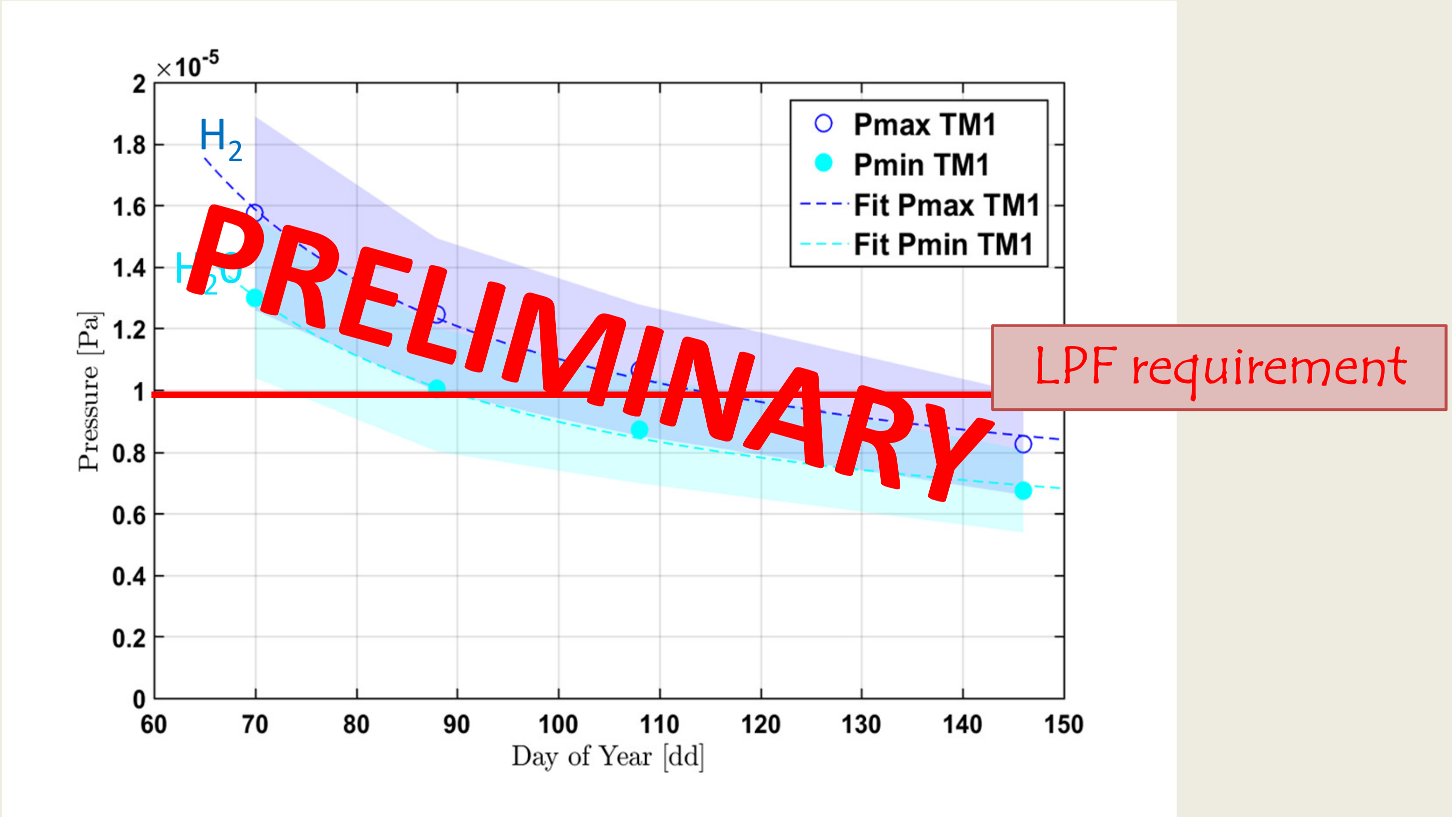
$$P = P_{vc} + Q_0 e^{-\frac{\Theta}{T_0}} \frac{1}{C_{EH}}$$

From simulations\ torsion pendulum test with Electrode Housing prototypes :
-we have estimations for the other parameters (calibration error of about 20%)
-based also on literature →range of values for activation energy Θ (10000K, 20000K) that correspond respectively to H_2O and H_2

our estimation of P is calibrated at 20% and depends upon residual gas composition

Residual gas pressure estimation

Pressure inside electrode housing 1



Fit with a curve

$$\frac{1}{C_{vent}} \frac{Q_{eff}}{t - t_{vent}} + const.$$

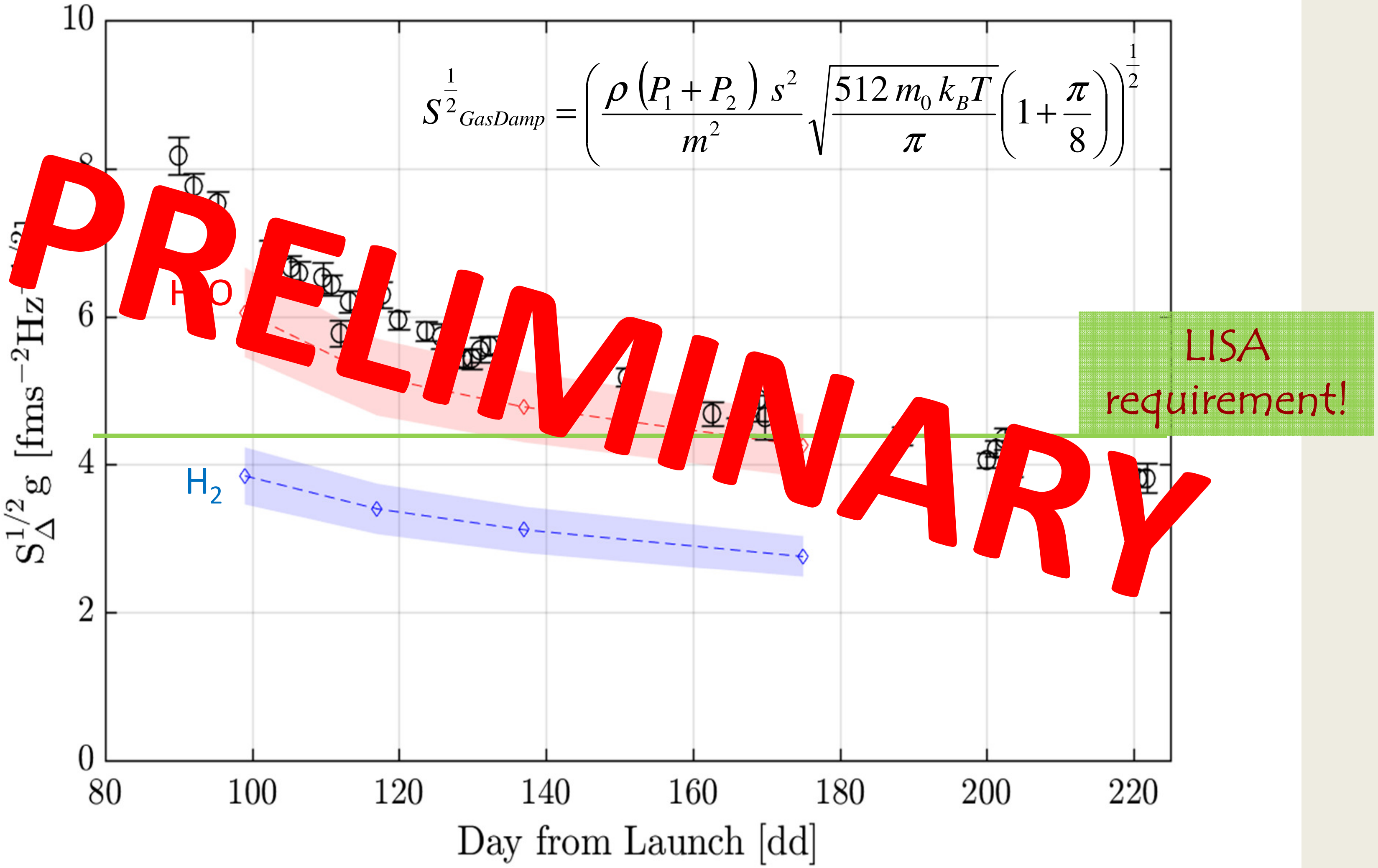
where t_{vent} (2 Febr 2016) is the day the sensors were vented to space

Comparison with LPF White Noise

Average in 3-8 mHz band in time

(effect of actuation removed) talk of Bill Weber

$$S^{\frac{1}{2}}_{GasDamp} = \left(\frac{\rho\left(P_1 + P_2\right) s^2}{m^2} \sqrt{\frac{512\, m_0\, k_B T}{\pi}} \left(1 + \frac{\pi}{8}\right) \right)^{\frac{1}{2}}$$



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LPF white Noise time decaying in time

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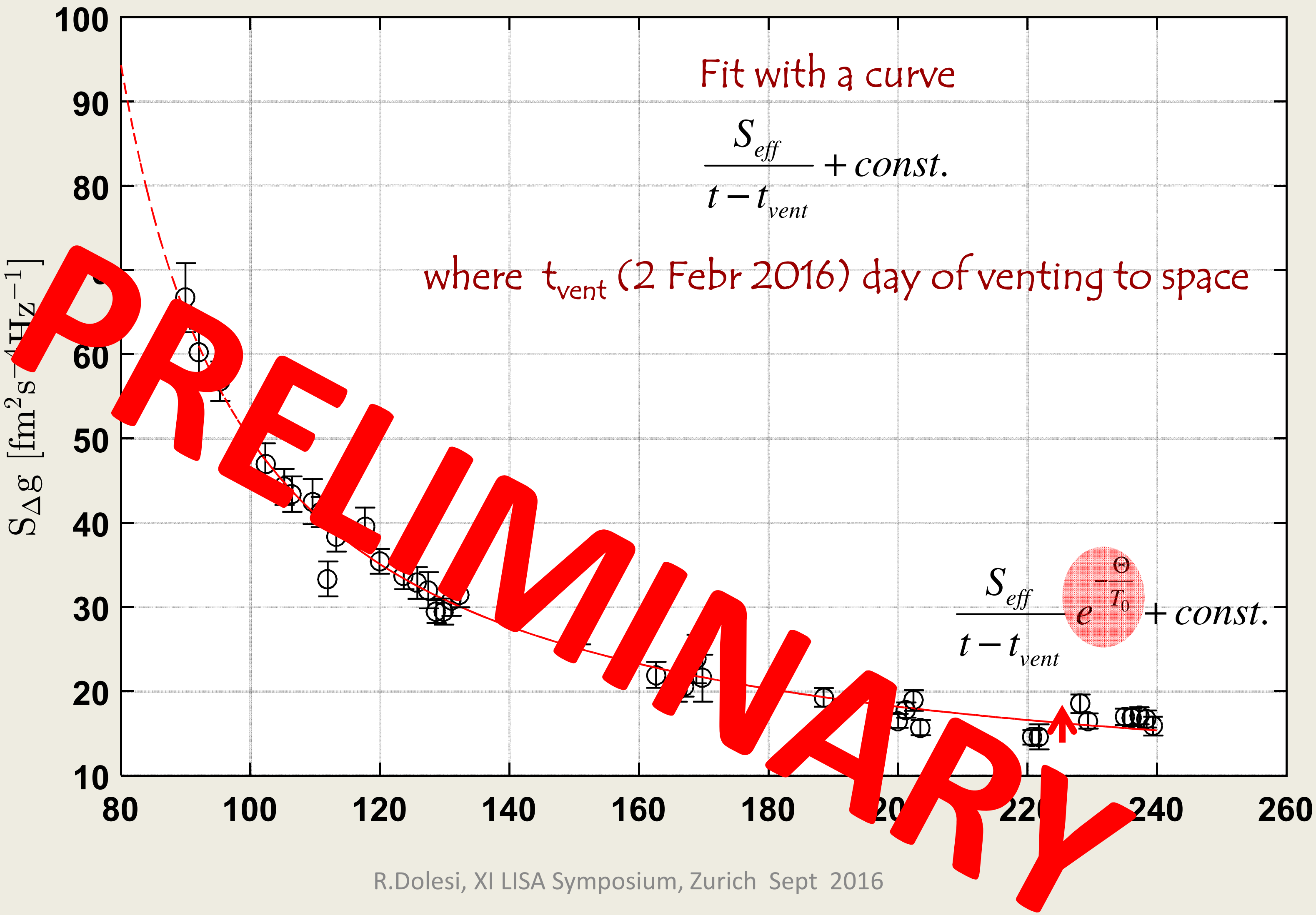
$$S_{GasDamp} = \frac{\rho\left(P_1 + P_2\right) s^2}{m^2}\sqrt{\frac{512\, m_0\, k_B T}{\pi}}\left(1+\frac{\pi}{8}\right) \propto \frac{S_{eff}}{t - t_{vent}}\, e^{-\frac{\Theta}{T}}$$



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Conclusions

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- LISA PF white noise floor compatible with residual gas Brownian noise
- Other possible white noise sources?
- LISA requirement achieved after about 130 days after venting to space
- Possible strategies can be implemented for further suppressing the residual gas pressure in LISA