LISA Pathfinder and MOND Towards a real space test

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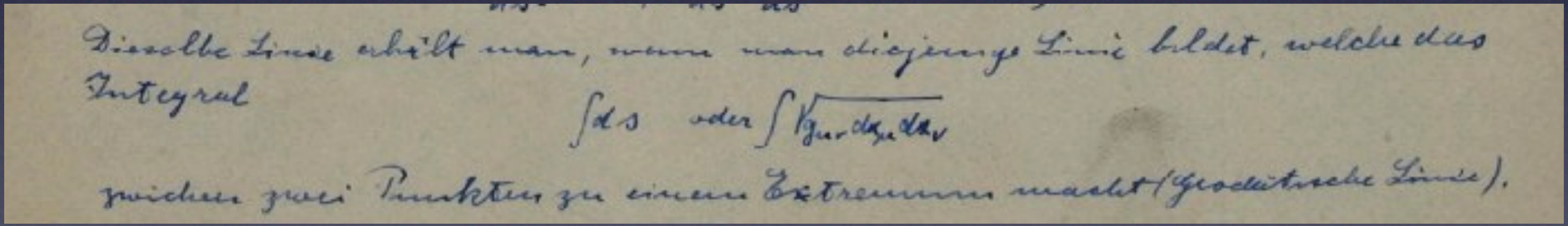
Summary

- LISA Pathfinder (LPF)
- MOND and LPF
- Conclusions and questions

Why LISA/NGO Pathfinder?

- LISA Pathfinder is being built by ESA to test
  - quality of free-fall (geodesy)
  - drag-free controls
  - high-precision rockets (FEEPs)
- It's a perfectly valid Pathfinder for any GW observatory with the same principles!



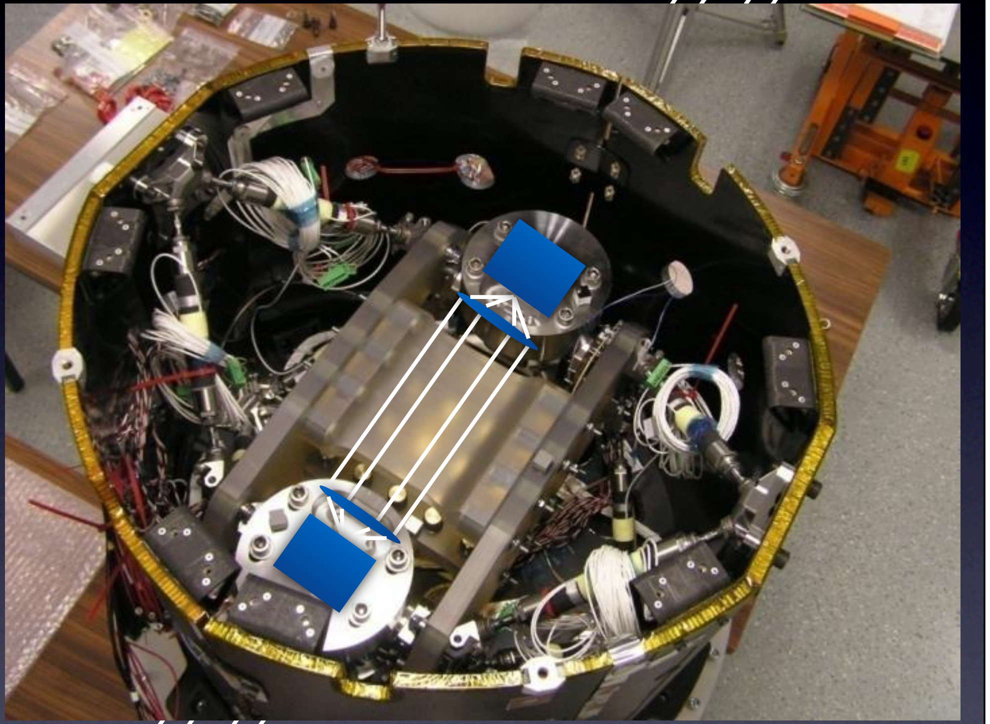
Dieselbe Linie erhält man, wenn man diejenige Linie bildet, welche das Integral

$$\int ds \quad \text{oder} \quad \int \sqrt{g_{\mu\nu} dx_\mu dx_\nu}$$

zwischen zwei Punkten zu einem Extremum macht (Geodätische Linie).

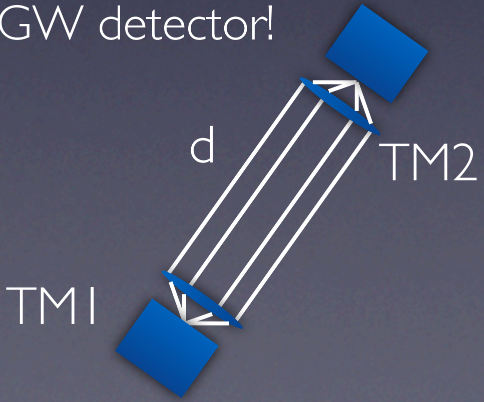
LISA Pathfinder in-flight test

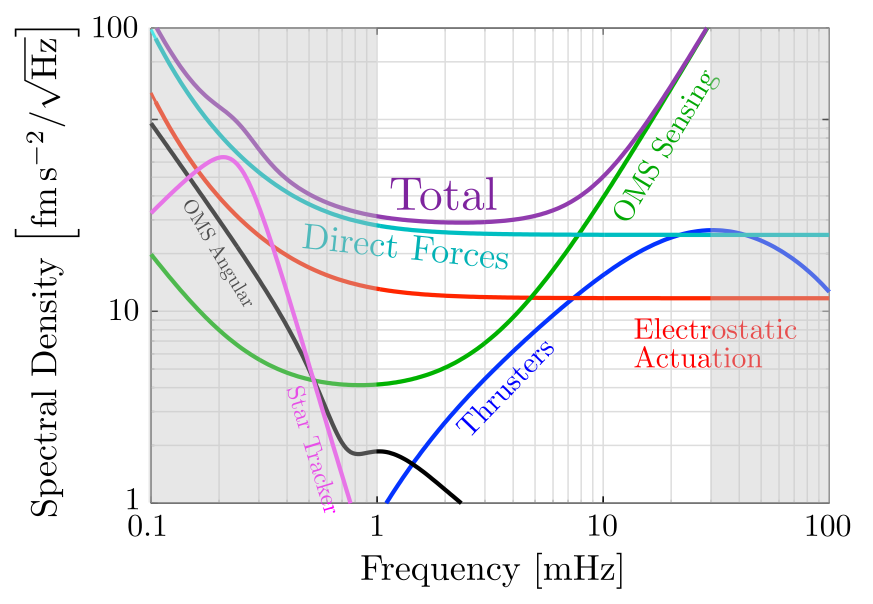
- Take 1 LISA's arm
  - Squeeze it to 38 cm
  - Fit into one spacecraft
  - Measure relative acceleration **Δ**a
    - Target is a factor 10 from LISA goals



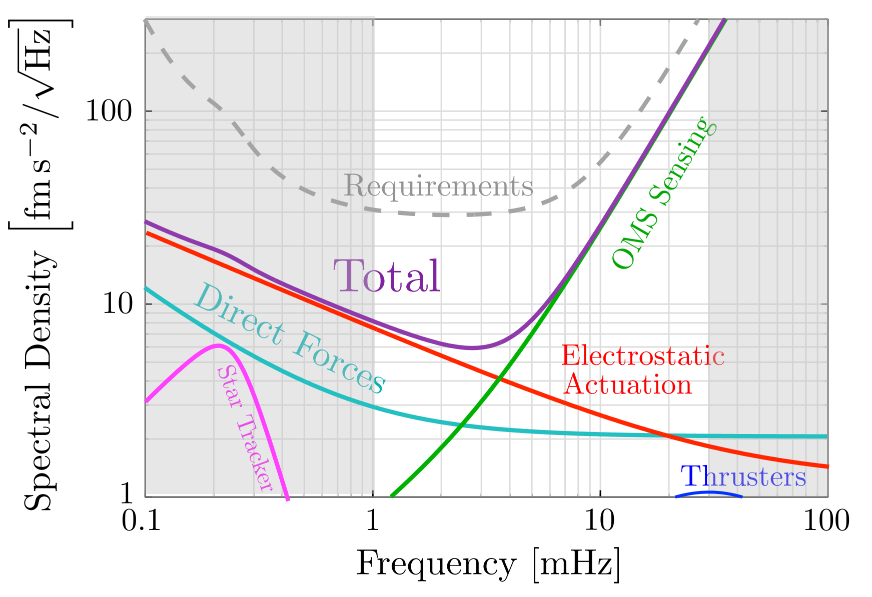
Instrument Performance

- Differential force measurement sensitivity:
  $\sim 1.3\times10^{-14}$ N/$\sqrt{}$Hz at 1mHz
- Platform free-fall quality:
  $\sim 1\times10^{-13}$ ms-2/$\sqrt{}$Hz at 1mHz
- Gradiometer sensitivity (~ Δa/d) requirement:
  $\sim 7.89\times10^{-14}$ s-2/$\sqrt{}$Hz at 3mHz
    - Current best estimate of mission performance shows a gradiometer sensitivity much lower at:
      $\sim 1.58\times10^{-14}$ s-2/$\sqrt{}$Hz at 3mHz
- But! LPF is NOT a GW detector!

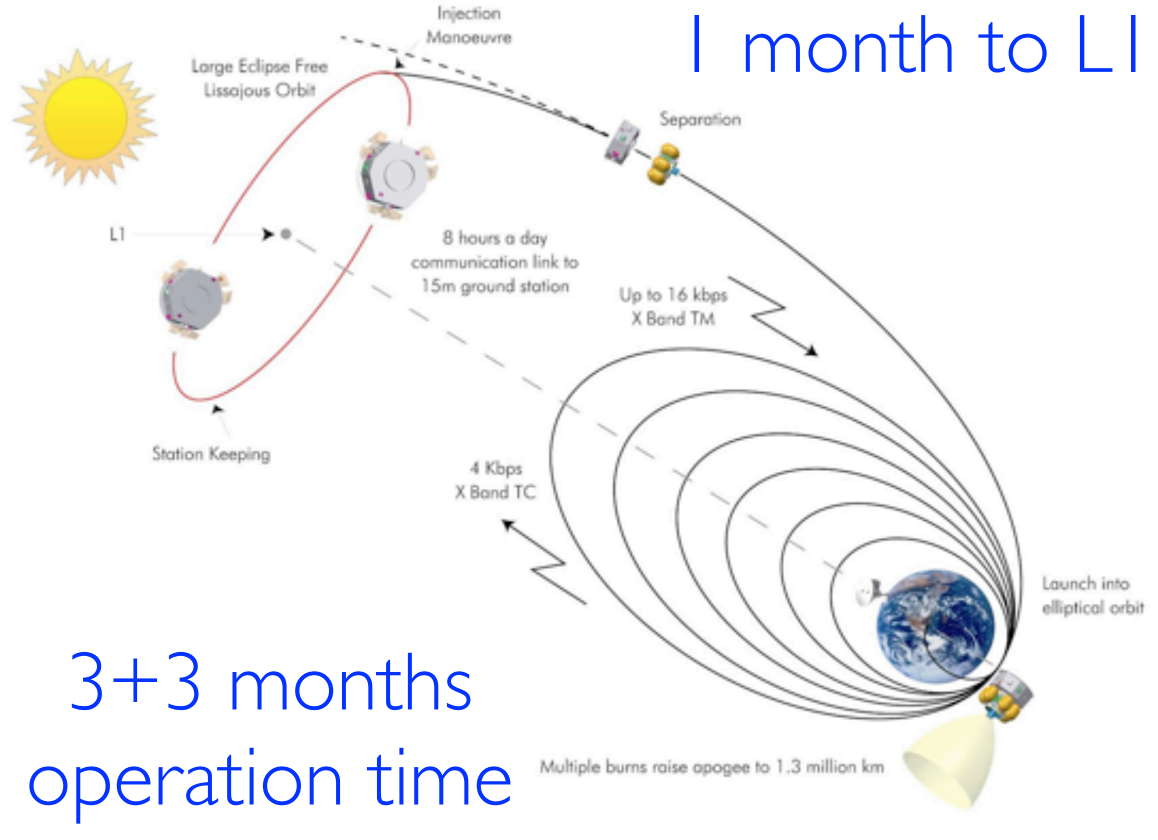




Top: mission requirement for noise in Δa
Bottom: current best estimate



LPF Orbit

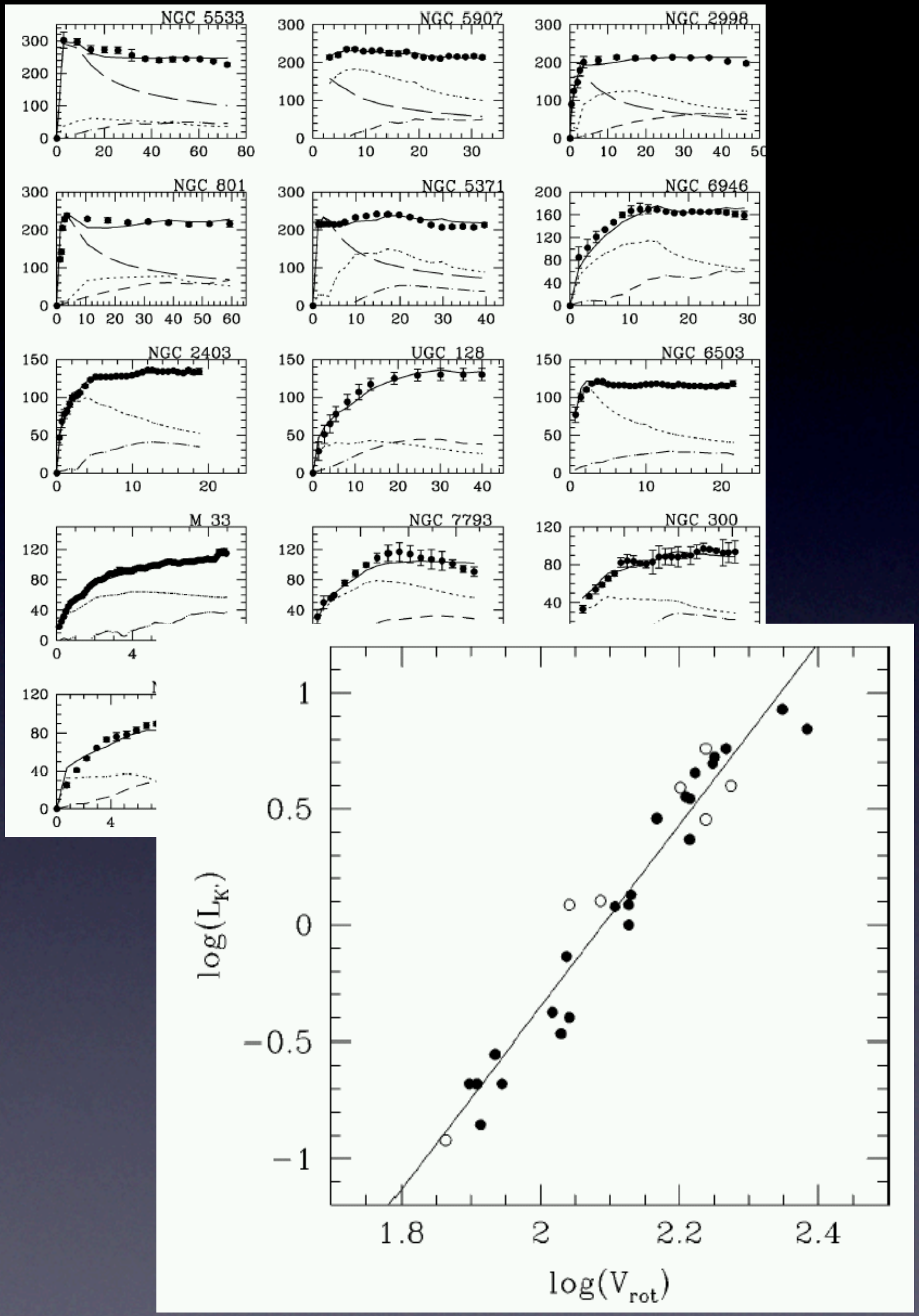


1 month to L1

3+3 months operation time

- The (Unique) Opportunity
  - The only high-precision calibrated gravity gradiometer for the next 10-20 years
  - ... ready to fly by the end of 2014 with a solid science case on its own...
  - ... along orbits (Lissajous around L1) that are excellent standpoints to go virtually anywhere in the Solar System

Dark Matter or...



- Appetizer: the problem of galactic rotation
  - Rotation curves are "flat" ~ Tully-Fischer (disagrees with Newton! ;-))
- Conventional explanation is that galaxies are surrounded by a halo of dark matter
- A more daring attack generated MOND:
  - a phenomenological formula to use when system acceleration falls below a0 ~ 10^{-10} m/s^2 (Milgrom 1983)
  - Successful in describing galactic rotation with no dark matter
  - TeVeS (Bekenstein 2004) embedded MOND as low-acceleration limit in a metric scalar-tensor-vector theory of gravity

Many field mechanisms, many MOND(s)

- The extension of Poisson equation is not unique. Many mechanisms are viable as low-acceleration limits of a GR "TeVeS-ian" scenario
- Ref. Magueijo and Mozzaffari, PRD, 85, 043527 (2012)

$$a_0 \simeq 10^{-10}\mathrm{m/s^2}$$

$$k \simeq 0.03$$

Type	Assumptions	Newtonian Poisson	MONDian Poisson
I	$\Phi = \Phi_{\rm N} + \phi$	$\nabla^2\Phi_N = 4\pi G\rho$	$\nabla\cdot\left(\mu_{\rm I}\left[\frac{k}{4\pi}\frac{\lvert\nabla\phi\rvert}{a_0}\right]\nabla\phi\right) = kG\rho$
II			$\nabla^2\phi = \frac{k}{4\pi}\nabla\cdot\left(\mu_{\rm II}\left[\frac{k^2}{(4\pi)^2}\frac{\lvert\nabla\Phi_{\rm N}\rvert}{a_0}\right]\nabla\Phi_{\rm N}\right)$
III	Unbreakable nonlinear Φ	$\nabla\cdot\left(\mu_{\rm III}\left[\frac{\lvert\nabla\Phi\rvert}{a_0}\right]\nabla\Phi\right) = 4\pi G\rho$	

$$\mu_{\#}(L) \underset{L\gg1}{\rightarrow} 1 \quad \mu_{\#}(L) \underset{L\ll1}{\rightarrow} \begin{cases} L & \# = \mathrm{I,\ III} \\ L^{-1/2} & \# = \mathrm{II} \end{cases}$$

Saddle points

- A direct test of modified gravity is difficult: the gravitational acceleration in the solar system is orders of magnitude above the MOND threshold a_0
  - at L1, the background acceleration is ~6×10^{-3} m/s^2
- If we look for the places where the Newtonian forces are 0 along the axis between two massive objects we shall see the non-Newtonian effects

$$r_s \quad | \quad \mathbf{F}^N(r_s) = \mathbf{0}$$

$$r_s \simeq R_{\odot\oplus}\left(1 - \sqrt{\frac{m}{M}}\right)$$

- These places are called "saddle points" (SP)
- They are no Lagrangian points (L1, L2, etc): SPs are not stable locations for a spacecraft
- There must exist "transition manifolds": ellipsoids of stronger MOND regime around saddle points, in polar coordinates:

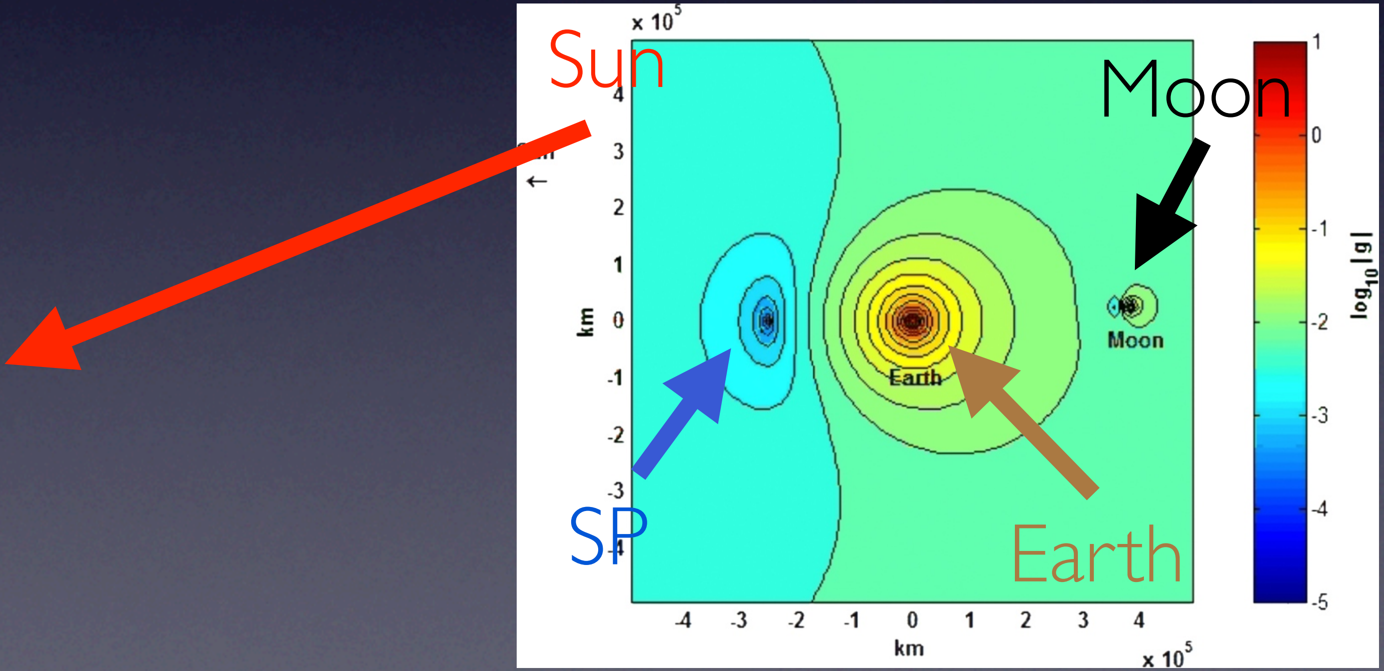
$$r^2\left(\cos^2\psi + \frac{1}{4}\sin^2\psi\right) = r_0^2$$

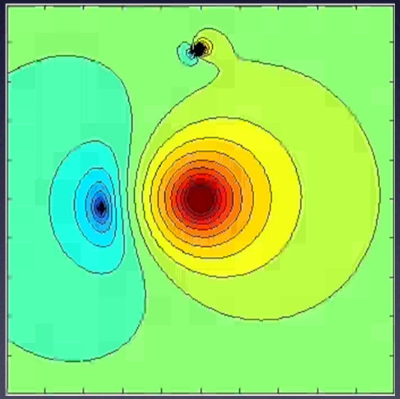
Characteristic MOND length: $r_0 = \dfrac{16\pi^2 a_0}{k^2 A}$

Tidal stress at SP along Sun-Earth line: $A = 2\dfrac{GM}{r_s^3}\left(1 + \sqrt{\dfrac{M}{m}}\right)$

Gravitational SPs in the Sun–Earth–Moon System

- In the Sun-Earth-Moon system, there are two SPs:
  - The "Earth-Moon SP" is hugely perturbed by the Sun (it's more a "Sun-Moon SP")
  - Much less position variability of Sun-Earth SP, easier mission planning!





Best orbit strategy

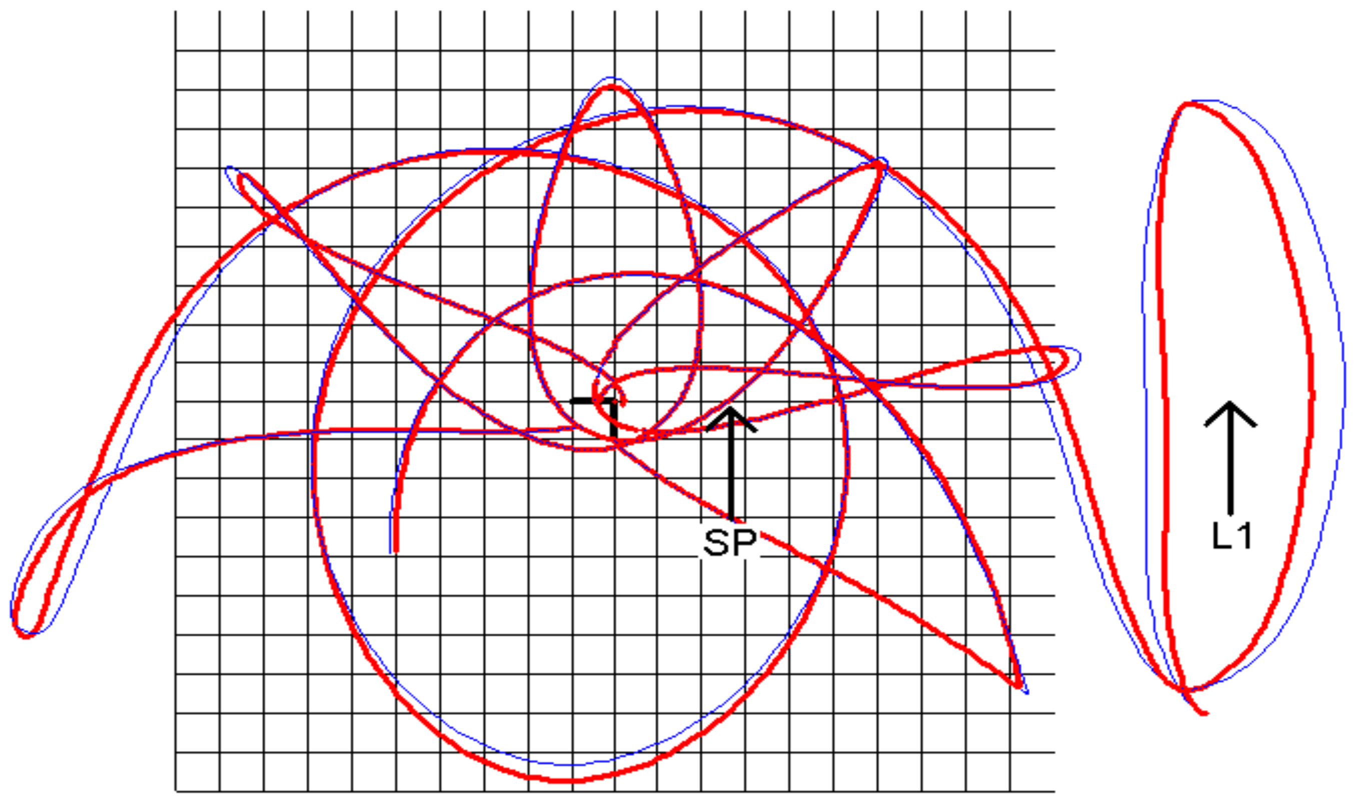
- Starting from a fixed Lissajous orbit
  - Adding manoeuvres after the first passage
  - Difficult to control speed when reaching the SP
  - Even if the spacecraft stays in an elliptic orbit
    - Such Earth-centred orbits tend to be unstable
    - Even if stable, hard synchronisation with SP rotation
  - Results:
    - No real good case has been found

- Starting from the SP, looking for double passages
  - Fix a date for first SP rendez-vouz
  - Simulation of trajectories from the SP
    - which one comes from L1 libration orbit?
    - which libration orbits are reachable?
  - Enables identification of good directions
  - merging with libration orbit is obtained by perturbing the trajectory and evolving backwards in time
    - several orbits found per initial condition!

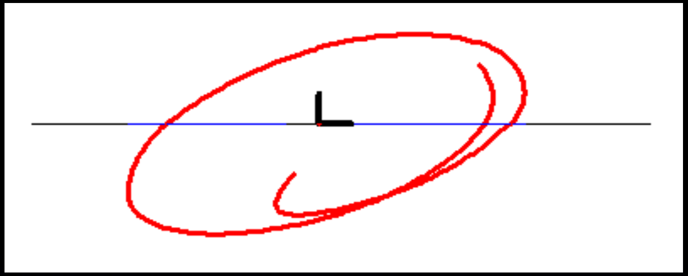
Orbit 1. To the SP from a Lissajous orbit

- Starting from a typical ROCKOT or VEGA launchers case
- Adding manoeuvre during the Lissajous orbit

- Resulting performance:
  - Miss distance ~ 130 km
  - Transfer time ~ 512 days o(1 year)



Orbit 2. Several SP passages starting from the SP



Major/minor axes of the libration orbit:
out of ecliptic: 417,000 km
in plane: 775,000 km

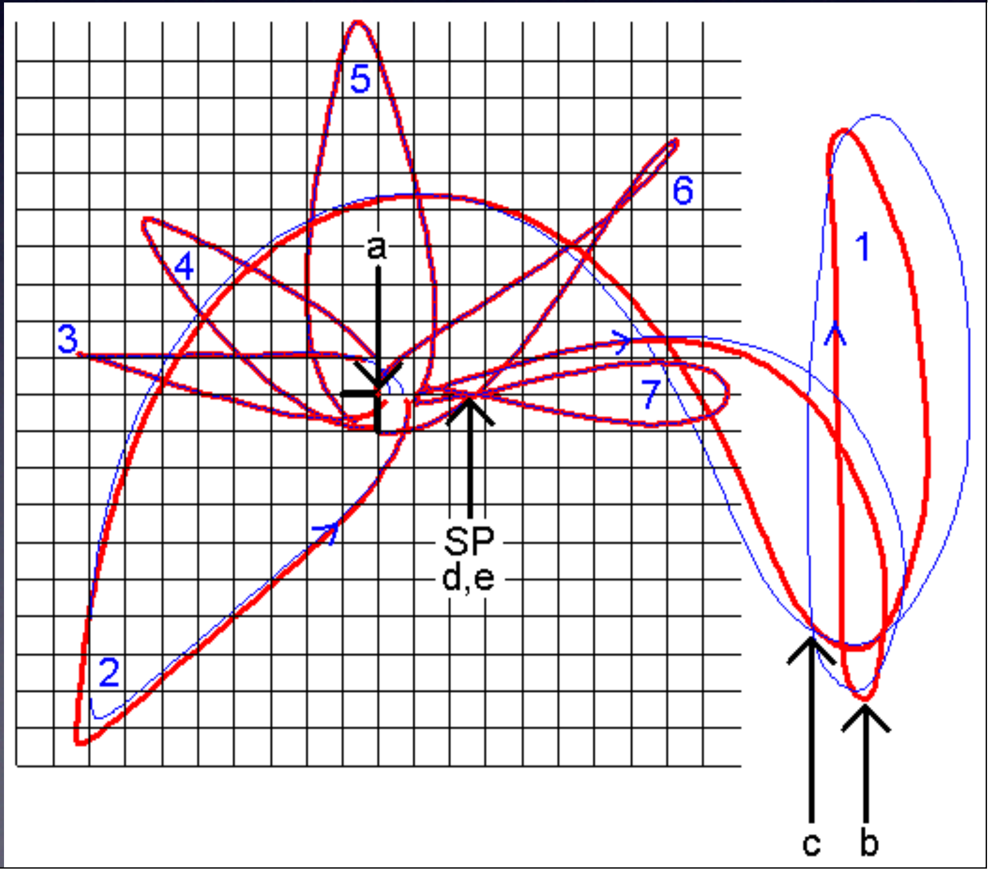
a. Launch 2013.02.24
inclination = 57.6°
perigee altitude = 322 km

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).

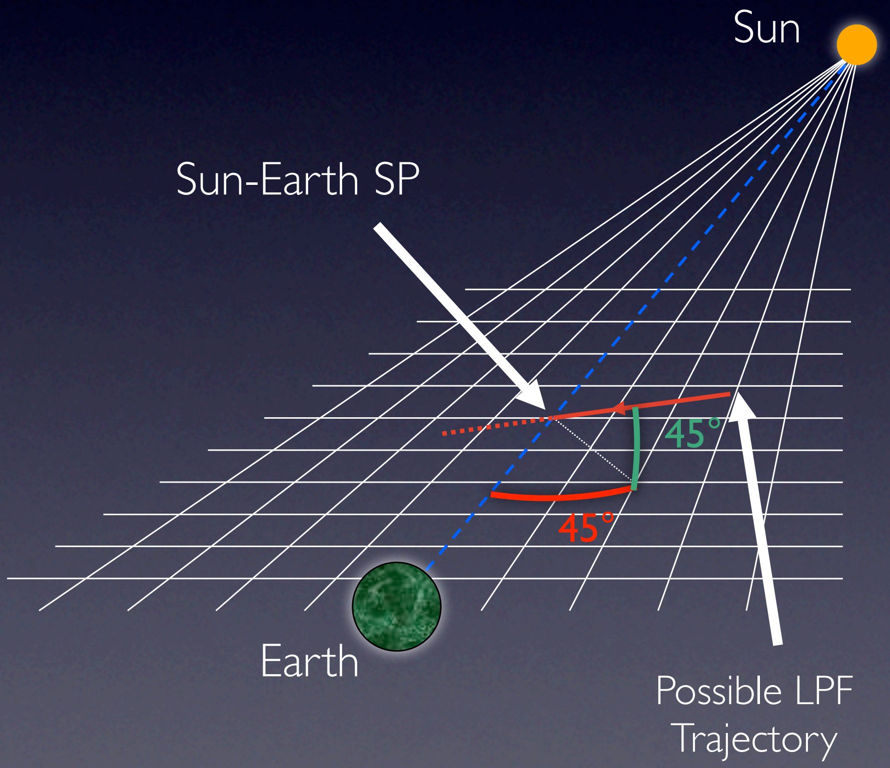
e. Reaching the SP for the second time, 582 days after launch (39 days after the first passage).



MOND/TEVES Anomalous Gradients

- Numerical evidence of anomalous gravity gradients that LISA Pathfinder will see
- MOND gradients for the 3-body problem in 3D:
  - Equation for ϕ solved for a cube volume containing the SP but large enough to get Newtonian at the boundary
  - Numerical methods yield cube volume with gradients at grid points (function of Sun, Earth and Moon position)
  - Representative LPF trajectory is propagated through the volume and the anomalous gradients are extracted at each point

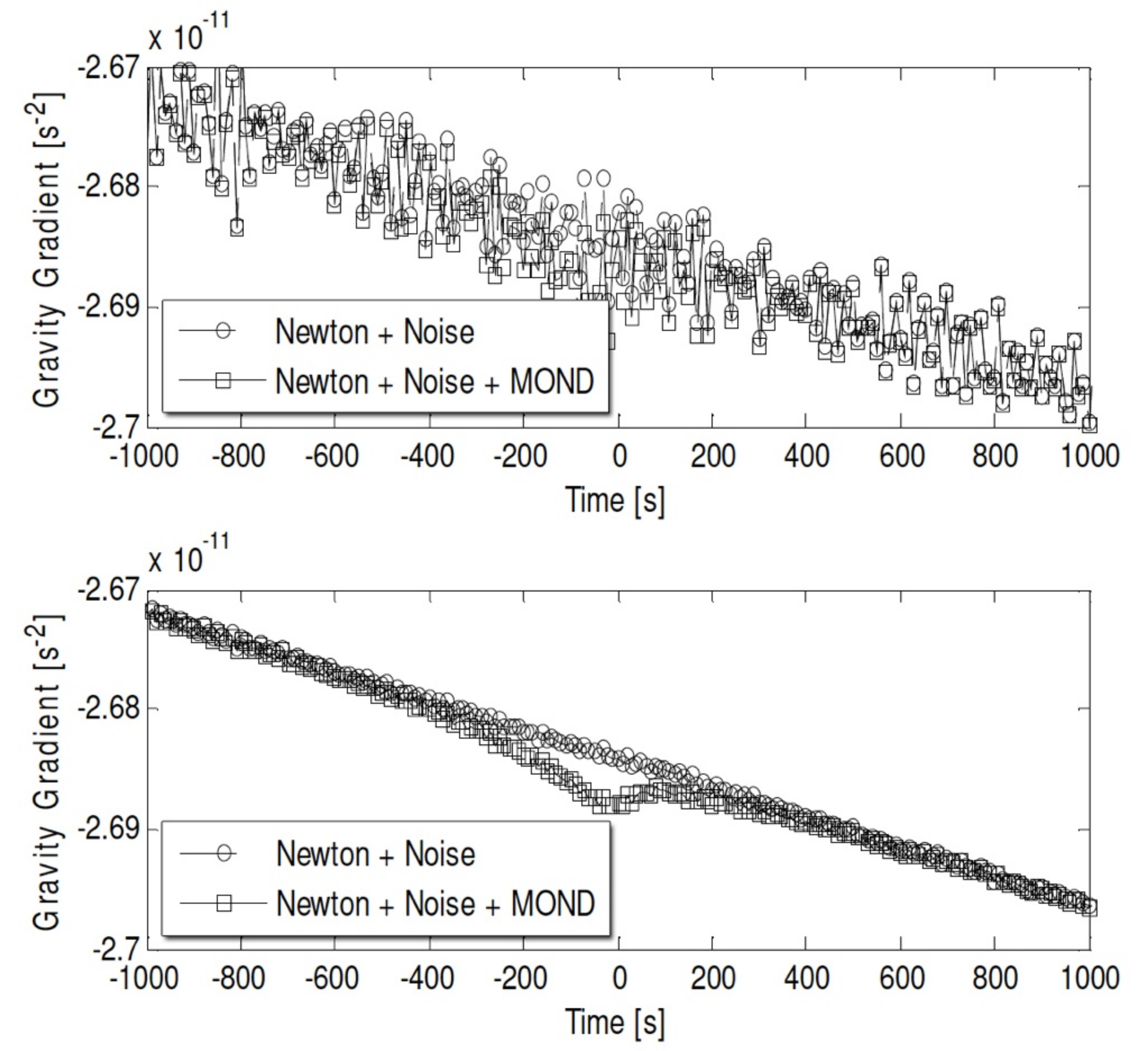
$$\omega_{ij} = \frac{\partial^2 \Phi}{\partial x_i \partial x_j}$$



The strategy of LPF

- After the nominal LPF mission, the spacecraft is navigated from its L1 orbit to an orbit which passes through the bubble around the SP
- We monitor the Newtonian gravity gradient as measured by the drag-free test masses
  - Any deviation from Newtonian theory will be evident!

Expected gradient signal at passage through the SP bubble. Top: raw signal with and without MOND. Bottom: same as top filtered via 10-point moving average. [Trenkel (2010)]

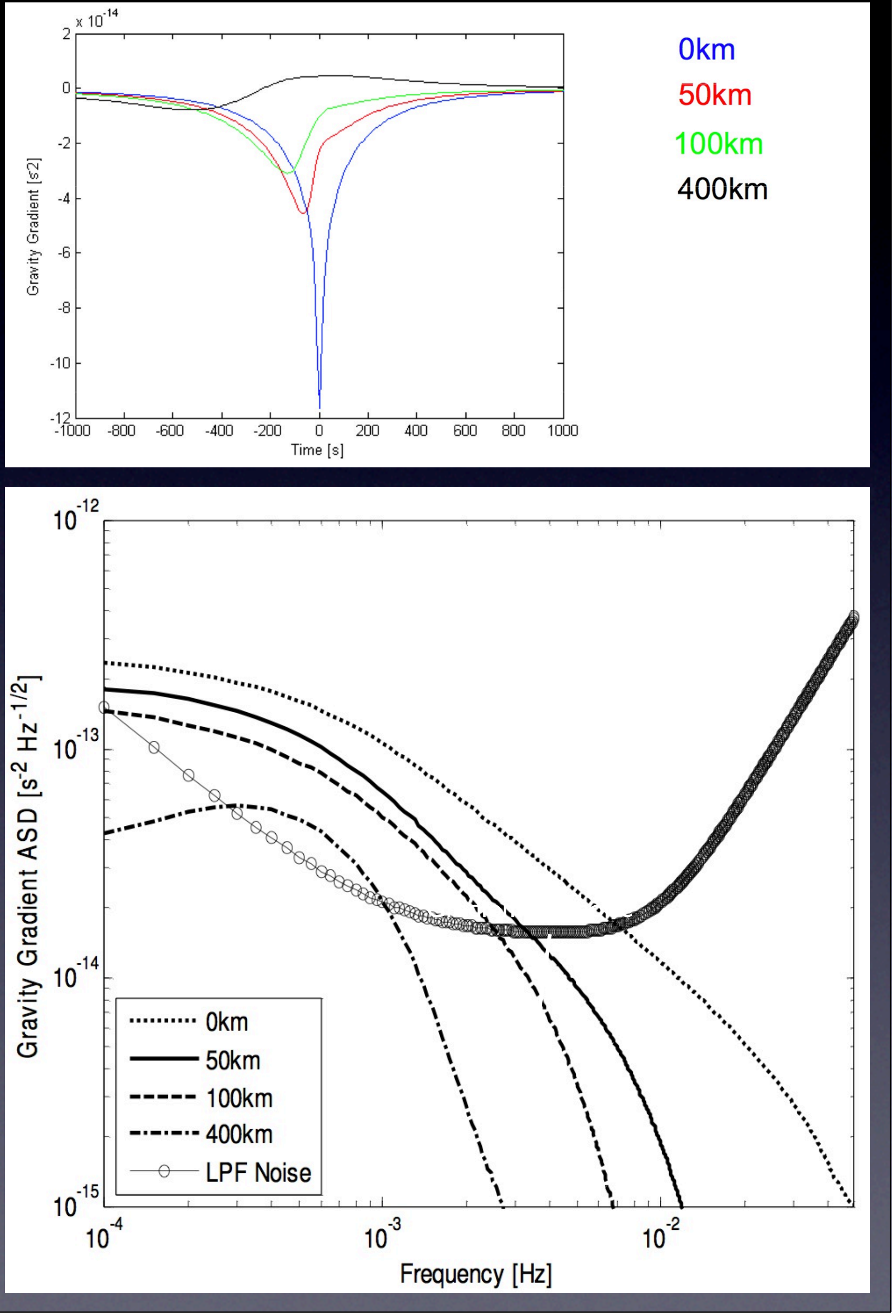


Signal Prediction

- The predicted signal as LPF passes through the SP bubble depends on several parameters:
    - v: Velocity of the spacecraft (typical 1.5 km/s)
    - b: Miss-distance from the SP
    - Transition function between the Newtonian regime and the MOND regime (“trigger” threshold)
    - MOND theoretical features
- Several papers have been published on the expected signal strengths
    - Magueijo (2009), Trenkel (2010), Magueijo (2011), Galianni (2011)...

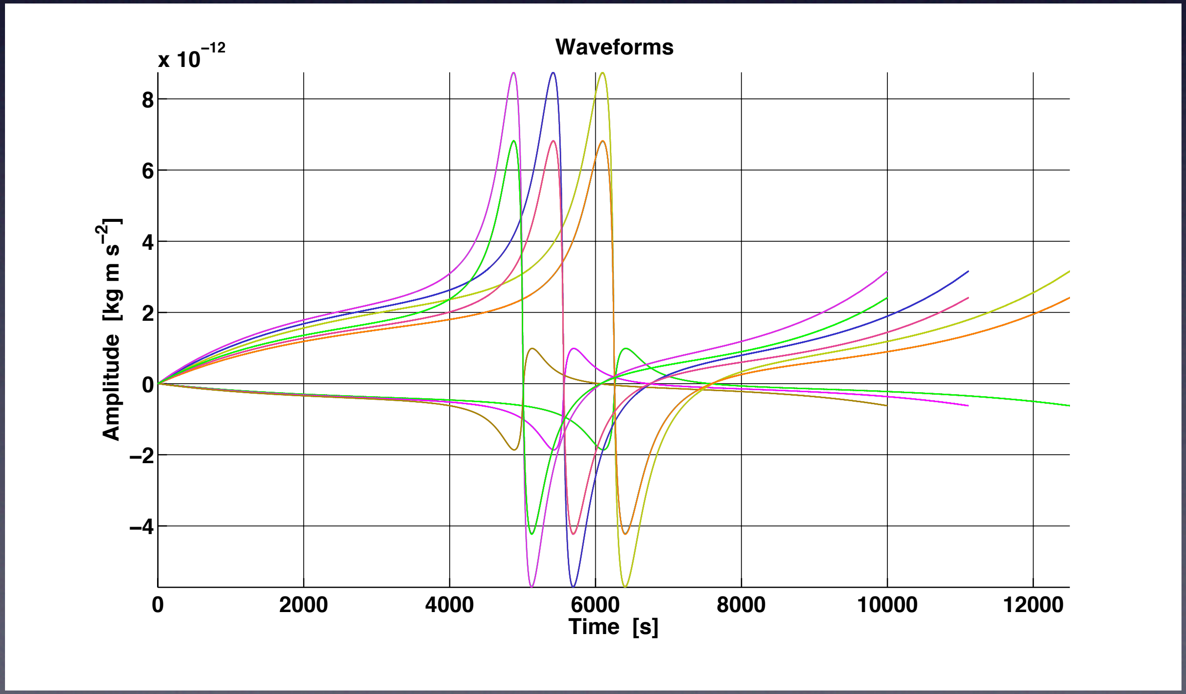
$$h(t) = n_i n_j \omega_{ij}\left[\mathbf{b}+\mathbf{v}t, a_{\mathrm{trig}}, k, \ldots\right]$$

Signal strength for various miss distances, as timeseries(top) and spectrum (bottom)



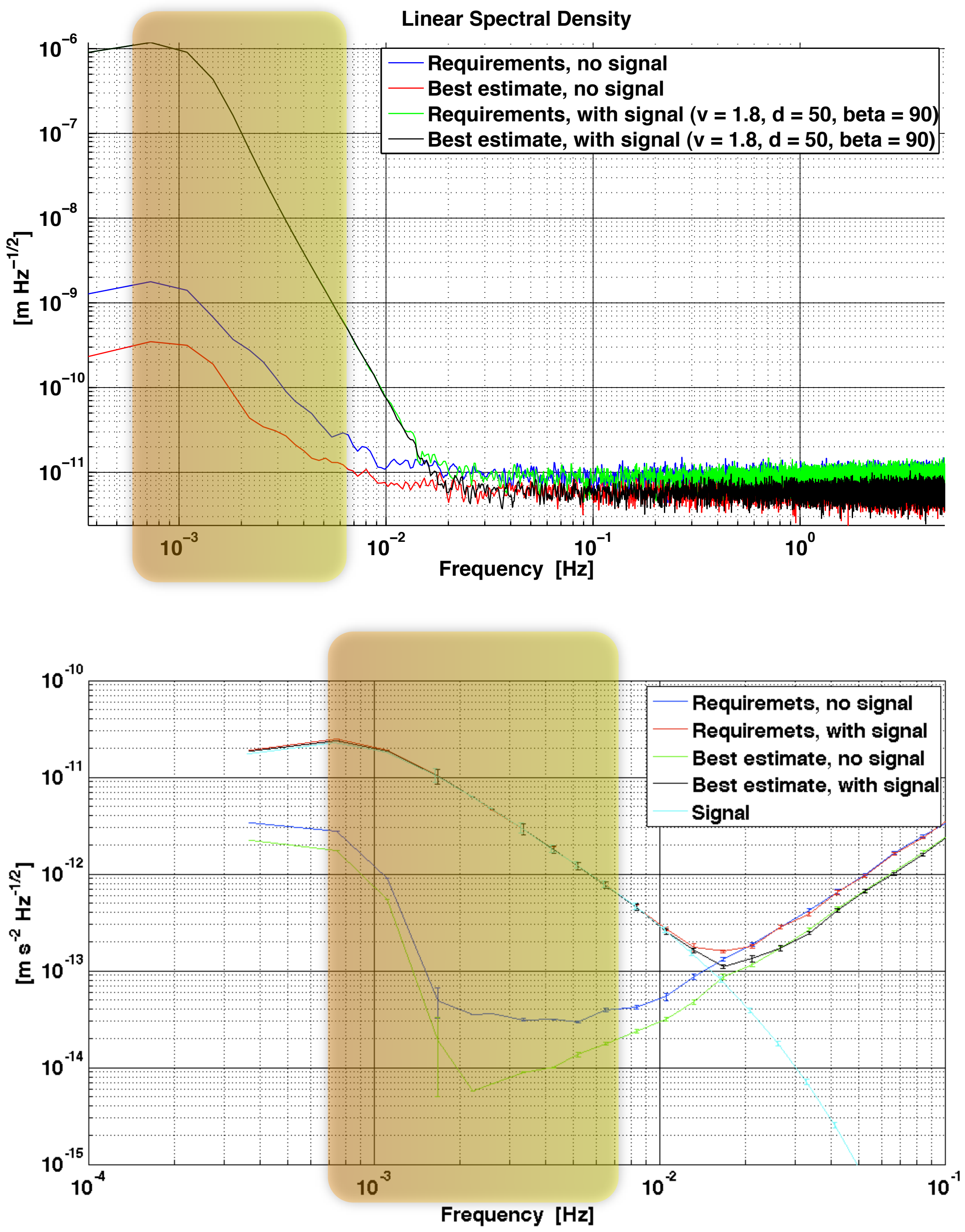
Templates vs noise

- Sum of the potential gradients at each point of the trajectory projected to the sensitive axis of LPF (x-axis)
  - Signal can be interpreted as an additional force acting on the Test Mass
- Templates can be generated as function of speed and SP impact parameter



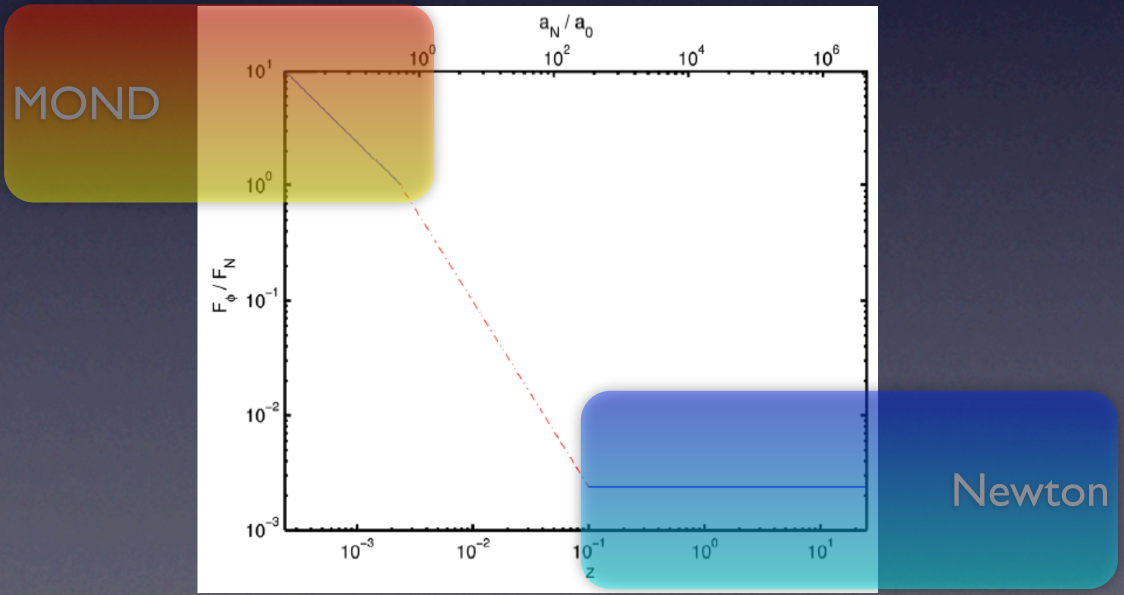
Displacement and acceleration

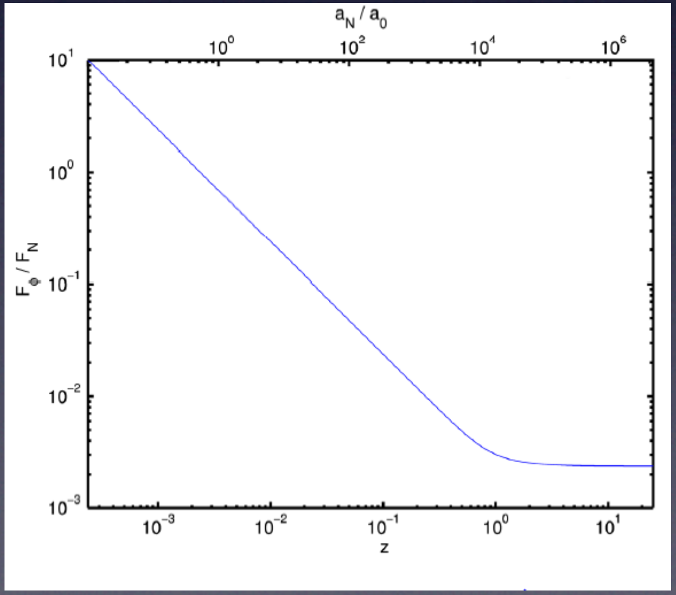
- The MOND signal is unmistakable!
  - MONDian signal is roughly at 1/1000 s = 1mHz, excellent for LPF (it calls for testing! ;-))
- Well above the LPF sensitivity, even at lowest performance!



Constraining the MOND free function

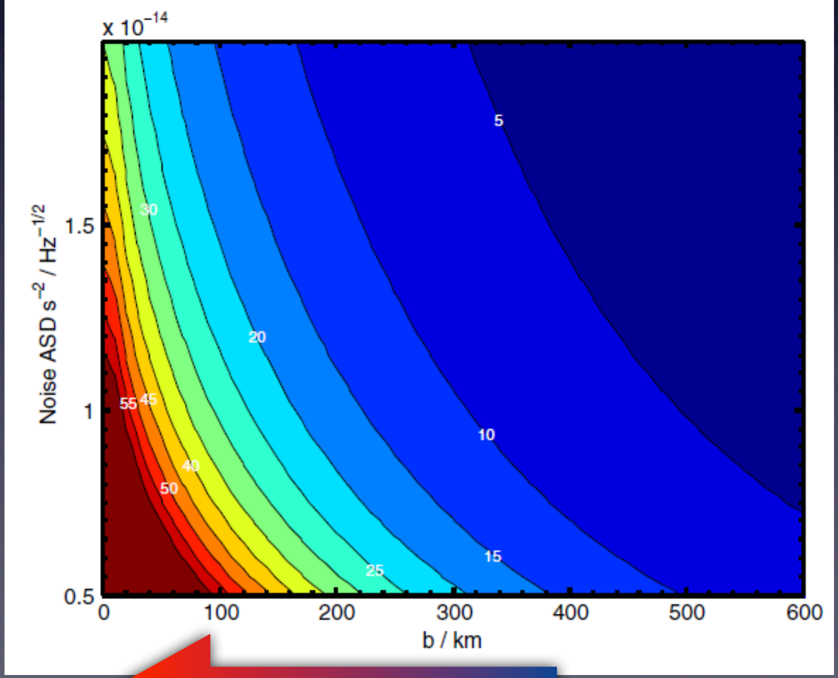
- Newtonian/MOND μ free function has distinctive behaviour for $a \ll a0$ (MOND is "active") and $a \gg a_0$ (Newtonian physics, gradient is DC)
  - The area in between hosts a scaling function that must be "credible" and "simple"
  - Notice that Type III ("nonlinear" MOND) can always be contrived to avoid signal
- Plot the strength of the extra field vs the Newtonian force as function of a/a_0

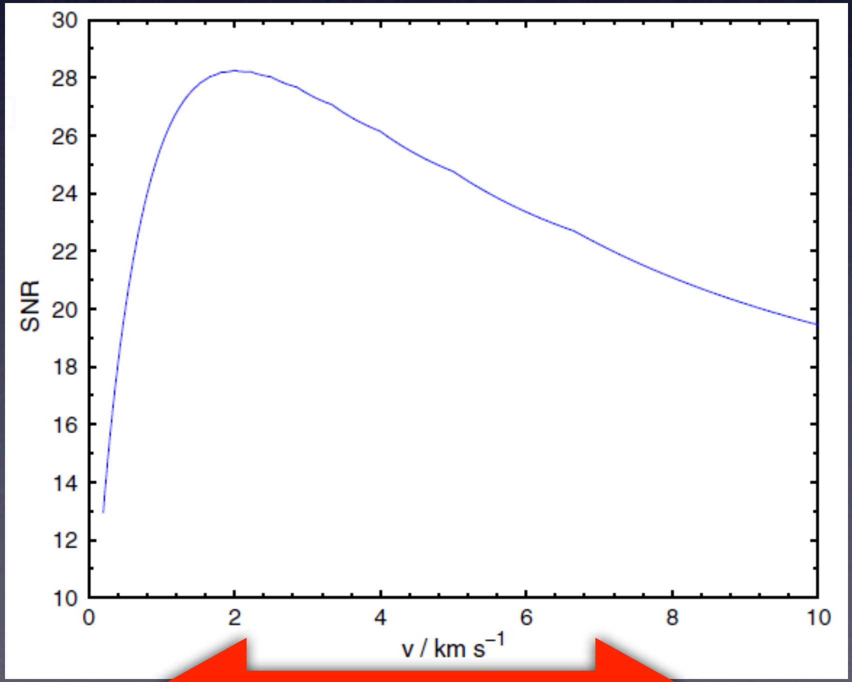




LISA Pathfinder Gradient Sensitivity

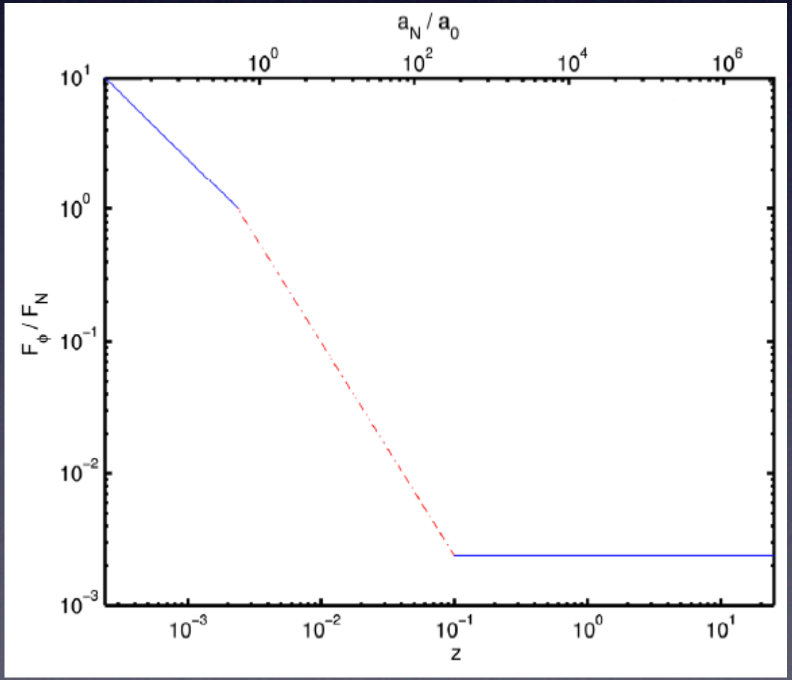
- To reduce the families of **μ** and be in the intermediate “triggered” regime is crucial to be
    - close to the MOND bubble (<400 km)
    - in high SNR (>10)
- Dependence on impact parameter, noise (and speed)

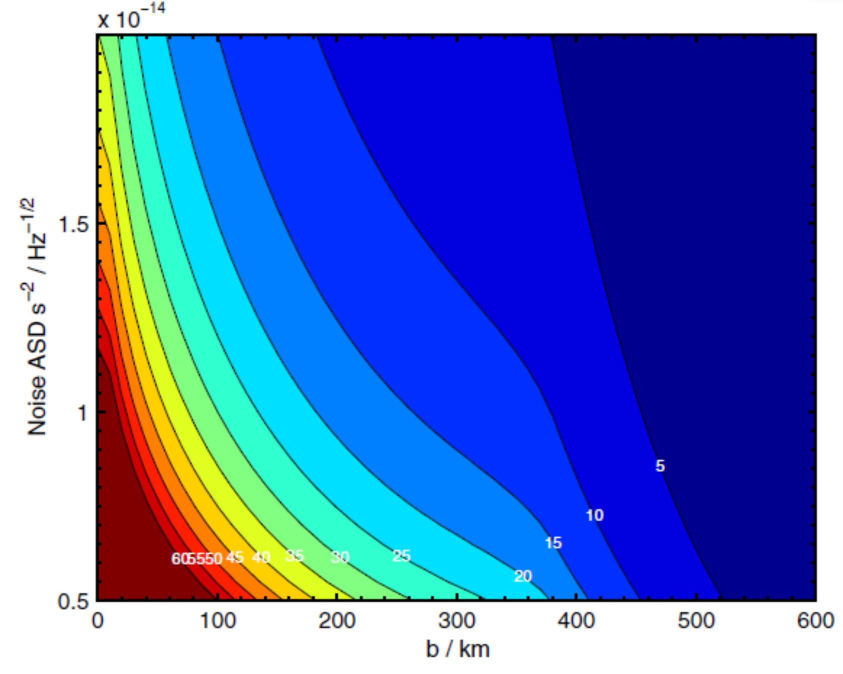




LISA Pathfinder Gradient Sensitivity

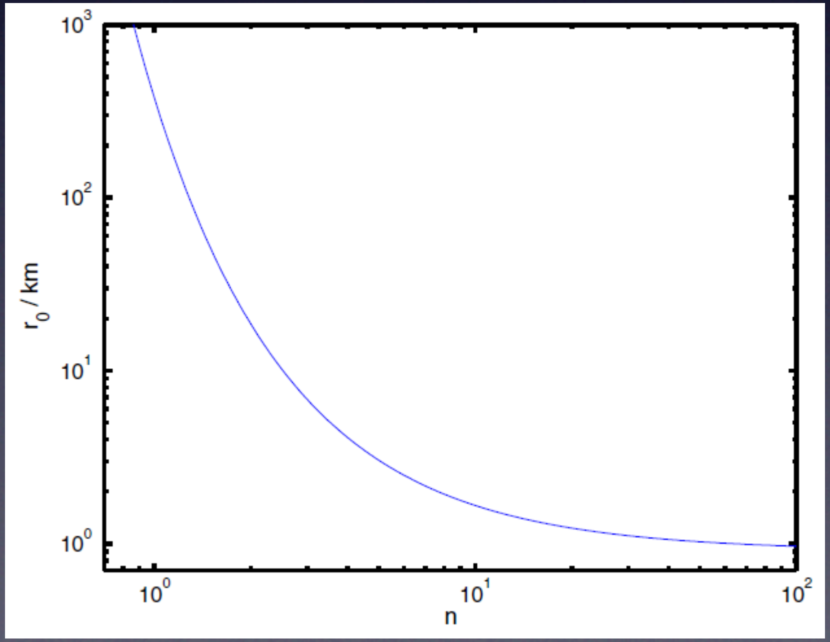
- Type II transfer functions, SNR = 1 contour curves for a worst-case of an "exponential" falloff
  - The SNR is not worsened, a null test would be credible!

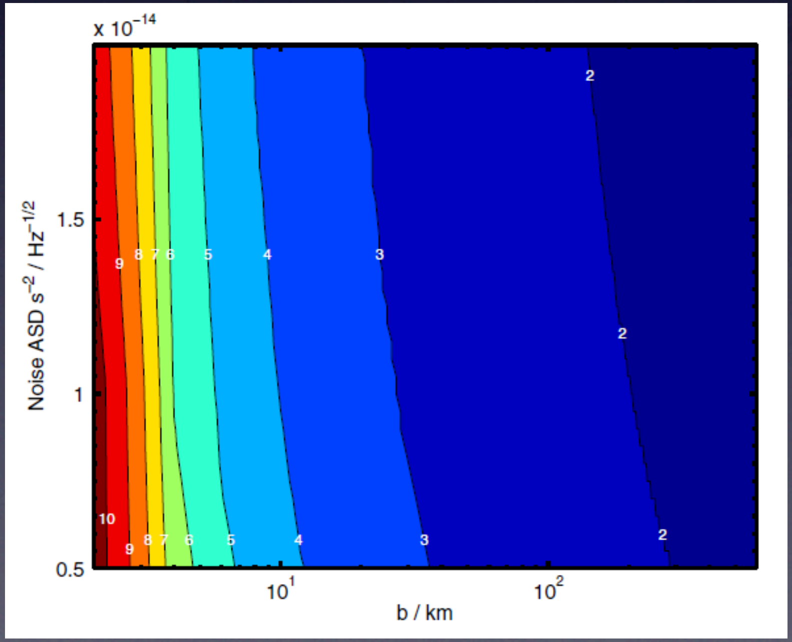




LISA Pathfinder Gradient Sensitivity

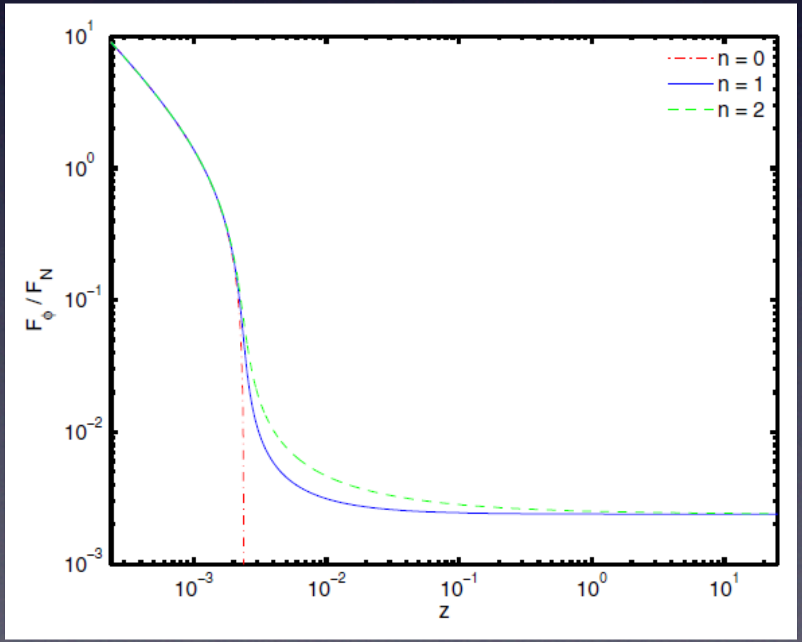
- Null result for type II transfer functions
  - Modelled the link with extra 1/n power
  - For n≠1 the function becomes very complicated to give SNR = 1 (the case of detection)

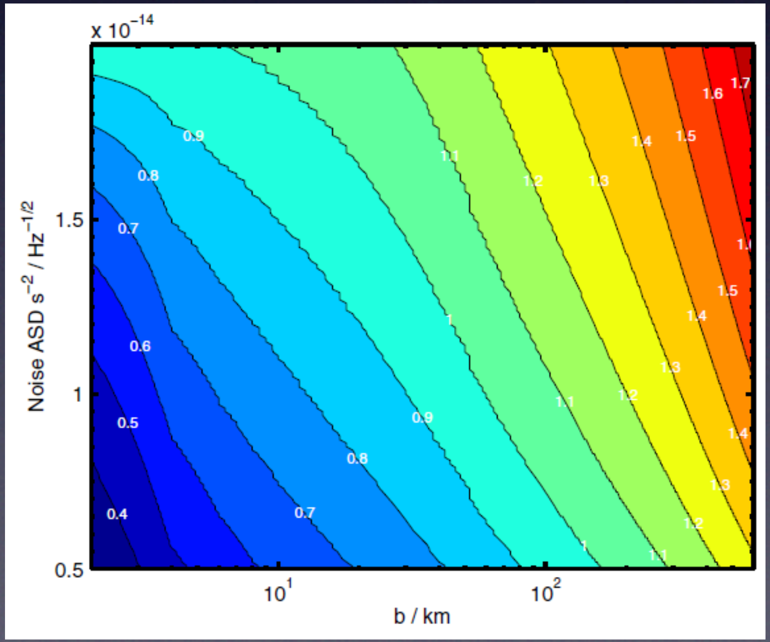




LISA Pathfinder Gradient Sensitivity

- Type III transfer functions parametrized with exponent "n"
  - Much looser bound (nonlinearity is "authorized")
  - 1 sigma null detection: upper limit on n





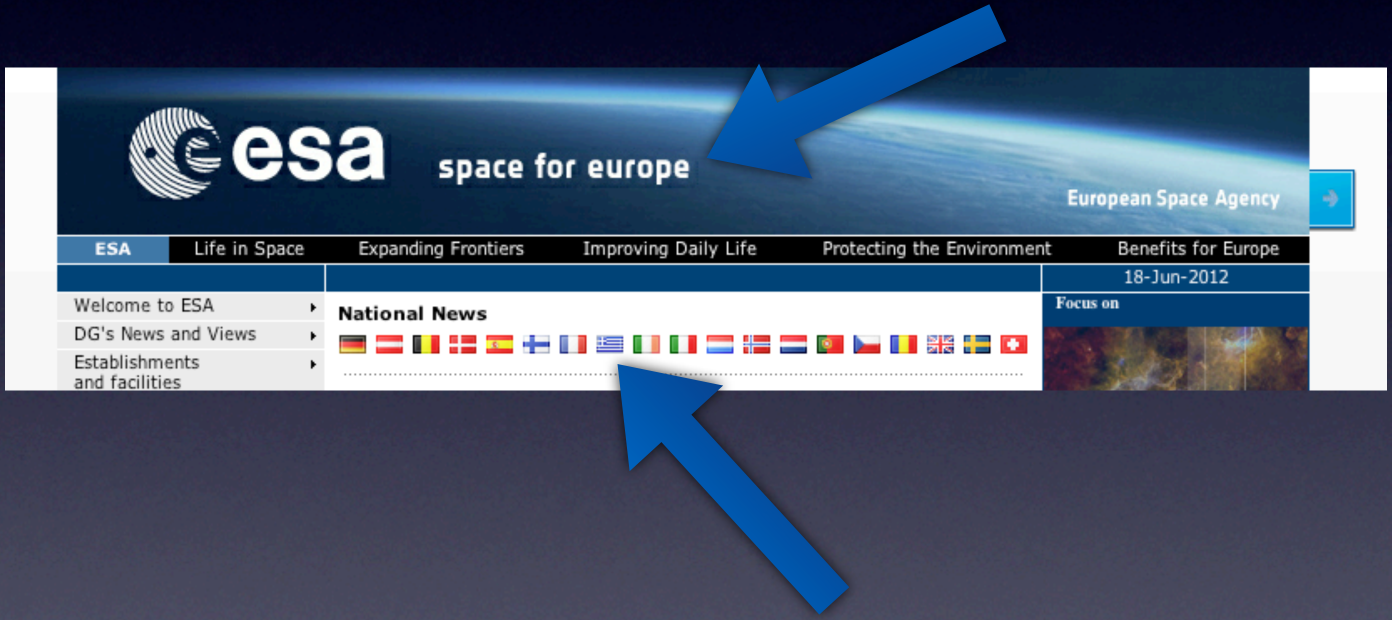
Conclusions

- LISA Pathfinder will be the first mission with the specific goal of demonstrating geodesic motion of a free-particle
- This outcoming physical acceleration and instrumental portrait is crucial for any interferometer-dragfree-micropropulsion based GW observatory
- LISA Pathfinder offers a unique opportunity to fly a sensitive gravity gradient instrument through the Sun-Earth Saddle Point
  - Very timely given evolving dark matter search programs
  - A positive result will be of enormous and far reaching importance
  - A null result will be conclusive for type I and II transfer functions
  - Type III transfer functions will be heavily constrained

Acknowledgement and References

- Many thanks to:
  - Tim Sumner, Christian Trenkel, Steven Kemble, Emilien Fabacher, Joao Magueijo, Ali Mozzaffari, Paul McNamara, Natalia Korsakova, Martin Hewitson
- LPF science status
  - http://iopscience.iop.org/0264-9381/26/9/094001/
- LPF and MOND/TeVeS
  - http://arXiv.org/abs/0912.0710

Questions?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