UNIVERSITÉ de Liège

ADVANCED CONCEPTS TEAM

# Pioneer anomaly: Implications for LISA?

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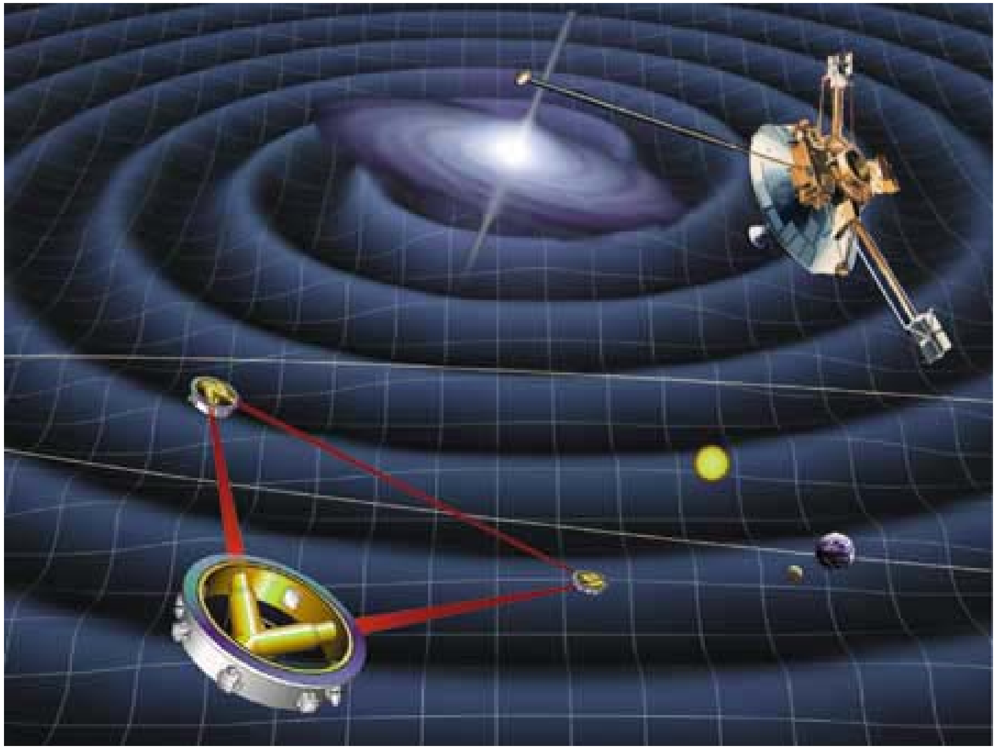

# Overview

1. The Laser Interferometer Space Antenna
2. The Pioneer anomaly as a blueshift
3. The anomaly and LISA
4. Implications for LISA
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        - Inside the sensitivity band
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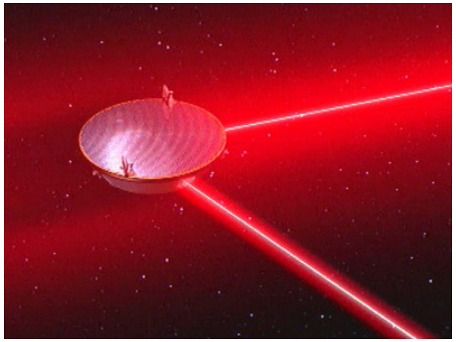
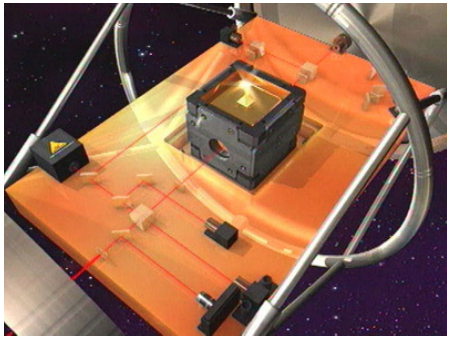
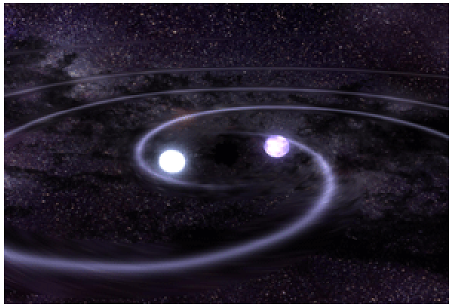
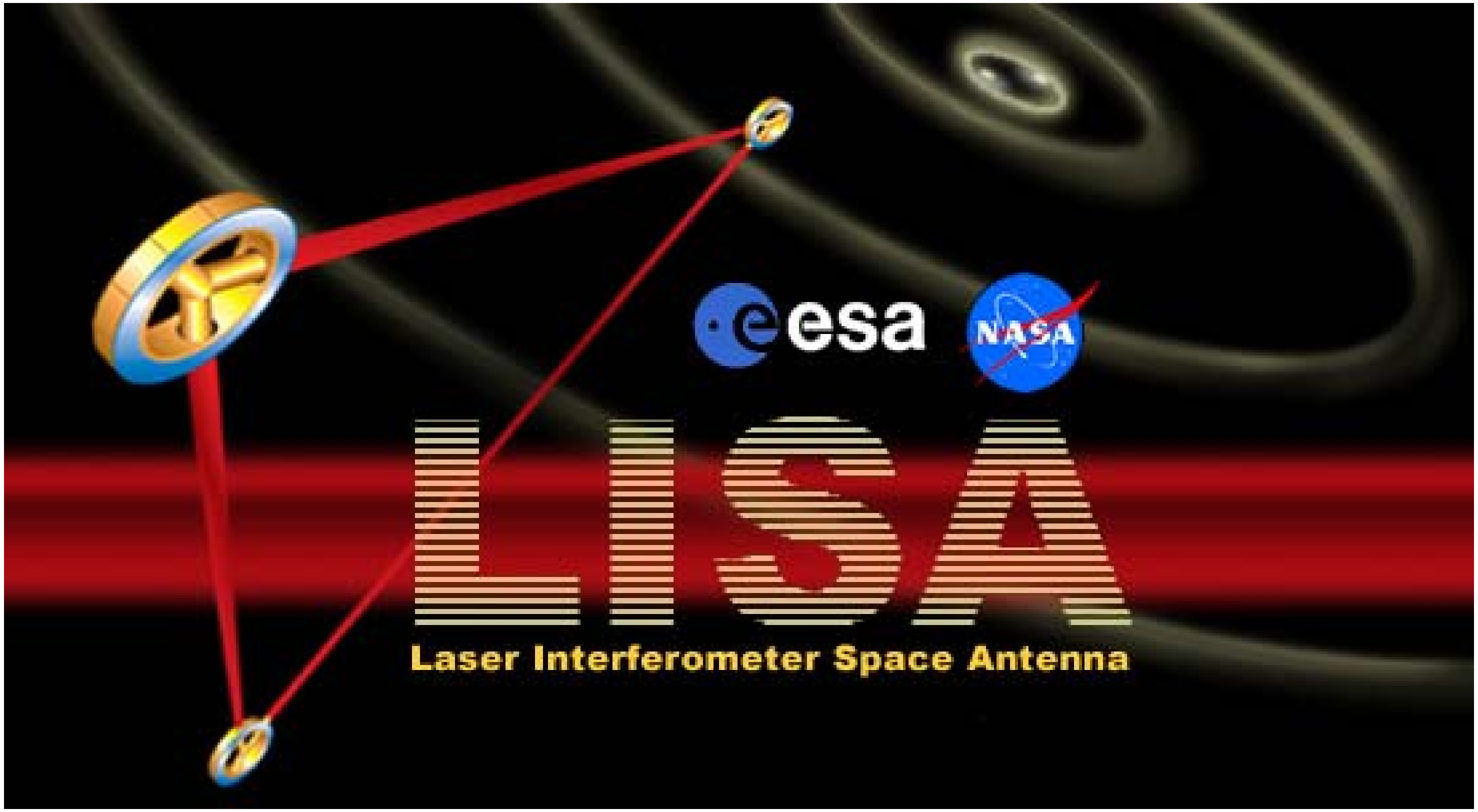
        - Fixed arm lengths
        - Effects of the orbital motion
5. Conclusions







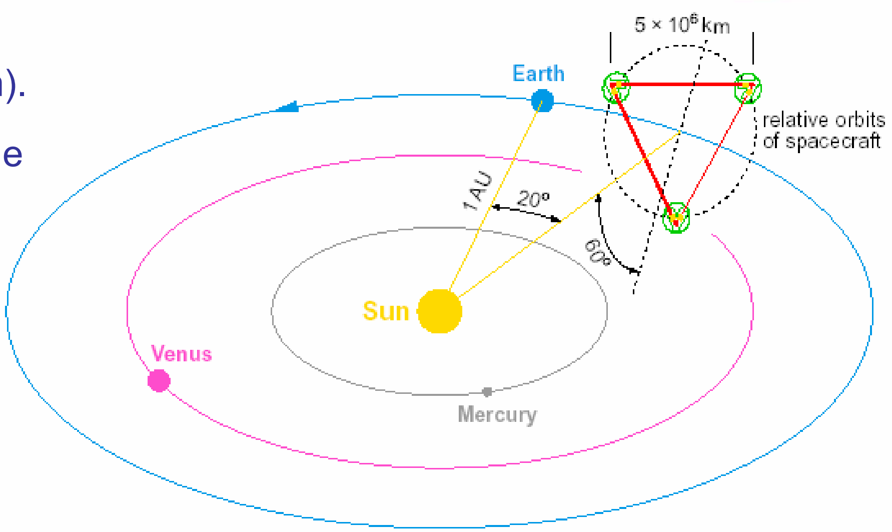

esa
NASA
LISA
Laser Interferometer Space Antenna

# Laser Interferometer Space Antenna (1/2)

## Mission overview

- What is the Laser Interferometer Space Antenna (LISA)?
  - ✓ ESA-NASA mission aimed at a launch in 2014.
  - ✓ First dedicated space-based gravitational wave observatory.
  - ✓ Duration of 10 years.

- Flight configuration and orbits of the spacecraft
  - ✓ 3 identical spacecraft forming an equilateral triangle (arms of 5 millions km).
  - ✓ Earth-trailing orbit Centre of the triangle follows the Earth orbit, 20° behind it.



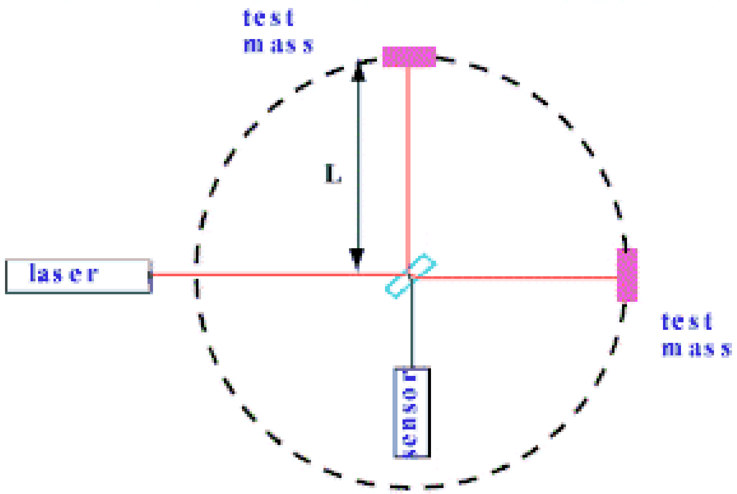

- Characteristics of spacecraft :
  - ✓ Distance measurement made by an infrared laser with respect to proof masses.
  - ✓ Drag-free system to shield the proof mass from perturbations. → Proof masses' trajectory determined only by gravity

# Laser Interferometer Space Antenna (2/2)

## GW interferometric measurement

- Gravitational waves detected as modulation of the distance between spacecraft by picometer interferometry.
- Intereferometry principles

1. A laser beam is split and sent along two arms.
2. The divided beams are reflected at the end mirrors.
3. The phases of returning signals are compared at the sensor to detect change in the arm length.




- The intensity of the fringe is monitored to detect the changes in the difference in the arm lengths.

# The Pioneer Anomaly as a blueshift

The Pioneer Anomaly as a blueshift (1/4)

# Problems with a real force

• Simplistic model of the Pioneer anomaly: Modified gravitational potential

$$V(r) = -\frac{\mu_\odot}{r} - a^* r\,, \quad a^* = 9 \times 10^{-10}\,\mathrm{m/s^2}$$

• But constraints from planetary orbits (Anderson et al. Ap.J. **448** (1995) 885) yield (using $M_\odot$ from best fit of inner planets):

$$a^*|_{\mathrm{Uranus}} \lesssim 1.3 \times 10^{-11}\,\mathrm{m/s^2}\,, \quad a^*|_{\mathrm{Neptune}} \lesssim 6.5 \times 10^{-13}\,\mathrm{m/s^2}$$

Planetary constraints are two orders of magnitude smaller than Pioneer anomaly.

• Anomaly seen in *both* Pioneer 10 and Pioneer 11 data at Neptune distance → acceleration could only be realised by mass-dependent violation of WEP (in particular cannot be modelled by a Yukawa force).

Blueshift models are attractive because they satisfy planetary constraints by construction.

• However, more contrived force models are also successful (Jaekel, Reynaud, gr-qc/0410148).

## The Pioneer Anomaly as a blueshift (2/4)

## **Blueshift models**

- Models of the Pioneer anomaly as a blueshift typically rely on the observation $a^* \approx cH$ , $H$ = Hubble constant = 71 km/sMpc.
- Two examples:
  - ✓ Rosales, arXiv:gr-qc/0401014, arXiv:quant-ph/0501041:
    Adiabatic change of phase of light in expanding universe.

    (Open-path Berry phase acquired by photons.)

  - ✓ Ranada, Found.Phys. **34** (2005) 1955, arXiv:gr-qc/0403013:
    Effective acceleration of time due to time-dependent homogeneous cosmological background potential.

    (Time dependence of the local metric leads to an acceleration of the time coordinate, also within the expression for the phase of a wave.)

**Universal and isotropic blueshift in the frequency of light.**

## The Pioneer Anomaly as a blueshift (3/4)

## Model of Rosales (2004), arXiv:gr-qc/0401014

- Expanding space time with Robertson-Walker metric

$$ds^2 = -c^2dt^2 + R(t)(dx^2 + dy^2 + dz^2)\,.$$

- Quantum state of a photon in this space time

$$|\Psi(t) >= \exp\left[-\frac{i}{\hbar}\int_0^t E_n(t)dt\right]\exp(i\gamma_n(t))|\Psi_n(\mathbf{R}(\mathbf{t})) >$$

- Berry phase given by $\gamma_n(C) = i\int_{\mathrm{R}(0)}^{R(t_f)} [< \Psi_n(\mathrm{R})|\nabla\Psi_n(\mathrm{R}) >]\cdot d\mathrm{R}$
- Wavefunction of a photon

$$A_\mu = Ne_\mu \exp i[\omega_0(1 + 2Ht)t - kR(t)z]\,,\ \text{where}\quad H \equiv \dot{R}/2R$$

Caveat: Description of open-path Berry phase might require additional gauge potential (Pati, Annals Phys. **270** (1998) 178). → Blueshift would become zero.

Our baseline model because blueshift does not affect gravitational waves (much lower frequency → adiabaticity does not hold).

## The Pioneer Anomaly as a blueshift (4/4)

### Magnitude

- At first order in v/c, blueshift along the light path given by

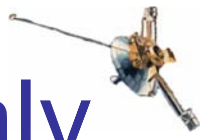
$$\frac{1}{\nu}\frac{d\nu}{dt} = -\frac{a_p}{c} \simeq 3 \times 10^{-18}/\mathrm{s}$$

$$\frac{\Delta\nu^*}{\nu} = -\frac{a_p}{c}\,t$$

( Expression similar to the redshift of a photon travelling in a homogeneous gravitational field, $\Delta\nu/\nu = gt/c$ .)

- Anomalous Doppler shift proportional to the light travel time and to the frequency of the signal.

# LISA and the anomaly



# LISA and the anomaly (1/3)

## A first estimate

- What can be learned from LISA?
  - ✓ LISA on Earth orbit : not suitable for studying a true acceleration on bodies (Earth orbit well known, strong violation of weak equivalence principle required).
  - ✓ As interferometer, suitable to study effect on light like a universal blueshift in the frequency of light coming from the cosmological expansion.
  - ✓ Effect of the cosmological expansion on the LISA spacecraft orbits is negligible (cf. Klioner, Soffel, arXiv:astro-ph/0411363 ).
- Corresponding “constant” blueshift on LISA arms : $\frac{\Delta\nu^*}{\nu} \simeq 0.5 \times 10^{-16}$
- Weakest gravitational wave detectable by LISA : $\frac{\Delta\nu}{\nu} = 10^{-22}$

**Impact of PA 5 orders of magnitude bigger than that of GWs: effect could be detectable.**

- But: Best sensitivity of LISA is far from the frequency $\nu$=0.
- Effect worth investigating.

## LISA and the anomaly (2/3)
# Effect on the GW response function

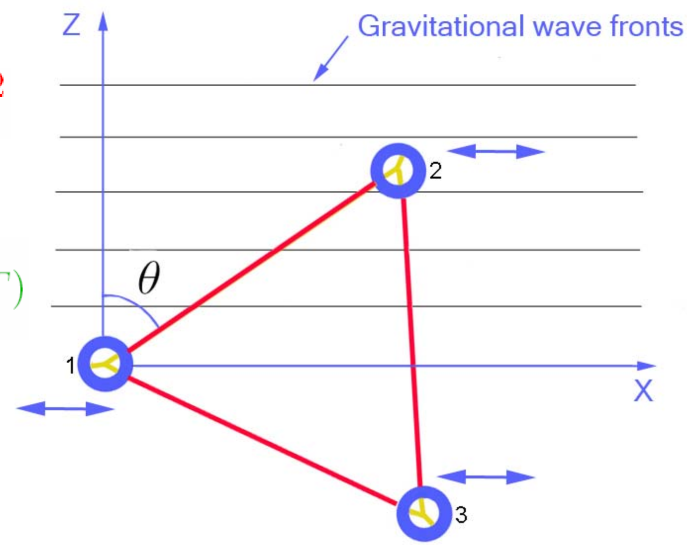
- Transverse and traceless gravitational wave contribution on one arm
  - ✓ Line element:

$$ds^2 = -c^2dt^2 + (1-h)dx^2 + (1+h)dy^2 + dz^2$$

  - ✓ Corresponding Doppler shift:

$$\frac{\Delta\nu}{\nu} = \frac{1}{2}(1+\alpha)\,h(t) - \alpha\,h\left(t+(1-\alpha)\frac{T}{2}\right) - \frac{1}{2}(1-\alpha)\,h(t+T)$$

(Estabrook, Wahlquist, Gen.Rel.Grav. **6** [1975] 439)




- Include anomalous blueshift
  - ✓ New generic two-way Doppler shift :

$$\frac{\Delta\nu}{\nu} = \frac{1}{2}(1+\alpha)\left(1-\frac{a^*}{2c}T\right)h(t) - \alpha\left(1-\frac{a^*}{2c}T\right)h\left(t+(1-\alpha)\frac{T}{2}\right) - \frac{1}{2}(1-\alpha)\left(1-\frac{a^*}{2c}T\right)h(t+T) - \frac{a^*}{c}T$$

**In sensitivity band**
**Second order term**

**Outside sensitivity band**
**First order term**

LISA and the anomaly (3/3)

## Effect on the dispersion of GWs

- Clock acceleration models would also cause blueshift of GWs (e.g. Ranada, Found.Phys. **34** (2005) 1955, arXiv:gr-qc/0403013).

  → Chirp patterns would be modified.

- Signature of effect could be studied analogous to “massive” GWs (cf. Will, Yunez, Class.Quant.Grav. **21** (2004) 4367).

- Not part of this study because

**effect is only present in specific models of the Pioneer anomaly as a blueshift**

# Implications for LISA

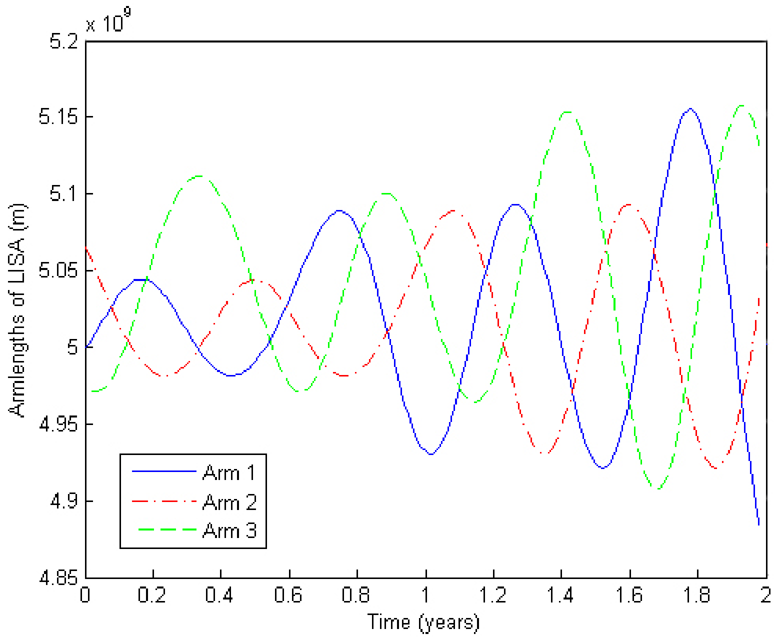
# Frequency domain method

**Giamperi & al: Opt. Comm. 123 (1996)**

# Frequency domain method (1/11)

## Principles

- Algorithm to cancel the laser phase noise.
- Use the data from one arm as a reference for the laser phase noise.
- Method developed for an interferometer, fixed in space.
- Additional constraint to remove sufficiently the laser phase noise coming from the orbital motion (arm lengths vary, up to 13 m/s).
- Observations thus restricted to finite time.




- Impact of the anomaly ?

The study follows **Giamperi & al: Opt. Comm. 123 (1996)** with updated values of the noises spectra and by taking into account the acceleration noise.

# Frequency domain method (2/11)

## The noises

- Leading LISA's noise :
  - ✓ Laser phase noise: comes from the time varying laser's cavity length and several orders of magnitude bigger than gravitational wave contributions.

    30 Hz $Hz^{-1/2}$    Necessity of cancellation method

  - ✓ Amplitude power spectra roughly decreasing in $1/f^2$ at the mHz level.
  - ✓ Power spectra becomes flat below about $10^{-8}$ Hz.
- Secondary noises :
  - ✓ Shot noise : Quantum-mechanical fluctuations in the arrival times of the photons.    $20 \times 10^{-12}$ m $Hz^{-1/2}$
  - ✓ Residual acceleration noise : Thermal distortion, Residual gas impacts on the proof mass, temperature difference across cavity,…

    Optical bench noise : $10 \times 10^{-9}$ m $Hz^{-1/2}$

    Proof-mass noise : $3 \times 10^{-15}$ m/sec² $Hz^{-1/2}$

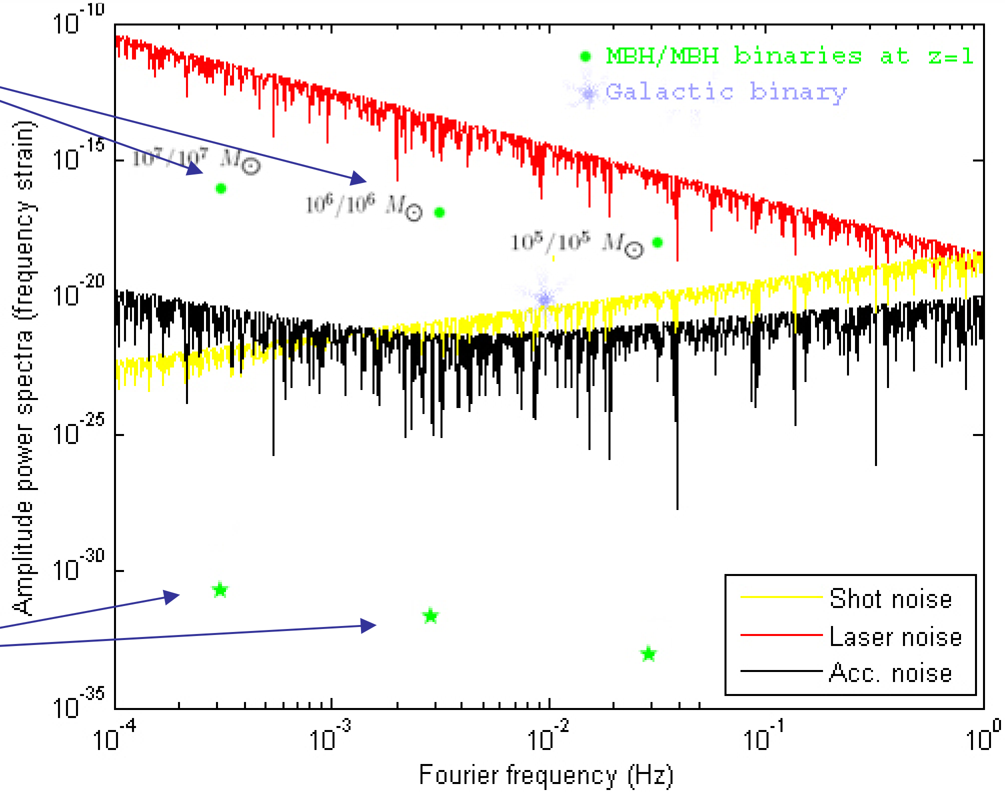
# Frequency domain method (3/11)

## 2-way Doppler signal (sensitivity band before cancellation)

$$\frac{\Delta\nu}{\nu} = \frac{1}{2}(1+\alpha)\left(1-\frac{a^*}{2c}T\right)h(t) - \alpha\left(1-\frac{a^*}{2c}T\right)h\left(t+(1-\alpha)\frac{T}{2}\right) - \frac{1}{2}(1-\alpha)\left(1-\frac{a^*}{2c}T\right)h(t+T) - \frac{a^*}{c}T$$

Gravitational wave contributions

Contributions of the anomaly (2nd order)

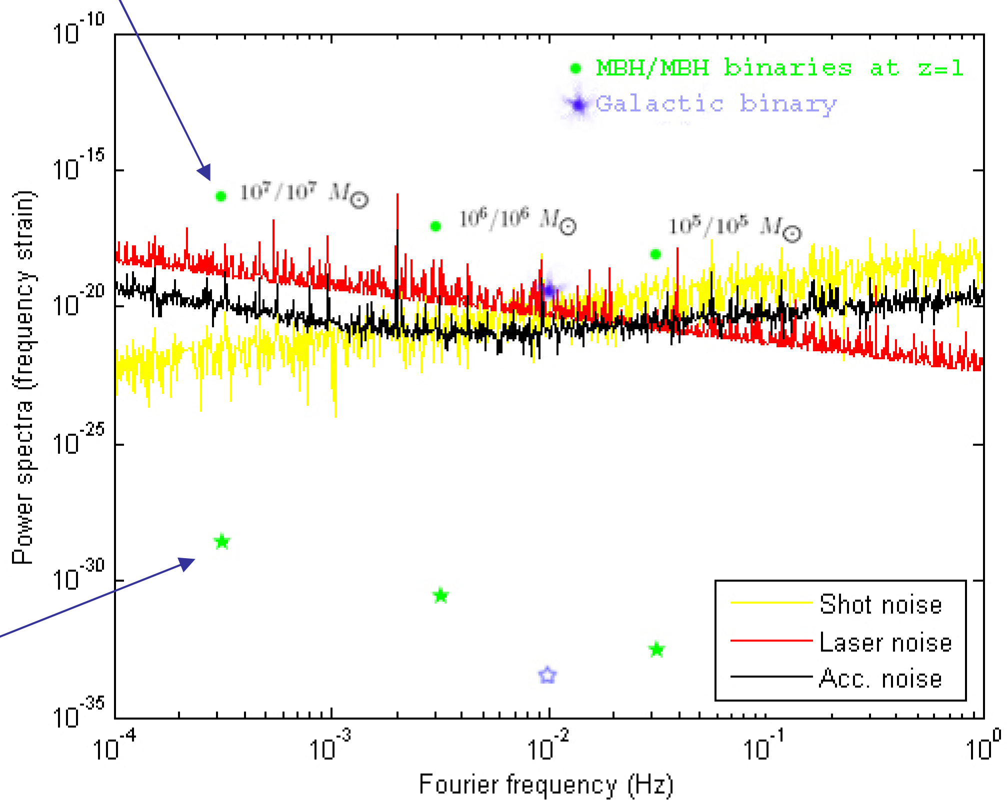



No GW/PA detectable, laser phase noise too big.

# Frequency domain method (4/11)

## After laser phase noise cancellation

After cancellation method, gravitational wave detectable

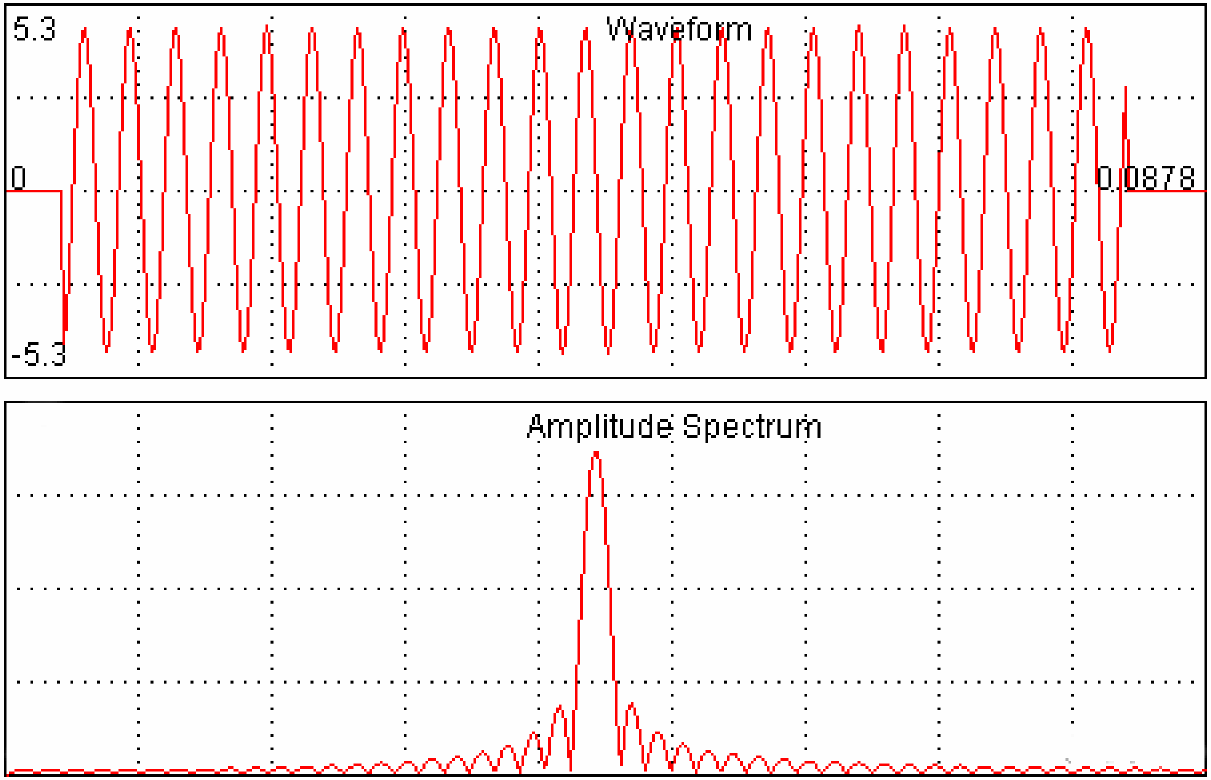



Obviously, Pioneer anomaly still below secondary noises

# Frequency domain method (5/11)

## Finite observation time: Spectral leakage

Finite observation time → spectral leakage ( the Fourier transform of a sine function, limited in time, is not a pulse anymore).



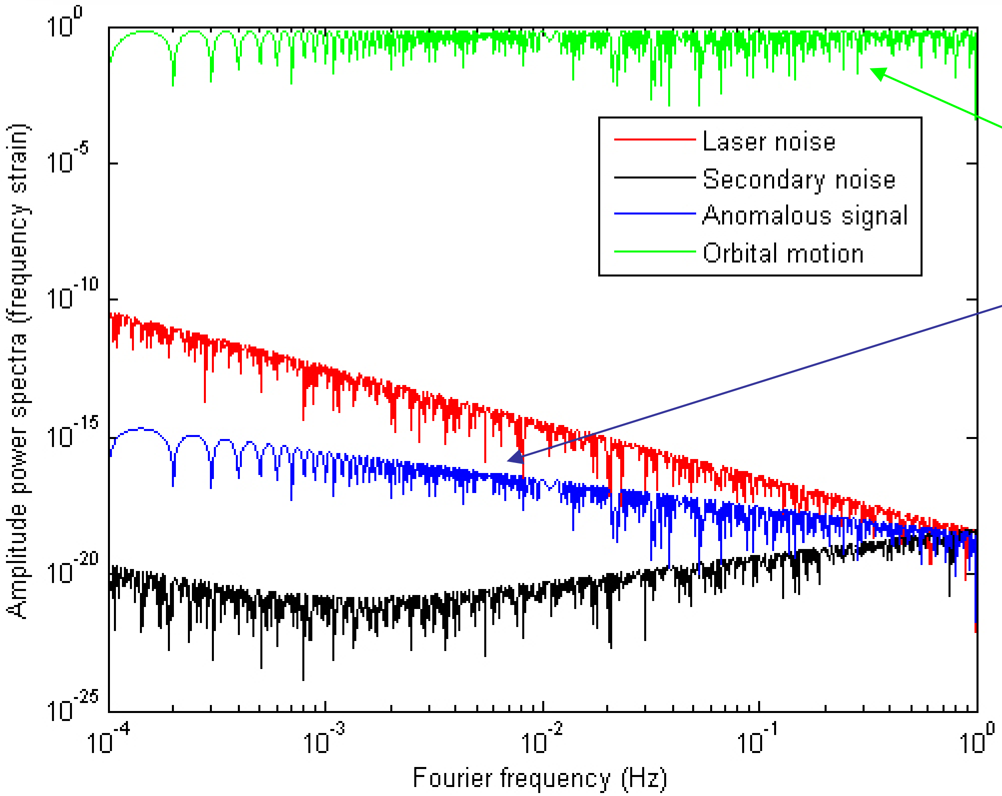
# Frequency domain method (6/11)

## Spectral leakage (before noise cancellation method)

- Two-way Doppler signal (phase shift)

$$\alpha^* \equiv -\frac{a^*}{c}\nu$$

$$z_1(f) = p_1(f)\left[e^{4\pi i f l_1} - 1\right] + n_1(f)\left[1 + e^{2\pi i f l_1}\right] + a_1(f)\left[e^{4\pi i f l_1} + 2e^{2\pi i f l_1} + 1\right] + 4\pi\nu l_i(f) - \frac{2\alpha^*}{if} l_i(f)$$




Leakage of the nominal term

Anomalous first order term leaks in the sensitivity band

- Assumption: no pre-processing against spectral leakage.

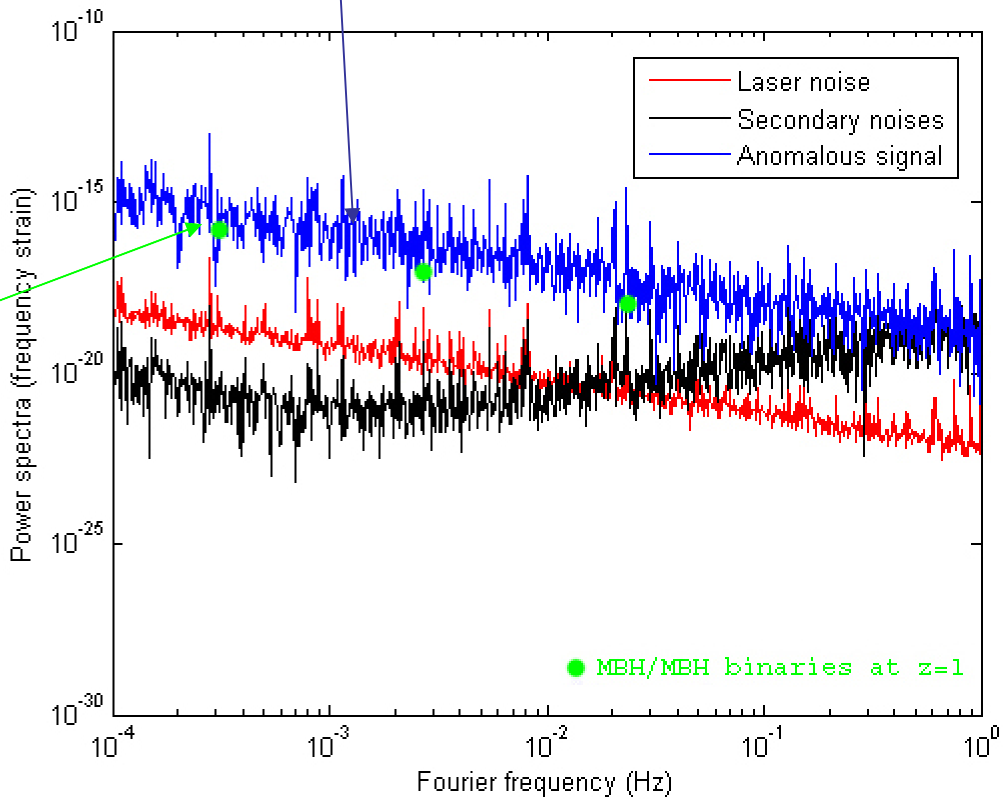
# Frequency domain method (7/11)

## Spectral leakage (after cancellation method)

After cancellation, anomalous term dominates

But: Even strongest gravitational waves not detectable

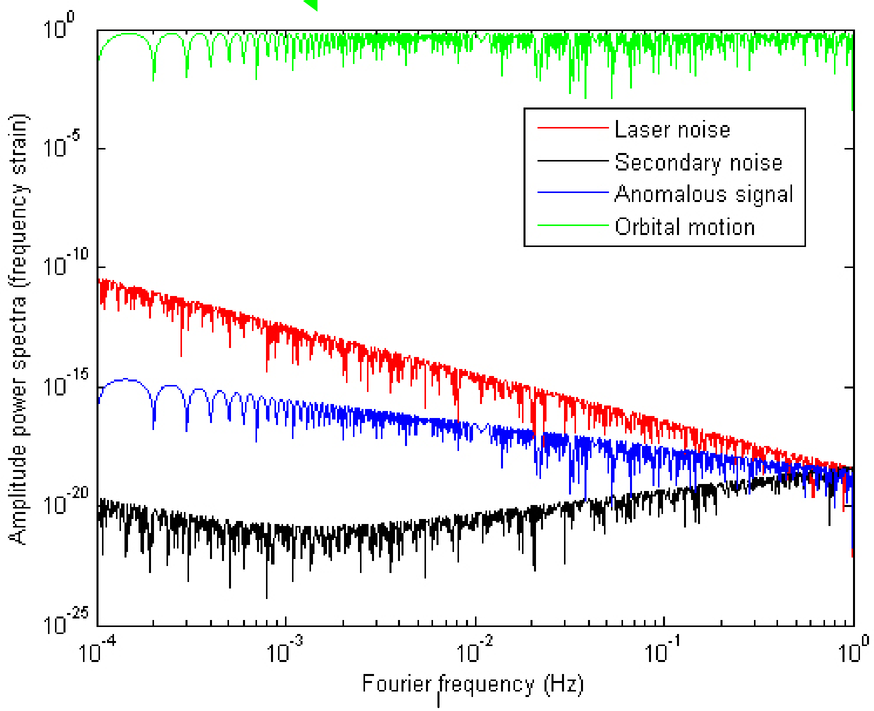
Gravitational wave detection unimpaired with pre-processing method against spectral leakage.



# Frequency domain method (8/11)

## In practice

- Pioneer anomaly could be seen if the nominal orbital term could sufficiently be removed
- Required a precision on the arm length of roughly $10^{-6}$ m !
- Best method, time delay interferometry ranging (TDIR), gives a precision at order of few meters.
- Anomalous signal not detectable in the sensitivity band of LISA.

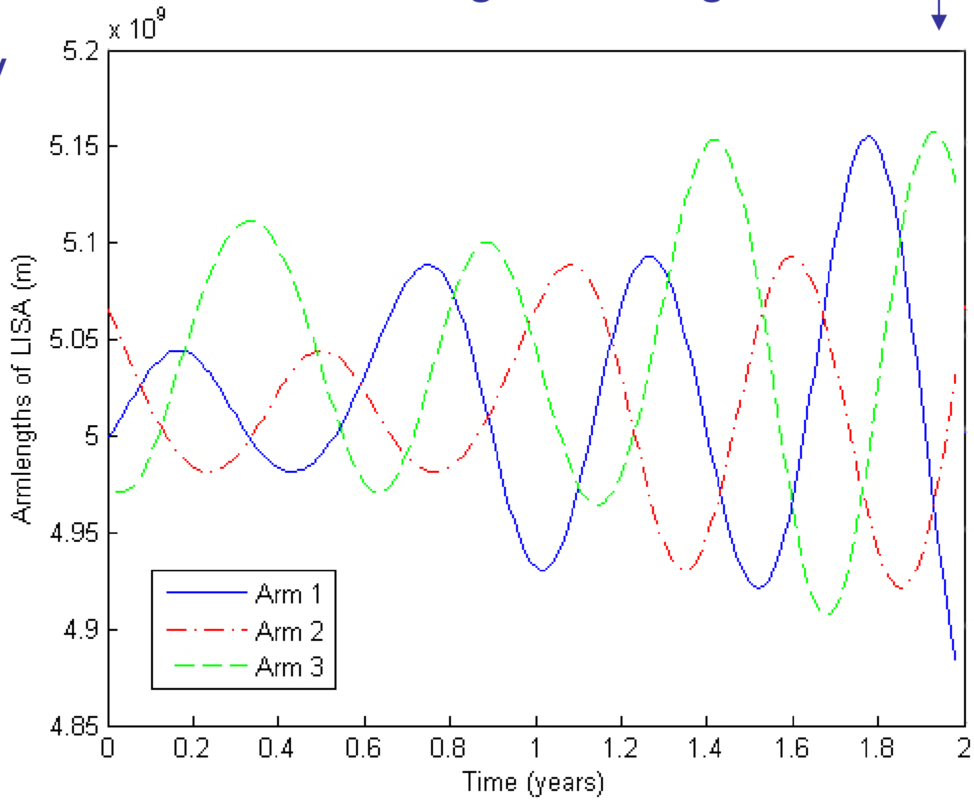


# Frequency domain method (9/11)

## Outside the sensitivity band

$$\frac{\Delta\nu}{\nu} = \frac{1}{2}(1+\alpha)\left(1-\frac{a^*}{2c}T\right)h(t) - \alpha\left(1-\frac{a^*}{2c}T\right)h\left(t+(1-\alpha)\frac{T}{2}\right) - \frac{1}{2}(1-\alpha)\left(1-\frac{a^*}{2c}T\right)h(t+T) - \frac{a^*}{c}T$$

- For several months integration time, the arm lengths change like
  - ✓ Place where the anomaly has its biggest impact (change in arm lengths due to orbital motion is important).
  - ✓ Minimal arm length change = 50 000 km.



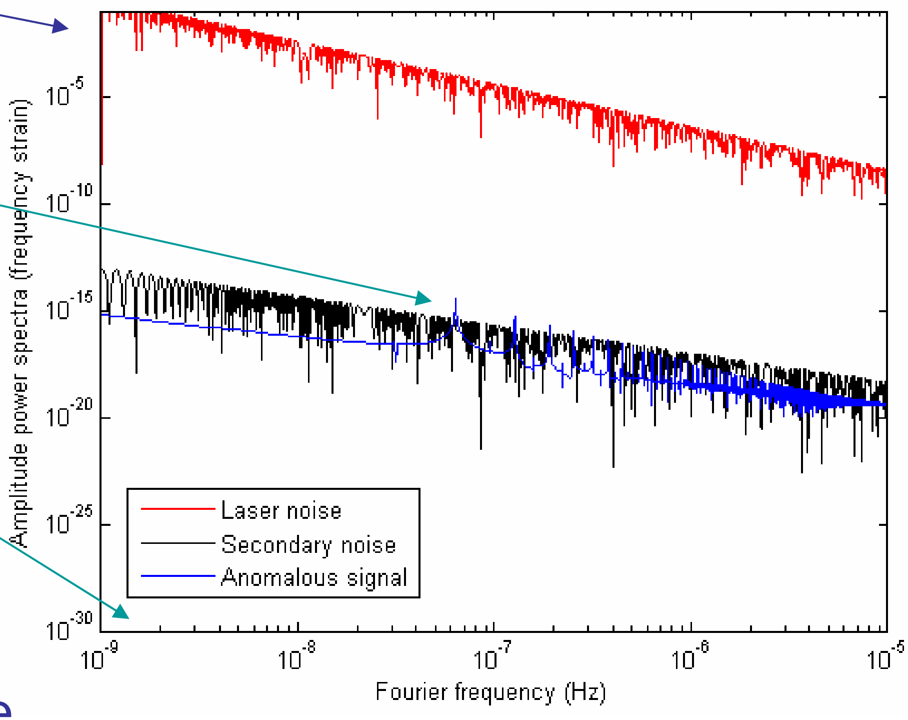
# Frequency domain method (10/11)

## Outside the sensitivity band (results)

- Two-way Doppler signal

First order anomalous term just above secondary noise

Integration time corresponds to several months




- Result
  - ✓ Arm length changes too large.
  - ✓ Outside the sensitivity band, the laser phase noise cannot be sufficiently cancelled.

## Frequency domain method (11/11)

### Conclusions

- Pioneer anomaly has no impact on the gravitational waves detection in the sensitivity band.
- Pioneer anomaly could be distinguished if the arm lengths were known sufficiently accurately.
  In practice, the precision ($10^{-6}$ m) is far beyond the achievable values.
- Outside the sensitivity band, the laser phase noise cannot be removed below the contribution of the anomaly.

**Pioneer anomaly not visible with frequency domain methods.**

# Time Delay Interferometry (TDI)

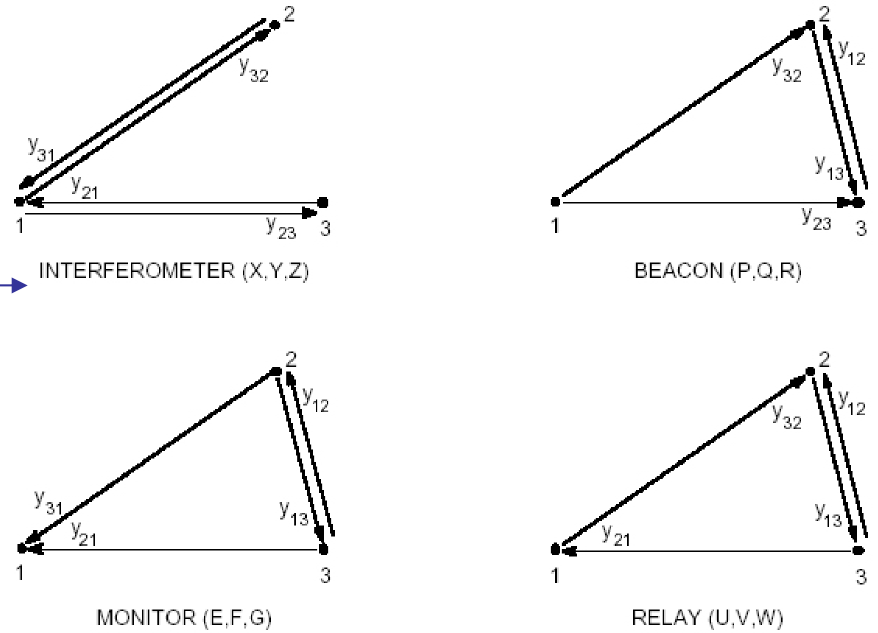
**Tinto & Armstrong, Phys. Rev. D. 59 (1999)**

# Time delay interferometry (1/3)

## Principles

- LISA can be analyzed symmetrically in terms of Doppler shifts on 6 one-way laser links $y_{ij}$ (+ intra-spacecraft metrology $z_{ij}$).
- Time-Delay interferometry = method to cancel laser leading noises by time shifting data from single laser links.
- Method originally developed in the limit of fixed interferometer in space.
- Overview of some combinations.
- Impact of an anomalous blueshift ?

The study follows **Tinto & Armstrong, Phys. Rev. D. 59 (1999).**



Time delay interferometry (2/3)

## Effect of orbital motion

- One example : unequal-arm length interferometric combination

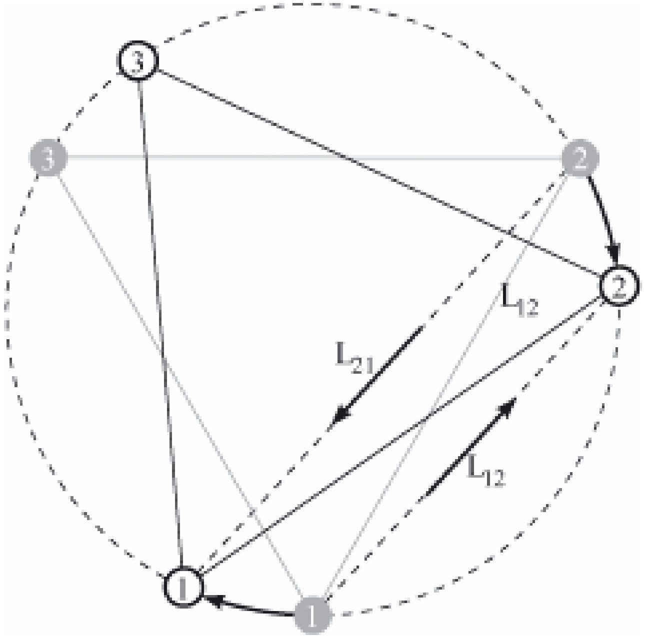
$$\begin{aligned} X = {} & y_{32,322} - y_{23,233} + y_{31,22} - y_{21,33} + y_{23,2} - y_{32,3} + y_{21} - y_{31} \\ & + \frac{1}{2}(-z_{21,2233} + z_{21,33} + z_{21,22} - z_{21}) \\ & + \frac{1}{2}(+z_{31,2233} - z_{31,33} - z_{31,22} + z_{31}) . \end{aligned}$$

- Several other combinations to remove the laser phase noise ($Y$, $Z$, $E$, $P$, $Q$, Sagnac,…).
- The anomalous first order term is totally cancelled in *all* the combinations.
- Contribution of the anomaly on the intra-spacecraft signals $z_{ij}$ negligible (light path very short).
- Effect of orbital motion?
  The study follows **Cornish & Hellings,Class. Quant. Grav. 20 (2003) 4851.**

Time delay interferometry (3/3)

## Effect of orbital motion on the data combinations

1. Effect of the rotation of the interferometer (Sagnac effect) $L_{ij}(t+\tau)=L_{ij}(t)$ →




- Residual effect of the anomaly only on the Sagnac combinations (α,β,γ and ζ)

$$\zeta^* = \alpha^*(\Delta l_- - \Delta l_+) \simeq 3 \times 10^{-22}$$

- Effect at DC frequency and is not detectable.

2. Effect of the flexion of the interferometer :

- Symmetry broken : $L_{ij}(t+\tau) \neq L_{ij}(t)$
- Effect on all the TDI combinations
- Unequal-arm length combination (idem for all combinations)

$$X^* = 4\alpha^*(V_{13} - V_{12})l = 6.47 \times 10^{-24} \qquad (V_{13} - V_{12}) < 13 \text{ m/s}$$

- Contribution below the detection threshold of LISA.

# Conclusions

- Interpretation of the Pioneer anomaly as a blueshift is a reasonable possibility.
- The Pioneer anomaly has no impact on gravitational wave detection by LISA (arises as $(a^*/c)h$ ).
- The Pioneer anomaly is not detectable by LISA — even outside the LISA sensitivity band, where its effect is bigger.
- Pioneer anomaly has to be tested in the outer Solar System (even more true for a real acceleration).