The ESA LISA Pathfinder and LISA missions in the new era of Gravitational Astronomy

Open Session-Séance Ouverte

« Cosmic Head News

Actualités Cosmiques »

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esa

Cité Internationale Universitaire de Paris, Maison de l'Argentine - March 29, 2018

OUTLOOK

- **The detection of gravitational waves**
- **Gravitational wave detection on Earth and in space**
- **Clues on gravitational wave existence before detection**
- **Orbit and characteristics of the ESA LISA Pathfinder mission**
- **The ESA LISA mission**
- **Environment impact on space interferometers for gravitational waves**
- **Ancillary physics with space interferometers**
- **Conclusions**

Detection of gravitational waves 2015

100 years after the publication of the General Relativity by A. Einstein (1915)

- During a press conference of the LIGO-Virgo collaboration on **February 11, 2016** the detection of gravitational waves with the Earth interferometers was announced to the world. The two LIGO interferometers in the United States detected for the first time the gravitational waves generated during the merging of two stellar black holes on **September 14, 2015**
- On **December 3, 2015** the ESA LISA Pathfinder mission was launched from the Kurou base in French Guiana for the testing of the instruments that will be placed aboard the first interferometer for gravitational wave detection in space

Milestones towards the Gravitational Universe

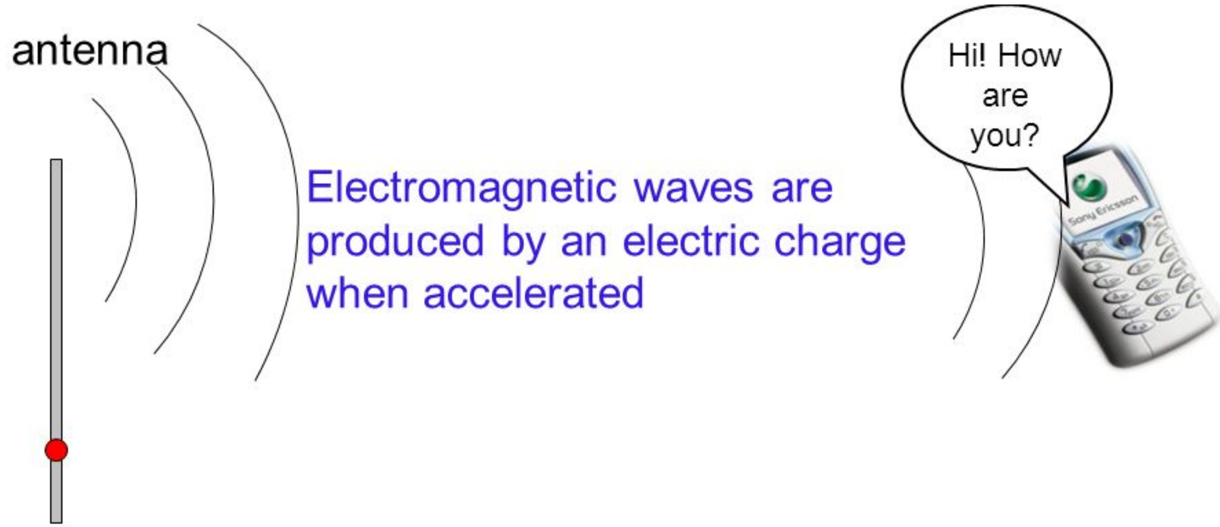
- **2013** The European Space Agency selected the Gravitational Universe as one of its corner-stone science theme (LISA mission selected as L3 mission concept)
- **2015** The two LIGO experiments detected for the first time a gravitational wave from two stellar black hole merging
- **2015** LISA Pathfinder launch
- **2017** The two LIGO+Virgo experiments detected the first NS-NS merging

4 forces control our known world

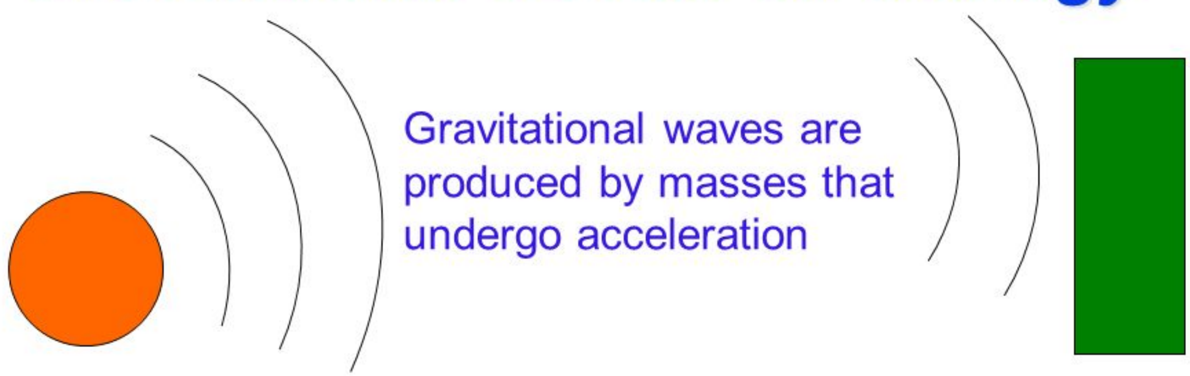
- Gravitational interaction (masses)
  (Newton; 1687 – Einstein; 1915)
- Electromagnetic interaction (charges/currents)
- Strong interaction (nucleons in nuclei)
- Weak interaction (radioactive decay)

Electromagnetic and Gravitational Waves

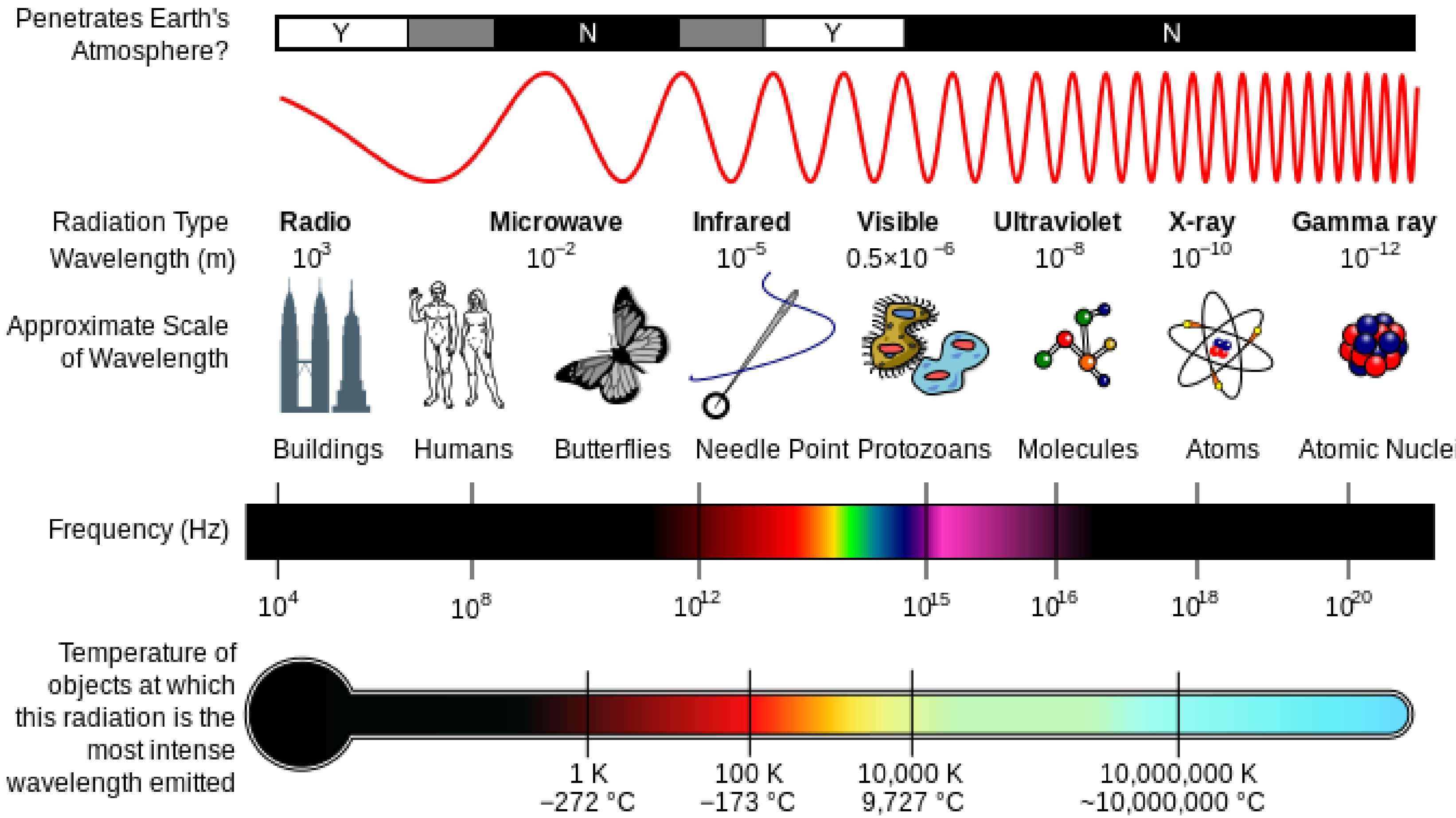
1886: Rudolf Heinrich Hertz descovers electromagnetic waves



Gravitational waves: an analogy

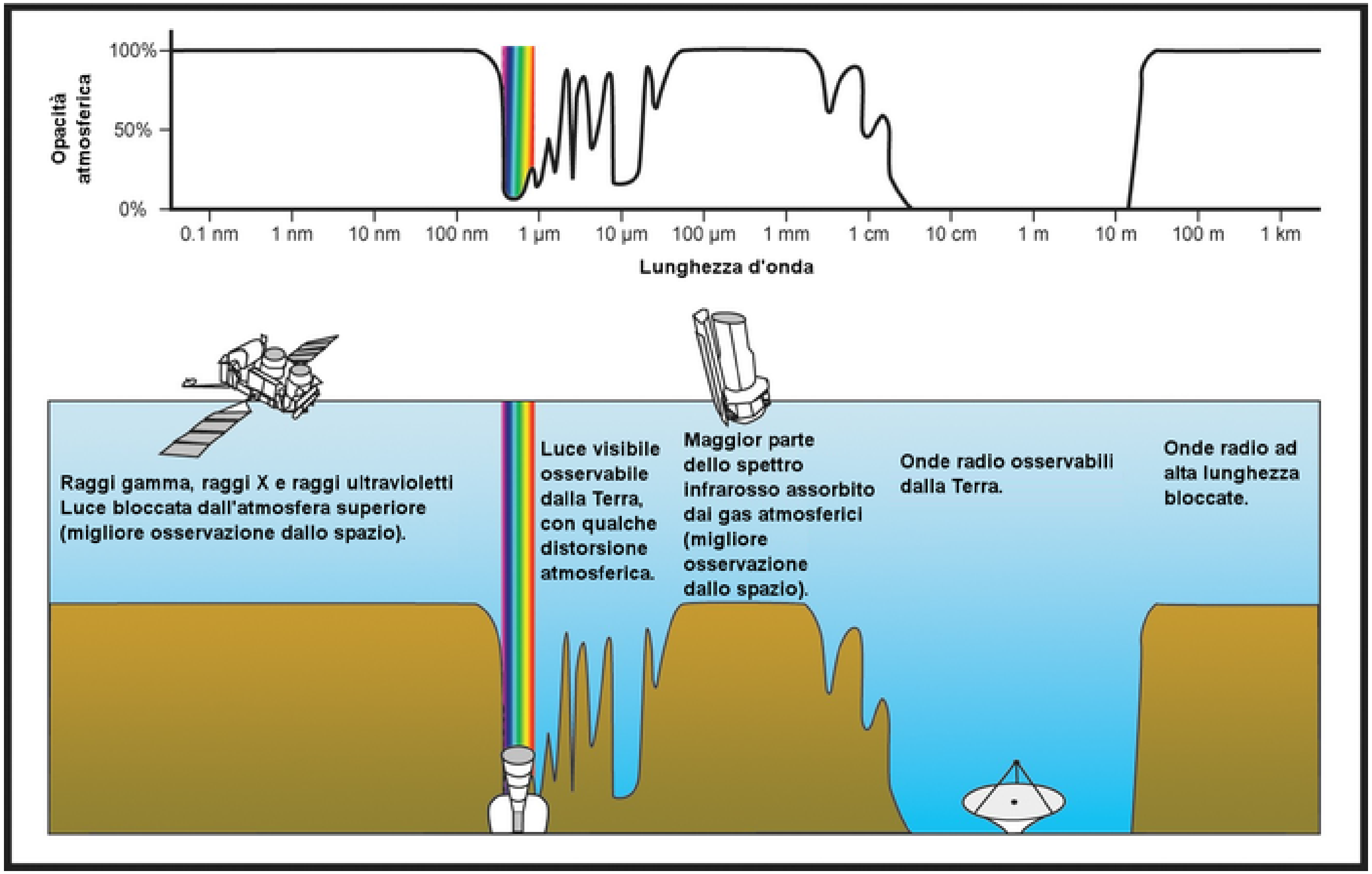


EM Spectrum

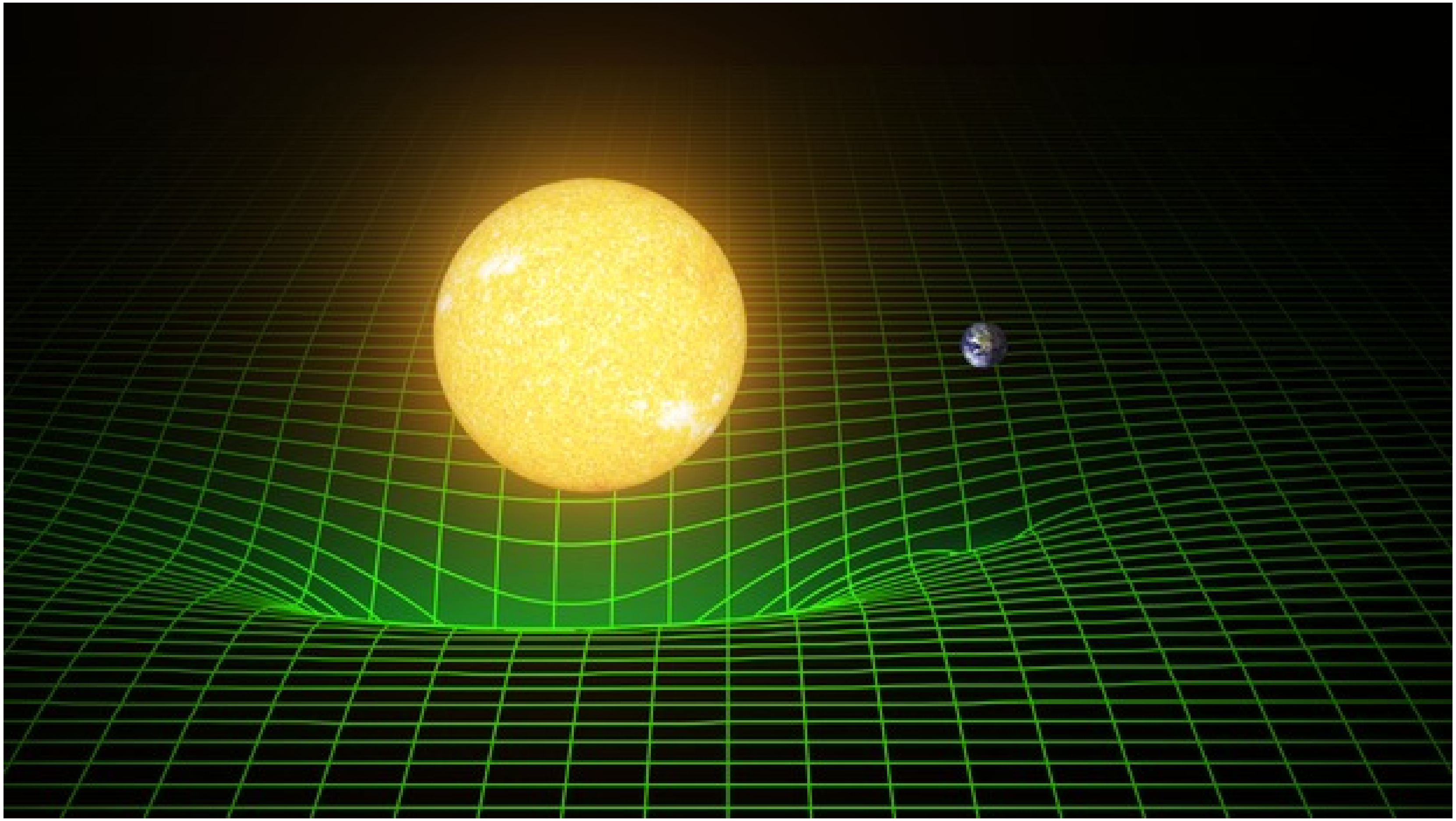


Penetrates Earth's Atmosphere?
Y
N
Y
N
Radiation Type
Wavelength (m)
Radio
10^3
Microwave
10^-2
Infrared
10^-5
Visible
0.5×10^-6
Ultraviolet
10^-8
X-ray
10^-10
Gamma ray
10^-12
Approximate Scale of Wavelength
Buildings
Humans
Butterflies
Needle Point
Protozoans
Molecules
Atoms
Atomic Nuclei
Frequency (Hz)
10^4
10^8
10^12
10^15
10^16
10^18
10^20
Temperature of objects at which this radiation is the most intense wavelength emitted
1 K
−272 °C
100 K
−173 °C
10,000 K
9,727 °C
10,000,000 K
~10,000,000 °C

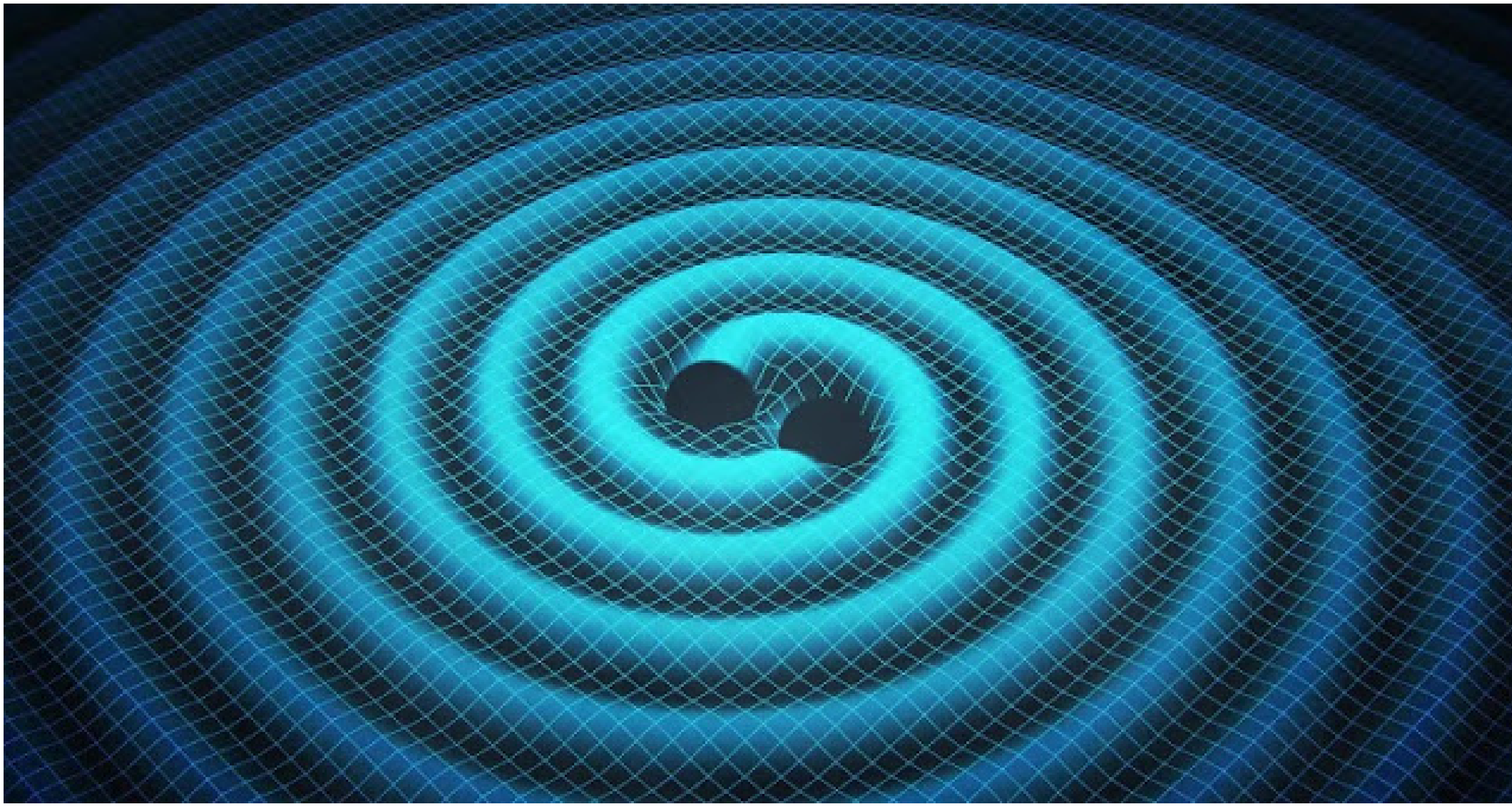
Electromagnetic waves from space to Earth



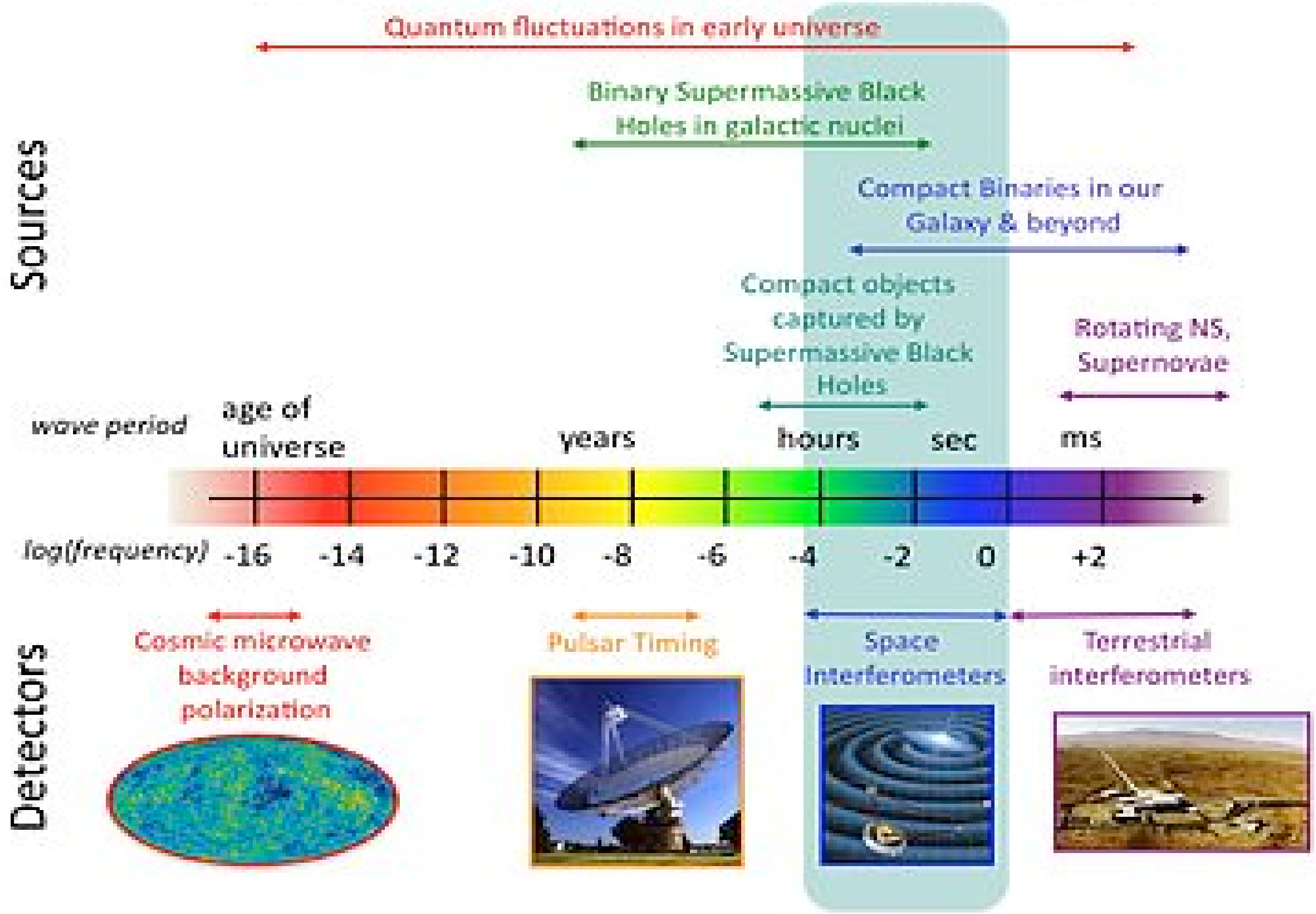
Masses bend the fabric of spacetime



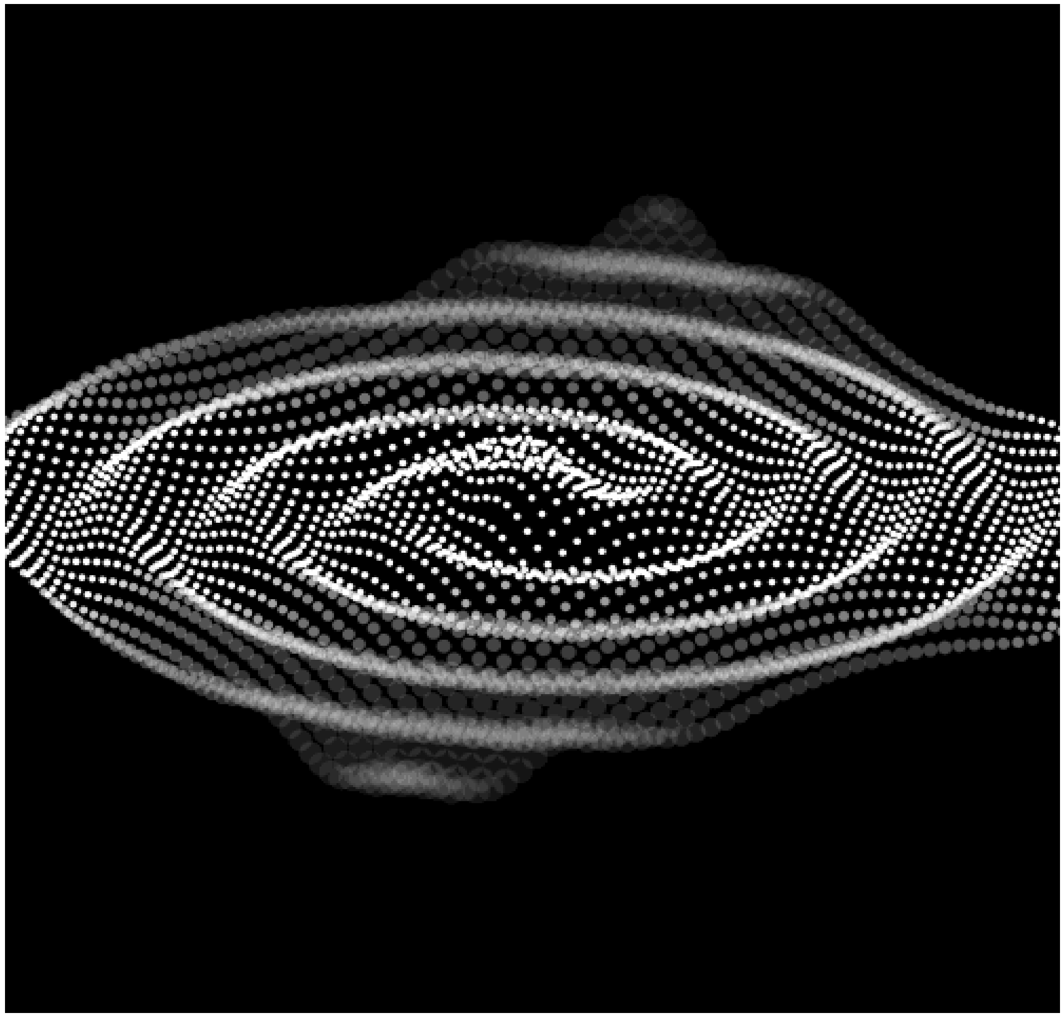
Gravitational wave generation



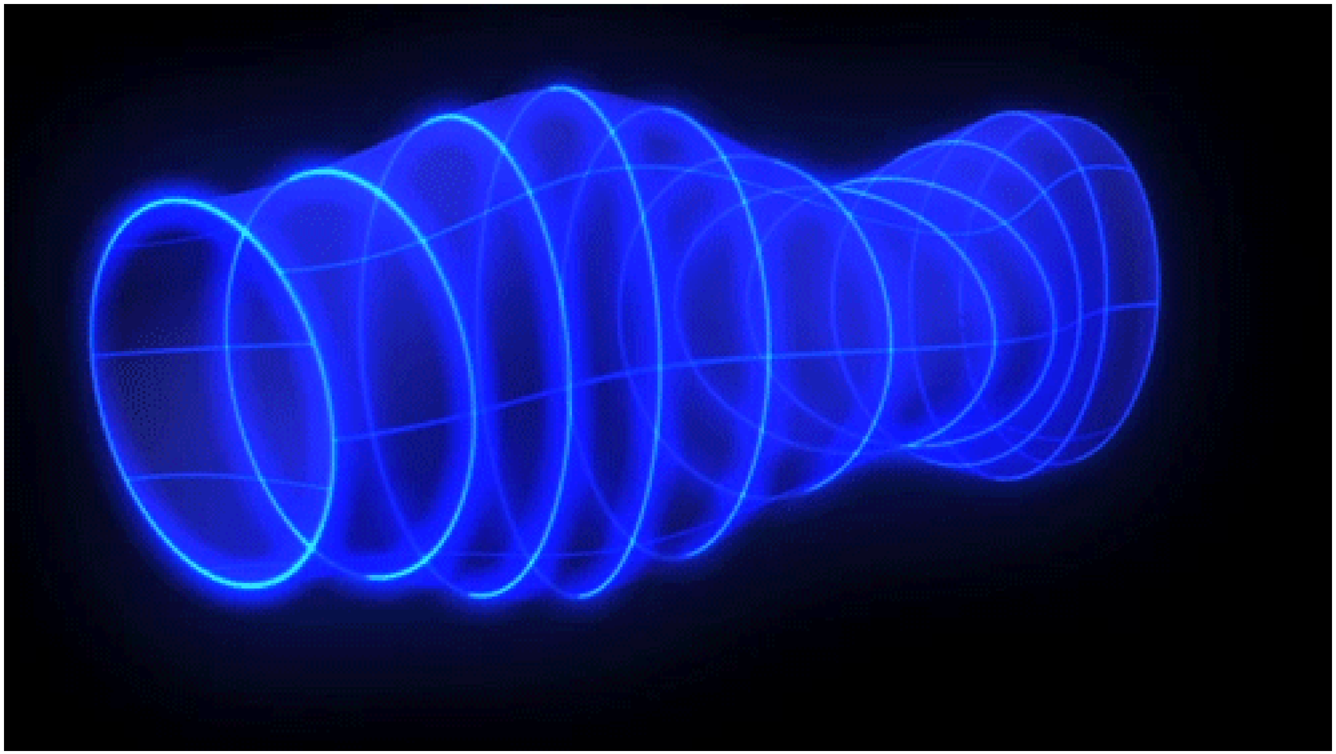
The Gravitational Wave Spectrum



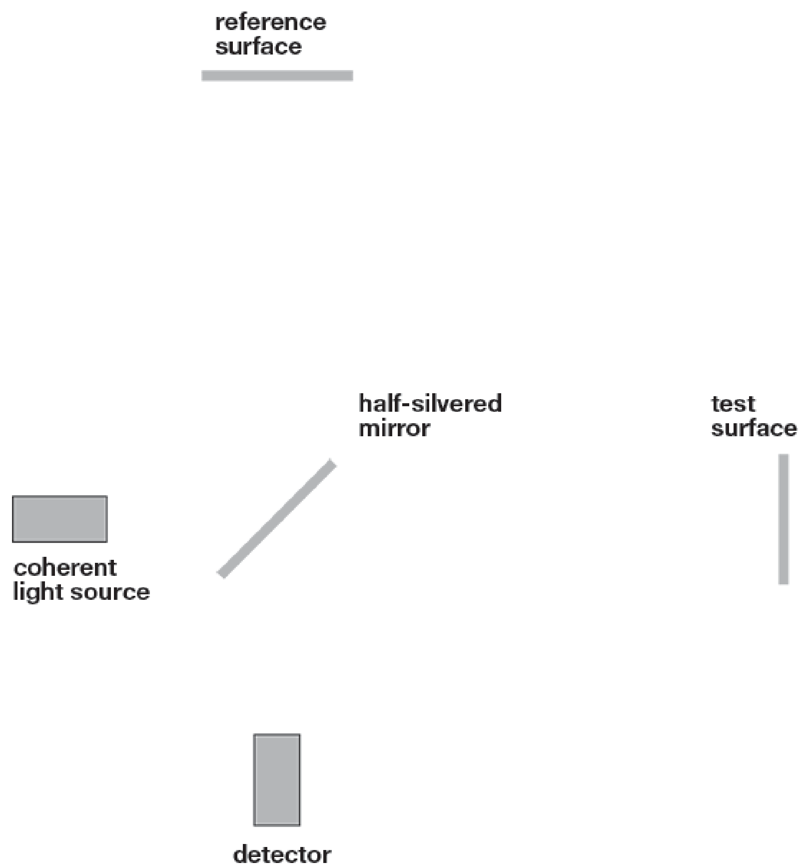
Gravitational waves



Gravitational waves: propagation

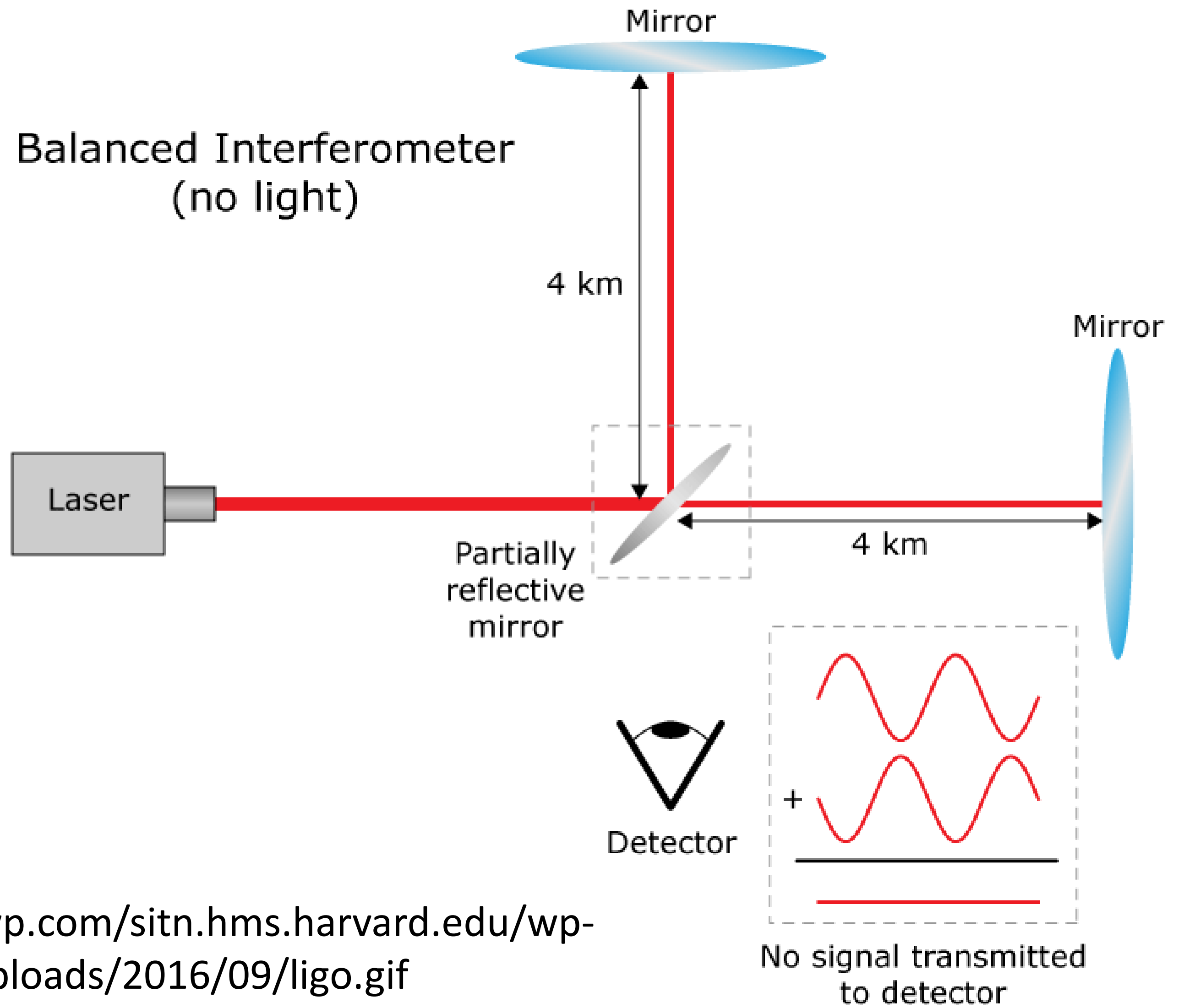


Interferometer



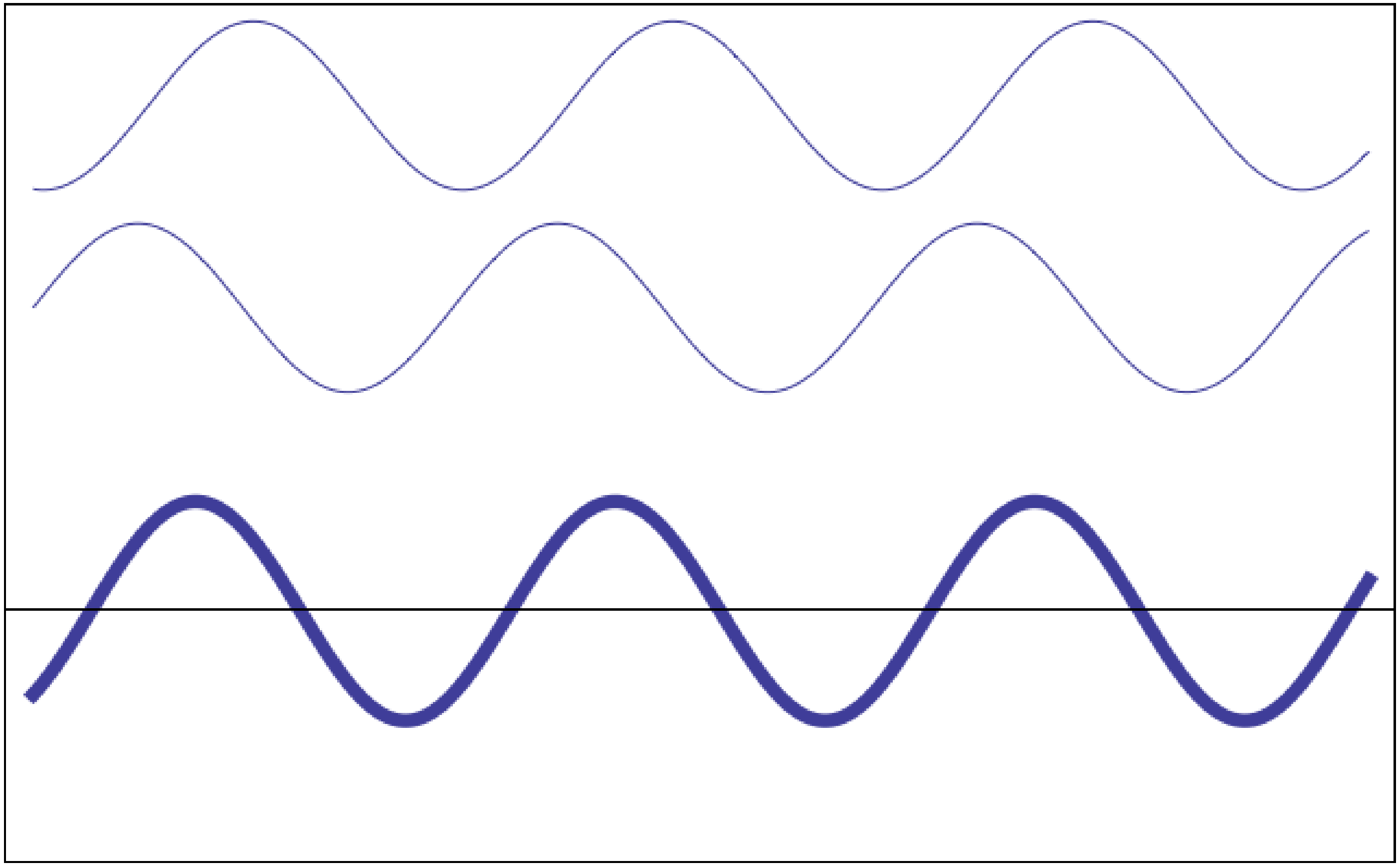
https://www.e-education.psu.edu/mcl-optpro/sites/www.e-education.psu.edu.mcl-optpro/files/Images/Basic%20Interferometer.gif

Interferometer



http://i2.wp.com/sitn.hms.harvard.edu/wp-content/uploads/2016/09/ligo.gif

Wave superposition

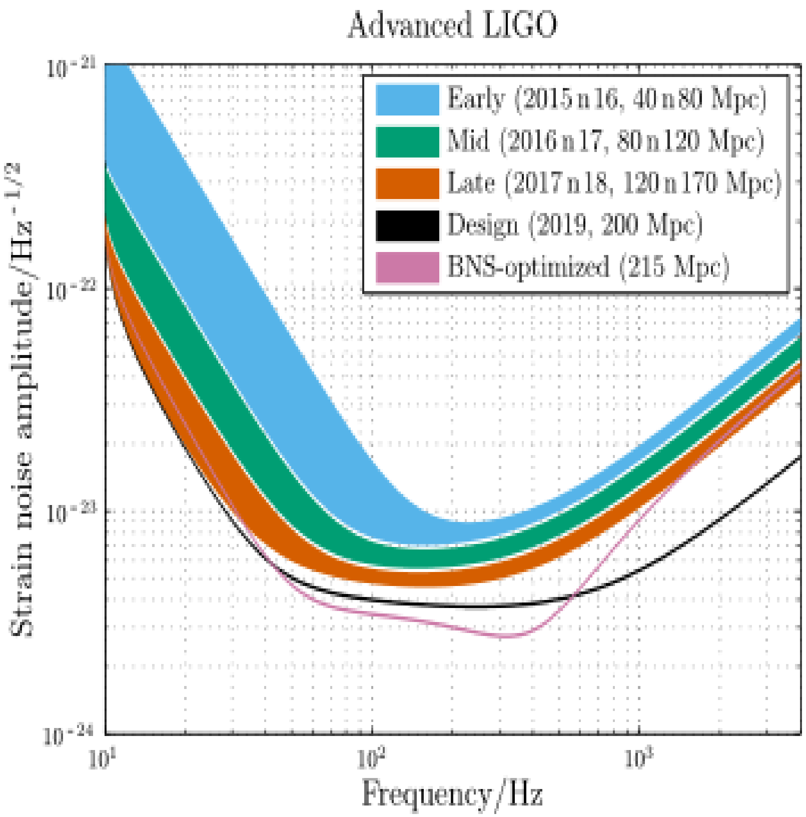


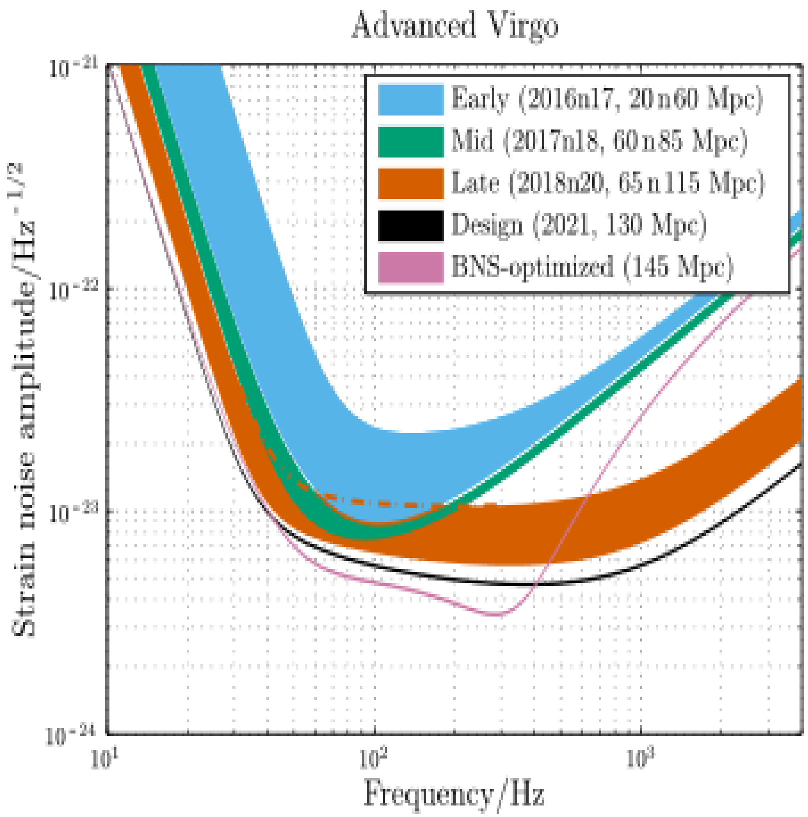
https://www.e-education.psu.edu/mcl-optpro/sites/www.e-education.psu.edu.mcl-optpro/files/Images/Interferometer-Scanning%20resultant.gif

LIGO Interferometers

Virgo interferometer

LIGO & Virgo Sensitivities



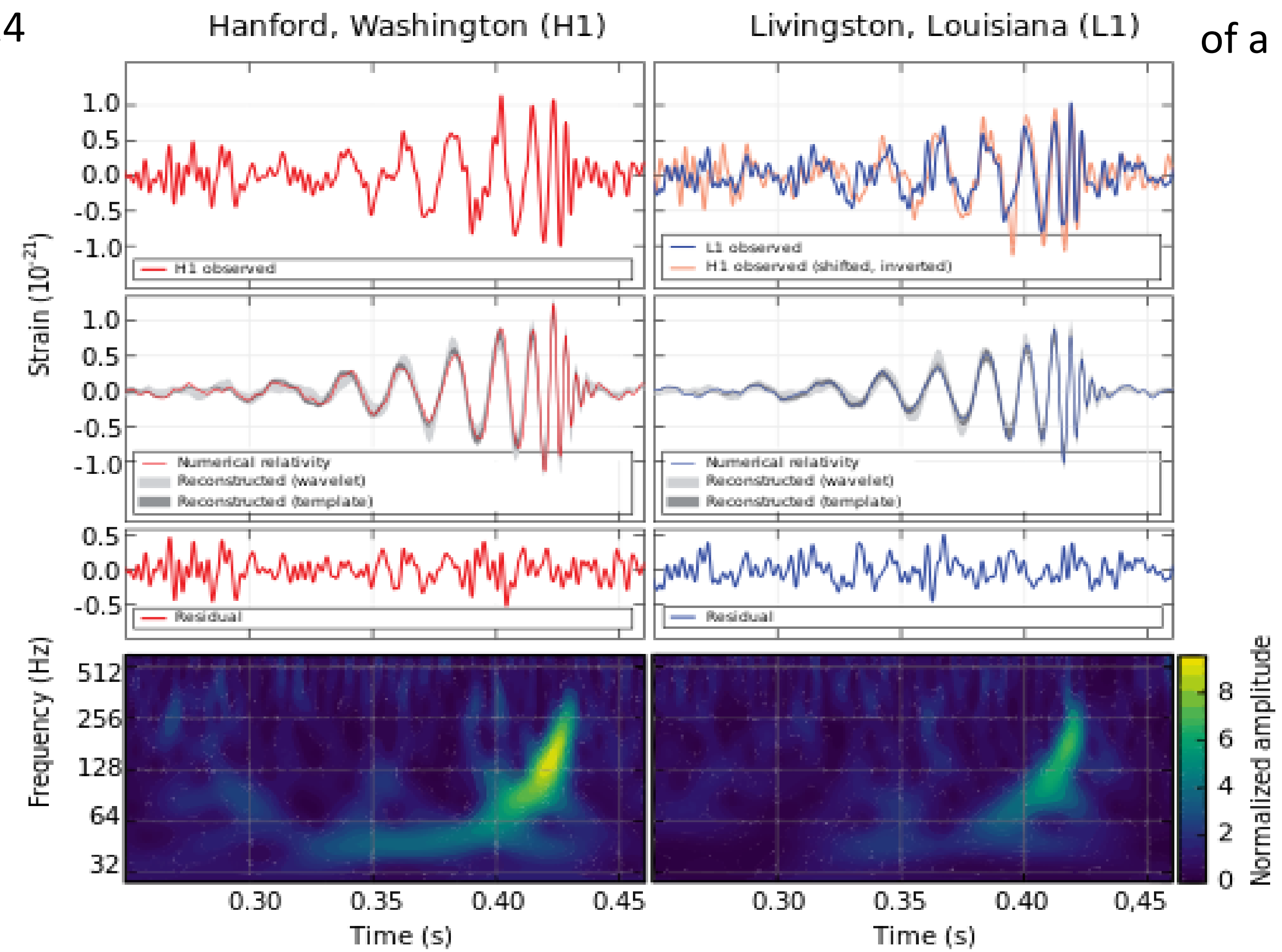


LIMITED AT LOW FREQUENCIES BY SISMIC NOISE!

FIRST GRAVITATIONAL WAVE DETECTION WITH LIGO

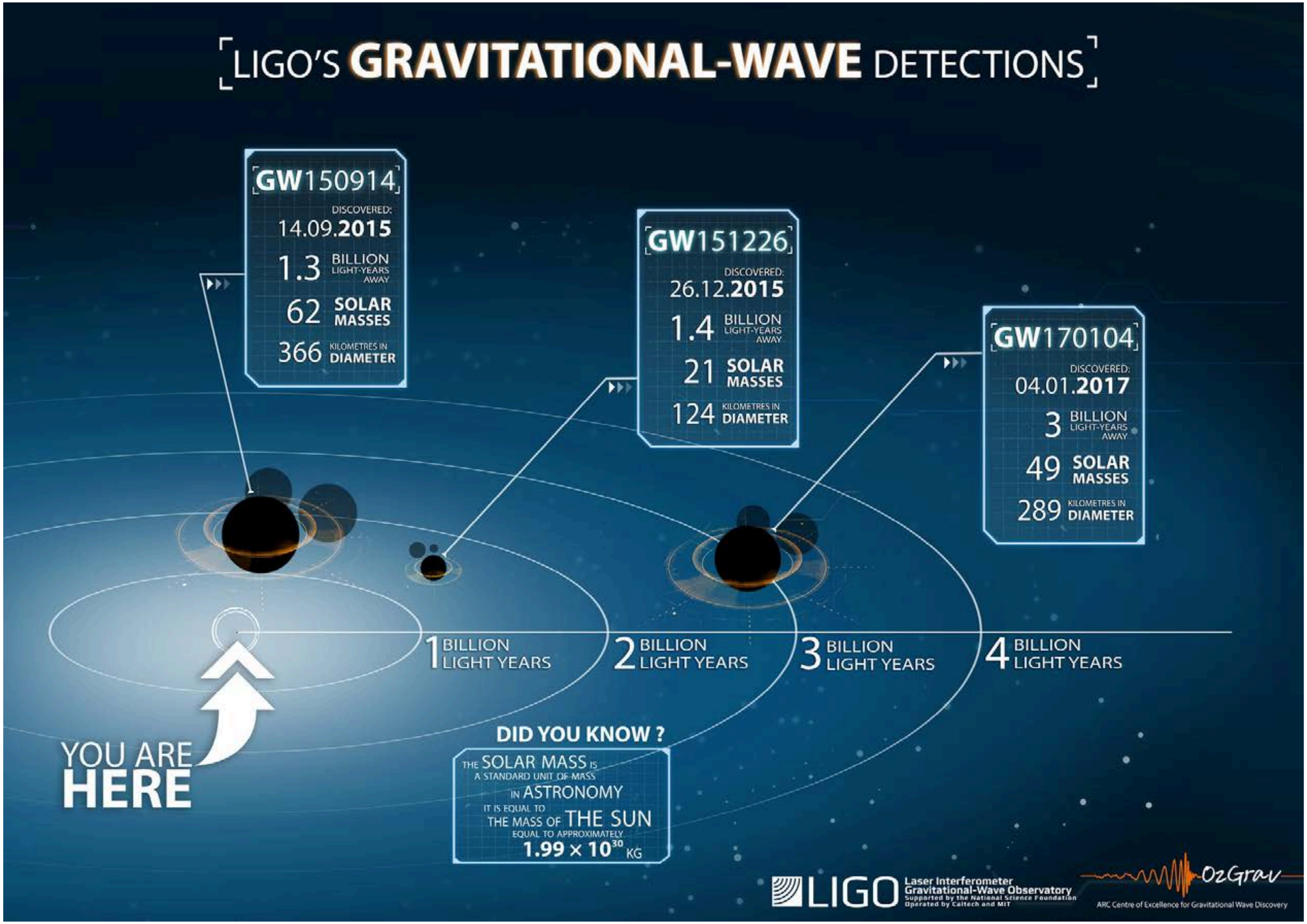
A billionth part of the dimension of a proton

GW150914



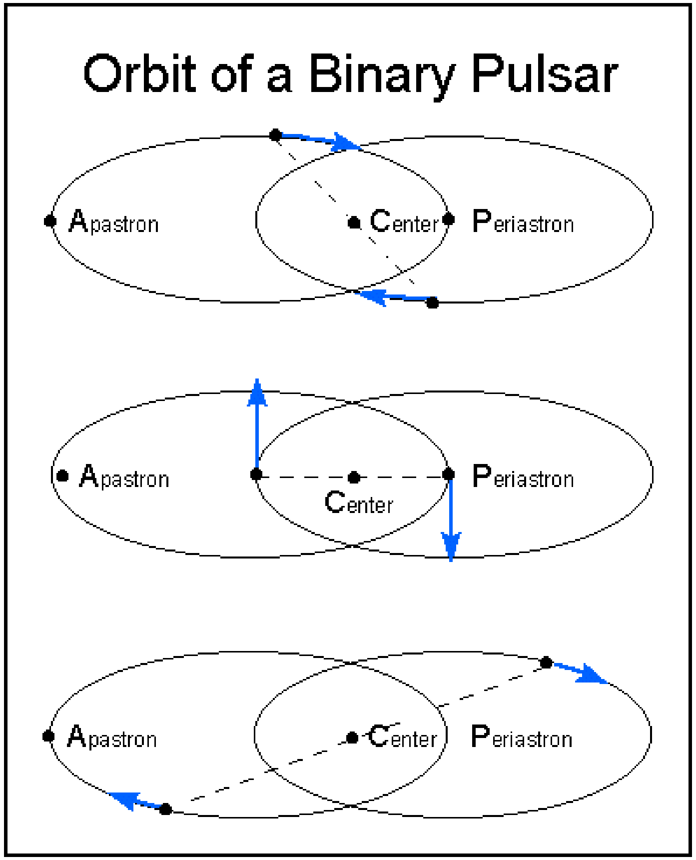
Merging of two stellar black holes 1 billion and 300 million lys away from the solar system

LIGO BH-BH detections

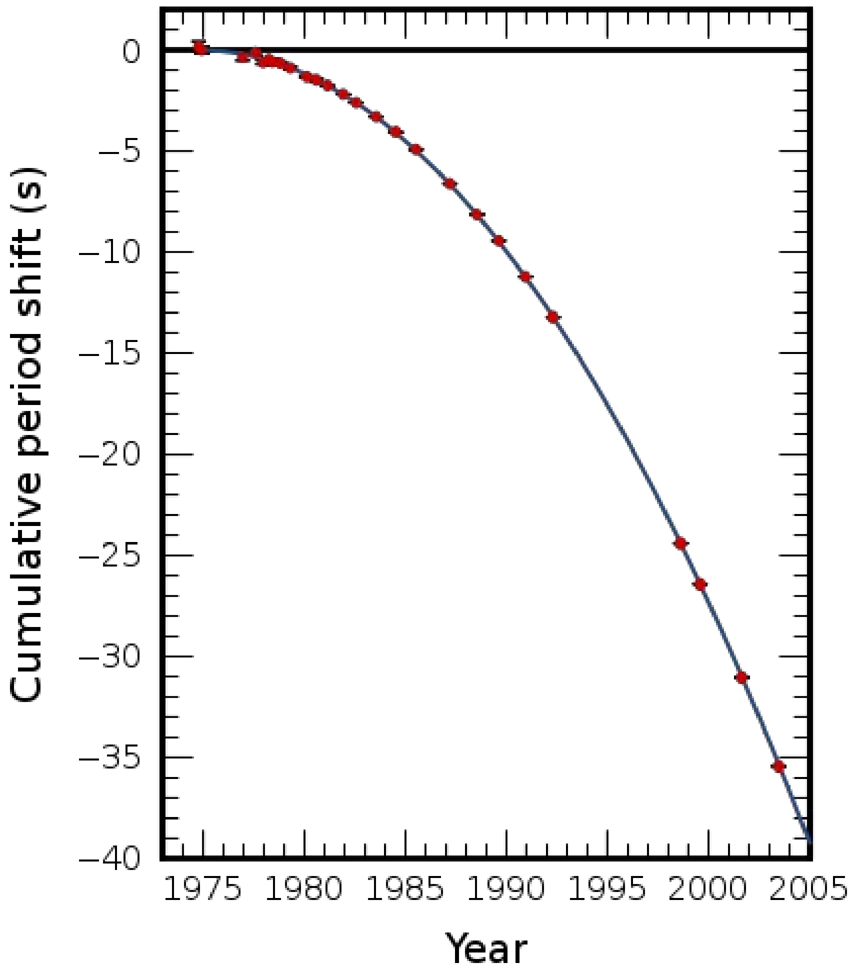


The indirect discovery

1993: The Physics Nobel prize is assigned to Russell Alan Hulse e Joseph Hooton Taylor for the discovery of the first binary system NS-NS (pulsar+NS) collapsing as predicted by GR

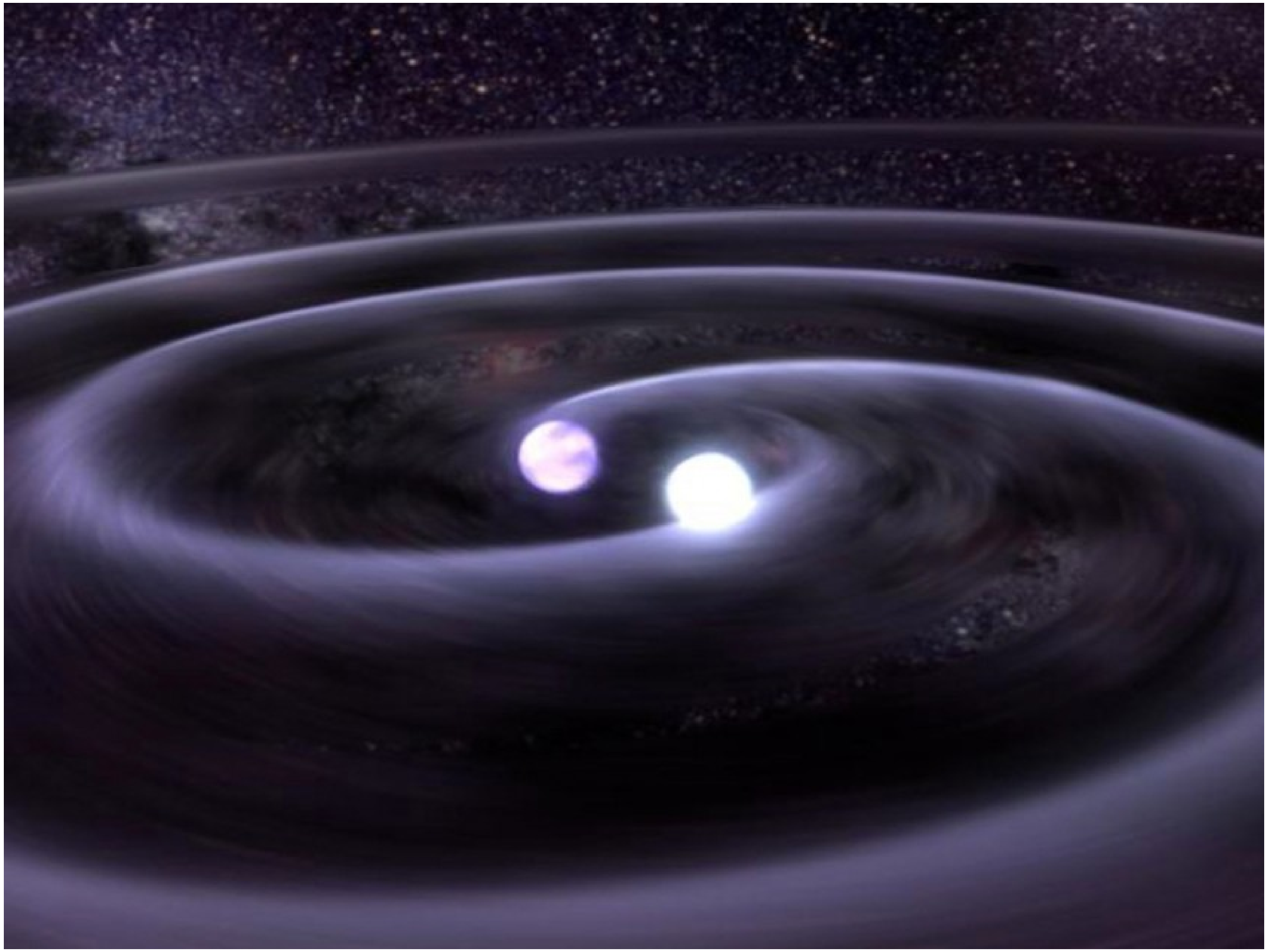


Variation of the PSR 1913+16 orbit

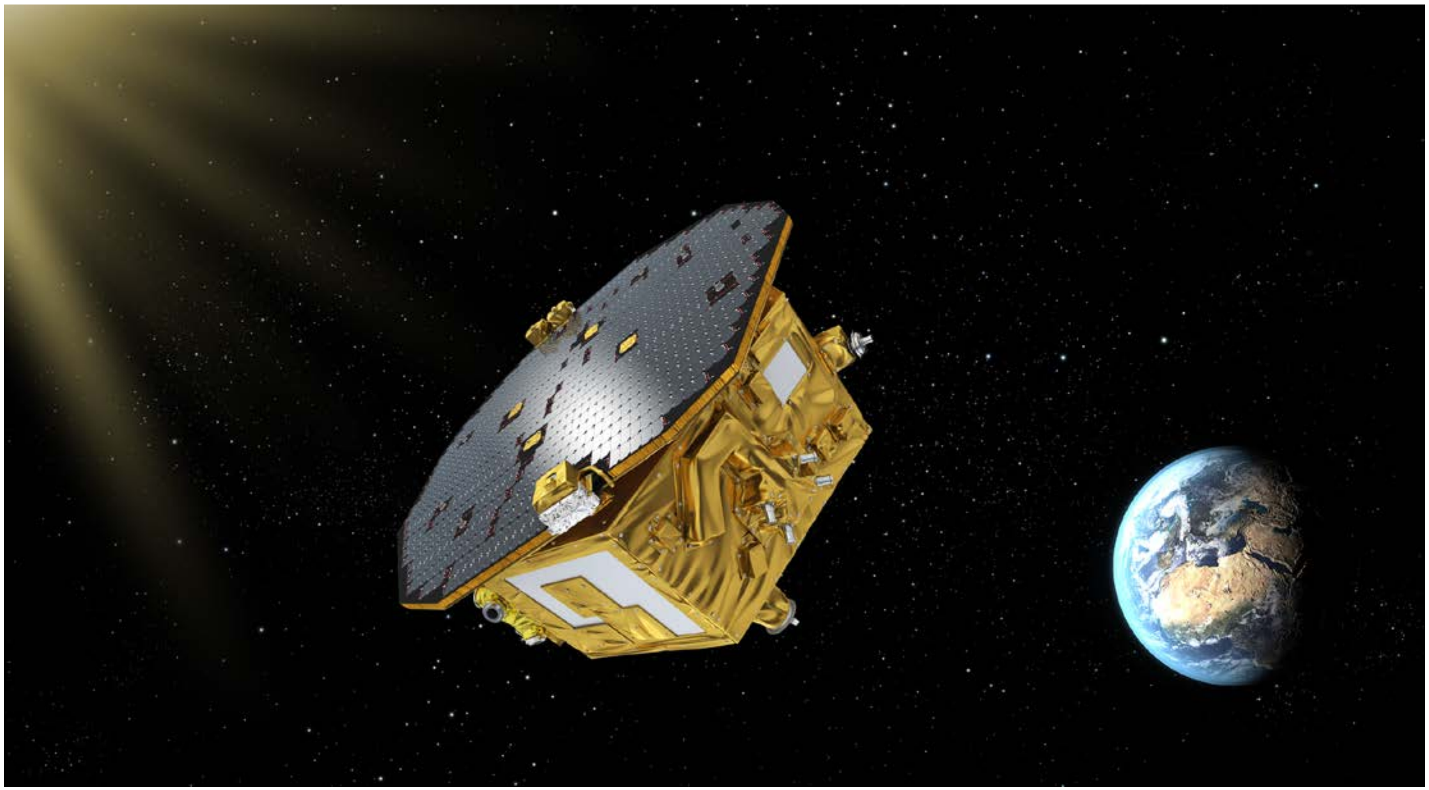


NS-NS merging

GW170817
GRB 170817A
1.7 s after
coalescence

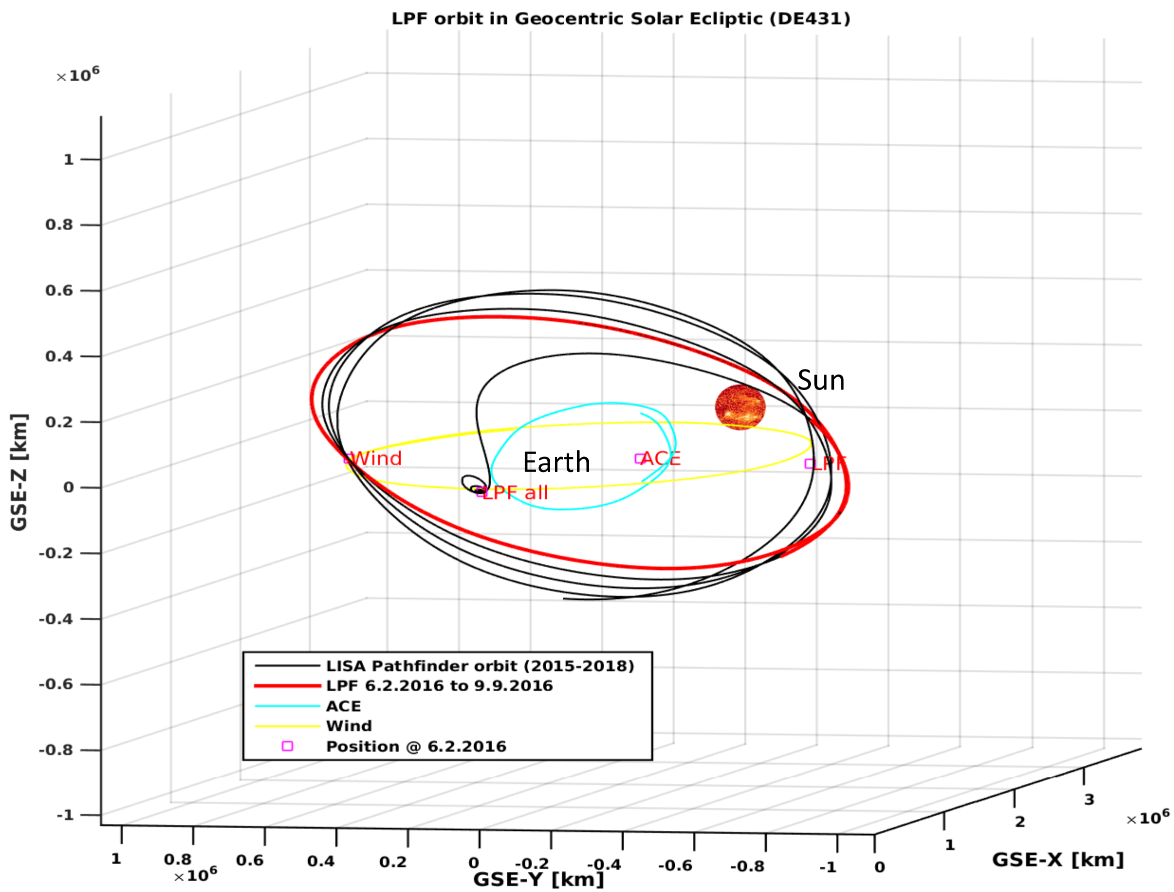


The ESA LISA Pathfinder mission



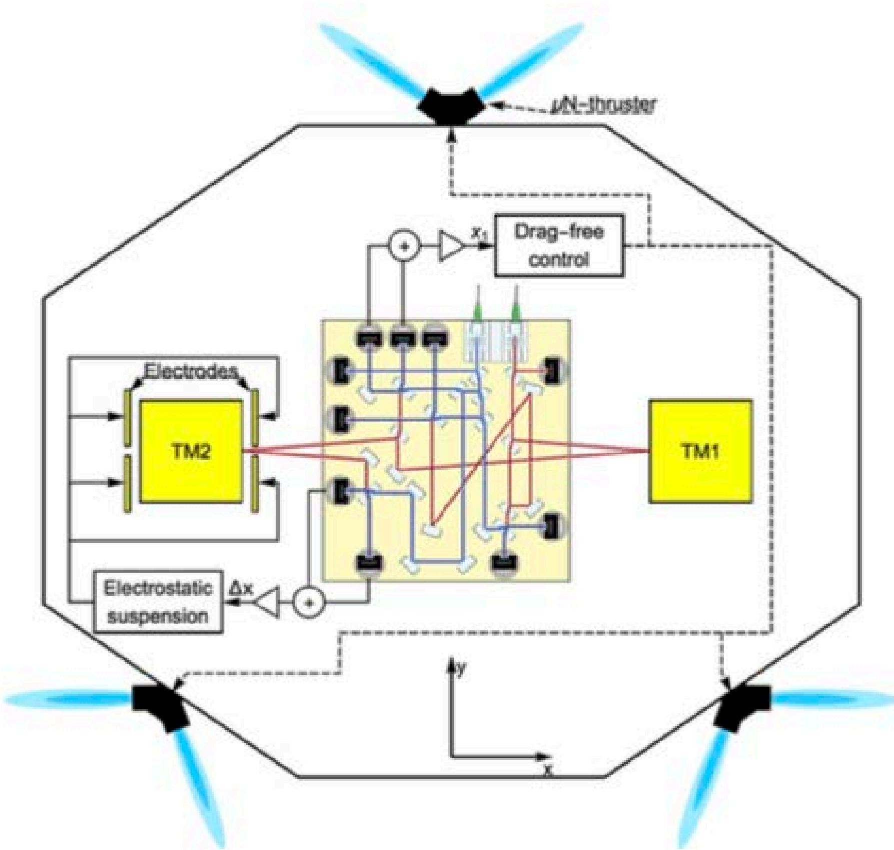
Lunch: 3 December 2015 from Kourou (French Guiana) 4:04 GMT
Mission end: 18 July 2017

LISA-PF orbit around L1



Courtesy of A. Cesarini

LISA Pathfinder experimental set-up



Test-masses: located within a metal enclosure for electromagnetic shielding and actuation on 6 degrees of freedom. Spurious forces act on the test-masses: the most intense being the coulombian forces at low frequencies due to galactic cosmic rays and solar energetic particles .

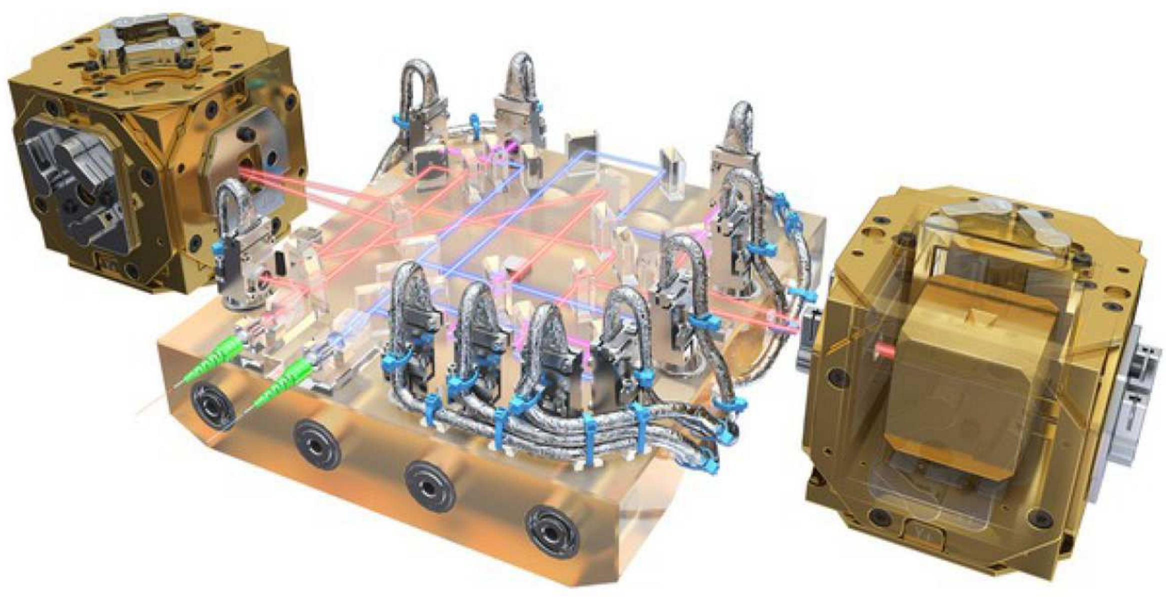
We developed a mission dedicated environmental study for LISA Pathfinder and the future space interferometers.

Masses are discharged with ultra violet light beams.

Two independent interferometers measure (1) the displacement between two test masses and (2) the displacement between test mass 1 and the spacecraft.

Armano et al., PRL, 116, 231101, 2016
Armano et al., PRL, 120, 061101, 2018

LISA Pathfinder test masses

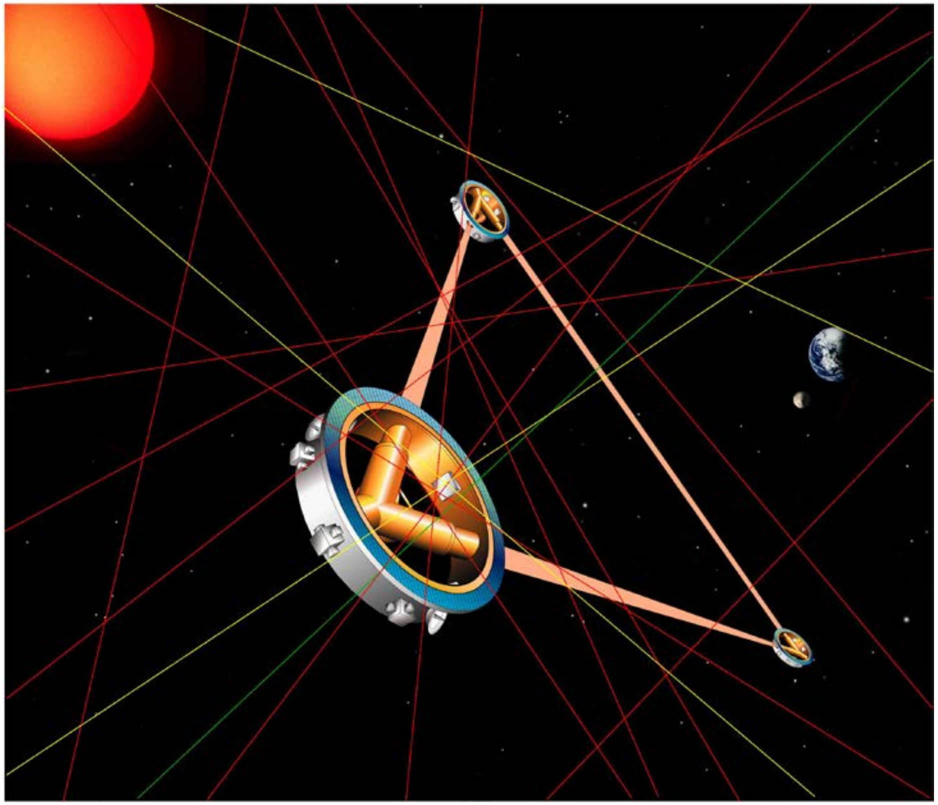


Test masses:
Cubes of 70% Pt-30% Au
4.6 cm side
2 kg mass
38 cm distance

Approximately 13 g cm^{-2} of material surround the test masses

Armano et al., PRL, 116, 231101, 2016

LISA mission



Three satellites

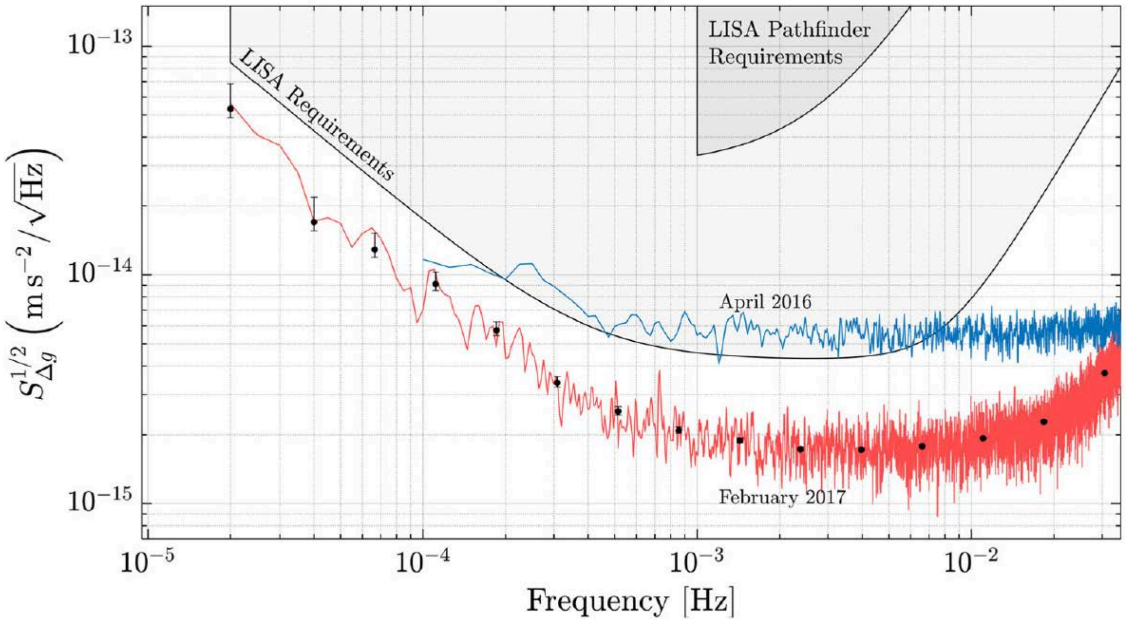
2.5 million kilometers arm

Orbiting on the ecliptic

50 million kilometers
behind Earth

Sources: 10^6-10^9 solar masses
black holes
Intermediate mass black holes
Galactic binaries

LISA-PF results



Armano et al., PRL, 120, 061101, 2018

Amplitude spectral density: at 1.74 ± 0.01 fm s^{-2} / $Hz^{0.5}$ above 2 mHz and (6 ± 1) x 10 fm s^{-2} / $Hz^{0.5}$ at 20 μHz

A factor of 10 better than LPF requirements before mission and better than a factor of two than LISA requirements.
Some residual brownian noise
And above 60 mHz there is noise of interferometer displacement

Lisa Pathfinder has shown to have a billionth of a ten millionth of gravitational acceleration

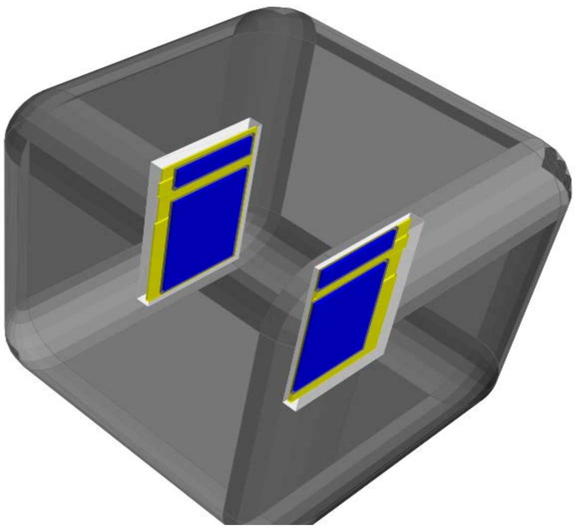
Diagnostics detectors for interplanetary medium monitoring

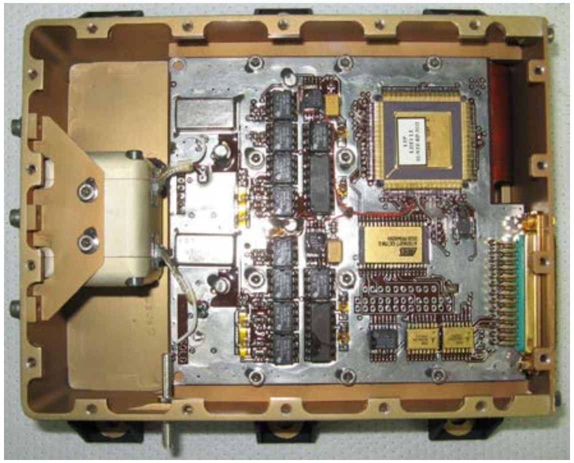
- Particle detectors (GCRs + SEPs: Particle integral fluxes E> 70 MeV/n)
- Magnetometers (a few nT resolution)

CHARACTERISTICS OF THE PARTICLE DETECTOR

P. Cañizares et al., CQG, 28, 094004, 2011

2 silicon wafers 1.4x1.05x0.03 cm^3
allocated in a copper box of 6.4 mm thickness
detect minimum ion energies of 70 MeV/n



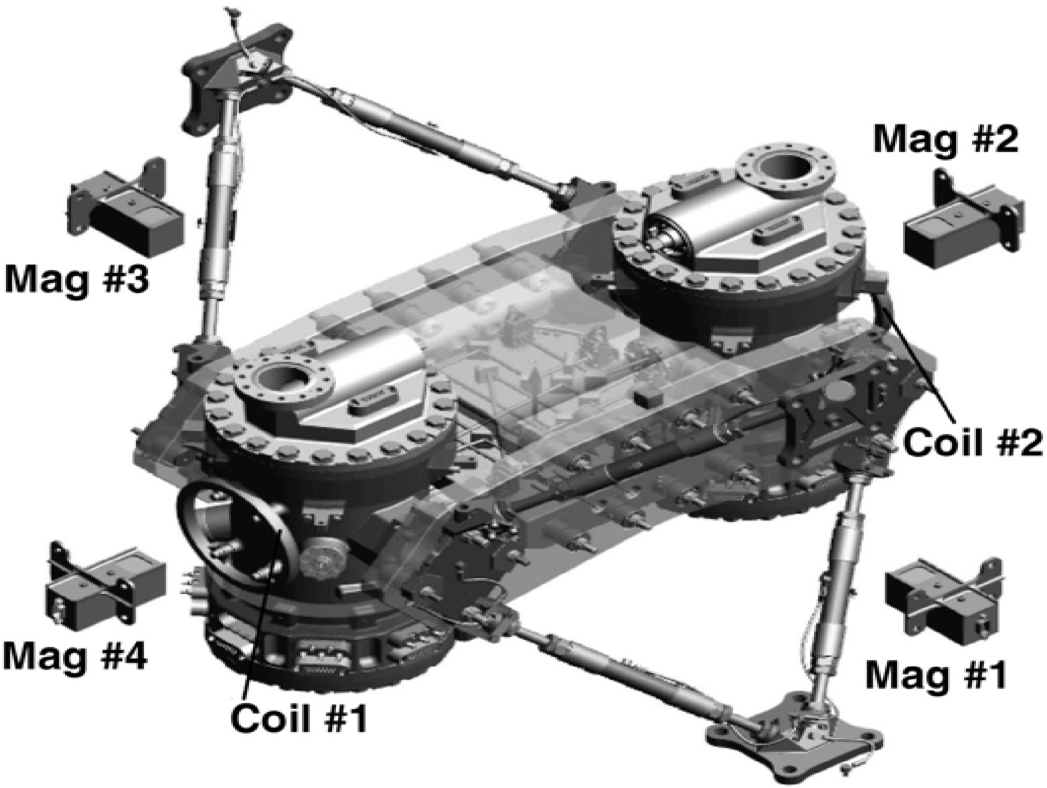


Counting rate GCR 0.067 Hz. Variations of the order of 1% will be observed with one hour binned data

$$\frac{S}{N} \simeq \frac{A}{\sigma}\sqrt{N_{TB}}$$

C. Grimani et al., CQG, 32, 35001, 2015

LISA-PF MAGNETOMETERS

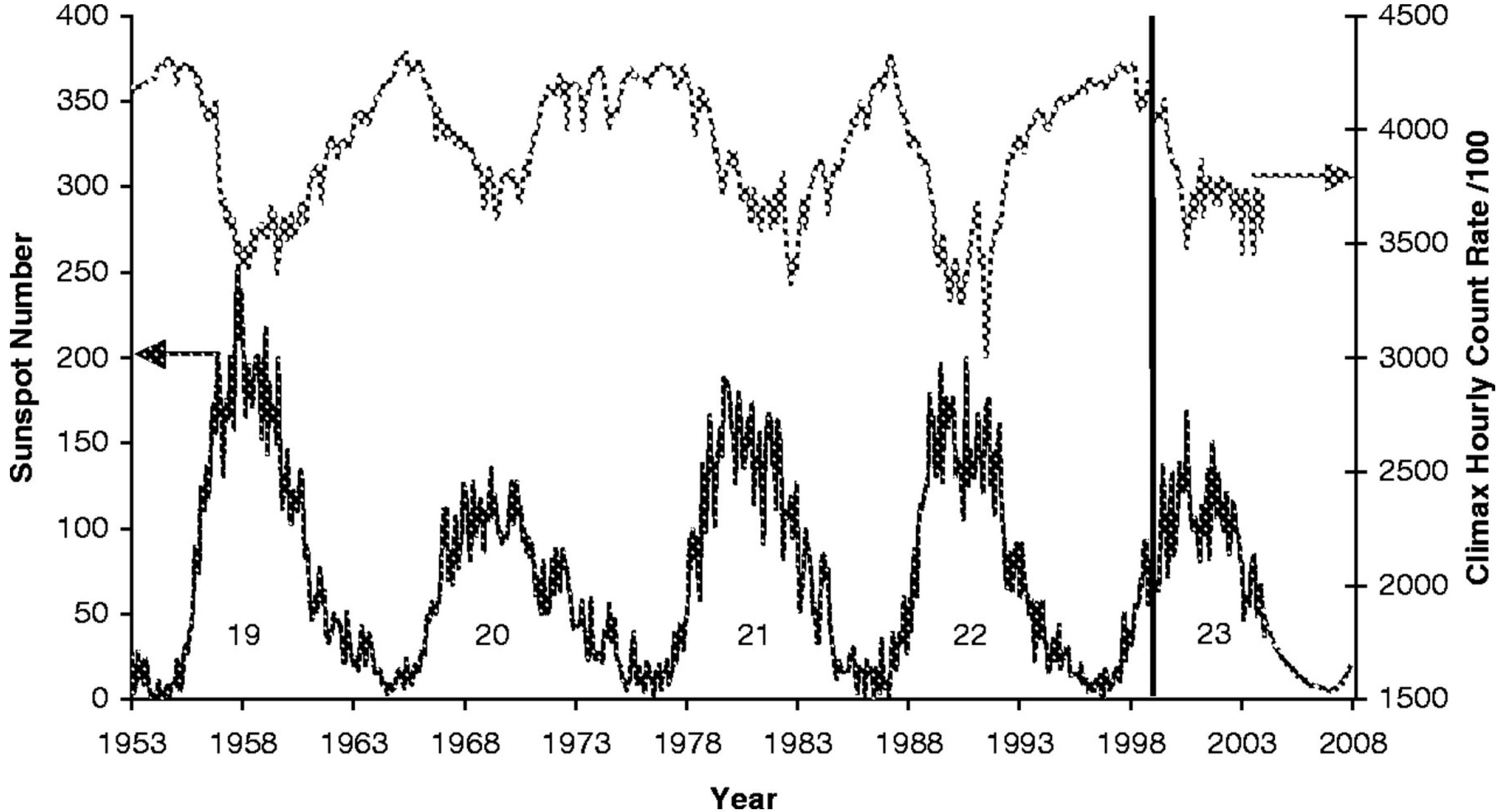


Courtesy of M. Nofrarias

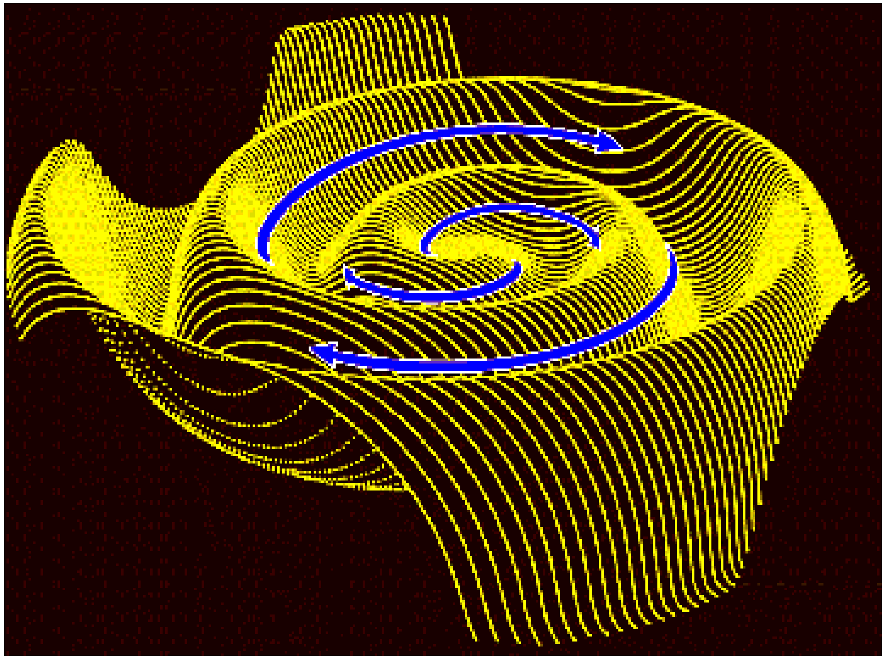
4 fluxgate magnetometers
and 2 coils are placed around the test masses
Present a few nT resolution in the IP magnetic field measurements

Sunspot and cosmic-ray intensity

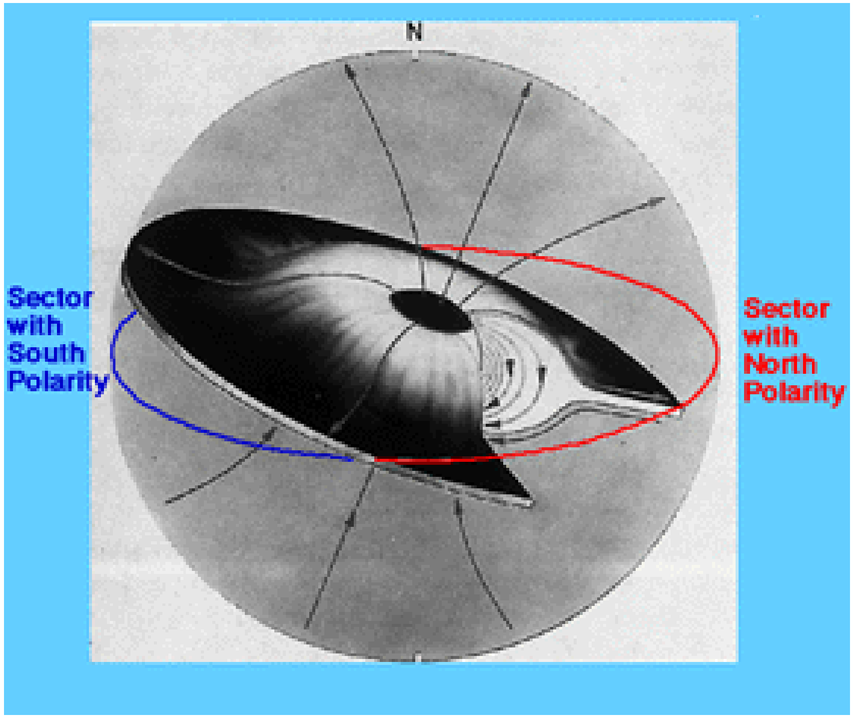
We provide projections of galactic cosmic-ray spectra



INTERPLANETARY MAGNETIC FIELD SHAPE

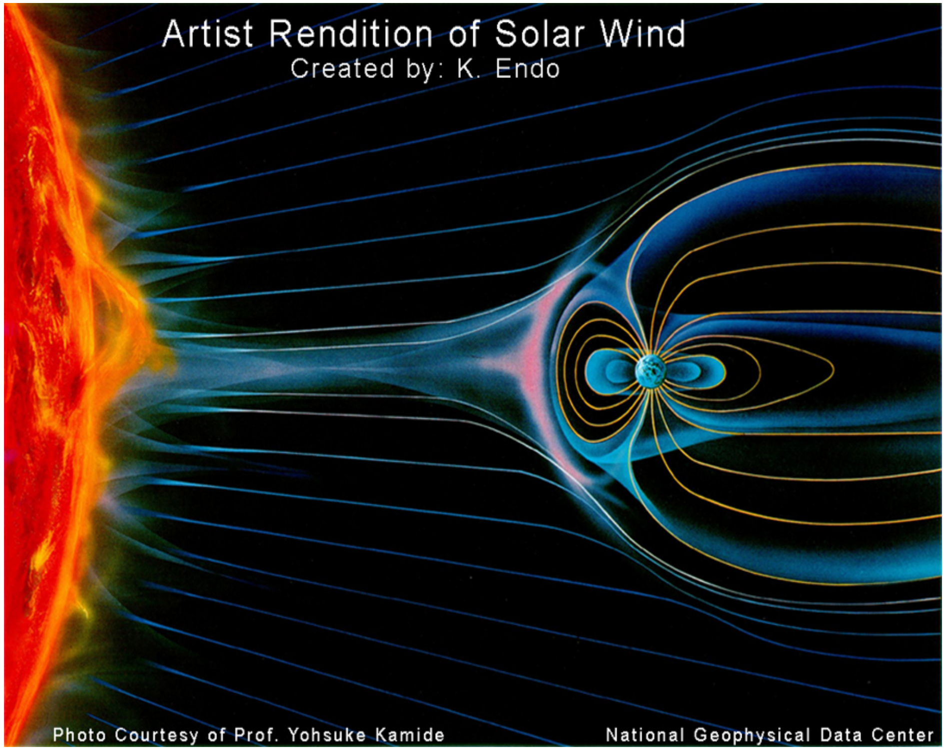


IP magnetic field near Earth: 7 nT



GCRs modulation

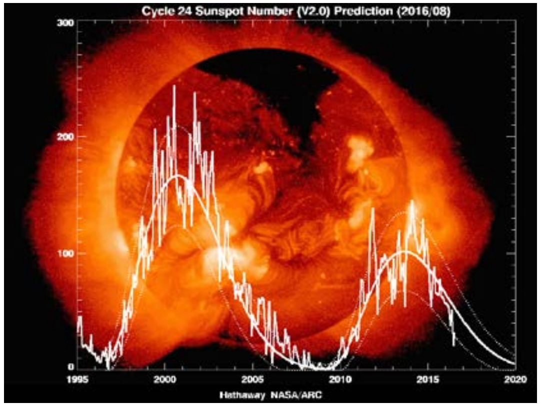
- Solar activity intensity (11 year cycle)
- Effects of the interplanetary magnetic field (22-year cycle; last change of polarity in december 2013: now positive polarity)



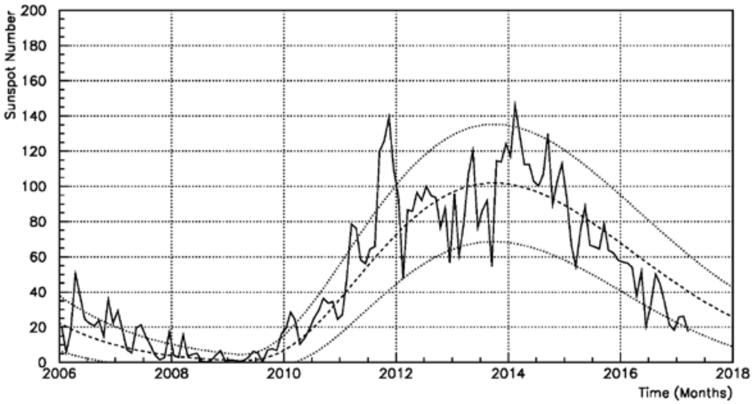
10^6 tons/s p,e^-
6 part/cm^3 near Earth

200-800 km/s
0.3-5 keV

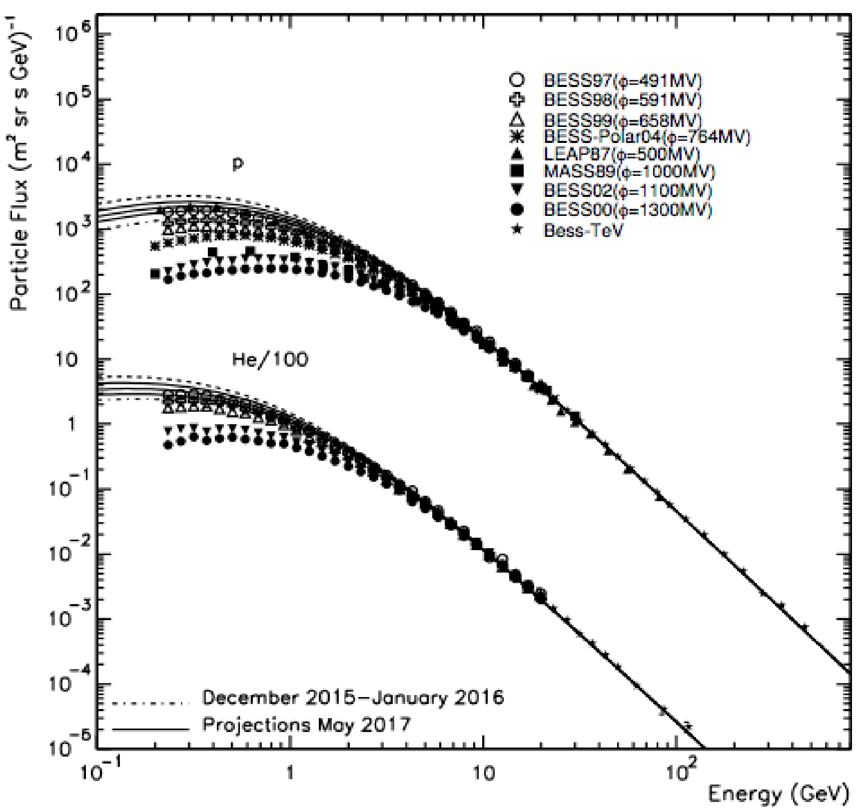
solarscience.msfc.nasa.gov/predict.shtml

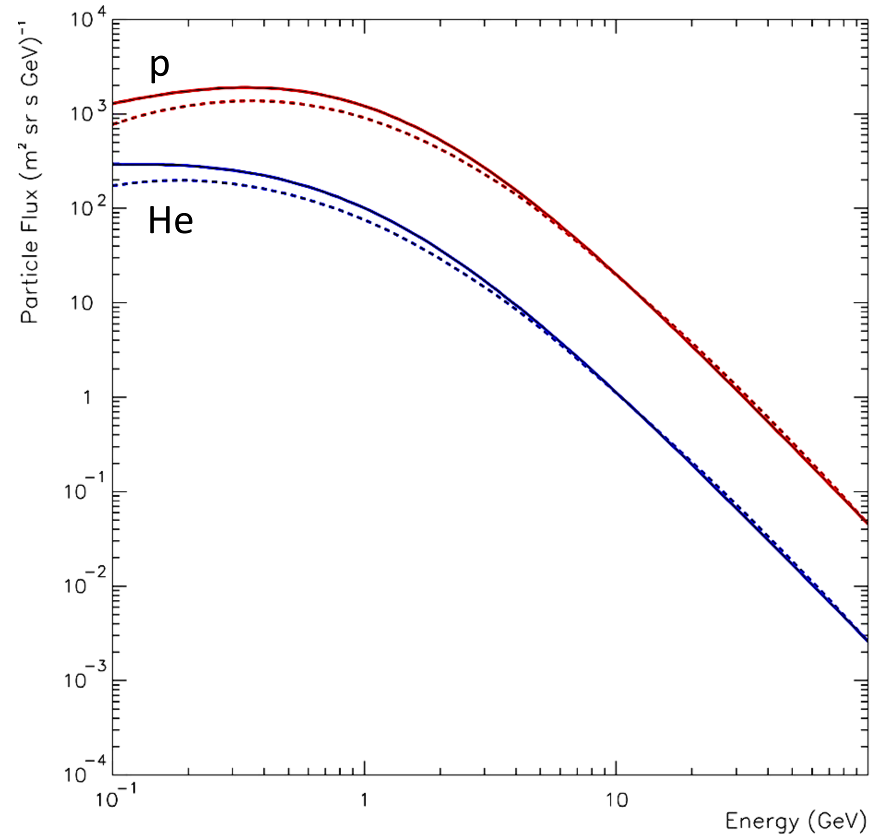


Solar cycle N 24 projections



GCR energy spectra and LPF projections





CG et al., CQG, 29, 105001, 2012
Shikaze et al., Astropart. Phys., 28, 154, 2007

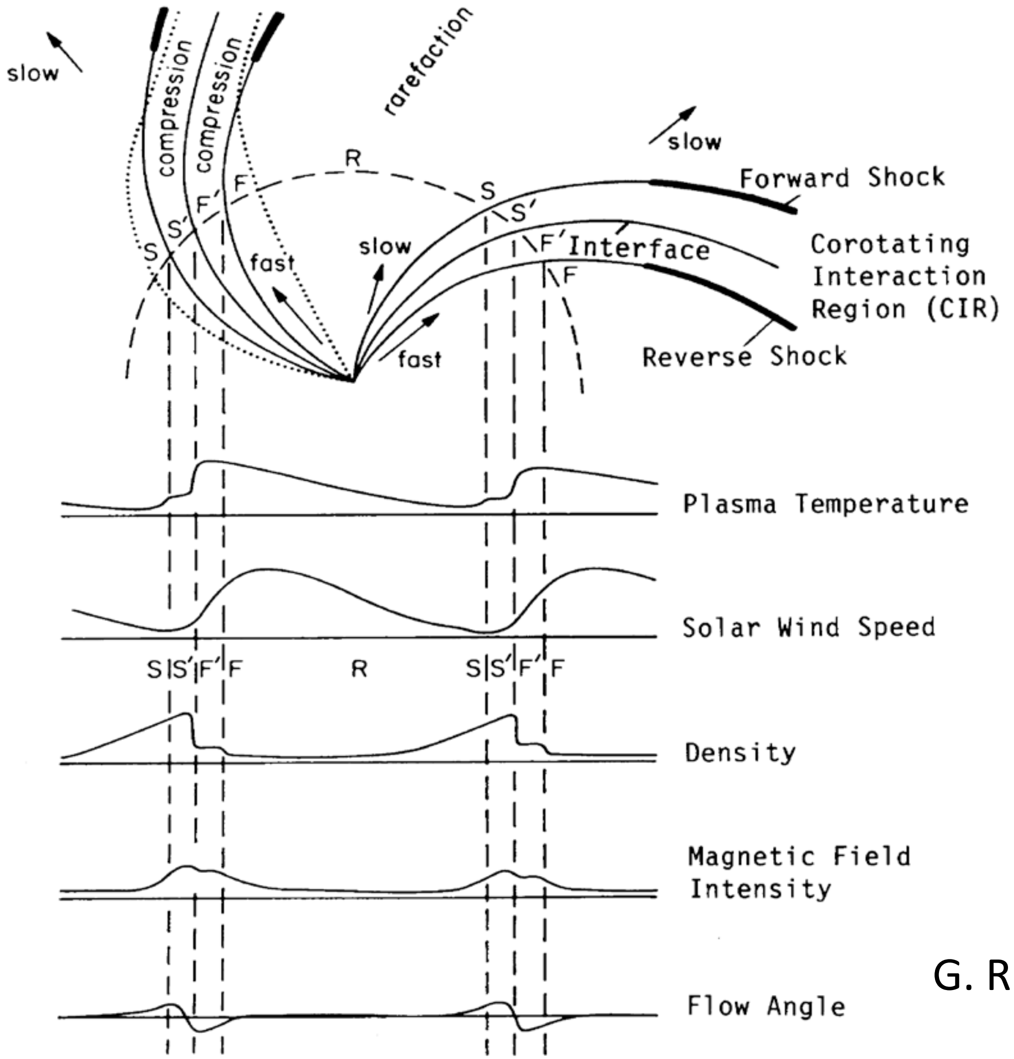
Boella et al., JGR, 106, 29, 355, 2001

GCR SHORT-TERM VARIATIONS

- Duration < 1 Bartels rotation (number of 27-day rotations of the Sun since 8 February 1832 – day one rotation one)
- GCR short-term variations appear correlated to the Sun rotation periodicity and its harmonics (Sabbah and Kudela, 2011; Mlynczak et al.; 2008)
- Two Forbush decreases were observed after the LISA-PF launch (ONE INCOMPLETE DUE TO MISSION END)
- The interplanetary plasma key parameters are studied to find correlations with interplanetary structures
- The solar wind plasma parameters measured by the ACE spacecraft are considered

CG et al.; CQG, 32, 35001, 2015

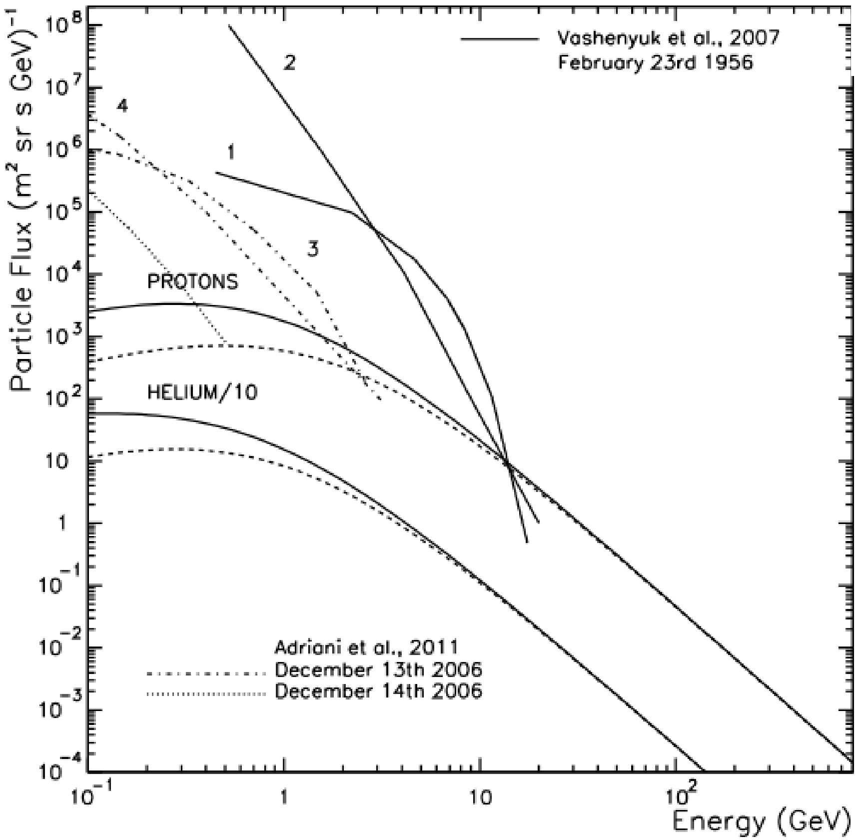
FAST-SLOW SOLAR WIND INTERACTIONS



G. Richardson, Sp. Sc. Rev., 2004

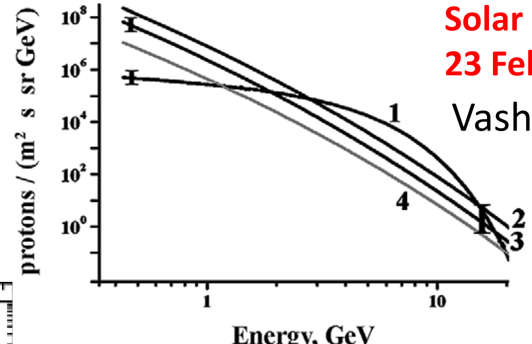
RCG in 2015 and SEP events

CG et al., JPCS 409 (1), 012159,2013

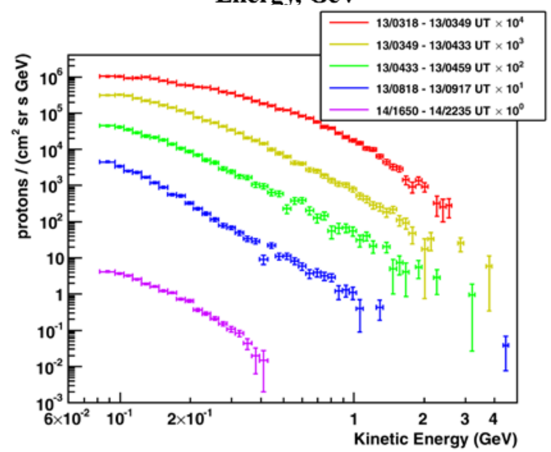


Solar particle event
23 Febbraio 1956

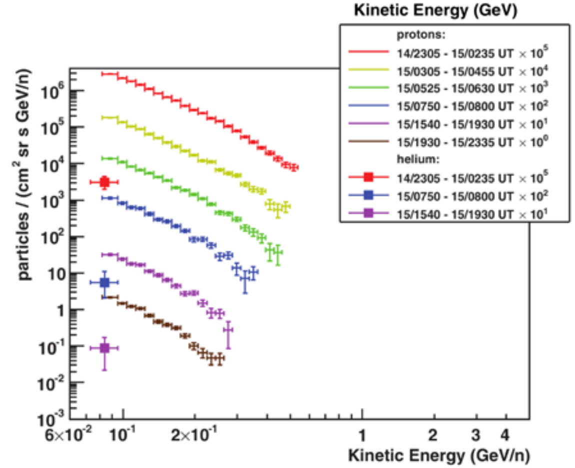
Vashenyuk et al., 2007



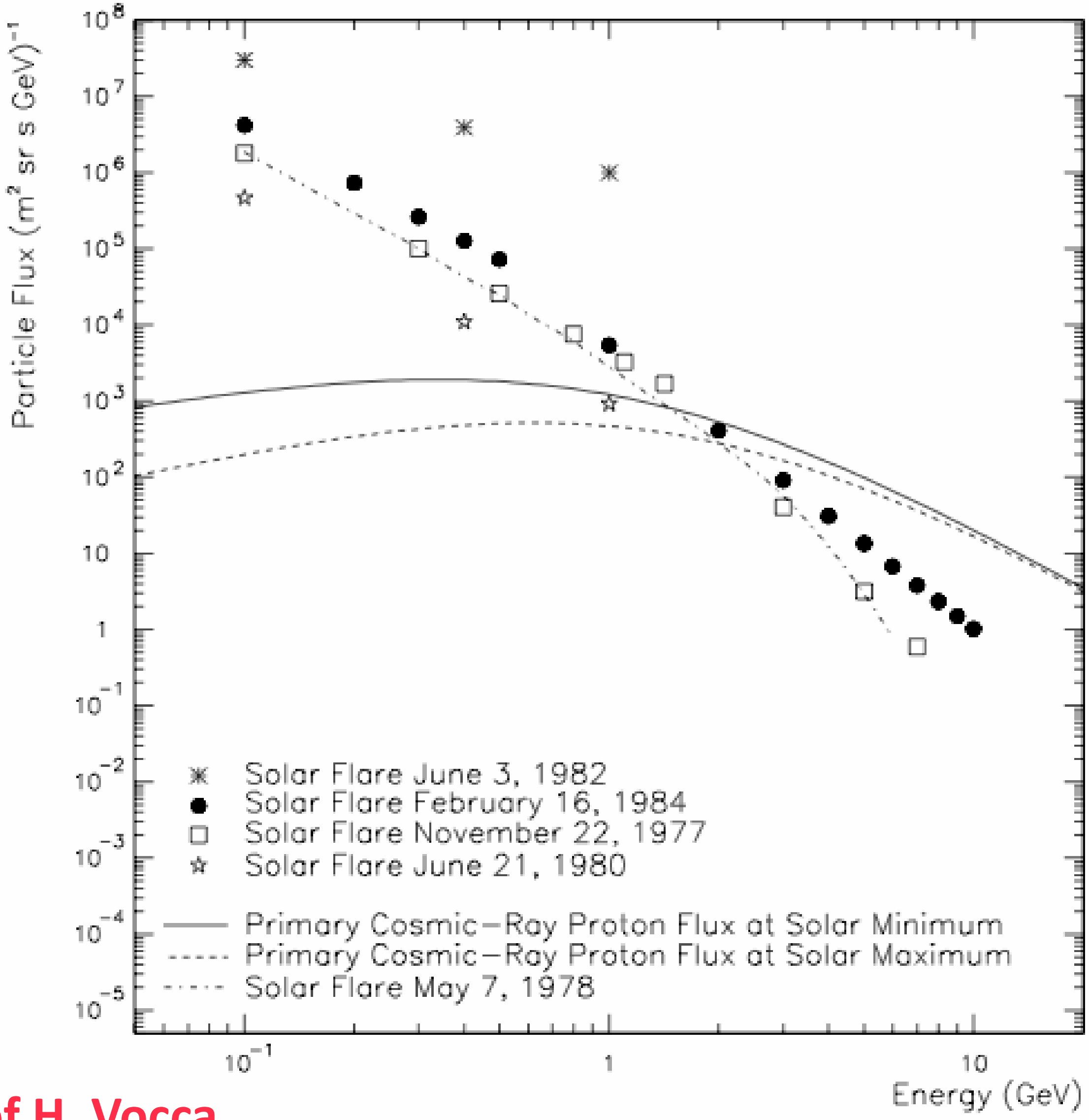
Solar particle events
13 Dicembre 2006 e
14 Dicembre 2006



Adriani et al., 2011

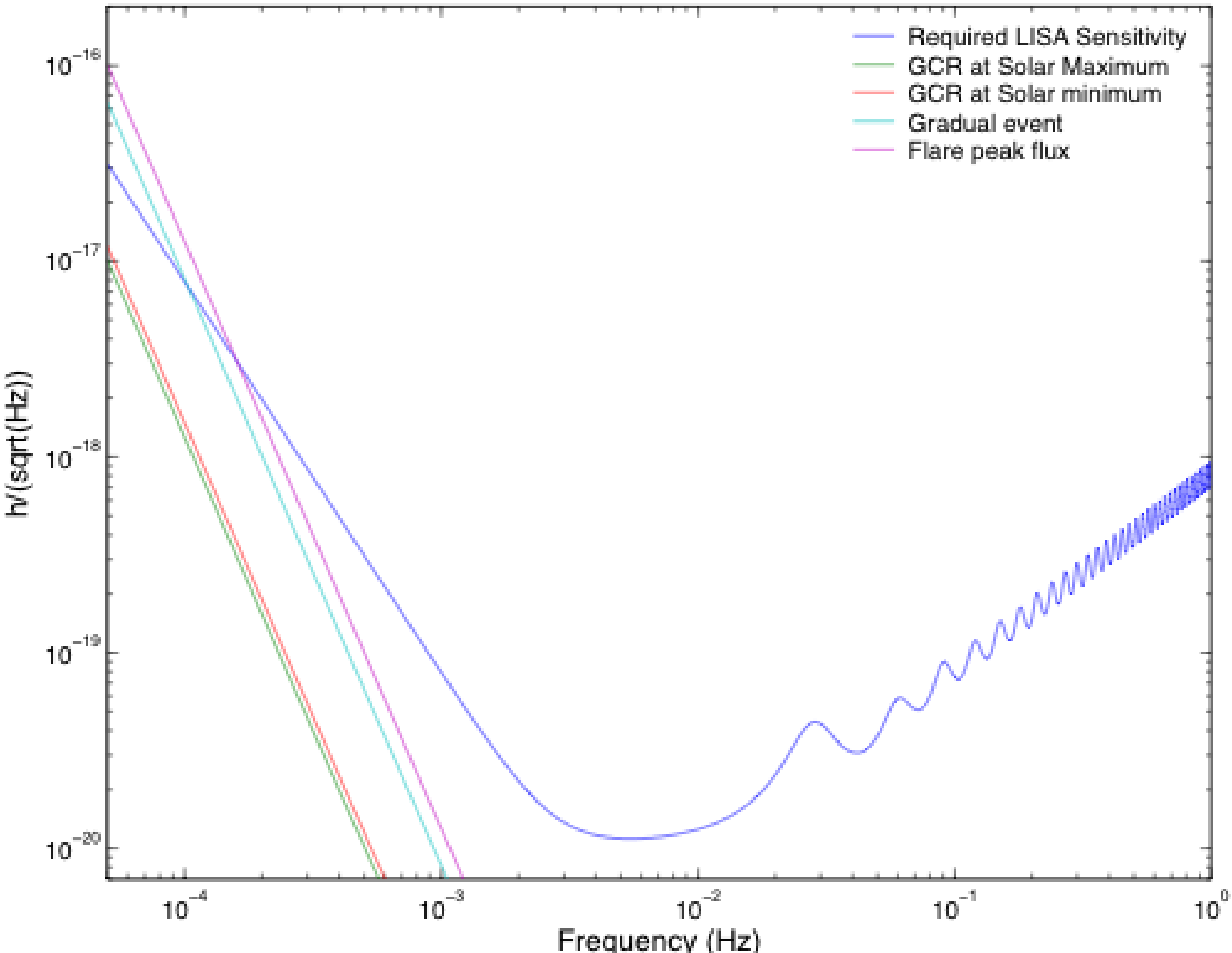


Galactic and solar particle fluxes



Courtesy of H. Vocca

LISA sensitivity curve



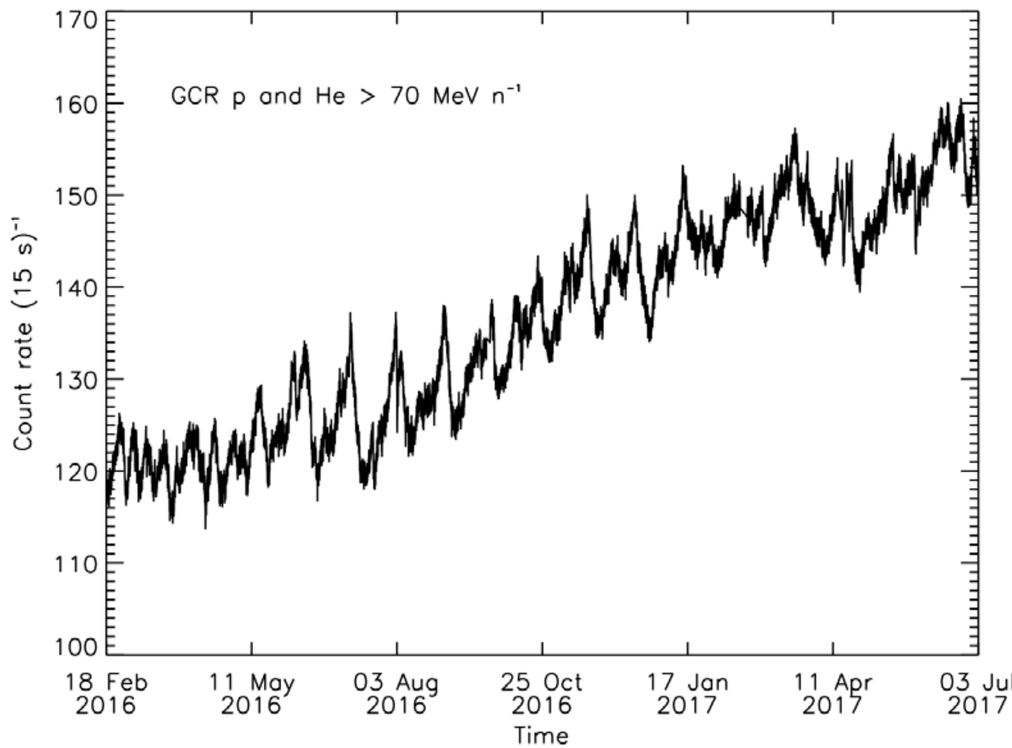
Courtesy of H. Vocca

LISA Pathfinder GCR count rate

* Increasing trend

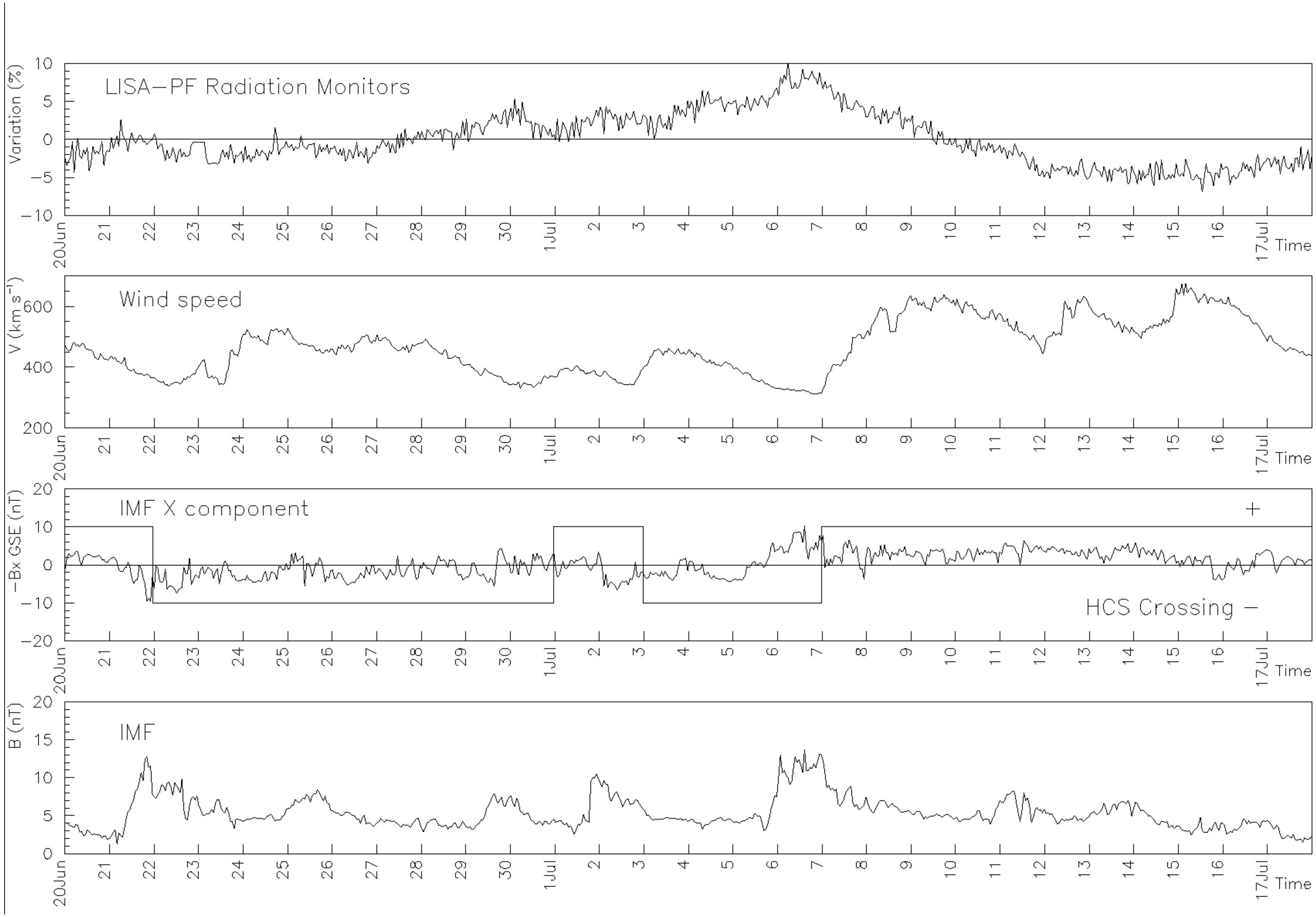
* 45 GCR short-term depressions

* 3 Forbush decreases



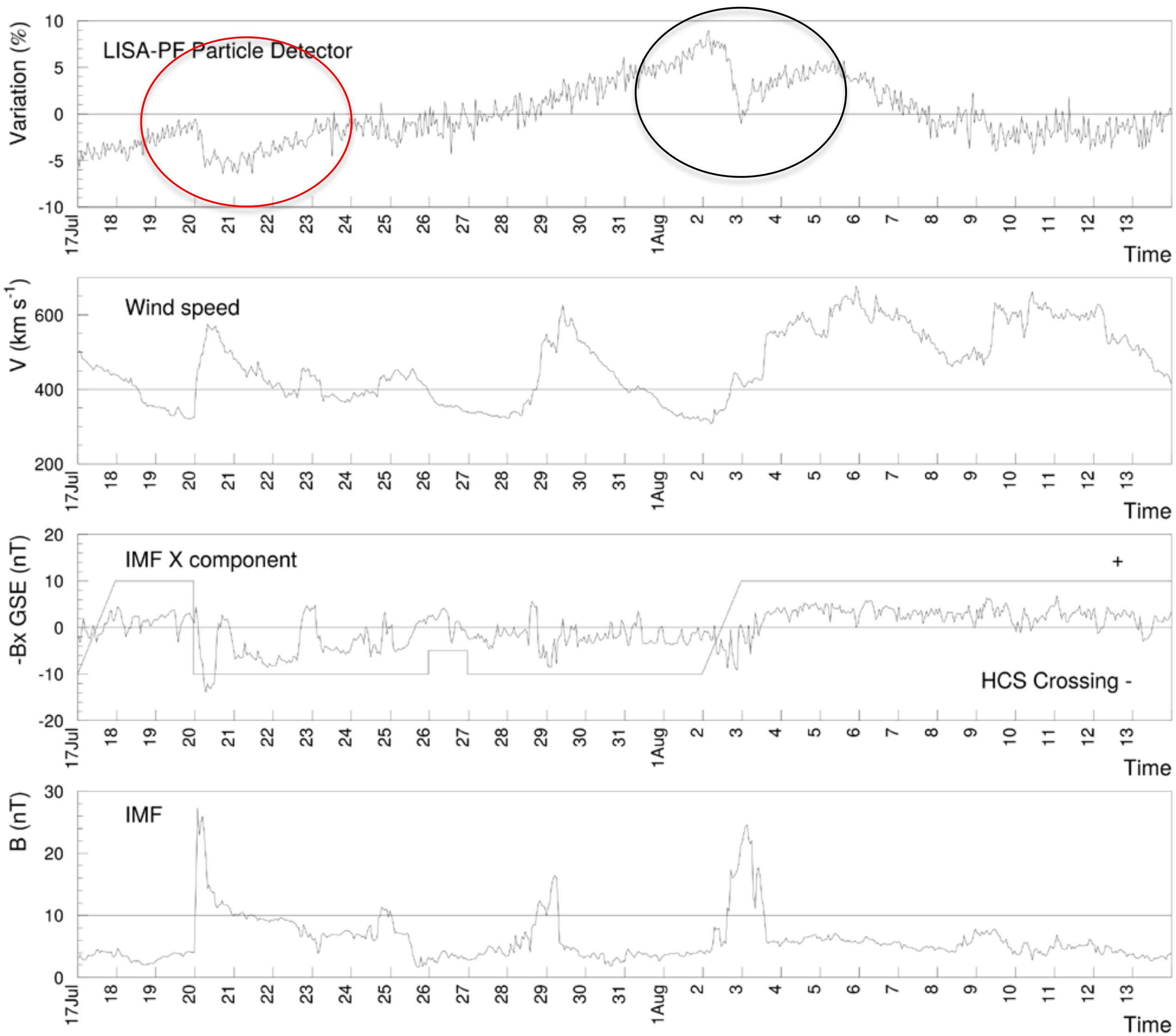
Armano et al.; ApJ, 854, 113, 2018

BR 2495

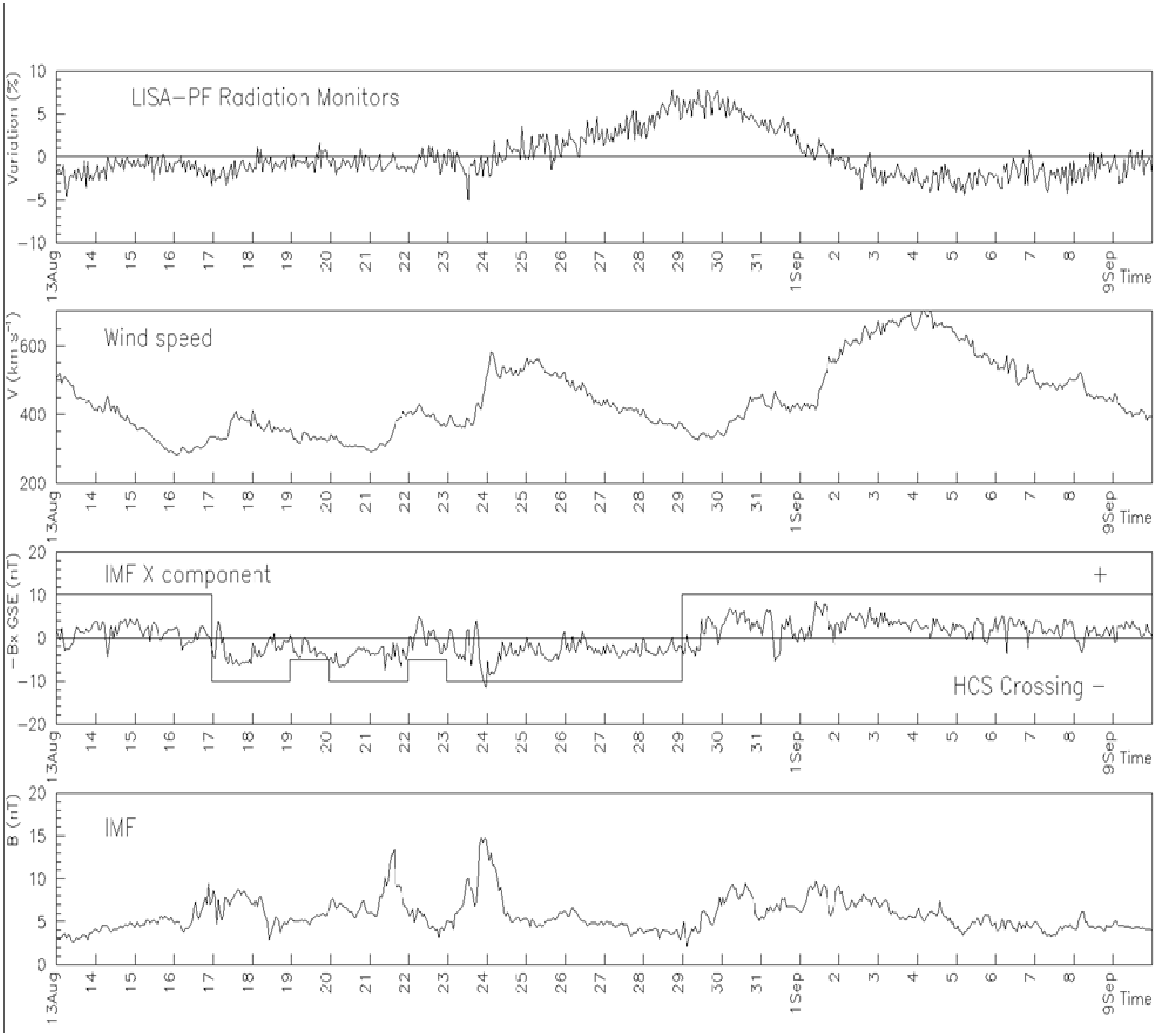


LISA–PF Radiation Monitors
Variation (%)
Wind speed
V (km s⁻¹)
IMF X component
–Bx GSE (nT)
HCS Crossing –
+
IMF
B (nT)
Time
20Jun
1Jul
17Jul

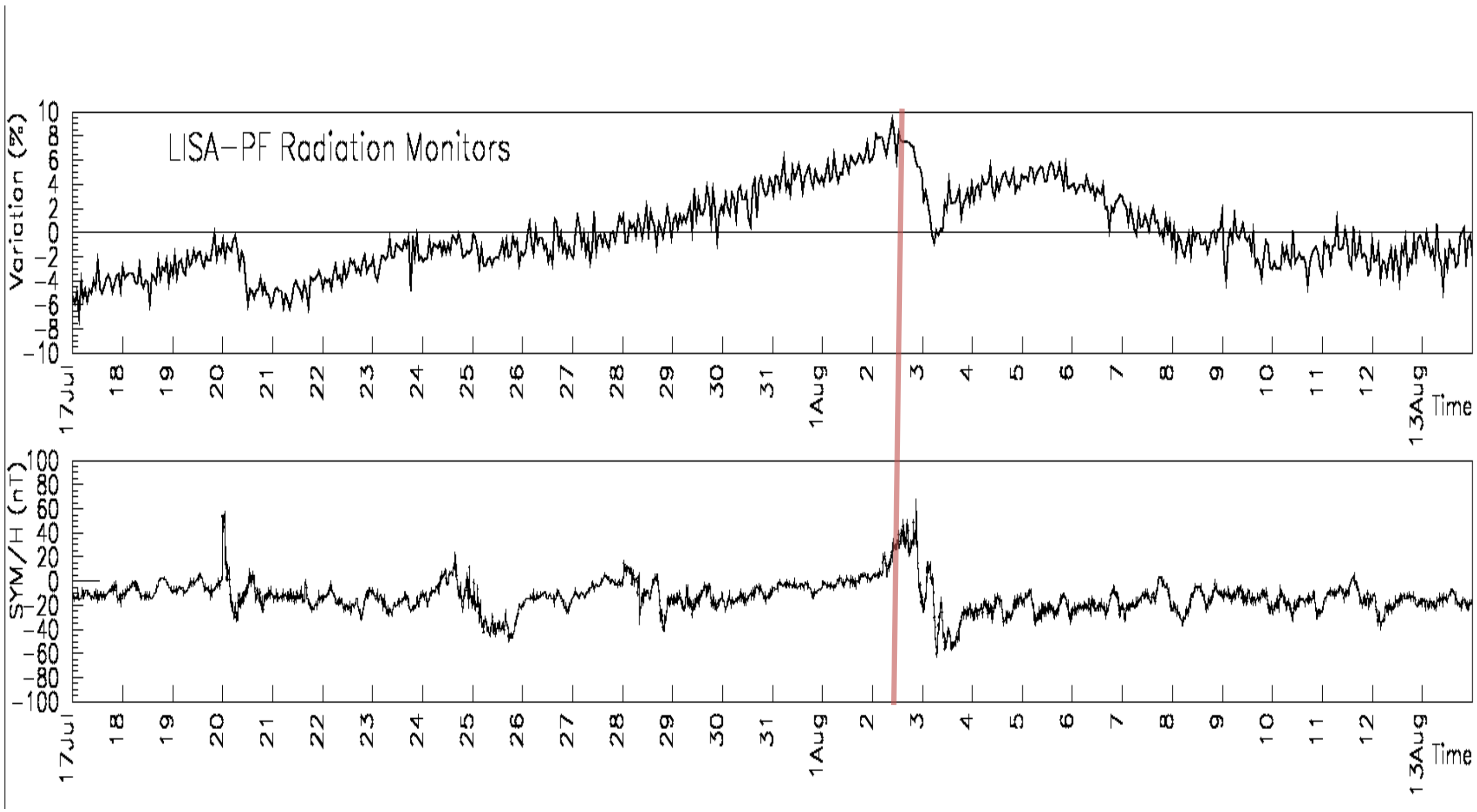
2 Forbush decreases – BR 2496



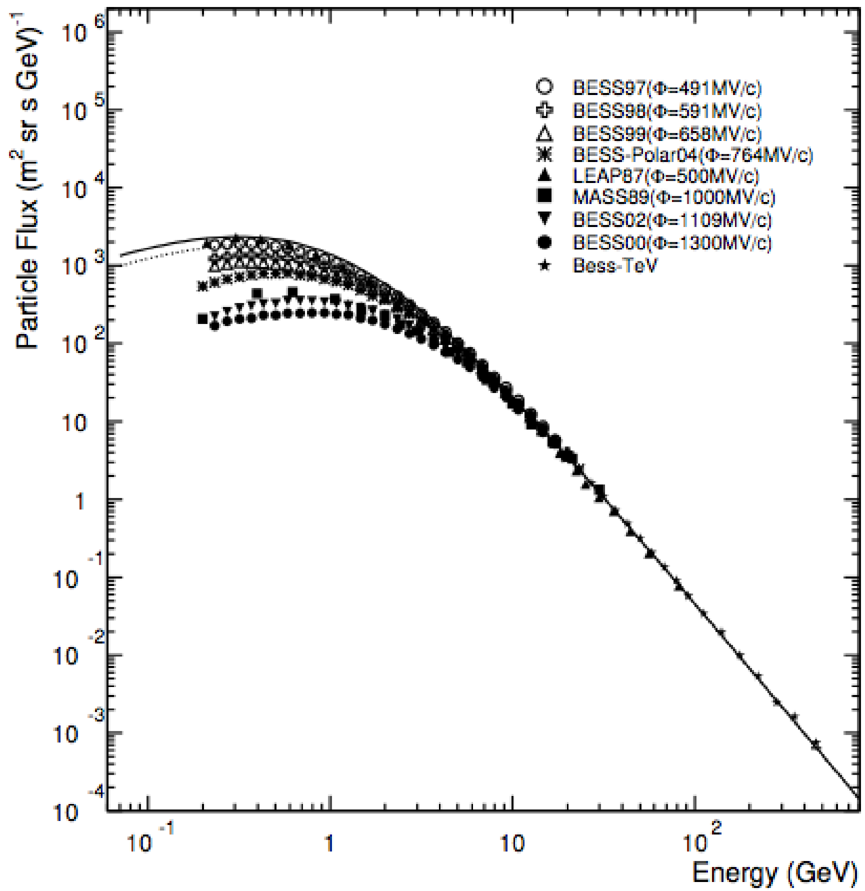
BR 2497


LISA–PF Radiation Monitors
Variation (%)
Wind speed
V (km s⁻¹)
IMF X component
−Bx GSE (nT)
HCS Crossing −
+
IMF
B (nT)
Time

LISA-PF: A SENTINEL FOR GEOMAGNETIC ACTIVITY?

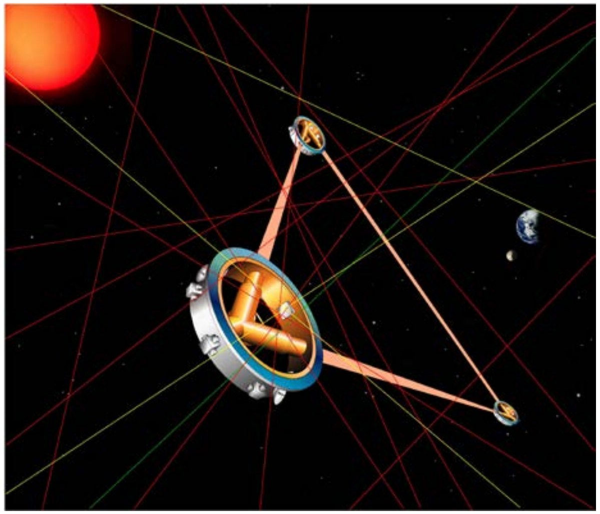


Energy-dependence of the August 2, 2016 Forbush decrease

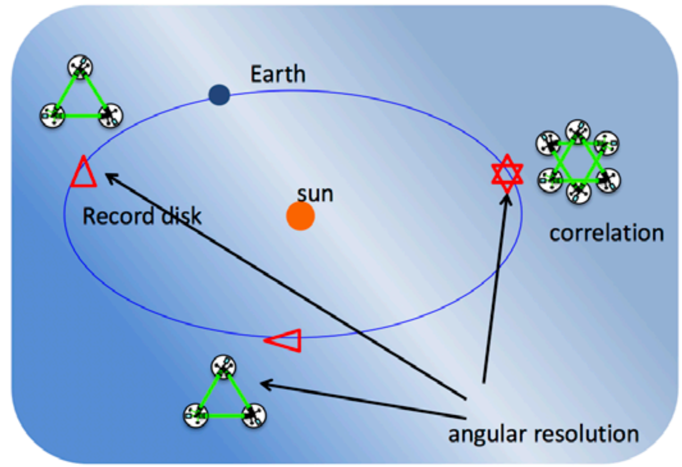


Gravitational wave detectors in space

LISA



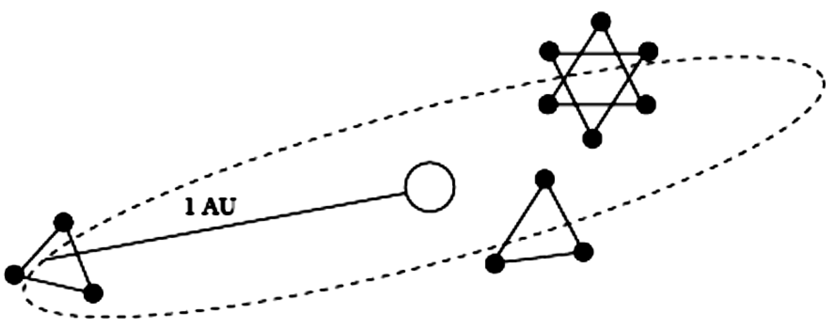
DECIGO : pre-conceptual design



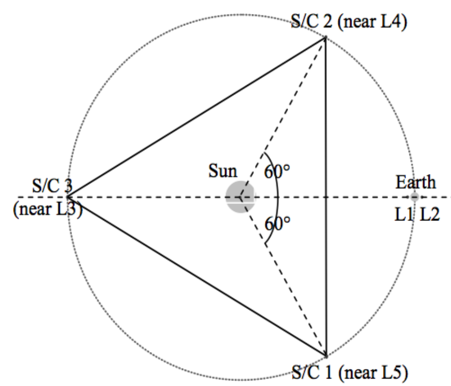
Orbit : record disk around the sun
Constellation :
4 interferometer units
2 overlap units : cross correlation for stochastic background
2 separated units : increase angular resolution

ICSO2014 (Oct,8,2014@Tenerife, Spain)

Mitsuru Musha, DECIGO Collaborations



BBO Cutler and Harms, 2006

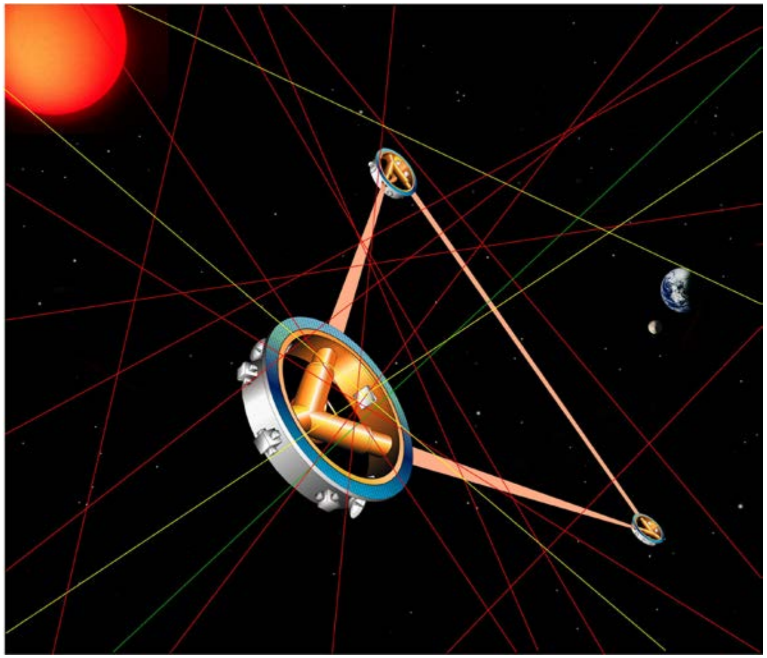


ASTROD-GW

Wei-Tou Ni, 2012

What’s missing for LISA-like interferometers?

- It will NOT possible to start th etest mass charging investigations before next solar cycle will begin
- Short-term variations of GCR energy spectra were measured aboard LPF
- Solar particle flux investigations over the three S/C of LISA will be carried our over 2 degrees in longitude between S/C and 20 degrees in longitude with respect to Earth
- This will provide clues precious for space weather investigations and applications



- Cosmic-ray flux radial dependence: 3%/AU
- Cosmic-ray flux latitude dependence: 0.33%/deg

We are proposing to improve

It may be useful to place at least one magnetometers outside the spacecraft

CONCLUSIONS

- After 100 years from the publication of the General Relativity, gravitational waves were detected by Earth interferometers
- The technology for gravitational wave detection in space is ready
- The ESA first space interferometer, for low frequency gravitational wave detection, LISA may be sent to orbit by 2030
- Inteplanetary physics investigations and space weather alerts could be allowed by future space interferometers