Electrostatic forces on the LISA Pathfinder test masses

Interaction of test mass charge with stray electric fields

Peter Wass

LISA Pathfinder collaboration

GP-B

Electrostatic forces from patch potentials had major impact on science

Rev.Sci.Inst. 82 074502 (2011) Buchman & Turneaure

Image credit: Katherine Stephenson, Stanford University and Lockheed Martin Corporation

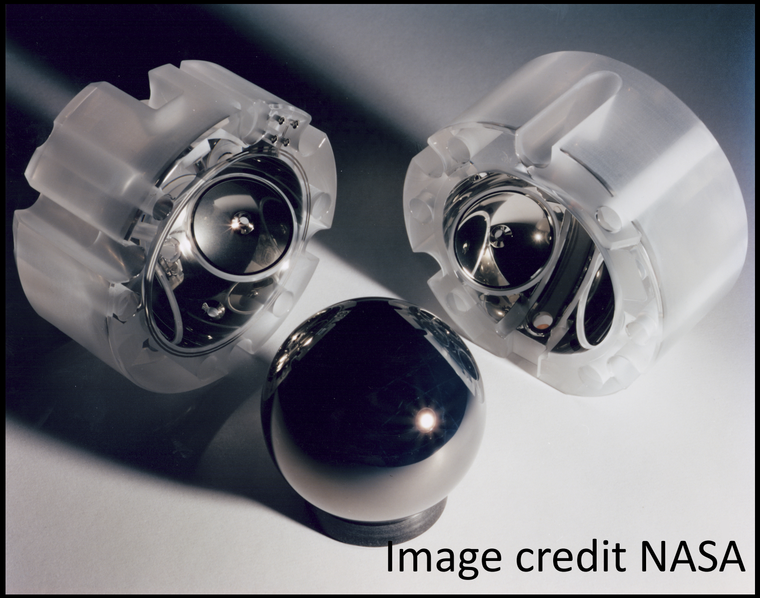
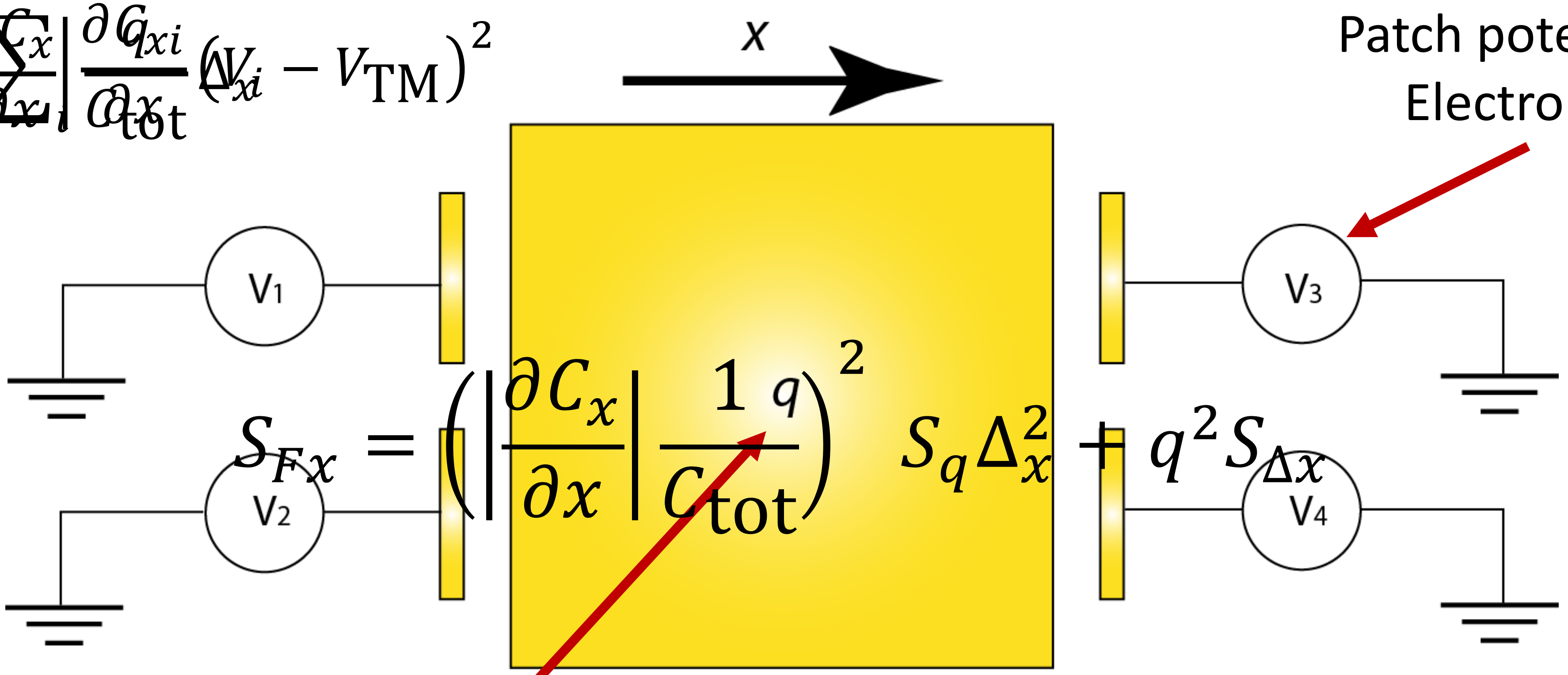


Image credit NASA

The problem

$$F_x \approx -\frac{1}{2}\sum_i \left|\frac{\partial C_{xi}}{\partial x}\right| \left(V_i - V_{\mathrm{TM}}\right)^2$$

$$F_x = -\left|\frac{\partial C_x}{\partial x}\right| \frac{q}{C_{\mathrm{tot}}} \Delta_x$$

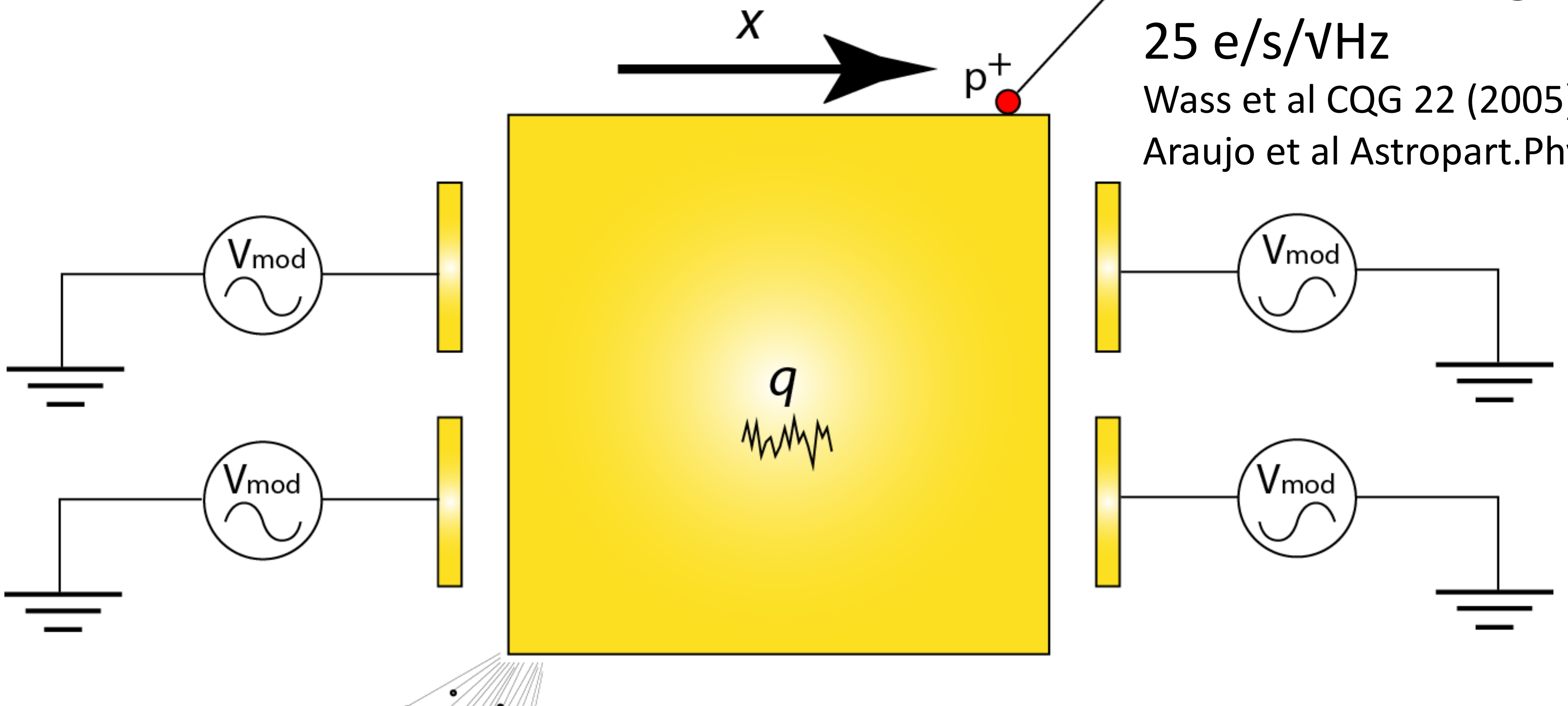


$$S_{Fx} = \left(\left|\frac{\partial C_x}{\partial x}\right| \frac{1}{C_{\mathrm{tot}}}\right)^2 \left(S_q \Delta_x^2 + q^2 S_{\Delta x}\right)$$

Patch potentials, Electronics

Test mass charging

Charge noise



Predictions using GEANT4

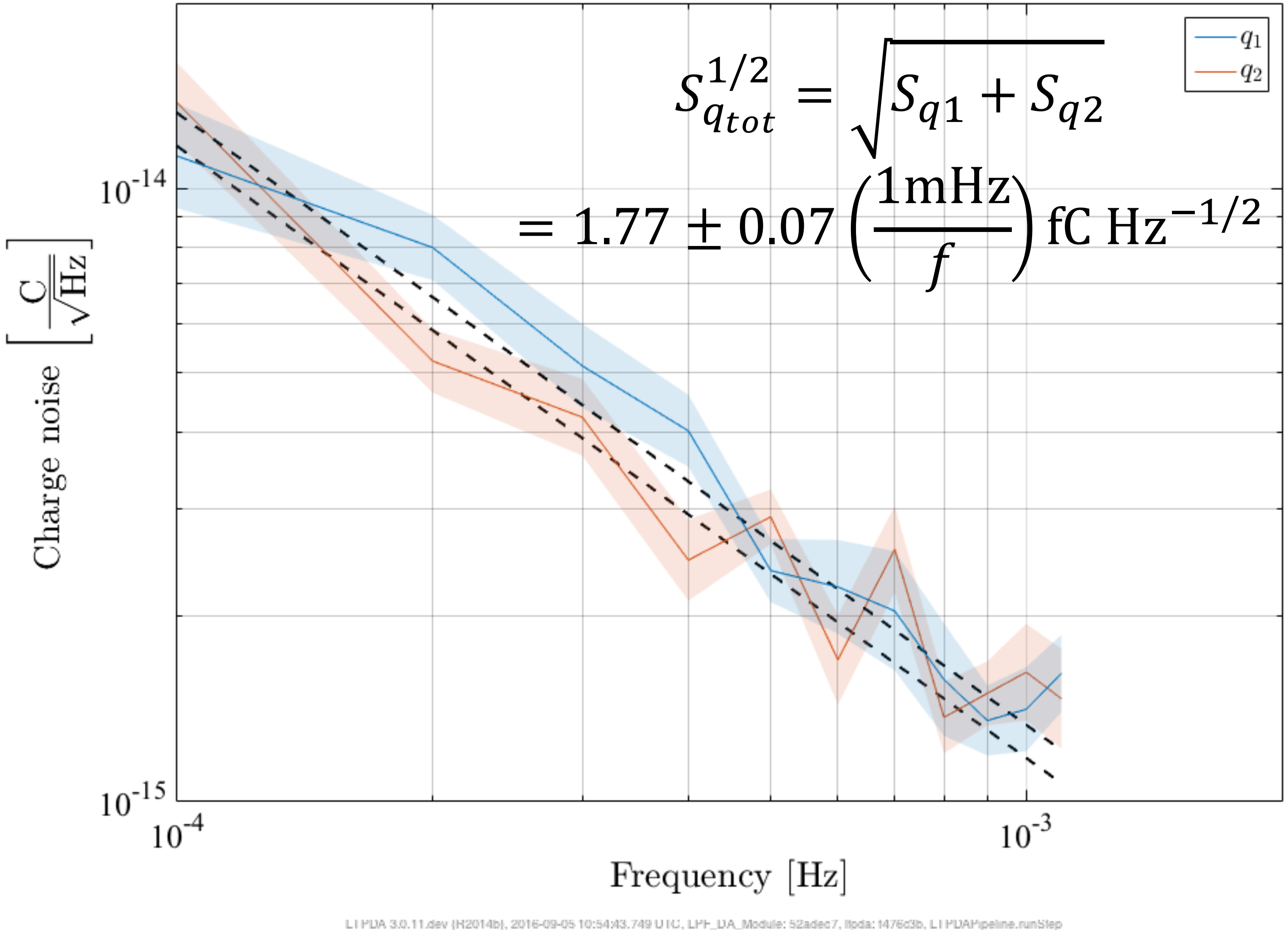
25 e/s/√Hz

Wass et al CQG 22 (2005) S311

Araujo et al Astropart.Phys 22 (2005) 451

$$\Delta_g = -\frac{1}{m}\left|\frac{\partial C_x}{\partial x}\right|\left(\frac{q_1}{C_{\text{tot}}} V_{\text{mod}} \sin\omega_1 t + \frac{q_2}{C_{\text{tot}}} V_{\text{mod}} \sin\omega_2 t\right)$$

Charge noise



$$S_{q_{tot}}^{1/2} = \sqrt{S_{q1} + S_{q2}}$$

$$= 1.77 \pm 0.07 \left(\frac{1\mathrm{mHz}}{f}\right) \mathrm{fC\ Hz}^{-1/2}$$

Current Shot noise

$$S_q = \frac{S_i}{(2\pi f^2)}$$

TM1: 46±2e/s/√Hz

TM2: 52±2e/s/√Hz

First measurement…

2x higher than predicted

Charge noise

$$S_{\Delta g}^{1/2} = -\frac{1}{m}\left|\frac{\partial C_x}{\partial x}\right|\frac{1}{C_{\text{tot}}}\sqrt{S_{q1}\Delta_{x1}^2 + S_{q2}\Delta_{x2}^2}$$

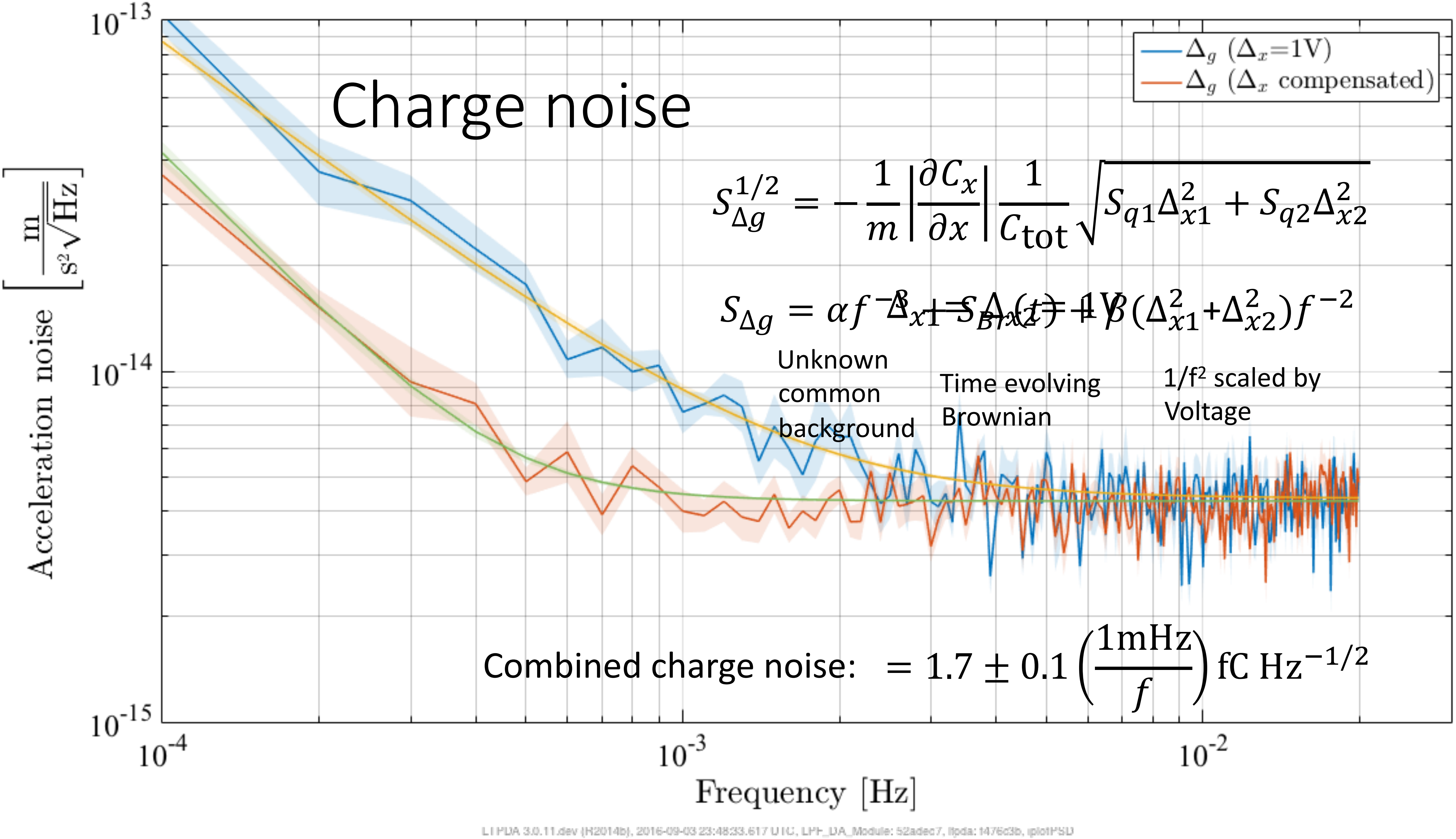
$$S_{\Delta g} = \alpha f^{-\beta} + S_{Br}(t) + \gamma(\Delta_{x1}^2+\Delta_{x2}^2)f^{-2}$$

$$\Delta_{x1} = \Delta_{x2} = 1V$$

Unknown common background

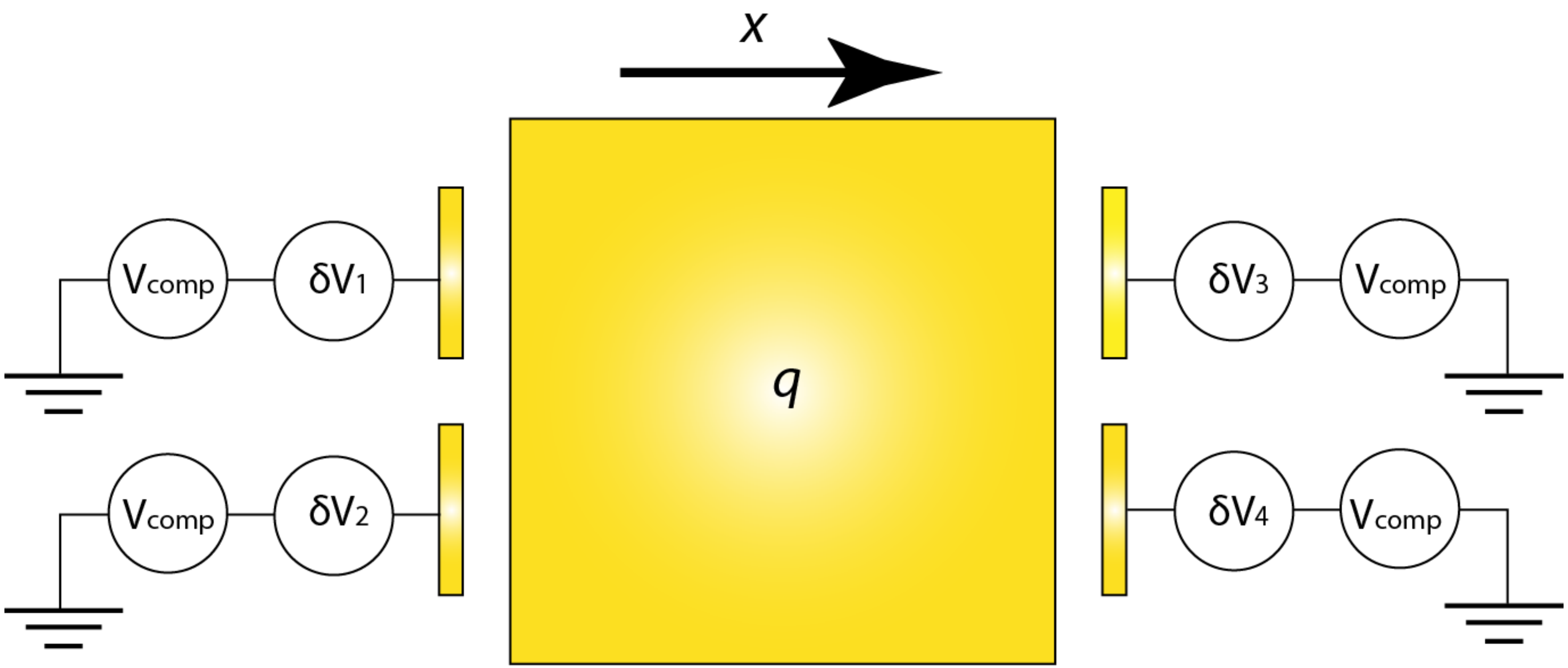
Time evolving Brownian

1/f² scaled by Voltage



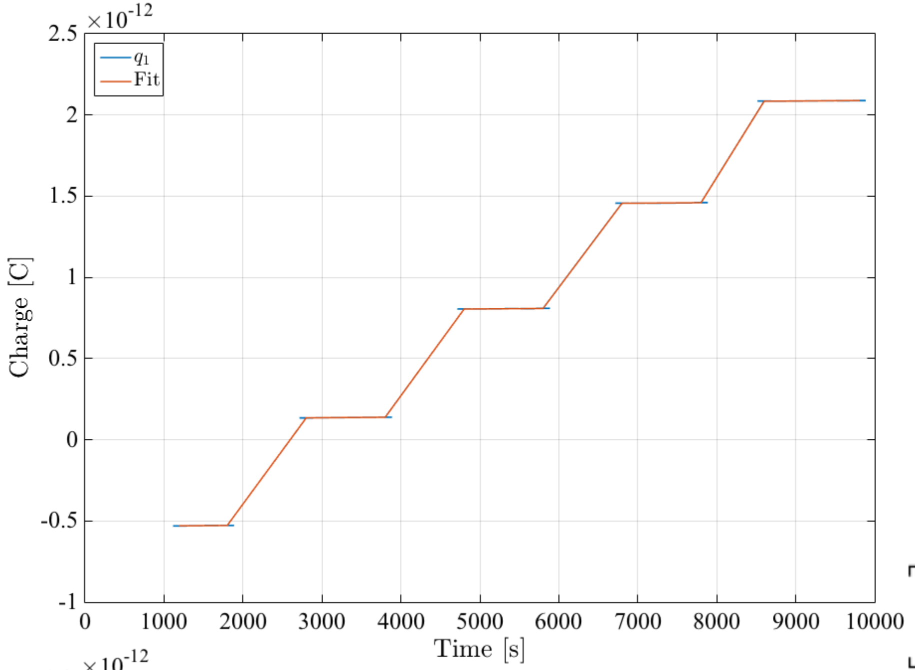
Combined charge noise: $= 1.7 \pm 0.1\left(\frac{1\text{mHz}}{f}\right)\text{fC Hz}^{-1/2}$

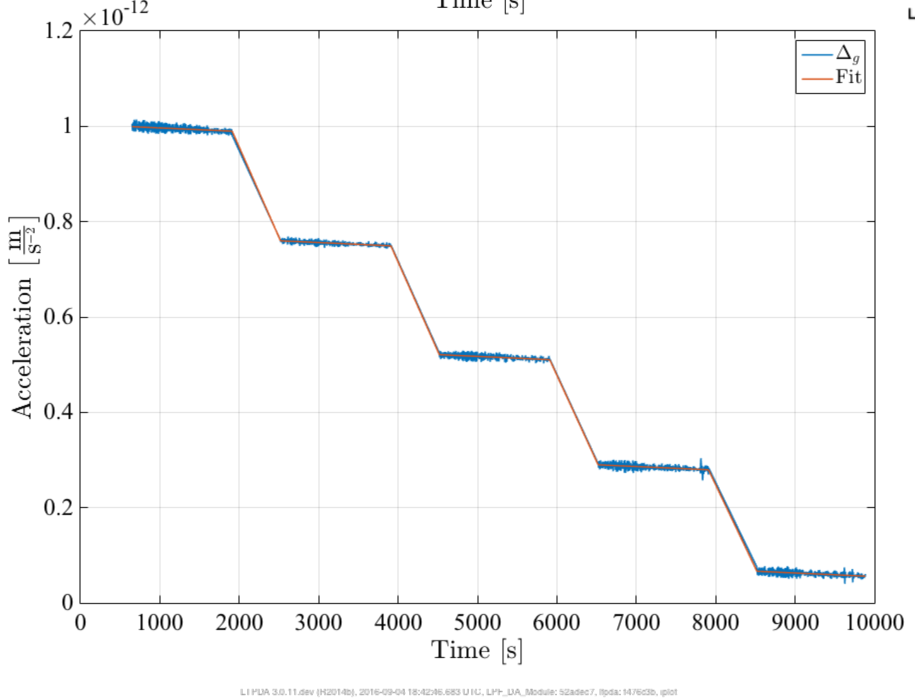
Stray potentials

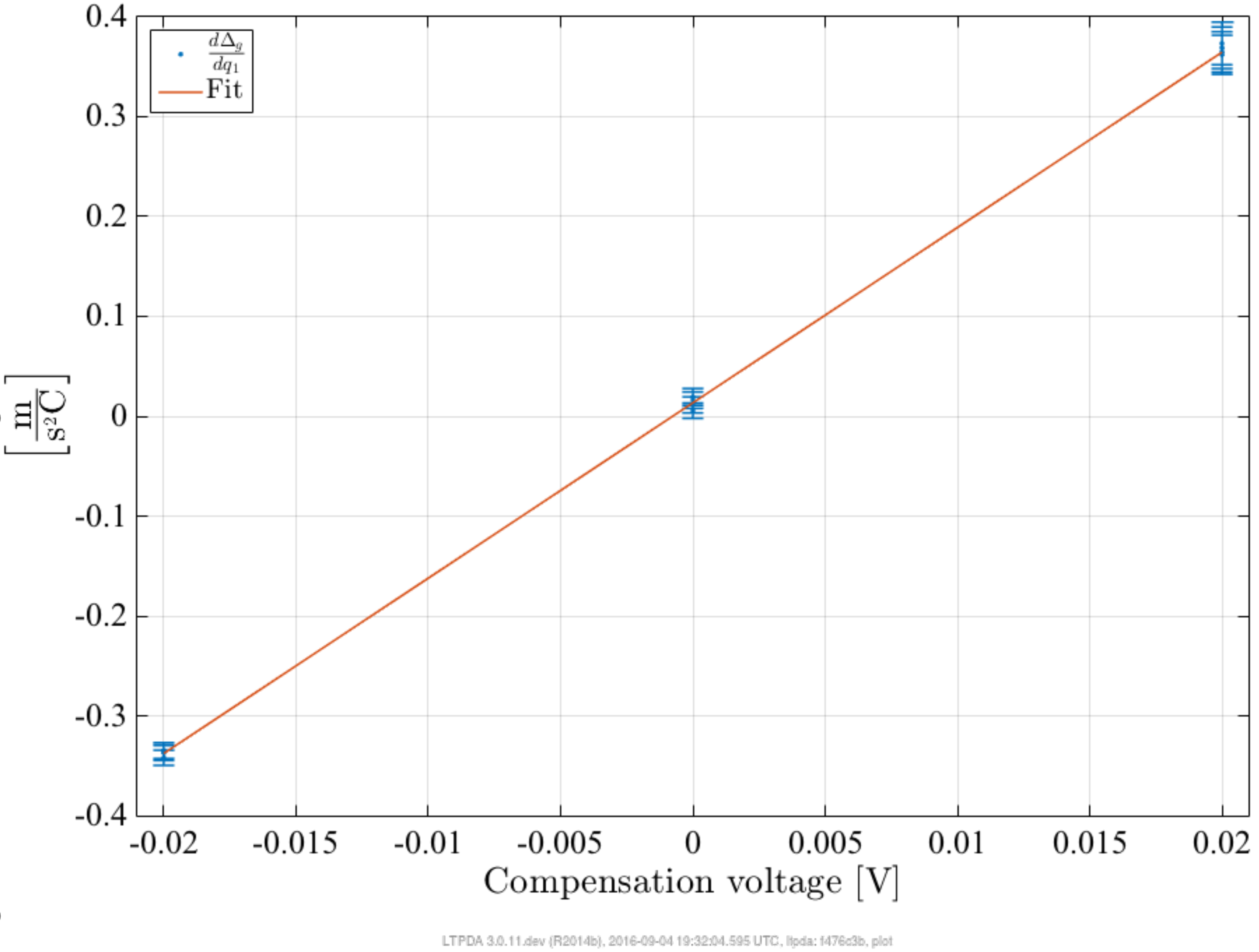


$$\frac{d\Delta_g}{dq_n} = -\frac{1}{m}\left|\frac{\partial C_x}{\partial x}\right|\frac{1}{C_{\text{tot}}}\left(\Delta_{xn} + 4V_{\text{comp}}\right)$$

Demonstrated on ground eg
Phys.Rev.Lett 108 181101 (2012) Antonucci et al


×10^-12
q1
Fit
Charge [C]
Time [s]


×10^-12
Δg
Fit
Acceleration [m/s²]
Time [s]


dΔg/dq1
Fit
[m/(s²C)]
Compensation voltage [V]
LTPDA 3.0.11.dev (R2014b), 2016-09-04 19:32:04.595 UTC, ltpda: f476c3b, plot

Stray potentials

DC stray potentials TM1 Δ_x = 21±0.2 mV

TM2 Δ_x = 0±0.2 mV

In-line with ground-based measurements

Compensated TM1: -3.0±1.0mV … -3.1±0.7mV (45 days later)

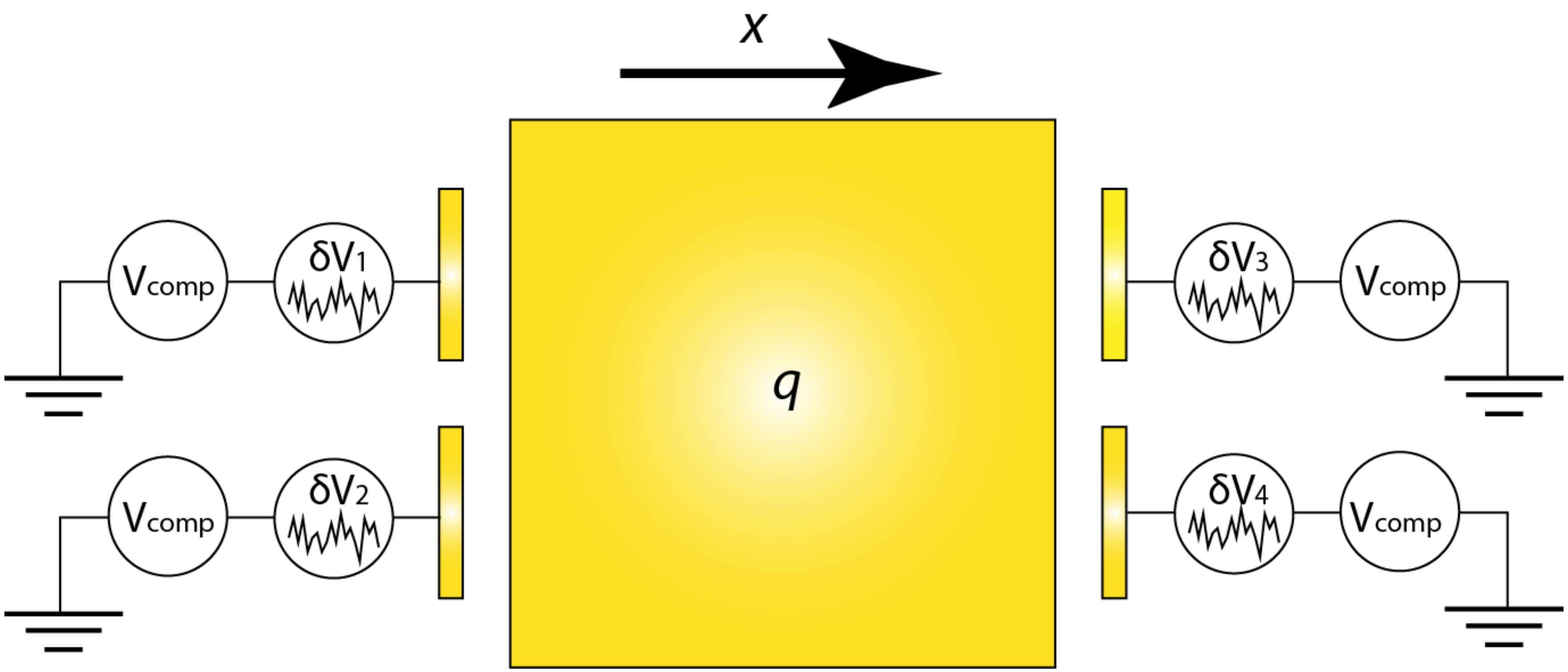
TM2: -0.6±0.4mV … +1.1±0.4mV (45 days later)

Stable over long timescales

With Δ_x~3mV, $S_{\Delta g}$ ~ 0.23 fm s^{-2} $Hz^{-1/2}$ at 0.1mHz

Noise budget contribution well within requirements

Stray potential fluctuations

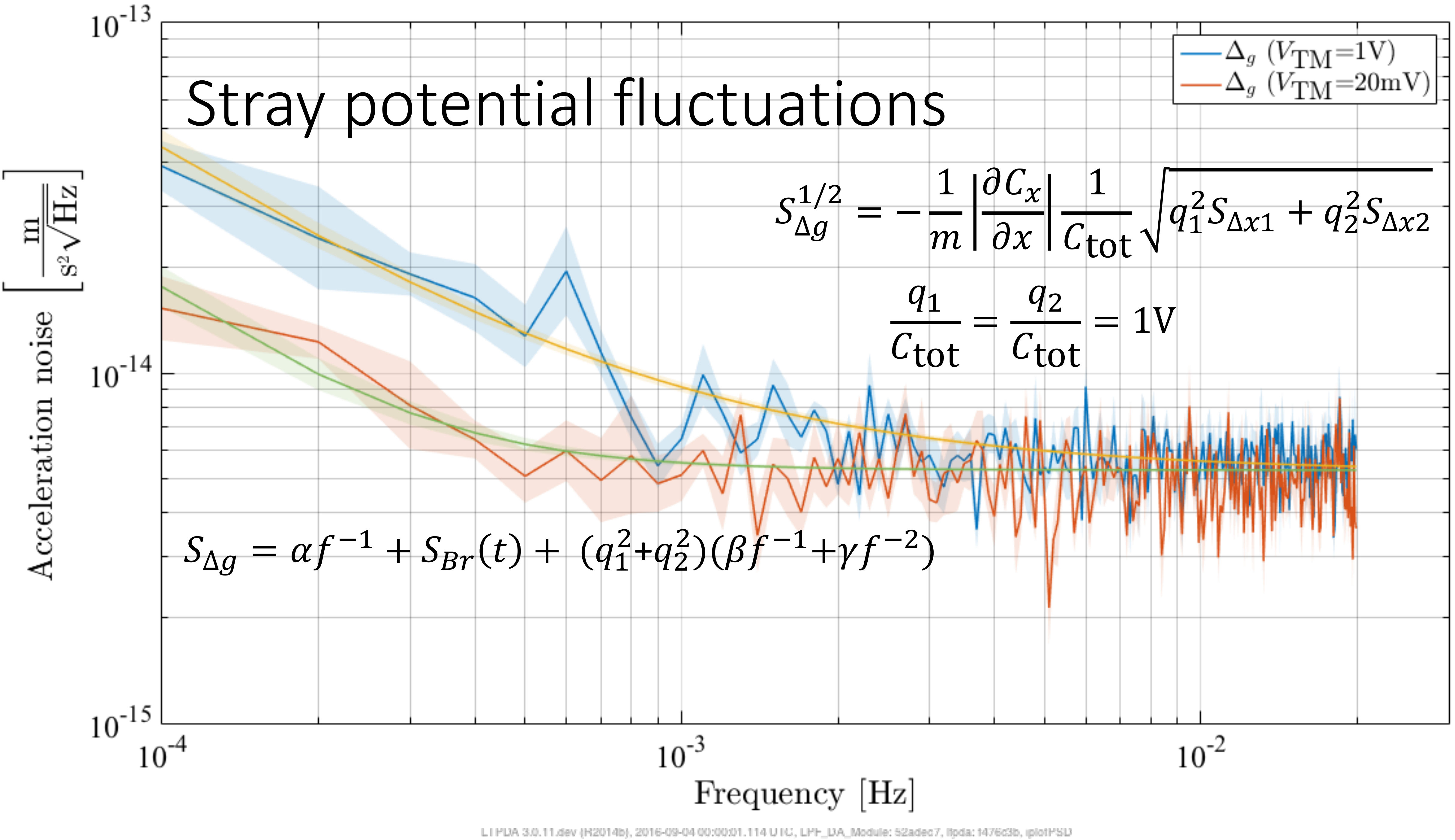


Stray potential fluctuations

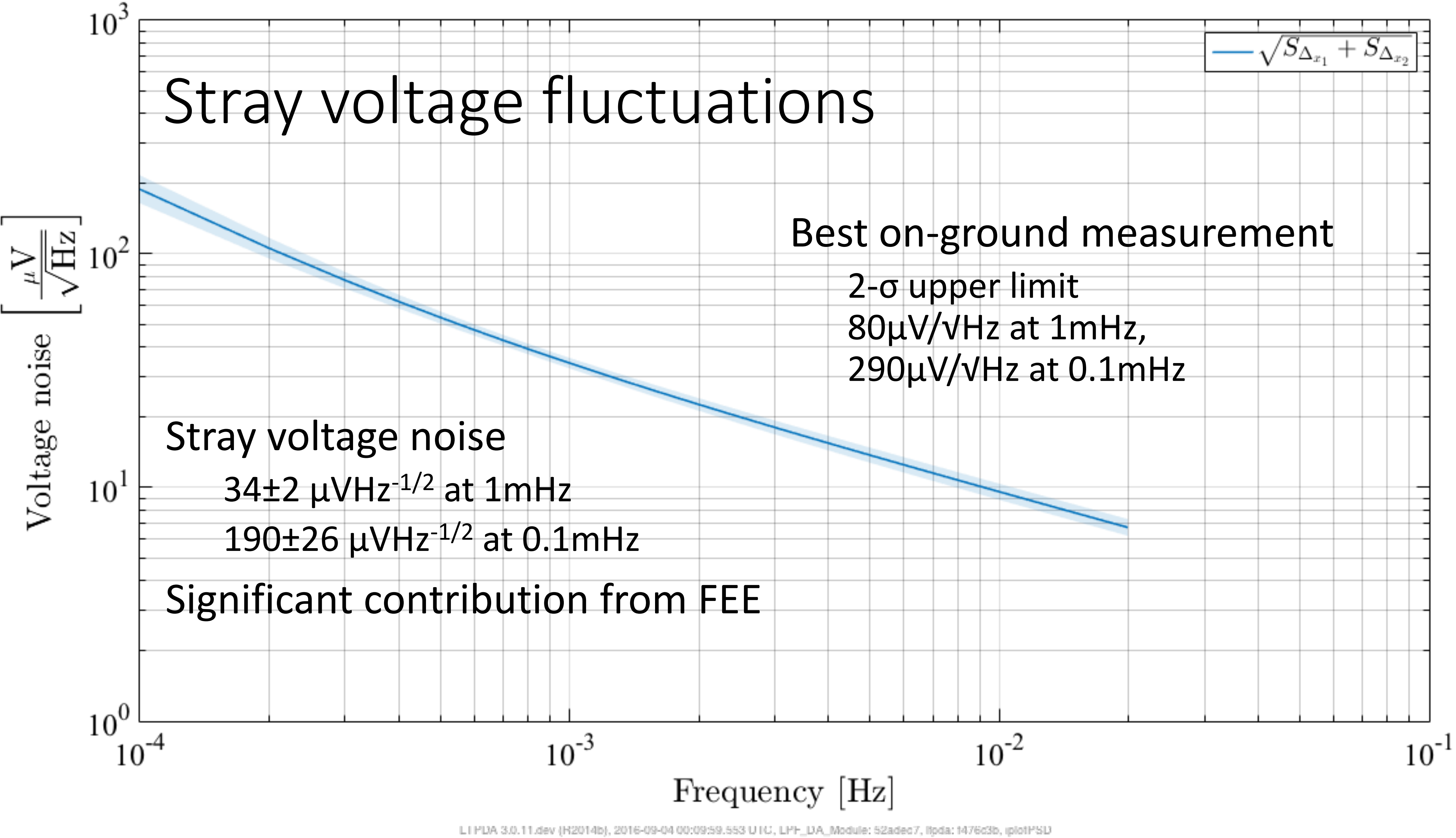
$$S_{\Delta g}^{1/2} = -\frac{1}{m}\left|\frac{\partial C_x}{\partial x}\right|\frac{1}{C_{\mathrm{tot}}}\sqrt{q_1^2 S_{\Delta x1} + q_2^2 S_{\Delta x2}}$$

$$\frac{q_1}{C_{\mathrm{tot}}} = \frac{q_2}{C_{\mathrm{tot}}} = 1\mathrm{V}$$

$$S_{\Delta g} = \alpha f^{-1} + S_{Br}(t) + \ (q_1^2{+}q_2^2)(\beta f^{-1}{+}\gamma f^{-2})$$



Stray voltage fluctuations



Best on-ground measurement

2-σ upper limit
80µV/√Hz at 1mHz,
290µV/√Hz at 0.1mHz

Stray voltage noise

34±2 µVHz$^{-1/2}$ at 1mHz
190±26 µVHz$^{-1/2}$ at 0.1mHz

Significant contribution from FEE

Charge control

Environmental charge rate ~20e/s

Periodic discharging achieved with UV lamps

Target V_{TM} achieved <1mV (<50fC, $2x10^5$e)

V_{TM}<40mV (1.4pC $8.5x10^6$e)

$S_{\Delta g}$ ~1.6 fm s^{-2} $Hz^{-1/2}$ at 0.1mHz with rms V_{TM} 40mV

Lower with improved electronics/ continuous discharging

Posters: Daniel Hollington (UV LEDs)
Davor Mance (FEE)

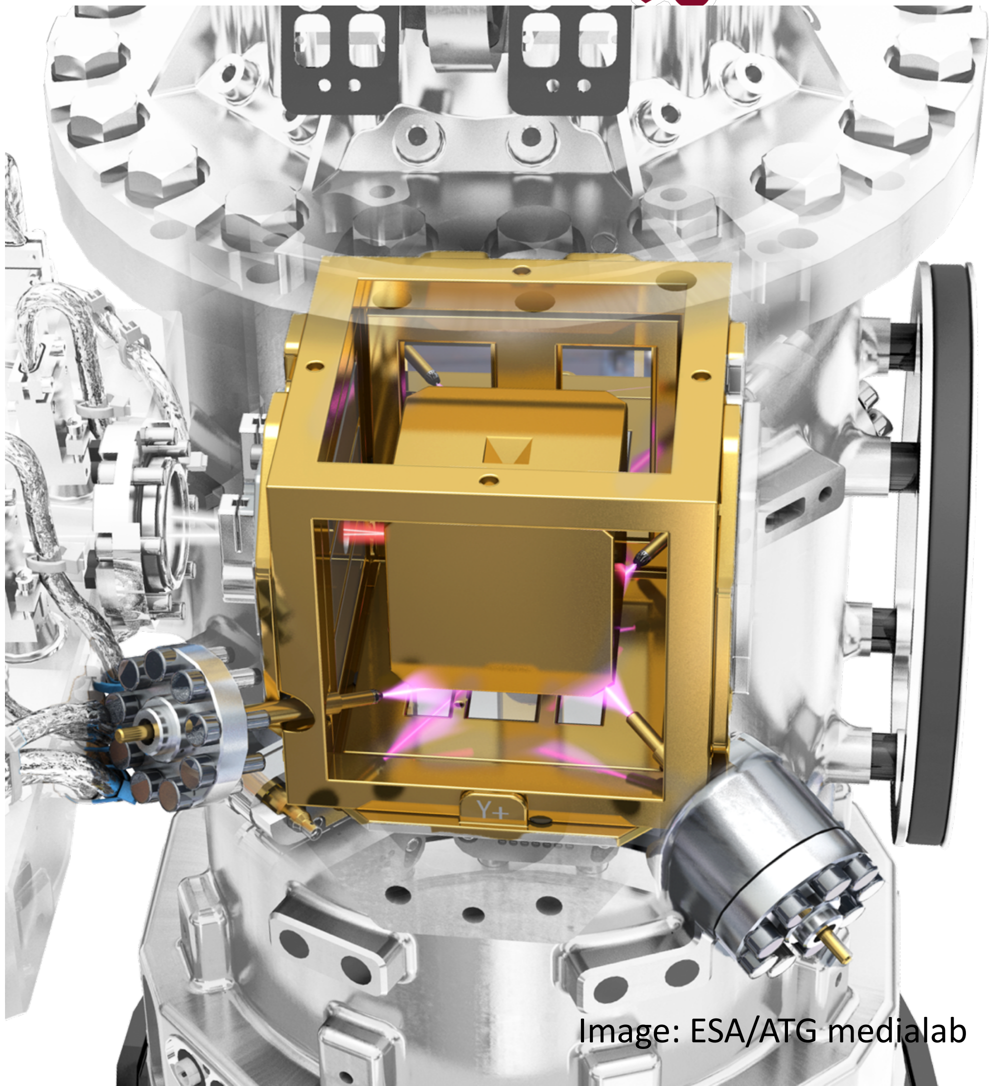


Image: ESA/ATG medialab

Conclusions

In-band fluctuations of test mass potential, patch potentials and electrode voltages

Well within noise budget for LISA at 0.1mHz,

We know how to do better

Electrostatics not a limiting factor for LISA or future gradiometers with large TMs and mm gaps