Riding the Dark Matter Wave:
General dark photon limits from LISA Pathfinder

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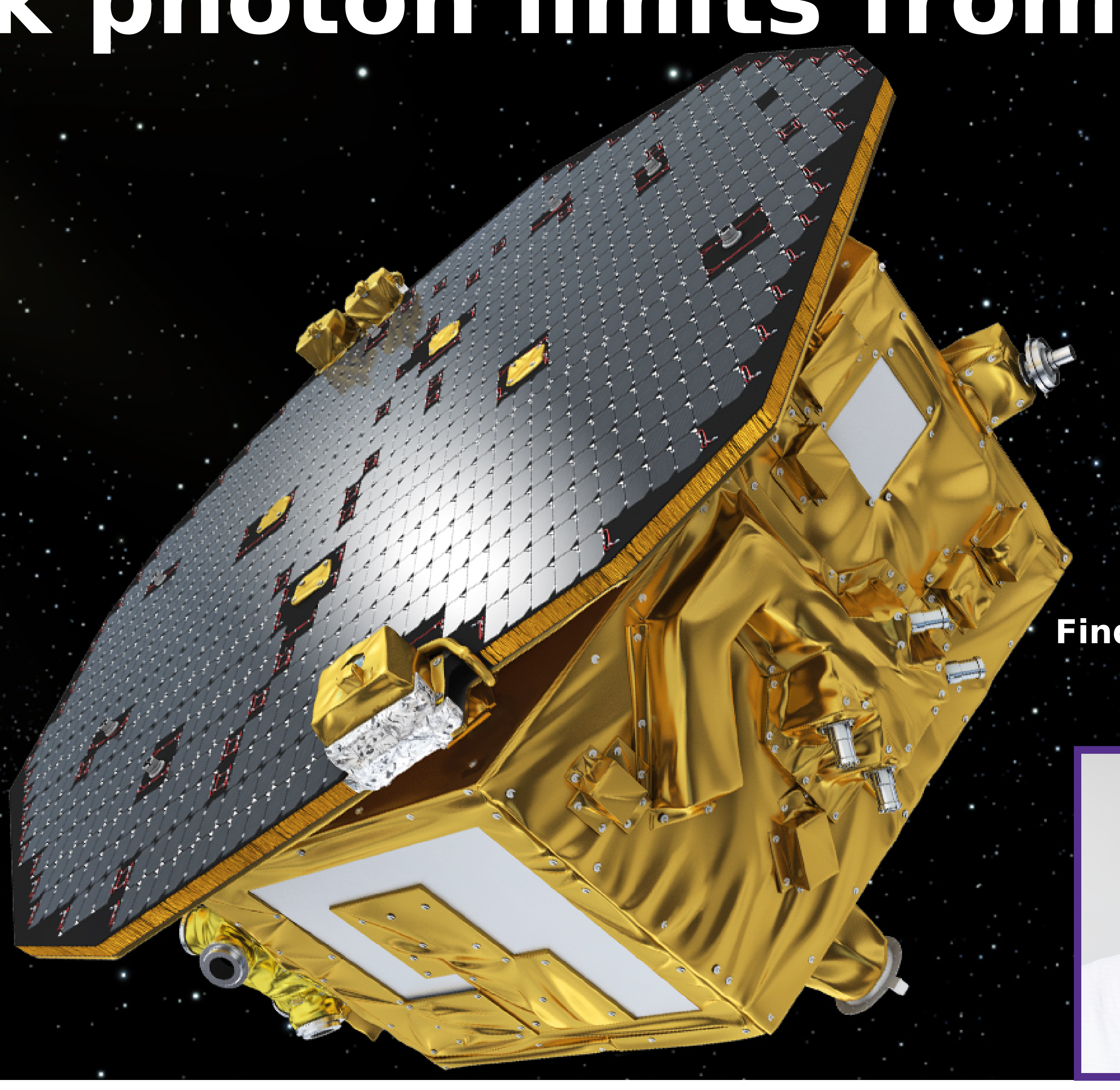
Jonas Frerick[1*]
Joerg Jaeckel[2]
Felix Kahlhoefer[3]
Kai Schmidt-Hoberg[1]

[1]Deutsches Elektronen-Synchrotron, DESY, Hamburg
[2]Institut für Theoretische Physik, Universität Heidelberg, Heidelberg
[3]Institute for Theoretical Particle Physics (TTP), Karlsruhe Institute of Technology (KIT), Karlsruhe

*jonas.frerick@desy.de



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1. General Dark Photons

Recently, the interest in light (DM) candidates has increased, and a standout example of such a WISPy candidate is the Dark Photon (DP) associated to a dark $U(1)_X$

$$\mathcal{L} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{\epsilon_{\rm KM}}{2}F'_{\mu\nu}F^{\mu\nu} + \frac{m^2}{2}A'_\mu A'^\mu - \epsilon_g e A'_\mu J^\mu_g \,.$$

Kinetic mixing
(Suppressed by plasma effects in direct detection)

Direct coupling to some current

We chose to gauge SM global symmetries for the current. Maybe the most prominent example is gauging $B{-}L$ which will be our focus. Nevertheless, our work is applicable to more general choices [1]. We have dubbed this larger class of DPs **general Dark Photons**.

3. Sensitivity & Advantages of LISA Pathfinder

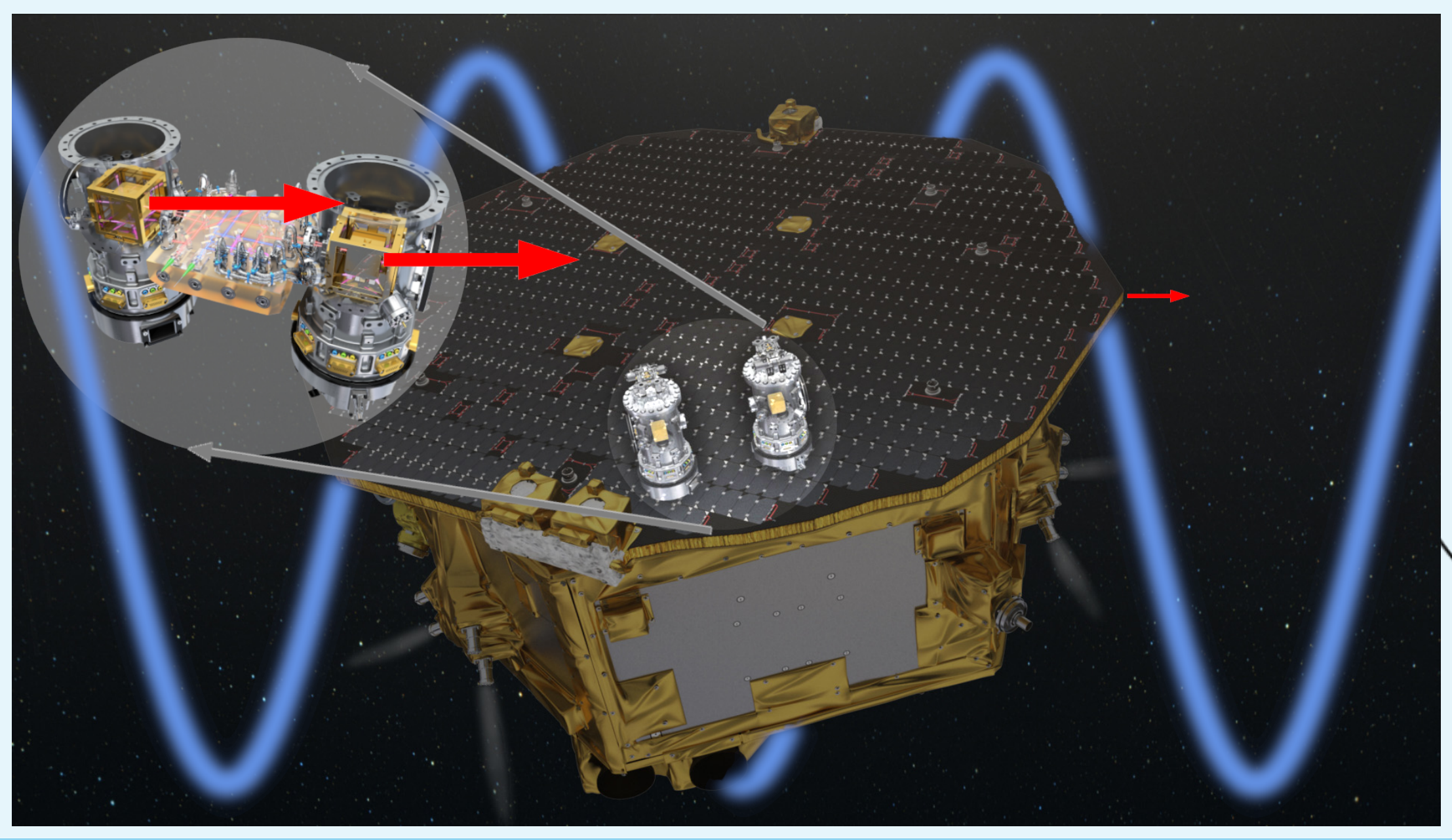
The LISA Pathfinder (LPF) mission tested technology feasibility for space-borne GW interferometry. The key facts are:

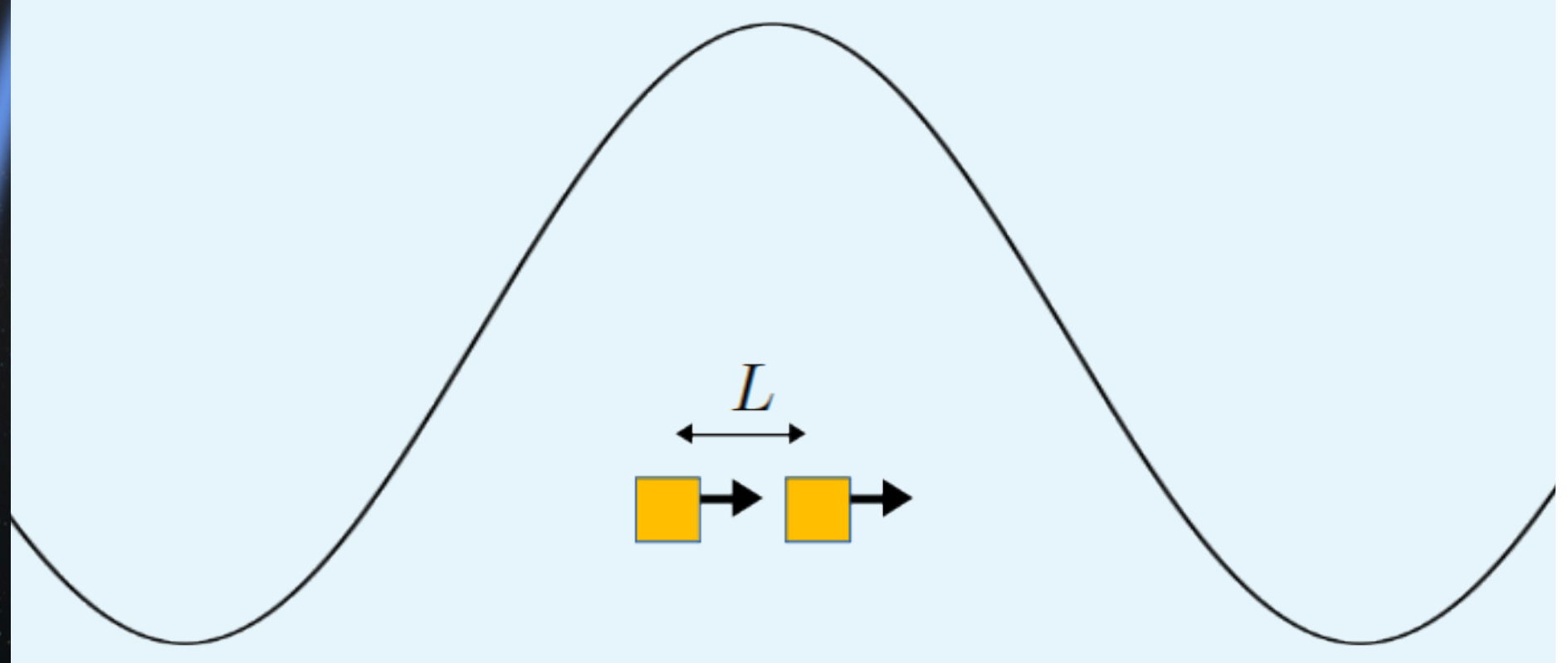
- the LPF science module houses two AuPt alloy test masses (TMs)
    - mass: 2kg
    - relative distance: 40cm
- an onboard laser interferometer measures the **relative acceleration** $S_a^{1/2}$
- signal expectation: **no net motion** ($\Delta(q/M){=}0$)

The workaround we found involves utilizing the module's **auxiliary channels**:

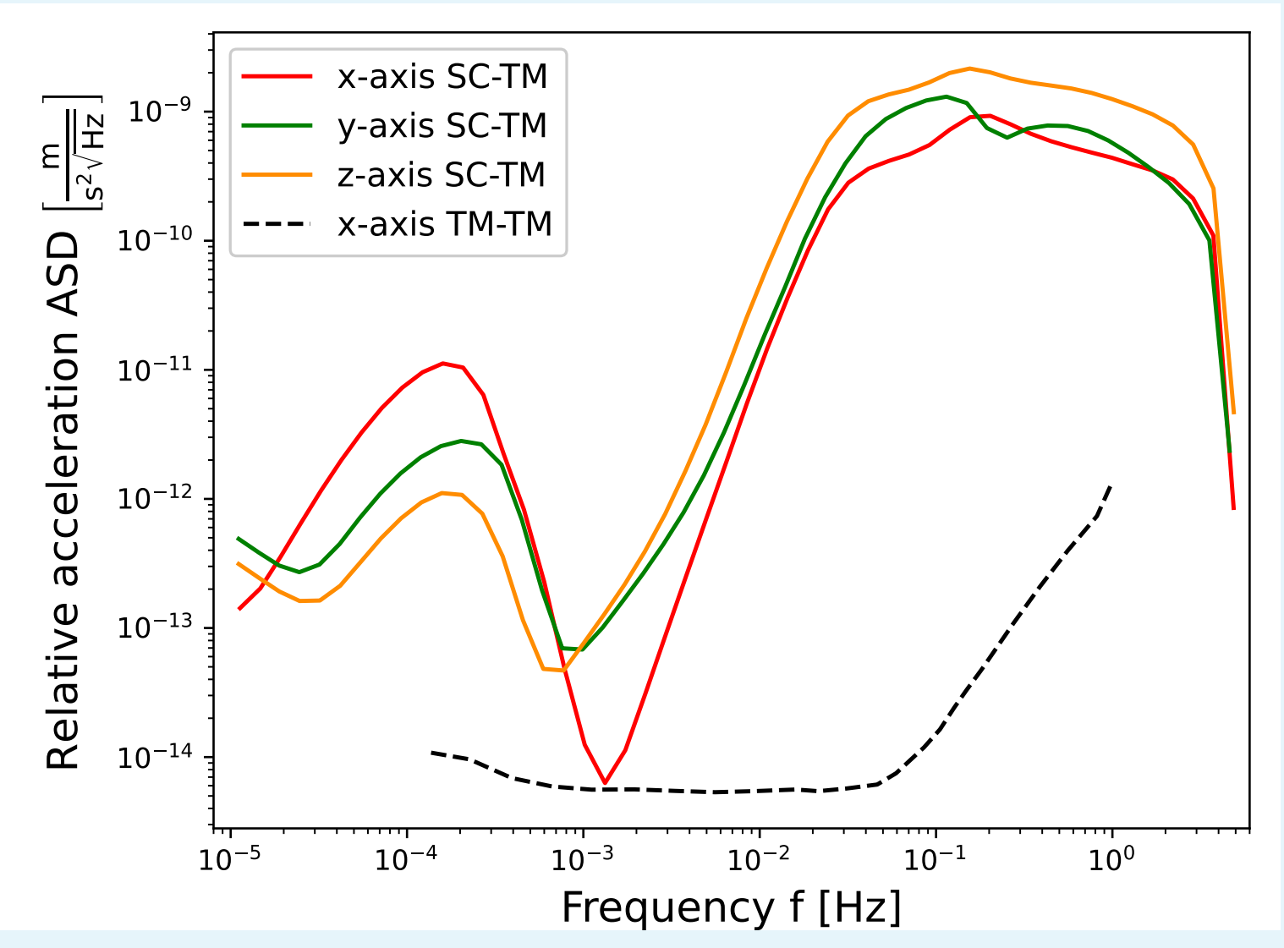
- space craft (SC) has a **different charge-to-mass ratio** than the TMs (conservatively $\Delta(q/M) > 0.018\,(\text{GeV})^{-1}$)
- sensitivity on more than one axis
- amplitude spectral densities (ASDs) are readily available for a simplified analysis [4] to plug into the SNR

Sketch of the LPF setup. The two TMs are shown in their housings. Red arrows on the TMs and spacecraft indicate the different Lorentz forces. (Copyright: ESA/ATG medialab)





Insensitivity of the main channel
since this measurement can only observe the gradient in the Lorentz force



ASDs for all three sensitive axes in LPF, in comparison to the main channel (TM-TM).

2. Signals of general Dark Photon Dark Matter

Ultralight Dark Photon Dark Matter (DPDM) benefits from diverse DM production mechanisms spanning fuzzy ($\simeq 10^{-21}$ eV) to light ($\simeq 1$ eV) DM masses. In the this regime, DM can be described by a classical wave

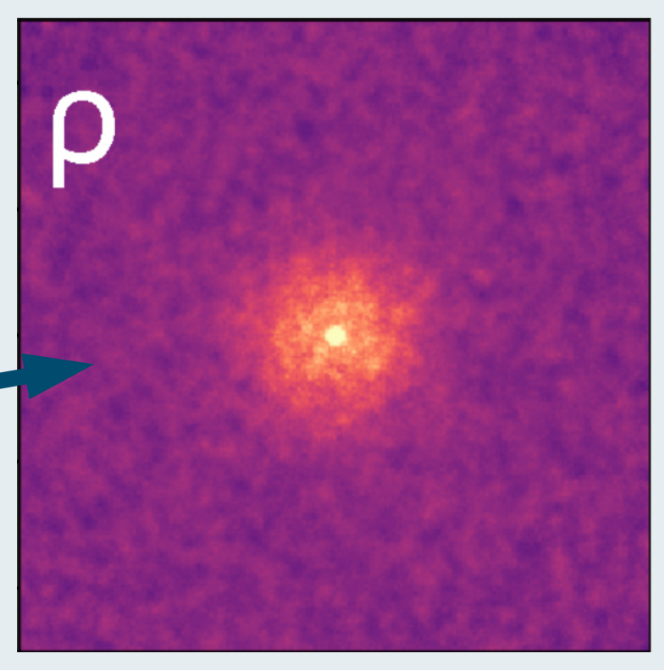
$$\mathbf{A}(x,t) = \mathbf{A}_{\rm DM}e^{-i\omega t+\mathbf{k}\cdot\mathbf{x}+\phi}\,.$$

This field is:

- non-relativistic $v = k/\omega \approx k/m \simeq 10^{-3}$
- **coherent** $\lambda_c \simeq 2\pi/(mv)$ & $t_c = 2\pi/(mv^2)$
- exercising a quasi-**Lorentz force** on charges q with mass M

$$\mathbf{a}(t) \simeq i\omega\epsilon_g e\frac{q}{M}\mathbf{A}_{\rm DM}e^{-i\omega t} = i\epsilon_g e\frac{q}{M}\sqrt{2\rho_{\rm DM}}\,\hat{\mathbf{e}}_A\,e^{-i\omega t}$$

$$\Rightarrow \Delta a_i = \epsilon_g e\left(\Delta\frac{q}{M}\right)\sqrt{2\rho_{\rm DM}}\cos\theta_{A,i}\,.$$



Wave DM density
with coherence structure
(image from [5])

Difference in charge-to mass ratio

Intrinsic directionality
(unlike for scalars)

This is our theory prediction for the DPDM signal at an accelerometer [2,3]. We get the following **signal-to-noise ratio (SNR)** for the induced acceleration

$$\text{SNR} = \frac{\Delta a_i}{S_a^{1/2}(f)}\sqrt{T_{\rm eff}}$$

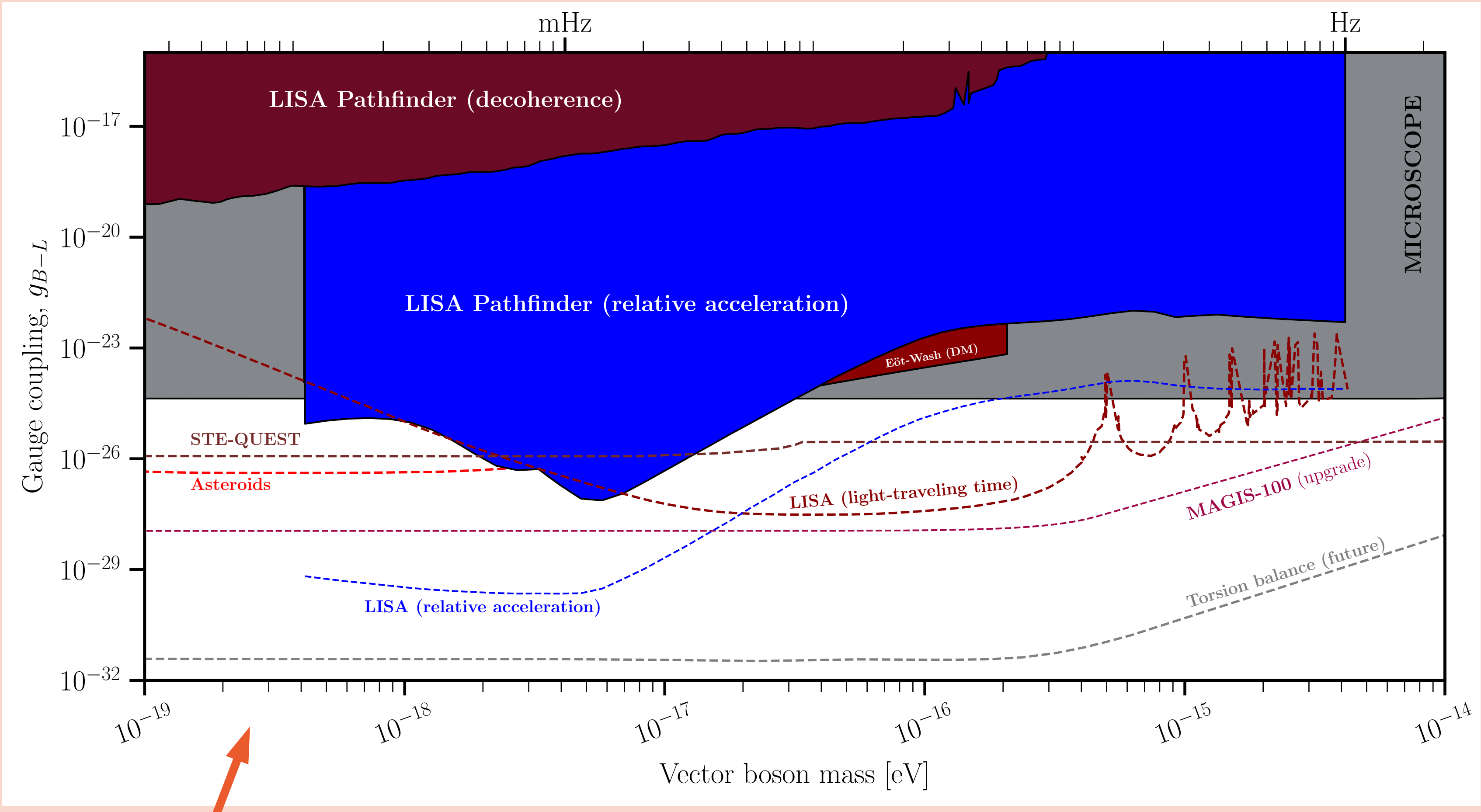
$$T_{\rm eff} = \begin{cases} T_{\rm obs}\ , & T_{\rm obs} \le t_c \\ \sqrt{T_{\rm obs}t_c}\ , & T_{\rm obs} > t_c \end{cases}\,.$$

Side notes:

$\rho_{\rm DM} \sim 0.4\,\text{GeV/cm}^3$

$q = N_{\text{neutron}}$

4. Results, Conclusions & Outlook

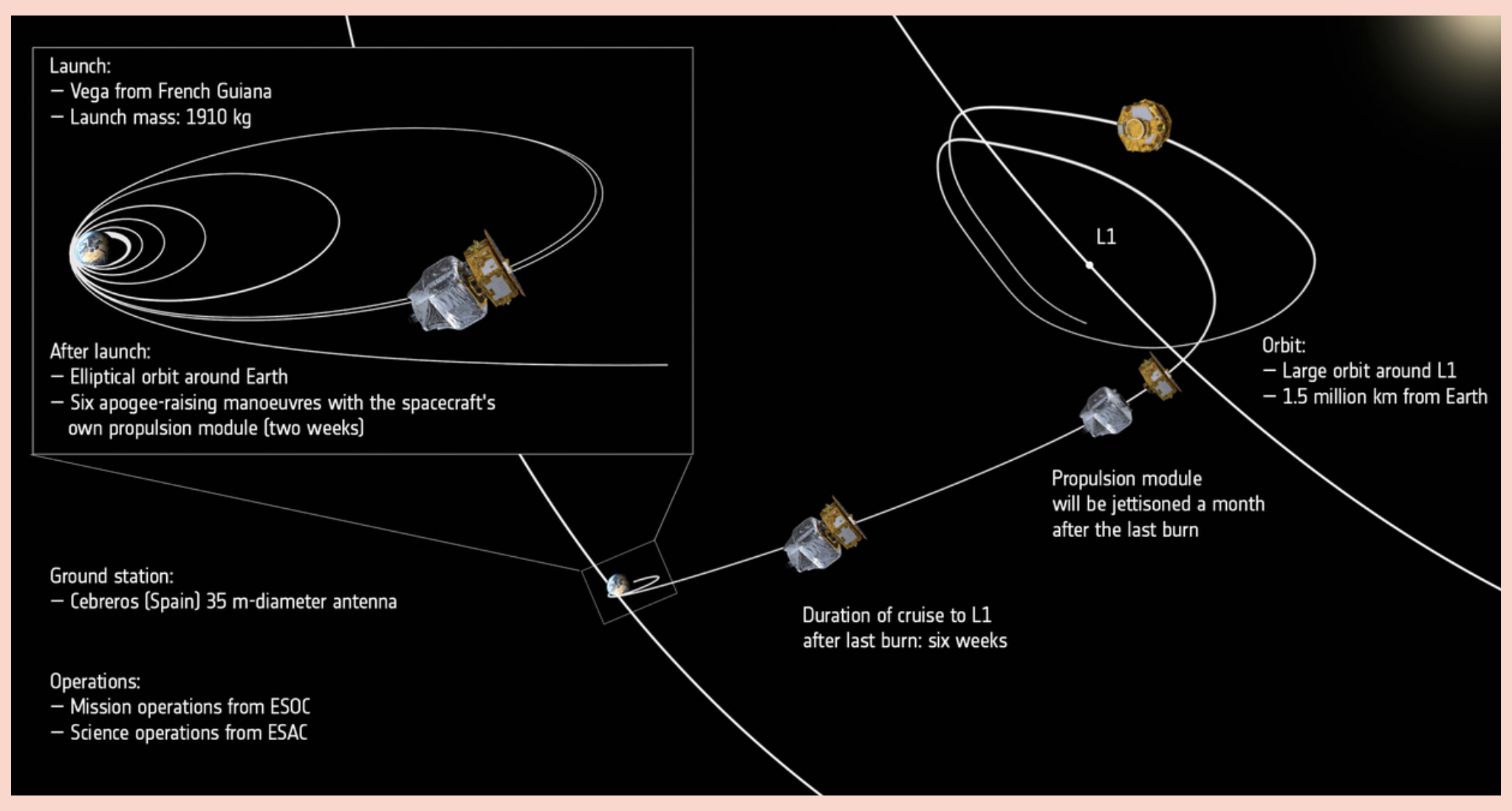


Compilation of $B{-}L$ DP(DM) limits. Previous direct detection limits are displayed in red, with our limits in blue. Additionally, the optimistic LISA forecast offers further reach and complements earlier projections.

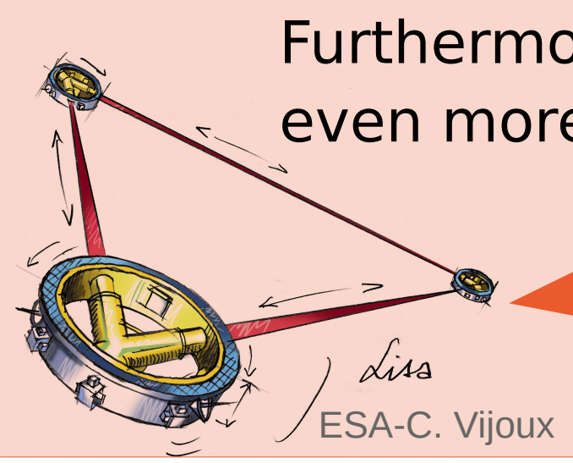
Using the aforementioned simplifications and assumptions, we can set a conservative yet **world-leading limit on $B{-}L$ DPDM**.

A planned, more rigorous approach requires a detailed analysis of the **publicly available data**, taking into account the orbit and the directions of the spacecraft axes w.r.t. the DM polarization as well as theory considerations of the DP distribution.

Furthermore, this idea can also be **studied for LISA** directly which will most likely feature even more sensitive main and auxiliary channels as indicated in our naive forecast.



LPF's journey to L1, starting in December 2015. L1 was reached in January 2016. Data taking began in March 2016 and ended in June 2017. (Copyright: ESA/ATG medialab)



ESA-C. Vijoux

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