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Background for gravitational wave signal at LISA from refractive index of solar wind plasma

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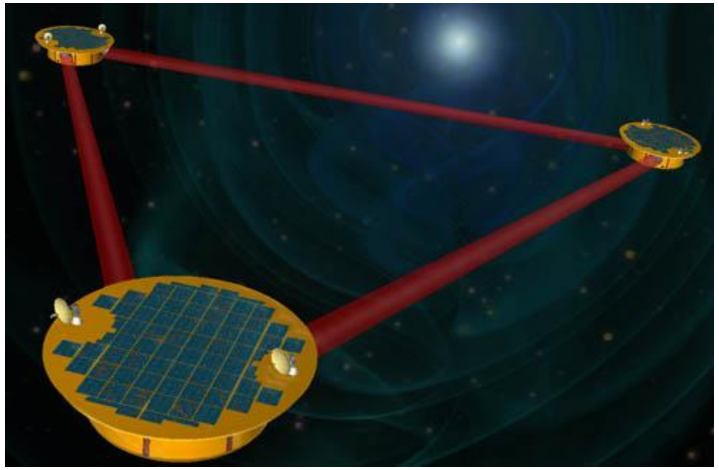
Gravitational wave antennas



Ground-based GW antennas (LIGO, VIRGO)

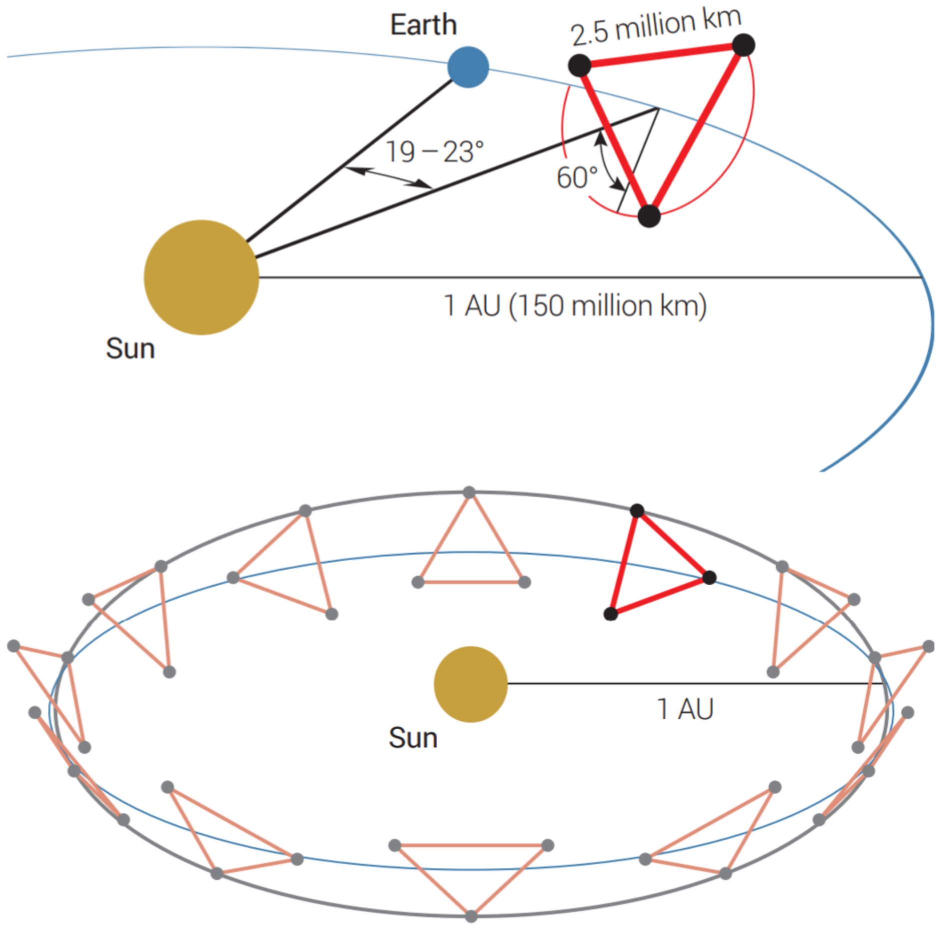
- Size limitation
- Seismic noise
- Vacuum technology
- Ultra-high vacuum ($\sim 10^7$ molecules/cm^3)
- Vacuum (im)purity under control

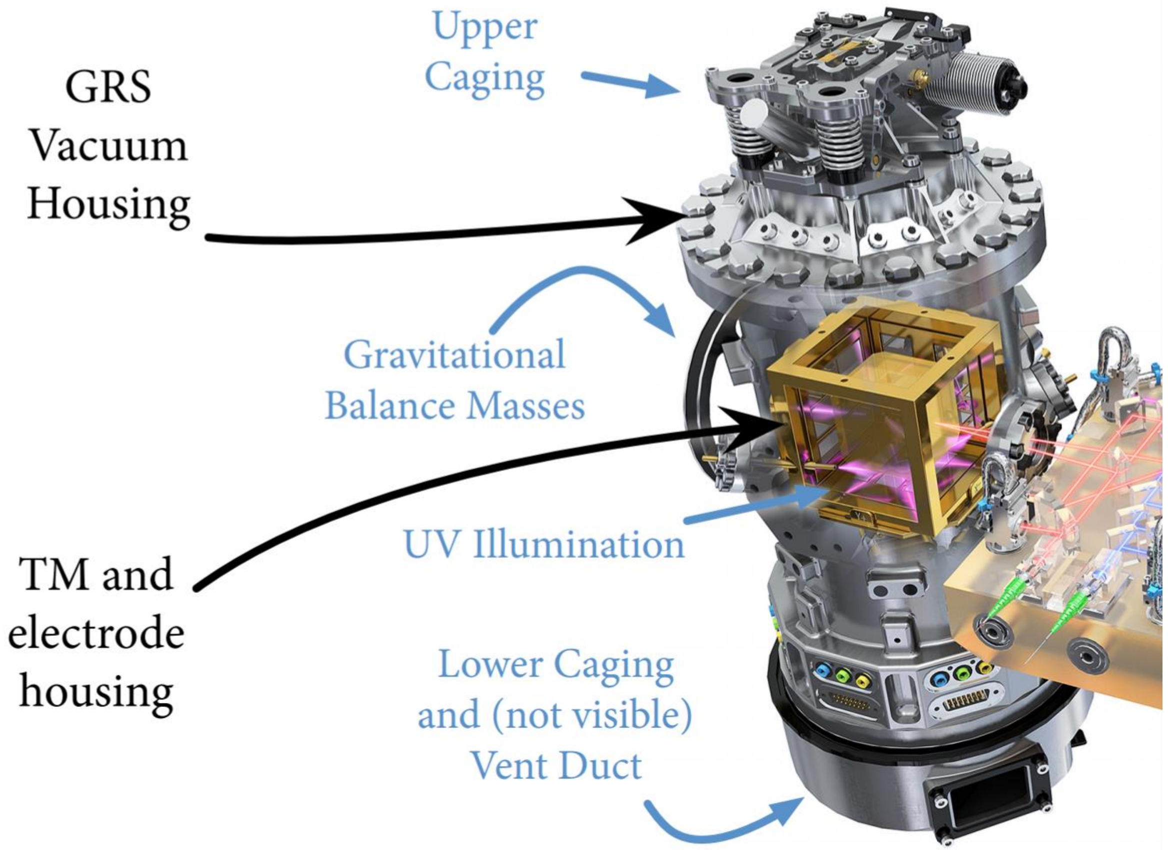
Space-based GW antennas (LISA)

- Free of size limitation
- No seismic noise
- Vacuum for free
- Better vacuum (~ 10 particles/cm^3)
- Vacuum (im)purity **NOT** under control

Amaro-Seoane P., et al., 2017, Laser Interferometer Space Antenna (arXiv:1702.00786)

LISA – Laser Interferometer Space Antenna





LISA challenges

Amaro-Seoane P., et al., 2017, Laser Interferometer Space Antenna (arXiv:1702.00786)

Interferometry with

- Variable arm length ($\Delta l \approx 50.000\ \mathrm{km}$) during the orbit
- Single laser path (no coherent beams)
- Overwhelming laser wavelength noise due to unequal arm length -> Time delayed interferometry
- Doppler shifted laser beam ($\pm 5\ \mathrm{m/s}$)
- Mechanical, Thermal, Electronic, Optical noise
- Test mass charging
- High energy cosmic rays
- Solar wind jitter
- Timing and Clock Synchronisation
- Laser stability
- Optical impurity

LISA parameters

- 6 laser links operating on the wavelength

$$\boxed{\lambda = 1064\,\mathrm{nm}}$$

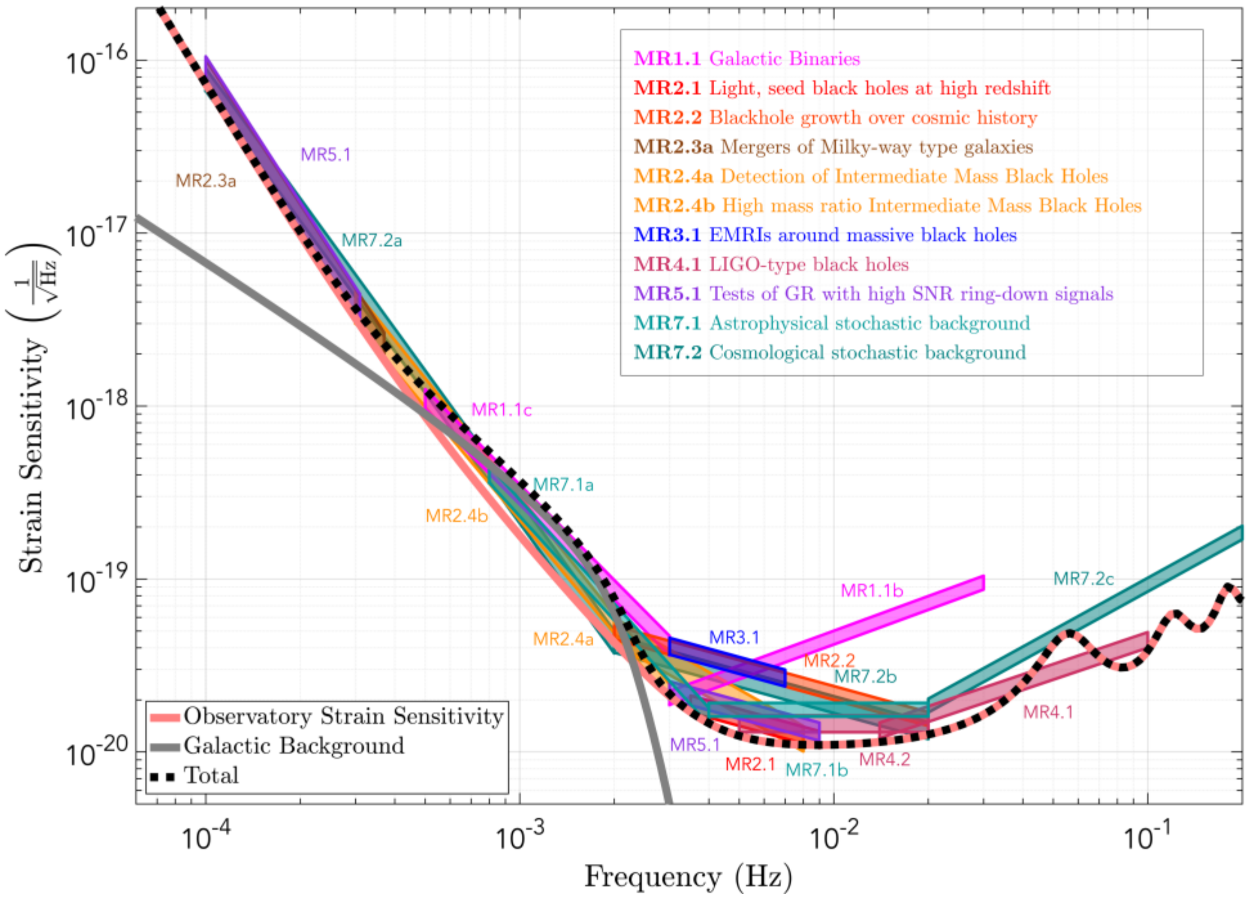
- Variable arm length with average

$$\boxed{L = 2.5 \times 10^6\ \mathrm{km}}$$

- Displacement noise linear spectral density

$$\boxed{\sqrt{S_{\mathrm{IFO}}} \le 10^{-11}\,\frac{\mathrm{m}}{\sqrt{\mathrm{Hz}}}\sqrt{1+\left(\frac{2\mathrm{mHz}}{f}\right)^4} \quad \text{for} \quad 10^{-4}\mathrm{Hz} \le f \le 10^{-1}\mathrm{Hz}\,,}$$

Amaro-Seoane P., et al., 2017, Laser Interferometer Space Antenna (arXiv:1702.00786)



Refractive index of solar wind plasma

Solar wind (SW)

- Composition: electrons ~ protons > alpha > heavier ions
- at 1 AU from the Sun (LISA‘s and Earth‘s orbit)
  - average particle density ~ 10 cm^{-3} and quasi-neutrality → $n_e \approx n_p \approx 5\ cm^{-3}$
  - at scales of optical wavelengths range ~ 1 μm, SW is practically **a collision-less ideal plasma**
  - electron component is characterized by plasma frequency

$$\boxed{\omega_p^2 = \frac{n_e e^2}{\epsilon_0 m_e}}$$

  - Which dominates the Sellmeier equation for refractive index n for elmag wave of frequency ω

$$\boxed{n = \sqrt{1 - \frac{\omega_p^2}{\omega^2}} \doteq 1 - \frac{1}{2}\frac{\omega_p^2}{\omega^2} + \dots}$$

For optical elmag wave $\Delta n \sim 10^{-21}$

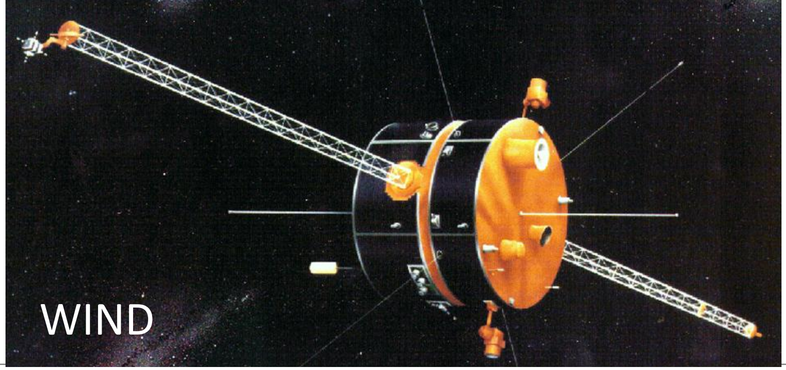
Estimation of the background for LISA from the solar wind plasma effect

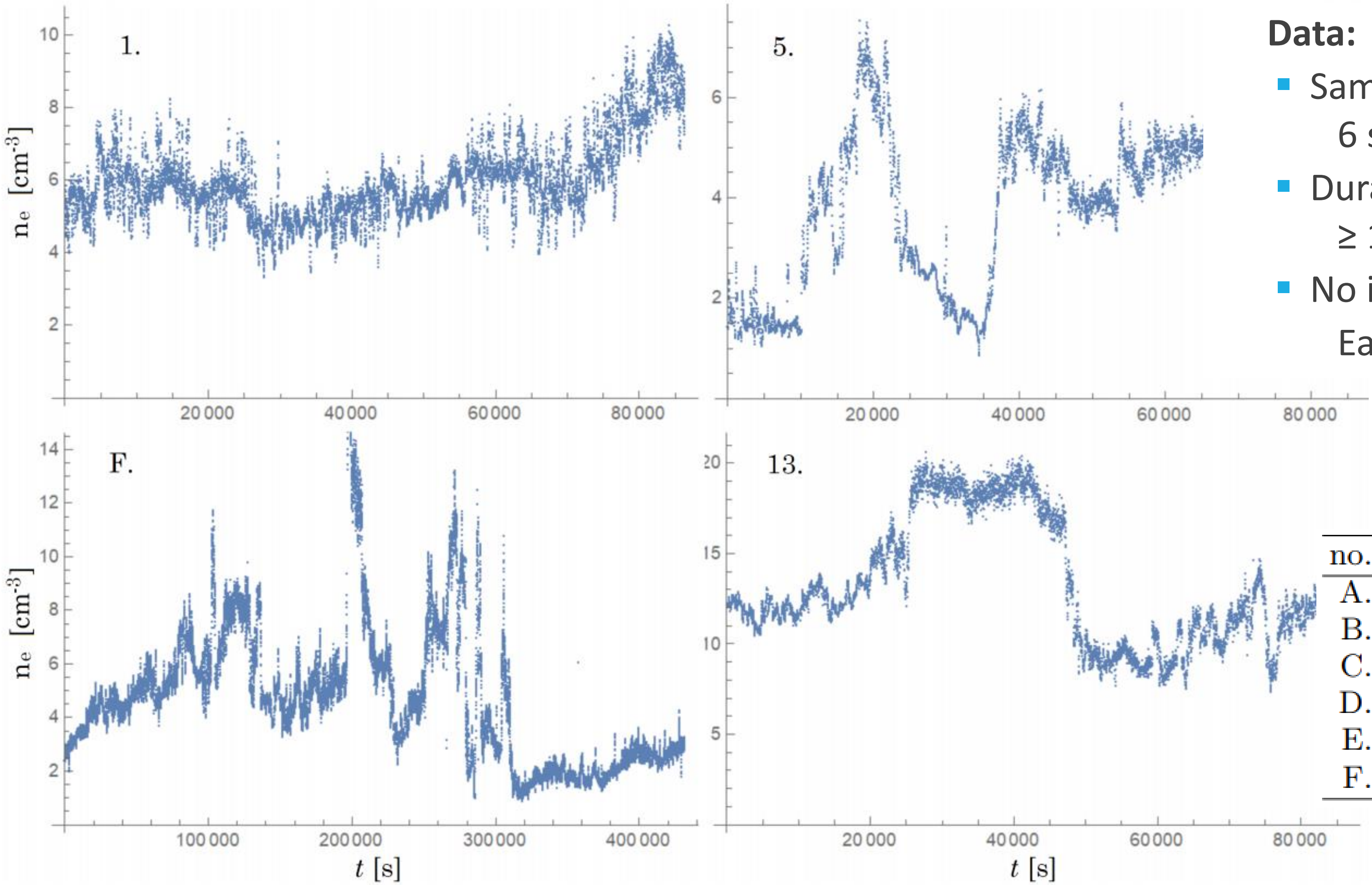
- **Effective displacement:** $$\boxed{h_{\mathrm{SW}}(t) = \frac{1}{2}\frac{n_e(t)e^2}{\epsilon_0 m_e \omega^2}L}$$

- **Effective strain:** $\boxed{h_{\mathrm{SW}} / L}$

- **Linear spectral density:** $\boxed{\sqrt{S_{\mathrm{SW}}(f)}}$ **to be compared with LISA's required** $\sqrt{S_{\mathrm{IFO}}}$

Solar wind data





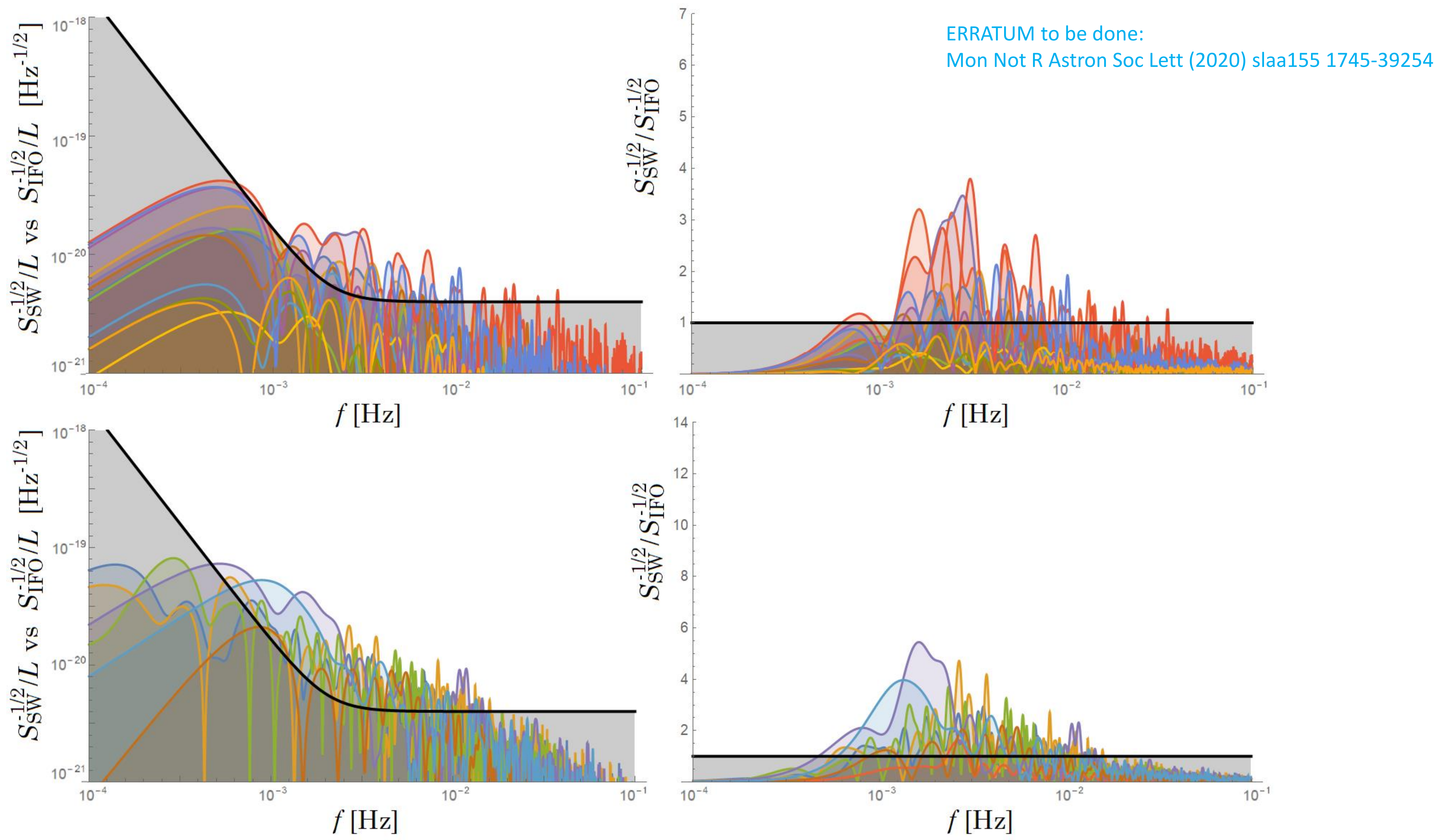
Data:

- Sampling frequency
  6 s – 12 s
- Duration ≥ 24 h
  ≥ 10*(0.1 mHz)$^{-1}$
- No interference with
  Earth's magnetosphere

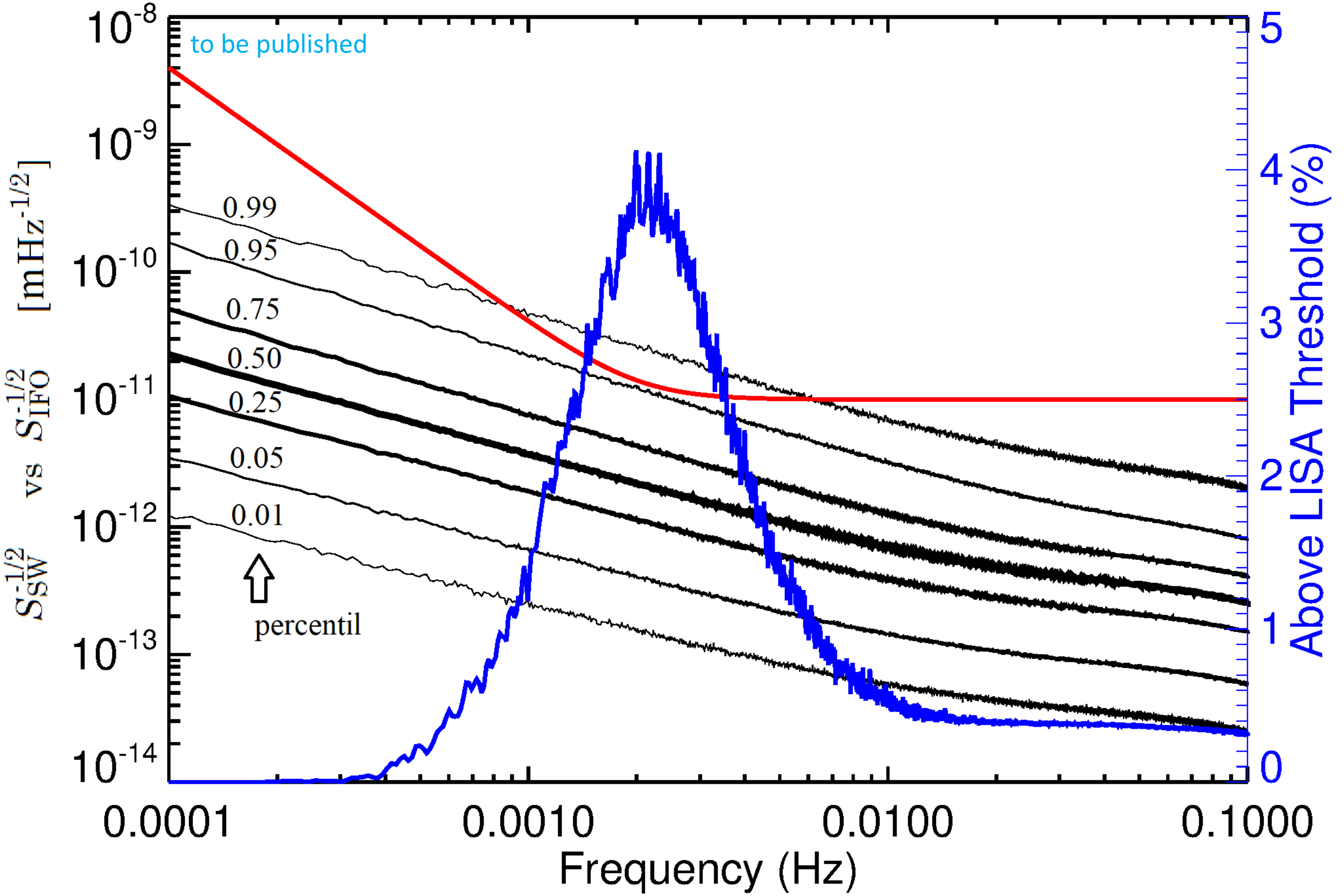
no.	initial date	length	$\overline{n_e}$	n_e^{max}	n_e^{min} [cm^{-3}]
1.	1997/07/11	24 h	5.9	10.0	3.0
2.	1997/08/11	24 h	6.4	10.5	3.5
3.	1997/09/11	24 h	4.4	7.3	2.7
4.	1997/10/11	24 h	7.6	13.5	4.0
5.	1997/12/11	24 h	4.0	7.2	0.8
6.	1998/01/11	24 h	7.4	10.3	4.6
8.	1998/03/11	24 h	3.4	4.5	2.6
9.	1998/04/11	24 h	5.6	9.2	2.2
10.	1998/05/11	24 h	3.3	4.4	2.3
11.	1998/06/11	24 h	6.6	13.5	0.1
12.	1998/07/11	24 h	5.3	11.4	1.4
13.	1998/09/11	24 h	13.1	20.6	7.4
14.	1998/10/11	24 h	4.0	6.0	2.4

no.	event	initial date	length	$\overline{n_e}$	n_e^{max}	n_e^{min} [cm^{-3}]
A.	ISTP-SEC	1997/11/04	24 h	6.1	12.0	4.0
B.	ISTP-SEC CME	1998/01/21	24 h	8.0	22.0	3.5
C.	ISTP-SEC CME	1998/04/15	24 h	4.2	7.2	3.1
D.	ISTP-SEC CME-Geostorm	1998/04/29	96 h	5.4	15.0	1.2
E.	ISTP-SEC Solar-GeoStorm	1998/09/23	96 h	5.5	15.0	0.5
F.	ISTP-SEC Solar-GeoStorm	1998/08/24	120 h	4.7	14.5	1.0

Preliminary results



More detailed results



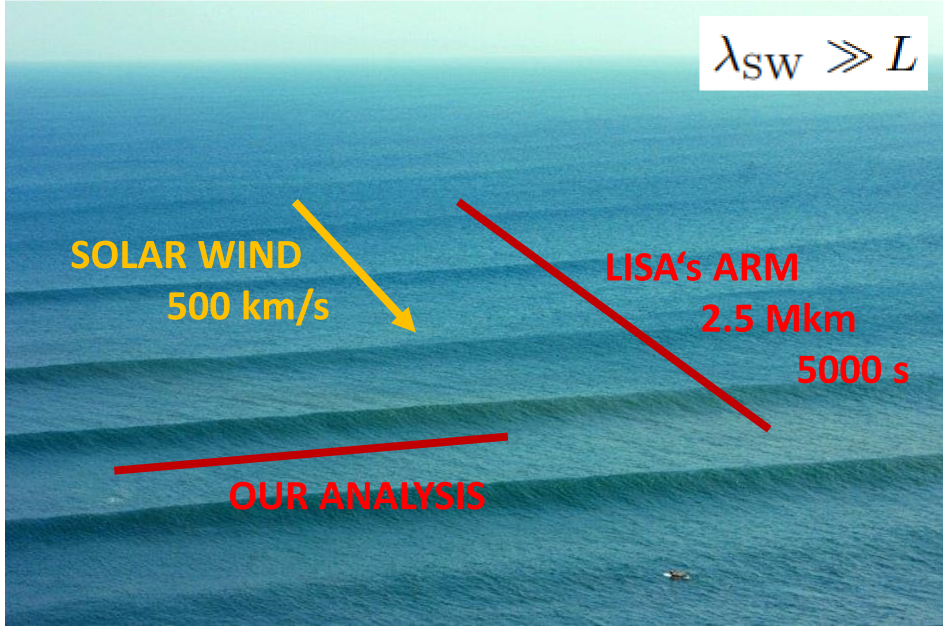
- WIND data
- 2004 – 2019
- 24h window
- shifted by 1h

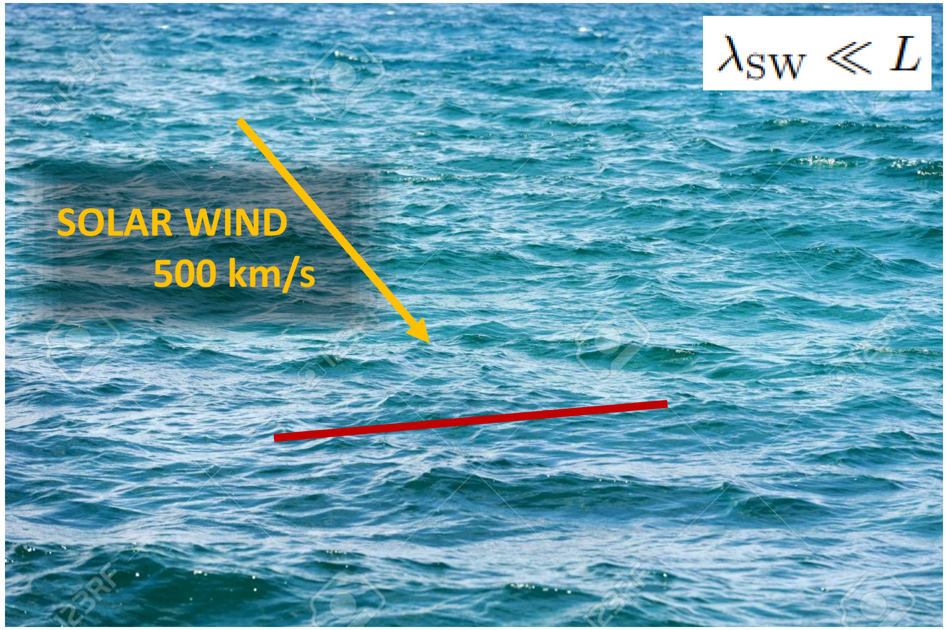
→ 76210 spectra

- interpolated data resampled to 10 Hz

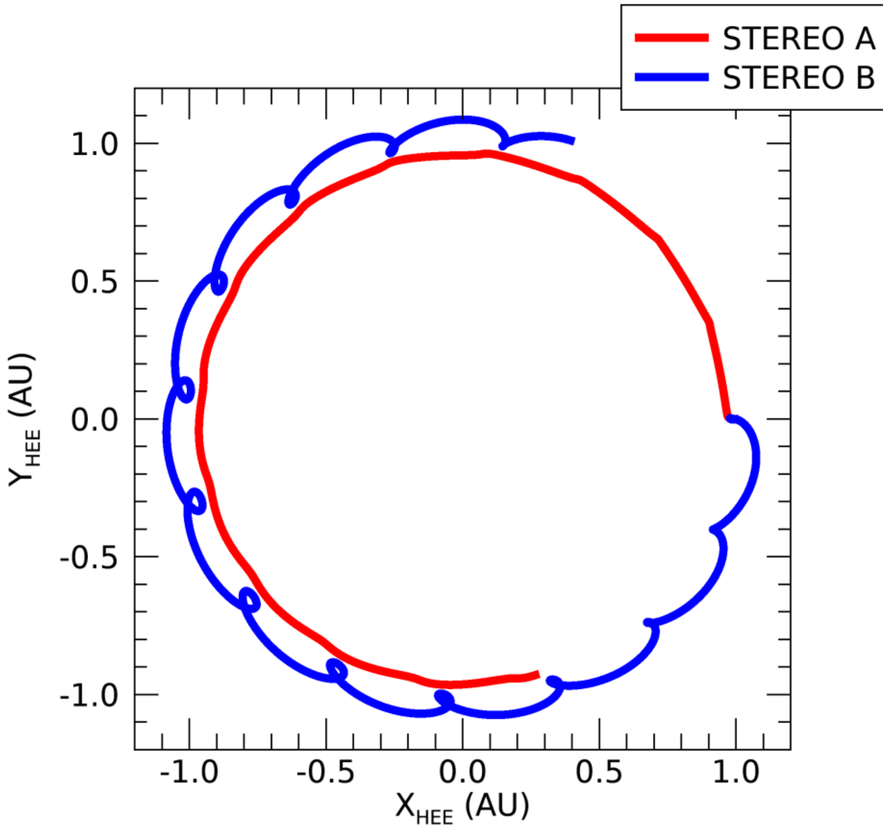
Discussion of the result

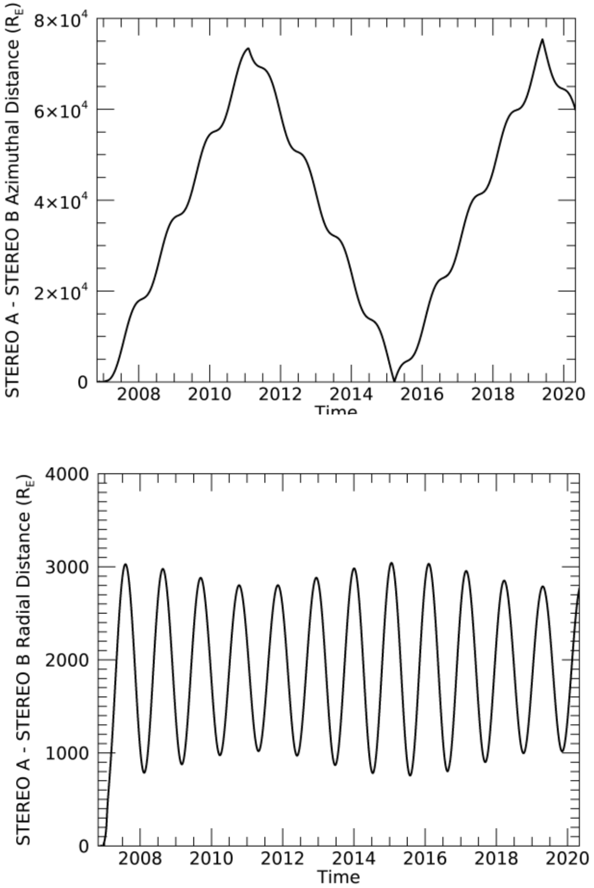
- The result is applicable to any space-based intereferometer of the LISA‘s type
- The effect will be observable only at the full scale LISA, no „Pathfinder“ mission would discover it
- Averaging-out effect
  - After all the situation does not need to be so severe **shall we take the risk?** - subject of future modelling

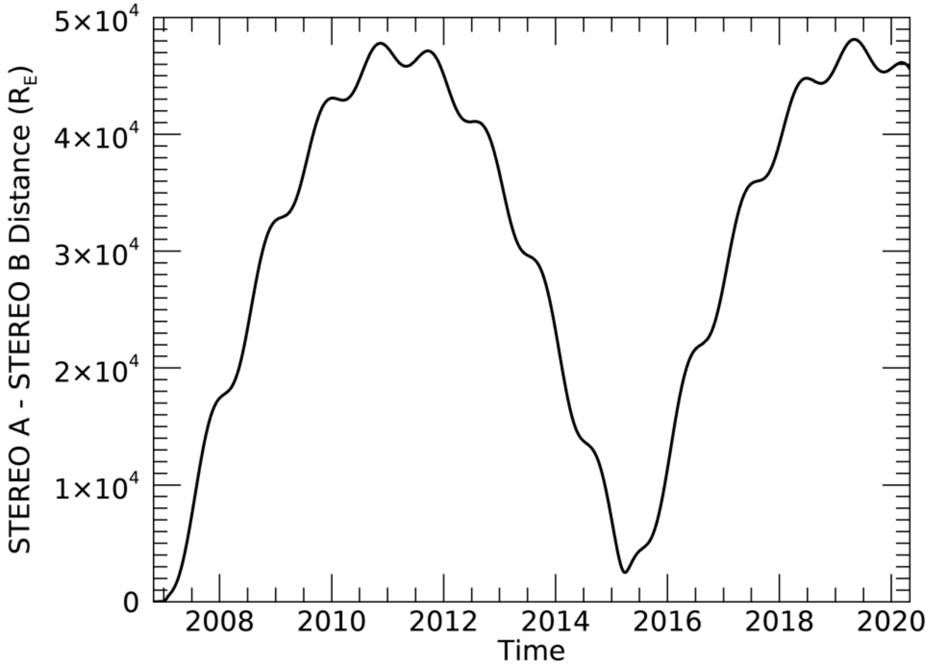




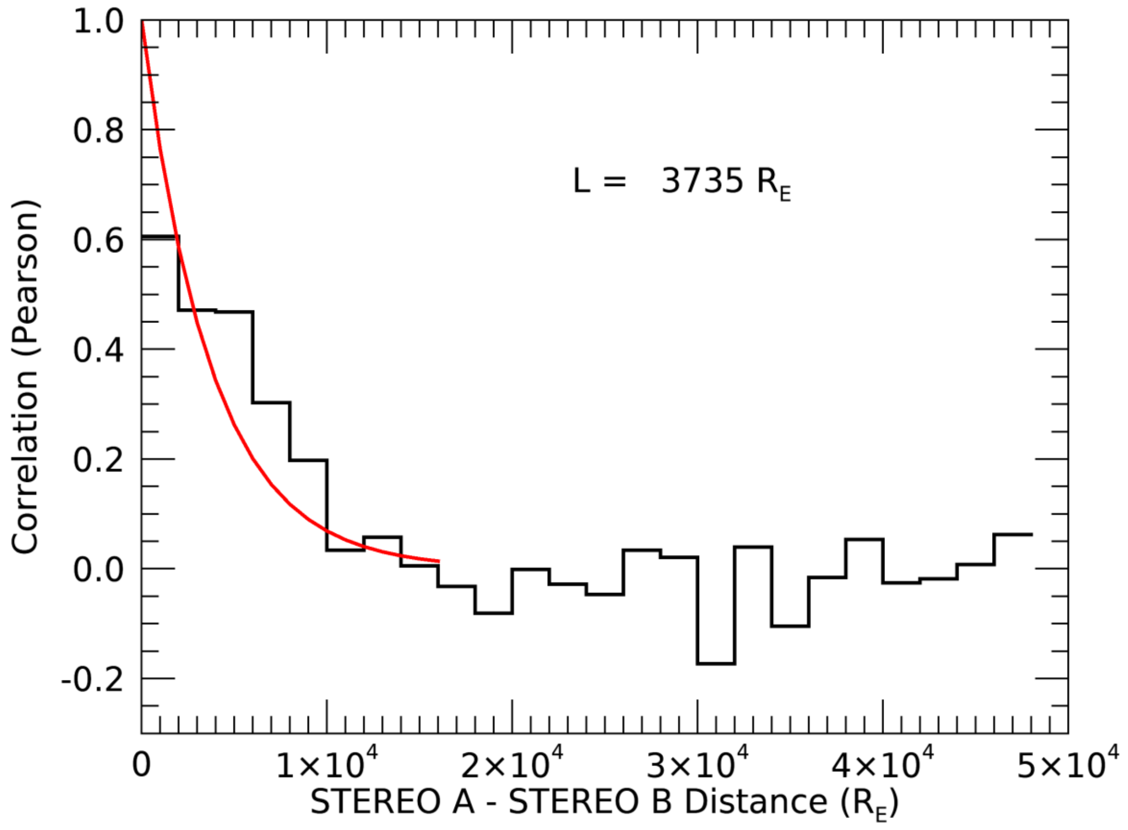
Hint from STEREO - trajectories







Hint from STEREO - correlations

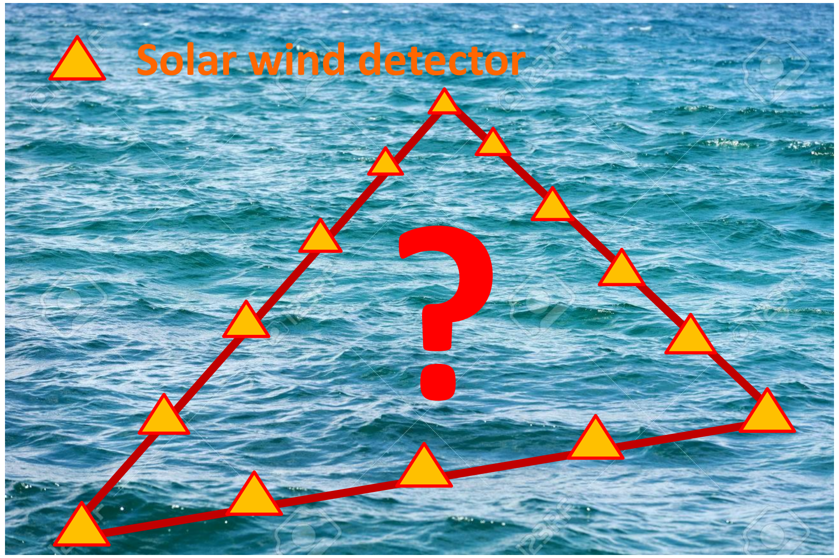


Correlation length:

L = 24 mil. km

Proposed solutions

1. Measure the solar wind density along the LISA's arms
   - **What accuracy is needed?**
   - **How many detectors?**



2. Deploy second laser system of different wavelength

$$\boxed{\lambda' = r\lambda}$$

and subtract their signals

$$\boxed{\Delta h(t) = r^2 h(t) - h'(t)}$$

   - **What is a systematic bias introduced?**

J. W. Armstrong,
"Low-Frequency Gravitational Wave Searches Using Spacecraft Doppler Tracking",
Living Rev. Relativity, 9 (2006)

Current status

Cross check with LISA collaboration – has been made

- Sept 1-3 2020, LISA Symposium
- Conclusion from 90‘s was that the effect is not significant for LISA – not published
- The effect was described in the context of the Doppler mission
  - J. W. Armstrong, "Low-Frequency Gravitational Wave Searches Using Spacecraft Doppler Tracking", *Living Rev. Relativity*, 9 (2006)
- The error of factor ~3 in the LSD was detected and removed
  - ERRATUM to be done to Mon Not R Astron Soc Lett (2020) slaa155 1745-39254

Collaboration with Charles University – has been established

- Correlation length estimates based on real data (STEREO, L1 missions)
- More complex analysis of WIND data has been performed
- 3D modelling (average conditions, events)
- Simulation of the 3-arm LISA response is needed – further suppression of the effect is expected