LISA Pathfinder and Tests of Modified Gravity

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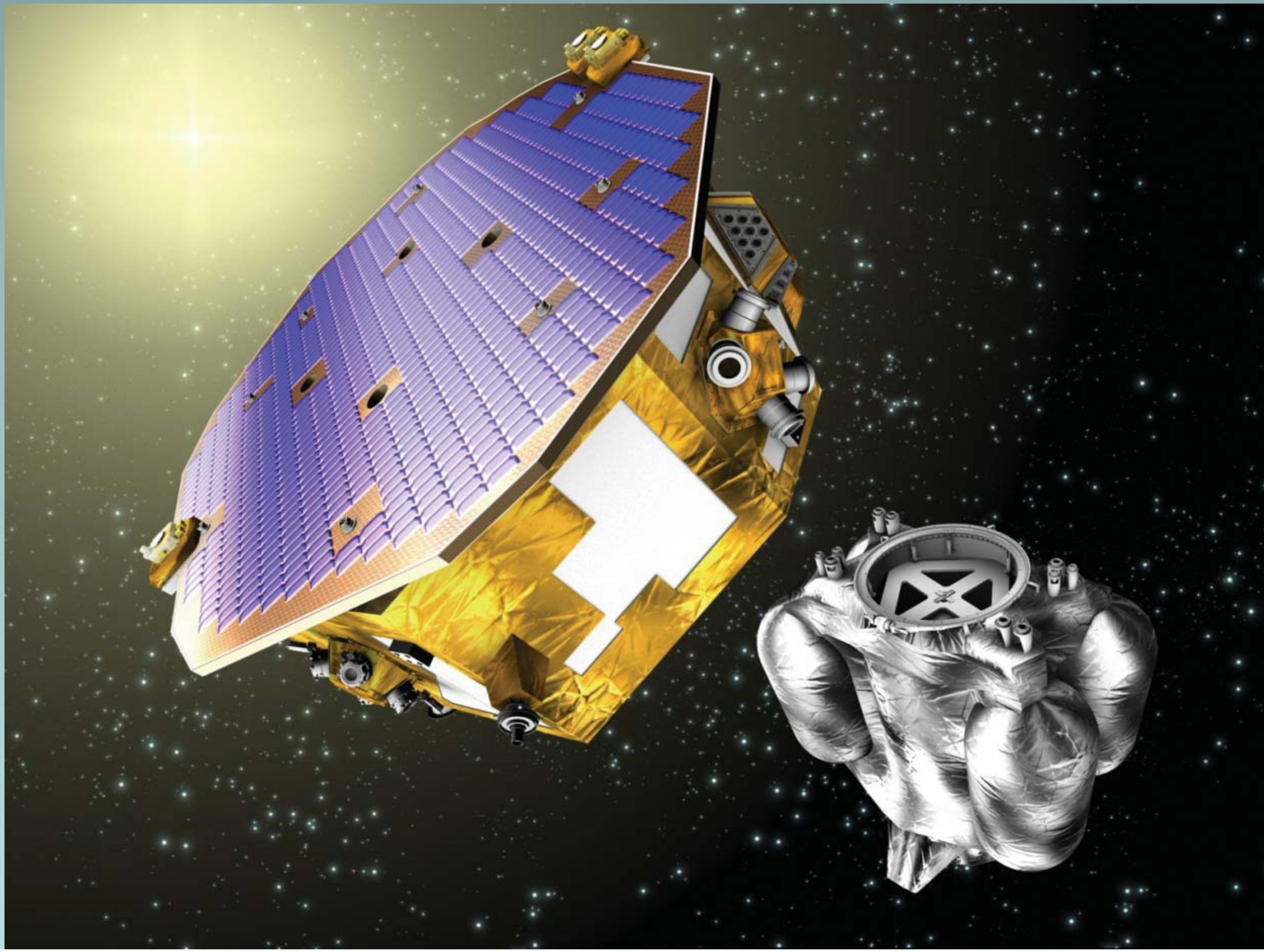

Overview

- Dark Matter or Modified Gravity?
- Modified Gravity – inspired by MOND
- LISA Pathfinder
- Testing Modified Gravity with LISA Pathfinder
- Future Prospects
- Summary and Discussion

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Dark Matter or Modified Gravity?

- **If we apply the standard gravitational laws that we have to what we can see outside the Solar System, the observations do not make sense…**

- **This may be because:**

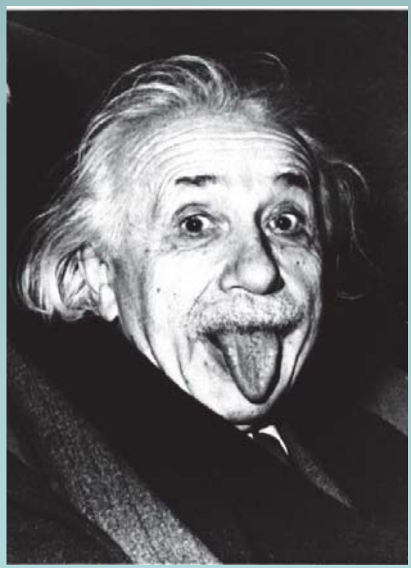
  - **there are other gravitating constituents that we cannot see (Dark Matter, Dark Energy)**

  - **our laws of Gravity are incomplete and require modifications**

These possibilities are not mutually exclusive

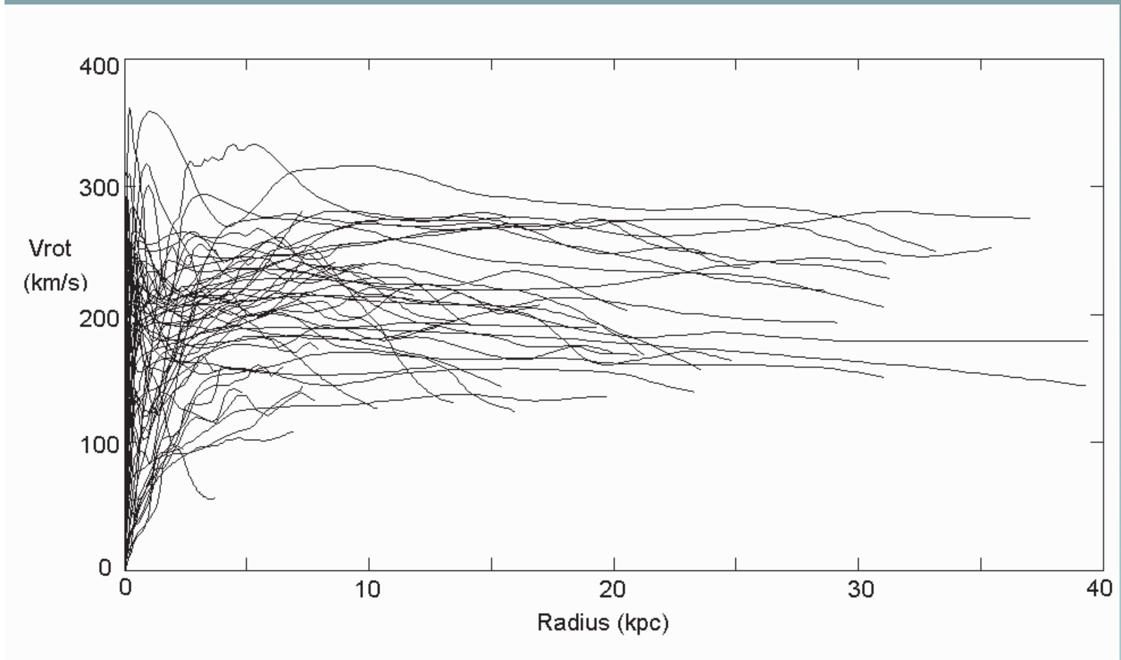
Dark Matter or Modified Gravity?

- This problem is not new – we used to have it *within* the Solar System:
  - Le Verrier predicted Neptune from Uranus orbital anomalies using Newtonian gravity (1846) – Dark Matter was discovered!
  - Attempts to explain anomalous precession of Mercury with "Vulcan", which was never found – eventually explained through General Relativity (1915)
- So we have already had precedents for both – Dark Matter *and* Modified Gravity!



Dark Matter or Modified Gravity?

- **Now the problem has moved to galactic and extragalactic scales**
- **Already around 80 years ago (~1934) Zwicky noticed that we have a "missing mass" problem at galactic scales:**



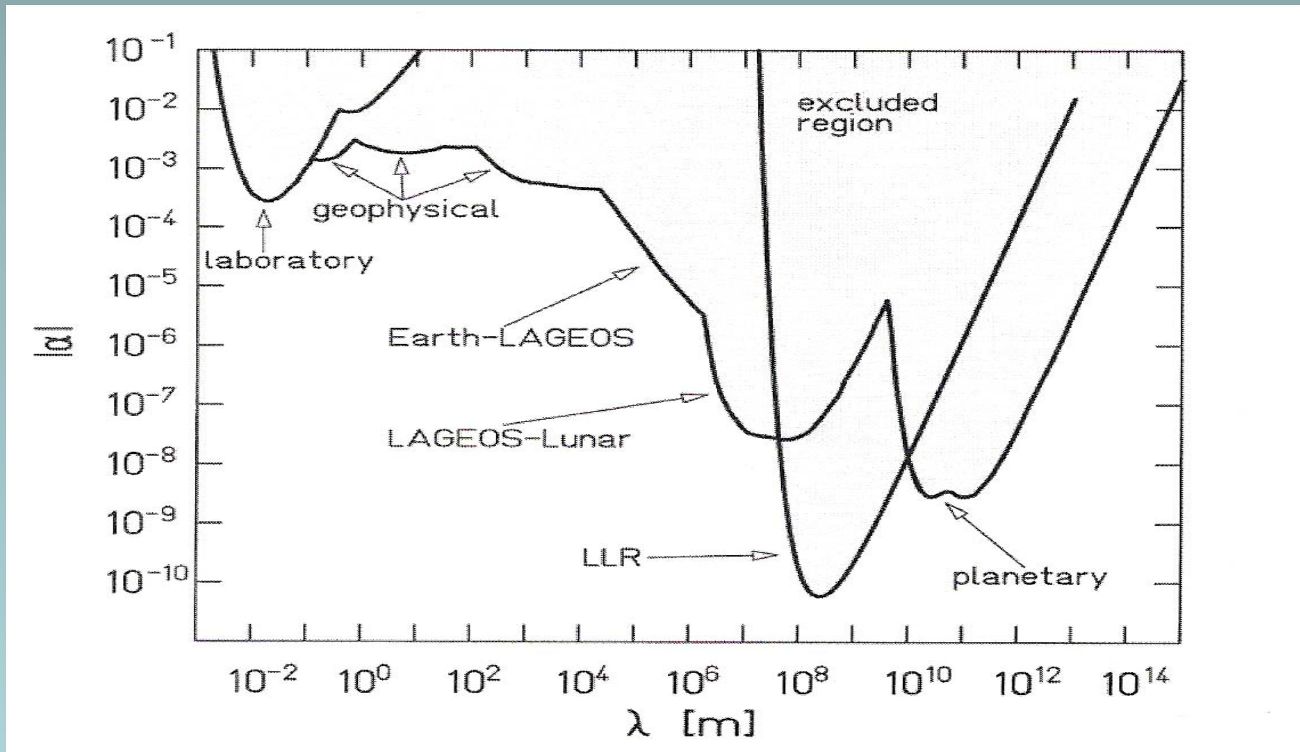
- **Expect** $$\frac{GM}{r^2} = \frac{v^2}{r} \Rightarrow v \propto \frac{1}{\sqrt{r}}$$ **, not flat rotation curves!**

Dark Matter or Modified Gravity?

- **What is the correct explanation this time – Dark Matter, Modified Gravity, a combination of both…?**
  - **Direct search for Dark Matter particles underway (dedicated underground searches, LHC and predecessors) for decades now – so far no unambiguous detection**
  - **Problem with most proposed Gravity modifications: almost by definition they predict significant deviations only *outside* the Solar System – hard to test directly!**
- **It becomes increasingly hard to explore new parameter space – we should grab every opportunity!**

Dark Matter or Modified Gravity?

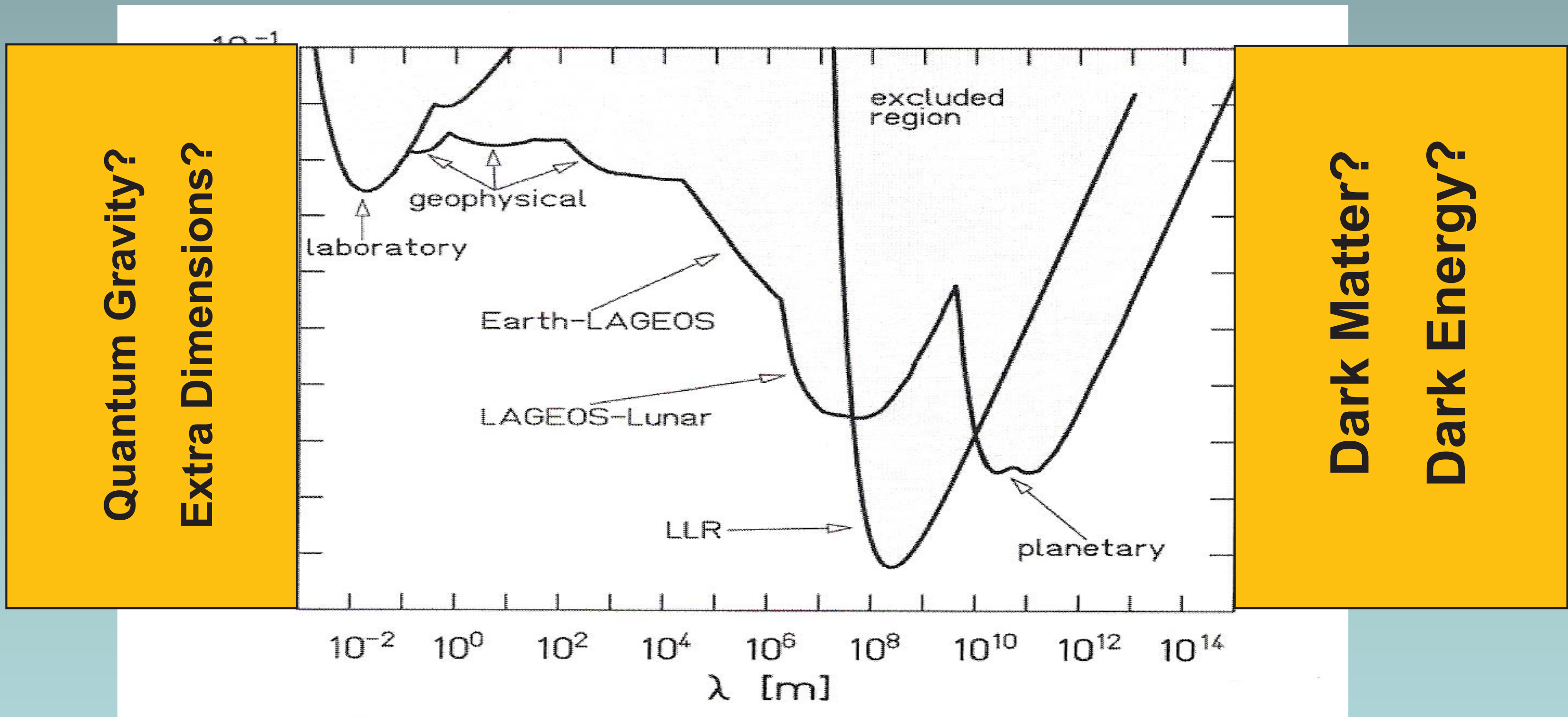
- **Interplay between Theory and Experiment in Gravity**
  - **In the parameter space accessible to “experimentation”, we don’t have a problem with Gravity:**



Dark Matter or Modified Gravity?

- **Interplay between Theory and Experiment in Gravity**

  - **…but outside this accessible parameter space, we run into trouble!**



- **Are at least some of the proposed Gravity modifications accessible to direct test?**

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Modified Gravity – inspired by MOND

- **Newtonian dynamics are modified if system COM gravitational acceleration approaches $a_0 = 10^{-10}\text{ms}^{-2}$ (Milgrom 1983):**

$$F = m\mu\left(\frac{a}{a_0}\right)a$$

with

$$a >> a_0 \Rightarrow \mu\left(\frac{a}{a_0}\right) \approx 1$$

Newtonian

$$a \le a_0 \Rightarrow \mu\left(\frac{a}{a_0}\right) \approx \frac{a}{a_0}$$

"MONDian"

- **Many forms possible for $\mu(a/a_0)$:**

$$\mu(a/a_0) = \frac{a/a_0}{(1 + a/a_0)} \qquad \mu(a/a_0) = \frac{a/a_0}{\left(1 + (a/a_0)^2\right)^{1/2}}$$

- **Automatically describes flat rotation curves; low acceleration limit:**

$$F = m\frac{a^2}{a_0} \Rightarrow \frac{GM}{r^2} = \frac{v^4}{a_0 r^2} \Rightarrow v = \left(\frac{GM}{a_0}\right)^{1/4}$$

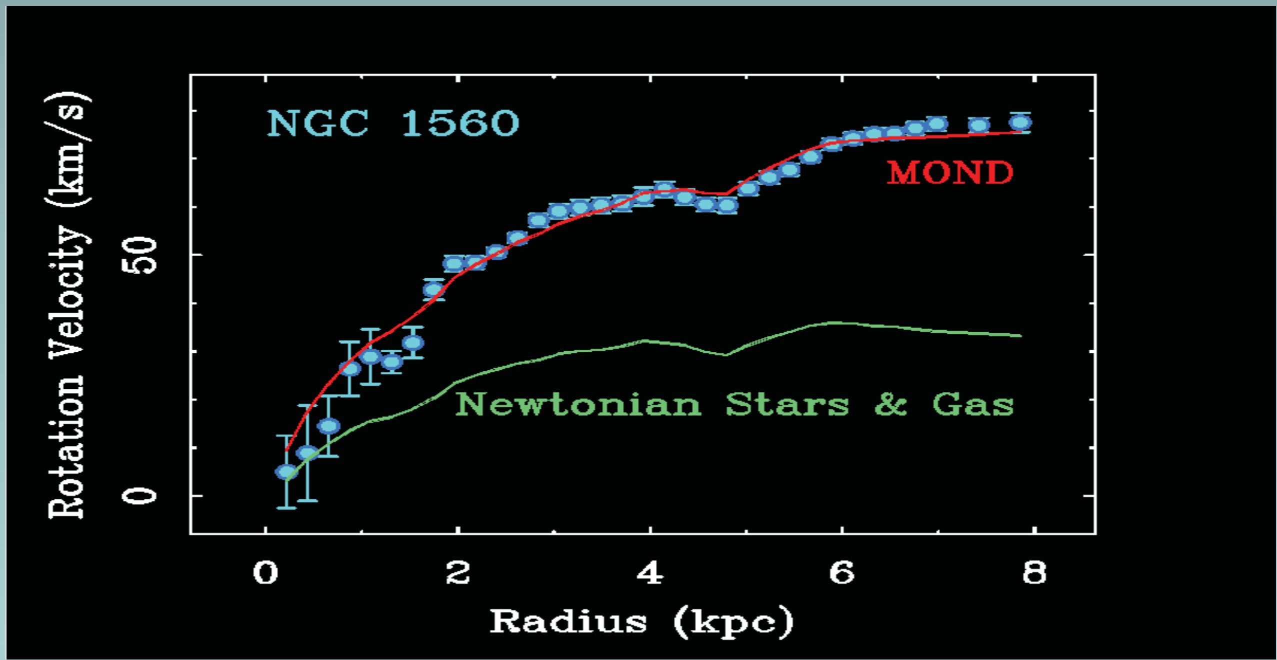
- **Equivalent view as modification of Newton's law of Gravity:**

$$a_N \le a_0 \longrightarrow a_{grav} = \sqrt{a_0 \frac{GM}{r^2}} = \sqrt{a_0}\sqrt{a_N}$$

Modified Gravity – inspired by MOND

- **Purely phenomenological, non-relativistic formula with no underlying relativistic theory**

- **Extremely successful in describing many galactic rotation curves without Dark Matter:**



- **Less successful on extragalactic scales**

- **Bullet cluster still needs Dark Matter (but less)**

Modified Gravity – inspired by MOND

- **MOND respectability increased when a relativistic theory (TeVeS) was developed with non-relativistic MONDian limit (Bekenstein 2004)**

- **Since TeVeS, many other theories with MONDian non-relativistic limit have been developed…**

- **Systematic classification of such theories into three types (Magueijo & Mozaffari 2012) :**

  - Type I: The total gravitational potential is sum of Newtonian potential and new scalar field:

$$\Phi_{grav} = \Phi_N + \phi$$

The new scalar field is solution of modified Poisson equation

$$\nabla \cdot \left(\mu\left(\frac{\kappa|\nabla\phi|}{4\pi a_0} \right) \nabla\phi \right) = \kappa G \rho$$

Modified Gravity – inspired by MOND

- Type II: Total potential as for type I, but the source driving the scalar field now depends on the Newtonian potential:

$$\nabla^2\phi = \frac{\kappa}{4\pi}\nabla\cdot\left(\nu\left(\left(\frac{\kappa}{4\pi}\right)^2\frac{|\nabla\Phi_N|}{a_0}\right)\nabla\Phi_N\right)$$

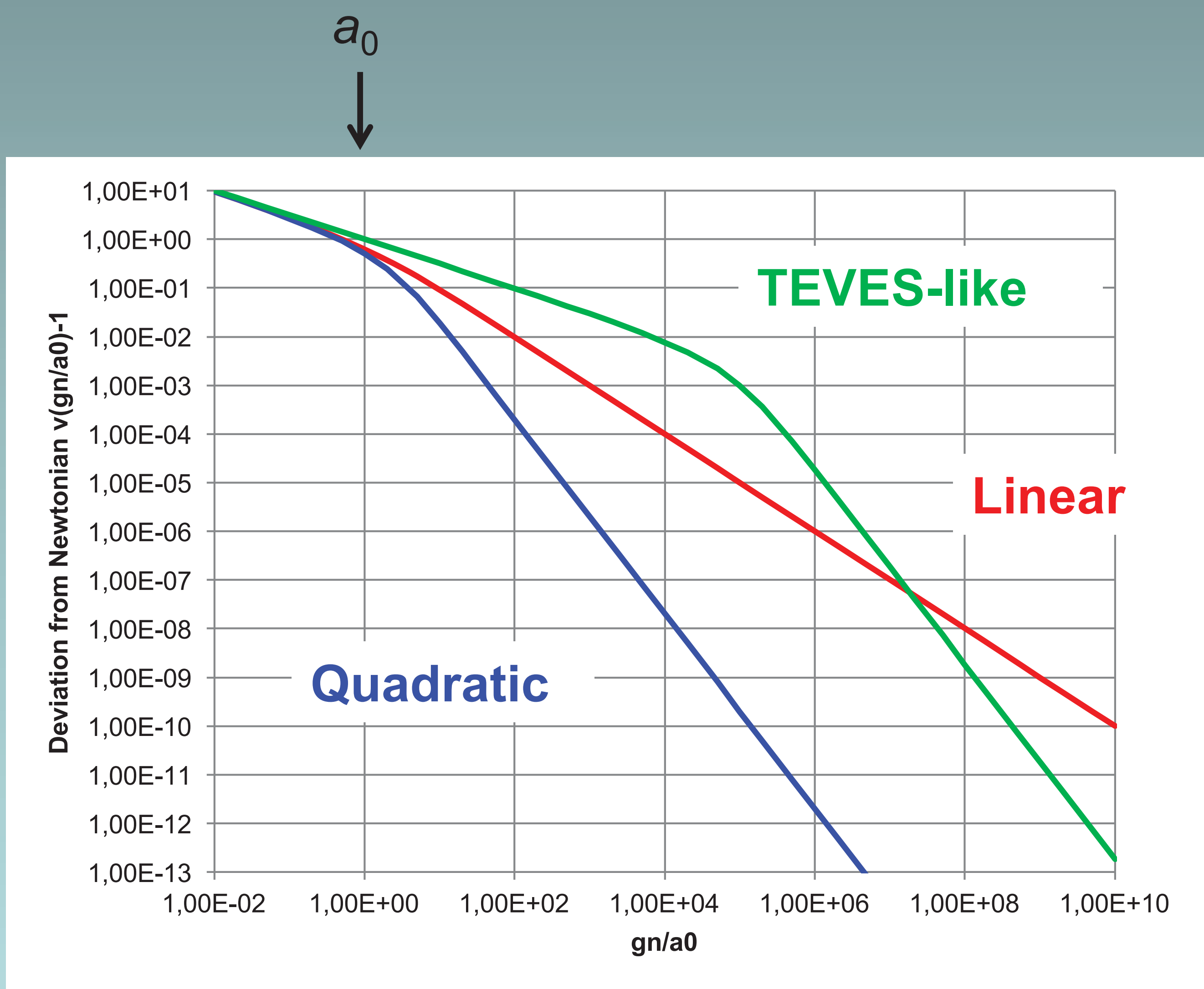
- Type III: The total gravitational potential is a single field which satisfies a non-linear Poisson equation:

$$\nabla\cdot\left(\tilde{\mu}\left(\frac{|\nabla\Phi_{grav}|}{\pi a_0}\right)\nabla\Phi_{grav}\right) = 4\pi G\rho$$

- **All these theories incorporate (different) free interpolating functions describing the transition between MONDian and Newtonian regimes**

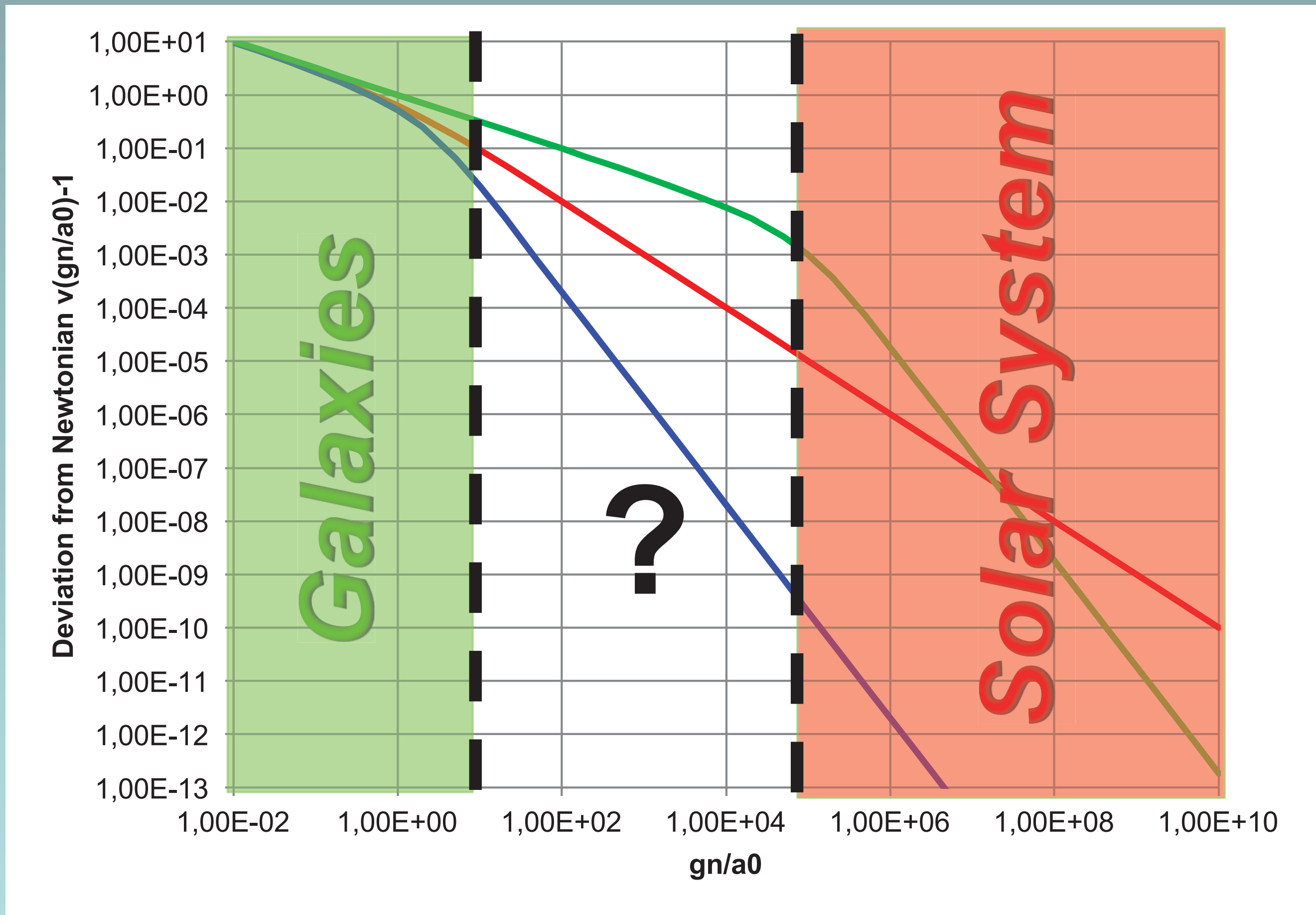
Modified Gravity – inspired by MOND

- **Approximate comparison of some proposed functions (Galianni et al 2011):**



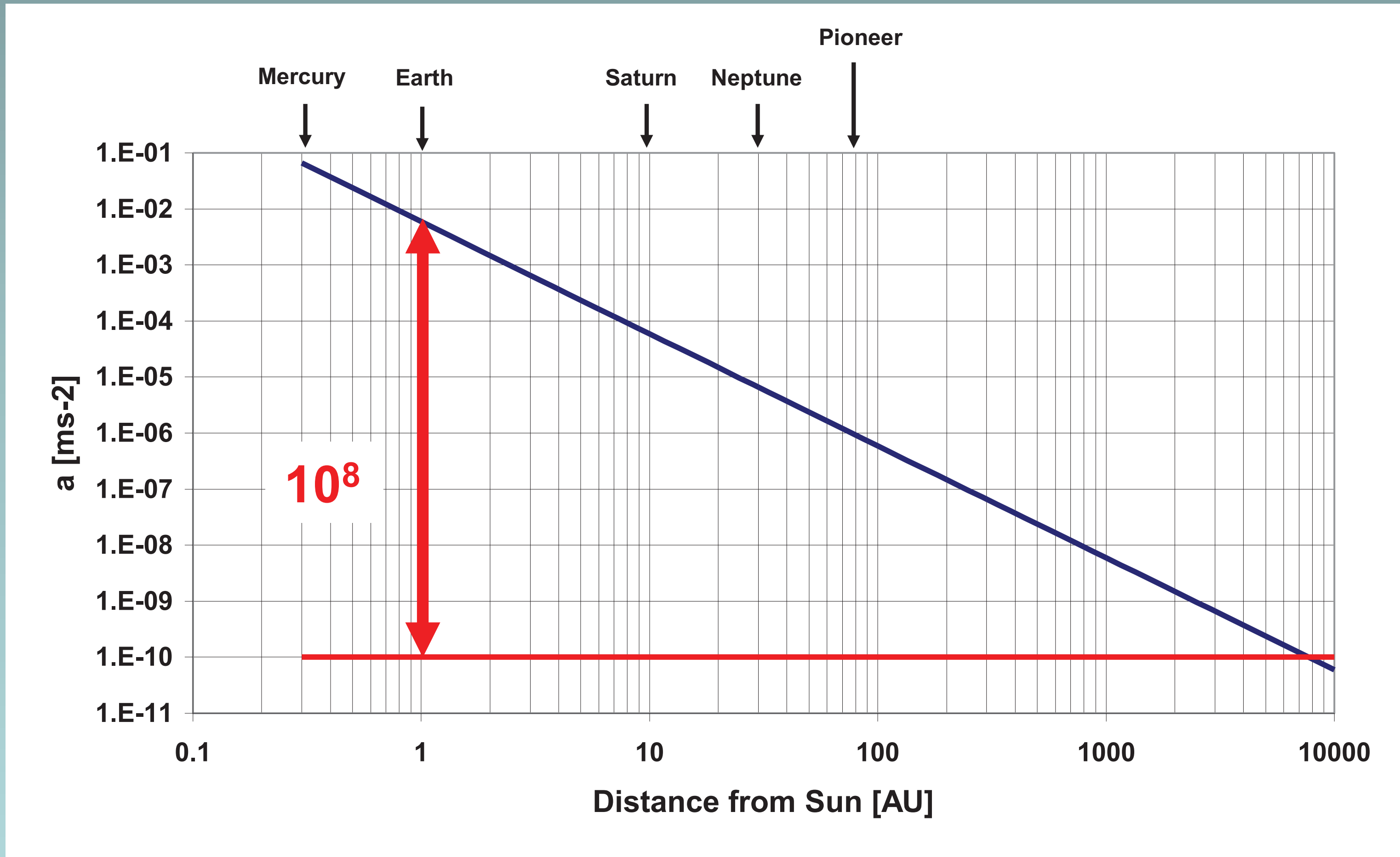
Modified Gravity – inspired by MOND

- **Problem: galactic rotation curves only tell us something up to $\approx 10a_0$**
- **Significant solar system constraints only reach down to $\approx 10^5 a_0$**
- **Can we access the acceleration regime in between?**



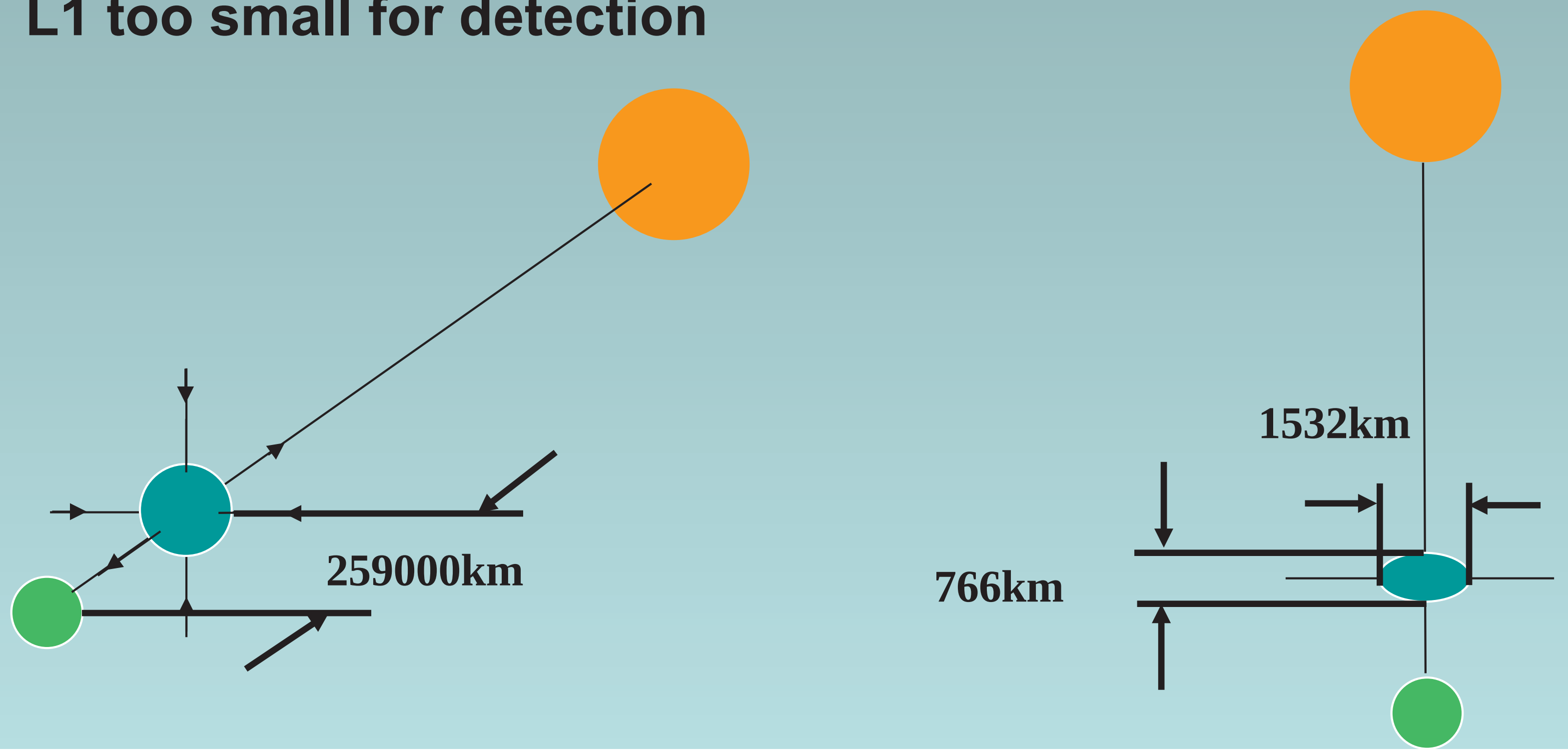
Modified Gravity – inspired by MOND

- **A priori, prospects of tests within Solar System poor:**



Modified Gravity – inspired by MOND

- **Bekenstein & Magueijo (2006): gravitational Saddle Points provide MONDian “habitats” within the Solar System**
- **Around Sun-Earth SP, anomalous TeVeS gravity gradients of $\geq 10^{-13} s^{-2}$ predicted within elliptical “bubble”**
- **LISA Pathfinder is explicitly mentioned – but effects around L1 too small for detection**



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LISA Pathfinder

- LISA Pathfinder (LPF) is a technology demonstrator for Laser Interferometer Space Antenna (LISA) – a low-frequency gravitational wave detector in space

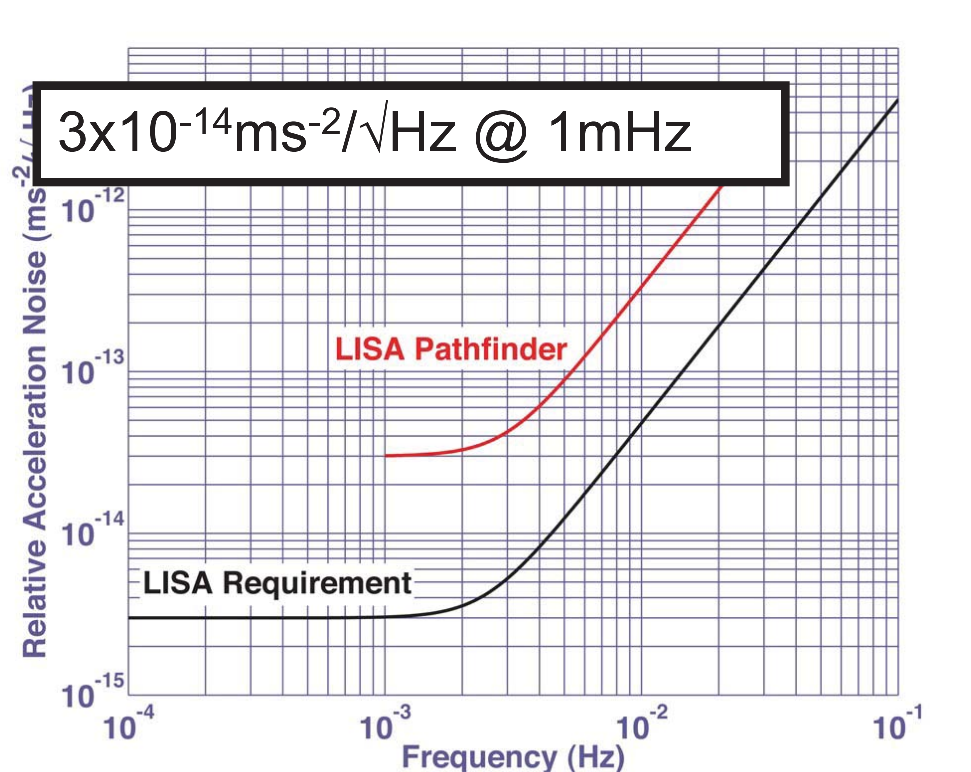
- LPF demonstrates two key requirements for gravitational wave detection:

  - Reduction of acceleration noise on macroscopic Test Masses in Space at ~1mHz

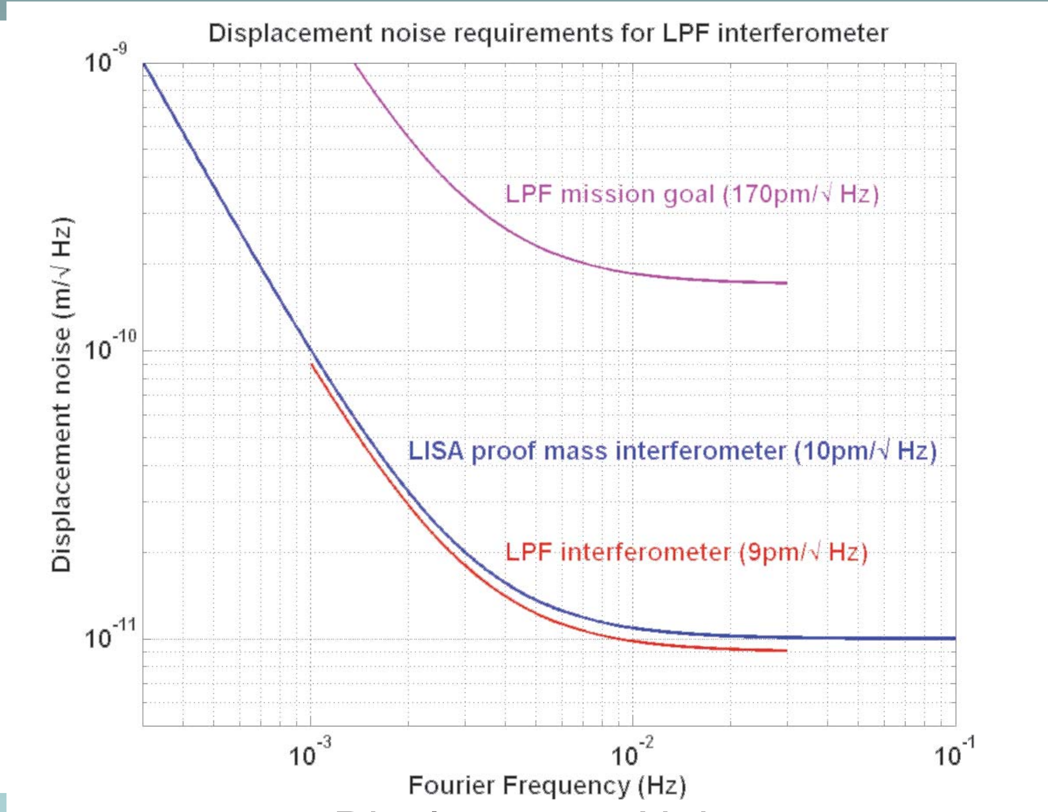
  - Positional read-out of Test Masses in Space with sufficiently low displacement noise at ~1mHz

LISA Pathfinder

- **Quantitative Science Requirements:**
  - **Differential Acceleration Noise between 2 Test Masses**
  - **Displacement Noise**



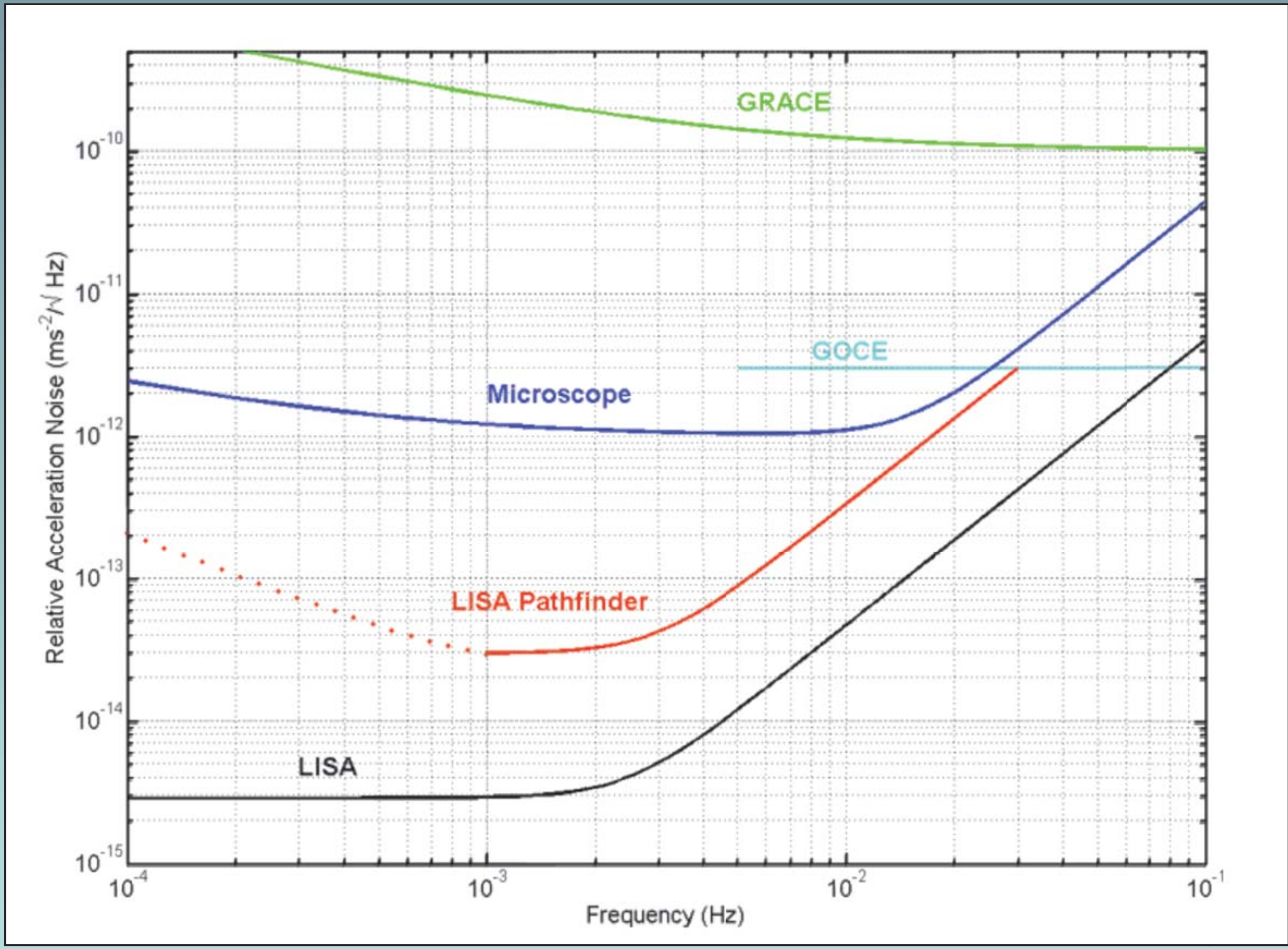
Acceleration Noise



Displacement Noise

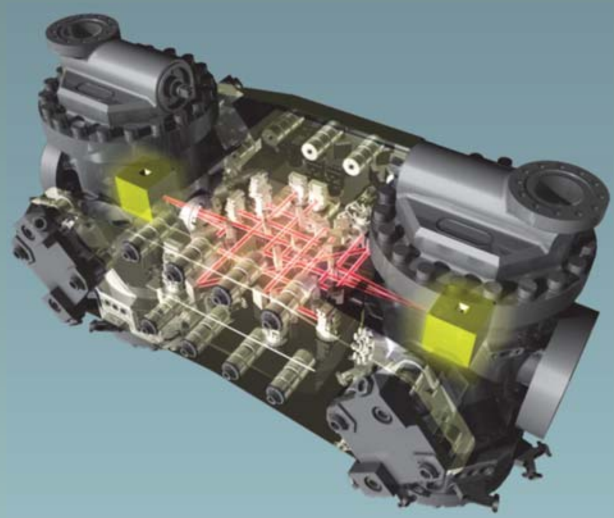
LISA Pathfinder

- **LPF performance compared to other missions (not quite fair – but certainly shows ambition!):**



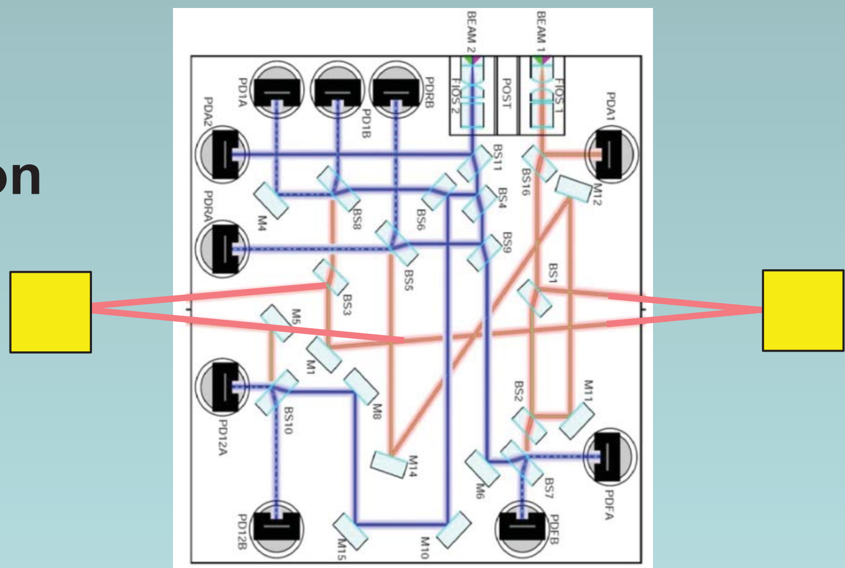
LISA Pathfinder

- **Instrument at the core of LISA Pathfinder:**



- **Two Au/Pt Test Masses of ~2kgs, housed in separate vacuum enclosures baseline ~ 0.4m (manufactured by CGS in Milano ☺)**

- **Relative position of Test Masses read-out by:**
  - **Heterodyne laser interferometry on sensitive axis**
  - **Capacitive sensing on all axes**



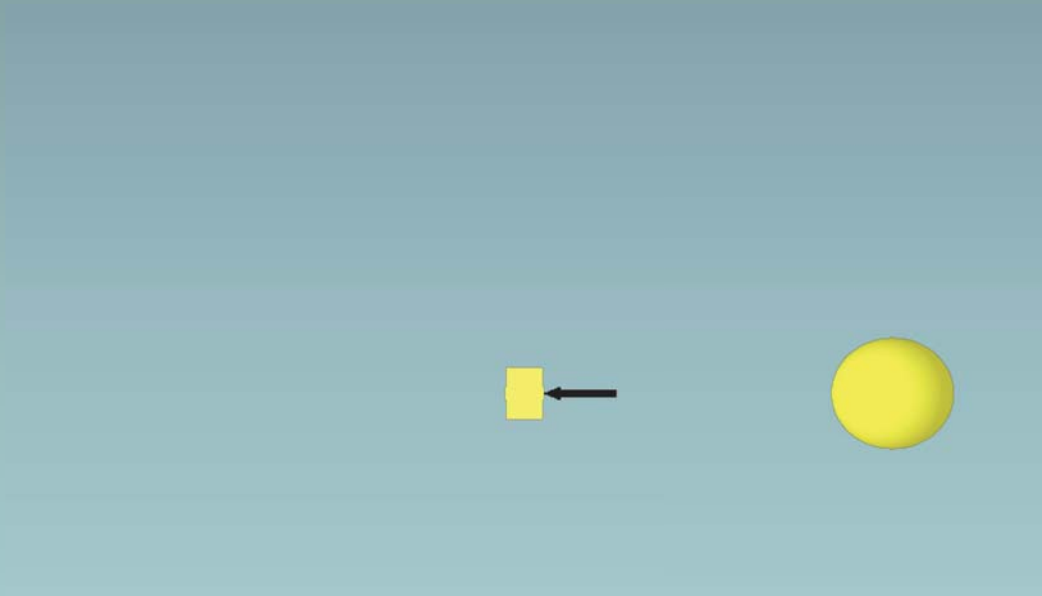
LISA Pathfinder

- **Key technology to reduce acceleration noise on Test Masses: Drag-Free Attitude Control System (DFACS)**

Problem: a “free” Test Mass in space…

LISA Pathfinder

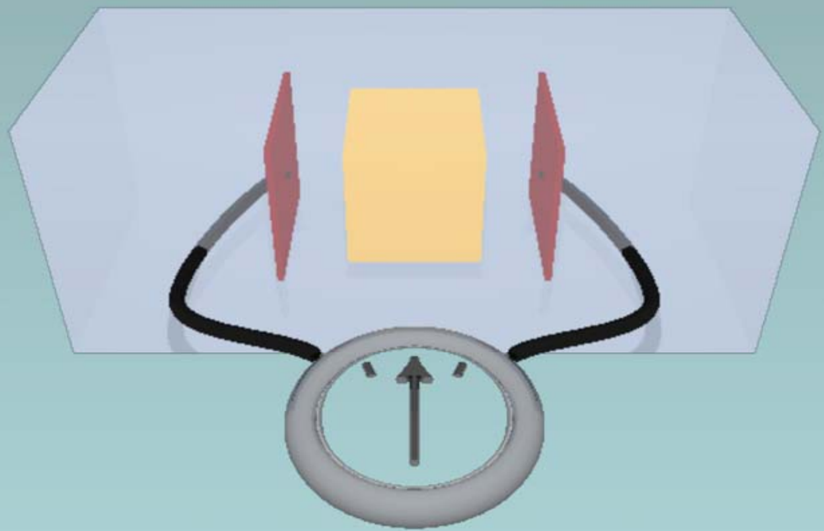
…would be subject to solar radiation pressure. For 2kg LPF Test Masses, at 1AU, the acceleration is around $10^{-8}ms^{-2}$



- Solar radiation fluctuations around 1mHz are >0.2%/√Hz
- >$2x10^{-11}ms^{-2}$/√Hz acceleration noise at 1mHz: 1000 x LISA Pathfinder requirements… and 10000 x LISA requirements!

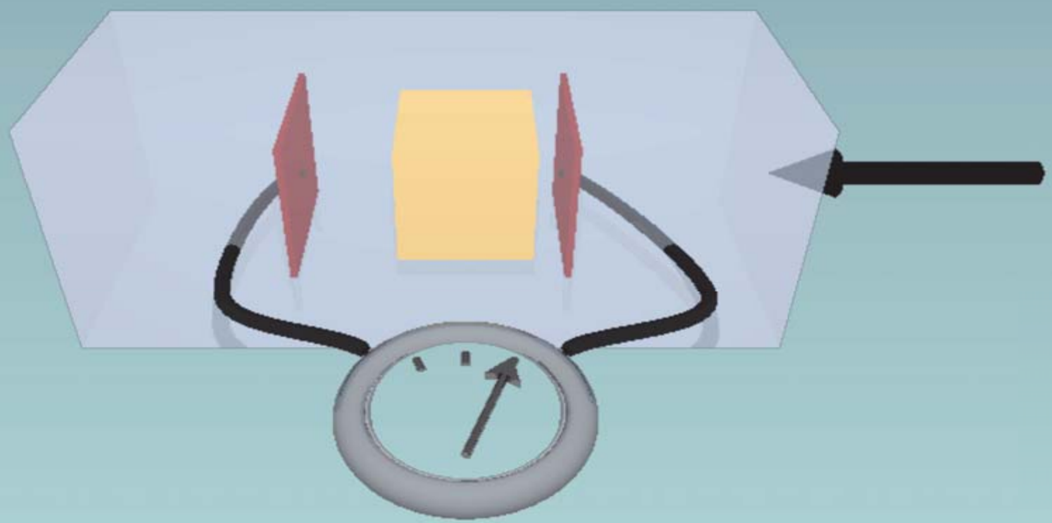
LISA Pathfinder

- Solution: surround Test Mass with Spacecraft and measure relative position…



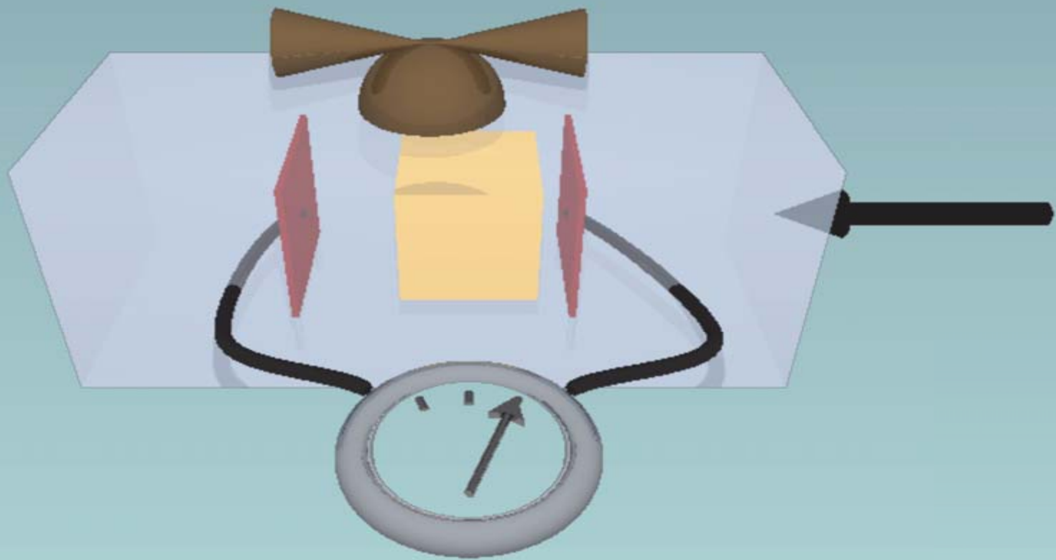
LISA Pathfinder

…now solar radiation pressure pushes on Spacecraft, not Test Mass, and the relative position change is measured…



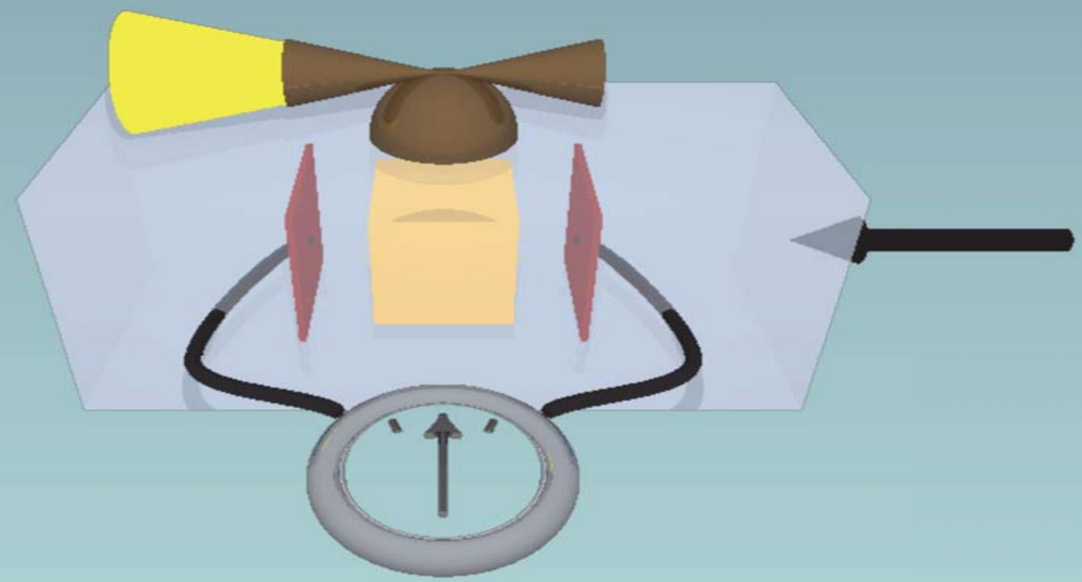
LISA Pathfinder

…this measurement is then fed back to the micropropulsion system…



LISA Pathfinder

… which pushes the Spacecraft back:



Net result: the Spacecraft “follows” the Test Mass

LISA Pathfinder

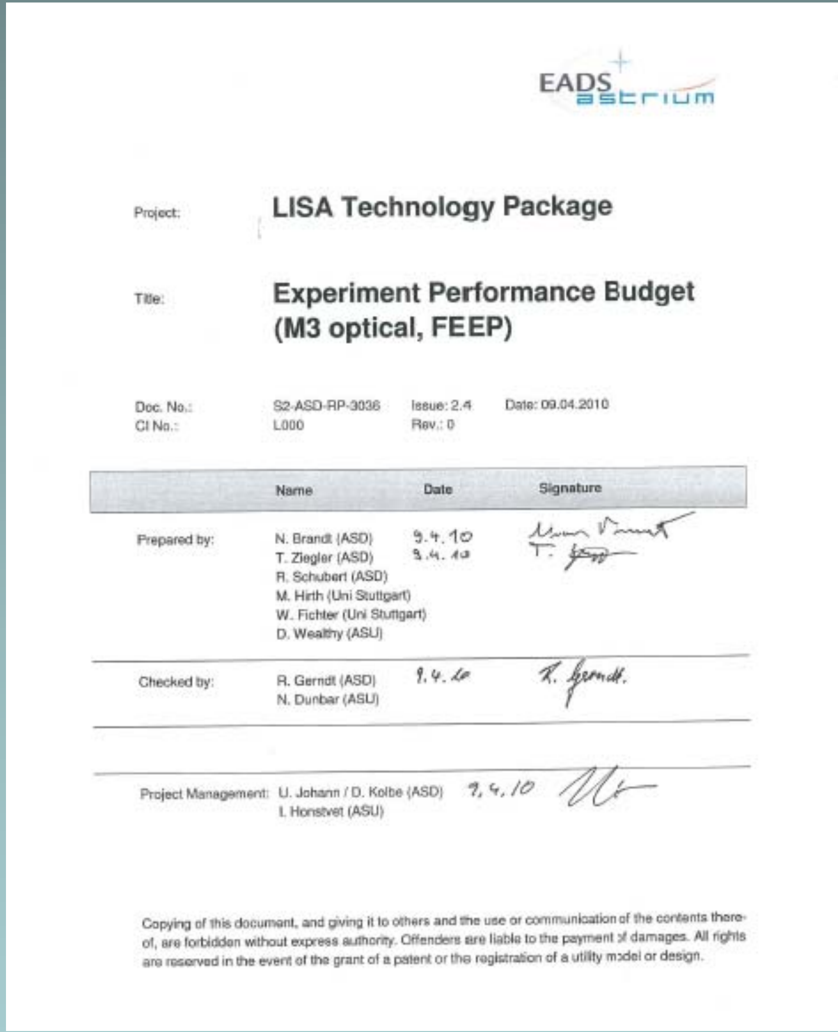
- **Drag-free control eliminates Solar Radiation as significant noise source**

- **Now we “only” need to worry about the following noise sources – mainly couplings between SC and TMs):**

  - Electrostatics
  - Magnetism
  - Self-gravity
  - Thermal Effects
  - Charging
  - Residual Gas Damping
  - …

LISA Pathfinder

- The main purpose of LPF is to understand the noise sources that limit its performance
- A detailed noise budget has been created with over 120 entries
- Where possible, relevant parameters have been verified by test on the ground
- A suite of experiments has been run during the mission to investigate specific couplings and noise sources



EADS astrium

Project: LISA Technology Package

Title: Experiment Performance Budget (M3 optical, FEEP)

Doc. No.: S2-ASD-RP-3036 Issue: 2.4 Date: 09.04.2010
CI No.: L000 Rev.: 0

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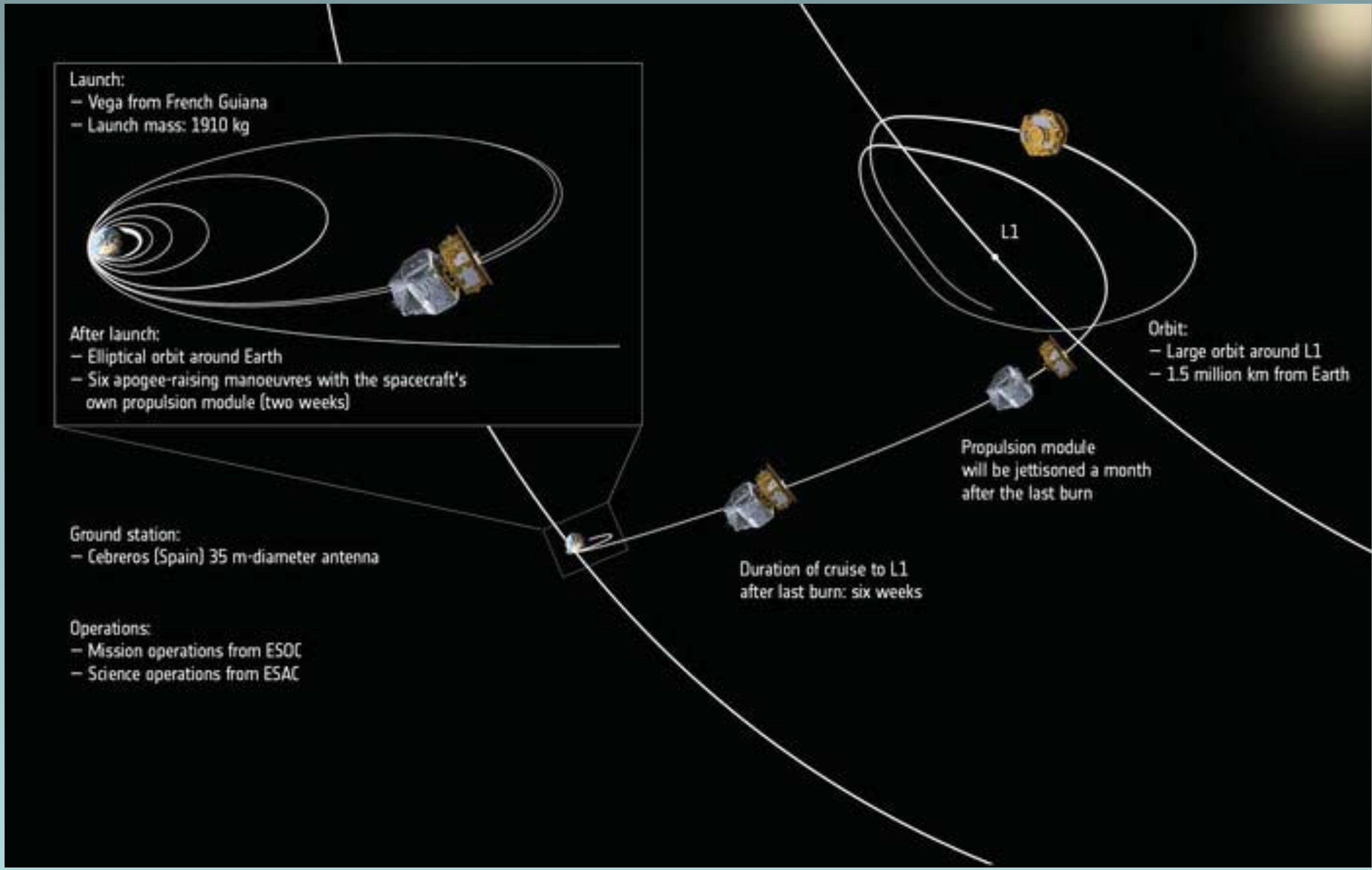
LISA Pathfinder

- **Following its launch in Dec 2015, LISA Pathfinder made its way to its final destination – a large halo orbit around L1**



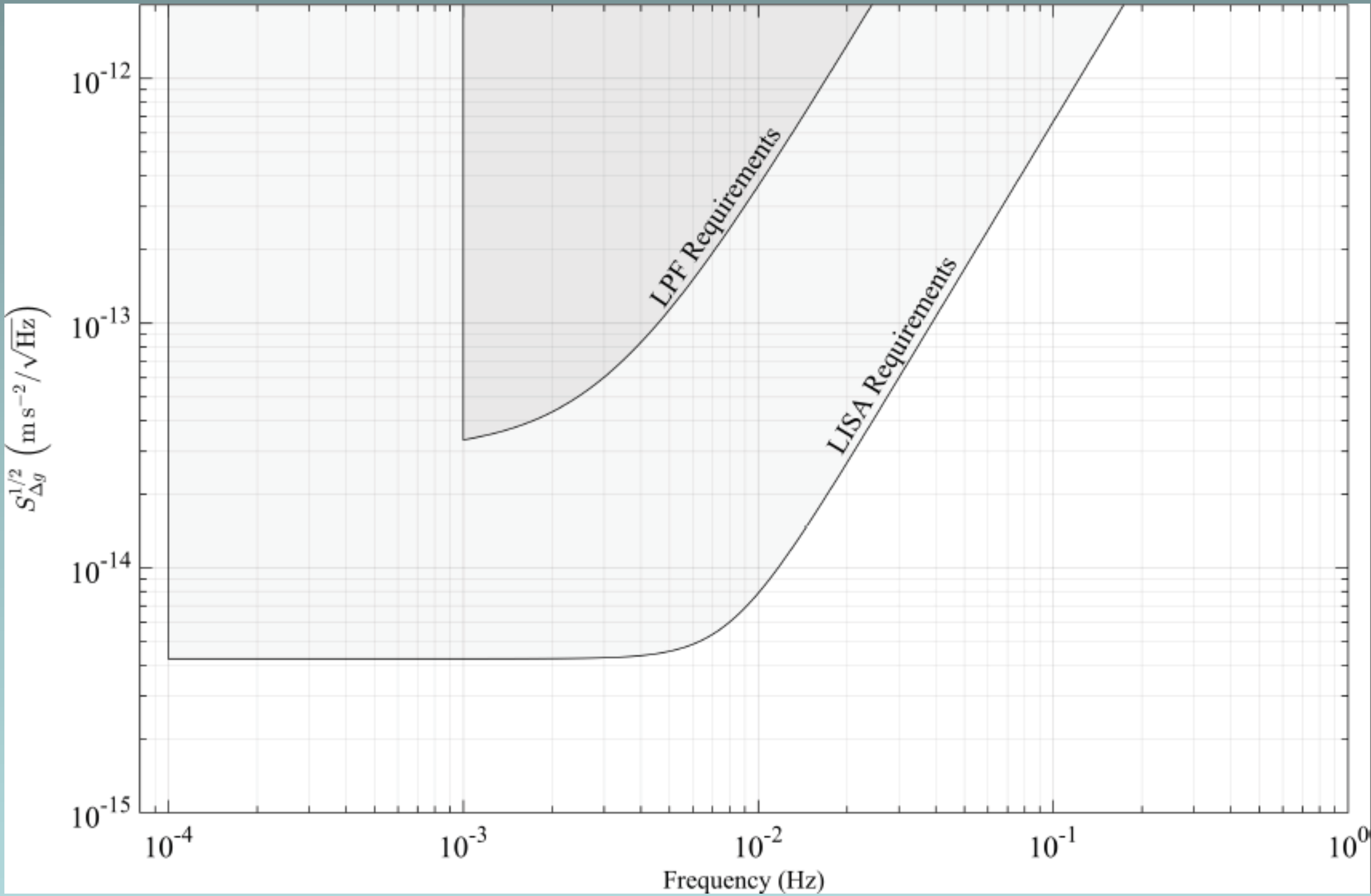
LISA Pathfinder

- Operations Timeline

Date	Milestone
3 December 2015	Launch
11 January 2016	LISA Technology Package Switch-on
22 January	Spacecraft / Propulsion Module Separation
2 February	Release of Test Mass Launch Lock & Venting Mechanism
15 / 16 February	Test Mass Release
18 February	Alignment of Laser Interferometer
22 February	First Entry into Science Mode
1 March	Start of Science Operations
25 June	End of LTP Operations
27 June	DRS Commissioning and Operations
15 December 2016	End of Nominal Mission / Start of Extended Mission
31 May 2017	End of Extended Mission
18 July	LISA Pathfinder Switch-off

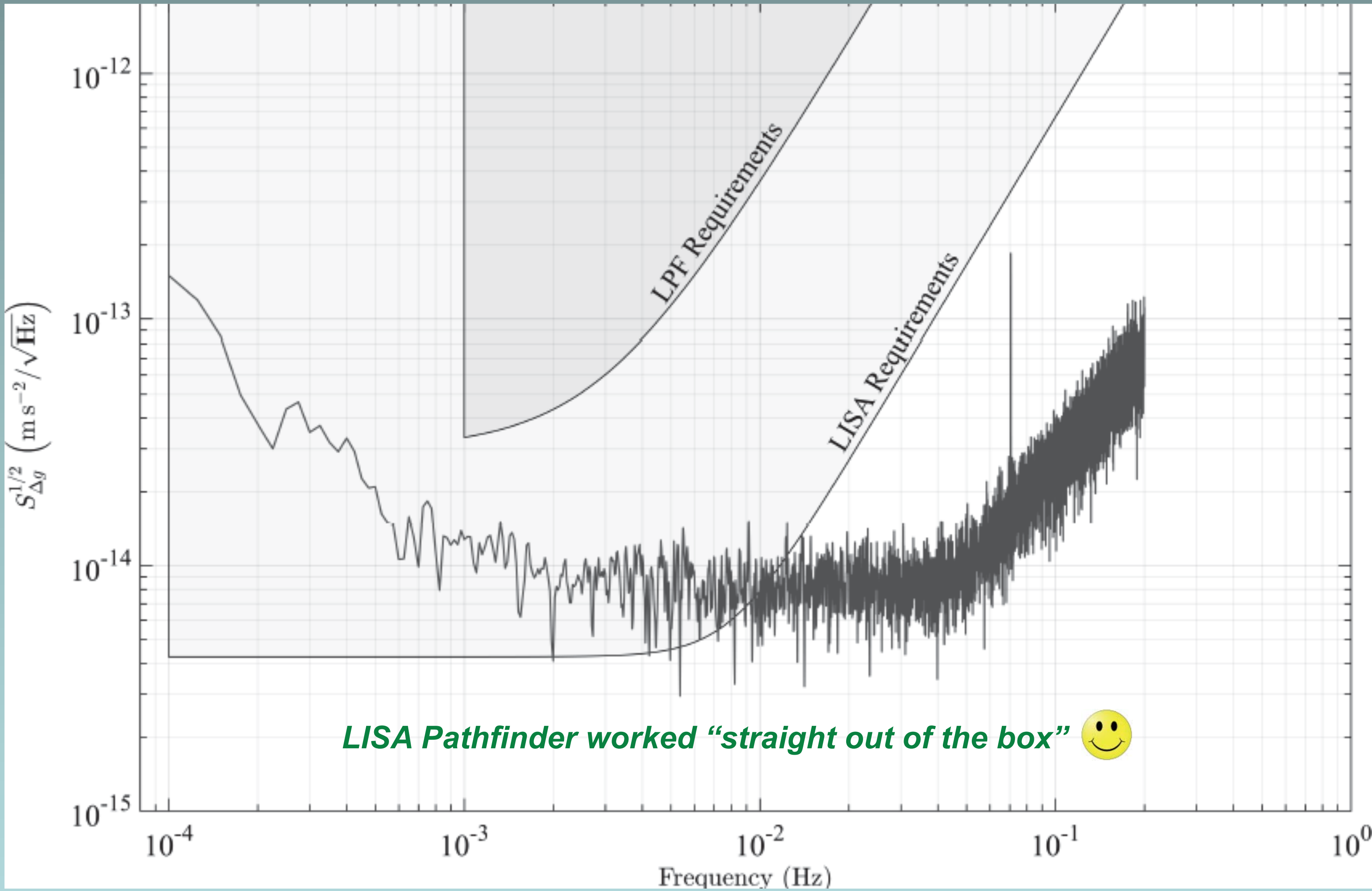
LISA Pathfinder

- **LISA Pathfinder Requirements**



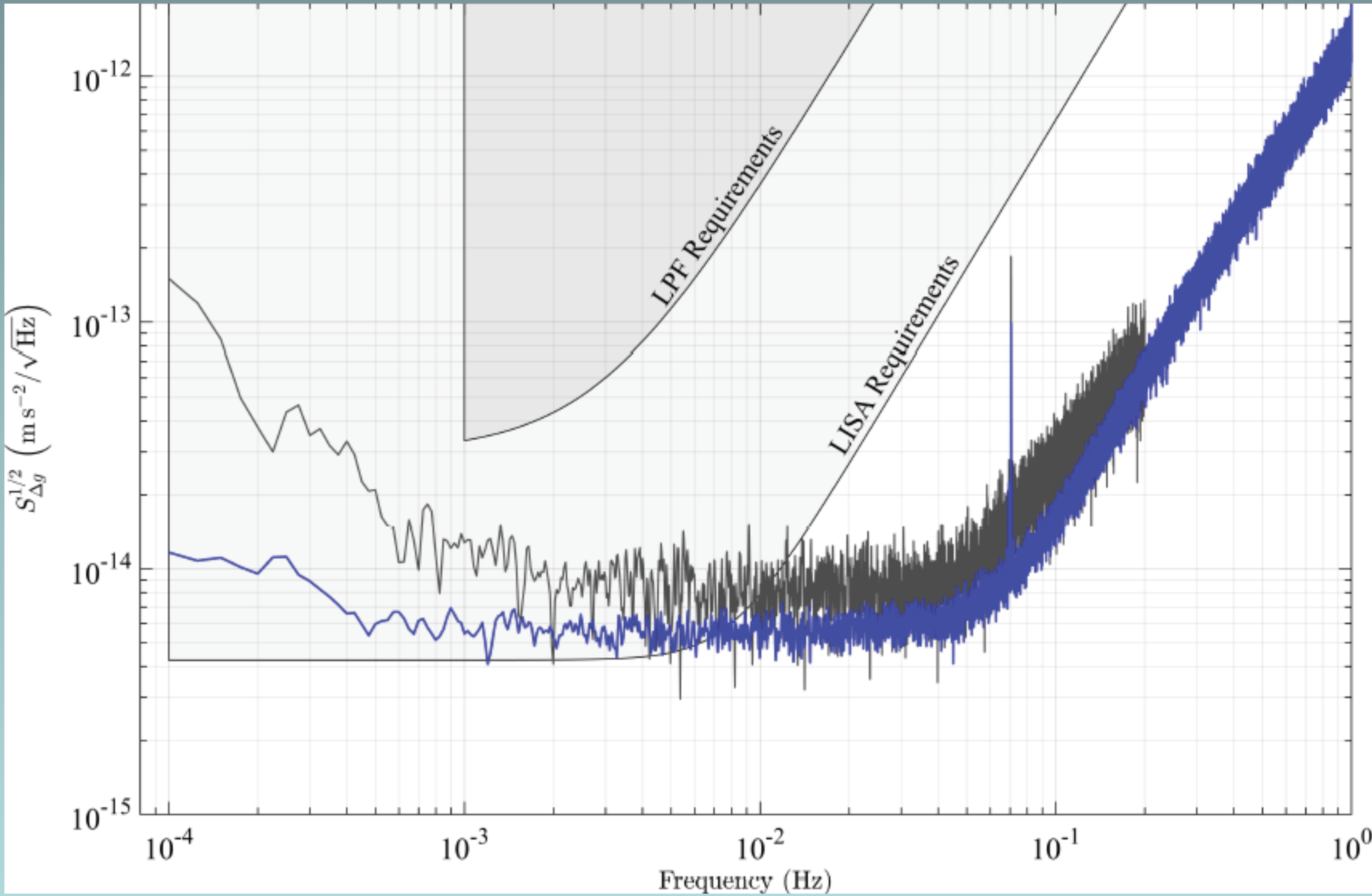
LISA Pathfinder

- **First Day of Science Operations (March 1st 2016)**



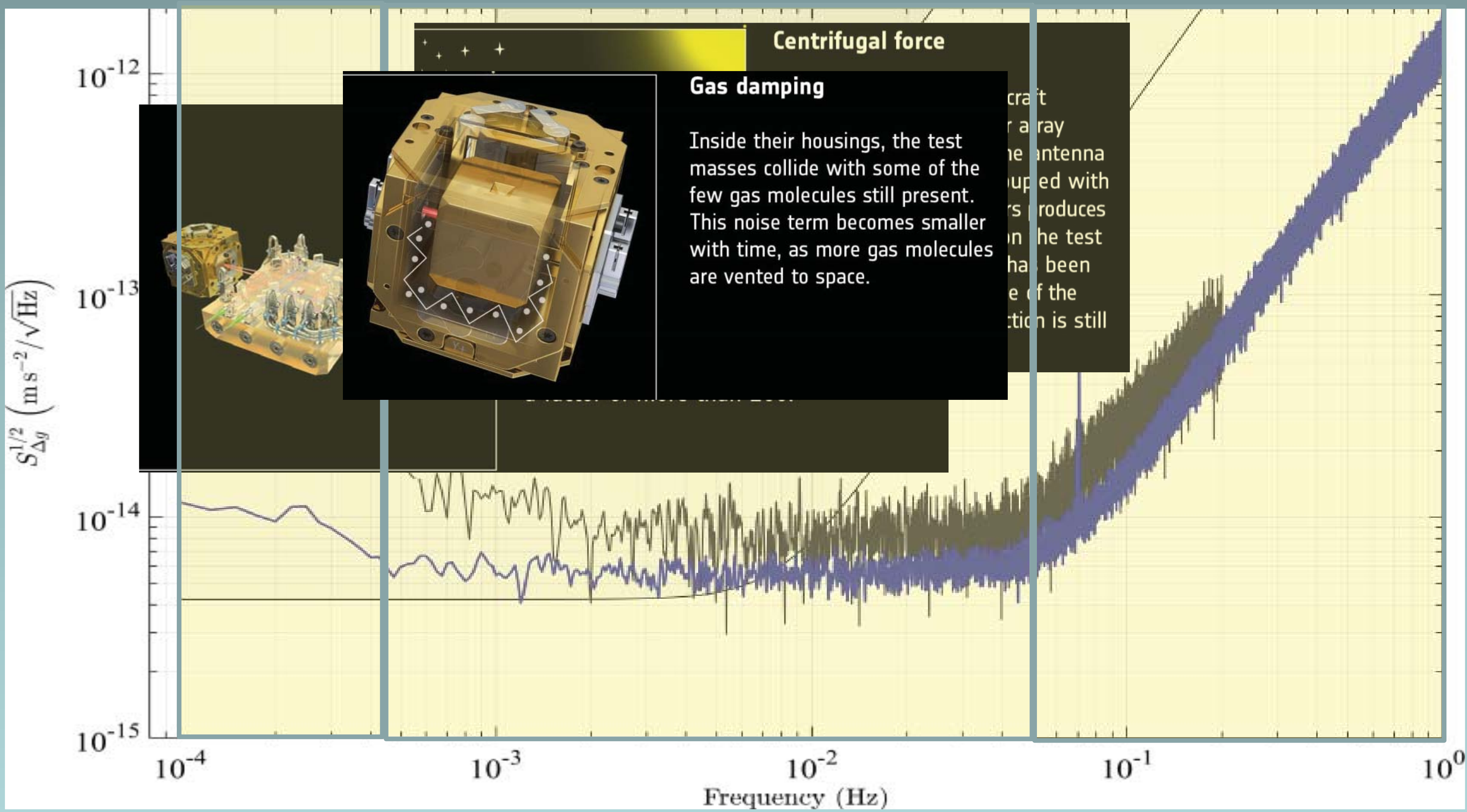
LISA Pathfinder

- **Five Weeks later (April 8th – 14th 2016)**



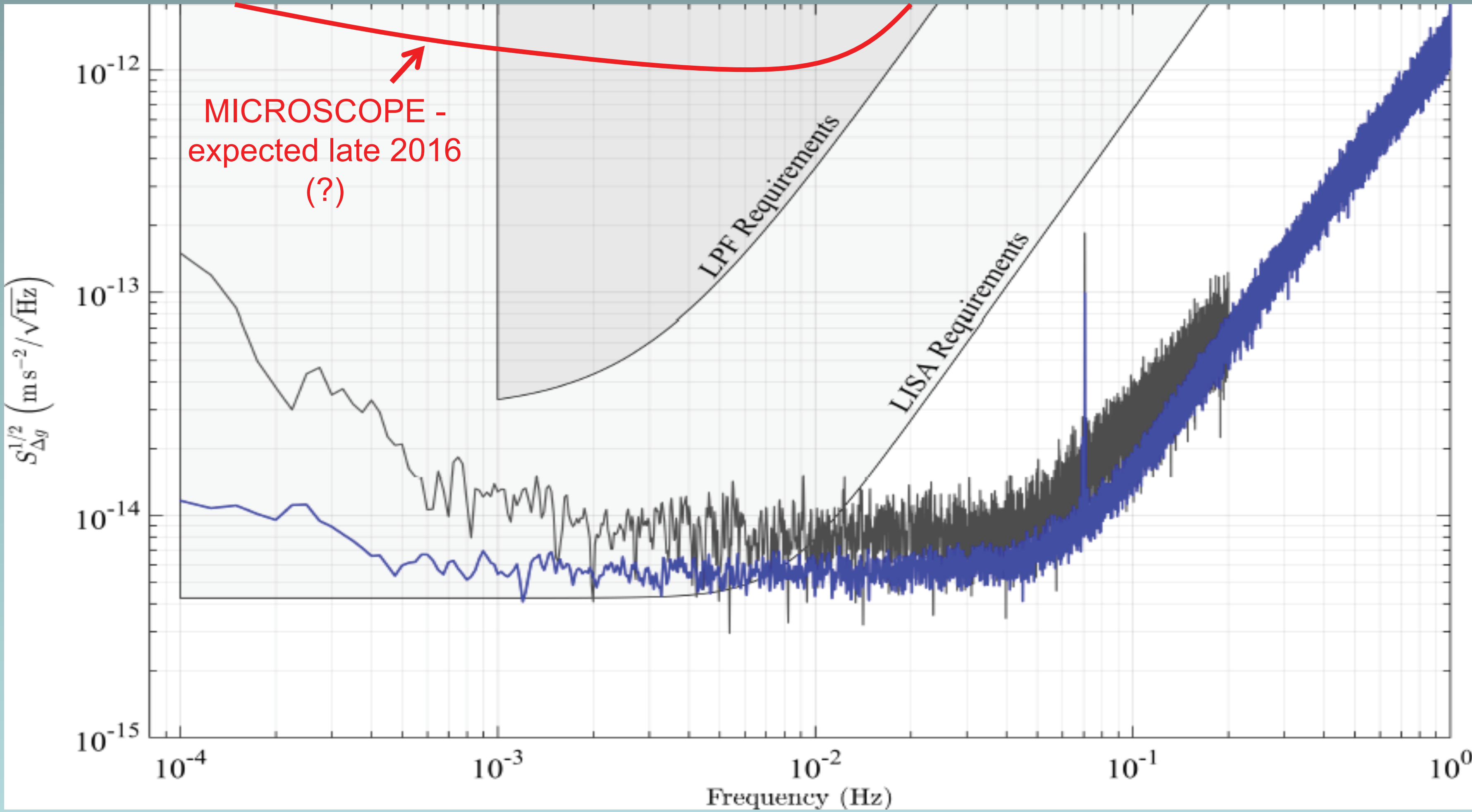
LISA Pathfinder

- **Understanding the Noise Sources**



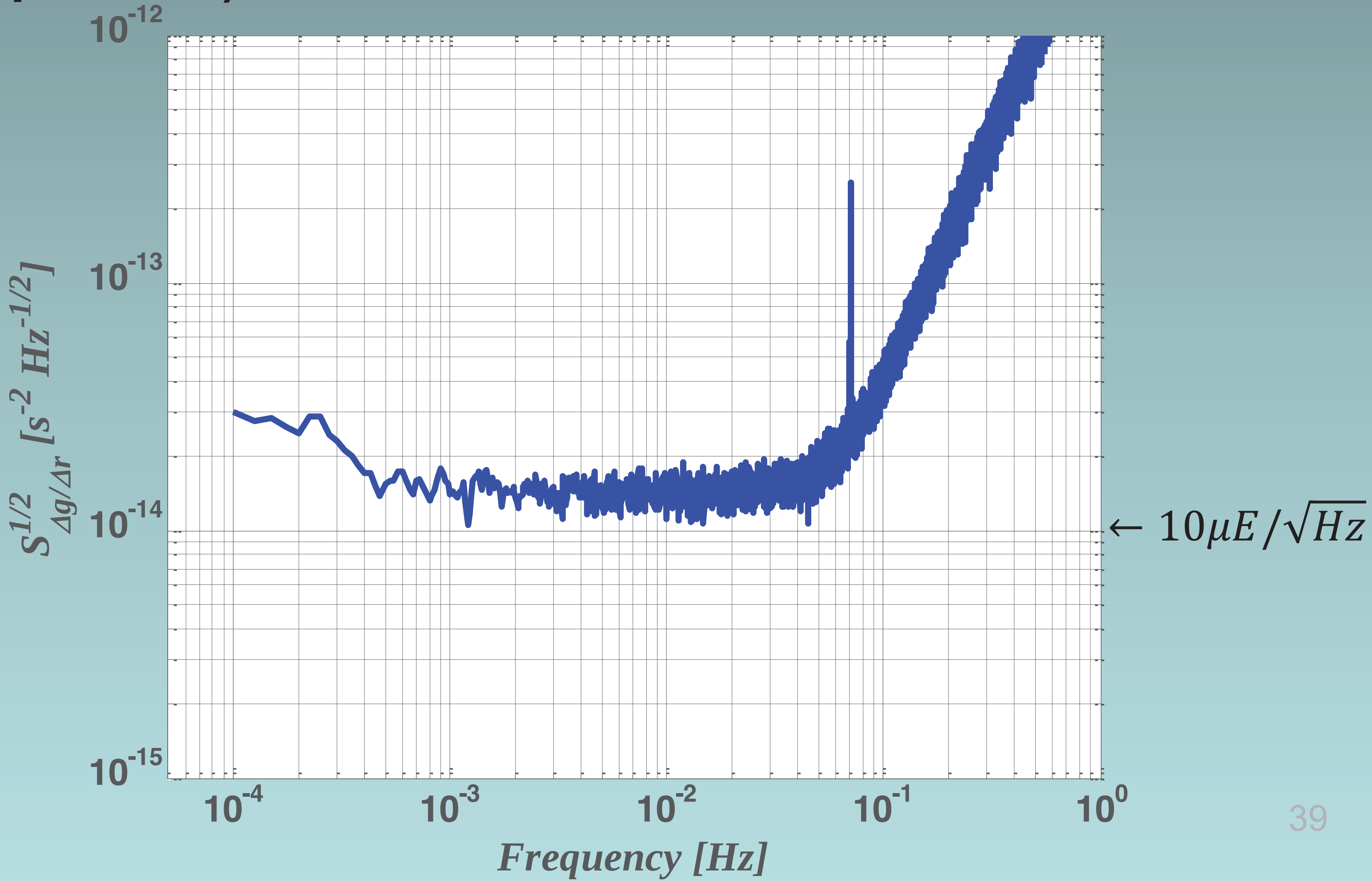
LISA Pathfinder

- **LISA Pathfinder does not represent a small improvement - the differential acceleration noise is *orders of magnitude* better than anything achieved previously**



LISA Pathfinder

- **Differential acceleration performance translated into gradiometer performance (simply dividing by 0.4m TM separation):**



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Testing Modified Gravity with LISA Pathfinder

- **TEVES and other theories inspired by MOND predict potentially measureable anomalous gravity gradients in macroscopic regions around gravitational Saddle Points**

- **In LISA Pathfinder we have a spacecraft with arguably the most sensitive gravity gradiometer ever on-board, with best sensitivity in the mHz frequency band, orbiting L1**

→ ***Can we use LISA Pathfinder to look for MONDian effects?***

Testing Modified Gravity with LISA Pathfinder

- **Need to:**
  - **Understand dynamic location of gravitational Saddle Points (SPs) in the Sun-Earth-Moon System**
  - **Establish that LPF can be made to fly through the region around a SP following its nominal mission**
  - **Calculate the anomalous MONDian gravity gradients that LPF will experience, including temporal behaviour**
  - **Confirm that the gravity gradiometer on-board LPF is sensitive enough to detect the anomalous gradients**
- **… without changes to LPF hardware or nominal mission!**

Testing Modified Gravity with LISA Pathfinder

- Saddle Points are defined by zero *total* gravitational field
- In th… could
  pote…

SP Trade-off:

	Sun-Earth SP	Lunar SP
Characteristic Target Region ("Bubble") Size	**≈380km** for most of the time; down to about 330km for short periods every month	**≈50km**; varies between 30km and 80km with lunar phase
"Launch Windows" from nominal LPF orbit	**Many:** SP motion limited and therefore more "stable" target	**Fewer:** departure time needs to be synchronised with lunar motion
Speed relative to Earth – Sun system	**<< 1km/s** for most of the time; > 0.1km/s only for short periods every month	Typically of order **1km/s** as it follows the Moon on its orbit around Earth
External Newtonian gravity gradients	≈ $\mathbf{4x10^{-11}s^{-2}}$ along the Sun-Earth line ≈ $\mathbf{-2x10^{-11}s^{-2}}$ transverse	Max ≈$\mathbf{1x10^{-9}s^{-2}}$ depending on lunar phase

→ Focus has been on Sun-Earth SP

Testing Modified Gravity with LISA Pathfinder

- **The Sun-Earth SP position is shifted from its nominal two-body position due to the influence of other gravitating bodies:**
  - Moon: ≤ 6000km
  - Jupiter: ≤ 20km
  - Venus: ≤ 10km
  - …
  - Milky Way: ≤ 10m
- **Eccentricity of Earth orbit around Sun results in shifts of order ±4000km (annual modulation)**
- **Effects are well-known and predictable. True gravitational SP can easily be pinpointed to <<1km (Galianni et al 2012: ≤ 5m!).**

Testing Modified Gravity with LISA Pathfinder

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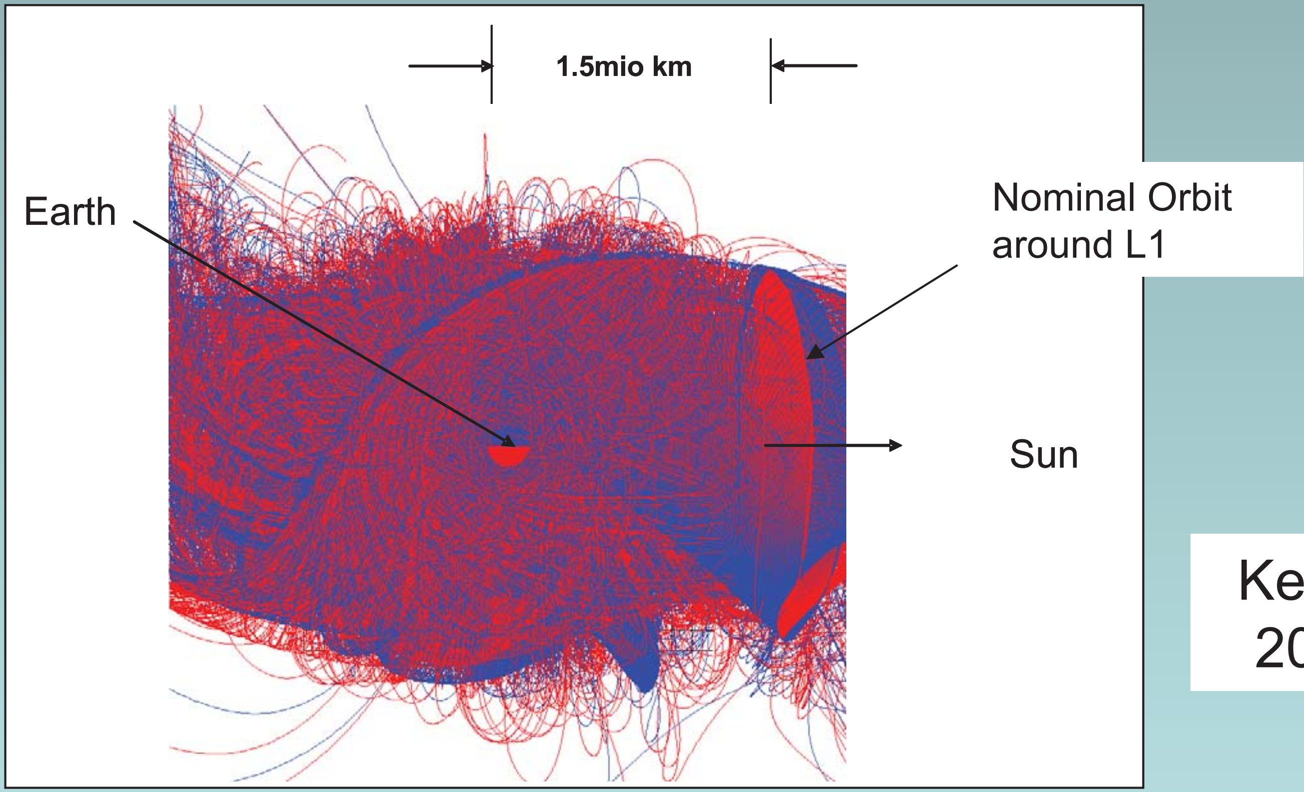
  - **Confirm that the gravity gradiometer on-board LPF is sensitive enough to detect the anomalous gradients**

Testing Modified Gravity with LISA Pathfinder

- **LPF will lie nominally on a stable manifold whilst orbiting the Earth-Sun L1 point**
- **Only a small manoeuvre is needed to reach an unstable manifold**
- **This allows an option to return towards Earth and access the gravitational saddle point between Sun and Earth**



Kemble, 2007/8

Testing Modified Gravity with LISA Pathfinder

Search for suitable trajectories - assumptions and constraints:

- **Single dV manoeuvres up to 2m/s have been considered:**
  - **compatible with estimated cold gas control authority following nominal mission (expected to be 4-5m/s)**
  - **reasonable timescales for manoeuvres, including single thruster failure**
- **Control parameters: dV magnitude and time**
- **Consider both Rockot and VEGA launch options**
- **Proof of principle only, prior to actual mission**
- **Figures of merit for trajectories:**
  - **transfer time from L1 to SP**
  - **SP fly-by distance**

Testing Modified Gravity with LISA Pathfinder

- **Significant progress has been made over the last few years, in three phases:**

(1) Single dV manoeuvre
  - understanding search space
  - difference in launchers
  - trajectory "families"
  - typical transfer times and SP flyby distances

(2) Double and multiple dV manoeuvres – minimising flyby distances

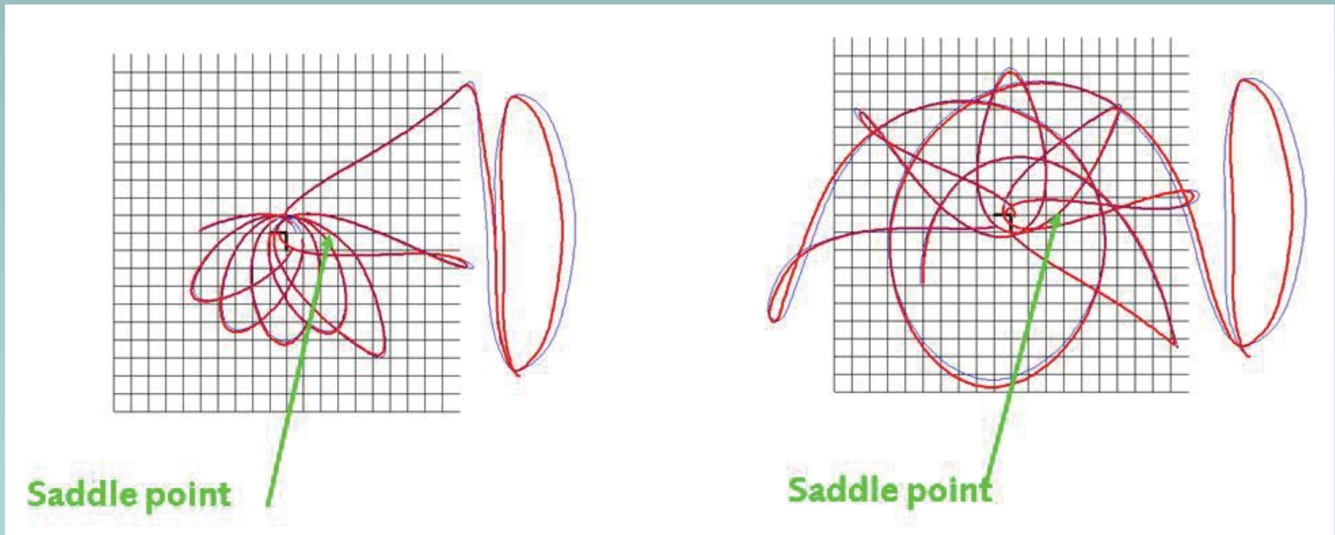
(3) Search for trajectories with more than one SP flyby

- **In parallel, feasibility of spacecraft navigation has been investigated**

Testing Modified Gravity with LISA Pathfinder

- **Results from phase (1) – single dV manoeuvre:**
  - Many possible trajectories exist to take LPF from L1 to the SP – many "needles in the haystack"
  - Chaotic search space for single manoeuvre if no subsequent corrections are applied
  - Lunar Gravity Assist can potentially be used as additional manoeuvre
  - Transfer time to reach the SP from L1 is typically 1.5 years with Rockot, and potentially of order 1 year with VEGA
  - Typical SP flyby distances of 100-1000kms

VEGA examples:



348days, 2333km

512days, 130km

Testing Modified Gravity with LISA Pathfinder

- Results from phase (2) – multiple manoeuvres
  - Add second manoeuvre at the apogees, starting with the best solutions from the single-manoeuvre search:

		Rockot 1635	Rockot LGA	VEGA LGA fast	VEGA 130
One manoeuvre strategy	Total DV	0.3225 m/s	0.8673 m/s	0.2301 m/s	-1.232 m/s
	Flyby distance	1635 km	396 km	2333 km	130 km
Two manoeuvres strategy	DV1	0.3225 m/s	0.8673 m/s	0.2301 m/s	-1.232 m/s
	DV2	1.4 m/s	1.8 m/s	1.87 m/s	0.05 m/s
	Total DV	1.7225 m/s	2.6673 m/s	2.1001 m/s	1.282 m/s
	Flyby distance	242 km	253 km	355 km	72 km

  - Additional manoeuvres (keeping total dV manageable) show: SP flyby distance can be reduced to “zero”

Testing Modified Gravity with LISA Pathfinder

- **Results from phase (3) – trajectories with more than one SP flyby (Fabacher et al 2013):**
  - Unconventional simulation method required:
    - Start at first SP flyby and identify orbits that fly by SP again, at least once
    - Then propagate trajectory *backwards* from first SP flyby to see if it can be reached from LPF orbit around L1
  - Early result: trajectories with ≥ 3 SP flybys are *too stable*

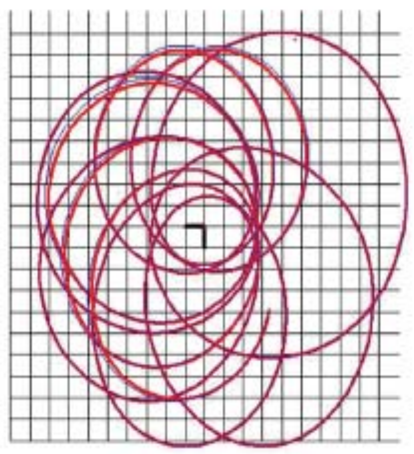
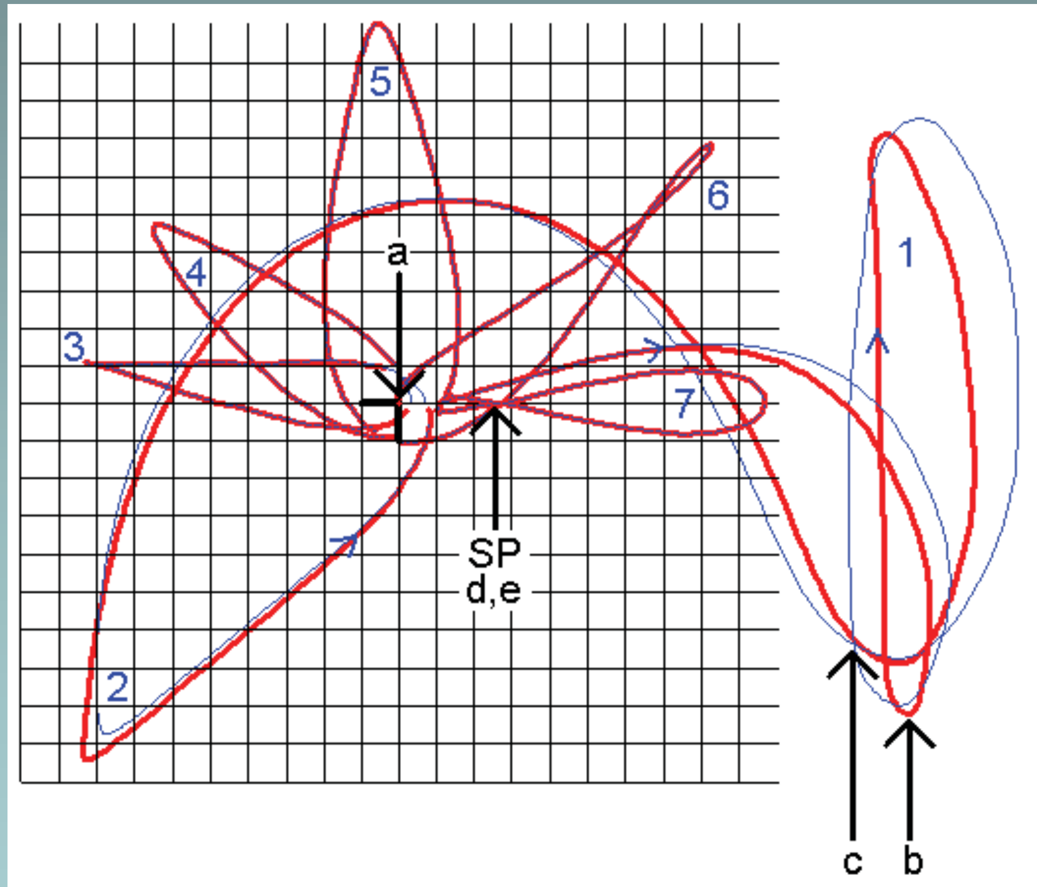


Figure 7: Example of an orbit considered as too stable - viewed in rotating reference frame, grid is 1 million km from centre to edge

Testing Modified Gravity with LISA Pathfinder

- Promising trajectories with double SP flybys have been found:

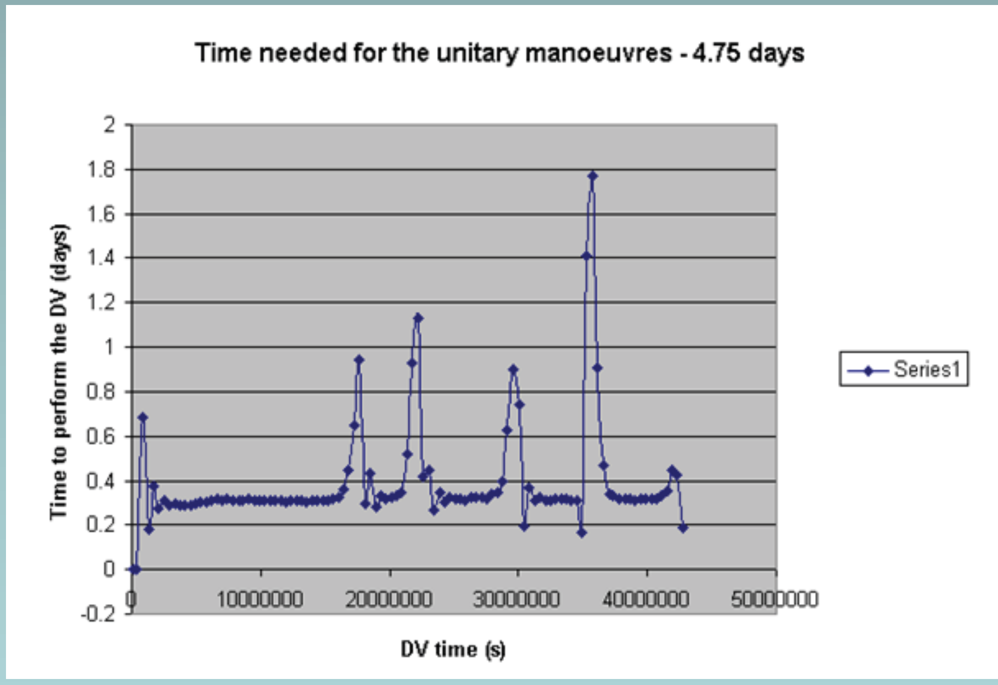
- **a: Launch, 24/2/2013. inclination = 57.6° perigee altitude: 322 km**
- **b: Libration orbit, 73 days after launch**
- **c: Exiting libration orbit, 258 days after launch. The spacecraft has spent 185 days around L1.**
- **d: Reaching the SP for the first time, 543 days after launch (285 days after escaping from L1).**
- **e: Reaching the SP for the second time, 582 days after launch (39 days after the first passage).**



- Potentially violates “golden rule” (no effect on nominal LPF)

Testing Modified Gravity with LISA Pathfinder

- **Navigation feasibility**
  - Can LPF be navigated along a nominal trajectory, given the limitations of the micropropulsion system and navigation errors?
  - Preliminary results: the navigation appears feasible



  - Ground contact with SC required every few days – affects operational costs

Testing Modified Gravity with LISA Pathfinder

- **Trajectory analysis summary:**
  - It seems certain that LPF can be made to fly by the Sun-Earth SP following the nominal mission, at least once
  - Trajectories exist that would result in double SP flybys – however suitability of these trajectories (eg impact on LPF launch window) still to be confirmed
  - The time to reach the SP (for the first time) will be between 1 and 1.5 years following departure from L1
  - The knowledge of SP flyby distance will be dominated by spacecraft tracking errors (ground station dependent but ≤10km)
- **FULTT work (2016/17) confirmed that viable trajectories could have been found**

Testing Modified Gravity with LISA Pathfinder

- **Gravitational environment during SP flyby – a few relevant parameters:**

  - LPF speed through SP region typically ≈1.5km/s (free-fall – not much can be done about this)

  - For a flyby distance of 10km, the lowest gravitational acceleration level experienced by LPF will be $a_g \approx 2\text{x}10^{-7}\text{ms}^{-2}$

  - Even if LPF flies through the SP *exactly*, it will spend, at most, ≈6s in an environment with $a_g \leq 1\text{x}10^{-7}\text{ms}^{-2}$

This has pros and cons…

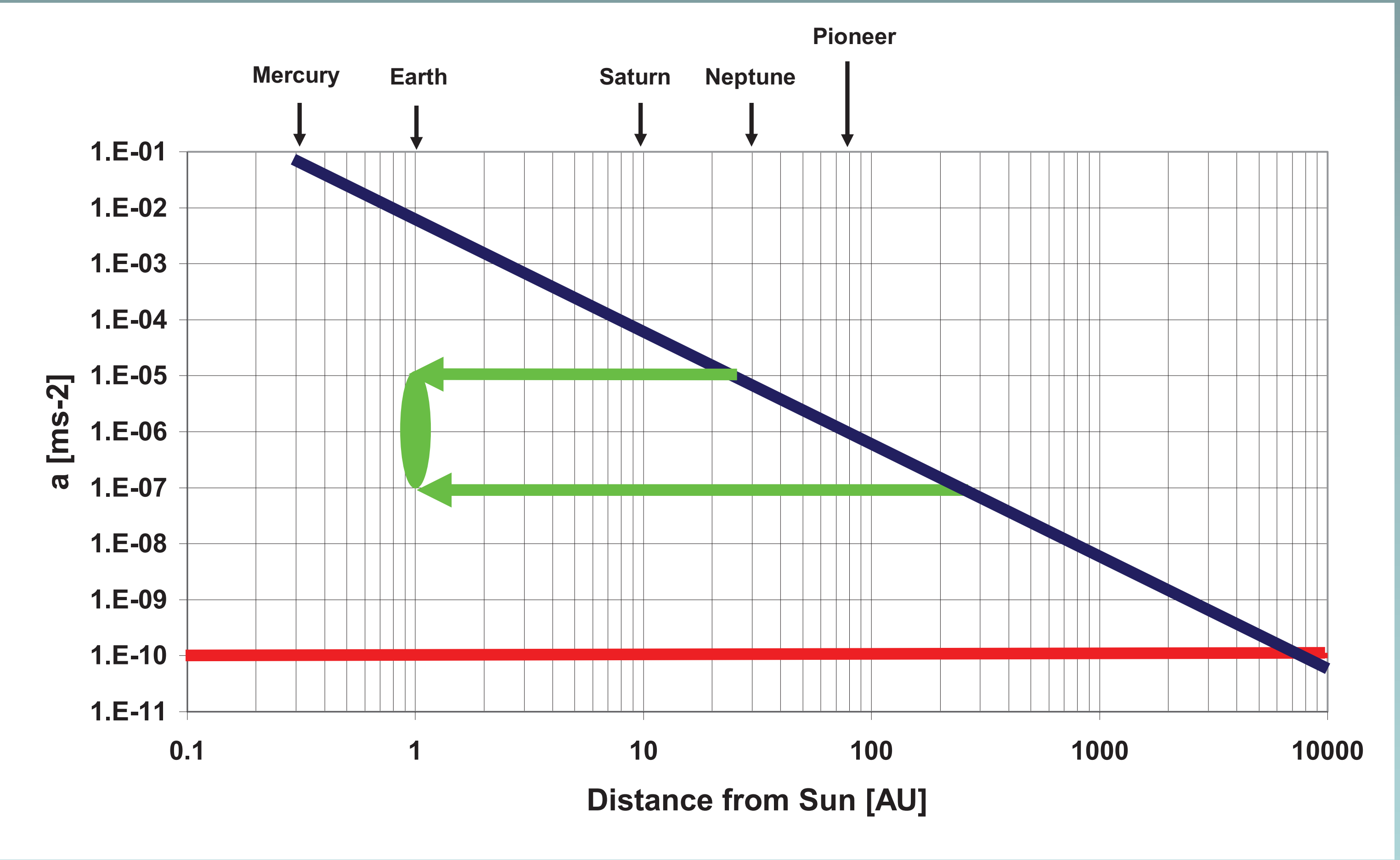
Testing Modified Gravity with LISA Pathfinder

- **Cons:**
  - LPF will only be able to test the intermediate MOND region (10^3 a_0)

- **Pros:**
  - Spacecraft self-gravity ($\leq 10^{-8} ms^{-2}$) was not expected to be an issue at this level (but see later…)
  - Demands on Navigation / SC tracking not too onerous (1-10km adequate)

Testing Modified Gravity with LISA Pathfinder

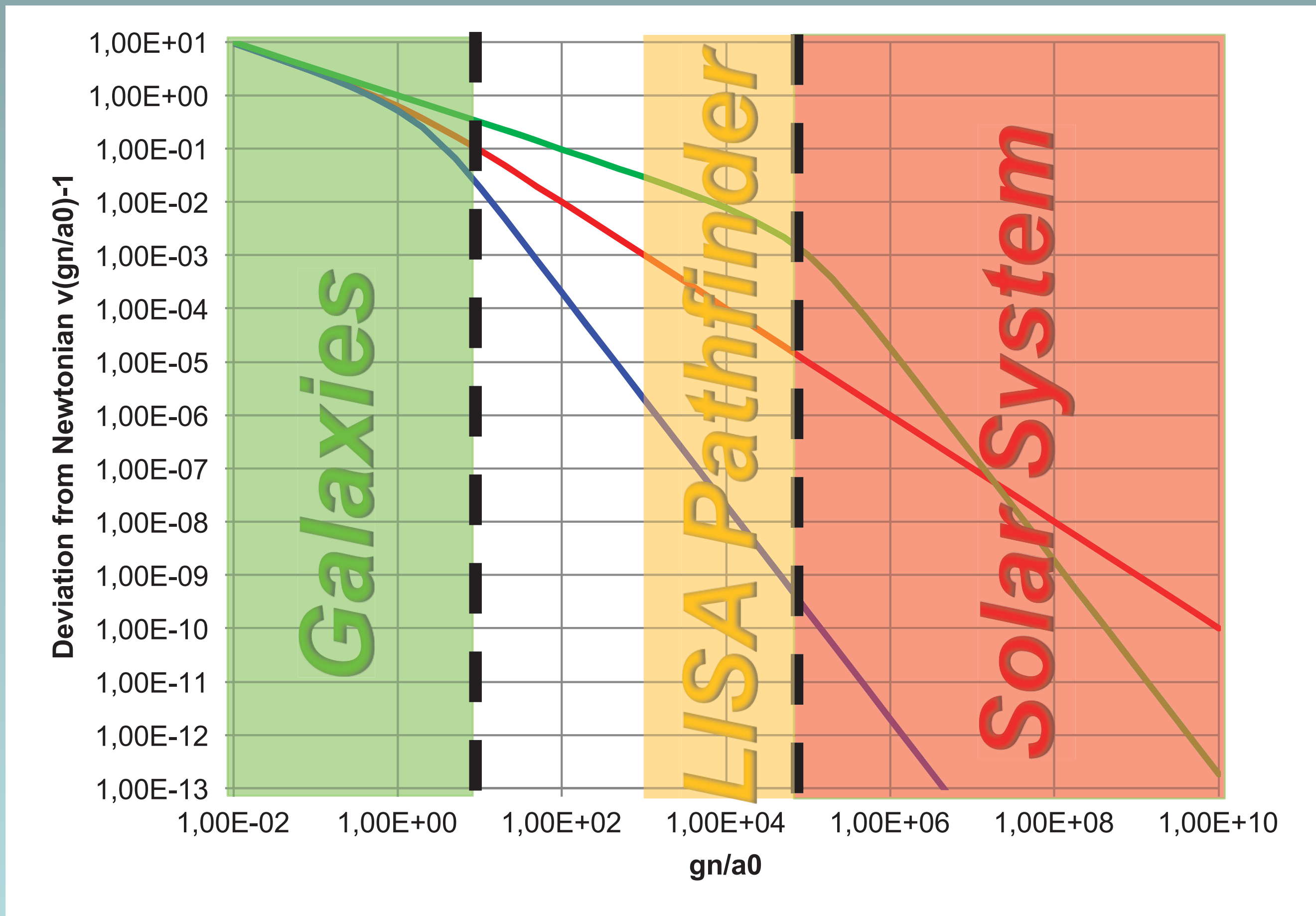
- **Experiencing $a_g \approx 1x10^{-7}ms^{-2}$ to $1x10^{-5}ms^{-2}$ at 1AU from the Sun is not too bad:**



- **Equivalent to travelling out to between 25 and 250 AU!**

Testing Modified Gravity with LISA Pathfinder

- **LPF can access about half the "acceleration gap", between 10^3 and $10^5 a_0$ – but to what (integrated) sensitivity, compared to predicted signals…?**

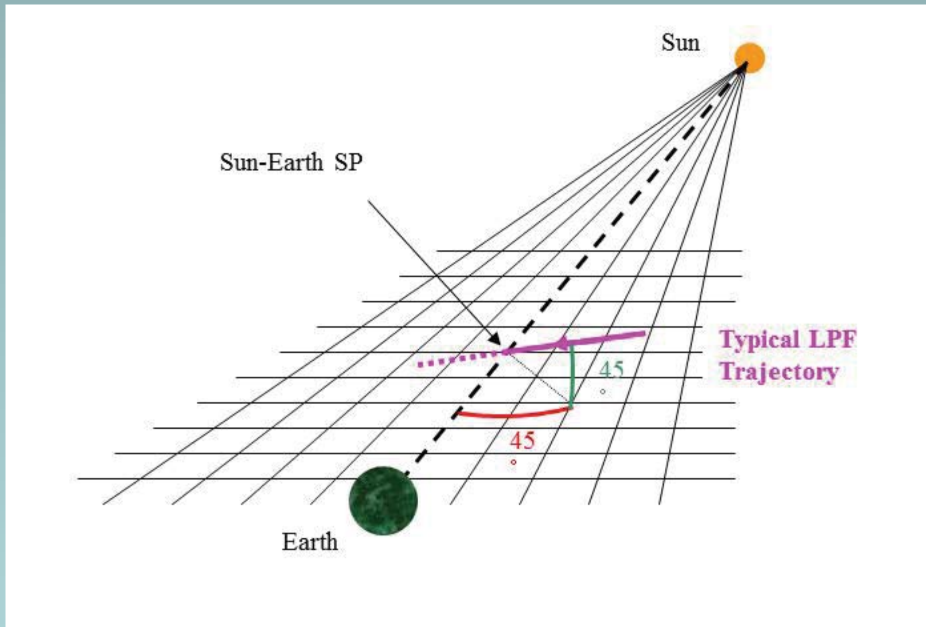


Testing Modified Gravity with LISA Pathfinder

- **Need to:**
  - **Understand dynamic location of gravitational Saddle Points (SPs) in the Sun-Earth-Moon System**
  - **Establish that LPF can be made to fly through the region around a SP following its nominal mission**
  - **Calculate the anomalous MONDian gravity gradients that LPF will experience, including temporal behaviour**
  - **Confirm that the gravity gradiometer on-board LPF is sensitive enough to detect the anomalous gradients**

Testing Modified Gravity with LISA Pathfinder

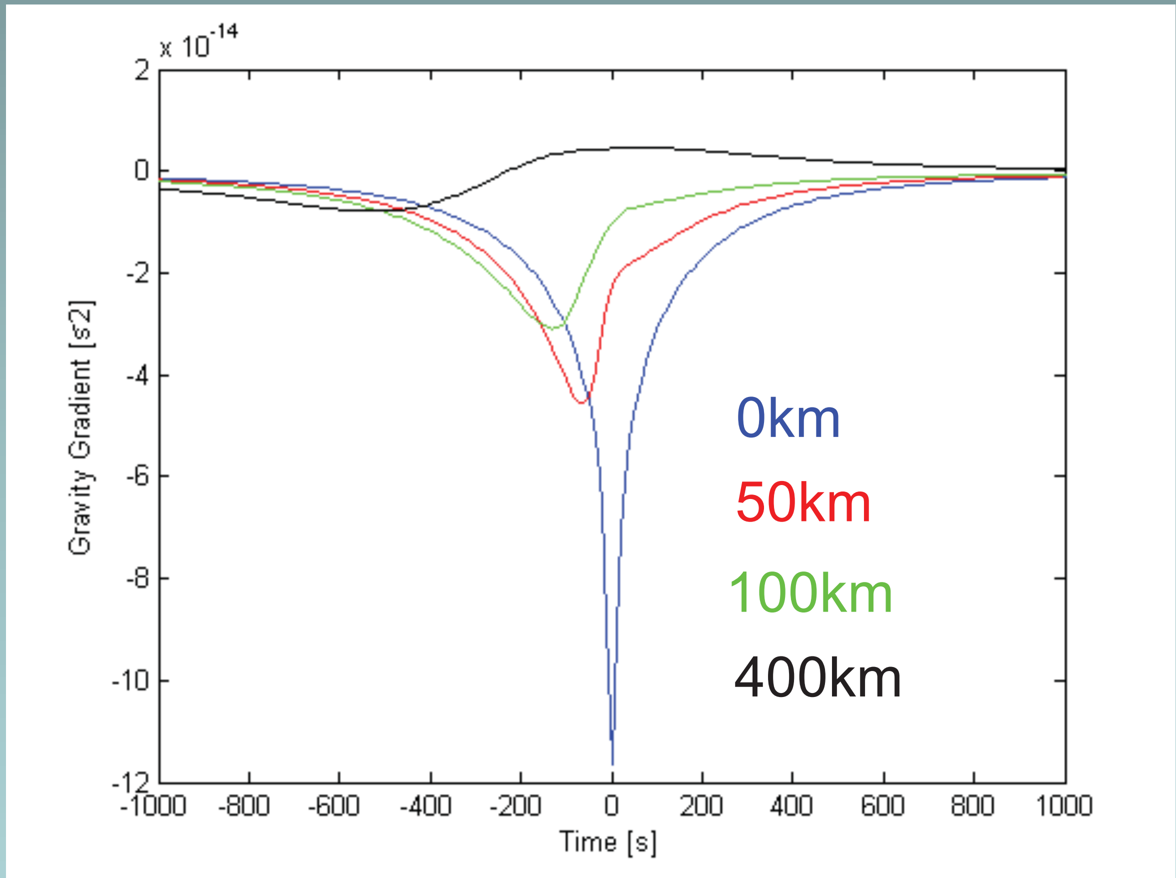
- **Signal prediction of anomalous TeVeS gravity gradients (Bevis et al 2010):**
  - Numerical method used to calculate anomalous gradients at grid points of cubic volume around SP
  - A typical LPF trajectory is then propagated through the volume and the anomalous gradients are extracted at each point:



  - LPF speed through SP region – 1.5km/s – is then used to convert spatial into temporal gradient variations

Testing Modified Gravity with LISA Pathfinder

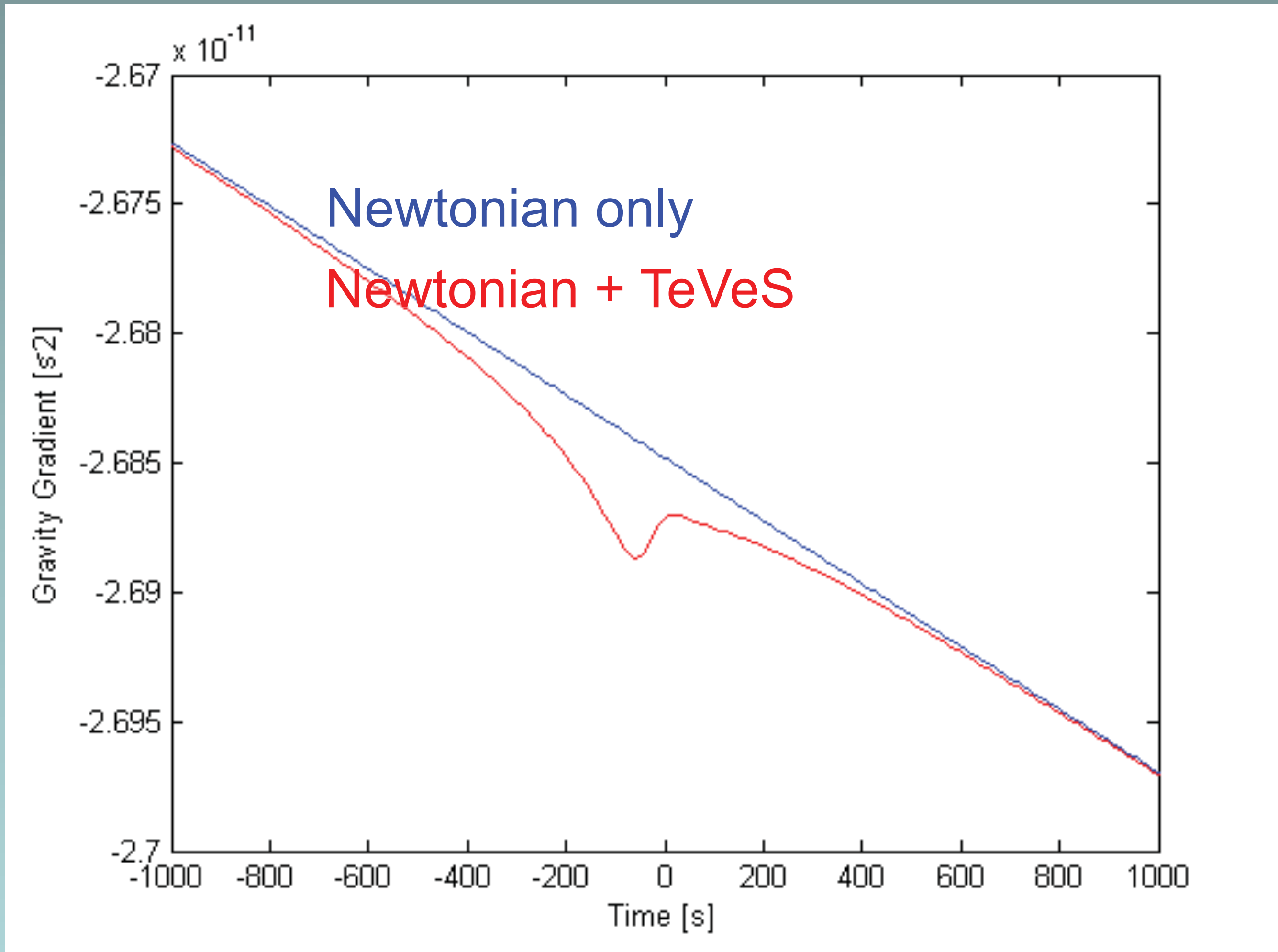
- **Results**
  - Anomalous gravity gradients as a function of flyby distance:



  - Signal duration 500 – 1000s ≈ mHz (!)

Testing Modified Gravity with LISA Pathfinder

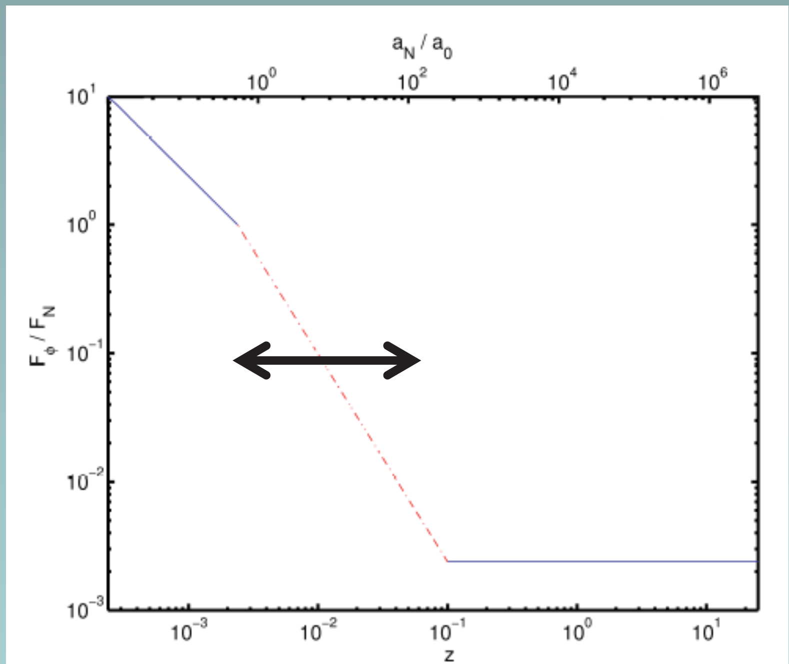
- Total external gravity gradient seen by LPF for 50km flyby distance:



- Newtonian background is predictable and can be subtracted to at least $10^{-15}s^{-2}$

Testing Modified Gravity with LISA Pathfinder

- **MONDian signal prediction for theories other than TeVeS are also available:**
  - Some theories with “designer transition functions” (Magueijo & Mozzafari 2012):



  - Quasilinear MOND (QMOND), a type II theory (Galianni et al 2011)

Testing Modified Gravity with LISA Pathfinder

- **Spacecraft Self-Gravity revisited**
  - All early signal predictions (Bevis et al, Magueijo & Mozzafari, Galianni et al) simply ignored spacecraft mass distribution
  - Conventional view: with external gravity $\geq 10^{-7} ms^{-2}$, internal SC gravity, at levels $\leq 10^{-8} ms^{-2}$, can safely be ignored
- **But…**
  - In the true MOND “spirit”, the gravitational interaction between SC and TMs should be modified in low external fields (EFE)
  - Internal gravity gradients ($\approx 10^{-7} s^{-2}$) are approximately 3-4 orders of magnitude larger than external ones ($\approx 2\text{-}4 \times 10^{-11} s^{-2}$)

Testing Modified Gravity with LISA Pathfinder

- **The effect of Spacecraft Self-Gravity – investigated in QMOND (Trenkel & Wealthy 2014)**
  - In QMOND, non-Newtonian signals are due to “Phantom Dark Matter” with density given by:

$$4\pi G\rho_{PDM} = \vec{\nabla}\cdot\left(\bar{\upsilon}\left(\frac{|g_N|}{a_0}\right)\vec{\nabla}\Phi_N\right)$$

with $\bar{\upsilon}\left(\frac{|g_N|}{a_0}\right) = \upsilon\left(\frac{|g_N|}{a_0}\right) - 1$ and

$\upsilon\left(\frac{|g_N|}{a_0}\right)$ is the inverse of the μ-function.

Weak field limit $g_N \ll a_0$: $\upsilon\left(\frac{|g_N|}{a_0}\right) \rightarrow \left(\frac{|g_N|}{a_0}\right)^{-1/2}$

Strong field limit $g_N \gg a_0$: $\upsilon\left(\frac{|g_N|}{a_0}\right) \rightarrow 1$

Testing Modified Gravity with LISA Pathfinder

- **Why did we work with QMOND?**
  - *Not* out of personal preference – we are not theorists ☺
  - Mainly because "numerical recipe" for how to compute PDM density already existed (Famey & McGaugh 2012)
  - PDM source equation above can be expanded:

$$4\pi G\rho_{PDM} = -\left(\vec{\nabla}\nu\left(\frac{|g_N|}{a_0}\right)\right)\cdot\vec{g}_N + \left(\nu\left(\frac{|g_N|}{a_0}\right) - 1\right)\nabla^2\Phi_N$$

$$= -\left(\frac{1}{a_0}\nu'\left(\frac{|g_N|}{a_0}\right)\vec{\nabla}|g_N|\right)\cdot\vec{g}_N + \left(\nu\left(\frac{|g_N|}{a_0}\right) - 1\right)4\pi G\rho_{matter}$$

Dominated by local SC gradients

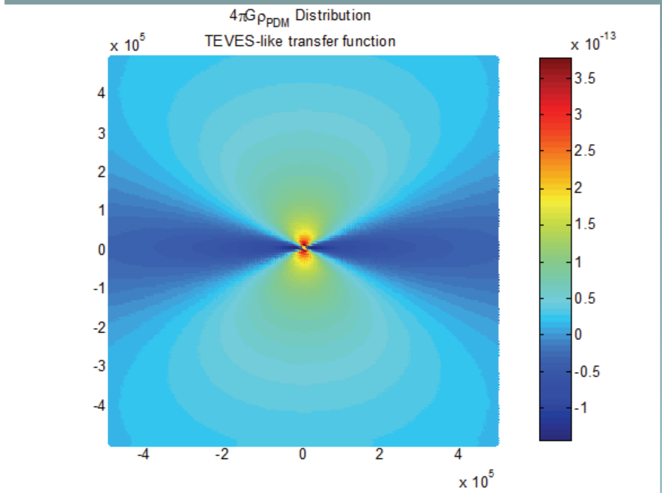
Dominated by external field at >10km from SP

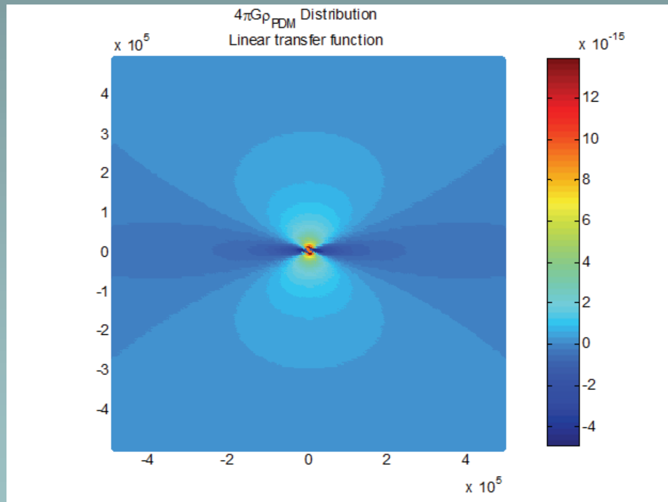
Non-zero only with SC present

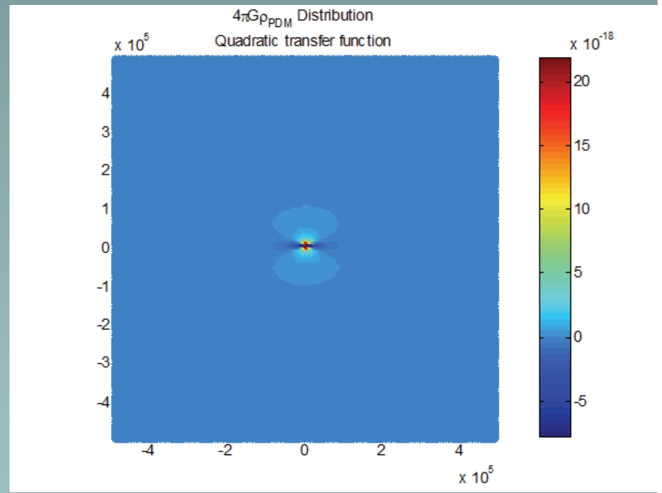
- Expect significant impact of Spacecraft!

Testing Modified Gravity with LISA Pathfinder

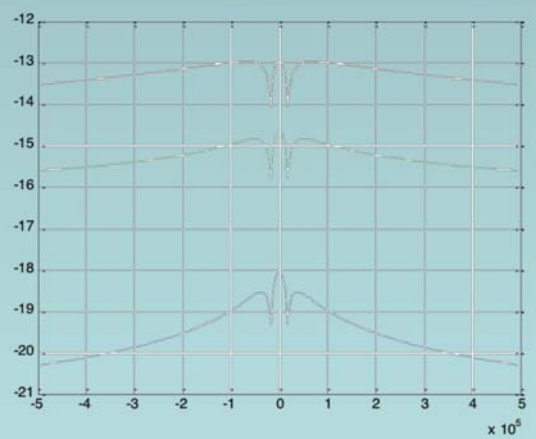
- **Free Space Checks & Validation**
  - Calculate PDM around Sun-Earth SP (ignore SC)

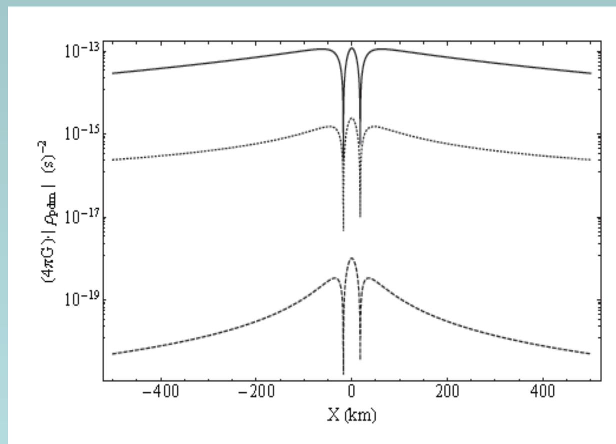






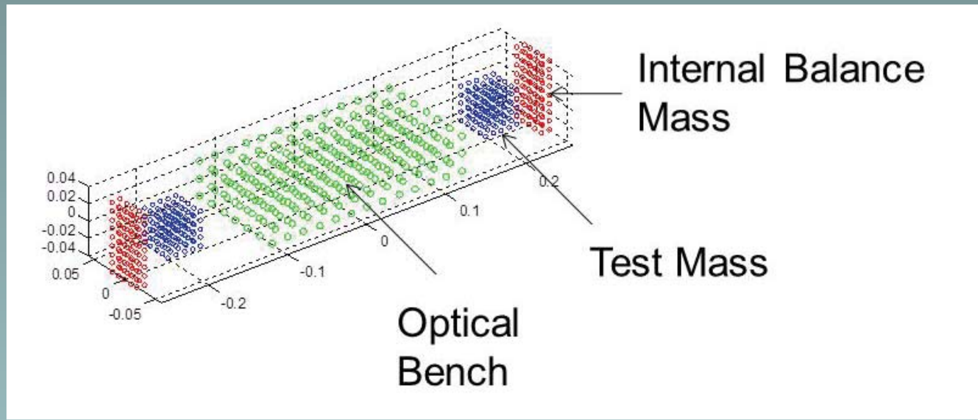
  - Compare with Galianni et al (2011)



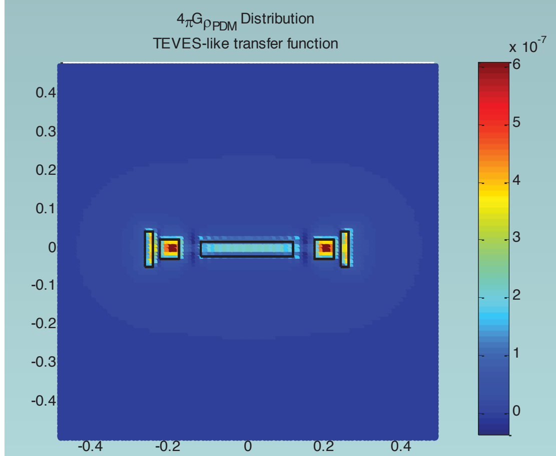


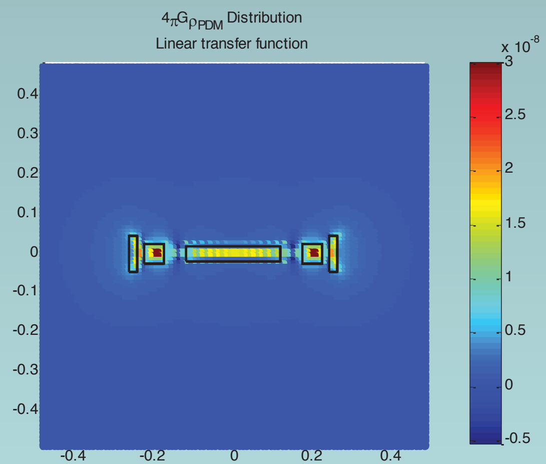
Testing Modified Gravity with LISA Pathfinder

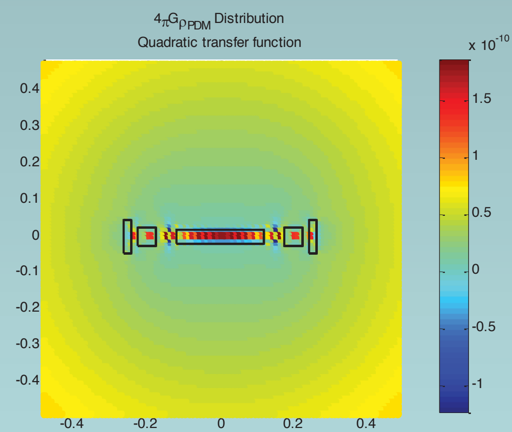
- **Generate simplified Mass Models**



- **Place Model near Sun-Earth SP & calculate PDM density around mass distribution**



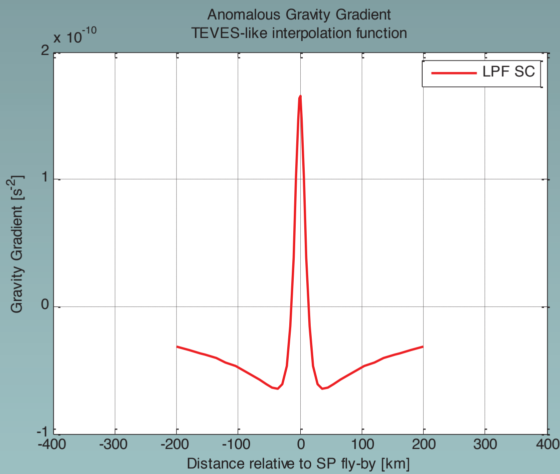


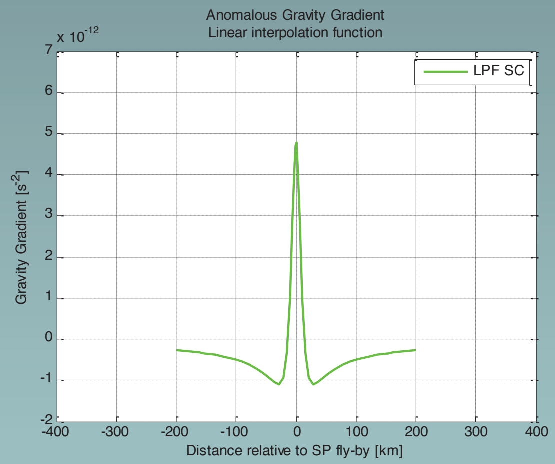


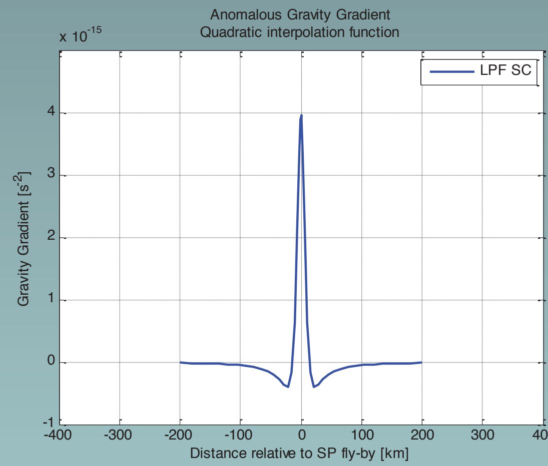
- **Calculate non-Newtonian (PDM) TM acceleration / gradient**

Testing Modified Gravity with LISA Pathfinder

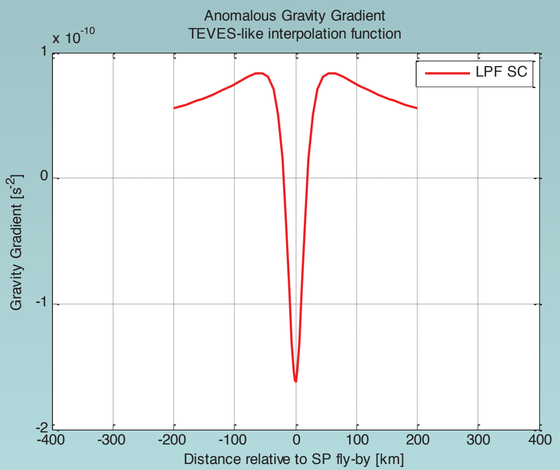
- **Send models along trajectories past the SP and compute anomalous signal vs time:**
  - Parallel to Sun-Earth line with 25km miss distance:

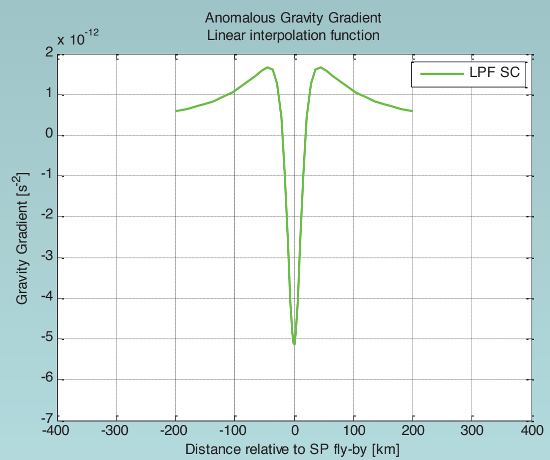


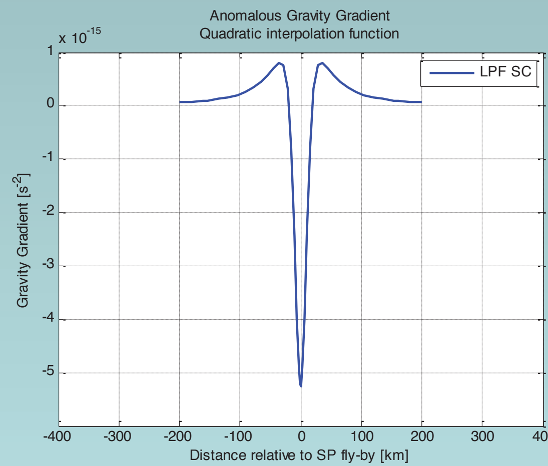




  - Orthogonal to Sun-Earth line with 10km miss distance:







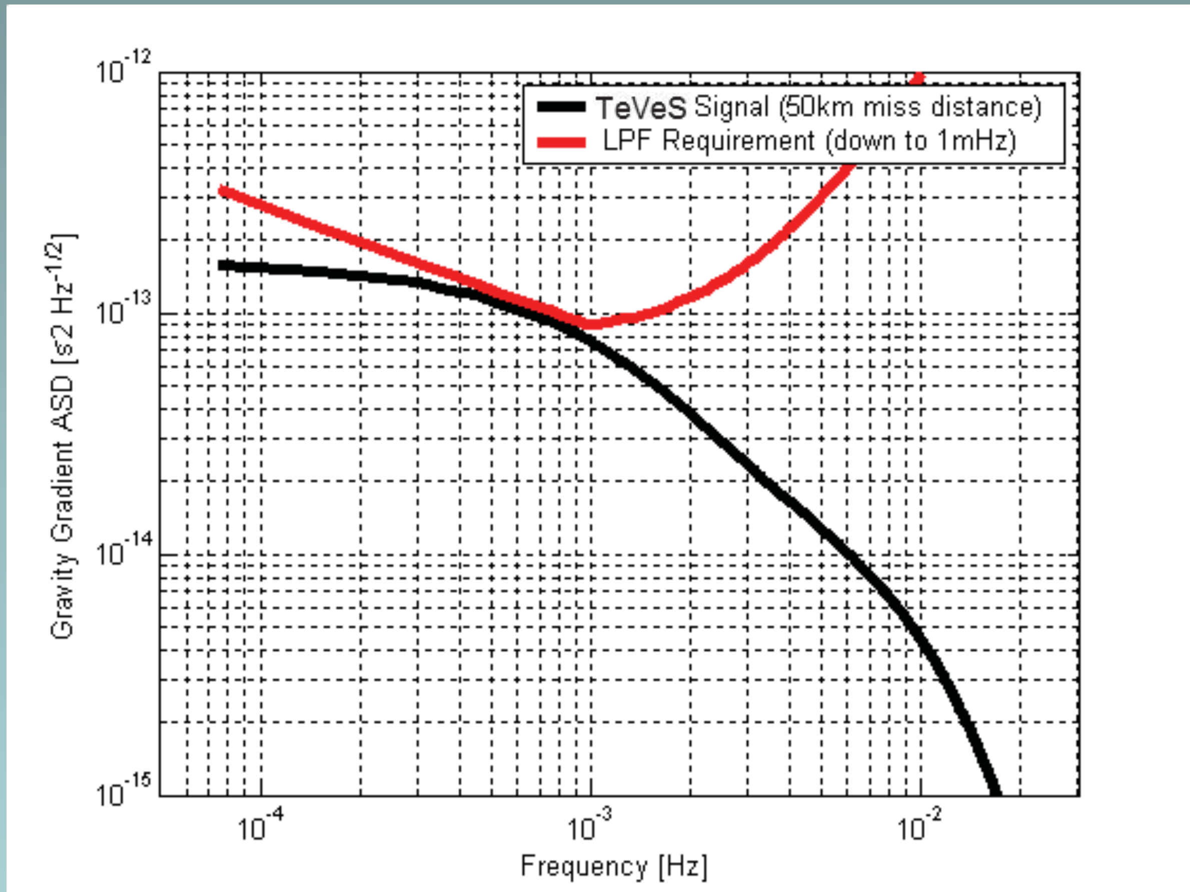
  - Peak signal 2-6x10^3 times *larger* than predicted by Galianni et al

Testing Modified Gravity with LISA Pathfinder

- **Need to:**
  - **Understand dynamic location of gravitational Saddle Points (SPs) in the Sun-Earth-Moon System**
  - **Establish that LPF can be made to fly through the region around a SP following its nominal mission**
  - **Calculate the anomalous MONDian gravity gradients that LPF will experience, including temporal behaviour**
  - **Confirm that the gravity gradiometer on-board LPF is sensitive enough to detect the anomalous gradients**

Testing Modified Gravity with LISA Pathfinder

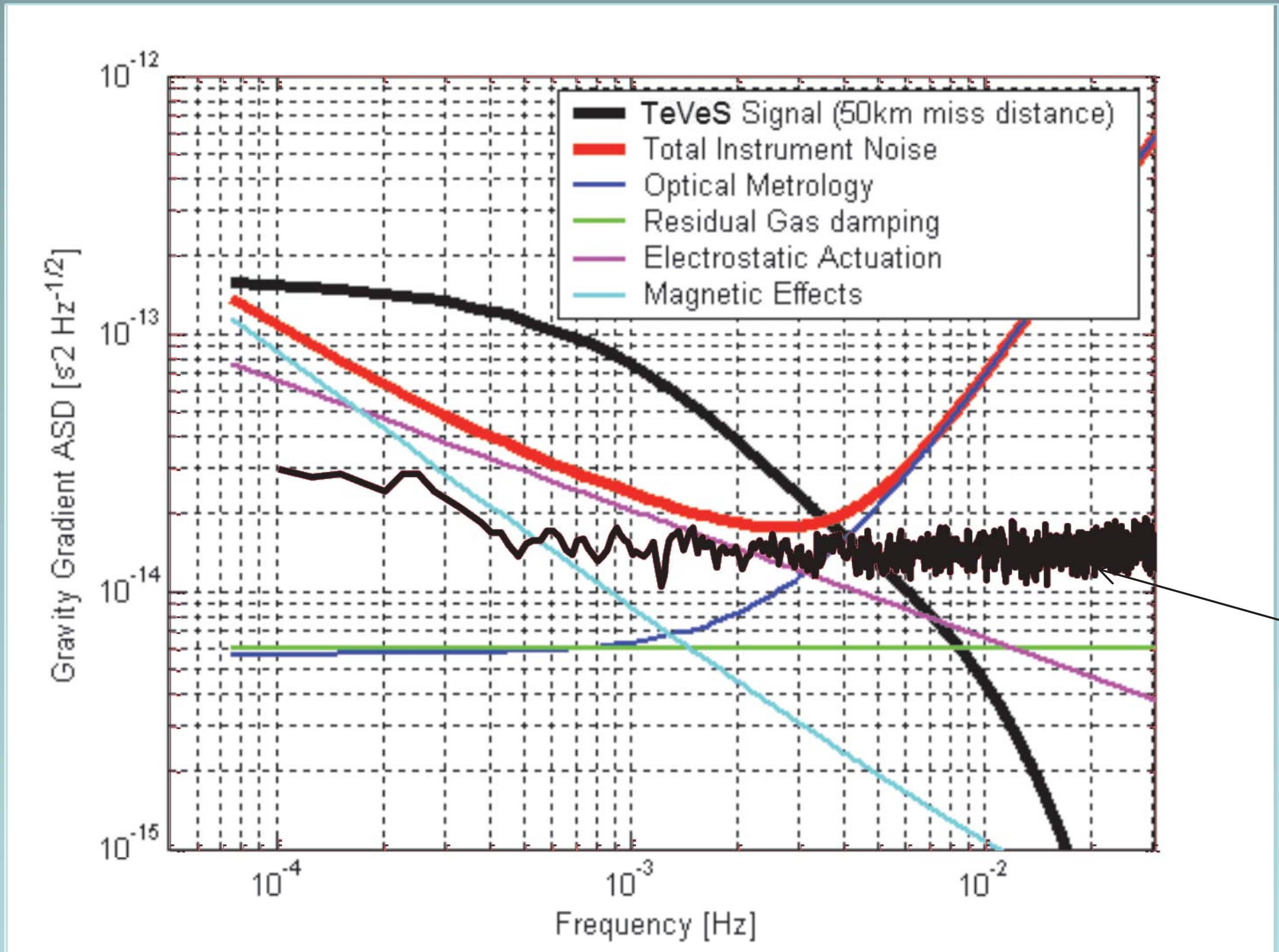
- **Comparison of predicted TeVeS signal (ignoring SC presence) to LPF differential acceleration performance requirement:**



→ If LPF "only" meets its requirements, TeVeS gradient detection is marginal

Testing Modified Gravity with LISA Pathfinder

- **Extensive pre-flight test campaigns showed that the expected LPF performance was substantially *better* than the requirement:**



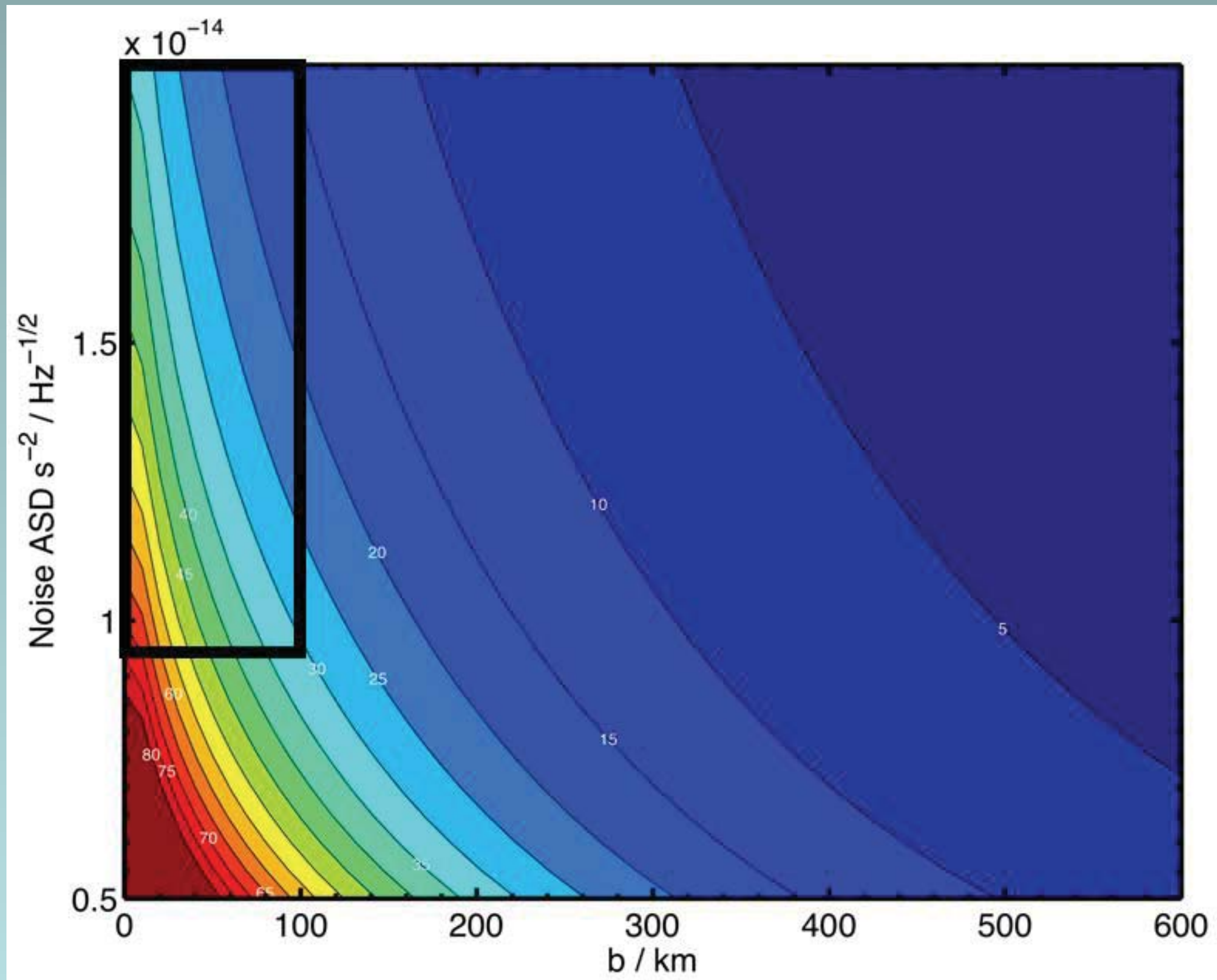
In-flight performance

Testing Modified Gravity with LISA Pathfinder

- Signal-to-Noise Ratios can be calculated in analogy with gravitational wave detection (matched filters).
- The following SNR plot was obtained for TeVeS (Magueijo 2010) assuming ≈ pre-flight expected noise levels:

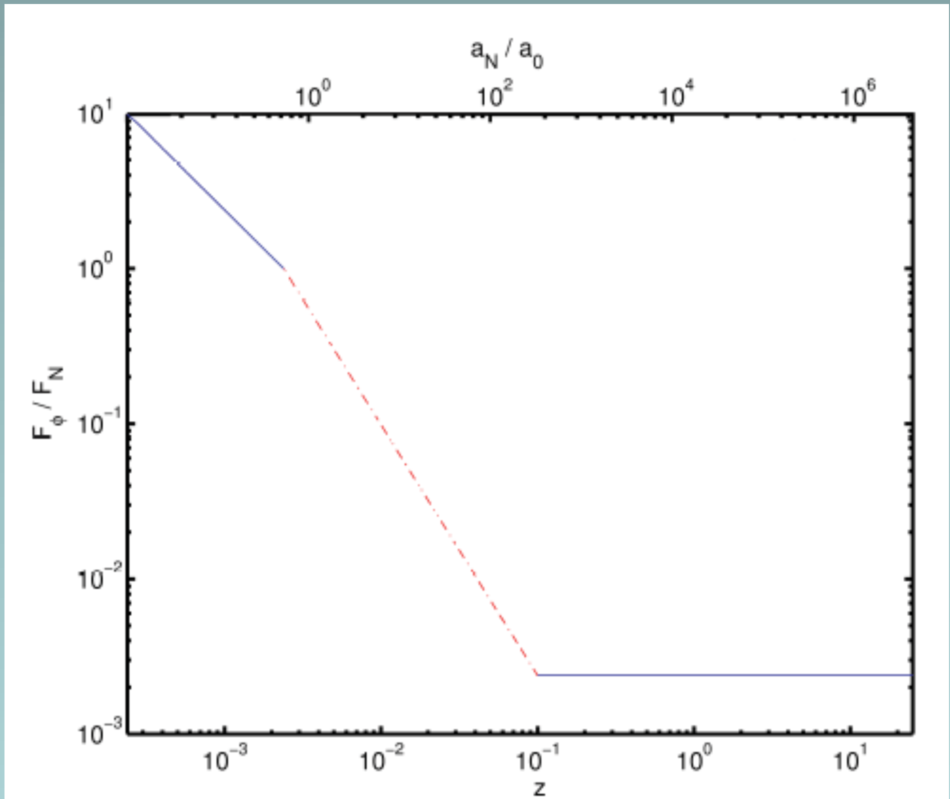
→ SNRs between 15 and 70!

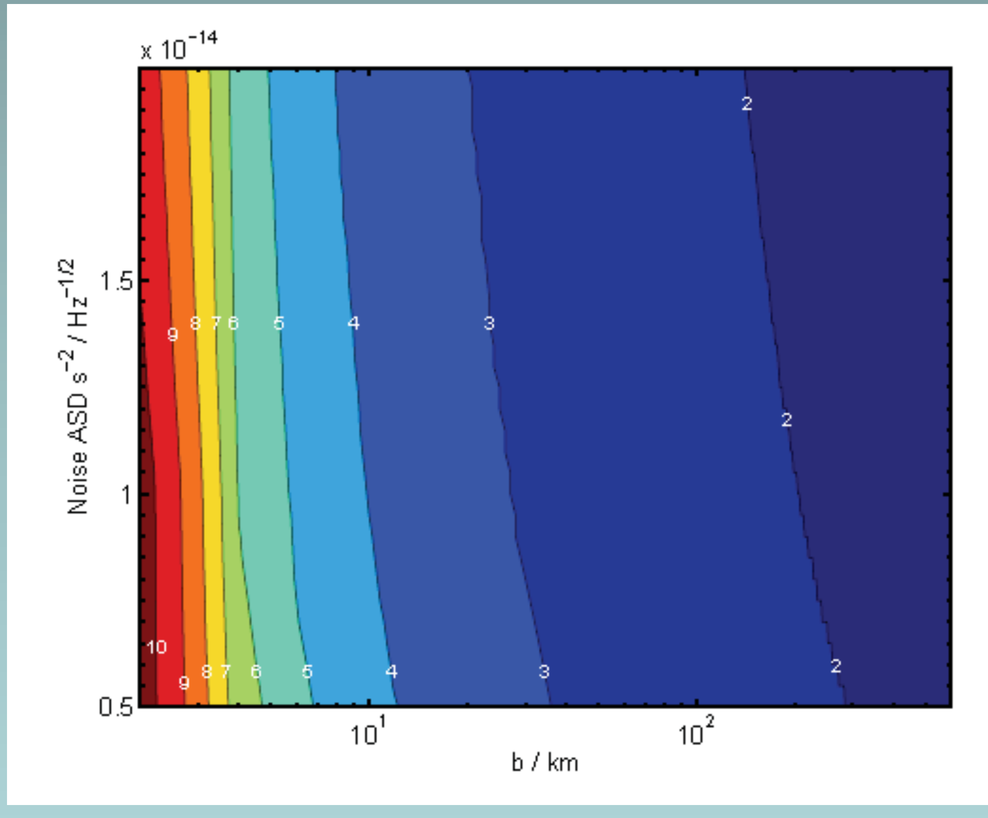
$$\rho^2 = 4\int_0^{\infty} \frac{|\tilde{h}(f)|^2}{S_h(f)} df,$$



Testing Modified Gravity with LISA Pathfinder

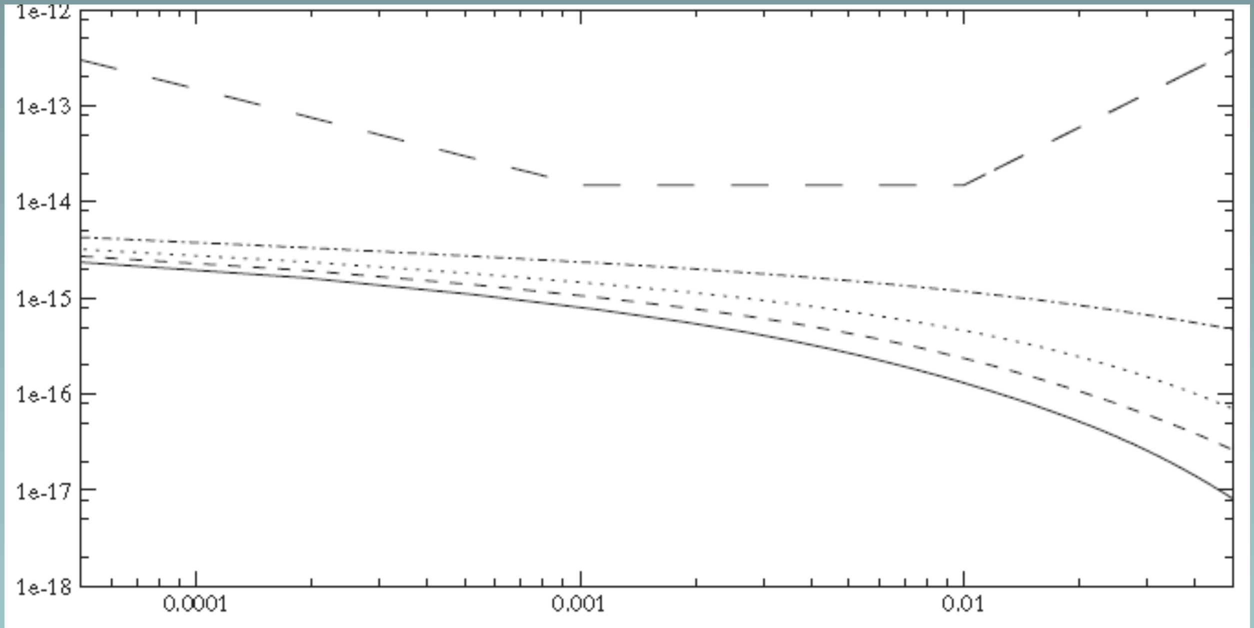
- **Results for other theories:**
  - Designer functions: slope that can be ruled out as function of noise and SP flyby distance (Magueijo & Mozzafari 2012):





Testing Modified Gravity with LISA Pathfinder

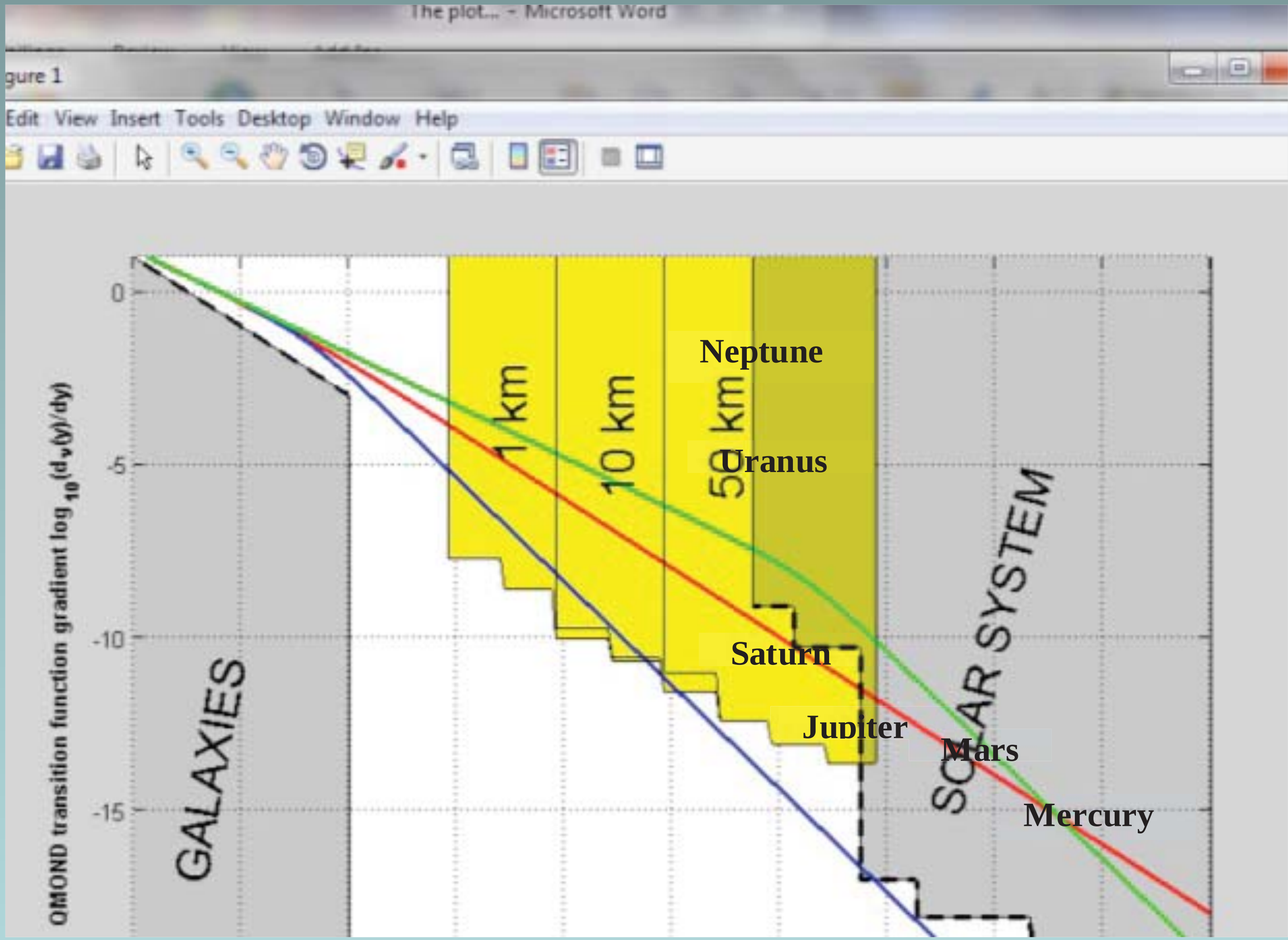
- **Other results:**
  - QMOND (Galianni et al 2011):



  - SP flyby distance of 10km required for unity SNR (detection), flyby distance of 1km required for SNR ≈ 2
  - Type III theories can always avoid detection by being “steep enough”

Testing Modified Gravity with LISA Pathfinder

- **QMOND Parameter Space accessible to LISA Pathfinder – including self-gravity effect & based on pre-flight best estimate**



- **Solar System constraints derived by limits on anomalous planetary precessions (Sanders 2006, Hees 2014)**

Testing Modified Gravity with LISA Pathfinder

- **Conclusions:**
  - If LPF is made to fly through the Sun-Earth SP, it can
    - Conclusively detect, or rule out, anomalous MONDian gradients predicted by the original TeVeS
    - Detect, or rule out, some of the designer functions and other “soft” (linear) transition functions
    - Directly explore (as yet) unexplored parameter space
    - ***Not*** rule out all MONDian possibilities
  - Solar System observations may already indirectly constrain transition functions beyond quadratic via the galactic EFE (Blanchet & Novak 2011)

Testing Modified Gravity with LISA Pathfinder

- **Need to:**
  - **Understand dynamic location of gravitational Saddle Points (SPs) in the Sun-Earth-Moon System**
  - **Establish that LPF can be made to fly through the region around a SP following its nominal mission**
  - **Calculate the anomalous MONDian gravity gradients that LPF will experience, including temporal behaviour**
  - **Confirm that the gravity gradiometer on-board LPF is sensitive enough to detect SOME anomalous gradients**

Overview

- Dark Matter or Modified Gravity?
- Modified Gravity – inspired by MOND
- LISA Pathfinder
- Testing Modified Gravity with LISA Pathfinder
- Future Prospects
- Summary and Discussion

Future Prospects

- **LISA Pathfinder**
  - In the end, the scientific case for sending LPF to the Sun-Earth SP was not considered strong enough:
    - No fully conclusive MONDian test – and MOND / TEVES are not "mainstream" theories
    - Comprehensive characterisation of LPF instrument for LISA was deemed higher priority
  - Even so…
    - any positive detection would have represented a major breakthrough…
    - LPF was (almost) the perfect instrument in the perfect place!

Future Prospects

- **Looking ahead…**
  - MOND, TEVES etc are still not well regarded in the scientific community
  - Therefore any future proposed test needs to
    - Be definite – ie inequivocally either detect or rule out MOND (no “parameter tuning” allowed)
    - Be relatively low-cost (LPF final cost was ≈ 400M€)
  - With everything we have learned with the LPF “exercise” – can we come up with a definitive test of these theories at a relatively low cost?

Future Prospects

- **Need to address main shortcomings of LPF proposal:**

  - We really have to explore $\leq 10^{-10} ms^{-2}$ (= a_0) gravitational field regime – removes dependence on transition function

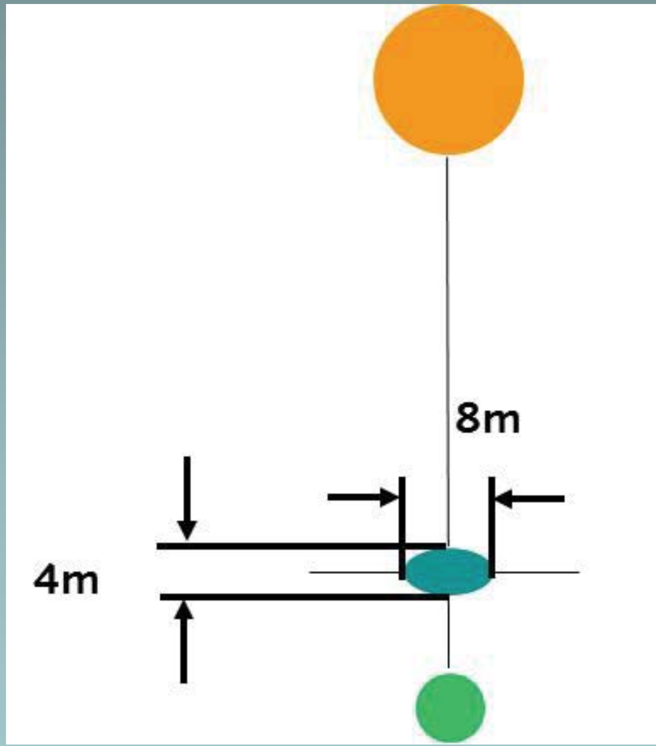
  - Spacecraft speed (and therefore signal modulation) needs to be matched to instrument peak sensitivity frequency

  - Need to improve navigation accuracy & knowledge from ≈ km scale to ≈ m scale

- **…ideally, using COTS hardware and keeping costs as low as possible!**

Future Prospects

- **Accessing the a_0 gravitational field regime**
  - $g_N \leq 10^{-10} ms^{-2}$ only within very small ellipsoid around true Sun-Earth SP*
  - Approaches SP position knowledge (see above)
  - Completely different challenge in terms of navigation & orbit determination!
    - "Formation flying" between SC and SP at the ≈1m level required
    - Knowledge of SC position to <1m required (LLR?)

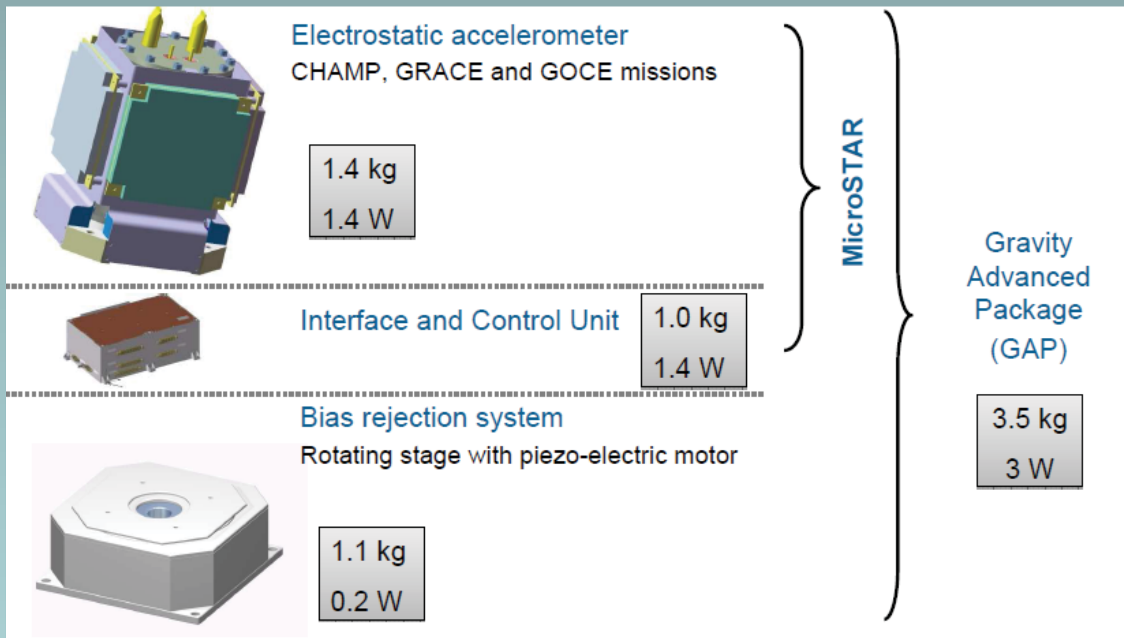


*10x smaller around Moon-Sun SP…

Future Prospects

- **The LPF gradiometer cannot be rebuild at low cost - what are the alternatives?**

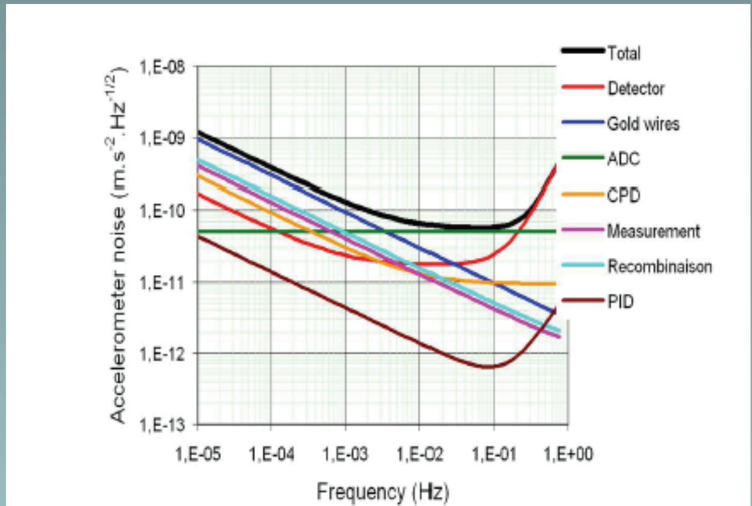
- **GAP (ONERA) – Gravity Advanced Package: Closest to a commercial accelerometer for space**



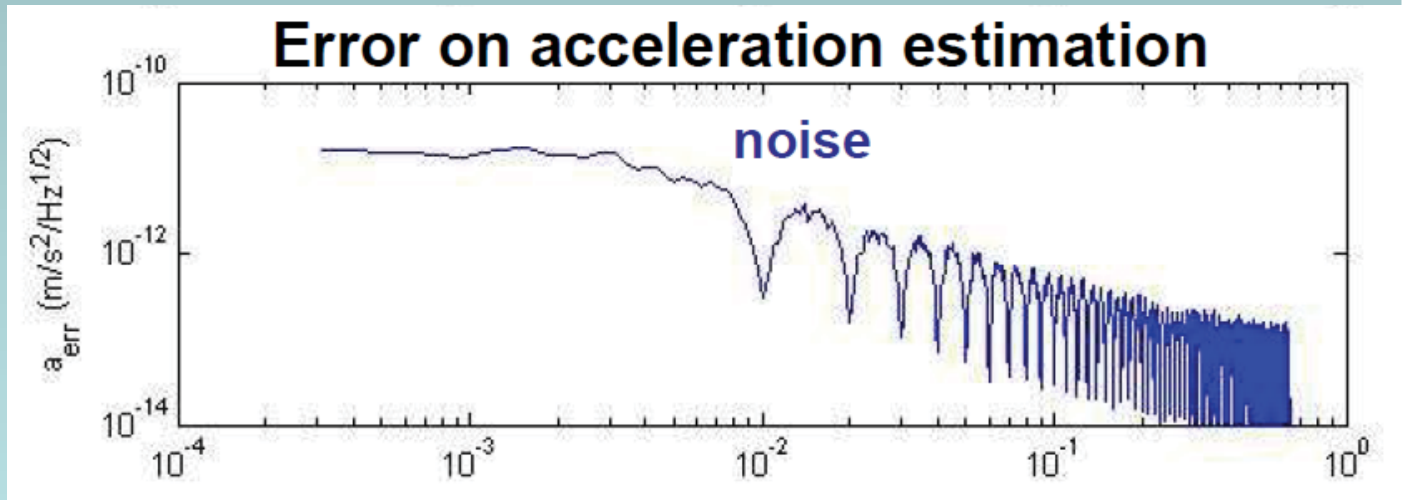
  - Triaxial sensing
  - Bias rejection stage may not be required

Future Prospects

- **Single accelerometer performance:**

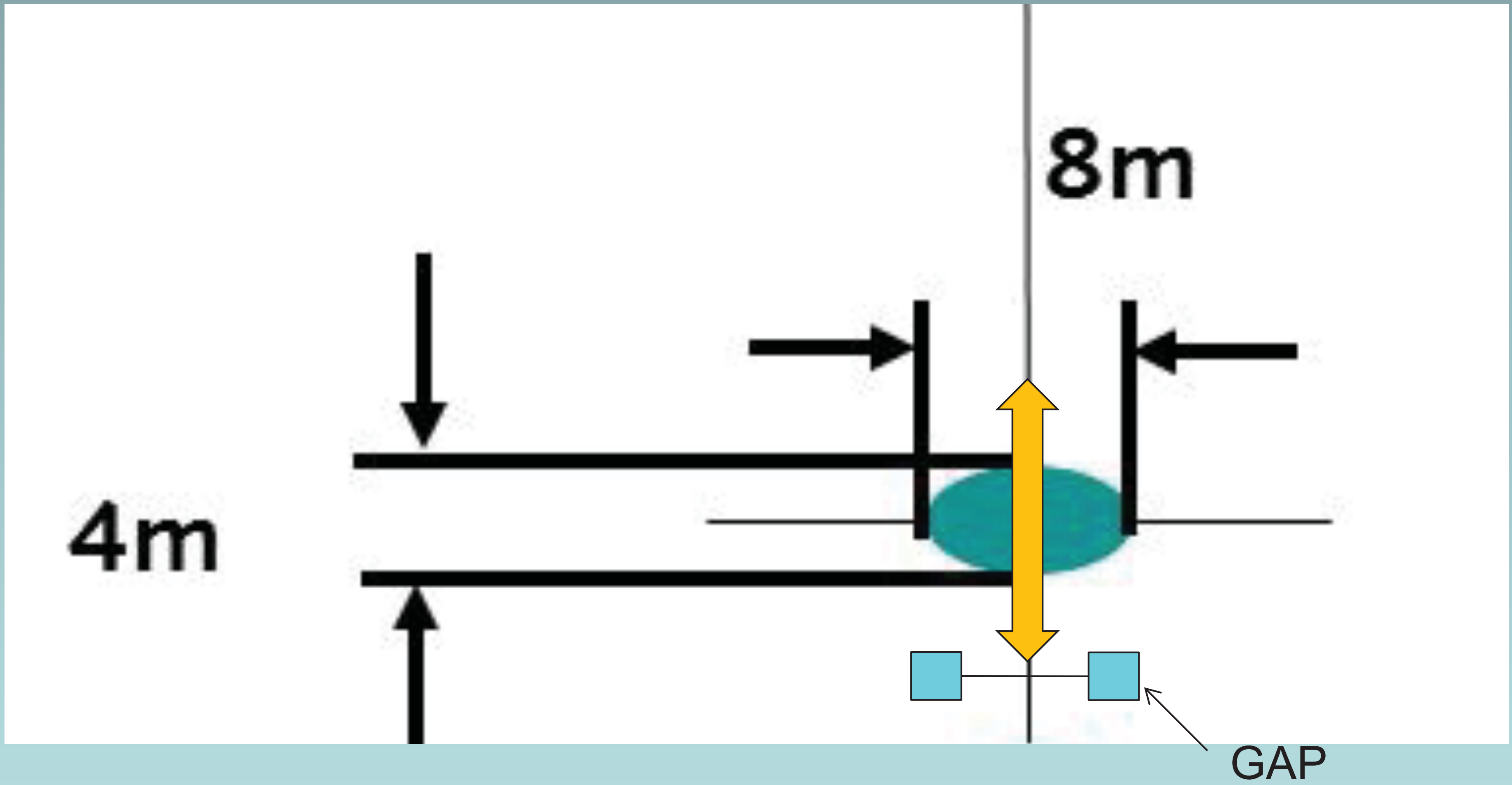


- **Bias correction mechanism can achieve 1pm/s^2 after 3 hours integration (the same can be achieved by modulating the signal)**



Future Prospects

- **So conceptual proposal:**
  - Send two GAPs (in formation / rigidly attached) through or around the "a_0 bubble" and look for differential acceleration:



Future Prospects

- **But presence of GAPs (or more generally a massive spacecraft) could affect bubble very strongly:**
  - A 3.5kg mass will generate $10^{-10}ms^{-2}$ at a distance of 1.5m
  - But complex interplay between gravity and gravity gradients – as QMOND exercise demonstrates
  - Is it best to keep GAPs further away from the bubble?
  - Can GAP (or SC) mass itself be used to shape the bubble?

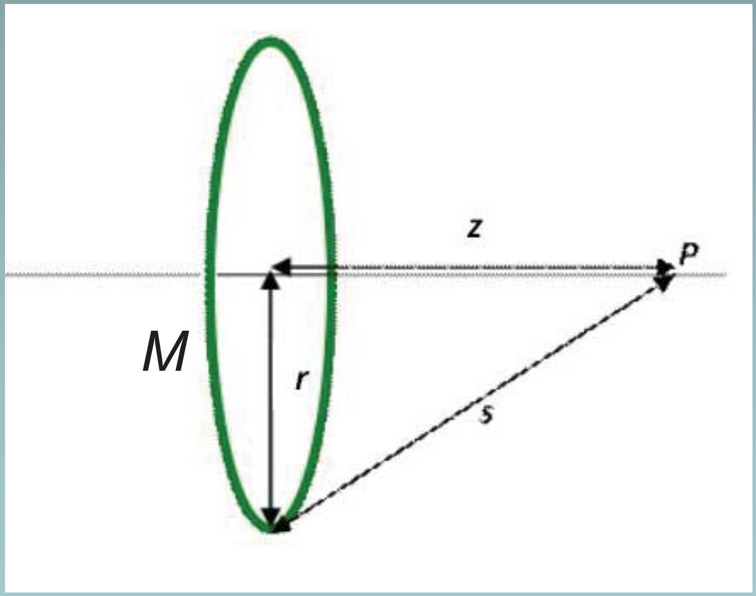
Future Prospects

- **One possibility: flatten the local gravitational environment!**

  - A mass ring of mass *M* and radius *r* generates, at its center, the following gradients:

$$\frac{\partial g_z}{\partial z} = -\frac{GM}{r^3}$$

$$\frac{\partial g_x}{\partial x} = \frac{\partial g_y}{\partial y} = -\frac{\partial g_z}{2\partial z} = \frac{GM}{2r^3}$$



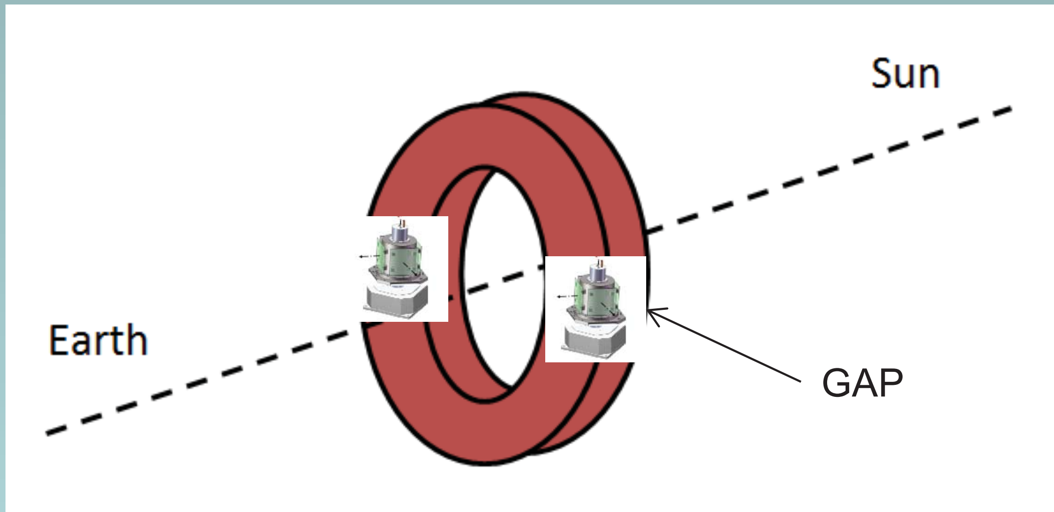
  - A large enough ring around the SP could *increase* the size of the region within which $g_N \leq 10^{-10} \mathrm{ms}^{-2}$

Future Prospects

- Mass ring required to generate axial $4.6e^{-11}s^{-2}$ around Sun-Earth SP – to match and cancel the natural gradient:

Ring Mass [kg]	Ring Radius [m]	Mass per length [kg/m]
5	1.94	0.41
10	2.44	0.65
20	3.07	1.04
50	4.17	1.91
100	5.25	3.03

- In principle, GAP accelerometers (at least two) could be part of the mass ring:



- Is this all completely impractical??
  - … deployable structures?

Future Prospects

- **MANY issues to be investigated and resolved:**
  - What would be the expected MONDian signal?
  - Could (two) GAP(s) measure it, is the sensitivity high enough?
  - What would be the ideal SC / GAP trajectory relative to the SP?
  - Are the navigation & knowledge requirements (<1m) feasible?
  - Can the above be combined with a realistic SC concept?
  - **…and at a relatively low cost??**

Overview

- Dark Matter or Modified Gravity?
- Modified Gravity – inspired by MOND
- LISA Pathfinder
- Testing Modified Gravity with LISA Pathfinder
- Future Prospects
- Summary and Discussion

Summary and Discussion

- **LISA Pathfinder has been a tremendously successful mission, with its in-flight performance exceeding even the pre-flight best estimates. Its payload constitutes, effectively, the most sensitive gradiometer ever flown!**

- **LPF *could* have been used to explore, directly, some of the parameter space still allowed by some alternative theories of gravity, specifically those inspired by MOND**

- **A conclusive test would, however, not have been possible – while a positive detection would have represented a major breakthrough in physics & cosmology, a null result would not have represented much progress**

- **On balance, the scientific case was not deemed strong enough and the mission extension (and available propellant) was devoted to further characterisation of the instrument**

Summary and Discussion

- **Although almost 10 years have passed since testing alternative gravitational theories with LPF was first considered, Dark Matter remains as mysterious as ever, and the motivation to come up with direct tests of alternatives to the Dark Matter paradigm has not diminished**

- **A lot has been learned from the work on LPF, and it would be good if this knowledge were to be used to come up with a realistic proposal for a definite test of MONDian theories within the Solar System**

Ideas and suggestions welcome!