LISA Dynamics & Control

DFACS Simulation and Optimization, Noise assessment and Data processing

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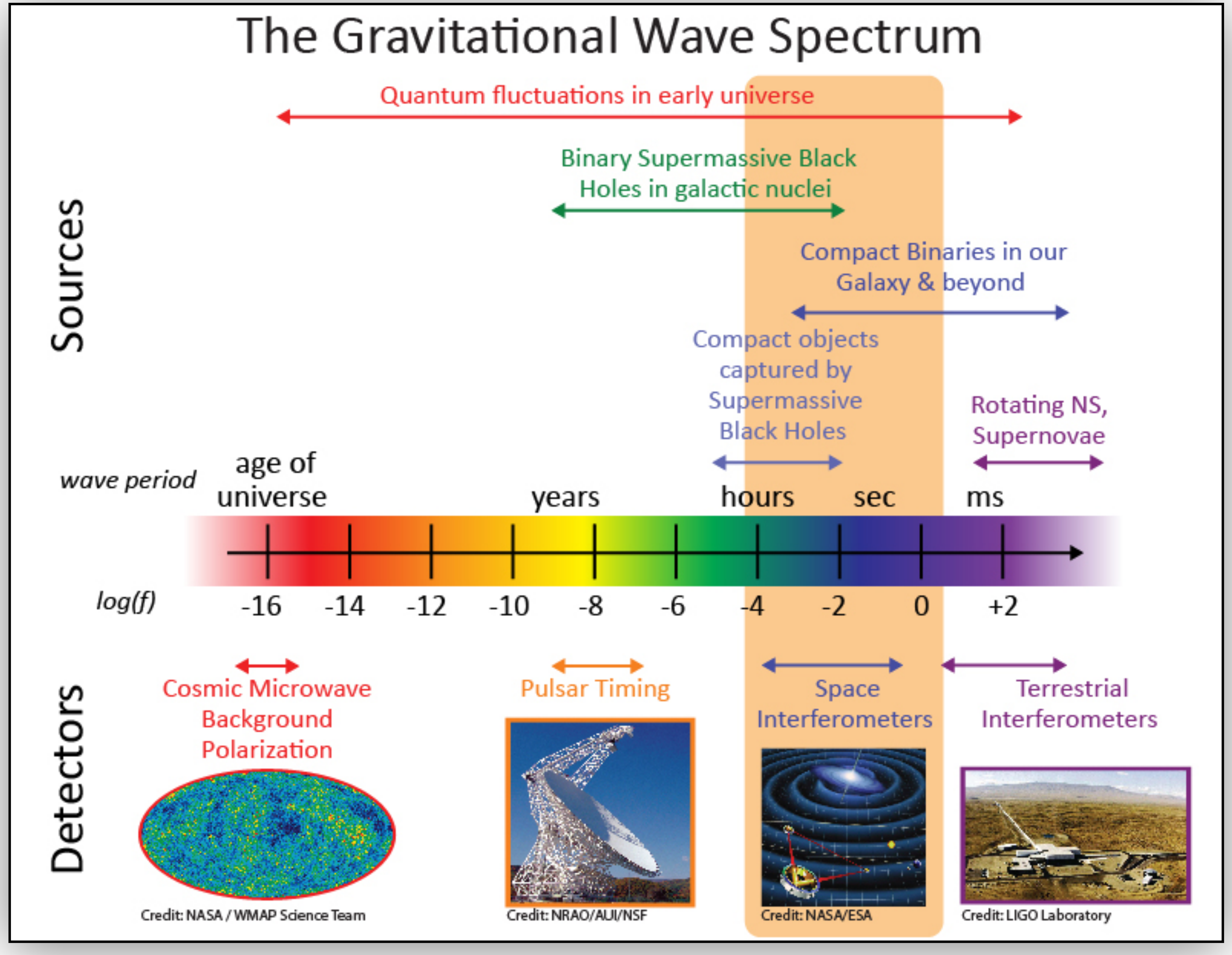
LISA sources and instrument

Opening up a large and unexplored frequency band on the Universe

- Going to space : unlocking the bandwidth ~ {1e-4 Hz, 1.0 Hz}, with the help of **arm length** (2.5 Gm) and **space environment**.

- **Very rich bandwidth for astrophysics:**
  Supermassive and stellar black holes, EMRIs, Galactic Binaries, Cosmological Sources

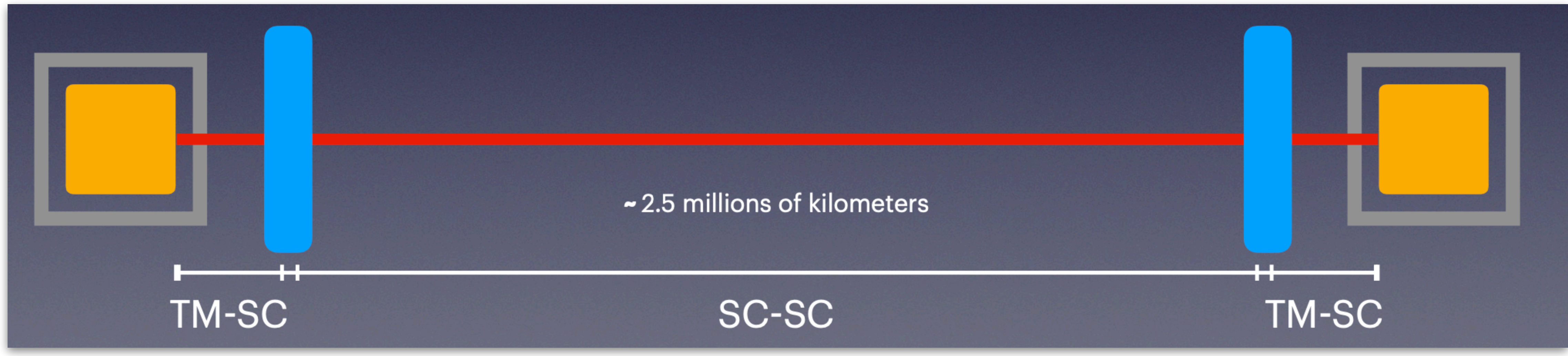
- GW and LISA: *free particles* vs. *satellites*, test masses and spurious forces, **local inertial frames.**
  Targeted sensitivity ~ pm / $Hz^{-1/2}$

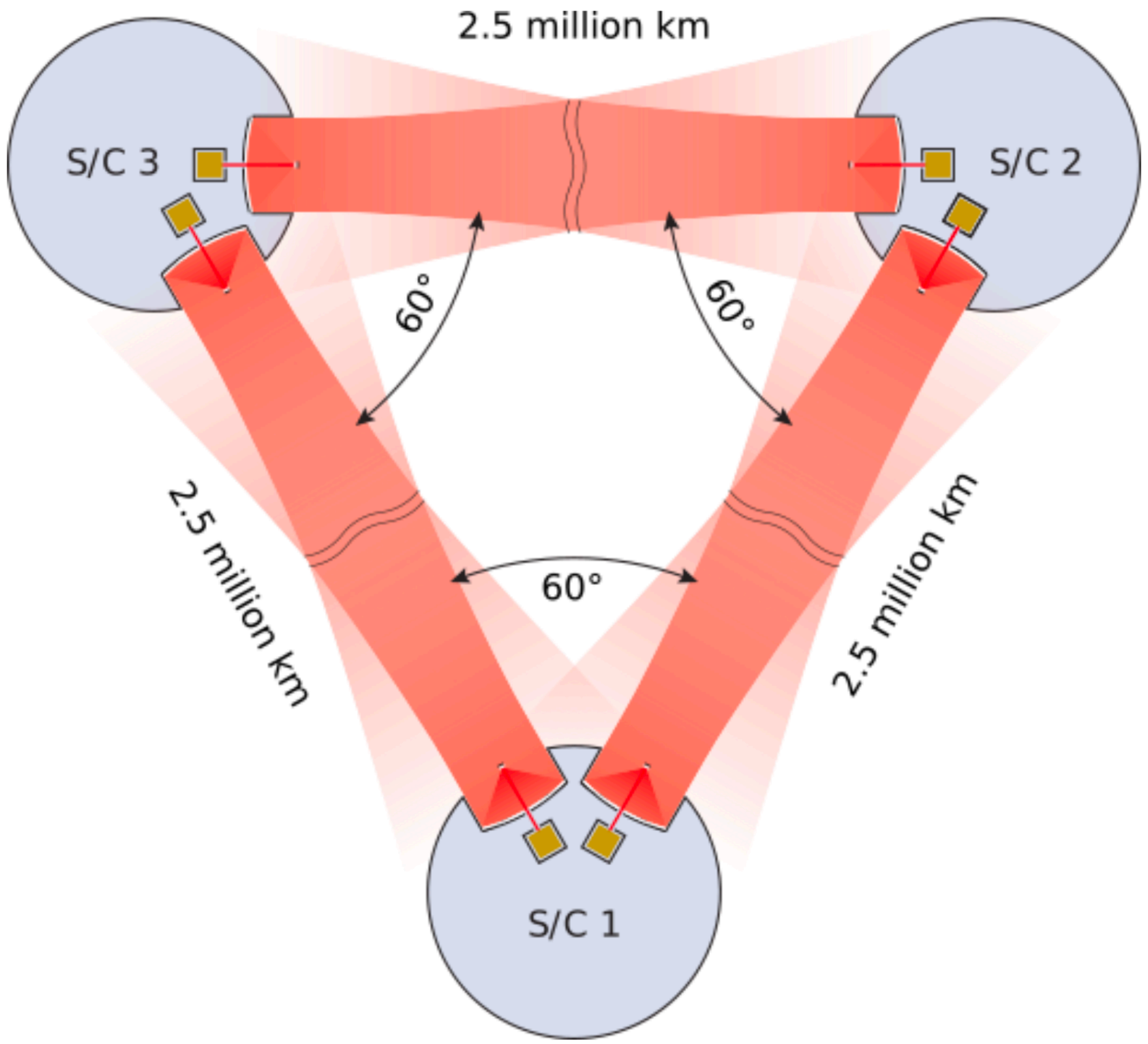


LISA detection principle and TDI

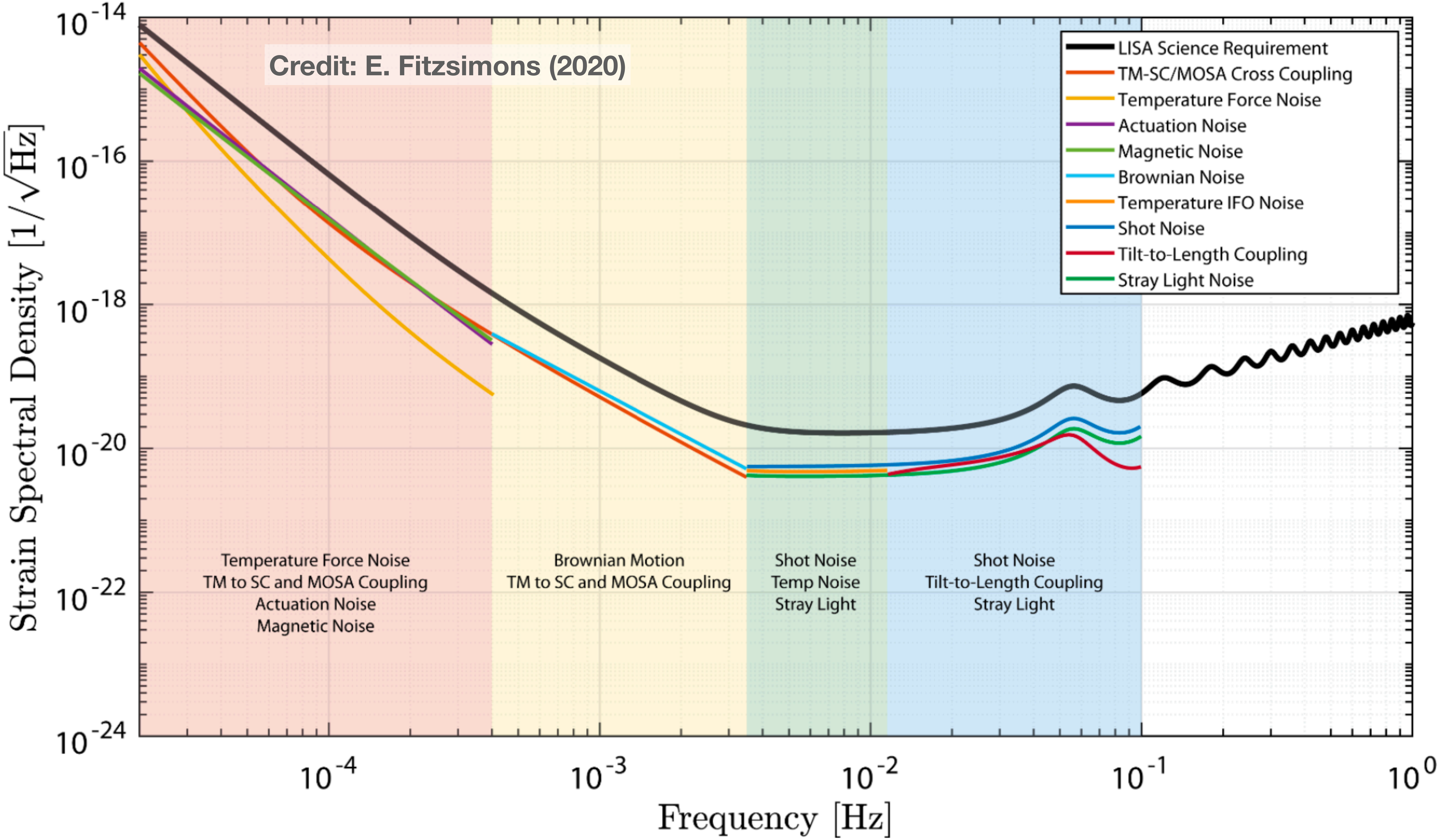
Simulating LISA

- Long-range metrology, Time Delay Interferometry, Measurement chain / breakdown: **numerous key elements not tested with LISA Pathfinder**
- … and which cannot be experimented on-ground (low frequency stability, arm-length, free-fall..)
- **Time Delay Interferometry (TDI)**
- **Critical need of Models and Simulation tools**





Performance and Noise budget



Credit: E. Fitzsimons (2020)

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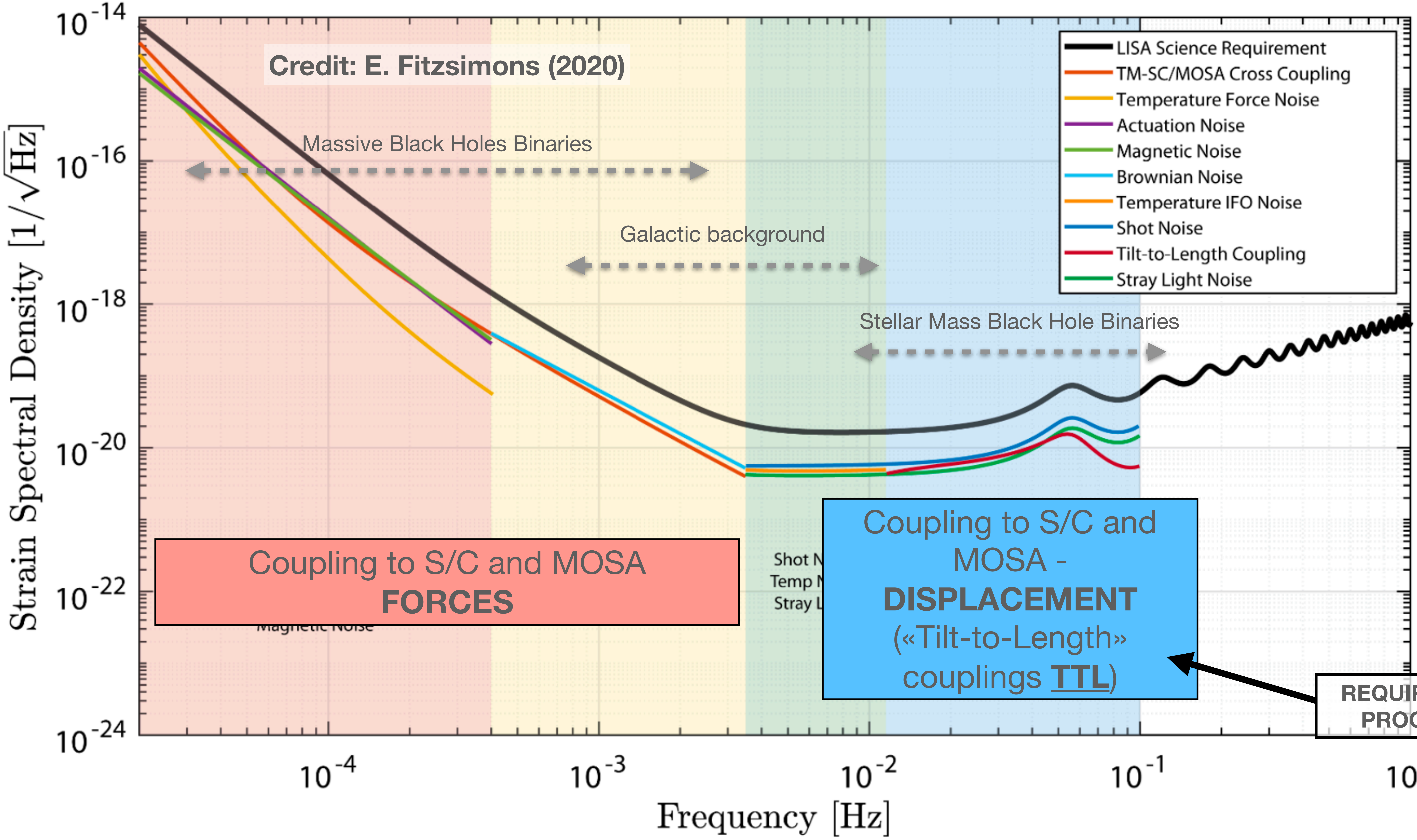
Performance and Noise budget



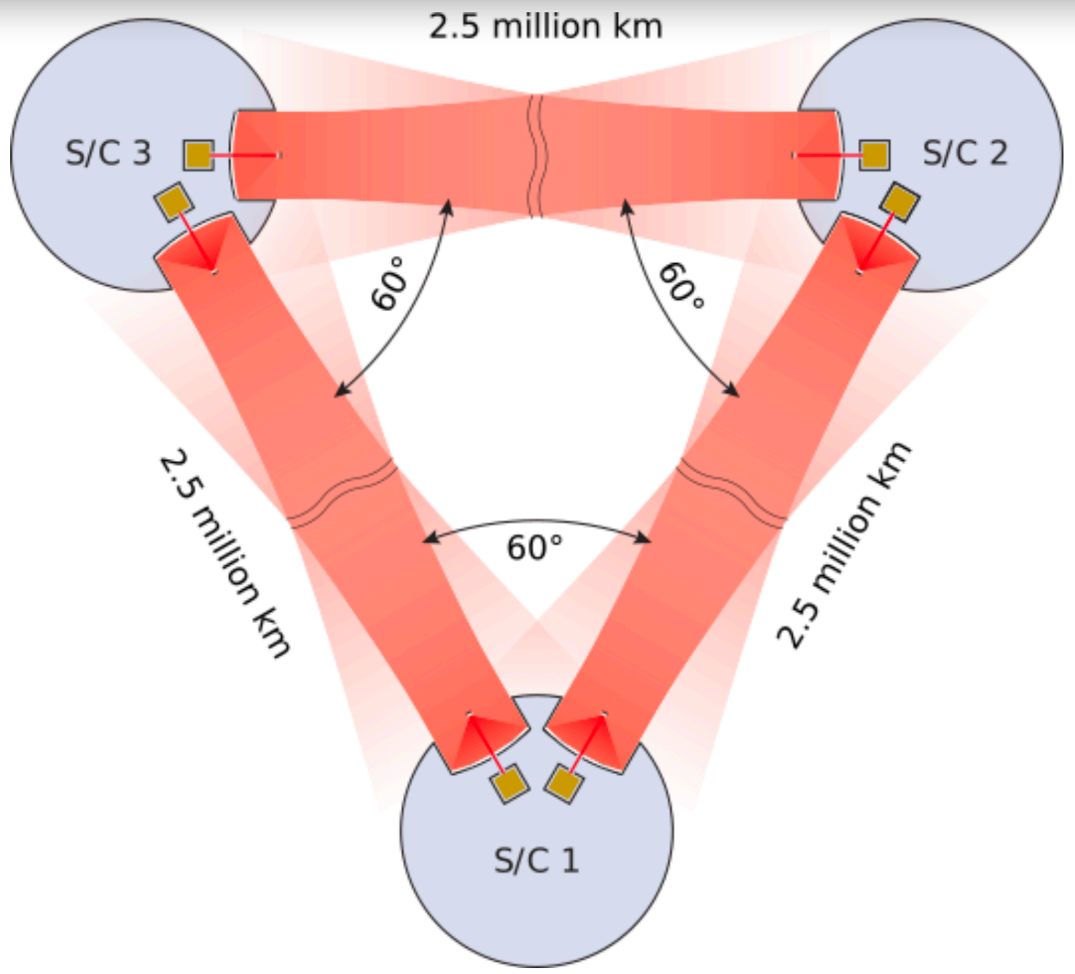
Credit: E. Fitzsimons (2020)

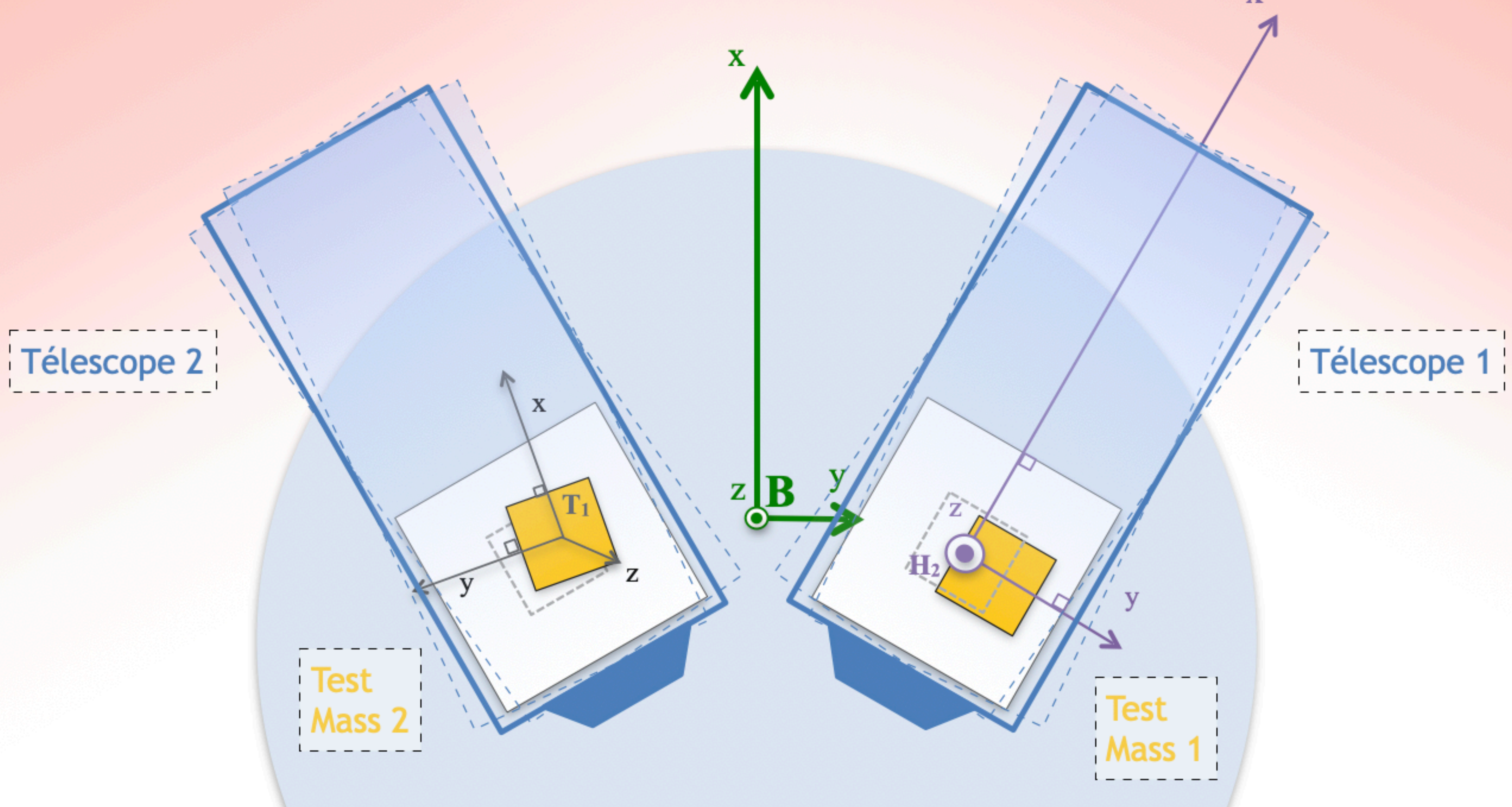
Coupling to S/C and MOSA
FORCES

Coupling to S/C and MOSA - **DISPLACEMENT** («Tilt-to-Length» couplings **TTL**)

REQUIRES POST-PROCESSING

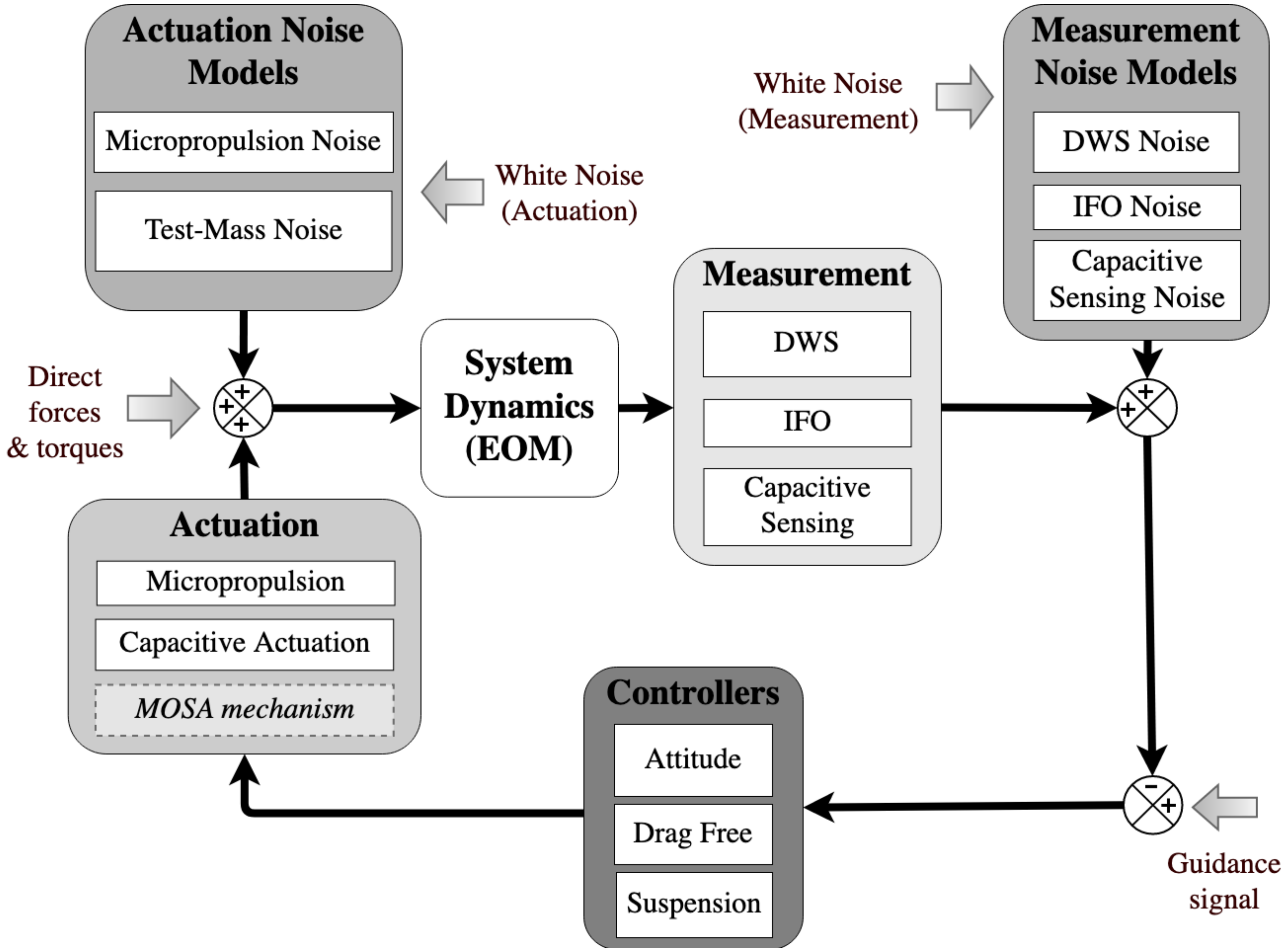
Simulation





- Two simulators available:
  - LISADyn *(Linear, MATLAB)*
  - LISANode/Dynamics *(General, Python)*
- Longitudinal, Angular equations of motion for test mass, spacecraft, MOSAs. Sensing and Actuation.
- Closed-loop Dynamics:
  Attitude Control, Drag-Free, Suspension
- 15 main d.o.f [x]

$$[\Theta, H, \Phi, x_1, y_1, z_1, \theta_1, \eta_1, \phi_1, x_2, y_2, z_2, \theta_2, \eta_2, \phi_2]$$



Actuation Noise Models
Micropropulsion Noise
Test-Mass Noise

White Noise (Actuation)

White Noise (Measurement)

Measurement Noise Models
DWS Noise
IFO Noise
Capacitive Sensing Noise

Direct forces & torques

System Dynamics (EOM)

Measurement
DWS
IFO
Capacitive Sensing

Actuation
Micropropulsion
Capacitive Actuation
MOSA mechanism

Controllers
Attitude
Drag Free
Suspension

Guidance signal

Simulation - `LISADyn`

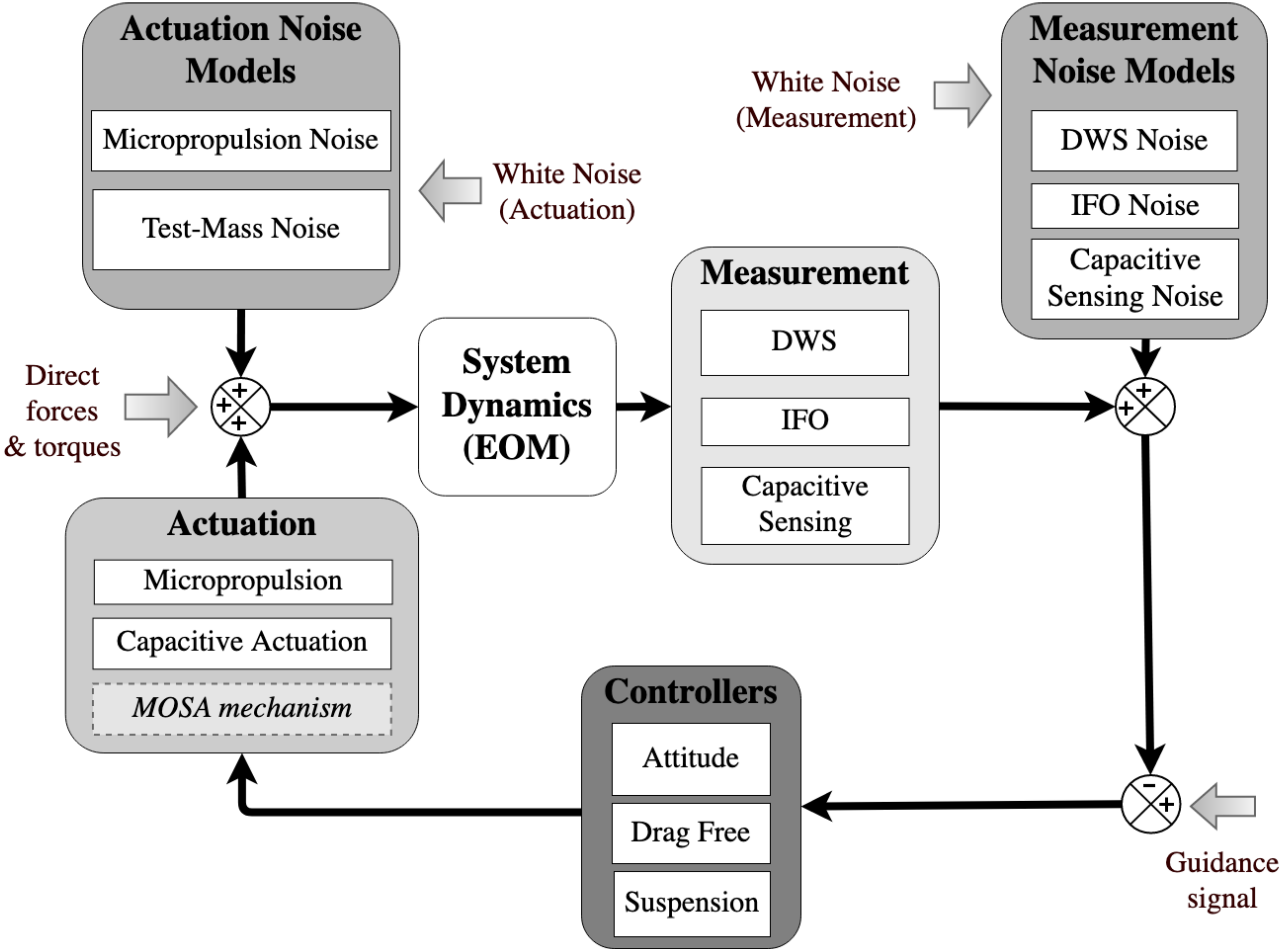
- Matlab `LISADyn`

  https://gitlab.in2p3.fr/hinchaus/LISADyn.git

  Linear Time Invariant (LTI) model of the closed-loop Dynamics.

- Ideal for light / fast simulations, DFACS study and optimization, noise breakdown.

- Accurate and parameterized estimate of S/C and Test mass jitters.



Simulation - LISAD

- Matlab `LISADyn`

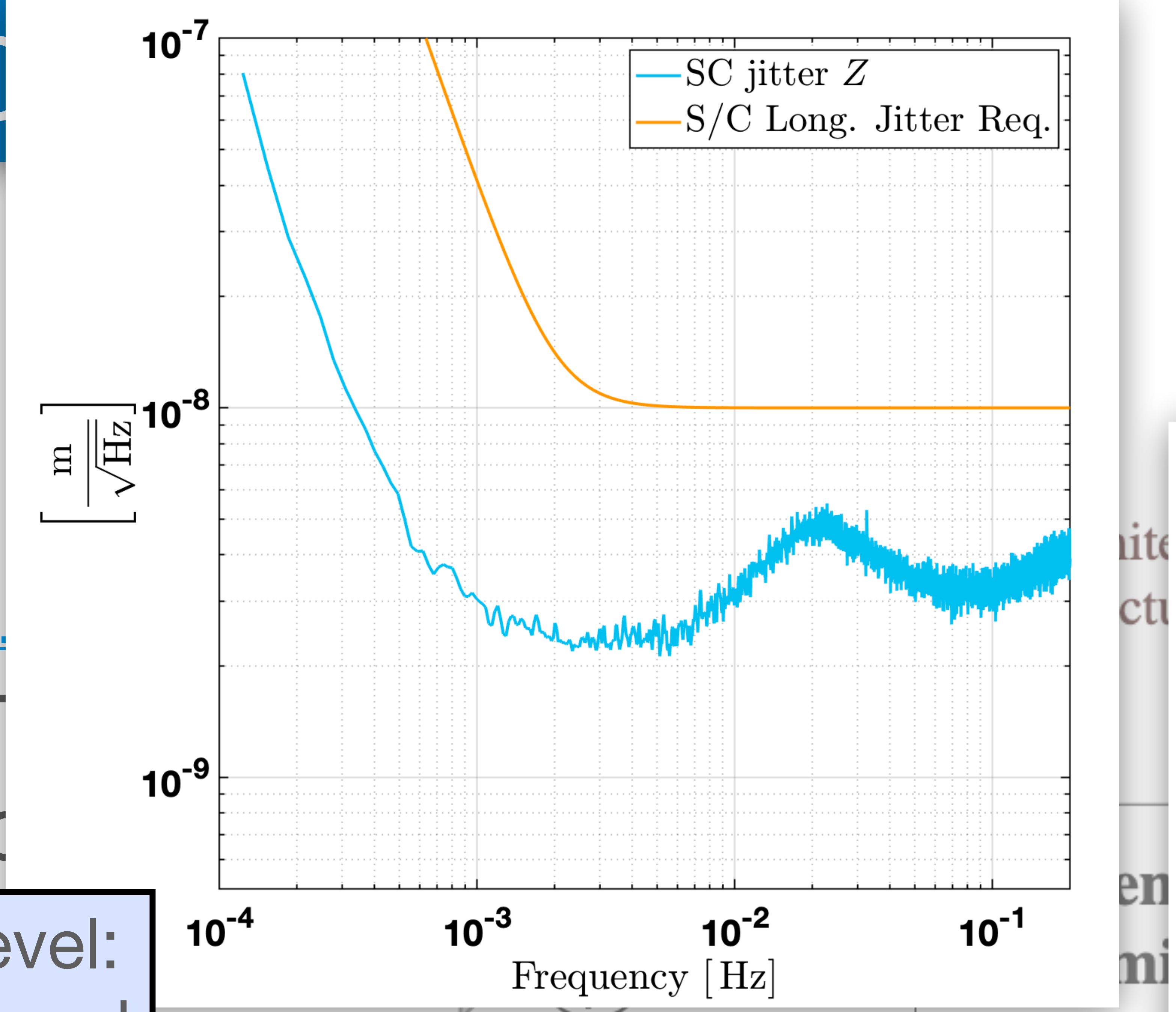
  https://gitlab.in2p3.fr/hinchaus/LISADyn.

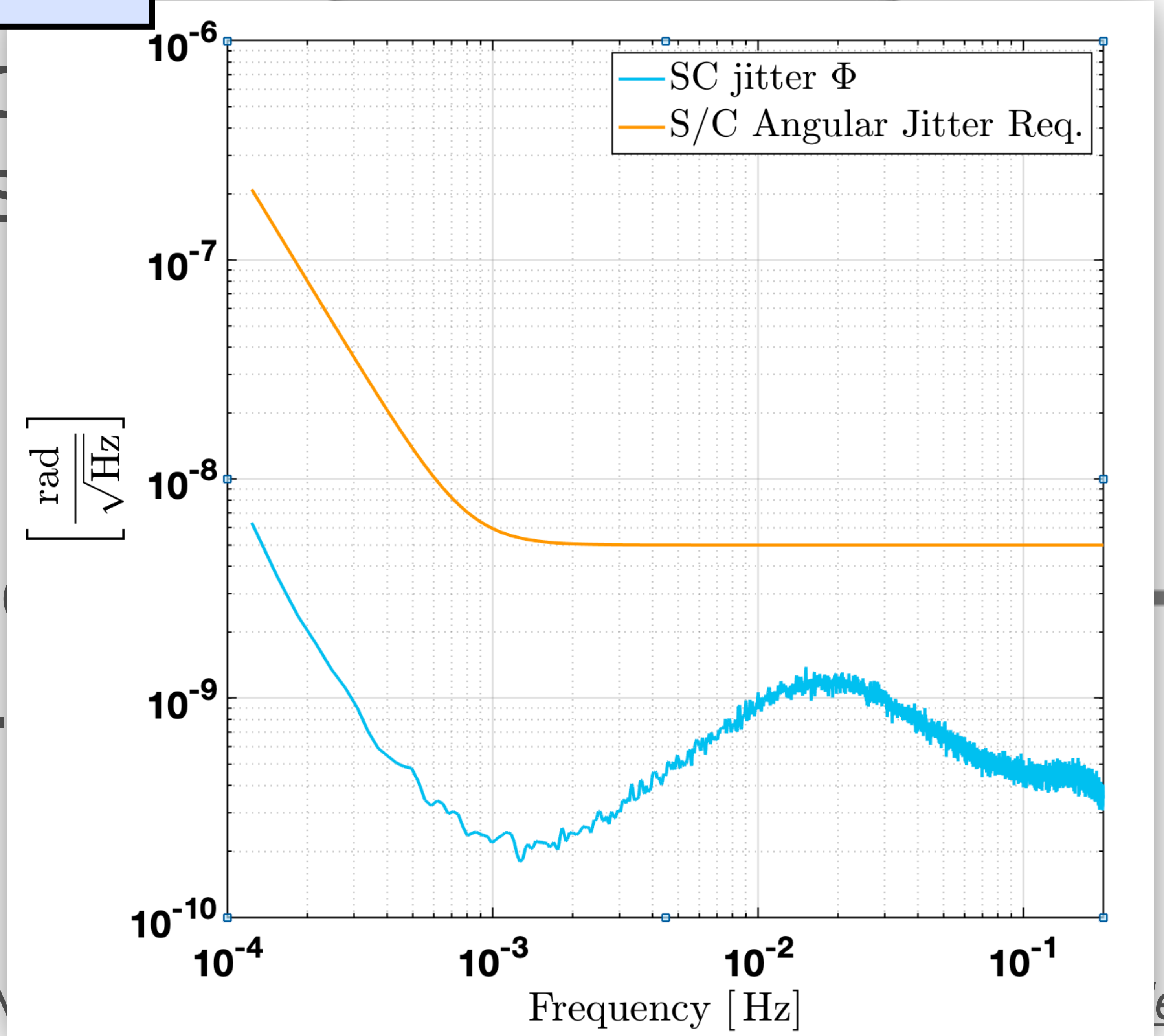
  Linear Time Invariant (LT model of the closed-loo Dynamics.

- Ideal for lig simulations, DFACS stu and optimization, nois breakdown.

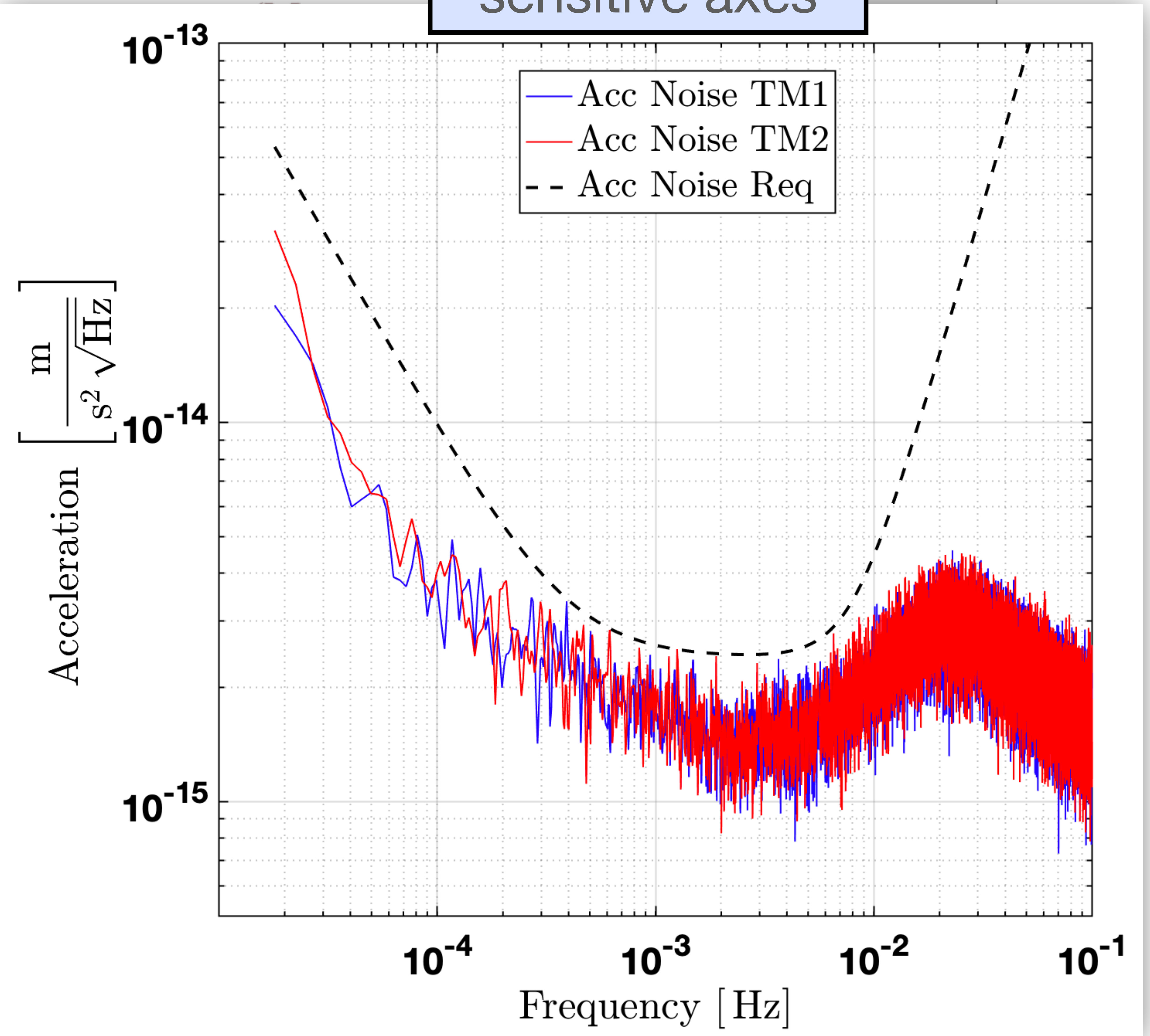
- Accurate an parameterized estimate S/C and Test mass jitters.

S/C Jitter Level: Longitudinal and Angular





TM acceleration noise along sensitive axes



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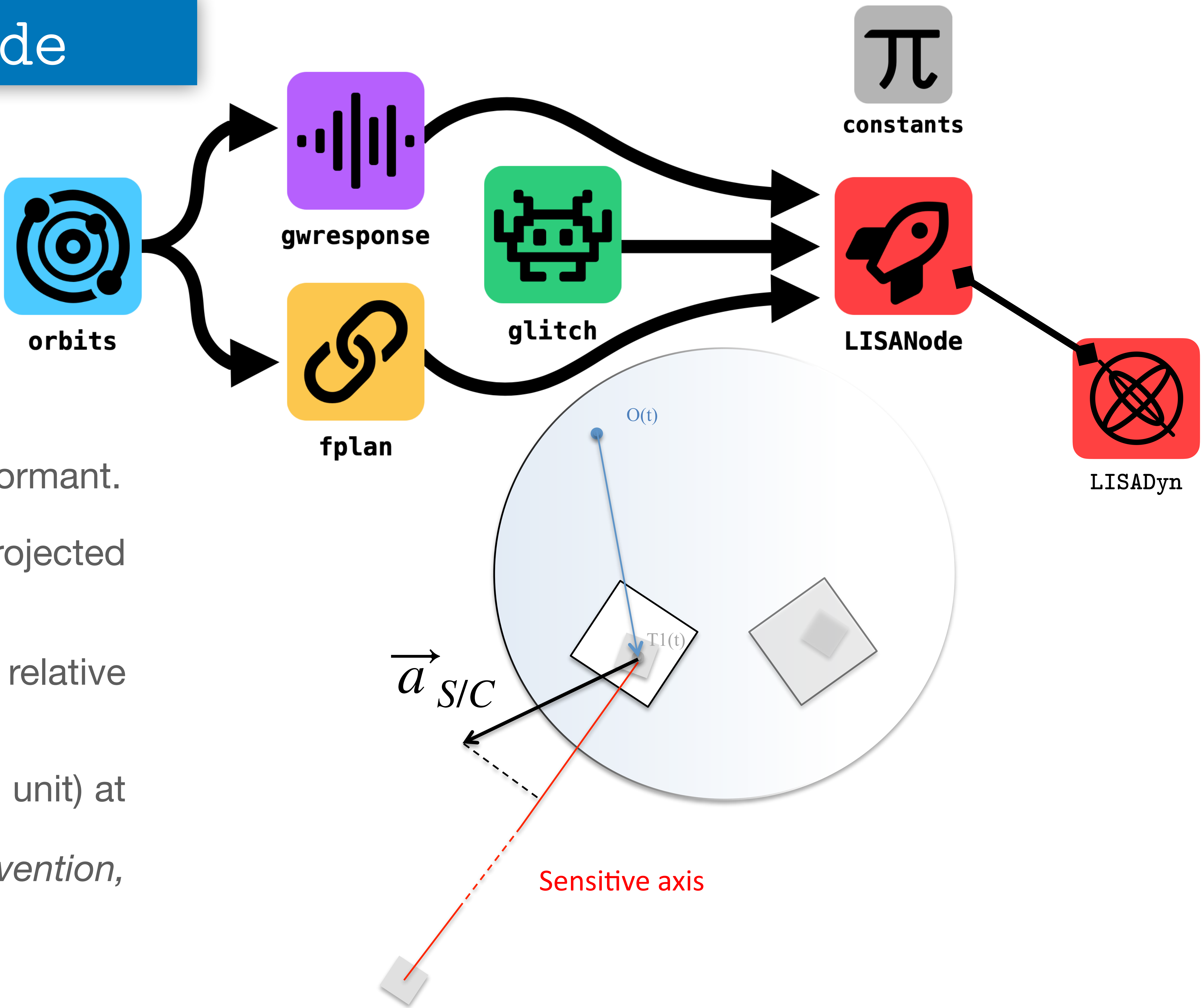
Suspension
Guidance signal

Simulation - `LISANode`



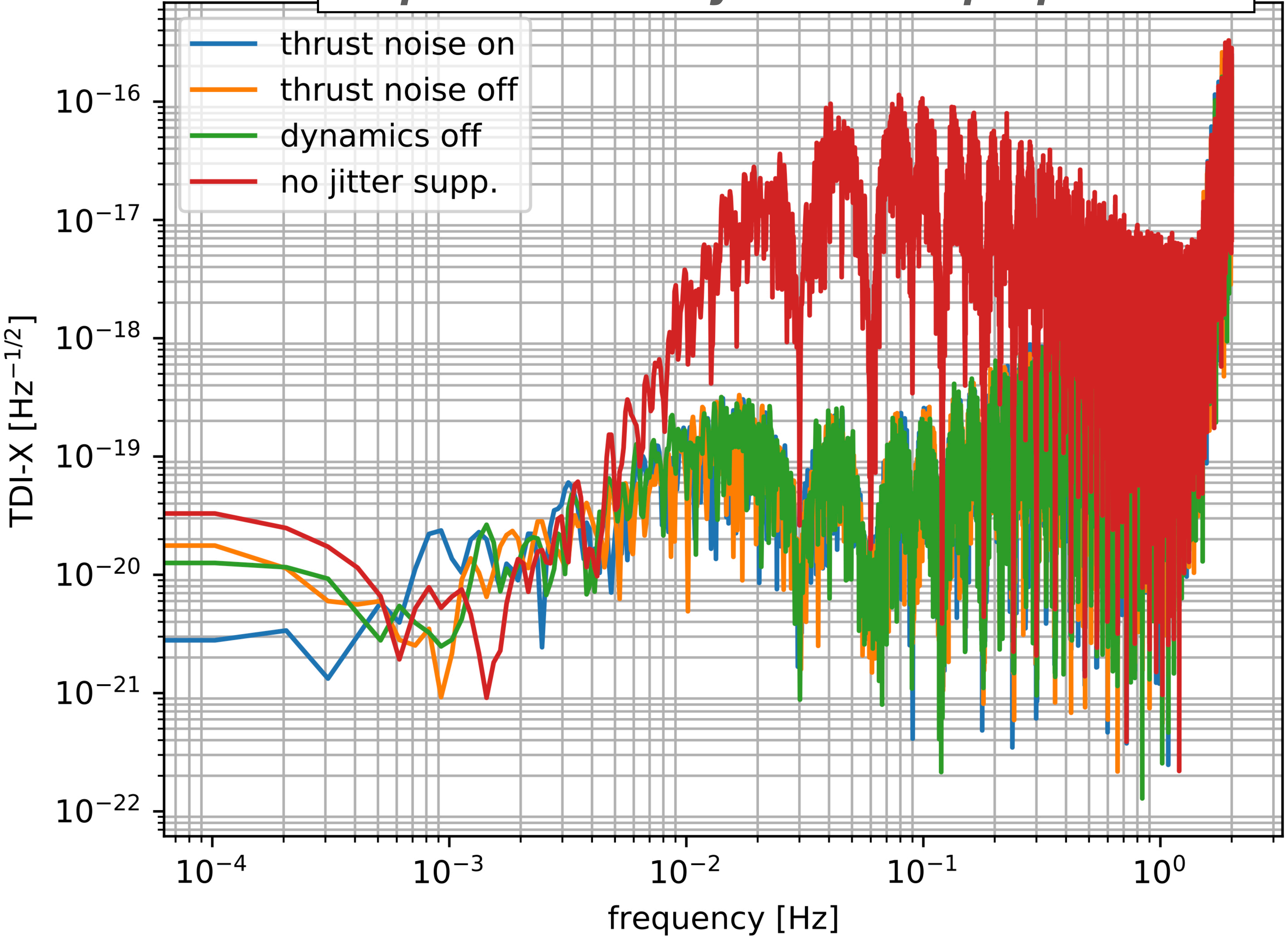
- `LISADyn`: Implementation in `LISANode`.
  https://gitlab.in2p3.fr/j2b.bayle/LISANode.git
  Python wrapping of C code. More performant.
- S/C jitter w.r.t. local inertial frame is projected on the sensitive axes.
  Test mass in-loop velocity is extracted.
  Everything is converted into frequency relative variation.
- Translated as phase variation (rel. freq. unit) at photodiode level.
  Long arm travel time delay, sign convention, Sci and TM IFO.

Simulation - `LISANode`

- Simulate beatnotes and phase measurements.
- Processing dynamical jitters of S/C and test masses through TDI !
- **First demonstration of suppression of S/C jitter by TDI algorithm.**
- Includes also rotational dynamics of all bodies: **We have now everything to do accurate simulation of TTL (next step).**

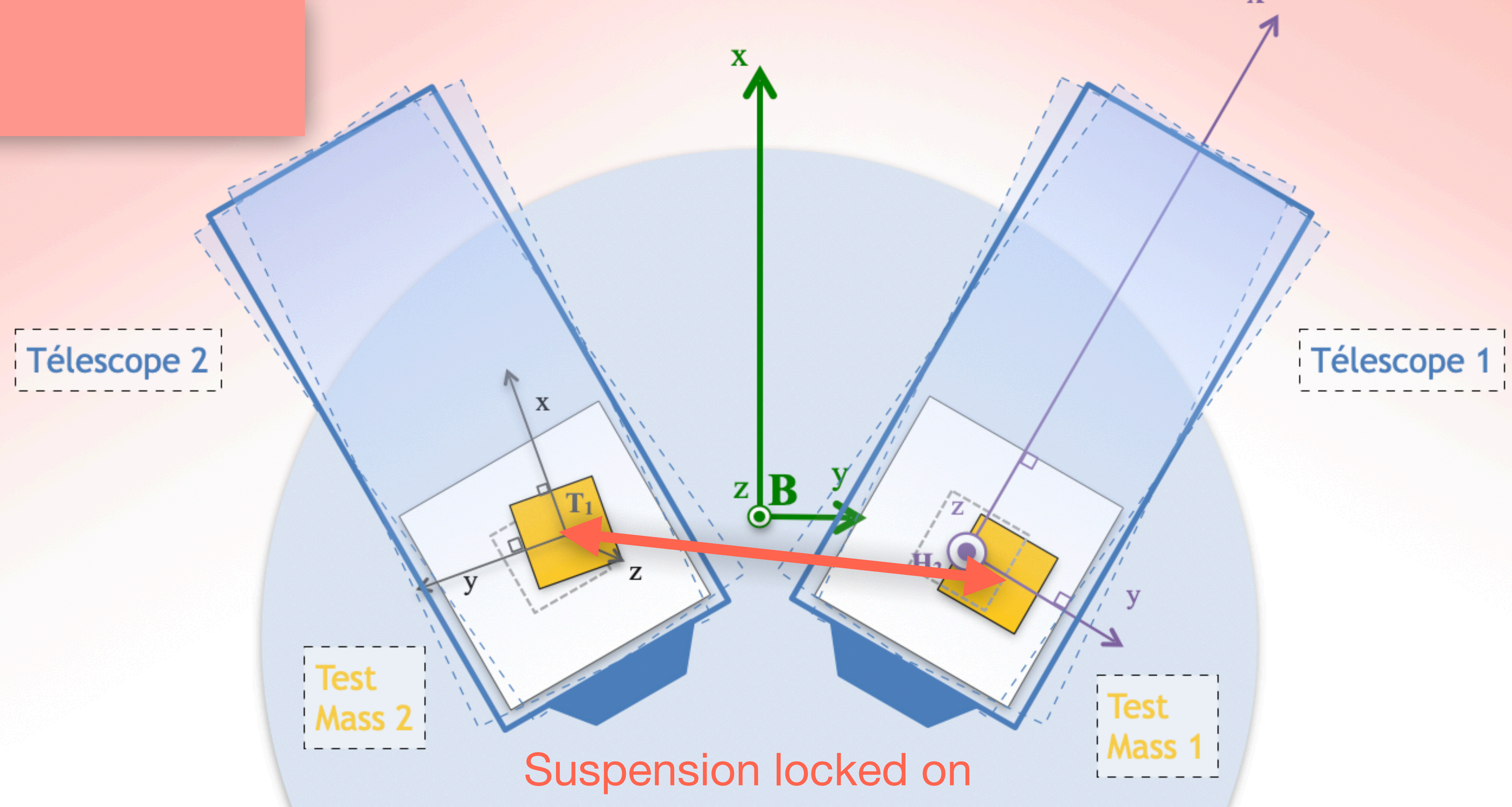
PRELIMINARY

Paper on LISA Dynamics in preparation



DFACS optimization

- Parallel project: need of a control strategy that distinguishes common mode (S/C motion) to differential mode (TM motion).
- Goal: do not apply force on TMs trigged by S/C noisy motion. Mitigates crosstalk
- **Lock drag-free on common mode displacement.**
- **Lock test mass control (suspension) on test mass differential displacement.**



Suspension locked on differential TM position

$$F^{sus}_{y_1} \propto y^{grs}_1$$
$$F^{sus}_{y_2} \propto y^{grs}_2$$
$$F^{sus}_{z_1} \propto z^{grs}_1$$
$$F^{sus}_{z_2} \propto z^{grs}_2$$

Simple,
Commonly used

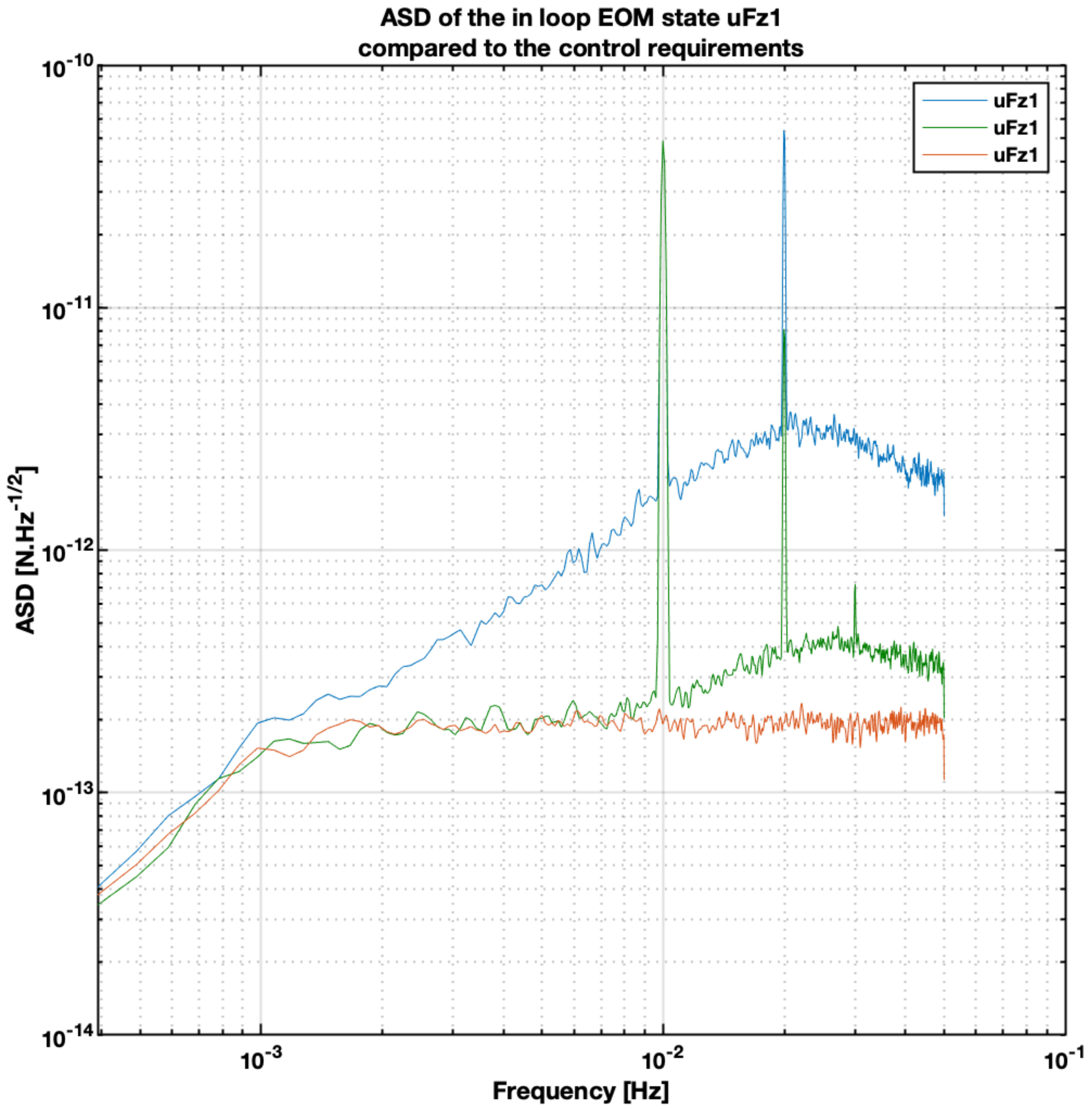
⟷

$$F^{sus}_{y_1} \propto f(x^{ifo}_1, x^{ifo}_2, y^{grs}_1, \Phi^{dws})$$
$$F^{sus}_{y_2} \propto f(x^{ifo}_1, x^{ifo}_2, y^{grs}_2, \Phi^{dws})$$
$$F^{sus}_{z_1} \propto f(z^{grs}_1, z^{grs}_2, \Theta^{dws})$$
$$F^{sus}_{z_2} \propto f(z^{grs}_1, z^{grs}_2, \Theta^{dws})$$

Optimized

DFACS optimization

- New scheme: Very good isolation performance and attenuation of cross-talks (Suspension plots)
- Interesting Impact on noise


ASD of the in loop EOM state uFz1 compared to the control requirements

PRELIMINARY

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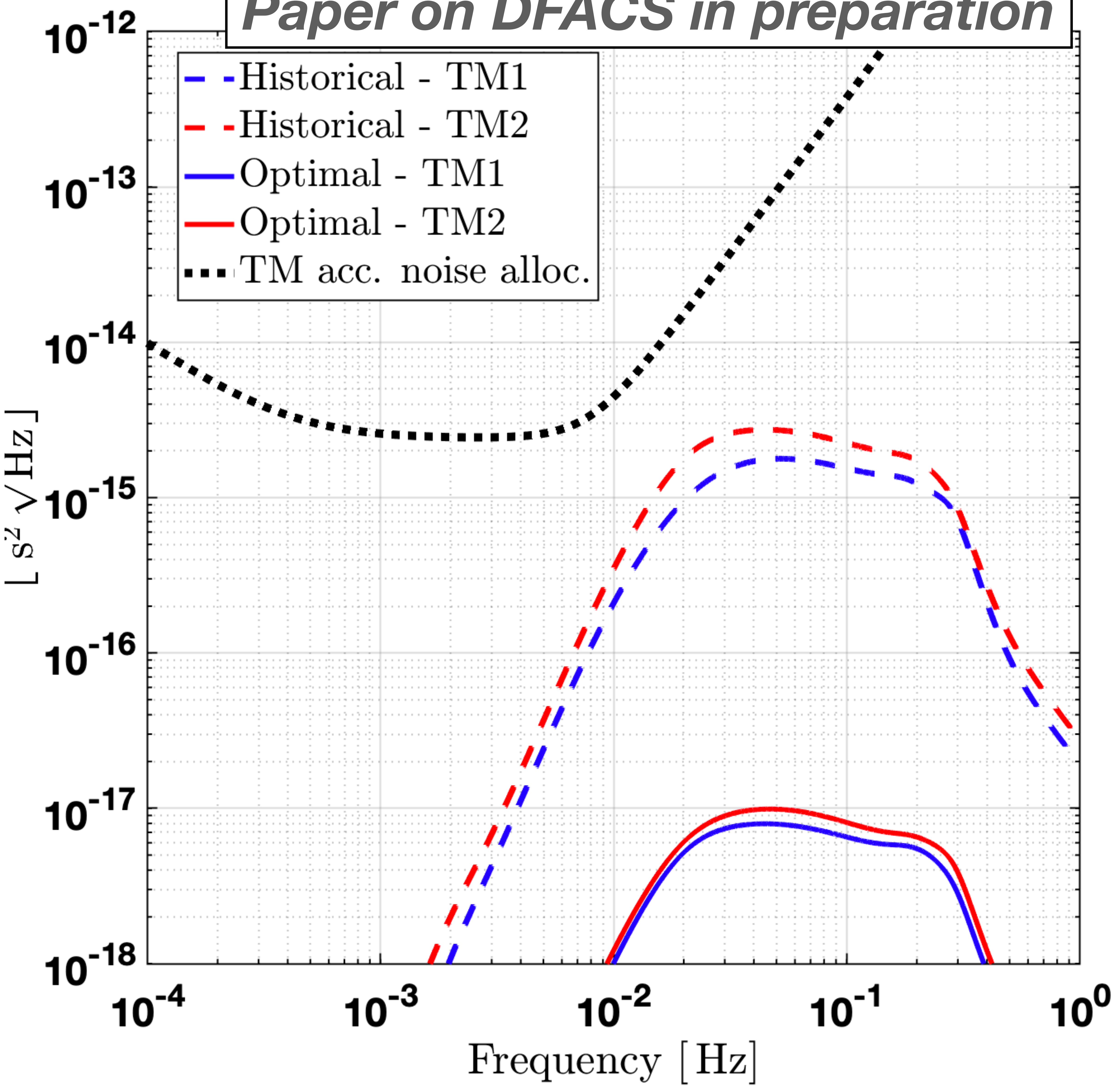


DFACS optimization

- Suspension optimization requires estimate of diff. acc. projected along y and z axes:
  We can do the same trick along sensitive axes !

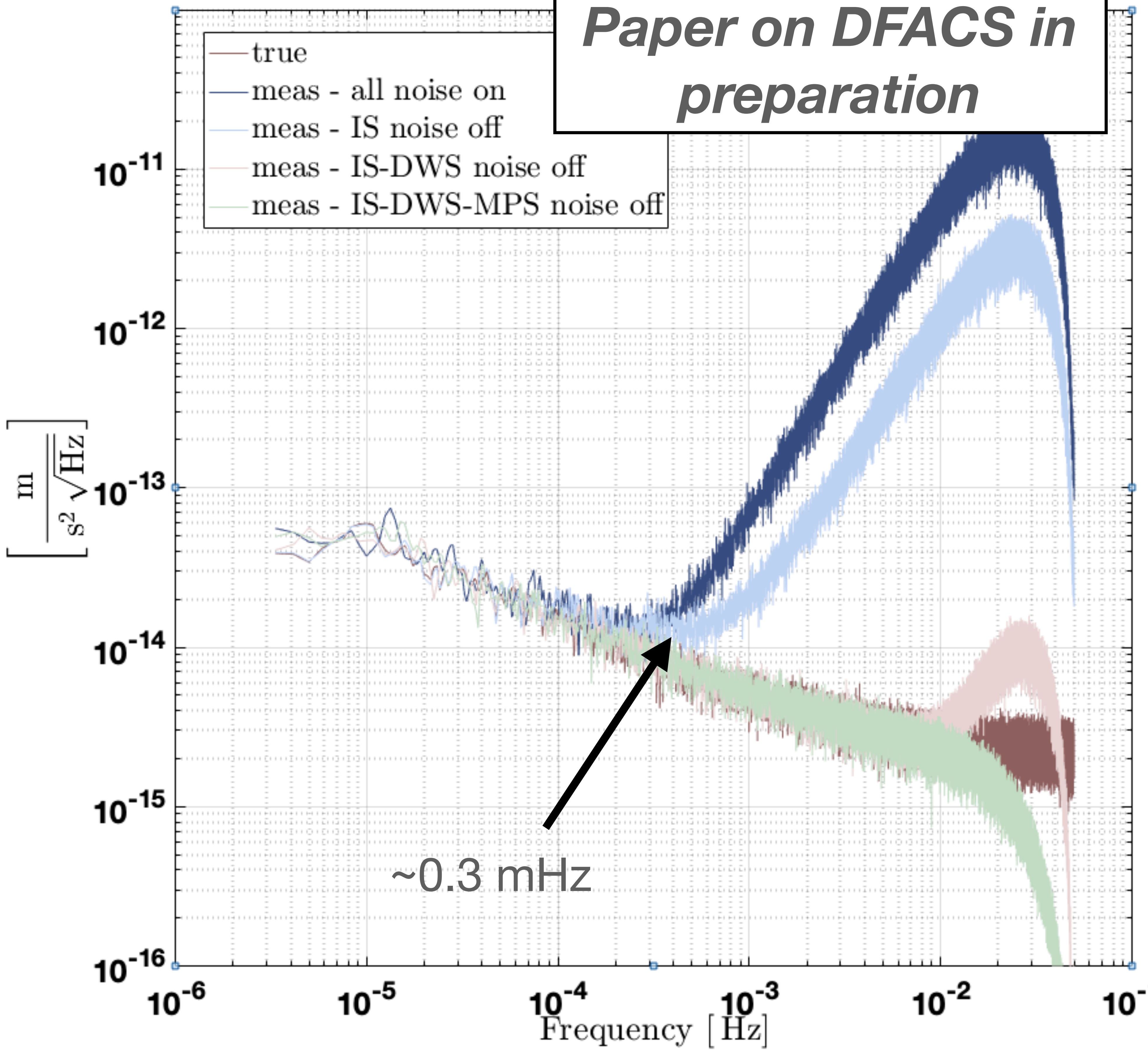
➡ **Strategy to measure acceleration noise locally.**

- Use of GRS and DWS sensors introduces large noise at hight frequency.
- Although at low frequency: fairly accurate upper limit on the acceleration noise.
- Use: sanity check, glitch detection and measurement, data processing / analysis.

$$a^{x_1}_{diff} = f\left(\ddot{x}^{ifo}_1, \ddot{y}^{grs}_1, \ddot{y}^{grs}_2, \ddot{\Phi}^{dws}, F^{sus}_{y_1}, F^{sus}_{y_2}\right)$$

$$a^{x_2}_{diff} = f\left(\ddot{x}^{ifo}_2, \ddot{y}^{grs}_1, \ddot{y}^{grs}_2, \ddot{\Phi}^{dws}, F^{sus}_{y_1}, F^{sus}_{y_2}\right)$$

PRELIMINARY
Paper on DFACS in preparation



~0.3 mHz

Conclusion

- Spacecraft and MOSA stability critical aspects of LISA performance and science. Impact low frequency (force coupling) as well as high frequency (cross-couplings).

- Need of accurate closed-loop dynamic simulation in order to:
  - *Verify suppression of platform jitter through pos-processing (Time delay interferometry).* ✅
  - *Test / evaluate performance of post-processing correction of Tilt-to-Length.* 👷

- **Generally: further exploration of closed-loop dynamics and auxiliary channels for post-processing critical: still a lot to be done there.**
  example: acceleration noise channel, post-processing test mass interferometers…